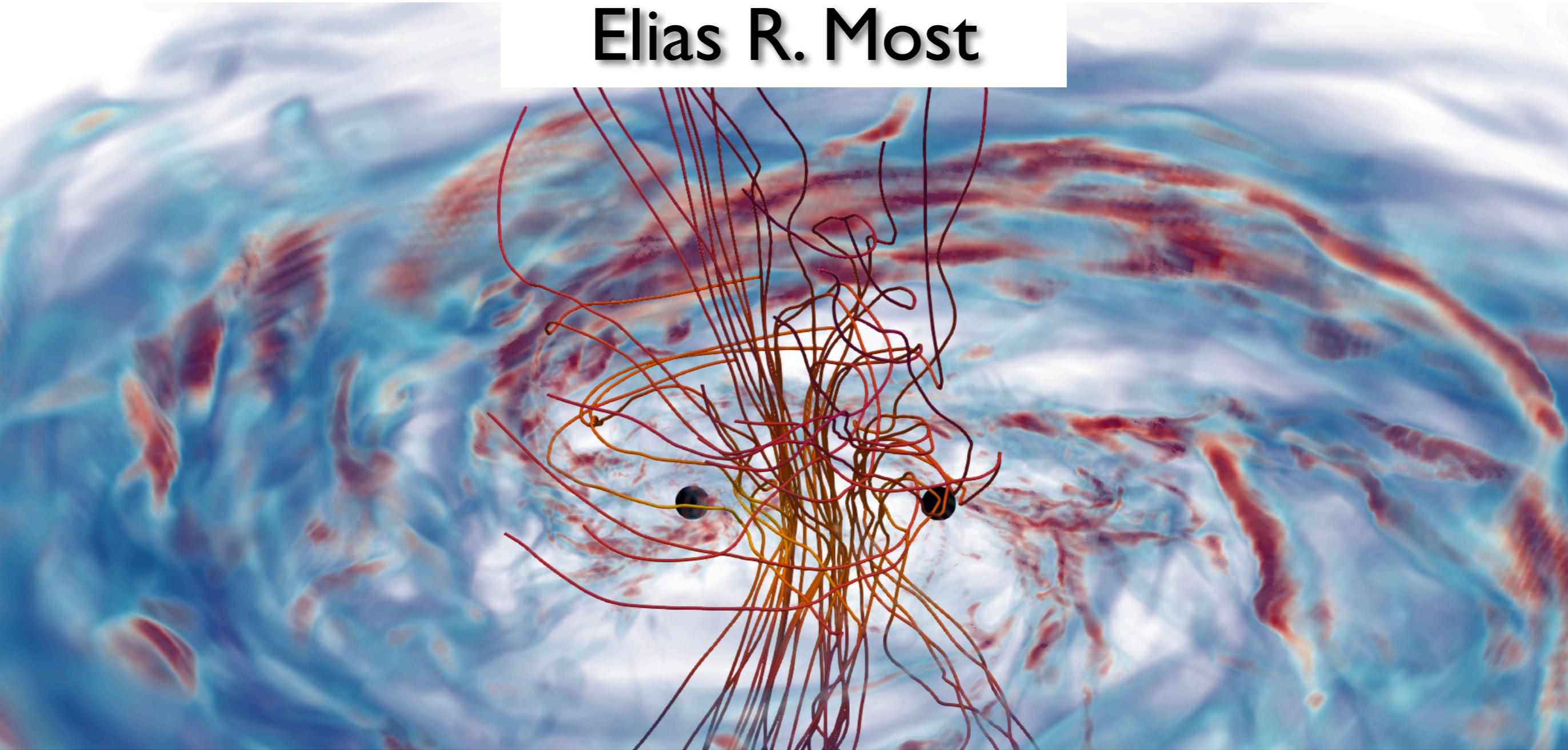


# New Frontiers of Extreme Plasma Physics Modeling in Relativistic Astrophysics

Elias R. Most

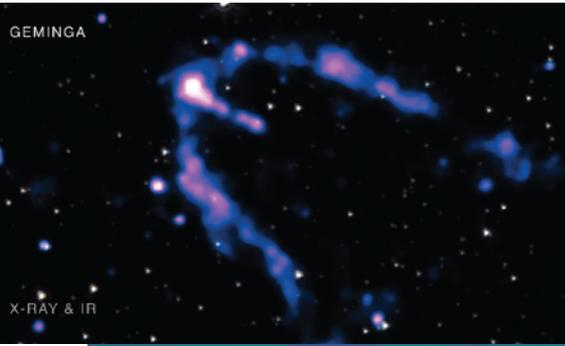


**Caltech**

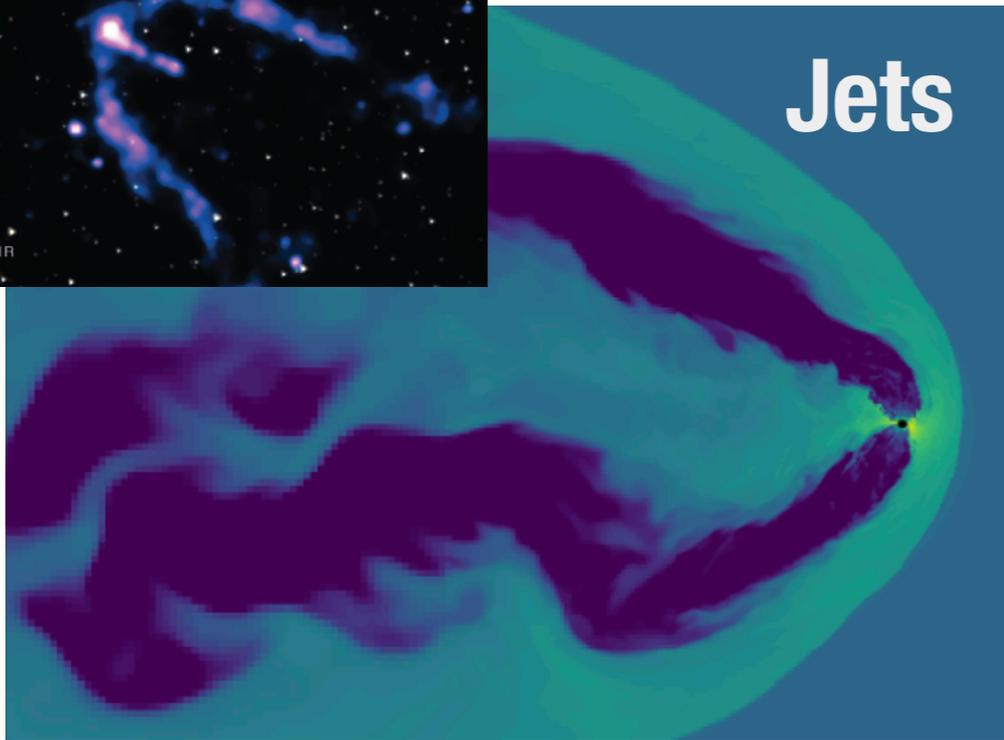
Computational Relativistic Astrophysics  
[comp-relastro.caltech.edu](http://comp-relastro.caltech.edu)



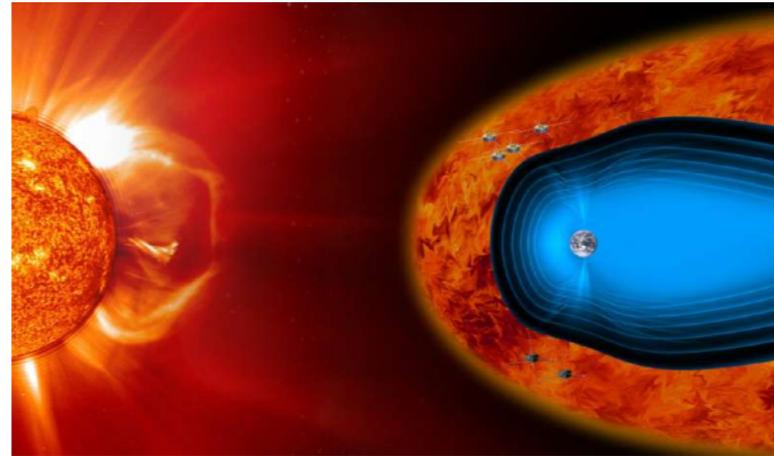
# Plasmas in the universe



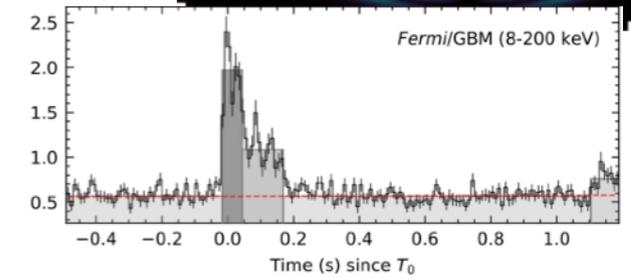
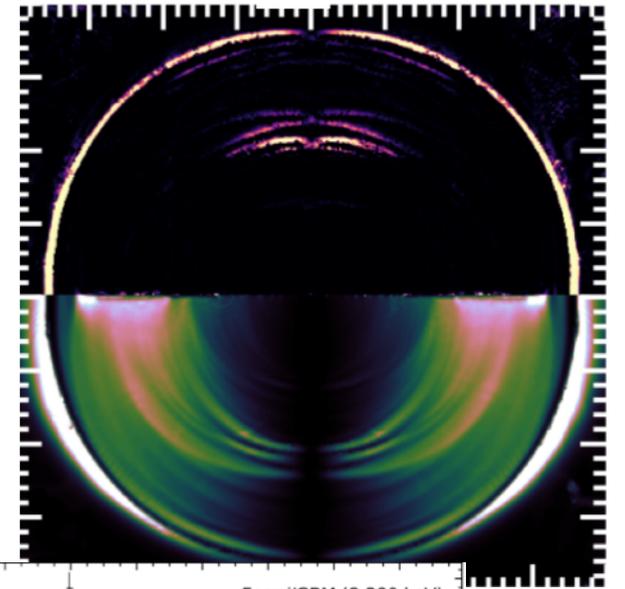
## Jets



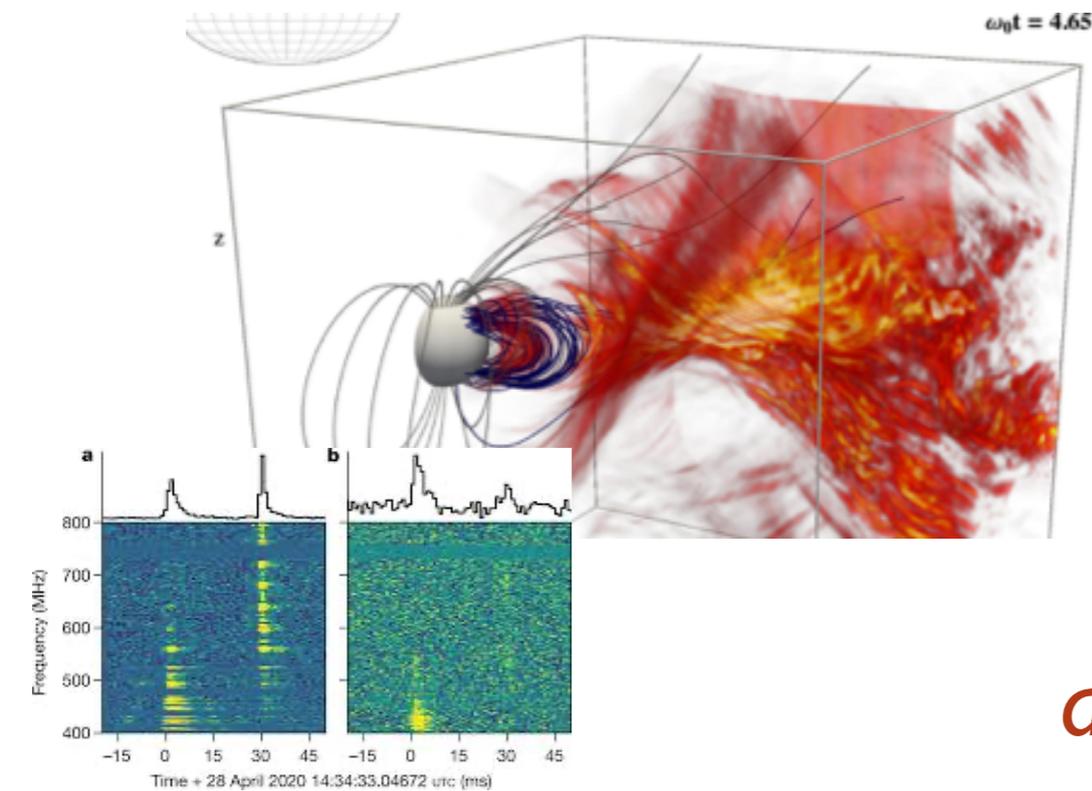
## Winds



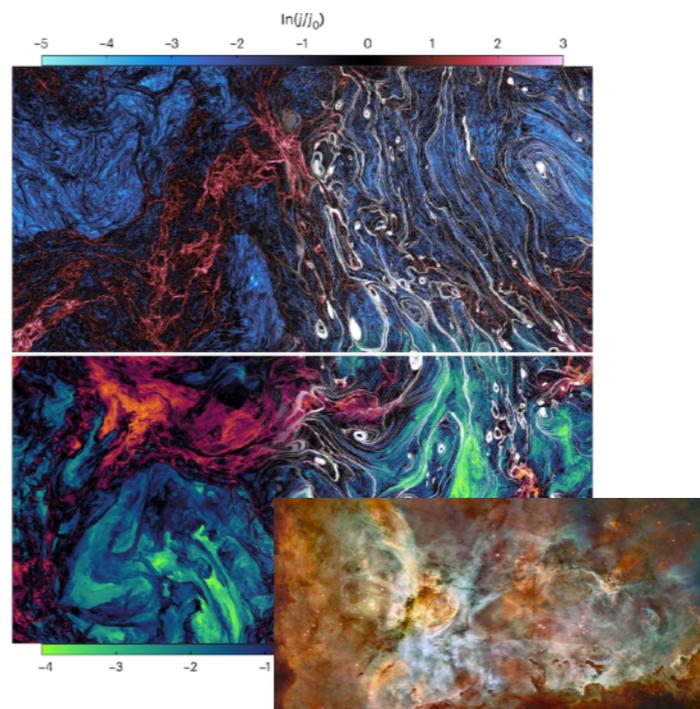
## Shocks



## High-energy transients

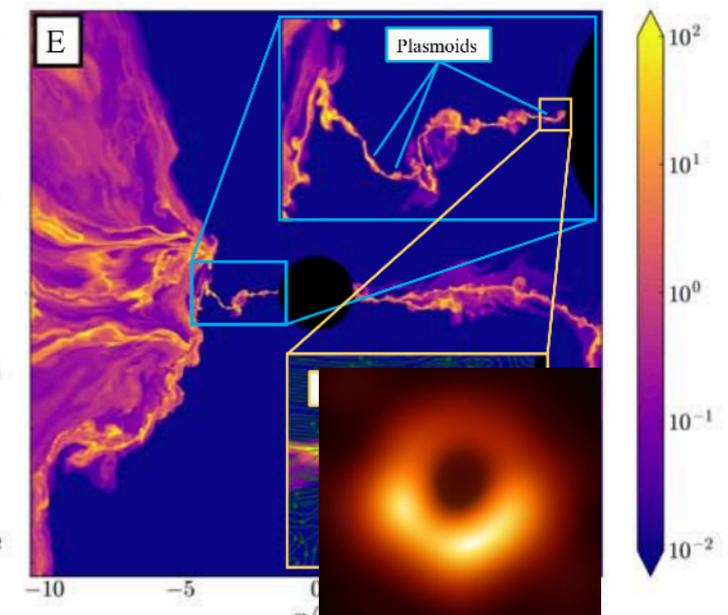


## Turbulence

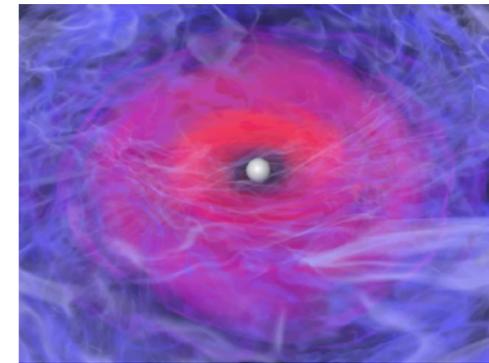
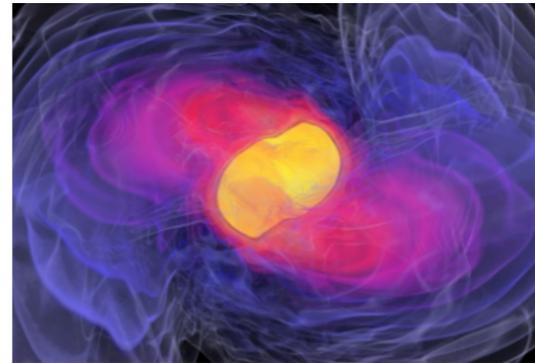
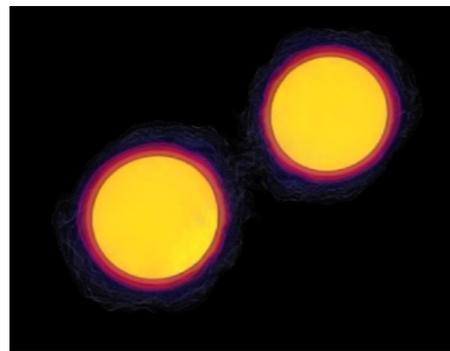


*an incomplete list...*

## Accretion

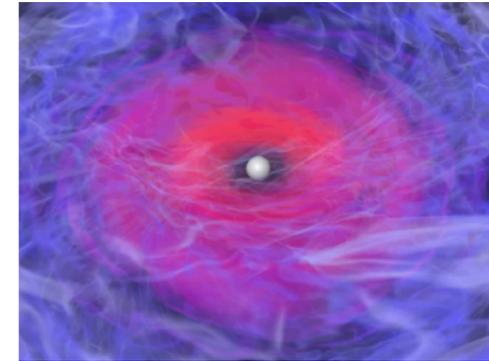
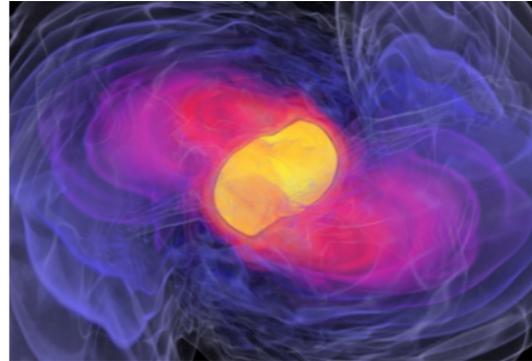
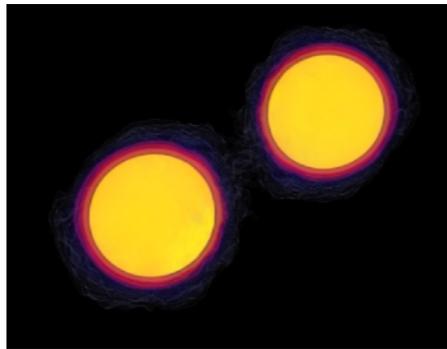
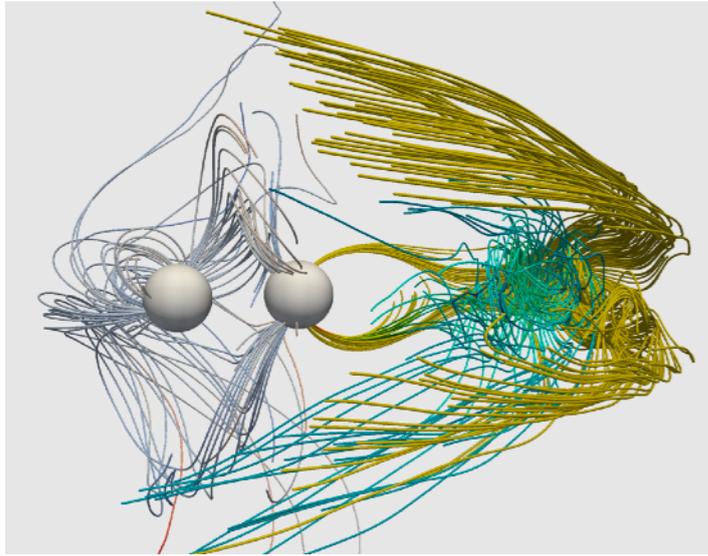


# Neutron star Coalescence



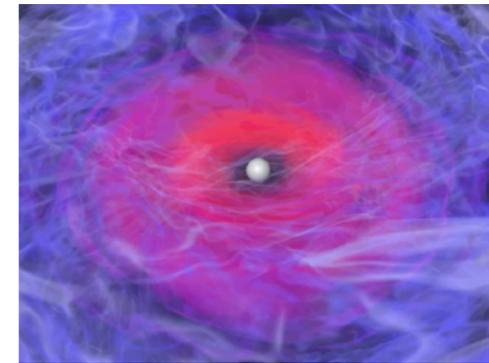
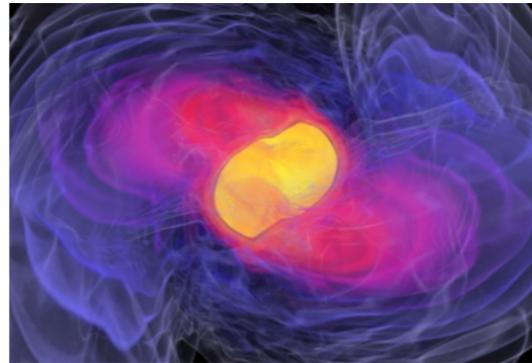
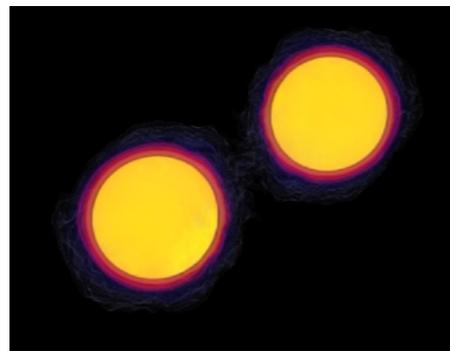
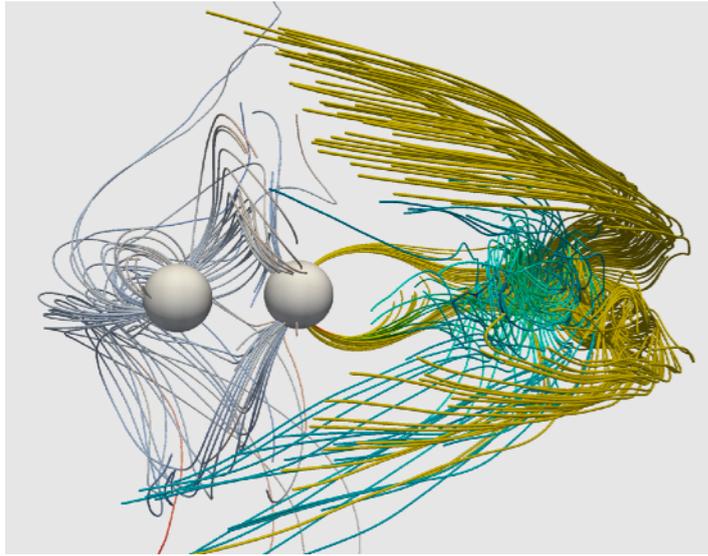
# Neutron star Coalescence

## Magnetospheric interactions

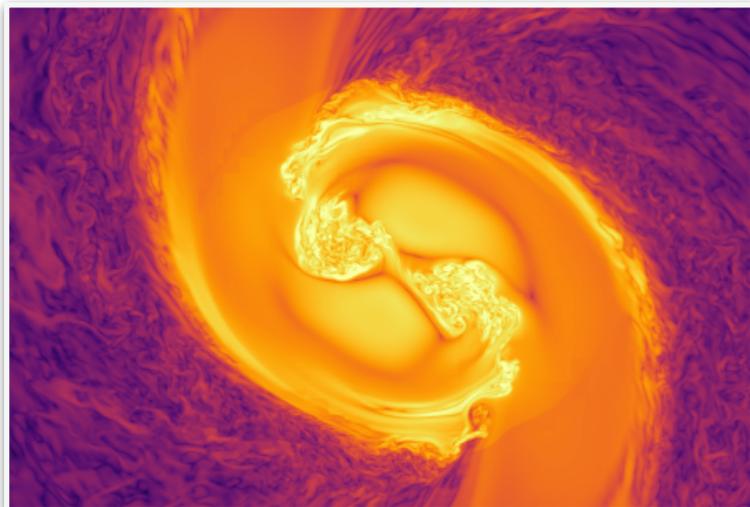


# Neutron star Coalescence

## Magnetospheric interactions

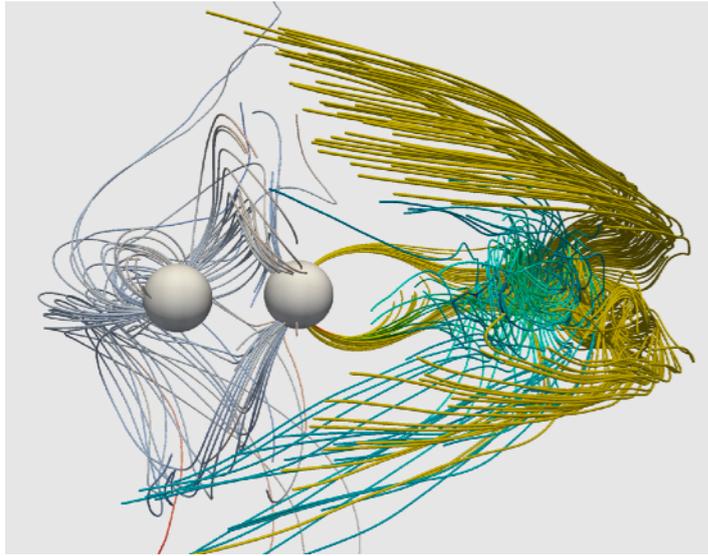


## Magnetoturbulence and Dynamos

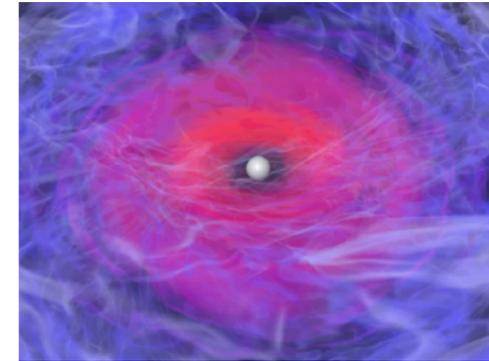
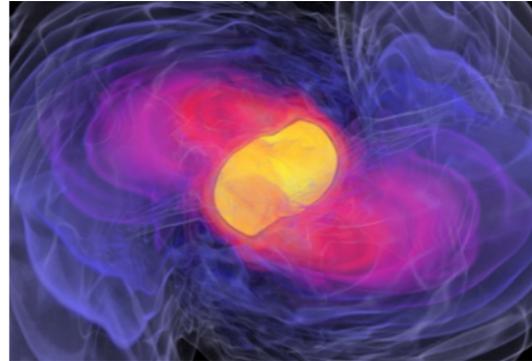
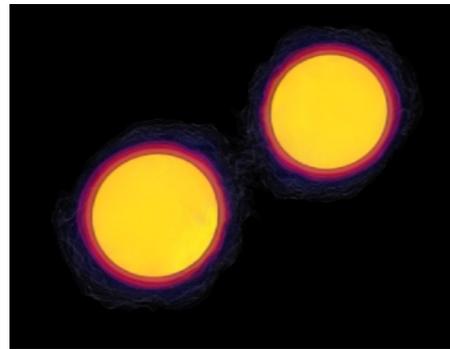
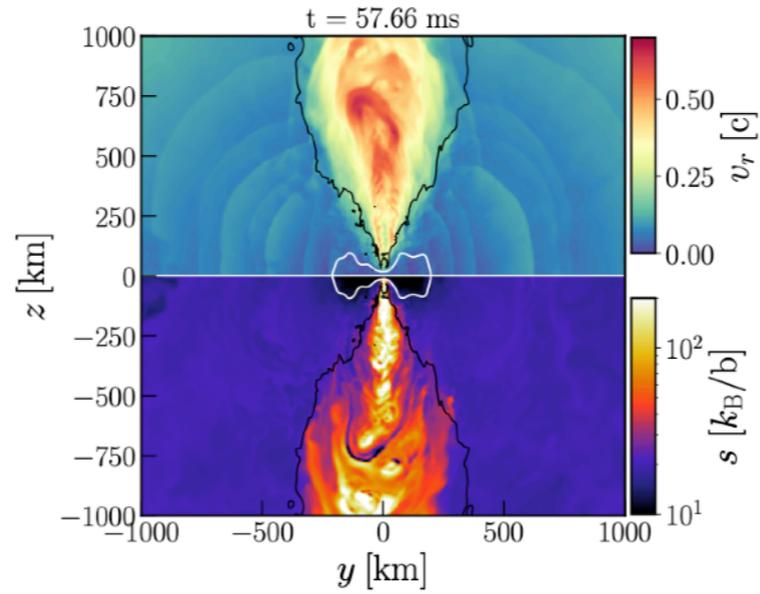


# Neutron star Coalescence

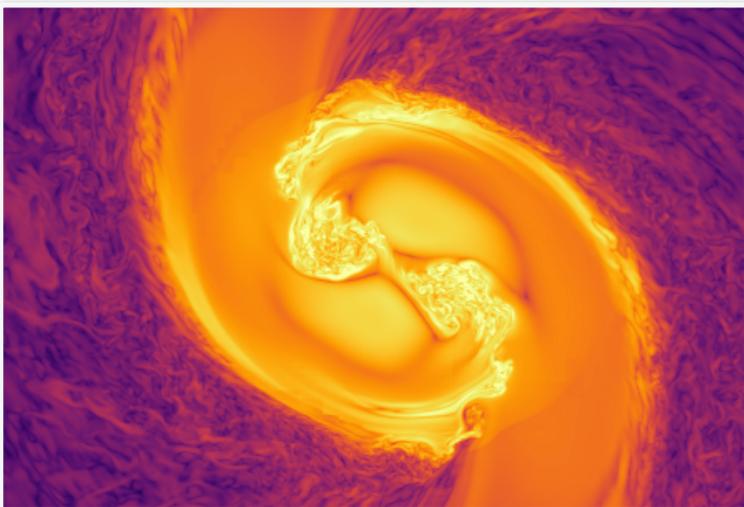
## Magnetospheric interactions



## Neutron star jet/wind

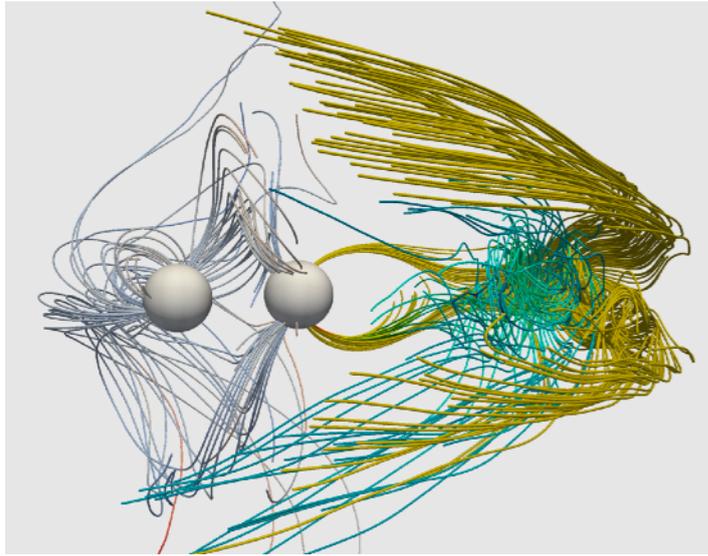


## Magnetoturbulence and Dynamos

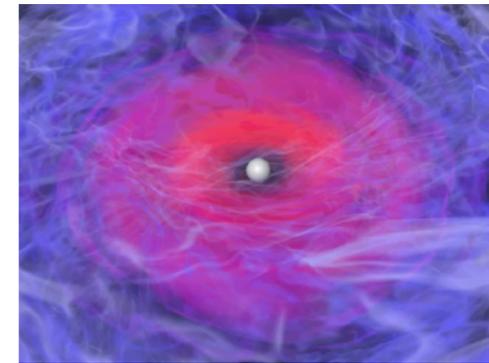
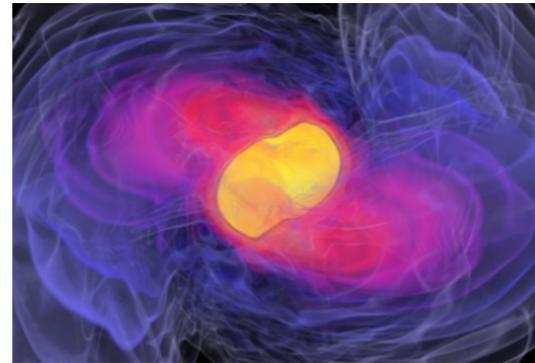
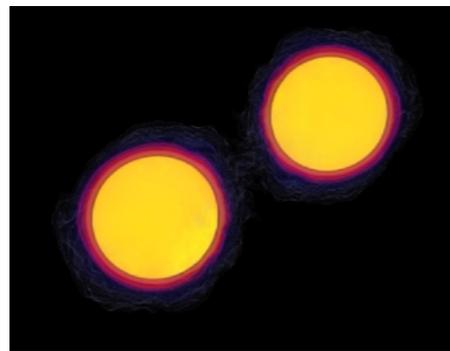
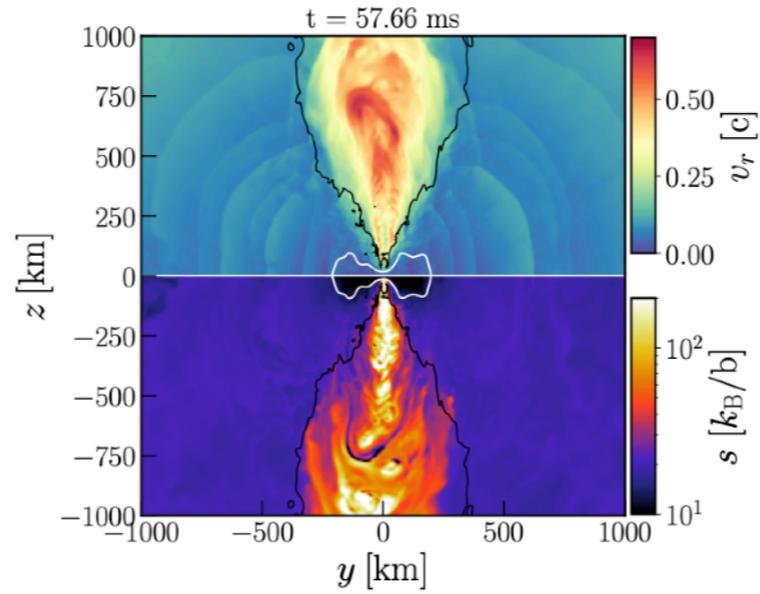


# Neutron star Coalescence

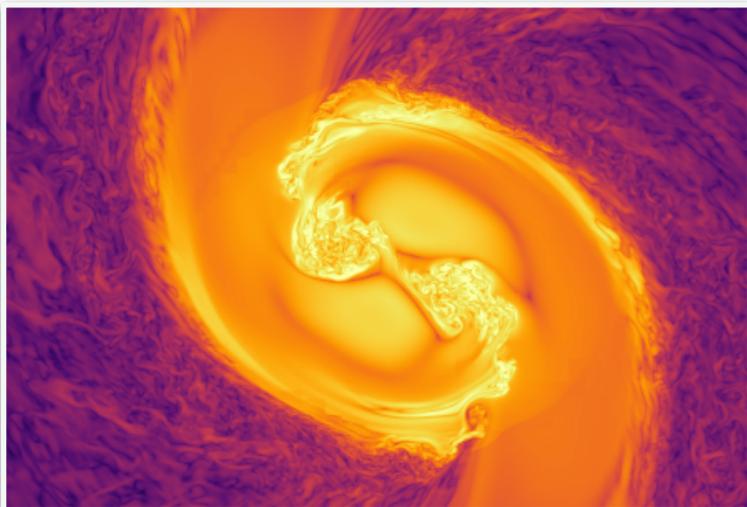
## Magnetospheric interactions



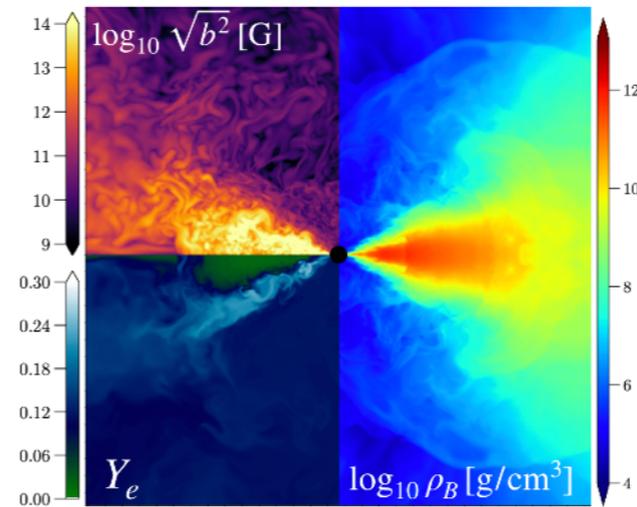
## Neutron star jet/wind



## Magnetoturbulence and Dynamos

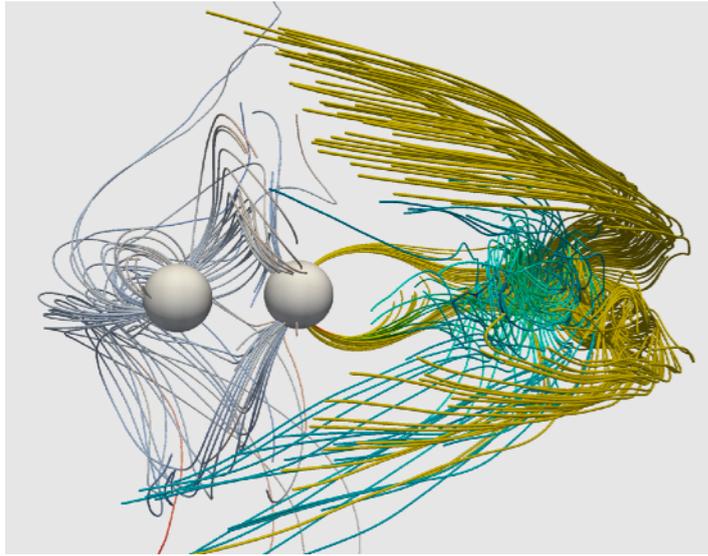


## Disk winds

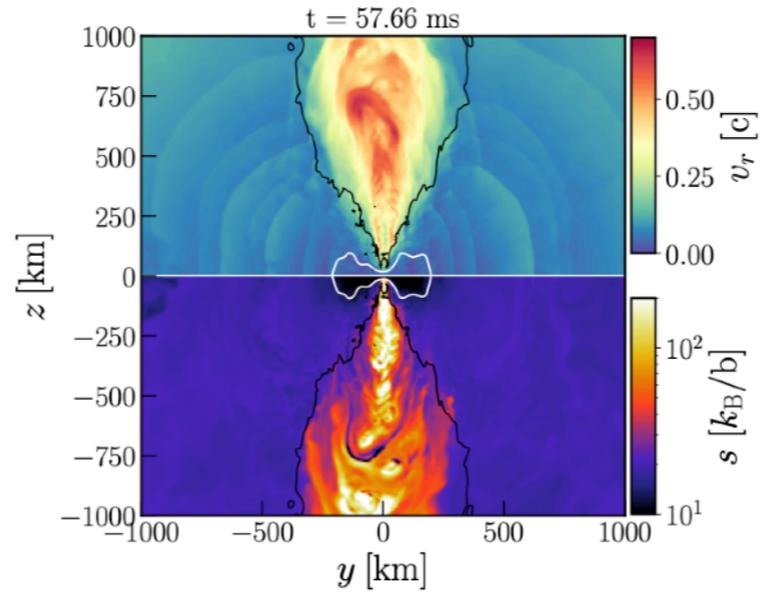


# Neutron star Coalescence

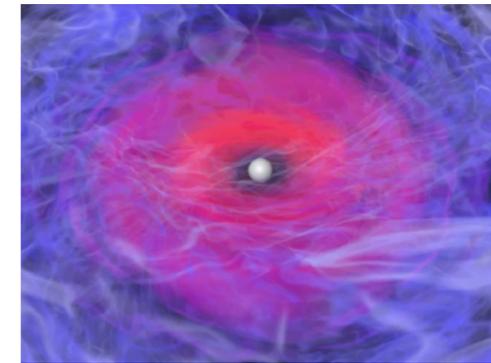
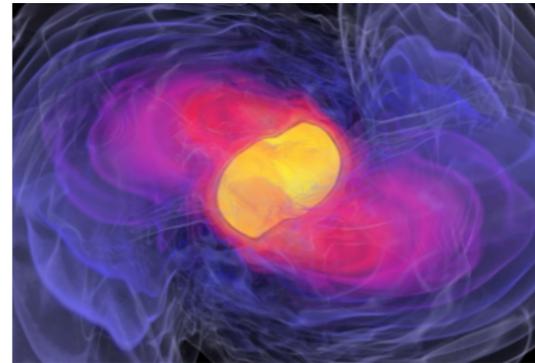
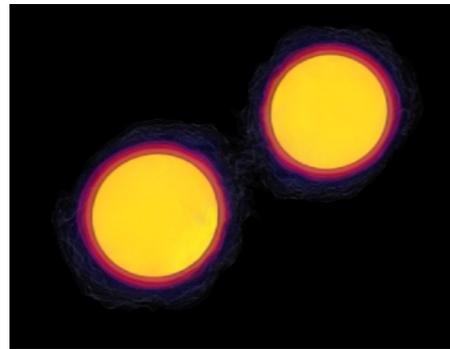
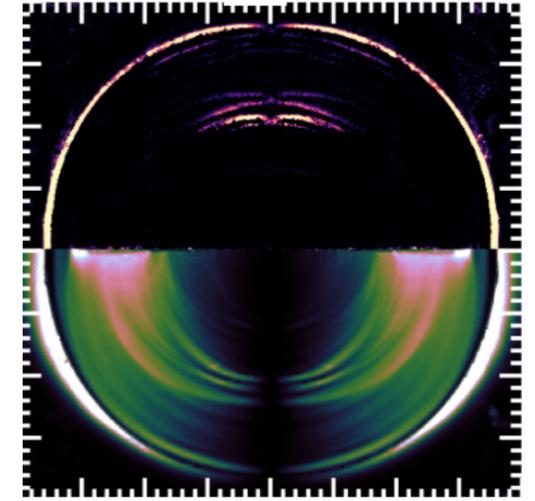
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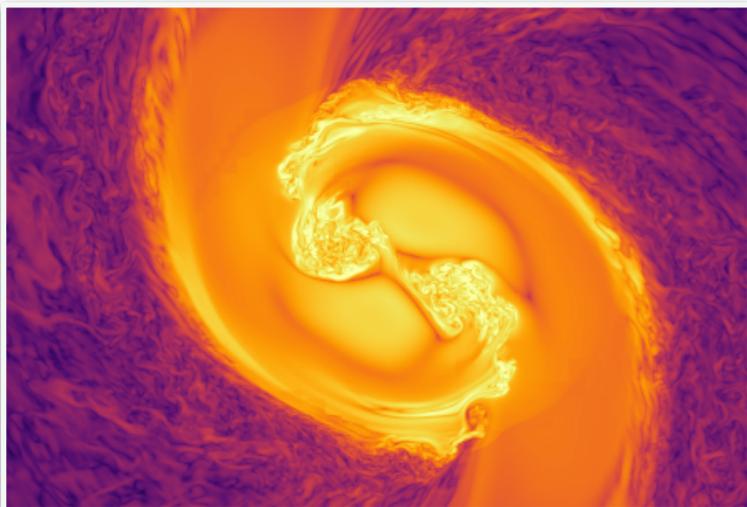
## Neutron star jet/wind



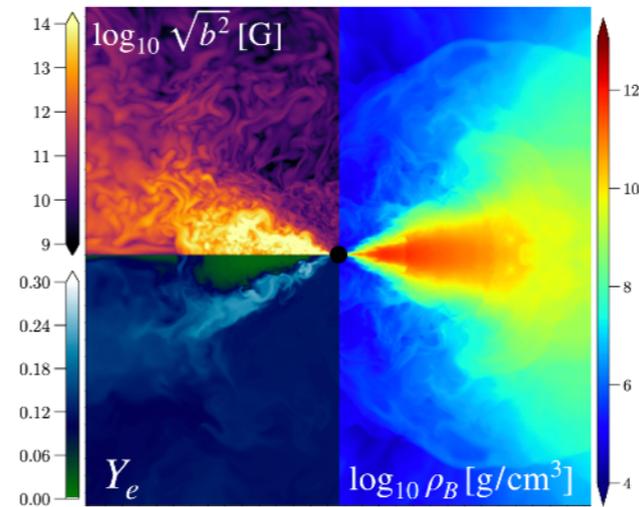
## Shocks



## Magnetoturbulence and Dynamos

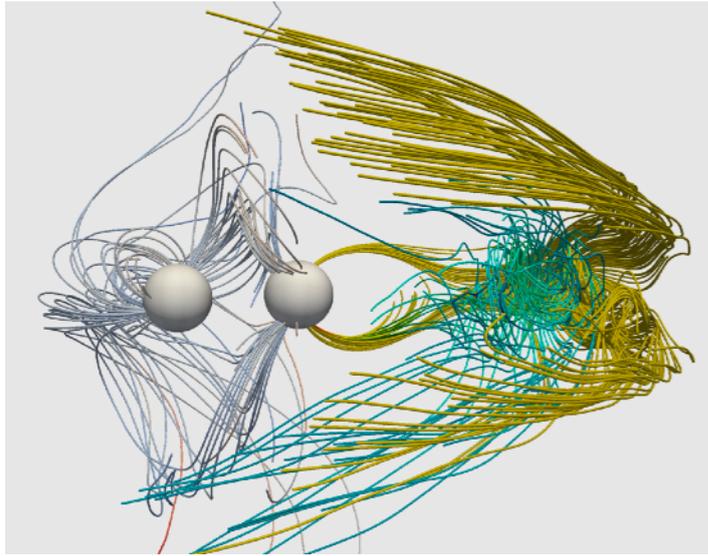


## Disk winds

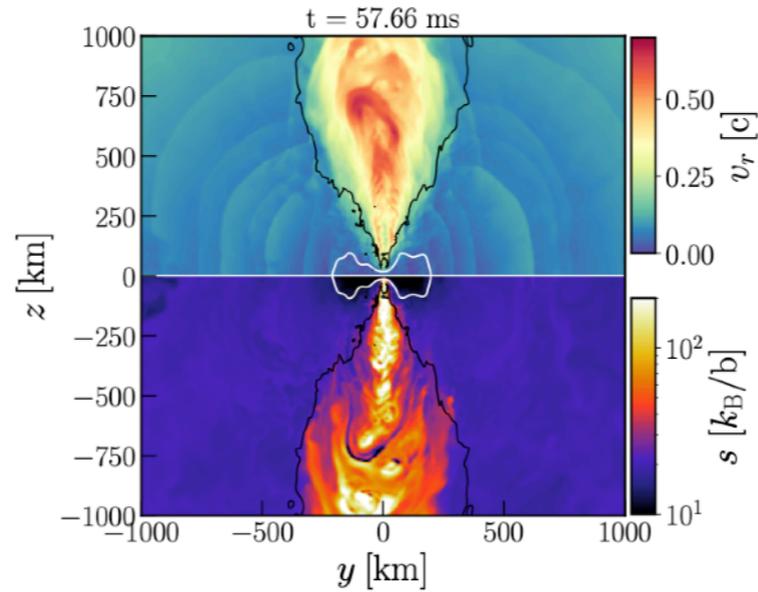


# Neutron star Coalescence

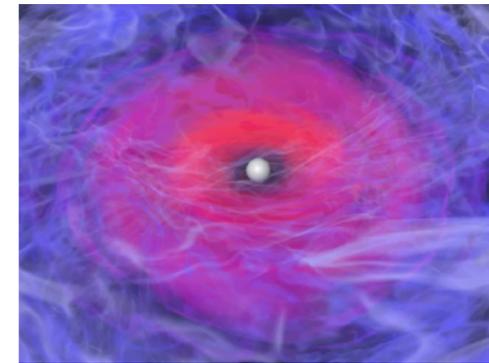
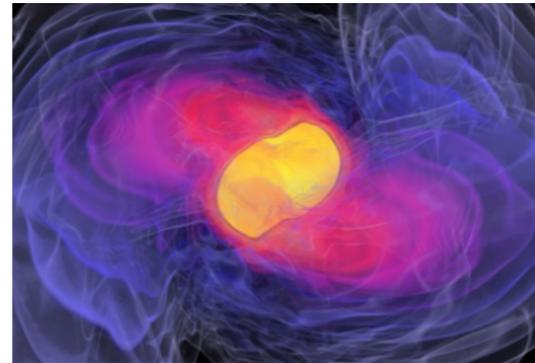
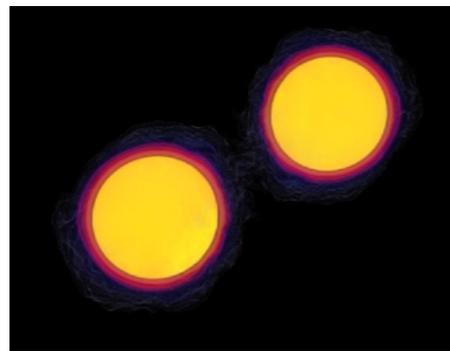
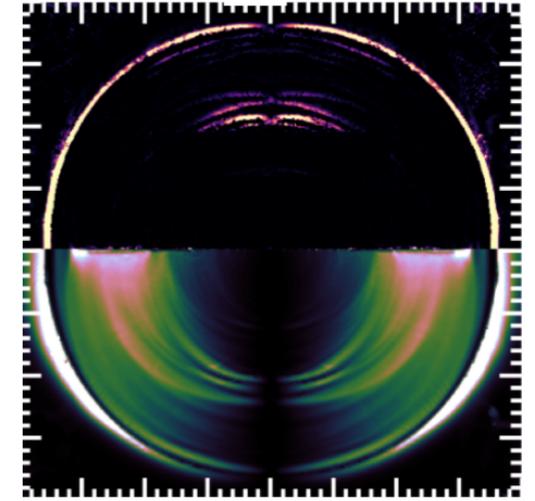
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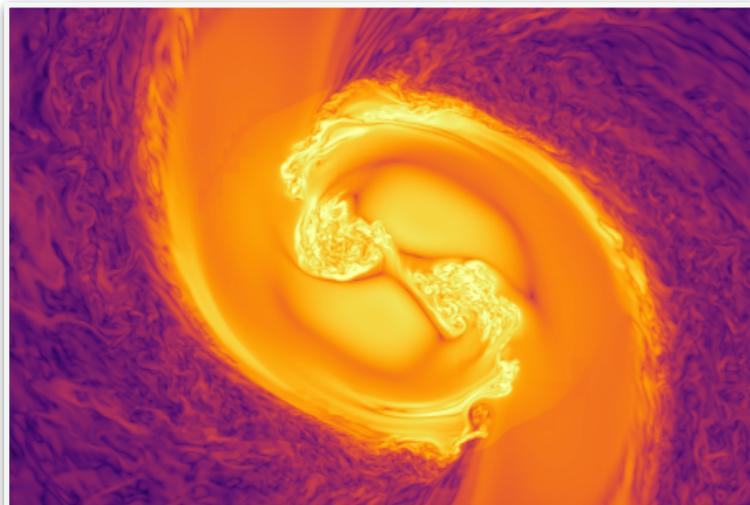
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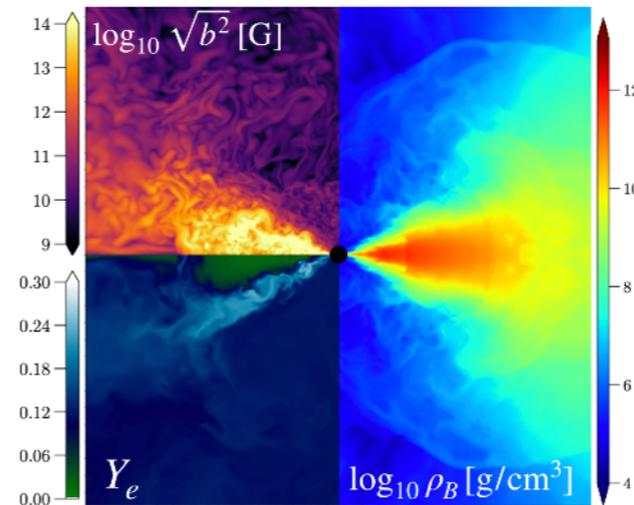
## Shocks



## Magnetoturbulence and Dynamos



## Disk winds

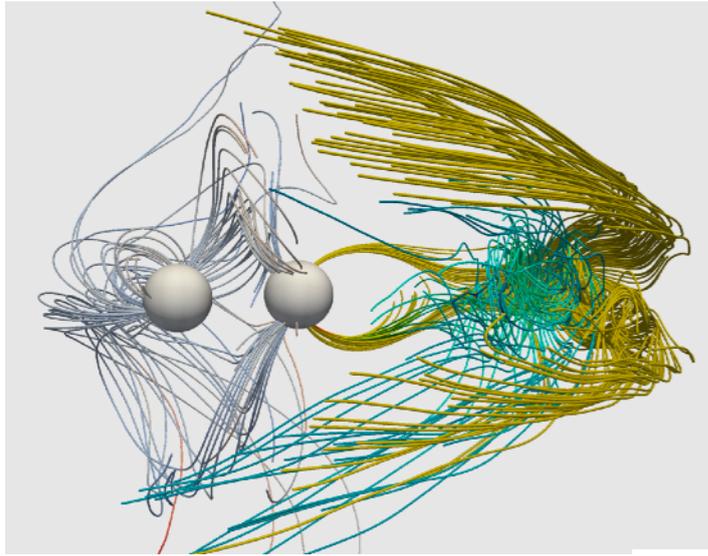


## Black hole Jet

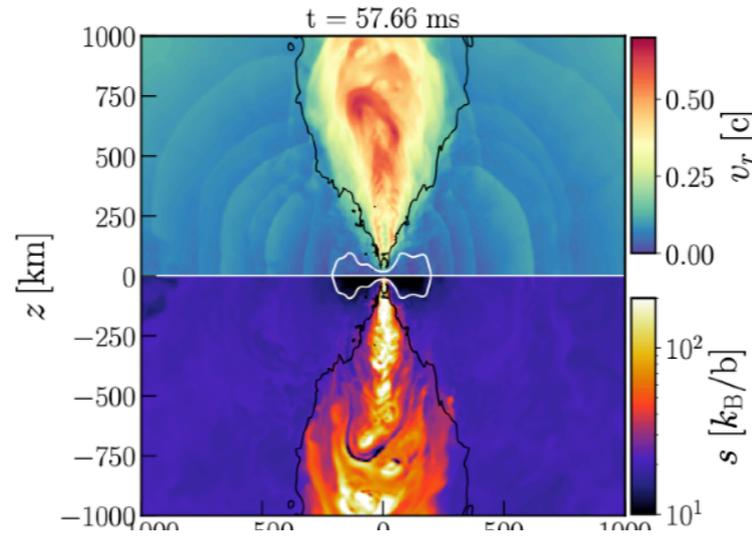


# Neutron star Coalescence

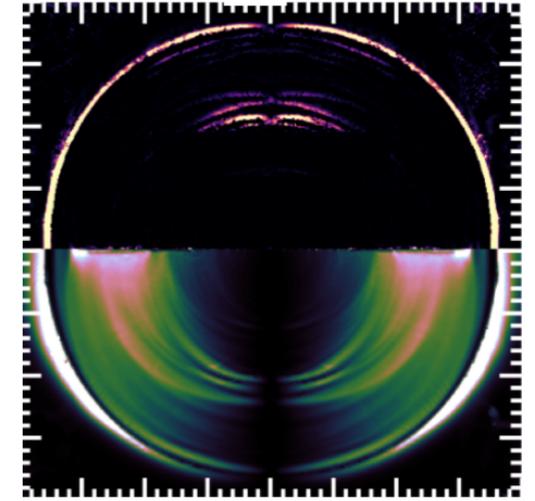
## Magnetospheric interactions



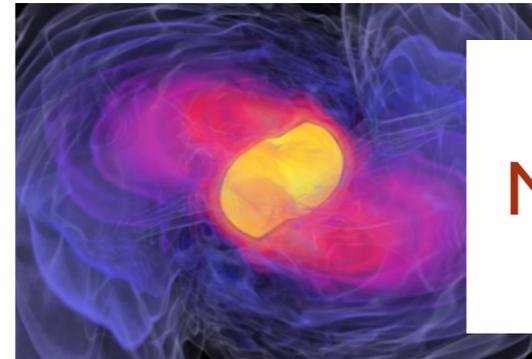
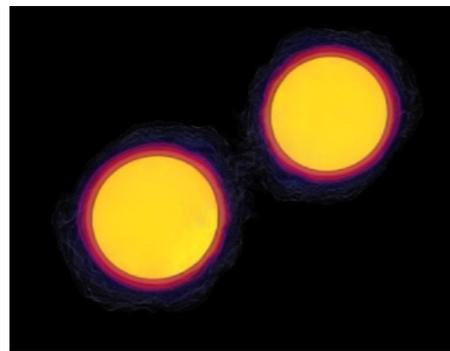
## Neutron star jet/wind



## Shocks



see talks by Desai



see talks by  
Miravet-Tenes,  
Reboul-Salze

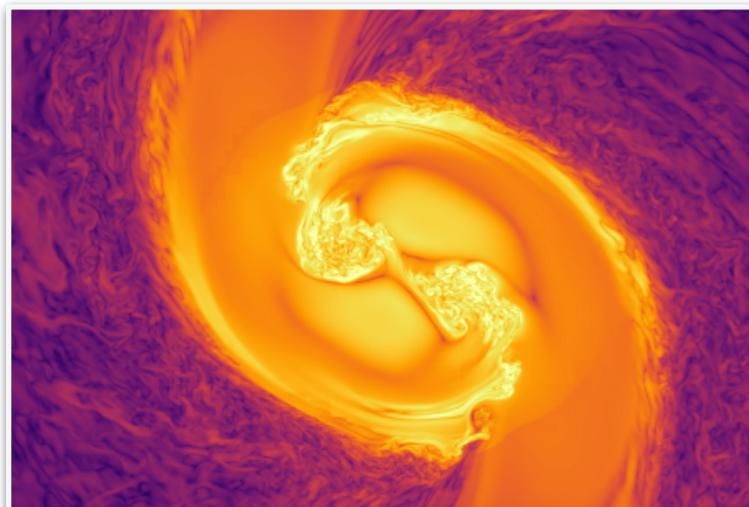


see talks  
by Hayashi,  
Janiuk

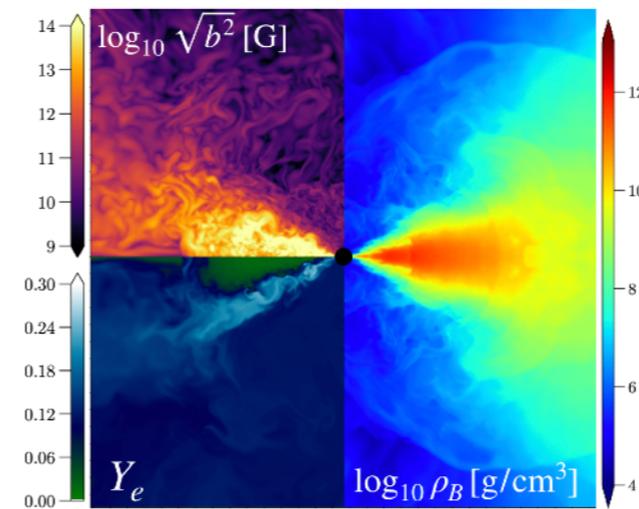
## Magnetoturbulence and Dynamos

## Disk winds

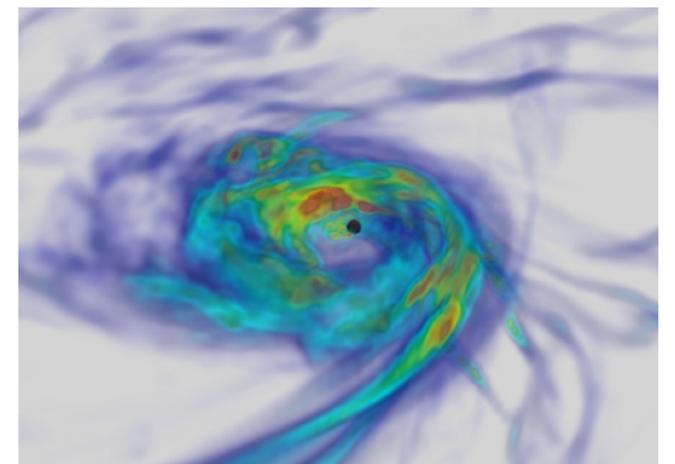
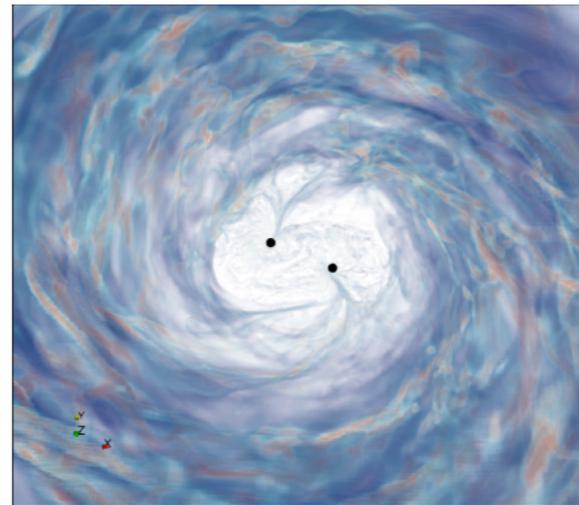
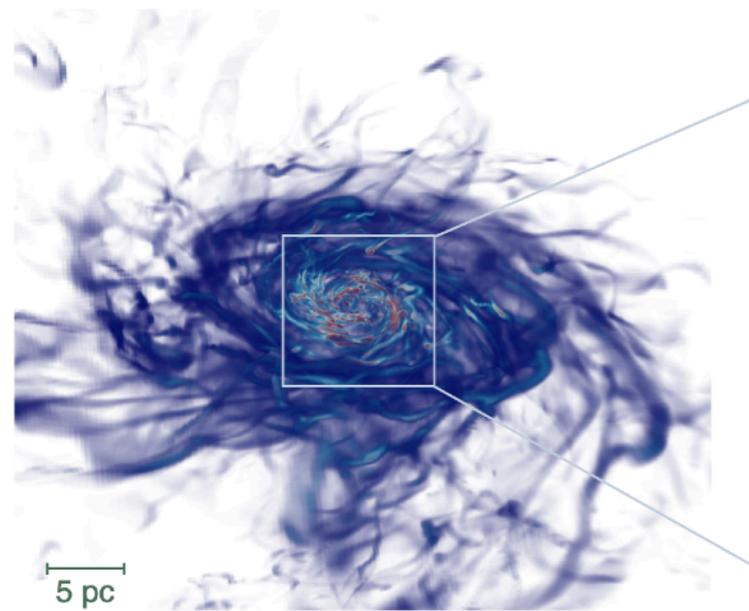
## Black hole Jet



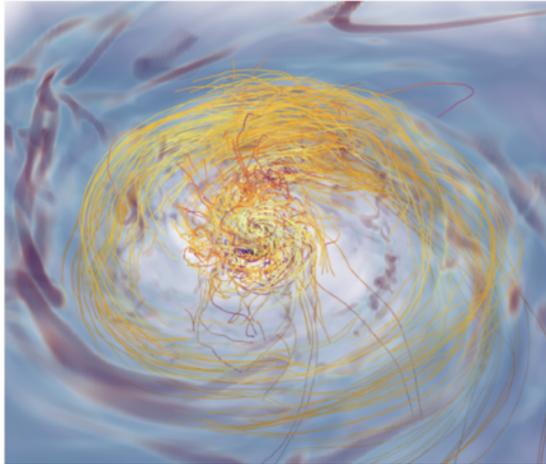
see talks by  
Radice,  
Gutierrez,  
Dietrich



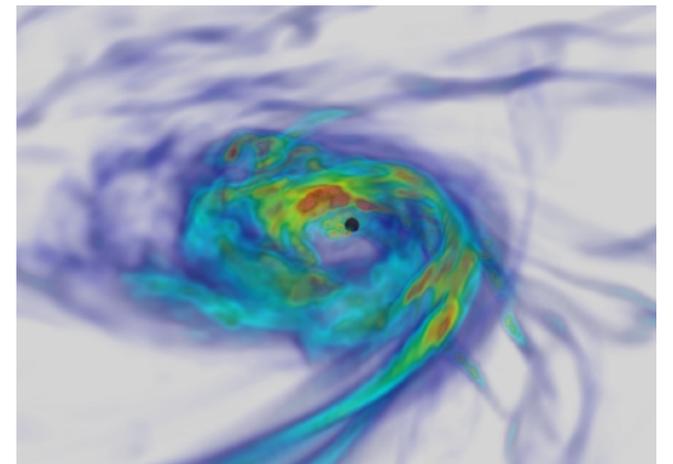
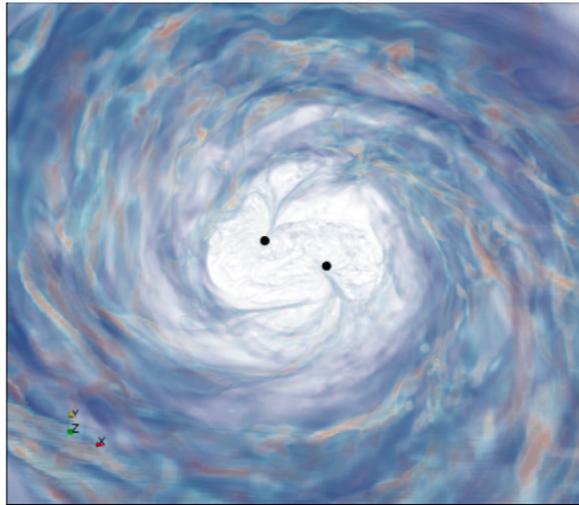
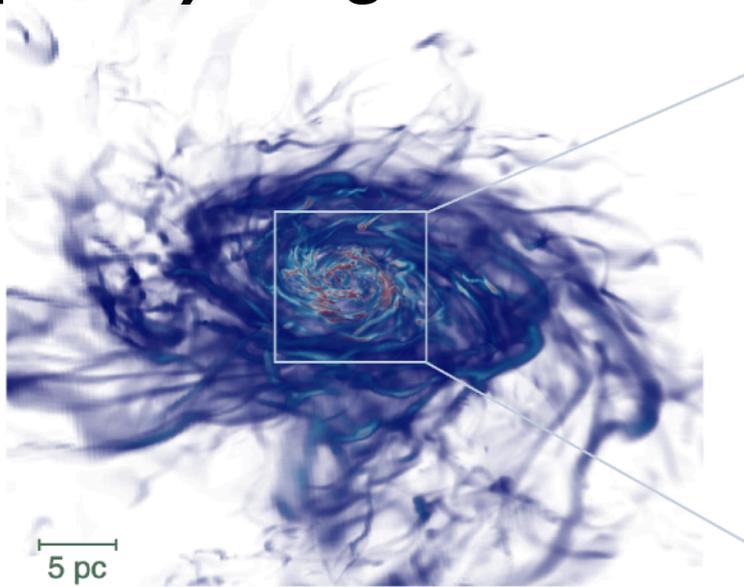
# Supermassive Black Hole Coalescence



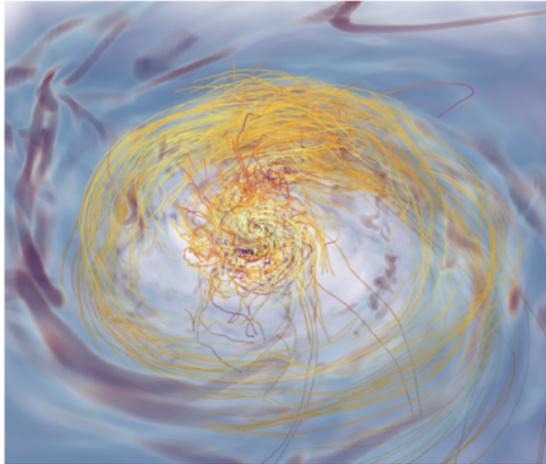
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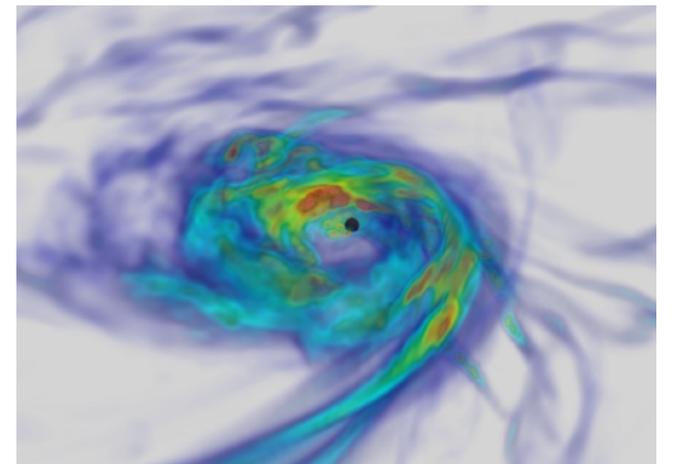
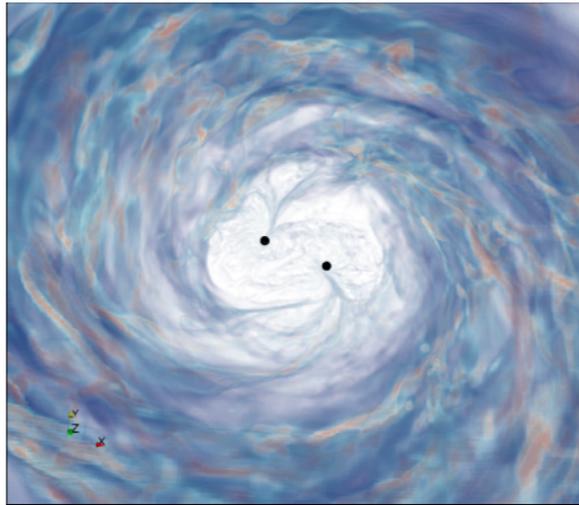
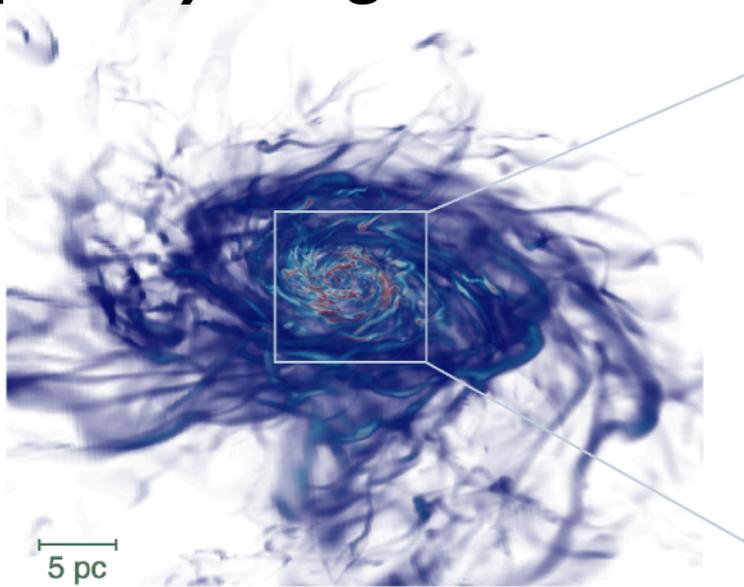
**(Hyper??)-Magnetized disks**



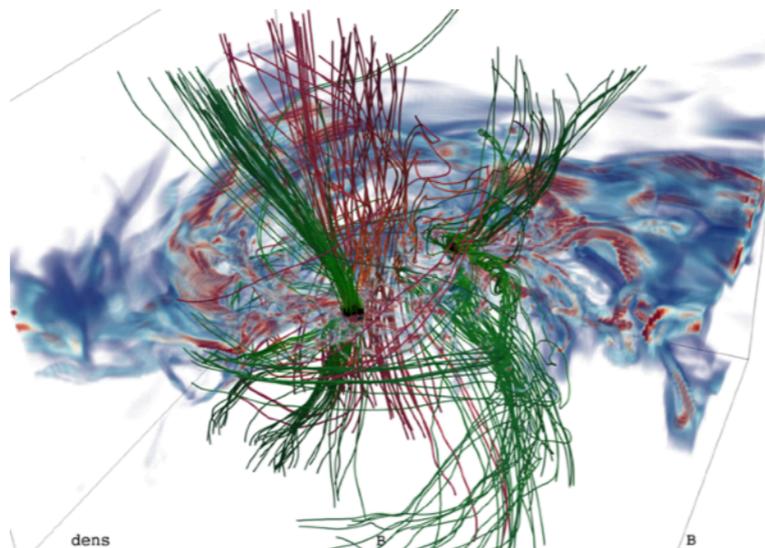
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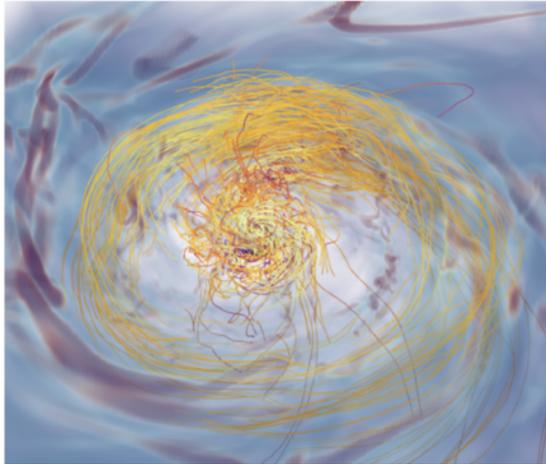
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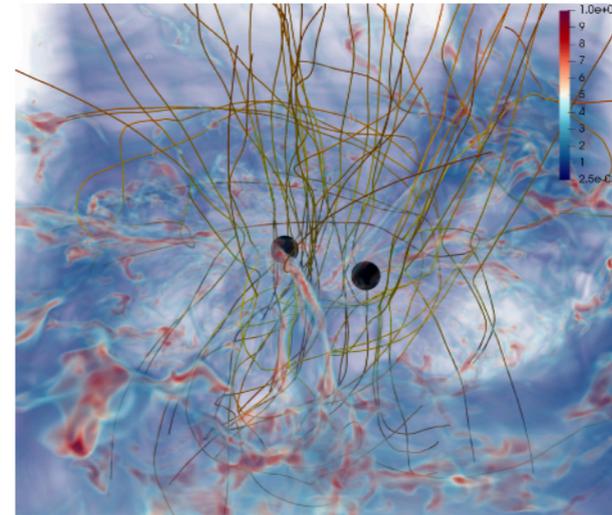
**Circumbinary  
driven inspiral?**



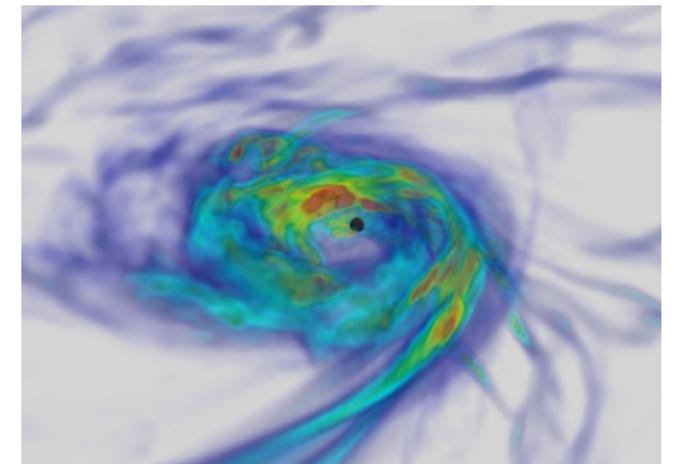
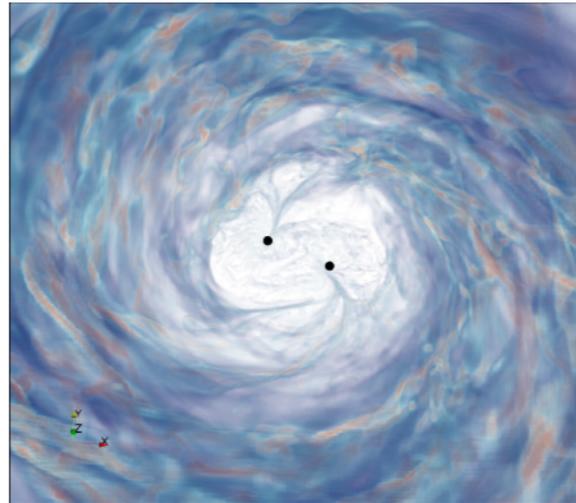
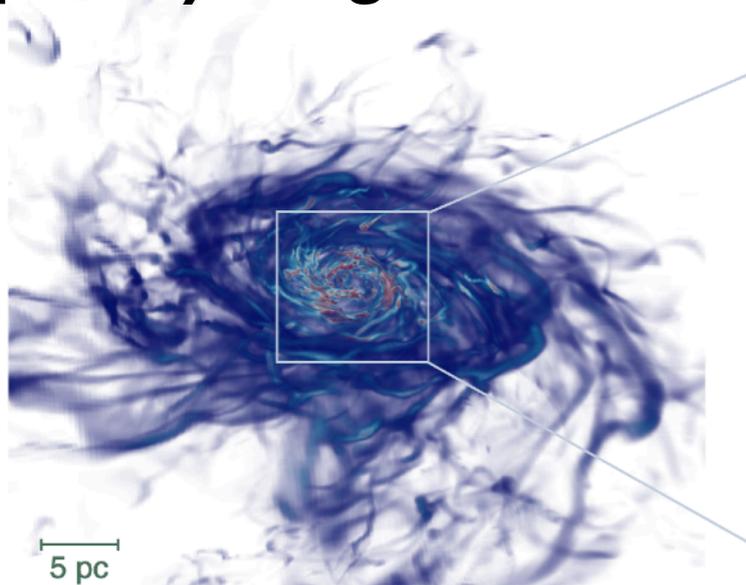
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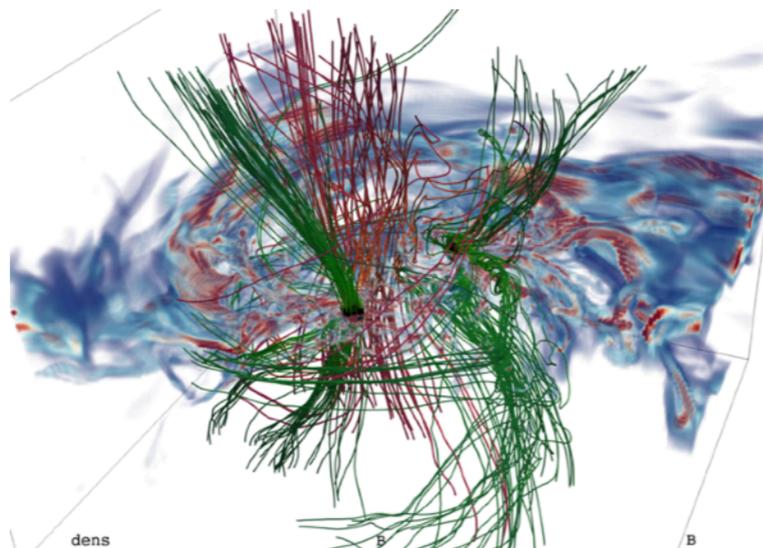
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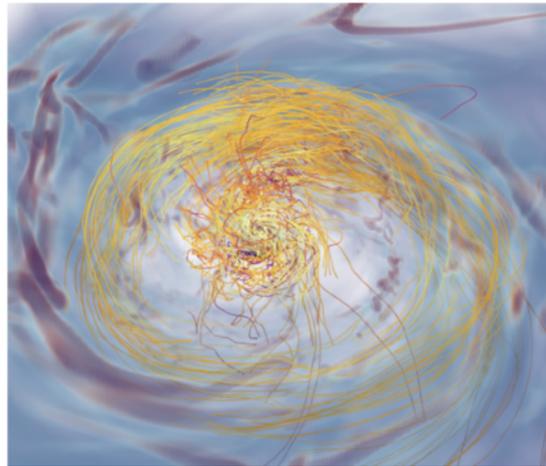
**EM transients leading up to merger**



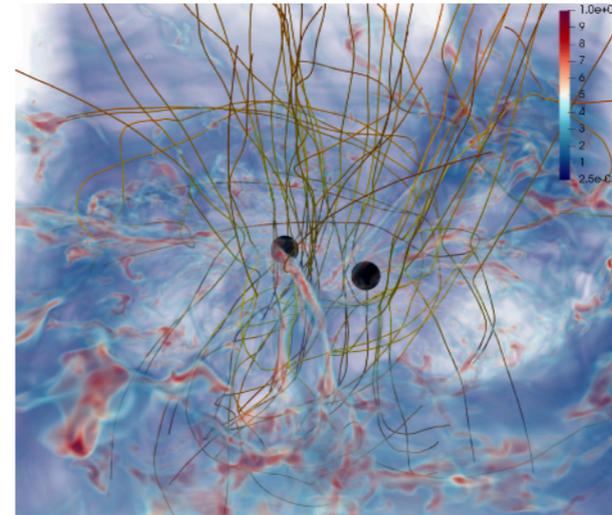
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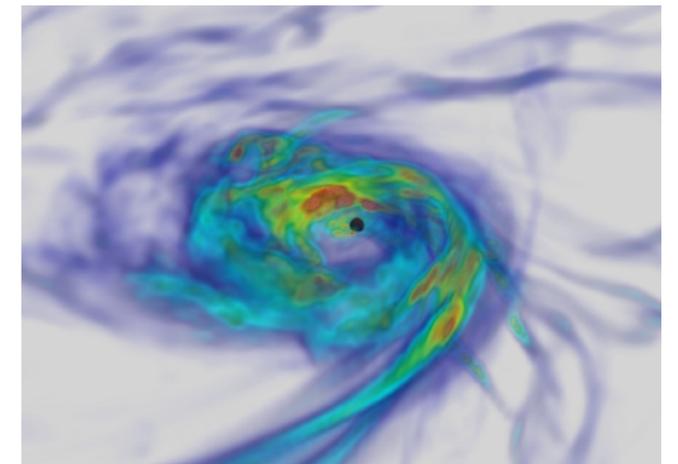
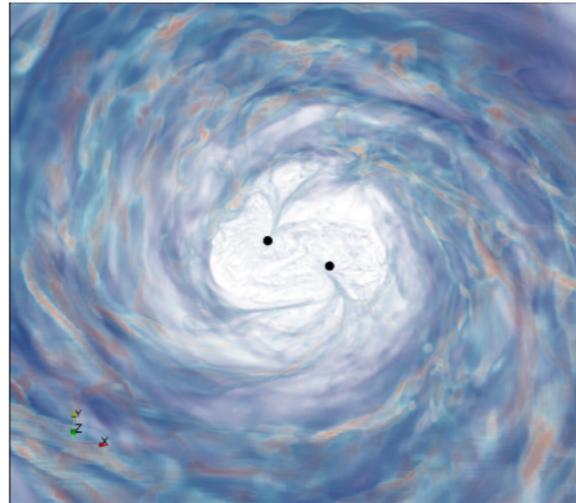
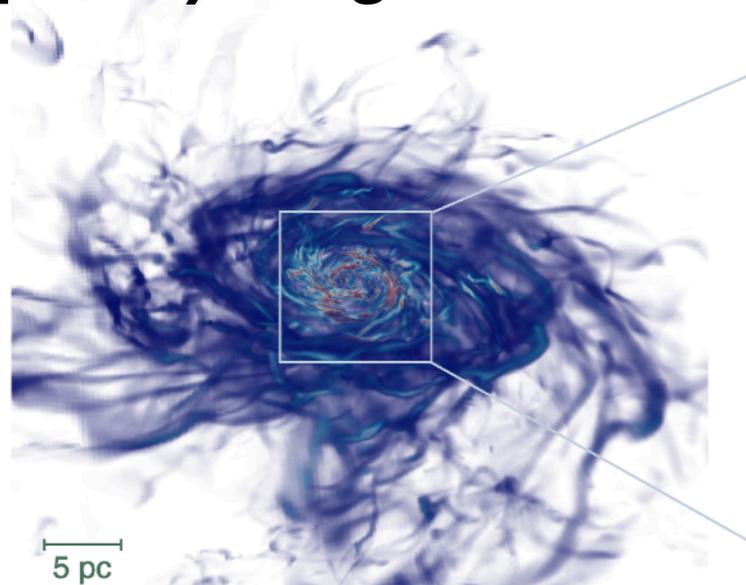
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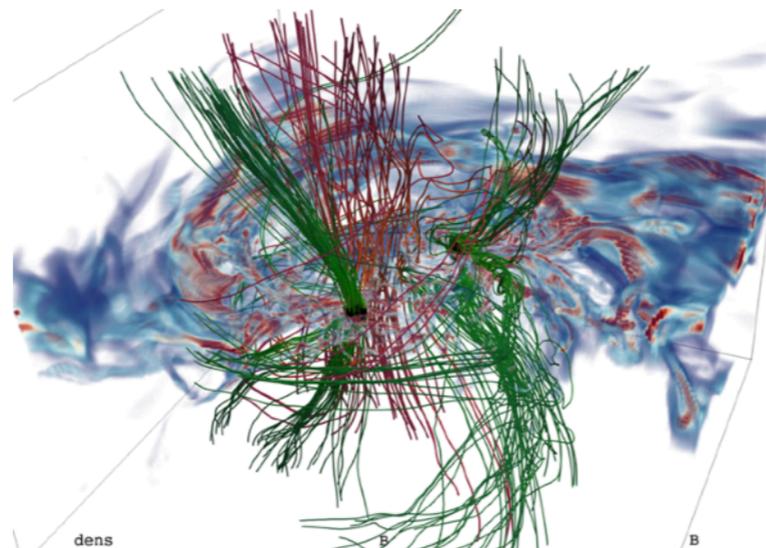
**(Hyper??)-Magnetized disks**



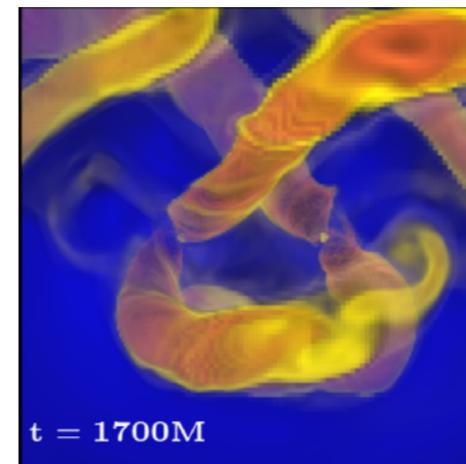
**EM transients leading up to merger**



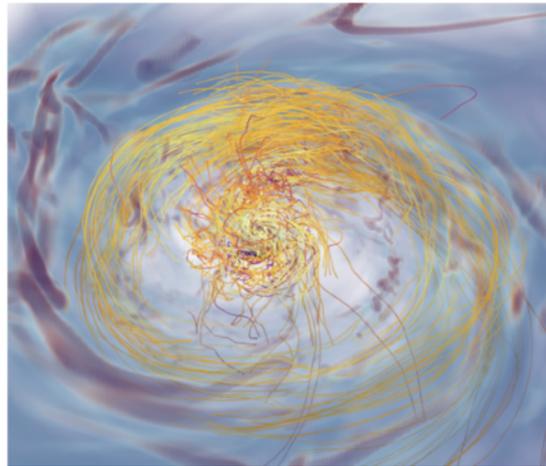
**Circumbinary driven inspiral?**



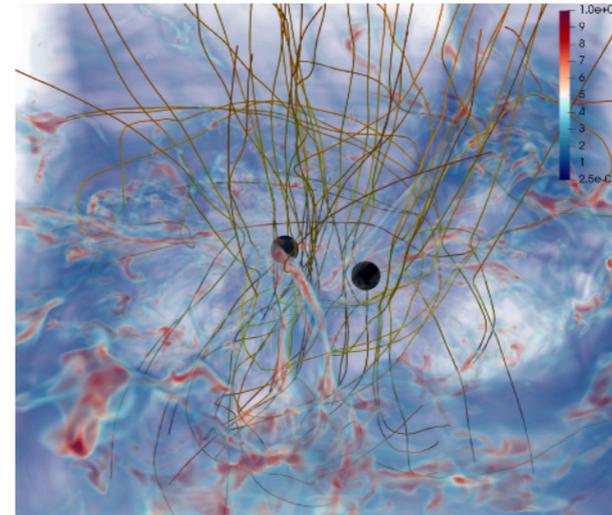
**Jet interaction**



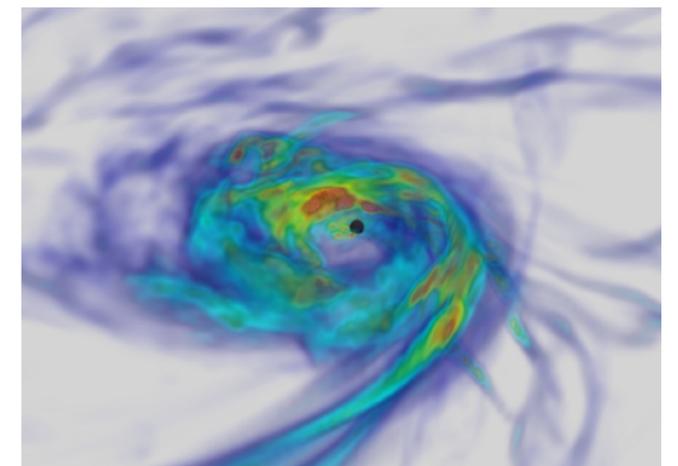
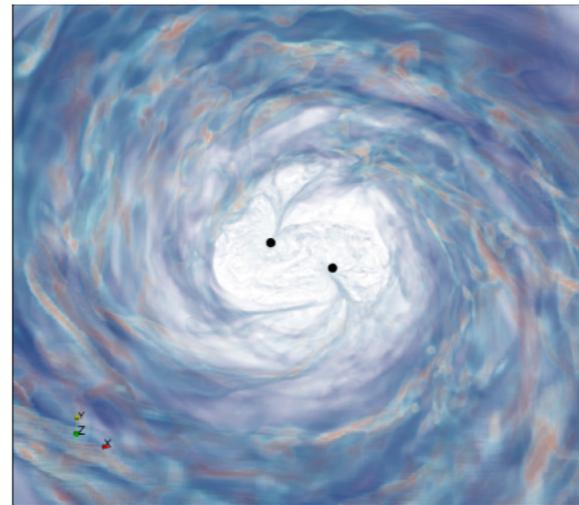
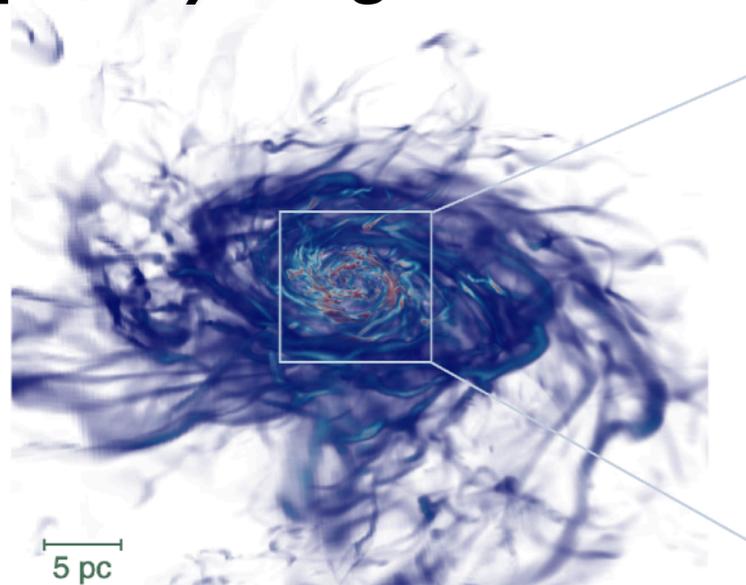
# Supermassive Black Hole Coalescence



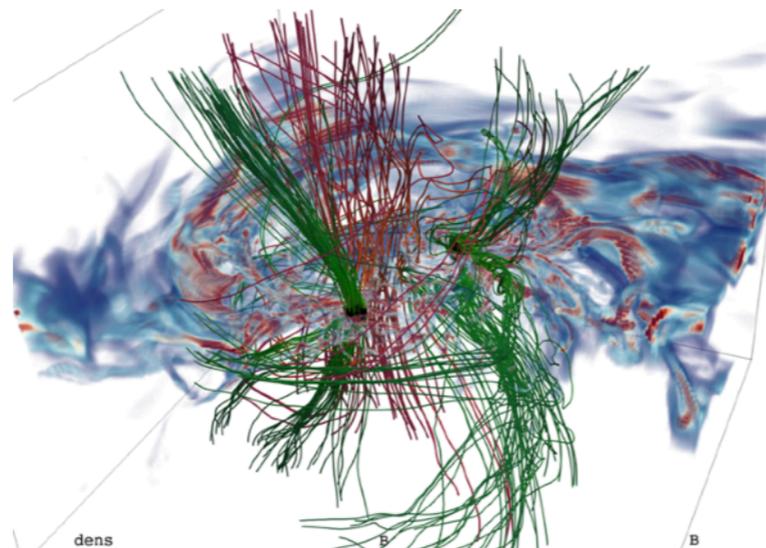
**(Hyper??)-Magnetized disks**



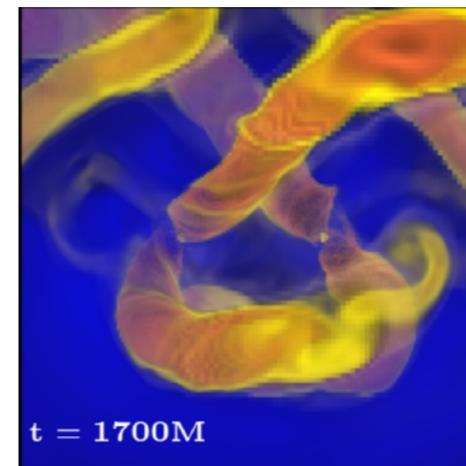
**EM transients leading up to merger**



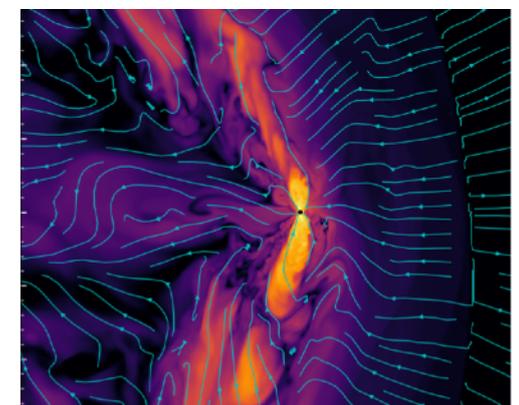
**Circumbinary driven inspiral?**



**Jet interaction**

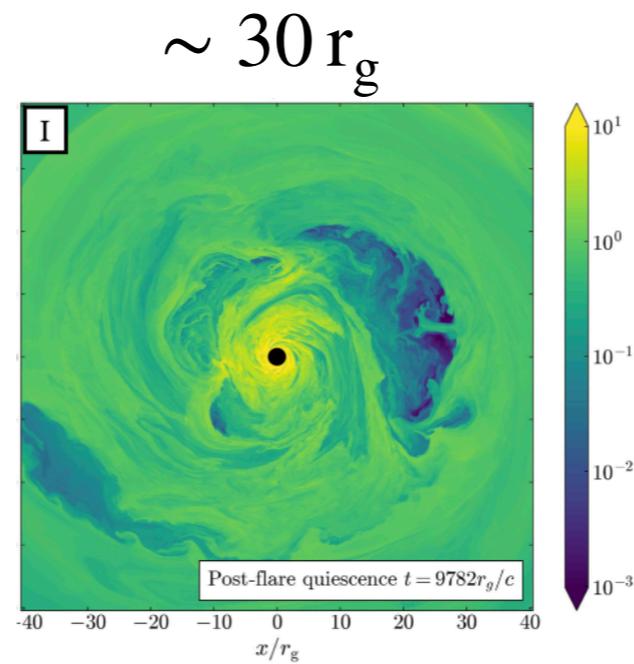


**Recoil transients?**



# Vastly different scales

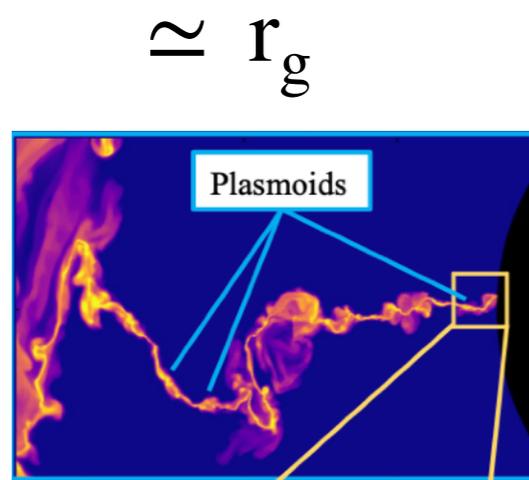
Image credit: Ripperda+, Liska+



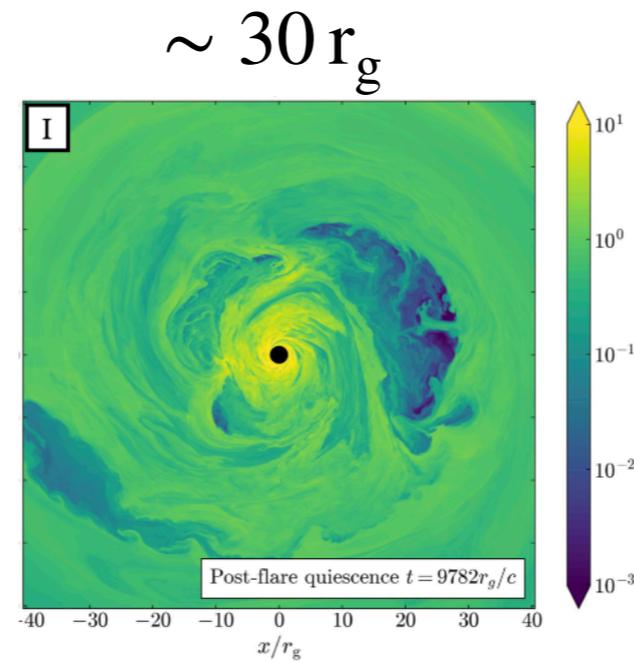
**Flare-disk  
interaction**

# Vastly different scales

Image credit: Ripperda+, Liska+



**Current  
sheet**

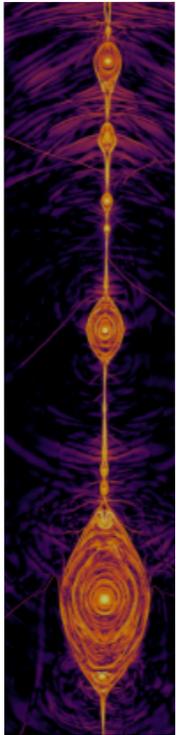


**Flare-disk  
interaction**

# Vastly different scales

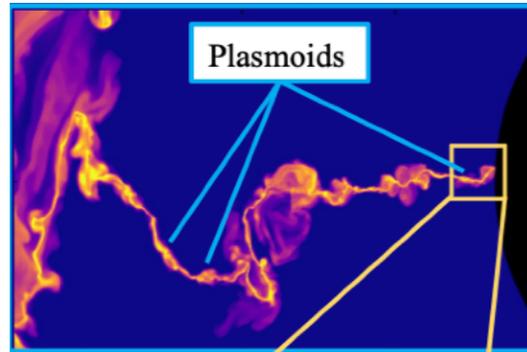
Image credit: Ripperda+, Liska+

$\ll 10^{-7} r_g$

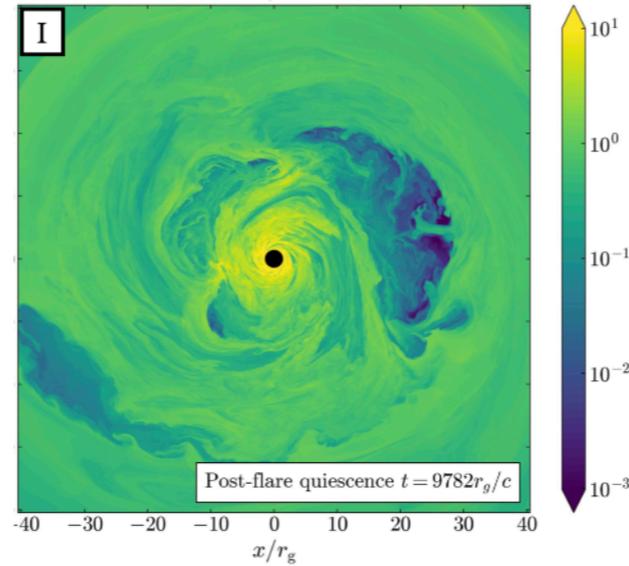


**Current sheet**

$\approx r_g$



$\sim 30 r_g$



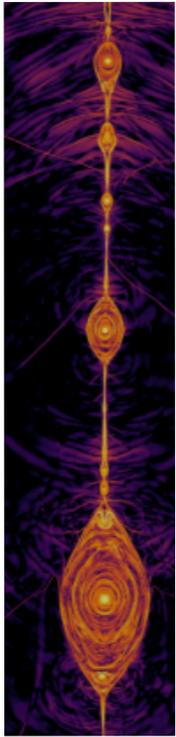
**Flare-disk interaction**

**Reconnection**

# Vastly different scales

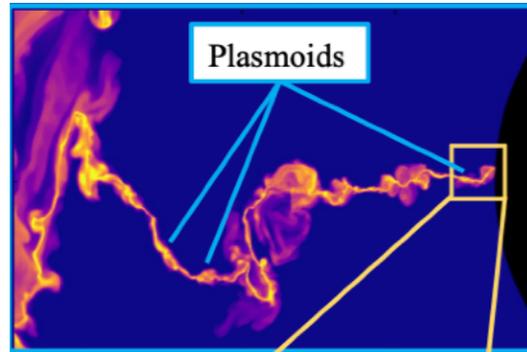
Image credit: Ripperda+, Liska+

$\ll 10^{-7} r_g$

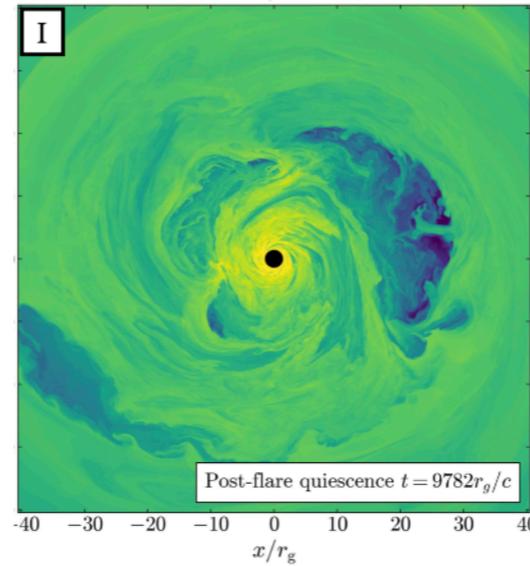


**Current sheet**

$\approx r_g$

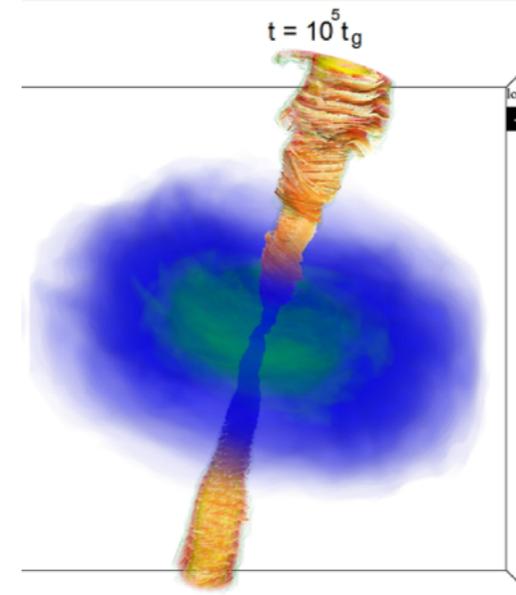


$\sim 30 r_g$



**Flare-disk interaction**

$\gg 10^4 r_g$



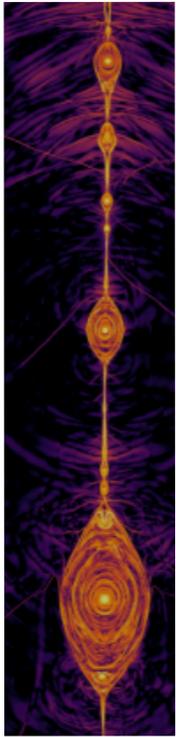
**Jet**

**Reconnection**

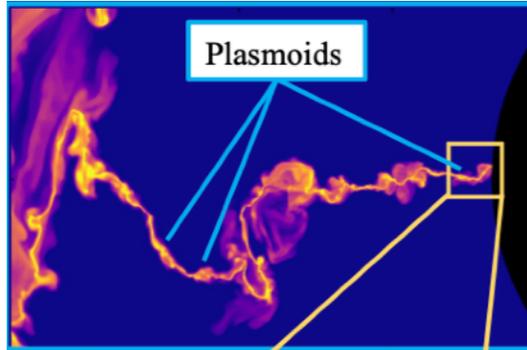
# Vastly different scales

Image credit: Ripperda+, Liska+

$\ll 10^{-7} r_g$

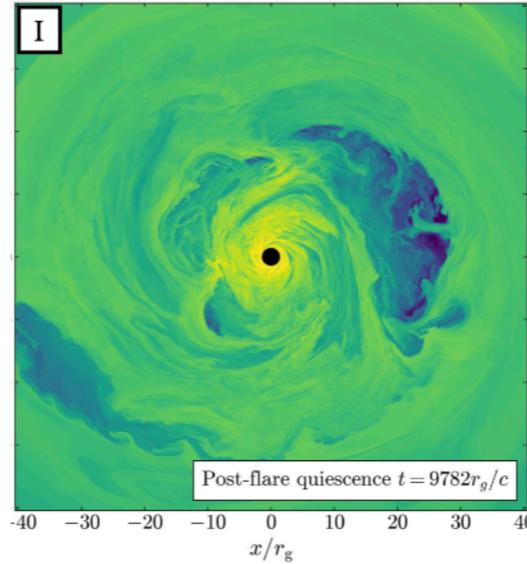


$\approx r_g$



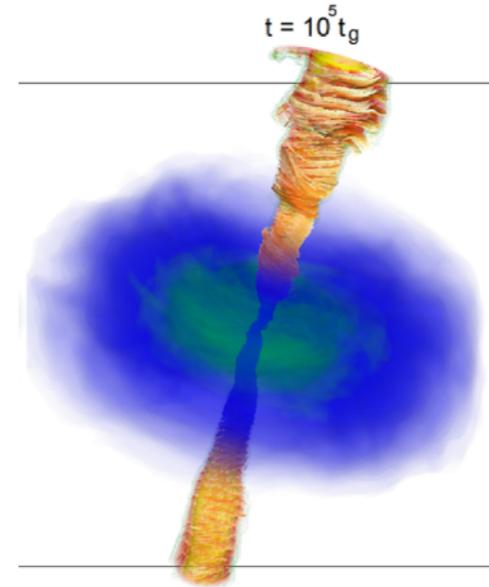
**Current sheet**

$\sim 30 r_g$



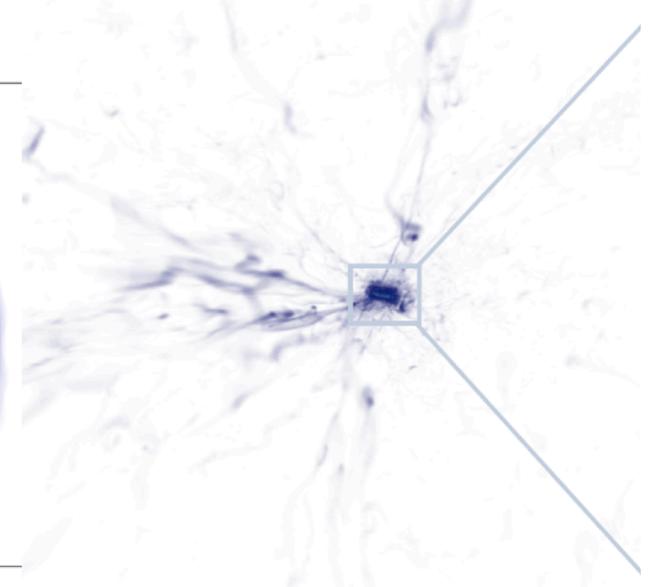
**Flare-disk interaction**

$\gg 10^4 r_g$



**Jet**

$\gg 10^7 r_g$



**Galactic scale feeding\***

**Reconnection**

# Vastly different scales

Image credit: Ripperda+, Liska+

Microscales

Macroscales

$\ll 10^{-7} r_g$

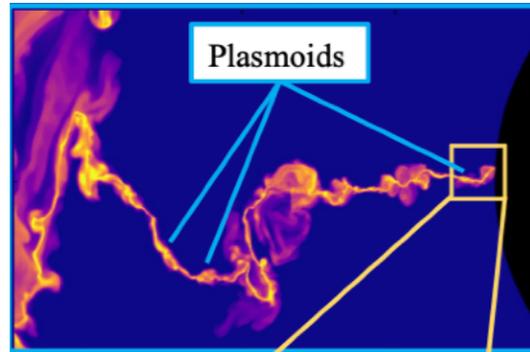
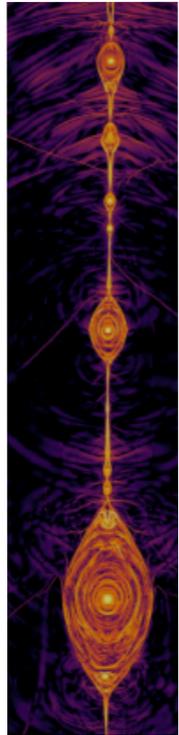


$\sim r_g$

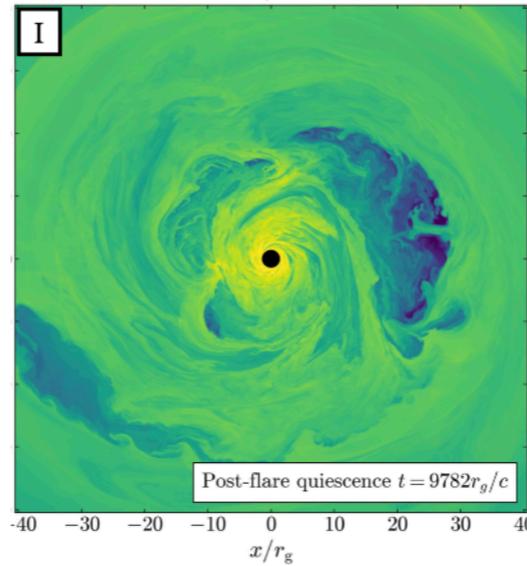
$\sim 30 r_g$

$\gg 10^4 r_g$

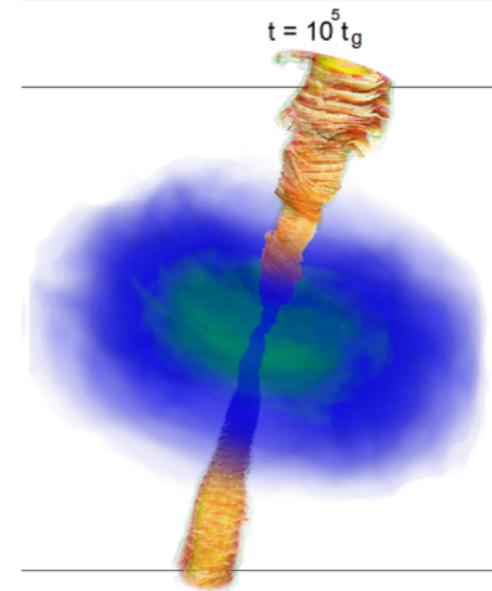
$\gg 10^7 r_g$



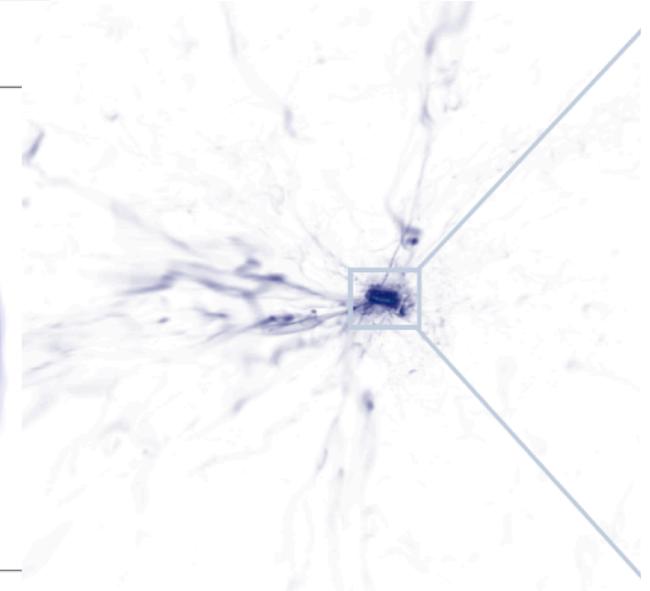
Current sheet



Flare-disk interaction



Jet



Galactic scale feeding\*

Need **different** multi-scale approach to capture physics on all scales!

# Vastly different scales

Image credit: Ripperda+, Liska+

Microscales

Macroscales

$\ll 10^{-7} r_g$

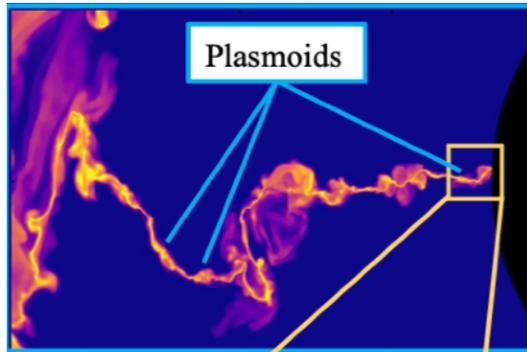
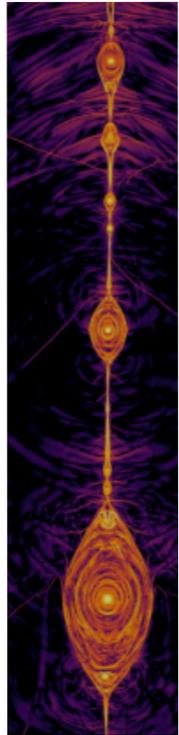


$\sim r_g$

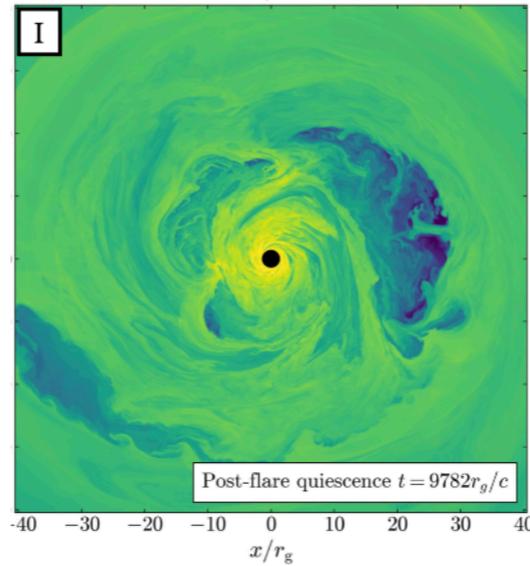
$\sim 30 r_g$

$\gg 10^4 r_g$

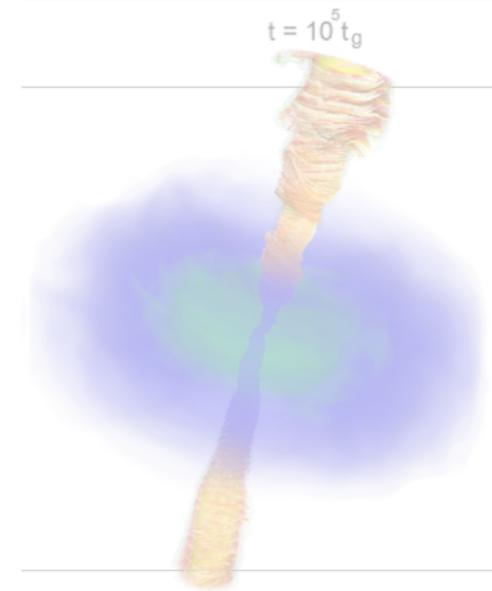
$\gg 10^7 r_g$



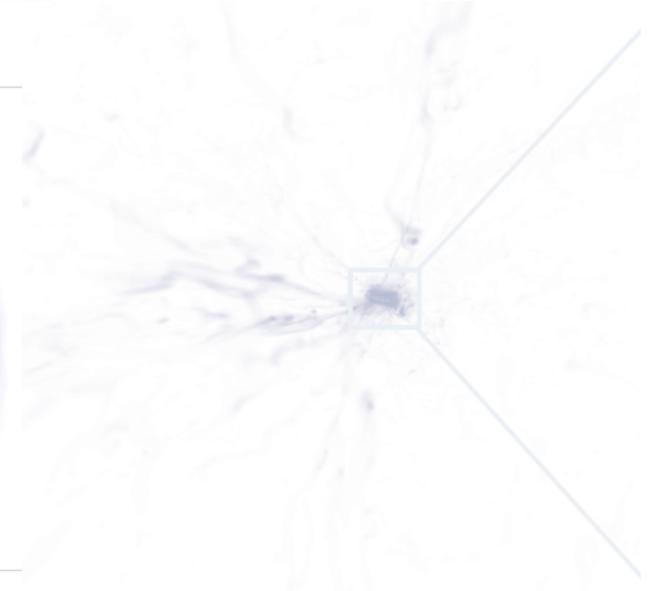
Current sheet



Flare-disk interaction



Jet



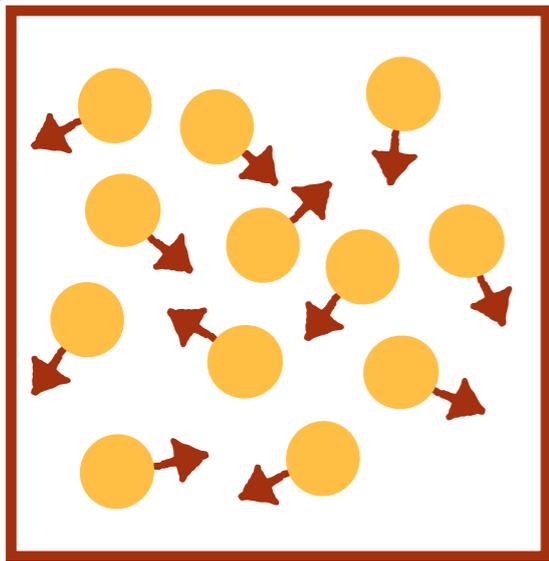
Galactic scale feeding\*

Need **different** multi-scale approach to capture physics on all scales!

# Hydrodynamics as an effective theory

## Magnetohydrodynamics

$$\nabla_{\mu} T_{\text{hydro}}^{\mu\nu} = 0$$



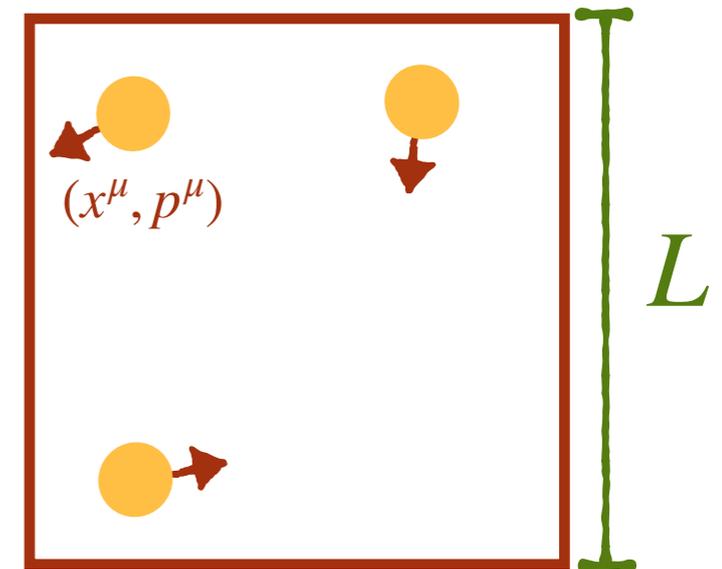
**Collisional** ( $\lambda \simeq 0$ )

mean free path  $\lambda$



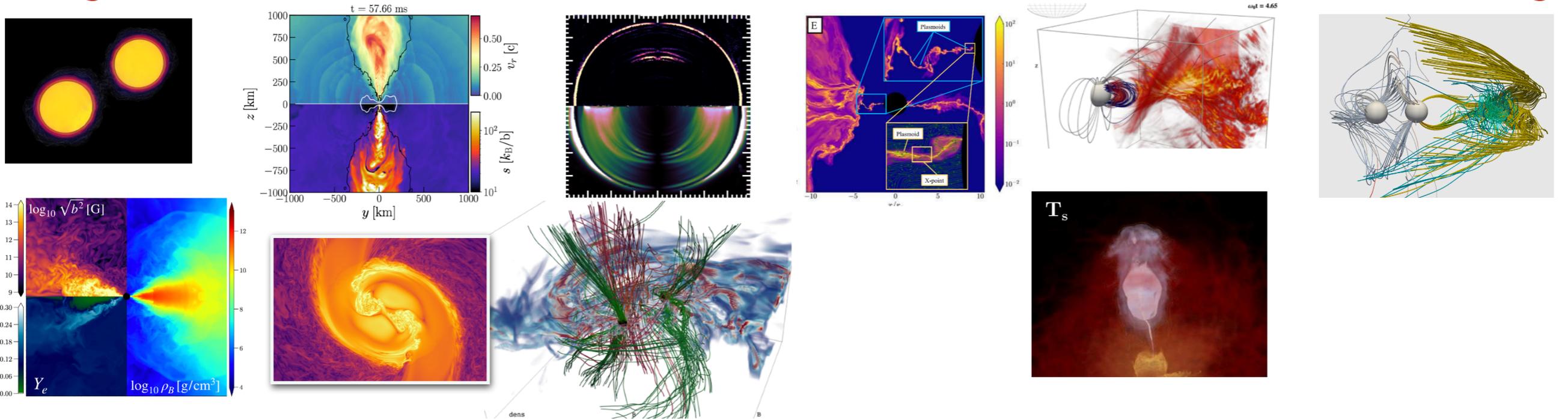
## Kinetic theory

$$p^{\mu} \partial_{\mu} f = \mathcal{C} [f]$$



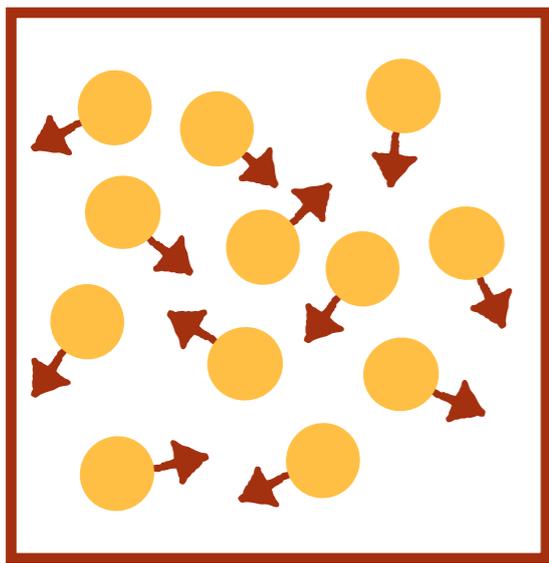
**Collisionless** ( $\lambda \simeq L$ )

# Hydrodynamics as an effective theory



## Magnetohydrodynamics

$$\nabla_{\mu} T^{\mu\nu}_{\text{hydro}} = 0$$



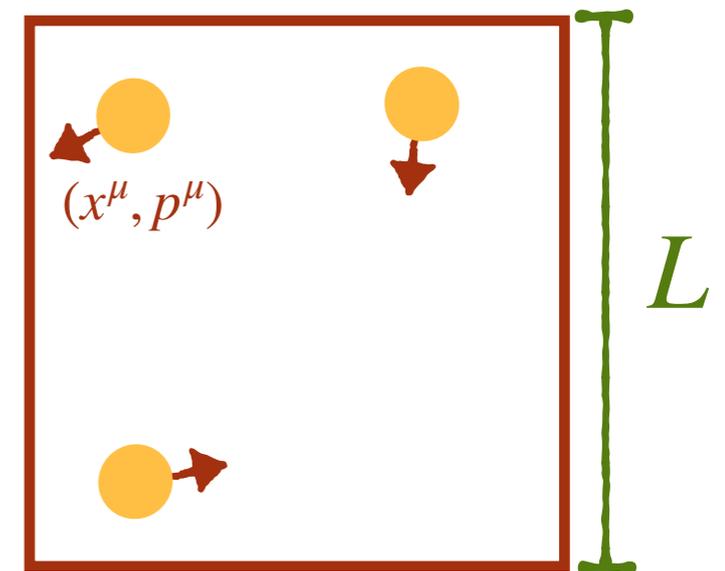
**Collisional** ( $\lambda \simeq 0$ )

**mean free path  $\lambda$**



## Kinetic theory

$$p^{\mu} \partial_{\mu} f = \mathcal{C} [f]$$



**Collisionless** ( $\lambda \simeq L$ )

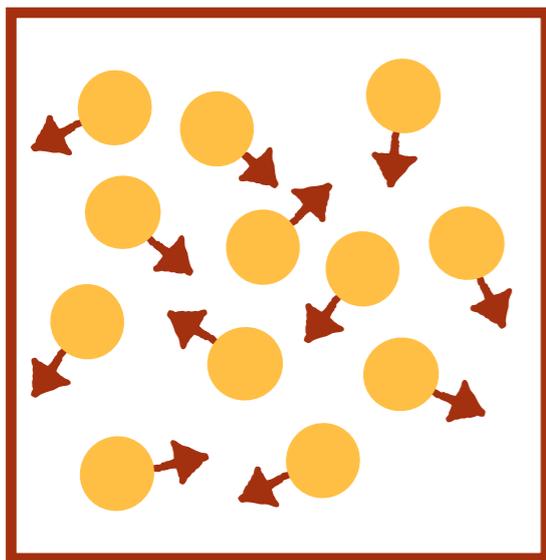
# Hydrodynamics as an effective theory

*Perturbatively* include corrections to hydrodynamics

$$T^{\mu\nu} = \boxed{T^{\mu\nu}_{\text{hydro}}} + \boxed{\epsilon T^{\mu\nu}_{(1)} + \epsilon^2 T^{\mu\nu}_{(2)} + \dots} \quad \epsilon \sim \frac{\lambda}{L} \ll 1$$

**Hydrodynamics**

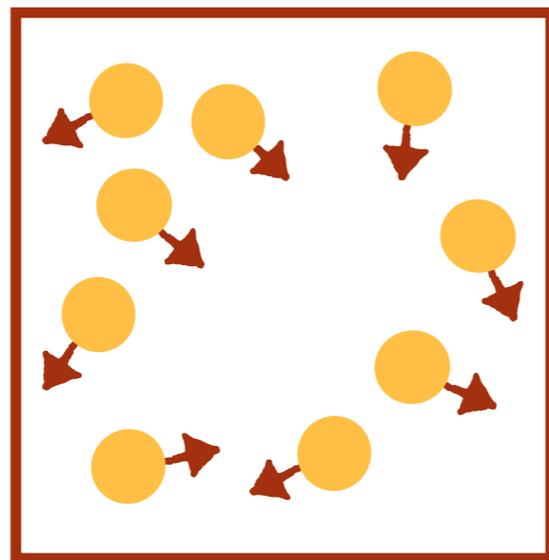
$$\nabla_{\mu} T^{\mu\nu}_{\text{hydro}} = 0$$



**Collisional** ( $\lambda \simeq 0$ )

**Dissipative Hydrodynamics**

$$\nabla_{\mu} T^{\mu\nu} = 0$$

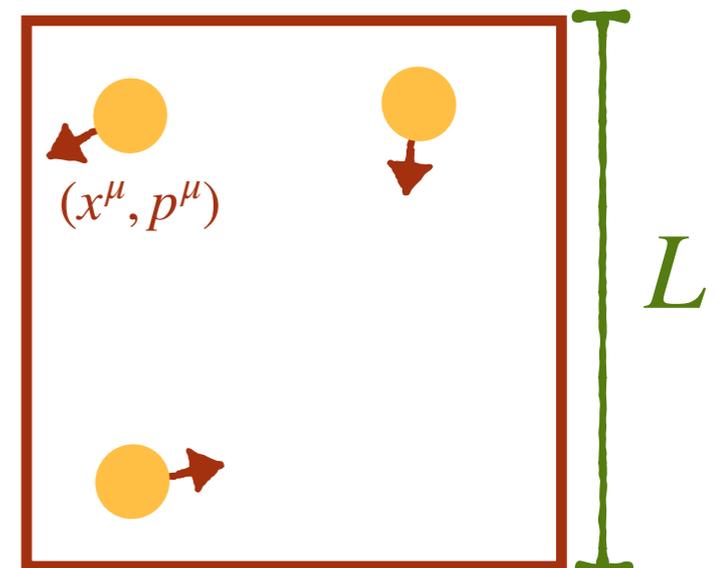


**mean free path  $\lambda$**



**Kinetic theory**

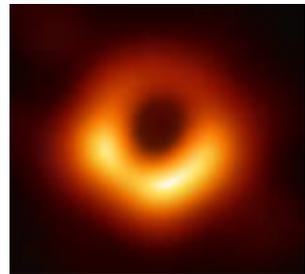
$$p^{\mu} \partial_{\mu} f = \mathcal{C}[f]$$



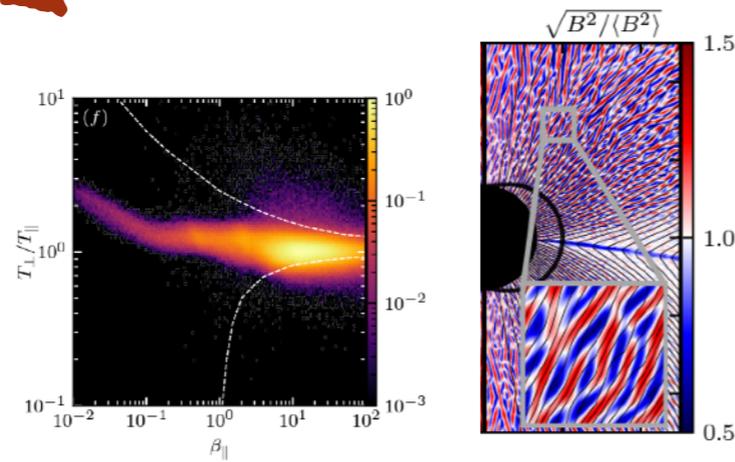
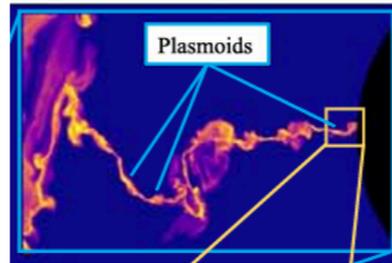
**Collisionless** ( $\lambda \simeq L$ )

# A path towards better microphysics

## Single-fluid-based



Ideal GRMHD



Braginskii-like non-resistive GRMHD

- ✿ Heat flux
- ✿ Anisotropic viscosity

## Two-fluid-based

Dissipative resistive GRMHD

- ✿ Scalar resistivity + Hall

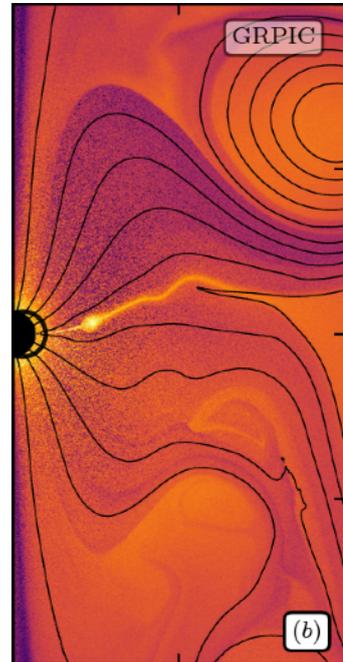
Two Fluid Dissipative GRMHD

- ✿ Anisotropic electron pressure

See also 10-moment in Newtonian context

Reconnection physics

## Particle-based



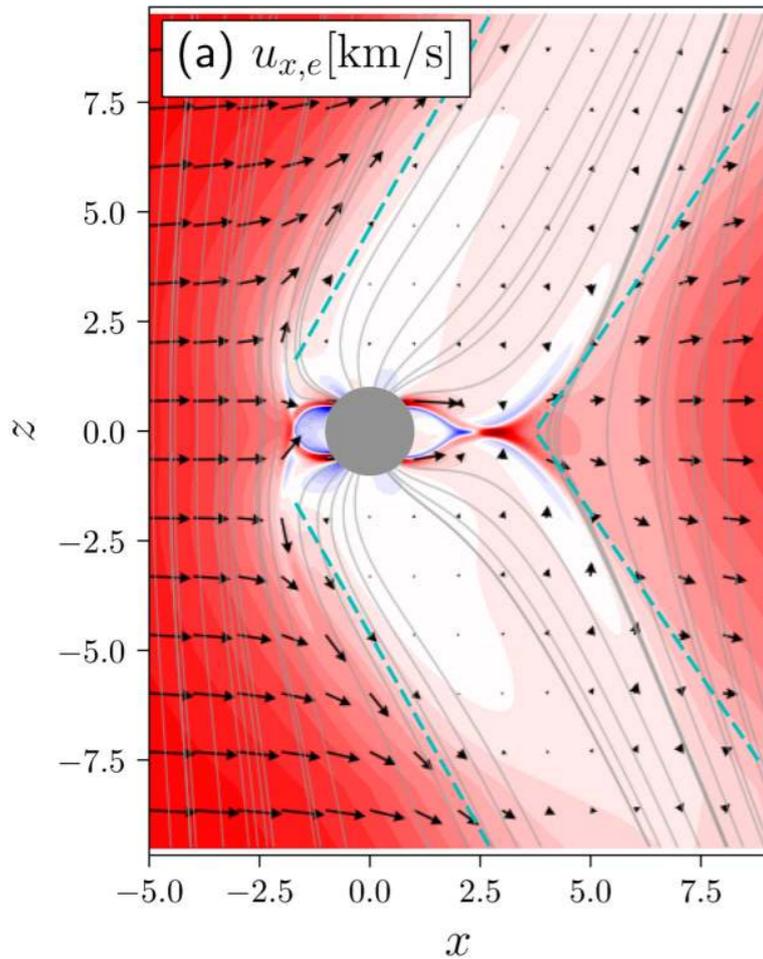
GRPIC



# Inspiration from space physics

$$\epsilon^2 T^{\mu\nu} \quad (2)$$

## Ganymede



Generalize 10-moment **two-fluid** approach from space physics to relativistic setting!

$$\frac{\partial (m_s n_s)}{\partial t} + \frac{\partial (m_s n_s u_{j,s})}{\partial x_j} = 0,$$

number density

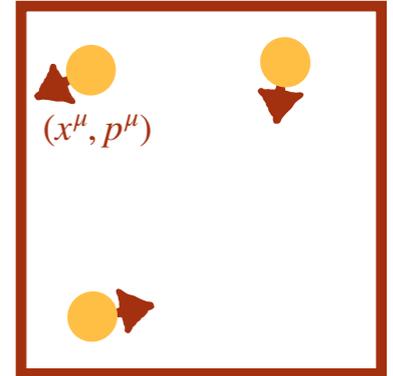
$$\frac{\partial (m_s n_s u_{j,s})}{\partial t} + \frac{\partial \mathcal{P}_{ij,s}}{\partial x_j} = n_s q_s (E_i + \epsilon_{ijk} u_{j,s} B_k),$$

momentum density

$$\frac{\partial \mathcal{P}_{ij,s}}{\partial t} + \frac{\partial \mathcal{Q}_{ijm,s}}{\partial x_m} = n_s q_s u_{[i,s} E_{j]} + \frac{q_s}{m_s} \epsilon_{[iml} \mathcal{P}_{mj],s} B_l.$$

(an-)isotropic stresses

Wang+(2018)



Need generalized Ohm's law to model **collisionless** physics.

$$\vec{E} = - \underbrace{\vec{v} \times \vec{B}}_{0\text{th order}} + \underbrace{\eta \vec{J}}_{1\text{st order}} + \underbrace{\vec{J} \text{div } v + \text{div } \overleftrightarrow{\mathcal{P}}}_{2\text{nd order}} + \dots$$

0th order

1st order

2nd order

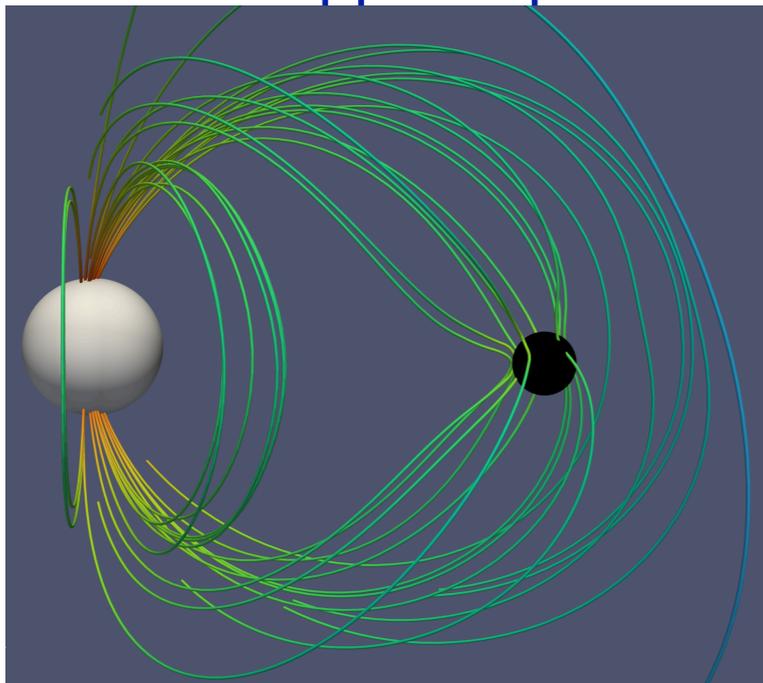
Bessho&Bhattacharjee (2008)

Need  
2nd order!

# Inspiration from space physics

$$\epsilon^2 T^{\mu\nu} \quad (2)$$

ERM & Philippov (ApJL 2023)



Generalize ~~10~~<sup>14</sup>-moment approach from space physics to relativistic setting!

number density

$$\nabla_\mu N_e^\mu = 0$$

$$\nabla_\mu N_p^\mu = 0$$

total energy-momentum

$$\nabla_\mu T^{\mu\nu} = 0$$

electron temperature

$$U^\mu \nabla_\mu e_e = \dots$$

electron current

$$U^\mu \nabla_\mu \mathcal{J}_e^{<\nu>} = \dots$$

anisotropic electron pressure

$$U^\mu \nabla_\mu \pi_e^{<\alpha\beta>} = \dots$$

➔ Dissipative Two-Fluid MHD

ERM, Noronha & Philippov (MNRAS 2022)

Need generalized Ohm's law to model collisionless physics.

$$e^\mu = \eta \mathcal{J}_e^{<\nu>} - \tau U^\mu \nabla_\mu \mathcal{J}_e^{<\nu>} + \delta_J \mathcal{J}_e^{<\nu>} \nabla_\mu U^\mu + \delta_\pi \nabla_\mu \pi_e^{\mu\nu} + \dots$$

0th order

1st order

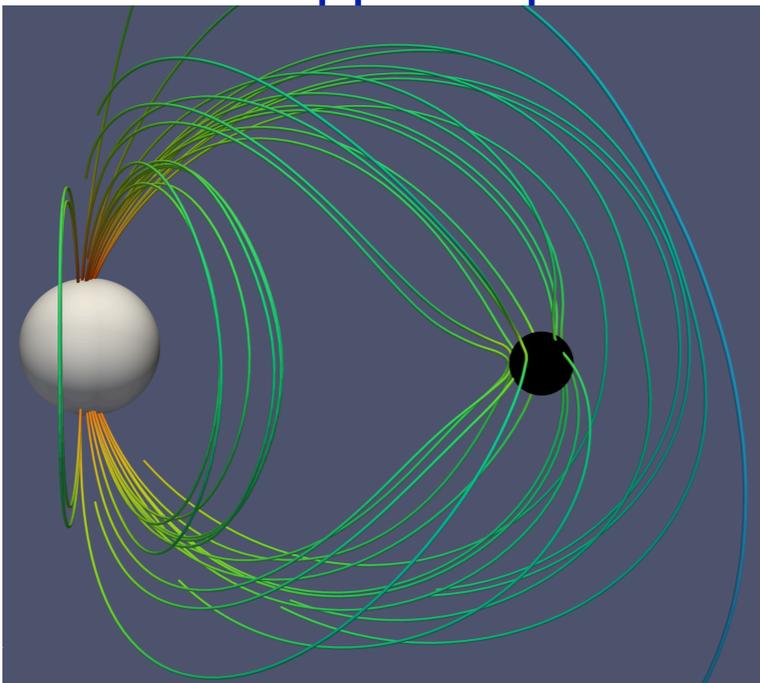
dynamical part

2nd order

# Inspiration from space physics

$$\epsilon^2 T^{\mu\nu} \quad (2)$$

ERM & Philippov (ApJL 2023)



Generalize ~~10~~<sup>14</sup>-moment approach from space physics to relativistic setting!

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0th order

1st order

dynamical part

2nd order

# Dissipative Magnetohydrodynamics

First numerical scheme to handle general viscosities in the presence of magnetic fields for relativistic fluids.

ERM & Noronha (PRD 2021)

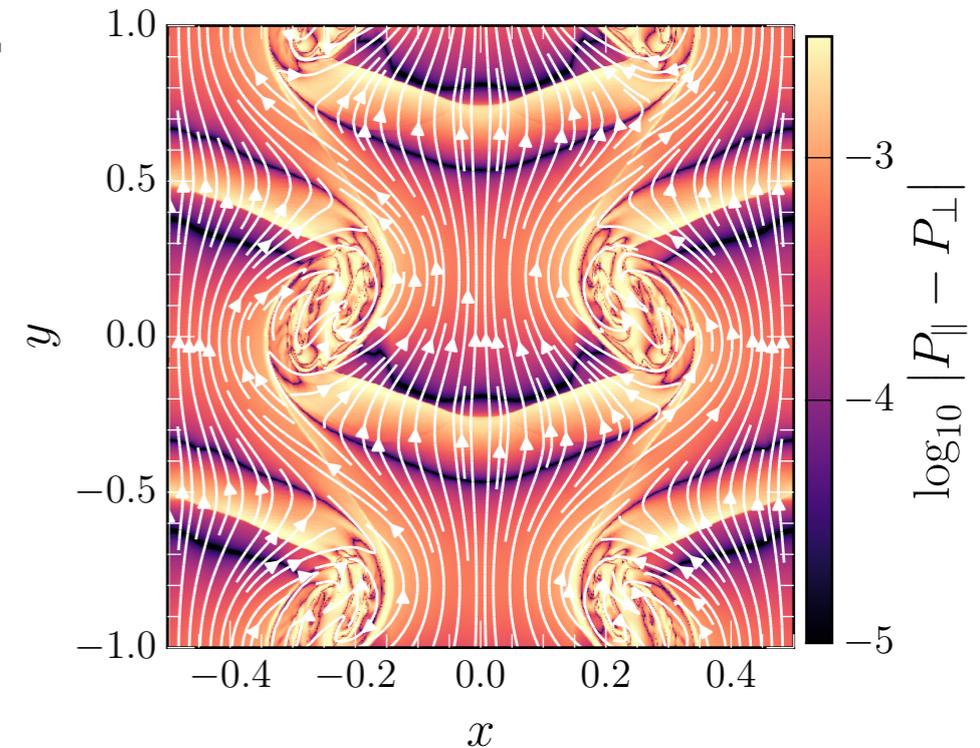
Leverages a 14-moment closure derived from kinetic theory by the nuclear physics community.

Denicol+(2018,2019)

Novel fully flux conservative approach with stiff relaxation.

Well suited to handle highly turbulent astrophysical flows!

## Pressure anisotropy



ERM & Noronha (PRD 2021)

$$u^\alpha \nabla_\alpha \Pi = -\zeta \nabla_\beta u^\beta + \dots$$

$$u^\alpha \nabla_\alpha q^\mu = -\kappa \nabla^\mu T - \tau^{-1} q^\mu + \dots$$

$$+ \Omega_T b^{\mu\nu} q_\nu + \dots$$

$$u^\alpha \nabla_\alpha \pi^{\mu\nu} = -\eta \sigma^{\mu\nu} - \tau^{-1} \pi^{\mu\nu} + \dots$$

$$+ \delta_B b^{\langle \mu\alpha} \pi_{\alpha}^{\nu \rangle} \dots$$

# Dissipative visco-resistive GRMHD

Building the first dissipative resistive GRMHD code that incorporates all first order dissipation terms Dunham & Most (in prep)

See also Lier+ for BDNK approaches.



Sam Dunham  
(Caltech)

**Bulk** & shear viscosities, heat conduction, resistivity and Hall terms using 14-moment formulation Denicol+ (2019)

## Retain electron degrees of freedom

$$\mathcal{J}^\mu = qu^\mu + V^\mu$$

dissipative current

$$\omega_{p,e} = \sqrt{\frac{4\pi n_e e^2}{m_e}}$$

$$u^\kappa \nabla_\kappa V^{<\mu>}$$

advective term

$$= -\frac{1}{\tau} V^\mu + \omega_{p,e}^2 e^\mu$$

resistive coupling

$$+ \omega_{g,e} b^{\mu\nu} V_\nu$$

Hall

$$\omega_{g,e} = \frac{eb}{m_e}$$

Dunham & Most (in prep)

# Dissipative visco-resistive GRMHD

ERM & Noronha (2021)

Extend novel flux-conservative formulation to full visco-resistive system in full GR.

On GPUs!



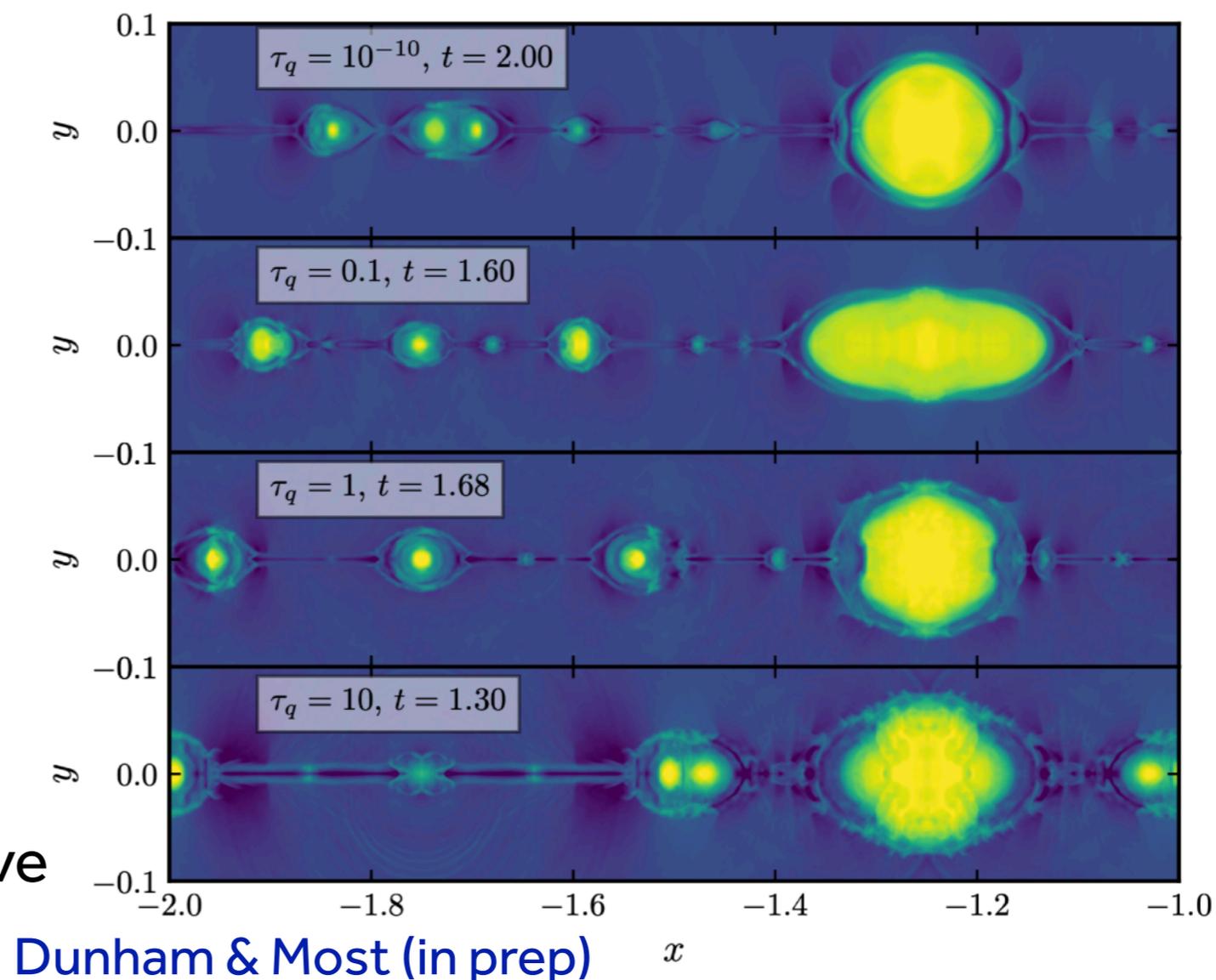
Sam Dunham  
(Caltech)

Dissipative sector is fully implicit (SSP-RK3 IMEX).

New flooring model to treat highly magnetized and nonideal regions.

AMReX-based fully GPU compatible

On A100 GPU about 3x more expensive than ideal (~15 Mio. cell-ups/s)



Dunham & Most (in prep)

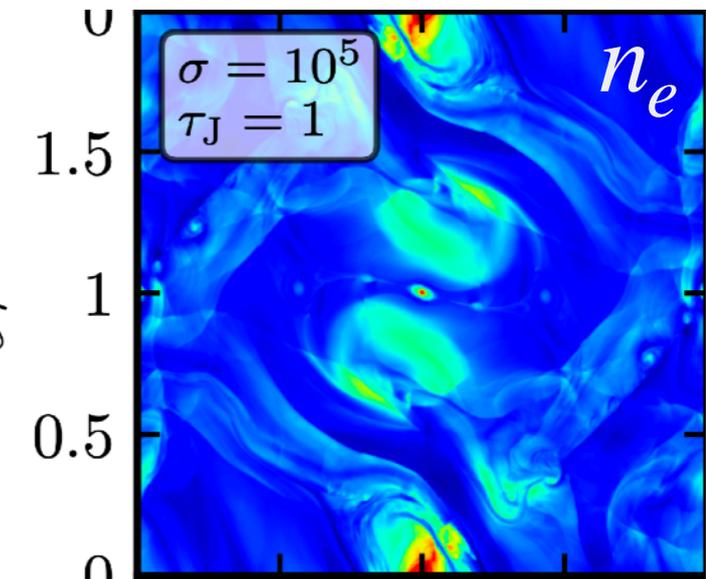
# Dissipative GRMHD

Dunham & Most (in prep)



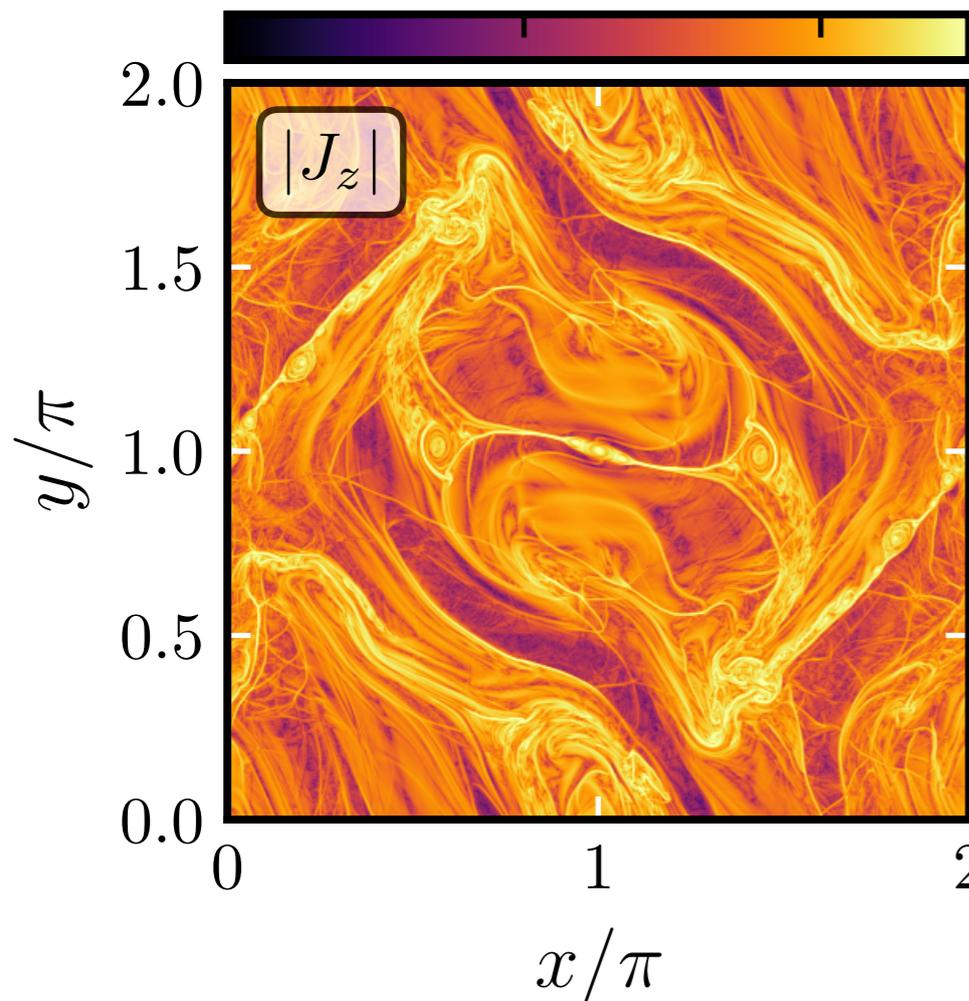
Sam Dunham  
(Caltech)

## Electron number density



## Dissipative current

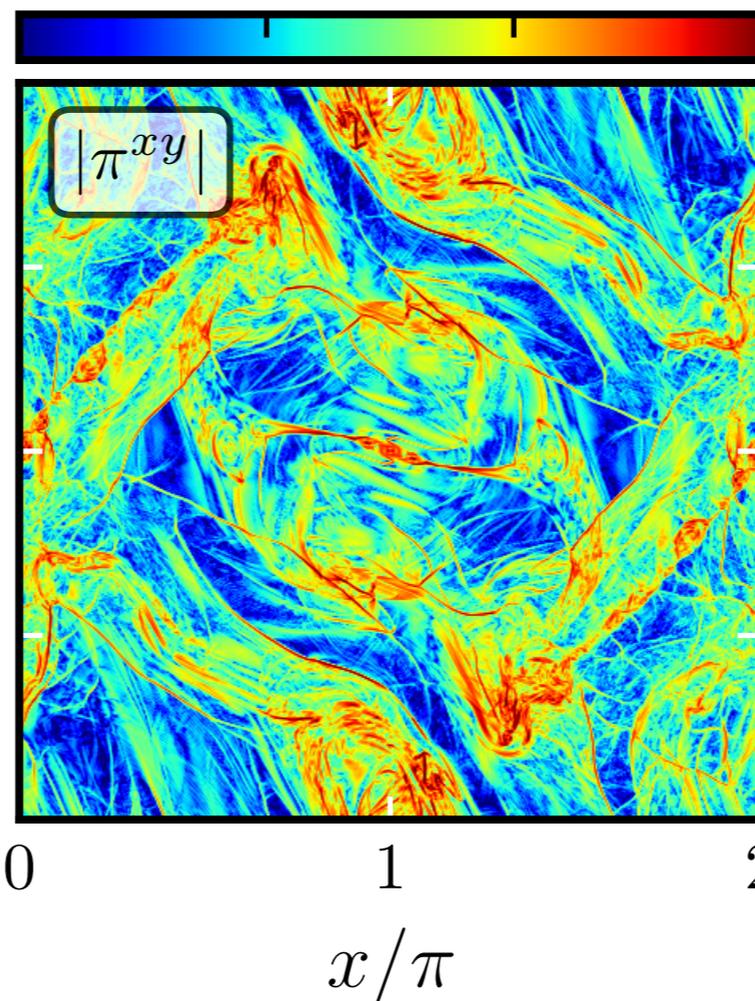
$10^{-3}$     $10^{-1}$    10



## Viscous stress

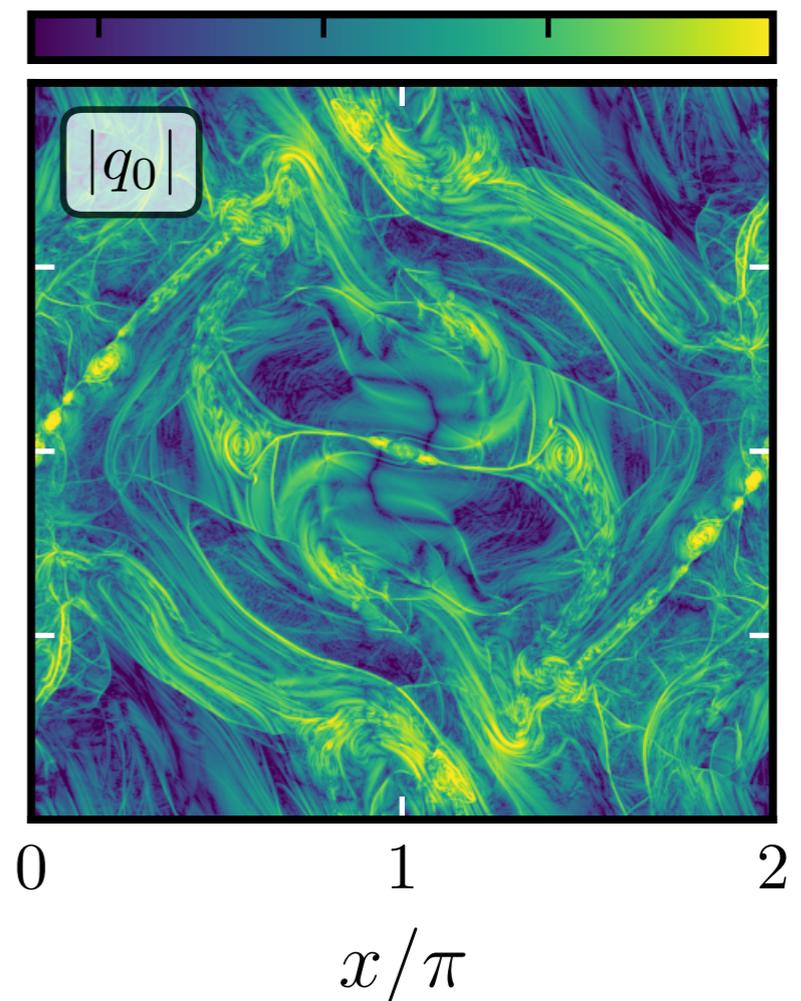
$t = 10$

$10^{-6}$     $10^{-5}$     $10^{-4}$



## Heat flux

$10^{-7}$     $10^{-6}$     $10^{-5}$



# Dynamos in action!

Magnetic **dynamos** are one of the key ingredients in the merger!

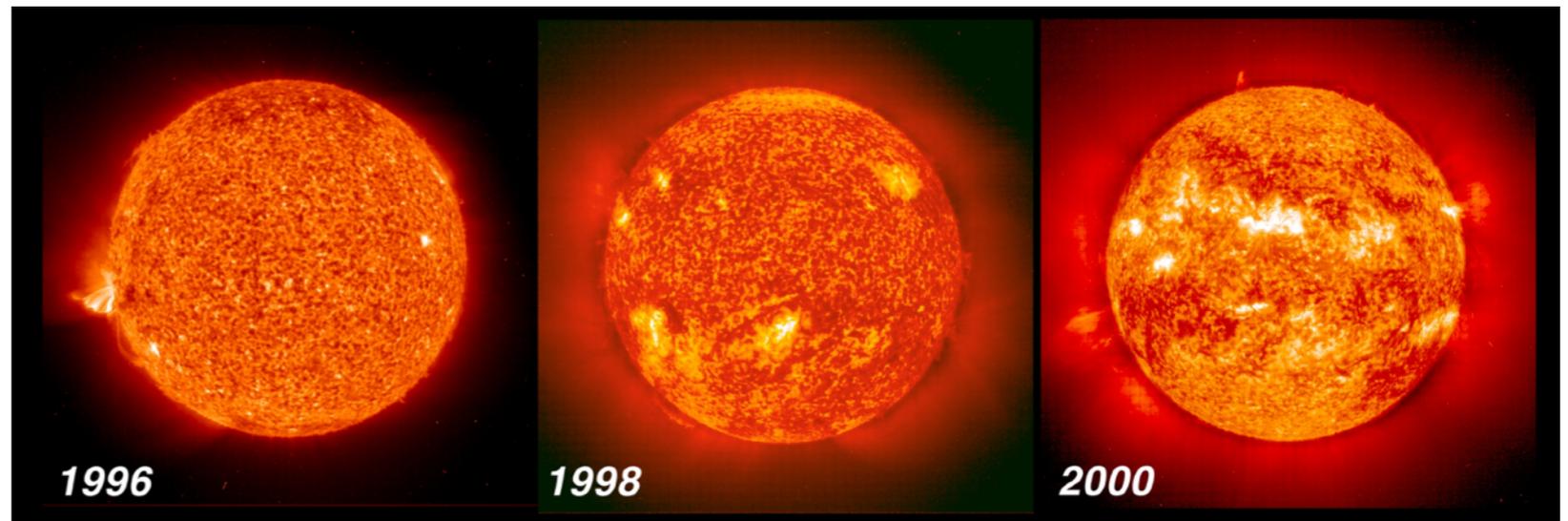
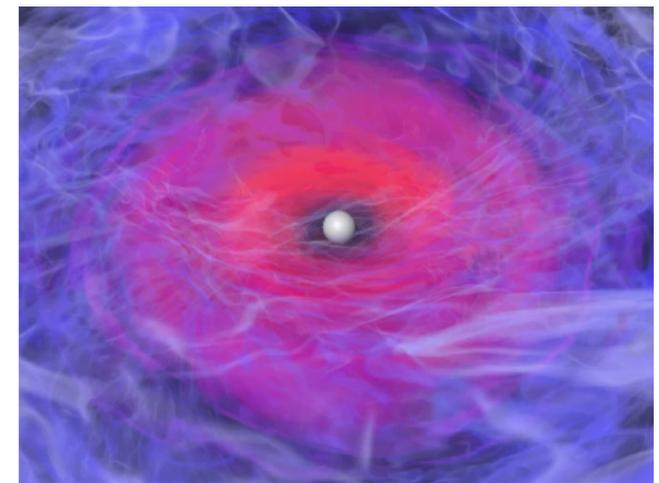
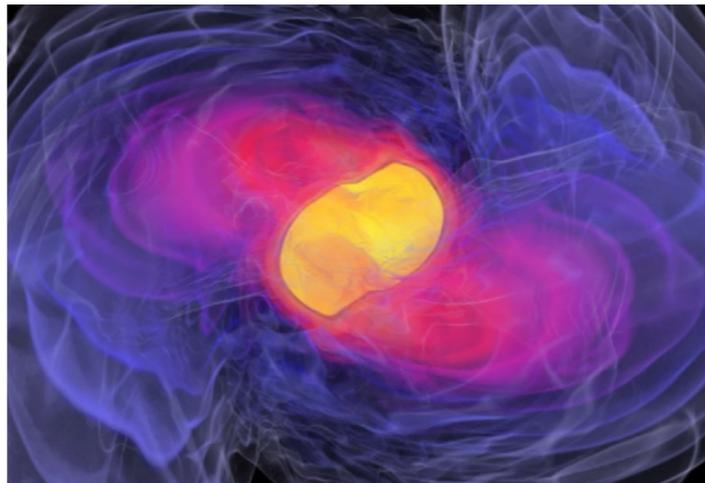
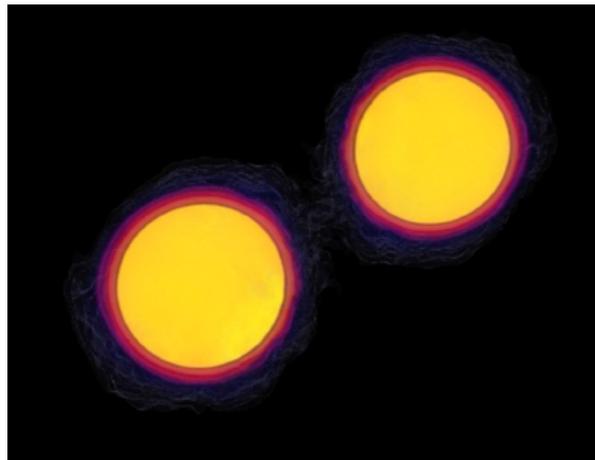


Image credit: NASA



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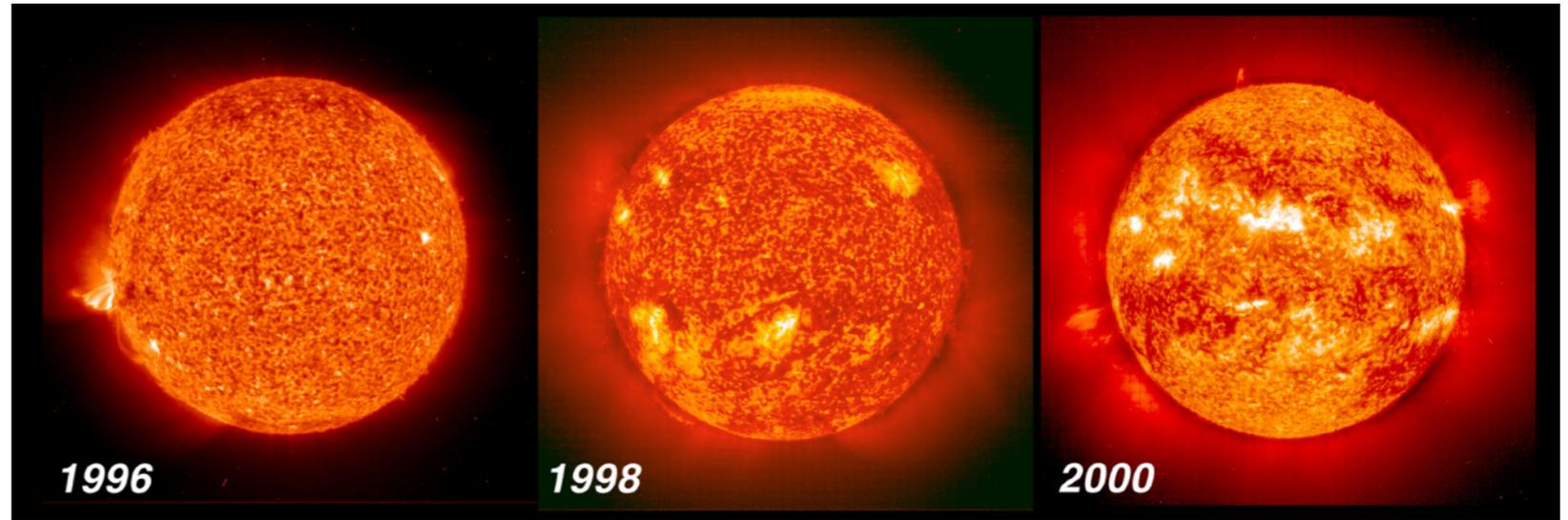
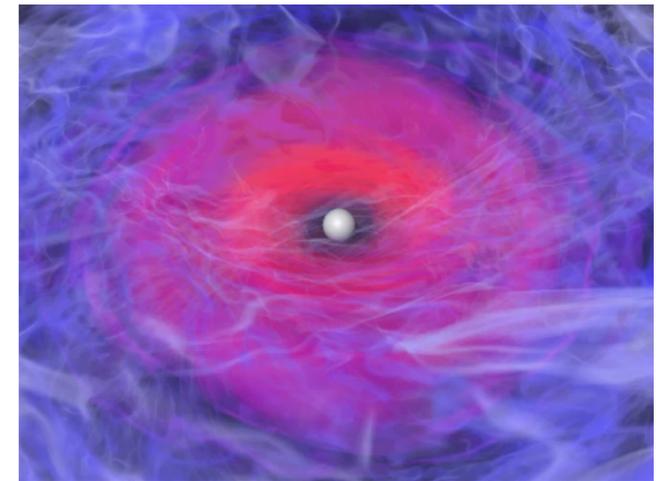
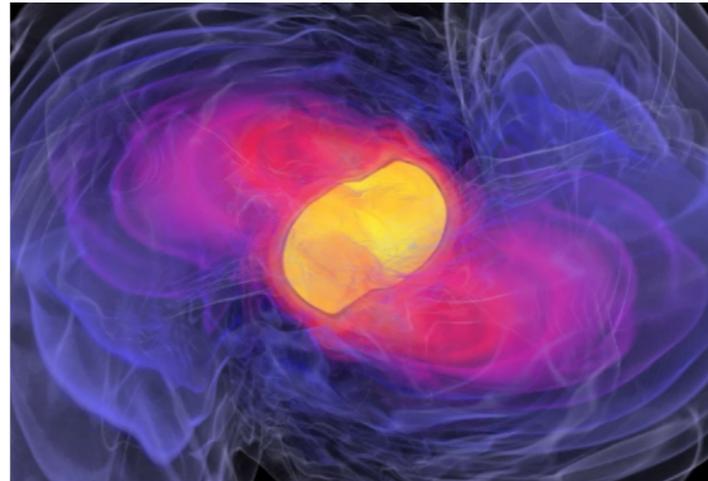
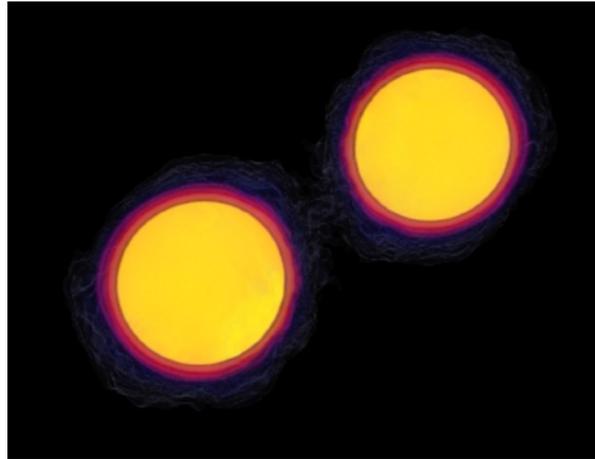
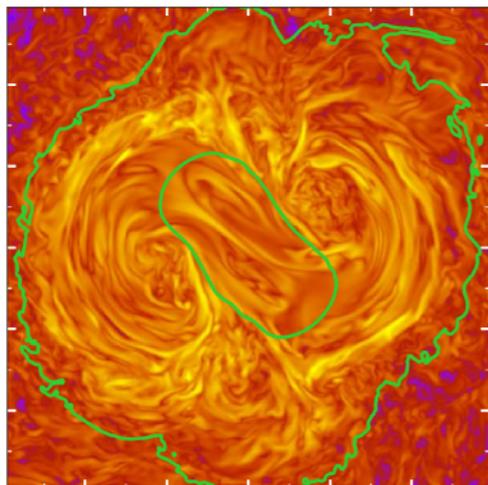


Image credit: NASA



**Small scale**



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Magnetic dynamos are one of the key ingredients in the merger!

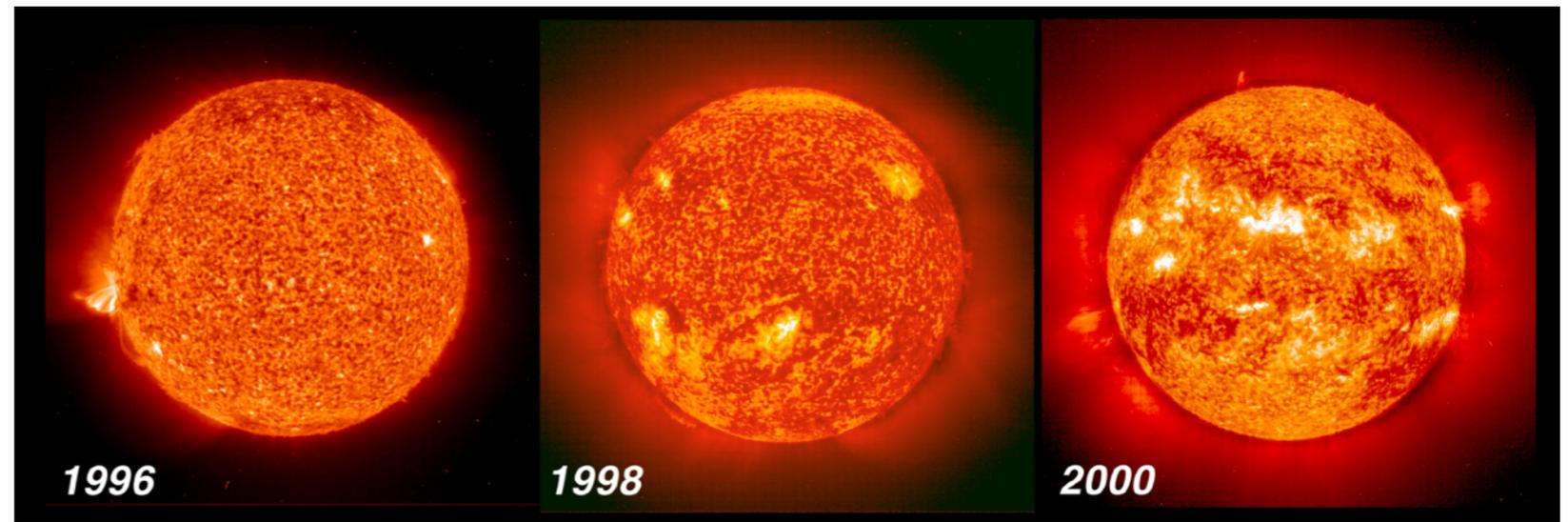
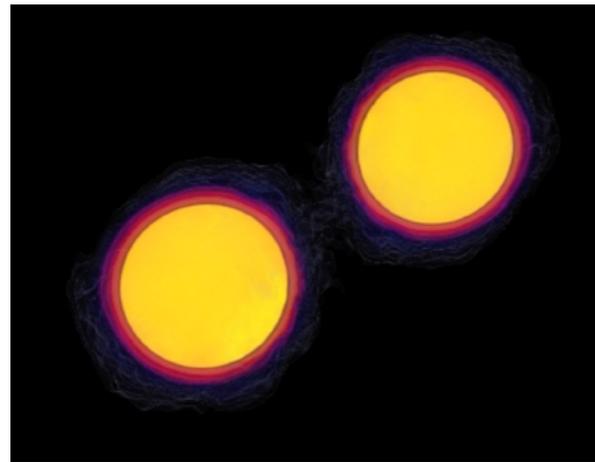
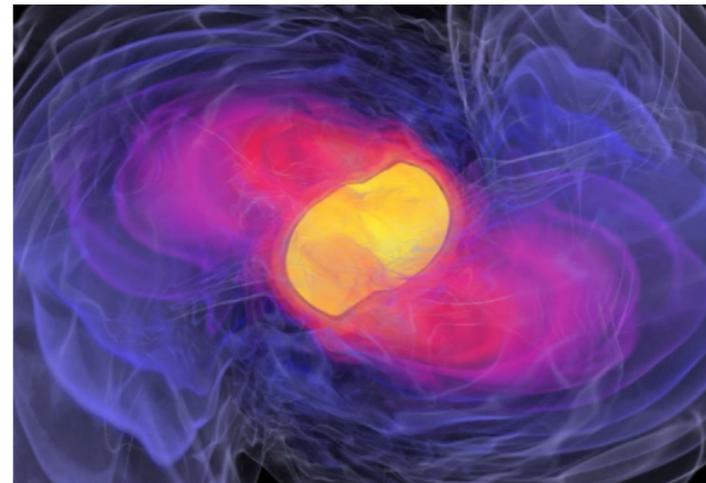


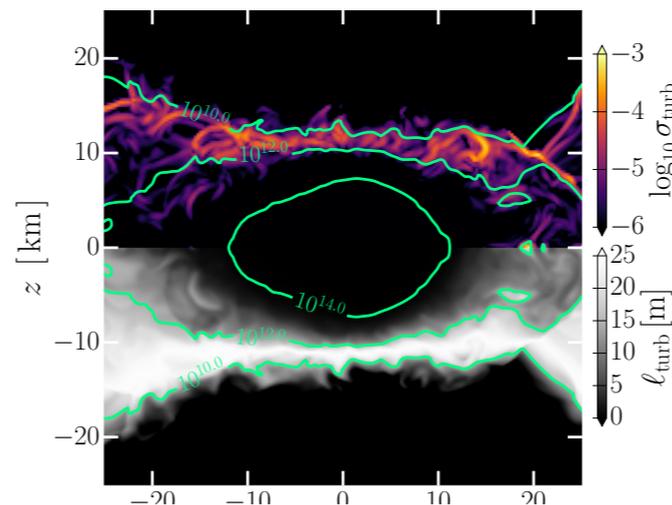
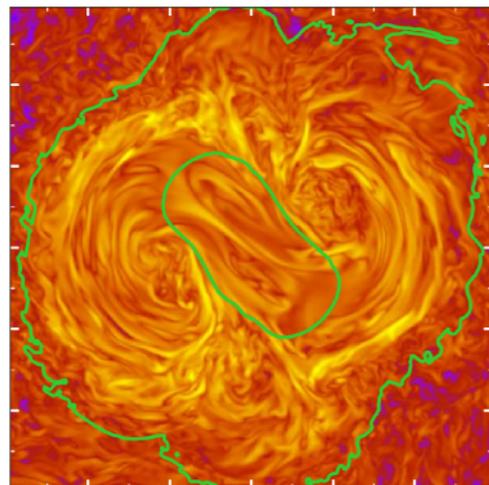
Image credit: NASA



### Small scale



### Large scale



Price+, Kiuchi+, Palenzuela+, Aguilera-Miret+, Chabanov+, Liska+, Christie+, Jacquemin-Ide+, Hogg+, Musoke+, Galishnikova+, Gutierrez+ others

# Dynamamos in action!

Magnetic dynamamos are one of the key ingredients in the merger!

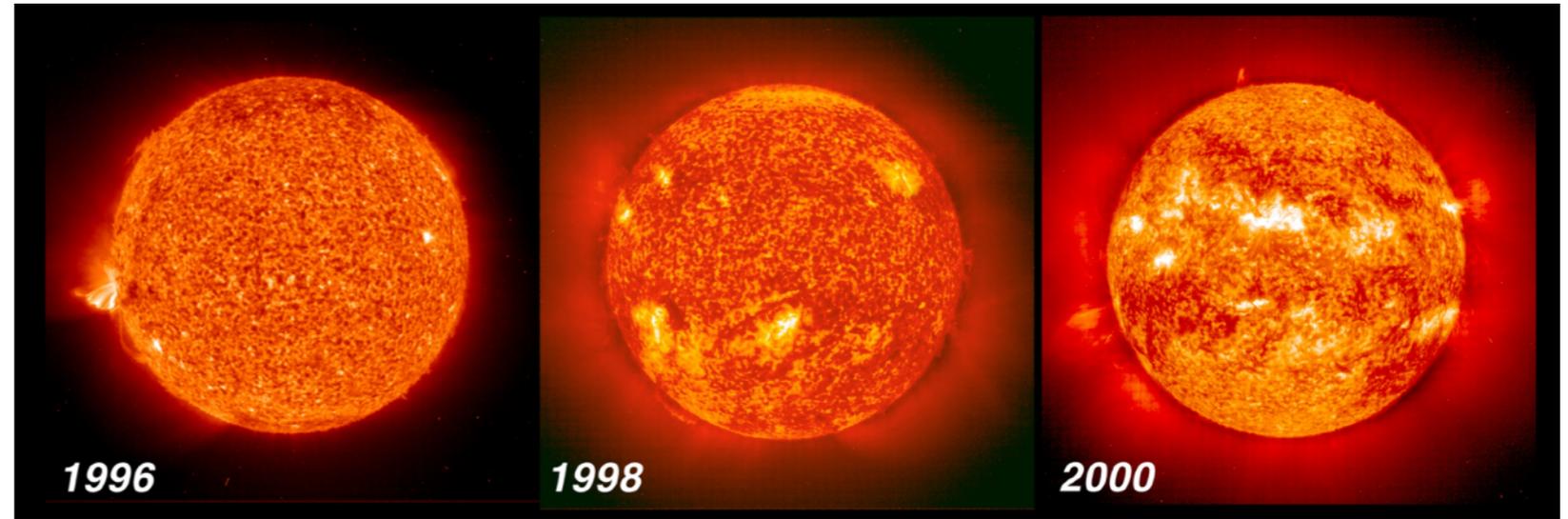
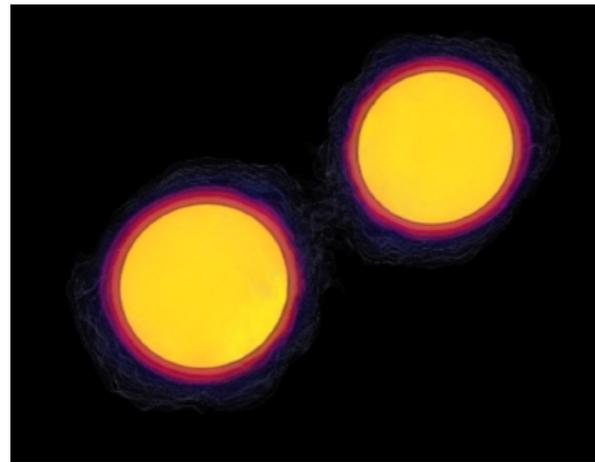
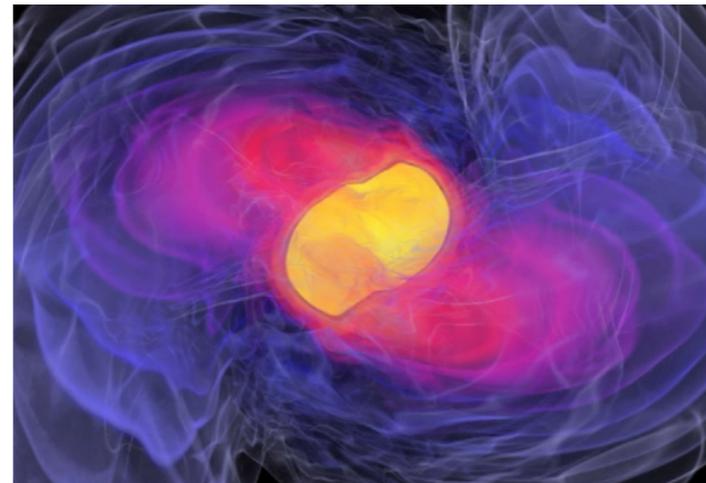
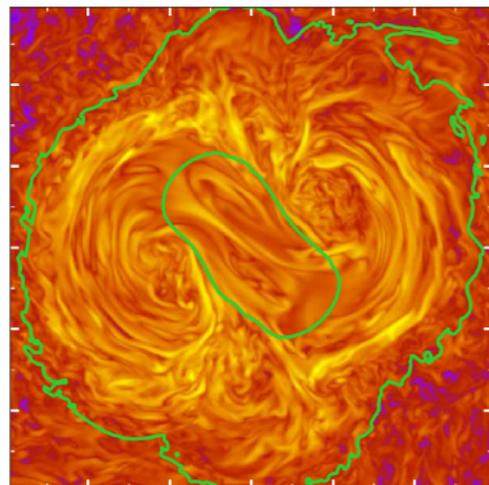


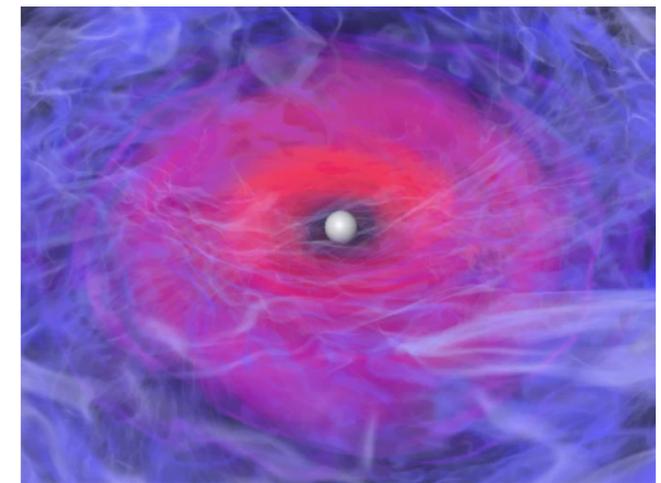
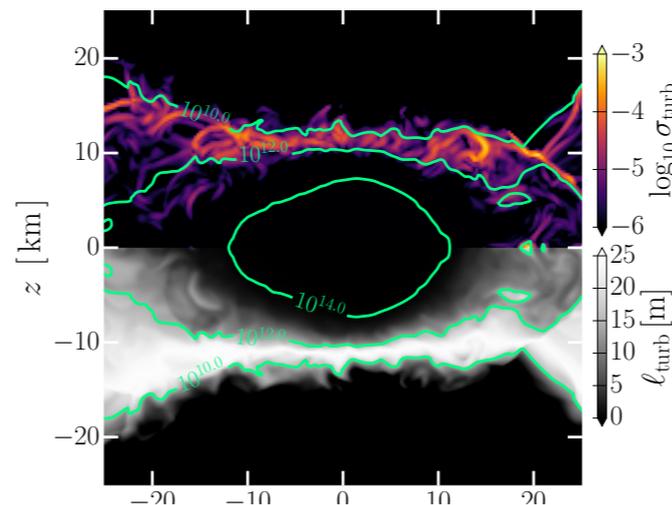
Image credit: NASA



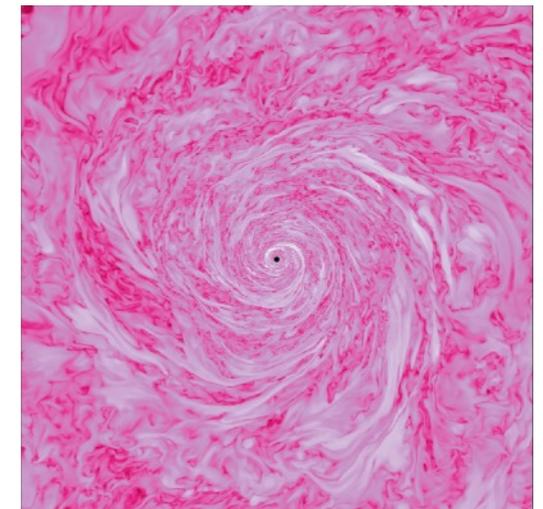
### Small scale



### Large scale



### Disk dynamo



Price+, Kiuchi+, Palenzuela+, Aguilera-Miret+, Chabanov+, Liska+, Christie+, Jacquemin-Ide+, Hogg+, Musoke+, Galishnikova+, Gutierrez+ others

# A simple global mean-field approach

New covariant formulation of **mean-field  $\alpha$ -term** for ideal GRMHD limit from dissipative MHD (non-stiff)

See also Bucciantini, Del Zanna, Shibata for stiff formulations.

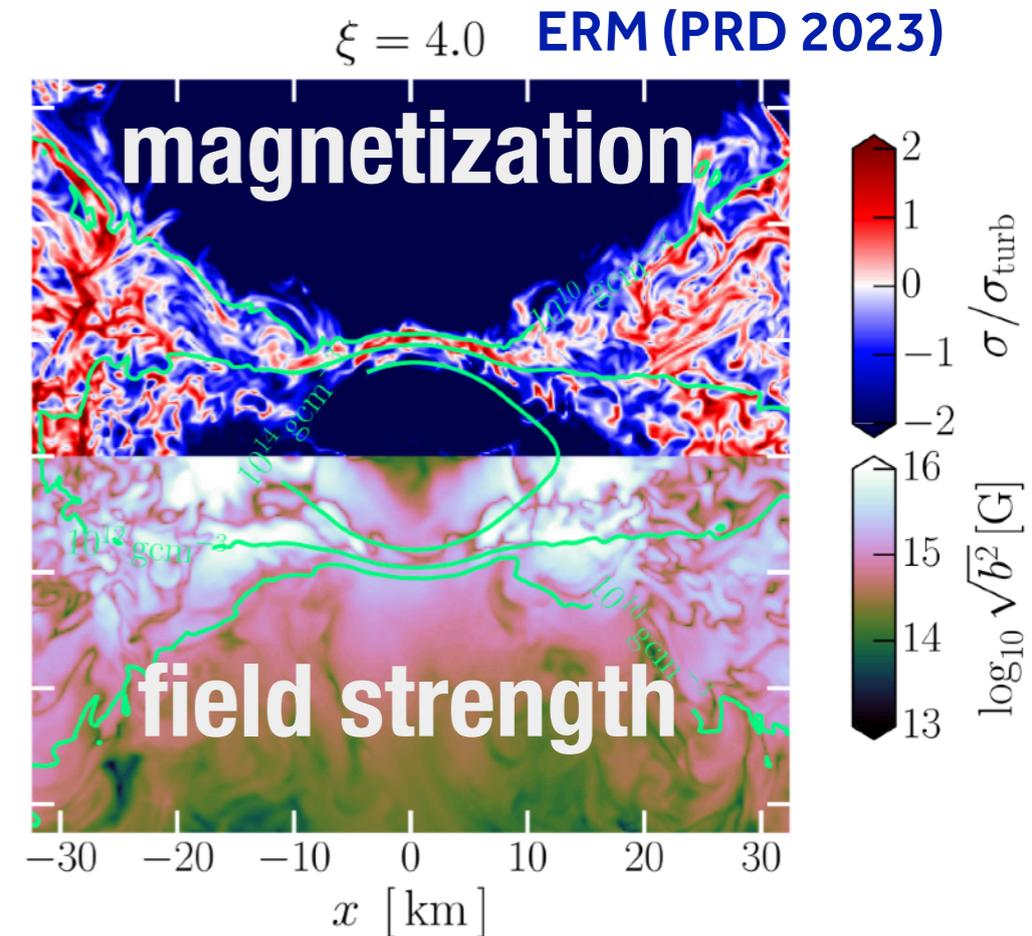
$$\tau u^\alpha \nabla_\alpha J_e^{<\mu>} + J_e^\mu = \sigma e^\mu + \alpha_\nu^\mu b^\nu + \beta \varepsilon^{\mu\nu\alpha\gamma} \hat{\beta}_\nu b_\alpha (J_e)_\gamma + \dots$$

$$\vec{E} = -\vec{v} \times \vec{B} + \overleftrightarrow{\kappa} \vec{B} + \overleftrightarrow{\beta} \vec{J}$$

Can formulate this perturbatively in the dynamo term, to allow easy coupling to existing GRMHD codes

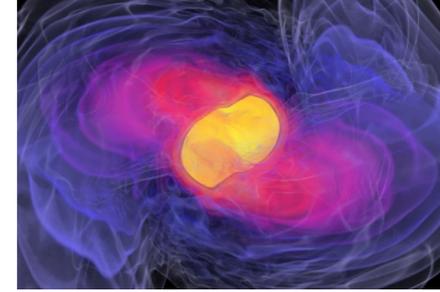
$$E^i = -\varepsilon^{ijk} v_j B_k + \kappa [(1 - v^2) B^i + (v_l B^l) v^i] + \mathcal{O}(\kappa^2)$$

ERM (PRD 2023)



see talks by  
Miravet-Tenes, Reboul-Salze

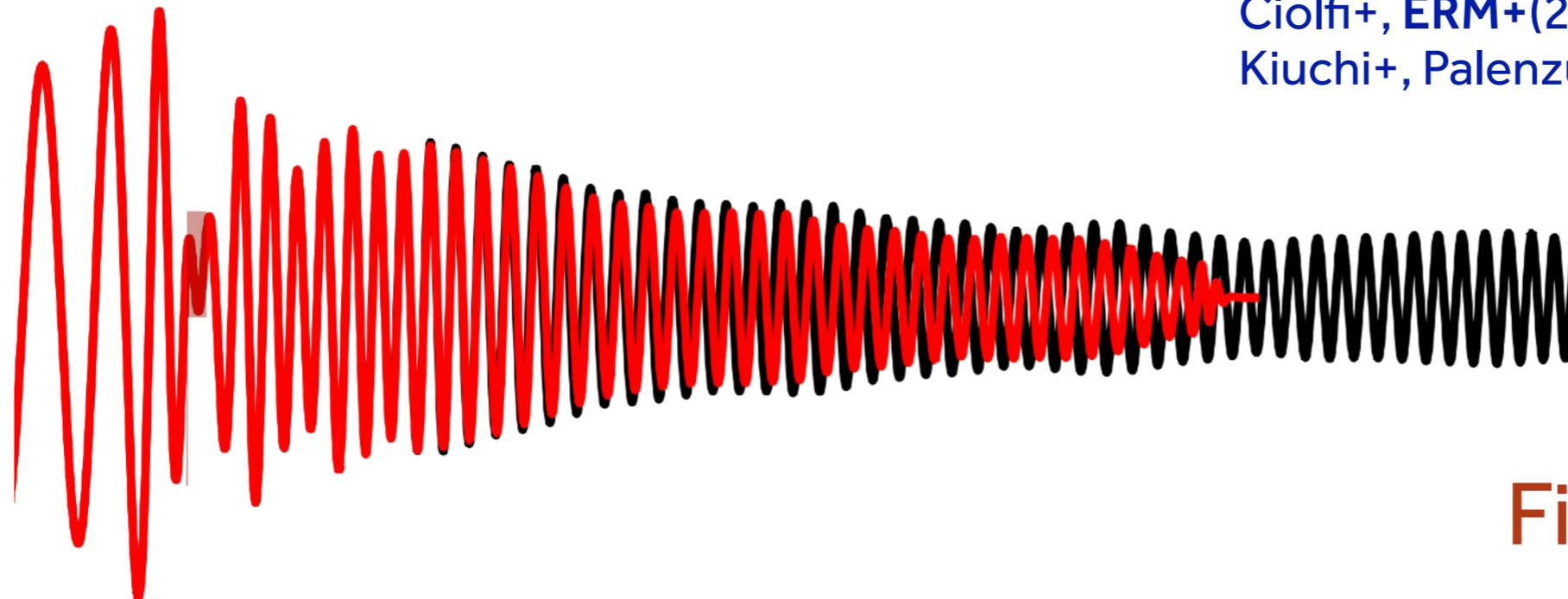
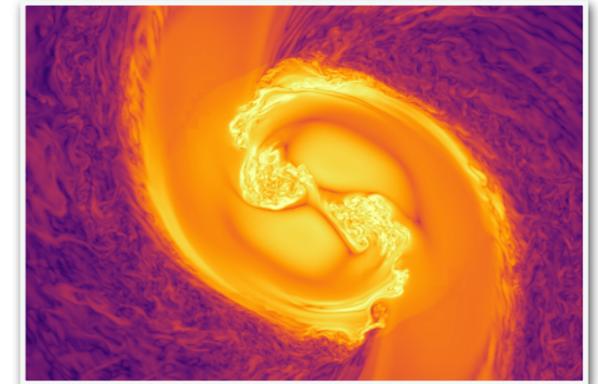
# A true multi-physics problem



Neutron star mergers probe new regimes of physics!

## Magnetic fields?

Ciolfi+, ERM+(2019,2021,2023), Giacomazzo+, Kiuchi+, Palenzuela+,...

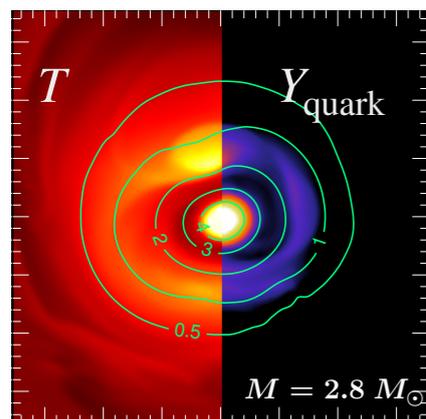


## Exotic degrees of freedom?

Bauswein+, Huang+, ERM+(2019,2020,2023), Prakash+, Radice+, Sekiguchi+, Weih+... (+ many more for EoS uncertainty!)

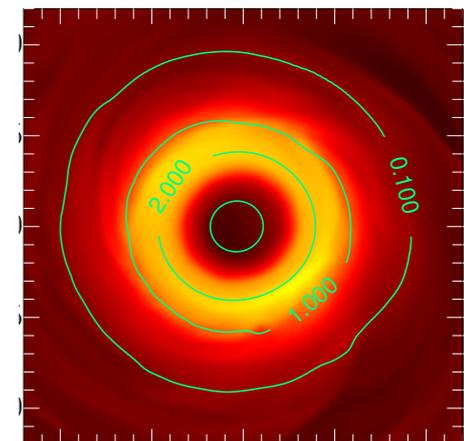
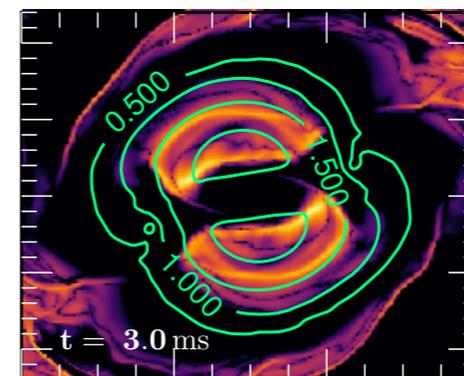
## Finite-temperature and composition?

Bauswein+, ERM+(2021), Figuera+, Hanauske+, Perego+, Raithel+...



## Neutrino effects? (in dense matter)

Alford+, Cameliolo+, Foucart+, Hammond+, ERM+(2022,arXiv), Radice+, Shibata+,...

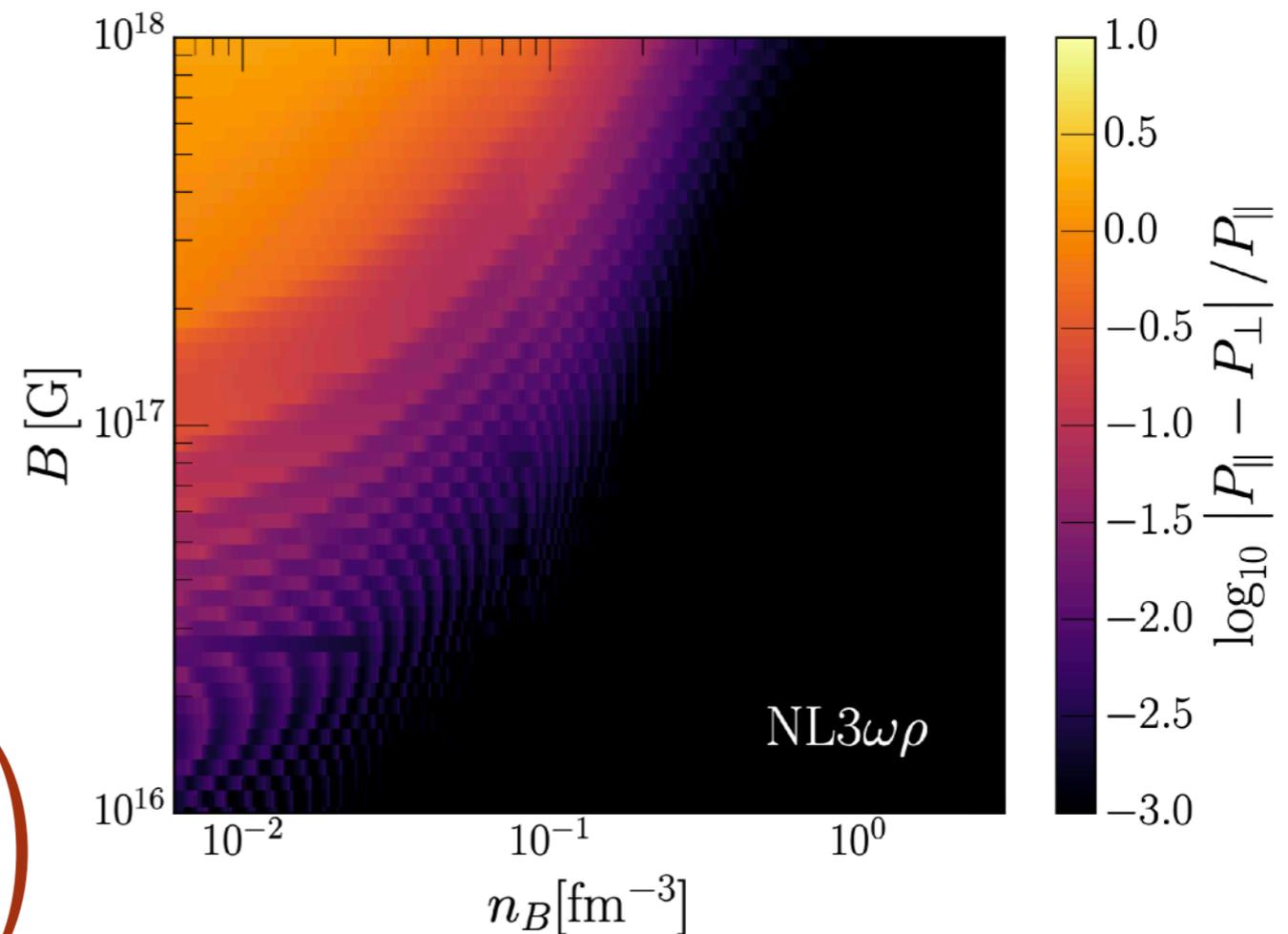
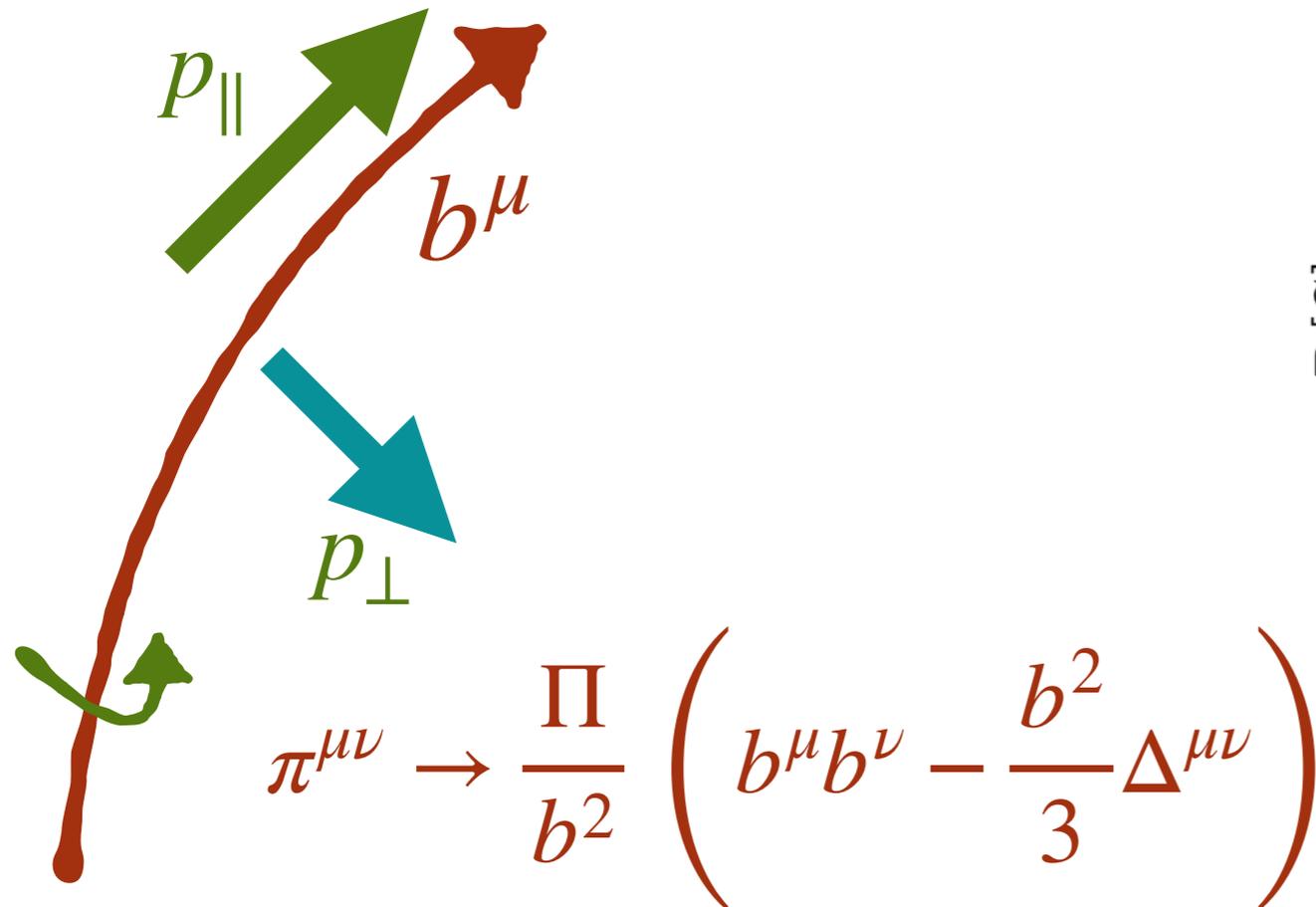


# Pressure anisotropies in the crust?

At near equipartition field strengths could have feedback on equation of state (Landau level quantization, de Haas-van Alphen effect)

Pressure anisotropy can be same order as viscosities or thermal effects.

$$\Pi = \frac{1}{2} (P_{\parallel} - P_{\perp})$$



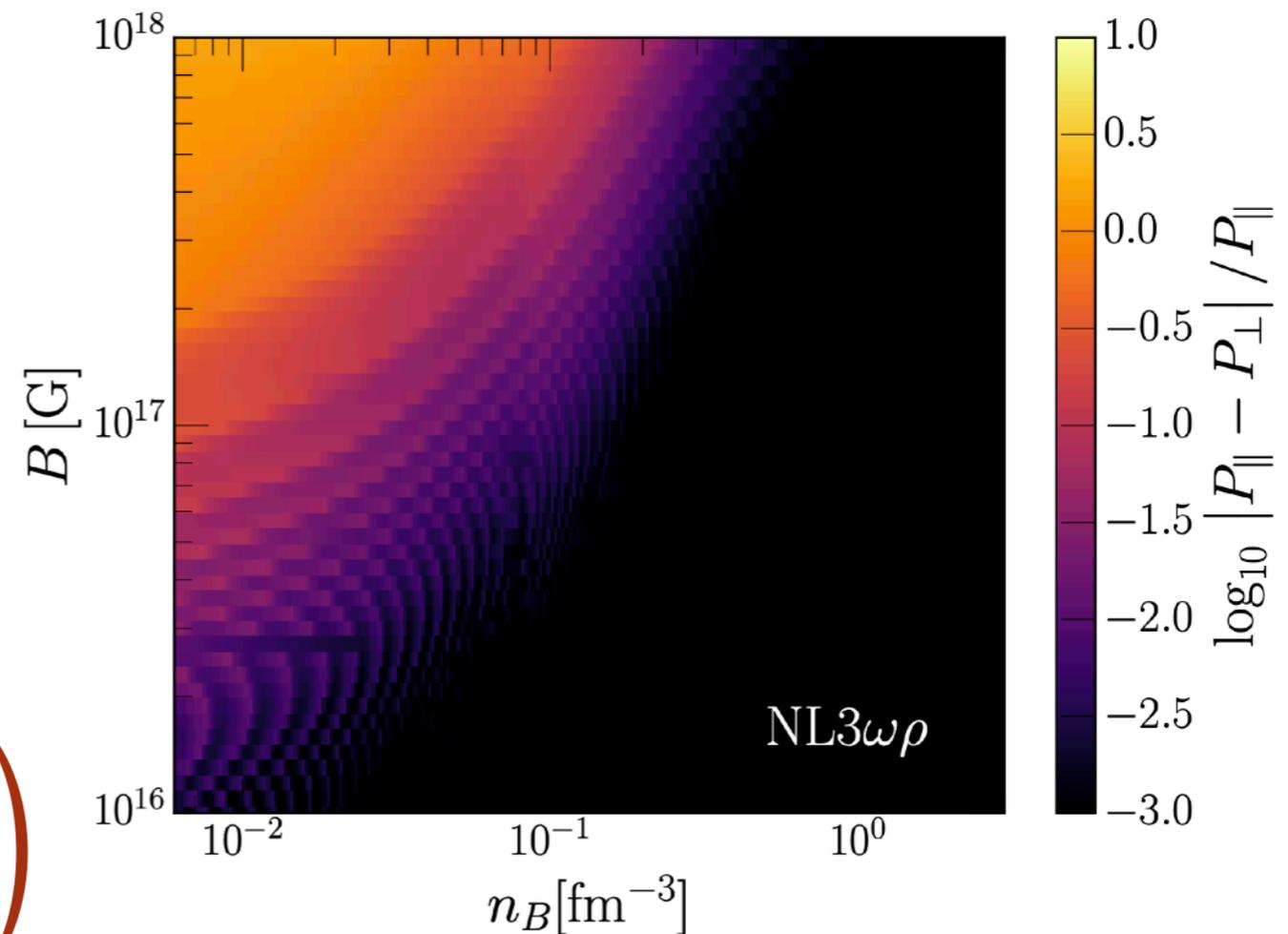
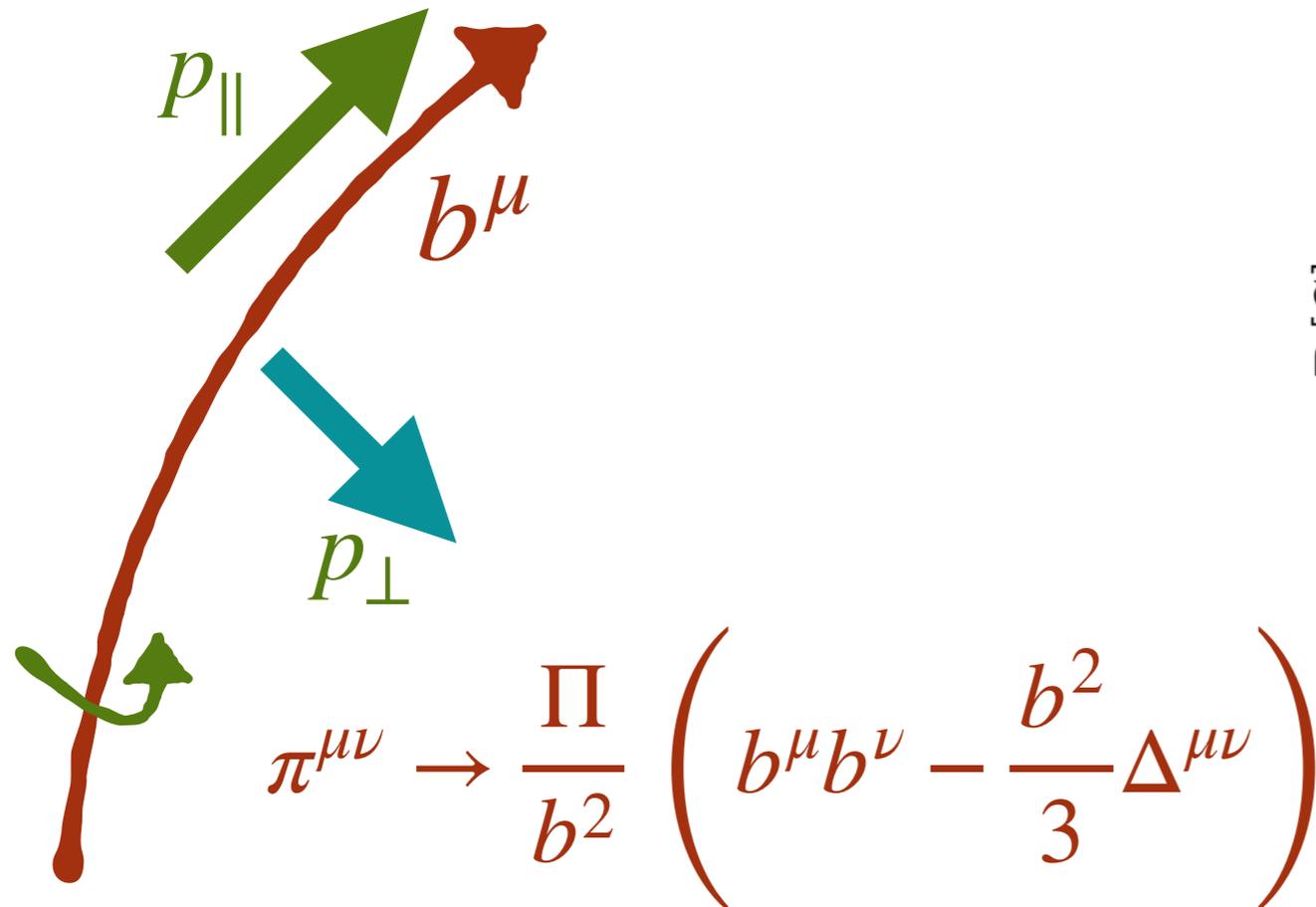
Based on Pais & Providencia (2016)

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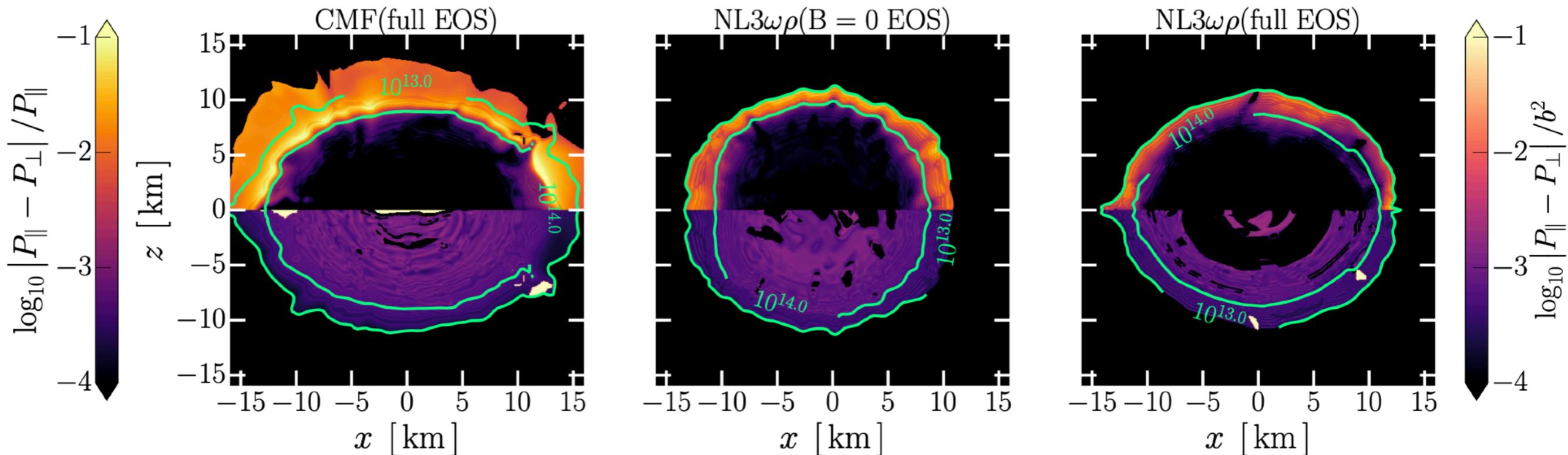


Based on Pais & Providencia (2016)

# Pressure anisotropies in the crust?

First upper bounds on pressure anisotropy in mergers (largely crust region).

ERM, Peterson, Scurto, Pais, Dexheimer (ApJL 2025)



Up to 10% in crust.

<0.1% in core

New multi-moment scheme for (non-)dissipative GRMHD scheme with polarization

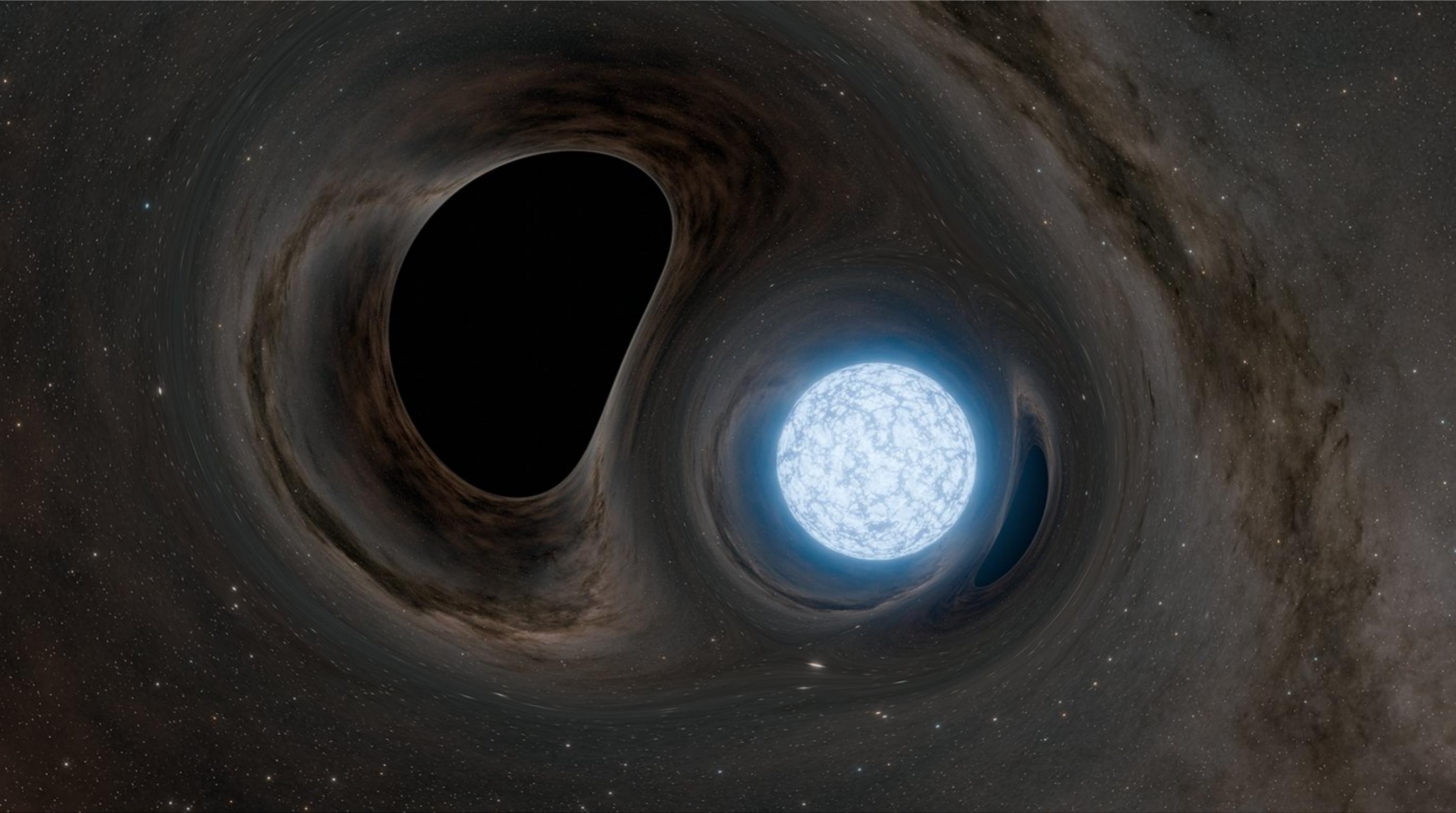
$$\Pi = -\frac{2}{3}\mu b^2$$

$$\pi^{\mu\nu} = \mu \left( b^{\mu} b^{\nu} - \frac{1}{3} \Delta^{\mu\nu} b^2 \right)$$

Susceptibility

$$\mu b^2 = (P_{\perp} - P_{\parallel})$$

# What about black hole - neutron star mergers?

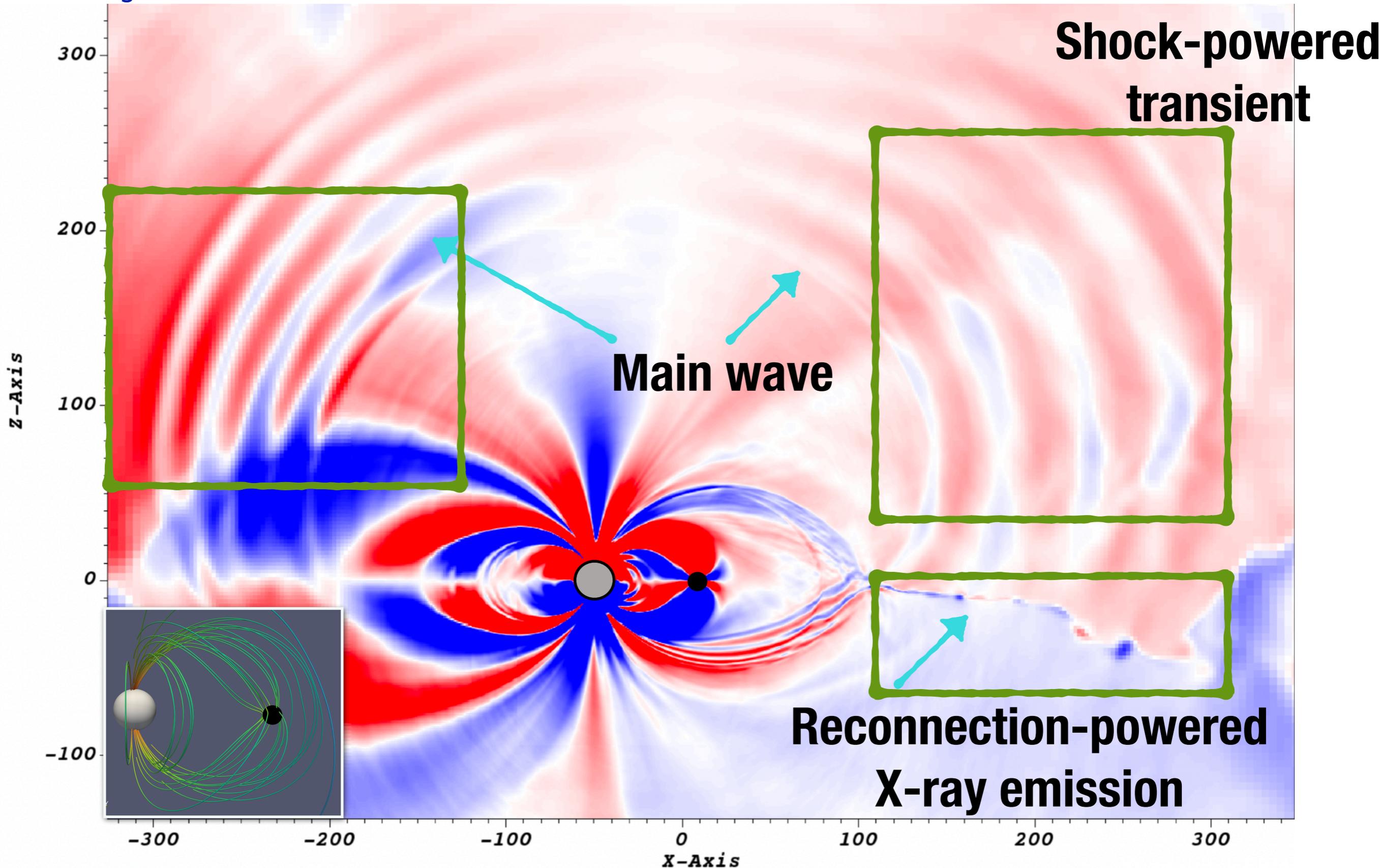


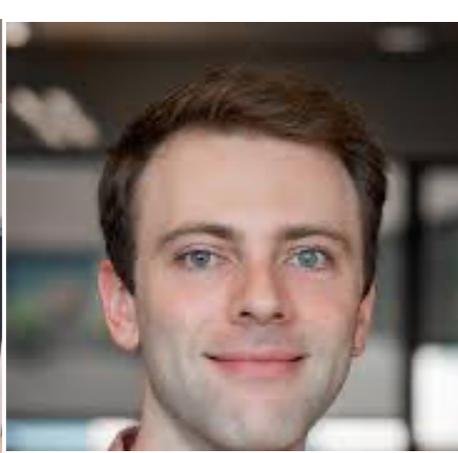
**In most cases, neutron star will be swallowed whole...**

# Crustal dynamics-powered transients?

see Tsang+, Penner+

ERM, Kim, Chatziioannou, Legred (ApJL 2024)





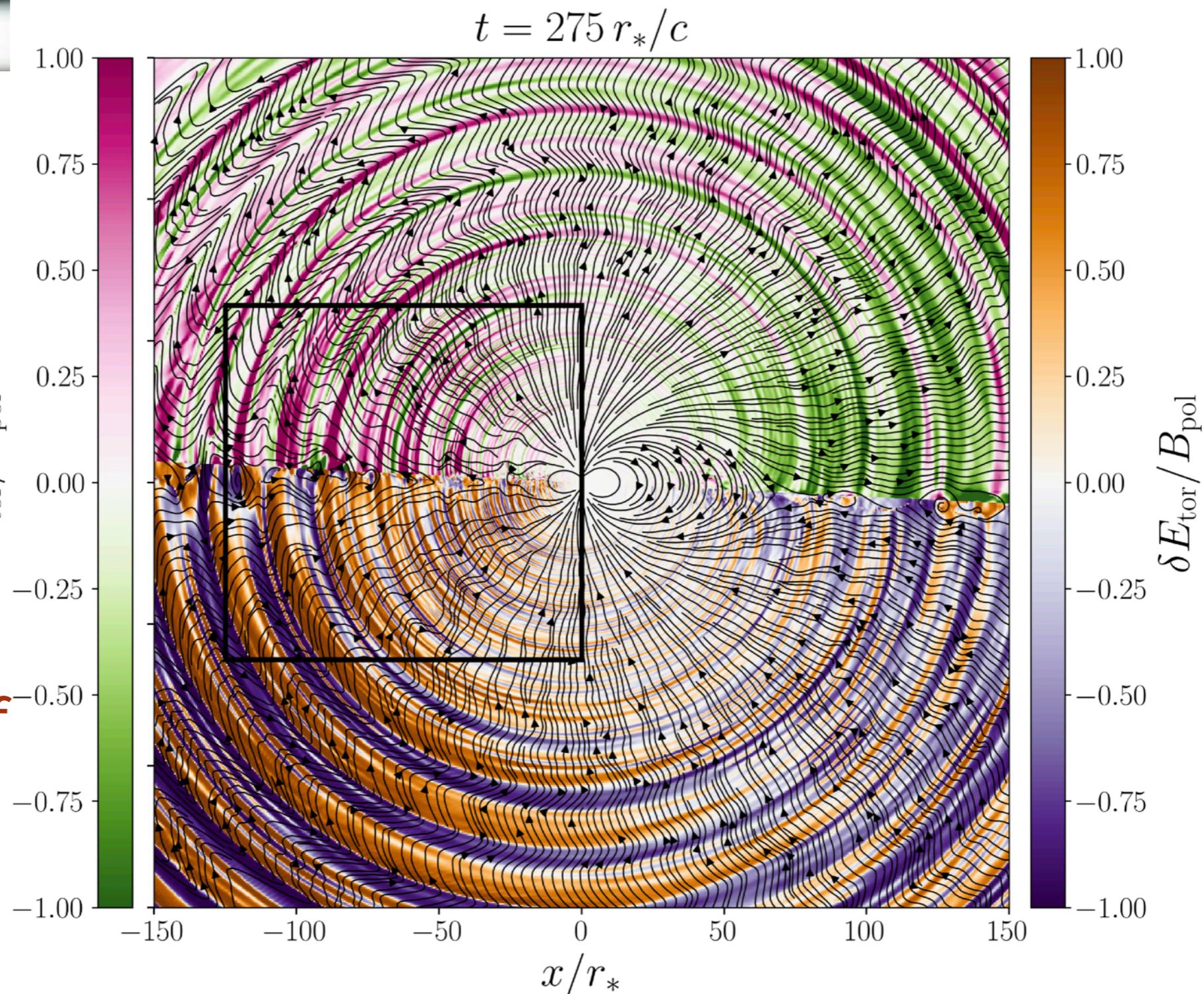
# Isolated magnetar quakes!

L. Burnaz  
(Caltech/Lyon)

A. Bransgrove  
(Princeton)

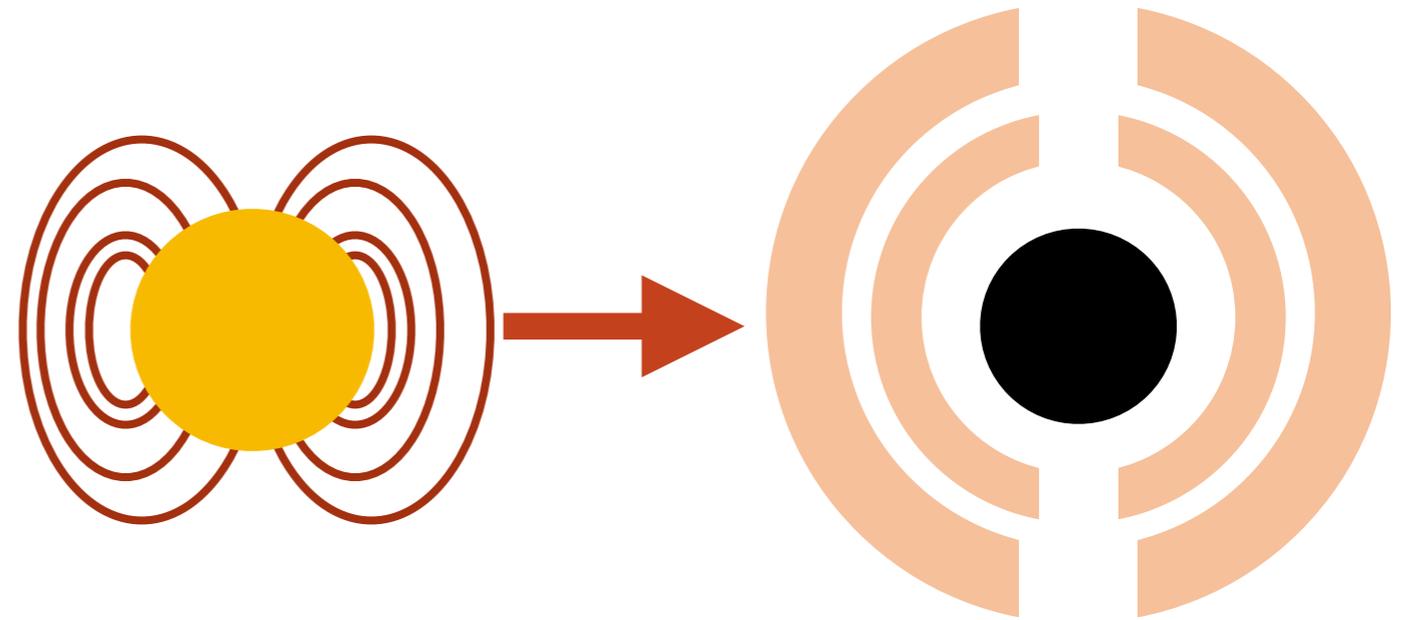
**Couple full crustal  
magnetoelasto-  
dynamics model  
to magnetosphere**

**Cosmic symphony of  
monster shocks,  
nonlinear Alfvén  
wave ejecta,  
reconnection**



Burnaz, ERM, Bransgrove (ApJL 2025)

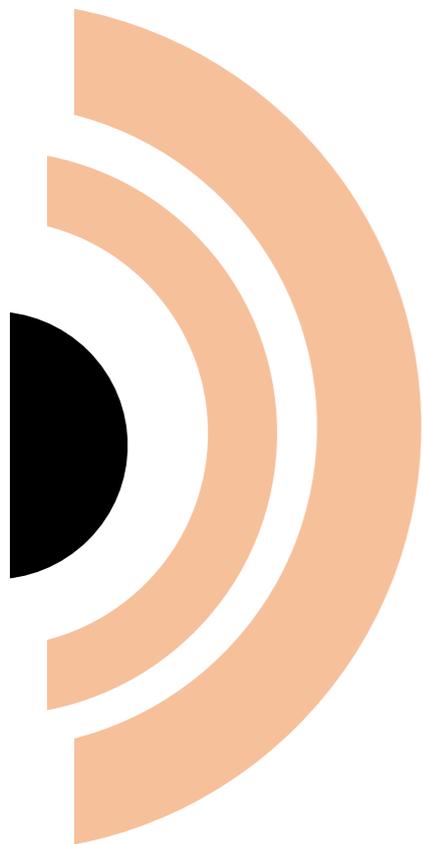
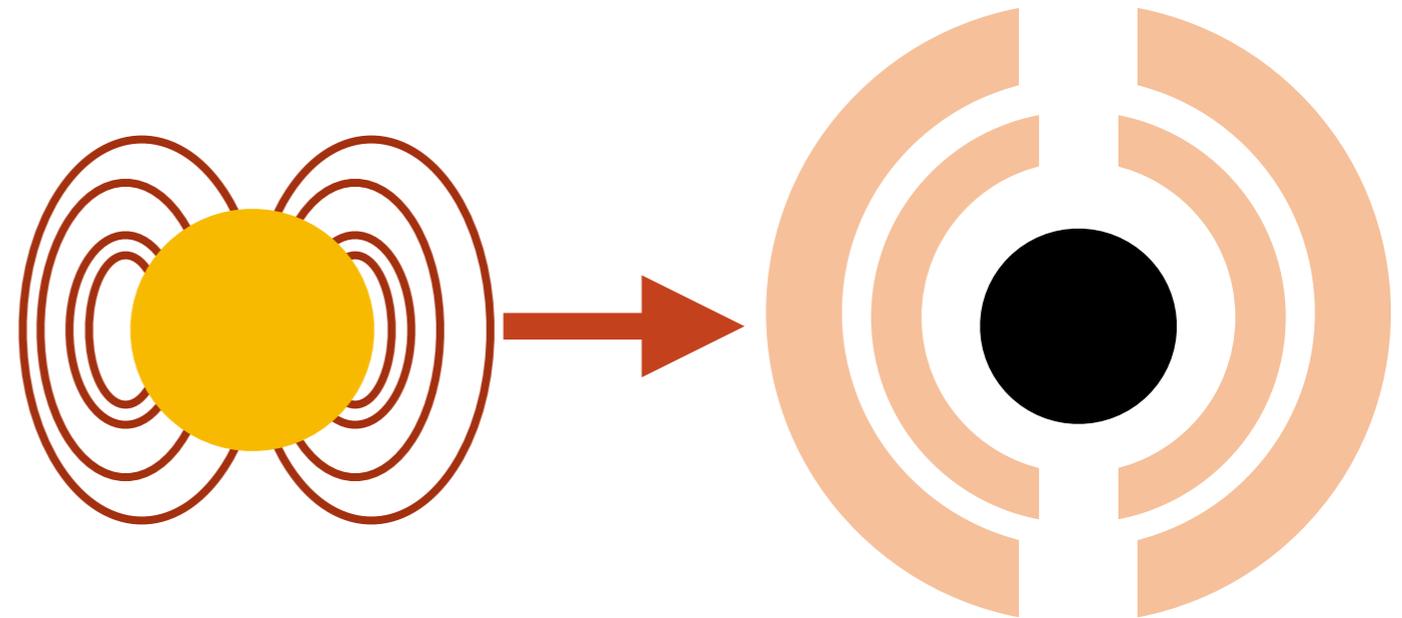
# A new take on collapsing neutron stars



# A new take on collapsing neutron stars

Thorne (1971), Price (1972), Baumgarte & Shapiro (2003), Lehner+ (2012), Palenzuela+(2013), ERM+(2018) See also Stark & Piran (1986)

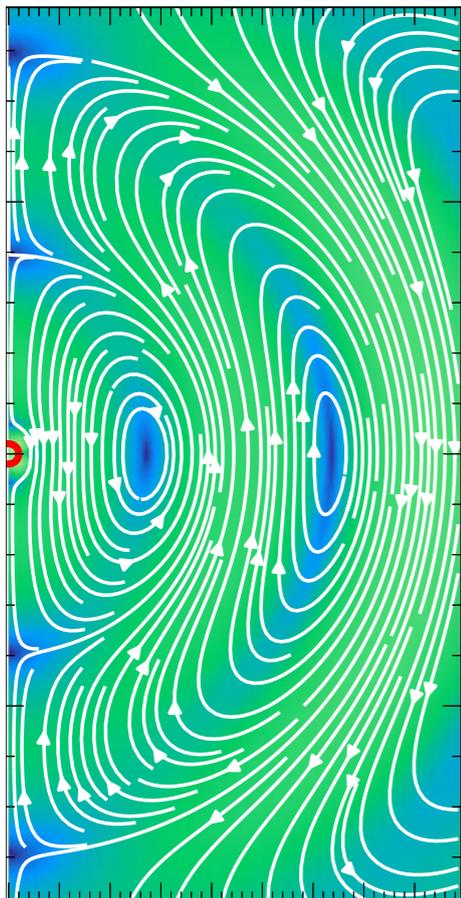
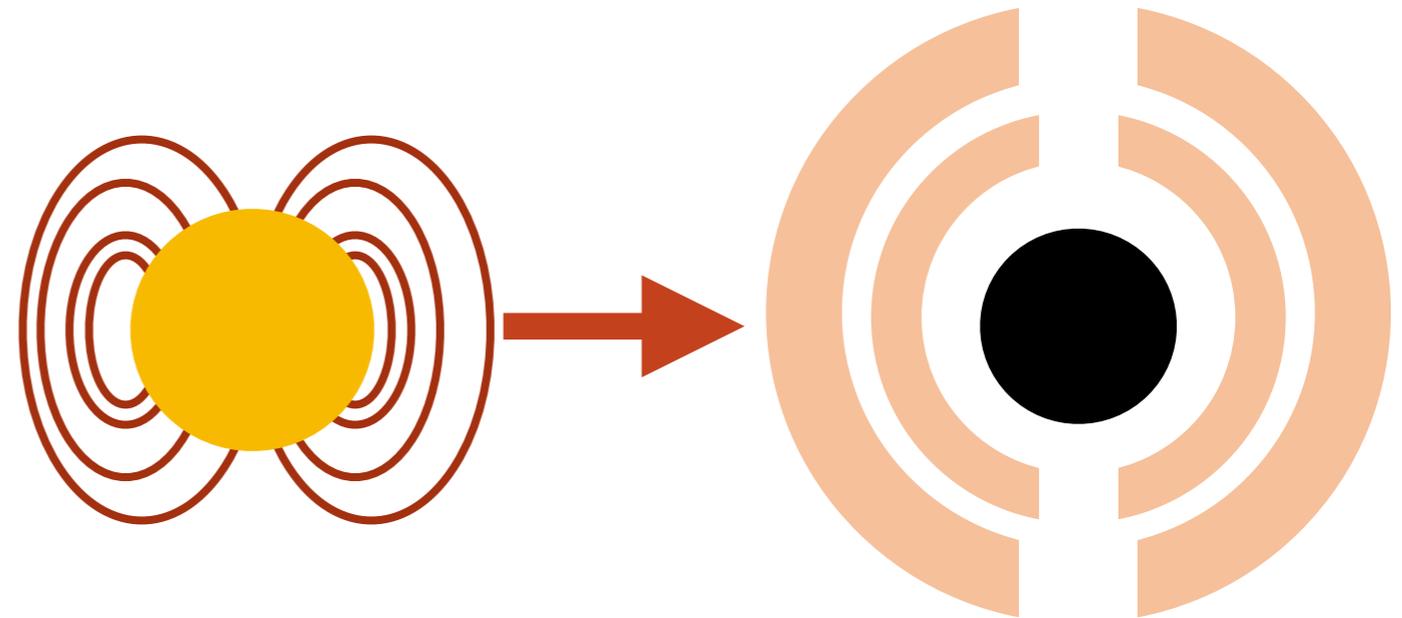
The collapse launches  
**fast magnetosonic waves!**



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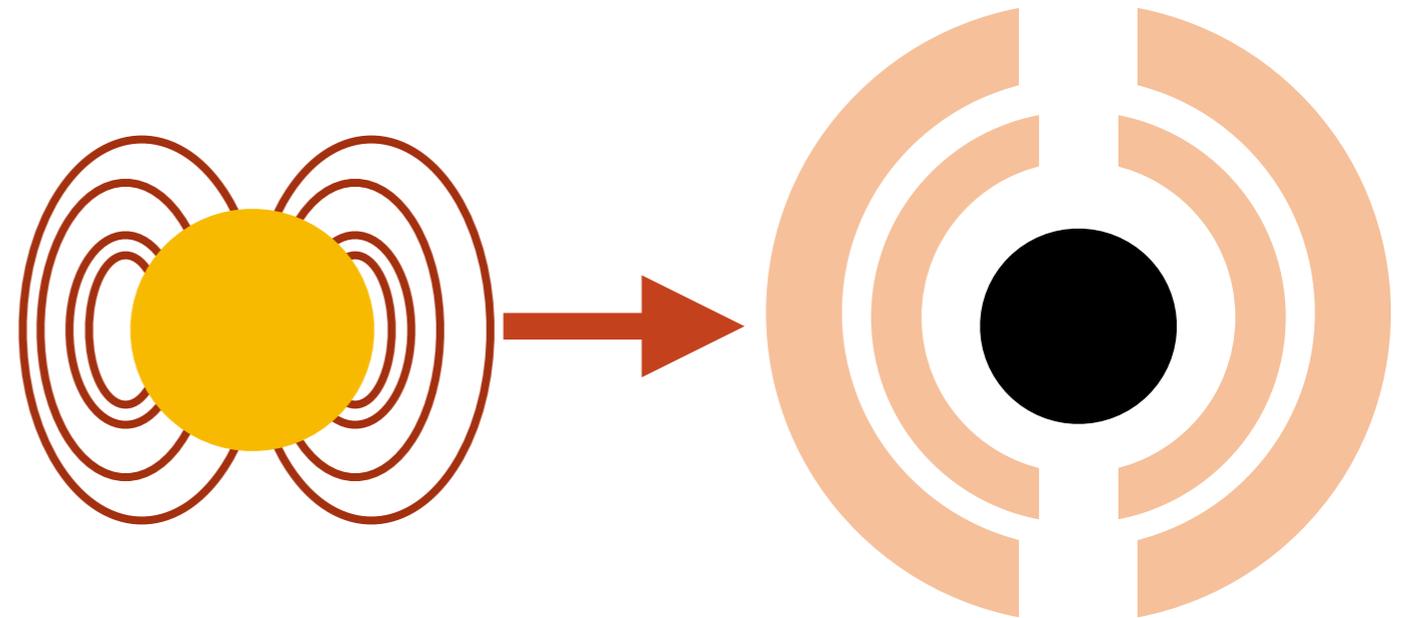


ERM+ (ApJ 2018), see also Baumgarte+, Palenzuela+, Lehner+

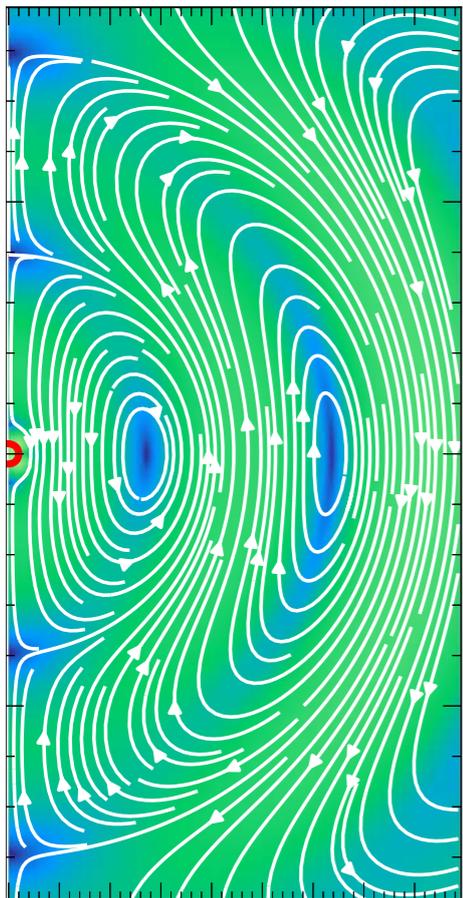
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**What happens following the collapse?**

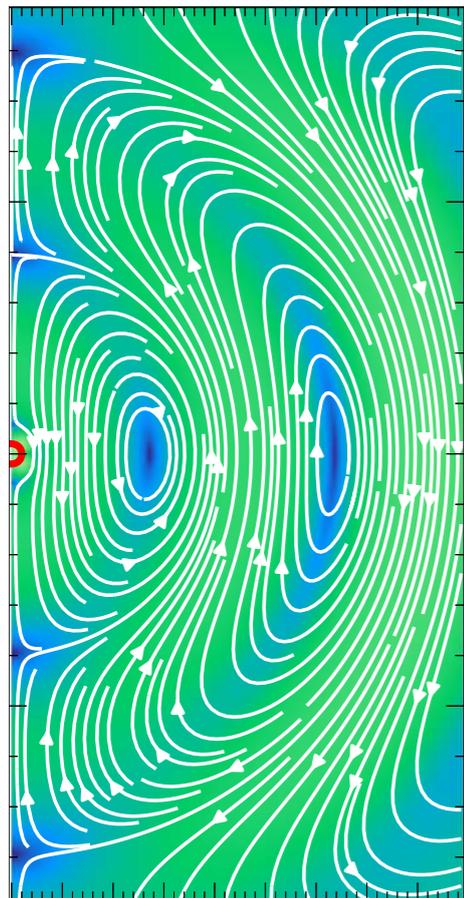
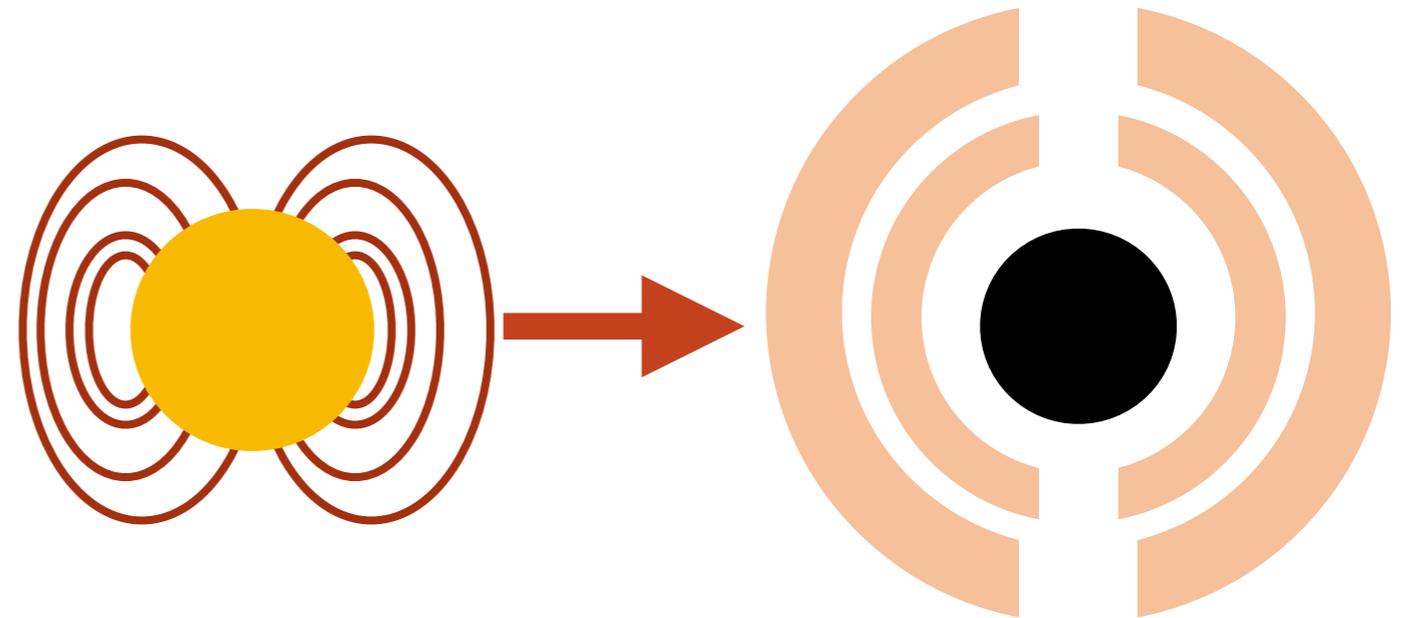


ERM+ (ApJ 2018), see also Baumgarte+, Palenzuela+, Lehner+

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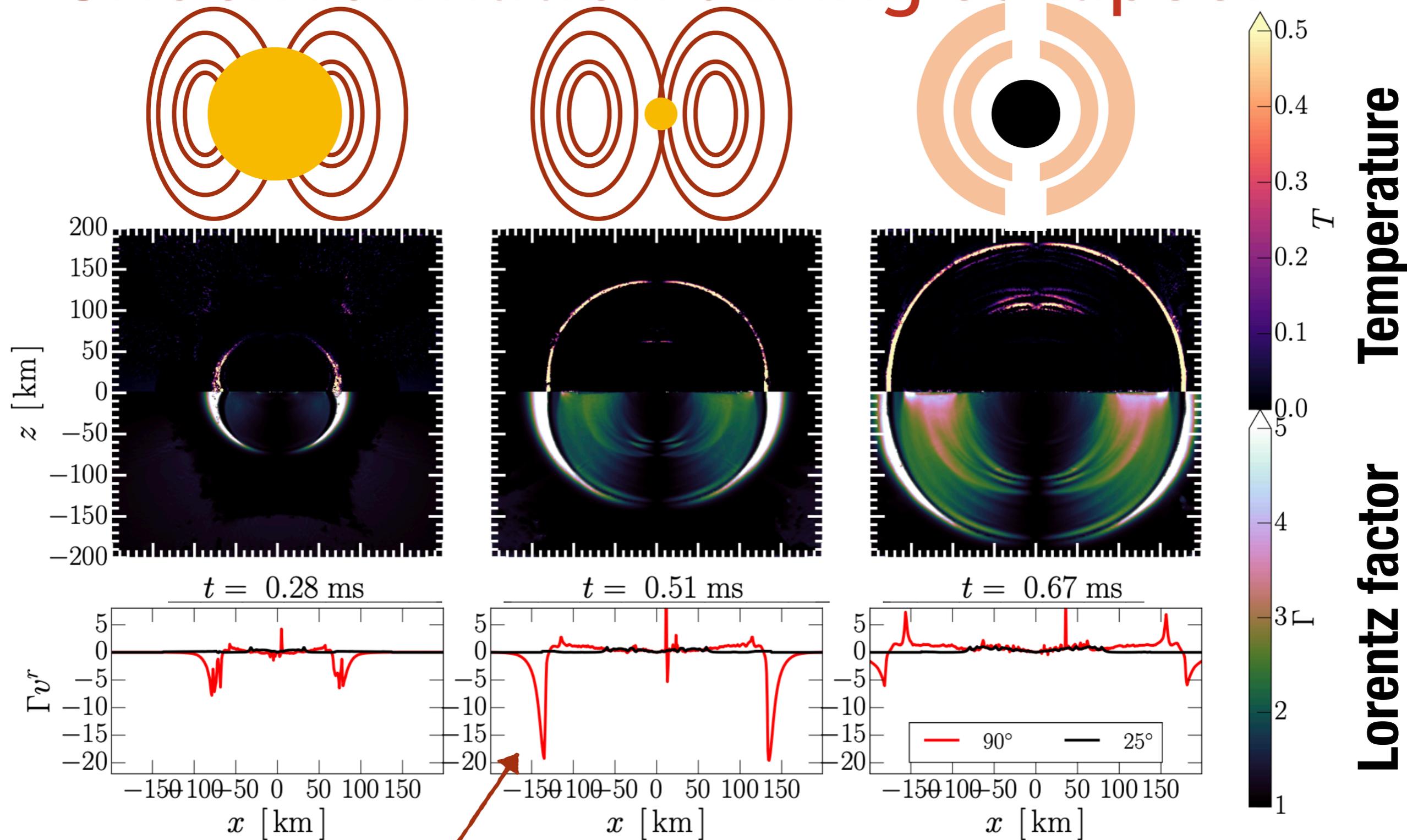
**What happens following the collapse?**



Image credit: Empire Engineering

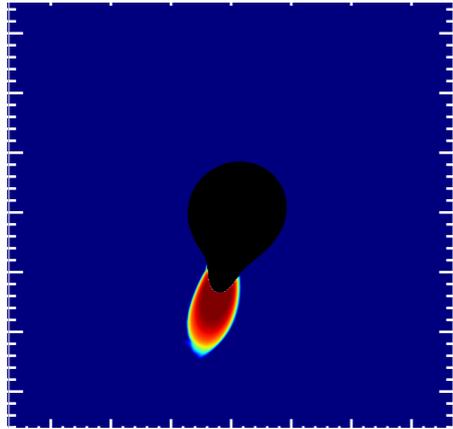
ERM+ (ApJ 2018), see also Baumgarte+, Palenzuela+, Lehner+

# Shock formation during collapse!



**Monster shock!**  
Beloborodov (2023)

ERM, Beloborodov, Ripperda (ApJL 2024)



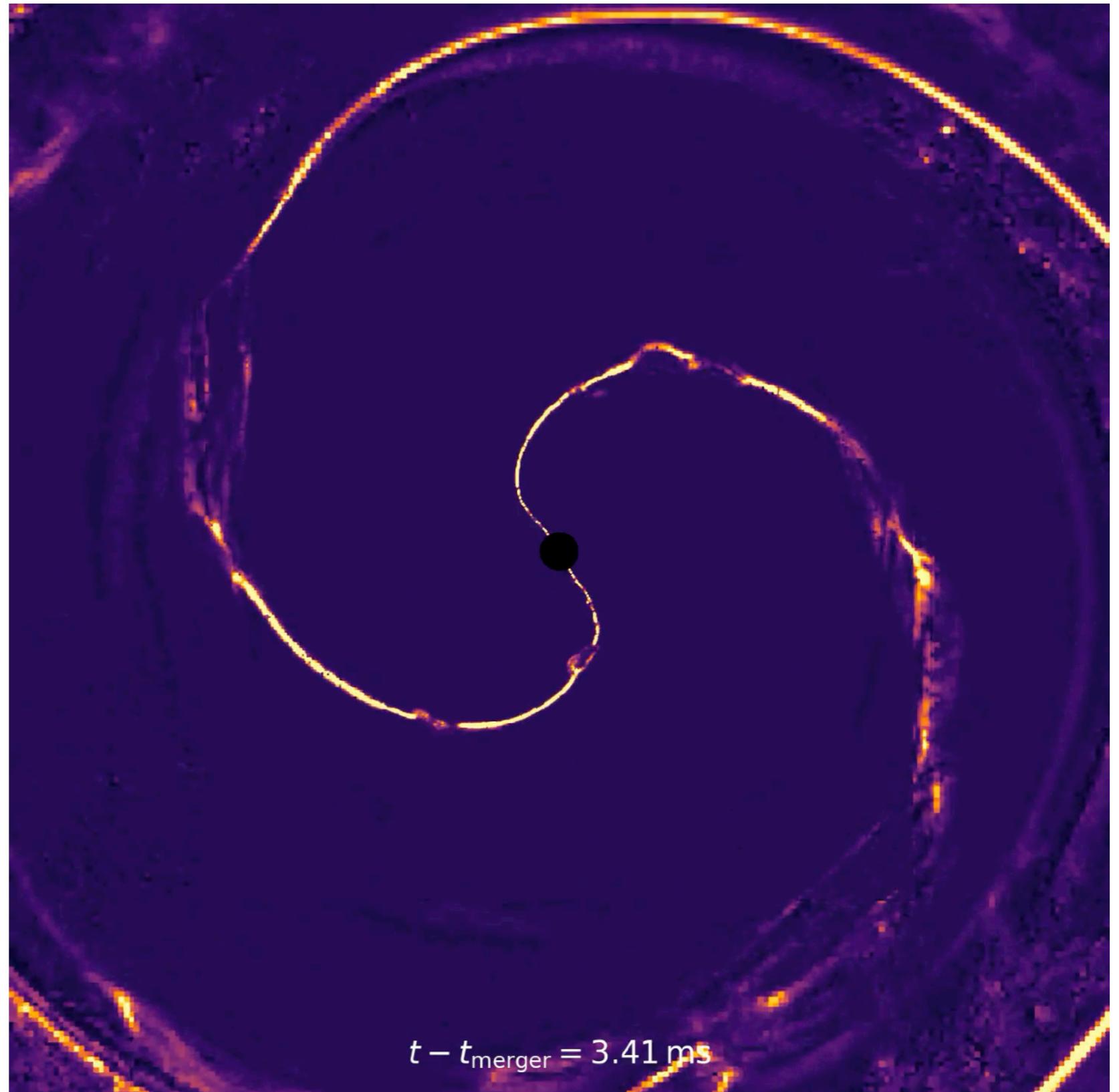
Kim, ERM, Beloborodov, Ripperda (ApJL 2025)

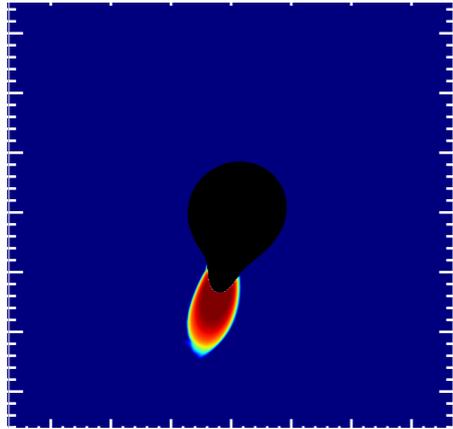
## First demonstration of black hole pulsar formation

*(Black hole no-hair  
theorem still holds,  
pulsar state is transient)*

Levin+ (2018), Selvi+ (2024)

**Striped wind (gamma/  
X-ray transient)**





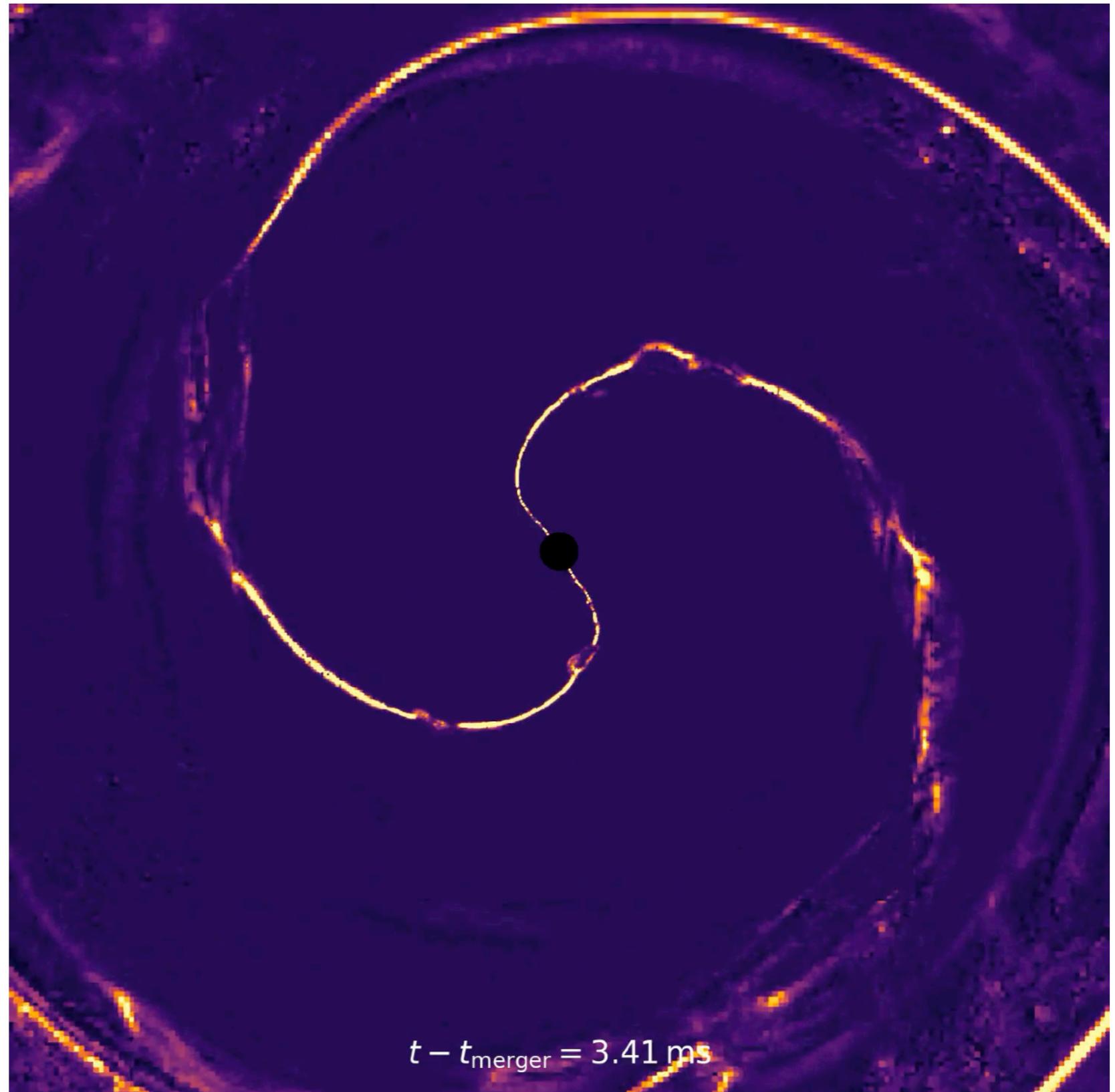
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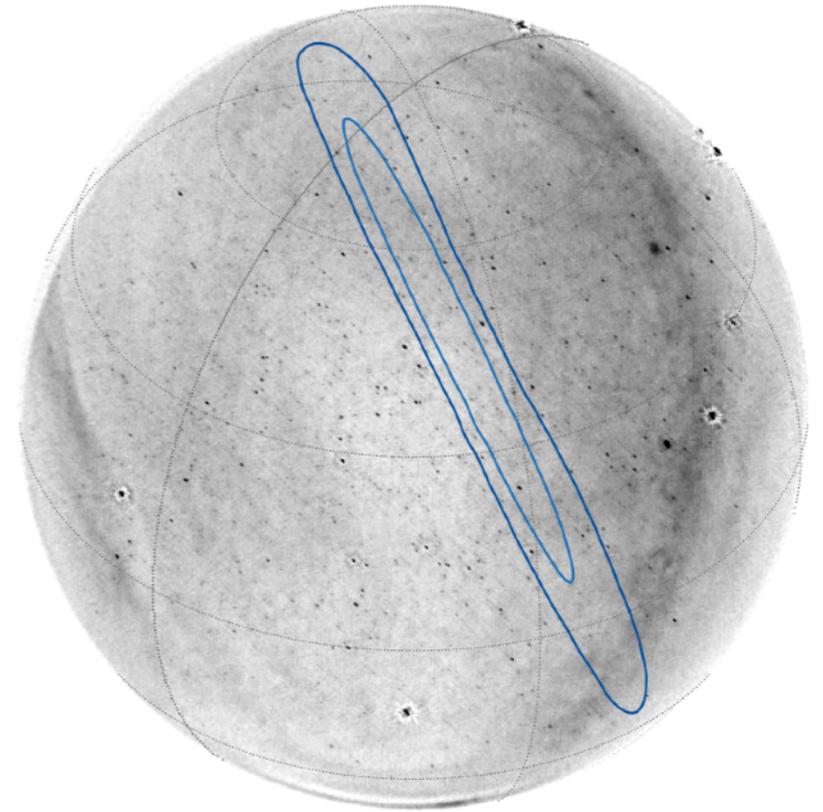
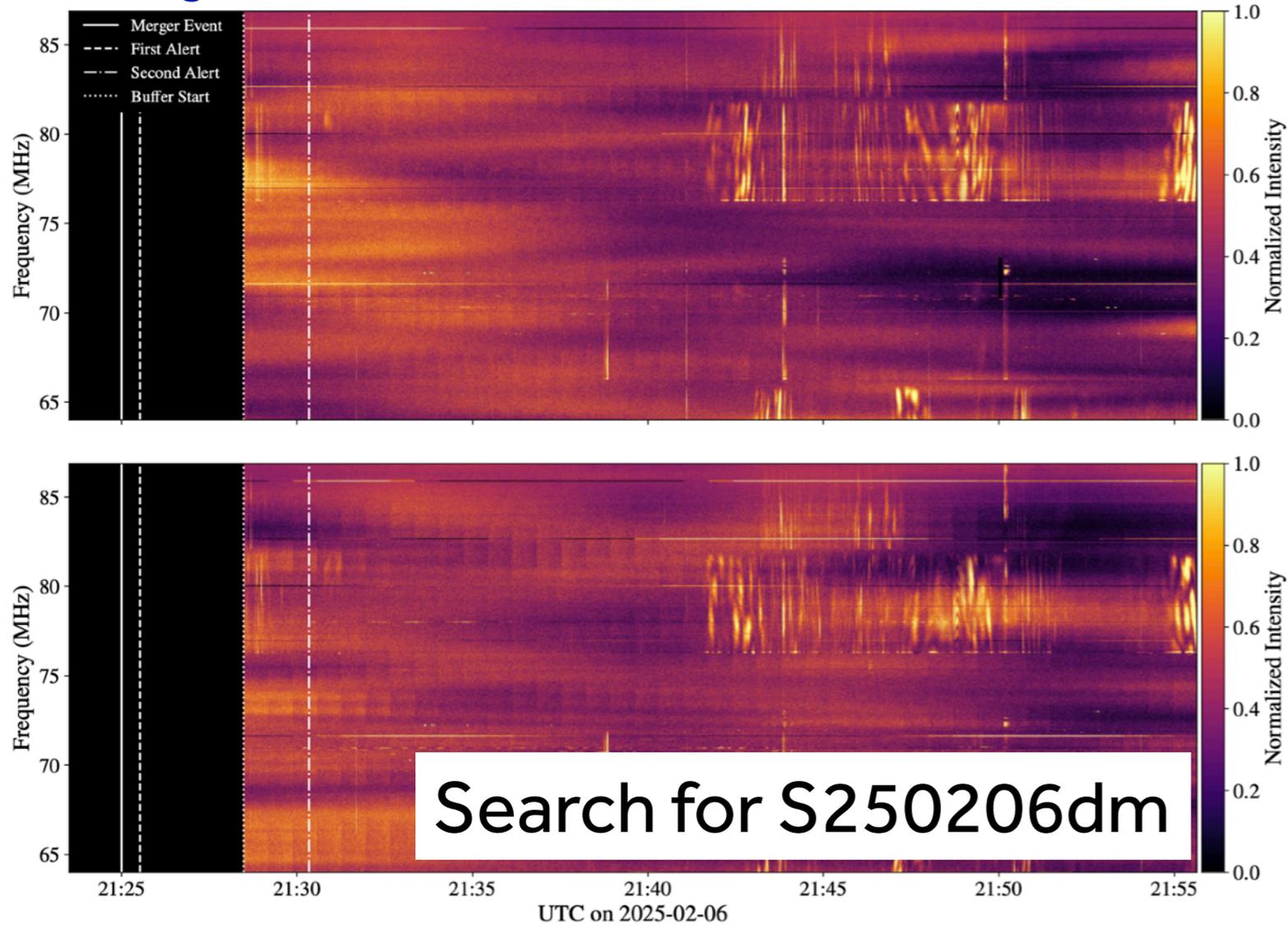
**Striped wind (gamma/  
X-ray transient)**



# Observational prospects

Callister+ (2019)

Kosogorov+(2026)



OVRO Long Wavelength Array



DSA-2000 (planned)

Caltech



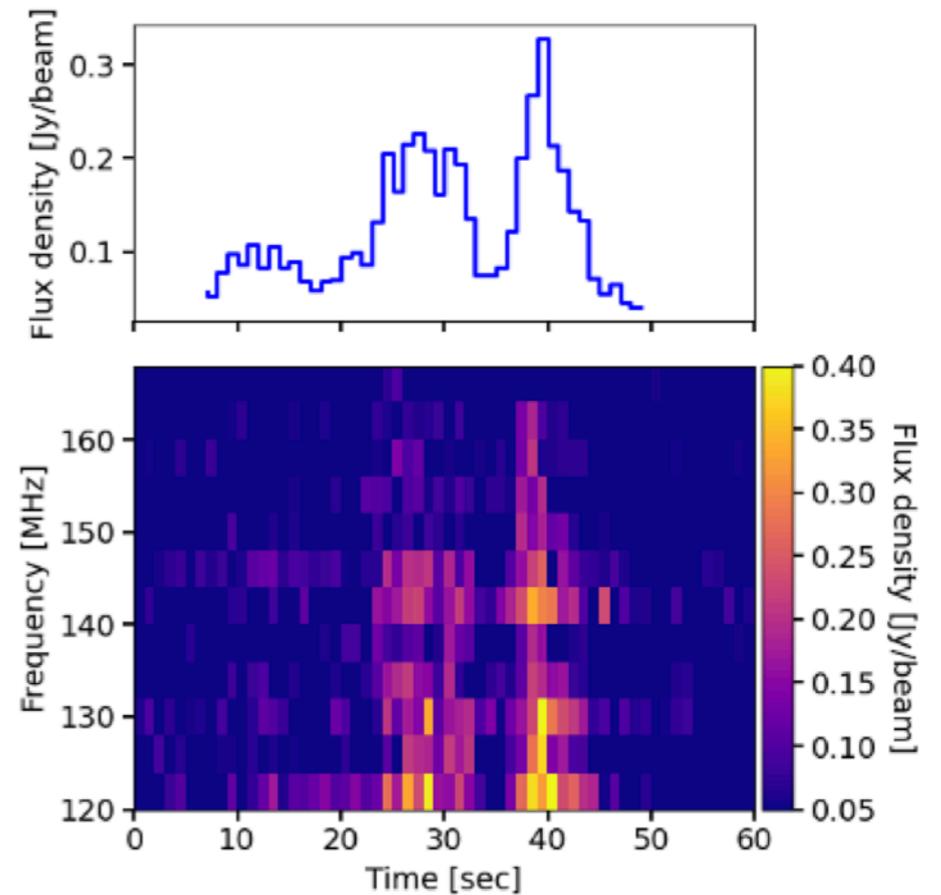
# Interacting White Dwarf binaries

New population (~12) of long-period radio transients with periods ranging from minutes to hours.

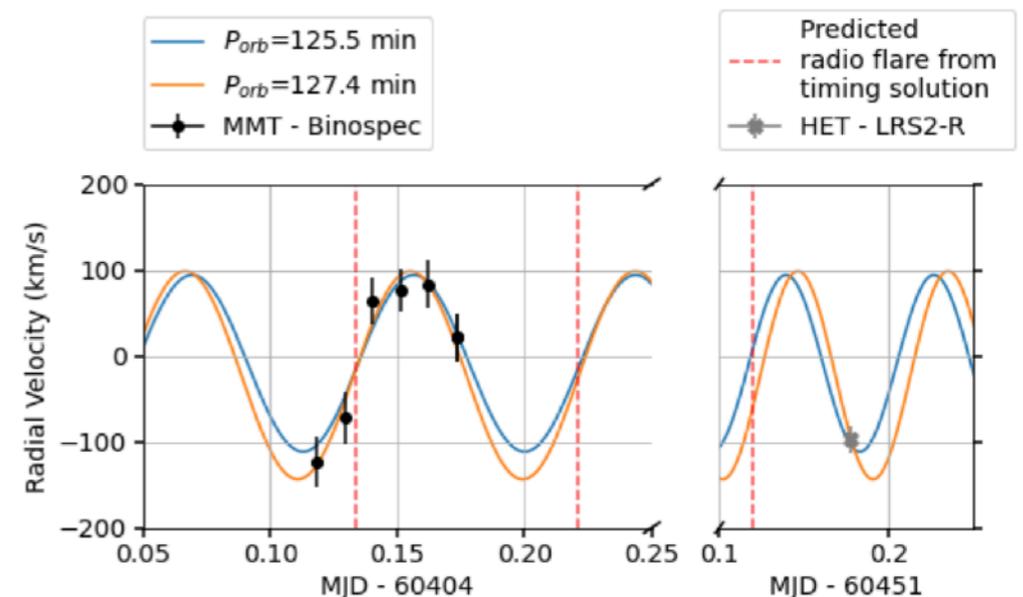
Two sources confirmed as galactic white-dwarf — M-dwarf binaries with hour-long period and minute long bursts

De Ruiter+ (2025)  
Hurley-Walker+ (2025)

No accretion, so radio emission magnetospheric



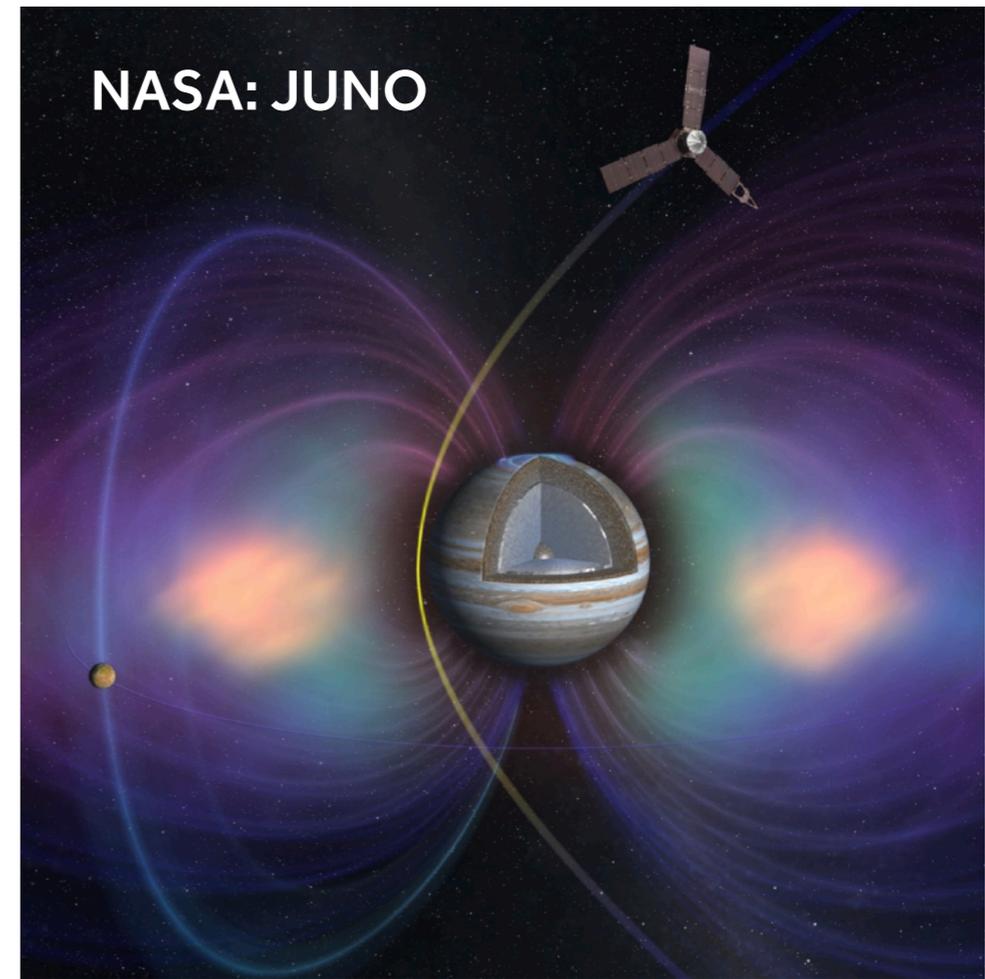
De Ruiter+ (2025)



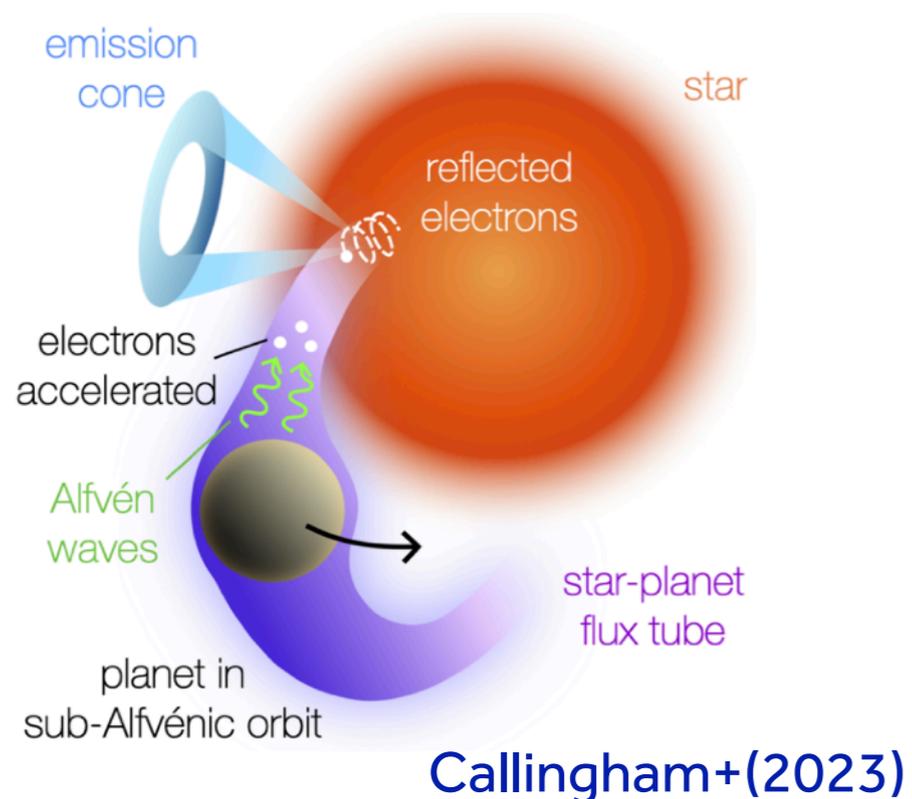
# Radio emission from white dwarfs??

Likely emission model in those near tidally locked systems is the relativistic **electron-cyclotron maser (ECM)** supports a **Jupiter-Io-like** emission scenario

Also Goldreich&Lynden-Bell (1968)  
Qu & Zhang (2025)



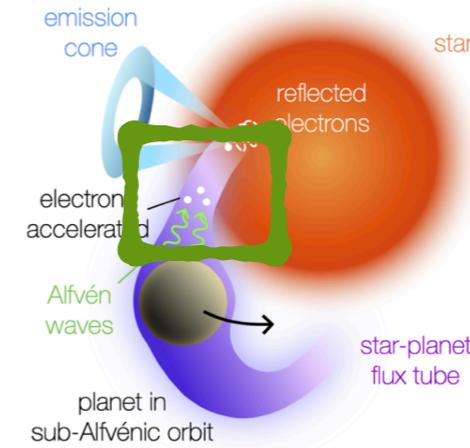
Question: How efficiently can the ECM operate in a WD system?



$$\mathcal{L}_{\text{radio}} \simeq 6.0 \times 10^{27} \text{ ergs}^{-1} \zeta_{\phi} \left( \frac{\Delta\Omega}{\Omega} \right) \left( \frac{P}{100 \text{ min}} \right)^{-13/3} \left( \frac{\xi}{10^{-2}} \right) \left( \frac{\mu}{10^{34} \text{ Gcm}^3} \right)^2 \left( \frac{M_{\star} + M_c}{0.8 M_{\odot}} \right)^{-5/3} \left( \frac{R_{\text{MD}}}{0.217 R_{\odot}} \right)^2$$

# Radio emission from white dwarfs??

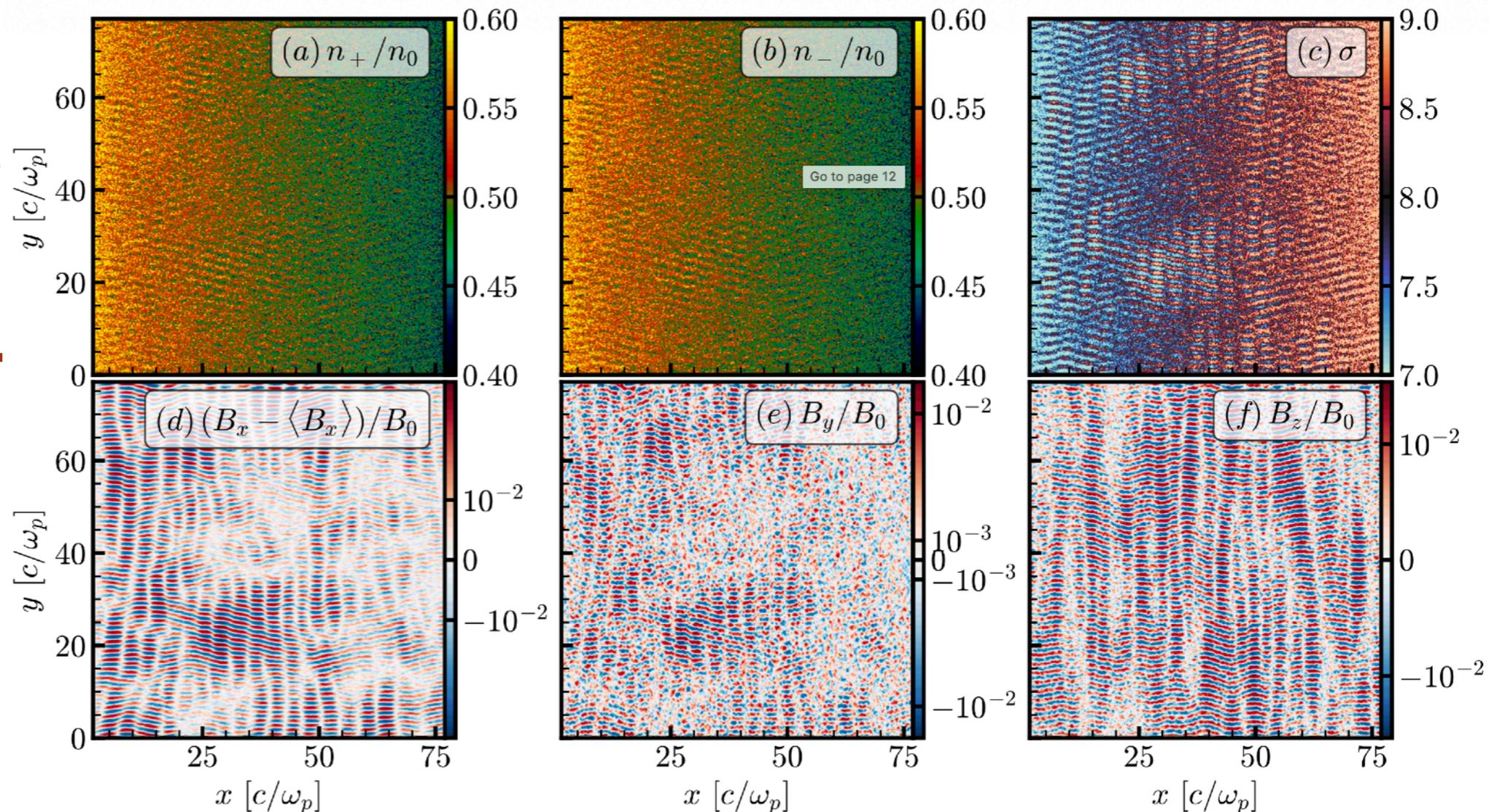
First kinetic simulations of relativistic **electron-cyclotron maser** under WDMD conditions supports a **Jupiter-Io-like emission scenario**



Yici Zhong  
(Caltech)

Zhong & ERM (arXiv 2025)

Nonlinear maser regime  
up to 10x more efficient for radio emission.



Linear polarization possible  
(with caveats!)

# Vastly different scales

Image credit: Ripperda+, Liska+

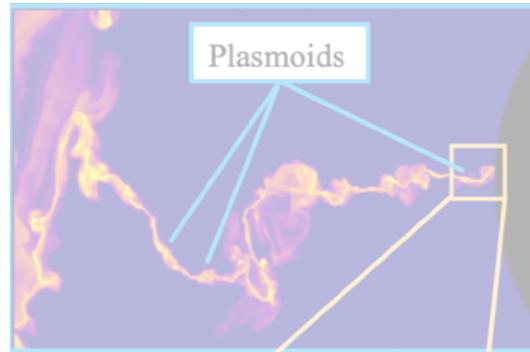
Microscales

Macroscales

$\ll 10^{-7} r_g$

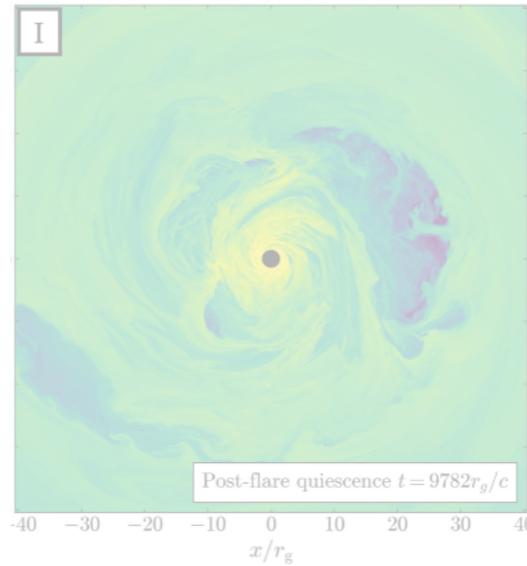


$\approx r_g$



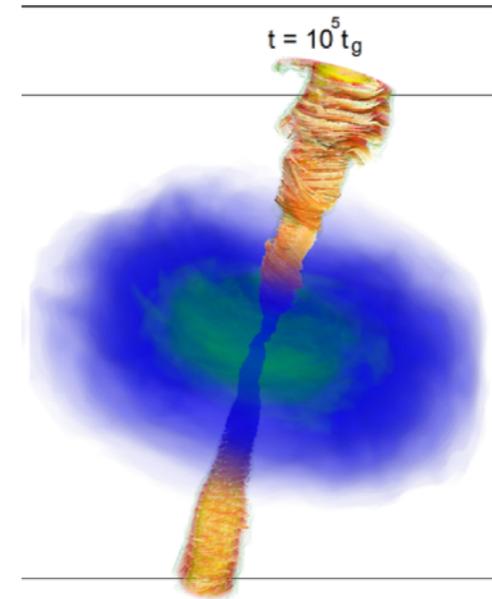
Current sheet

$\sim 30 r_g$



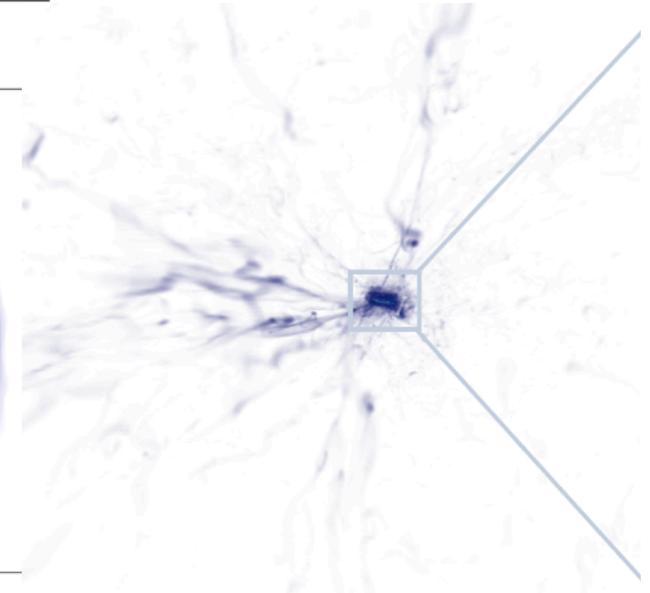
Flare-disk interaction

$\gg 10^4 r_g$



Jet

$\gg 10^7 r_g$



Galactic scale feeding\*

Need **different** multi-scale approach to capture physics on all scales!

# What about macro scales!

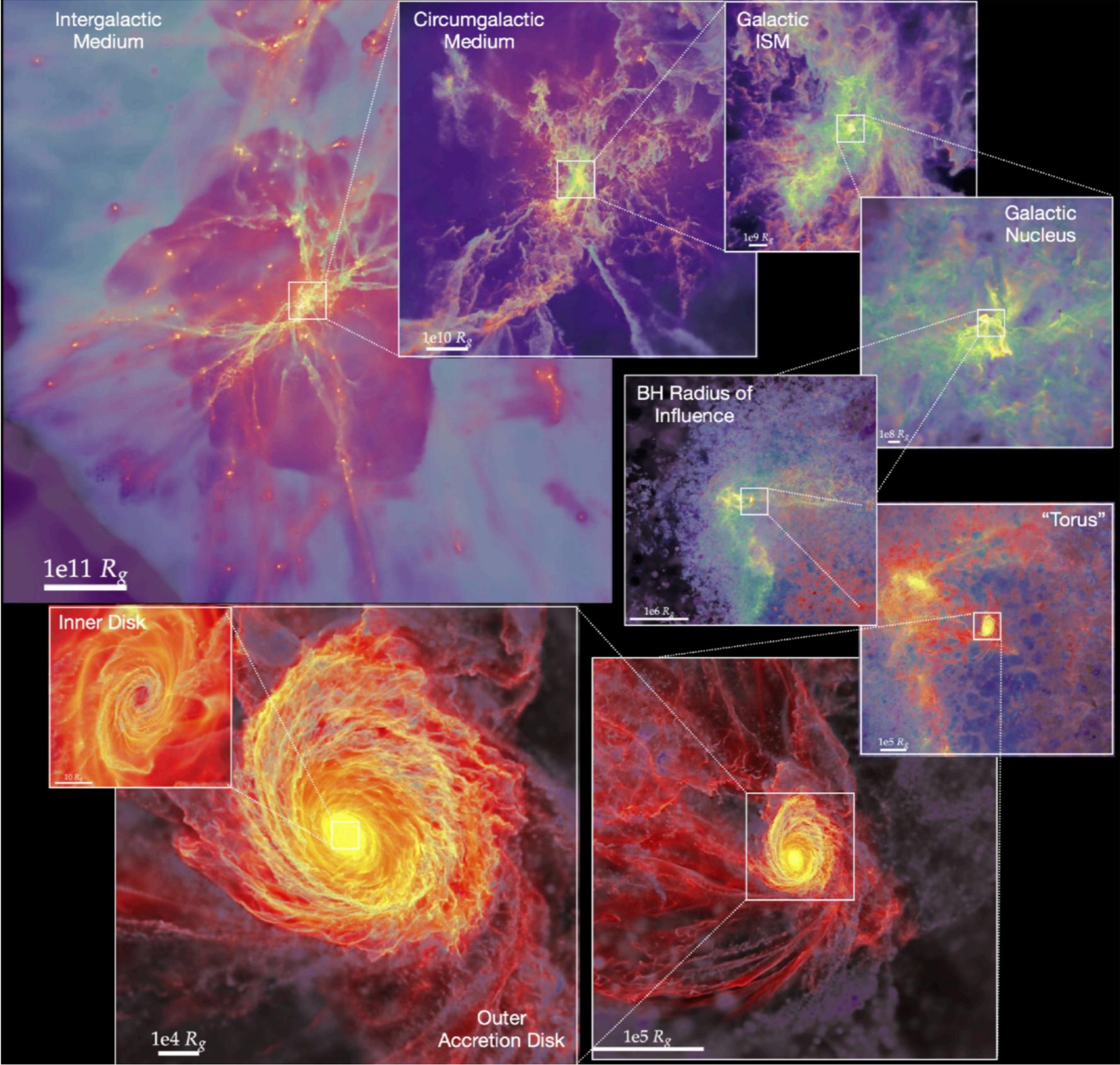
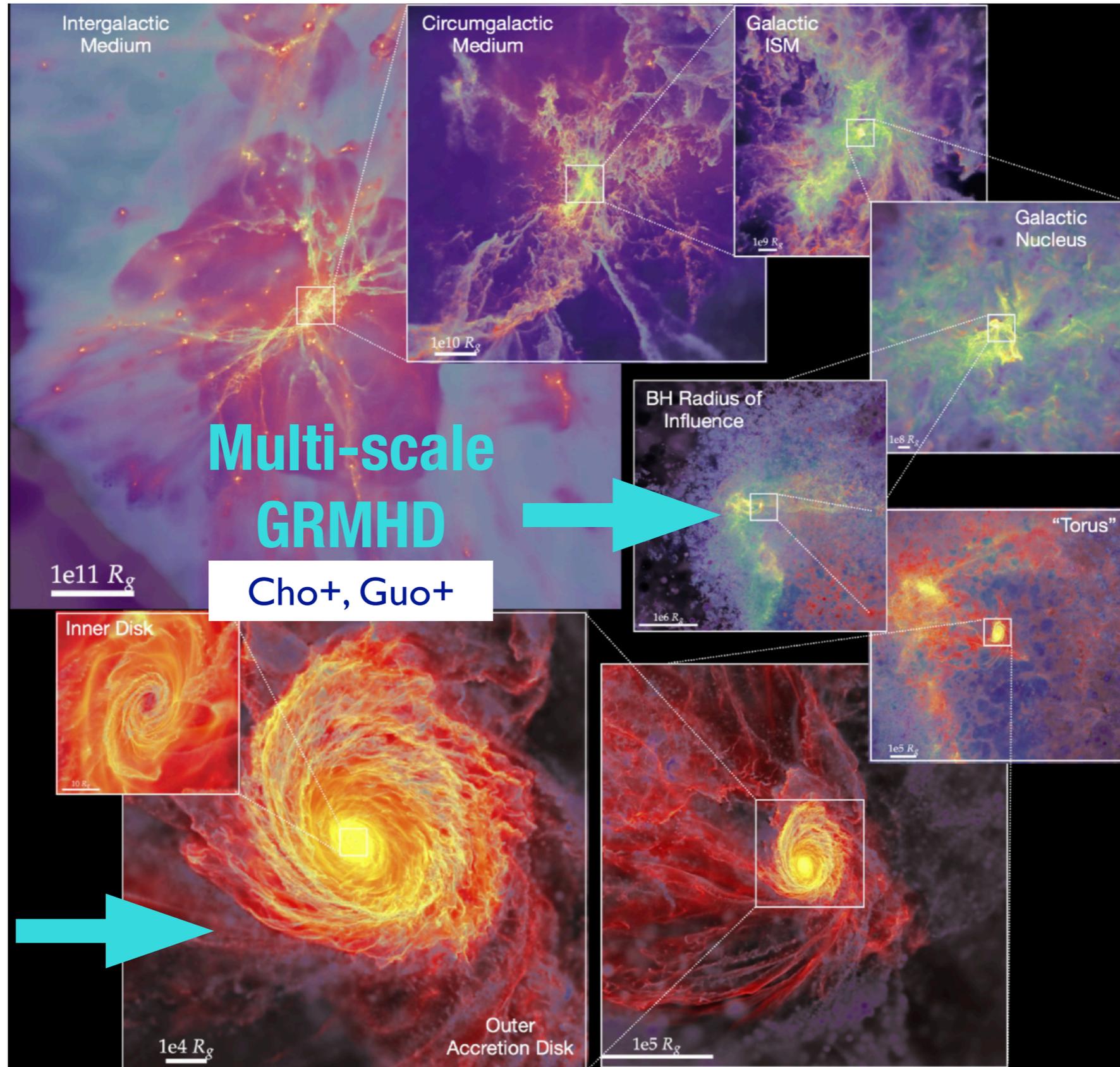


Image credit:  
Hopkins

# What about macro scales!

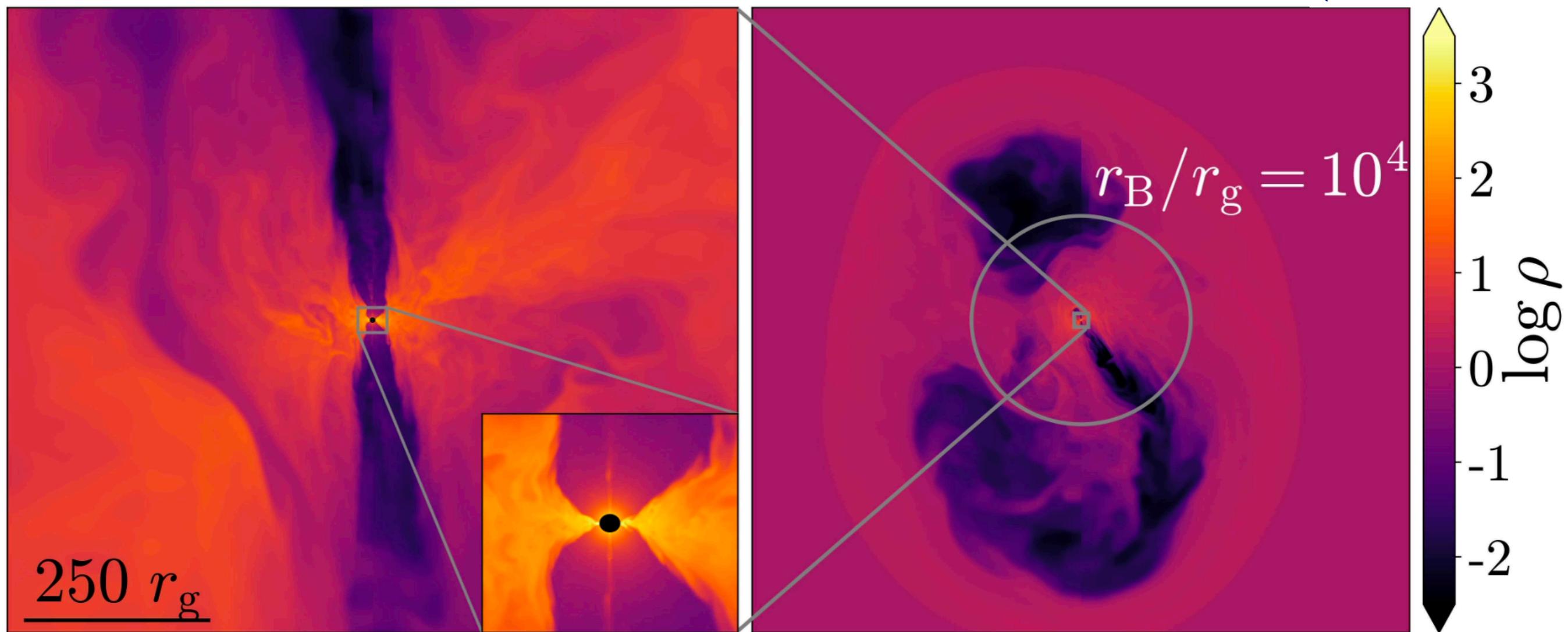


# Jet feedback

In reality, the jet (and other outflows) will feedback on the accretion flow. So for real flows,  $\dot{M}_{\text{BH}} \ll \dot{M}_B$



Aris Lalakos  
(Caltech=>CITA)



Largest contiguous GRMHD Bondi accretion simulation to date!

Lalakos+(incl. ERM 2025)



# Universal mass accretion

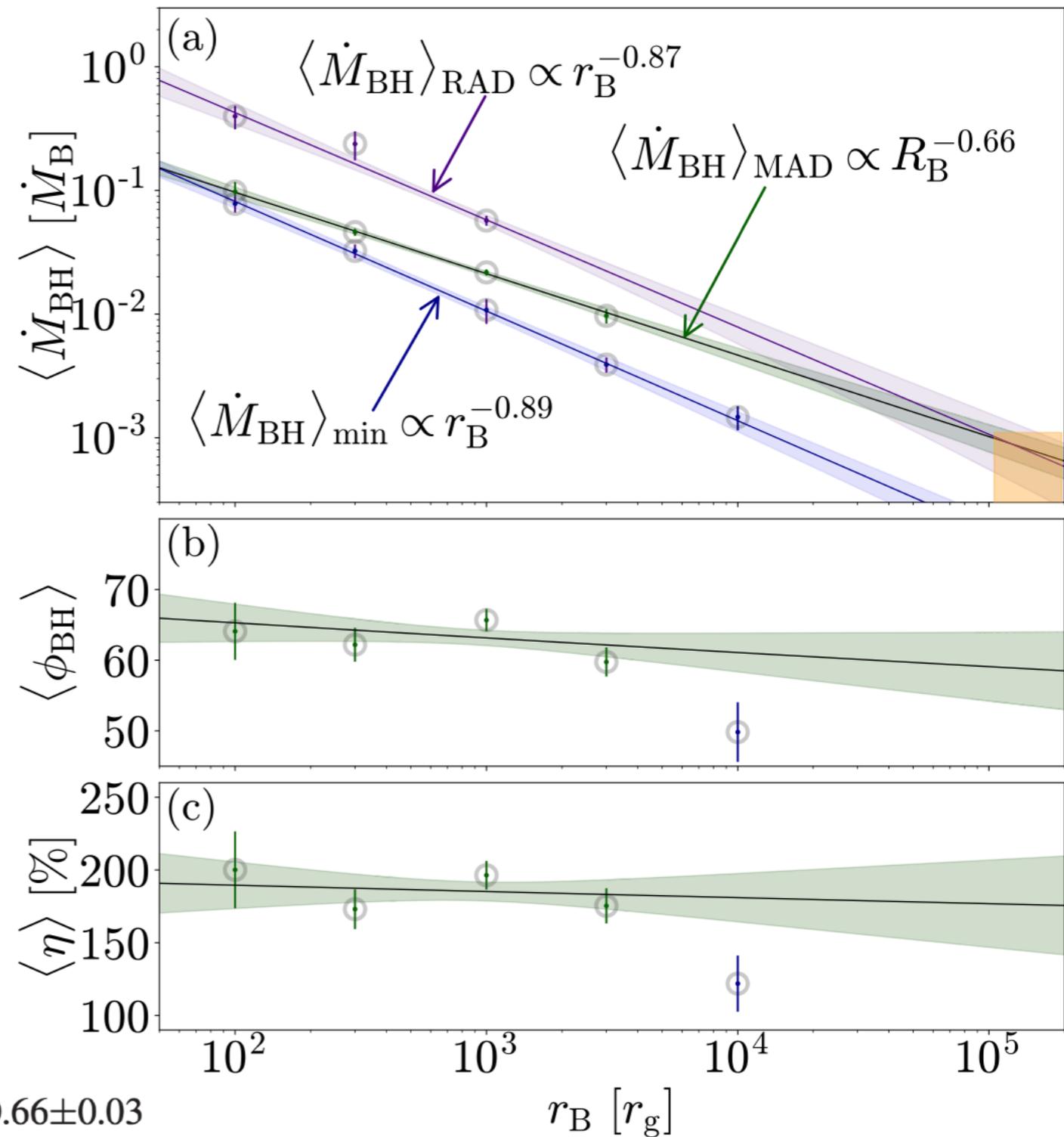
Lalakos+(incl. ERM 2025)

Aris Lalakos  
(Caltech)

Feedback in magnetically arrested regime leads to universal accretion behavior

For realistic scale separations, e.g., in M87, only sub-percent-level mass accretion from outer supply

$$\frac{\langle \dot{M}_{\text{BH}} \rangle}{\dot{M}_{\text{B}}} = (1.0 \pm 0.2) \times 10^{-3} \times \left( \frac{r_{\text{B}}}{10^5 r_{\text{g}}} \right)^{-0.66 \pm 0.03}$$



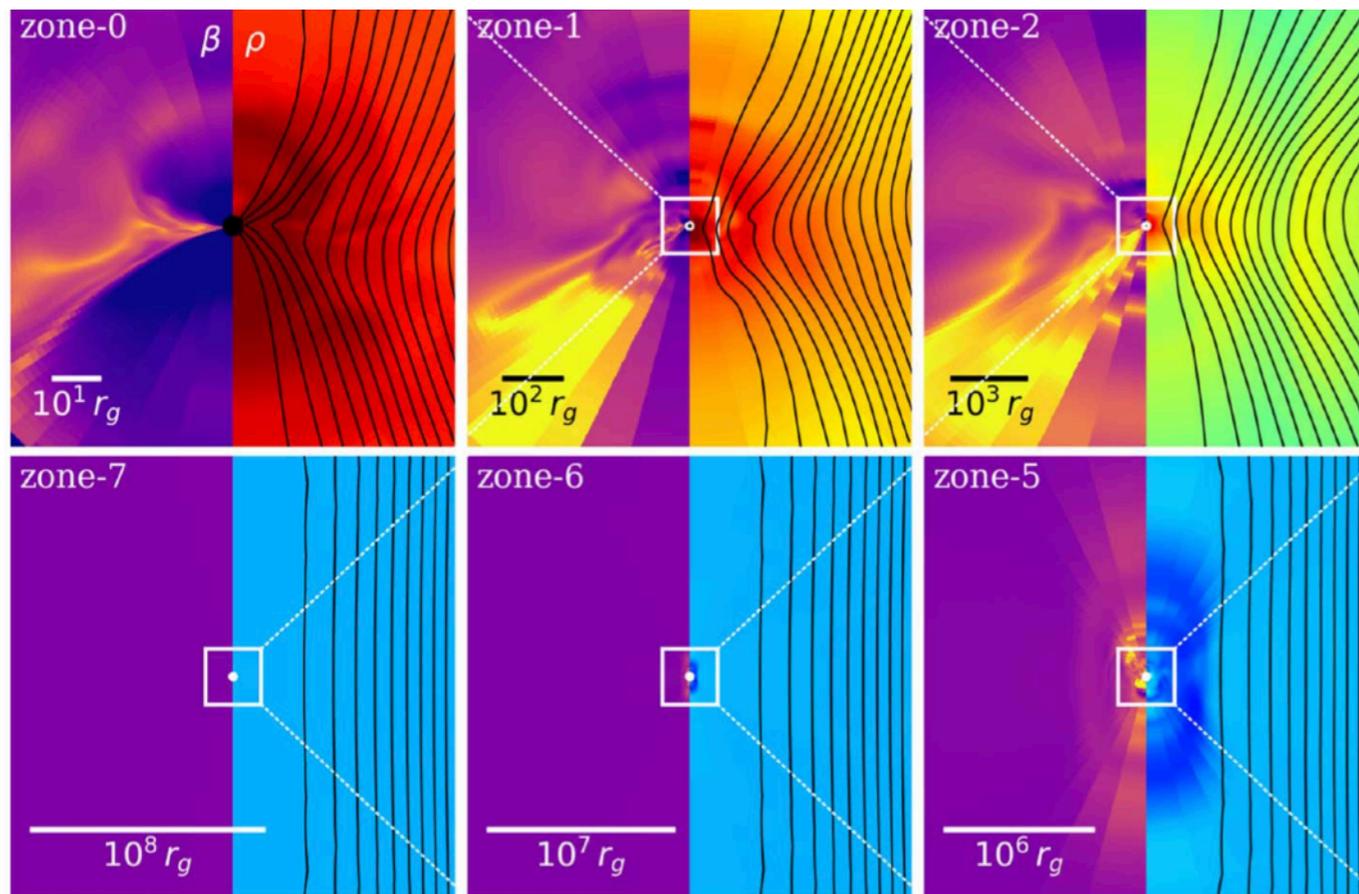
Compare also Feng+, Xu+, Tchekhovskoy+, Galishnikova+

# Brute force get's you only so far

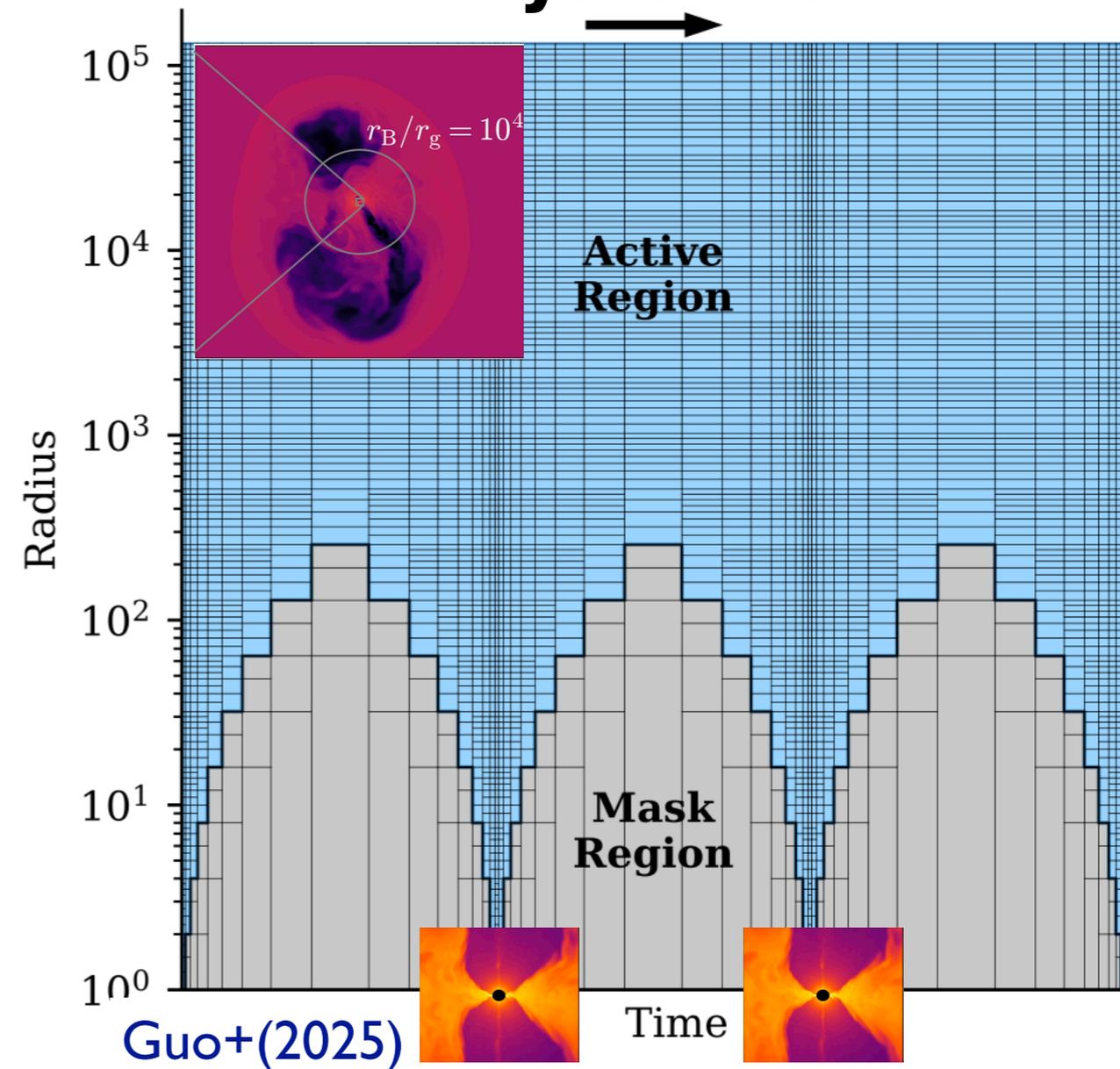
Community has developed and explored novel techniques to deal with large scale separation when steady state exists!

**Cyclic zoom**

## Multizone method



Cho+(2023;2024;2025)



**Work well for single stationary black hole in grid-based codes**

# Time dilation methods

New analytic method akin to reduced speed of light.

Can use sufficiently shallow dilation profile centered on accretor.

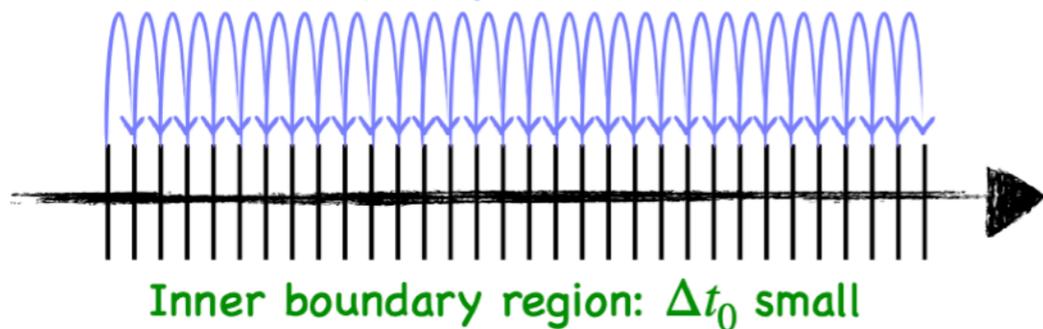
Hopkins & ERM (2025)

Standard:

$$\frac{DU_i}{Dt} = \mathcal{F}(\mathbf{x}, t, \mathbf{U}_j, \dots)$$

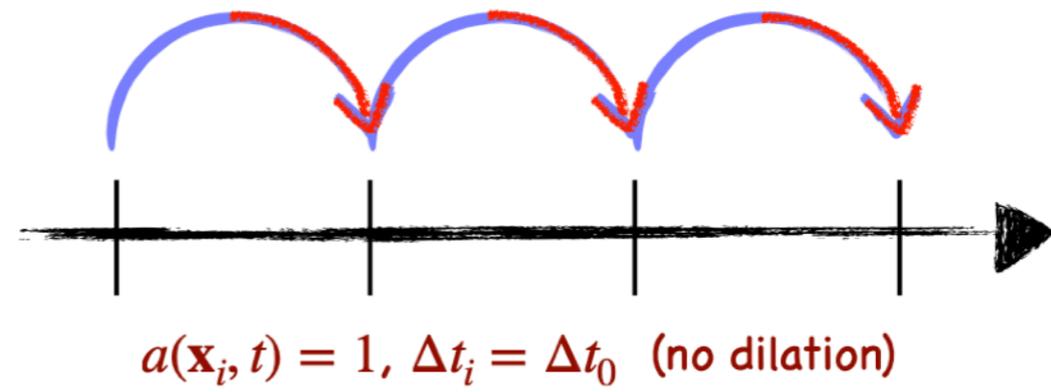
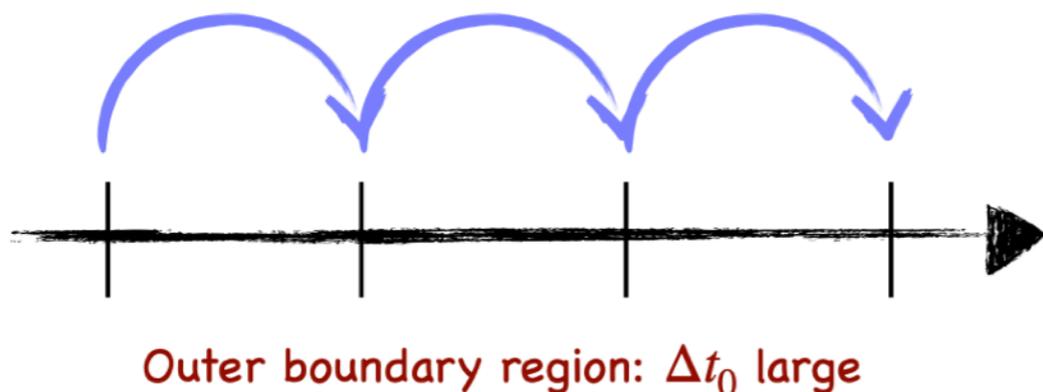
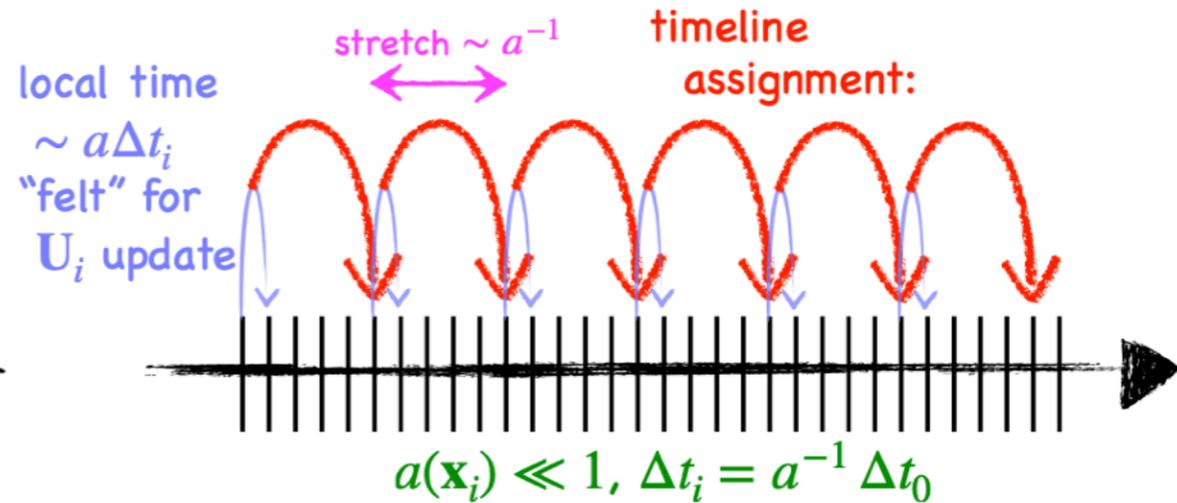
Global simulation timeline

local timesteps  $\Delta t_i$ :



Dilated:

$$\frac{1}{a} \frac{DU_i}{Dt} = \mathcal{F}(\mathbf{x}, t, \mathbf{U}_j, \dots)$$



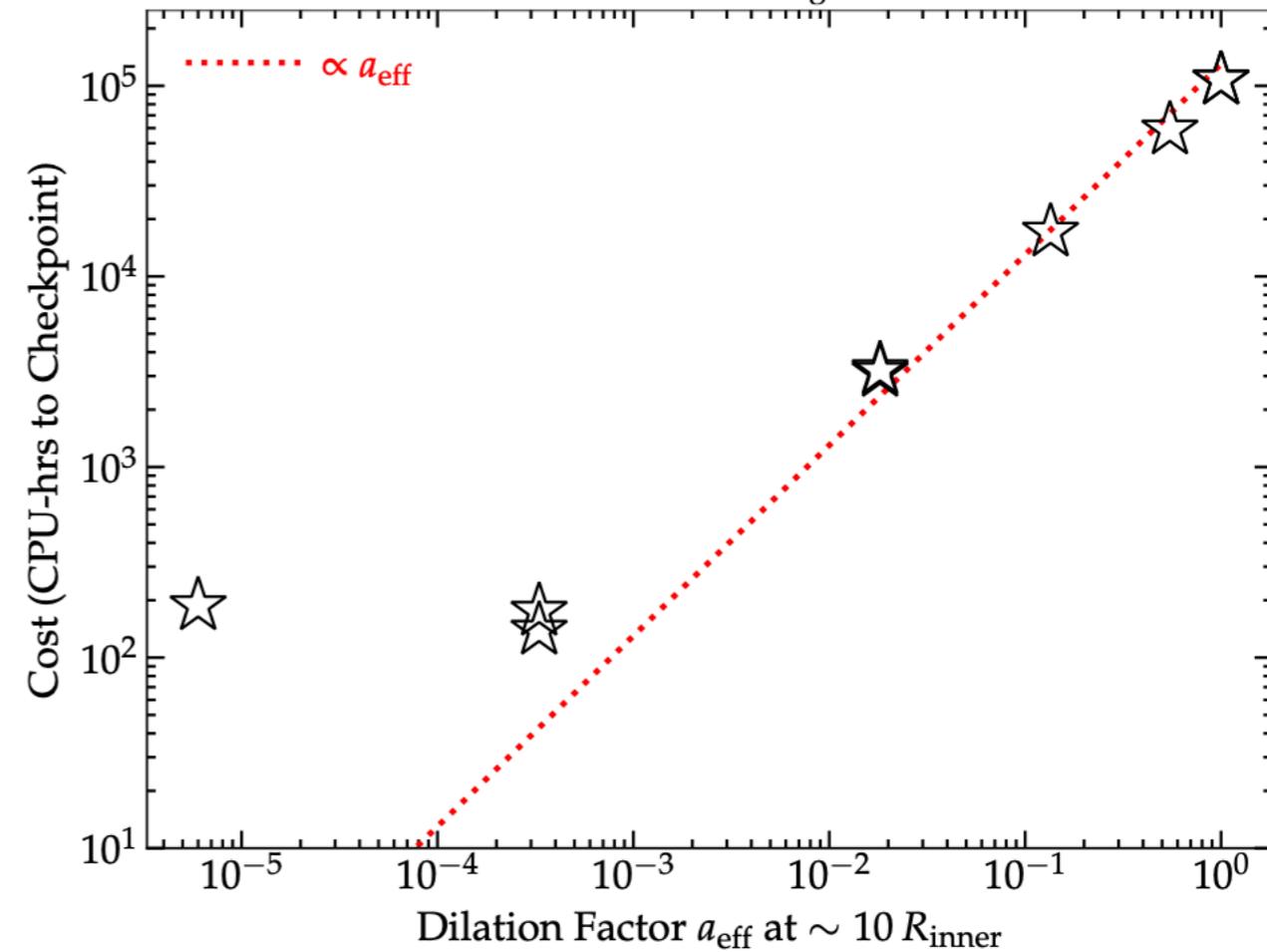
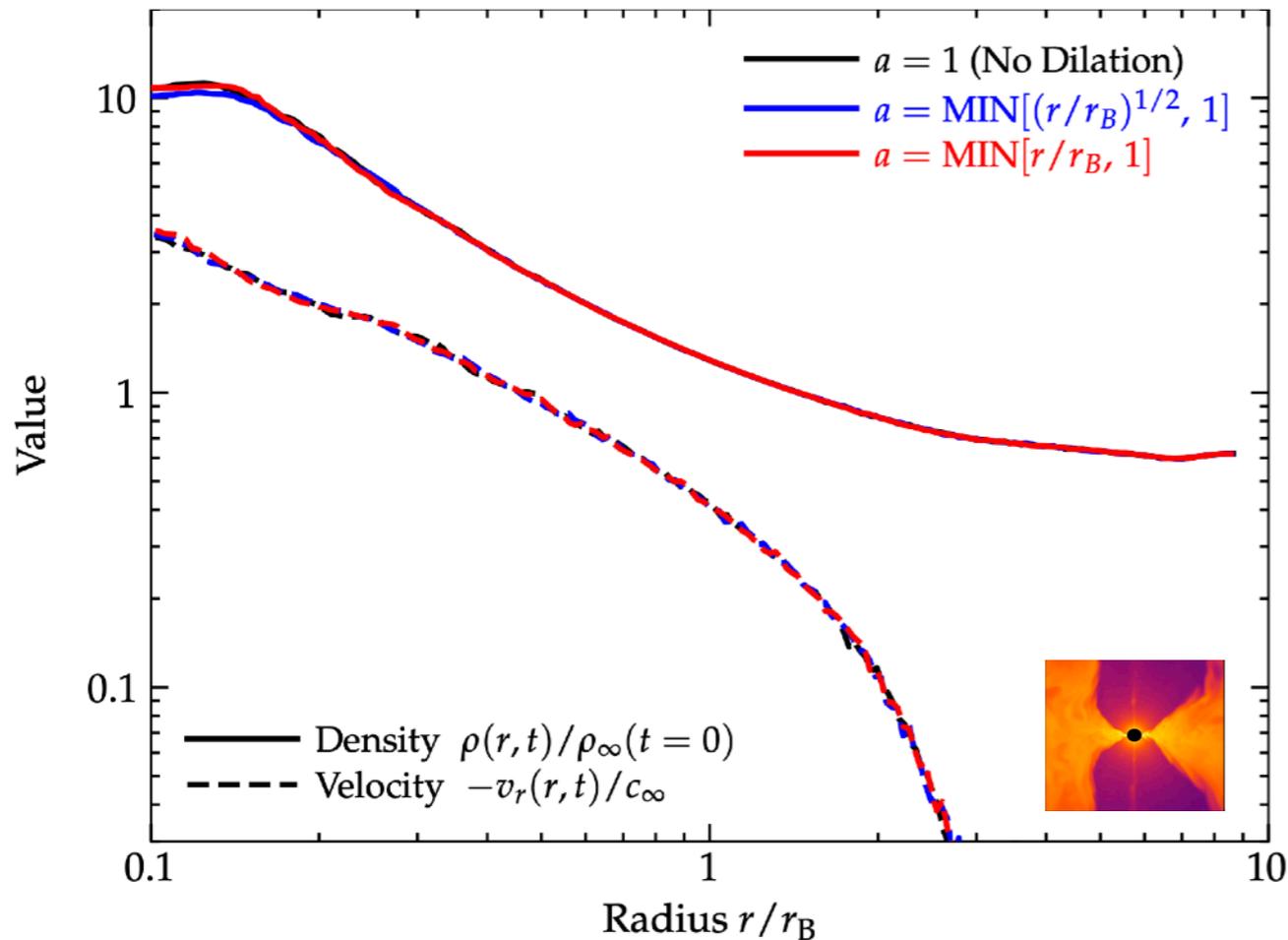
**Allows for generalization to binary motion, boosts etc.**

# Time dilation

Can use analytic time dilation profiles focus on central black hole even works with radiation!

Hopkins & ERM (2025)

**Bondi**



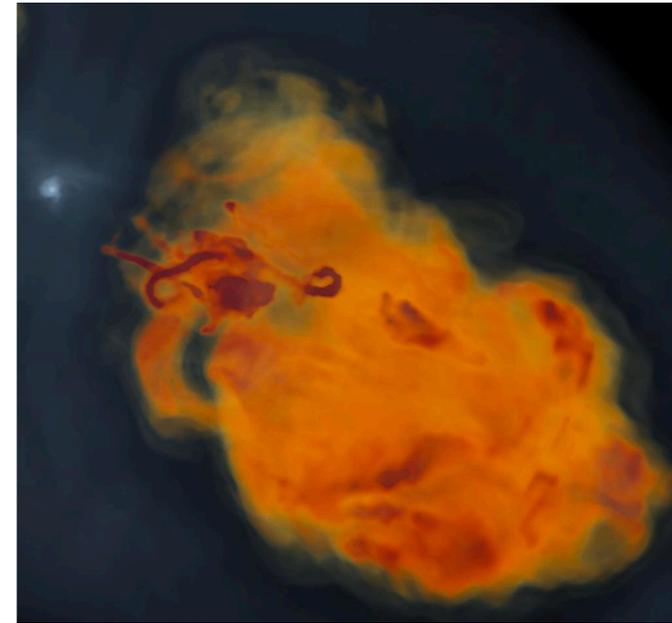
**Potential order of magnitude speed up just as for multi-zone / cyclic-zoom approaches**

# Cheating only get's you so far!

Especially for low angular momentum flows jet can start to become unstable.

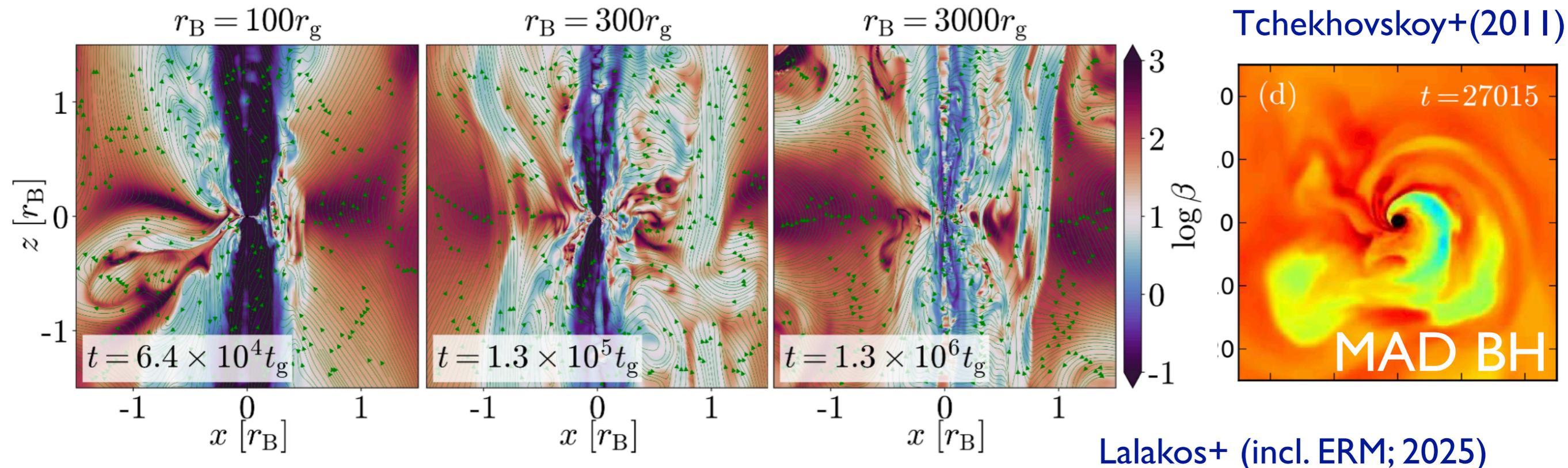
**Different steady state solution!**

e.g., Lalakos+2023; 2025(incl.ERM); Galishnikova+(2024); Cho+(2025)



Aris Lalakos (Caltech)

**Ejected magnetic flux tubes** in MAD regime propagate all the way out to the Bondi radius!



# A Neural Operator Black Hole

What's a better way to model small-scale feedback?

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**What about AI??**



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If accretion is described by a PDE (can be different ones for different states), we can write



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**Neural operators learn spectral representation of  $\mathcal{G}$ !**

Z. Li (2020;2021)



# A Neural Operator Black Hole



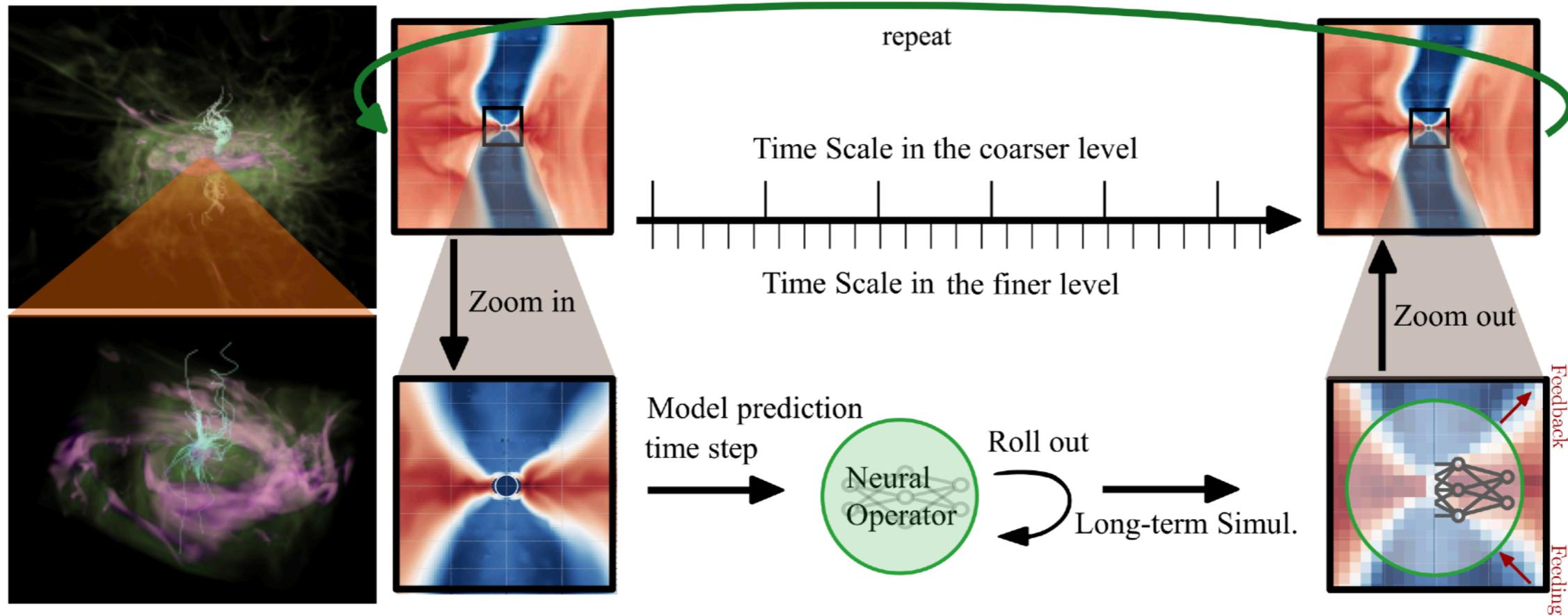
Nihaal Bhojwani  
(Maryland/Caltech)



Chuwei Wang  
(Caltech)



H. Wang  
(Caltech)



Bhojwani, C. Wang, H. Wang, ERM, Anandkumar (2025)

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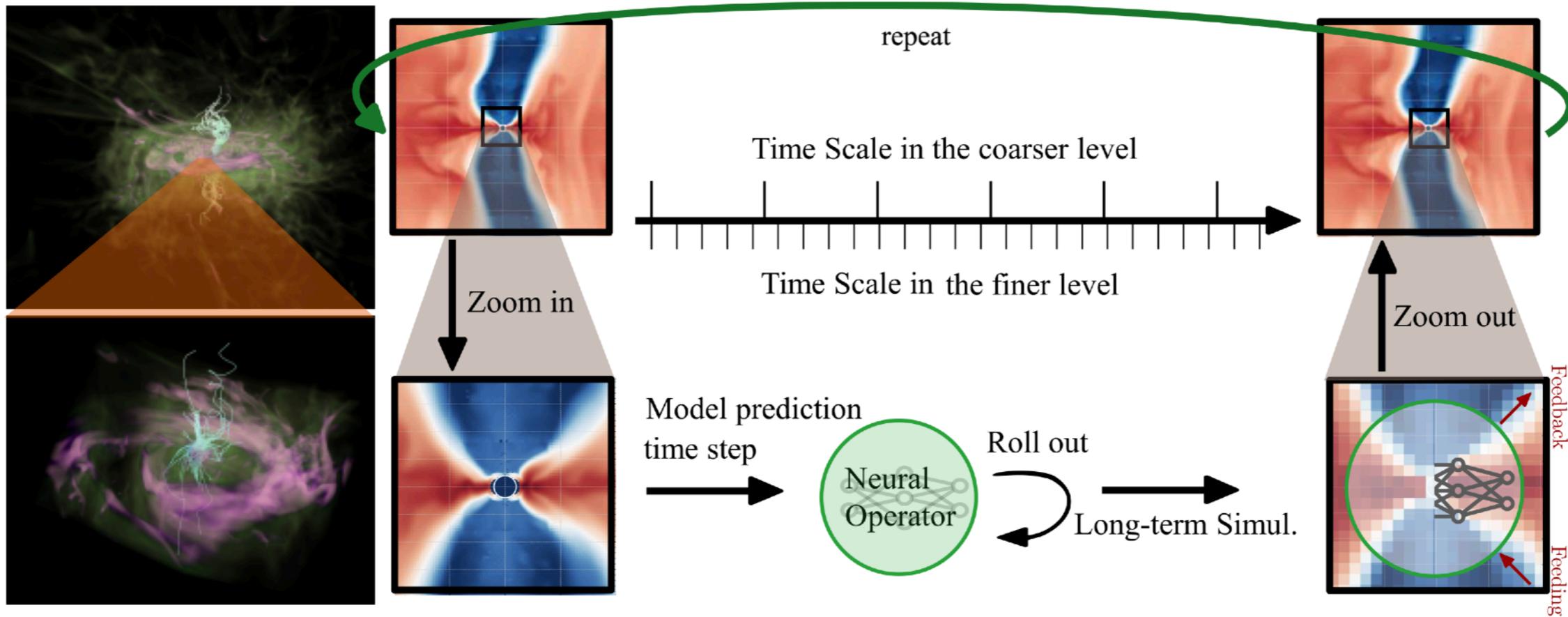
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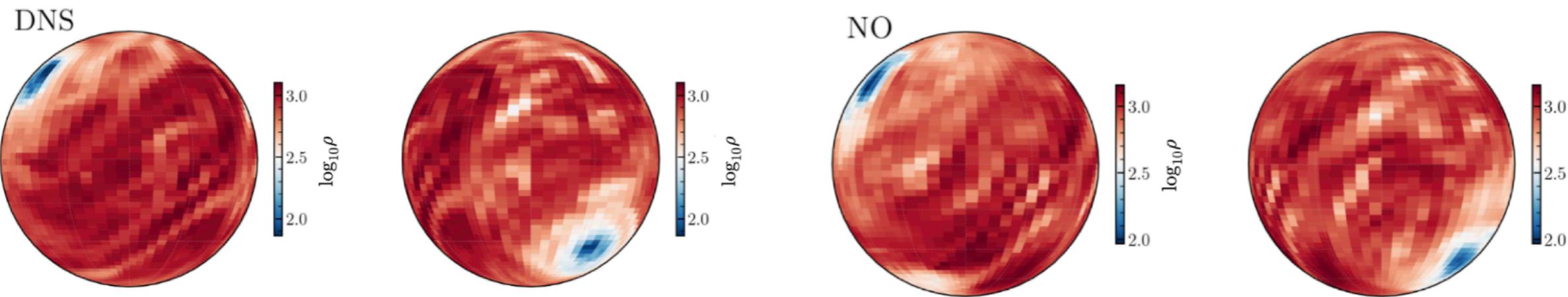
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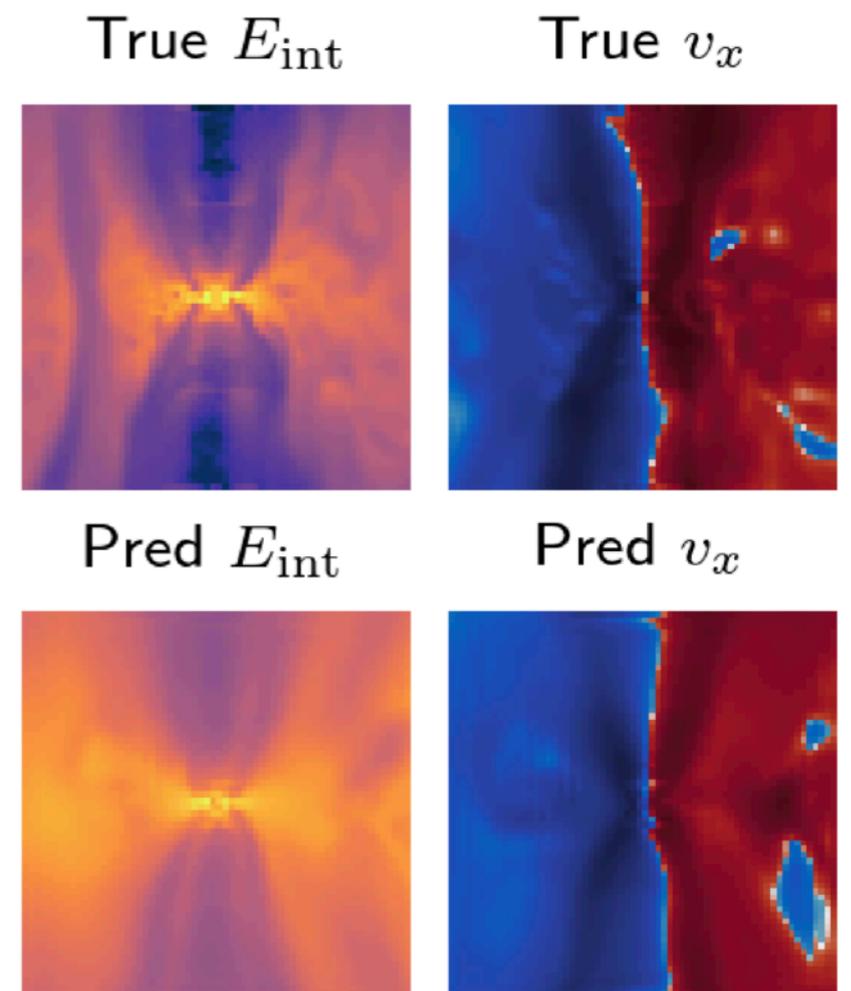
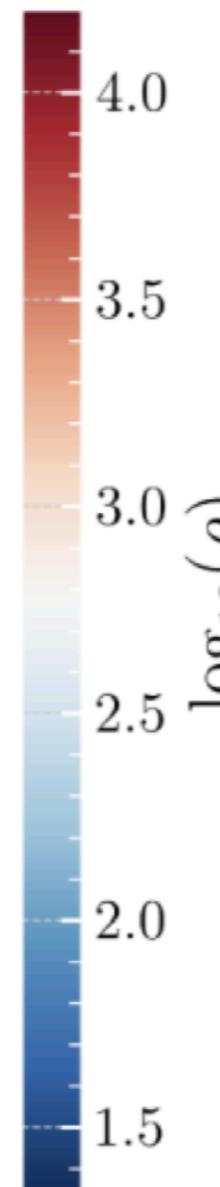
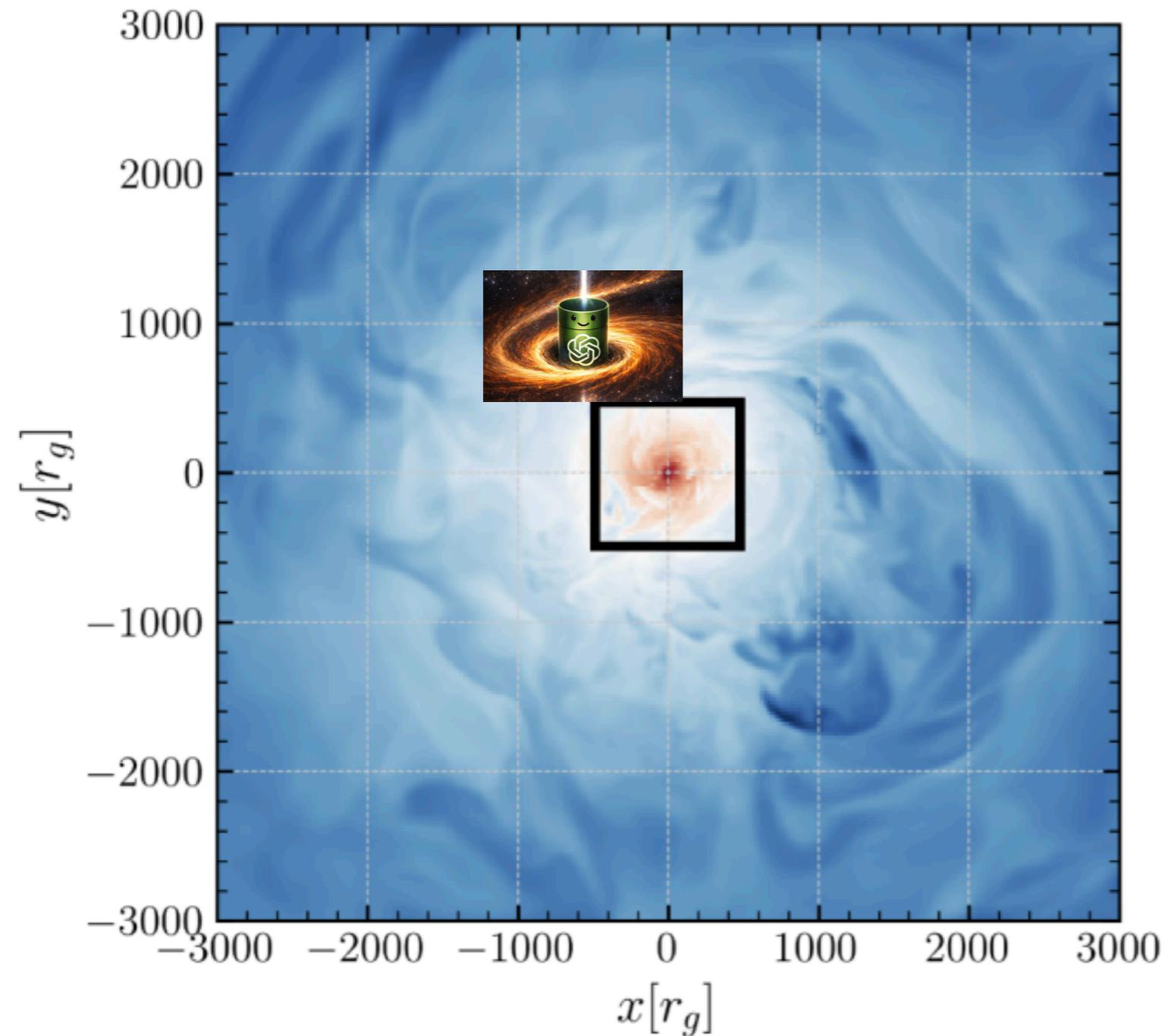
**Trained neural operator for Newtonian and GRMHD flows!**



Bhojwani, C. Wang, H. Wang, ERM, Anandkumar (2025)

# Neural operator can capture variability!

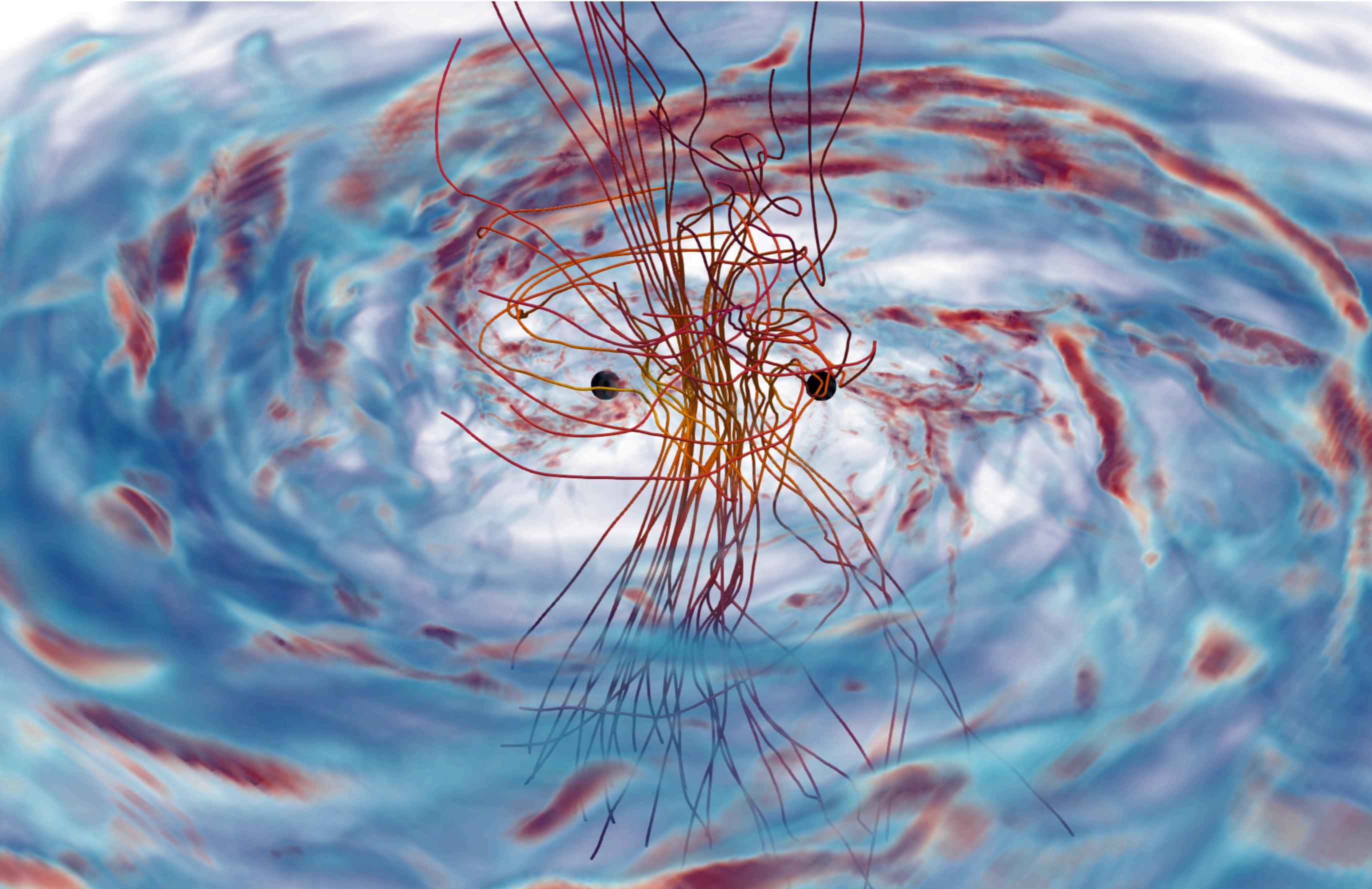
Need proper matching to different regimes, and jet feedback.



Newtonian MHD in AthenaK

Bhojwani, C. Wang, H. Wang, ERM, Anandkumar (2025)

# What about black holes?

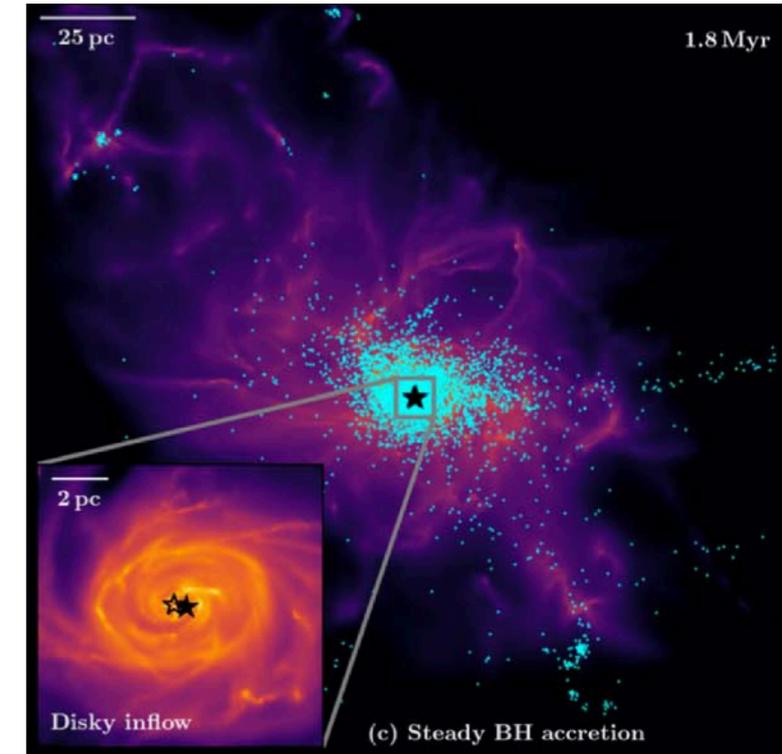


# Circumbinary accretion disks

Circumbinary disks can form in galaxy mergers, potentially with strongly magnetized disks. e.g., Mayer+(2007), Shi+(2024)

Accretion from circumbinary disk could be a possible channel for driving the binary to sub-pc separation

Begelman+(1980), Pringle (1991), Milosavljevic & Merritt (2003), Merritt & Milosavljevic (2005), Colpi (2014)



Shi, Kremer, Hopkins (2024)

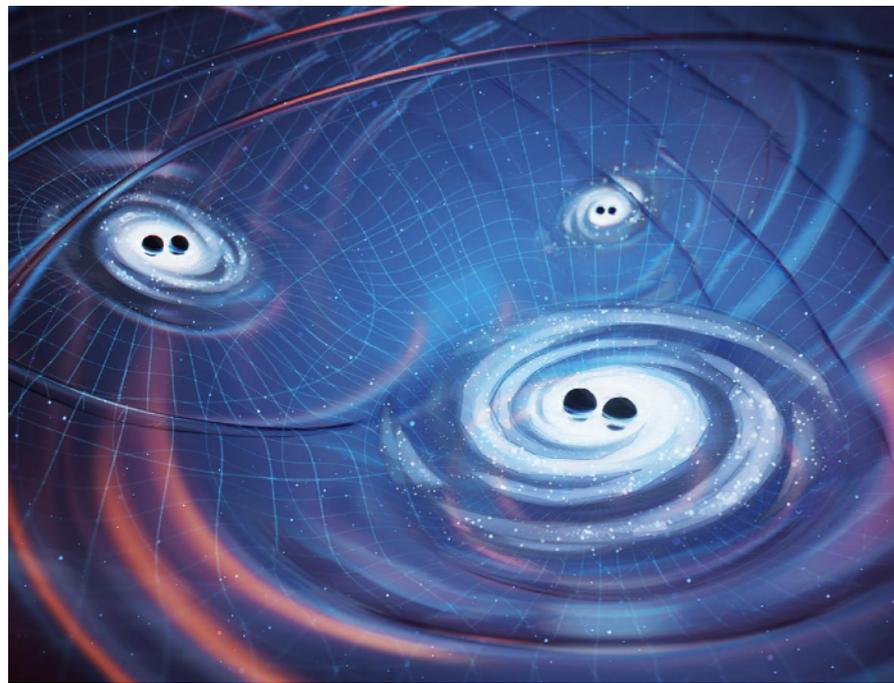


Image credit: NANOgrav

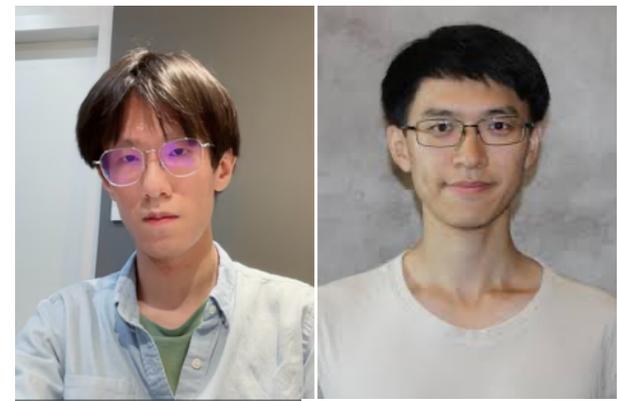
Interesting also in the context of merging binary population seen with **Pulsar Timing Arrays** or future **LISA** observations

Amaro-Seoane+(2017), Agazie+(2023)

Interaction with disk may also power electromagnetic signatures (LISA)

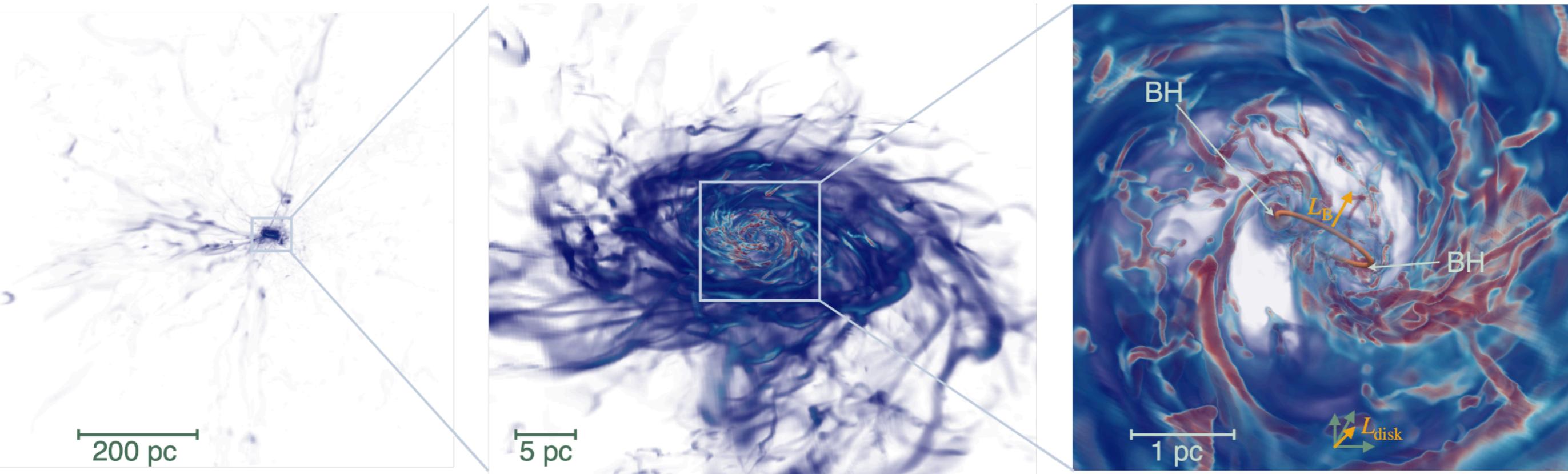
# Multi-phase galactic-scale binary accretion?

Wang, Guo, ERM+ (arXiv 2025)



H. Wang (Caltech) M. Guo (Princeton)

**Zoom-in** simulation of accretion onto a **binary** in an M87-like background with realistic ISM cooling from  $\sim$ kpc down to mpc (**6 order scale difference!**).



**Warped circumbinary disk on parsec scales!**

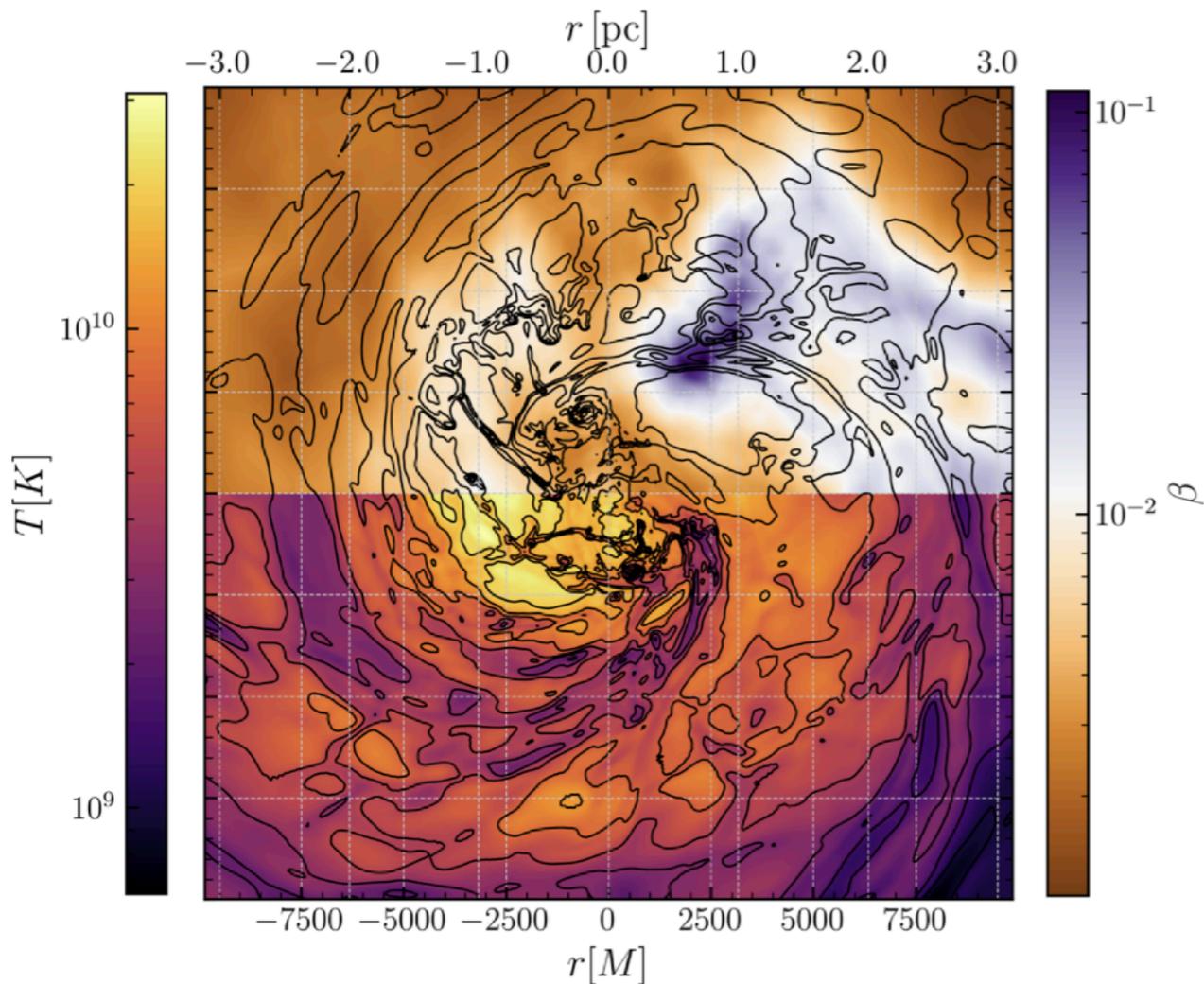
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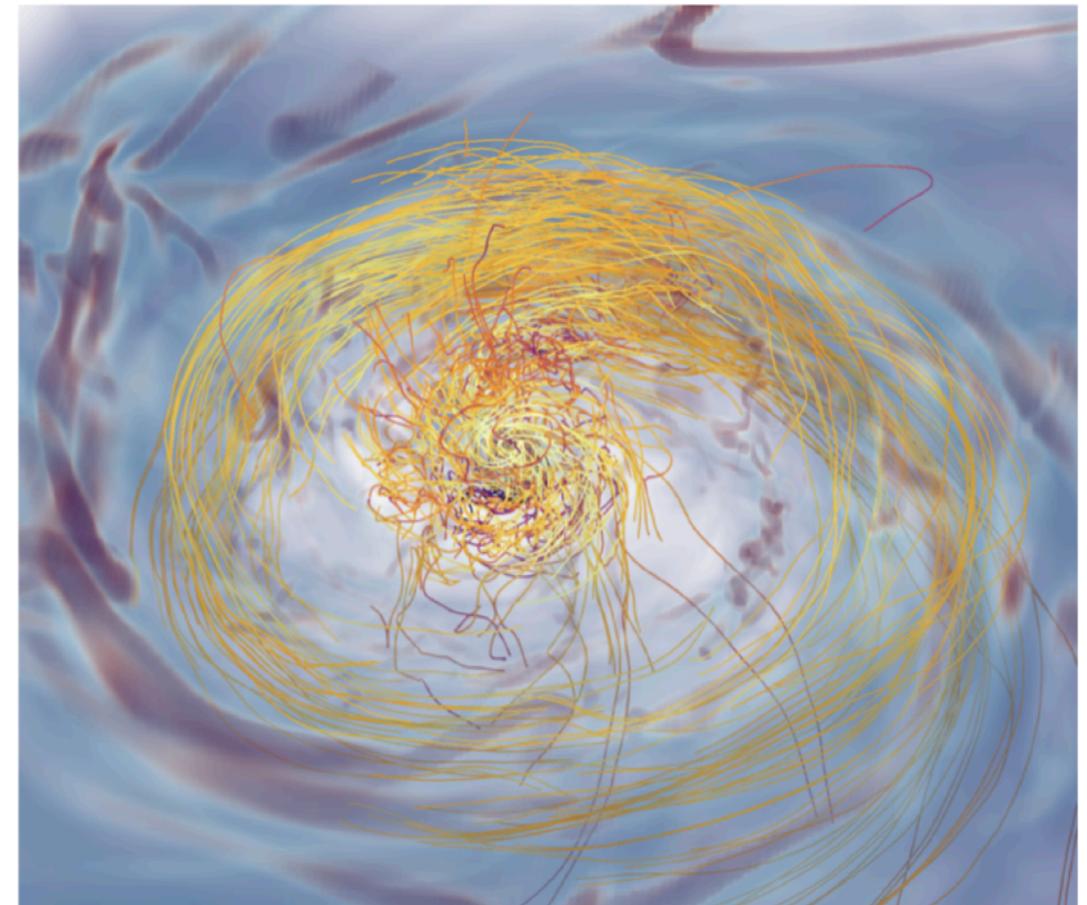
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[H. Wang](#) (Caltech) [M. Guo](#) (Princeton)

## Multi-phase flow

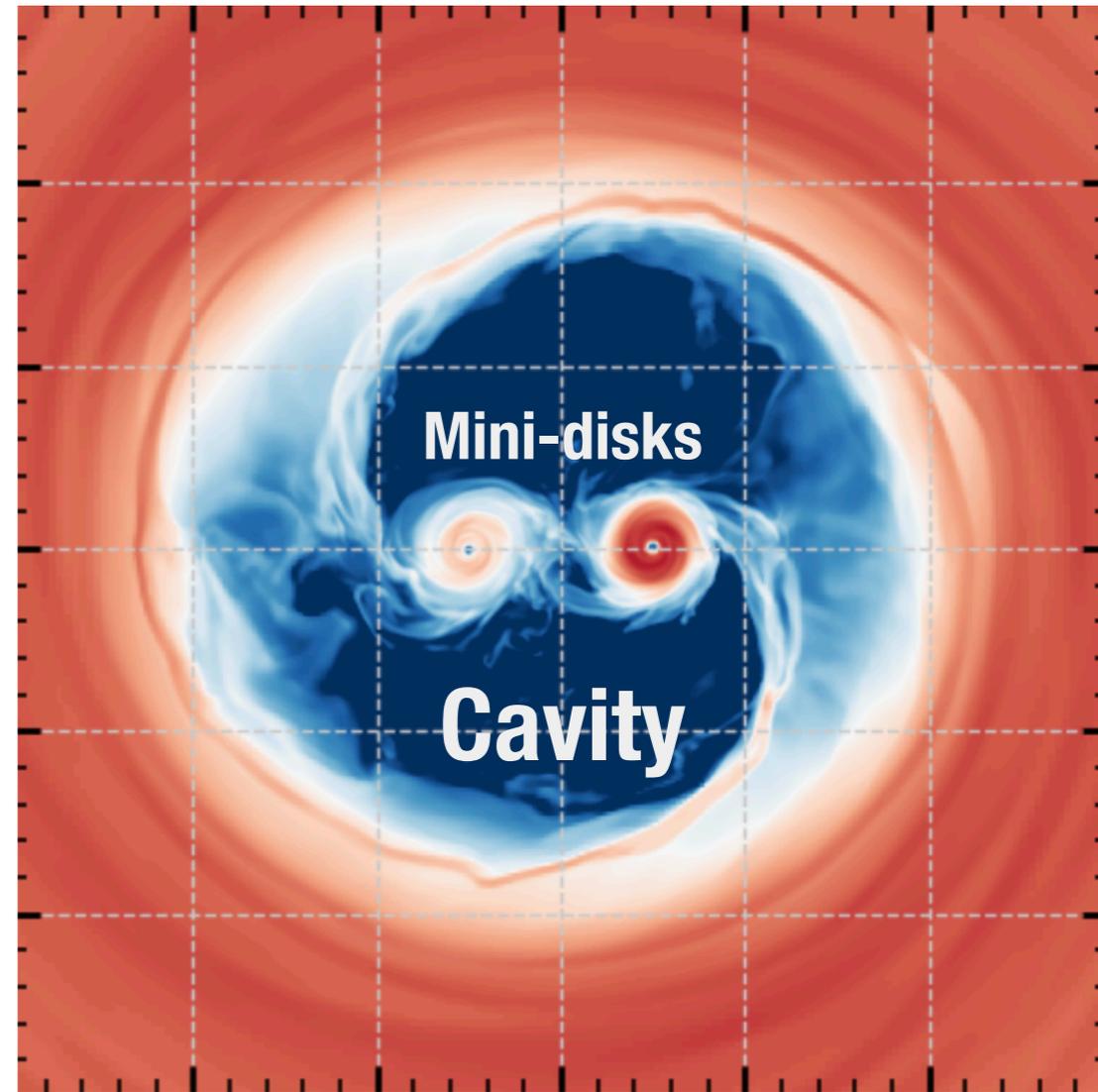


## Strong toroidal field and hypermagnetized disk



# Circumbinary accretion Wang & ERM (in prep)

Circumbinary accretion has been studied extensively using **2D simulations with  $\alpha$ -viscosity**  
early work by Artymowicz & Lubow (1994)



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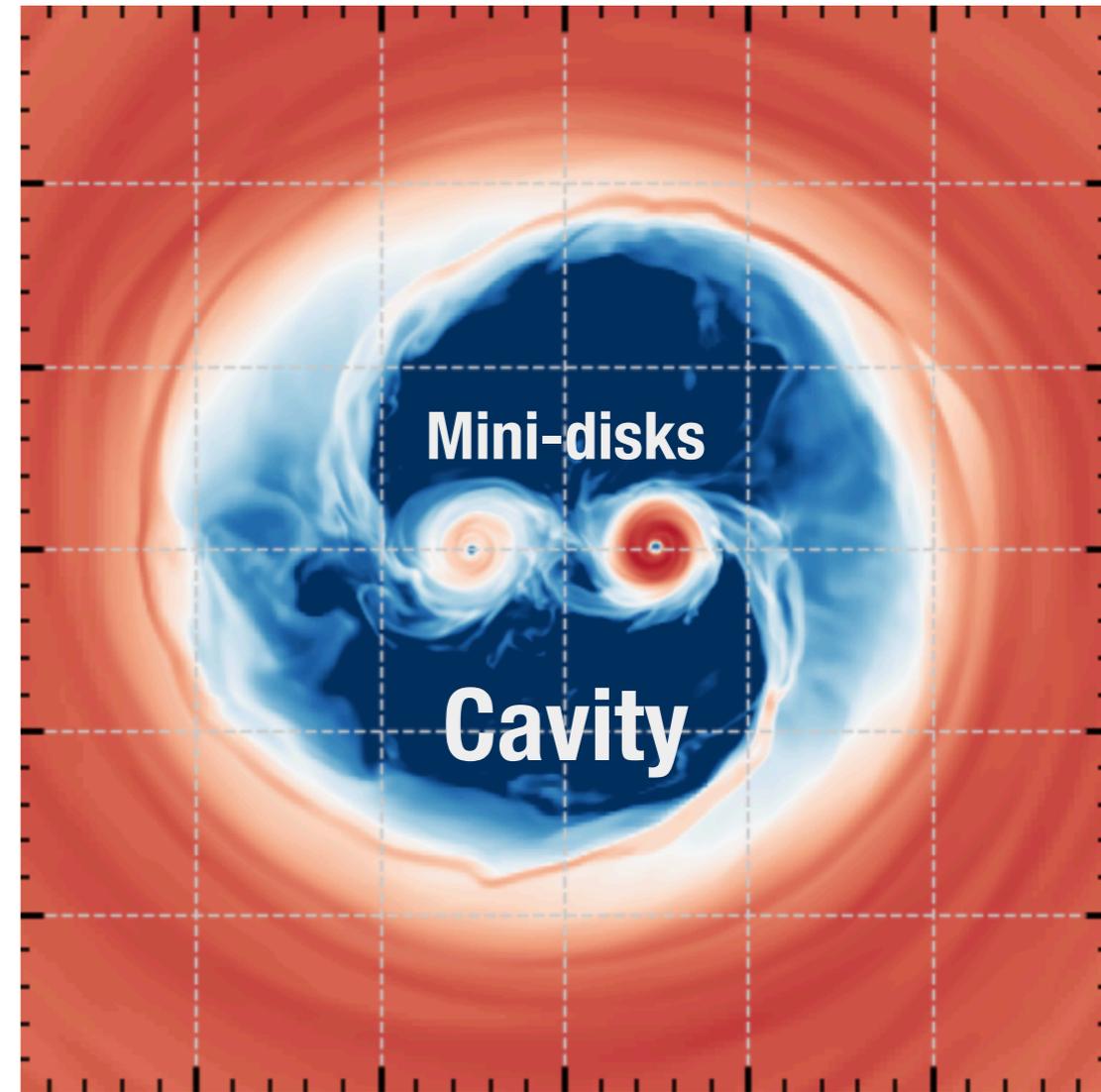
Detailed investigations over the past decade paint the following picture:

- Equal mass non-eccentric systems **spiral outwards** due to accretion

Munoz & Lai, Duffel+

- **For inspiral** need mass ratios  $0.3 \lesssim q \lesssim 0.8$   
at substantial orbital eccentricities  $e_b \simeq 0.4$   
or very thin disks  $H/R < 0.02$

Tiede+(2020), Dittmann & Ryan(2022)



Farris+(2014), Munoz+(2020),  
Duffel+(2020), Dittmann+(2021)  
Siwek+(2023)

Munoz+(2019), Zrake+(2021),  
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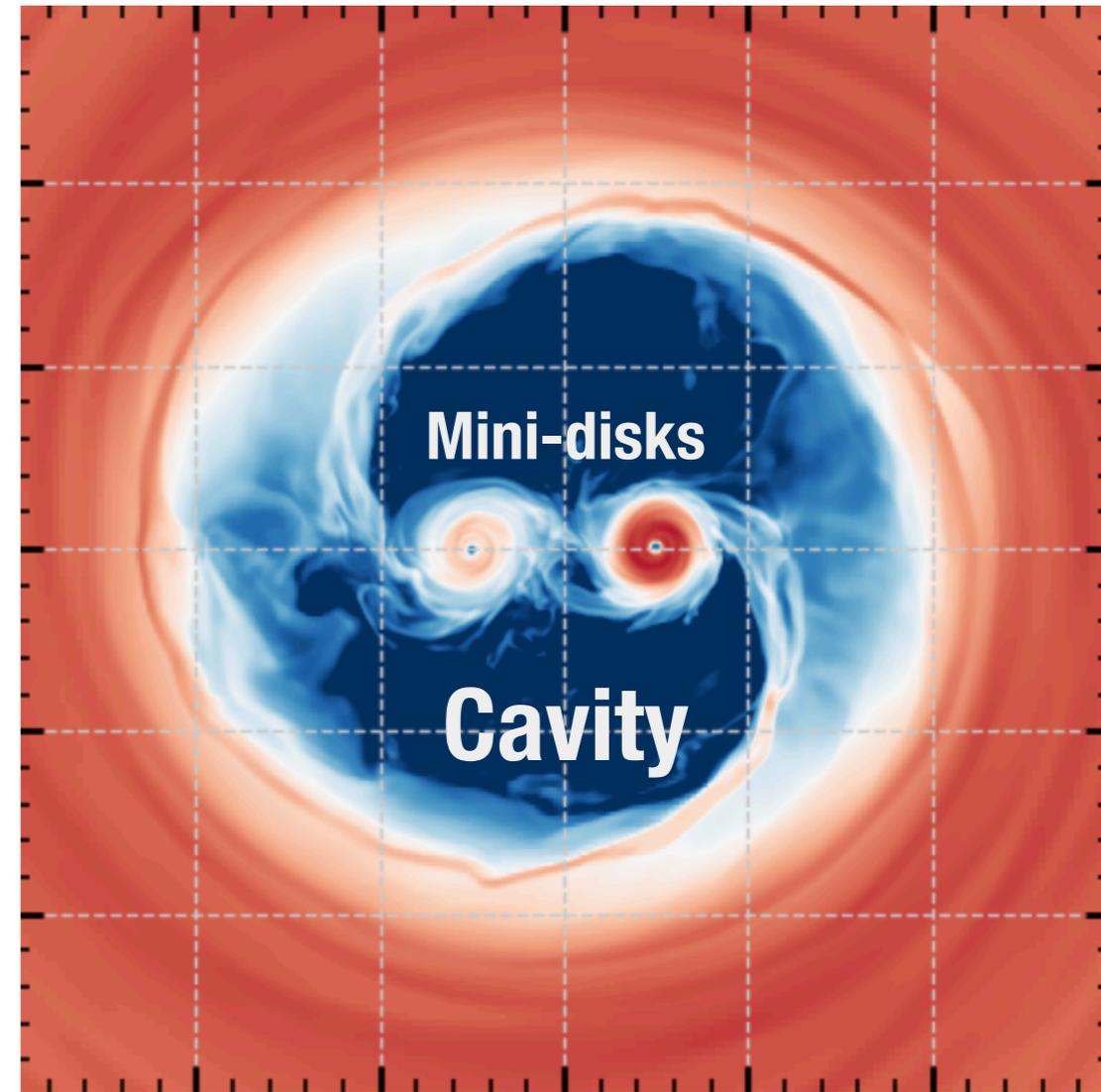
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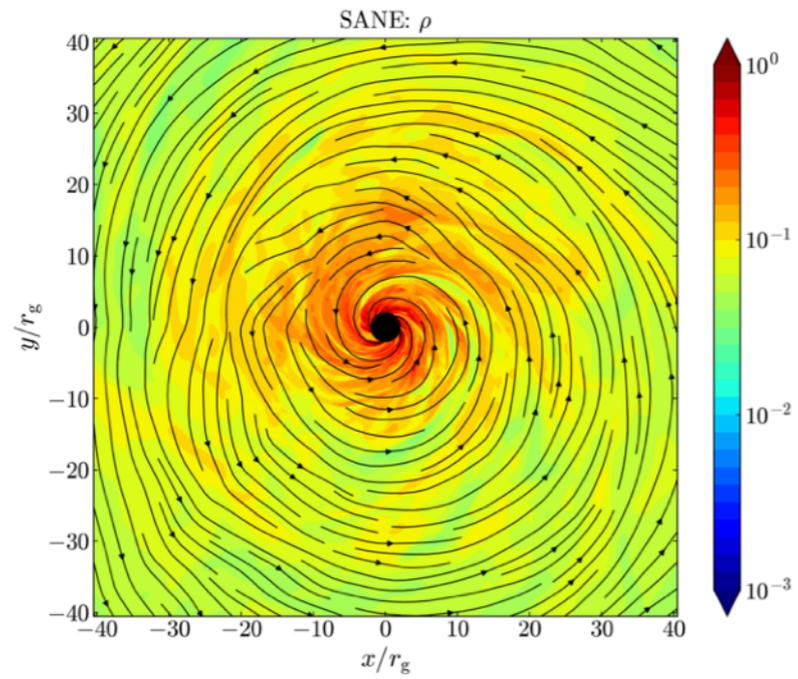
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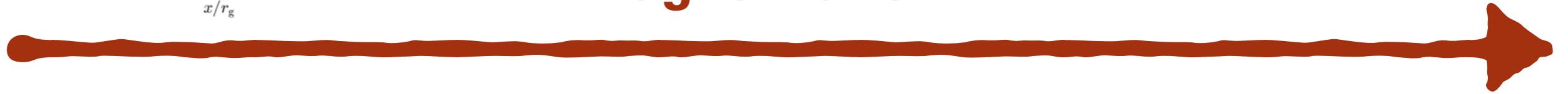
**Is this the full picture...?**

# Accretion regime

Chatterjee & Narayan



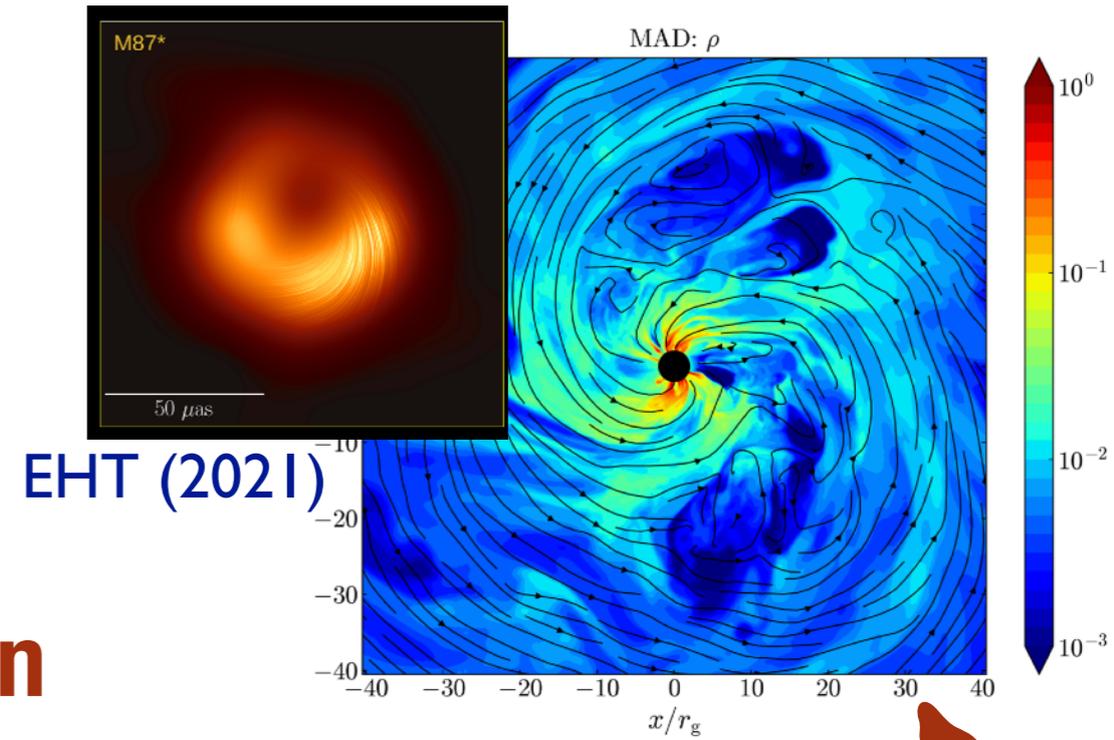
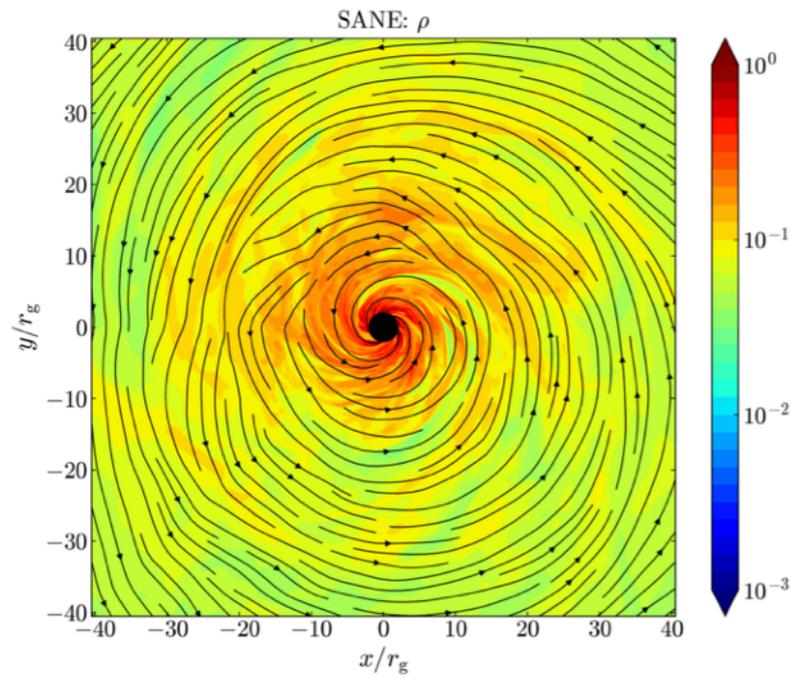
## Magnetization



# Accretion regime

Narayan+,  
Igumenshev+, Tchekhovskoy+,  
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Chatterjee & Narayan



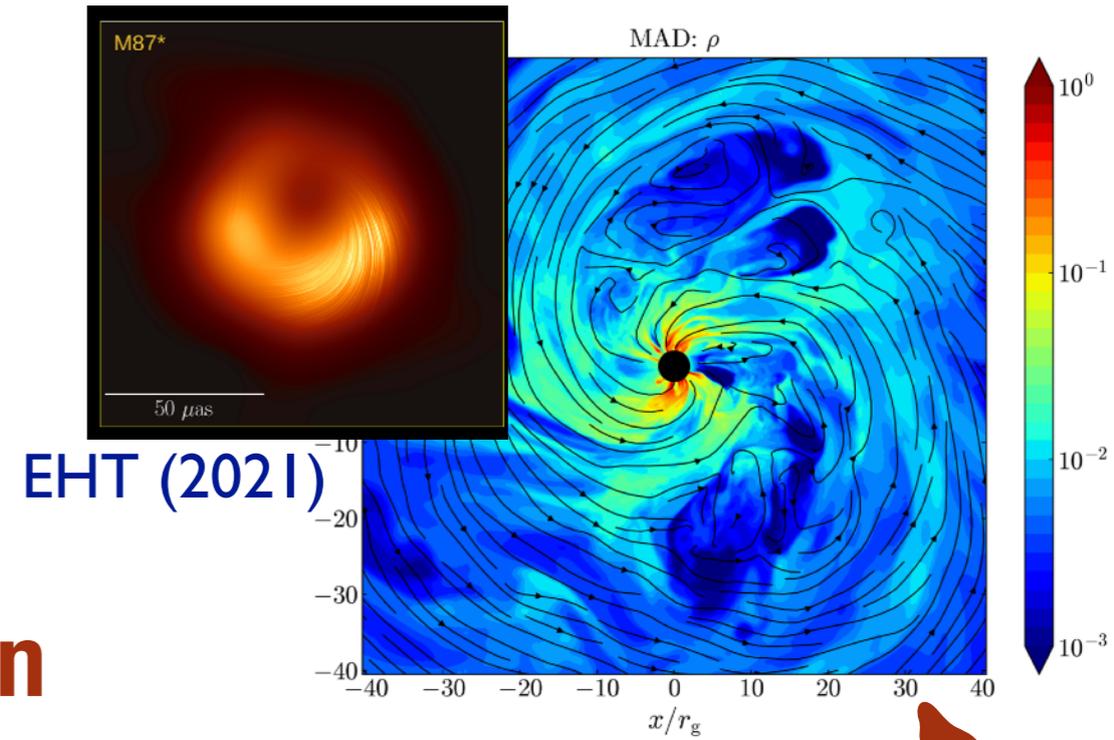
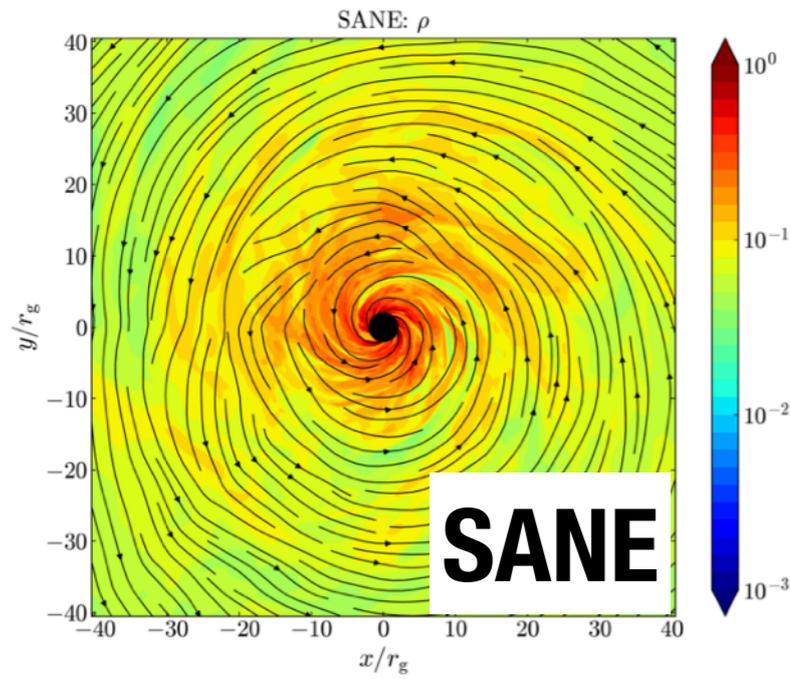
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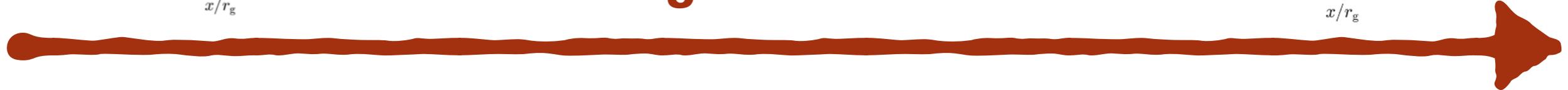
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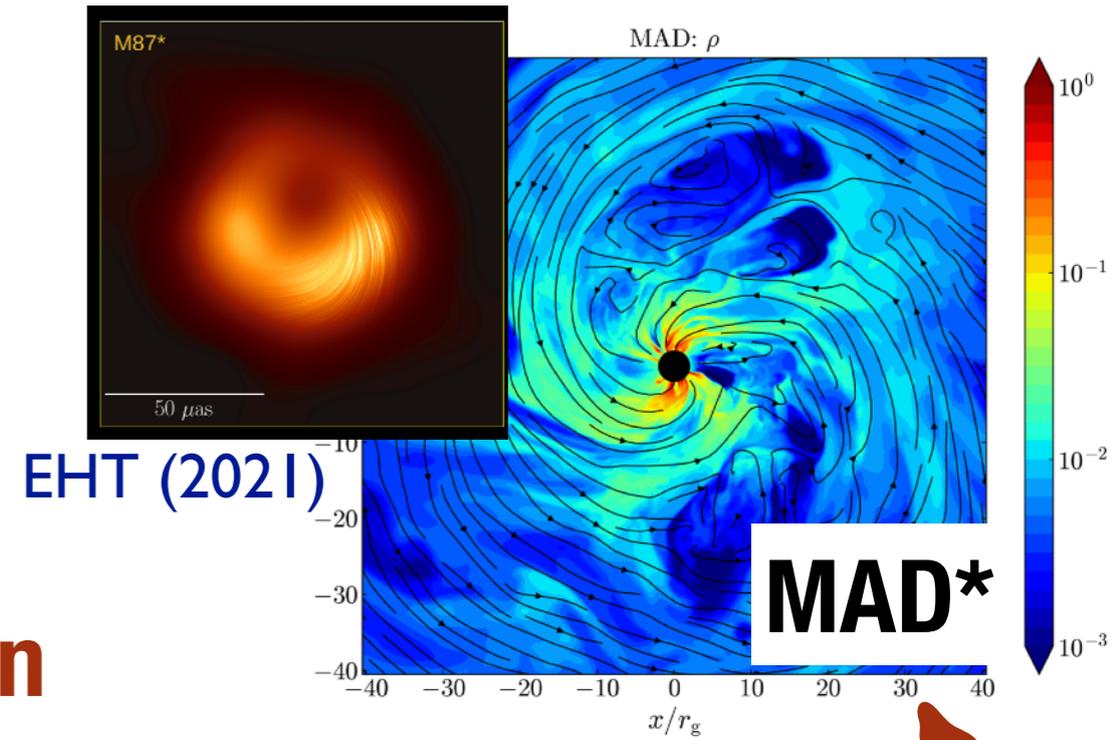
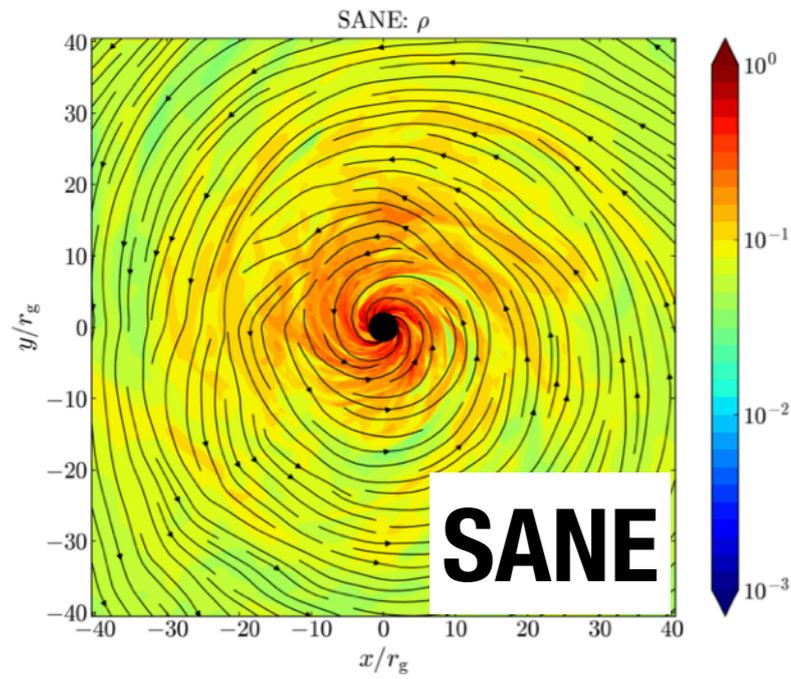
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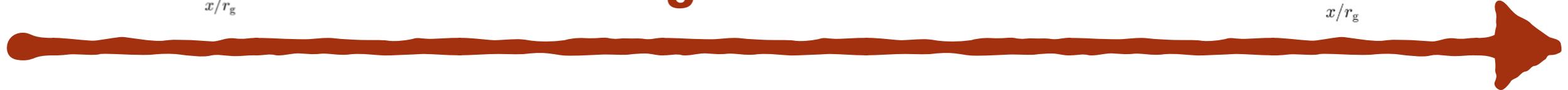
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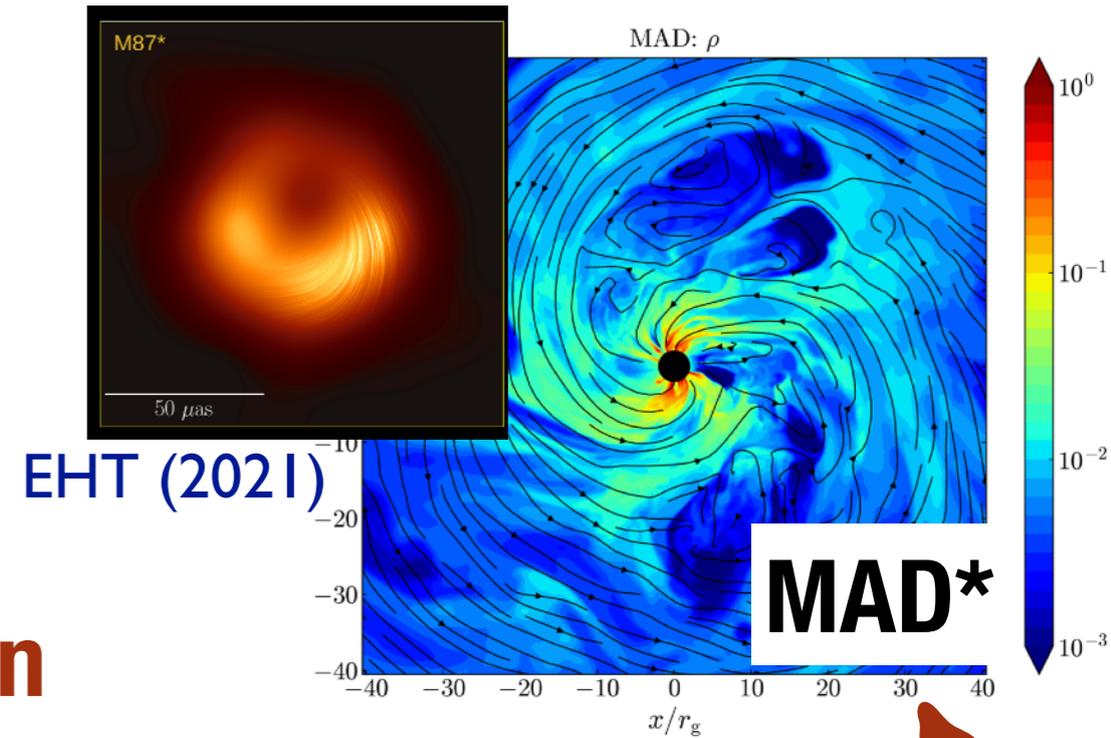
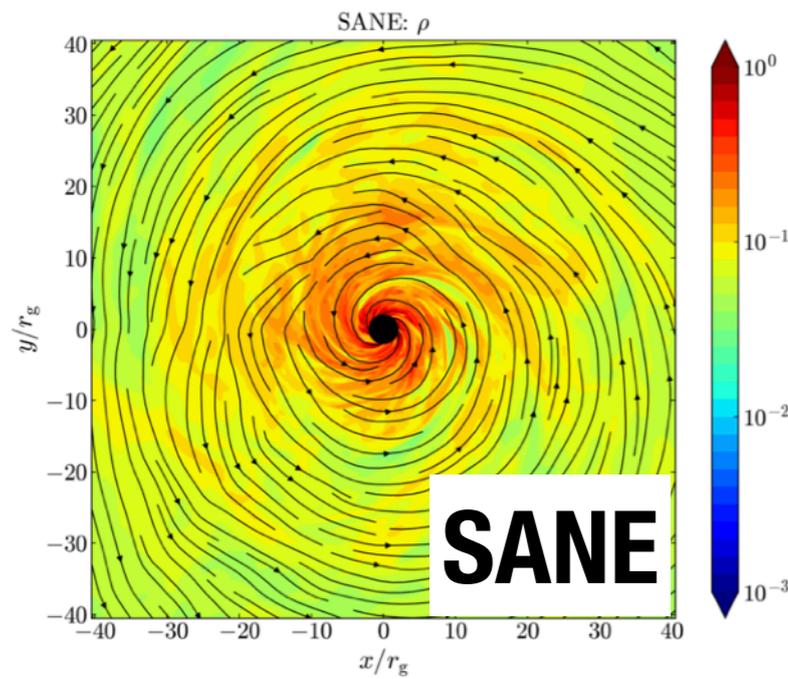
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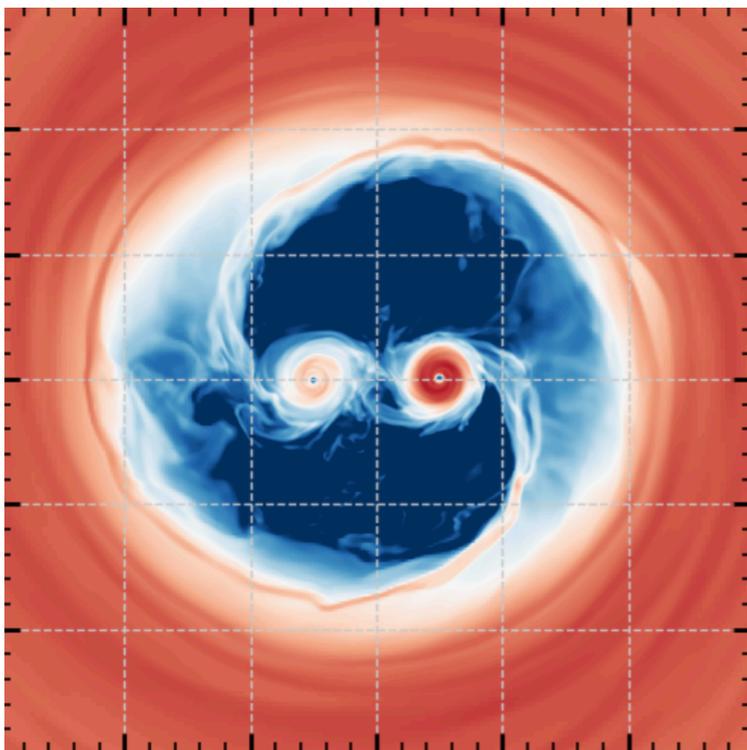
Chatterjee & Narayan



## Magnetization



Farris+(2014), Munoz+(2020), Duffel+(2020), Dittmann+(2021),  
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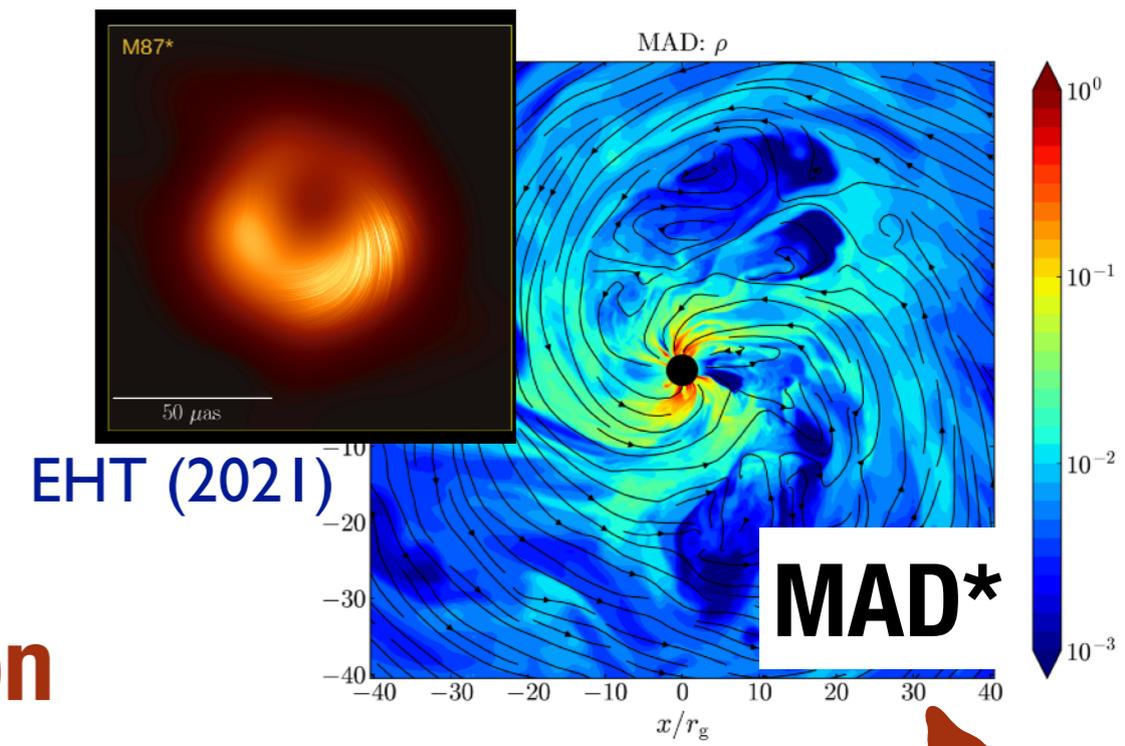
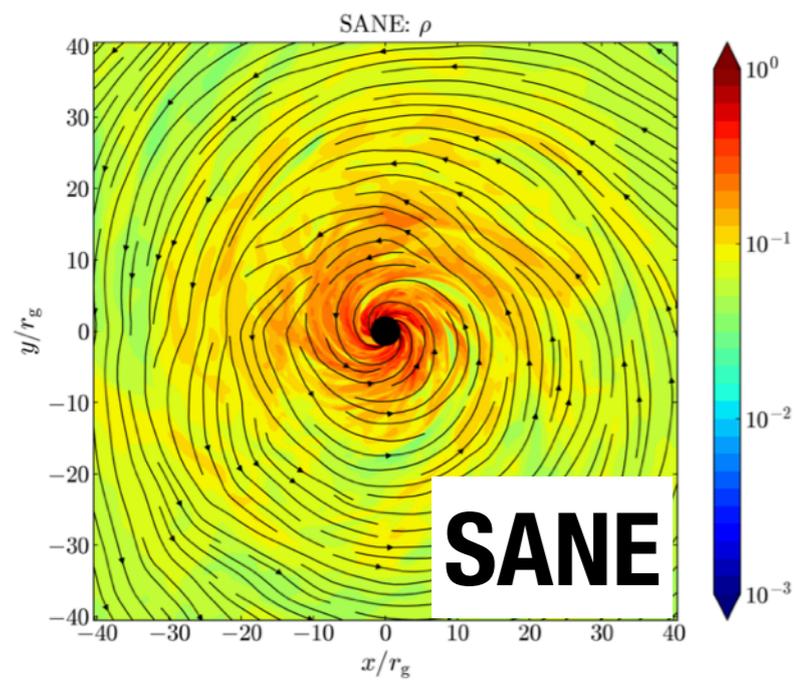


Circumbinary  
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# Accretion regime

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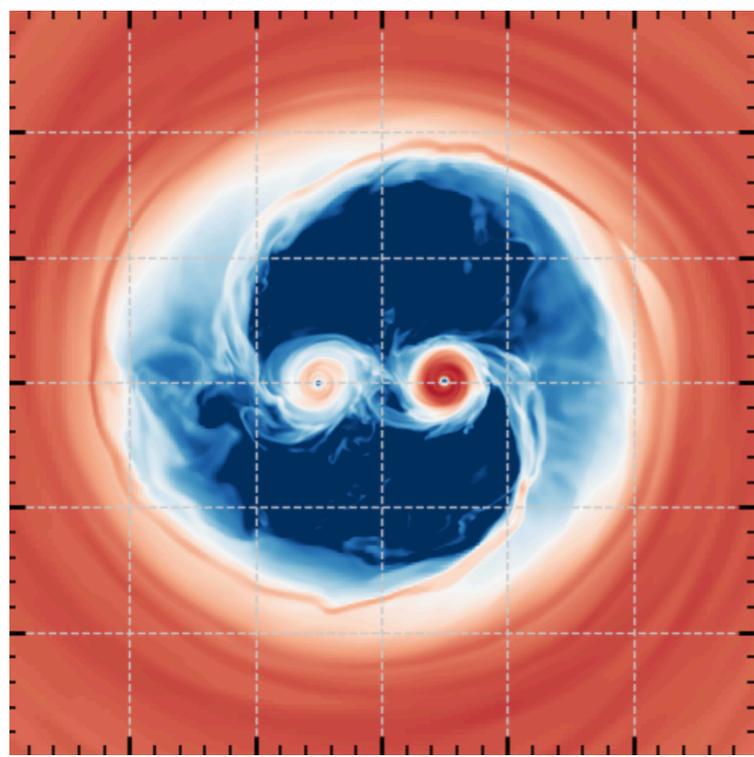
Chatterjee & Narayan



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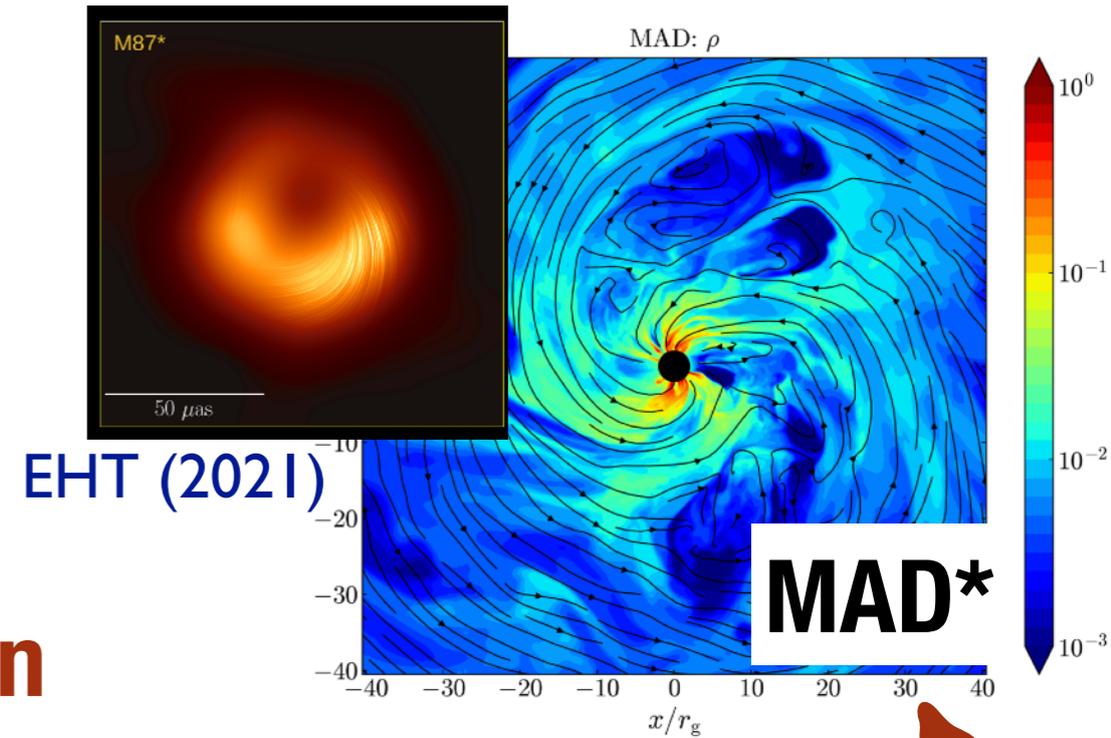
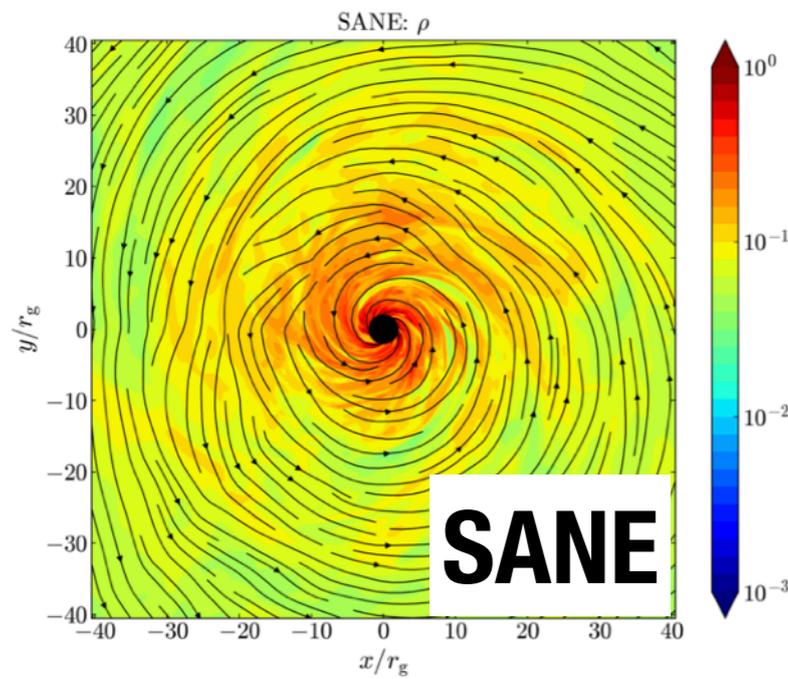
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???

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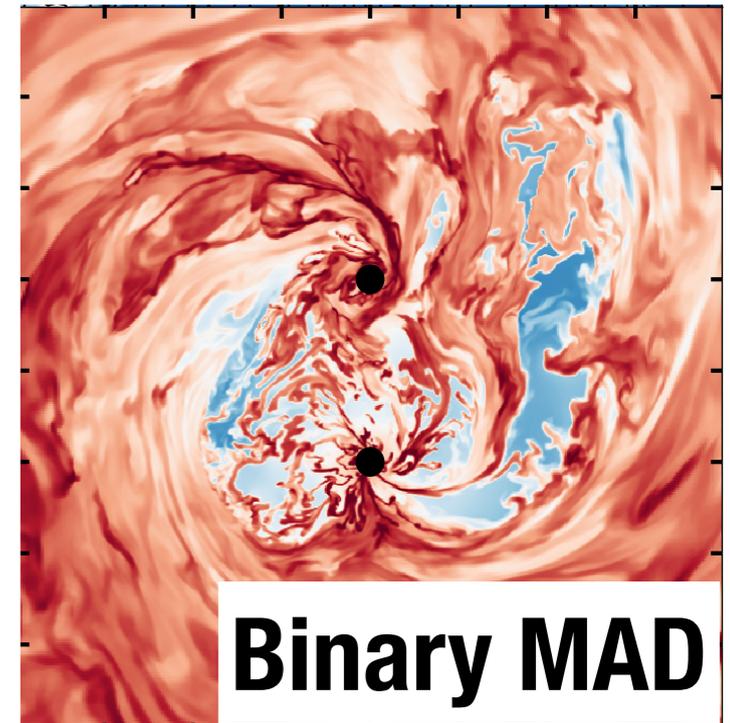
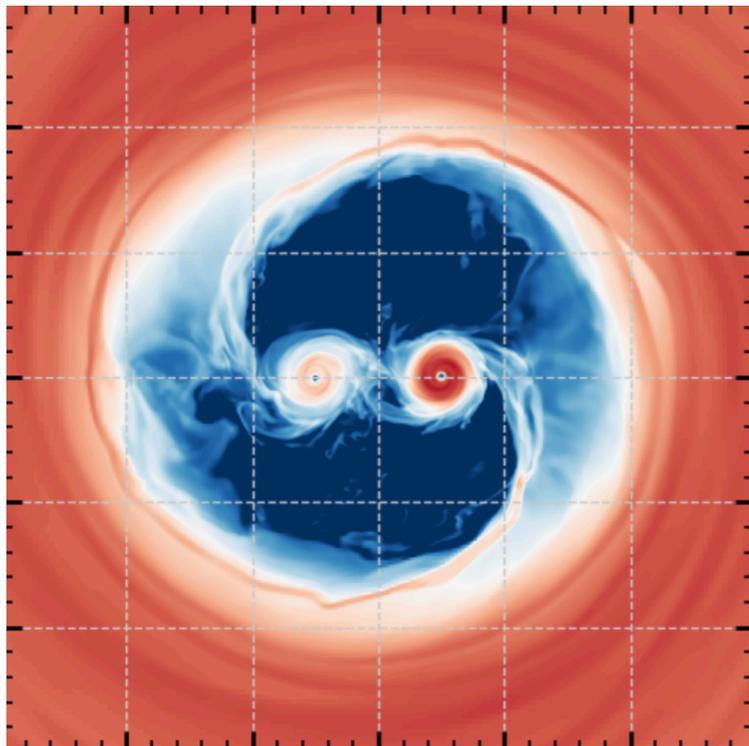


## Magnetization

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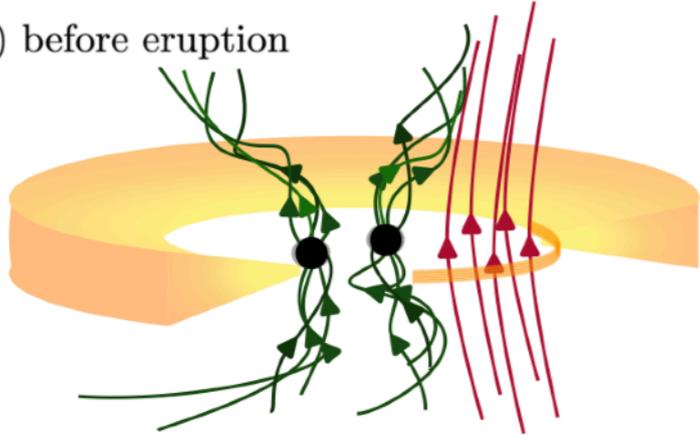
ERM & Wang (ApJL 2024)

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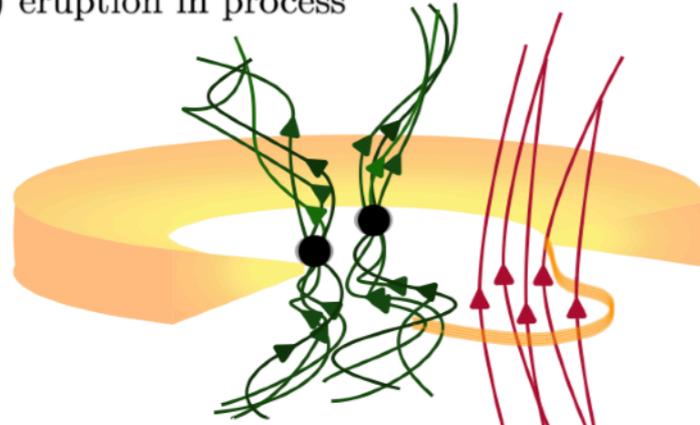


# Magnetically arrested circumbinary accretion

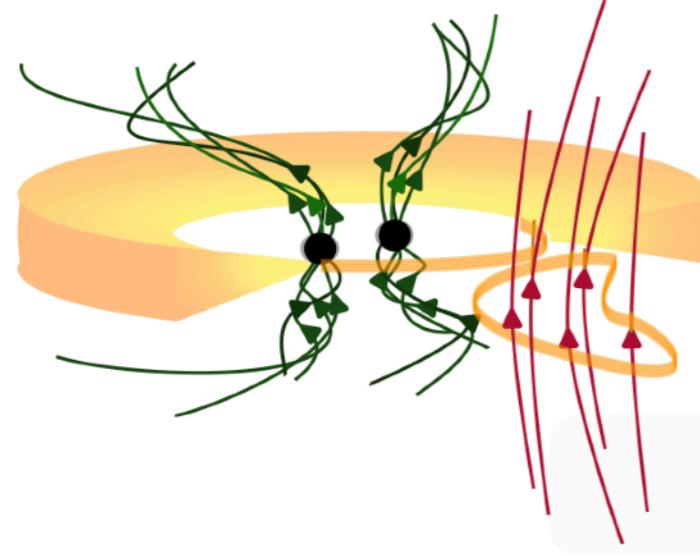
1) before eruption



2) eruption in process



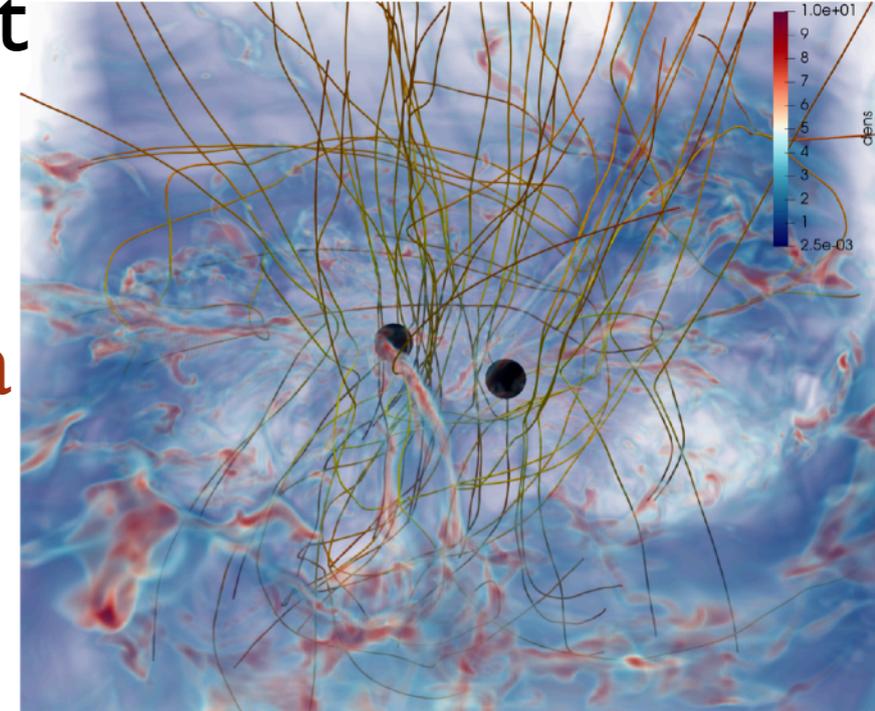
3) end of current eruption cycle



Interchange instabilities at the cavity wall trigger magnetic flux eruptions. This is the analogous to a MAD state of a single black hole!

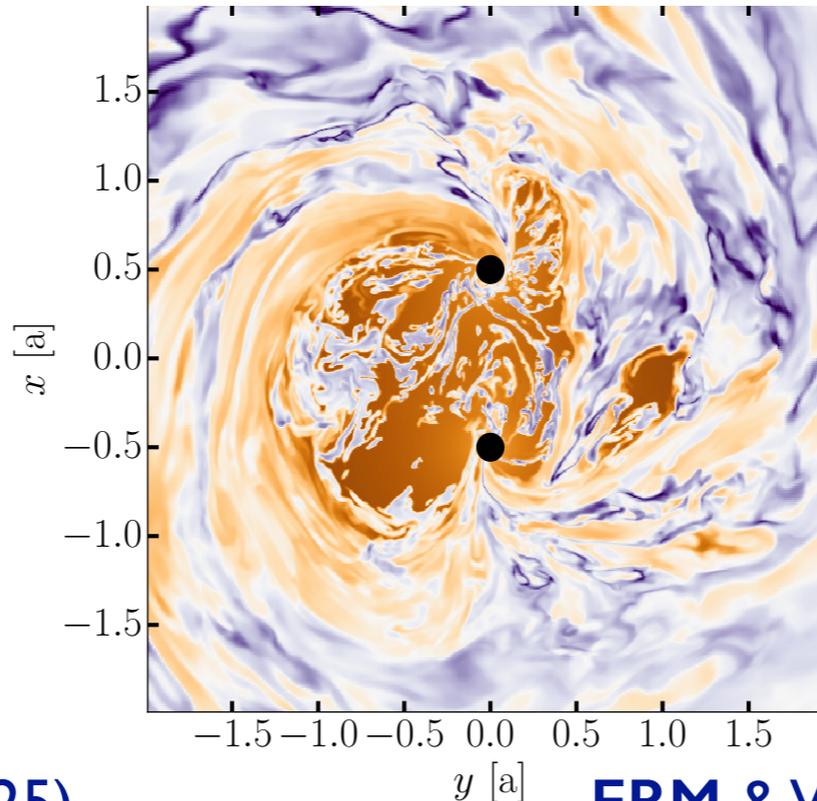
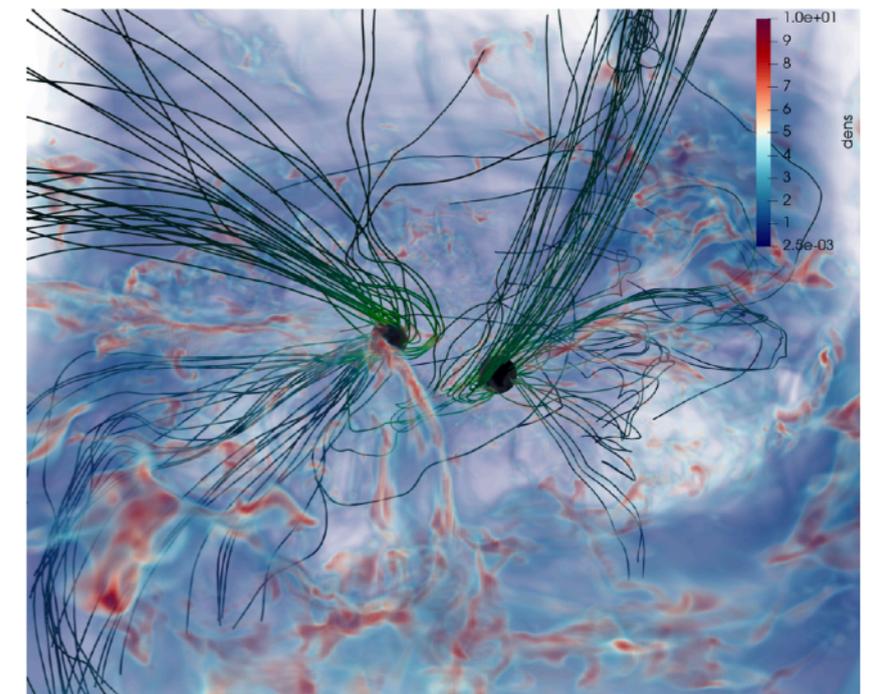
Narayan+(2003),  
Igumenchev+(2003),  
Begelmann+(2022)

aligned cavity flux



ERM & Wang (PRDL 2025)

twisted dual jets



ERM & Wang (ApJL 2024)

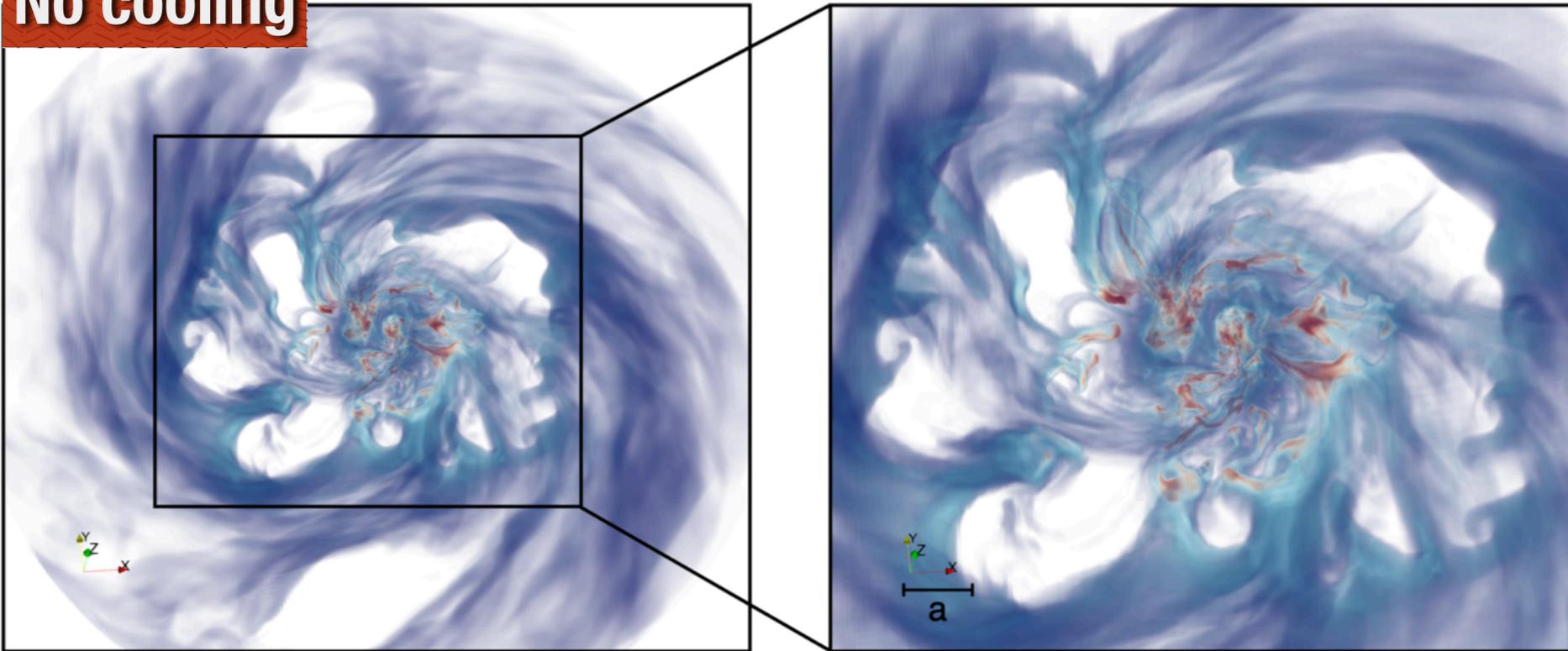
Wang, ERM, Hopkins (arXiv 2025)

# BMAD isn't cool (literally)!

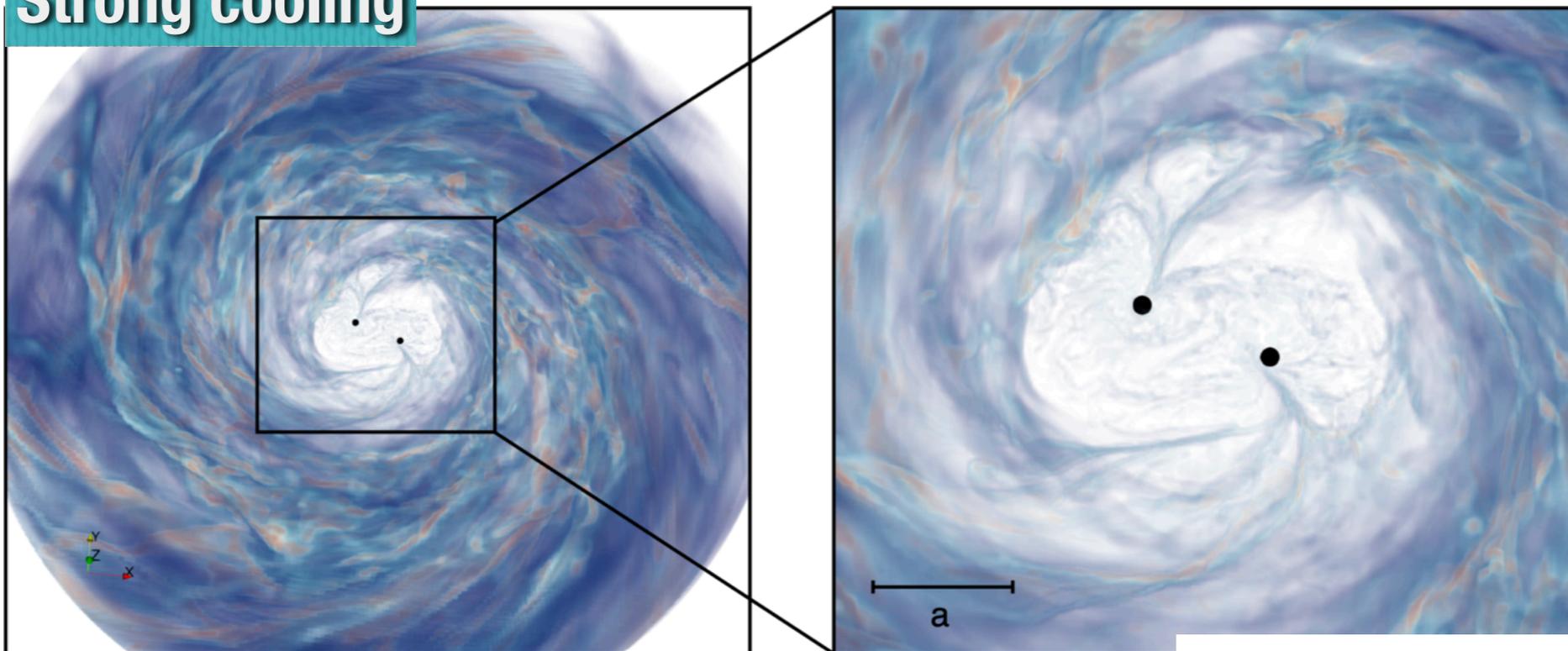


H. Wang  
(Caltech)

No cooling



Strong cooling



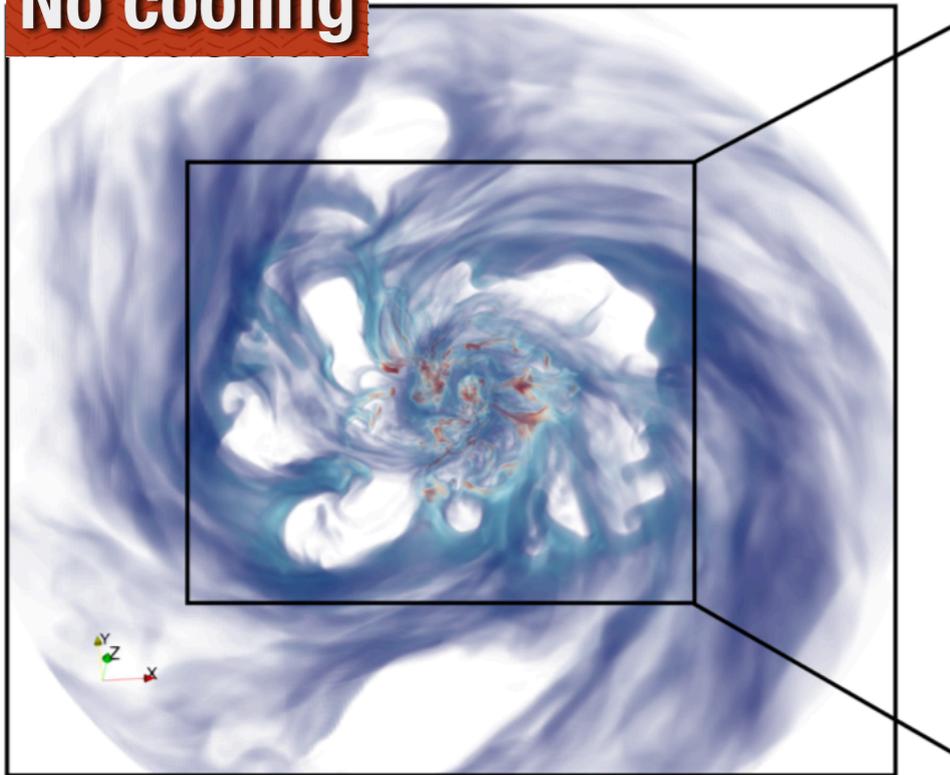
Wang, ERM, Hopkins (arXiv:2025)

# BMAD isn't cool (literally)!

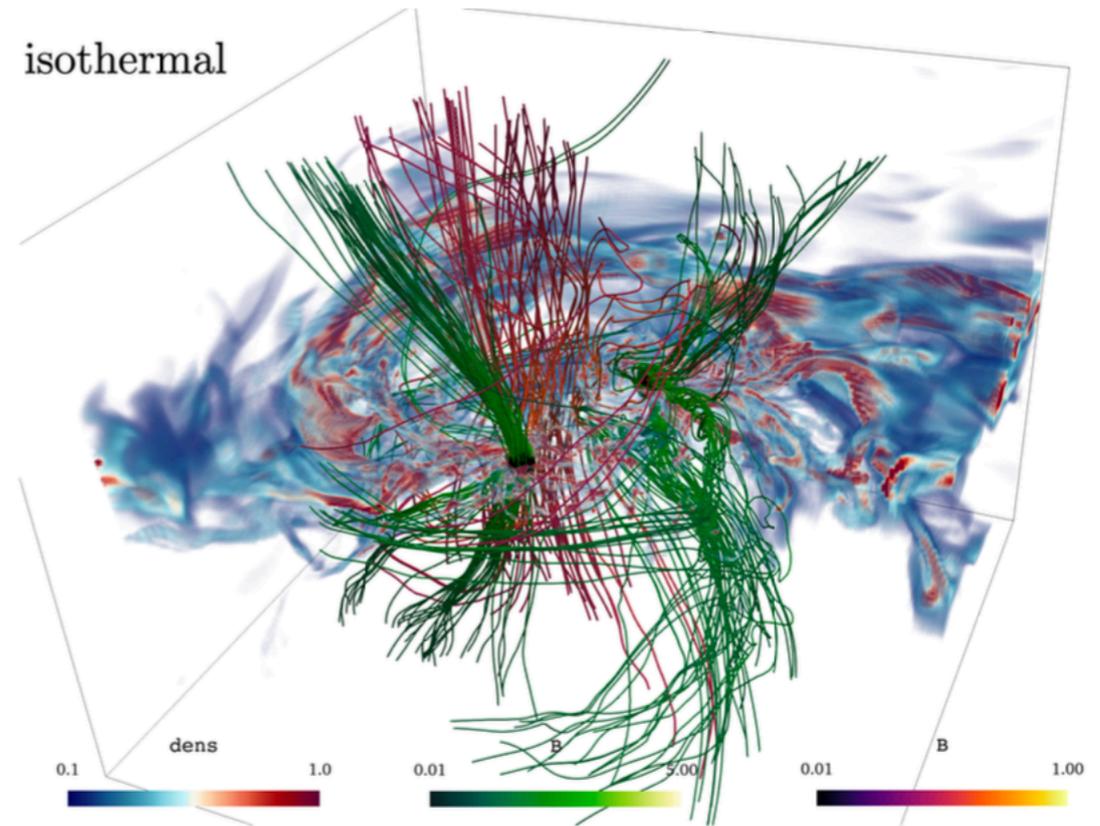


H. Wang  
(Caltech)

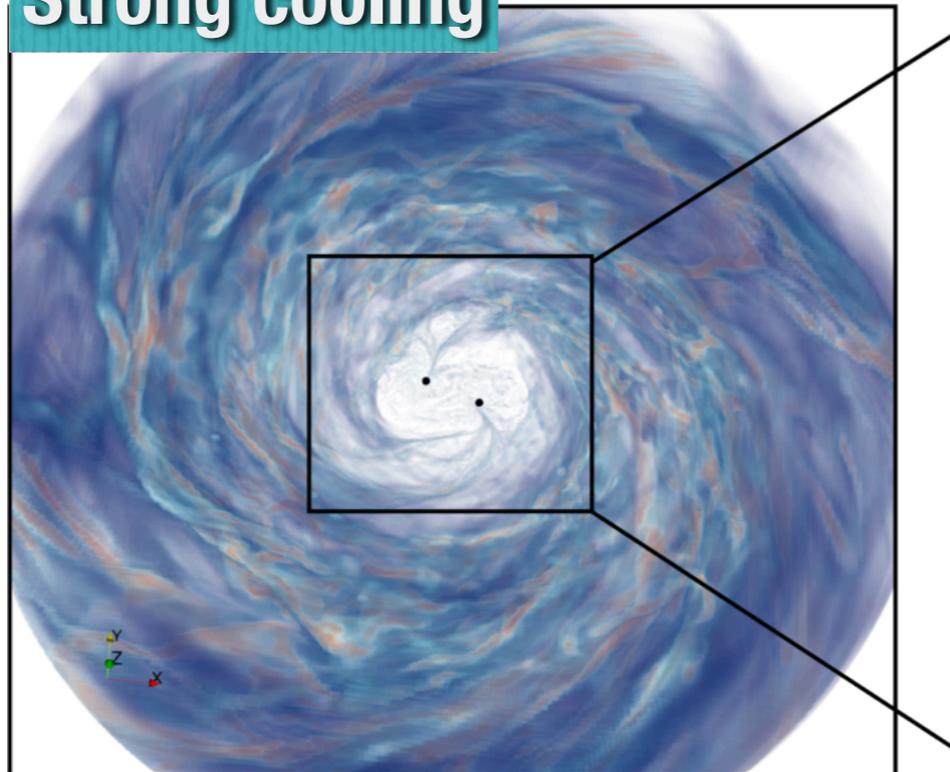
No cooling



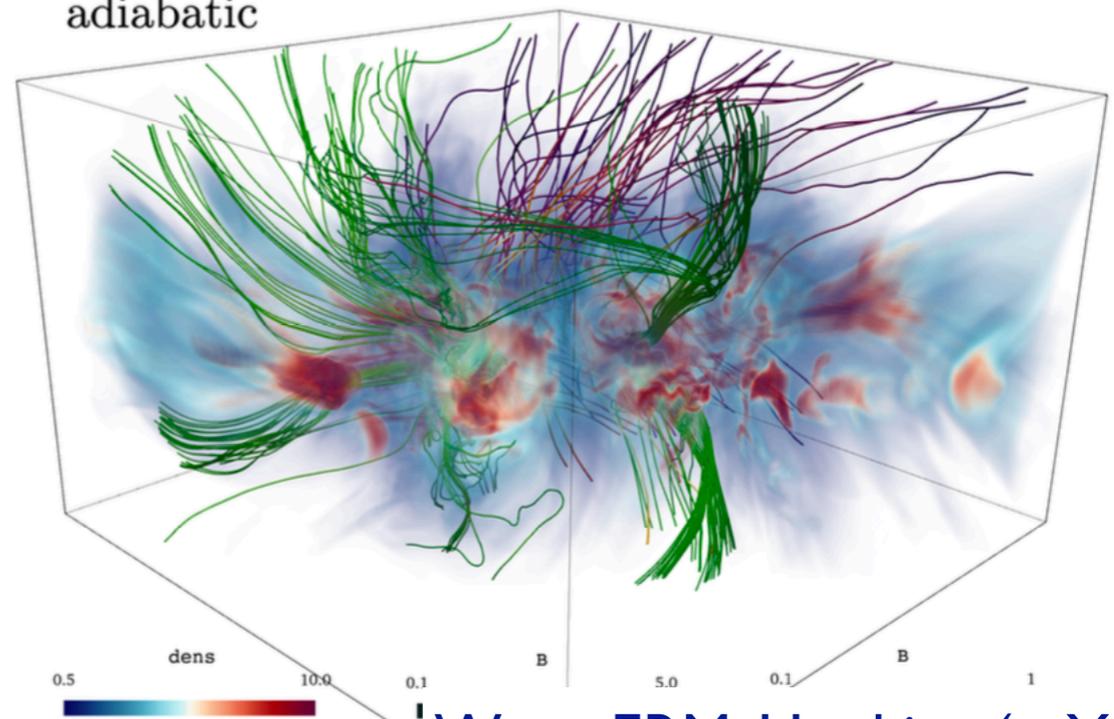
isothermal



Strong cooling

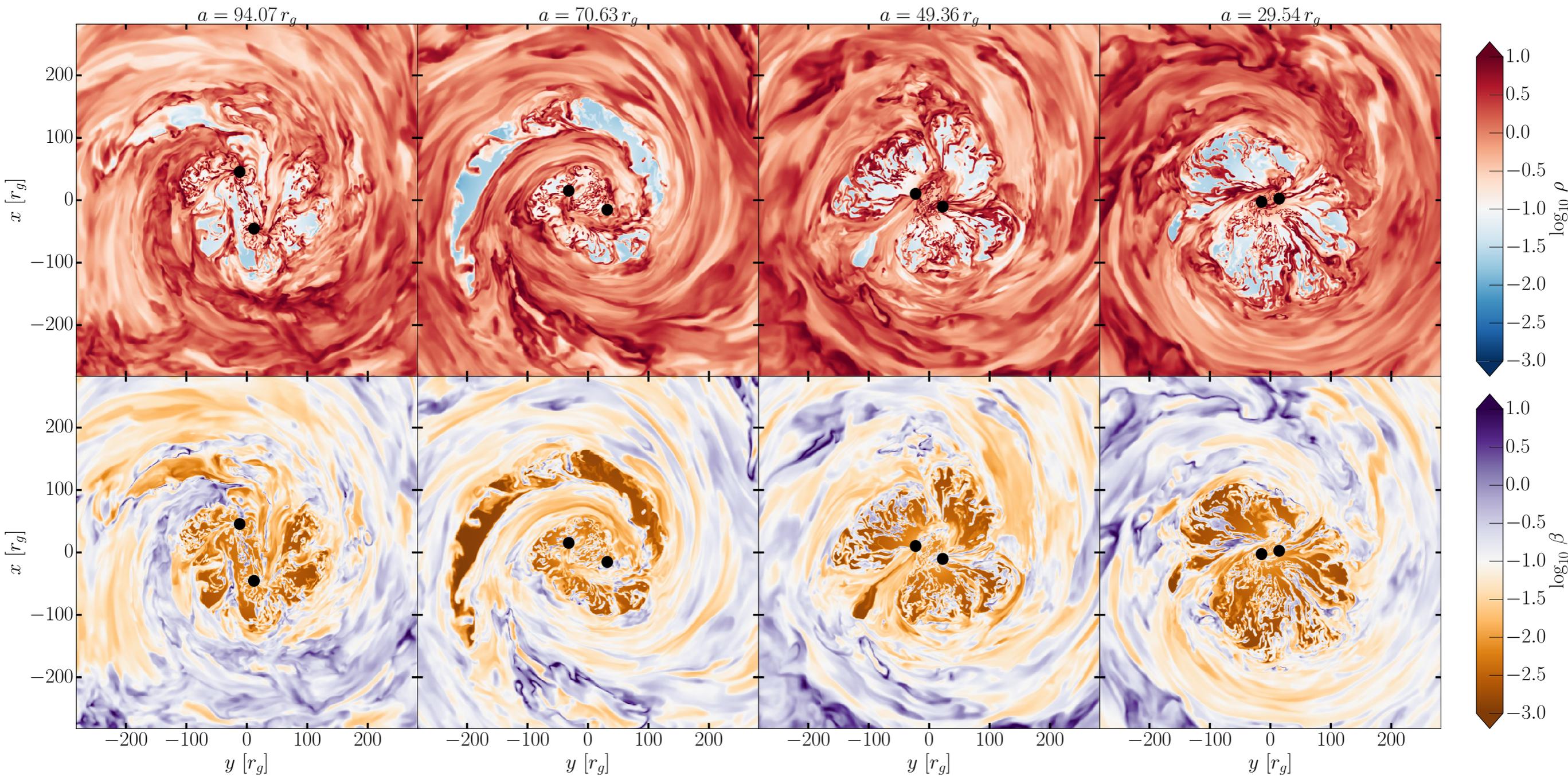


adiabatic



Wang, ERM, Hopkins (arXiv:2025)

# Towards merger: Decoupling regime



Magnetospheric accretion (Rayleigh-Taylor Fingers)  
during and after decoupling!

ERM & Wang (PRDL 2025)

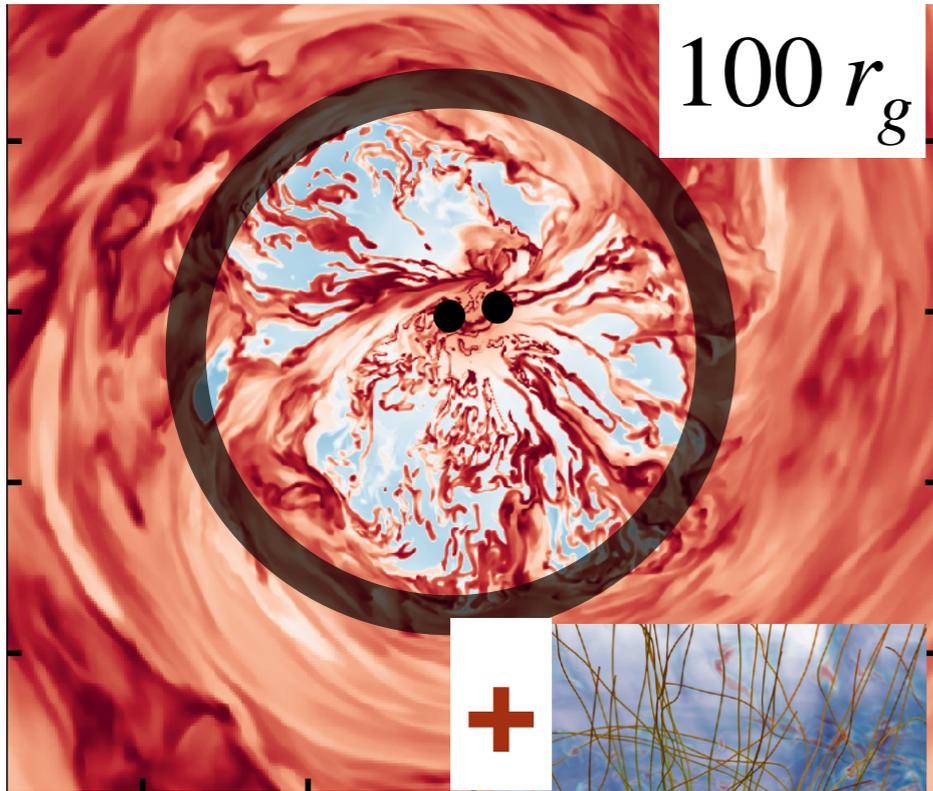
# Inspiral and merger

## Effective Bondi accretion from cavity wall

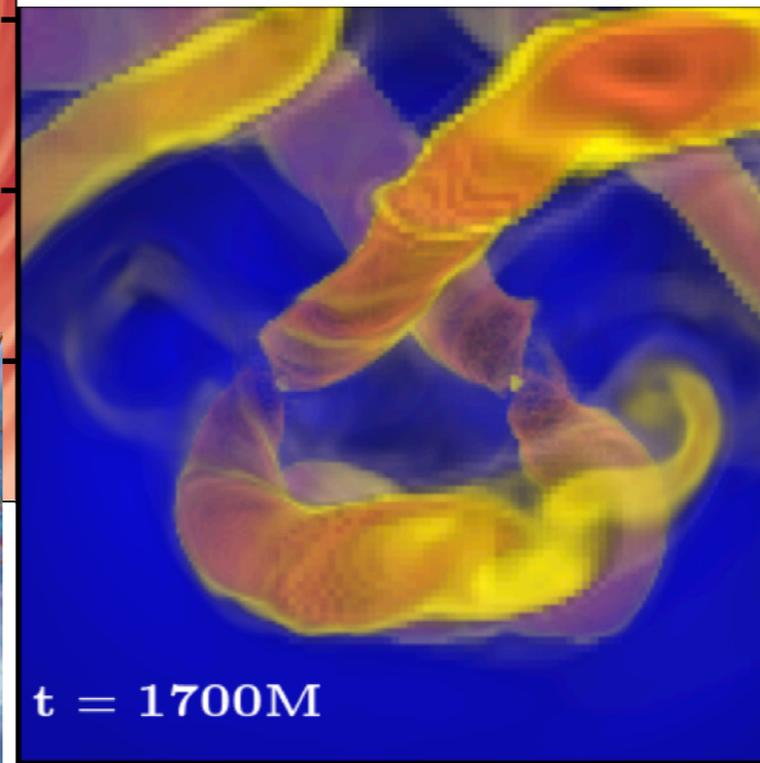
ERM & Wang (PRDL 2025)

Ressler, Combi, Ripperda, ERM (ApJL 2025)

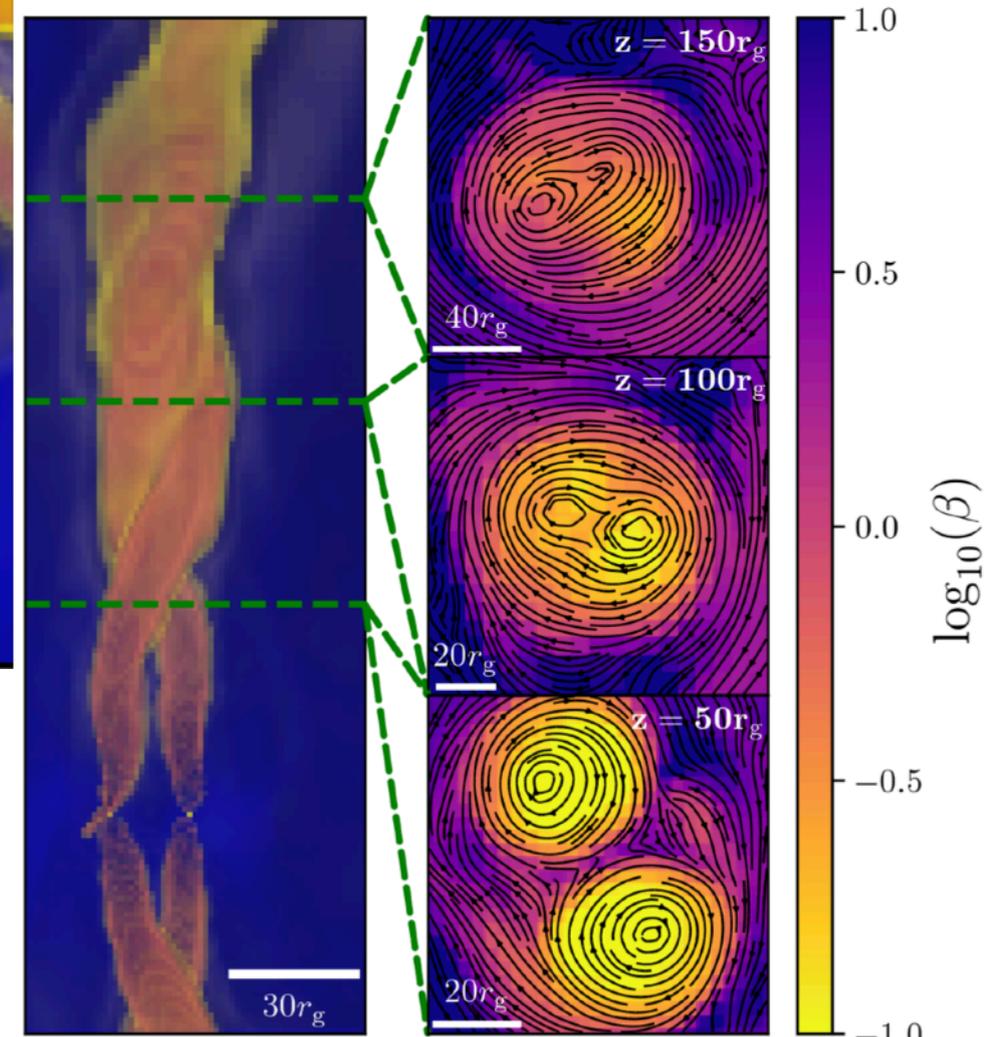
Full GRMHD simulations of inspiraling PN black holes with Bondi feeding!



Sean Ressler (CITA)



Non-thermal emission from jet interaction, and flares close to merger



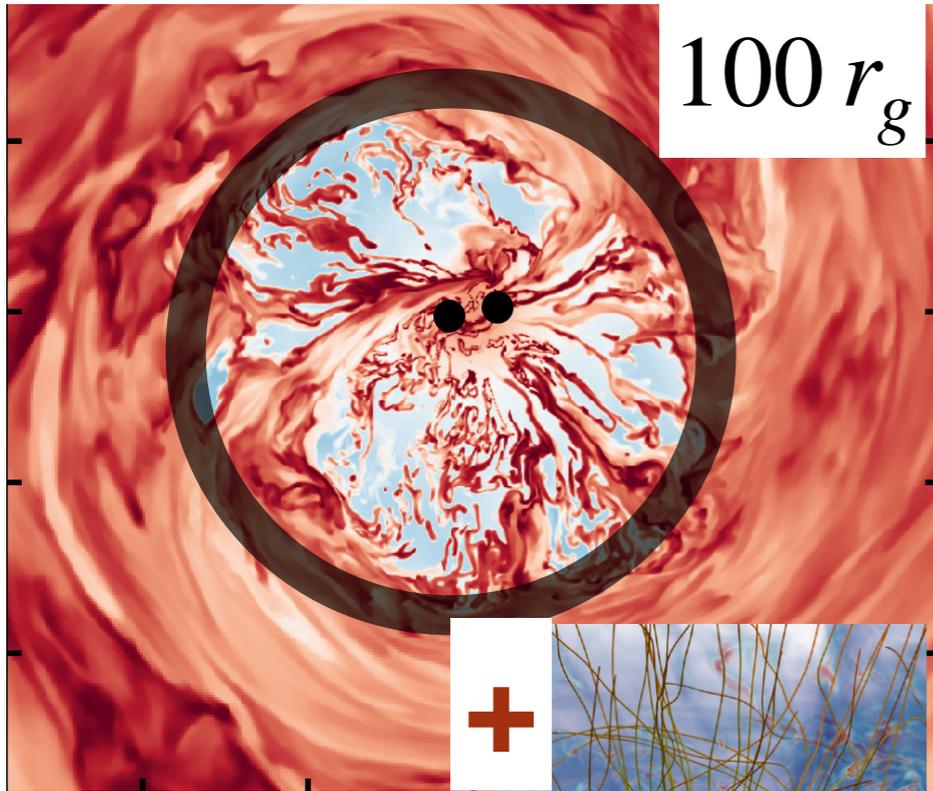
# Inspiral and merger

## Effective Bondi accretion from cavity wall

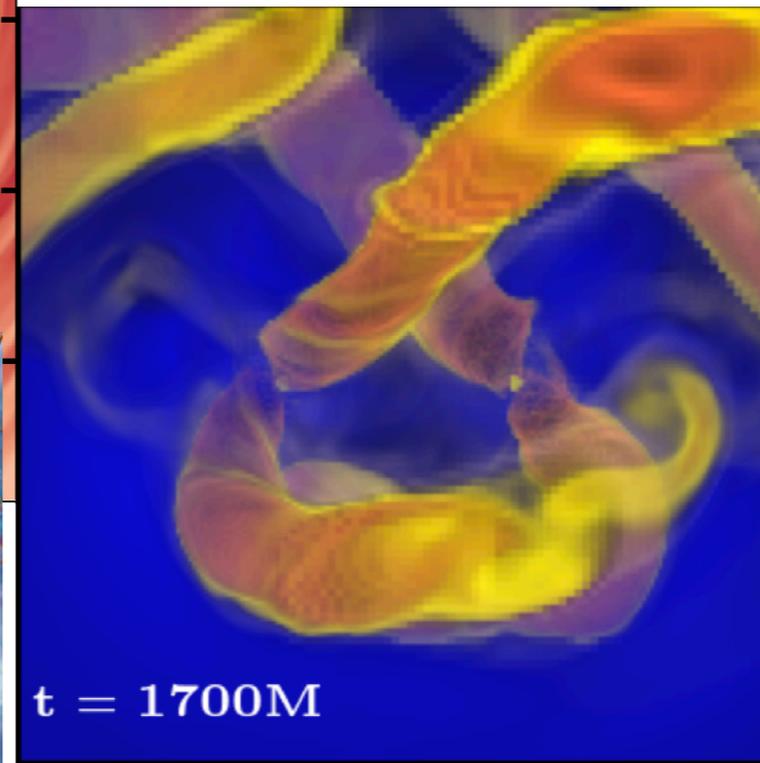
ERM & Wang (PRDL 2025)

Ressler, Combi, Ripperda, ERM (ApJL 2025)

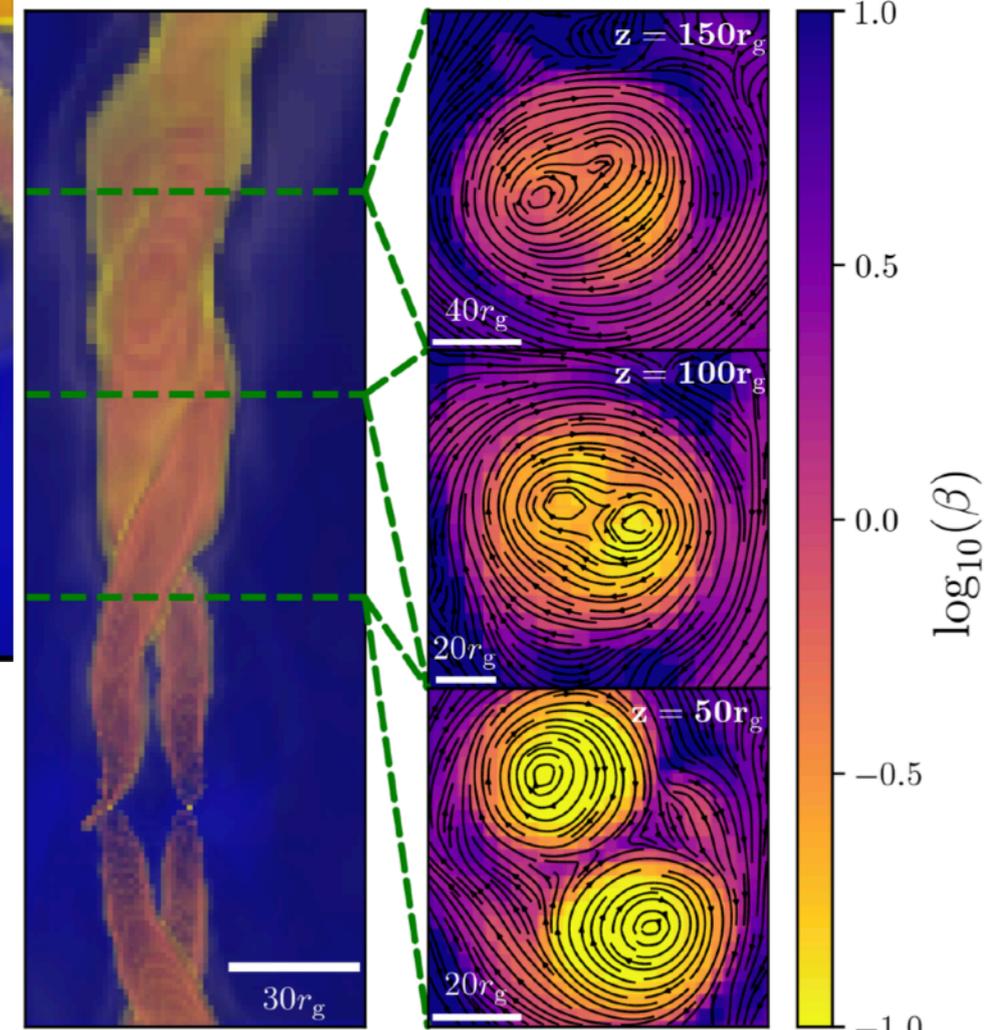
Full GRMHD simulations of inspiraling PN black holes with Bondi feeding!



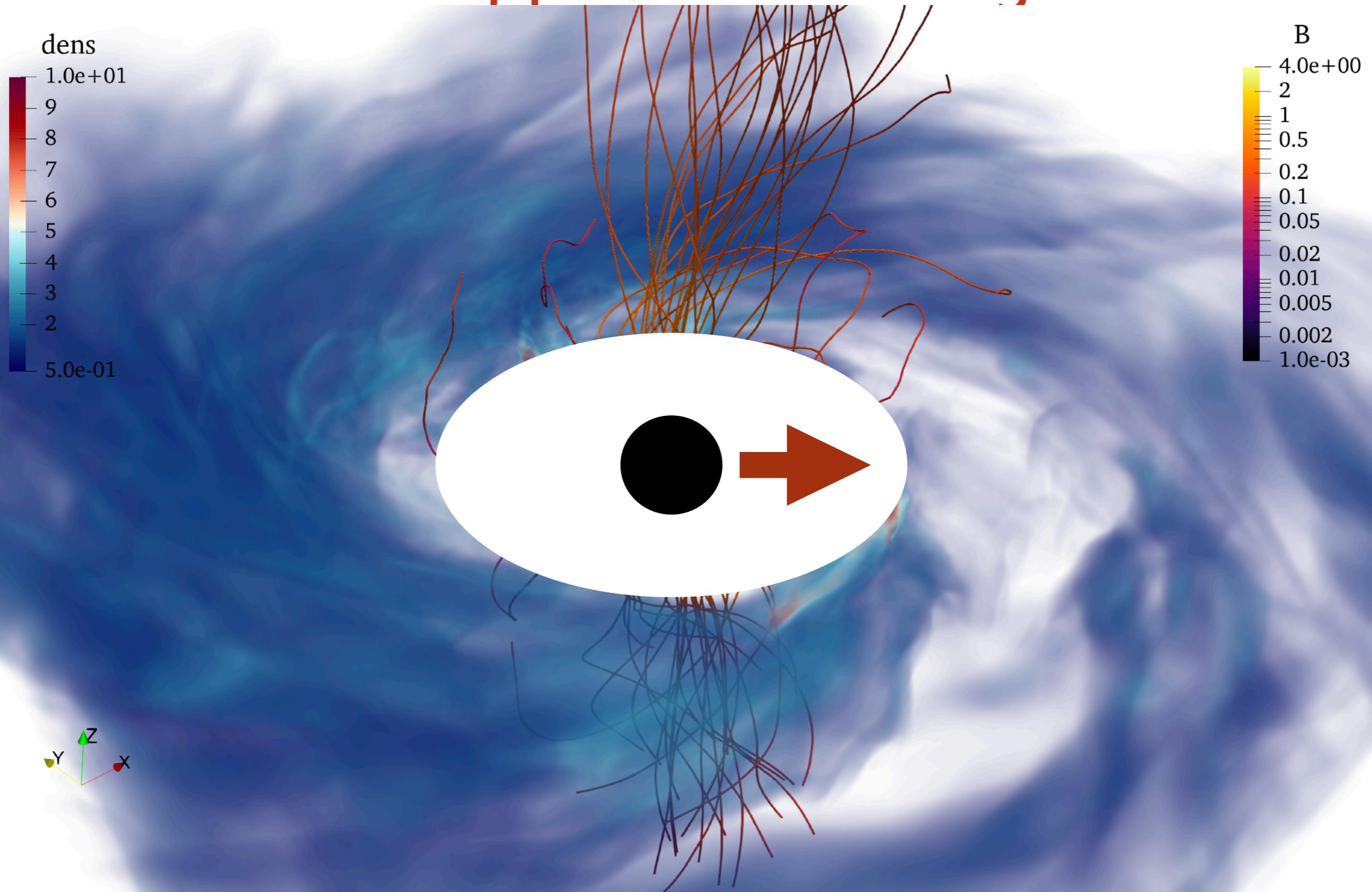
Sean Ressler (CITA)



Non-thermal emission from jet interaction, and flares close to merger



# What happens after merger?

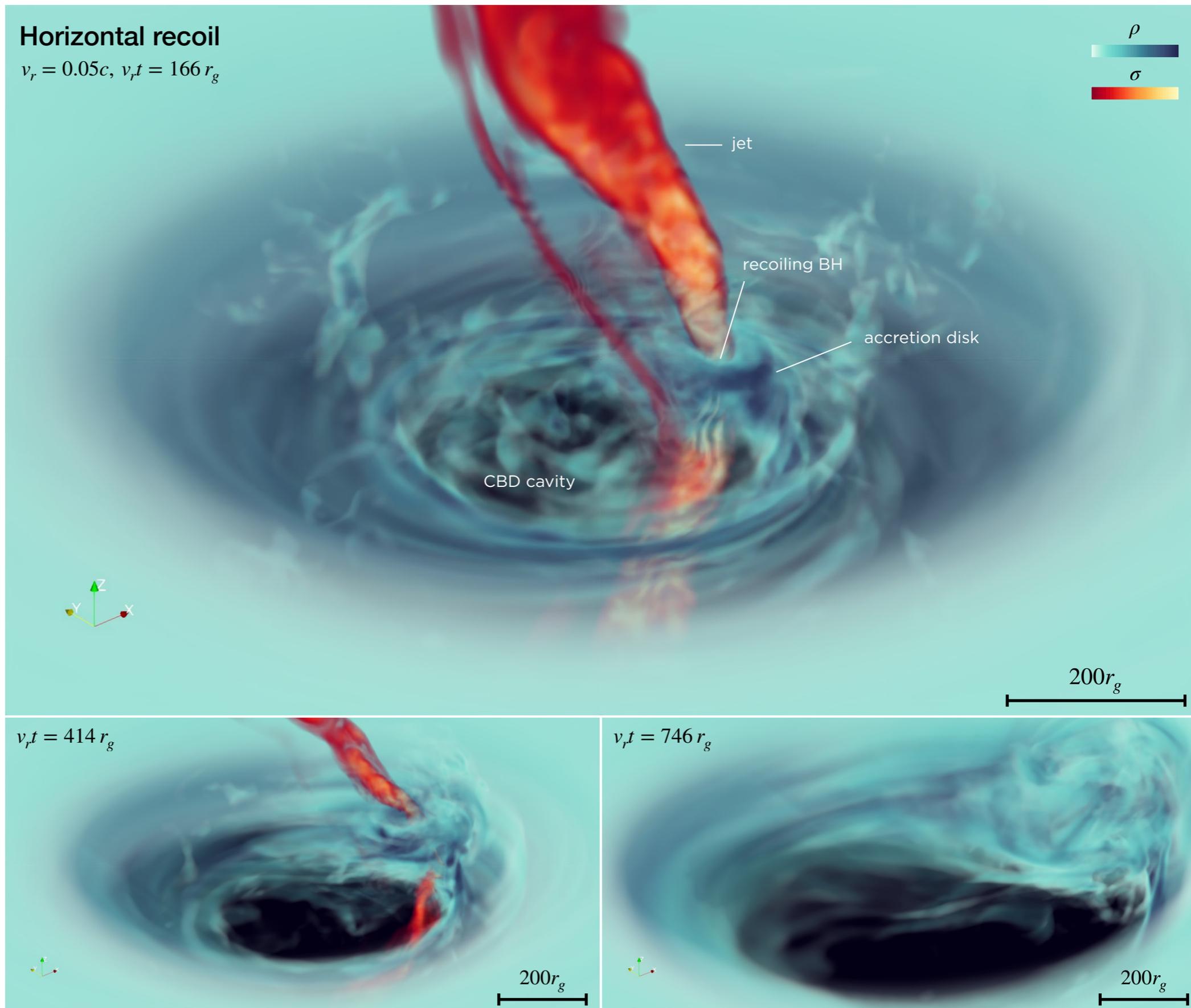


# Post-merger: Jets and disk collisions



Y. Kim

(Caltech => Princeton)



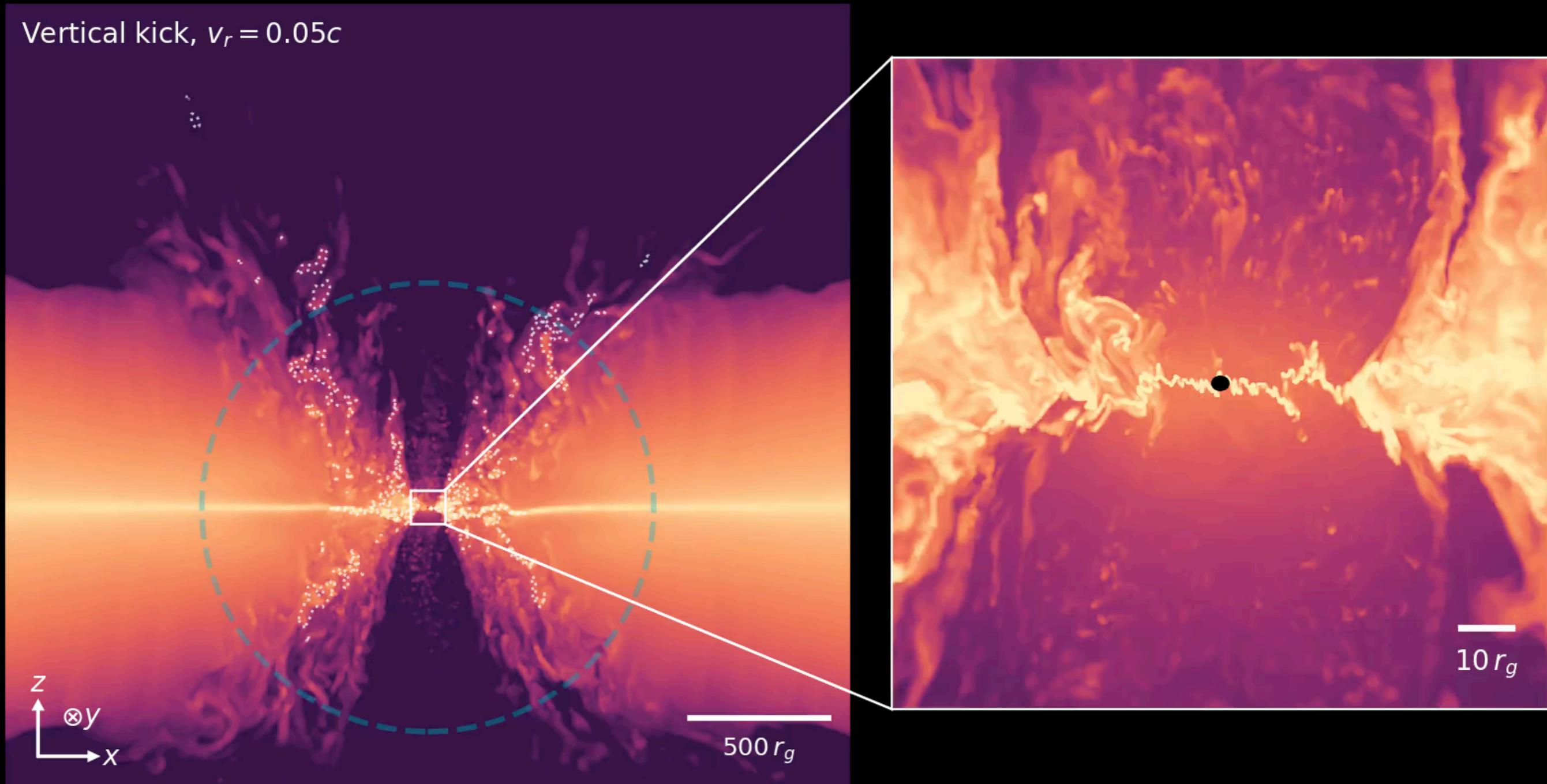
BMAD post-merger from consistently decoupled CBD

Kim, ERM+ (in prep)

see also de Simone+ for different regime

# Kick direction

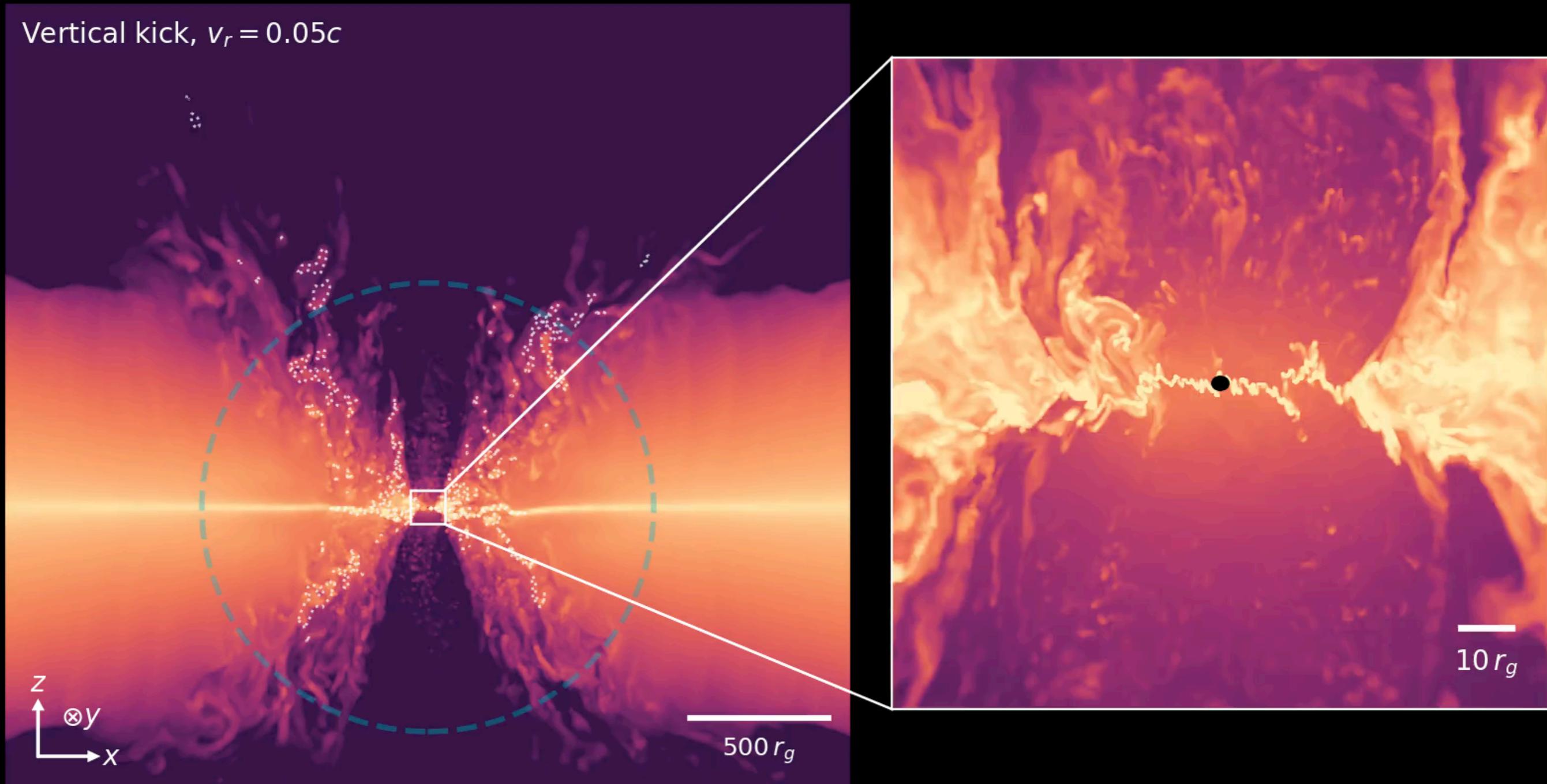
Systematic explication of kick direction and sub- and supersonic kick velocities



Kim, **ERM+** (in prep)

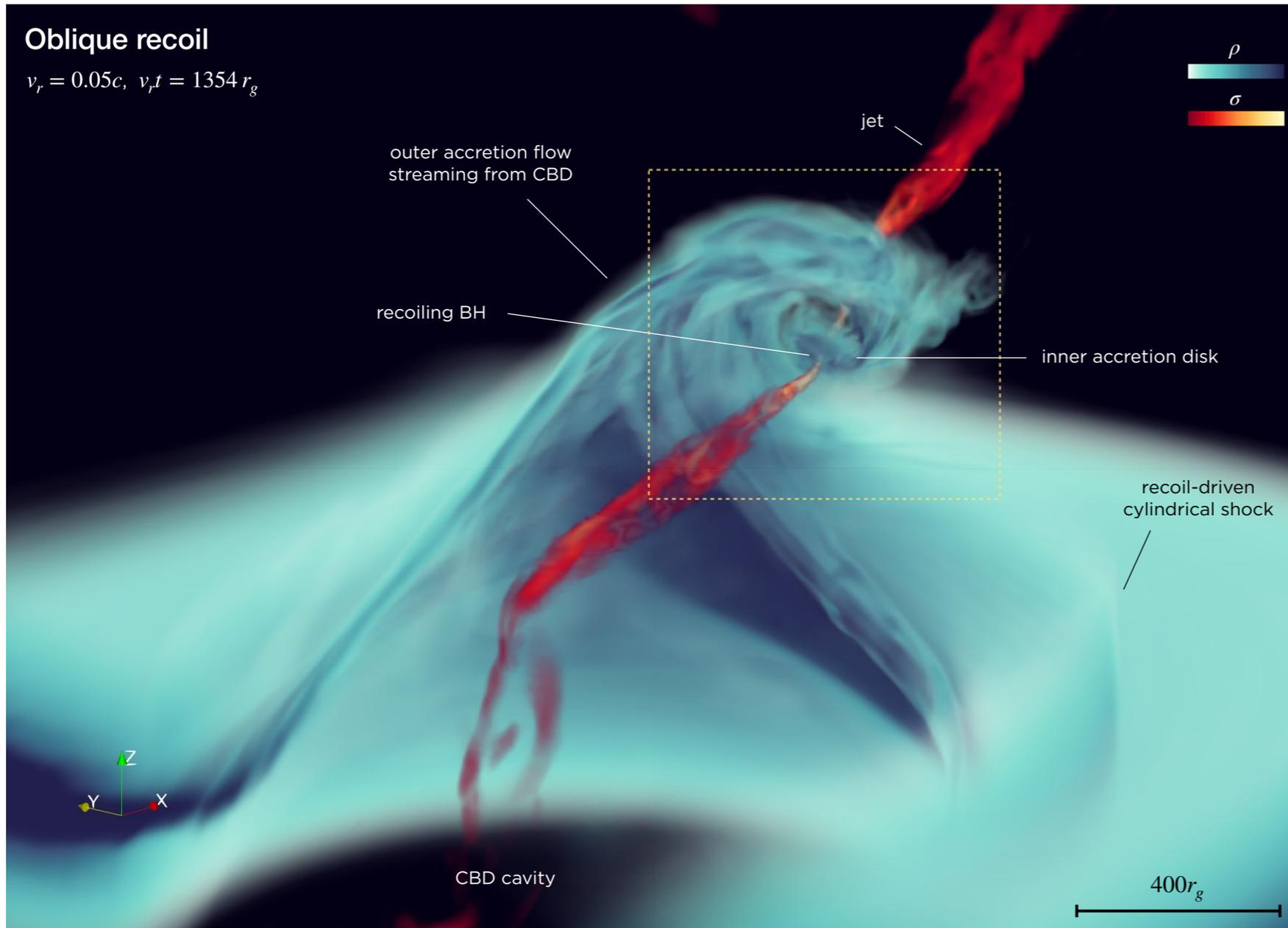
# Kick direction

Systematic explication of kick direction and sub- and supersonic kick velocities



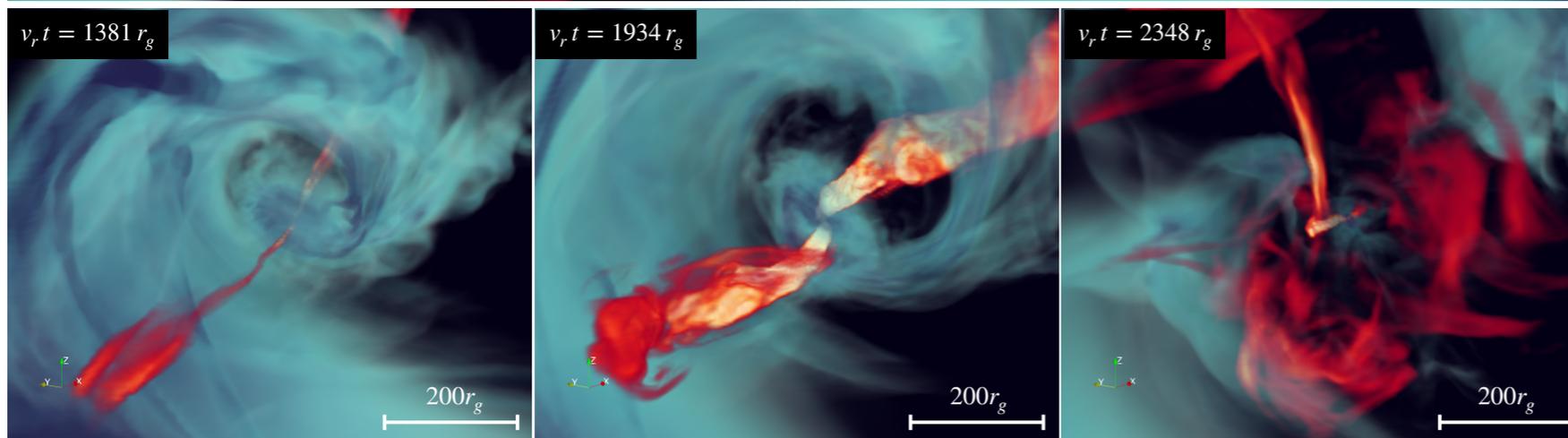
Kim, **ERM+** (in prep)

# Oblique cases feature complex behavior



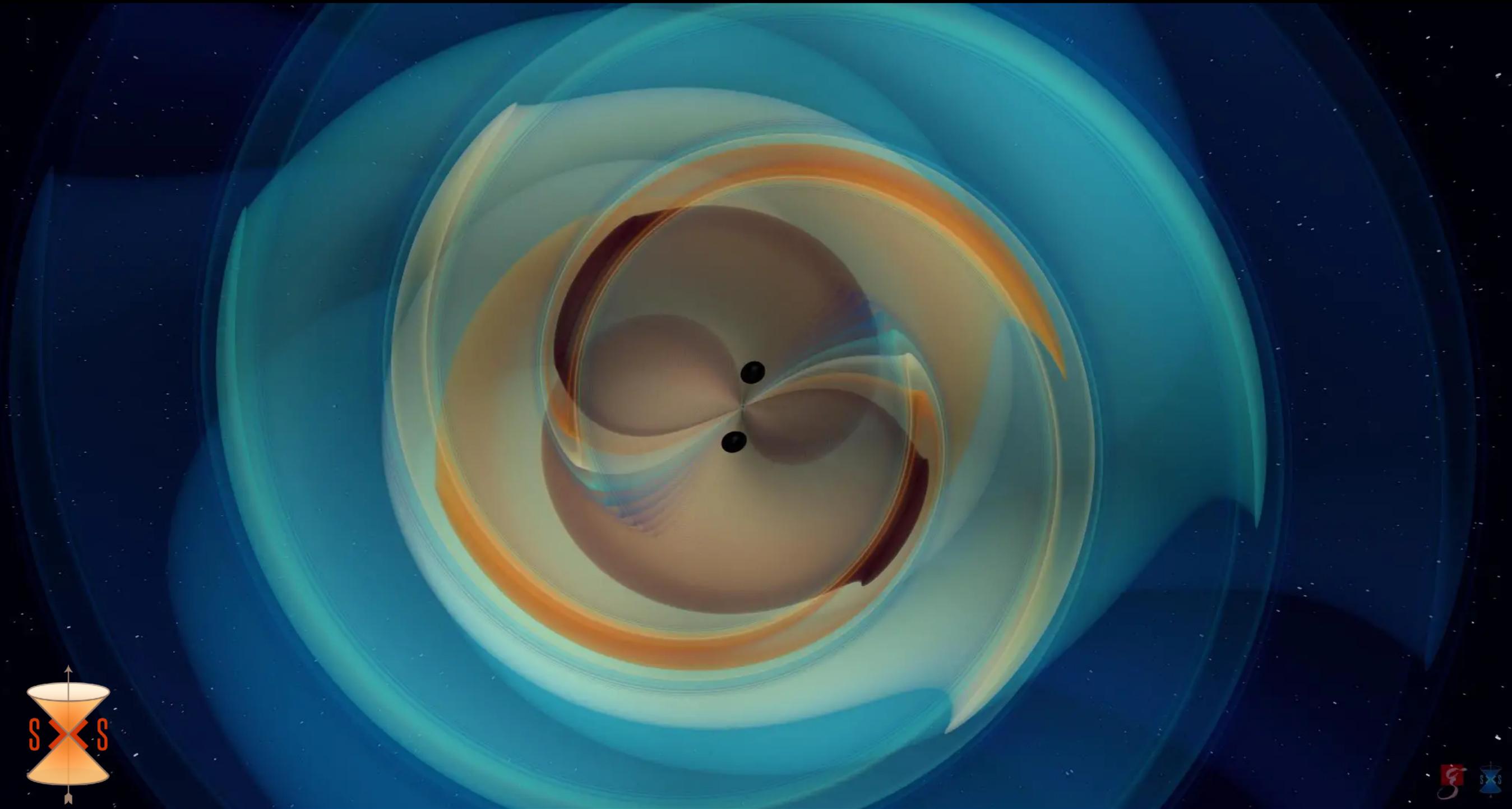
Y. Kim  
(Caltech => Princeton)

Parametric exploration:  
Jet lifetime seems to be correlated with  $t_{\text{jet}} \simeq v_{\text{BH}}^{-3}$



Kim, ERM+ (in prep)

# Dynamical Strong Field Gravity



**Can we use our intuition for relativistic plasmas and fluids to understand gravitational wave dynamics?**

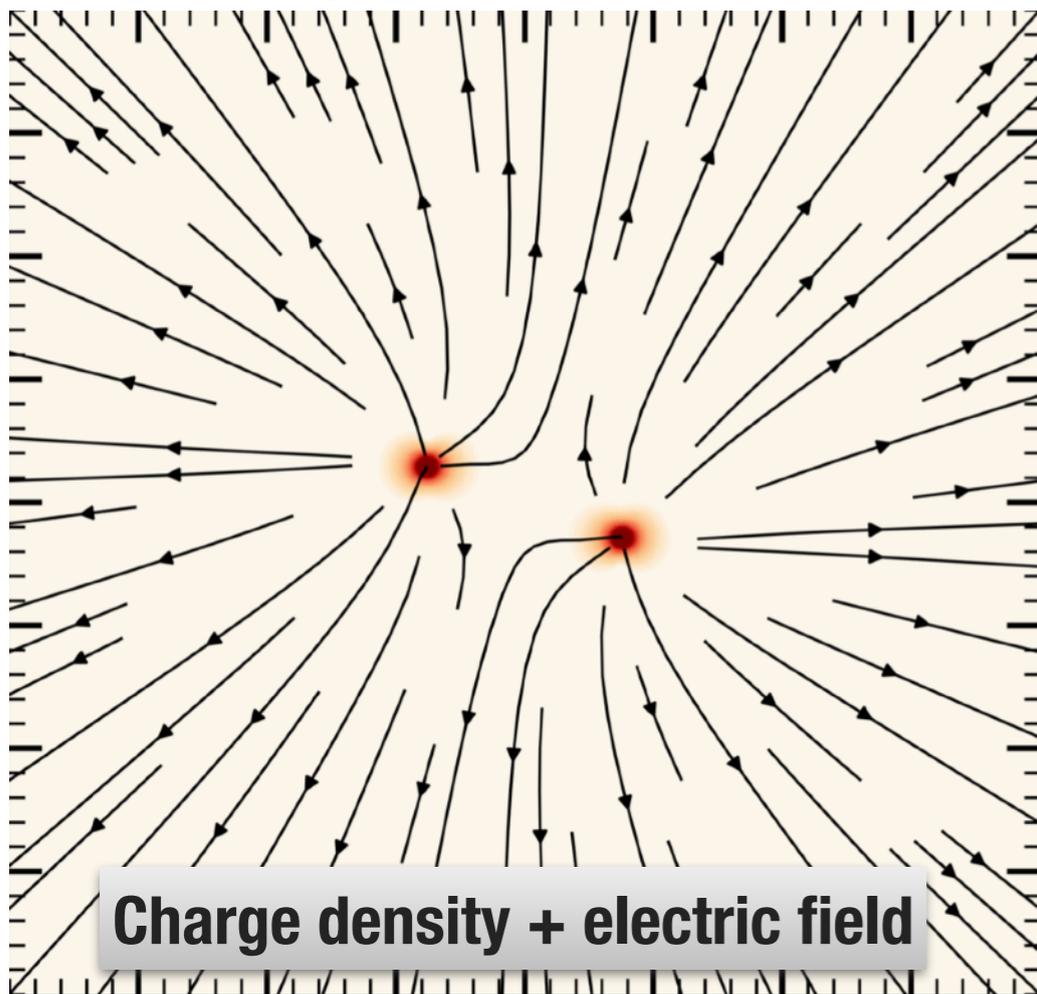
# Gravity = nonlinear electrodynamics!

See also Owen+ for vertex/tendex interpretation

General relativity can be **uniquely and exactly** recast as a **nonlinear electrodynamics system**

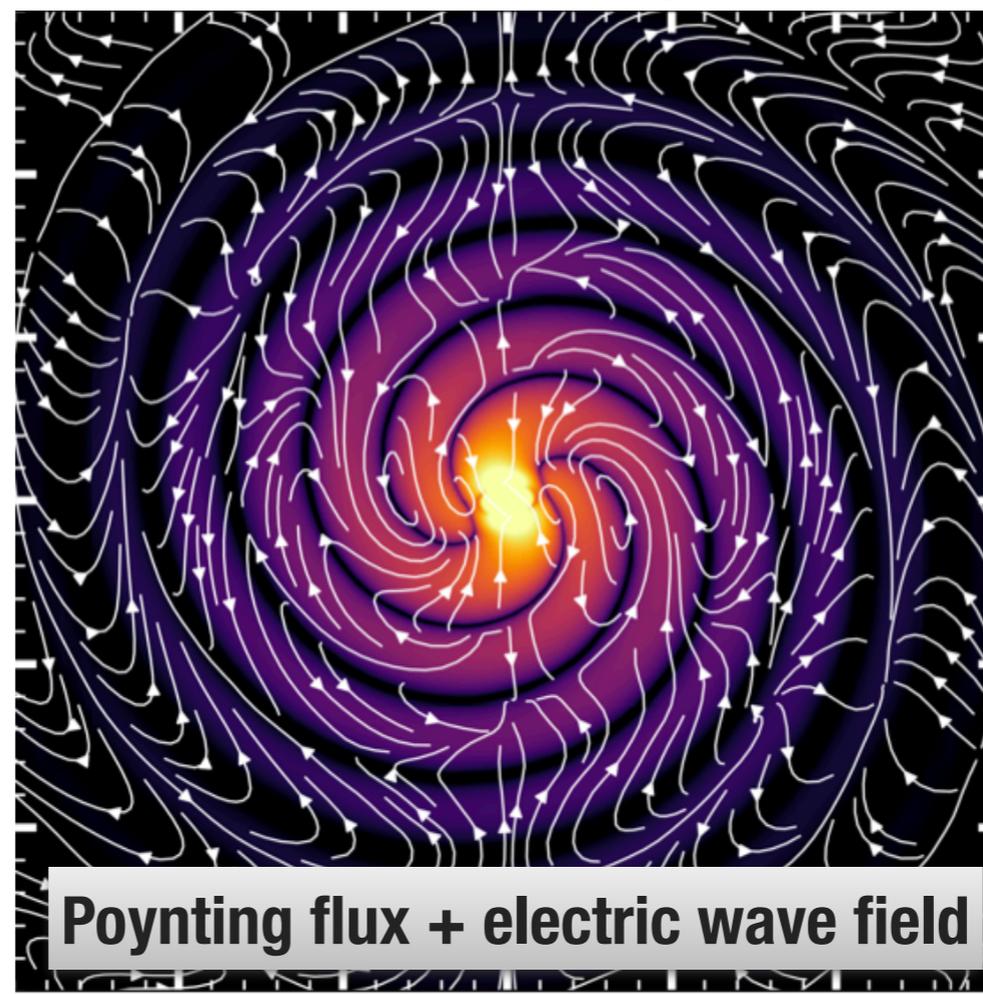
Olivares+ (2021, incl. ERM)  
also Estabrook+ (1997)

## Gravity = Lorentz force



$$E^{\hat{r}} \simeq \frac{M}{r^2} \quad \text{Coulomb law}$$

## Grav. Waves = Poynting flux



Boyeneri, Wu, ERM (PRL 2025)



Siddharth Boyeneri  
(Caltech)

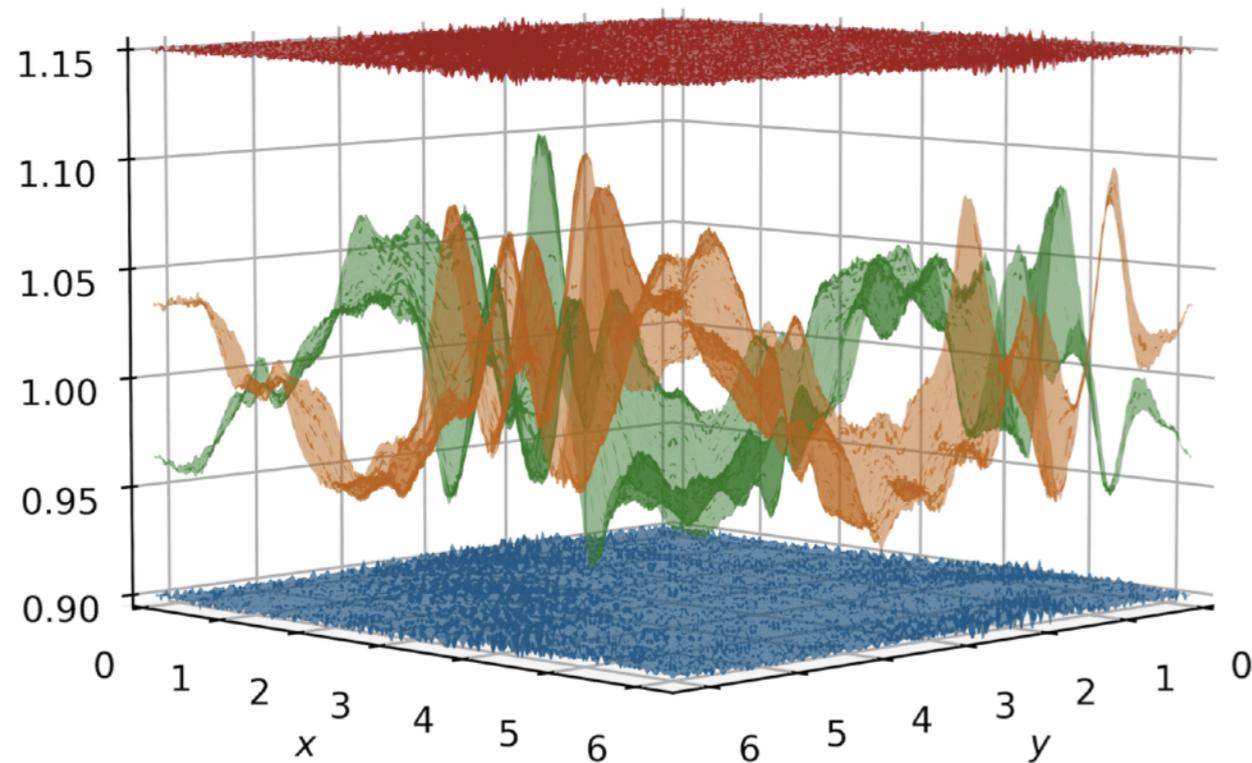


Jiaxi Wu (Caltech)

# Nonlinear gravitational wave interaction = Turbulence?

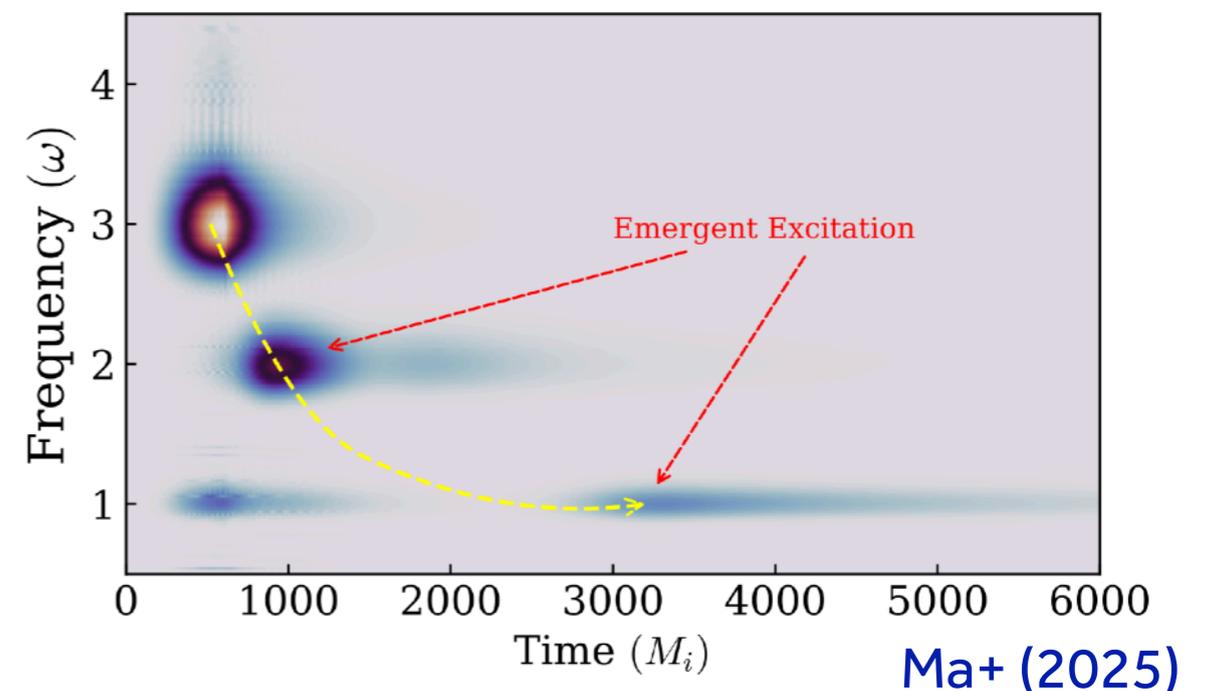
Recent interest in the community to understand nonlinear gravitational wave interaction giving rise to turbulent behavior

See also Carrasco+(2015), Green+(2014), Yang+(2015)



Galtier & Nazarenko (2017; 2021)

## Turbulent cascade?



**Mathematical theory, not there yet...**

# Gravitational wave turbulence

For small wavelengths, can show that **general relativity has same nonlinearity structure as MHD!**

Krynicky, Wu, ERM (arXiv 2025)

(Weak) turbulence arises from **Alfvénic interactions of gravitational waves.**

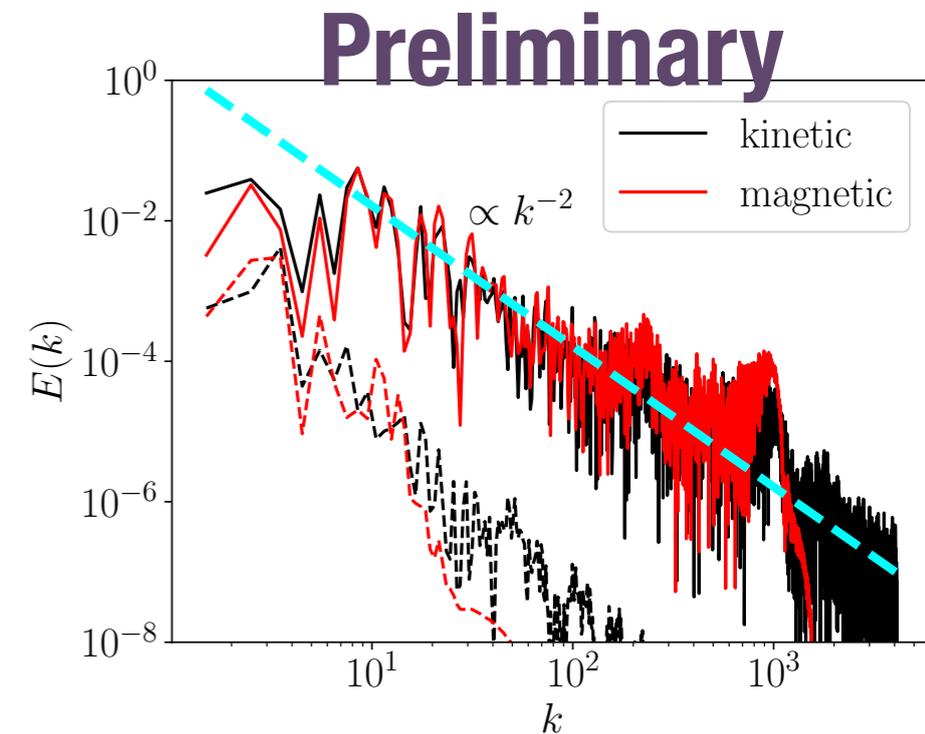
Preliminary numerical simulations consistent\* with weak MHD spectrum



Holly Krynicky  
(Caltech)



Jiaxi Wu  
(Caltech)

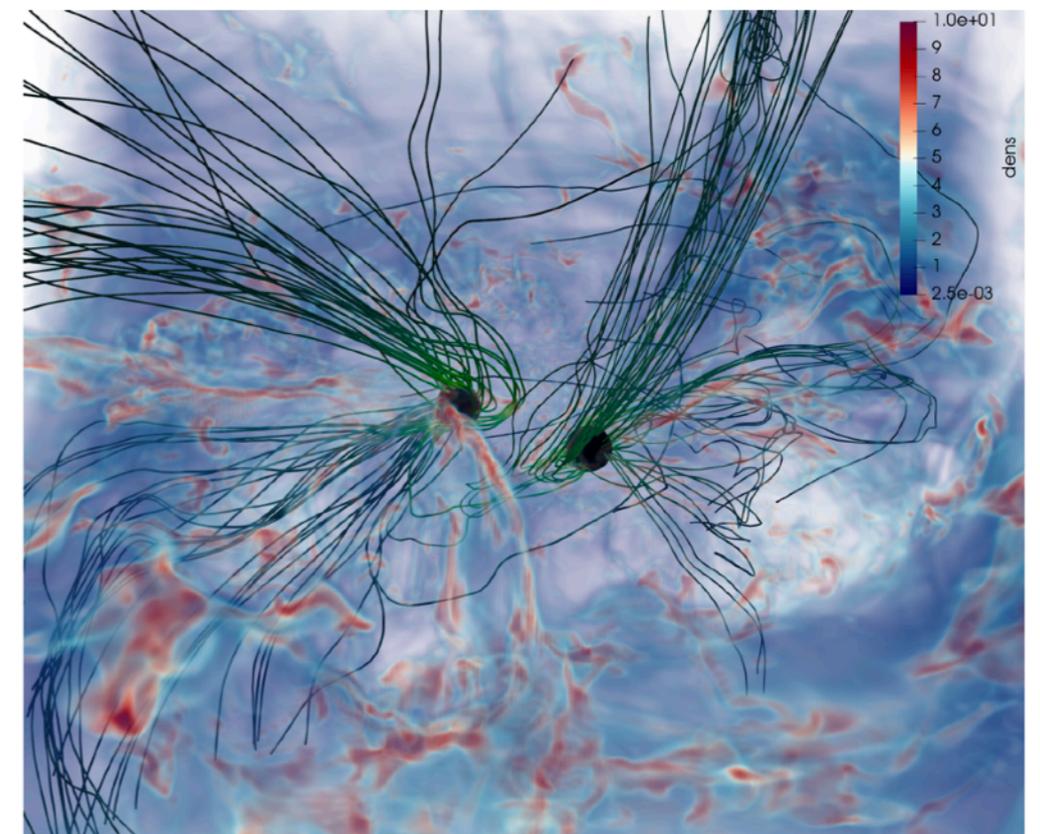
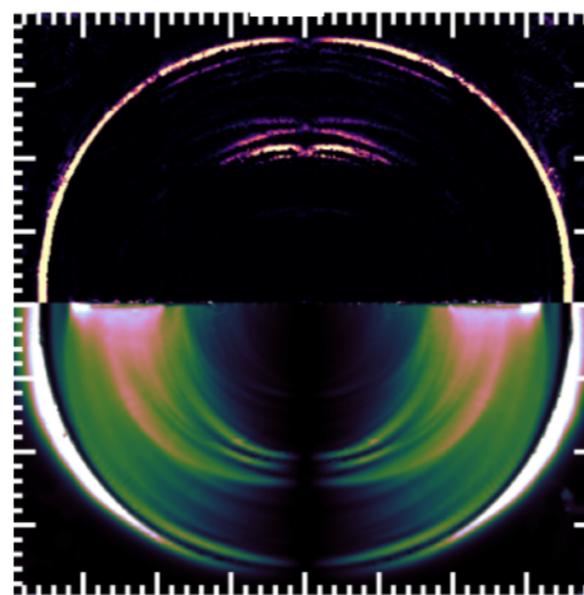
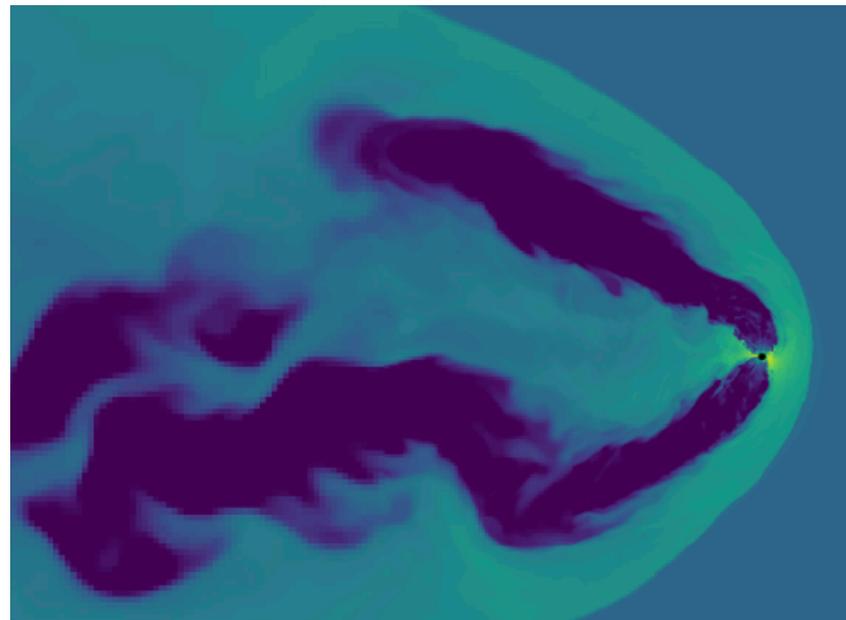
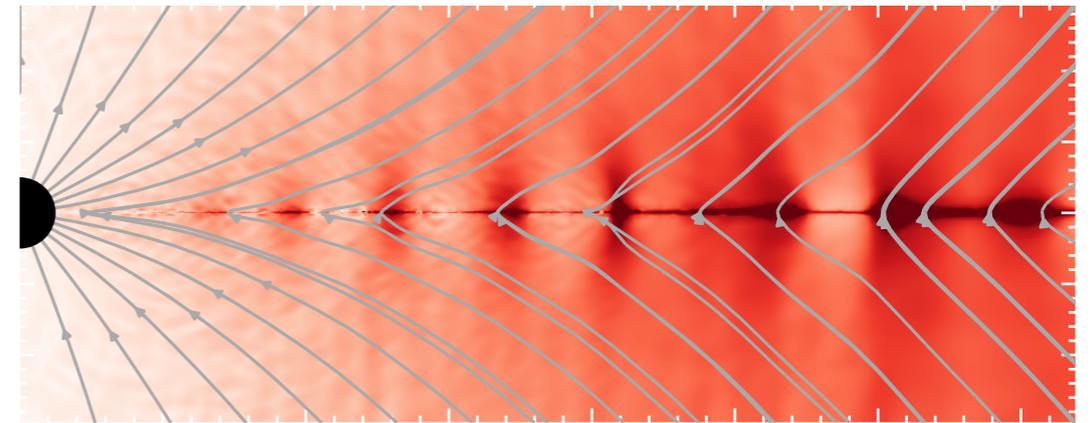
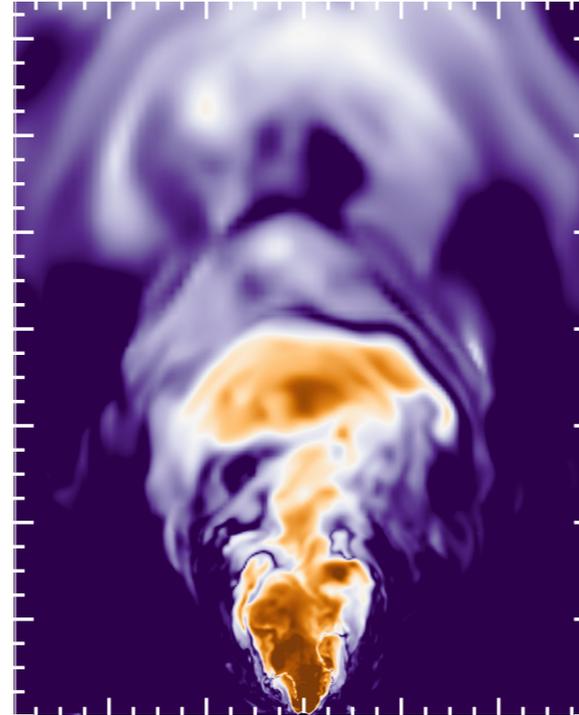
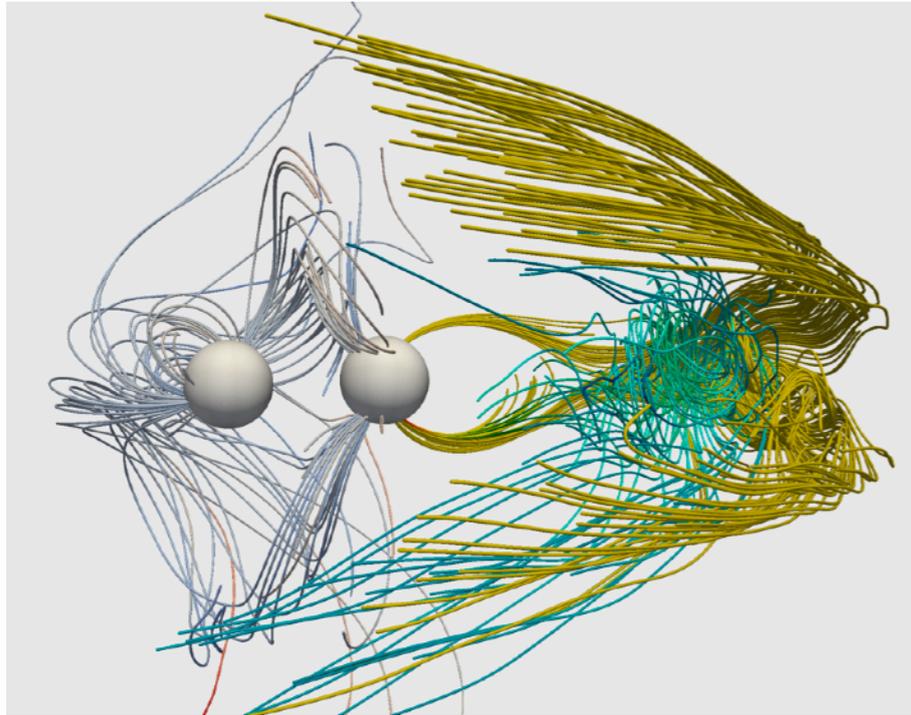


$$z_{\hat{\alpha}\pm}^{\mu} = u^{\mu} u_{\hat{\alpha}} \pm \left[ b_{\hat{\alpha}}^{\mu} - \frac{\text{Tr}(b)}{4} \delta_{\hat{\alpha}}^{\mu} \right]$$

**Elsasser equation of GR!**

$$\partial_{\mu} \left[ \sqrt{-g} \left( z_{\hat{\alpha}\pm}^{\mu} z_{\hat{\nu}\mp}^{\hat{\alpha}} + \Pi \delta_{\hat{\nu}}^{\mu} \right) \right] + \sqrt{-g} \left( z_{\hat{\alpha}\pm}^{\mu} z_{\hat{\nu}\mp}^{\hat{\alpha}} + \Pi \delta_{\hat{\nu}}^{\mu} \right) \frac{\partial_{\mu} \mathcal{E}}{\mathcal{E}} = 0$$

Krynicky, Wu, ERM (arXiv 2025)



# New Frontiers of Extreme Plasma Physics Modeling in Relativistic Astrophysics