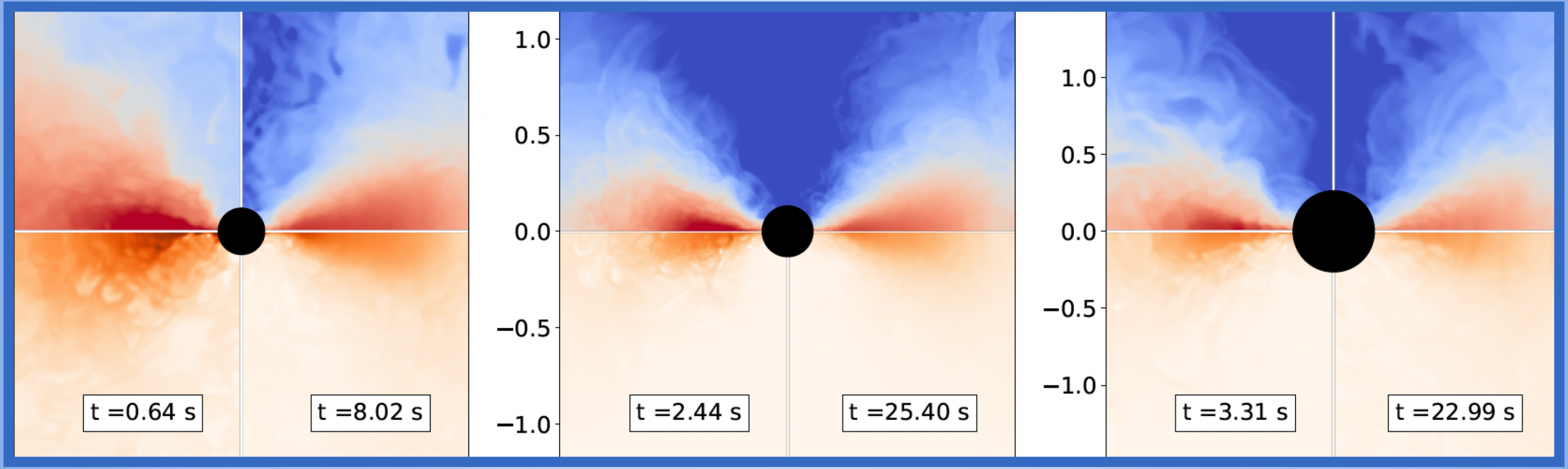
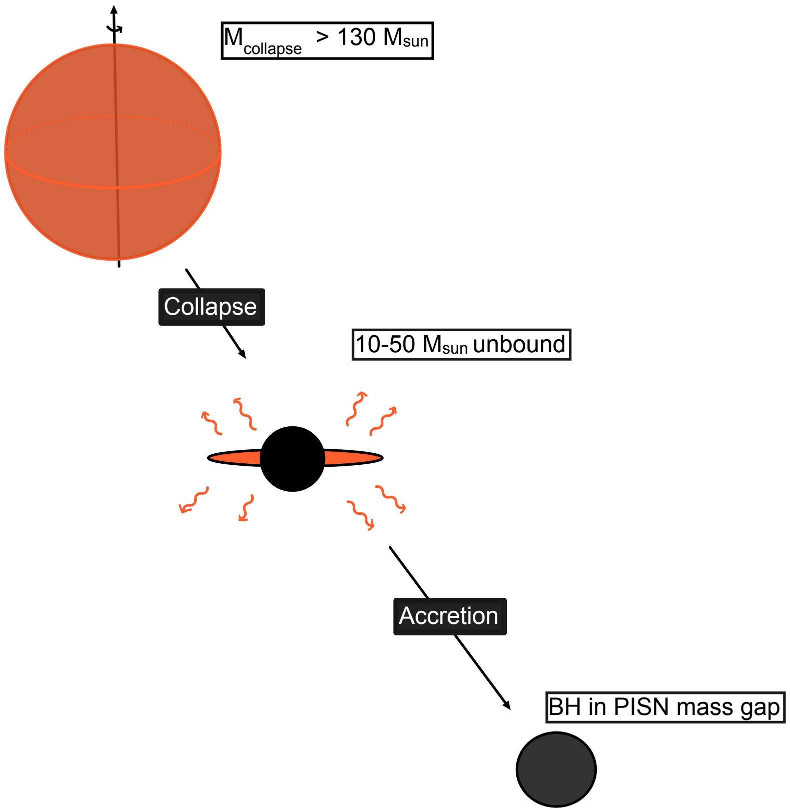
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Multi-messenger signals and r-process outflows from ‘supercollapsar’ accretion disks



Aman Agarwal, Ph.D. Student
University of Greifswald
YITP, 2026
Supervisor: Dr. Daniel Siegel



Supercollapsars

- collapse of massive (100-10000 M_{sun}) rotating stars

  S. S. Komissarov & M. V. Barkov 2010; P. Mészáros & M. J. Rees 2010; Y. Suwa & K. Ioka 2011; S.-C. Yoon et al. 2015

- might birth BHs in the pair-instability supernova mass gap

The pair-instability supernova(PISN) mass gap: theory

Stellar evolution models predict an **absence of BHs** in the mass range of ∼ **55-130 M_{sun}**

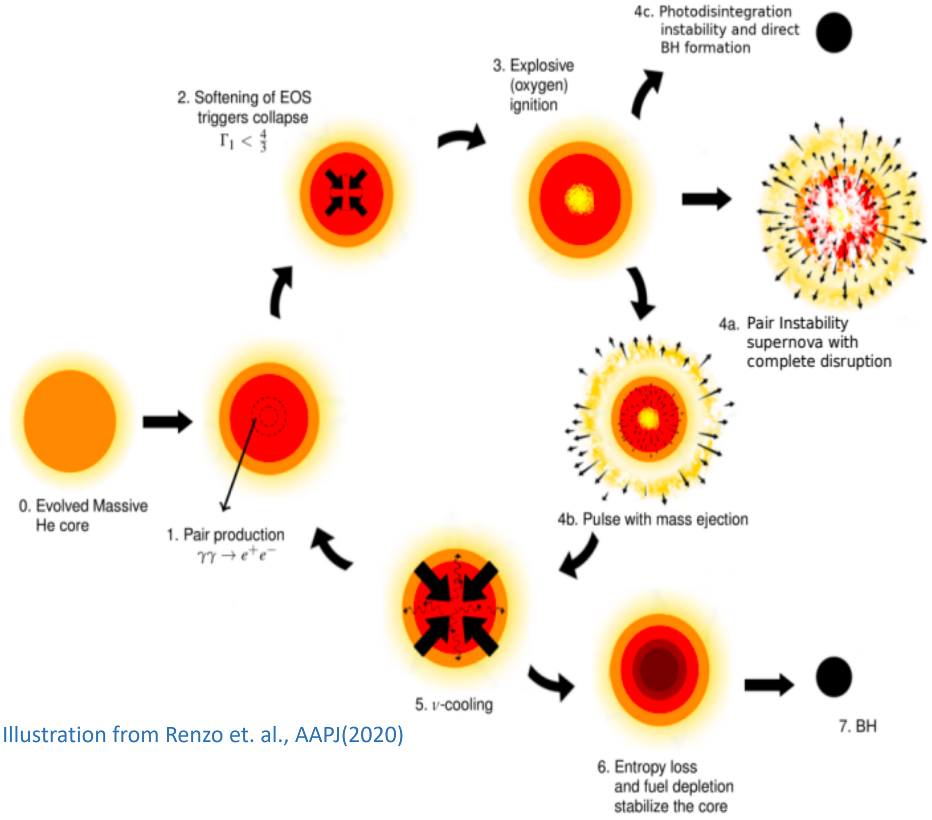


Illustration from Renzo et. al., AAPJ(2020)

2) The pair-instability supernova(PISN) mass gap: theory v/s observations

Stellar evolution models predict an **absence of BHs** in the mass range of $\sim$ **55-130 M_{sun}**

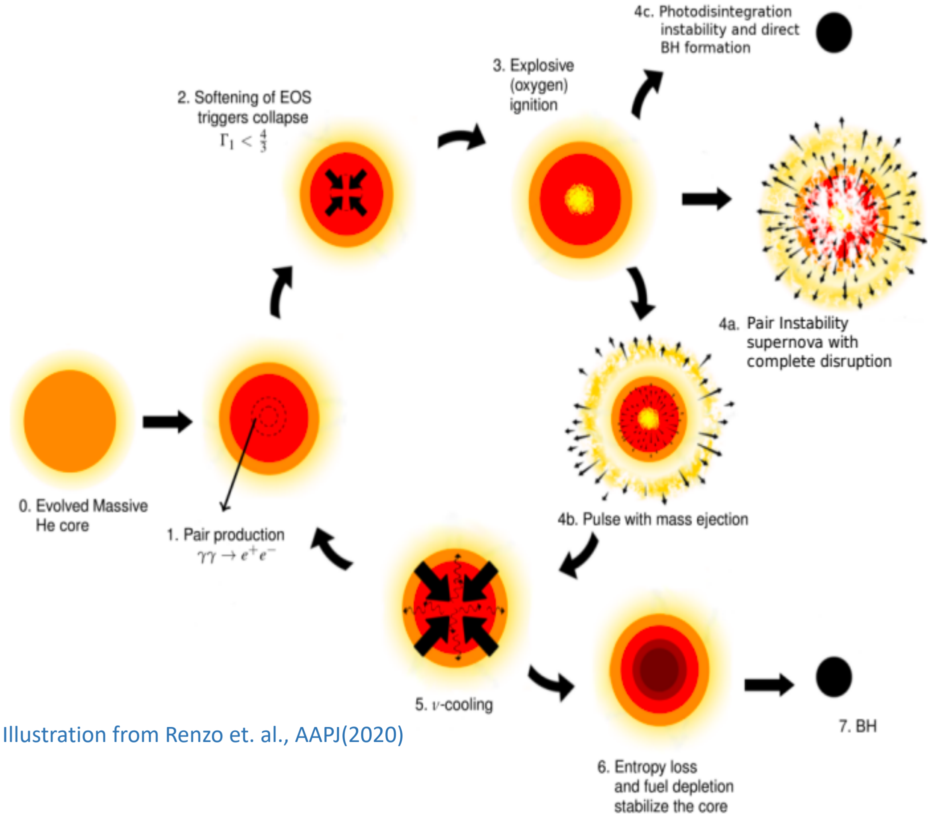
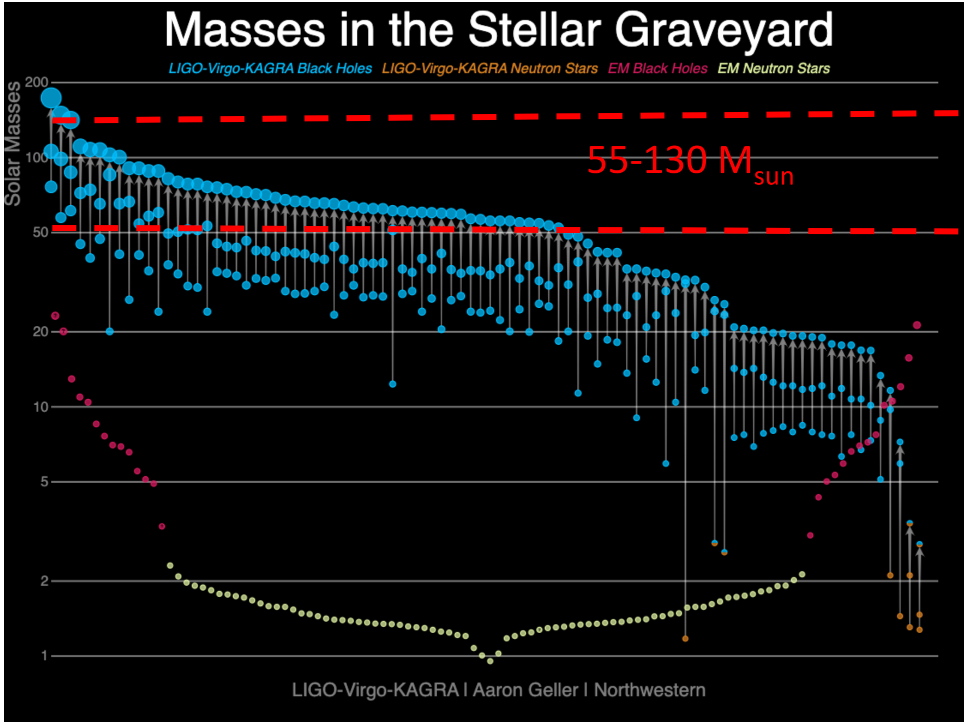
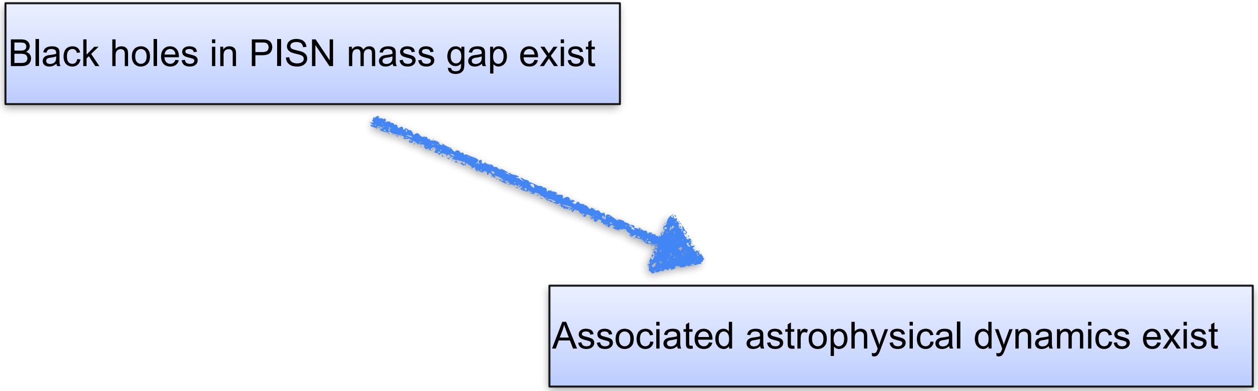


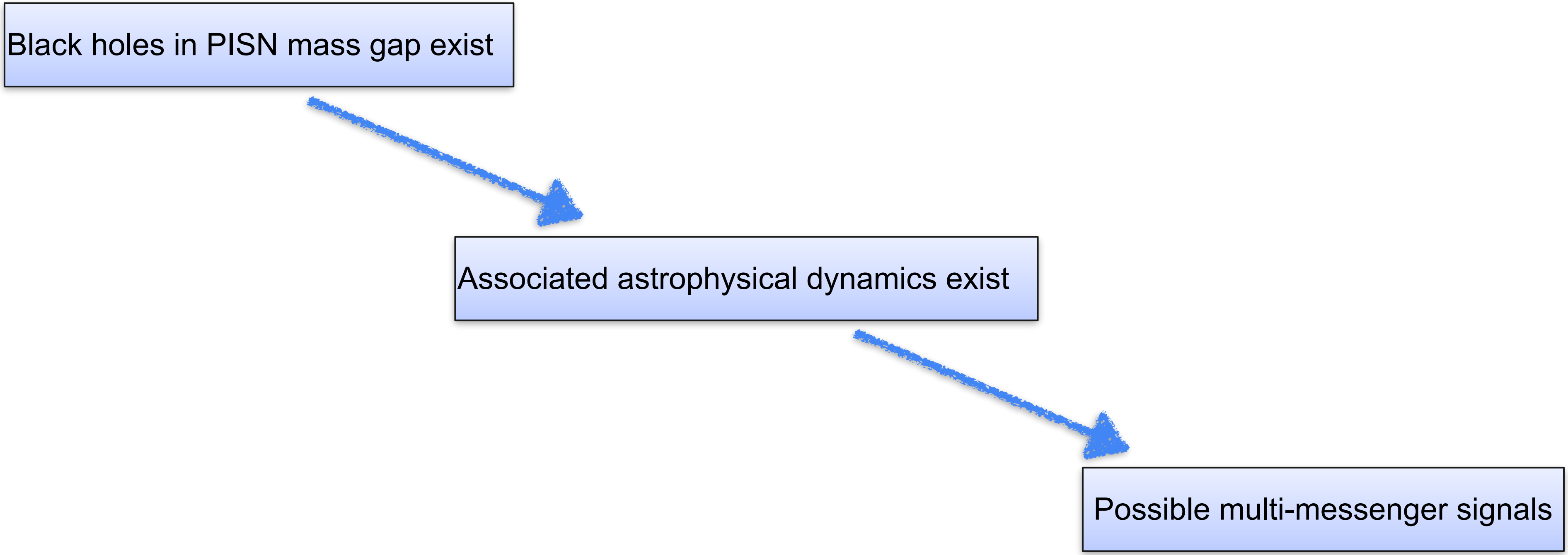
Illustration from Renzo et. al., AAPJ(2020)



but via gravitational wave observations, LVK found primary black-holes in the PISN mass gap.

Black holes in PISN mass gap exist

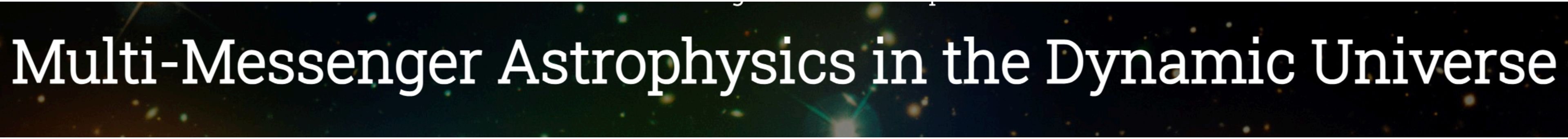

Black holes in PISN mass gap exist
Associated astrophysical dynamics exist


Black holes in PISN mass gap exist
Associated astrophysical dynamics exist
Possible multi-messenger signals

Black holes in PISN mass gap exist

Associated astrophysical dynamics exist

Possible multi-messenger signals



Dynamics

How are they born?

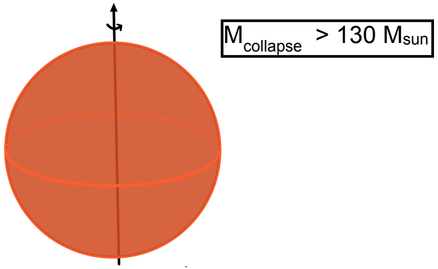
1) Hierarchical mergers (Antonini & Rasio 2016; Yang et al. 2019; Gerosa & Fishbach 2021; Tagawa et al. 2021)

2) Dynamical stellar mergers (Di Carlo et al. 2019, 2020; Renzo et al. 2020a)

3) Modifying stellar and nuclear physics inputs (Farrell et al. 2021; Vink et al. 2021; Tanikawa et al.2022)

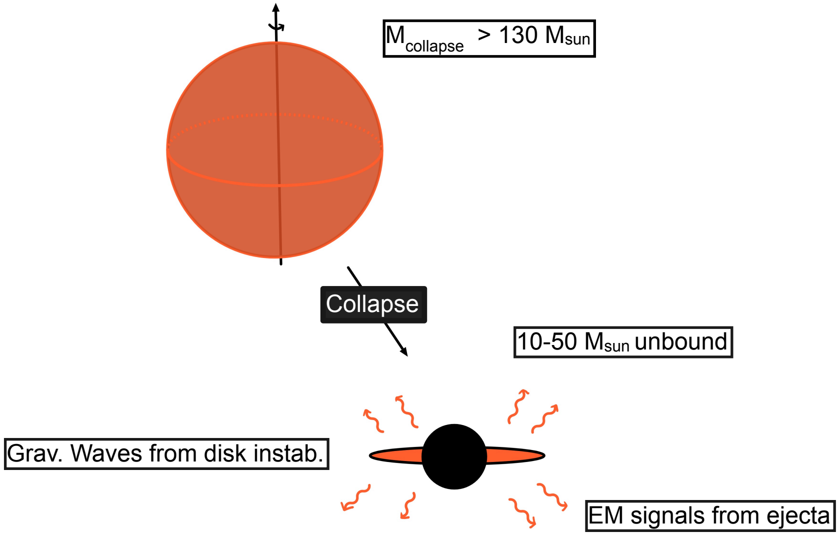
4) Massive rotating star collapse (Shibata et al. 2021, Siegel et al. 2022, Agarwal et al. 2026, Gottlieb et al. 2025, Shibata & Fujibayashi 2026)

The supercollapsar connection



Rapidly rotating stars with mass above the PISN mass gap

The supercollapsar connection

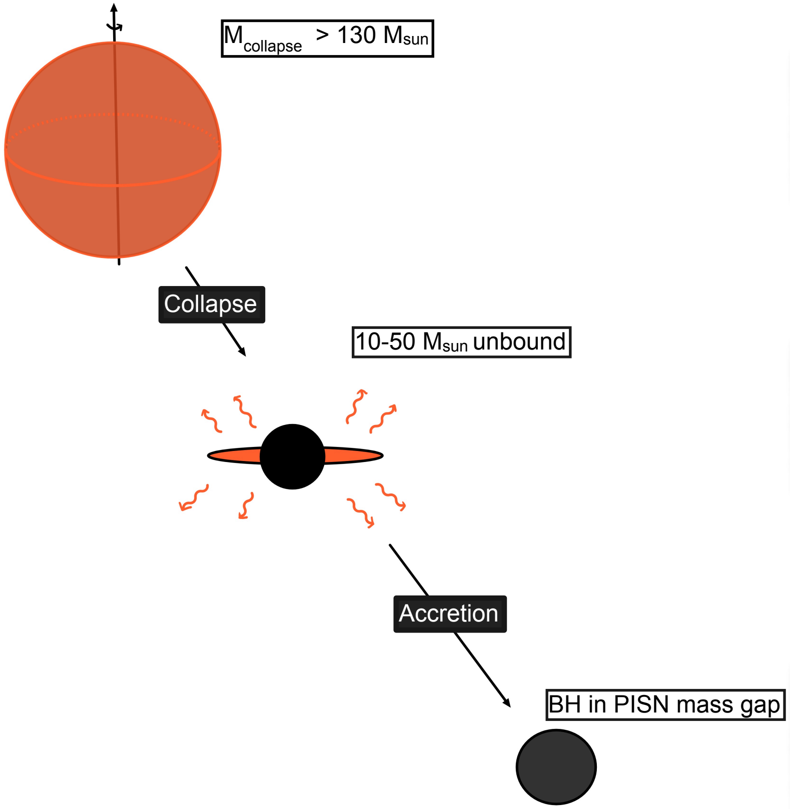


Rapidly rotating stars with mass above the PISN mass gap

↓

Black-hole accretion disk system ejecting mass via MHD turbulence: possible r-process

The supercollapsar connection



Rapidly rotating stars with mass above the PISN mass gap

⇩

Black-hole accretion disk system ejecting mass via MHD turbulence

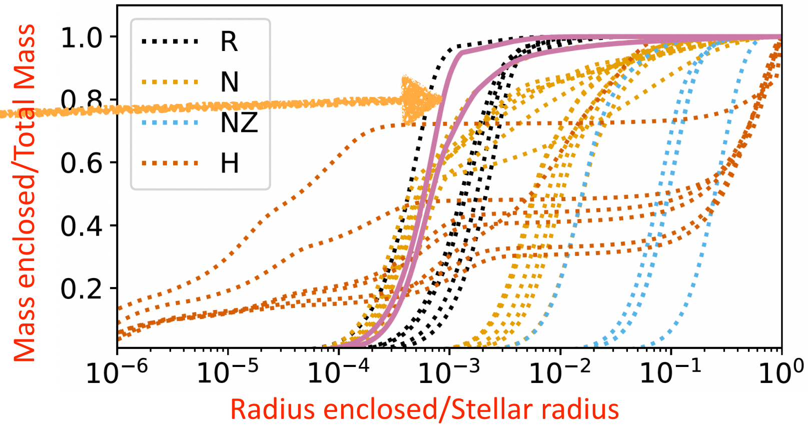
⇩

Final black hole lies in the PISN mass gap, due to loss of mass from winds.

Study: Semi-analytical modelling of supercollapsars

Semi-Analytical Model of supercollapsar accretion from compact stellar models

Start with : Stellar Models at collapse ~ 150-10^5 M_{sun}

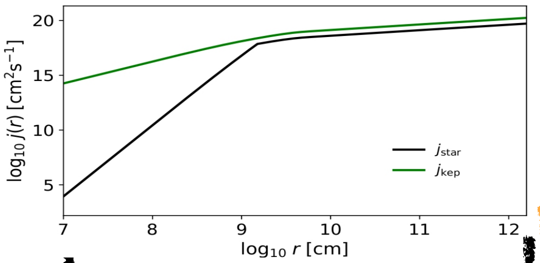


Renzo et. al. 2020,

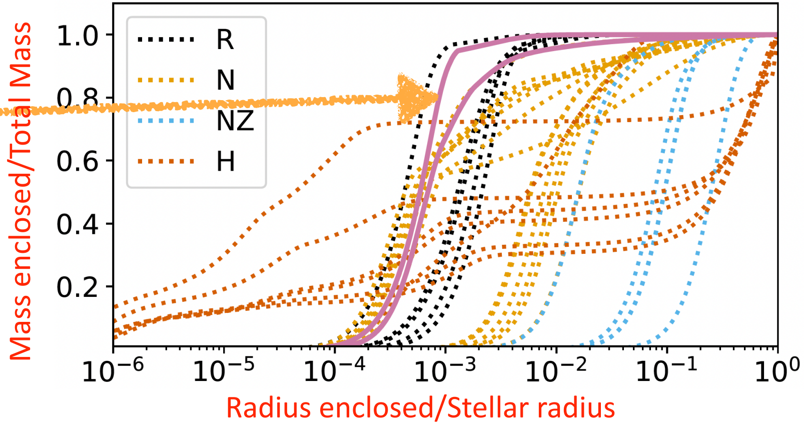
Nagele et. al. 2024

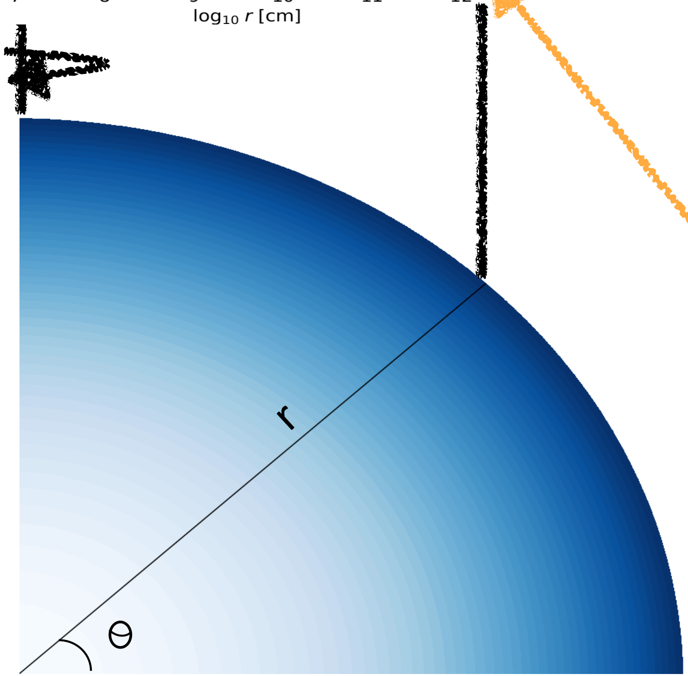
Heger et. al. 2000

Semi-Analytical Model of supercollapsar accretion from compact stellar models



Stellar Models at collapse ~ 150-10^5 M_{sun}

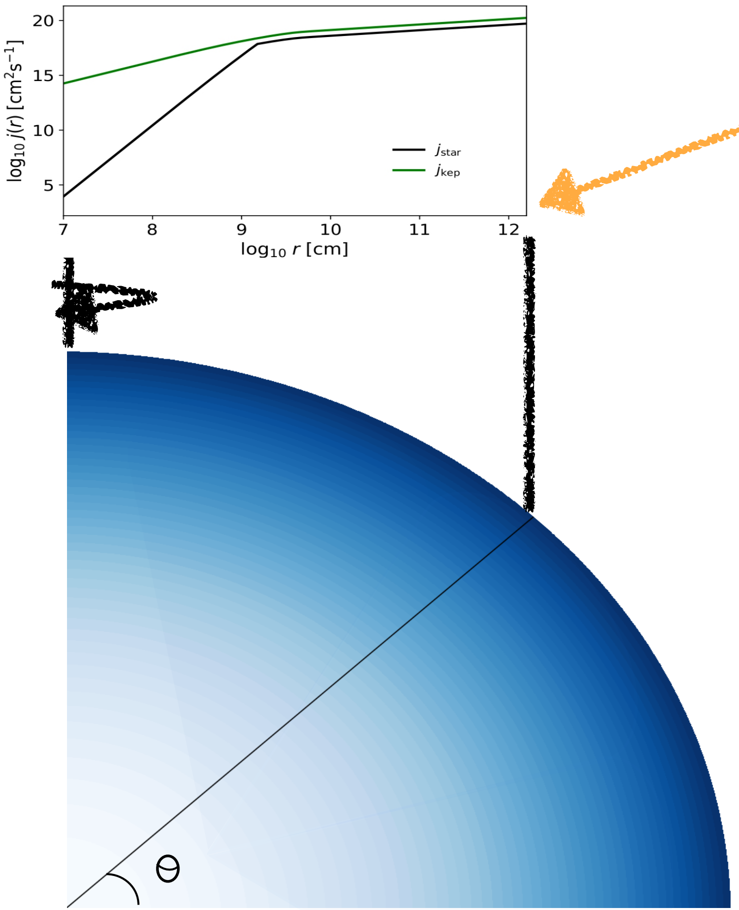




1) Stellar model is discretized into onion-like shells

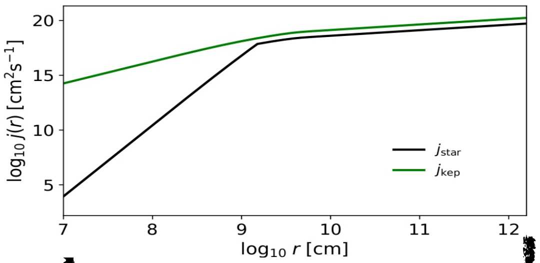
2) Angular momentum(j) of star at collapse is highly uncertain hence **a parametrized broken power-law** J profile is used

Semi-Analytical Model of supercollapsar accretion from compact stellar models



1) Stellar model is discretized into onion-like shells
2) Angular momentum(j) of star at collapse is highly uncertain hence **a parametrized broken power-law** J profile is used
3) Evolve using mass and angular momentum conservation

Semi-Analytical Model of supercollapsar accretion from compact stellar models



1) Stellar model is discretized into onion-like shells
2) Angular momentum(j) of star at collapse is highly uncertain hence **a parametrized broken power-law** J profile is used
3) Evolve using mass and angular momentum conservation

$$\frac{\mathrm{d}M_\bullet}{\mathrm{d}t} = \dot{m}_{\rm fb,\bullet} + \dot{m}_{\rm acc},$$

$$\frac{\mathrm{d}J_\bullet}{\mathrm{d}t} = \dot{J}_{\rm fb,\bullet} + \dot{m}_{\rm acc} j_{\rm ISCO},$$

$$\frac{\mathrm{d}M_{\rm disk}}{\mathrm{d}t} = \dot{m}_{\rm fb,disk} - \dot{m}_{\rm acc} - \dot{m}_{\rm wind},$$

$$\frac{\mathrm{d}J_{\rm disk}}{\mathrm{d}t} = \dot{J}_{\rm fb,disk} - \dot{m}_{\rm acc} j_{\rm ISCO} - \dot{J}_{\rm wind},$$

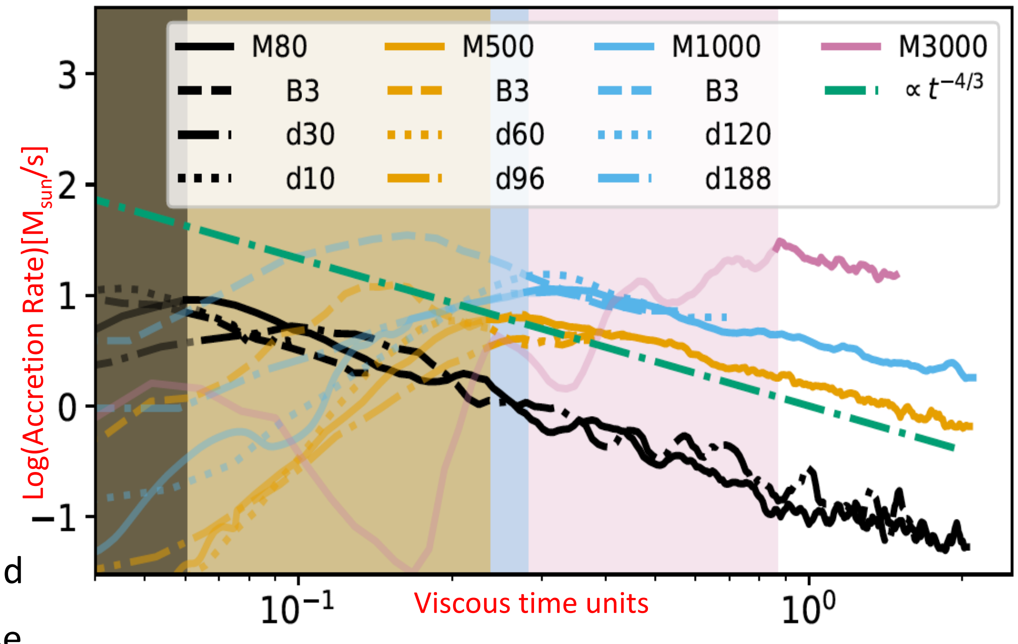
$$\dot{m}_{\rm acc} = f_{\rm acc} \frac{M_{\rm disk}}{t_{\rm visc}}$$

Study: GRMHD simulations of supercollapsar accretion disks

GRMHD simulations of black-hole accretion disk systems

We setup 4 simulations

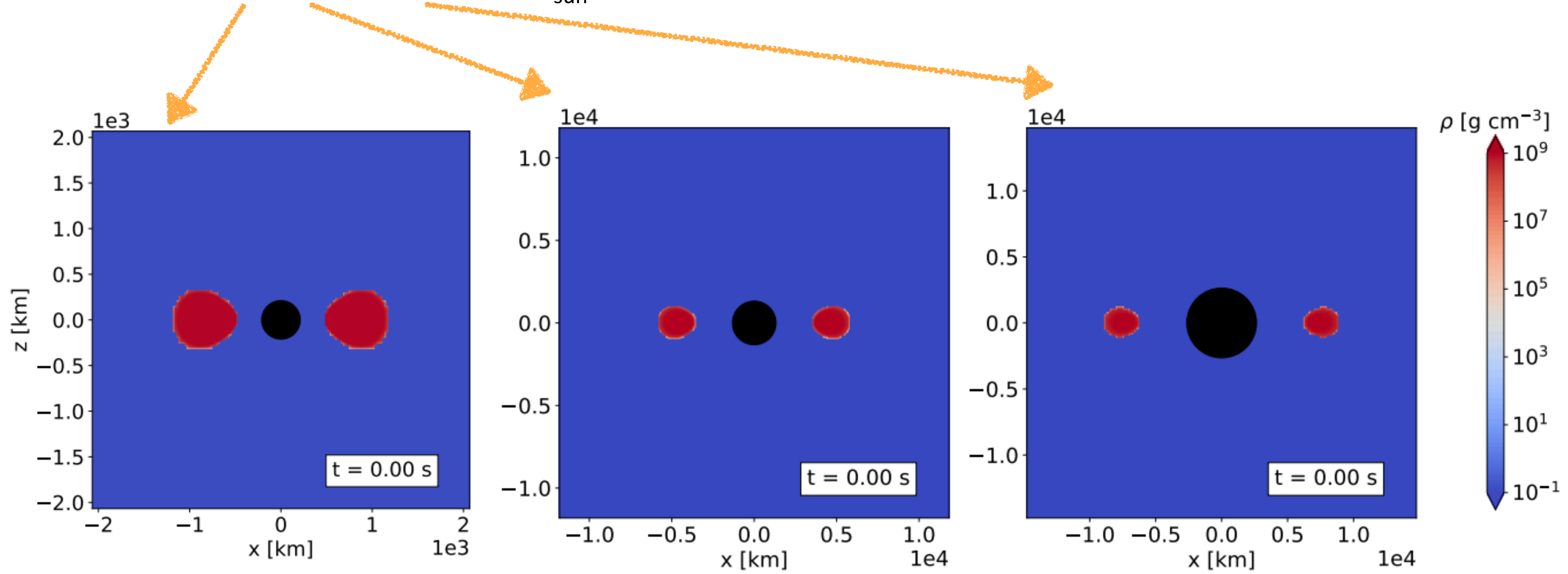
- ❑ 3D ideal GRMHD
- ❑ Einstein Toolkit with modified GRHydro
- ❑ Initial data: Kerr BH with a torus
- ❑ BH masses: 80, 500, 1000, 3000 Msun
- ❑ Neutrino Leakage treatment
- ❑ Spacetime fixed
- ❑ Helmholtz equation of state
- ❑ Dynamically insignificant poloidal initial B field
- ❑ Steady state accretion after a relaxation phase
- ❑ Evolved for ~2 viscous time units



Agarwal et. al. 2026

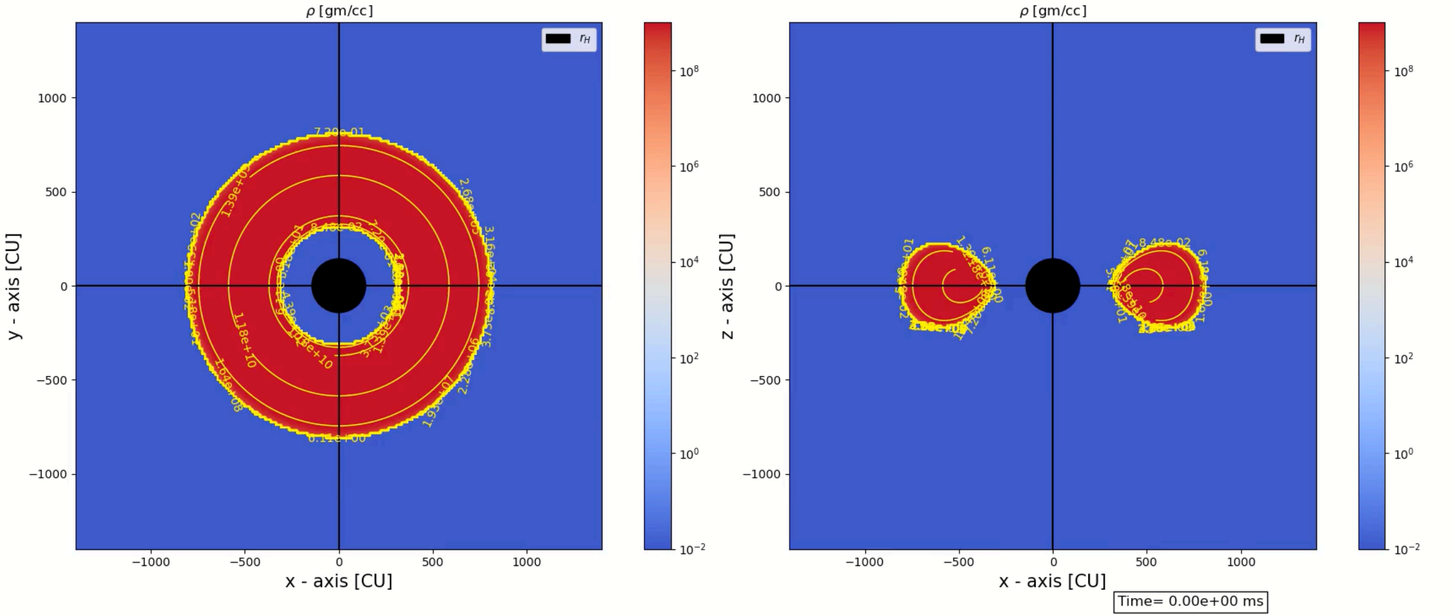
GRMHD simulations of black-hole accretion disk systems

- Initial data: Kerr BH with a torus
- BH masses: 80, 500, 1000, 3000 M_{sun}



Agarwal et. al. 2026

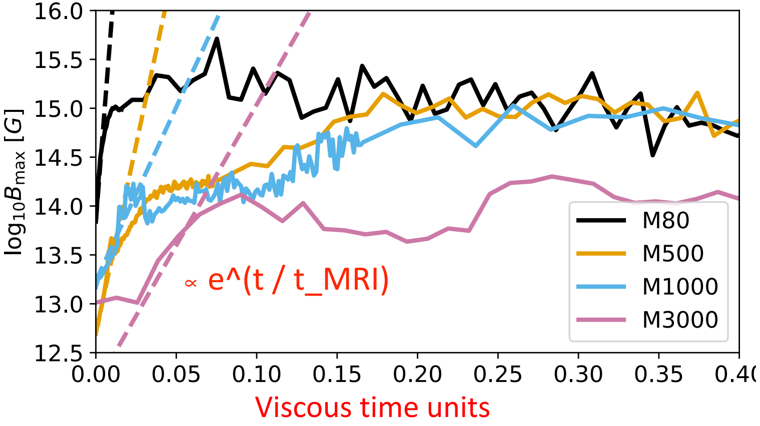
GRMHD simulations of black-hole accretion disk systems



CU = M_{sun}

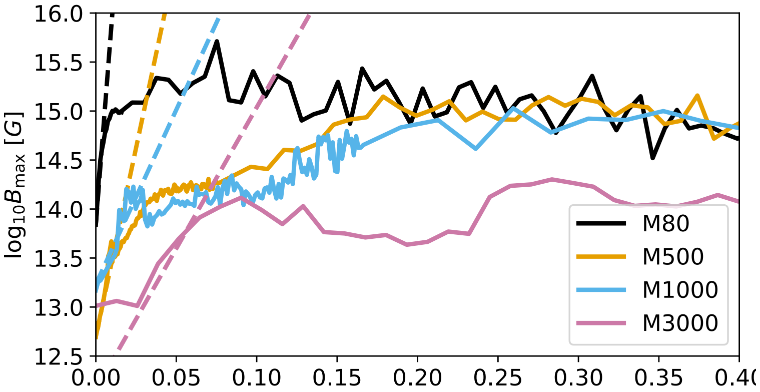
Supercollapsar accretion disks dynamics:
MHD turbulence driven outflows and signals

MRI-driven MHD turbulence

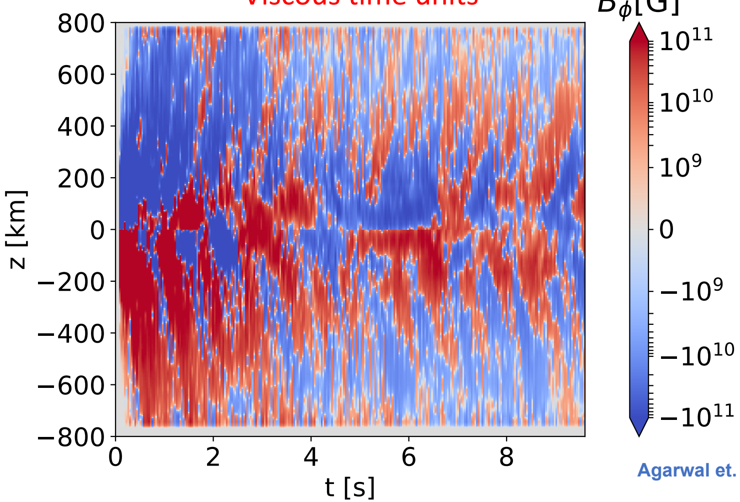


Agarwal et. al. 2026

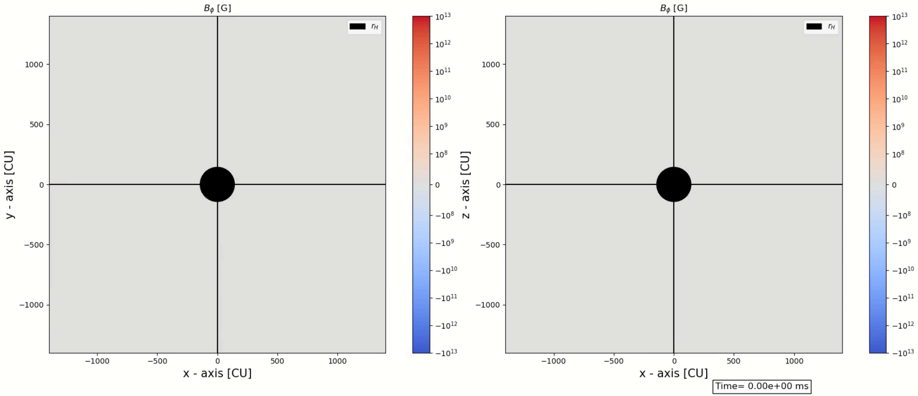
MRI-driven MHD turbulence



Viscous time units



Agarwal et. al. 202



Supercollapsar accretion disks dynamics: Ignition of weak interactions

Ignition of weak interactions and r-process nucleosynthesis

Ignition Threshold : the accretion rate above which neutrinos efficiently cool the accretion flow and e^- become degenerate

$$n \Rightarrow p + e^- + \bar{\nu}_e$$

$$p + e^- \Rightarrow n + \nu_e$$

Ignition →

$$n \Rightarrow p + e^- + \bar{\nu}_e$$

$$p + e^- \Rightarrow n + \nu_e$$

↓

Self-neutronization of the accretion flow conducive to r-process

R-process nucleosynthesis expected when accretion rate>Ignition Threshold

For a Keplerian Shakura-Sunyaev disk -

Black hole mass

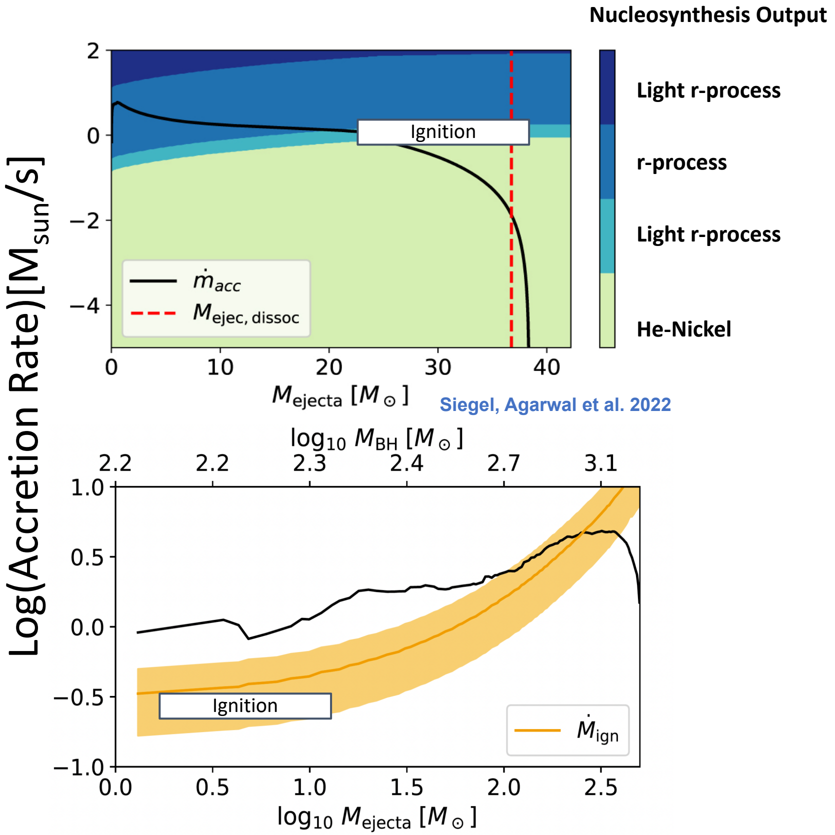
Viscosity parameter

$$\dot{M}_{\rm ign} \approx 0.15 \left(\frac{\alpha_{\rm eff}}{9 \times 10^{-3}}\right)^{5/3} \left(\frac{M_\bullet}{80 M_\odot}\right)^{4/3} M_\odot {\rm s}^{-1}.$$

(Agarwal et al. 2026, De & Siegel 2021)

Ignition threshold from the semi-analytical model

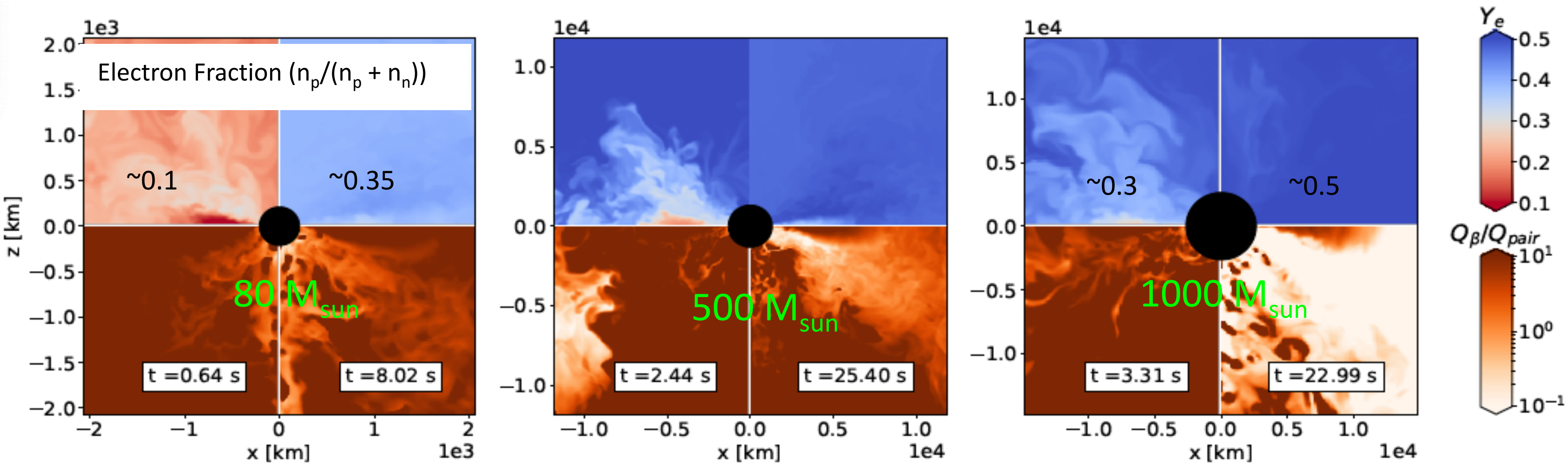
We find BHs from 10-1000 M_{sun} accreting above ignition - hence r-process conducive environment!



Siegel, Agarwal et al. 2022

Agarwal et. al. 2026

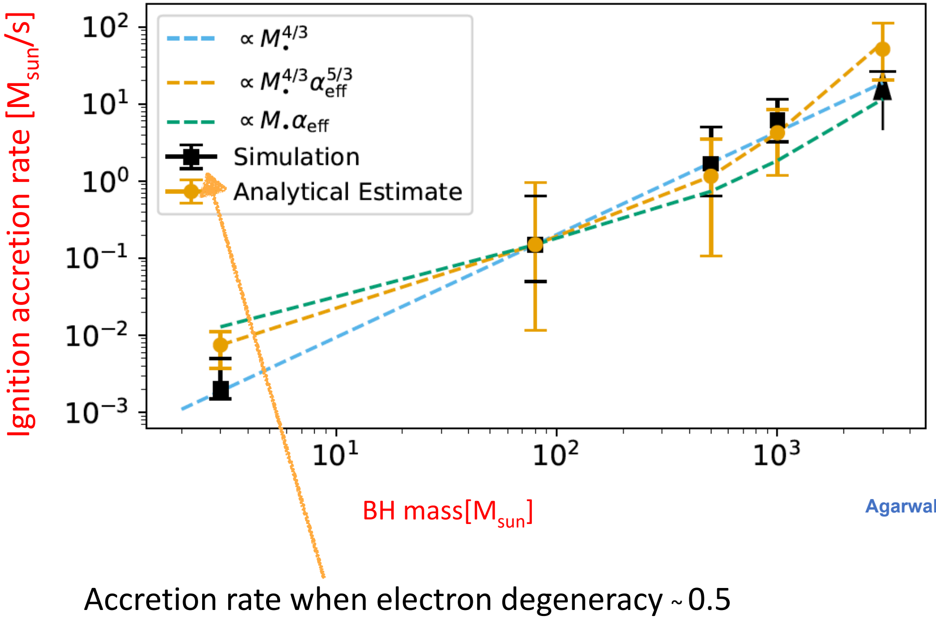
Ignition threshold and self-neutronisation in the GRMHD simulations



Agarwal et. al. 2026

The steady state accretion disks in all cases(except 3000 M_{sun}) are above ignition, are neutron-rich in the disk midplane ⇨ conducive to r-process nucleosynthesis when ejected

GRMHD simulations results: ignition scaling



Agarwal et. al. 2026

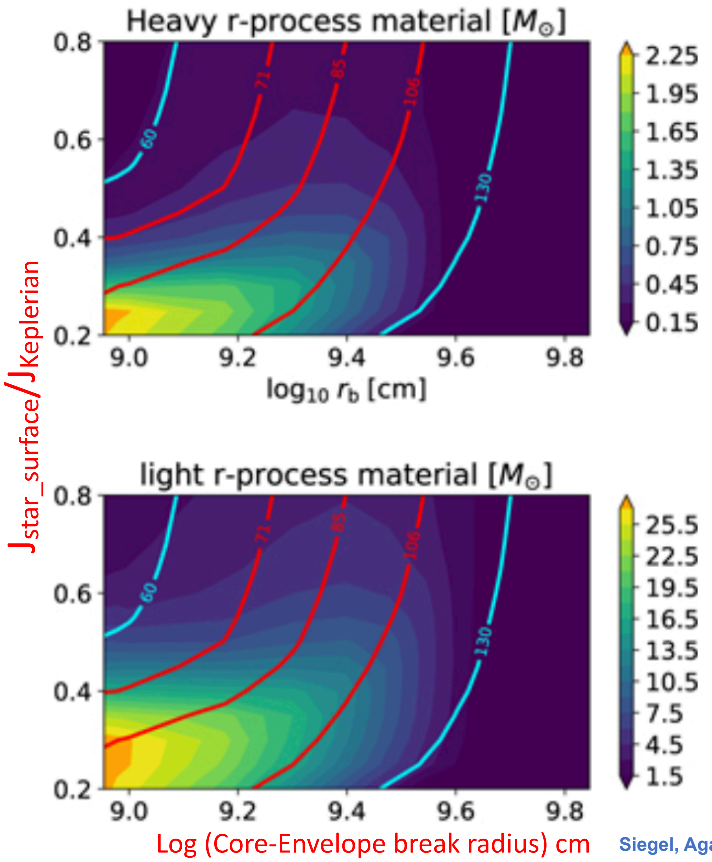
The GRMHD simulation results agree quite well with analytical expectations except 3000 M_{sun}

Ignition breakdown at 3000 Msun due to low disk temperatures.

Supercollapsar multi-messenger signals:
Super-Kilonova

Super-Kilonova prediction from the semi-analytical model

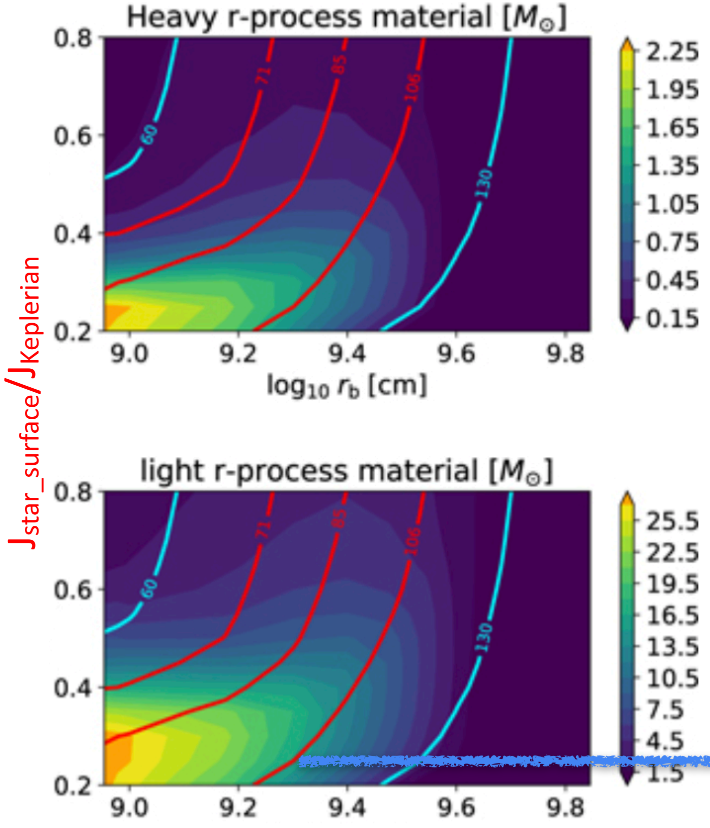
For a 250 M_{sun} star, depending on ang. momentum, we predict ~ O(1-10) M_{sun} r-process material from the disk



Siegel, Agarwal et al. 2022

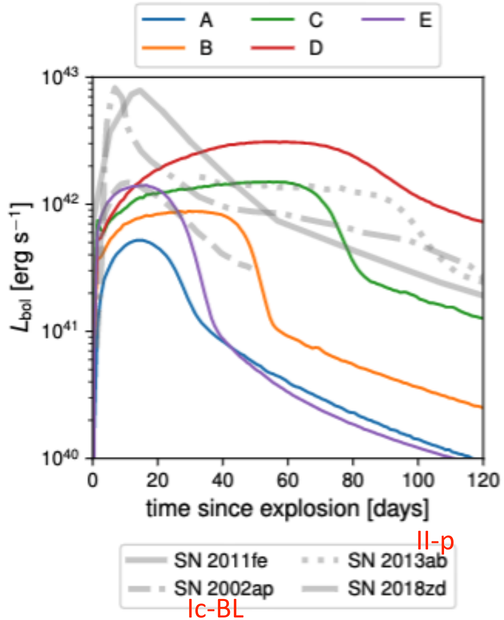
Super-Kilonova prediction from the semi-analytical model

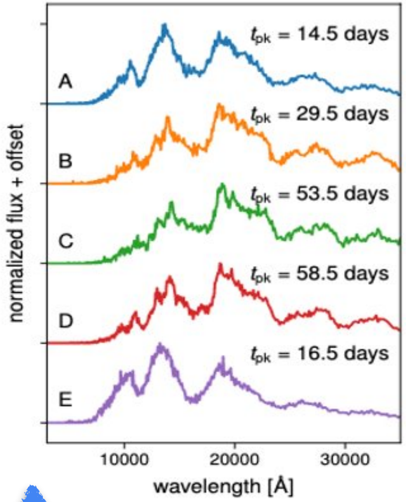
For a 250 M_{sun} star, depending on ang. momentum, we predict ~ O(1-10) M_{sun} r-process material from the disk



Log (Core-Envelope break radius) cm

Siegel, Agarwal et al. 2022





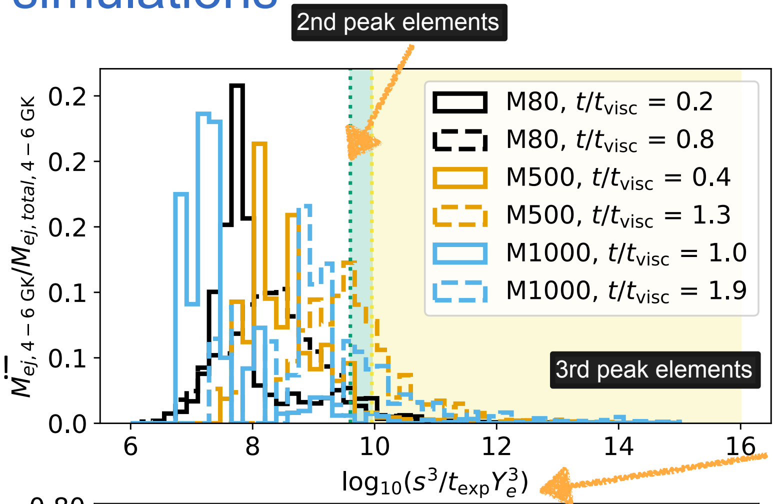
5 points from the left+ homogeneously mixed O(0.01-0.1) Ni^{56}

Outflow characteristics from GRMHD simulations

Early time: Low Ye, low entropy ejecta

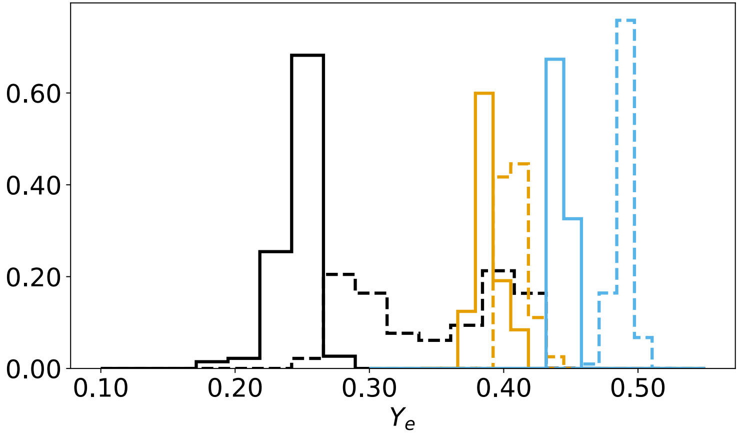
Late time: High Ye, high entropy ejecta

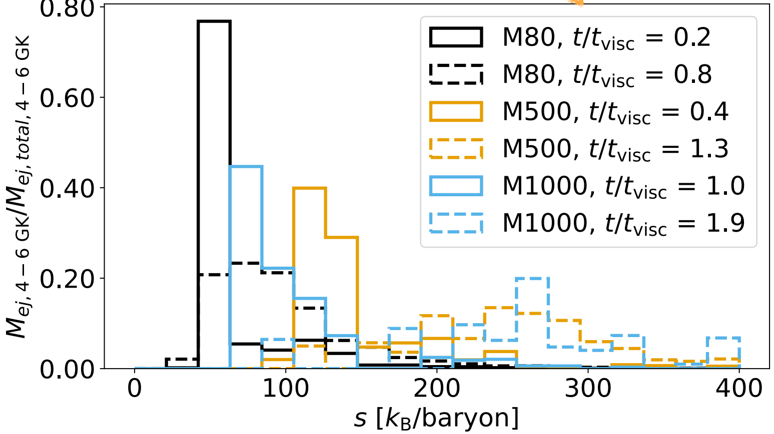
Could be one source of r-process material but not major source!



Hoffman et al. 1997

Ejecta mass fraction



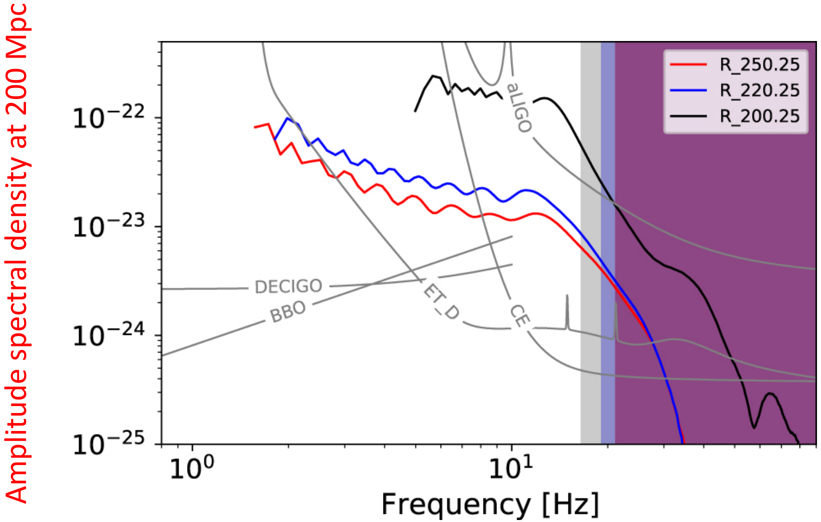


Agarwal et. al. 2026

Supercollapsar multi-messenger signals:
Gravitational waves from disk instabilities

Gravitational waves prediction from the semi-analytical model

Self-gravity induced Toomre disk instability can give rise to a gravitational wave strain.



Siegel, Agarwal et al. 2022

Different from jet related GW waves!

Supercollapsar significance

1) Black holes in the PISN mass gaps exist as evidenced by GW observations.
2) Supercollapsars may be a way to populate PISN mass gap.
3) They may produce r-process elements but are not expected to be a major contributor to cosmic r-process.
4) They can be a source of multi-messenger signals detectable by 3G detectors and Roman Space Telescope and Vera Rubin Observatory.
5) They can drive energetic GRBs with luminosity $\sim$O(10) times luminosity of typical GRBs.
6) GRMHD simulations upto 1000 M_{sun} BH with self-neutronising accretion flow(conducive for r-process)

Future Outlook

1) 3D GRMHD simulations of collapsar starting from a progenitor star with varying mass and rotation
2) Simulation of a few gravitationally unstable disk configurations in dynamical spacetimes
3) Chemical evolution calculations with multiple r-process sources : determining galactic source contributions from current observations .

Thank You