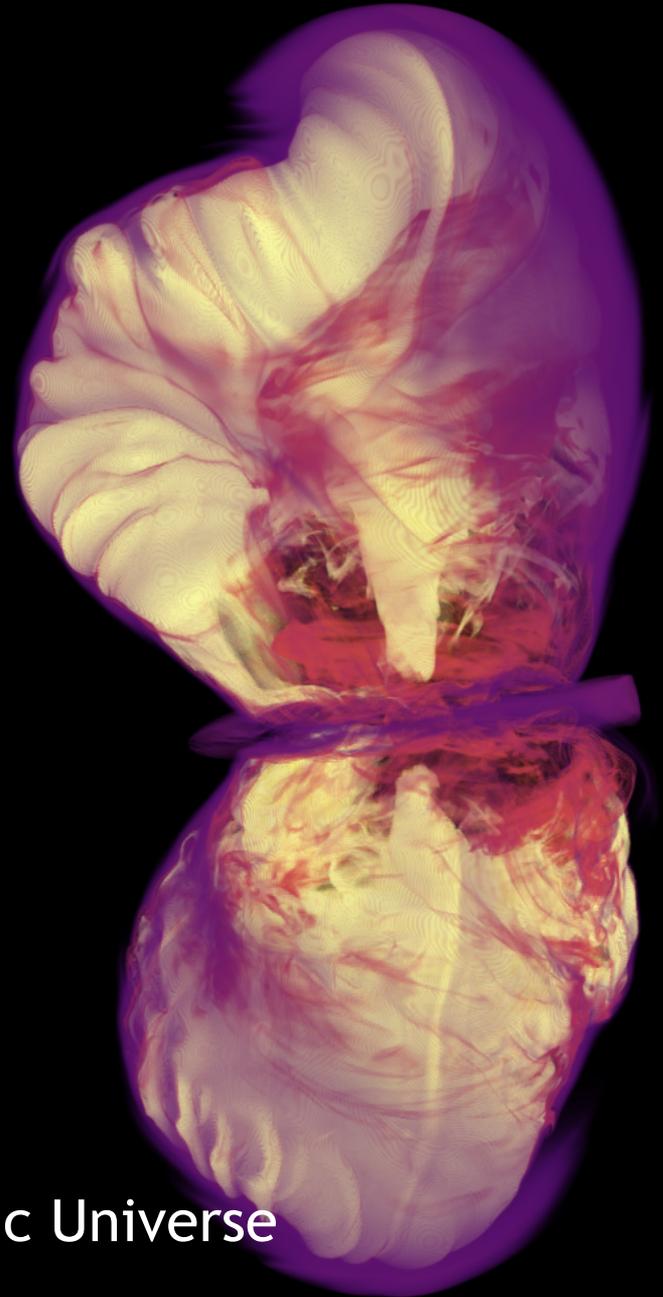# Magnetically-powered explosions in the multimessenger era

Philipp Mösta
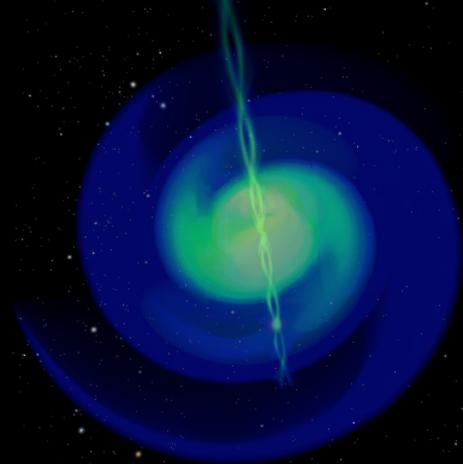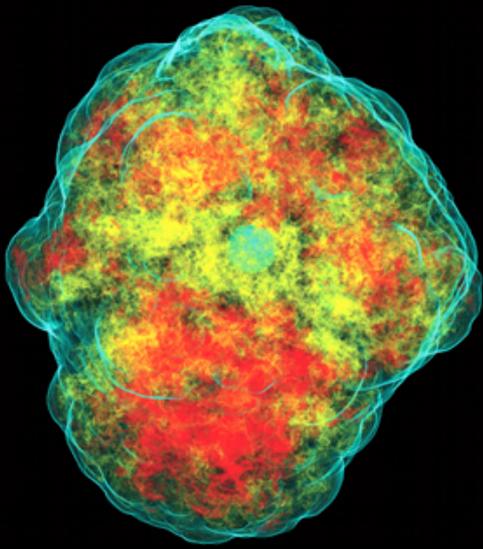
GRAPPA/API/IoP

University of Amsterdam

p.moesta@uva.nl

Multimessenger Astrophysics in the Dynamic Universe
YITP Feb 5, 2026

(Binary) black holes
accretion disks
EM counterparts

Core-collapse supernovae
neutrinos
turbulence

Multimessenger source modelling

Binary neutron stars
gravitational waves
kilonova/sGRBs

Extreme core-collapse
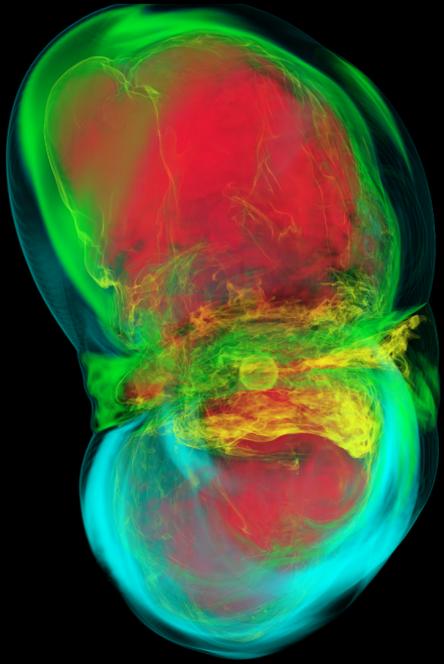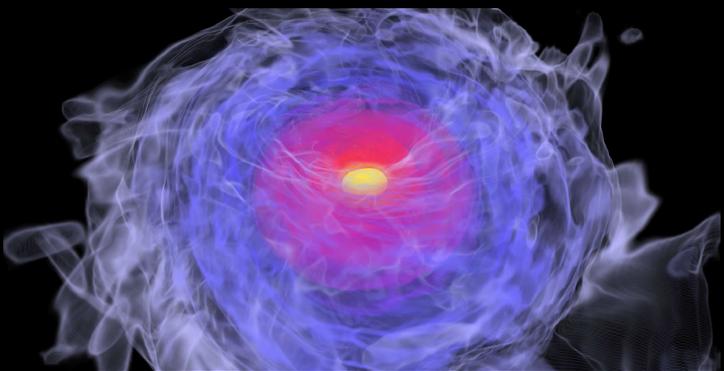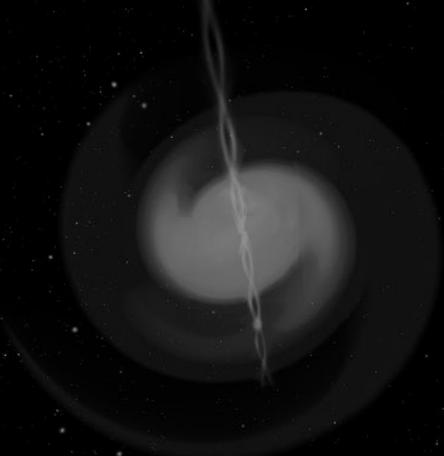hyperenergetic
superluminous
lGRBs

(Binary) black holes
accretion disks
EM counterparts

Core-collapse supernovae
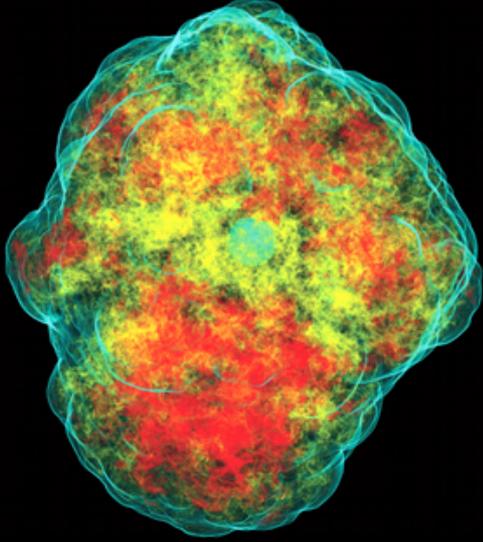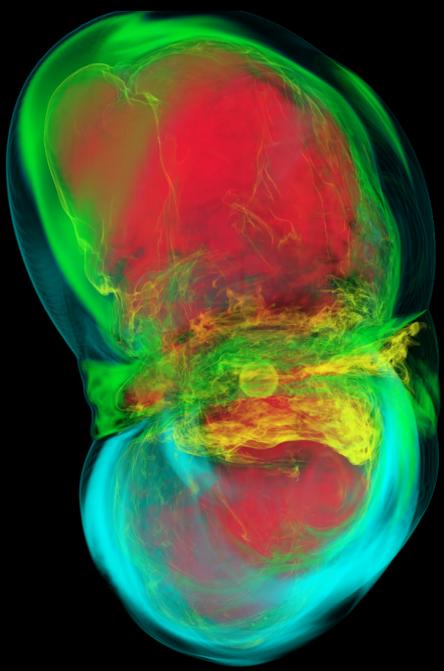neutrinos
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Multimessenger source modelling

Binary neutron stars
gravitational waves
kilonova/sGRBs
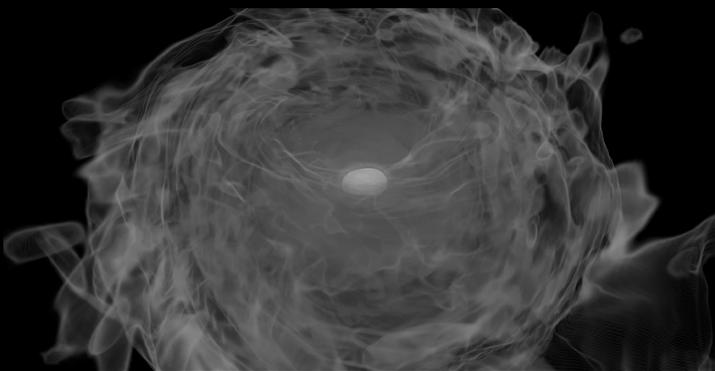
Extreme core-collapse
hyperenergetic
superluminous
lGRBs

Hypernovae & GRBs

Massive Star
~8 - 130 $M_\odot$

BSG

"WR"

RSG   (not to scale)

Core Collapse → Mechanism/Engine
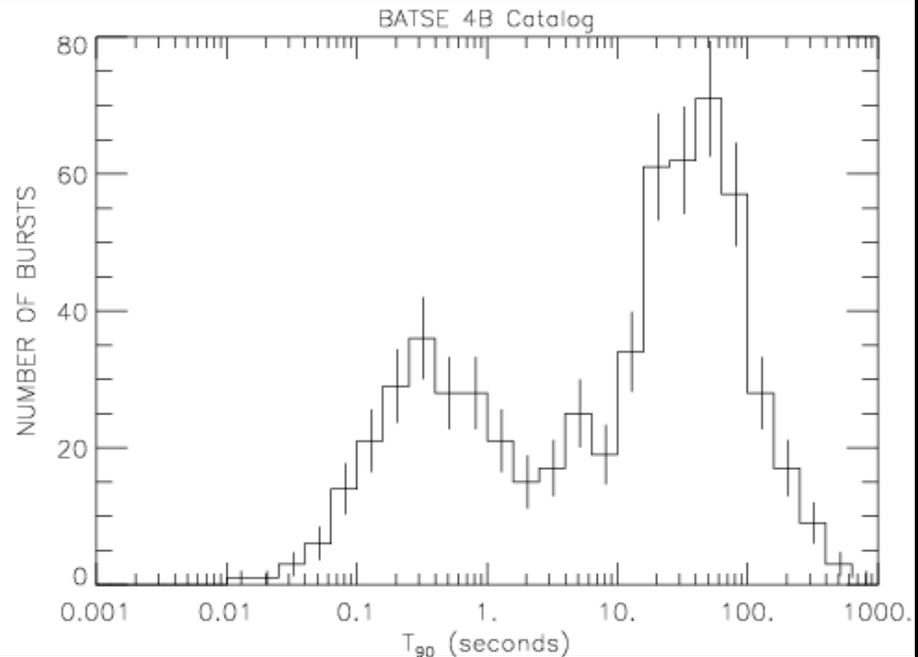
"**normal**" → Supernova
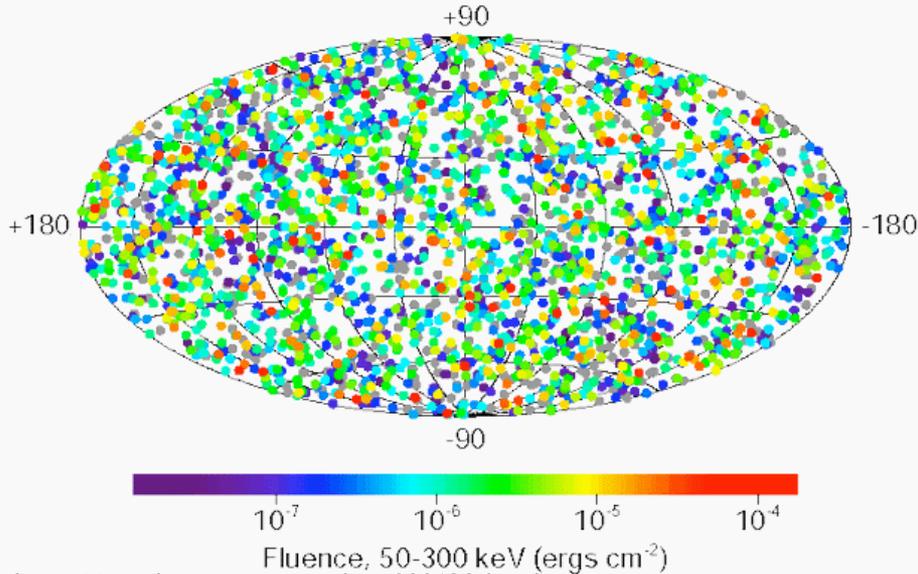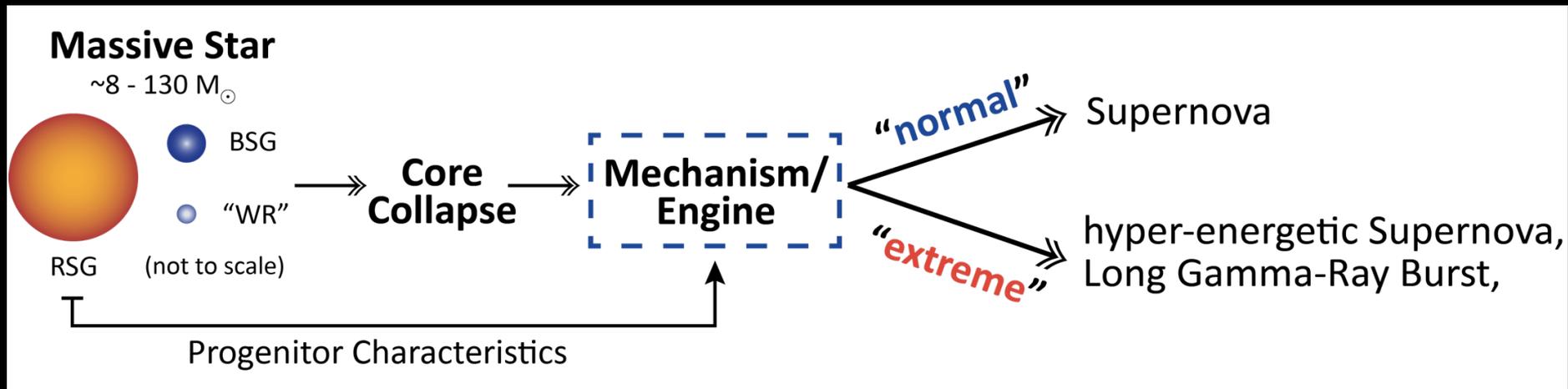
"**extreme**" → hyper-energetic Supernova, Long Gamma-Ray Burst,

Progenitor Characteristics

2704 BATSE Gamma-Ray Bursts

+90

+180   -180

-90

Fluence, 50-300 keV (ergs cm^{-2})
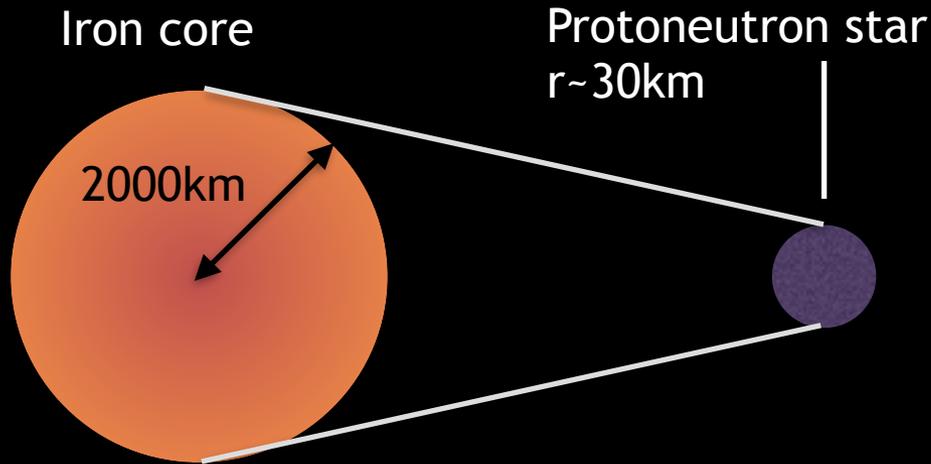
BATSE 4B Catalog

NUMBER OF BURSTS

T_{90} (seconds)

Extreme Supernovae and GRBs

- 11 long GRB – core-collapse supernova associations.
- **All GRB-SNe are stripped envelope, show outflows v~0.1c**
- But not all stripped-envelope supernovae come with GRBs
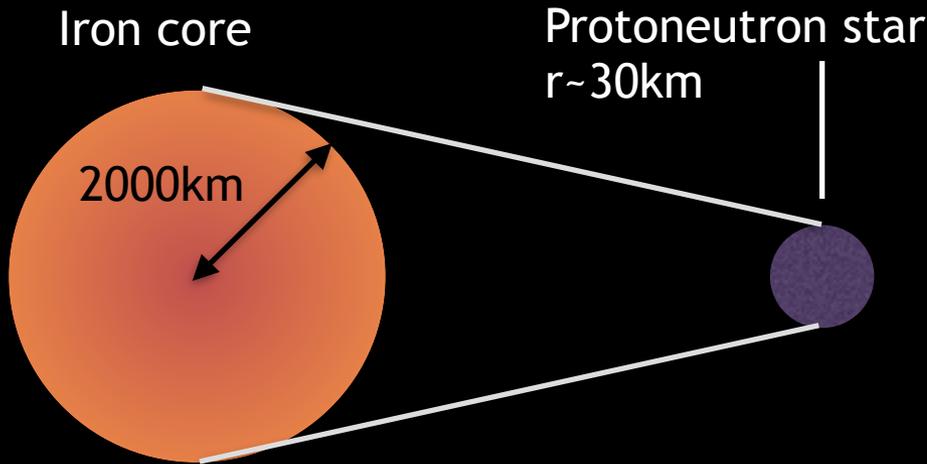- Trace low metallicity environments
- Some SLSNe share same characteristics

Core collapse basics

Iron core

Protoneutron star
r~30km

2000km

Nuclear equation of state stiffens at nuclear density

Inner core (~0.5 $M_\odot$)
-> protoneutron star + shockwave
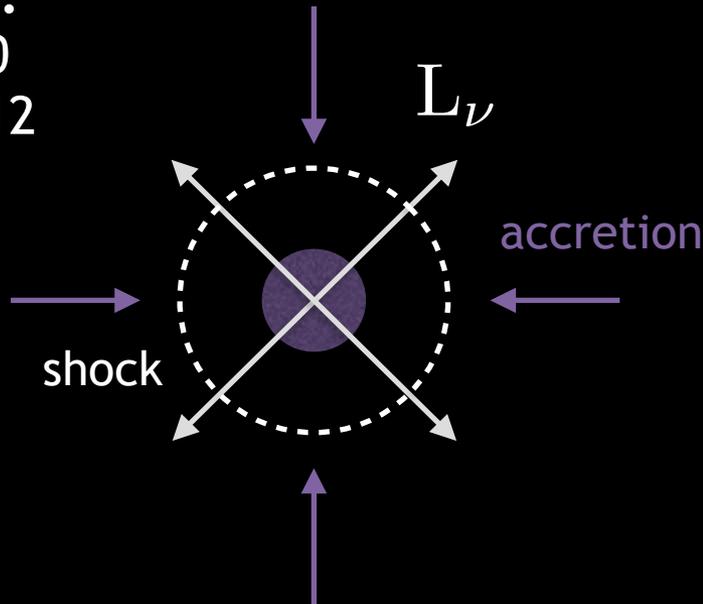
Core collapse basics

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r~30km

2000km

Nuclear equation of state stiffens at nuclear density

Inner core (~0.5 $M_\odot$)
-> protoneutron star + shockwave

Reviews:
Bethe'90
Janka+'12

L_ν

accretion

shock

Outer core accretes onto shock & protoneutron star with O(1) $M_\odot$/s

Shock stalls at ~ 100 km

Core collapse basics

Iron core

Protoneutron star
r~30km

2000km

Nuclear equation of state stiffens at nuclear density

Inner core (~0.5 $M_\odot$)
-> protoneutron star + shockwave

Reviews:
Bethe'90
Janka+'12
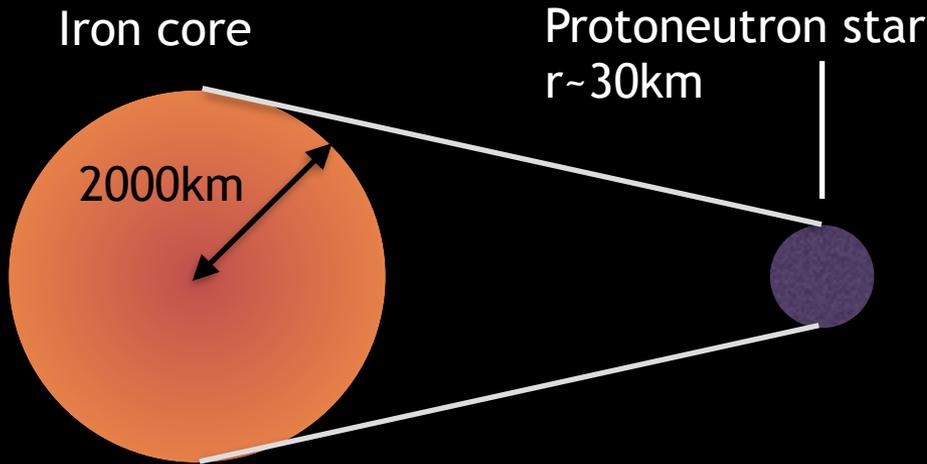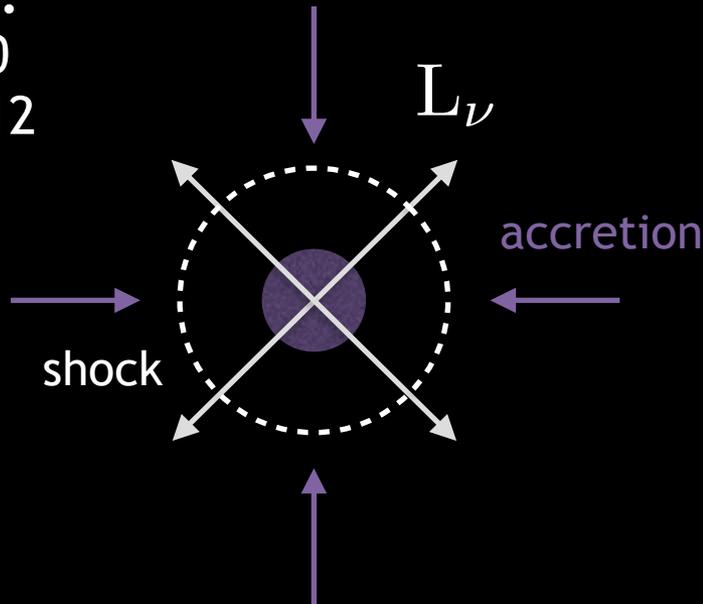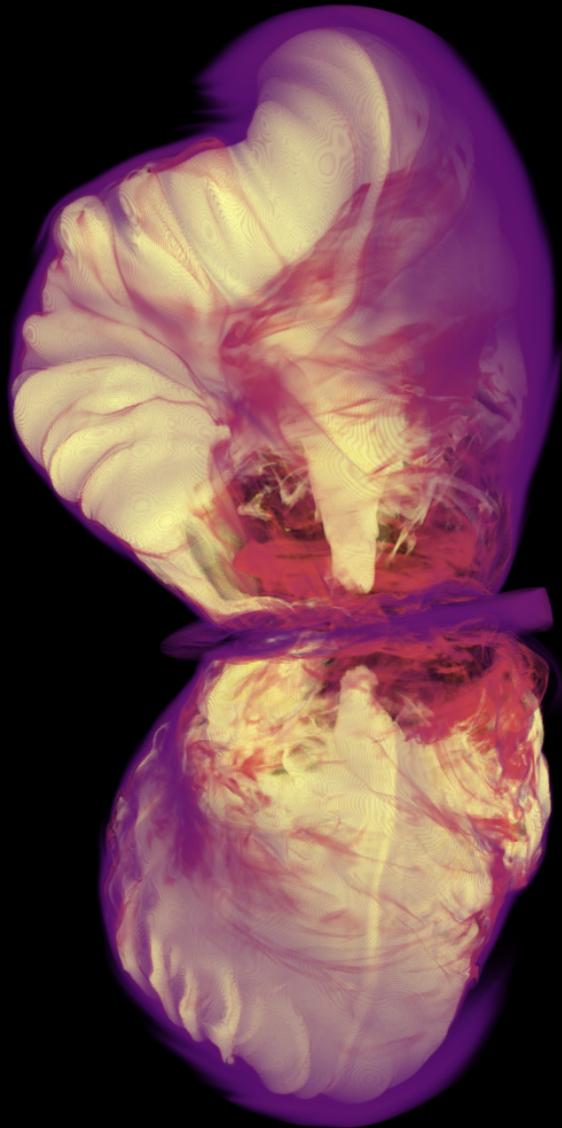
L_ν

accretion

shock

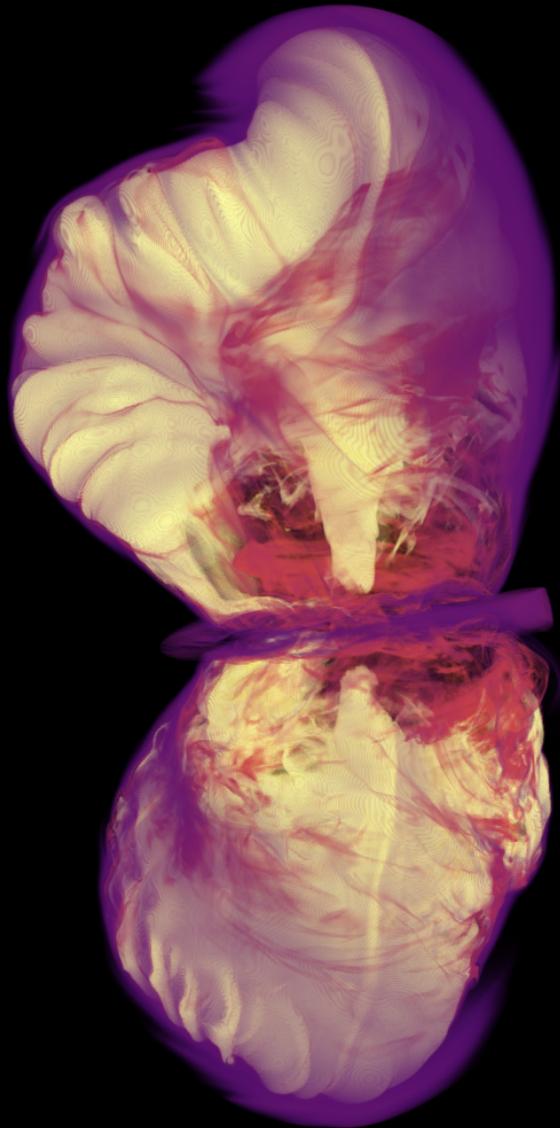**Magnetic field amplification?**

How to revive the shockwave?

MHD-supernova vs collapsar

MHD-supernova / magnetorotational supernova: outflows driven by protomagnetar
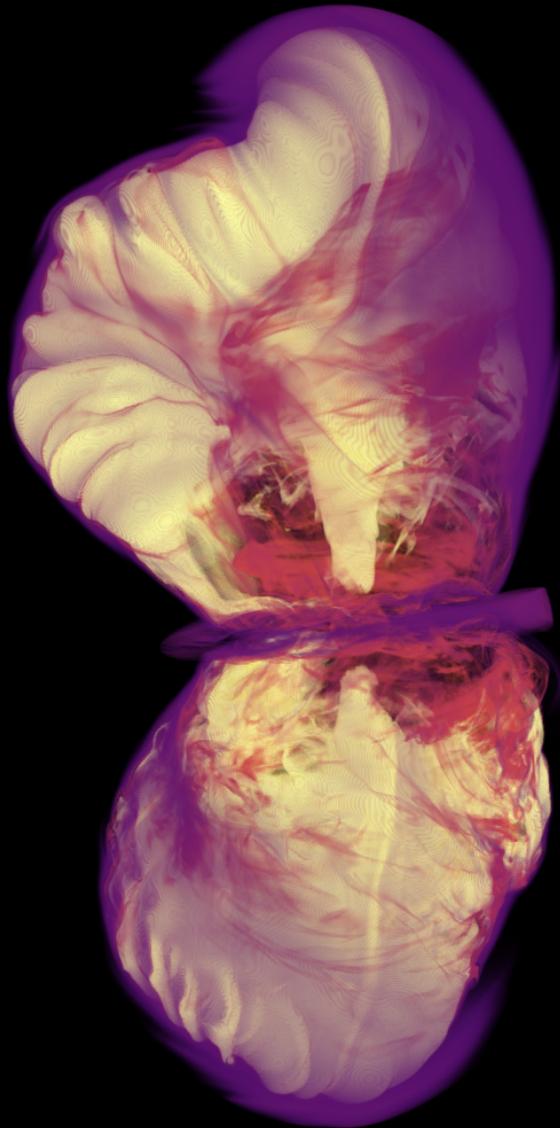
MHD-supernova vs collapsar

MHD-supernova / magnetorotational supernova: outflows driven by protomagnetar

Collapsar: Compact object (likely black hole) + accretion disk -> outflows driven by disk wind
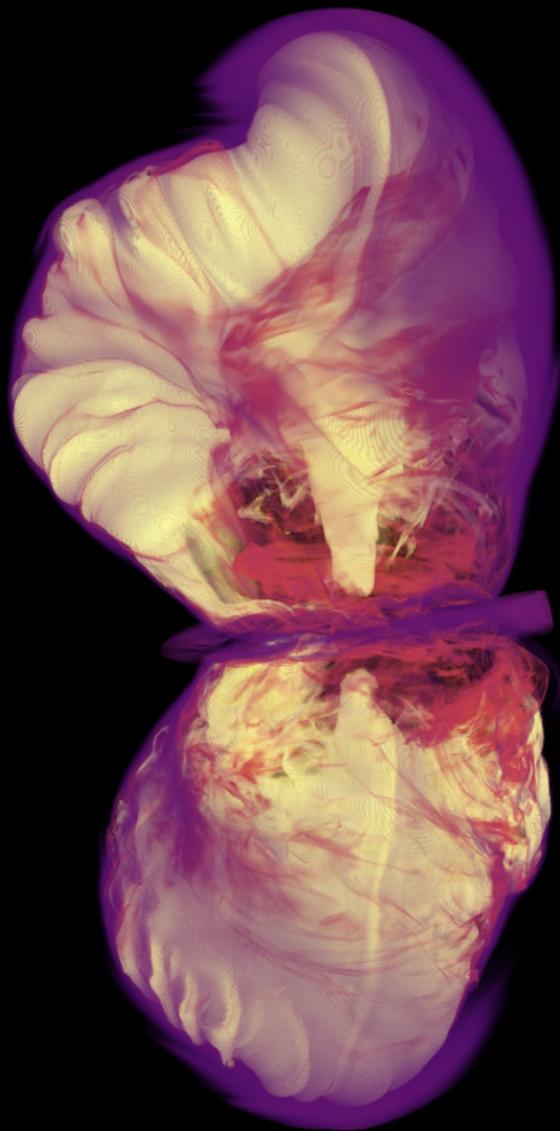
MHD-supernova vs collapsar

MHD-supernova / magnetorotational supernova: outflows driven by protomagnetar

Collapsar: Compact object (likely black hole) + accretion disk -> outflows driven by disk wind

Two different engines with different signatures!
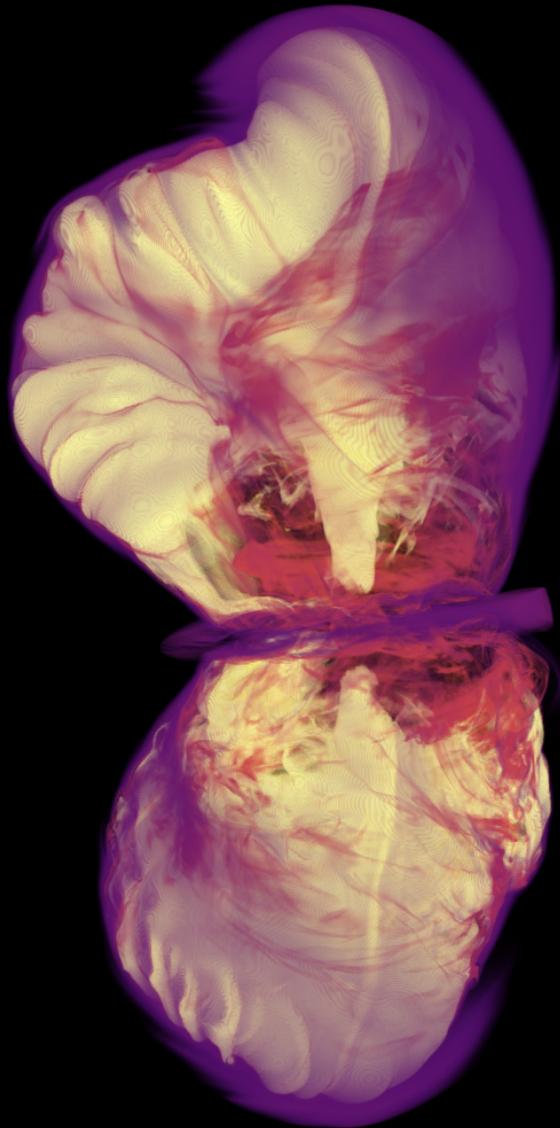
MHD-supernova vs collapsar

MHD-supernova / magnetorotational supernova: outflows driven by protomagnetar

Collapsar: Compact object (likely black hole) + accretion disk -> outflows driven by disk wind

Two different engines with different signatures!

Could be realized in same progenitor system but at different times
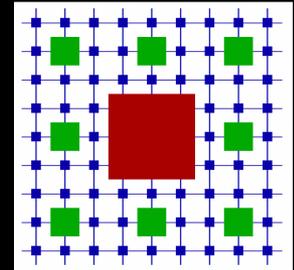
MHD-powered explosions

How do we make magnetars?

When do we form black holes?

What are the engines of type Ic-bl and GRB supernova?

http://einsteintoolkit.org

GRaM-X: GPUs

- Dynamical-spacetime simulations of supernova and neutron-star mergers

- Built to utilize GPUs at scale on the world's fastest supercomputers

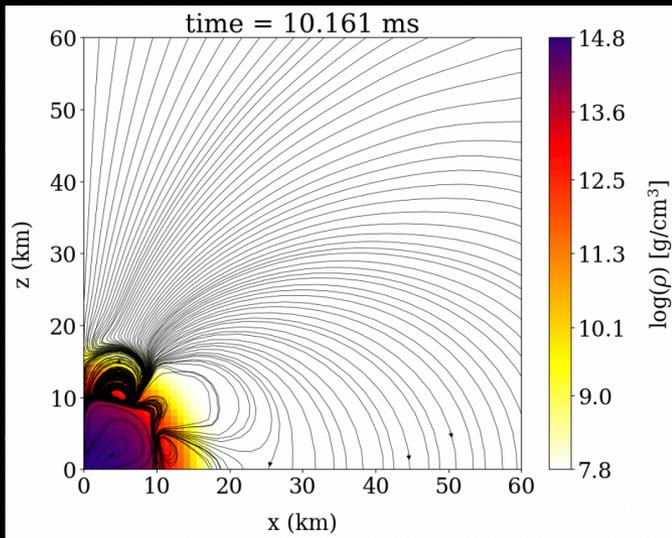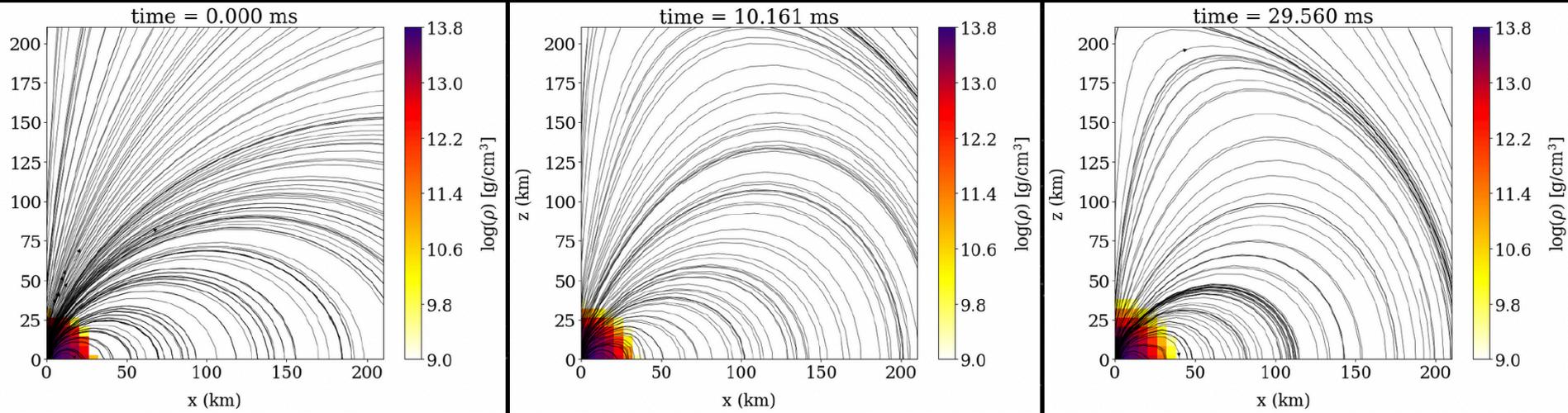- Embedded in the CarpetX/Einstein Toolkit framework

See Swapnil and Sara's talks

GRam-X extension to resistive GRMHD

Azizi, Shankar, PM+ 25

See Sara's poster

3D magnetic field structure

dx=500m   dx=200m   dx=100m   dx=50m

t =   0.00 ms   t =   0.00 ms   t =   0.00 ms   t =   0.00 ms

PM+ 15 Nature

BLUE WATERS
SUSTAINED PETASCALE COMPUTING

NSF
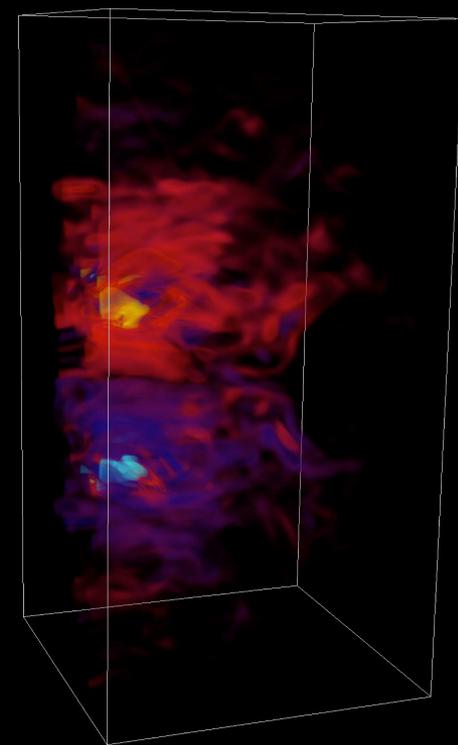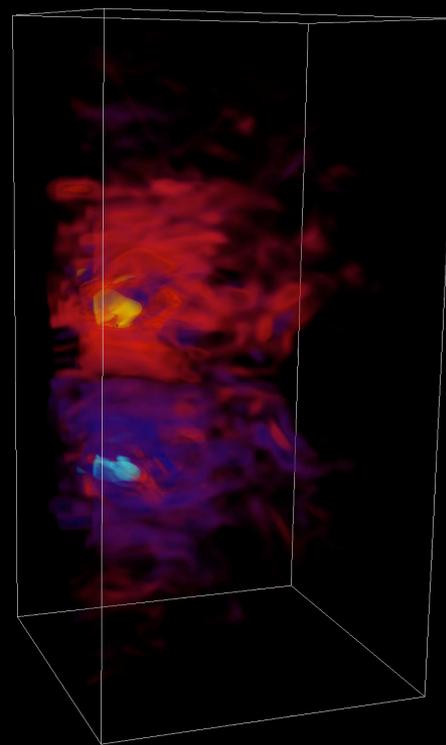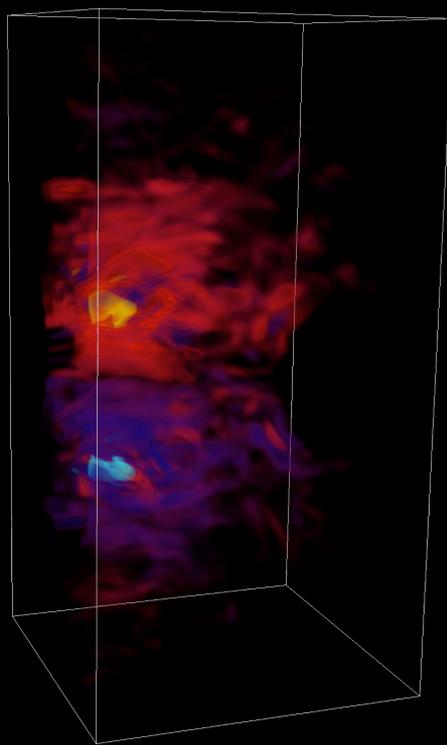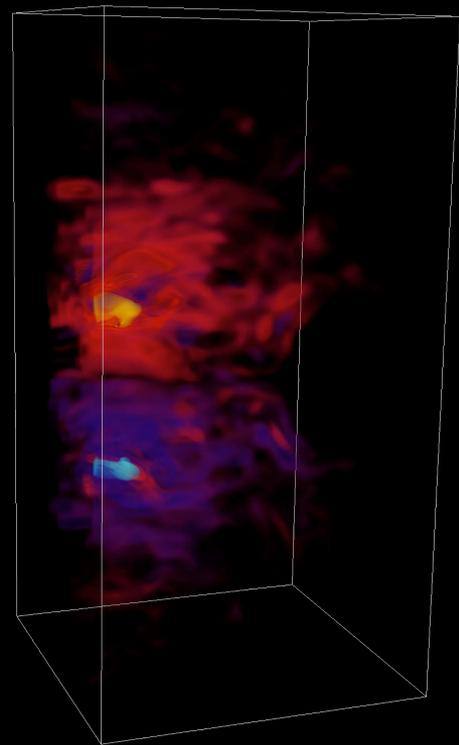
How do we make magnetars?

But ... This channel can't explain the entire magnetar population
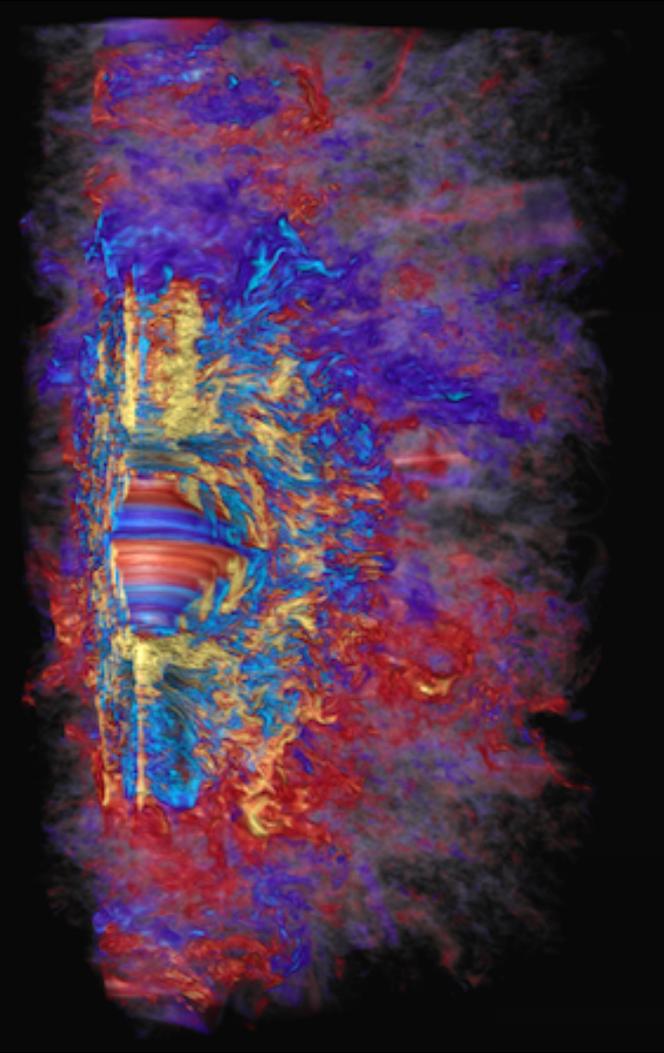
Raynaud+20

But ... This channel can't explain the entire magnetar population

Need ms-period proto-magnetar
-> rapidly-rotating massive stars

Raynaud+20
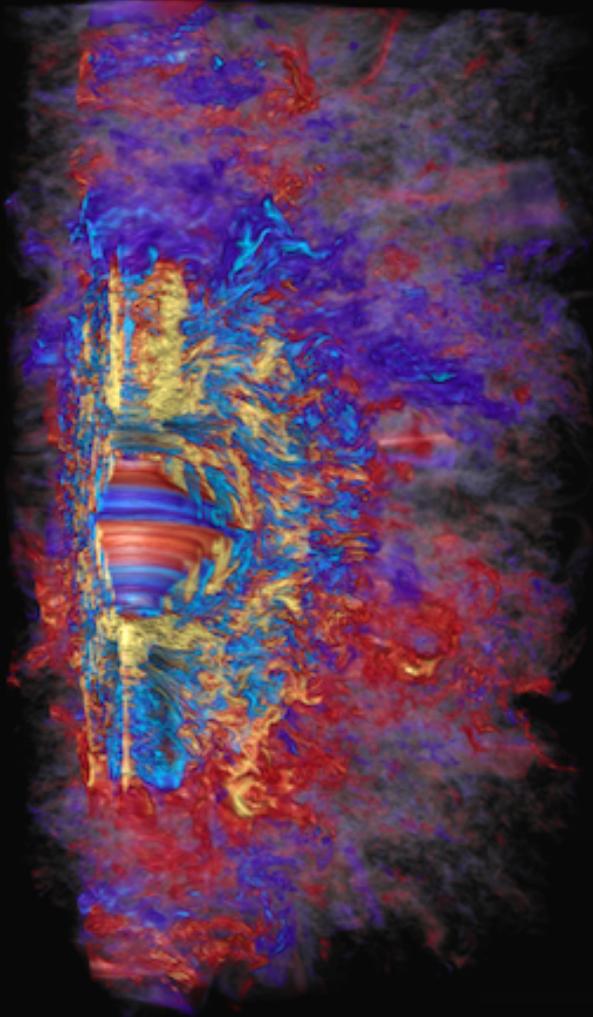
But ... This channel can't explain the entire magnetar population

Need ms-period proto-magnetar
-> rapidly-rotating massive stars

• Relax rotation rate requirement

• Start from highly-magnetized core of a massive star

see Miguel's talk

Raynaud+20
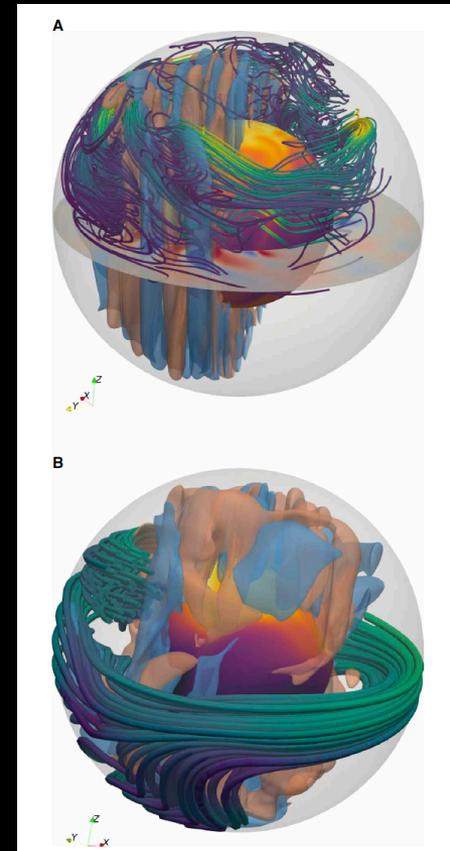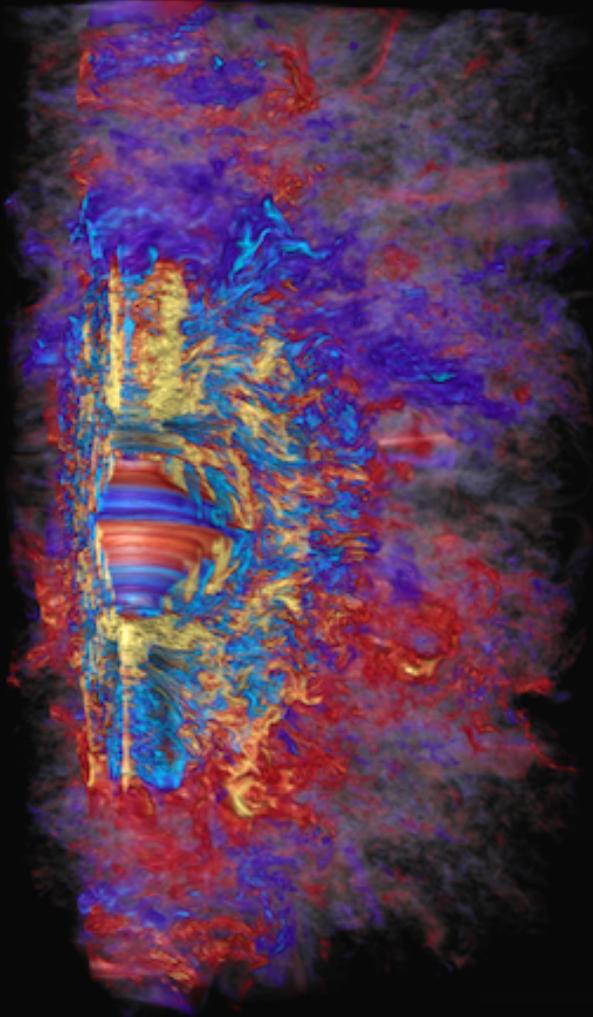
**3D Volume
Visualization of**

$t = $ -3.00 ms

Entropy

PM+ 14

Implications for long Gamma-Ray Bursts
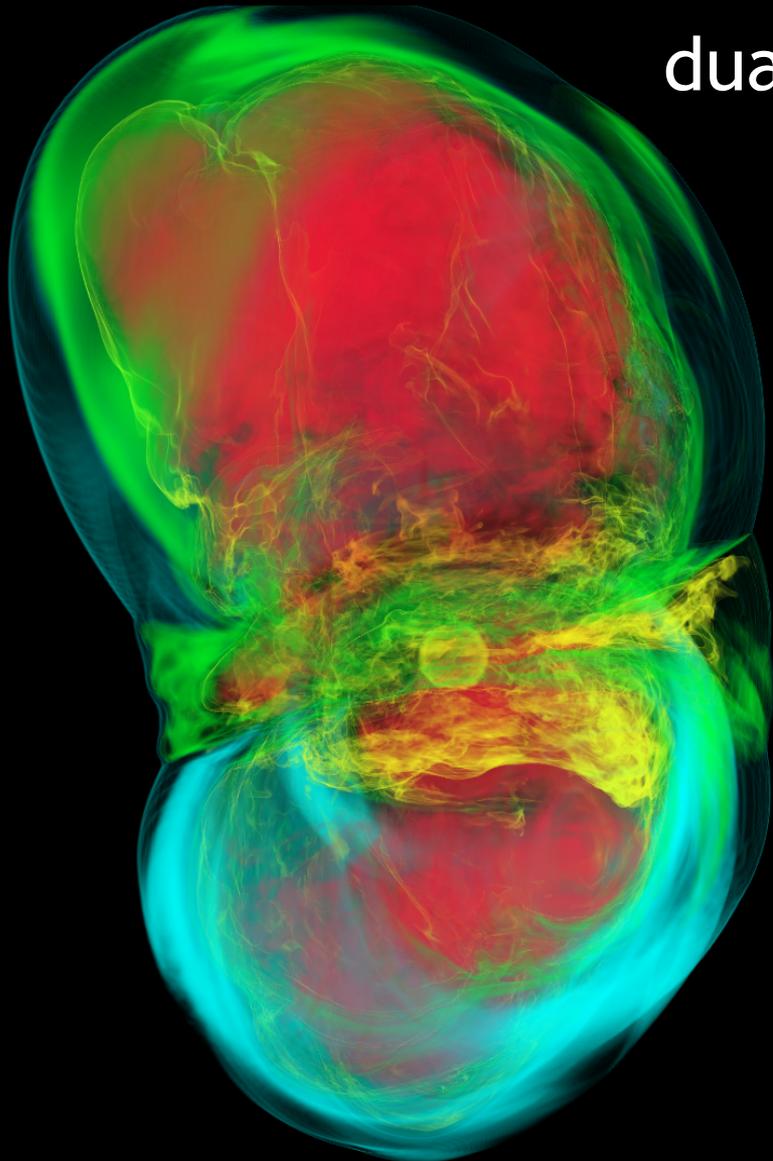
dual-lobe 'slow' explosion
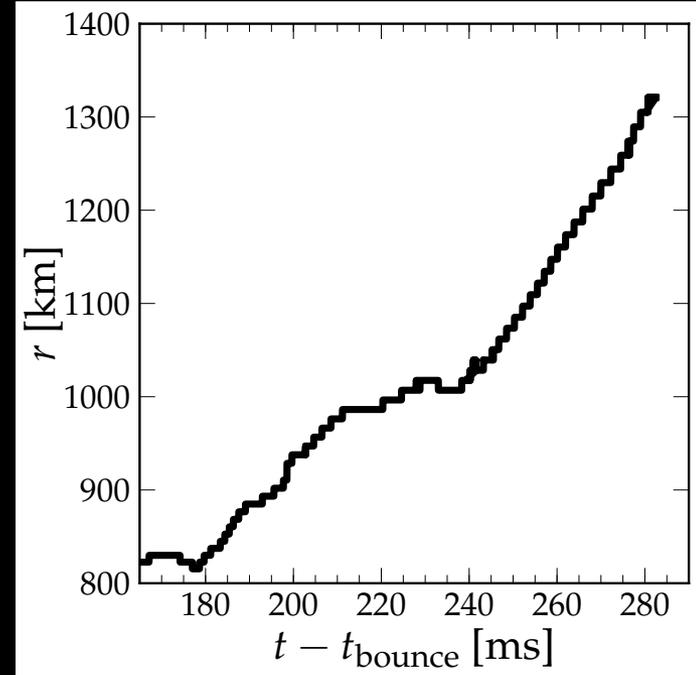
**Continued accretion ->
Black hole engine possible!**

Kink instability deforms/disrupts jet
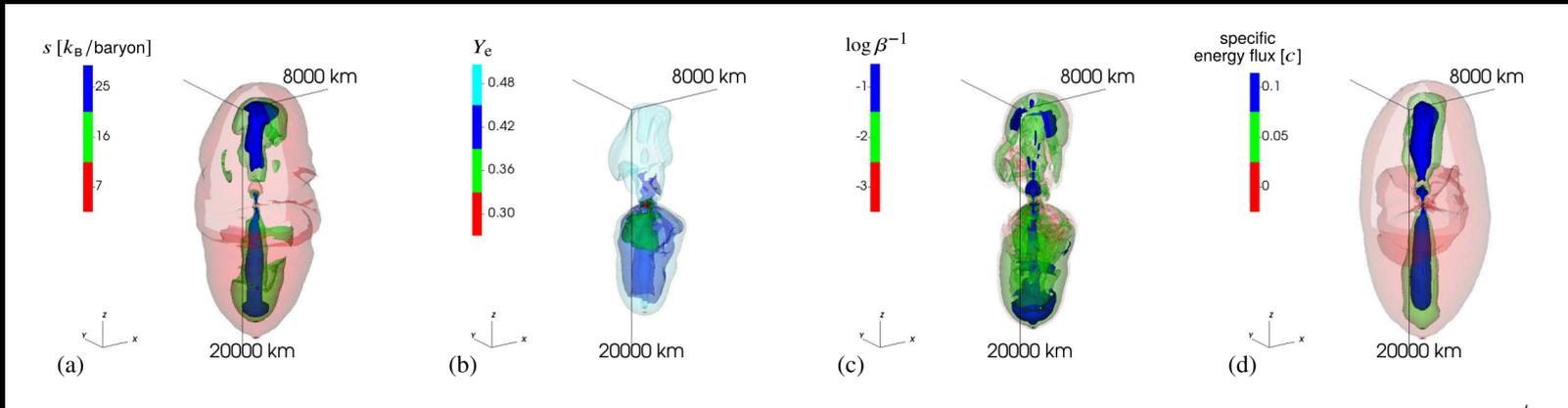
Obergaulinger+21

Detailed explosion geometry depends on lots of factors

-> code comparison led by Matteo Bugli
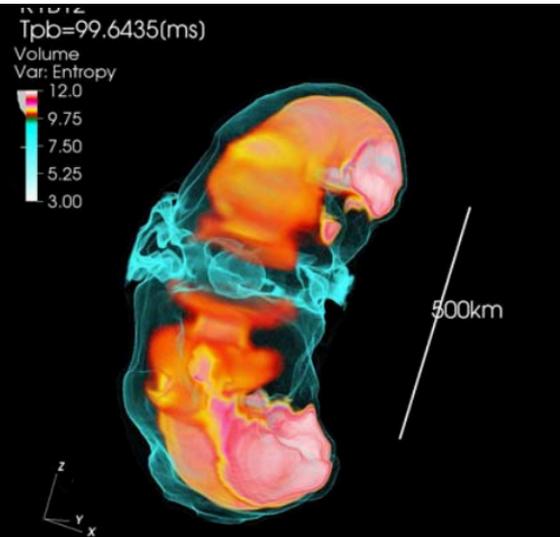
Kuroda+21

Shibagaki+24
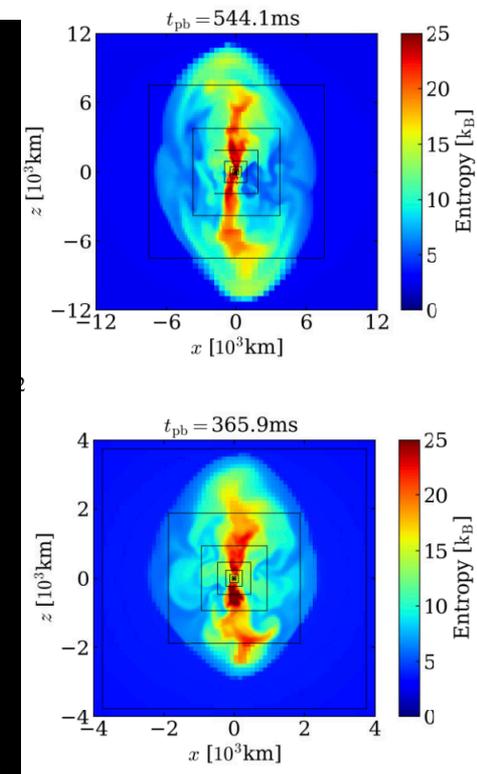
Towards a catalogue of 3D explosions
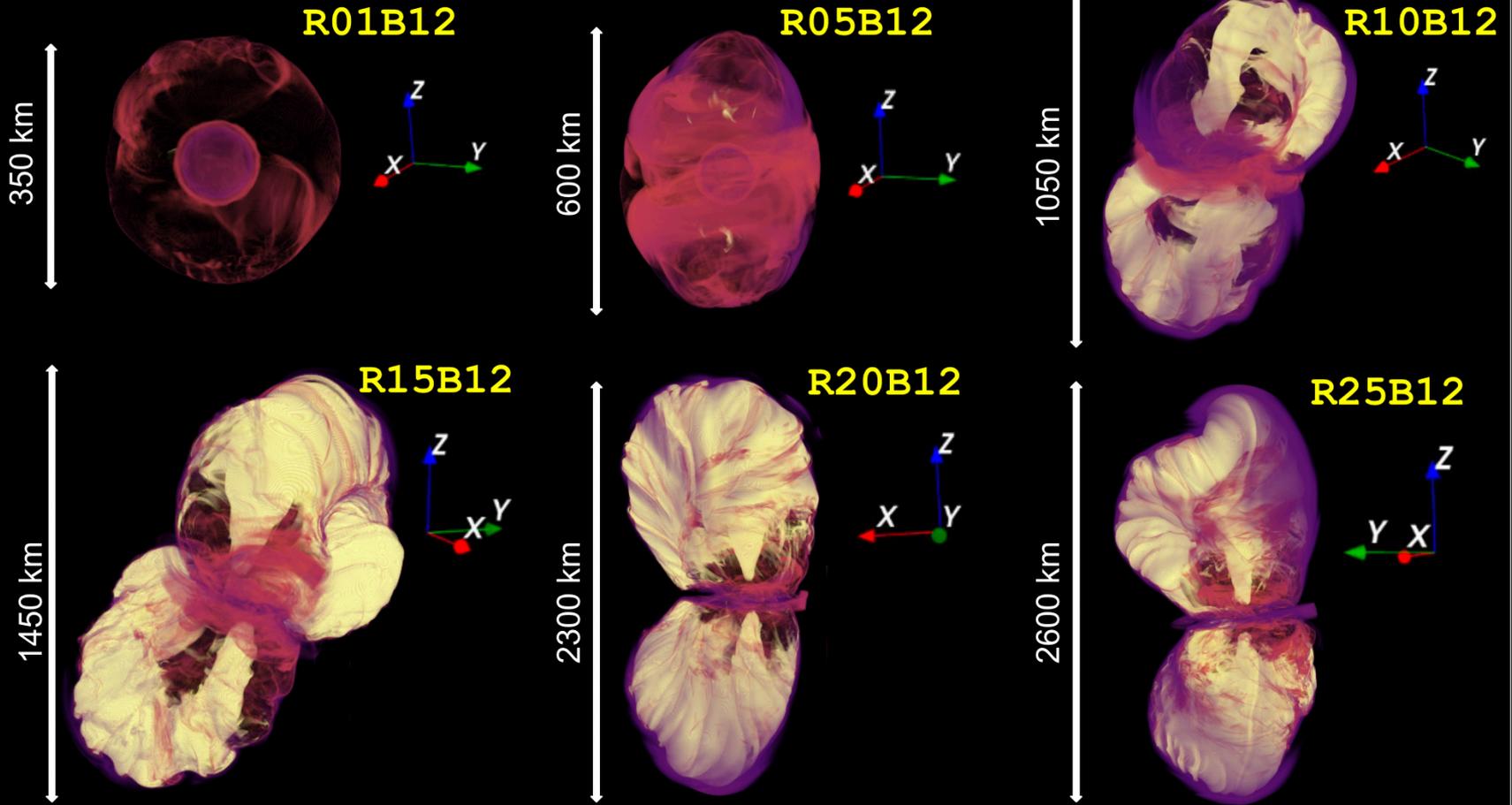
R01B12 · 350 km

R05B12 · 600 km

R10B12 · 1050 km

R15B12 · 1450 km

R20B12 · 2300 km

R25B12 · 2600 km

Shankar, **PM**+ 25

With Swapnil Shankar

Towards a catalogue of 3D explosions
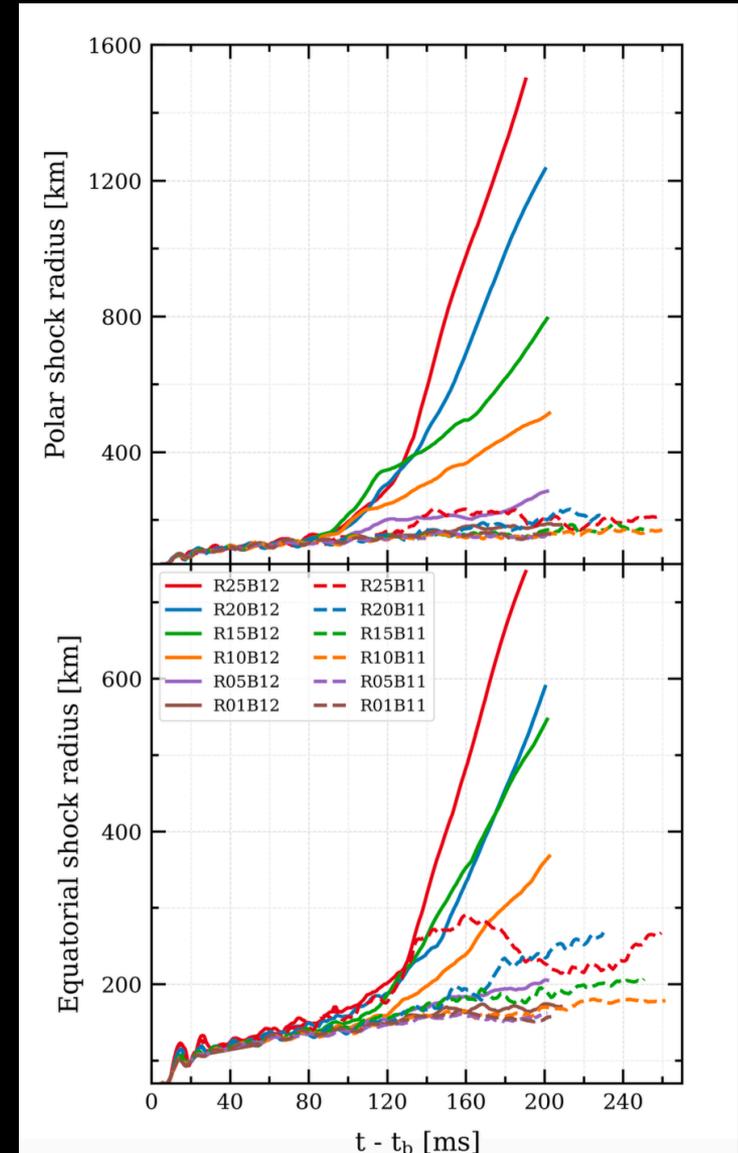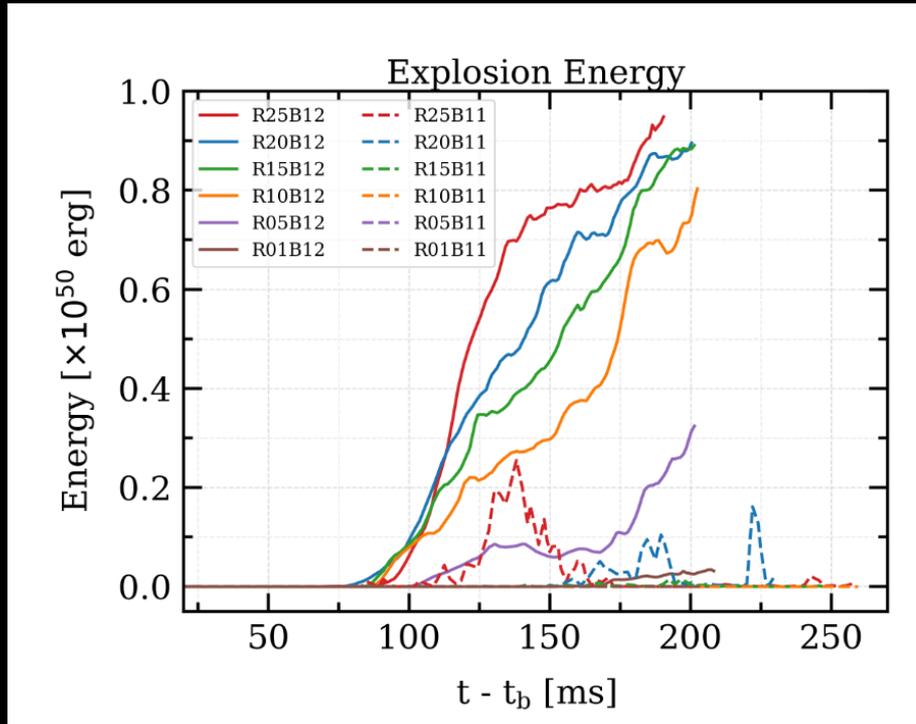
Shankar, **PM**+ 25

With Swapnil Shankar

Towards a catalogue of 3D explosions
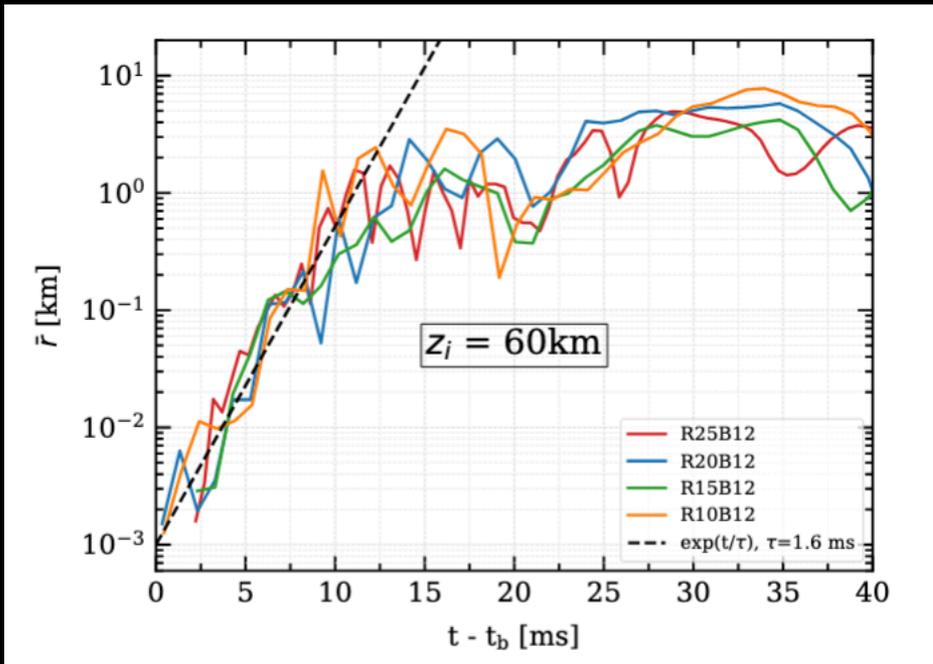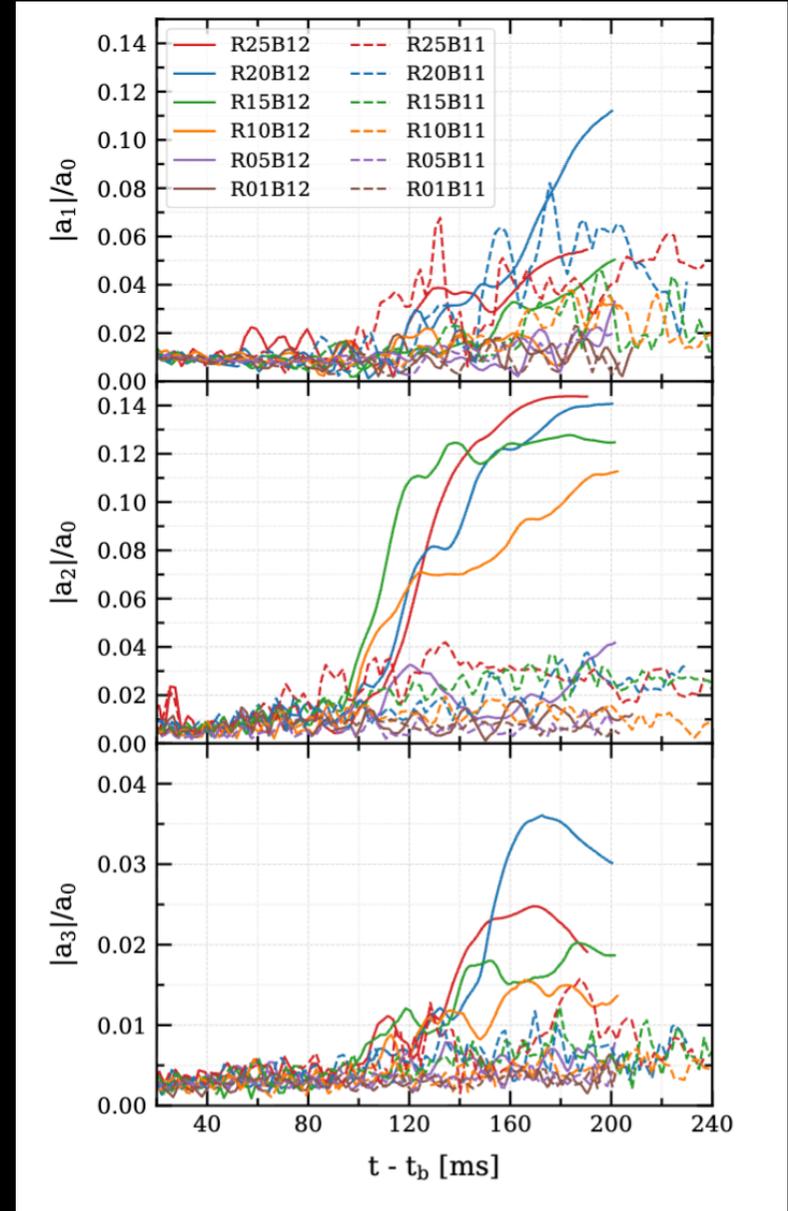
Shankar, **PM**+ 25

With Swapnil Shankar

Remnant properties
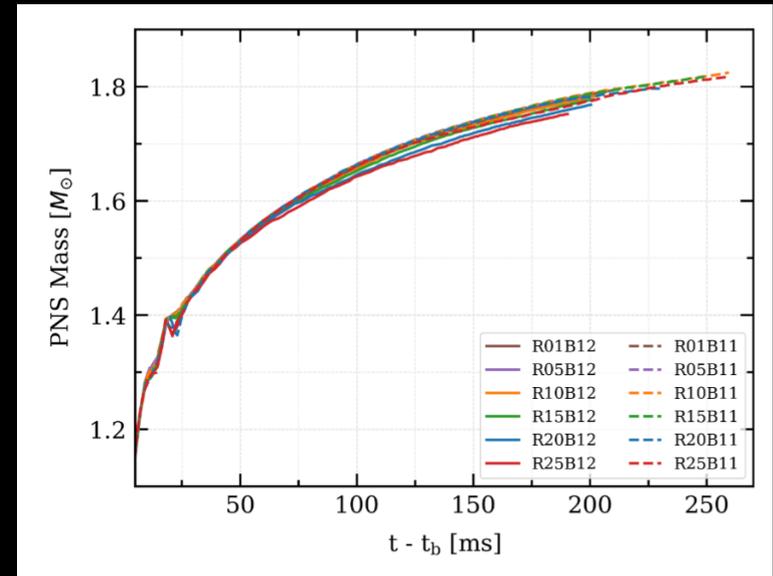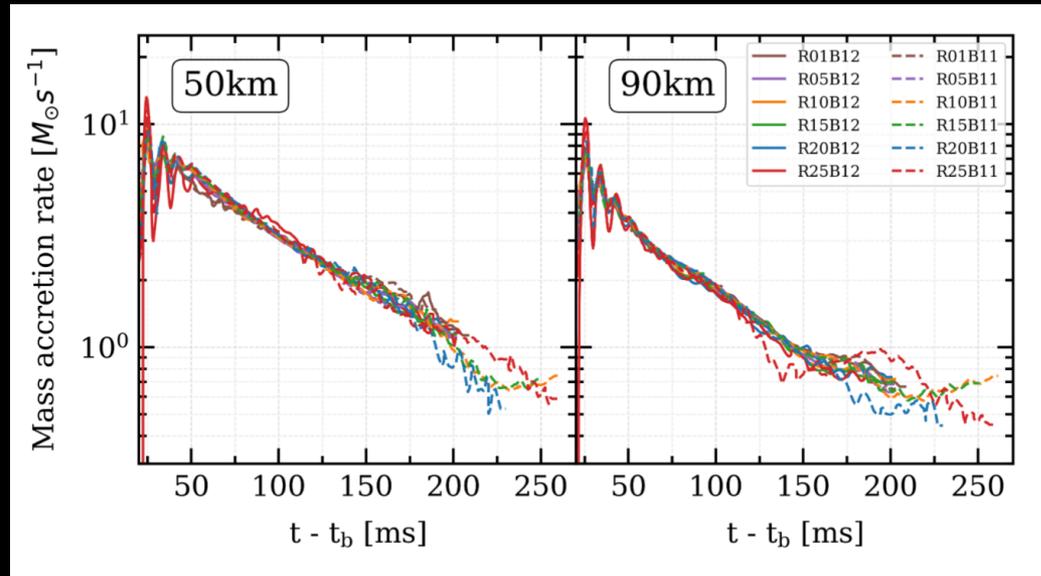
Shankar, **PM**+ 25
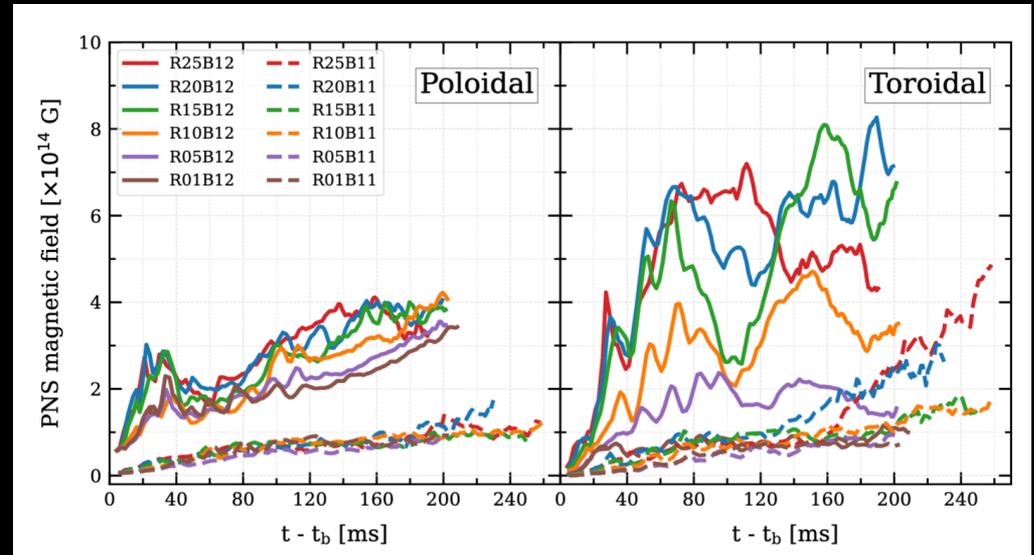
With Swapnil Shankar

Resolution matters but how much?

DB: rot5.it00000000.silo
Cycle: 0   Time:-168.5

Pseudocolor
Var: plasma_beta
— 100.0
— 10.00
— 1.000
— 0.1000
— 0.01000
Max: 3.910e+06
Min: 315.1
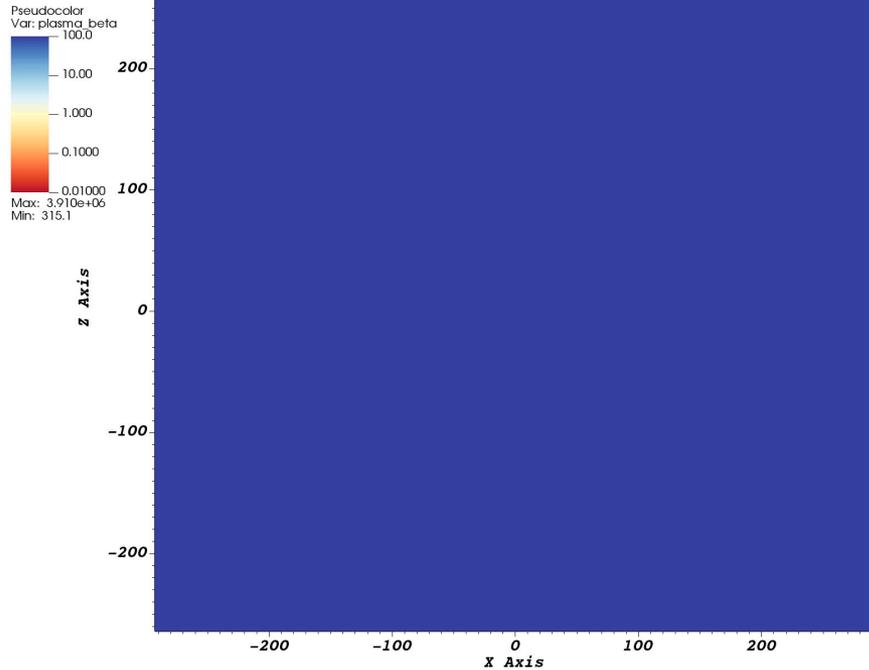
user: sshanka
Tue Nov 11 16:06:09 2025

$z_i = 60km$

R20B12 (high resolution)
R20B12 (fiducial resolution)
R10B12 (high resolution)
R10B12 (fiducial resolution)

Shankar, **PM**+ 25

With Swapnil Shankar
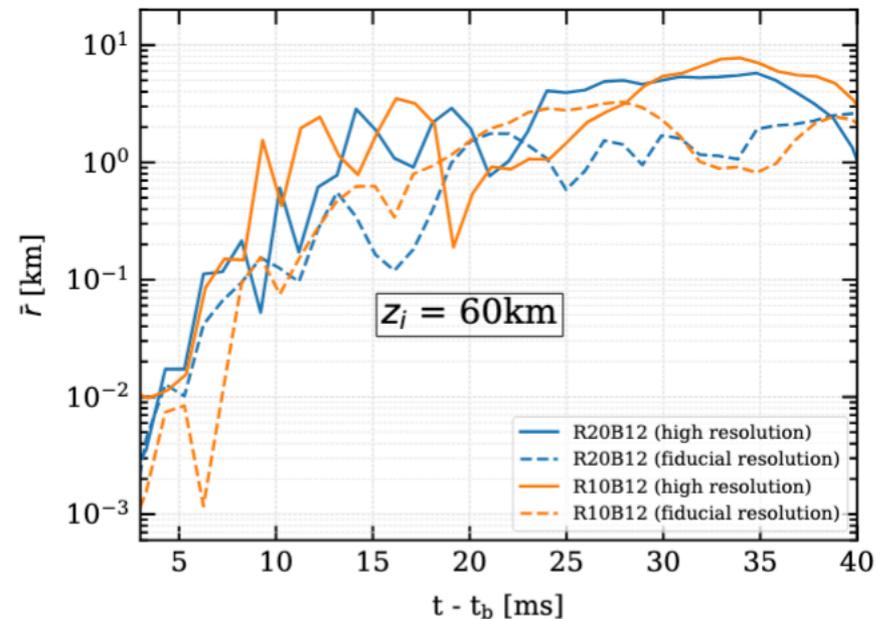
Resolution matters but how much?
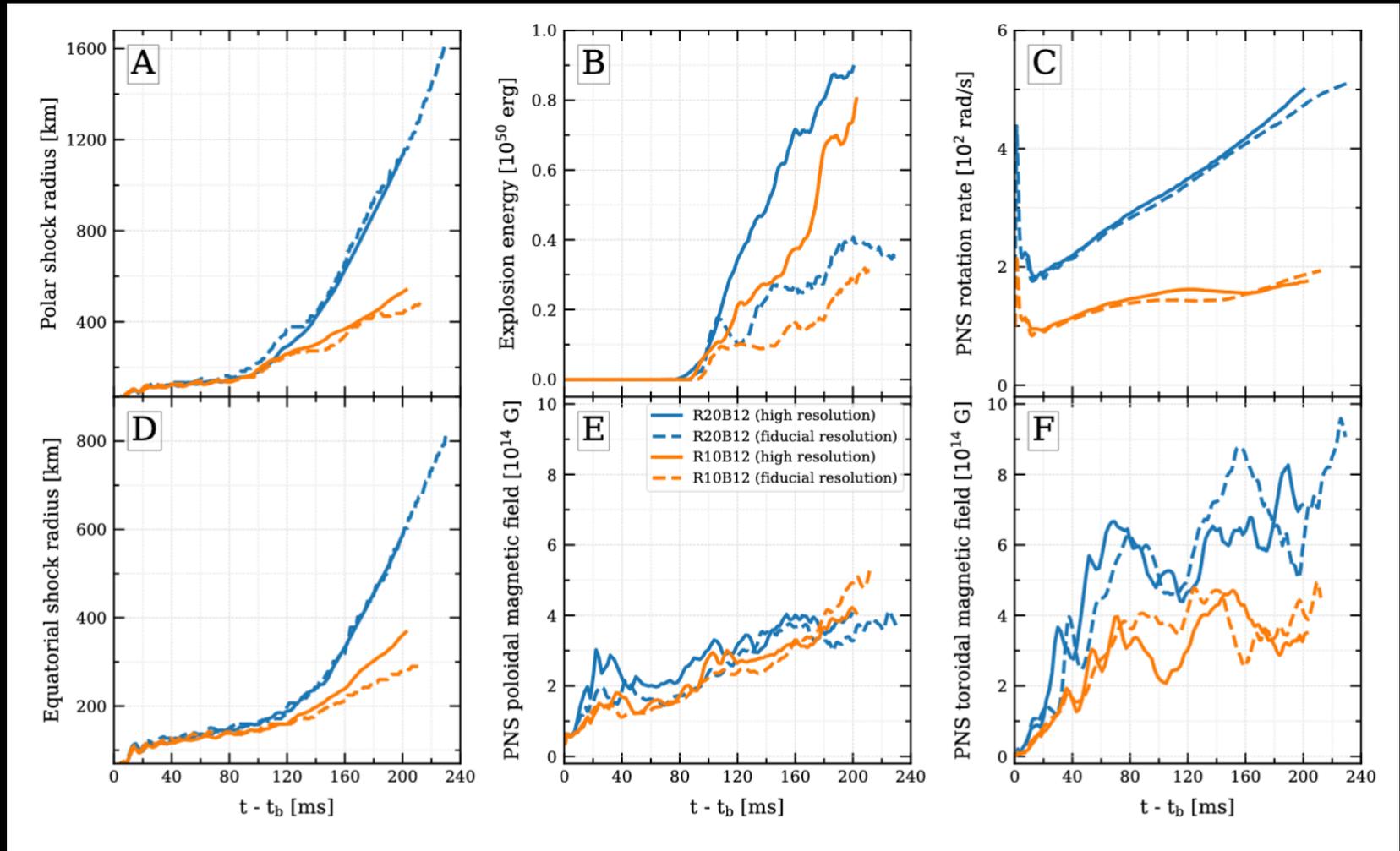
Shankar, **PM**+ 25
with Swapnil Shankar

Making the heaviest elements
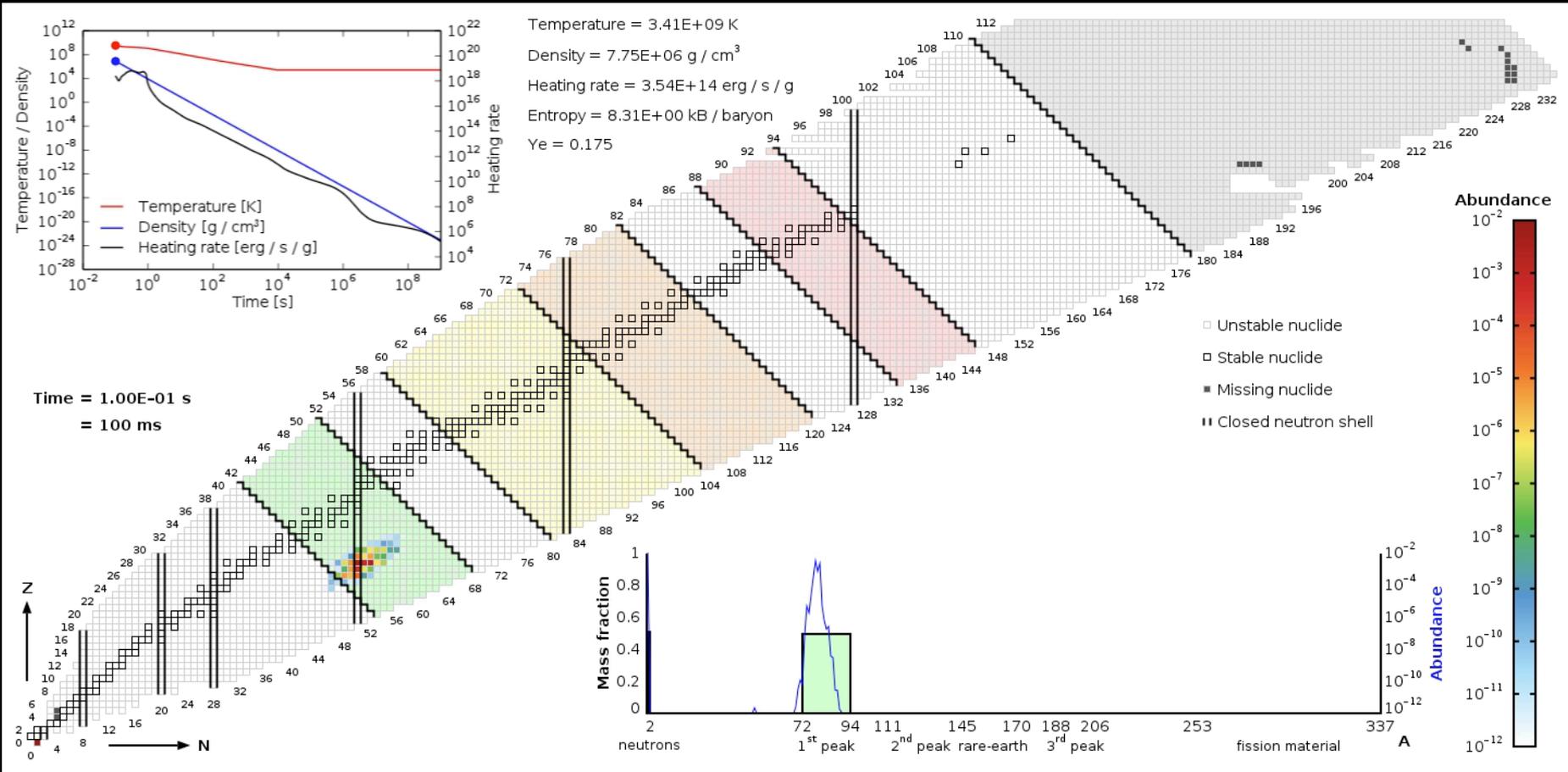
PM+ 18
Halevi, PM+ 18

with Goni Halevi

R-process in jet-driven supernovae

1600 km

B = 10^{13} G full 3D   B = 10^{12} G octant   B = 10^{12} G full 3D

PM+ 18
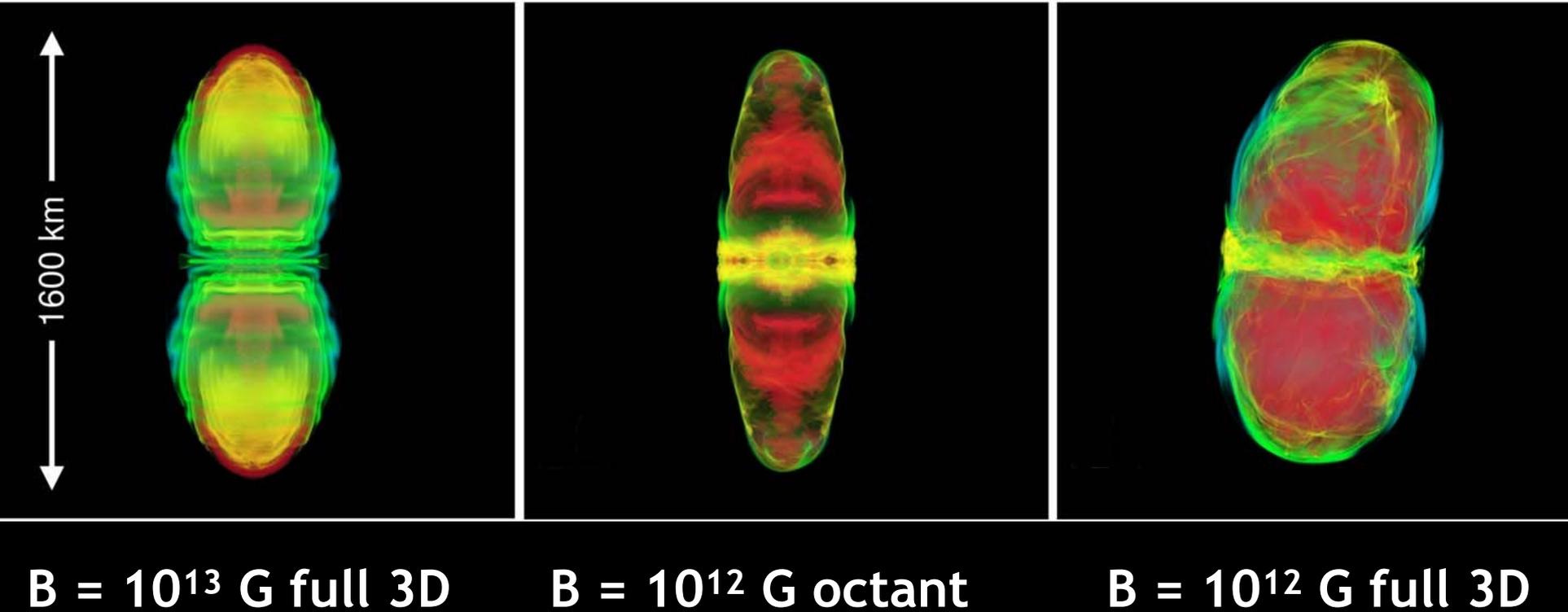
R-process nucleosynthesis in supernovae

Explosion type determines nucleosynthetic outcome

R-process in jet-driven supernovae

R-process in jet-driven supernovae
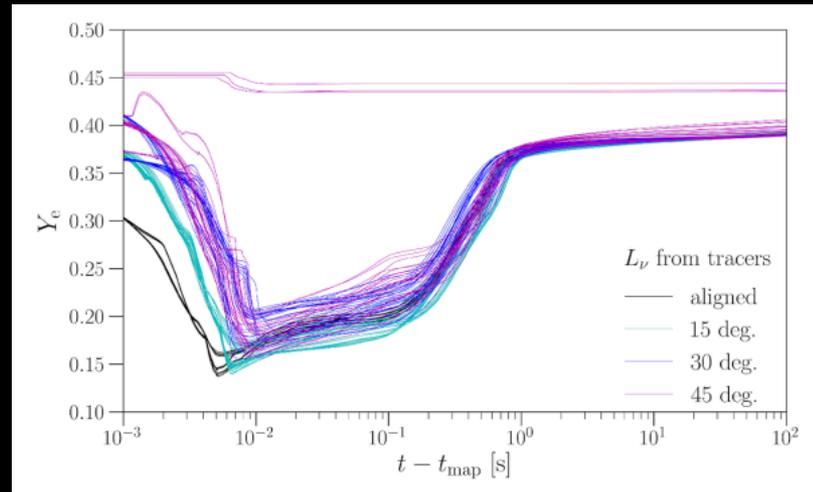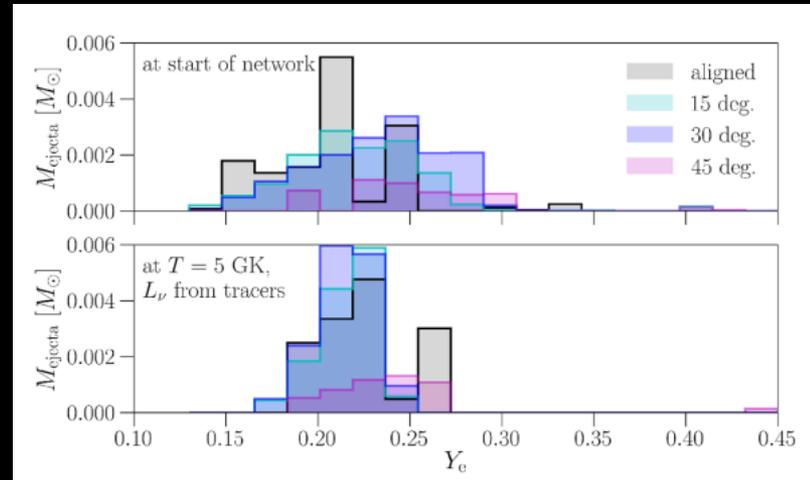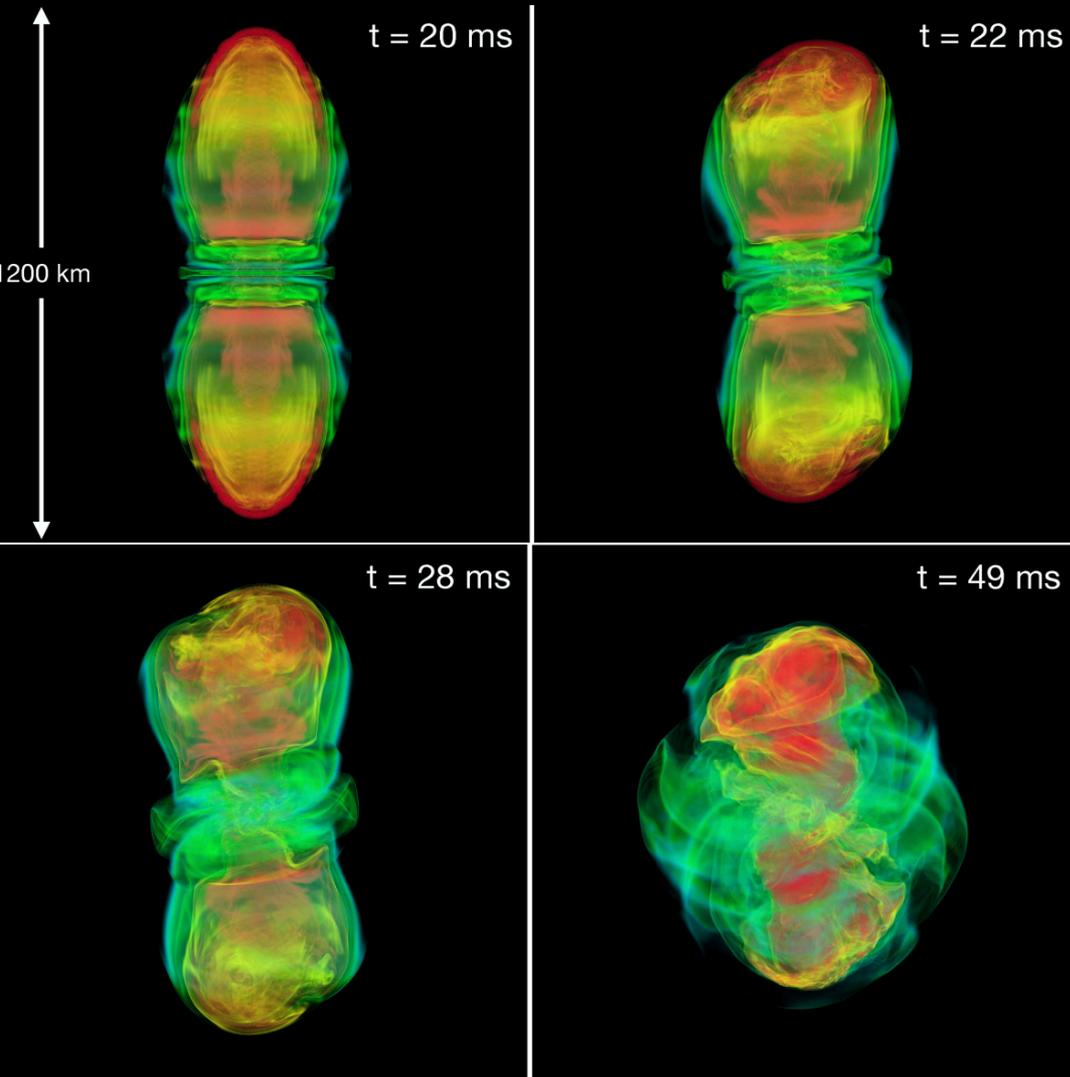
Halevi, PM 18

R-process nucleosynthesis in supernovae
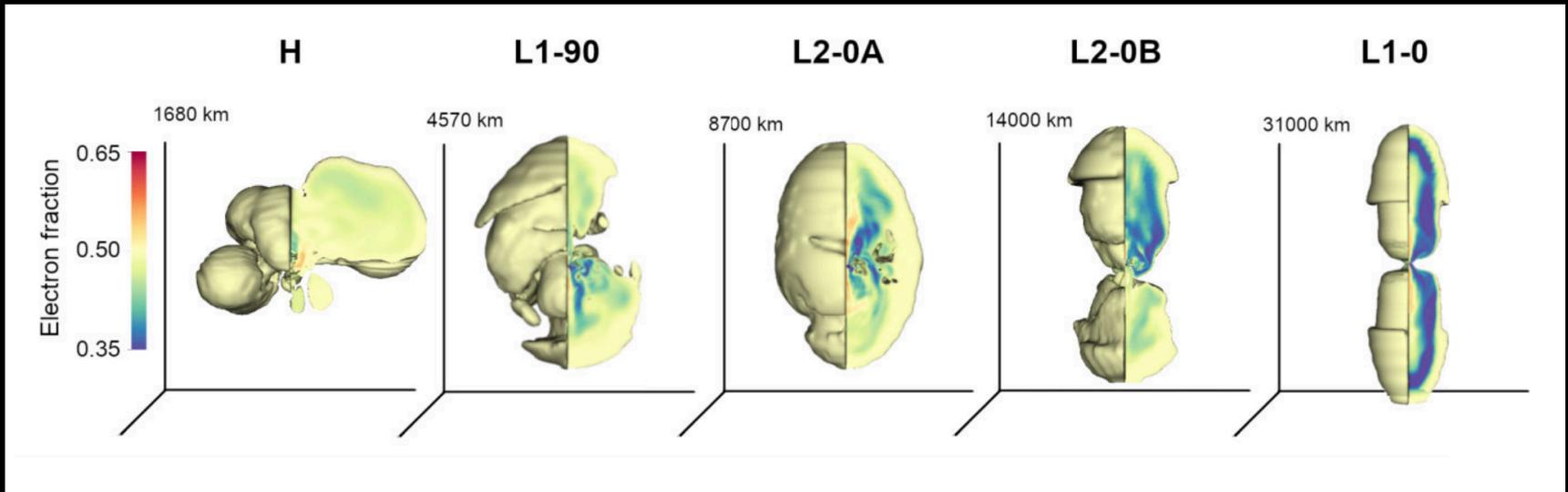
Reichert+ 23

Other groups find similar results, but there's still lots of details to be understood better
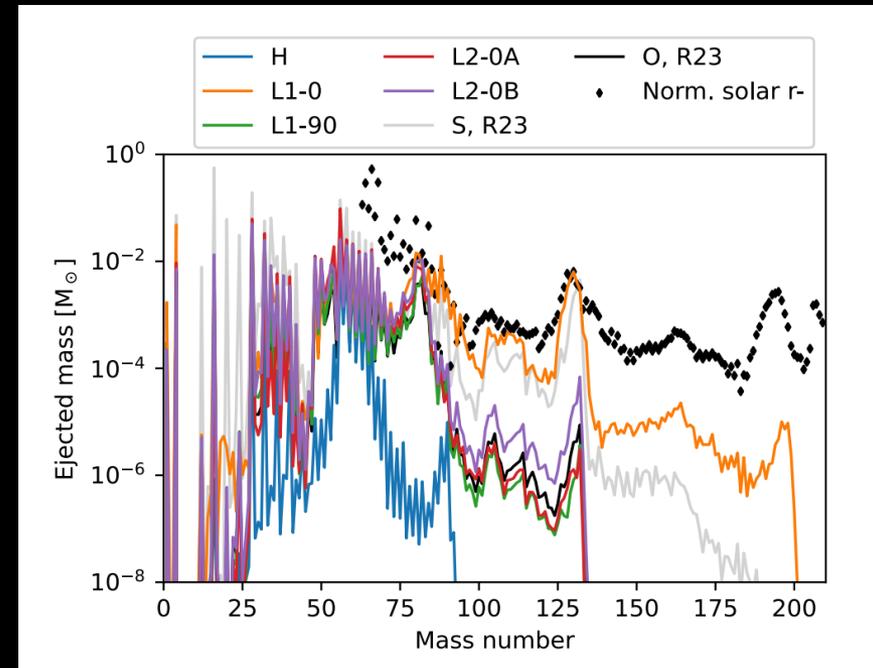
R-process nucleosynthesis in supernovae
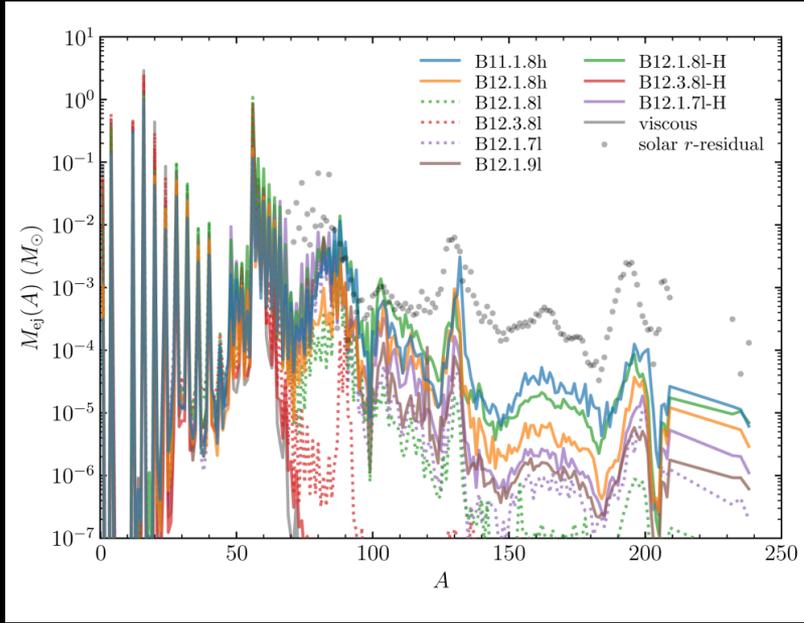
Shibata+ 25
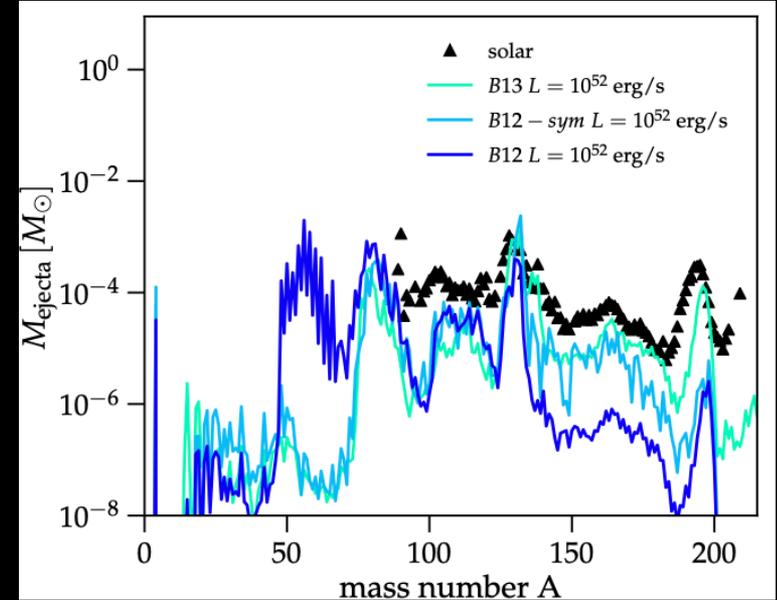
PM+ 18
Halevi, PM+ 18

Collapsar/MHD supernova
hard to distinguish!
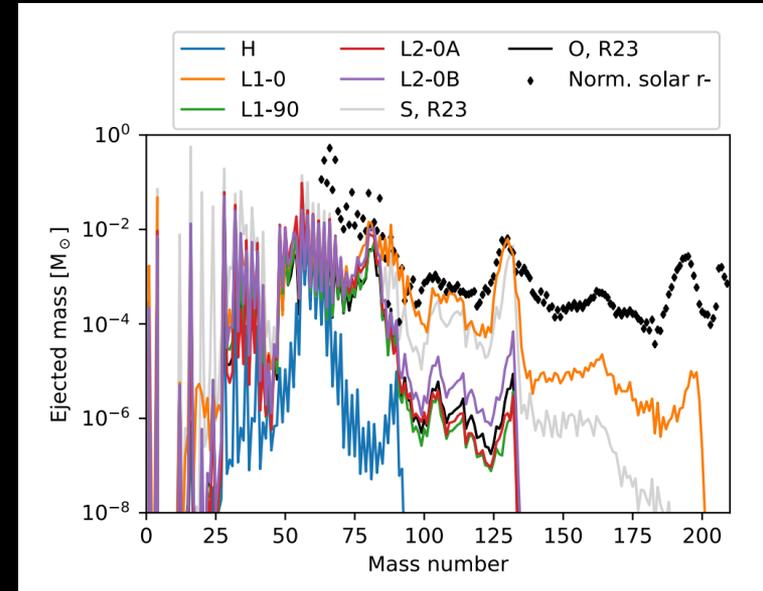
Reichert+ 23

R-process nucleosynthesis in supernovae

PM, Roberts, Halevi+ 18
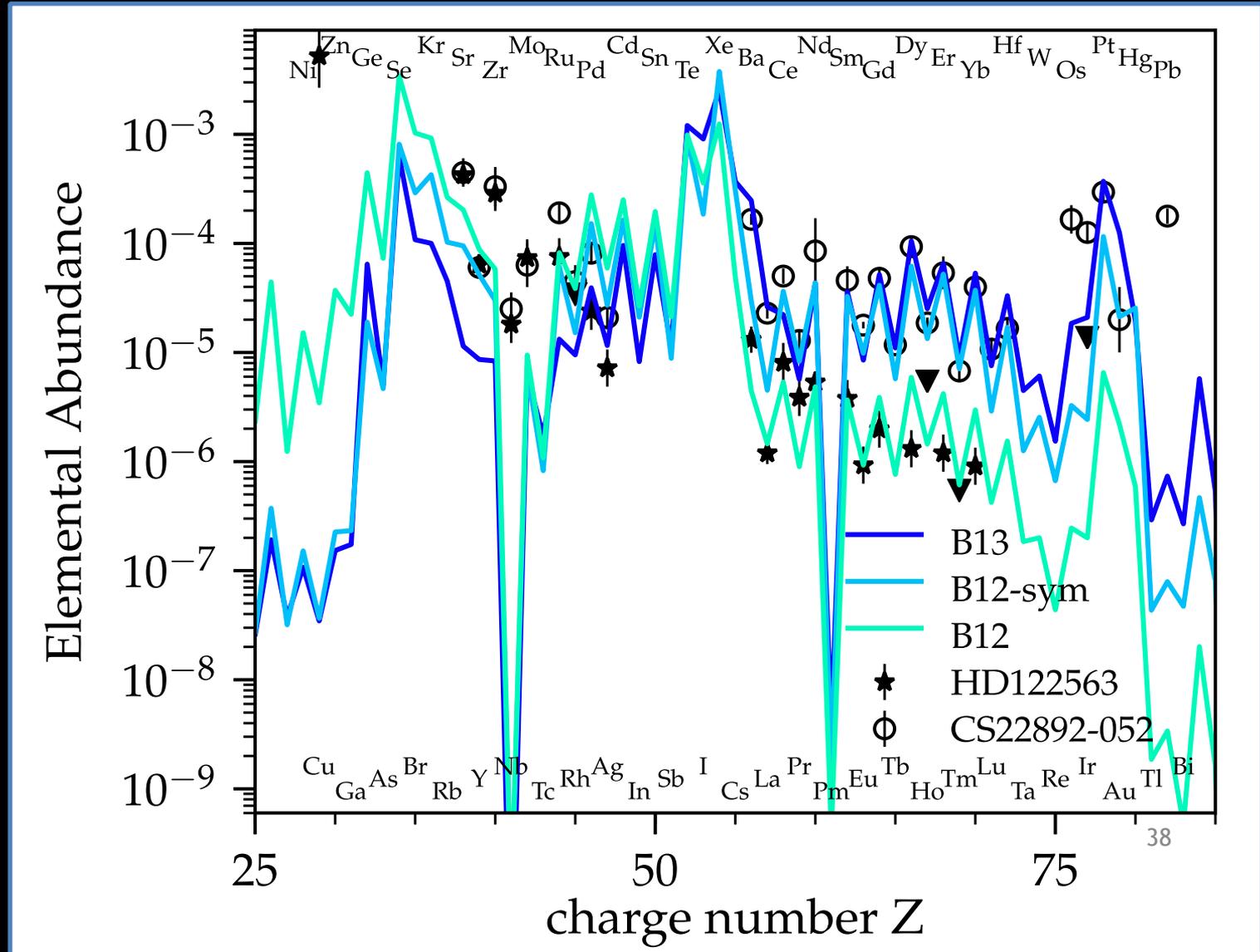
Gravitational-wave signatures

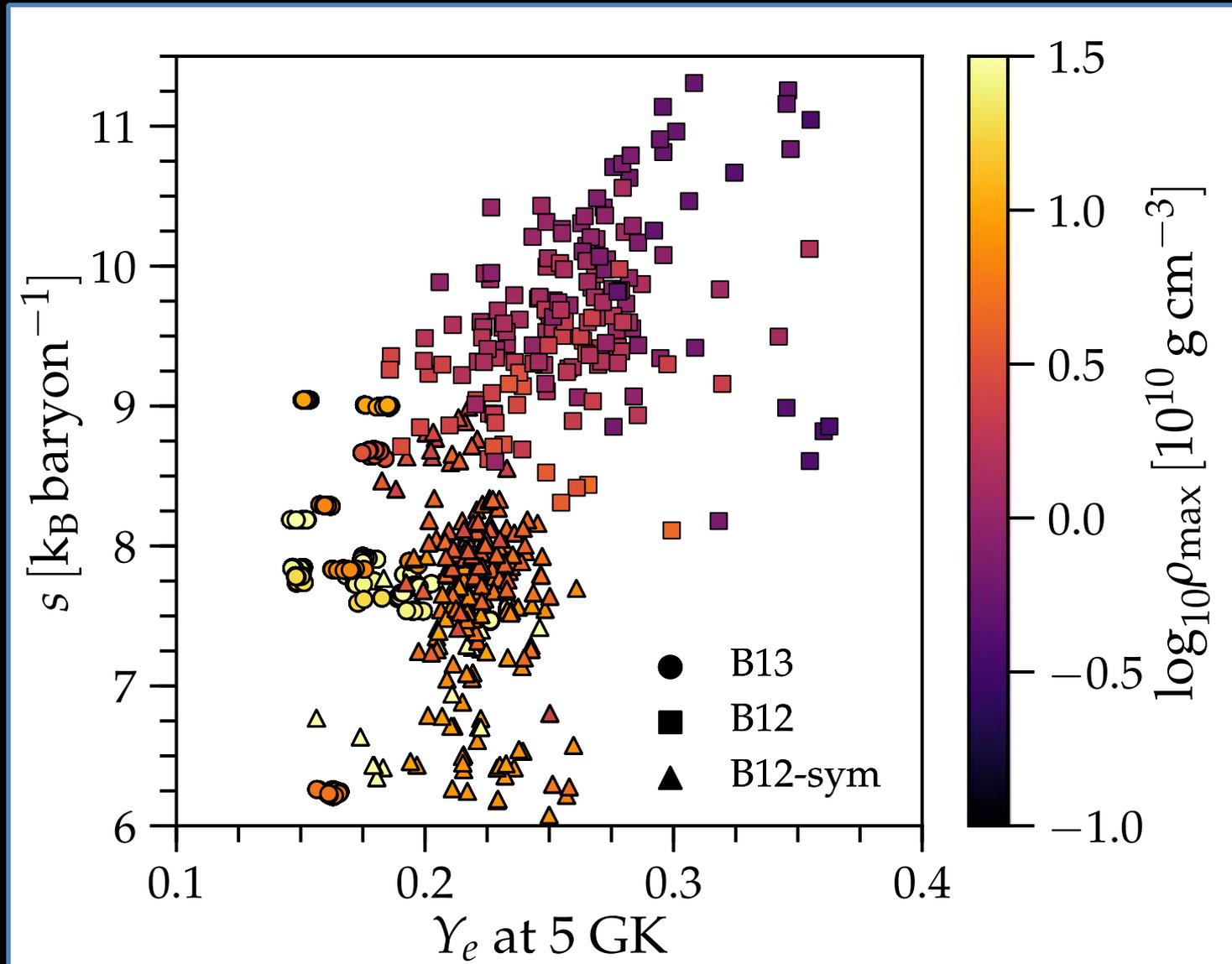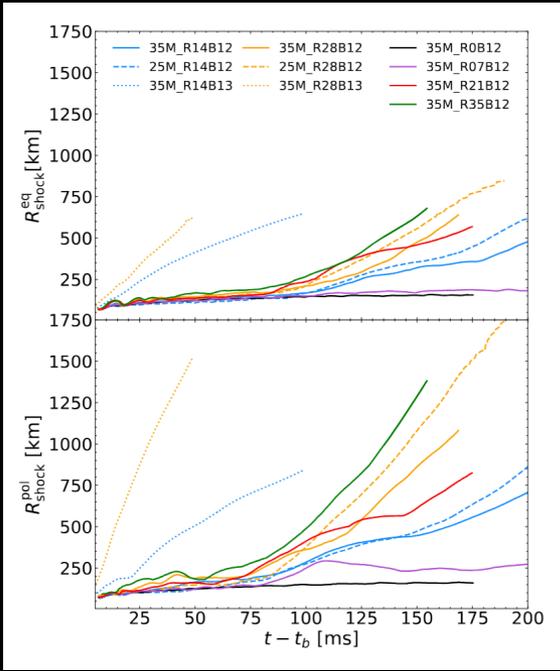| Model	Ω_0 [rad s^{-1}]	B_0 [10^{12} G]	M_{ZAMS} [$M_\odot$]	t_{pb} [ms]	t_b [ms]	P_{pre}[s]	E_{GW} [$10^{-9}\,M_\odot c^2$]	v_{sh}^{max} [km s^{-1}]	v_{jet}^{avg} [km s^{-1}]
35M_R0B12	0	1	35	175	387.29	-	0.027	5000	-
35M_R07B12	0.7	1	35	200	388.37	8.98	0.142	7800	-
35M_R14B12	1.4	1	35	200	391.58	4.49	1.428	7500	4300
35M_R21B12	2.1	1	35	175	397.00	2.99	6.407	9700	5900
35M_R28B12	2.8	1	35	169	404.73	2.24	15.791	14500	9200
35M_R35B12	3.5	1	35	155	414.93	1.80	21.90	21500	12200
35M_R14B13	1.4	10	35	99	477.19	4.49	4.5054	15000	7800
35M_R28B13	2.8	10	35	50	495.52	2.24	9.65	43200	30300
25M_R14B12	1.4	1	25	200	340.25	4.49	0.557	11500	5800
25M_R28B12	2.8	1	25	190	353.05	2.24	8.294	33000	13800

Schnauck, **PM**+ 25

with Sophia Schnauck

~ 720km

~ 750km
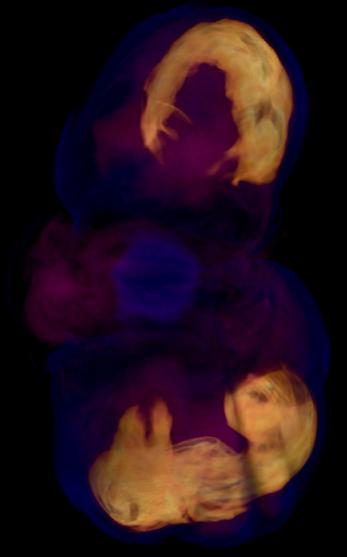
~ 3050km
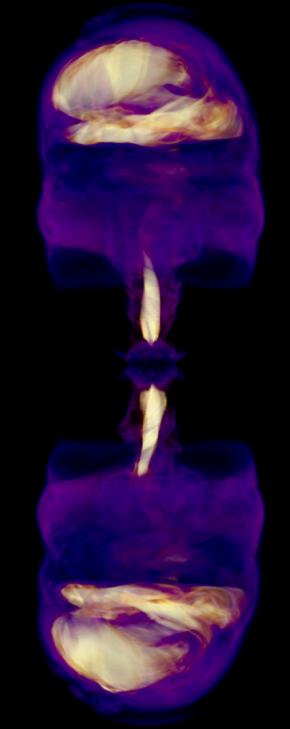
25M_R14B12

35M_R14B12

35M_R14B13

Gravitational-wave signatures
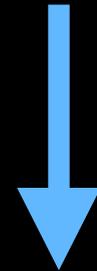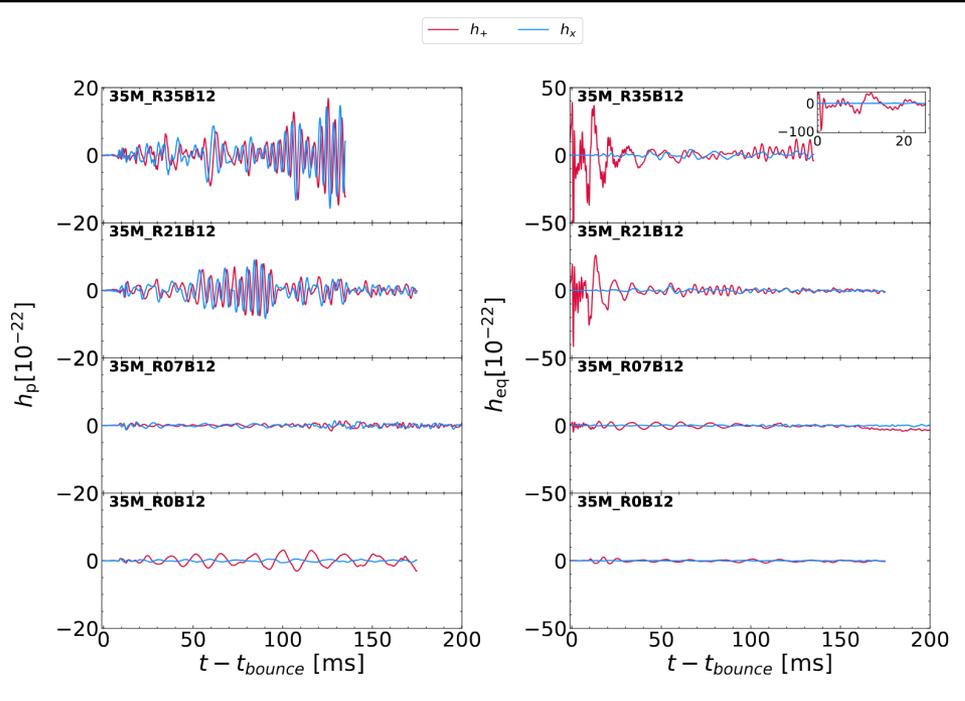
Rotation rate

Schnauck, **PM**+ 25

with Sophia Schnauck

Gravitational-wave signatures

Schnauck, **PM**+ 25

Rotation rate
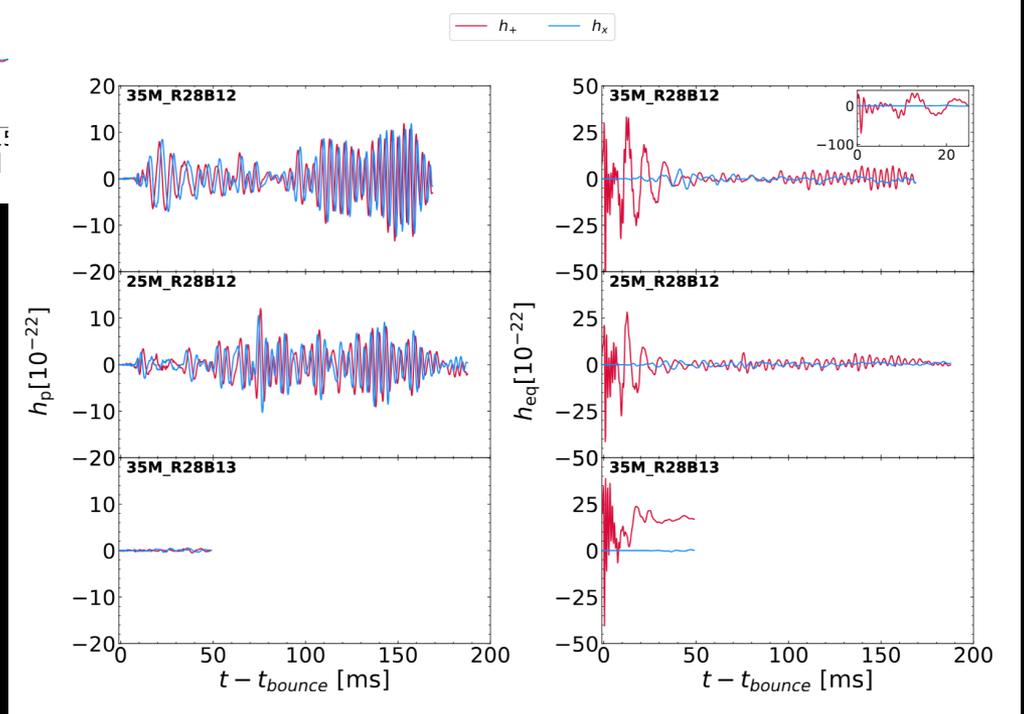
Progenitor

with Sophia Schnauck

Gravitational-wave signatures

- MHD-powered explosions promising gravitational-wave source for 3rd generation detectors

- but distance we can expect them at???

- Need to massively upgrade our understanding of systematics for rotating/MHD explosions

- first steps towards this

with Sophia Schnauck
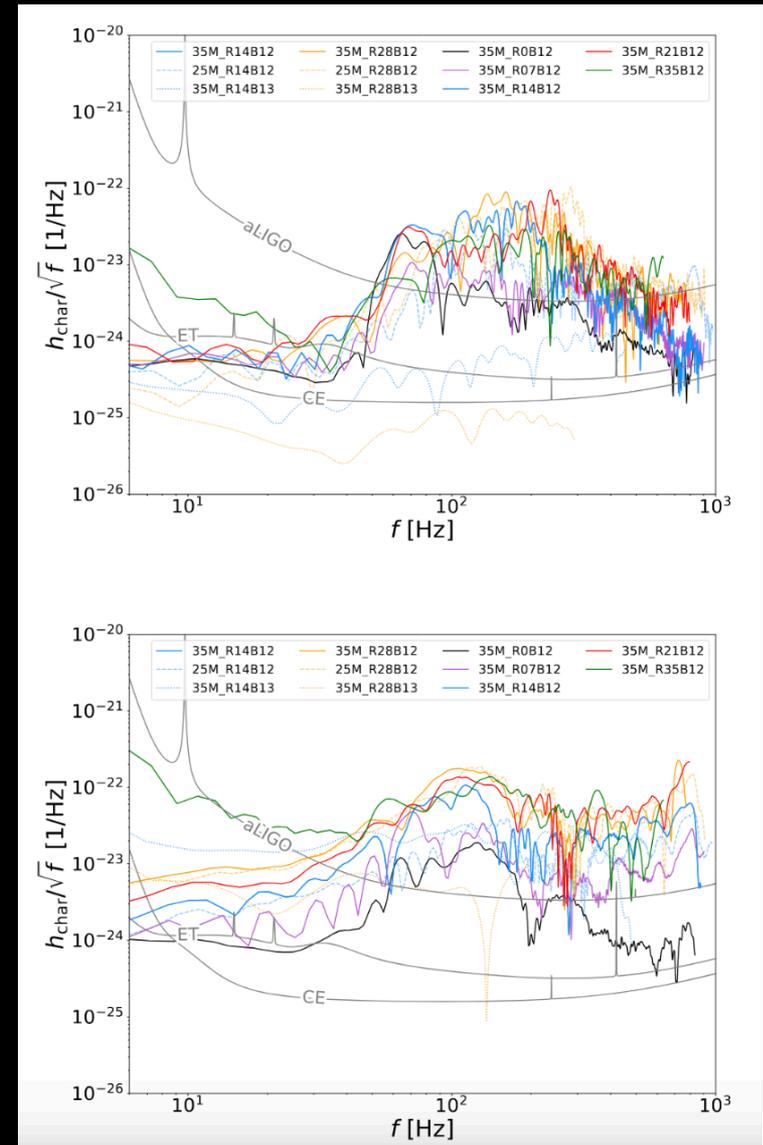
Schnauck, **PM**+ 25

Neutrino signals from MHD-supernovae
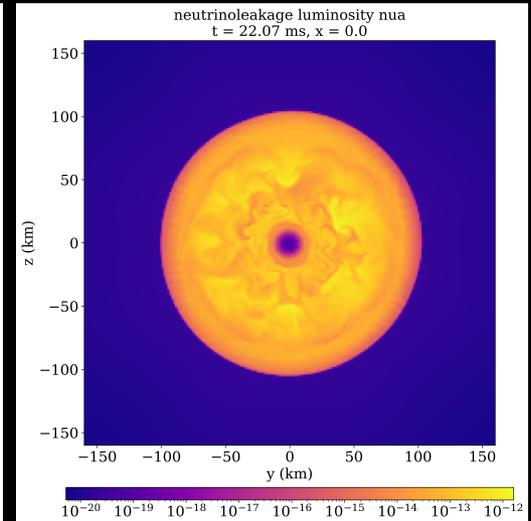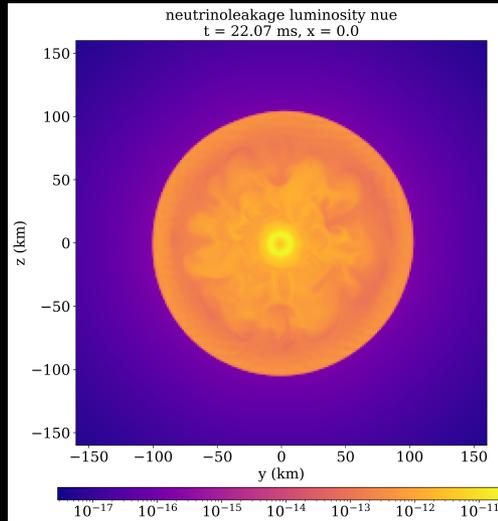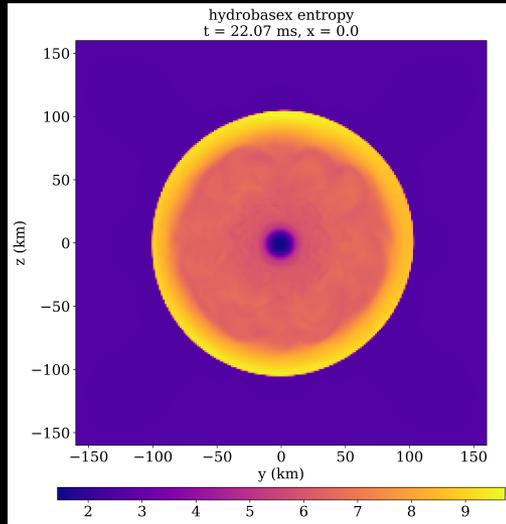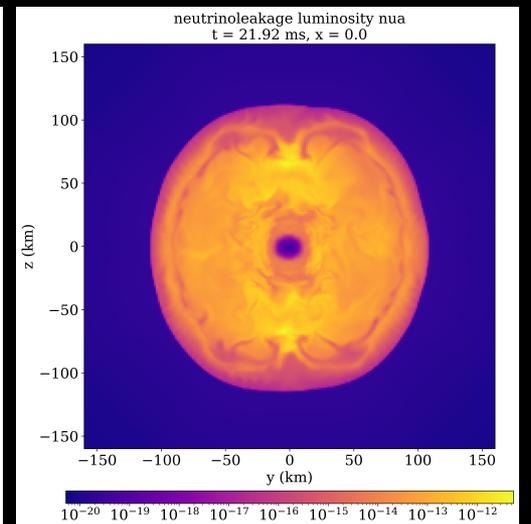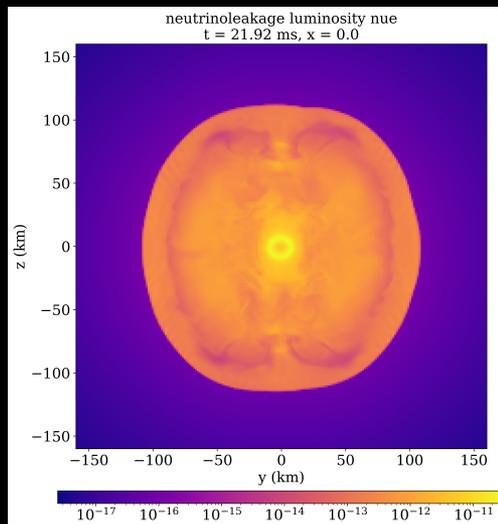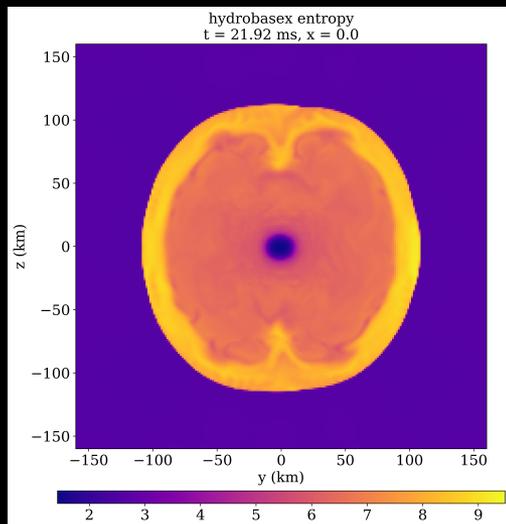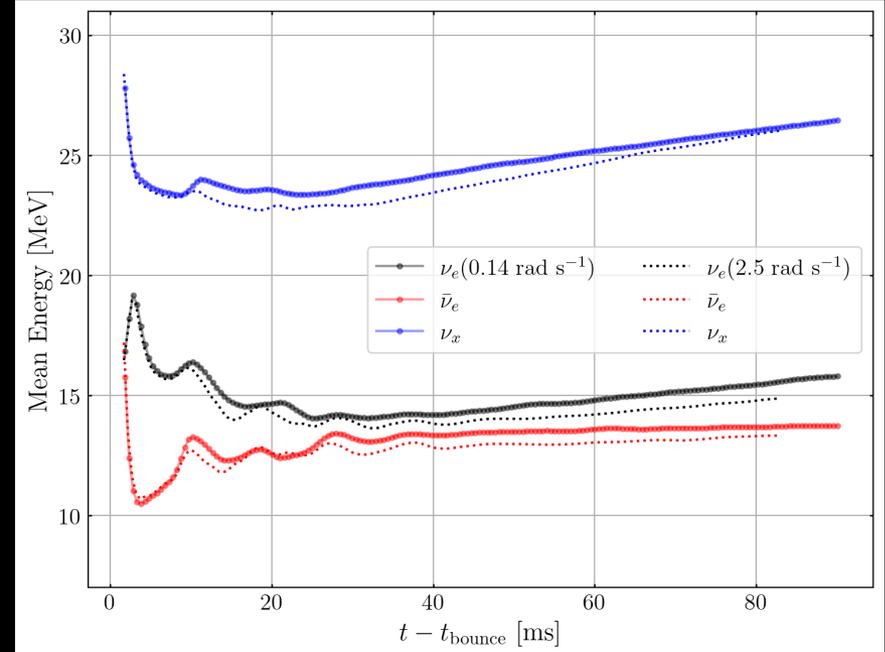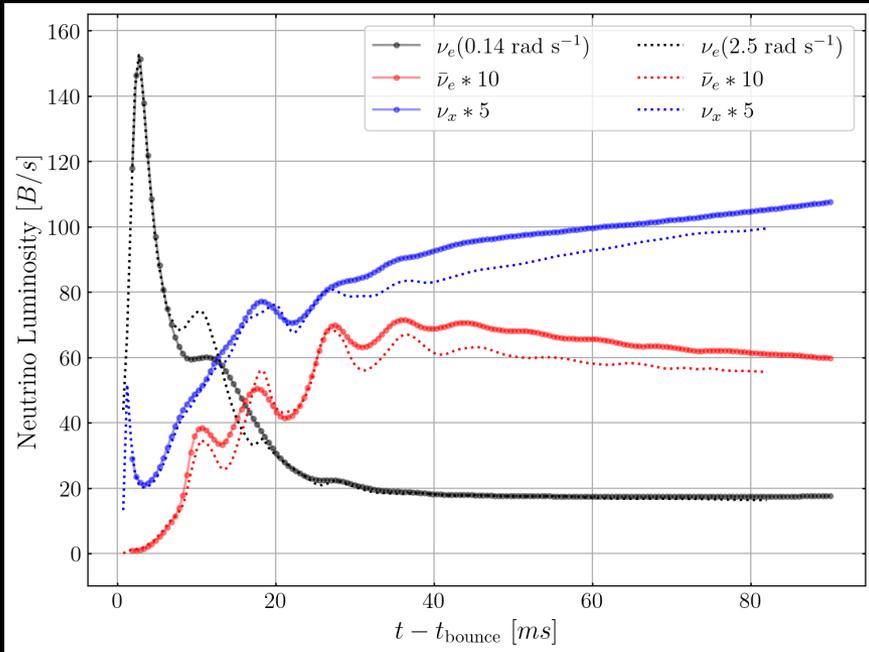
with Pravita Hallur

Simulating Detector Response

with Pravita Hallur

Simulating Detector Response

SNEWPY generated inverse beta decay counts in IceCube for different rotation

$$N_{\text{events}}(t_i) = N_{\text{targets}} \int_{E_{\text{min}}}^{E_{\text{max}}} \Phi_\nu(E, t_i)\, \sigma(E)\, dE$$
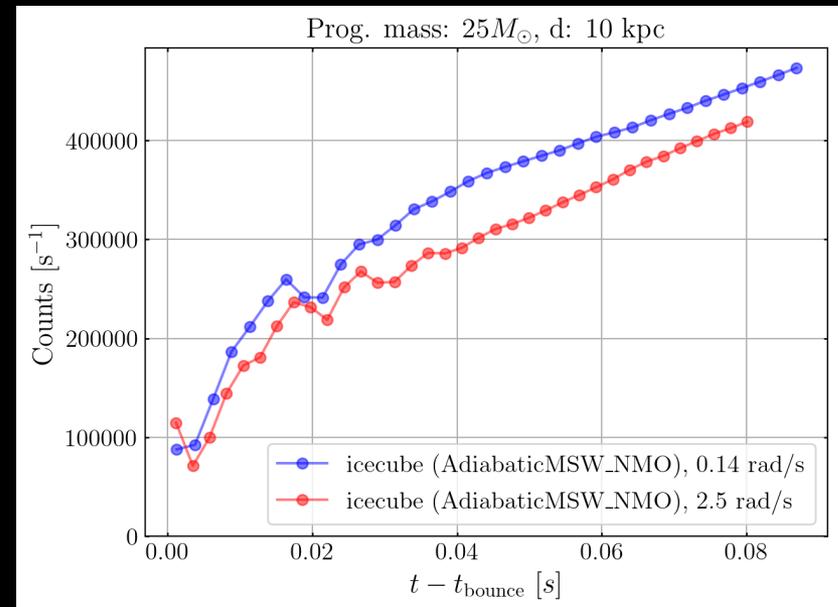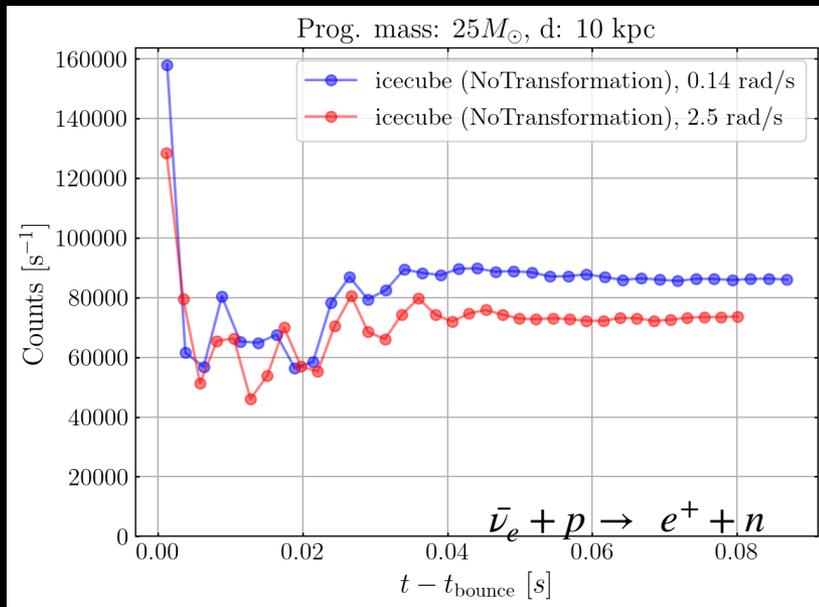
Prog. mass: $25 M_\odot$, d: 10 kpc

- icecube (NoTransformation), 0.14 rad/s
- icecube (NoTransformation), 2.5 rad/s

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

Counts [s^{-1}]

$t - t_{\text{bounce}}$ [s]

Prog. mass: $25 M_\odot$, d: 10 kpc

- icecube (AdiabaticMSW_NMO), 0.14 rad/s
- icecube (AdiabaticMSW_NMO), 2.5 rad/s

Counts [s^{-1}]

$t - t_{\text{bounce}}$ [s]

with Pravita Hallur

SNEWPY: Baxter et al. 2022

Simulating Detector Response

SNEWPY generated inverse beta decay counts in Juno for different rotation speeds

$$N_{events}(t_i) = N_{targets} \int_{E_{min}}^{E_{max}} \Phi_\nu(E, t_i)\, \sigma(E)\, dE$$

Prog. mass: $25 M_\odot$, d: 10 kpc

$$\nu_e + Ar^{40} \rightarrow e^- + K^{*40}$$

ar40kt (NoTransformation), 0.14 rad/s
ar40kt (NoTransformation), 2.5 rad/s

Prog. mass: $25 M_\odot$, d: 10 kpc

ar40kt (AdiabaticMSW_NMO), 0.14 rad/s
ar40kt (AdiabaticMSW_NMO), 2.5 rad/s

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with Pravita Hallur

SNEWPY: Baxter et al. 2022
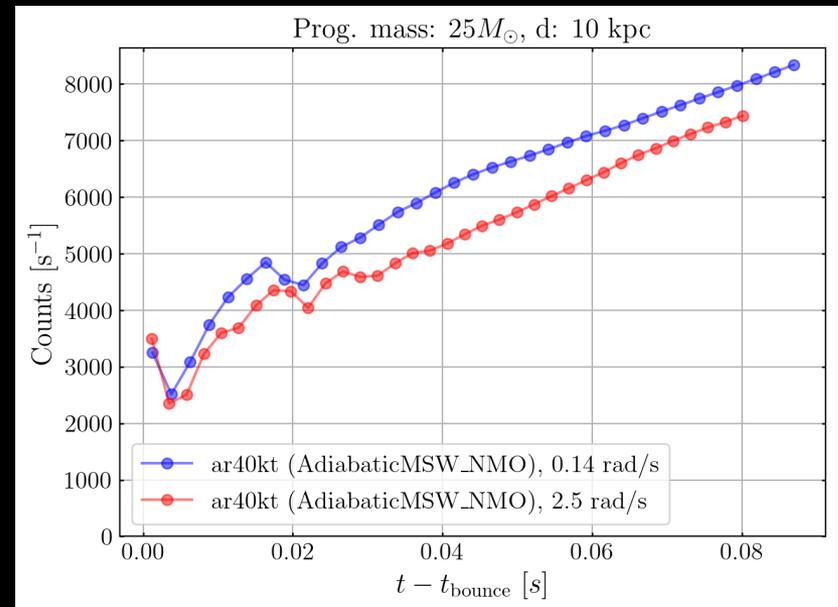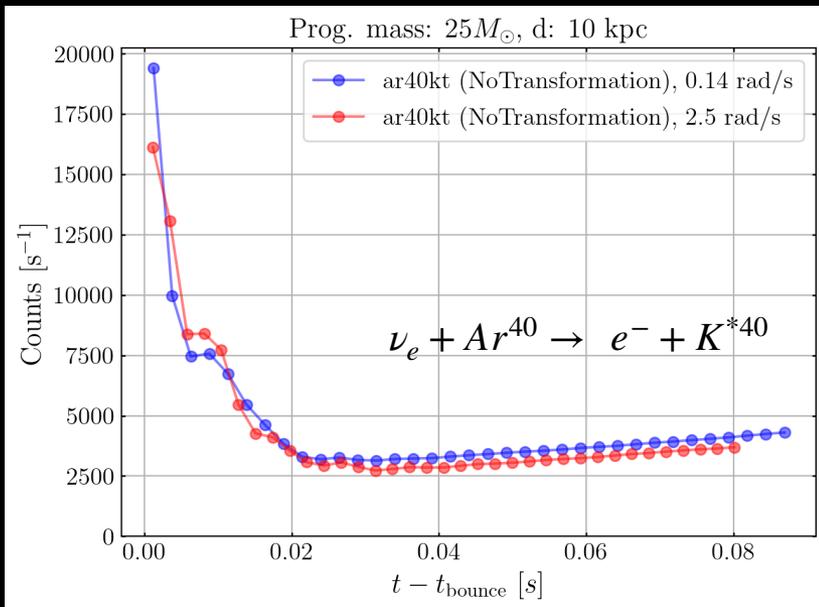
How do we make black holes?

- Most collapsar simulations require shallow density profiles for long GRB compatible jets

- But do we form these consistently in stellar collapse
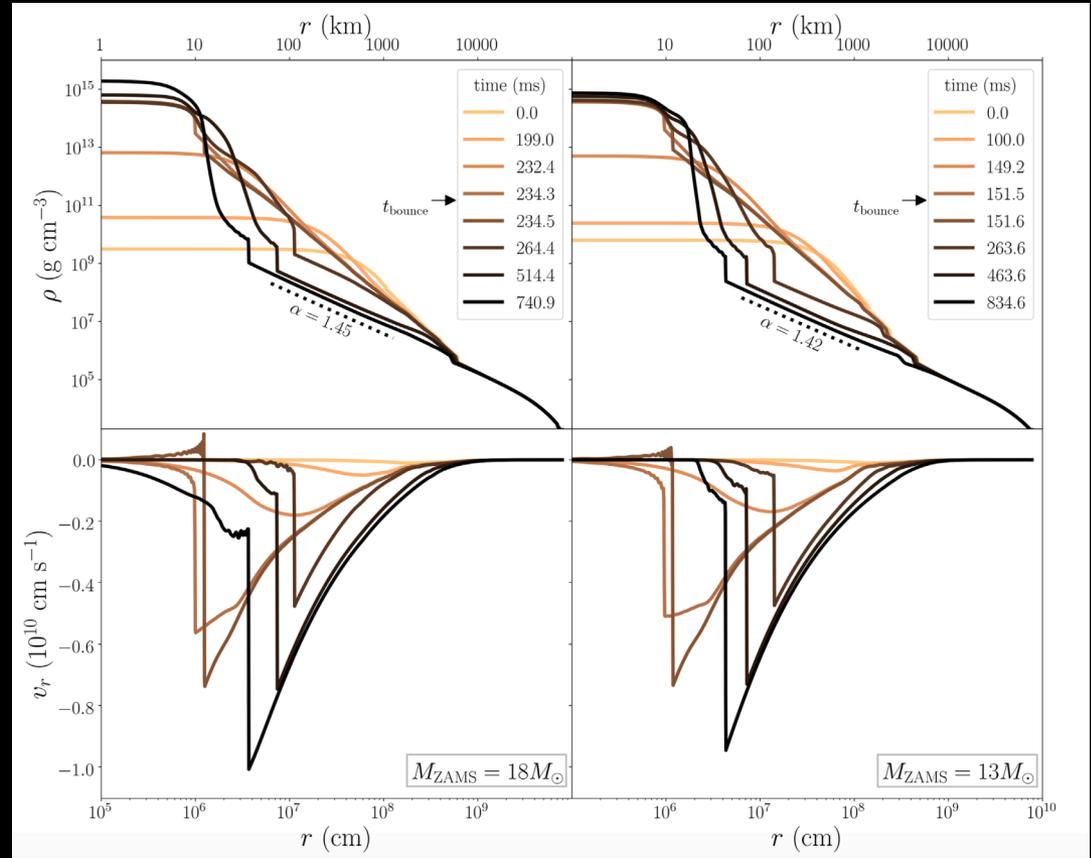
Halevi, Wu, **PM**+ 23

with Goni Halevi

All the way to black-hole formation
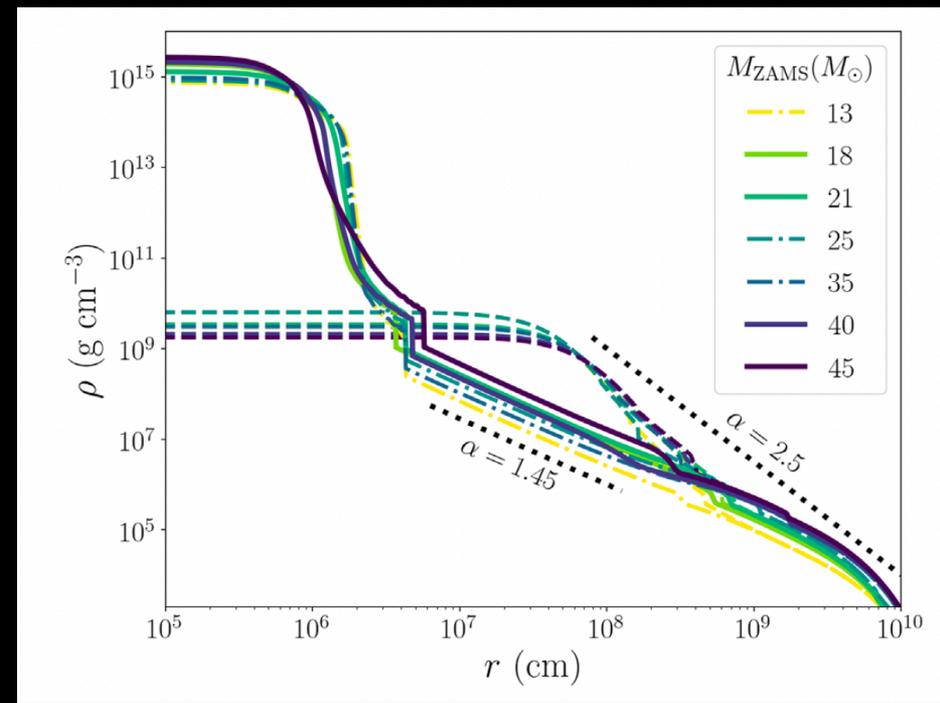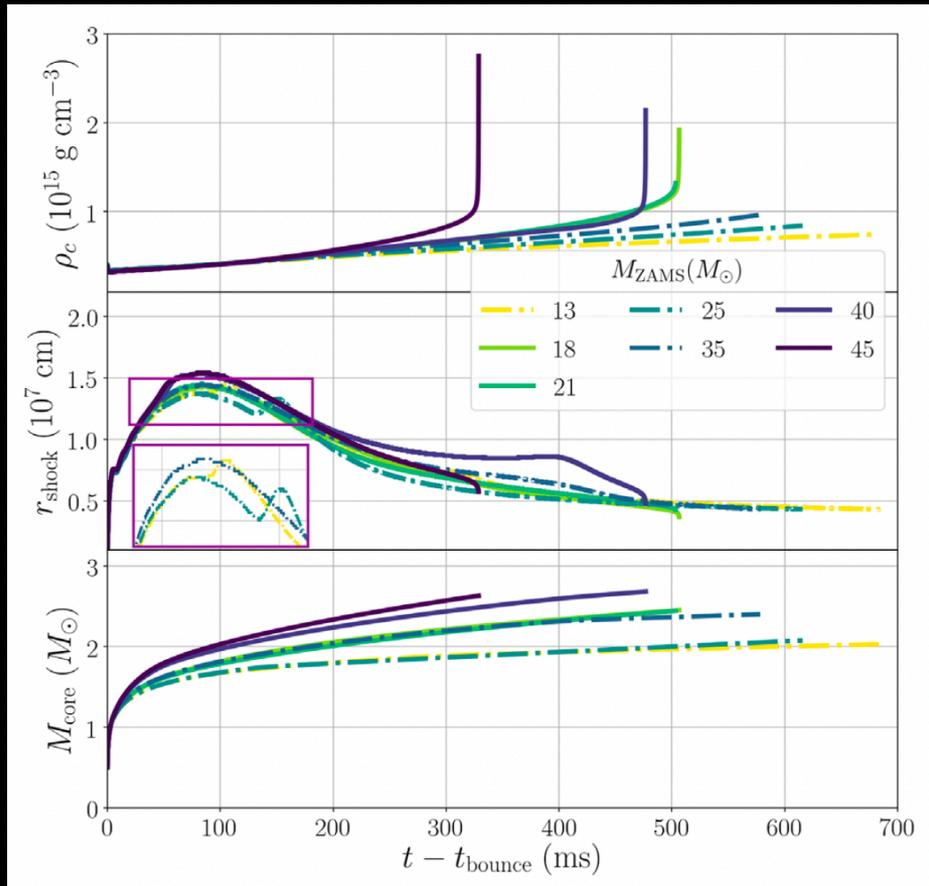
Halevi, Wu, **PM+ 23**

Simulations in 1.5d shows that these progenitors are favorable for lGRBs under the collapsar model

with Goni Halevi

Black-hole formation in 3D

$t - t_b = 1.9$ ms

Specific Entropy [k_B/baryon]

Halevi, Shankar, **PM**+ 25
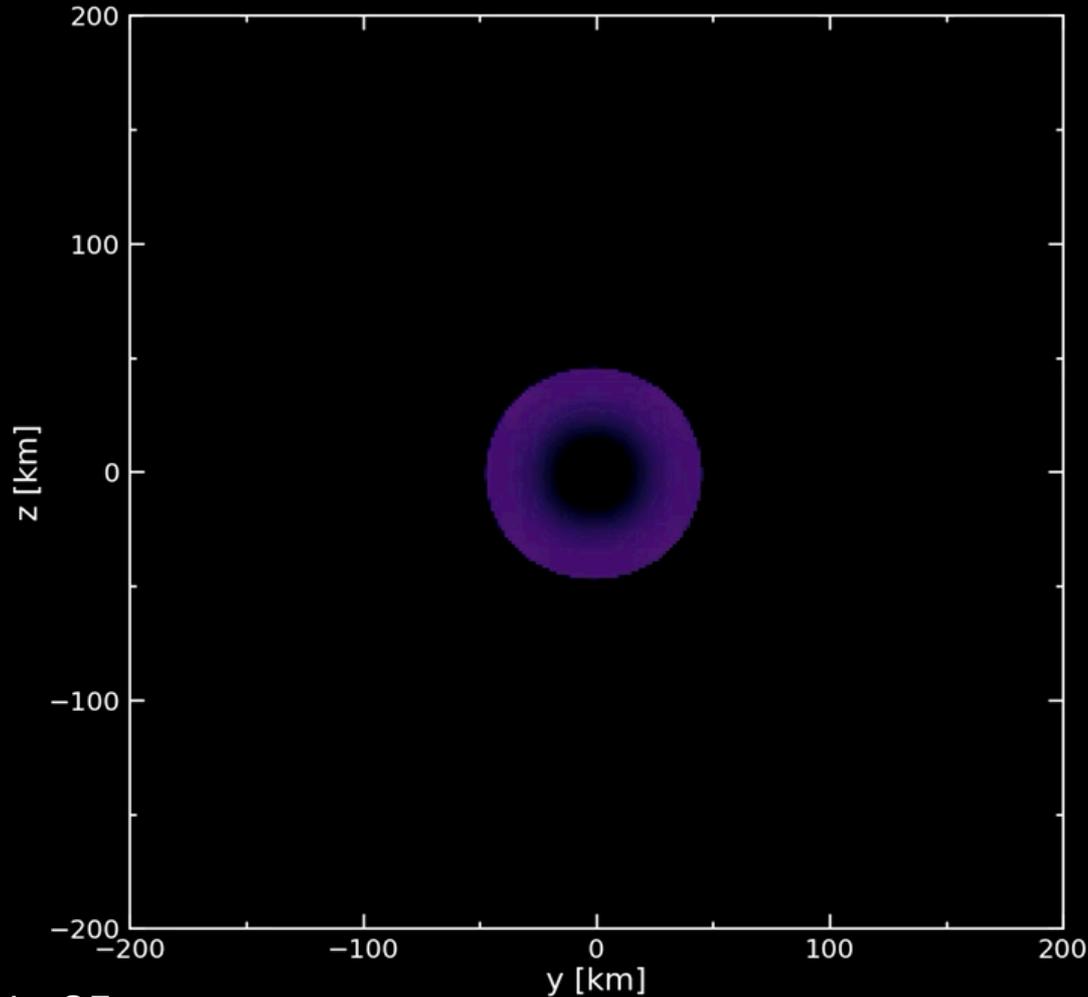
Black-hole formation in 3D
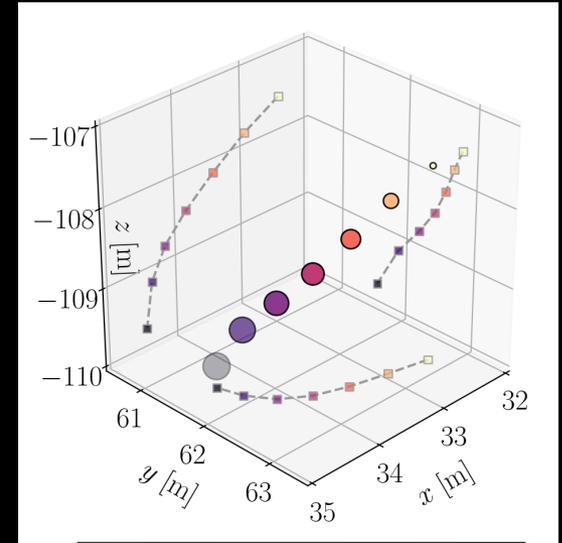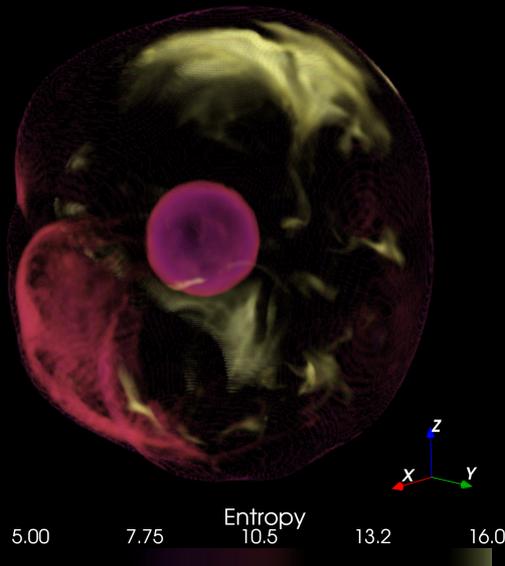
Halevi, Shankar, **PM**+ 25

with Goni Halevi and Swapnil Shankar
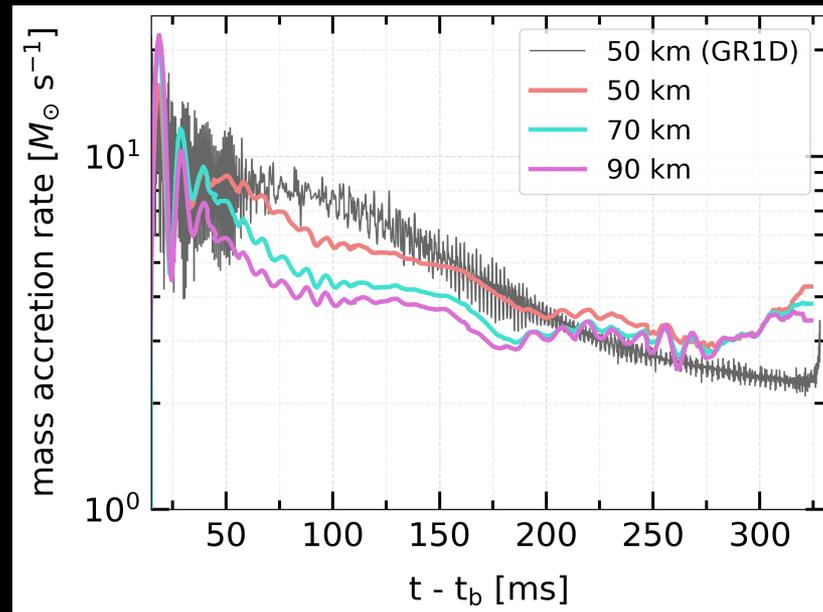
Collapsar formation implications?
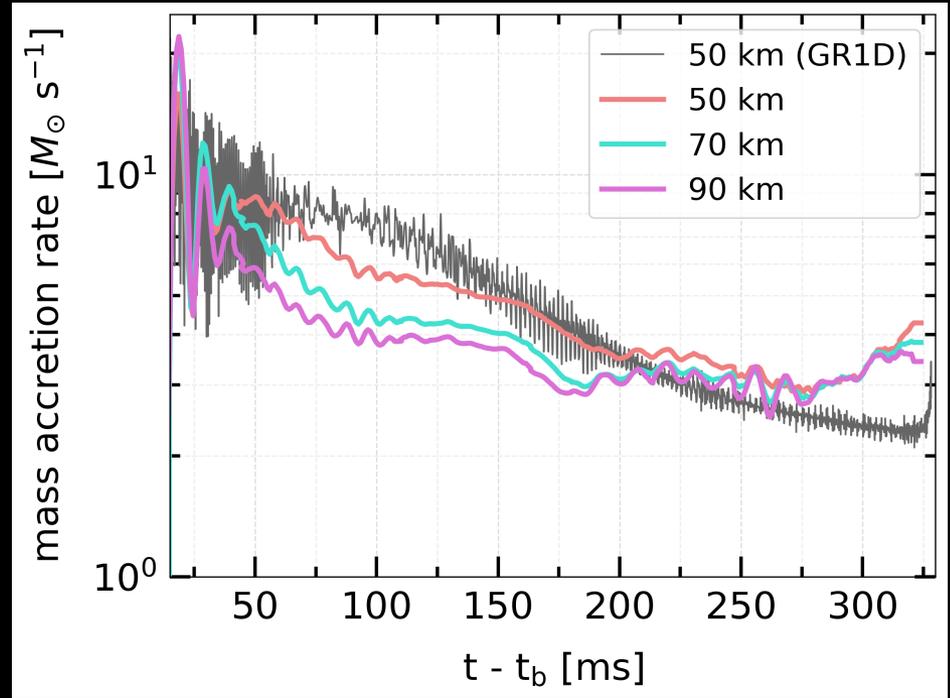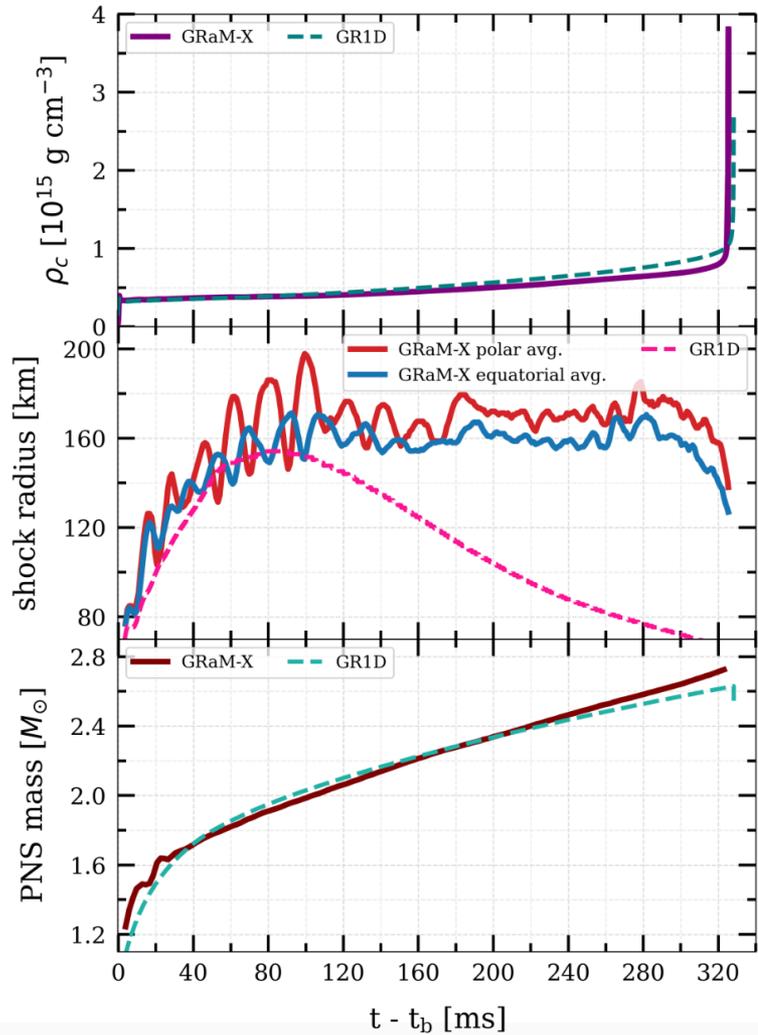
High accretion rates, currently analyzing angular momentum profile for faster-rotating progenitors -> collapsar formation?

Halevi, Shankar, **PM**+ 25

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From simulations to observations

Observations:

- new transients classes and subclasses
- need detailed predictions to constrain engines

Simulations

- 3D simulations open up diverse outcomes
- magnetic fields crucial component for signatures

Need mapping:

progenitor -> engine -> observations

From simulations to observations

State of the art now:

Detailed simulations
full physics
~1s
~10000km

engine formation/dynamics
gravitational waves
nucleosynthesis

From simulations to observations

State of the art now:

Detailed simulations
full physics
~1s
~10000km

From simulations to observations

State of the art now:

Detailed simulations
full physics
~1s
~10000km

Current frontier:

1) engine model from
full-physics simulations
2) simplified simulations
with engine model to
shock breakout

explosion geometry
explosion energy
nucleosynthesis
basic engine model

with Swapnil Shankar

From simulations to observations

State of the art now:

Detailed simulations
full physics
~1s
~10000km

Current frontier:

1) Engine model from
full-physics simulations
2) Simplified simulations
with engine model to
shock breakout

with Swapnil Shankar

Full star

Full 3D, full physics
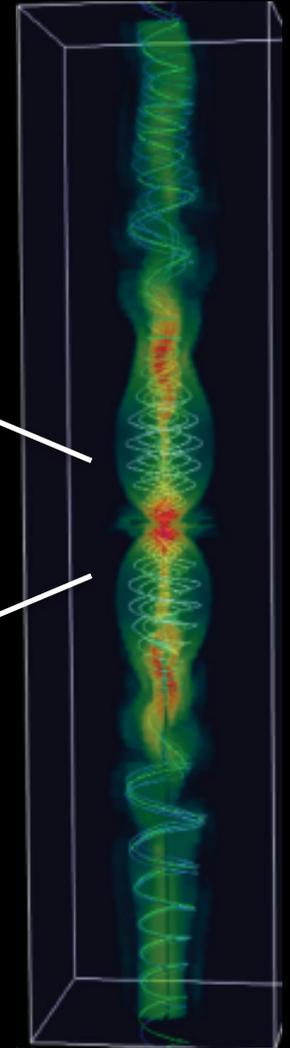
Shankar, **PM+** 21

From simulations to observations

Current frontier:

Shankar, **PM+** 21

From simulations to observations

Simplified simulations with engine model
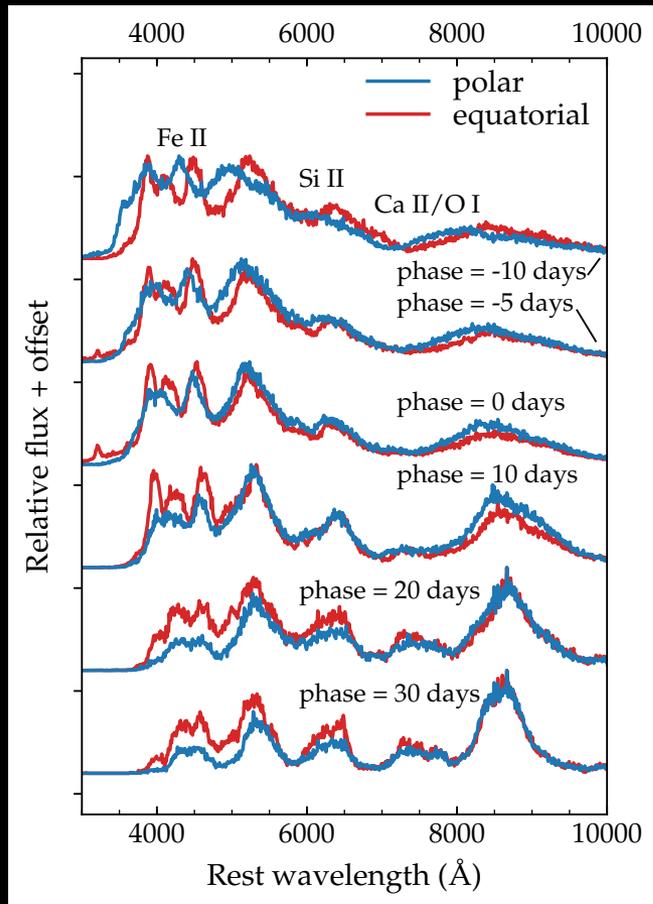
Barnes+ **18**

Engine model from full 3D simulation
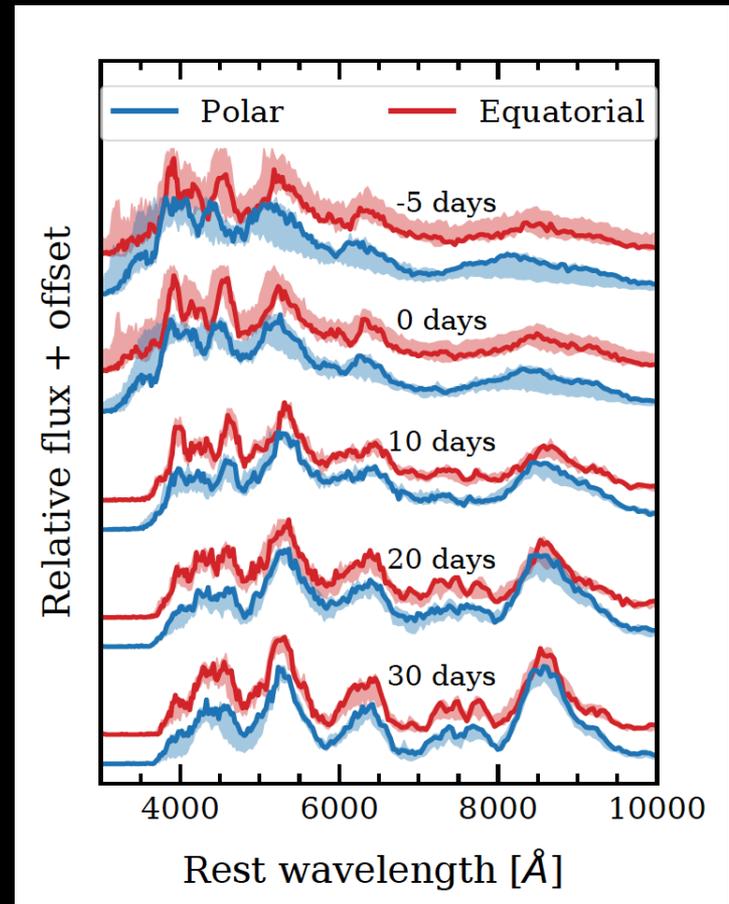
Shankar, **PM**+ 21

From simulations to observations
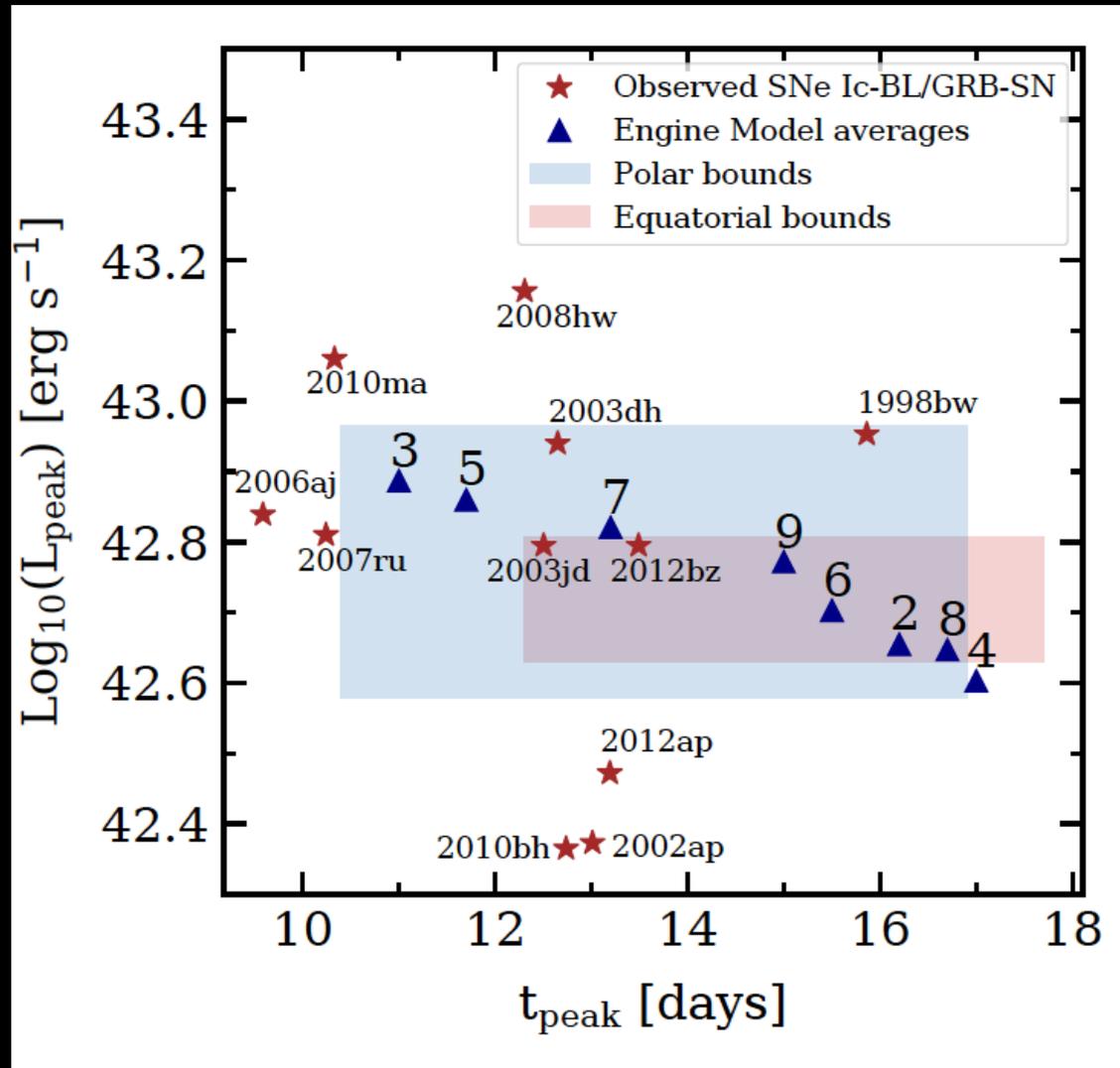
Shankar, **PM**+ 21

Summary

We are building a catalog of 3D GRMHD-supernova simulations - stayed tuned for M1

Black-hole formation in 3D GRMHD now possible

Need to really connect these models better to lightcurves/specta

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Mapping
progenitor -> engine -> observations

UC SANTA BARBARA
Kavli Institute for Theoretical Physics

HOME   DIRECTORY   ACTIVITIES   PROPOSE ACTIVITY   APPLY   FOR VISITORS   ONLINE TALKS   OUTREACH

Enigmatic Explosions: Observations, Modelling, and Microphysics of Extreme Transients

Coordinators: Francois Foucart, Raffaella Margutti, Philipp Moesta, and Rebecca Surman

The detection of bright electromagnetic (EM) transients powered by neutron star mergers, supernovae, and other extreme astrophysical events associated with compact objects will play a major role in nuclear astrophysics in the coming years. These events act as cosmic laboratories allowing us to study the properties of high-density matter and the origin of heavy ele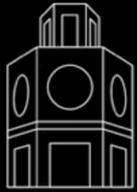ments. Transients may even reveal particle physics beyond the standard model in conditions that we cannot probe on Earth. The rapidly growing number and variety of observed EM transients now regularly challenge our incomplete theoretical understanding of the transient sky. These limitations inhibit our ability to leverage transient observations for high-energy and nuclear astrophysics. Despite significant improvements to the numerical accuracy and microphysics of numerical simulations, the impact of nuclear physics inputs, approximate physical modeling, and the large range in spatial scales and timescales that need to be resolved remain major issues. This program will address these issues with an interdisciplinary group of nuclear, theoretical, computational physicists and astronomers as we prepare for a new era of EM discovery and anticipated experiments on exotic nuclei.
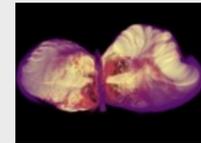
DATES

Oct 26, 2026 - Dec 18, 2026

INFORMATION

Apply

Application deadline is: Oct 24, 2025. Primary deadline above date.

Rolling admissions after until the program is filled.

ECT* workshop in September

21-25 **The Interplay of Magnetic Fields, Nuclear Physics, and Nucleosynthesis in Neutron-Star Mergers and Supernovae**
P. Mösta, A. Arcones, S. Curtis, E. O'Connor