RAGtime 28 · Opava · November 2026

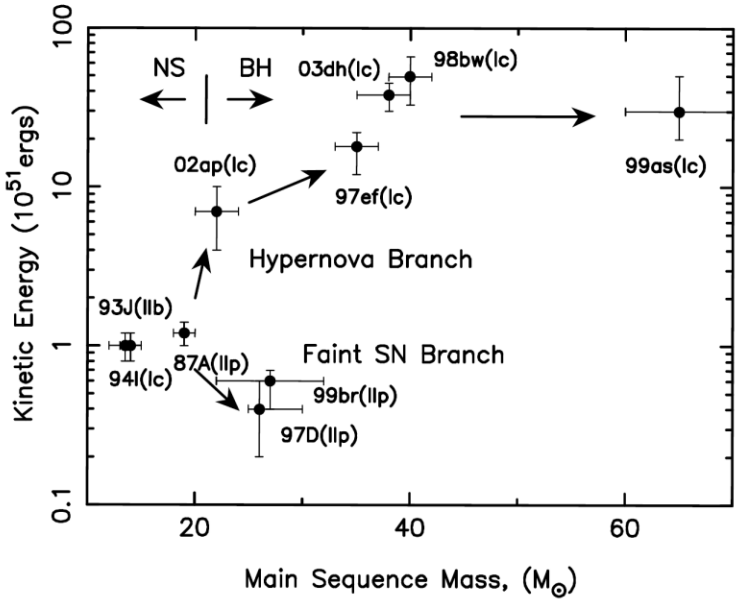
3D GRMHD Simulations of Magnetorotational Supernovae: Dynamics, Gravitational Waves, and Nucleosynthetic Implications

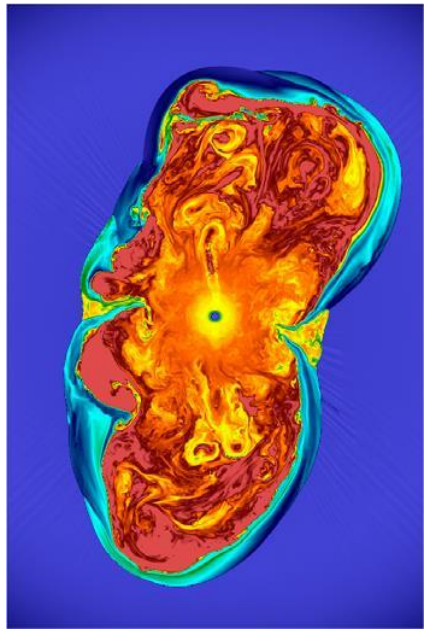
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MHD jets may power energetic SNe





Left: observed SNe · Right: 3D GRMHD, jet disrupted by a kink instability

1 · Energetic explosions

Hypernovae reach ~ 10^{52} erg; jets can tap rotational energy

2 · Signals from the core

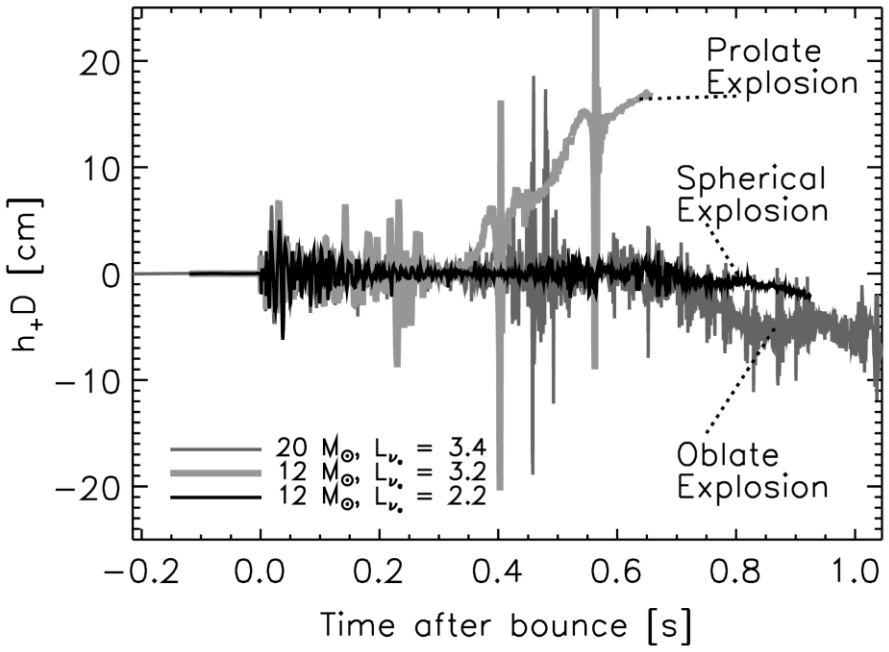
Rotation and jets imprint GWs and neutrinos

3 · Heavy elements

Neutron-rich jets: a candidate heavy r-process site

Nomoto+ 2005; Mösta+ 2014

Jets and neutrino emission both leave a GW memory



2D ν-driven explosions: prolate → $h_+ > 0$, oblate → $h_+ < 0$

Matter

Jets make the amplitude grow monotonically

Neutrinos

Anisotropic emission adds up over time:

$$h_\nu^{\mathrm{TT}}(t) = \frac{2G}{c^4 D}\int_{-\infty}^{t-D/c} L_\nu(t')\,\alpha(t')\,dt'$$

α: emission anisotropy · D: distance

Open question: which dominates in a jet-driven explosion?

Murphy+ 2009; Takiwaki & Kotake 2011; Müller & Janka 1997

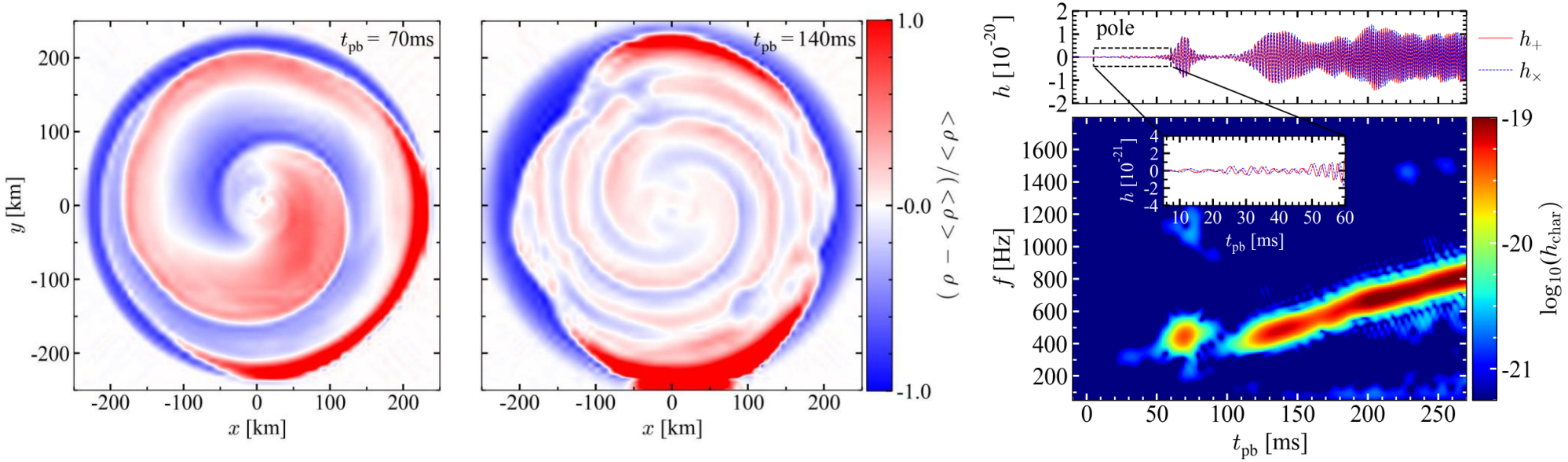
Previous work · 70 M⊙ Pop III, no B-field

Rotation alone: spiral modes emit narrow-band GWs

m = 1 spiral · 70 ms

m = 2 spiral · 140 ms

GW spectrogram · pole



Low-T/|W| instability: a one-armed, then a two-armed spiral emits narrow-band GWs ($f \approx 400 \rightarrow 800$ Hz)

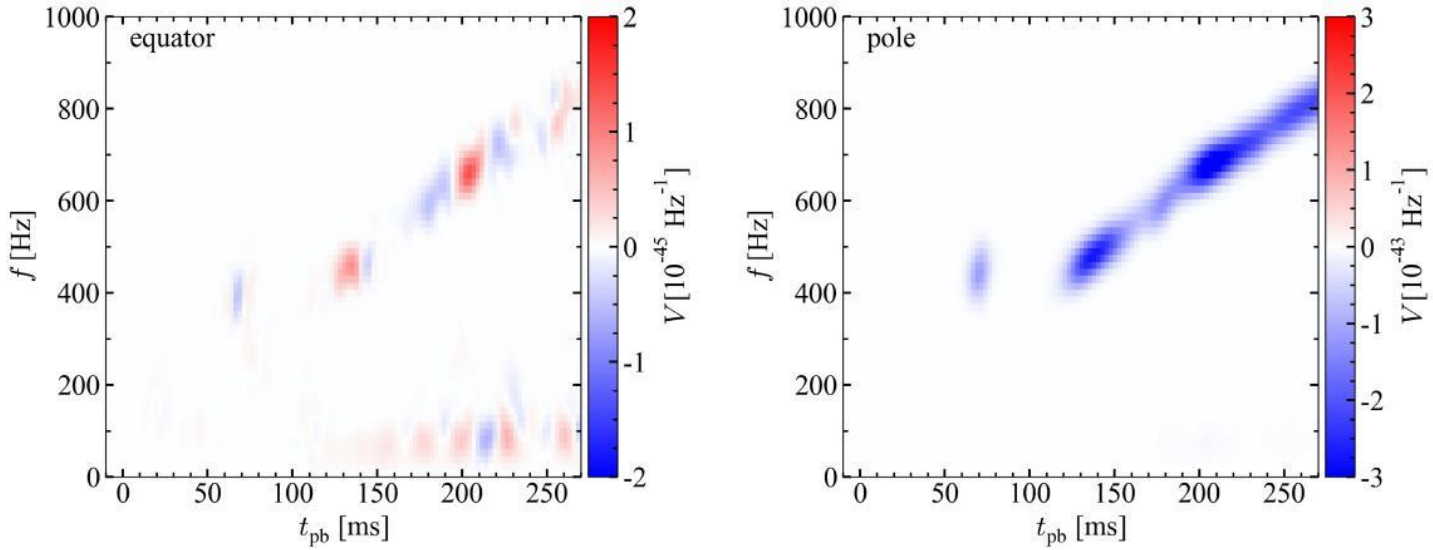
Shibagaki+ 2020, 2021, MNRAS

Previous work · 70 M⊙ Pop III, no B-field

Spiral modes emit circularly polarized GWs toward the pole

$$V \propto |\tilde{h}_{\rm R}|^2 - |\tilde{h}_{\rm L}|^2, \qquad h_{\rm R,L} = (h_+ \mp i\, h_\times)/\sqrt{2}$$

V ≠ 0 when h_+ and $h\times$ are out of phase; its sign gives the handedness

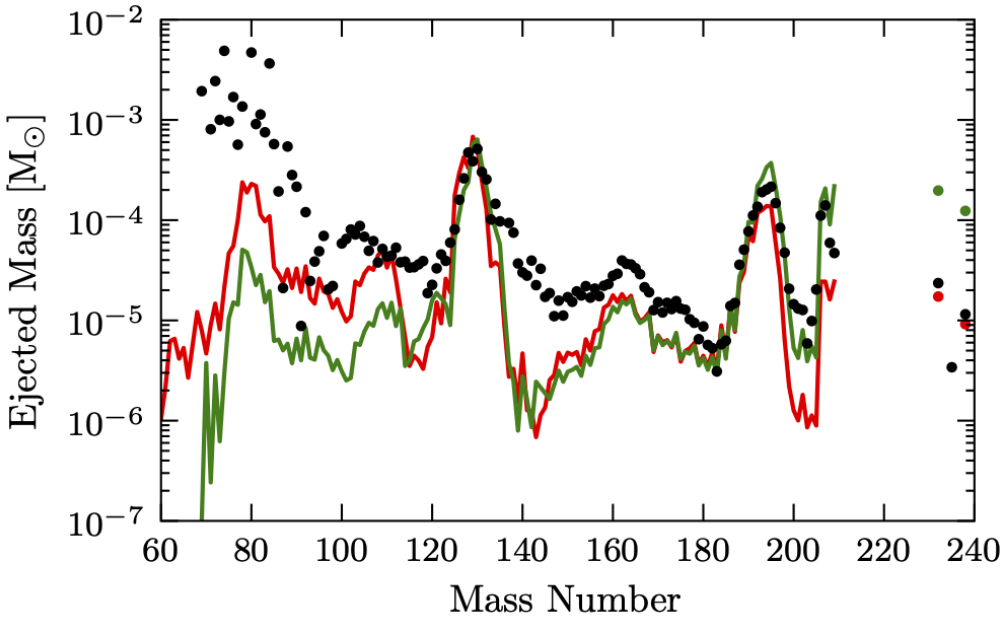


Left: equator (V in 10^{-45} Hz^{-1}) · Right: pole (10^{-43} Hz^{-1})

Open question: does this survive when strong fields launch jets?

Shibagaki+ 2021, MNRAS

MHD jets are a candidate site of the heavy r-process



Winteler+ 2012 (3D MHD): jet ejecta reproduce the 2nd and 3rd r-process peaks (dots: solar)

Heavy r-process needs Ye below ~ 0.22–0.30; fast jets keep Ye low

A possible second site besides NS mergers, especially early on

But 3D models disagree

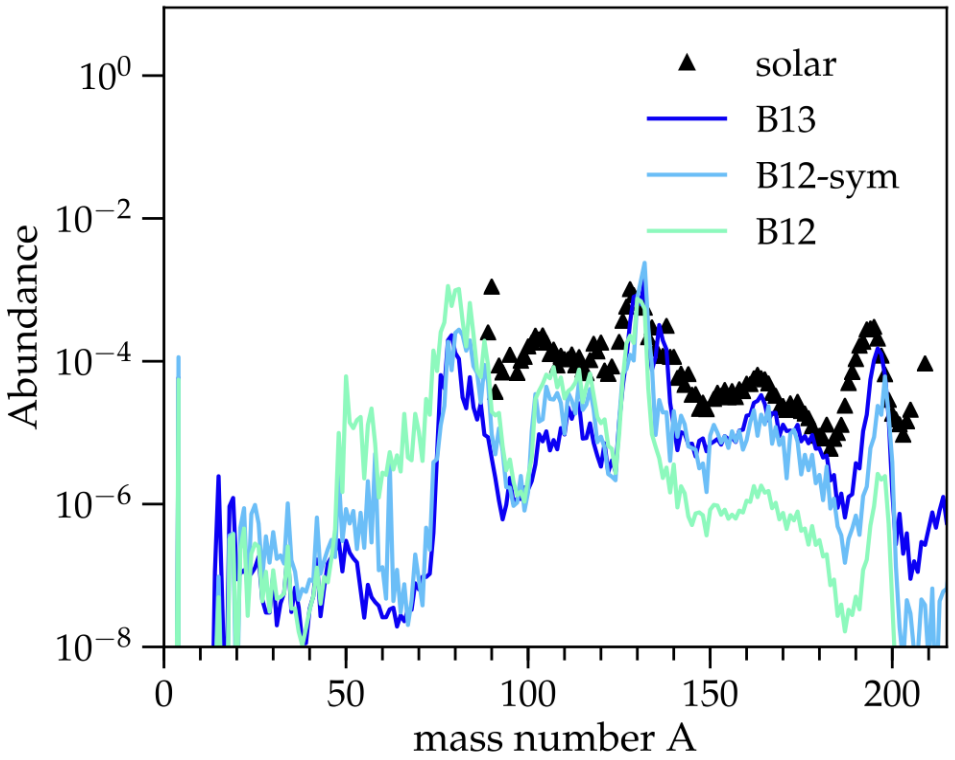
Mösta+ 2018 · 3D GRMHD, ν leakage: kink cuts heavy r-process ~ 100×

Reichert+ 2021, 2023 · approx. GR, spectral M1: heavy r-process only from prompt or late ejecta

Open question: what do full-GR 3D models with spectral ν transport give?

Winteler+ 2012; Mösta+ 2018; Reichert+ 2021, 2023

MHD jets are a candidate site of the heavy r-process



Mösta+2018 (3D GRMHD; B12 model): jet ejecta produce the 2nd r-process peak, but not the 3rd r-process peak (dots: solar)

Heavy r-process needs Ye below ~ 0.22–0.30; fast jets keep Ye low

A possible second site besides NS mergers, especially early on

But 3D models disagree

Mösta+ 2018 · 3D GRMHD, ν leakage: kink cuts heavy r-process ~ 100×

Reichert+ 2021, 2023 · approx. GR, spectral M1: heavy r-process only from prompt or late ejecta

Open question: what do full-GR 3D models with spectral ν transport give?

Winteler+ 2012; Mösta+ 2018; Reichert+ 2021, 2023

Three questions for magnetorotational core collapse

Q1

GW memory

Jets or neutrinos: which dominates the low-frequency GWs?

Q2

Circular polarization

Does rapid rotation still give circularly polarized GWs when jets form?

Q3

r-process

Are the jets neutron-rich enough for the third peak?

Approach 3D GR ν-radiation MHD with energy-dependent M1 transport · model R20B12

Shibagaki+ 2024, MNRAS; Shibagaki+ 2026, A&A

3D GR neutrino-radiation MHD of a magnetized 20 $M_\odot$ core

- Full GR MHD (BSSN) with energy-dependent M1 neutrino transport
- Progenitor s20 (Woosley & Heger 2007); EOS SFHo
- Nested Cartesian grid; finest cell 458 m

Model R20B12

2 rad s^{-1}
initial central rotation, cylindrical (ϖ_0 = 1000 km)

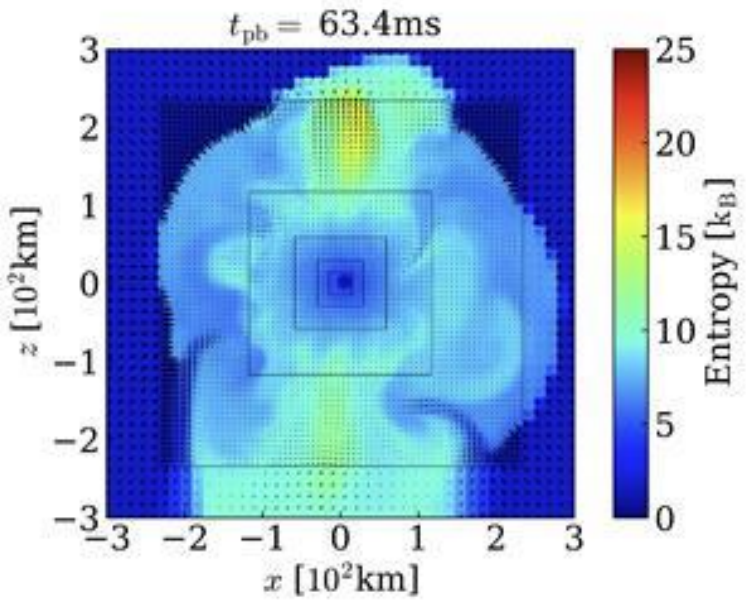
10^{12} G
$B_0/\sqrt{4\pi}$; uniform inside 1000 km, dipolar outside

545 ms
simulated after bounce

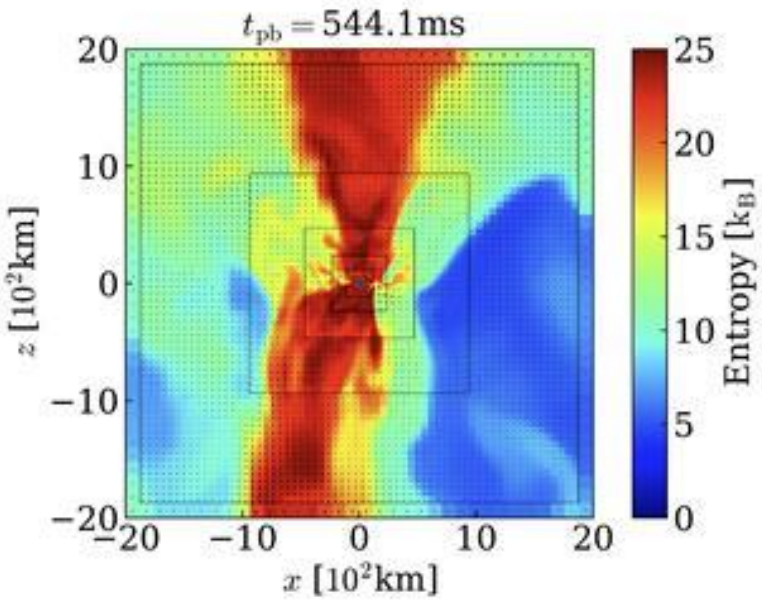
Shibagaki+ 2024, MNRAS; Kuroda+ 2020

R20B12 launches a bipolar MHD outflow

63 ms · inner ± 300 km



544 ms · inner ± 2000 km

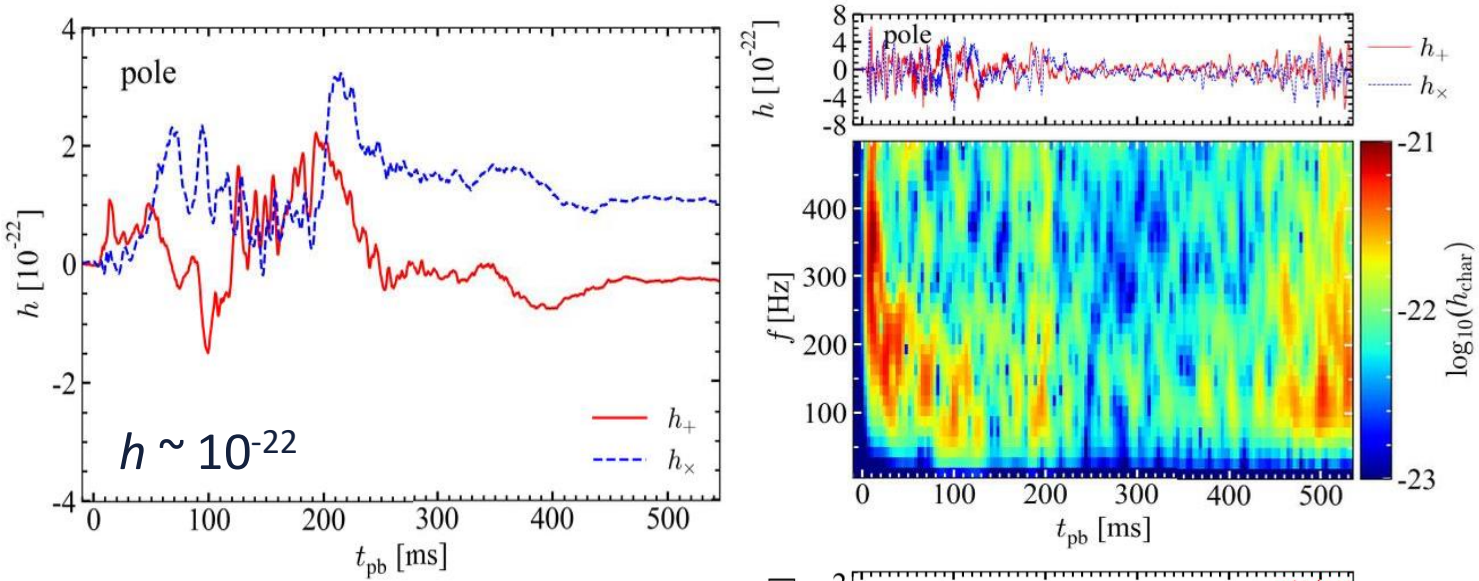


Entropy in the x–z plane (z = rotation axis): high-entropy matter flows out along the axis

Gravitational waves @ 10kpc

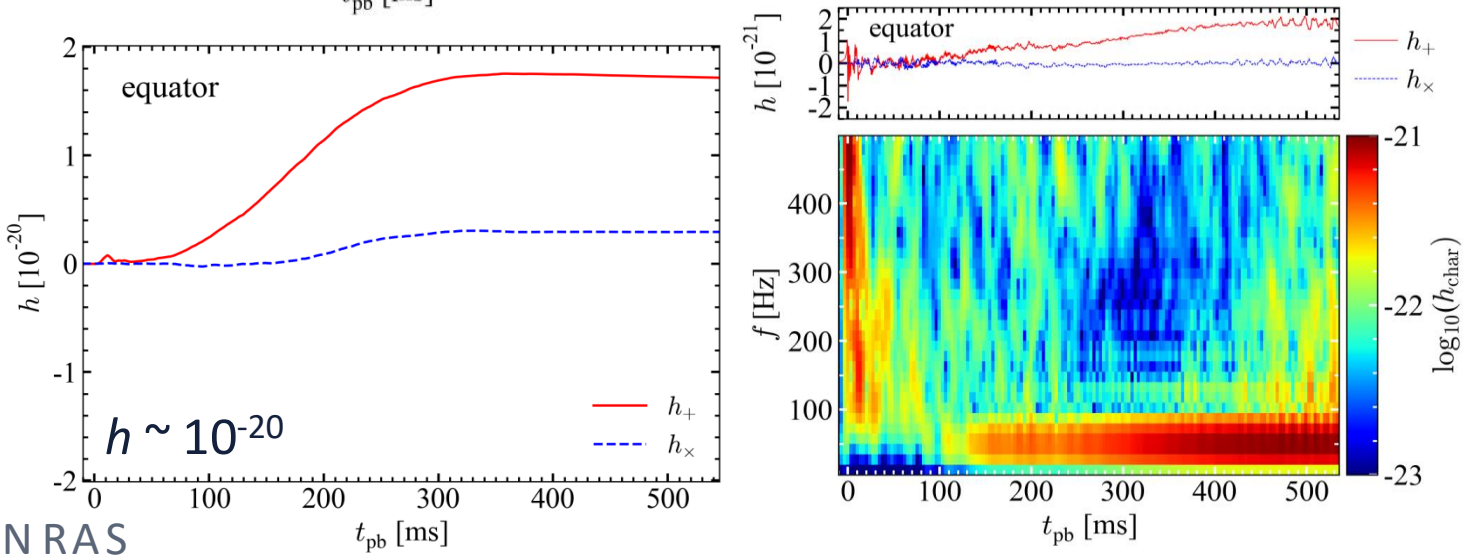
Neutrinos **Matter**

Pole



h ~ 10^{-22}

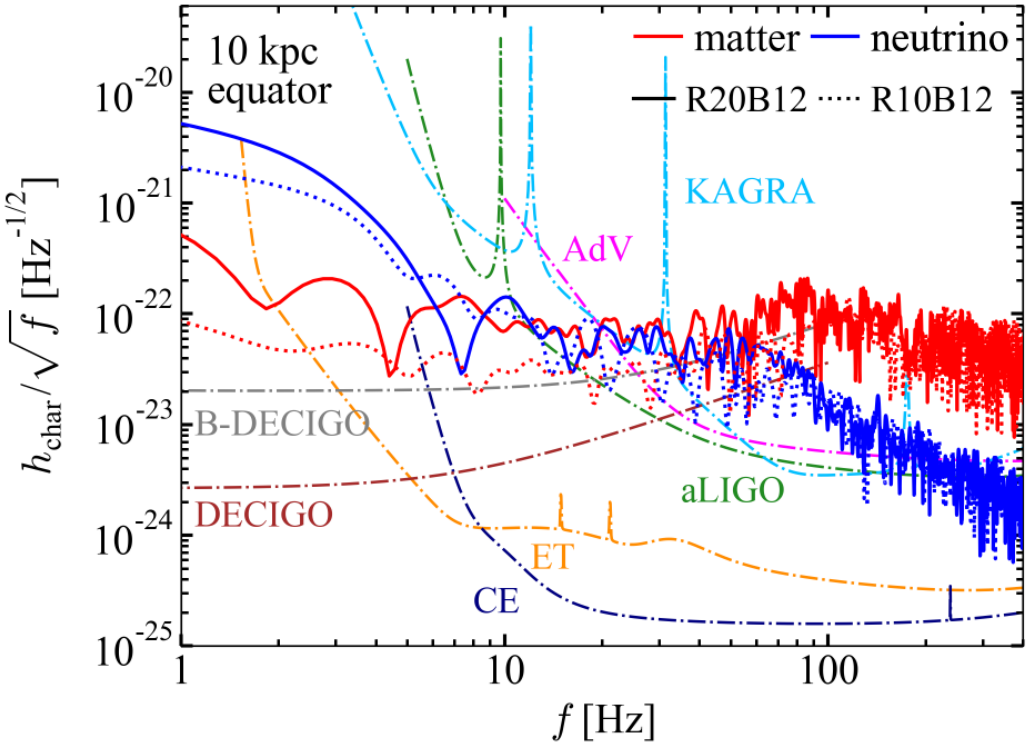
Equator



h ~ 10^{-21}

Shibagaki+ 2024, MNRAS

The ν memory dominates the GW spectrum below ~ 10 Hz



Neutrinos > matter below ~ 10 Hz

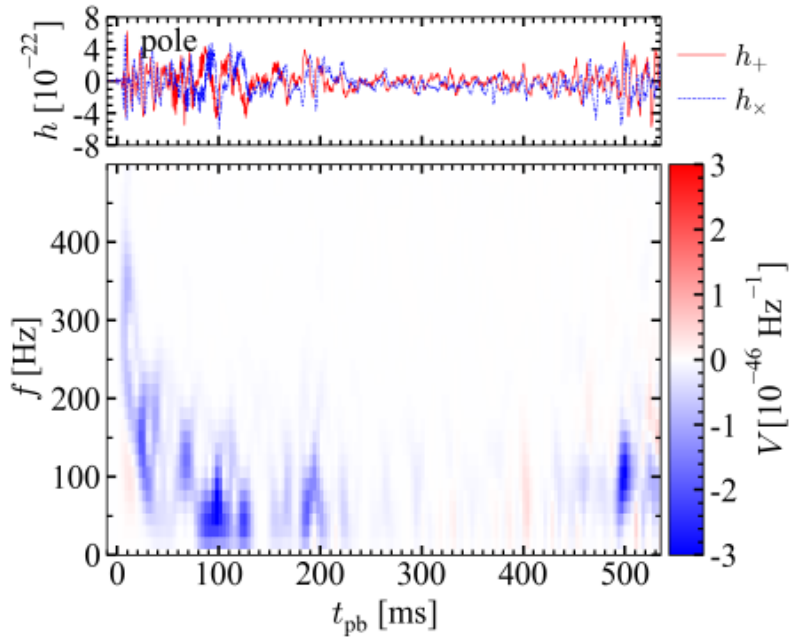
Needs DECIGO-class sensitivity for a Galactic event

The ν memory can mask the jet's low-frequency signal

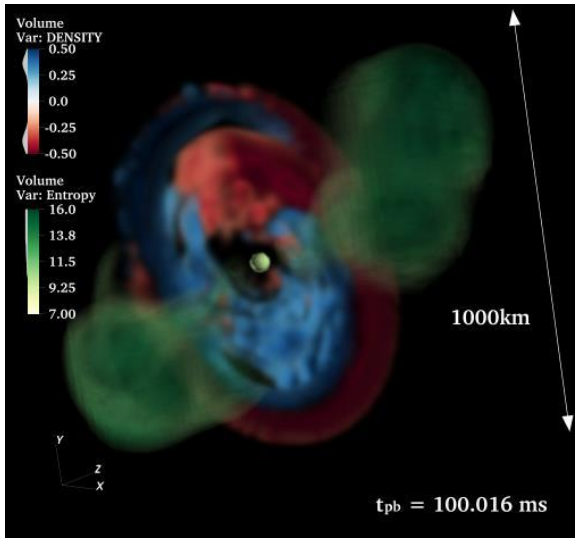
Solid lines: R20B12. Below ~ 2 Hz the spectrum depends on the 545 ms simulated time

Shibagaki+ 2024, MNRAS

Toward the pole, R20B12 is strongly circularly polarized



Strain and Stokes V ($10^{-46}\ \mathrm{Hz}^{-1}$)



3D view at 100 ms

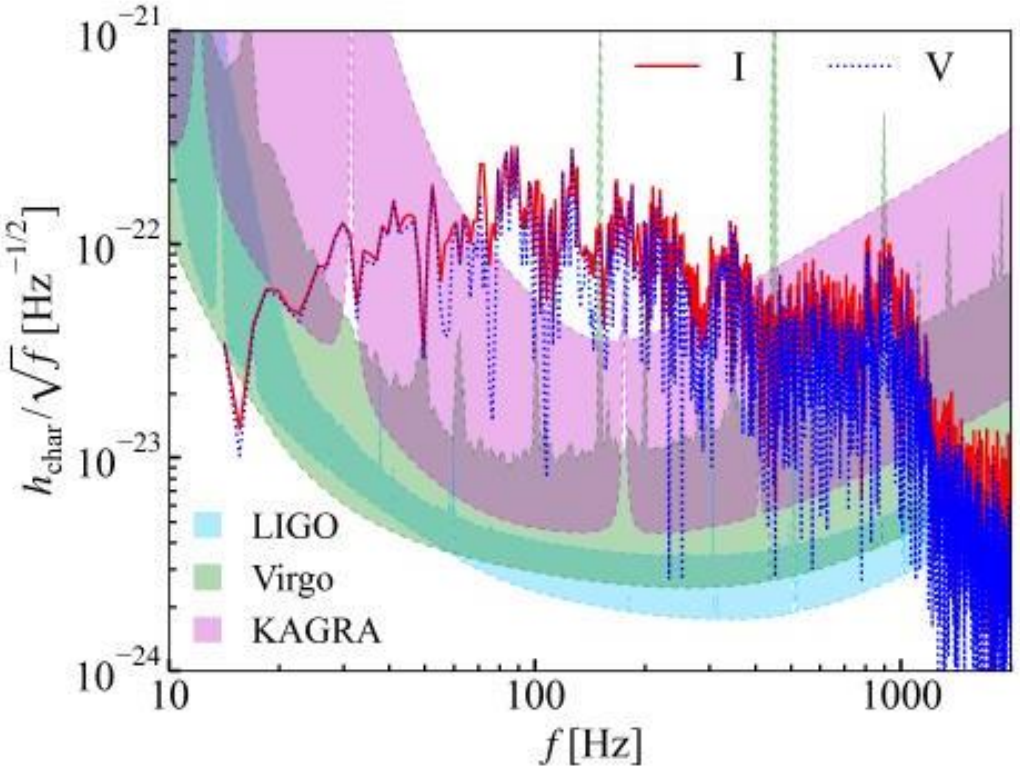
Strong V during the first ~230 ms

Peak ~90 Hz ≈ 2 × local rotation frequency near the PNS

From low-T/|W| flows near the PNS, not the jets

Shibagaki+ 2026, A&A 711, L6

The polarized GWs lie within O4–O5 sensitivity at 10 kpc



I ≈ V over a broad band: strongly circularly polarized
Bands: LIGO, Virgo, KAGRA, from O4 to O5

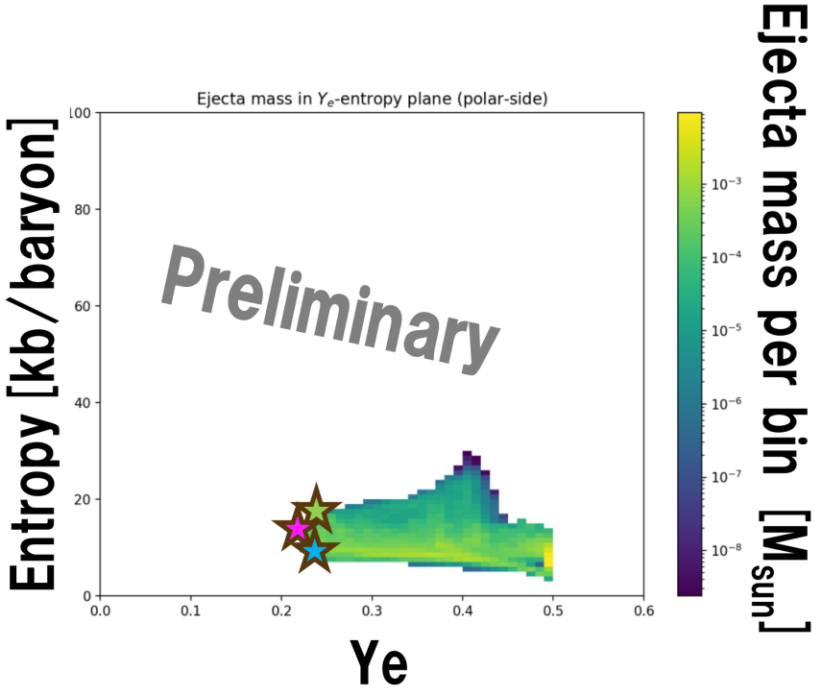
A potential probe of rapid core rotation

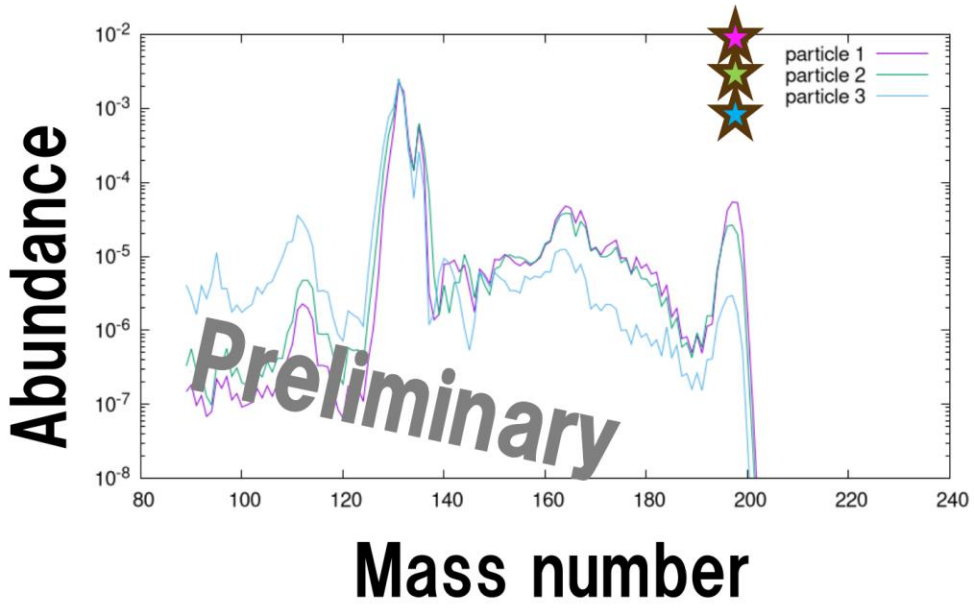
Assumes idealized noise and two co-located detectors

Shibagaki+ 2026, A&A 711, L6

Preliminary · polar-side ejecta

Even the lowest-Ye ejecta underproduce the third peak





Polar ejecta reach Ye ≈ 0.23; even the three lowest-Ye tracers (stars) underproduce the third peak

Full post-processing is ongoing

Work in progress

Summary

3D GR neutrino-radiation MHD of a rapidly rotating, magnetized 20 $M_\odot$ core (R20B12)

GW memory	Equatorial view: the ν memory (~ 10^{-20} at 10 kpc) exceeds matter GWs by > 10× below ~ 10 Hz and can mask the jet signal.
Circular polarization	Toward the pole: strongly polarized GWs (~ 90 Hz, first ~ 230 ms) from flows near the rapidly rotating PNS, within O4–O5 reach at 10 kpc.
r-process (preliminary)	Polar ejecta reach Ye ≈ 0.23, yet even these underproduce the third peak.