3D numerical relativity simulations of accretion induced collapse of rotating WDs

TK, Shibata, Kawaguchi, 2025, MNRAS, 541, 1649, arXiv:2503.17082

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YITP long-term workshop, “Multi-Messenger Astrophysics in the Dynamic Universe”

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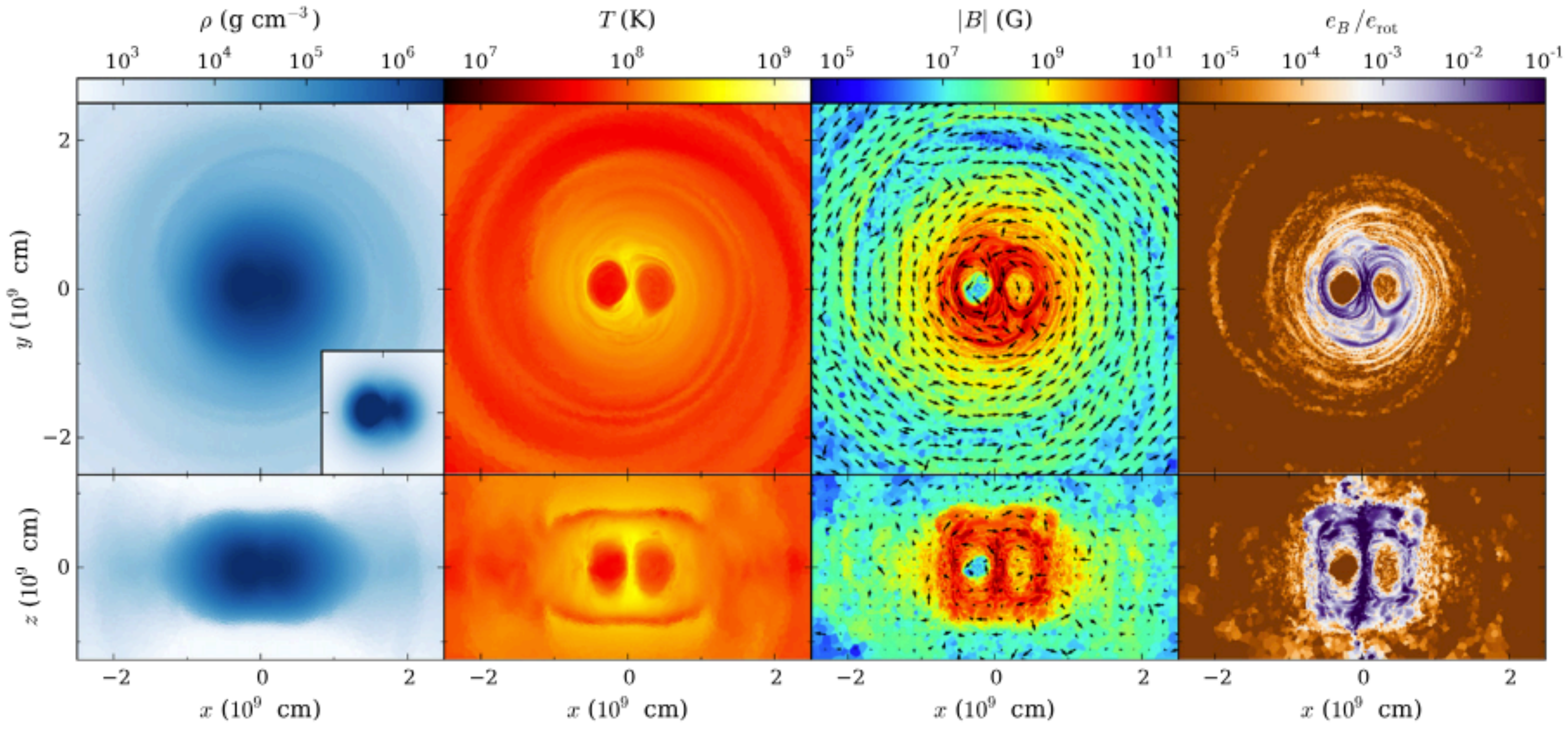
The AIC might be the origin of:

- **Millisecond pulsar (e.g. Tauris+13)**
  AIC could be another formation path to NS (CCSN and NSNS).
- **Magnetar (which may power GRB) (e.g. Metzger+08)**
  If the WD is strongly magnetized, then magnetar
  may naturally be formed.

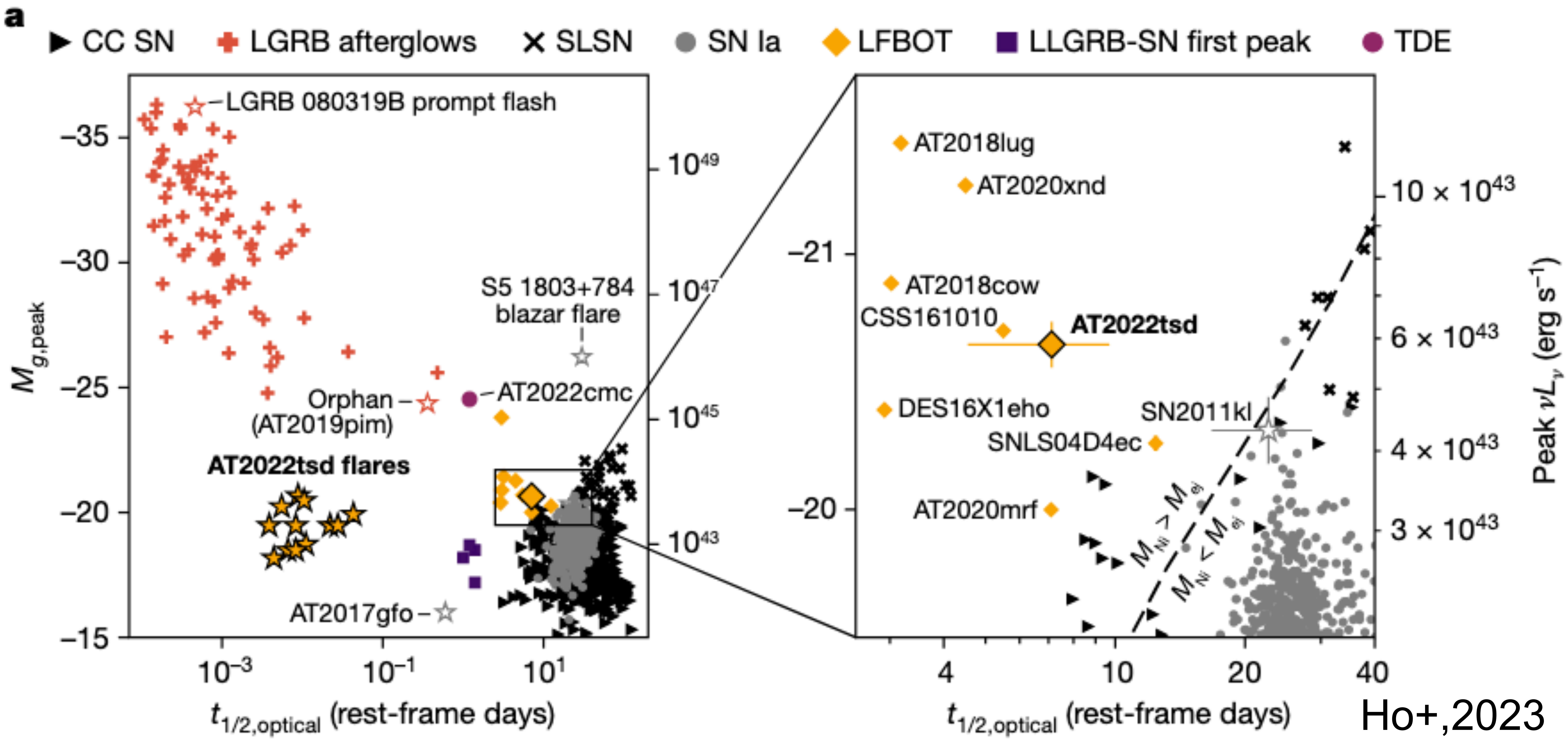


WDWD merger (Zhu+15)
(C.f. merger rate ~0.01-1 /yr/Galaxy
or ~10% of all WDs experience merger)

The AIC might explain:

- **Fast Radio Bursts (e.g. Waxman13, Margalit+19)**
- **Fast Blue Optical Transients (FBOT)**

Typical features of LFBOT, e.g., AT2018cow (c.f. Metzger22):



Ho+,2023

The AIC might explain:

- **Fast Radio Bursts (e.g. Waxman13, Margalit+19)**
- **Fast Blue Optical Transients (FBOTs)**

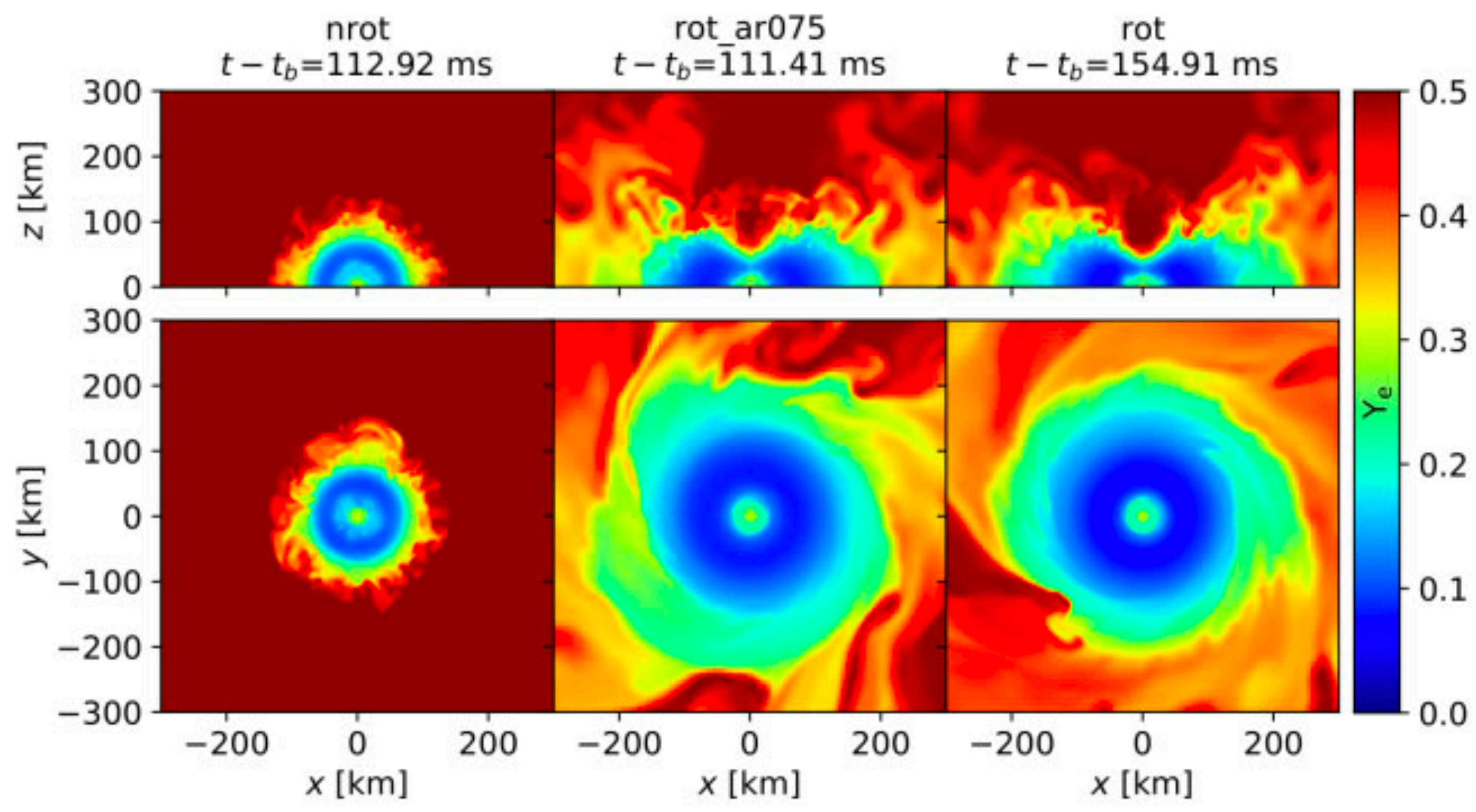
Typical features of LFBOT, e.g., AT2018cow (c.f. Metzger22):

- fast optical rise times of days or less
- peak luminosities $>10^{44}$ erg s^{-1}
- low ejecta mass $<\sim 0.1 M_{sun}$ ($^{56}Ni << 0.1 M_{sun}$ (?))
- aspherical ejecta with a wide velocity range

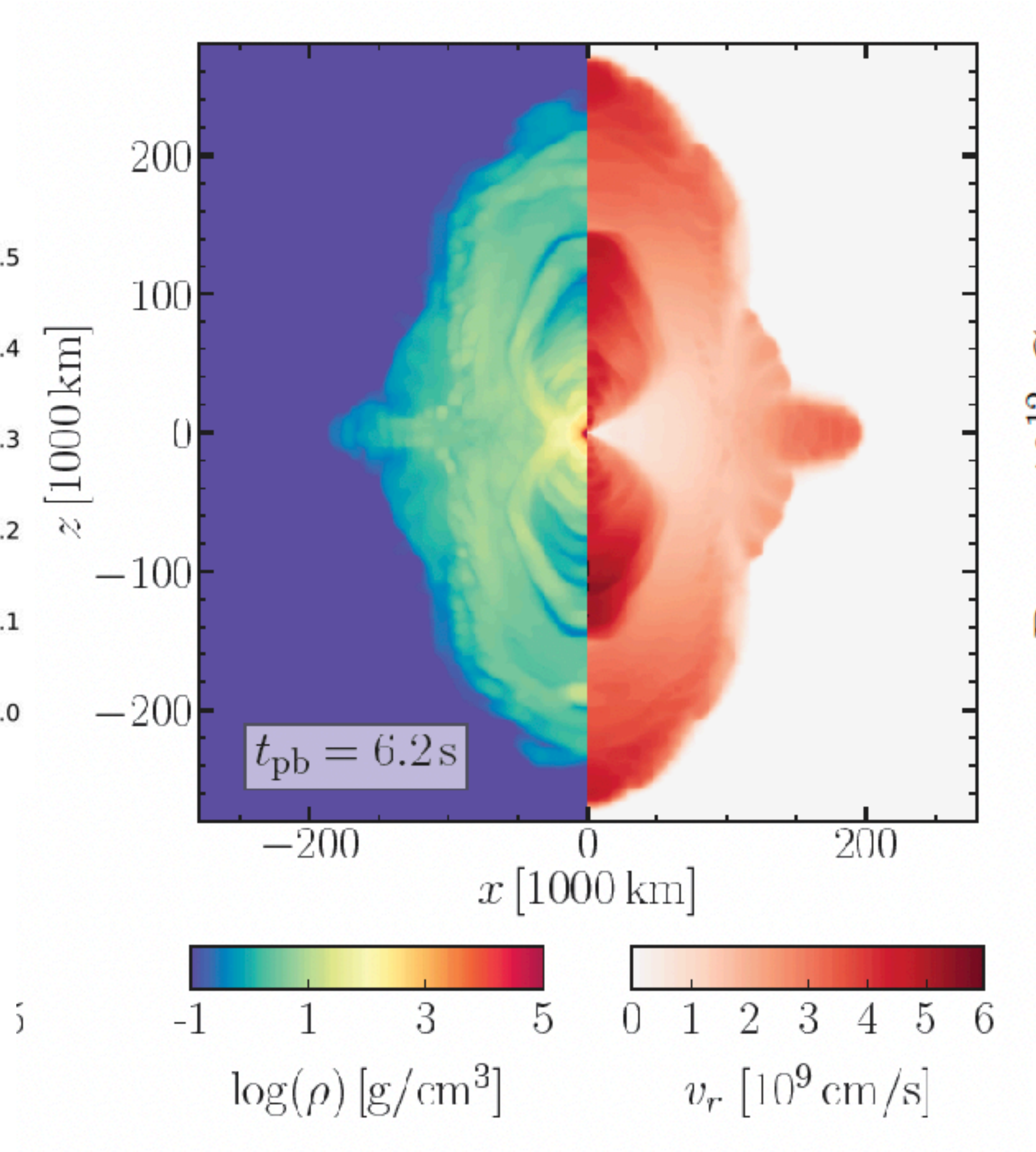
(<3000 km s^{-1} to >0.1–$0.5c$ with increasing polar latitude)

- presence of hydrogen-poor dense CSM

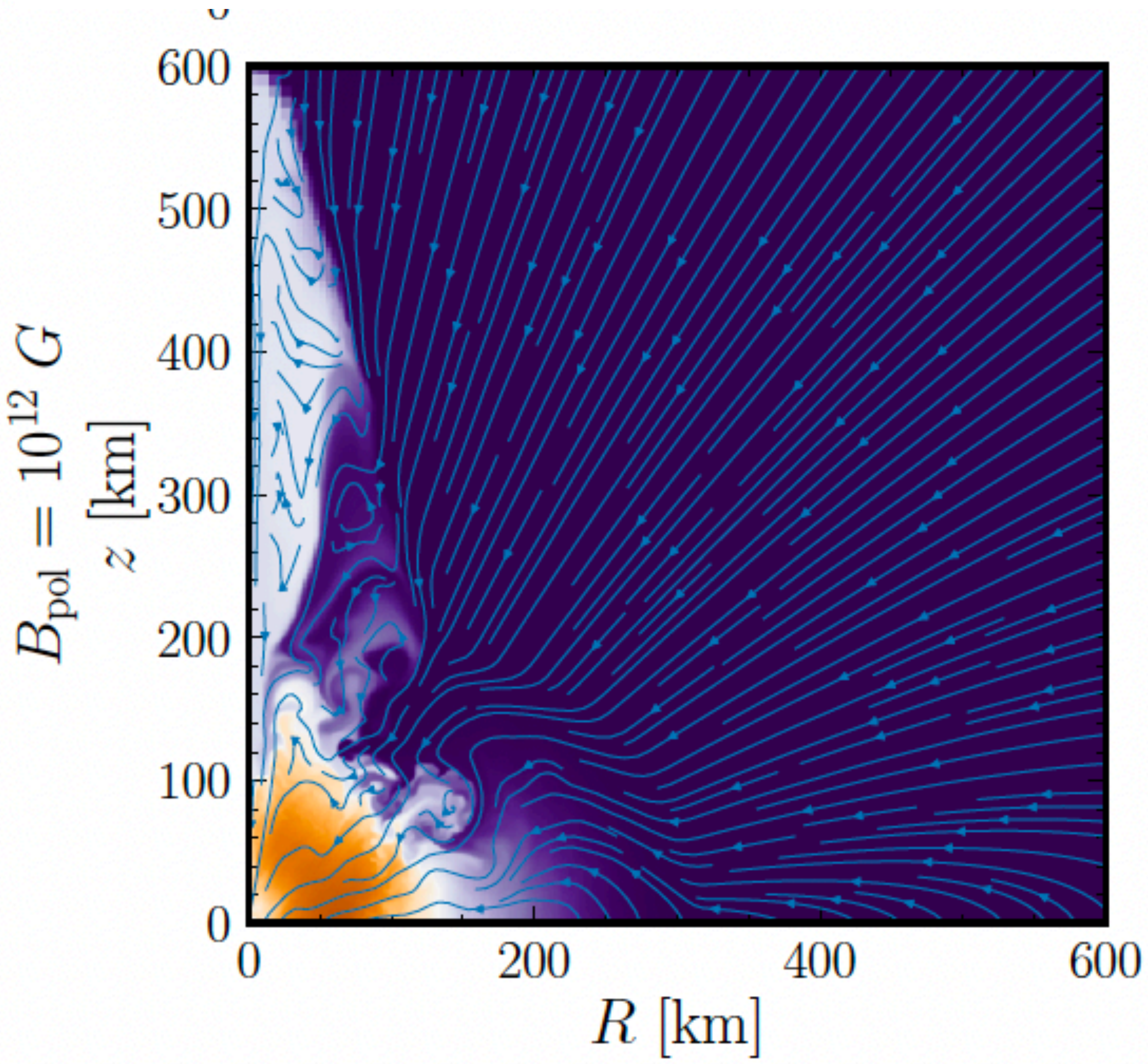
Recent AIC simulations



Micci+'23



Batziou+'25



Cheong+'25

Focus of this talk

For observed MM-signals from AIC,

“Are there any means to to distinguish it from other massive stellar collapse events?”

Initial models

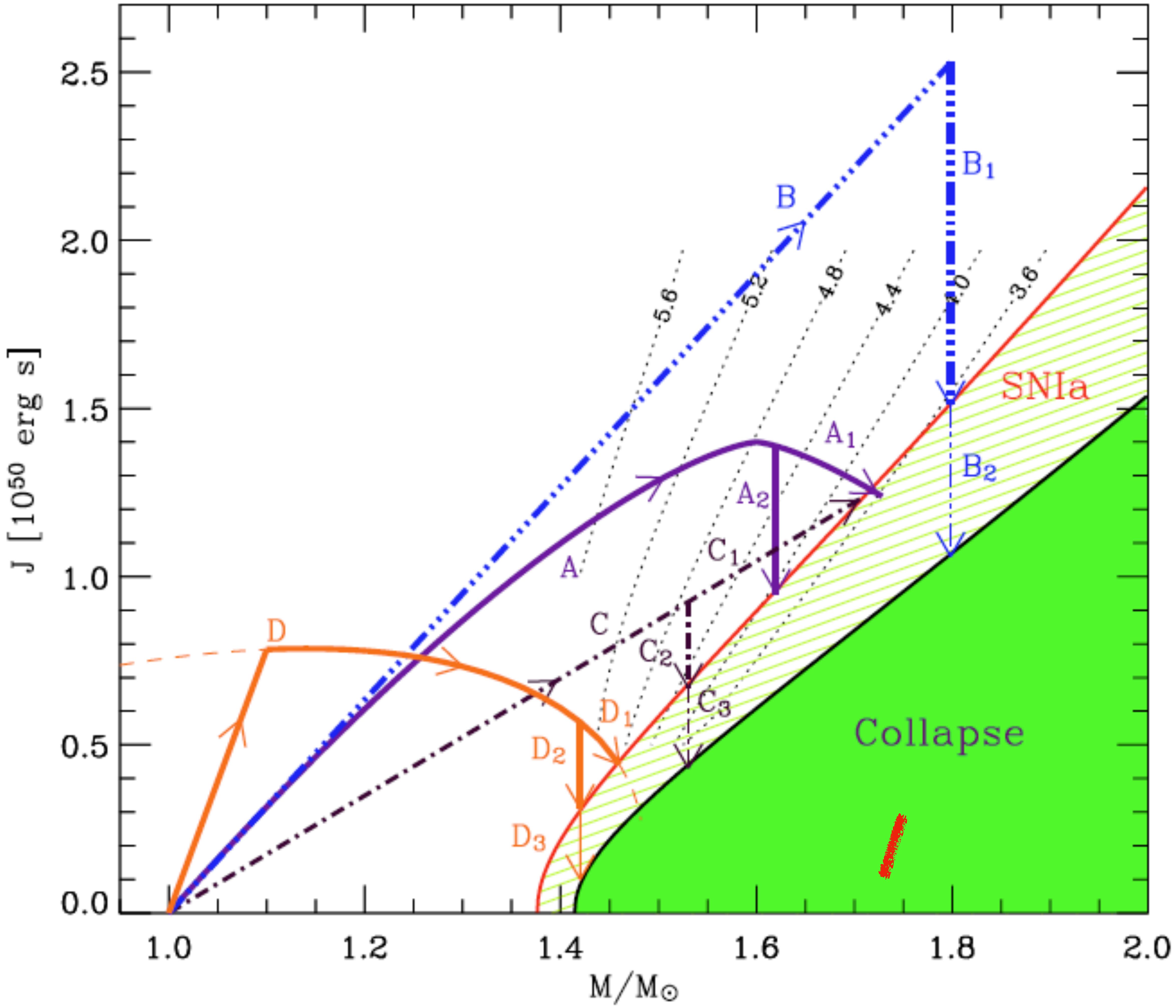
EOS: SFHo
Initial WDs: rigidly rotating models R01-R06
Integers 01-06 represent $|T/W|_{ini}$=0.1-0.6%.

R01: J=1.07e49 [erg s] & M=1.734M_{sun}

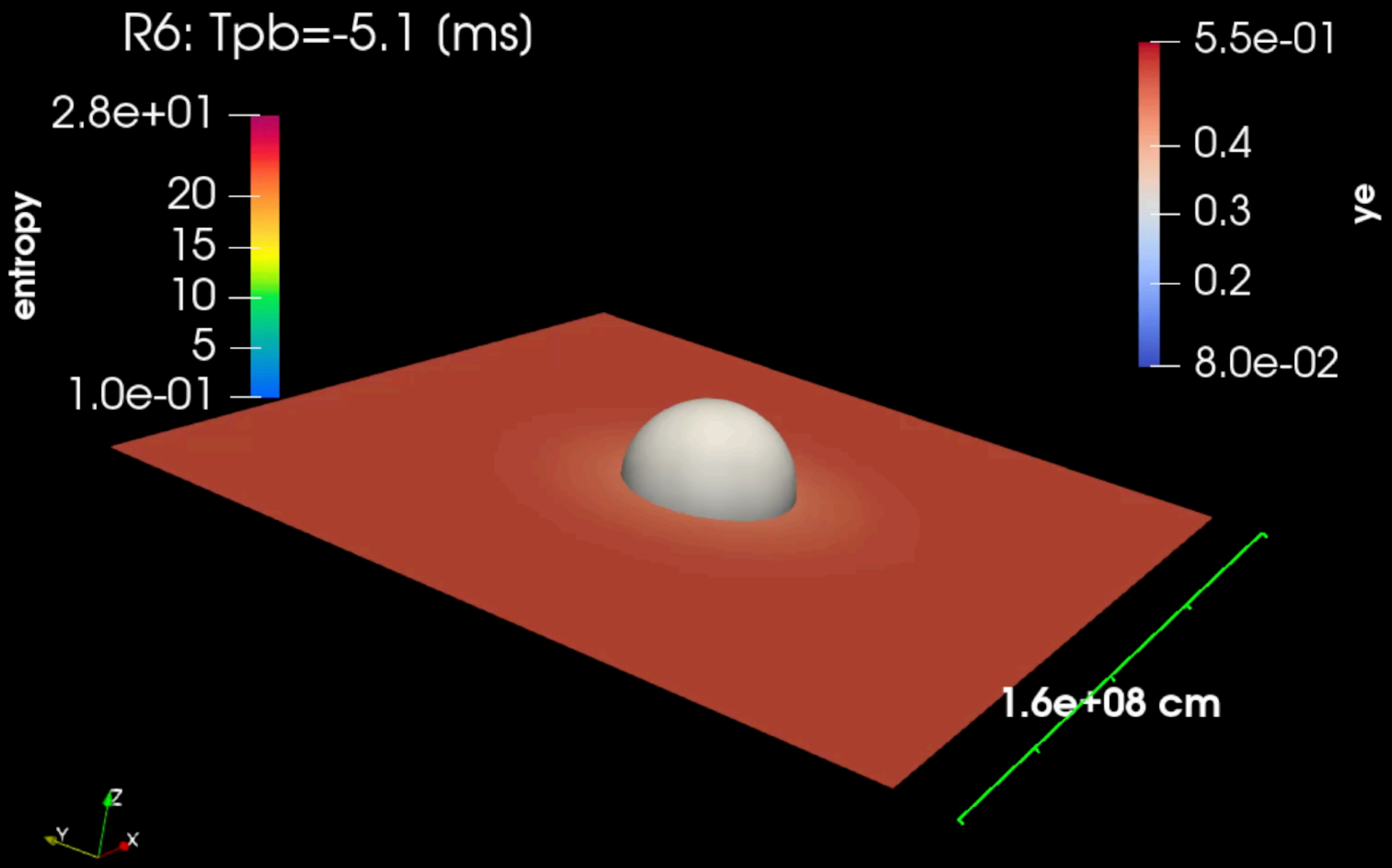
⋮

R06: J=2.72e49 [erg s] & M=1.762M_{sun}

NR+MHD code with multi-energy neutrino transport (TK+, 2016, 2020,2025)

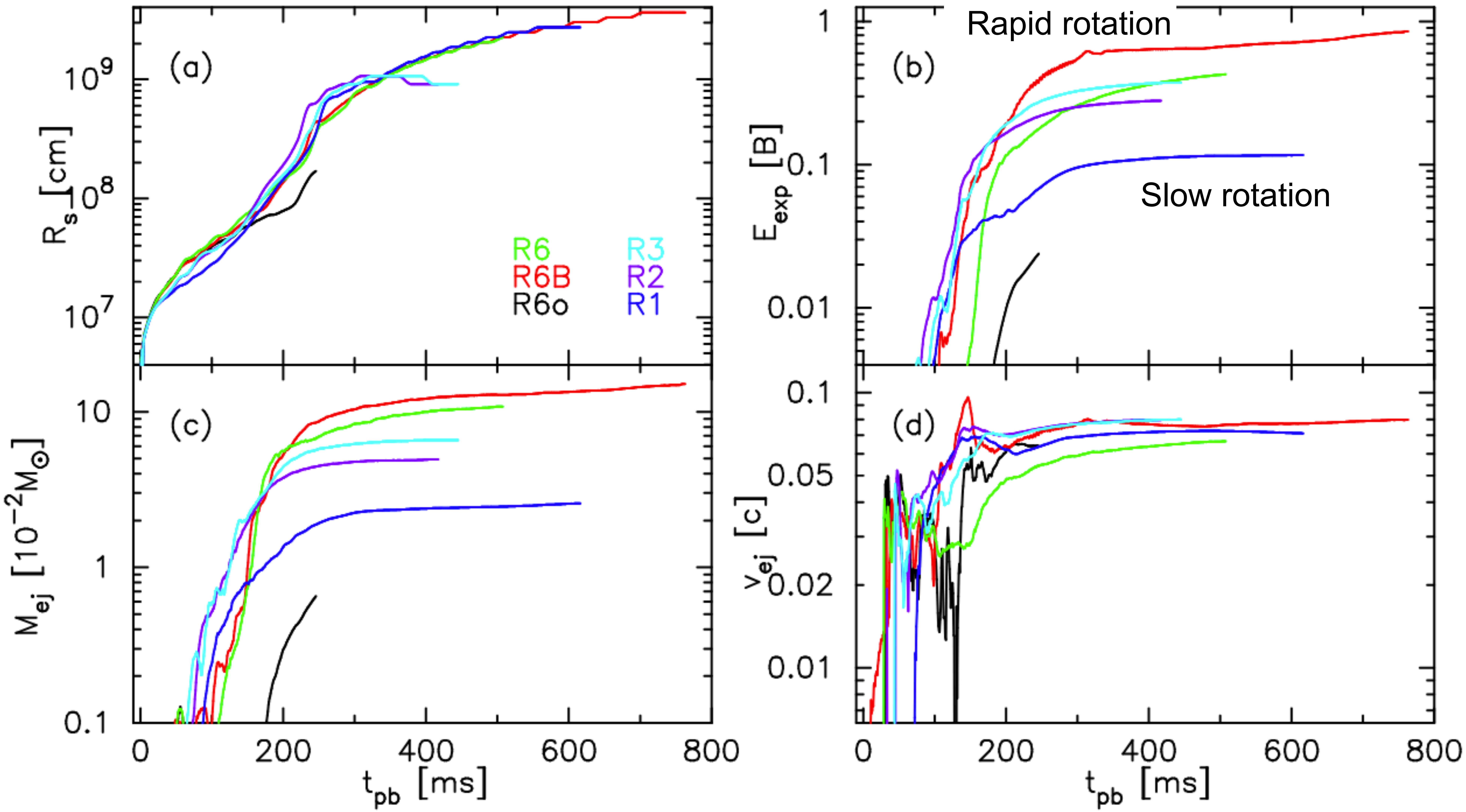


For potential pathways to these WDs, see Yoon&Langer05



TK, Shibata, Kawaguchi, 2025

Overall dynamics



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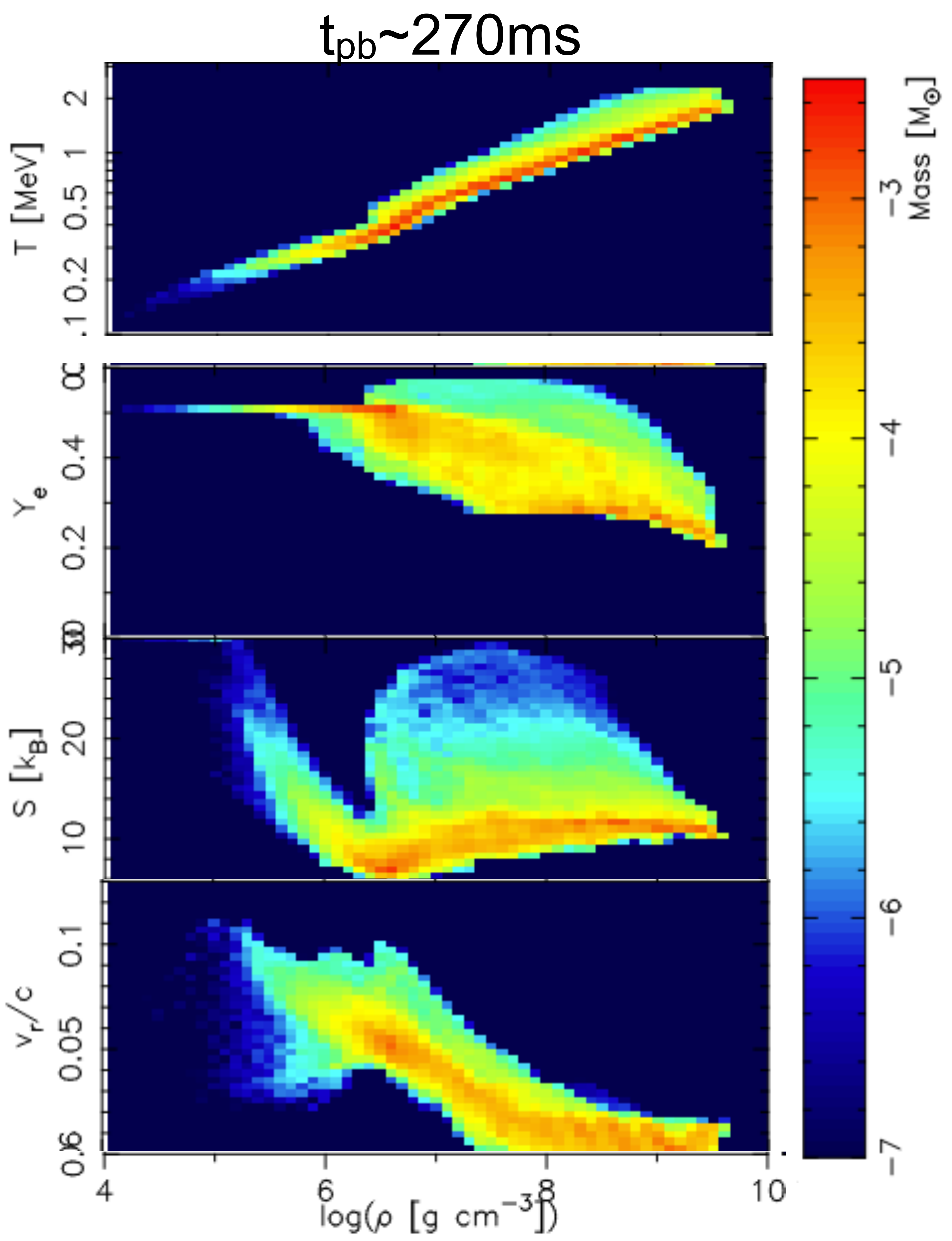
Rotation increases both E_{exp} & M_{ej}

But $v_{ej} \sim \sqrt{2E_{exp}/M_{ej}}$ remains nearly unchanged



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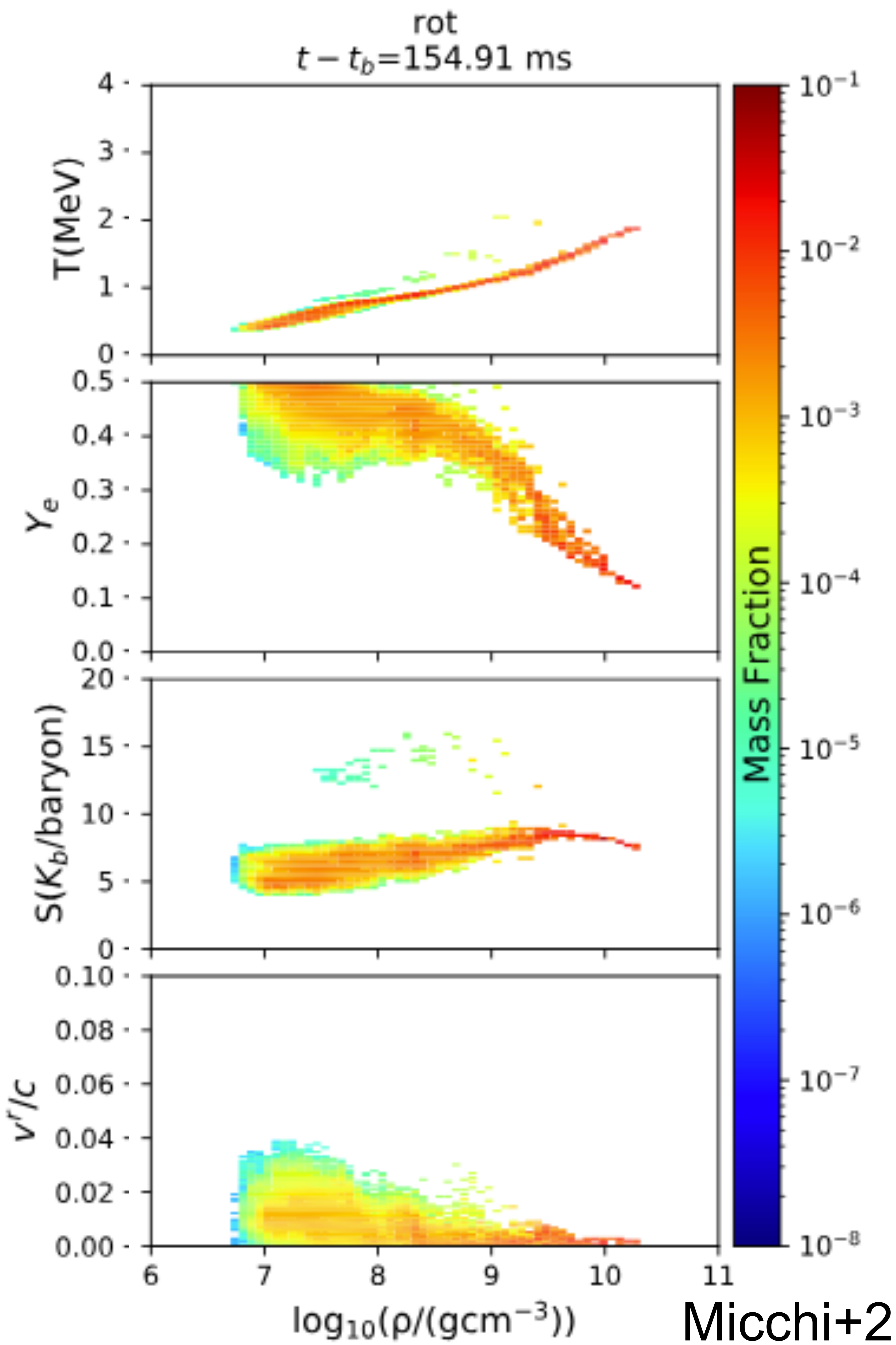
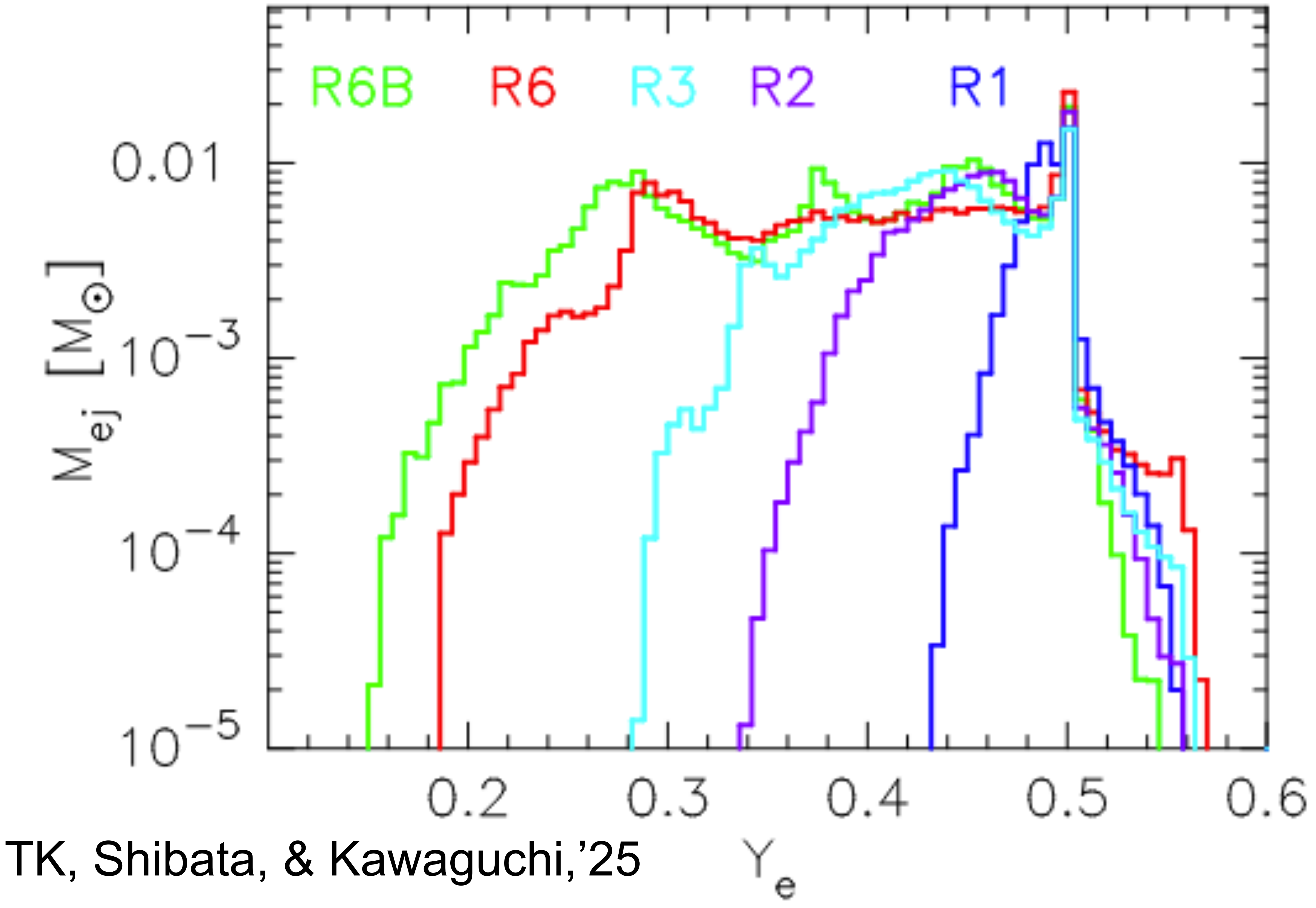


Micchi+23

Comparison of Ye-distribution with latest AIC models



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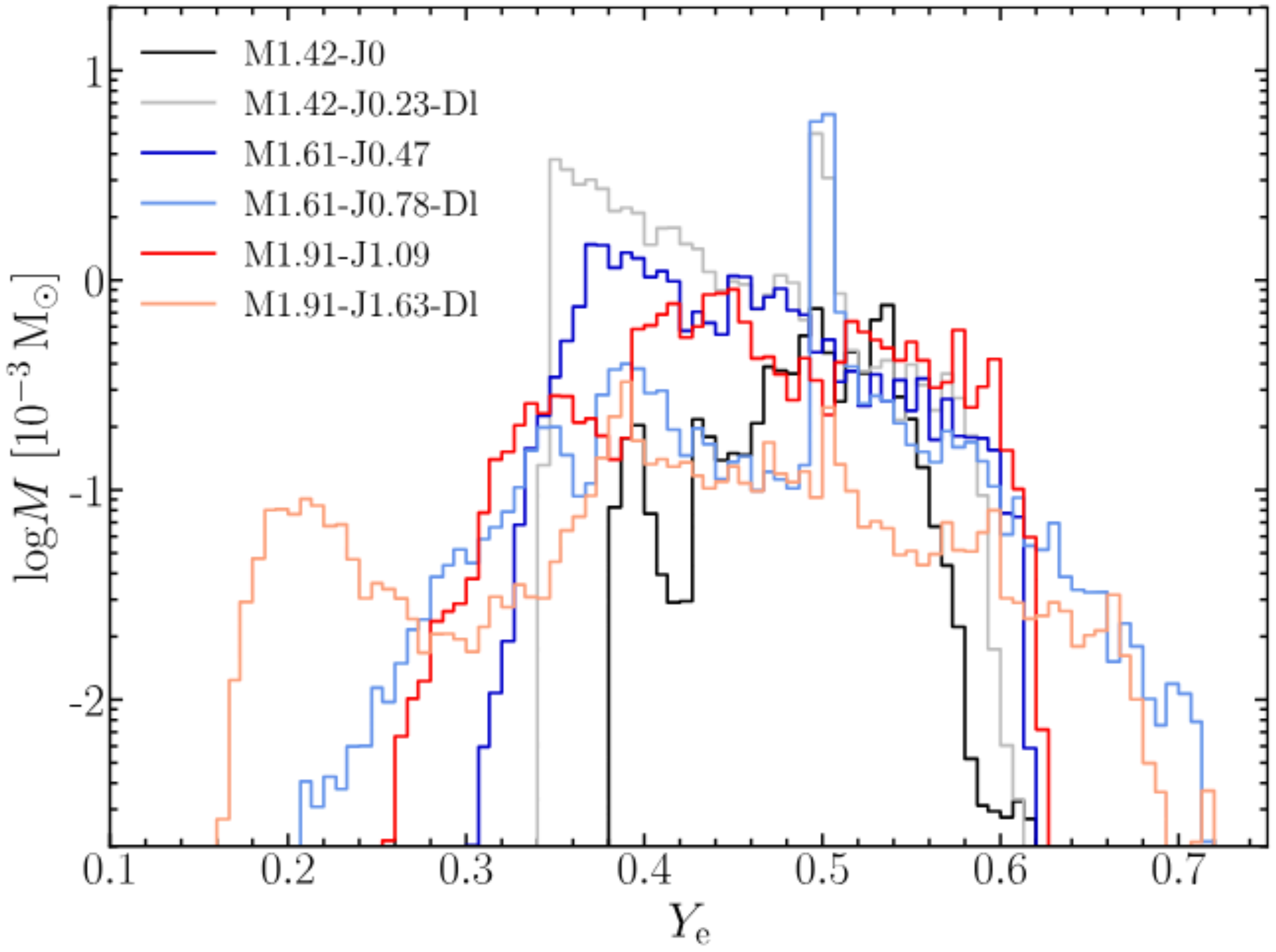
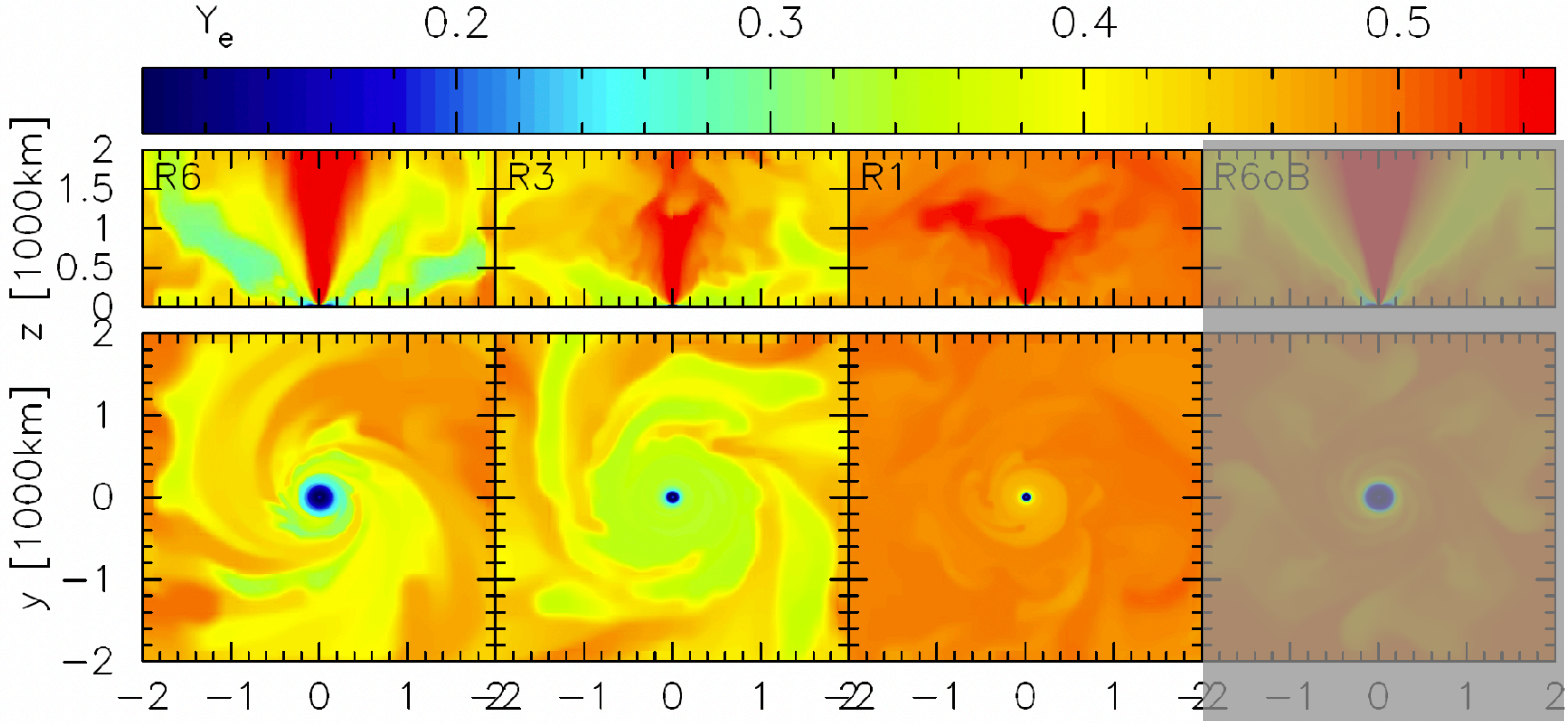


2D models of Batziou+'25

- Angular momentum increases low-Ye ejecta mass
- Non-axisymmetry plays significant contributions to ejecta profile

Impact of rotation and non-axisymmetry on low-Ye ejecta morphology



Rapid —> Moderate —> Slow

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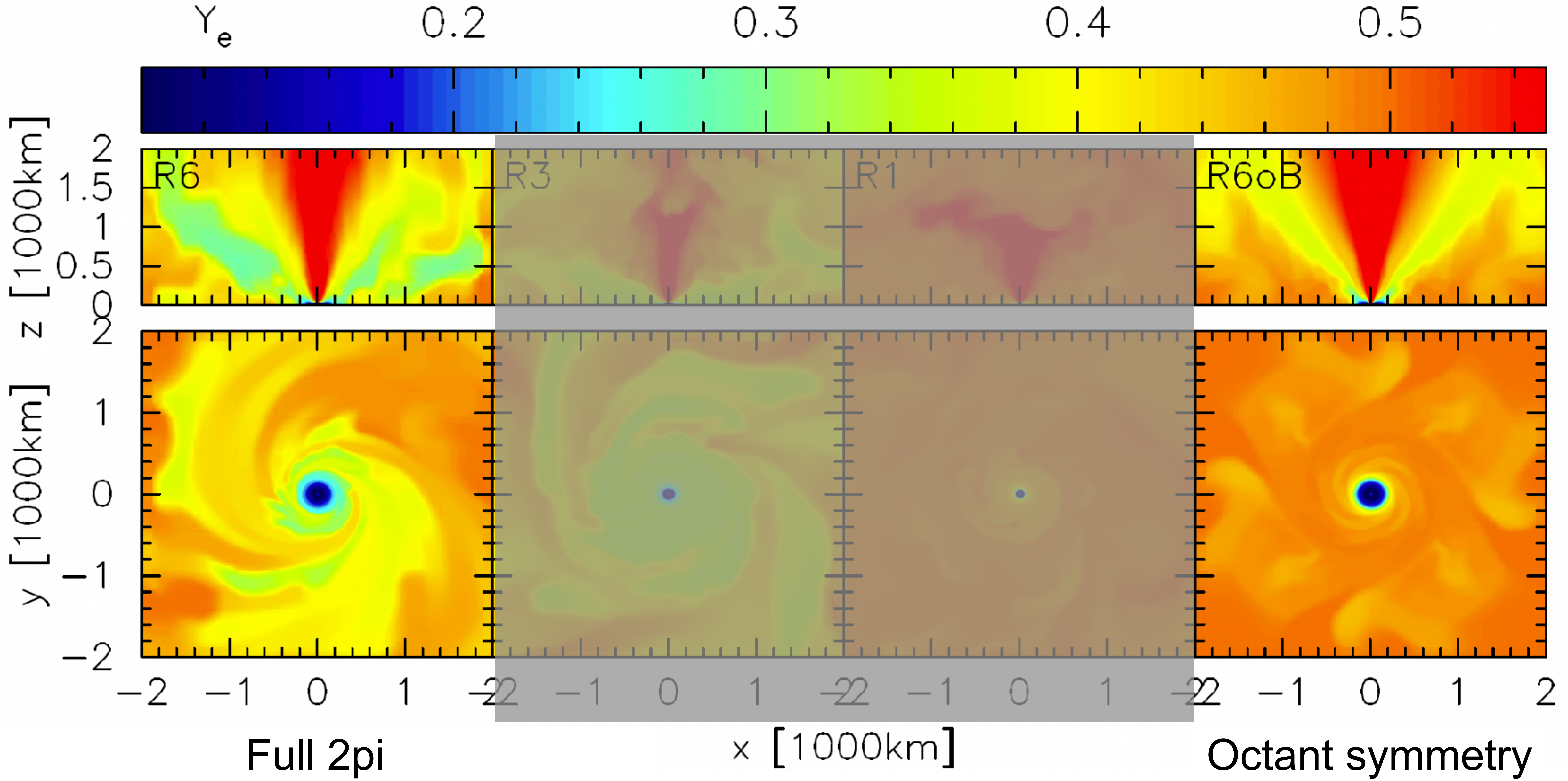
Centrifugal force ejects low-Y_e matters from PNS

Impact of rotation and non-axisymmetry on low-Ye ejecta morphology



Non-axisymmetry (m=1) enhances low-Y_e matter ejection

Key features of dynamics of rotating AICs

- Rotation works positively to the explosion
- 3D non-axisymmetric rotational instabilities boost the explosion
- B-fields also energize the explosion
- 3D non-axisymmetry & B-fields increase the neutron-rich ejecta mass

Multi-messenger signals: GWs

Kawaguchi,'25

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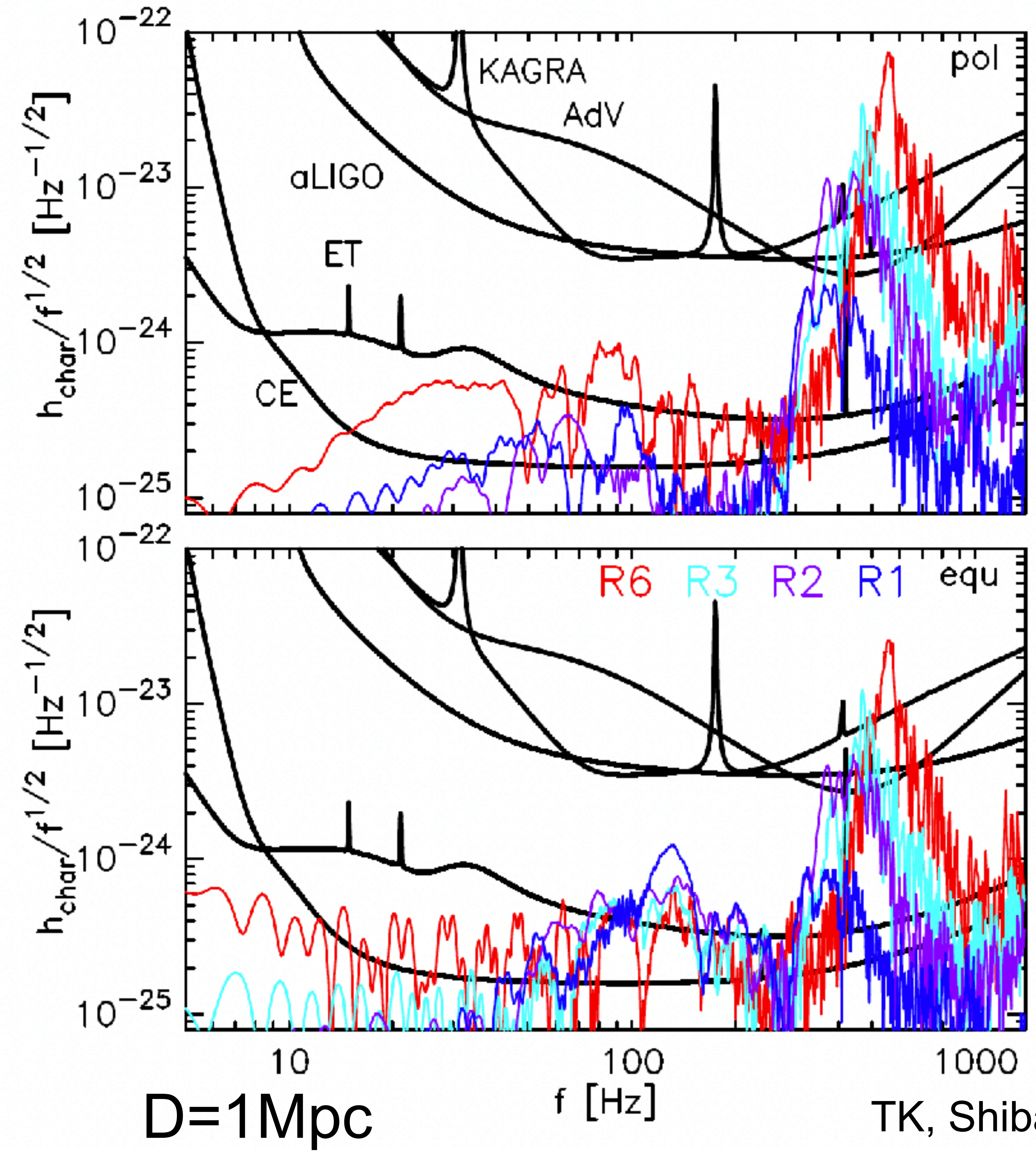
Micci+,'23

Multi-messenger signals: GWs



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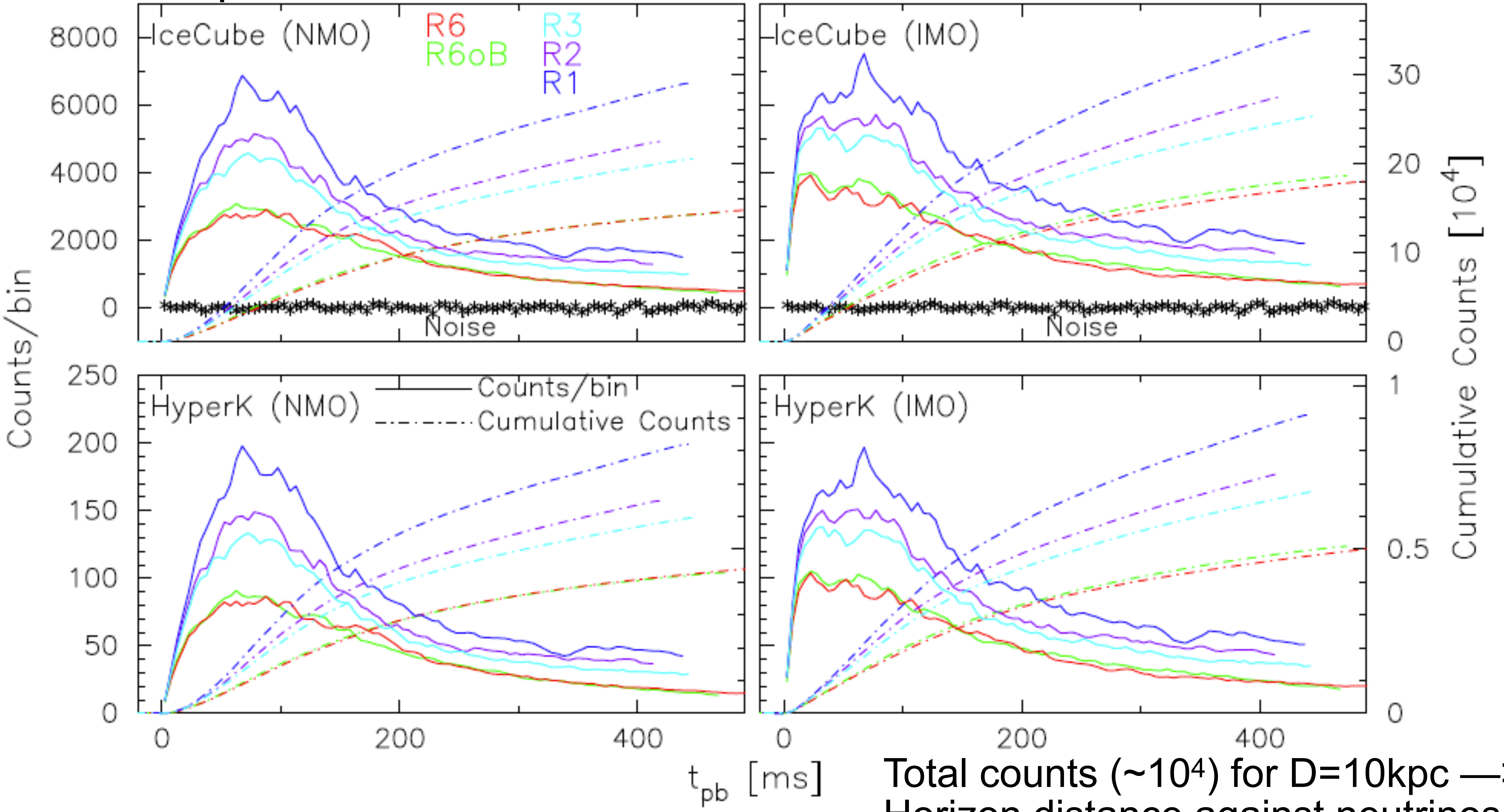
With 3rd generation detectors (ET & CE), we may observe these events up to D=1Mpc

Multi-messenger signals: Neutrinos

D=10kpc



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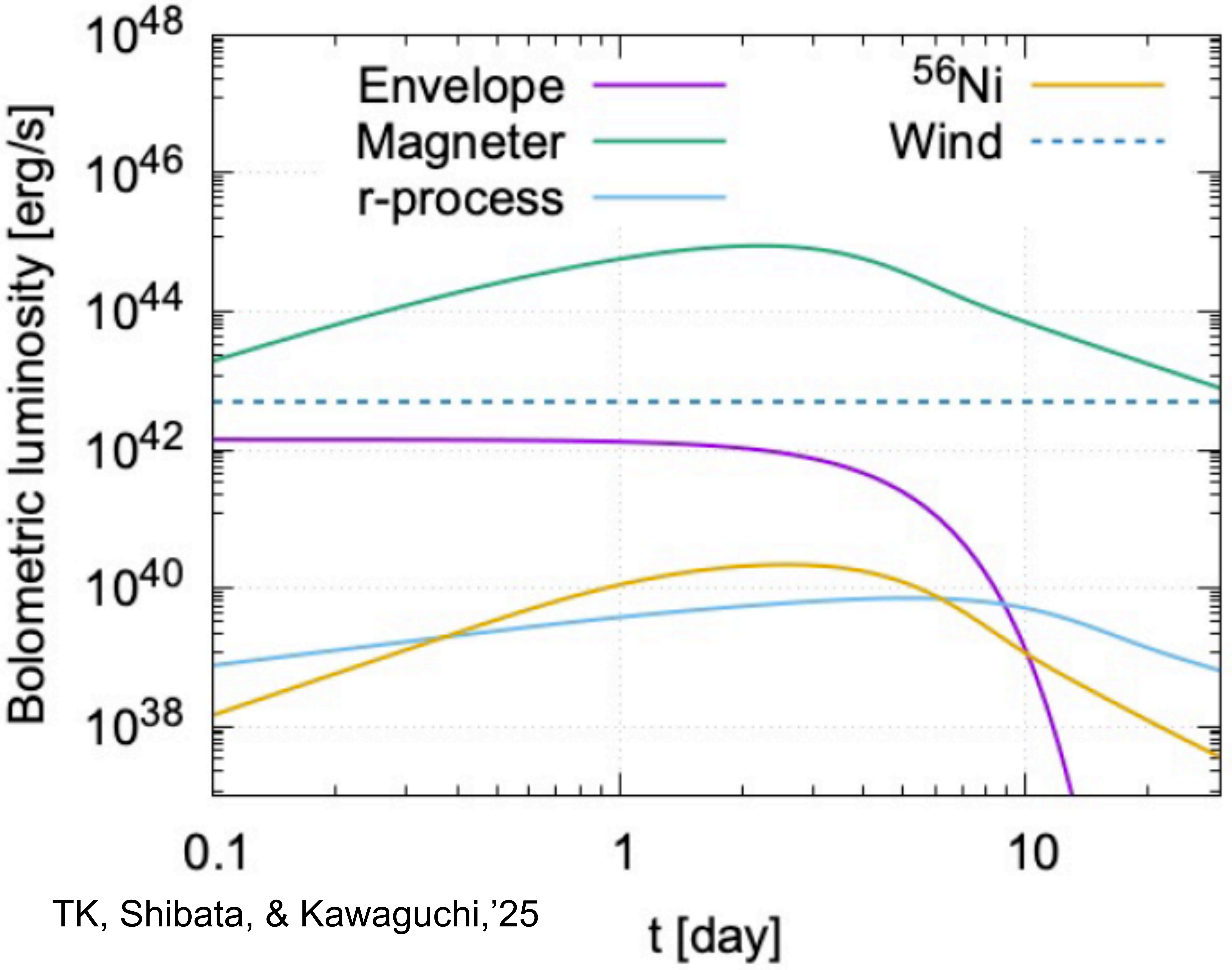
Total counts (~10^4) for D=10kpc —> Horizon distance against neutrinos is ~O(100kpc)

Electromagnetic Counterpart



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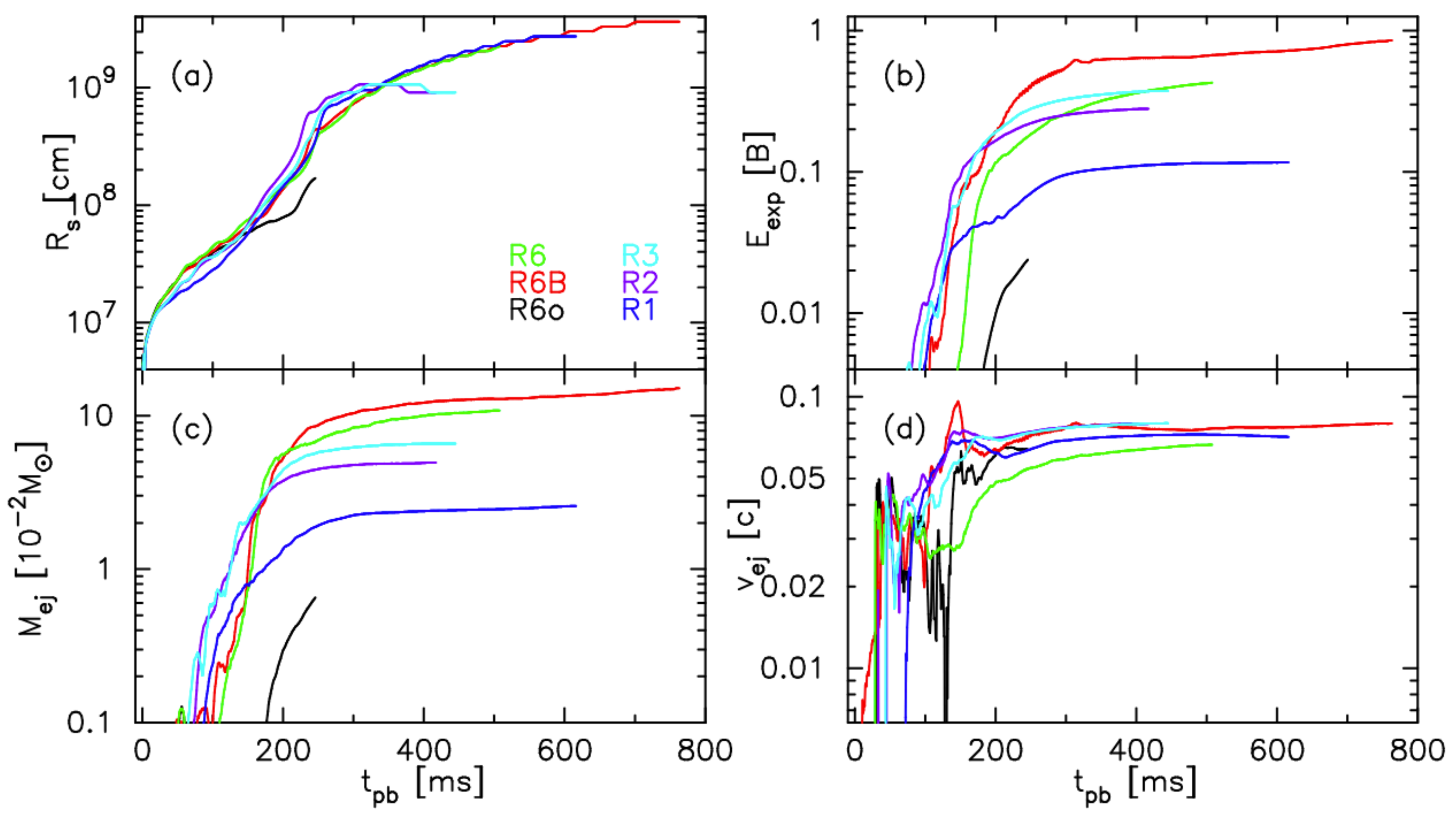


- $M_{\mathrm{ej}} \sim 0.01 - 0.1\, M_\odot$
- $E_{\mathrm{exp}} \sim 10^{50}\,\mathrm{erg}$
- $v_{\mathrm{ej}} \sim 0.1\, c$
- $M_{^{56}Ni} \sim 2 \times 10^{-3}\, M_\odot$
- Millisecond Magnetar

Summary of horizon distance

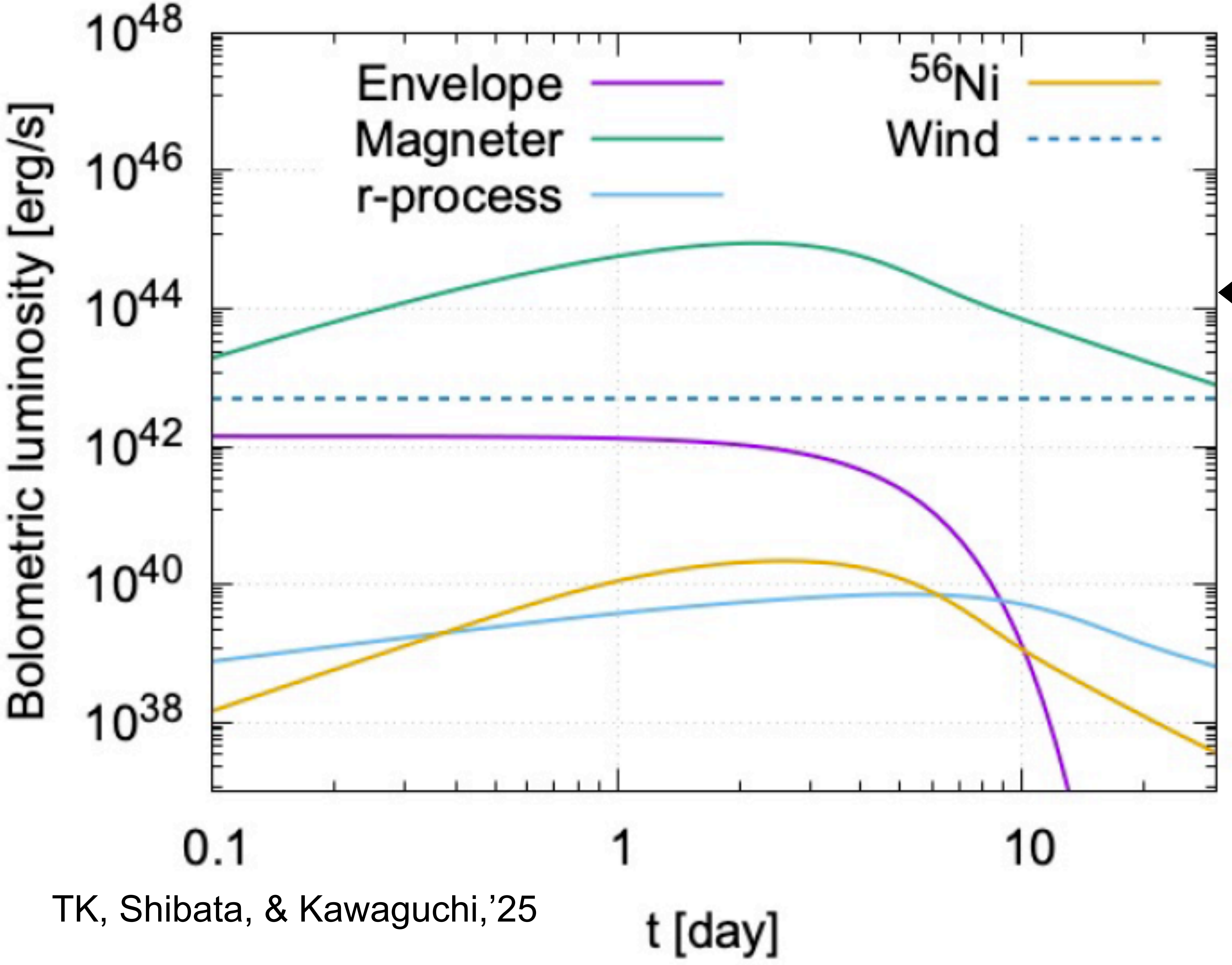
- $D_{Horizon}$(EM)~100Mpc (c.f. AT2018cow is D=60Mpc)

- $D_{Horizon}$(ν)~0.1Mpc (c.f. SN1987A —> 0.05Mpc)

- $D_{Horizon}$(GW) ~ 0.01Mpc(no rotation) — 1Mpc (rapid rotation)

If we luckily observe these 3 signals (~1-10 events in a life??)

What information can we infer from EM counterpart?



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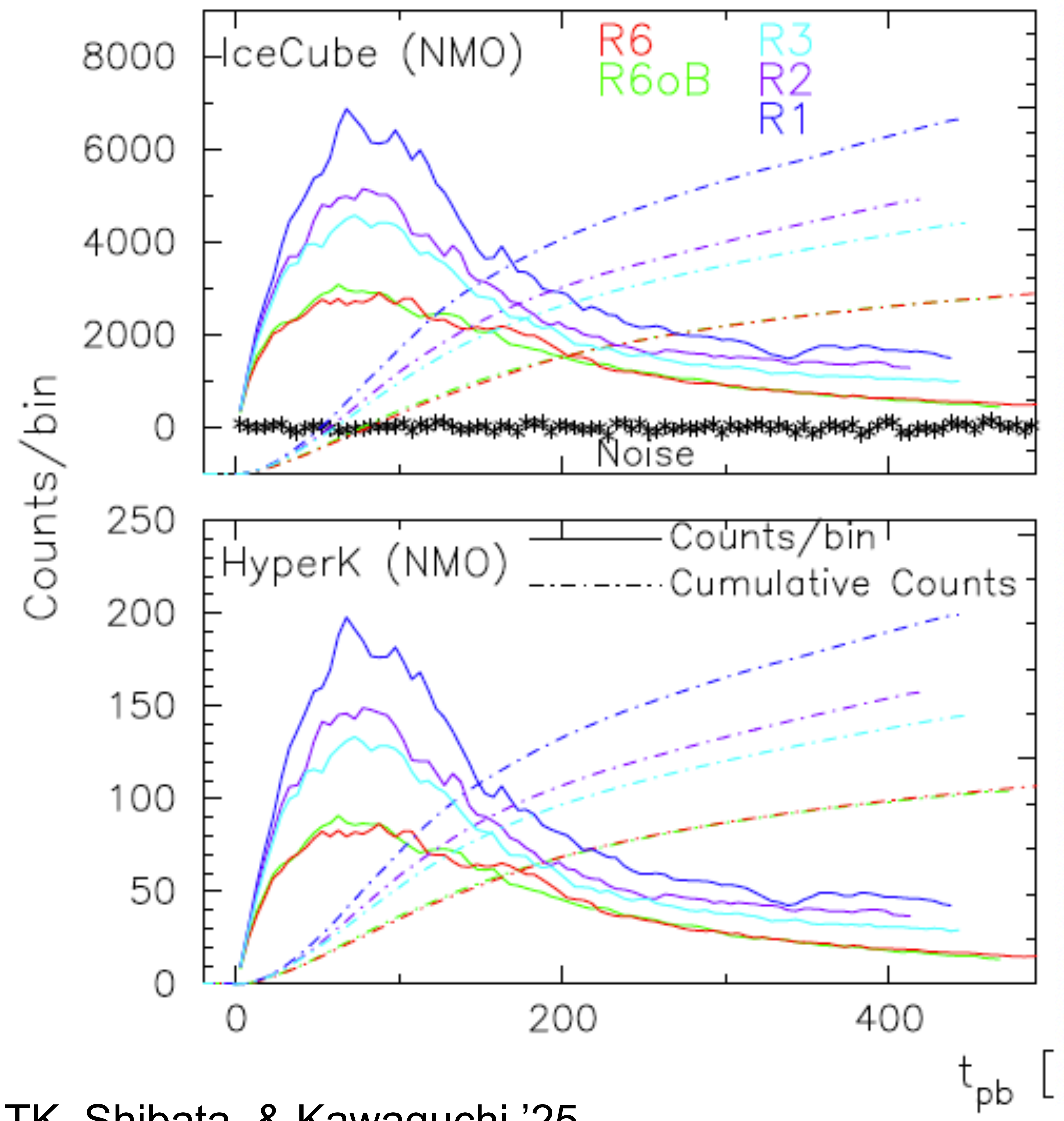
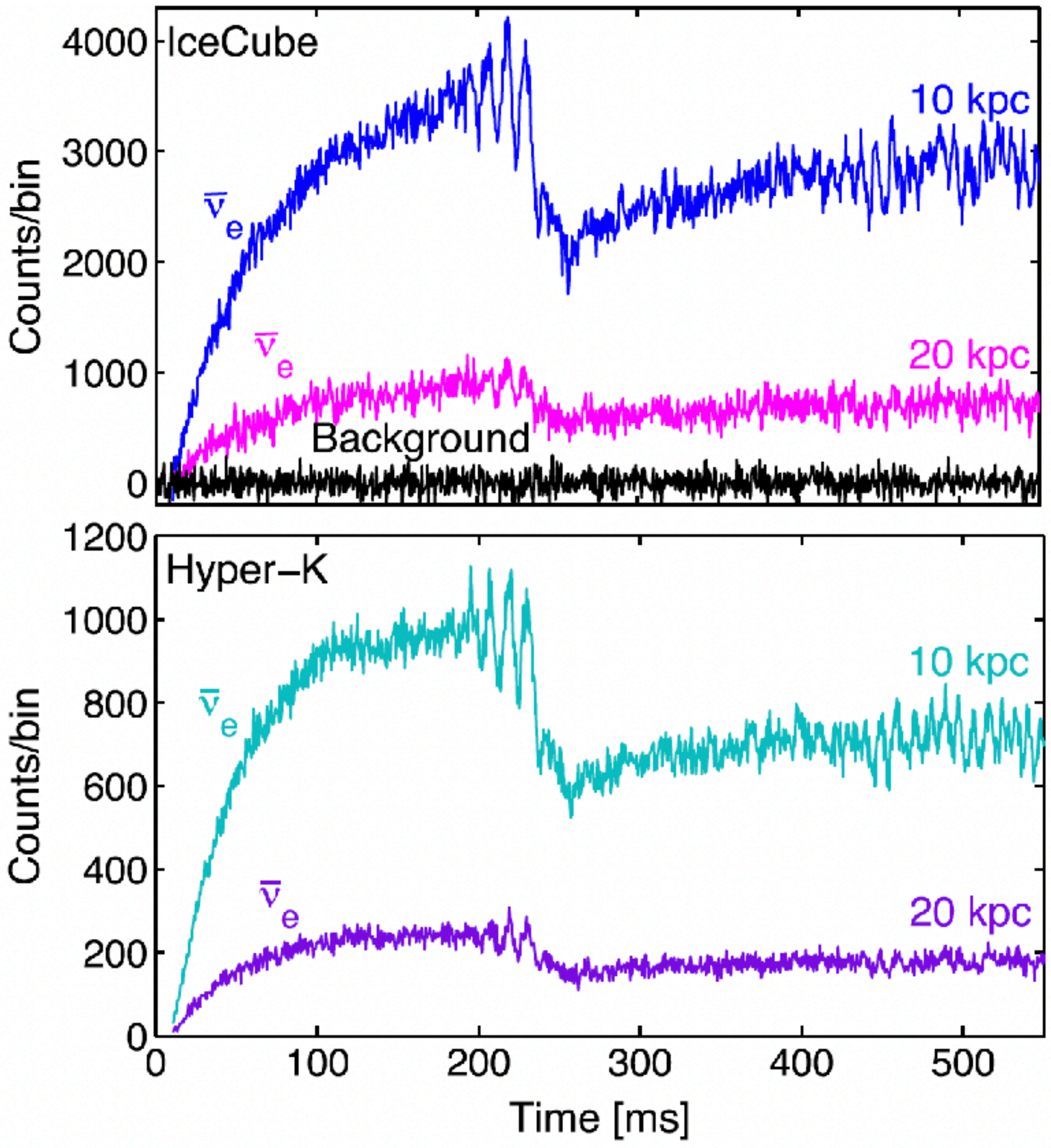
If we observe such EM event

- $M_{\rm ej} \sim 0.01 - 0.1\, M_\odot$
- $E_{\rm exp} \sim 10^{50}\,{\rm erg}$
- $v_{\rm ej} \sim 0.1\, c$
- $M_{^{56}Ni} \sim 2 \times 10^{-3}\, M_\odot$
- Millisecond Magnetar

What information can we infer from neutrinos?

D=10kpc





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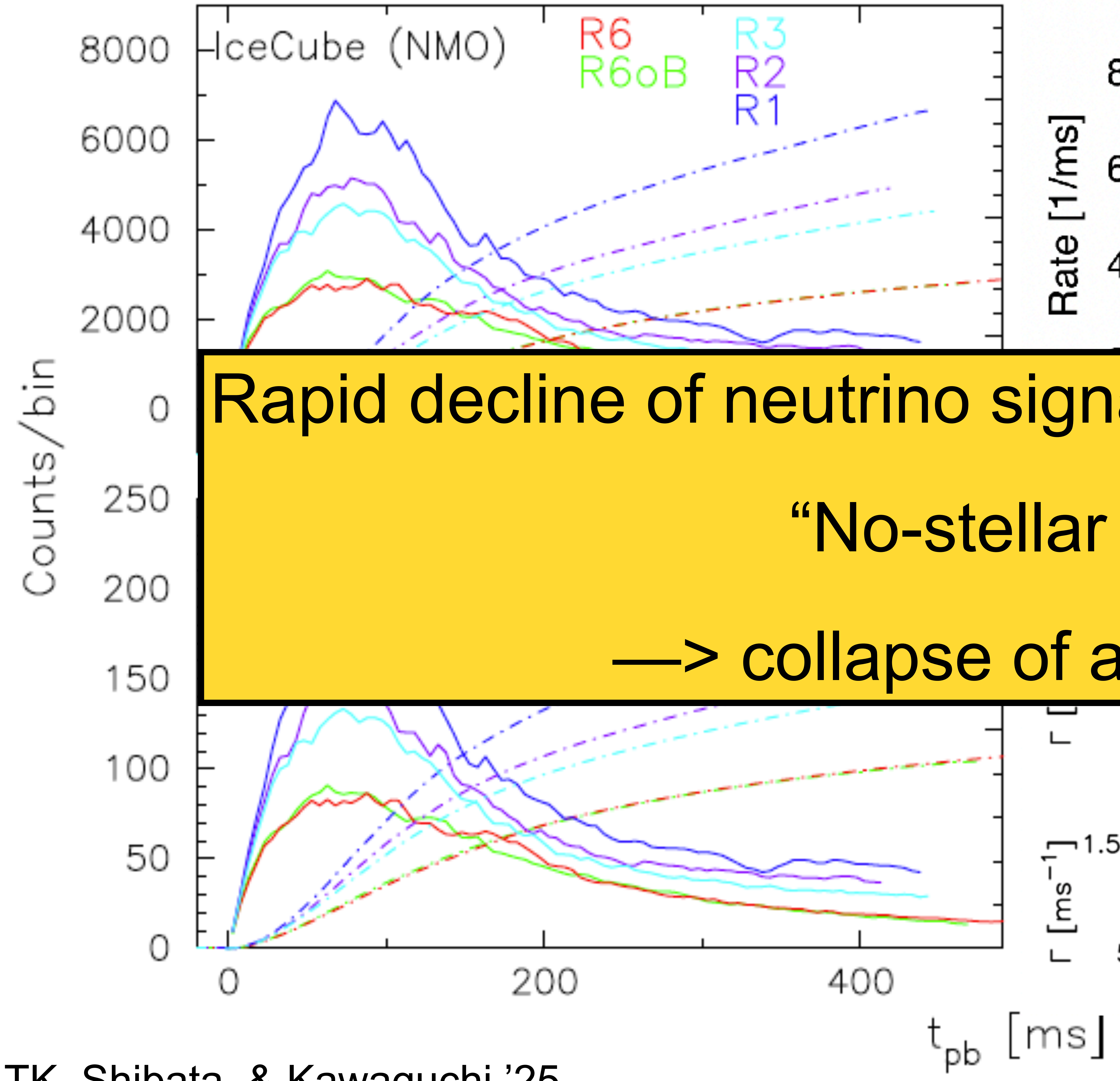
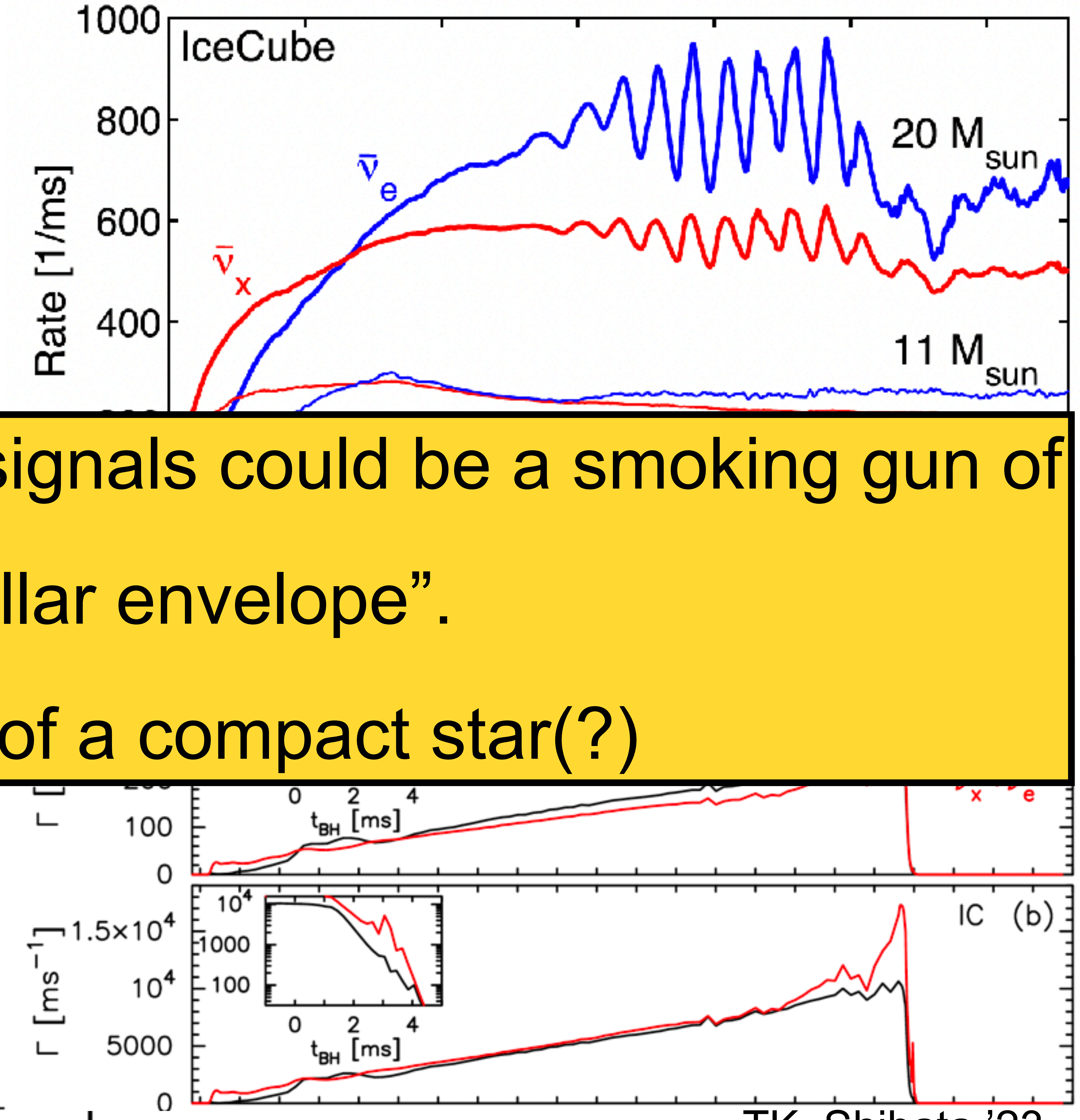
Tamborra+,'13

What information can we infer from neutrinos?

D=10kpc





Rapid decline of neutrino signals could be a smoking gun of

“No-stellar envelope”.

—> collapse of a compact star(?)

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What information can we infer from GWs?

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Information on rotation

Summary

- We have performed full 3DGR AIC and explosion simulations.
- The most rapidly rotating model presents very unique features.
    - ✓Bipolar explosion
    - ✓Low-Ye ejecta (similar to MHD model, rather than EC/CCSNe)
    - ✓Loud GW signals (Horizon distance ~several Mpc)
    - ✓Neutrino signalas (Horizon distance ~100 kpc)
- MM signals (if detected…..) may enable us to distinguish/identify the source origin