Millisecond proto-magnetars as gamma-ray burst central engines

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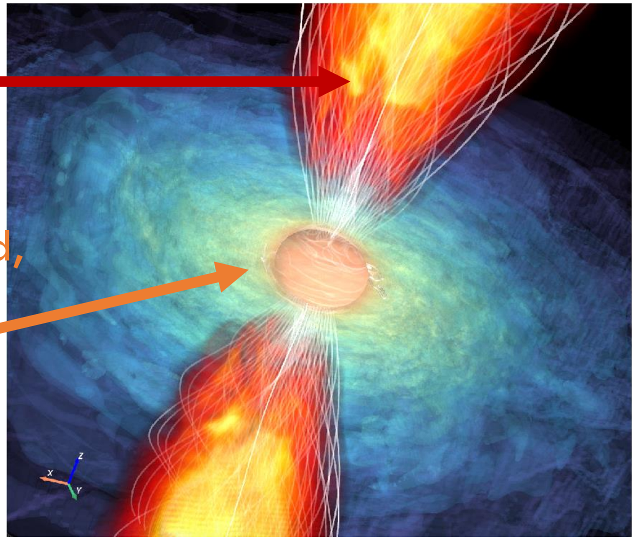
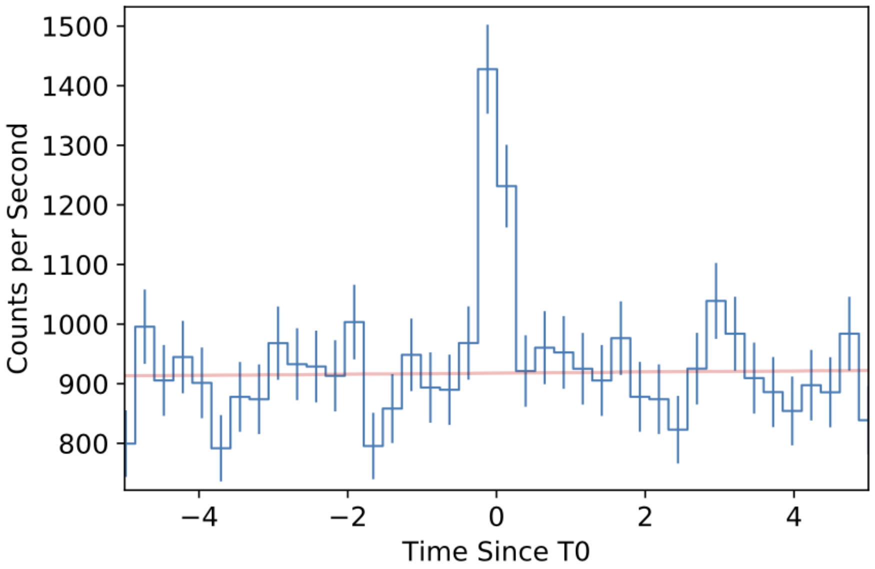
Gamma-ray bursts (GRBs)

- Seconds-long duration gamma-ray emission observable, e.g.
- Powered by dissipation of energy within a collimated relativistic jet
- Astrophysical sites:
  - Central engine – proto-magnetar or black hole
    - Remnants of compact object mergers or collapsed massive star cores
- Often discovered alongside other signals



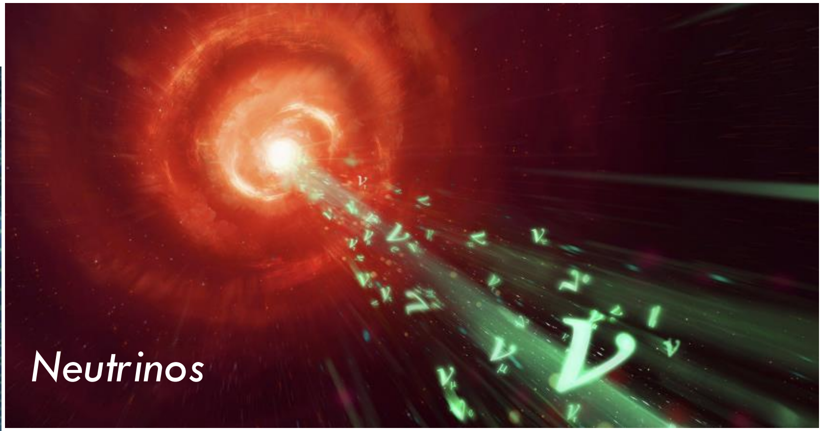
Desai+2026 (*submitted, ApJL*)



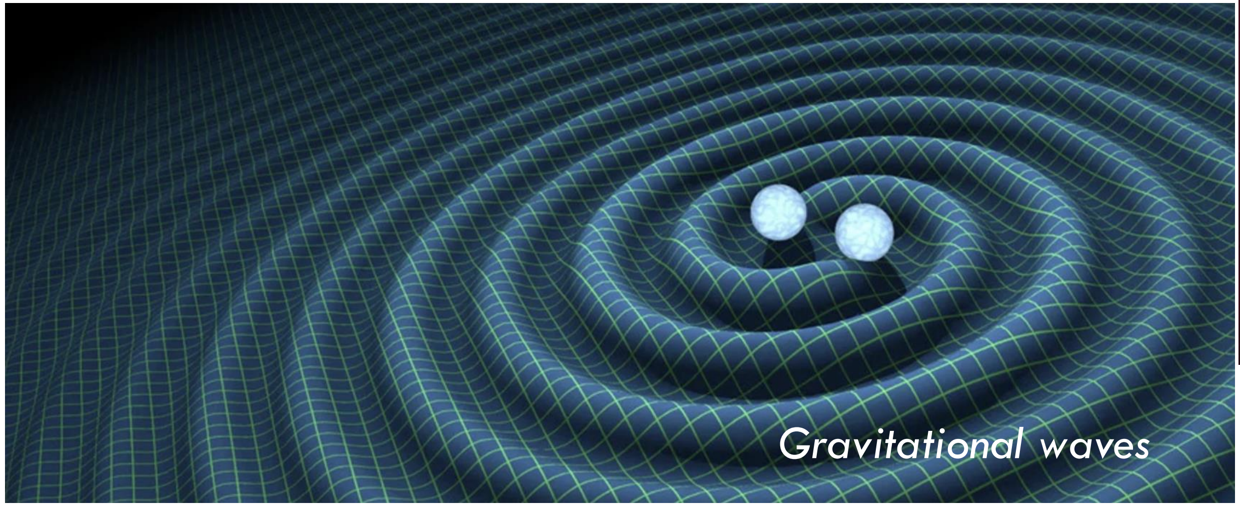
Goldstein+2017

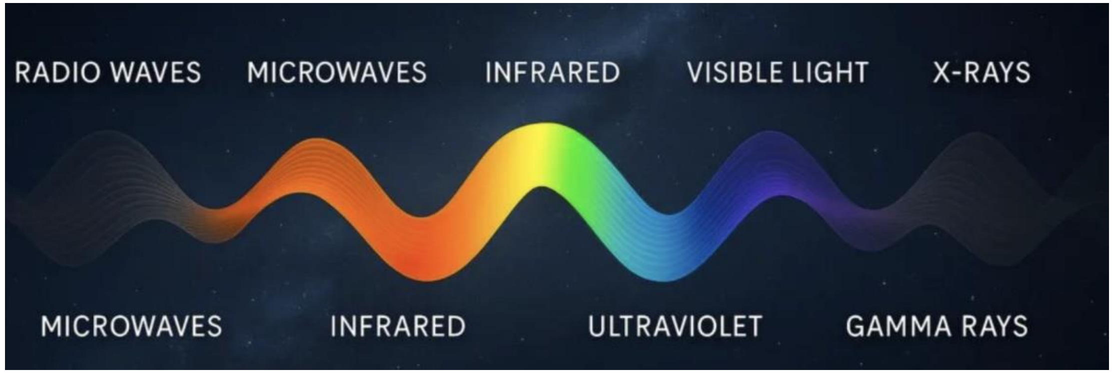
GRBs: one of many *multi-messenger* observations…

Maciej Rebisz, *Quanta Magazine*

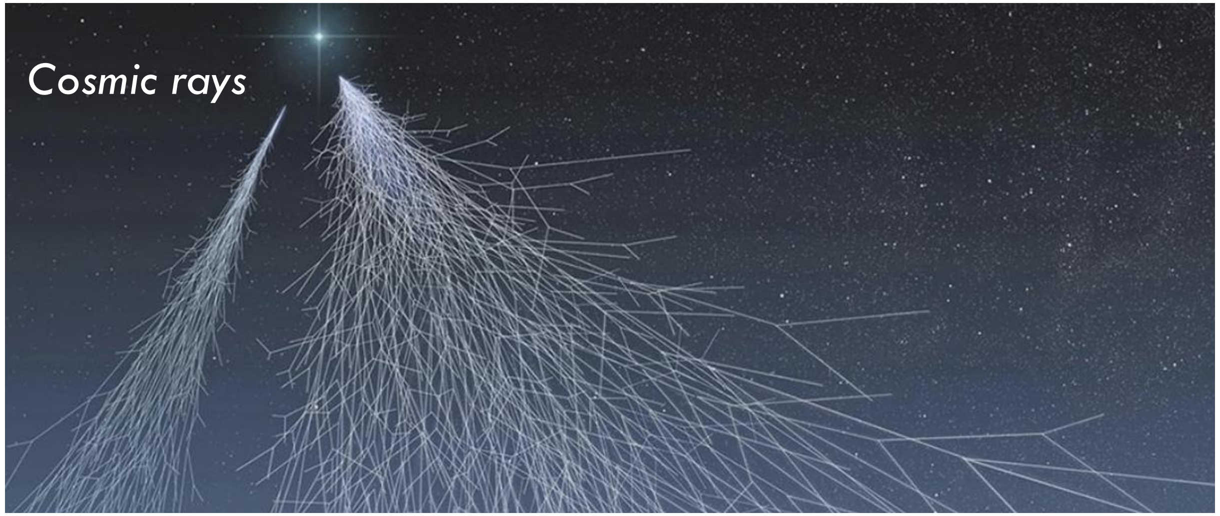


Caltech





solarblog.pl



ASPERA

Highlight: short duration GRB associated with GW170817

GRBs: one of many *multi-messenger* observations…

…which help us probe fundamental physics

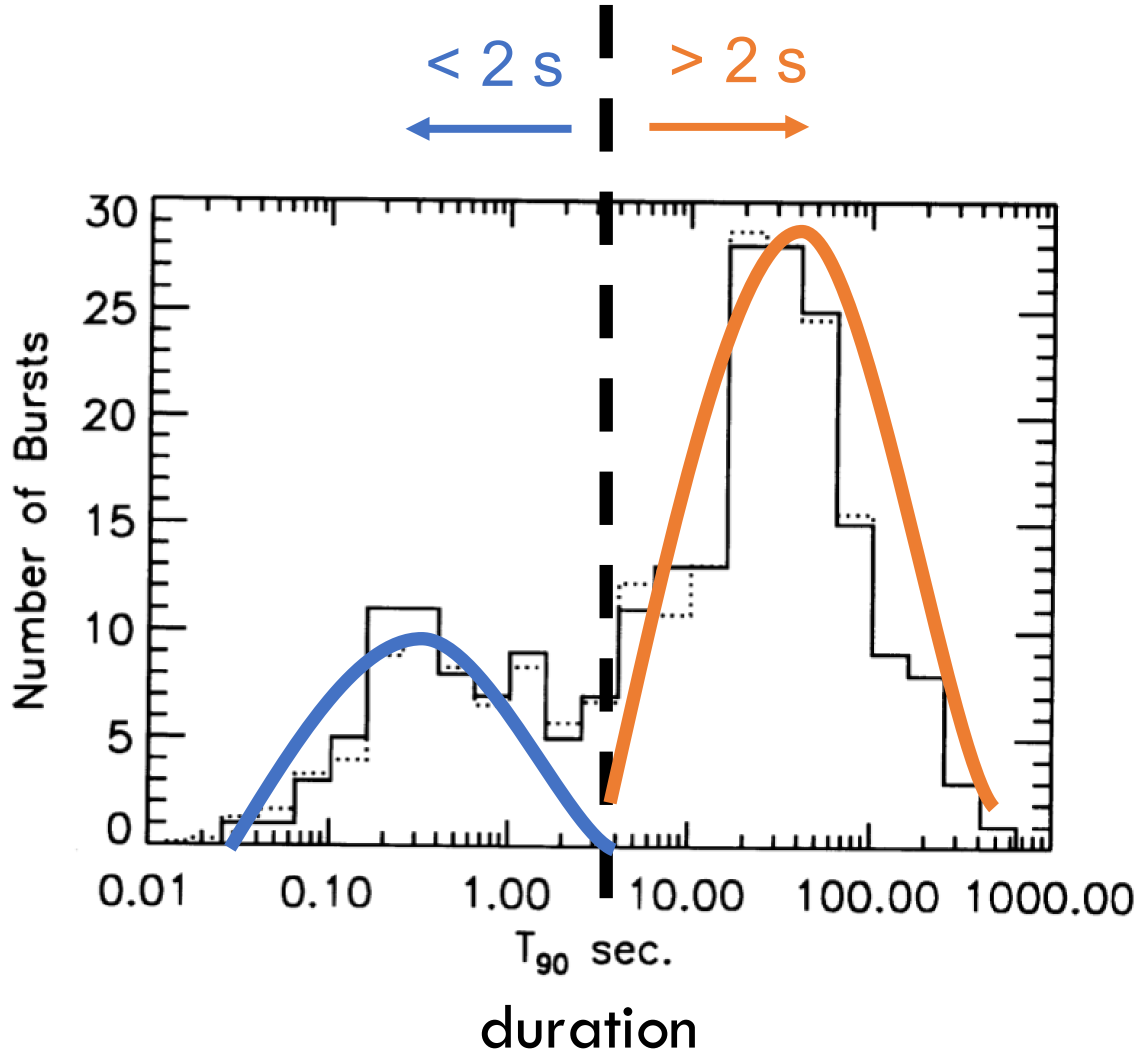
- Sites of r-process element production (among the heaviest elements in the periodic table)
    - Properties of neutron-rich matter
- Physics of neutrinos (e.g. flavor conversions)
- Tests of general relativity

Highlight: short duration GRB associated with GW170817

GRBs historically classified by duration: long vs. short

- Short GRBs

mergers



- Long GRBs

core-collapse supernovae

Duration thought to be set by accretion time-scales/disk size

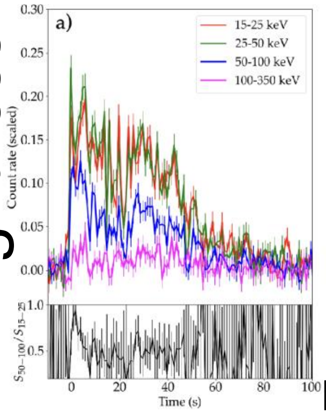
The line between long vs. short may be fuzzier than we thought

Though 1 Short GRB is linked directly to neutron star merger (GW170817),

An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: *Fermi*-GBM Detection of GRB 170817A

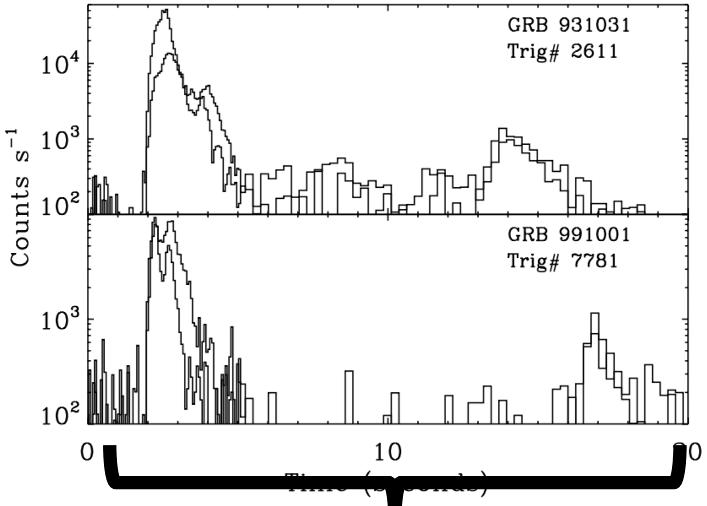
recent long GRBs linked to kilonovae (associated with neutron star mergers)

Brightness



Levan+23

60 s



20 s

Short GRB +

Extended emission

Big open questions

- What are the dominant astrophysical sites are responsible for the production of the heaviest elements?
- What are the central engines of gamma-ray bursts? How can they power a jet?

Central engine: proto-magnetar or black hole?

Black hole

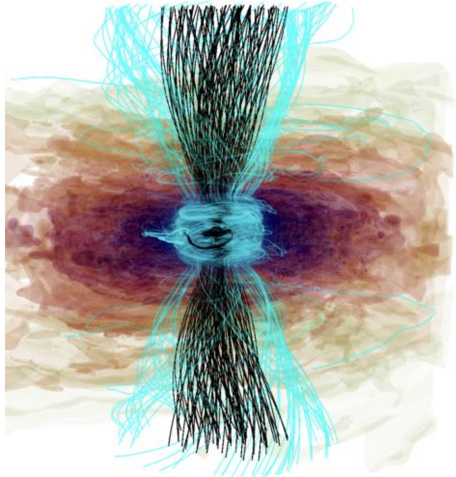
powered by accretion

Operates via Blanford-Znajek mechanism

Nasa

Proto-magnetar

Powered by its rotational energy



Central engine: proto-magnetar or black hole?

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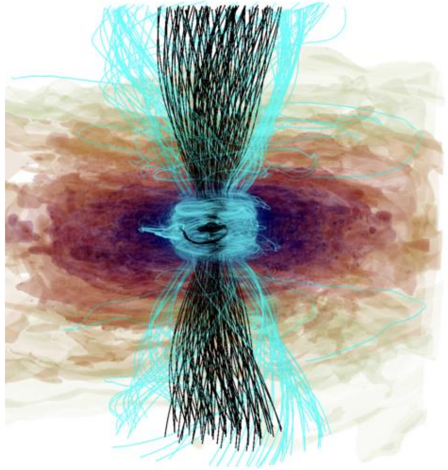
Proto-magnetar

Powered by its rotational energy

Favored because BH cannot baryon load polar jet



Central engine: proto-magnetar or black hole?

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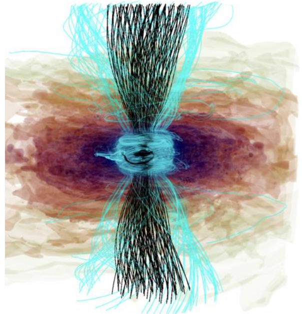
Proto-magnetar

Powered by its rotational energy

I focus on viability of proto-magnetars as central engines



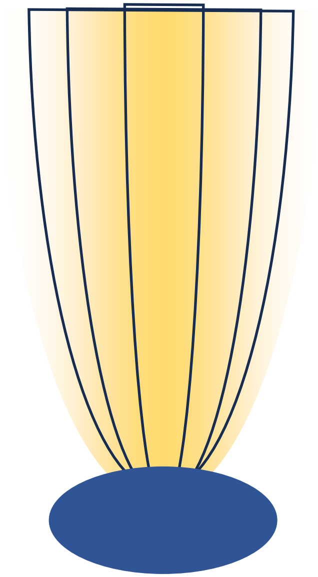
Central question of our latest work:

Can a proto-magnetar power a jet?

i.e., can it produce collimated, relativistic outflows?

Does such a steady-state solution exist?

Jets have large inferred Lorentz factors (>10). How?



$$\Gamma Mc^2 = E_{kin} + E_{mag} + E_{therm} + Mc^2$$

Total fluid energy

This is the energy budget for outflows

Jets have large inferred Lorentz factors (>10). How?

$$\Gamma_\infty Mc^2 = E_{kin} + E_{mag} + E_{therm} + Mc^2$$

Asymptotic Lorentz factor

If magnetically dominated…

$$E_{mag}/Mc^2 = \sigma \equiv b^2/4\pi\rho c^2$$

$$\Gamma_\infty = \sigma + 1 \approx \sigma$$

Jets have large inferred Lorentz factors (>10). How?

$$\Gamma_\infty Mc^2 = E_{kin} + E_{mag} + E_{therm} + Mc^2$$

If magnetically dominated…

$$\Gamma_\infty = \sigma + 1 \approx \sigma$$

Not my problem →

$E_{mag} \rightarrow E_{kin}$

(over distances ~ 10^4 km)

$$\sigma \equiv b^2/4\pi\rho c^2$$

Magnetization is key

reformulated:

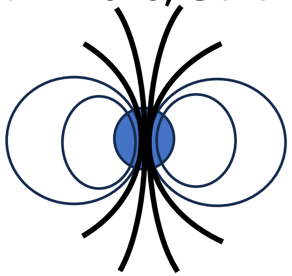
Can proto-magnetars have magnetically-dominated (high - σ) outflows?

Previous work + open questions

- Local/global simulations: How do proto-magnetar properties develop self-consistently?

e.g. Mösta+20, Kuroda+20, Combi+2023, Hayashi+2024, Kiuchi+2024, Kalinani+2025, Gutierrez+2026…

How to form strong, large-scale, ordered B fields???



Previous work + open questions

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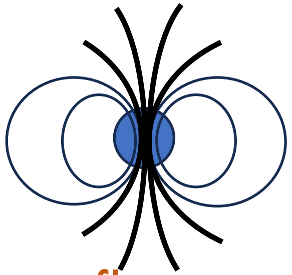


Assume we have strong, large-scale, ordered B fields

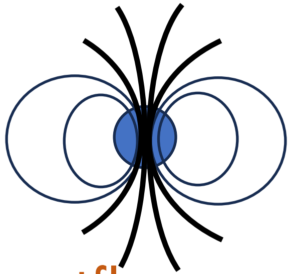
- Proto-magnetar outflows as central engines for GRBs? Are outflow properties compatible? e.g., Bucciantini+06, Metzger+07, +08, Prasanna+2024…

They are 1D or assume neutron star boundary conditions

Previous work + open questions

- Local/global simulations: How do proto-magnetar properties develop self-consistently?

e.g. Mösta+20, Kuroda+20, Combi+2023, Hayashi+2024, Kiuchi+2024, Kalinani+2025…



Assume we have strong, large-scale, ordered B fields

- Proto-magnetar outflows as central engines for GRBs? Are outflow properties compatible? e.g., Bucciantini+2006, Metzger+2007, +2008, Thompson+04, Prasanna+2024…

Assume we have outflow properties on scales ~1000 km

- Large scale jet studies to connect simulations to observations

eg., Ciolfi+2020, Pavan+2025, Dreas+2026…

Ingredients of proto-magnetars

3 key ingredients determine outflow properties

- Net neutrino heating
- Rotation rate (amplified from angular momentum conservation)
- Magnetic field strength/geometry (flux-freezing + dynamos)

Following a successful explosion or merger…

- There may be a phase where accretion disk is gone and other material is ejected

- Left with proto-magnetar winds

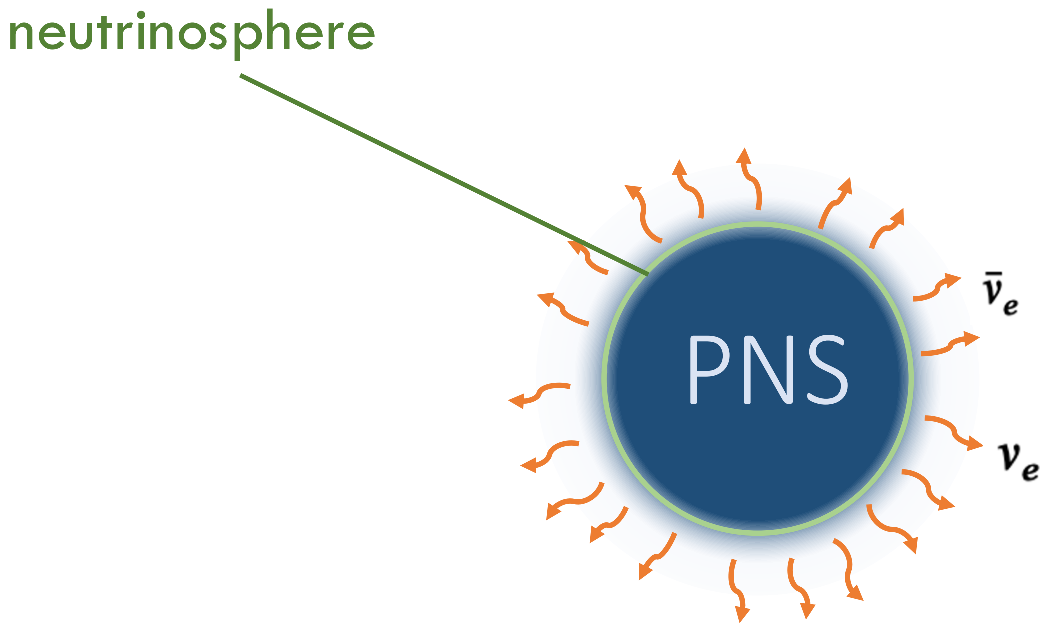
Net neutrino absorption drives baryonic wind

Heating (ν-absorption)

Dominant interactions: $\nu_e + n \longleftrightarrow e^- + p$ and $\bar{\nu}_e + p \longleftrightarrow e^+ + n$

(charge-current)

Cooling (ν-emission)



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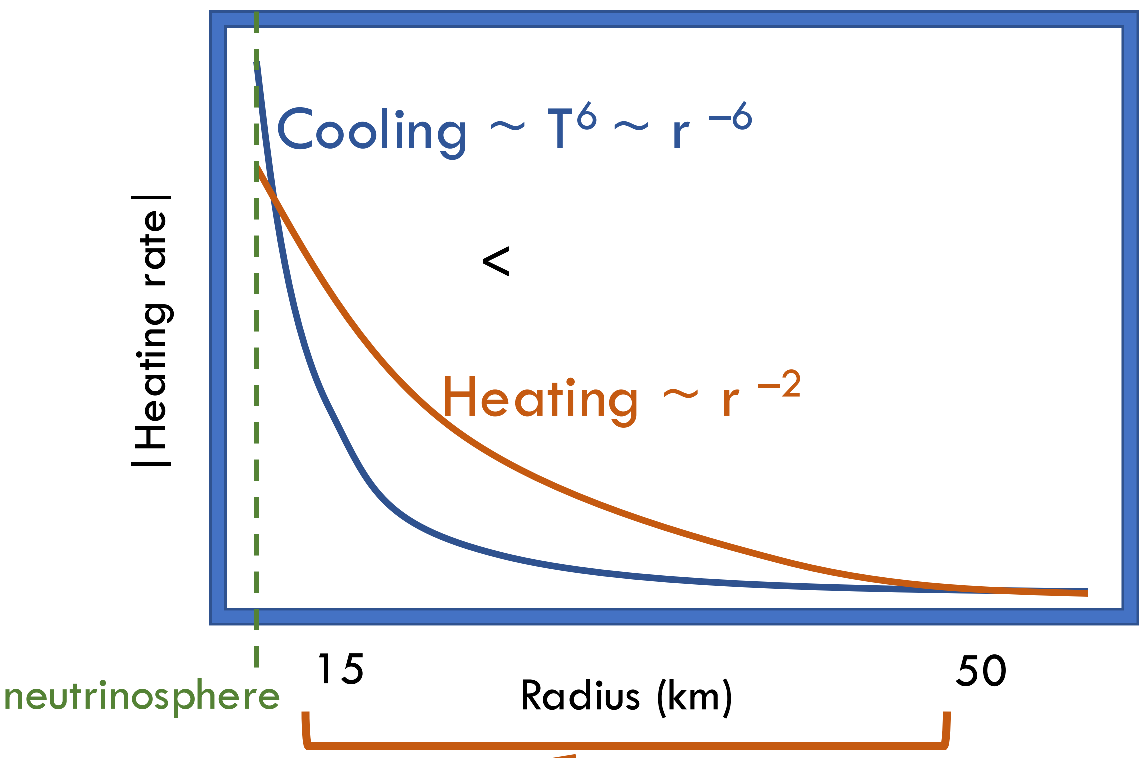

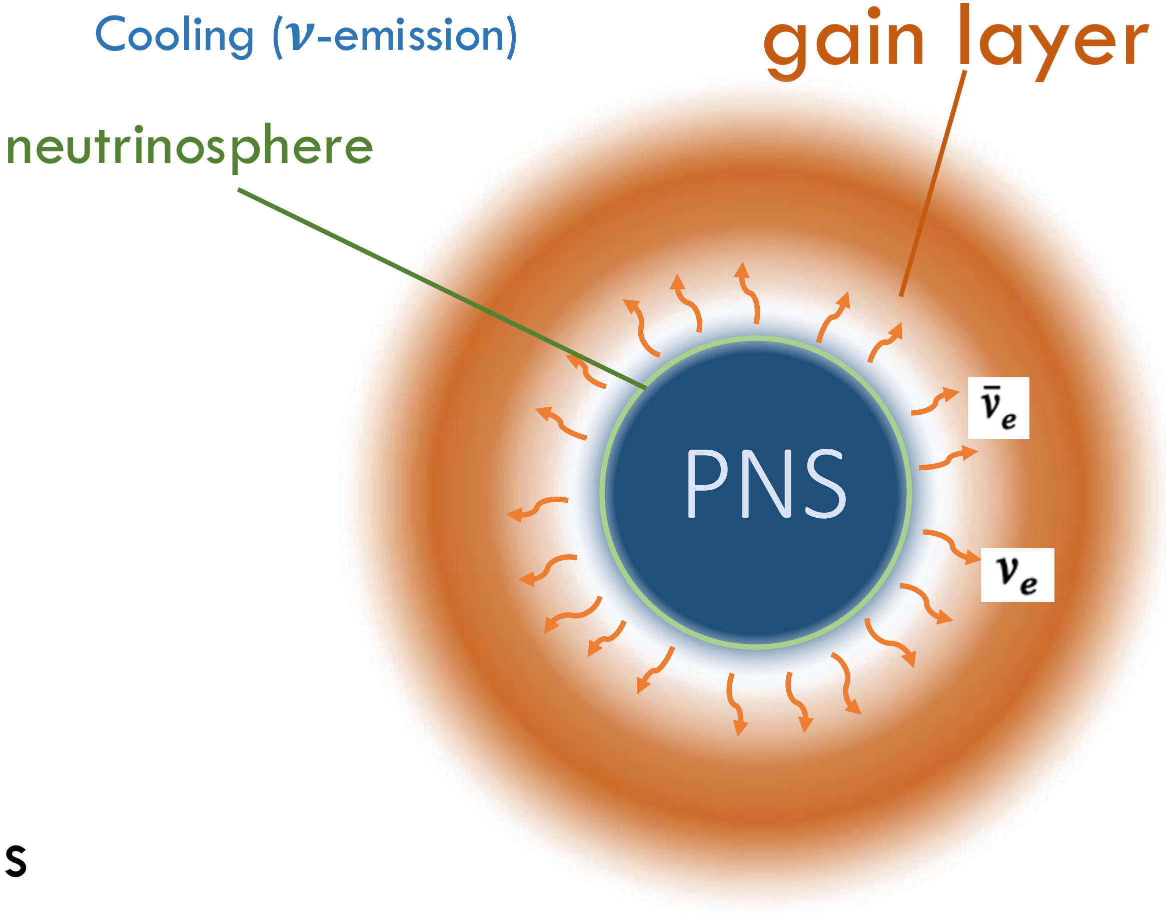

gain layer with net positive heating forms

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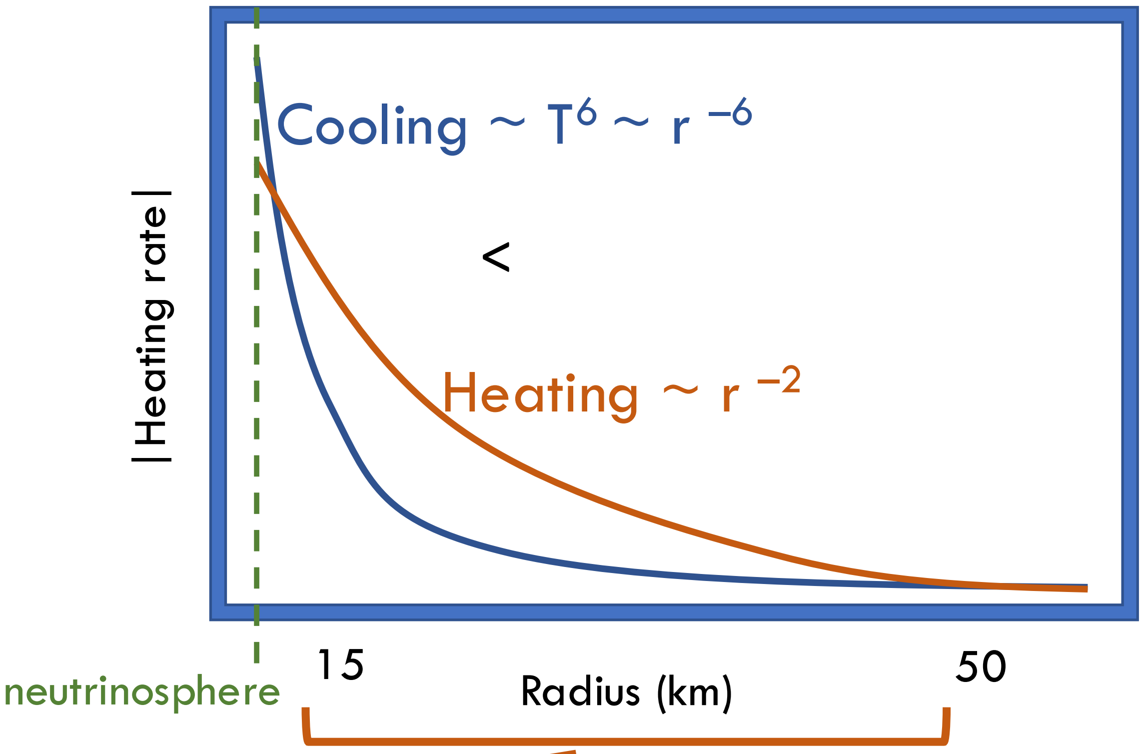
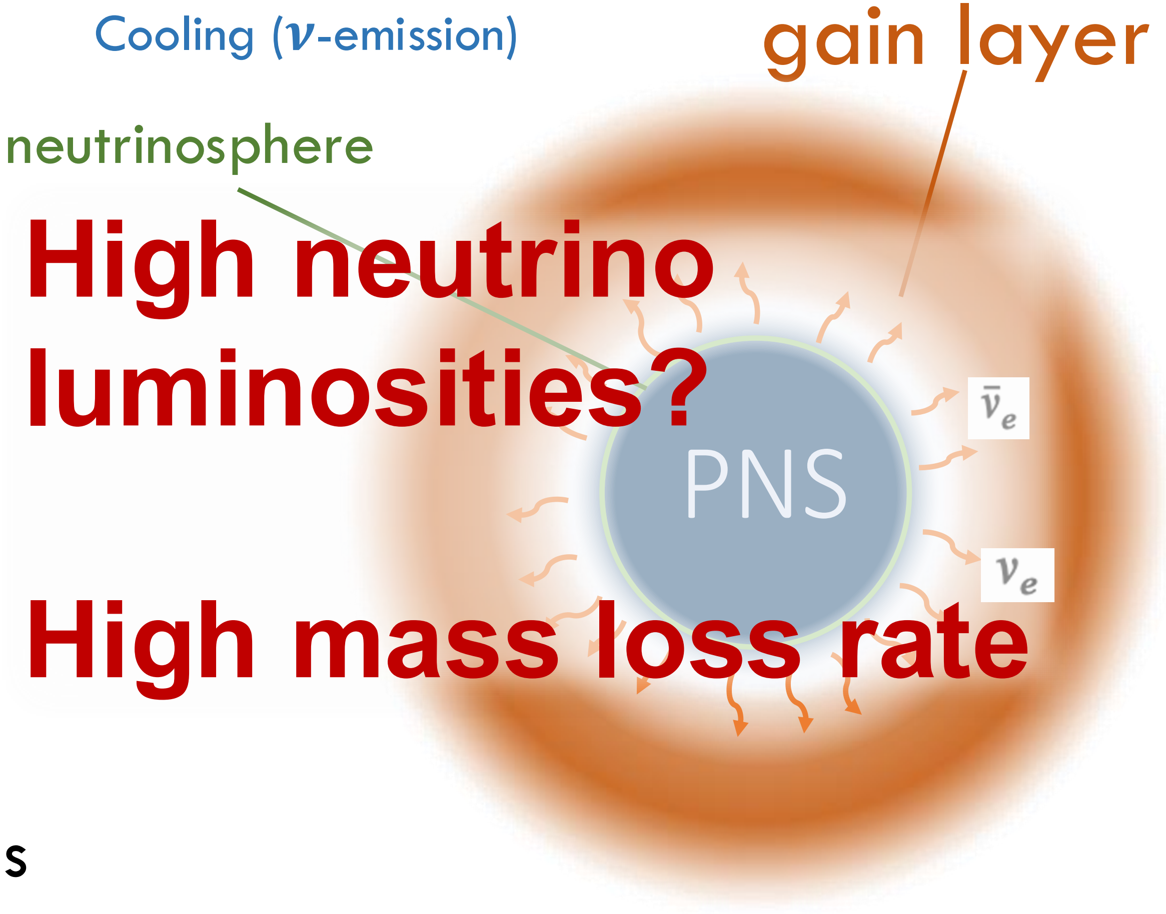
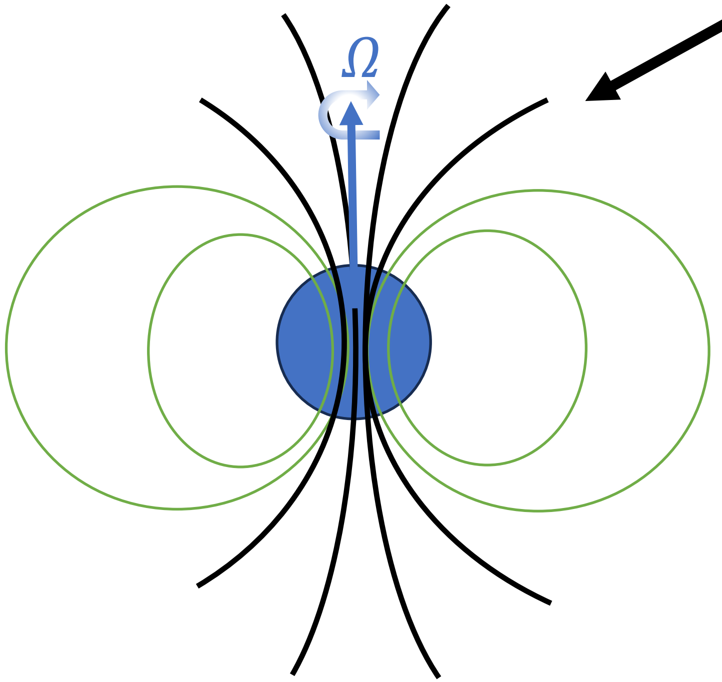




gain layer with net positive heating forms

magnetic fields and rotation can be amplified within ~100s of ms after collapse

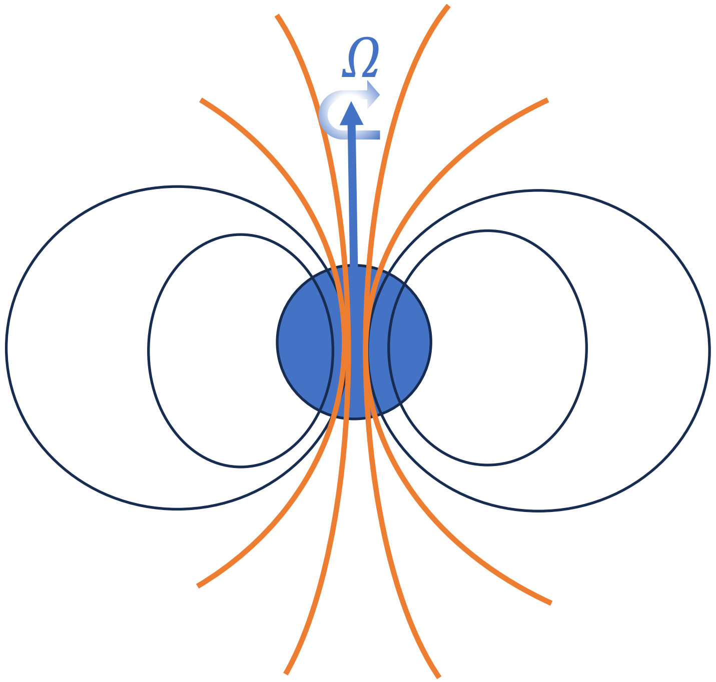
Neutrino heating loads field lines with baryonic matter

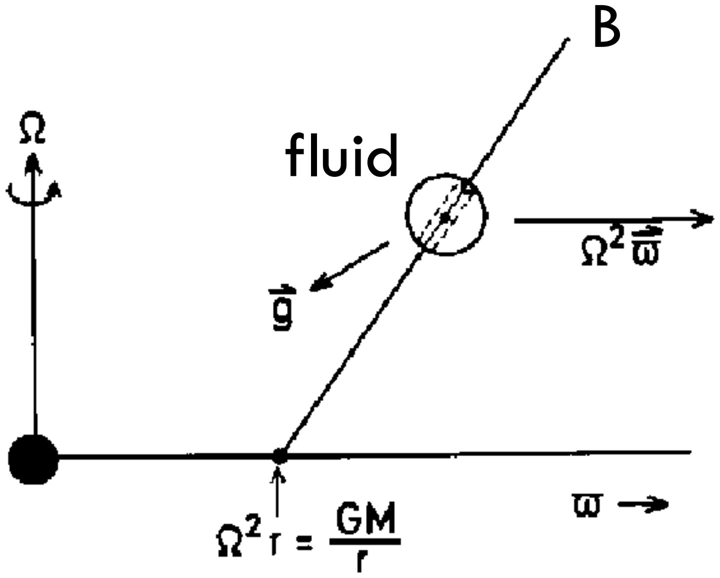


Matter along closed field lines are trapped

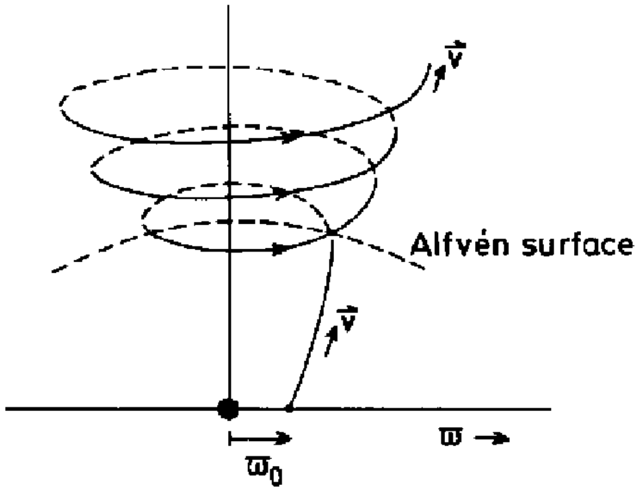
Physical intuition: The stronger the magnetic field the more rigid the wires along which fluid travels

Rotation + magnetic fields can sling fluid along open field lines





Spruit 96



The faster (stronger) the rotation (magnetic field), the greater the acceleration

Long-term global evolution (~seconds) of merger/collapse is uncertain/ has diverse outcomes

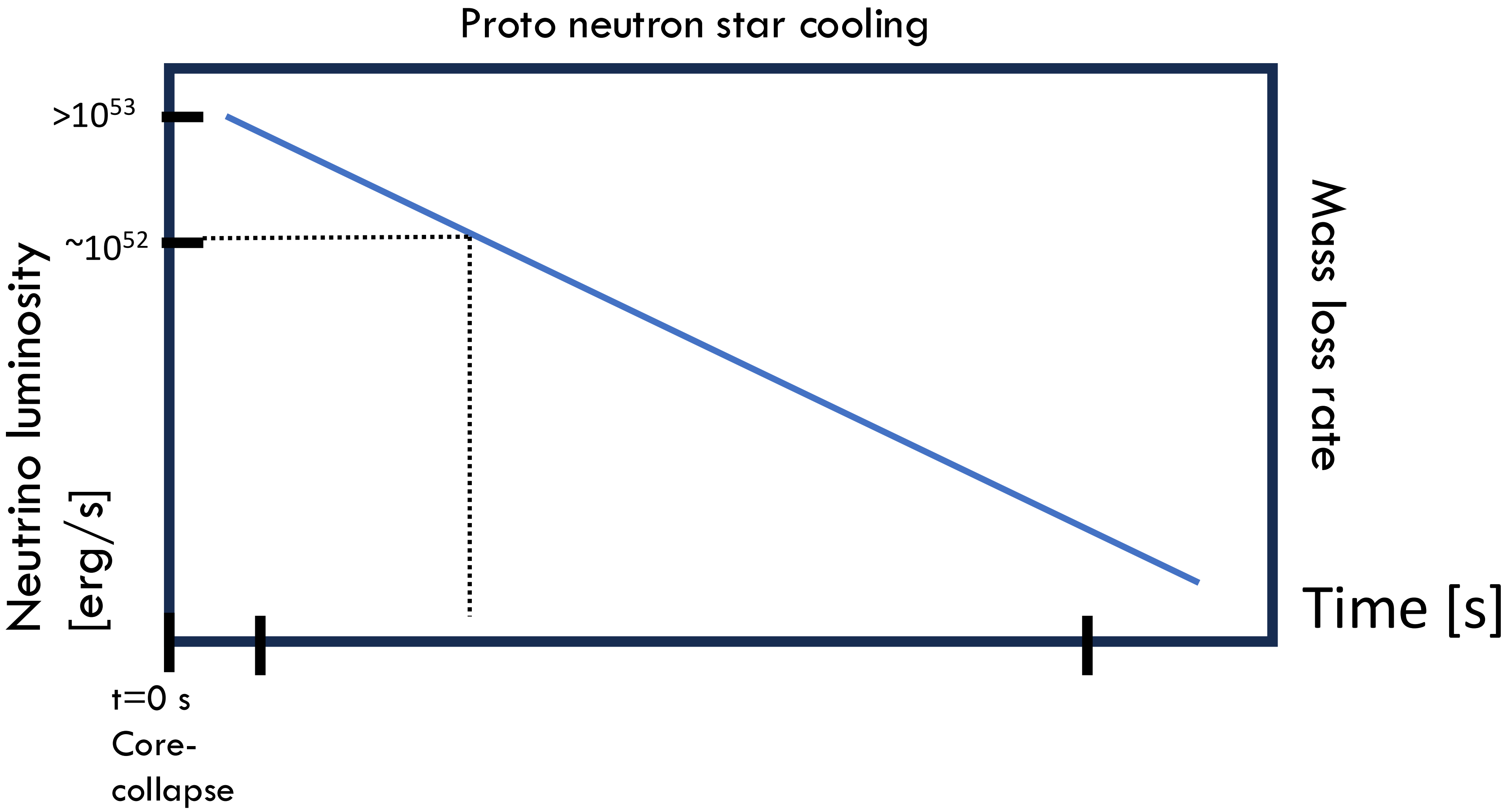
Uncertainties in the physics (e.g. EOS, progenitor models…)

Computationally challenging to simulate with all the key physical ingredients for ~seconds

Imagine the following *successful* supernova scenario producing a long-lived proto-magnetar…

Cooling time scale is ~seconds

Clean, baryonic wind may develop following successful, energetic supernova explosion after ~few seconds



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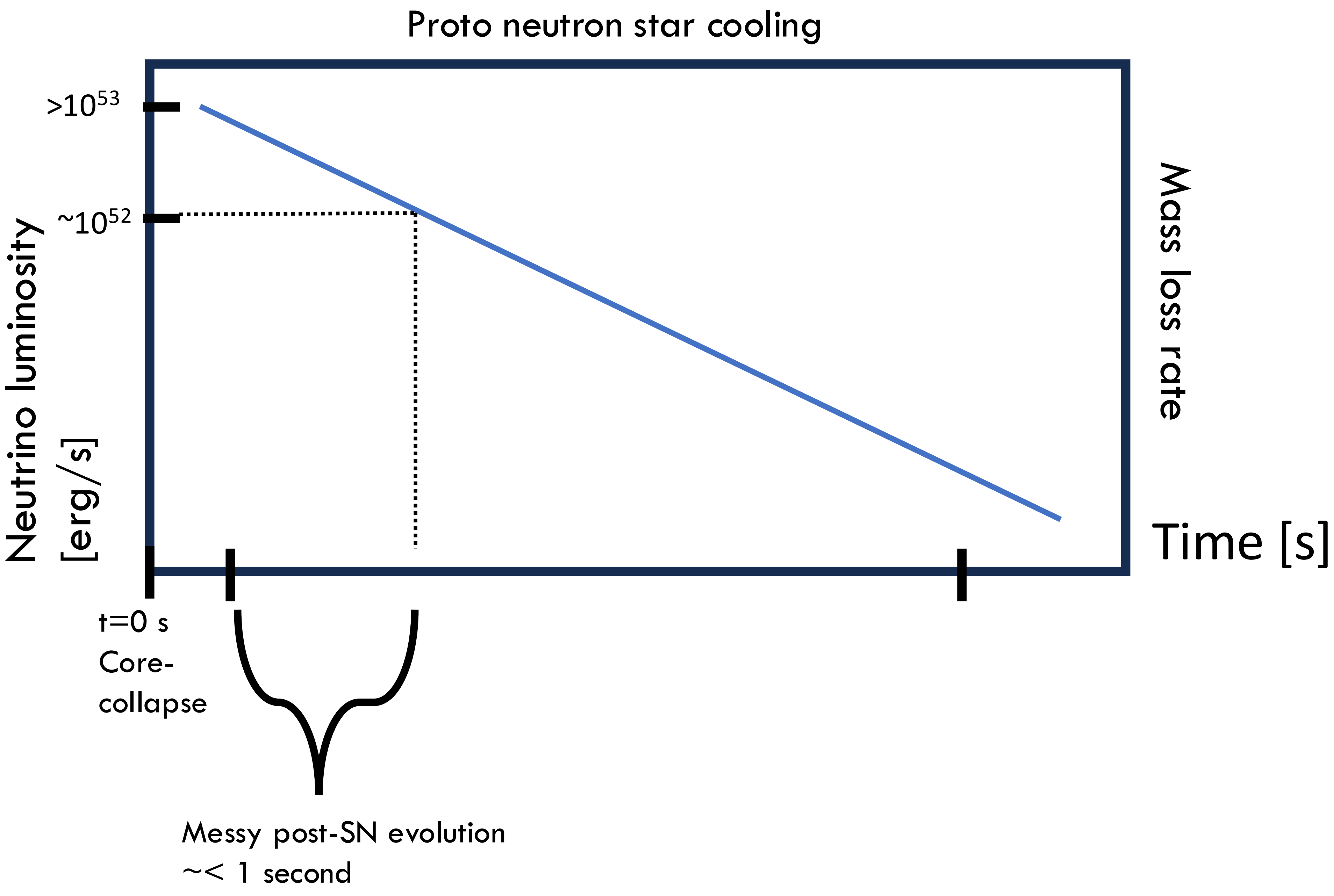

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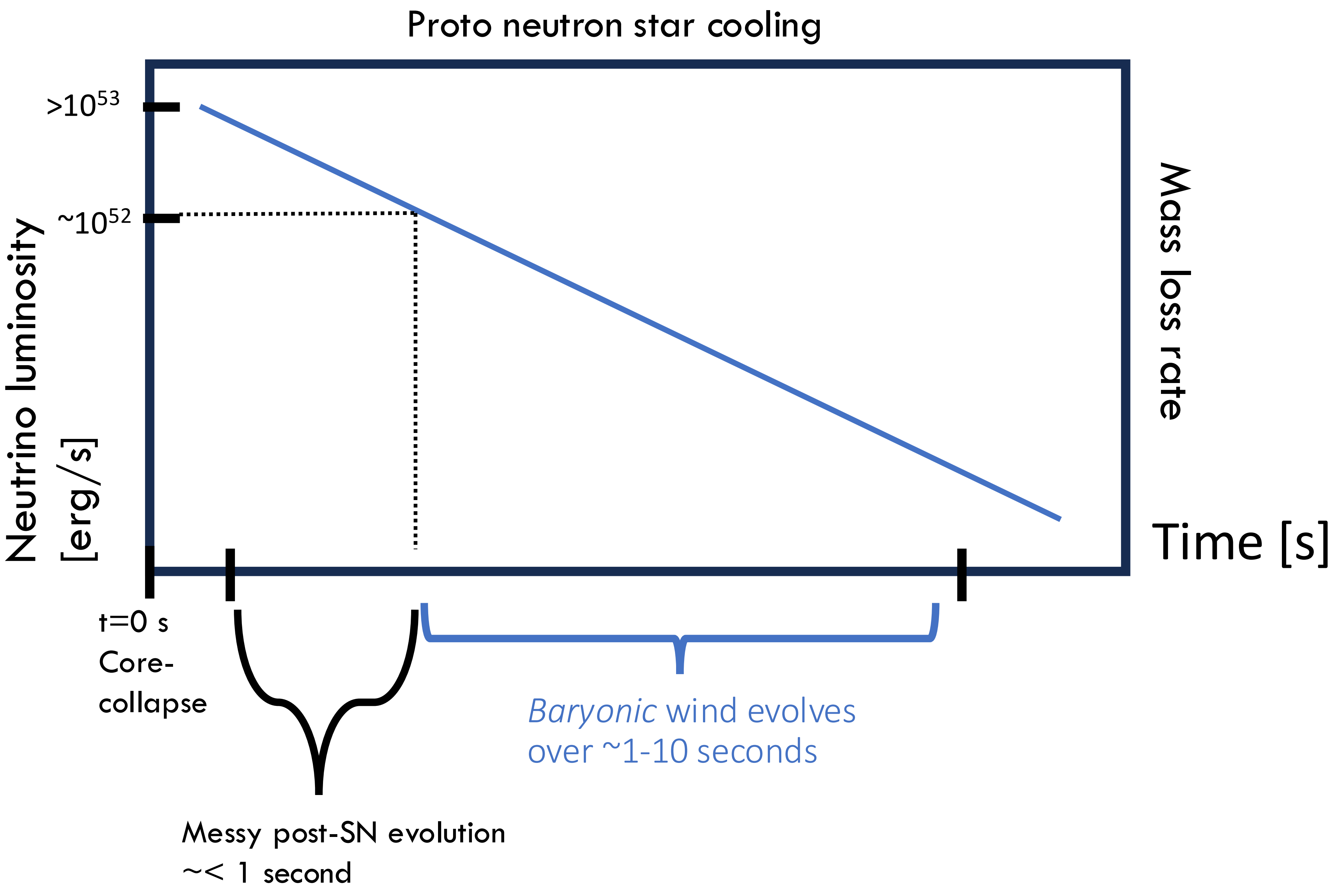

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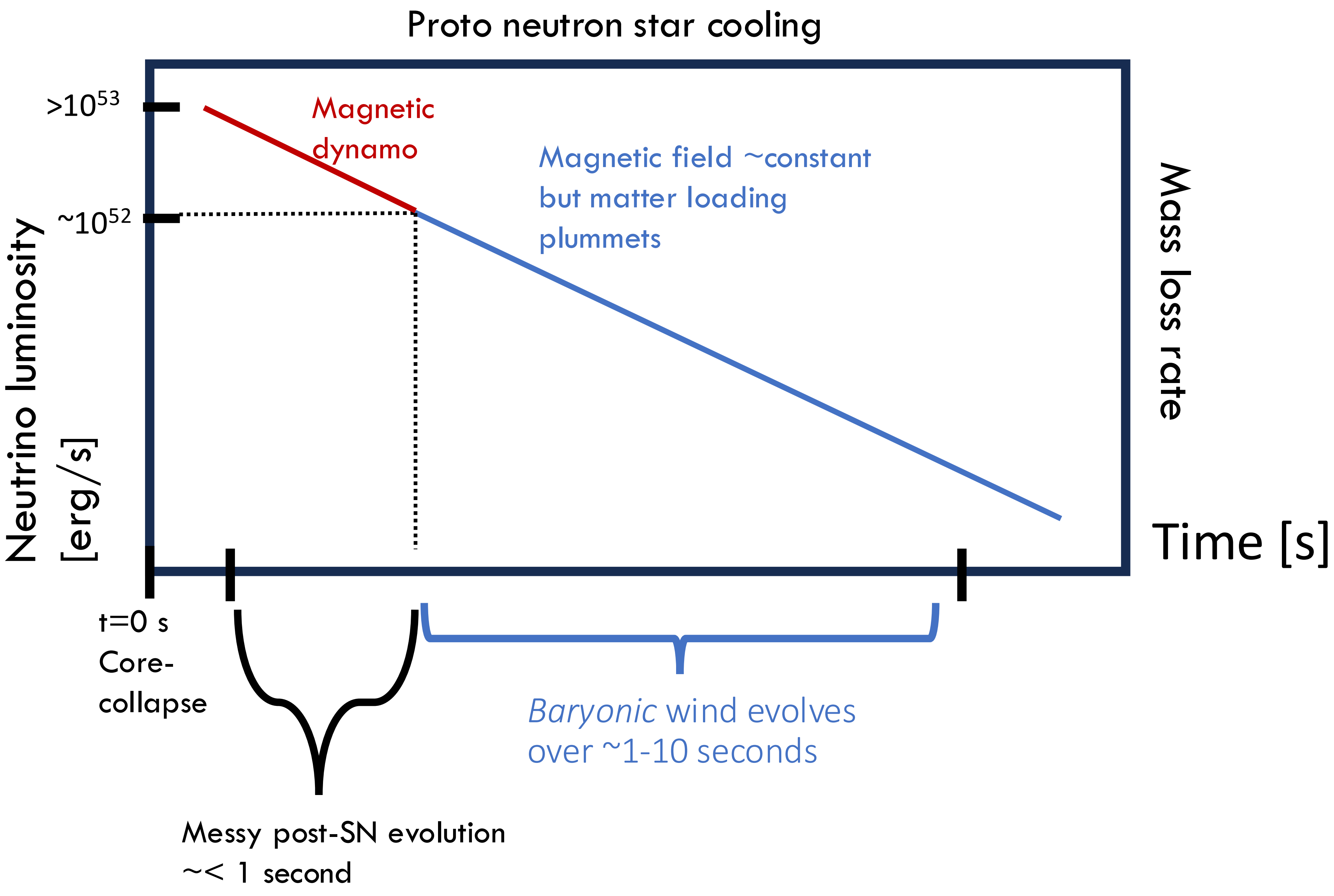

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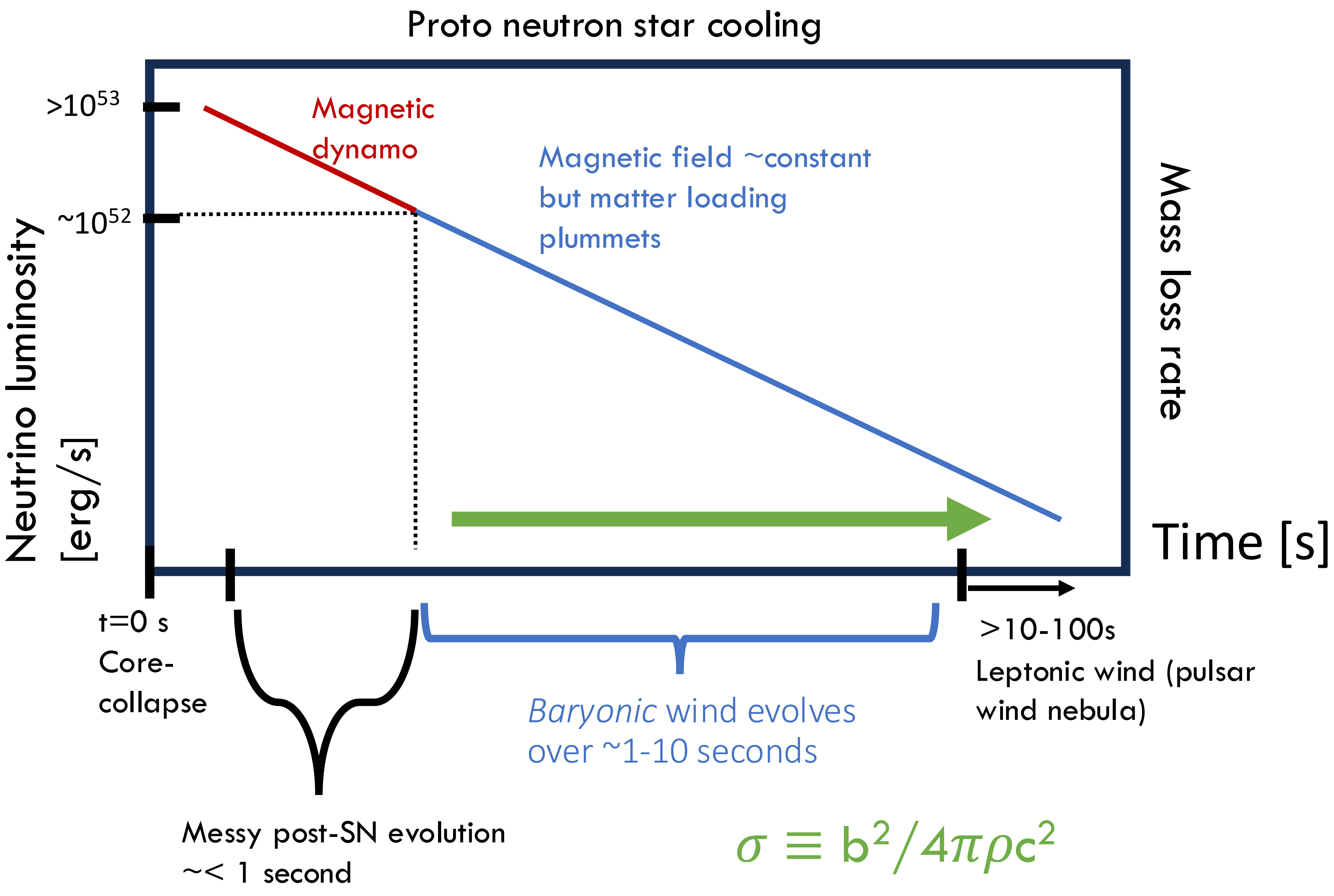


$$\sigma \equiv b^2/4\pi\rho c^2$$

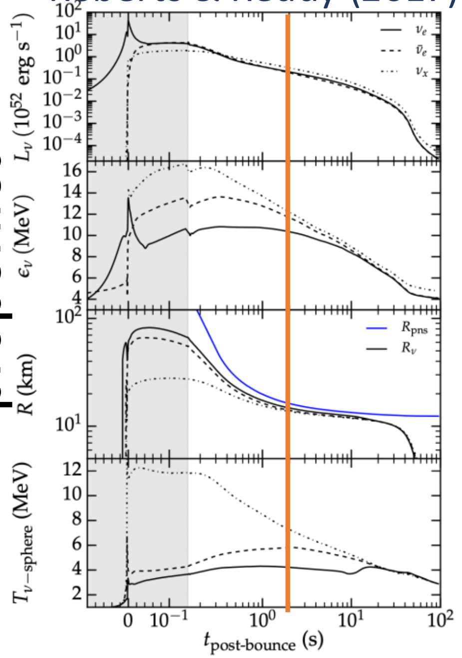
grows in time. Can reach ~1000

Aim: capture steady-state outflows for a variety of configurations

Previously: Isolated effects of rotation, magnetic fields (Desai+22, Desai+23)

Roberts & Reddy (2017)

Neutrino properties



Time

+ Magnetic fields

+ rotation

Wind properties, eg:

- Mass loss rate
- entropy
- Composition
- magnetization

The first 3D GRMHD simulations of neutrino-heated winds from rapidly rotating, strongly magnetized proto-magnetars

GRMHD simulations: toy models to better understand outflows

proto-magnetar not formed self-consistently from core-collapse simulation

idealized, controlled environment

GRMHD simulations as toy models allow us to…

Be agnostic of progenitor

- WD collapse
- massive star collapse
- merger

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Compare to observations - diverse

GRMHD simulations as toy models allow us to…

Be agnostic of progenitor
- WD collapse
- massive star collapse
- merger

Compare to observations - diverse

Disentangle physical mechanisms

Our 3D GRMHD toy model

Evolution code

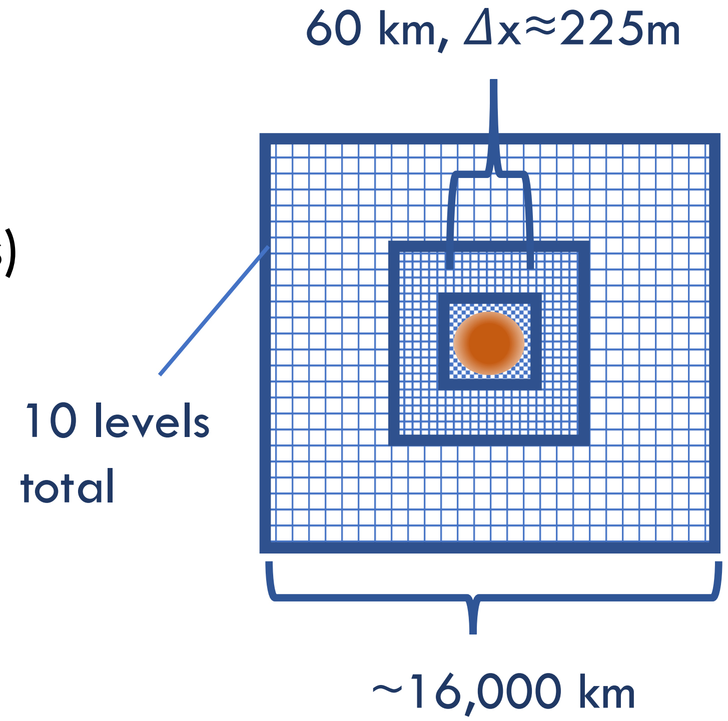
- GRMHD code (Siegel & Metzger 2018)
  - B-field evolution now using **vector potential formalism**
  - Hydro solver: HLLE + weno-z (adaptive scheme in high gradient regions, high magnetizations)

- Tabulated SFHo nuclear equation of state (Steiner+2013)

- 1-moment (M0) scheme for neutrino transport (Radial equations evolving neutrino mean energies/number densities along radial rays)
  - Emission + absorption (Radice+16, with modifications)
- Rotating models use RNS (Stergioulas+95)

Nested Grid setup

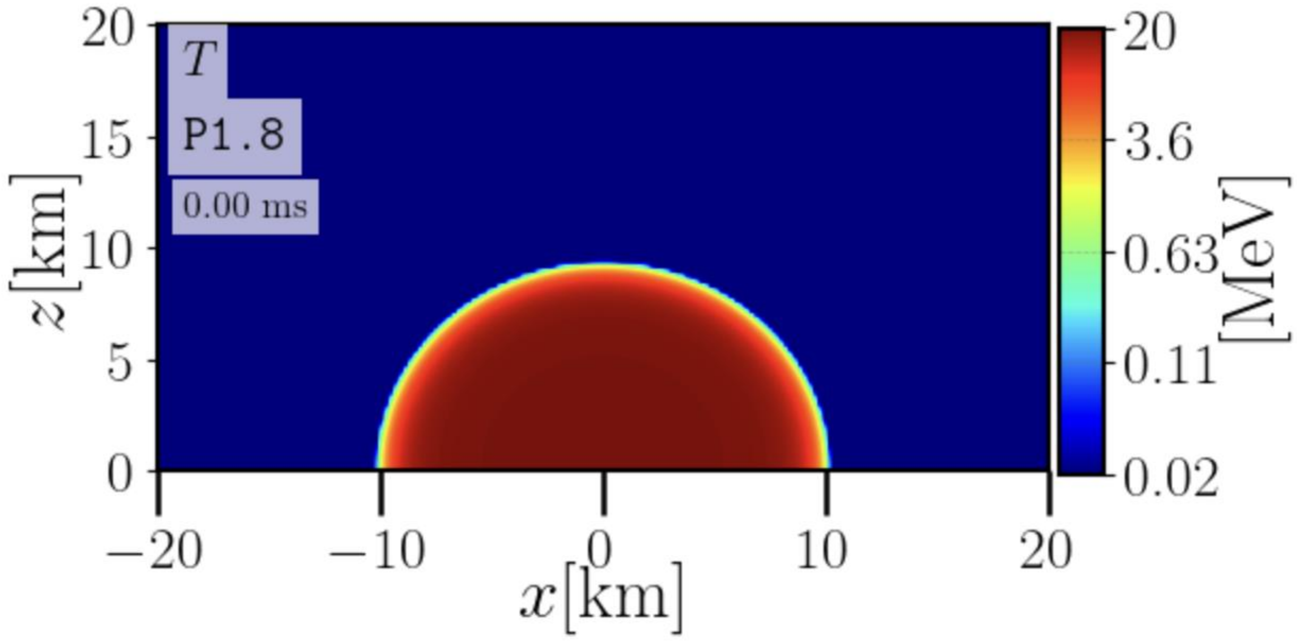
- Cartesian 3D grid with static mesh refinement. Reflection symmetry.



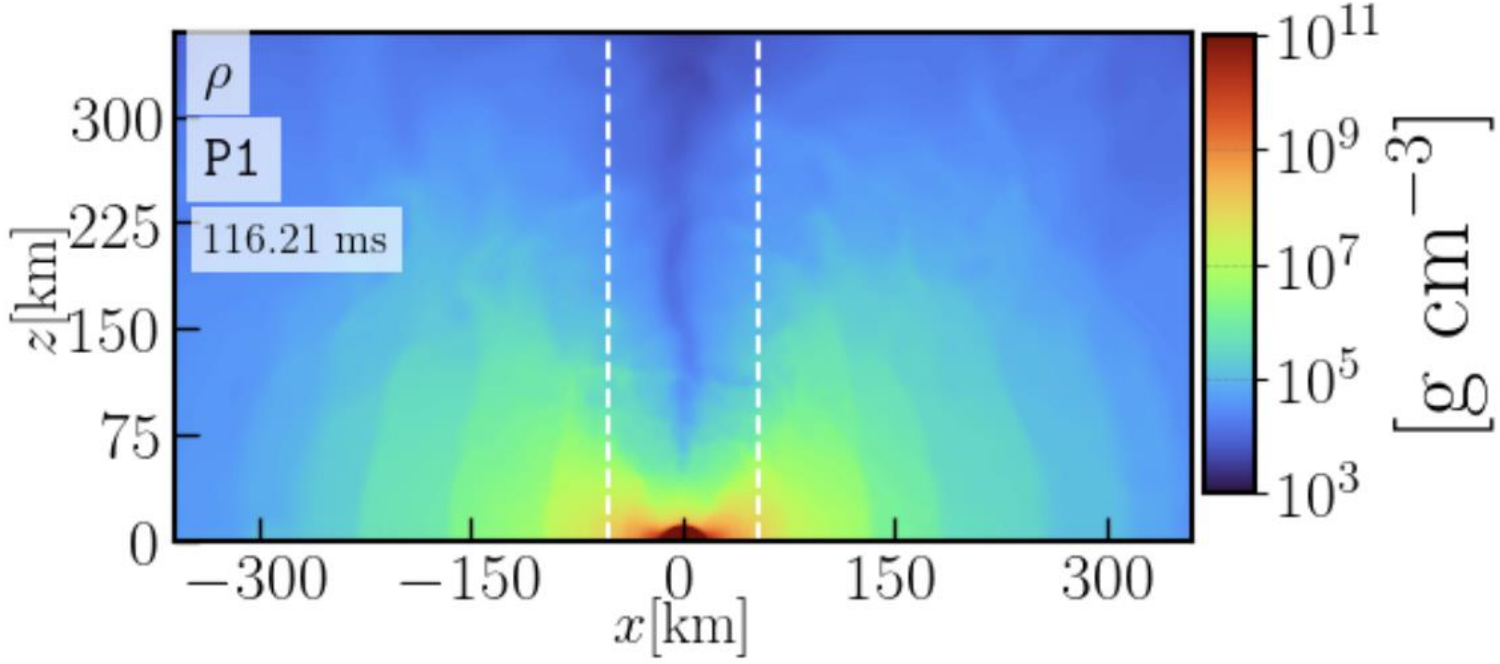
Our GRMHD toy model: Initial Conditions

- 1.4 solar mass NS
- Hot: T_c~20 MeV, chosen to reproduce steady state neutrino emission
- Metric fixed after initial time step (low mass loss rate)

Initial temperature profile



First: models evolved to steady-state outflows



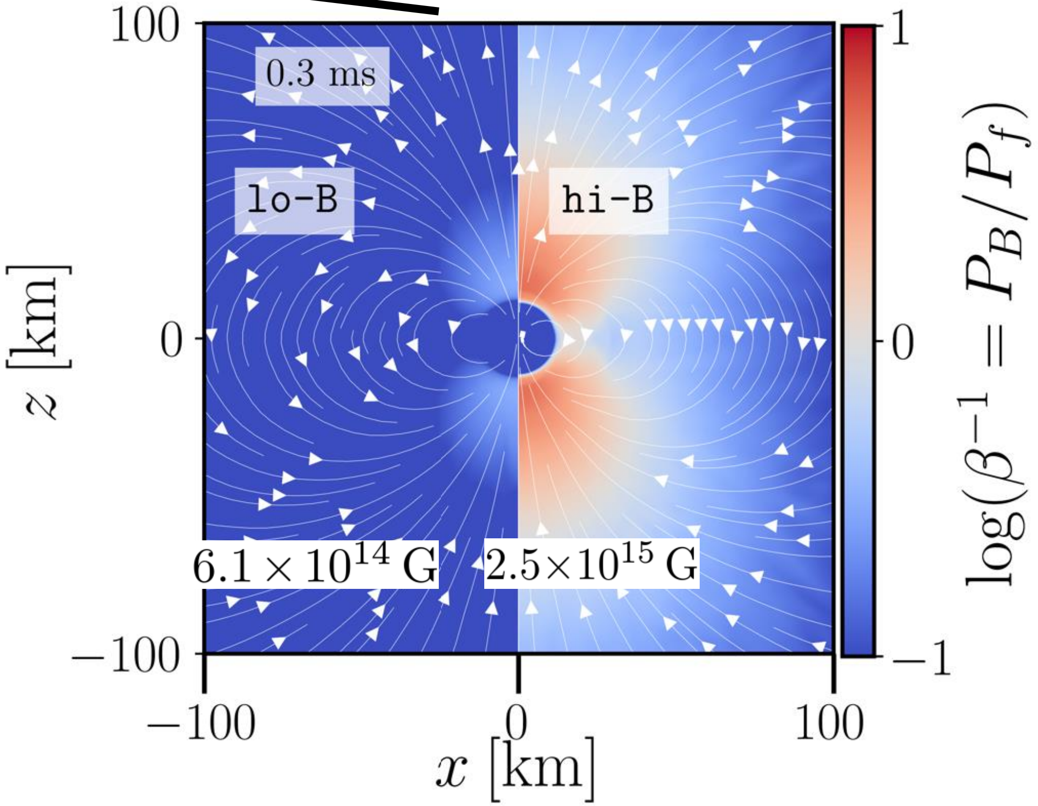
t~50-100 ms

https://arxiv.org/abs/2306.03973

Then, large-scale dipole magnetic field initialized

Again we evolve to steady-state outflows (~50 ms)

We present these outflows.



Desai+2023 (accepted)

Criterion for rotation to impact the wind

Rotation speed at neutrinosphere radius is comparable to the sound speed

$$P_c \approx 2\pi \frac{R_\nu}{c_s}$$

Speed of sound (isothermal):

$$c_s \simeq (kT/m_p)^{1/2}$$

Blackbody neutrino luminosity:

$$L_\nu \simeq 4\pi 7/8 R_\nu^2 \sigma T^4$$

In terms of neutrino properties:

$$P_c \approx 2\pi \frac{R_\nu}{c_s} \approx \boxed{3.4\ \mathrm{ms}} \left(\frac{R_\nu}{12\ \mathrm{km}}\right)^{5/4} \left(\frac{L_\nu}{10^{52}\ \mathrm{erg\ s^{-1}}}\right)^{-1/8}$$

Wind dynamics impacted for rotation periods **less than ~3 ms**

Desai+2022

Criterion for magnetic fields to impact the wind

Magnetic pressure is comparable to fluid pressure at base of wind

$$P_{\rm B} = B^2/8\pi$$

Fluid pressure (radiation-dominated):

$$P_f \simeq P_{\rm rad} = (11/12)aT^4$$

Blackbody neutrino luminosity:

$$L_\nu \simeq 4\pi 7/8 R_\nu^2 \sigma T^4$$

In terms of neutrino properties:

$$B_{\rm crit} \approx \boxed{1 \times 10^{15}\ {\rm G}} \left(\frac{L_\nu}{4 \times 10^{51}\ {\rm erg\ s^{-1}}}\right)^{1/2} \left(\frac{R_\nu}{10^6\ {\rm cm}}\right)^{-1}$$

Wind dynamics impacted for magnetic field strengths **greater than ~10^{15} G**

Desai+2022

Criteria to impact the wind dynamics

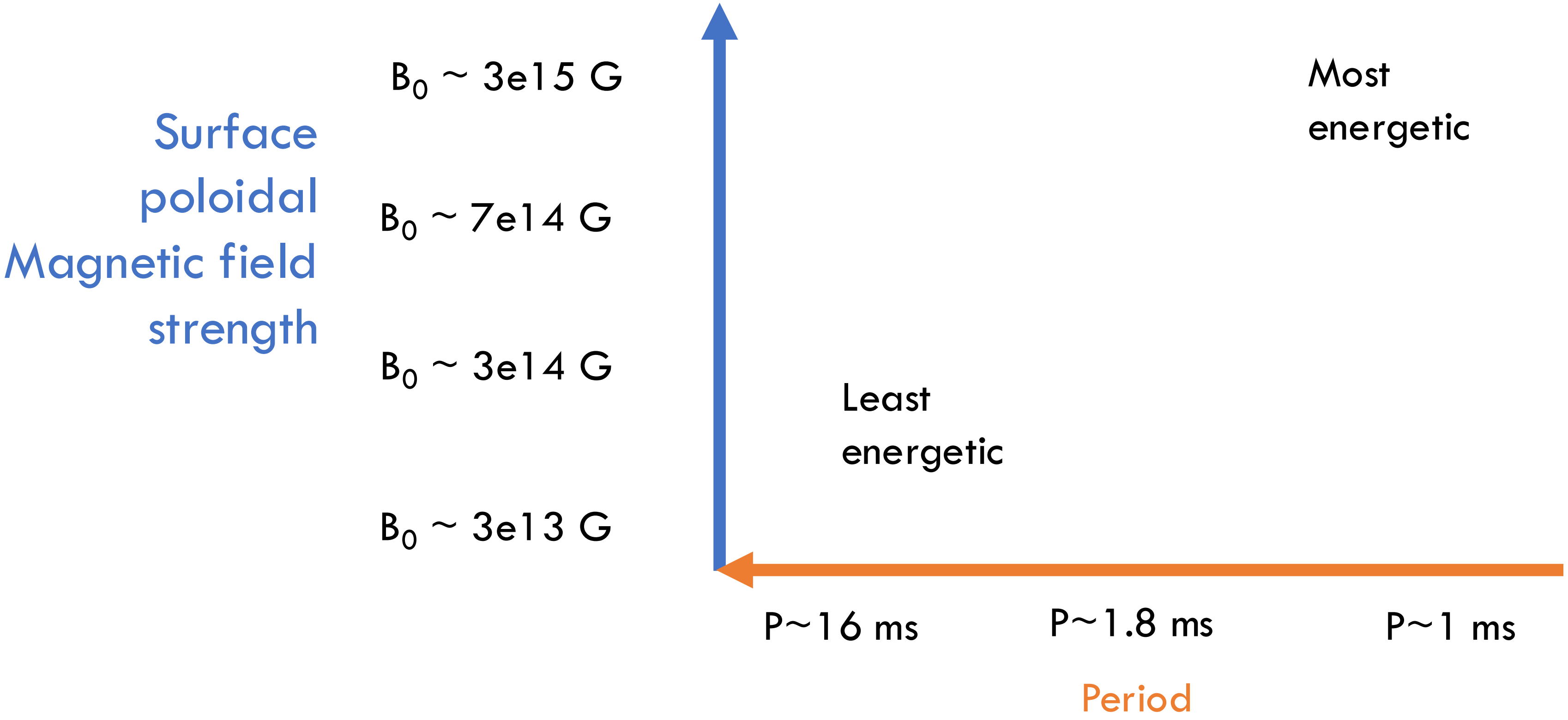
rotation periods **less than ~3 ms**

magnetic field strengths **greater than ~10^{15} G**

Desai+2022

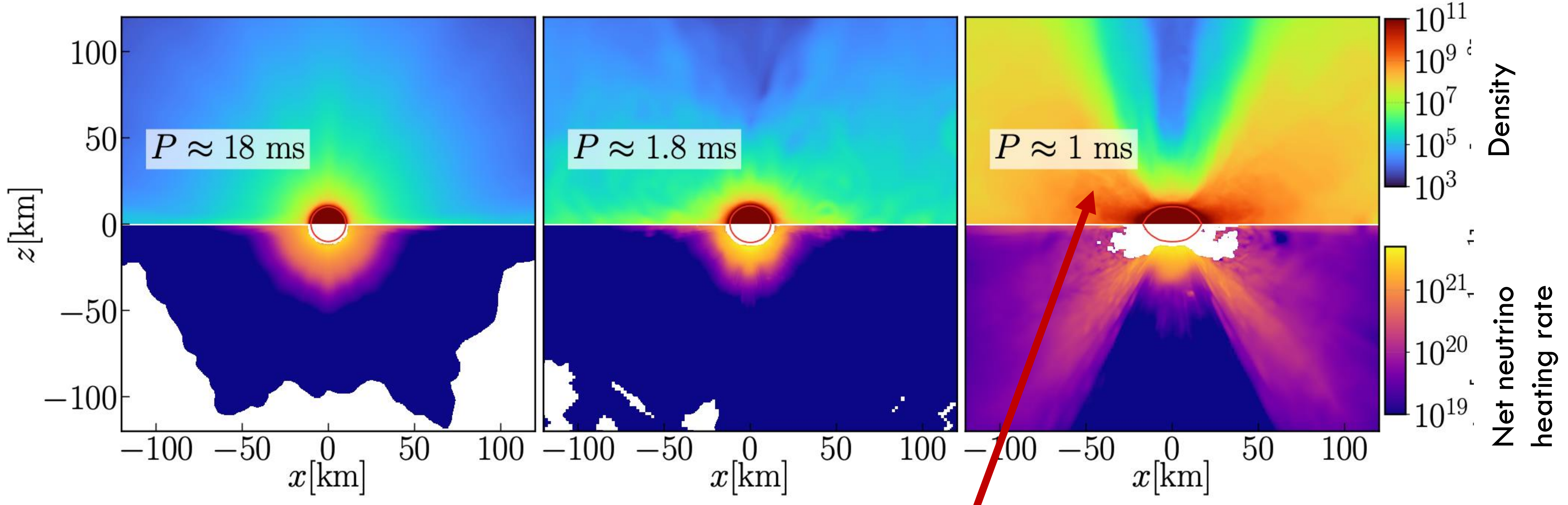
Combining Magnetic fields and rapid rotation

Models tested



B = 3 x 10^{15} G models

At break-up!



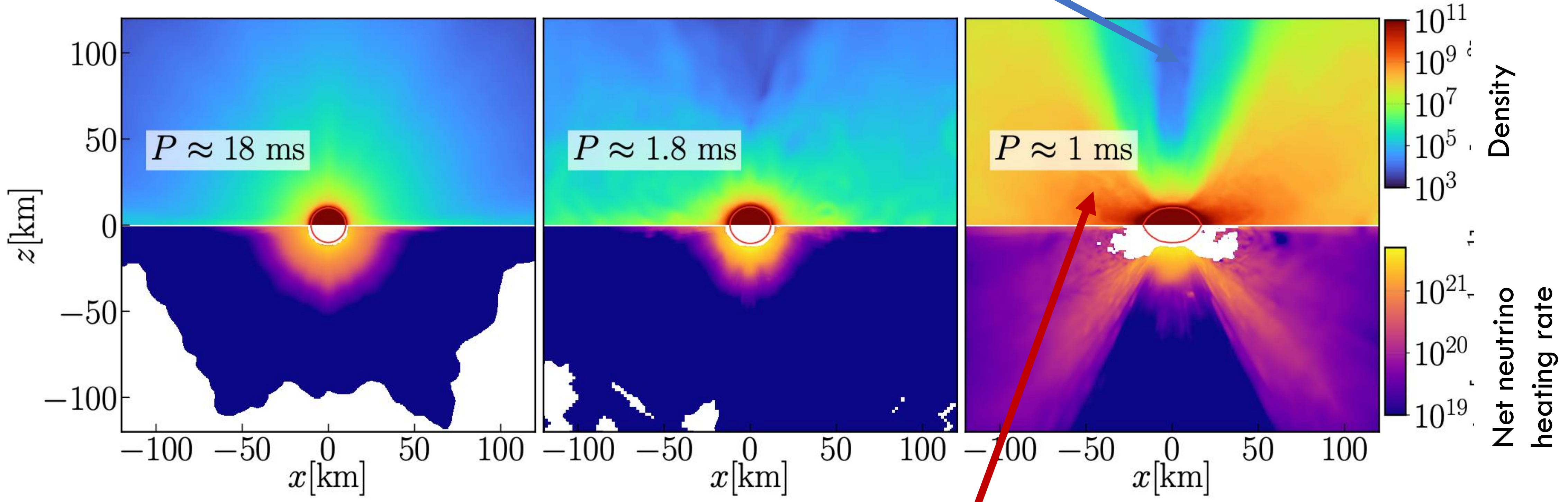
Dense equatorial outflows develop for P=1 ms model

Desai+2026 (submitted)

B = 3 x 10^{15} G models

At break-up!

Central funnel evacuated



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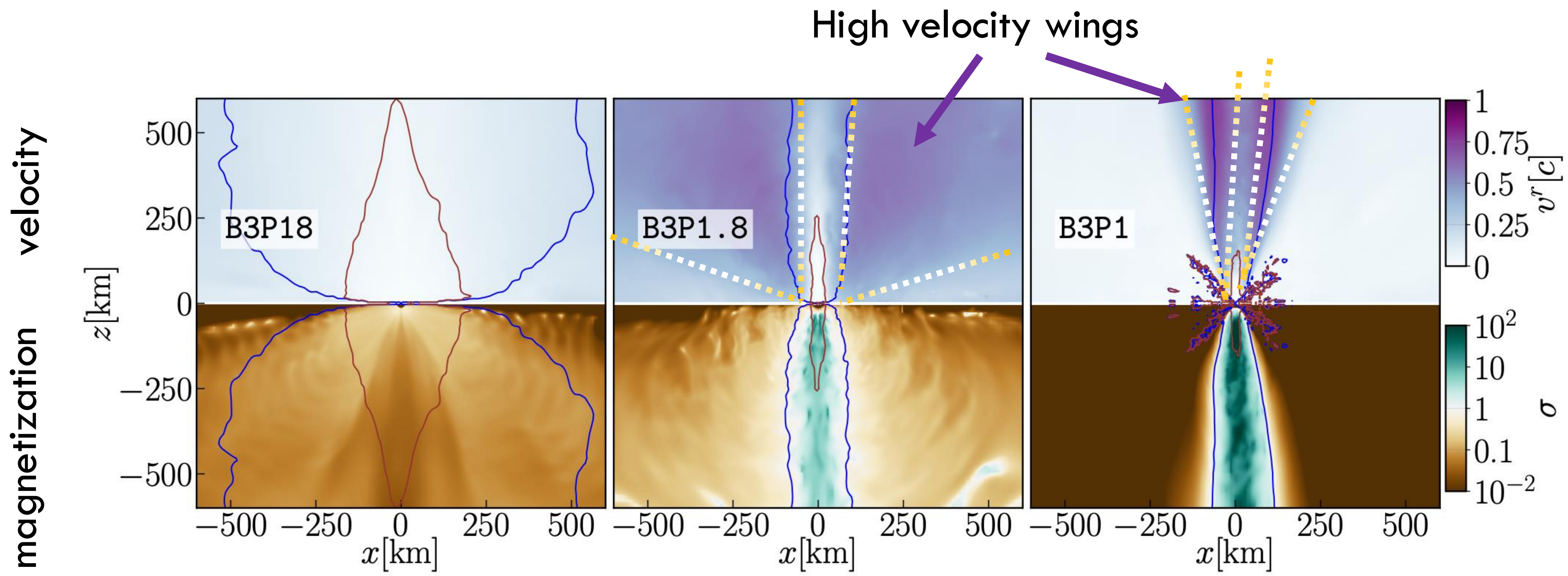
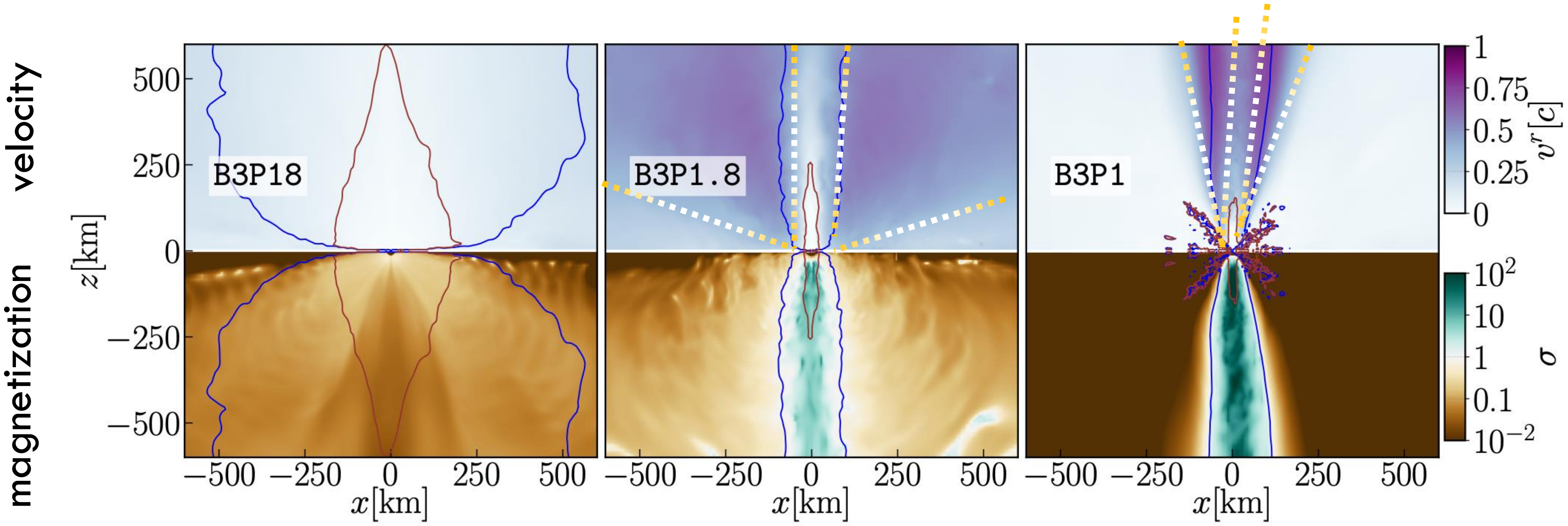


Smaller angular extent of high velocity region for P=1ms model

Desai+2026 (submitted)

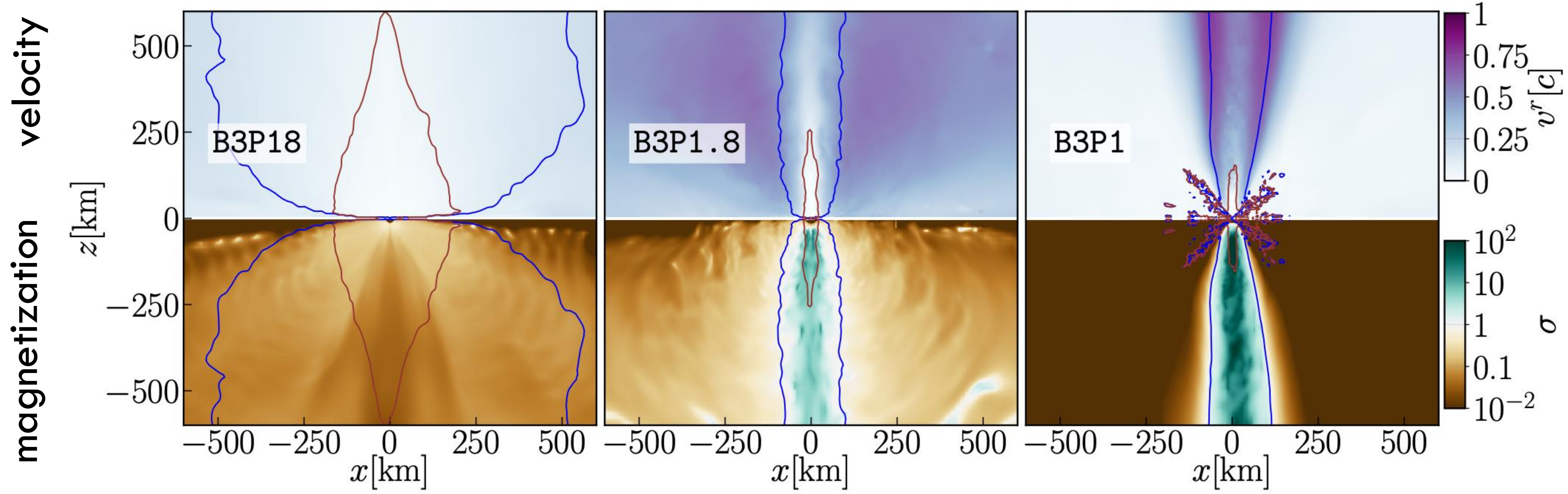
B = 3 x 10^{15} G



P=1 ms polar outflows *collimated by equatorial outflows*

Desai+2026 (submitted)

B = 3 x 10^{15} G



High sigma 'jet' even at neutrino luminosities ~10^{52} erg/s. Why??

Desai+2026 (submitted)

No centrifugal mass enhancement in polar direction

$$\sigma_{\text{outflow}} = \frac{\text{Poynting flux}}{\text{Mass flux}} = \frac{\Phi_B^2 \Omega^2}{\dot{M} c^3}$$

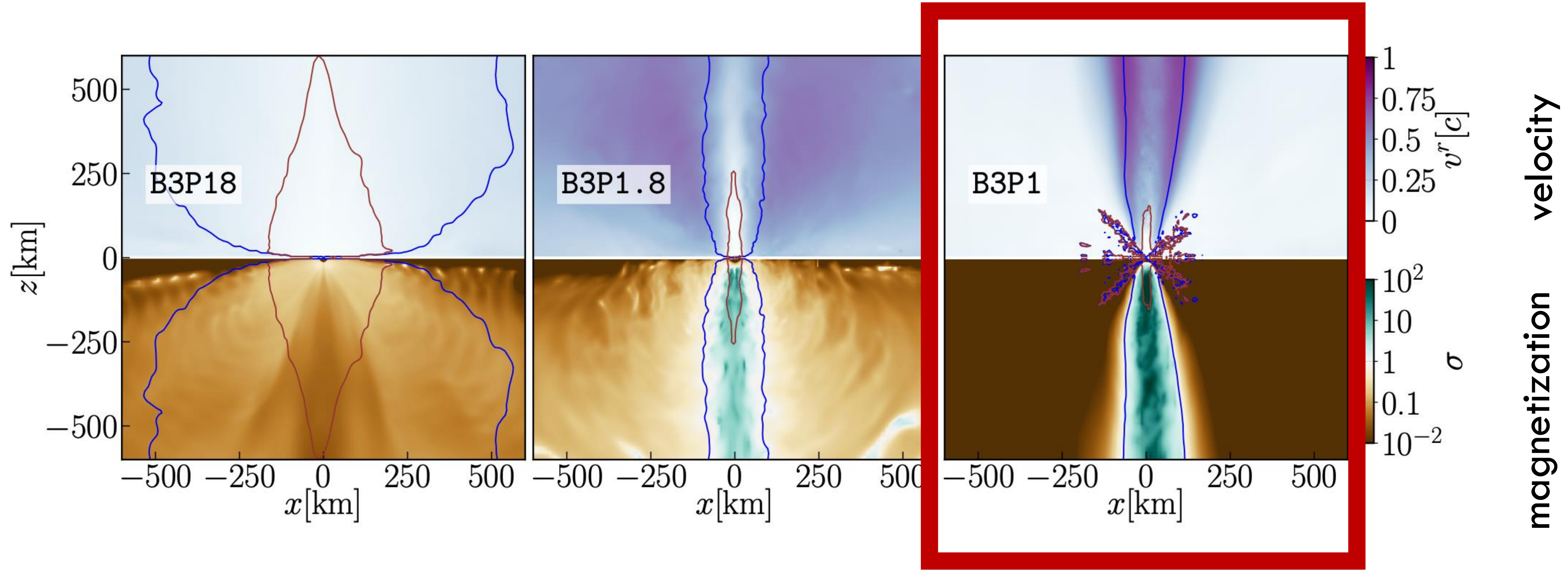
Magnetic flux

Rotation rate

mass flux
Reduced in polar funnel

Not surprising!

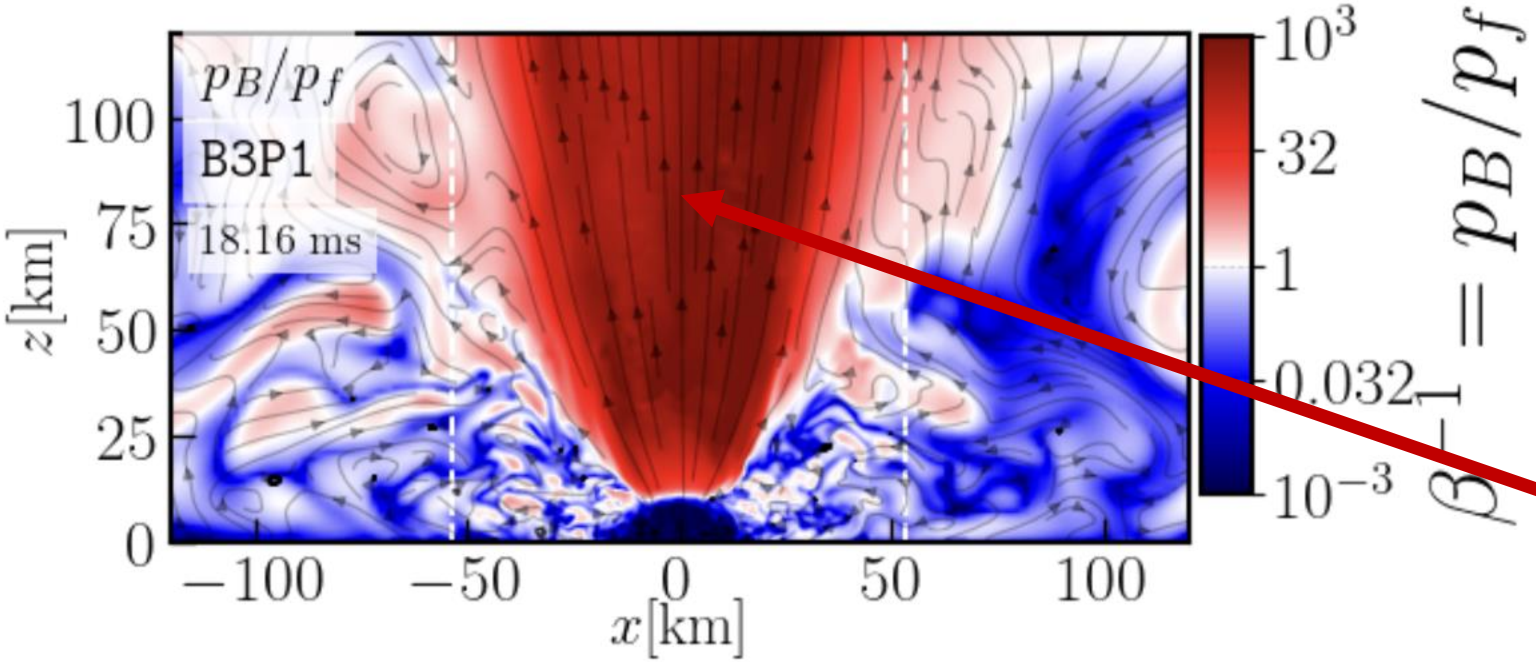
B = 3 x 10^{15} G



High sigma 'jet' even at neutrino luminosities ~10^{52} erg/s

Desai+2026 (submitted)

Significant magnetic pressure support in central funnel



If present, massive disk/ late time fall-back

must overcome

Centrifugal barrier + magnetic pressure in polar region

to impact outflows from such a protomagnetar

Desai+2026 (submitted)

Fractional energy contributions for P = 1 ms and P = 1.8 ms

B = 3 x 10^15 G
P = 1 ms

B = 3 x 10^15 G
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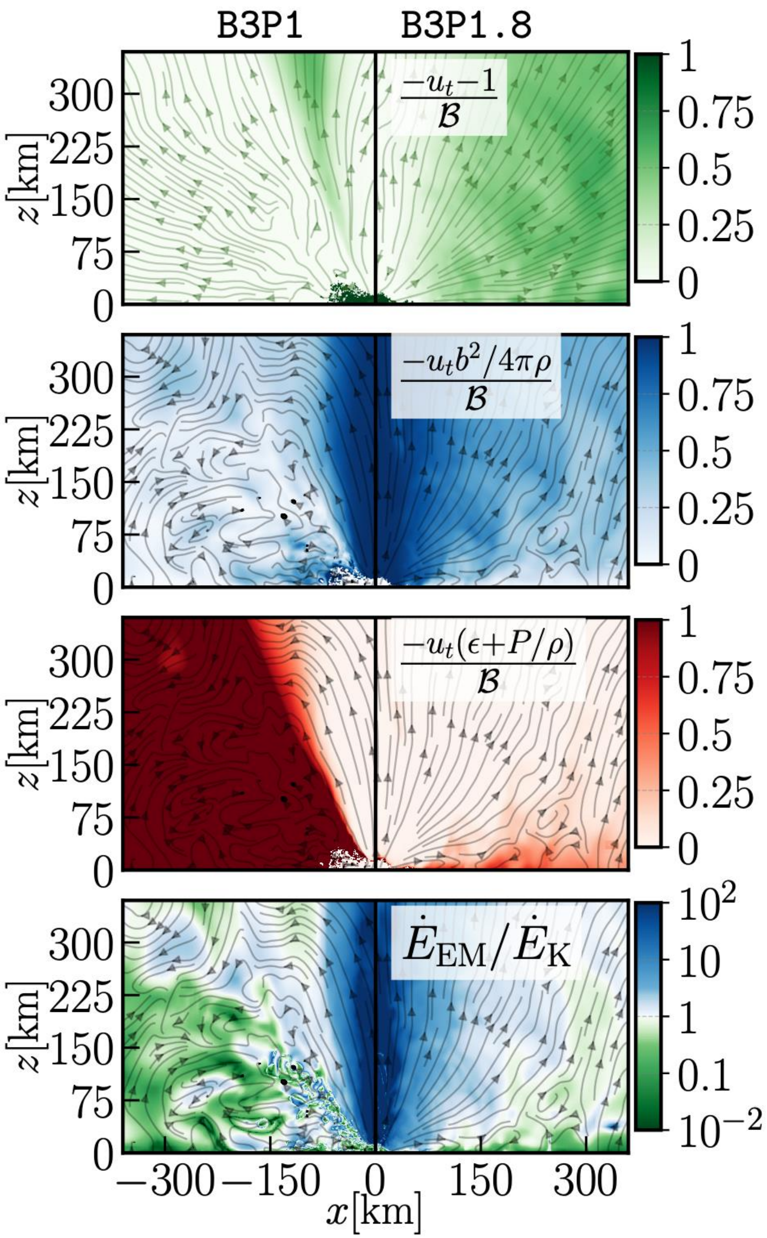
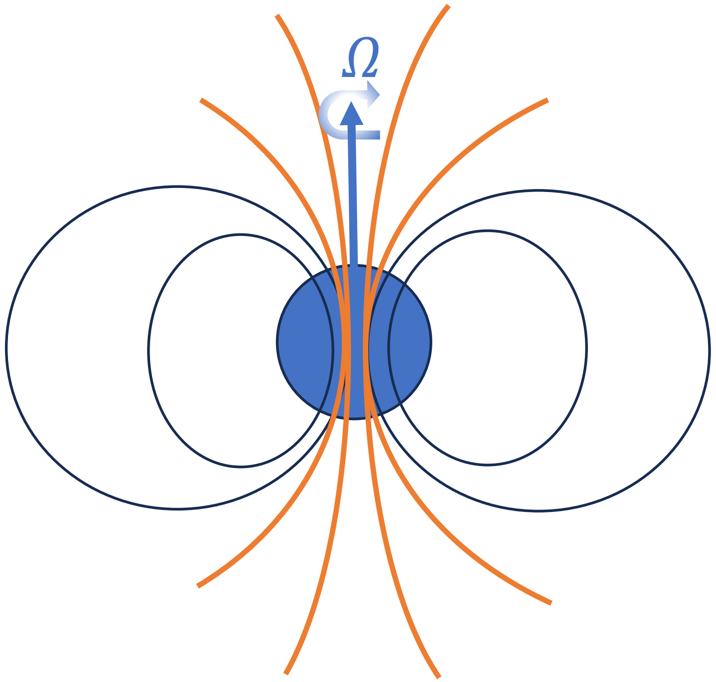
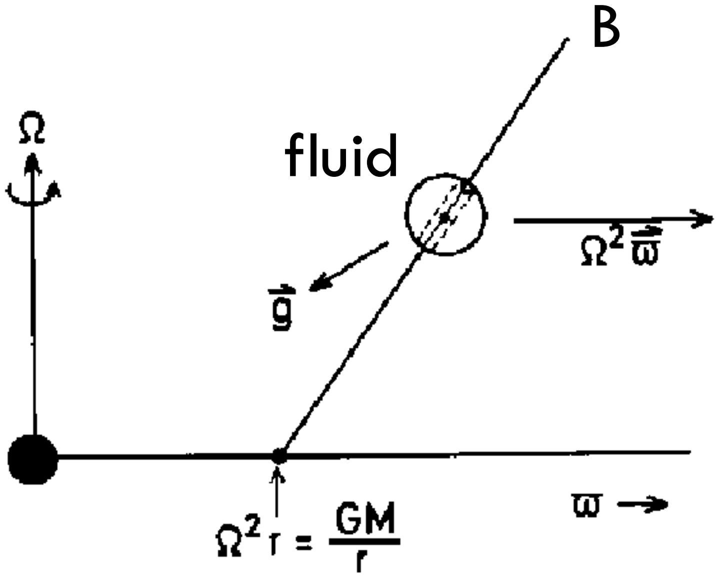


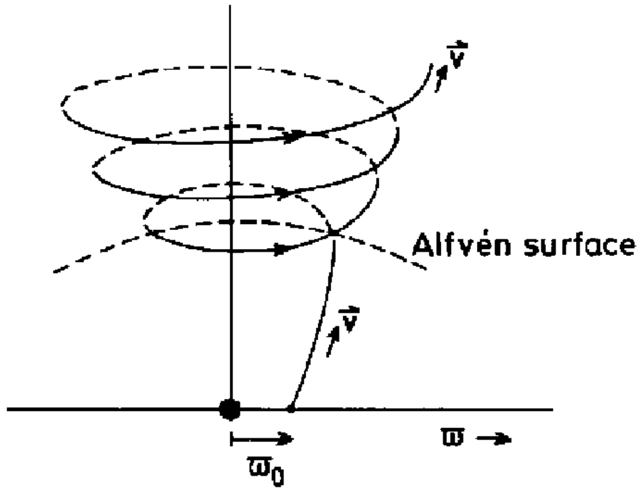
Desai+2026 (submitted, *ApJL*)

Rotation + magnetic fields can sling fluid along open field lines





Spruit 96



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Magnetic energy dominates core of the jet

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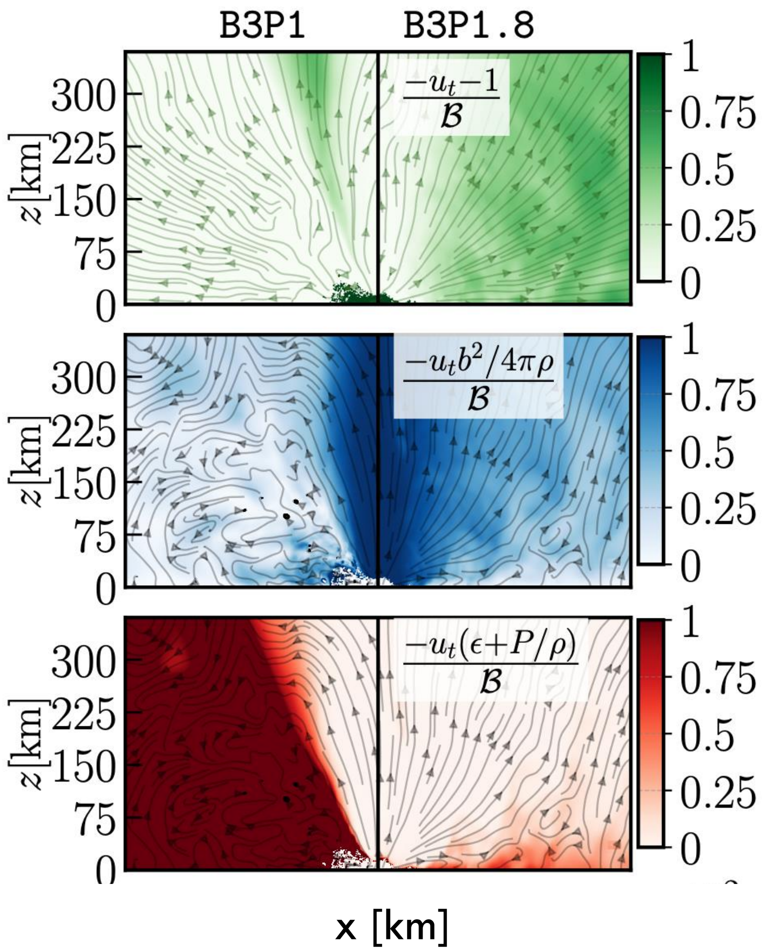

Desai+2026 (submitted, *ApJL*)

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Magnetic energy dominates core of the jet

1. Centrifugal slinging at play!

Energy converted to kinetic energy as fluid flows away from proto-magnetar

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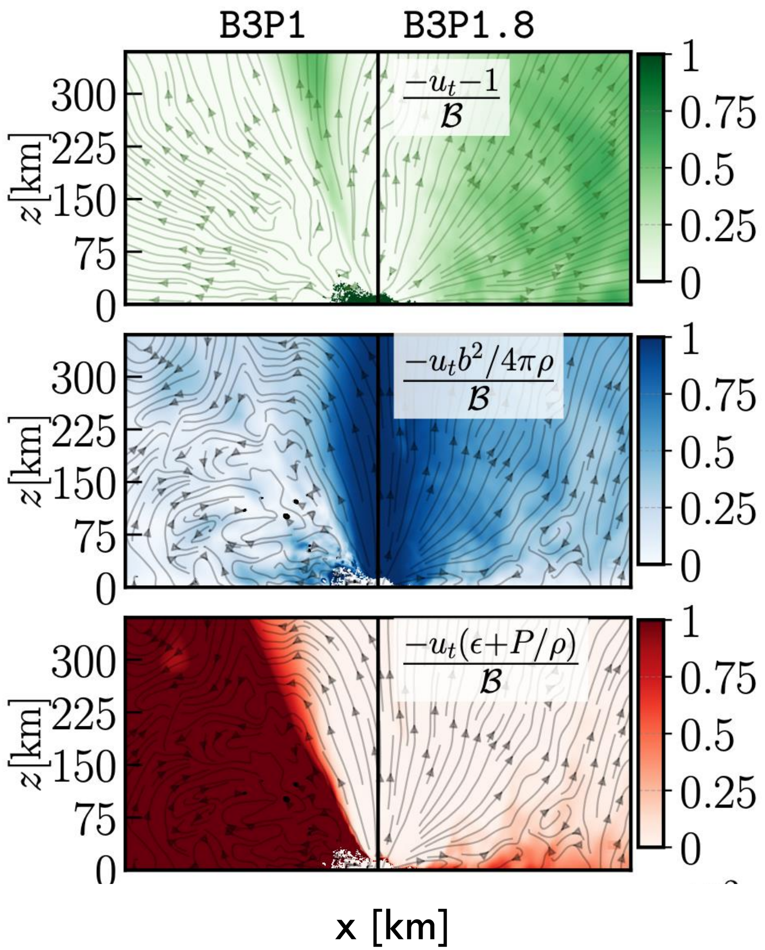

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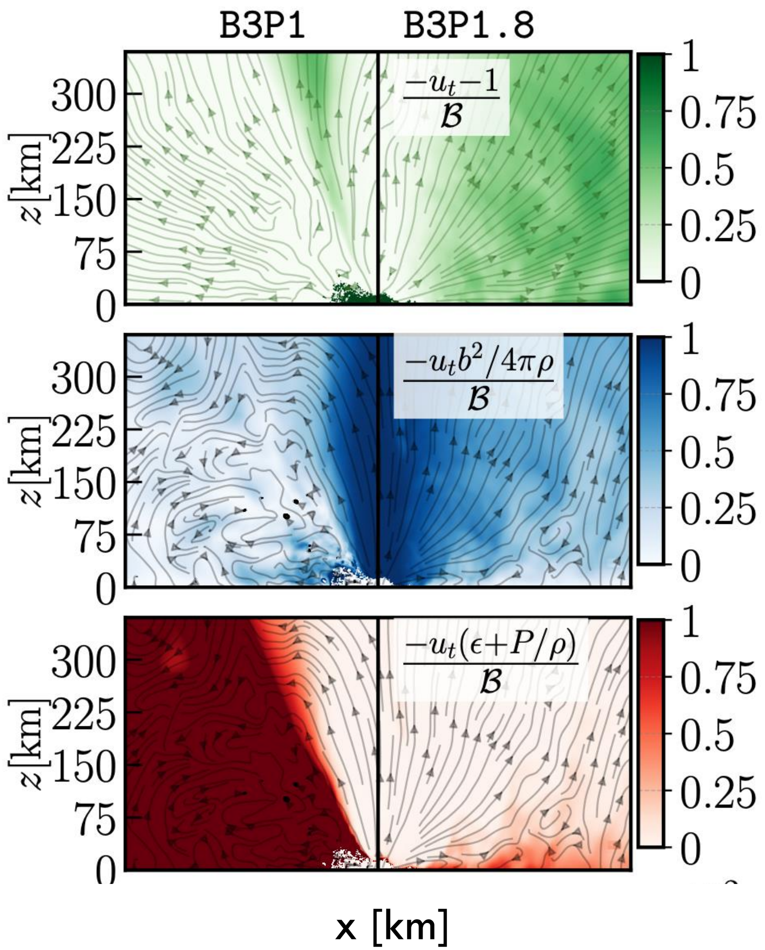

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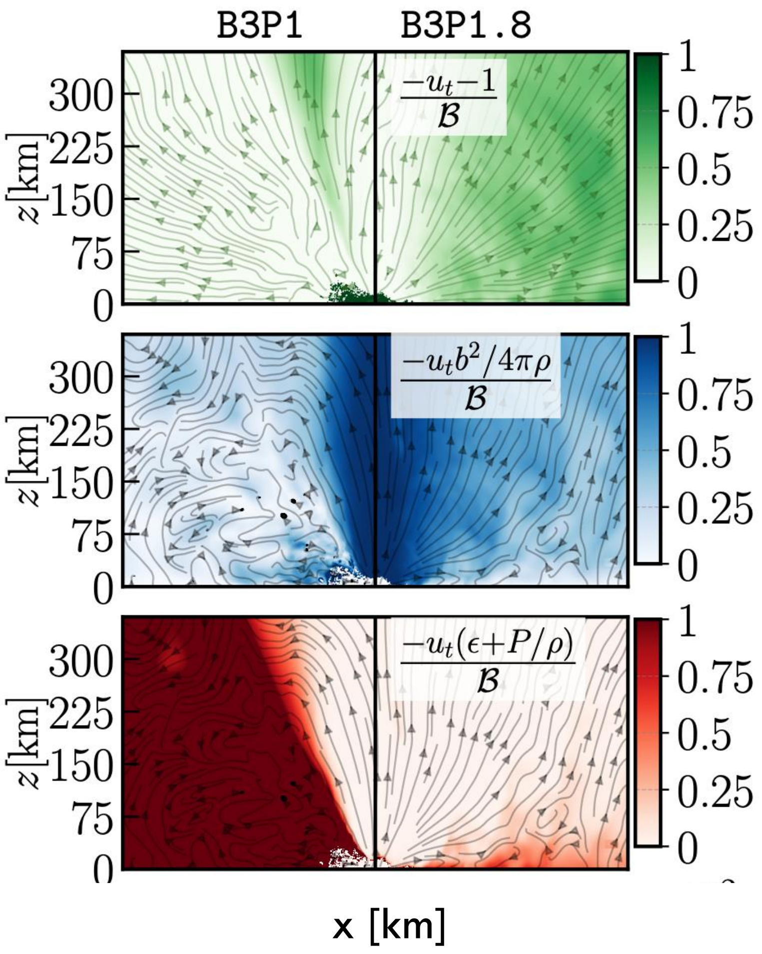
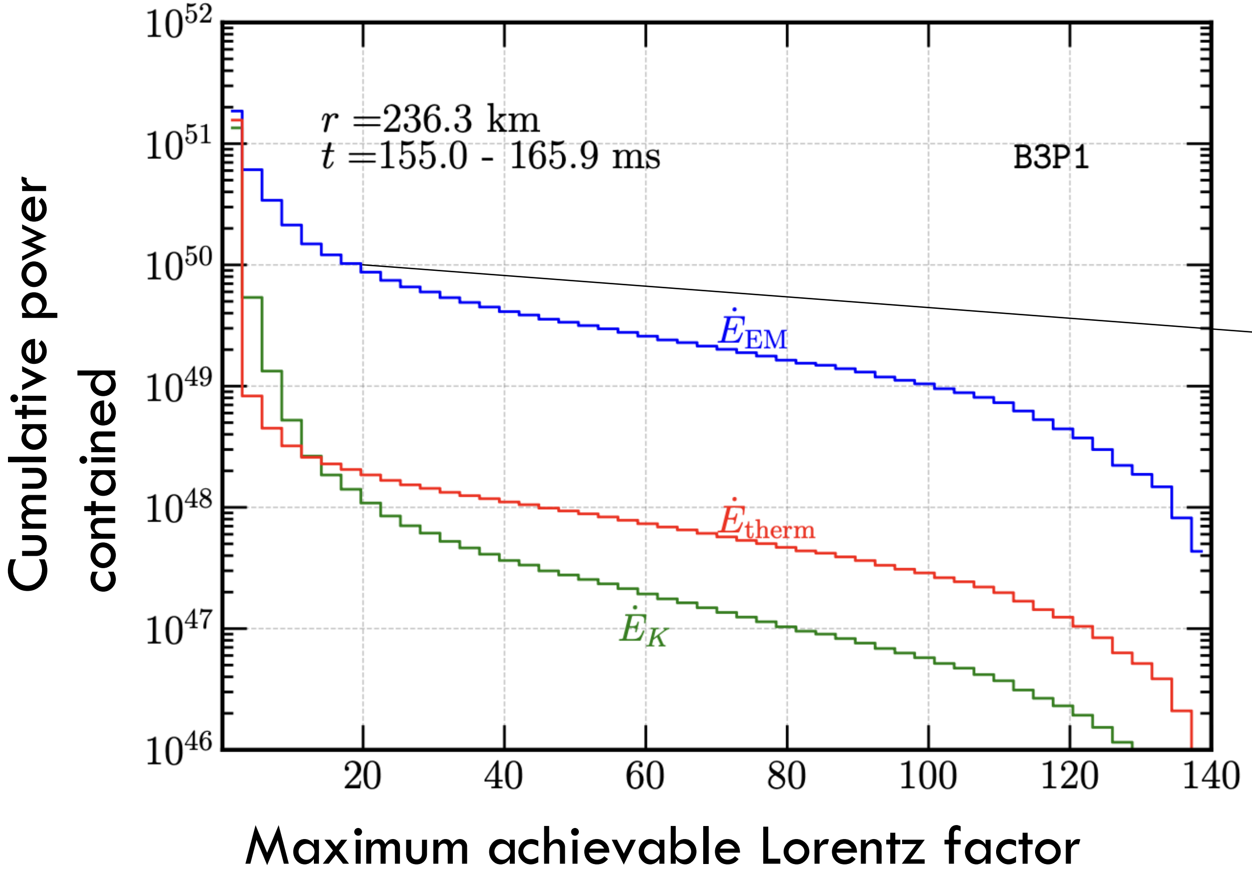


2. Dense equatorial outflows focus acceleration into a polar jet

Desai+2026 (submitted, *ApJL*)

Distribution of power to high Lorentz factors (~ > 100)



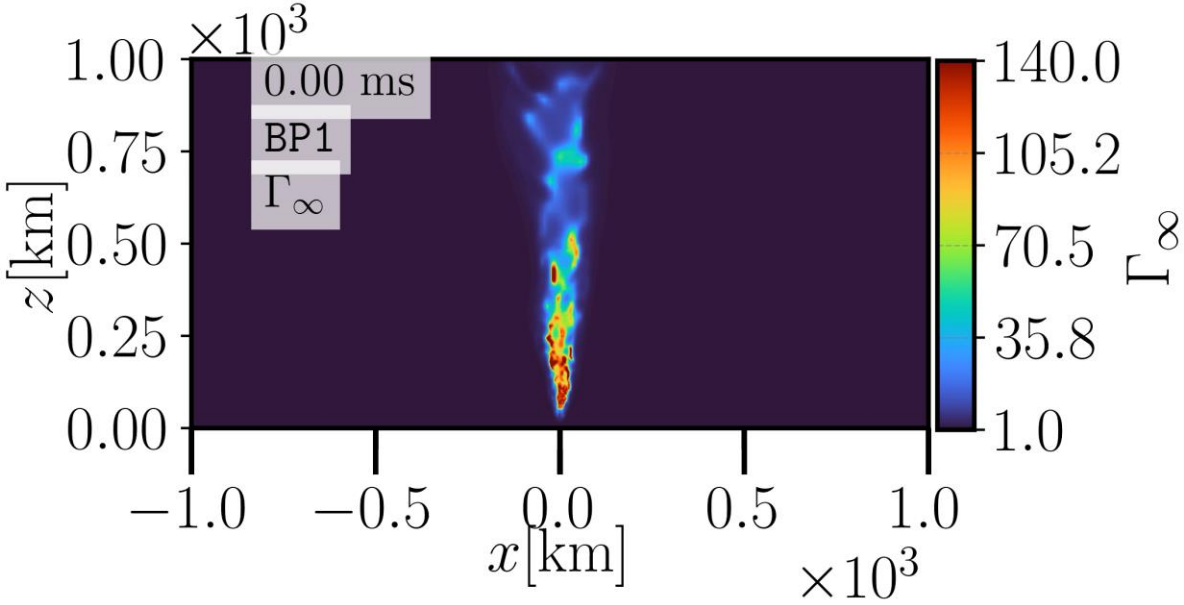
e.g., 10^{50} erg/s power contained in fluid with Lorentz factor > 20

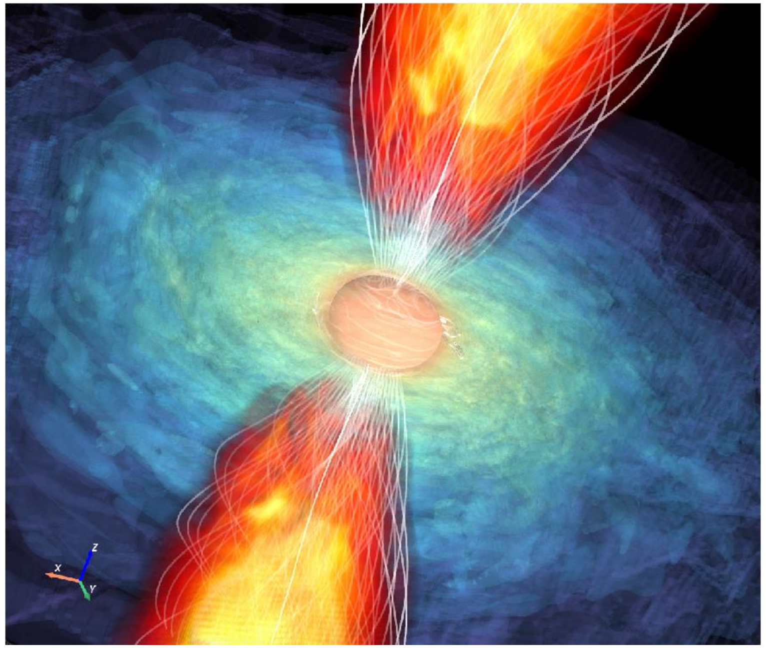
These are powerful outflows!

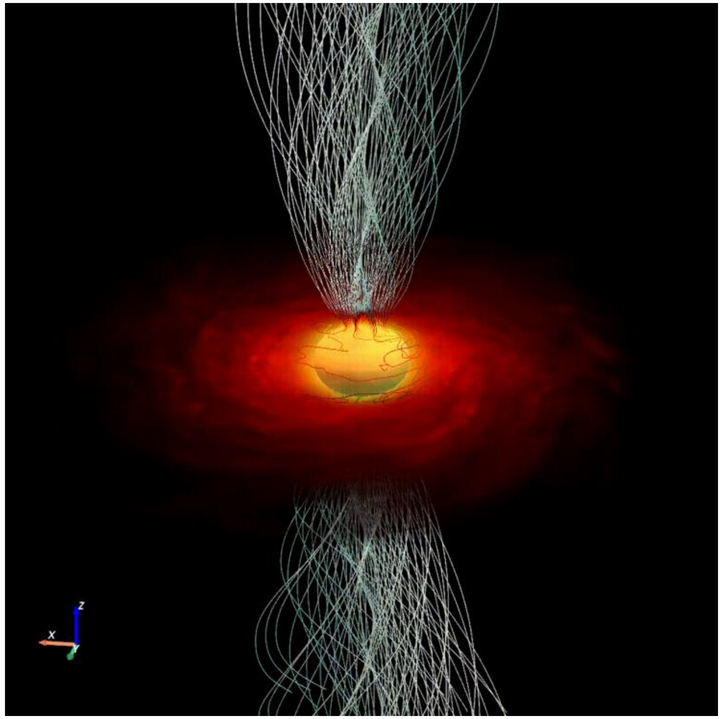
$$\Gamma_\infty \approx \sigma$$

Desai+2026 (submitted)

Such outflows from a rapidly rotating proto-magnetar are physically possible







B~3e15 G
P~1ms
neutrino luminosities
$\sim 10^{52}$ erg/s

Desai+2026
(submitted, *ApJL*)

Collimated, relativistic jet emergence is **not exceptional**

Rather a *natural consequence*
of rotation + magnetization

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Bonus: collimation arises intrinsically at small radii,
without requiring confinement by external envelope or
supernova

Aids in
$E_{mag} \rightarrow E_{kin}$
(over large distances)

When & where might such remnants be formed?

- Energetic supernova (rapidly rotating progenitors)
- White dwarf collapse
- Neutron star mergers

Magnetization evolves on neutrino cooling timescales

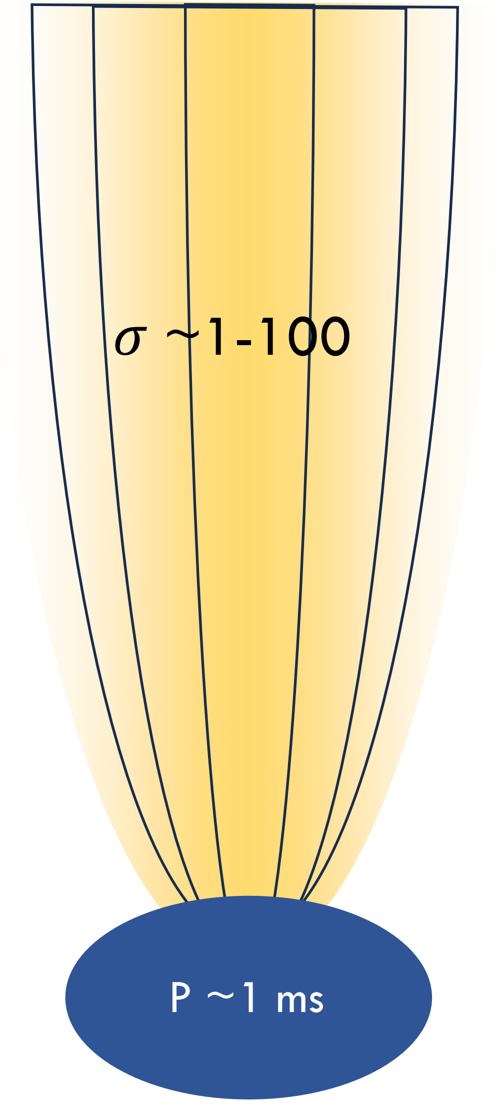
Magnetic field strength

Rotation rate slows

$$\sigma_{\rm outflow} = \frac{\text{Poynting flux}}{\text{Mass flux}} = \frac{\Phi_B^2 \Omega^2}{\dot{M} c^3}$$

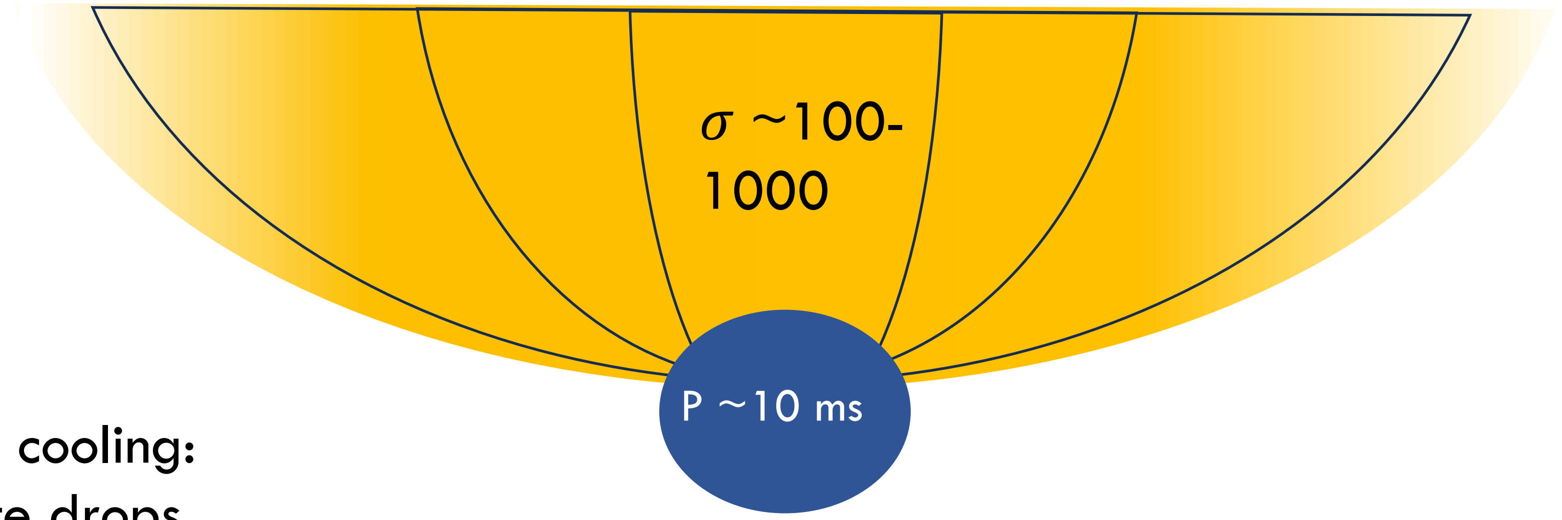
Mass loss rate drops drastically as proto-magnetar cools…

...so the jet becomes less collimated, more magnetized over ~10 seconds



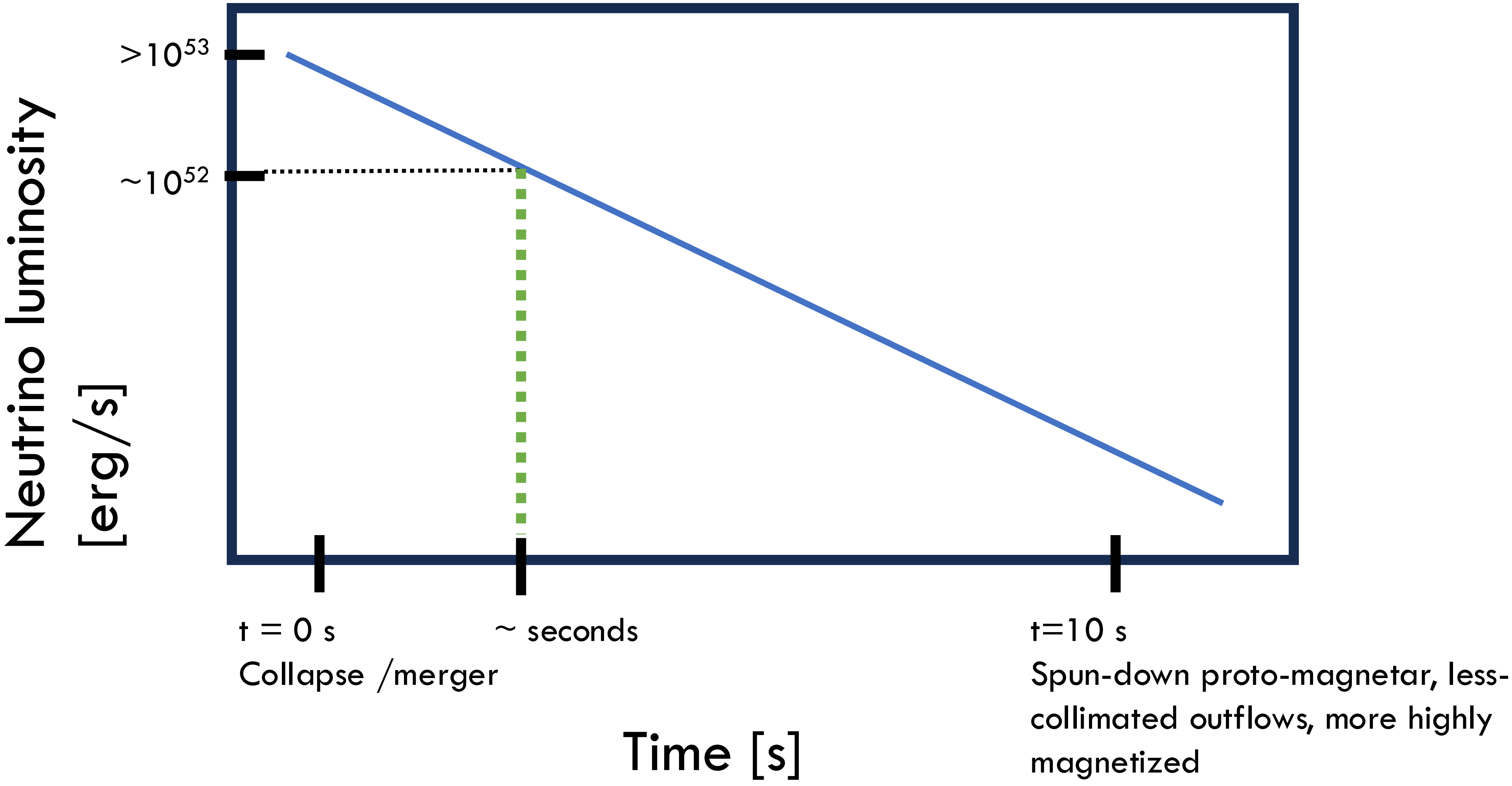
t ~2 s
(post-collapse)

t ~5-10 s of cooling:
mass loss rate drops

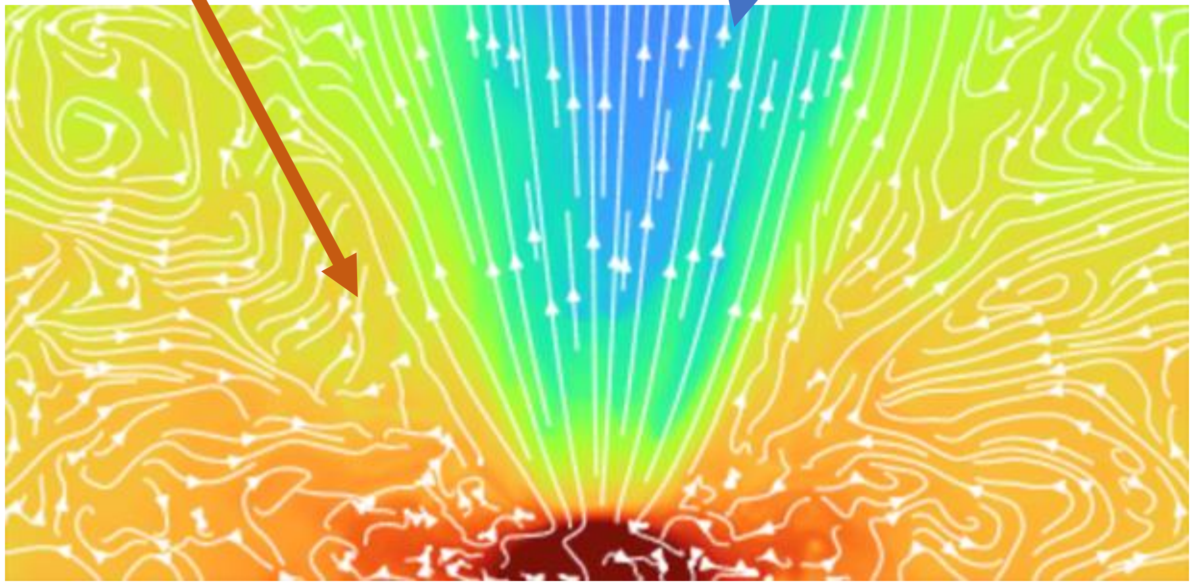


t ~10 s

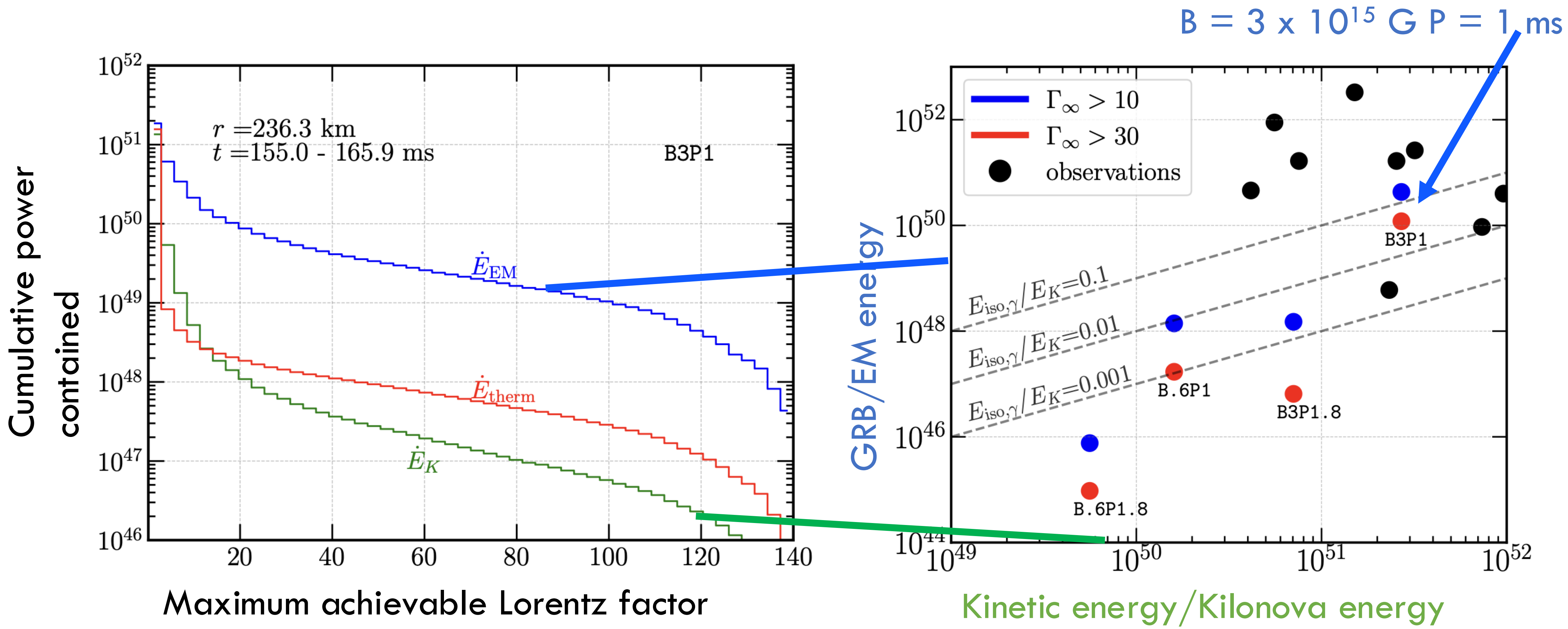
A jet would occur within seconds of an event (prompt)



Outflows potentially account for short GRB (jet) and simultaneously long-lived counterparts (equatorial outflows)

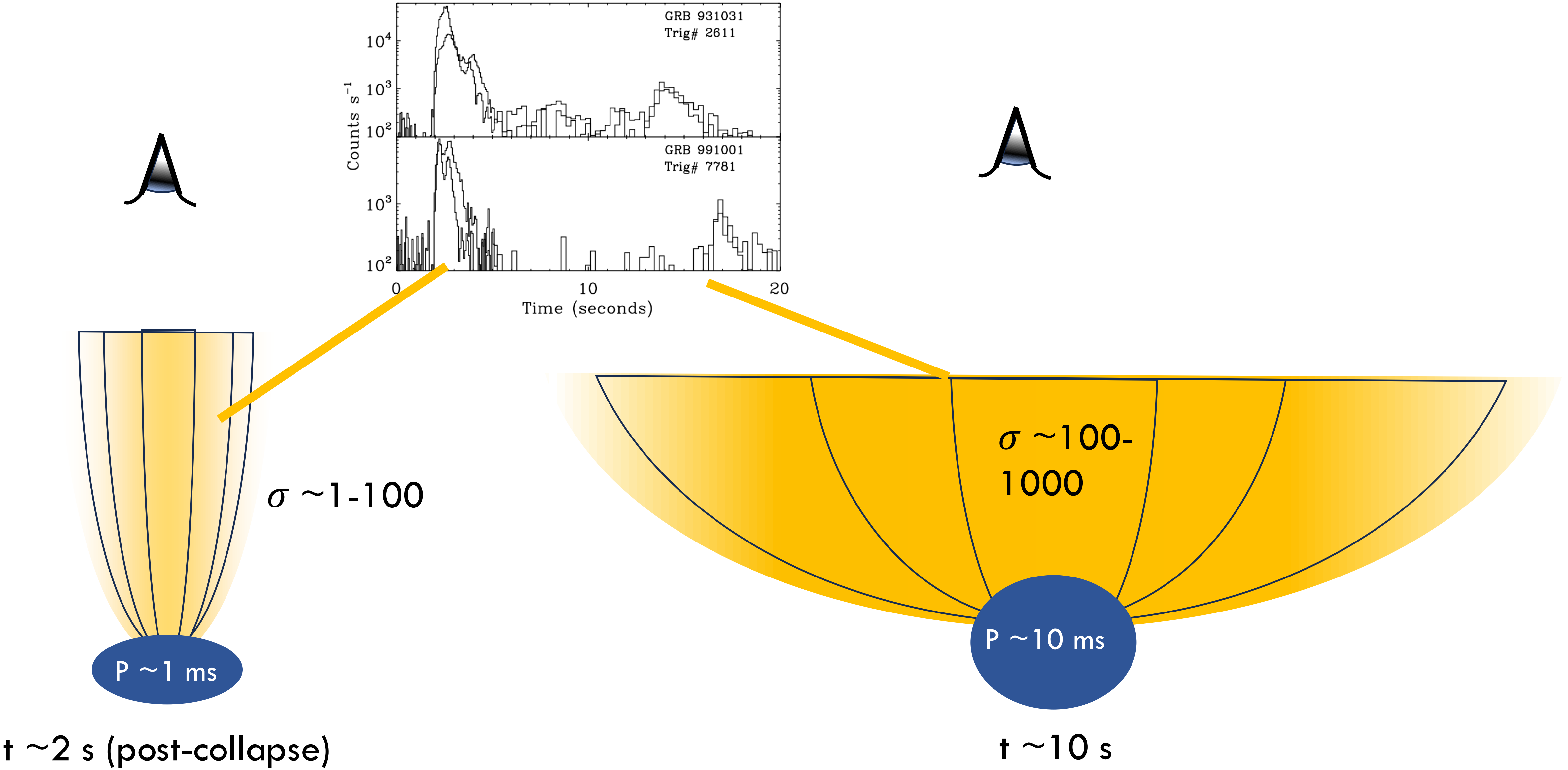


Outflows of millisecond proto-magnetar consistent with KN+ GRB observations

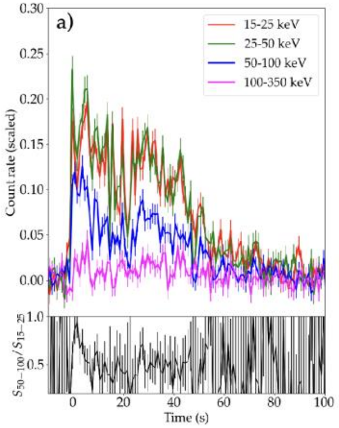


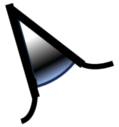
Desai+2026 (submitted)

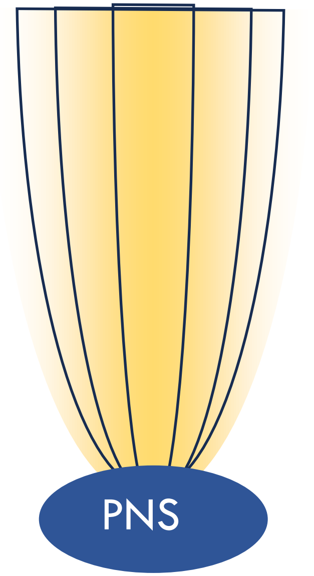
Head-on observation: Short GRB + extended emission



Off-angle observation:
X-ray flash/long GRB







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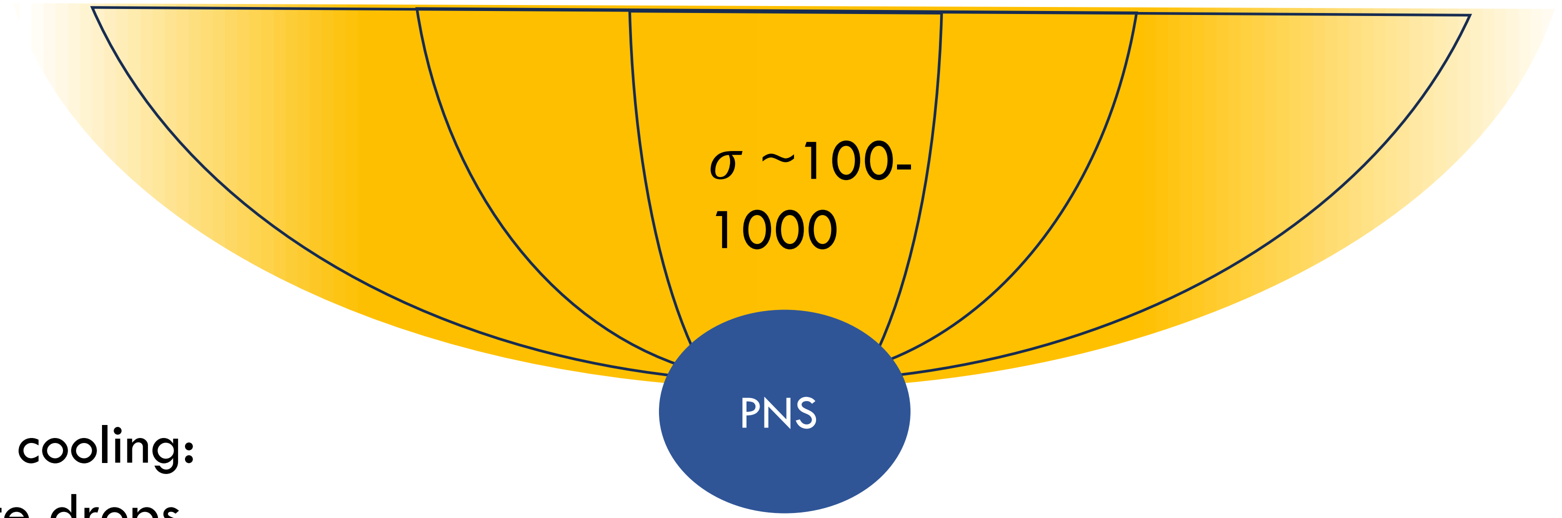

t ~10 s

Conclusions

- **continuous transition** in most proto-magnetar wind properties
  - low B → high B, & low Ω → high Ω
- Rapidly rotating model – B~3e15 G, P~1ms (unique)
  - massive equatorial outflows which help to naturally collimate jet; enables efficient conversion from magnetic to kinetic energy at large distances
  - produces steady-state, fast polar outflows (~0.7c), and material with high sigma (~50-150)
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Next steps

- Interplay between disk and slower rotating models
- Nucleosynthesis
- Global simulations and better neutrino transport
- Input to large-scale jet simulations


That's all Folks!