

Millisecond proto-magnetars as gamma-ray burst central engines

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Alexander von
HUMBOLDT
STIFTUNG

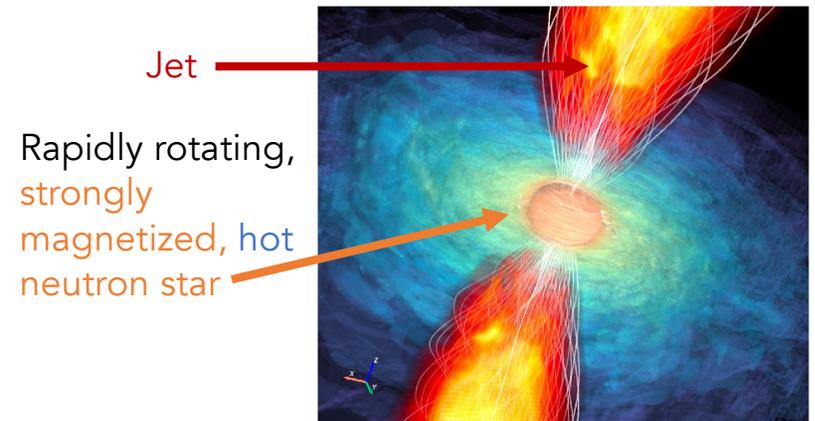
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Feb 6, 2026

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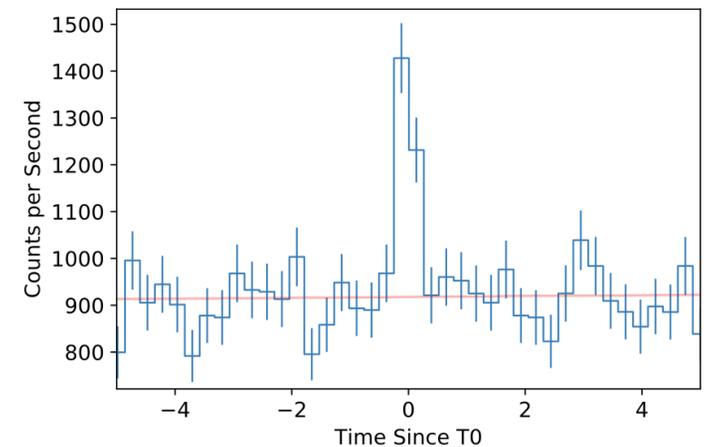


Gamma-ray bursts (GRBs)

- 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



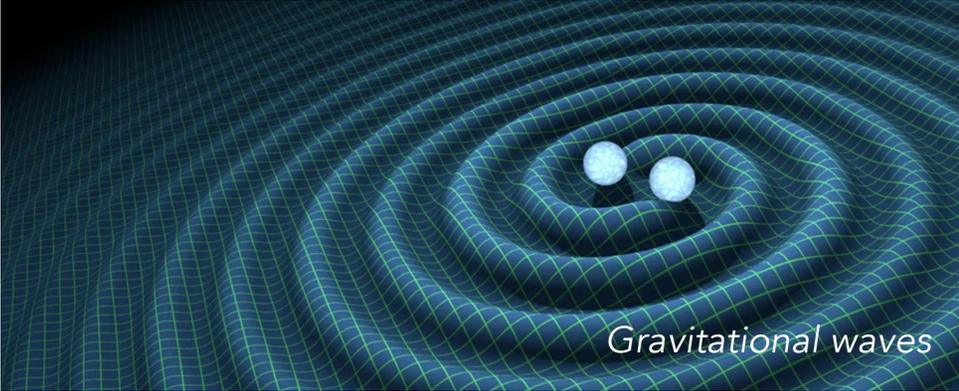
Desai+2026 (submitted, ApJL)



Goldstein+2017

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

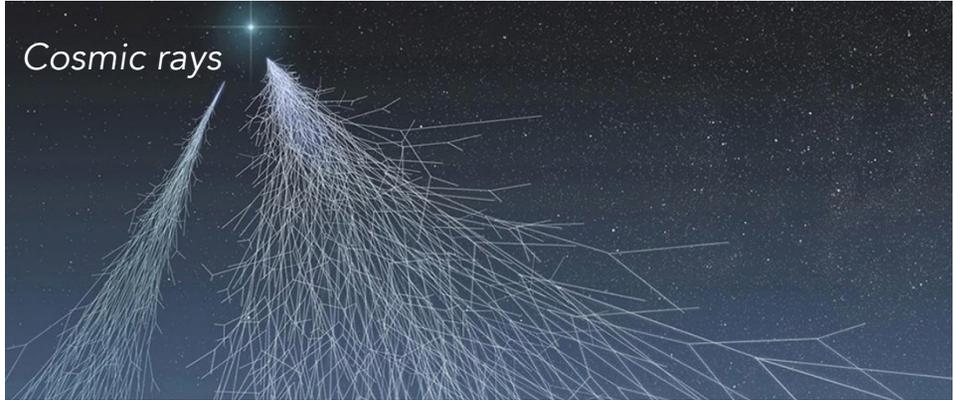
Caltech



Maciej Rebisz, Quanta Magazine



solarblog.pl



ASPERA

Highlight: short duration GRB associated with GW170817

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

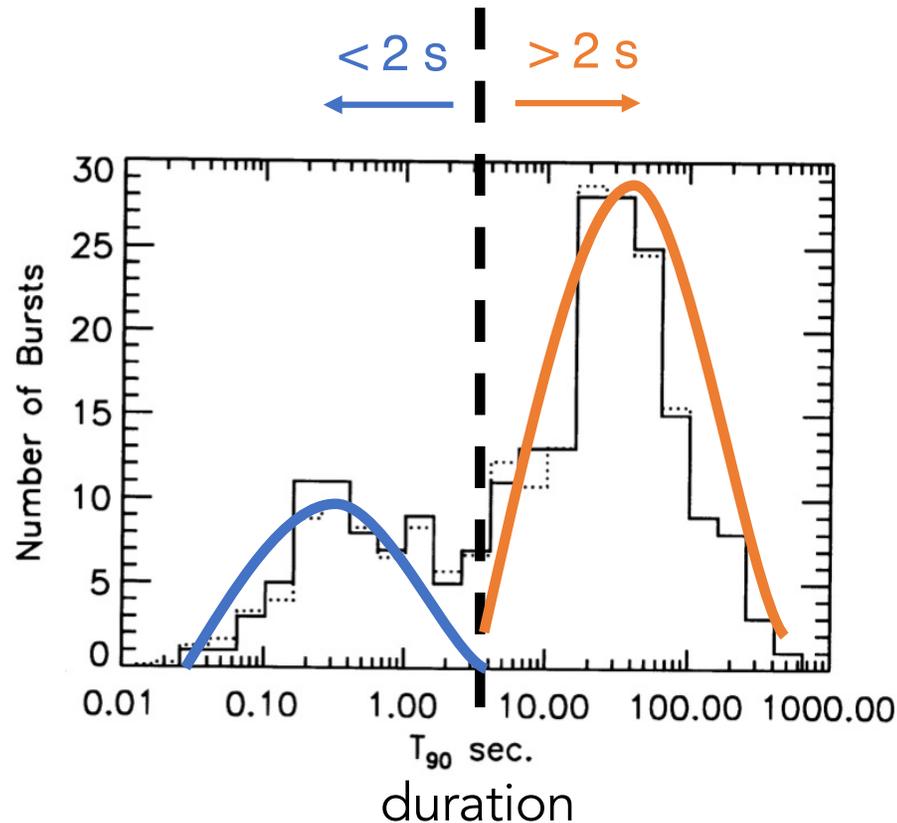
...which help us probe fundamental physics

- 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

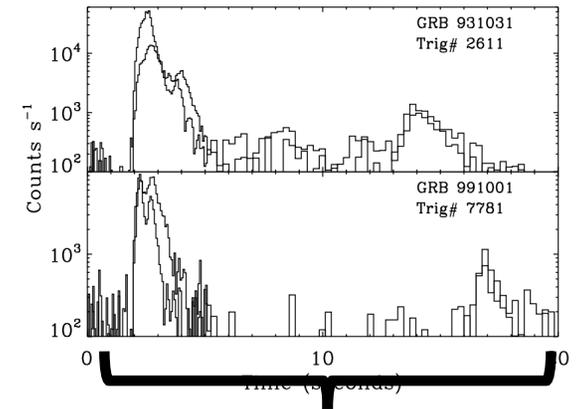
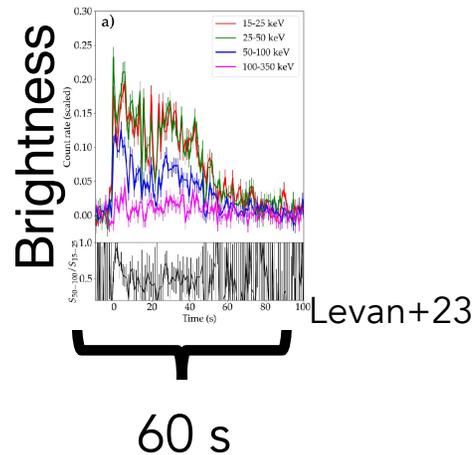
Duration
thought to be
set by
accretion
time-scales

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)



20 s

Short GRB +
Extended emission

Big open questions

- What are the dominant astrophysical sites 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

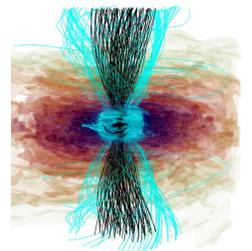
Operates via Blanford-Znajek mechanism



Nasa

Proto-magnetar

Powered by its rotational energy



Central engine: proto-magnetar or black hole?

Black hole jet

powered by accretion

Operates via Blanford-Znajek mechanism



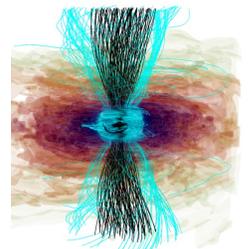
Nasa

Proto-magnetar jet

Powered by its rotational energy

Favored because BH cannot baryon load polar jet

(see Sho's talk)



Central engine: proto-magnetar or black hole?

Black hole

powered by accretion

Operates via Blanford-Znajek mechanism

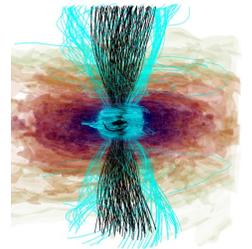


Nasa

Proto-magnetar

Powered by its rotational energy

I focus on viability of proto-magnetars as central engines

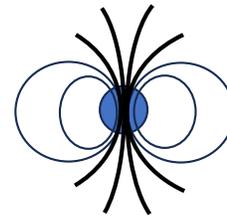


Previous work + open questions

- **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 (also see e.g. Alexis', Eduardo's, and Miguel's talk)...

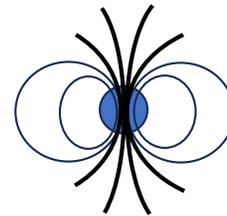
How to form strong, large-scale, ordered B fields???



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 (also see e.g. Alexis', Eduardo's, Sho's and Miguel's talk)...



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

- **Proto-magnetar outflows as central engines for GRBs? Are outflow properties compatible?**

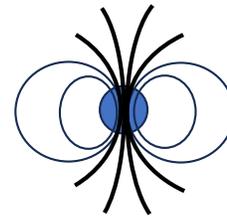
e.g., Bucciantini+06, Metzger+07, +08, Prasanna+2024...

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 (also see e.g. Alexis', Eduardo's, Sho's and Miguel's talk)...



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, 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, Gottlieb+21, 23... (also see Oliver's talk)

Central question of my latest work:

Can a proto-magnetar power a jet?

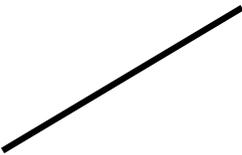
i.e., can it produce collimated,
relativistic outflows?

Does such a steady-state solution exist?

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

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

Total fluid energy



This is the energy budget for outflows

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

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

If magnetically dominated...

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

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

Magnetization is key

Asymptotic Lorentz factor

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

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

If magnetically dominated...

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

Not my
problem



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

(over large distances)

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

Magnetization is key

reformulated:

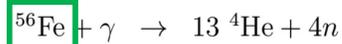
**Can proto-magnetars have
magnetically-dominated (high - σ)
outflows?**

Ingredients of proto-magnetars

3 key ingredients determine outflow properties

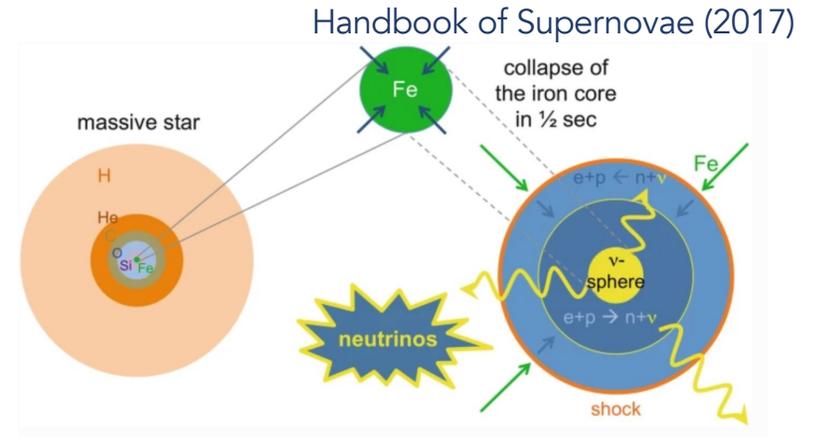
- Net neutrino heating
- Rotation rate (amplified from angular momentum conservation)
- Magnetic field strength/geometry (flux-freezing + dynamos)

Gravitational energy released in the form of neutrino emission



Neutrinos diffuse out of PNS, free-stream from neutrinosphere

Neutrinos of all species produced; only electron neutrino/antineutrinos interact with matter outside PNS



Approximate energy released:

$$E_{\text{SN}} \sim \frac{3GM_{\text{pns}}^2}{5r_{\text{NS}}} \approx 3 \times 10^{53} \text{ erg} \left(\frac{M_{\text{pns}}}{M_{\odot}} \right)^2 \left(\frac{r_{\text{NS}}}{12 \text{ km}} \right)^{-1}$$

Neutron star mass

Neutron star radius

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

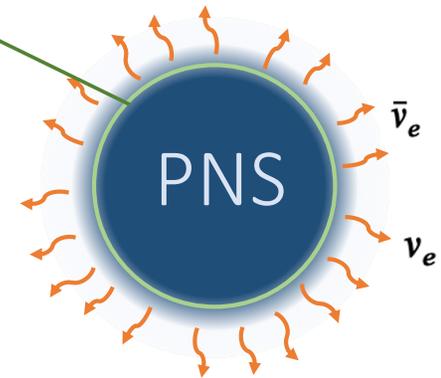
Net neutrino absorption drives baryonic wind

Dominant interactions: $\nu_e + n \leftrightarrow e^- + p$ and $\bar{\nu}_e + p \leftrightarrow e^+ + n$
(charge-current)

Heating (ν -absorption) 

Cooling (ν -emission) 

neutrinosphere



Net neutrino absorption drives baryonic wind

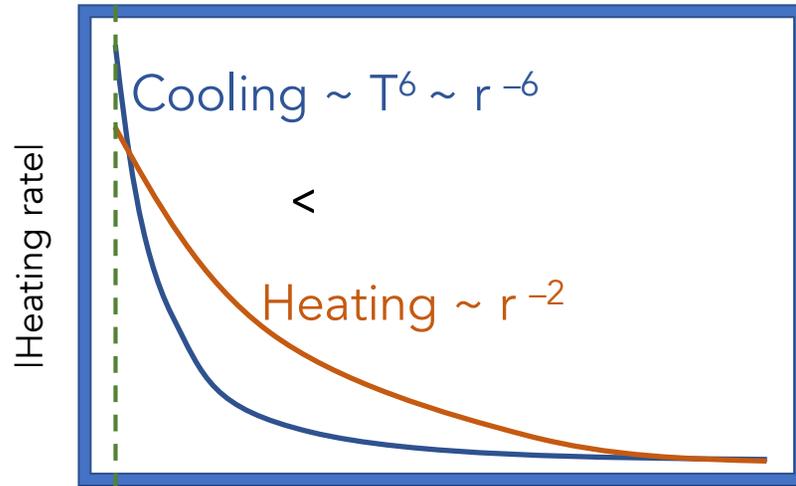
Heating (ν -absorption)



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

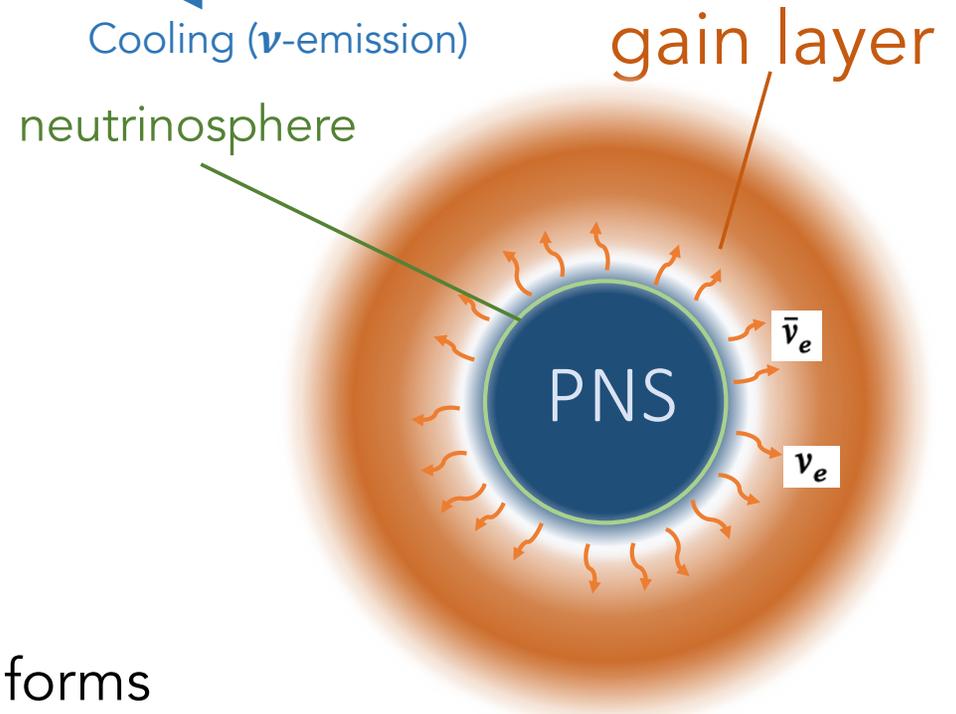


Cooling (ν -emission)

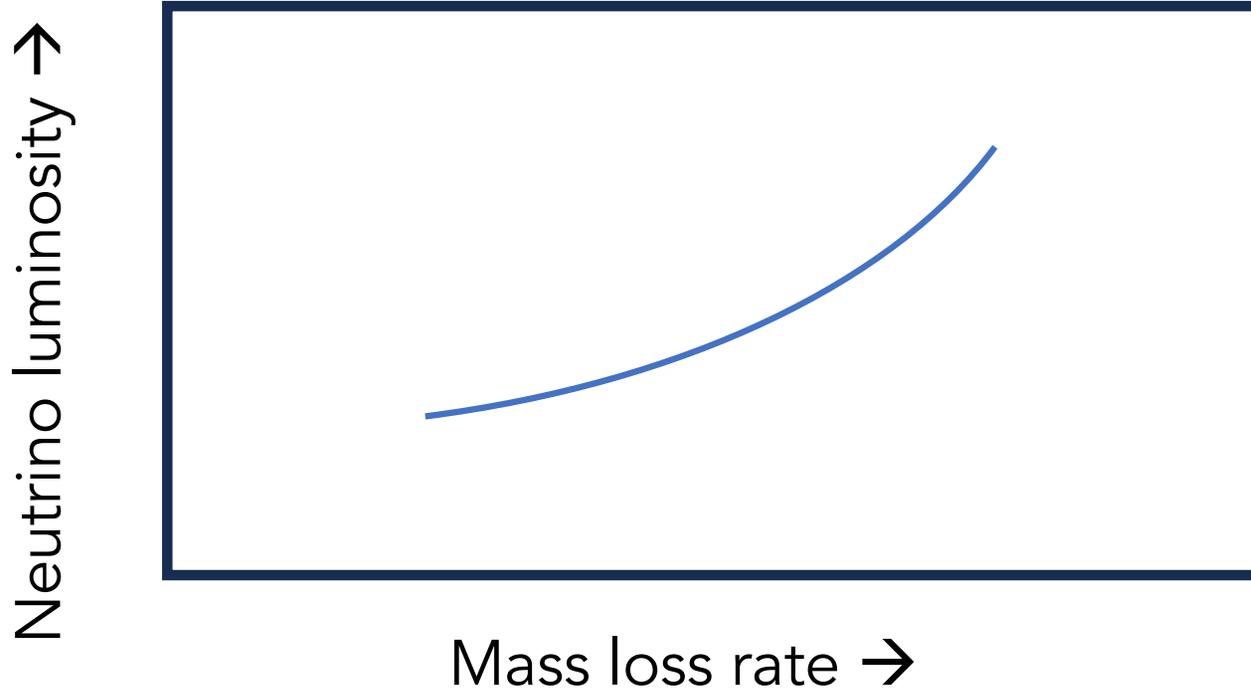


neutrinosphere 15 Radius (km) 50

gain layer with net positive heating forms

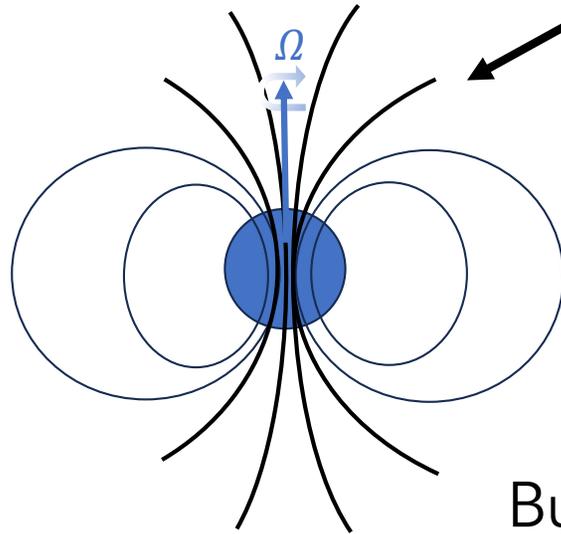


High neutrino luminosities? High mass loss rate



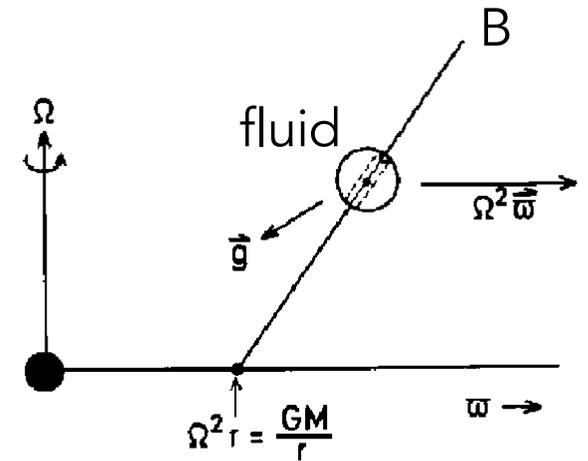
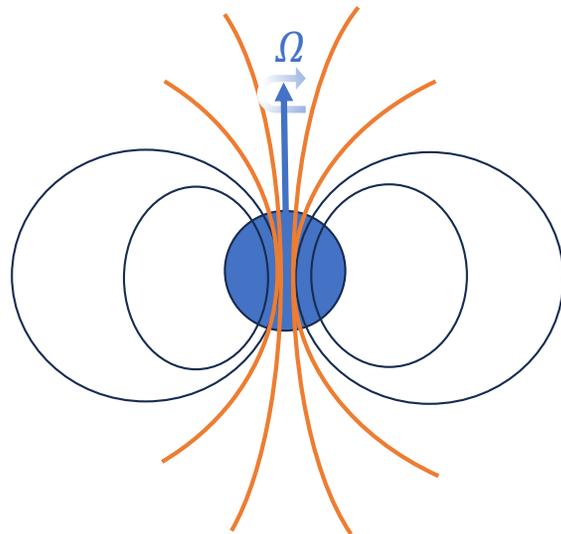
magnetic fields and rotation can be amplified within ~ 100 s ms after collapse

Neutrino heating loads field lines with baryonic matter

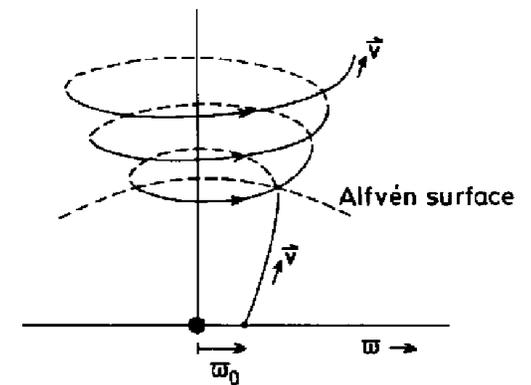


But neutrino absorption may no longer dominate acceleration mechanism

Rotation + magnetic fields can sling fluid along open field lines



Spruit 96

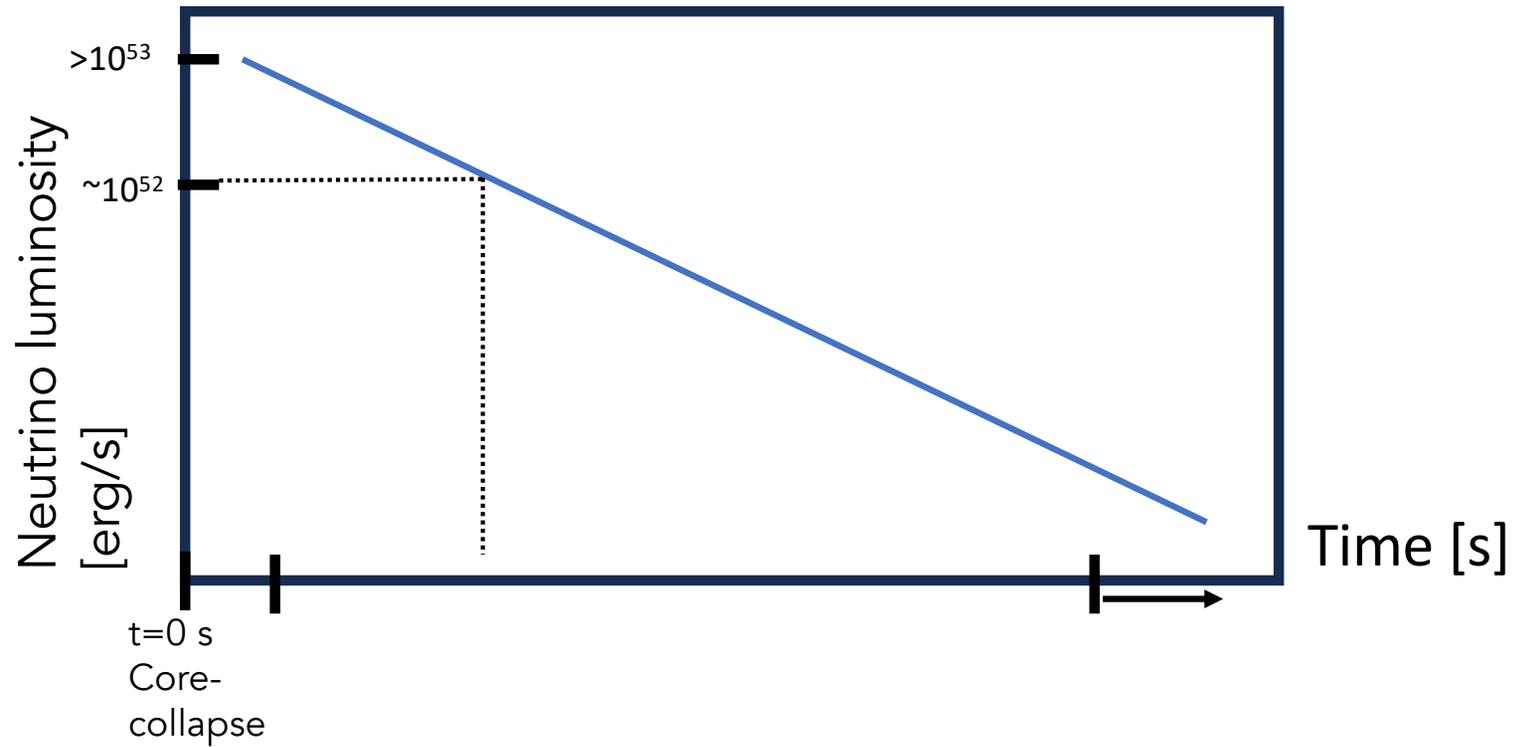


The faster (stronger) the rotation (magnetic field), the greater the acceleration

**Long-term evolution (~seconds)
uncertain/diverse**

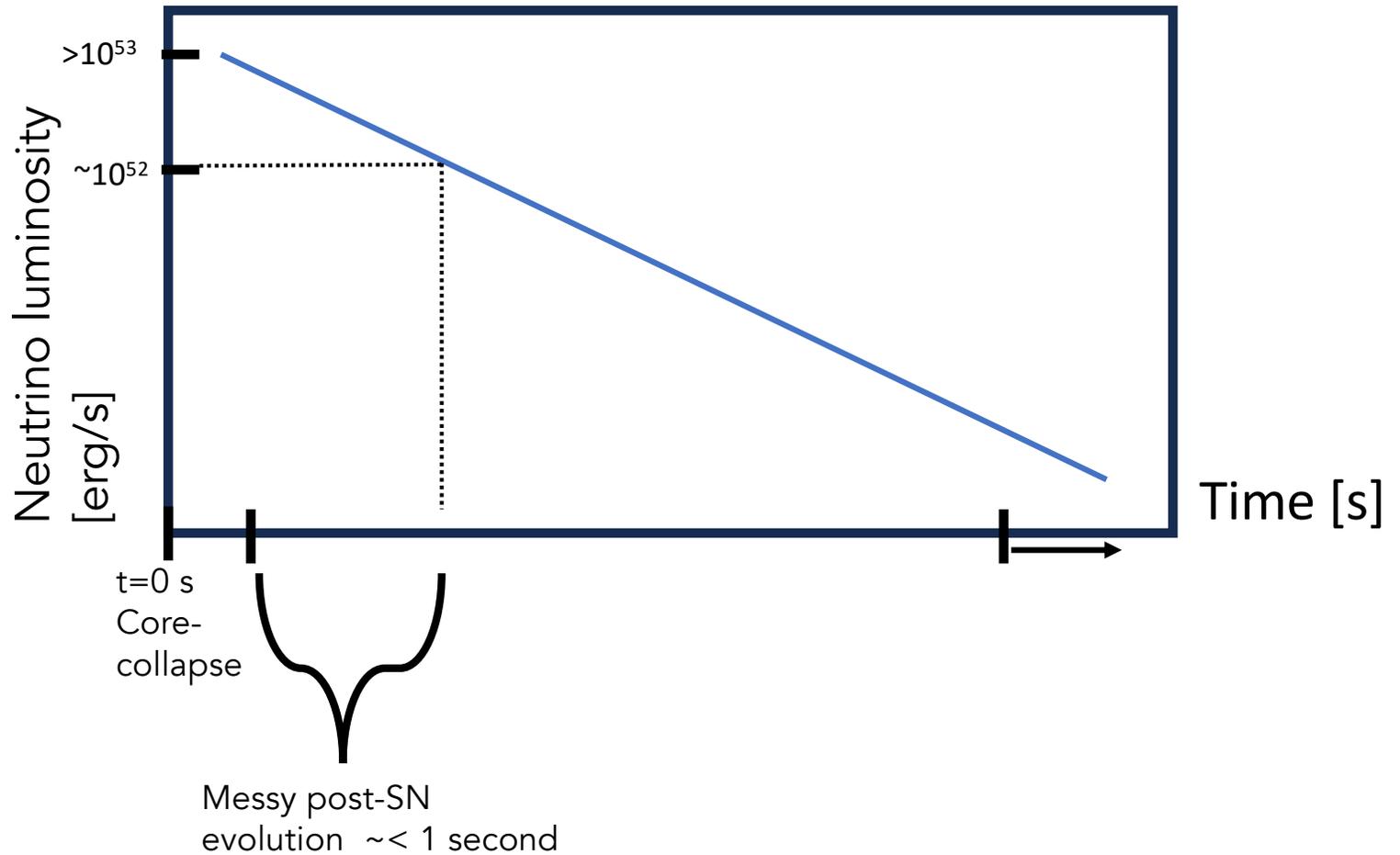
One possibility

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



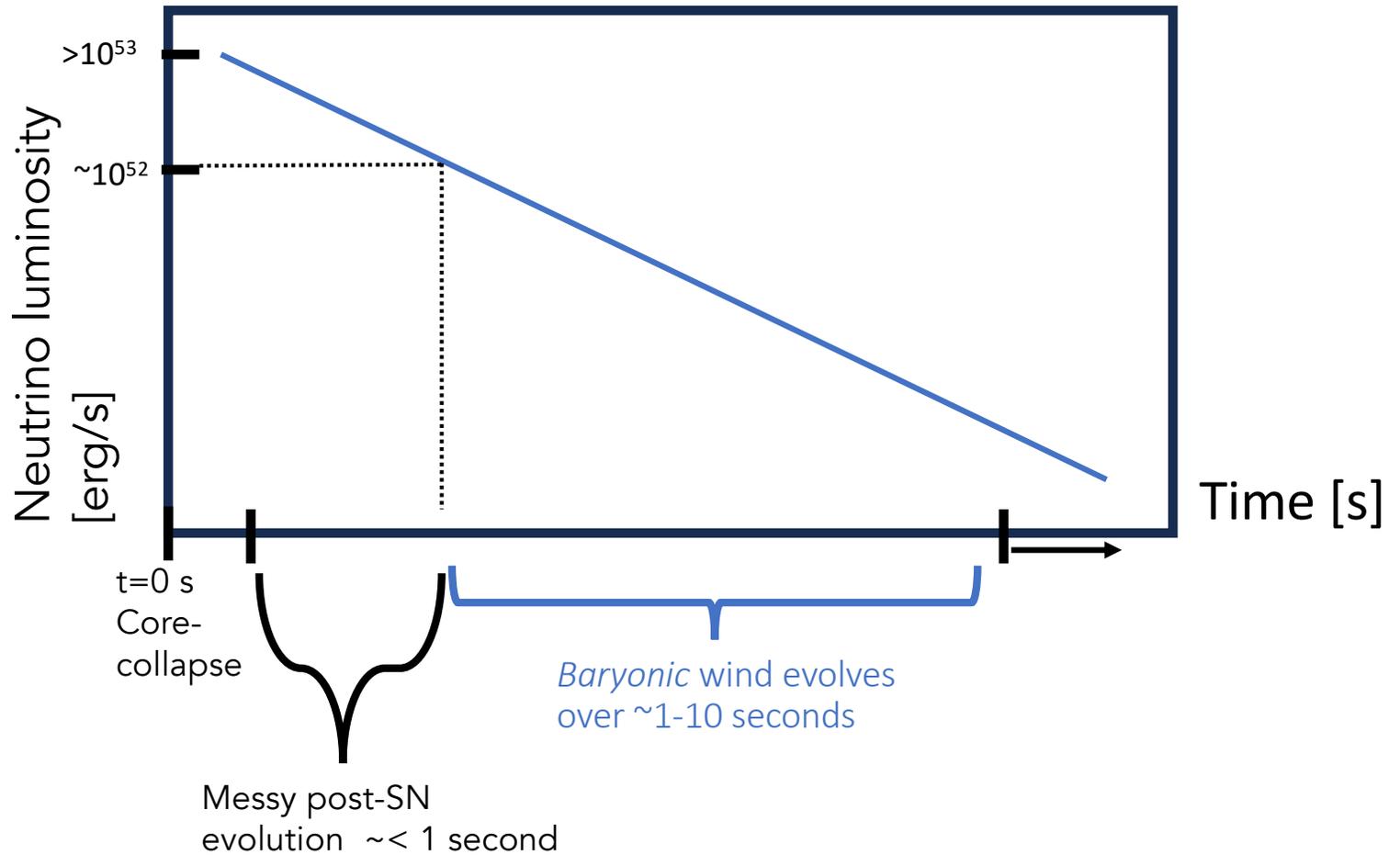
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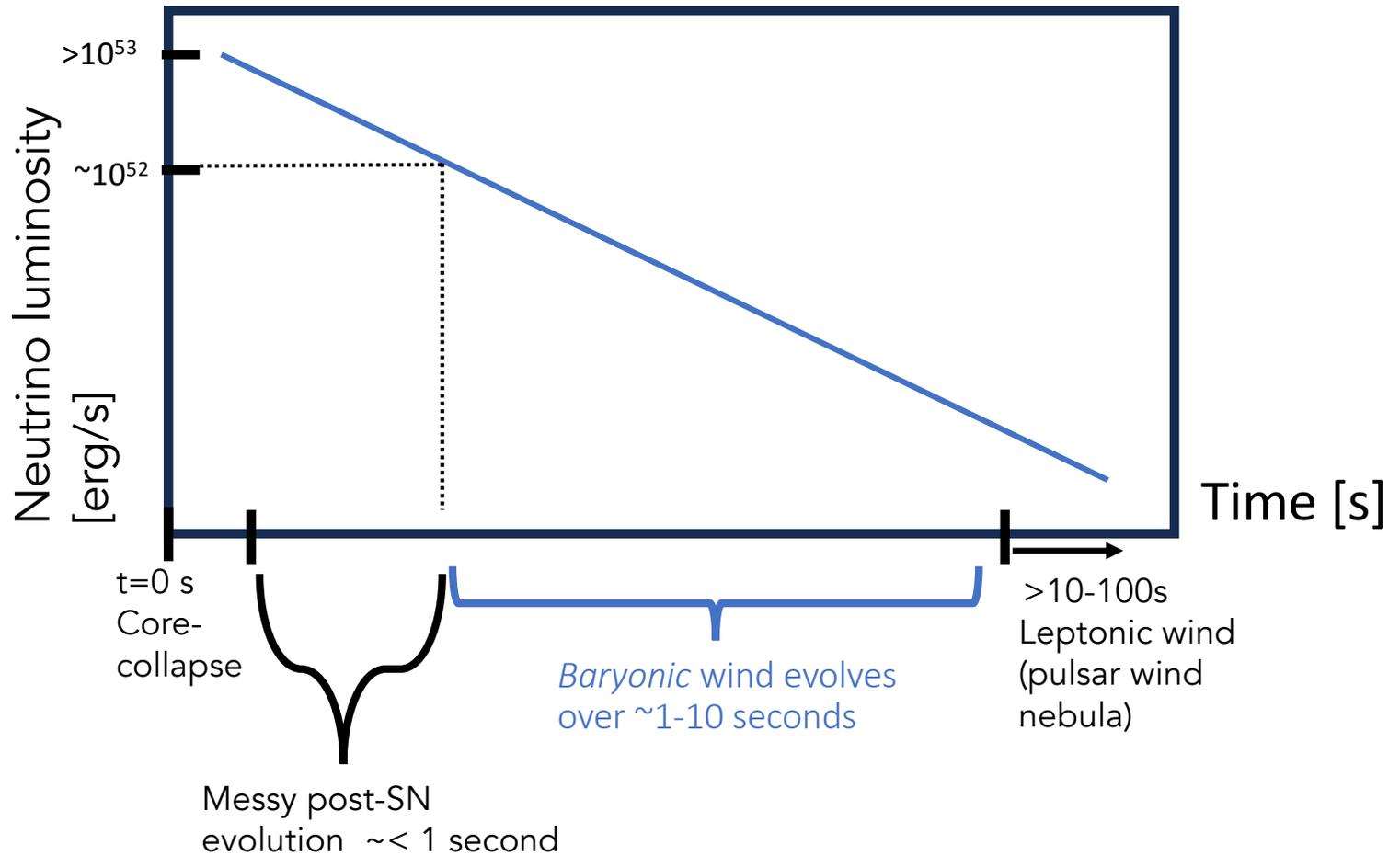
One possibility

Clean, *baryonic wind* can develop following *successful supernova explosion* after *~few seconds*



One possibility

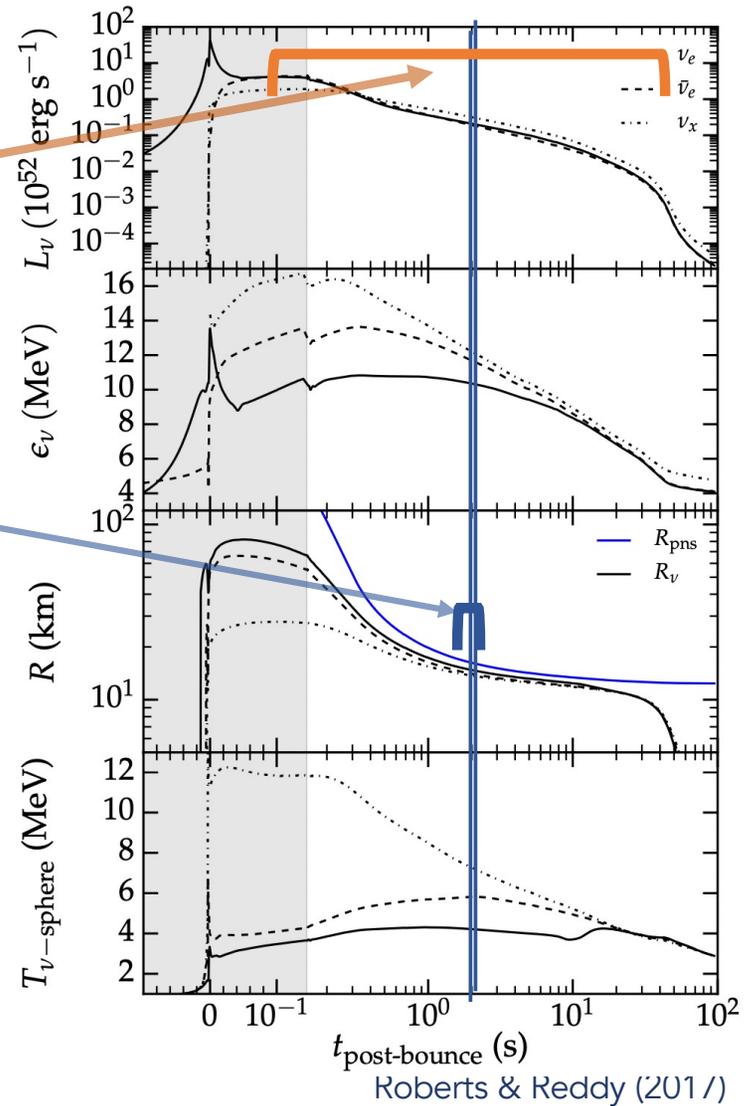
Clean, *baryonic wind* can develop following *successful supernova explosion* after *~few seconds*



Outflows from remnant evolve over **~seconds** (neutrino cooling timescale)

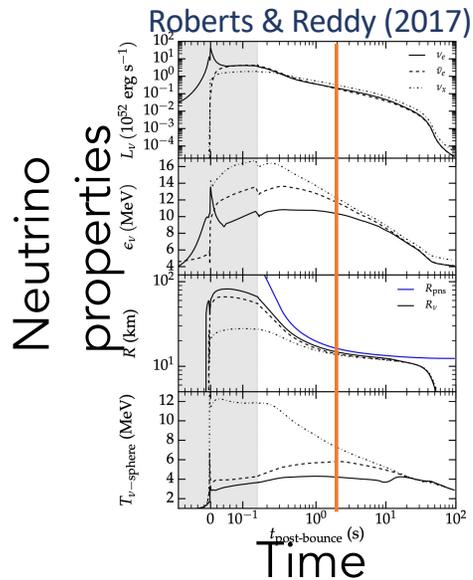
Can treat ~100 ms outflows as steady-state

- Neutrino properties **~2s** after bounce:
 - $L \sim 10^{51} \text{ erg s}^{-1}$
 - $E \sim 10\text{-}20 \text{ MeV}$
 - $R_v \sim 10 \text{ km}$ (where optical depth ~ 1)



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

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



+ 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

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Compare to observations - diverse

Disentangle physical mechanisms

Our 3D GRMHD toy model

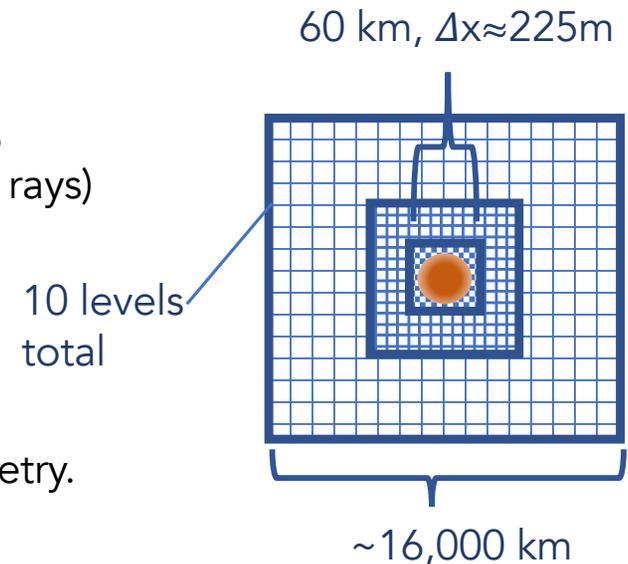


Evolution code

- 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)

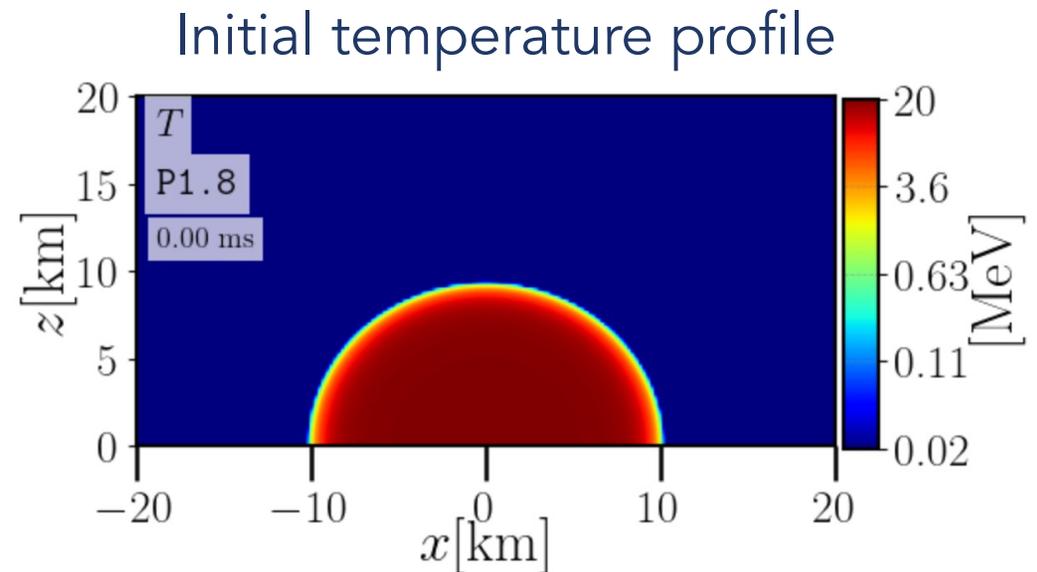
Nested Grid setup

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

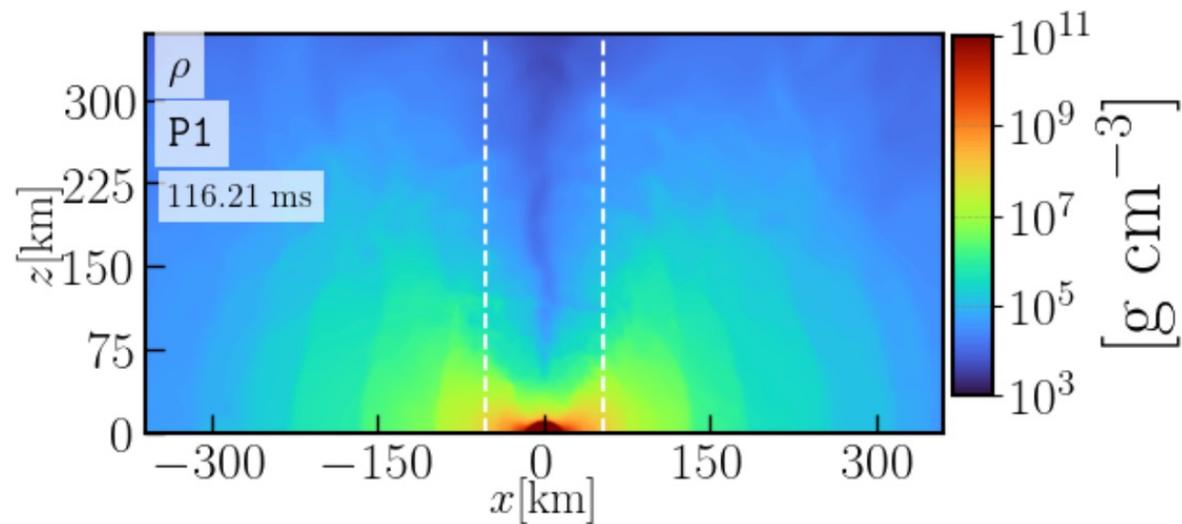


Our GRMHD toy model: Initial Conditions

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



First: models evolved to steady-state outflows

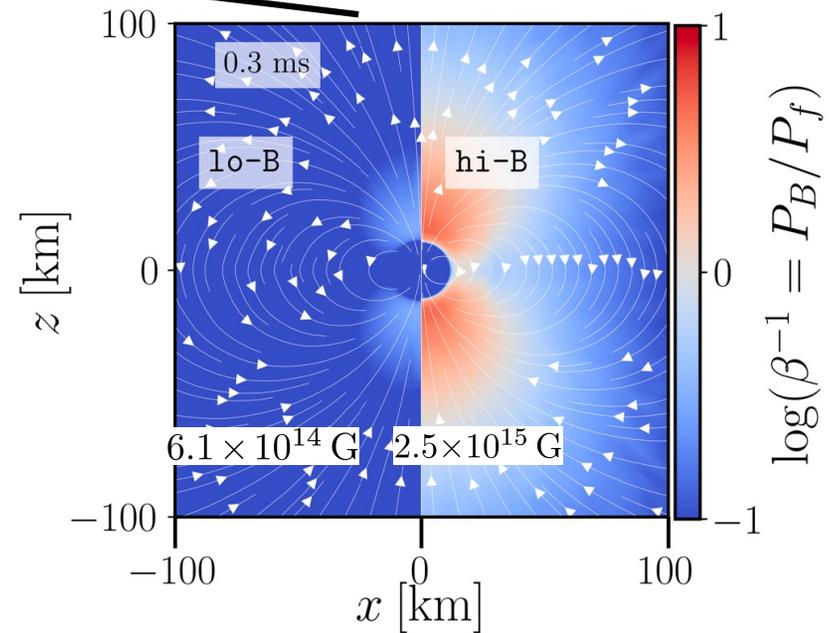


$t \sim 50-100$ ms

Then, large-scale dipole magnetic field initialized

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

We present these outflows.



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):

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

Blackbody neutrino
luminosity:

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

In terms of neutrino properties:

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

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

Criterion for magnetic fields to impact the wind

Magnetic pressure is comparable to fluid pressure at base of wind

$$P_B = B^2 / 8\pi$$

In terms of neutrino properties:

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

Fluid pressure (radiation-dominated):

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

Blackbody neutrino luminosity:

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

Wind dynamics impacted for magnetic field strengths greater than $\sim 10^{15} \text{ G}$

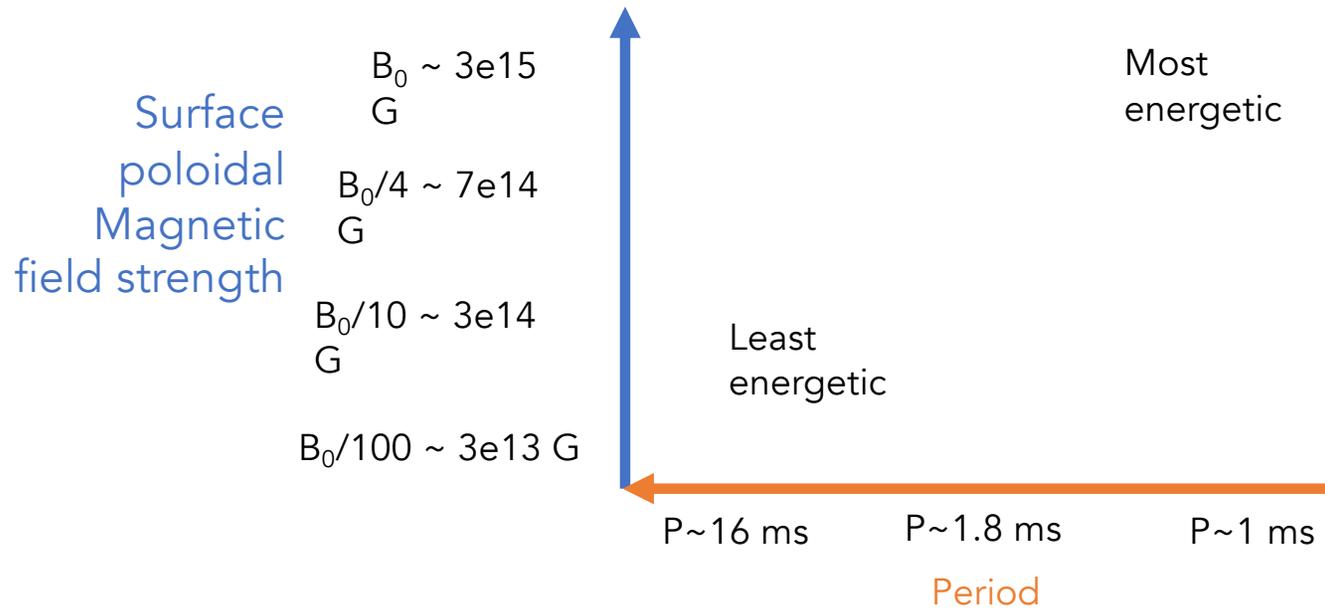
Criteria to impact the wind dynamics

rotation periods **less than ~ 3 ms**

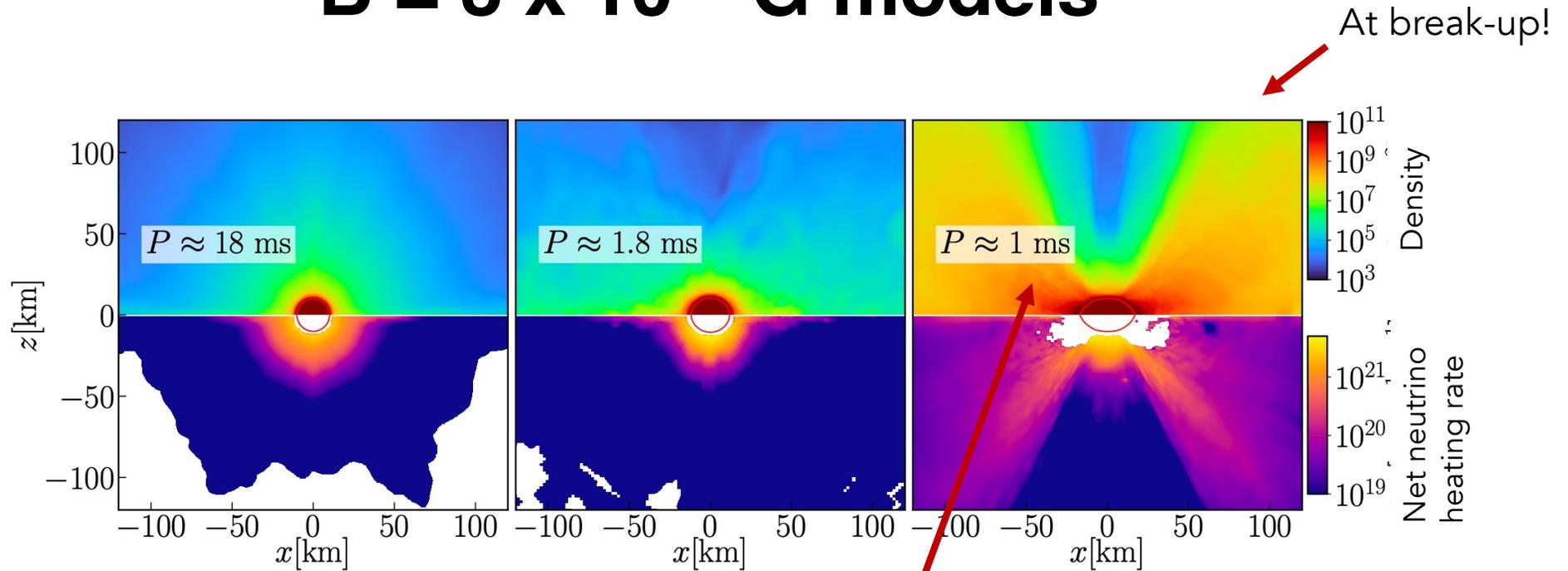
magnetic field strengths **greater than $\sim 10^{15}$ G**

Combining Magnetic fields and rapid rotation

Models
tested

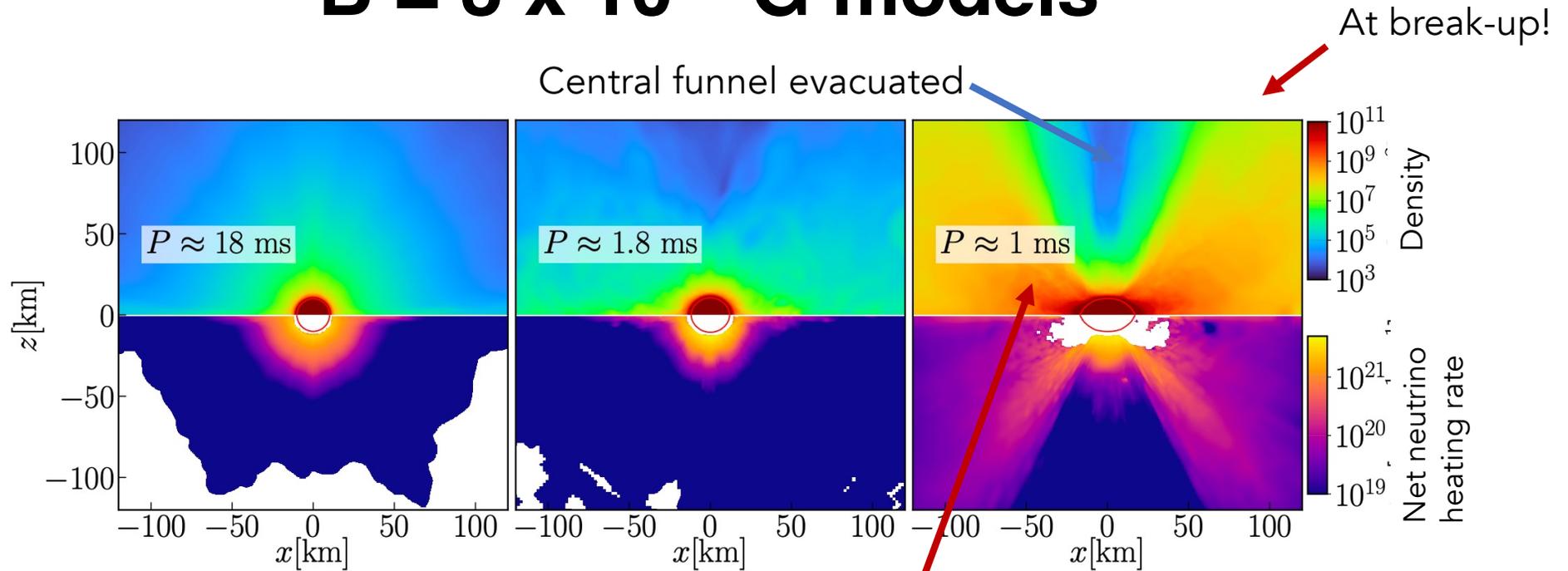


$B = 3 \times 10^{15}$ G models



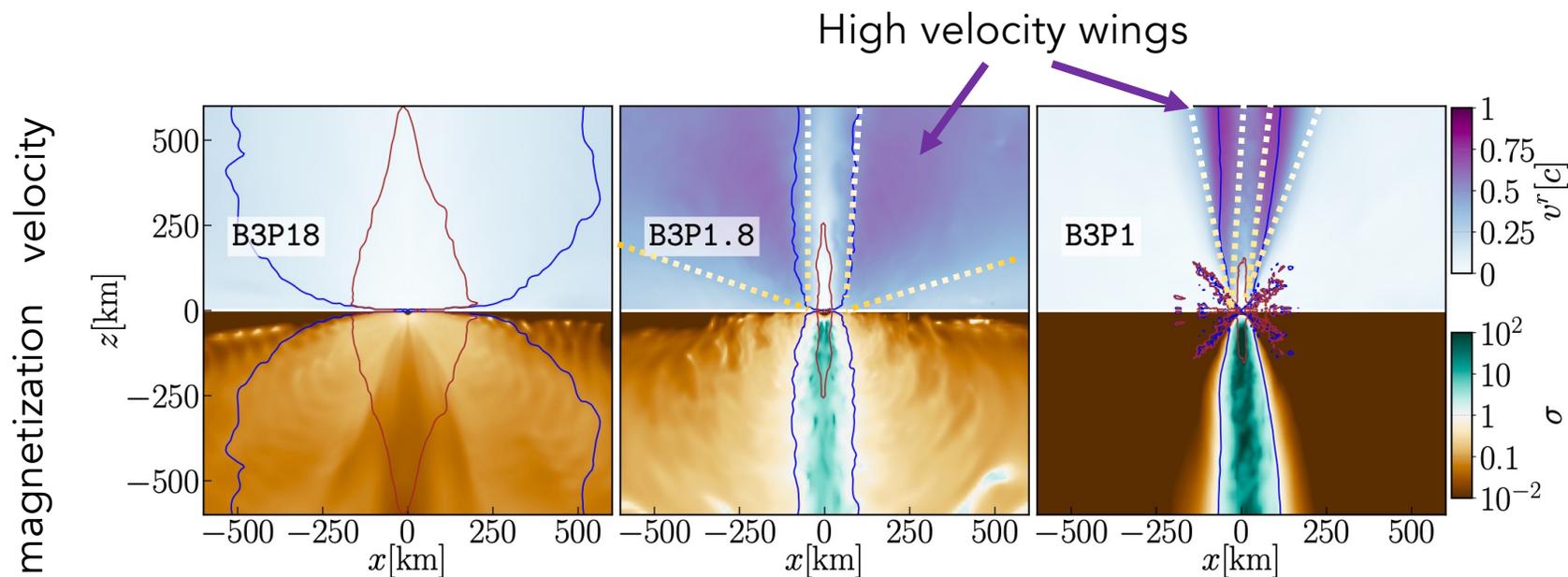
Dense equatorial outflows develop for $P=1$ ms model

$B = 3 \times 10^{15}$ G models



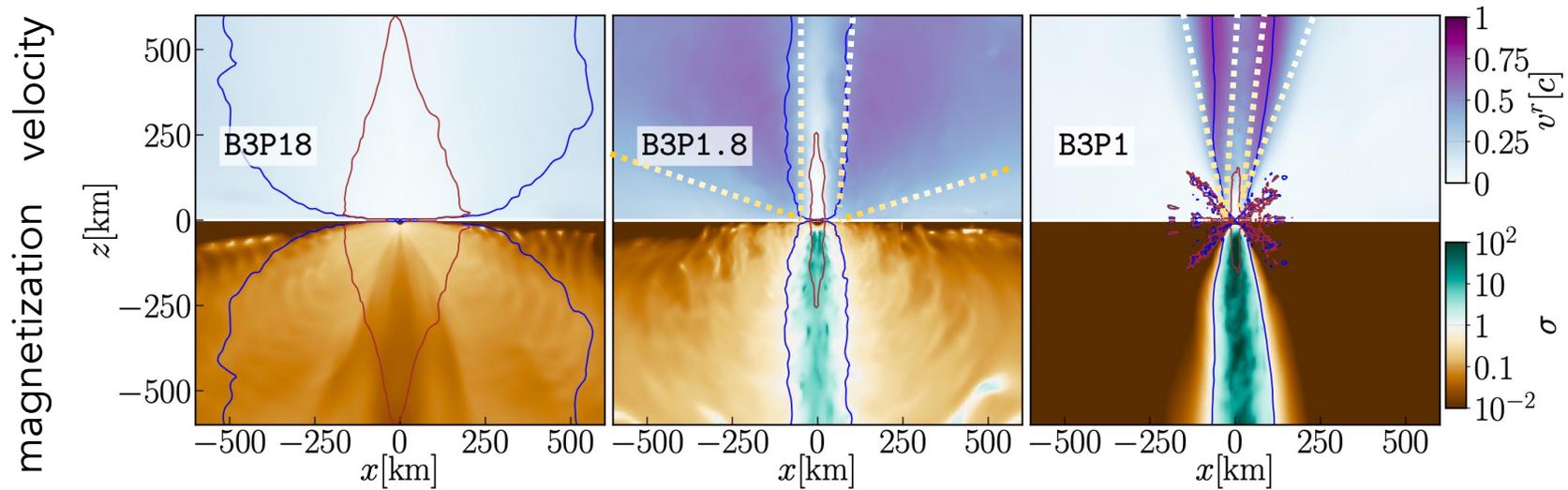
Dense equatorial outflows develop for $P=1$ ms model

$$\mathbf{B} = 3 \times 10^{15} \text{ G}$$



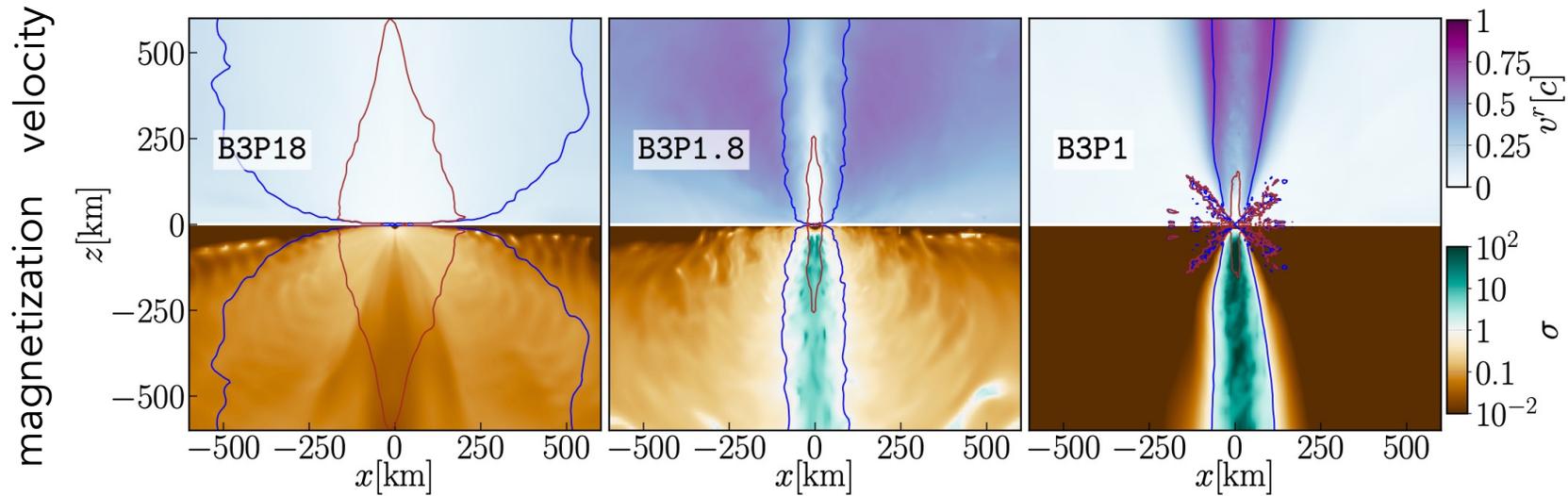
Smaller angular extent of high velocity region for $P=1$ ms model

$$\mathbf{B} = 3 \times 10^{15} \text{ G}$$



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

$$\mathbf{B} = 3 \times 10^{15} \text{ G}$$



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

No centrifugal mass enhancement in polar direction

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

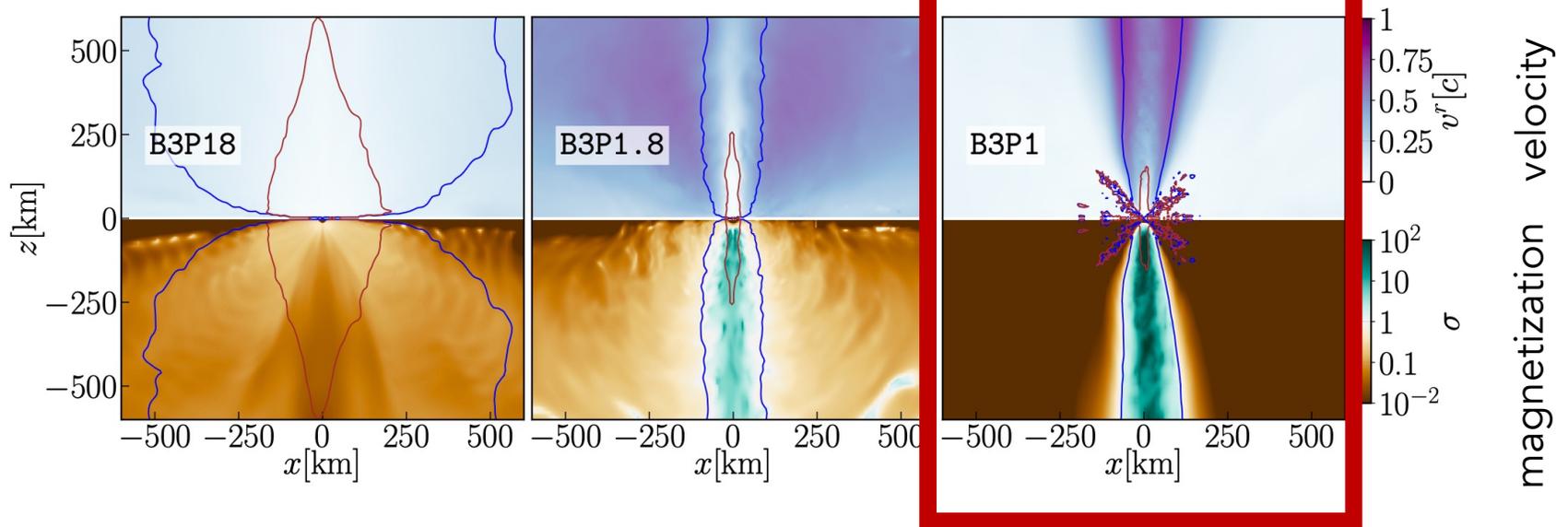
Magnetic flux

Rotation rate

mass flux
Reduced in polar funnel

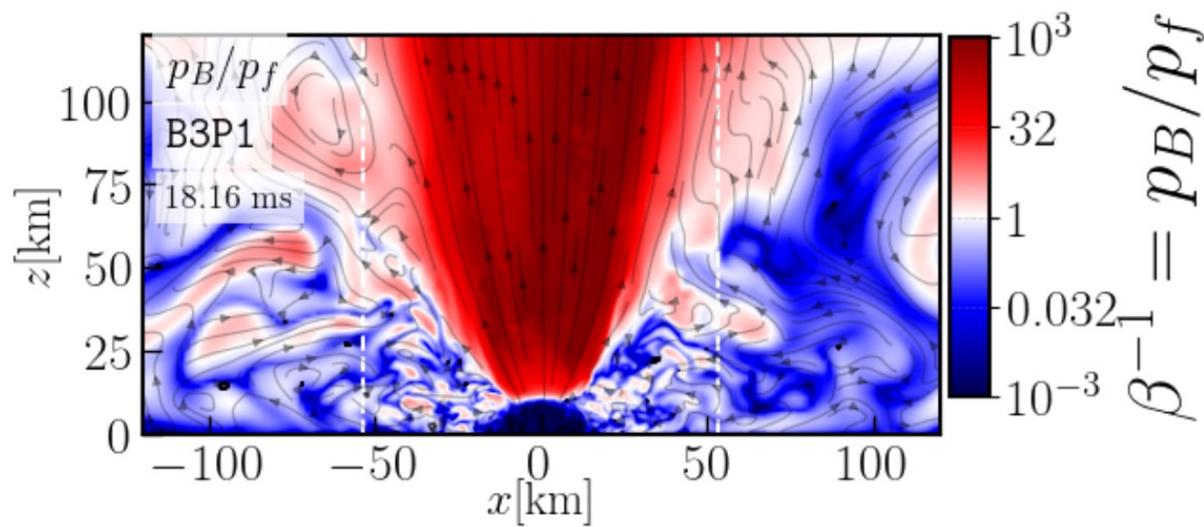
$B = 3 \times 10^{15} \text{ G}$

The chosen one



High sigma 'jet' even at neutrino luminosities $\sim 10^{52} \text{ erg/s}$

Significant magnetic pressure support in central funnel



Centrifugal barrier +
magnetic pressure

→

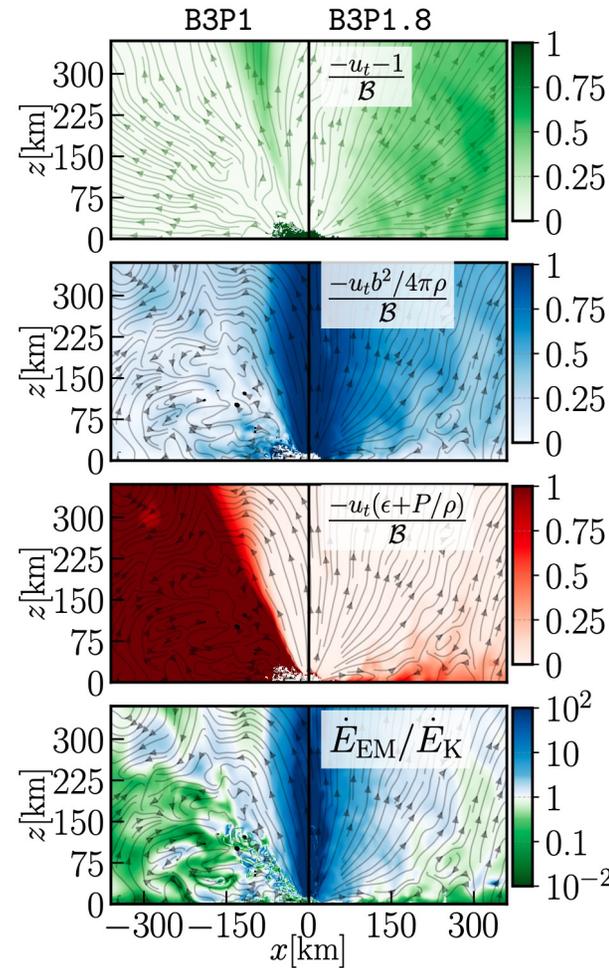
massive disk/
late time fall-back

may not affect polar
outflows

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

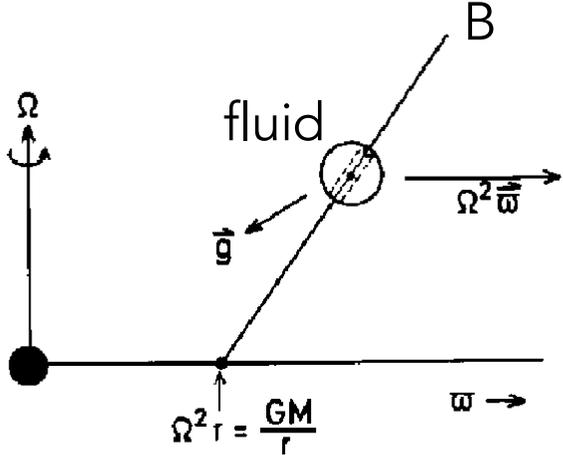
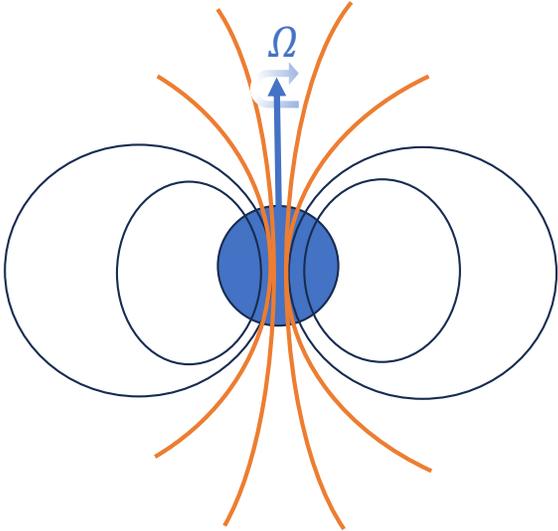
$B = 3 \times 10^{15}$ G
 $P = 1$ ms

$B = 3 \times 10^{15}$ G
 $P = 1.8$ ms

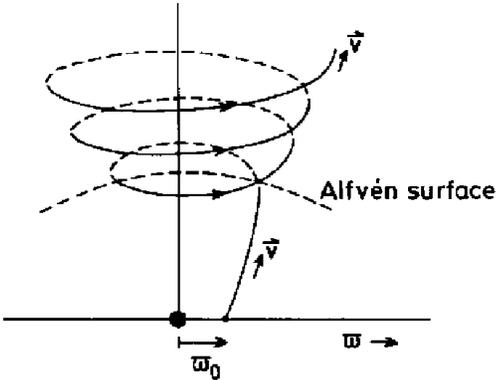


Desai+2026
(submitted, *ApJL*)

Rotation + magnetic fields can sling fluid along open field lines

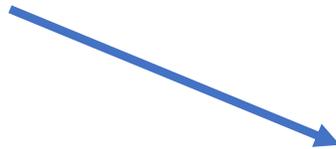


Spruit 96

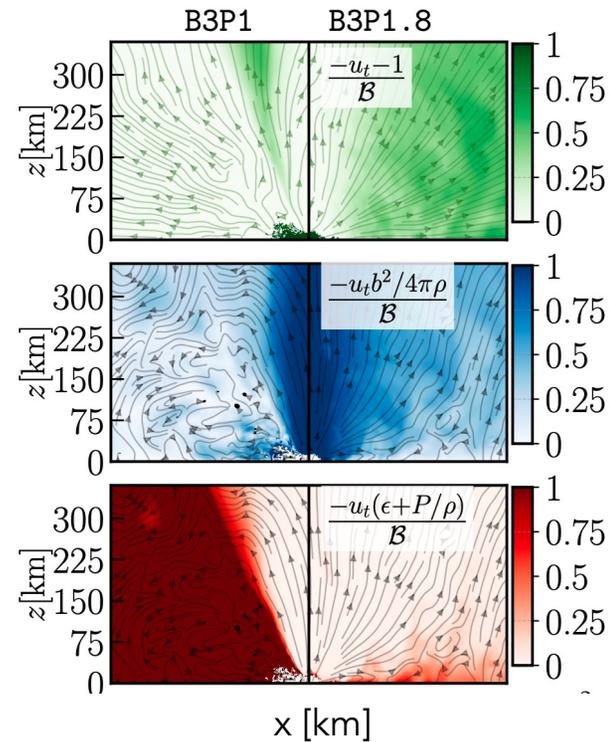


Fractional energy contributions for $P = 1$ ms and $P = 1.8$ ms

Magnetic energy dominates core of the jet



$B = 3 \times 10^{15}$ G $B = 3 \times 10^{15}$ G
 $P = 1$ ms $P = 1.8$ ms



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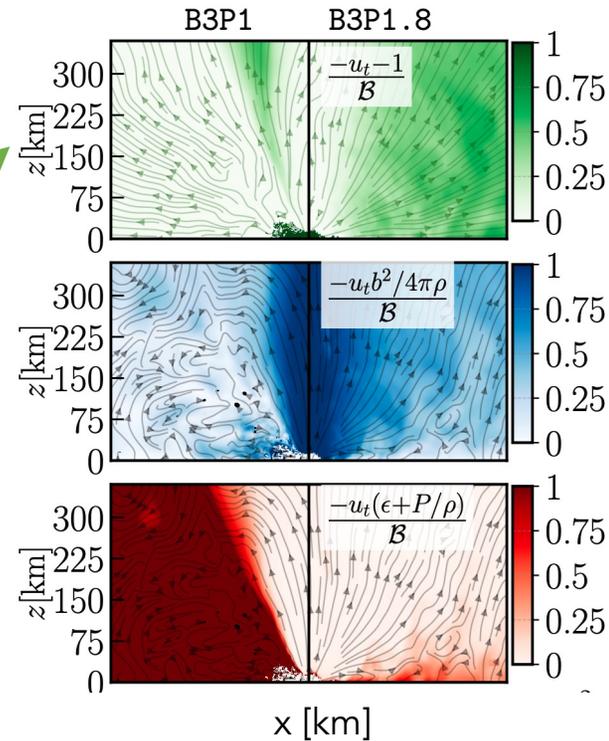
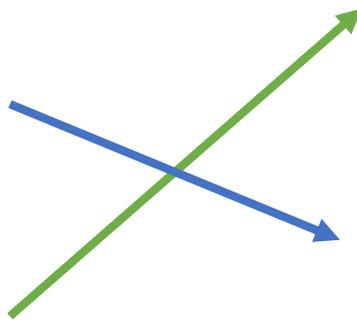
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1. Centrifugal slinging at play!

Magnetic energy dominates core of the jet



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



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

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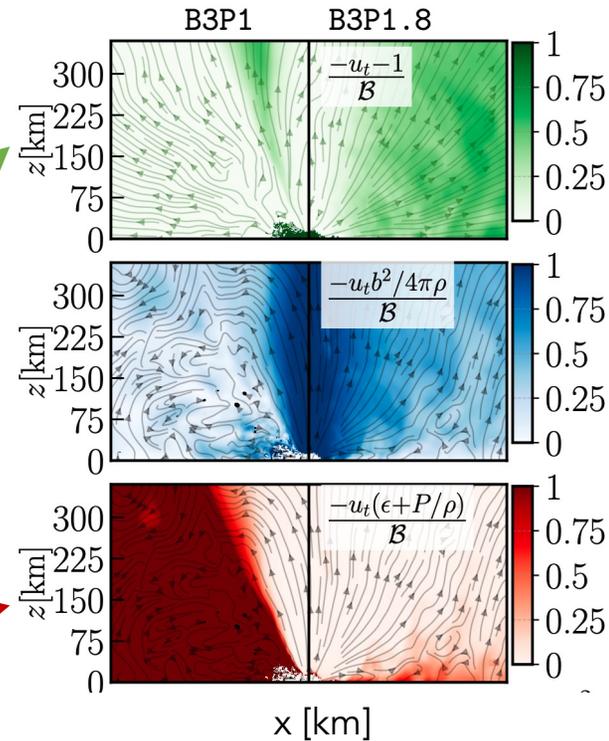


Energy converted to kinetic energy as fluid flows away from proto-magnetar

thermal energy negligible in pole

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1. Centrifugal slinging at play!

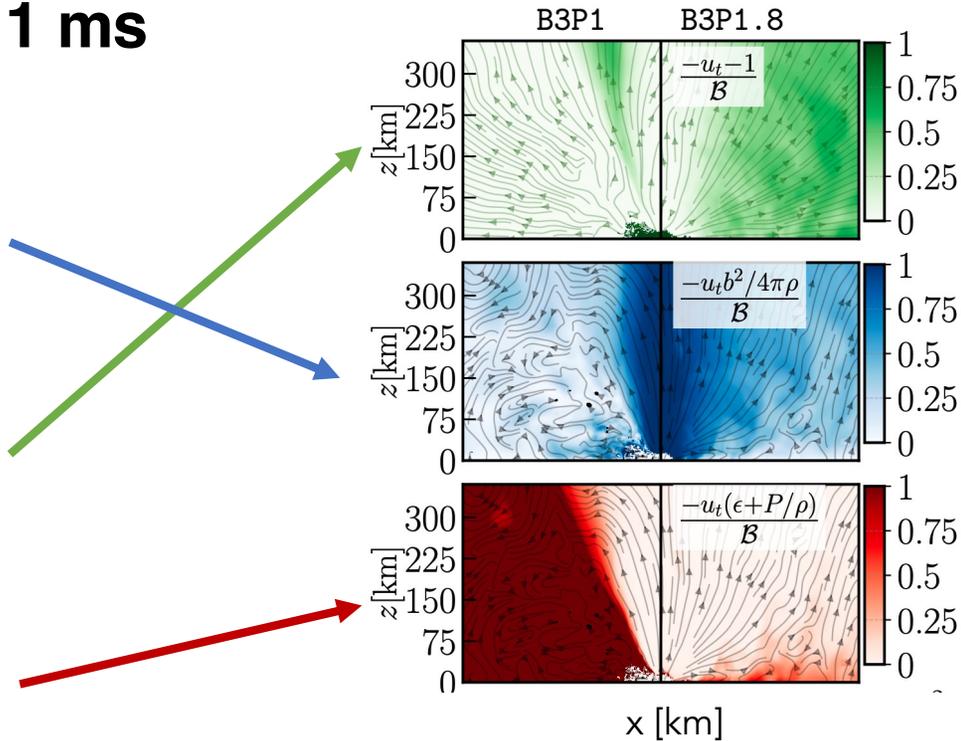
Magnetic energy dominates core of the jet



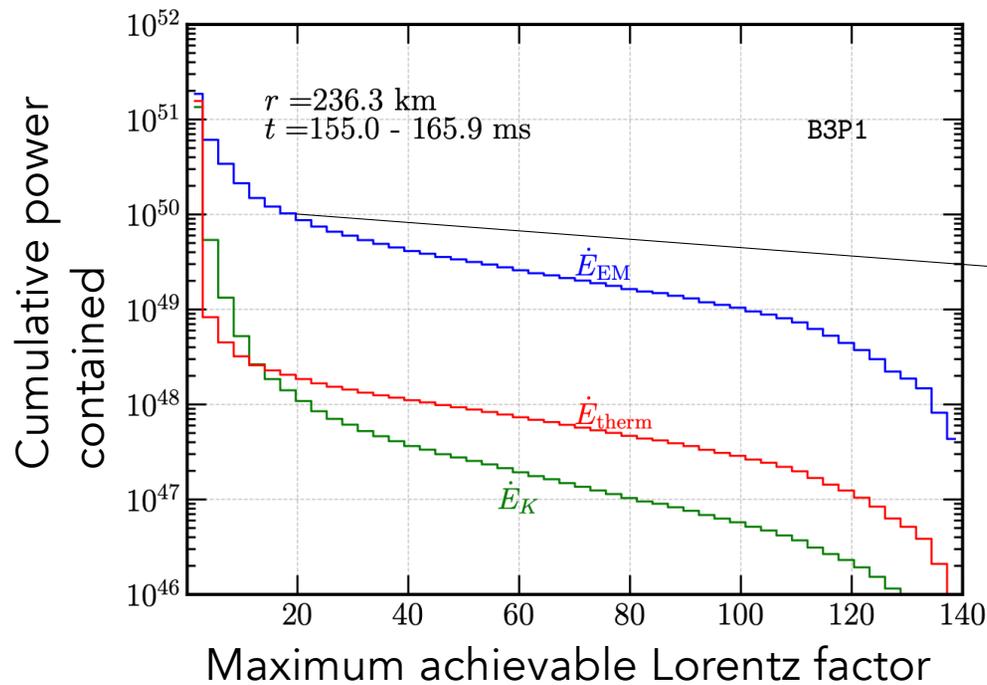
Energy converted to kinetic energy as fluid flows away from proto-magnetar

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2. Dense equatorial outflows focus acceleration into a polar jet

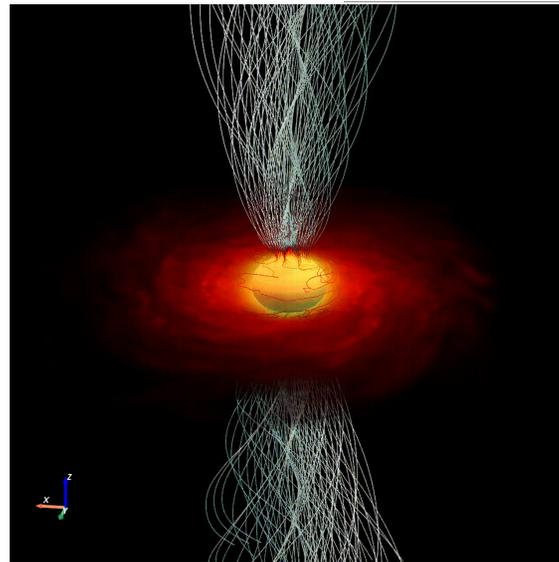
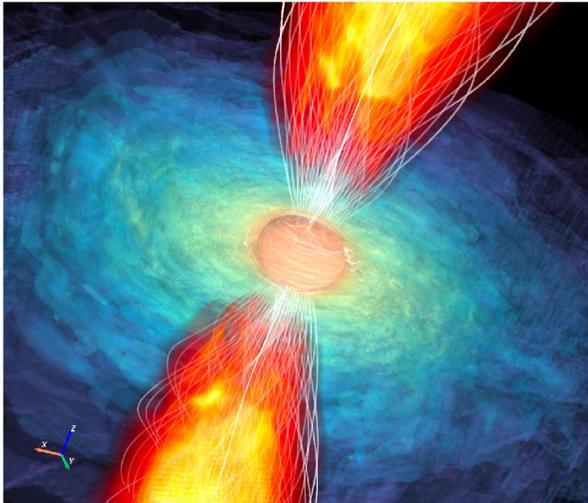
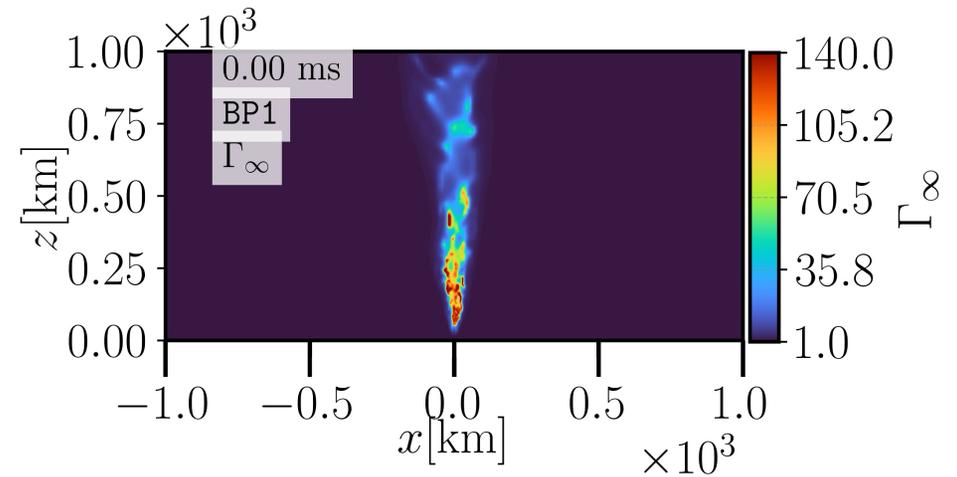


Distribution of power to high Lorentz factors ($\sim > 100$)



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

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



$B \sim 3e15$ G
 $P \sim 1$ ms
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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Rather a *natural consequence*
of rotation + magnetization

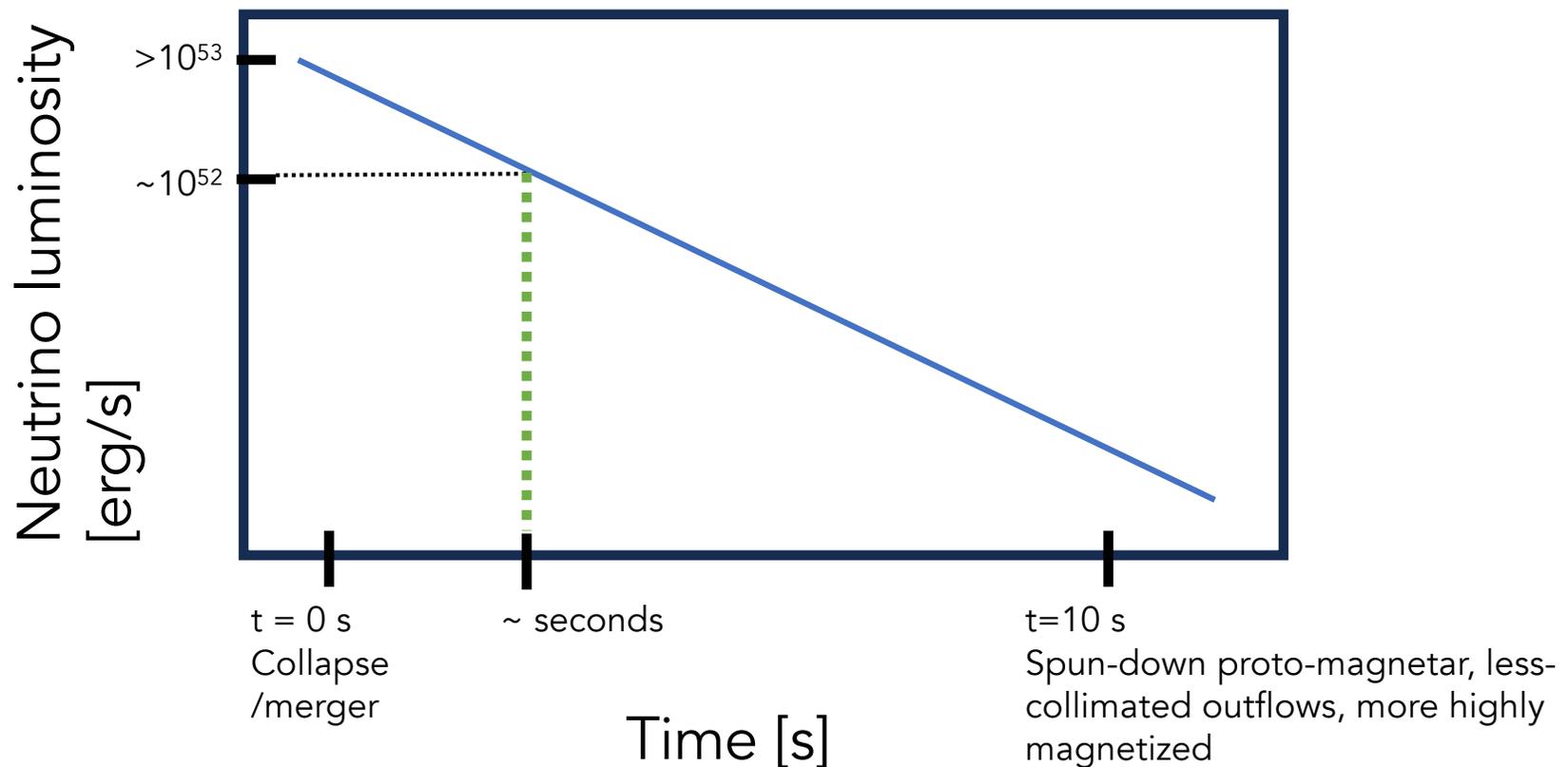
Bonus: *collimation* arises intrinsically at small
radii, without requiring confinement by external
envelope or supernova

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

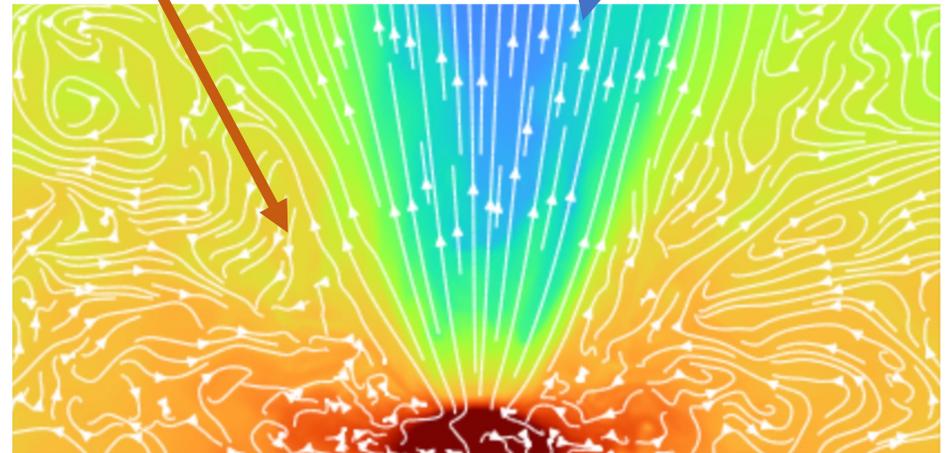
When & where might such remnants be formed?

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

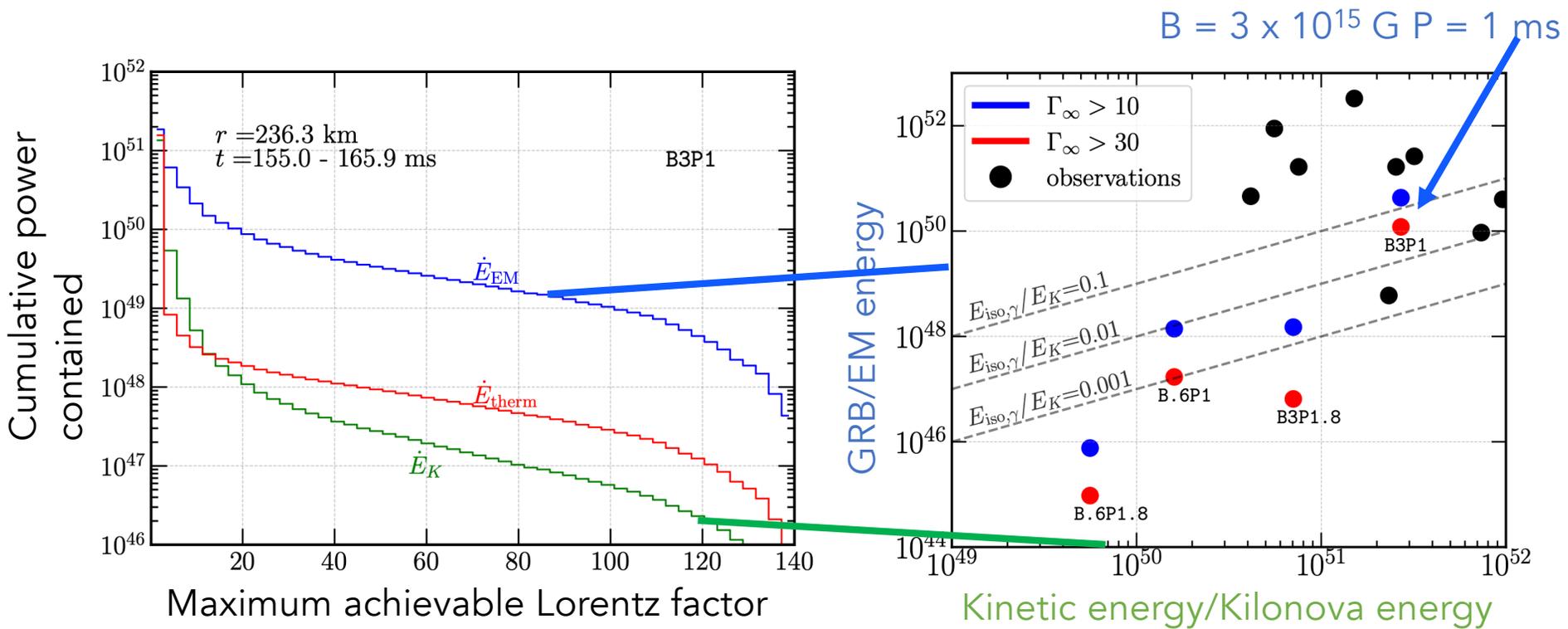
A **jet** would occur within seconds of an event (prompt)



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



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



Magnetization evolves on neutrino cooling timescales

$$\sigma_{\text{outflow}} = \frac{\text{Poynting flux}}{\text{Mass flux}}$$

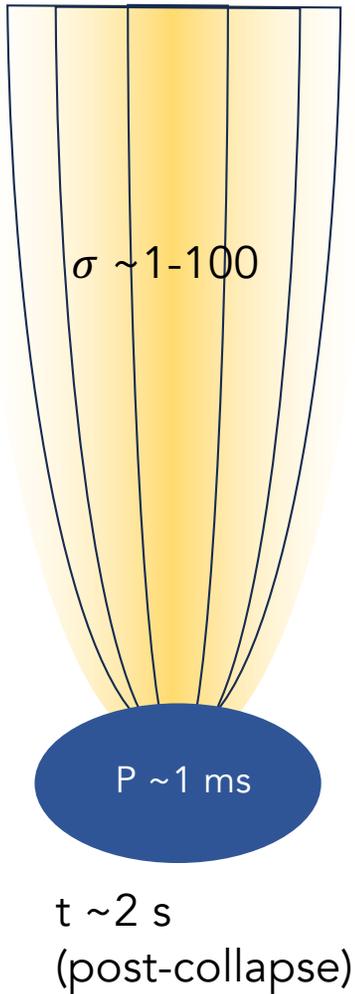
Magnetic
field strength

Rotation
rate slows

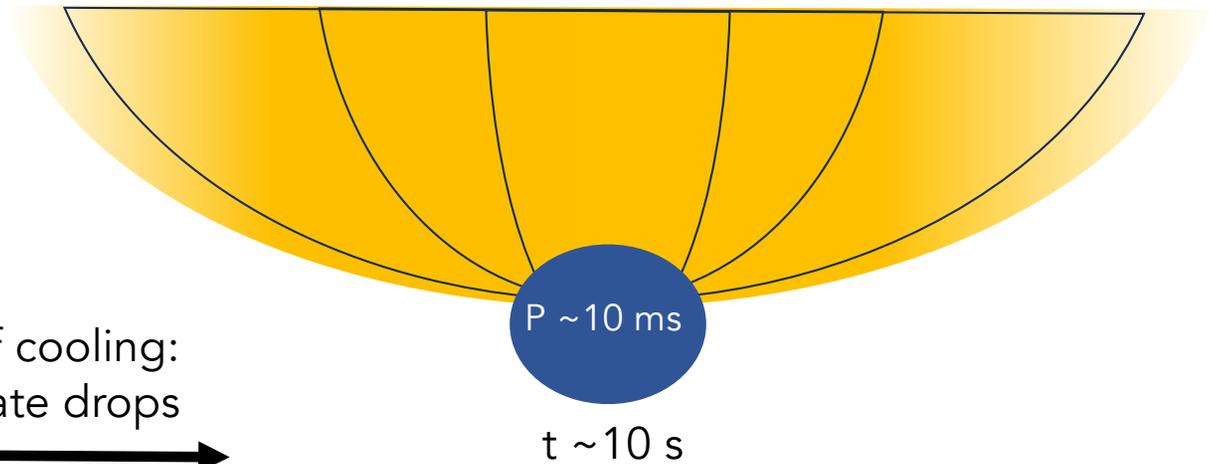
$$= \frac{\Phi_B^2 \Omega^2}{\dot{M} c^3}$$

**Mass loss rate drops
drastically as proto-magnetar
cools...**

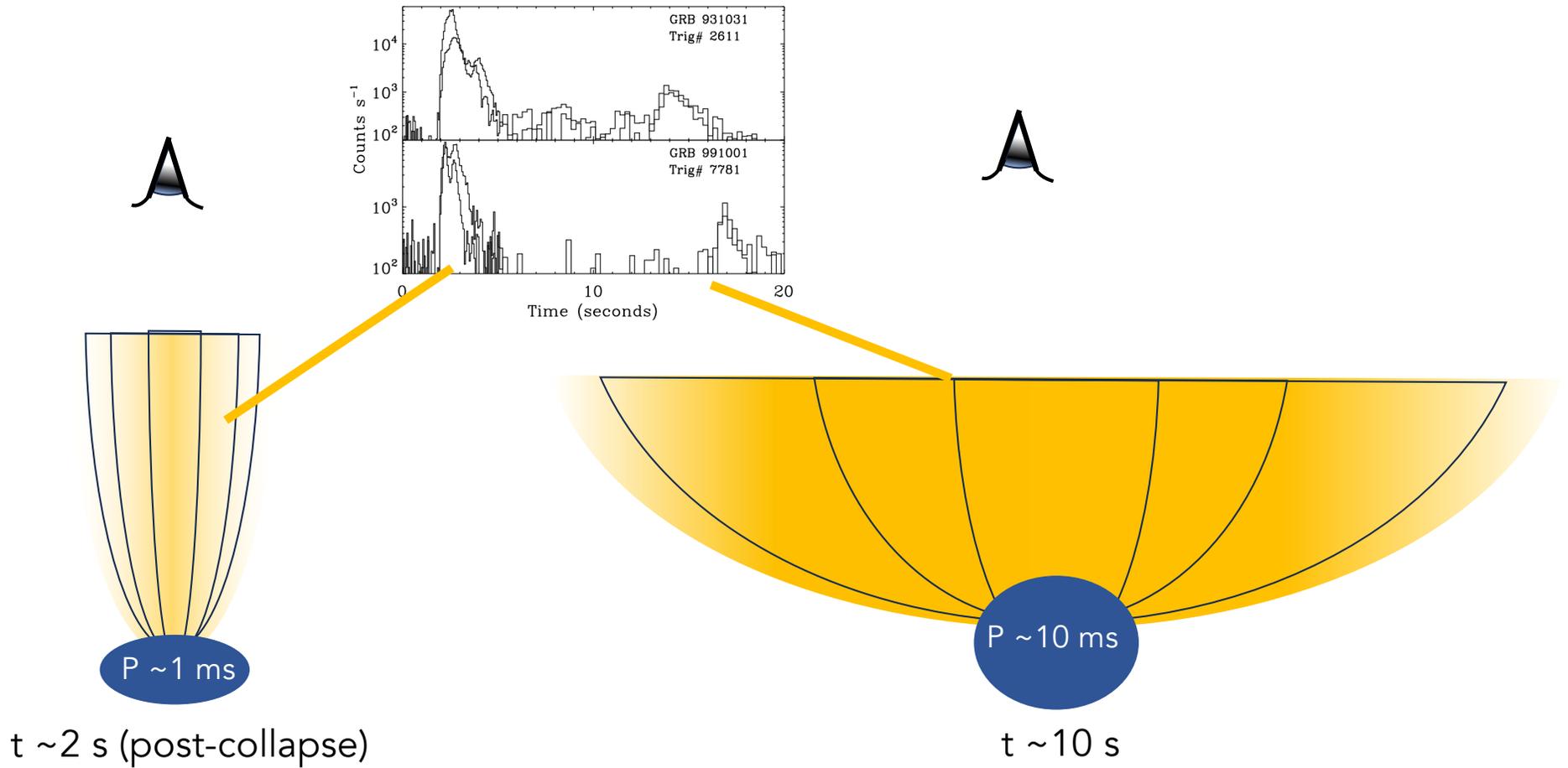
...so the jet becomes less collimated, more magnetized over ~10 seconds



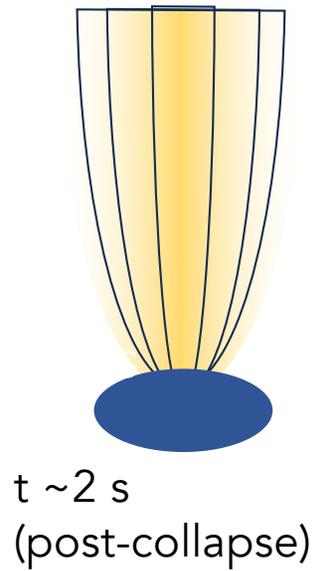
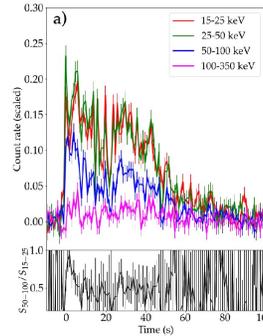
$t \sim 5-10 \text{ s}$ of cooling:
mass loss rate drops



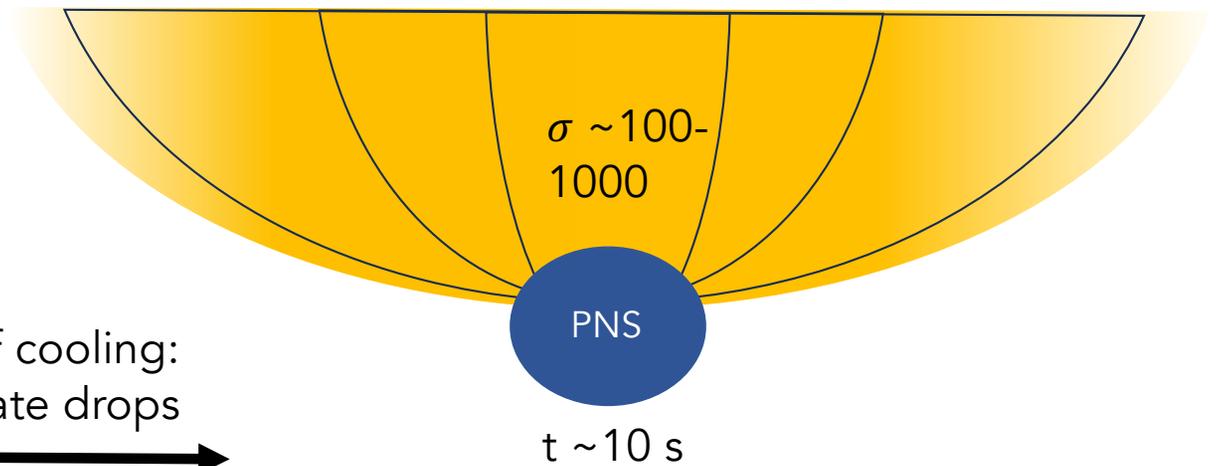
Head-on observation: Short GRB + extended emission



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



$t \sim 5-10$ s of cooling:
mass loss rate drops



Conclusions

- **continuous transition** in most proto-magnetar wind properties
 - low $B \rightarrow$ high B , & low $\Omega \rightarrow$ high Ω
- Rapidly rotating model – $B \sim 3 \times 10^{15}$ G, $P \sim 1$ ms (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 ($\sim 0.7c$), and material with **high sigma** ($\sim 50-150$)
 - Jet is *a generic consequence* of a ms proto-magnetar
 - Applicable to accretion-induced **white dwarf collapse, mergers and core-collapse**
 - Could explain a **diversity of observations** (prompt emission, long/short GRBs, extended emission, X-ray flash)

What next?

- Interplay between disk and slower rotating models
- Nucleosynthesis
- Input to large-scale jet simulations



That's all Folks!