Study on the effect of the outflow from young neutron stars and supernova fallback on the neutron star diversity

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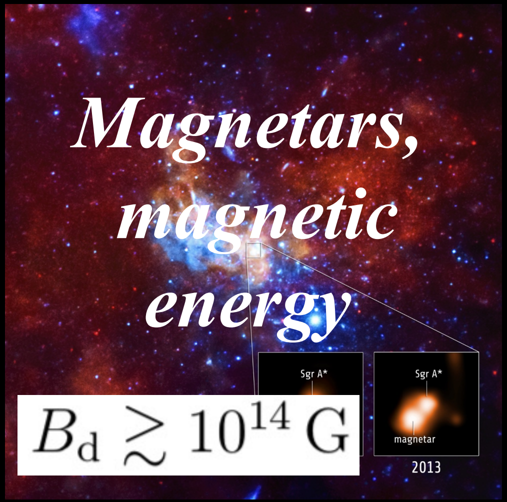
2021.08.27

The diversity of young isolated neutron stars (t_{age} < 1-10 kyr)

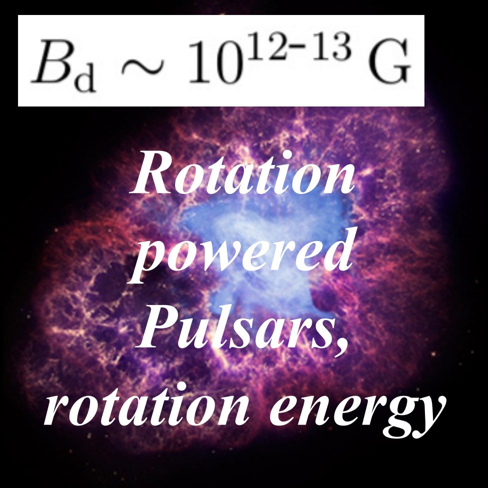


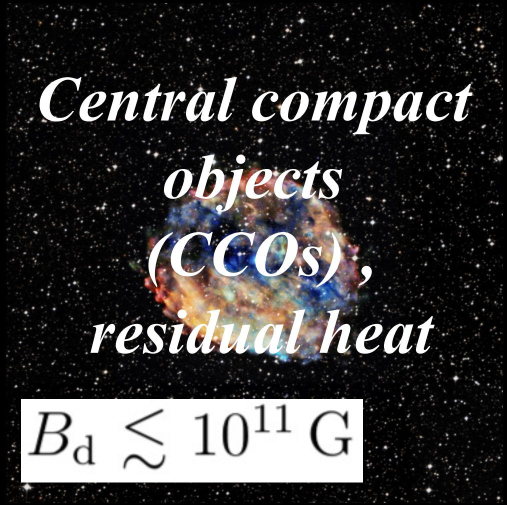
- Luminous in soft x-ray band
- $L_x > L_{sd}$: extra energy source

- Luminous in radio/x-ray band
- Pulsates regularly
- $L_x \sim L_{sd}$

?

why CCO's B_d field is so small?





- Luminous in x-ray band
- $L_x > L_{sd}$: extra energy source

Introduction: Fallback accretion onto NS

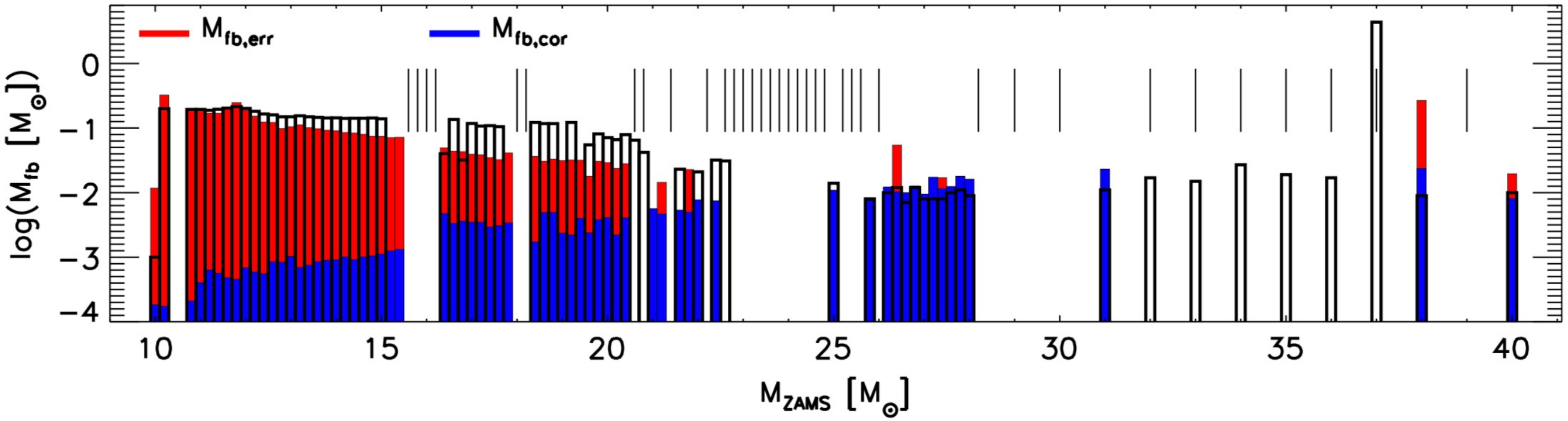
$$\dot{M}_{\rm fb} = \dot{M}_{\rm fb,ini} \times \begin{cases} 1 & t \le t_{\rm fb} \\ (t/t_{\rm fb})^{-5/3} & t > t_{\rm fb} \end{cases}, \quad \dot{M}_{\rm fb,ini} = \frac{2}{5}\frac{M_{\rm fb}}{t_{\rm fb}} \sim 4 \times 10^{-6}\, M_\odot\, {\rm s}^{-1}\, M_{\rm fb,-4} t_{\rm fb,1}^{-1}$$

The fallback mass is sensitive to the progenitor structure, the SN explosion mechanism, and so on.

$$M_{\rm fb} \sim 10^{-(2-4)}\, M_\odot$$

Dynamical range is large

e.g., Ugliano et al. 12; Ertl et al.16



It will proceed down to the NS surface and even bury the magnetosphere when $\dot{M}_{\rm crit,bury} \sim 10^{-5}\, M_\odot\, {\rm s}^{-1} \left(\frac{B_*}{10^{13}\,{\rm G}}\right)^{3/2}$

CCO formation!

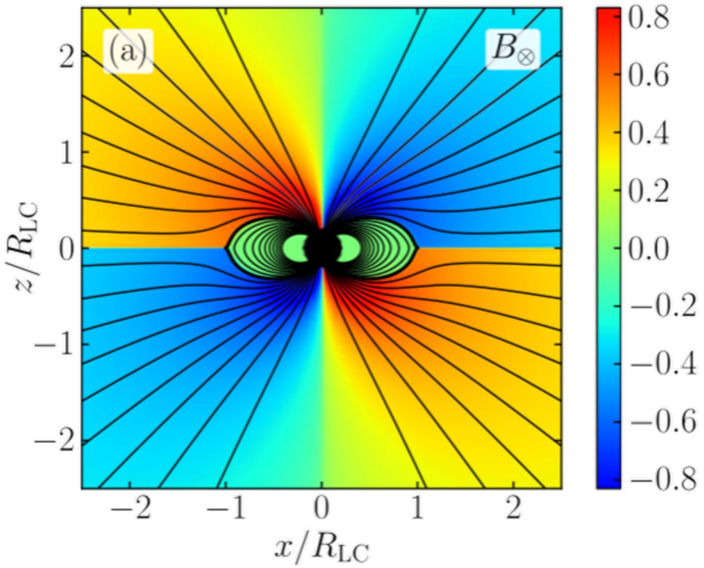
e.g., Torres-Forne ́ et al.16

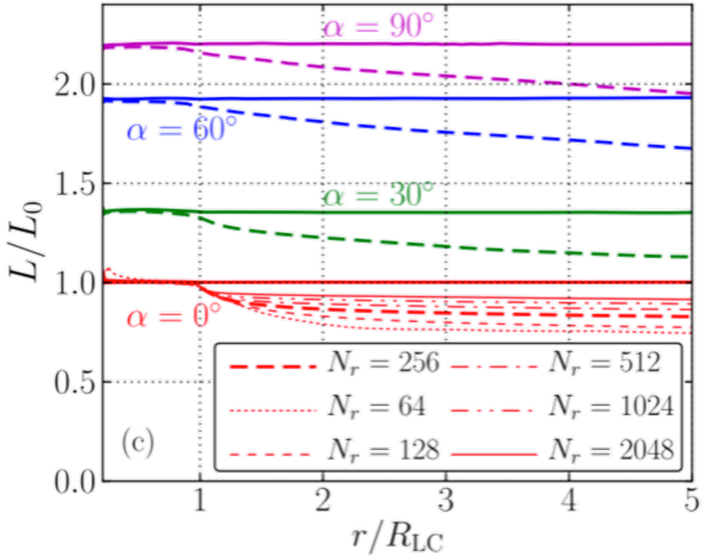
Relativistic outflow from NS

The electromagnetic waves associated with the angular momentum loss of the central NS is efficient for accelerating the charged particles being ejected to the magnetosphere to relativistic energy scale ($\Gamma_\infty \geq 100$)(*e.g., Gunn & Ostriker 69*), dominant component of wind after neutrino outflow ceases and fallback sets in.

$$L_{\rm sd} = \frac{{B_*}^2 {\Omega_{\rm i}}^4 R_*^6}{4c^3}\left(1+\sin\alpha^2\right) \sim 4.3\times 10^{41}{\rm erg\,s^{-1}}\left(1+\sin\alpha^2\right){B_{*,13}}^2 P_{\rm i,-2}^{-4}$$

Rotating dipole





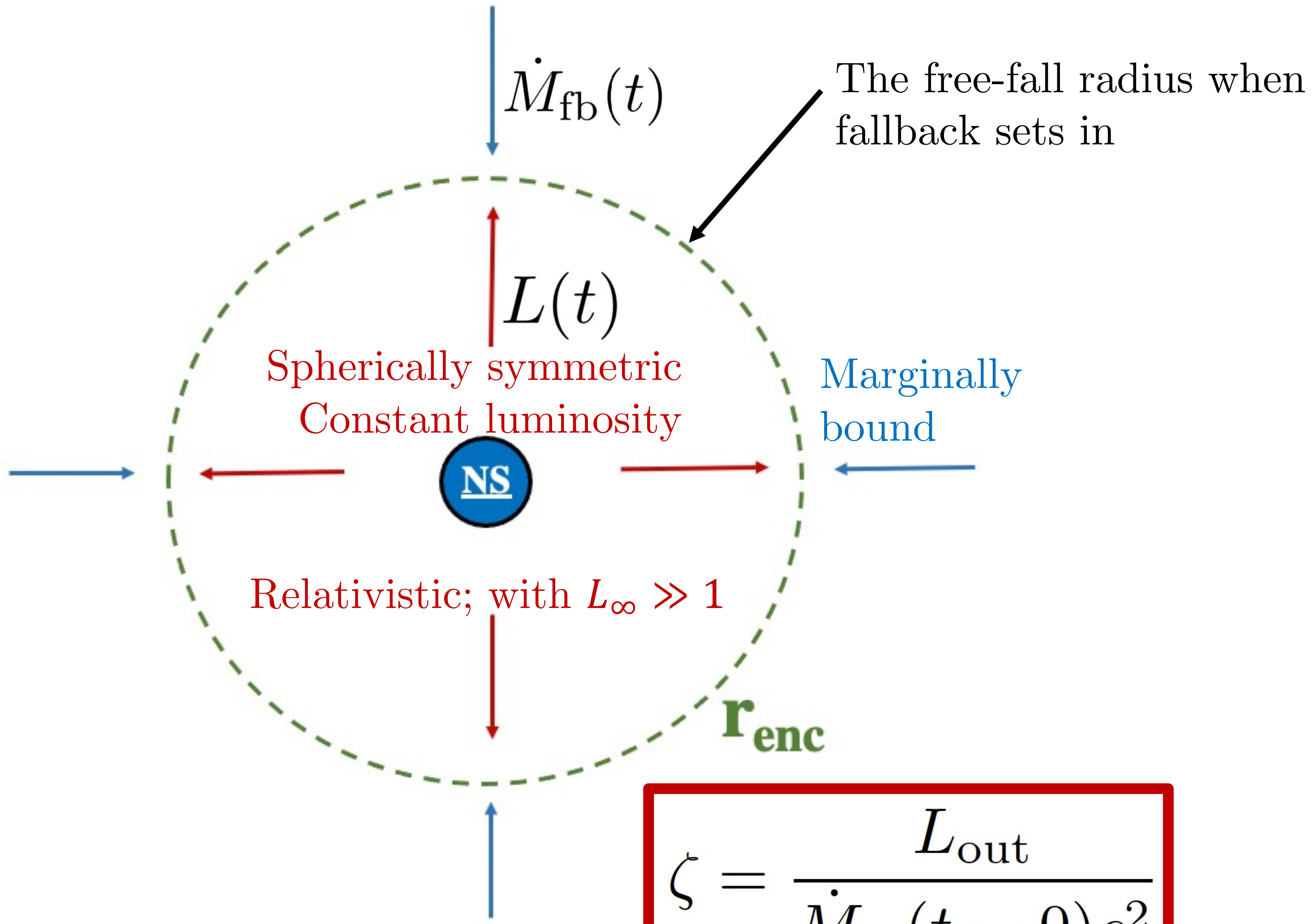
Radius-independent

Tchekhovskoy et al. 13

$$\zeta = \frac{L_{\rm sd}}{\dot{M}_{\rm fb,ini}c^2} = 10^{-3}\left(1+\sin\alpha^2\right){B_{*,14}}^2 P_{\rm i,-2}^{-4} M_{\rm fb,-4}^{-1}\, t_{\rm fb,1}$$

A competition between fallback matter and relativistic outflow → The neutron star diversity?

Physical picture & Methods



$$\zeta = \frac{L_{\rm out}}{\dot{M}_{\rm fb}(t=0)c^2}$$

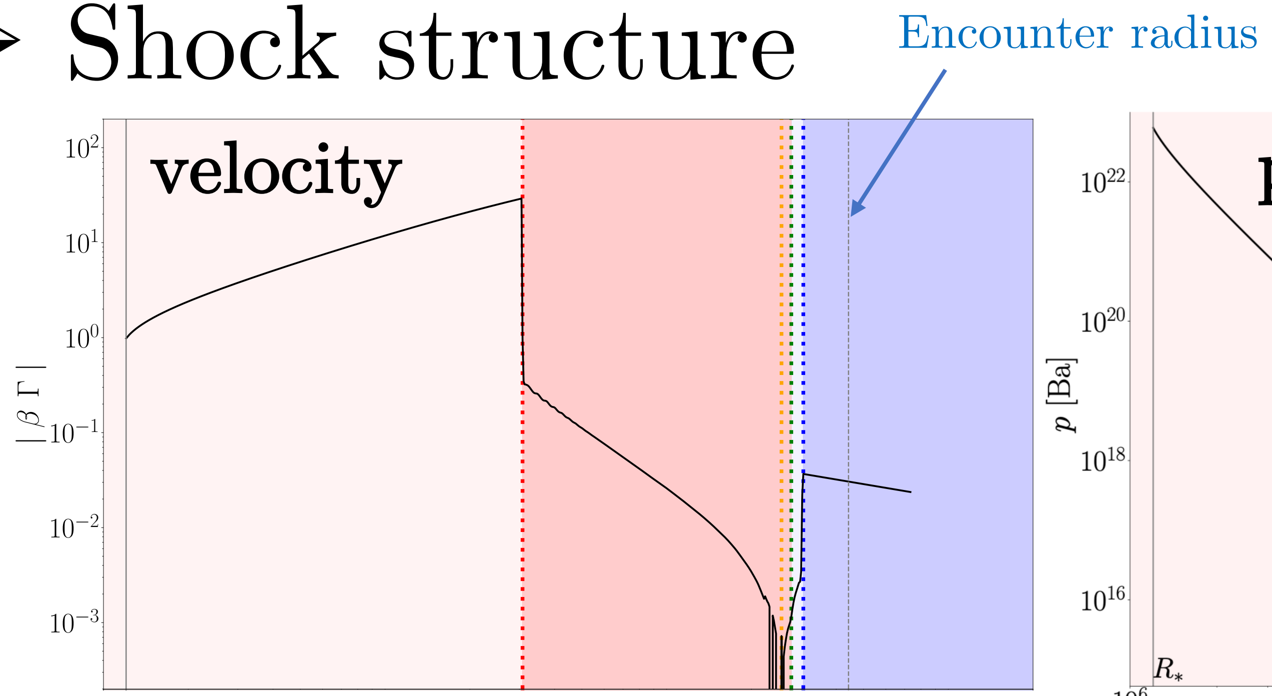
Governing equations:

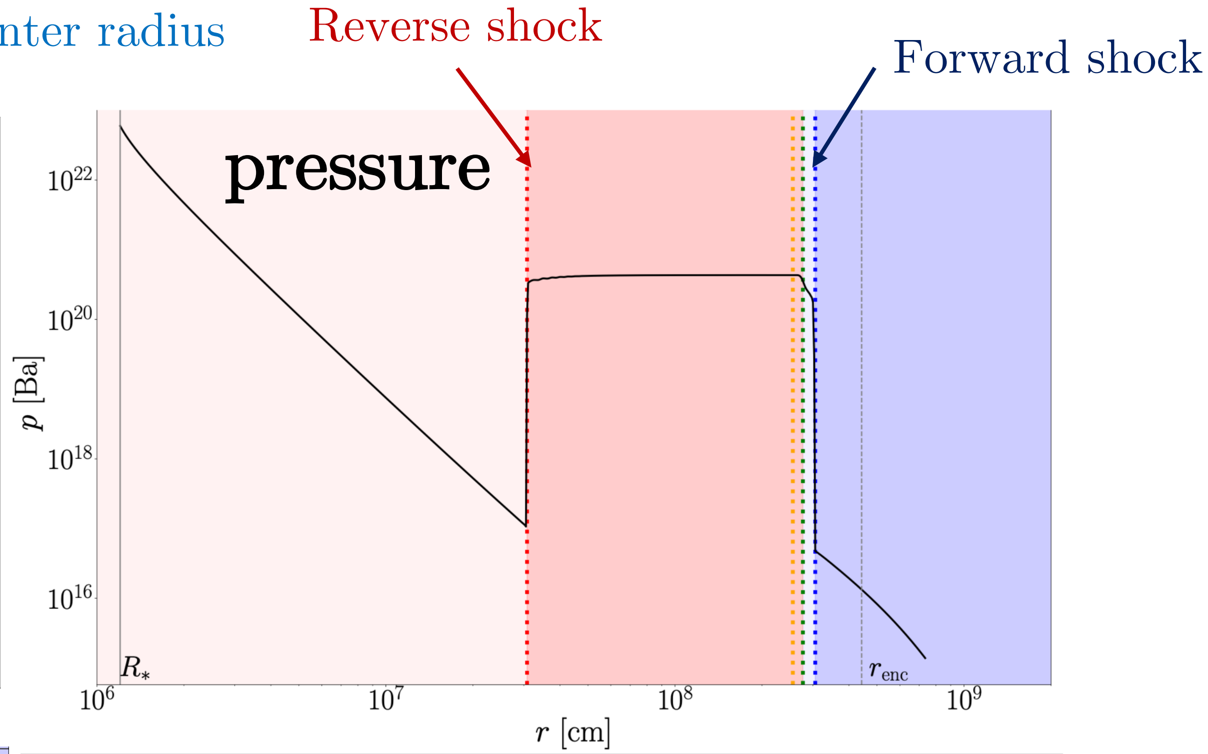
- 1-D **Relativistic Hydrodynamics equations** + point source central gravity

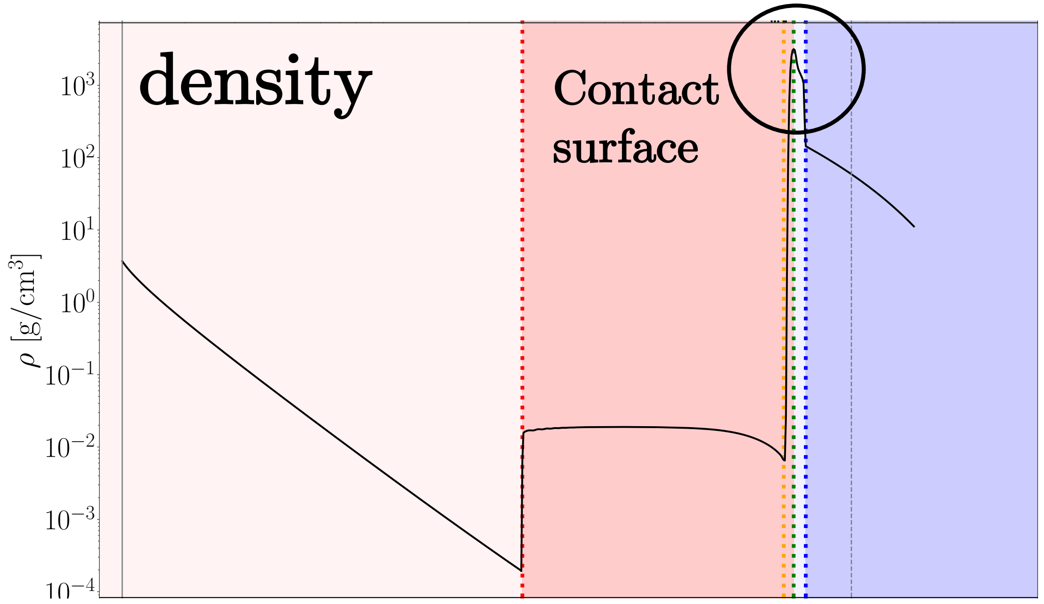
Numerical scheme:

- HLLC Riemann solver
- Spatial reconstruction : $2^{\rm nd}$ order PLM
- Time integration : $2^{\rm nd}$ order RK method
- CFL # of 0.1.

➢ Shock structure







- Red region: shocked wind
- **Light blue: shocked fallback matter**

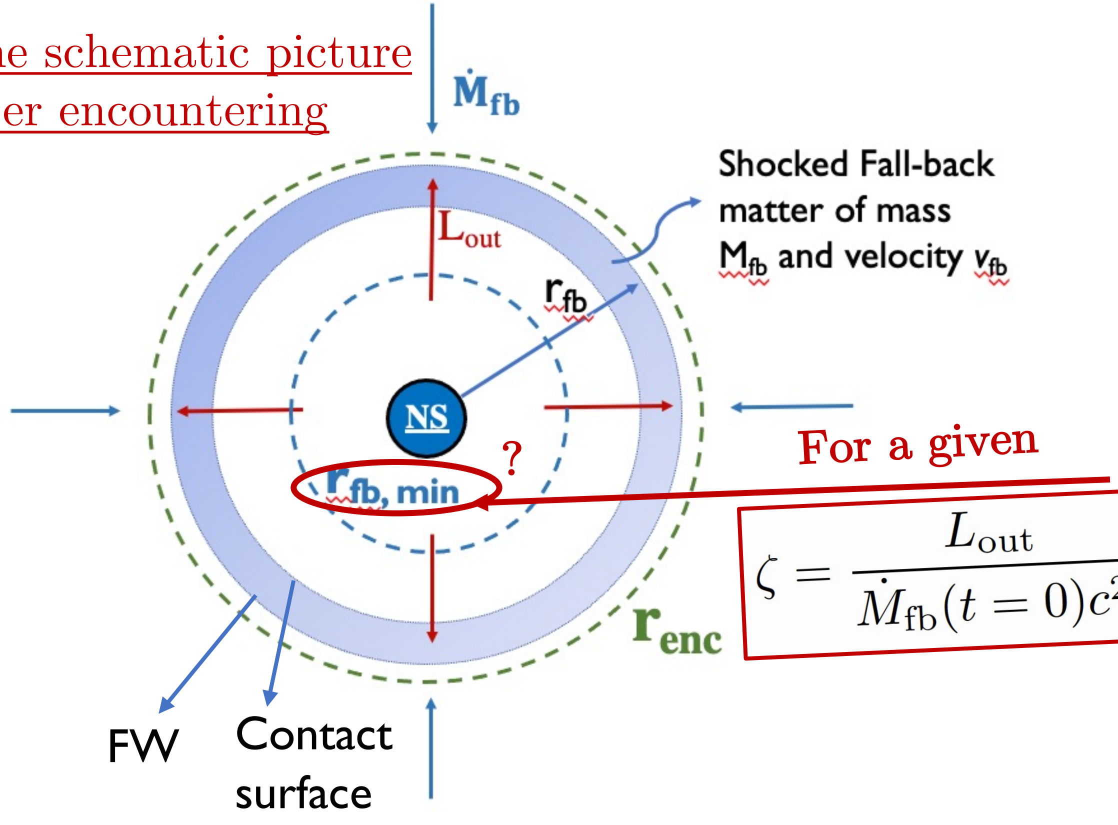
- Contact surface: non-relativistic

- How do the accretion shock evolve, especially the contact surface?

Analytical model for shocked fallback matter

Thin shell model with **central gravity**

The schematic picture after encountering



$$\zeta = \frac{L_{\rm out}}{\dot{M}_{\rm fb}(t=0)c^2}$$

- A simplified ver. of non-relativistic hydro Eqs. at the contact surface:

$$M_{\rm fb,0}=0 \qquad \frac{dM_{\rm fb}}{dt} = -4\pi r_{\rm fb}^2 \rho (v - v_{\rm fb}), \qquad v_{\rm fb,0} = (GM/r_{\rm enc})^{1/2}(\sqrt{\zeta/\zeta_{\rm cri}}-1)$$

$$\frac{d(M_{\rm fb}v_{\rm fb})}{dt} = 4\pi r_{\rm fb}^2 p - \dot{M}_{\rm fb,ini}\,(v - v_{\rm fb}) - \frac{GM_* M_{\rm fb}}{r_{\rm fb}^2}$$

$$4\pi r_{\rm enc}^2 P_0 = L/c \qquad r_{\rm fb,0} = r_{\rm enc}$$

$$3\frac{d}{dt}(pV) + p\frac{dV}{dt} = L, \qquad V = 4\pi r_{\rm fb}^3/3$$

Analytical model for shocked fallback matter

Inner-most position $r_{\rm fb,\,min}$

Inner-most position achieves if:

- Integrating the governing equations till $v_{\rm fb} = 0$ ($t=t_{\rm min}$), meanwhile the condition that the thin shell marginally become gravitationally unbound

$$dv_{\rm fb}/dt = 0$$

shall also be realized.
Which leads to:

$$4\pi r_{\rm fb,min}^2 p = \dot{M}_{\rm fb,i}\sqrt{2GM/r_{\rm fb,min}} + \frac{GM_* M_{\rm fb}}{r_{\rm fb,min}^2}$$

$$r_{\rm fb,min} = r_{\rm enc}[\zeta f(t_{\rm min}) - g(t_{\rm min})]^{2/3}\left(\frac{c^2 r_{\rm enc}}{2GM}\right)^{1/3}$$

Where:

$$f(t_{\rm min}) = 1 + \frac{c\int_0^{t_{\rm min}} dt' r_{\rm fb}(t')}{r_{\rm enc}^2},$$

time-integrated outflow luminosity injected to the shocked fallback shell

$$g(t_{\rm min}) = \frac{GM_* M_{\rm fb}(t_{\rm min})}{c r_{\rm enc}^2 \dot{M}_{\rm fb,i}}$$

work exerted by the gravitational force

Analytical model for shocked fallback matter

Invading condition: $r_{\text{fb, min}} = R_*$

- The critical energy flux ratio ζ_{min} for the fallback matter to reach the near NS surface region ➡️ $r_{\text{fb, min}} = R^*$, and since $R^* << r_{\text{enc}}$:

$$r_{\text{fb,min}} = r_{\text{enc}}[\zeta f(t_{\text{min}}) - g(t_{\text{min}})]^{2/3} \left(\frac{c^2 r_{\text{enc}}}{2GM}\right)^{1/3}$$

$[\zeta f(t_{\text{min}}) - g(t_{\text{min}})] = 0$

- When $t_{\text{min}} <= t_{\text{fb}}$:

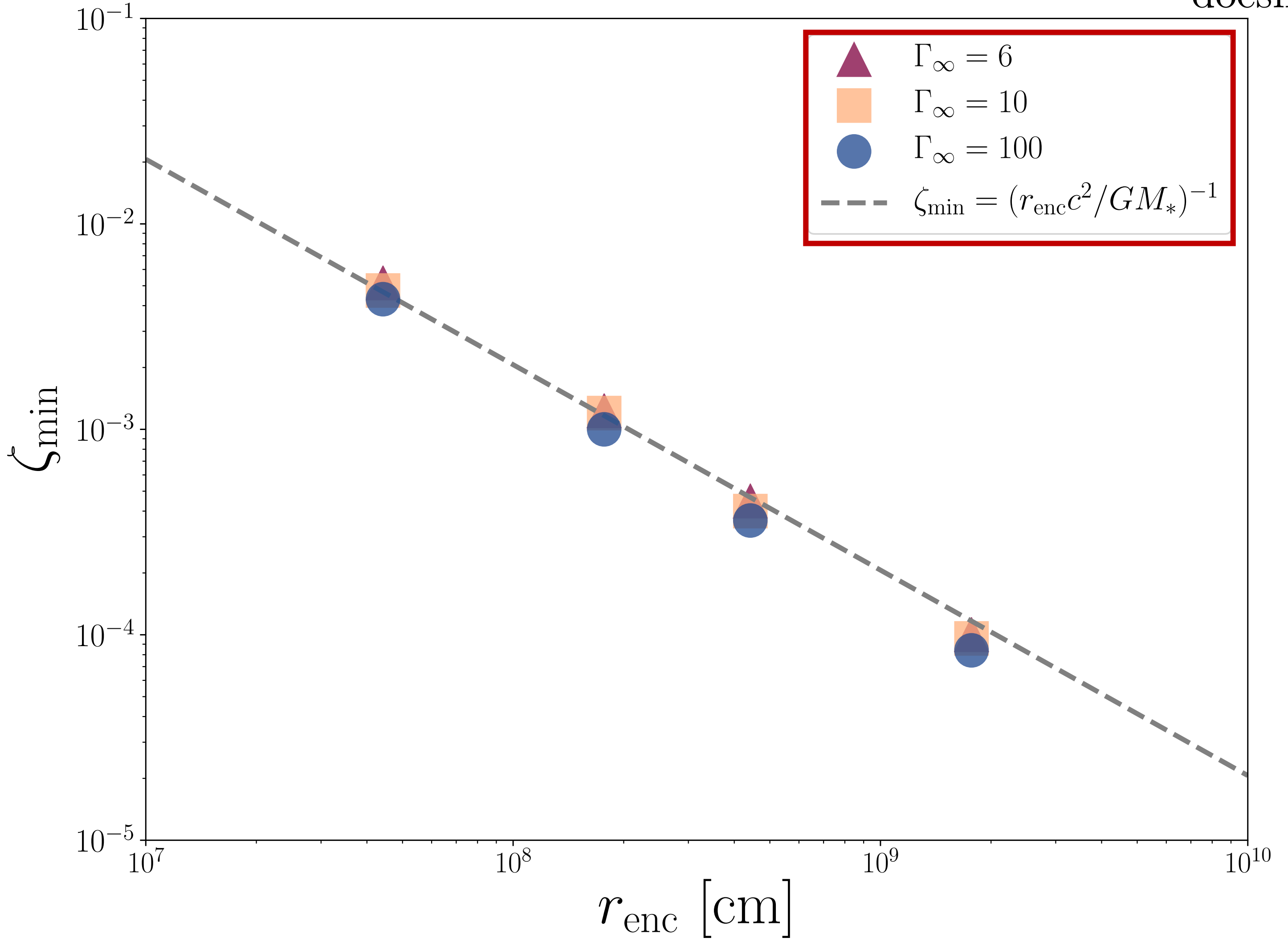
$$f(t_{\text{min}}) = 1 + \frac{c \int_0^{t_{\text{min}}} dt' r_{\text{fb}}(t')}{r_{\text{enc}}^2} \approx ct_{\text{fb}}/r_{\text{enc}} \quad \text{outflow}$$

$$g(t_{\text{min}}) = \frac{GM_* M_{\text{fb}}(t_{\text{min}})}{cr_{\text{enc}}^2 \dot{M}_{\text{fb,i}}} \approx GM_* t_{\text{fb}}/c{r_{\text{enc}}}^2 \quad \text{gravity}$$

⇨ $$\zeta_{\text{min}} \approx g(t_{\text{min}})/f(t_{\text{min}}) \approx GM_*/c^2 r_{\text{enc}}$$

Condition for the shocked fallback matter to reach down to the NS; determined by the competition between gravity and outflow

➢ This is what Numerical results tell us



As long as the outflow luminosity remains the same, the outflow velocity (or baryon loading details) doesn't affect the results.

$$\frac{L}{\dot{M}_{\rm fb,crit}c^2} \approx \left(\frac{r_{\rm enc}c^2}{GM_*}\right)^{-1}$$

$$\dot{M}_{\rm fb,ini} = \frac{2}{5}\frac{M_{\rm fb}}{t_{\rm fb}}$$

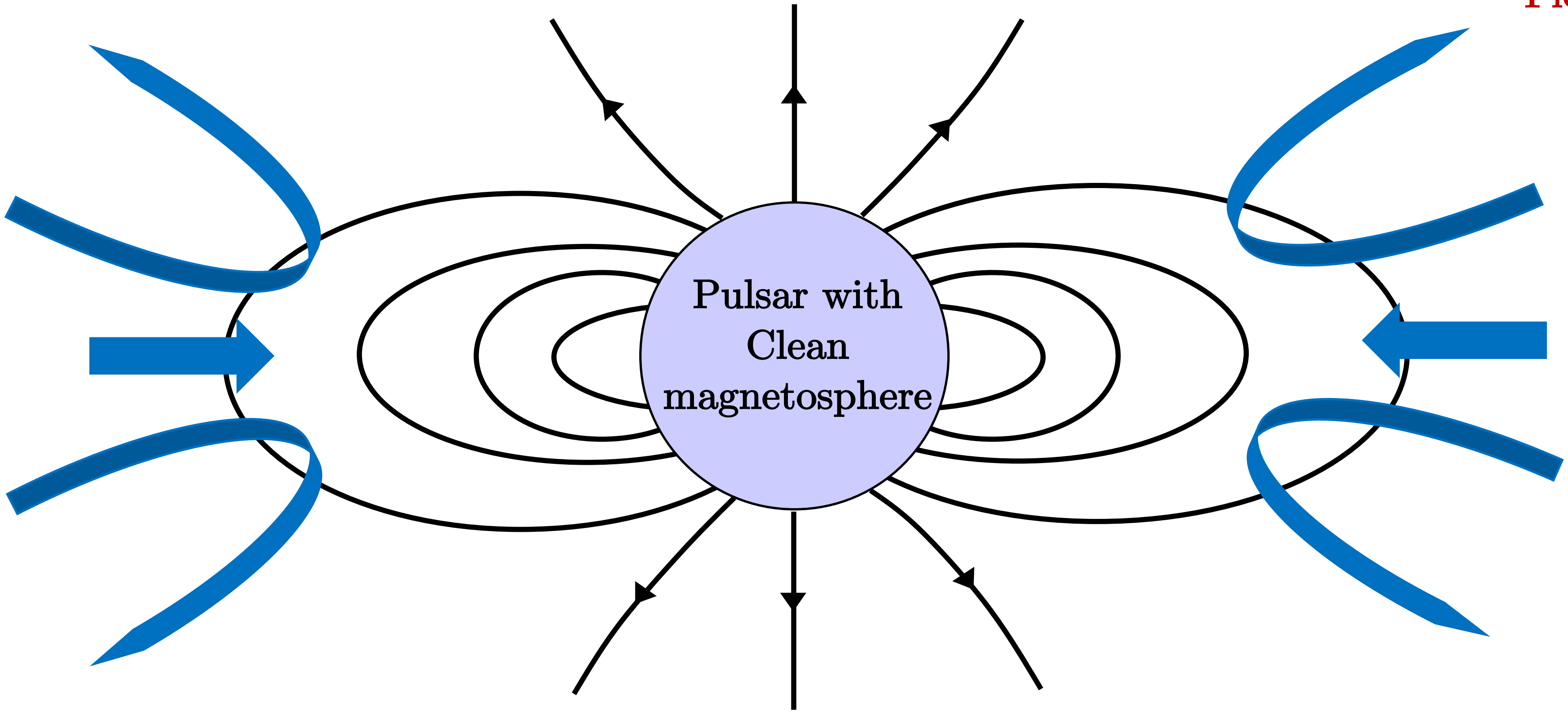
$$M_{\rm fb,crit} \approx \frac{5}{2} \times (GM_*)^{-2/3} L(B_*, P_i) {t_{\rm fb}}^{5/3}$$

Field configuration

Implications on the NS diversity

$$\zeta_{\min} \approx \left(\frac{r_{\rm enc} c^2}{G M_*}\right)^{-1} \;\Rightarrow\; M_{\rm fb,crit} \approx \frac{5}{2} \times (GM_*)^{-2/3} \boxed{L(B_*, P_i)} t_{\rm fb}{}^{5/3}$$

Field configuration



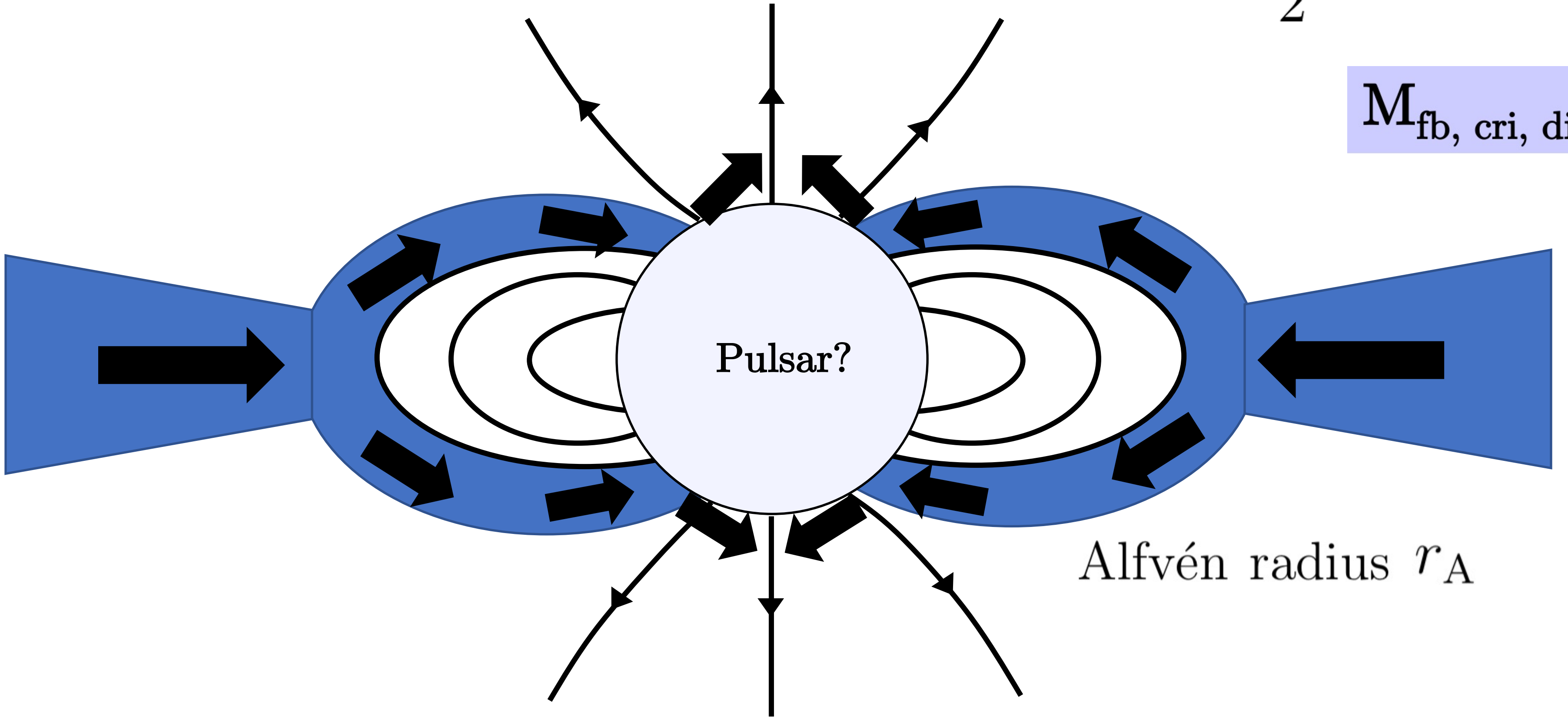
$M_{\rm fb} < M_{\rm fb,\,cri,\,dipole}$

Fallback matter is repelled by the dipole magnetic field

$$L_{\rm d} = \frac{B_*{}^2 \Omega_{\rm i}{}^4 R_*^6}{4c^3}(1 + \sin\chi^2) \sim 4.3 \times 10^{41}\,{\rm erg\,s^{-1}}\,(1 + \sin\chi^2)\, B_{*,13}{}^2 P_{{\rm i},-2}{}^{-4},$$

Implications on the NS diversity

$$M_{\rm fb,crit} \approx \frac{5}{2} \times (GM_*)^{-2/3} L(B_*, P_i) t_{\rm fb}^{5/3}$$



$$\mathbf{M_{fb,\ cri,\ dip} < M_{fb} < M_{fb,\ cri,\ mon}}$$

Advanced channeled fallback inflow proceeds to the NS surface and opens the closed field lines (the magnetosphere is locally pressed to Alfven radius r_A by R-T finger), the outflow luminosity is enhanced.

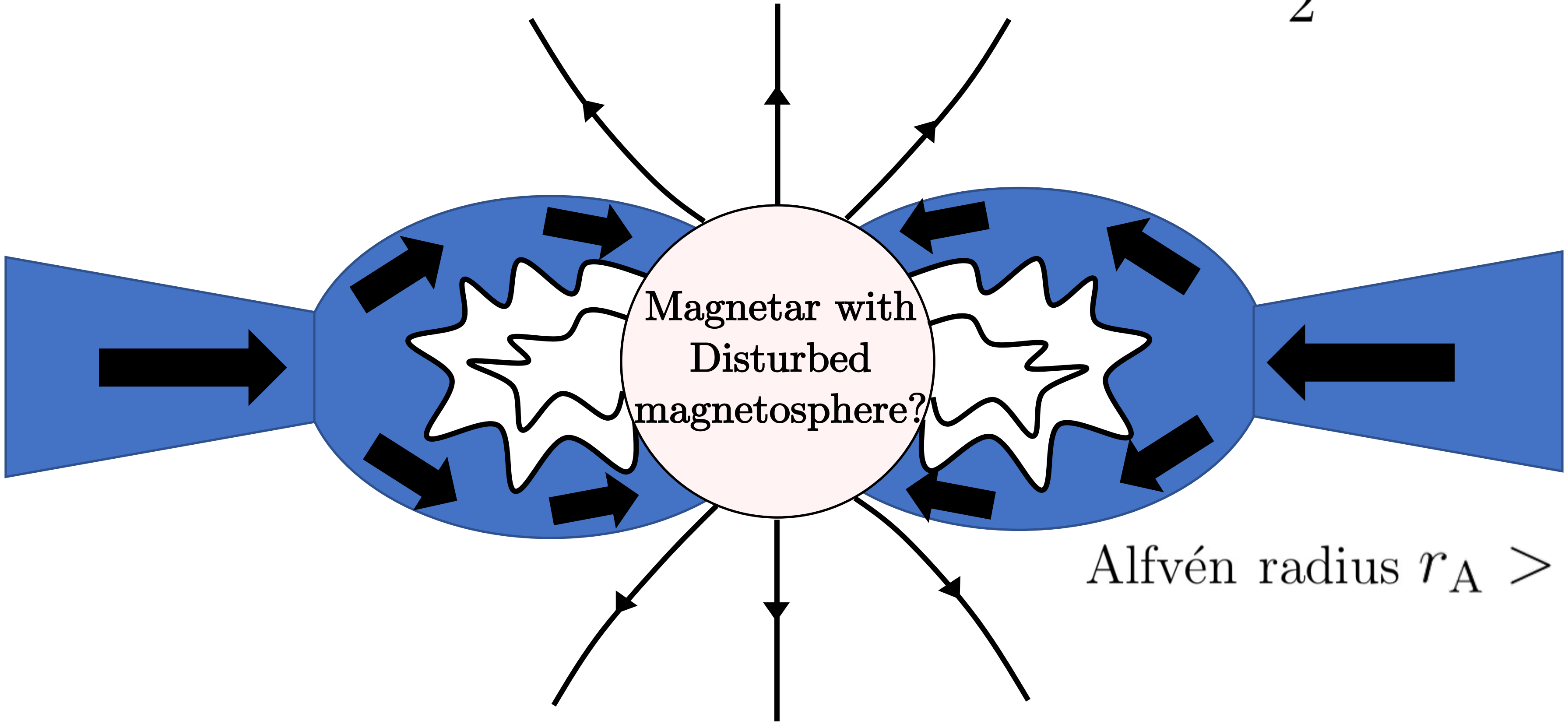
$$L_{\rm m} \approx (B_*^2 \Omega_{\rm i}^4 R_*^6 / c^3) \times (r_{\rm lc}/r_{\rm A})^2 \sim 3.1 \times 10^{45}\,{\rm erg\,s^{-1}}\, B_{*,13}^{6/7} P_{\rm i,-2}^{-2} M_{\rm fb,-4}^{4/7} t_{\rm fb,1}^{-4/7}$$

Field lines are forced to be open

Implications on the NS diversity

$$M_{\mathrm{fb,crit}} \approx \frac{5}{2} \times (GM_*)^{-2/3} \boxed{L(B_*, P_i)} t_{\mathrm{fb}}{}^{5/3}$$

$M_{\mathrm{fb}} > M_{\mathrm{fb,\ cri,\ mon}}$



Fallback accretion outweighs the outflow luminosity enhanced by the opened field lines

Alfvén radius $r_{\mathrm{A}} > R_*$

$$L_{\mathrm{m}} \approx (B_*{}^2 \Omega_{\mathrm{i}}{}^4 R_*^6 / c^3) \times \boxed{(r_{\mathrm{lc}}/r_{\mathrm{A}})^2} \sim 3.1 \times 10^{45}\,\mathrm{erg\,s^{-1}}\, B_{*,13}{}^{6/7} P_{\mathrm{i},-2}{}^{-2} M_{\mathrm{fb},-4}{}^{4/7} t_{\mathrm{fb},1}{}^{-4/7}$$

Field lines are forced to be open

Implications on the NS diversity

$$M_{\rm fb,crit} \approx \frac{5}{2} \times (GM_*)^{-2/3} L(B_*, P_i) t_{\rm fb}{}^{5/3}$$

$M_{\rm fb} > M_{\rm fb,\ cri,\ mon}$

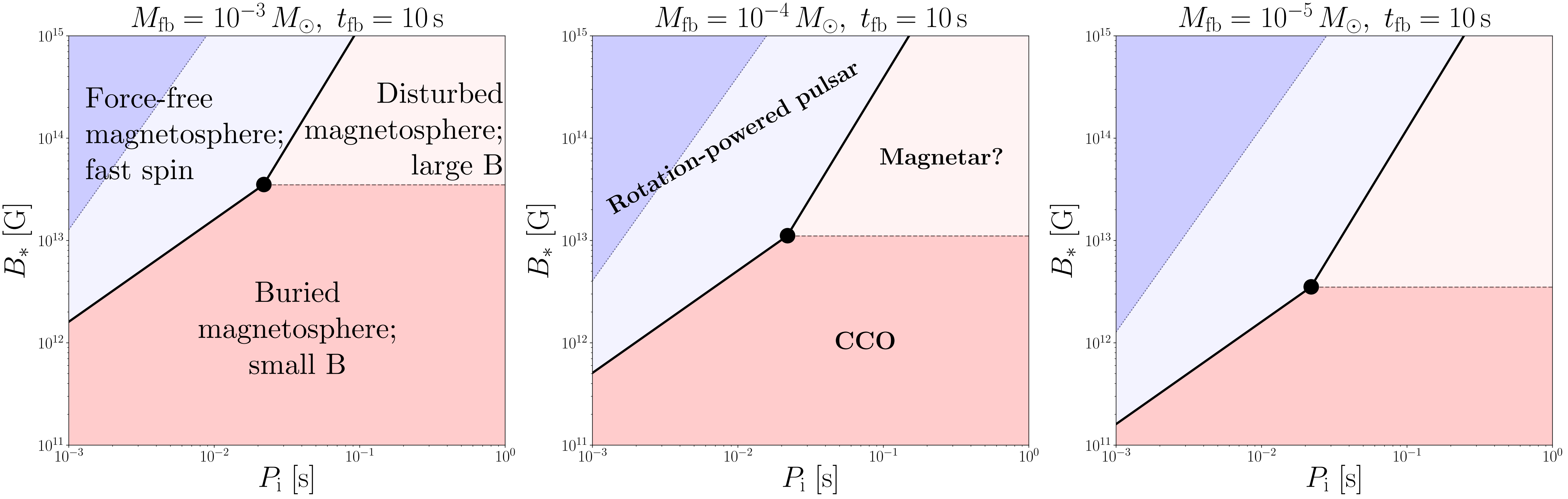
Fallback accretion outweighs the outflow luminosity enhanced by the maximumly opened field lines. It's strong enough bury the magnetosphere

Alfvén radius $r_{\rm A} \leq R_*$

$$L_{\rm m} \approx ({B_*}^2 {\Omega_{\rm i}}^4 R_*^6 / c^3) \times (r_{\rm lc}/R_*)^2 \sim 2.7 \times 10^{45}\,{\rm erg\,s^{-1}}\,{B_{*,13}}^2 {P_{\rm i,-2}}^{-2}$$

Maximum luminosity of split monopole-like field configuration

We can summarize these four cases as...

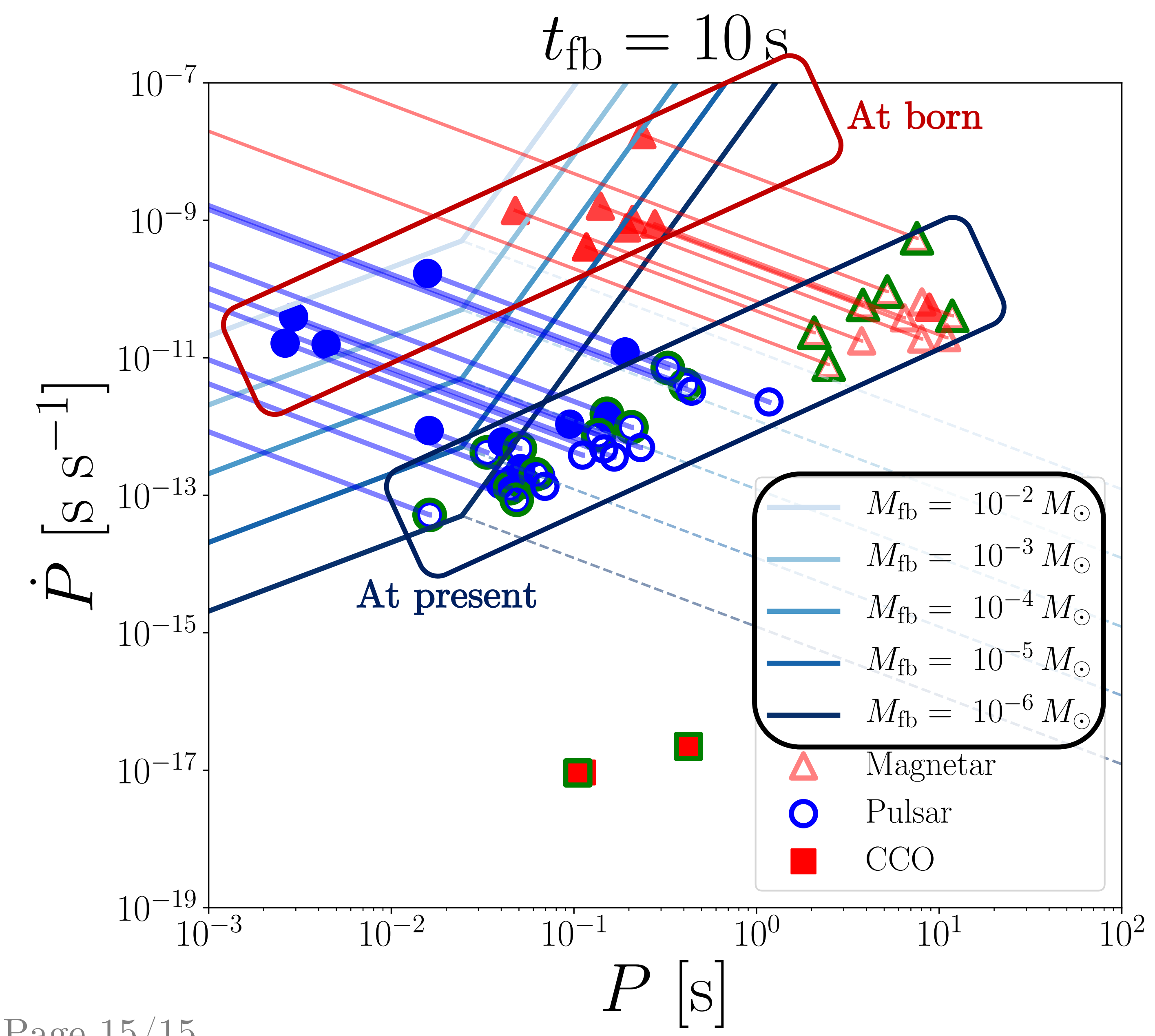


➢ Trifurcation point:

$$B_{*,\mathrm{tri}} \approx 1.1 \times 10^{13}\,\mathrm{G}\,{M_{\mathrm{fb},-4}}^{1/2}{t_{\mathrm{fb},1}}^{-1/2}$$

$$P_{\mathrm{i,tri}} \approx 24\,\mathrm{ms}\,t_{\mathrm{fb},1}^{1/3}.$$

Broadly consistent with typical galactic rotation-powered Pulsar ($B_* \sim 10^{13}$G, $P_i \sim O(10)$ ms) assuming typical accretion ($M_{\mathrm{fb}} \sim 10^{-(2-4)}\,M_\odot$, $t_{\mathrm{fb}} \sim$ 1-100 s); implies a roughly comparable formation rate of pulsars, magnetars and CCOs.



More information?

(under construction)

The P-Ṗ-at-born of know pulsars/magnetars can be traced back with their current value (the simplest way is following the moving direction given by pulsar model) and compared with our phase diagram

➡️A birth-line of NSs may be obtained; for each of the samples:

- There exists a maximum $M_{\rm fb}$ for our model to work: does this somehow correlate to its SN explosion energy, progenitor mass etc. ?

Summary

What do we want to know?

- The origin of the diversity of young neutron stars

What did we do?

- To Investigate the impact of the relativistic wind from the magnetosphere of a newborn neutron star and supernova fallback

What have we done?

- 1-D Hydrodynamics and analytical calculations

What have we learned?

- There exists a critical luminosity ratio of the out- and inflow ζ_{min} that determines the criterion that fallback matter can invade down to the near NS surface region → the criterion for a NS to form into CCOs, magnetars or rotation-powered Pulsars

- The trifurcation point given by our study is broadly consistent with known galactic pulsar formation (roughly comparable formation rate of each kinds of NSs?)

Remaining questions: magnetar formation? Other observational imprints? (e.g., progenitor mass, SNRs and etc.)

Thanks for listening