How much supernova fallback can invade newborn pulsar wind and magnetosphere?

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With

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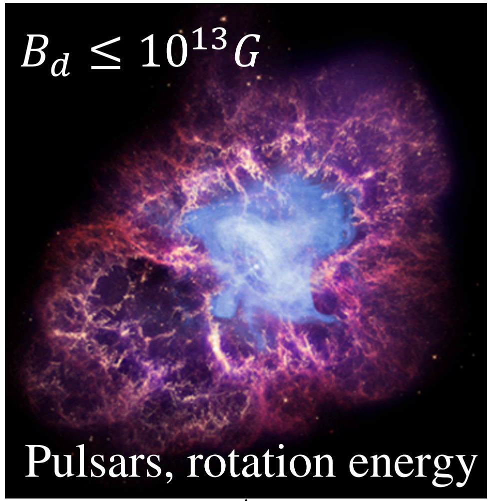
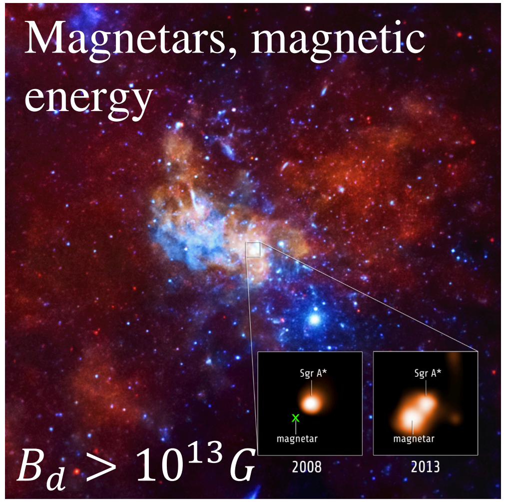
The diversity of young neutron stars

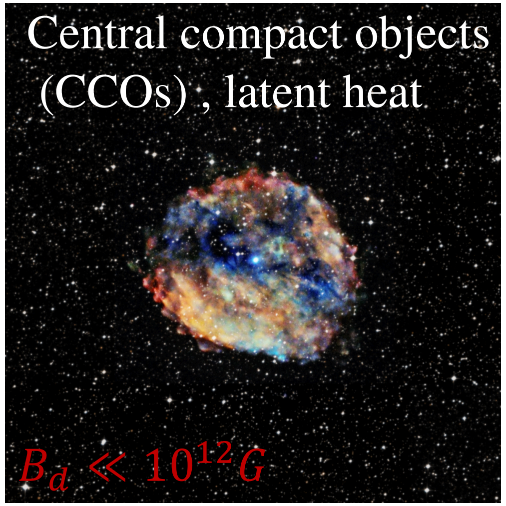
- (t_{age} < 1-10 kyr)
- Formation rates ~ 1/100-1000 yr.



?

why CCO's B_d field is so small?





significantly small dipole magnetic field

Fallback accretion onto NS

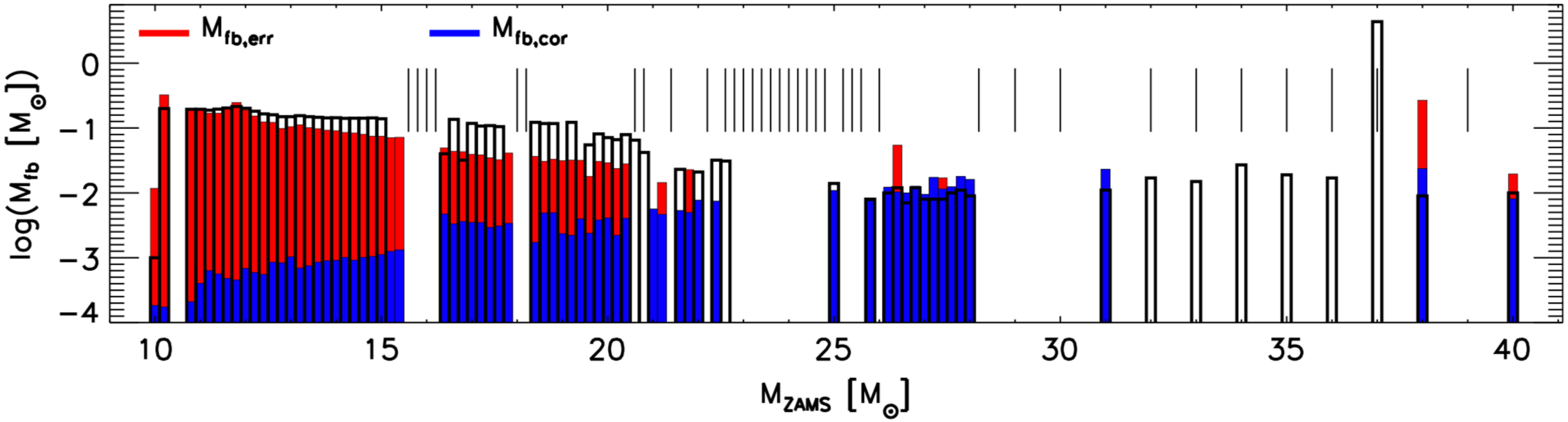
The fallback typically starts when the neutrino luminosity significantly decreases after the core bounce.

$$\dot{M}_{\rm fb} = \frac{M_{\rm fb}}{3t_{\rm fb}}\left(\frac{t}{t_{\rm fb}}\right)^{-5/3} \sim 3\times10^{-6}\,M_\odot\,s^{-1}\left(\frac{M_{\rm fb}}{10^{-4}\,M_\odot}\right)\left(\frac{t_{\rm fb}}{10\,{\rm s}}\right)^{-1}$$

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

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

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



CCO formation

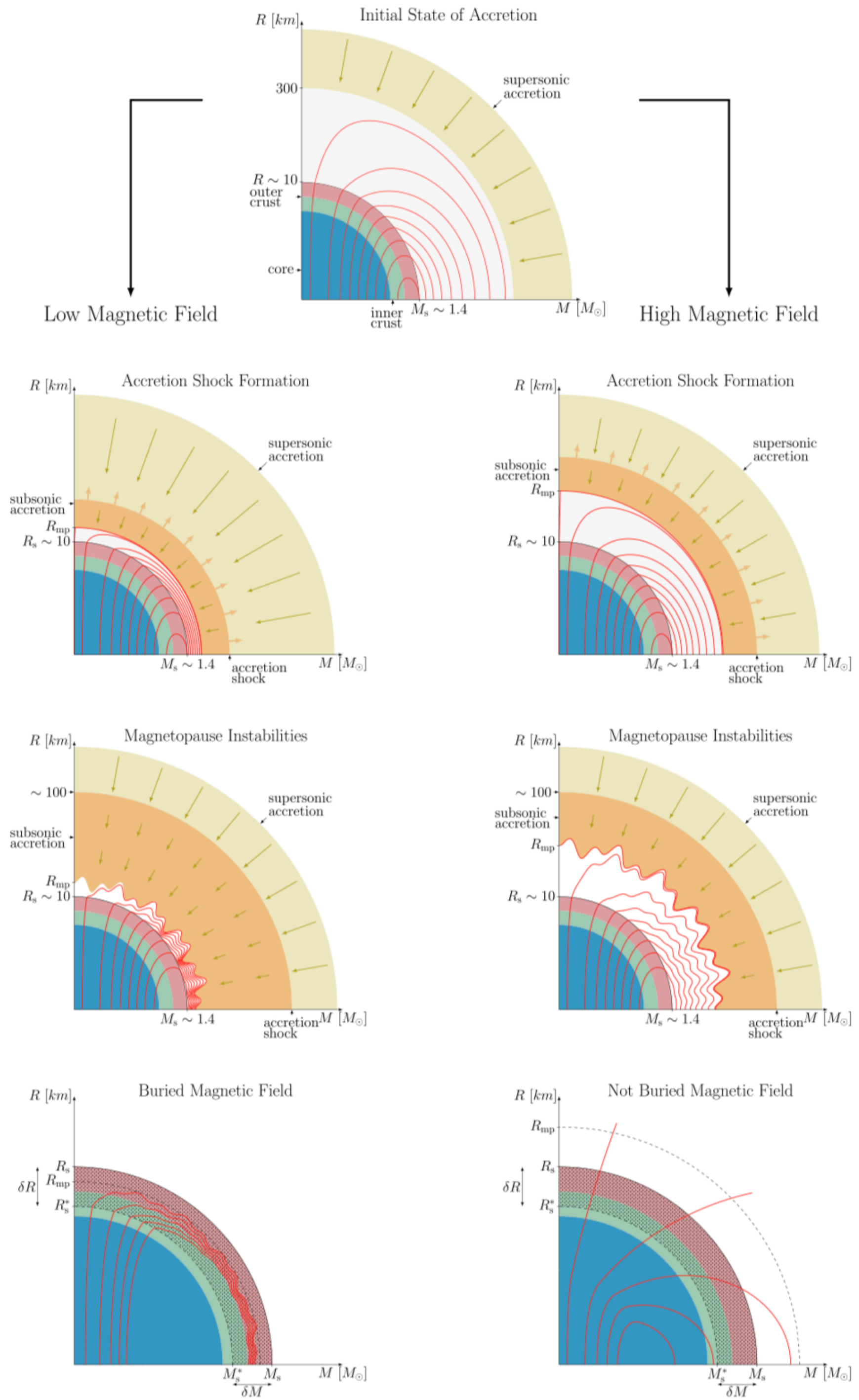
Fallback accretion may be crucial!

Fallback accretion can bury the B field if Mdot is smaller than

$$\dot{M}_{\rm crit,bury} \sim 10^{-5}\, M_{\odot}\, {\rm s}^{-1} \left(\frac{B_*}{10^{13}\,{\rm G}}\right)^{3/2}$$

e.g., Torres-Forne ´ et al.16

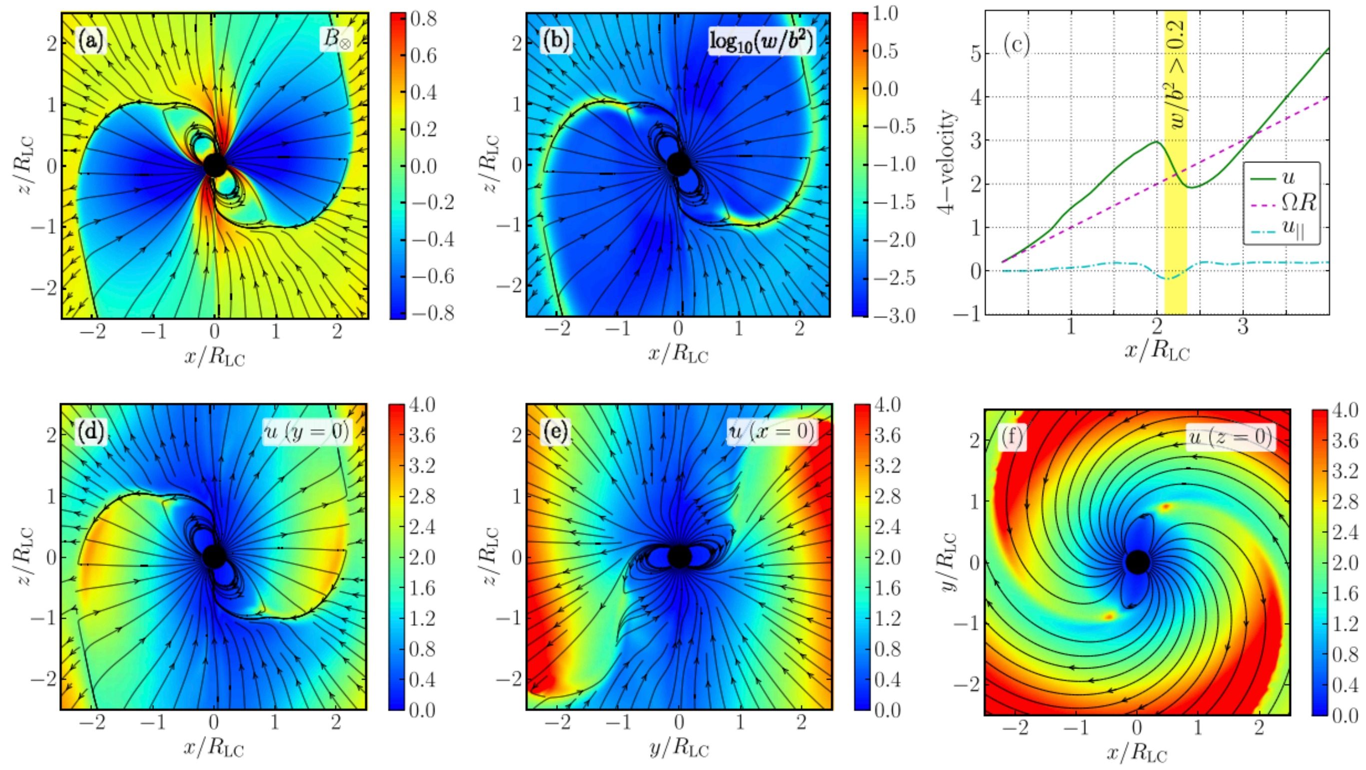
OK, then how to make pulsars?



Relativistic outflow from NS

Extracting the rotation energy by the unipolar induction (Gunn & Ostriker 69; ...)

$$L_{\rm sd} \approx \frac{{B_{\rm d}}^2 \Omega^4 R^6}{4c^3}(1+\sin\chi^2) \sim 4.3\times 10^{35}\,{\rm erg\,s^{-1}}\,(1+\sin\chi^2)\,{B_{\rm d,14}}^2 {P_0}^{-4}$$

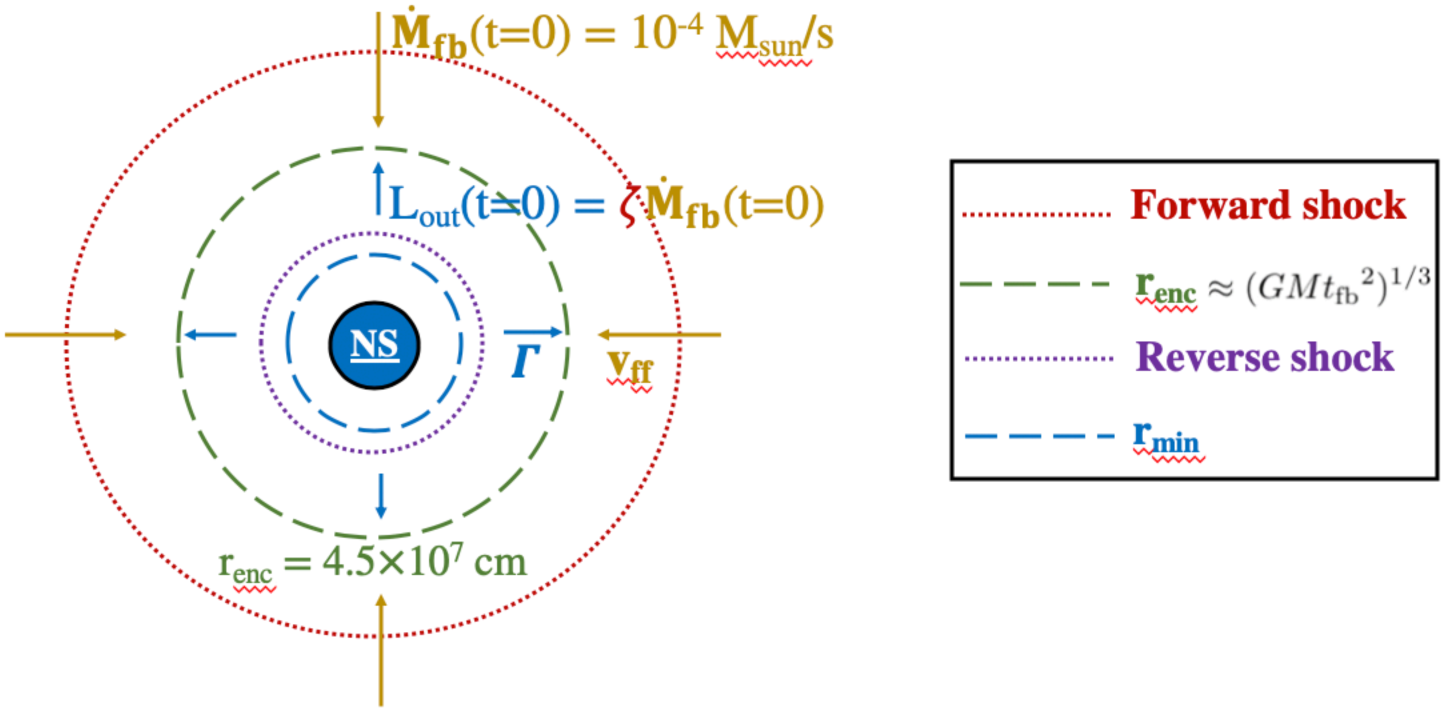


Tchekhovskoy et al. 13

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

Numerical set-ups

With the Athena++ code
- HLLC Riemann solver
- Spatial reconstruction : 2^{nd} order PPM
- Time integration : 2^{nd} order RK method
- CFL # of 0.1.



$\dot{M}_{fb} :\propto t^{-l}$, time scale~$t_{fb}$

L_{out}: constant, spin-down time scale~t_{out}(>> t_{fb})

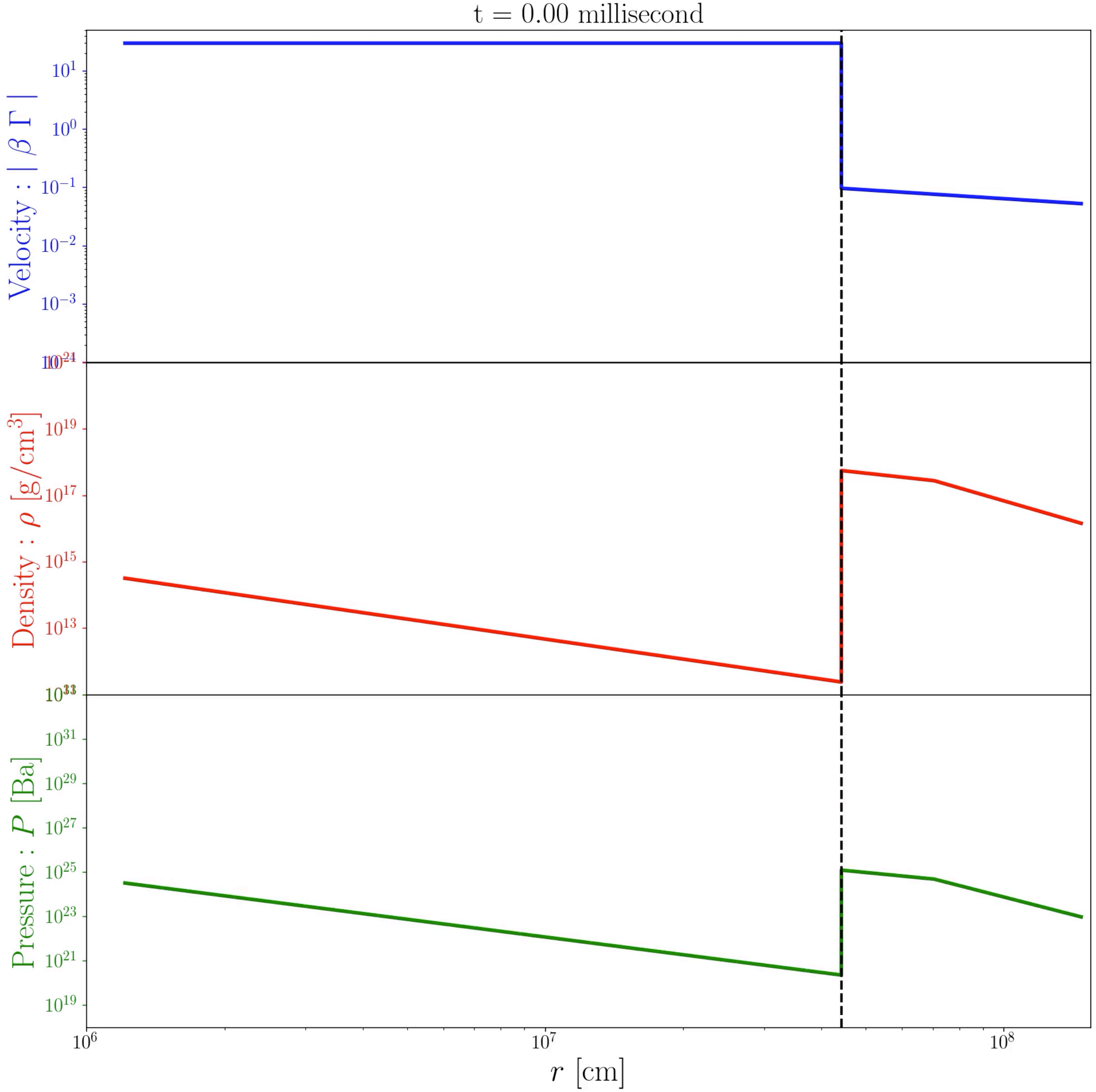
$\zeta \equiv (L_{out}/\dot{M}_{fb})_{t=0}$

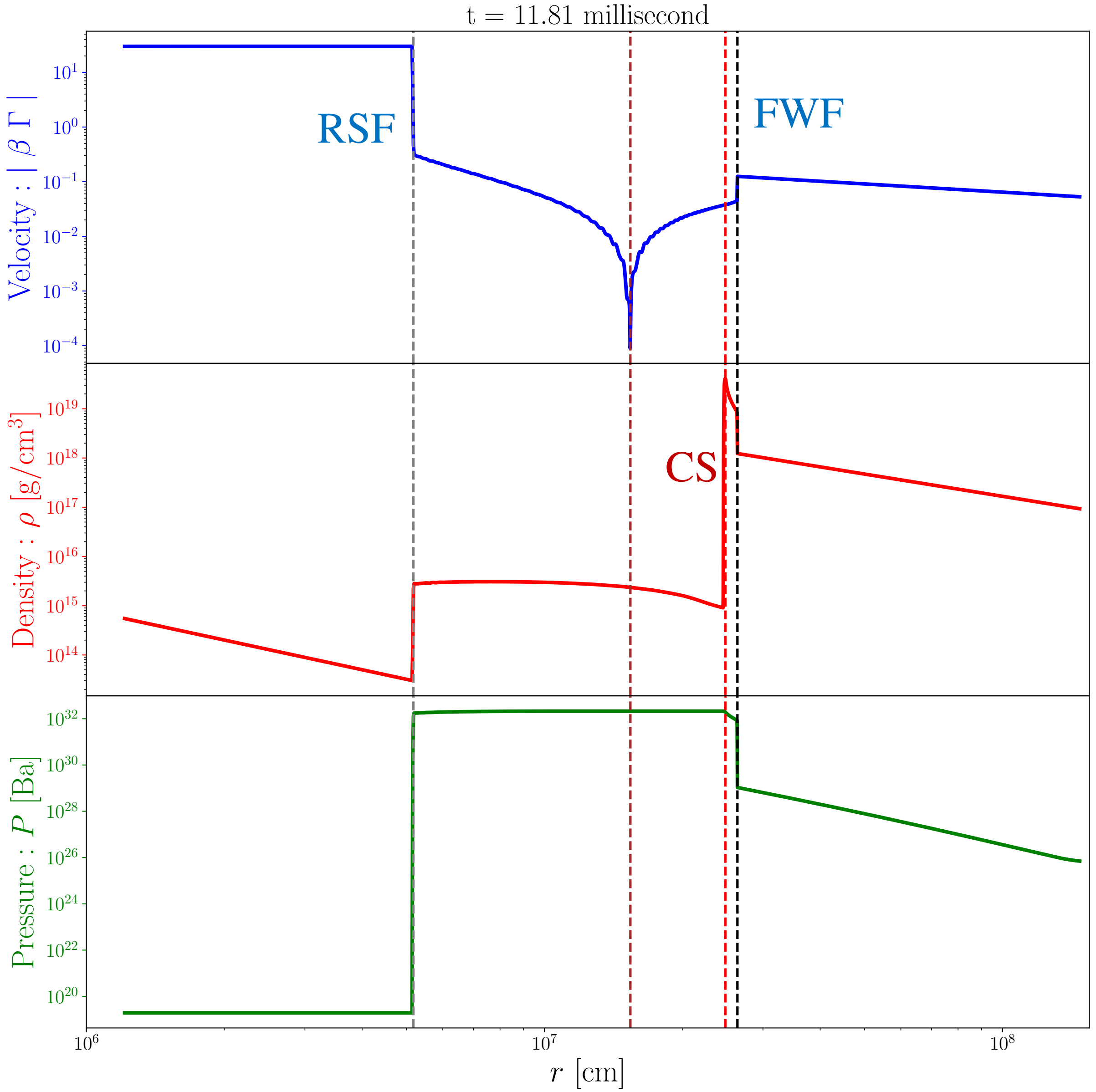
❖ ζ, Γ, l and r_{enc}

- Hydrodynamics & special relativity : Relativistic HD
- Central gravity source √, self gravity ×
- Setting initial & boundary conditions based on $\dot{M}_{fb}$, L_{out} and r_{enc} numerically

❖ **evolution of accretion shock**, e.g. shock structure, minimum fall-back radius r_{min} $\begin{Bmatrix} r_{RSF,min} \\ r_{fb,min} \end{Bmatrix}$

Time evolution of the accretion shock: shock structure

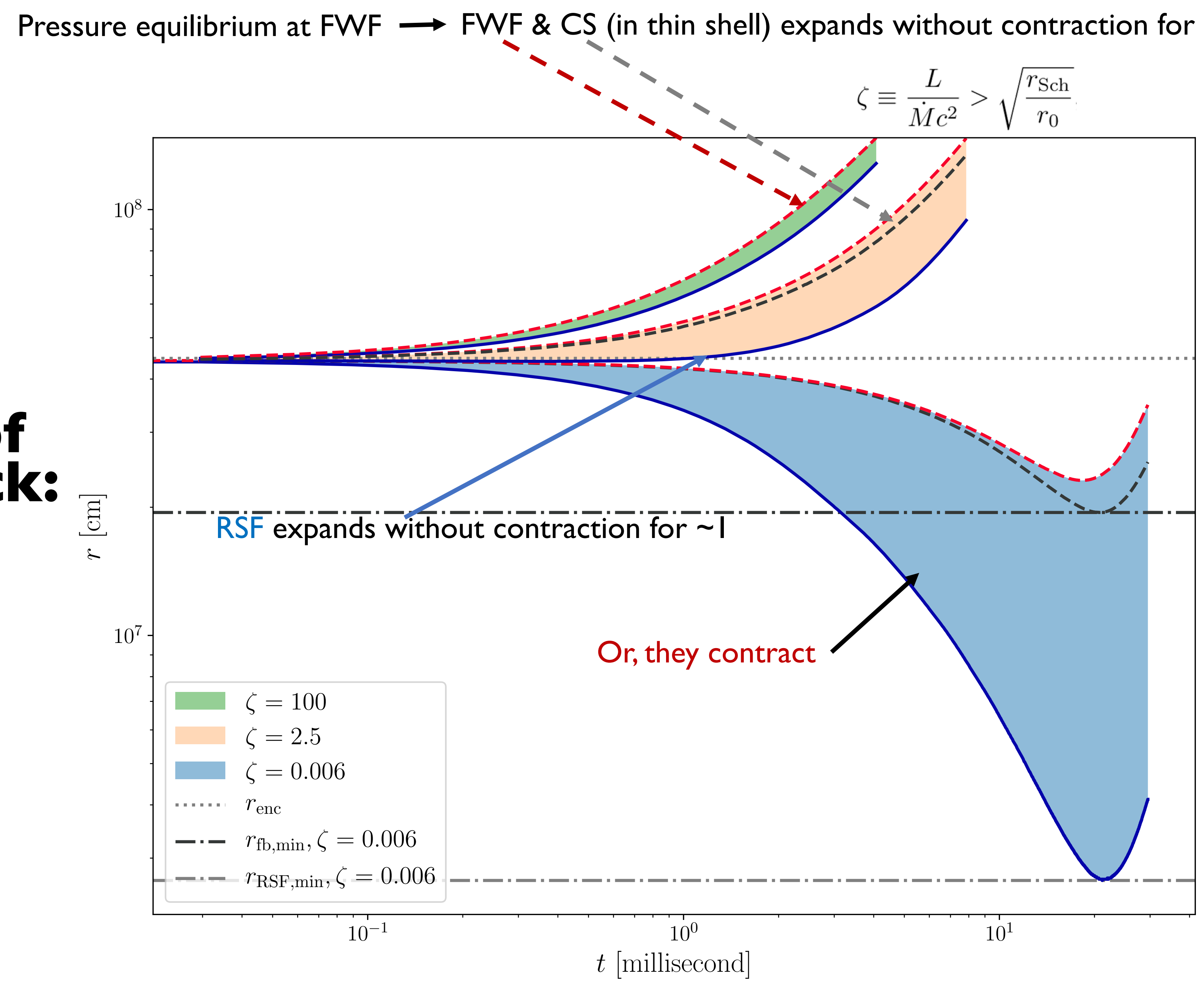




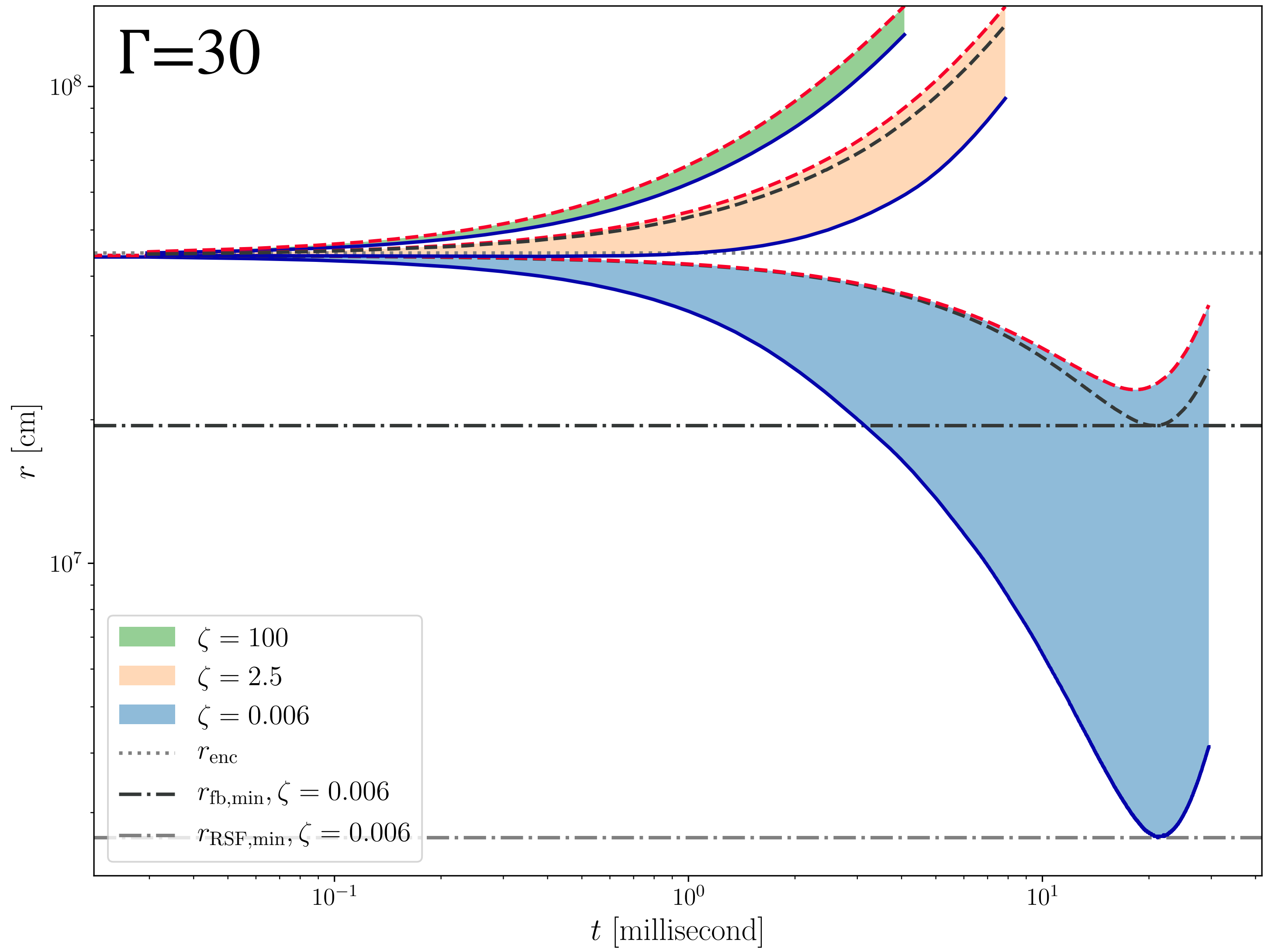
- $\zeta = 0.006, \Gamma = 30, \dot{M}_{\rm fb} \propto t^{-5/3}$

Time evolution of the accretion shock: FWF, CS & RSF

Γ=30



Time evolution of the accretion shock: r_{min}



The minimum radius of the fallback matter or *"invasion radius"*, $r_{fb,min}$

The minimum radius of the reverse shock, $r_{RSF,min}$

Analytical model of fall-back accretion

The thin shell approximation

A simplified ver. of hydro Eqs. for the contact surface

$$\frac{dM_\mathrm{s}}{dt} = -4\pi r^2 \rho (v - v_\mathrm{s}),$$

$$\frac{d}{dt}(M_\mathrm{s} v_\mathrm{s}) = 4\pi r_\mathrm{s}^2 P - \dot{M}(v - v_\mathrm{s}),$$

$$3\frac{d}{dt}(PV) + P\frac{dV}{dt} = L,$$

can be integrated analytically

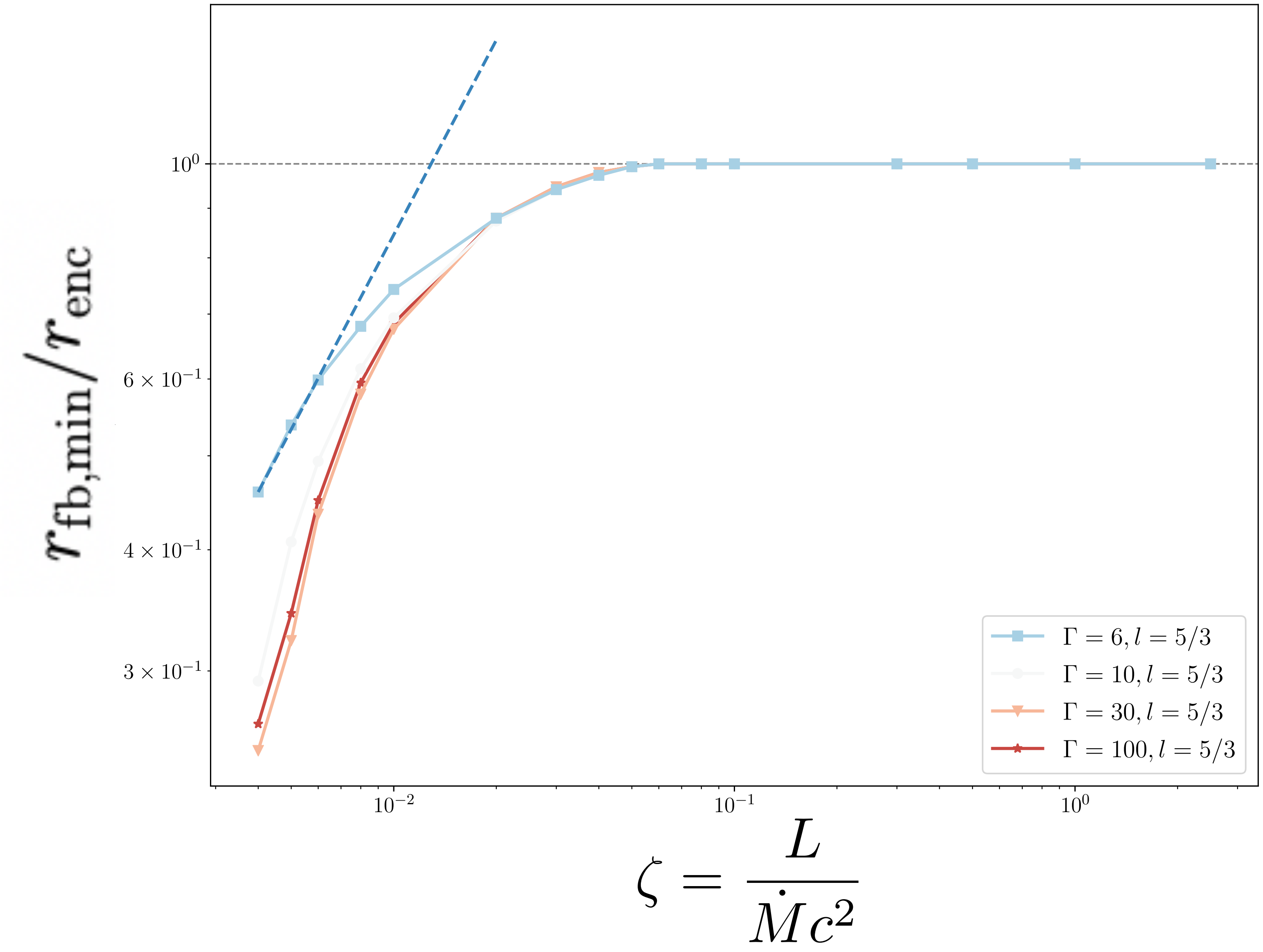
Invasion radius

$$r_\mathrm{s,min} = r_0 \zeta^{2/3} \left(\frac{r_0}{r_\mathrm{Sch}}\right)^{1/3} f(t_\mathrm{min}),$$

$$f(t) = \left[1 + \frac{c\int_0^t dt' r_\mathrm{s}(t')^3}{r_0^4}\right]^{2/3}$$

a functional d.o.f to be fitted by the numerical results

The invasion radius



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$$r_\mathrm{s,min} = r_0 \zeta^{2/3} \left(\frac{r_0}{r_\mathrm{Sch}}\right)^{1/3} f(t_\mathrm{min}),$$

$$f(t) = \left[1 + \frac{c\int_0^t dt' r_\mathrm{s}(t')^3}{r_0^4}\right]^{2/3}$$

a functional d.o.f to be fitted by the numerical results

Based on the numerical experiments so far,

$$f(t) \approx \xi (r_0/r_\mathrm{Sch})^{1/3} \text{ where } \xi \sim 0.2$$

$$r_\mathrm{s,min} \approx r_0 \xi \zeta^{2/3} \left(\frac{r_0}{r_\mathrm{Sch}}\right)^{2/3}$$

Implications on the NS diversity

$$r_{\rm s,min} \approx r_0 \xi \zeta^{2/3} \left(\frac{r_0}{r_{\rm Sch}} \right)^{2/3}$$

The invasion condition down to the light cylinder

$$\dot{M}_{\rm fb} > \dot{M}_{\rm fb,lc} \equiv 2 \times 10^{-7}\, M_\odot\, {\rm s}^{-1} \left(\frac{\xi}{0.2} \right)^{3/2} {B_{13}}^2 {P_{-2}}^{-11/2} {t_{\rm fb,1}}^{10/3}$$

The invasion condition down to the NS surface

$$\dot{M}_{\rm fb} > \dot{M}_{{\rm fb},R} \equiv 7 \times 10^{-5}\, M_\odot\, {\rm s}^{-1} \left(\frac{\xi}{0.2} \right)^{3/2} {B_{13}}^2 {P_{-2}}^{-4} {t_{\rm fb,1}}^{10/3}$$

e.g., the magnetosphere of a Crab-like pulsar can be marginally invaded with a typical fallback, which may indicate that the Crab is at around the bifurcation point of NS sequences…

Summary

What do we want to know?

- The origin of the diversity of young neutron star

What do we do?

- To Investigate the impact of fallback accretion onto the magnetized wind and magnetosphere of a newborn neutron star

What have we done?

- 1-D Numerical and analytical calculations of a fallback accretion confronting with a relativistic wind

What have we learned?

- The "invasion radius" by the fallback matter can be determined by the luminosity ratio of the in- and outflow and the encounter radius → connection to the diversity of young neutron star?

Future work

- Keep digging into "invasion radius" and its implication to NS diversity
- Enlarging the r_{enc} (shorter t_{fb} would be more realistic)
- Applying results to specific astrophysical problem: neutron star formation in crab-like pulsar
- 2-D simulations: multi-dimensional effect on the 1D result, e.g. a region in the corresponding 1-D shock structure that is unstable with respect to the RT instability
- ……