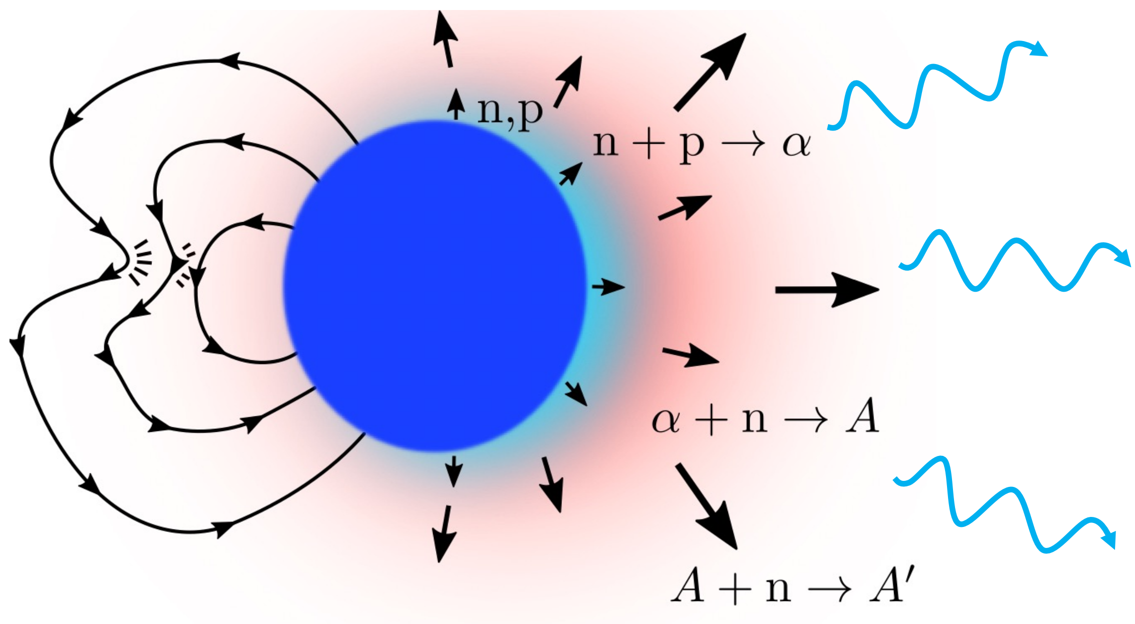
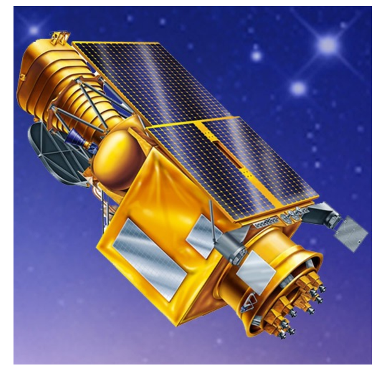
Magnetar Giant Flares: a new site for the r-process





ULTRASAT

FLATIRON INSTITUTE

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

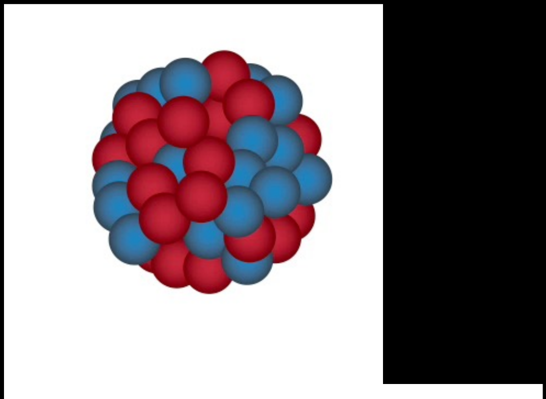
Brian Metzger

with **Jakub Cehula**, Todd Thompson, **Ani Patel**, Jared Goldberg, Mathieu Renzo

Rapid Neutron Capture Nucleosynthesis: Cosmic Alchemy

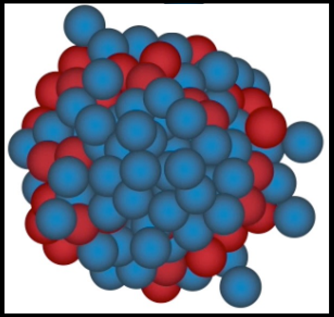
<u>"Iron" Seed</u>

26 protons, 30 neutrons



<u>"Gold"</u>

79 protons, 118 neutrons

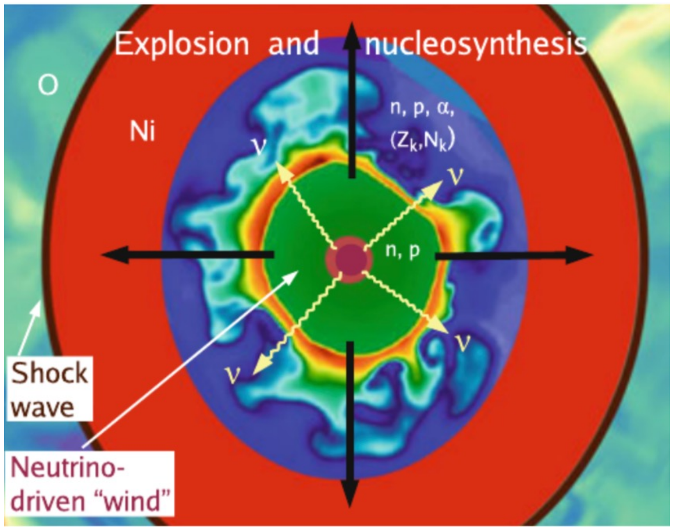


Animation: Courtesy A. Frebel

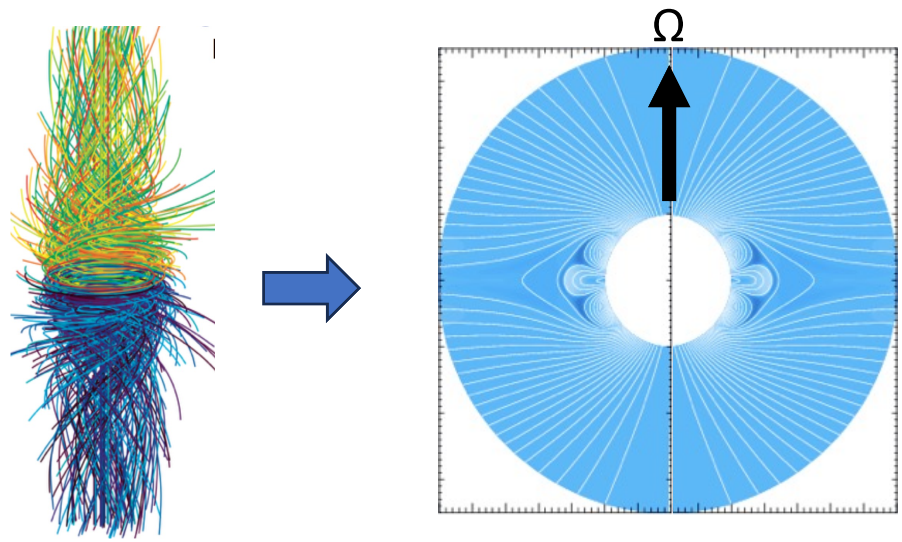
Key: high neutron/seed ratio

Astrophysical sites of the r-process

“normal” Supernovae
(ν-driven proto-NS wind)

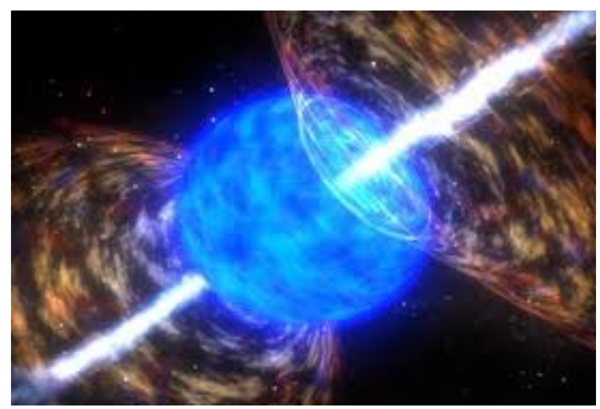


Magneto-rotational Supernova
(e.g. Nishimura+06, Burrows+07, Winteler+12, Mosta+14)
+ Magnetized Proto-NS Wind
(e.g. Thompson+04, Metzger+07, Desai+23, Prasanna+23)



Neuton Star Mergers
(e.g. Lattimer & Schramm 74; Freiburghaus+99)

“Collapsars” (BH accretion disk winds)
(e.g. Pruet+05, Surman+06, Siegel+19,)



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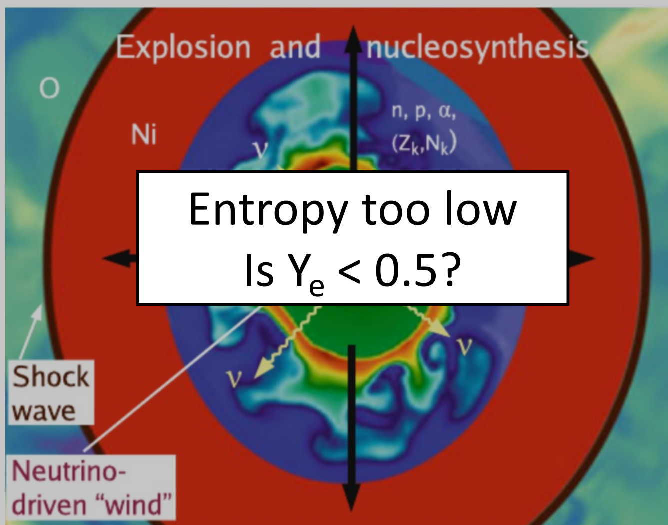

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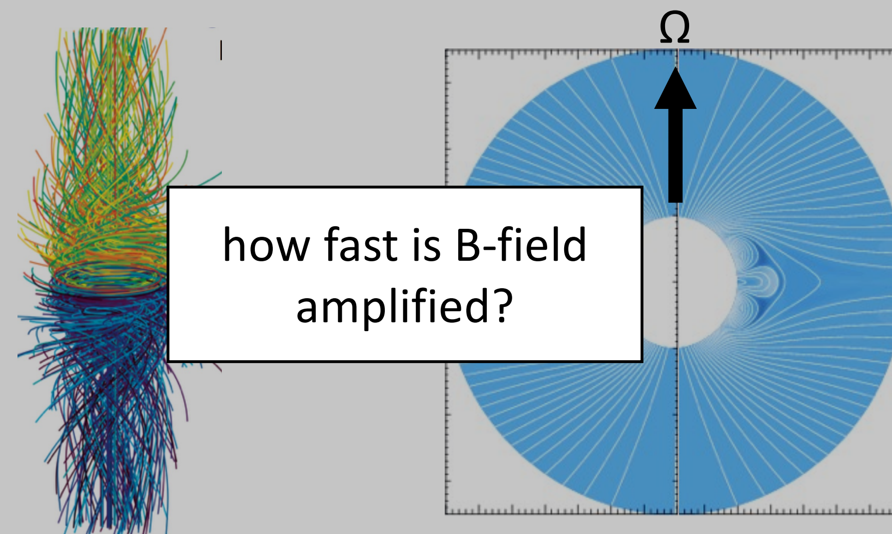

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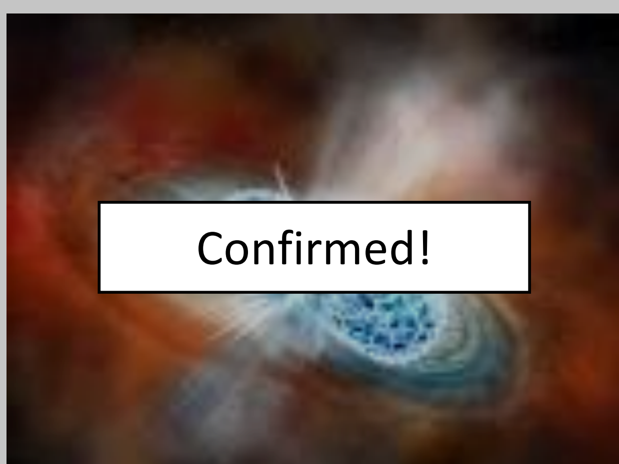

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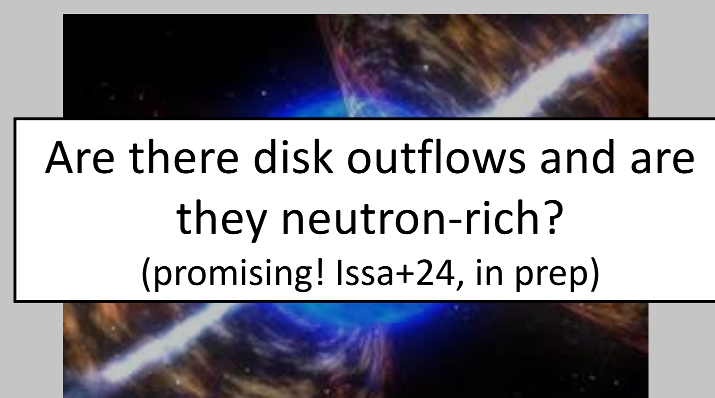
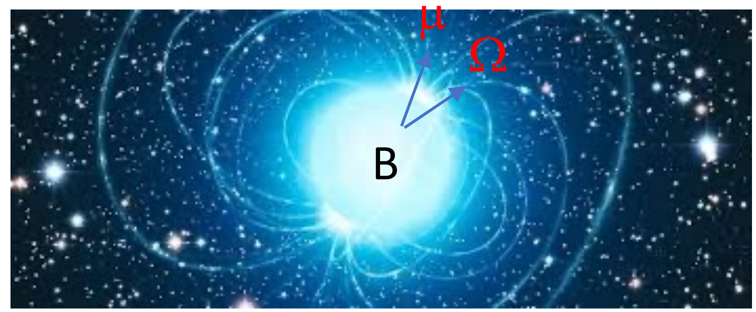


Magnetar Giant Flares

Magnetars: neutron stars powered by magnetic energy (Duncan & Thompson 93)

$$E_{\rm mag} \sim 3 \times 10^{49} {\rm erg} \left(\frac{B}{10^{16}{\rm G}}\right)^2$$



Constitute ~10-60% of neutron star birth (e.g. Beniamini+19)

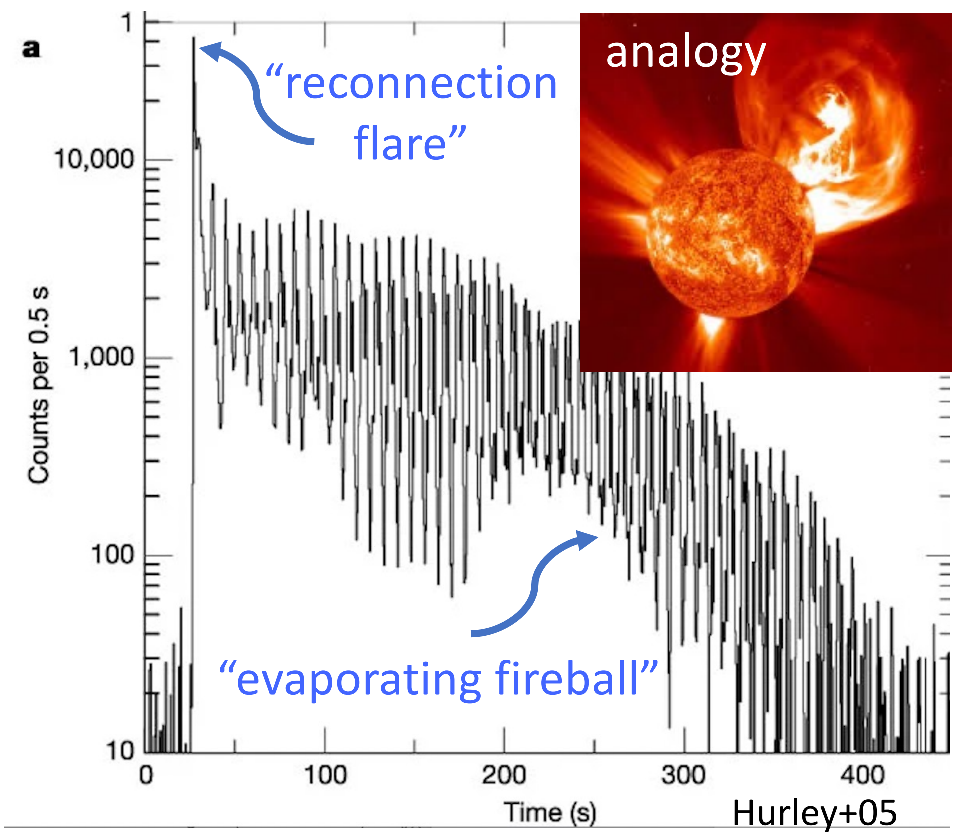
Giant flares (1979, 1998, 2004) release ~$10^{44\text{-}46}$ erg each

GF detectable in Milky Way and nearby galaxies as short "gamma-ray bursts"

Rates: every decade-century

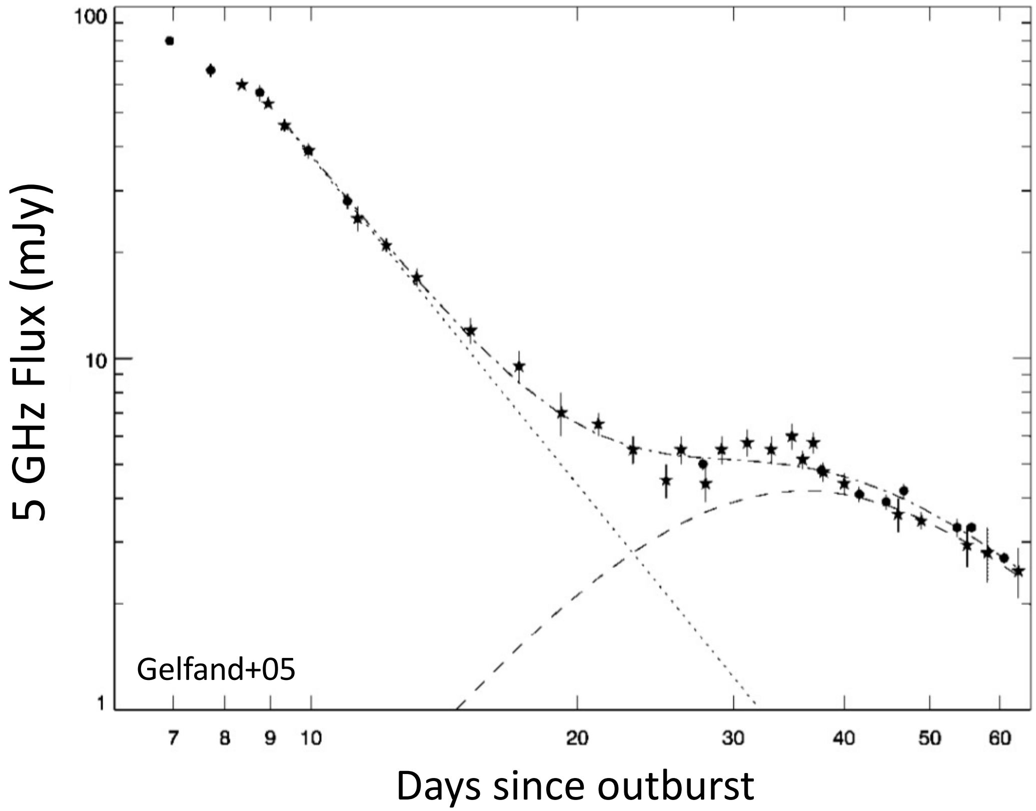
<u>Recent:</u>
Nov. 2023 giant flare in M82 (3.7 Mpc)

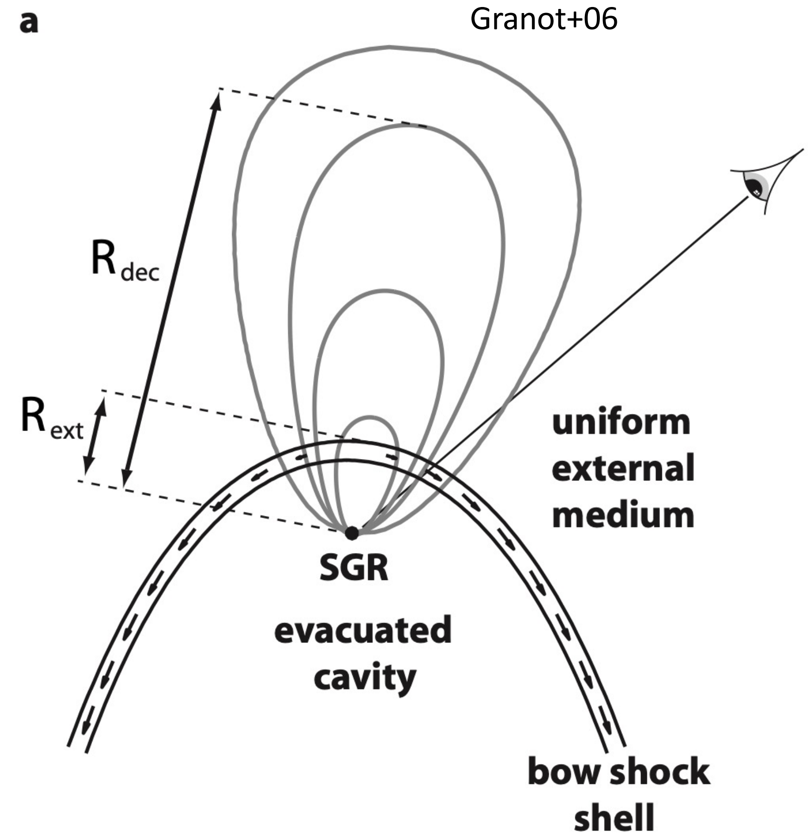
SGR 1806-20 (Dec. 2004)



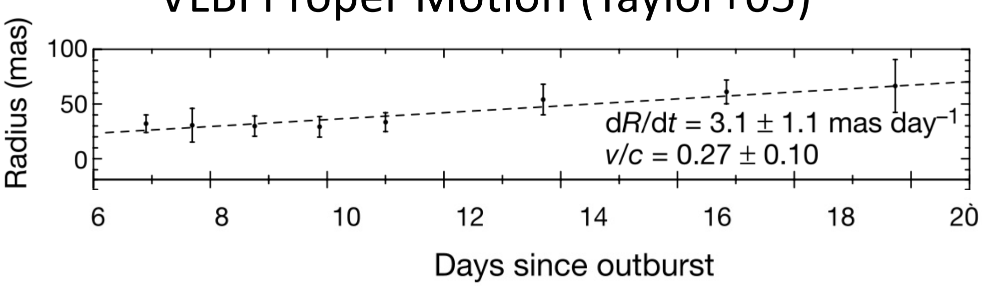
Hurley+05

radio afterglow: evidence for baryon ejection



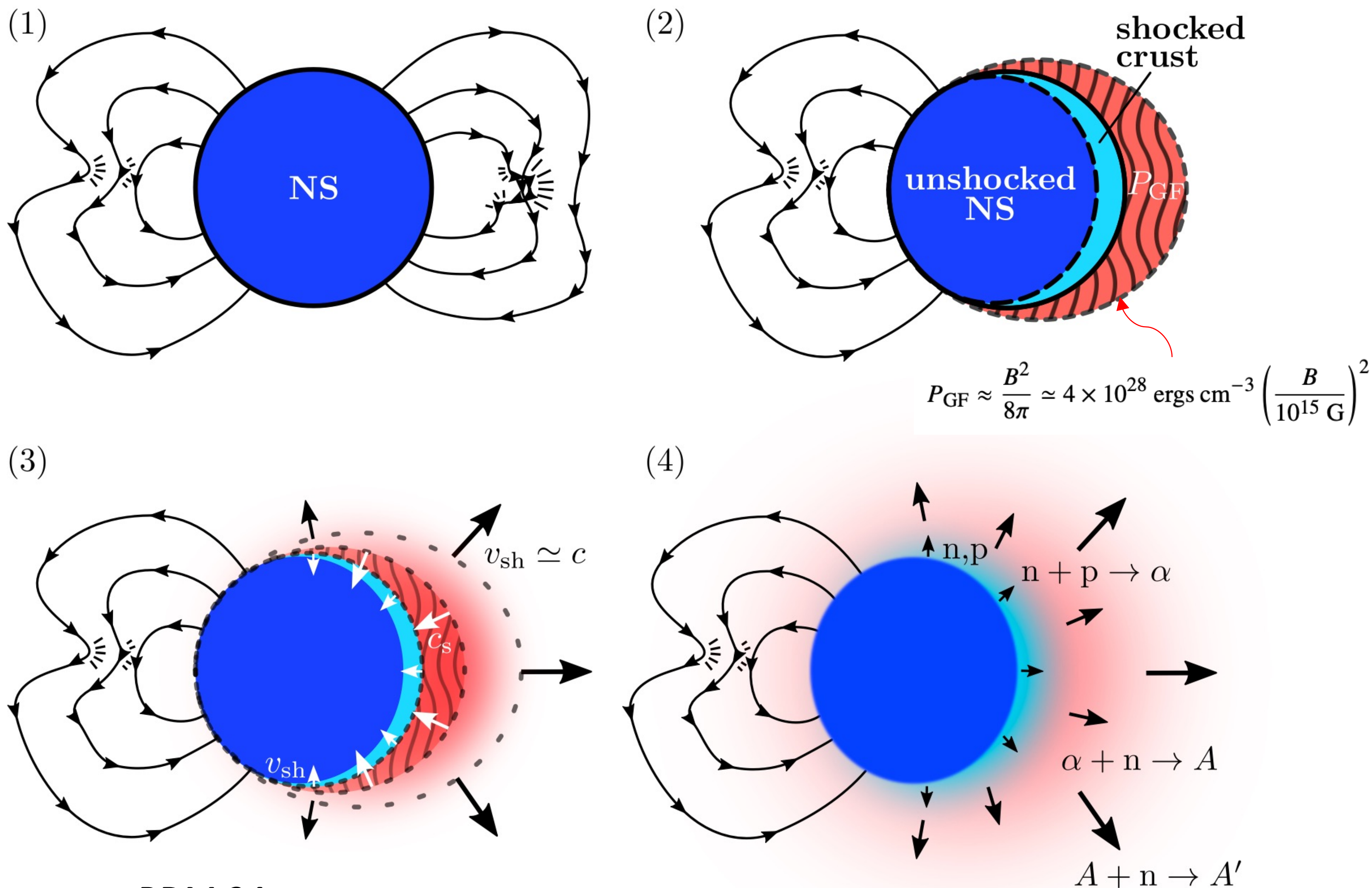


VLBI Proper Motion (Taylor+05)



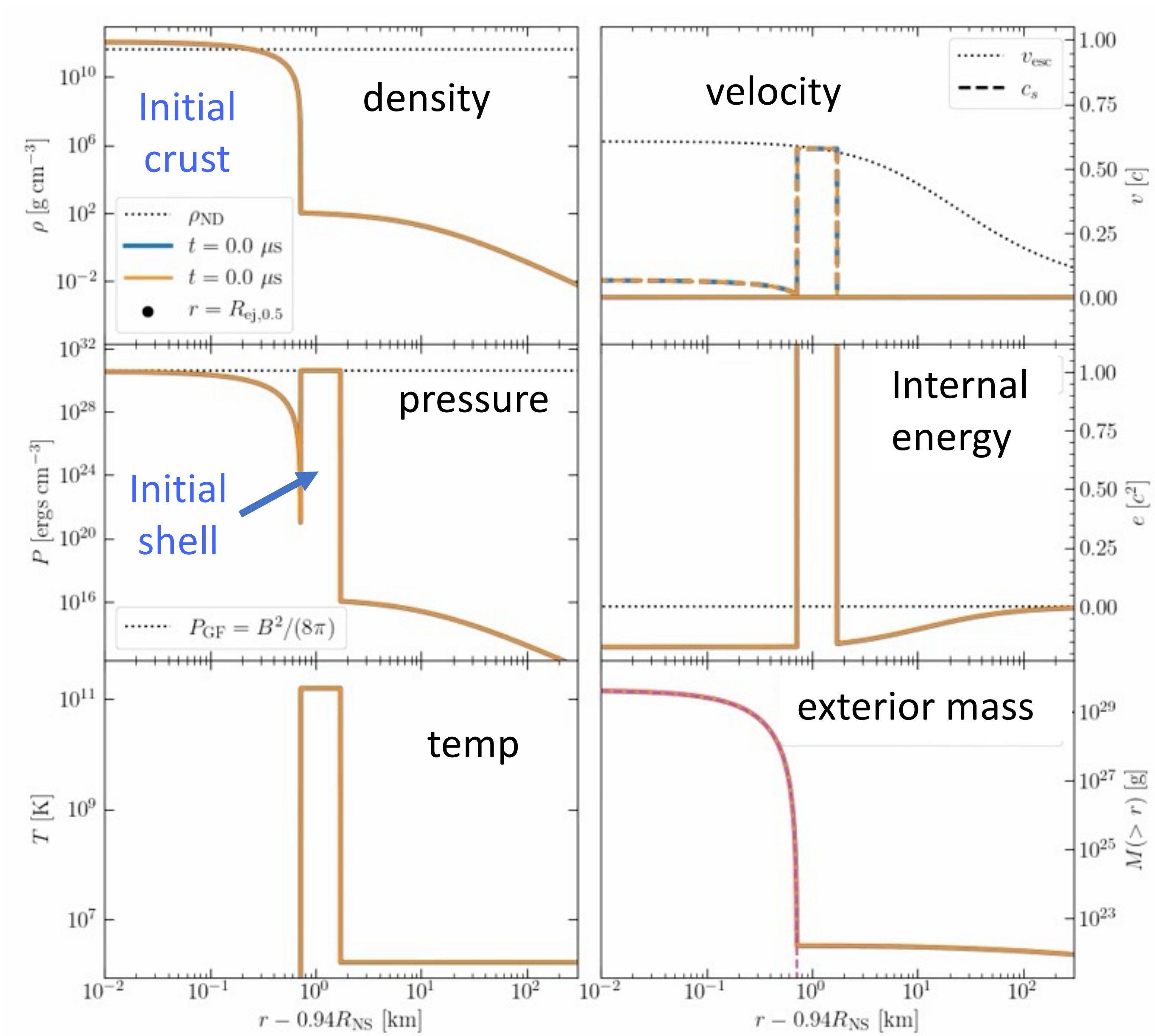
ejecta mass: M_{ej} ~10^{25}-10^{26} g
velocity: v_{ej} ~ 0.3-0.7 c
Baryonic composition
(a pure $e^{+/-}$ fireball would expand ultra-relativistically)

Dynamics of baryon ejection

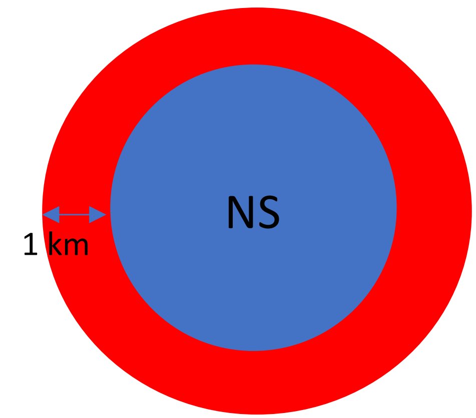


Cehula, Thompson, BDM 24

1D hydrodynamic simulations

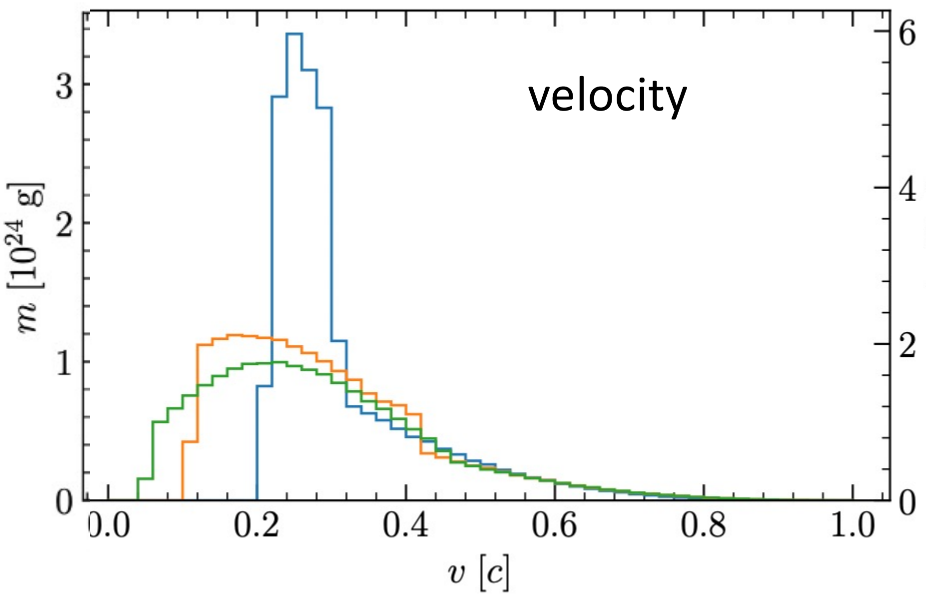


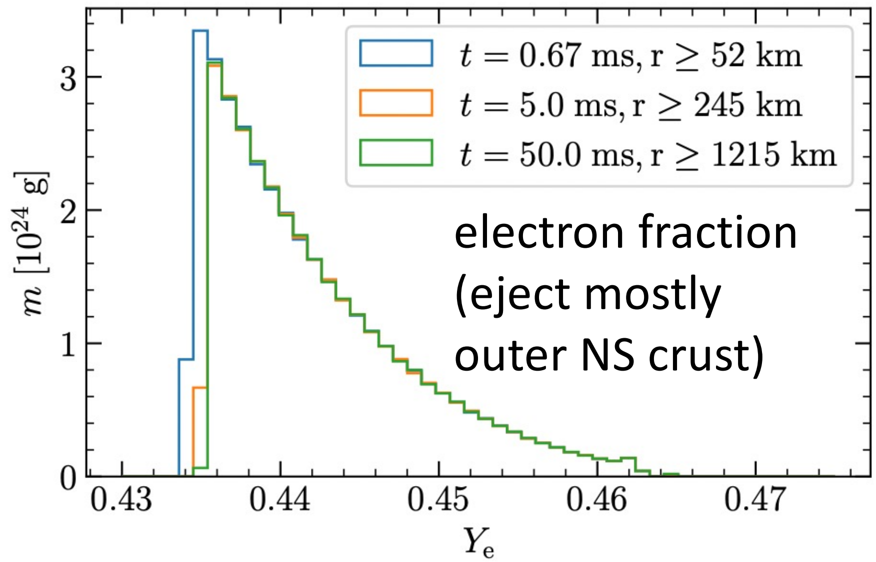
$P_0 \sim 10^{30}$ erg cm^{-3}

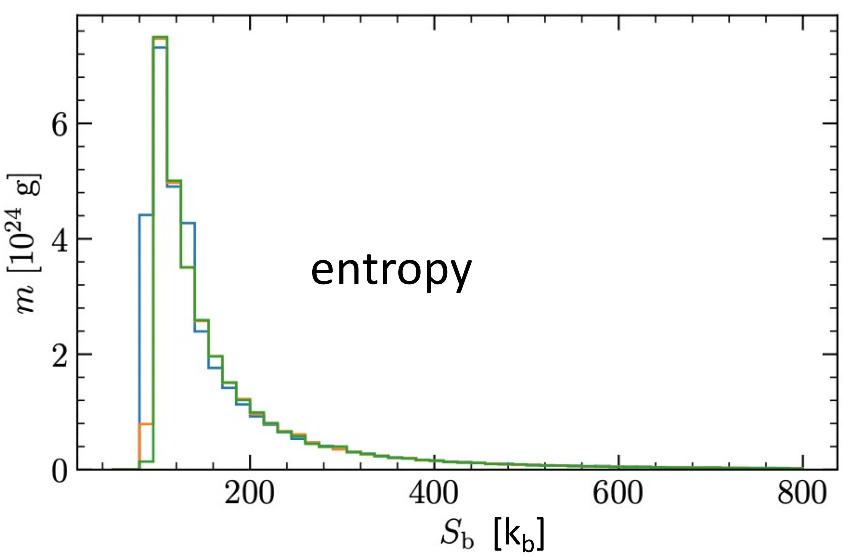


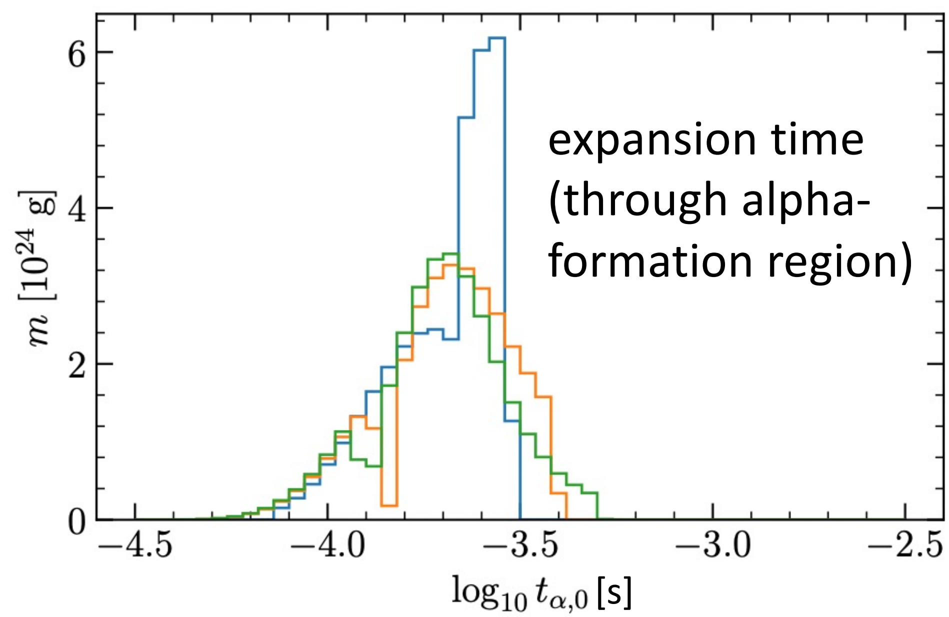
Jakub Cehula

Unbound Ejecta Properties

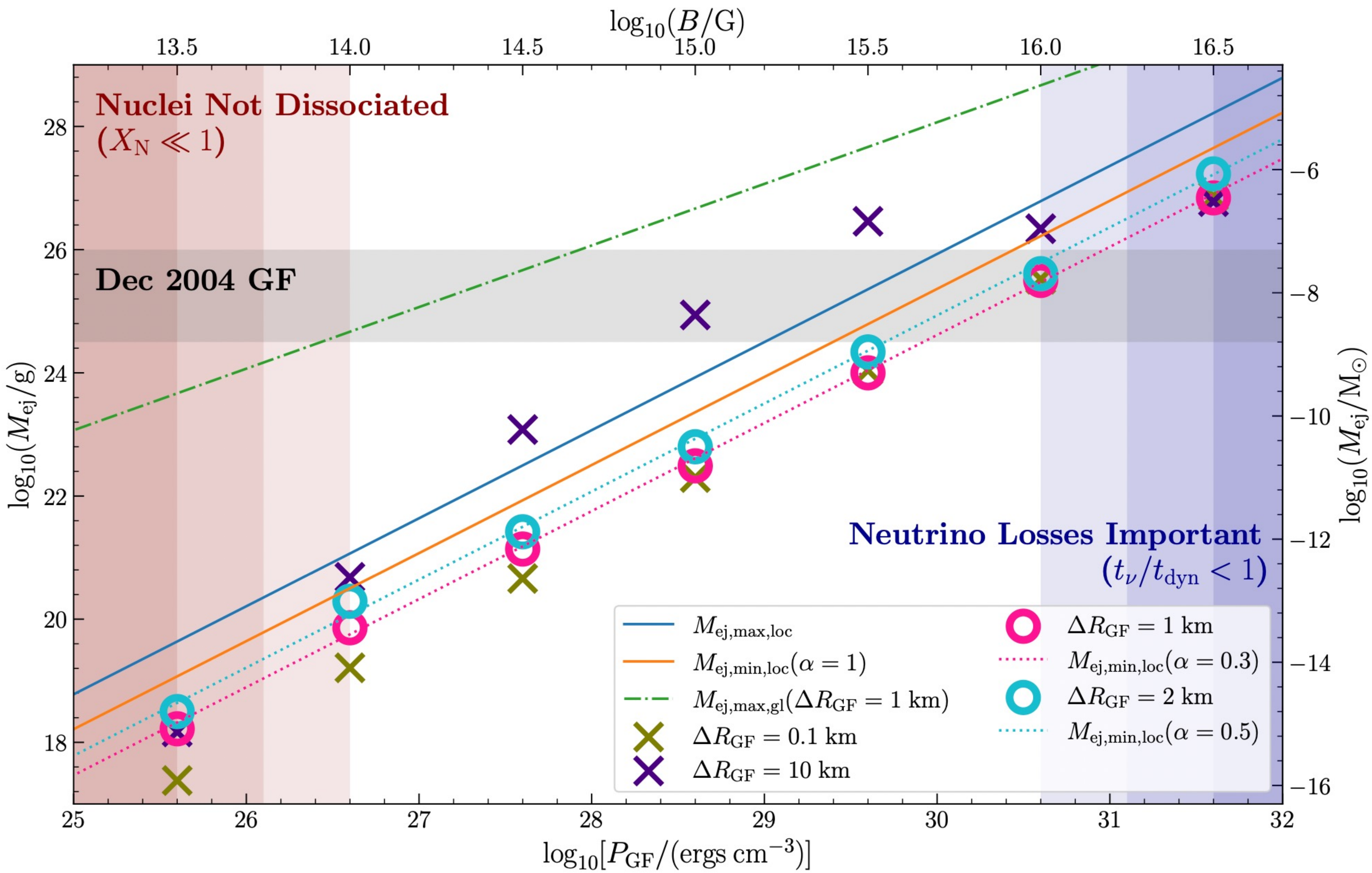








Parameter Study



Ejecta mass

Flare “strength” →

five stages of a hot r-process

1. **Dynamical ejection** ($t \sim R_g/v \lesssim$ ms, $T \gtrsim 3$ MeV, $\rho \gtrsim 10^{10}$ g/cc)
2. **Weak freeze-out** ($t \sim$ ms, $T \gtrsim$ MeV)
   Fixes Y_e following the $e^{\pm}/\nu$ captures above
3. **Alpha formation** ($t \sim 1 - 100$ ms, $T \lesssim 1 - 0.5$ MeV)

$$2n + 2p \rightarrow \alpha + \gamma$$

   is usually efficient (NSE) at capturing all the protons,

$$X_\alpha \simeq 2Y_\mathrm{e}; \quad X_\mathrm{n} = 1 - X_\alpha$$

4. **Seed formation** ($t \sim 1 - 100$ ms, $T \sim 0.5 - 0.1$ MeV),
   Neutron-aided 4-body "triple-alpha" reaction:

$$\alpha(\alpha n, \gamma)^9\mathrm{Be}(\alpha, n)^{12}\mathrm{C}$$

   Additional α-captures rapidly build seed nuclei

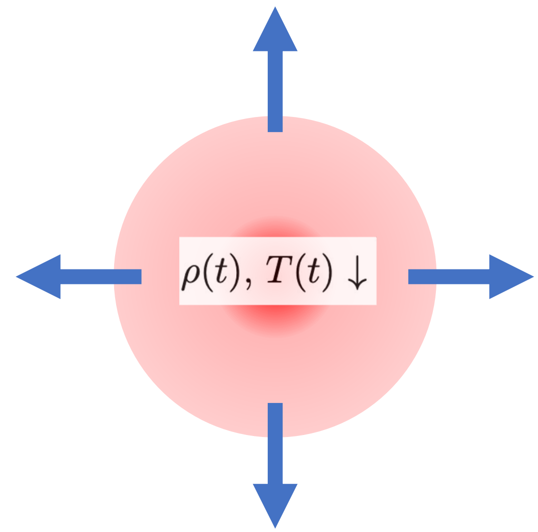
$$^{12}\mathrm{C} + \mathrm{N}\alpha \rightarrow \{A_\mathrm{seed} \sim 80 - 100, \bar{Z}_\mathrm{seed} \approx 32 - 36\}$$

5. **R-Process** ($t \sim 0.1 - 1$ s, $T \sim 0.2 - 0.01$ MeV).

$$(Z, A) + n \rightarrow (Z + 1, A + 1) + e^- + \bar{\nu}_\mathrm{e} + \gamma,$$

Maximum isotope reached A_max depends on neutron-to-seed ratio,

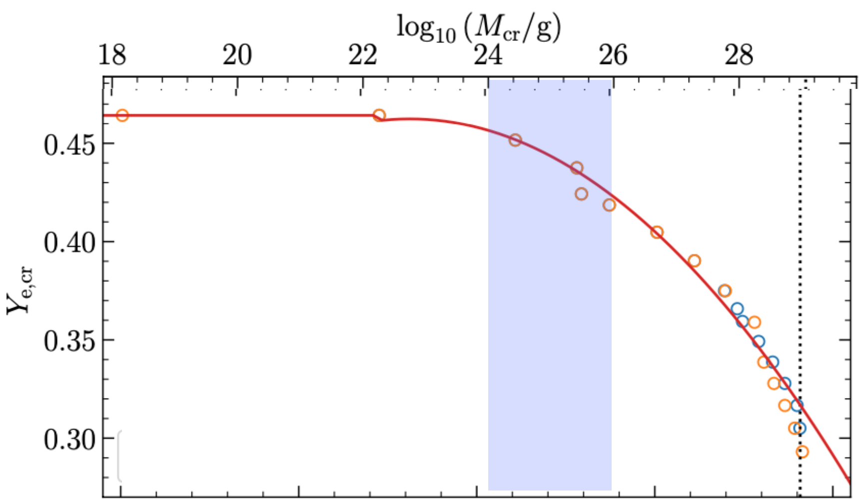
$$\frac{n}{s} \equiv \frac{Y_n}{Y_s},$$



$$\{Y_e, S \leftrightarrow \rho(T), t_\mathrm{exp} \leftrightarrow v\},$$

1. Electron fraction
2. Entropy
3. Expansion time

Alpha-rich freeze-out

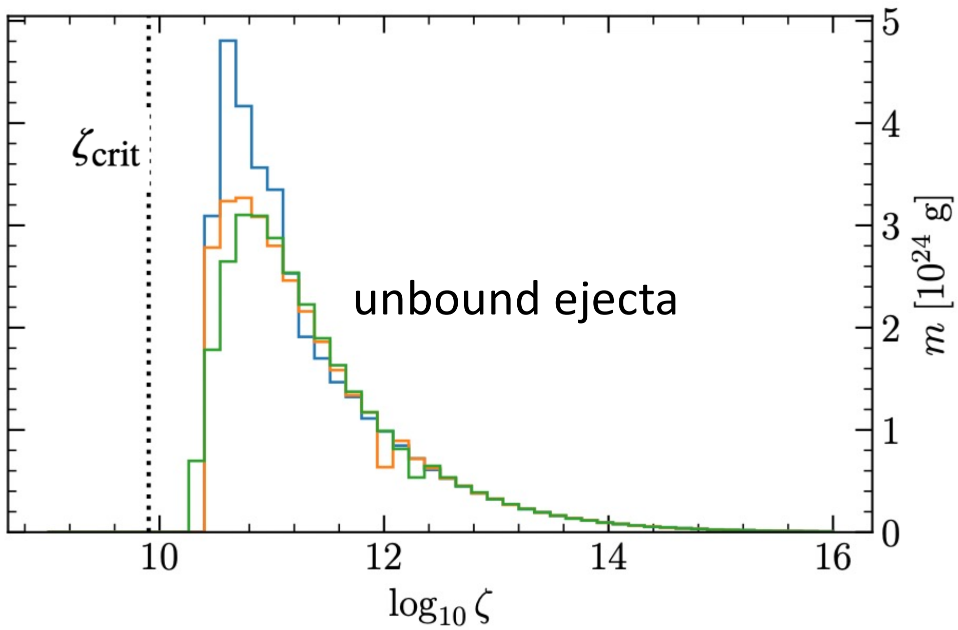


Ejecta not very neutron-rich, $Y_e \sim 0.43$-0.45

Q: Is a (heavy) r-process still possible?

A: Yes!
alpha-rich freeze-out (e.g. Meyer+92)
=> suppress seed formation to increase n/s ratio

$$X_{12} \propto R \cdot t_{\rm exp} \propto \rho^3 t_{\rm exp} \underset{T\approx const}{\propto} t_{\rm exp}/S^3$$

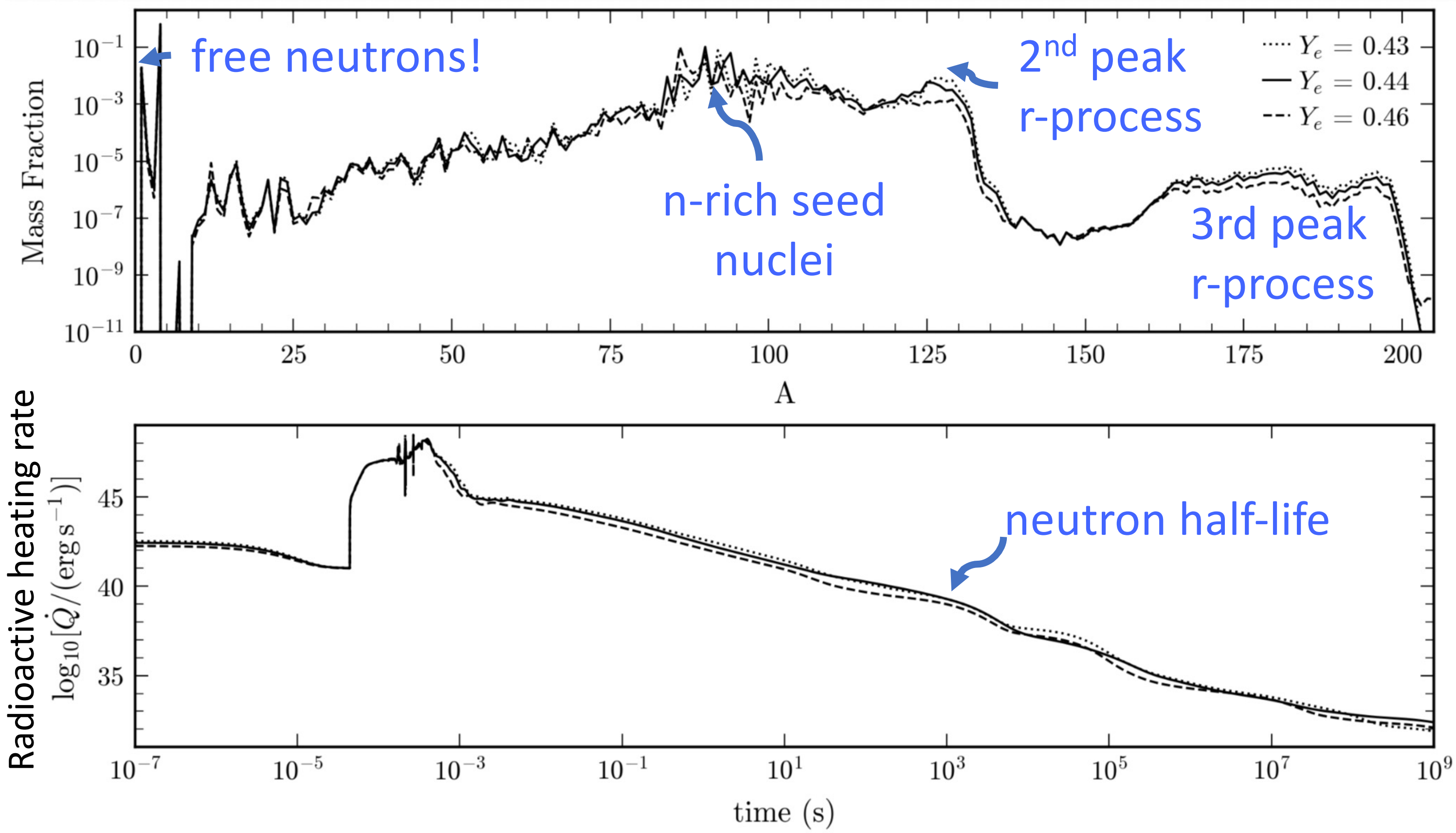


Threshold condition for 3rd peak r-process
(e.g. Hoffman+97)

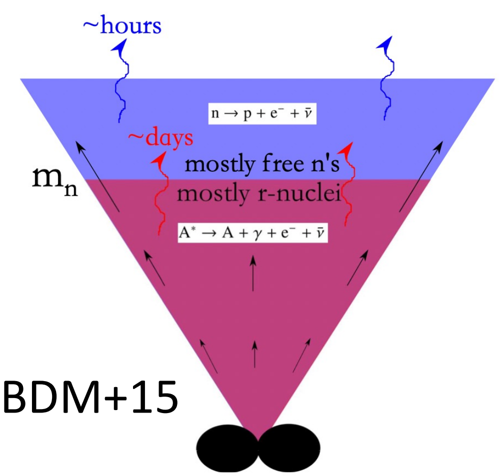
$$\zeta \equiv \frac{S_{\rm b}^3}{Y_{\rm e}^3 t_{\alpha,0}} > \zeta_{\rm crit} \approx 8 \times 10^9$$

Nucleosynthesis Yields

Ani Patel



Neutron precursor



BDM+15

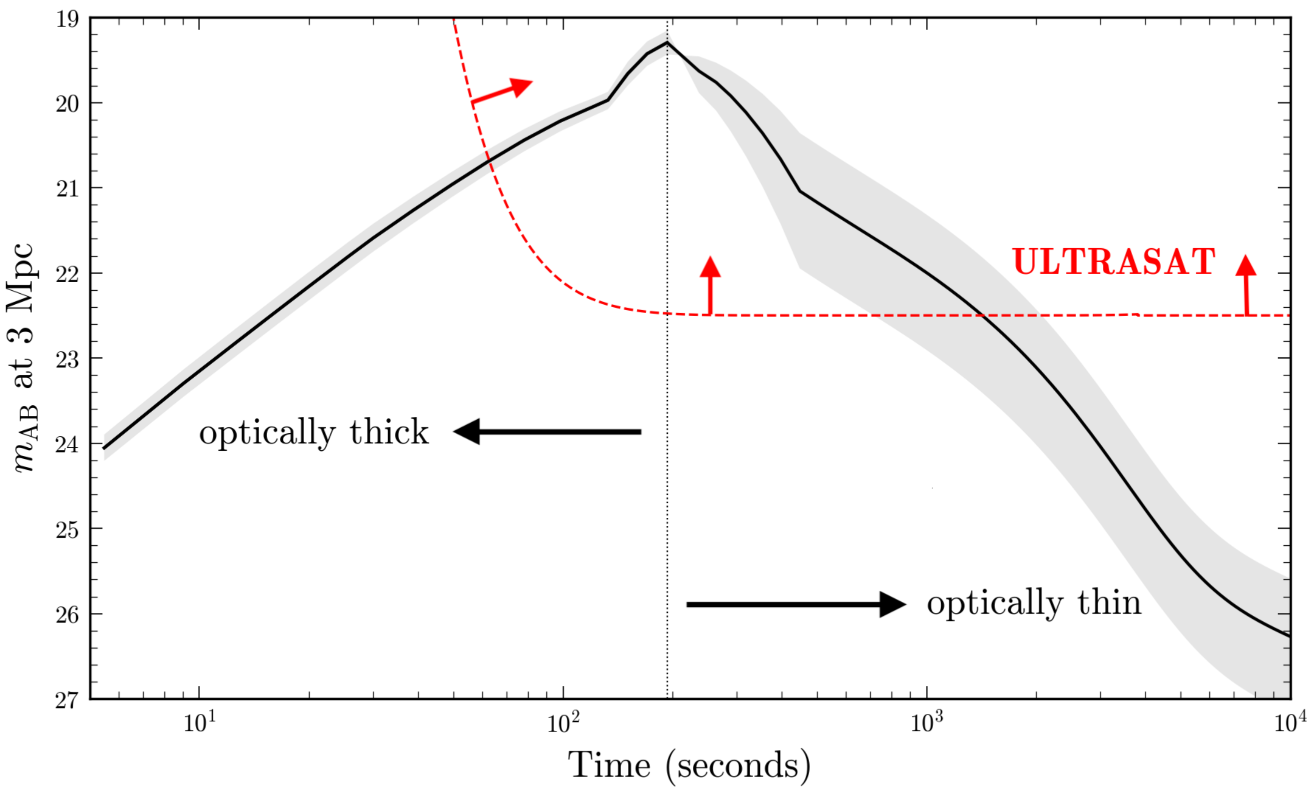
neutron-capture freeze-out of fastest layers

$$(Z, A) + n \rightarrow (Z+1, A+1) + e^- + \bar{\nu}_e + \gamma,$$

mini-kilonova ("nova brevis")

$$t_{\rm pk} \approx \sqrt{\frac{M_{\rm ej}\kappa}{4\pi v_{\rm ej}c}} \simeq 300\ {\rm s} \left(\frac{M_{\rm ej}}{10^{26}\ {\rm g}}\right)^{1/2} \left(\frac{v_{\rm ej}}{0.3c}\right)^{-1/2} \left(\frac{\kappa}{3\ {\rm cm^2\ g^{-1}}}\right)^{1/2}$$

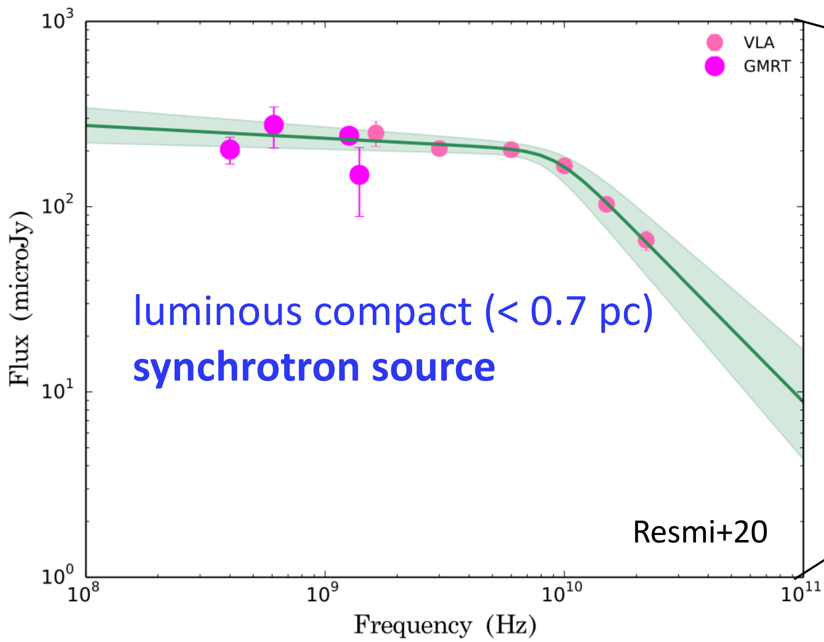
$$L_{\rm pk} \approx 10^{39}\ {\rm ergs\ s^{-1}} \left(\frac{M_{\rm ej}}{10^{26}\ {\rm g}}\right)^{0.35} \left(\frac{v_{\rm ej}}{0.3c}\right)^{0.65} \left(\frac{\kappa}{3\ {\rm cm^2\ g^{-1}}}\right)^{-0.65}$$

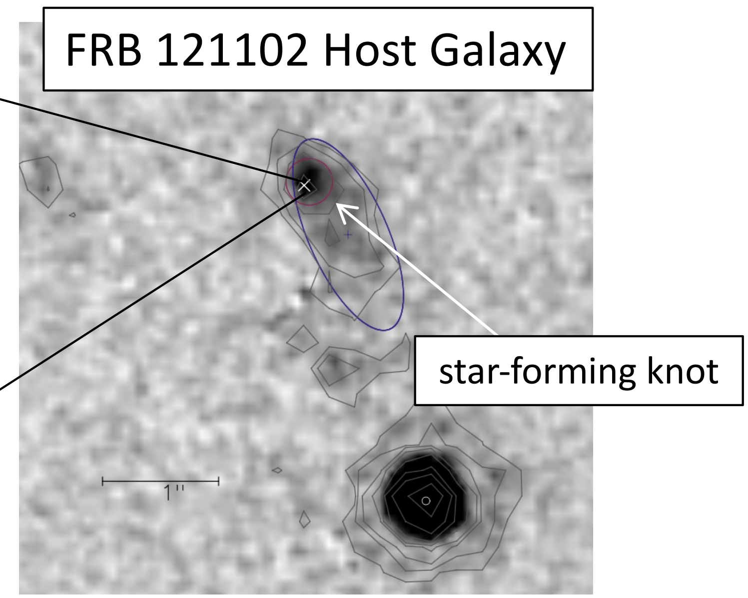


slews in <15 min to external (e.g. gamma-ray) trigger

Property	Value
Spacecraft parameters	
Orbit	GEO
Real-time download of data	Continuous
Slew rate	$> 30°$/min
Transient alert after observation end	< 15 min
Sky accessibility at any given moment	$> 50\%$
Observation start after ToO trigger	< 15 min

Magneto-ionic environs of a fast radio burst



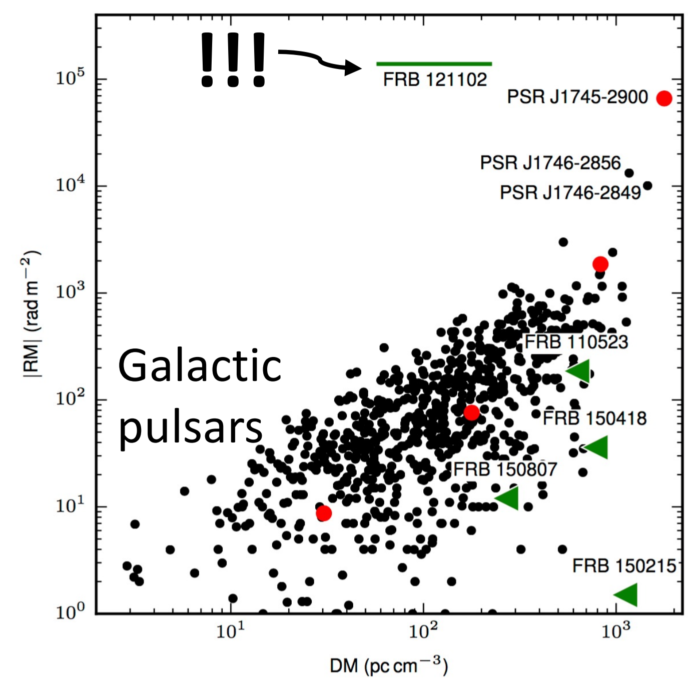


Spitler+16, Chatterjee+17, Tendulkar+17, Bassa+17, Michilli+19

Rotation Measure

$$\mathrm{RM} = \frac{e^3}{2\pi m_e^2 c^4} \int n_e B_{\|} \, ds$$

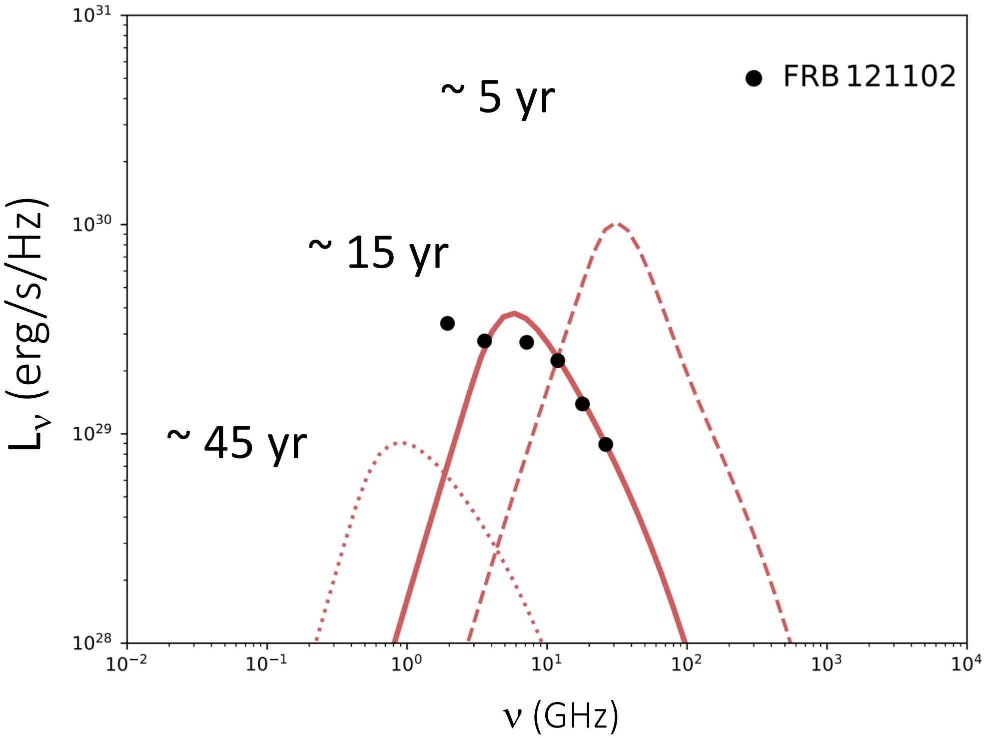
Electron-ion plasma!
($e^{+/-}$ produces no net RM)

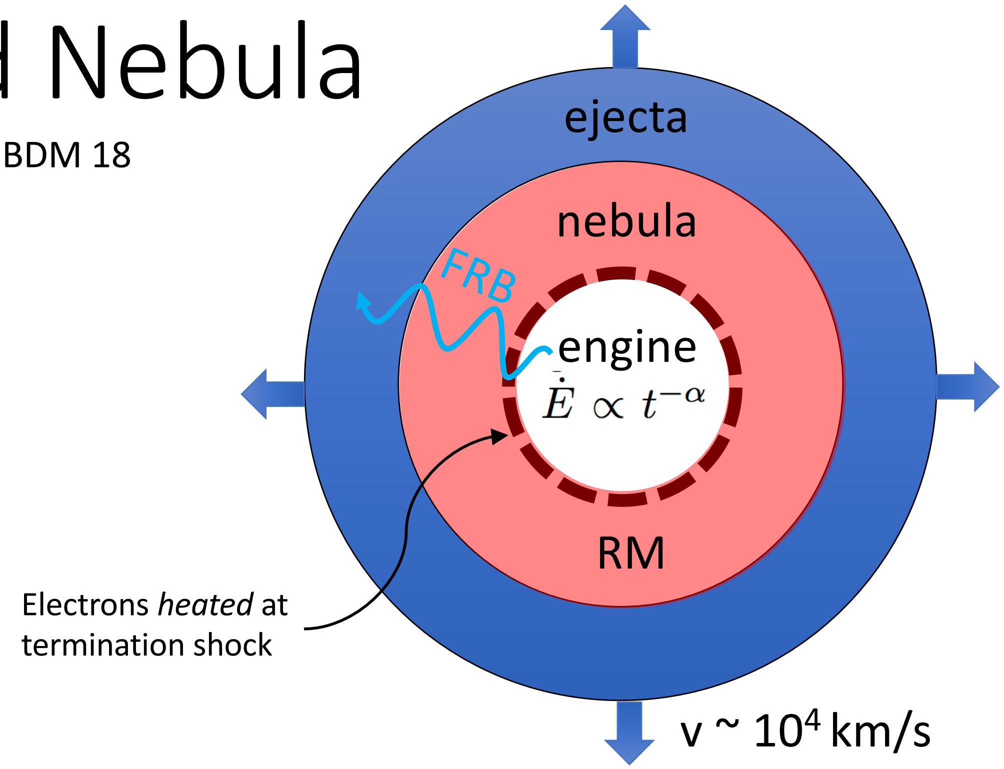


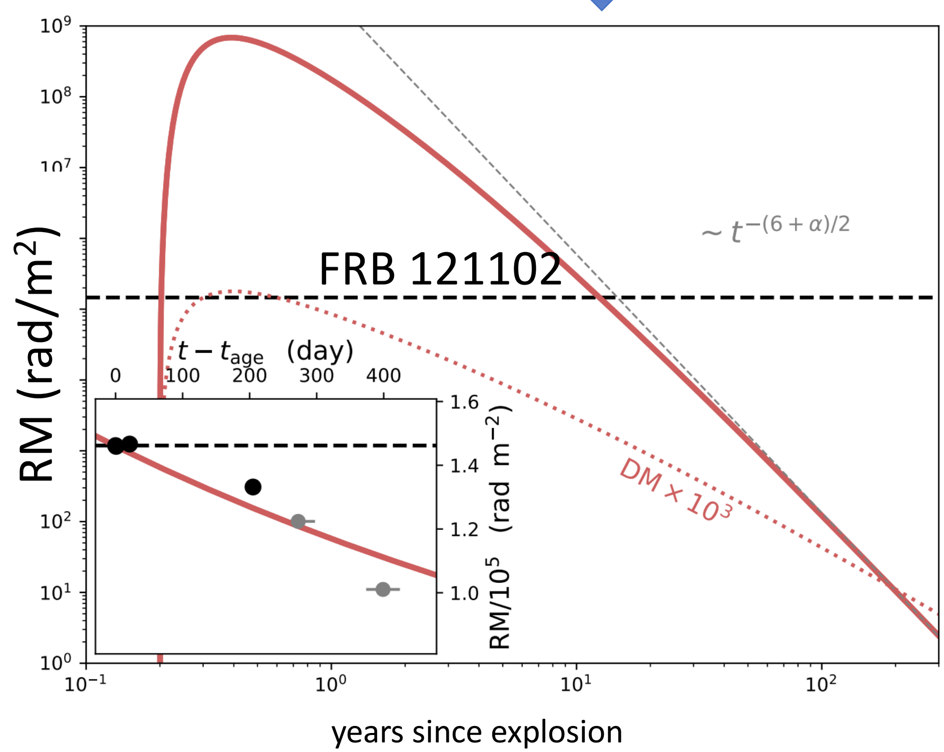
Michilli+18

Magnetar-Powered Nebula

Margalit & BDM 18







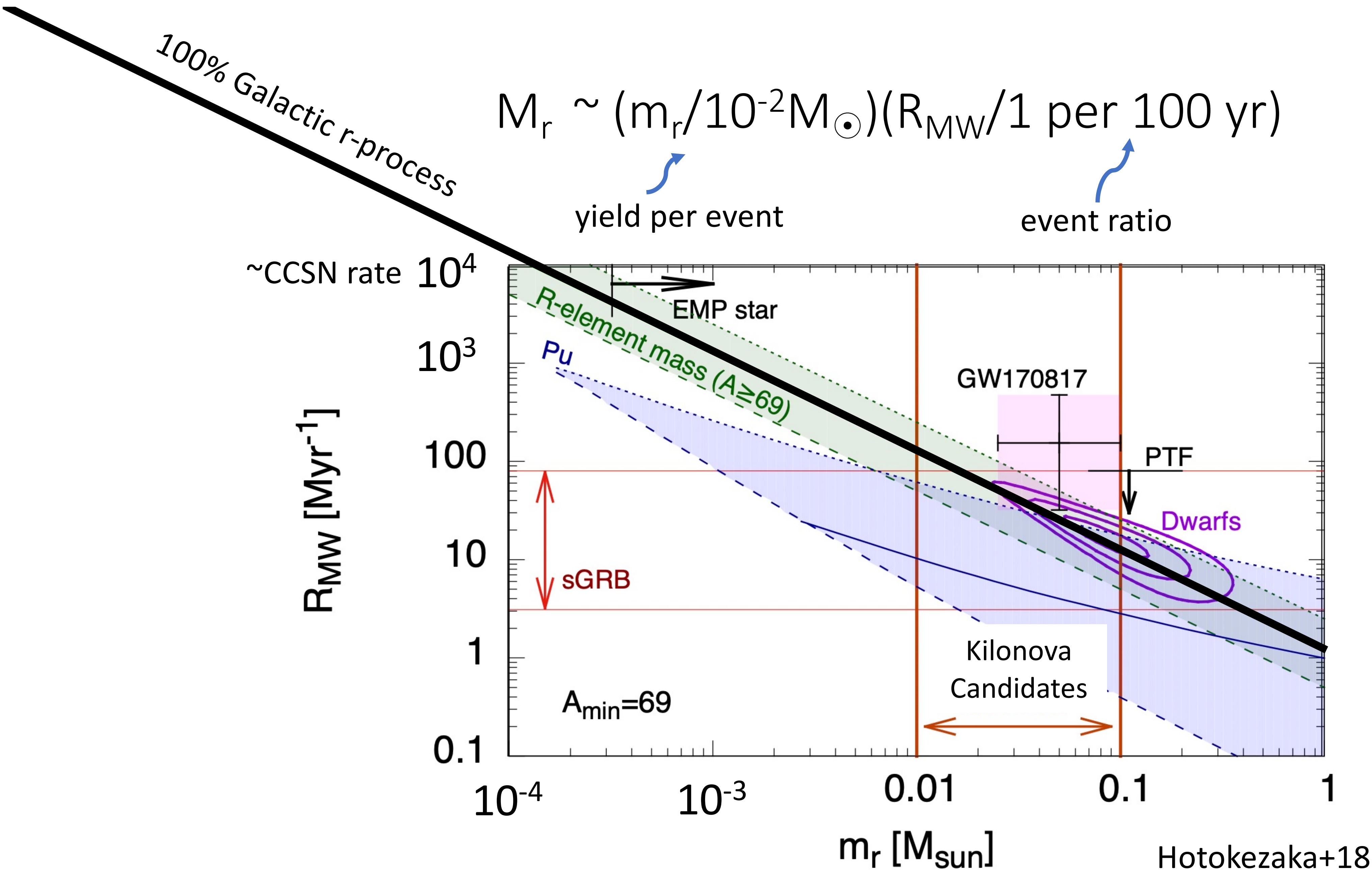
=> explosion age t_{age} ~ 10-50 yr
& total energy E ~ $10^{49\text{-}50}$ erg

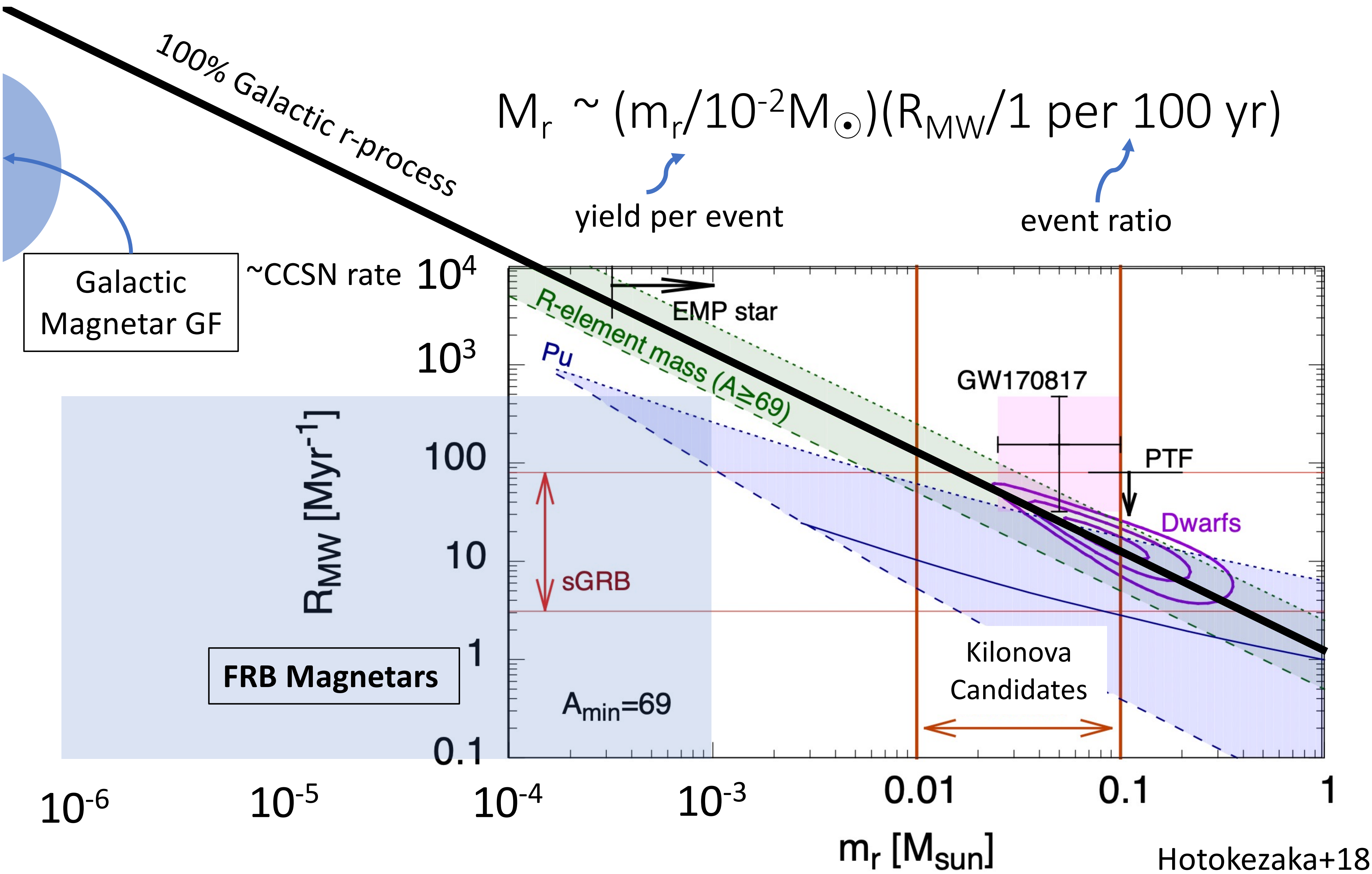
Ion ejection rate: ~1e20-1e21 g/s

$\Rightarrow$ **SGR 1806-20 like GF every week!**

$\Rightarrow$ **10^{-5} – 10^{-3} $M_\odot$** over ~10-100 yr lifetime

$$M_r \sim (m_r/10^{-2}M_\odot)(R_{MW}/1 \text{ per } 100 \text{ yr})$$

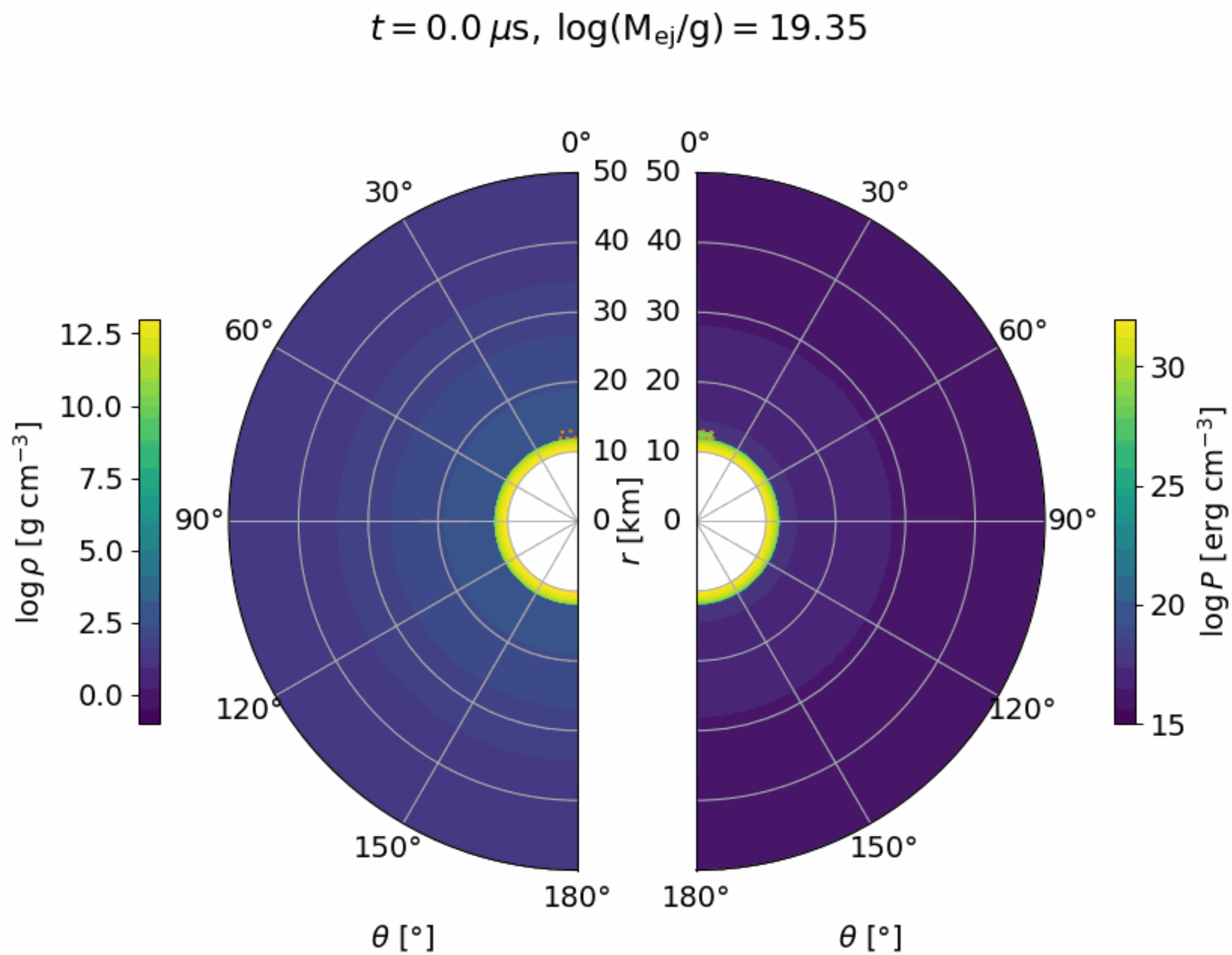




Magnetar GF contribute <~1-10% of Galactic r-process
(but can occur at low metallicity)

Conclusions

- Magnetar giant flares: the most powerful non-cataclysmic neutron star outbursts
- Both direct (radio afterglow) and indirect (FRB rotation measures) evidence supports substantial baryon ejection during GFs.
- We model the GF in one-dimension as the sudden application of a high-pressure shell above the neutron star surface, which drives a shock wave into the crust.
- The heated crustal material is dissociated into free nucleons, which can undergo nucleosynthesis as it decompresses into space.
- Shock heating raises the entropy of the unbound ejecta layers sufficiently high to enable an alpha-rich freeze-out, thus permitting a heavy r-process.
- Some ejecta layers expand so quickly the r-process itself freezes out with a substantial free neutron abundance.
- Radioactive decay powers a brief optical/UV transient ("nova brevis"), akin to a scaled-down kilonova, which may be detected with UV satellites like ULTRASAT.
- Much of the r-process may not come from rare GF like those from magnetars in our Galaxy, but the extremely active magnetars which power fast radio bursts.
- The total GF r-process yields is likely not sufficient to contribute most of Galactic r-process, but could contribute significantly at low metallicity.



$t = 0.0\,\mu$s, $\log(\mathrm{M_{ej}}/\mathrm{g}) = 19.35$
0°
30°
60°
90°
120°
150°
180°
50
40
30
20
10
0
r [km]
$\log\rho$ [g cm^{-3}]
12.5
10.0
7.5
5.0
2.5
0.0
$\log P$ [erg cm^{-3}]
30
25
20
15
θ [°]