

Three Preludes on a Theme of Magnetars

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Credit: NASA/ESA

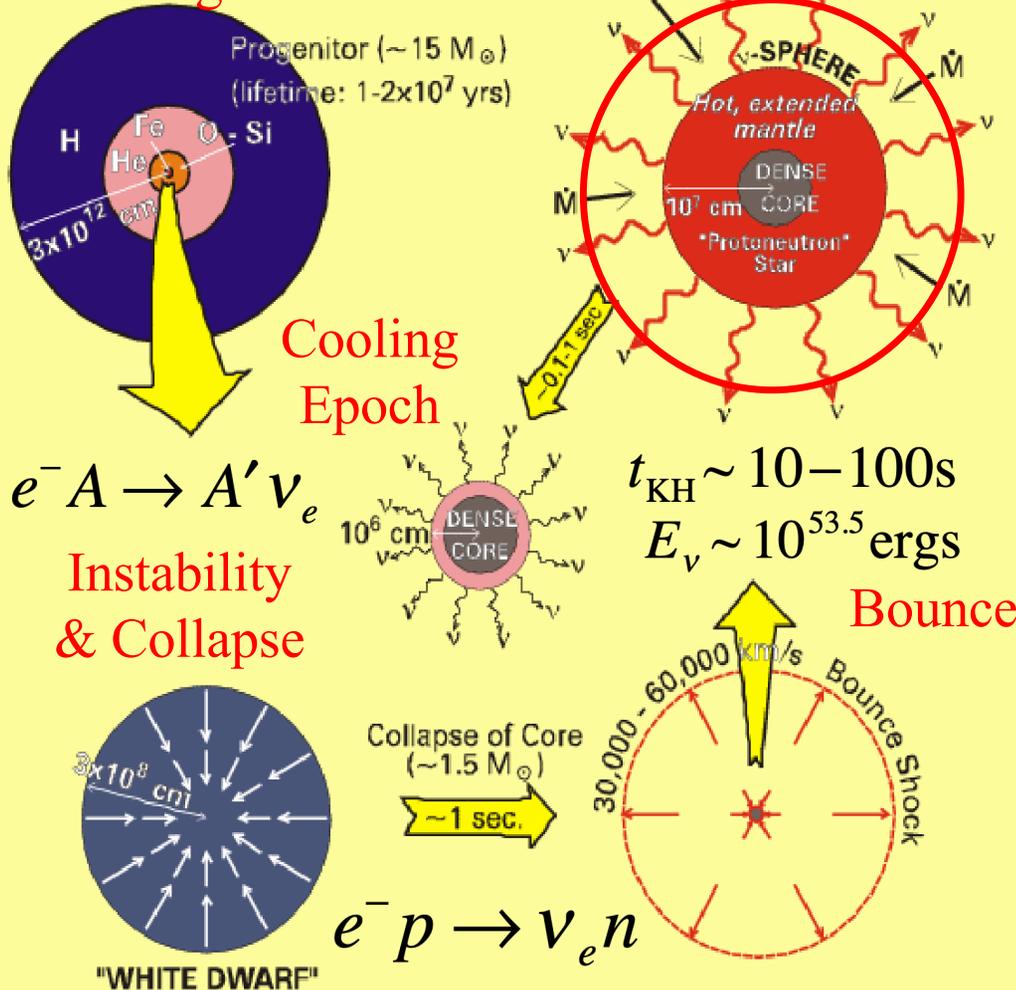
Stars with mass $> \sim 10 M_{\text{sun}}$
fuse $\text{H} \rightarrow \text{He}$, then heavier
elements up to Iron group.

One dies every century in
the Milky Way. Several per
second in the visible
Universe. 100s per year in
wide-field optical surveys.

Somehow, collapse leads to
explosion.

... At least sometimes.

The Progenitor



0. Star lives $\sim 10^7$ years.
1. Instability and collapse (0.1s)
2. Bounce & shock formation:
 $T_{\text{core}} \sim 10$'s of MeV
 $\rho_{\text{core}} \sim 10^{14.5}$ g/cm³
3. Shock breakout & stall (\sim ms)
5. Shock revival before black hole formation (\sim 1s)
6. NS cooling + Wind (1 min)
7. Shock breakout (min – hour)

Before Feb 23, 1987

On Feb 23, 1987!



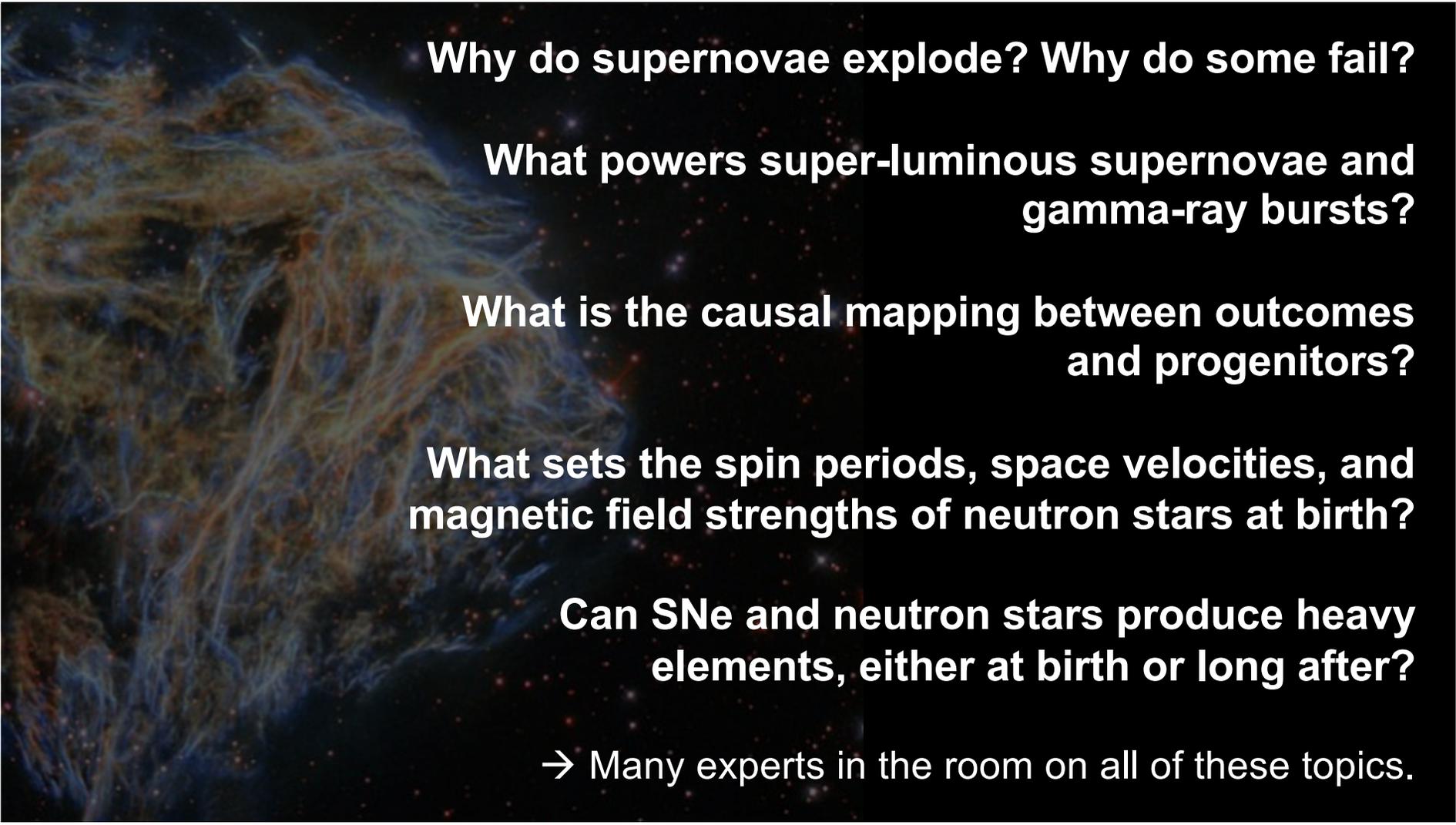
Credit: Australian Astronomical Observatory - Malin

SN 1987A

Accompanied by
the detection of 20
neutrinos over 10
seconds.

Total energy,
timescale, spectrum
consistent with
expectations!

Mostly.



Why do supernovae explode? Why do some fail?

What powers super-luminous supernovae and gamma-ray bursts?

What is the causal mapping between outcomes and progenitors?

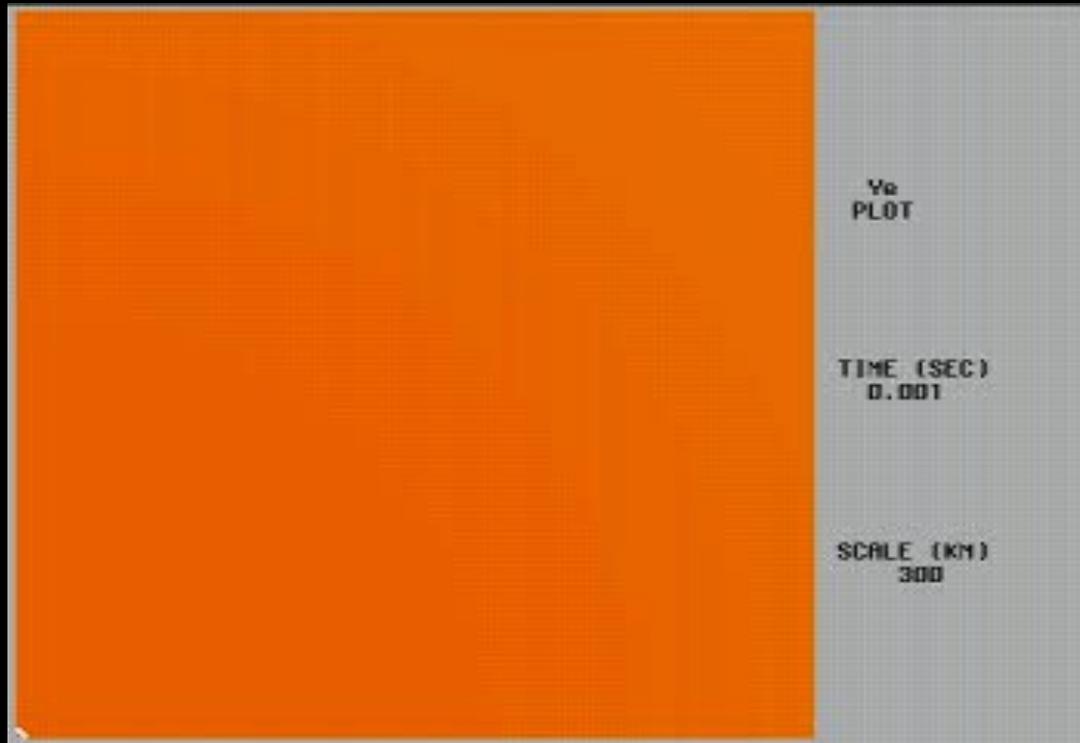
What sets the spin periods, space velocities, and magnetic field strengths of neutron stars at birth?

Can SNe and neutron stars produce heavy elements, either at birth or long after?

→ Many experts in the room on all of these topics.

I. Proto-Magnetar Winds & Spindown

Collapse, Bounce, Stall, Wind-Driven Explosion, Cooling



300 km

Electrons combine
with protons to make
a neutron star:

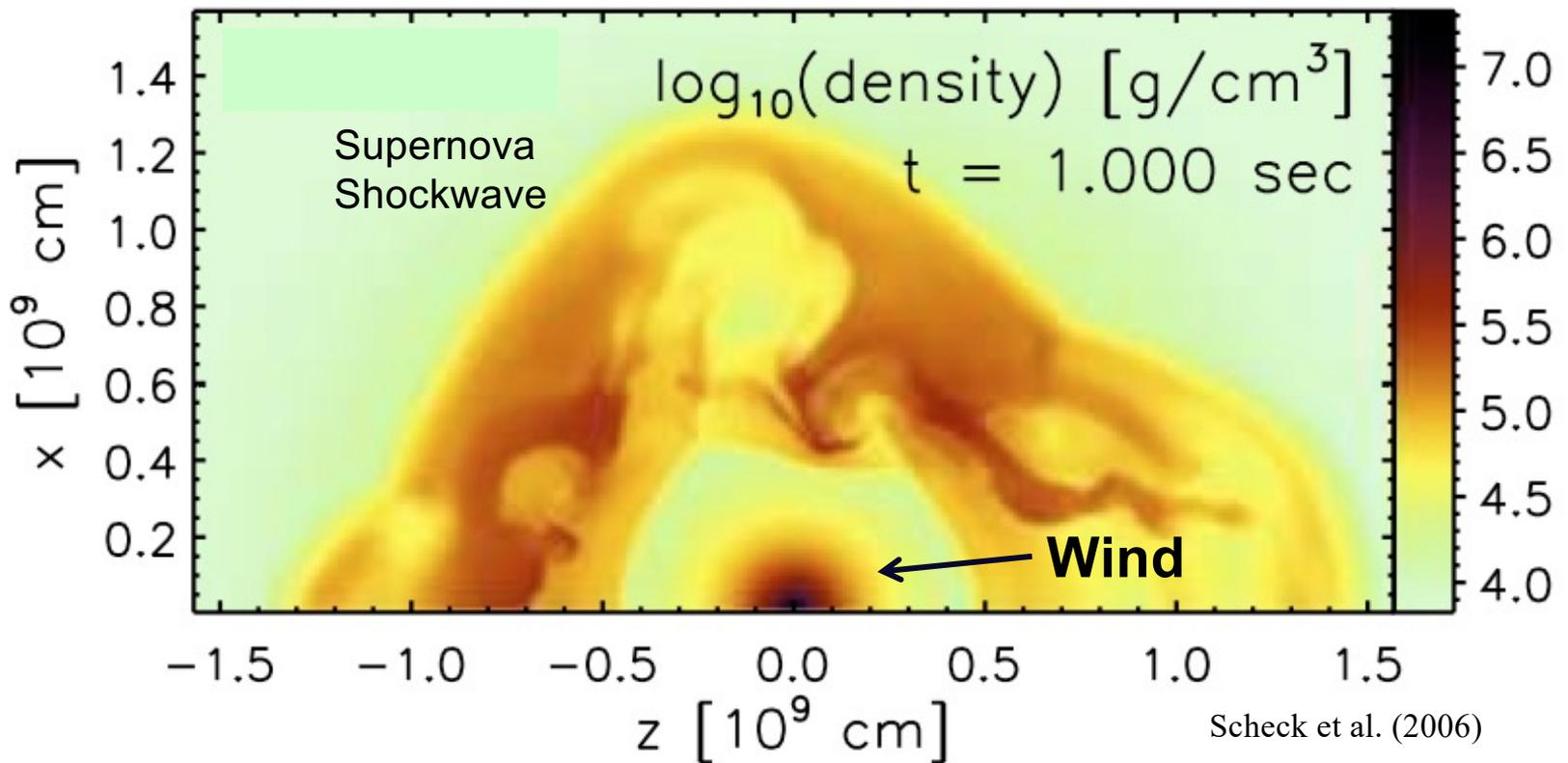


Escaping neutrinos
interact with infalling
matter, heating it:



Explosion in ~ 1 second,
or a BH will form.

Wind Emergence: Common to many SN Explosions



The SN Explosion is accompanied by a wind-driven bubble.

Neutrino-driven winds accompany explosions.

- Duration : Kelvin-Helmholz time \sim few – 100s.
- Mass loss : $\sim 10^{-3} M_{\text{sun}}$ total.

$$\dot{M}_{\text{wind}} \sim 3 \times 10^{-7} L_{\nu,51}^{5/2} M_{\odot} \text{ s}^{-1}$$

- Energy : $\sim 10^{49}$ ergs/s; $V_{\infty} \sim 0.1c$
- Initial Interest : Production site for r-process nuclei?

e.g. Duncan et al. 1986; Woosley & Hoffman 1992; Woosley et al. 1994; Qian & Woosley 1996; Sumiyoshi et al. 2000; Otsuki et al. 2000; Wanajo et al. 2001; Thompson et al. 2001

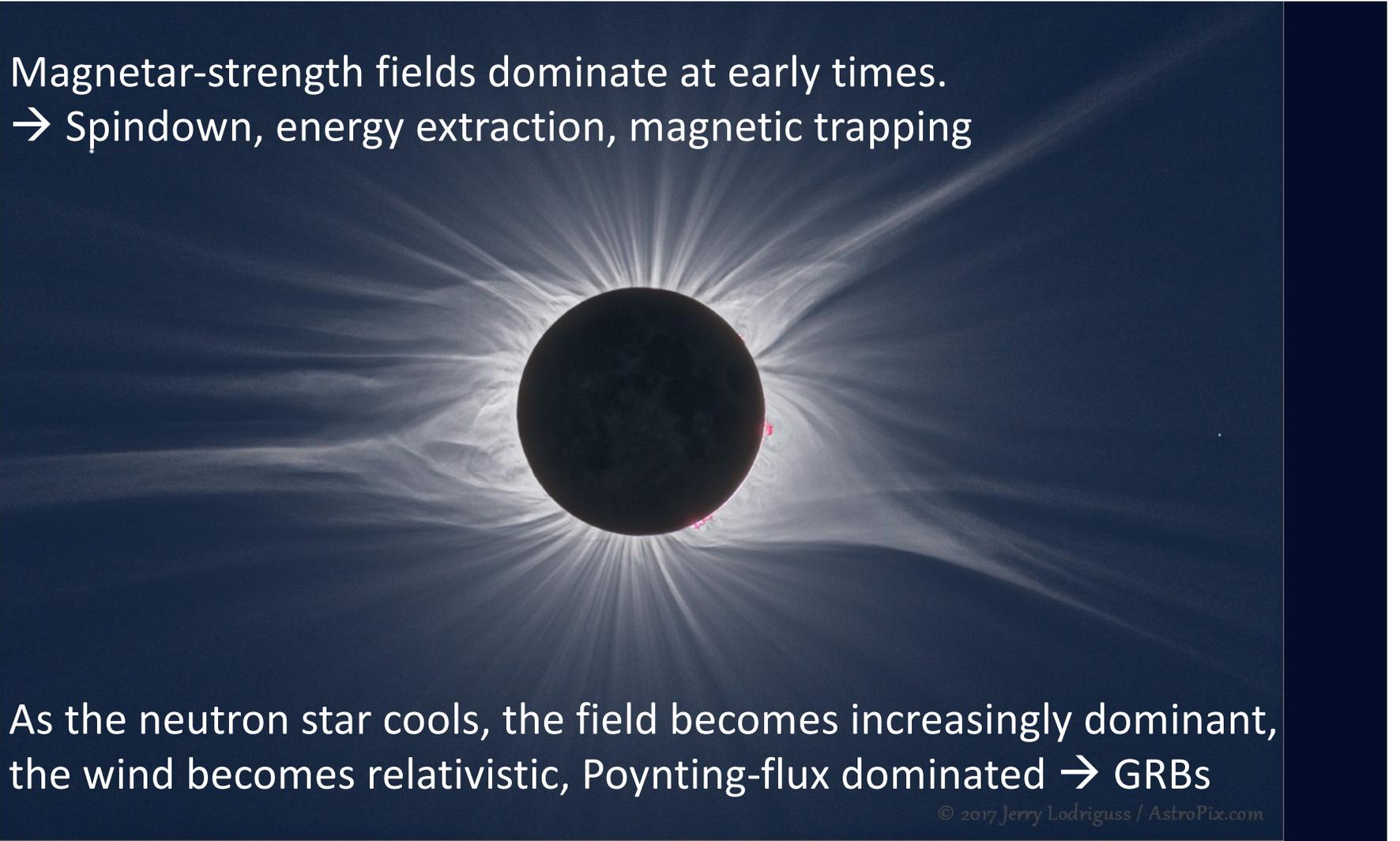
Magnetic fields and Rotation?

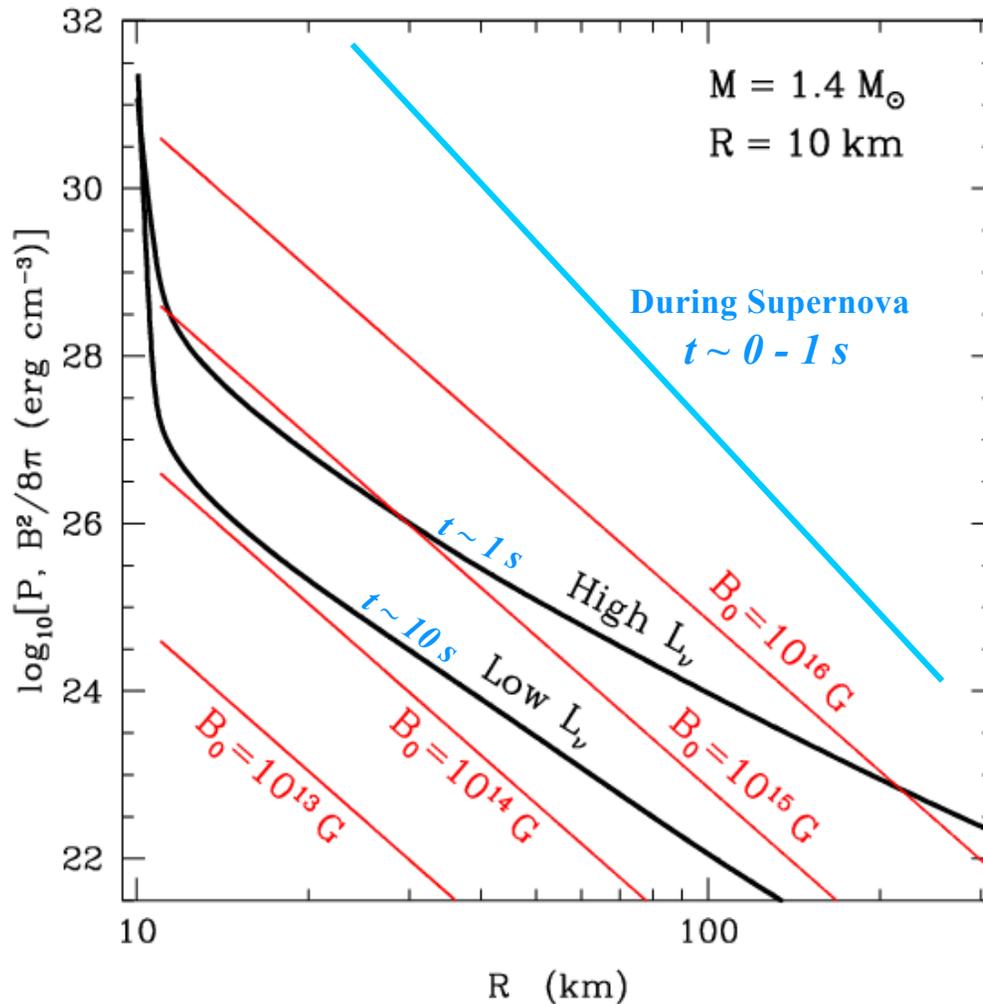


Magnetar-strength fields dominate at early times.
→ Spindown, energy extraction, magnetic trapping

As the neutron star cools, the field becomes increasingly dominant,
the wind becomes relativistic, Poynting-flux dominated → GRBs

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Magnetic Field

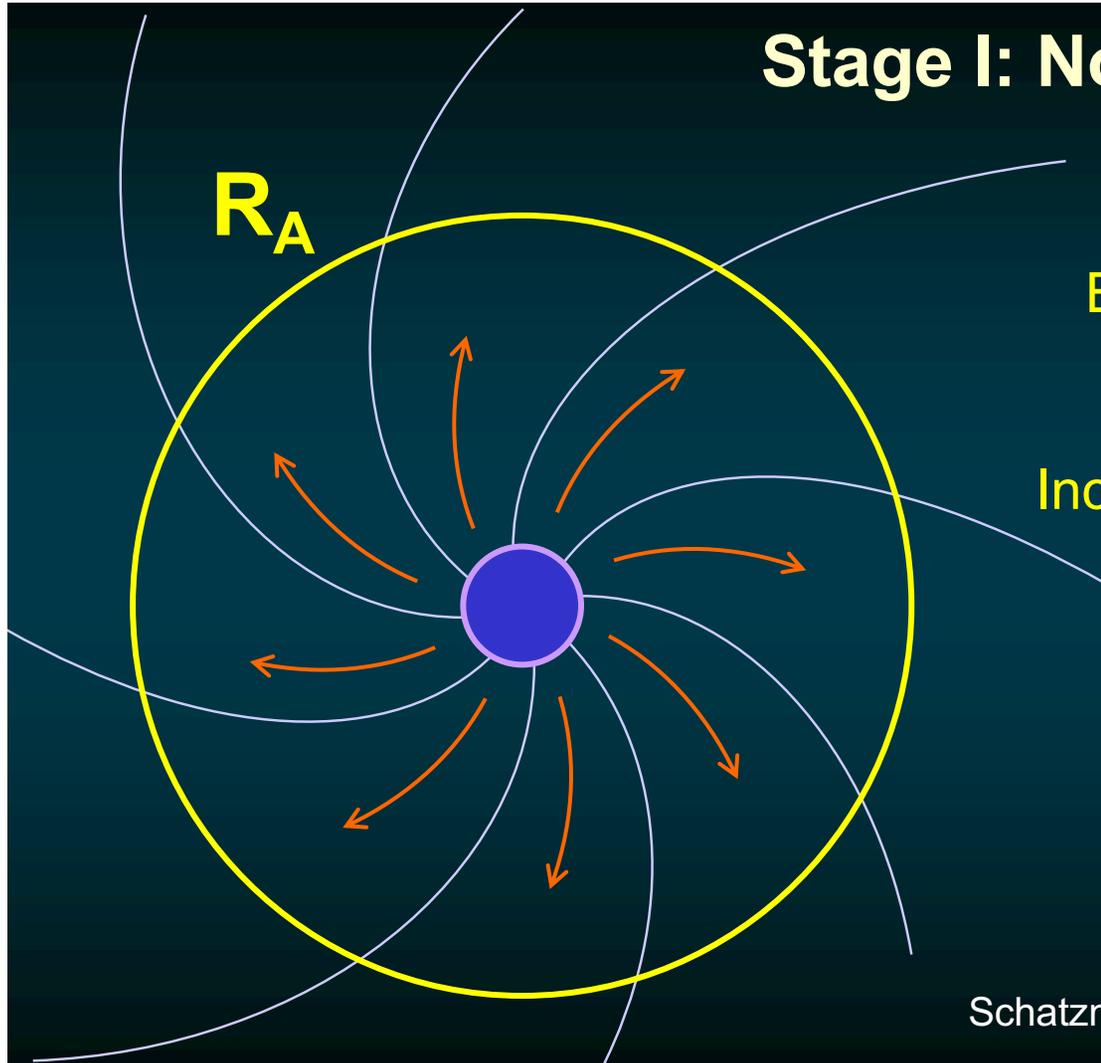
Magnetar-strength fields dominate wind/cooling epoch.

Become increasingly important with time as NS cools.

How does this combine with rotation?

Thompson (1994), Thompson (2003),
Thompson et al. (2004)

Stage I: Non-relativistic Magneto-Centrifugal Wind



B-field forces wind to corotate to Alfvén point R_A .

Increases V_∞ and J & E loss rates. Efficient spindown. Energy is extracted from rotation.

R_A increases as $L_v(t)$ decrease in time.

Schatzman 1959,1962; Weber & Davis 1967

Stage II: Transition to relativistic Magneto-Centrifugal Wind

$R_L = c/\Omega$ bounds R_A .
As $R_A \rightarrow R_L$, $V_\infty \rightarrow c$.

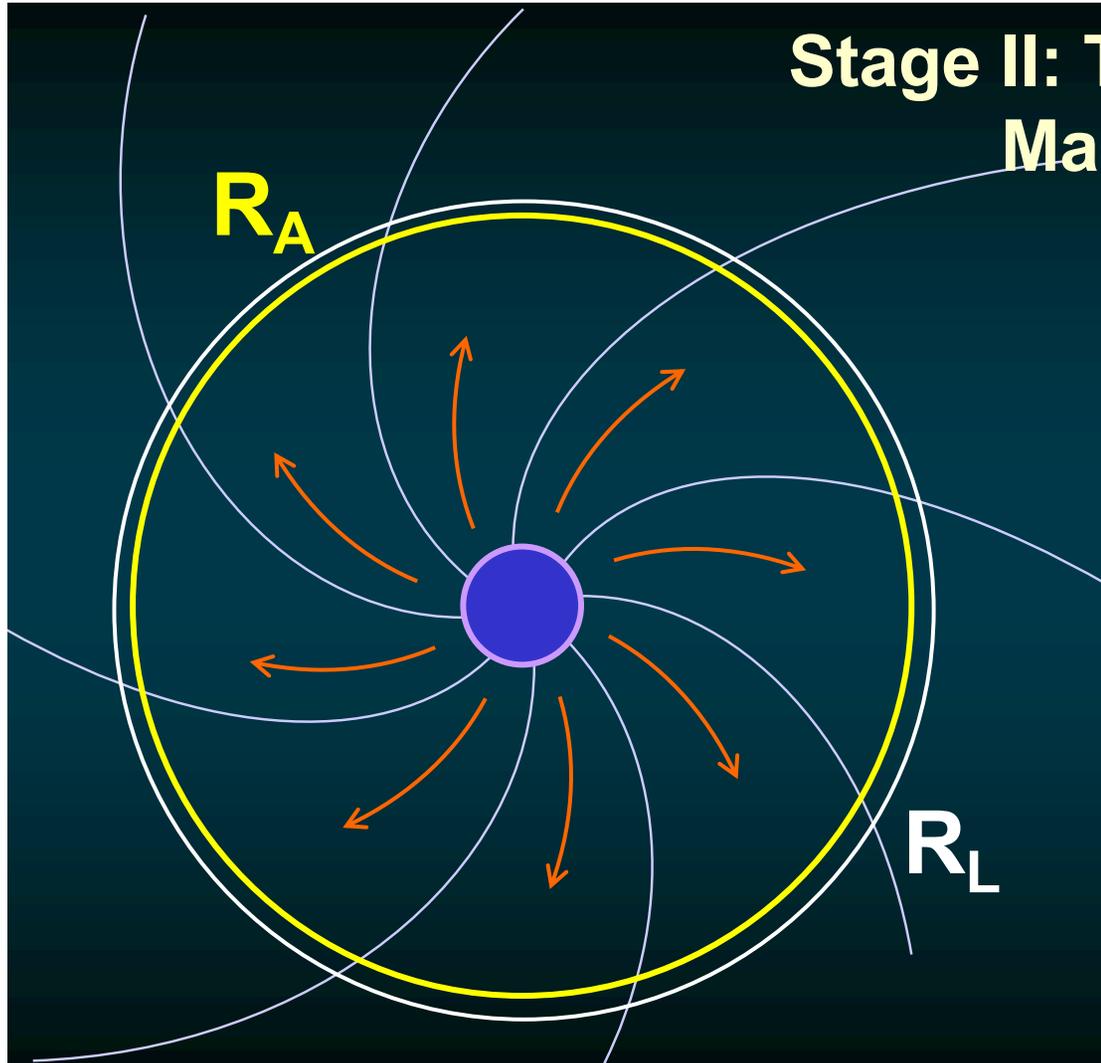
The flow becomes relativistic,
Poynting flux-dominated

$$\sigma(R_L) = B^2/(4\pi\rho c^2) > 1$$

$$\sigma(t) \propto \dot{M}(t)^{-1}$$

$$\dot{M} \sim 3 \times 10^{-7} L_{v,51}^{5/2} M_\odot \text{ s}^{-1}$$

$L_v(t)$ dictates evolution.



What we've done

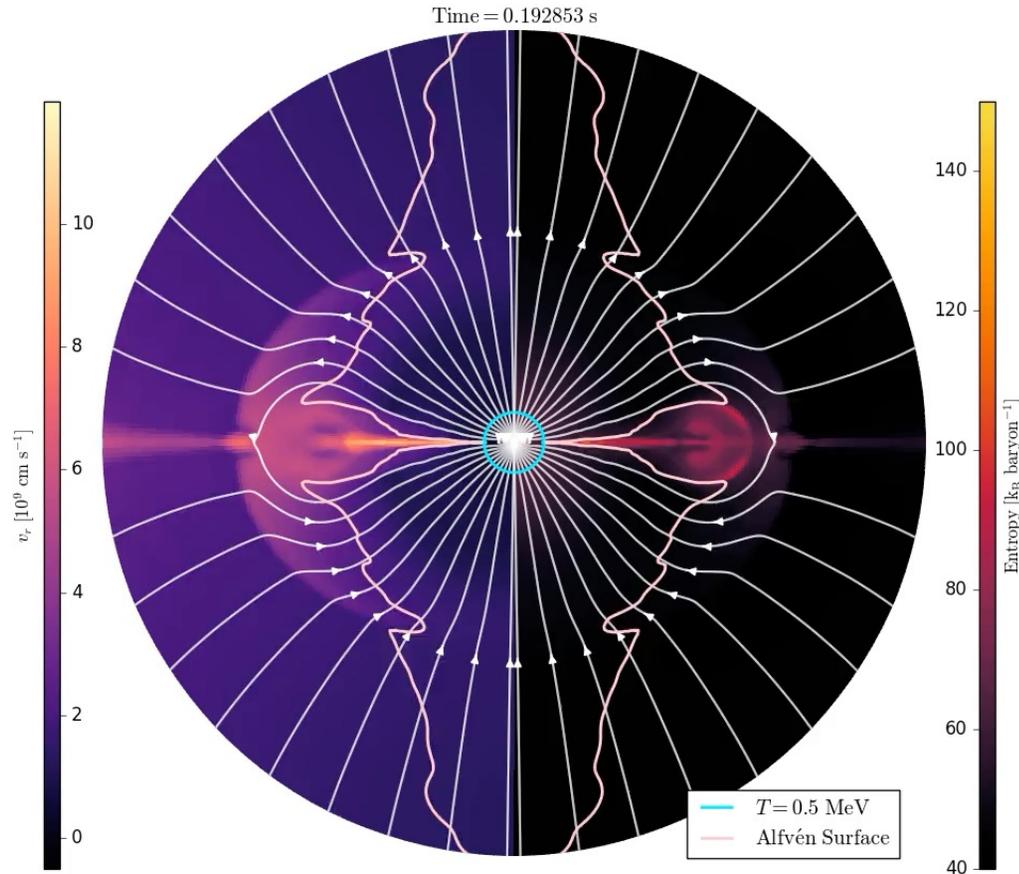
+ **1D equatorial NON-relativistic** neutrino-heated magneto-centrifugal wind from a proto-magnetar: spindown rate, mass loss rate, kinetic power (monopole field!). [Thompson+04](#); [Metzger+07](#), [08](#), [09](#), [11](#)

+ **2D axisymmetric relativistic MHD**, but NO microphysics [Bucciantini+06](#), [07](#), [08](#), [09](#), [12](#); or with FIXED field geometry [Vlasov+17](#), [18](#)

+ **2D axisymmetric NON-relativistic MHD** with neutrino heating/cooling and general EOS [Thompson & ud-Doula 18](#)

→ [Prasanna+22](#), [23](#), [24](#), [25](#)

Prasanna, Coleman et al. 22, 23, 24, 25



$P = 200$ ms, $B = 3 \times 10^{15}$ G, high L

Athena++ Non-Rel. MHD, general EOS, neutrino heating & cooling.

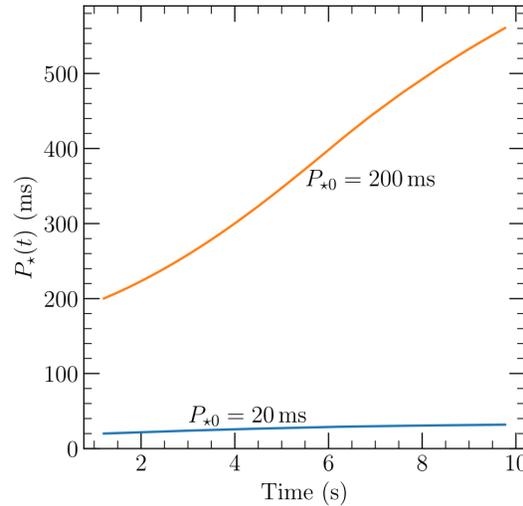
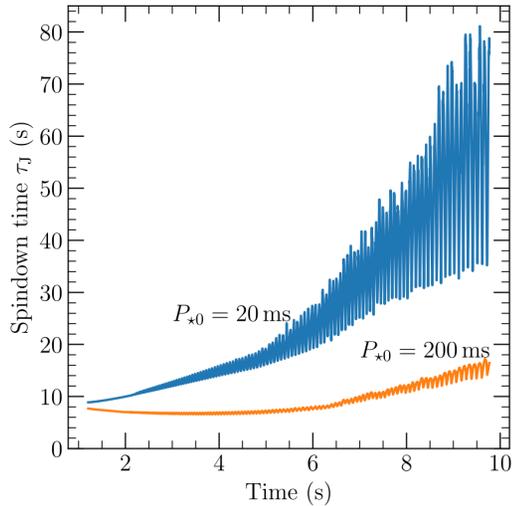
Large suite of simulations
 $P = 1.5 - 500$ ms. $B = 0 - 10^{16}$ G.

$R_A \gg R_{NS}$

High power for “fast” rotators with
 $P \sim 1.5 - 10$ ms.
 $\dot{E} \sim 10^{49} - 10^{51}$ ergs/s.
SLSN and GRBs.

Rapid spindown for “slow” rotators
with $P \sim 100 - 500$ ms.

$t_{\text{spindown}} < t_{\text{cool}}$

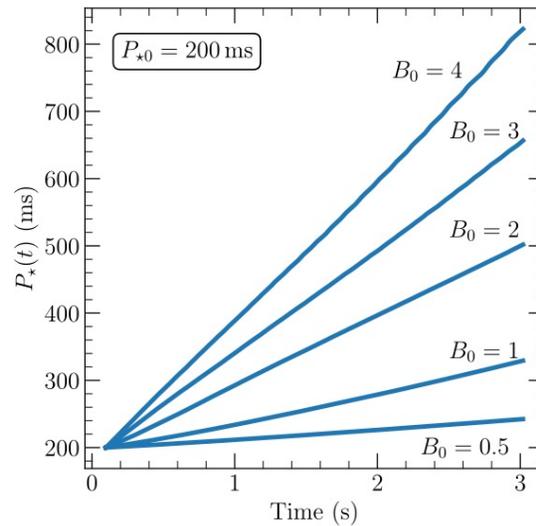
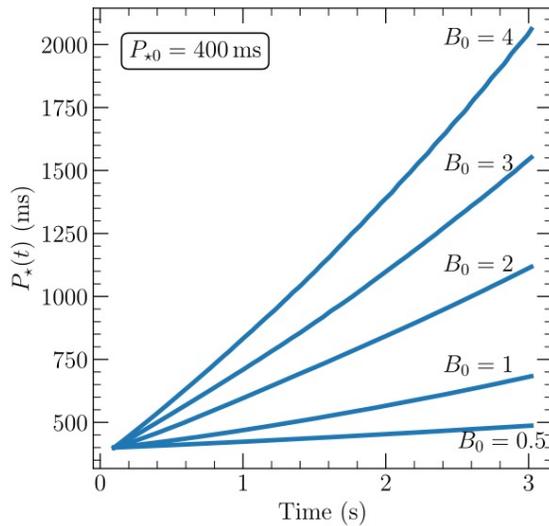


Rapid spindown for “slow” rotators with $P \sim 100 - 500$ ms

$$R_A \gg R_{NS}$$

$$t_{\text{spindown}} < t_{\text{cool}}$$

A magnetar could spin down significantly in just a few s!



(Stopped as $V_A \rightarrow c$. We need long-term relativistic simulations.)



Observational evidence for early spindown?

SNR Kes 73 hosts a magnetar
 $P \simeq 11.8$ s, $B_0 \simeq 7 \times 10^{14}$ G

The “dipole spindown” age is

$$P/2\dot{P} \sim 4.7 \text{ kyr}$$

But, the SNR age is 0.5 – 1 kyr.

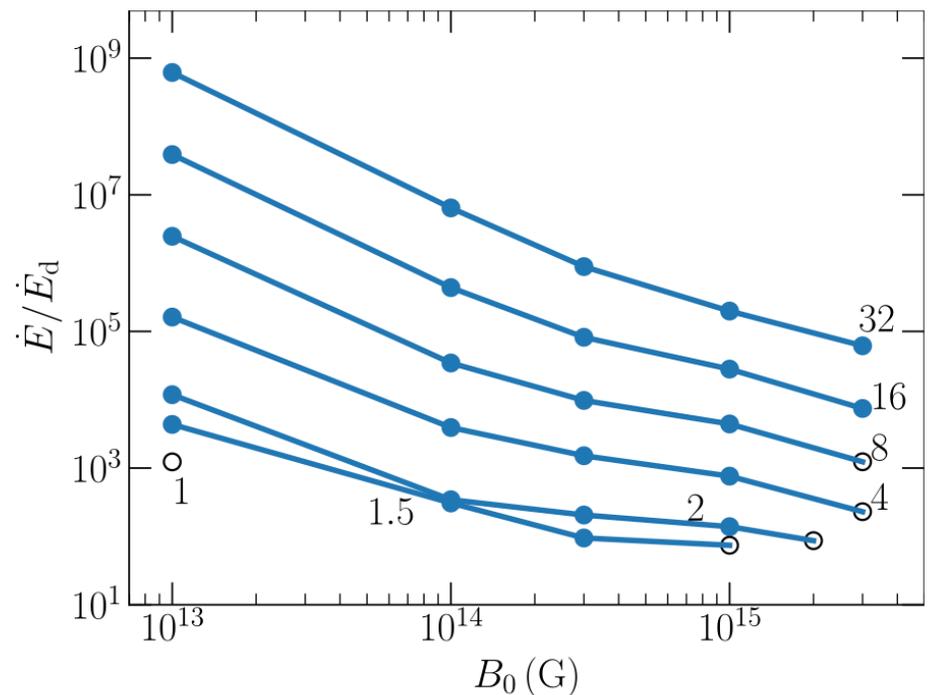
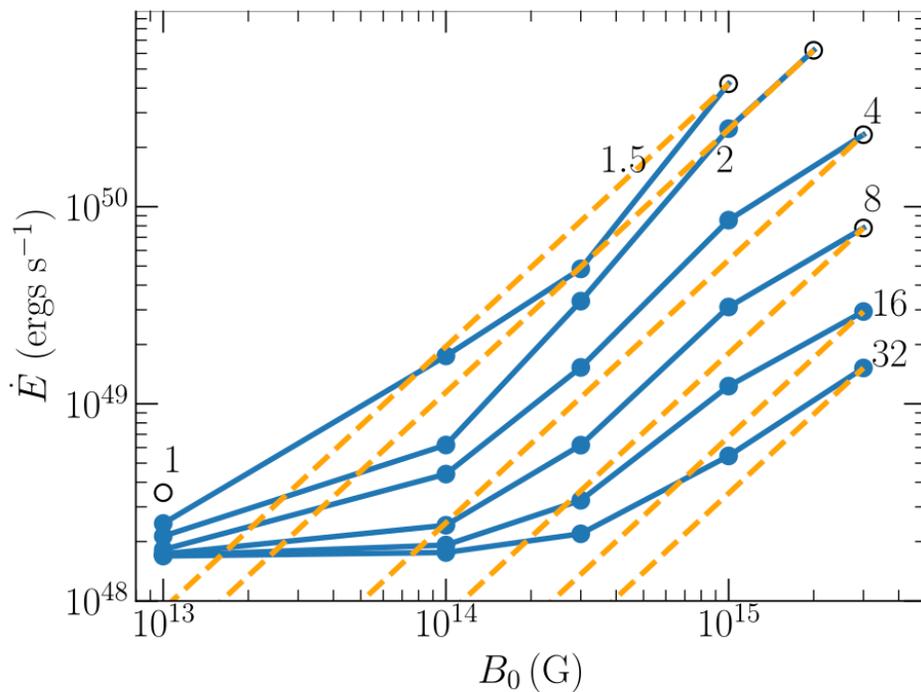
If **only** dipole spindown, initial
required $P_0 \sim 10.5 - 11.2$ s.

Implication: Maybe rapid spindown
at early times.

GRBs & SLSNe : proto-magnetars remain a viable central engine

\dot{E} versus B_0 for $P_0 = 1.5 - 32$ ms

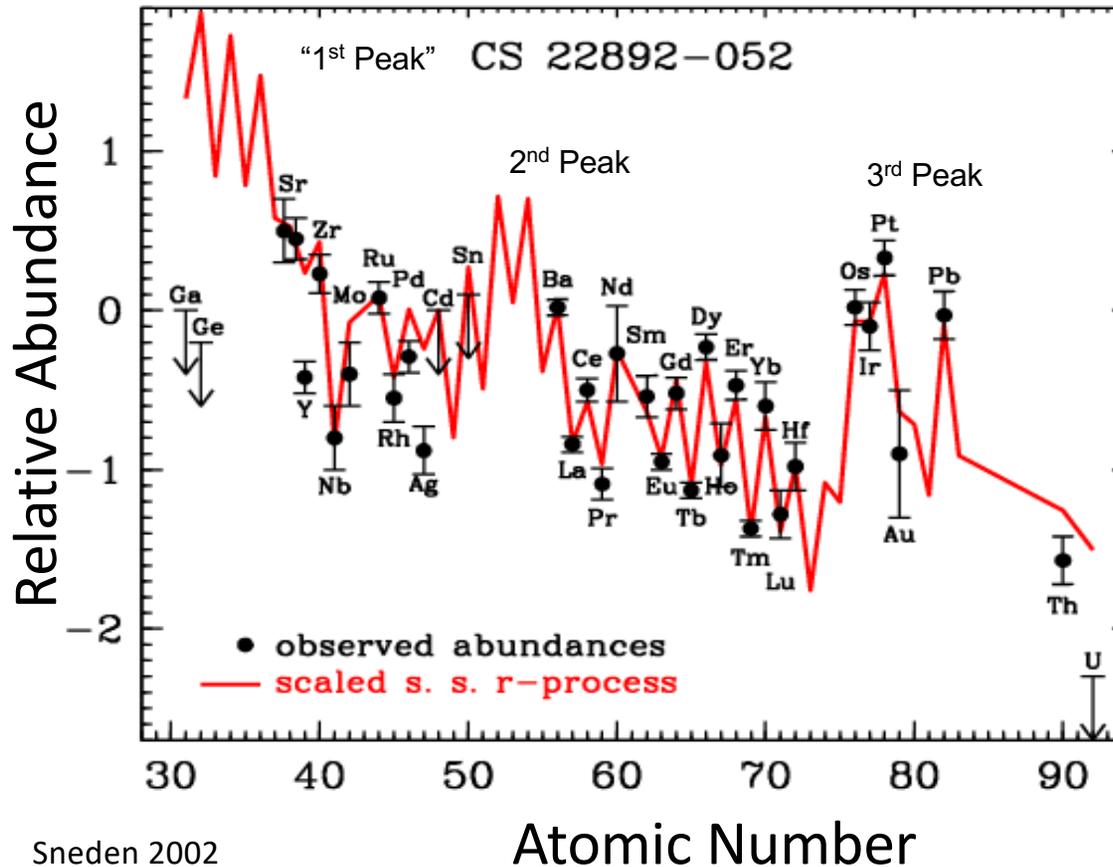
$\dot{E}/\dot{E}_{\text{dipole}} \sim 10^2 - 10^9$ at early times



Many experts in the field here. Power, timescale, etc. seem consistent with observations for some GRB subsets.

II. Proto-Magnetar Nucleosynthesis

A Remarkable Concordance



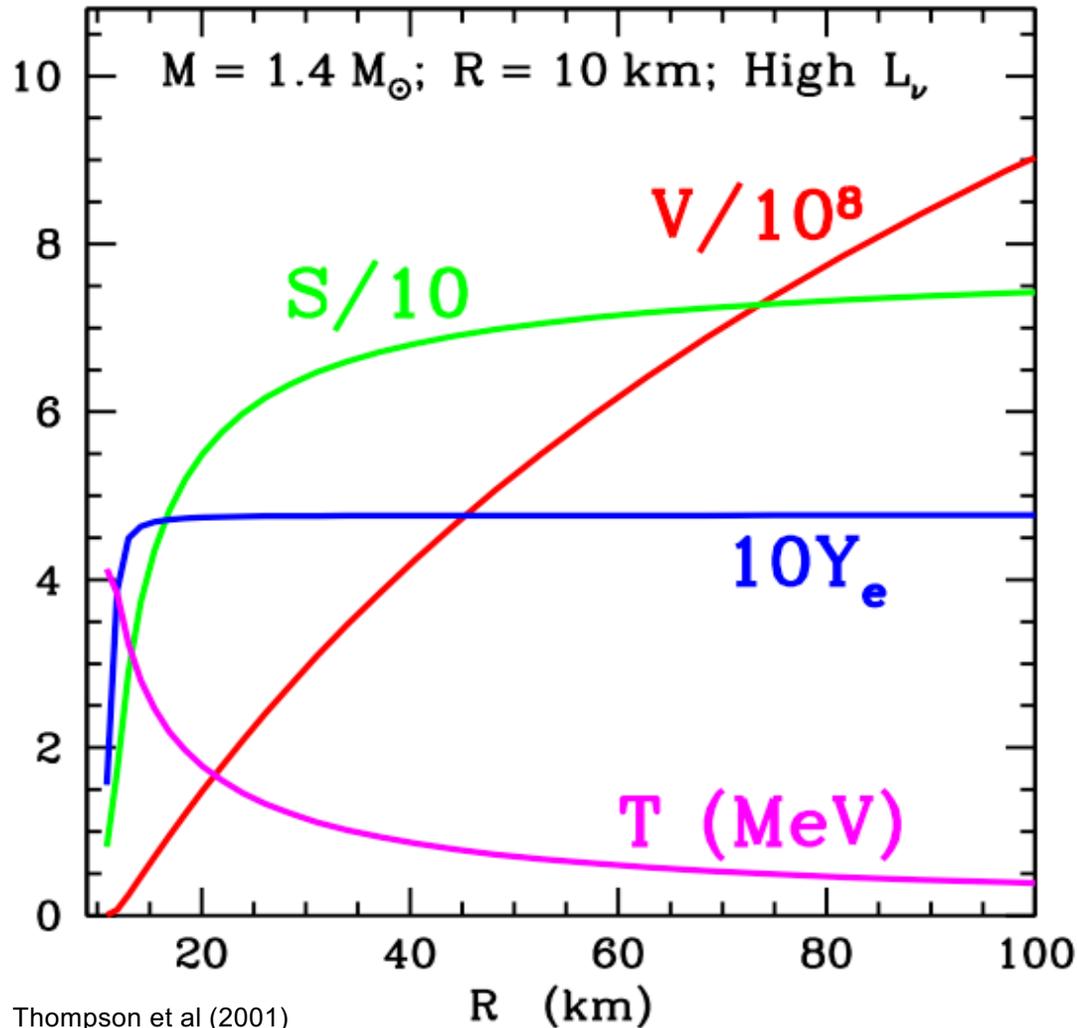
Snedden 2002

Ultra metal-poor halo stars exhibit Solar relative r-process abundances

Suggests a “universal” r-process site.

→ NS-NS mergers:
GW 170817

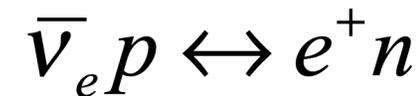
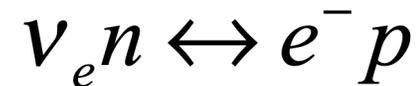
What about proto-NS winds? Could the conditions be right?



$$V_{\infty} \sim 0.1c$$

$S \sim 60$ & $Y_e \sim 0.5$ quickly asymptote.

$$L_{\nu_e} / L_{\bar{\nu}_e} \text{ sets } Y_e$$



α -process starts $T \sim 0.5 \text{ MeV}$

r-process starts $T \sim 0.1 \text{ MeV}$

Normal winds fail.

r -process abundances determined by the neutron/seed ratio after the α -process at ~ 0.5 MeV.

Rate limiting α -process reaction (Hoffman+97)



Derive single figure of merit for 3rd peak:

$$\zeta_{\text{crit}} \sim S^3 / (t_{\text{dyn}} Y_e^3) \sim 8 \times 10^9 (k_B / \text{baryon})^3 \text{s}^{-1}$$

S is too low, t_{dyn} too long, Y_e is too high, or some combination.

→ Only produce 1st peak at \sim Sr, Y, Zr. No lanthanides, actinides.

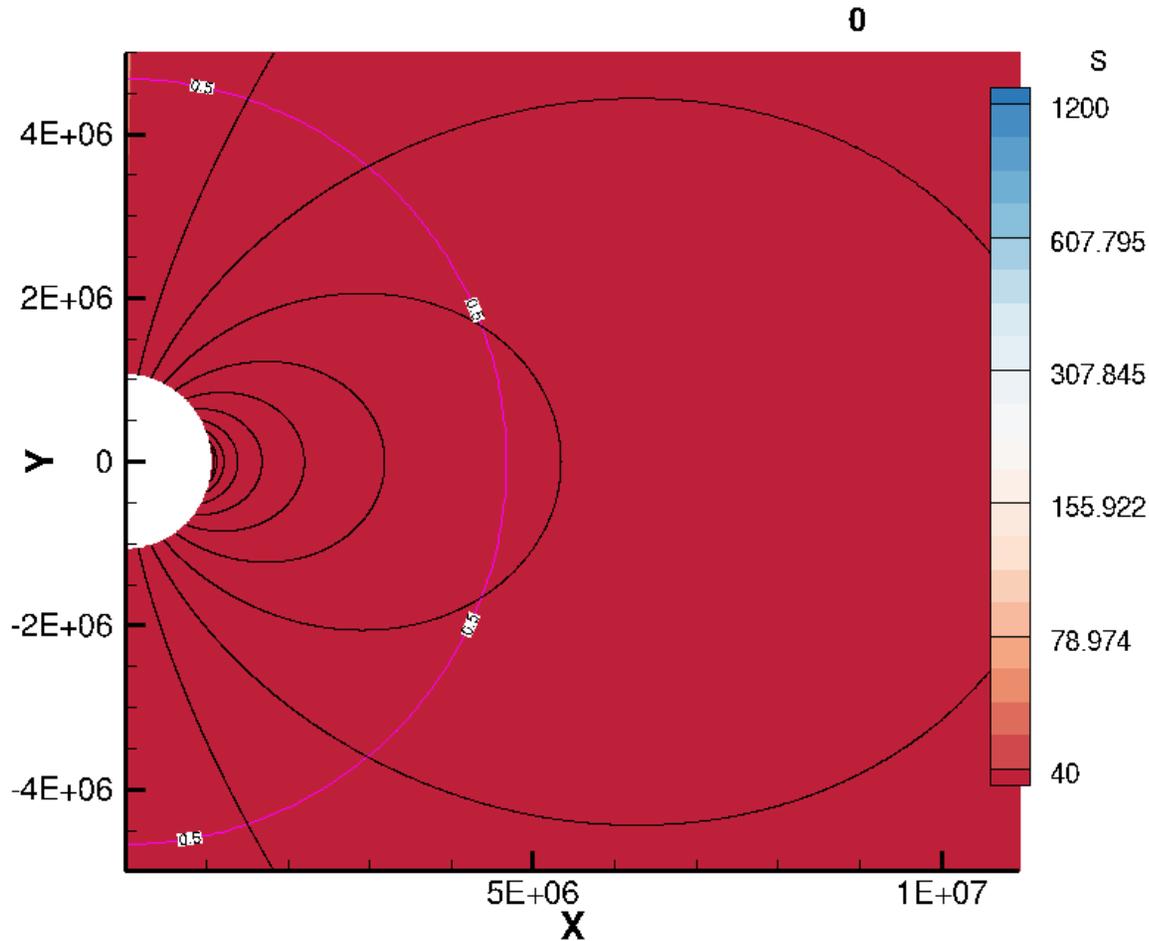
What about magnetar-strength magnetic fields?



Change nucleosynthesis?

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Thompson & Ud-Doula, 2018



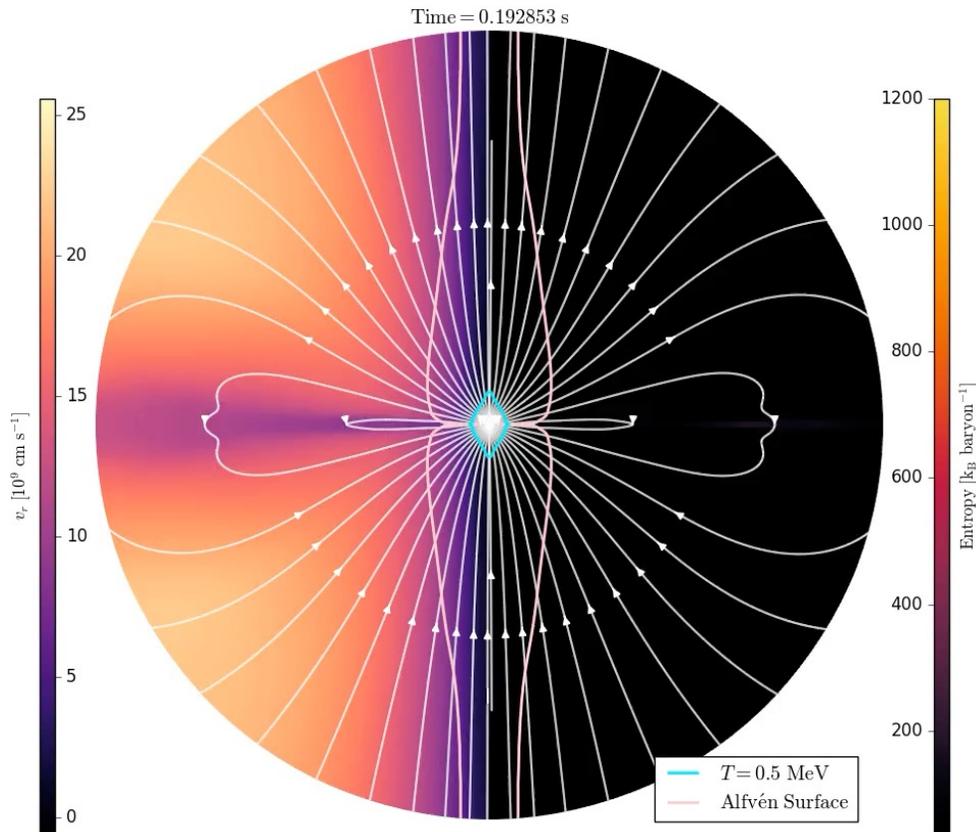
Episodic mass loss on
~100ms timescale.

Agrees with analytic theory.

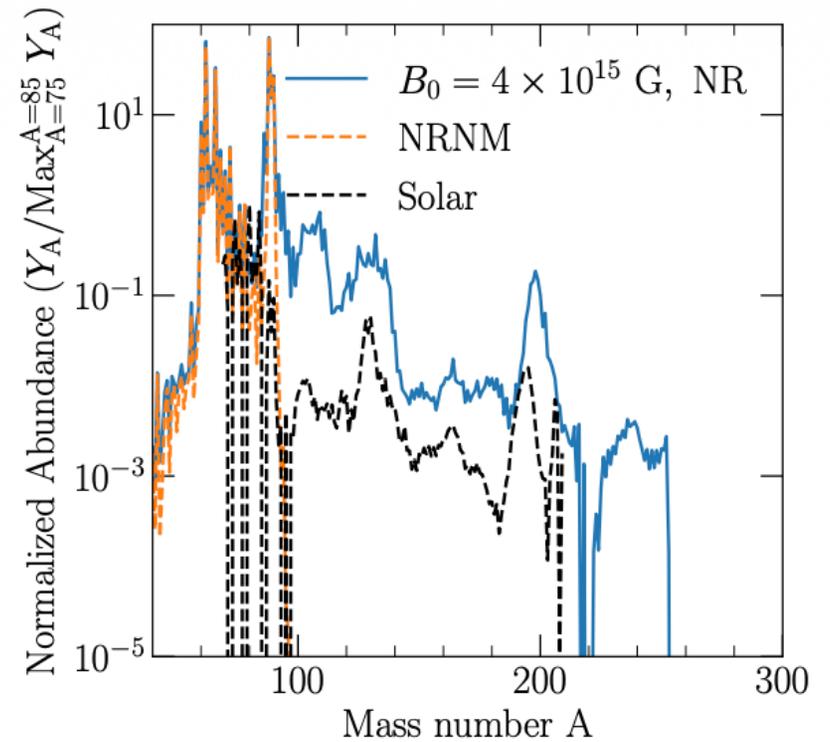
High-latitude wind produces
normal non-magnetized
conditions.

Plasmoids are unique high-
S environment.

Prasanna et al. 25



Nucleosynthesis now calculated directly with Lagrangian tracers.



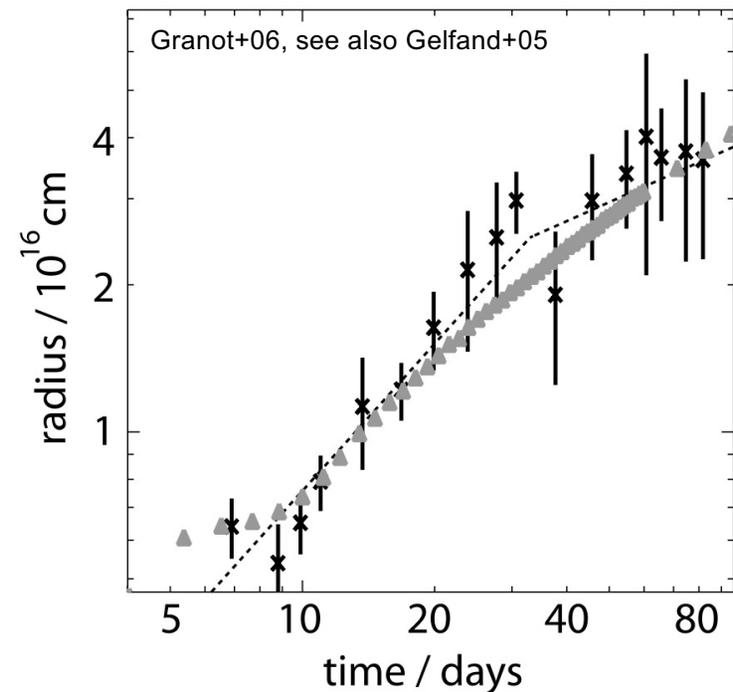
**III: Baryon Ejection in Giant Magnetar Flares,
the *r*-Process, and late-time gamma-ray
emission from SGR 1806**

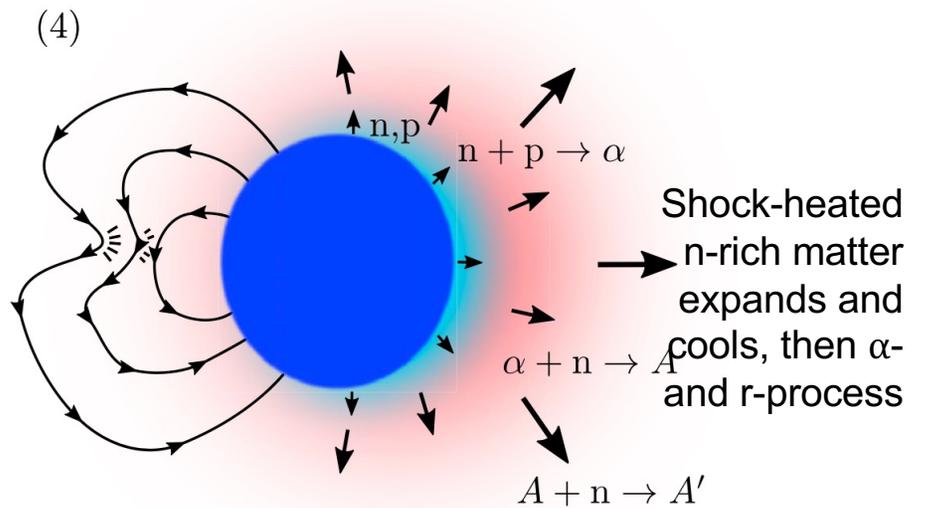
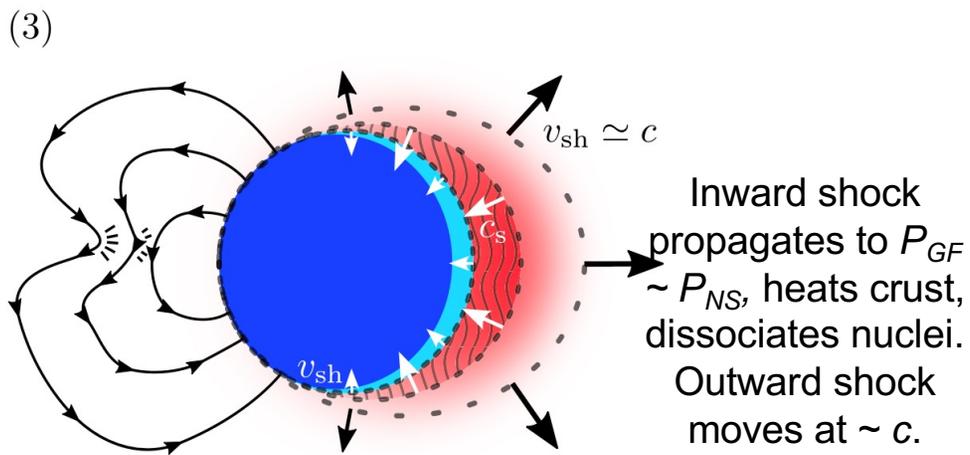
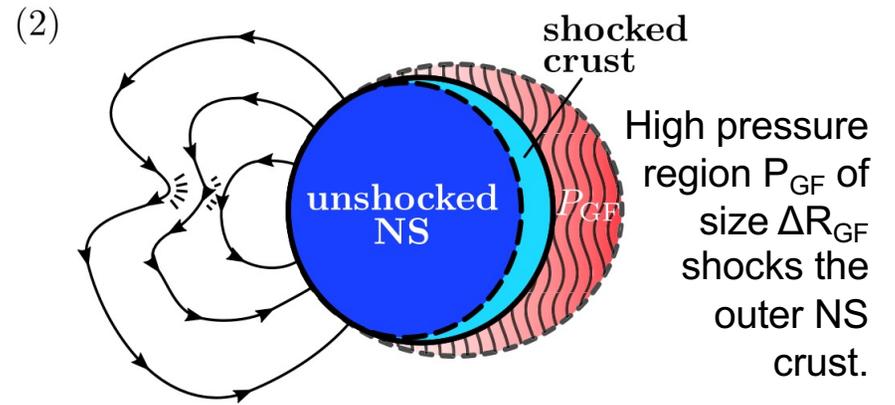
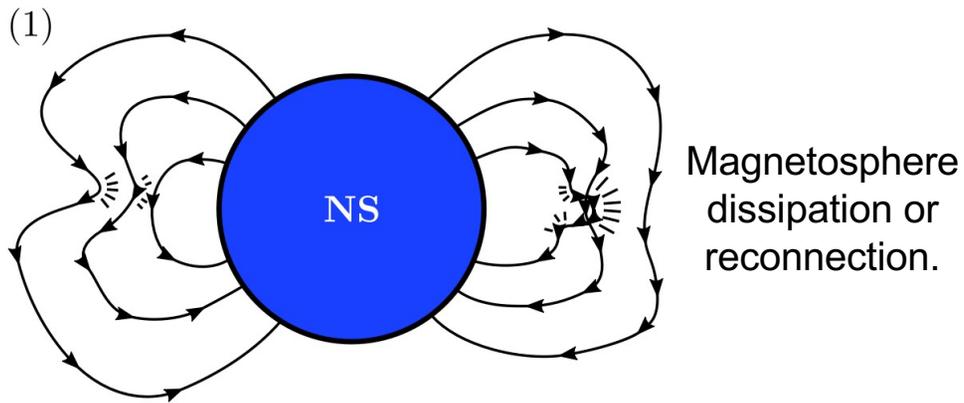
III: Baryon Ejection in Giant Magnetar Flares

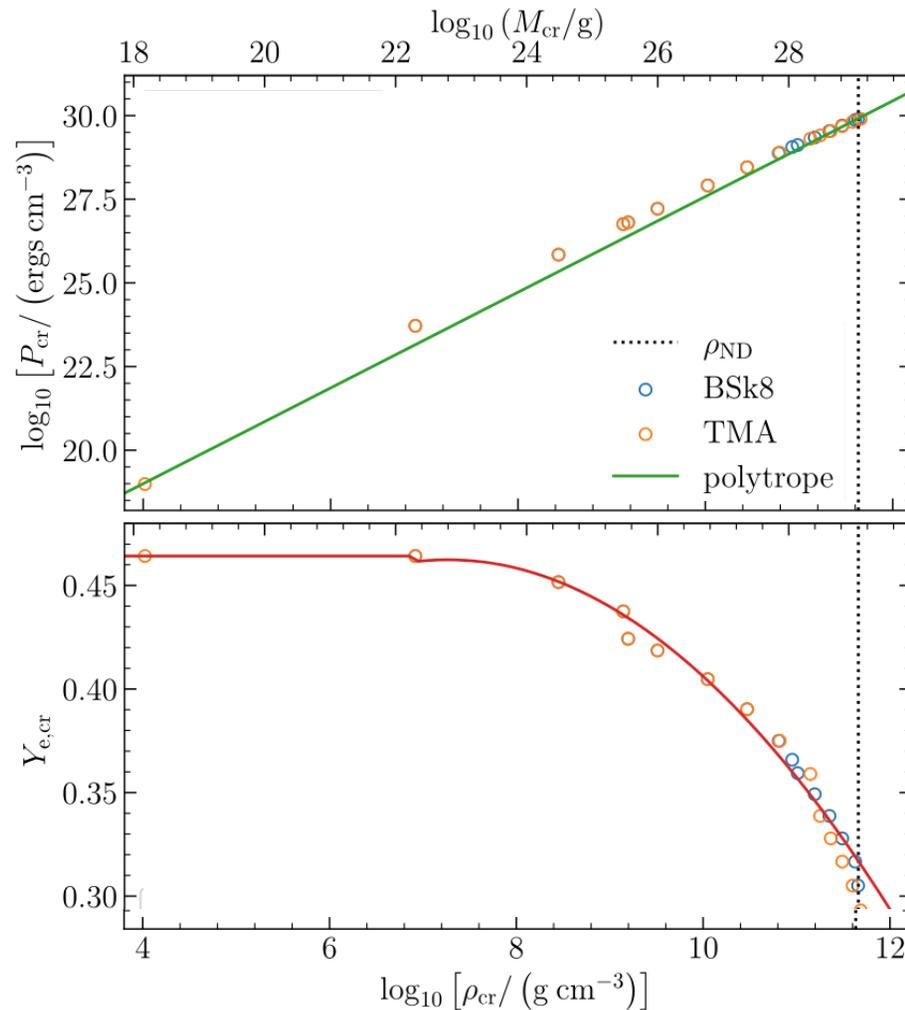
- Magnetars exhibit a spectrum of flares.
- Energy ranges over $E_{GF} \sim 10^{44} - 10^{47}$ ergs.
- Most spectacular is the December 27, 2004, flare of SGR 1806-20.
(Palmer+, Hurley+, Gaensler+, Gelfand+, Taylor+05)
- Granot+06 use the radio emission (source size, brightness, motion) to deduce $10^{24.5} - 10^{26}$ g of ejecta moving at $\sim 0.2 - 0.7c$.
One-sided asymmetric ejection.

→ **How to eject this mass NS material?**

(Cehula, Thompson, Metzger 2024)







Pressure & composition of a NS as a function of depth.

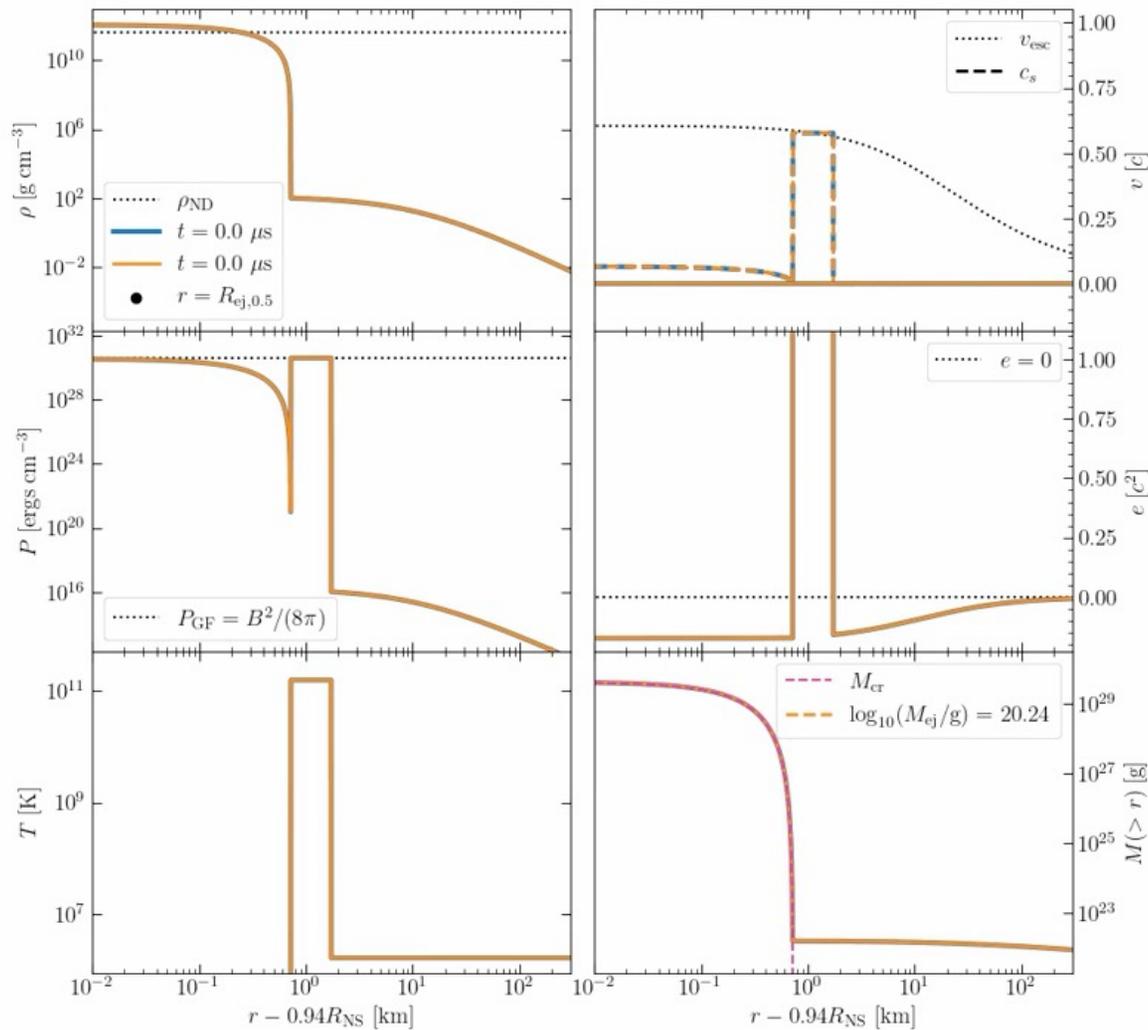
Pressure of the SGR 1806 flare:

$$P_{GF} \sim E_{GF}/V \sim 10^{27} - 10^{29} \text{ ergs/cm}^3.$$

→ Corresponding Mass: $\sim 10^{27} \text{ g}$
 → Electron Fraction: ~ 0.375
 → ~ 100 meters.

But, shock becomes weak as it goes up the pressure gradient.

Rapid rarefaction as outward shock expands relieves inward pressure.



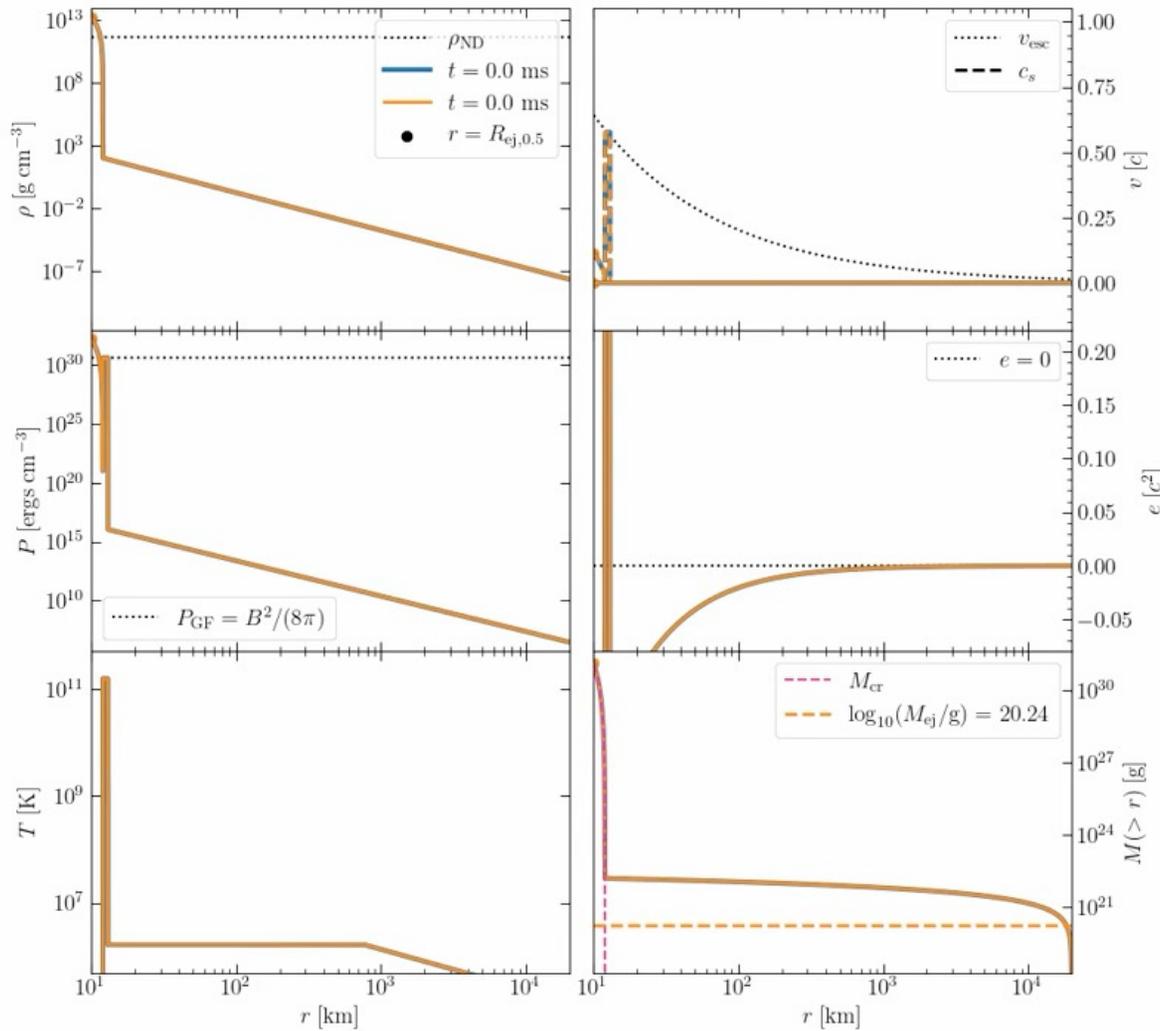
1D PLUTO Simulations:
relativistic hydrodynamics,
polytropic EOS (4/3), no
heating/cooling. Not MHD.

Hot high-P shell at $t = 0$.

Shocks expand outwards
and inwards.

Inward propagating shock
moves up density gradient
and reflects.

Shock-heated crust
expands.



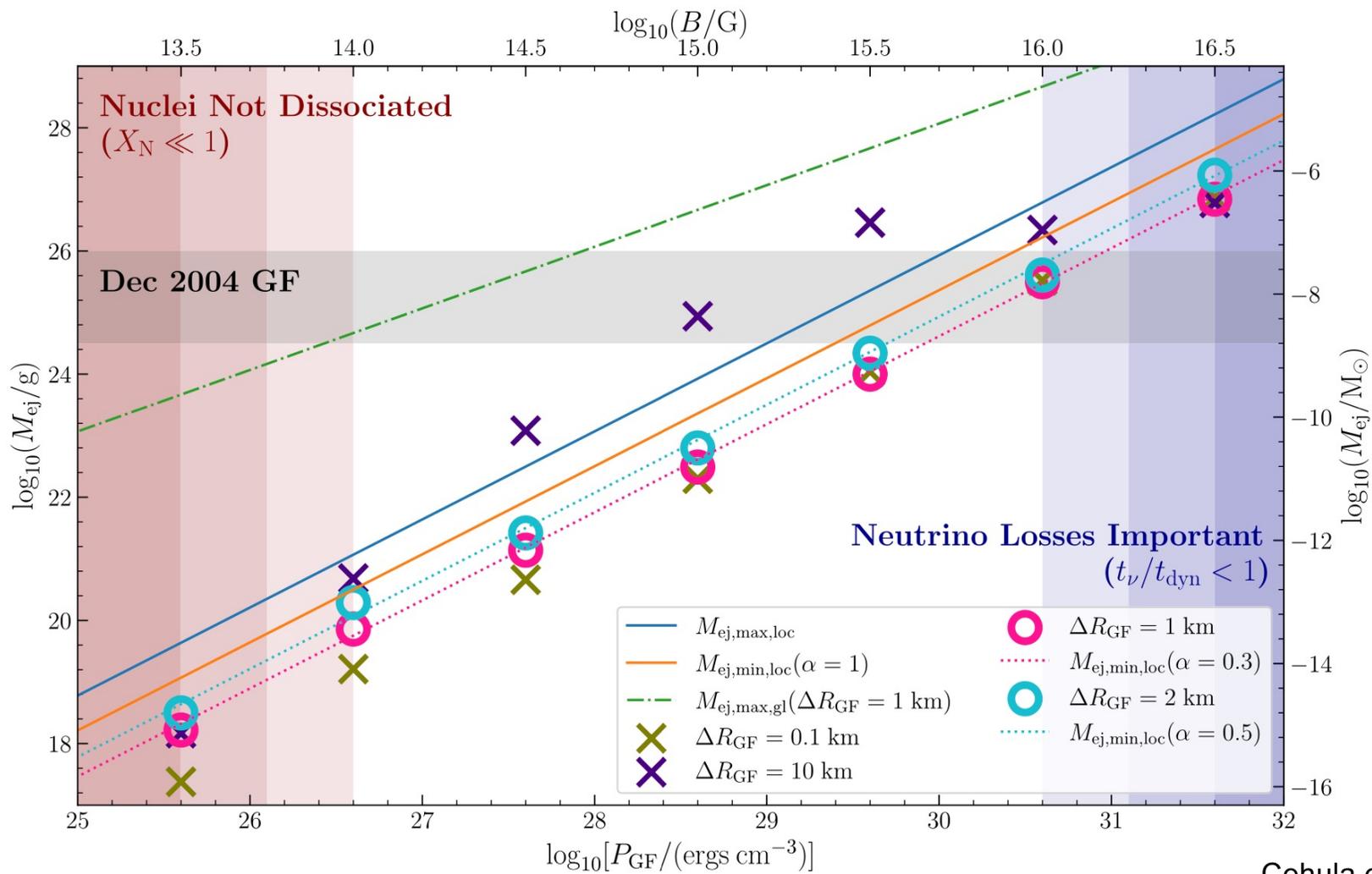
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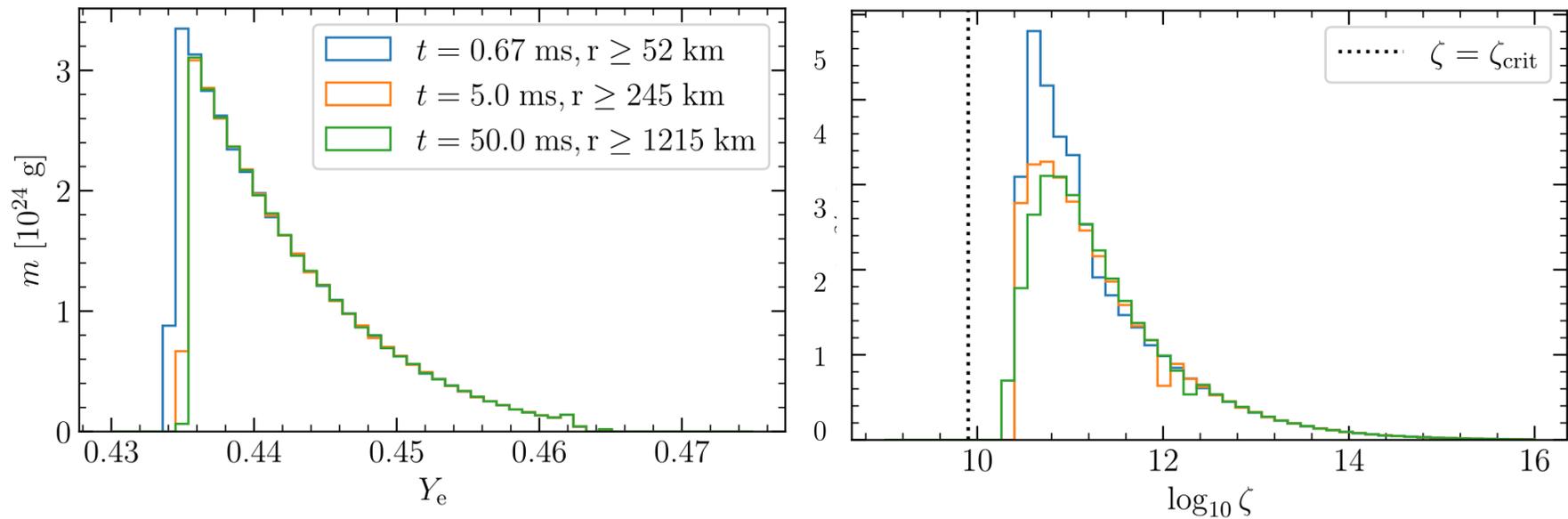
Shock-heated crust
 expands.



Implications: Cehula+24

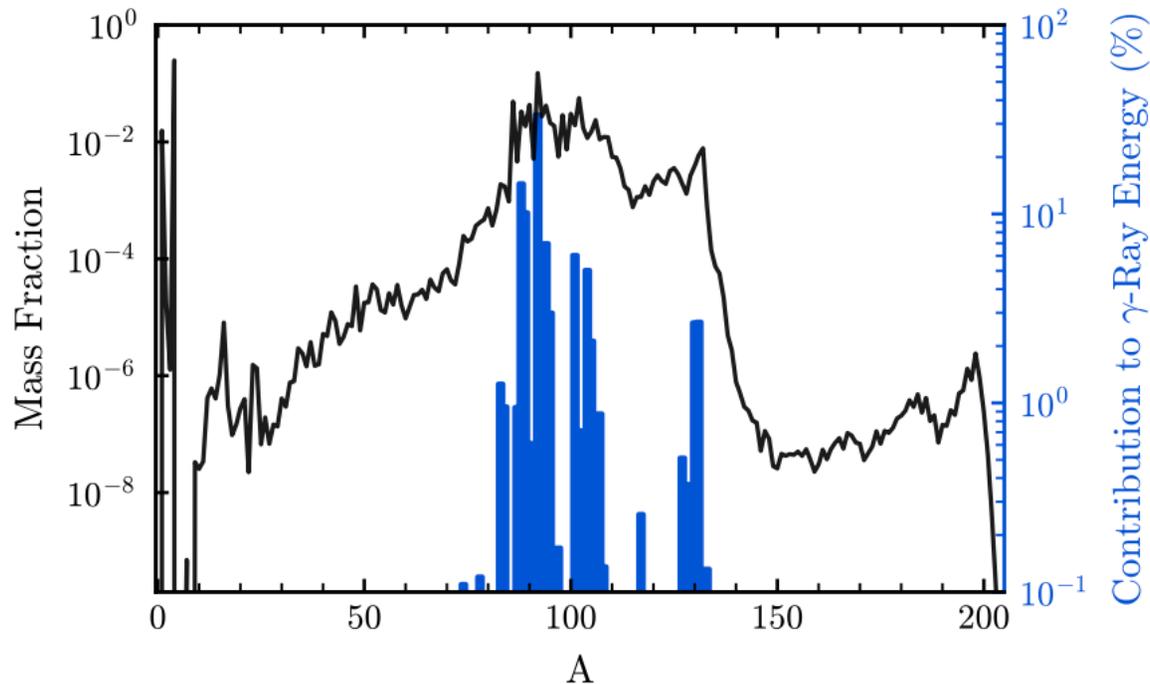
Super-heated neutron-rich crustal material expands at $0.1 - 0.8c$ with very high entropy and relatively low Y_e .

Material reaches thermodynamic conditions required for successful r-process.



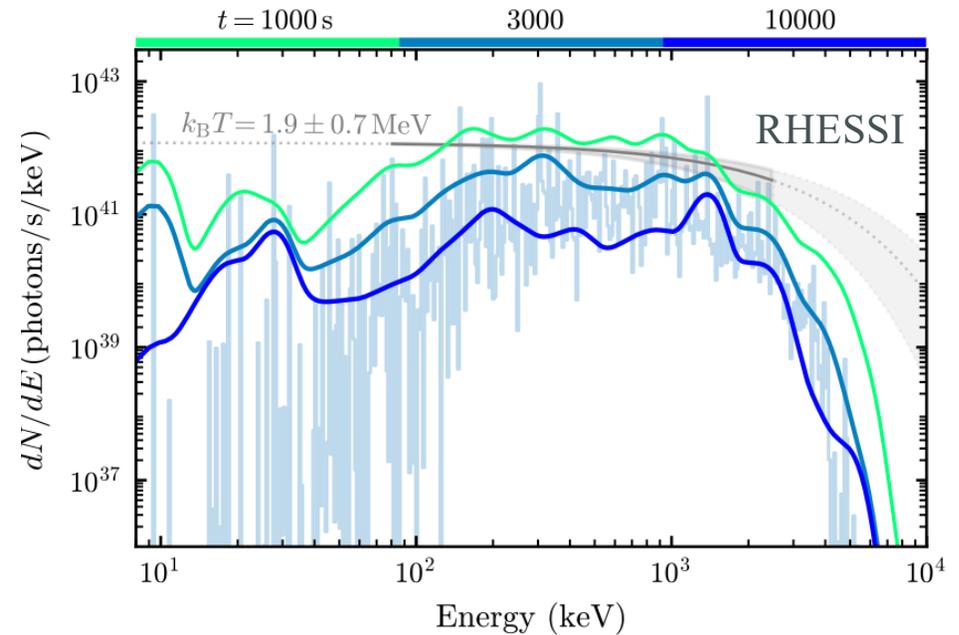
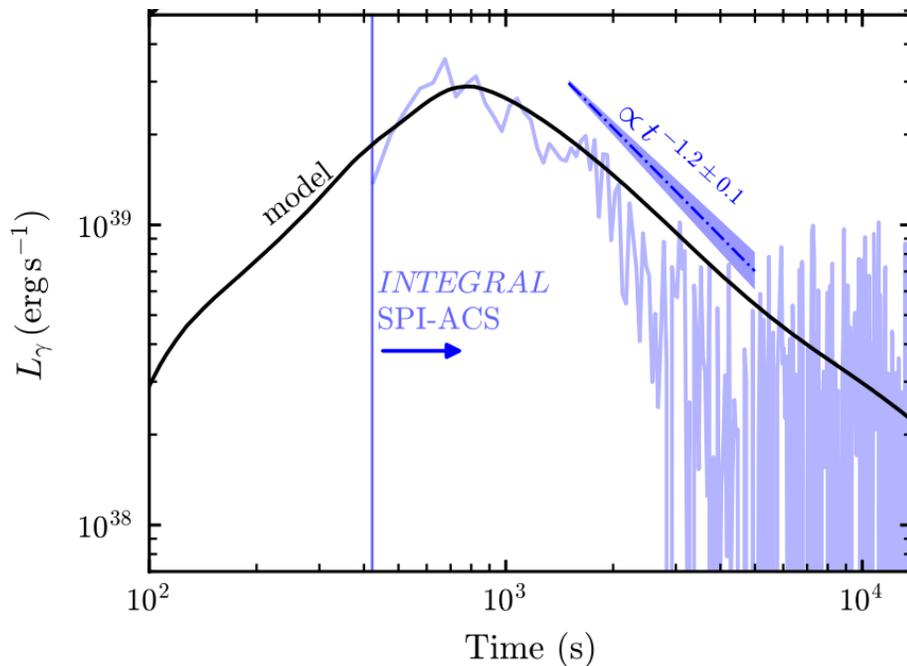
Magnetar flare ejecta nucleosynthesis. Patel+25ab

Direct nucleosynthesis calculations show that the material in fact undergoes alpha-rich freezeout and r-process. Note gamma-ray production rate.



Direct evidence of r-process from SGR1806. Patel+25ab

$\sim 10^{-6} M_{\text{sun}}$ of ejecta becomes optically-thin and produces gamma-ray transient that matches observations of SGR 1806 late-time gamma-ray emission!



Lines of Kr, Rb, Sr, Y, Zr, Mo, Tc, Sn

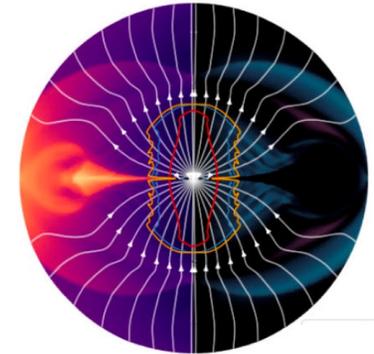
I. Proto-magnetars can spin down rapidly. [Prasanna+22,23](#)

Magneto-centrifugal wind: $R_A \gg R_{NS}$

Normal magnetars: potentially very rapid spindown.

GRBs: $P < 2\text{ms}$, $B > 10^{15}\text{ G}$, relativistic flow, jets, spindown.

→ Need Relativistic MHD! ([See Desai+2026 and others!](#))

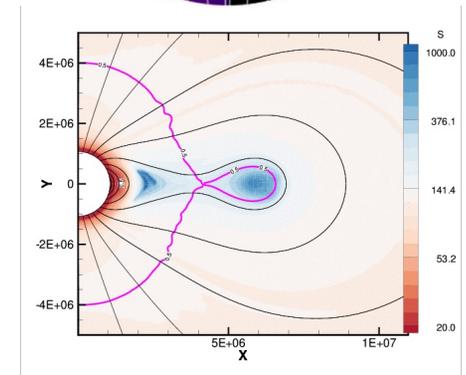


II. Proto-magnetars can produce heavy nuclei. [Prasanna+24,25](#)

If $Ye < 0.5$, generically, only 1st peak (Sr, Y, Zr).

3rd peak in plasmoids.

If $Ye \sim 0.5$, high S will yield Mo, Pd via p-process



III. Magnetar flares eject baryons. [Cehula+24](#), [Patel+25ab](#)

Velocity, mass, and energy produced by 10^{48}erg event.

→ Unique nucleosynthetic signatures.

→ Gamma-rays from r-process predicted and match late-time emission from SGR 1806 flare.

