UNIVERSITY OF TARTU
Tartu Observatory

BARYON-LOADED OUTFLOWS AND R-PROCESS NUCLEOSYNTHESIS FROM MAGNETAR GIANT FLARES

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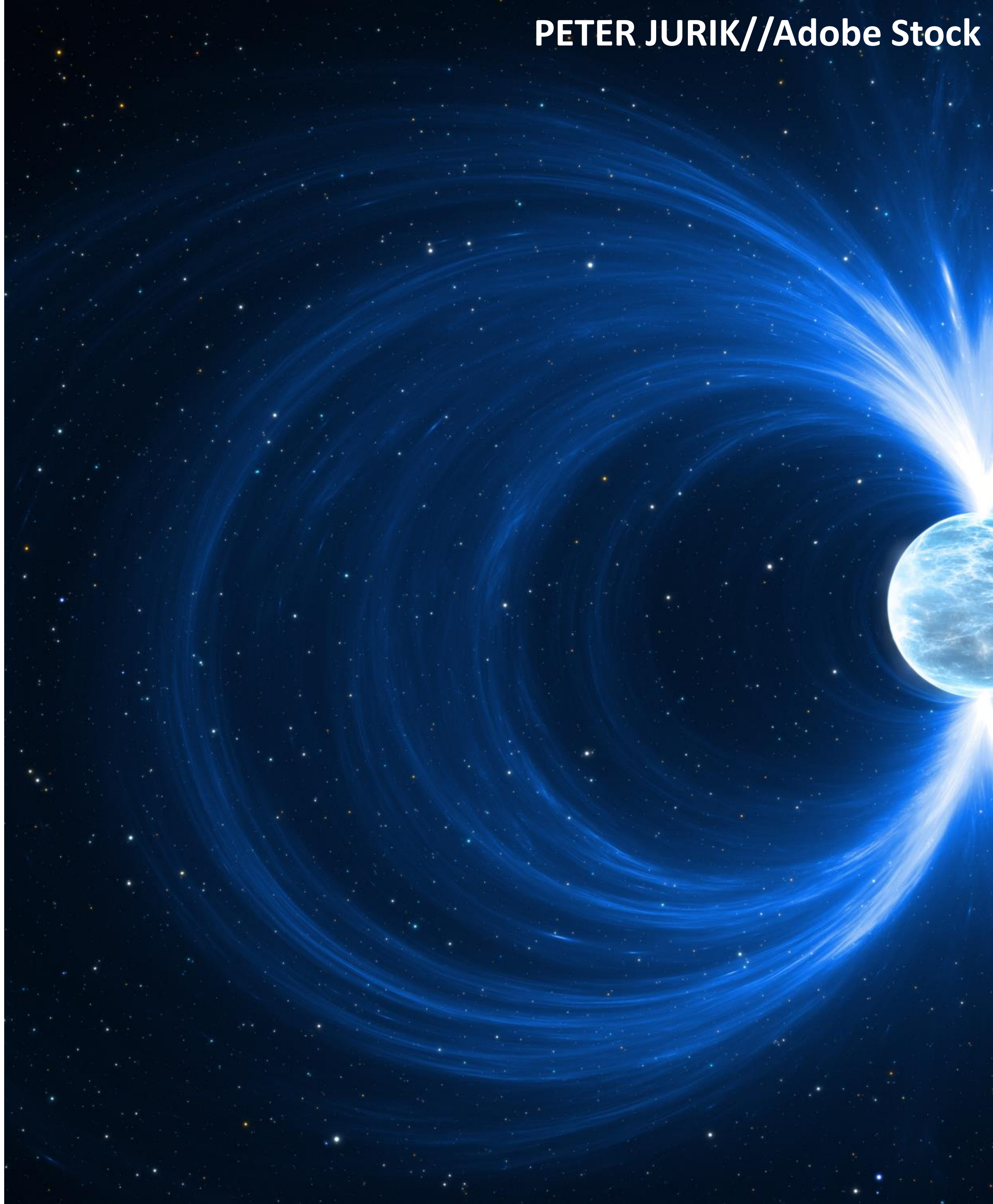
MAGNETAR GIANT FLARES

- magnetars:
  - neutron stars (NSs) with extremely strong magnetic fields ($B \gtrsim 10^{14}$ G; $\mathrm{B}_\odot \sim 1$ G)
  - produced in tens of per cent of CCSNe (Beniamini+2019)
- giant flares (GFs):
  - sub-second gamma-ray flashes
  - the most powerful non-cataclysmic NS outbursts ($L_{\mathrm{GF}} \in 10^{44} - 10^{47}\,\mathrm{erg/s}$; $\mathrm{L}_\odot \sim 4 \times 10^{33}$ erg/s)
  - galactic GFs: three in 50 years (Mazets+1979; Hurley+1999, 2005)
  - extragalactic GFs: 13 candidates in 20 years (Trigg+2025)
  - most notable GF: the **2004 GF from SGR 1806-20** (Hurley+2005)

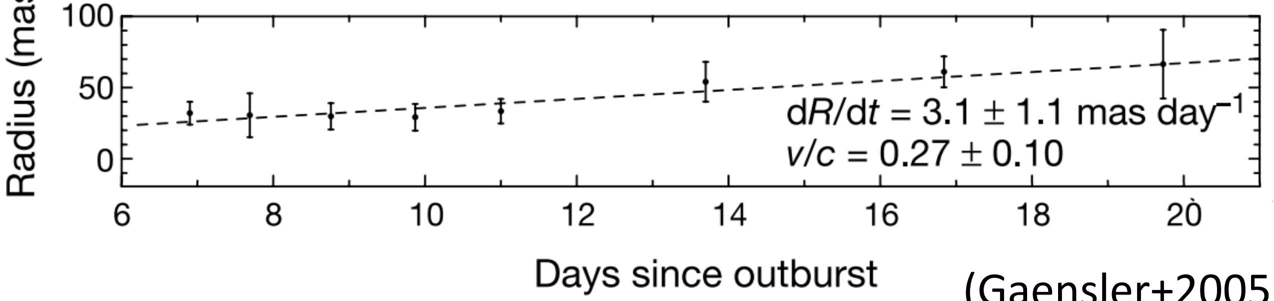


PETER JURIK//Adobe Stock

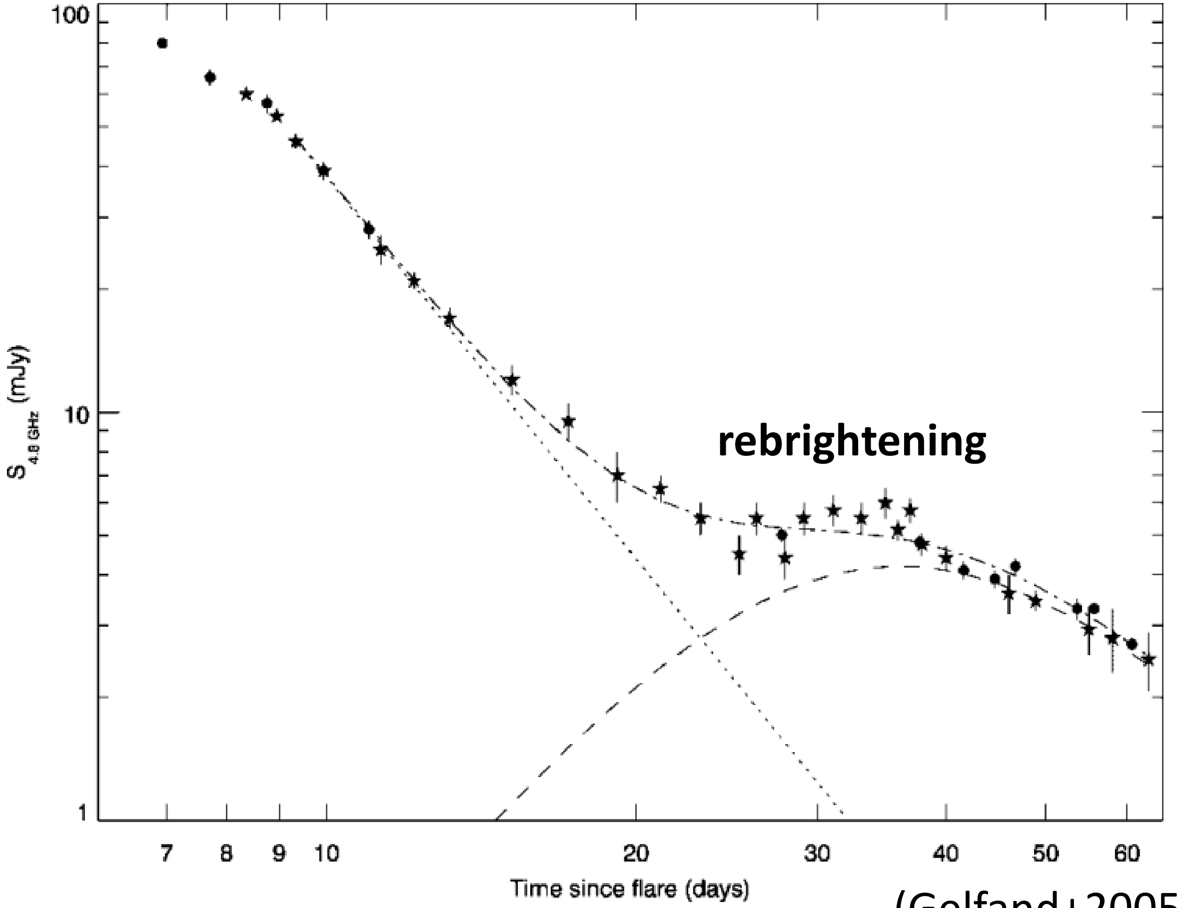
DECEMBER 2004 GF: RADIO AFTERGLOW

- radio afterglow (Cameron+2005; Gaensler+2005; Gelfand+2005):
  - **rebrightening** around Day 25 lasting for about a week
- modelling of the radio light curve:
  - expanding ejecta in an ambient medium
  - mildly relativistic ($v_{\mathrm{ej}} \sim 0.3 - 0.7c$) ejecta of mass $M_{\mathrm{ej}} \gtrsim 10^{-8} - 10^{-7}\ \mathrm{M}_{\odot}$ (Gelfand+2005, Granot+2006)
- **HOW** to eject $10^{-7}\ \mathrm{M}_{\odot}$ from a NS?!

Radio modelling - VLBI



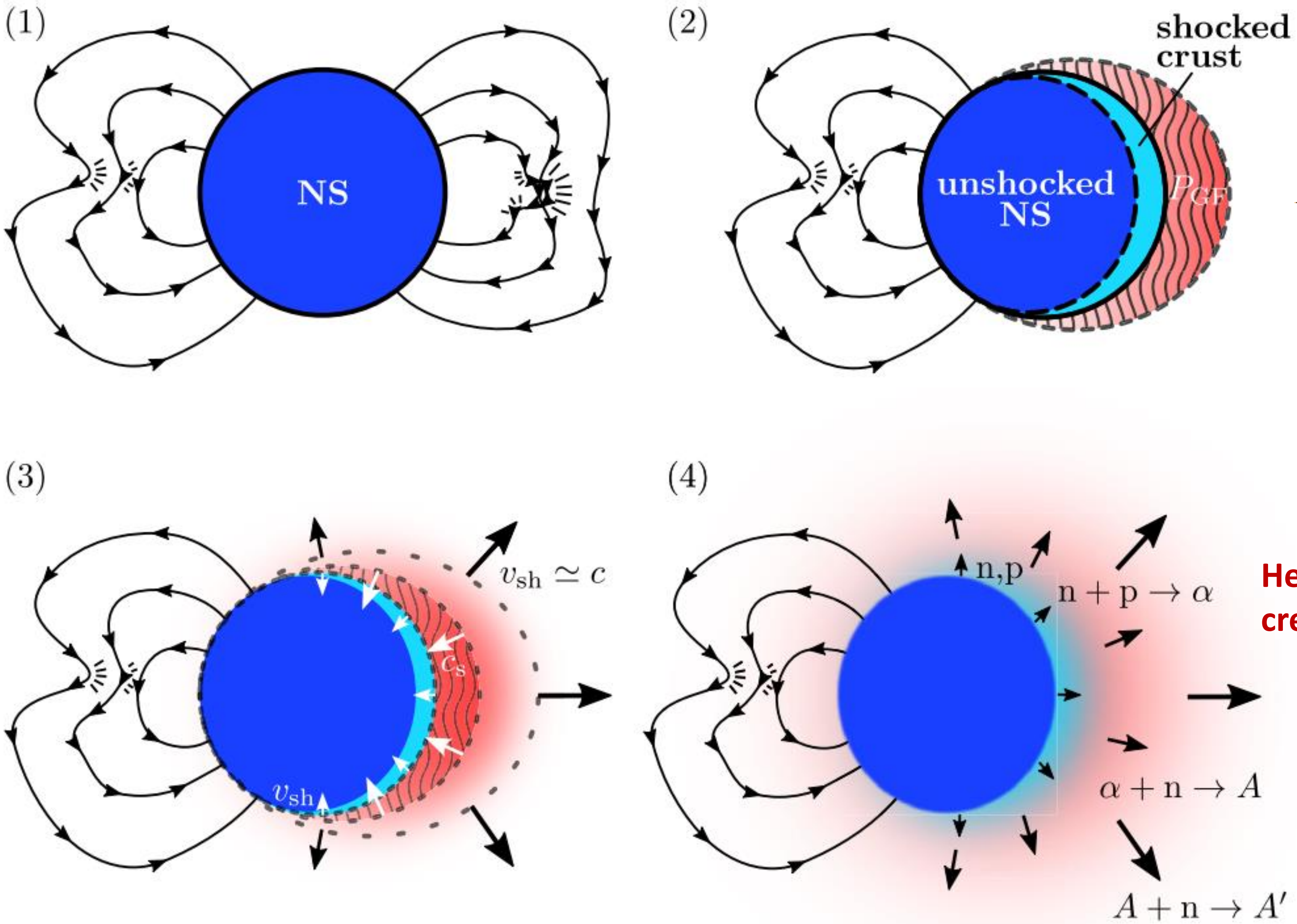
(Gaensler+2005)



rebrightening

(Gelfand+2005)

PHYSICAL PICTURE FOR BARYON EJECTION

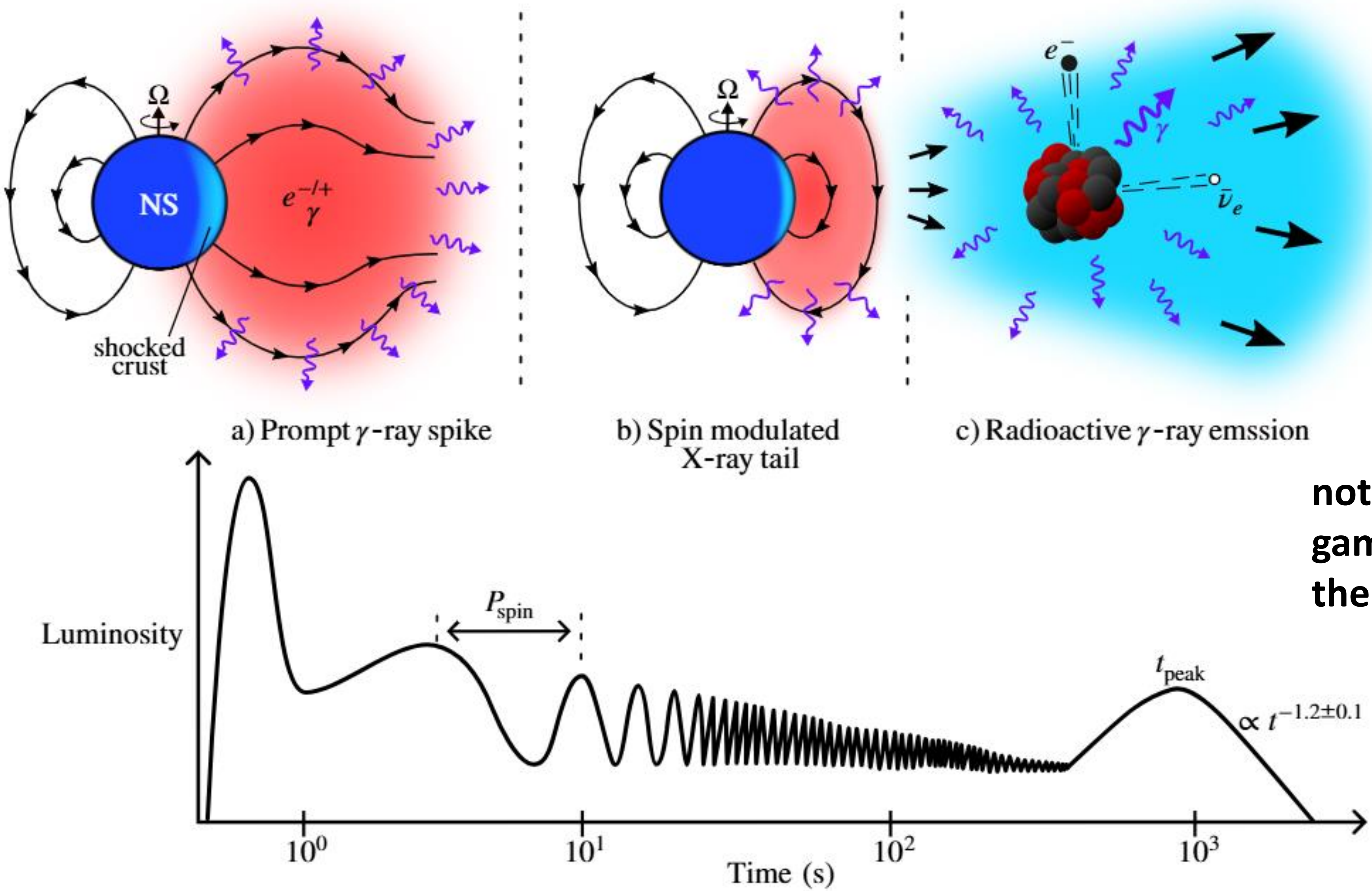


$$P_{\rm GF} \approx \frac{B^2}{8\pi}$$

Heavy element creation ≡ r-process

(JC, Thompson, & Metzger 2024)

PICTURE FOR GAMMA-RAY EMISSION



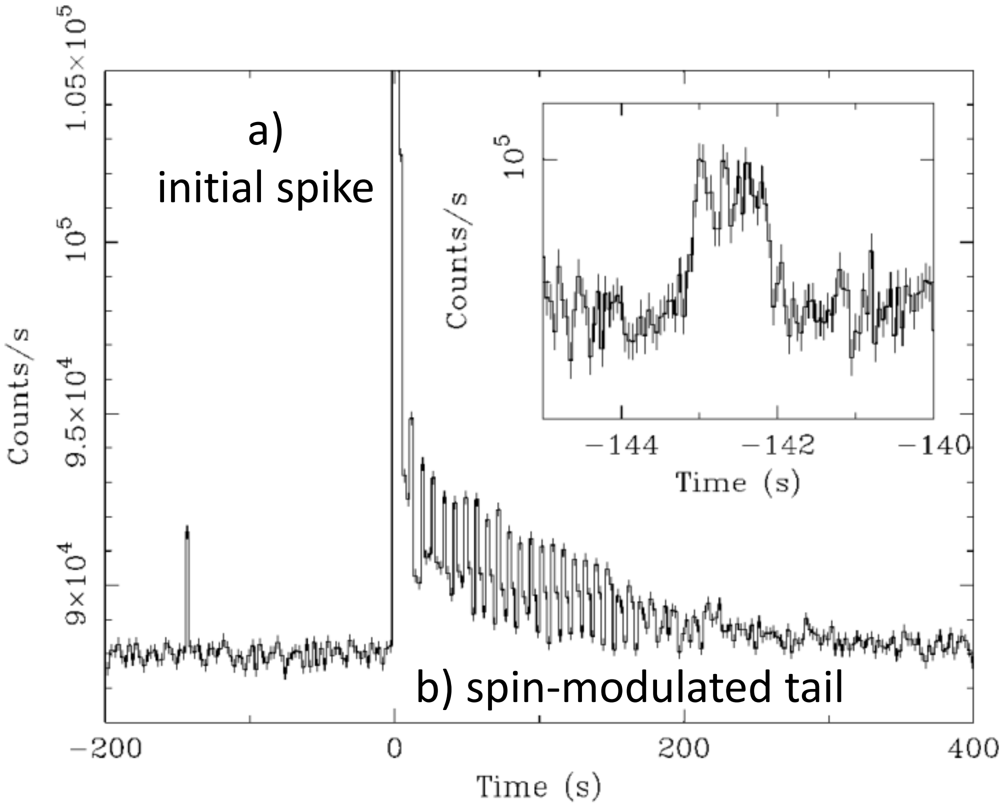
not all β-decay gamma-rays get thermalized!

(Patel, Metzger, JC, Burns, Goldberg, & Thompson, 2025)

DEC 2004 GIANT FLARE: GAMMA-RAYS

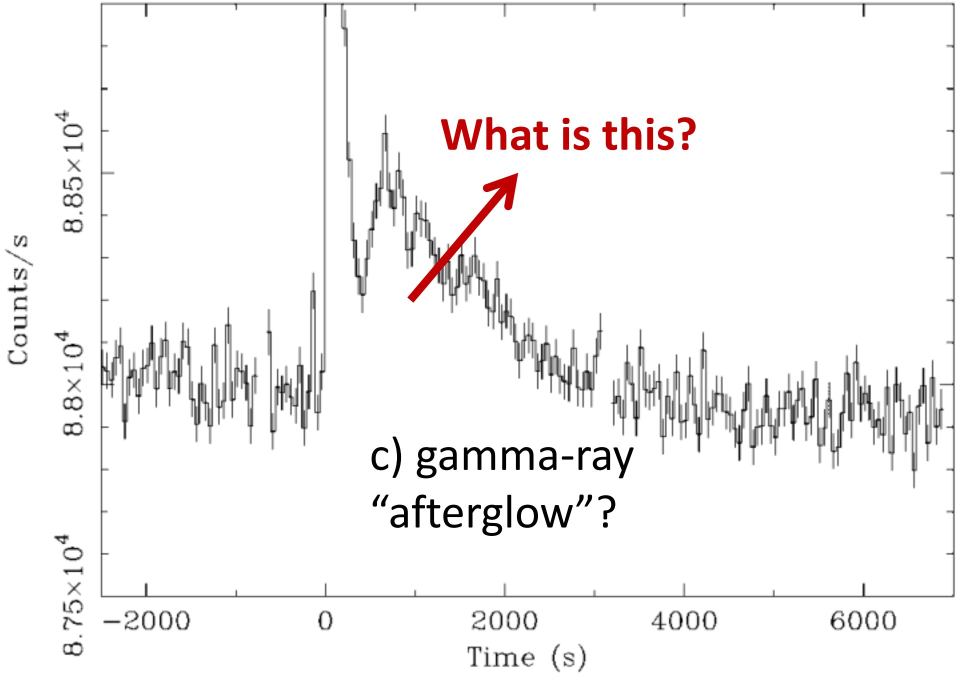
- a) $\sim 2-4\times10^{46}$ erg in gamma rays during the $0.2-0.5$ s long initial spike
- b) $\sim 10^{44}$ erg in decaying minutes-long tail modulated at the NS period
- c) $\sim 10^{43}$ erg in hour-long gamma-ray “afterglow” that peaked after ~600–800 s

(Hurley+2005; Palmer+2005; Mereghetti+2005; Boggs+2007; Frederiks+2007)



a)
initial spike

b) spin-modulated tail



What is this?

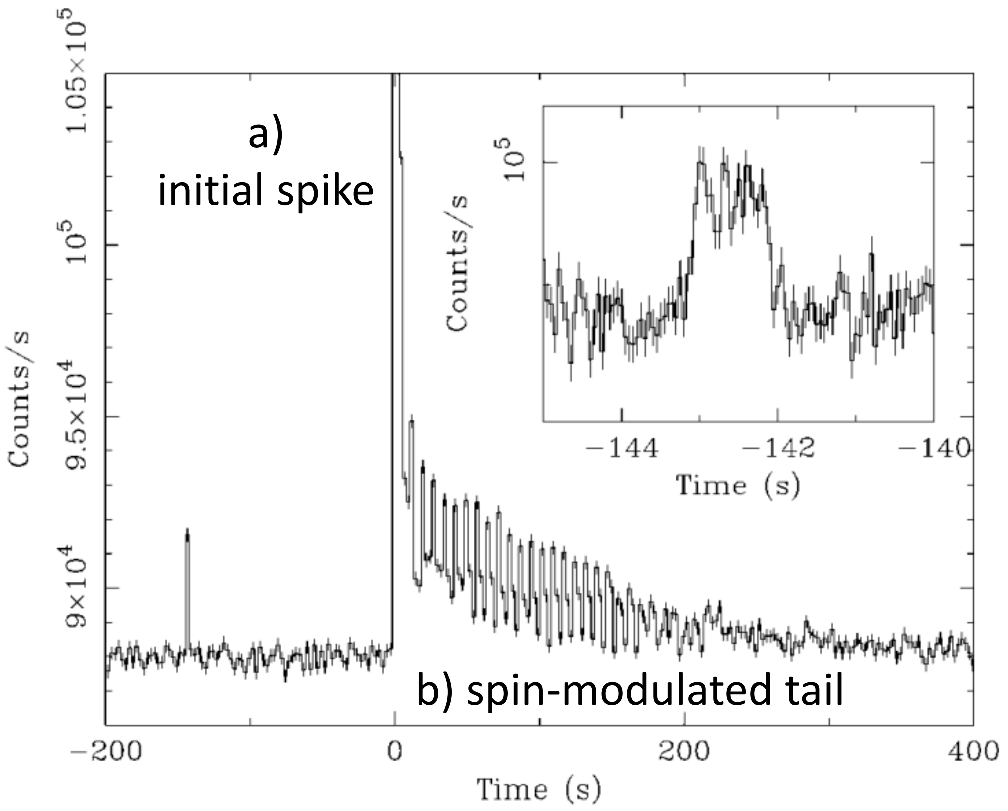
c) gamma-ray “afterglow”?

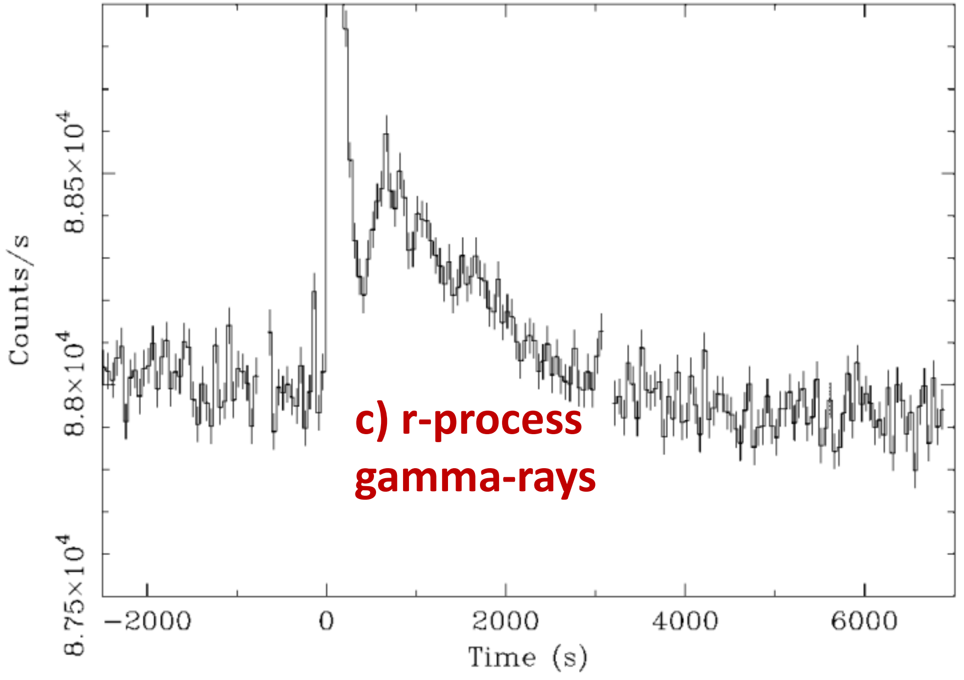
(Mereghetti+2005)

DEC 2004 GIANT FLARE: GAMMA-RAYS REVISITED

- a) $\sim 2 - 4 \times 10^{46}$ erg in gamma rays during the $0.2 - 0.5$ s long initial spike
- b) $\sim 10^{44}$ erg in decaying minutes-long tail modulated at the NS period
- **c) $\sim 10^{43}$ erg in hour-long delayed gamma-ray emission that peaked after ~600–800 s**

(Hurley+2005; Palmer+2005; Mereghetti+2005; Boggs+2007; Frederiks+2007; **Patel+2025a**)

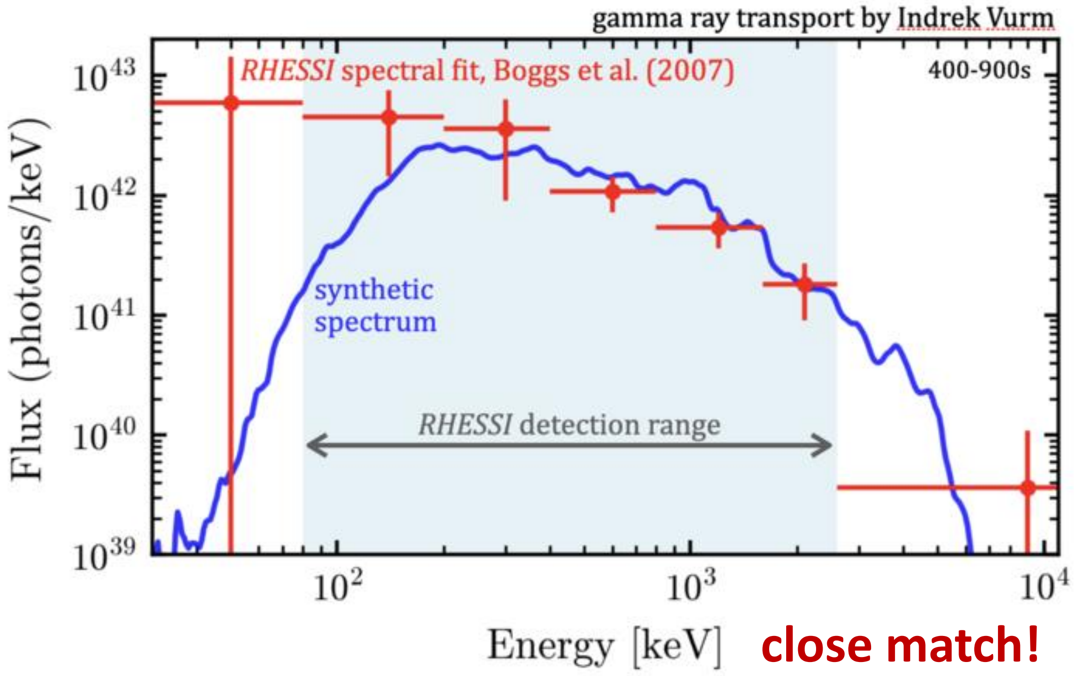




(Mereghetti+2005)

GAMMA-RAY TRANSIENT & DEC 2004 GF

synthetic **spectra** (Doppler broadened) vs. observations of **2004 GF** (Boggs+2007)

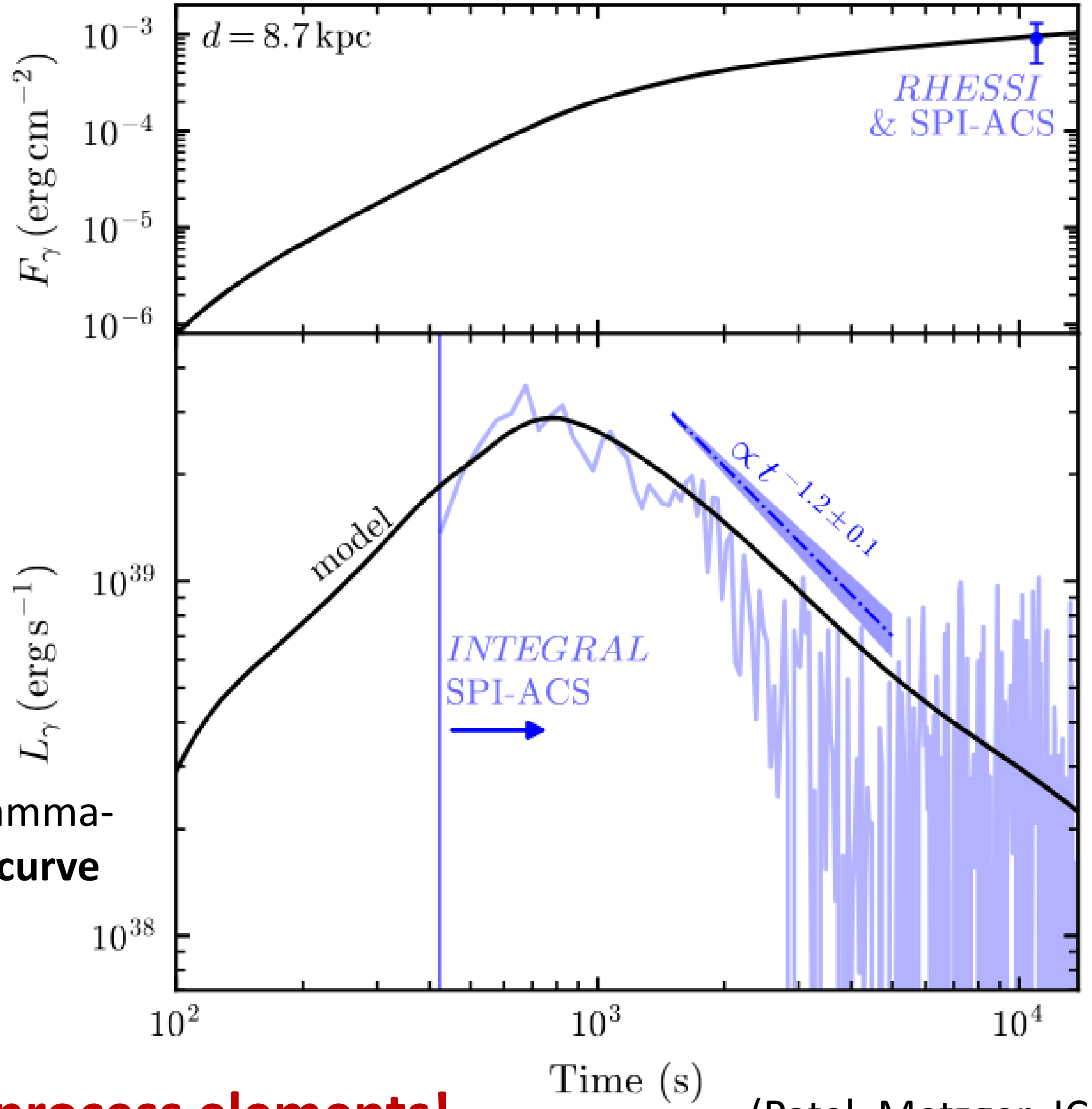


close match!

close match!

cumulative **fluence**

~ MeV gamma-ray **light curve**

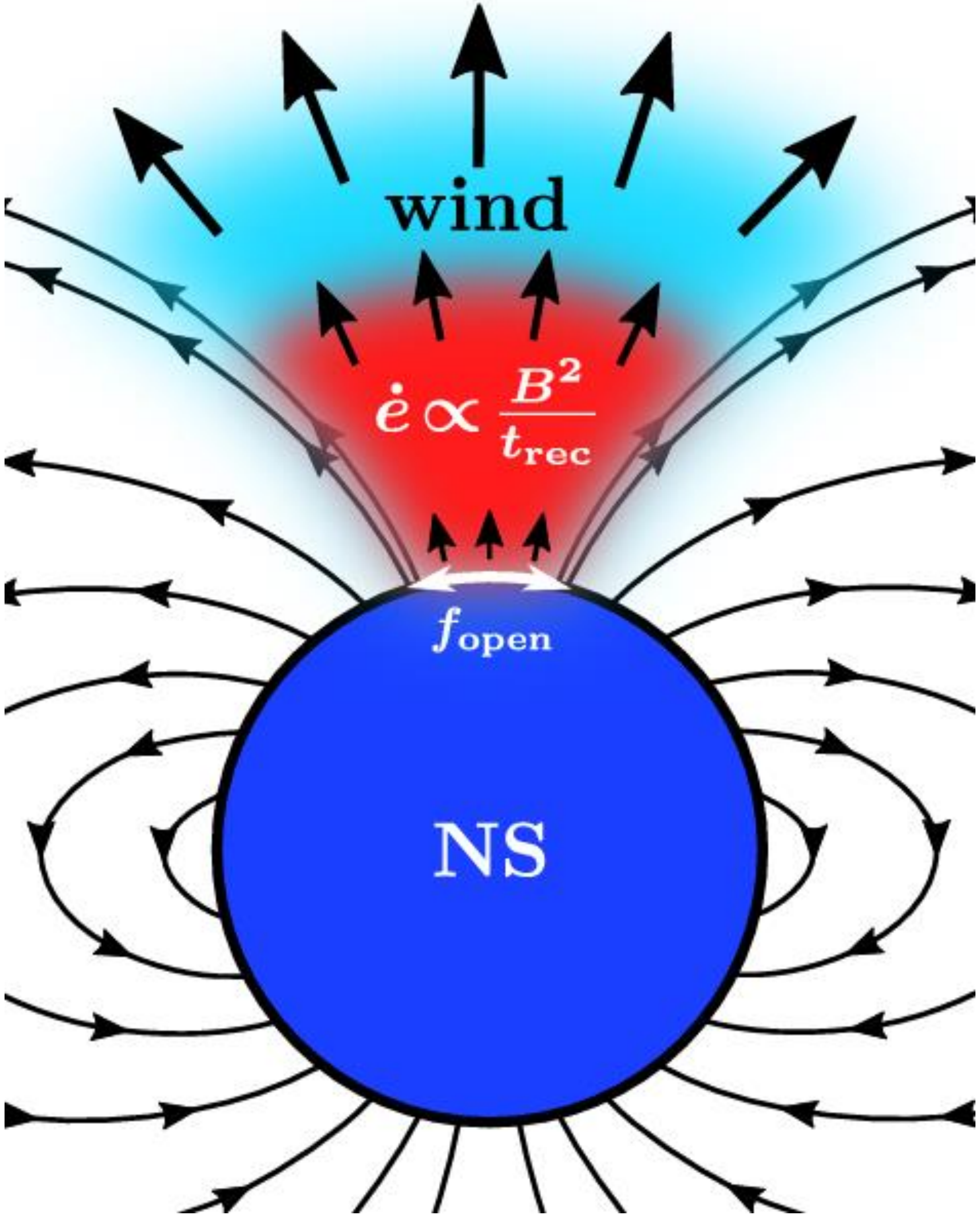


(Patel, Metzger, JC, Burns, Goldberg, & Thompson 2025; + Vurm)

- conclusion: **direct evidence for $\sim 10^{-6}\ \mathrm{M}_\odot$ of r-process elements!**
  - **GFs** could contribute **1 – 10 %** of r-process elements

NEW PICTURE FOR BARYON EJECTION

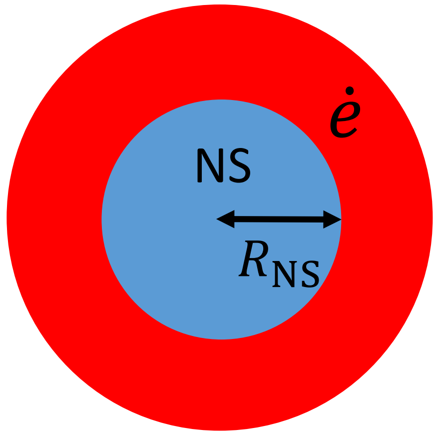
- the process in mind: magnetic reconnection in radiative strong-field plasma (e.g. Uzdensky 2011)
- a phenomenological prescription for **heating** $\dot{e}$ that covers a fraction f_{open} of the NS surface:
  - $\dot{e} = \frac{B^2}{8\pi\, t_{\mathrm{rec}}}$, where t_{rec} corresponds to the duration of the main GF spike, i.e. $t_{\mathrm{rec}} \sim 0.2\ - 0.5\ \mathrm{s}$
- $t_{\mathrm{rec}} \gg t_{\mathrm{dyn}} \sim \sqrt{\frac{R_{\mathrm{NS}}^3}{G M_{\mathrm{NS}}}} \sim 0.1\ \mathrm{ms}$ => a **wind** forms
- heating profiles corresponding to: $B(r) \propto r^{-n}$
  - $n = 3$: dipole, or $n = 2$: open field lines
- 1D vs 2D
- relativistic HD vs non-relativistic semi-analytical (Vurm)

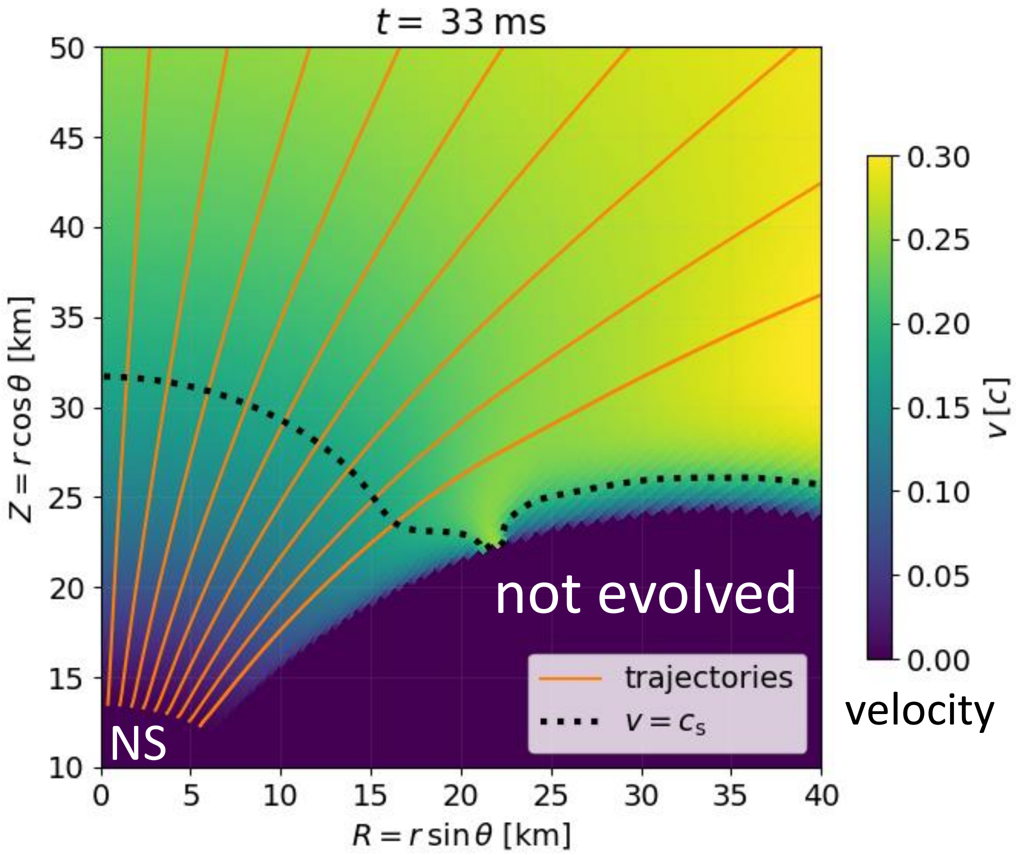


(JC & Vurm in prep.)

NEW PICTURE: 1D vs 2D

1D vs 2D





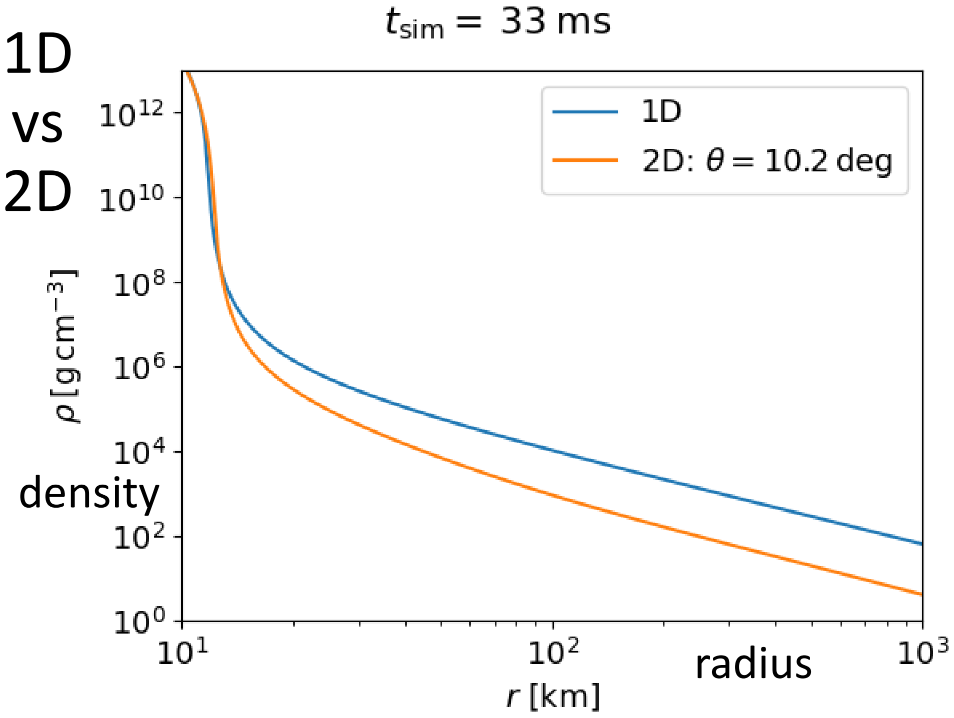
*no B in the simulation

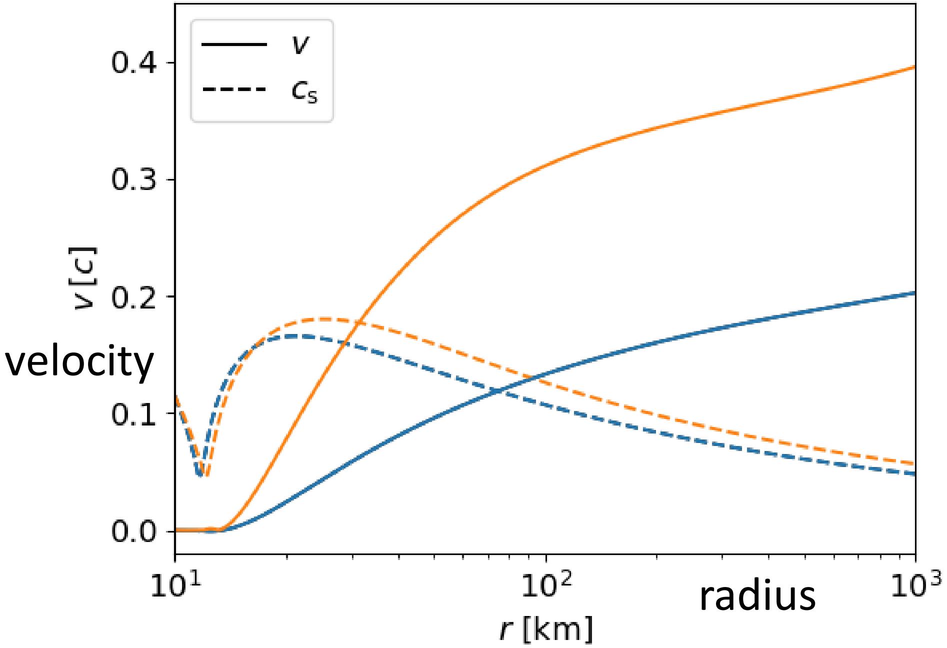
**the trajectories are extracted assuming a steady-state

(PLUTO: Mignone+2007,2024)

- the outflow is faster and more rarefied in 2D => stronger freeze-out in 2D

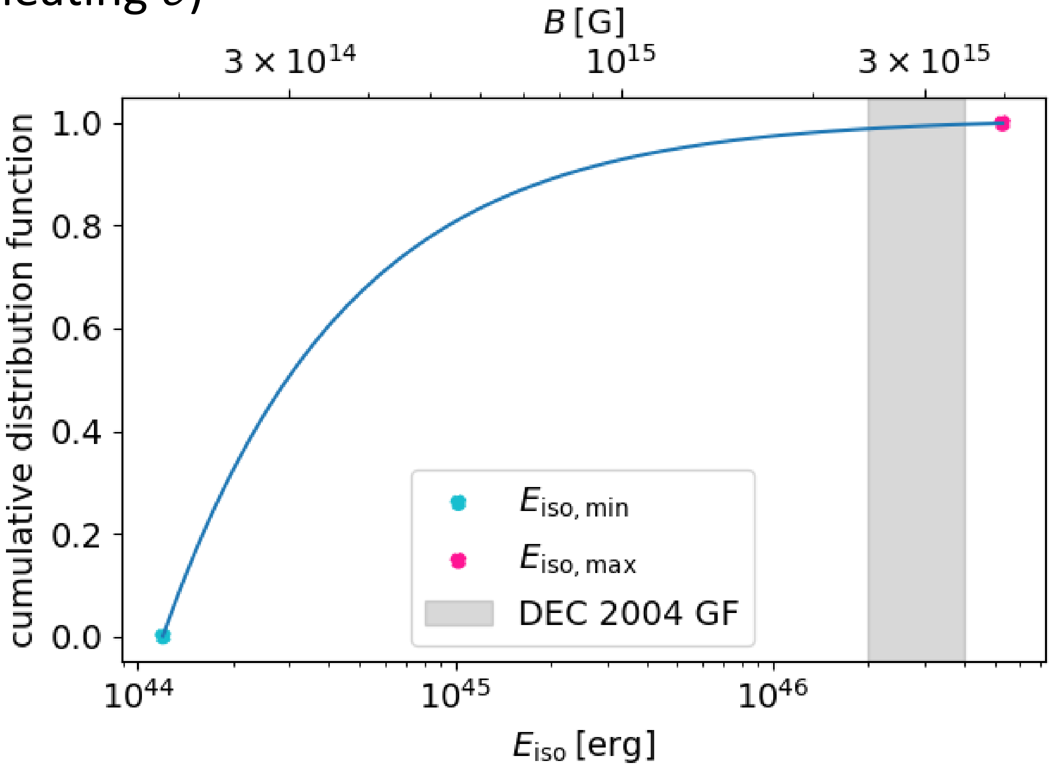
1D vs 2D



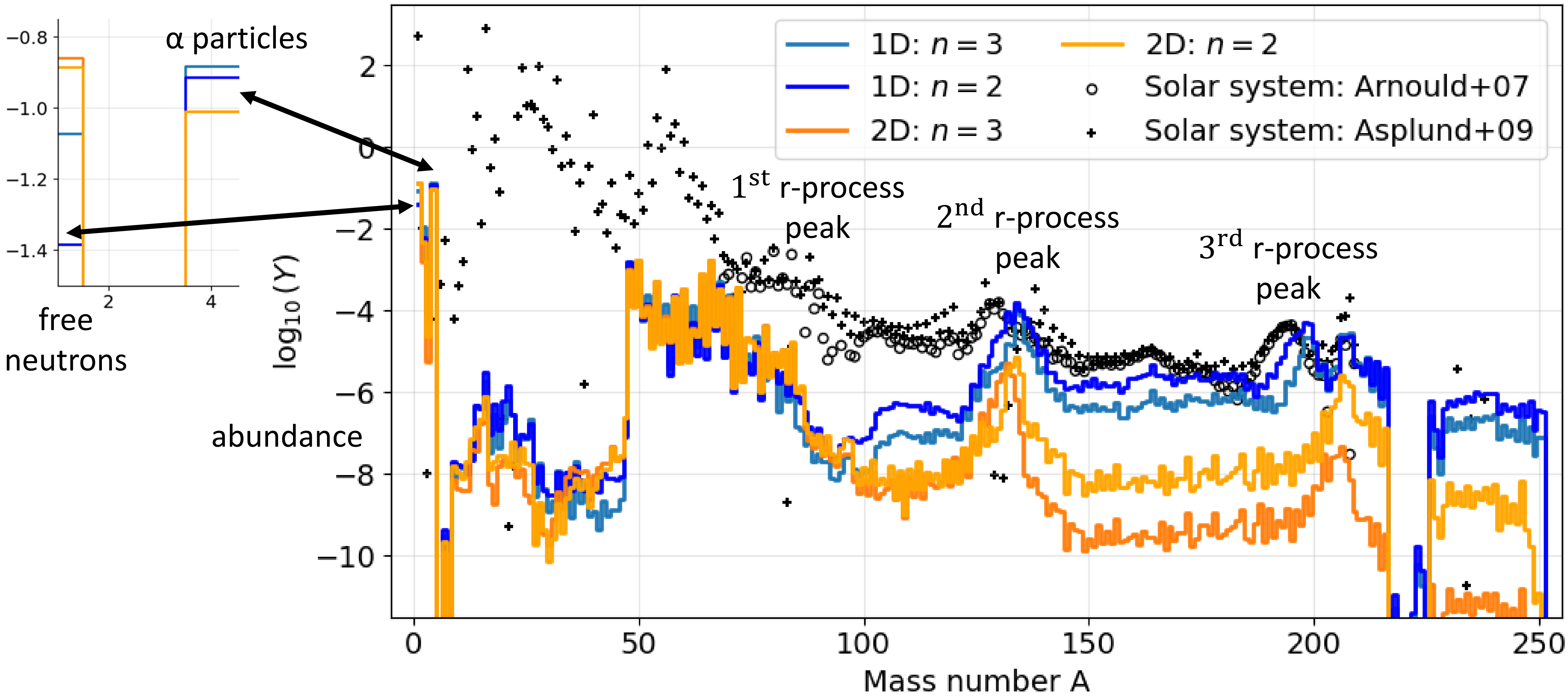


MAGNETAR GIANT FLARE NUCLEOSYNTHESIS

- nucleosynthesis calculations along trajectories using SkyNet (Lippuner&Roberts 2017)
- an observable for GFs: E_{iso} – isotropic-equivalent energy emitted in gamma rays
- to relate $\dot{e}$ in the simulation with the observable E_{iso} we assume:
  1) $t_{\mathrm{GF}} \sim t_{\mathrm{rec}} \sim 0.3\ \mathrm{s}$
  2) $f_{\mathrm{open}} \sim 0.05 - 0.10$ (fraction of the surface covered by heating $\dot{e}$)
  3) $\sim 10 - 20\ \%$ of the injected energy emitted in γ-rays
- this also yields a relation for $B(E_{\mathrm{iso}})$
- we further assume a power-law for the probability distribution function (PDF) of E_{iso} (Burns+2021, Trigg+2025): $p(E_{\mathrm{iso}}) \propto 1/E_{\mathrm{iso}}^{\alpha}$, where $\alpha = 1.76$
- we performed simulations for different values of E_{iso} (or $\dot{e}$) in 1D and 2D, for $n = 2, 3$ ($B \propto r^{-n}$), and weighted them according to the PDF



MAGNETAR GIANT FLARE NUCLEOSYNTHESIS



- mass fraction X_r in r-process elements: ~20% in 1D, ~5% in 2D (stronger freeze-out)

SUMMARY

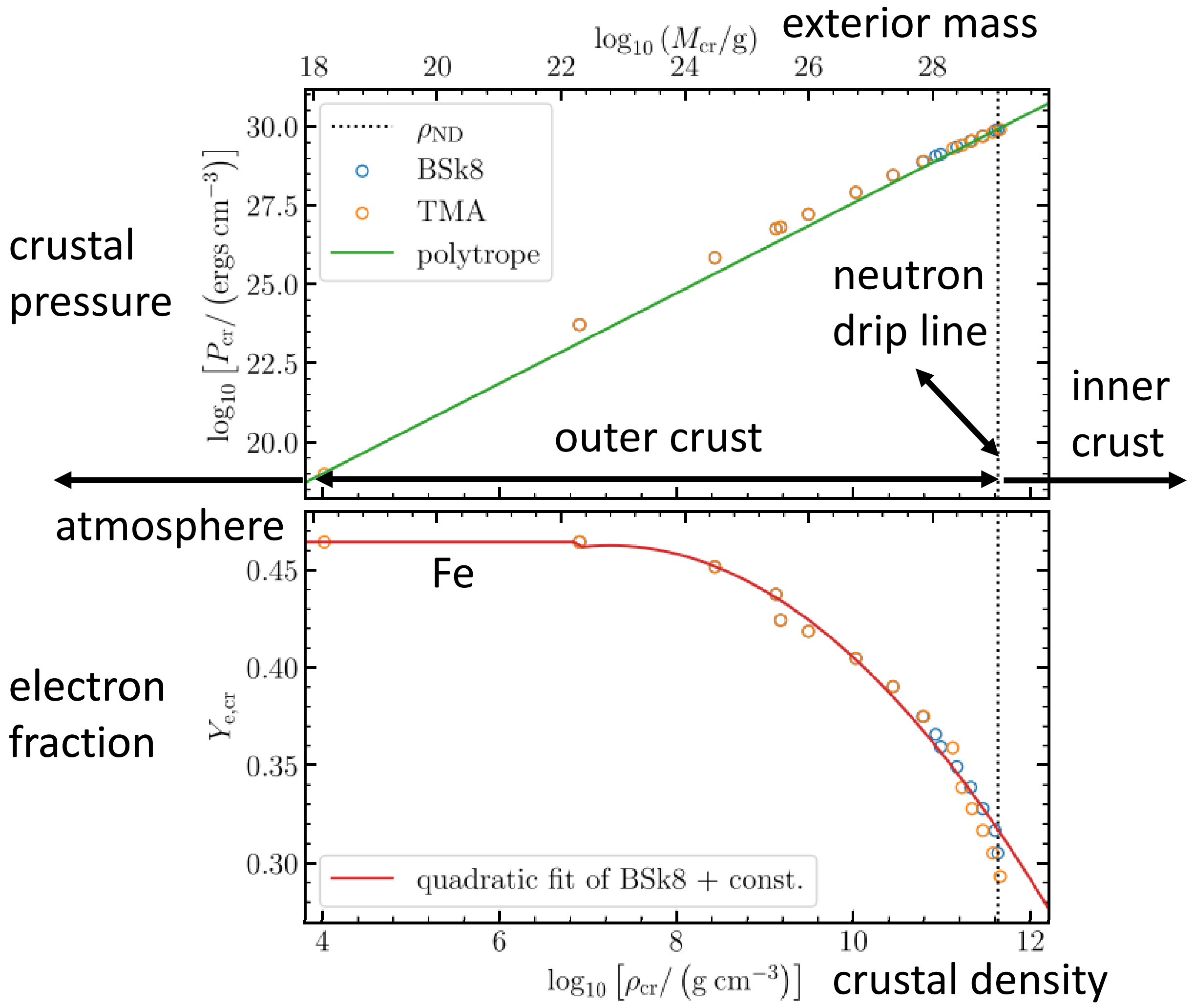
- GFs eject mass (Gelfand+2005, Granot+2006)
- the ejecta undergoes r-process nucleosynthesis
- r-process gamma rays are consistent with the delayed MeV gamma-ray emission observed after the Dec 2004 GF from SGR 1806-20 => **magnetar GFs** are the second **confirmed r-process site**
- currently explored questions:
  - ➢ Can the ejecta be modeled as a wind?
  - ➢ What is the underlying physical mechanism?
  - ➢ What is the integrated contribution of GFs to r-process elements?
  - ➢ 1D vs 2D: How much mass is in r-process elements?
  - ➢ Is a strong freeze-out scenario consistent with the gamma-ray observations?

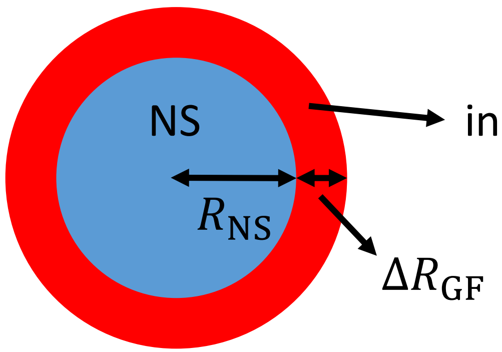
(**1**. JC, Thompson, & Metzger, 2024; **2**. Patel, Metzger, Goldberg, JC, Thompson, & Renzo 2025; **3**. Patel, Metzger, JC, Burns, Goldberg, & Thompson 2025; **4.** JC & Vurm in prep.)

BACKUP SLIDES

NUMERICAL APPROACH

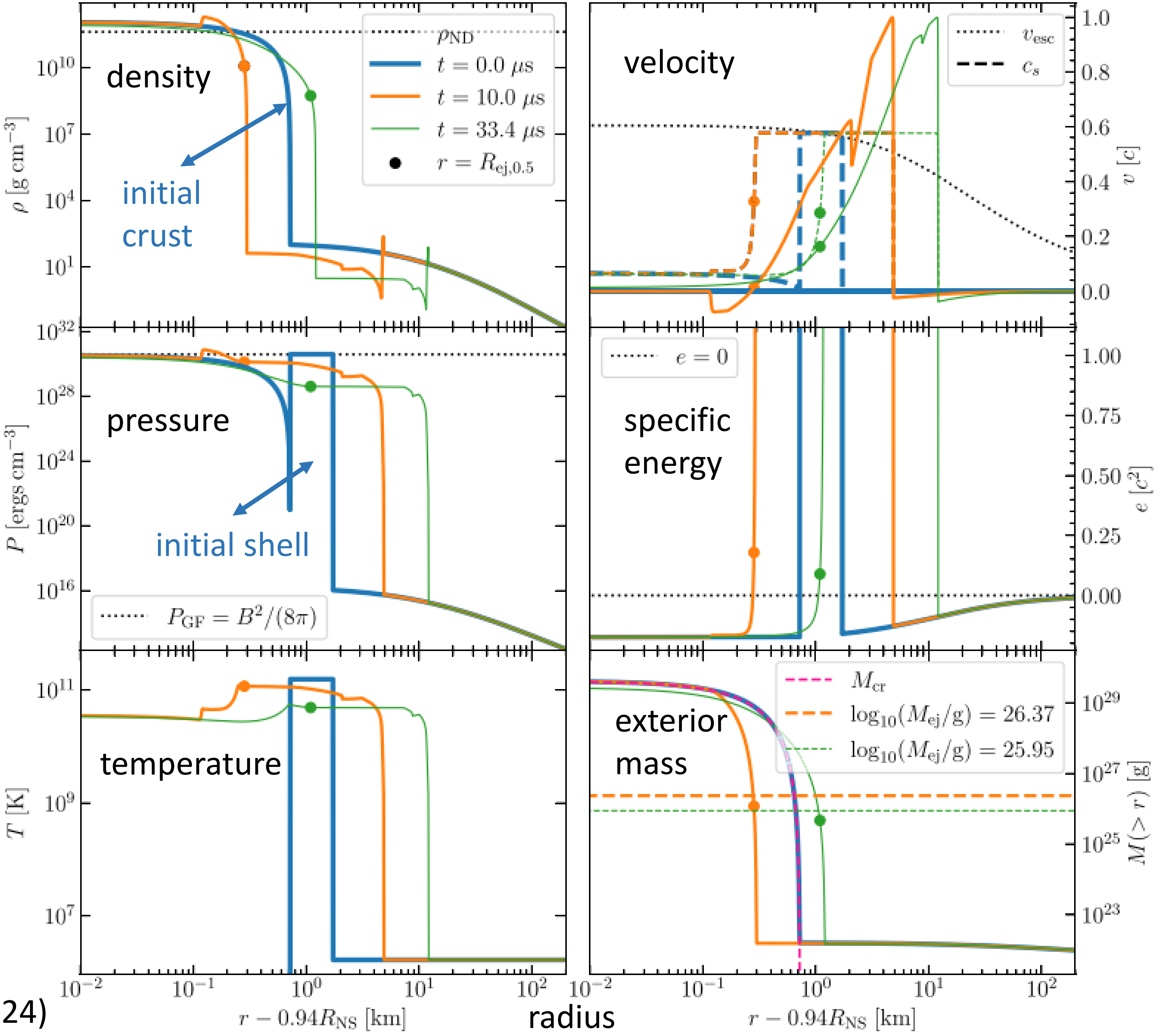
- **1D** special-relativistic hydrodynamic simulations
- crust model:
  - simple polytropic model $P_{\rm cr} = K\rho_{\rm cr}^{\Gamma_*}$, where $\Gamma_* = 1.43$, fits the cold (i.e. non-accreting) crust model well
- simulation set-up:
  - **initial shell** of uniform pressure $P_{\rm GF} = B^2/8\pi$ and width $\Delta R_{\rm GF} \leq R_{\rm NS}$ above the NS surface
  - **no magnetic field** in the simulation
  - **ideal gas** constant-Γ EOS ($\Gamma = 4/3$ corresponding to the hot shocked gas)
  - $M_{\rm NS} = 1.4\ {\rm M}_\odot$, $R_{\rm NS} = 12\ {\rm km}$
  - reflective inner boundary: $R_{\rm in} = 10\ {\rm km}$, outflow outer boundary: $R_{\rm out} = 20000\ {\rm km}$





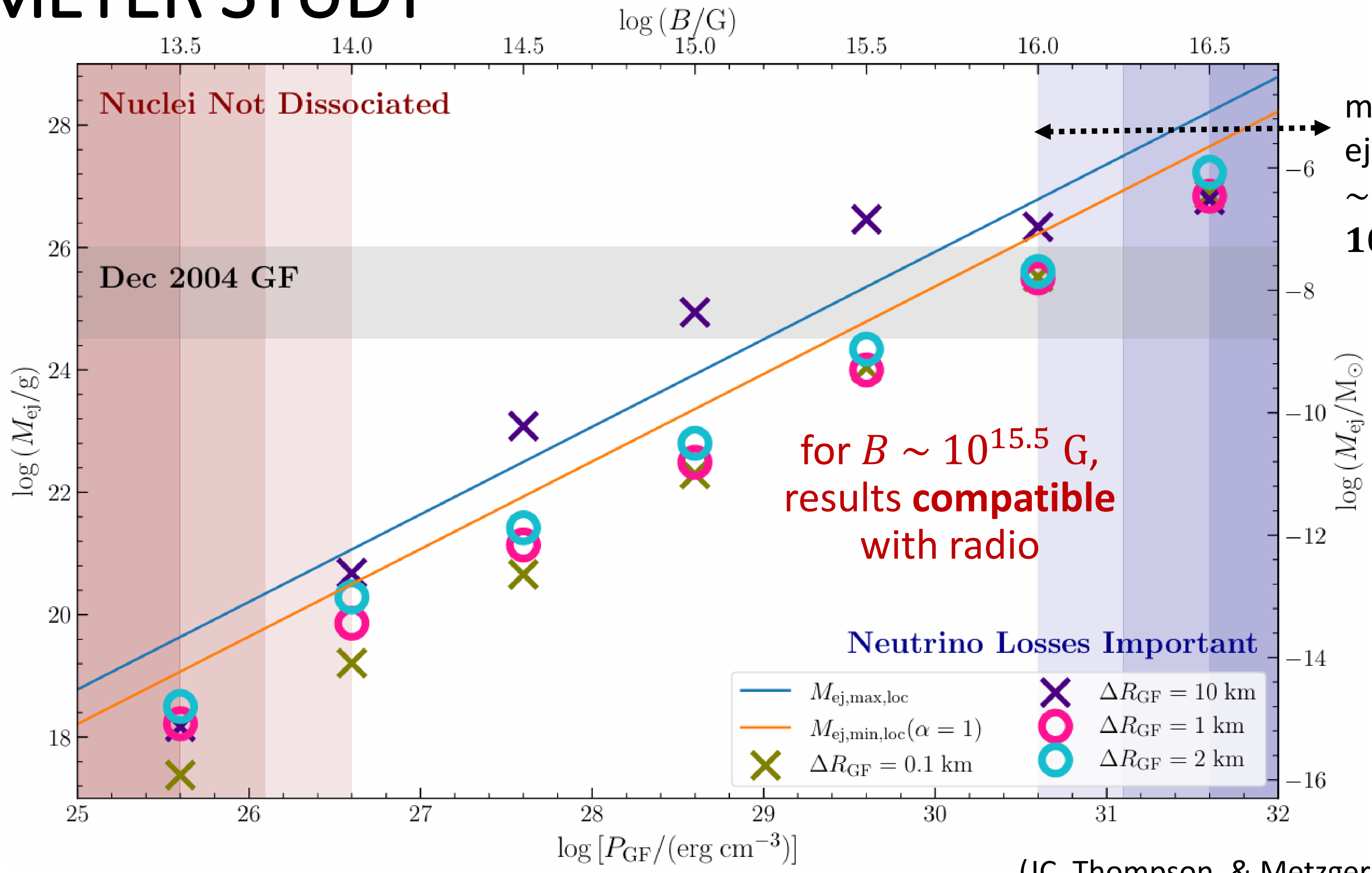
NUMERICAL APPROACH

- 1D special-relativistic hydrodynamic simulations
- fiducial model:
  - ➢ $B = 10^{16}\ \mathrm{G}$ $(P_{\mathrm{GF}} = 10^{30.6}\ \mathrm{erg \cdot cm^{-3}})$
  - ➢ $\Delta R_{\mathrm{GF}} = 1\ \mathrm{km}$
- gives:
  - ➢ $\boldsymbol{M_{\mathrm{ej}} \approx 10^{-8} - 10^{-7}\ \mathrm{M}_{\odot}}$
  - ➢ $\overline{v_{\mathrm{ej}}} \approx 0.3c$
- **compatible** with the 2004 GF from SGR 1806-20 (Gelfand+2005; Granot+2006)



(PLUTO: Mignone+2007,2024)

PARAMETER STUDY



maximum ejecta mass $\sim 10^{-5}$ – $\mathbf{10^{-6}}$ $\mathrm{M}_\odot$

ejecta mass

for $B \sim 10^{15.5}$ G, results **compatible** with radio

giant flare strength

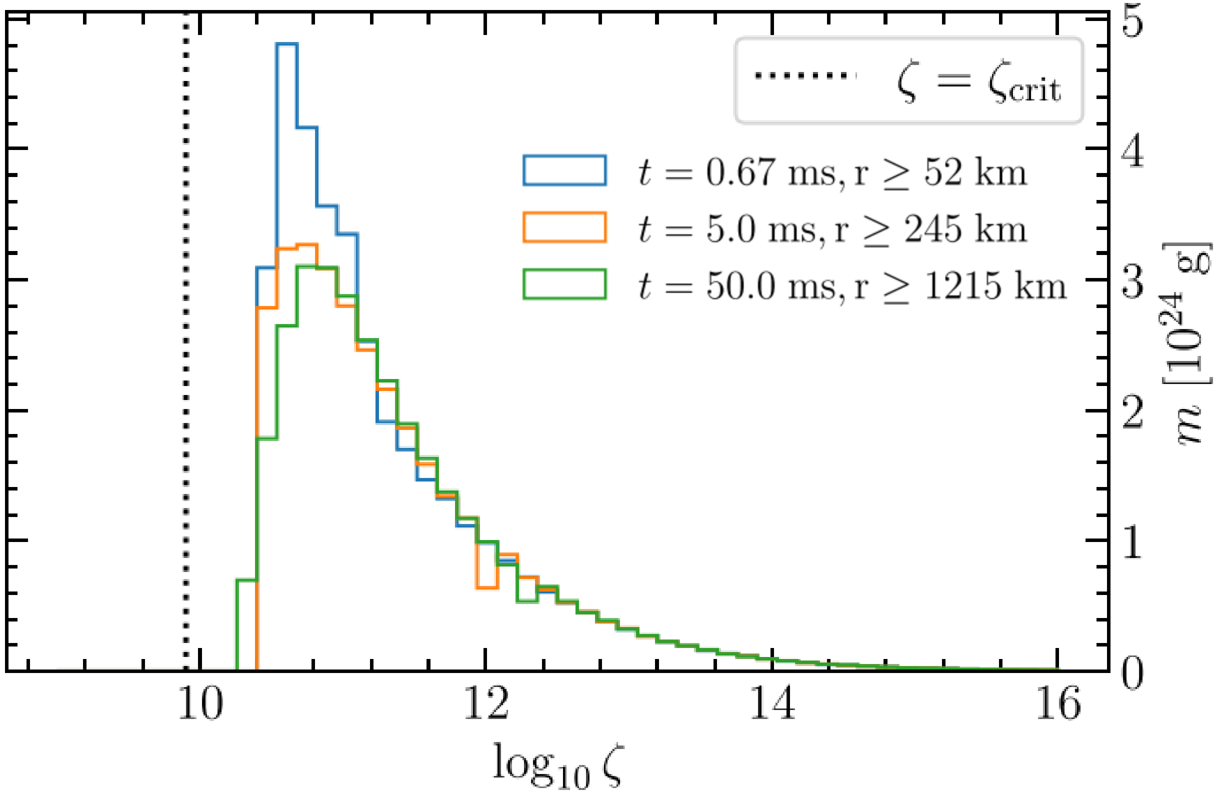
(JC, Thompson, & Metzger, 2024)

HEAVY ELEMENT CREATION

- ***r*-process**: if $\zeta > \zeta_{\rm crit}$, then heavy r-process is happening (Hoffman+1997)
- it holds:

$$\zeta \equiv \frac{S_{\rm b}^3}{Y_{\rm e}^3 t_{\alpha,0}}$$

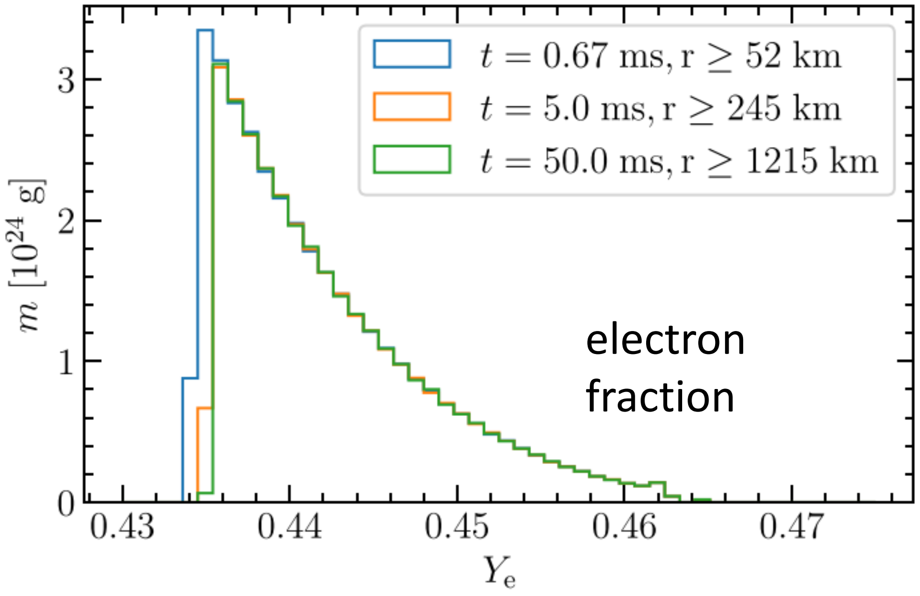
$$\zeta_{\rm crit} \approx 8 \times 10^9$$



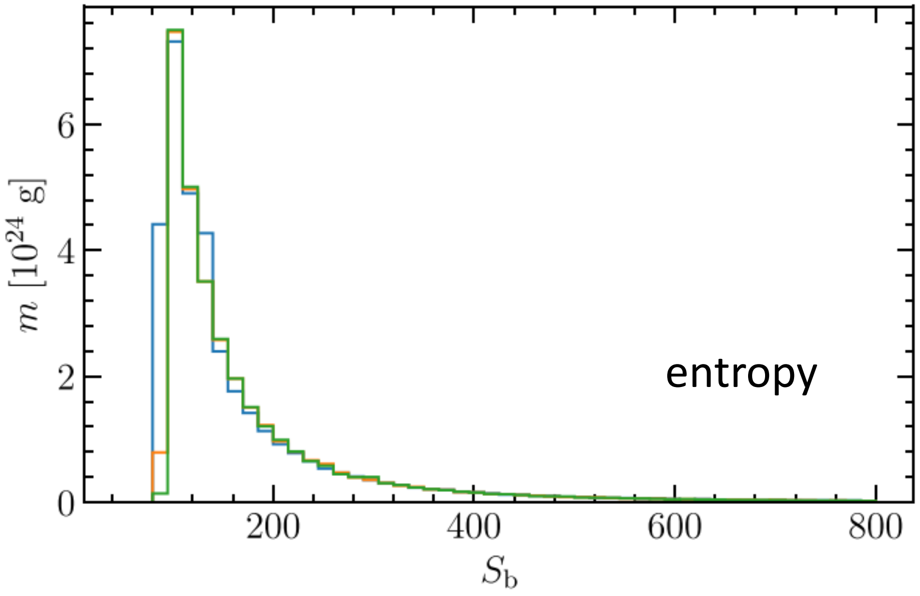
- we see that we **have heavy *r*-process**!

(JC, Thompson, & Metzger 2024)

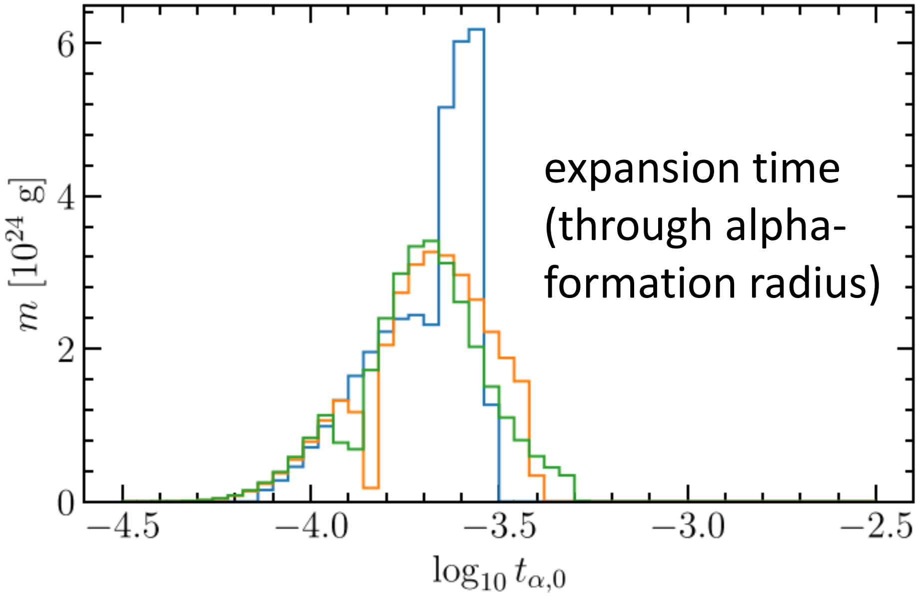
R-PROCESS? YES!



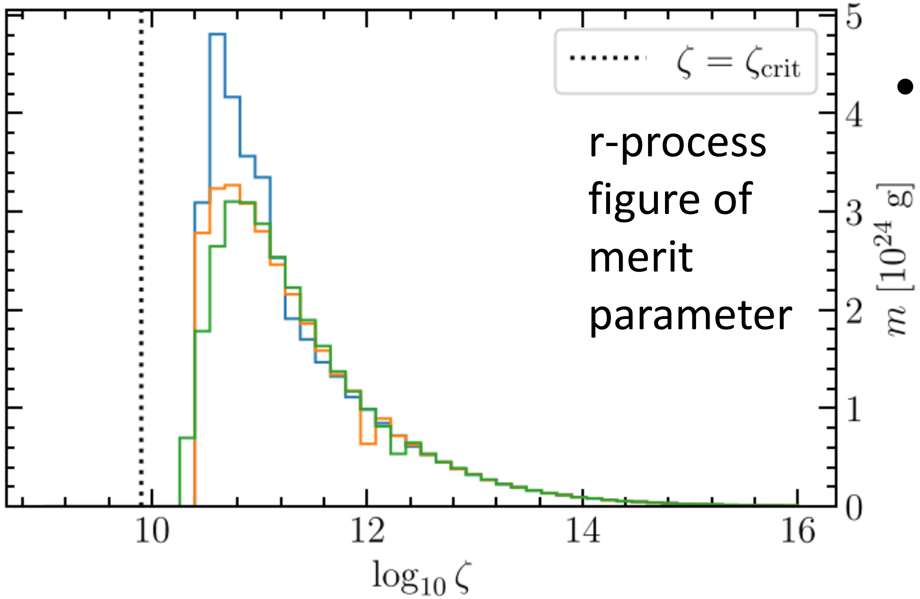
electron fraction



entropy



expansion time (through alpha-formation radius)



r-process figure of merit parameter

- if $\zeta > \zeta_\mathrm{crit}$, then we have 3rd r-process peak (Hoffman+1997)
- it holds:

$$\zeta \equiv \frac{S_\mathrm{b}^3}{Y_\mathrm{e}^3 t_{\alpha,0}}$$

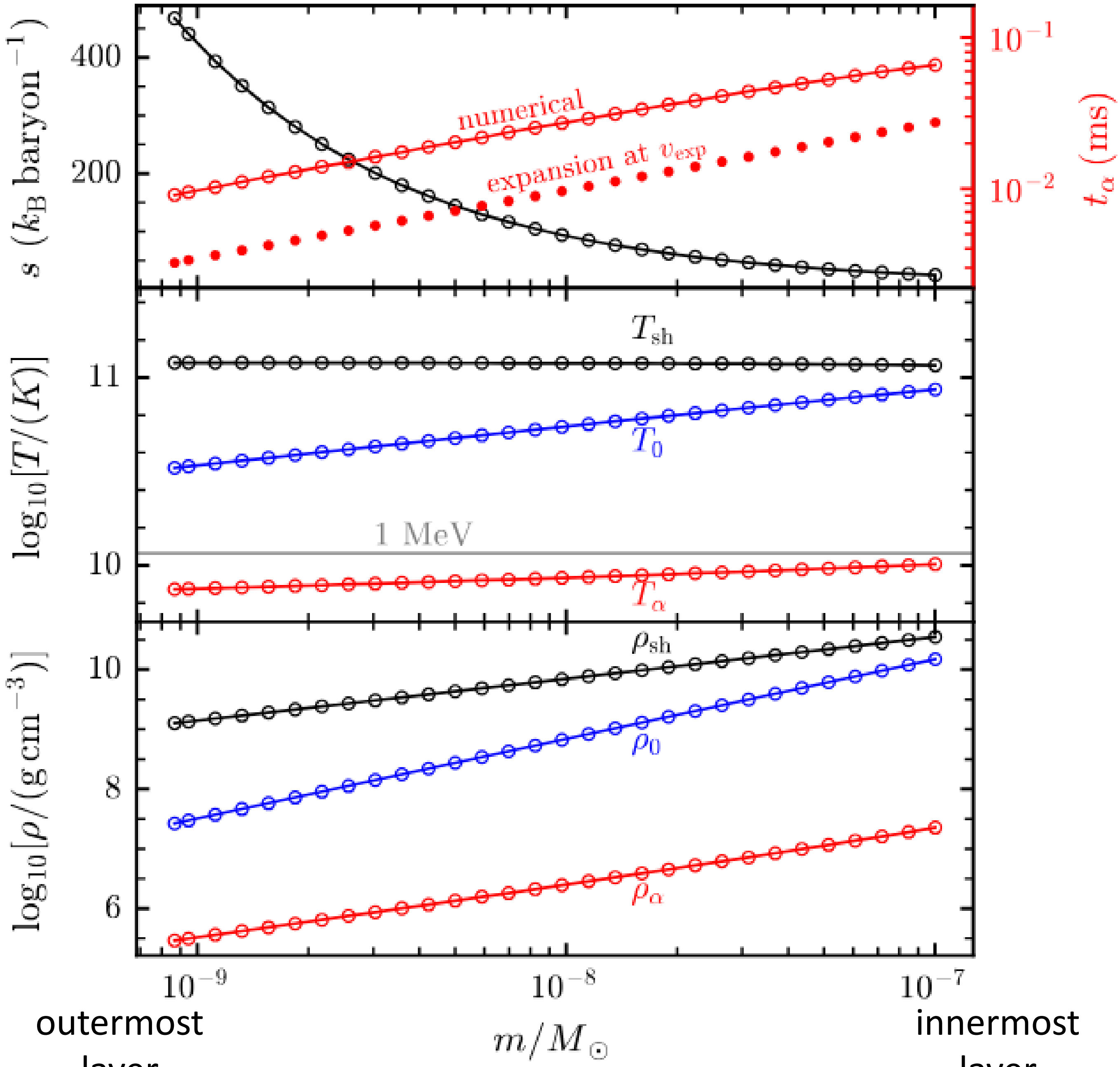
$$\zeta_\mathrm{crit} \approx 8 \times 10^9$$

- we **have 3rd r-process peak!**

EJECTA THEROMDYNAMICS

- modified Helmholtz EOS (Timmes&Swesty2000)
- constant entropy s in each layer
- fiducial model:
  - ➢ $B = 6 \times 10^{15}$ G ($P_{\mathrm{GF}} = 1.4 \times 10^{30}$erg $\cdot$ cm^{-3}) => $M_{\mathrm{ej}} \sim 10^{-7} \mathrm{M}_{\odot}$
  - ➢ $Y_{\mathrm{e}} = 0.44$
  - ➢ 30 grid zones (circles)

- black – immediately post-shock
- blue – at the start of nucleosynthesis
- red – at α-formation

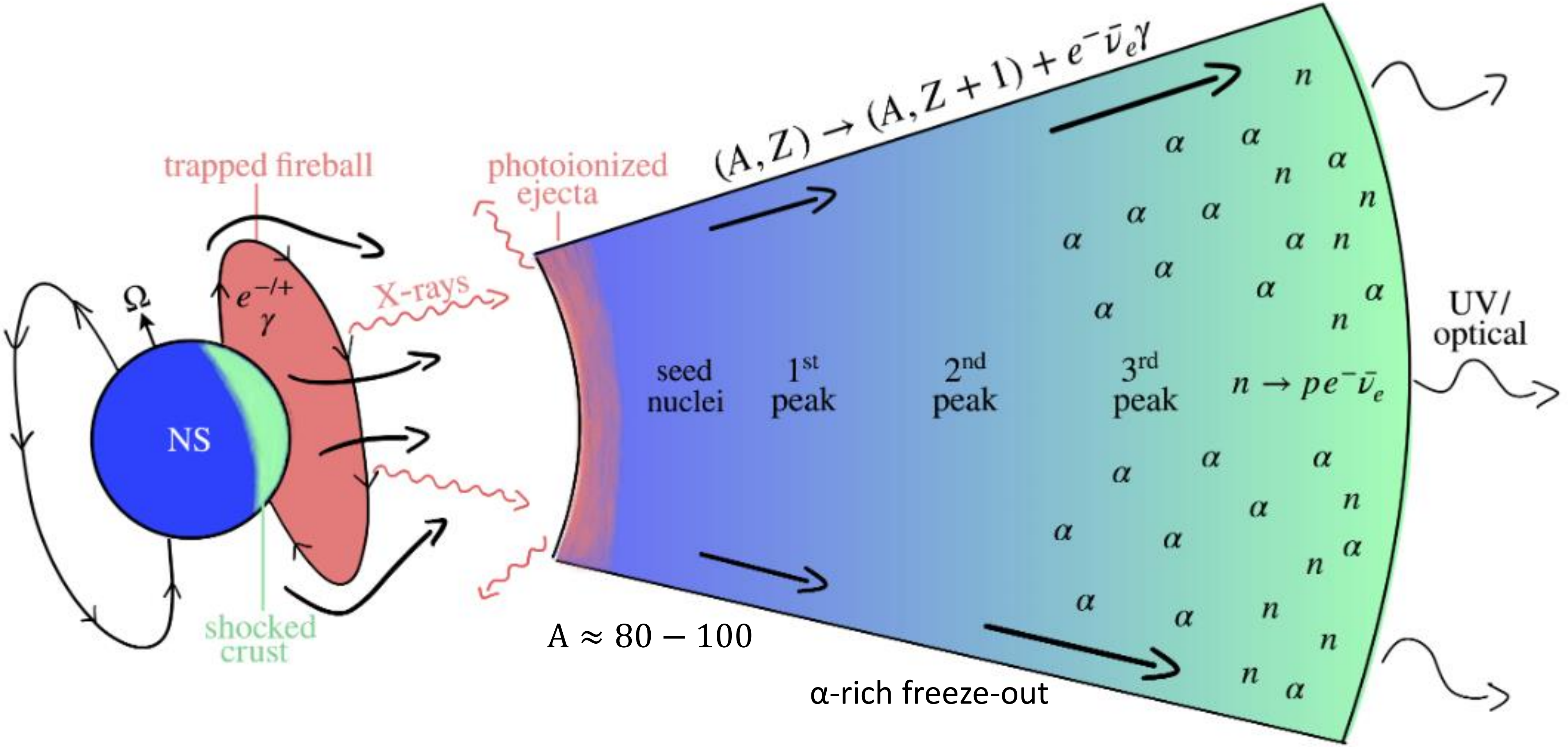


outermost layer

lagrangian mass coordinate

innermost layer

PICTURE FOR R-PROCESS NUCLEOSYNTHESIS



$A \approx 80 - 100$

α-rich freeze-out

n-capture freeze-out

(Patel, Metzger, Goldberg, JC, Thompson, & Renzo, submitted)

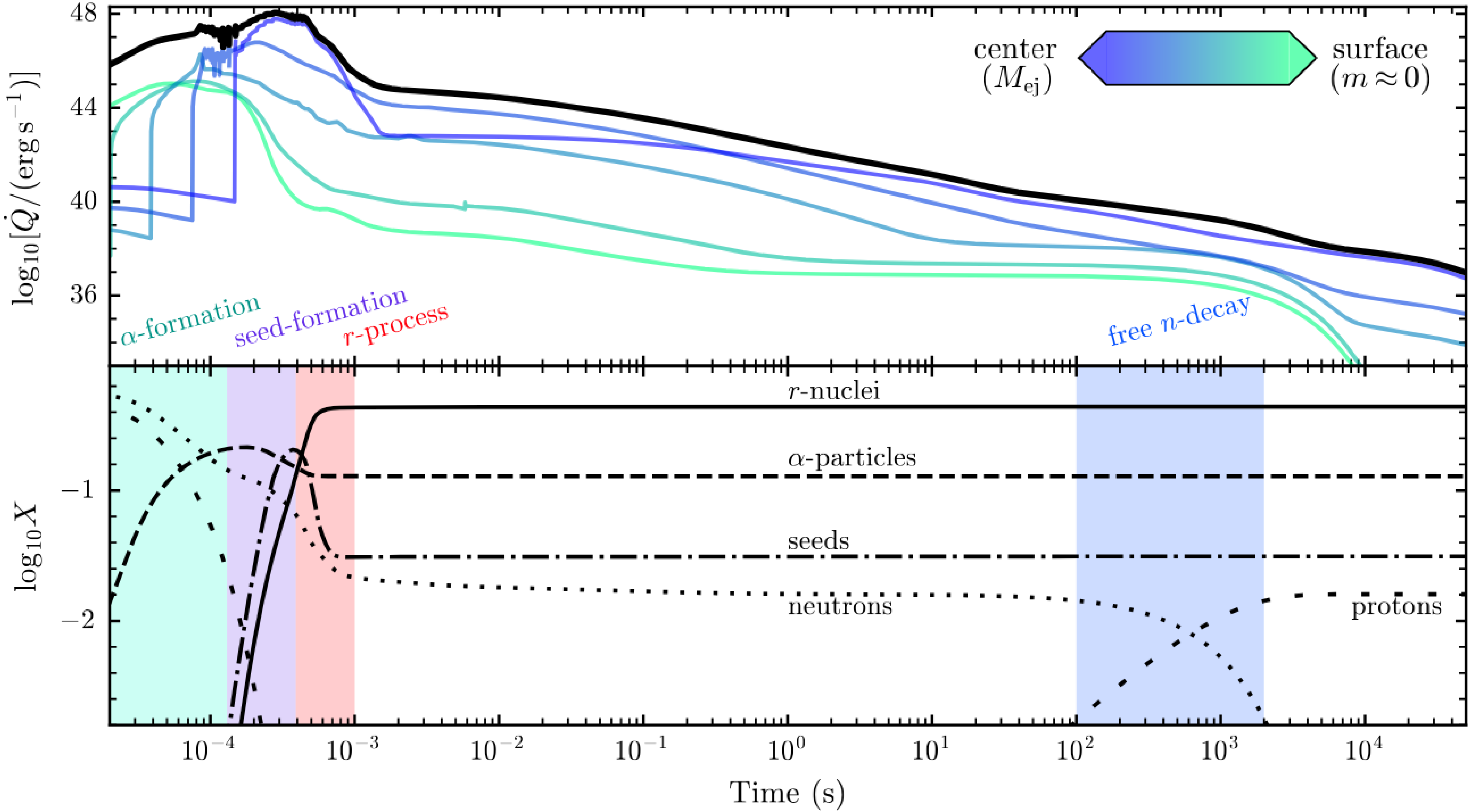
R-PROCESS NUCLEOSYNTHESIS

- initial state: $T_{\mathrm{MeV}} \gg 1$ => nucleons are free and $\mathrm{e}^-/\mathrm{e}^+$ are relativistic
- alpha-rich freeze-out mechanism:
  1) $T_9 \approx 10$ $(t \sim t_\alpha)$: α-particle production via
     $2\mathrm{n} + 2\mathrm{p} \rightarrow \alpha + \gamma$,
     remaining neutrons are free (n-capture freeze-out)
  2) $T_9 \approx 5$: carbon production via
     1) "normal" 3α-reactions: ${}^4\mathrm{He}(\alpha,\gamma)\ {}^8\mathrm{Be}(\alpha,\gamma)\,{}^{12}\mathrm{C}$,
     2) neutron-aided 3α-reactions: ${}^4\mathrm{He}(\alpha\mathrm{n},\gamma)\ {}^9\mathrm{Be}(\alpha,\gamma)\,{}^{12}\mathrm{C}$
  3) $T_9 \approx 2.5$: production of heavier **seed nuclei** up to the Fe-group ($A_{\mathrm{seed}} \sim 60$) via
     (α,γ) reactions,
     remaining α-particles are free (α-rich freeze-out)
  4) $T_9 \lesssim 2.5$: **r-process** proceeds to heavier nuclei via
     $(\mathrm{A},\mathrm{Z}) + \mathrm{n} \rightarrow (\mathrm{A}+1,\mathrm{Z}+1) + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + \gamma$,
     potentially up to the 3^{rd} peak ($A \approx 190$) or beyond, depending on the
     neutron to seed ratio

NUCLEOSYNTHESIS CALCULATIONS

total radioactive heating rate

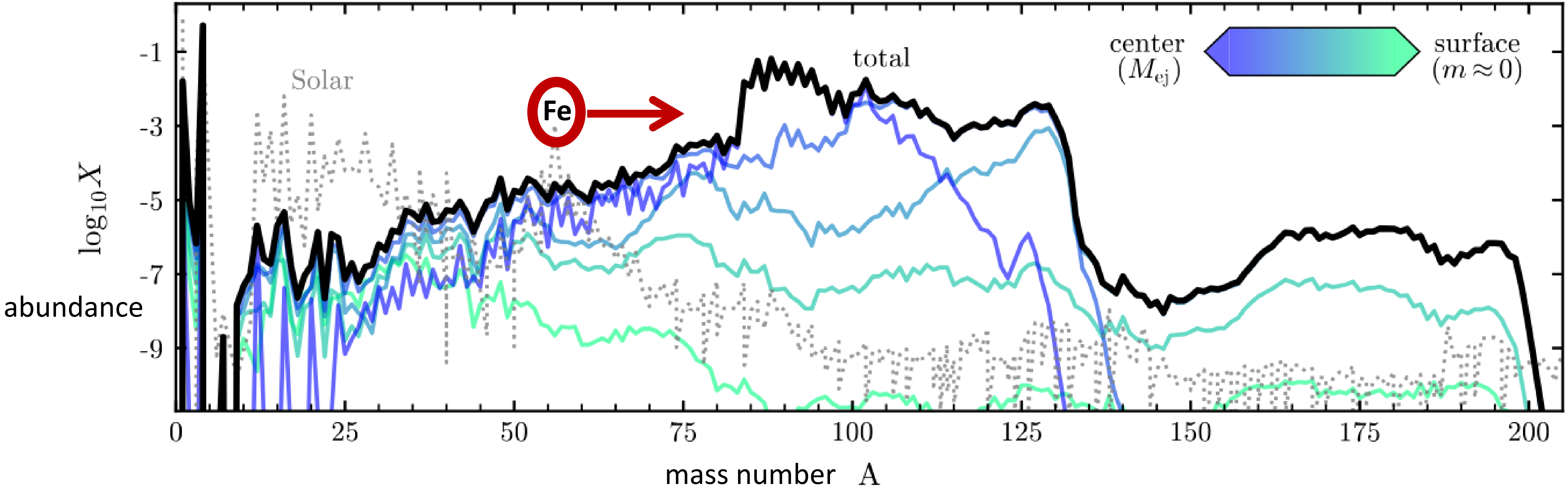
compositional evolution



(SkyNet: Lippuner&Roberts2015,2017)

NUCLEOSYNTHETIC YIELDS

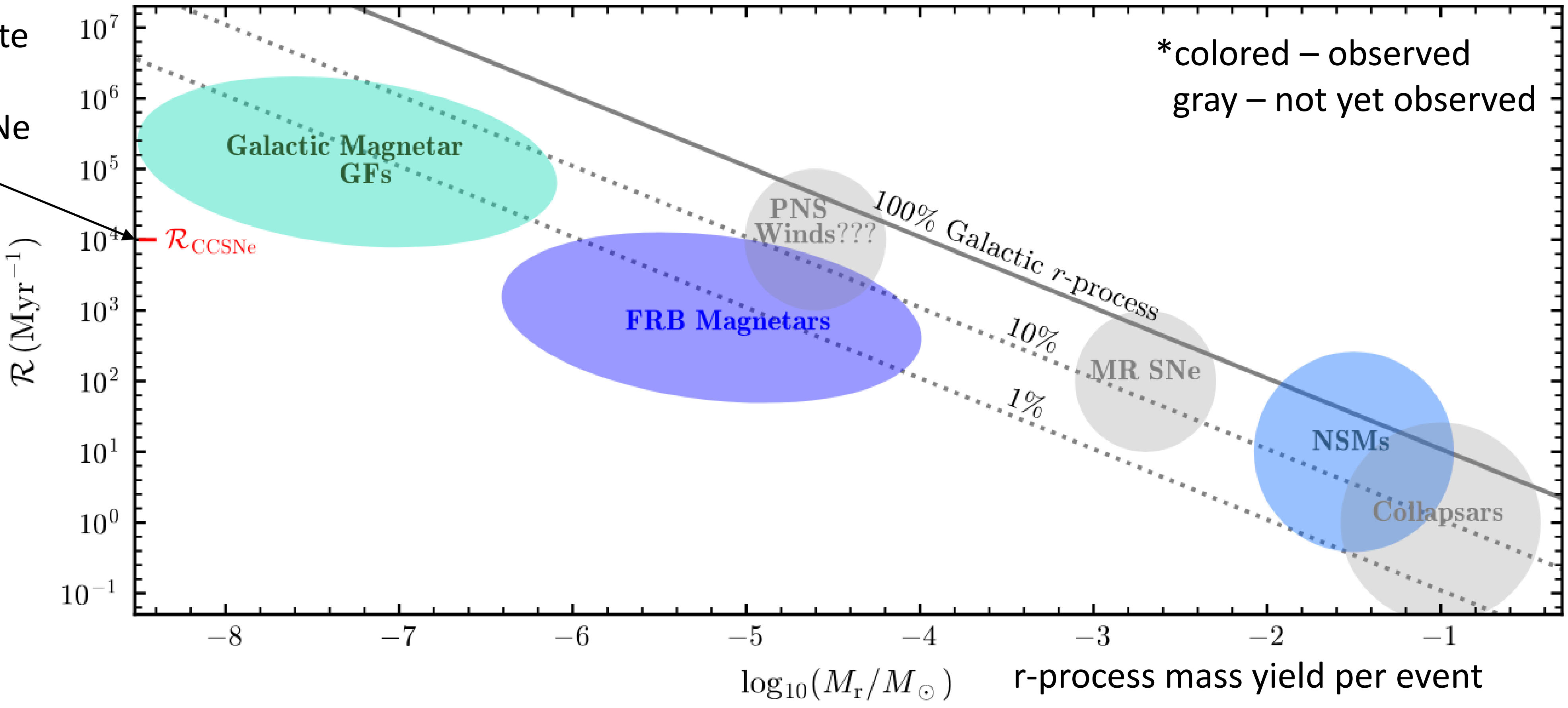
WE HAVE HEAVY ELEMNTS!



(Patel, Metzger, Goldberg, JC, Thompson, & Renzo 2025)

(SkyNet: Lippuner&Roberts2015,2017; Solar System abundances: Lodders2020)

GALACTIC R-PROCESS



Galactic rate of core-collapse SNe

event rate

*colored – observed
gray – not yet observed

r-process mass yield per event

- **Galactic Magnetars** could contribute **1 – 10 %** of the Galactic r-process

(Patel, Metzger, Goldberg, JC, Thompson, & Renzo 2025)

RADIOACTIVELY POWERED TRANSIENTS

- semi-analytic layer-by-layer model (Metzger2019):
  - optical depth: $\tau(v,t) = \int_v^\infty \kappa(v',t)\rho(v',t)dv'$, with opacity given by

$$\kappa(t) = X_p(t)\kappa_p + X_\alpha\kappa_\alpha + X_{\rm seed}\kappa_{\rm seed} + X_{\rm 2nd}\kappa_{\rm 2nd} + X_{\rm 3rd}\kappa_{\rm 3rd},$$

  - specific heating rate: $\dot{q}_{\rm heat}(m,t) = f_{\rm th}(m,t)\dot{q}(m,t)$, where the thermalization efficiency is:

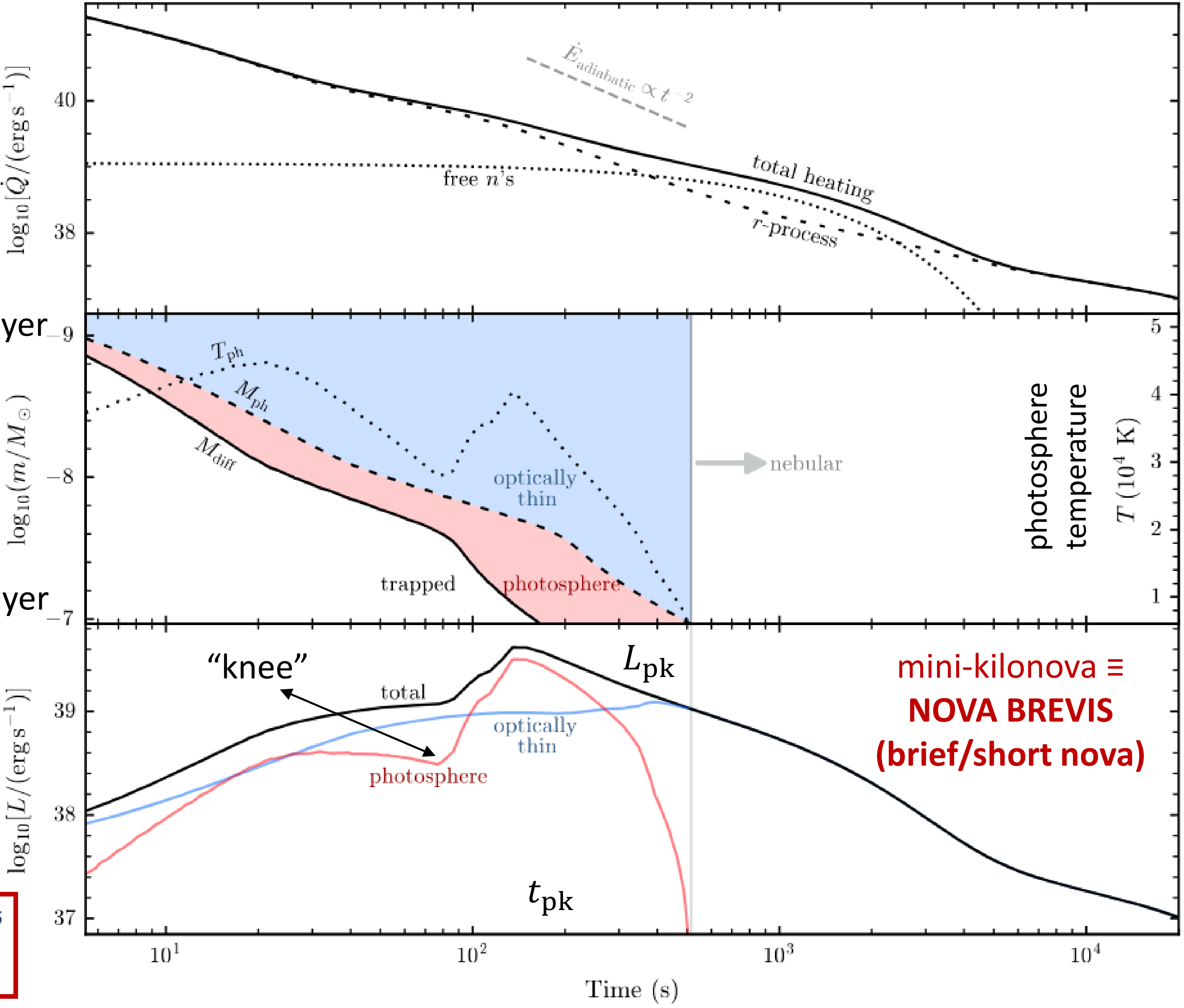
$$f_{\rm th}(t) = \underbrace{0.38}_{\beta\text{-decay } e^-}\underbrace{\frac{\dot{q}_n(t)}{\dot{q}(t)}}_{\text{neutron heating}} + \underbrace{\frac{\dot{q}_r(t)}{\dot{q}(t)}}_{\text{r-process heating}}\left[\underbrace{0.25}_{\beta\text{-decay } e^-} + 0.4\left\{\underbrace{1 - \exp\left(-\tau(t)\kappa_\gamma/\kappa(t)\right)}_{\beta\text{-decay gamma-rays}}\right\}\right],$$

  - diffusion surface: $\tau(r) = \frac{c}{v} \Rightarrow M_{\rm diff}$, and photosphere: $\tau(r) = \frac{2}{3} \Rightarrow M_{\rm ph}$
  - Arnett's law (Arnett1980):

    1) optically thick ("**photospheric**") emission: $L_{\rm ph} = \int_{M_{\rm ph}}^{M_{\rm diff}} \dot{q}_{\rm heat} dm$

    2) optically thin ("**nebular**") emission: $L_{\rm neb} = \int_0^{M_{\rm ph}} \dot{q}_{\rm heat} dm$

MINI-KILONOVA
(“nova brevis”)



radioactive heating
(with thermalization
correction)

outermost layer

lagrangian mass
coordinate

innermost layer

luminosity

photosphere
temperature

“knee”

$L_{\rm pk}$

$t_{\rm pk}$

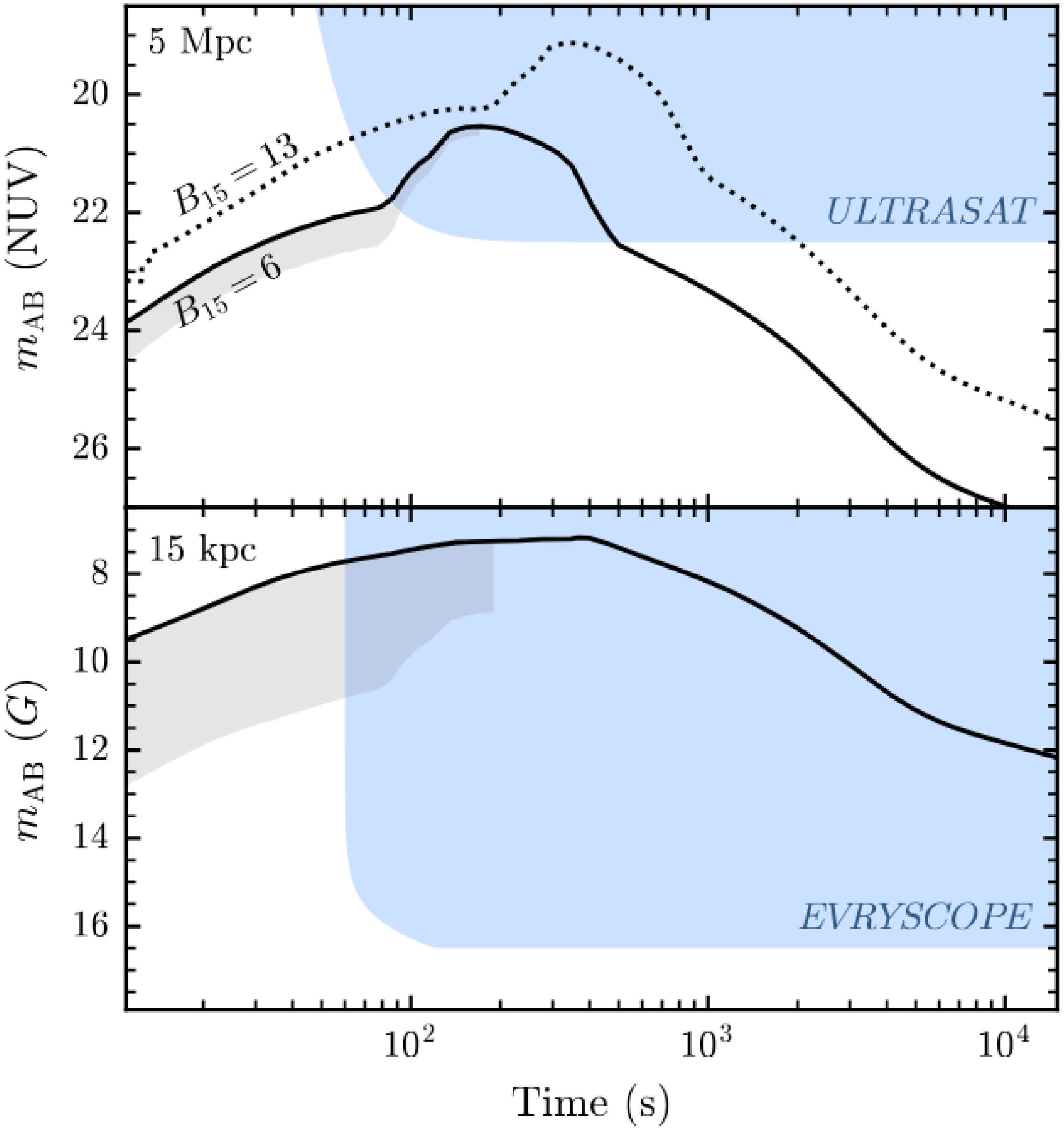
mini-kilonova ≡
NOVA BREVIS
(brief/short nova)

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

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

RADIOACTIVELY POWERED OPTICAL/UV EMISSION ≡ A BRIEF “NOVA”

- in the Milky Way (Local Group):
  - ➢ very large instantaneous field of view: **EVRYSCOPE** (38% of the night sky with a 2-minute cadence Law+2014)
- in the nearby universe ($\lesssim$ 10 Mpc):
  - ➢ a rapidly slewing space-based optical/UV telescope: **ULTRASAT** (Sagiv+2014, launch in **2027**), UVEX (Kulkarni+2021), or QUVIK (Werner+2023)
  - ➢ GF rate within $\lesssim$ 5 Mpc is $\sim 0.1\ \mathrm{yr}^{-1}$, for GFs with energy $\geq 10^{45}$ erg (Burns+2021)

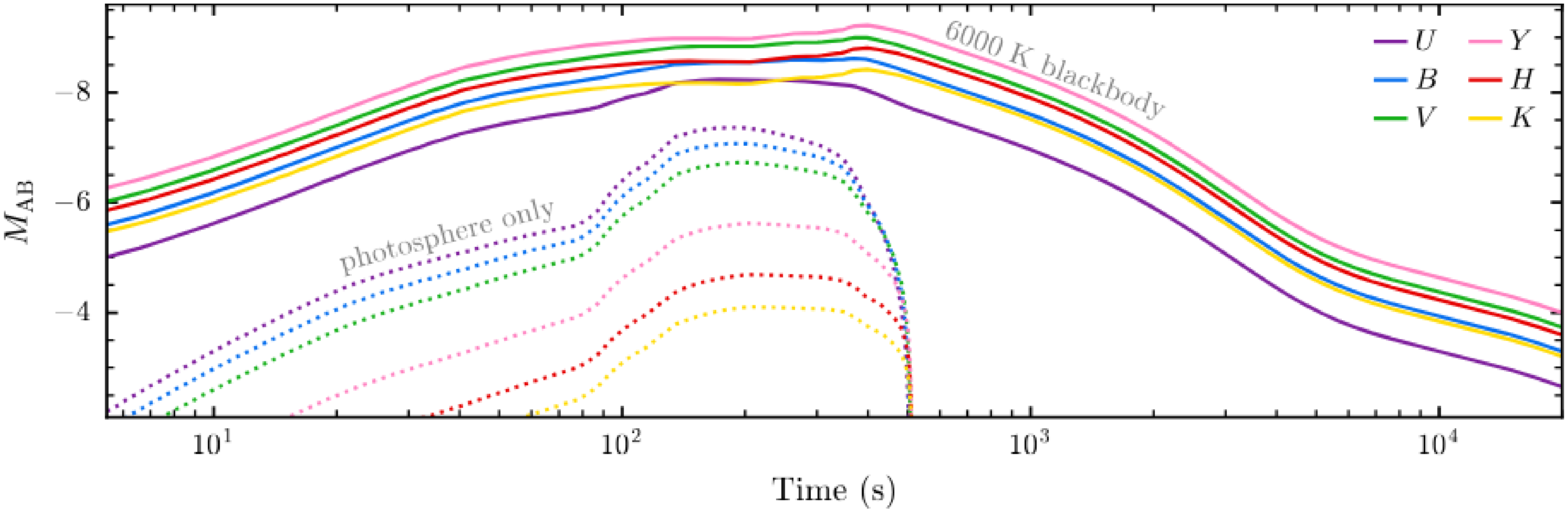


(Patel, Metzger, Goldberg, JC, Thompson, & Renzo 2025)

NOVA BREVIS SPECTRA

- two blackbody radiators:
  - optically thick ("photospheric") emission: $T_{\rm ph} = \left(\dfrac{L_{\rm ph}}{4\pi\sigma R_{\rm ph}^2}\right)^{1/4}$,
  - optically thin ("nebular") emission: $T_{\rm eff} = 6000\,{\rm K}$
- total flux: $F_\nu = F_{\nu,\,{\rm ph}} + F_{\nu,\,{\rm neb}} = \dfrac{1}{4d^2\sigma_{\rm SB}}\left[\dfrac{L_{\rm ph}}{T_{\rm ph}^4}B_\nu(T_{\rm ph}) + \dfrac{L_{\rm neb}}{T_{\rm eff}^4}B_\nu(T_{\rm eff})\right]$

absolute AB magnitudes in UV, optical, and infrared bands

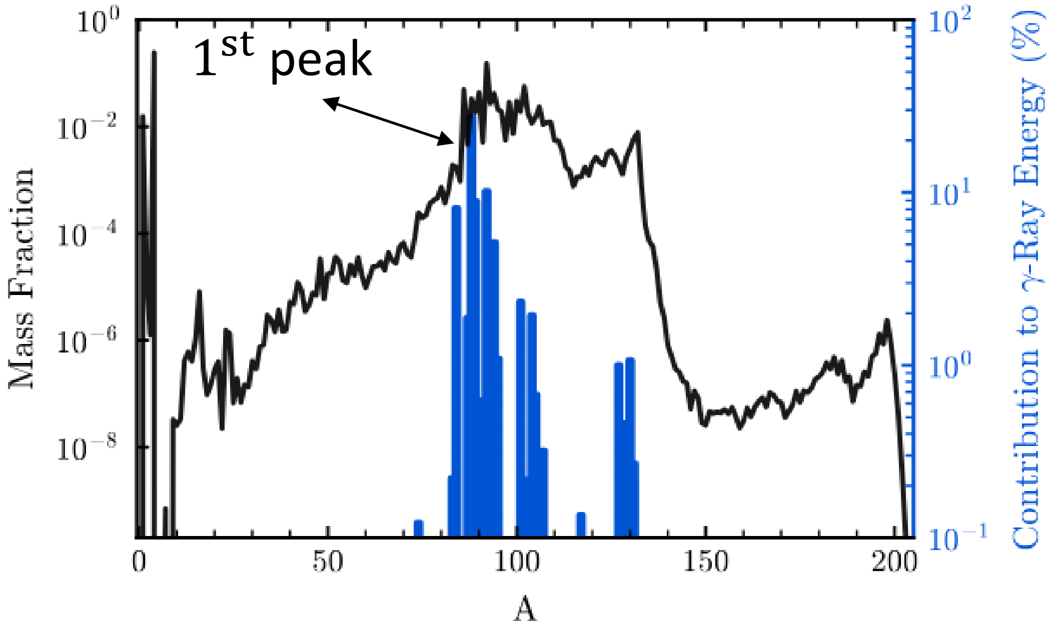


GAMMA-RAY EMISSION

- the same layer-by-layer approach
- approximate gamma-ray thermalization treatment of Hotokezaka+2016
- assuming constant opacity $\kappa_\gamma = 0.1\ \mathrm{cm}^2 \cdot \mathrm{g}^{-1}$
- considering all nuclear species that contribute at least 1% between 10 s and 14 000 s
- effective decay mode: $\mathrm{i} \rightarrow \mathrm{f} + \mathrm{e}^- + \bar{\upsilon}_\mathrm{e} + \gamma$
- weak reaction rates from JINA REACLIB database (Cyburt+2010)

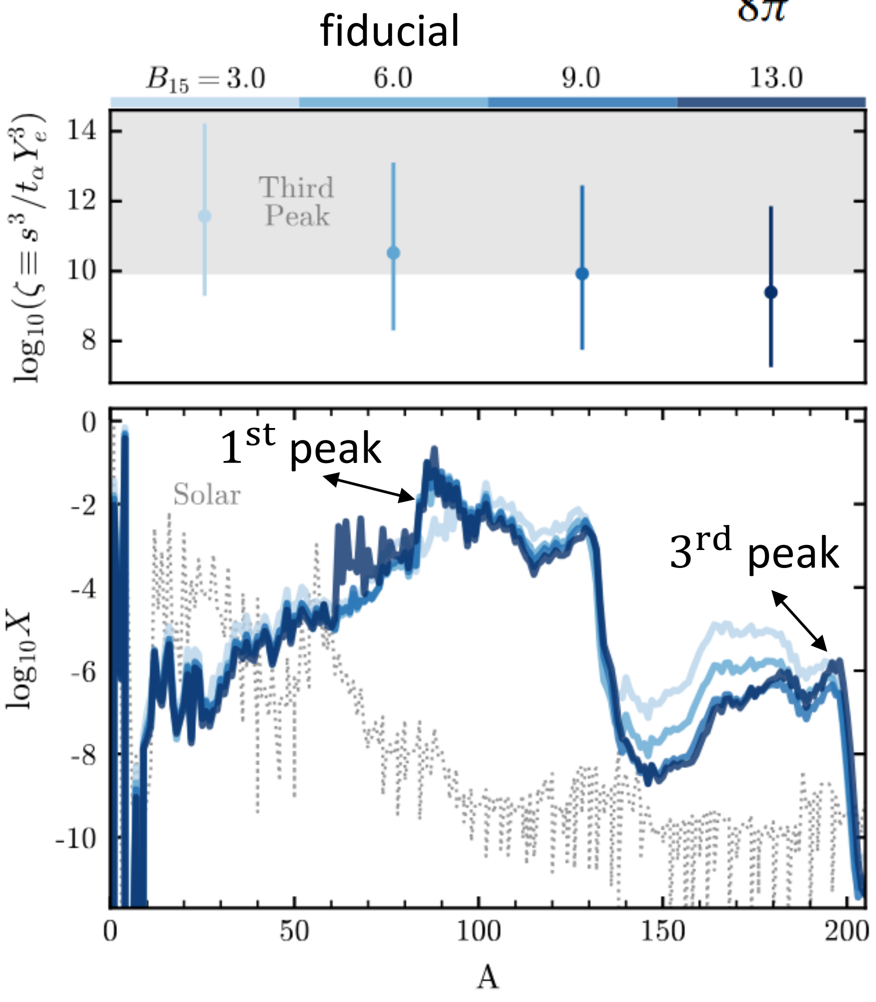
- fiducial model:
  - $\boldsymbol{M_{\mathrm{ej}} = 1.2 \times 10^{-6} M_\odot}$ $\boldsymbol{(M_\mathrm{r} = 7 \times 10^{-7} M_\odot)}$
  - $Y_\mathrm{e} = 0.40$
  - $\bar{v} = 0.15c$
  - $\beta = 6$
  - $f_\Omega = 3/4$

$$\rho(r,t) = \frac{\beta - 3}{4\pi f_\Omega} \frac{M_{\mathrm{ej}}}{(\bar{v}t)^3} \left(\frac{v}{\bar{v}}\right)^{-\beta}, v > \bar{v},$$



IMPACT OF VARYING THE FLARE STRENGTH

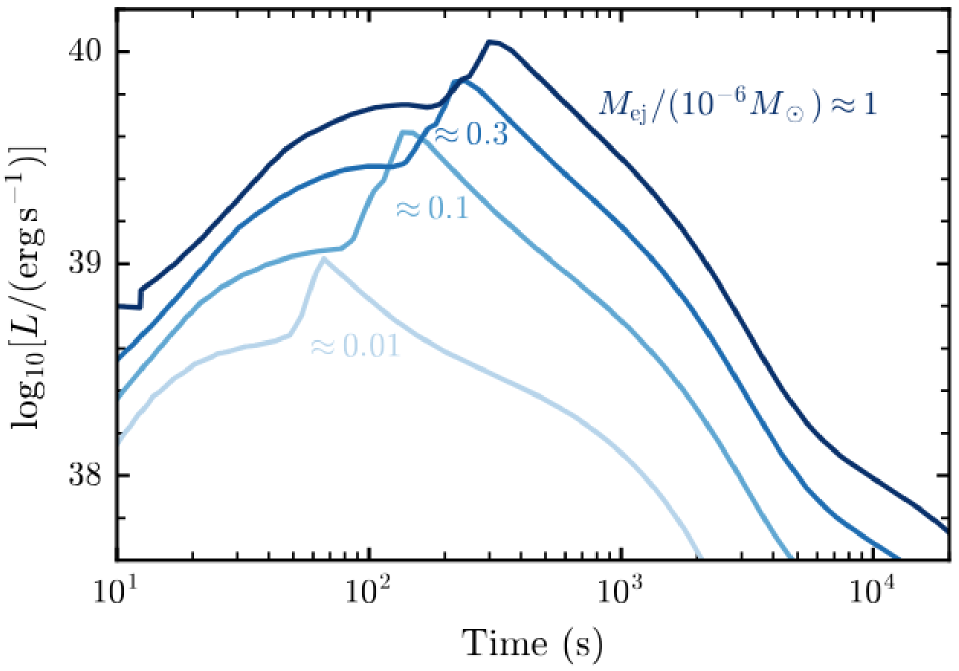
$$P_{\rm GF} \approx \frac{B^2}{8\pi}$$



r-process figure of merit parameter

mass-weighted nucleosynthesis yields

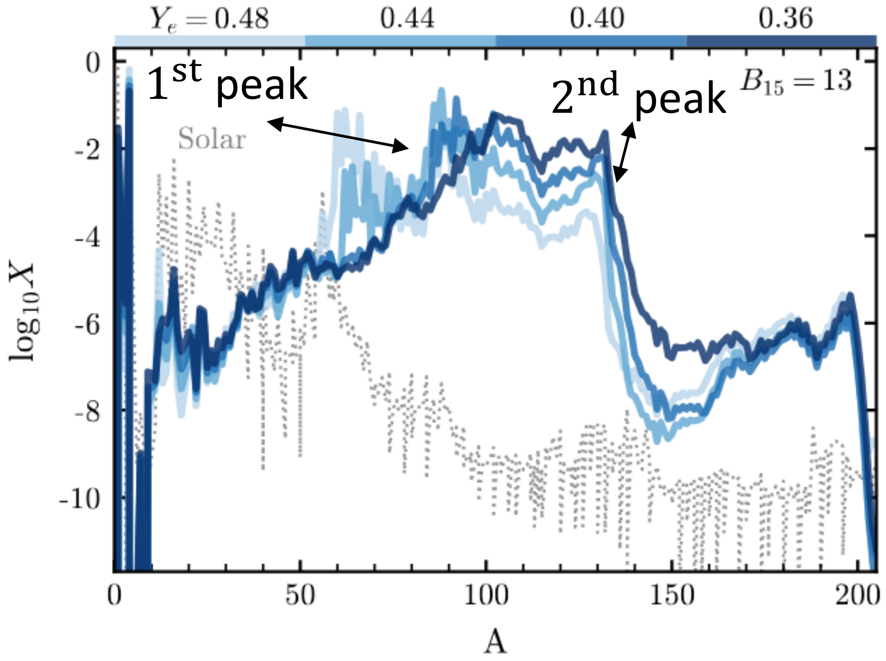
- $M_{\rm ej}/{\rm M}_\odot \in (10^{-8} - 10^{-6})$ for $B_{15} \in (3,13)$
- $X_{\rm r}$ increases with flare strength
- stronger flares produce brighter and longer duration transients

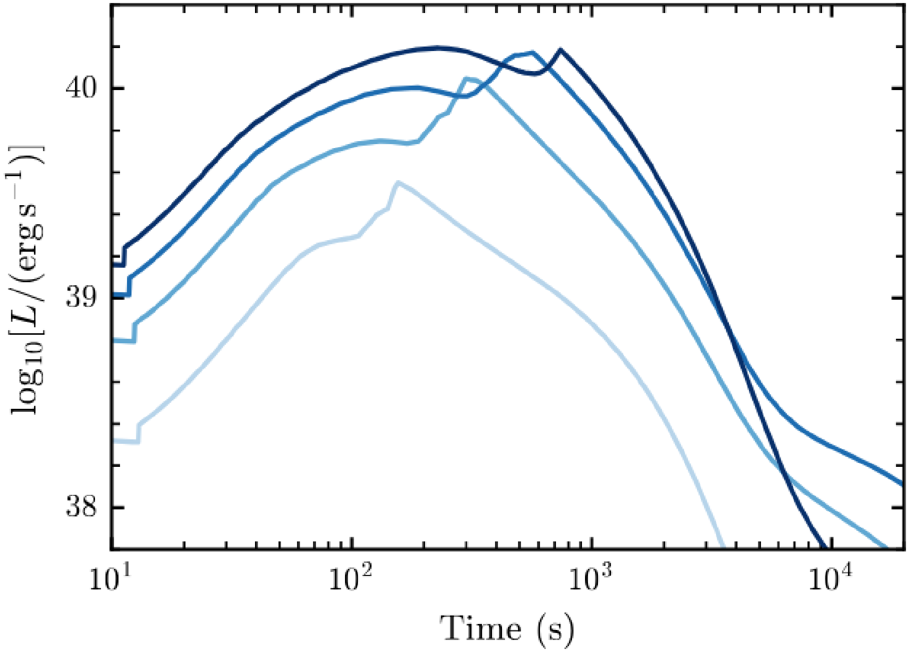


IMPACT OF VARYING THE ELECTRON FRACTION

- for $B_{15} = 13 \left(M_{\mathrm{ej}} \sim 10^{-6} \mathrm{M}_{\odot}\right)$ we explore $Y_{\mathrm{e}} = 0.36, 0.40, 0.44, 0.48$
- X_{r} decreases with Y_{e}
- lighter elements with increasing Y_{e}
- higher X_{r} increases luminosity, different composition affects opacity => t_{pk}

mass-weighted nucleo-synthesis yields





IMPACT OF VARYING THE MODEL PARAMETERS

- larger Y_e:
  - lower X_r => reducing the gamma-ray emission
- larger $\bar{v}$:
  - ejecta becomes optically-thin earlier when the energy generation rate is larger => earlier and brighter peak emission
- larger β:
  - less mass in the outer ejecta layers => steeper light-curve rise
- **larger $\boldsymbol{M}_\mathbf{ej}$**:
  - increases the peak timescale and gamma-ray luminosity **significantly**