MAGNETAR GIANT FLARES AS A NEW SITE OF R-PROCESS NUCLEOSYNTHESIS

GA UK

Jakub Cehula
Charles University, Prague
→
Astronomical Institute, SAS & Tartu Observatory, Estonia

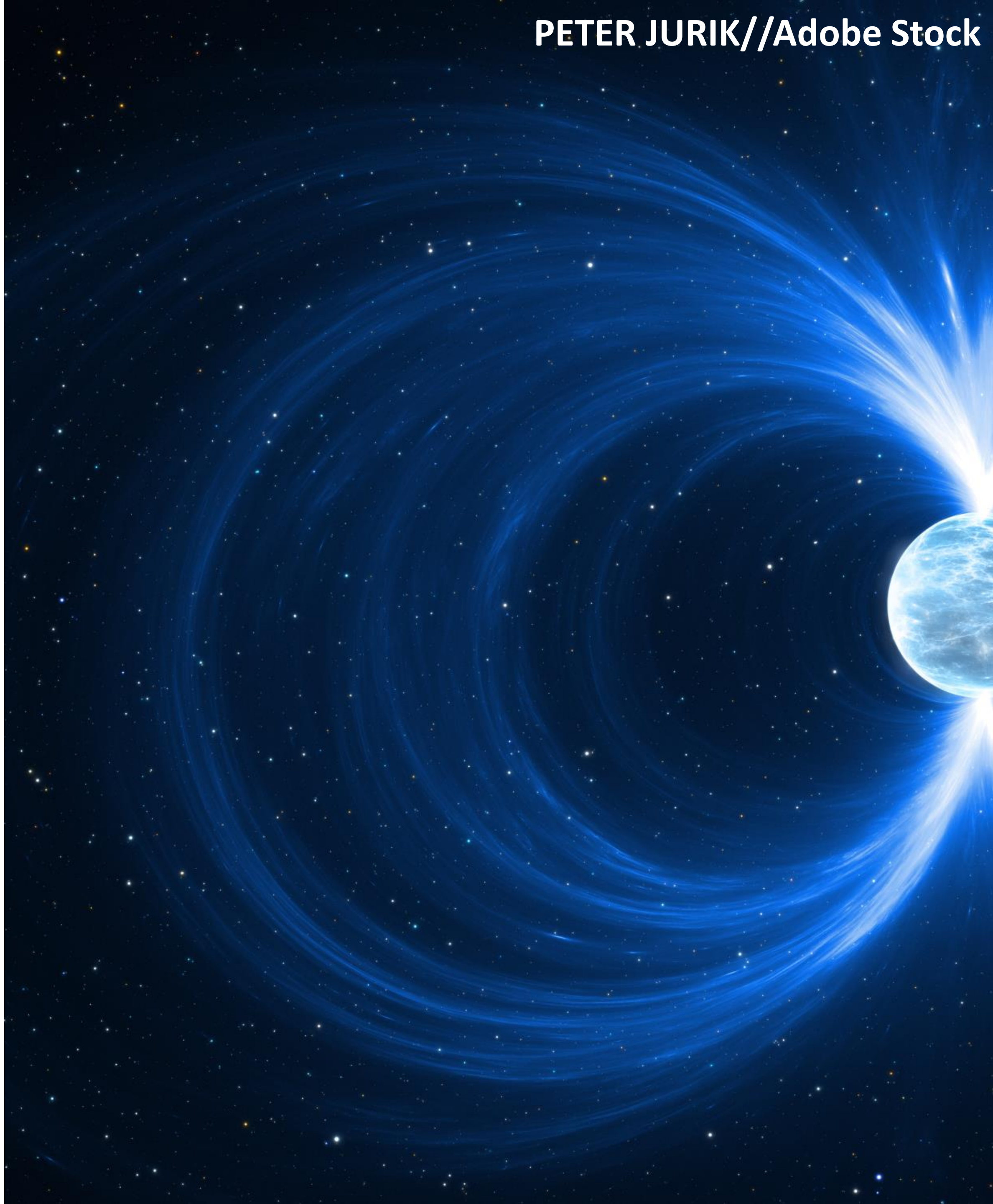
Charles University

with **Anirudh Patel** (Columbia U.), Brian Metzger (Columbia U./Flatiron), Todd Thompson (Ohio State U.), and collaborators

Tatra Astro Summit 2025, September 24, 2025

MAGNETAR GIANT FLARES

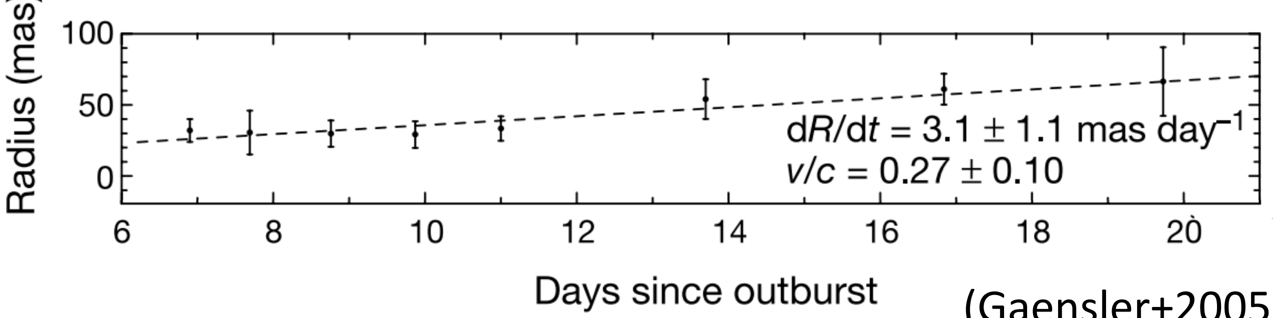
- magnetars:
  - neutron stars (NSs) with extremely strong magnetic fields ($B \gtrsim 10^{14}$ G; $\mathrm{B}_{\odot} \sim 1$ G)
  - produced in tens of per cent of CCSNe (Beniamini+2019)
- giant flares (GFs):
  - the most powerful non-cataclysmic NS outbursts ($E \in 10^{44} - 10^{47}$ erg, $\mathrm{L}_{\odot} \sim 4 \times 10^{33}$erg / s)
  - galactic GFs: three in 50 years (Mazets+1979; Hurley+1999, 2005)
  - extragalactic GFs: seven candidates in 20 years (Beniamini+2024; Rodi+2025)
  - most notable GF: the **2004 GF from SGR 1806-20** (Hurley+2005)



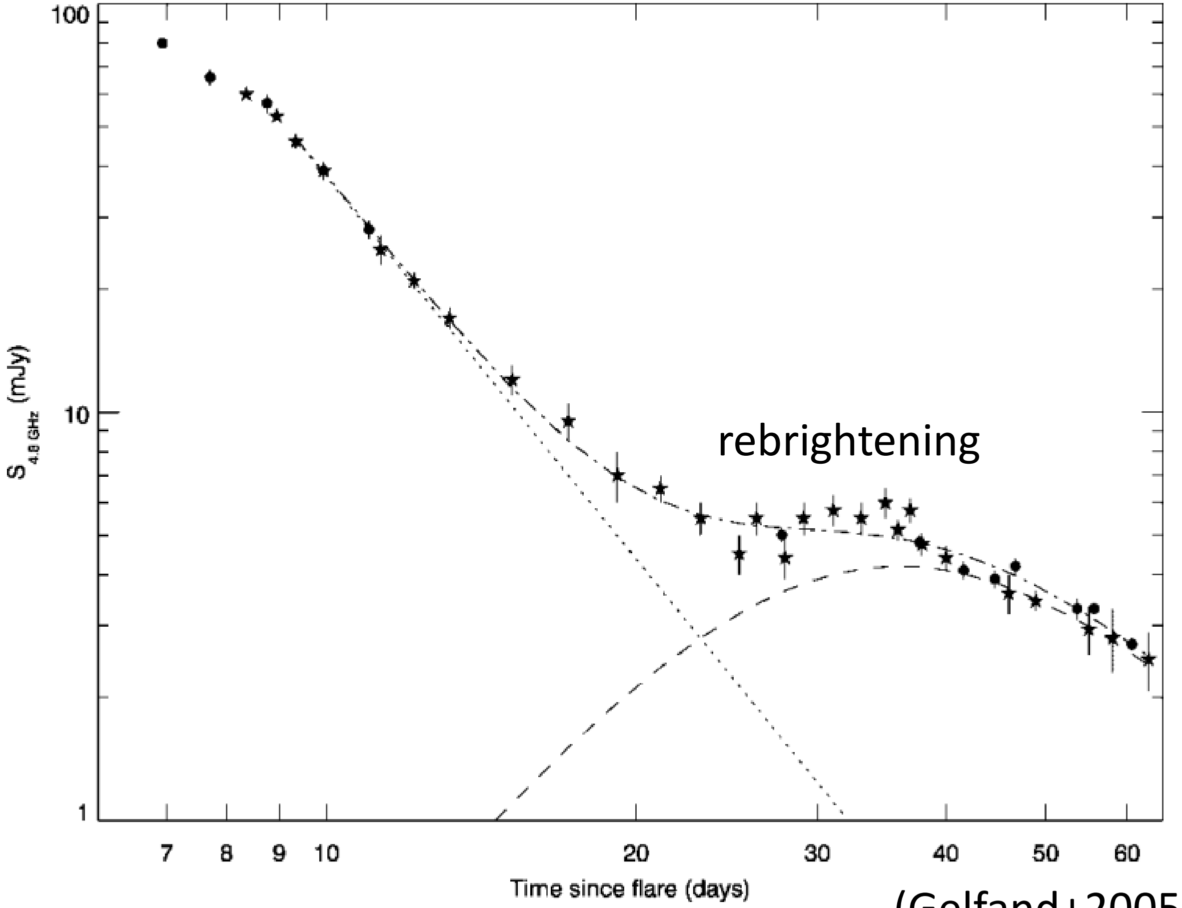
DECEMBER 2004 GF: RADIO AFTERGLOW

- GF: $\sim 2 - 4 \times 10^{46}$ erg during $0.2 - 0.5\ s$ in soft gamma-rays and hard X-rays (Hurley+2005, Palmer+2005)
- radio afterglow (Cameron+2005; Gaensler+2005; Gelfand+2005):
  - ➢ **rebrightening** around Day 25 lasting for about a week
- modelling of the radio light curve:
  - ➢ ejecta hitting a pre-existing shell
  - ➢ mildly relativistic ($v_{\mathrm{ej}} \sim 0.3 - 0.7c$) ejecta of mass $M_{\mathrm{ej}} \sim 10^{-7}\ \mathrm{M}_{\odot}$ (Gelfand+2005, Granot+2006)
- **HOW** to eject $10^{-7}\ \mathrm{M}_{\odot}$ from a NS?!

Radio modelling - VLBI

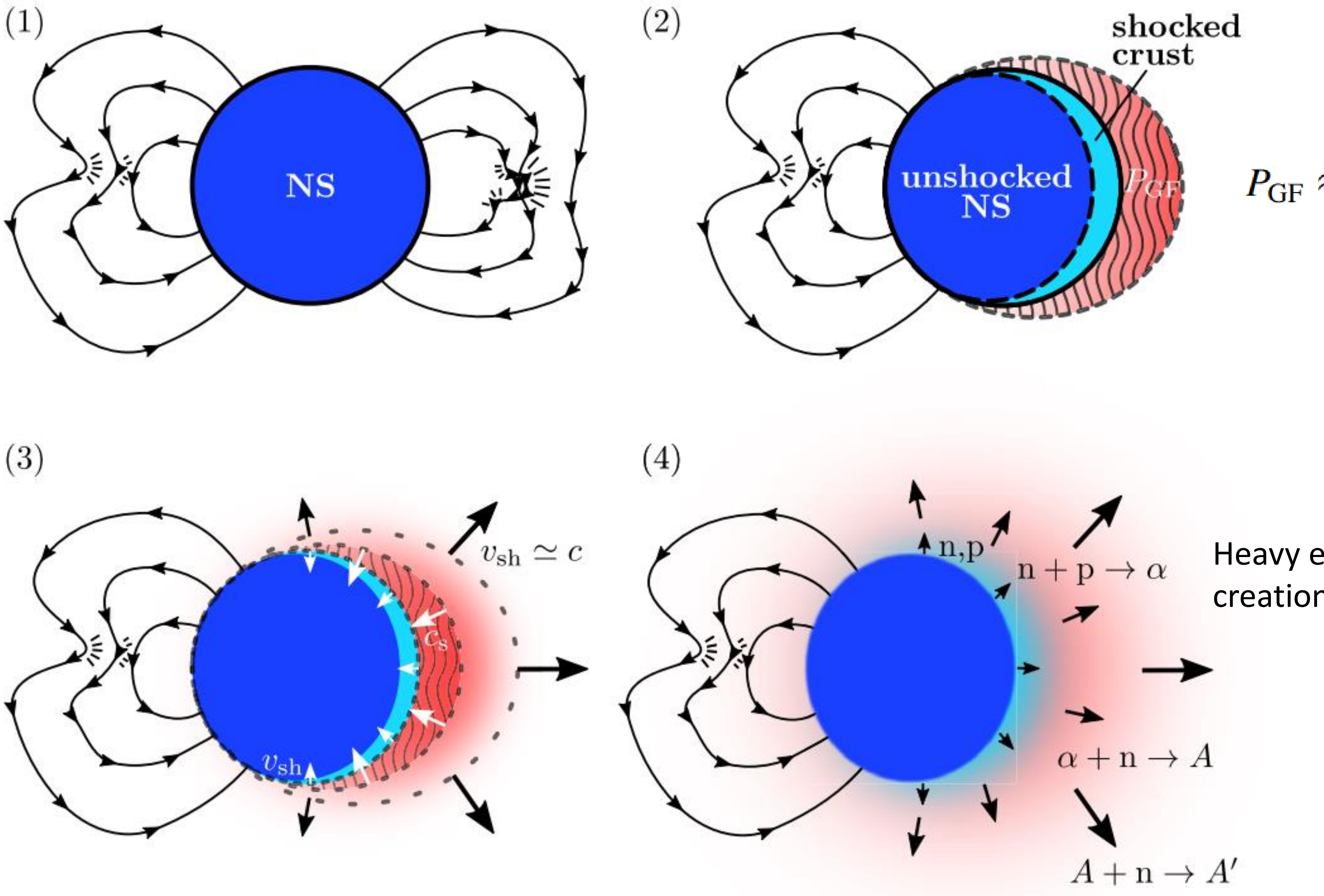


(Gaensler+2005)



(Gelfand+2005)

PHYSICAL PICTURE FOR BARYON EJECTION



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

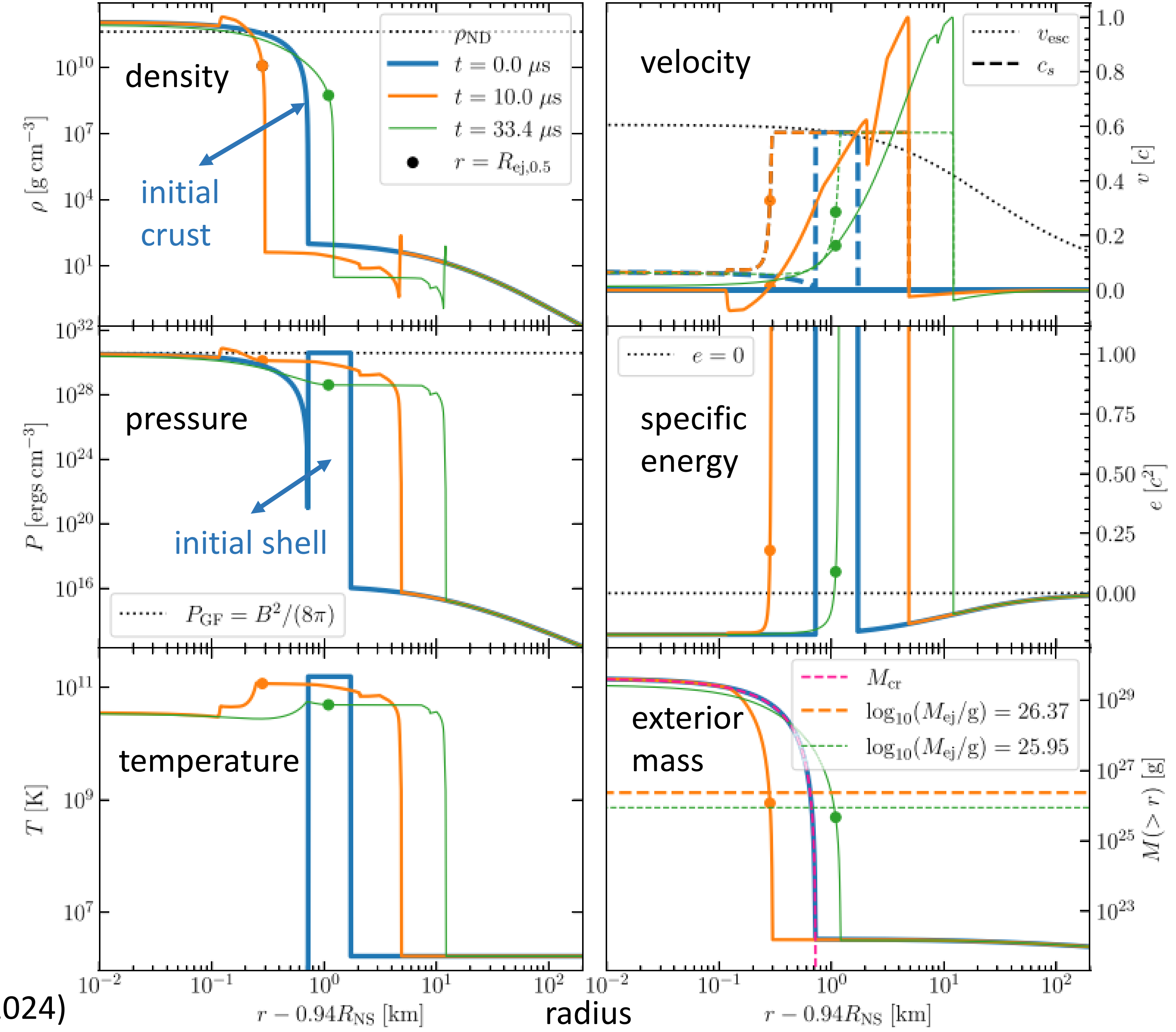
Heavy element creation?

(JC, Thompson, & Metzger 2024)

NUMERICAL APPROACH

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

(PLUTO: Mignone+2007,2024)

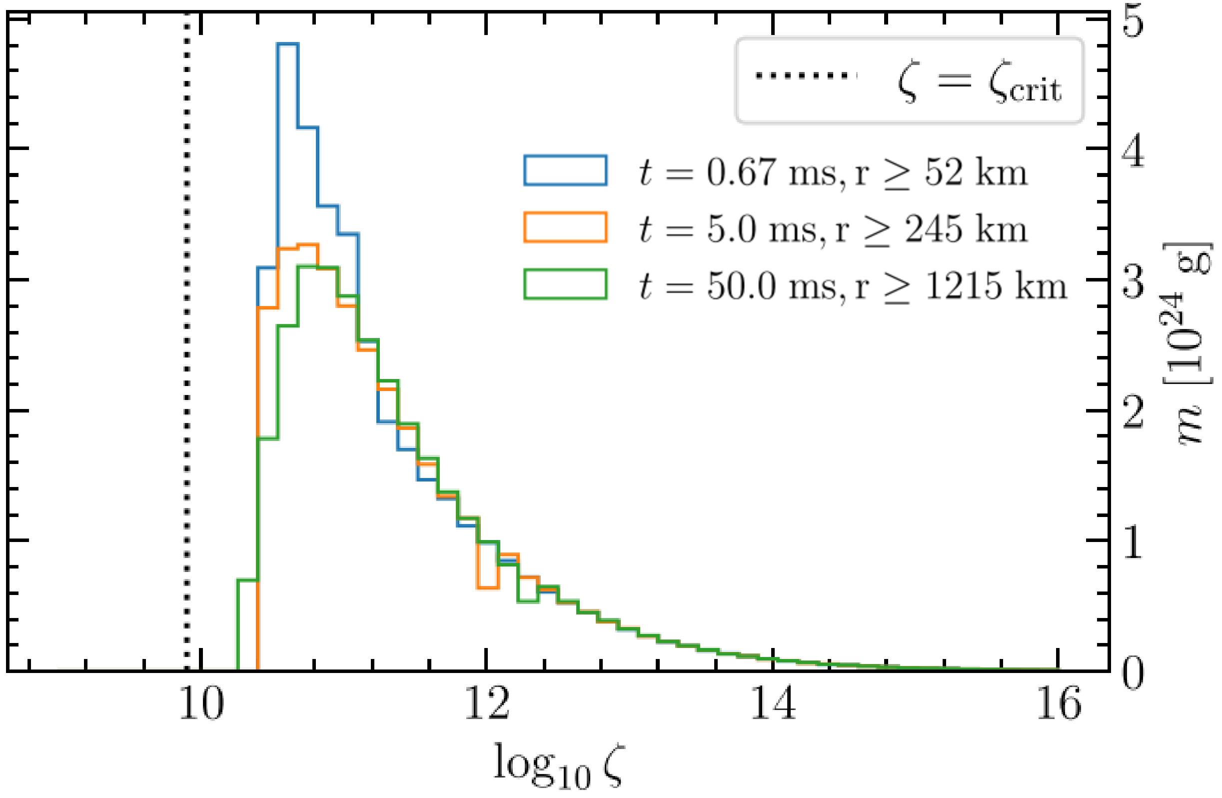


HEAVY ELEMENT CREATION

- rapid neutron-capture process (***r*-process**): a set of nuclear reactions responsible for the creation of approx. half of the atomic nuclei heavier than iron
- ***r*-process**: if $\zeta > \zeta_{\rm crit}$, then heavy r-process is happening (Hoffman+1997)
- it holds:

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

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

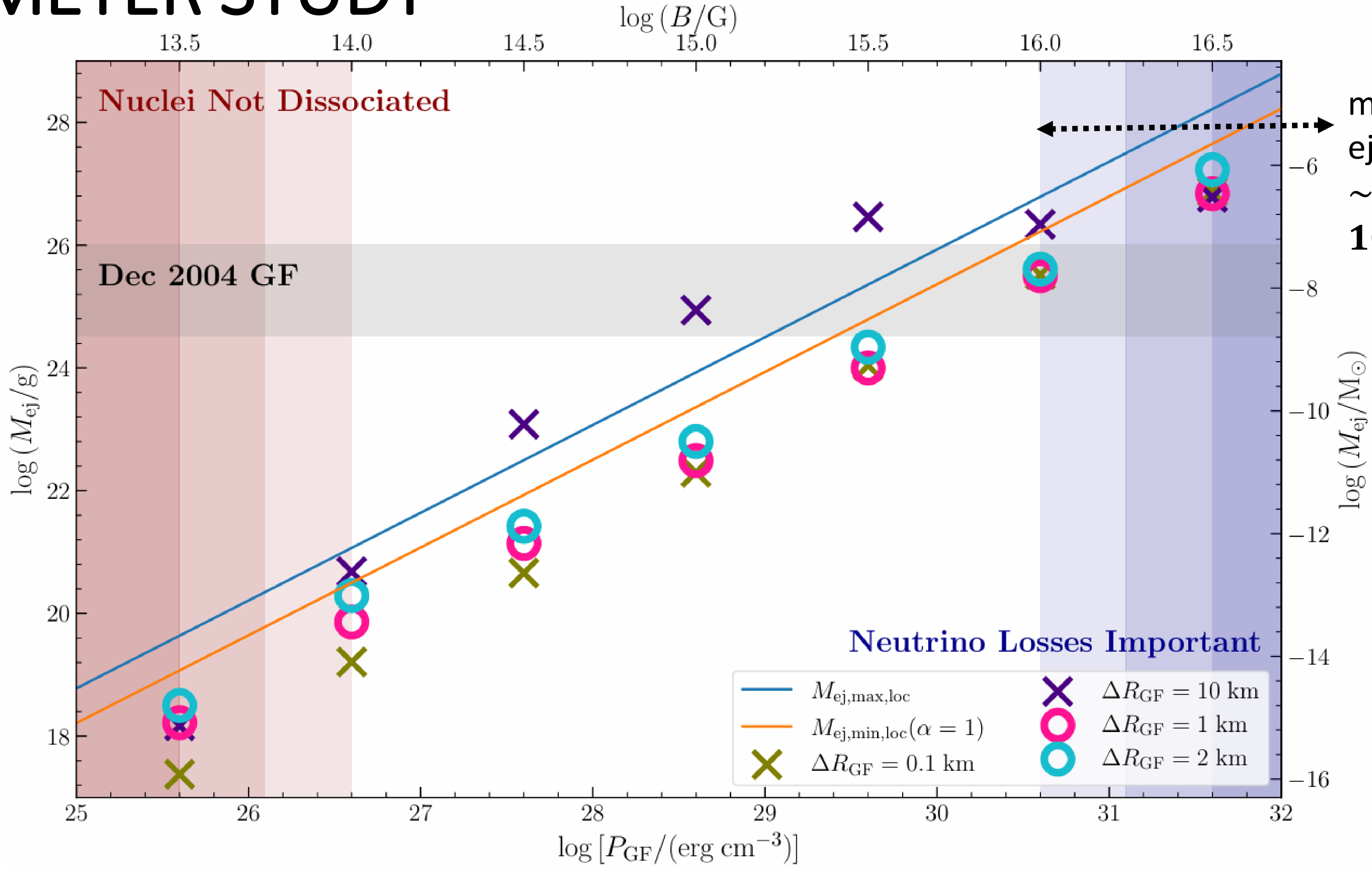


- we see that we **have heavy *r*-process**!

(JC, Thompson, & Metzger 2024)

PARAMETER STUDY

ejecta mass



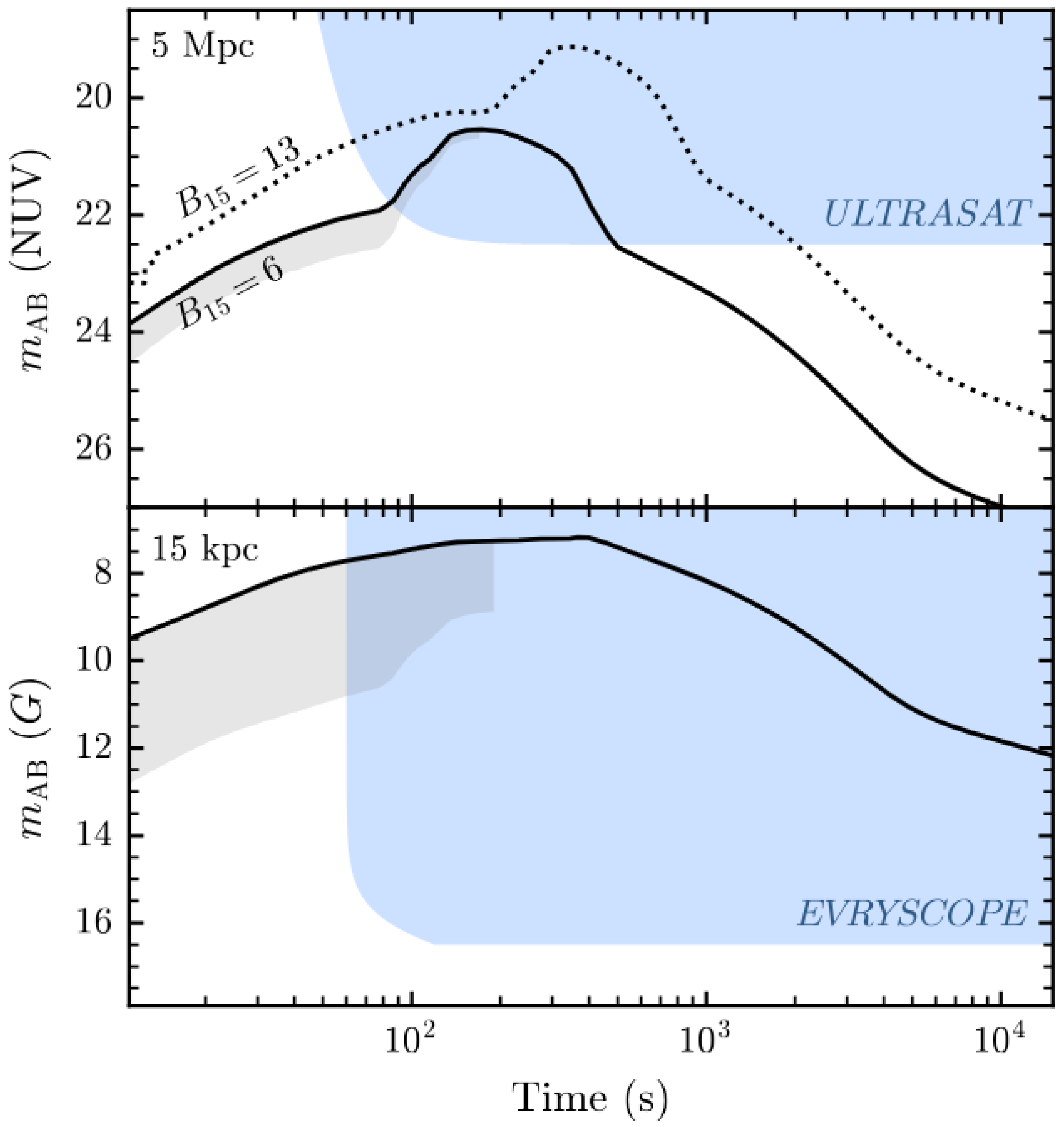
maximum ejecta mass $\sim 10^{-5} - \mathbf{10^{-6}}\ \mathrm{M}_\odot$

giant flare strength

(JC, Thompson, & Metzger, 2024)

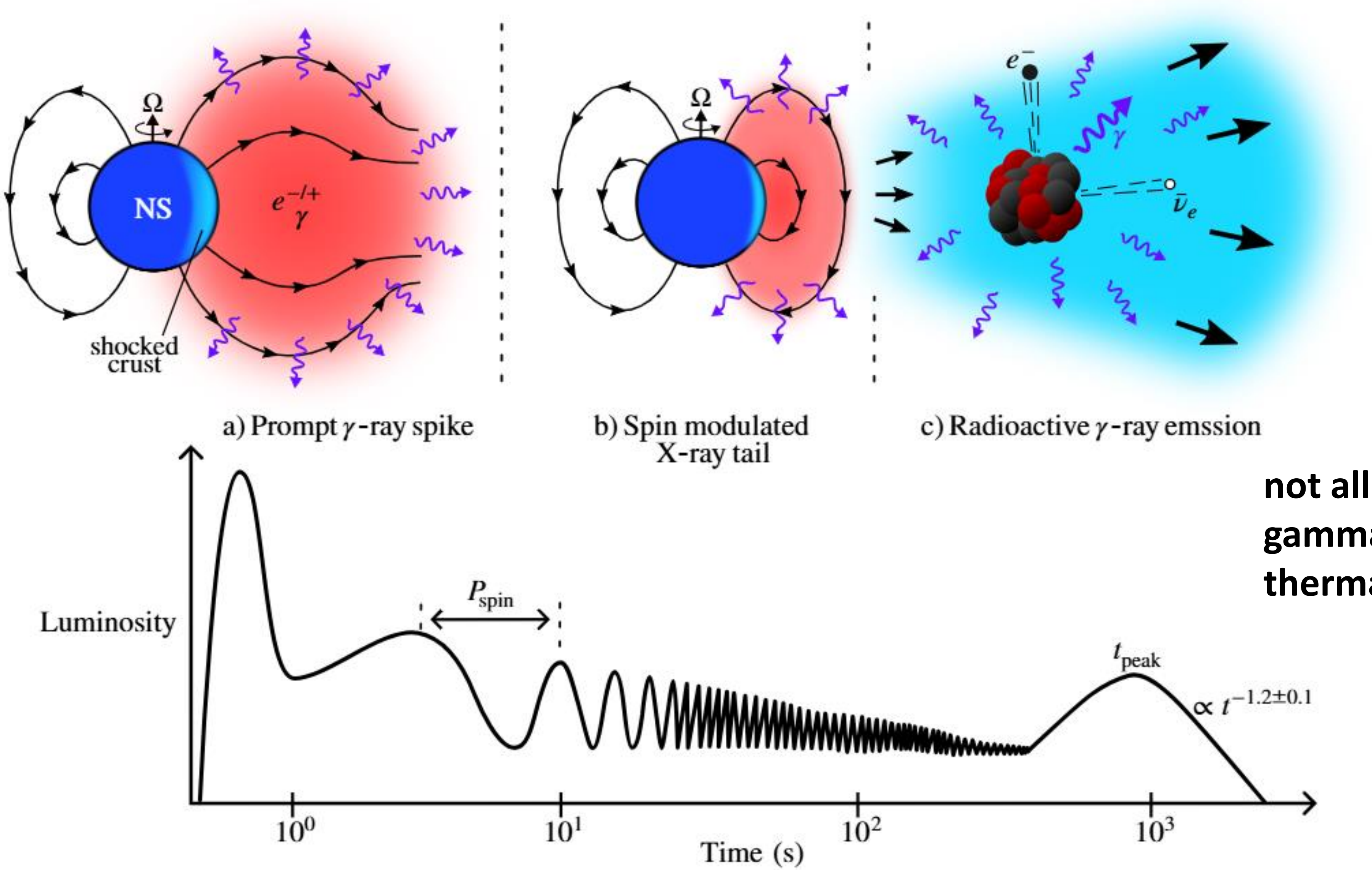
MINI-KILONOVA (≡ NOVA BREVIS) DETECTION PROSPECTS

- r-process => radioactive heating => kilonova-like optical/UV transient:
  - rough estimate: short ~ minutes long, luminous ~ 10^{39} erg s^{-1} optical/UV transient ≡ '**NOVA BREVIS**' (a brief/ short 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+2024)



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

PICTURE FOR GAMMA-RAY EMISSION

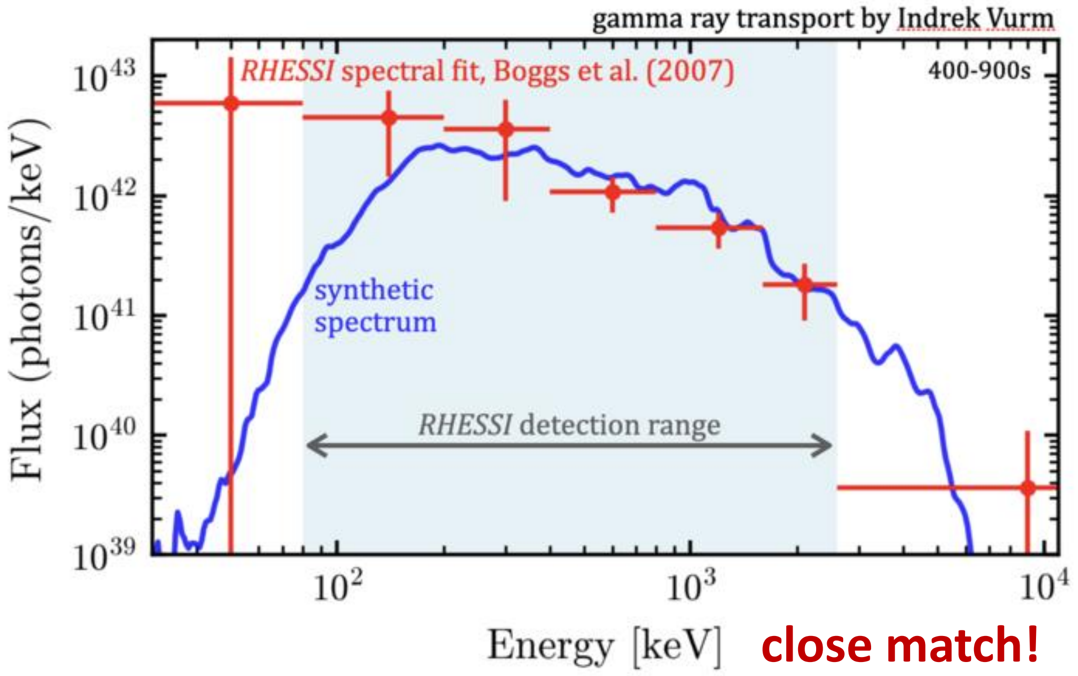


not all β-decay gamma-rays get thermalized!

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

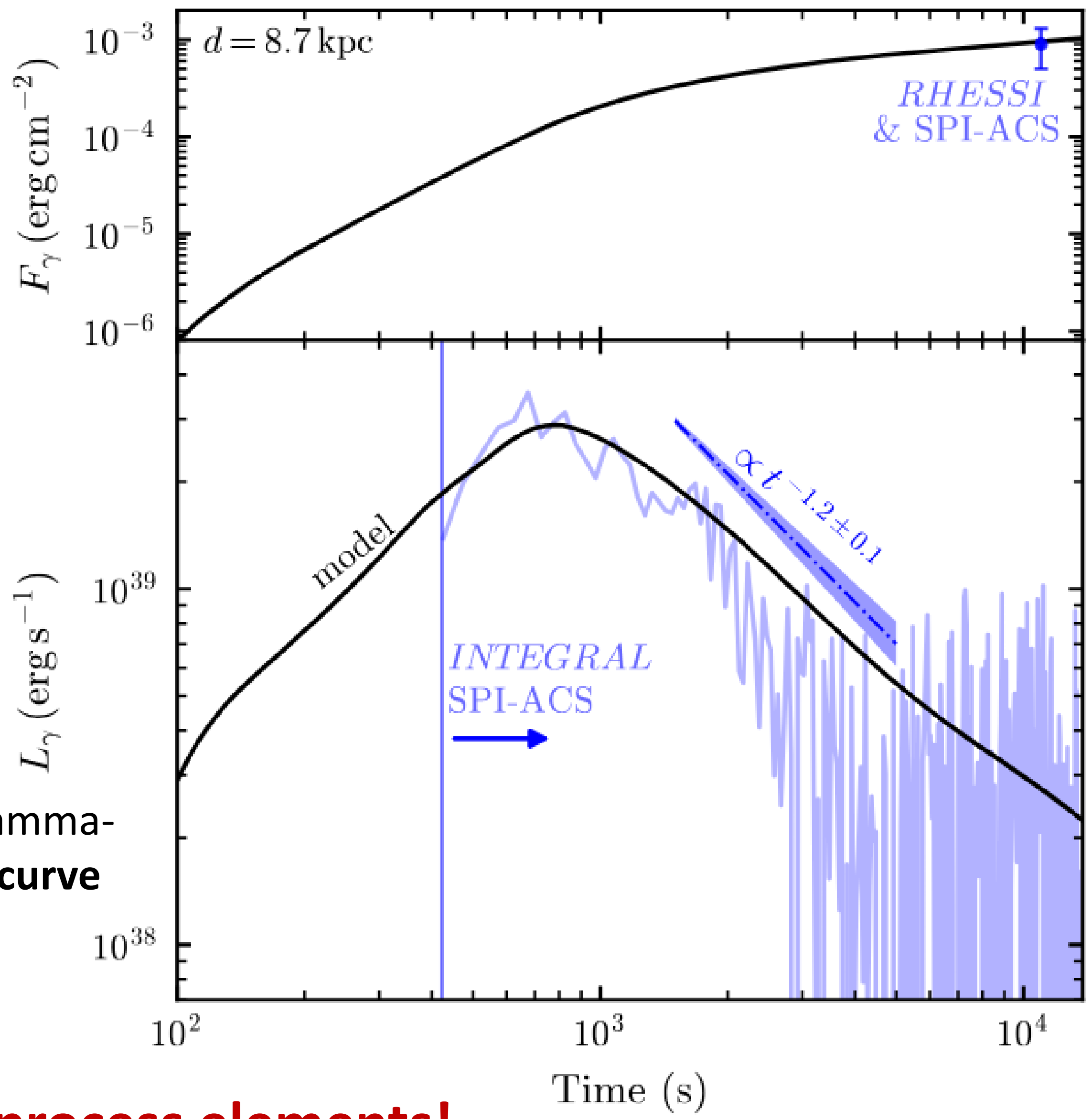
DECEMBER 2004 GF: GAMMA-RAY EMISSION

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



close match!

cumulative **fluence**

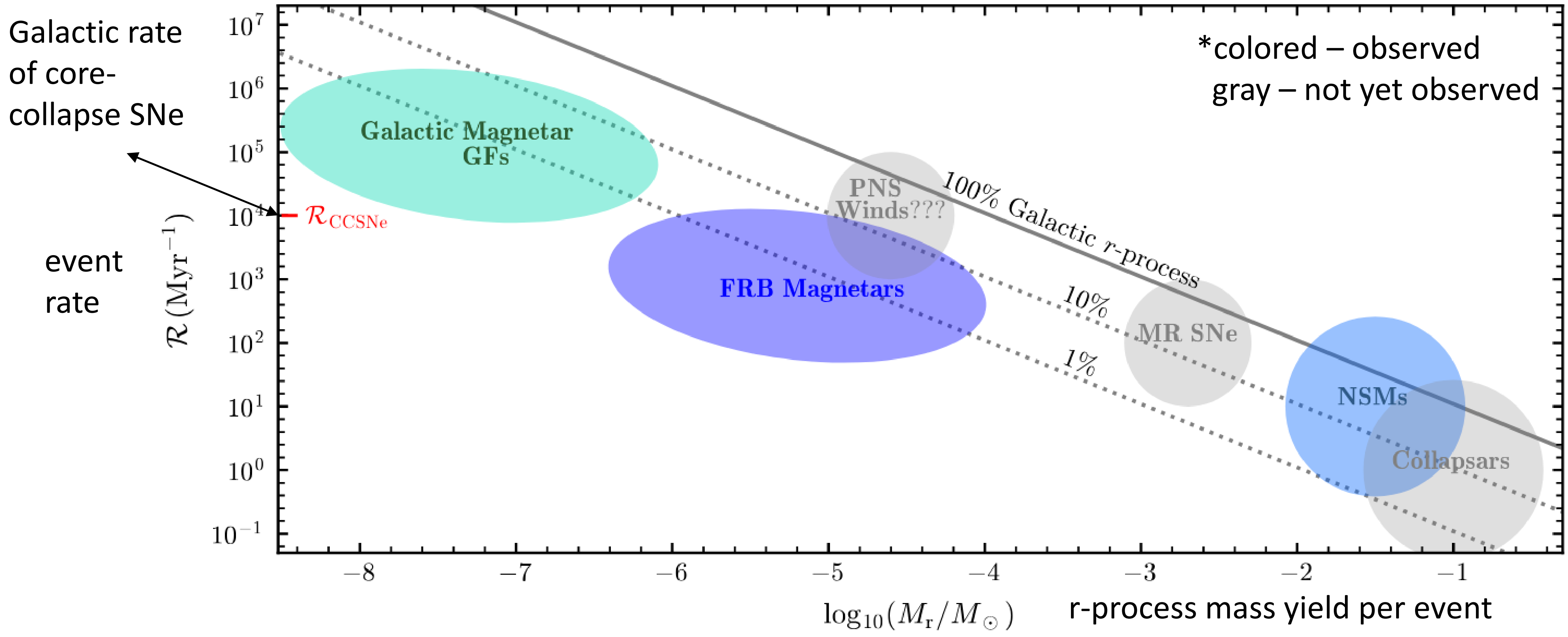


~ MeV gamma-ray **light curve**

- conclusion: **direct evidence for $\sim 10^{-6}$ $M_\odot$ of r-process elements!**

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

GALACTIC CHEMICAL EVOLUTION



- **Galactic Magnetars** could contribute **1 – 10 %** of the Galactic r-process
- FBR Magnetars are rarer but more active (e.g. Margalit+2020) => similar r-process yield
- magnetar GFs **track star formation**, some studies argue for such a channel (e.g. Lian+2023)

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

SUMMARY

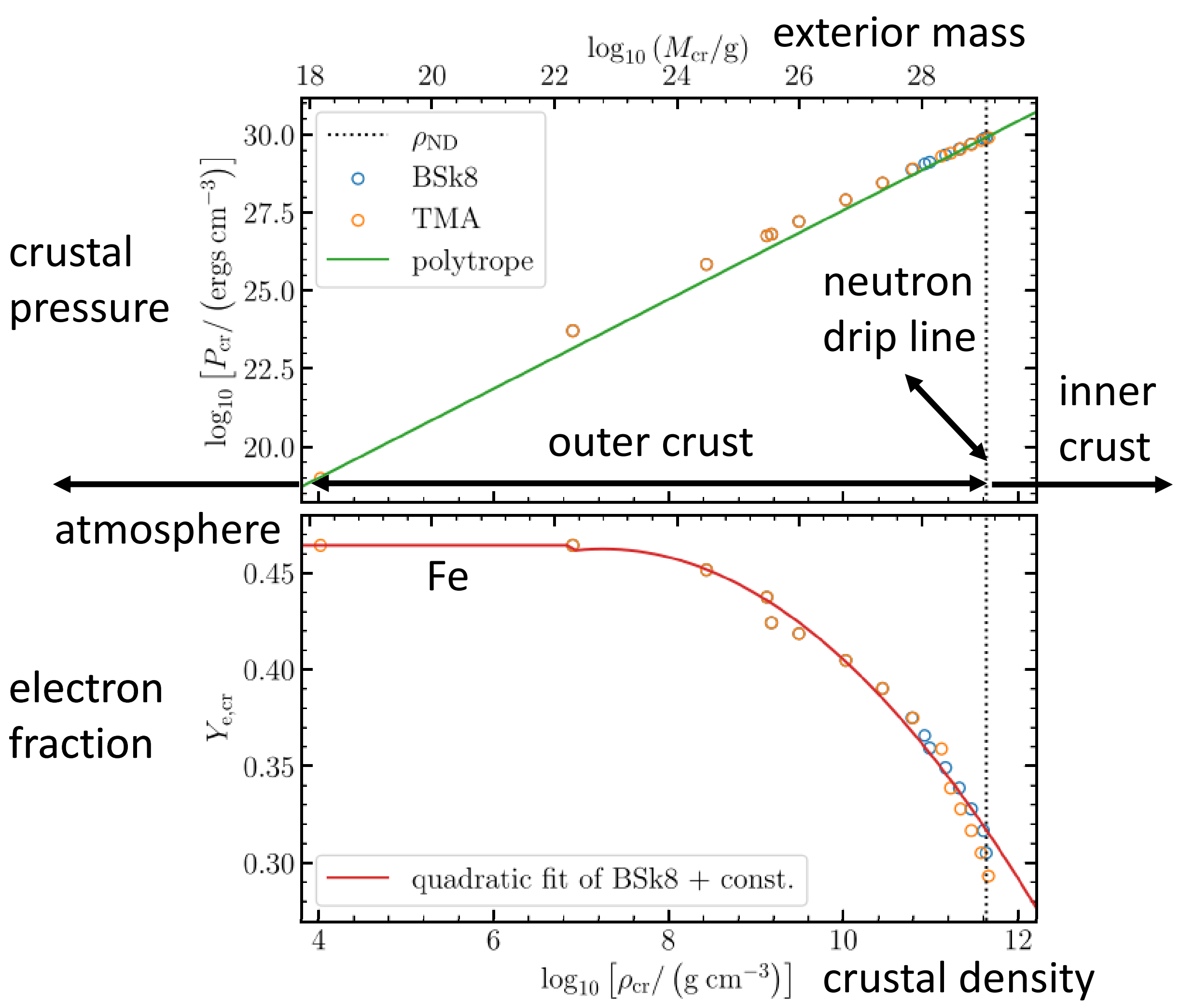
- motivation: modeling of the radio afterglow of the Dec 2004 GF from SGR 1806-20 indicates baryon ejection (Gelfand+2005,Granot+2006)
- hypothesis: GF drives a relativistic shock into the NS crust, leading to mass ejection
- methods: 1D modeling, both analytical and numerical
- results:
  - ejecta properties **align with radio** afterglow observations: mildly relativistic & $M_{\rm ej} \sim 10^{-8} - 10^{-6}\ \mathrm{M}_\odot$
  - r-process? **yes!**
  - radioactively powered kilonova-like transient – "**nova brevis**" (brief/short nova): $t_{\rm peak}\sim$ 10 – 15 min, $L_{\rm peak} \sim 10^{39} - 10^{40}$ erg/s. Potentially detectable within a few Mpc (ULTRASAT/QUVIK/UVEX)
  - radioactive **gamma-ray emission**: Doppler-broadened gamma-ray lines at $\sim$ 1 MeV, **matching an unexplained signal** following the Dec 2004 GF (**fluence, light curve, spectrum for $M_{\rm ej} \sim 10^{-6}\ \mathrm{M}_\odot$**)
  - **magnetar GFs** are the second **confirmed r-process site**, contributing **1-10 %** of the Galactic r-process budget. This channel tracks star formation
- future work: 2D/3D relativistic MHD simulations with neutrino cooling

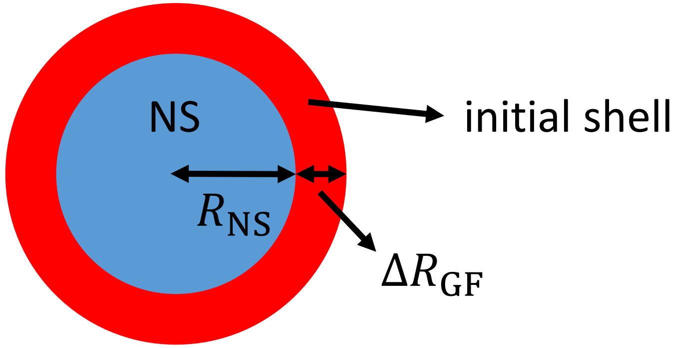
(**1**. JC, Thompson, & Metzger, 2024; **2**. Patel, Metzger, Goldberg, JC, Thompson, & Renzo 2025; **3**. Patel, Metzger, JC, Burns, Goldberg, & Thompson 2025)

BACKUP SLIDES

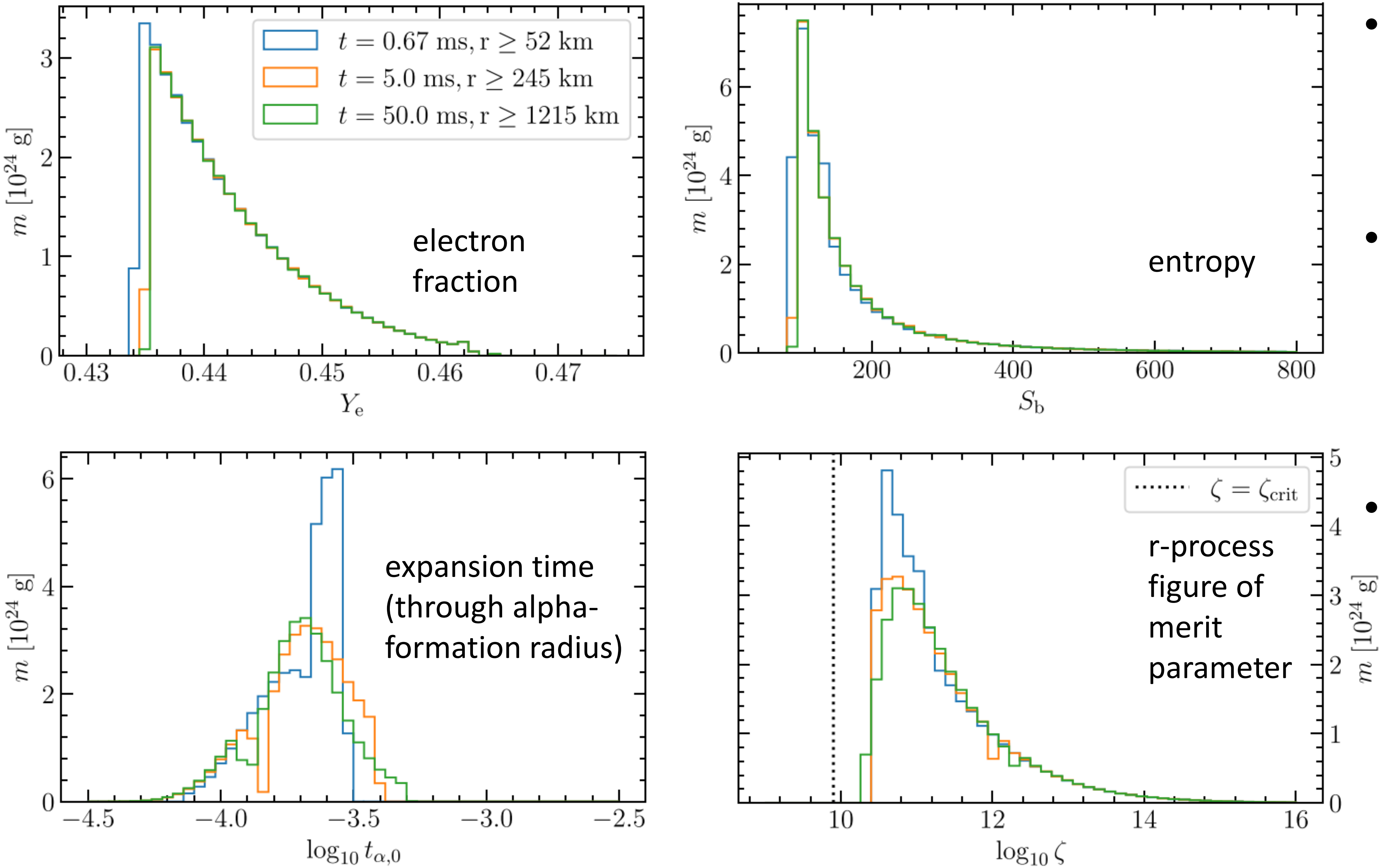
NUMERICAL APPROACH

- **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)
  - $M_{\rm NS} = 1.4\ {\rm M}_\odot$, $R_{\rm NS} = 12$ km
  - reflective inner boundary: $R_{\rm in} = 10$ km, outflow outer boundary: $R_{\rm out} = 20000$ km





R-PROCESS? YES!



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

$$\zeta \equiv \frac{S_b^3}{Y_e^3 t_{\alpha,0}}$$

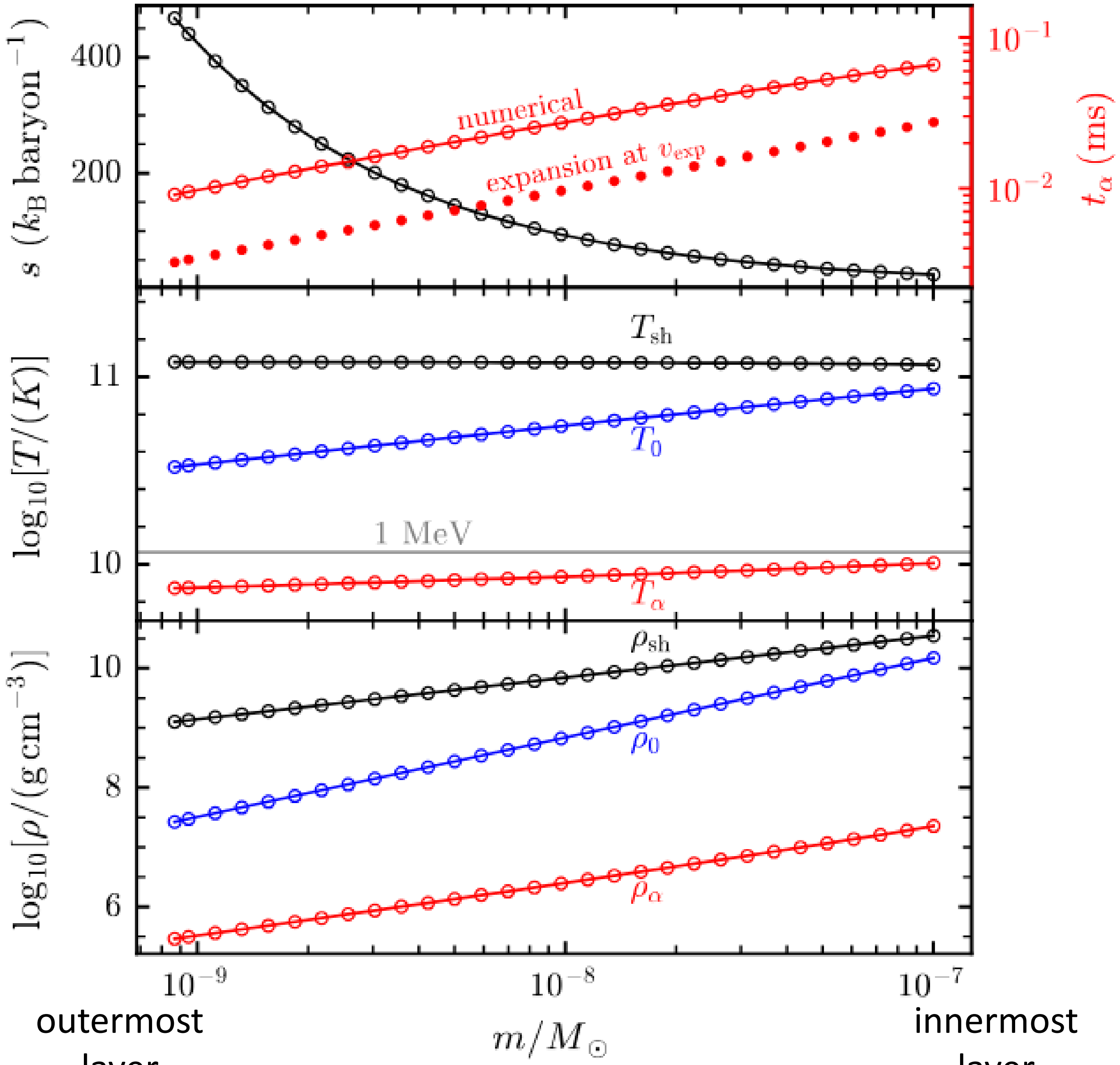
$$\zeta_{crit} \approx 8 \times 10^9$$

- 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 ($P_{\mathrm{GF}} = 1.4 \times 10^{30}\,\mathrm{erg} \cdot \mathrm{cm}^{-3}$) => $M_{\mathrm{ej}} \sim 10^{-7} \mathrm{M}_{\odot}$
  - $Y_{\mathrm{e}} = 0.44$
  - 30 grid zones (circles)

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

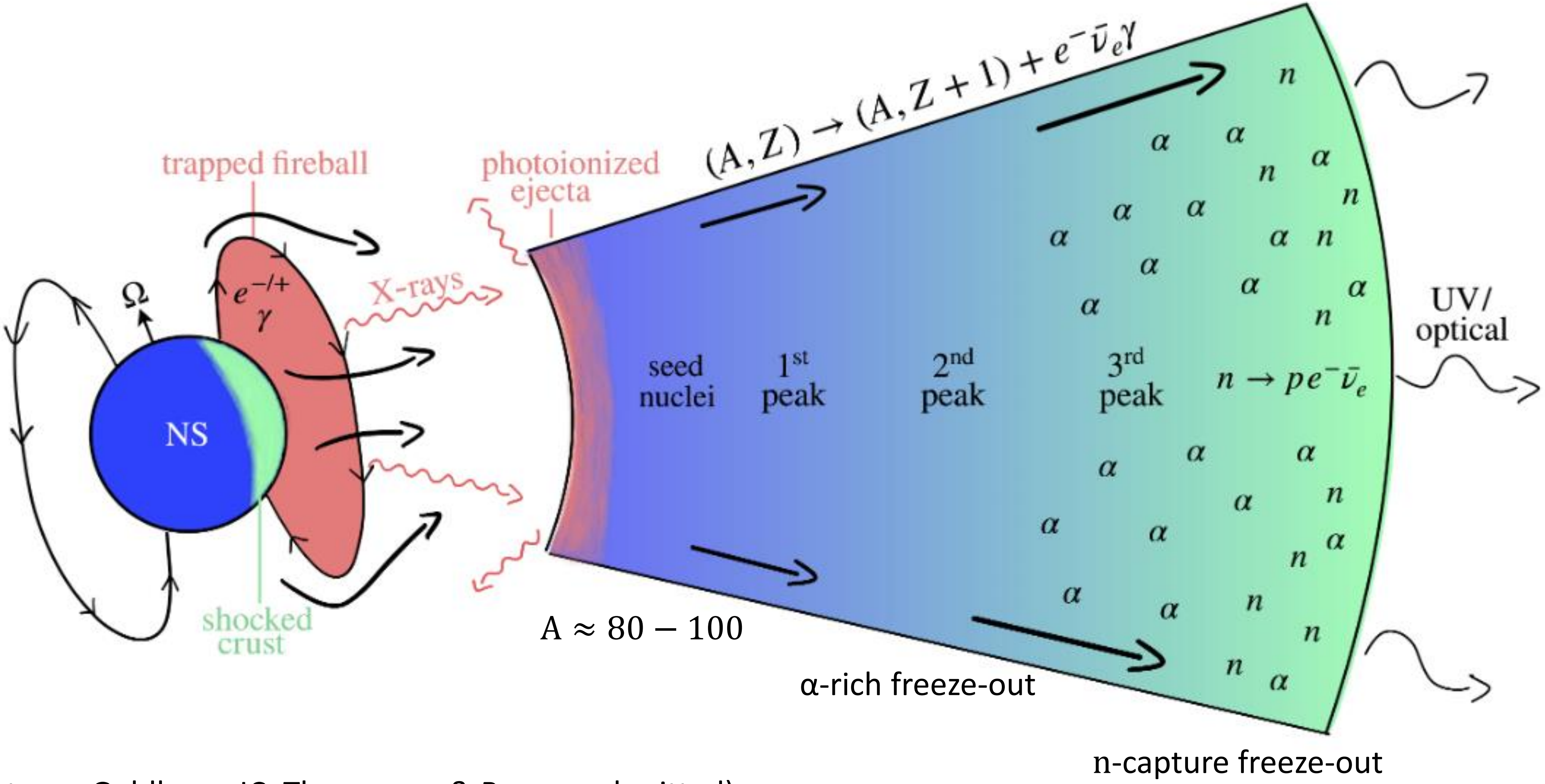


outermost layer

lagrangian mass coordinate

innermost layer

PICTURE FOR R-PROCESS NUCLEOSYNTHESIS



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

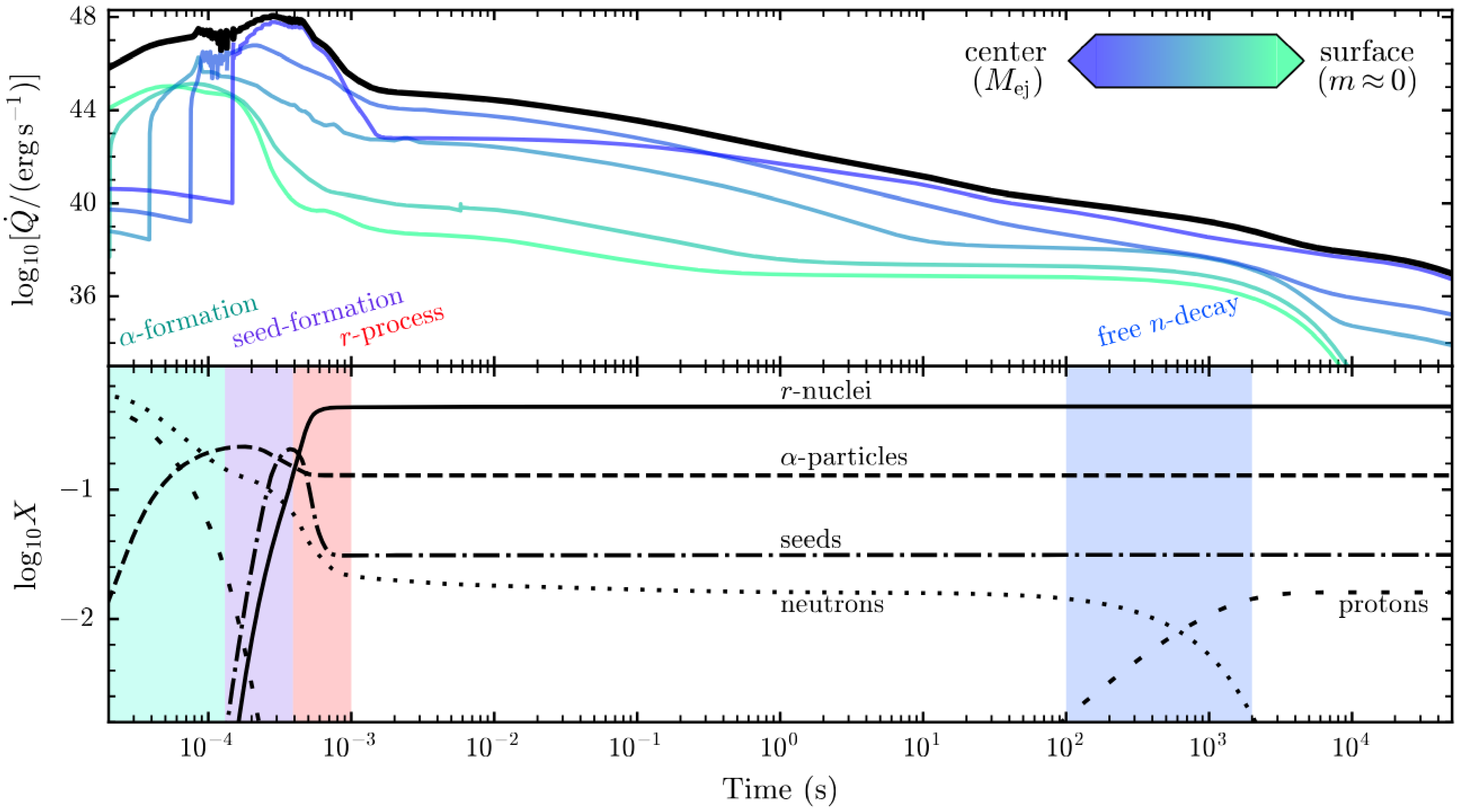
R-PROCESS NUCLEOSYNTHESIS

- 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

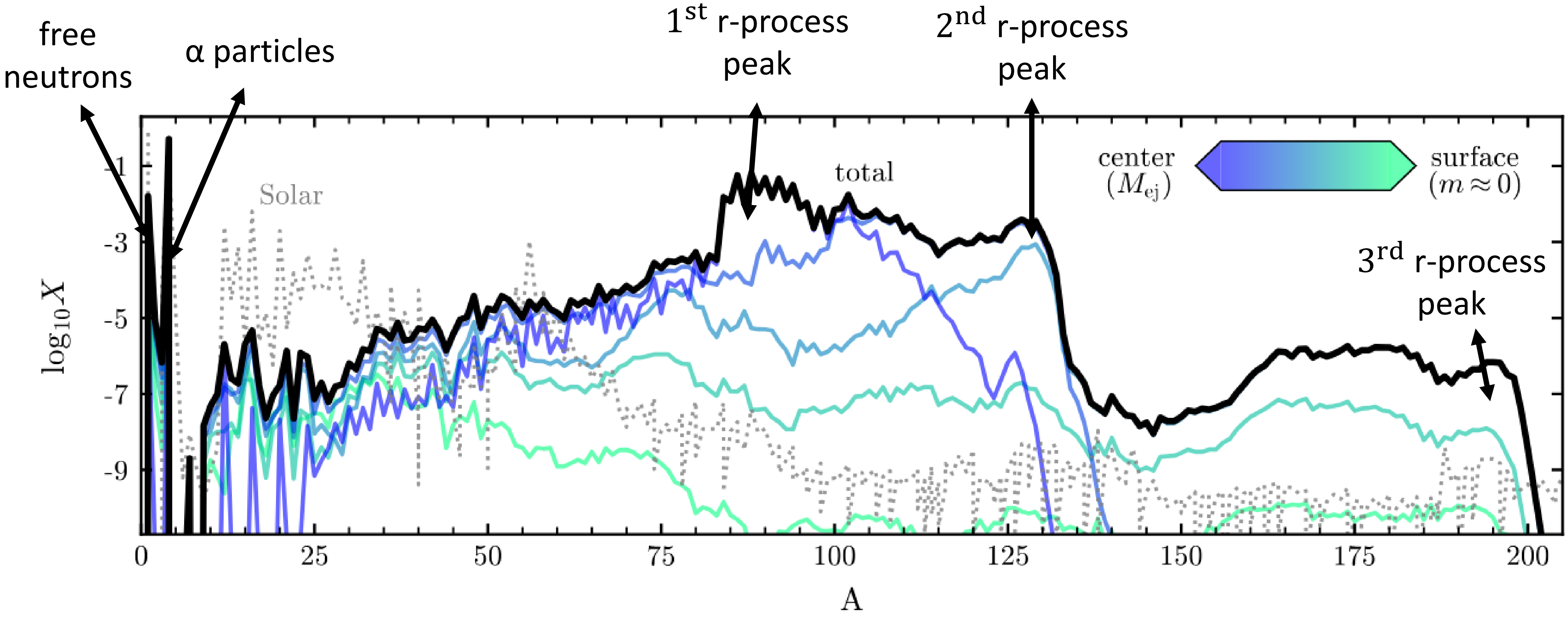
total radioactive heating rate

compositional evolution



(SkyNet: Lippuner&Roberts2015,2017)

MASS-WEIGHTED NUCLEOSYNTHETIC YIELDS



(Patel, Metzger, Goldberg, JC, Thompson, & Renzo, accepted in ApJ)

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

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:

$$f_{\rm th}(t) = 0.38\frac{\dot{q}_n(t)}{\dot{q}(t)} + \frac{\dot{q}_r(t)}{\dot{q}(t)}\left[0.25 + 0.4\left\{1 - \exp\left(-\tau(t)\kappa_\gamma/\kappa(t)\right)\right\}\right],$$

β-decay e^- | neutron heating | r-process heating | β-decay e^- | β-decay gamma-rays

  - 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")

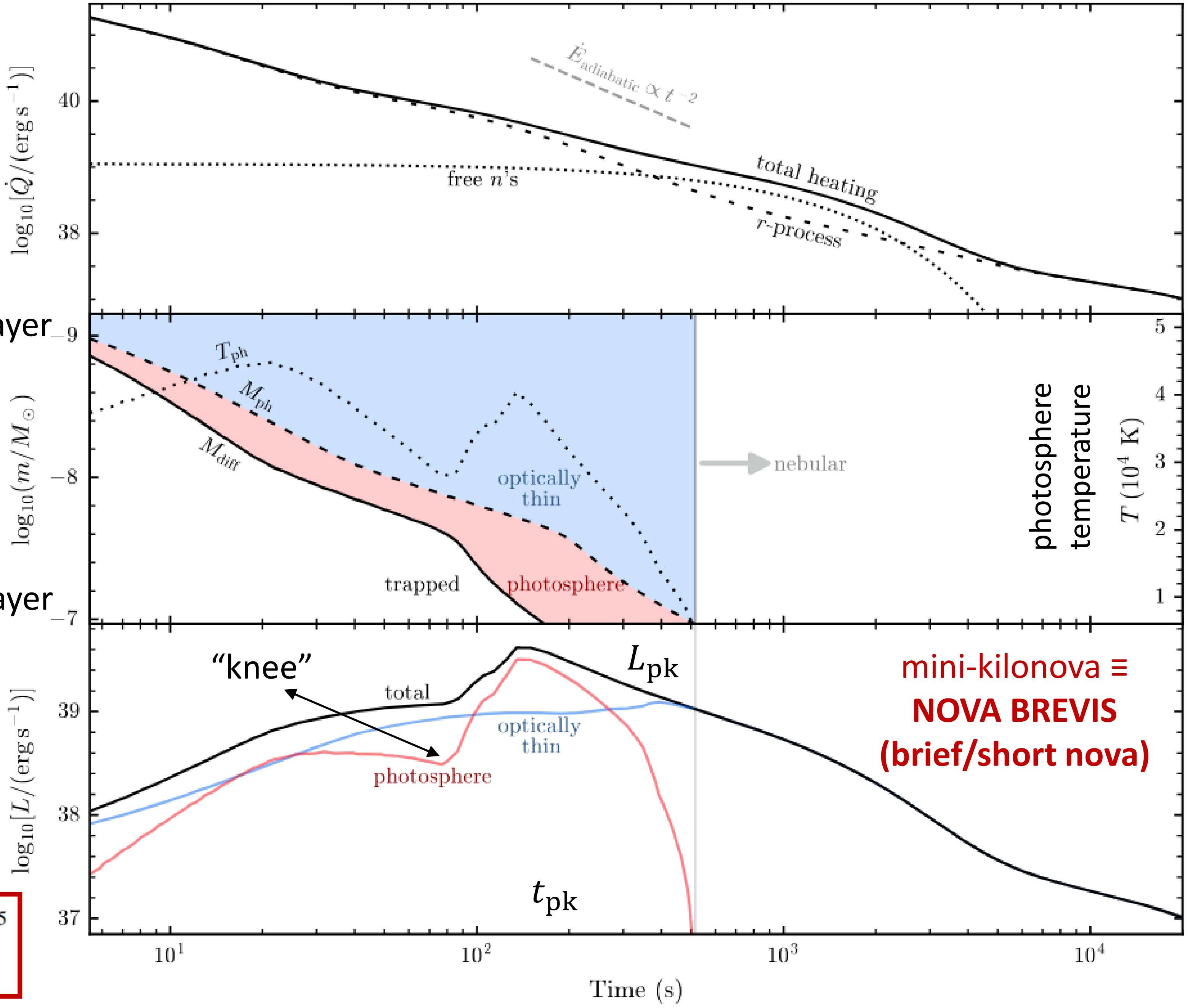
radioactive heating
(with thermalization
correction)

outermost layer

lagrangian mass
coordinate

innermost layer

luminosity



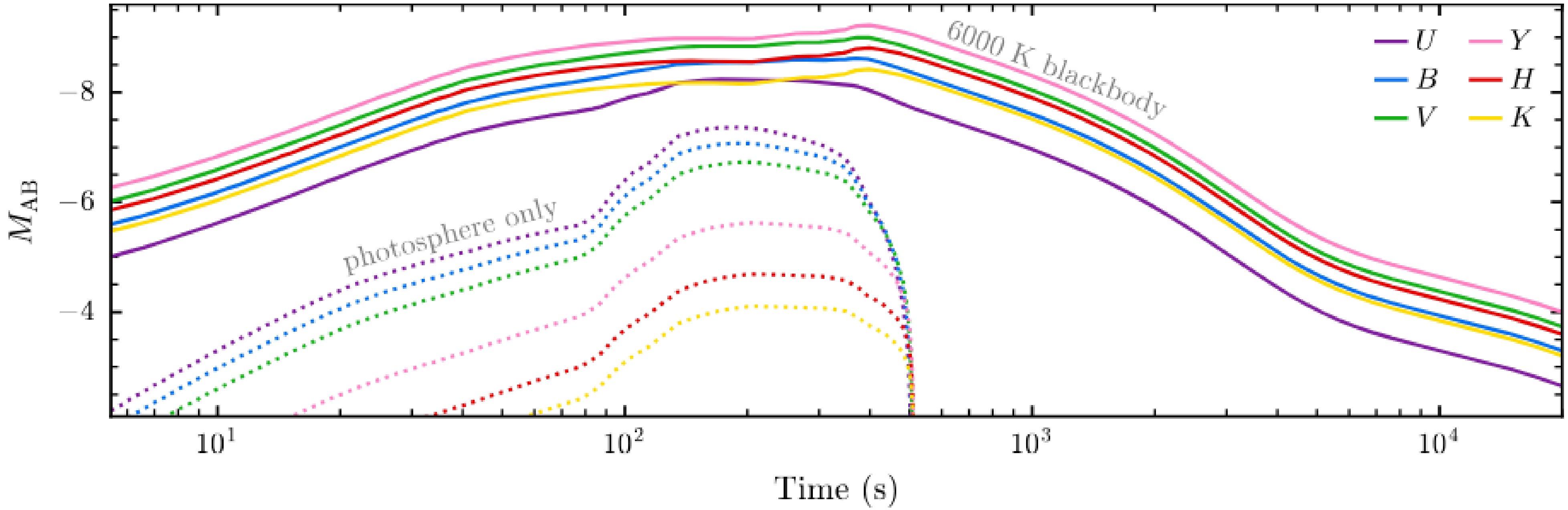
$$t_{\mathrm{pk}} \approx 300\mathrm{s}\left(\frac{M_{\mathrm{ej}}}{10^{26}\mathrm{g}}\right)^{1/2}\left(\frac{v_{\mathrm{ej}}}{0.3c}\right)^{-1/2}\left(\frac{\kappa}{3\,\mathrm{cm^2\,g^{-1}}}\right)^{1/2},$$

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

NOVA BREVIS SPECTRA

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

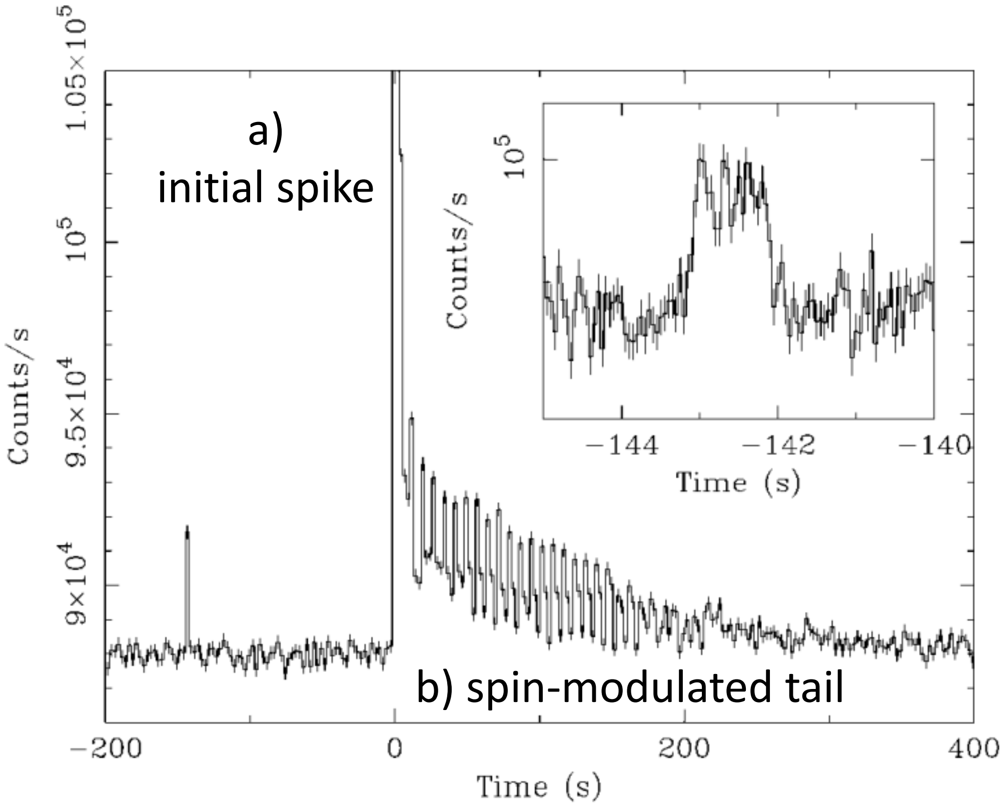
absolute AB magnitudes in UV, optical, and infrared bands

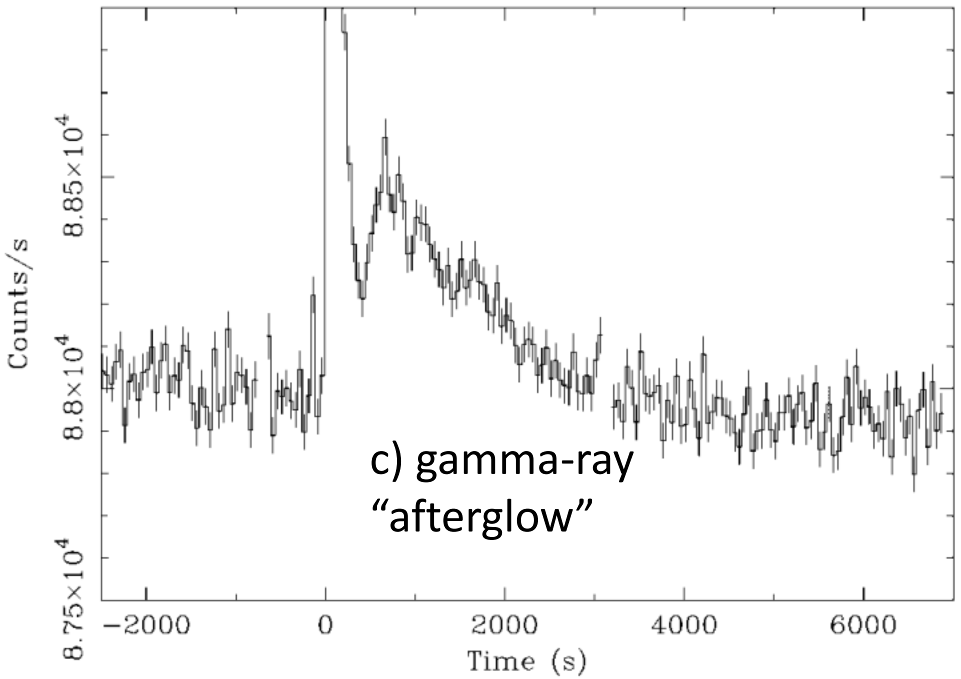


DEC 2004 GF FROM SGR 1806-20

- 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)



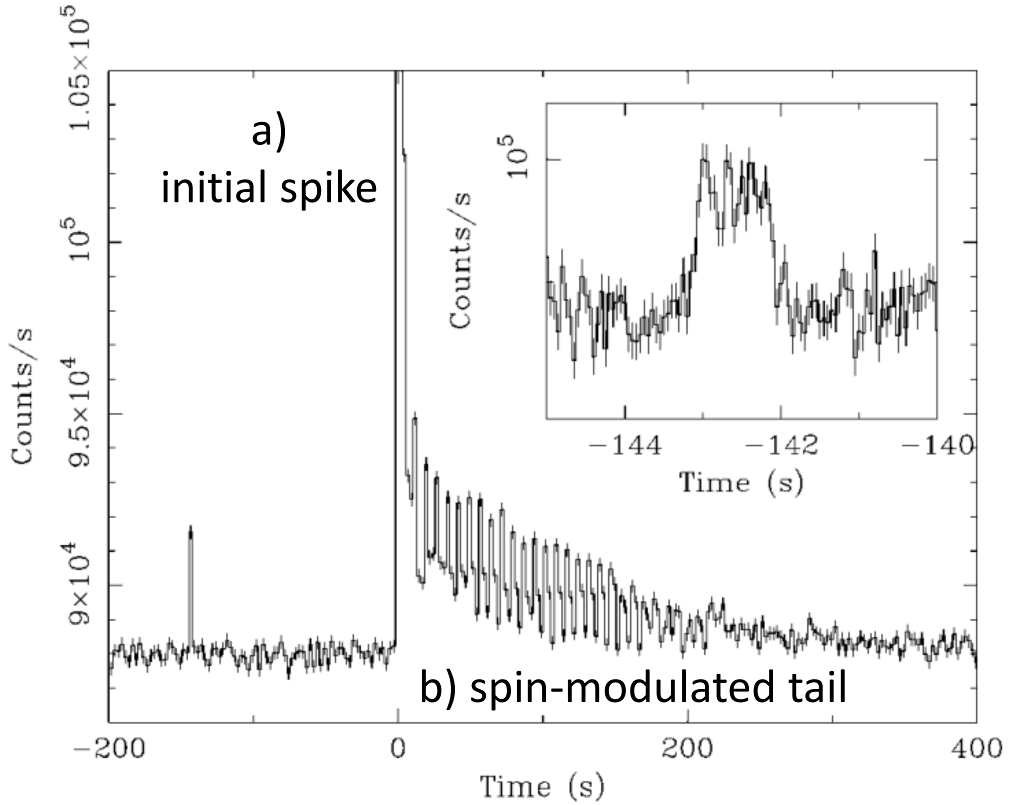


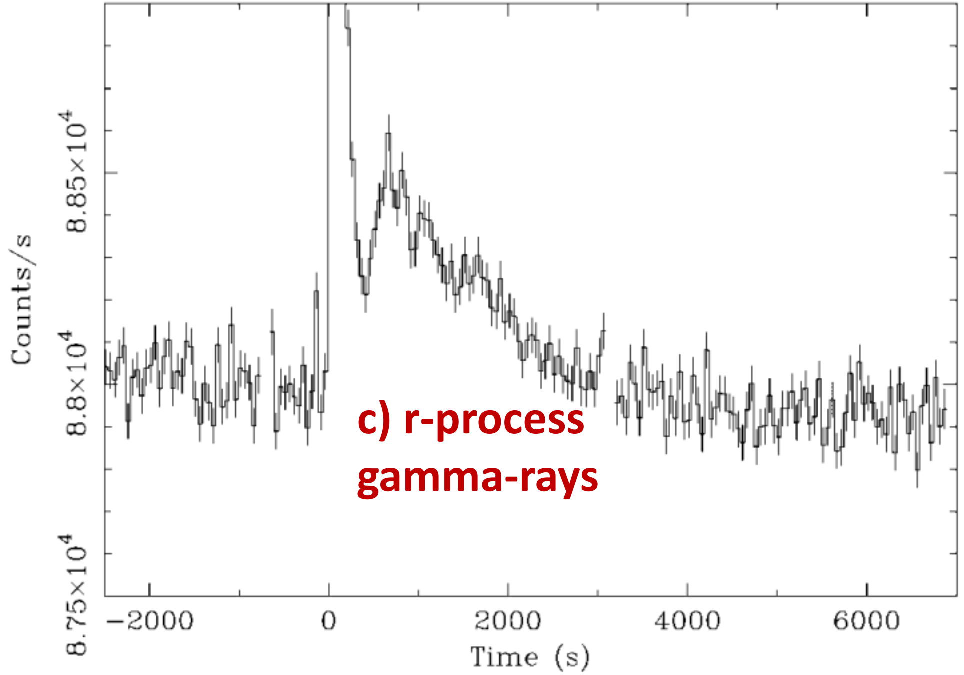
(Mereghetti+2005)

DEC 2004 GF FROM SGR 1806-20 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+2025**)





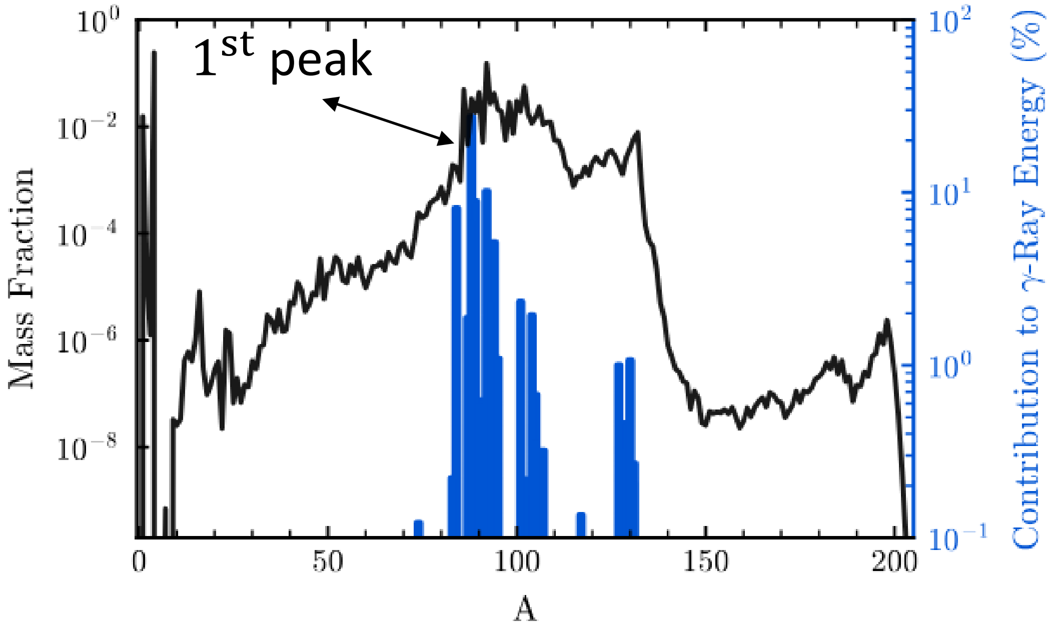
(Mereghetti+2005)

GAMMA-RAY EMISSION

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

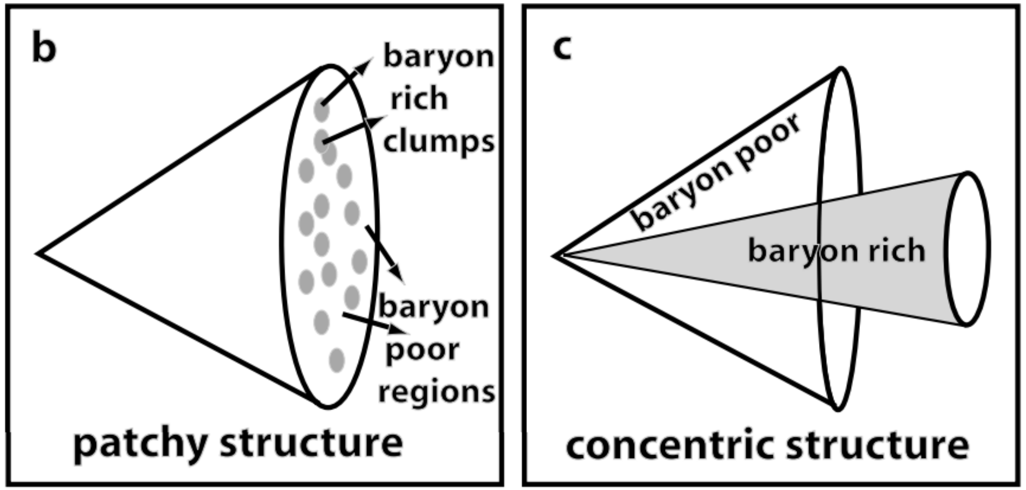
- fiducial model:
  - $\boldsymbol{M_{ej} = 1.2 \times 10^{-6} M_\odot\ (M_r = 7 \times 10^{-7} M_\odot)}$
  - $Y_e = 0.40$
  - $\bar{v} = 0.15c$
  - $\beta = 6$
  - $f_\Omega = 3/4$

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

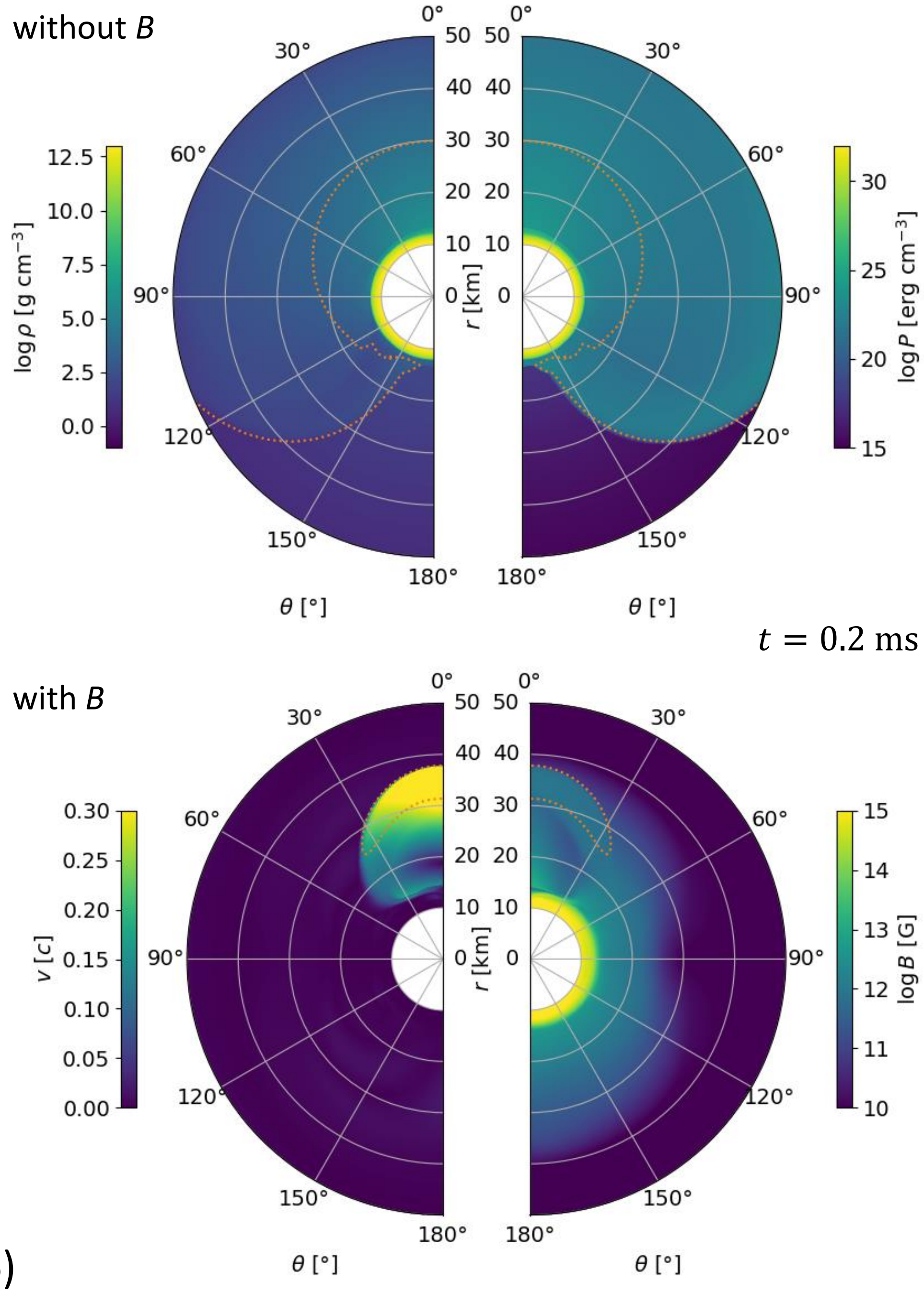


CURRENT WORK

- 2D special-relativistic MHD simulations
- motivation: magnetic field confines ejecta, preventing full **surface obscuration**, as ruled out by observations (Gelfand+2005,Granot+2006)
- preliminary result: the ejecta is more confined



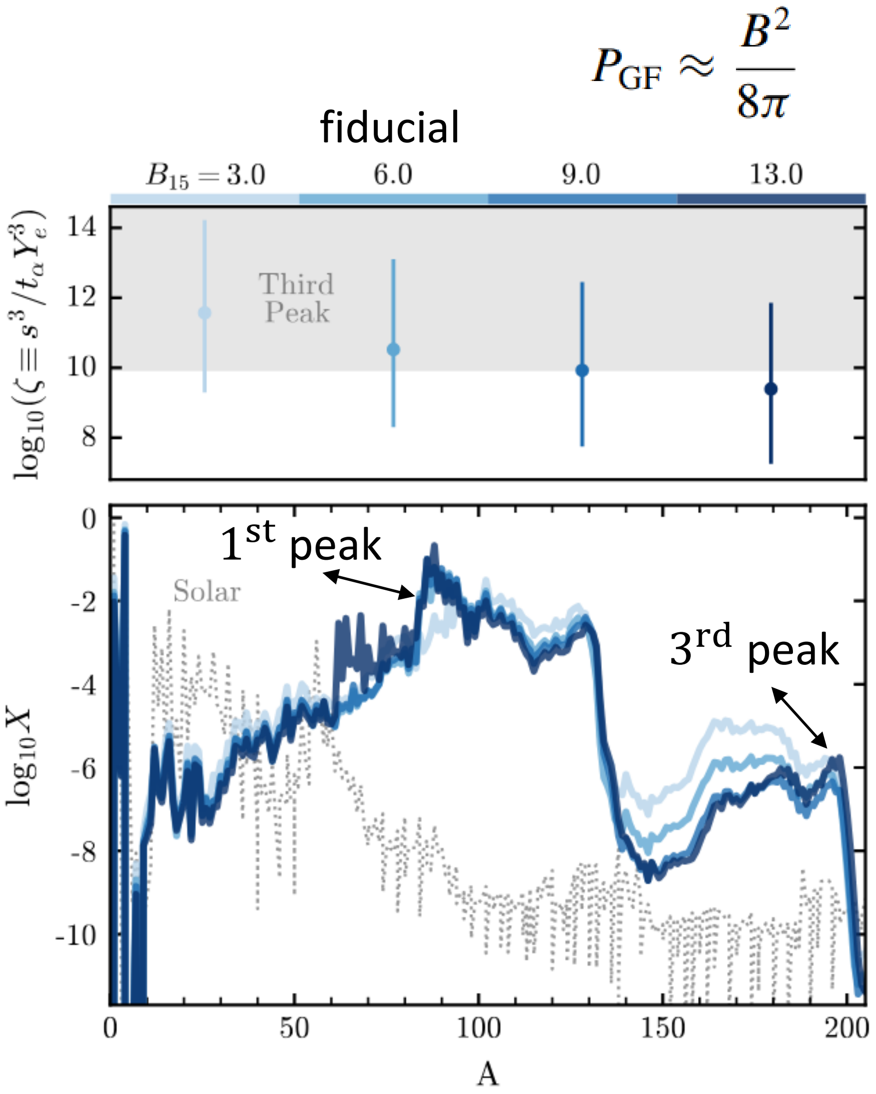
(Granot+2006)



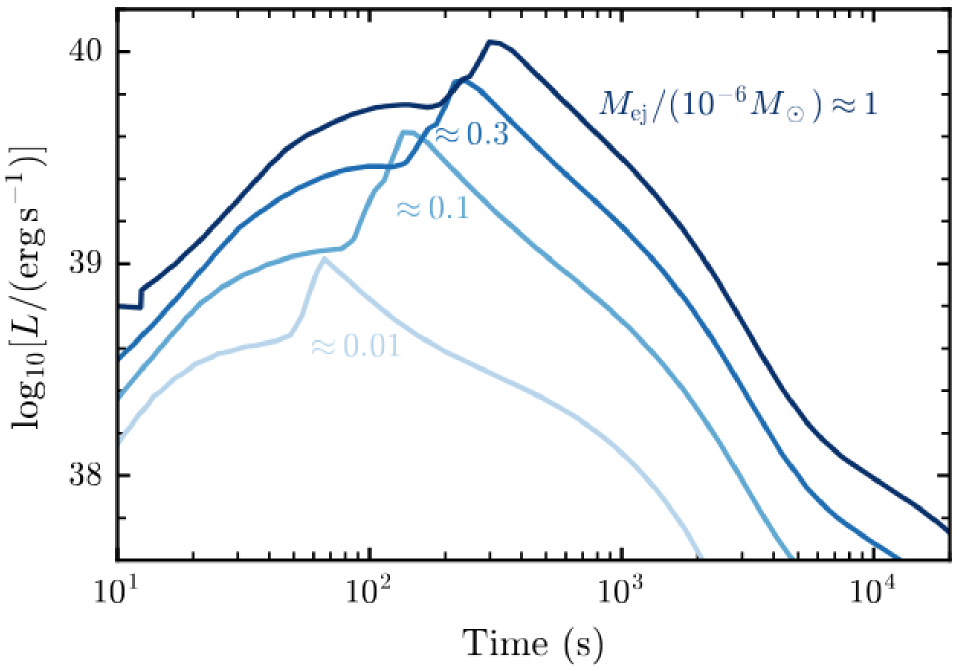
IMPACT OF VARYING THE FLARE STRENGTH

r-process figure of merit parameter

mass-weighted nucleo-synthesis yields



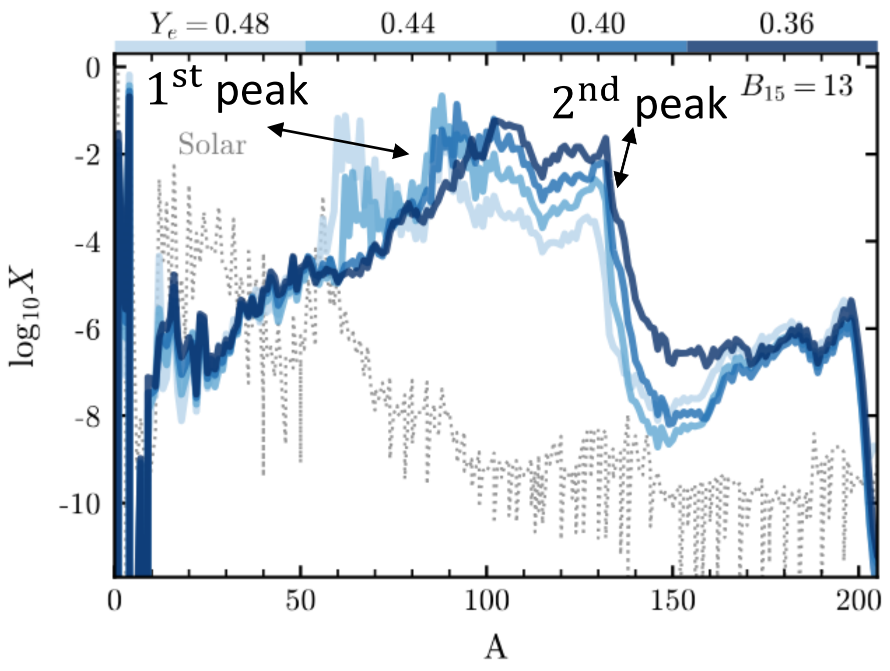
- $M_{ej}/M_\odot \in (10^{-8} - 10^{-6})$ for $B_{15} \in (3,13)$
- X_r increases with flare strength
- stronger flares produce brighter and longer duration transients

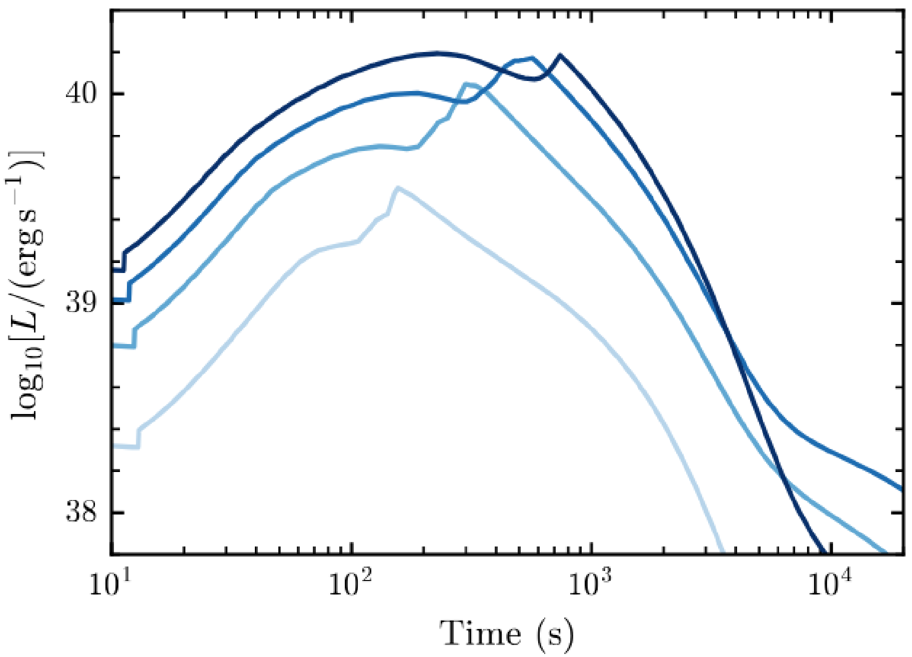


IMPACT OF VARYING THE ELECTRON FRACTION

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

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 $\boldsymbol{M_{\mathrm{ej}}}$:**
  - increases the peak timescale and gamma-ray luminosity **significantly**