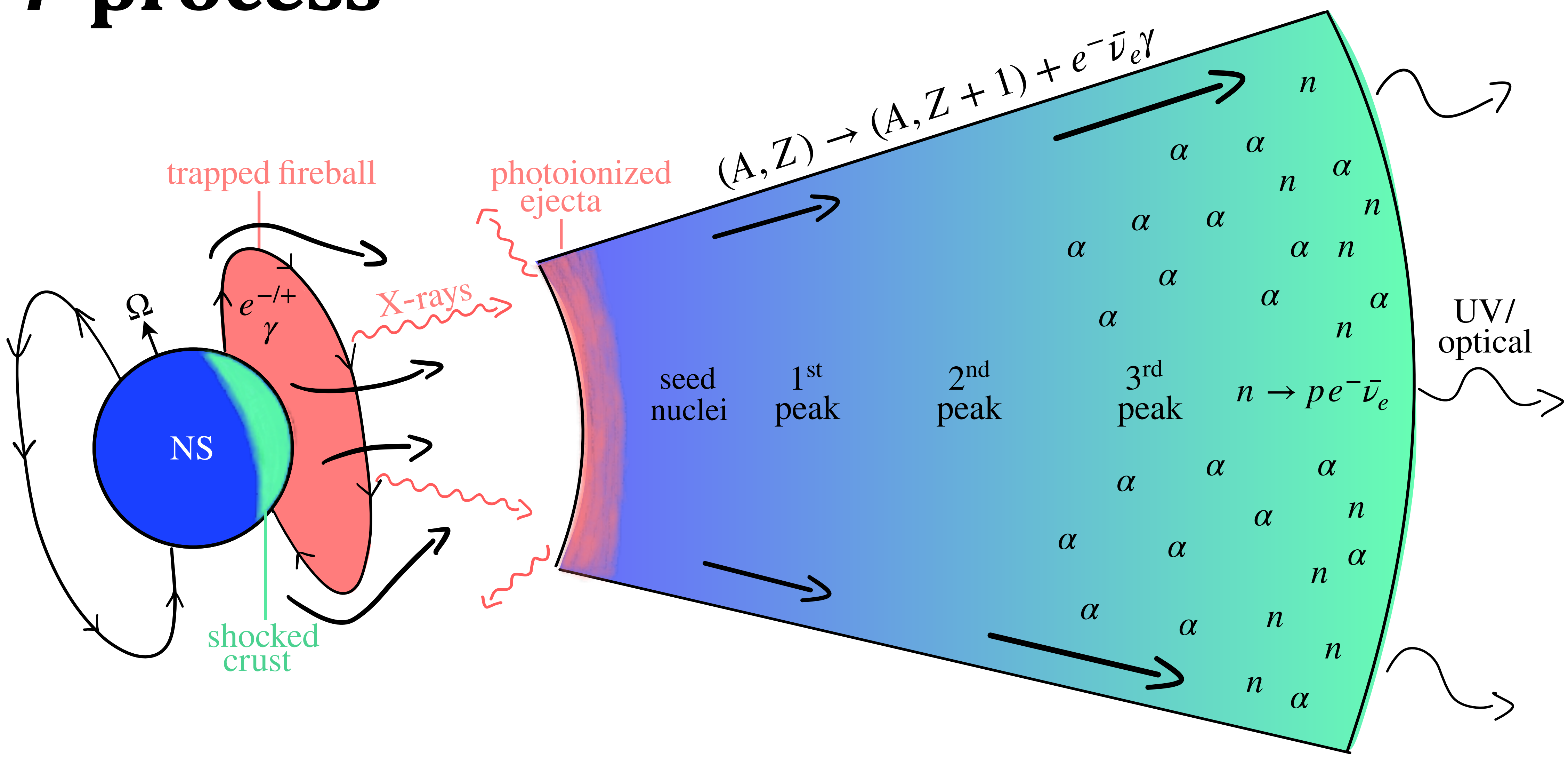
Magnetar giant flares: a new site for the *r*-process



Ani Patel - sirEN Conference - Giulianova, Italy - June 10, 2025.

Direct evidence for *r*-process nucleosynthesis in delayed MeV emission from the SGR 1806-20 magnetar giant flare

Anirudh Patel,[1] Brian D. Metzger,[1,2] Jakub Cehula,[3] Eric Burns,[4] Jared A. Goldberg,[2] and Todd A. Thompson[5,6,7]

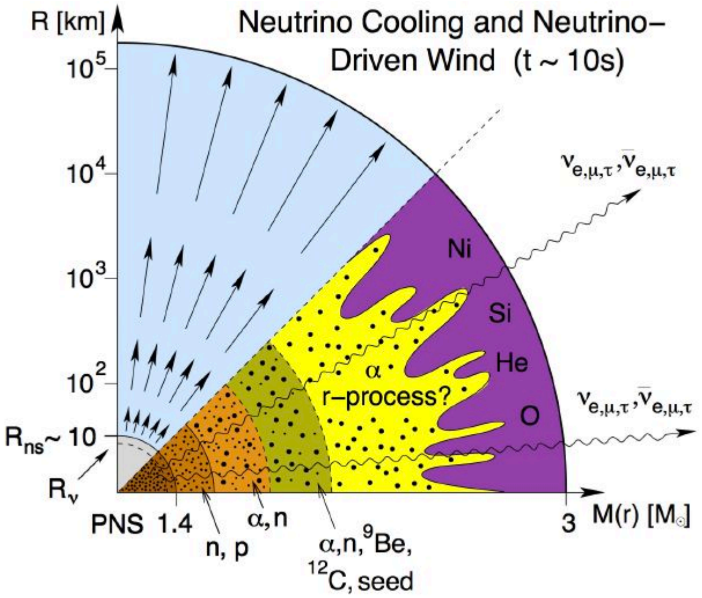
***r*-Process Nucleosynthesis and Radioactively Powered Transients from Magnetar Giant Flares**

Anirudh Patel,[1] Brian D. Metzger,[1,2] Jared A. Goldberg,[2] Jakub Cehula,[3] Todd A. Thompson,[4,5,6] and Mathieu Renzo[7,2]

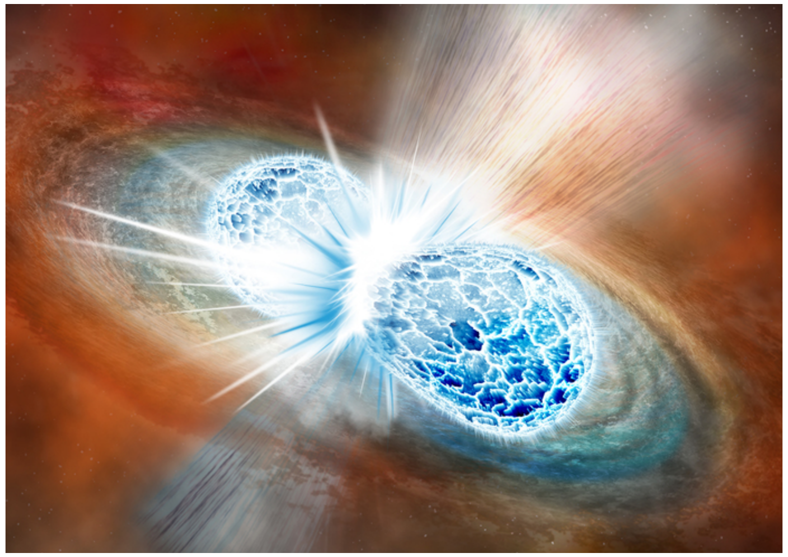
Columbia University

Flatiron Institute
Center for Computational Astrophysics

Current landscape of *r*-process sites

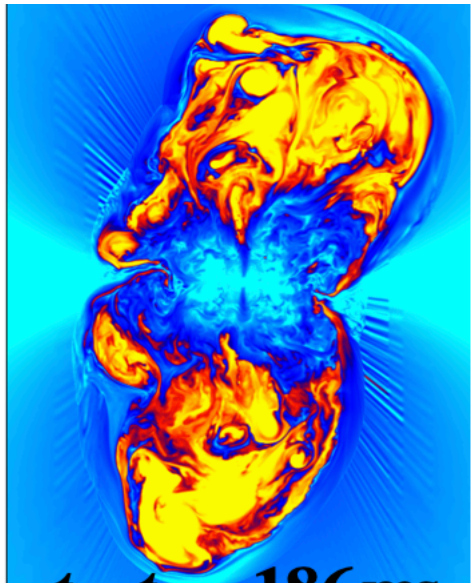


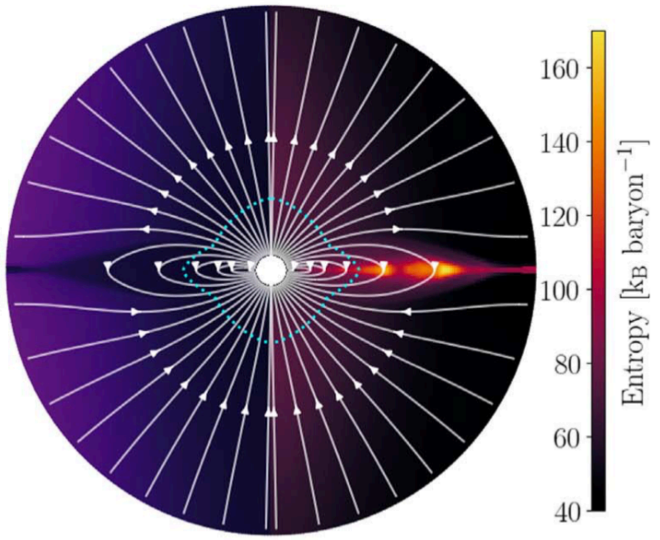
ν-driven proto-NS winds
("normal" CCSNe)

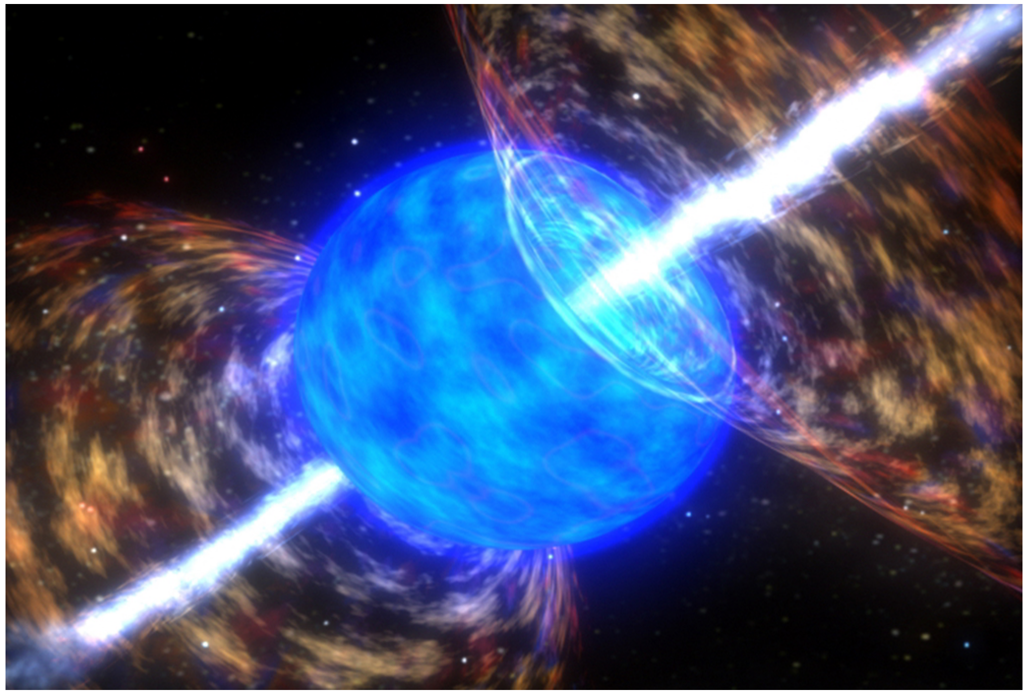


Neutron Star Mergers

e.g. Lattimer & Schramm 74, 76; Freiburghaus+99







magneto-rotational SNe + proto-magnetar winds

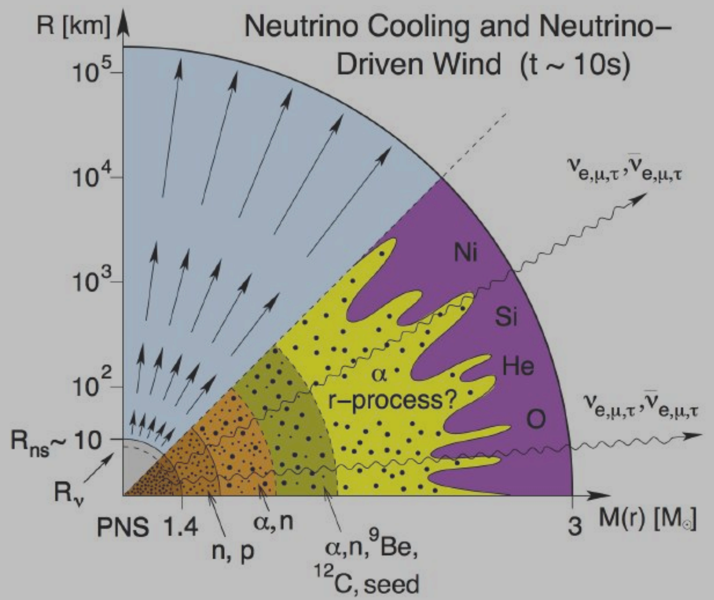
(e.g. Nishimura+06, Burrows+07, Winteler+12, Mosta+14)

(e.g. Thompson+04, Metzger+07, Desai+23, Prasanna+24, Prasanna+**including A.P.** in prep.)

Collapsar Disk winds

(e.g. Kohri+2005, Siegal+2019)

Current landscape of *r*-process sites



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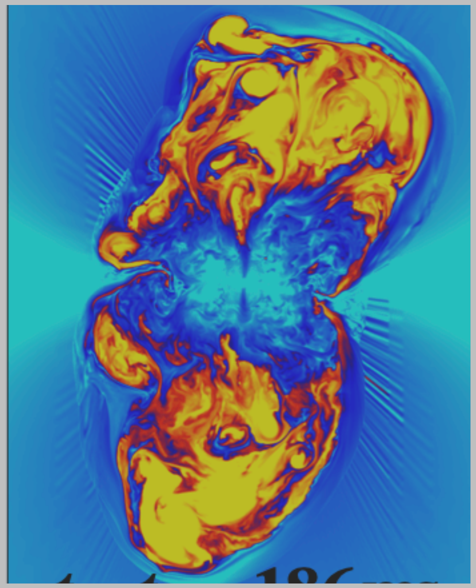

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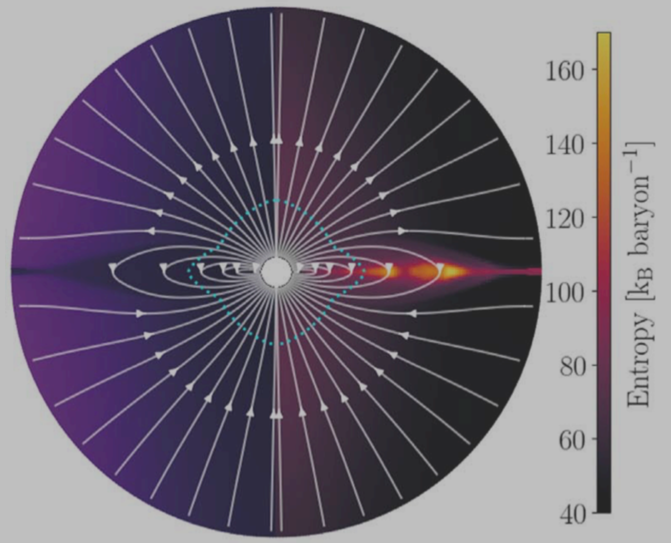
(e.g. Nishimura+06, Burrows+07, Winteler+12, Mosta+14)



proto-magnetar winds

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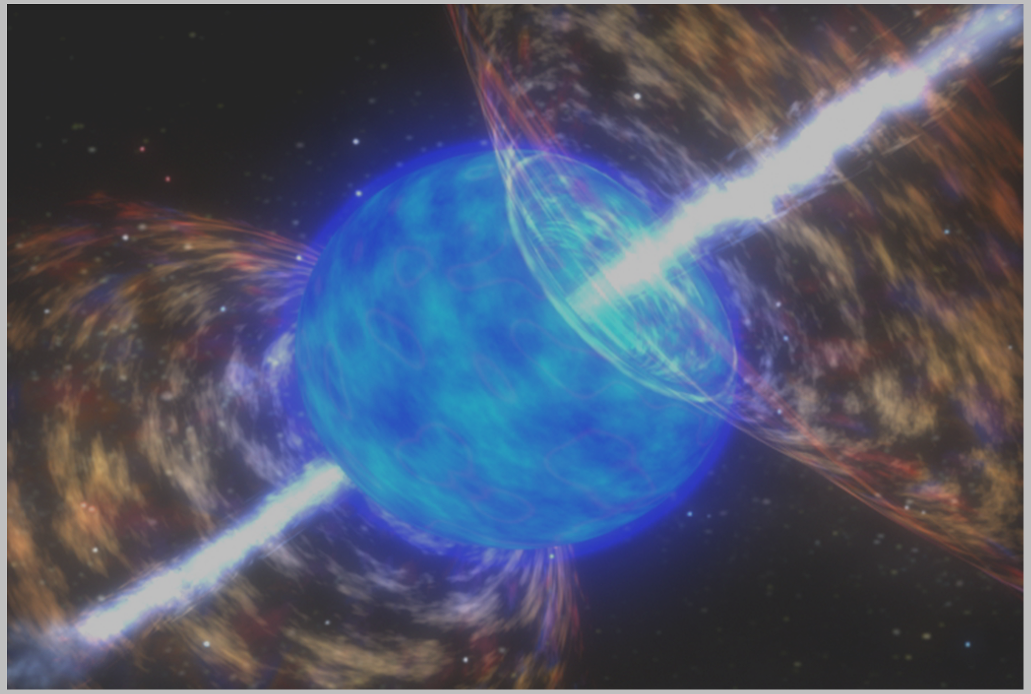
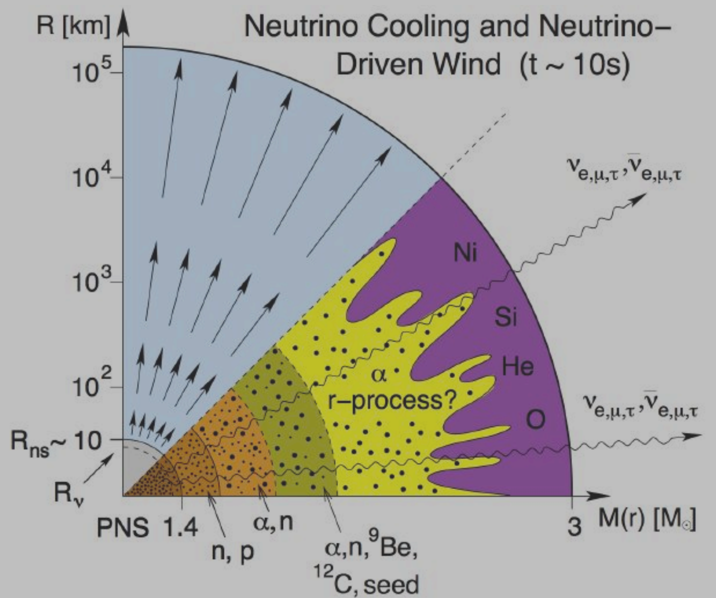


Collapsar Disk winds

(e.g. Kohri+2005, Siegal+2019)

New landscape of *r*-process sites

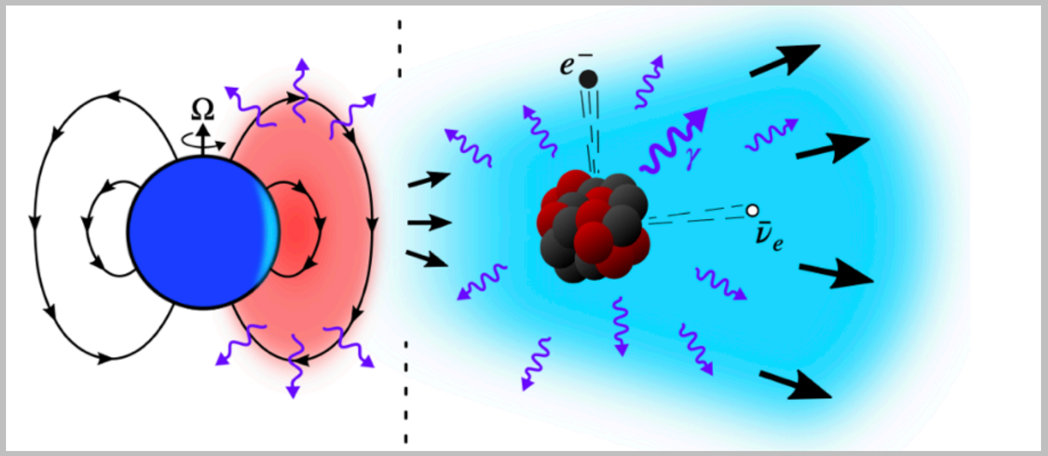


ν-driven proto-NS winds
(“normal” CCSNe)

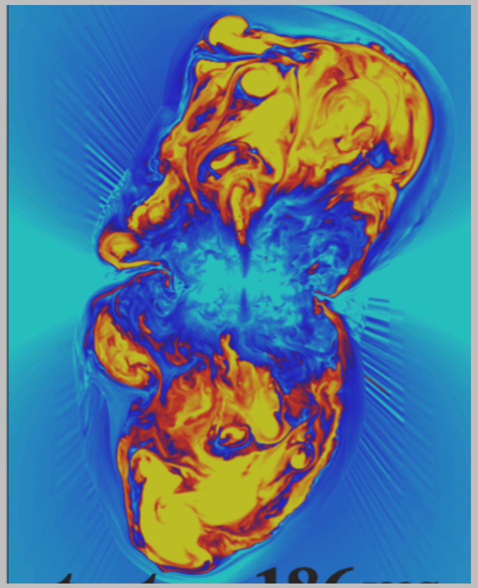
Neutron Star Mergers

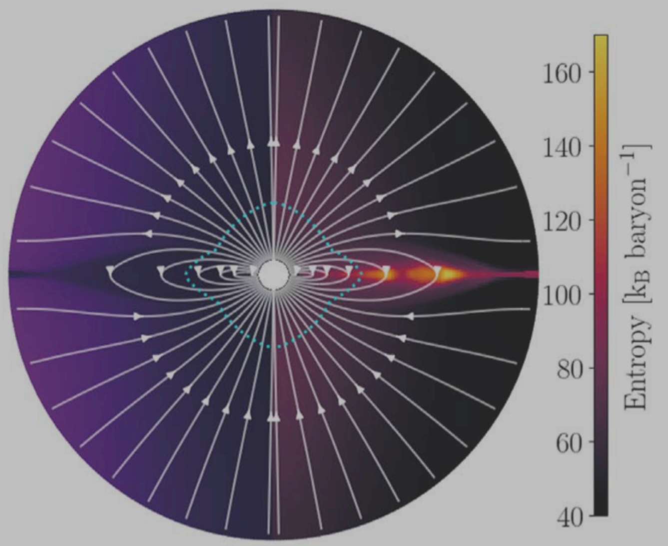
e.g. Lattimer & Schramm 74, 76;
Freiburghaus+99

Confirmed



Magnetar Giant Flares
Cehula+24, Patel+(2025a, 2025b)





magneto-rotational SNe + proto-magnetar winds

(e.g. Nishimura+06, Burrows+07,
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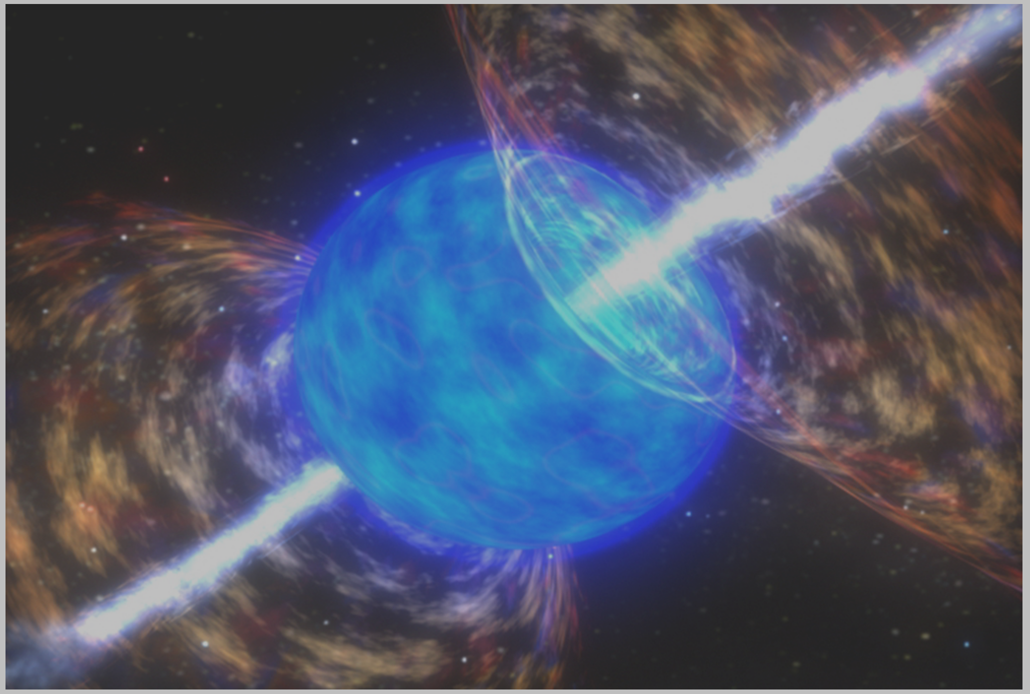


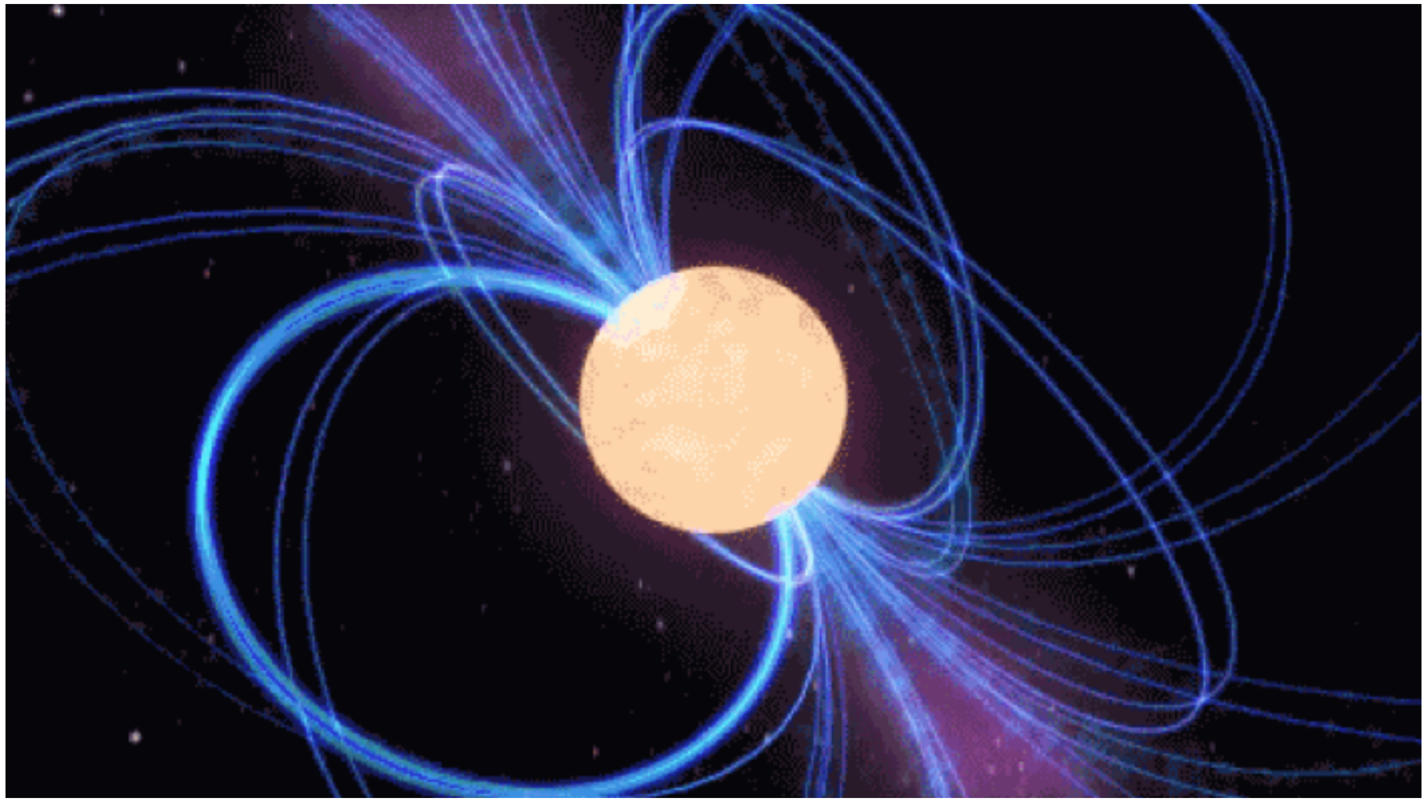
Collapsar Disk winds

(e.g. Kohri+2005, Siegal+2019)

Magnetars (soft gamma repeaters) vs. Pulsars (“normal” neutrons stars)

	Pulsars	Magnetars
B (G)	$\sim 10^{12-13}$	$\sim 10^{14-15}$
P (s)	$\lesssim 5$	$\lesssim 10$
Lifetime (yr)	$\sim 10^{7}$	$\sim 10^{3-4}$
Power Source	Rotation	Magnetic Field

Born in
~10-50% of
CCSNe



Magnetar Giant Flares (GFs)

$B \sim 10^{14} - 10^{15}$ G

$E_{\mathrm{GF}} \sim 10^{44} - 10^{46}$ erg

3 nearby events: 1979, 1998, **2004**

Unstable magnetic field

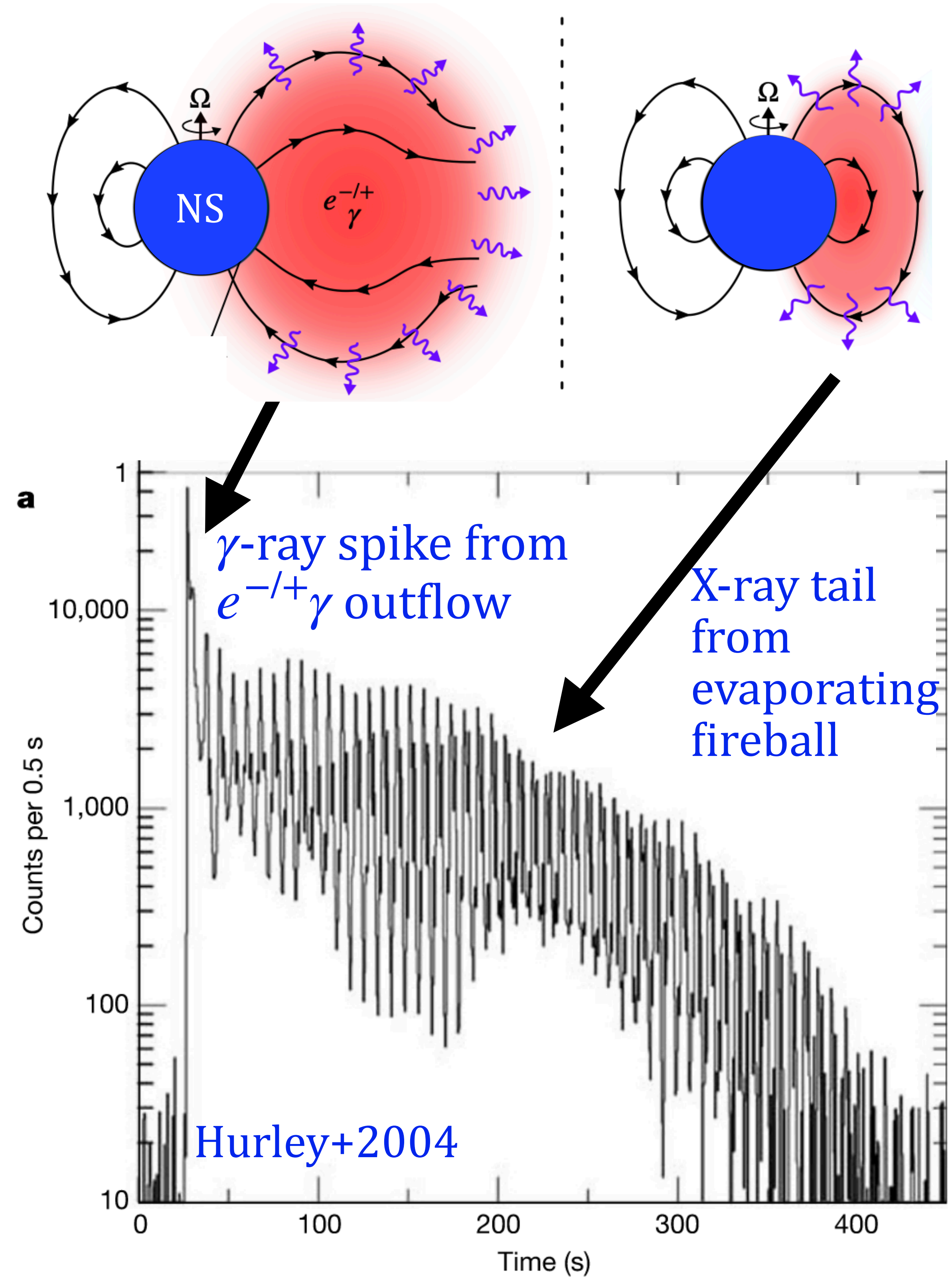
↓

Magnetic reconnection

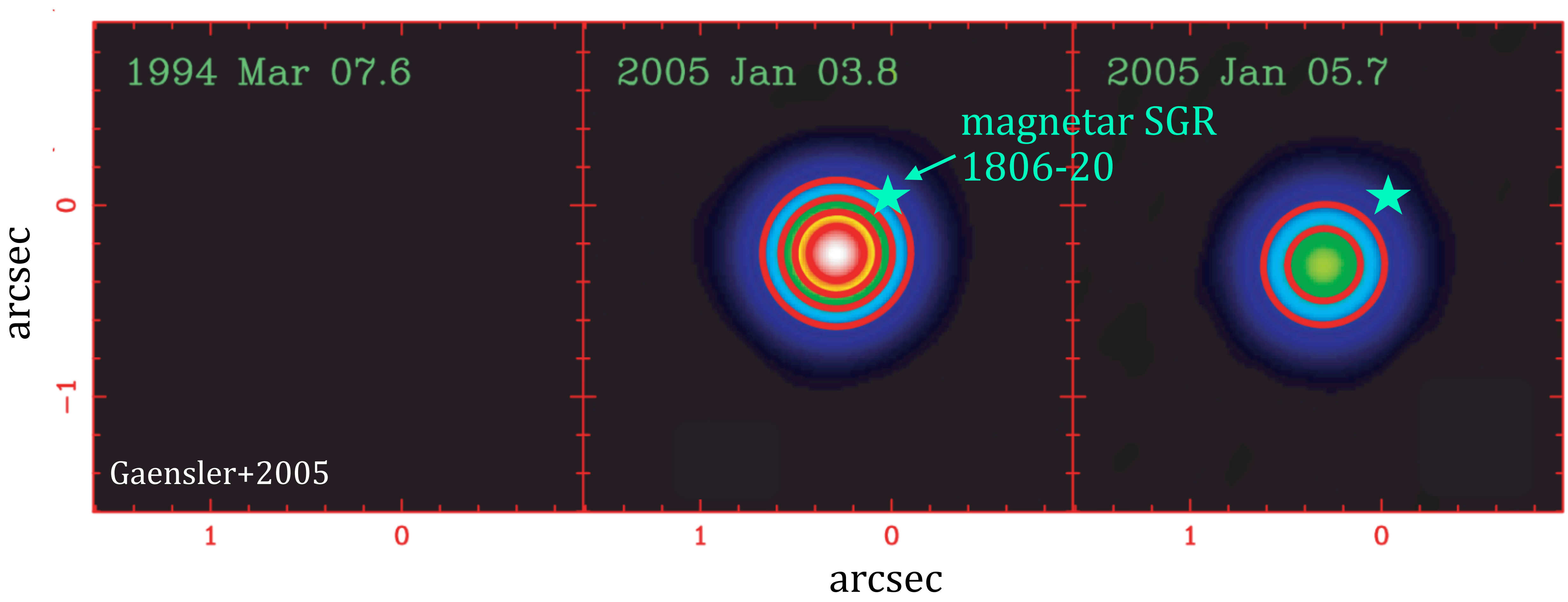
$E_{\mathrm{magnetic}} \rightarrow E_{\mathrm{thermal}}$

↓

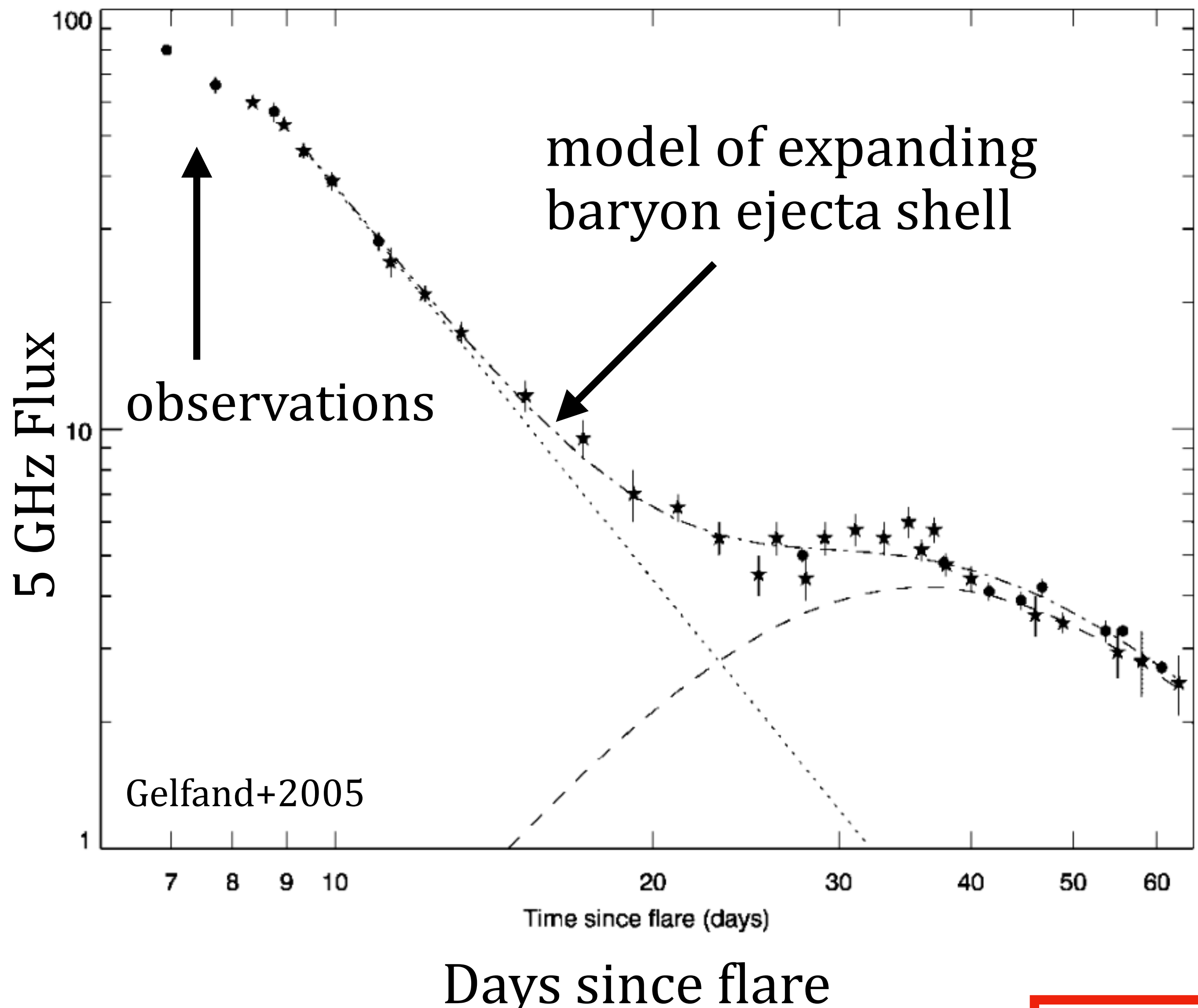
$e^{-/+}$-pair photon outflow

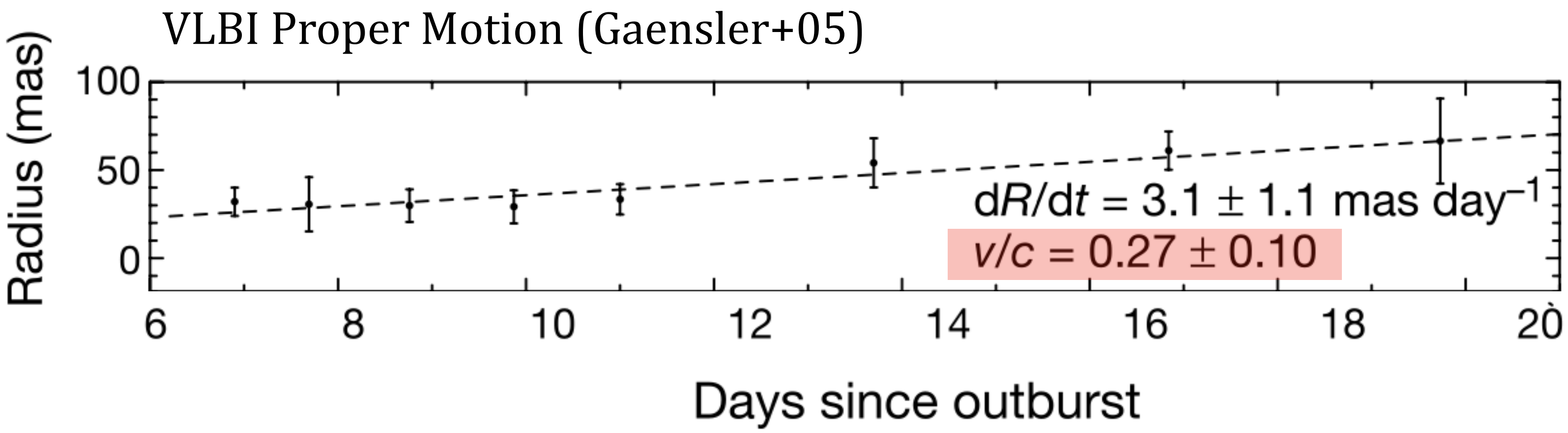


Radio Afterglow From GFs



Radio Afterglow: Evidence for Baryon Ejection

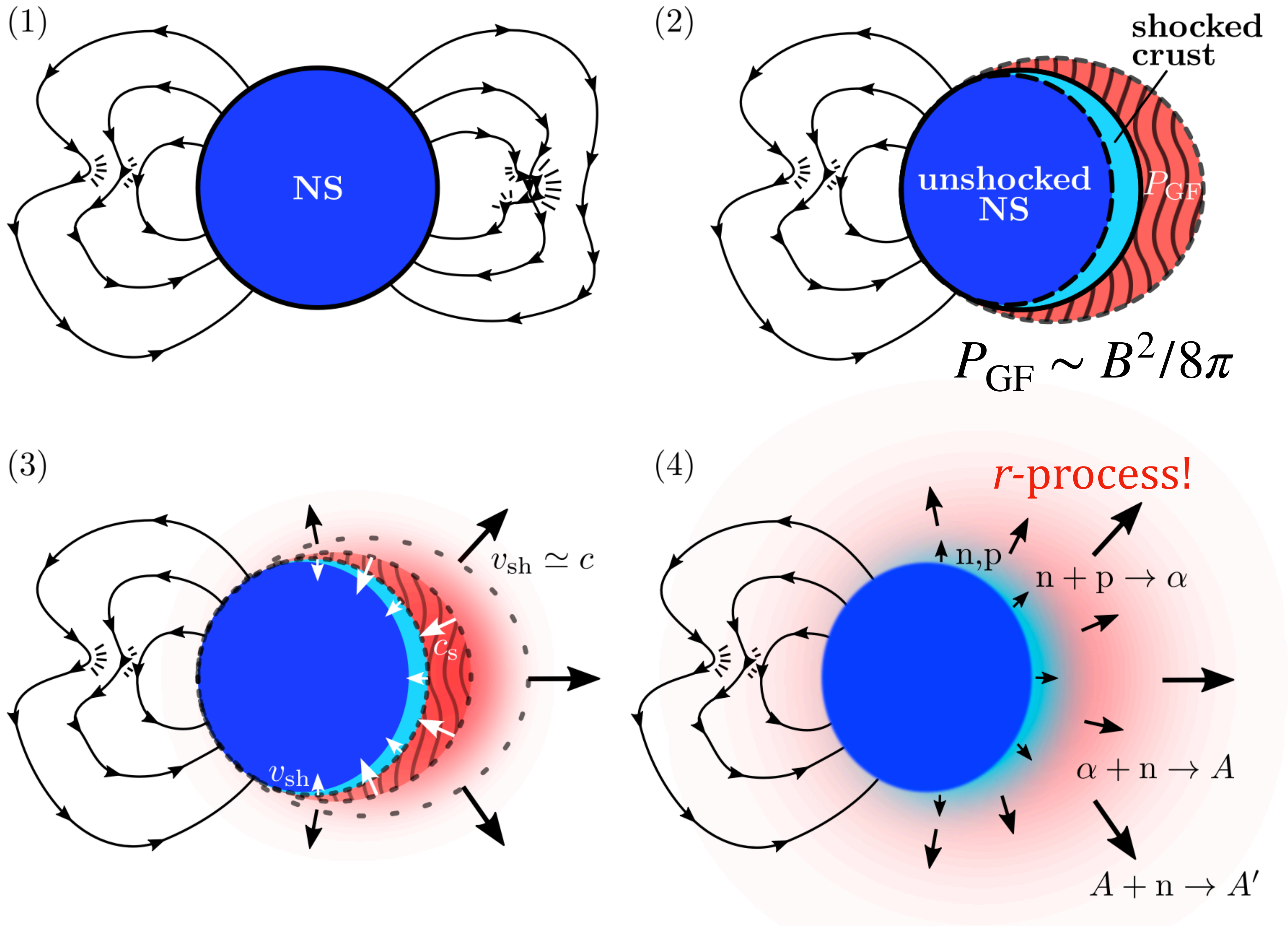




Key properties:

$M_{\rm ej} \sim 10^{-8}$-$10^{-6} M_\odot$
$v \sim 0.1c$

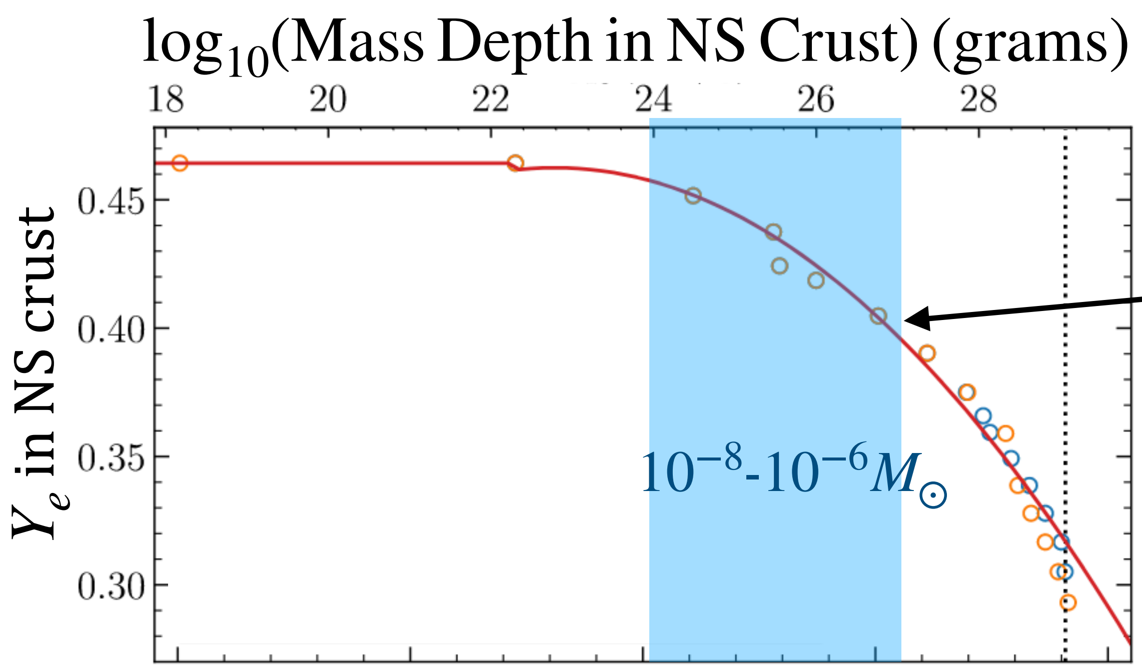
A Possible Mechanism for Baryon Ejection



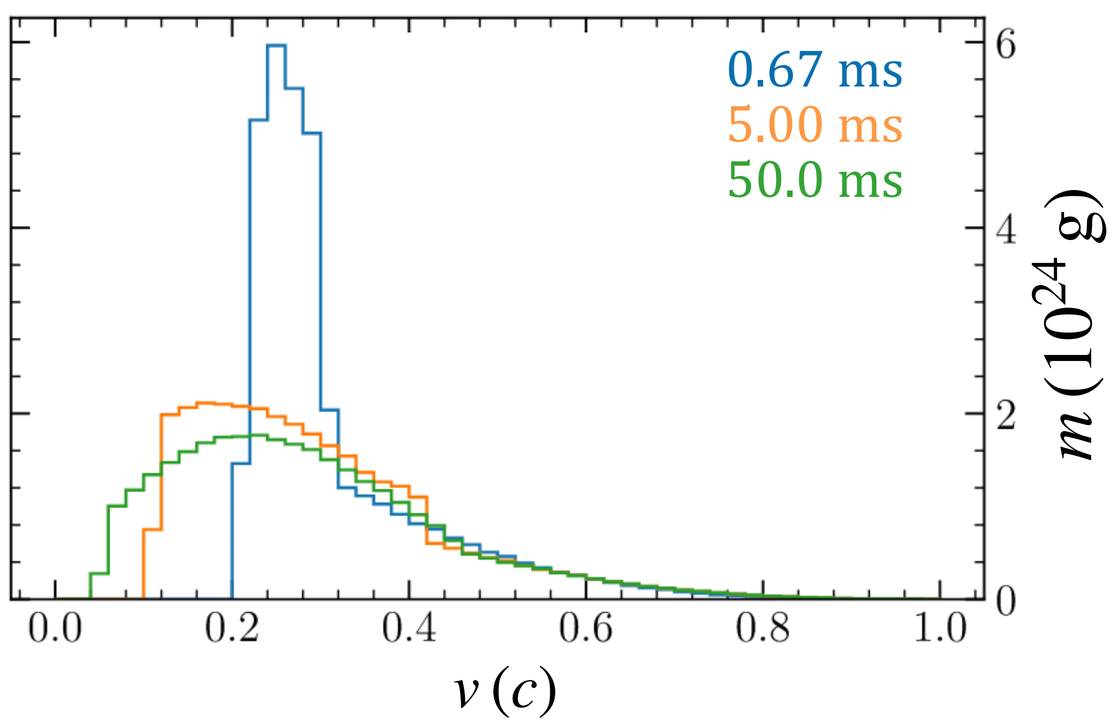
Jakub Cehula et al. (2024)

Properties of Unbound Ejecta (Cehula+2024)

Shock jump conditions: $\rho, e \rightarrow \text{EOS} \rightarrow s, T$



$Y_e \approx 0.40$ for $M_{ej} \approx 10^{-6} M_\odot$



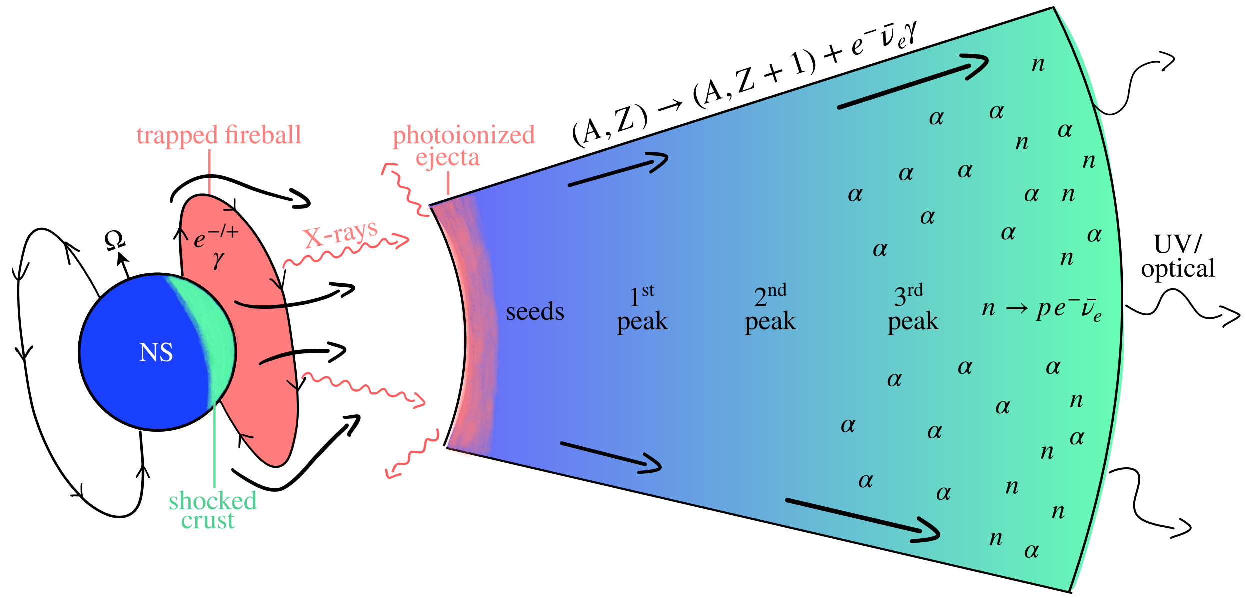
density profile & mass distribution for homologous expansion

$$\rho(v) \propto v^{-6}$$

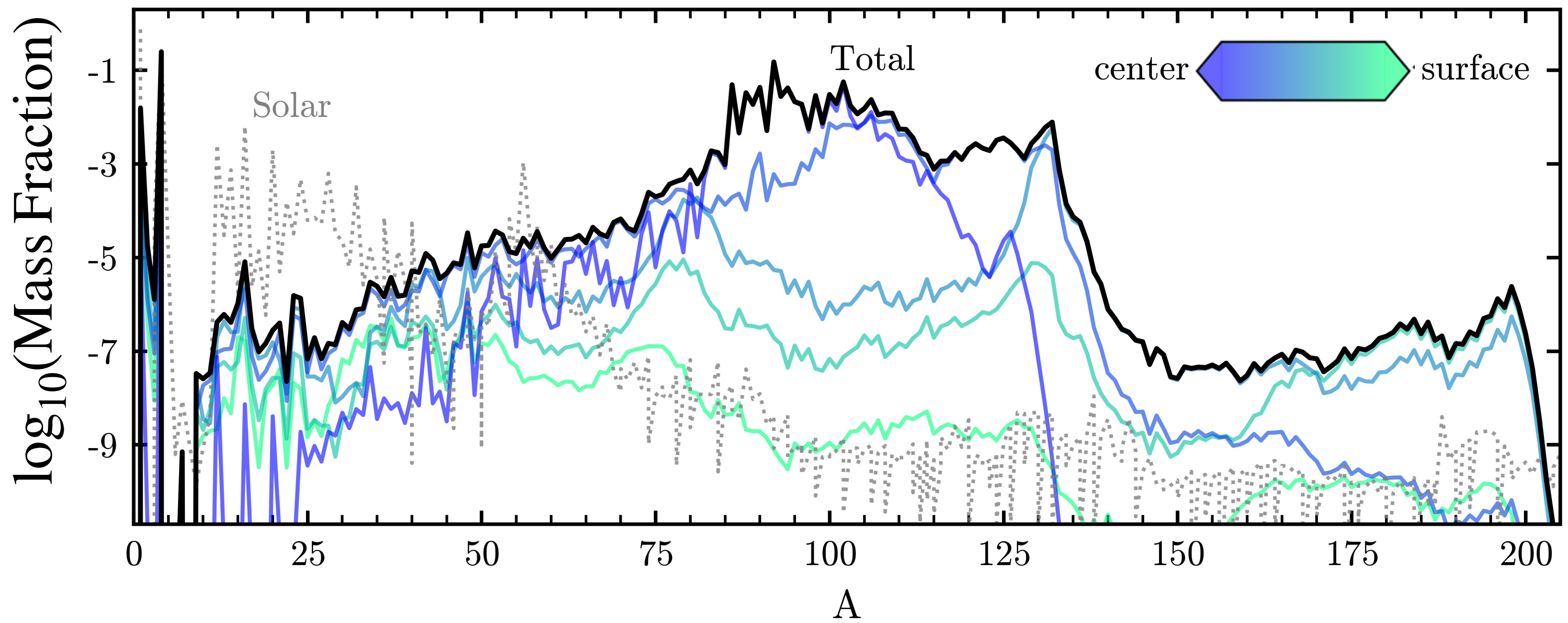
$$m(v) \propto v^{-3}$$

bulk velocity $\bar{v} \sim 0.1\text{-}0.2c$

Nucleosynthesis Calculations



Sky Net
bitbucket.org/jlippuner/skynet



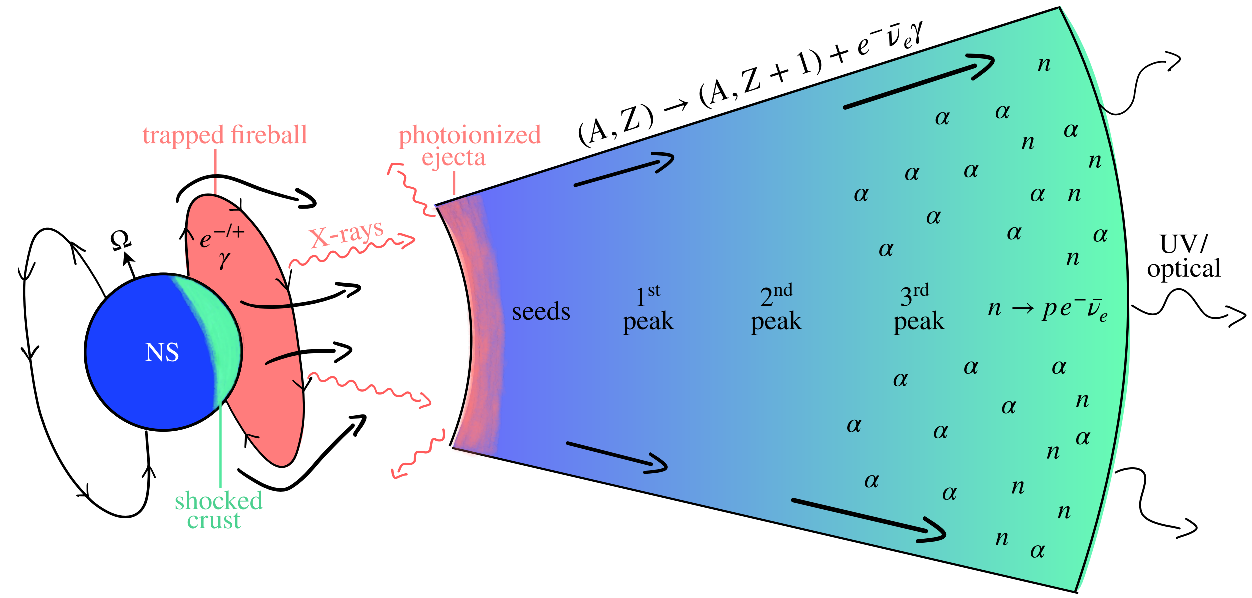
1D multi-zone model

$$M_{\mathrm{ej}} \approx 10^{-6} M_{\odot}$$

$$Y_e = 0.40$$

$$\bar{v} = 0.15c$$

Nucleosynthesis Calculations



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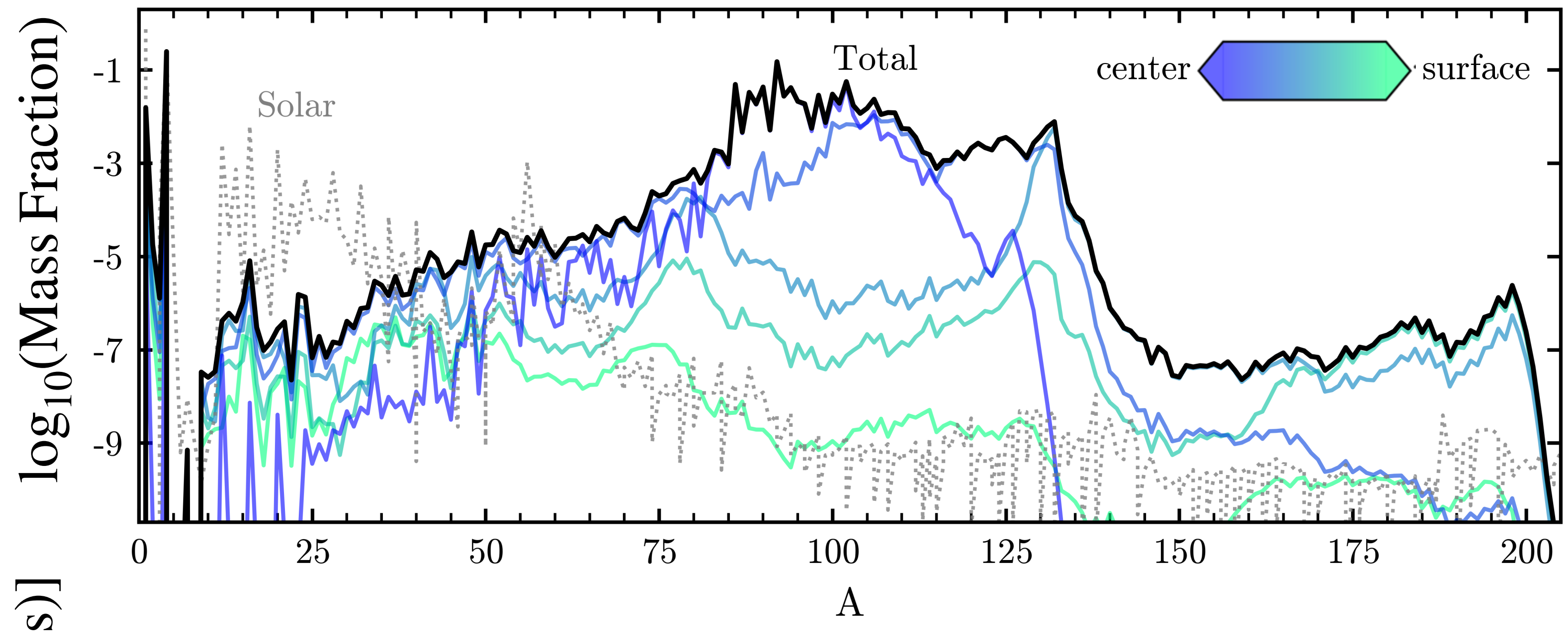
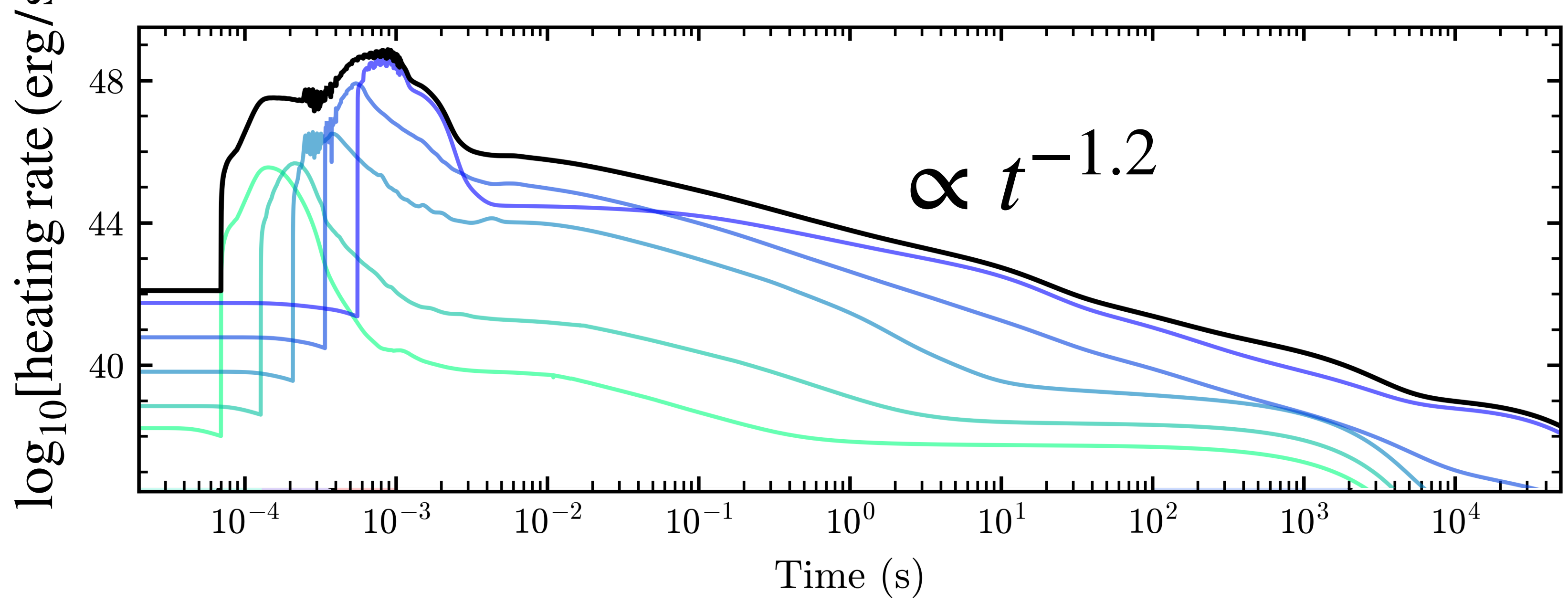
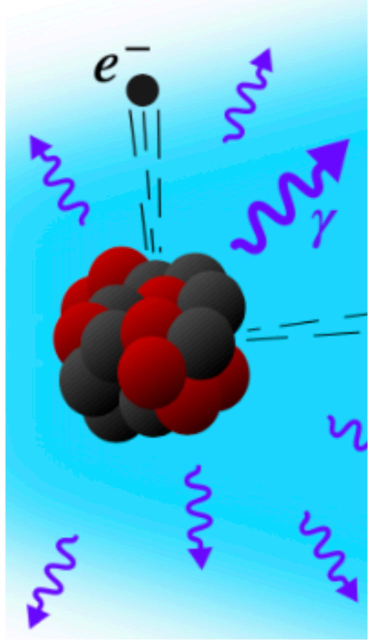




Optical/UV Emission: a "Mini-Kilonova"

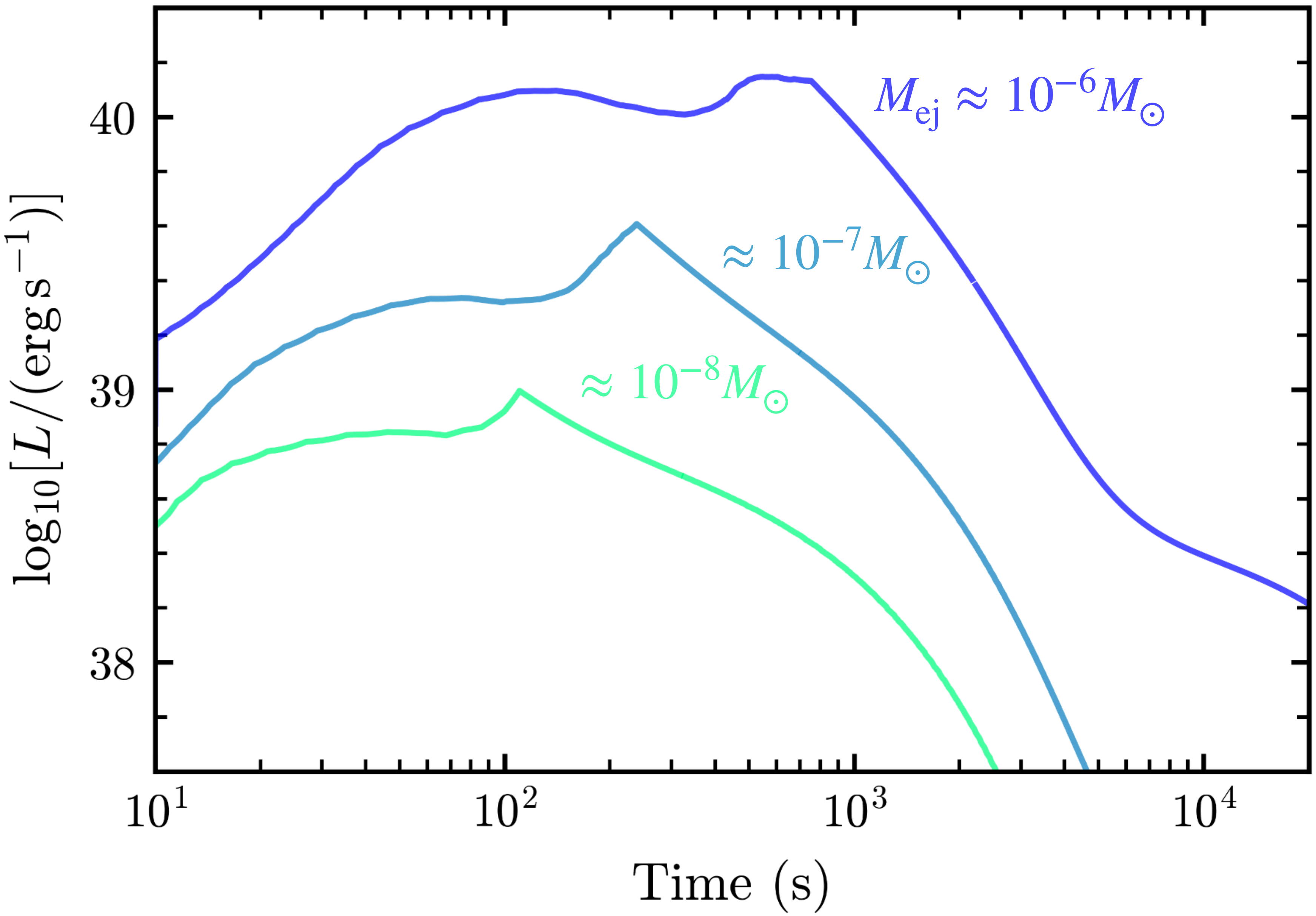
Heating: $\dot{Q}(t)$

Opacity: $X(t) \rightarrow \kappa(t)$

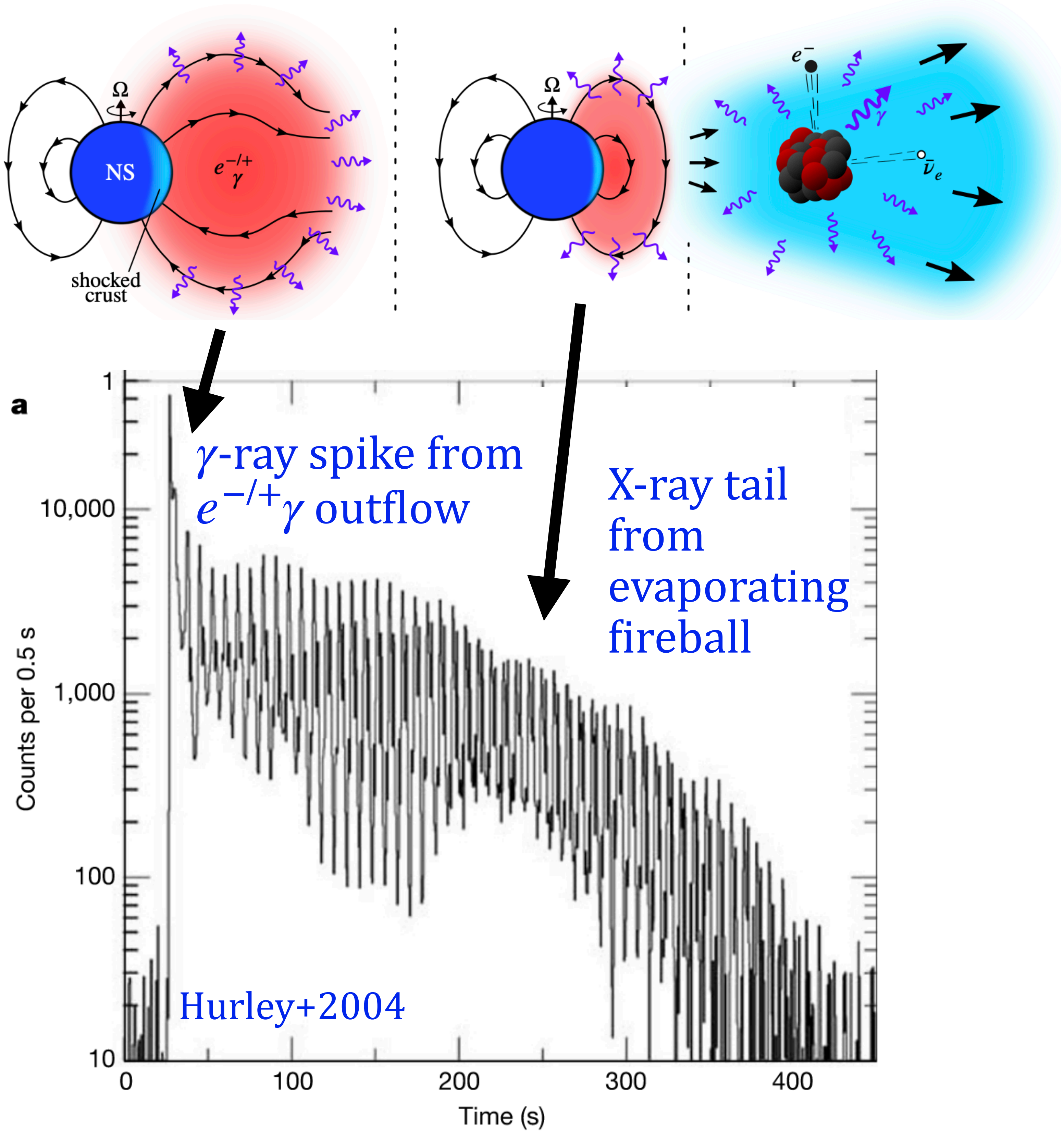


kilonova-like light-curve model

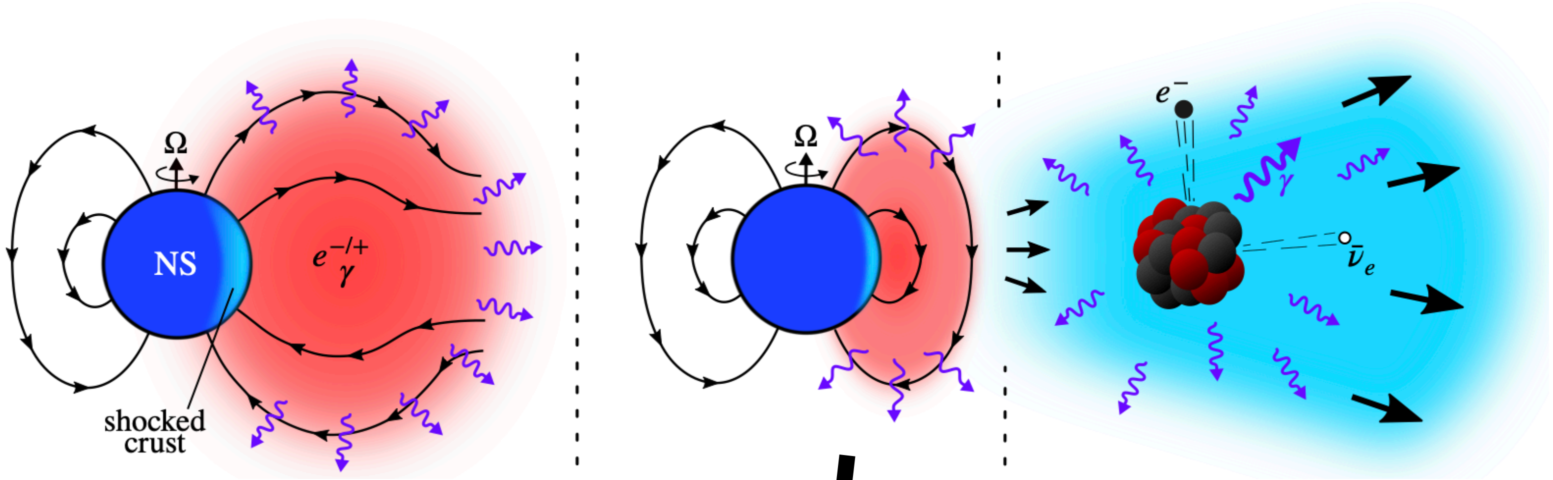
Mini-kilonovae: less mass, shorter duration

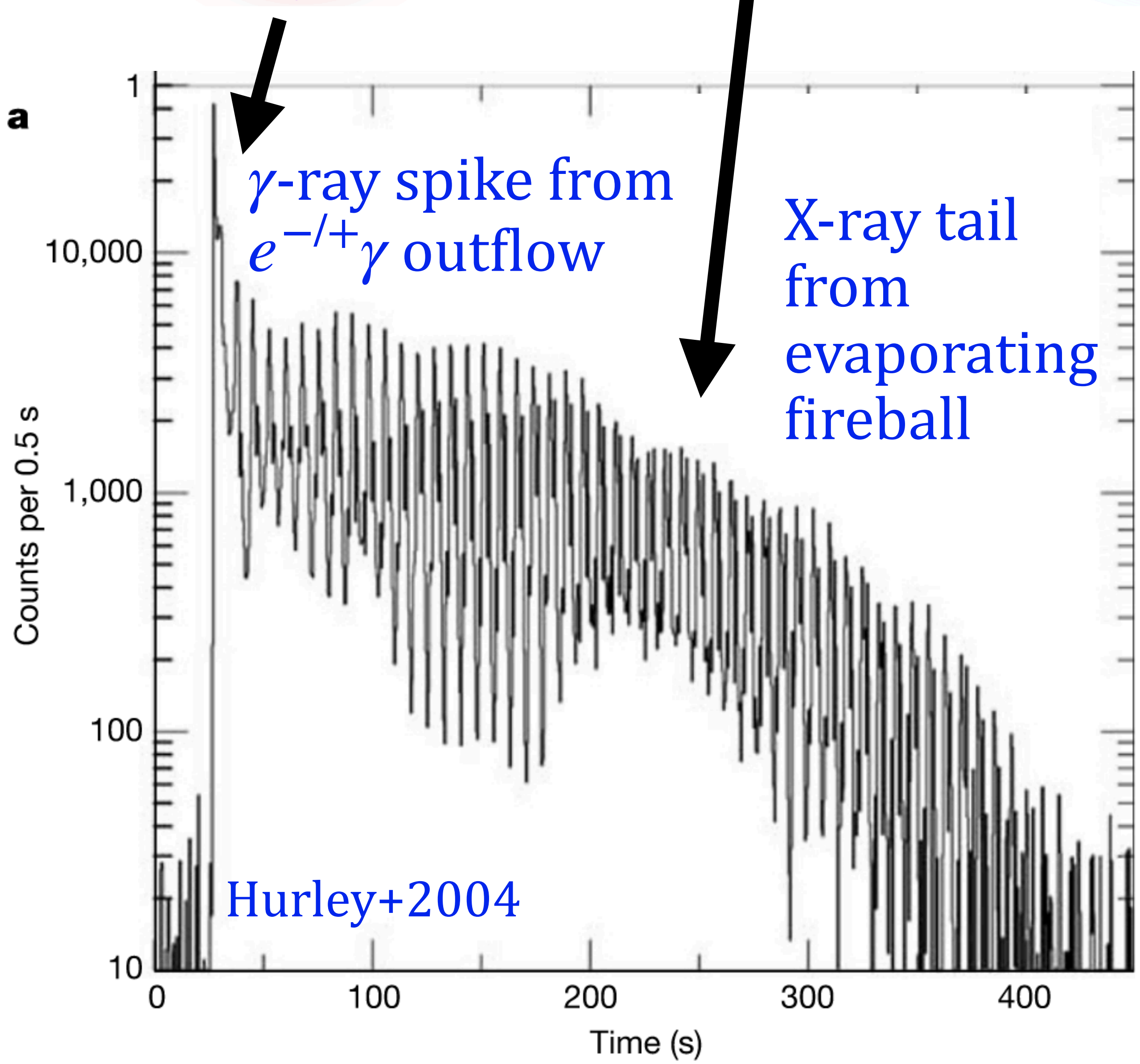


A third EM component in ~MeV?



Radioactive Gamma Ray Emission





$$\rho \sim \frac{M_{\rm ej}}{4\pi R^3} \propto t^{-3}$$

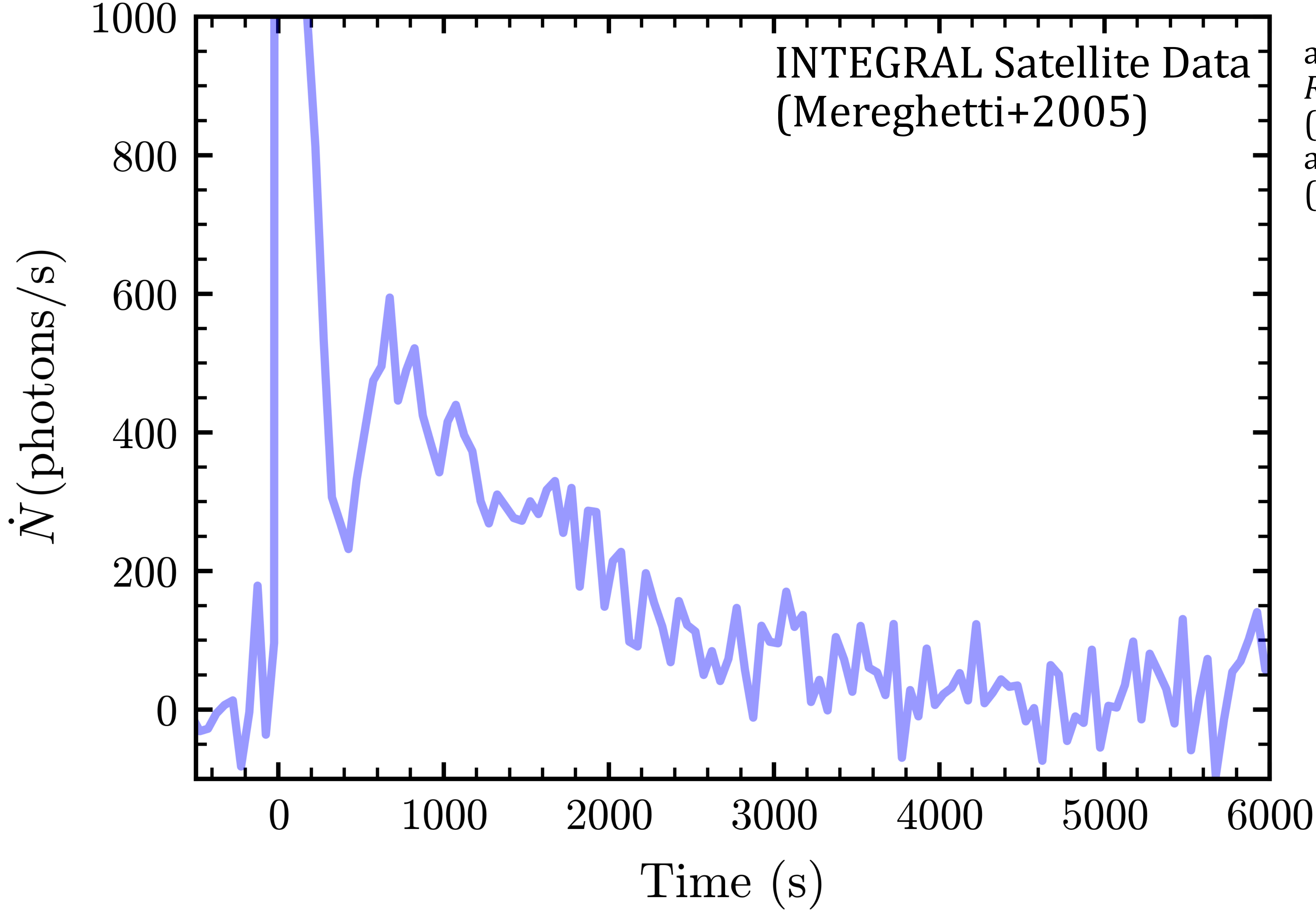
$$R \approx \bar{v}t$$

$$\tau_\gamma \sim \kappa\rho R \propto t^{-2}$$

$$t_{\rm peak} \approx t_{\tau=1} \sim \left(\frac{\kappa M_{\rm ej}}{4\pi\bar{v}^2}\right)^{1/2}$$

$$\sim 650\,{\rm s}\left(\frac{M_{\rm ej}}{10^{-6}M_\odot}\right)^{1/2}\left(\frac{\bar{v}}{0.2c}\right)^{-1}$$

A 20 year old mystery: delayed MeV emission in the SGR 1806-20 GF



also observed by *RHESSI* (Boggs+2007) and *Konus Wind* (Frederiks+2007)

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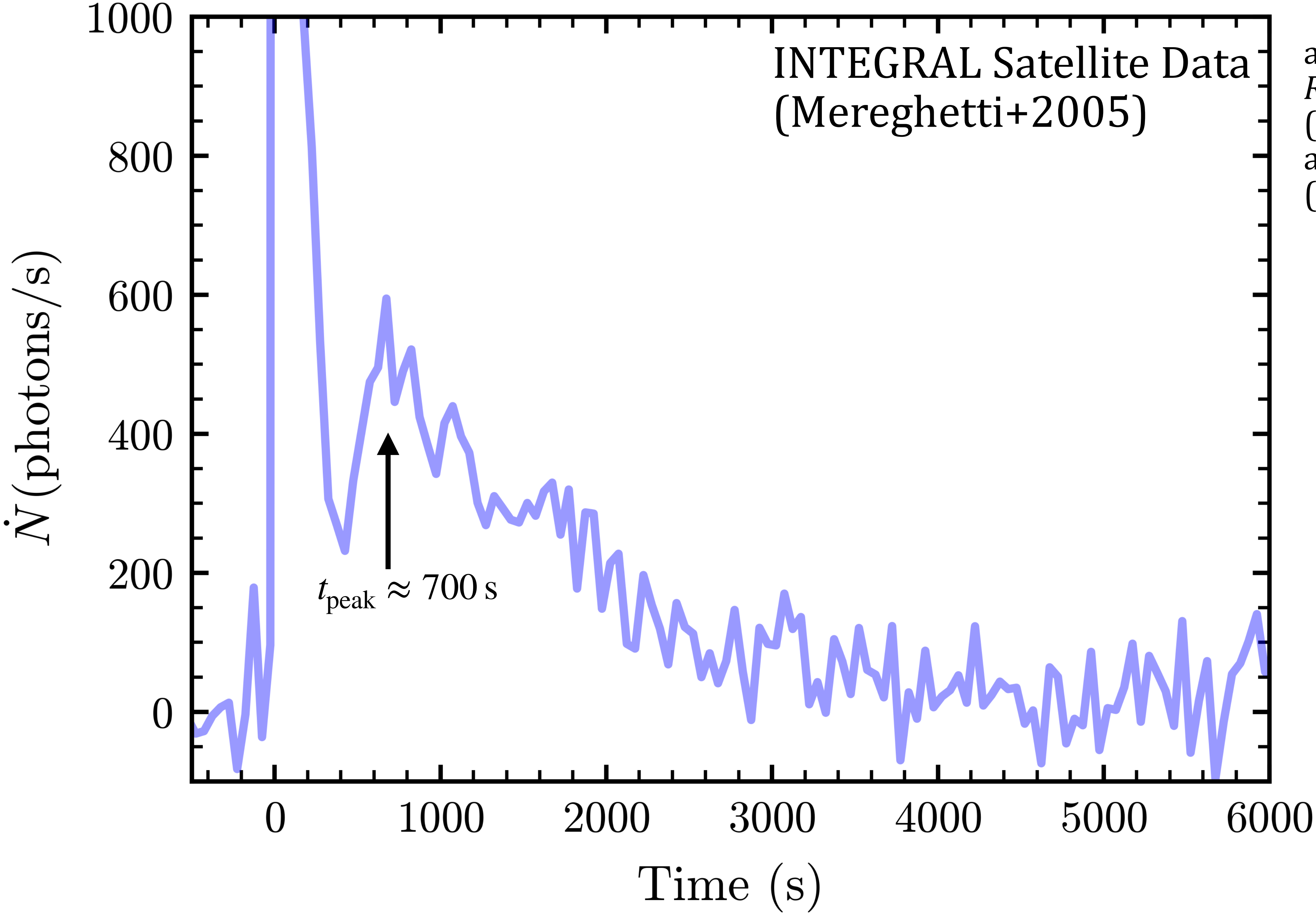

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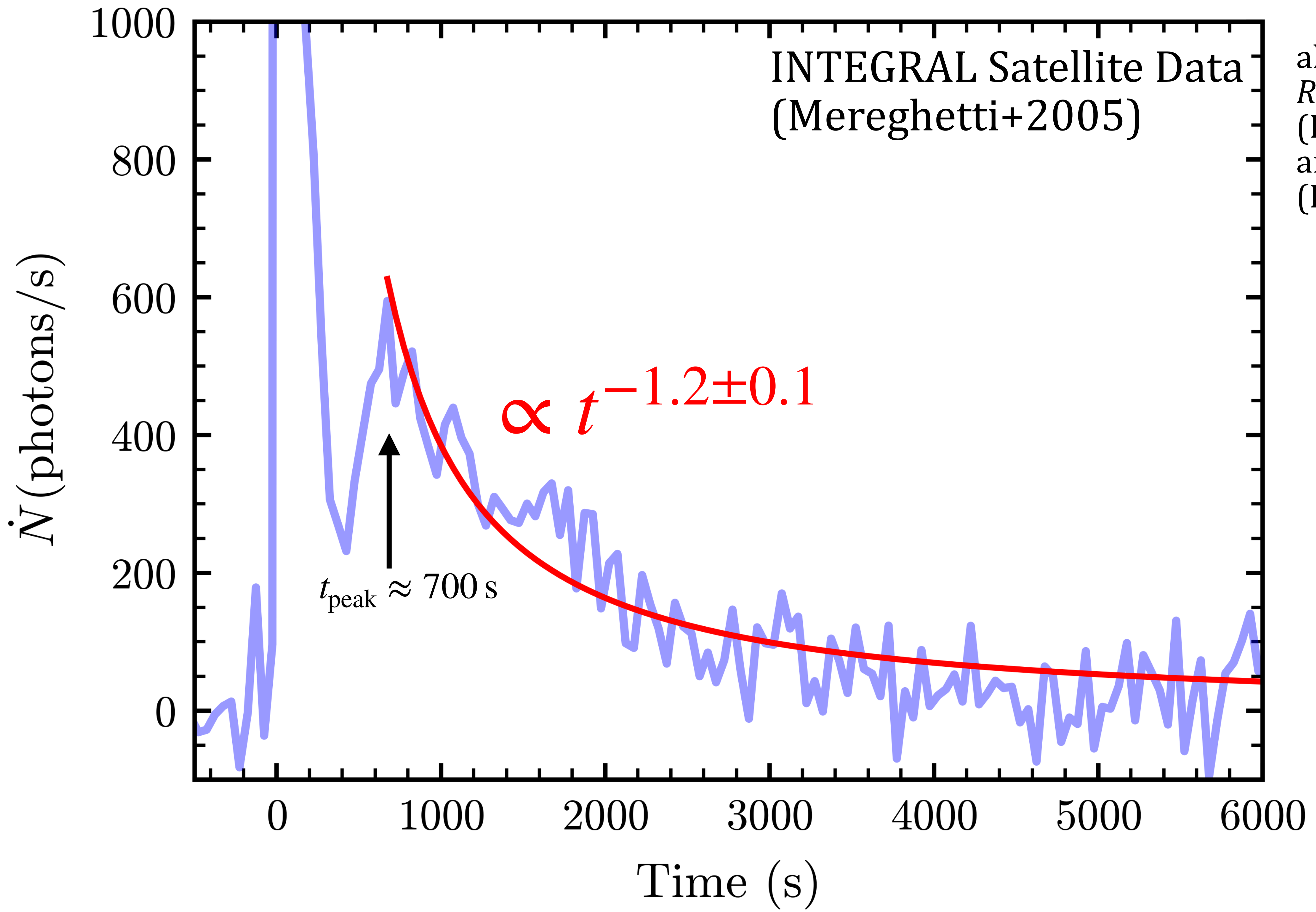


also observed by *RHESSI* (Boggs+2007) and *Konus Wind* (Frederiks+2007)

Calculating gamma-ray emission

$$\dot{q}_\gamma(t) = N_\mathrm{A} \sum_i Y_i(t) \lambda_i b_i \sum_j I_{ij} \varepsilon_{ij},$$

For a nuclear species i:

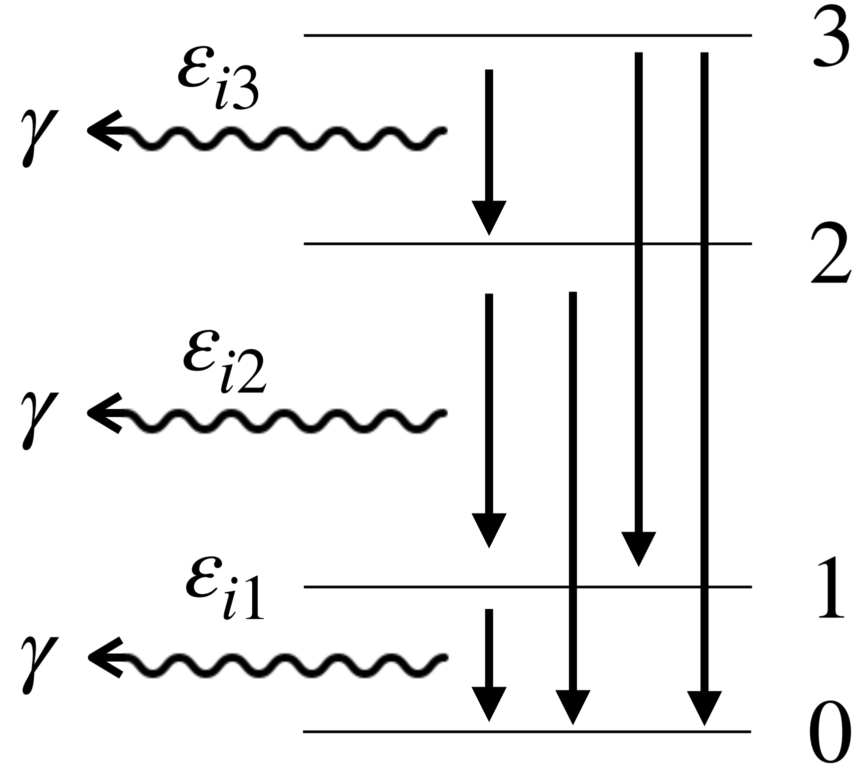
$Y_i(t)$: number abundance

λ_i: beta-decay rate

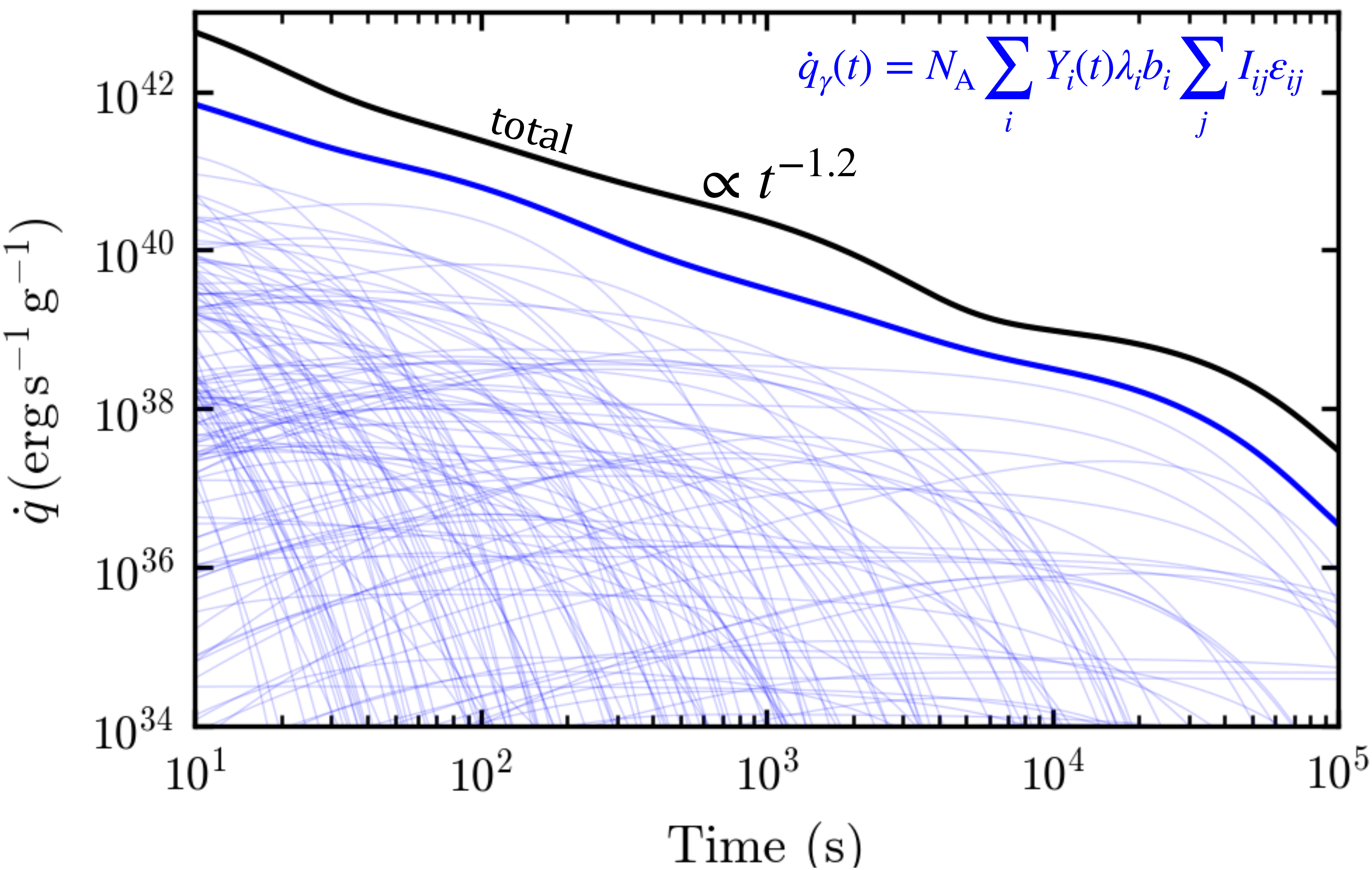
b_i: photon branching ratio (% of beta decay energy emitted as γ)

I_{ij}: relative intensity per decay of photon with energy ε_{ij}

e.g. $i \rightarrow f^* \rightarrow f + \gamma$



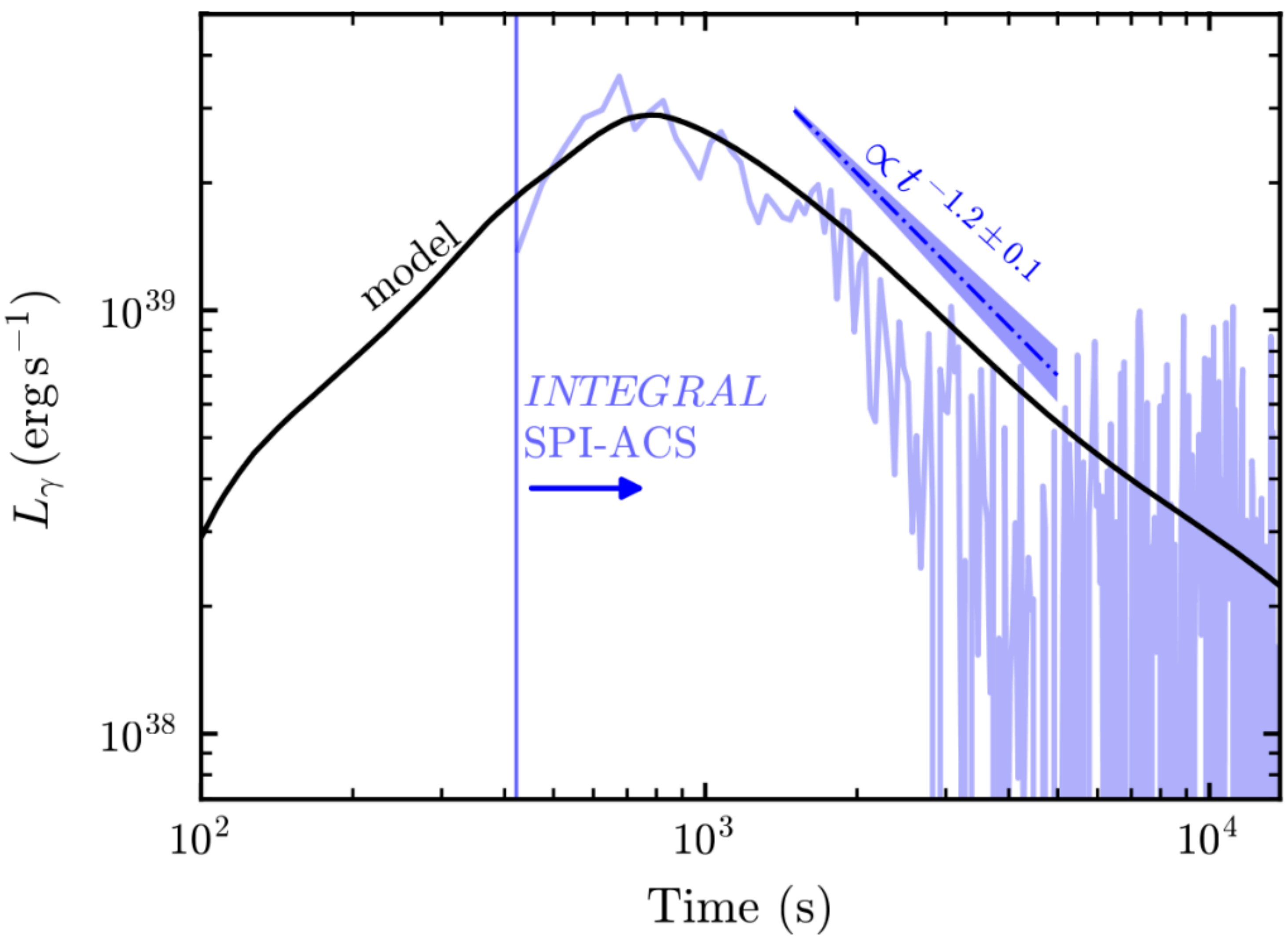
Calculating gamma-ray emission



Light-Curve and Fluence

$$M_{\rm ej} \approx 10^{-6} M_\odot$$
$$Y_e = 0.40$$
$$\bar{v} = 0.15c$$
$$L_\gamma = \dot{Q}_\gamma (1 - f_{\rm th})$$

Hotokezaka+ 2016
Barnes+ 2016



Light-Curve and Fluence

Peak time, decay rate, and fluence consistent with data.

$$M_{\rm ej} \approx 10^{-6} M_{\odot}$$

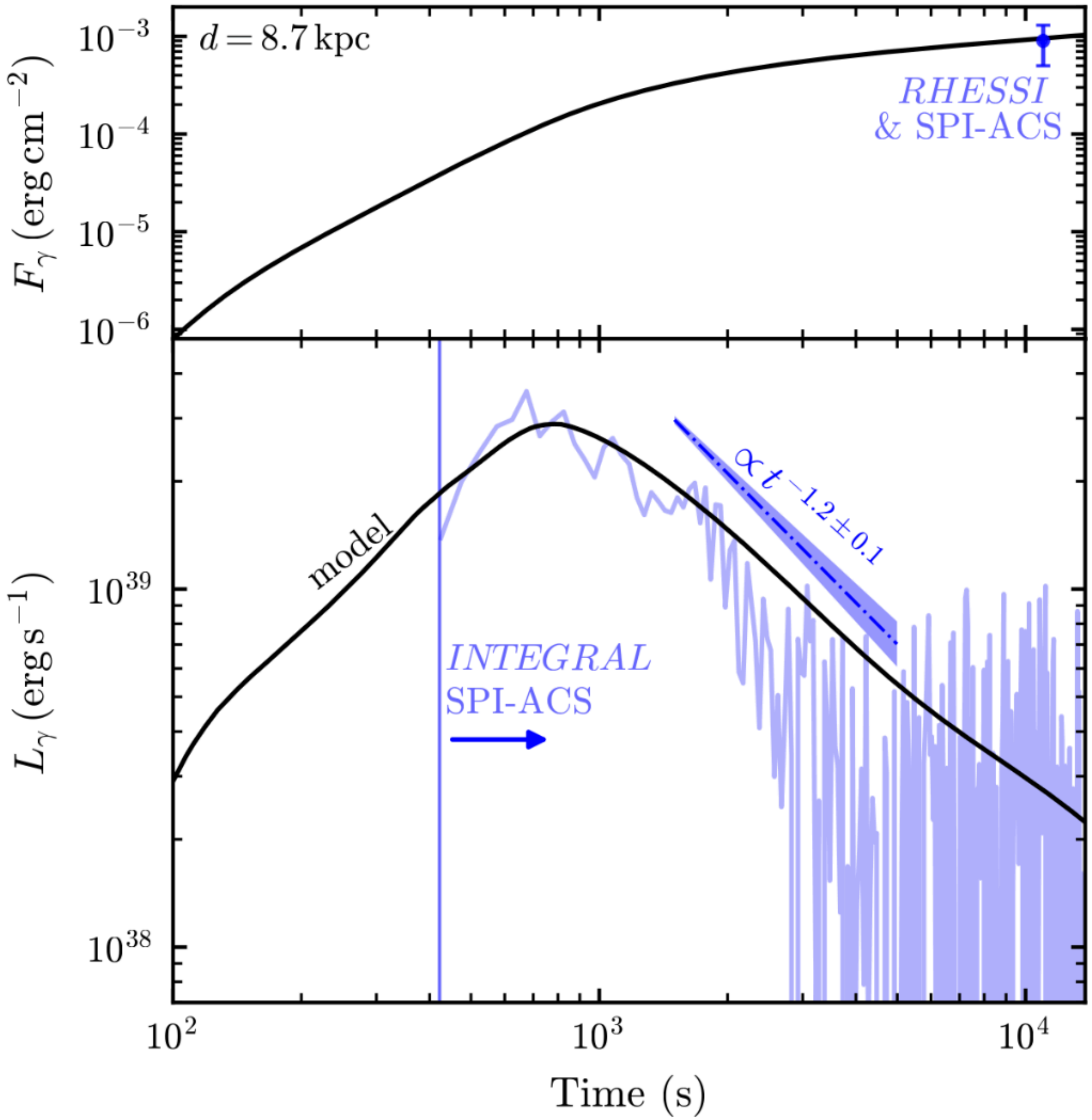
$$Y_e = 0.40$$

$$\bar{v} = 0.15c$$

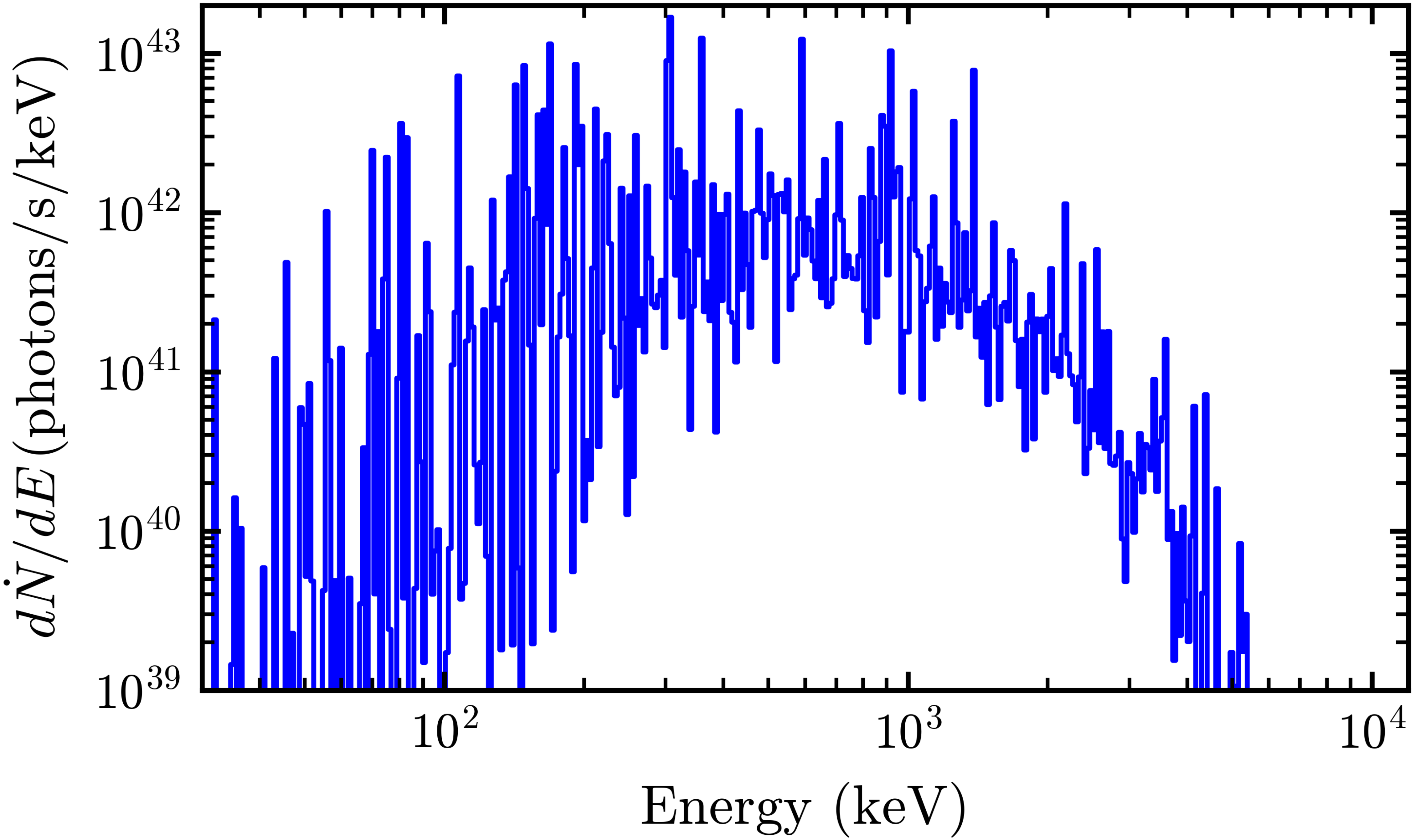
$$L_\gamma = \dot{Q}_\gamma (1 - f_{\rm th})$$

Hotokezaka+ 2016

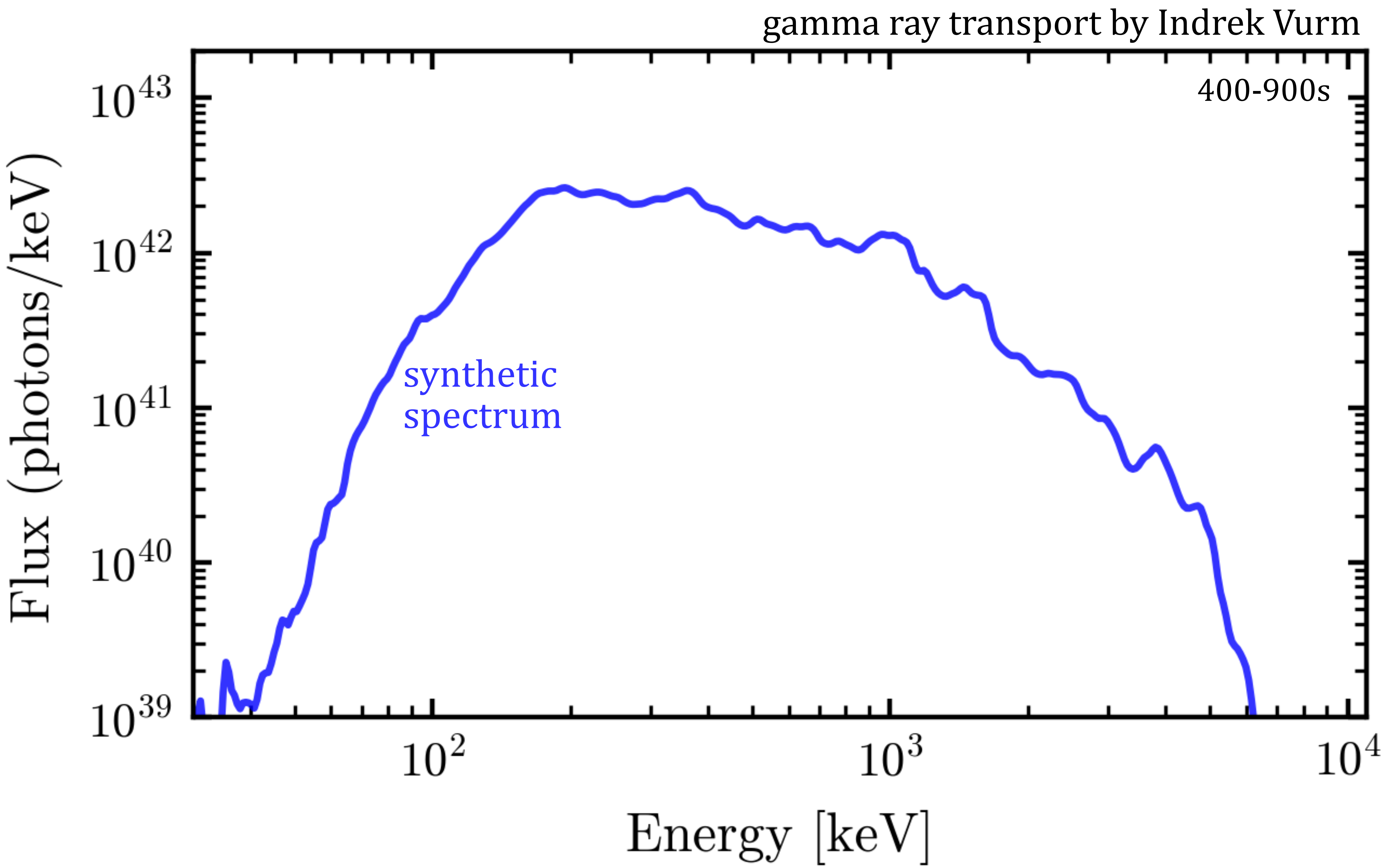
Barnes+ 2016



Spectra (unattenuated)



Spectra with (preliminary) MC radiation transport



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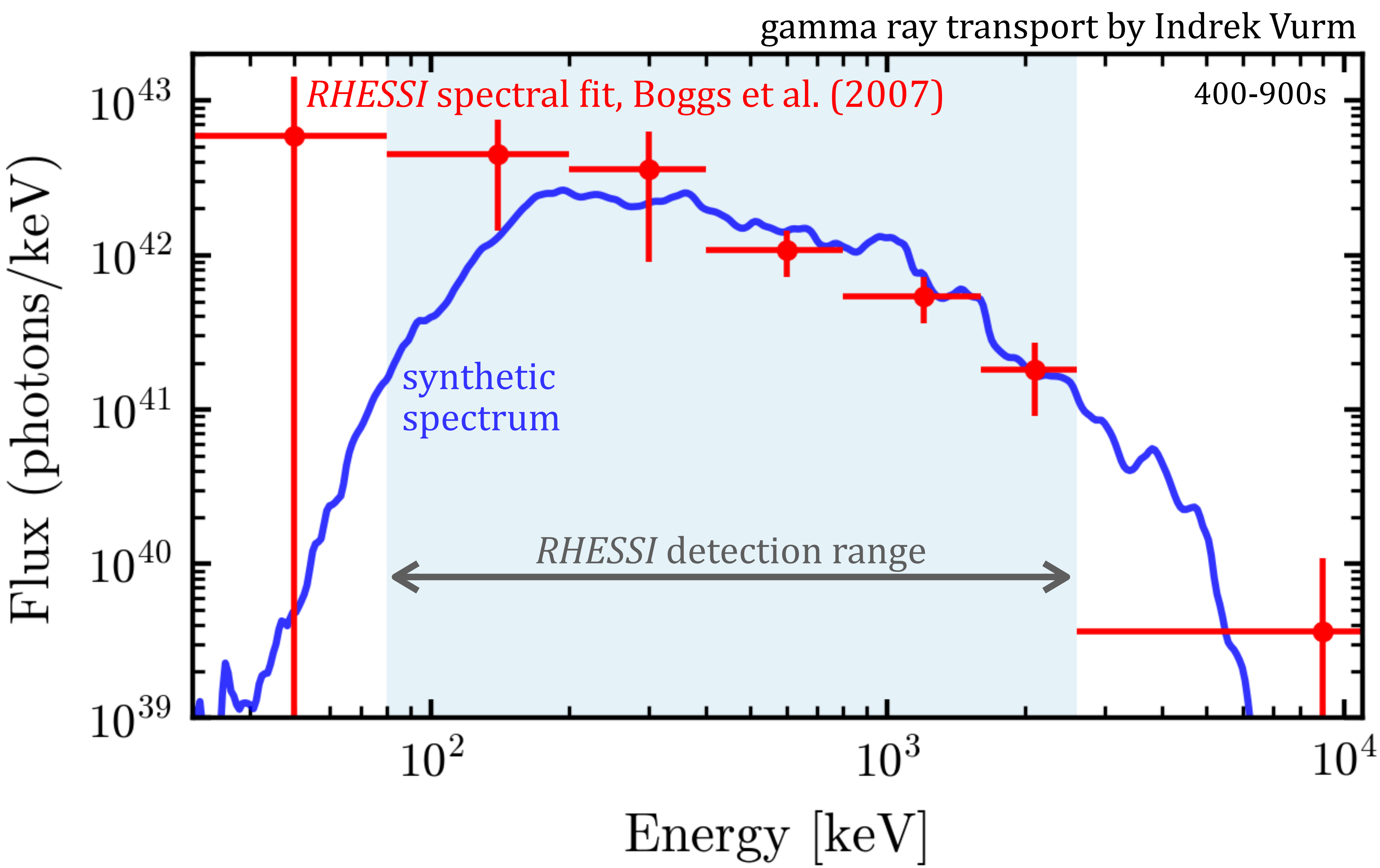
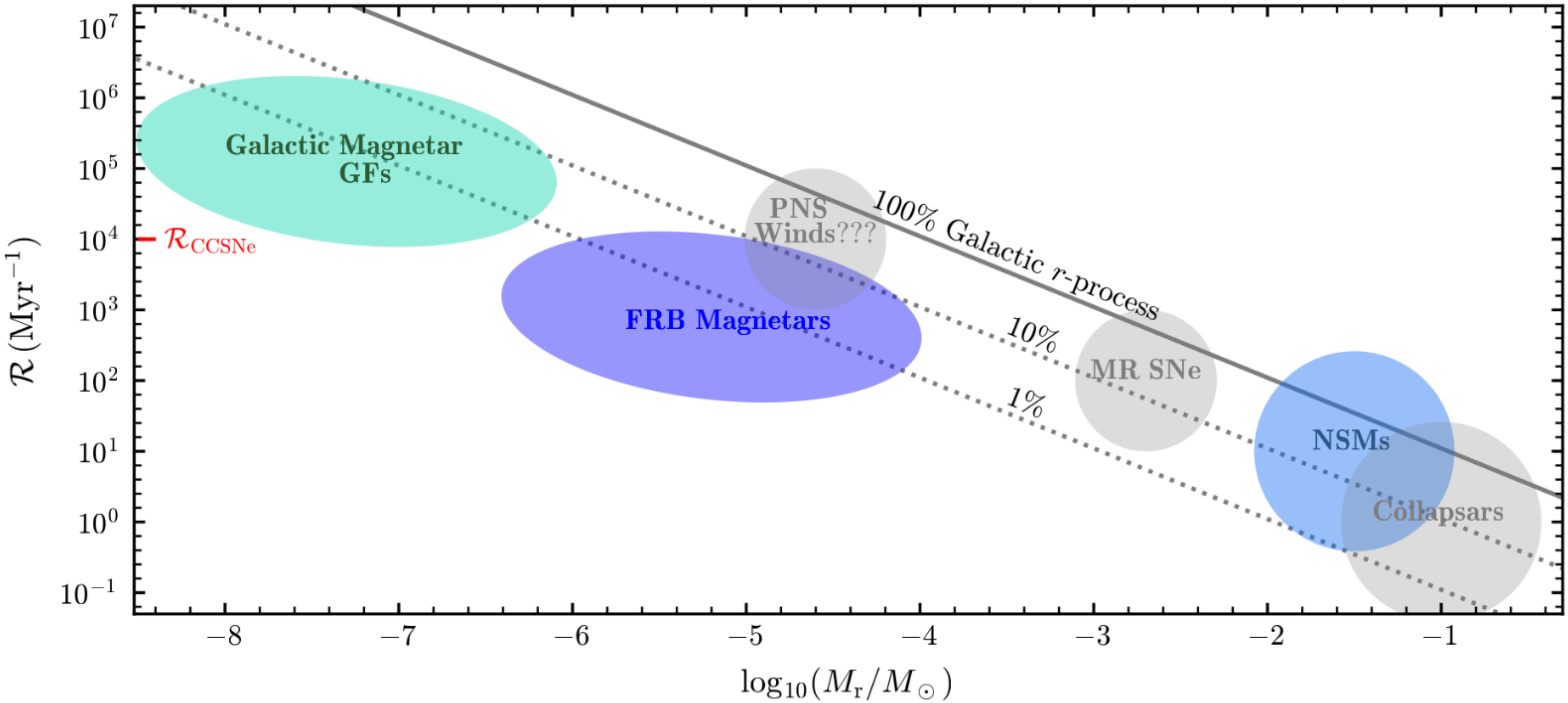
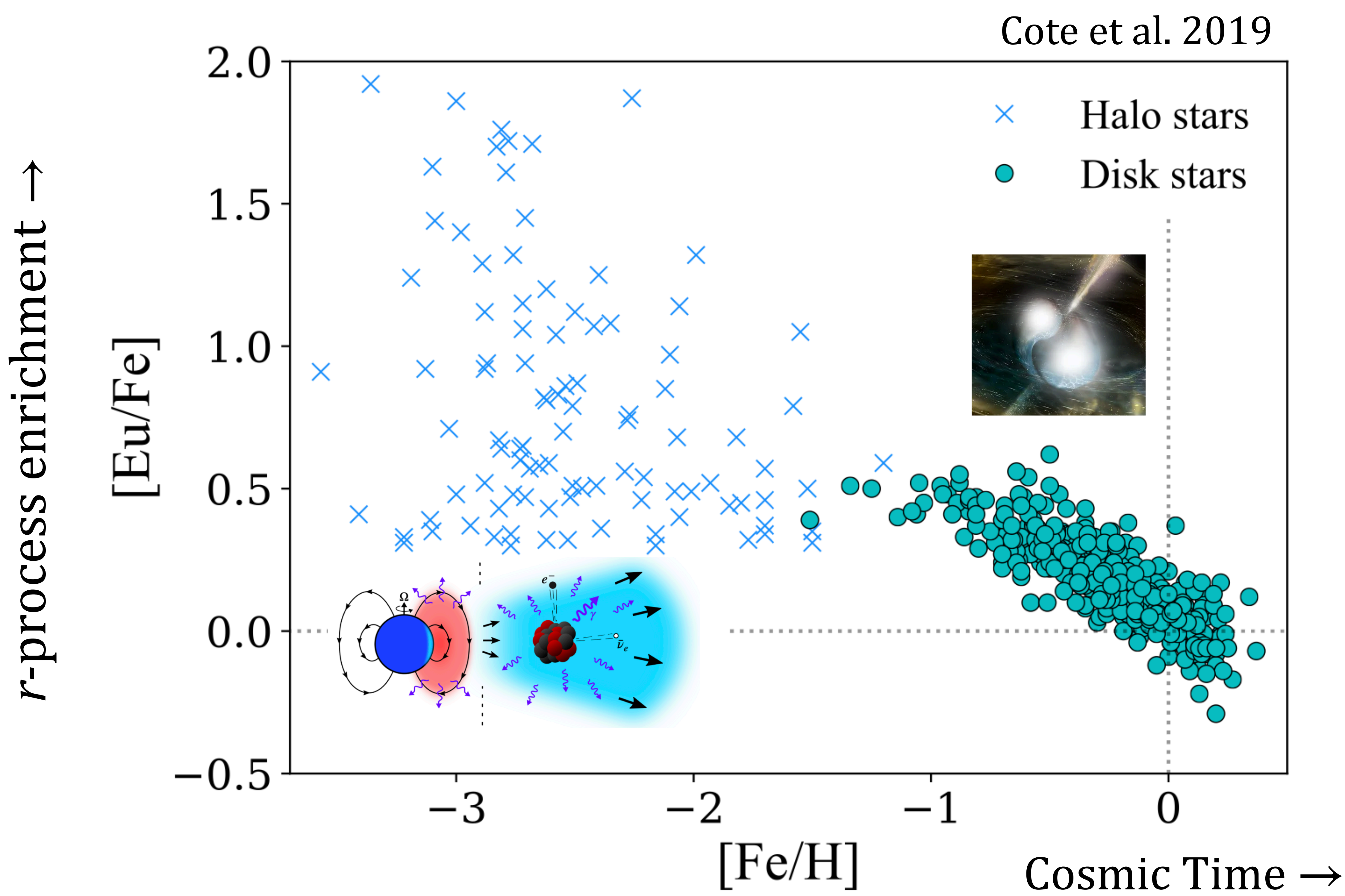


Magnetar GFs can contribute ~1-10% of Galactic *r*-process



$\langle R \rangle \approx 6\text{-}9 \times 10^{-2}\,\mathrm{yr}^{-1}\,(E_{\rm GF}/10^{46}\,\mathrm{erg})^{-0.75} \quad M_{\rm r}\langle R \rangle = \langle \dot{M}_{\rm r} \rangle \quad \approx 0.4\text{-}6 \times 10^{-8}\,M_\odot \mathrm{yr}^{-1}$

Magnetars are born early in Galactic history!



Summary: Delayed MeV detection from the SGR 1806-20 GF is consistent with gamma ray emission from $\sim 10^{-6} M_\odot$ of *r*-process

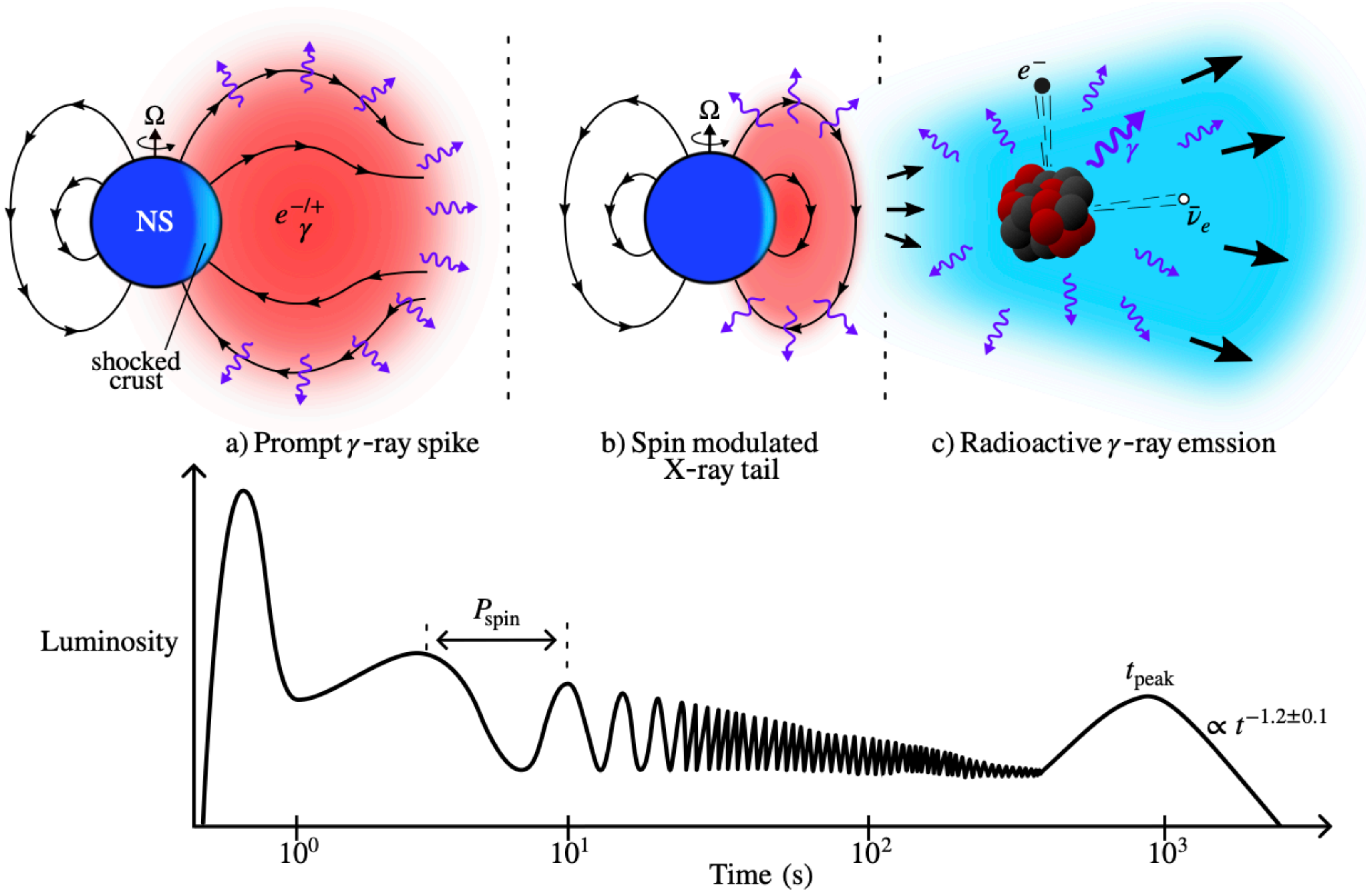
<u>Radio Observations</u>

- ☑ Ejecta Mass
- ☑ Velocity

<u>~MeV Observations</u>

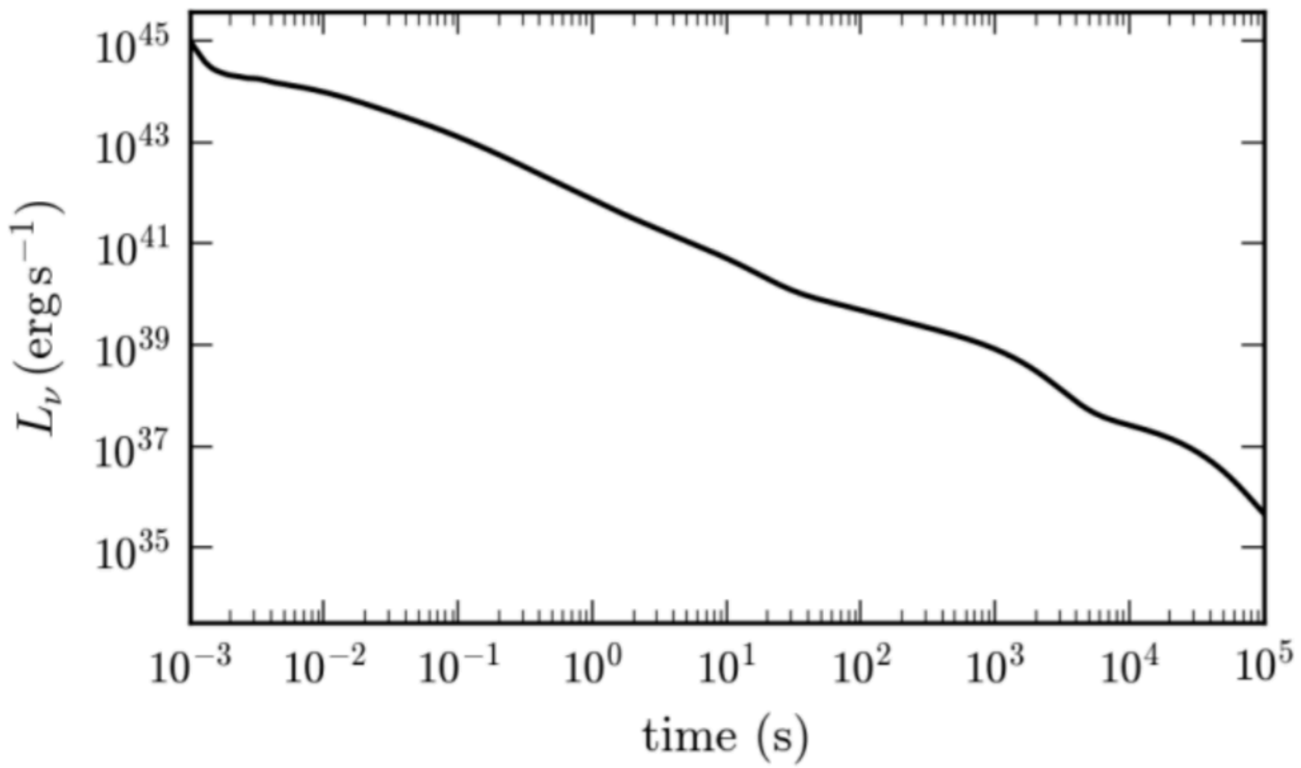
- ☑ Peak Time-Scale
- ☑ Fluence
- ☑ Decay Rate
- ☑ Hard Spectrum

- At least 1-10 % of Galactic *r*-process
- Operates early in galactic history
- Provides first opportunity to directly observe nuclear line emission from the *r*-process
- Can constrain GF operating mechanism and probe magnetar field evolution



Backup

Neutrinos detectable?



Assuming 35% of r-process decay energy emitted as neutrinos, $E_\nu \sim 10^{43}$ erg.

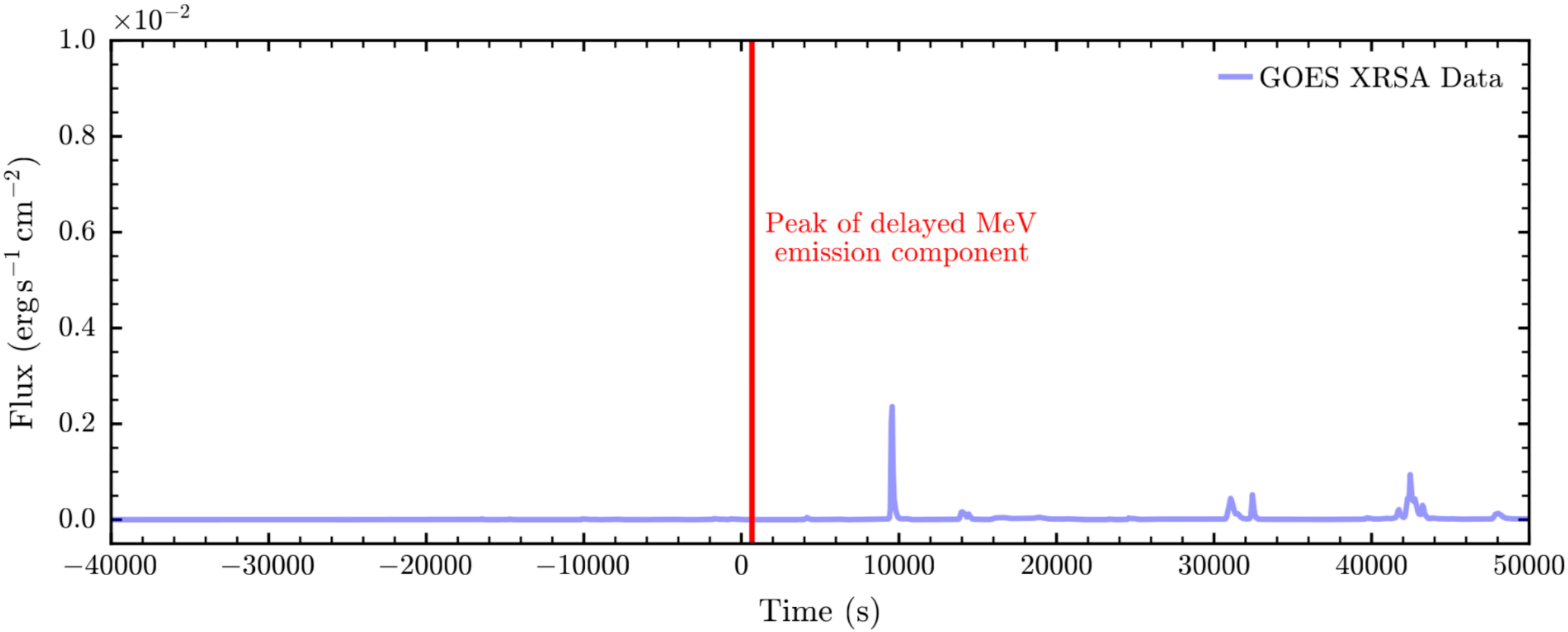
$\langle \varepsilon_\nu \rangle \sim 5$ MeV

For a supernova with $E_{\nu,\mathrm{SN}} \sim 10^{53}$ erg and $\langle \varepsilon_{\nu,\mathrm{SN}} \rangle \sim 5$ MeV, HyperK will detect $N_{\nu,\mathrm{SN}} \sim 10^4 - 10^5$ neutrinos for a ~ 10 kpc source.

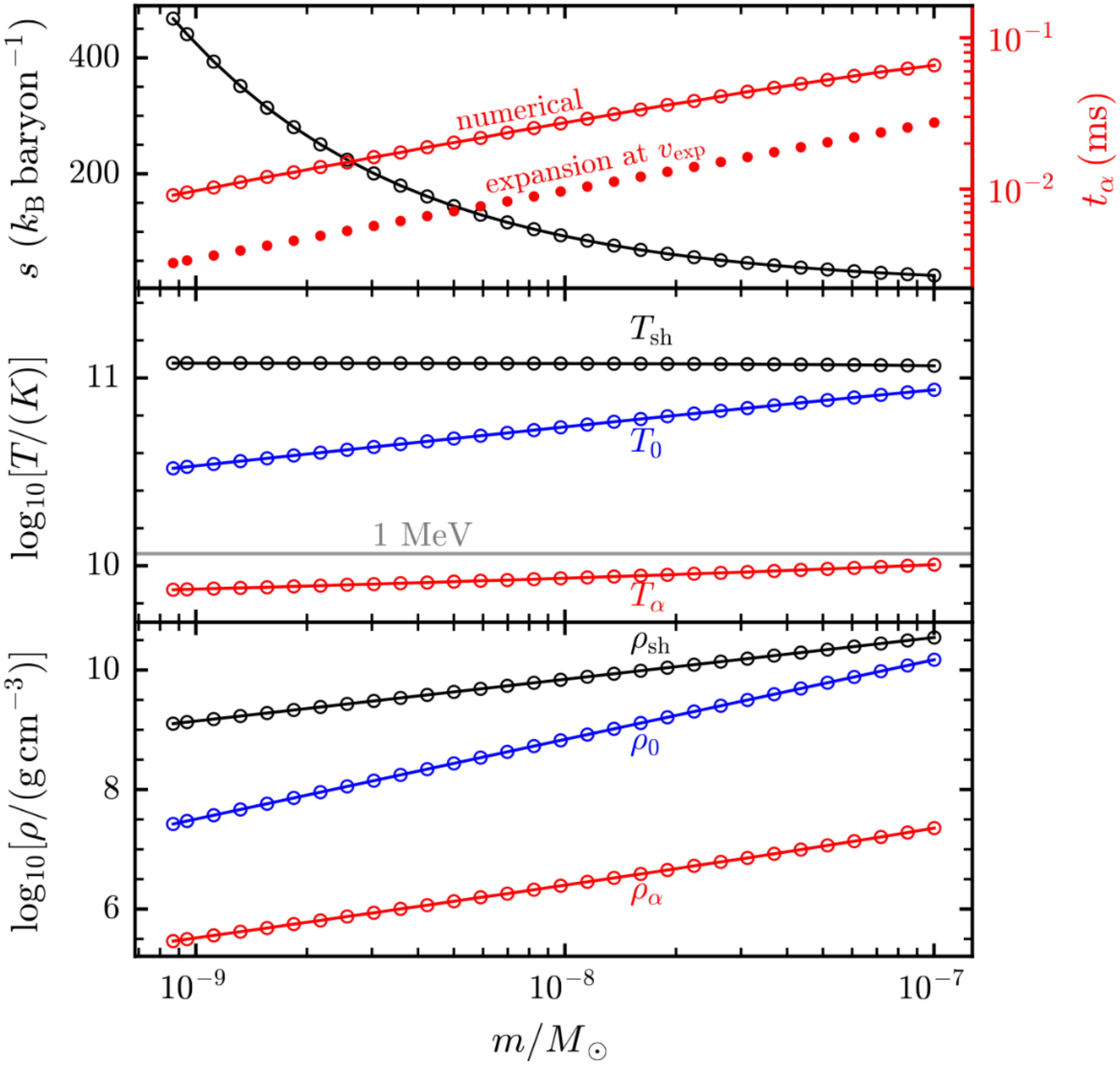
For a magnetar giant flare at similar distance:

$$N_\nu \approx N_{\nu,\mathrm{SN}} \frac{E_\nu}{E_{\nu,\mathrm{SN}}} \left(\frac{\langle \varepsilon_\nu \rangle}{\langle \varepsilon_{\nu,\mathrm{SN}} \rangle} \right)^2 \sim 10^{-6} - 10^{-5}$$

No, it's not from the Sun.

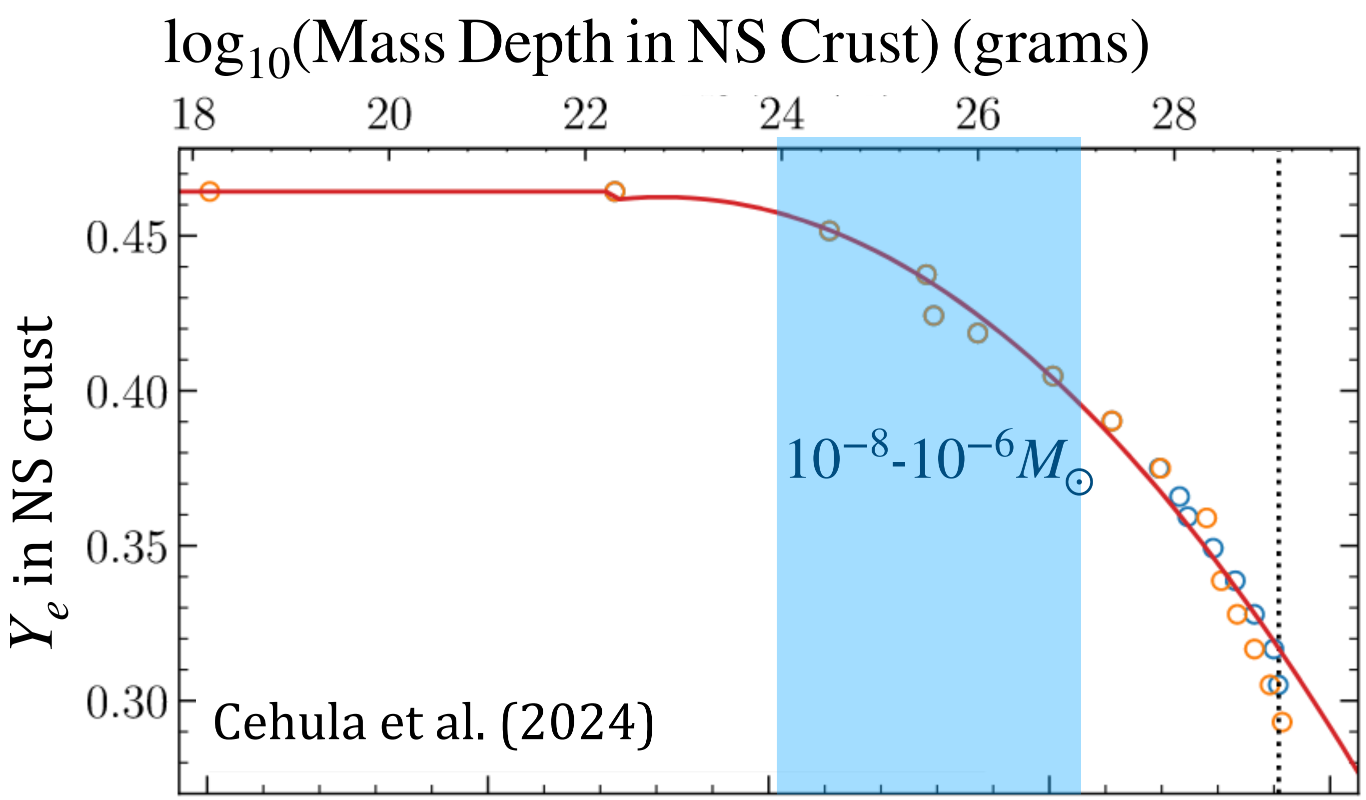


Nucleosynthesis



$$\rho(t) = \rho_{\rm D} \begin{cases} \left(\frac{t}{t_{\rm D}}\right)^{-1}, & t_0 \le t \le t_{\rm D} \\ \left(\frac{t}{t_{\rm D}}\right)^{-3}, & t \ge t_{\rm D}, \end{cases}$$

EOS, Y_e



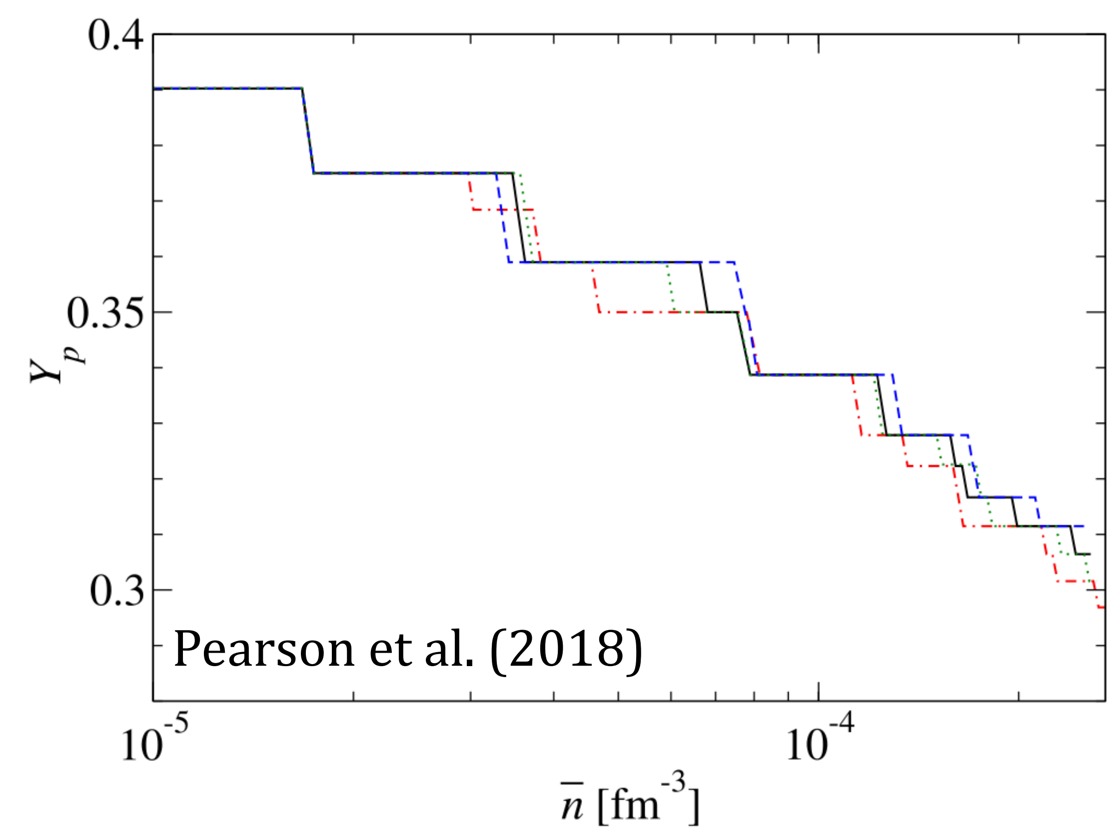
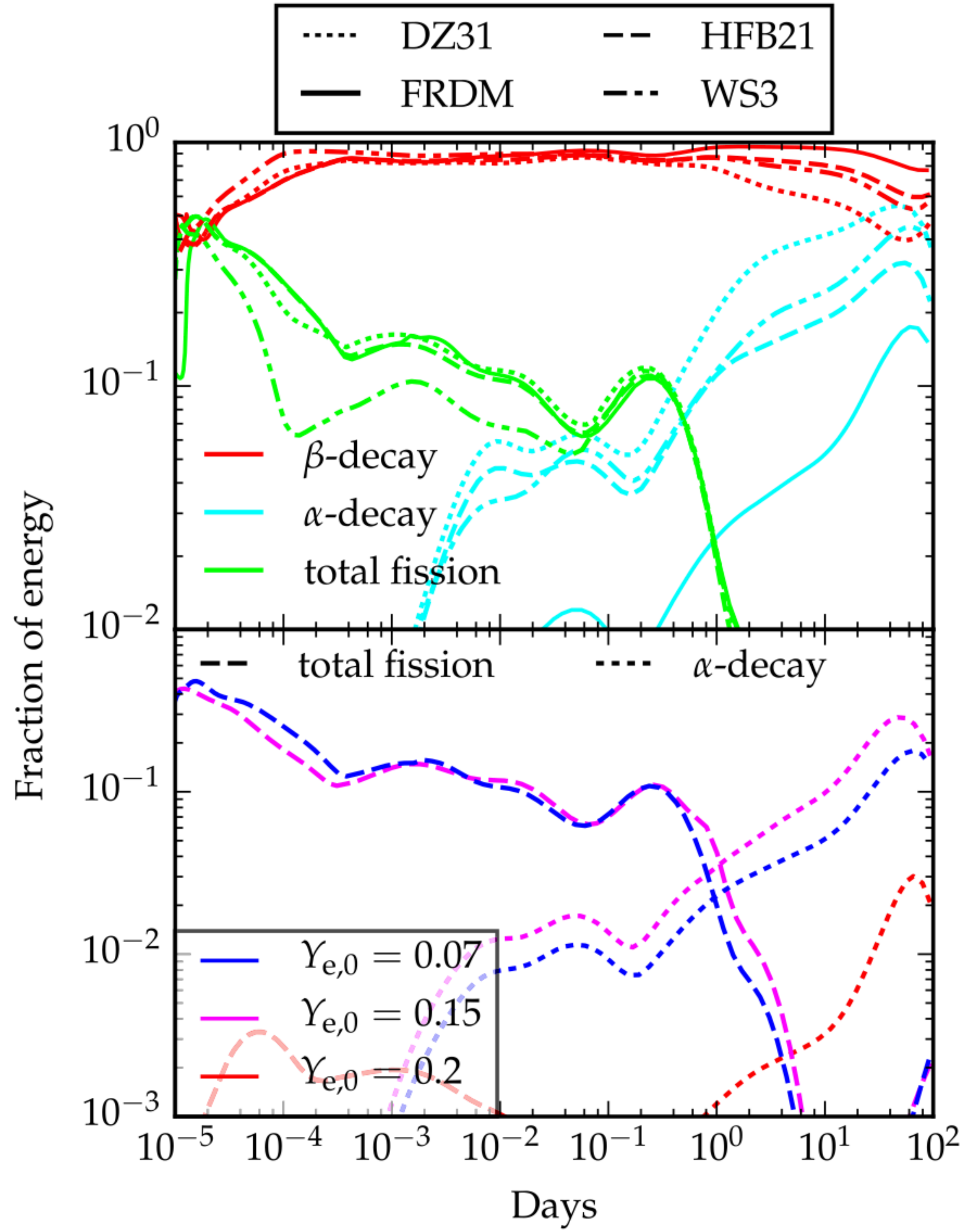


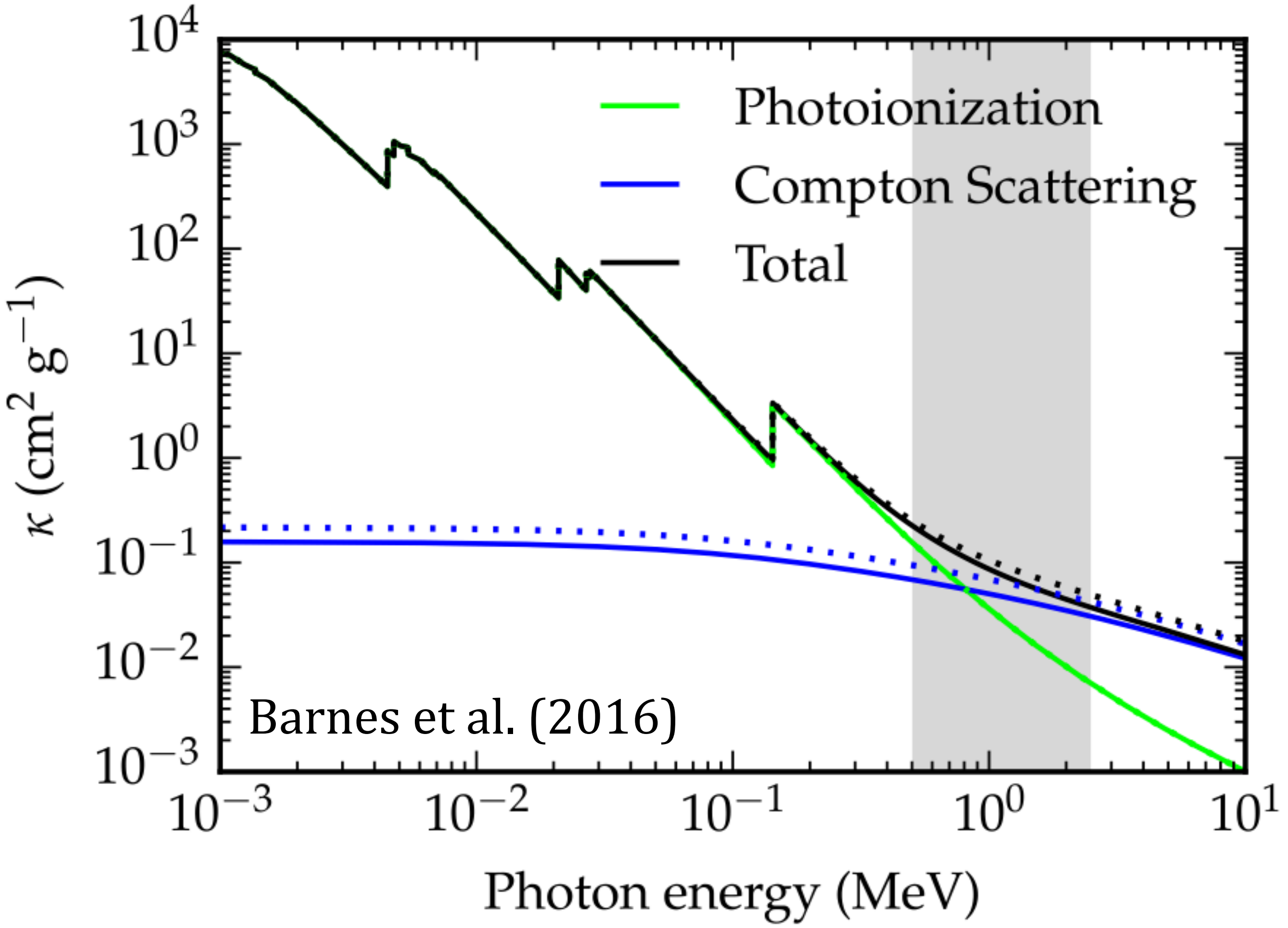
Figure 7. Variation of the proton fraction Y_p as a function of the mean baryon number density in the outer crust for the nuclear mass models HFB-22, HFB-24, HFB-25, and HFB-26.

Decays



Barnes+2016

Gamma ray Thermalization



$$\kappa_\gamma \approx 0.1\,\mathrm{cm^2\,g^{-1}}$$

$$\tau_\gamma(r) = \int_r^\infty \kappa_\gamma \rho(r', t) dr'$$

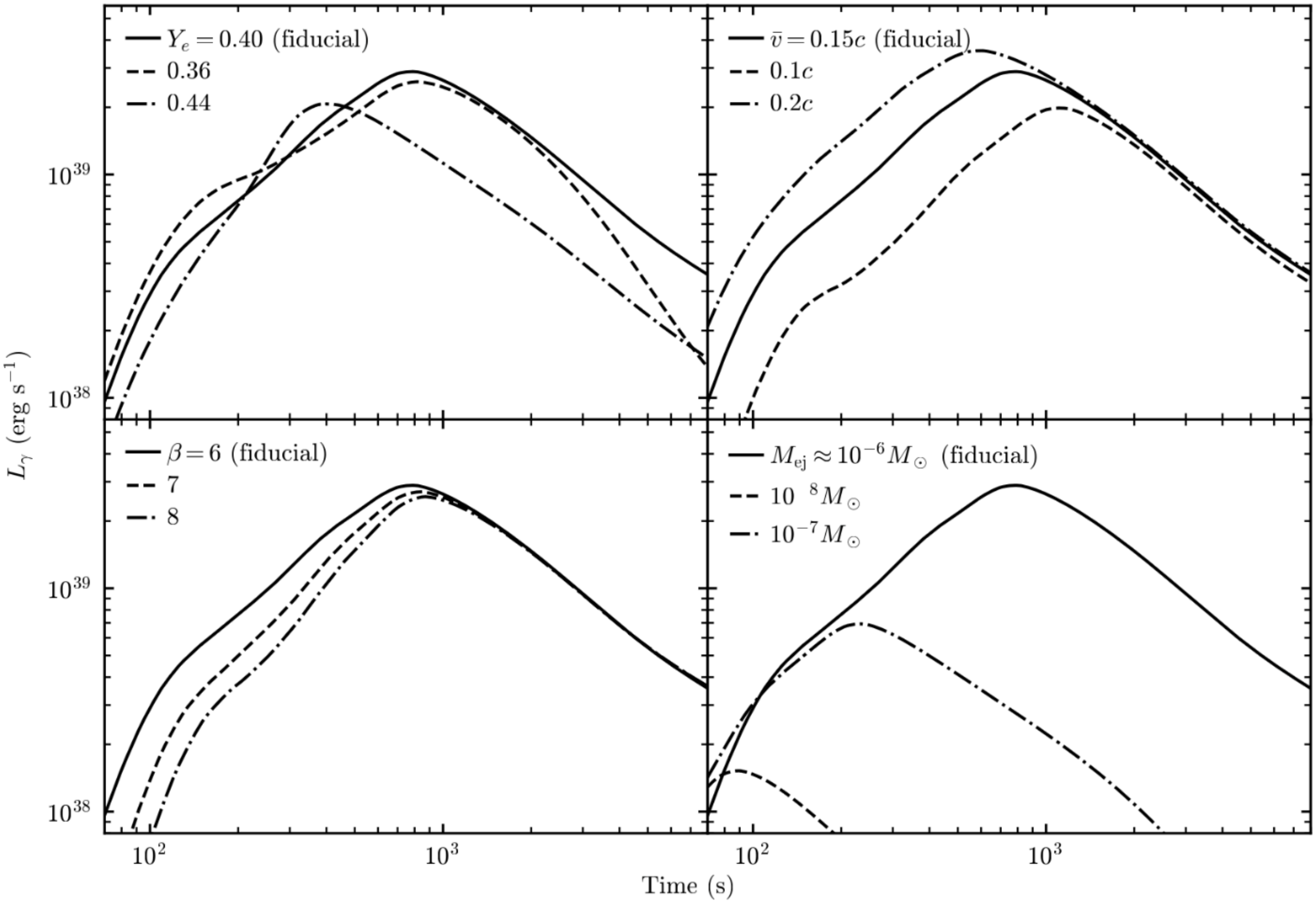
$$N = \max(\tau_\gamma, \tau_\gamma^2)$$

$$f_{\mathrm{th}} \approx \begin{cases} 1 - (1/2)^N, & \tau_\gamma \geq 1 \\ N/2, & \tau_\gamma \leq 1 \end{cases}$$

$$L_\gamma = \dot{Q}_\gamma (1 - f_{\mathrm{th}})$$

Hotokezaka et al. (2016)

Gamma Ray LC Parameters



Nova Brevis LC model

Opacity:

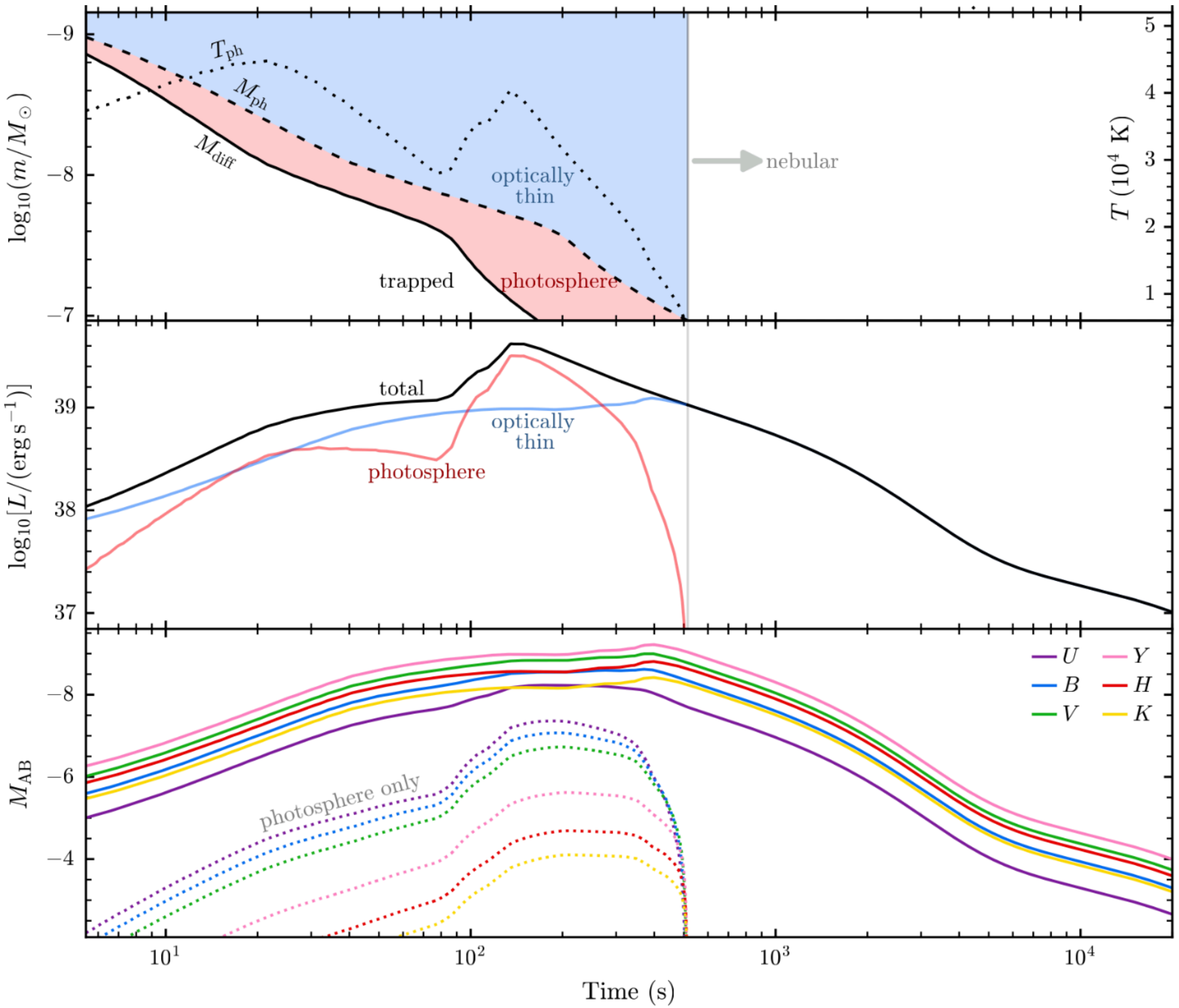
$$\kappa(t) = X_p(t)\kappa_p + X_\alpha\kappa_\alpha + X_1\kappa_1 + X_2\kappa_2 + X_3\kappa_3$$ (Kasen+2013, Tanaka+2020)

Thermalization:

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

Attenuated light-curve: $\dot{q}_{\rm heat}(t) = f_{\rm th}(t)\dot{q}(t)$

LC model



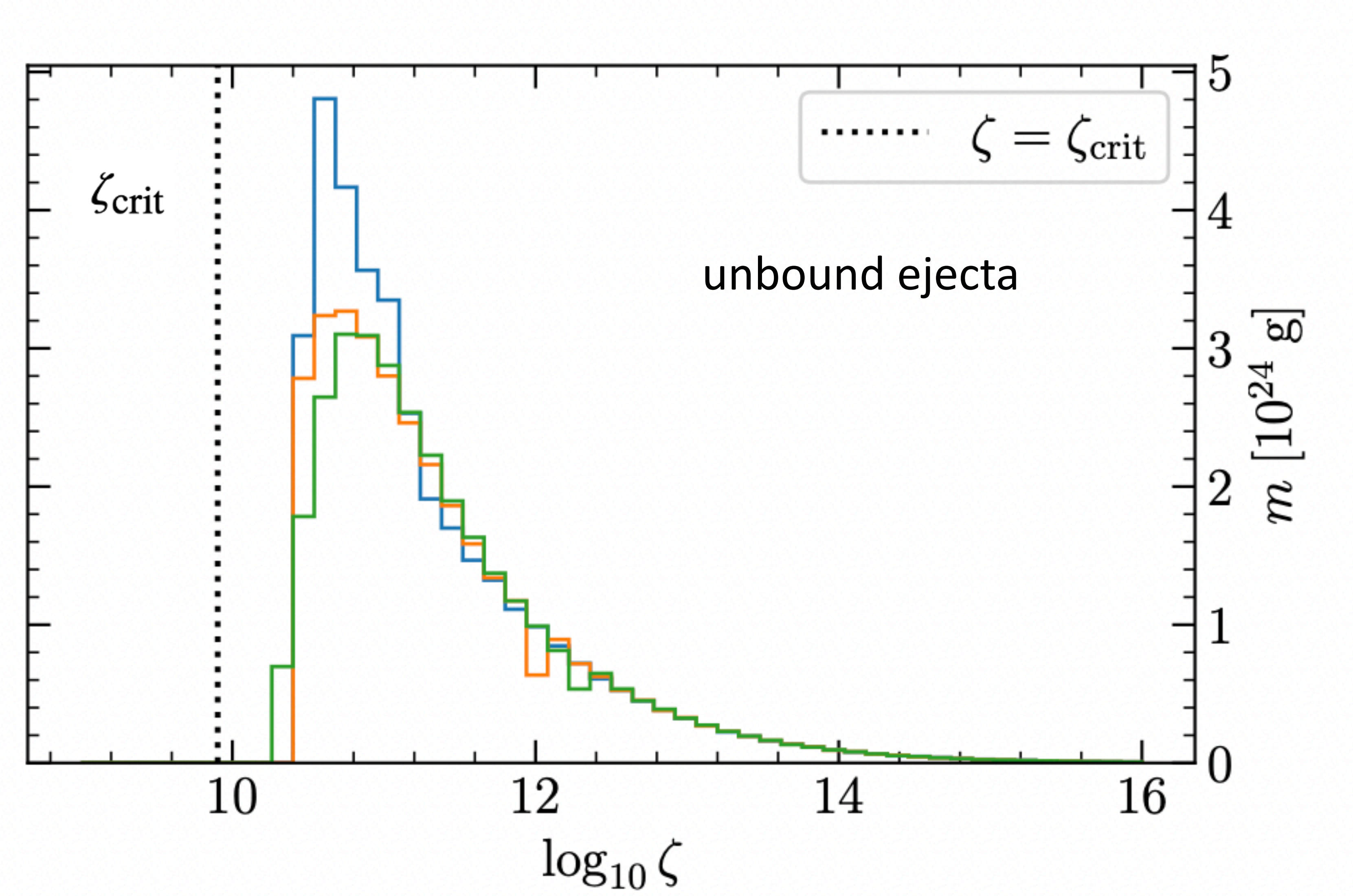
T_{ph}
M_{ph}
M_{diff}
optically thin
trapped
photosphere
nebular
$\log_{10}(m/M_\odot)$
$T\ (10^4\ \mathrm{K})$
total
optically thin
photosphere
$\log_{10}[L/(\mathrm{erg\,s^{-1}})]$
photosphere only
M_{AB}
U
B
V
Y
H
K
Time (s)

Alpha Rich Freeze-out 1

Hoffman+(1997)

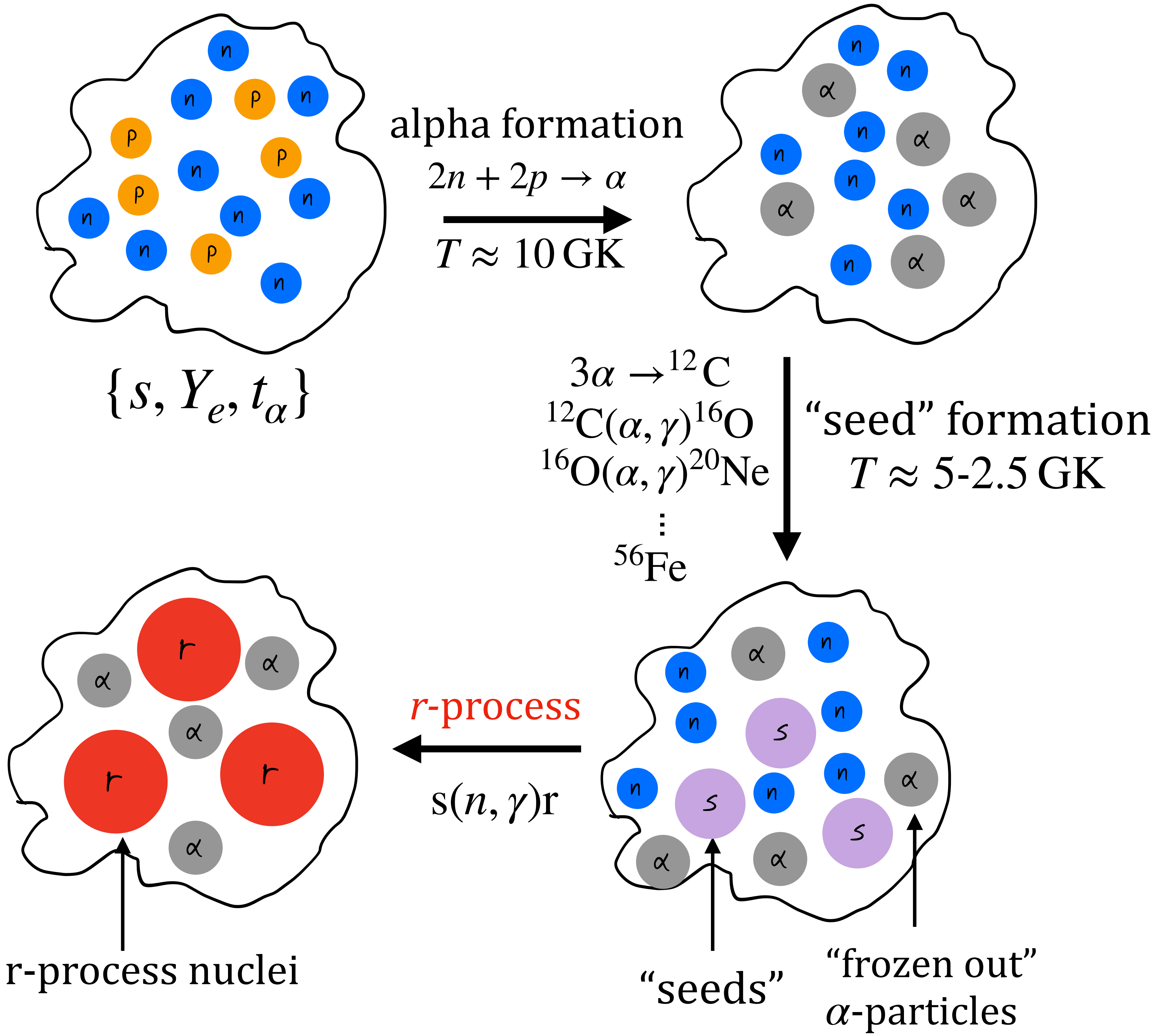
$$\zeta \equiv \frac{s^3}{Y_e^3 t_\alpha}$$

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

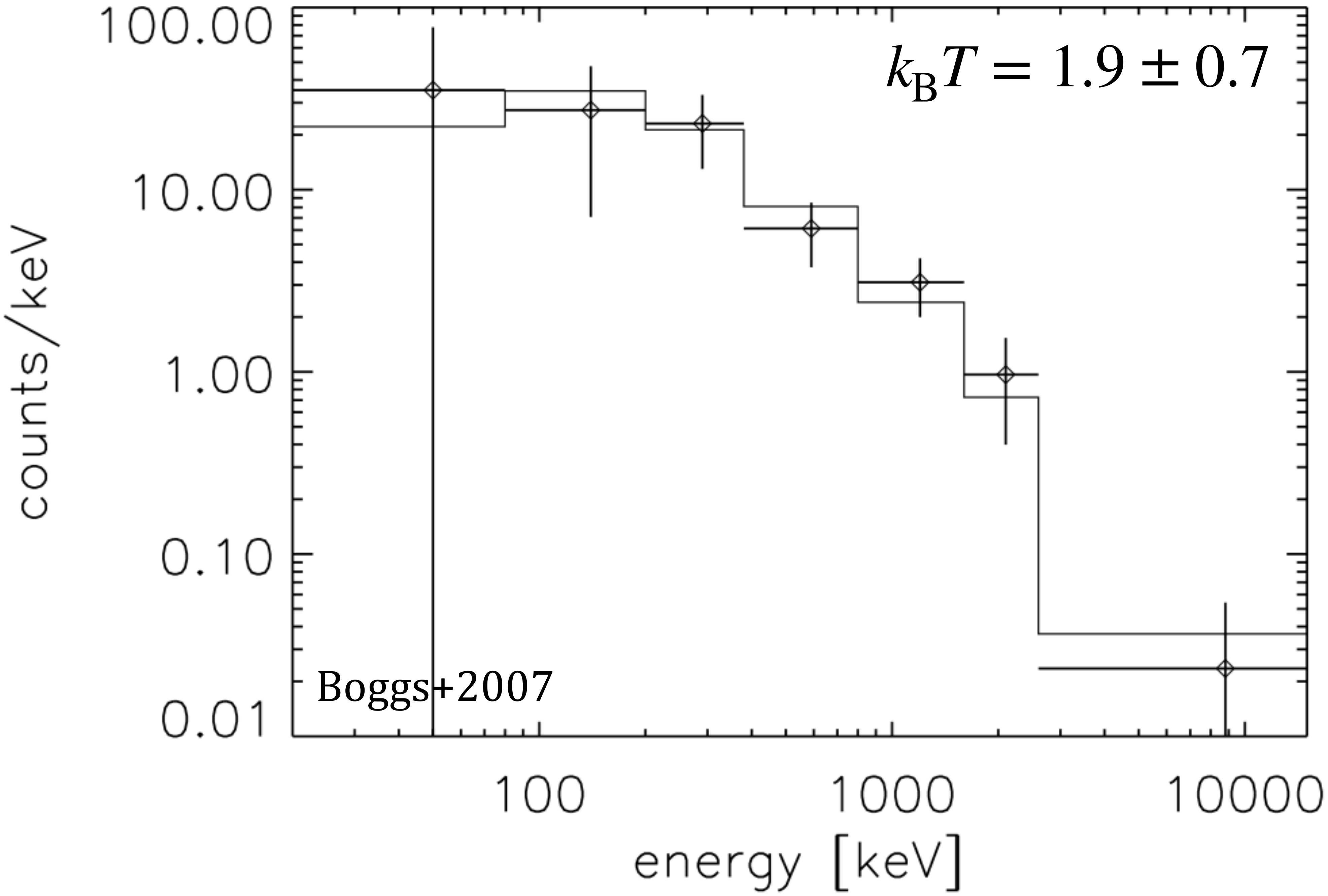


(Cehula+2024)

Alpha Rich Freeze-out 2



Observed spectrum



Nova Brevis vs Kilonova

Property	Kilonova	Nova Brevis
What	merging neutron stars	flaring neutron stars
Ejecta mass	~$10^{-2} – 10^{-1}$ $M_\odot$	~$10^{-8} – 10^{-6}$ $M_\odot$
Ejecta velocity	~0.1 – 0.3 c	~0.1 – 0.7 c
Peak luminosity	~$10^{41} – 10^{42}$ erg/s	~$10^{38} – 10^{40}$ erg/s
Peak duration	~1 - 10 days	~1 – 10 min
Rate per galaxy	~1 / $10^4 – 10^5$ years	~1 / 10 – 100 years
Follows	short* GRB	short "GRB"
Followed by	broadband afterglow	radio afterglow

Nuclei contributing to gamma ray signal