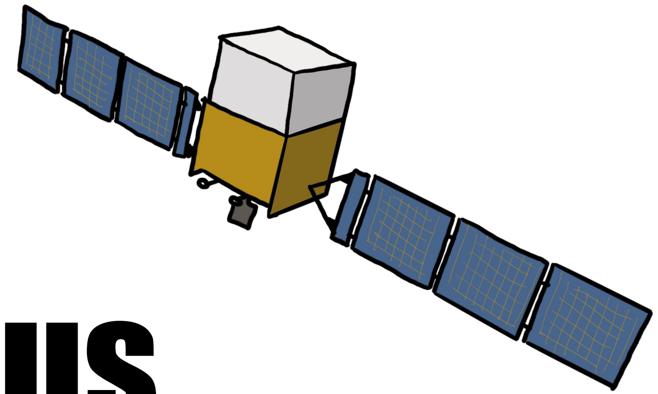
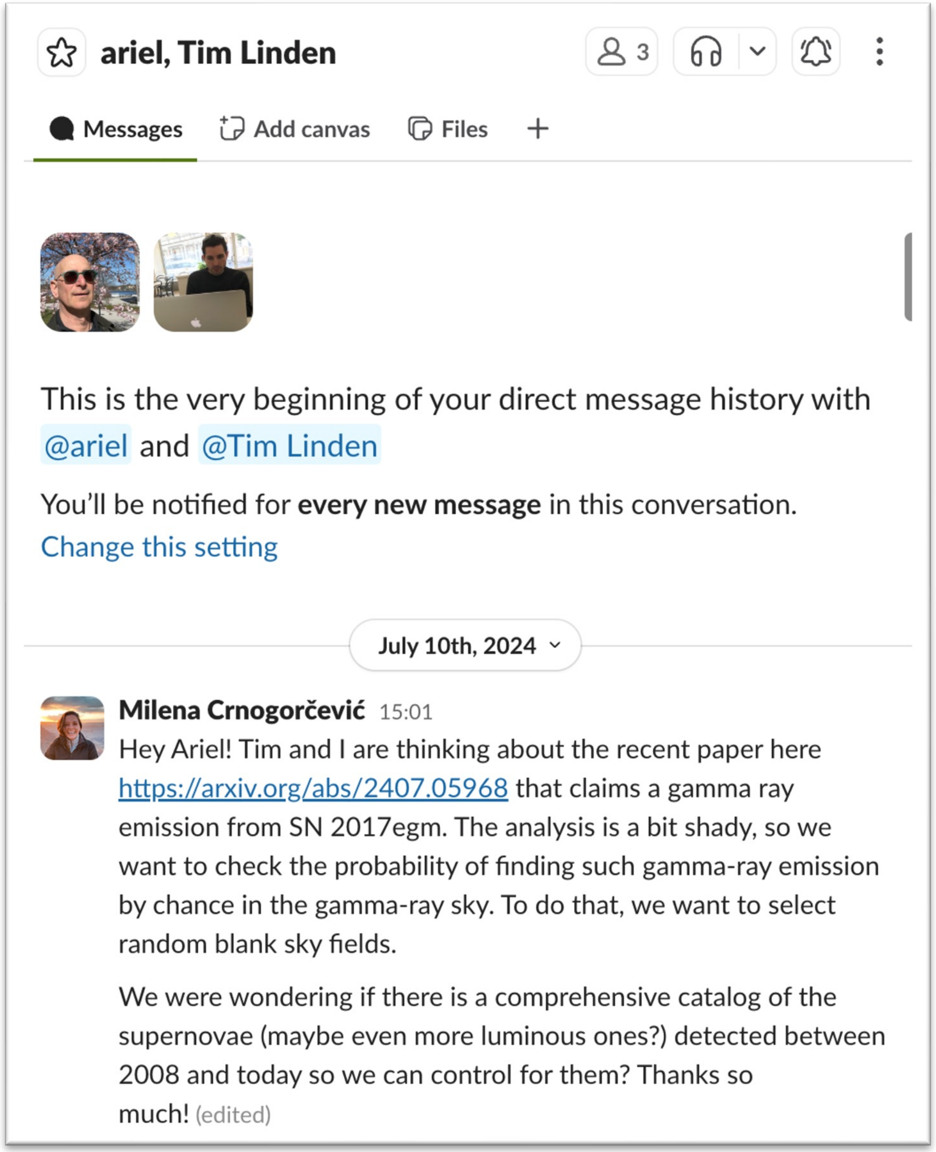


Do We See Superluminous Supernovae in Gamma Rays?

Milena Crnogorčević – OKC, Stockholm University

Co-authors: Tim Linden, Ariel Goobar, Brian D. Metzger

arXiv:2604.16595



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July 10th, 2024

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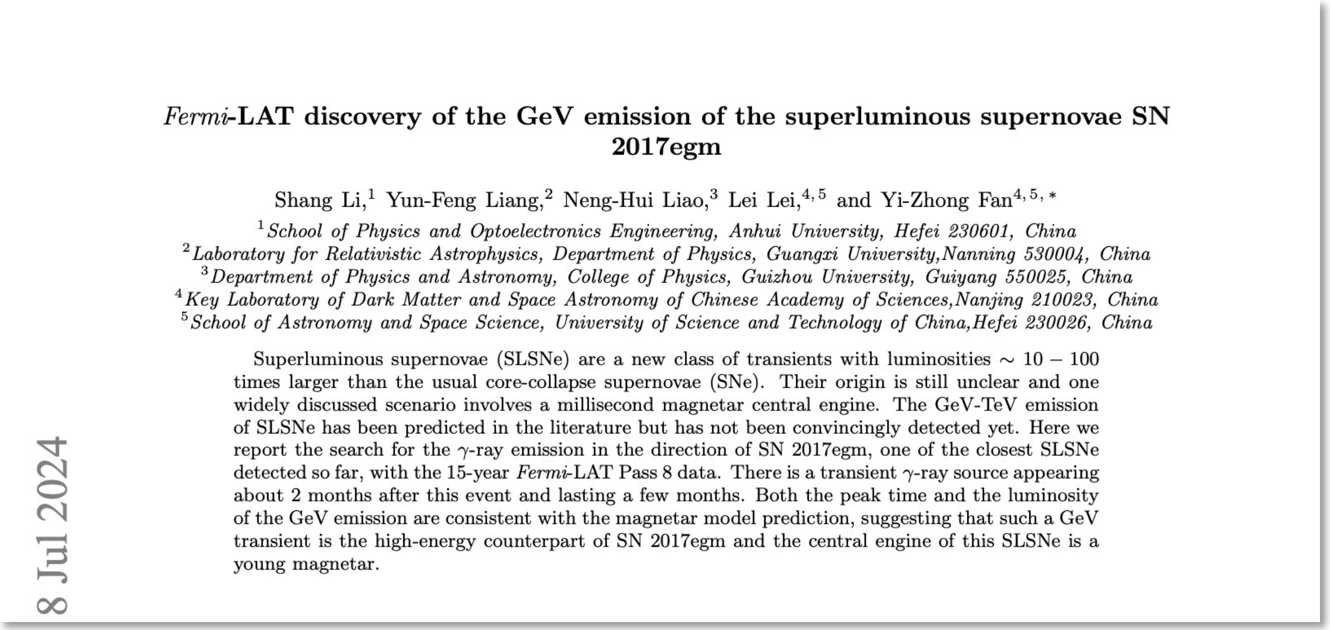

Fermi-LAT discovery of the GeV emission of the superluminous supernovae SN 2017egm

Shang Li,[1] Yun-Feng Liang,[2] Neng-Hui Liao,[3] Lei Lei,[4,5] and Yi-Zhong Fan[4,5,*]

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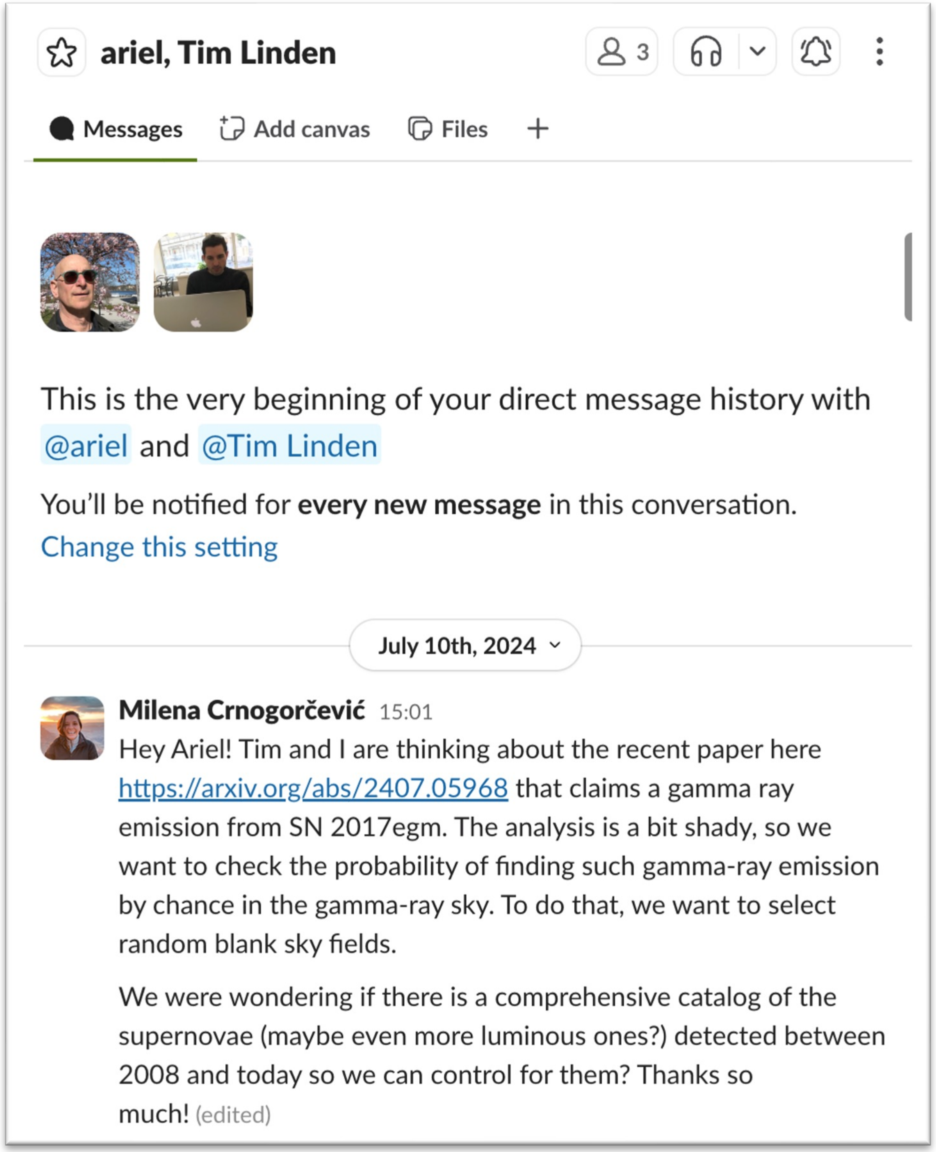
8 Jul 2024

Superluminous supernovae (SLSNe) are a new class of transients with luminosities $\sim 10-100$ times larger than the usual core-collapse supernovae (SNe). Their origin is still unclear and one widely discussed scenario involves a millisecond magnetar central engine. The GeV-TeV emission of SLSNe has been predicted in the literature but has not been convincingly detected yet. Here we report the search for the γ-ray emission in the direction of SN 2017egm, one of the closest SLSNe detected so far, with the 15-year *Fermi*-LAT Pass 8 data. There is a transient γ-ray source appearing about 2 months after this event and lasting a few months. Both the peak time and the luminosity of the GeV emission are consistent with the magnetar model prediction, suggesting that such a GeV transient is the high-energy counterpart of SN 2017egm and the central engine of this SLSNe is a young magnetar.



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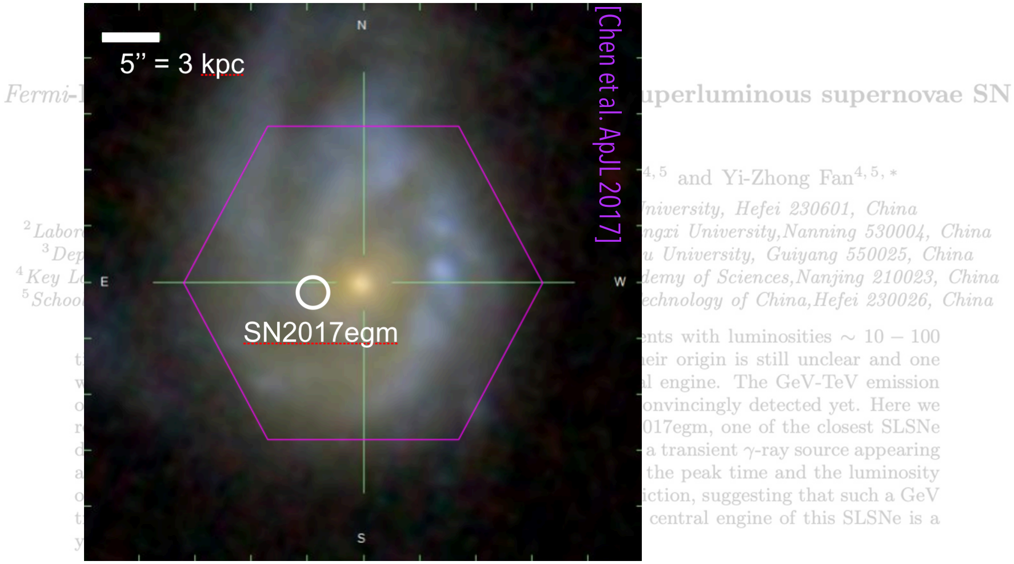
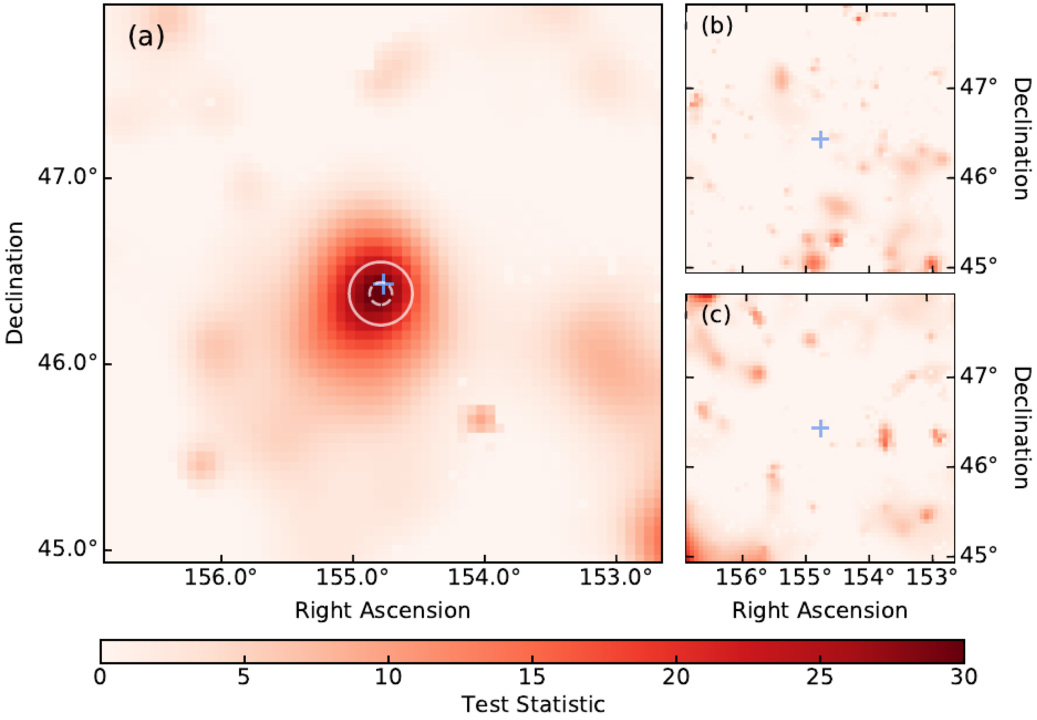
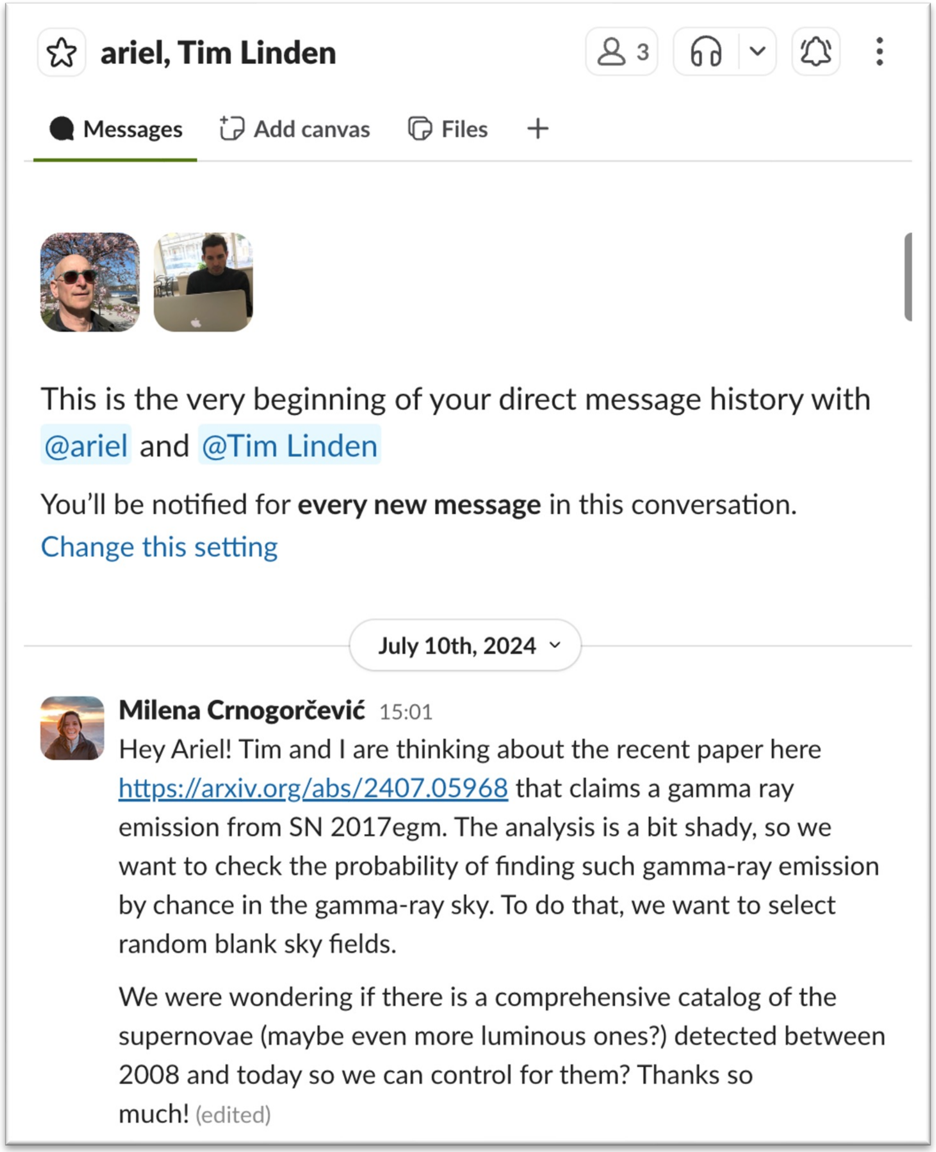


[Chen et al. ApJL 2017]



[Li et al. PRL 2026]



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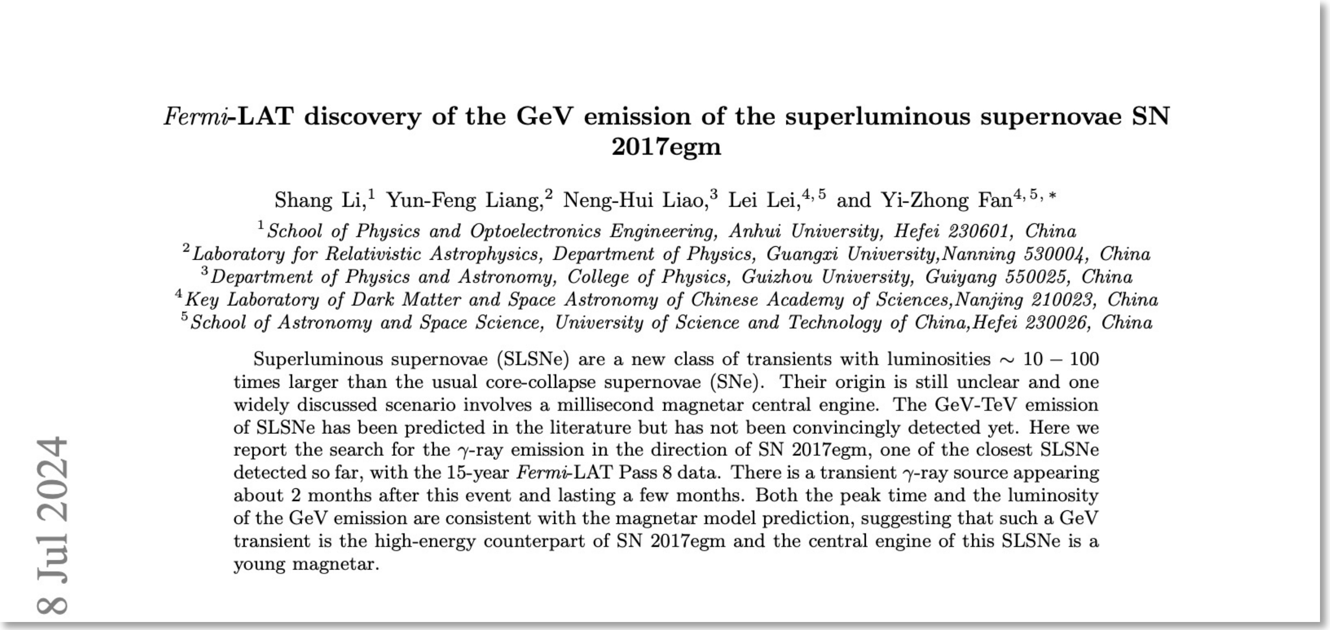

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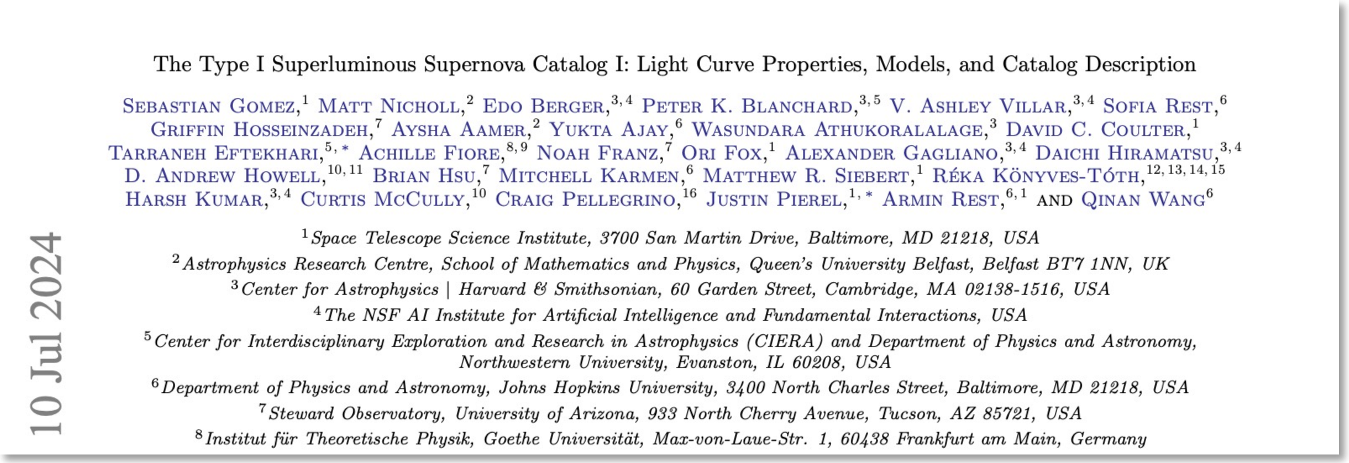

10 Jul 2024

The Type I Superluminous Supernova Catalog I: Light Curve Properties, Models, and Catalog Description

Sebastian Gomez,[1] Matt Nicholl,[2] Edo Berger,[3,4] Peter K. Blanchard,[3,5] V. Ashley Villar,[3,4] Sofia Rest,[6] Griffin Hosseinzadeh,[7] Aysha Aamer,[2] Yukta Ajay,[6] Wasundara Athukoralalage,[3] David C. Coulter,[1] Tarraneh Eftekhari,[5,*] Achille Fiore,[8,9] Noah Franz,[7] Ori Fox,[1] Alexander Gagliano,[3,4] Daichi Hiramatsu,[3,4] D. Andrew Howell,[10,11] Brian Hsu,[7] Mitchell Karmen,[6] Matthew R. Siebert,[1] Réka Könyves-Tóth,[12,13,14,15] Harsh Kumar,[3,4] Curtis McCully,[10] Craig Pellegrino,[16] Justin Pierel,[1,*] Armin Rest,[6,1] and Qinan Wang[6]

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[2] *Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, UK*
[3] *Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138-1516, USA*
[4] *The NSF AI Institute for Artificial Intelligence and Fundamental Interactions, USA*
[5] *Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) and Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA*
[6] *Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218, USA*
[7] *Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA*
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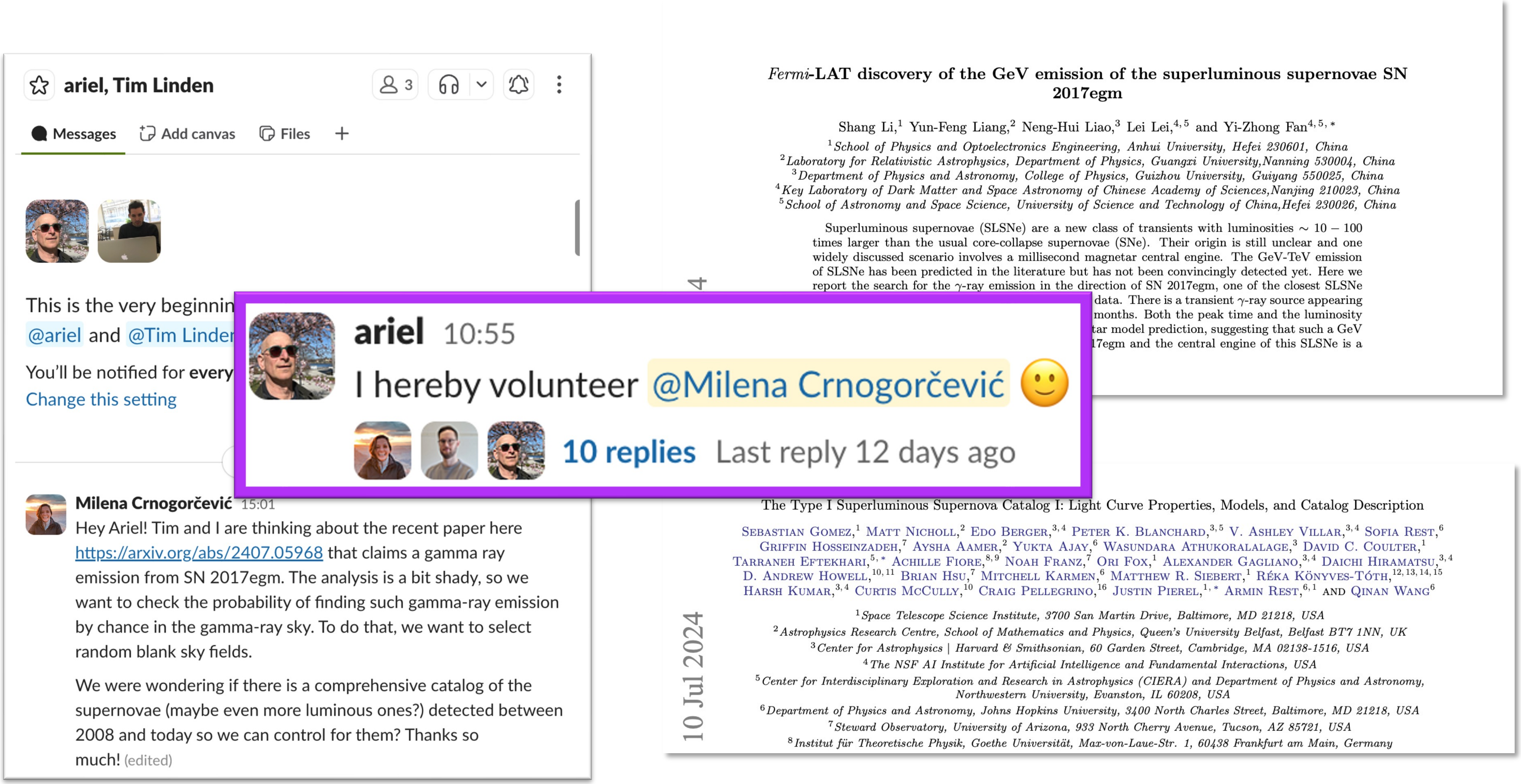

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ariel 10:55

I hereby volunteer @Milena Crnogorčević 🙂

10 replies Last reply 12 days ago

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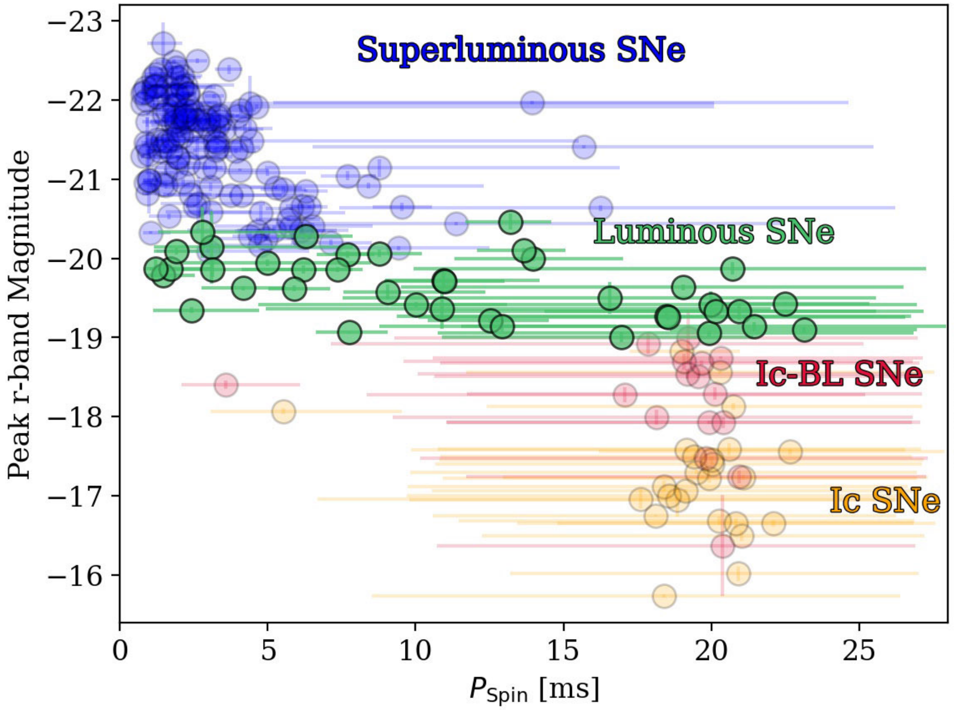
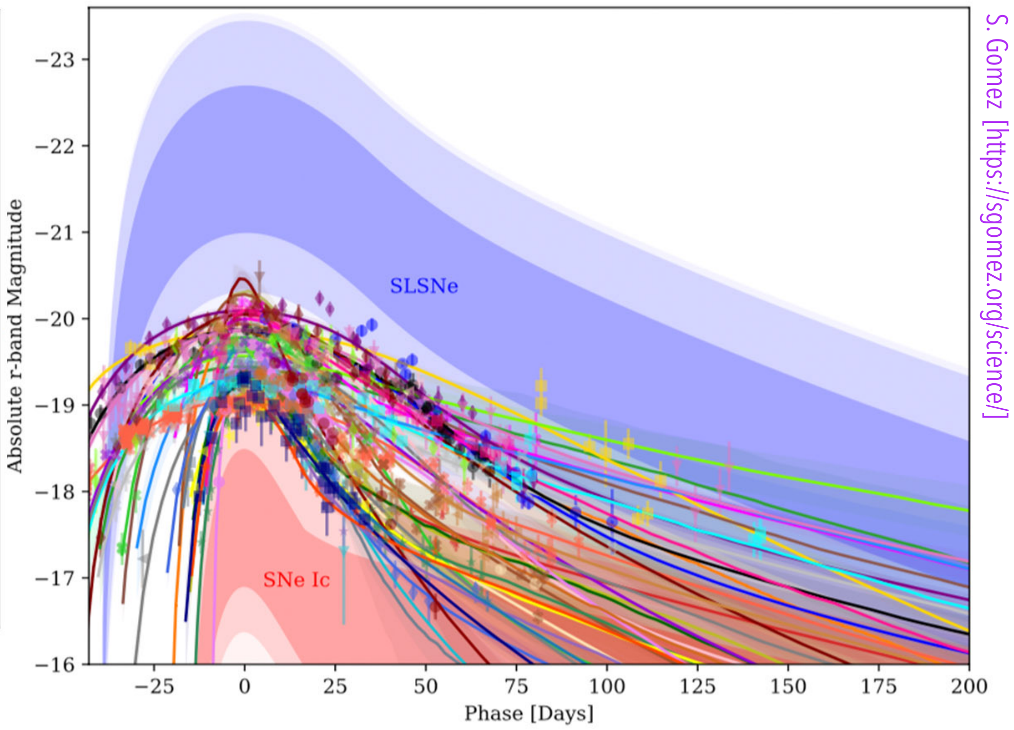
Superluminous supernovae



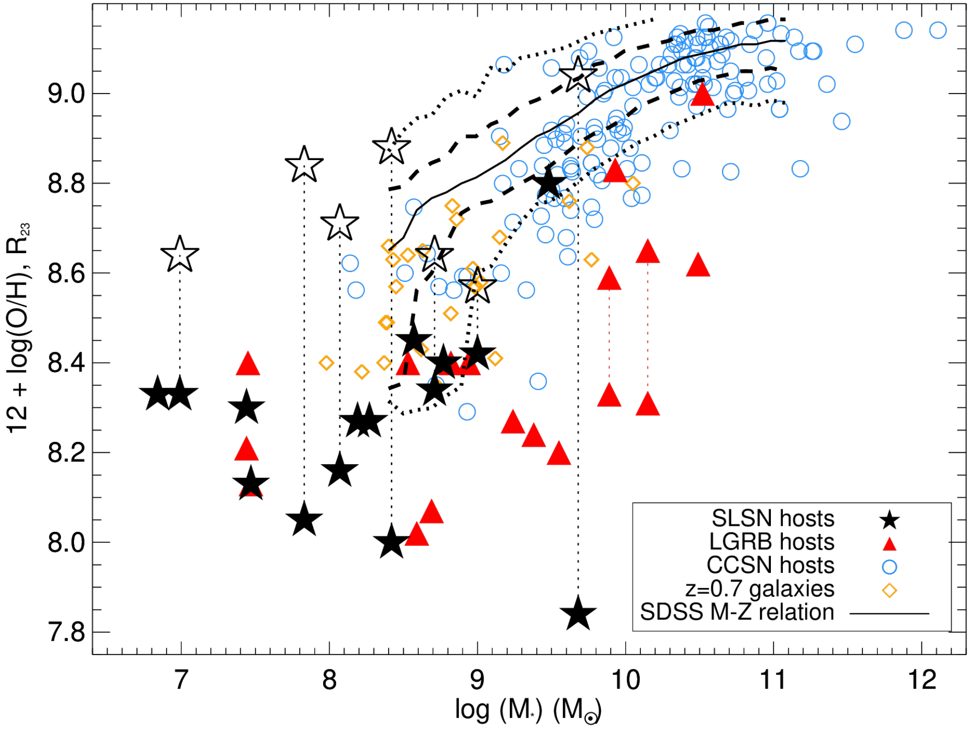


S. Gomez [https://sgomez.org/science/]

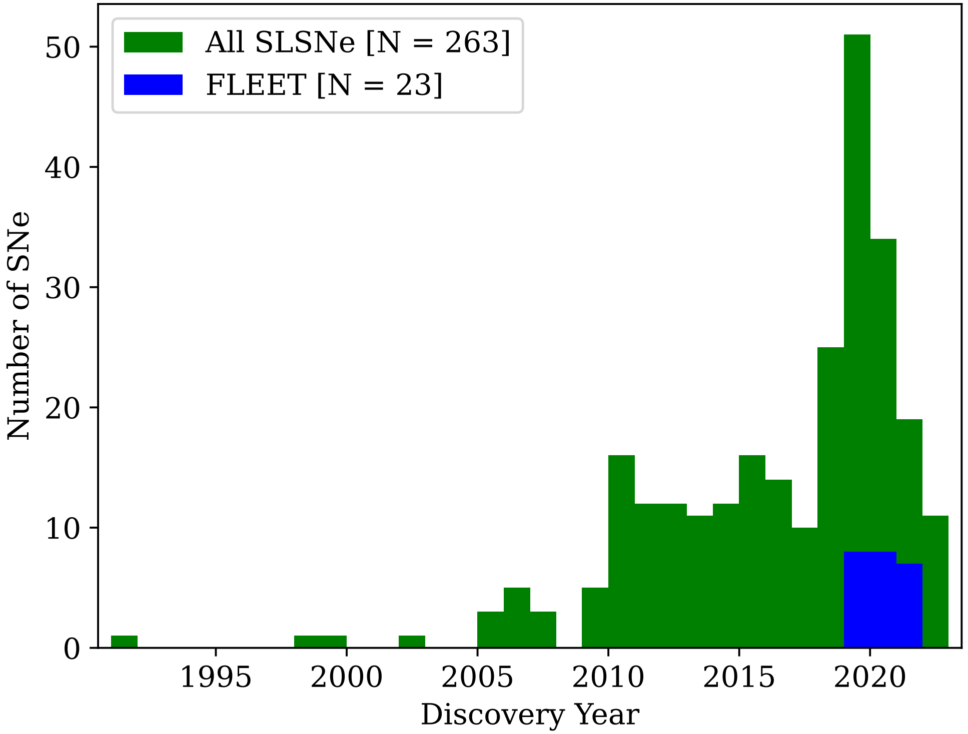
- Supernovae with a peak absolute magnitude of $L_{\text{peak}} > 10^{44}$ erg s^{-1} (~10-100 x brighter than canonical SNe)
- Optical spectra without or with hydrogen lines (Type I vs. Type II)

Superluminous supernovae (Type I)

[Quimby+07, Barbary+09, Pastorello+10, Chomiuk+11, Leloudas+12, Berger+12, Lunnan+14, Inserra+13]



[Lunnan+13]



[Gomez+24]

- Supernovae with a peak absolute magnitude of $L_{\text{peak}} > 10^{44}$ erg s^{-1} (~10-100 x brighter than canonical SNe)
- Optical spectra **without** or with hydrogen lines (**Type I** vs. Type II)
- Faint metal-poor host galaxies, similar to long GRBs
- Rate ~10^{-4} x core-collapse SN → field advanced with large SN surveys dictating the need for a new class

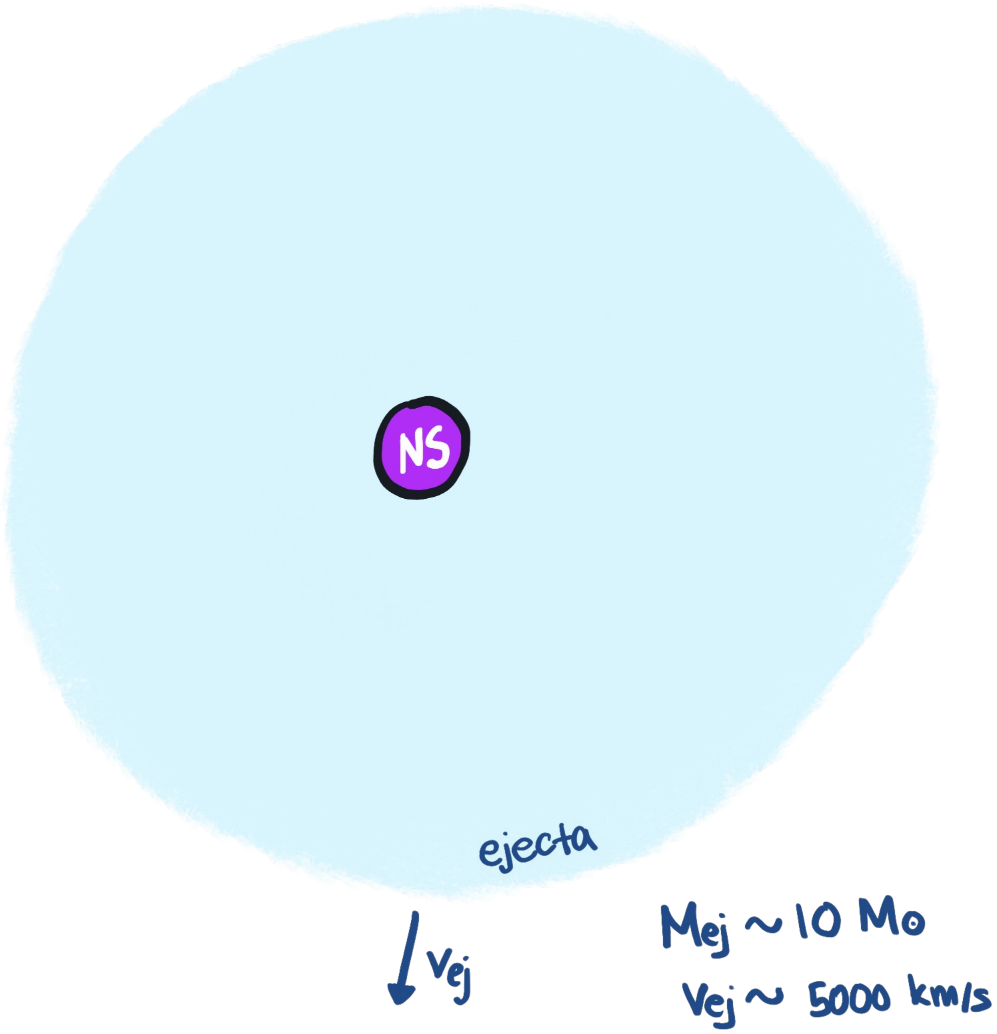
How do you produce gamma rays* in SLSNe?

*extended emission

Magnetar model

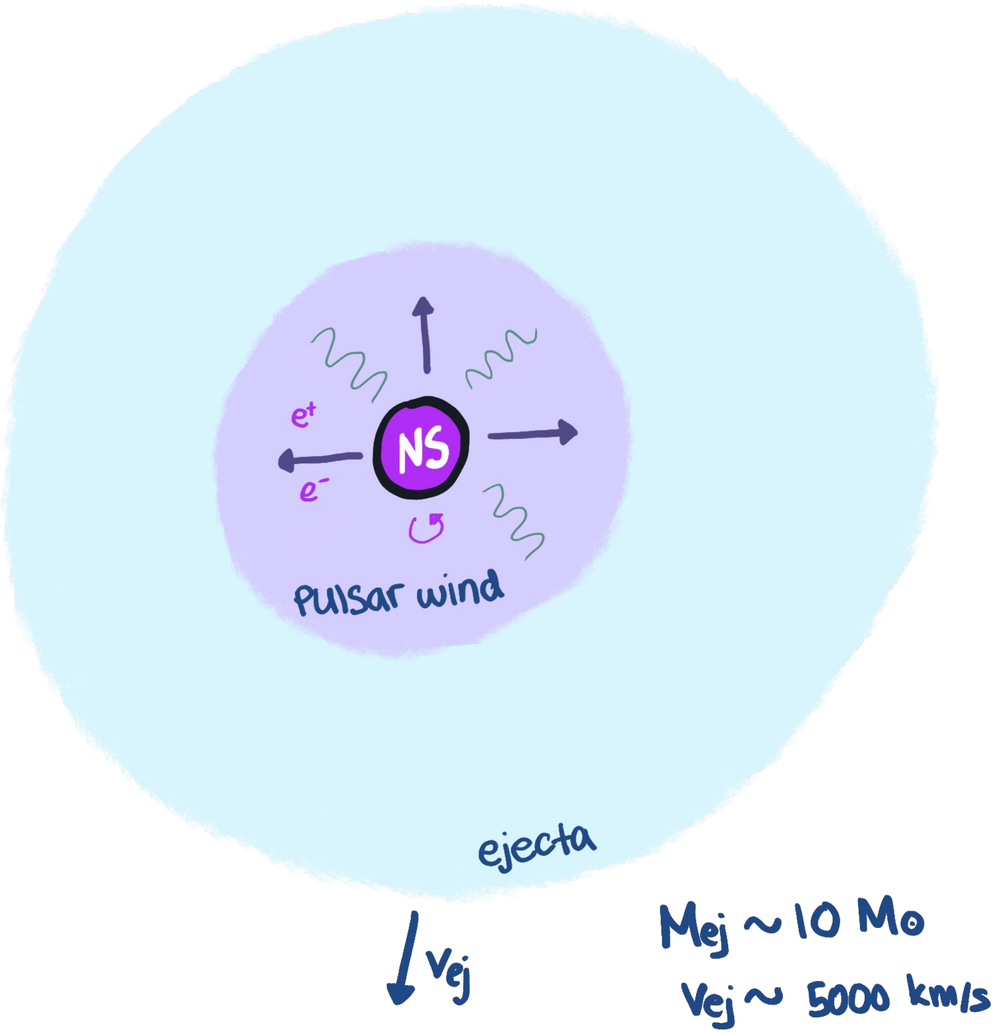
Massive star explodes, leaves behind a NS.

Magnetar model



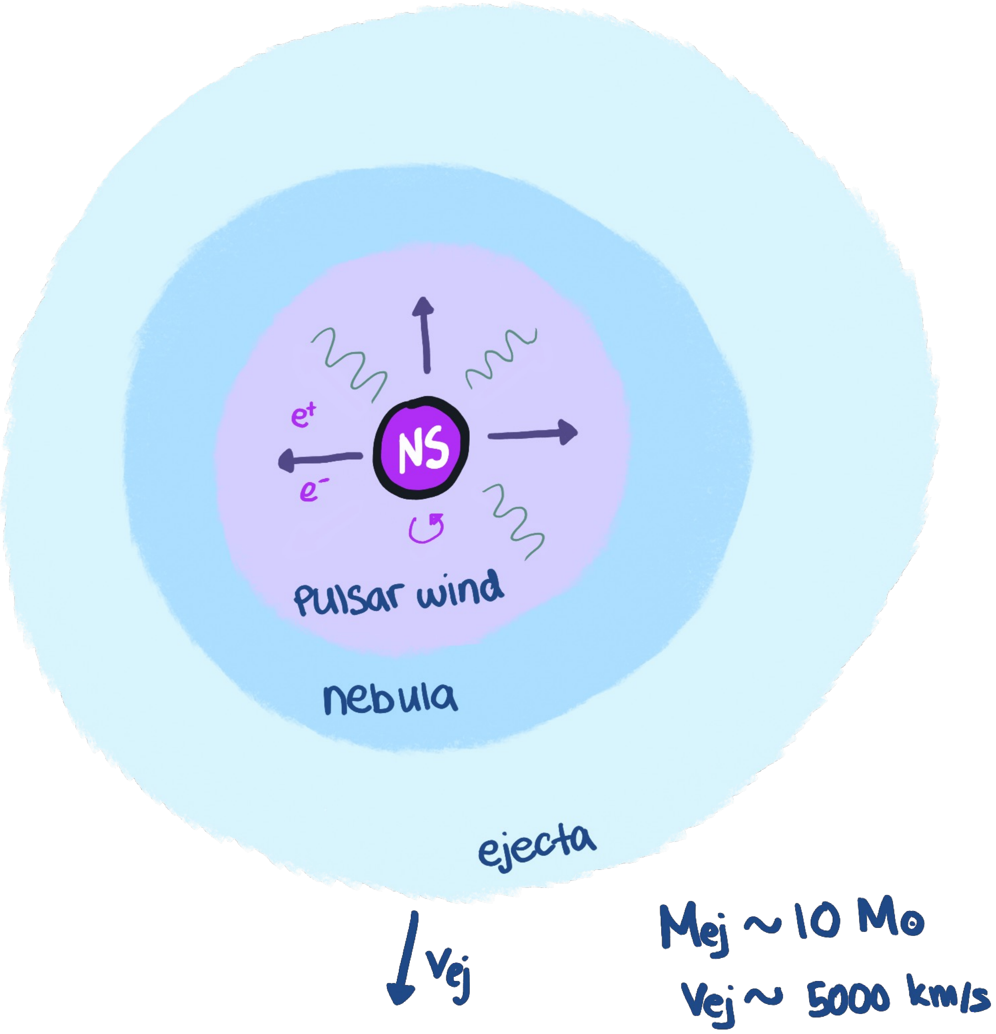
The NS lies inside the SN ejecta

Magnetar model



The NS spins down, rotational energy reservoir ~10^{52} erg → launches relativistic wind.

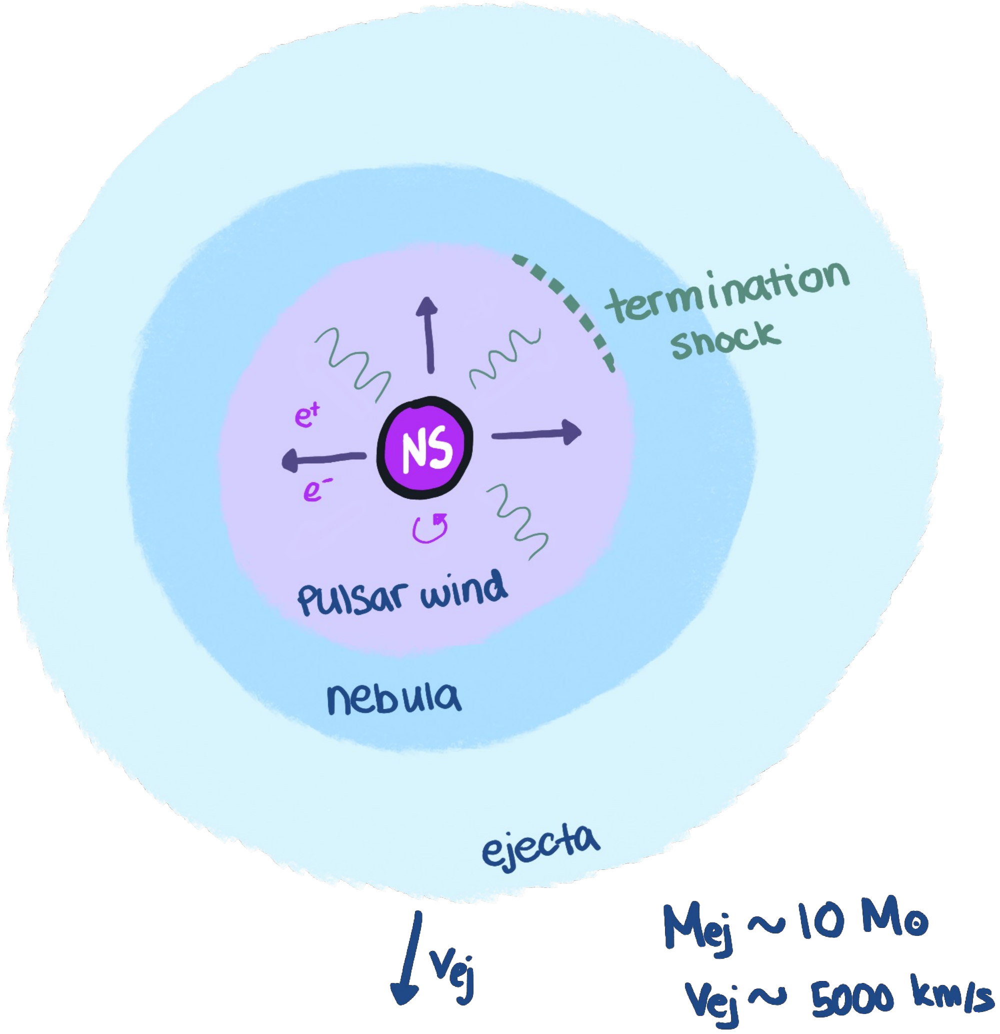
Magnetar model



$M_{ej} \sim 10\ M_\odot$
$v_{ej} \sim 5000$ km/s

The wind inflates a relativistic e^+e^- pair nebula.

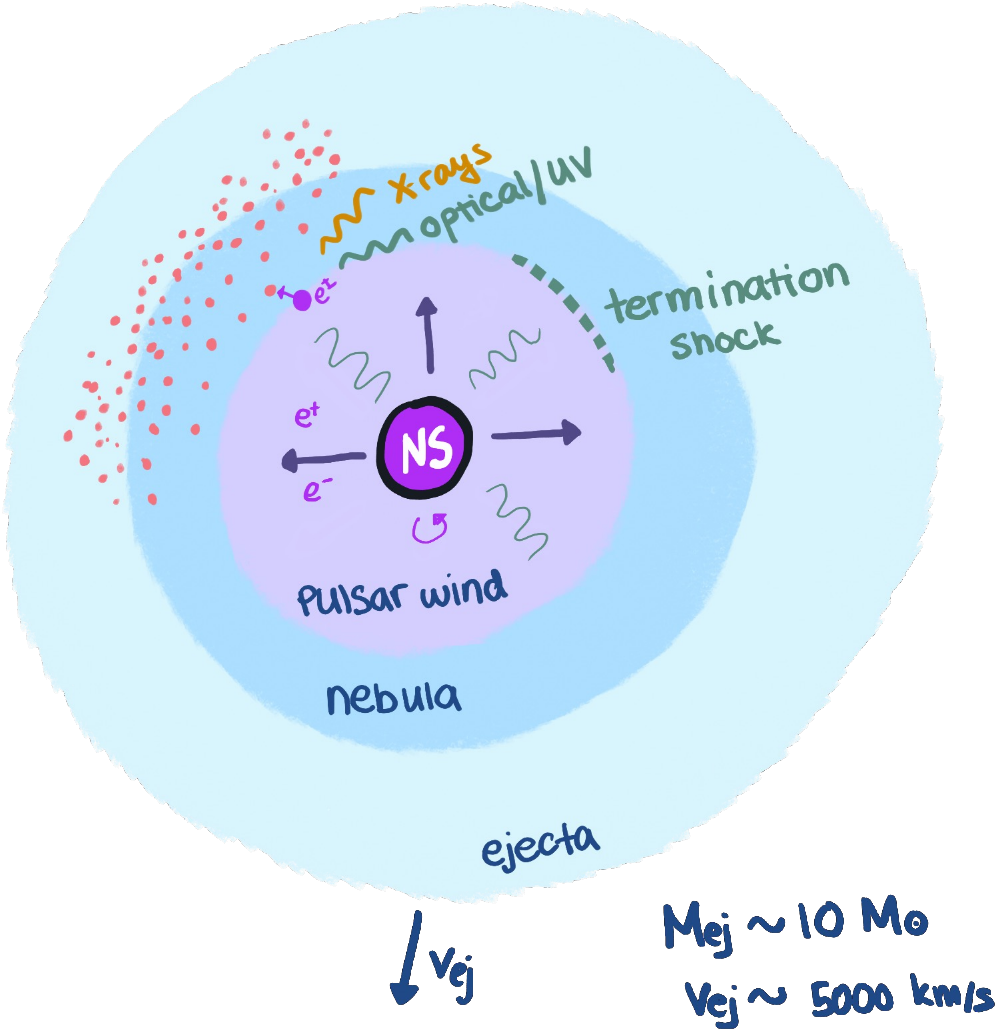
Magnetar model



The outward wind pressure meets the pressure of the surrounding ejecta → termination shock.

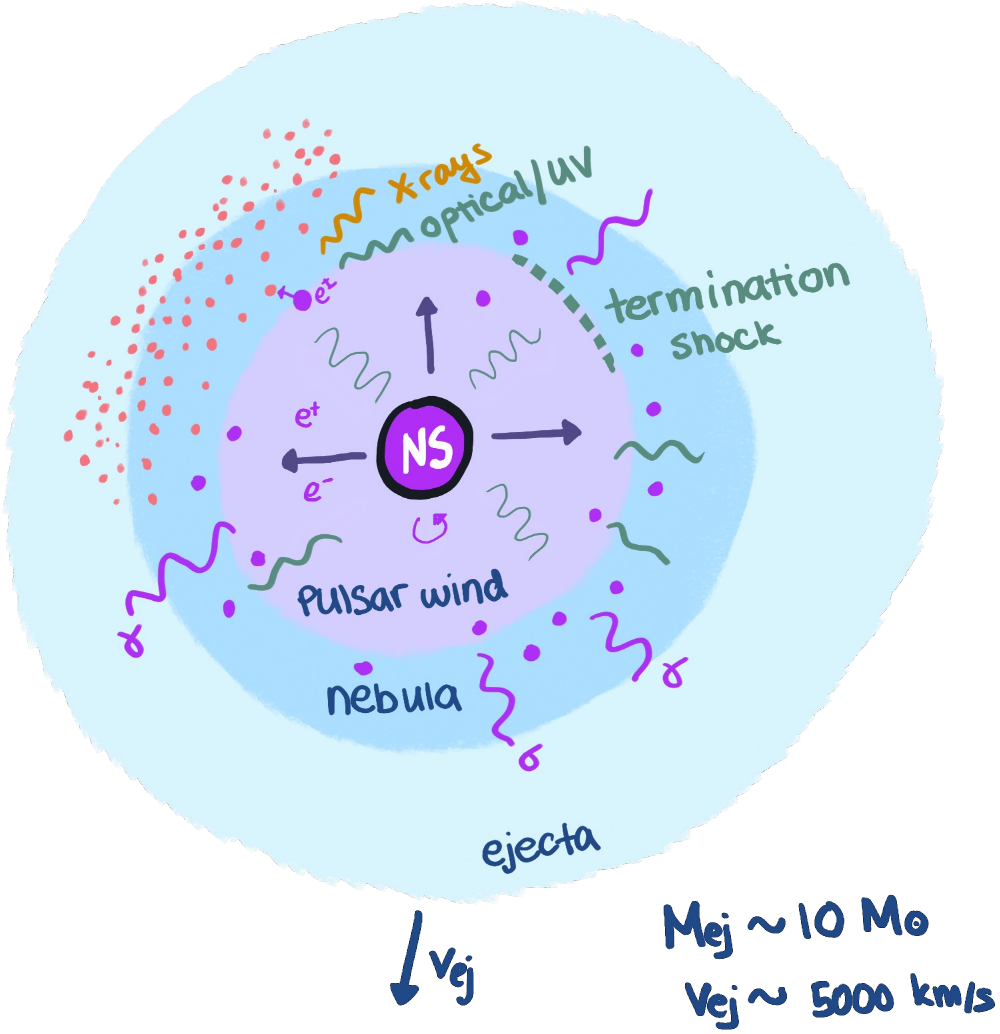
The wind slows down → random particle energy. Pairs are now hot, relativistic, and ~randomized.

Magnetar model



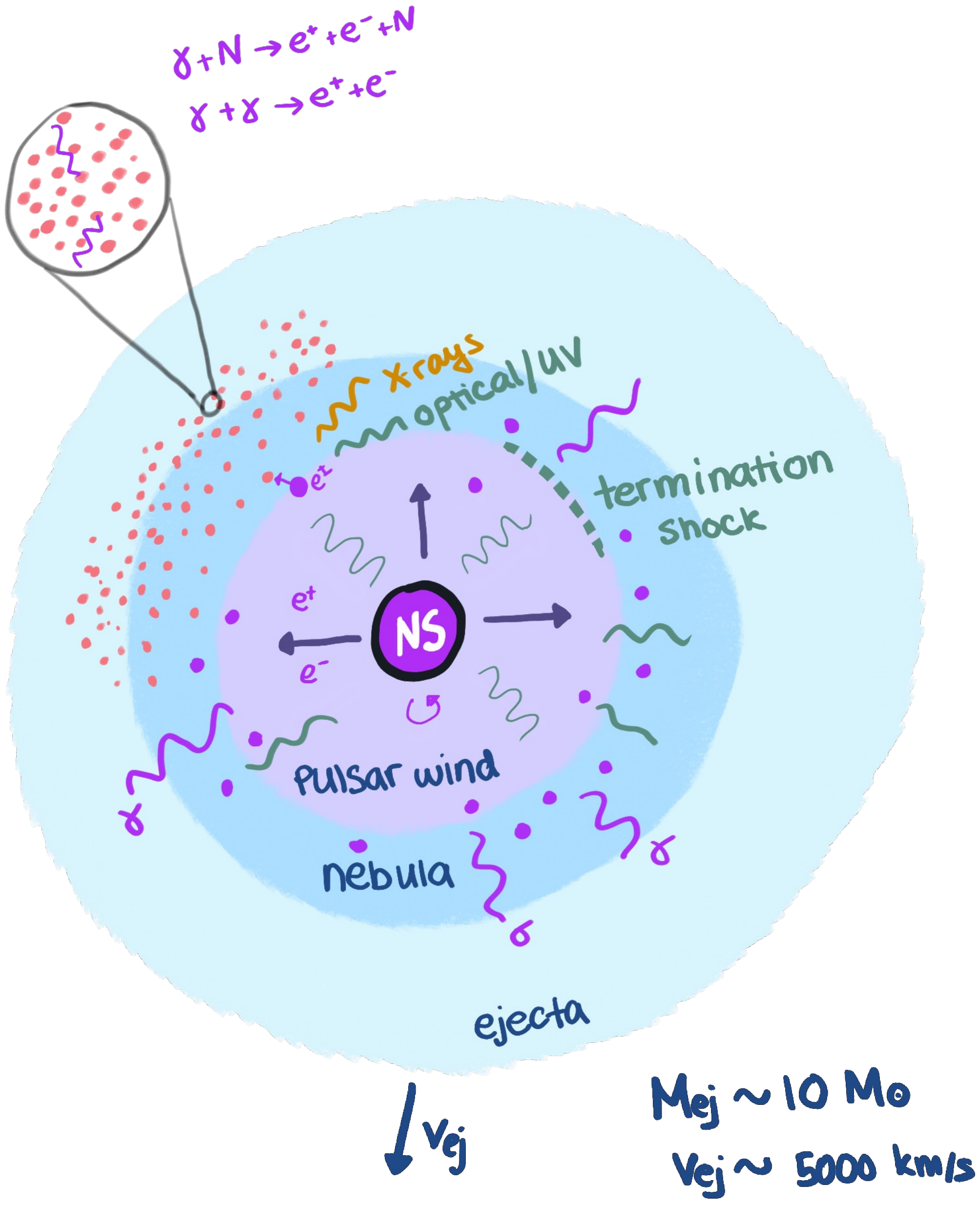
Synchrotron → X-rays. Inverse Compton → UV/optical.

Magnetar model



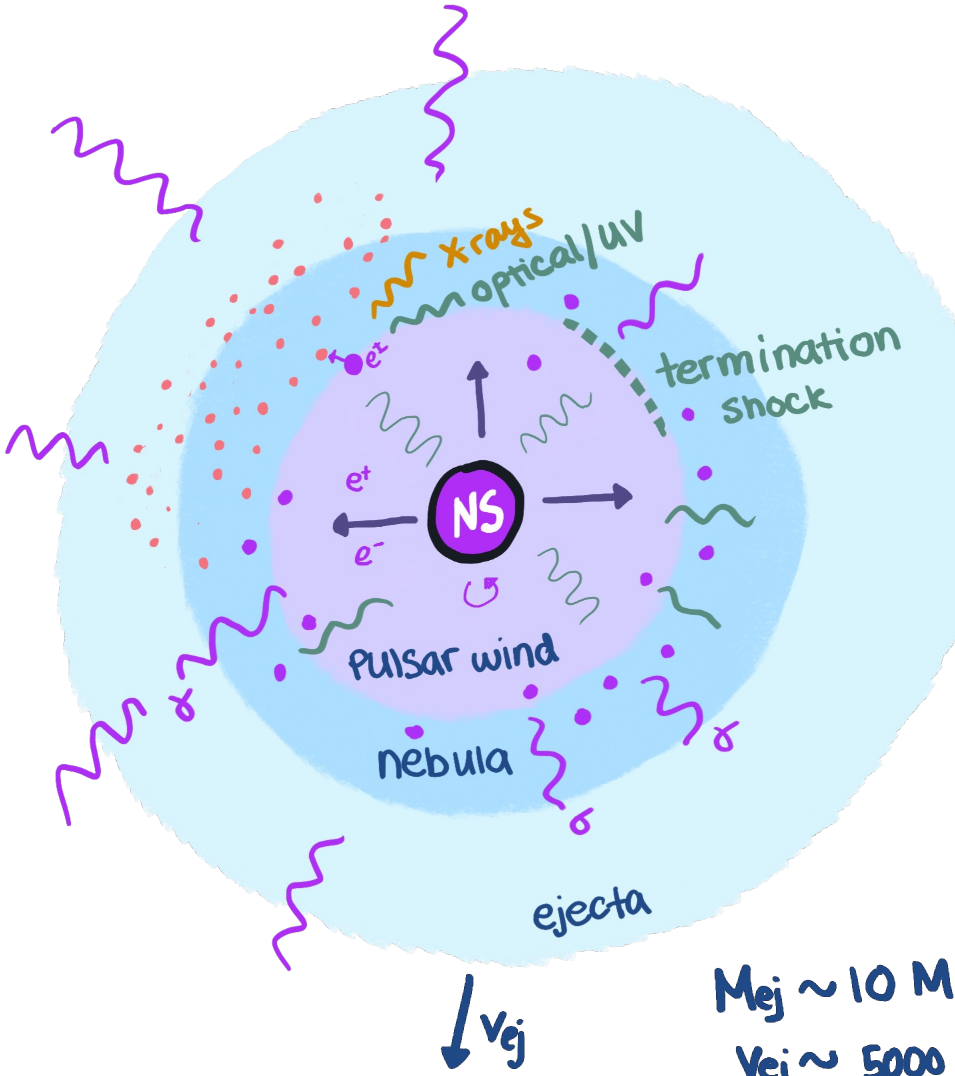
Relativistic pairs upscatter UV/optical light to HE photons.

Magnetar model



Early times: the ejecta is dense and HE photons are absorbed. e$^{+/-}$ formed again.

Magnetar model



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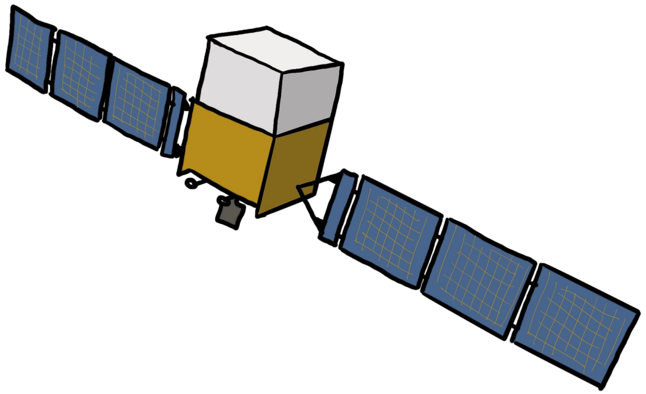
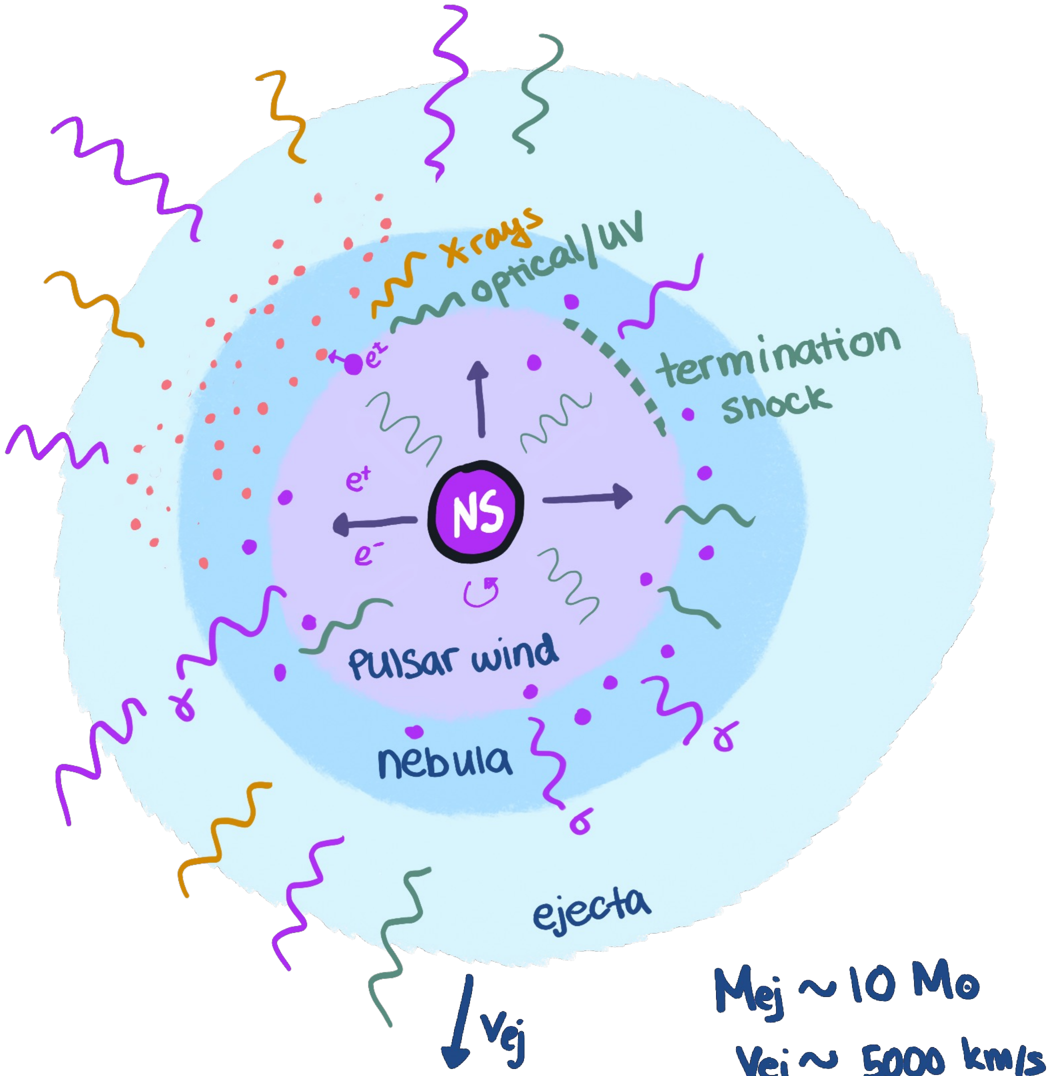
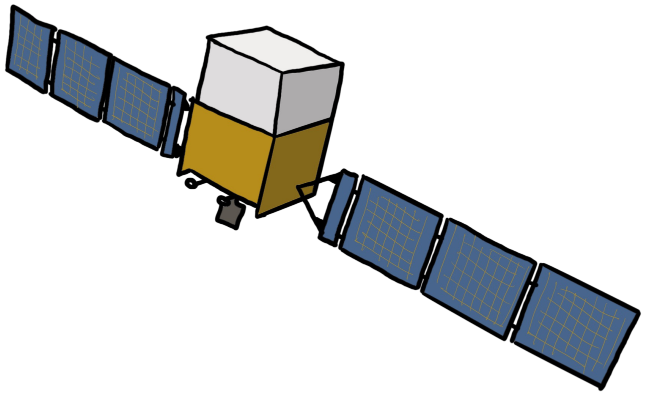


The ejecta expands → gamma rays leak out.

Magnetar model





The optical light we observe is actually reprocessed engine power.

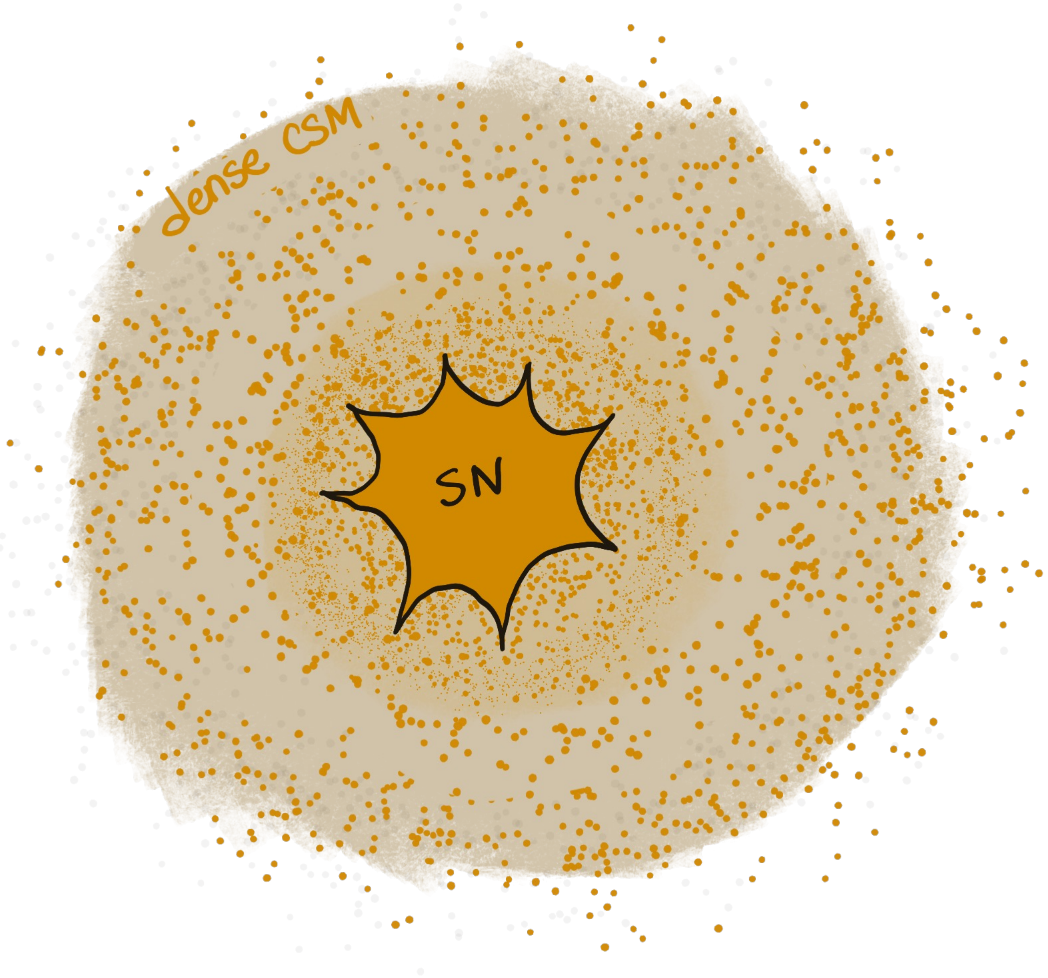
CSM Interaction

Massive progenitor expels large amounts of mass in an episodic or steady wind.

CSM Interaction

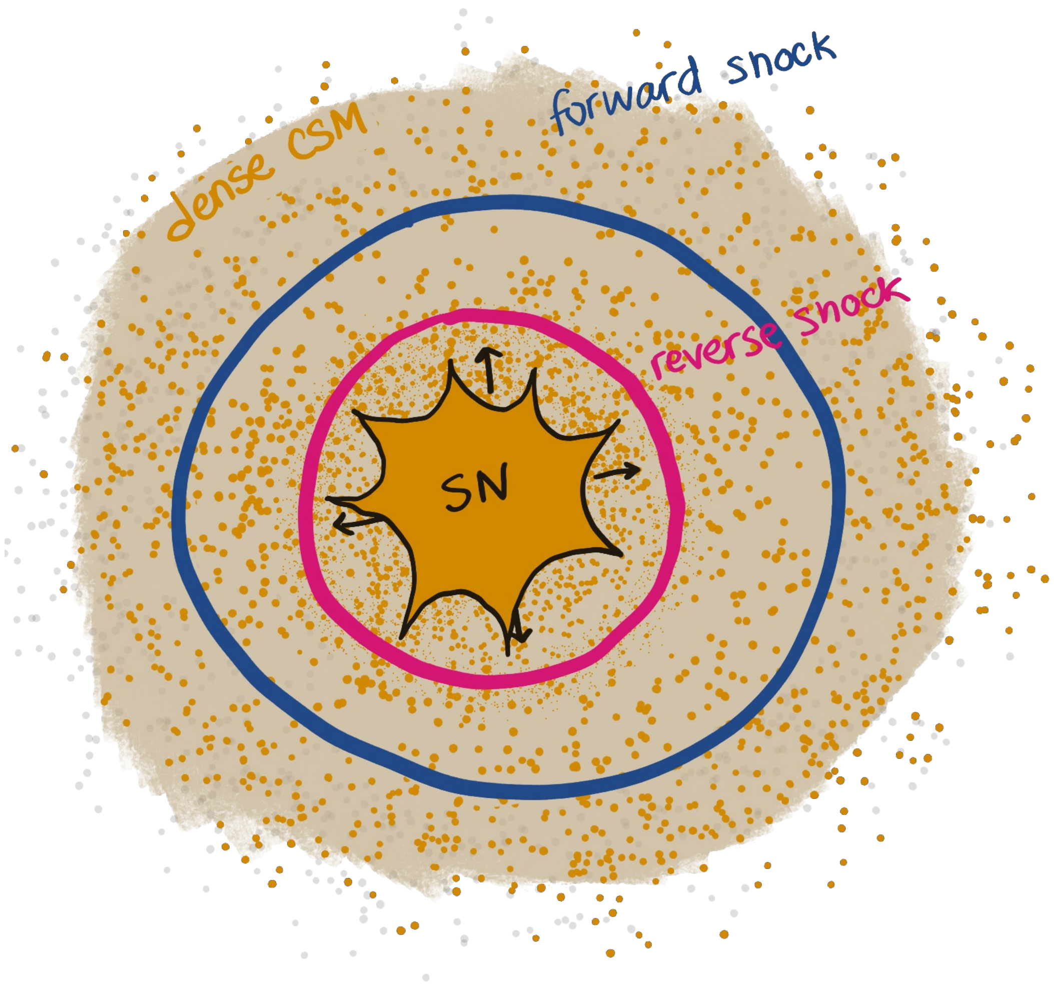
The progenitor is embedded in a dense CSM cloud.

CSM Interaction



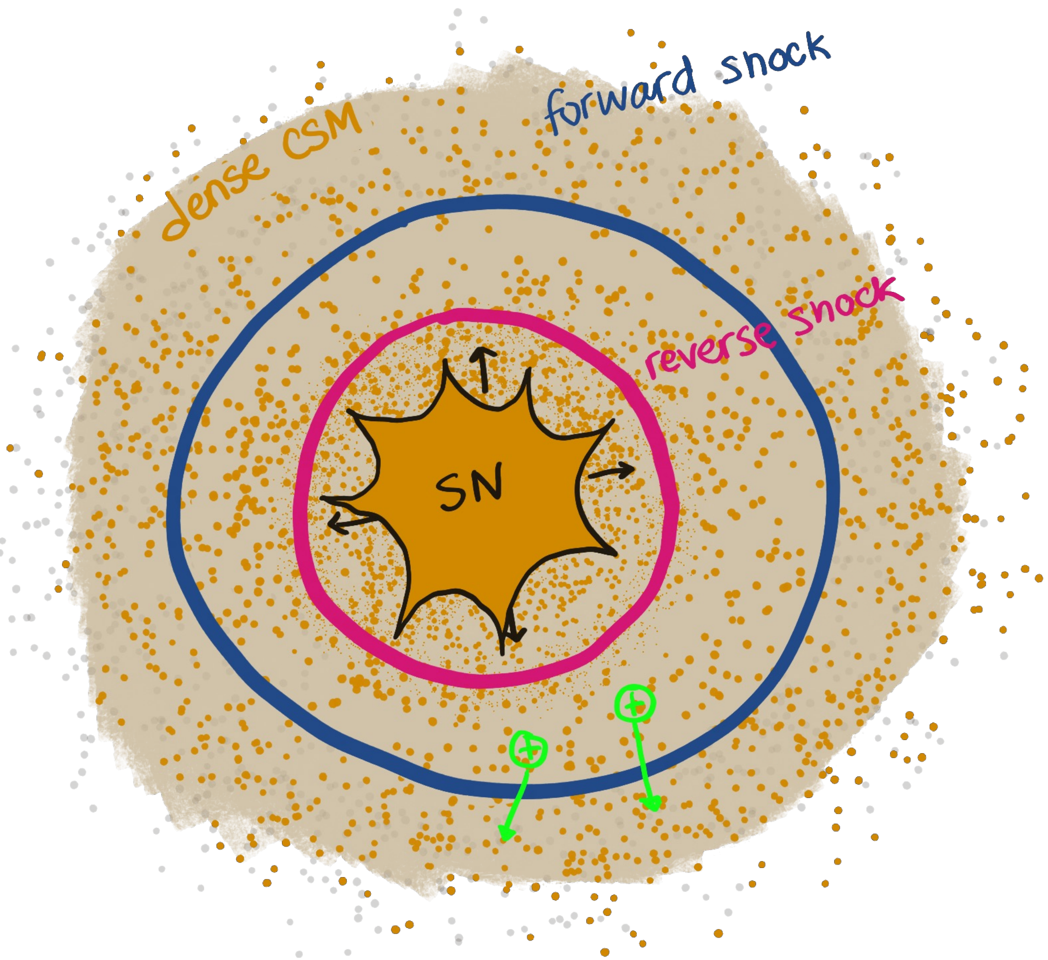
It goes SN.

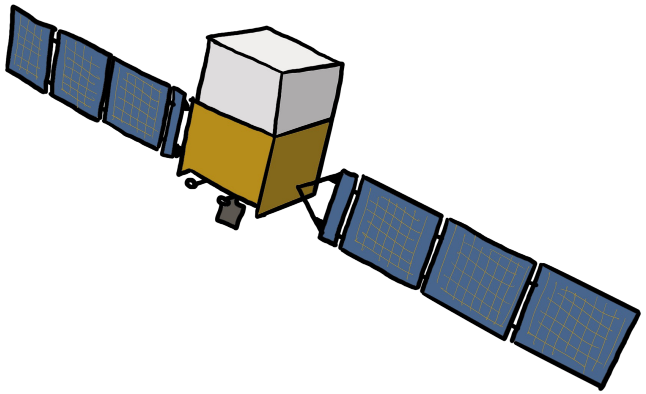
CSM Interaction



The SN ejecta expand and collide with the dense CSM. Forward and reverse shocks form. (Thermal emission)

CSM Interaction



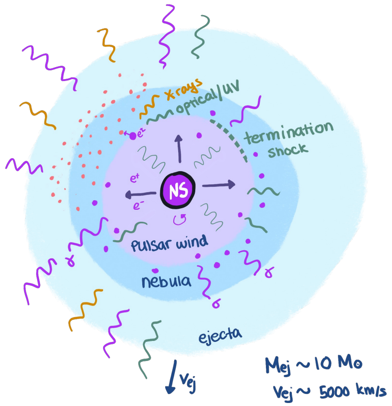


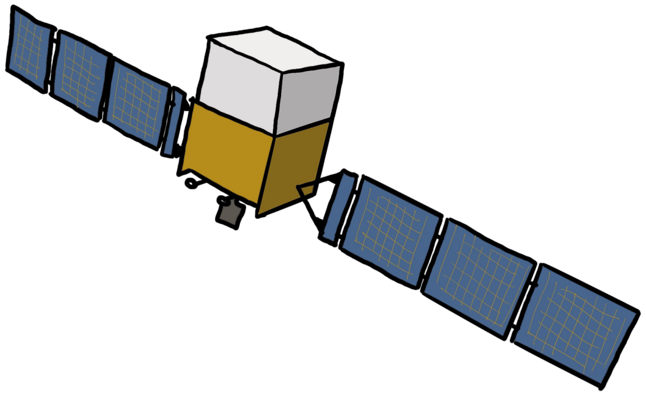
$$p + p \rightarrow \pi^0 + \ldots$$

$$\pi^0 \rightarrow \gamma + \gamma$$

CR are accelerated by shocks and hit the CSM particles producing pions → gamma rays.

Why gamma rays?





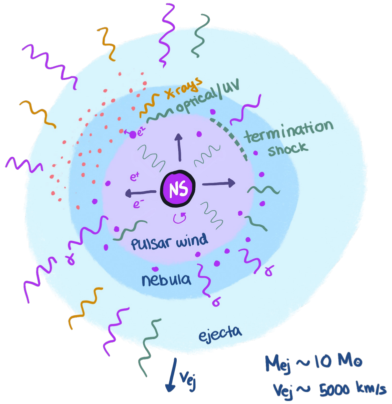
MAGNETAR IC NEBULA

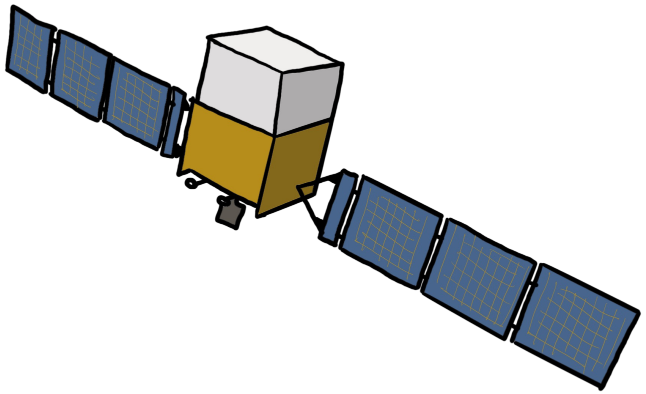
Direct probe of the relativistic pair plasma

Pulsar wind ⟶ $e^{\pm}$ ⟶ IC scattering on the nebular thermal bath. The GeV channel **is** the engine's non-thermal output – optical only sees the reprocessed product.

Kasen & Bildsten 2010 · Woosley 2010 · Metzger+ 2014 · Murase+ 2015 · Vurm & Metzger 2021

Why gamma rays?





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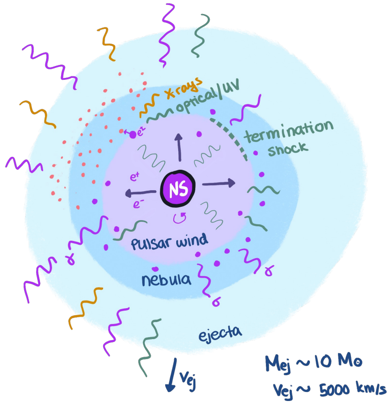
CSM HADRONIC SHOCKS

Calorimetric on shock energetics

p–p collisions in the post-shock CSM produce $\pi^0 \longrightarrow \gamma$. Flux $\propto \varepsilon_{sh} \cdot \dot{E}_{sh}$ – a near-direct measure of CR acceleration efficiency.

Murase+ 2014, 2019 · Petropoulou+ 2016, 2017 · Fang+ 2019 · Sarmah+ 2022



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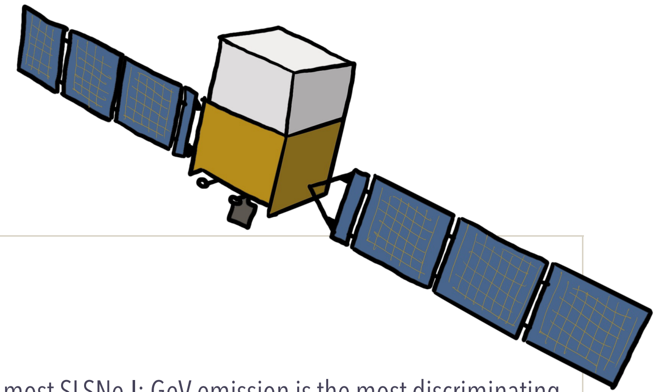

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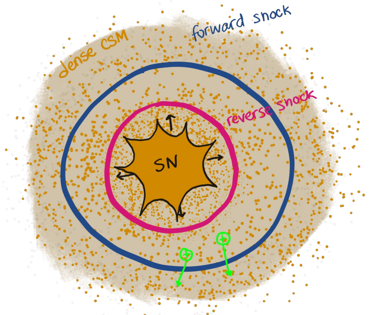
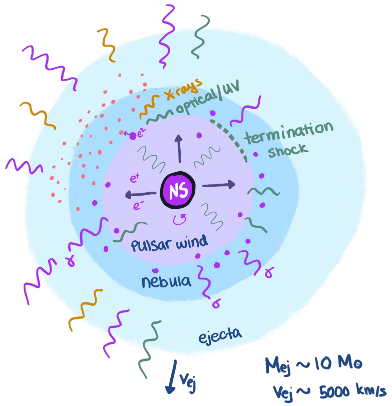
OPTICAL DEGENERACY

Light curves don't break the model

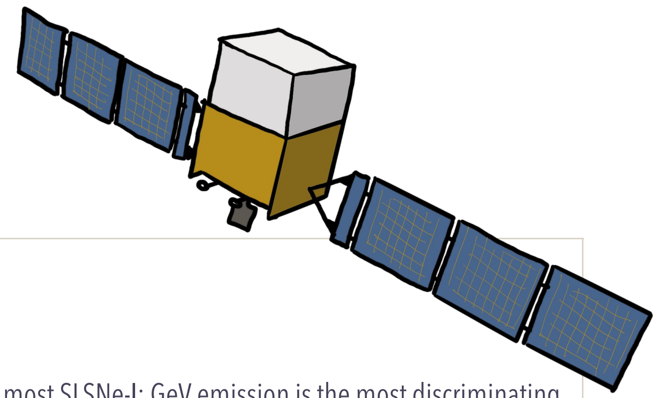
Magnetar and CSM models both fit $L_{opt}(t)$ for most SLSNe-I; GeV emission is the most discriminating observable.

Inserra+ 2013 · Chatzopoulos+ 2013 · Nicholl+ 2017 · Gomez+ 2024





Why gamma rays?



MAGNETAR IC NEBULA

Direct probe of the relativistic pair plasma

Pulsar wind ⟶ $e^{\pm}$ ⟶ IC scattering on the nebular thermal bath. The GeV channel **is** the engine's non-thermal output – optical only sees the reprocessed product.

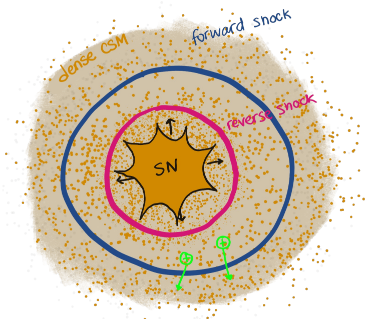
Kasen & Bildsten 2010 · Woosley 2010 · Metzger+ 2014 · Murase+ 2015 · Vurm & Metzger 2021

CSM HADRONIC SHOCKS

Calorimetric on shock energetics

p–p collisions in the post-shock CSM produce $\pi^0 \longrightarrow \gamma$. Flux $\propto \boldsymbol{\varepsilon}_{sh} \cdot \dot{E}_{sh}$ – a near-direct measure of CR acceleration efficiency.

Murase+ 2014, 2019 · Petropoulou+ 2016, 2017 · Fang+ 2019 · Sarmah+ 2022



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Light curves don't break the model

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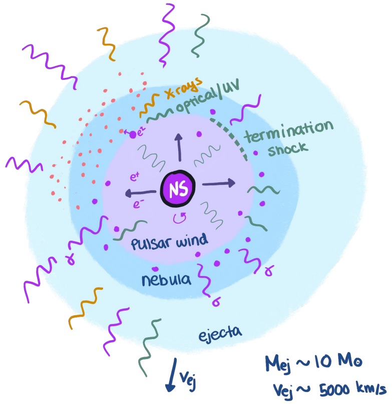

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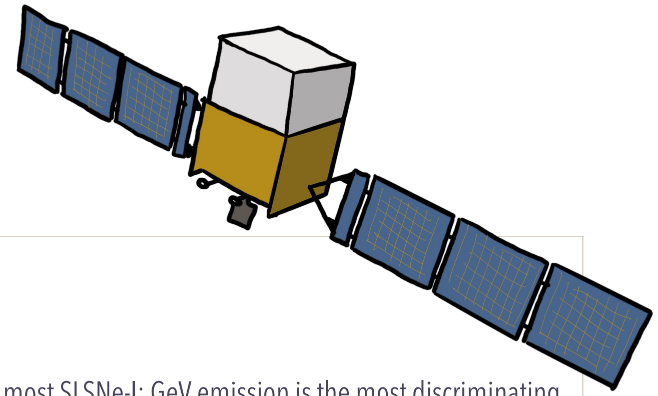

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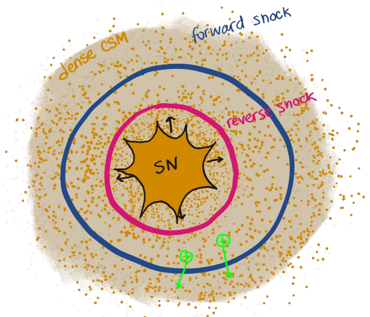

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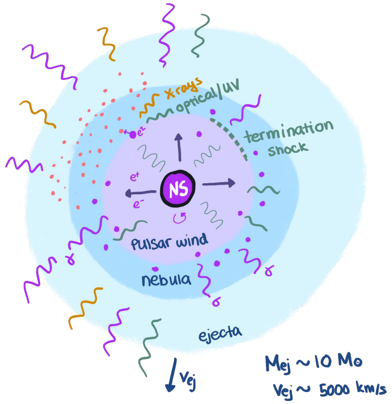
COMPLEMENTARY CHANNELS

Neutrinos & TeV

p-p **γ**-rays come with **ν** of comparable luminosity (IceCube: Stein 2019). TeV adds **γγ**-attenuation leverage – VERITAS, CTAO.



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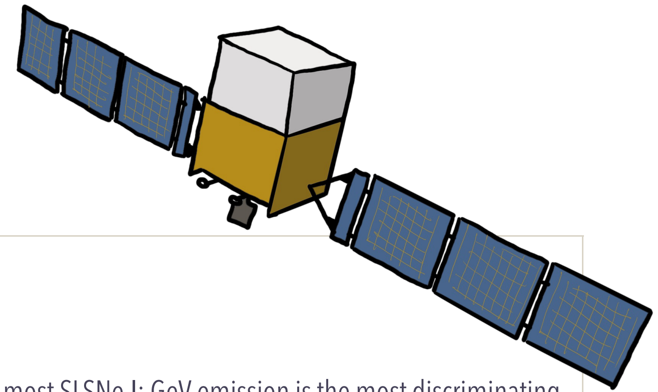

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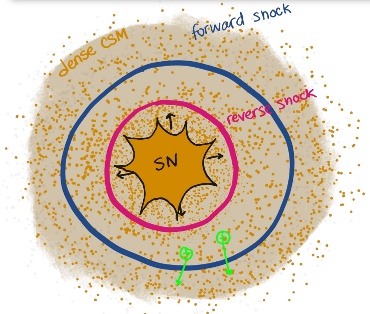

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The discriminator: η

$$\boxed{\eta \equiv \frac{L_\gamma}{L_{\rm opt}(t \sim t_{\rm BH})}}$$

with $t_{\rm BH} \approx 91\ {\rm d} \left(\frac{M_{\rm ej}}{5\ M_\odot} \right)^{1/2} \left(\frac{v_{\rm ej}}{6000\ {\rm km\ s^{-1}}} \right)^{-1}$

[Bethe-Heitler transparency]

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Magnetar scenario

- Weakly magnetized nebula ($\epsilon_B \leq 10^{-3}$): IC dominates → GR
  $\rightarrow \eta \sim 1$ @ $t \sim t_{\rm BH}$
- Strongly magnetized nebula → Synchrotron dominates → X-rays
  $\rightarrow \eta \ll 1$ @ $t \sim t_{\rm BH}$

[Vurm & Metzger 2021]

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[Vurm & Metzger 2021]

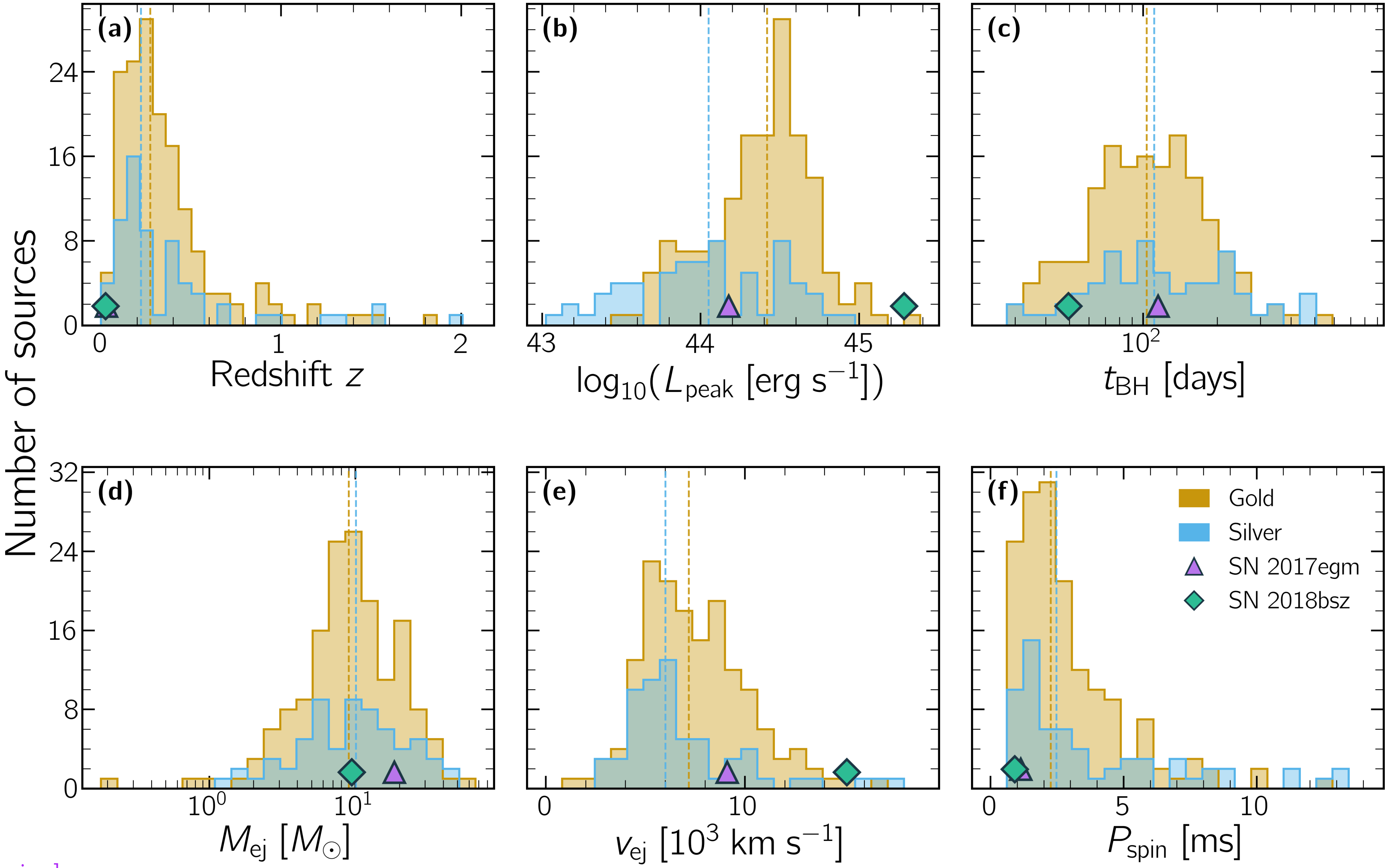
CSM Scenario

- GR luminosity bounded by shock power
  $\rightarrow \eta \sim 10^{-2}$

[Fang+ 2020, Caprioli & Spitkovsky 2014]

Our sample

STEP	CRITERION	REMOVED	REMAINING
Start	Gomez et al. 2024 – gold + silver SLSNe-I	–	241
1	Search window inside Fermi mission span	15	226
2	Galactic latitude $\|b\| > 10°$	2	224
3	Outside 95% containment of bright 4FGL-DR4 source	0	224
4	Valid pre-/post-explosion control window	1	223
Final	**SLSNe-I sample**	–	**223**



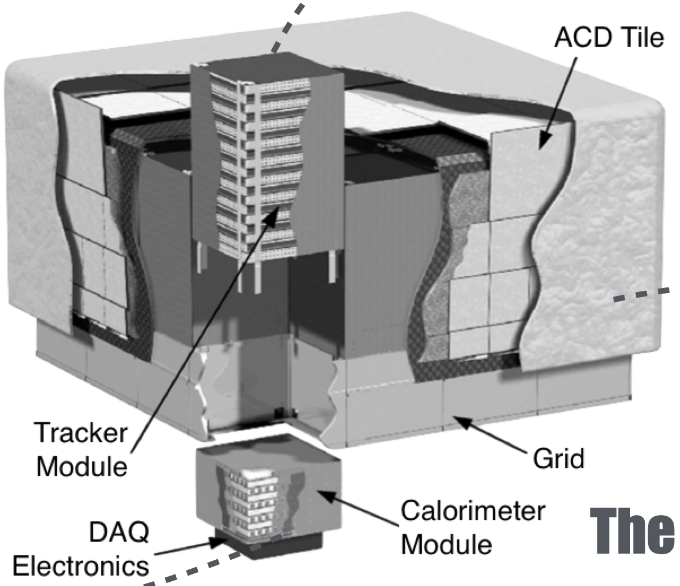
[MOSFiT posteriors]

Fermi-LAT

e^+e^- pair-conversion telescope

individual γ rays convert into e^+e^- pairs
→ tracks (localization) & deposited energy

…it also detects electrons.

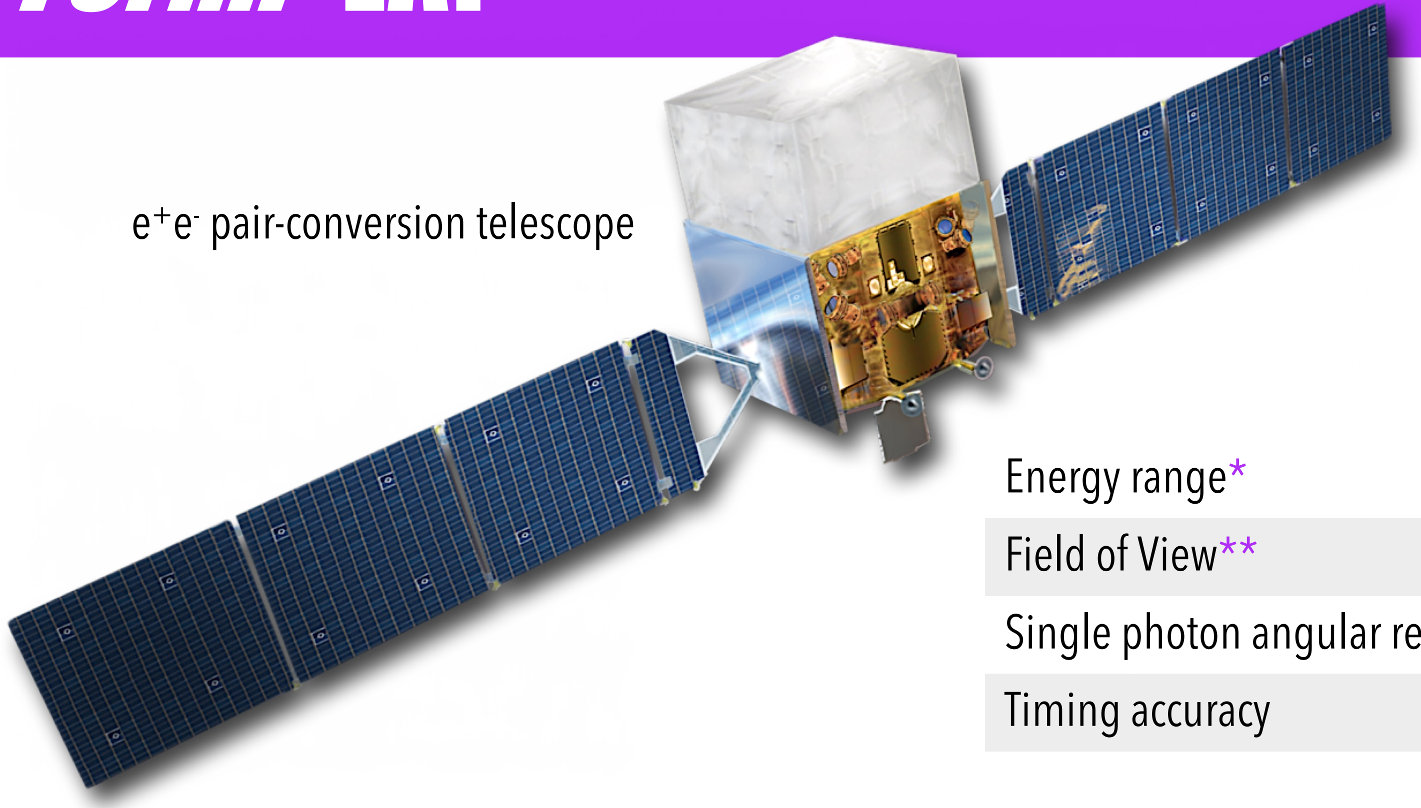


The Tracker-converter

The Calorimeter

The Anti-coincidence Detector

Fermi-LAT



e^+e^- pair-conversion telescope

Energy range*	20 MeV to > 300 GeV
Field of View**	2.4 sr (~1/5 of the whole sky)
Single photon angular resolution***	< 1 deg at 1 GeV
Timing accuracy	1 microsecond

*ideally suited for WIMP searches
**whole sky every ~3 hours
***point-source localization <0.5 arcmin

individual γ rays convert into e^+e^- pairs
→ tracks (localization) & deposited energy

…it also detects electrons.

Analysis set-up

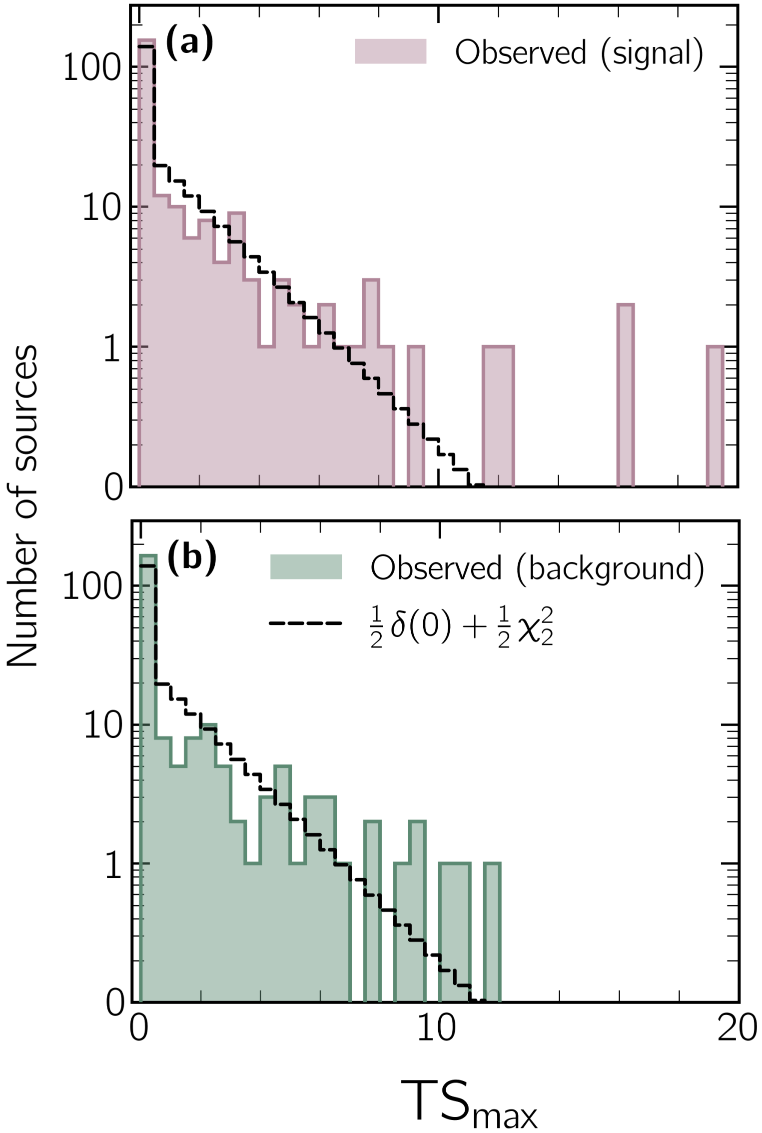
- Source specific time windows:

$$[t_0 + 0.5\, t_{BH}(1+z)\,,\, t_0 + 3.0\, t_{BH}(1+z)]$$

- Background modeling: matched-duration windows
- Energy range: (100) 500 MeV – 500 GeV
- Software: Fermipy v1.2.0 + Fermitools v2.2.0
- ROI: 10° × 10° (model extended to 15° × 15° for PSF spillover)
- Background sources from 4FGL-DR4
- Modeled as point source with a power-law spectrum in **Γ** [1.5, 4]
- Binned likelihood analysis per energy bin

TEST STATISTIC

$$TS(N_0, \Gamma) = 2\,[\,\log L(N_0, \Gamma) - \log L_0\,]$$



Joint Likelihood Analysis

→ Use **joint-likelihood analysis**, summing log-likelihoods from all 223 sources

$$\log L_{total} = \sum_i \log L_i \left(w_i, \Gamma \mid D_i\right)$$

→ Common spectral shape (power law index **Γ**) across all sources

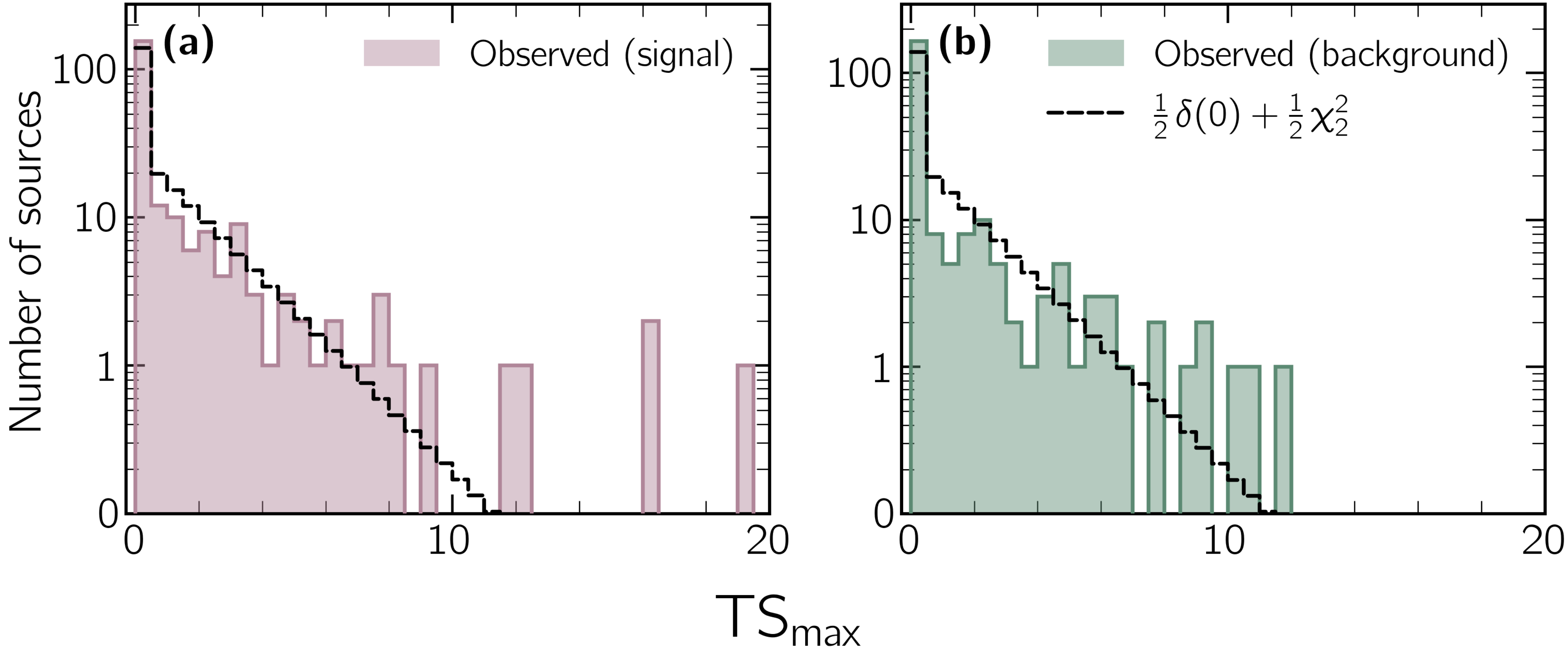
→ Source normalizations tied by physical weights w_i

#	MODEL	WEIGHT W_I	PROBES
a	Uniform	1	Control — no spurious correlations
b	Standard candle	$d_{L,i}^{-2}$	Common L_γ
c	Optical luminosity at t_{BH}	$L_{opt}(t_{BH}) / d_L^2$	**$\eta = L_\gamma / L_{opt}(t_{BH})$**
d	Magnetar spin-down	$L_{sd}(t_{BH}) / d_L^2$	$\varepsilon_{sd} = L_\gamma / L_{sd}$
e	Kinetic energy	E_k / d_L^2	L_γ / E_k
f	Shock power	$(E_k/t_{rise}) / d_L^2$	$\varepsilon_{sh} = L_\gamma \cdot t_{rise} / E_k$

All model inputs (M_{ej}, v_{ej}, L_0, T_{sd}, κ_γ) propagated from MOSFiT posteriors of Gomez et al. 2024.

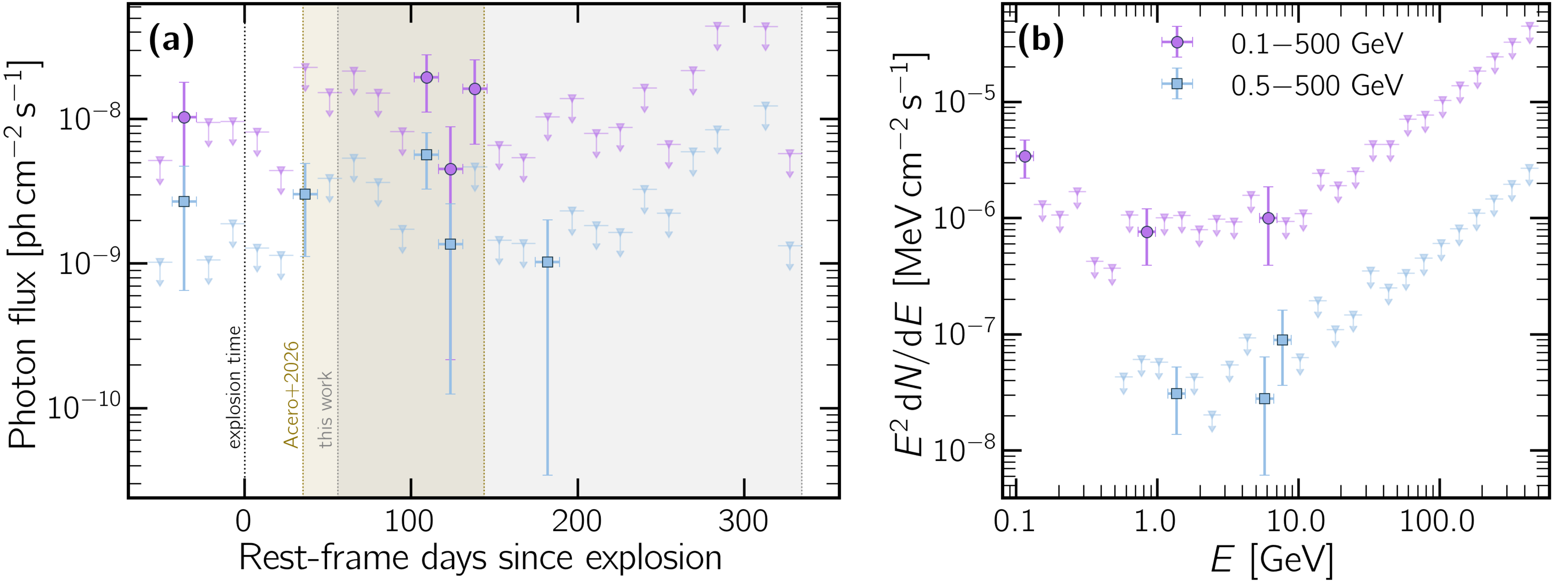
Results.

Signal vs. control



- The high-TS tail is **not unique to the signal window** .
- Empirical null is broader than the asymptotic bounded-Wilks expectation – known LAT feature for short windows.
- No population-level excess.

SN 2017egm (~4σ)



Highest in the sample; 2nd nearest source; best-fit **Γ** = 2.04.

Can we trust this detection?

I · TEMPORAL

$TS_{sig} = 19.5 \cdot TS_{ctrl} = 0.09$

Excess concentrated in rest-frame days 109–138, dominant bin TS = 19.2. Background steady-state ruled out.

II · SPECTRAL

$\Gamma = 2.04 \pm 0.32$

Consistent with both magnetar IC and hadronic π^0. $\Sigma TS_{bin} / TS_{RoI} \approx 1.5$ – typical of marginal 4FGL detections.

III · EXTENDED ENERGY

0.1–500 GeV consistent

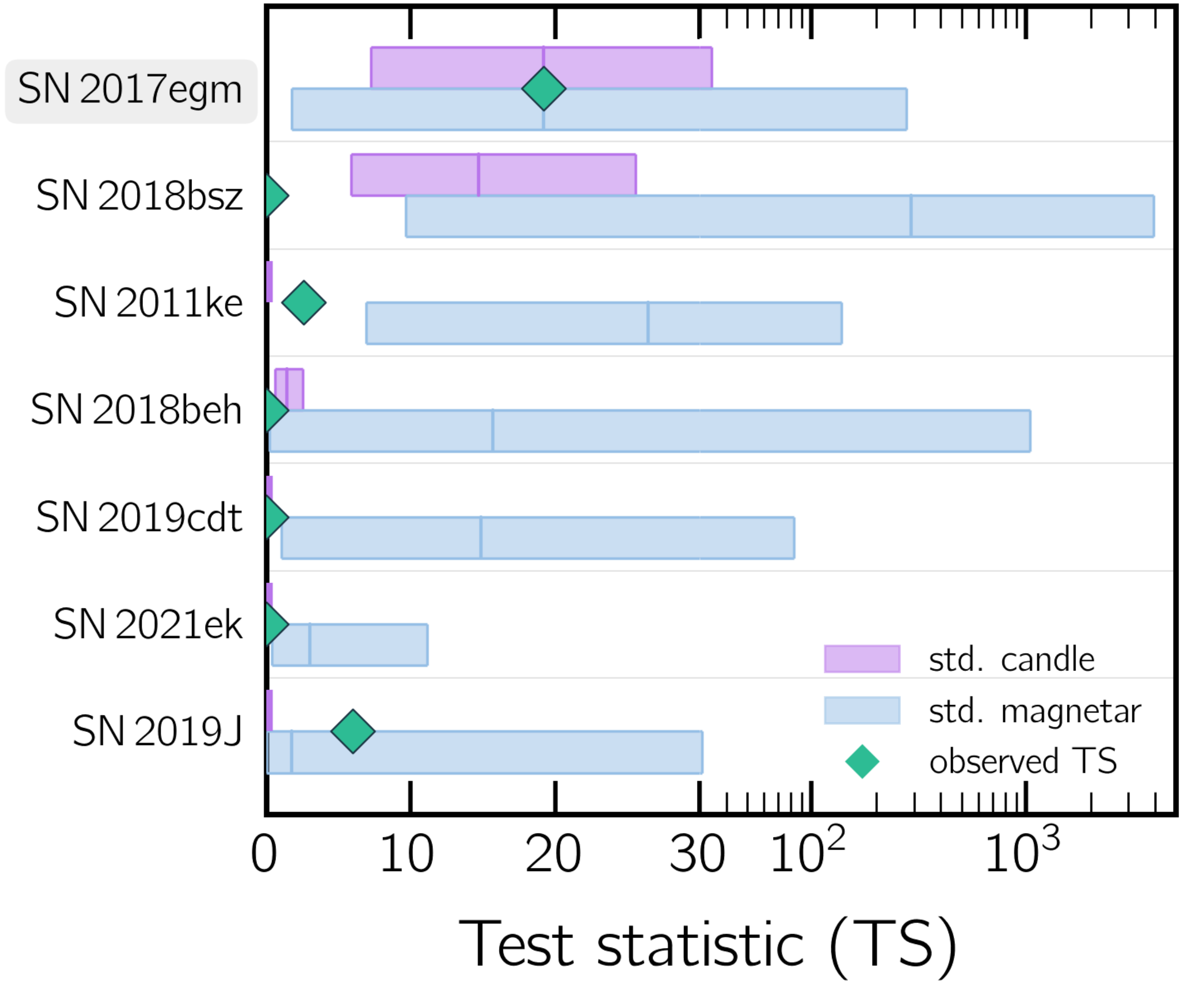
Excess appears at the same time in both bands. Dominant bin: TS = 16.6 at 100 MeV, TS = 19.2 at 500 MeV.

IV · BLAZAR CONTAMINATION

4FGL J1015.0+4926 – clear

3.06° away. PSF at 7.7 GeV: 0.15° – fully resolved. No flaring during the window; long-term flux below average.

Is 2017egm representative?



- No, but we can't know for sure.

Maybe…

→ The GeV efficiency varies between sources by more than an order of magnitude.

→ The two events are powered by fundamentally different engines.

Side-by-side: 2017egm vs 2018bsz

▲ 2017EGM

TS = 19.5 ~ 4.5σ

Z · D_L	0.031 · 139 Mpc
HOST	NGC 3191 – massive, near-solar Z spiral
SPECTRA	Canonical SLSN-I, O II features
LIGHT CURVE	Fast rise, no plateau
LATE-TIME	No H lines, no X-ray/radio

◆ 2018BSZ

TS = 0

Z · D_L	0.027 · 121 Mpc – closer
HOST	Low-mass, sub-solar Z dwarf
SPECTRA	Strong C II, no O II features
LIGHT CURVE	Long pre-max plateau
LATE-TIME	H emission · X-ray · radio (CSM signs)

Supplementary ZTF sources

- 11 nearby SLSNe-I discovered after the Gomez catalog. **SN 2024jlc may be of interest.**

REDSHIFT · DISTANCE

$z = 0.039 \cdot d_L \approx 178$ Mpc

TEST STATISTIC

$TS_{obs} = 7.07 \cdot TS_{ctrl} = 0$

BEST-FIT SPECTRAL INDEX

$\Gamma \approx 2.11$

STANDARD-CANDLE PREDICTION

$TS^{sc} \approx 9.0$

2nd nearest source to show a temporally coincident excess at a physically motivated index.

Likely still inside its transparency window – current data cover only ~600 d post-peak; no late-time photometry yet to fix t_{BH}.

Population-level: Null across all weighings

MODEL	N_{EFF}	QUANTITY	FULL SAMPLE	EXCL. DOMINANT	SN 2017EGM
Std. candle	19.3	L_γ	$< 1.5 \times 10^{40}$ erg s^{-1}	$< 2.4 \times 10^{40}$	3.5×10^{41}
Optical lum.	12.8	**η**	**$< 3.4 \times 10^{-4}$**	$< 1.3 \times 10^{-3}$	2.8×10^{-2}
Magnetar SD	14.3	ε_{sd}	$< 3.1 \times 10^{-4}$	$< 1.3 \times 10^{-3}$	2.5×10^{-2}
Kinetic E	4.6	L_γ/E_k	$< 4.4 \times 10^{-12}$ s^{-1}	$< 3.5 \times 10^{-11}$	3.6×10^{-11}
Shock power	2.4	ε_{sh}	$< 2.2 \times 10^{-6}$	$< 9.7 \times 10^{-6}$	9.5×10^{-5}

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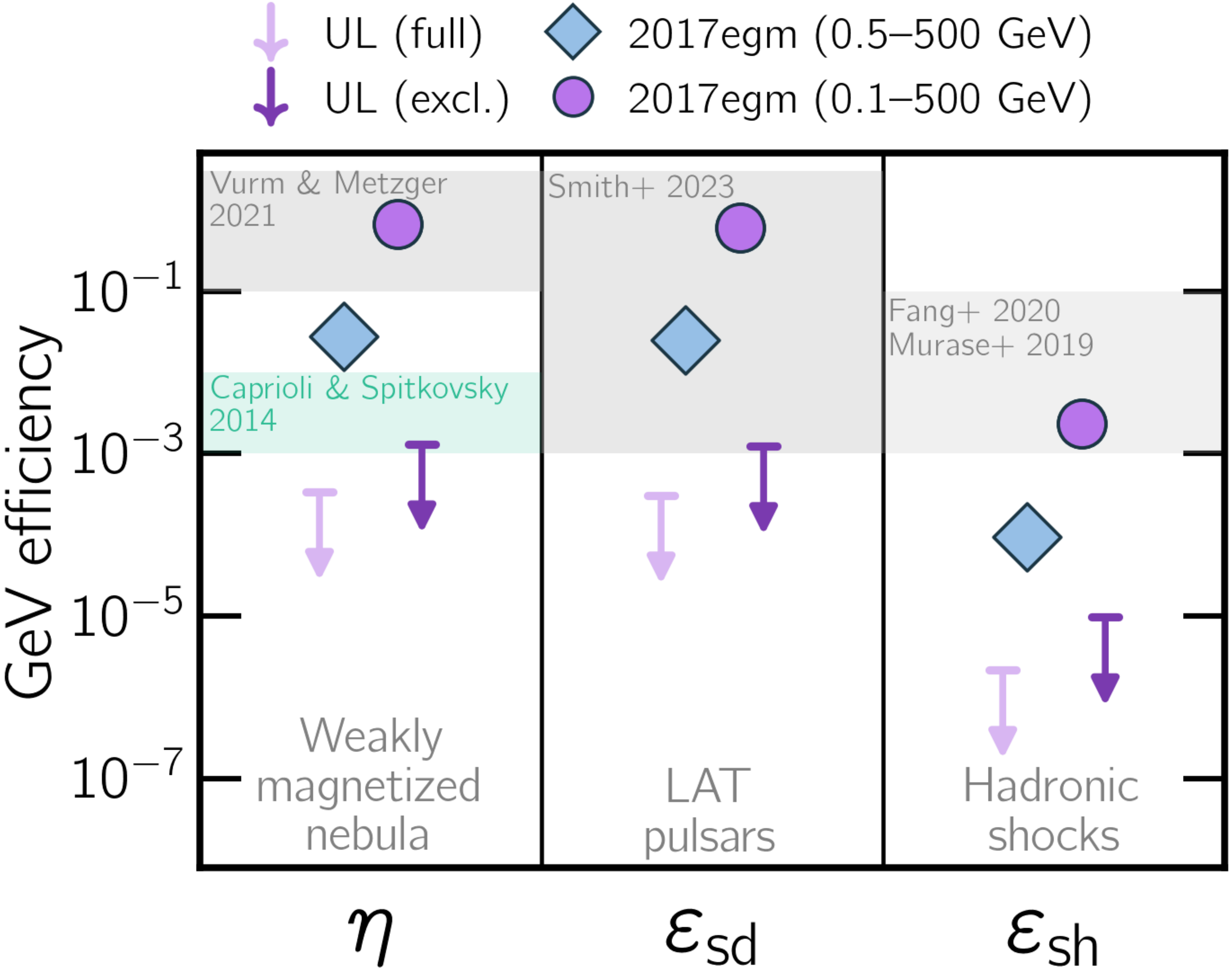
Assuming a log-normal
distribution of η, less than 0.4%
of SLSNe can have $\eta > 0.1$


UL (full)
UL (excl.)
2017egm (0.5–500 GeV)
2017egm (0.1–500 GeV)
GeV efficiency
10^{-1}
10^{-3}
10^{-5}
10^{-7}
Vurm & Metzger 2021
Caprioli & Spitkovsky 2014
Smith+ 2023
Fang+ 2020
Murase+ 2019
Weakly magnetized nebula
LAT pulsars
Hadronic shocks
η
ε_{sd}
ε_{sh}

Where next?

CHALLENGE

Volumetric rate

~100 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ · only ~0.2–0.5 SLSNe-I per year at $z < 0.03$.

NEED

Up to a decade of Fermi

Need another $z \lesssim 0.03$ SLSN-I during LAT lifetime. $m_r \lesssim 18$–19 – well within ZTF / ATLAS / LSST.

FUTURE

VLAST > CTA > Fermi

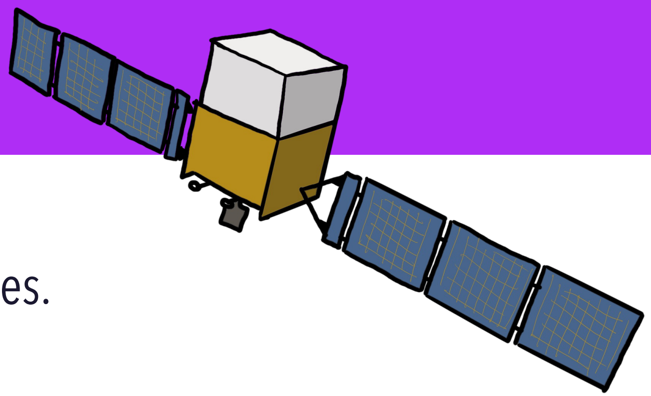
CTA: useful for hard spectra above 100 GeV, pointed only. **VLAST** – proposed all-sky, ~5× LAT effective area – would transform the field.

LSST: ~100–150 SLSNe-I at $z < 0.1$ over a decade – meaningful population improvement.

2024jlc and any future nearby event: continued Fermi-LAT monitoring as t_{BH} windows close.

CTAO-North · 50 h on the next 2017egm-class event would detect both magnetar and CSM models – magnetar emission peaks at $t_0 + 300$ d, mostly < 1 TeV

Take-away messages



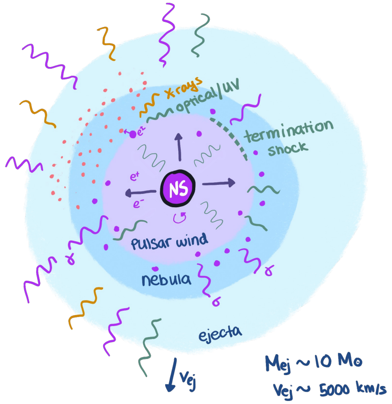
No population-level GeV signal across **223 SLSNe-I**, six weighting models, all spectral indices.
Joint $TS_{max} = 0$ throughout.

$\eta < 3.4 \times 10^{-4}$ – three orders of magnitude below weakly magnetized magnetar nebula predictions.
Conservative bound after removing dominant sources: $\eta < 1.3 \times 10^{-3}$.

First population constraint: $< 0.4\%$ of SLSNe-I can have $\eta > 10^{-1}$ (95% C.L.).
Even a small GeV-bright subpopulation is disfavored.

SN 2017egm: $\sim 4\sigma$ excess, $\eta \sim 0.7$ in 0.1–500 GeV – favors magnetar IC, unlikely representative.
Tension with non-detection of nearer SN 2018bsz; possibly two distinct engine channels.

SN 2024jlc: suggestive · still inside transparency window · **to be continued**.



arXiv:2604.16595 · milena.crnogorcevic@fysik.su.se · Thank you.