Multi-Peaked Non-Thermal Light Curves from Magnetar-Powered Gamma-Ray Bursts

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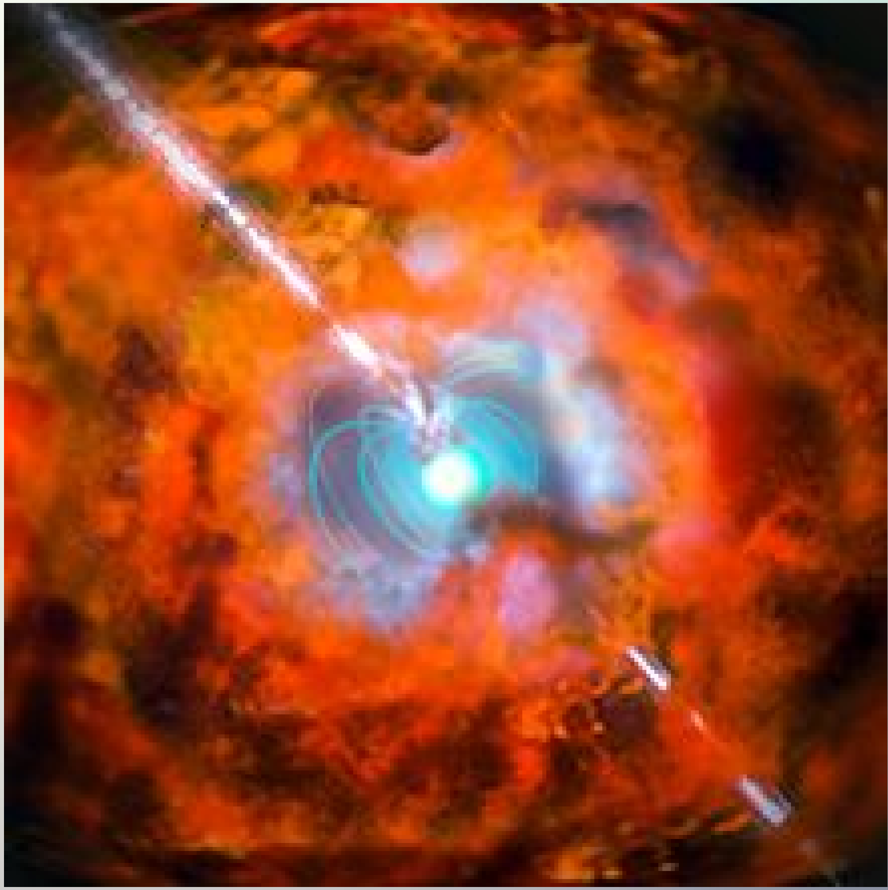
Based on Omand, Sarin, and Lamb (2025)



Credit: ESO

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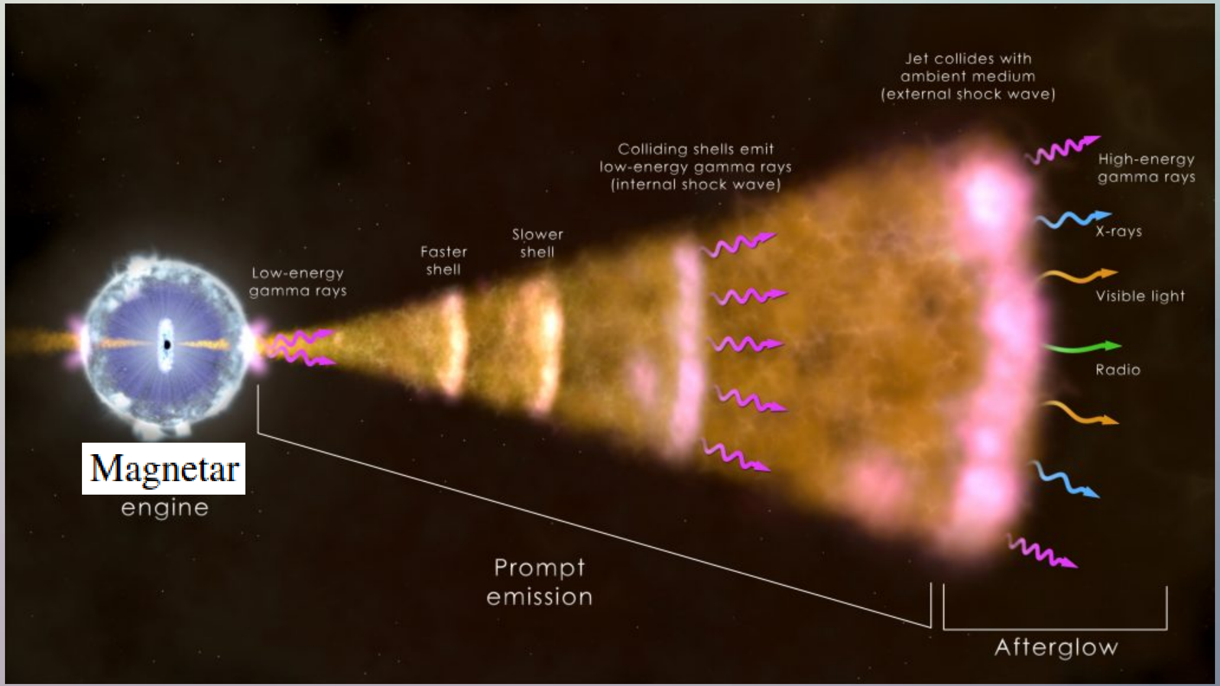
Magnetar-Driven GRBs

- Several features observed in LGRBs (extended emission, plateaus) may imply the presence of a long-lived magnetar engine
- Magentar have been invoked to explain high-luminosity thermal transients that can accompany GRBs (SNe Ic-BL, SLSNe)
- A small fraction of BNS mergers (< 5%) should produce a SGRB and have a stable neutron star remnant
- This systems should have multi-component non-thermal (post-prompt) emission from the GRB afterglow, pulsar wind nebula, and ejecta afterglow.
- We aim to calculate the peak timescales for each component and simulate their light curves to determine whether all three components will be distinct and detectable.

GRB Afterglow

- Synchrotron emission from the jet colliding with the external CSM, has broken power law spectrum.
- Peak time depends on when the spectral break crosses the observed band (or when the jet decelerates).
Later for
off-axis observers

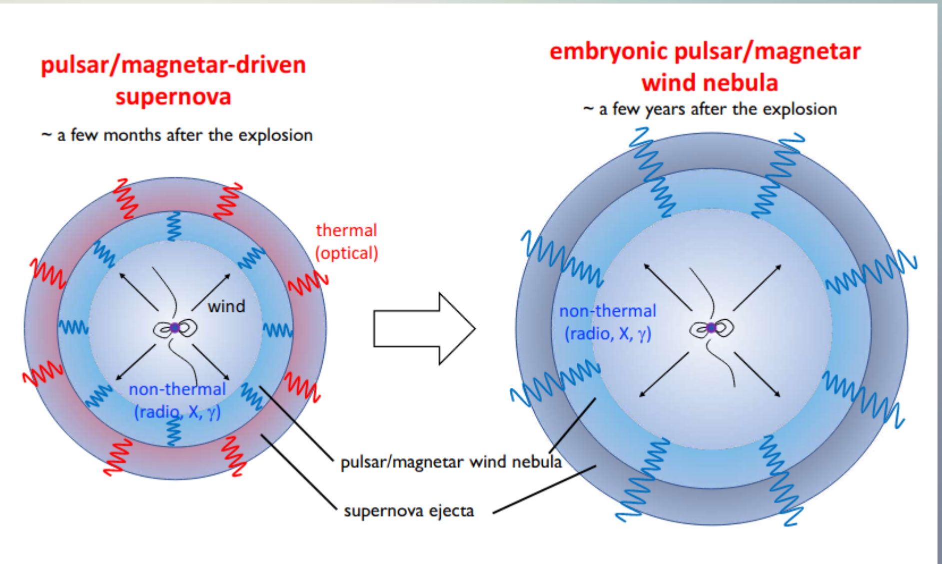


Credit: M. de los Reyes

Pulsar Wind Nebula (PWN)

- Pulsar spin-down generates energetic particles that are expelled from the neutron star via a pulsar wind.
- This wind collides with the inner ejecta and the confined particle wind produces a termination shock, which accelerates particles to ultrarelativistic energies
- Particles emit broadband synchrotron radiation and can scatter photons to gamma-ray energies
- Peak timescale is given by the optical depth in the observed band

Murase, Omand+ 2021



Ejecta Afterglow

- Also known as ejecta-CSM interaction or kilonova afterglow.
- Caused by the collision between the transient ejecta and the external CSM. The ejecta is accelerated by the magnetar so can be very bright.
- Peak timescale is caused by the deceleration timescale of the ejecta (or when the spectral breaks cross the observed band)

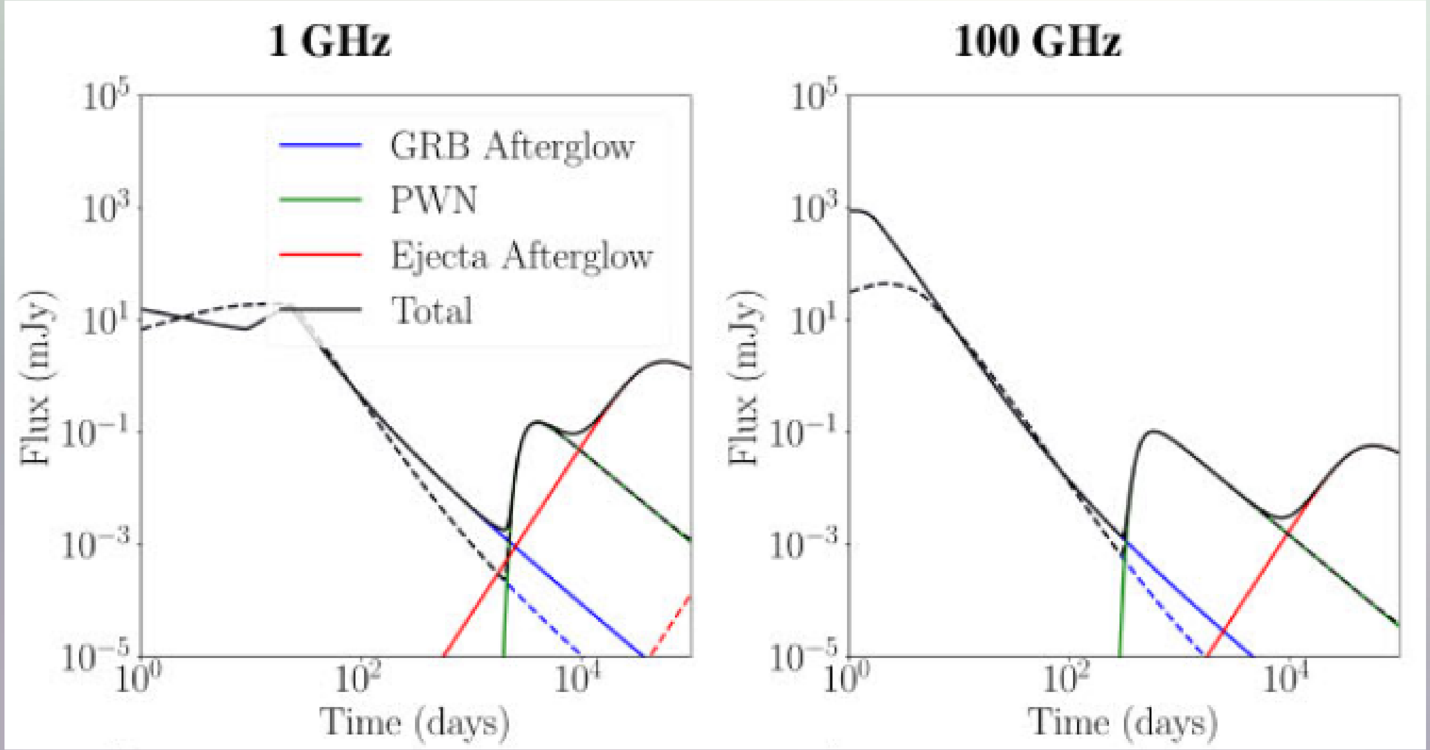
Peak Timescales

- With fiducial parameters, order is (almost) always GRB afterglow, PWN, ejecta afterglow
- Most scenarios have significant separation between the three timescales
- Full expressions including parameter scalings are in the paper

Transient	Component	1 GHz	100 GHz	1 keV	100 keV
	GRB afterglow	70 d	3 d	100 s	100 s
SN/LGRB	PWN	10 yr	500 d	60 yr	100 d
	Ejecta afterglow	80 yr	80 yr	80 yr	80 yr
	GRB afterglow	7 d	8 hours	20 s	20 s
KN/SGRB	PWN	100 d	15 d	6 yr	2 d
	Ejecta afterglow	3 yr	3 yr	3 yr	3 yr

Radio from SNe/LGRBs

- PWN is detectable in both bands, time window depends strongly on ambient density.
- PWN is the dominant component after ~ 6 yr at 1 GHz and after ~1 yr at 100 GHz



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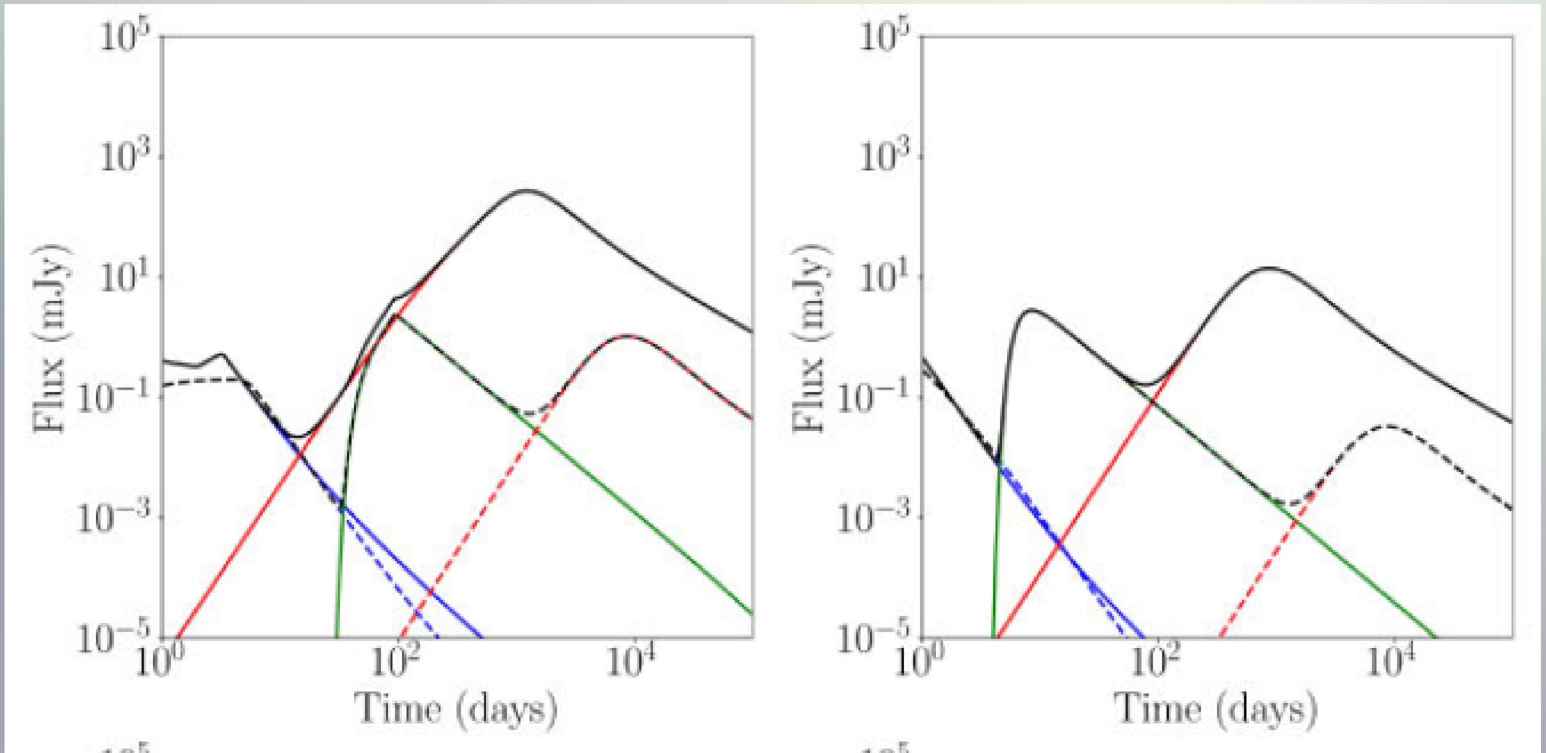
Radio from KNe/SGRBs

- PWN strongly detectable at 100 GHz, but marginally at 1 GHz at highest ambient density
- Timescale is a few weeks/months, can last years in a low density medium



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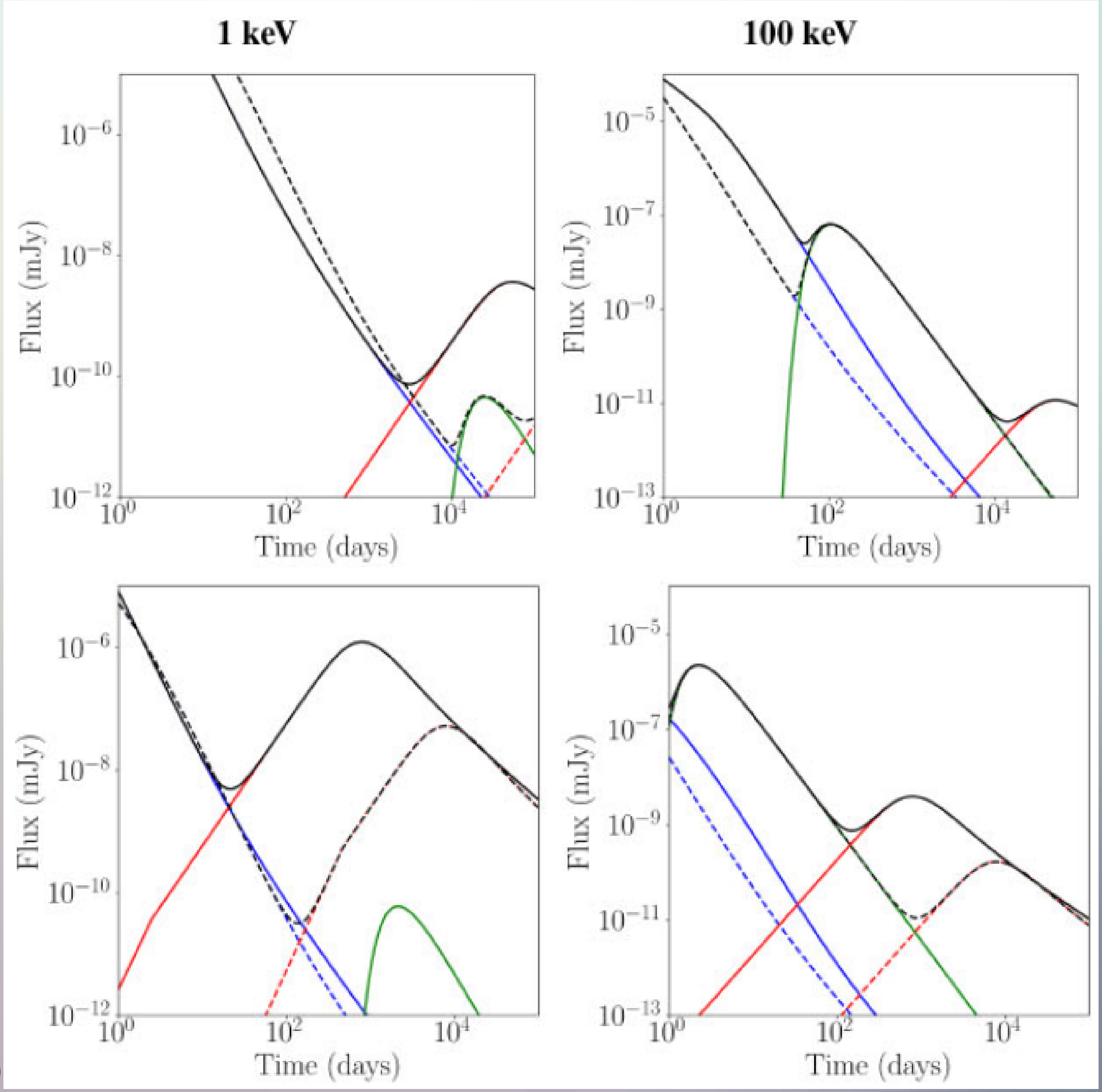
X-ray Emission

- 1 keV PWN emission is late and faint due to high ejecta opacity
- 100 keV PWN emission dominates early, but too faint to see beyond ~30 Mpc



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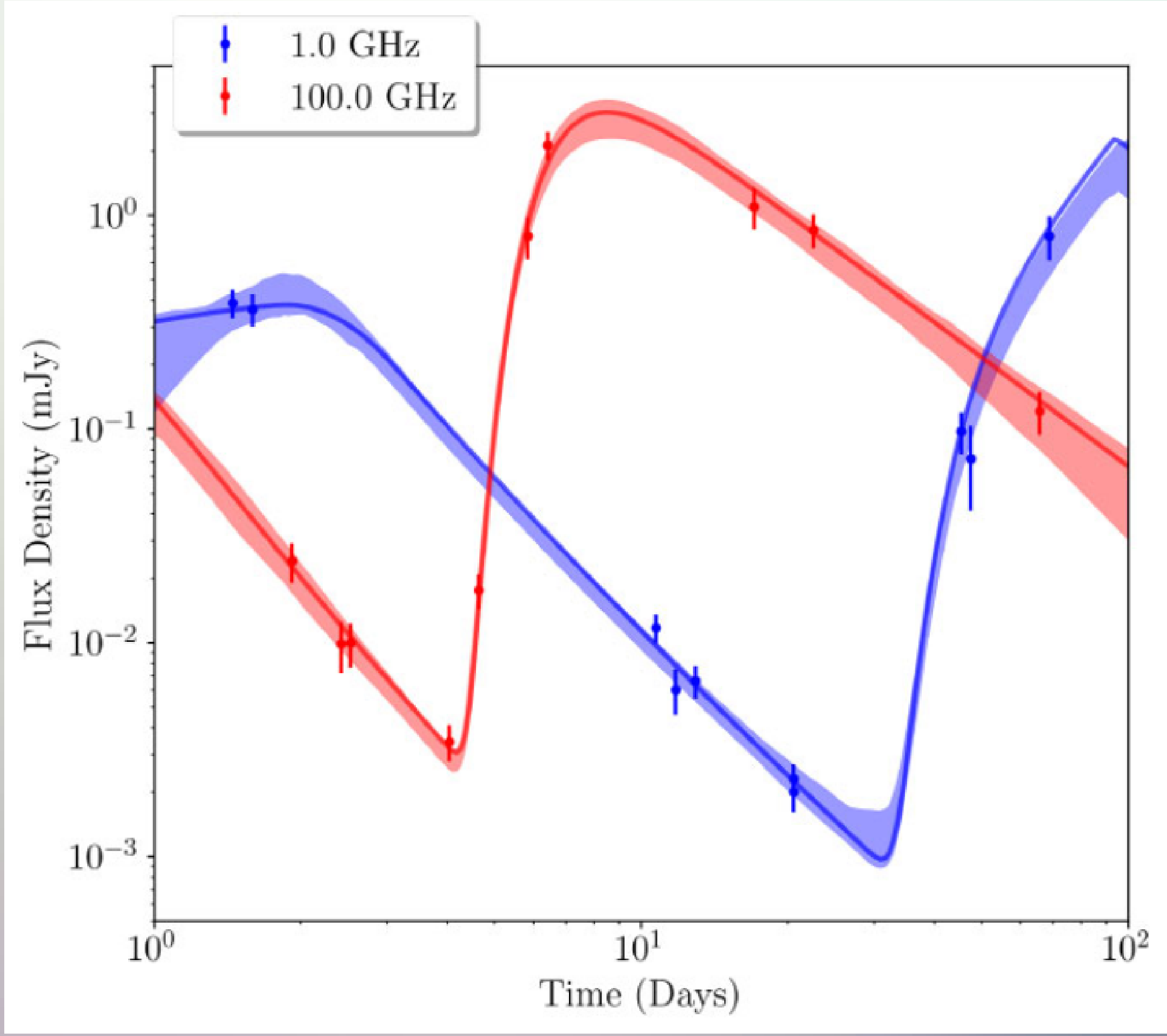
Fitting a Simulated Event

- Simulated observations of a fiducial KN/SGRB at 100 Mpc in two bands
- Attempted to fit models with and without a PWN
- Found that we could not reproduce the emission without a PWN
- Exponential rise to peak and frequency-dependent rise time are the strongest signals



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Horizon for Detecting PWN Emission

SNe/LGRBs	1 GHz	100 GHz
Current Gen (e.g. VLA, ALMA)	~250 Mpc (z ~ 0.06)	~200 Mpc (z ~ 0.05)
Next Gen (e.g. DSA-2000, ngVLA)	~ 1.0 Gpc (z ~ 0.2)	~ 1.5 Gpc (z ~ 0.3)

KNe/SGRBs	1 GHz	100 GHz
Current Gen (e.g. VLA, ALMA)	~ 1.5 Gpc (z ~ 0.3)	~ 1.0 Gpc (z ~ 0.2)
Next Gen (e.g. DSA-2000, ngVLA)	~ 4 Gpc (z ~ 0.7)	10 Gpc (z ~ 1.5)

Summary

- We calculated peak timescales for the three non-thermal components in magnetar-driven GRBs.
- We find that the PWN should be detectable at 1-100 GHz in both SN/LGRBs and KN/SGRBs.
- The first two peaks can not be reproduced by just a GRB and ejecta afterglow if the observations are well sampled.
- Current instruments don’t probe much of the GRB sample, but next-gen will probe some LGRBs and most SGRBs.