Investigate the impact of magnetar on the kilonova afterglow emission in short GRBs through late-time radio observations

UNIVERSITY OF JOHANNESBURG
CAPP
Centre for Astro-Particle Physics

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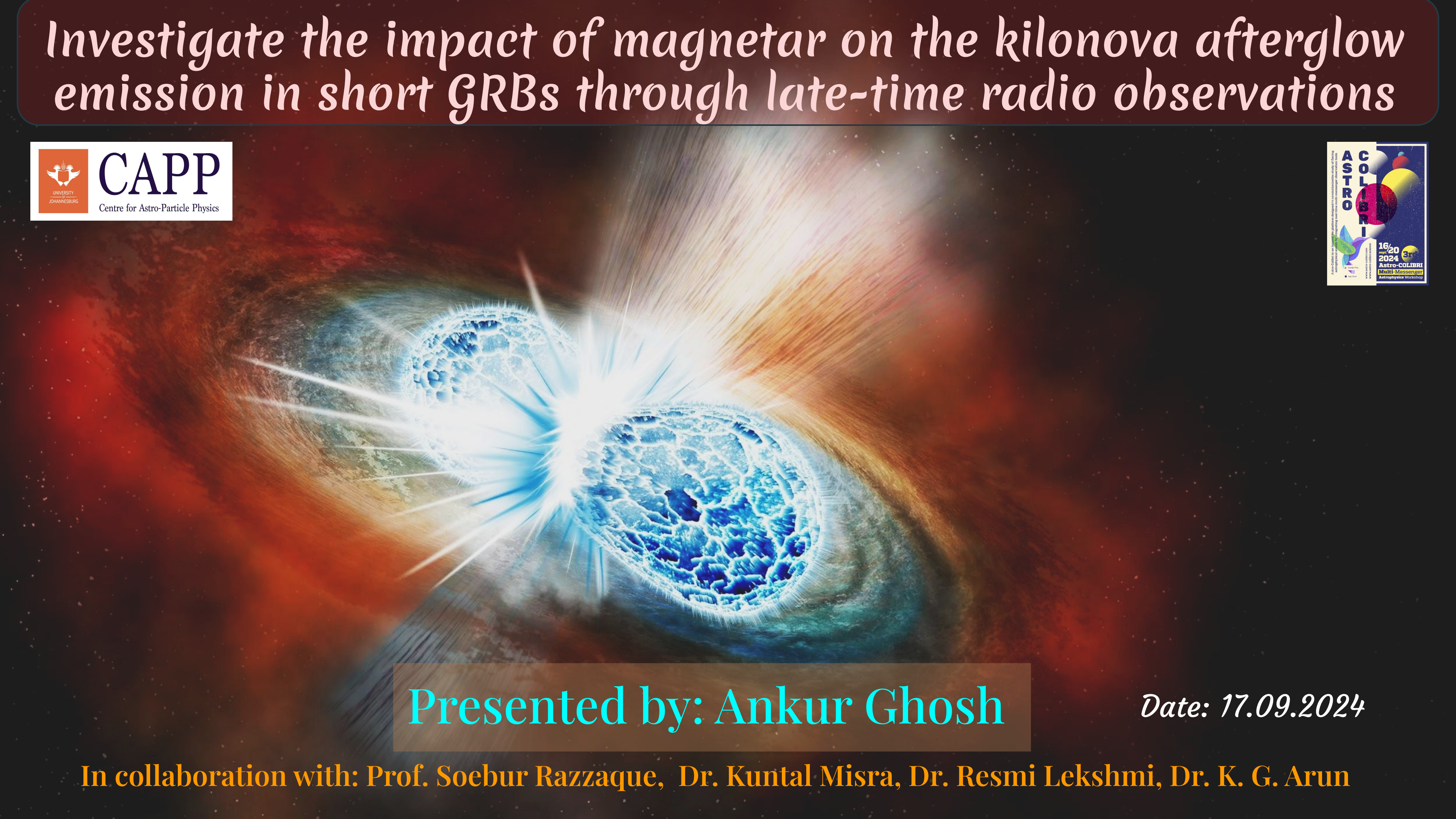
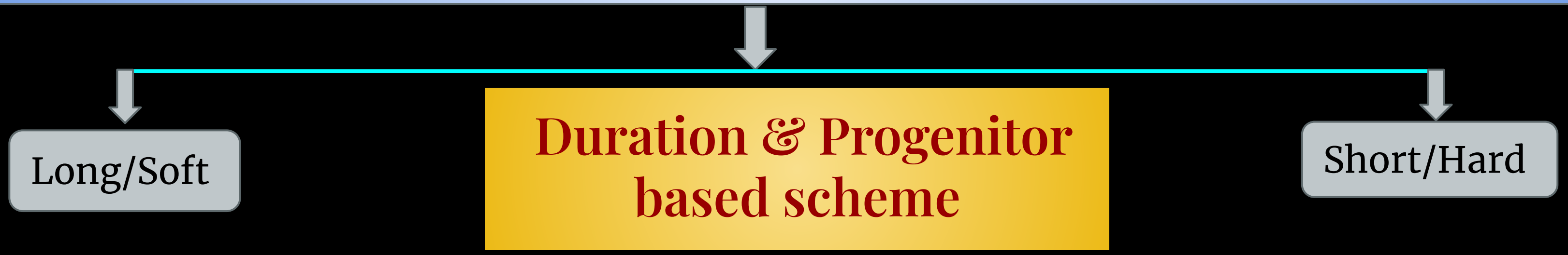


Presented by: Ankur Ghosh

Date: 17.09.2024

In collaboration with: Prof. Soebur Razzaque, Dr. Kuntal Misra, Dr. Resmi Lekshmi, Dr. K. G. Arun

Classification scheme of the GRBs



Long/Soft

Duration & Progenitor based scheme

Short/Hard

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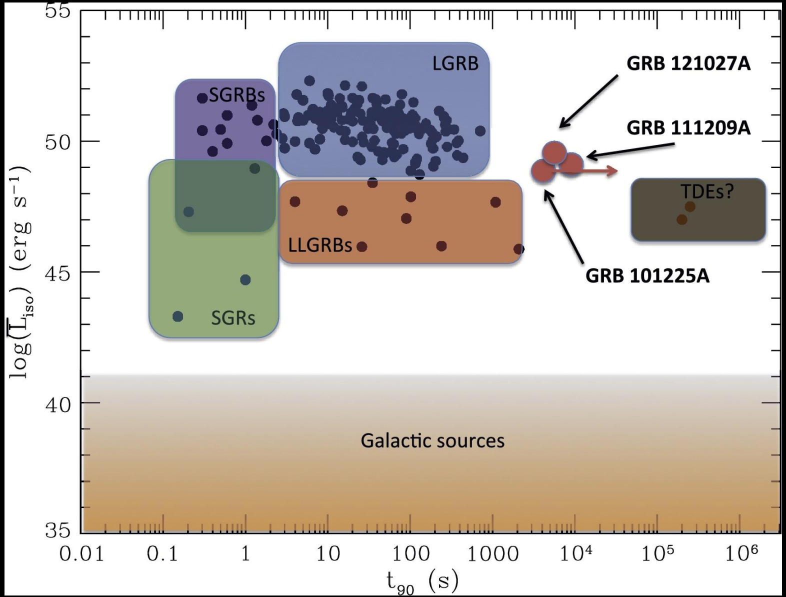

Courtesy: NASA and A. Feild (STScl)

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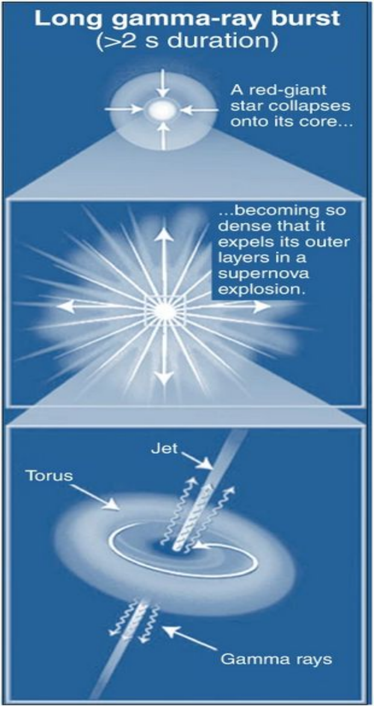
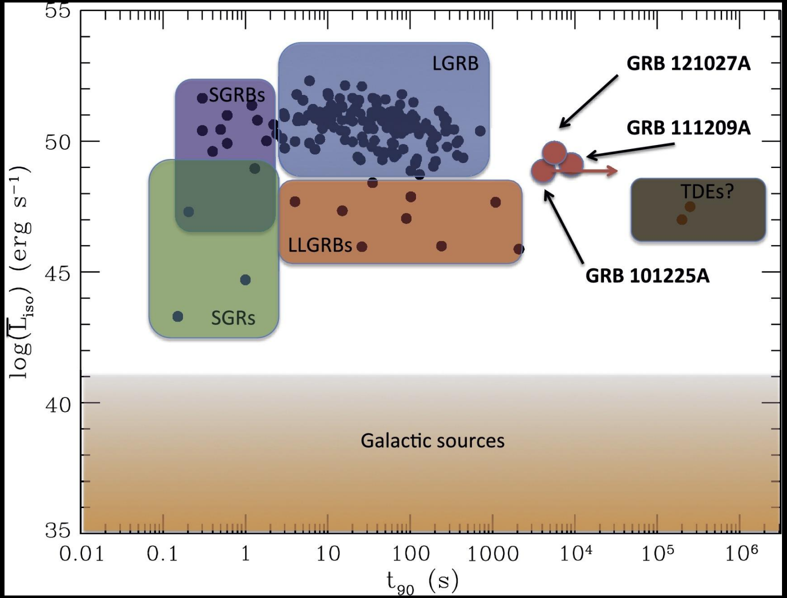
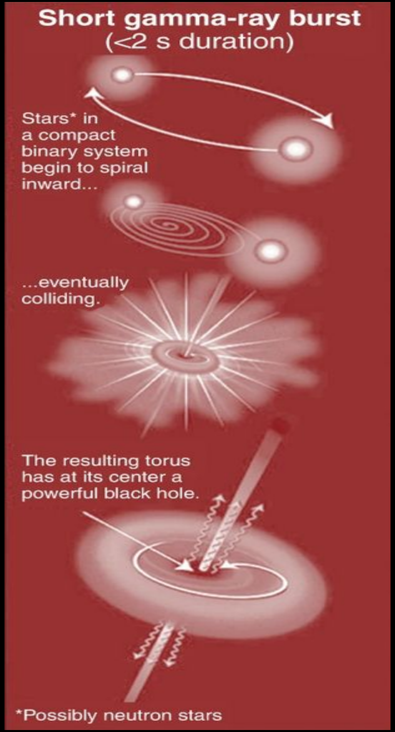
Duration & Progenitor based scheme

Long/Soft

Short/Hard







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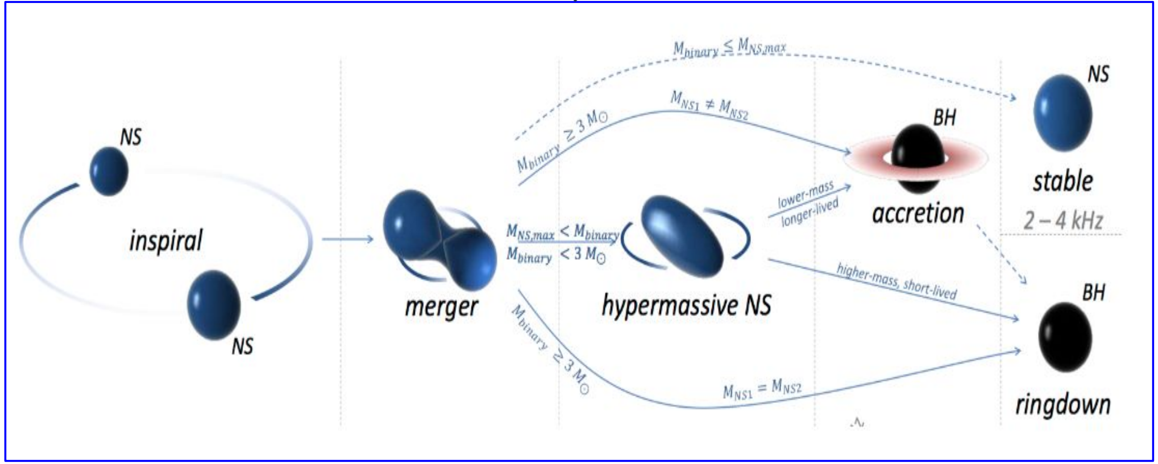
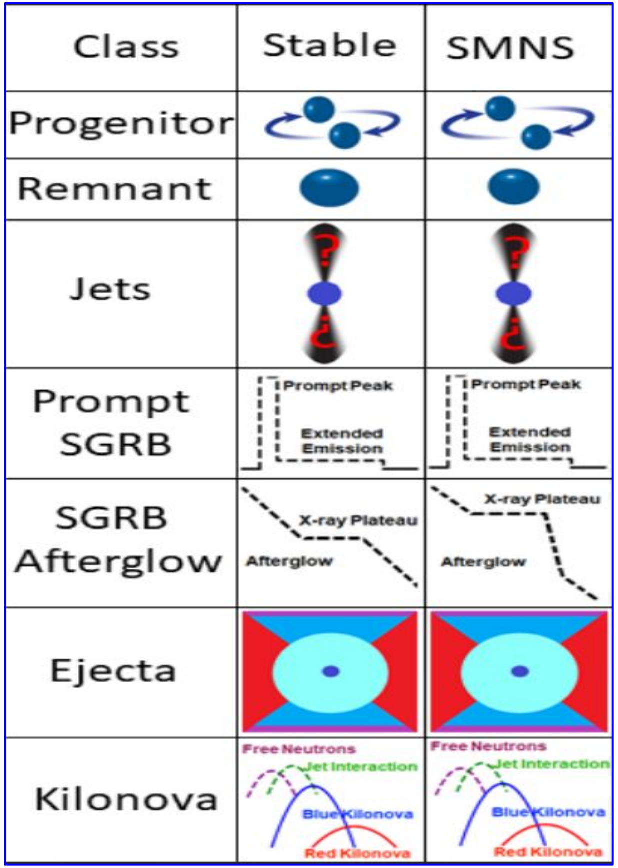
Progenitors of short GRBs

Aftermath of BNS merger



Bartos, Brady and Marka 2013



Class	Stable	SMNS
Progenitor		
Remnant		
Jets	? ¿	? ¿
Prompt SGRB	Prompt Peak Extended Emission	Prompt Peak Extended Emission
SGRB Afterglow	X-ray Plateau Afterglow	X-ray Plateau Afterglow
Ejecta		
Kilonova	Free Neutrons Jet Interaction Blue Kilonova Red Kilonova	Free Neutrons Jet Interaction Blue Kilonova Red Kilonova

Peter Mészáros, 2019

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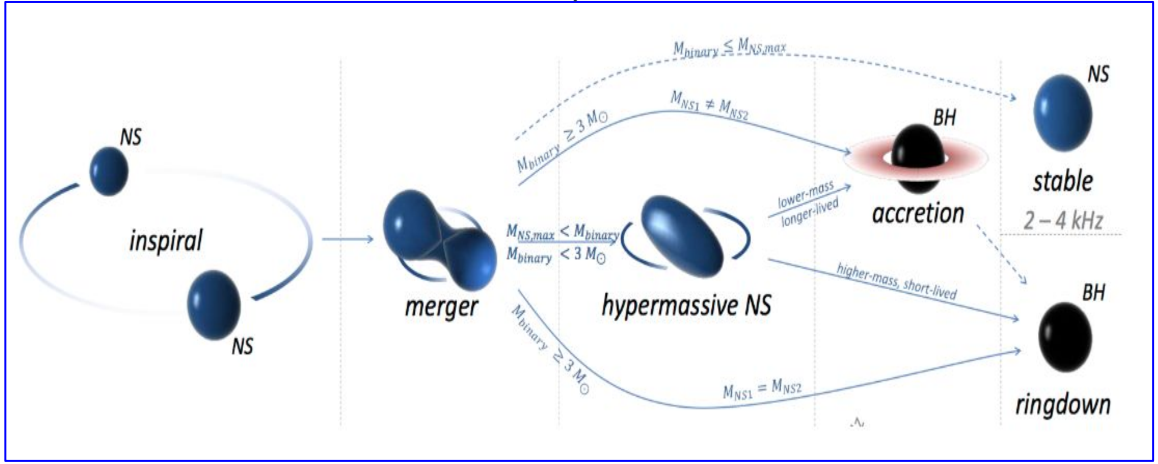

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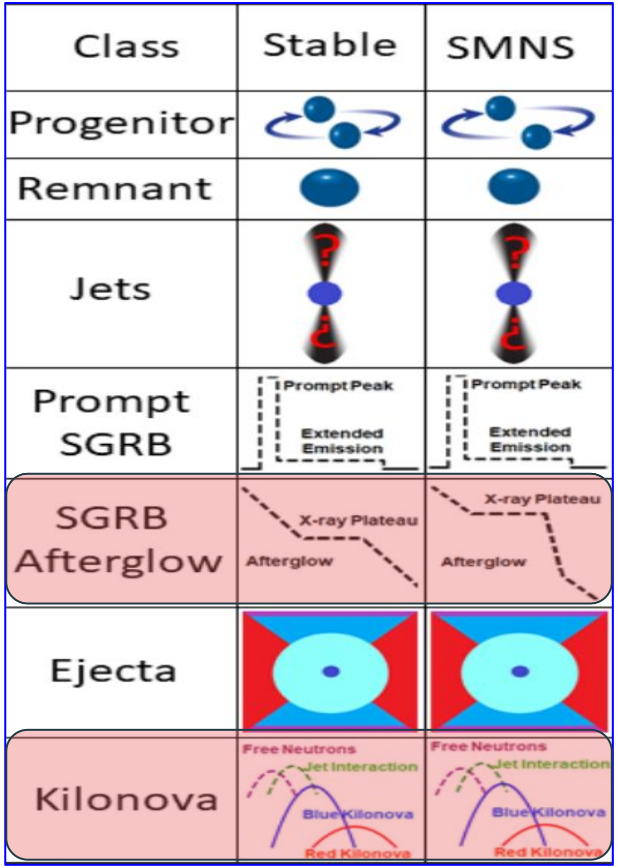

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Peter Mészáros, 2019

LATE-TIME RADIO EMISSION FROM KILONOVA EJECTA

- The tidal ejecta that generates the kilonova emission is also capable of driving a shock when it interacts with the ambient medium.

- This mildly-relativistic shock is expected to decelerate at time scales of a few years, depending on the density of the ambient Medium and mass ejection rate (Nakar & Piran 2011).

- If the resultant product of the merger is a millisecond magnetar, even if short-lived, it imparts the rotational energy to the merger ejecta which can enhance the radio flux.

- Detection, or even limits of the radio emission from the merger ejecta will provide a joint constraint on the magnetar rotational energy, amount of tidally ejected mass and density of the ambient medium.

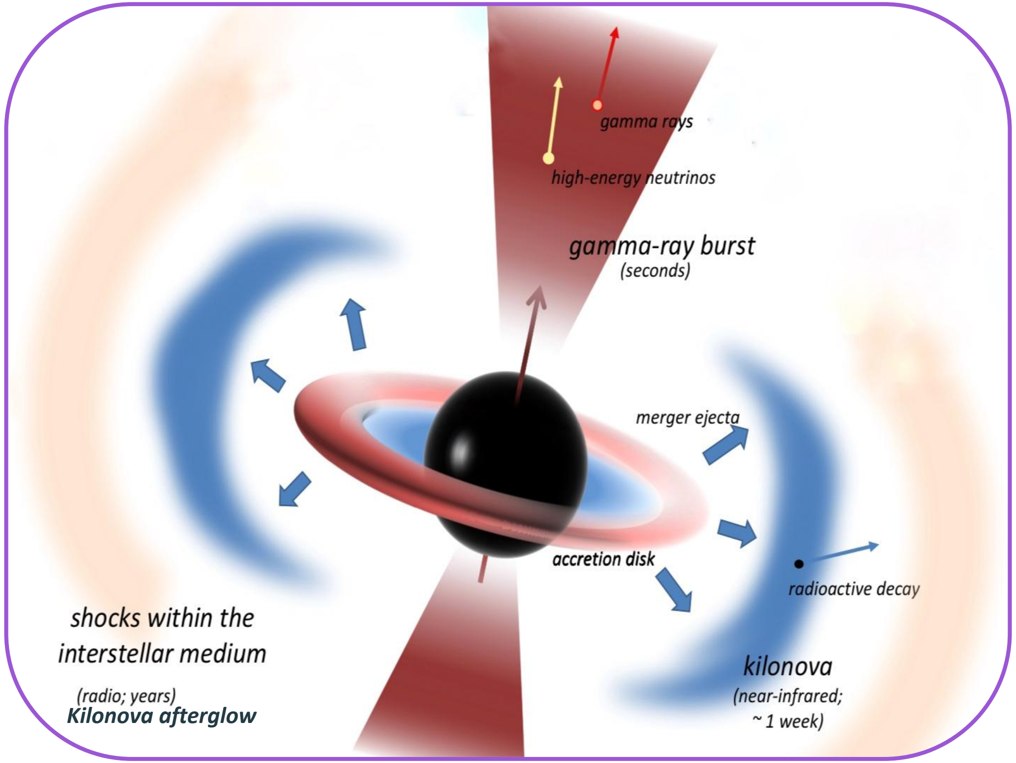
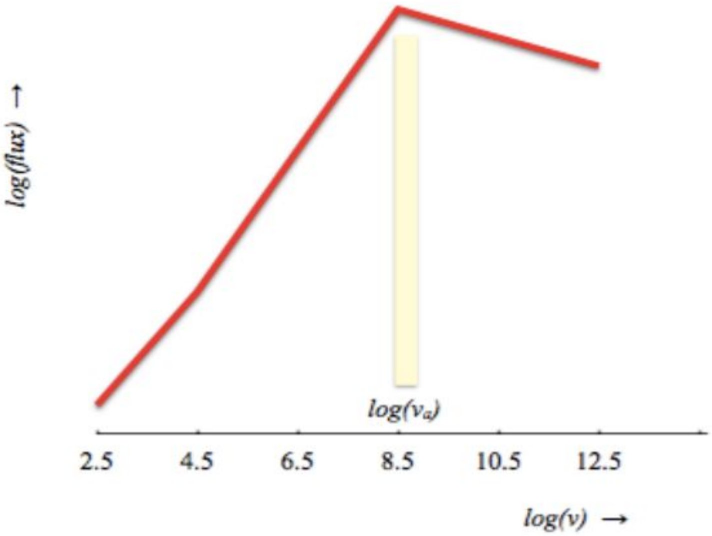


Fig 1: Different electromagnetic counterparts from NS–NS and BH–NS mergers which includes jet afterglow, kilonova emission, and late time kilonova afterglow emission.

Necessary parameters for the search

- The radio flux is expected to peak around the time of deceleration (~2-10 yrs since the burst).
- From the figure, we can see the radio flux peaks near 600 MHz which is close to GMRT 610 MHz band.



Expected spectrum at deceleration time

- For spherical outflow, we can calculate deceleration timescale

$$t_{dec} \sim \frac{R_{dec}}{c\beta_0} \approx 1.2yr\left(\frac{E_{rot}}{10^{52}erg}\right)^{1/3}\left(\frac{n_0}{cm^{-3}}\right)^{-1/3}\beta_0^{-5/3}$$

- Observed frequency $\nu_{\mathrm{a}} \sim 2\mathrm{GHz}\mathrm{E}_{52}^{0.1}\mathrm{n}_0^{0.6}\beta_0$
- The observed peak flux can be calculated from Nakar & Piran (2011):

$$F_{\nu,obs,pk} = 3mJy\left(\frac{E_{rot}}{10^{52}erg}\right)\left(\frac{n}{cm^{-3}}\right)^{0.83}\left(\frac{\epsilon_B}{0.1}\right)^{0.83}\left(\frac{\epsilon_e}{0.1}\right)^{1.3}\beta_0^{2/3}d_{28}^{-2}$$

Sample Selection :

❑ **Exclusion:**

- ★ Sample from previous studies (Metzger & Bower 14, Horesh+16, Fong+16).
- ★ Redshift greater than 0.5, since the expected signal is weak
- ★ Low ambient number density through afterglow modeling.
- ★ No potential signature of magnetar in X-ray afterglow light curve and kilonova signature in optical/IR light curves.
- ★ Bursts having southern declination due to inaccessibility of GMRT.

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Signature of magnetar as a central engine

1. Early time prolonged x-ray emission (10 - 100 s since burst)
2. Temporary flattening or plateau in x-ray lightcurve (100 - 1000 s since burst)
3. Late time x-ray excess (almost fews days since burst)

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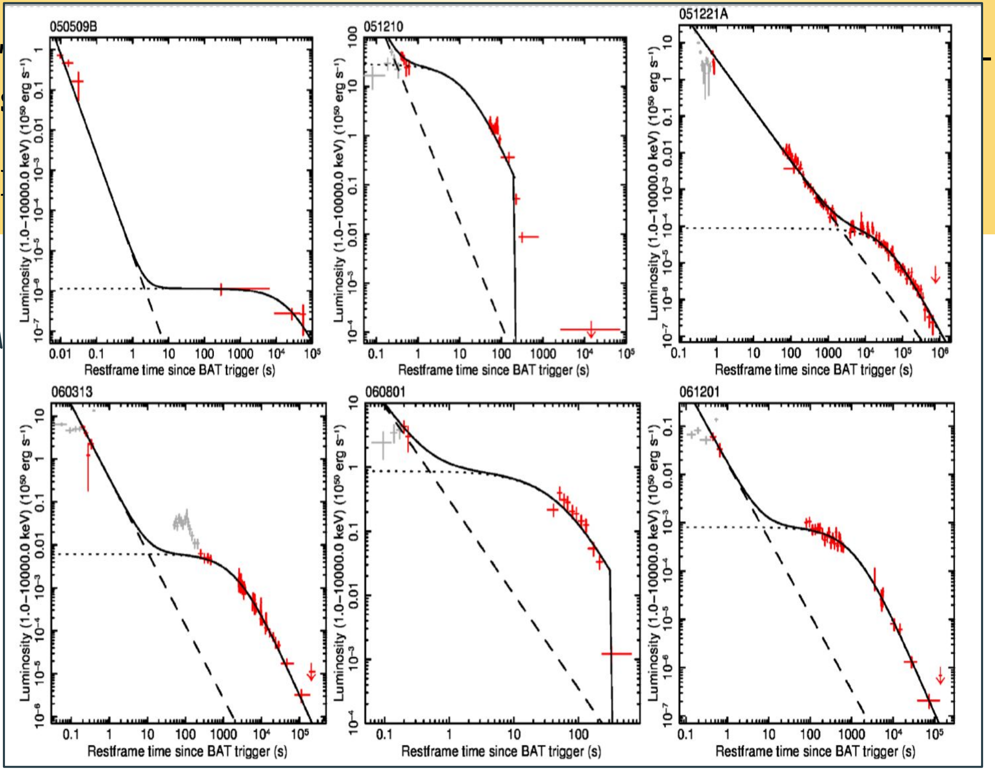

Rowlinson et al. 2013

Observation :

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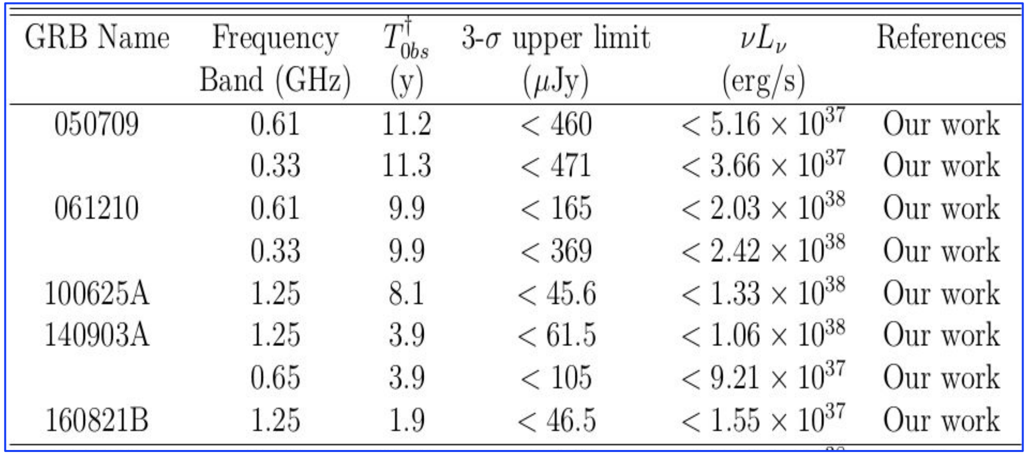
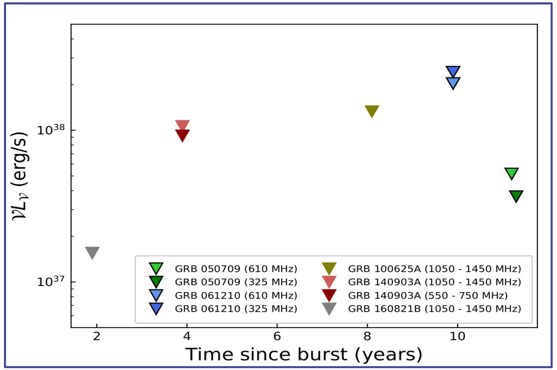
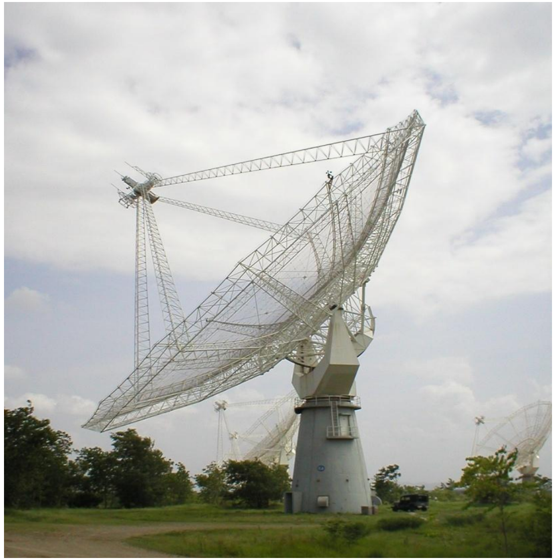


GRB Name	Frequency Band (GHz)	$T^{\dagger}_{0bs}$ (y)	3-σ upper limit (μJy)	νL_ν (erg/s)	References
050709	0.61	11.2	< 460	$< 5.16 \times 10^{37}$	Our work
	0.33	11.3	< 471	$< 3.66 \times 10^{37}$	Our work
061210	0.61	9.9	< 165	$< 2.03 \times 10^{38}$	Our work
	0.33	9.9	< 369	$< 2.42 \times 10^{38}$	Our work
100625A	1.25	8.1	< 45.6	$< 1.33 \times 10^{38}$	Our work
140903A	1.25	3.9	< 61.5	$< 1.06 \times 10^{38}$	Our work
	0.65	3.9	< 105	$< 9.21 \times 10^{37}$	Our work
160821B	1.25	1.9	< 46.5	$< 1.55 \times 10^{37}$	Our work

Table 1: Details of the observation





Magnetar Model

Dynamics of the ejecta

$$E_k = \Gamma M_{ej} c^2 + (\Gamma^2 - 1) M_{sw} c^2$$

$$\frac{d\Gamma}{dR} = \frac{4\pi R^2 n m_p}{M_{ej} + 2\Gamma M_{sw}} \left[\frac{L(t)}{c^2} \frac{dt}{dM_{sw}} - (\Gamma^2 - 1) \right]$$

For spherical outflow, the deceleration radius and deceleration time scale

$$R_{dec} \simeq \left(\frac{3E_{rot}}{4\pi n_0 m_p c^2 \beta_0^2} \right)^{1/3}$$

$$\approx 1.2 \times 10^{18} cm \left(\frac{E_{rot}}{10^{52} erg} \right)^{1/3} \left(\frac{n_0}{cm^{-3}} \right)^{-1/3} \beta_0^{-2/3}$$

and

$$t_{dec} \sim \frac{R_{dec}}{c\beta_0} \approx 1.2 yr \left(\frac{E_{rot}}{10^{52} erg} \right)^{1/3} \left(\frac{n_0}{cm^{-3}} \right)^{-1/3} \beta_0^{-5/3}$$

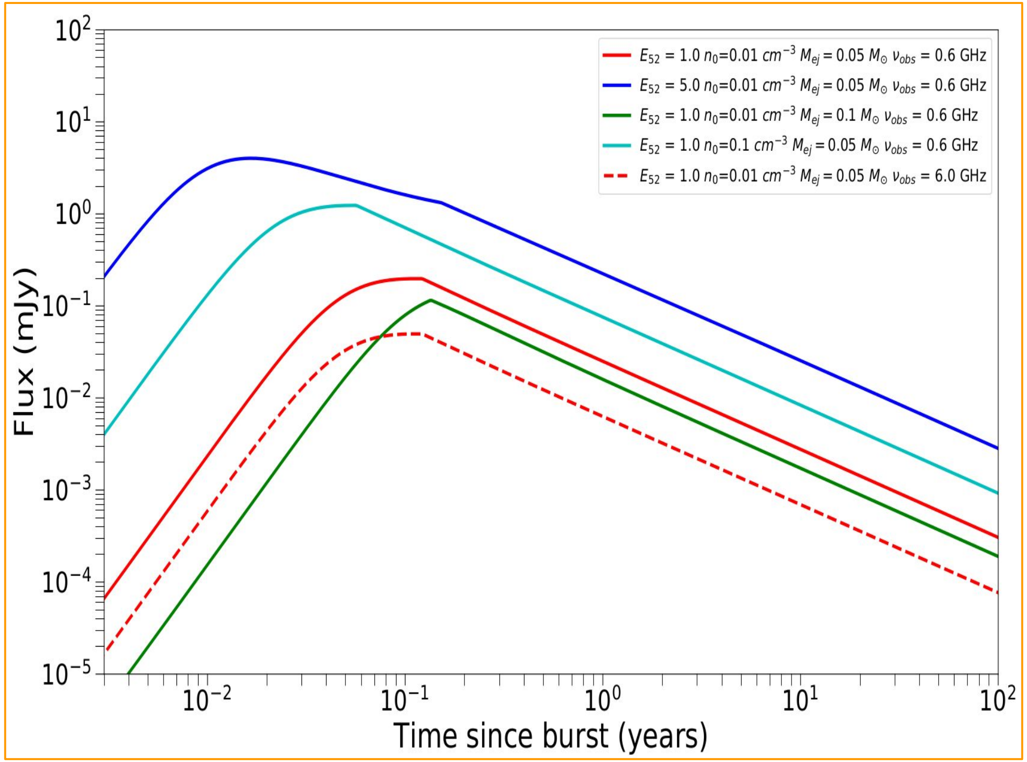
The synchrotron frequency and peak flux estimation

$$\nu_a = \frac{398\ \mathrm{MHz}}{1+z} n_{0,-2}^{7/10} r_{\mathrm{pc}}^{3/10} (\gamma(t) - 1)^{7/10} \gamma(t)^{7/20} \epsilon_B^{7/20} \epsilon_e^{2/5}$$

$$\nu_m = \frac{4190\mathrm{MHz}}{(1+z)} \frac{B(t)}{\mathrm{mG}} \gamma_m(t)^2 \gamma(t),$$

$$f_m = 240\mu\mathrm{Jy}\ (1+z)\ n_{0,-2} \frac{B(t)}{\mathrm{mG}} \gamma(t) \frac{r_{\mathrm{pc}}(t)^3}{d_{\mathrm{L,Gpc}}^2}.$$

Ghosh et al. 2024a



Model light-curves with varying model parameters

Light curve analysis

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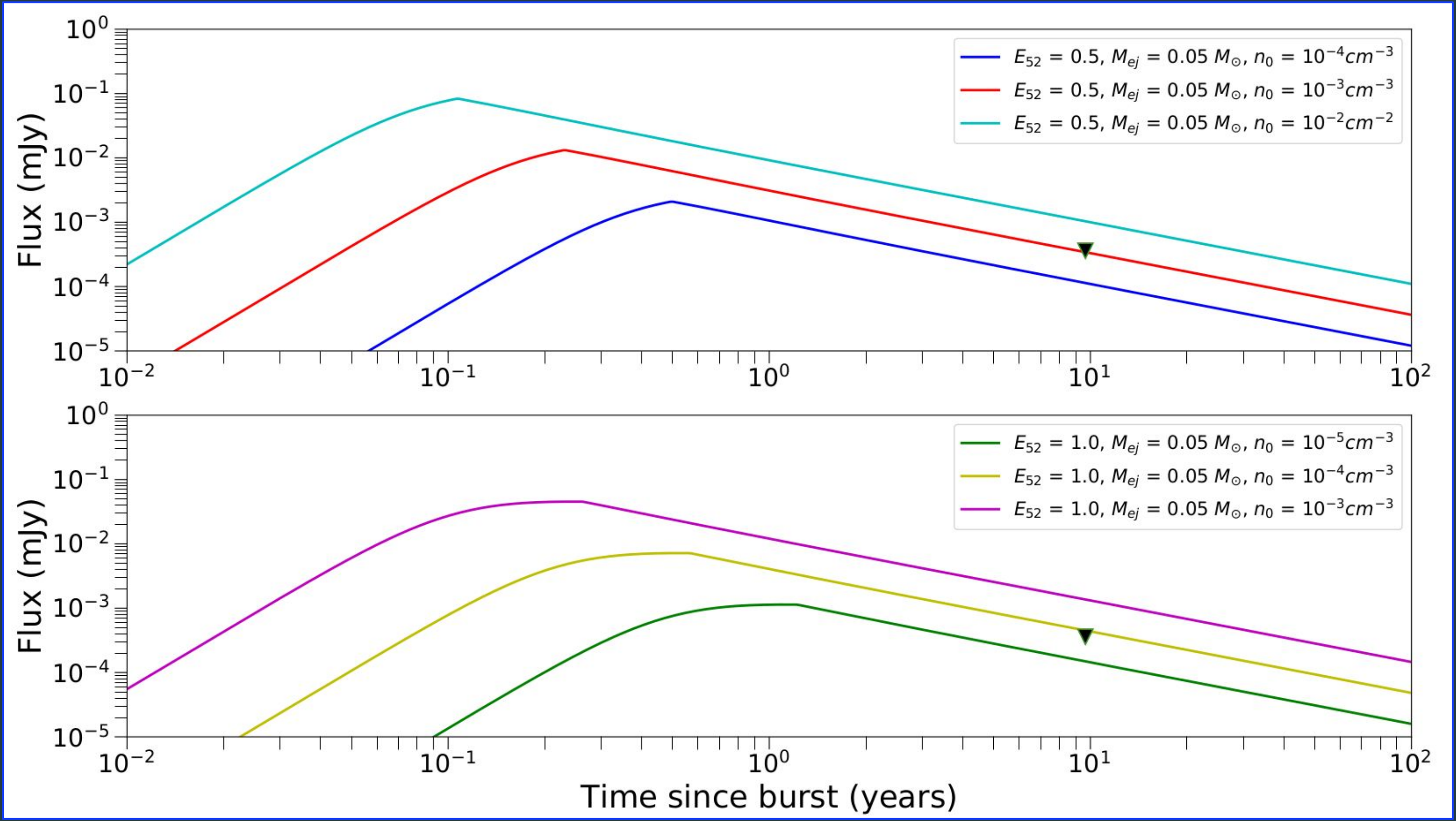


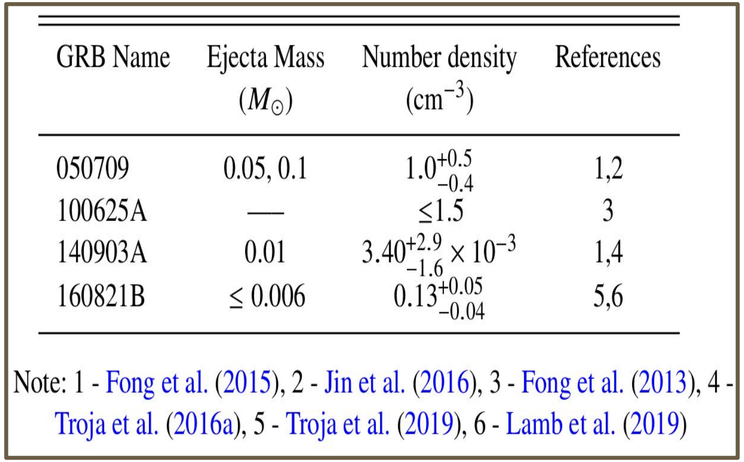
Allowed maximum rotational energy of a magnetar

$$t_{dec} \sim \frac{R_{dec}}{c\beta_0} \approx 1.2yr\left(\frac{E_{rot}}{10^{52}erg}\right)^{1/3}\left(\frac{n_0}{cm^{-3}}\right)^{-1/3}\beta_0^{-5/3}$$

$$F_{\nu,obs,pk} = 3mJy\left(\frac{E_{rot}}{10^{52}erg}\right)\left(\frac{n}{cm^{-3}}\right)^{0.83}\left(\frac{\epsilon_B}{0.1}\right)^{0.83}\left(\frac{\epsilon_e}{0.1}\right)^{1.3}\beta_0^{2/3}d_{28}^{-2}$$

- Parameter space plot has been constructed with different combination of rotational energy and number density of ambient medium.
- Maximum allowed energy estimation.
- Model flux < 3 sigma upper limit
  Allowed space

  Model flux > 3 sigma upper limit
  Forbidden space



GRB Name	Ejecta Mass ($M_\odot$)	Number density (cm^{-3})	References
050709	0.05, 0.1	$1.0^{+0.5}_{-0.4}$	1,2
100625A	—	≤ 1.5	3
140903A	0.01	$3.40^{+2.9}_{-1.6} \times 10^{-3}$	1,4
160821B	≤ 0.006	$0.13^{+0.05}_{-0.04}$	5,6

Note: 1 - Fong et al. (2015), 2 - Jin et al. (2016), 3 - Fong et al. (2013), 4 - Troja et al. (2016a), 5 - Troja et al. (2019), 6 - Lamb et al. (2019)

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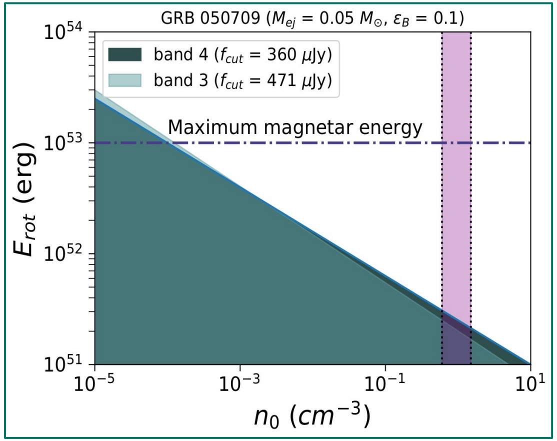

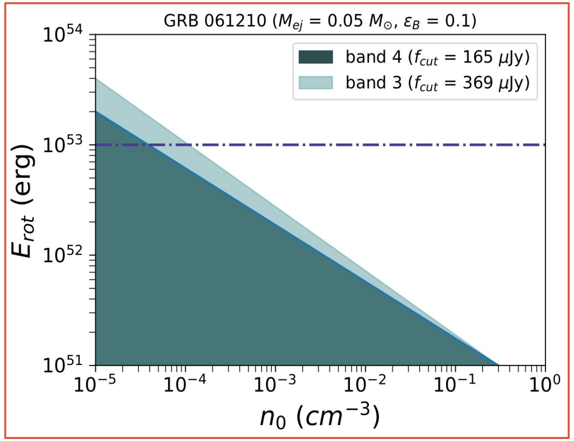

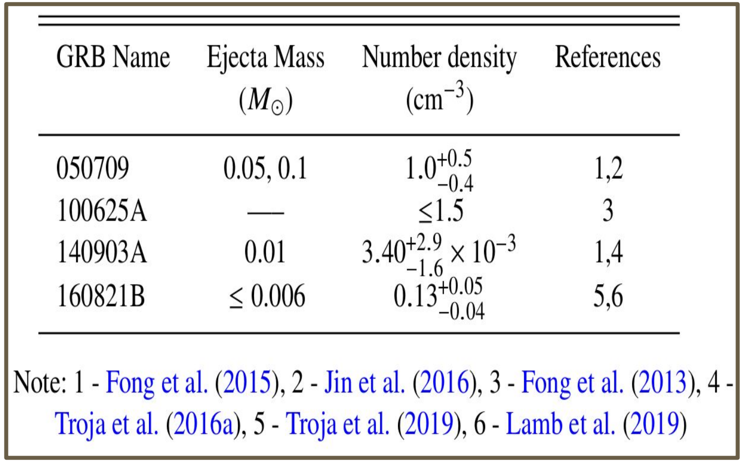

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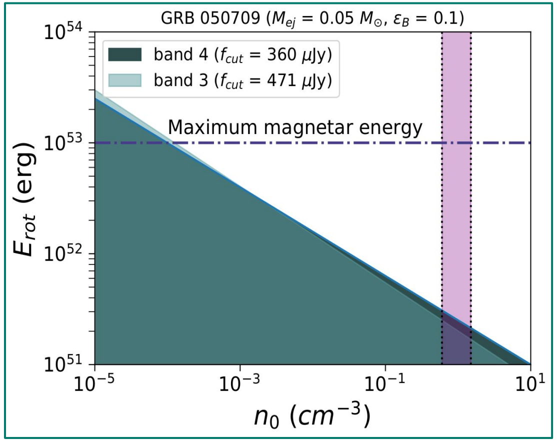

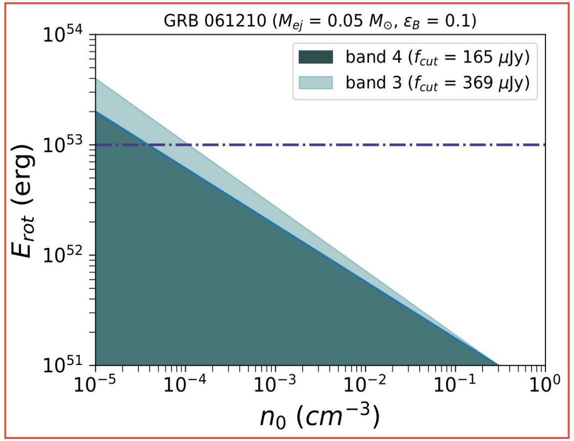

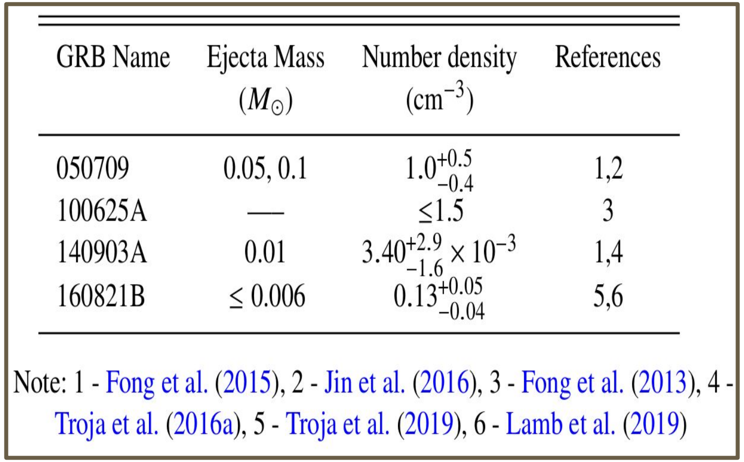

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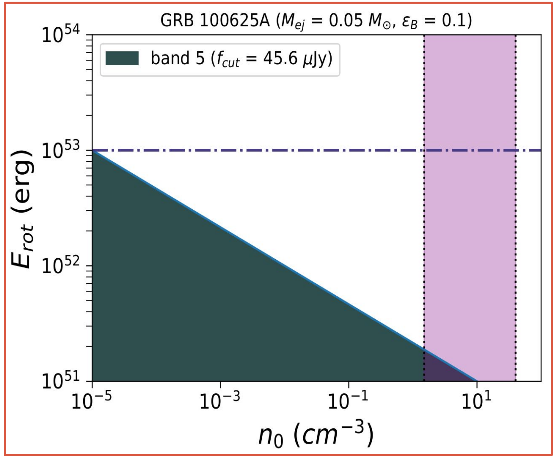
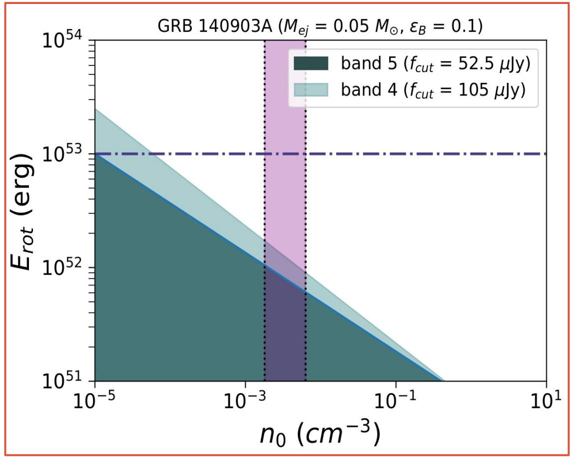
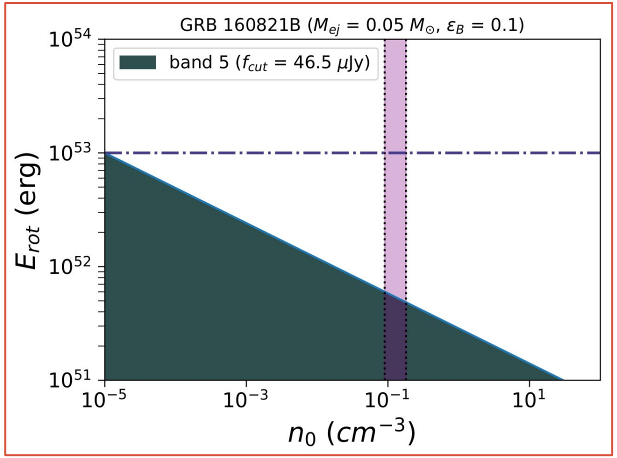






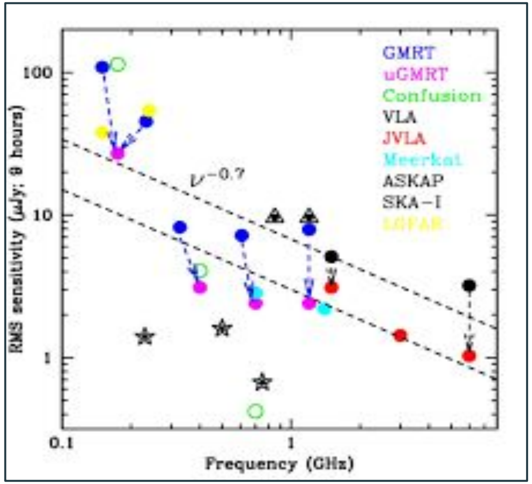
Summary

- ❑ The radio spectrum is expected to peak in MHz band with the deceleration time 2-10 years dependent on the ejecta mass, rotational energy of magnetar and ambient medium density.
- ❑ GMRT observations aimed at searching the signature of late time merger ejecta emission powered by a magnetar at 610, 325 MHz and 1.4 GHz.
- ❑ If the emission was detected, it could be the first ever detection of tidal ejecta in radio. But we found no late time emission at the x-ray afterglow location.
- ❑ null detection provided us stringent constraints on the magnetar rotational energy and ambient medium density.

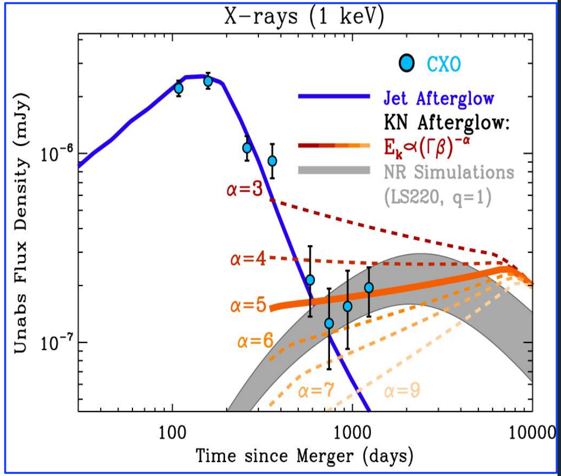
Future Prospect

❖ Square Kilometer Array (SKA - I) in lower frequencies will be highly beneficial for the observation of late time radio detection of merger ejecta.

1. RMS Sensitivity will be highly improved (muJy level).
2. Better angular resolution.



courtesy : Nissim Kanekar, NCRA)



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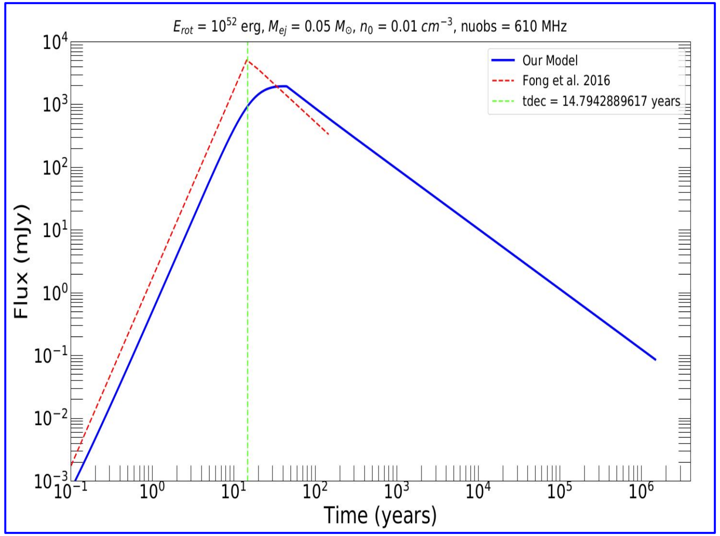
THANK YOU

For your attention

For more information: https://academic.oup.com/mnras/article/527/3/8068/7475893

Comparison with Previous Studies

	Our work	Horesh et al. 2016	Fong et al. 2016	Metzger & Bower 2014	Nakar & Piran 2011
Time of observation since burst	2-11	1-6	3-5	1-3	Theoretical
Observed Frequency	GMRT 610 MHz,325MHz , 1.4 GHz	VLA 3 GHz, ATCA 2.1 GHz	VLA 6 GHz	VLA 3 GHz	Theoretical
Energy injection from magnetar	Y	Y	Y	Y	N
Synchrotron frequencies	Y	Y	Y	Y	Y
Doppler effect	Y	Y	N	N	N
Non-relativistic transition	Y	N	N	N	N



Most energetic explosion in the Universe

Gamma-Ray Bursts ???

Energy in a blink: How powerful GRBs are?

A window
to the
extraordinary & extreme Universe