NCfA

Magnetars as the engine of GRBs and FRBs

Bing Zhang

Nevada Center for Astrophysics
University of Nevada, Las Vegas

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桃花源记
——陶渊明 (东晋)

The Peach Colony
(A prose by TAO Yuanming from Jin Dynasty)

（The Dream Field)

初极狭，才通人；复行数十步，豁然开朗。

At first the opening was very narrow, barely wide enough for one person to go in. After a dozen steps, it opened into a flood of light.

桃花源记
——陶渊明 (东晋)

The Peach Colony
(A prose by TAO Yuanming from Jin Dynasty)

（The Dream Field)

土地平旷，屋舍俨然。阡陌交通，鸡犬相闻。

He saw before his eyes a wide, level valley, with houses and fields and farms (and chikens and dogs).

桃花源记
——陶渊明 (东晋)

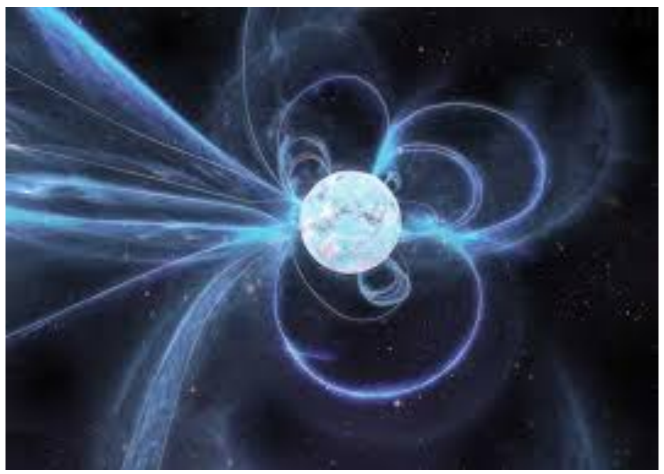
The Peach Colony
(A prose by TAO Yuanming from Jin Dynasty)

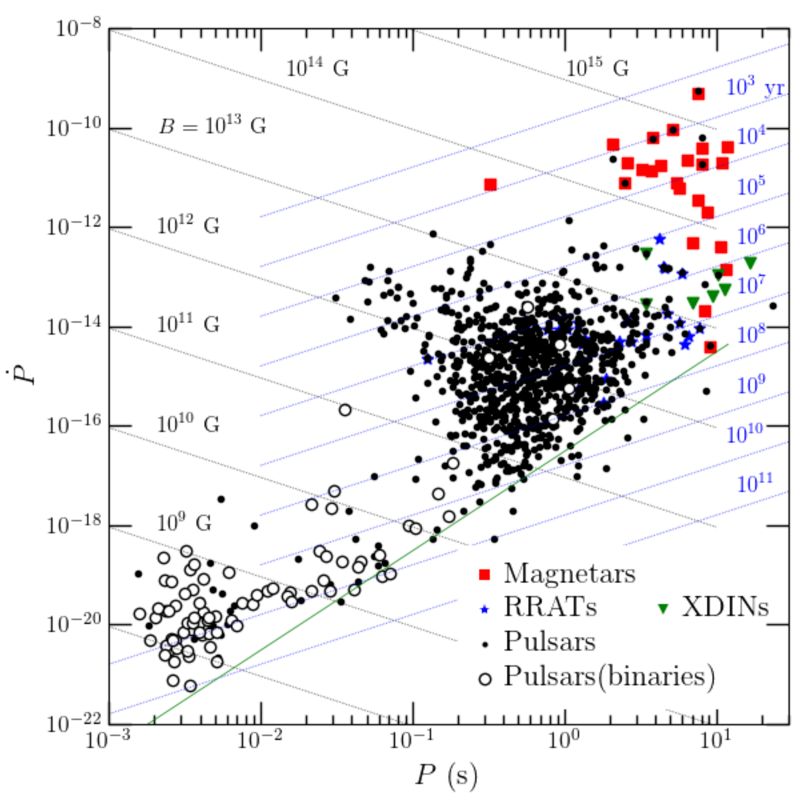
（The Dream Field)

男女衣着，悉如外人；黄发垂髫，并怡然自乐。

The dresses of the men and women were like those of the outside world, and the seniors and youngsters all appeared very happy and contented.

Magnetars

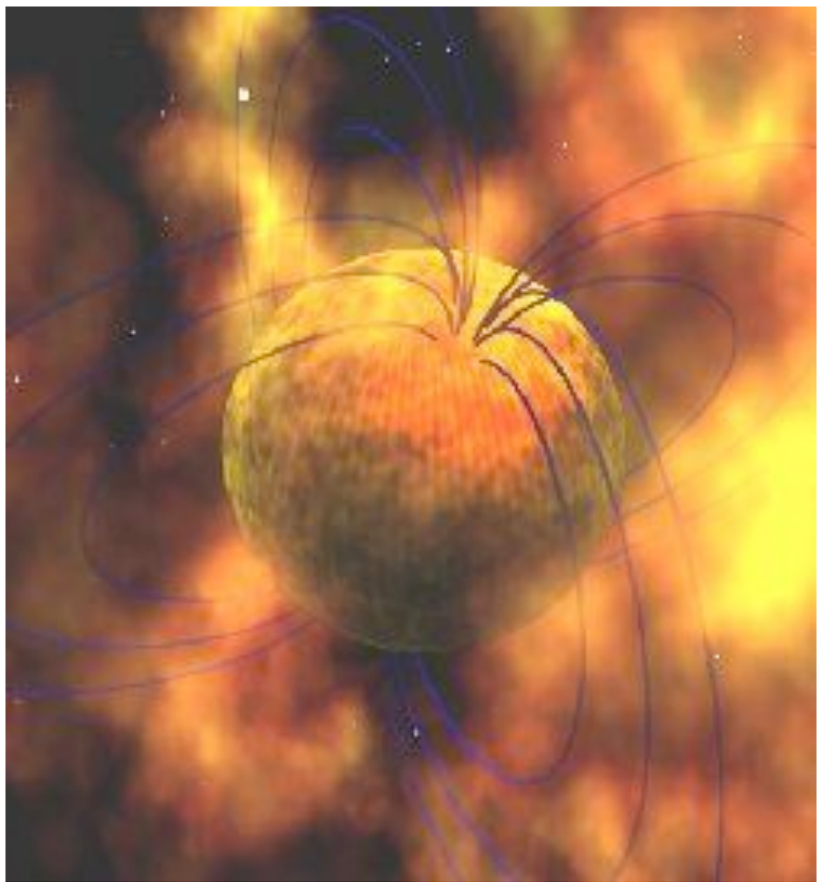


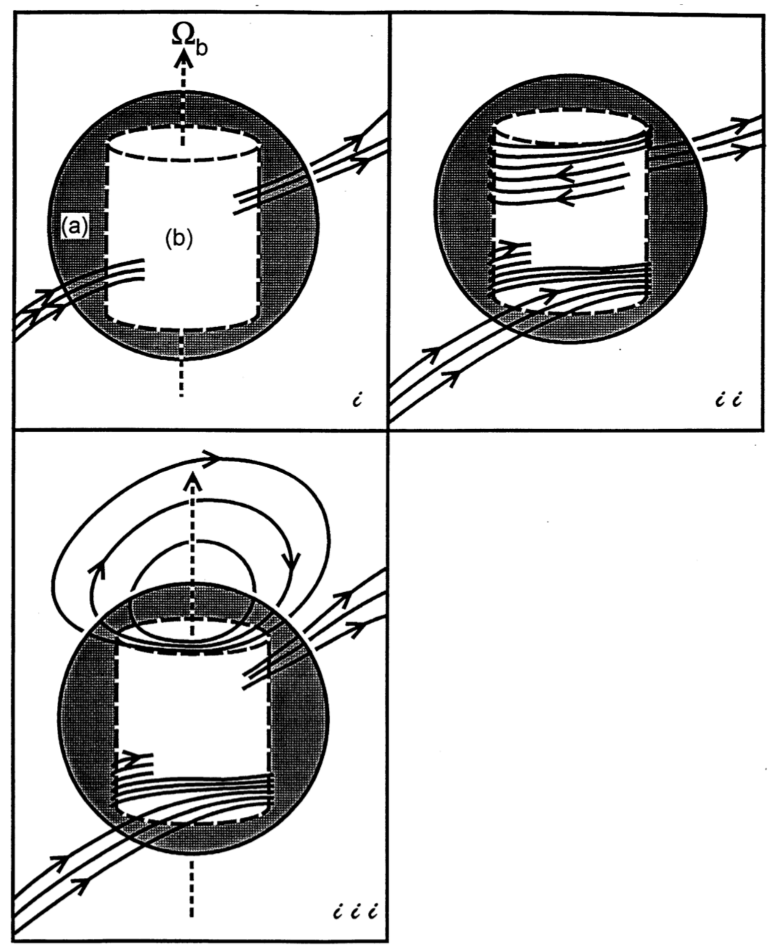


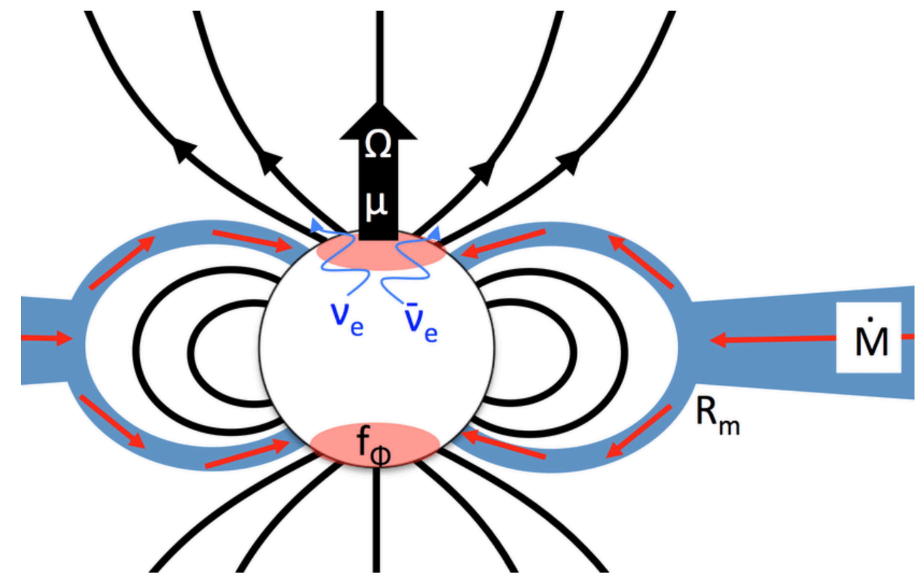
- Neutron stars with superstrong surface magnetic field strength ($B_p > 10^{14}$ G)
- Known magnetars:
  - Soft gamma-ray repeaters (SGRs)
  - Anomalous X-ray pulsars (AXPs)
  - Source of the Galactic FRB 20200428A (SGR 1935+2154)
  - 30 currently known, 16 SGRs, 14 AXPs
  - Slow: $P \sim (1.36 - 11.79)$ s
- Imaginary magnetars (millisecond magnetars):
  - One of the leading channels of forming magnetars
  - Imaginary central engine for gamma-ray bursts (GRBs), superluminous supernovae (SLSNe), and fast blue optical transients (FBOTs), …

Millisecond magnetars as engine of GRBs

Three ways of making a GRB from a magnetar







Usov 1992

Spin down

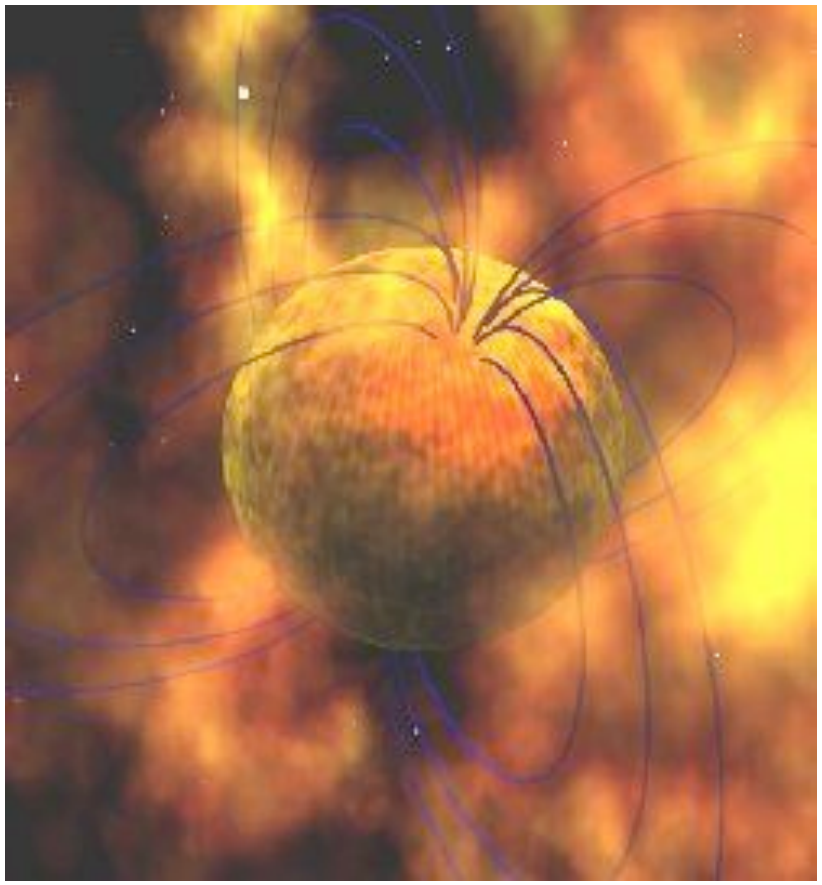
Kluzniak & Ruderman 1998

Differential rotation

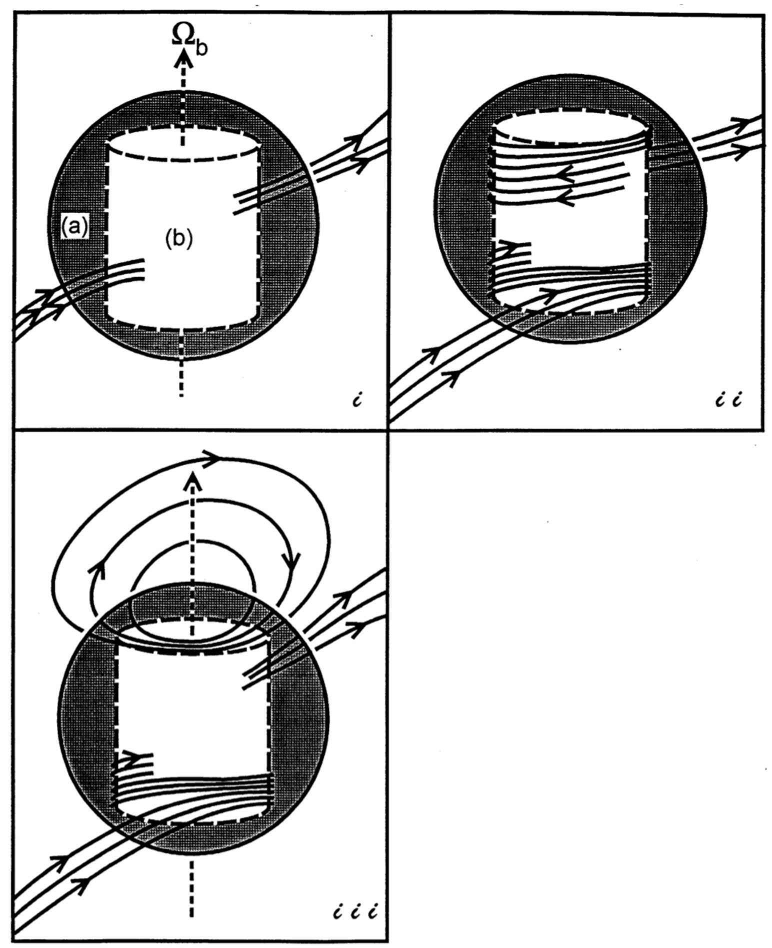
Metzger et al. 2018

Accretion

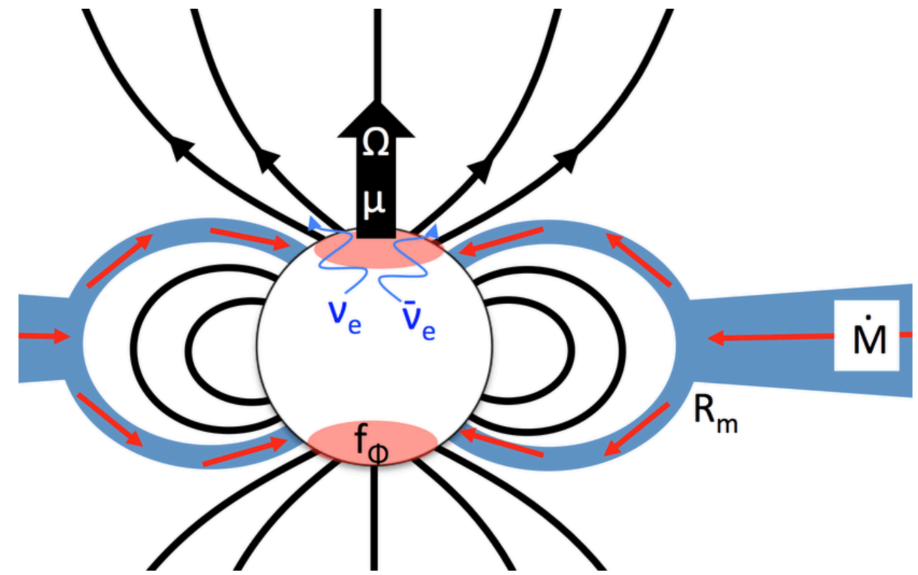
Three ways of making a GRB from a magnetar



Usov 1992



Kluzniak & Ruderman 1998

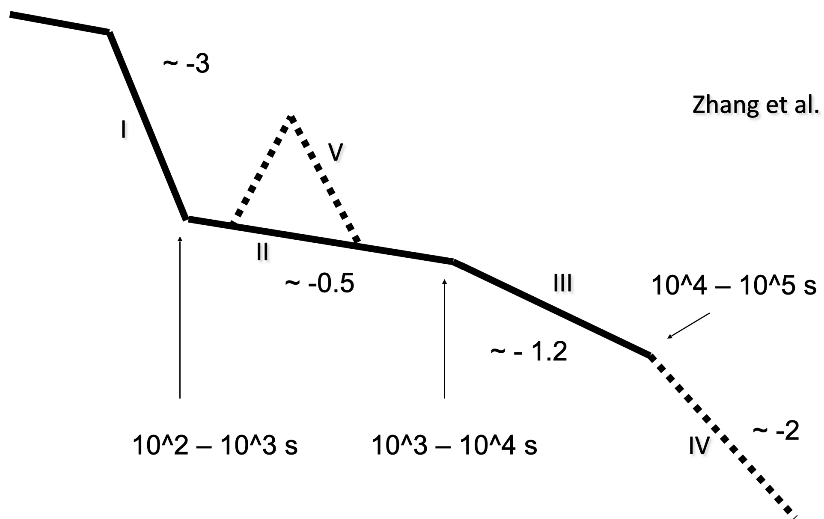


Metzger et al. 2018

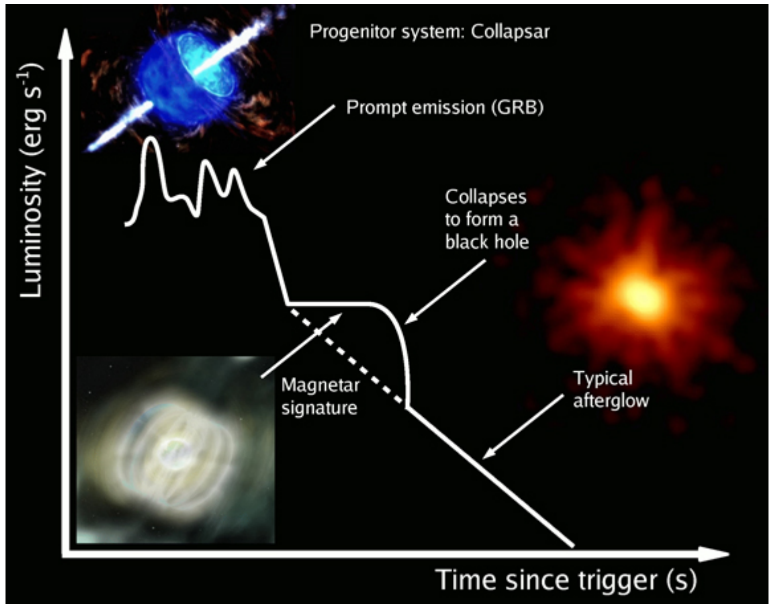
Nonetheless gives afterglow signatures

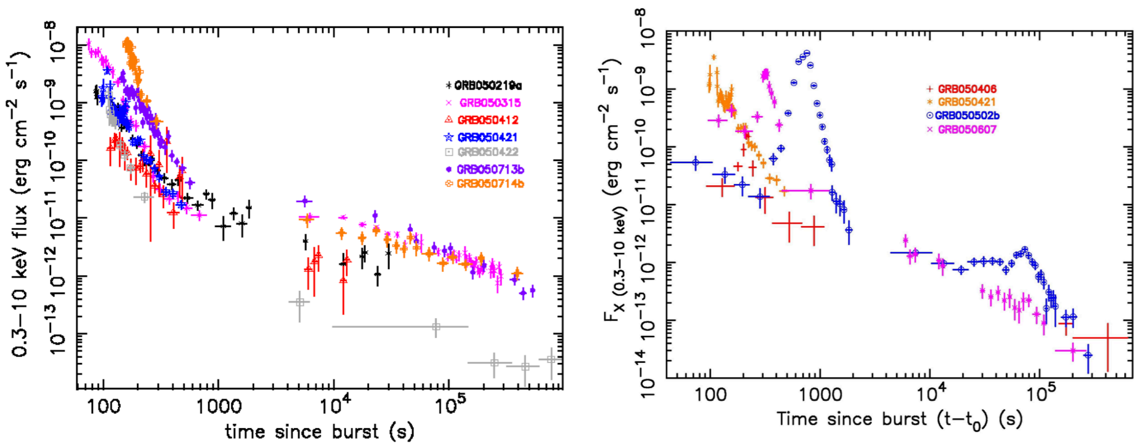
Magnetar signature:
Energy injection due to spindown

(Dai & Lu 1998; Zhang & Meszaros 2001 …)

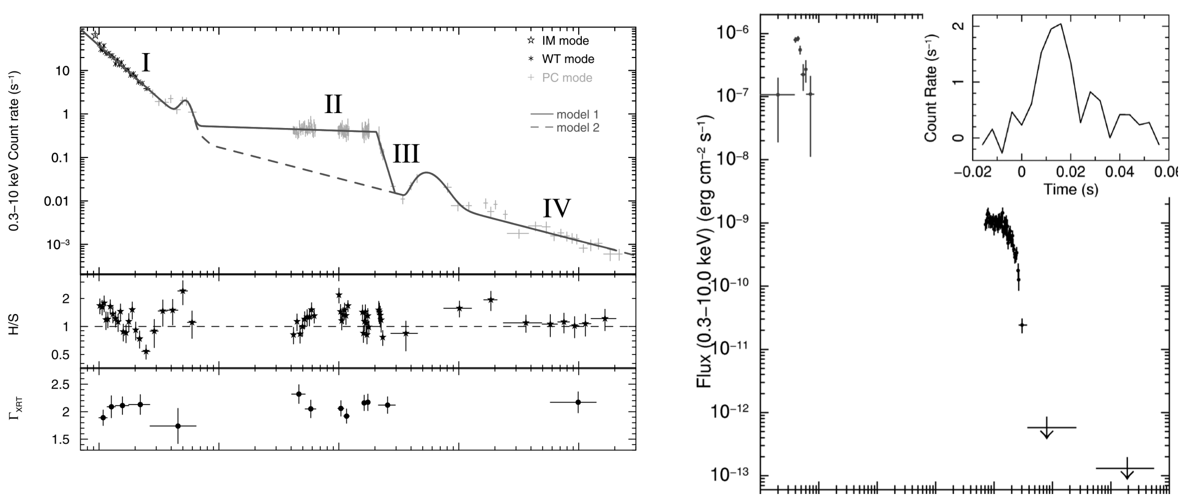


Zhang et al. (2006)





Nousek et al. 2006



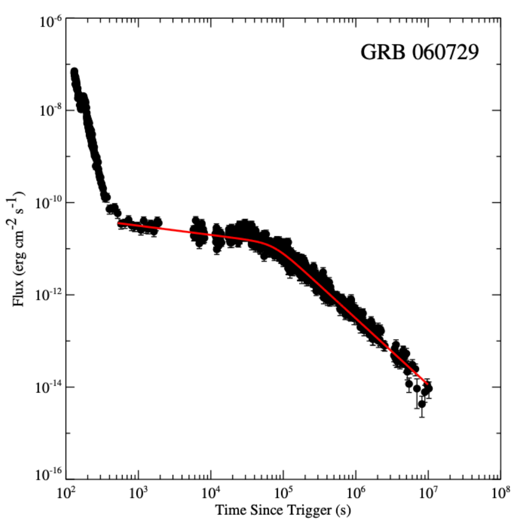
Troja et al. 2007; Lyons et al. 2010; Rowlinson et al. 2010

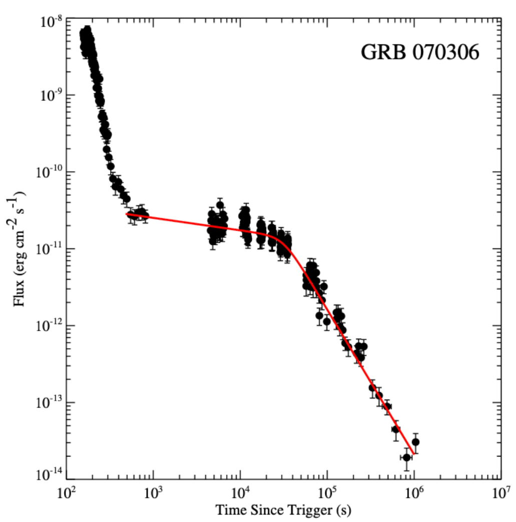
External plateaus

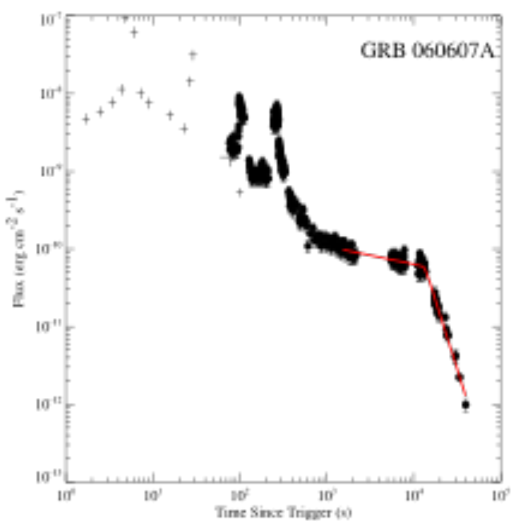
“Internal” plateaus

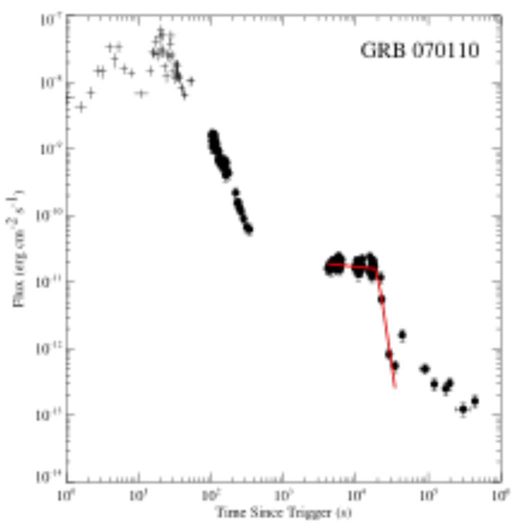
Consistent vs. Demanded

- Is a magnetar engine demanded?
  - external plateau:
    - Energy injection (Engine or Gamma distribution)
    - Many other possibilities (geometric, wind medium, evolution of parameters, dust …)
  - internal plateau:
    - “smoking gun” signature of a long-lived engine
    - Can a BH engine do it?









Lü & Zhang 2014, ApJ, 785, 74

How to tell Magnetars from black holes?

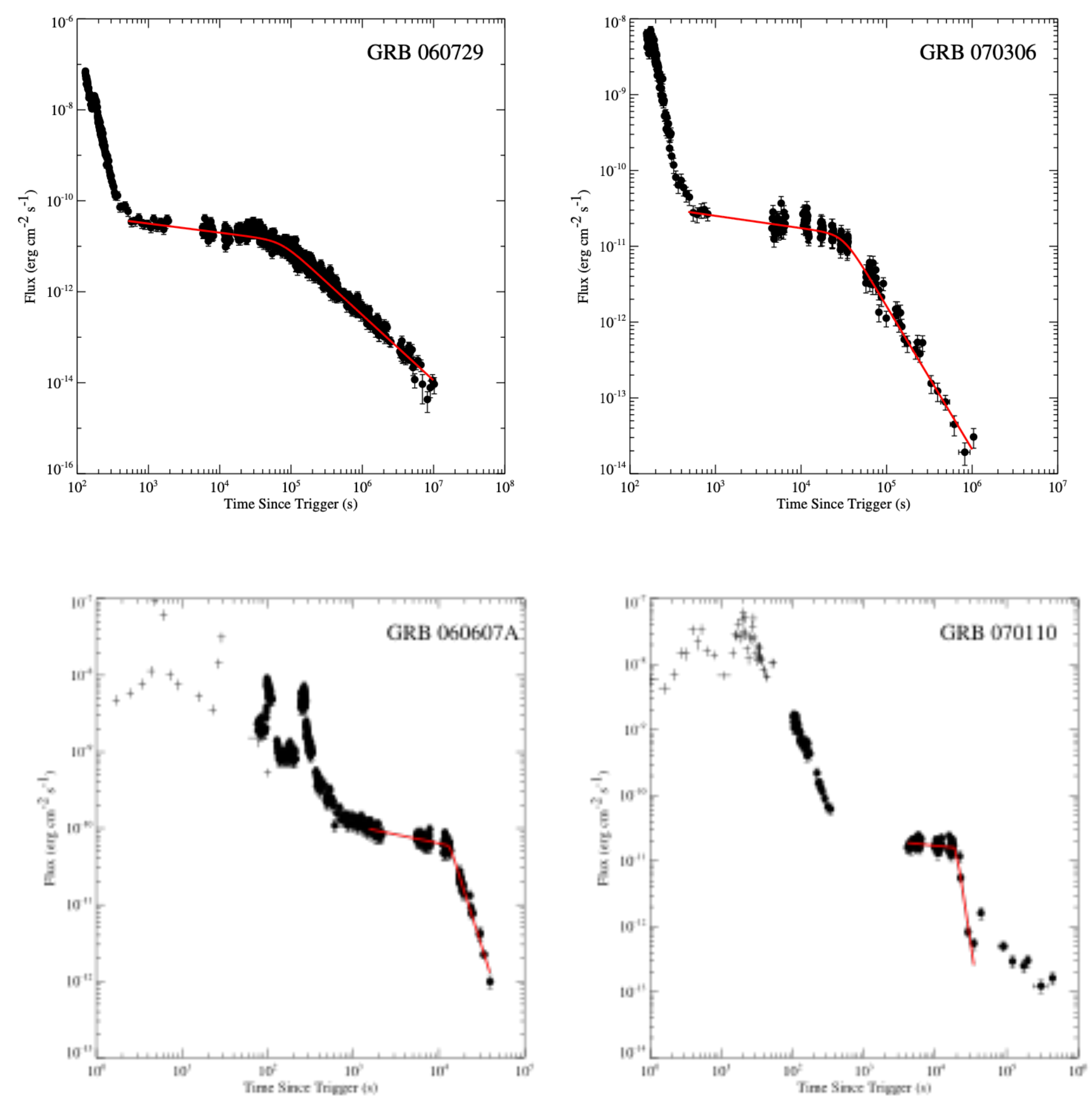
- Anti-correlation between L and τ
- A maximum total energy limited by the initial spin energy of the magnetar
  - Need to account for both prompt emission and afterglow energy
  - Need to know the beaming angle to derive a beaming-corrected energy

$$E_{\rm rot} = \frac{1}{2} I \Omega_0^2 \simeq 2 \times 10^{52}\,{\rm erg}\, M_{1.4} R_6^2 P_{0,-3}^{-2},$$

$$L(t) = L_0 \frac{1}{(1+t/\tau)^2} \simeq \begin{cases} L_0, & t \ll \tau, \\ L_0 (t/\tau)^{-2}, & t \gg \tau. \end{cases}$$

$$L_0 = 1.0 \times 10^{49}\,{\rm erg\,s^{-1}} (B_{p,15}^2 P_{0,-3}^{-4} R_6^6)$$

$$\tau = 2.05 \times 10^3\,{\rm s} (I_{45} B_{p,15}^{-2} P_{0,-3}^2 R_6^{-6})$$

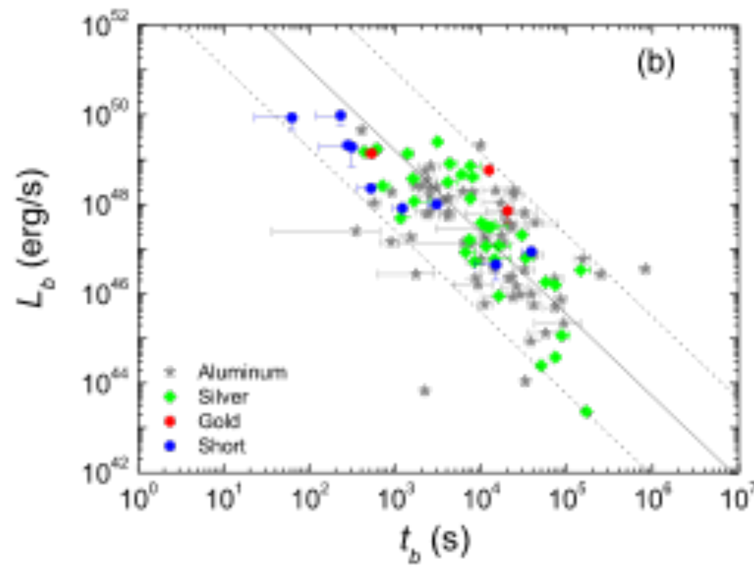


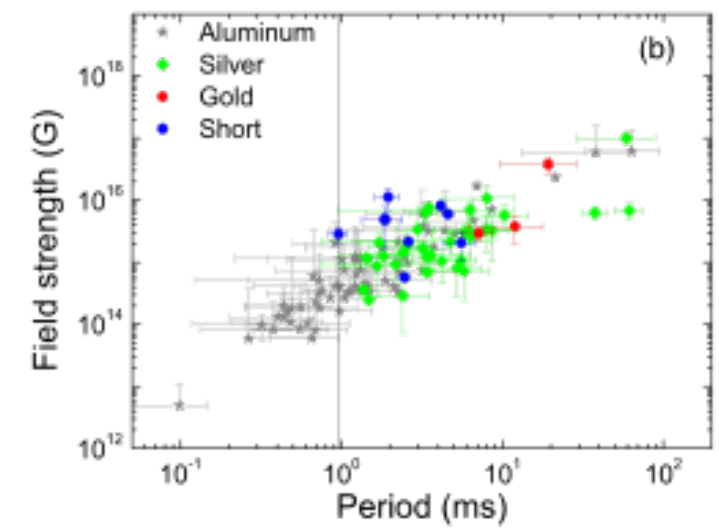
Lü & Zhang 2014, ApJ, 785, 74

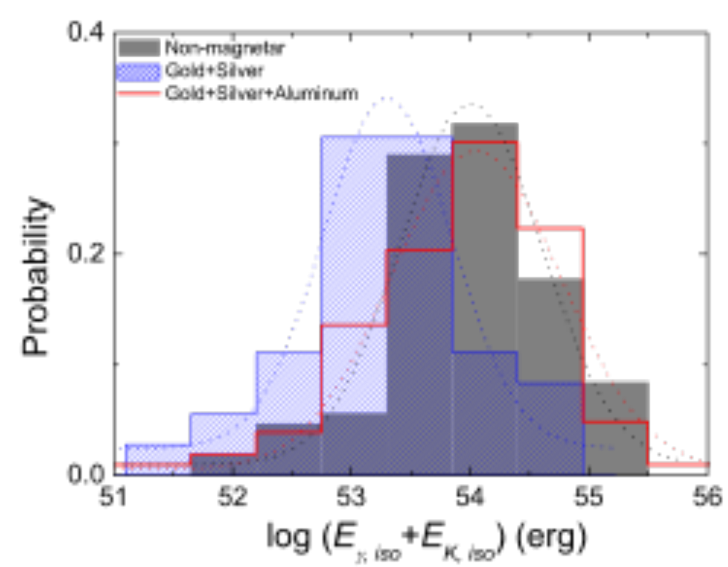
Millisecond magnetars in long GRBs

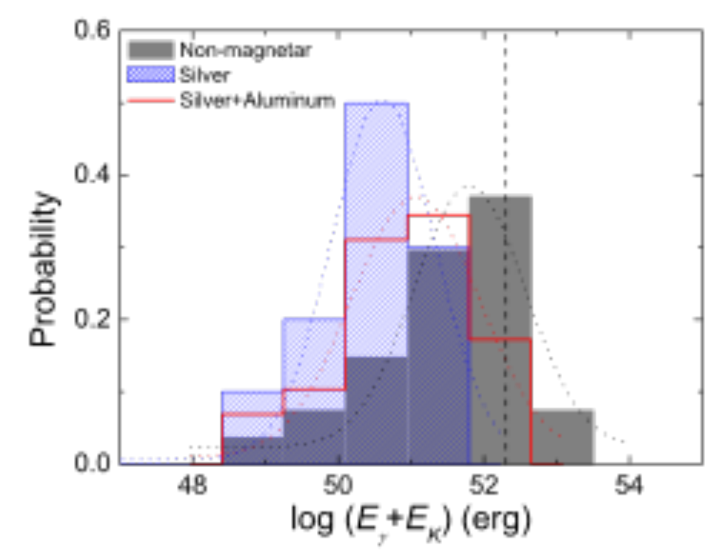
Lü & Zhang 2014, ApJ, 785, 74

- 750 Swift GRBs detected before Dec. 2013
- Gold sample (internal plateaus): 9 altogether, 3 with redshifts
- Silver sample (external plateaus satisfying magnetar criteria): 69 altogether, 33 with redshifts
- Aluminum sample (other external plateaus): 135 altogether, 67 with redshifts
- Non-magnetars (no evidence): over 400, 111 with redshifts









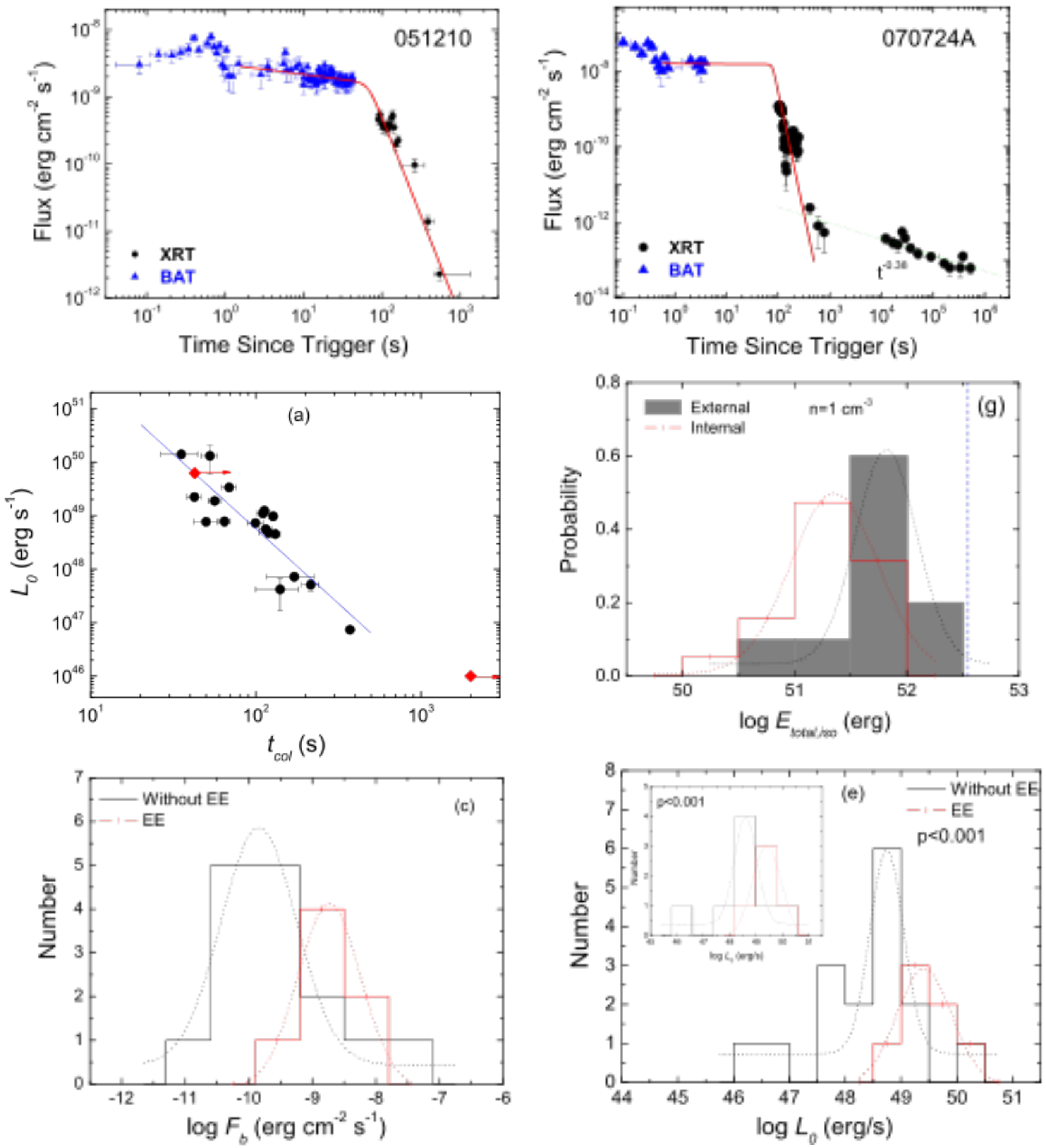
Up to ~ 1/3 of all Swift long GRBs may have a magnetar engine

Millisecond magnetars in short GRBs

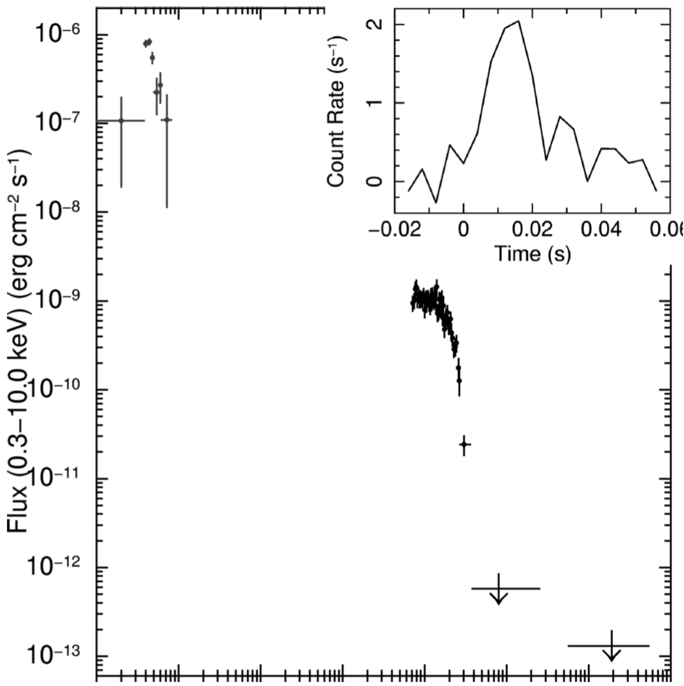
Lü et al. 2015, ApJ, 805, 89

- 40 Swift short GRBs or short GRBs with extended emission (EE), Jan. 05 – Aug. 14
- 22 internal plateaus!
- 10 external plateaus
- 8 without plateau

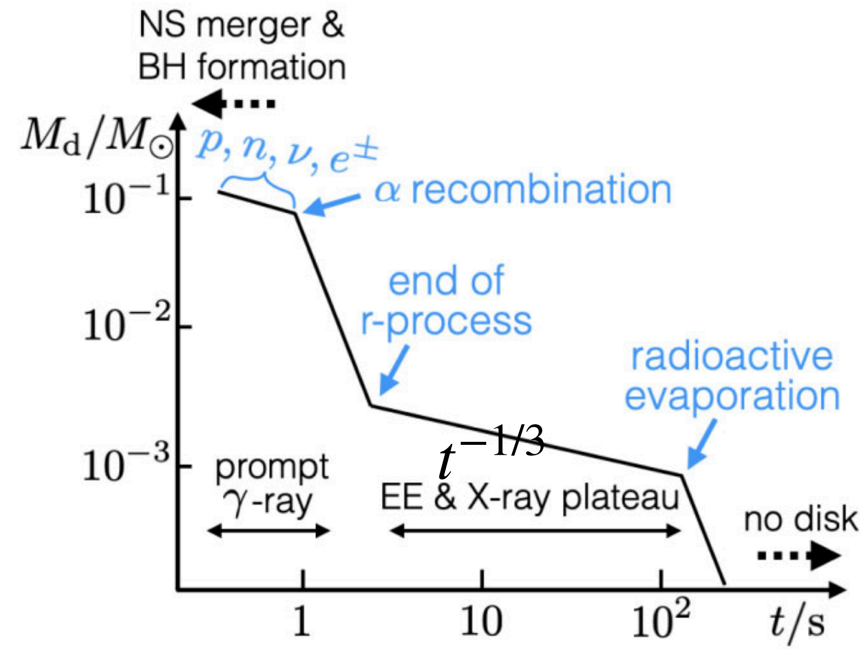
- EE and internal plateaus are the same thing!
- The prevalence of the internal plateau likely a result of low medium density



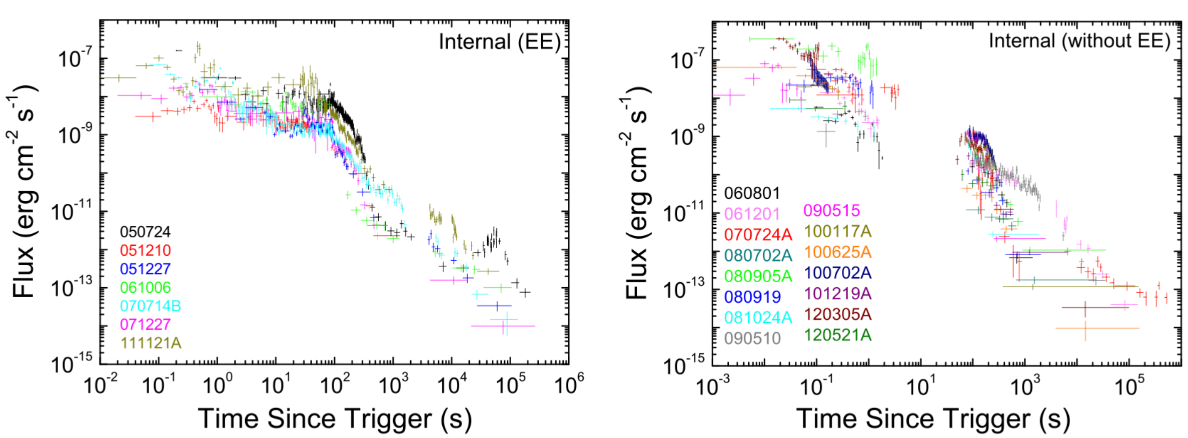
Magnetar engine from NS-NS mergers?
Can a BH engine do it?



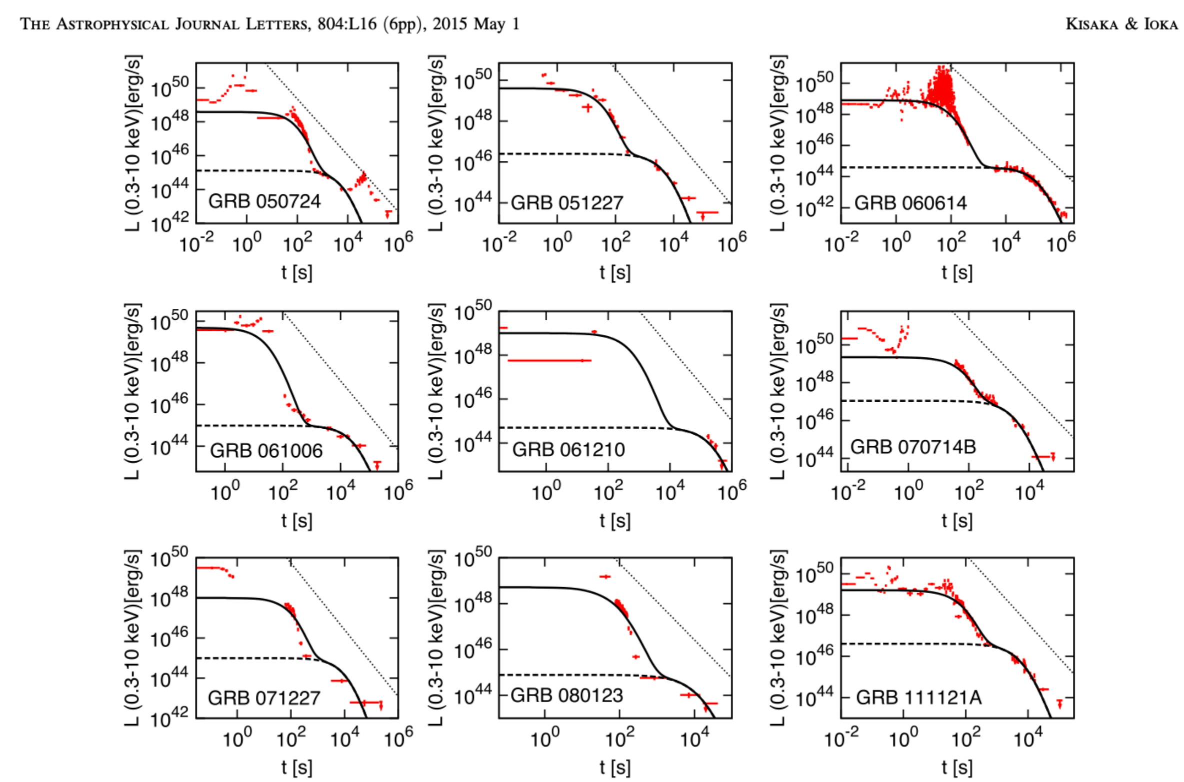
Rowlinson et al. (2010)



Lu & Quataert (2023)



Lü et al. (2015)

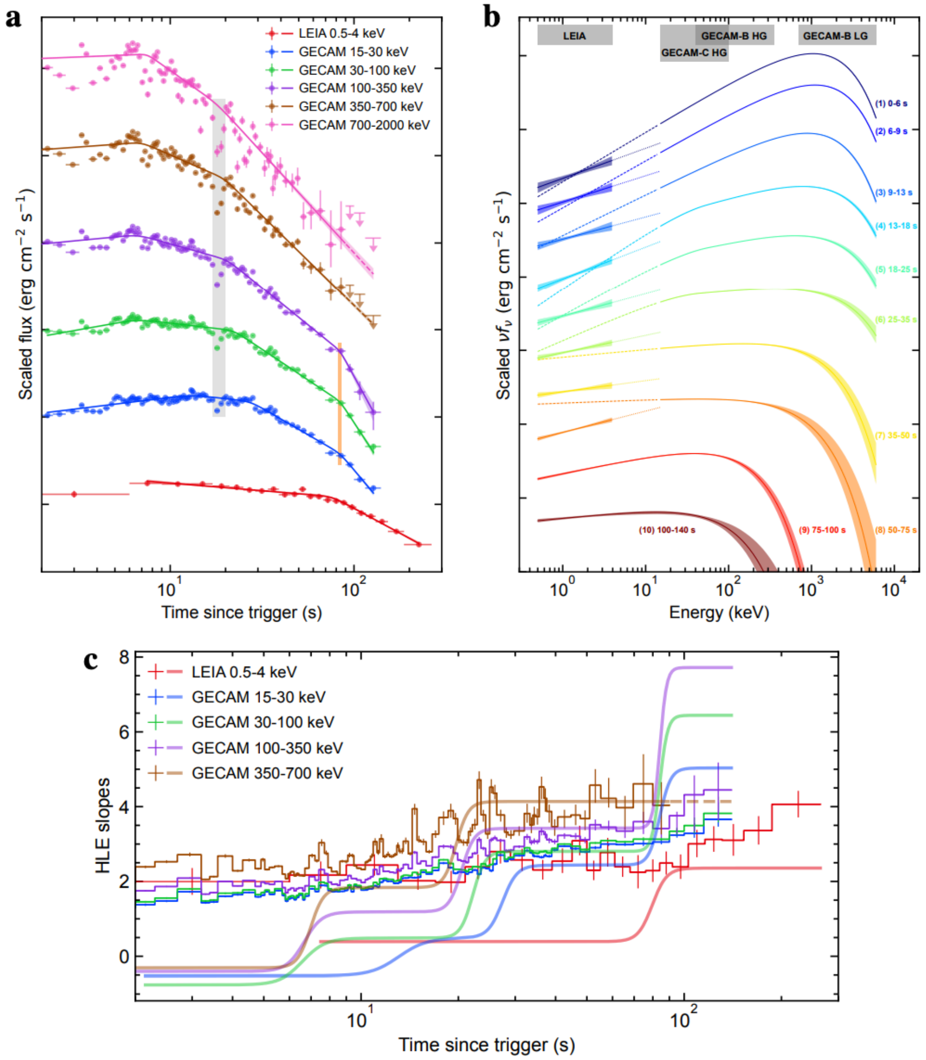


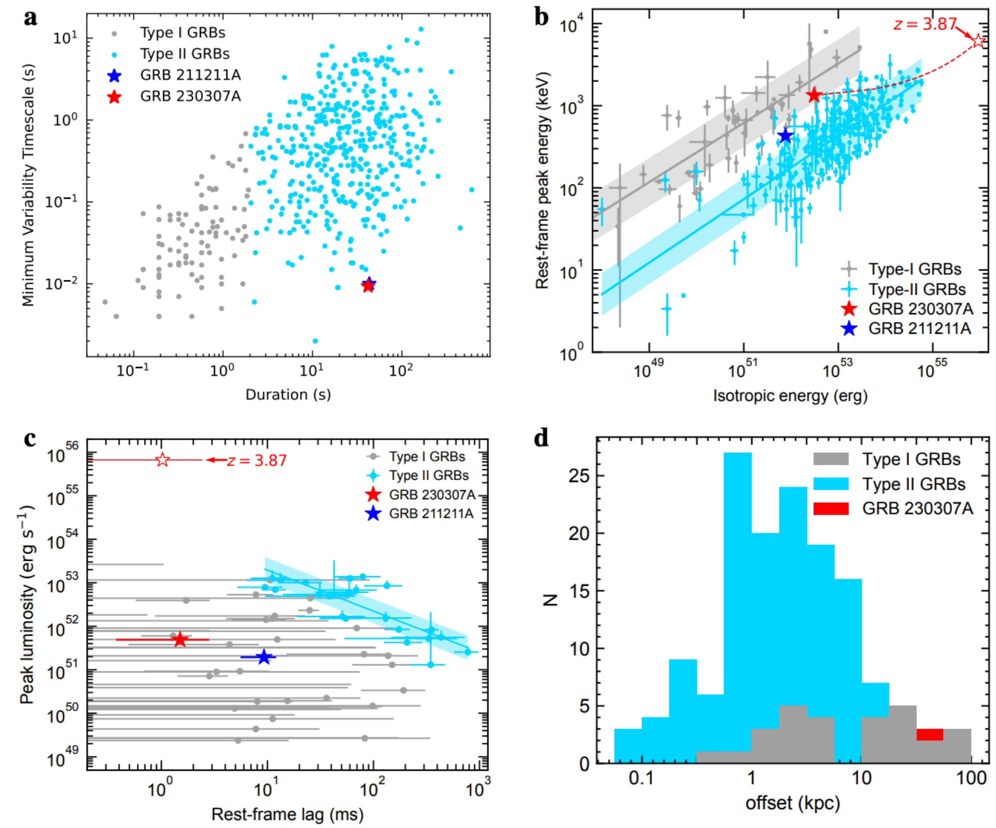
Kisaka & Ioka (2015)

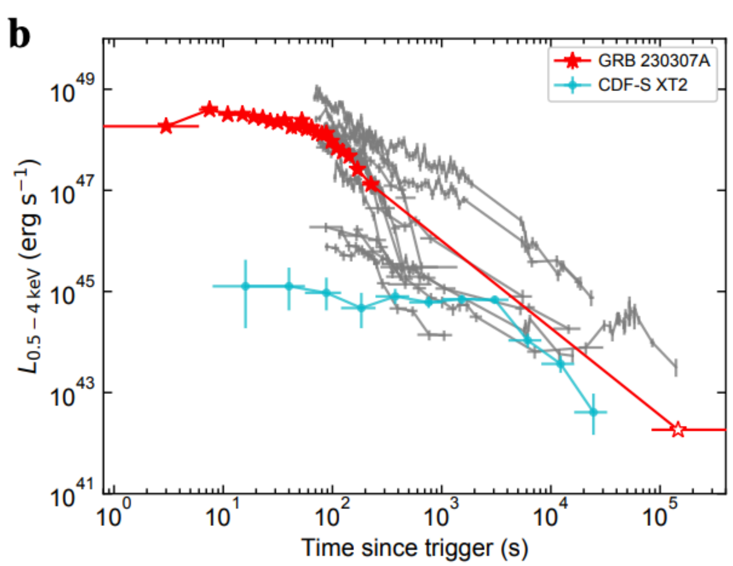
Evidence

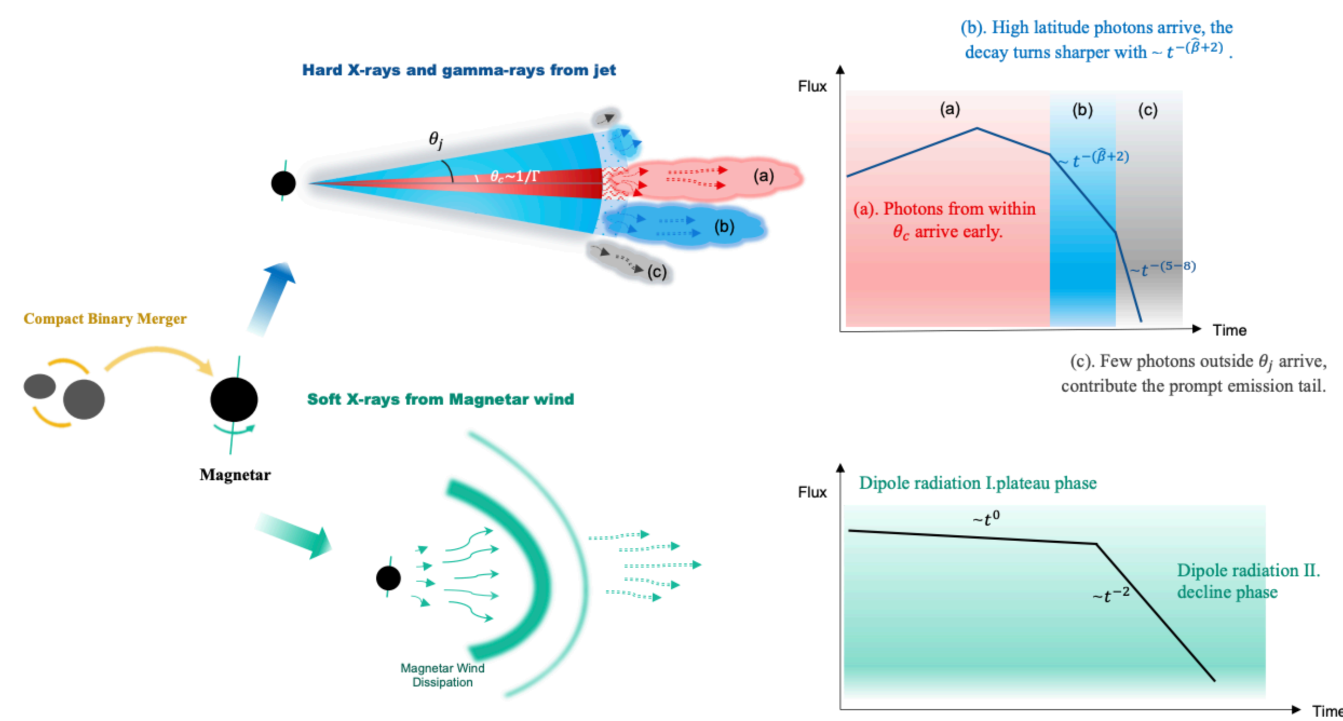
Smoking gun: GRB 230307A

Sun et al. arXiv:2307.05689

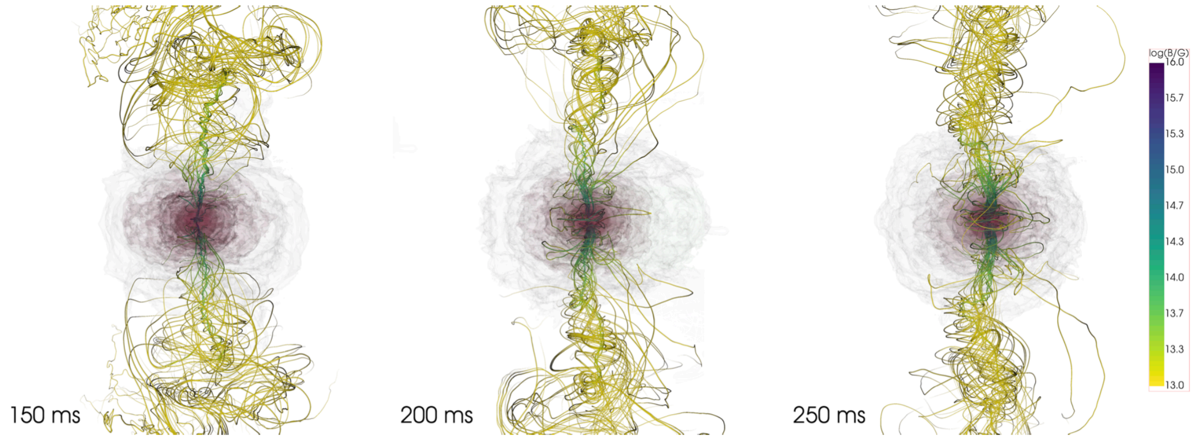








Magnetar engine from NS-NS mergers?
Theoretical difficulty: I. Can a relativistic jet be launched?

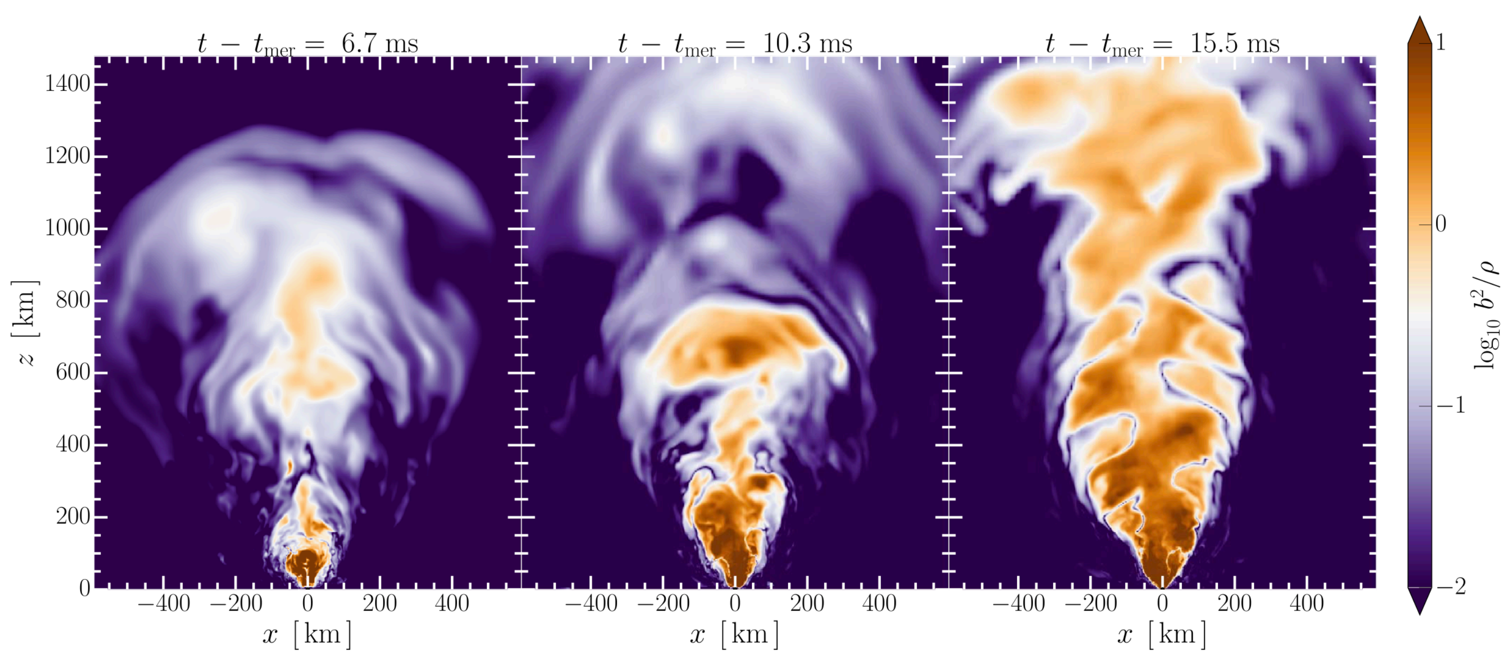


Magnetically collimated outflow but not a short GRB jet yet (heavy baryon loading)

Ciolfi (2020)

Most & Quataert (2023)

Bamber et al. (2024)

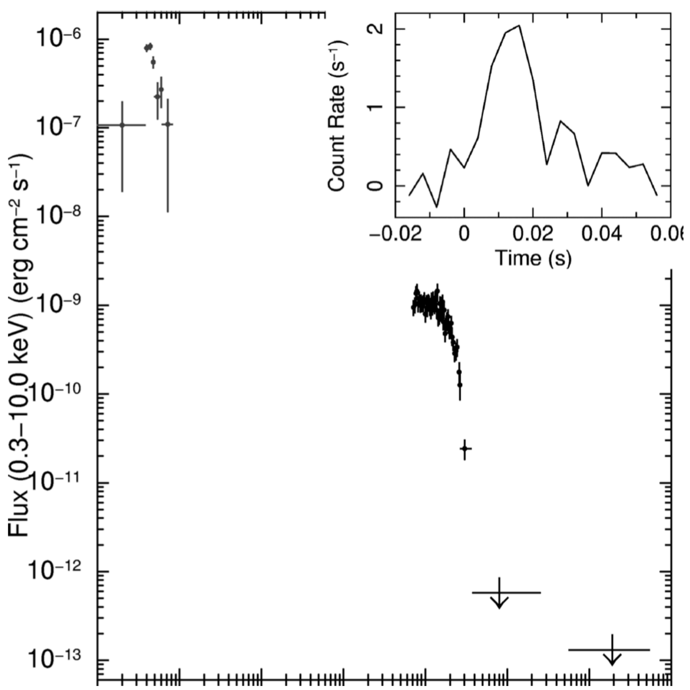


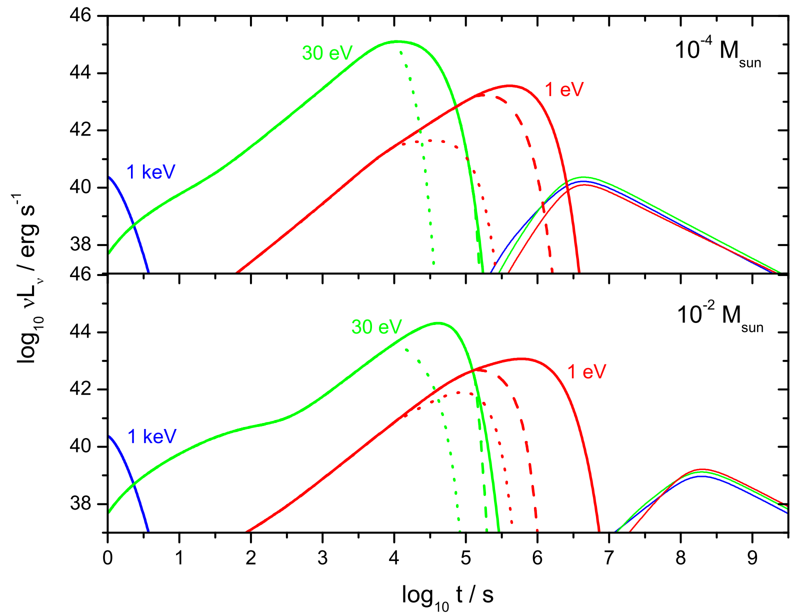
Difficulty & Encouragement

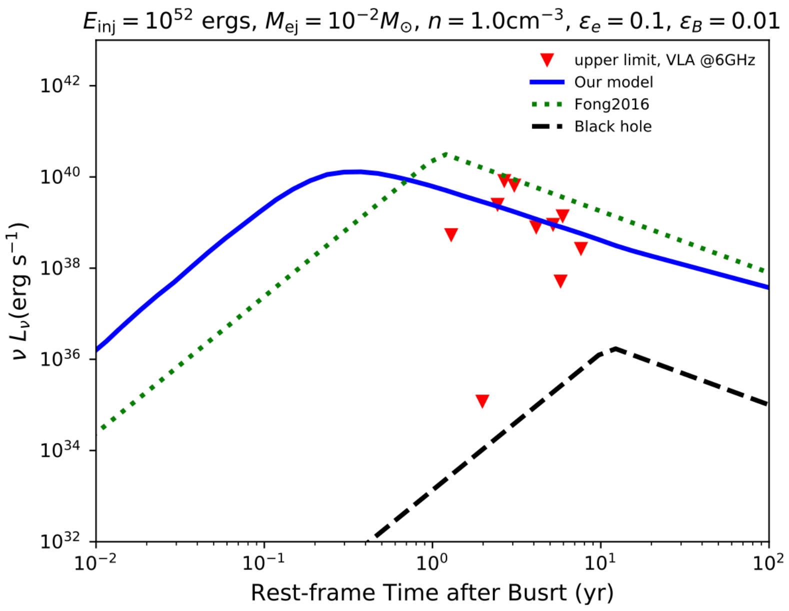
Magnetar engine from NS-NS mergers?
Theoretical difficulty: II. Missing energy

$$E_{\rm rot} = \frac{1}{2} I \Omega_0^2 \simeq 2 \times 10^{52}\,{\rm erg}\, M_{1.4} R_6^2 P_{0,-3}^{-2},$$

Where does the energy go?

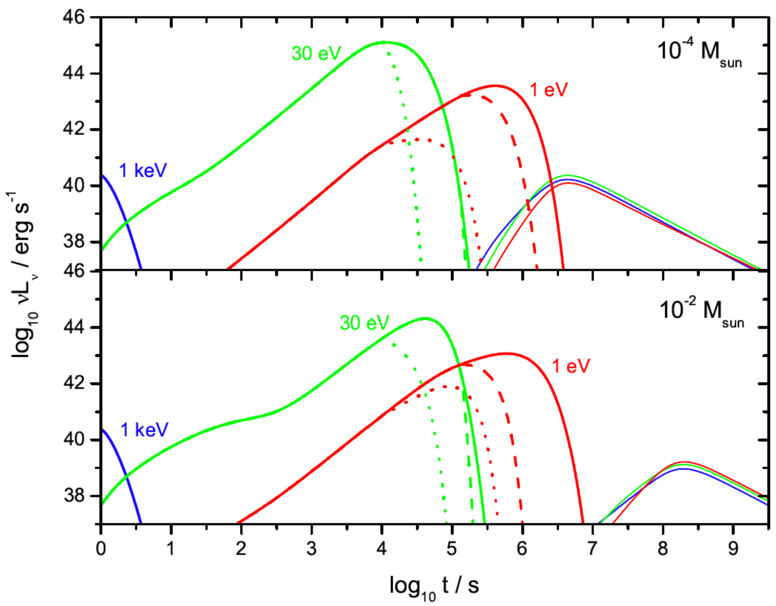


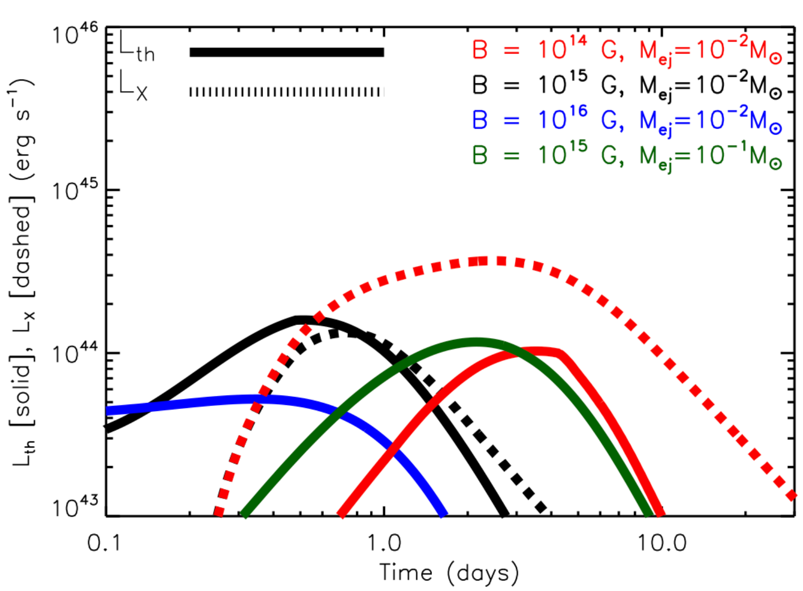


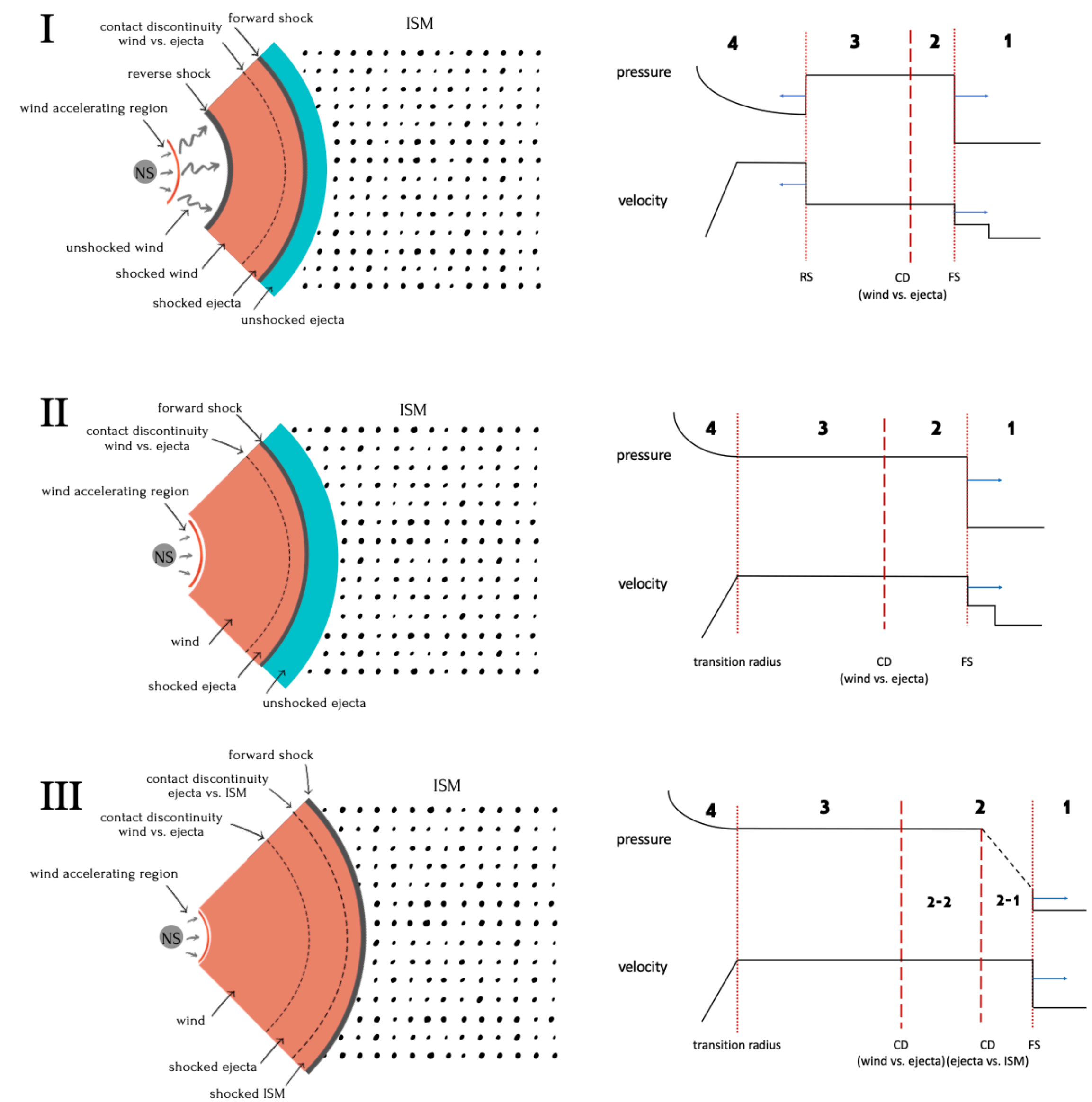


SGRB and plateau energy < 10^52. Predicted engine-driven kilonova too bright? Predicted radio afterglow too bright?

Engine-fed kilonova (mergernova)



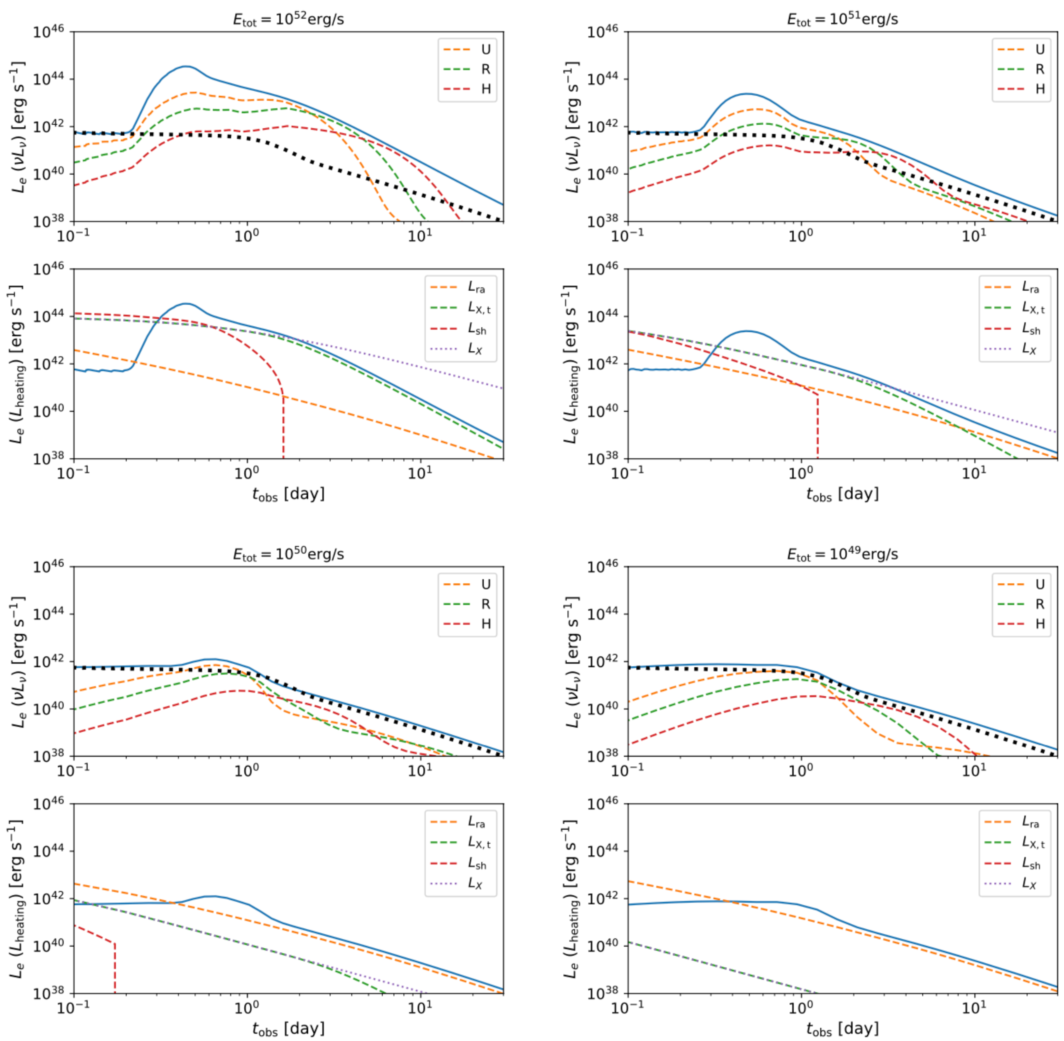




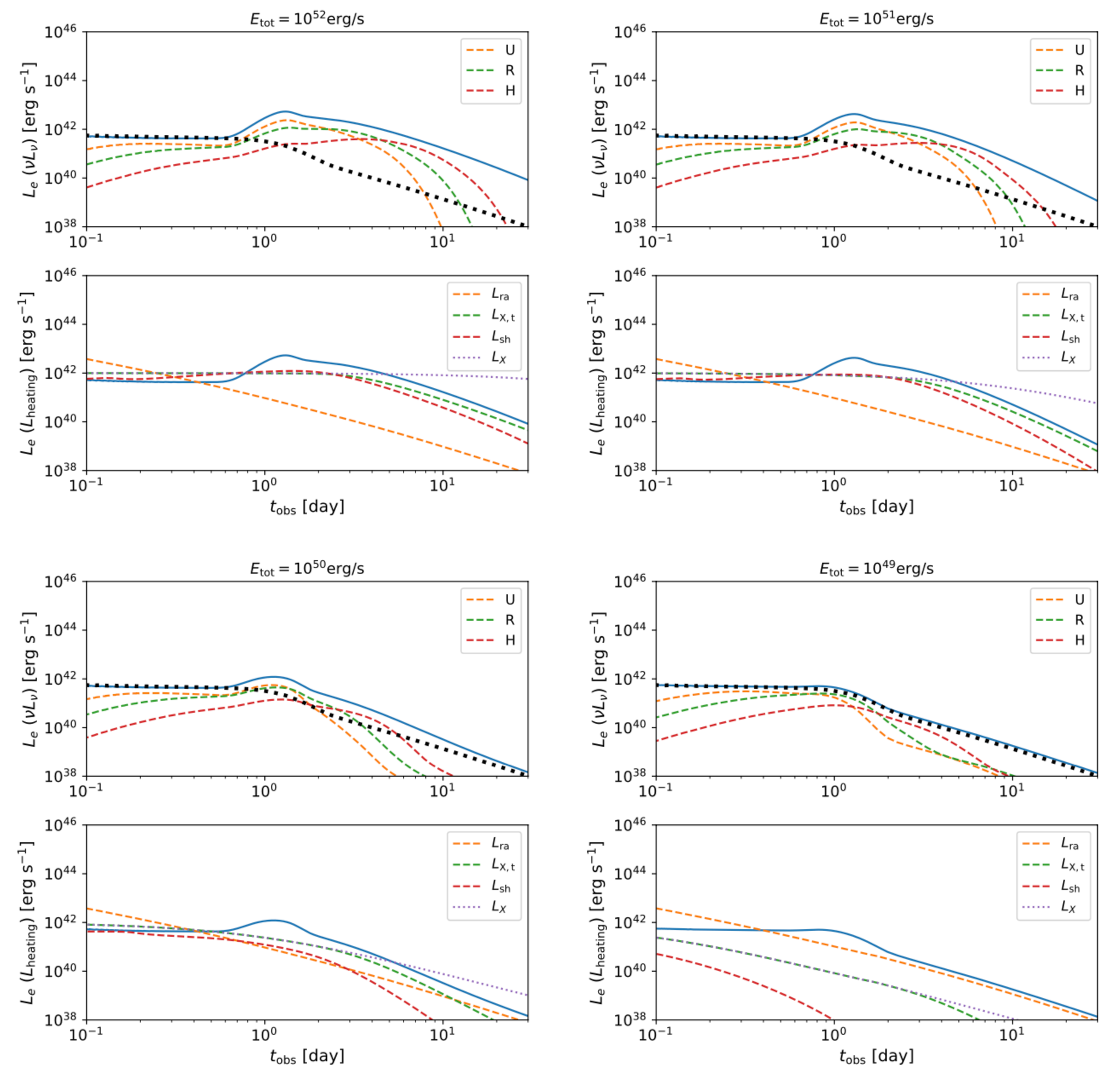
Efficient ejecta heating only happens before forward shock crossing

Yu, Zhang, Gao 2013, ApJL, 776, L40; Metzger & Piro, 2014, MNRAS, 439, 3916
Ai, Zhang & Zhu, 2022, MNRAS, 516, 2614

Engine-fed kilonova (mergernova)



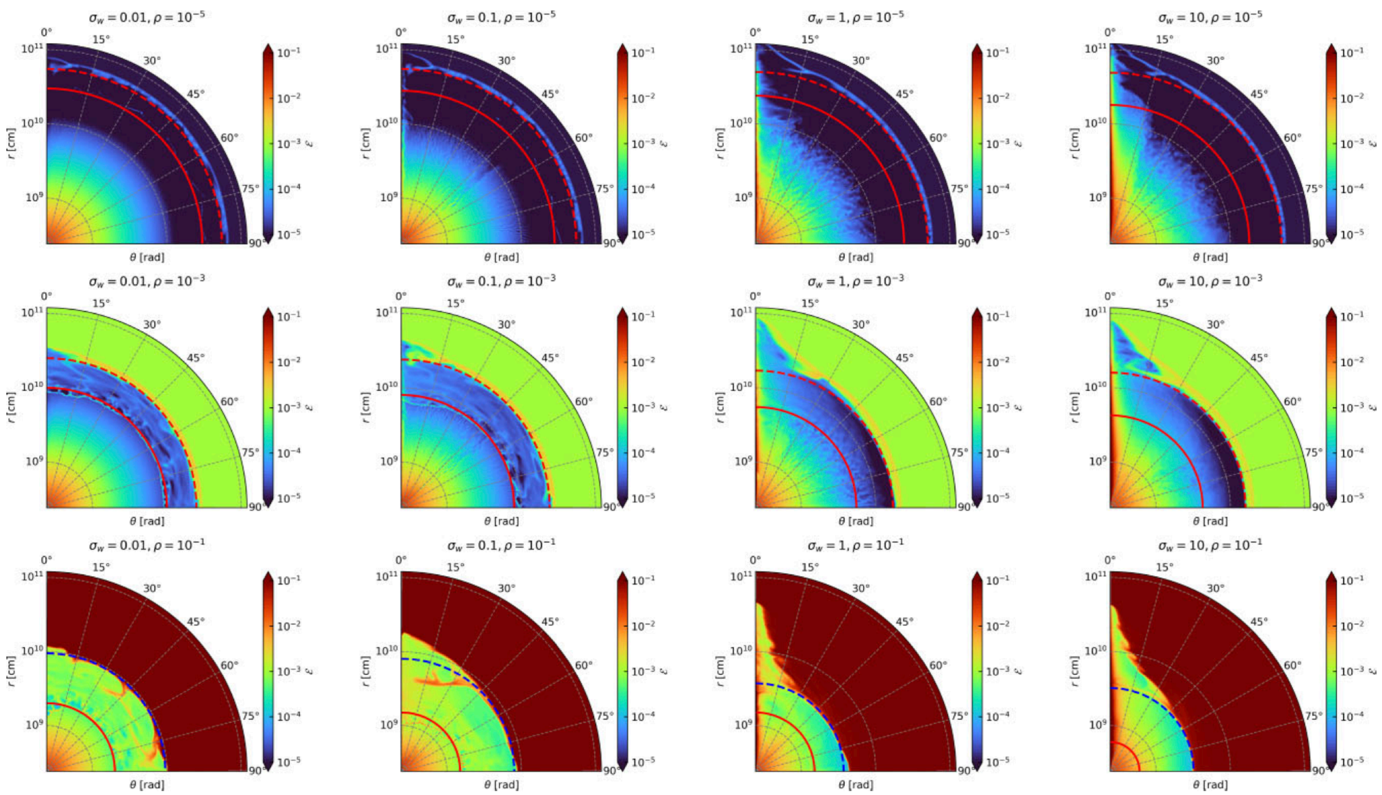
$L_{sd} = 10^{47}$ erg s^{-1}

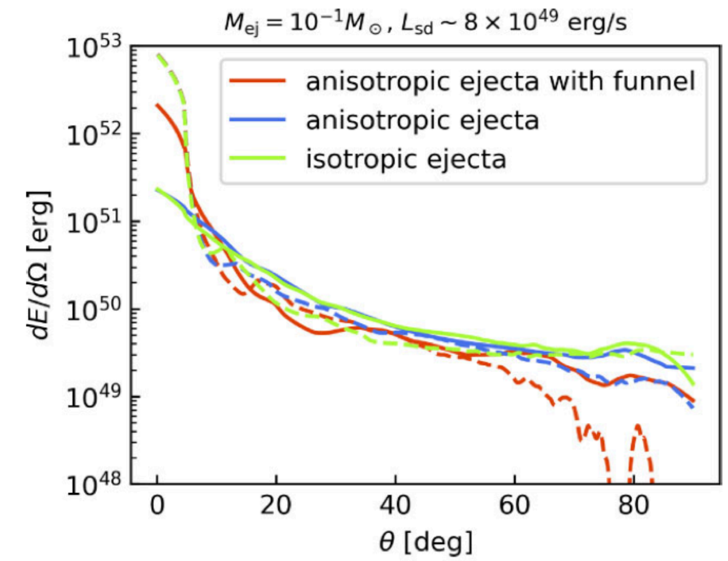


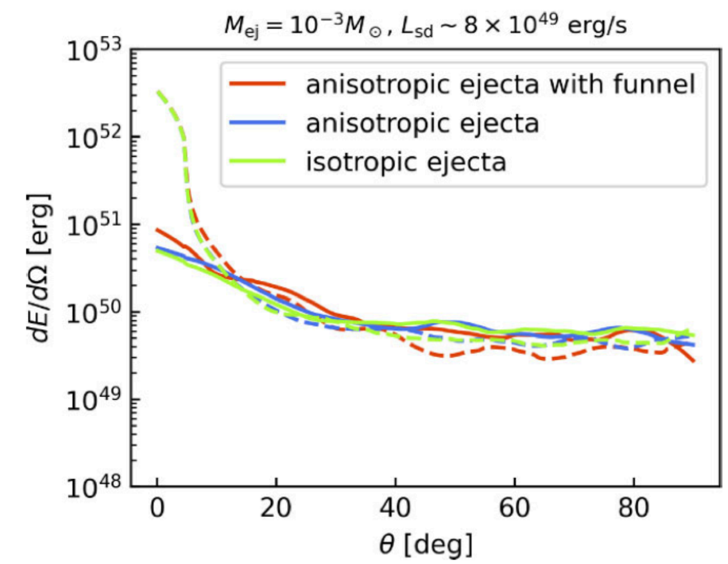
$L_{sd} = 10^{45}$ erg s^{-1}

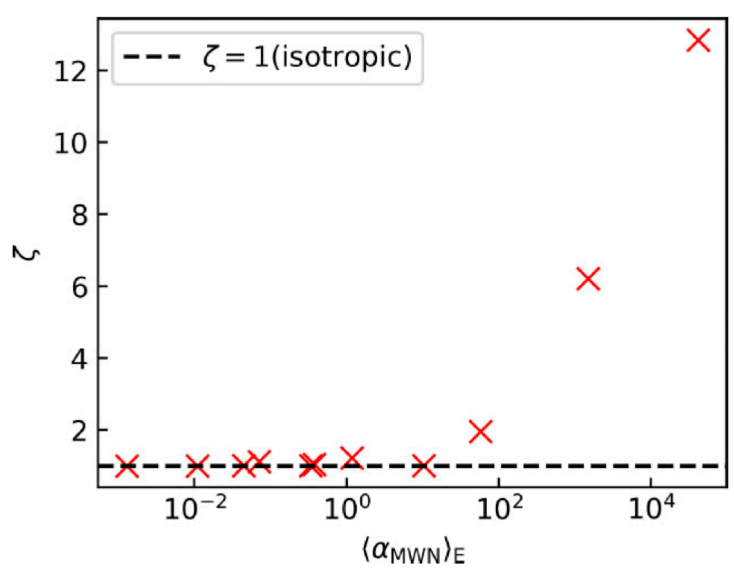
Ai, Gao & Zhang, 2024, arXiv:2405.00638

Anisotropic energy injection in engine-fed kilonova









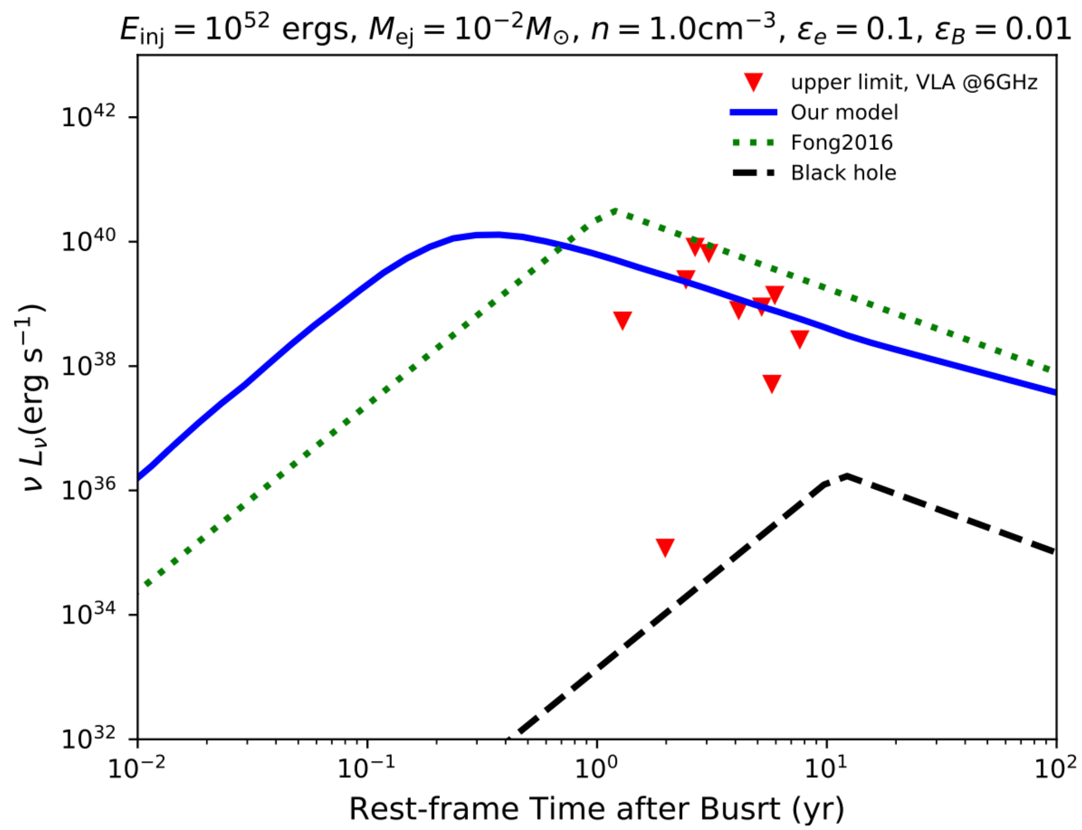
$$\langle \alpha_{\rm MWN} \rangle_{\rm E} = \frac{\int \alpha \mathcal{E} \mathrm{d}V}{\int \mathcal{E} \mathrm{d}V}$$

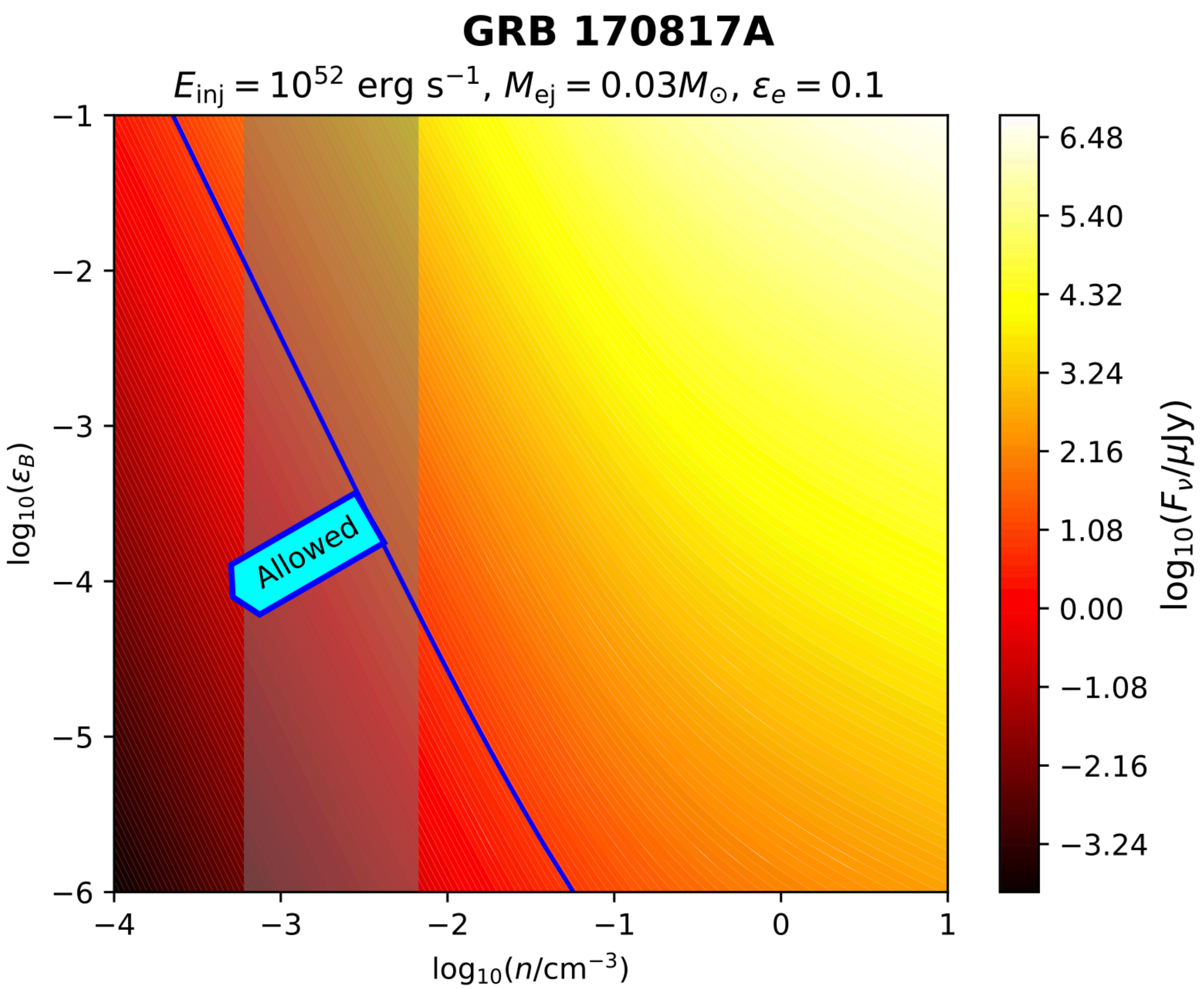
$$\alpha = \frac{u_{\rm A}}{u_{\rm MWN}},$$

Energy injection is not isotropic!
Channeling energy to the jet axis direction
Effects of kilonova energy injection are smaller

Y.-H. Wang, Zhang & Zhu, 2024, MNRAS, 528, 3705

Radio afterglow



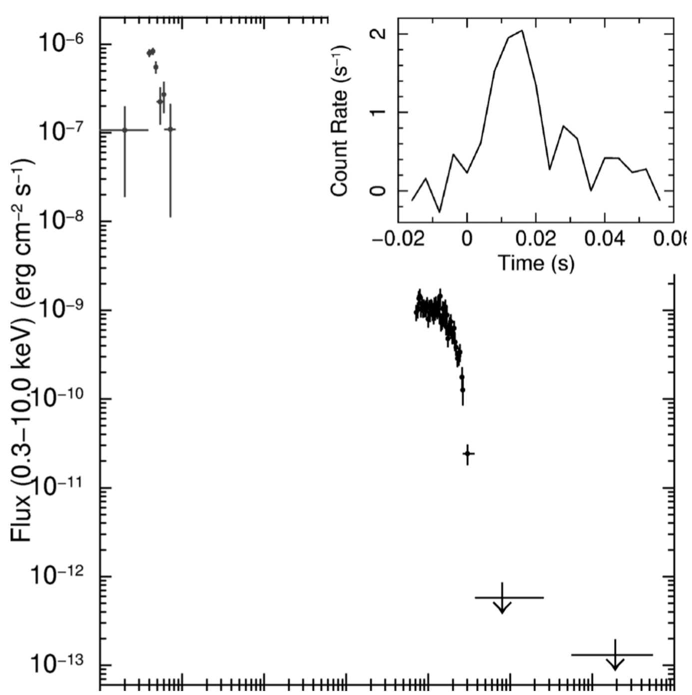


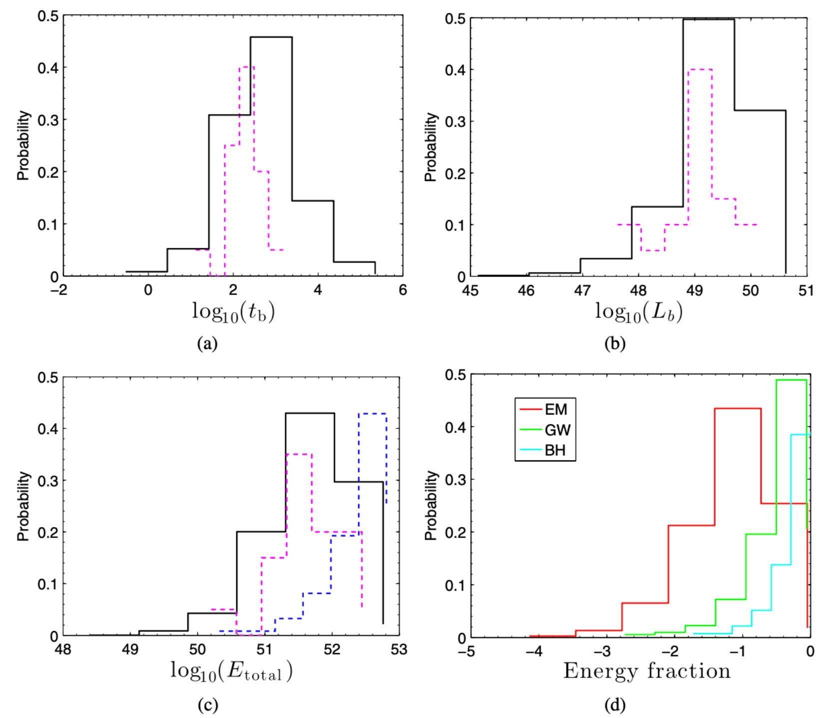
Proper treatment of non-relativistic dynamics
Freedom of micro-physics parameters

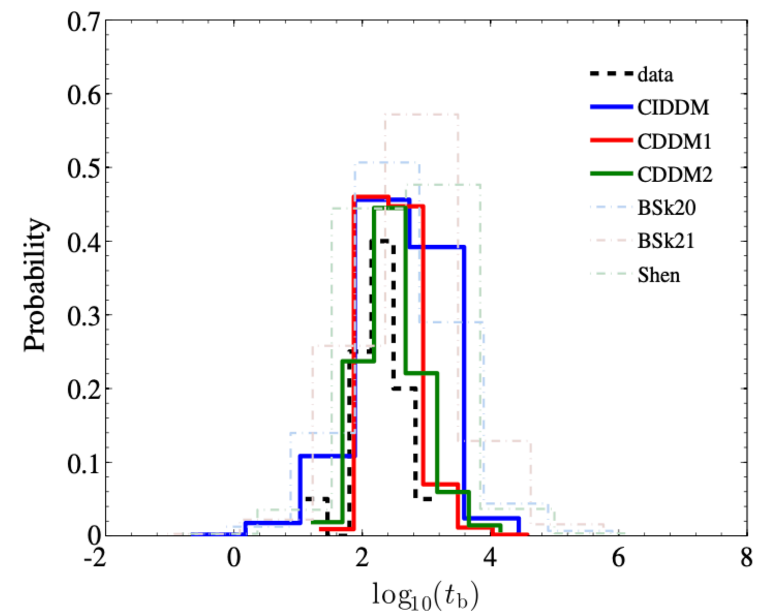
—- A large kinetic energy up to 10^52 erg is still allowed

Liu, Gao & Zhang, 2020, ApJ, 890, 102

Prompt emission and X-ray plateau







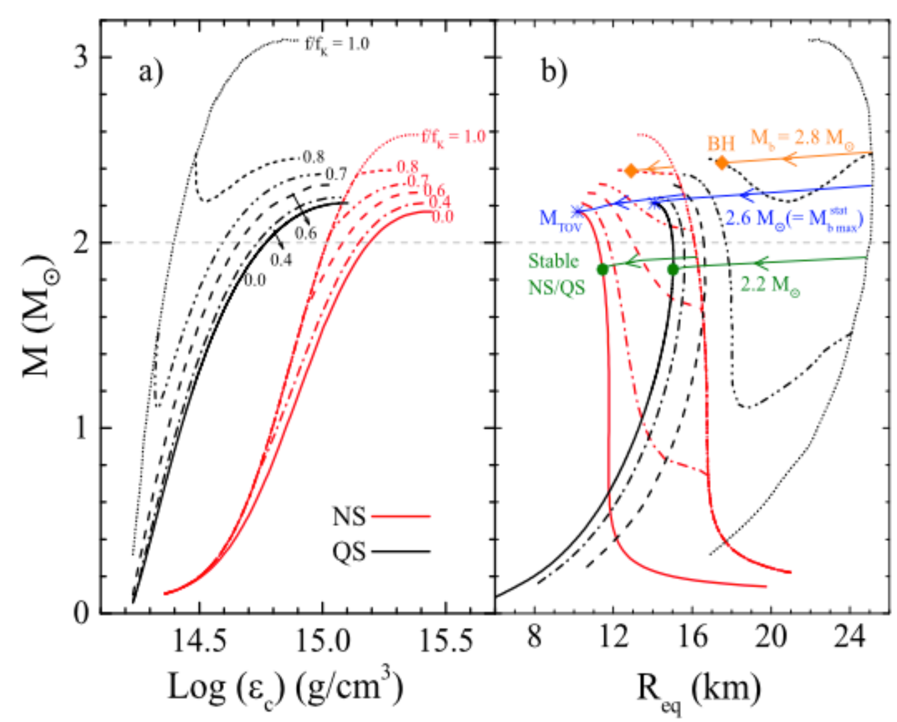
SGRB and plateau energy < 10^52 erg

Some energy depletion mechanisms needed:

Secular gravitational wave losses?

— $M_{\rm TOV} \sim 2.3\ M_\odot$ or higher
— $\epsilon \sim 10^{-4} - 10^{-3}$

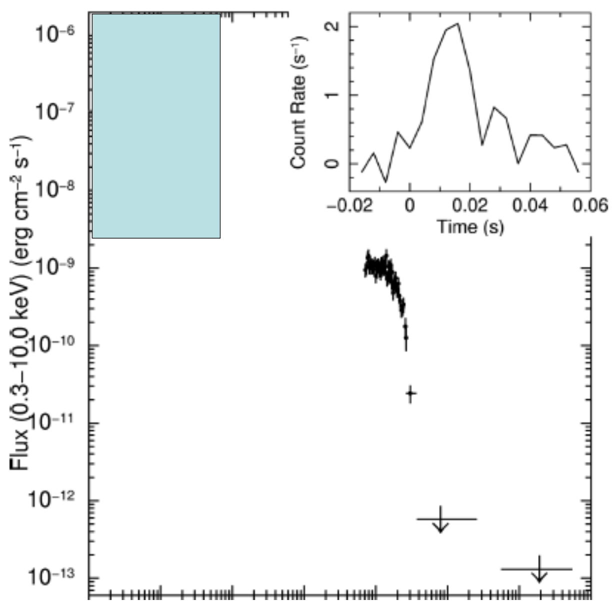
See Shunke Ai’s talk!

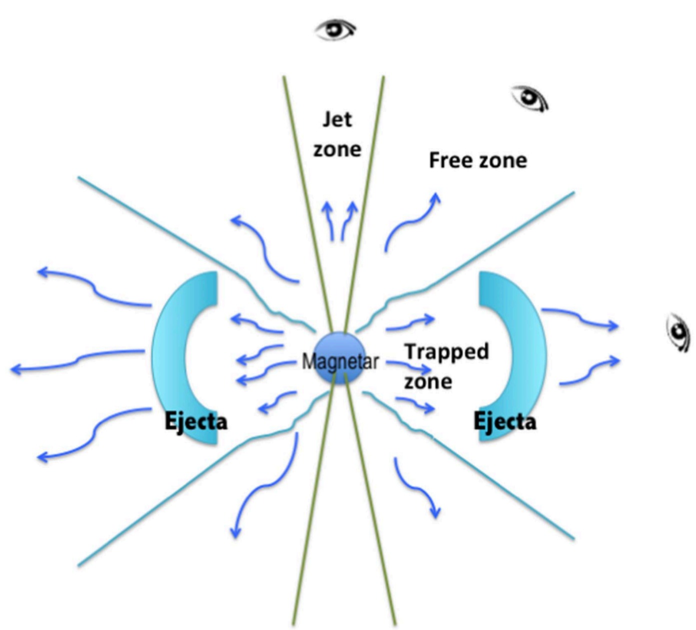


Gao et al. 2016, PRD, 93, 044056; A. Li et al. 2016, PRD, 94, 083010
S. Ai et al. 2023, MNRAS, 526, 6260

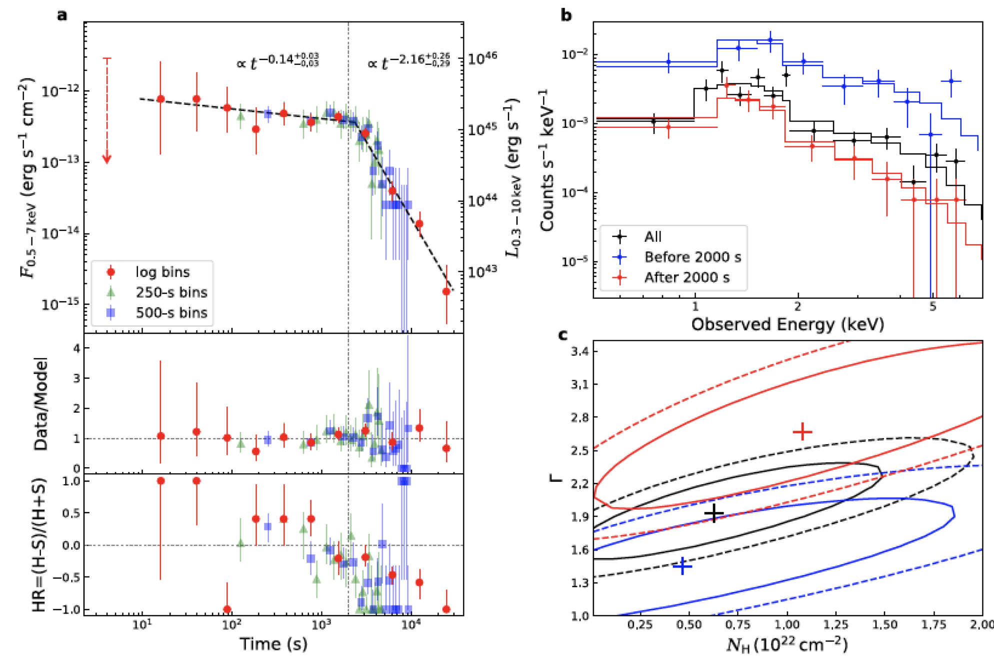
Consequences of a magnetar engine in NS-NS mergers?

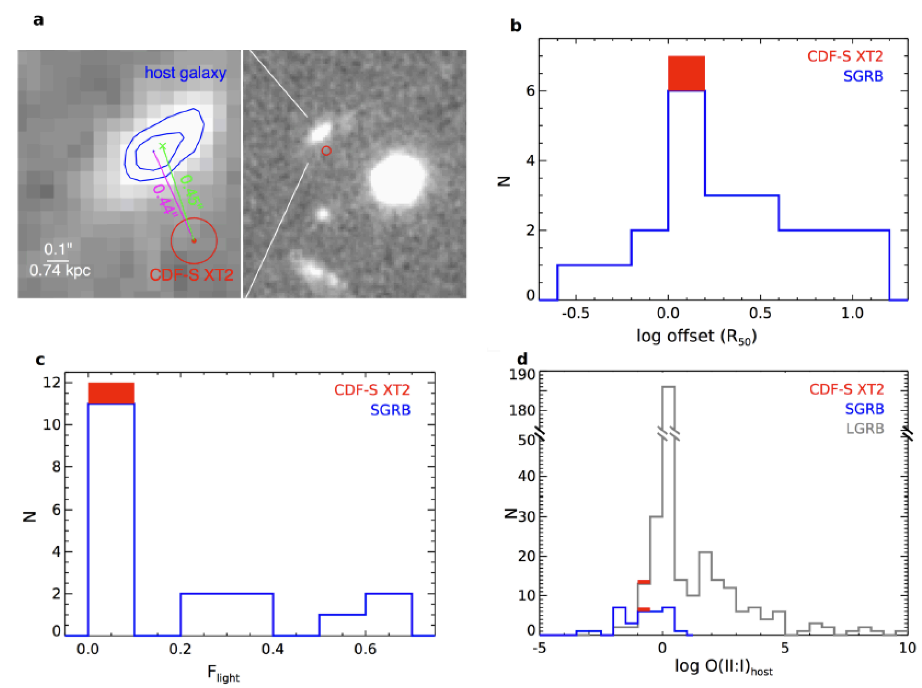
I. GRB-less fast X-ray transients & CDF-S XT2





Zhang, 2013, ApJL, 763, L22
Sun, Zhang & Gao, 2017, ApJ, 835, 7

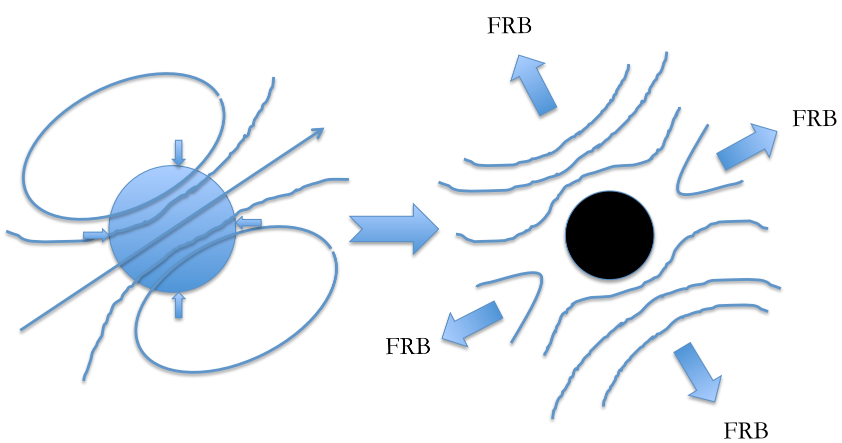


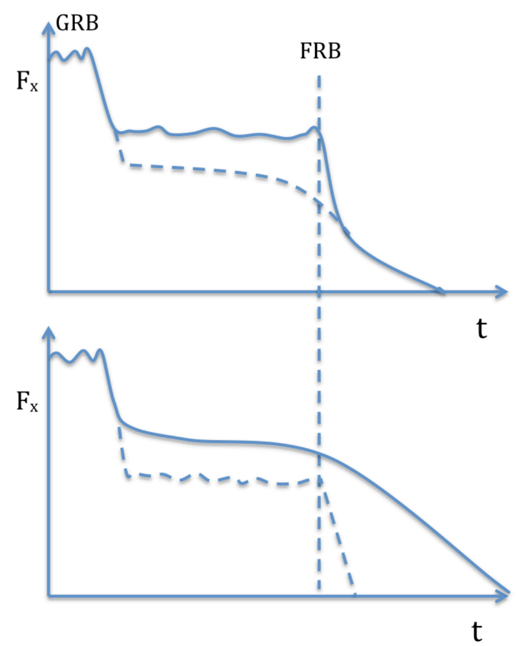


Xue et al. 2019, Nature, 568, 198

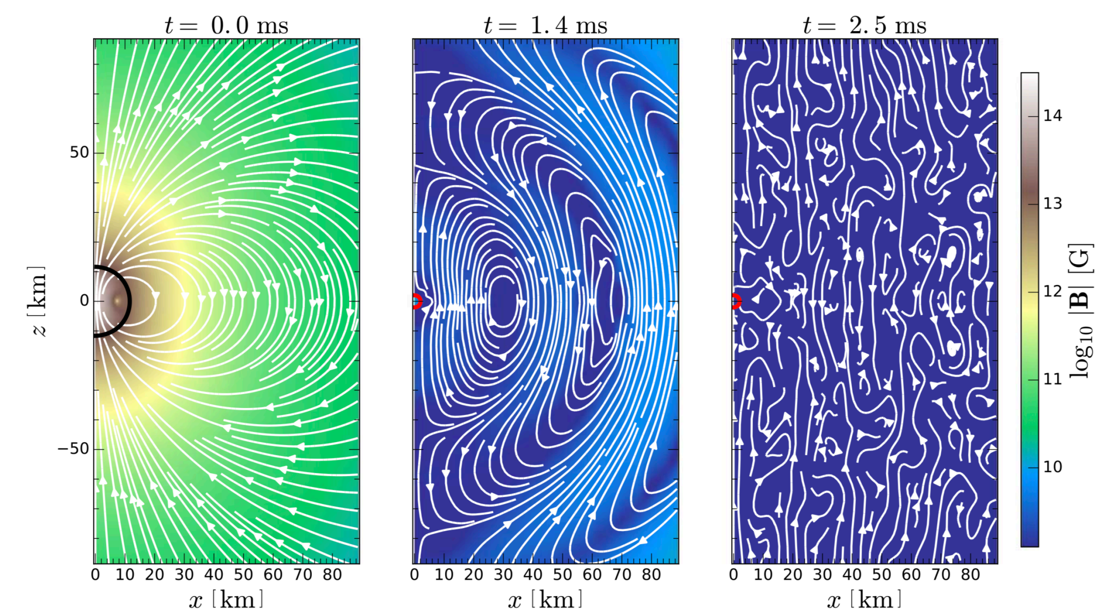
Consequences of a magnetar engine in NS-NS mergers?

II. Signature of supramassive NS collapse — an FRB?



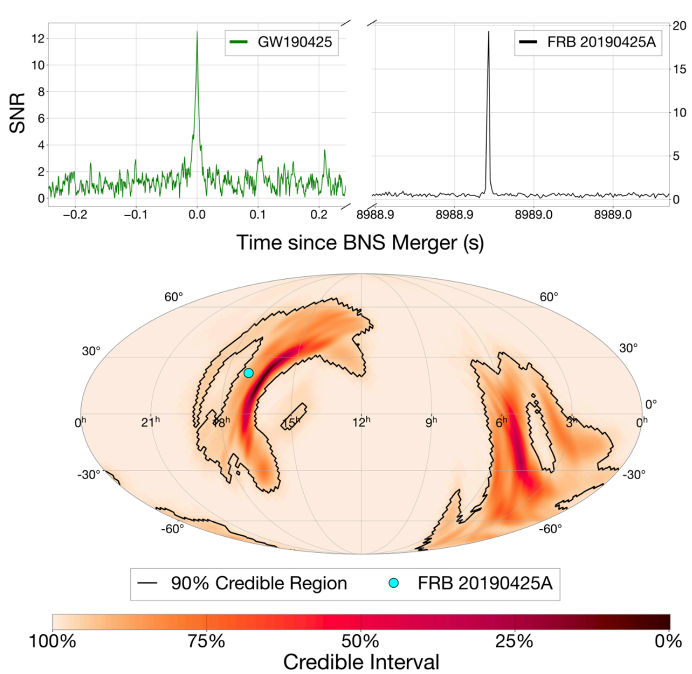


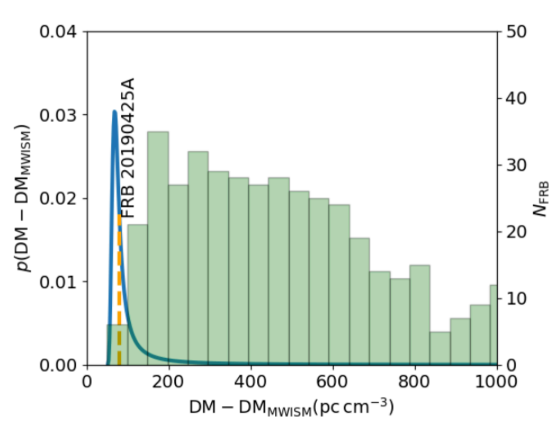
Zhang, 2014, ApJL, 780, L21



Flack & Rezzolla (2014); Most et al. (2018)

GW190425 / FRB 20190425A association? - 2.5h delay



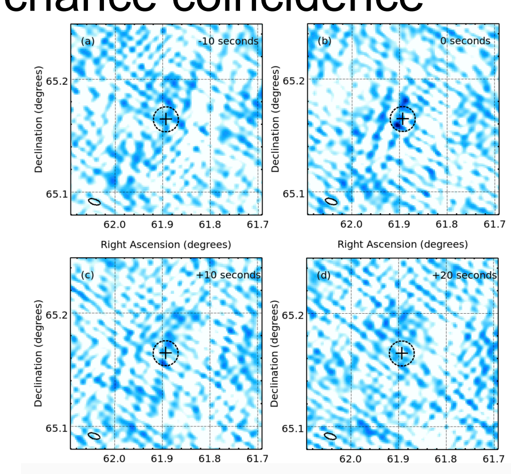


Random chance: 1.9×10^{-4}

sGRB 201006A / LOFAR radio transient association?

- 76.6 min delay, $< 10^{-6}$ chance coincidence

Rowlinson et al. 2023



Moroianu et al. 2023, NA;
Panther et al. 2023, MNRAS;

But see
Bhardwaj et al. 2023

Dialogue @ Dream Field:

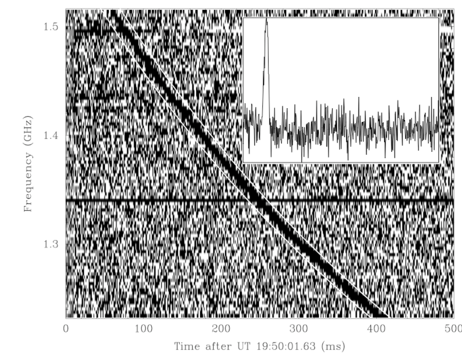
- To numerical people:
  - Please seriously consider and simulate jet launching from a long-lived neutron star!
- To EoS people:
  - Please consider how a $M_{\rm TOV}$ constraint complements other criteria to jointly constrain the NS EoS!
  - Please consider the mechanisms to induce significant secular GW emission from a post-merger object!

Magnetars as engine of FRBs

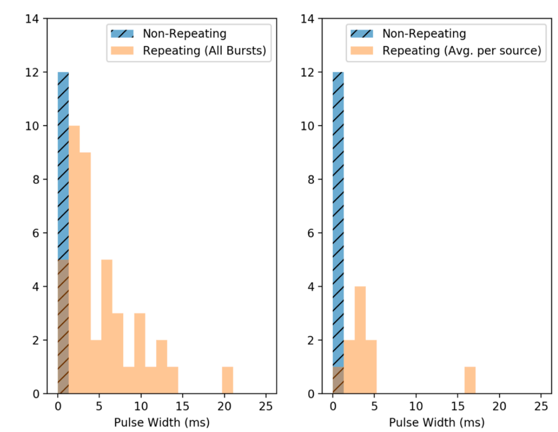
FRB observational properties

Petroff, Hessels & Lorimer, 2019, A&AR
Cordes & Chatterjee, 2019, ARAA
Katz, 2016, 2018; Popov et al. 2018
Xiao, Wang & Dai, 2021, SCMPA

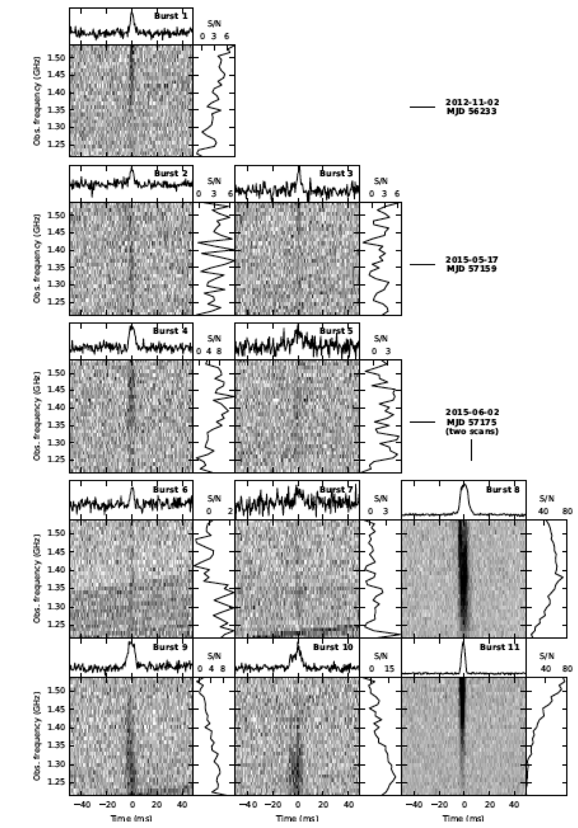
BZ, 2020, Nature, 587, 45
BZ, 2023, RMP, 95, 035005



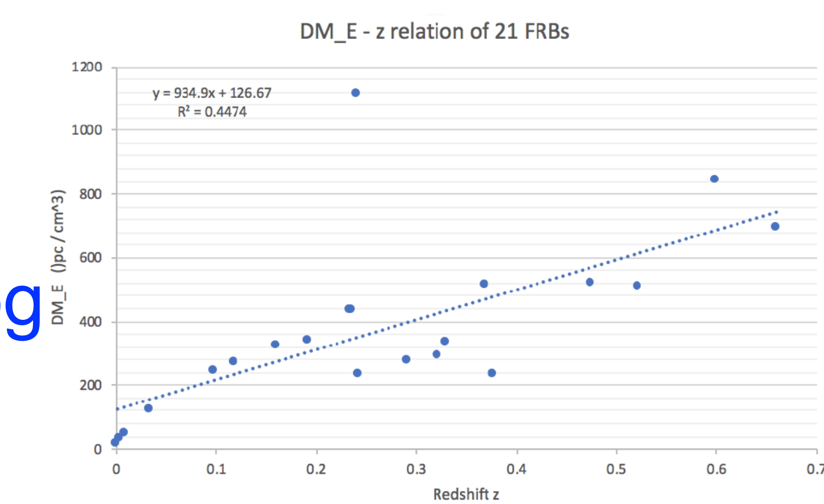
Lorimer et al. 2007



CHIME/FRB Collaboration, 2019


Spitler et al. 2016

- Short duration (milliseconds)
- Internal structure & scattering tail
- Repetition
- Periodicity
- Spectrum, down-drifting
- Polarization: linear/circular, RM
- DM and redshift: extragalactic and cosmolog
- Luminosity, brightness temperature



FRBs vs. GRBs

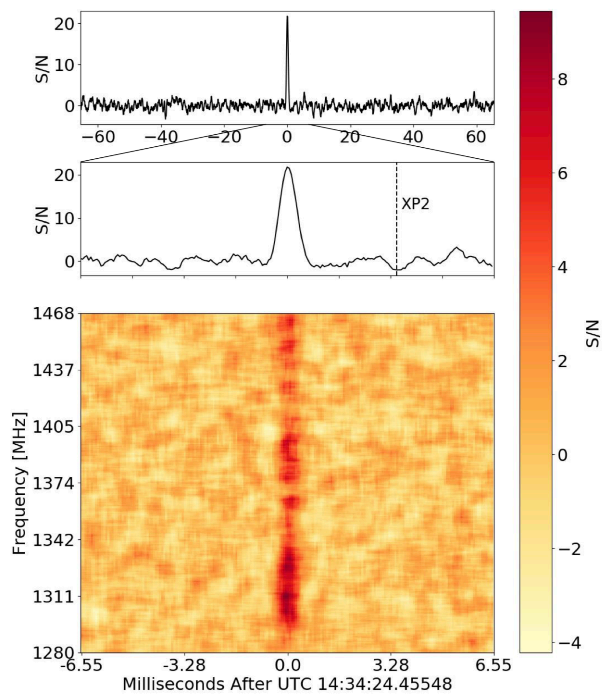
	GRBs	FRBs
Are they astrophysical?	**1967**: Discovery **1973**: Yes (first paper published)	**2007**: Discovery **2013–15**: Yes (new FRBs and microwave-oven-origin of perytons)
Are there multiple types?	**1979**: Soft gamma-ray repeaters **1992**: Long versus short	**2016**: Repeaters **2020**: Do all FRBs repeat?
Where are they?	**1979**: SGRs are Galactic (or nearby) **1997**: Long GRBs are cosmological **2004**: Short GRBs are cosmological	**2017**: Extragalactic and comological (FRB 121102) **2020**: Galactic (FRB 200428)
What makes them?	**1998**: SGRs from magnetars **1998**: Long GRBs from massive star core collapse **2017**: Short GRBs from neutron star–neutron star mergers	**2020**: FRB 200428 from a magnetar **2020**: Can other sources produce FRBs?

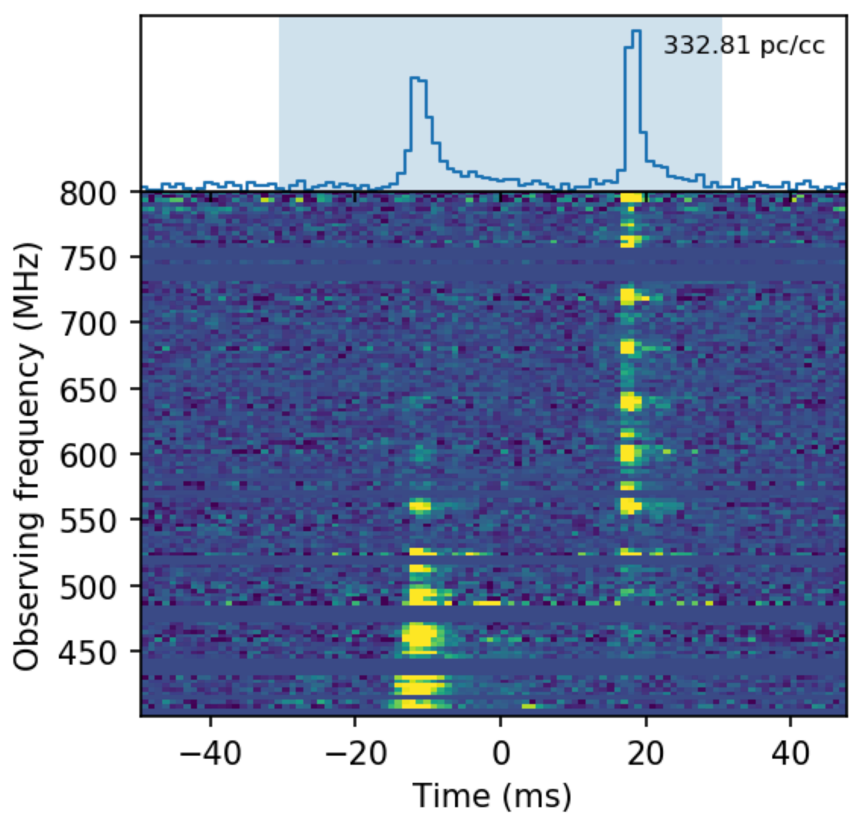
Fig. 1 | A historical comparison between the GRB and FRB fields.

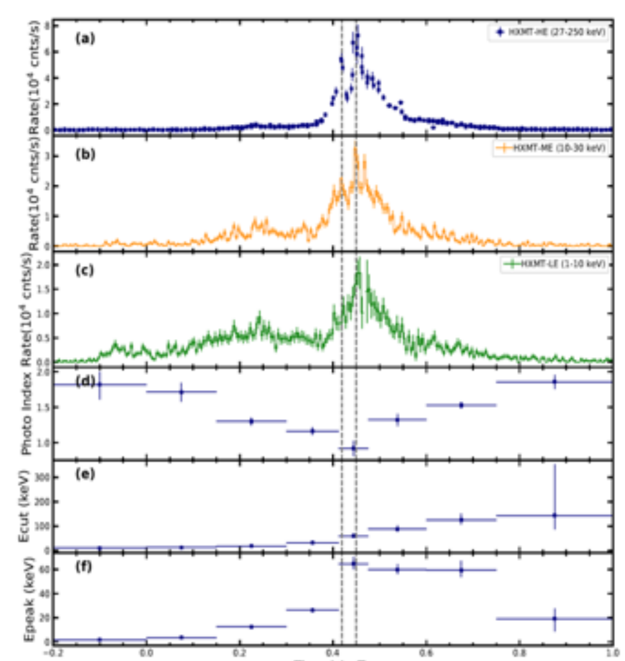
BZ, 2020, Nature, 587, 45

What: FRB 200428-SGR Association

CHIME/FRB Collaboration 2020; Bochenek et al. 2020;
Li+ 20; Mereghetti+ 20; Ridnaia+ 20; Tavani+ 20

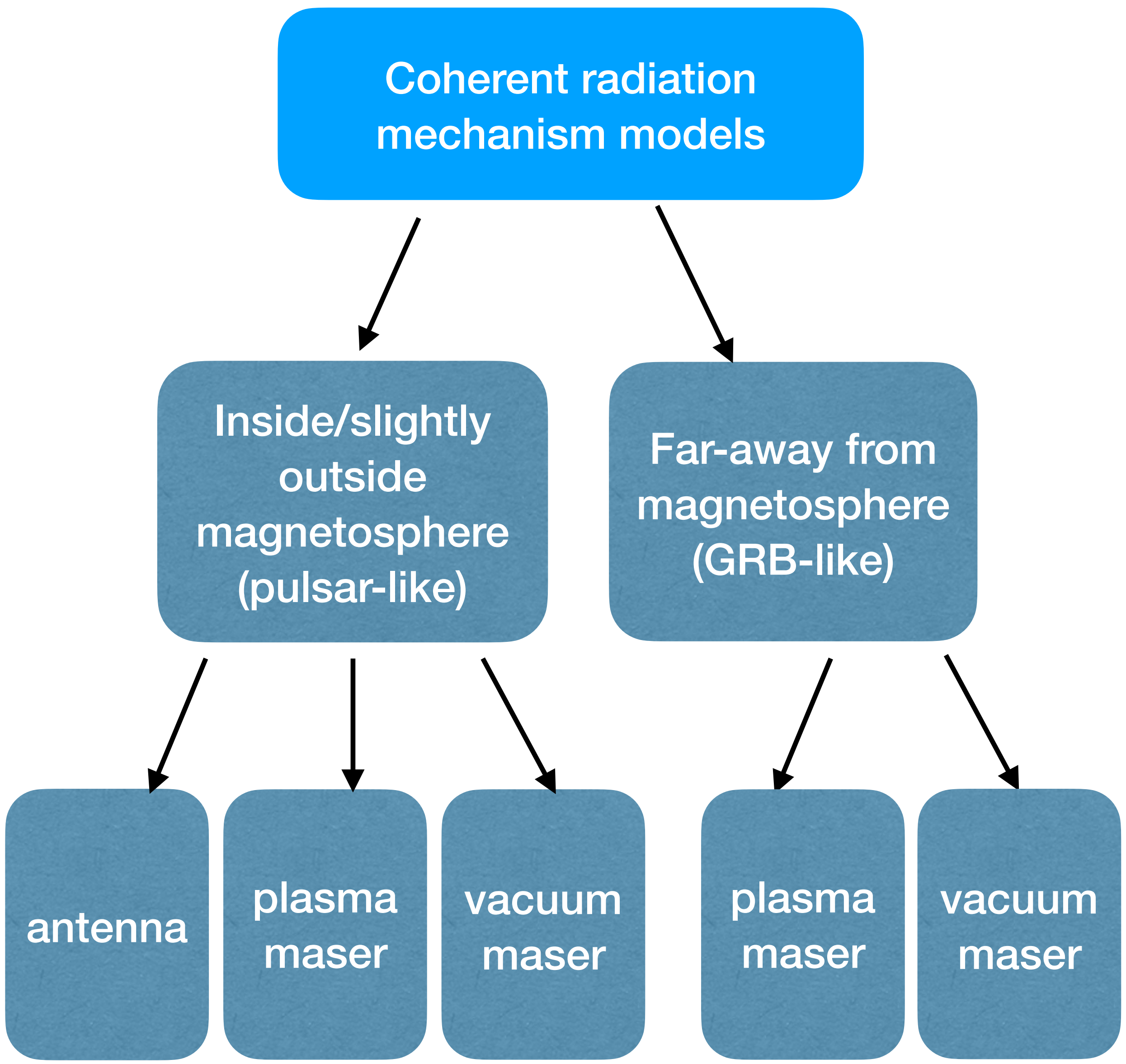


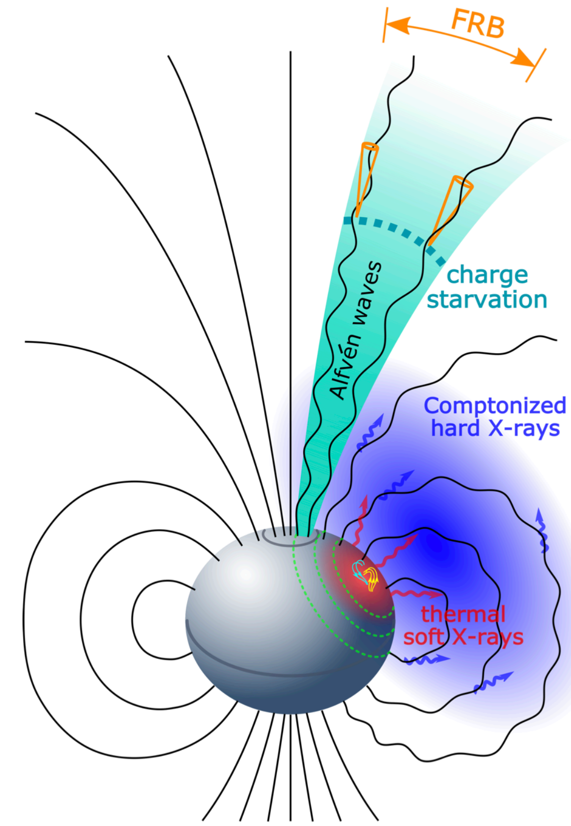




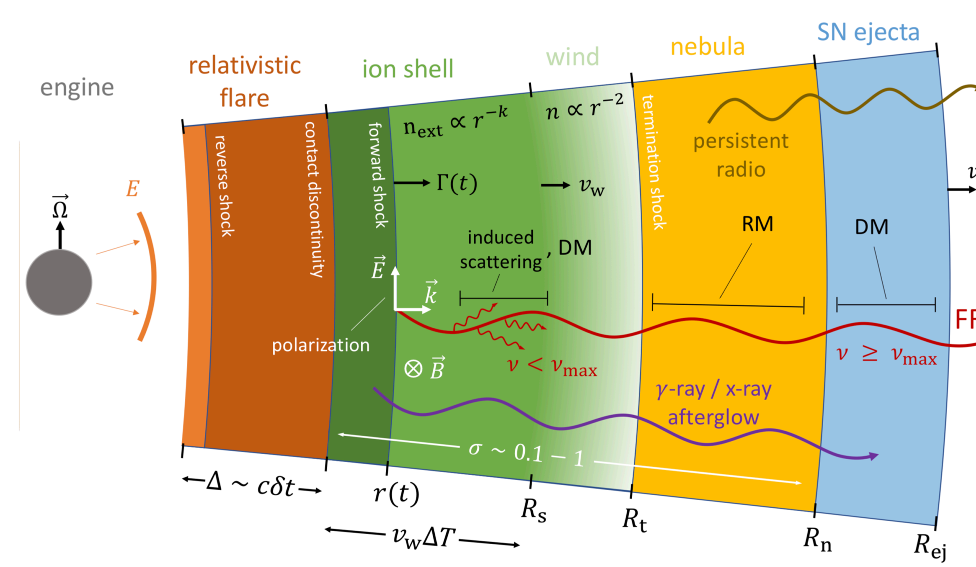
At least some FRBs are produced by magnetars!

Coherent Radiation Mechanisms
Where and how?





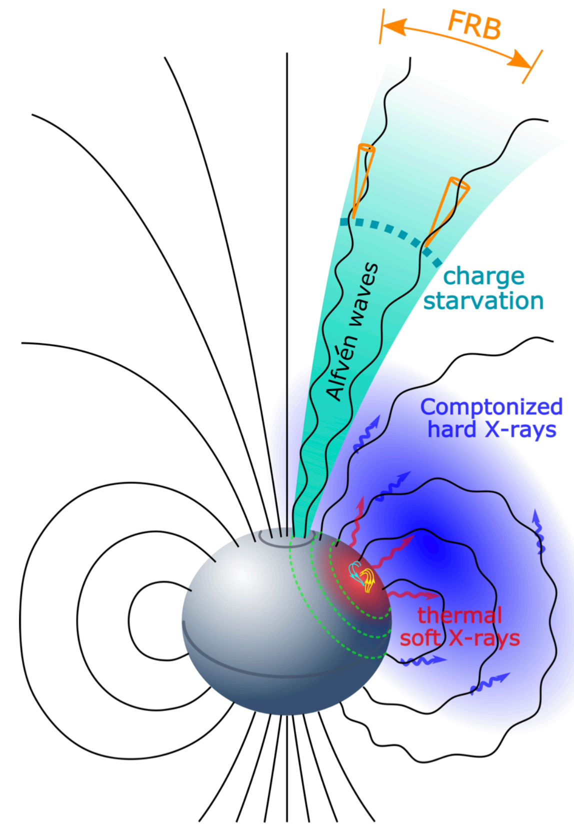
Pulsar-like: from Lu et al. 2020

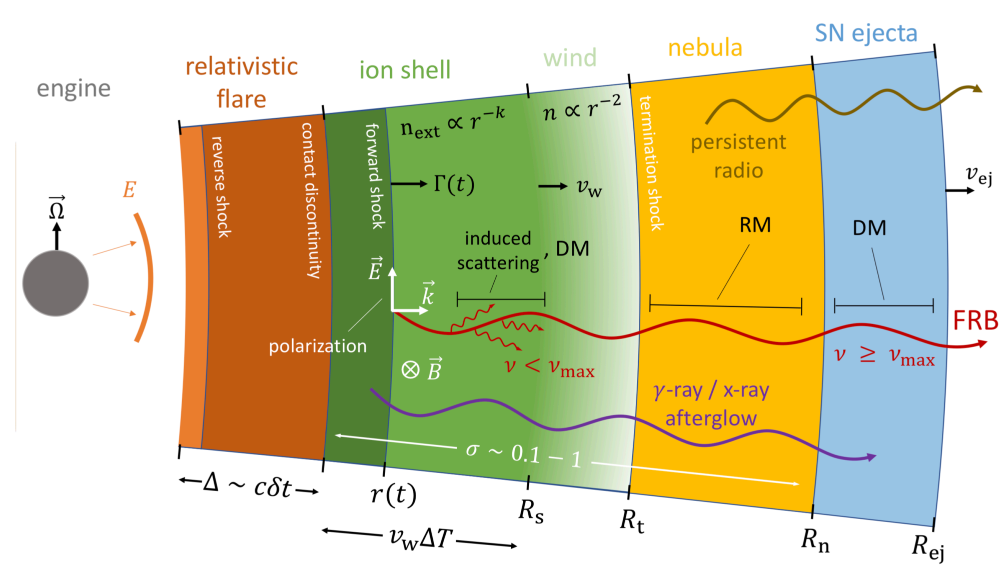


GRB-like: from Metzger et al. 2019

Where? 1-slide summary

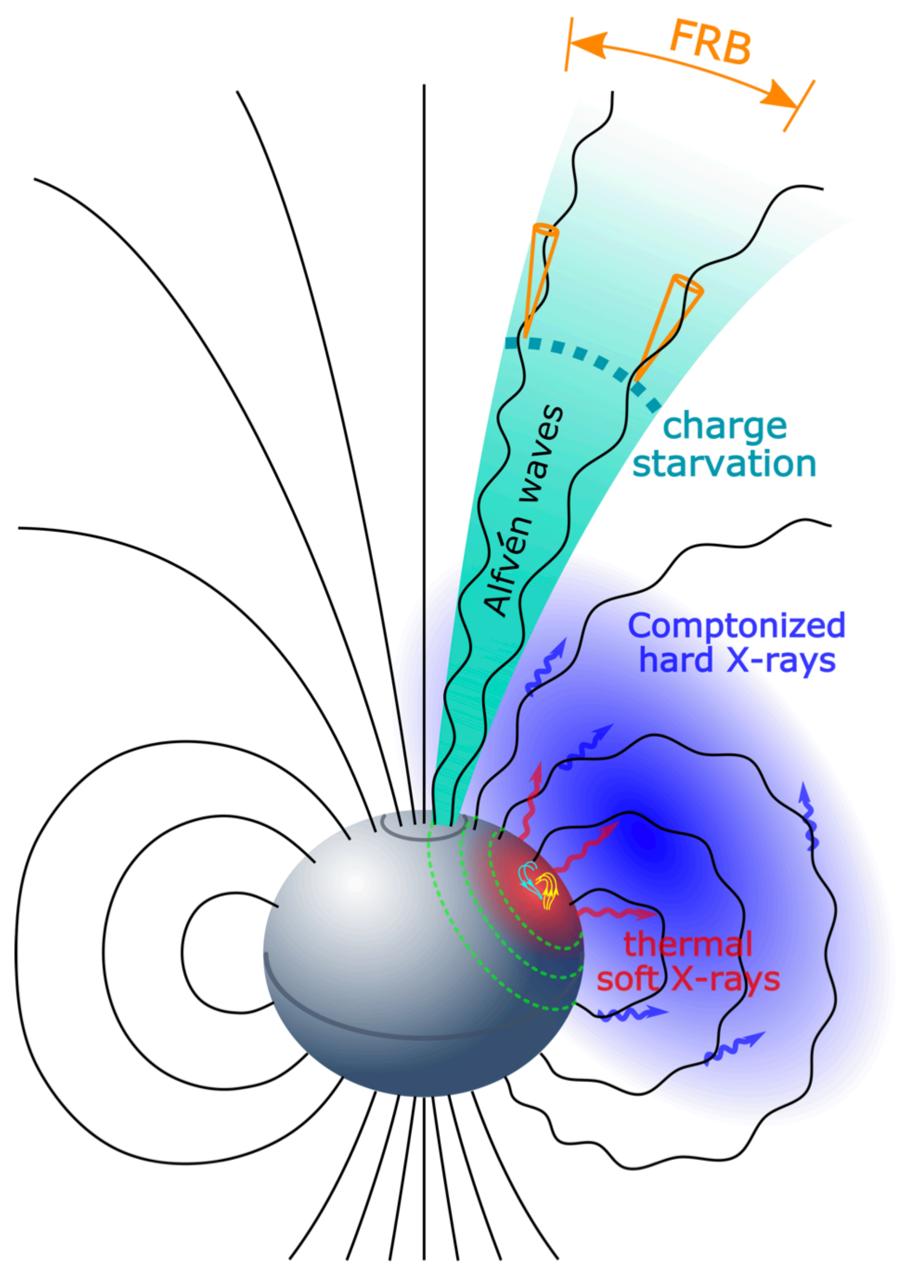
- Several model-independent arguments suggest that magnetospheric models are favored.
- Models involving relativistic shocks have been ruled out or greatly disfavored by the following facts:
  - PA swing
  - Intrinsic circular polarization
  - Narrow spectra
  - Large energetics required for such models



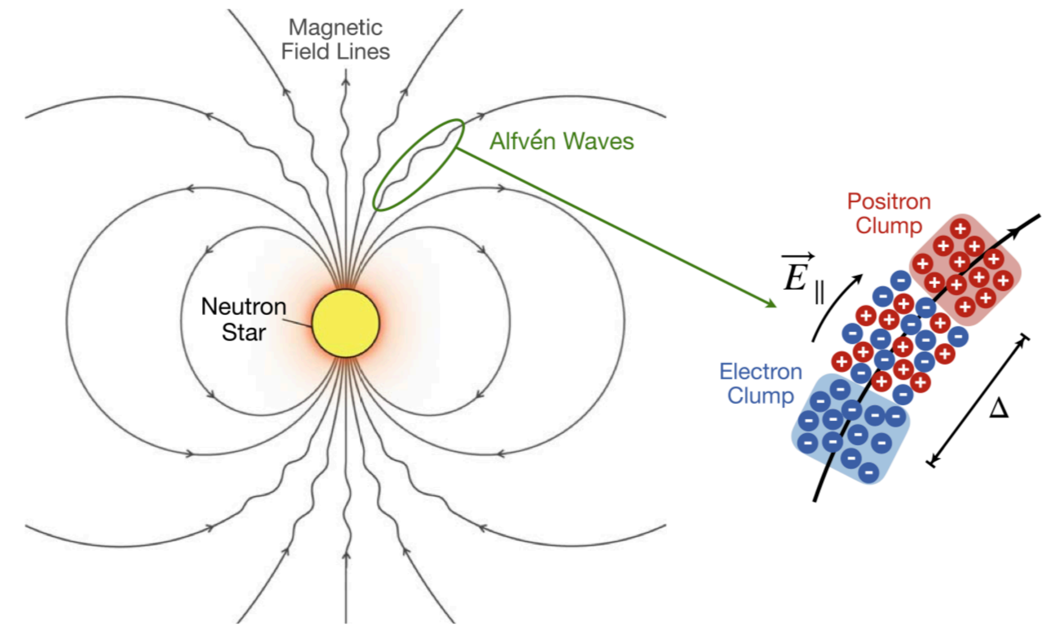


Also Kunihito Ioka’s talk

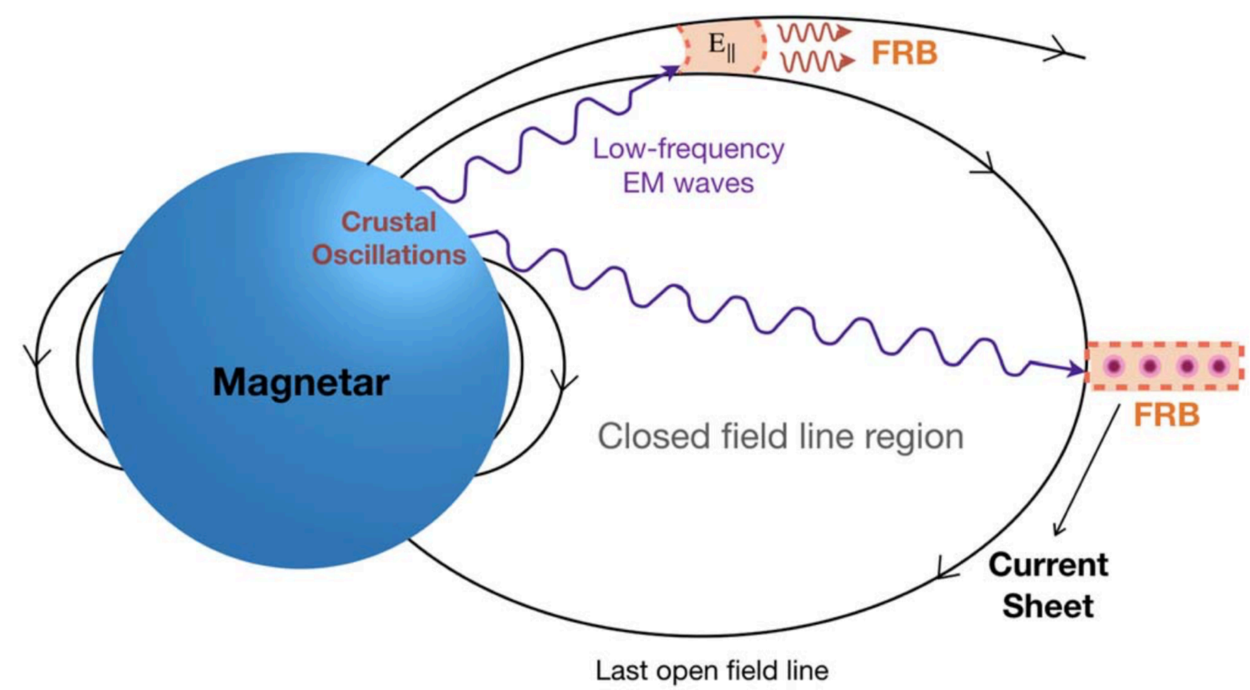
How? FRBs from magnetar magnetospheres



Lu, Kumar & Zhang 2020, MNRAS, 498, 1397



Yang et al., 2020, ApJL, 901, L13

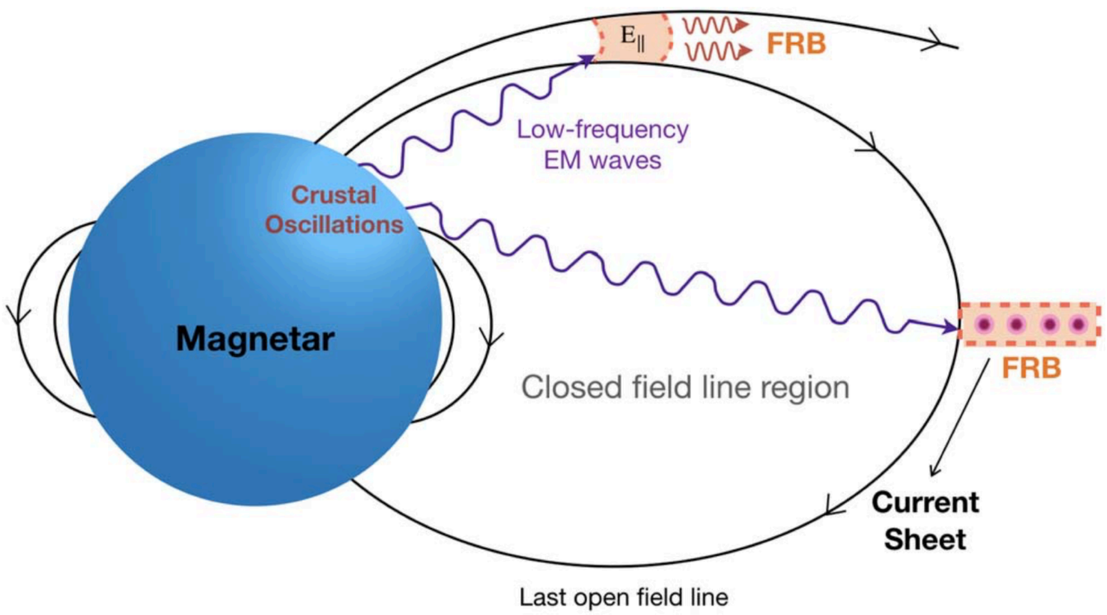


Zhang, 2022, ApJ, 925, 53

Wave-wave interaction?? — Ioka's talk

Inverse Compton scattering

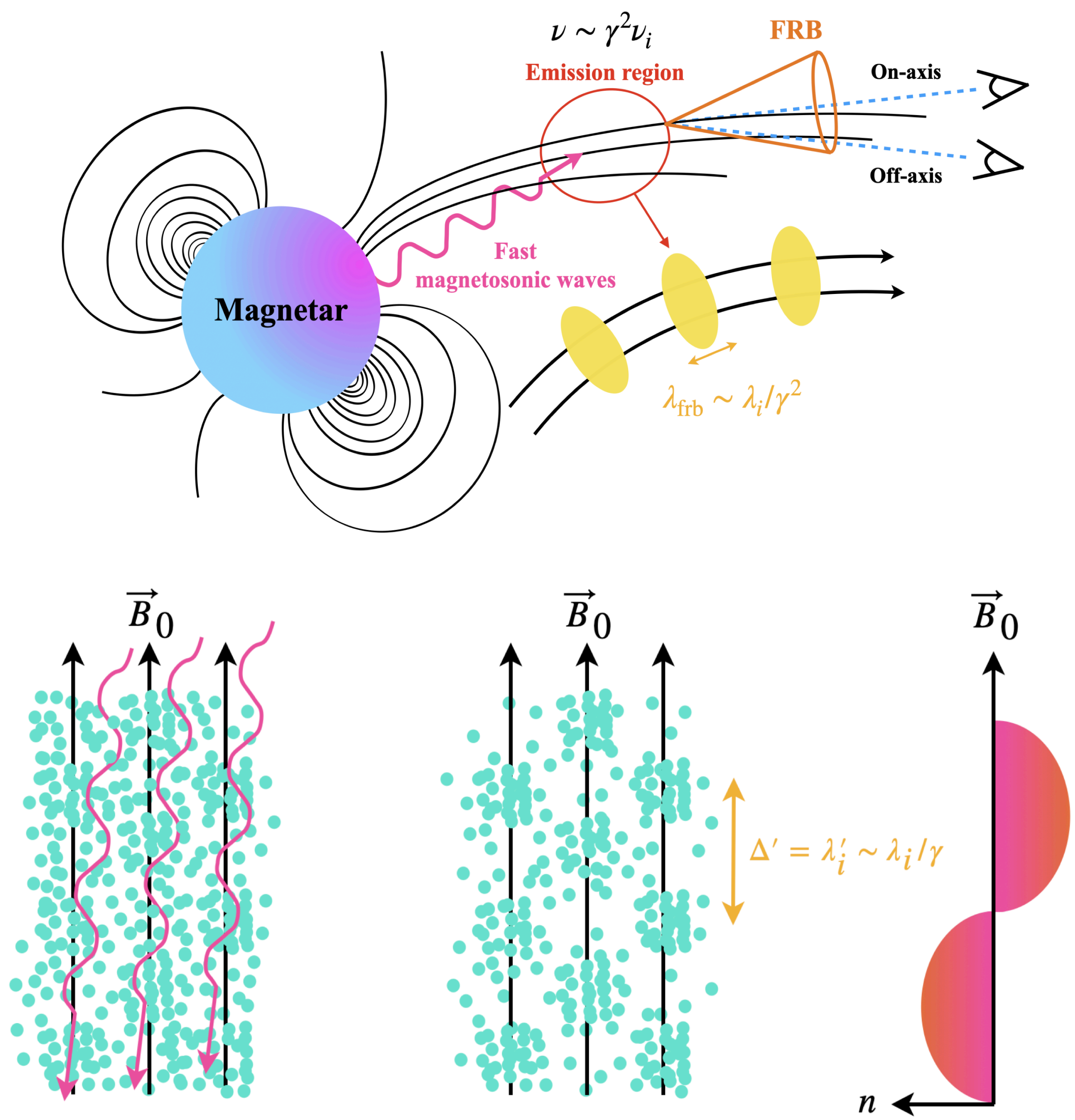
Zhang, 2022, ApJ, 925, 53
Qu & Zhang, 2024, arXiv:2404.1194



- Physical motivation:
  - Crustal cracking -> charge oscillations -> kHz low frequency waves (Alfven mode or X-mode - fast magnetosonic mode or F-mode
  - Observed emission: coherent GHz wave
  - Bridge: relativistic particles with Lorentz factor of a few 100s, inverse Compton scattering off X-mode (F-mode) EM waves

Inverse Compton scattering

Zhang, 2022; Qu & Zhang 2024



- Advantages of the model:
  - ICS is more efficient than curvature radiation; less degree of coherence needed
  - narrow spectrum
  - linear & circular polarization
  - Bunch generation and maintenance:
    - low-frequency waves naturally bunch particles (collective ICS, or induced Compton scattering — K. Ioka);
    - parallel E field from Alfven waves;
    - radiation reaction limited

FAST: Five-hundred-meter Aperture Spherical radio Telescope

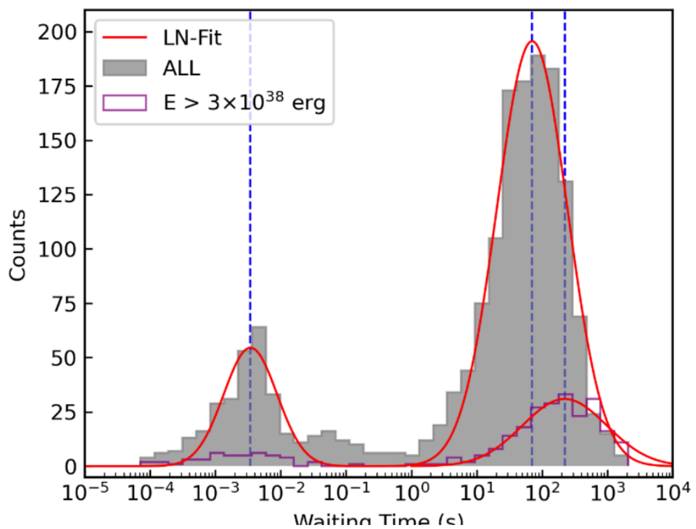
FAST observations of FRBs:

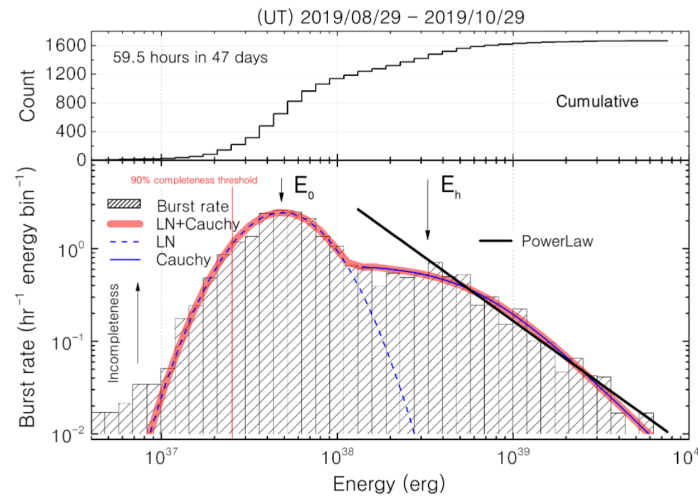
- FAST FRB Key Science Project (KSP, PI: **B. Zhang** / **W. W. Zhu**)
  - A 5-year project, ~150 hours per year, monitoring repeating FRBs
  - A team of > 100 people from 16 institutions from 4 countries
  - >10 publications, 5 Nature, 1 Science, many more to come
- CRAFTS (PI: **D. Li**) & GPPS (PI: **J. L. Han**)
  - Survey programs discovering new, faint FRBs

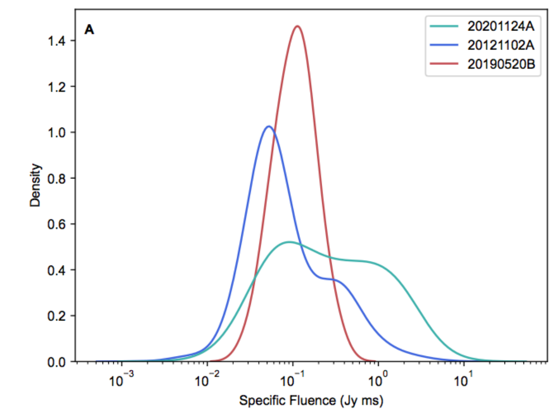
FAST:
From Anywhere Spotting Thousands

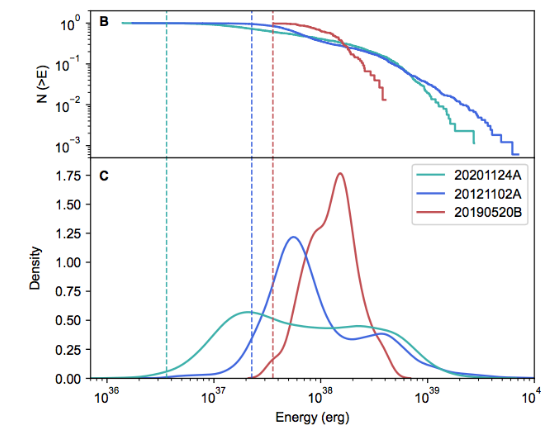
Global energetics

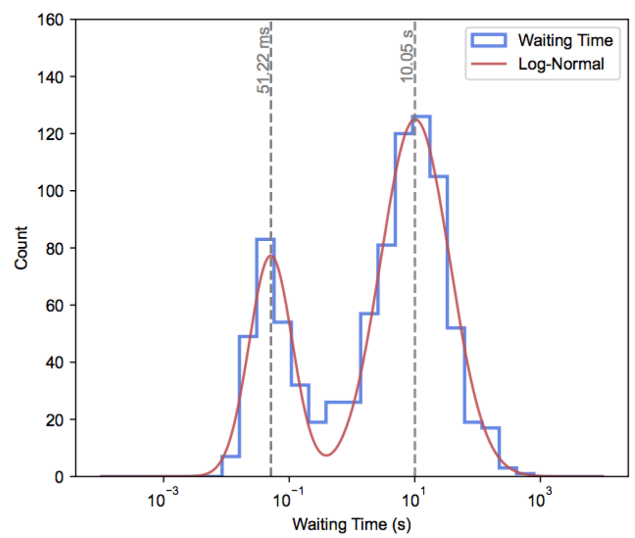
D. Li et al. 2021, Nature; H. Xu et al. 2022, Nature;
Y. K. Zhang et al. 2022, RAA; Y. K. Zhang et al. 2023

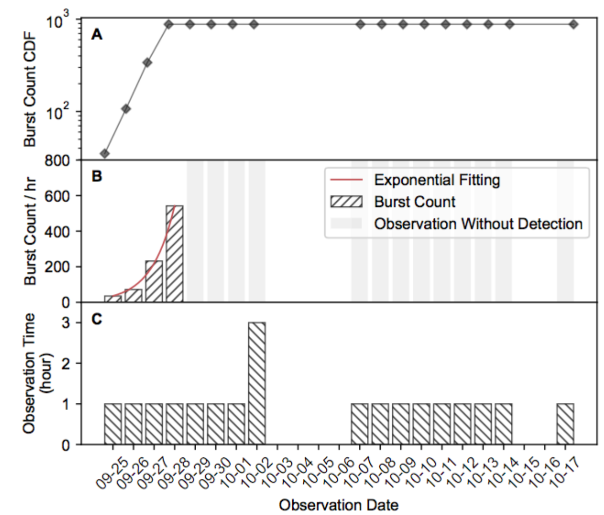












(FRB 20121102 in 47 days)

$$E_{\rm bursts} = (6.4\times10^{45}\ {\rm erg})\left(\frac{E_{\rm radio}}{3.4\times10^{41}\ {\rm erg}}\right)\left(\frac{F_b}{0.1}\right)\left(\frac{\eta}{10^{-4}}\right)^{-1}\left(\frac{\zeta}{0.053}\right)$$

$(3.85\times10^{45}\ {\rm erg})$ (FRB 20201124A in 4 days)

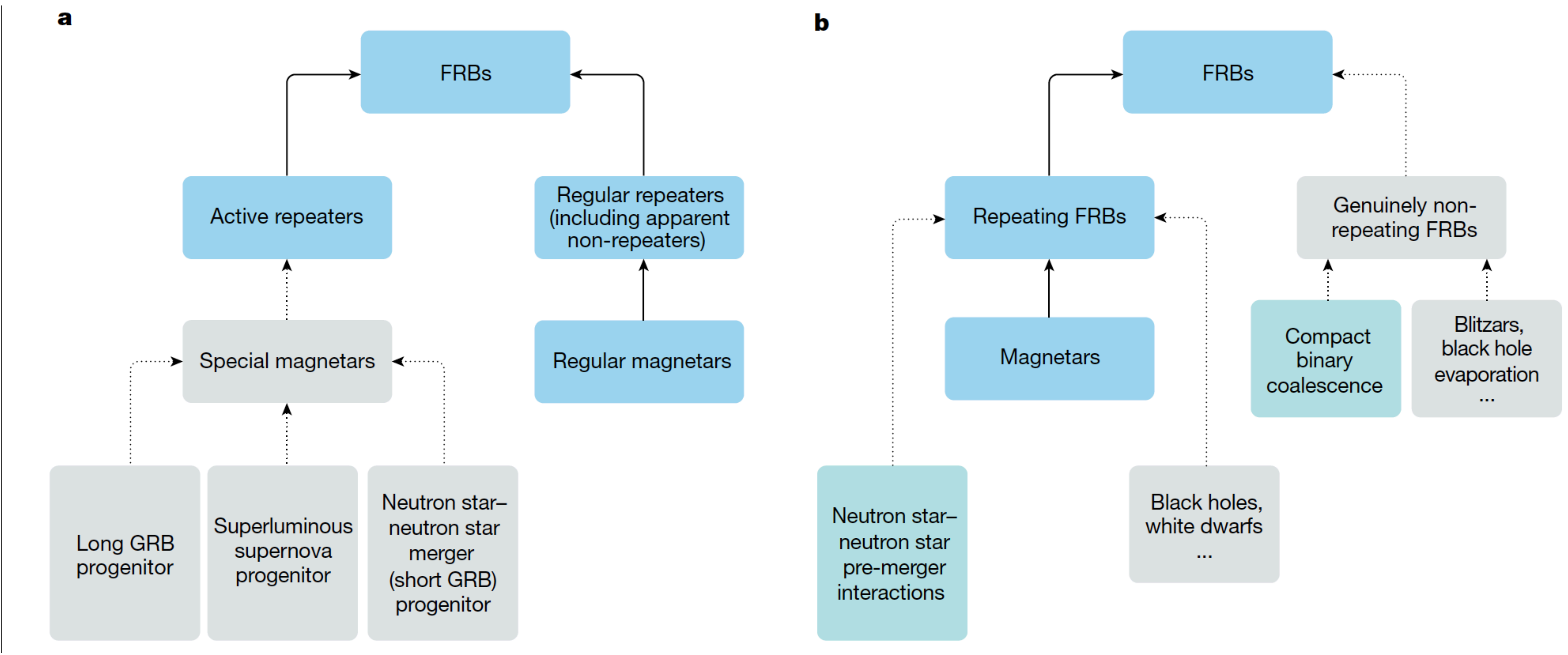
$$E_{\rm mag} \simeq (1.7\times10^{47}\ {\rm erg})B_{*,15}^2 R_6^3$$

Challenges to synchrotron maser shock (GRB-like) models:

* Very high repetition rate (>500/hr for FRB 20201124A on Sep. 28, 2021)
* Short waiting time (<50 ms)
* Total energy exceeds 10% of (dipolar) magnetic energy (FRB 20121102A in ~1.5 month and FRB 20201124A in 4 days) if not efficient

More extreme case of FRB 20240114A
500 per hour for many days — 10^4 bursts

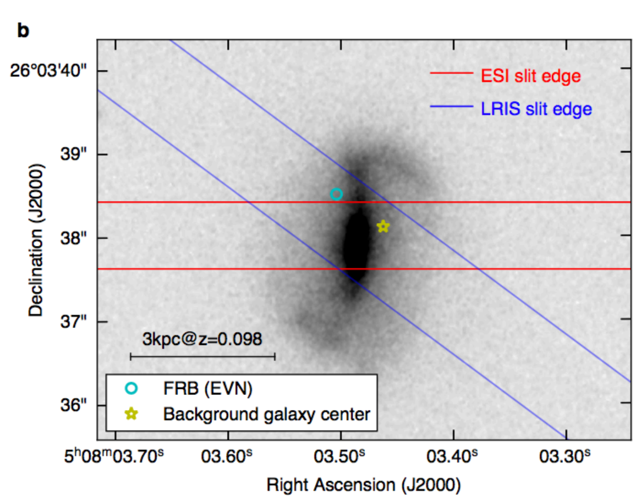
What else?
Two extreme versions of source models

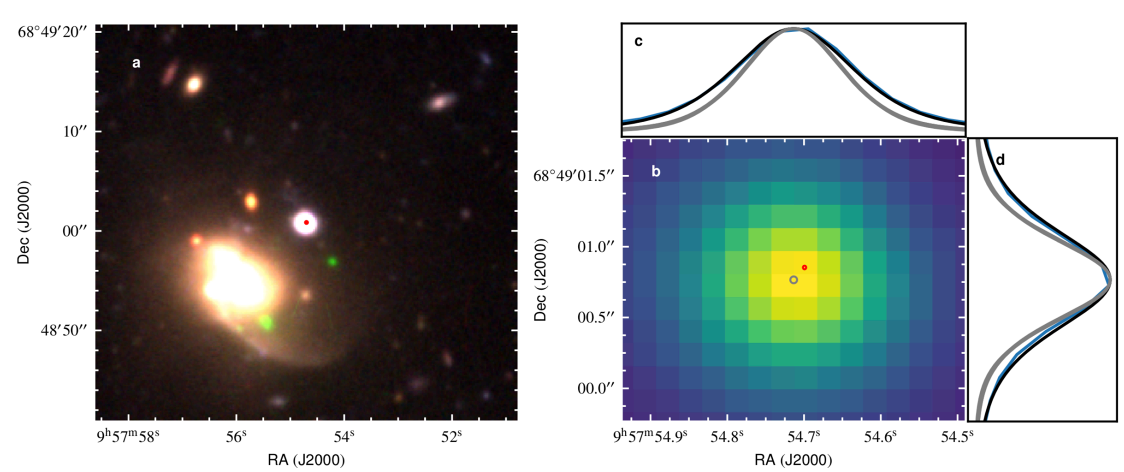


BZ, 2020, Nature, 587, 45

Several types of magnetars?

- Under “Magnetars make them all” hypothesis, at least three types of magnetars are needed
  - Young magnetars that make active repeaters?
  - Regular magnetars (the one we observe in MW) that make less active repeaters and/or apparent non-repeaters?
  - Some special magnetars that make M81 GC-like repeaters?
  - A unified magnetar formation framework?





Dialogue @ Dream Field:

- To neutron star / quark star people:
  - Please consider the tiny crust more
  - Total energy budget problem? (Weiyang Wang's talk)
  - Please consider mechanisms to trigger FRBs so frequently! (~500 / hr FRBs only, even more when XRBs are included)

Summary

- GRBs
  - Millisecond magnetars are an attractive type of central engine for both long and short GRBs
  - Direct evidence: multi-messenger observations of a long-lived post-merger product after an NS-NS merger
  - Theoretical difficulties remain and progress is encouraging
  - Dialogue: launch jets, $M_{\rm TOV}$, secular GW from post-merger remnant
- FRBs
  - At least some FRBs are made by magnetars. Are they all made by magnetars? — not sure.
  - Magnetospheric origin is favored, some sort of inverse Compton scattering is at play (more personal)
  - Dialogue: triggering mechanism