Magnetars:

Unveiling the Cosmic Drama in X-rays, Gamma-rays, and Beyond

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HEAD 21 Gamma-ray SIG
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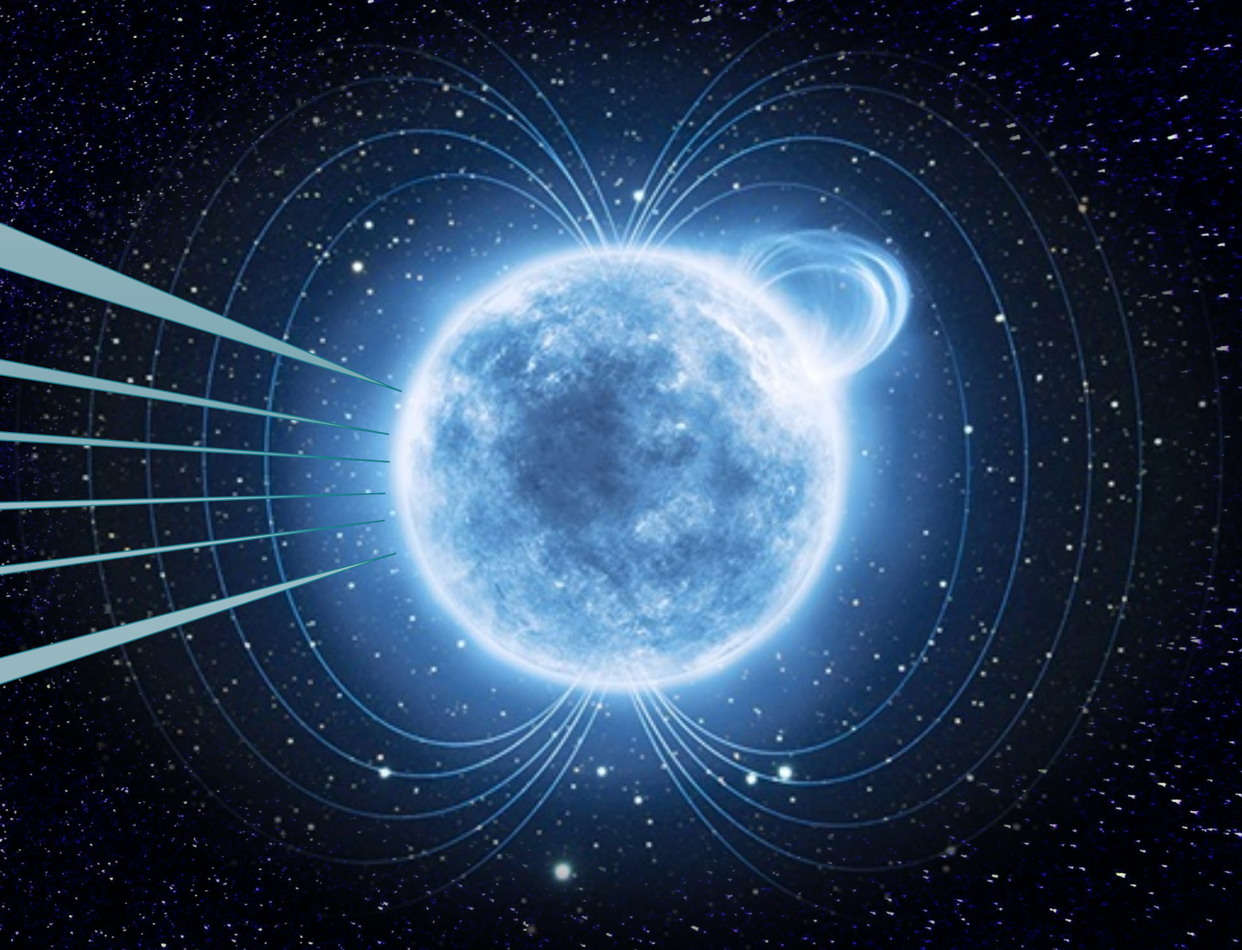
MAGNETARS

- Young neutron stars (NS): $\sim 10^4$ yrs
- Extreme magnetic fields: $>10^{13}$ G
- Rotational Periods: 2-12 s
- ~30 known objects
- Quiescent Emission
- Host to wide variety of high energy transient activity



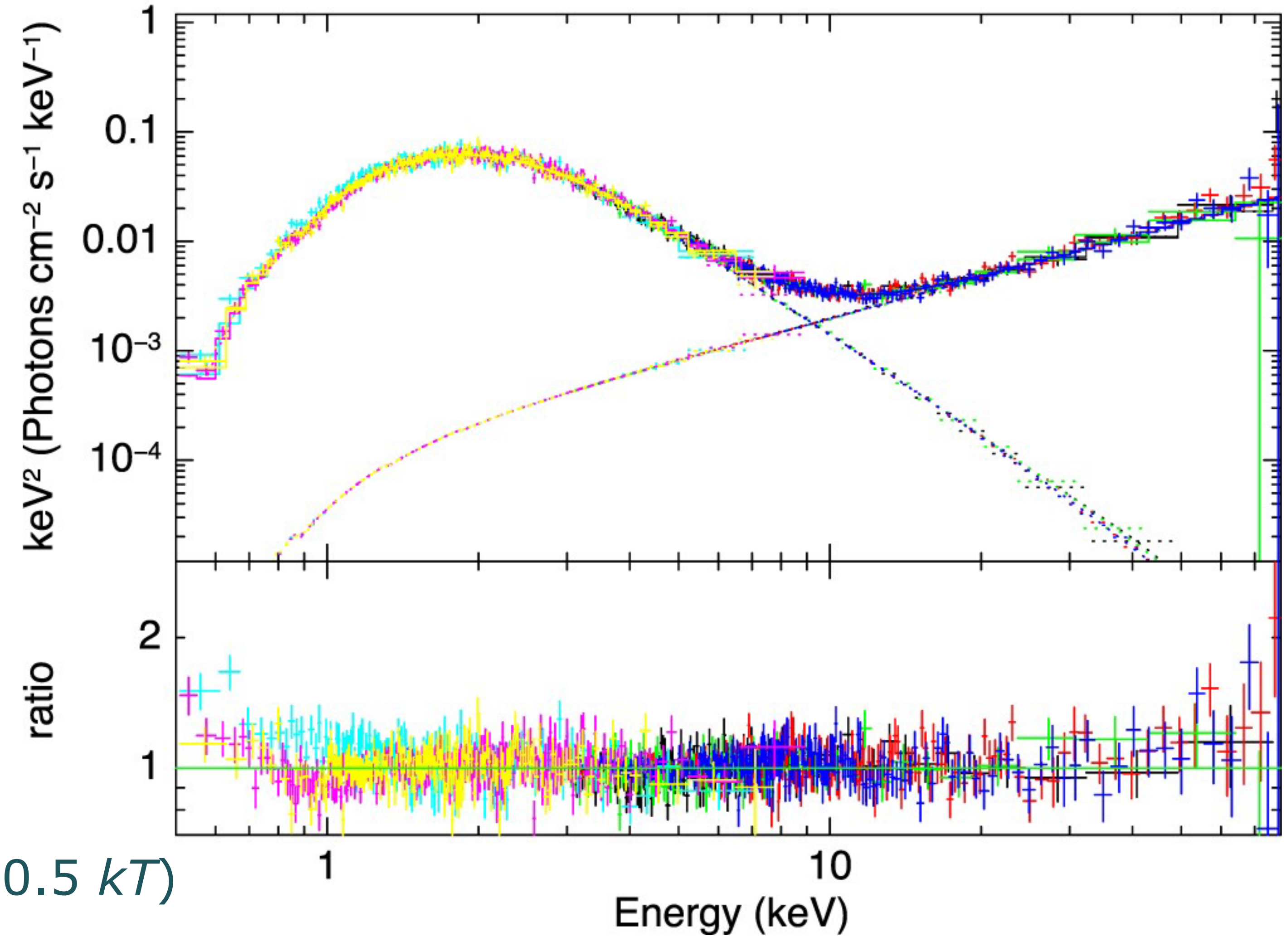
ESA/ATG medialab

Magnetar Quiescent Emission

- L~10^{30}-10^{35} erg s^{-1} (2-10 keV)
- Somewhat bi-modal distribution
    - "Persistent" magnetars

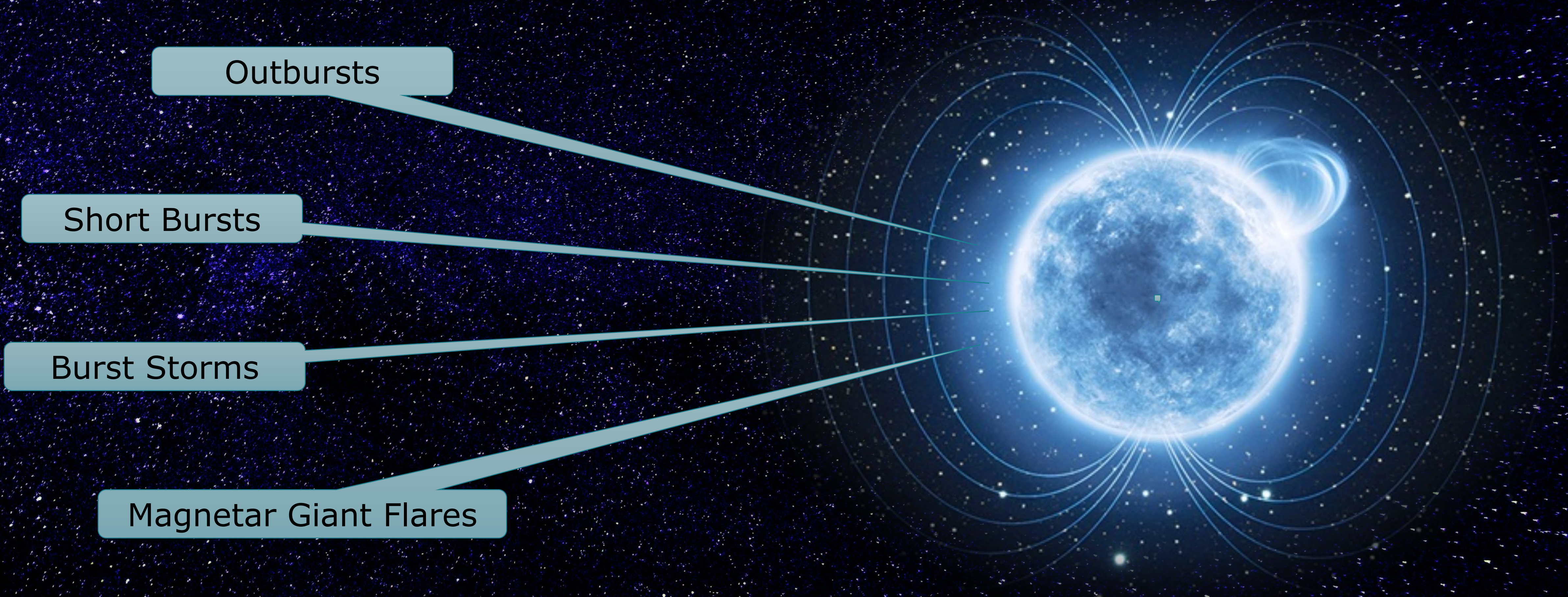
      $L \gtrsim 10^{33}\,\mathrm{erg\,s^{-1}}$
    - "Transient" magnetars

      $L \lesssim 10^{33}\,\mathrm{erg\,s^{-1}}$
- Spectra: absorbed blackbody (~0.3 – 0.5 kT) + power-law (Γ ~ -2 to -4)



Vogel et al. 2014

Transient activity of magnetars



ESA/ATG medialab

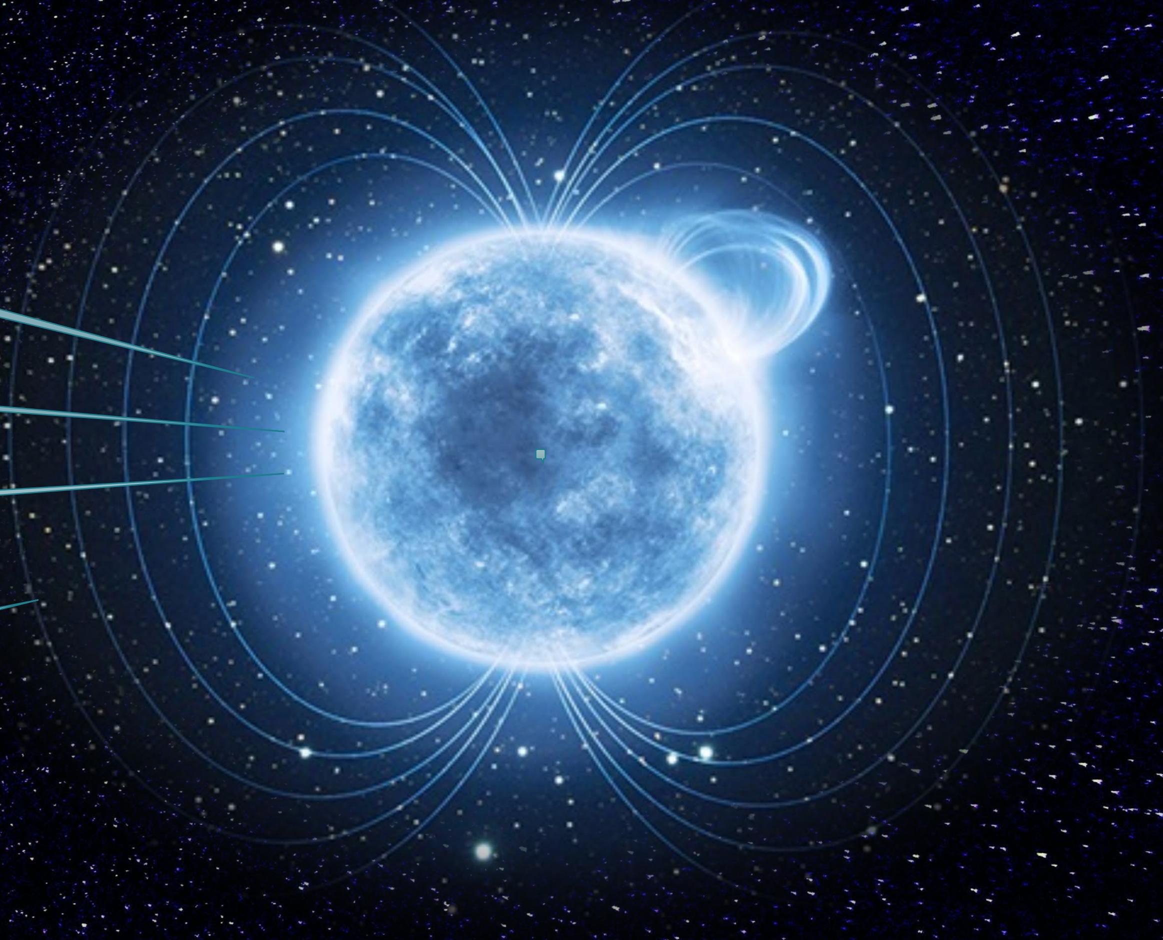
Transient activity of magnetars

Outbursts

<u>Outbursts</u>

- Emissions increase ~3 orders of magnitude
  - $L \sim 10^{36}$ erg s^{-1}
  - Fast rise in flux (hours — days)
  - Slower decay (weeks – years)

Magnetar Giant Flares



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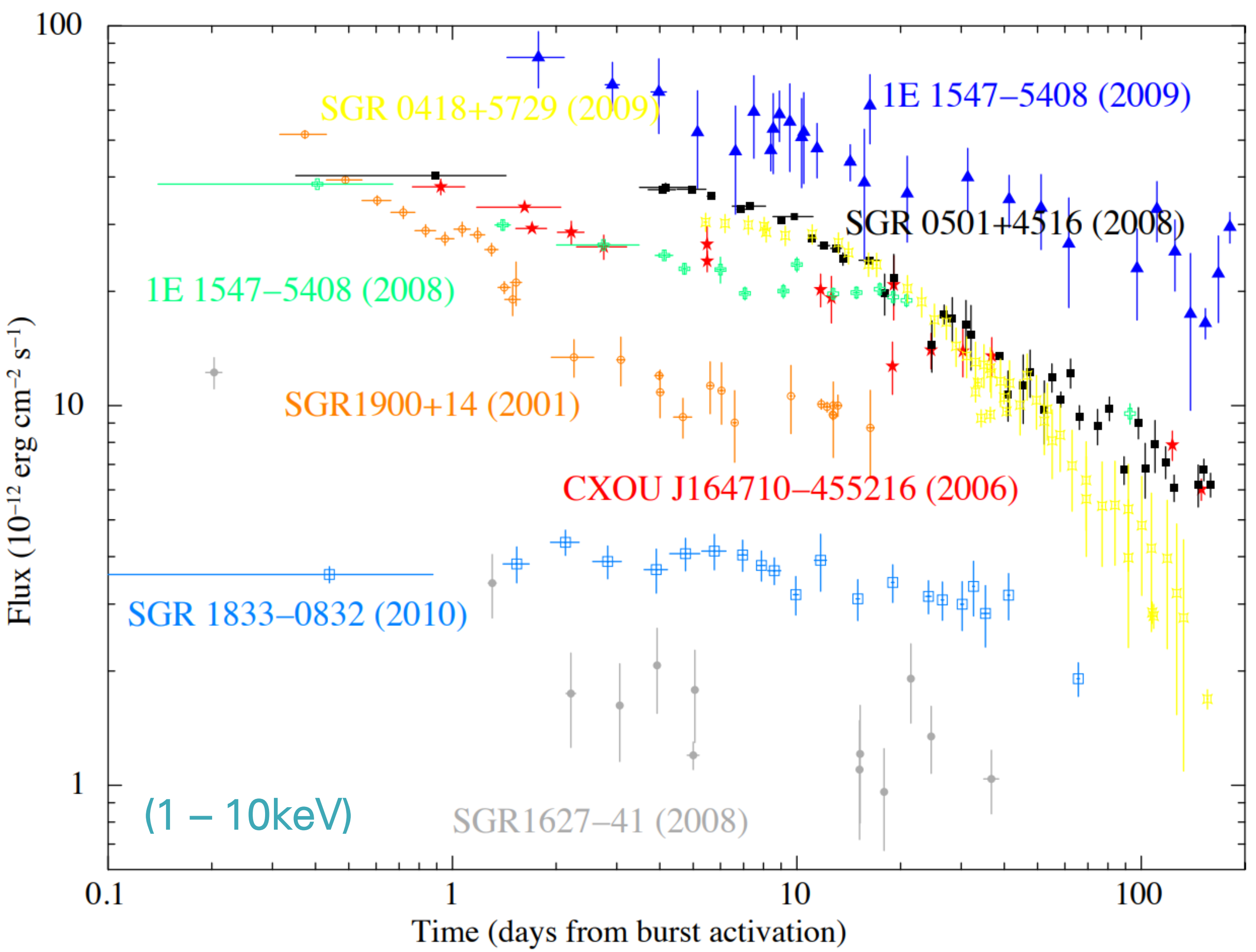
Magnetar Outbursts

- Radiative anomalies
  - Spectral hardening
  - Decrease in pulse fraction
- Timing anomalies
  - Spin-up “glitch”
  - “anti-glitch’

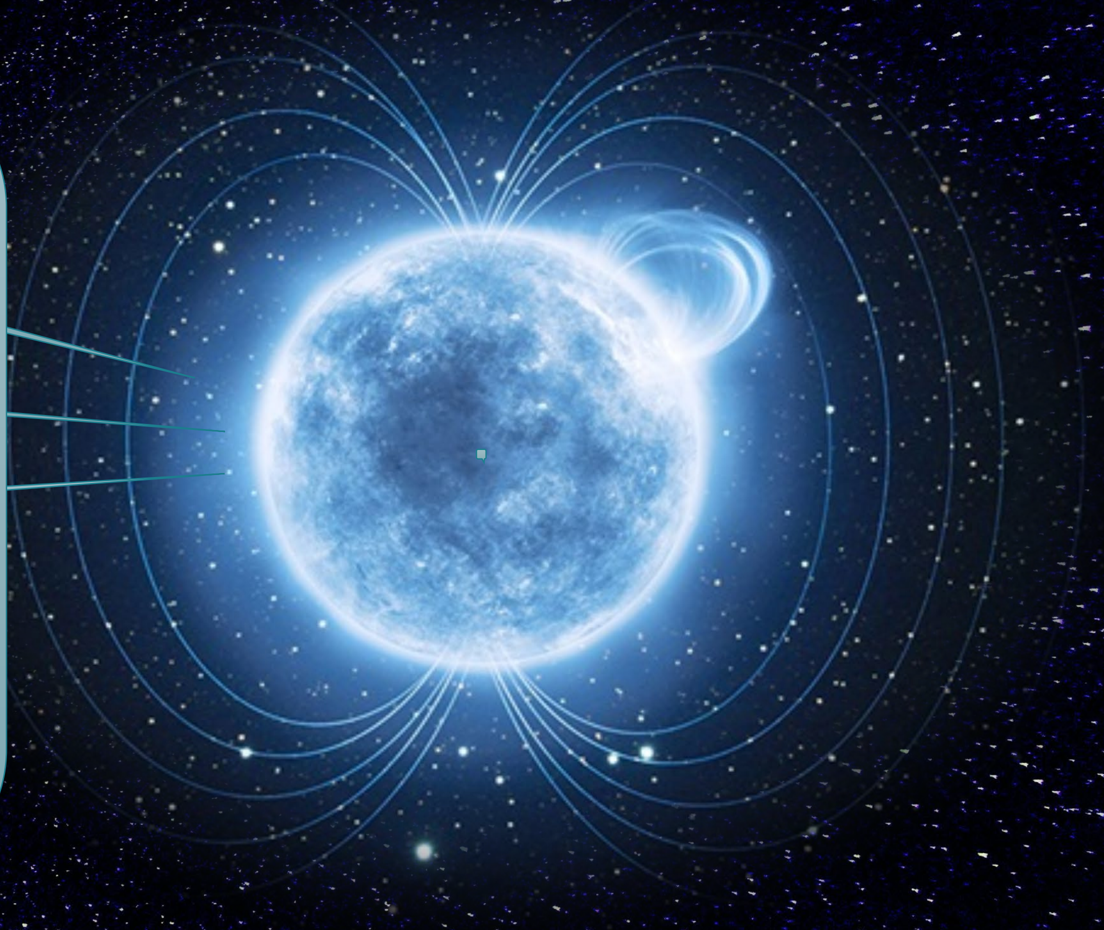


Rea & Esposito 2011

Transient activity of magnetars

<u>Short Bursts</u>

- The most common emission
  - Thousands clustered together (Soft Gamma Repeaters)
  - A handful of bursts (Anomalous X-ray Pulsars) or none
- Durations: ~ms
- $L \sim 10^{39}$ - 10^{42} erg s^{-1}



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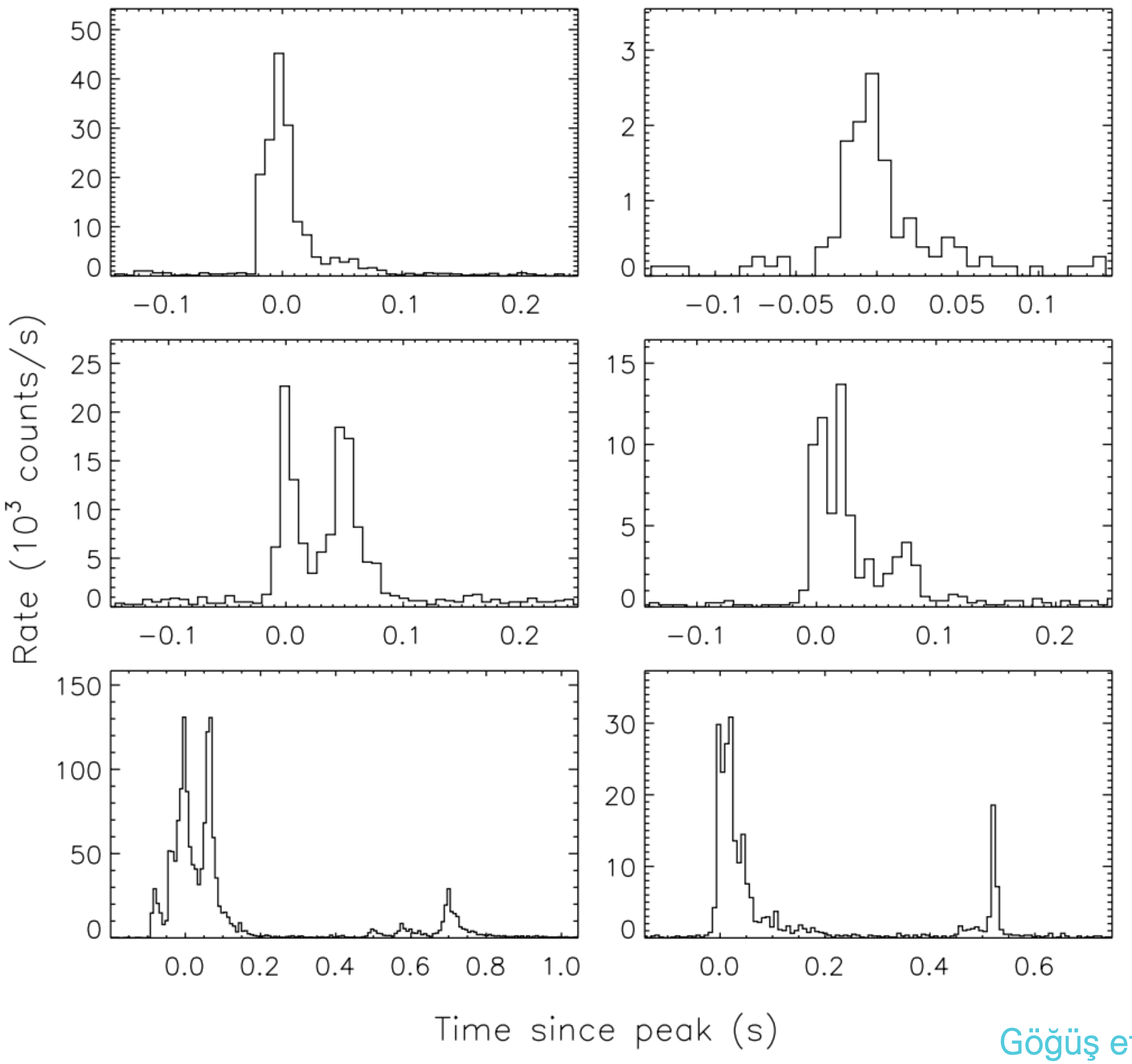
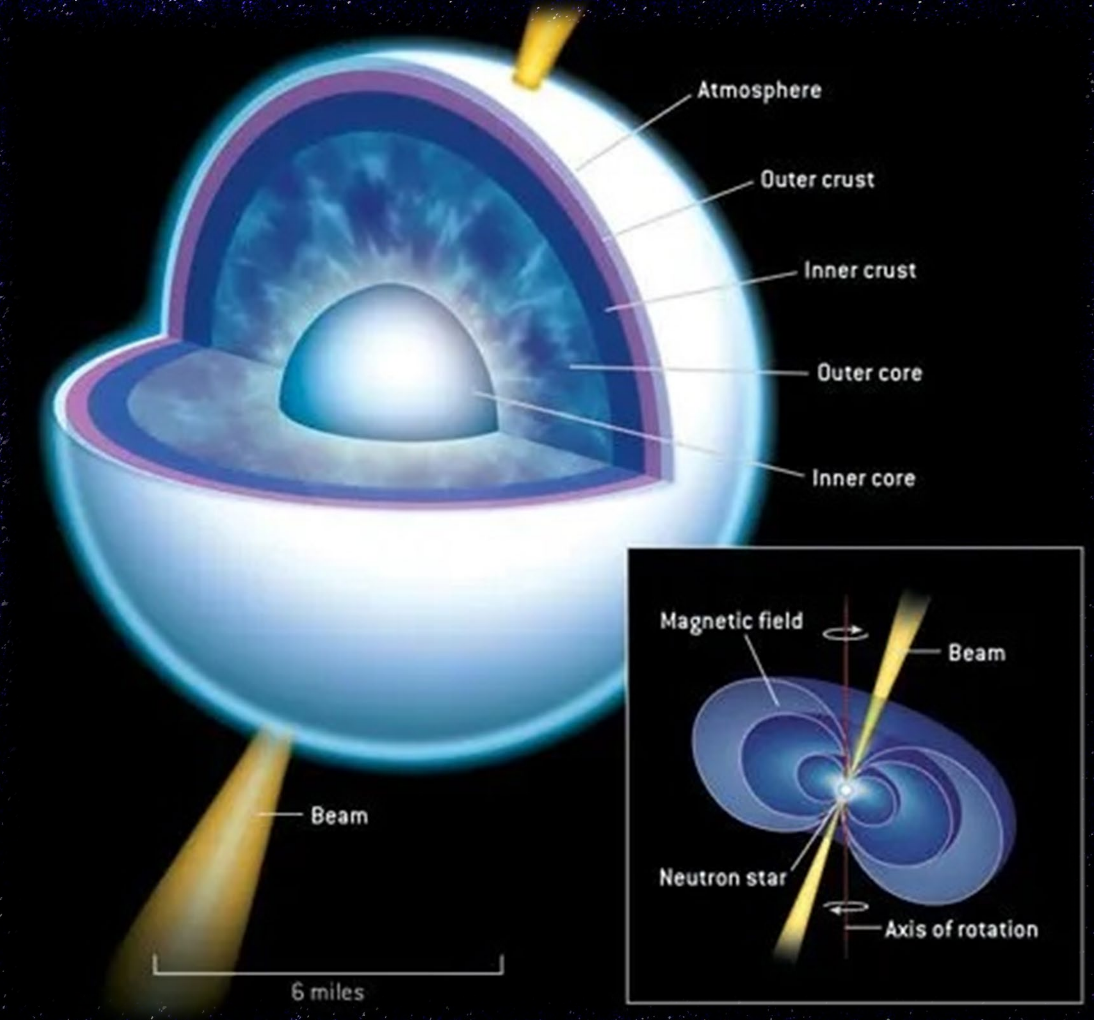
Magnetar Short Bursts

Time profiles of some SGR 1900+14 and SGR 1806-20 → short bursts
(on 7 ms timescale)



Göğüş et al. 2001

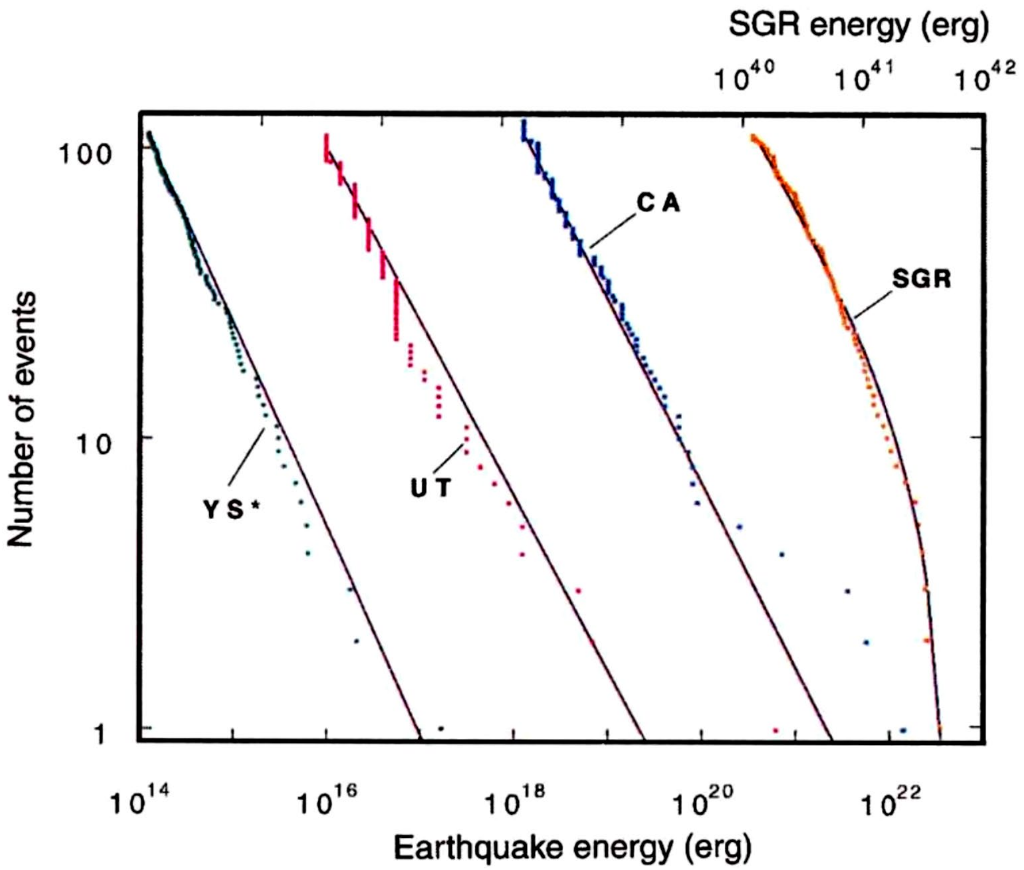
Starquakes

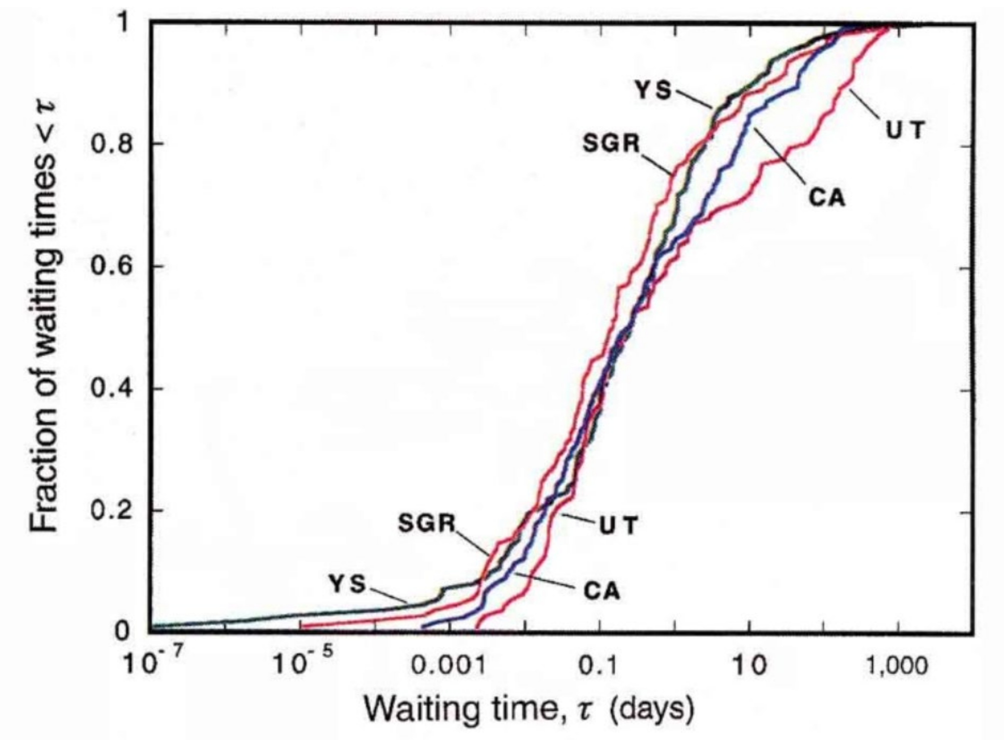


Astronomy, March 2005

- Nearly incompressible crust
- Growing magnetic stresses build up in the crust
- STARQUAKE!
- Plasma fireball results

Magnetar Short Bursts





Fluence distribution: Gutenberg-Richter power law.

The frequent starquakes needed to produce SGR events require an energy source that can maintain a high level of strain in the crust. A possible candidate for this source is an evolving, super-strong stellar magnetic field of flux density ~ 10^{15} G

B. Cheng et al. 1995

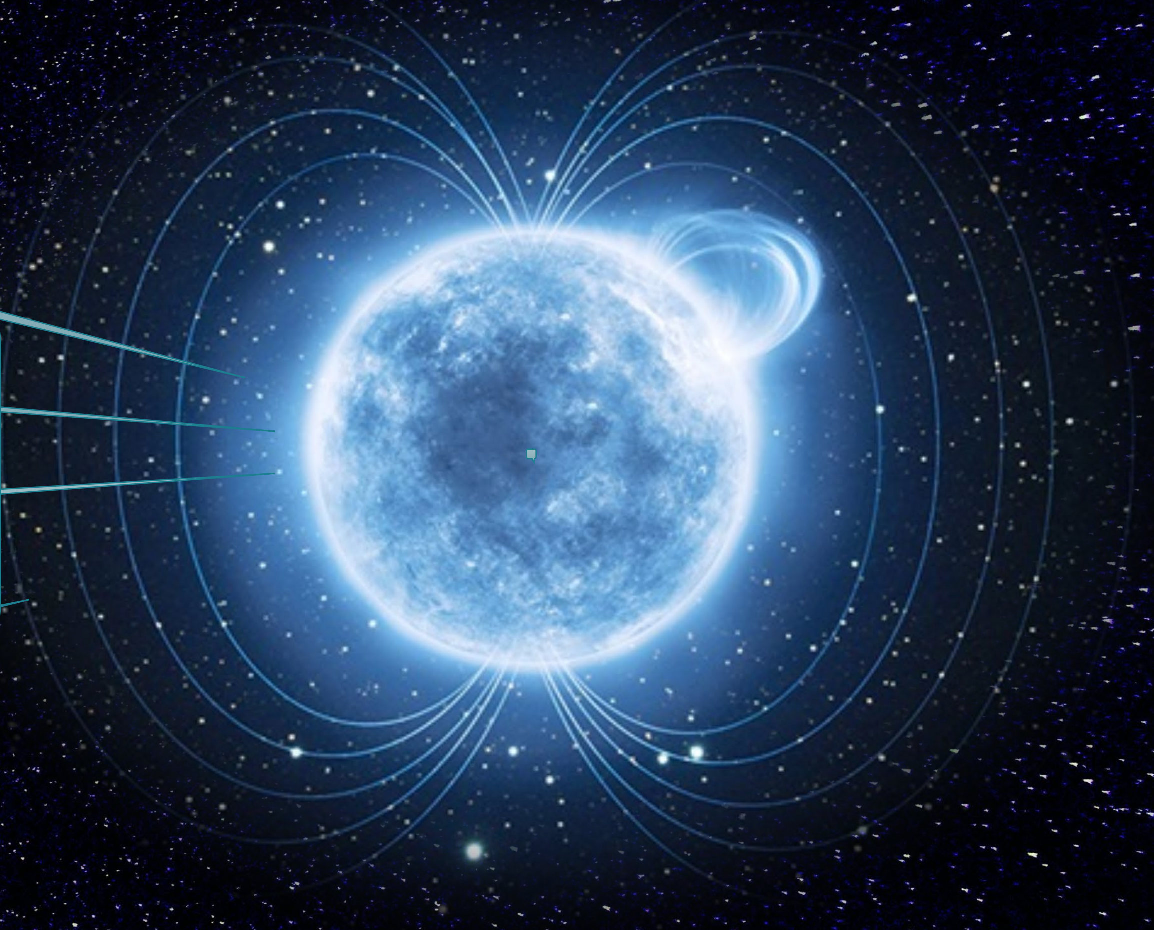
Transient activity of magnetars

Outbursts

Burst Storms

- Tens to thousands of bursts in short succession
  - Minutes – days
- $L \sim 10^{36}$ - 10^{42} erg s^{-1}

Magnetar Giant Flares



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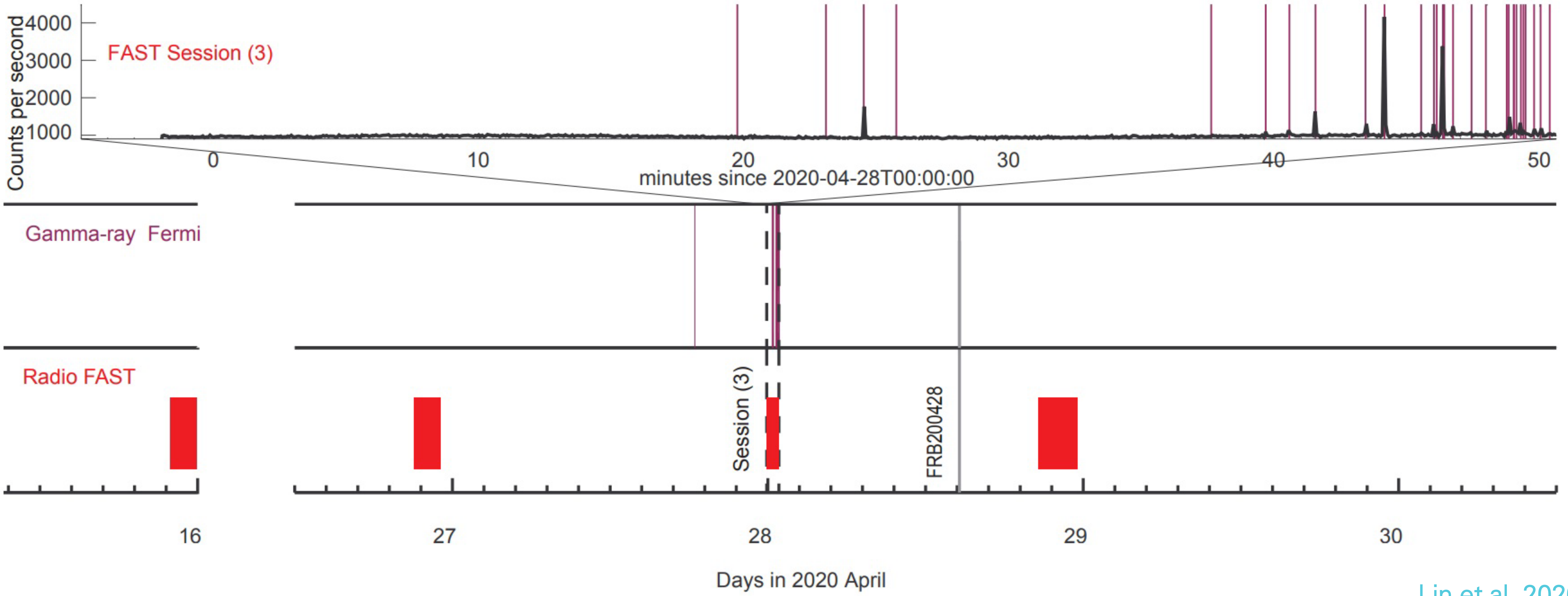
Burst Storms

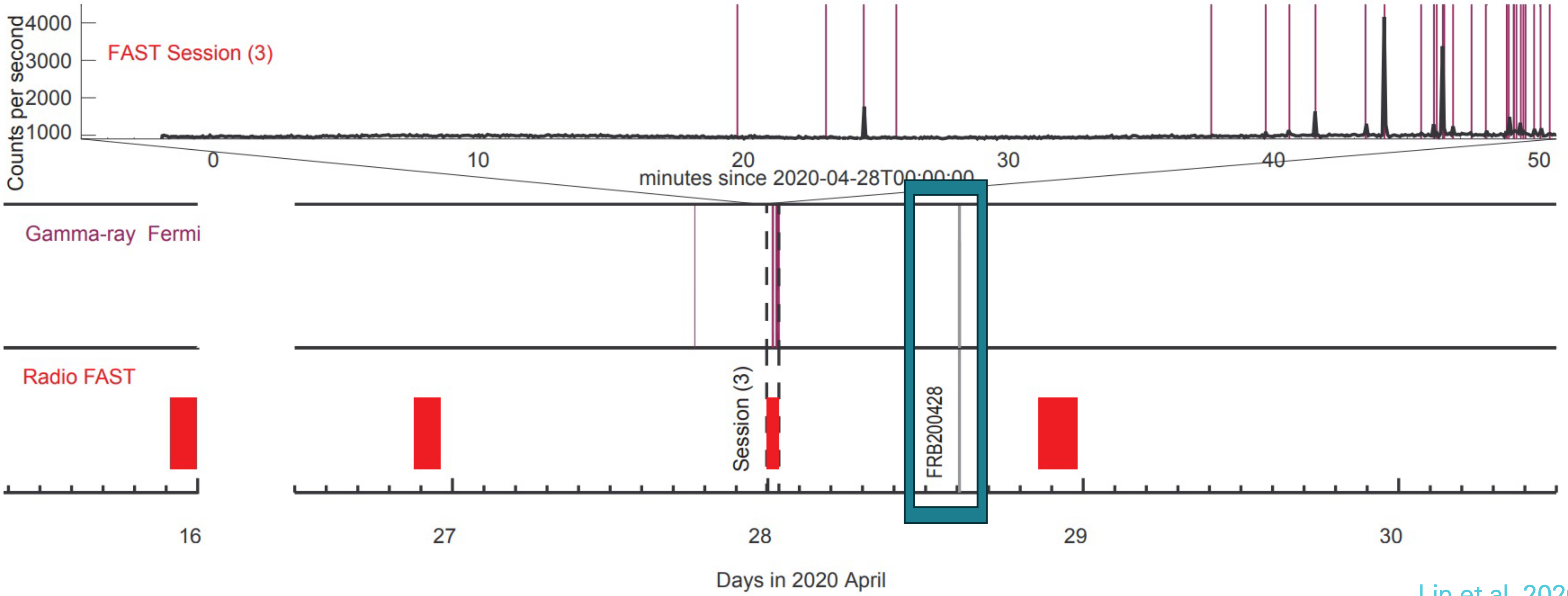
SGR 1935+2154



Lin et al. 2020

Burst Storms

SGR 1935+2154



Lin et al. 2020

Transient activity of magnetars

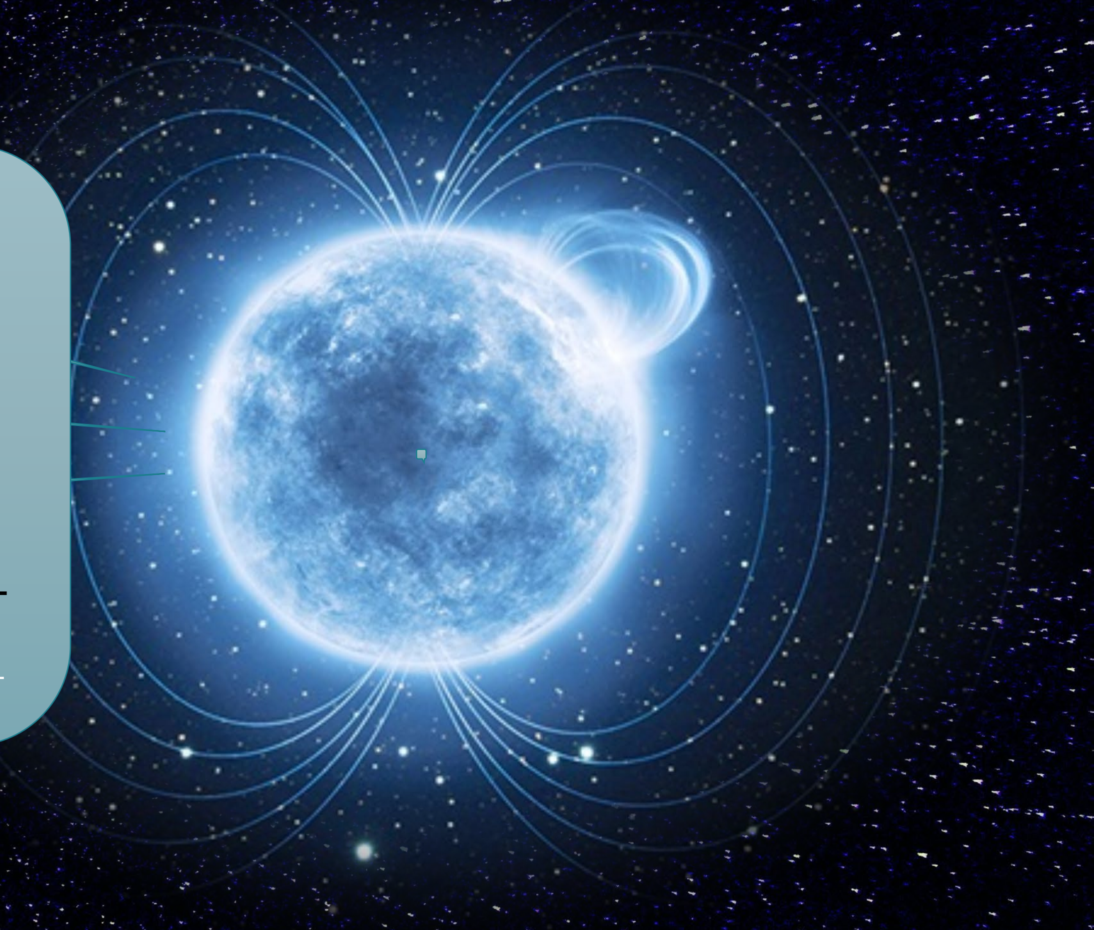
Outbursts

Magnetar Giant Flares (MGFs)

- Prompt (~0.1 ms) emission
- $L_{\text{peak}} \sim 10^{44} - 10^{48}\ \text{erg s}^{-1}$
- 7 observed: 3 Galactic, 4 Extragalactic
- Inferred volumetric rate: $R_{MGF} = 3.8^{+4.0}_{-3.1} \times 10^{5}\text{Gpc}^{-3}\ \text{yr}^{-1}$

Burns et al. 2021

Magnetar Giant Flares



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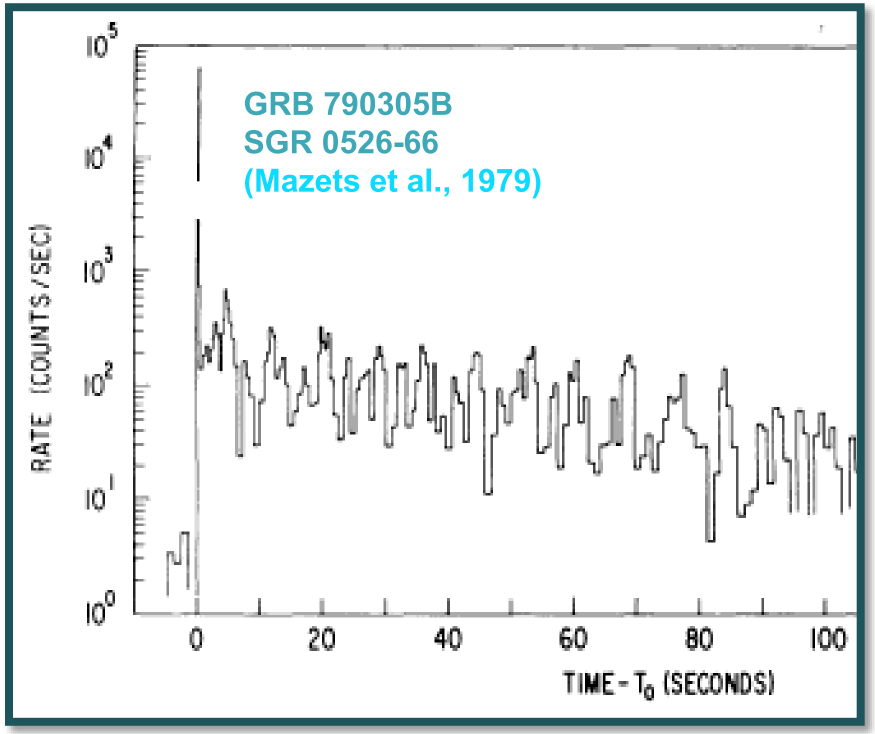
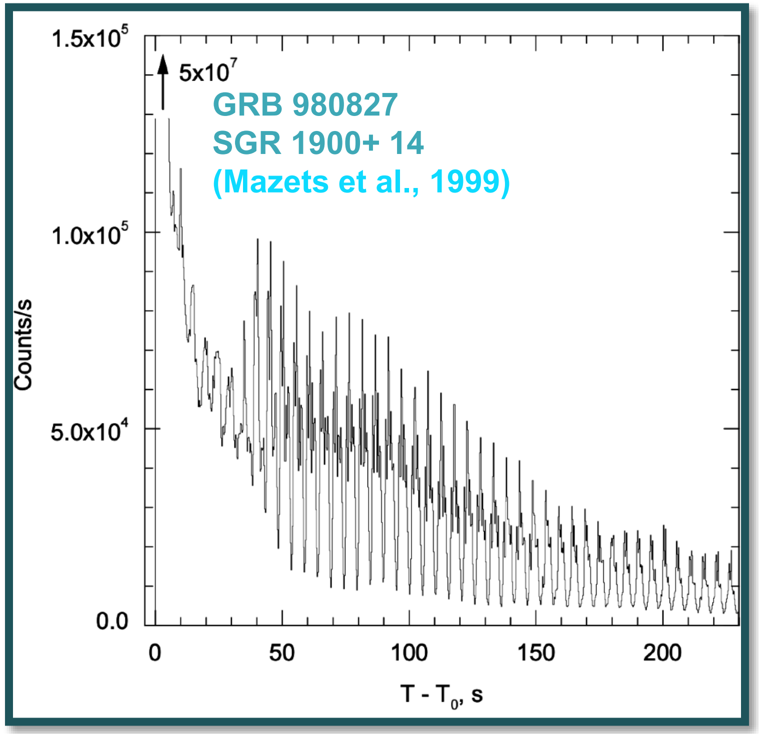
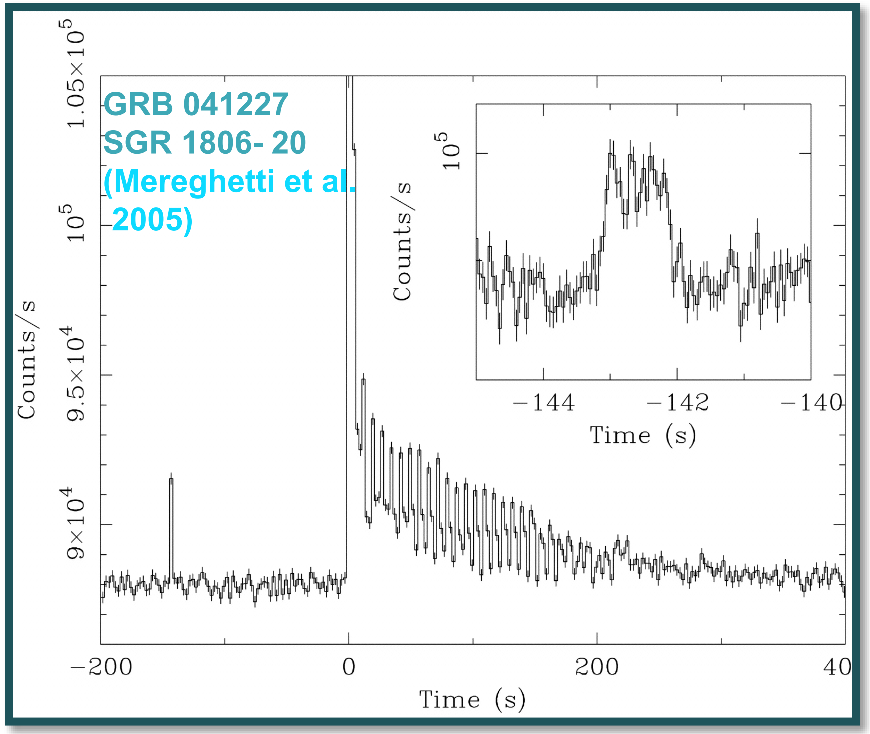
Galactic MGFs



	Initial Spike	Pulsating Tail
Duration (s)	0.25	200
Isotropic *E* (erg)	1.6 x 10^{44}	3.6 x 10^{44}
Periodicity (s)		~8



Initial Spike	Pulsating Tail
0.35	400
1.5 x 10^{44}	1.2 x 10^{44}
	5.16



Initial Spike	Pulsating Tail
0.5	380
2.3 x 10^{46}	1.3 x 10^{44}
	7.56

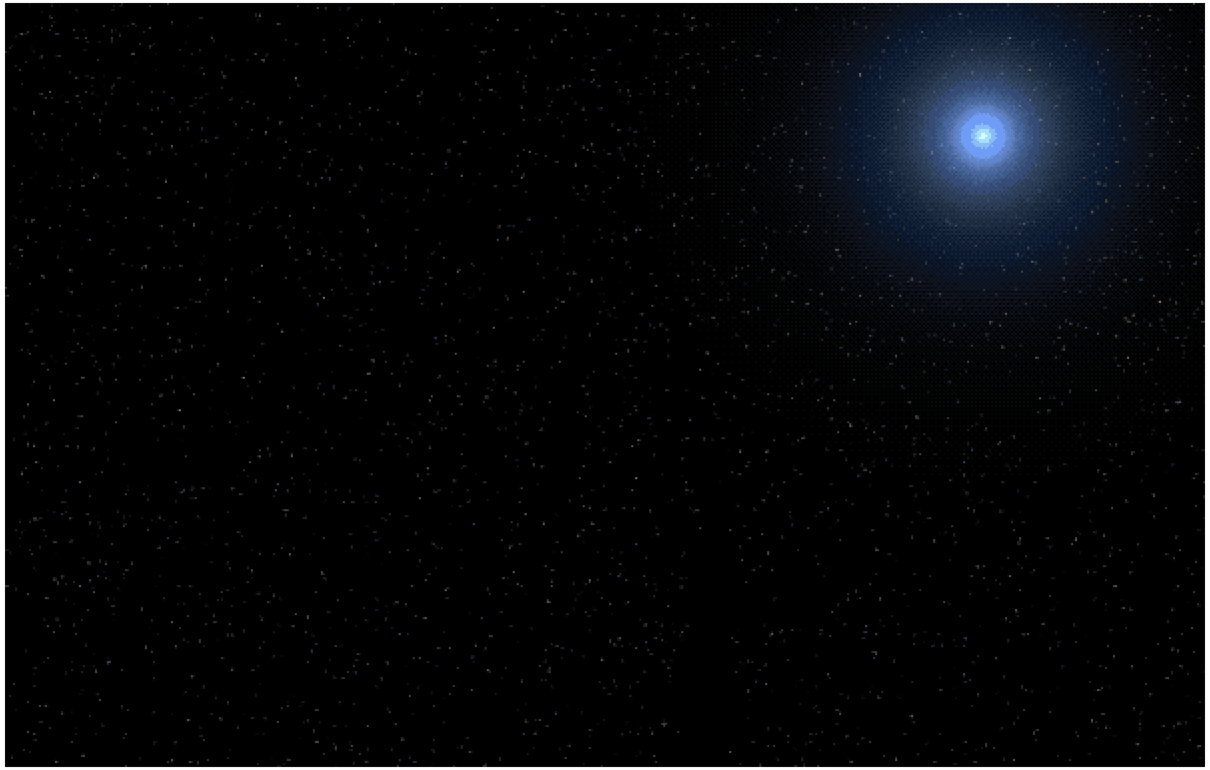
Galactic vs. Extragalactic MGFs

Galactic MGFs:

- Prompt (ms) emission
- Followed by periodic tail

Extragalactic MGFs:

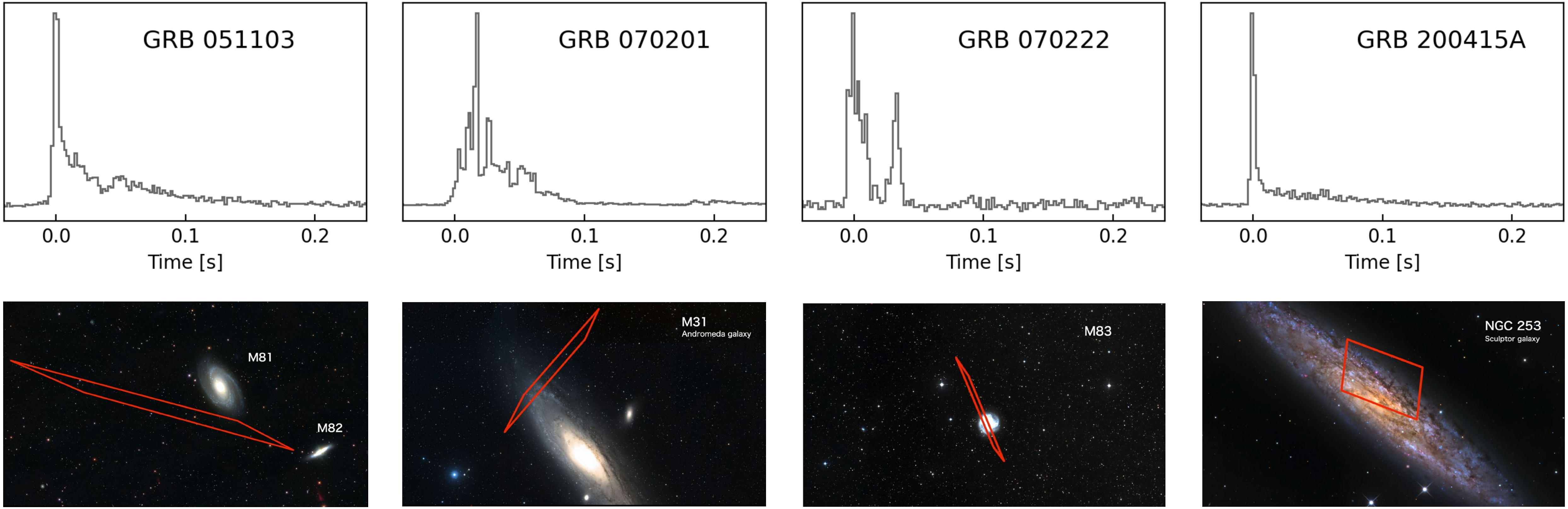
- Current instrumentation has not detected periodic tail emission
- Many could be masquerading as short GRBs
- Identification requires spatial alignment with nearby star forming galaxies



Credit: NASA Goddard/S. Wiessinger

Extragalactic MGF Candidates

Burns et al. 2021

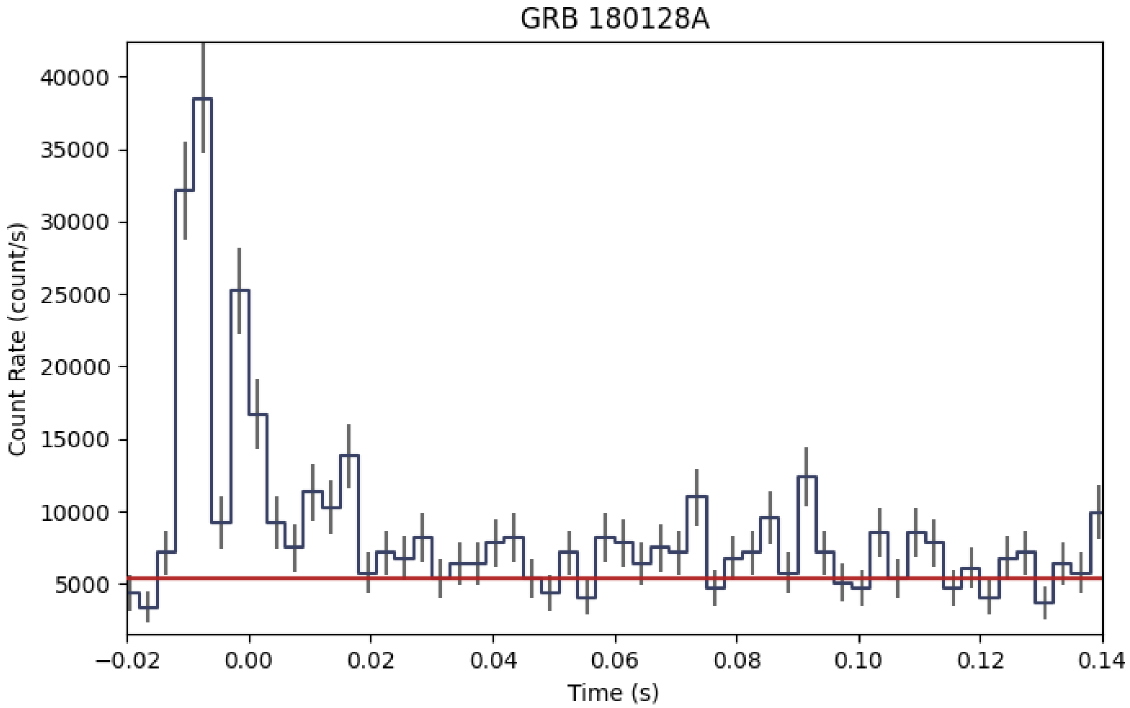


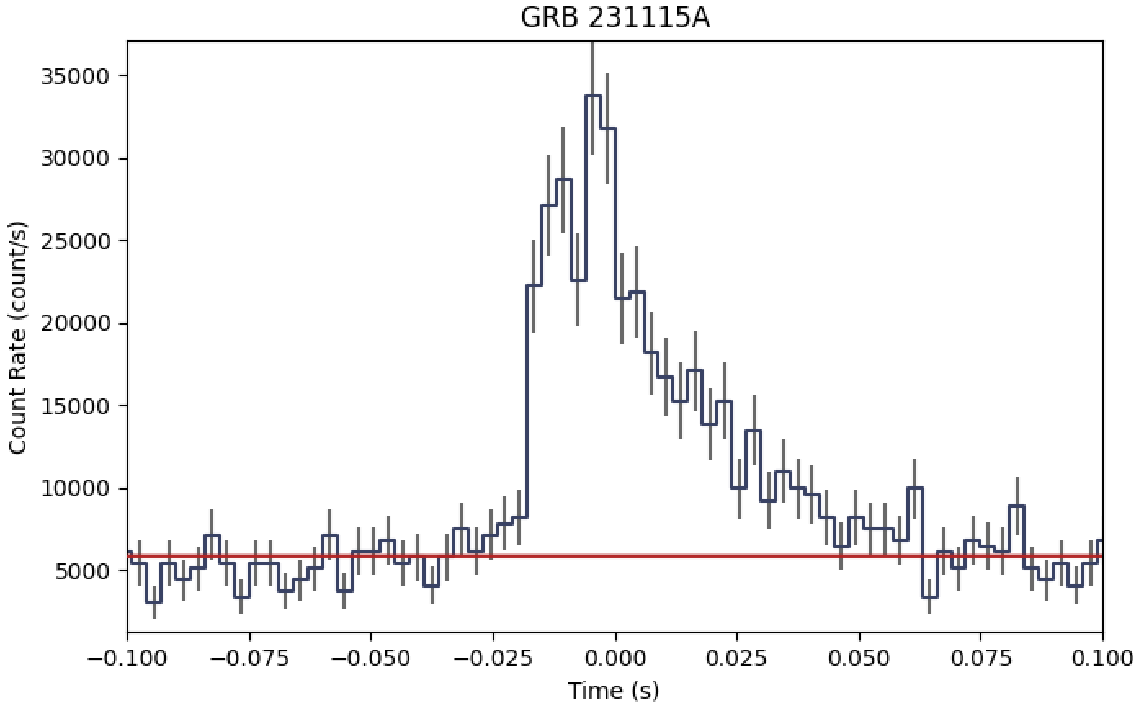
- Peak rise time: ~1-4 ms
- Burst duration: ~40-180 ms
- $E_{\mathrm{iso}} \sim 1.5 \times 10^{45}\mathrm{erg} - 9.2 \times 10^{46}\mathrm{erg}$

- No optical transients detected: SN origin ruled out
- No gravitational wave: Binary NS merger excluded
- Multi-pulse variability observed in three most recent

Extragalactic MGF Candidates

Two new candidates!





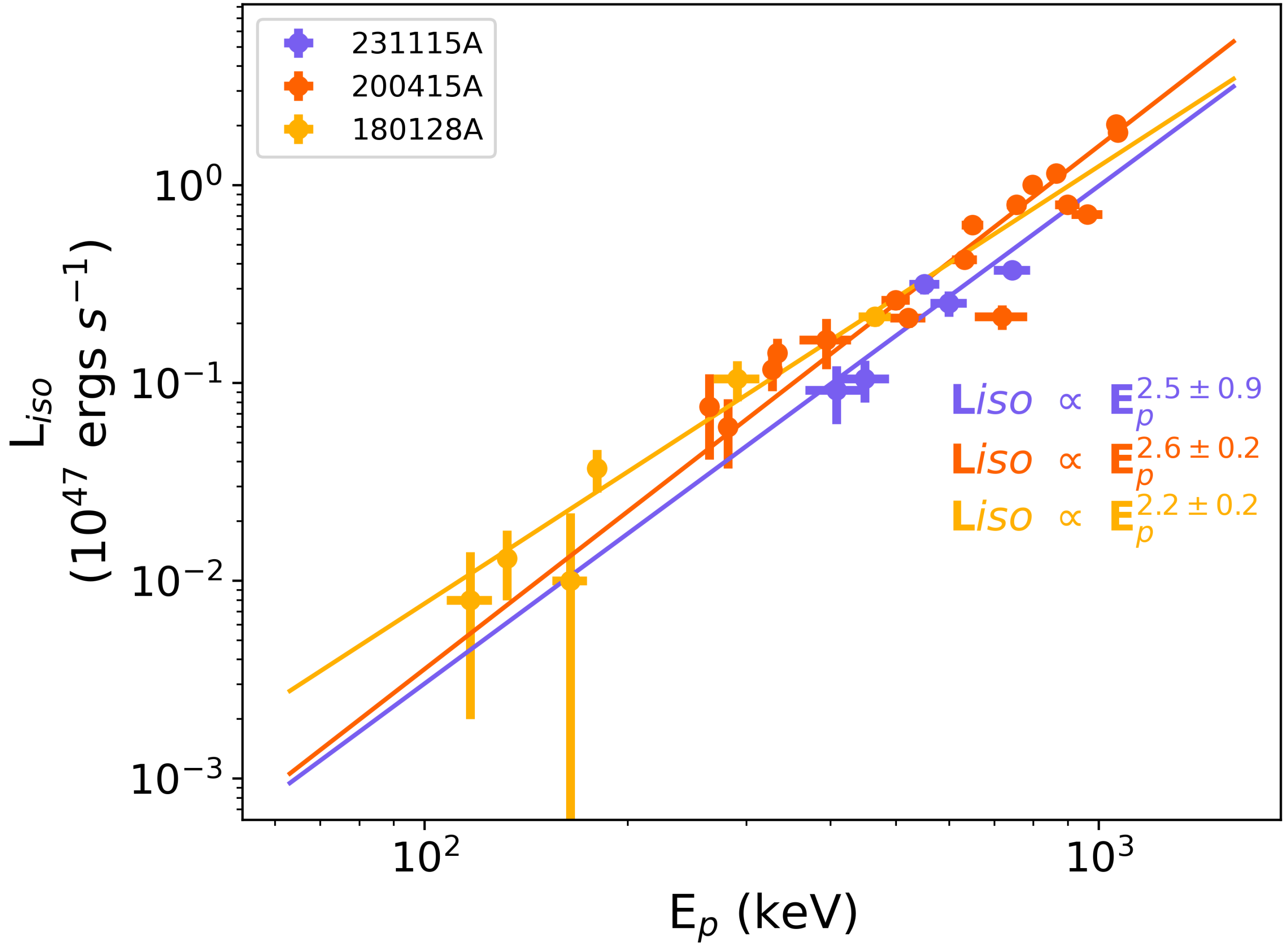
- Localized to NGC 253
- $E_{\mathrm{iso}} = 3.9 \times 10^{45}\mathrm{erg}$ (Trigg et al., 2024)

- Localized to M82
- $E_{\mathrm{iso}} = 2.2 \times 10^{45}\mathrm{erg}$ (Trigg et al., in preparation; Mereghetti et al., 2023; Wang et al., 2023)

Extragalactic MGF Candidates

$L_{iso} \propto E_p^2$ strong signature of relativistic winds (Doppler boosting)

(Roberts et al., 2021)



Gravitational Waves (GW)

MGF tails exhibit quasi-periodic oscillations (QPOs)

→ Attributed to with quakes in NS crust (NS modes) (Abbot et al., 2008; Levin et al., 2011; Abadie et al., 2012)

	GRB 790305B	GRB 980827	GRB 051103
QPO frequencies (Hz)	43	28, 54, 84, 155	18, 30, 92.5, 150, 625, 1480

Fundamental *f*-modes plausible sources for GW

→ Previous searches reported upper limits (Abbot et al., 2008; Abadie et al., 2012)

GW detector network was ~100x less sensitive

→ Next generation detectors will be ~10,000x increase in sensitivity from past to future interferometers (Burns et al., 2023)

What can all this tell us?

Polarization measurements of magnetars

→ Determine magnetic field geometry and shape, dimension, and physical state of emitting region

Origin and physical mechanism of FRBs

→ Why FRB to burst activity not 1:1?

→ Time delay between radio and X-ray emission

GW, QPOs to probe NS equation of state

→ Observations will give unique insights into dense matter, the crust/core interface of these objects, and origins of SGR flares

Understanding MGFs

→ Understanding the emission mechanism

→ Constrain intrinsic rates and energetics of MGFs

Magnetar formation channels

→ Explore formation channels beyond CCSN model

Thank You!

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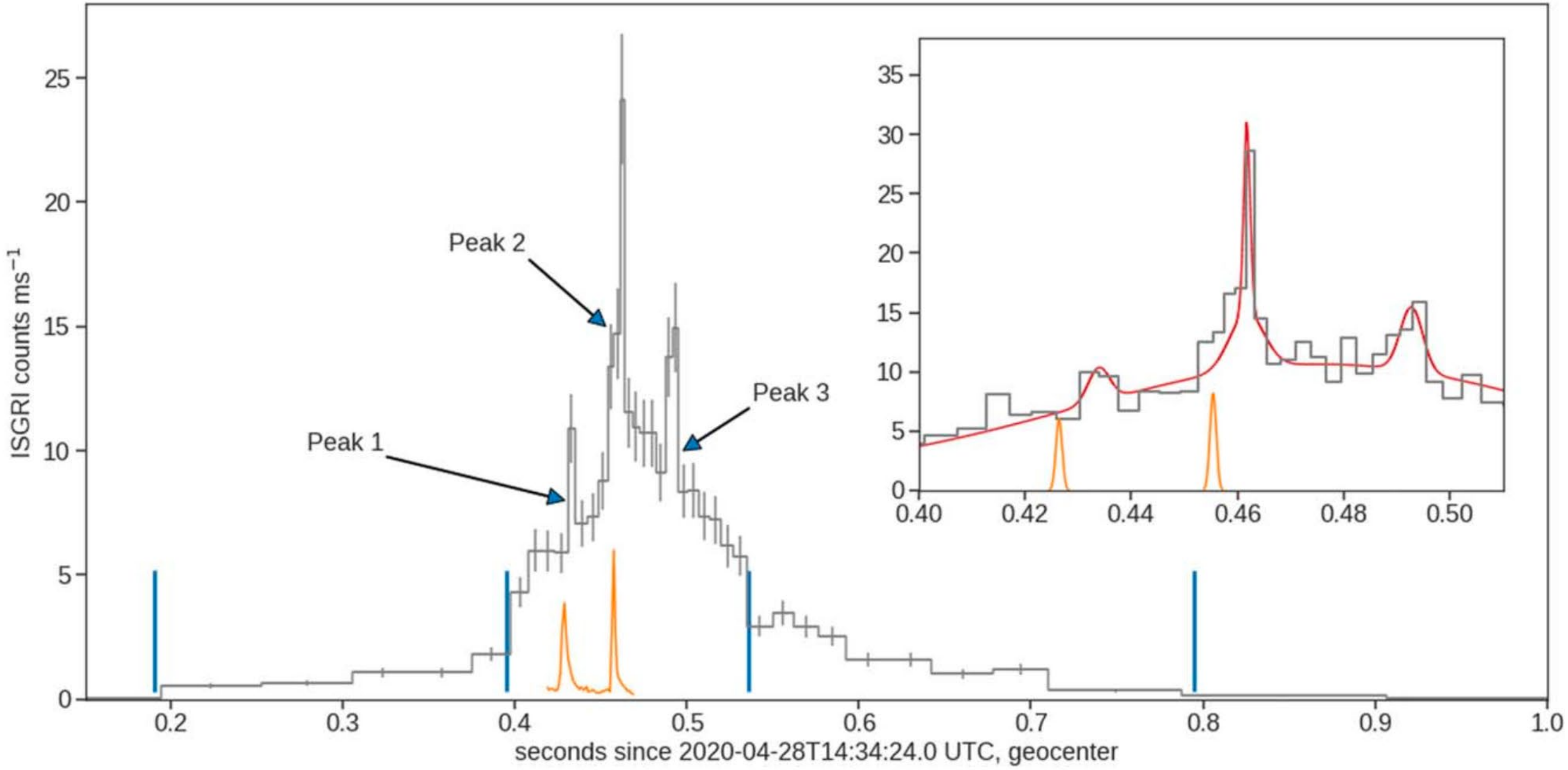
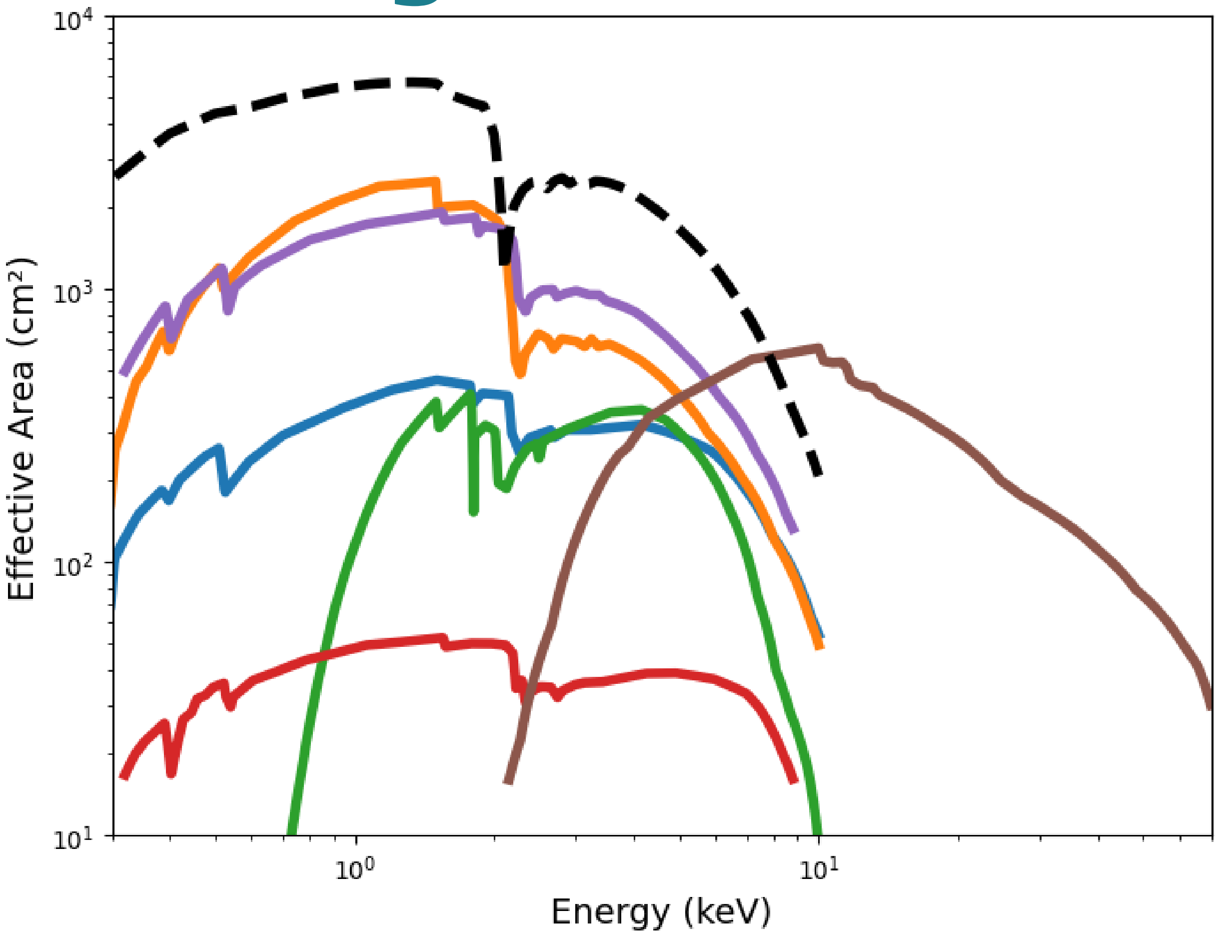
Burst Storms

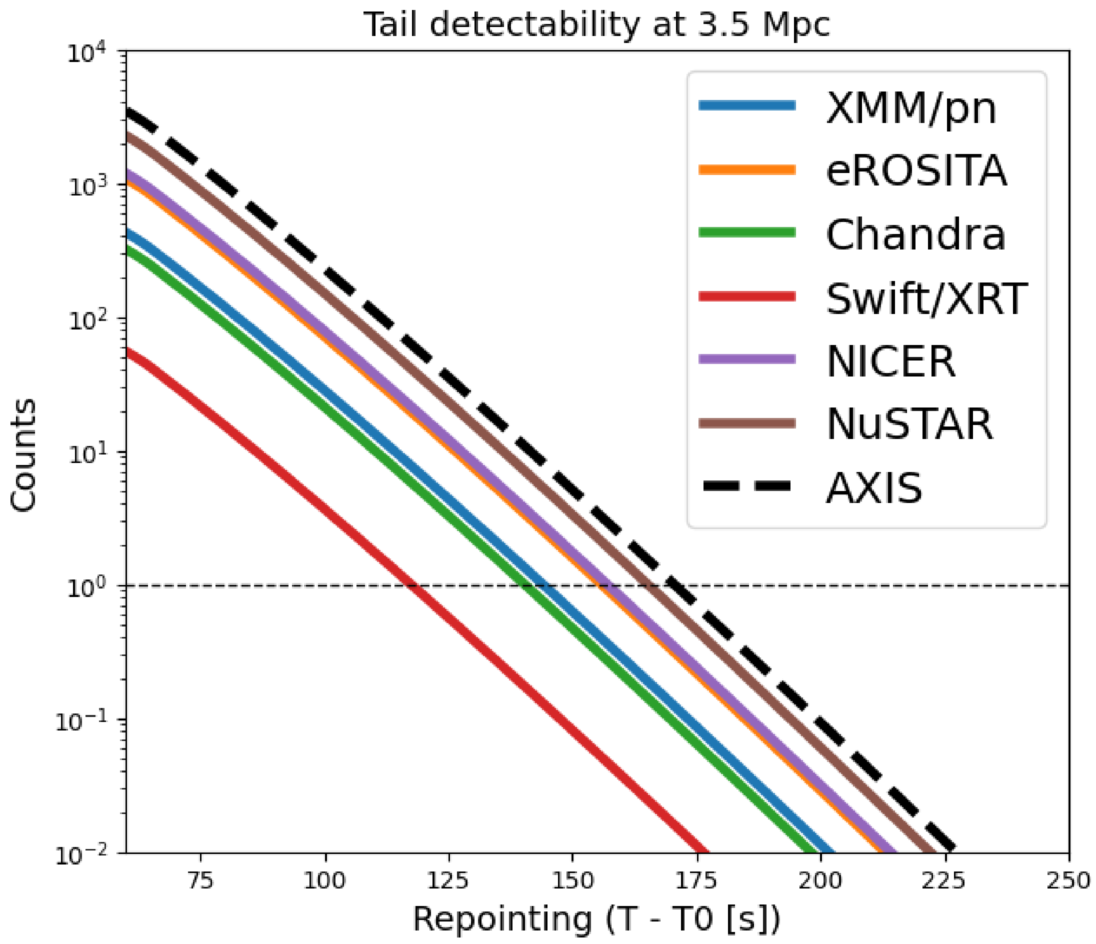
Fast radio burst observed from SGR 1935+2154



Mereghetti et al. 2020

Extragalactic MGF tails





Rapid repointing of existing/future instruments could recover the tail
→ lead to unambiguous identification of extragalactic MGFs

Negro et al. (submitted)