Overview and Recent Progress of Magnetar Observations

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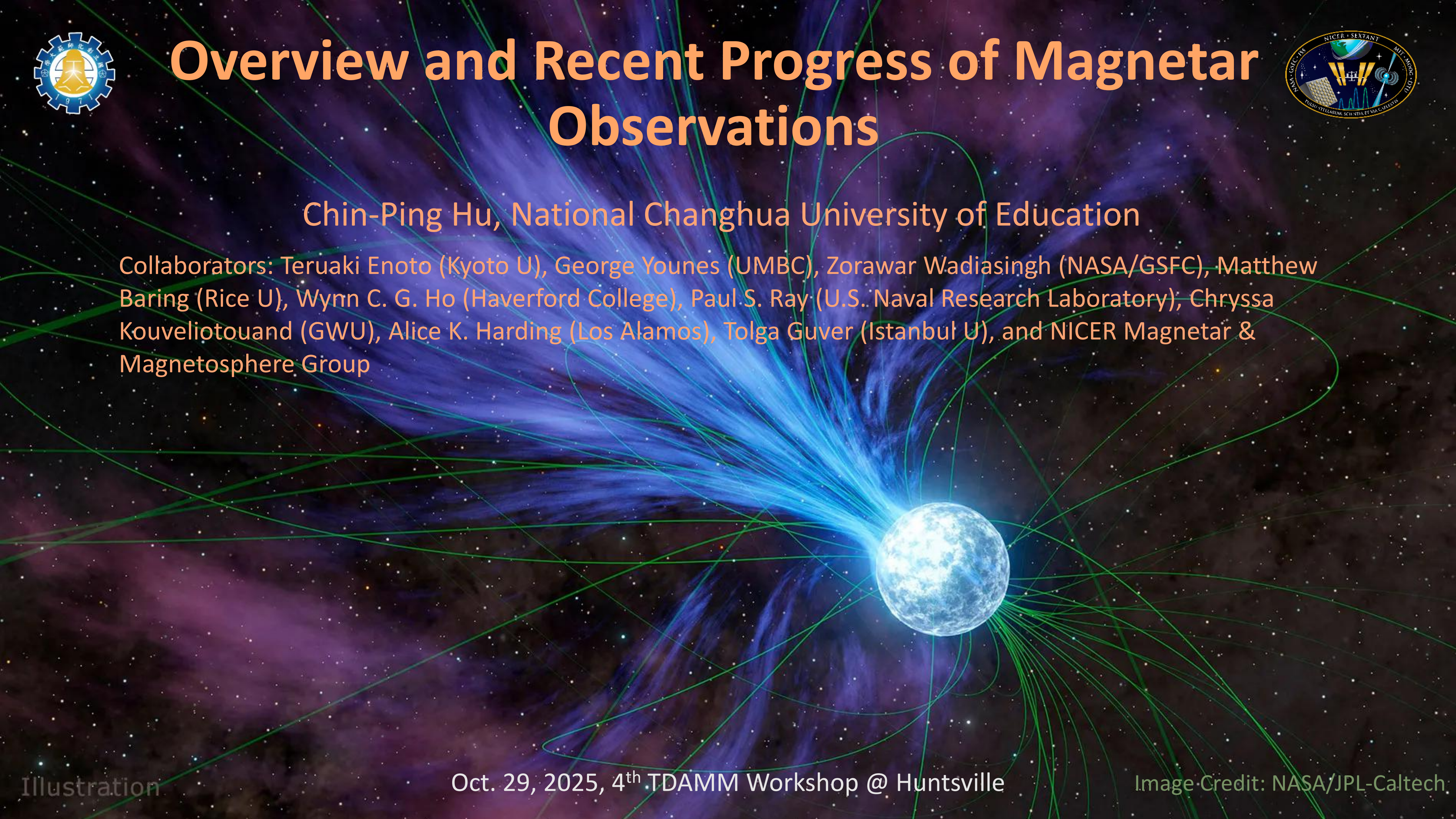


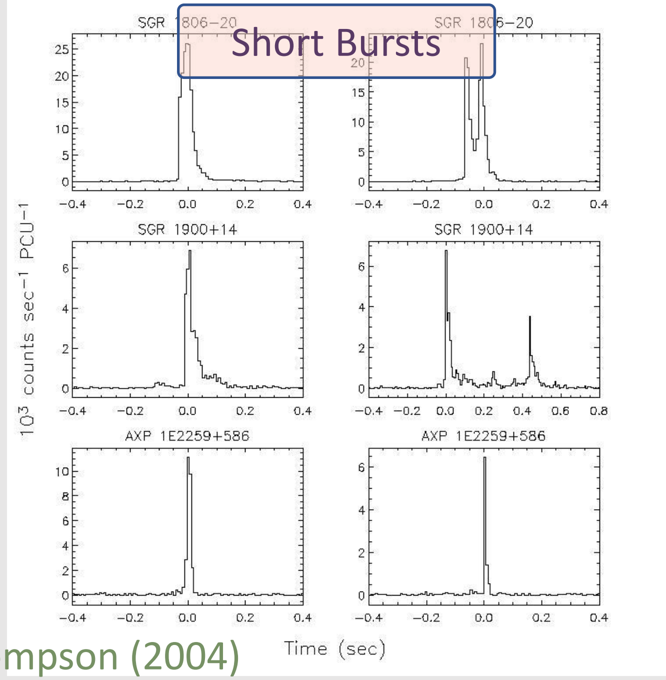
Oct. 29, 2025, 4th TDAMM Workshop @ Huntsville

Image Credit: NASA/JPL-Caltech

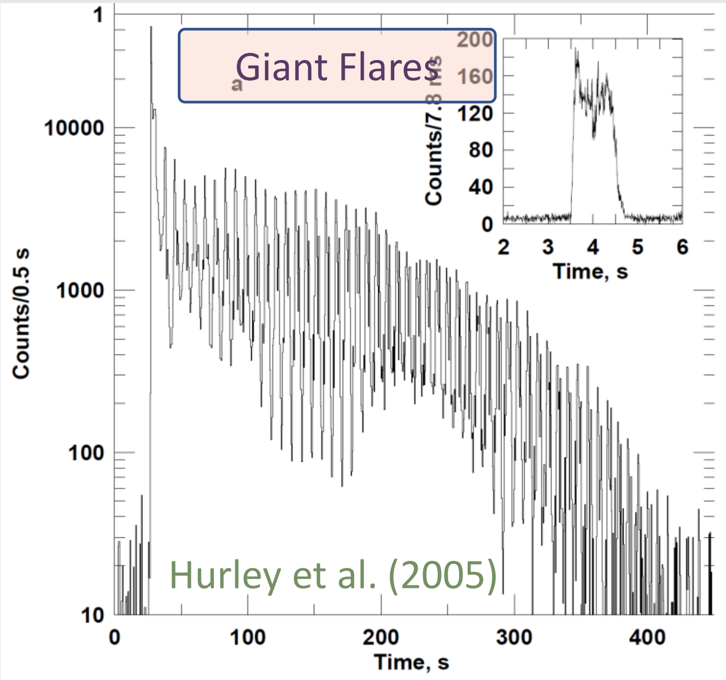
Magnetars: Discoveries and Early Observations

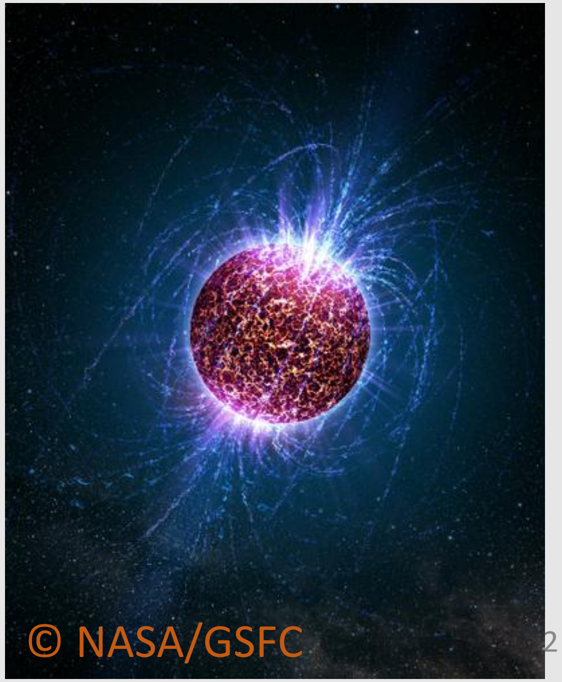
- A powerful GRB was detected in 1979
  - Softer than regular GRBs
  - Repeat bursts.
- A few more SGRs are discovered in 1980s
  - Short burst ($10^{39} - 10^{41}$ ergs)
  - Intermediate flares ($10^{41} - 10^{43}$ ergs)
  - Giant flares (> 10^{44} ergs)

- SGRs are neutron stars
  - No stellar companions
  - Long rotation period (2-12 s)
  - Large spin-down rate $\dot{P} \sim 10^{-13} - 10^{-11}\, s\, s^{-1}$
  - Large magnetic fields $\gtrsim 10^{14}$ G
  - Powered by extremely high magnetic fields – magnetars



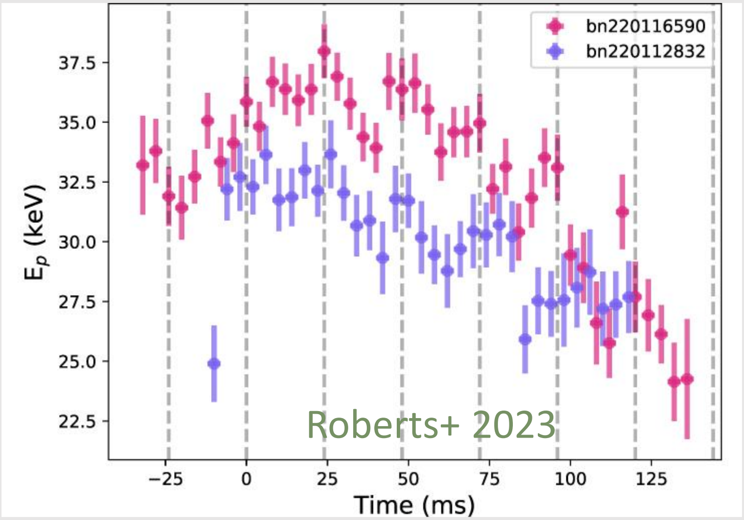
Woods & Thompson (2004)



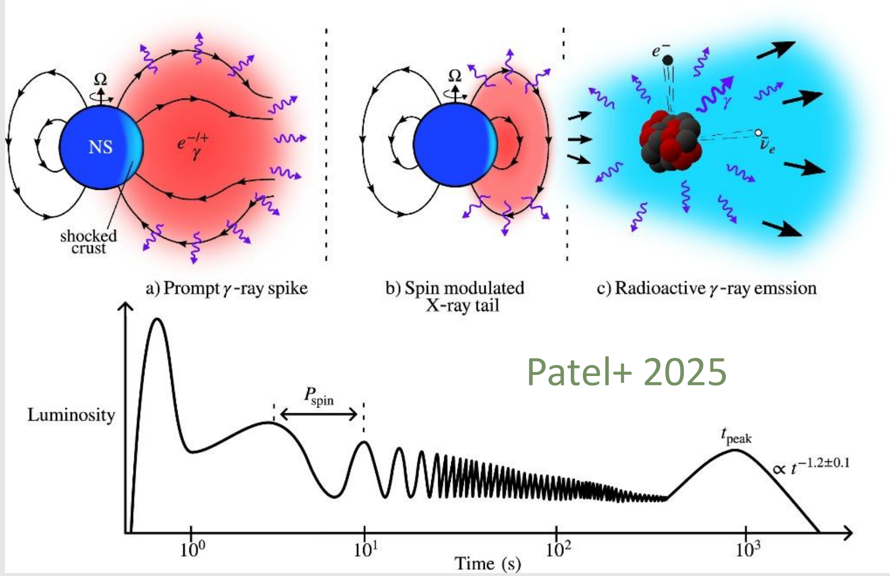


Giant Flares

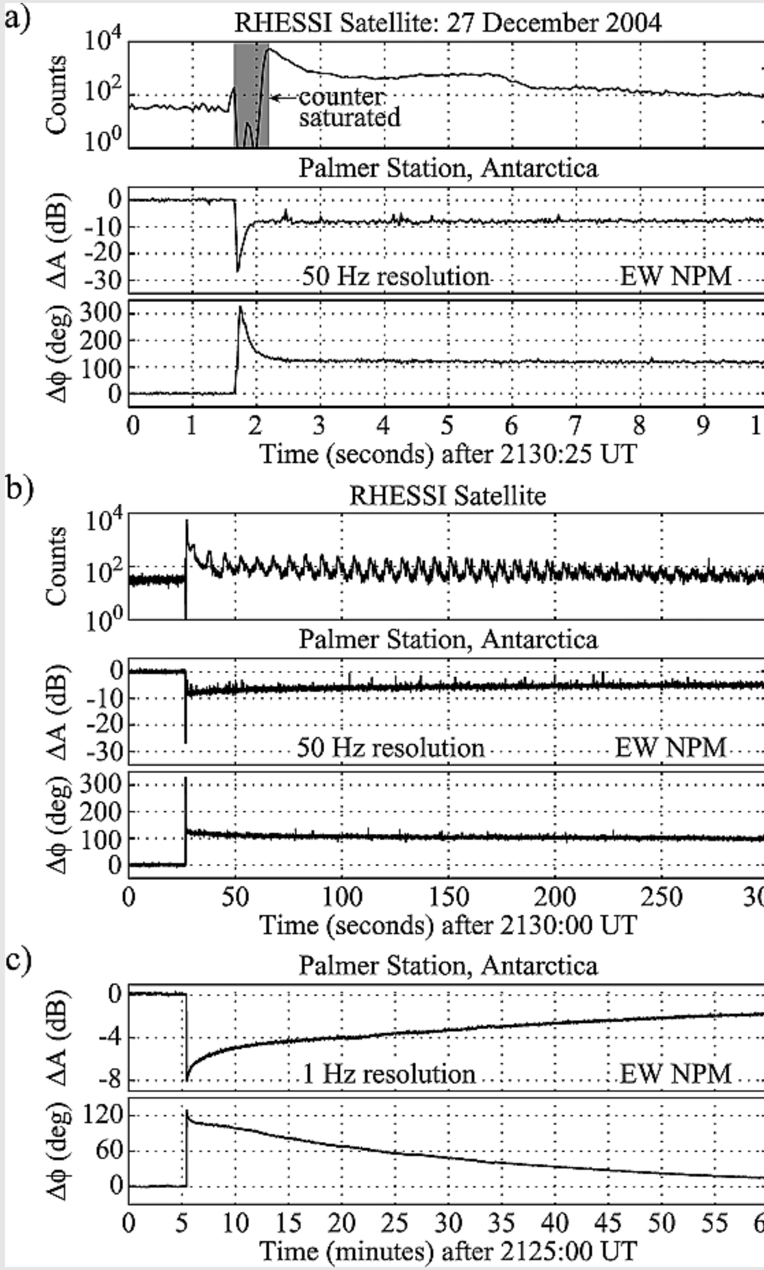
- Giant flares are usually followed by a long-lasting quasi-thermal pulsating tail.
- Detailed nucleosynthesis calculations confirms the r-process in the magnetar giant flare in SGR 1806+20.
- Possible quasi-periodic oscillation were detected in magnetar giant flares (e.g., Miller+2019) and short bursts (e.g., Roberts+2023).
- The giant flare from SGR 1806+20 disturbed heavily on Earth's ionosphere.



Roberts+ 2023



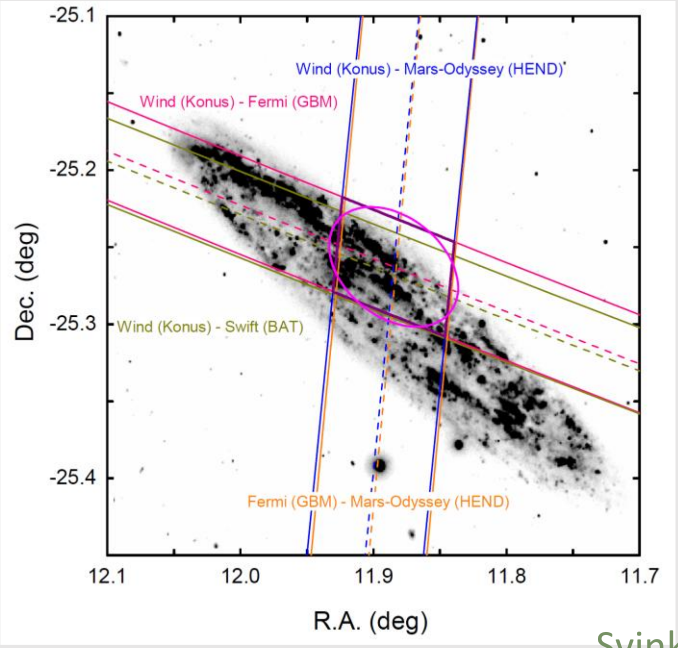
Patel+ 2025

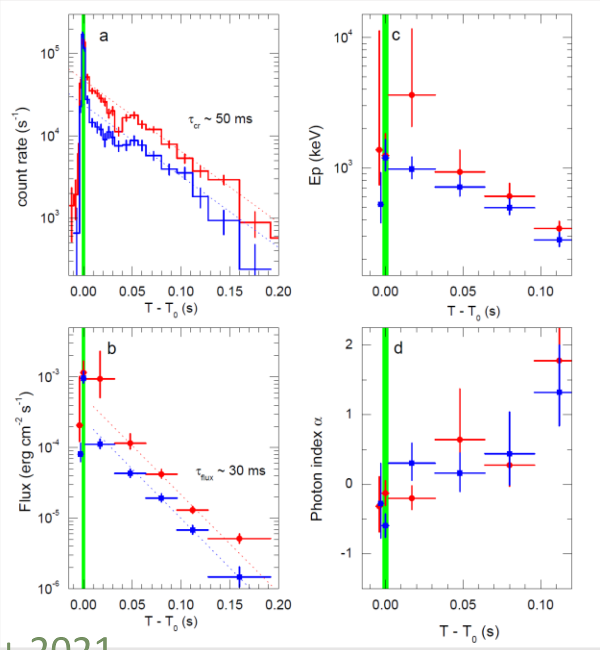


Inan+ 2007

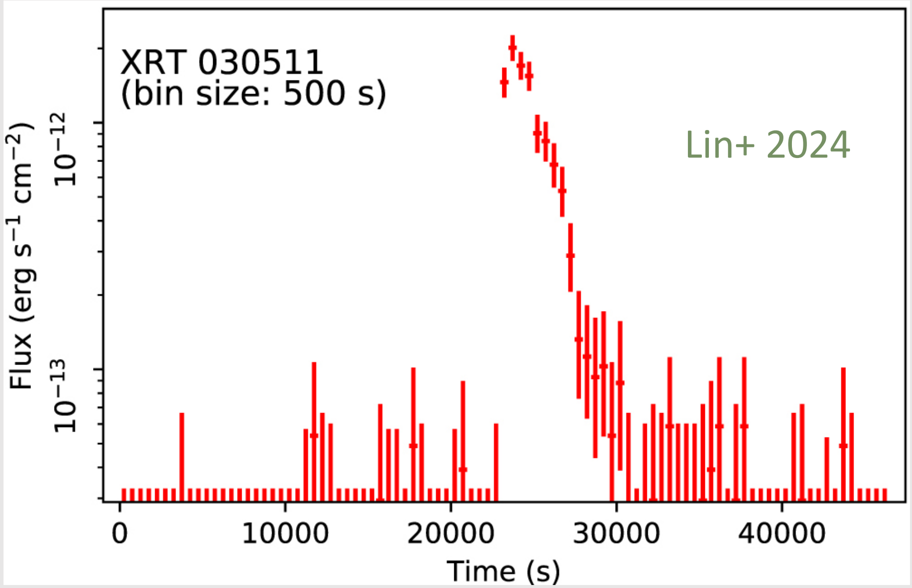
Extragalactic Giant Flares

- GRB 200415A (in NGC 253) and GRB 231115A (in M82, Mereghetti+2024) are most likely powered by magnetar giant flares.
  - Hard initial spike + softening tail
- Comprehensive analyses of short GRBs indicate occurrence rates consistent with magnetar giant flares (MGFs), at approximately $4 \times 10^5\ Gpc^{-3}\ yr^{-1}$ (Burns+2021)
- Magnetar flares are strong candidates for some fast X-ray transients (e.g., Lin+2024, Negro+2025)



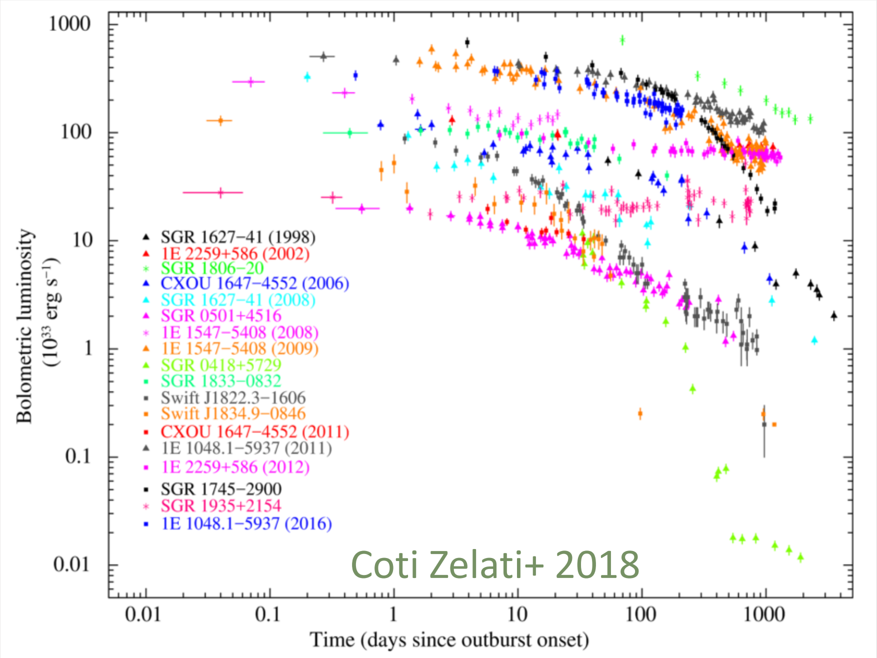


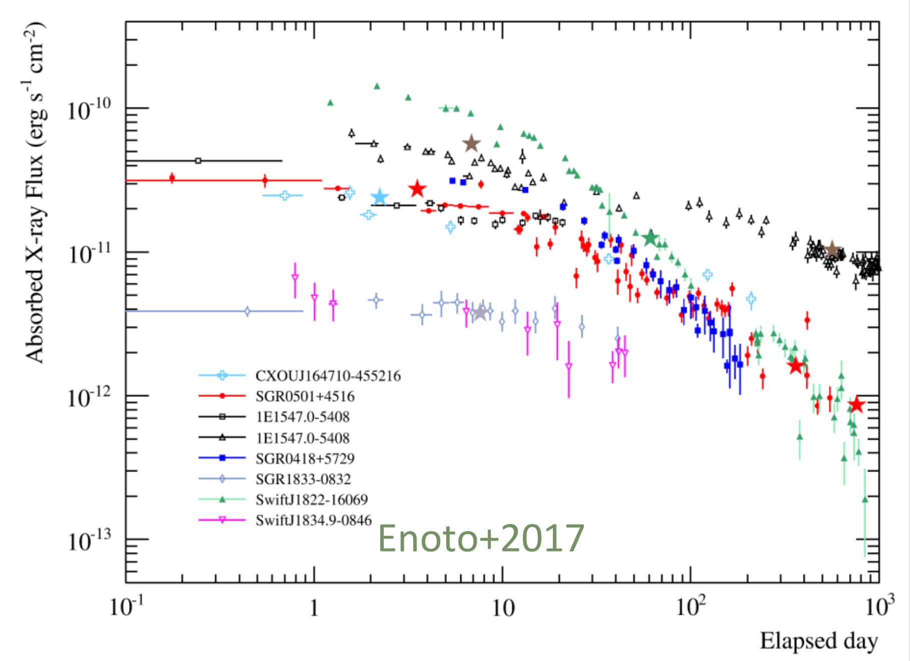
Svinkin+ 2021



Magnetars: Transients

- Prompt follow-up observations clarify magnetar outburst properties.
  - Magnetars with lower quiescent luminosity exhibit a larger increase in luminosity during outbursts.
  - X-ray light curves of magnetar outbursts are best modeled by a "plateau-decaying" function (Enoto+2017) or multiple exponential components (Coti Zelati+2018)
  - High B-field magnetars show outbursts with slower and more prolonged decay (Enoto+2017).
  - No strong correlation found between B-field strength and either maximum outburst luminosity or decay timescale. A stronger link exists between magnetic field and total outburst energetics (Coti Zelati+2018).
  - All findings point to the B-field dissipation as the main energy source for magnetar outbursts.



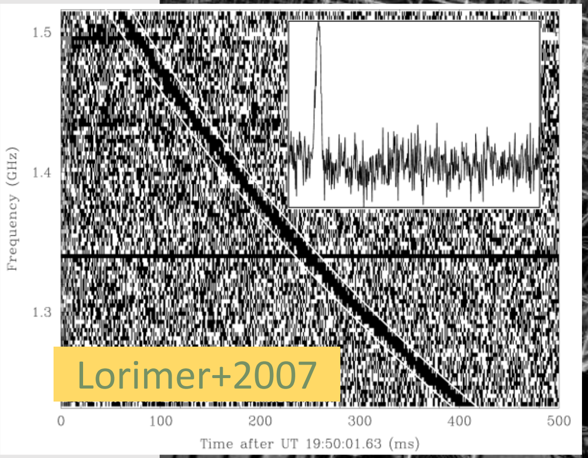


Magnetars: NICER Era

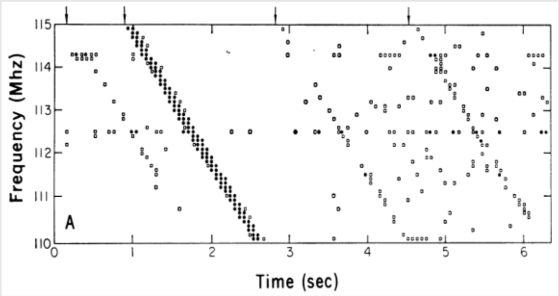
Year	Source	Note	Reference
2017 Jul.	4U 0142+61	Re-brightening; pulse profile change	
2019 Feb.	XTE J1810-197	Re-brightening; radio loud magnetar	Guver+2019 Borghese+2021
2020 Mar.	Swift J1818.0-1607	New magnetar; radio-loud; fast-spinning; RPP-like	Hu+2020 Rajwade+2022
2020 Apr.	SGR 1935+2154	FRB-like event; burst storm	Younes+2020 Younes+2021
2020 Aug.	PSR J1846-0258	Magnetar-like RPP; second outburst	Hu+2023
2020 Oct.	SGR 1935+2154	Radio pulsating; spin-down Glitch	Younes+2023
2020 Oct.	SGR 1830-0645	New magnetar; pulse peak migration	Younes+ 2022a,b Coti Zelati+2021
2021 Jun.	Swift J1555.2-5402	New magnetar; long-lasting outburst	Enoto+2021
2022 Oct.	SGR 1935+2154	FRB-like event; burst storm; double glitch; spectral change	Hu+2024 Hu+2025
2024 Aug.	1E1841-045	Re-brightening; glitch; profile evolution; polarization measurement (with IXPE)	Younes+2025 Stewart+2025

Fast Radio Bursts (FRBs)

- Short radio pulses (~millisecond)
  - Compact origin? ($R \sim c\Delta t \sim 30R_{NS}$)
- Large dispersion (DM ~ 300-1600 cm^{-3} pc)
  - Extragalactic sources
- Very energetic (up to ~10^{42} ergs)
  - Solar luminosity: 3.8 x 10^{33} ergs/s
- Their origins are largely unknown
  - Periodic: binary system, …
  - Repeating: magnetars/pulsars, …
  - Non-repeating: mergers, … ?

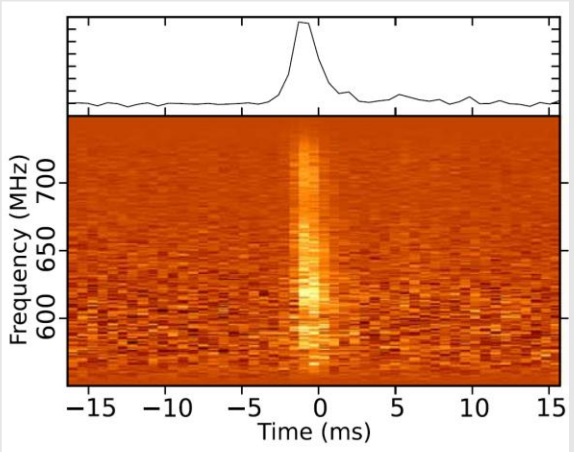


NS/Magnetar – FRB Connection



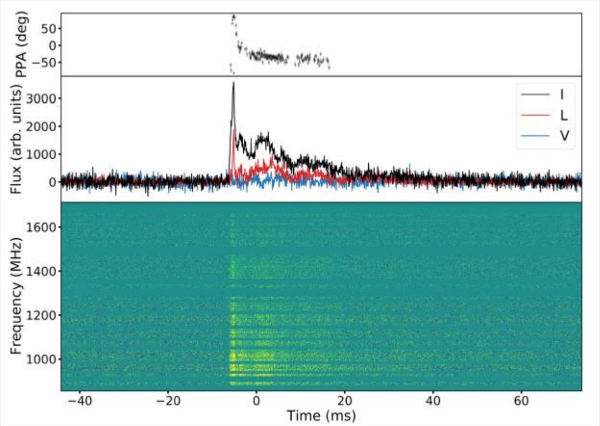
Giant Radio Pulses from Crab: before the detection of pulsation

Staelin+1968



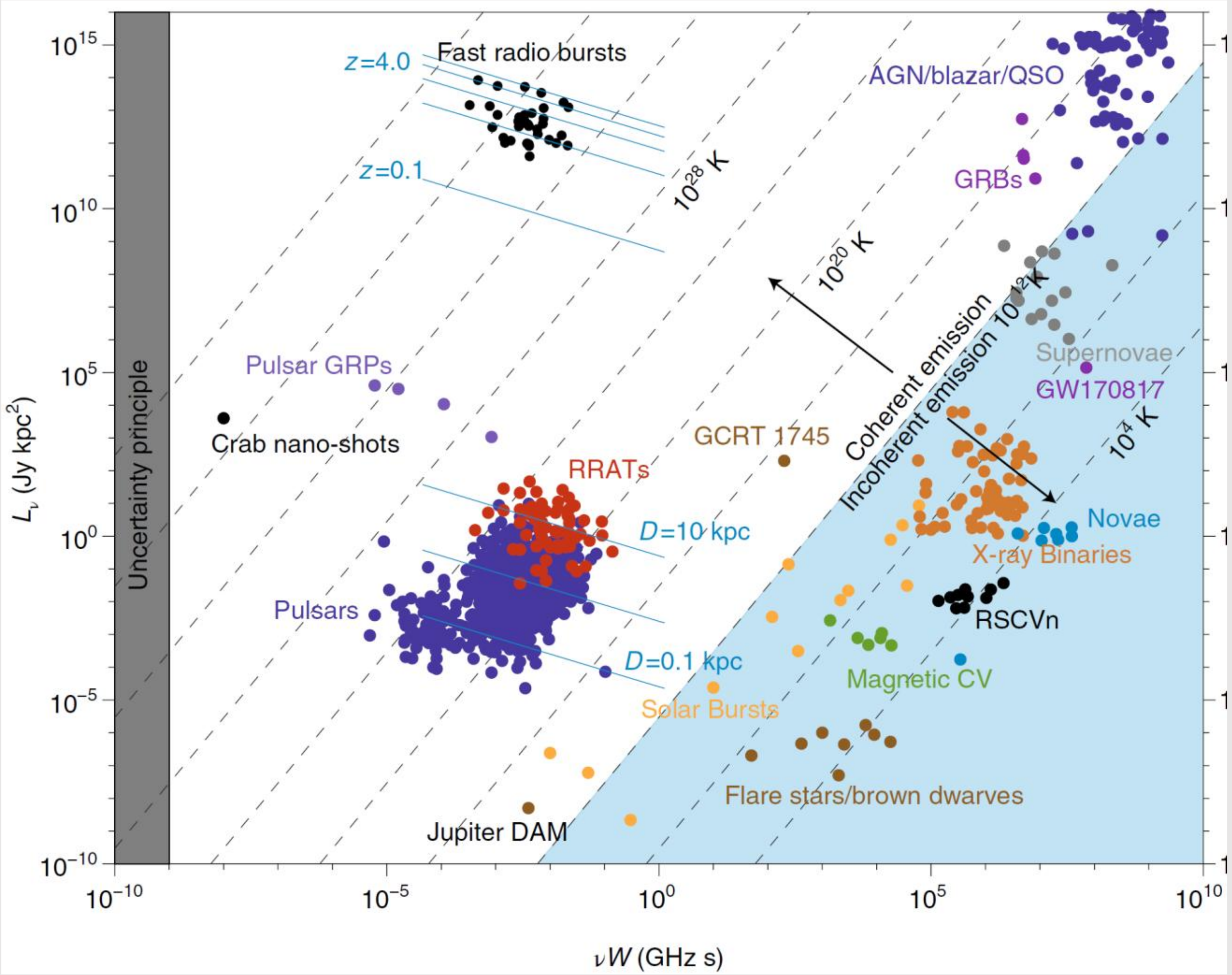
Radio burst from a radio-emitting magnetar XTE J1810+197

Maan+2019



Radio burst from an X-ray dim isolated neutron star 2XMM J104608.7-594306

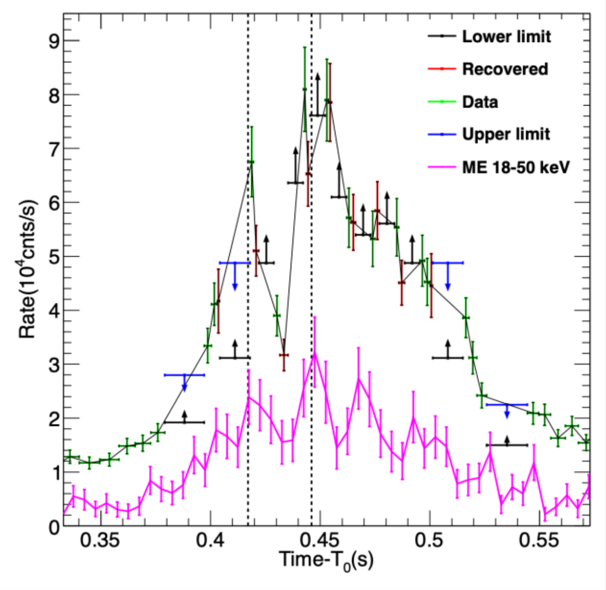
Rajwade+2025

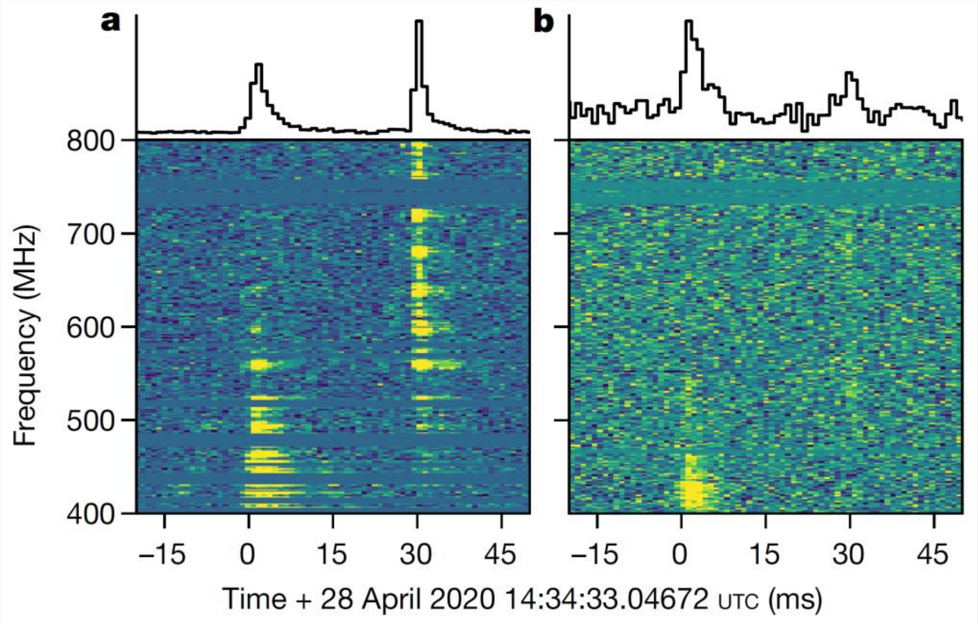


Keane+2018

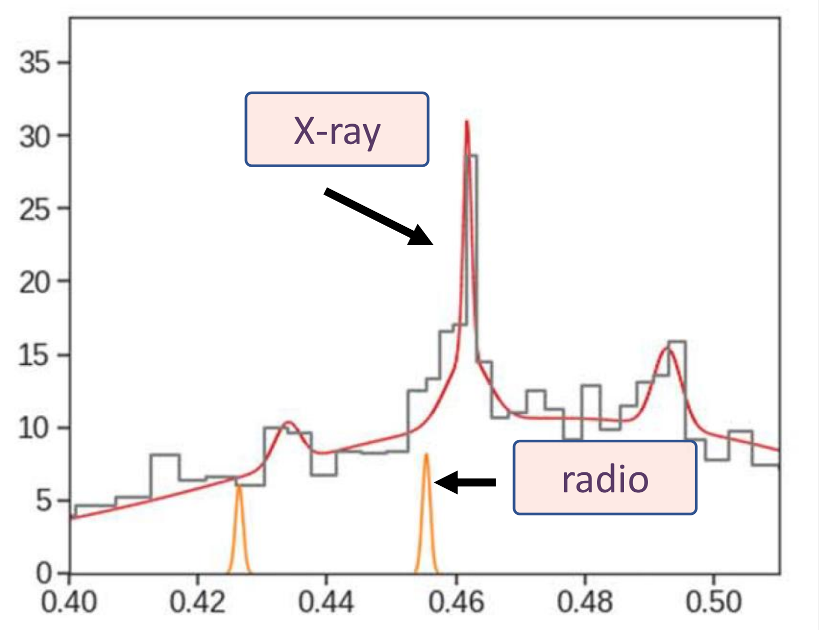
FRB from Magnetar: SGR 1935+2154

- The first (and currently the only) known magnetar that emits fast radio bursts (FRBs)
  - A fraction of repeating FRBs are from magnetars
- An X-ray burst coincide with FRB is detected by Insight-HXMT and INTEGRAL IBIS
  - Power-law dominated emission, indicating a non-thermal origin
  - Quasi-periodic oscillations – crustal oscillations?

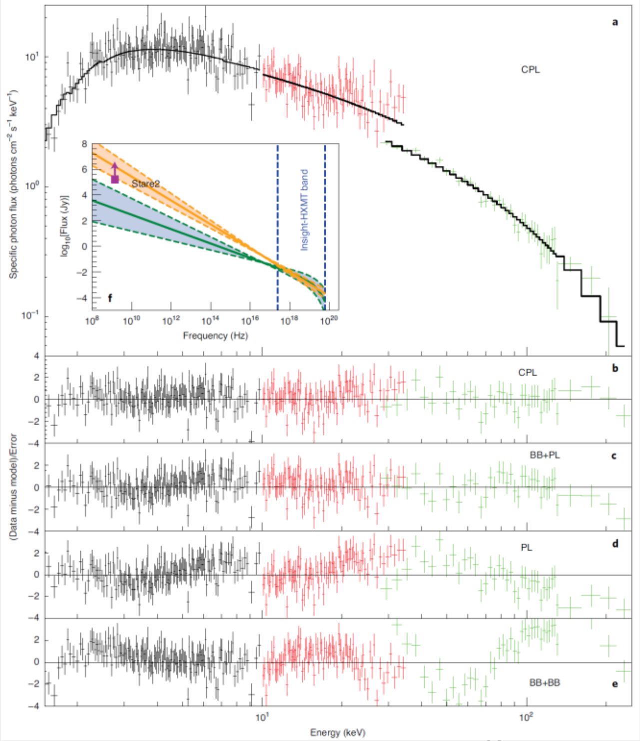




CHIME/FRB Collaboration (2020)



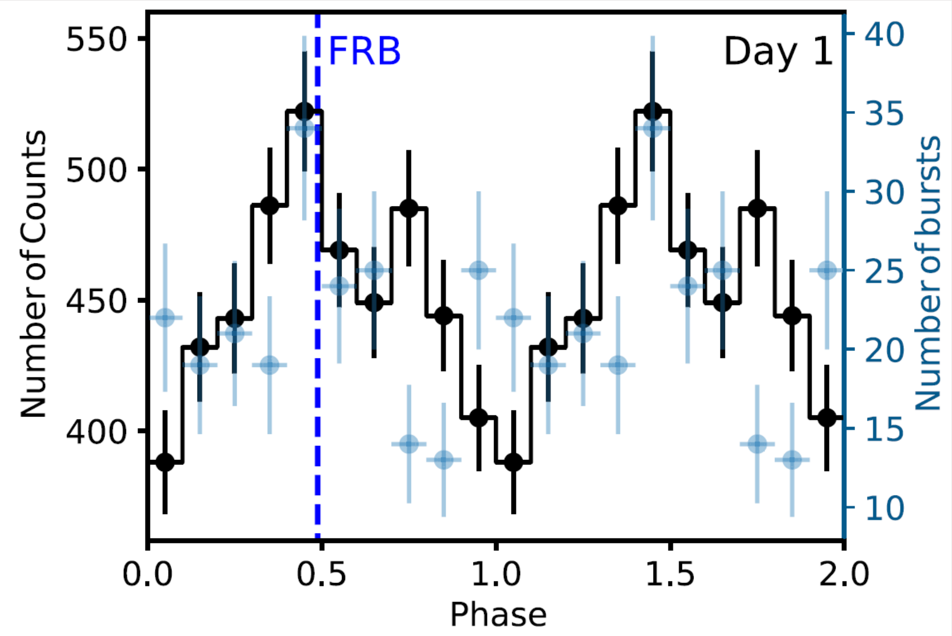
Mereghetti+ 2020

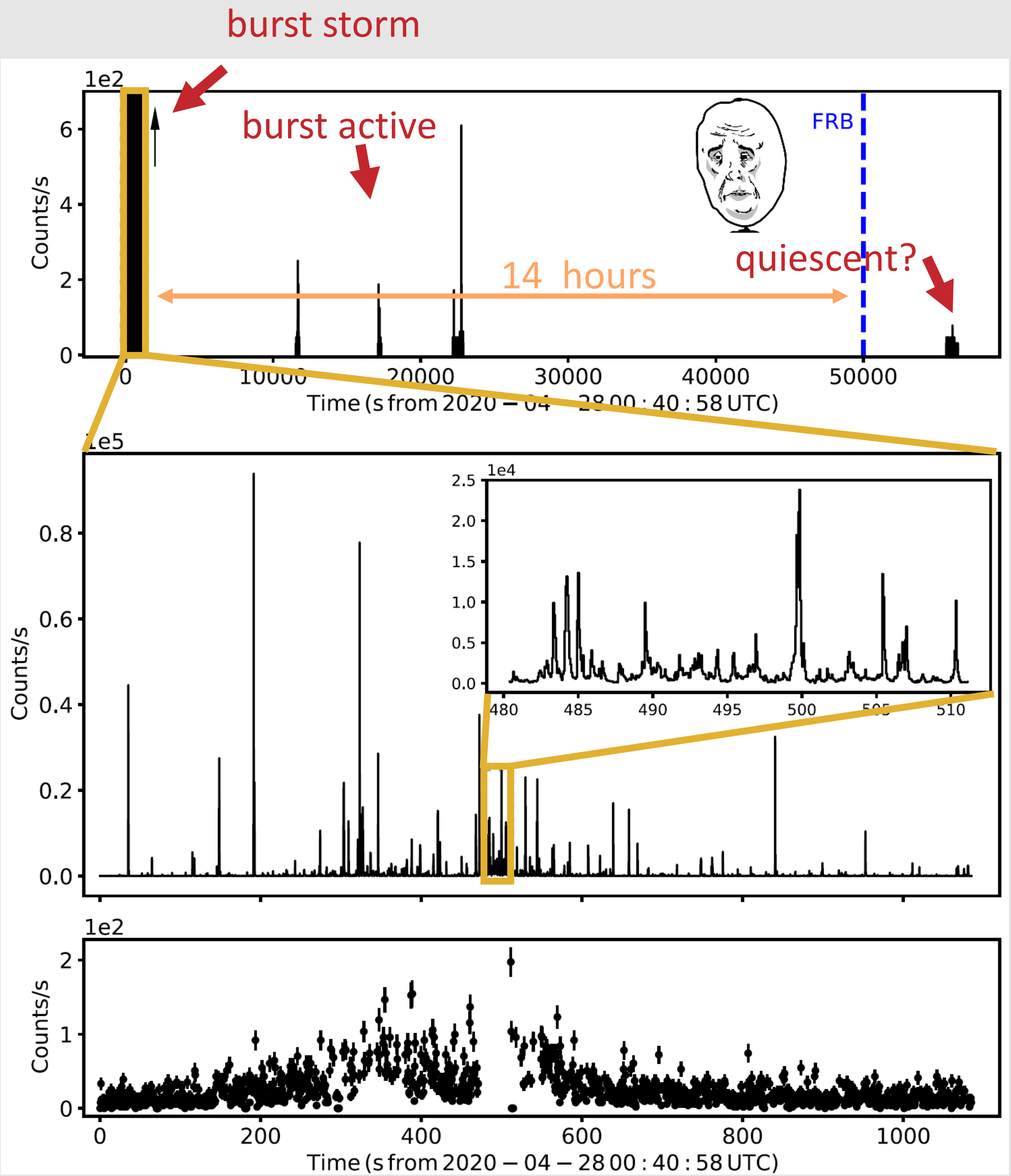


Li+ 2020

NICER Prompt Follow-Up

- NICER M&M team started ToO observation promptly.
  - We did not catch the FRB-related X-ray burst.
- We detected an intense bursting activity half-days before the FRB.
  - > 217 bursts in 1120 s: burst storm!

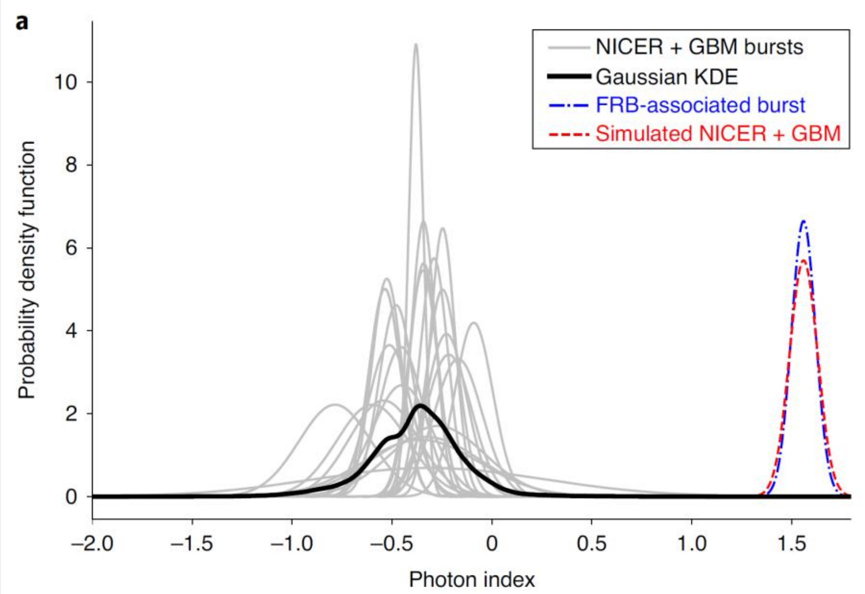


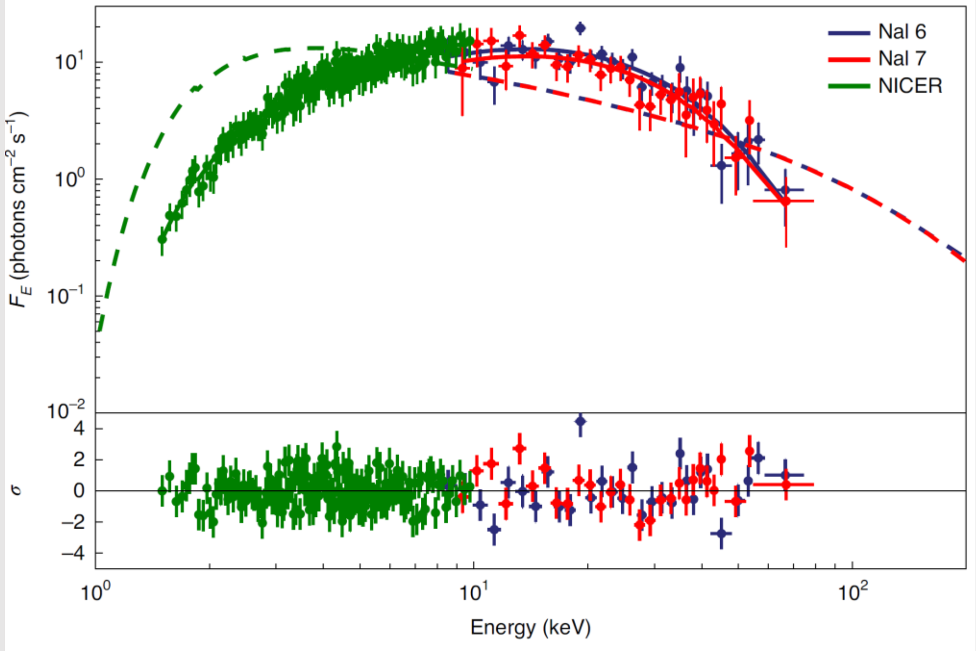


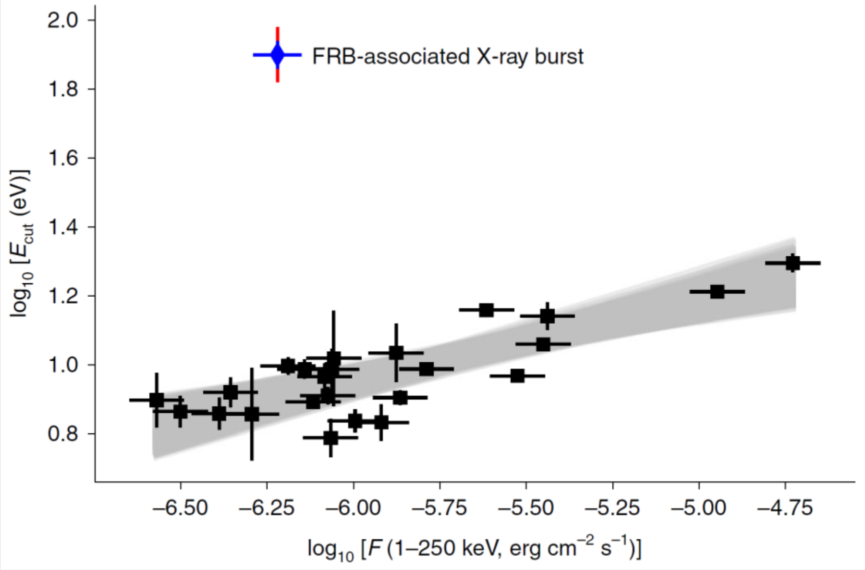
Younes+2020

Broadband Burst Spectroscopy

- 24 bursts in the burst storm were detected by NICER and GBM jointly.
  - The FRB-associated X-ray burst (FRB-X) has an X-ray flux similar to these bursts
  - However, the spectral behavior of FRB-X is significantly different from other bursts.
  - X-ray bursts have different origins/populations?



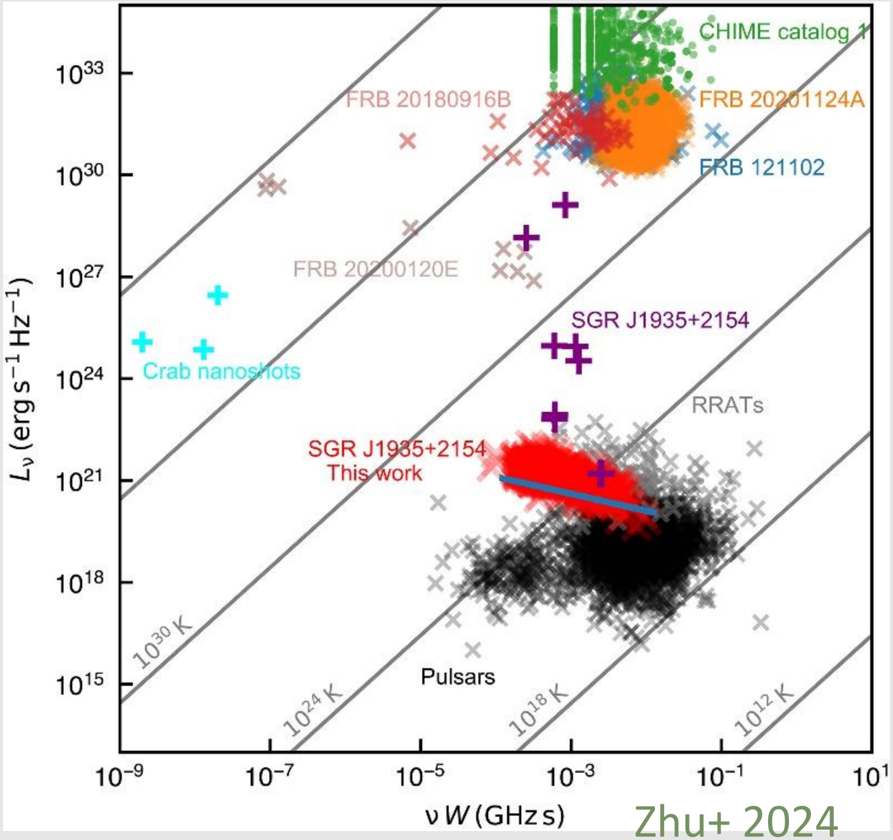




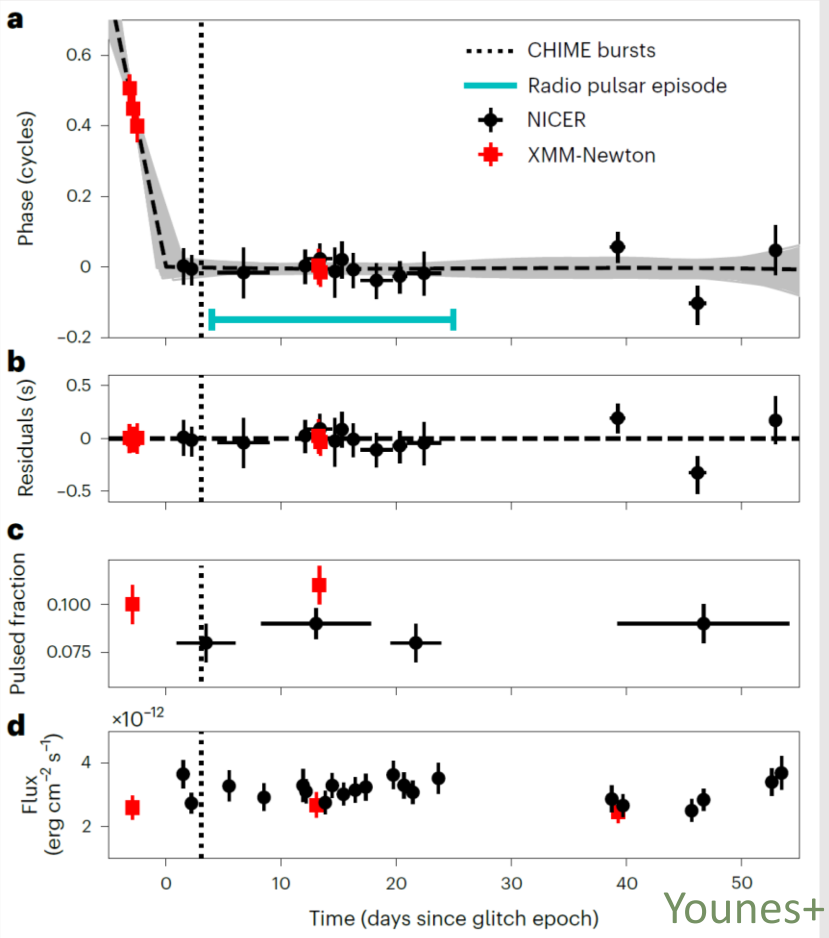
Younes+2020

Radio Pulsating Epoch of SGR 1935+2154

- SGR 1935+2154 entered a radio pulsating phase in 2020 Oct.
  - Much fainter than FRB
  - We detect a (possible) spin-down glitch with an uncertainty of a few days
    - Rotation speed suddenly decreased

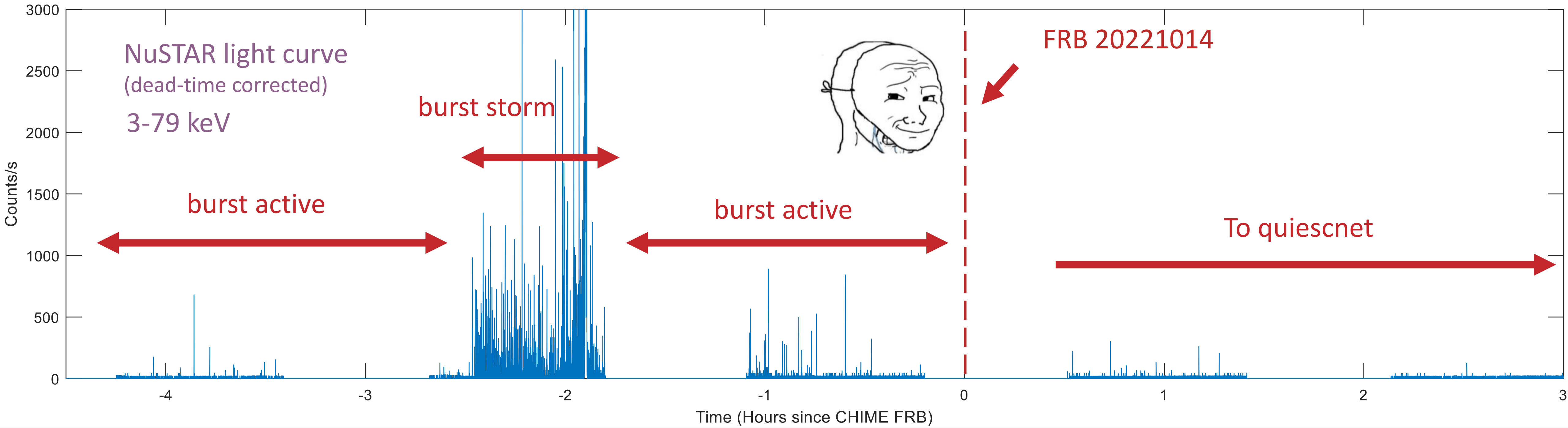


Zhu+ 2024



Younes+ 2023

SGR 1935+2154: 2022 Outburst

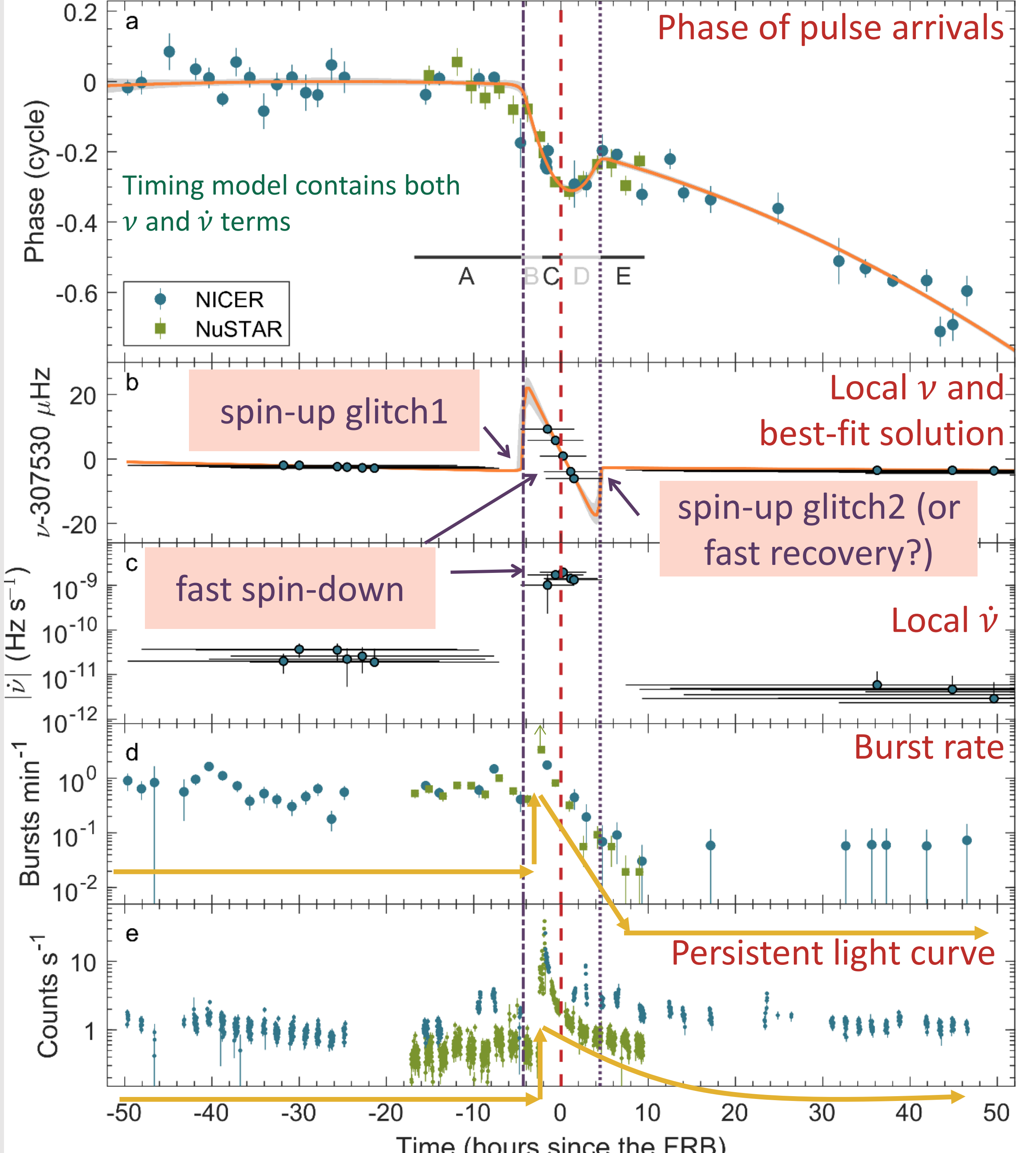


- SGR 1935+2154 reactivated around October 10, 2022
    - Observed using long-term, high-cadence NICER/NuSTAR monitoring
    - CHIME and GBT detect a bright radio burst ! (we missed it again)
- A burst storm was detected 2.5 hours before the FRB
    - The burst occurrence rate decreases significantly after the FRB

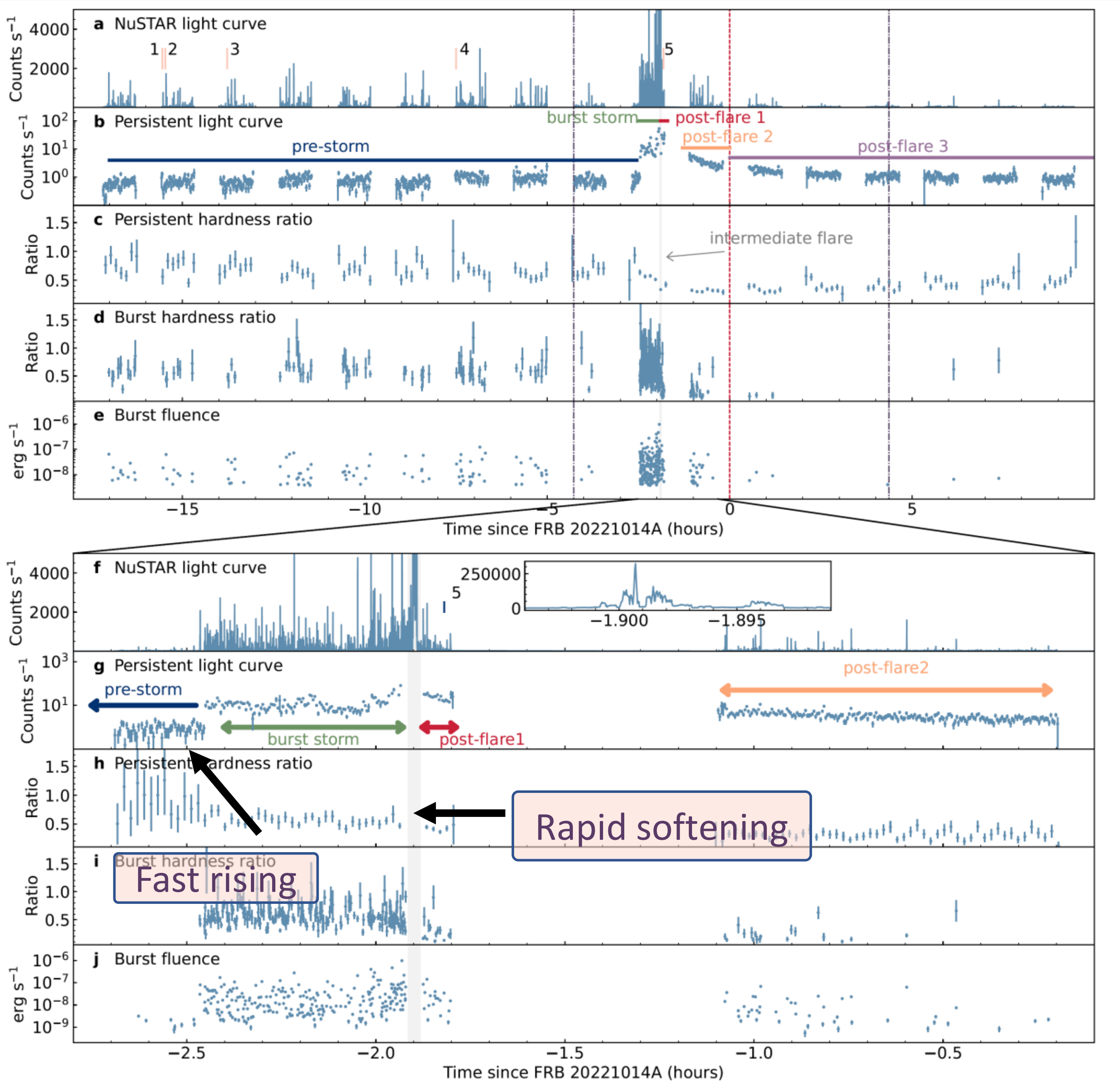
Double Glitches

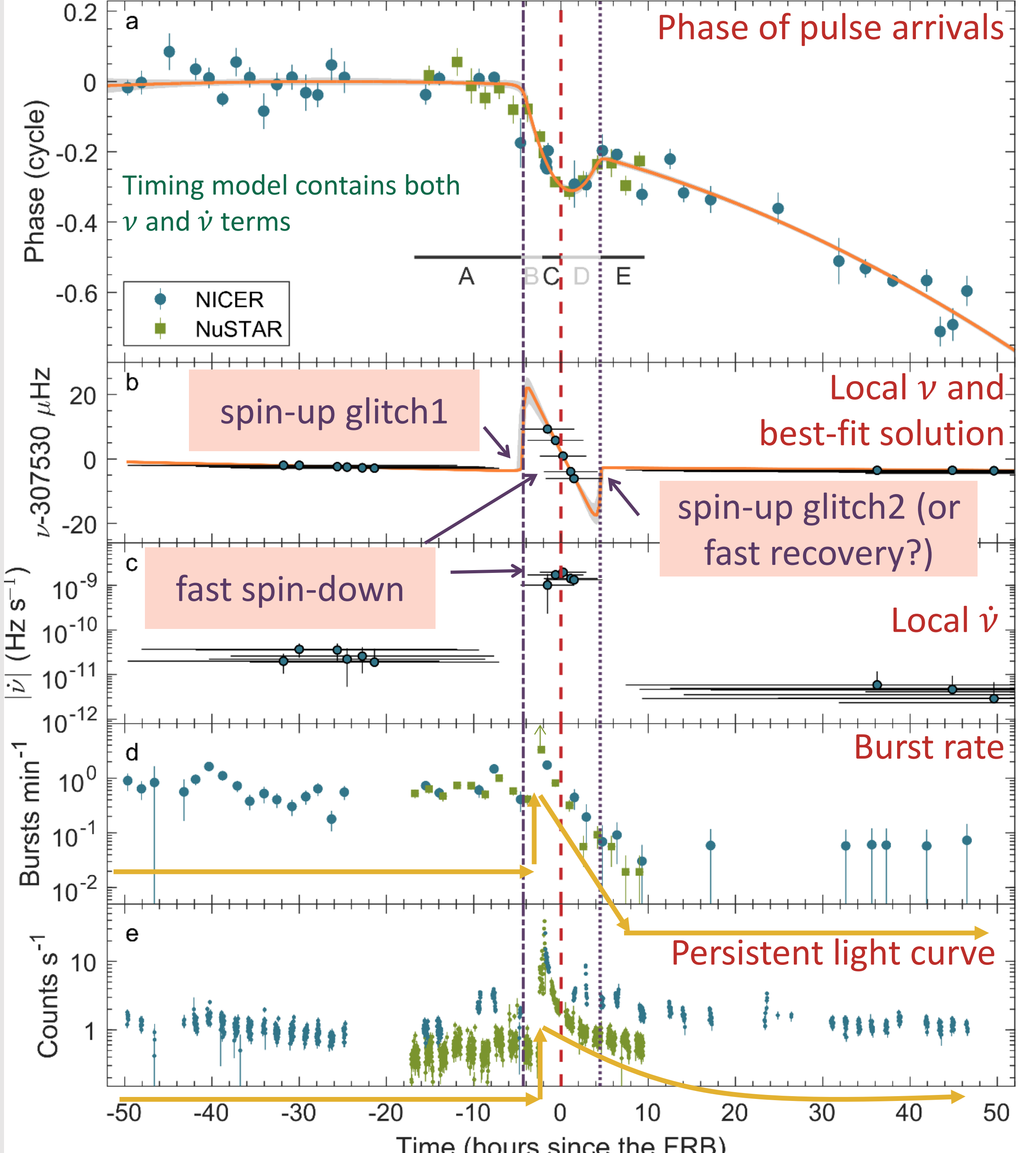
- High-cadence NICER and NuSTAR monitoring enable us to trace the spin frequency evolution in detail
- Two strong spin-up glitches were detected, occurring approximately 4.5 hours before and after the FRB.
  - A rapid spin-down epoch was found between them.
  - Two glitches happened 4.5 hours before and after the FRB
  - The burst storm took place about 1.5 hours after the first glitch.
  - The total released rotational energy is estimated to be 6.5×10^{41} ergs.

Hu+ 2024



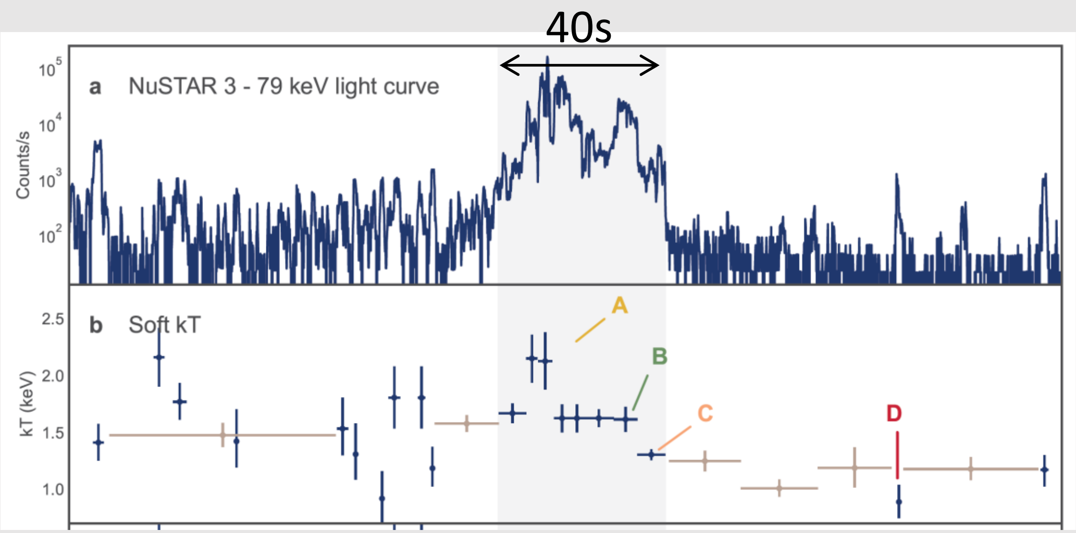
Double Glitches

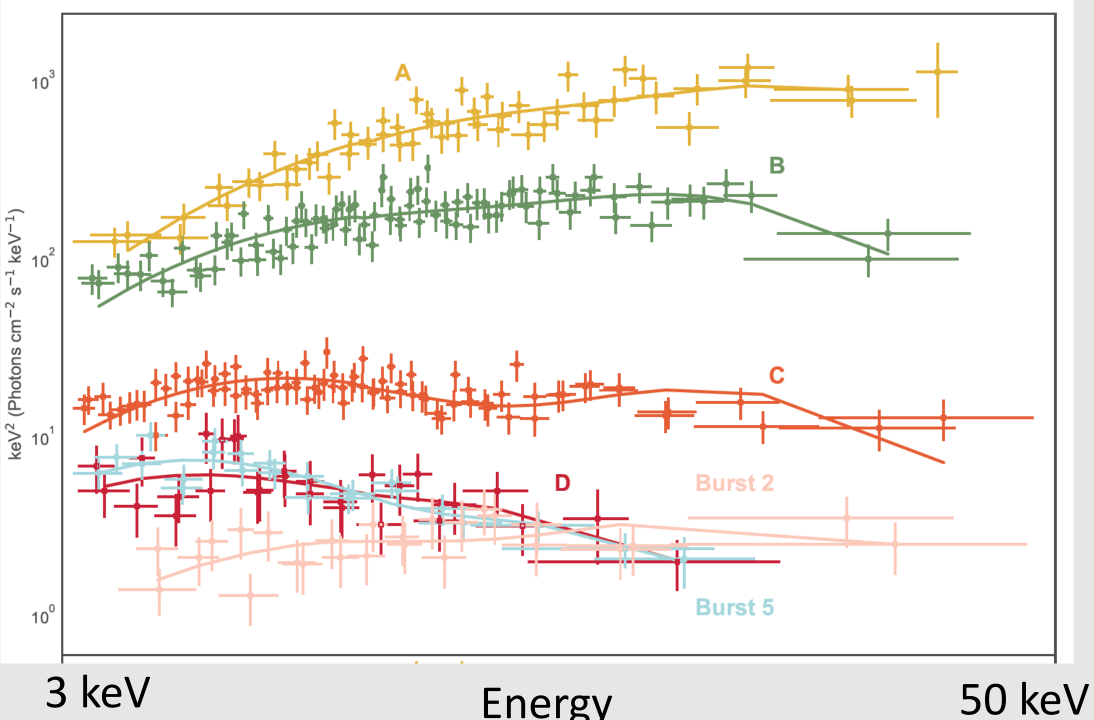


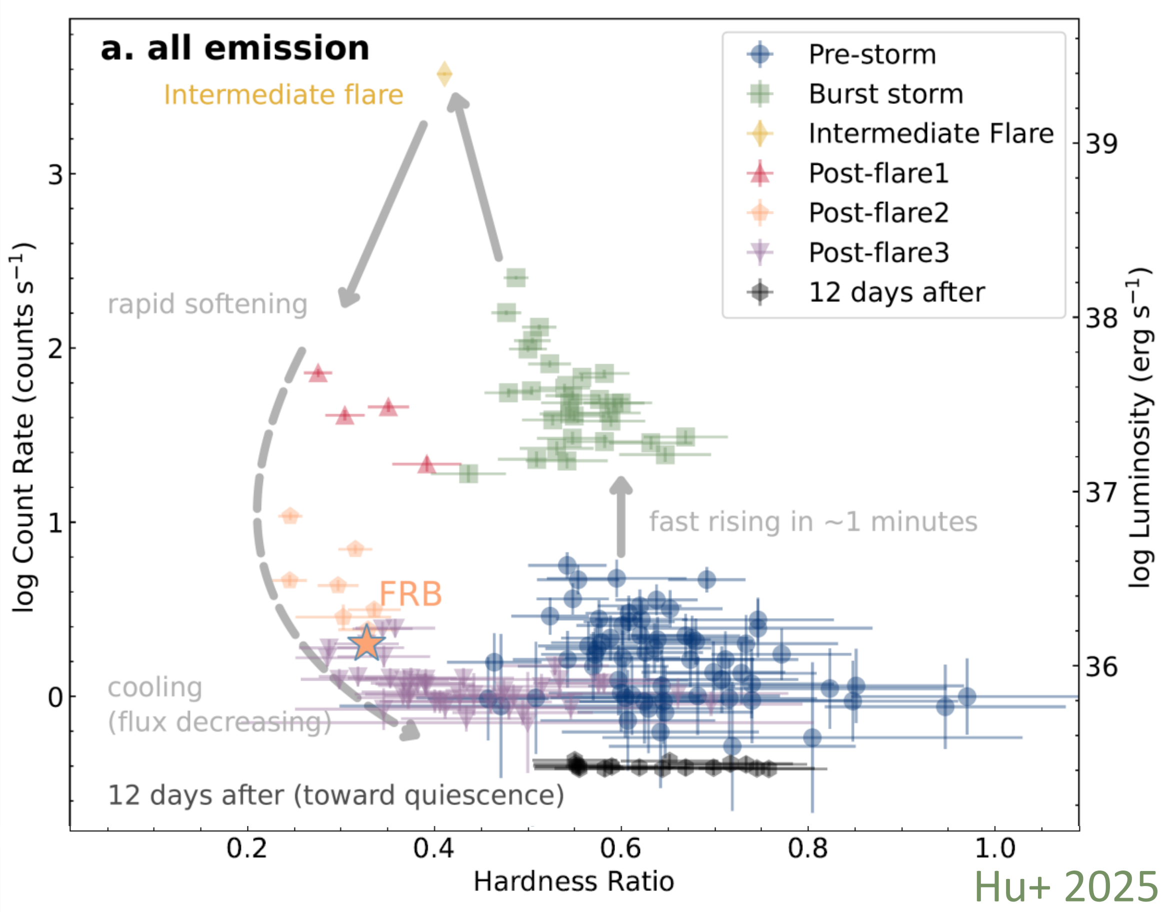


Hu+ 2024, 2025

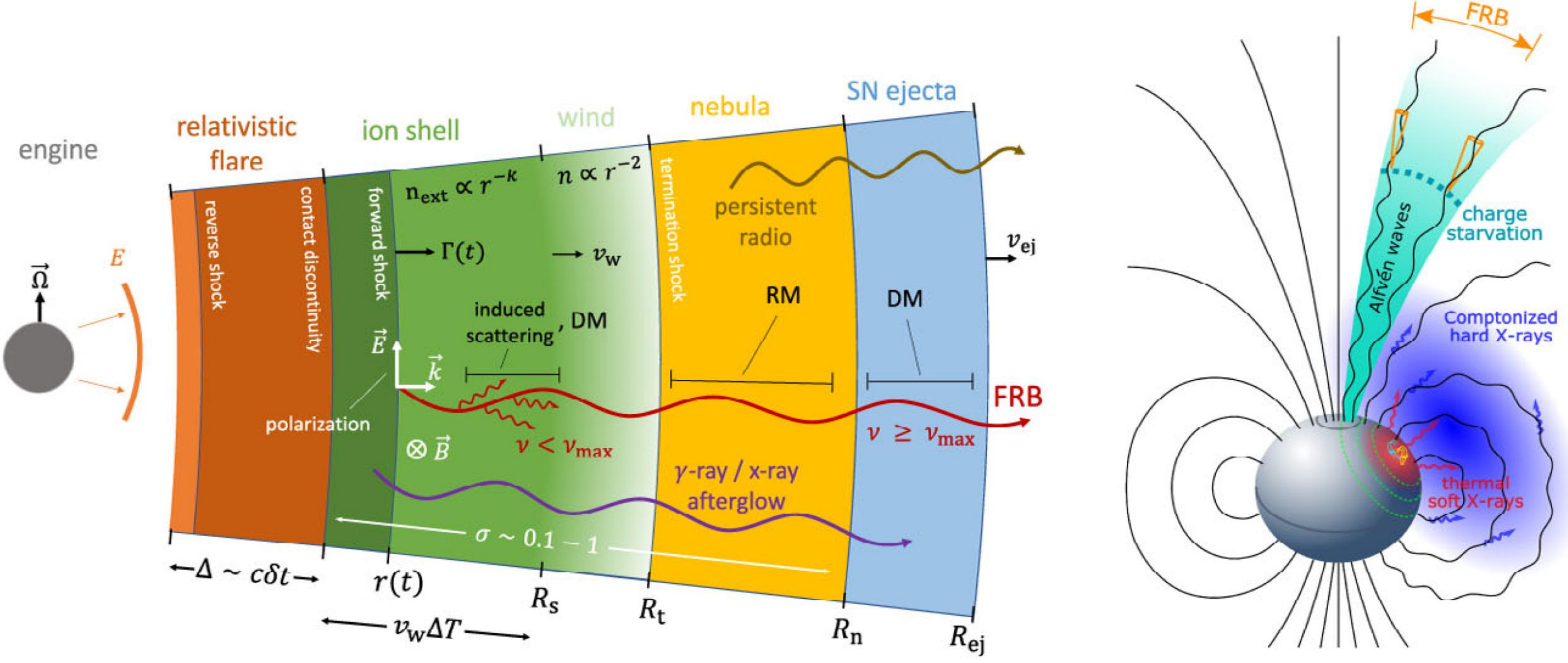
Spectral Softening and FRB Emission







FRBs may not be directly triggered by giant or intermediate flares. Instead, these flares could change the magnetospheric environment, creating favorable conditions for radio emission.

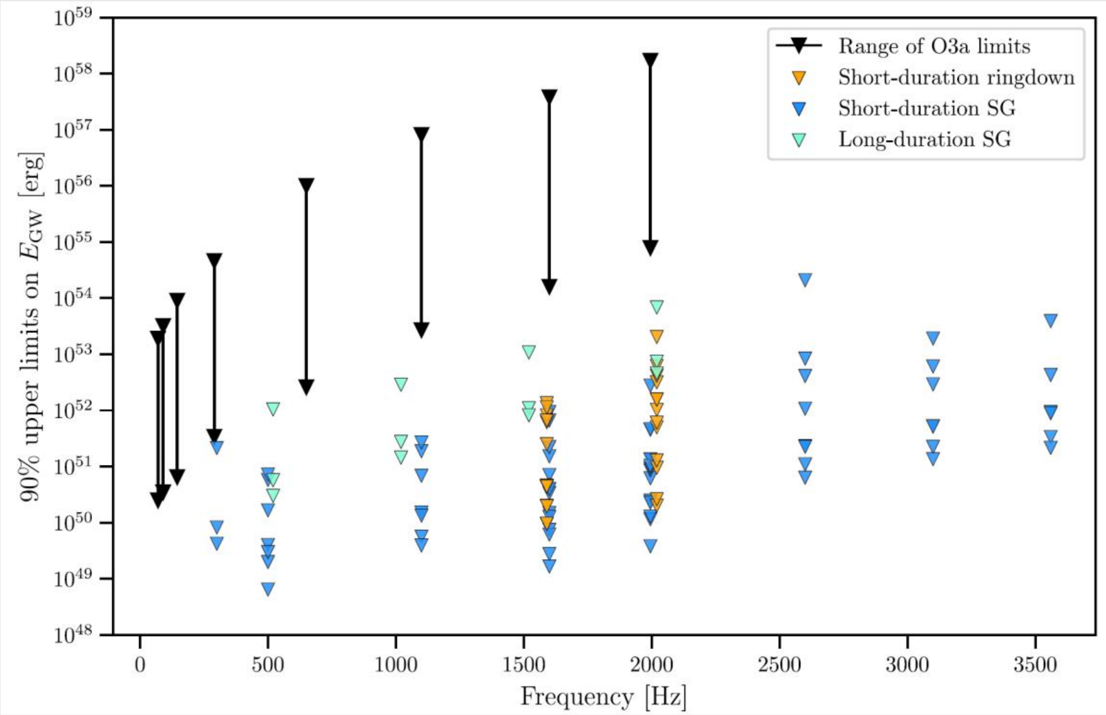


a Shock models **b** Magnetospheric models

Petroff+2022

Gravitational Wave Signal?

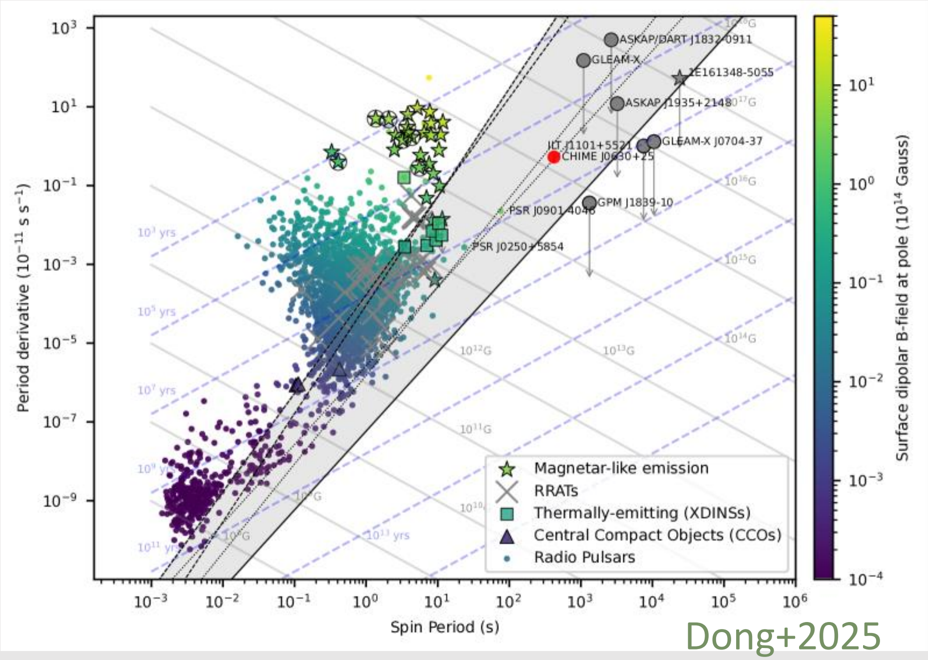
- Magnetars are plausible gravitational wave sources owing to possible crustal fractures or magnetic reconnection, especially during energetic outbursts and FRBs.
- The LVK collaboration searched for gravitational wave signals in GEO 600 data near the FRB and glitch epochs
  - LIGO, Virgo, and KAGRA were not operational.
  - The GW waveform remains unknown
  - No significant GW emission has been detected so far.
  - An upper limit on gravitational wave emission and the GW-to-radio ratio has been derived as $< 10^{14} - 10^{16}$.



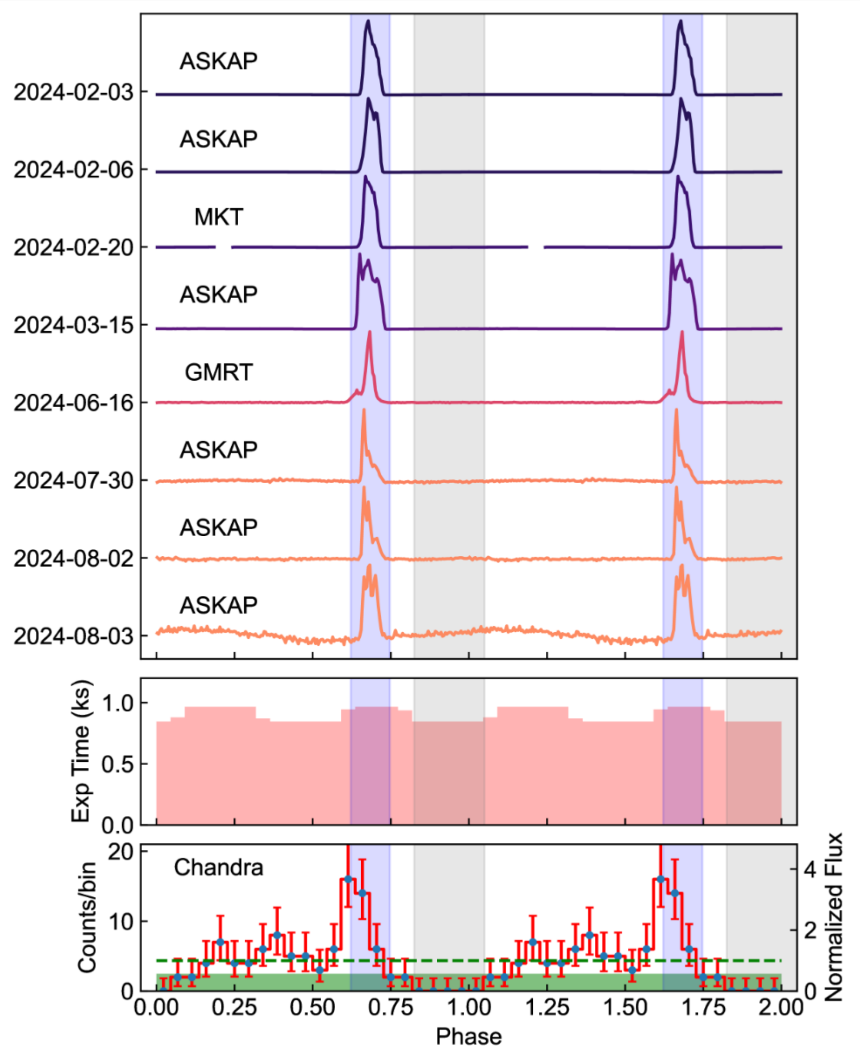
LVK Collaboration+2024

New Population: Long-Period Radio Transient

- Long-period radio transients have been discovered (e.g., Hurley-Walker+2022, 2023; Caleb+2024).
  - These objects lie beyond the "death line" of conventional pulsars.
- Transient, pulsating X-ray emission was detected from ASKAP J1832-0911.
  - Evolved magnetars, WD pulsars, or binary systems.
  - The detection of X-ray emission indicates these sources are more energetic than previously believed.



Dong+2025

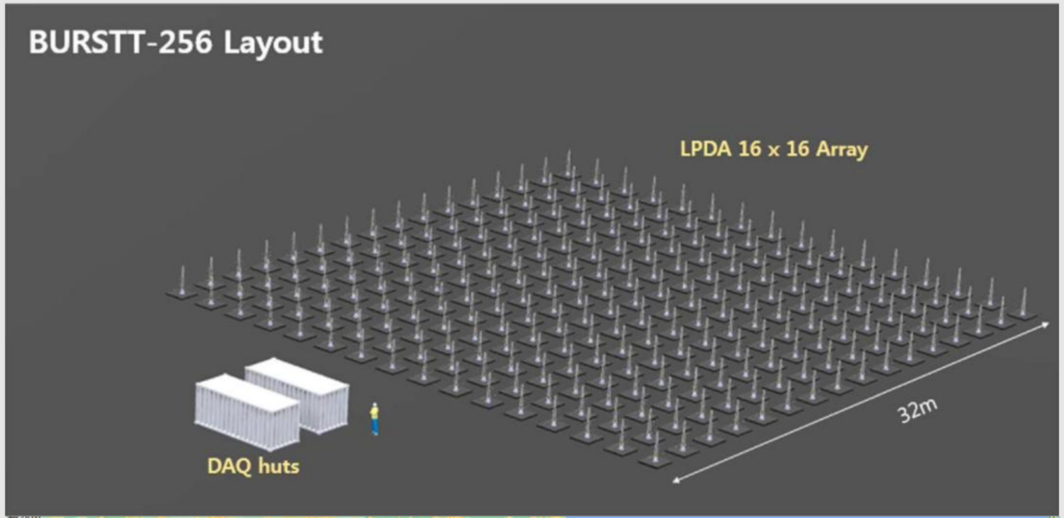


Wang+2025

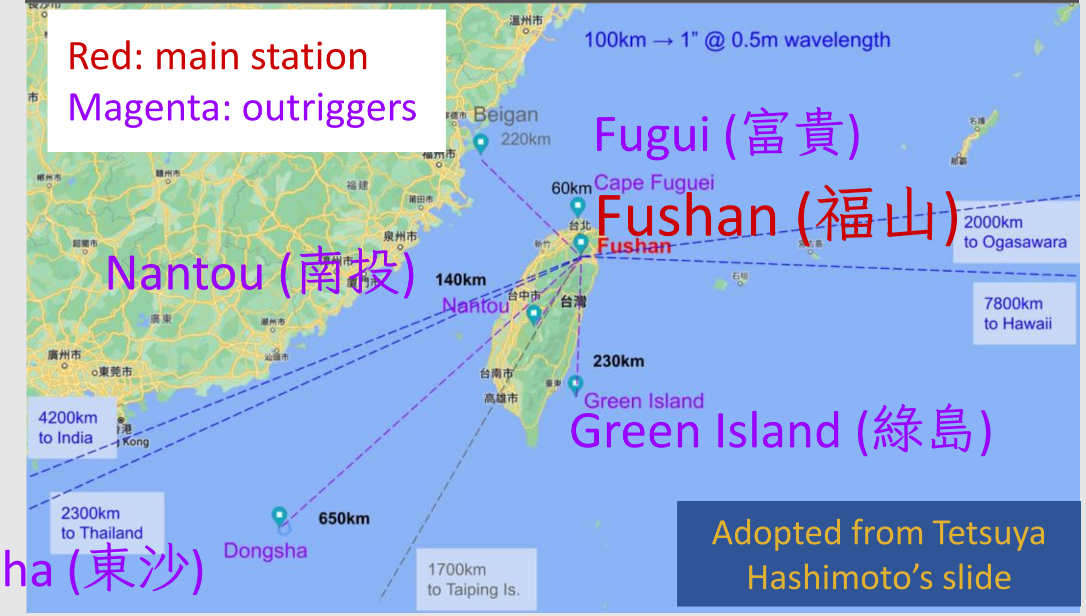
Radio Surveys

Bustling Universe Radio Survey Telescope in Taiwan (BURSTT): An FRB-dedicated instrument

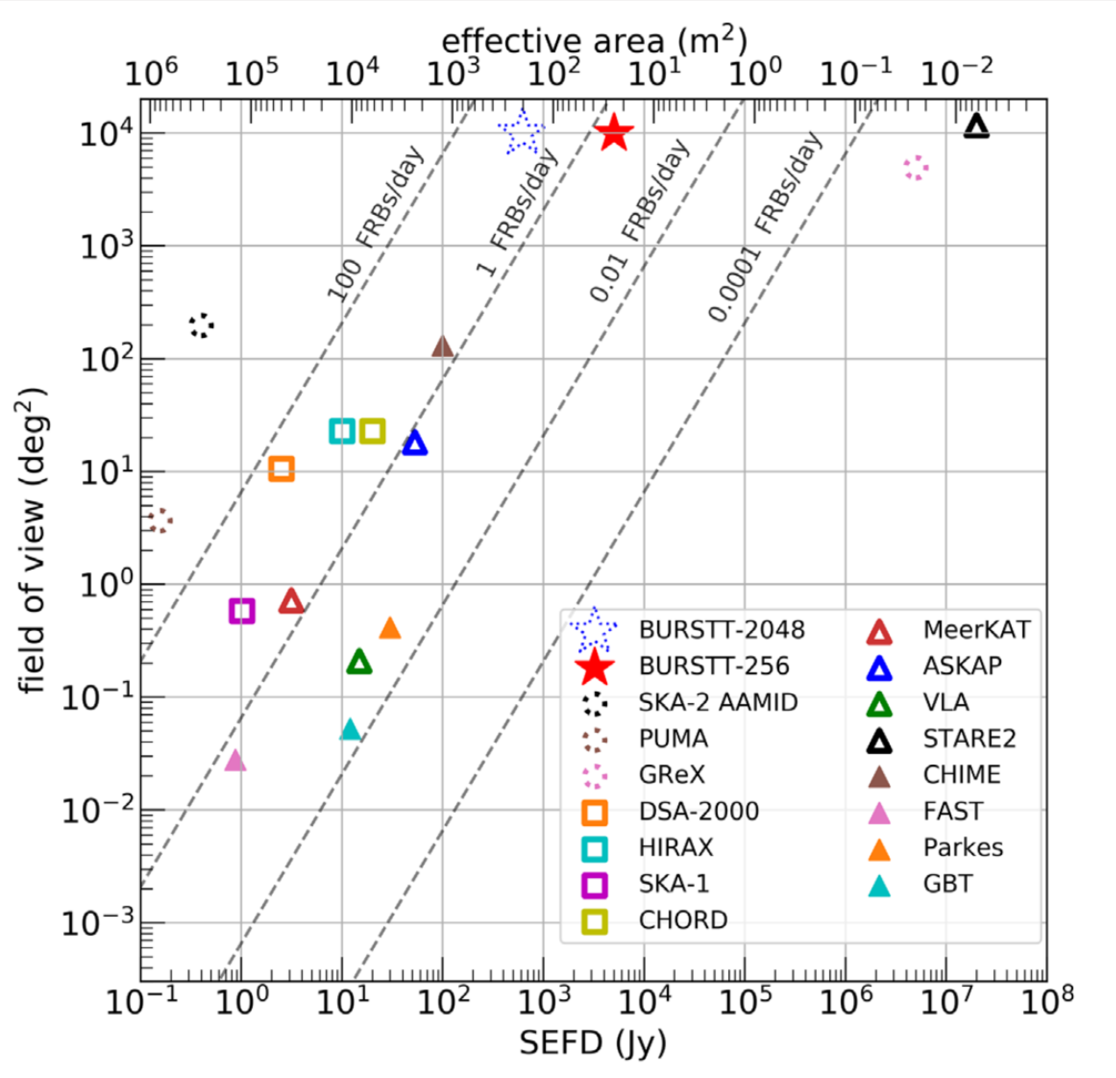
Wide FoV



VLBI



Dongsha (東沙)



Summary

- Magnetars: laboratories for fundamental physics under extreme magnetic fields
  - Built on 40 years of observational and theoretical progress
  - Key questions remain: equation of state, high-B QED, hot spot migration, complex magnetic geometry, crustal oscillations…
- Magnetar giant flares: third population of GRBs
  - Strong candidates for fast X-ray transients
- Magnetars as FRB central engines
  - SGR 1935+2154: the only source directly linked
  - Glitches may trigger both X-ray activities and radio bursts
  - Intermediate flares likely change the magnetospheric environment and enabling radio emission
- Ultra-long radio transients: a new population
  - May represent evolved magnetars
  - Detecting their X-ray emission is crucial for understanding origins
- Prompt follow-up, high-cadence, and long-term monitoring are essential

Glitches: Neutron Star Interior

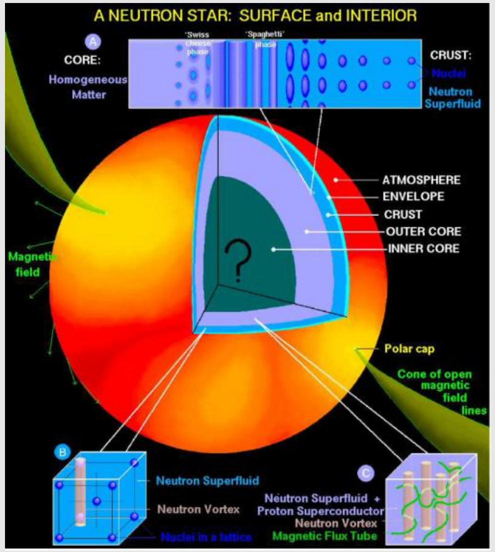
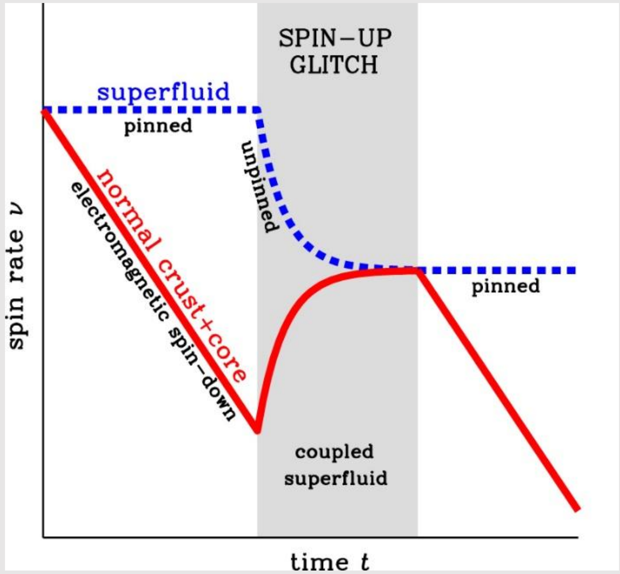


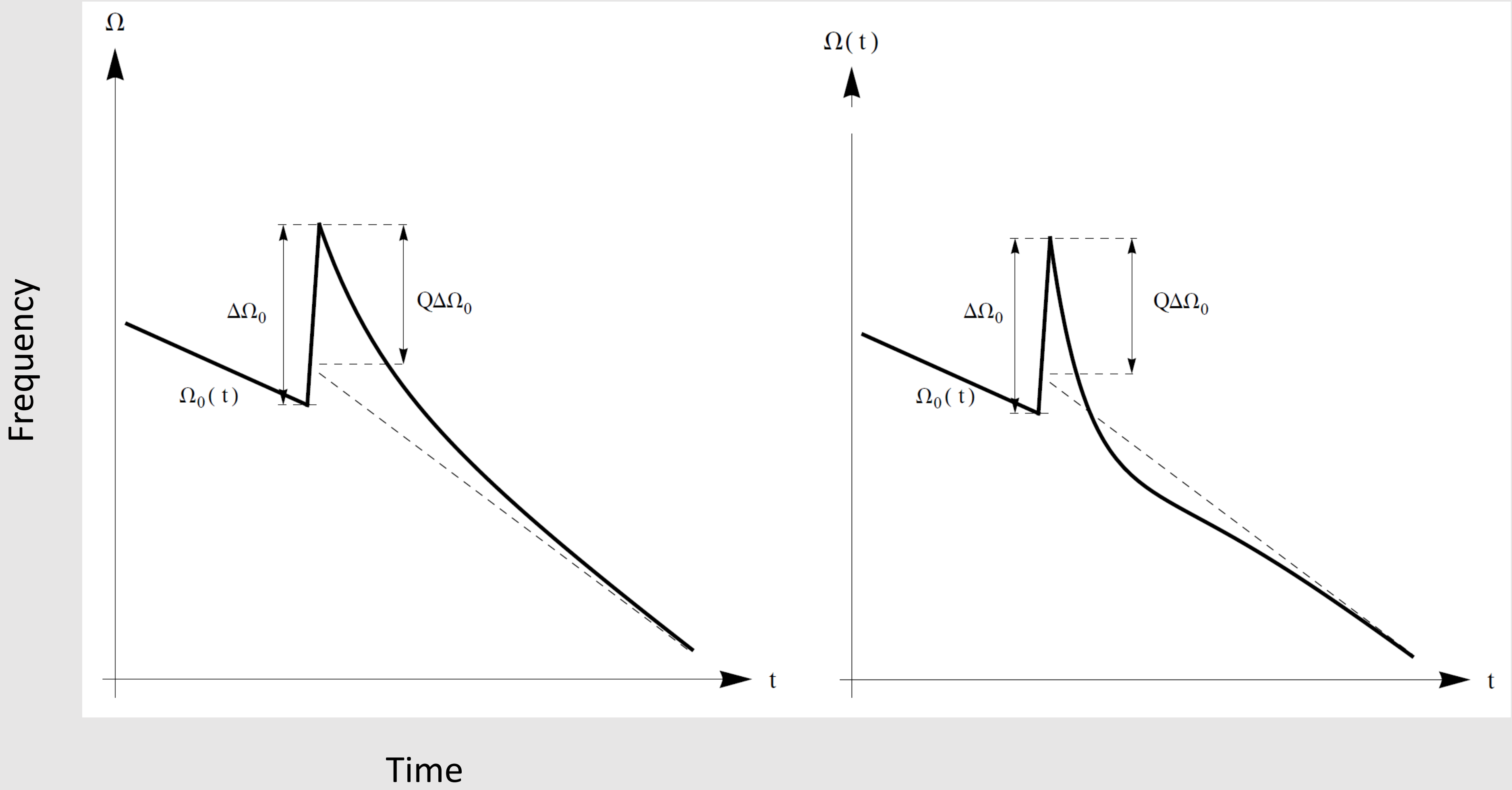
Figure courtesy D. Page.



Ray et al. (2019)

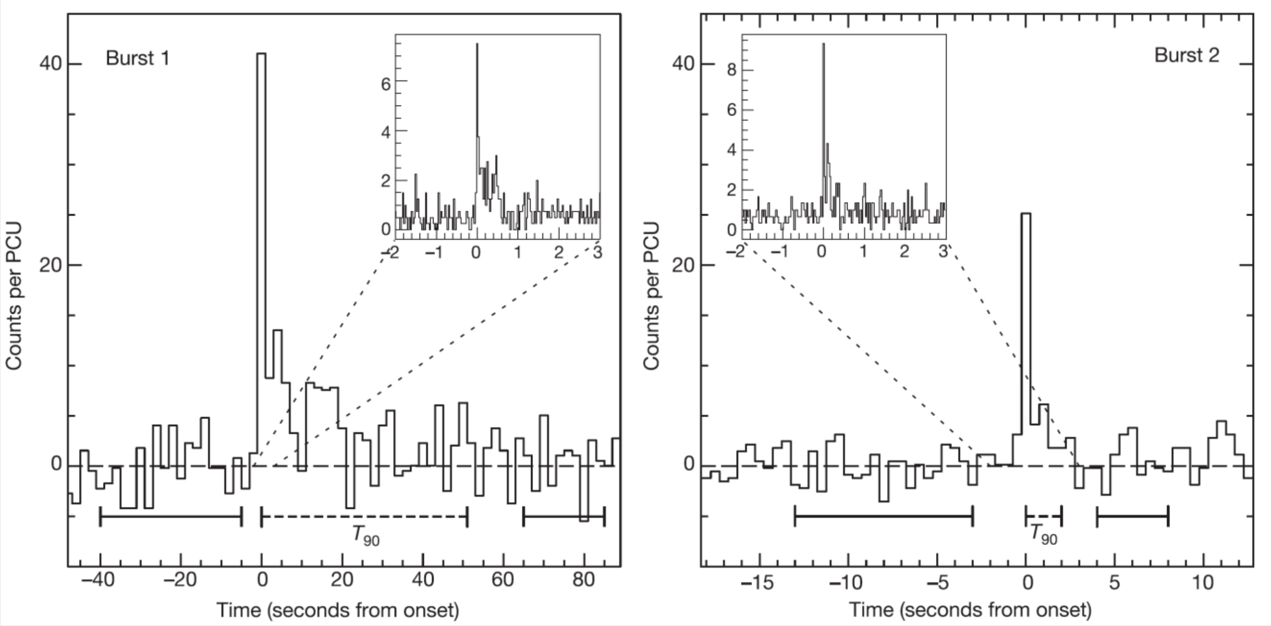
- The superfluid component is detached from other parts of the neutron star, while the other parts being slowed over long times by magnetospheric torques.
- At the glitch, the superfluid component attached to the rest of the star.
- The rapid spin-down after the first glitch is probably caused by a dynamically strong baryon-loaded wind.
  - The fast spin-down introduced a spin lag between the superfluid component and the rest of the star, and hence triggers the second glitch.
- The radiative energy lag the glitch time at the thermal timescale
- The temporal correlation of the burst rate and the persistent emission enhancement suggests they are driven by the same sub-surface energy deposition

Glitches: Probe Structures of Neutron Stars

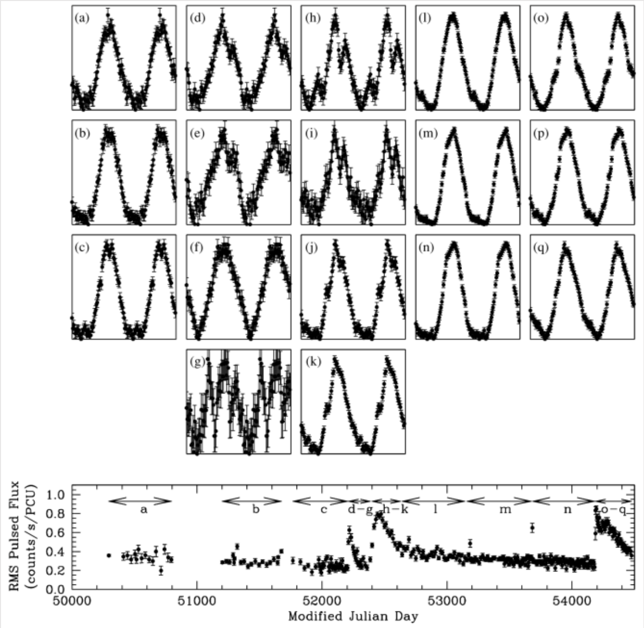


Magnetars: Discoveries and Early Observations

- After the launch of X-ray telescopes, astronomers found X-ray emitting pulsars
  - Generally young pulsars (e.g., Crab, rotational-energy) or X-ray binaries (gravitational potential energy)
  - Isolated X-ray pulsars usually have stable X-ray flux, and $L < L_{sd}$
    - But AXPs usually have $L > L_{sd}$
  - AXPs also have similar timing properties as SGRs
    - No stellar companions, long rotation period (2-12 s), large spin-down rate $\dot{P} \sim 10^{-13} - 10^{-11}\ s\ s^{-1}$, large magnetic fields $\gtrsim 10^{14}$ G
    - The detection of a short X-ray burst from an AXP confirms that SGRs and AXPs are from the same population.

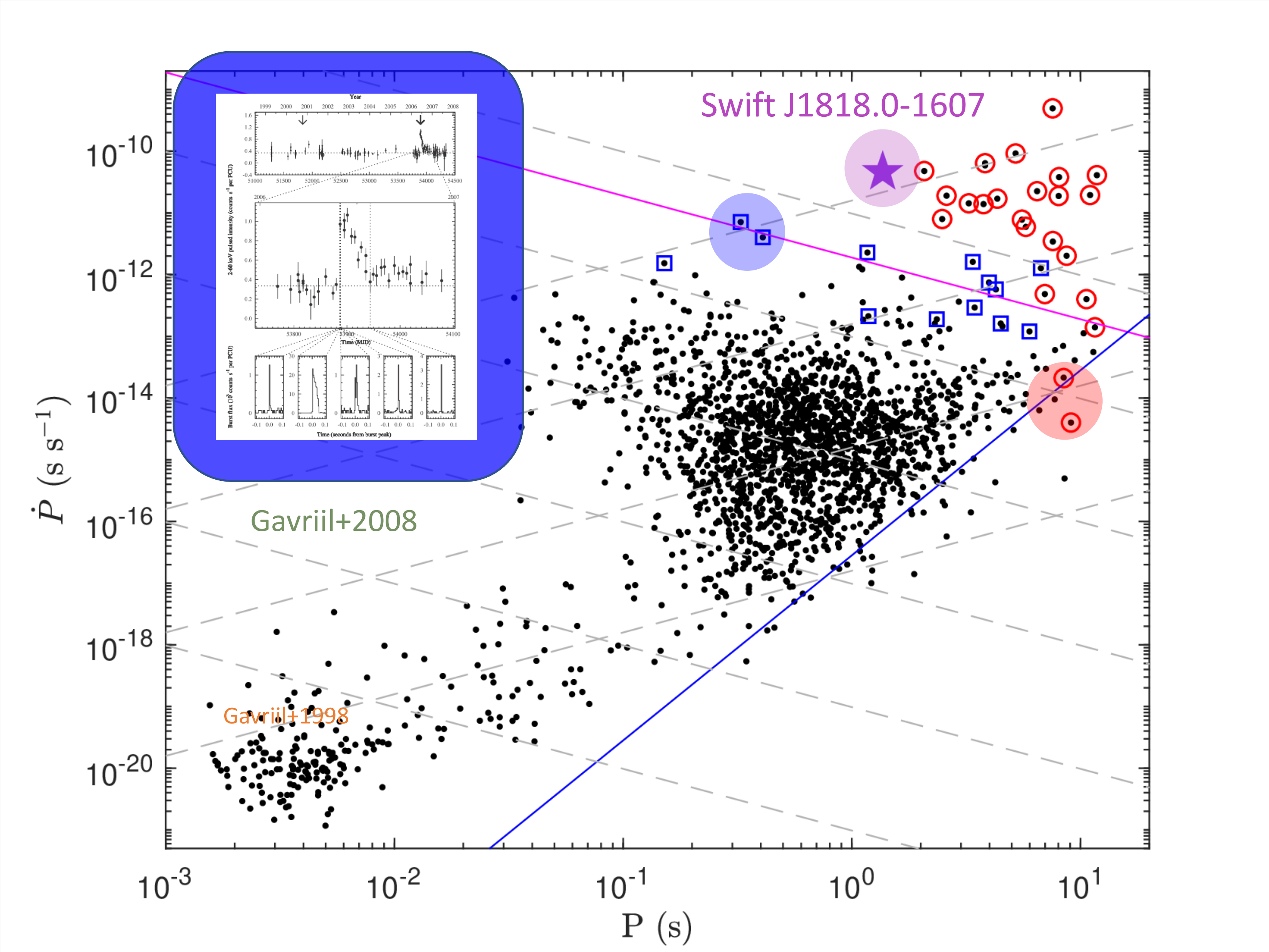


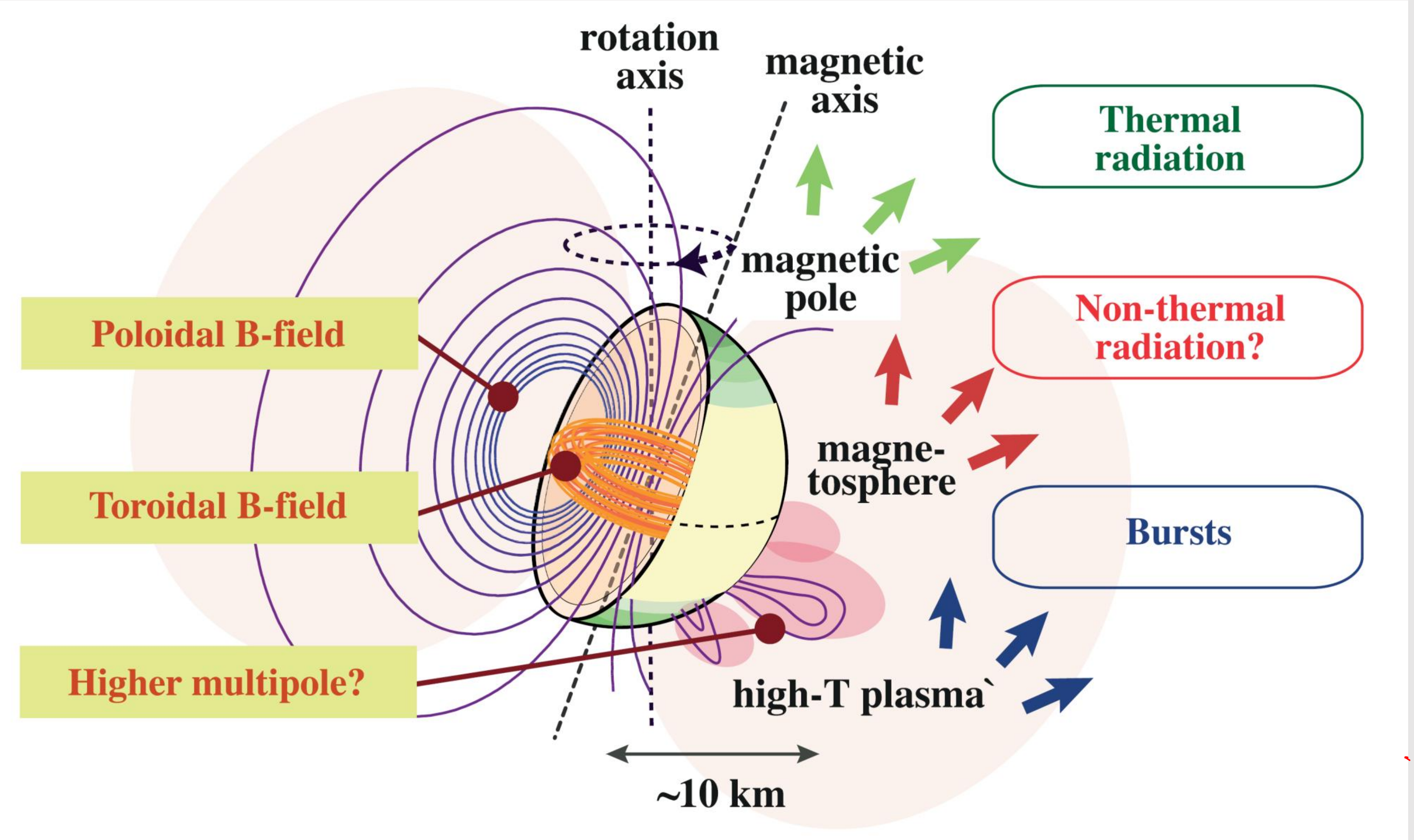
Gavriil+ (2002)



Dib+ (2009)

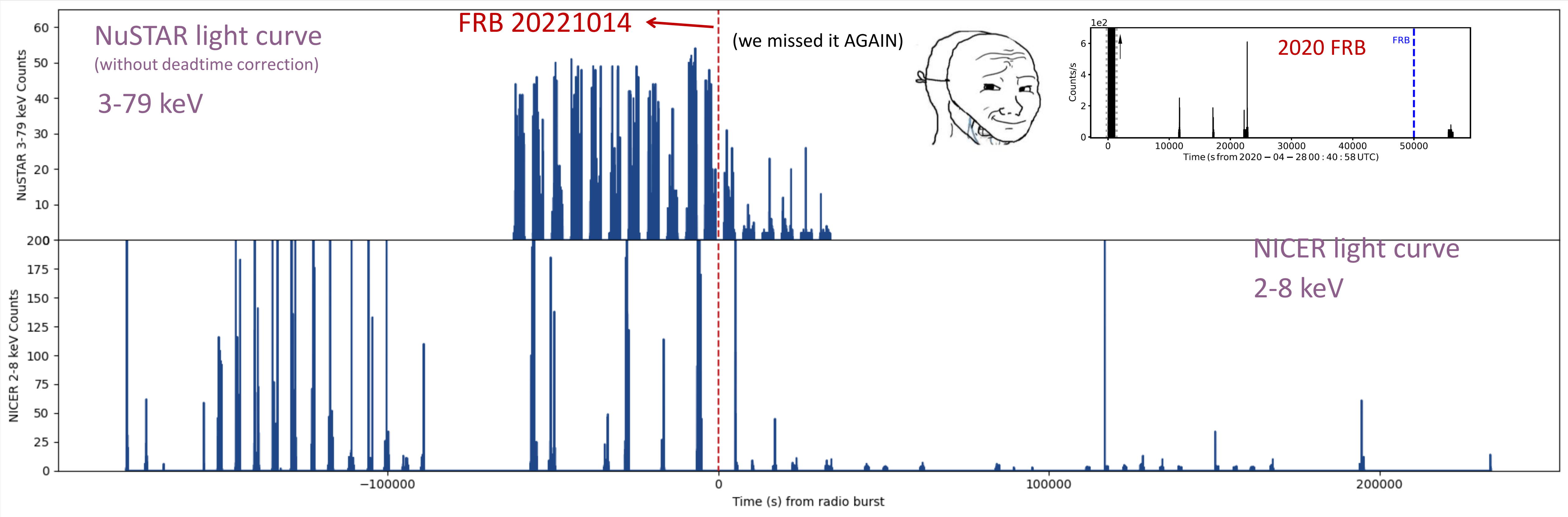
Boundary Between Magnetars and RPPs




rotation axis
magnetic axis
Thermal radiation
magnetic pole
Poloidal B-field
Non-thermal radiation?
magne-tosphere
Toroidal B-field
Bursts
Higher multipole?
high-T plasma`
~10 km

Enoto (2019)

SGR 1935+2154: 2022 Outburst



- SGR 1935+2154 reactivated around October 10, 2022
  - 21:28:25.8 UTC on 2022-10-14, INTEGRAL (GCN 32675)
  - Observed using long-term, high-cadence NICER/NuSTAR monitoring
  - CHIME and GBT detect a bright radio burst ! (we missed it again)

Future X-ray Observatories

- Prompt response and high-cadence monitoring remain critical for magnetar science.
- NICER is unlikely to resume operations in the near future....
  - Swift, XMM, and NuSTAR are still actively observing.
  - Future opportunities: Strobe-X? CubeSats?