Magnetars,

possible engines of FRBs

-- the first smoking gun from SGR J1935+2154

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on behalf of the HXMT magnetar-FRB and the FAST FRB collaboration

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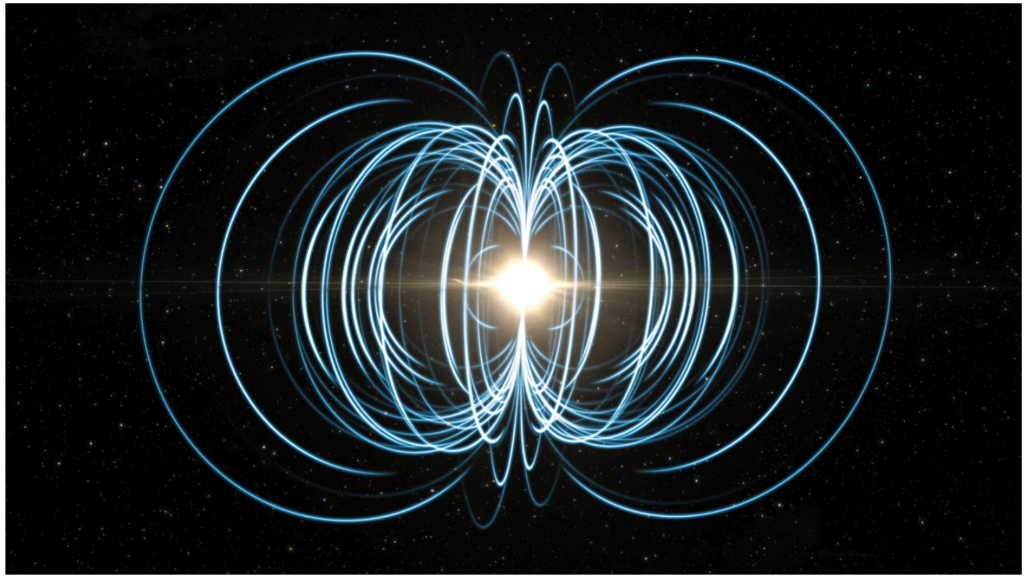
Snapshots of science

Astronomy

A fast radio burst in our own Galaxy

Three papers published in *Nature* report the detection of a phenomenon called a fast radio burst (FRB) coming from a source in our Galaxy. Intriguingly, the FRB was accompanied by a burst of X-rays. The discovery was made and understood by piecing together observations from multiple space- and ground-based telescopes. The name 'fast radio bursts' is a good description of what they are: bright bursts of radio waves with durations roughly at the millisecond scale. First discovered in 2007, their short-lived nature makes it particularly challenging to detect them and to determine

Found: elusive source of fast radio bursts



Magnetars are neutron stars with magnetic fields 100 million times stronger than that of any magnet on Earth. © PITRIS/DREAMSTIME.COM

Everyone loves a good mystery. Take fast radio bursts (FRBs)—short, powerful flashes of radio waves from distant galaxies. For 13 years, they tantalized astronomers keen to understand their origins. One running joke said there were more theories explaining what causes FRBs than there were FRBs. (Currently, astronomers know of more than 100.)

Now, cosmic sleuths have fingered a likely culprit: magnetars, neutron stars that fizzle and pop with powerful magnetic fields. Because FRBs are so fast, they must come from a small but intense energy source like a magnetar, which are formed when burned-out stars collapse to the size of a city. But although a handful of FRBs had been traced to particular galaxies, no telescope had sharp enough vision to connect them to an individual magnetar at such great distances.

Then, in April, an FRB went off in the Milky Way—close enough that astronomers could examine the scene. The Canadian Hydrogen Intensity Mapping Experiment, a pioneering survey telescope in British Columbia responsible for the discovery of many FRBs, narrowed the source to a small area of

Article

A bright millisecond-duration radio burst from a Galactic magnetar

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Check for updates

The CHIME/FRB Collaboration*

Magnetars are highly magnetized young neutron stars that occasionally produce enormous bursts and flares of X-rays and γ-rays[1]. Of the approximately thirty magnetars currently known in our Galaxy and the Magellanic Clouds, five have exhibited transient radio pulsations[2,3]. Fast radio bursts (FRBs) are millisecond-duration bursts of radio waves arriving from cosmological distances[4], some of w

Article

A fast radio burst associated with a Galactic magnetar

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C. D. Bochenek[1,2]✉, V. Ravi[2], K. V. Belov[3], G. Hallinan[2], J. Kocz[2,4], S. R. Kulkarni[2] & D. L. McKenna[5]

Since their discovery in 2007[1], much effort has been devoted to uncovering the sources of the extragalactic, millisecond-duration fast radio bursts (FRBs)[2]. A class of neutron stars known as magnetars is a leading candidate source of FRBs[3,4]. Magnetars have surface magnetic fields in excess of 10^{14} gauss, the decay of which powers a range of high-energy phenomena[5]. Here we report observations of a millisecond-duration

Article

No pulsed radio emission during a bursting phase of a Galactic magnetar

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L. Lin[1,19], C. F. Zhang[2,3,19], P. Wang[3,19], H. Gao[1], X. Guan[3], J. L. Han[3,4], J. C. Jiang[2,3], P. Jiang[3], K. J. Lee[3,5]✉, D. Li[3,4]✉, Y. P. Men[2,3], C. C. Miao[3], C. H. Niu[3], J. R. Niu[3], C. Sun[3], B. J. Wang[2,3], Z. L. Wang[3], H. Xu[2,3], J. L. Xu[3], J. W. Xu[2,3], Y. H. Yang[6], Y. P. Yang[7], W. Yu[8], B. Zhang[9]✉, B.-B. Zhang[6,9,10], D. J. Zhou[3,4], W. W. Zhu[3], A. J. Castro-Tirado[11,12], Z. G. Dai[6,10], M. Y. Ge[13], Y. D. Hu[11,14], C. K. Li[13], Y. Li[4,15], Z. Li[1], E. W. Liang[16], S. M. Jia[13], R. Querel[17], L. Shao[18], F. Y. Wang[6,10], X. G. Wang[16], X. F. Wu[15], S. L. Xiong[13], R. X. Xu[2,5], Y.-S. Yang[6], G. Q. Zhang[6], S. N. Zhang[3,4,13], T. C. Zheng[16] & J.-H. Zou[18]

CHIME/FRB Collaboration, *Nature*, Vol. 587, p. 54, 4 November 2020
C. D. Bochenek *et al.*, *Nature*, Vol. 587, p. 59, 4 November 2020
L. Lin *et al.*, *Nature*, Vol. 587, p. 63, 4 November 2020

- Li et al. arXiv:2005.11071
- Younes et al. arXiv:2006.11358

This is an efficient and successful collaboration of a large community!

HXMT magnetar-FRB project

- HXMT team @ IHEP
- Magnetar team @ BNU

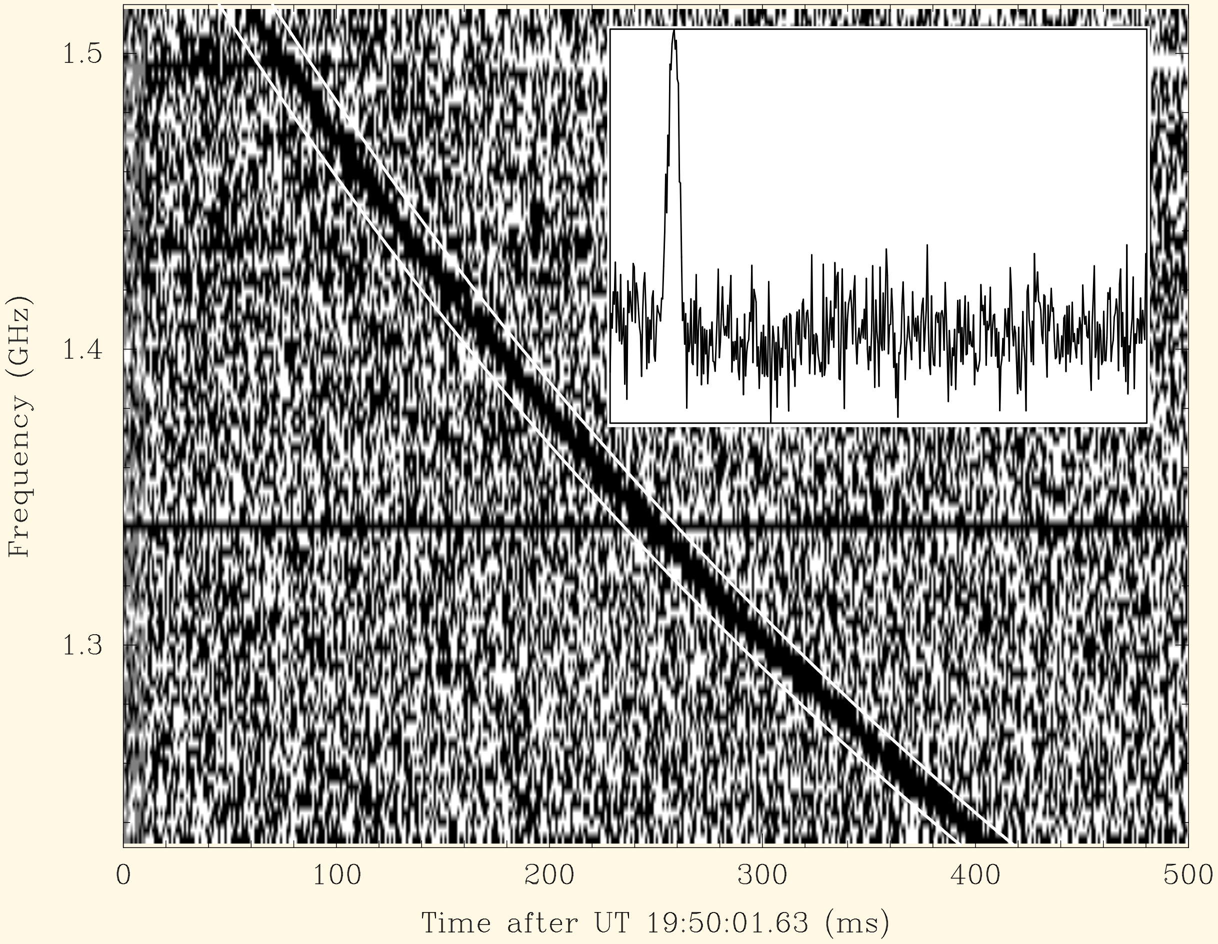
FAST FRB project

- FRB team @ NAOC, PKU-KIAA
- Multi-wavelength observation @ IHEP, GXU, NJU, SHAO, BNU …
- Magnetar team @ BNU
- Theory team @ UNLV, NJU, PMAO, YNU, BNU …

Outline

- Introduction on FRBs and magnetars
- SGR J1935+2154, one of the most active magnetars
- The hard X-ray burst from SGR J1935+2154 associated with FRB 200428
- Such association is rare
- Conclusion

Introduction: FRBs



Lorimer et al. (2007)

The "Lorimer burst"
FRB 010724

- the 1st reported FRB
- Short: <5 ms
- Bright: ~30+/-10 Jy
- Far away: z~0.2
- High event rate
- NO counterpart in other wavelength

the Parkes radio telescope
http://www.scienceimage.csiro.au

Introduction: FRBs

Thornton et al. (2013) reported four FRBs detected in the high Galactic latitude region of the High Time Resolution Universe (HTRU) survey in 2011 and 2012.

- Cosmological distance, z~0.5-1.0
- FRB rate is ~0.001 per galaxy per year
- Energy released is ~10^{38-40} erg

Giant flares from Soft-Gamma Repeaters (magnetars)
Rate ~0.0001 per SGR per year; Energy budget ~10^{47} erg
Ofek (2007)

- NO counterpart in other wavelength

the Parkes radio telescope
http://www.scienceimage.csiro.au

Introduction: FRBs

FRB 121102, the first reported repeating FRB

FRB 180916.J0158+65, the closest FRB and repeating FRB

- z~0.0337, 149.0+/-0.9 Mpc
- in a star-forming region of a spiral galaxy

? Radio pulses from a newborn magnetar

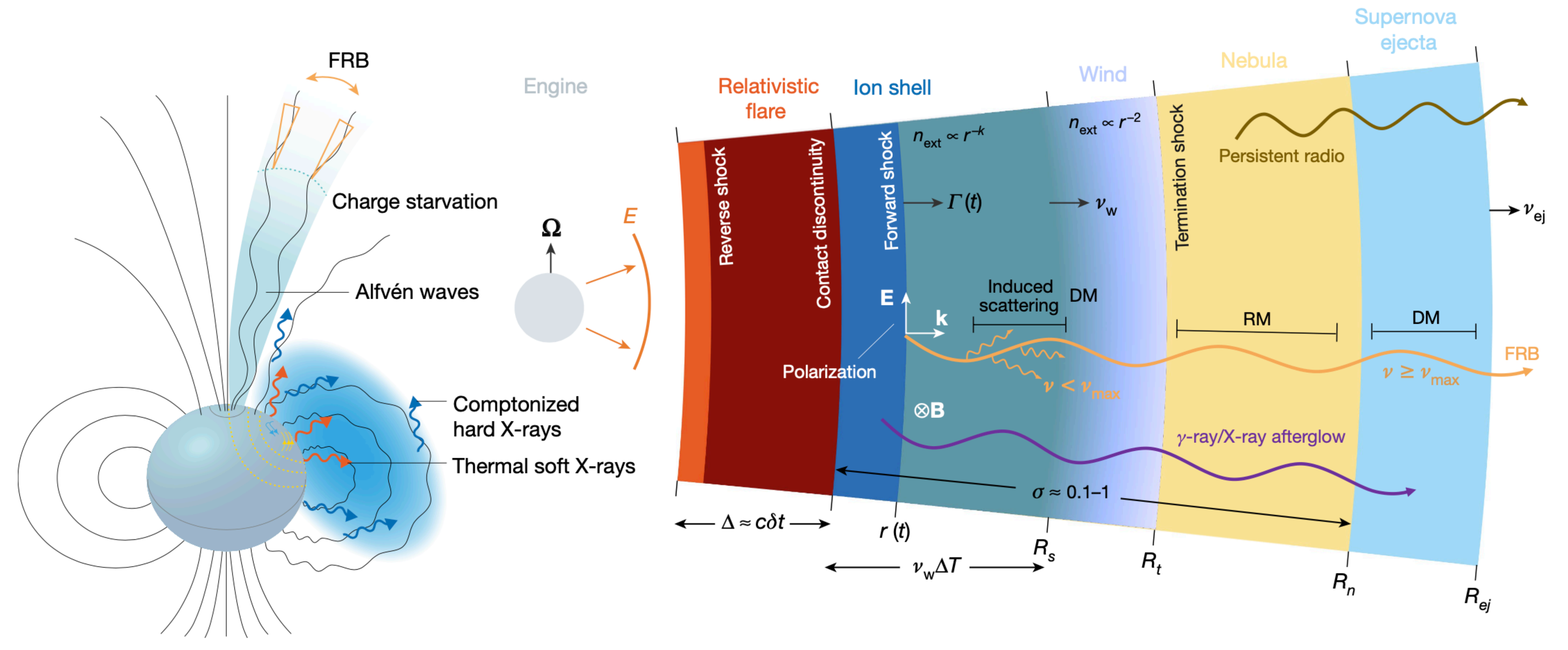
With large FOV and sensitive radio survey projects (CHIME/FRB, STAIRE2, CRAFT et al.), more FRBs will be detected and well localized.

! Still NO counterpart in other wavelength

An X-ray counterpart would be too dim to detect at such large distances.

Spitler et al. 2016
Marcote et al. 2020

Introduction: FRBs

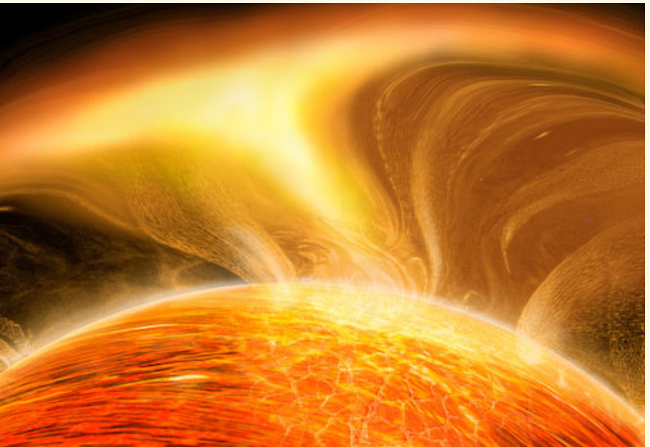


FRB review by Bing Zhang 2020 Nature

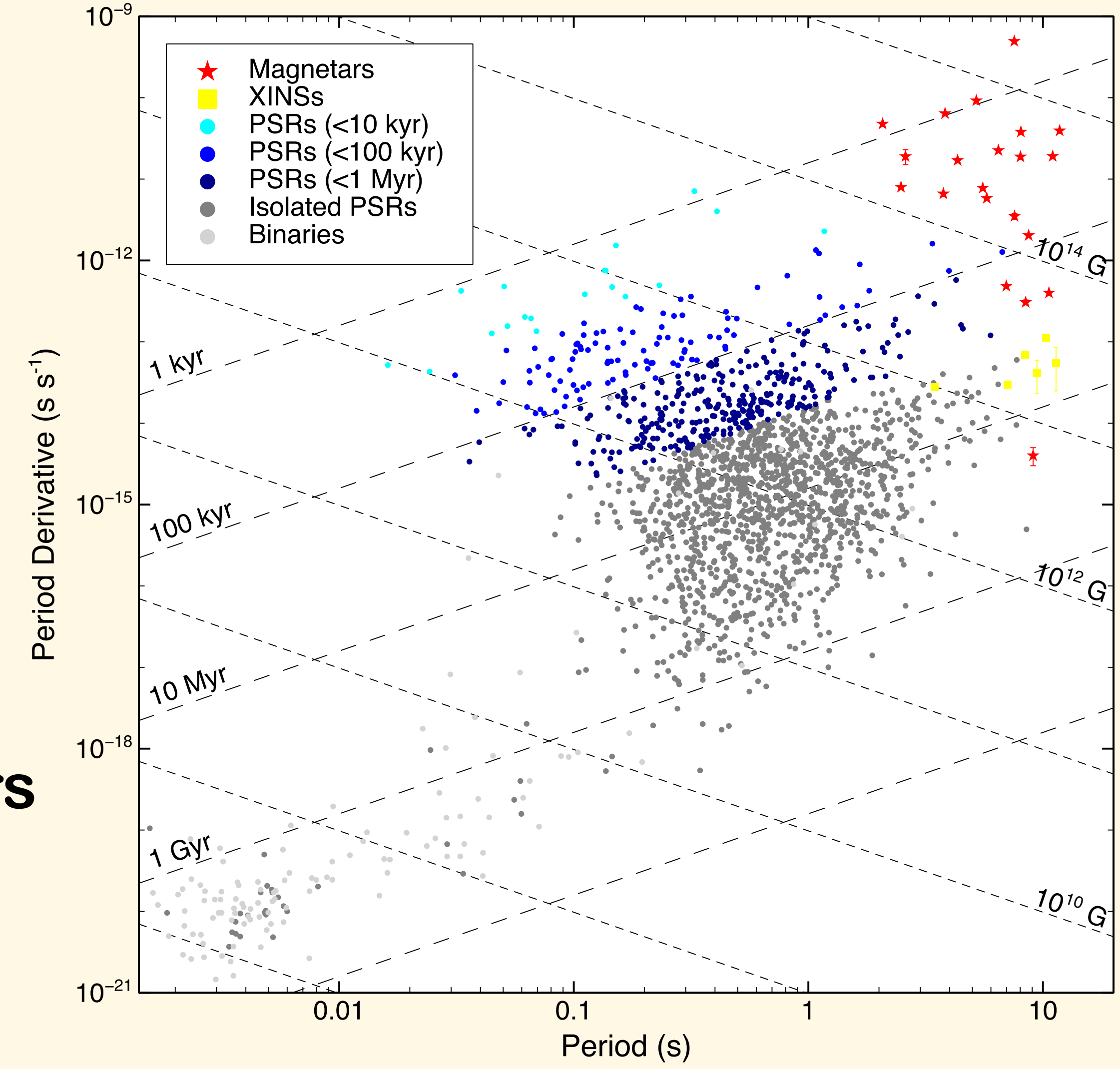
Introduction: magnetars

Neutron stars with extremely strong magnetic fields

- **Soft-Gamma Repeaters (SGRs)& Anomalous X-ray Pulsars (AXPs)**
- $L_X \sim 10^{33} - 10^{35} \mathrm{erg/s} > L_{rot}$
- $P = 2 \sim 12\ \mathrm{s}, \dot{P} = 10^{-10} \sim 10^{-13}\ \mathrm{s} \cdot \mathrm{s}^{-1}$
- $B_{surf} \sim 10^{14} - 10^{15}\ \mathrm{G}$

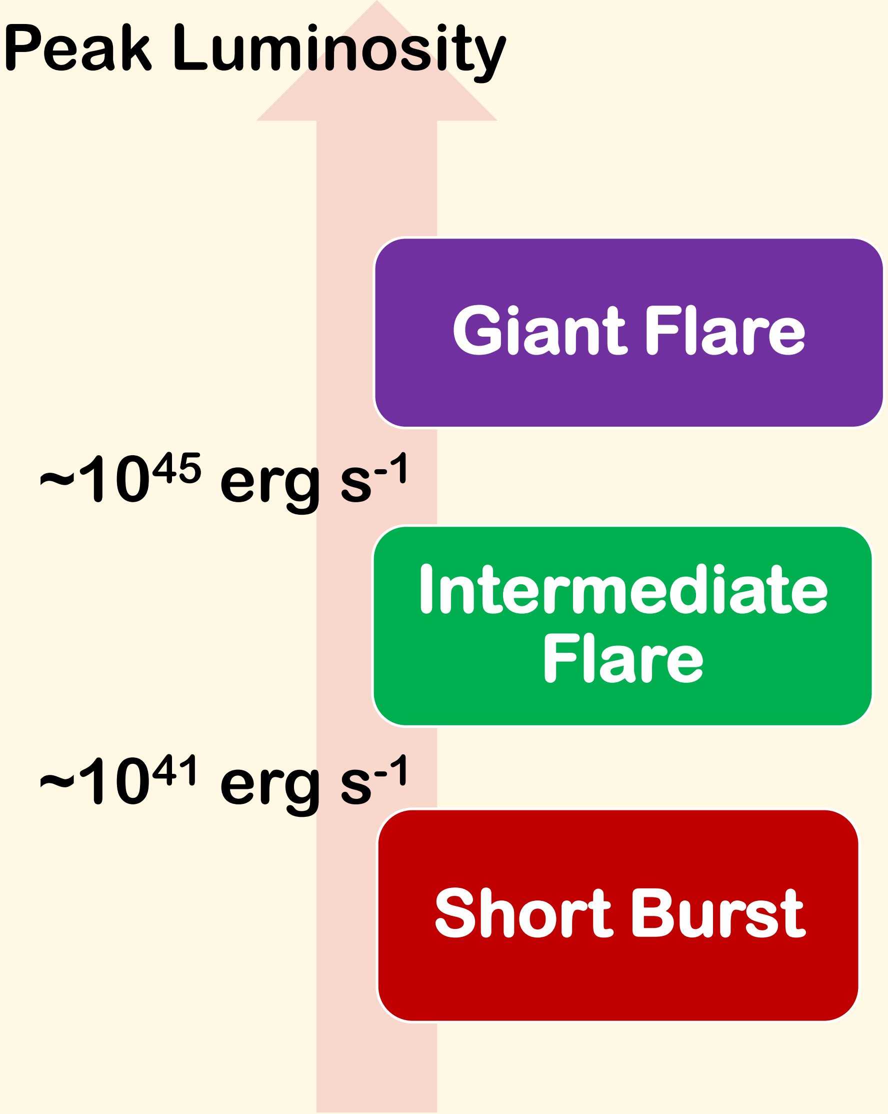


- **~30 known magnetars**
- **Most are galactic sources, only two in S/LMC each**



Olausen & Kaspi 2014

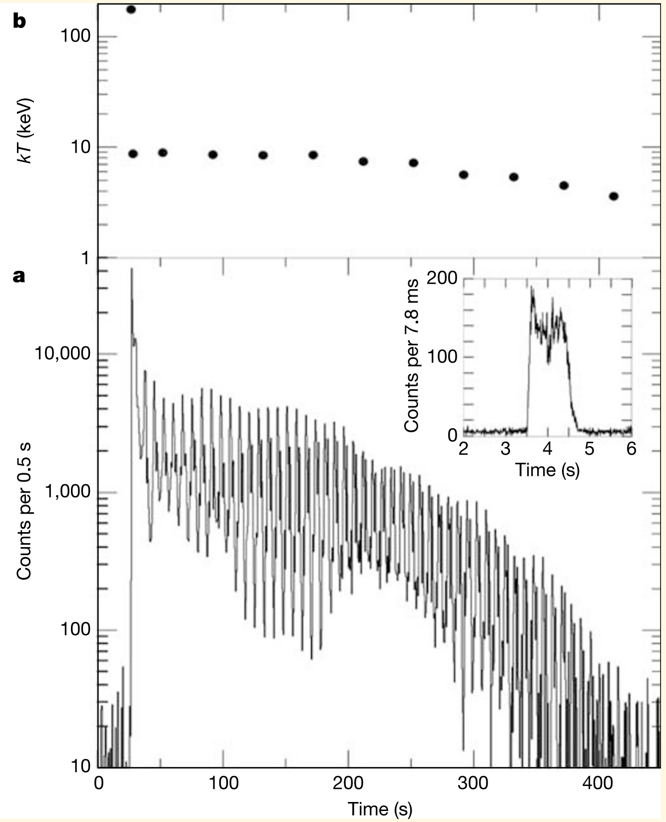
Introduction: magnetars



Giant Flare: the most energetic but the rarest event

- **Short hard spike + long soft periodic tail**
- **3 GFs form 3 SGRs**
  SGR 0526-66, 1979-3-5
  SGR 1900+14, 1998-8-27
  SGR 1806-20, 2004-12-27
- **Radio NONE-detection of SGR 1806-20 GF with Parkes side lob**

(Tendulkar et al. 2016)



Hurley et al. 2005

Introduction: magnetars

Peak Luminosity

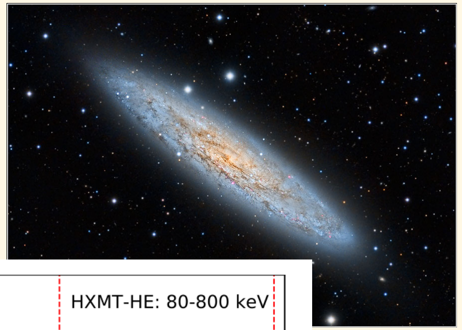
Giant Flare

$\sim 10^{45}$ erg s^{-1}

Intermediate Flare

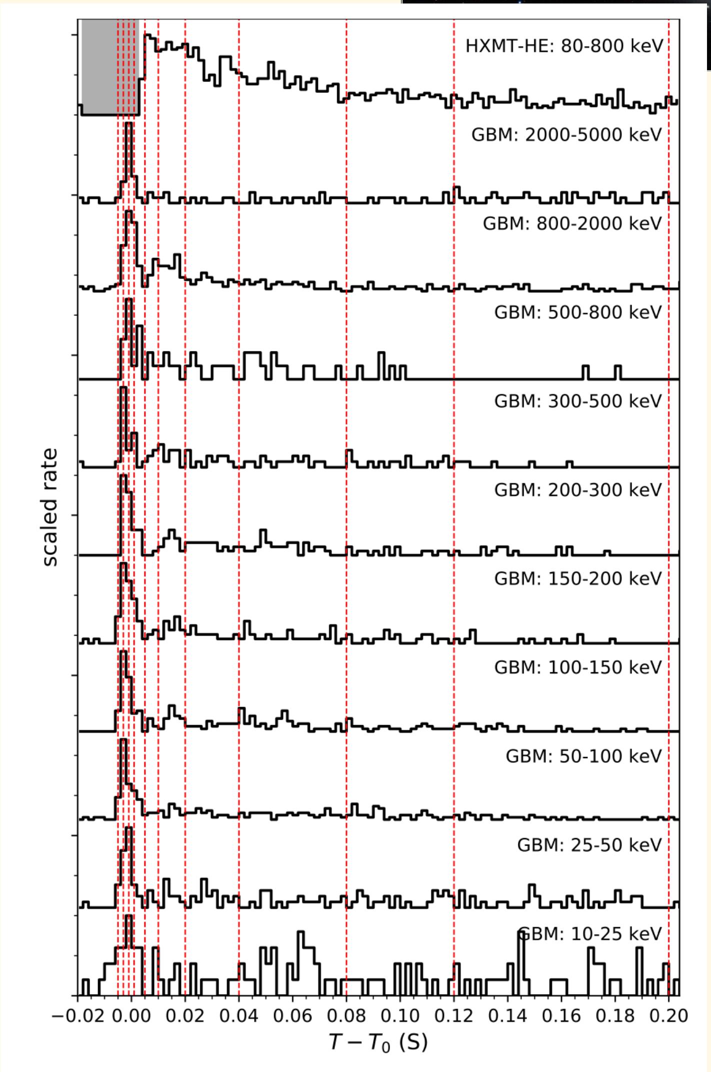
$\sim 10^{41}$ erg s^{-1}

Short Burst



Giant Flare:

GRB 200415A @
The Sculptor Galaxy
(3.5 Mpc)



Yang et al. 2020

Introduction: magnetars

Peak Luminosity

Giant Flare

~10^{45} erg s^{-1}

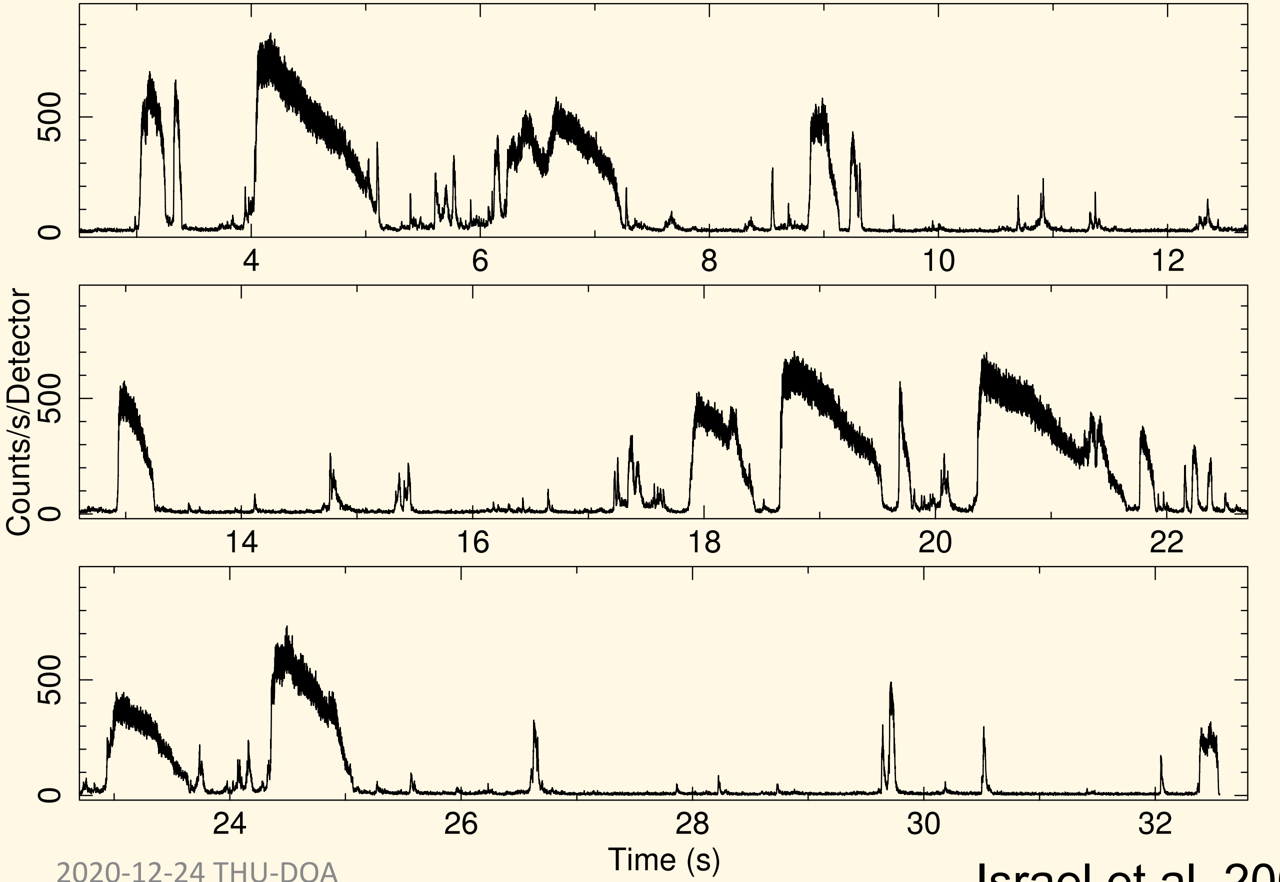
Intermediate Flare

~10^{41} erg s^{-1}

Short Burst

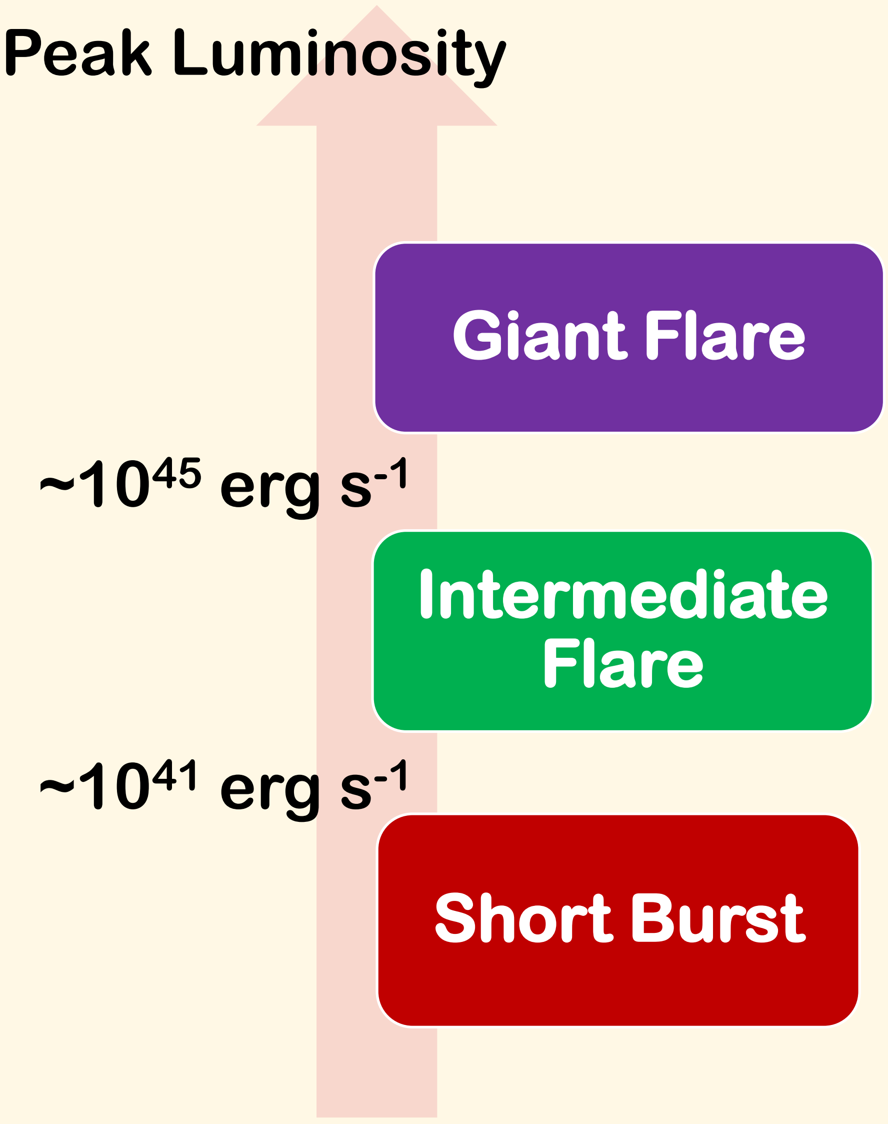
Intermediate Flares

Burst forest from SGR 1900+14 on 2006-3-29 observed with Swift/BAT in 15-100 keV



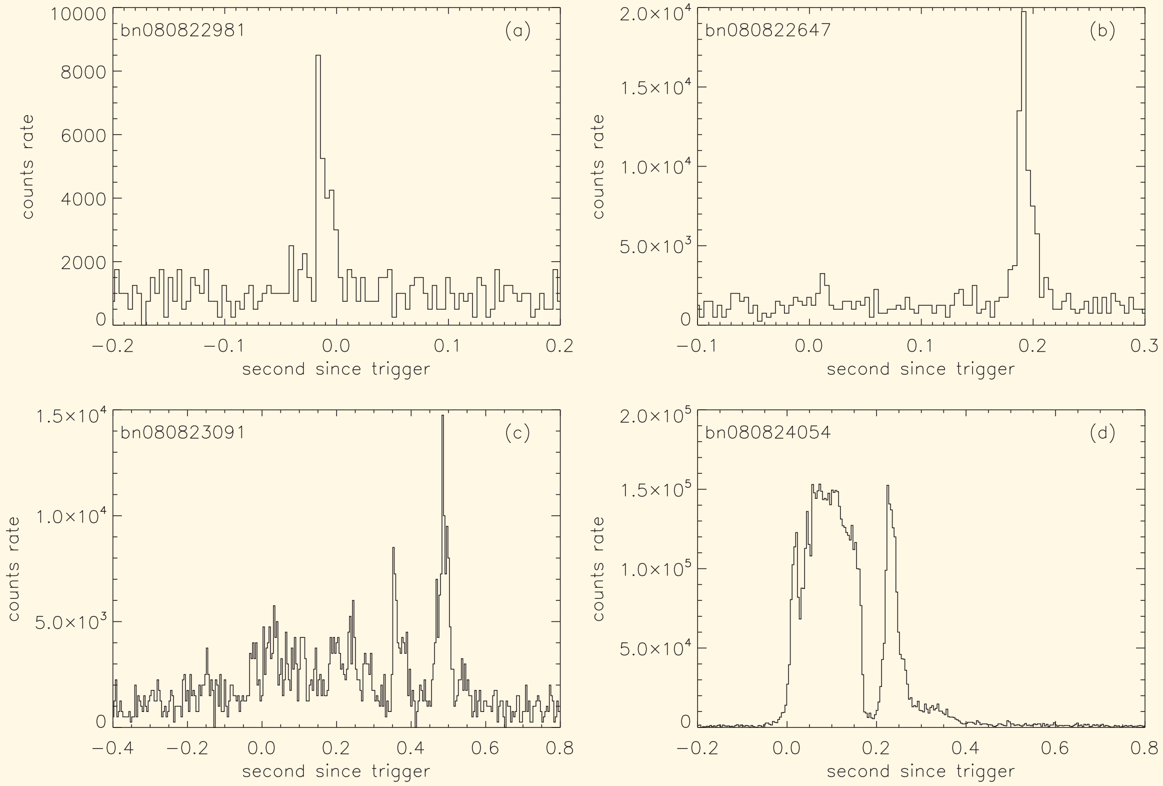
Israel et al. 2008

Introduction: magnetars



Short Burst

- The most common events but unpredictable
- From both SGRs and AXPs



2020-12-24 THU-DOA

SGR J0501+4516 Fermi/GBM Lin et al. 2011

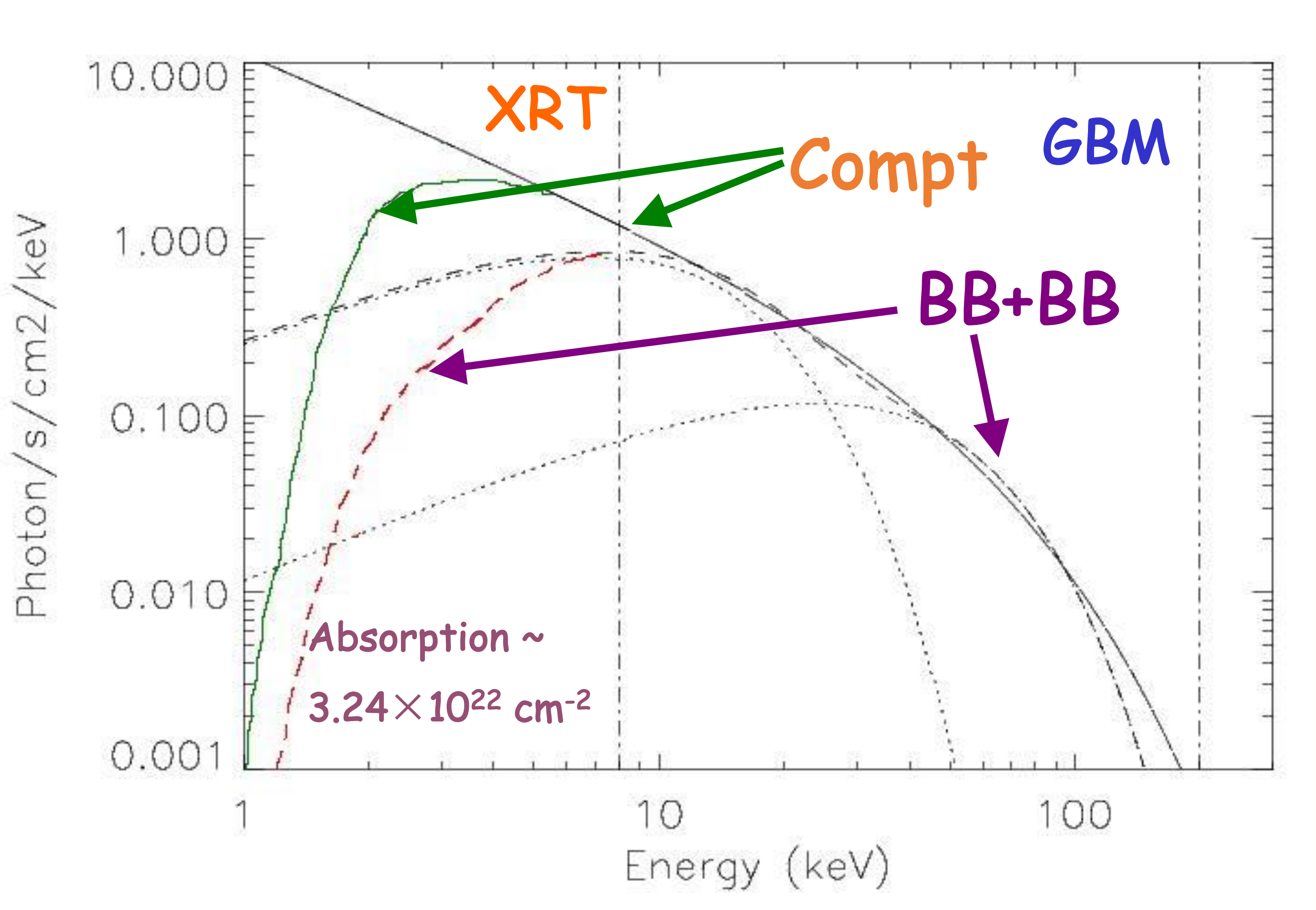
Introduction: magnetars

The burst spectrum : BB+BB is preferred over CutoffPL

Low kT ~ 4.4 keV

High kT ~ 16 keV

Epeak ~ 45 keV



We need the broad energy coverage (e.g. 1-200 keV) to study the burst spectra.

Israel et al. 2008, Lin et al. 2012

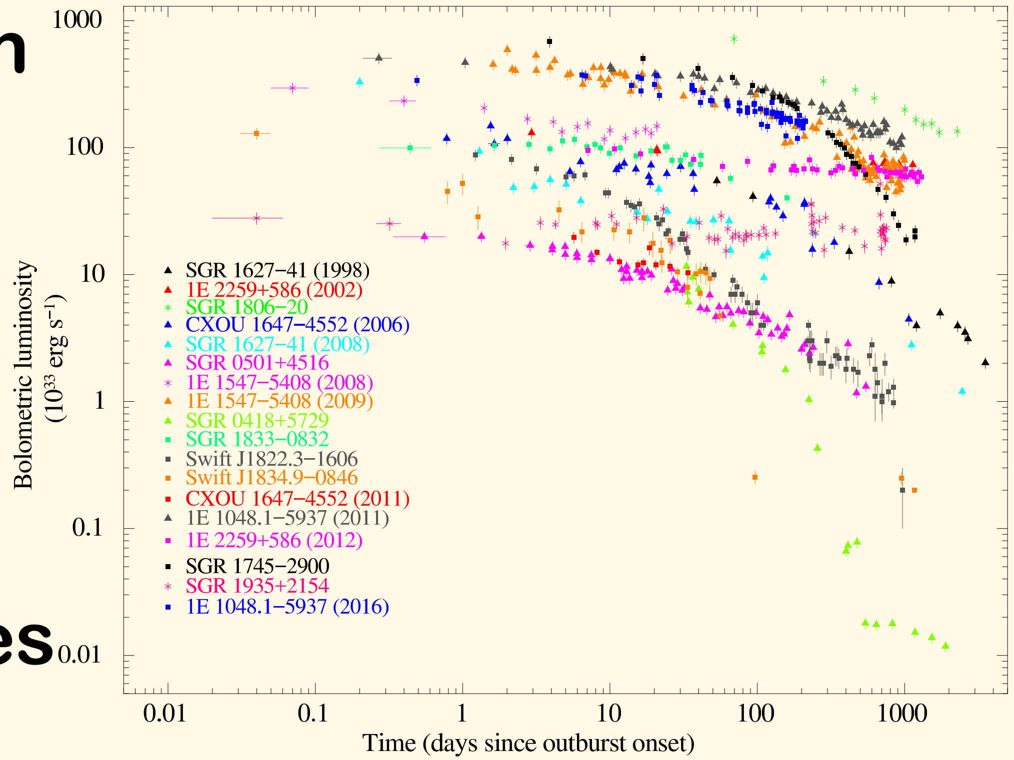
Introduction: magnetars

Magnetar outbursts: brightening of the persistent emission

Different types of magnetar based on the burst and outburst activities:

- Prolific bursters
  - Magnetars with GFs
- Prolific transients
  - SGR J1550-5418, SGR J1935+2154 …
- AXPs with SGR-like bursts
- Transients SGRs with low burst rates

(Gogus et al. 2014)

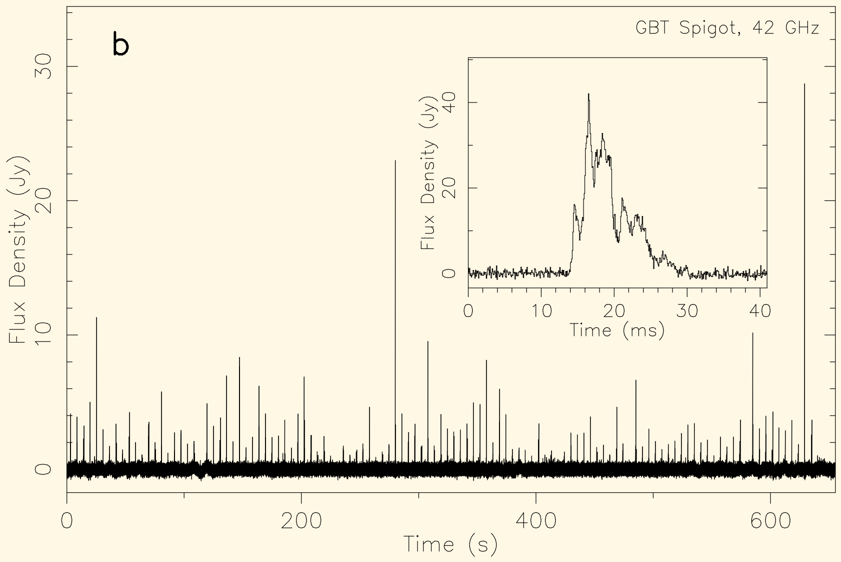


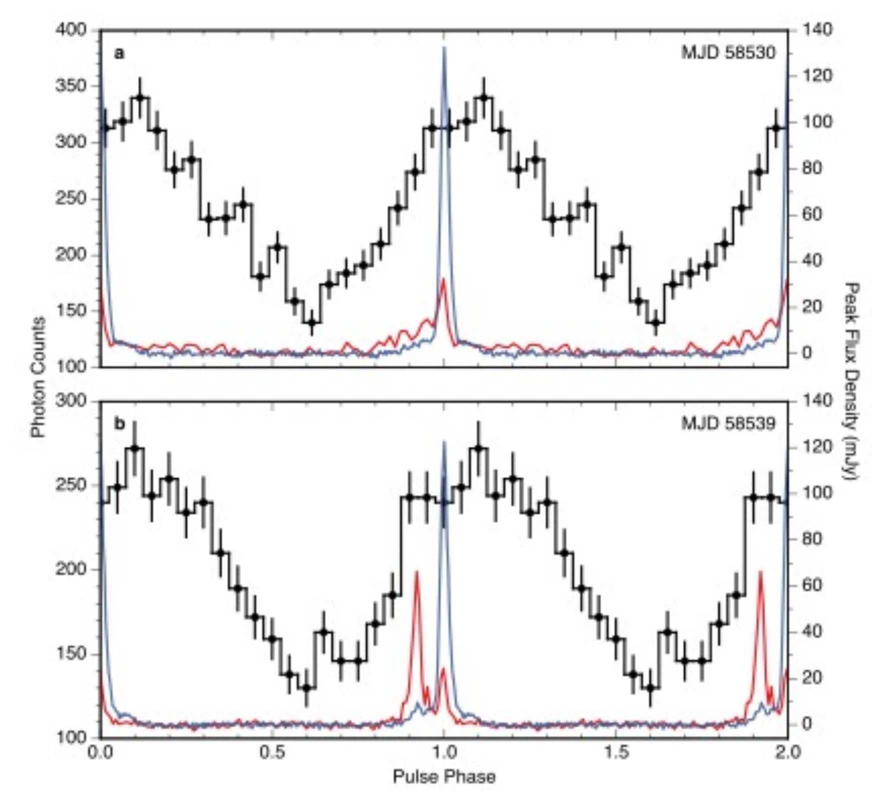
Magnetar outbursts
Coti Zelati et al. 2018

Introduction: magnetars

Radio emission from XTE J1810-197

- A transient radio related with the X-ray outburst
- Short strong radio pulses, still can't be seen at FRB distances

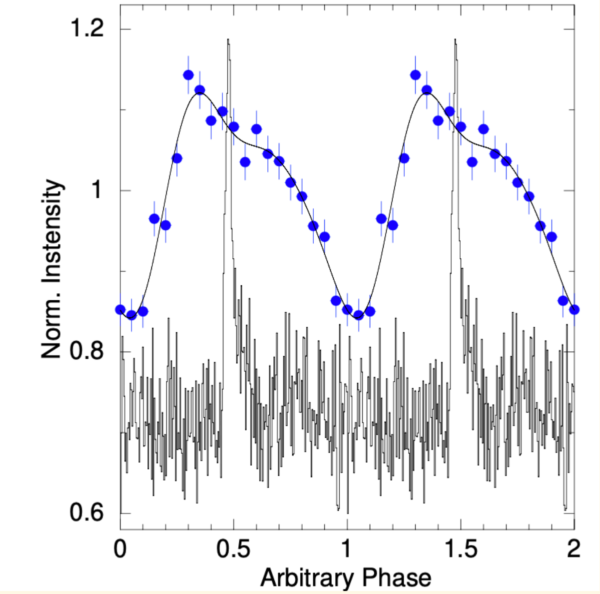




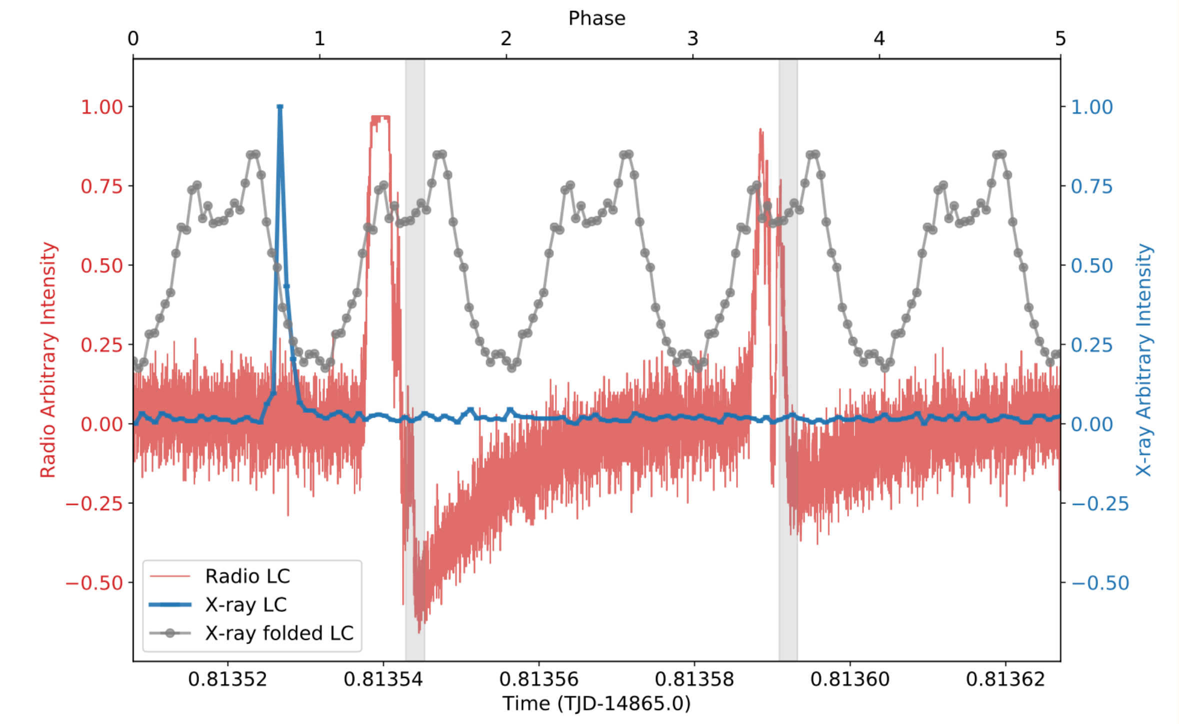
Camilo et al. 2006,
Pearlman et al. 2020

Introduction: magnetars

Bright radio pulses from SGR J1550-5418 covered by X-ray observations



- 2019-02-03, ~5 days after the peak of the burst forest
- The radio pulse highly saturated the Parkes.
- The 6 GHz radio flux >1Jy, pulse width ~200 ms
- An X-ray burst was detected ~1 s ahead of one radio pulse



Israel et al. 2020

Introduction: FRBs and magnetars

FRBs may come from magnetars

but

the smoking gun is still missing.

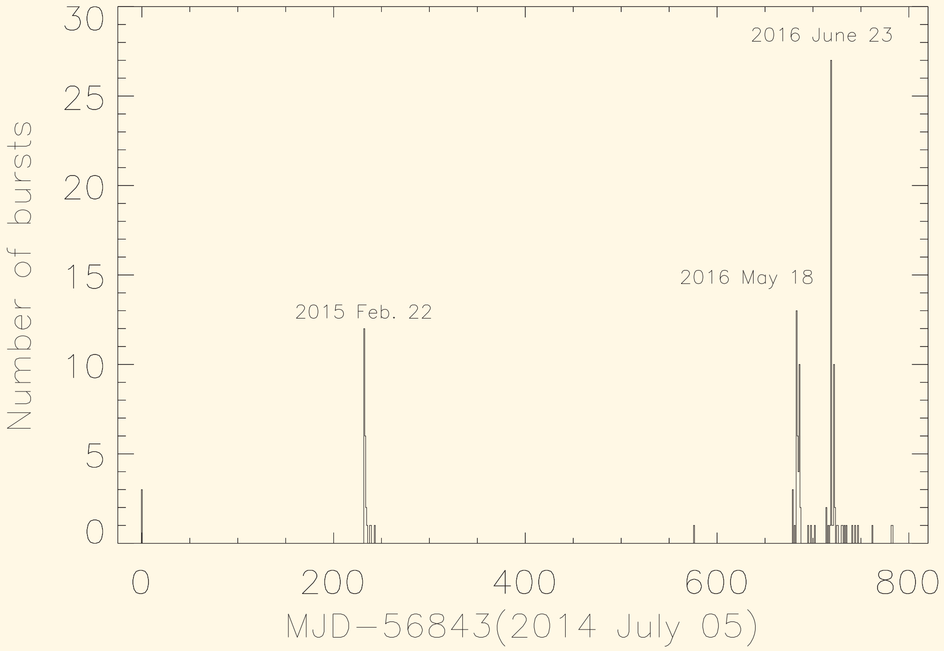
SGR J1935+2154

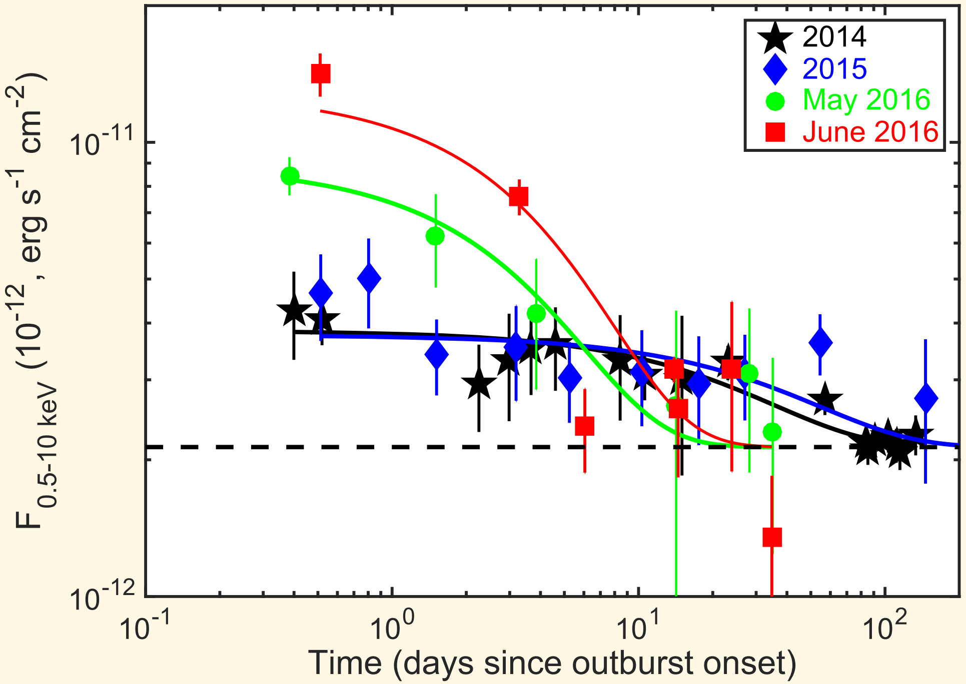
- $P = 3.25\ \mathrm{s}, \dot{P} = 1.4\times10^{-11}\ \mathrm{s}\cdot\mathrm{s}^{-1}$
- $B_{surf} = 2.2\times10^{14}\ \mathrm{G}$
- **Close to the center of SNR G57.2+0.8**
- **One of the most active magnetars**

2014-07 **(discovery)**
2015-02
2016-05
2016-06
2019-11
2020-04

Several isolated burst/flares detected between active episodes.

Israel et al. 2016
Younes et al. 2017
Lin et al. 2020a





SGR J1935+2154

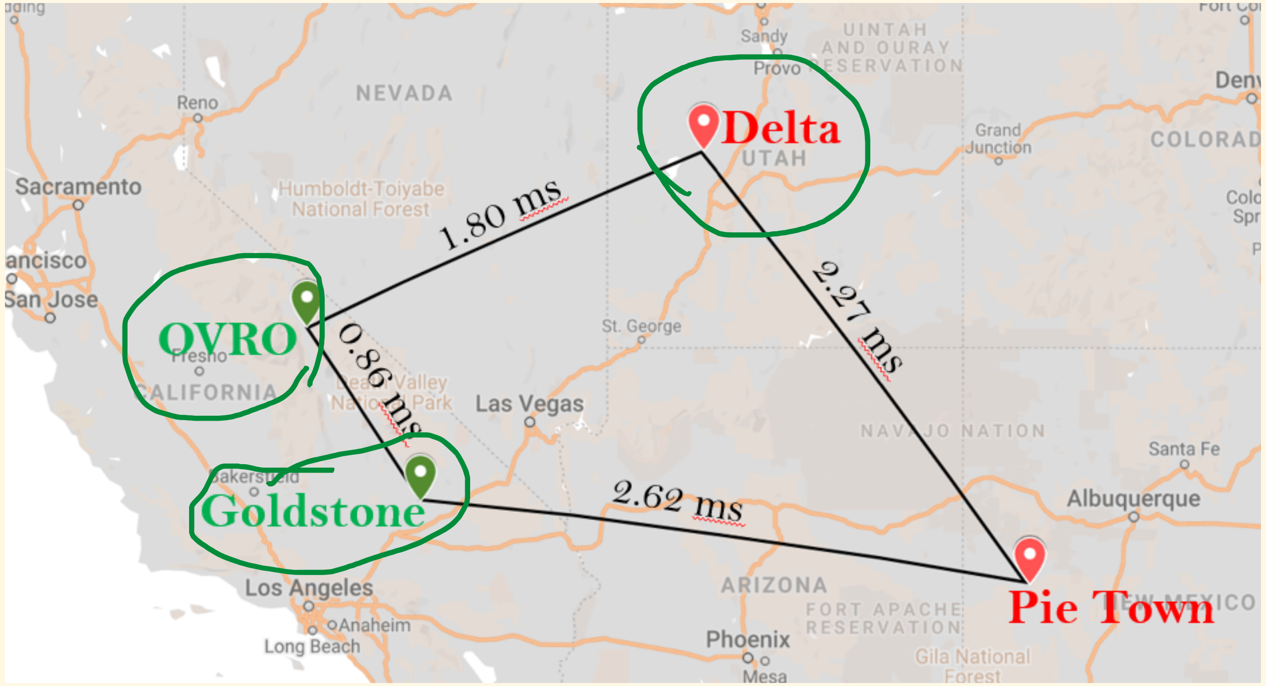
Time (UTC)	Events	Telescope
April 10 & 22	2 bright bursts	Konus-Wind, Fermi/GBM, CALET/GRBM
April 27 18:26:20 [T0]	Many bursts + burst forests (~300 s)	Swift/BAT, Fermi/GBM, ….
April 27 23:55:00 [~T0+5 hr]	FAST started a series monitoring observation	
April 28 07:14:50 [~T0+13 hr]	Insight/HXMT started 60 ks pointing observation	
April 28 14:34:24	FRB 200428	CHIME/FRB and STARE2
	Hard X-ray burst	Insight/HXMT, Konus-Wind, INTEGRAL
April 30 06:58:25 – May 31	the long ToO observation of Insight/HXMT	
April 30	A weak radio pulse	FAST

FRB 200428

Detected with CHIME/FRB and STARE2

CHIME: 400-800 MHz, FOV ~ 3 deg * 120 deg

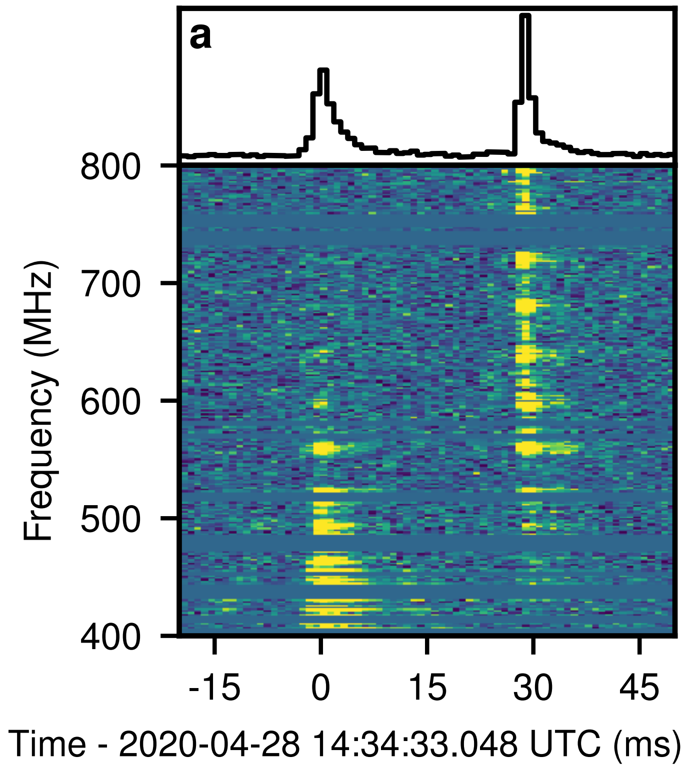
STARE2: 1280-1530 MHz



Bochenek et al. 2020a

FRB 200428

CHIME/FRB: two sub-bursts



STARE2: the 2^{nd} sub-burst

~ 1.5 MJy ms

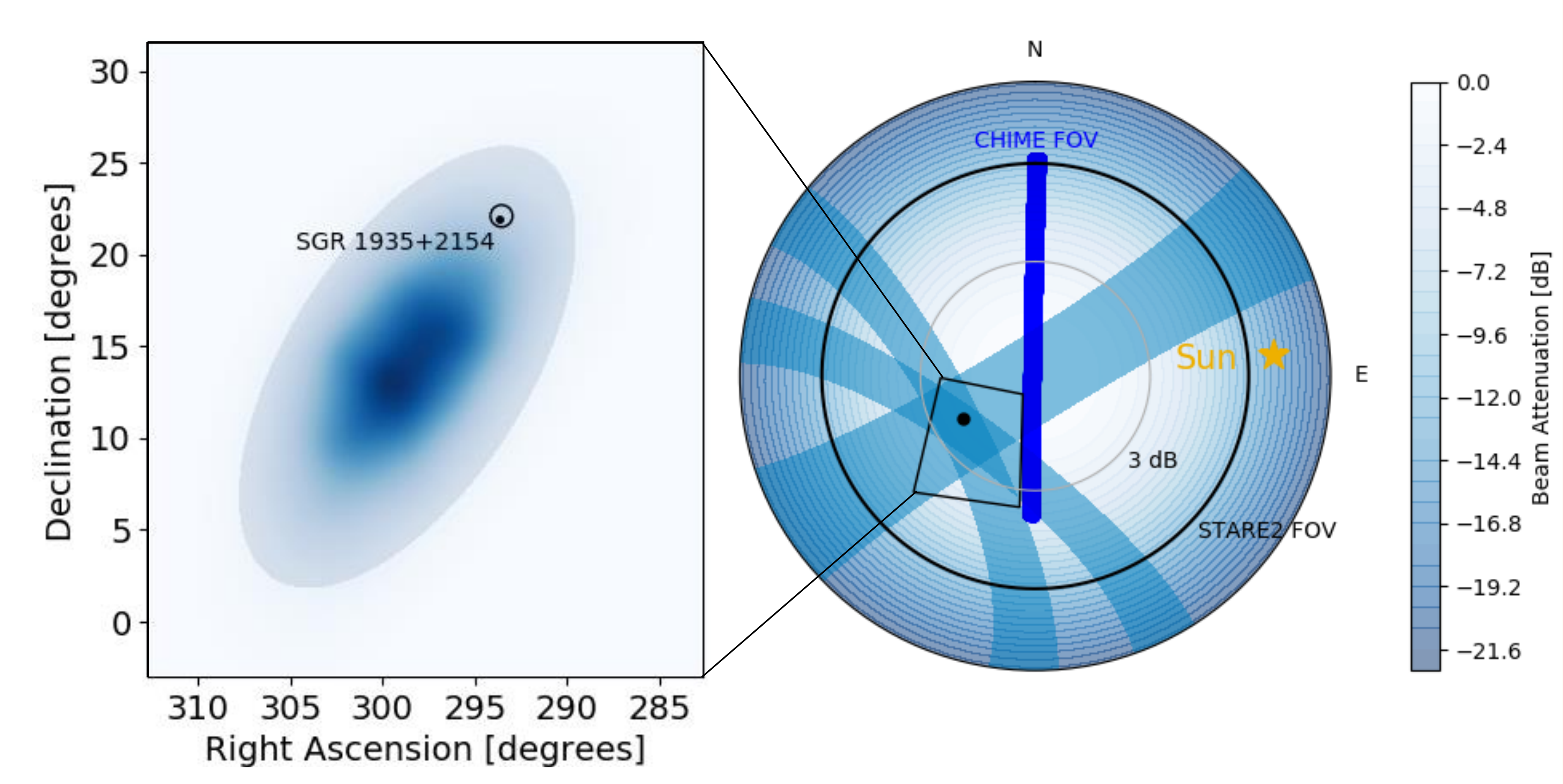
Table 1 | Data on FRB 200428

Property	Measurement
OVRO arrival time at v = 1,529.267578 MHz	28 April 2020 14:34:25.02657(2) UTC
OVRO arrival time at $v = \infty$[a]	28 April 2020 14:34:24.43627(3) UTC
Earth centre arrival time at $v = \infty$[a]	28 April 2020 14:34:24.45548(3) UTC
Fluence (MJy ms)	1.5(3)
Dispersion measure, DM (pc cm^{-3})	332.702(8)
Intrinsic burst FWHM[b] (ms)	0.61(9)
Isotropic-equivalent energy release[c] (erg)	$2.2(4) \times 10^{35}$

Standard errors in the final significant figures (68% confidence) are given in parentheses.
[a]The correction to the infinite-frequency ($v = \infty$) arrival time is carried out using the DM quoted in this table, and assuming a dispersion constant of $(1/2.41) \times 10^4$ s MHz^2 pc^{-1} cm^3 (ref. [31]).
[b]FWHM of the Gaussian used to model the intrinsic burst structure (Methods).
[c]This assumes a distance to SGR 1935+2154 of 9.5 kpc.

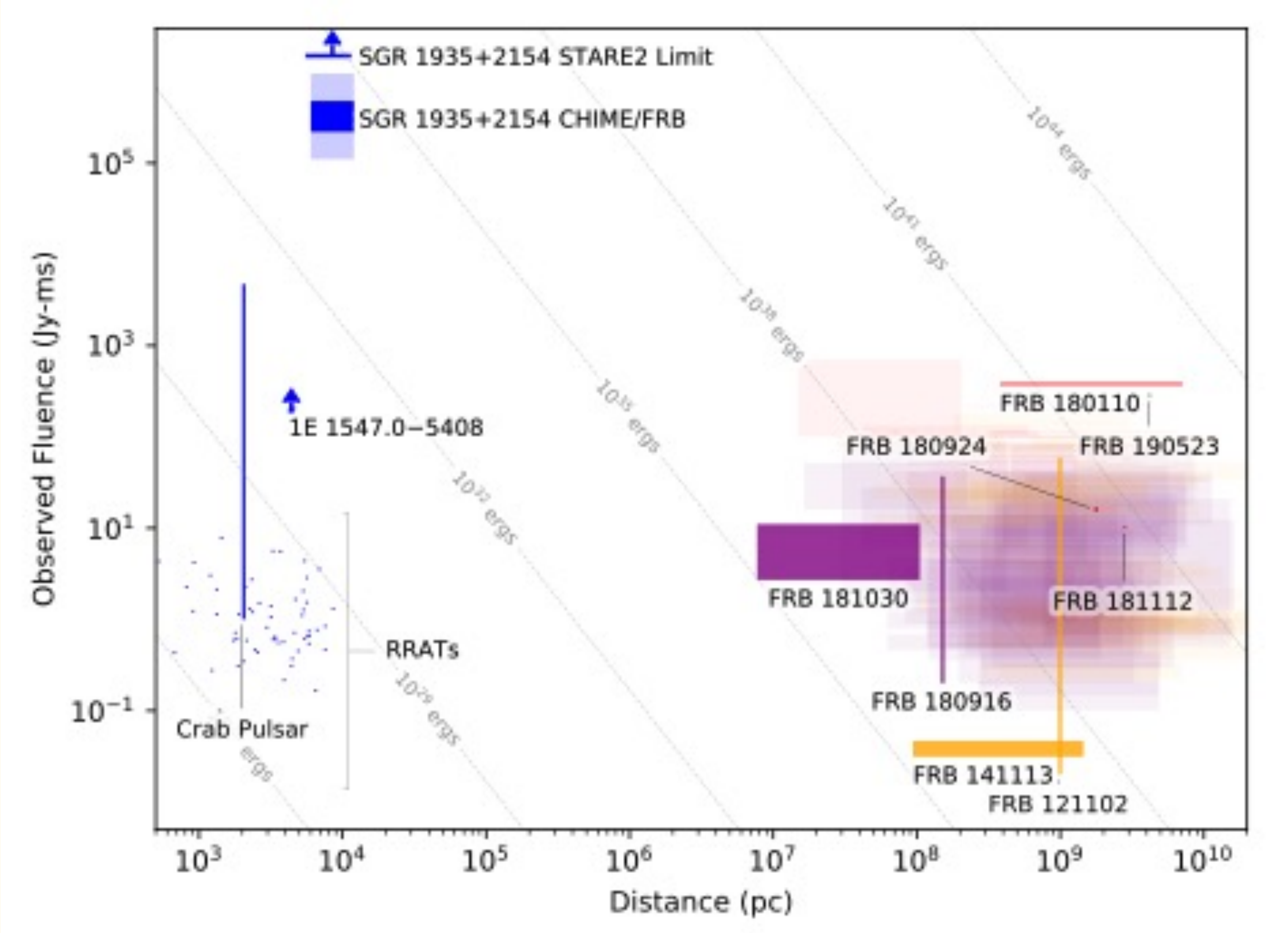
FRB 200428

The radio localization of FRB 200428



FRB 200428

- The **<u>most energetic</u>** radio pulse from galactic magnetars
- The **<u>weakest</u>** FRB, but still visible at cosmological distance

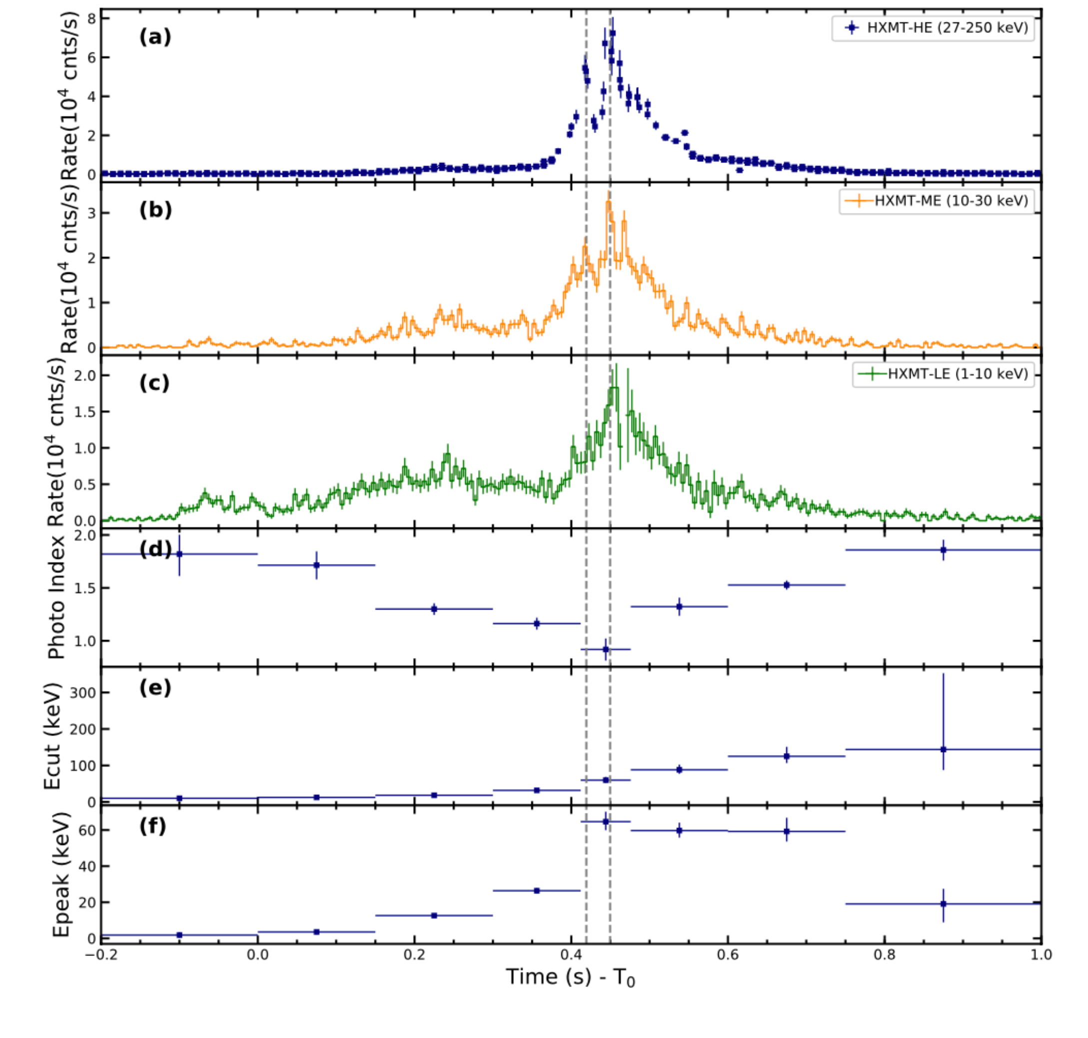


FRB 200428 is a Galactic analogue of the extragalactic FRBs.

FRB 200428—the hard X-ray burst

11 Bursts detected with HXMT on April 28

Trigger time (UTC)	Fluence 10^{-8}erg cm^{-2}	Duration s	Δt s
2020-04-28T08:03:34.35	5.65 ± 1.14	0.11	-23458.65
2020-04-28T08:05:50.15	5.04 ± 1.39	0.07	-23322.85
2020-04-28T09:08:44.30	1.37 ± 1.86	0.06	-19548.70
2020-04-28T09:51:04.90	25.58 ± 2.51	0.42	-17008.10
2020-04-28T11:12:58.55	1.30 ± 1.41	0.06	-12094.45
2020-04-28T12:54:02.20	0.87 ± 1.09	0.40	-6030.80
2020-04-28T14:20:52.50	2.93 ± 1.17	0.60	-820.50
2020-04-28T14:20:57.90	2.06 ± 2.45	0.06	-815.10
2020-04-28T14:34:24.00	63.68 ± 6.62	0.53	-9.00
2020-04-28T17:15:26.25	0.25 ± 0.42	0.08	9653.25
2020-04-28T19:01:59.85	3.01 ± 1.22	0.16	16046.85



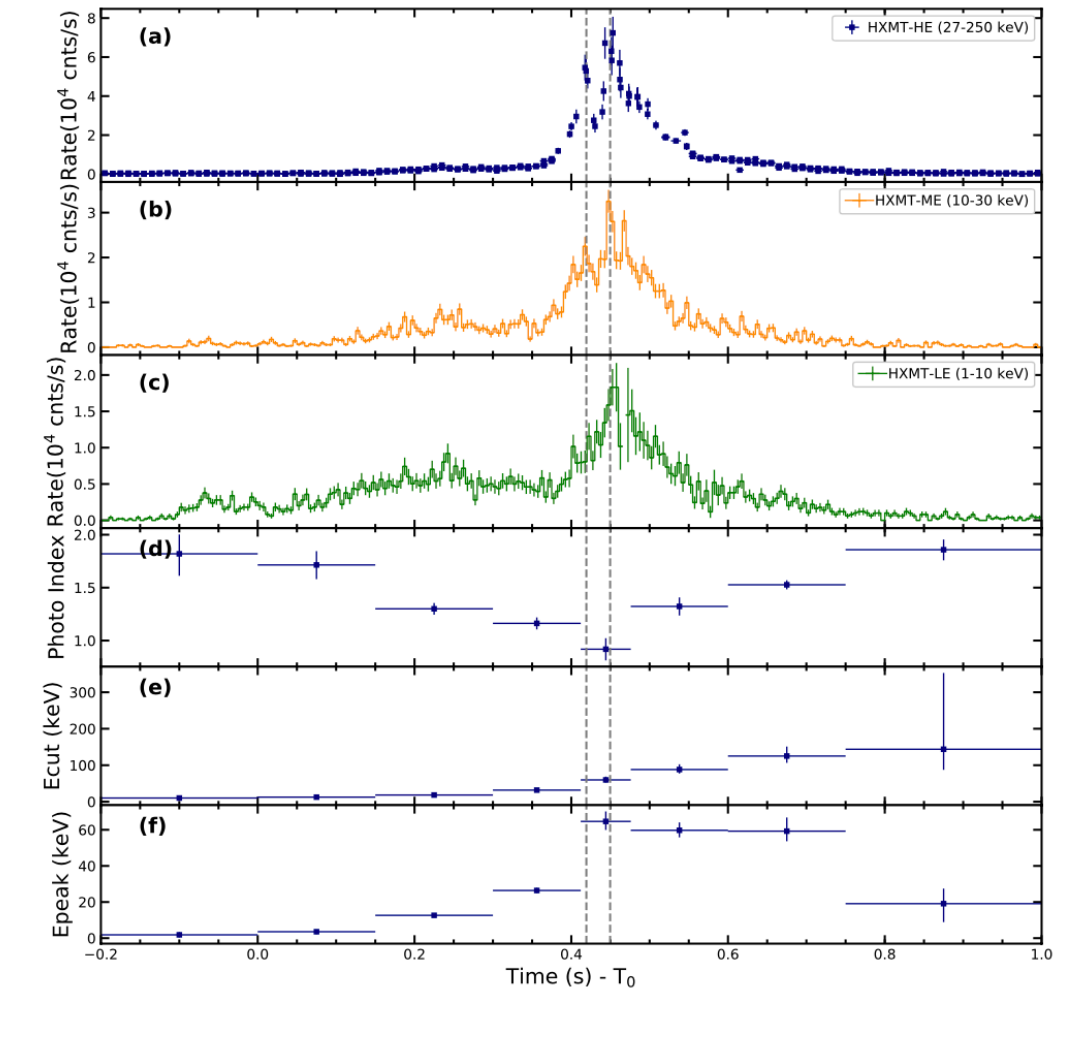
Li et al. 2020

FRB 200428—the hard X-ray burst

The radio LC (CHIME)v.s. the X-ray LC (HXMT)

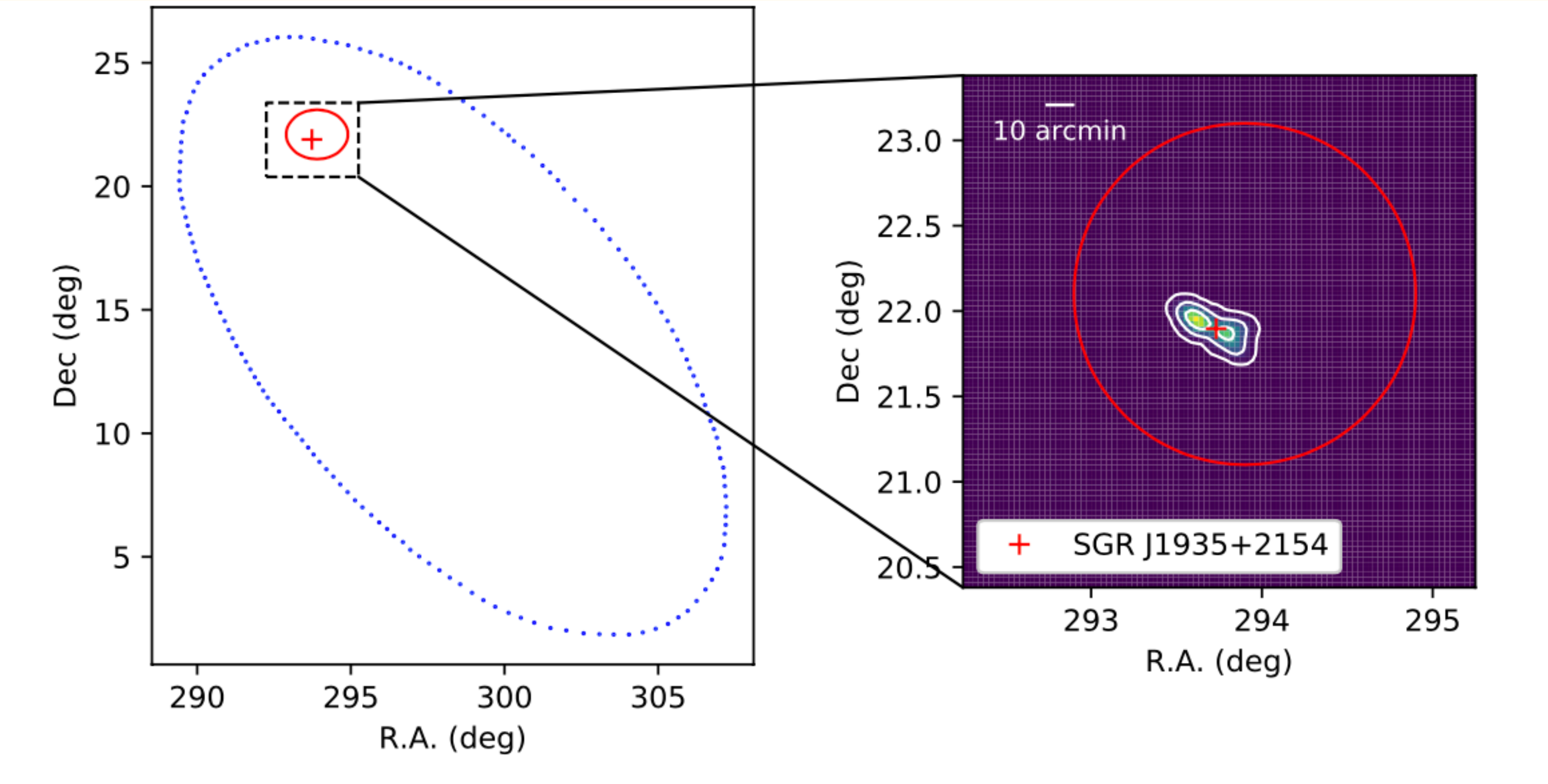
- Two short spikes, separated by ~30ms
- The time difference between radio and X-ray is ~8.62s, agree with the DM prediction.

These two spikes are the key evidence of the association between FRB and the hard X-ray burst.



Li et al. 2020

FRB 200428—the hard X-ray burst



The burst location using HXMT data is 3.7 arcmin away from SGR J1935+2154, with 1σ uncertainty of 10 arcmin. This agrees with the Integral result.

Li et al. 2020

FRB 200428—the har

Non-thermal: cutoffPL

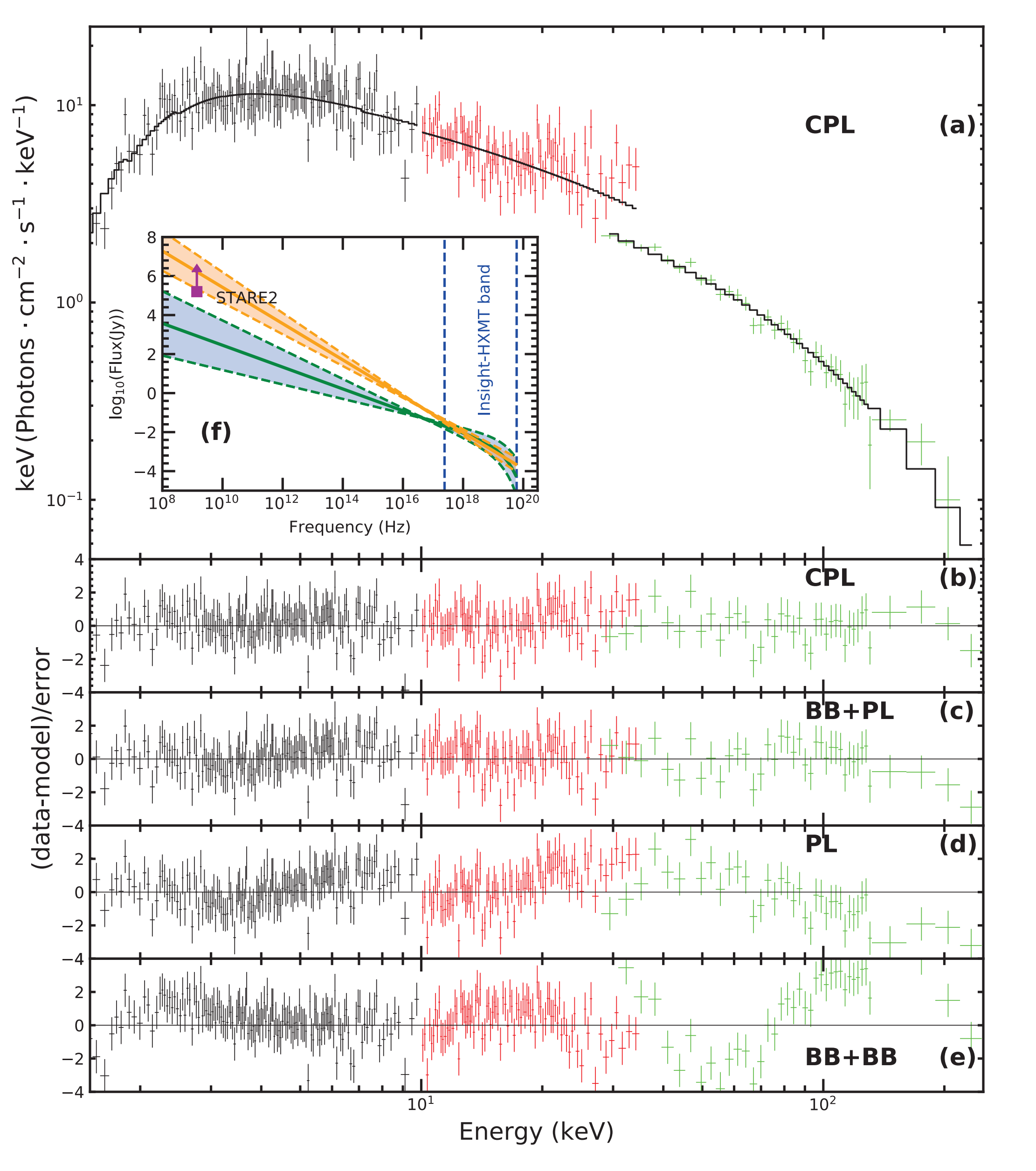
$$n_{\rm H} = (2.79^{+0.18}_{-0.17}) \times 10^{22}\ {\rm cm}^{-2}$$

$$\Gamma = 1.56 \pm 0.06$$

$$E_{\rm cut} = 83.89^{+9.08}_{-7.55}\ {\rm keV}$$

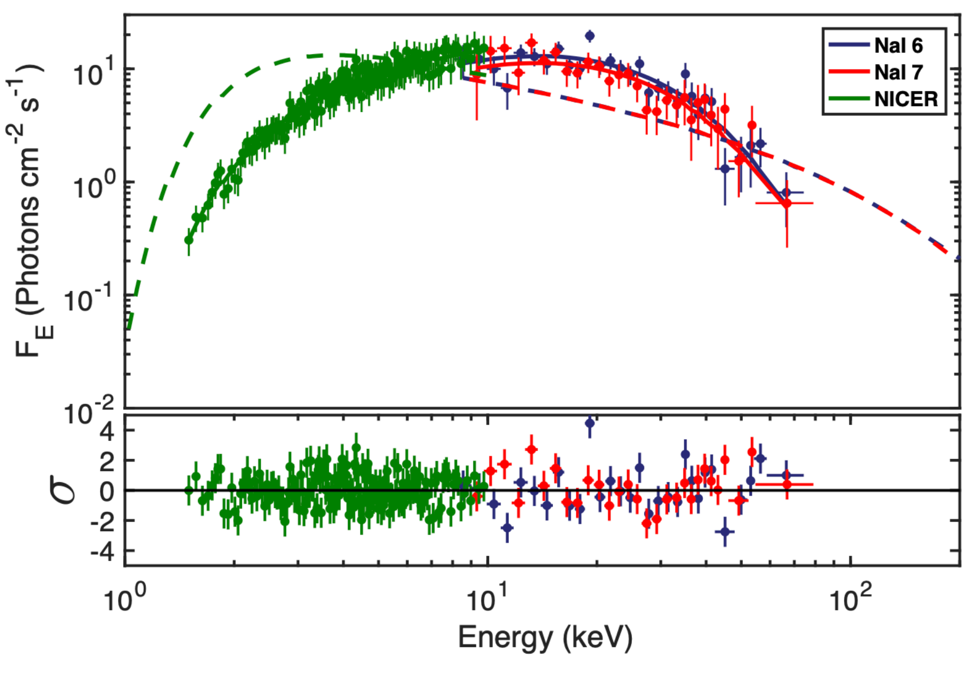
The unabsorbed fluence is $(7.14^{+0.41}_{-0.38}) \times 10^{-7}$ erg cm^{-2}

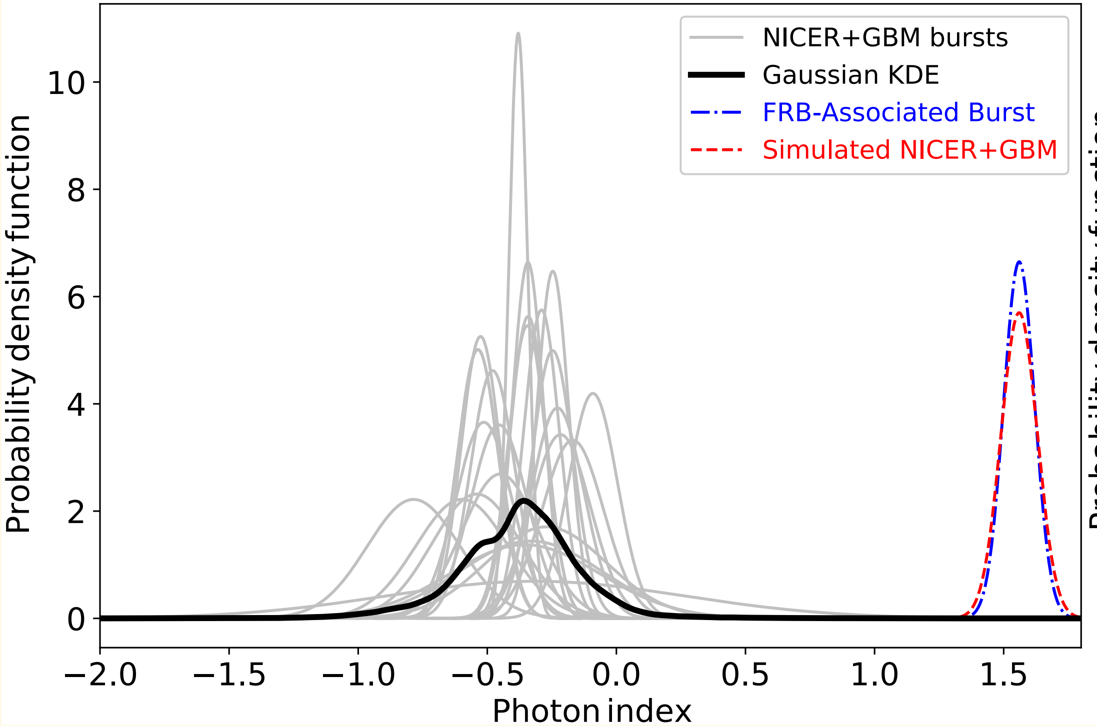
Such X-ray burst is non-detectable if placed at a normal FRB distance.

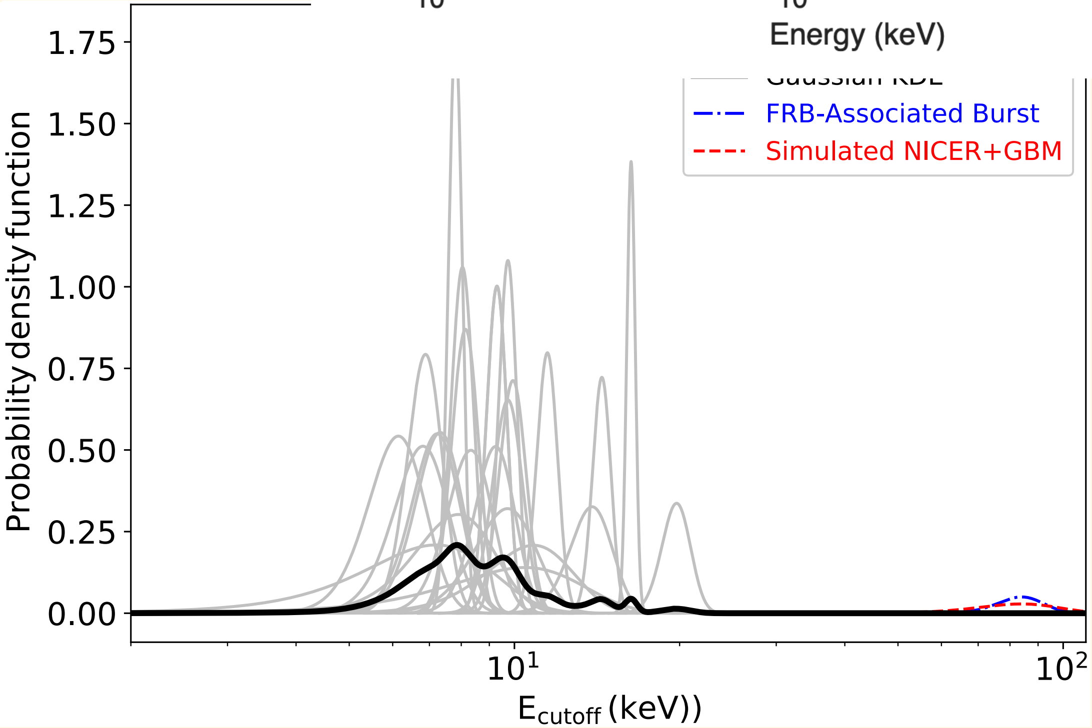


FRB 200428—the hard X

This burst is spectrally different from other X-ray bursts from SGR1935







Younes et al. 2020

SGR J1935+2154

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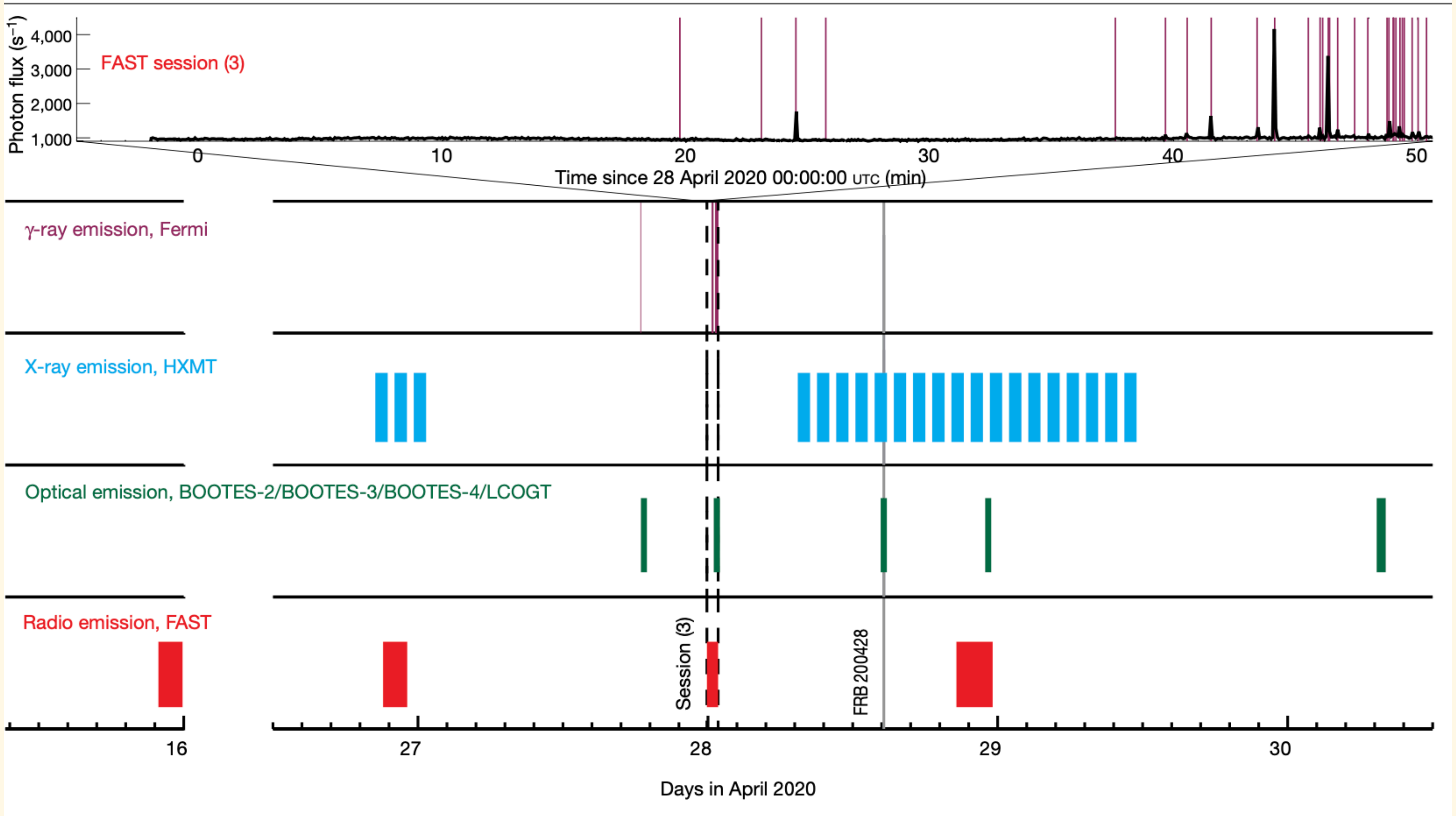
April 27 18:26:20 [T0]	Many bursts + burst forests (~300 s)	Swift/BAT, Fermi/GBM, ….
April 27 23:55:00 [~T0+5 hr]	FAST started a series monitoring observation	
April 28 07:14:50 [~T0+13 hr]	Insight/HXMT started 60 ks pointing observation	
April 28 14:34:24	FRB 200428	CHIME/FRB and STARE2
	Hard X-ray burst	Insight/HXMT, Konus-Wind, INTEGRAL
April 30 06:58:25 – May 31	the long ToO observation of Insight/HXMT	
April 30	A weak radio pulse	FAST

FRB v.s. SGR burst

FAST detected NO radio pulse at the time of 29 X-ray bursts.

The non-detection places a fluence upper limit that is 8 orders of magnitude lower than the fluence of FRB 200428.



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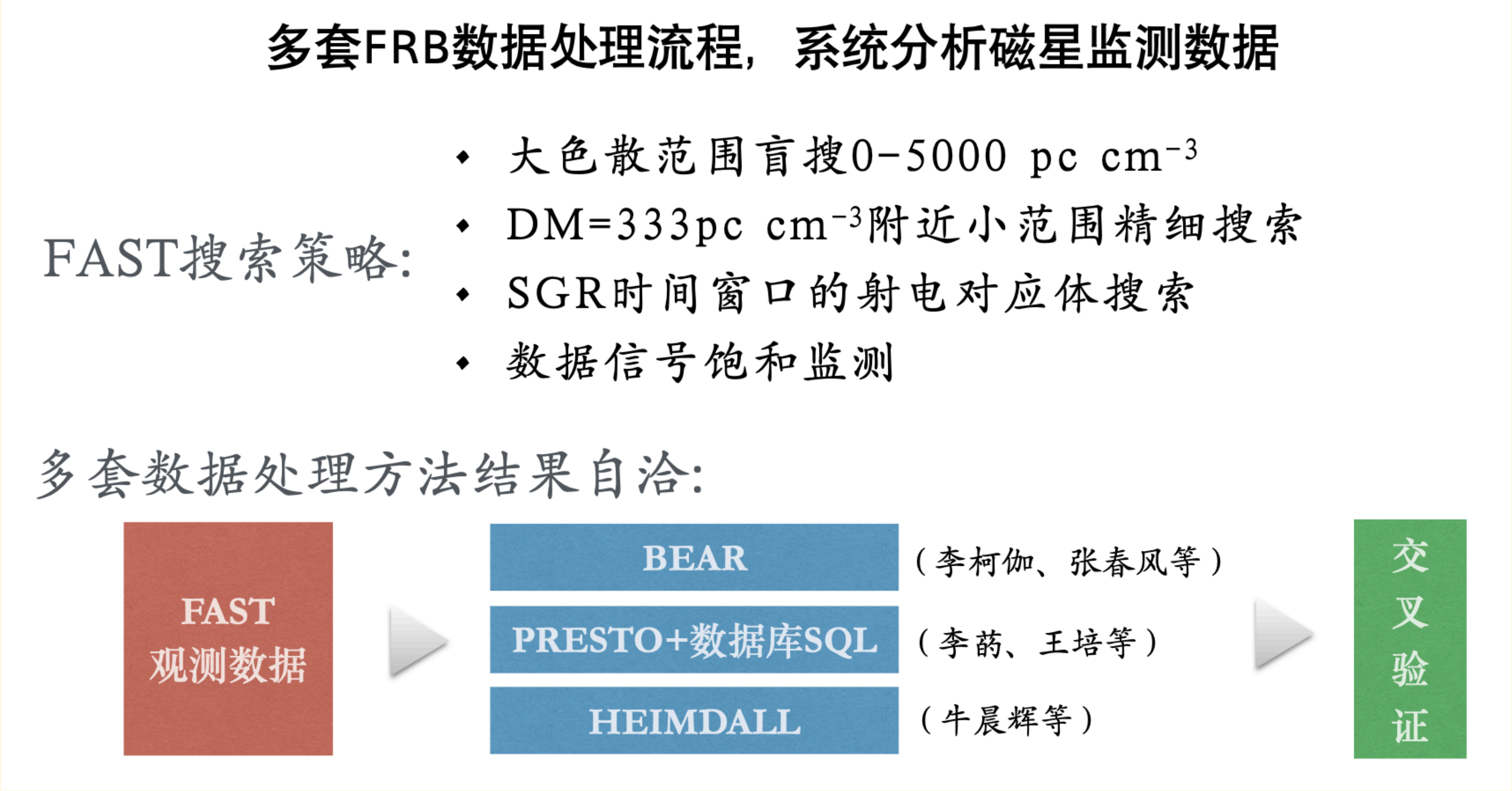
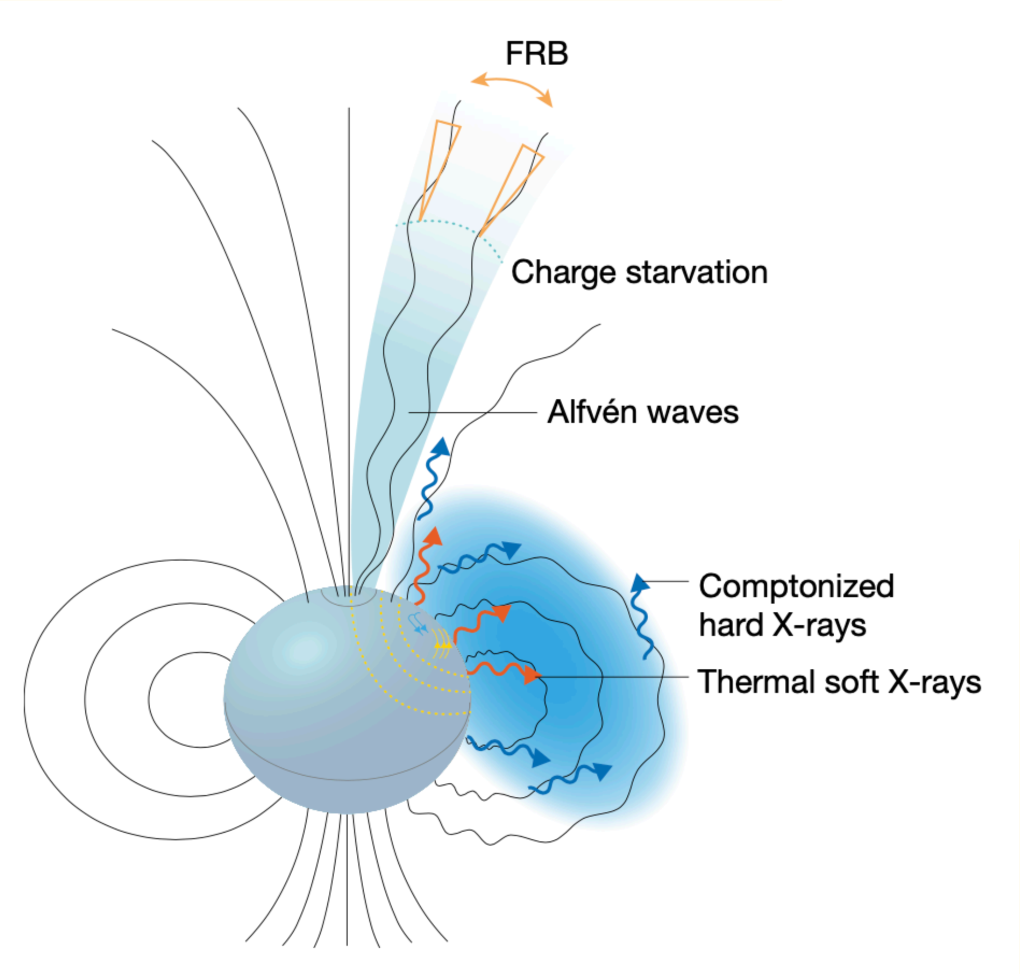


From Pei Wang's PPT

FRB v.s. SGR burst

FRB–SGR burst associations are rare.

- FRBs may be highly relativistic and geometrically beamed.
- FRB-like events associated with SGR bursts may have narrow spectra and characteristic frequencies outside the observed band of FAST.
- The physical conditions required to achieve coherent radiation in SGR bursts are difficult to satisfy, and that only under extreme conditions could an FRB be associated with an SGR burst.



FRB review by Bing Zhang 2020 Nature

Conclusions

✓Part, if not all, of FRBs are from magnetars.

✓FRBs from magnetars can be associated with X-ray bursts.

✓FRB–SGR burst associations are rare.