Fast Radio Bursts: A Mystery Being Solved?

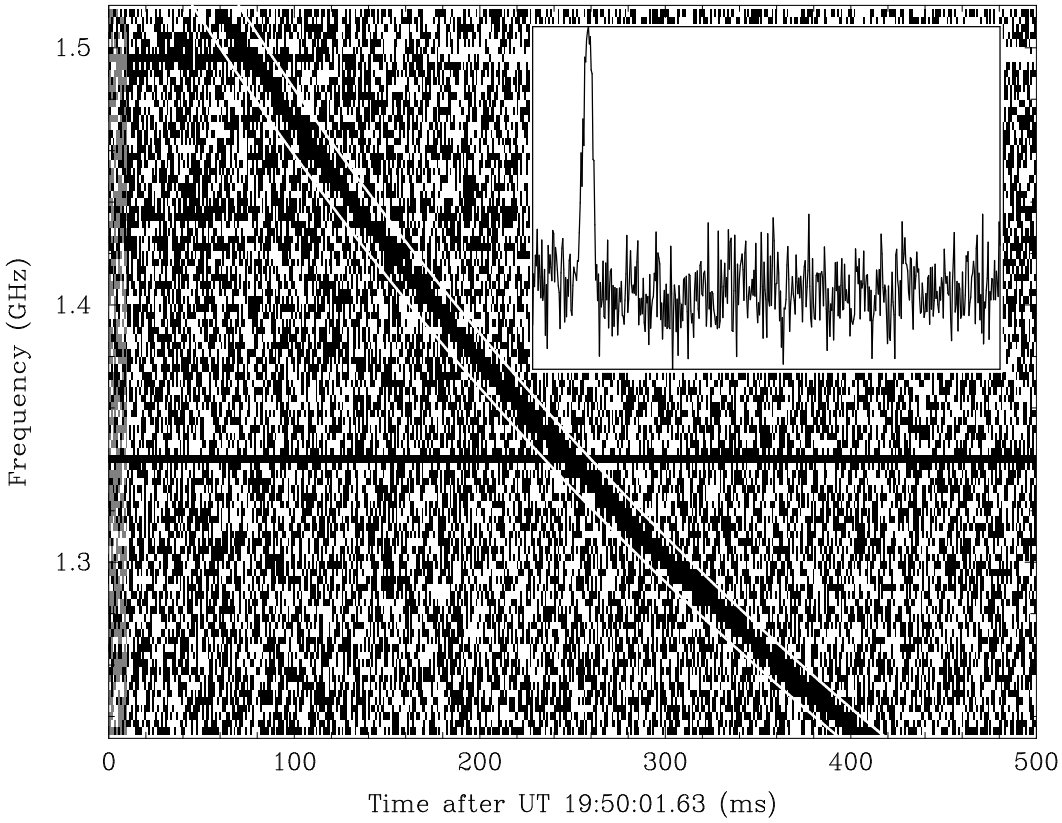
Kazumi Kashiyama (U. of Tokyo)

Fast radio bursts (FRB)

- $\tau \sim 1$ ms
- $S_\nu \sim 1$ Jy [Jy = 10^{-23} erg/s/cm^2/Hz]
- $\nu \sim$ GHz ($\Delta\nu/\nu \sim 0.1$)
- event rate ~ 10^3 day^{-1} sky^{-1}
- $\delta t_\nu \sim \nu^{-2}$

  & DM ~ 100-1000 cm^{-3} pc

Lorimer+07

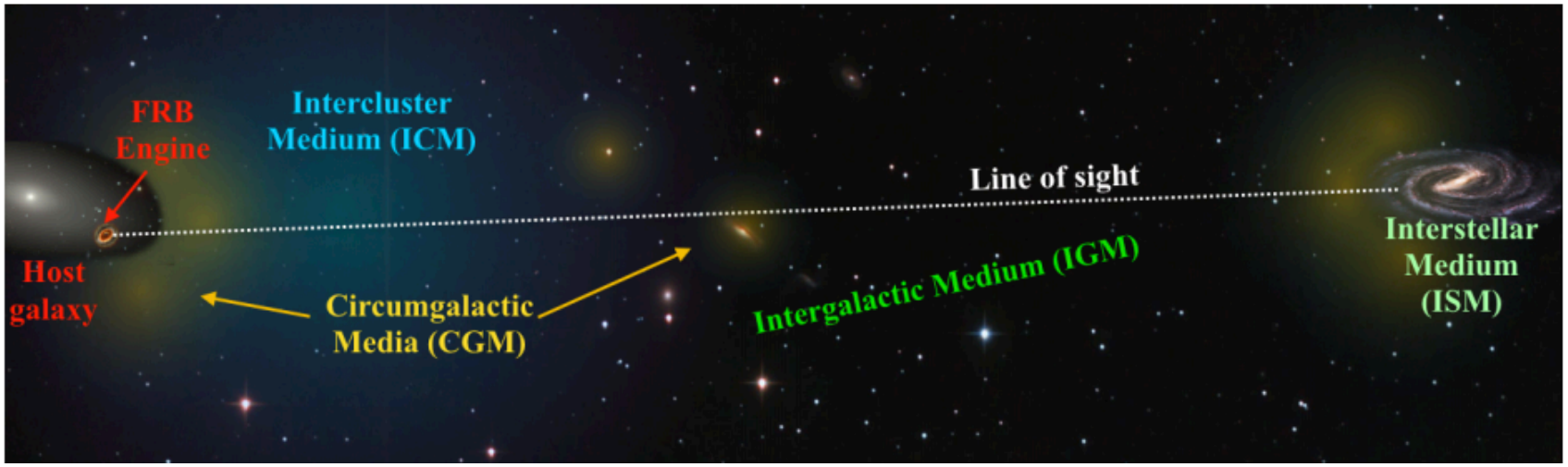


Why FRB?

Because

1. FRB is a unique probe of the cosmological plasma,
2. FRB is the most powerful laser in the Universe,
3. and the source is still unknown.

FRB = *A Unique Probe of the Cosmological Plasma*

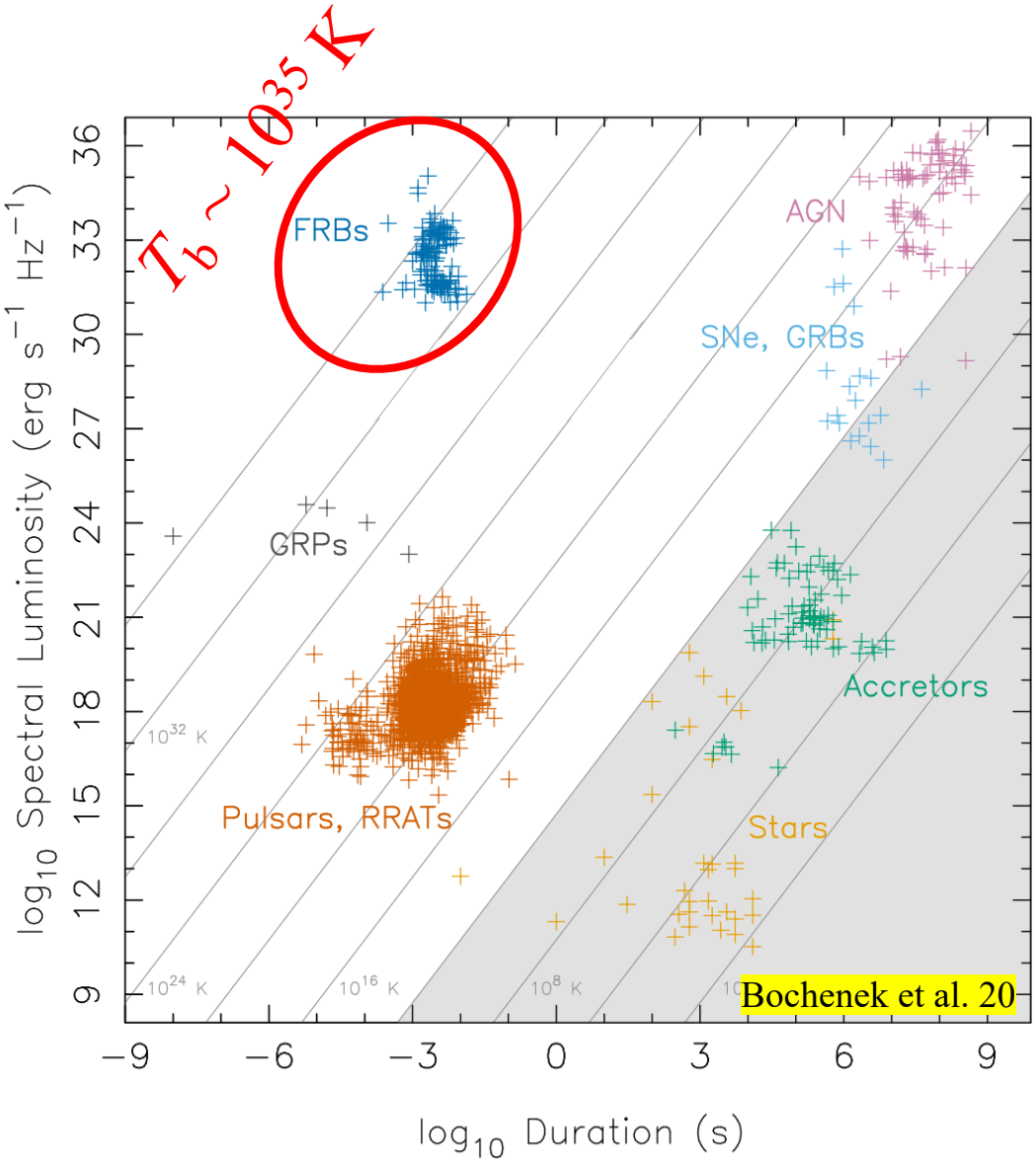


Ioka 03; Inoue 04; …

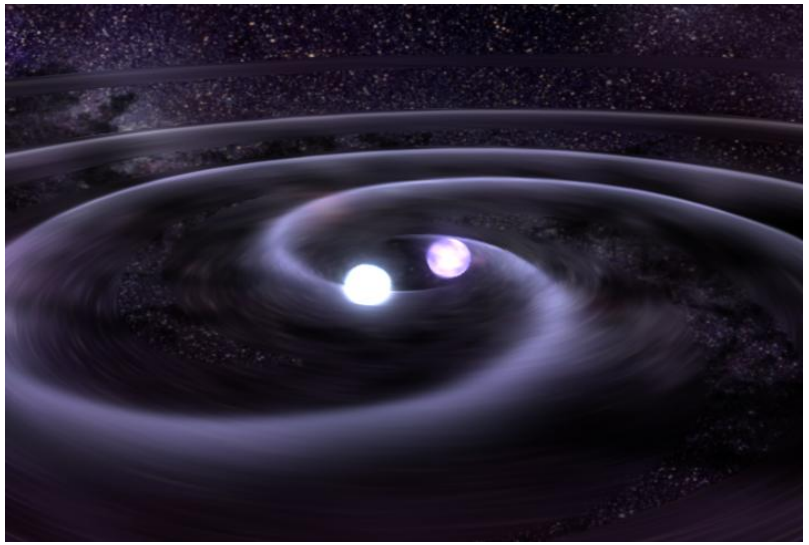
$$\mathrm{DM_{FRB}}(z) = \mathrm{DM_{MW,ISM}} + \mathrm{DM_{MW,halo}} + \mathrm{DM_{cosmic}}(z) + \mathrm{DM_{host}}(z)$$

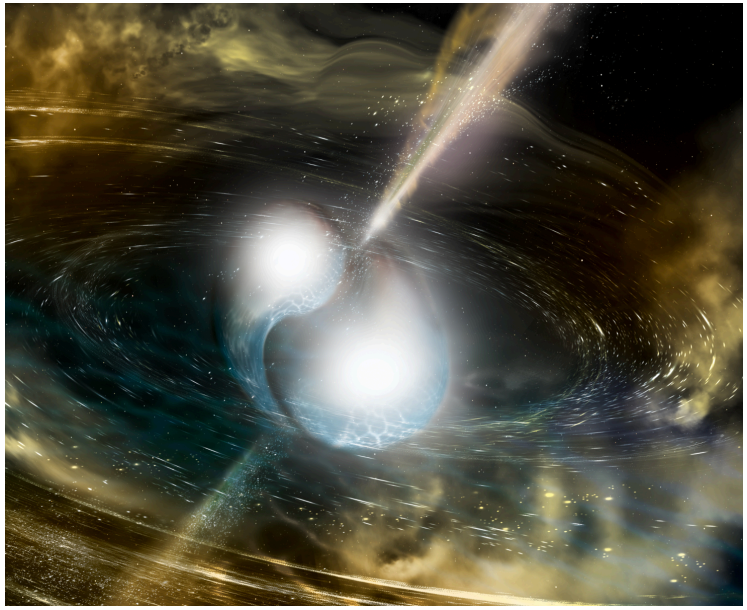
$$\langle \mathrm{DM_{cosmic}} \rangle = \int_0^{z_{\mathrm{FRB}}} \frac{c\bar{n}_{\mathrm{e}}(z)\mathrm{d}z}{H_0(1+z)^2\sqrt{\Omega_{\mathrm{m}}(1+z)^3+\Omega_\Lambda}}$$

FRB = *The Most Powerful Coherent Emission in the Universe*



FRB = ??? (*The source is still unknown*)





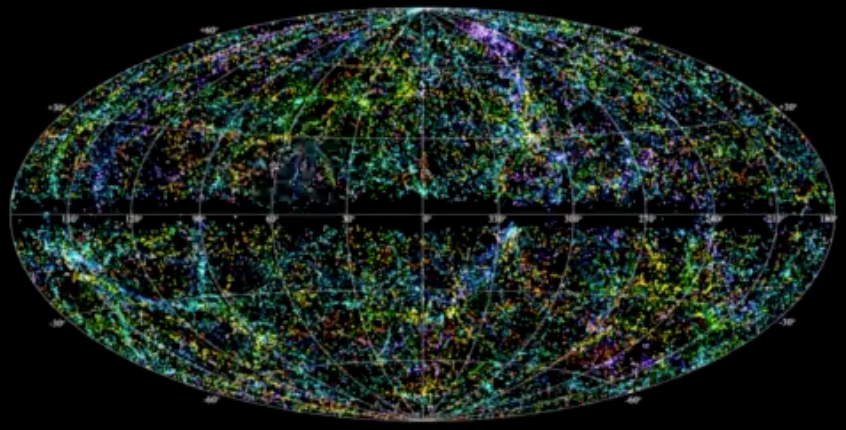
Up-to-date fact sheet

- A few 100 events so far with Parkes, Arecibo, GBT, UTMOST, ASKAP, CHIME, STARE2, …
- ~10 host galaxies known;

  FRB121102, FRB180916.J0158+65,

  FRB180924, FRB181112, FRB190523, …

  "FRB"200428 (MW)



- Roughly ~10 % are repeating;

  FRB121102, FRB180916.J0158+65, …

  2 show periodicity.

- 2 counterparts detected;

  FRB121102 (persistent radio) and "FRB"200428 (X-ray burst)

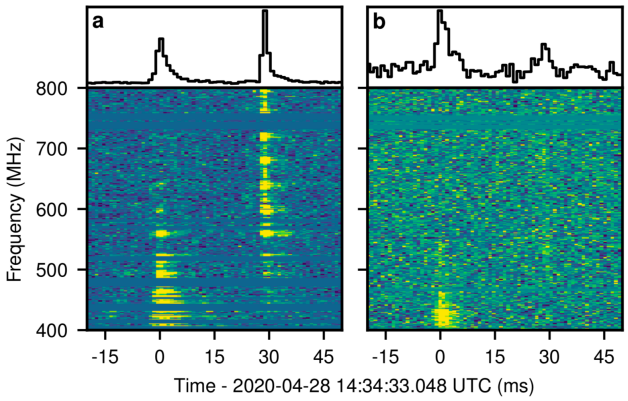
http://frbcat.org/

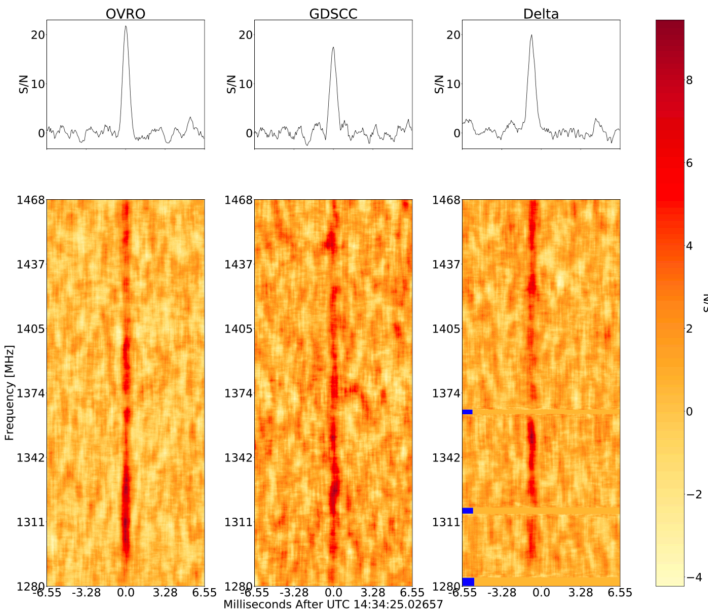
- 1 source identification;

  "FRB"200428 = SGR1935+2154

FRB200428 from SGR 1935+2154

detected by CHIME (~kJy @ 400-800 MHz) and STARE2 (~Mega Jy @ 1.3GHz)

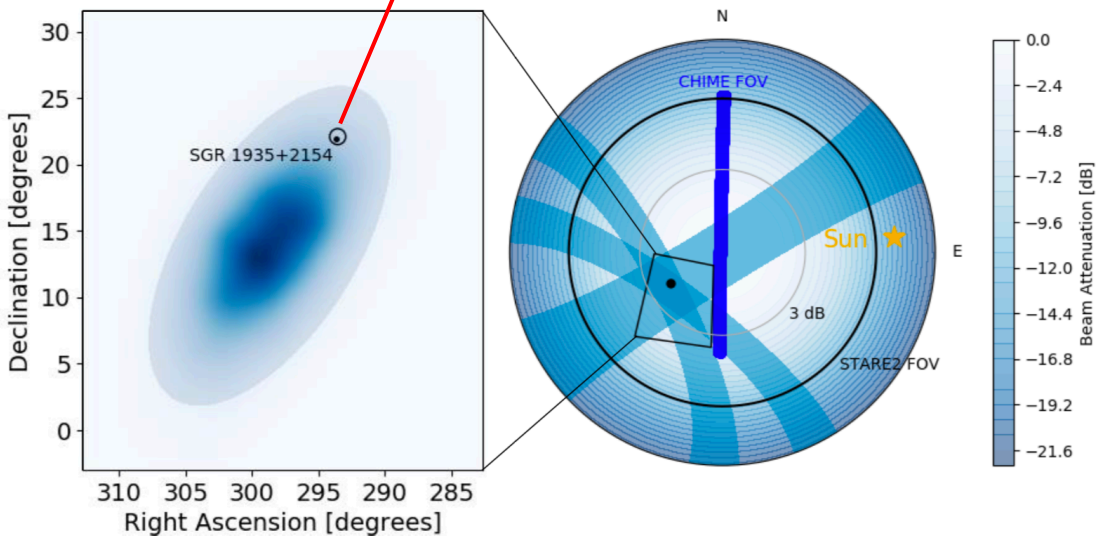




$$P = 3.25\,\mathrm{s}$$

$$\dot{P} = 1.4 \times 10^{-11}\,\mathrm{s}\cdot\mathrm{s}^{-1}$$

$$B_\mathrm{d} = 2.2 \times 10^{14}\,\mathrm{G}$$



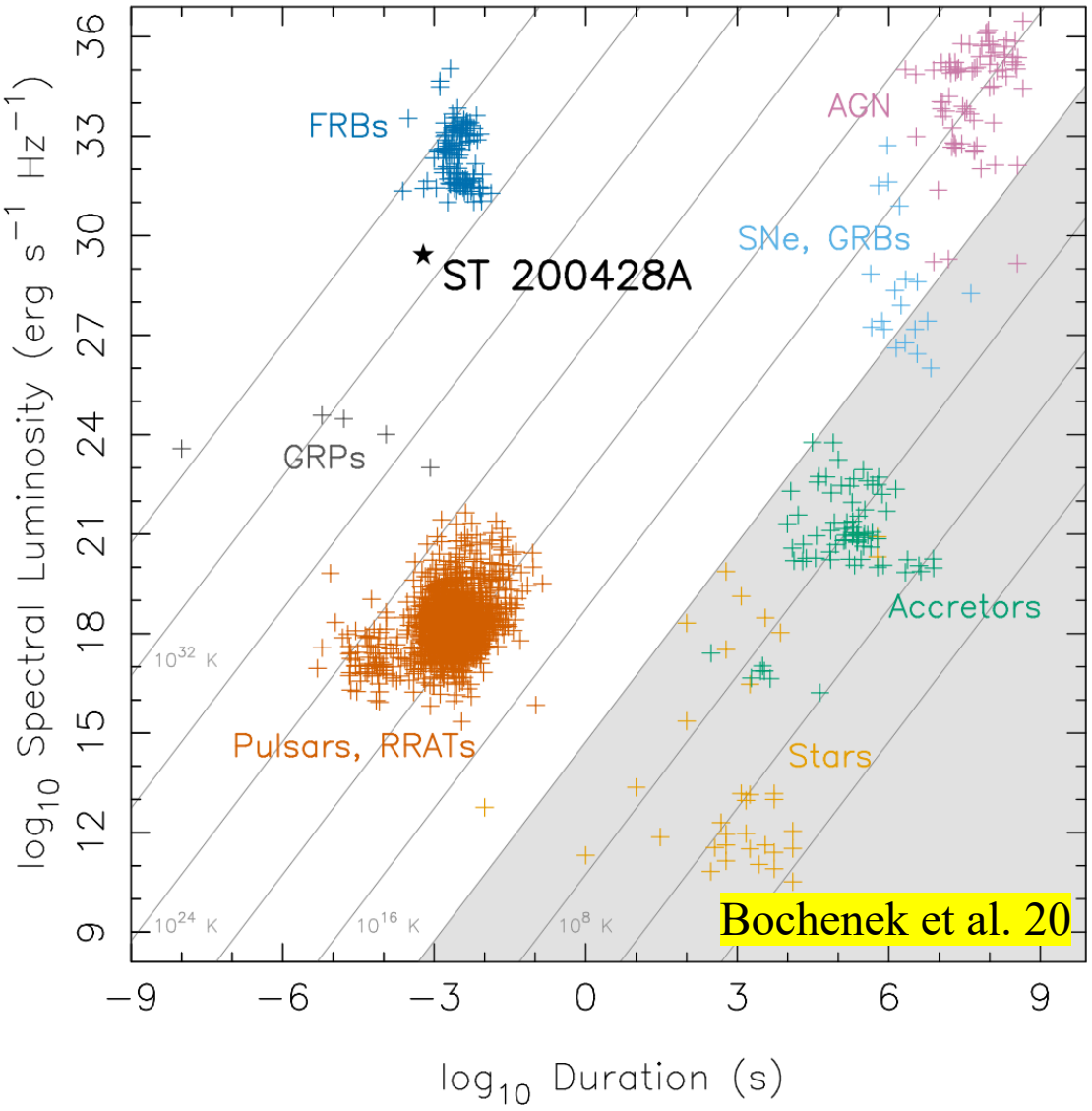
The CHIME/FRB Collaboration et al. 20; Bochenek et al.20

Mind the Gap?

$$E_{\rm iso,FRB} \sim 10^{37\text{-}41}\ {\rm erg}$$

$$\Lsh$$

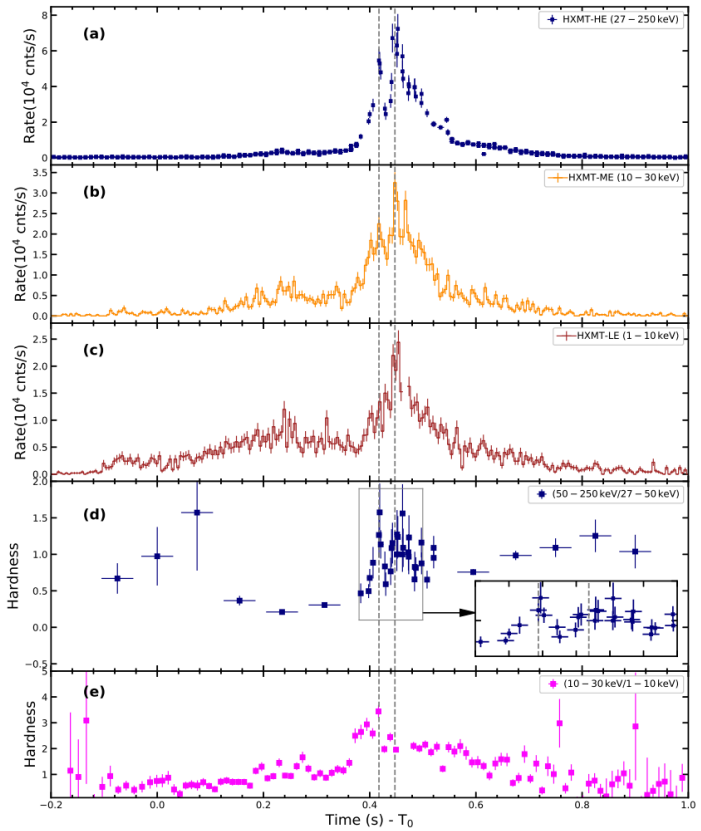
$$E_{\rm iso,FRB,MW} \sim 10^{35}\ {\rm erg}$$

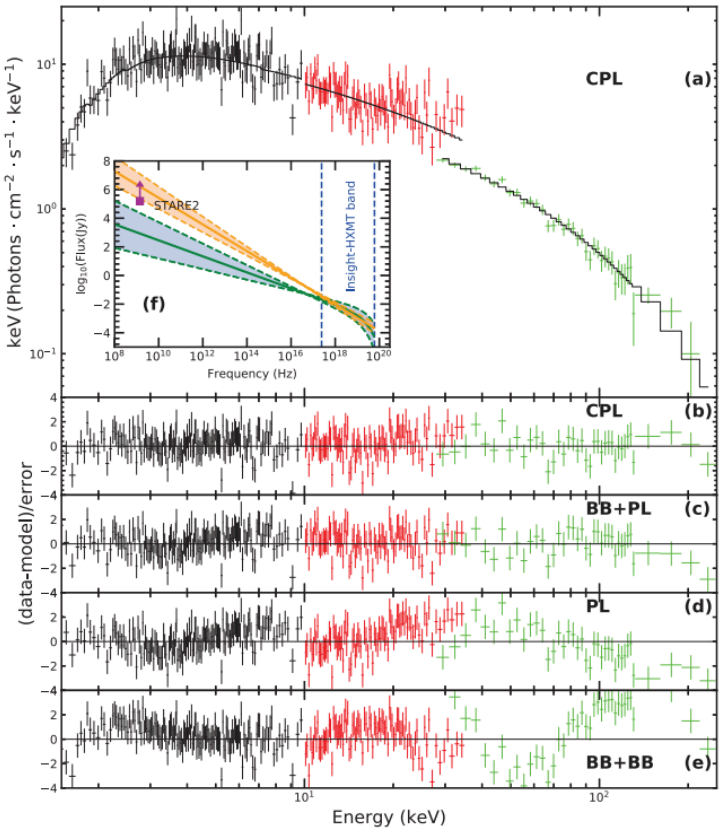


The X-ray burst counterpart of "FRB"200428

- ✓ detected by Integral, *Konus*-wind, AGILE, and *Insight*-HXMT in coincidence with the FRB.
- ✓ Flux and timescale is consistent with the intermediate magnetar flare,
- ✓ though the spectrum is significantly harder.

$$E_{\rm iso,X} \sim 10^{40}\,{\rm erg} \sim 10^{5} E_{\rm iso,MW-FRB}$$





Lu et al. 20; Mereghetti et al. 20; Ridnaia et al. 20; Tavani et al. 20; …

The X-ray burst counterpart of "FRB"200428

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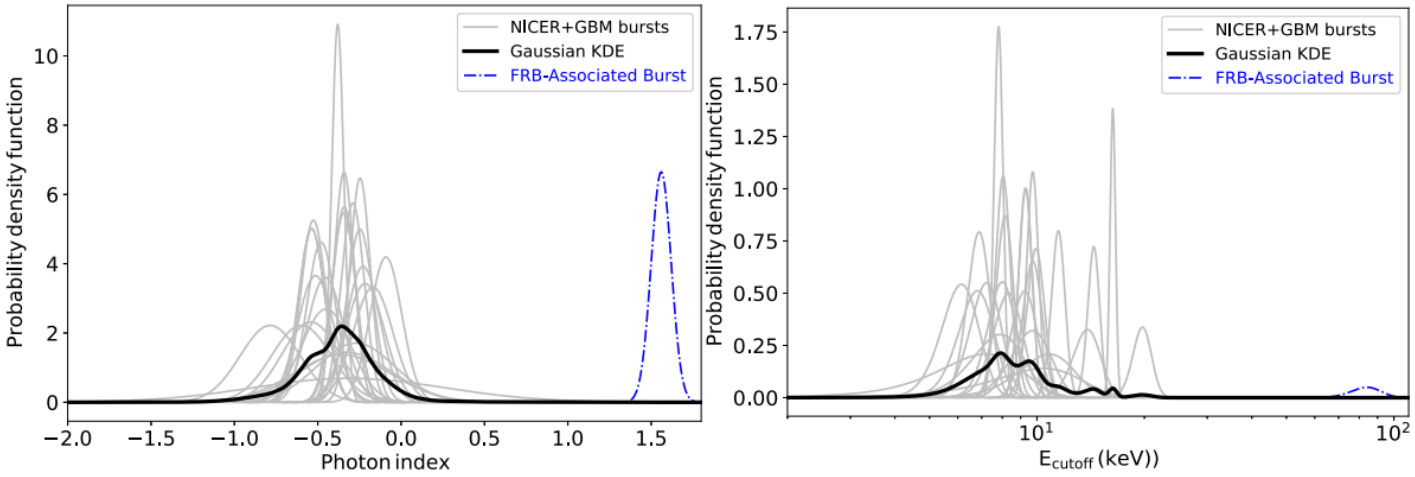
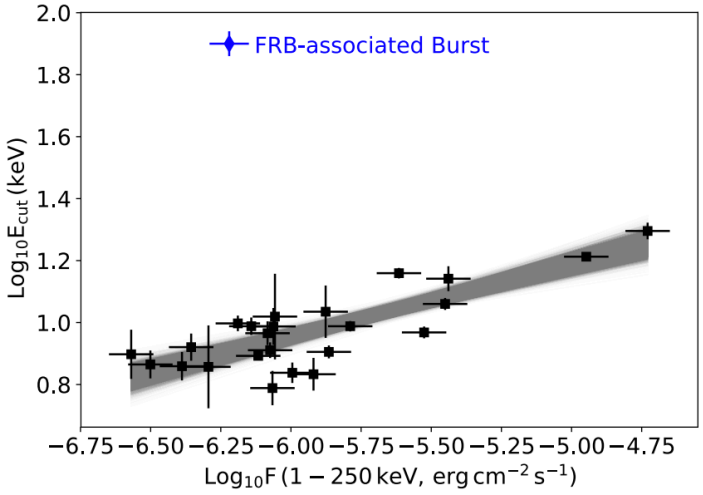
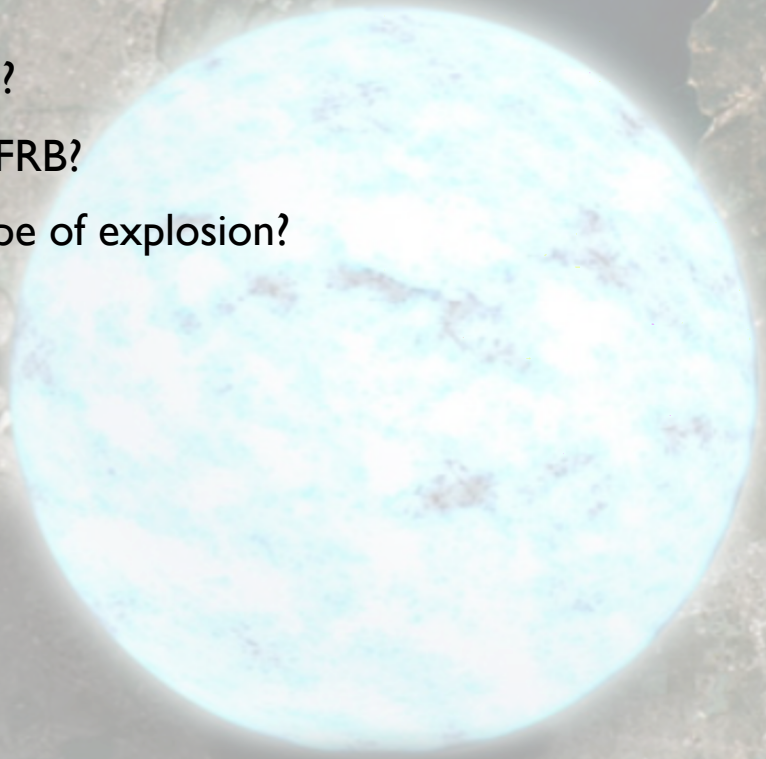




Younes et al. 20

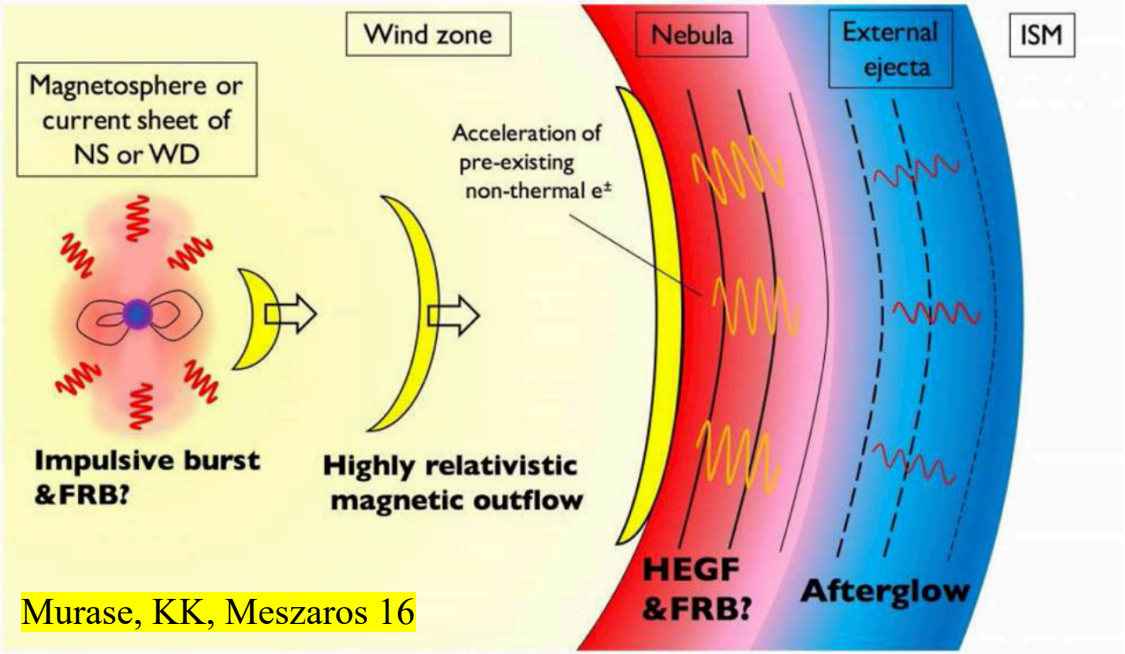
Questions on the neutron star model

- What is the emission mechanism of FRB?
- What type of NSs can be the source of FRB?
- How such NSs are formed with what type of explosion?



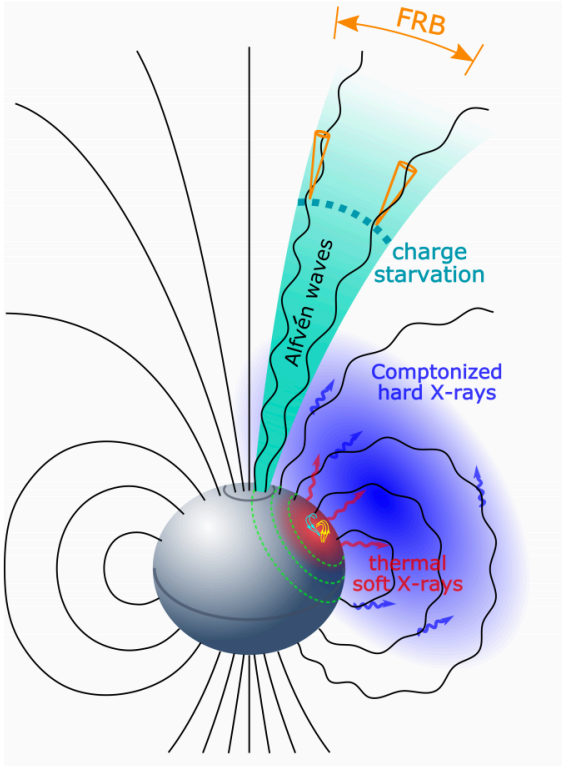
What is the FRB emission mechanism?

- ✓ **Energy budget?**
  magnetic field or rotation
- ✓ **Emission site?**
  magnetosphere or
  wind zone or
  nebula
- ✓ **Emission process?**
  coherent curvature emission or
  synchrotron maser or
  else



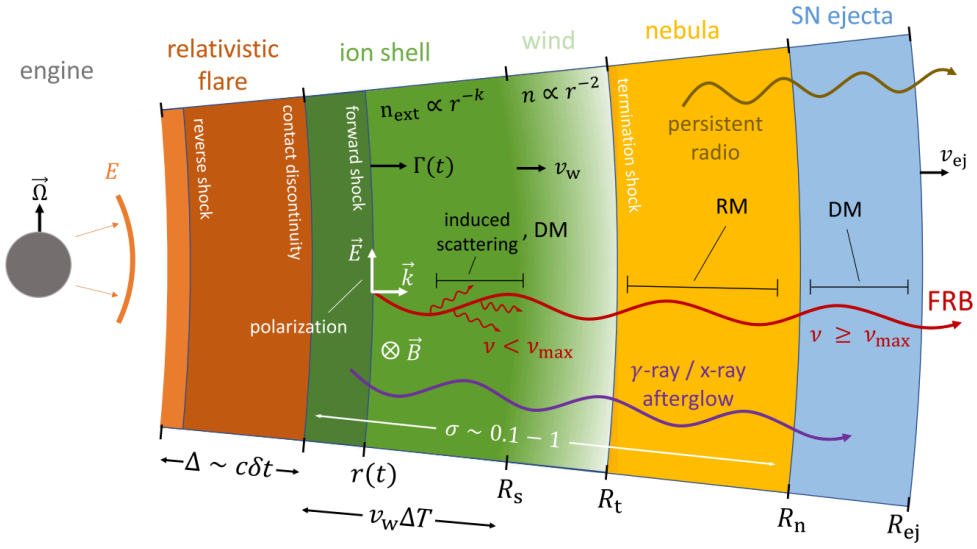
How to produce FRB with X-ray burst?

✓ Trapped fireball + coherent curvature?



Falcke & Rezzolla 13; KK et al, 13; Pen & Connor 15; Cordes & Wasserman 16; Lyutikov et al. 16; Kumar et al. 17; Zhang 17; Lu et al. 20; Ioka 20; …

✓ shock + synchrotron maser?

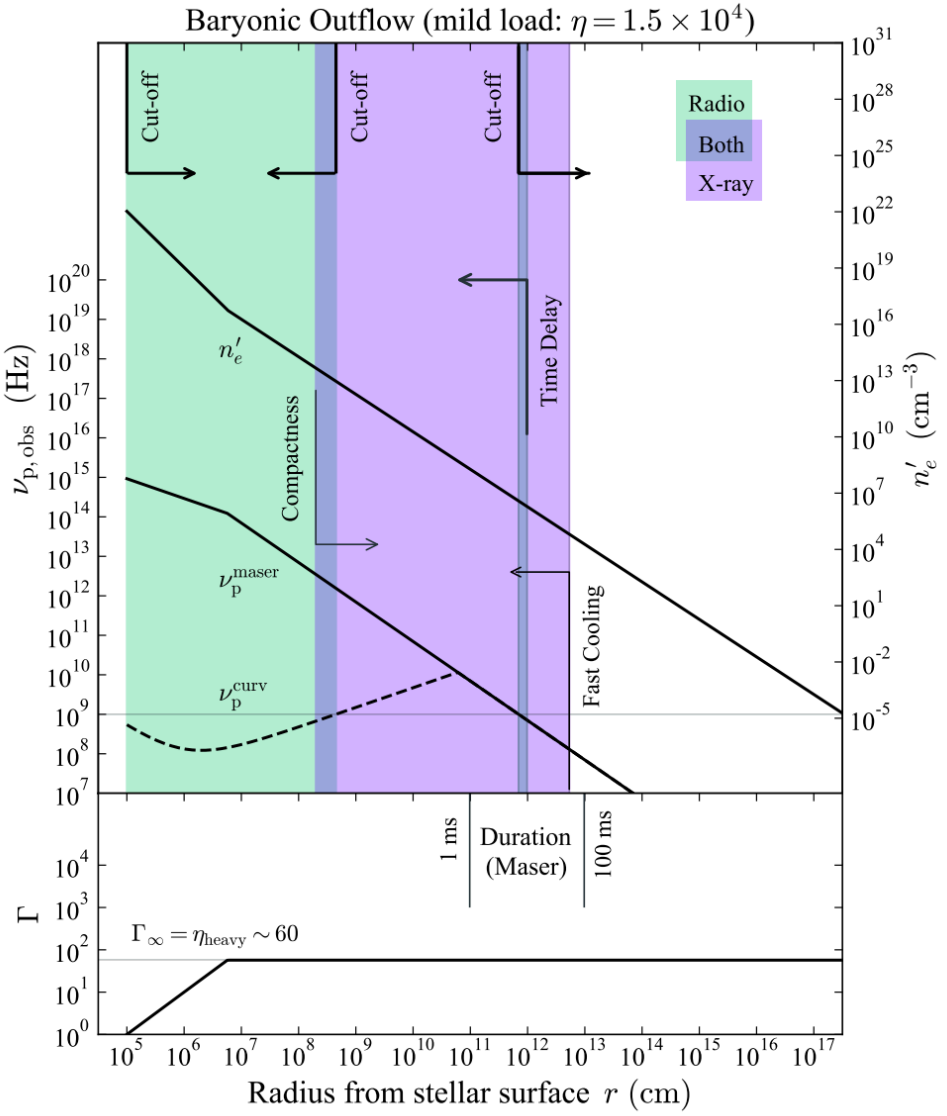


Hoshino & Arons 91; Gallant, Hoshino, et al. 92 Lyubarsky 14; Murae, KK, Meszaros 16;Waxman 17; Beloborodov 17, 19; Metzger et al. 19; Margalit et al. 20; …

Multi-Wavelength Constraints on the Outflow Properties

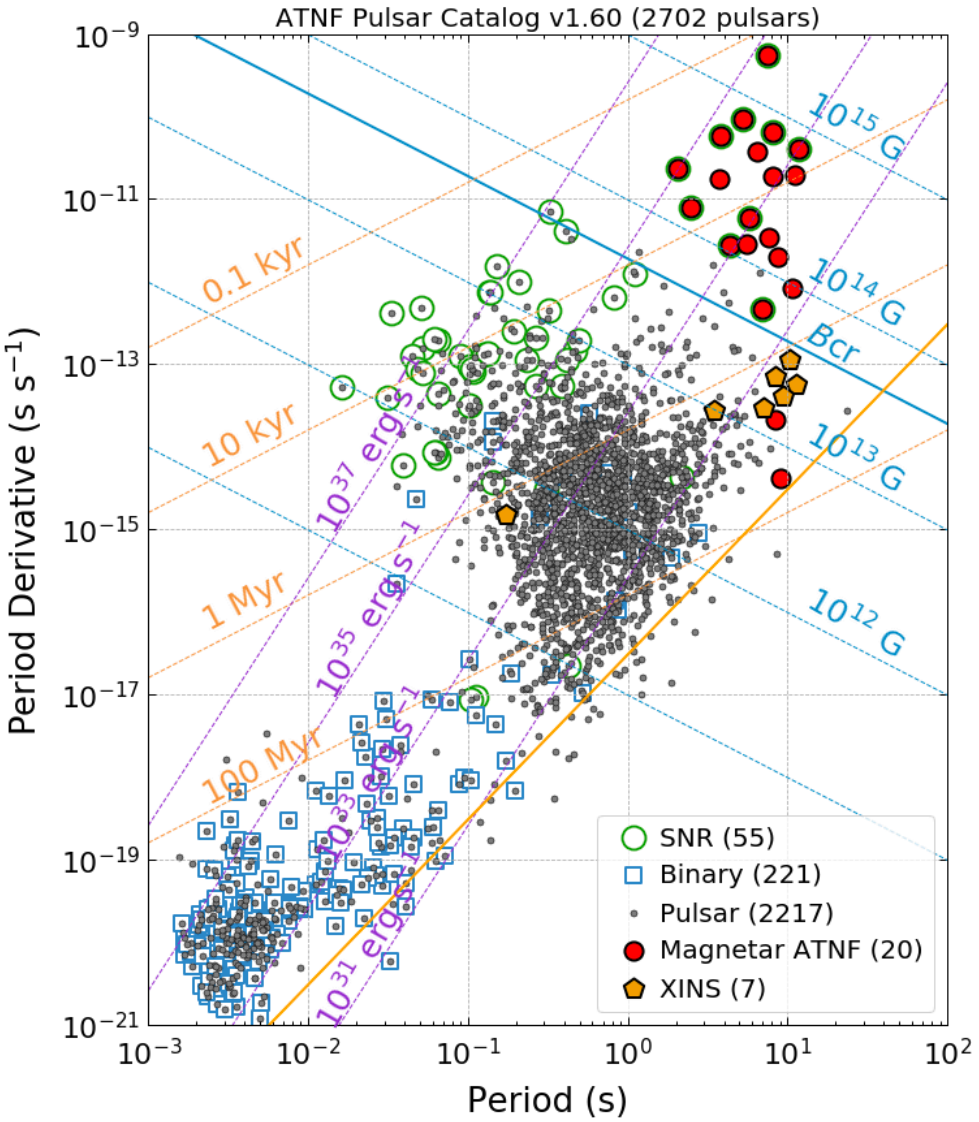
- No time delay between FRB and X-ray flare
- The non-thermal spectrum of the X-ray flare
  → compactness problem in X-ray
- Plasma cutoff frequency
  → compactness problem in radio

- The emission radii are strongly constrained for both the CCR and SMI models.
- Extremely clean ($\eta > 10^4$) and/or highly magnetized ($\sigma_0 > 10^3$) outflows are implied, which may be consistent with the rarity of FRB20048 like events.



Yamasaki, KK, Murase 20

What type of NSs can be the source of FRB?



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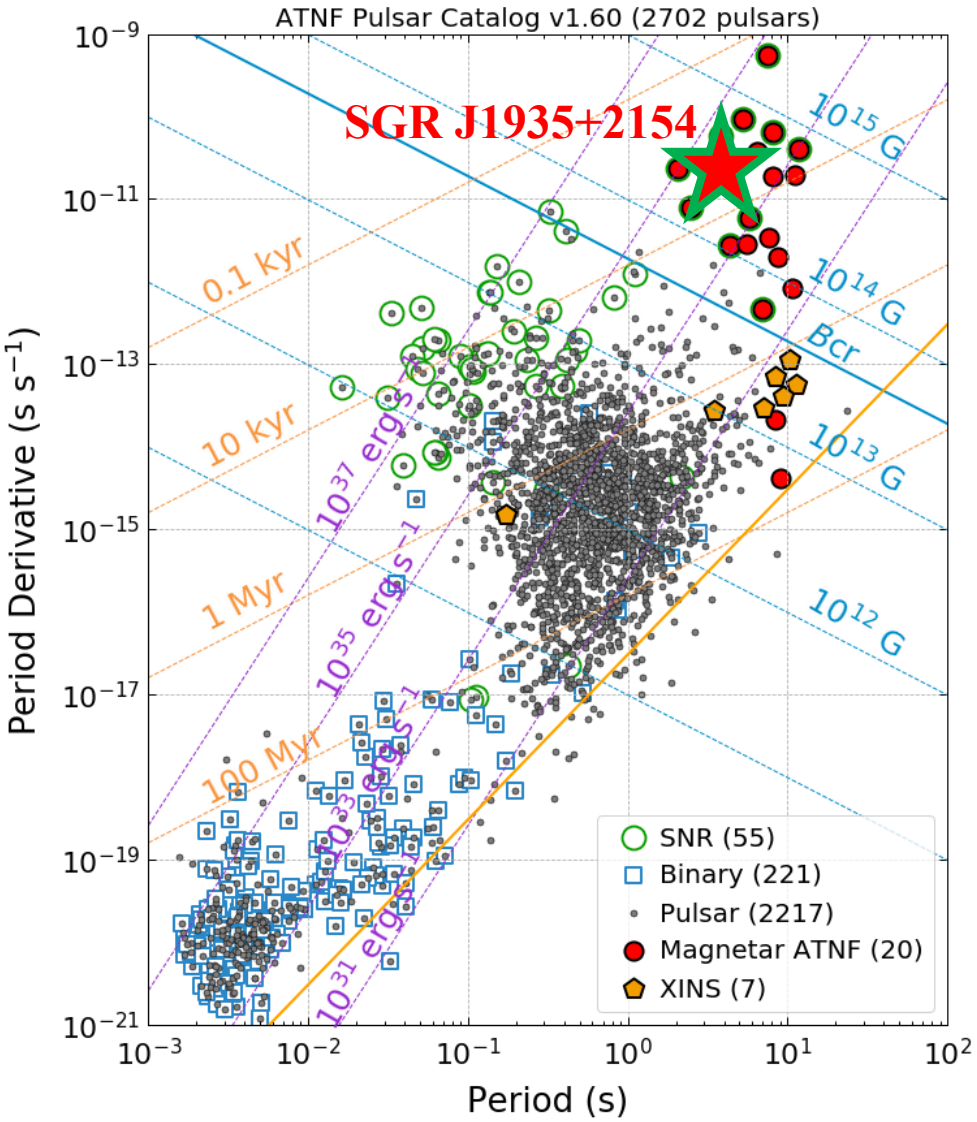

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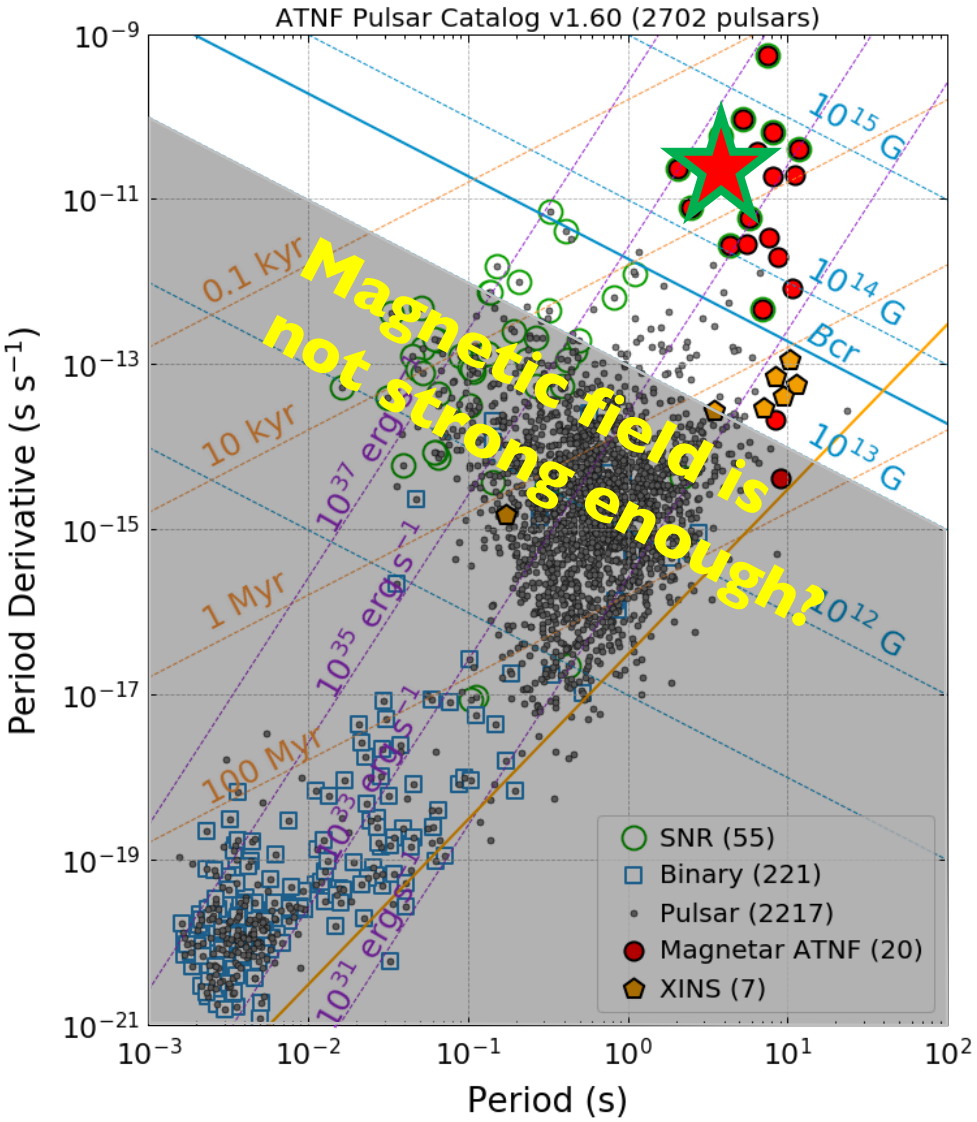

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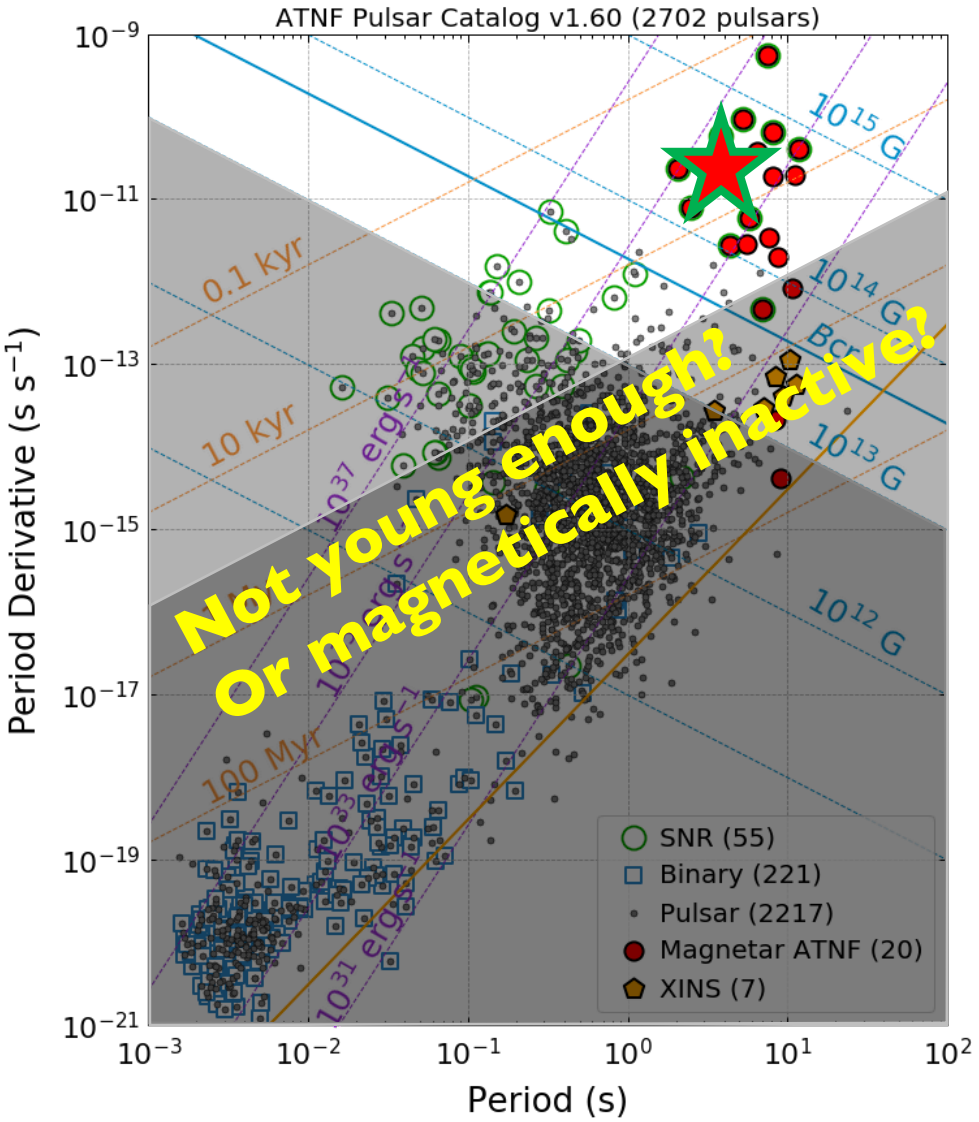

Tanaka-san's talk

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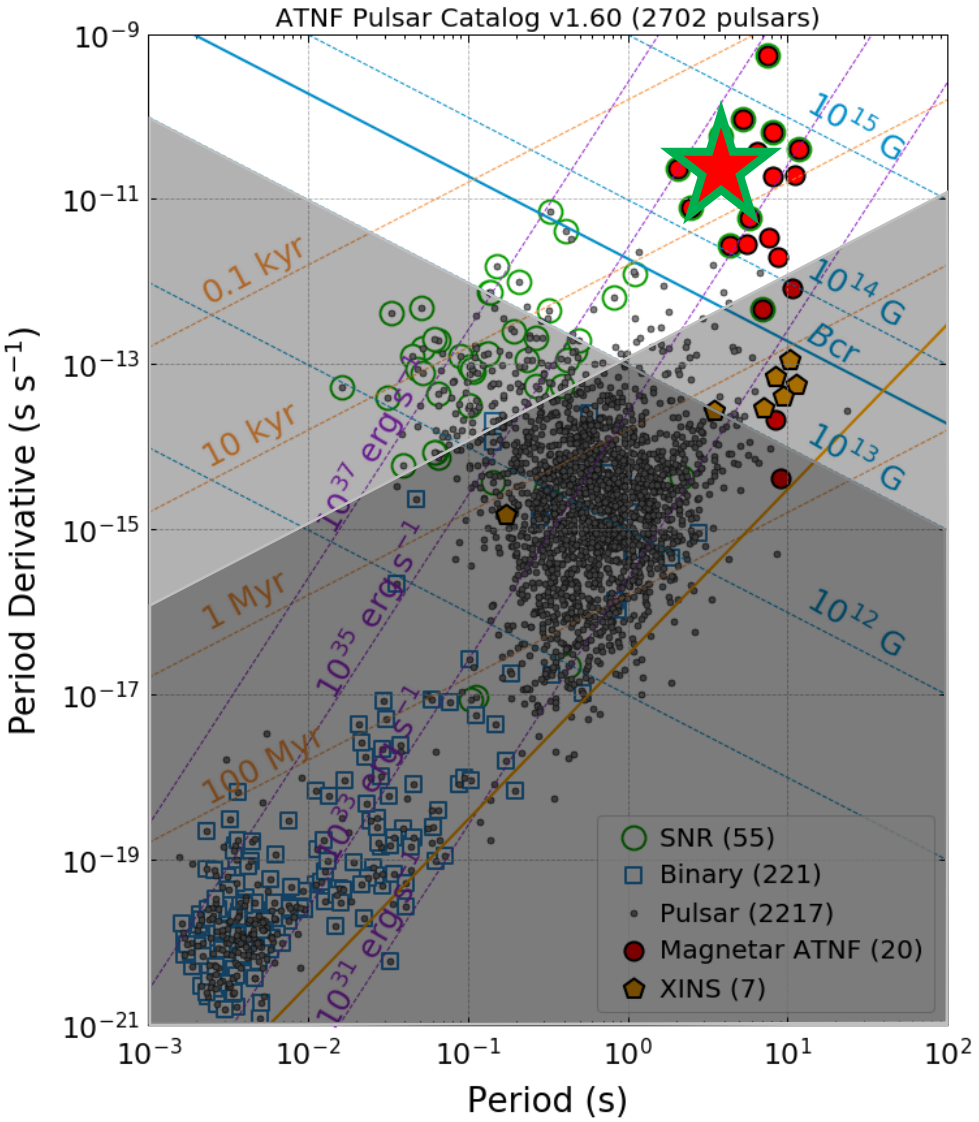
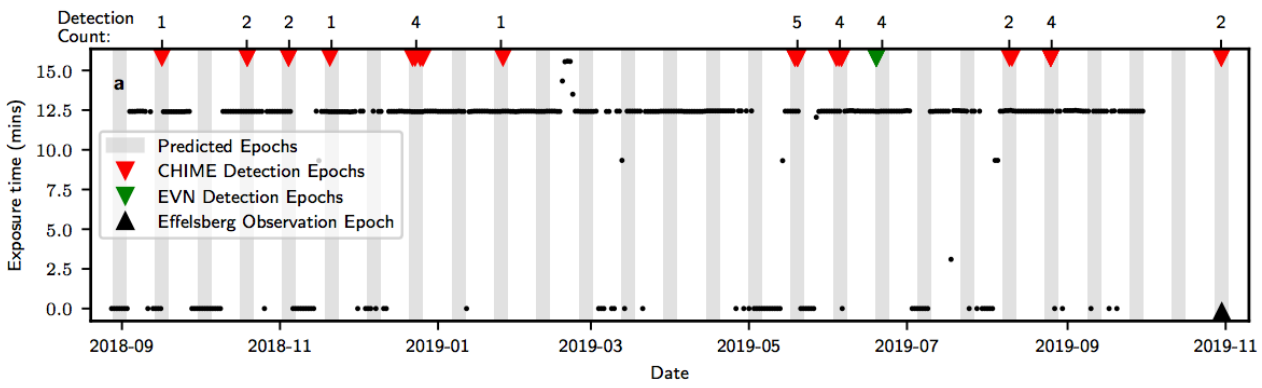
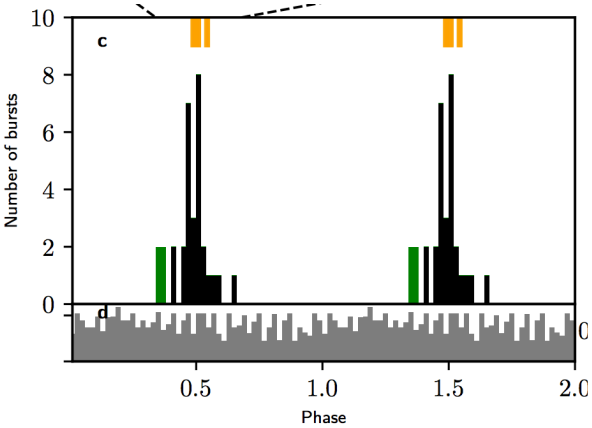


Periodically repeating FRB

✓ FRB 180916.J0158+65 : T = 16.5 day

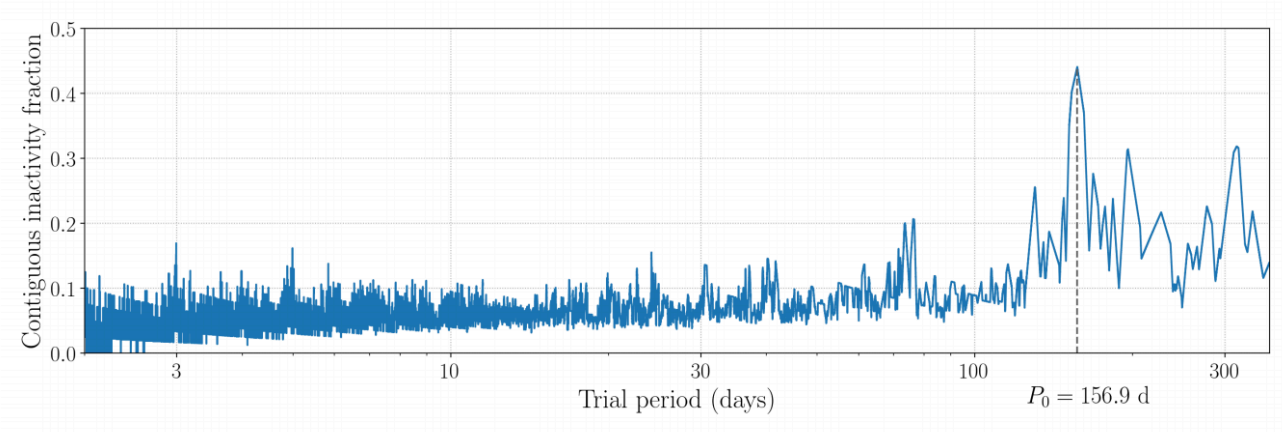
CHIME/FRB Collaboration et al. 20

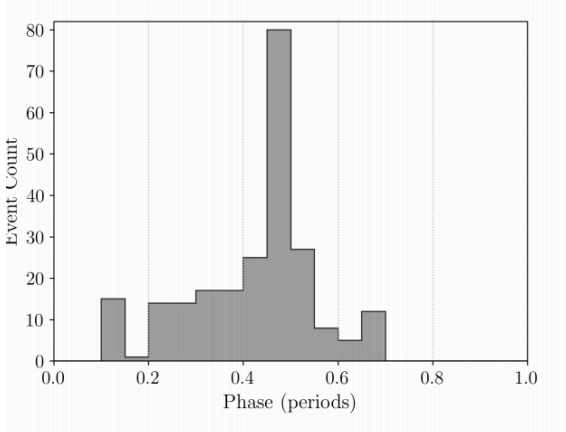




✓ FRB 121102 : T = 156.9 day

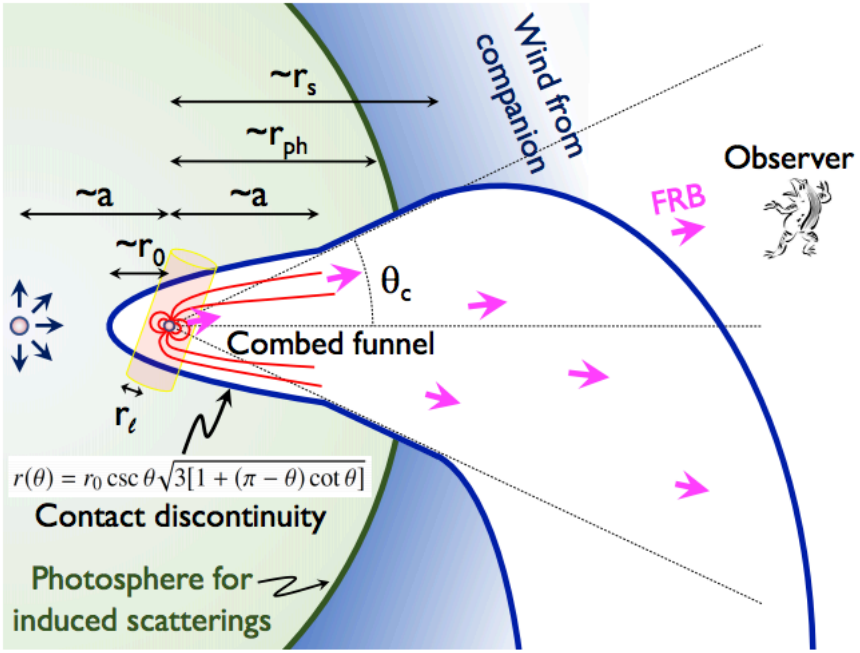
Rajwade et al. 20





Periodically repeating FRB

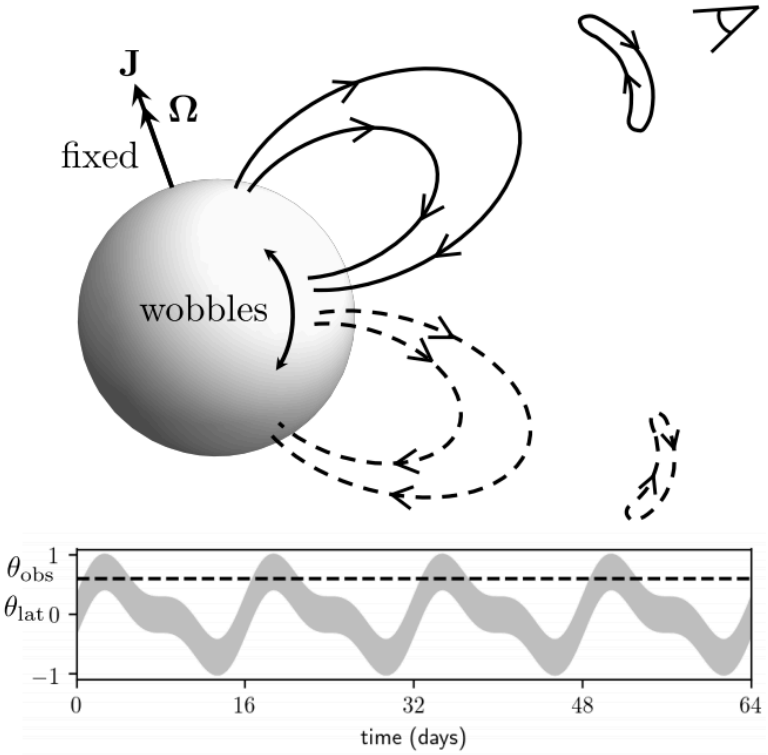
✓ In a binary? e.g., Ioka & Zhang 20



$$P_{\rm orb} = 2\pi\sqrt{\frac{a^3}{G(M+M_{\rm c})}}$$

$$\sim 120\,{\rm day}\,{a_{13}}^{3/2}\left(\frac{M+M_{\rm c}}{2.8\,M_\odot}\right)^{-1/2}$$

✓ Precession? Levin et al. 20; Zanazzi & Lai 20

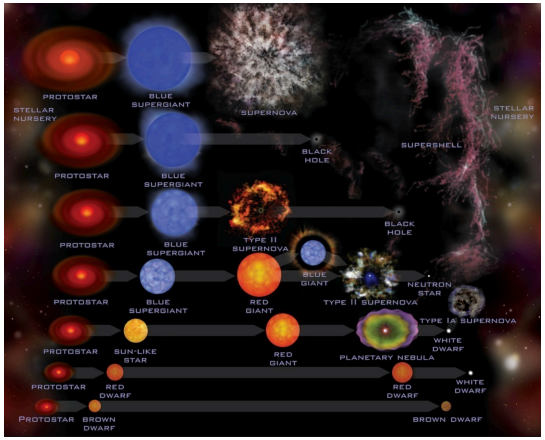


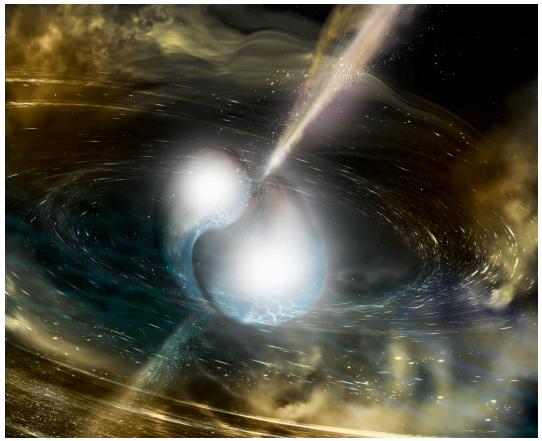
$$P_{\rm pr} \approx P/\epsilon \sim 11.6\,{\rm day}\,{\epsilon_{-6}}^{-1}P_0$$

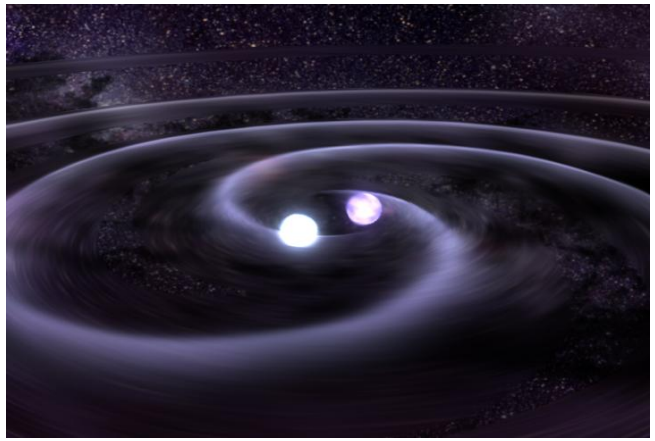
How such NSs are formed with what type of explosion?

In general, NSs can be formed via

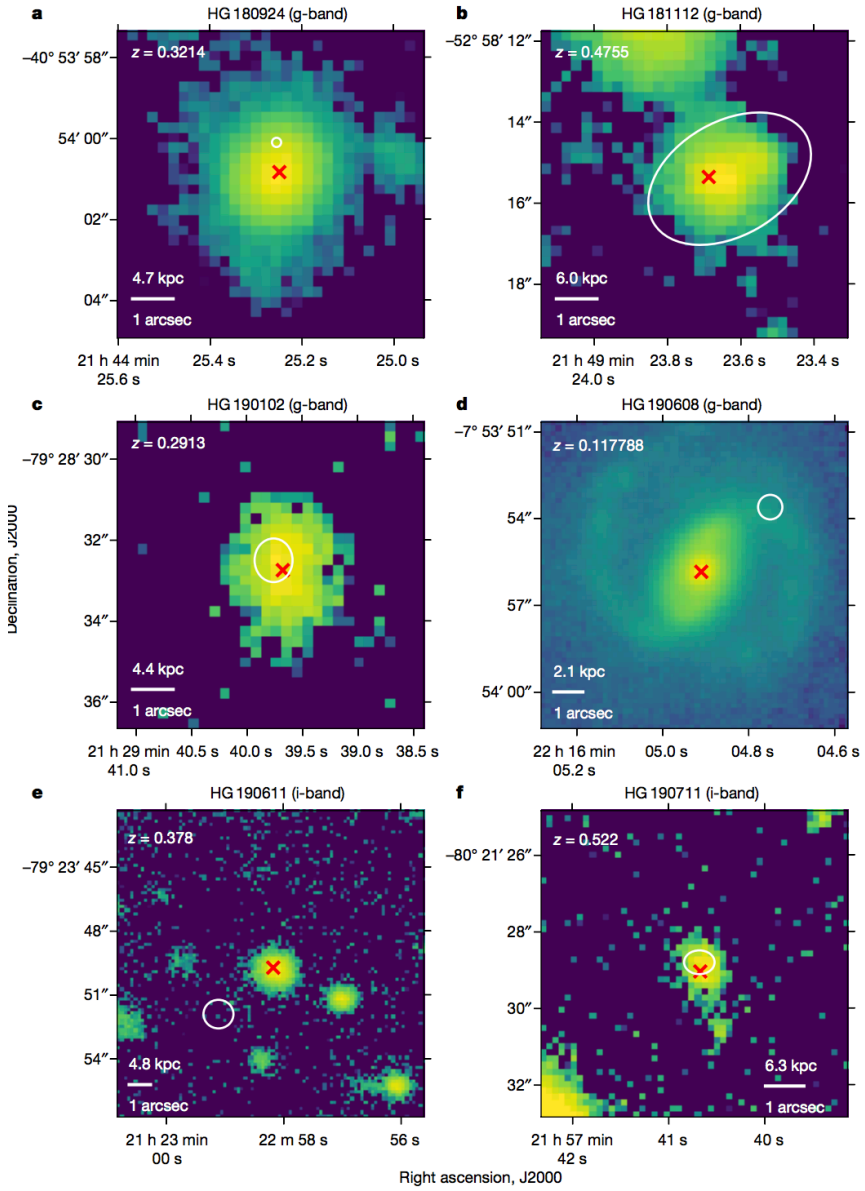
1. core collapse of (single or binary) massive stars
2. accretion induced collapse of white dwarfs
3. coalescence of binary neutron stars ← Haoxiang-san's talk

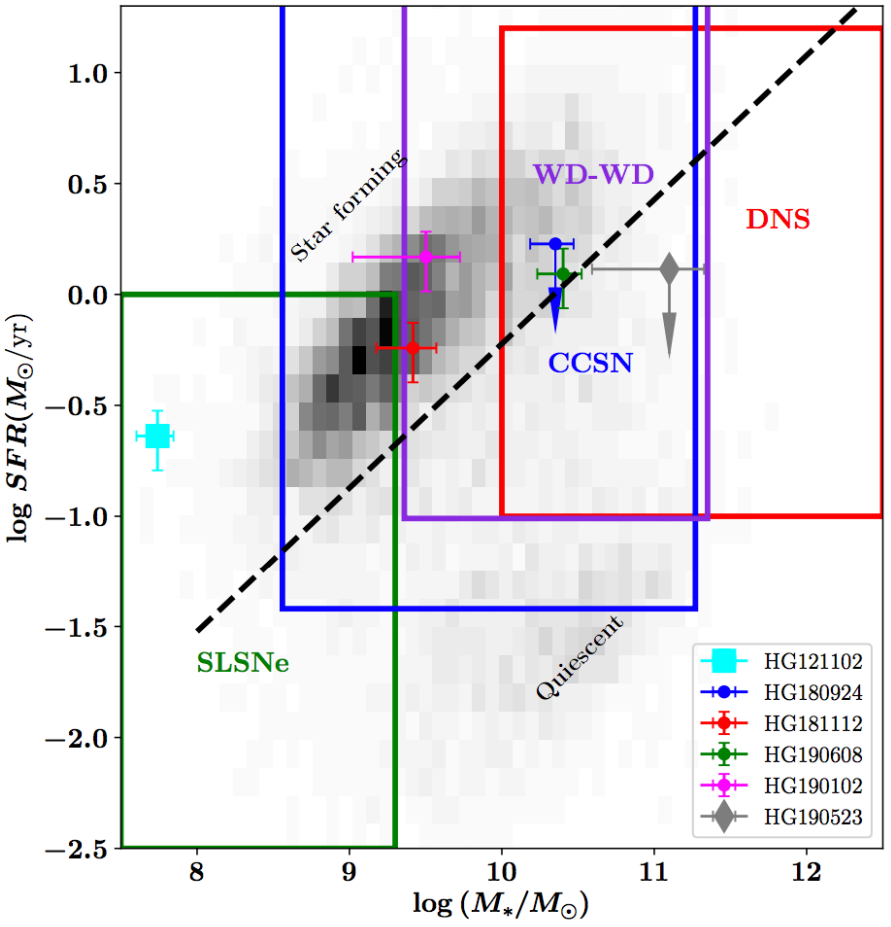






FRB Host Galaxy

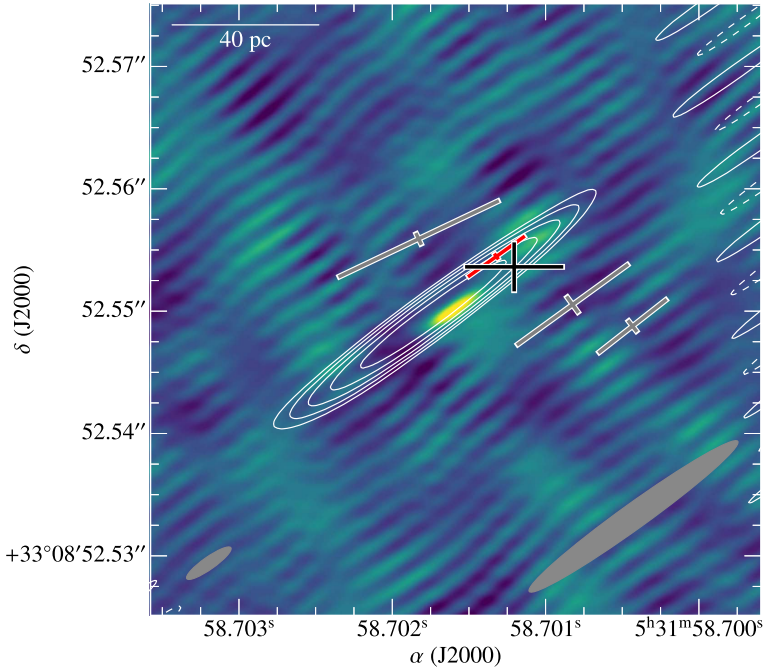


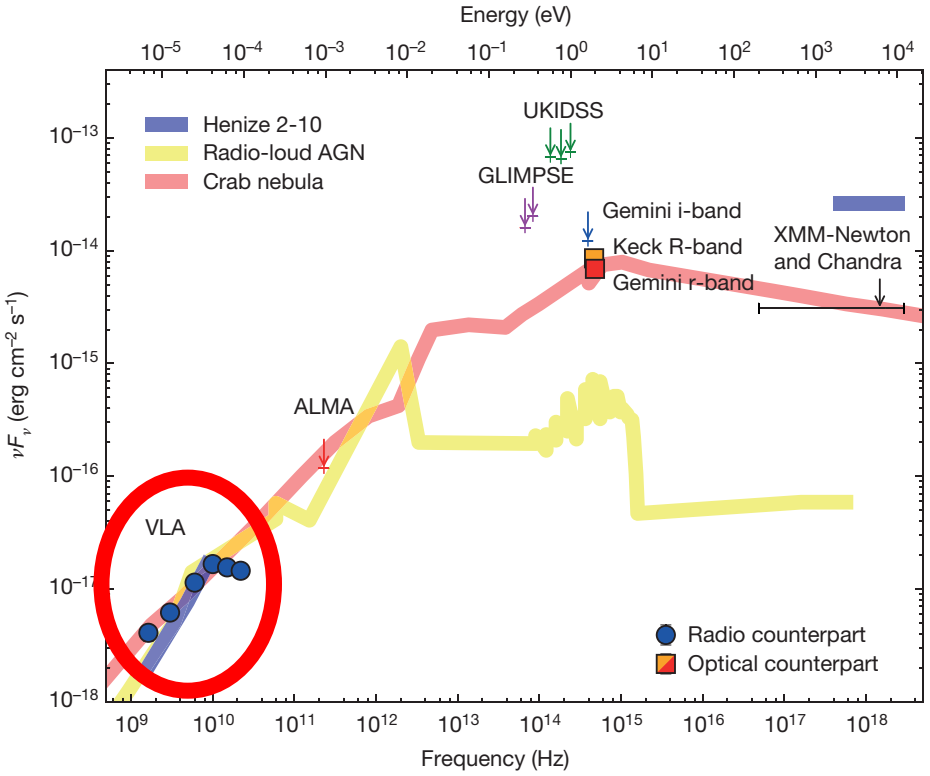


Macquart et al. 20; Bhandari et al. 20

The Persistent Radio Counterpart of FRB121102

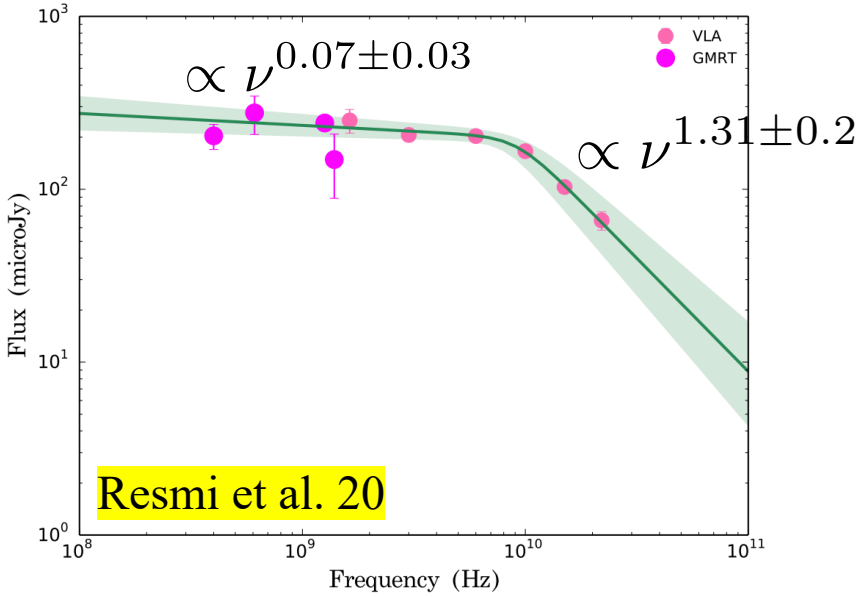
The source is localized within ~ 0.7 pc, associated with a star forming region in a dwarf star bursting galaxy





A few x 10^{39} erg/s @ 1-10 GHz

The minimum requirements on the electrons



The flat SED indicates a hard electron spectrum, $dN/\gamma \propto \gamma^{-p}$ with $p \sim 0$-1

The difference in the spectral indices is $\Delta\alpha_{\rm obs} \sim 1.25$, different from what is expected due to synchrotron cooling of continuously injected electrons ($\Delta\alpha_c \sim 0.5$).

The parent electron spectrum is also "spiky"?

Synchrotron emission

$$L_\nu \approx 3\,\frac{e^3 B}{m_e c^2}\,\frac{dN}{d\ln\gamma_e}$$

$$\nu \approx 0.2\gamma_e^2 eB/2\pi m_e c$$

$$\gamma_e \sim \gamma_{\rm br} \approx 10^2 B^{-1/2}$$

$$B \sim 0.06\,\sigma^{2/7} R_{17}^{-6/7}\ {\rm G}$$

$$N \sim 3\times 10^{51}\,\sigma^{-2/7} R_{17}^{6/7}$$

$$E_N \sim 10^{48}\,\sigma^{-3/7} R_{17}^{9/7}\ {\rm erg}$$

where $\sigma = R^3 B^2/3E_N$

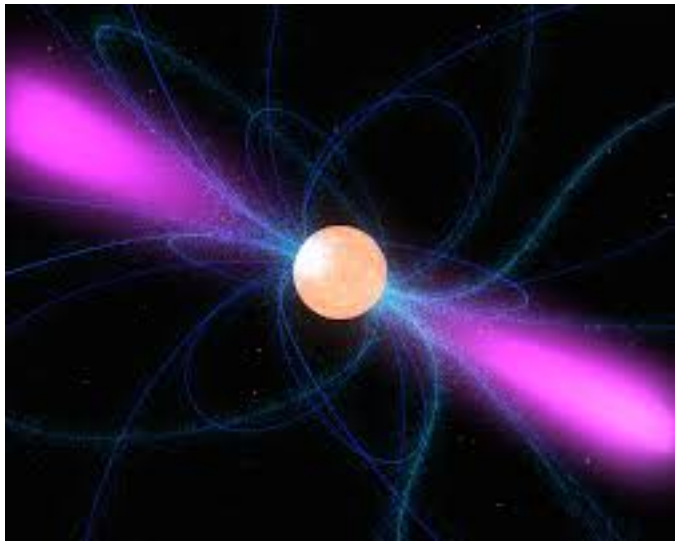
Beloborodov 17;KK & Murase 17

The source of the electrons

spindown luminosity

and/or

magnetic flare



Electron/position pair dominated

Ion + electron dominated?

The NS is born with a millisecond rotation and a sufficiently high magnetic field

The magnetar is less than ~100 years old, significantly more active than those in our galaxy.

✓ *A superluminous supernova at its birth?*

✓ *compatible with the synchrotron maser model*

KK & Murase 17 also Kotera-san's talk

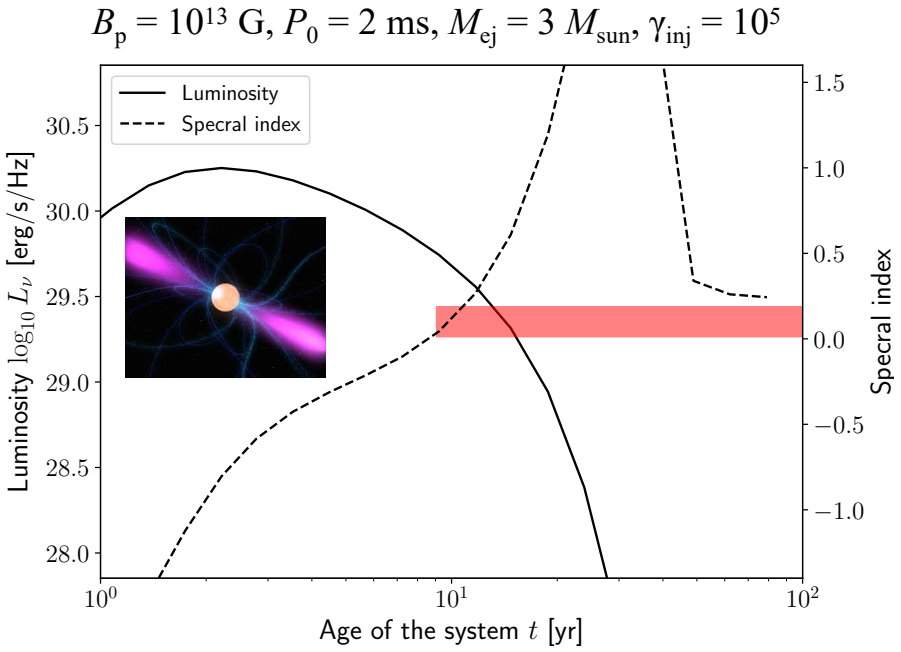
Margalit+17

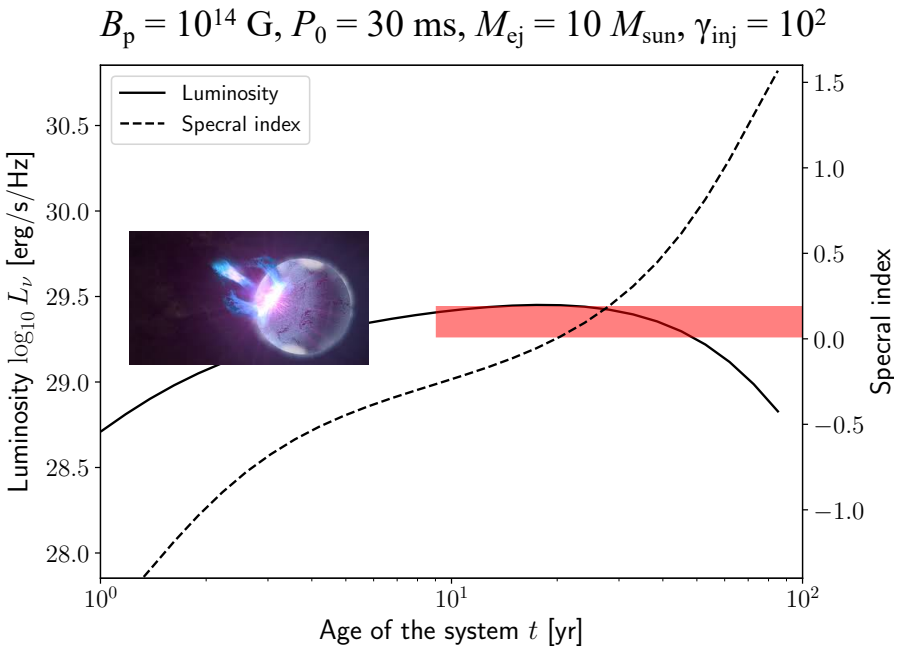
Beloborodov 17

Synchrotron boiler for FRB121102

calculate how the emission spectrum evolve with time depending on the history of injection, heating, and cooling of the parent electrons in the nebula

KK et al. in prep





- ✓ Both scenarios can work if and only if the magnetization is quite high, $\epsilon_B \gtrsim 0.1$, which is qualitatively different from Galactic young pulsars.
- ✓ The scenarios can be distinguished from the time evolution.

preliminary

Summary and Outlook

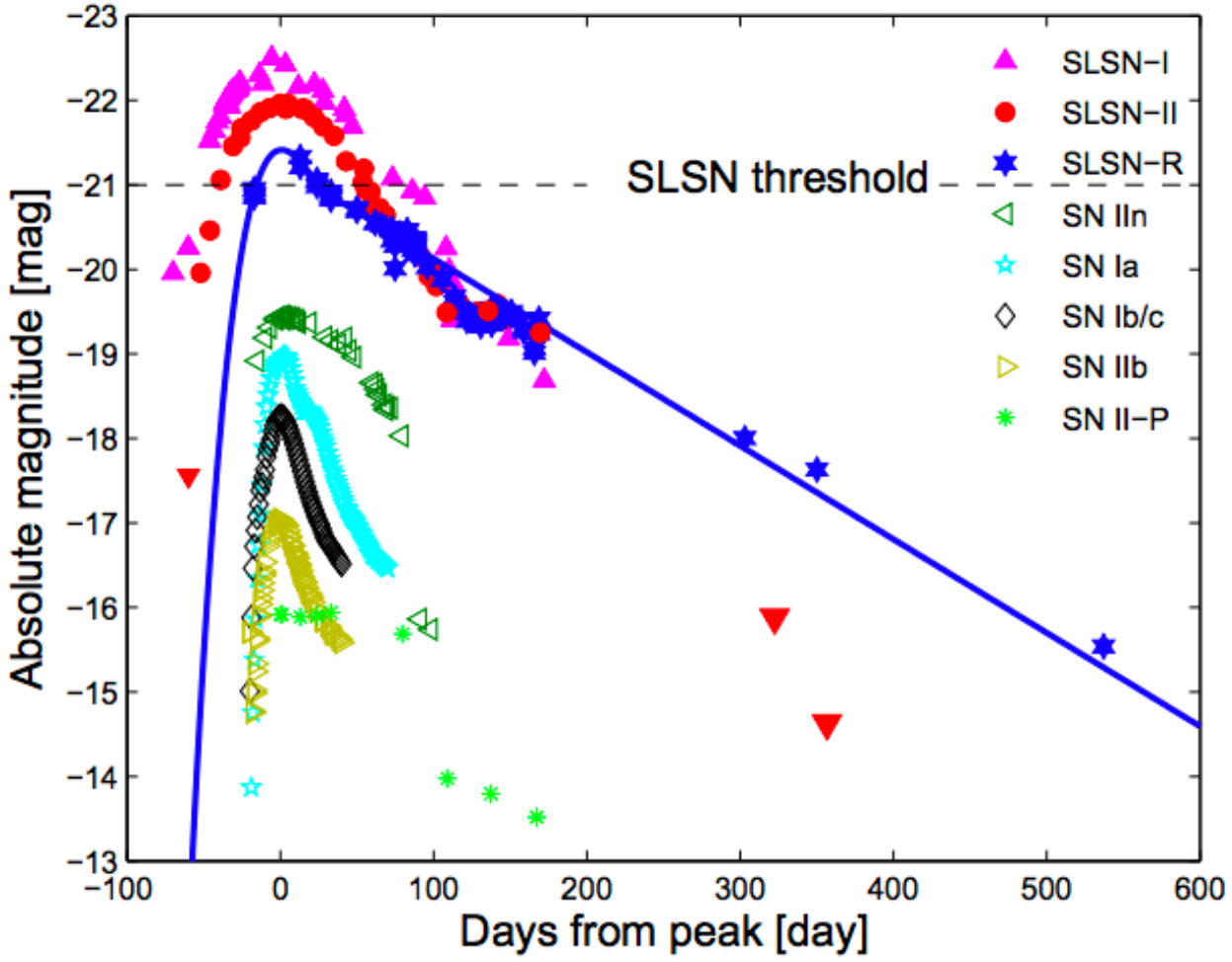
- FRB is exciting because
  1. FRB is a unique probe of the cosmological plasma, ← **Very promising**
  2. FRB is the most powerful laser in the Universe,
  3. and the source is still unknown.
- The recent discovery of an FRB-like burst from a galactic magnetar with an X-ray flare motivates us to investigate the neutron star model more intensively.
- Questions on the neutron star model
  1. What is the emission mechanism of FRB?
  2. What type of NSs can be the source of FRB?
  3. How such NSs are formed with what type of explosion?

Q1 would be the most difficult, but Q2 and Q3 could be solvable in the coming decade.

In a sense, I also hope that all my expectations are wrong (more puzzles, more fun), except for that for the FRB cosmology.

appendix

Supernova Zoo



Gal-Yam 12

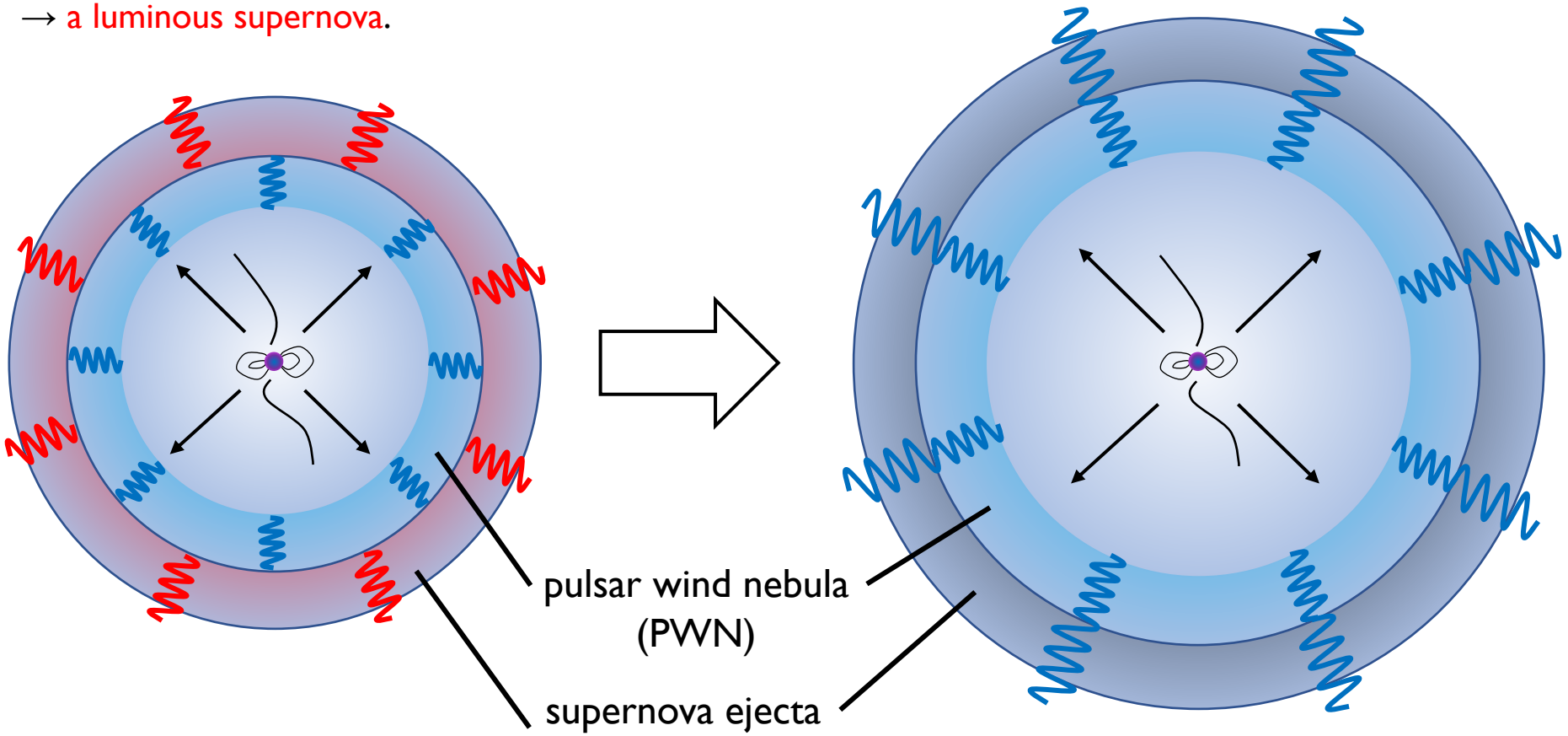
A Very Young NS in a Bubble

~ a few days to months after the explosion

The non-thermal pulsar wind nebula (PWN) emission is absorbed and thermalized in the supernova ejecta.
→ a luminous supernova.

~ 1-100 yr after the explosion

The PWN emission starts to escape the supernova ejecta.
And, also (repeating) FRBs?



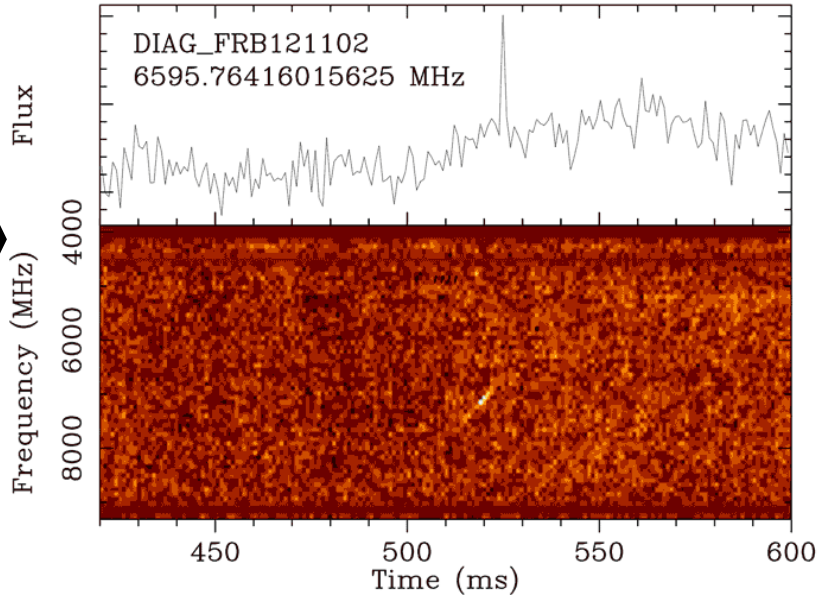
SLSN-FRB connection?

Murase, KK, Meszaros 16; KK & Murase 17; Metzger+16; Margalit+17

Superluminous supernova

~10-100 yrs later…

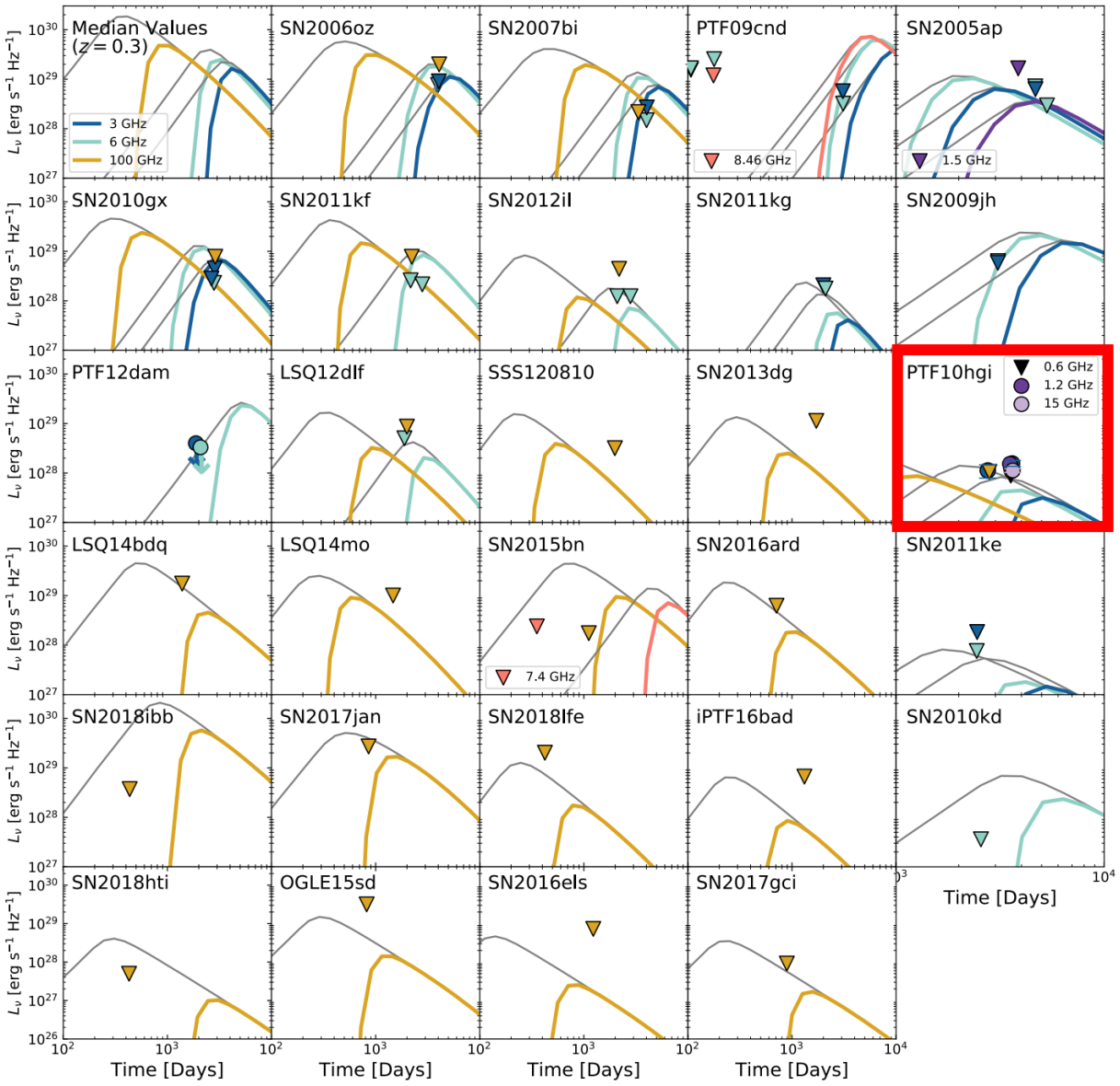
Repeating FRBs?



Follow-up observations of ~10 yr old SLSN remnants with VLA, ALMA

Law, Omand et al. 19; Eftekhari et al. 19,20

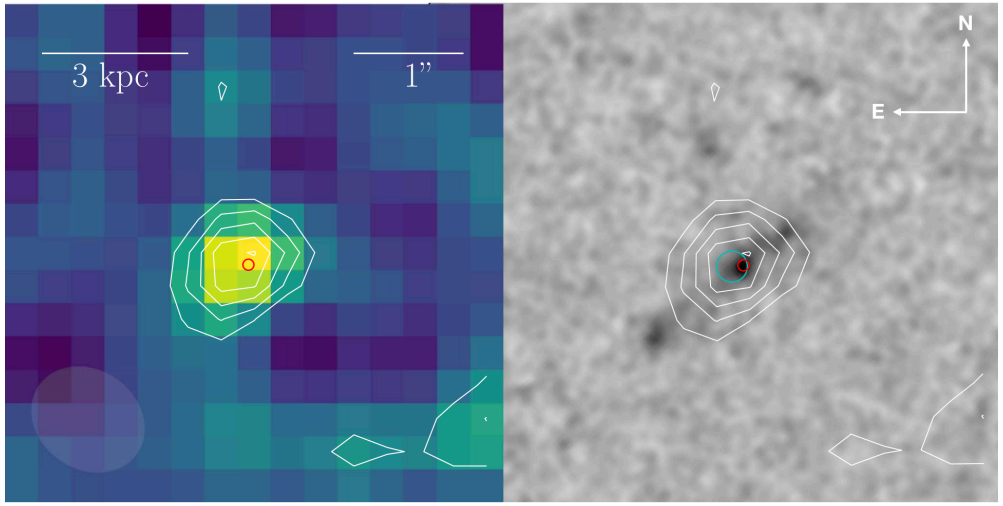
The radio counterpart of SLSNe

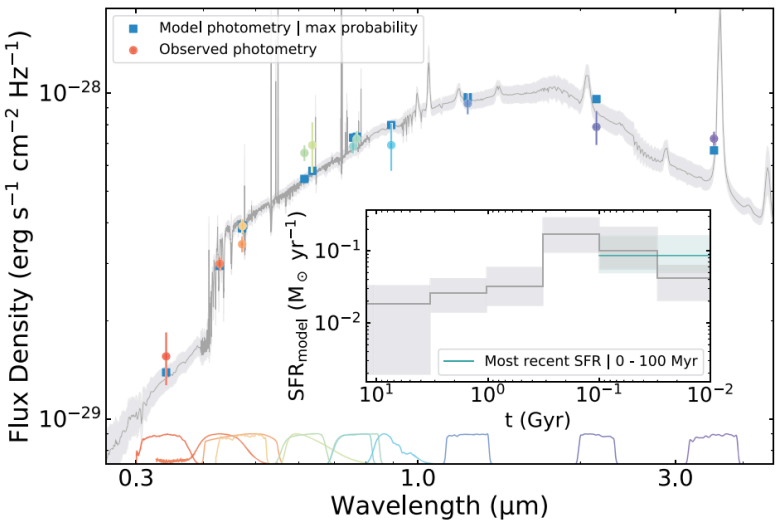


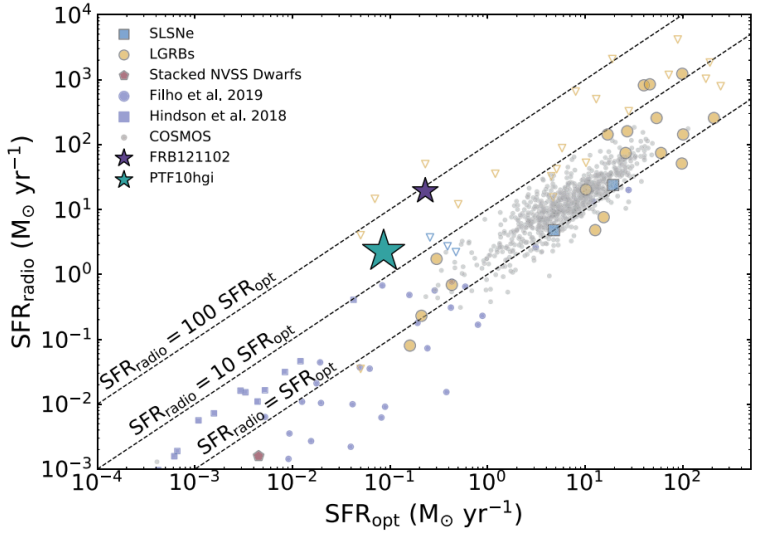
Eftekhari et al. 20

Host galaxy of PTF10hgi

= a dwarf star bursting galaxy as FRB121102

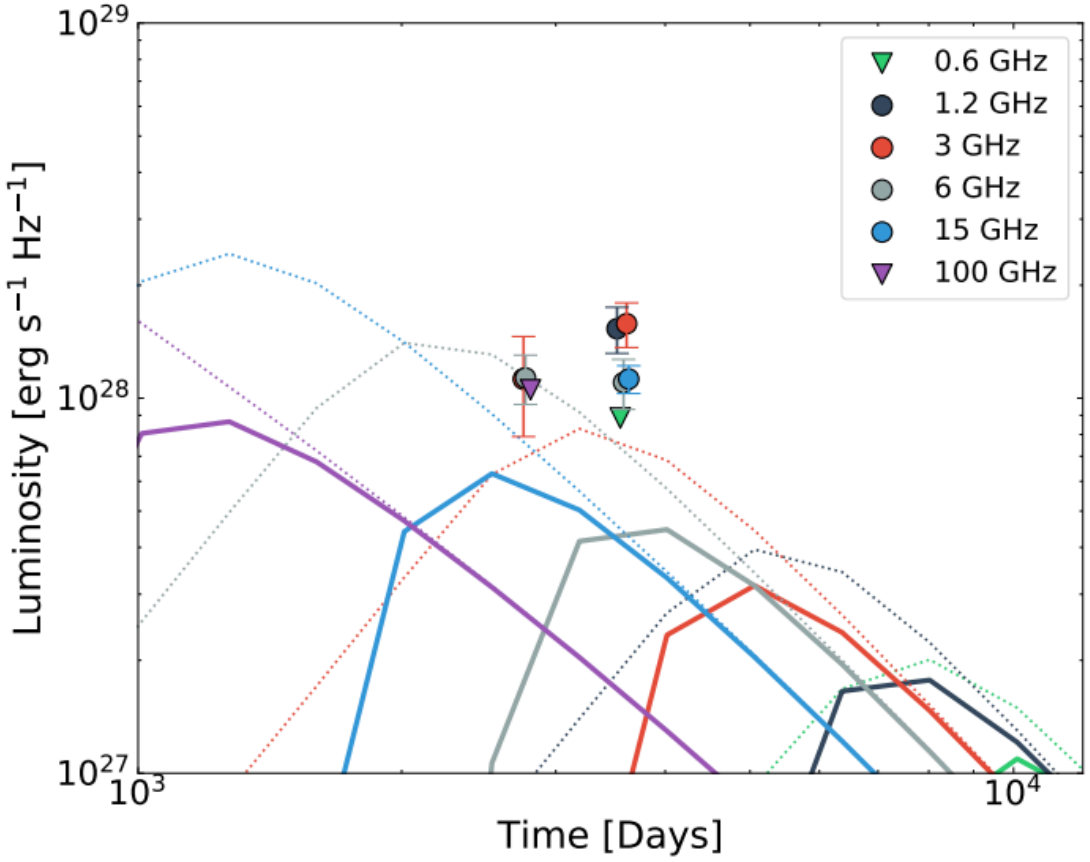






The radio counterpart is NOT likely due an obscured star formation.

The radio counterpart of PTF10hgi



Eftekhari et al. 20

- The theoretical model with relevant electron cooling processes (Murase, KK, et al. 15)
  - ✓ SLSN light curve → the model parameters : $B_p \sim 2\text{x}10^{14}$ G, $P_0 \sim 5$ ms, $M_{ej} \sim 2\ M_{sun}$
  - ✓ The injection spectrum of electron : a broken power law consistent with the crab
  - ✓ The model slightly underpredicts the radio fluxes