The Physical Mechanisms of Fast Radio Bursts

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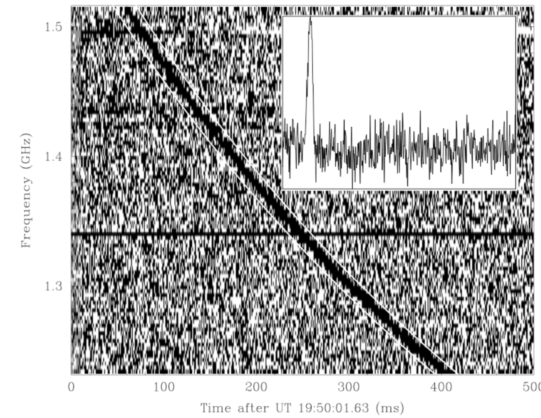
YITP International Molecule-type Workshop
Fast Radio Bursts: A Mystery Being Solved?
Feb. 6-19, 2021, Online Zoom meeting

FRB observational properties

Lorimer talk

Petroff, Hessels & Lorimer, 2019, A&AR
Cordes & Chatterjee, 2019, ARAA
Katz, 2016, 2018; Popov et al. 2018
Zhang 2020 (Nature, 587, 45)
Xiao, Wang & Dai, 2021, SCMPA

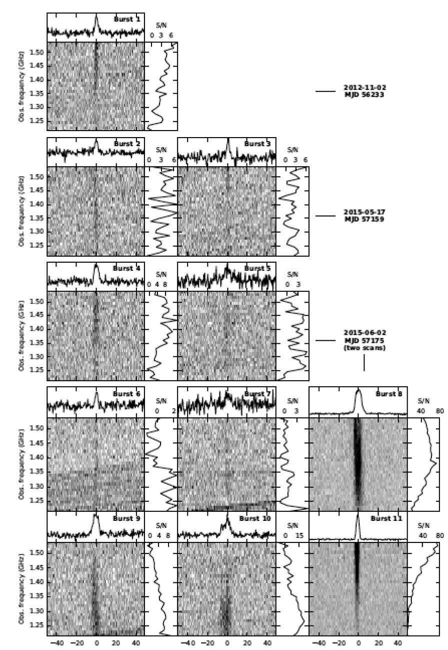


Lorimer et al. 2007

- Short duration: milli-seconds (compact objects)

  $l_{\rm eng} \sim cw = (3 \times 10^7)\ {\rm cm}\ (w/{\rm ms})$

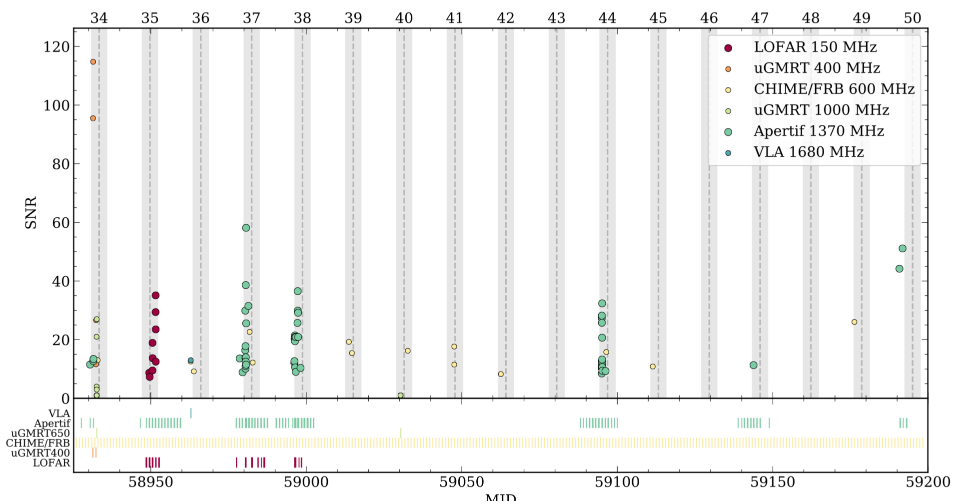
- Repetition:
  - At least some FRB sources repeat (Arecibo; CHIME; FAST …);
  - Maybe the majority of, if not all, FRBs repeat (Ravi 2019, rate argument);
  - Some have very high repetition rate (Di Li's talk)
  - No-detection of repeated bursts following some bright events (Petroff et al. 2015)

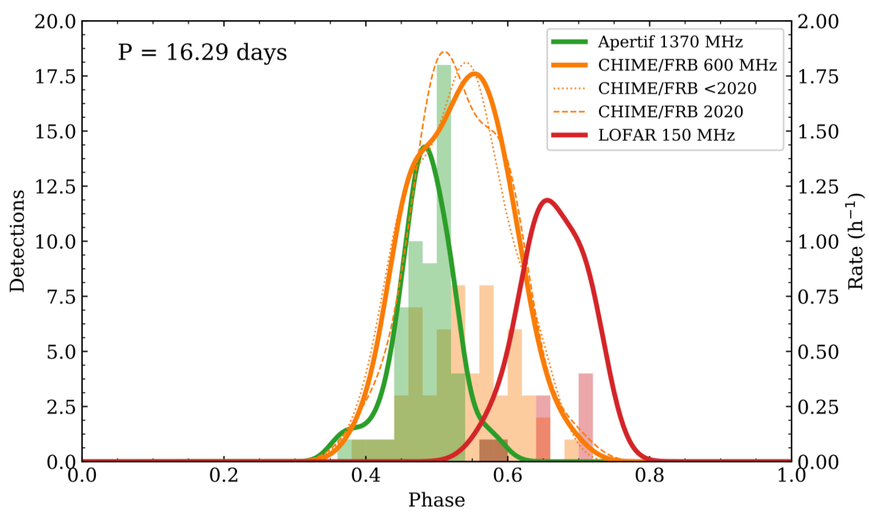


Spitler et al. 2016

FRB observational properties

- Periodicity:
  - No periodicity above 10ms for FRB 121102 (Y. Zhang et al. 2018)
  - ~16-day period of FRB 180916.J0158+65 (CHIME/FRB Collaboration 2020)
  - ~157-day period of FRB 121102 (Rajwade et al., 2020)?
  - Frequency-dependence of active phase (Pastor-Marazuela et al., 2020; Pleunis et al. 2020)

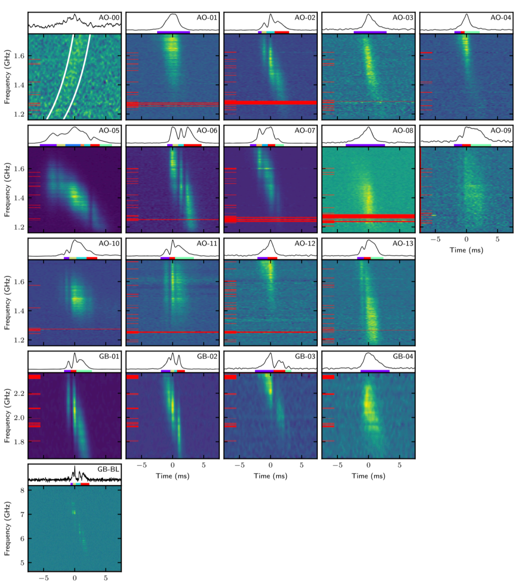




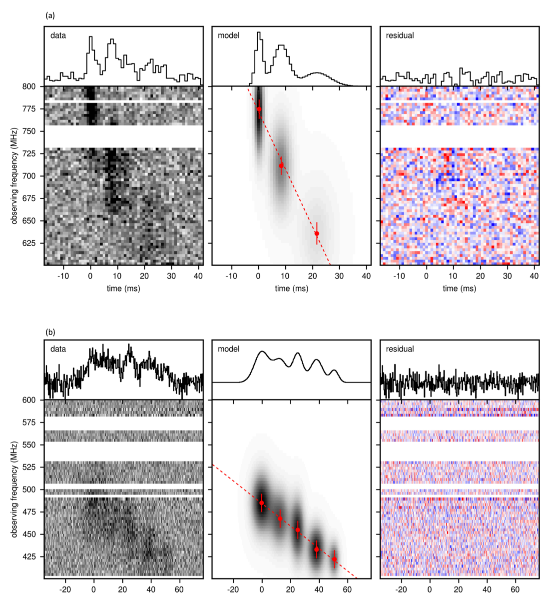
Pastor-Marazuela et al. 2020

FRB observational properties

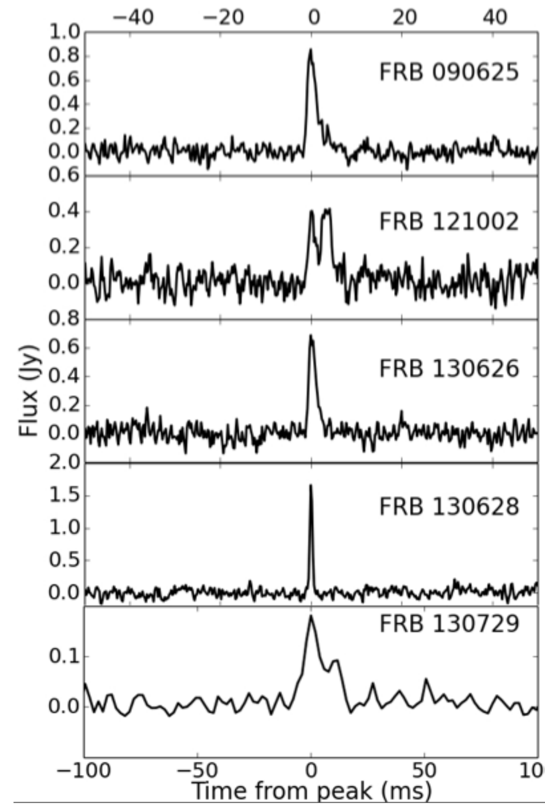
- Typical frequency (300 MHz to 8 GHz)
- Spectral index: -10 top +14 (FRB 121102)
- Internal structure & scattering tail
- Frequency down drifting (sad trombone)



FRB 121102
Hessels et al. 2019



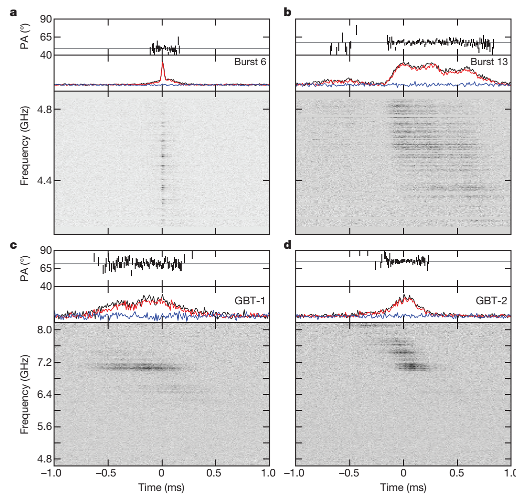
FRB 180814.J0422+73
CHIME/FRB collaboration 2019



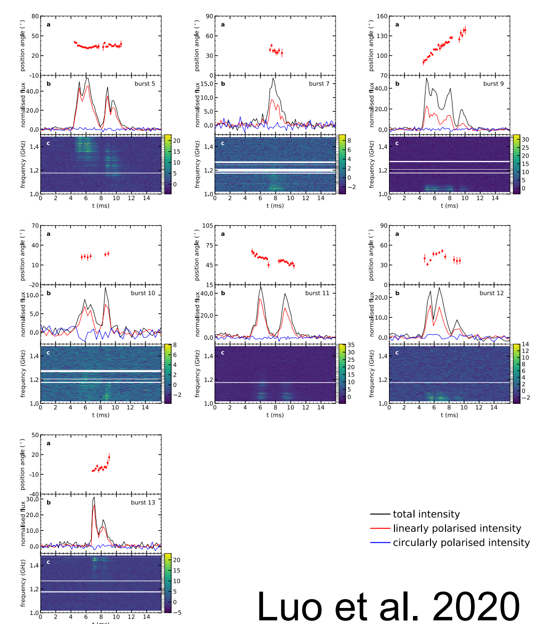
Champion et al. 2016

FRB observational properties

- Mixed polarization properties:
- ~100% linear polarization for some, low polarization degree for some others
- Constant polarization angle in each burst in some sources (FRB 121102); varying polarization angle in each burst in some other sources (FRB 180301)
- Large rotation measure (RM) for FRB 121102, regular or low RM for some others. Secular & short-term variations

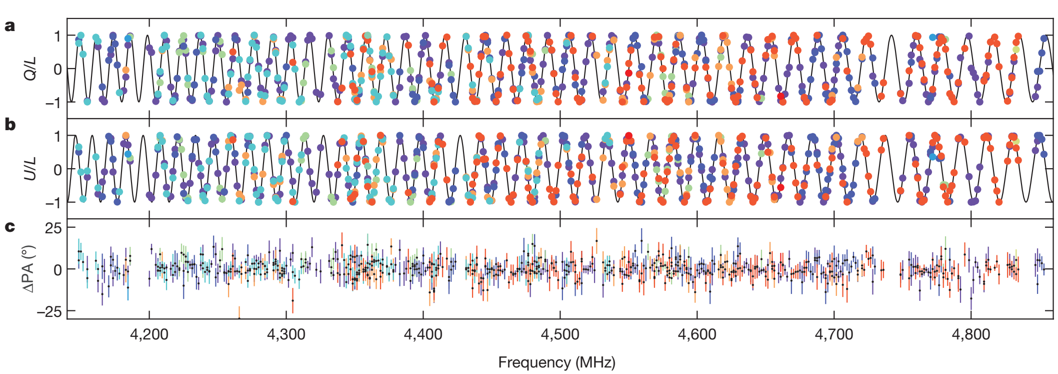


Michilli et al. 2017



Luo et al. 2020

$$\Delta\theta = \frac{2\pi e^3}{m^2 c^2 \omega^2} \int_0^d n B_{\parallel} ds. \qquad \mathrm{RM} = \int_0^d n B_{\parallel} ds$$



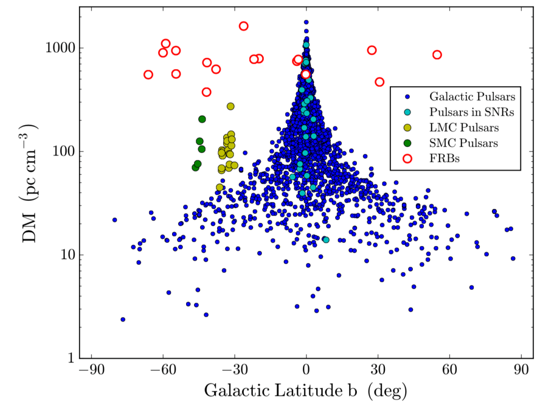
Michilli et al. 2017

FRB observational properties

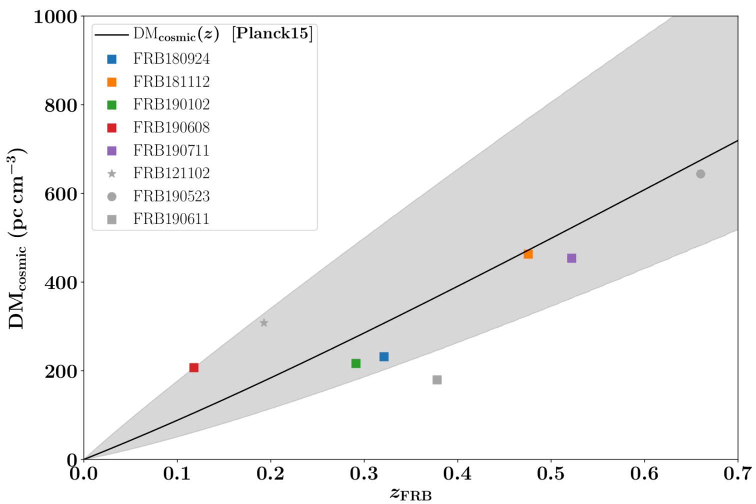
- Excess dispersion measure (DM)

$$\mathrm{DM} = \int_0^{D_z} \frac{n_e(l)}{1+z(l)}\, dl,$$

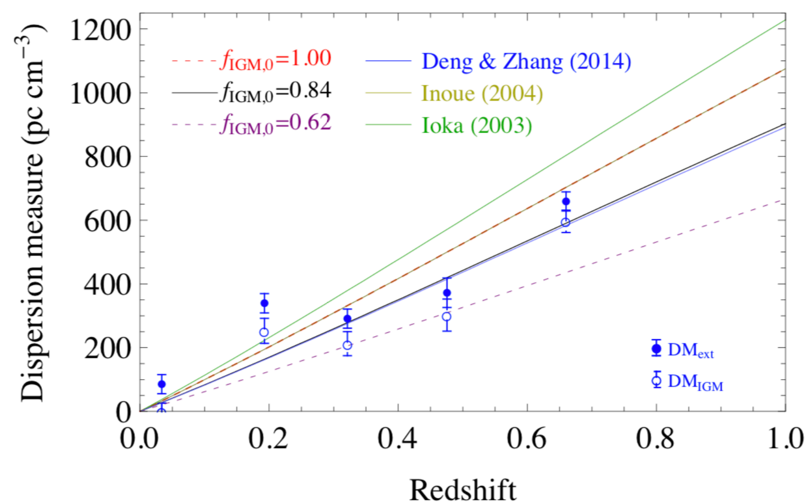
- Redshifts:
  - From DM: z << 1 to z > 3;
  - Measured: 0.1-0.7



Cordes +, 2016, ApJ



Macquart et al. 2020, Nature, 581, 391



Li et al. 2020, MNRAS, 496, L28

$$z \sim \mathrm{DM_{IGM}}/855\mathrm{pc\ cm^{-3}}$$

Zhang, 2018, ApJL, 867, L21

FRB observational properties

- Luminosity and energetics

$$L_p \simeq 4\pi D_{\rm L}^2 \mathcal{S}_{\nu,p}\nu_c = (10^{42}\ {\rm erg\ s^{-1}}) 4\pi \left(\frac{D_{\rm L}}{10^{28}\ {\rm cm}}\right)^2 \frac{\mathcal{S}_{\nu,p}}{\rm Jy}\frac{\nu_c}{\rm GHz},$$

$$E \simeq \frac{4\pi D_{\rm L}^2}{(1+z)}\mathcal{F}_\nu \nu_c = (10^{39}\ {\rm erg}) \frac{4\pi}{(1+z)} \left(\frac{D_{\rm L}}{10^{28}\ {\rm cm}}\right)^2 \frac{\mathcal{F}_\nu}{\rm Jy \cdot ms}\frac{\nu_c}{\rm GHz},$$

  - Isotropic peak luminosity: $10^{38} - 10^{46}$ erg/s
  - Isotropic energy: $10^{35} - 10^{43}$ erg
  - These numbers are smaller by a factor of $f_b \equiv \Delta\Omega/4\pi$ if FRBs are beamed; the total number of bursts may increase by the same factor (if isotropic).

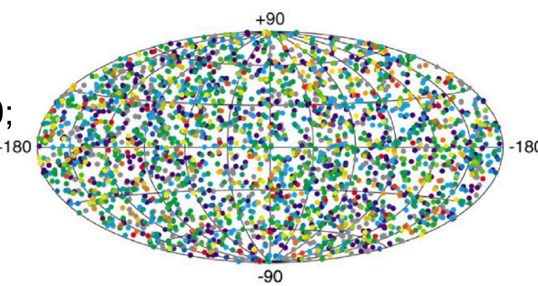
- Brightness temperature (imaginary temperature if radiation is from a blackbody)

$$T_b \simeq \frac{\mathcal{S}_{\nu,p} D_{\rm A}^2}{2\pi k(\nu w)^2} = (1.2\times 10^{36}\ {\rm K}) \left(\frac{D_{\rm A}}{10^{28}\ {\rm cm}}\right)^2 \frac{\mathcal{S}_{\nu,p}}{\rm Jy} \left(\frac{\nu}{\rm GHz}\right)^{-2} \left(\frac{w}{\rm ms}\right)^{-2}$$

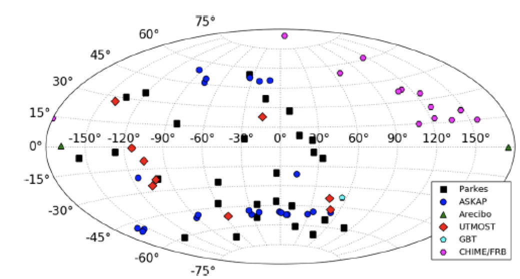
Radiation mechanism must be Coherent!

FRB observational properties (global)

- High Galactic latitudes (extragalactic), isotropic but non-Euclidean (cosmological)
- High observed event rate: $\sim (10^3 - 10^4)\ \mathrm{day}^{-1}$ all sky (larger by a factor of $f_b^{-1} = 4\pi/\Delta\Omega$ if FRBs are beamed)
- Large event rate density: $3.5^{+5.7}_{-2.4} \times 10^4\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ above $10^{42}\ \mathrm{erg\ s}^{-1}$ (larger by a factor of $f_b^{-1} = 4\pi/\Delta\Omega$ if FRBs are beamed) Luo et al. 2020
- Energy/luminosity function:
  - Power law: $dN/dE \propto E^{-\alpha}, \alpha \sim 1.8$ Luo et al. 2018, 2020; Lu & Piro 2019
  - More complicated functions: Lu et al. 2020
    - Cutoff at the high end? Luo et al. 2020
    - New component in the low end? D. Li et al. 2021
- Redshift distribution: not known
  - Tracking star formation rate?
  - Tracking compact object merger?
  - No evolution model disfavored R. C. Zhang et al. 2021 James et al. 2021

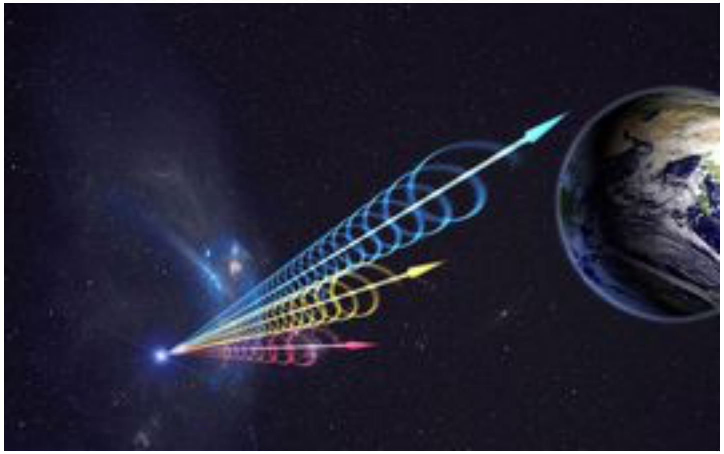


GRBs



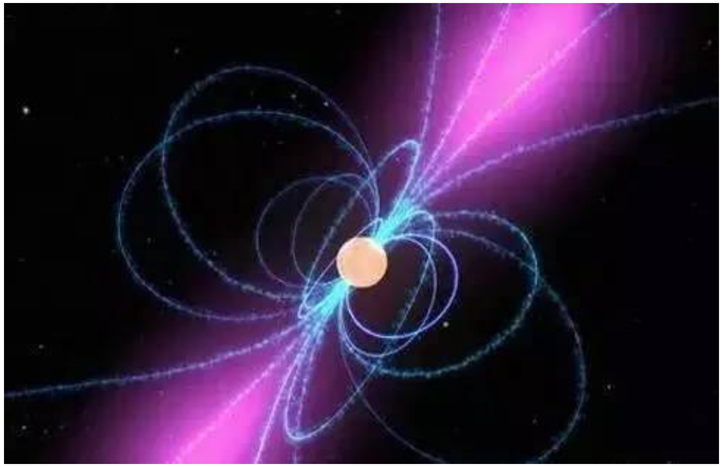
FRBs

Relatives of FRBs



FRBs

GRBs



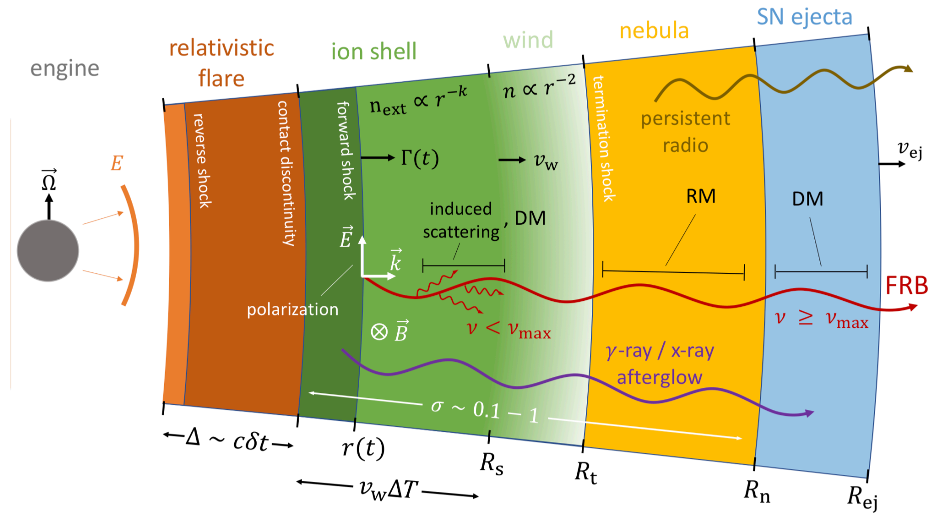
radio pulsars

Lessons from GRBs

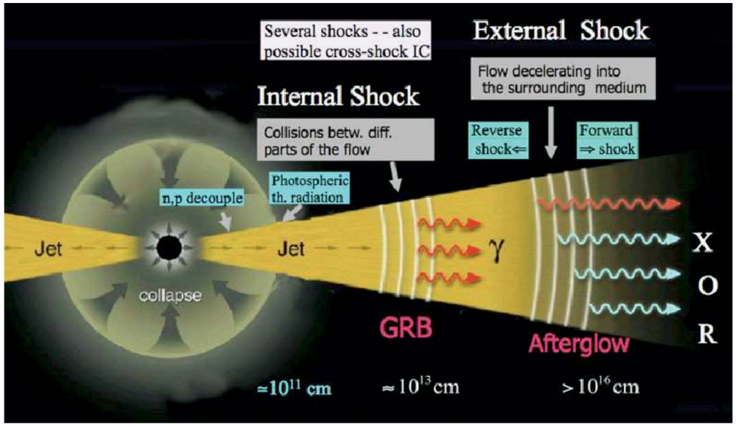
- Many GRB models (>110) reinvented for FRBs (>50).
- Relativistic outflow; internal vs. external shocks
- Some ideas (not observationally confirmed) on coherent radio emission
  - Synchrotron masers

Lyubarsky, Waxman, Beloborodov, Metzger, Sironi …

Metzger talk, Sironi talk

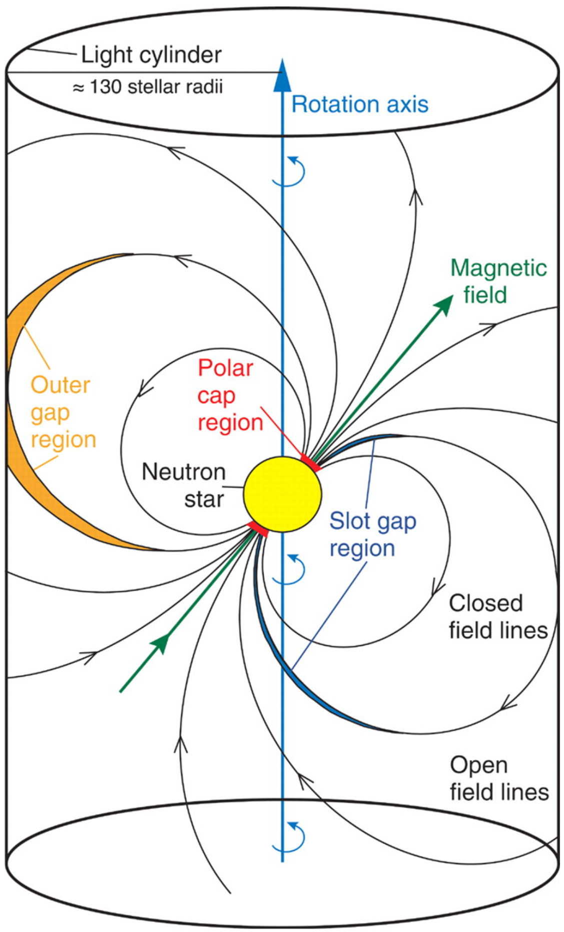


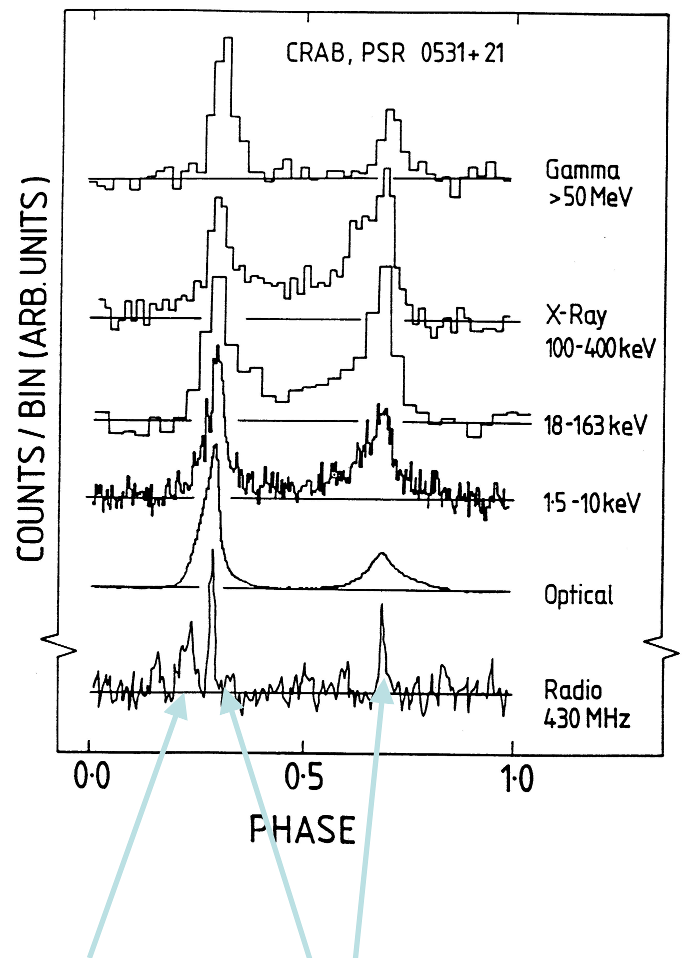
Metzger et al. 2019



Meszaros 2001

Lessons from radio pulsars



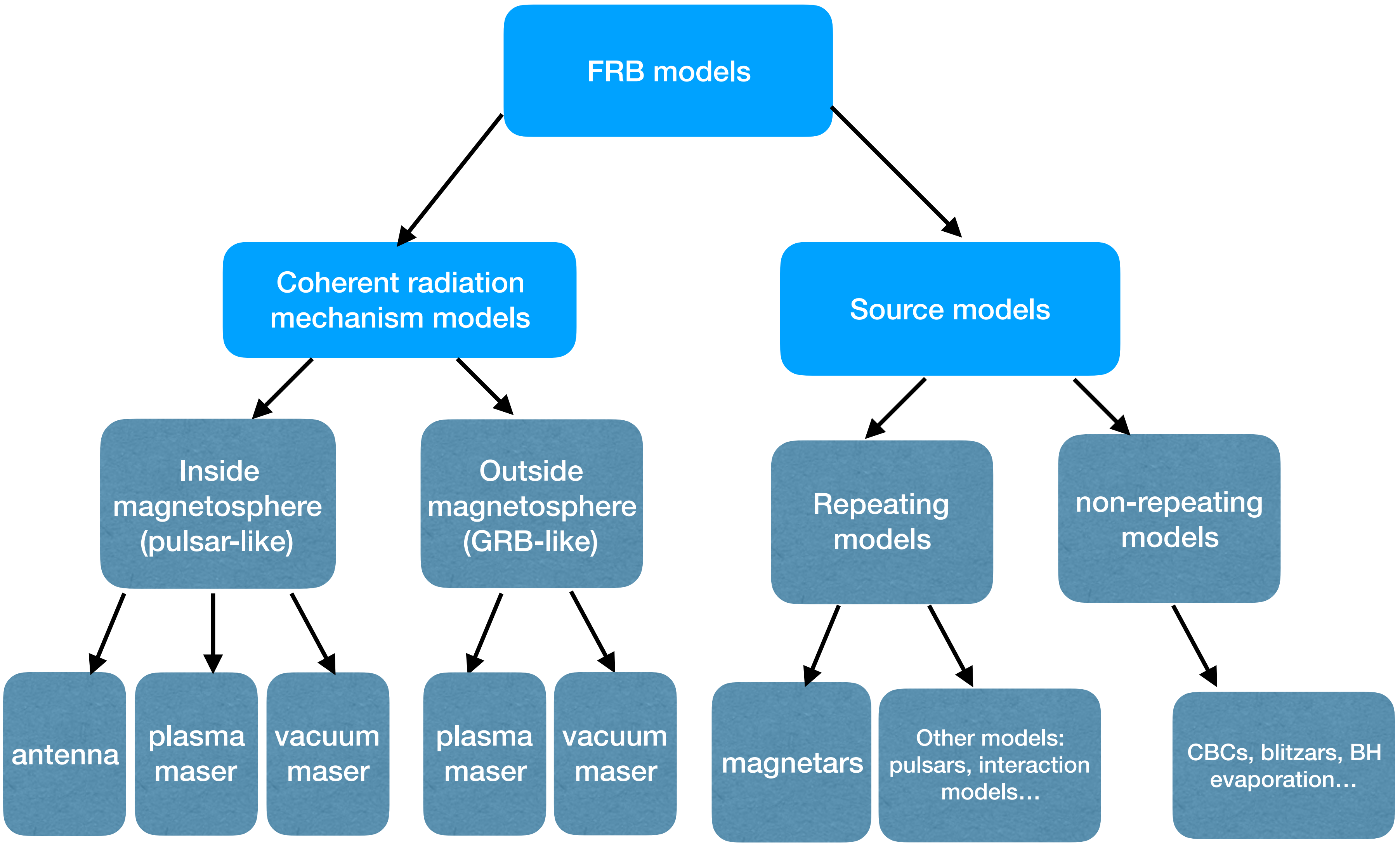


Inner gap vs. outer gap

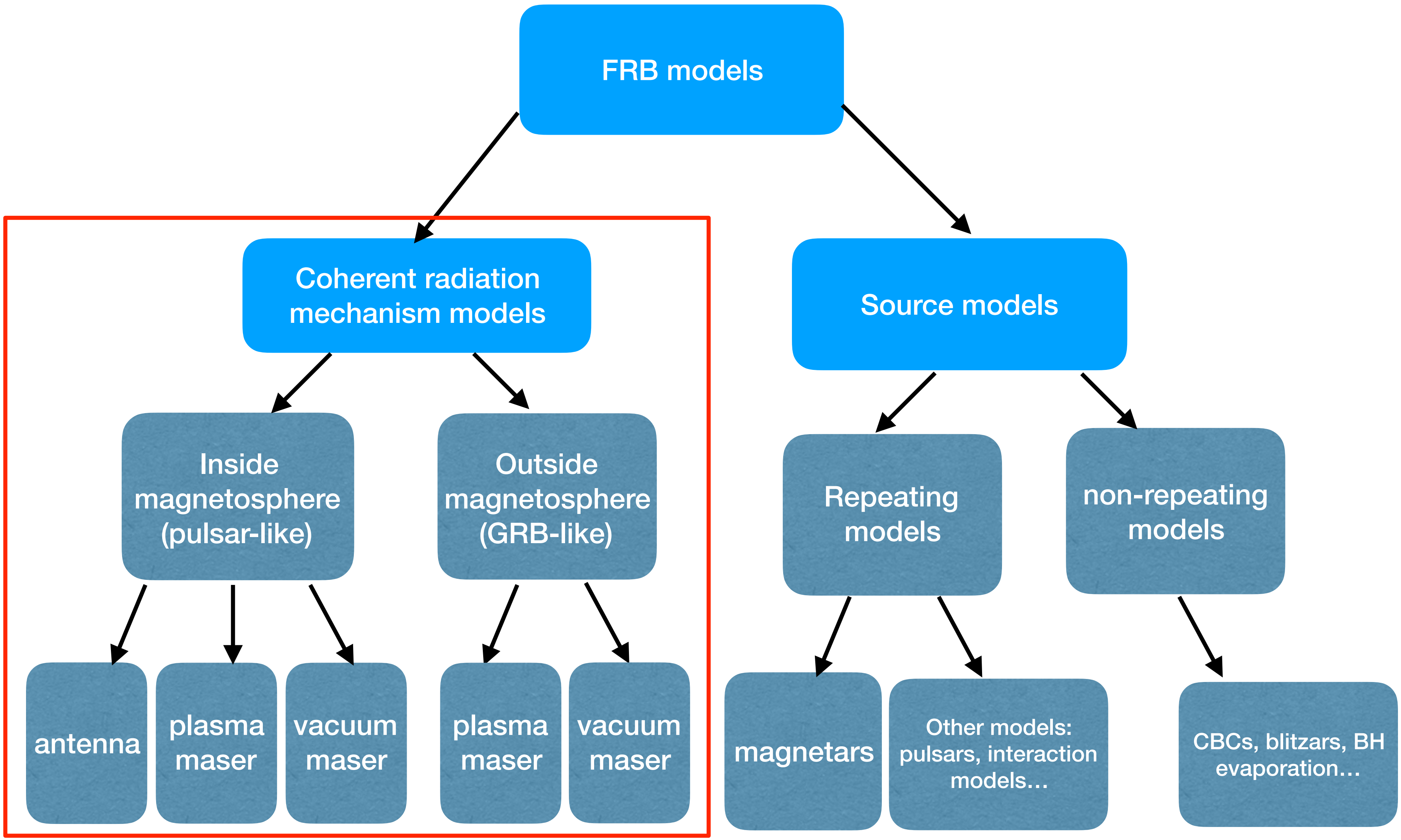
from polar cap?

from outer magnetosphere?

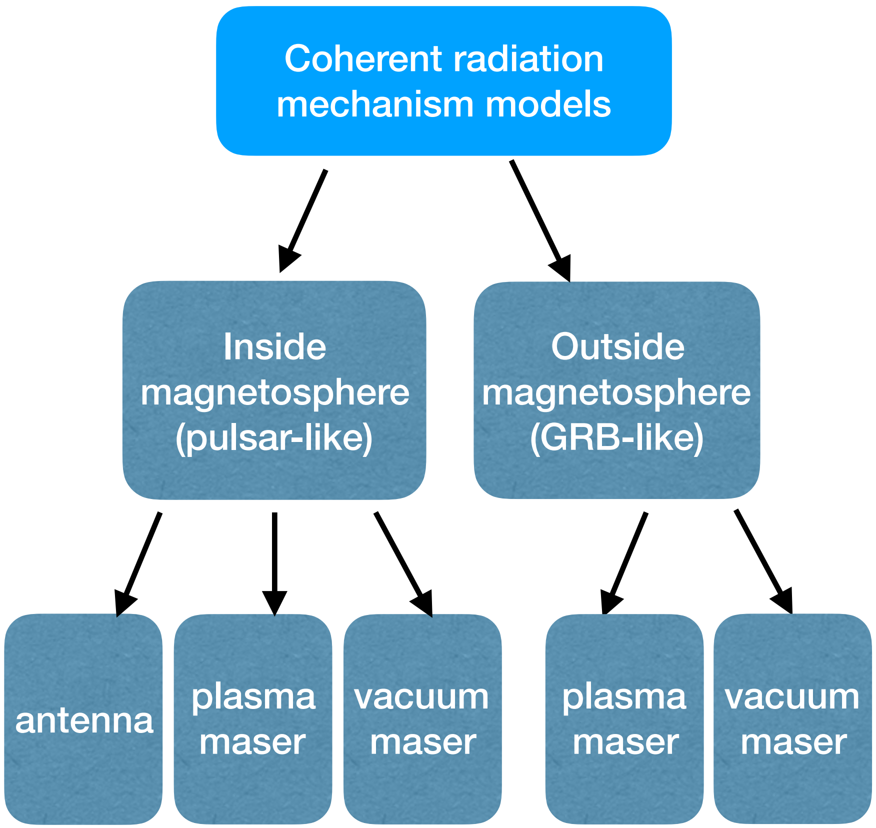
Components of FRB Models



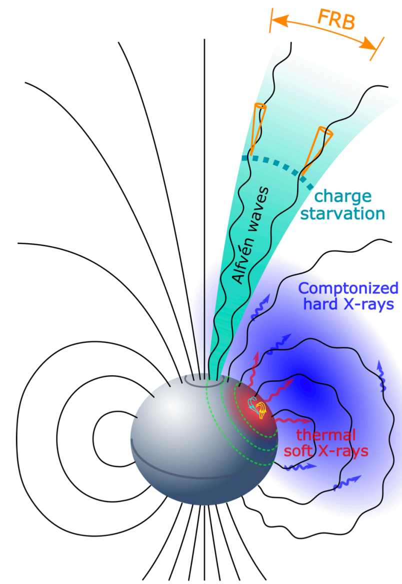
Components of FRB Models



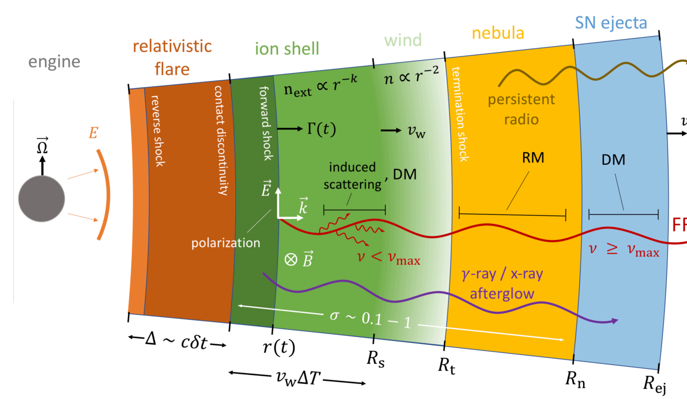
Coherent Radiation Mechanisms



Talks by Lu, Kumar, Metzger & Sironi



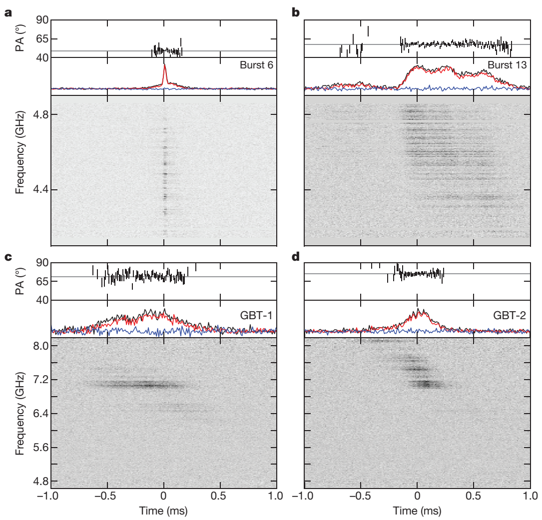
Pulsar-like: from Lu et al. 2020



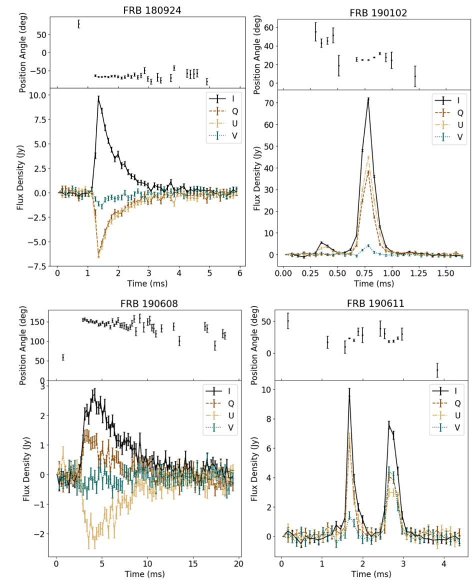
GRB-like: from Metzger et al. 2019

	Pulsar-like models	GRB-like models
Beaming angle	• Likely narrow	• Likely wide
Radio efficiency	• Relatively high	• Relatively low
High energy counterparts	• Moderately bright X-ray / gamma-ray emission	• bright X-ray / gamma-ray / optical emission
Polarization properties	• High (up to 100%) linear polarization degree • Non-varying (straight field lines, slow rotation) or diverse swings of polarization angles (inner magnetosphere)	• No polarization (low-B version) • High (up to 100%) linear polarization degree & constant polarization angle (high-B version)

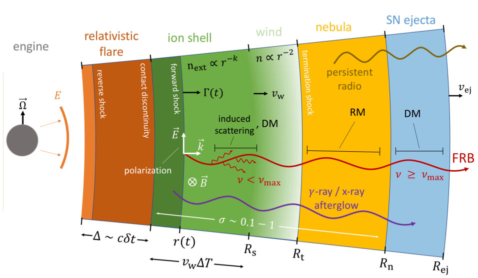
Polarization properties as a clue: Polarization angle swings

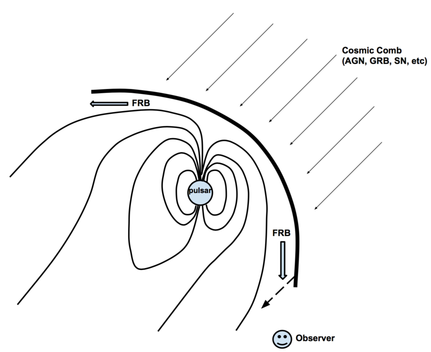


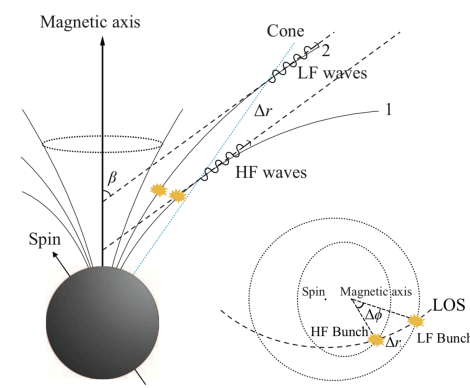
FRB 121102
Michilli et al. 2017



ASKAP FRBs
Day et al. 2020

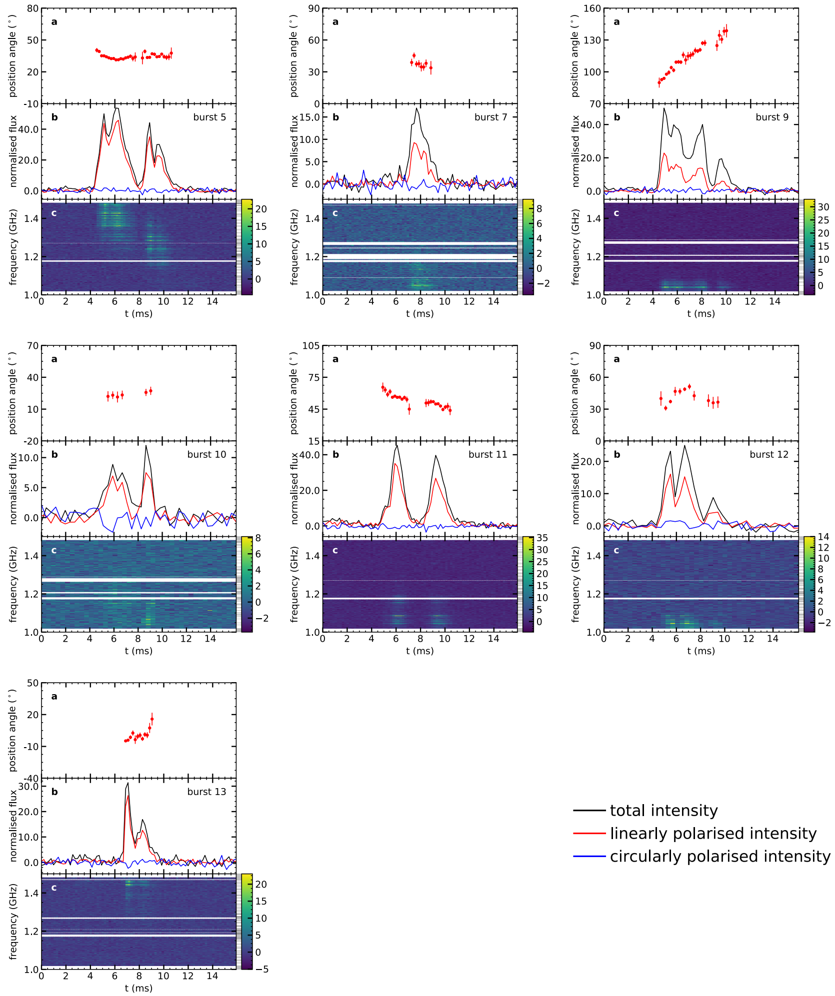






FRB 180301

Luo et al. 2020, Nature, 586, 693; also K. J. Lee's talk

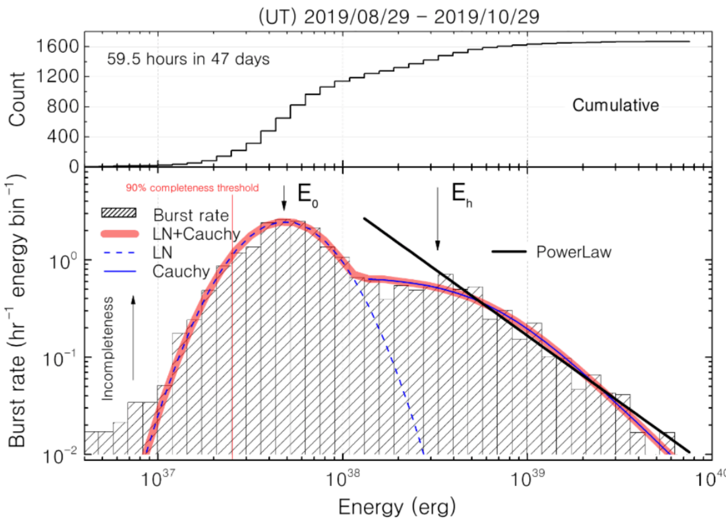


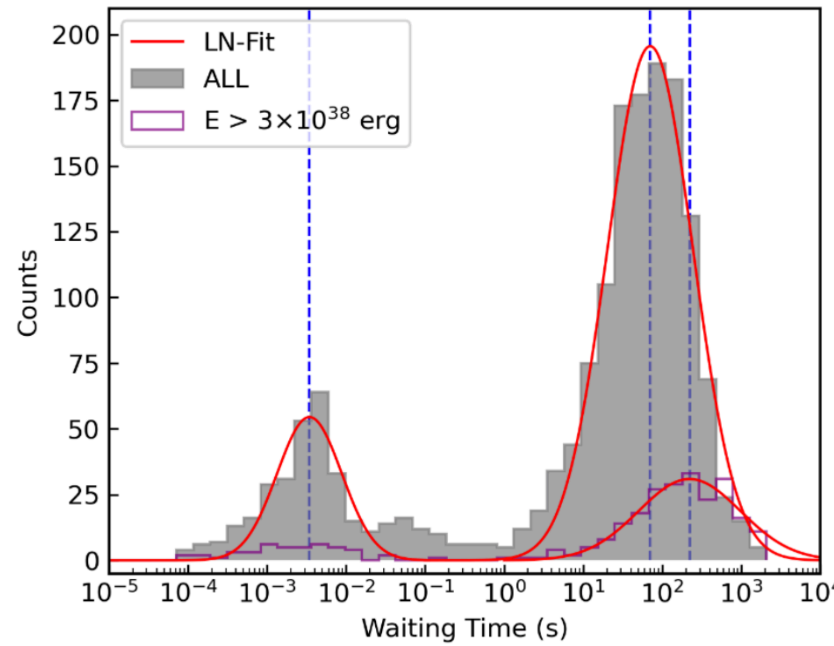
Detected with FAST

Diverse polarization angle swings: A magnetospheric origin!

FRB 121102

Li et al. 2020, submitted; also D. Li's talk





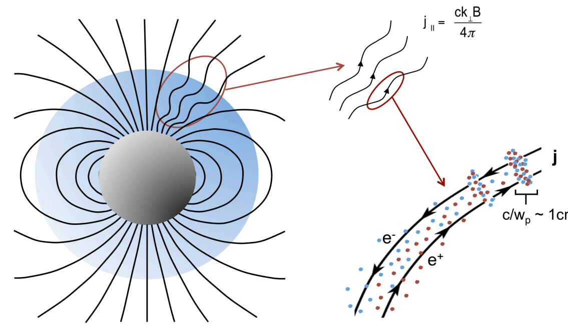
Challenges to GRB-like models:

* Very high repetition rate
* Short waiting time
* ~47-day burst energetics is at least 1% of a magnetar's magnetic energy

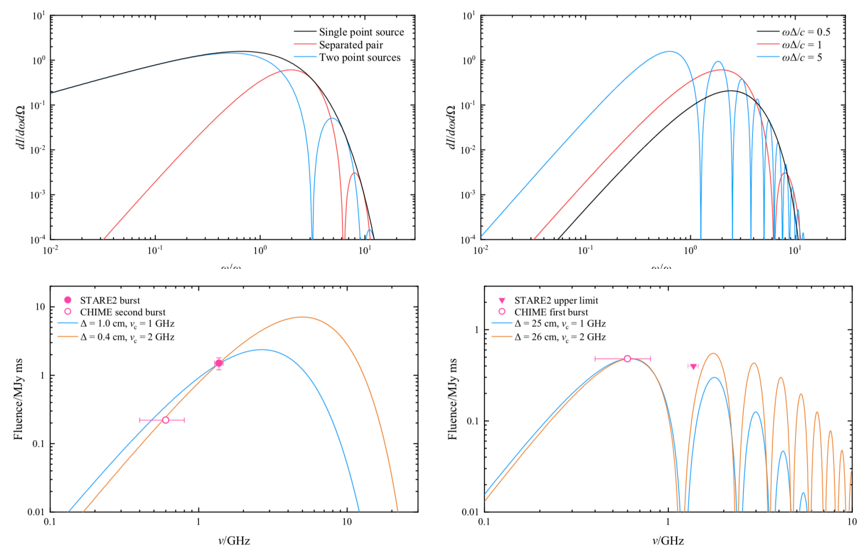
One plausible magnetospheric mechanism: Coherent radiation by bunches

Katz, Kumar & Lu, Yang & Zhang …

- Mechanism invoked in early pulsar theories (Ruderman & Sutherland 1975)
  - Criticized:
    - Melrose: bunch formation and maintenance?
    - Lyubarsky et al: Plasma effect
  - Pulsar radio data consistent with model
- Revived for FRBs:
  - Kumar et al. (2017): Requirement of $E_{||}$
  - Yang & Zhang (2018): 3D coherent bunches
  - Kumar & Bosnjak (2020): Alfven-wave induced $E_{||}$, see also Chen et al. (2020)
  - Lu, Kumar & Zhang (2020): Unified magnetar model for all FRBs
  - Yang et al. (2020): Charge separation, bunch maintenance, plasma effect removed, narrow spectrum



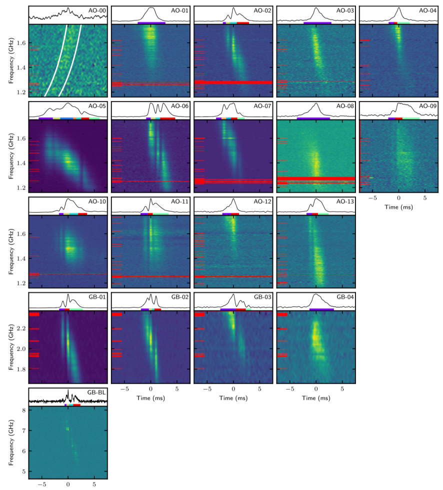
Kumar & Bosnjak (2020)

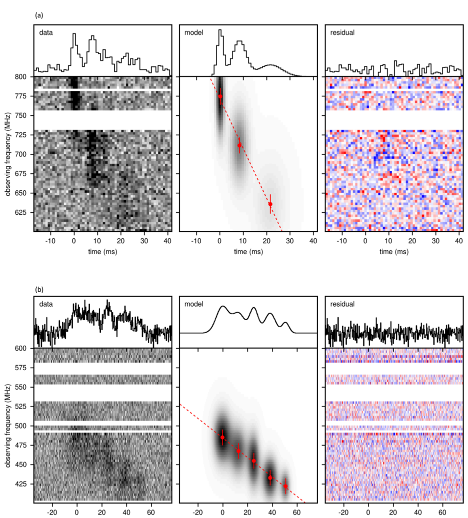


Yang et al. 2020, ApJL, 901, L13

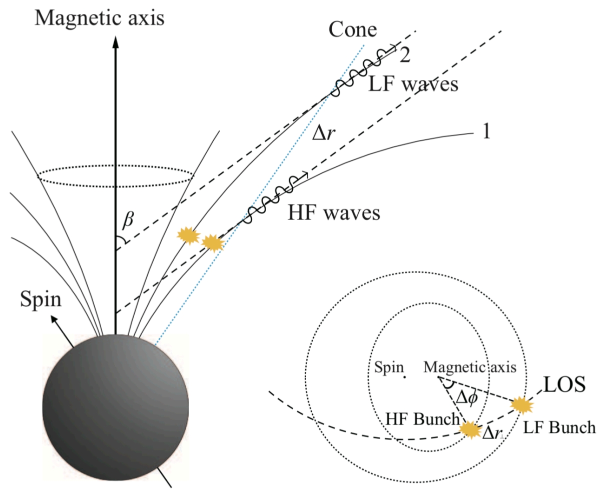
Time-frequency down-drifting

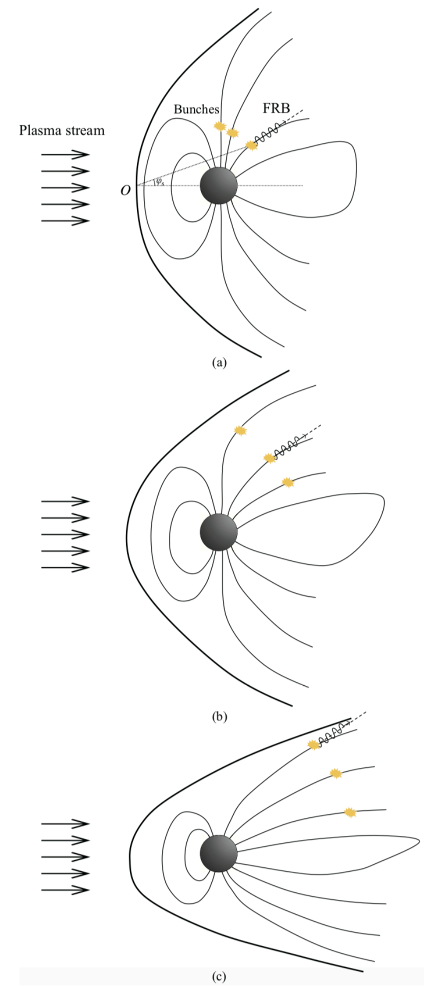
Wang et al., 2019, ApJL, 876, L15





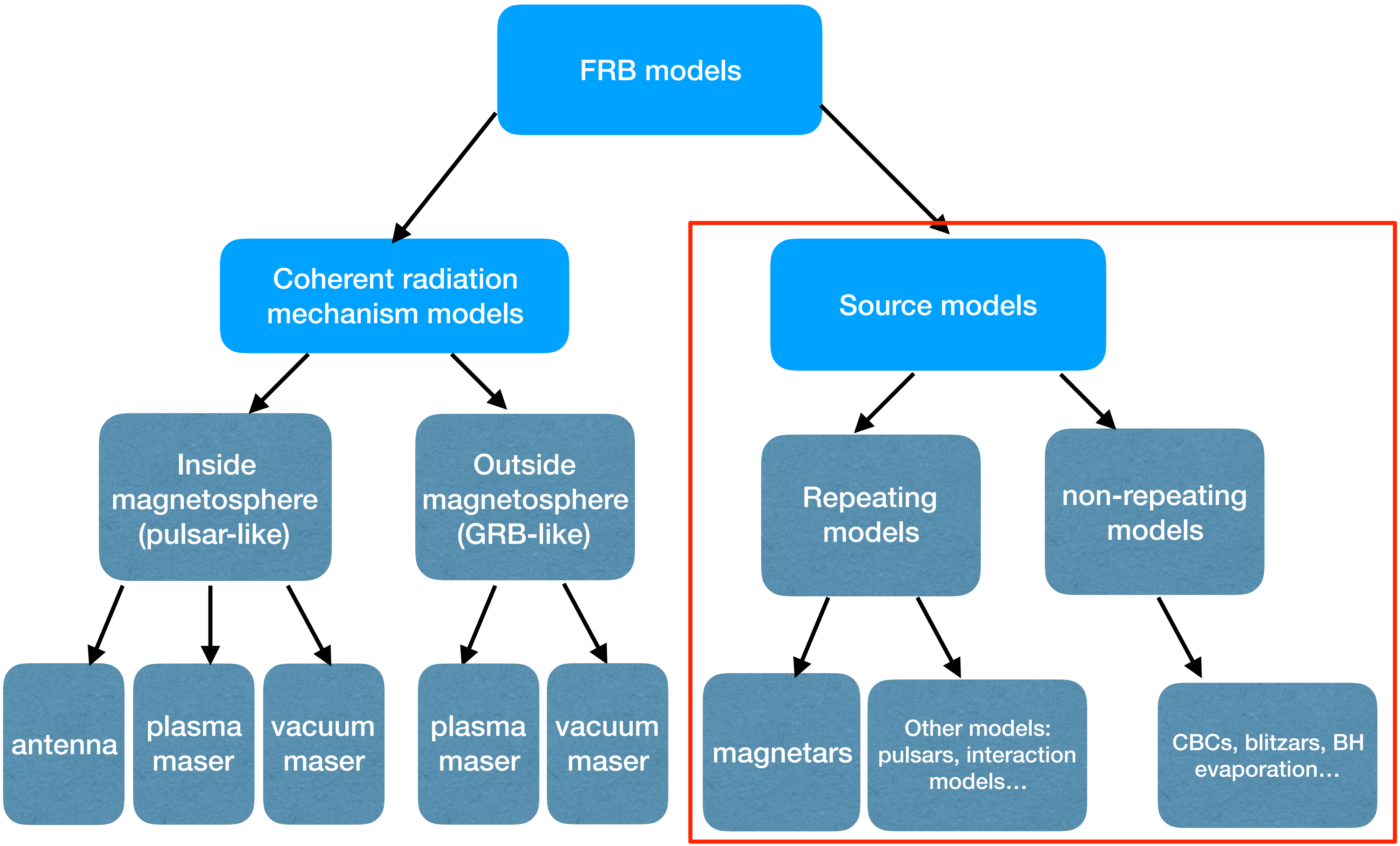
Hessels et al; CHIME/FRB Collaboration





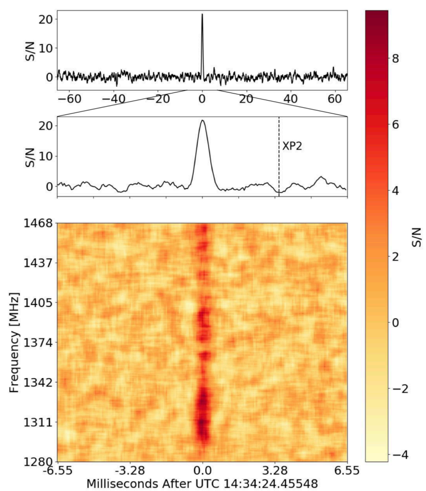
- Radius-to-frequency mapping
- Difficult to “re-calibrate” in the shock models

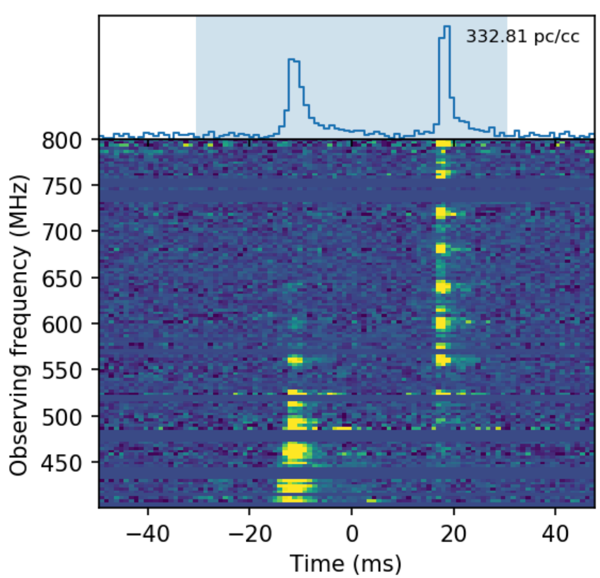
Components of FRB Models

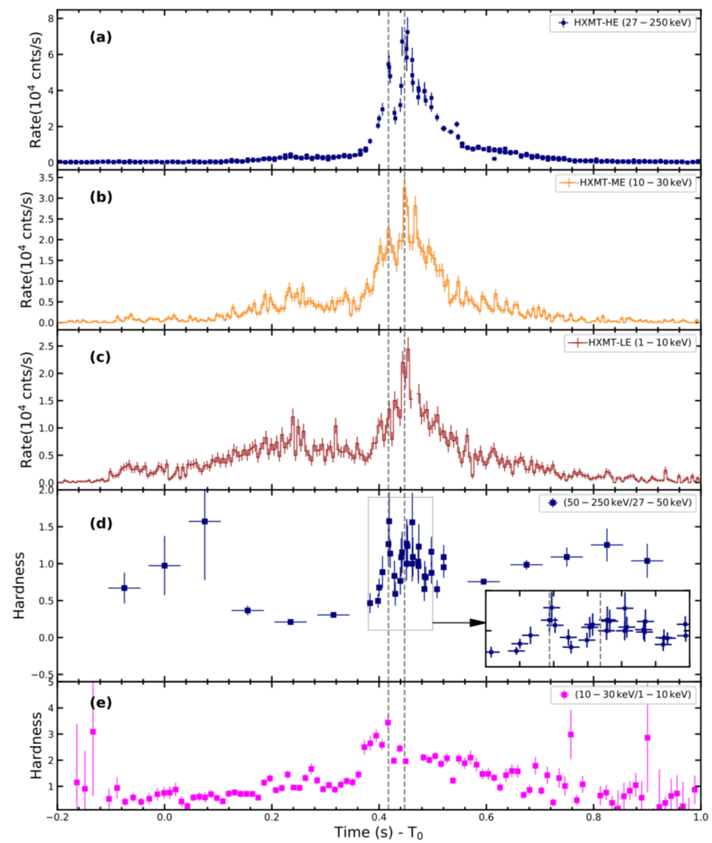


FRB 200428-SGR Association

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



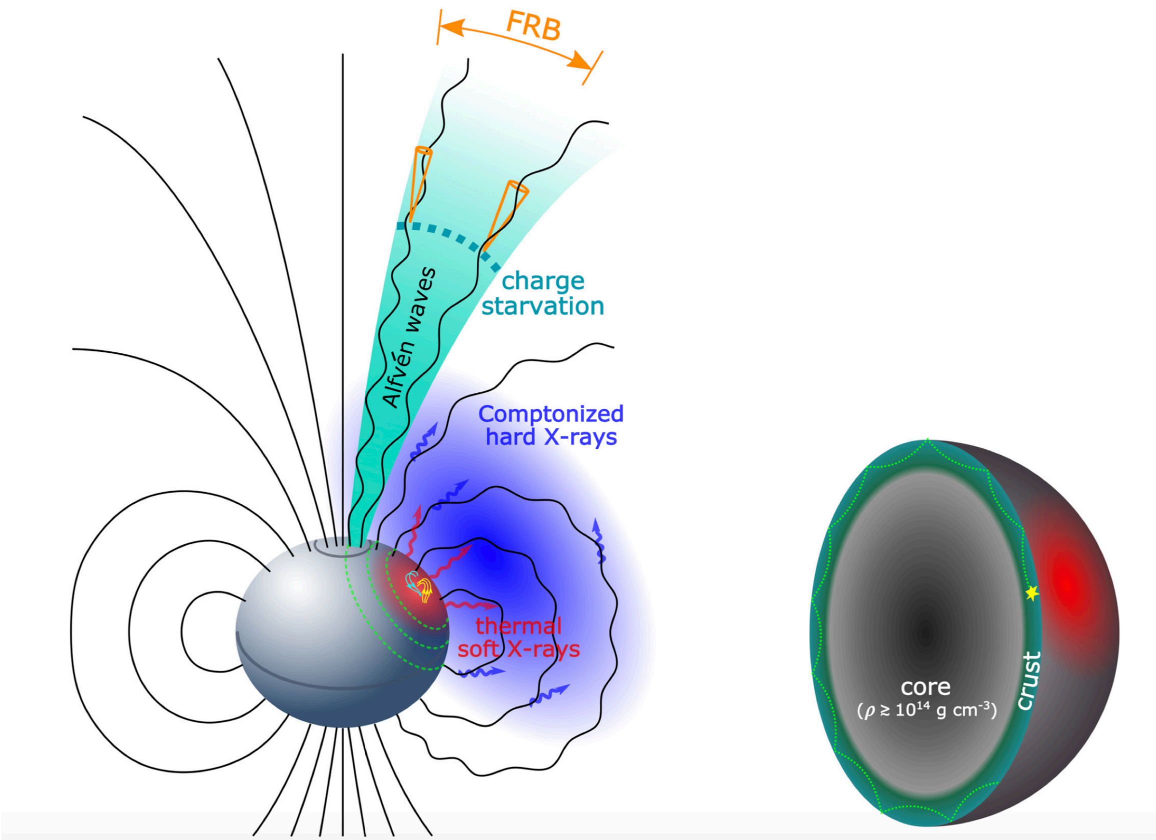




At least some FRBs are produced by magnetars!

FRB 200428-SGR Association

How?



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

Lu talk & Kumar talk

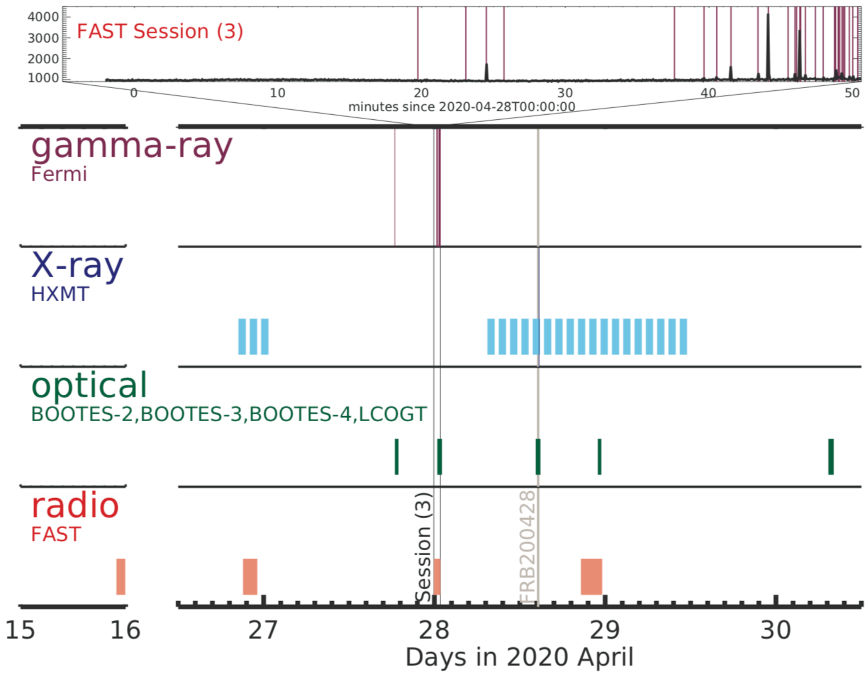
Other ideas:

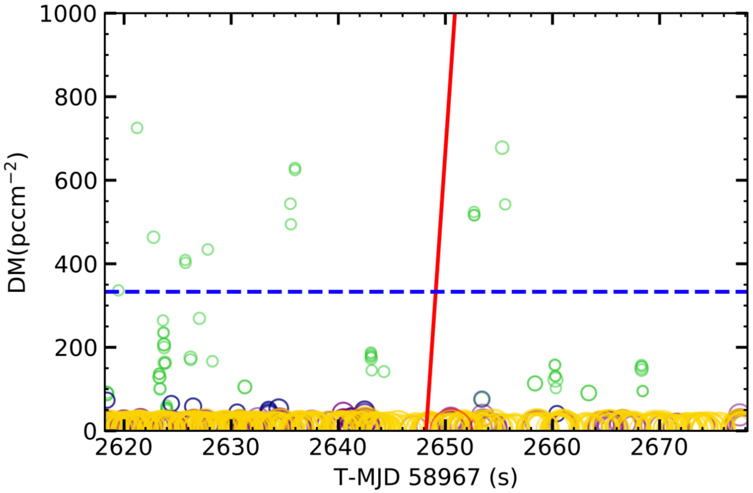
Margalit et al. 2020
(Metzger talk
Sironi talk)

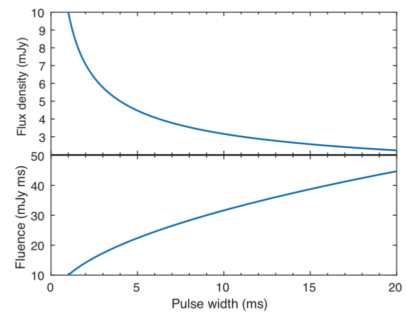
Dai (2020)

FRB-SGR burst non-associations

Lin et al. 2020, Nature, 587, 7832; also L. Lin's talk







Twenty-Nine GBM bursts did not have associated radio emission: Stringent flux/fluence upper limits

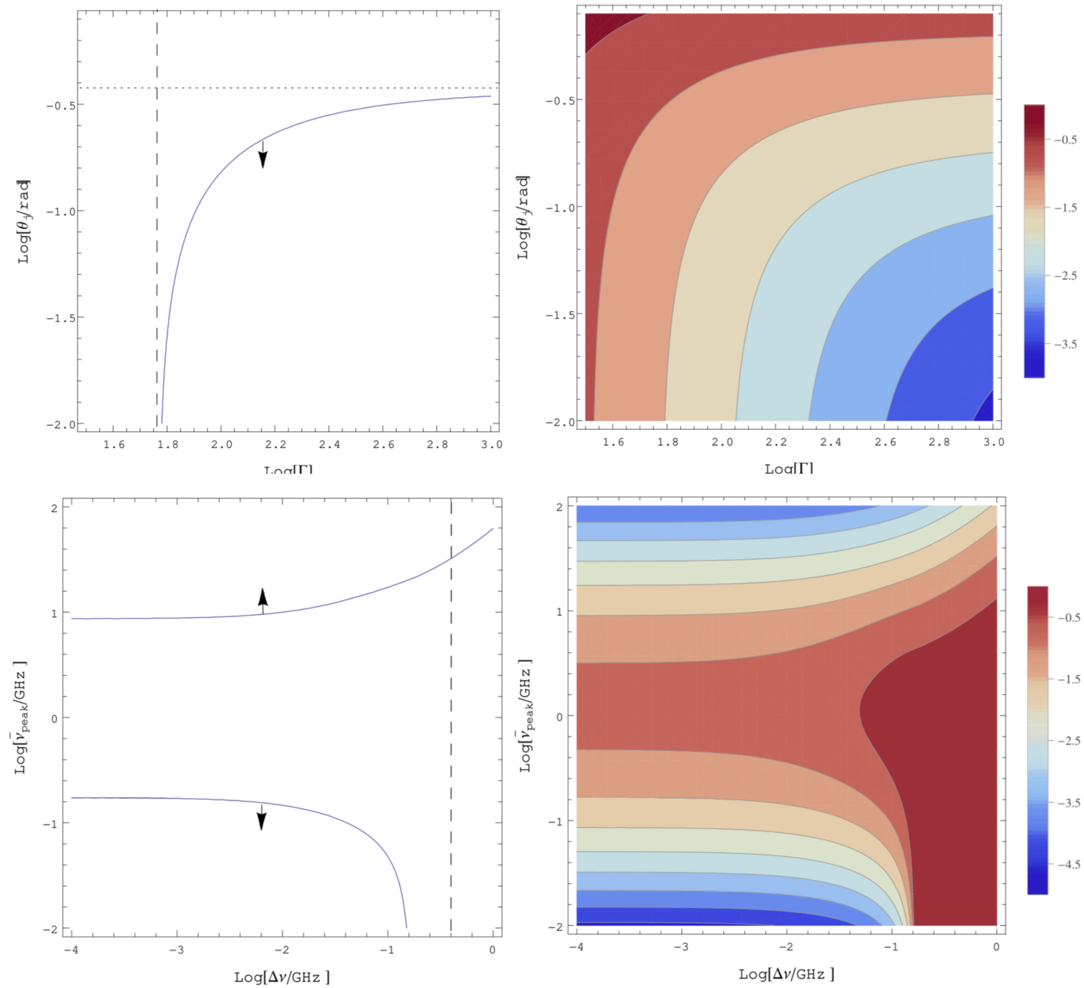
FRB-SGR burst non-associations

Lin et al. 2020, Nature, 587, 7832

Three possibilities:

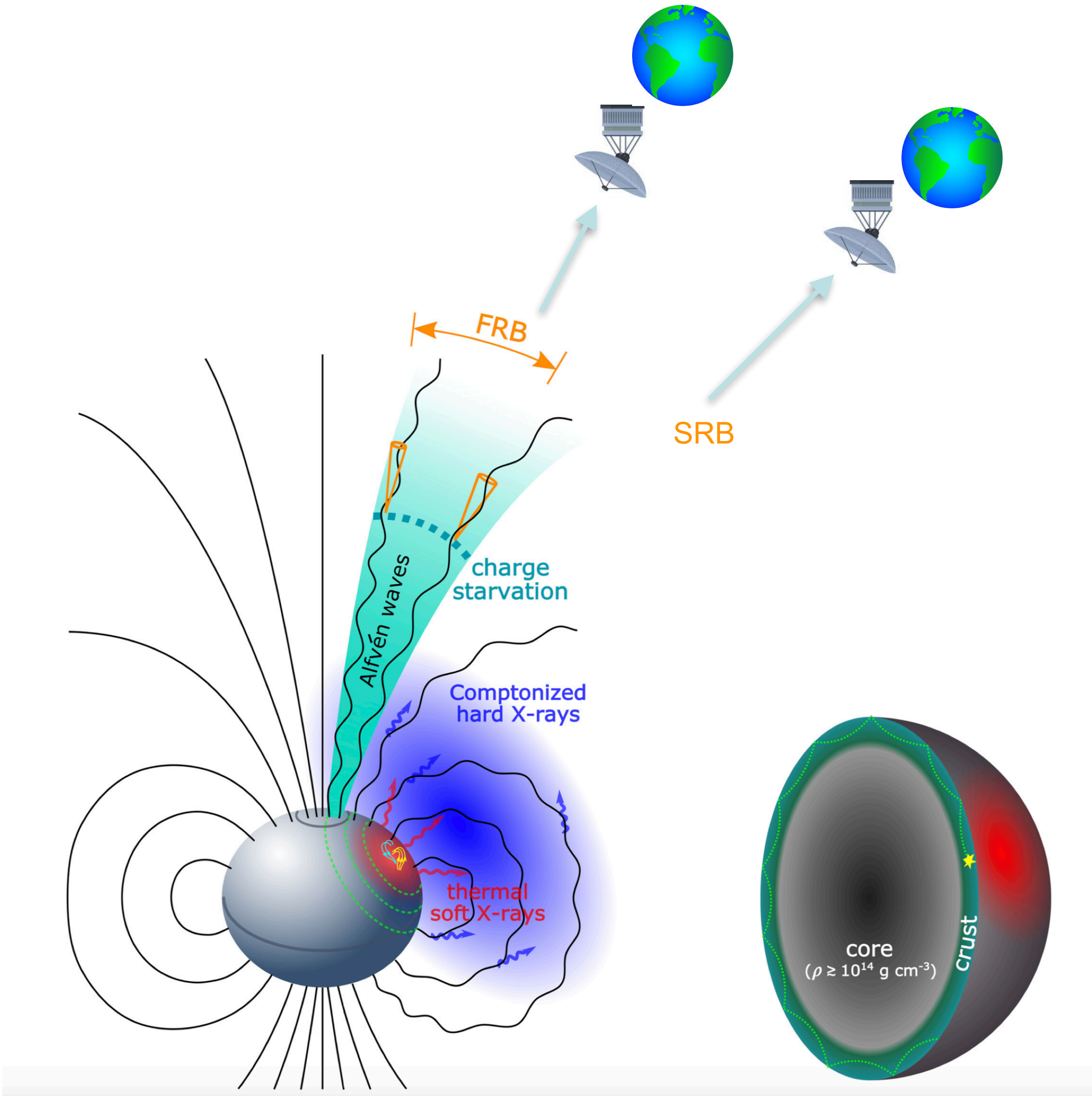
- Narrow beaming
- Narrow spectrum, wrong frequency
- Special SGR burst

  Insight/HXMT
  Integral
  Konus/Wind
  AGILE
  Nicer



Slow Radio Bursts (SRBs)

Zhang, 2021, ApJL, 907, L17



Slow Radio Bursts (SRBs)

Zhang, 2021, ApJL, 907, L17

Doppler factor & transformation:

$$\mathcal{D}(\theta) = \begin{cases} \mathcal{D}_{\rm on} = \dfrac{1}{\Gamma(1-\beta)} \simeq 2\Gamma, & \theta \leqslant \theta_j, \\ \mathcal{D}_{\rm off} = \dfrac{1}{\Gamma(1-\beta\cos(\Delta\theta))}, & \theta > \theta_j, \end{cases}$$

$$\begin{aligned} \nu &= \mathcal{D}\nu', \\ \Delta t &= \mathcal{D}^{-1}\Delta t', \\ L_\nu &= \mathcal{D}^3 L'_{\nu'}, \end{aligned}$$

$$\mathcal{R}_\mathcal{D} \equiv \frac{\mathcal{D}_{\rm on}}{\mathcal{D}_{\rm off}} > 1$$

Slow Radio Bursts (SRBs)

Zhang, 2021, ApJL, 907, L17

Closure relations:
relationships among specific fluence, width & observing frequency between FRBs and SRBs

Power-law spectrum:

$$L'_{\nu'}(\nu') = L'_{\nu'}(\nu'_0)\left(\frac{\nu'}{\nu'_0}\right)^{-\alpha}$$

$$\left(\frac{\mathcal{F}_\nu^{\rm SRB}}{\mathcal{F}_\nu^{\rm FRB}}\right)\left(\frac{w^{\rm SRB}}{w^{\rm FRB}}\right)^{2+\alpha}\left(\frac{\nu^{\rm SRB}}{\nu^{\rm FRB}}\right)^{\alpha} = 1,$$

Gaussian spectrum:

$$L'_{\nu'}(\nu') = L'_{\nu'}(\nu'_0)\exp\left[-\frac{1}{2}\left(\frac{\nu' - \nu'_0}{\delta\nu'}\right)^2\right],$$

$$\left(\frac{\mathcal{F}_\nu^{\rm SRB}}{\mathcal{F}_\nu^{\rm FRB}}\right)\left(\frac{w^{\rm SRB}}{w^{\rm FRB}}\right)^2 \times \exp\left[\frac{1}{2}\left(\frac{\nu^{\rm FRB}}{\delta\nu^{\rm FRB}}\right)^2\left(\frac{w^{\rm SRB}\nu^{\rm SRB}}{w^{\rm FRB}\nu^{\rm FRB}} - 1\right)^2\right] = 1.$$

Slow Radio Bursts (SRBs)

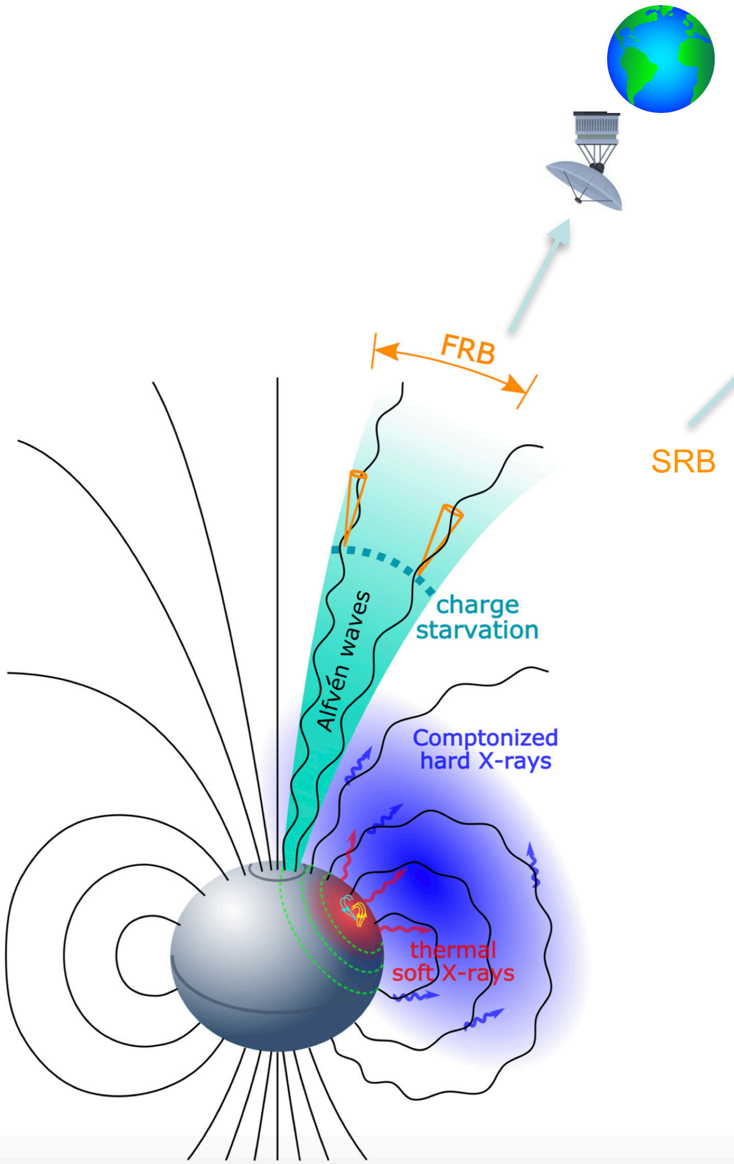
Zhang, 2021, ApJL, 907, L17

Example bursts from SGR J1935+2154:

	F_ν (Jy ms)	w (ms)	ν (GHz)	SRB of FRB 200428 ?	SRB of typical FRB ?
FRB 200428	1.5 M	0.61	1.52		
typical FRB	100 M	1	1.2		
BSA/LPI burst	308	340	0.111	Yes (PL)	Yes (PL or Gaussian)
FAST weak burst (Zhang et al.)	0.06	1.97	1.25	Yes (Gaussian)	Yes (Gaussian)
Wb B1 (Kirsten et al.)	112	0.427	1.324	No	No
Wb B2 (Kirsten et al.)	24	0.219	1.324	No	No

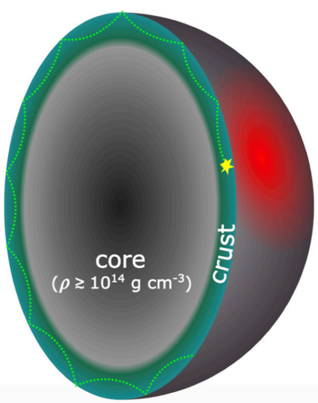
Slow Radio Bursts (SRBs)

Zhang, 2021, ApJL, 907, L17



$$\Delta\theta_{\max} \simeq \frac{1}{\Gamma}\left[\left(\frac{\mathcal{F}_\nu^{\rm FRB}}{\mathcal{F}_{\nu,\rm th}}\right)^{1/(2+\alpha)} - 1\right]^{1/2} \simeq \frac{1}{\Gamma}\left(\frac{\mathcal{F}_\nu^{\rm FRB}}{\mathcal{F}_{\nu,\rm th}}\right)^{1/(4+2\alpha)} = \frac{\xi}{\Gamma} \gg \frac{1}{\Gamma},$$

$$\mathcal{R}_{\Delta\Omega} \equiv \frac{\Delta\Omega^{\rm SRB}}{\Delta\Omega^{\rm FRB}} \simeq \frac{\pi[(\theta_j + \Delta\theta_{\max})^2 - \theta_j^2]}{\pi\theta_j^2} = \left(\frac{\Delta\theta_{\max}}{\theta_j}\right)^2 + 2\left(\frac{\Delta\theta_{\max}}{\theta_j}\right) = \left(\frac{\xi}{\Gamma\theta_j}\right)^2 + \left(\frac{2\xi}{\Gamma\theta_j}\right).$$



$\theta_j \gg \xi/\Gamma$ less SRBs

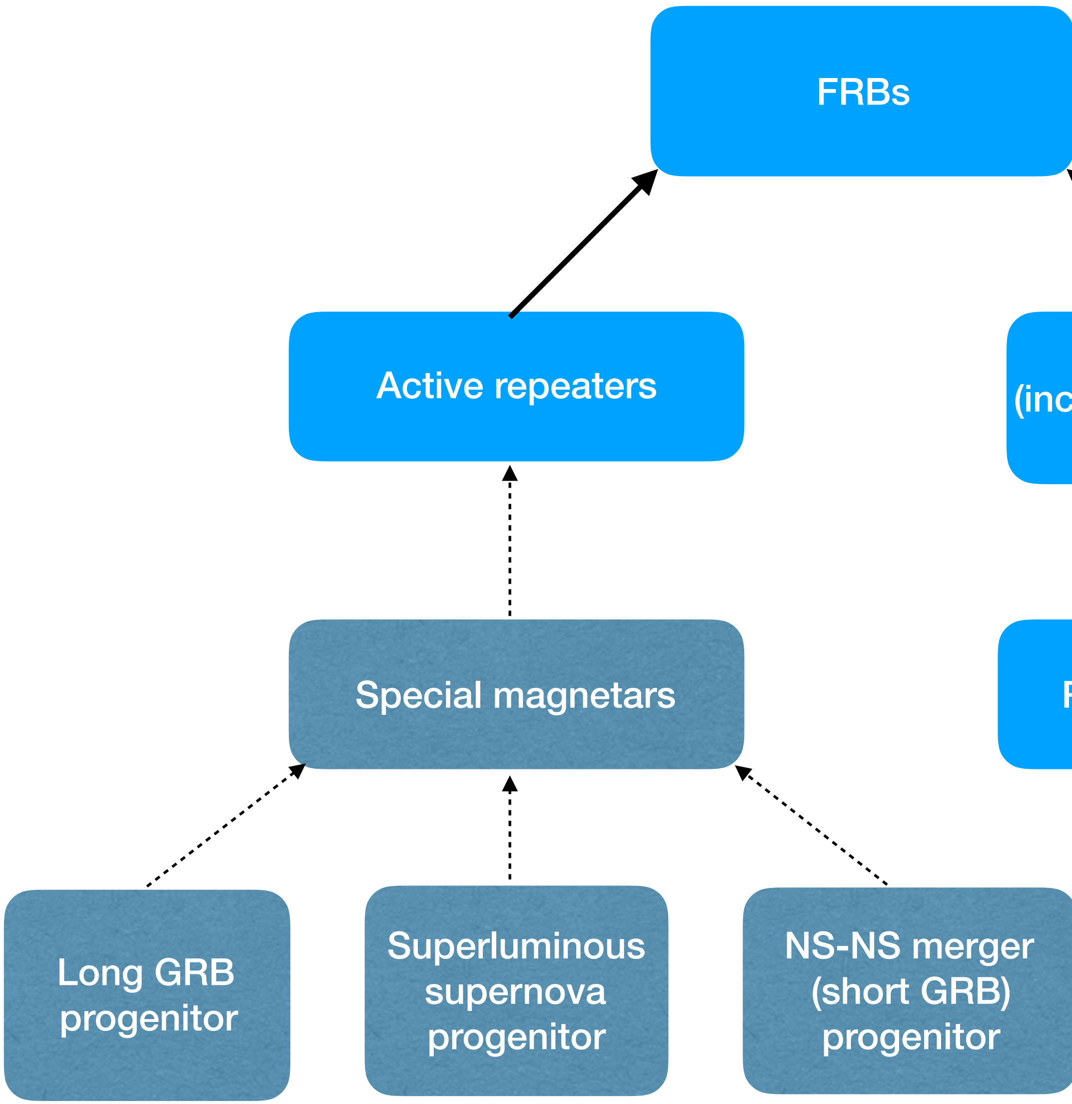
$\theta_j \ll \xi/\Gamma$ more SRBs

None detection of abundant SRBs disfavor the beaming hypothesis

Open Questions

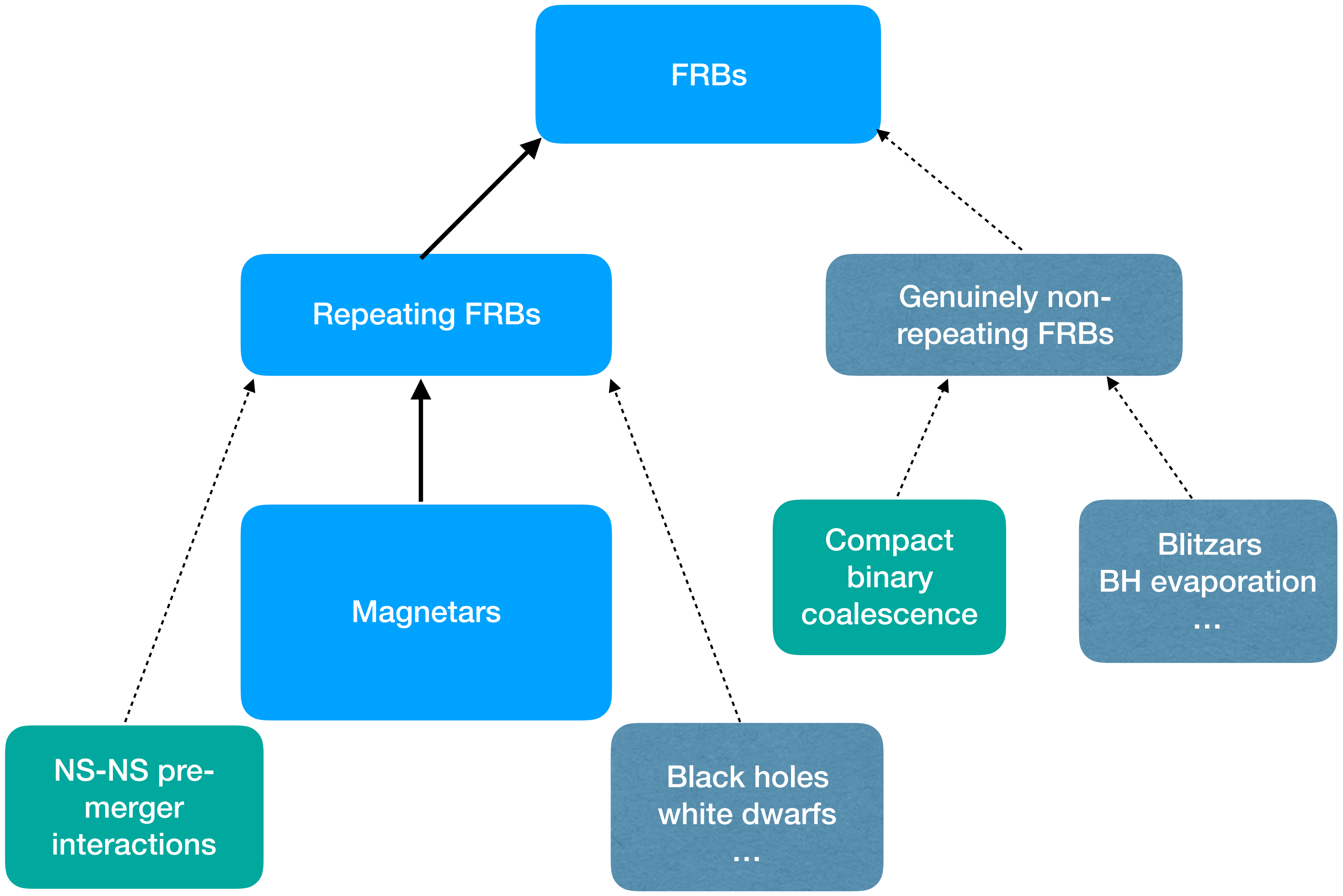
- Where is FRB emission generated (magnetosphere or shock)? What is the coherent mechanism?
- Are there engines other than magnetars that power FRBs? If so, what could be the plausible sources?
- Are there genuinely non-repeating FRBs? If so, what could be the plausible sources?

The Most Conservative Picture: A Unified Picture for FRBs within the Framework of Magnetar Engines



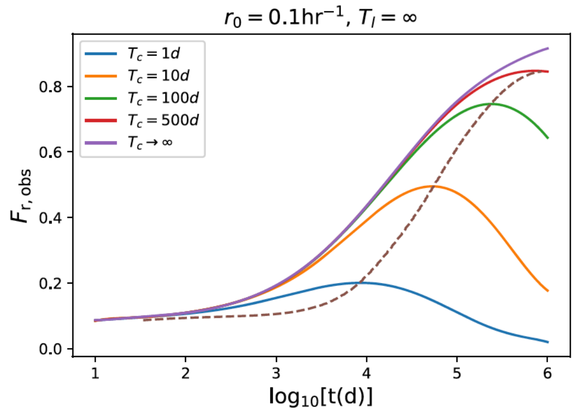
see also
Lu, Kumar & Zhang (2020)
Wenbin Lu's talk

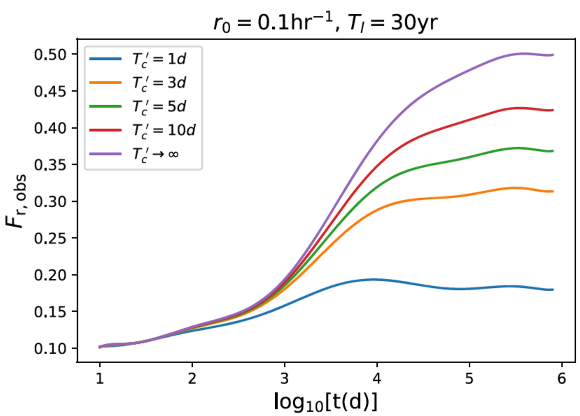
The Most Speculative Picture for FRBs

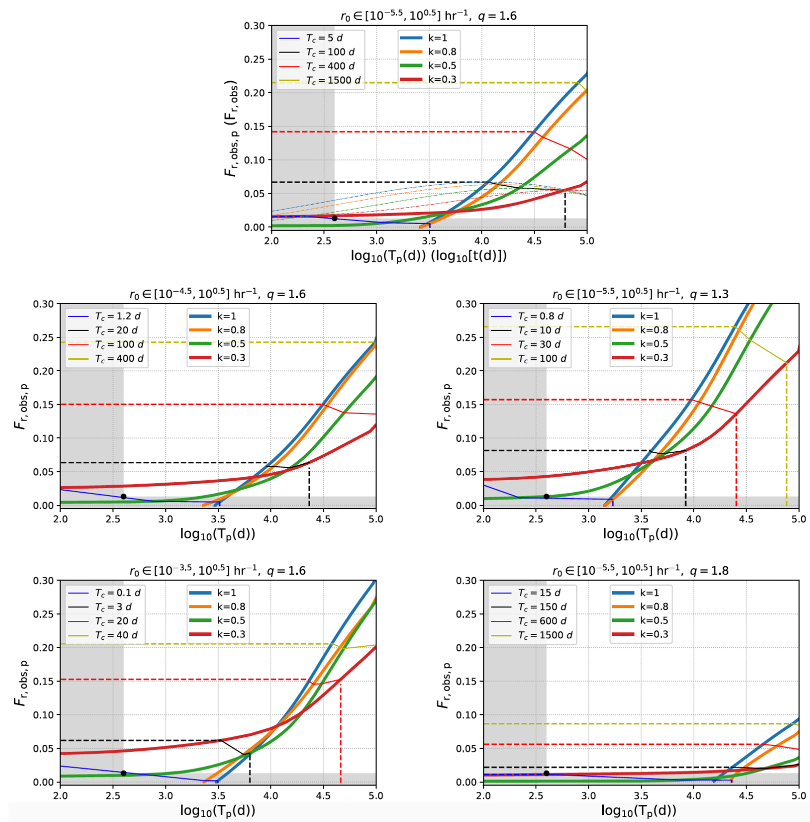


Are there genuinely non-repeating FRBs?

Ai, Gao & Zhang, 2021, ApJ, 906, L5







$$T_c \equiv \frac{N_r}{\dot{N}_n},$$

If there is an observed maximum repeater fraction, then likely there are!

CHIME: $F_{\mathrm{r,obs}} \sim 0.013$ at $t \sim 400$ d

Summary

- Coherent radio emission models
  - Location: magnetosphere vs. shocks
  - Coherent mechanism: bunched curvature radiation vs. plasma instabilities (long way to go)
- Source models
  - Most conservative: magnetars do it all
  - Most speculative: repeaters and non-repeaters; multiple progenitors in both categories; GW connection
- Prospects
  - Observations:
    - Galactic FRBs hold the key to identify sources
    - Searching for SRBs from magnetars may offer clue regarding beaming
    - Multi-messenger observations/data analyses hold the key to identify/eliminate models
  - Theory:
    - Debate on coherent mechanism will continue (cf. pulsar field)
    - Magnetar physics: physics of other systems (with observational breakthroughs made in the future)