On the Physical Origin(s) of Fast Radio Bursts

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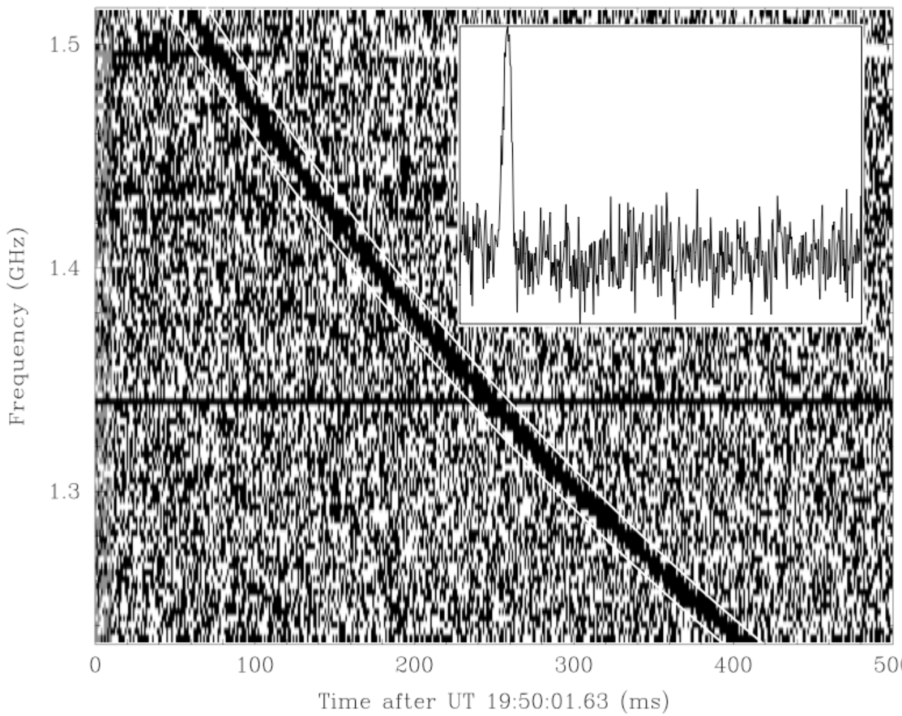
Fast Radio Bursts (FRBs)



Lorimer et al. (2007)

First event: FRB 010125

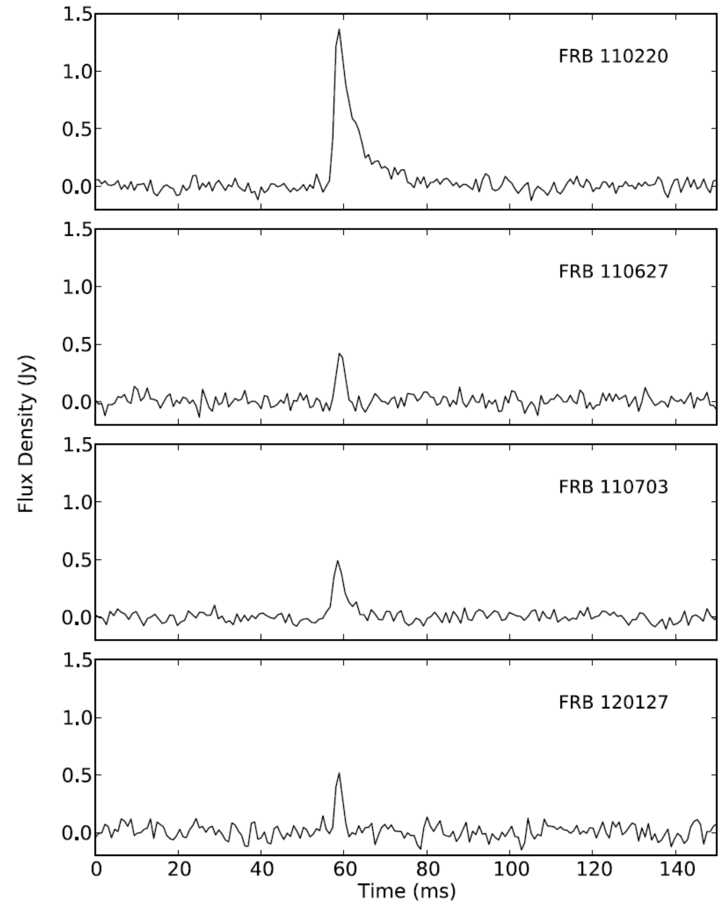


Fig. 1. The frequency-integrated flux densities for the four FRBs. The time resolutions match the level of dispersive smearing in the central frequency channel (0.8, 0.6, 0.9, and 0.5 milliseconds, respectively).

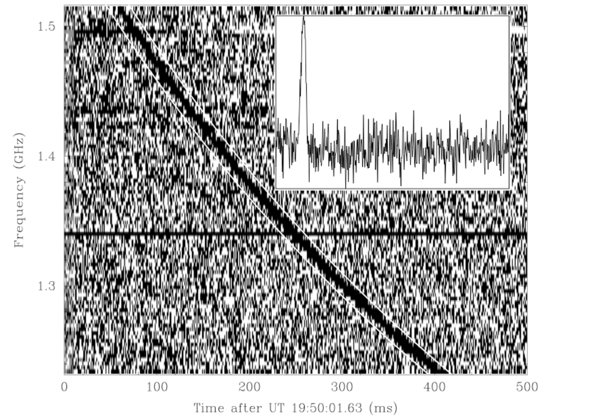
Thornton, et al., 2013, Science

Observations

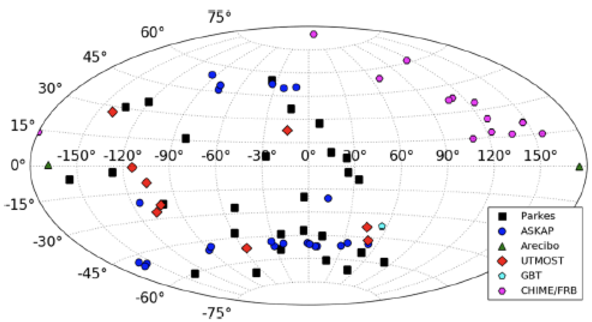
Adam Deller’s talk

FRBs: Observational properties

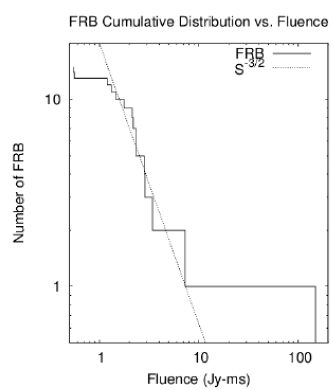
Petroff, Hessels & Lorimer, 2019, A&AR
Cordes & Chatterjee, 2019, ARAA
Katz, 2016, 2018; Popov et al. 2018

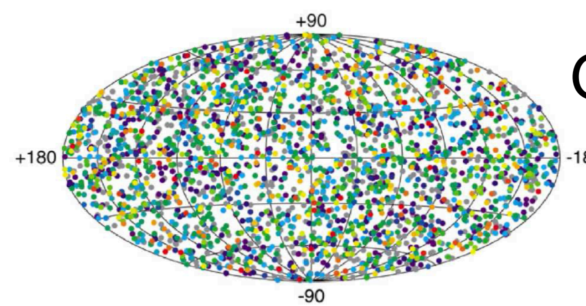


- Short duration: milli-seconds (compact objects)
  $$l_{\rm eng} \sim cw = (3\times10^{7})\ {\rm cm}\ (w/{\rm ms})$$
- High Galactic latitudes (extragalactic), isotropic (cosmological), non-Euclidean
- High rate: $\sim 10^4\ {\rm day}^{-1}$ all sky, $3.5^{+5.7}_{-2.4}\times10^4\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$ above $10^{42}\ {\rm erg\ s}^{-1}$

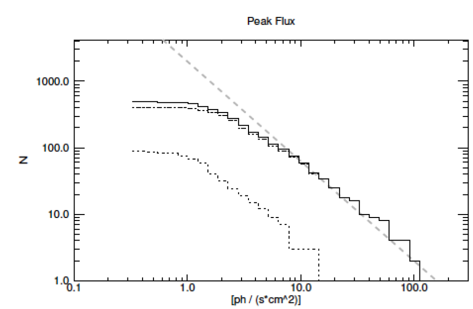


FRBs



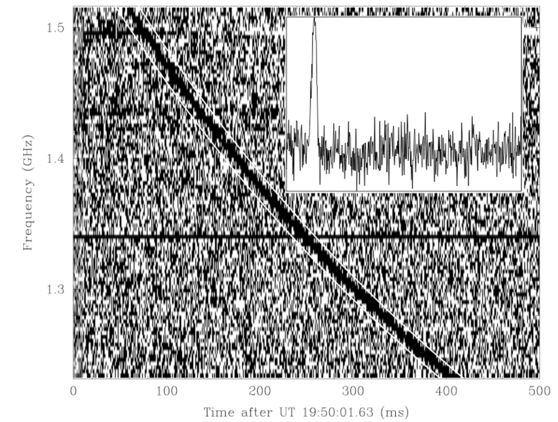


GRBs



FRBs: Observational properties

- High dispersion measure (DM)
- Redshift (~ 0.1 - 3)
  - Isotropic peak luminosity: 10^{42} -10^{44} erg/s
  - Isotropic emission energy: 10^{39}-10^{42} erg



$$\mathrm{DM} \equiv \int_0^L n_e dl \equiv \langle n_e \rangle L$$

$$t_2 - t_1 = 4.15 \text{ ms DM} \left[\left(\frac{\nu_1}{1 \text{ GHz}} \right)^{-2} - \left(\frac{\nu_2}{1 \text{ GHz}} \right)^{-2} \right]$$

$$\mathrm{DM_{obs}} = \mathrm{DM_{MW}} + \mathrm{DM_{HG}} + \mathrm{DM_{IGM}}$$

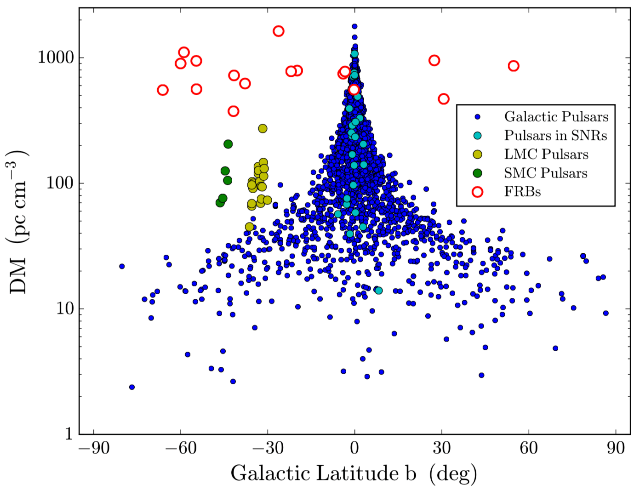
$$\mathrm{DM_E} \equiv \mathrm{DM_{obs}} - \mathrm{DM_{MW}} = \mathrm{DM_{IGM}} + \mathrm{DM_{HG}}$$

$$\mathrm{DM_{IGM}} = \frac{3cH_0\Omega_b f_{\mathrm{IGM}}}{8\pi G m_p} \int_0^z \frac{\chi(z)(1+z)dz}{[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}}$$

$$\chi(z) = \frac{3}{4} y_1 \chi_{e,\mathrm{H}}(z) + \frac{1}{8} y_2 \chi_{e,\mathrm{He}}(z)$$

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

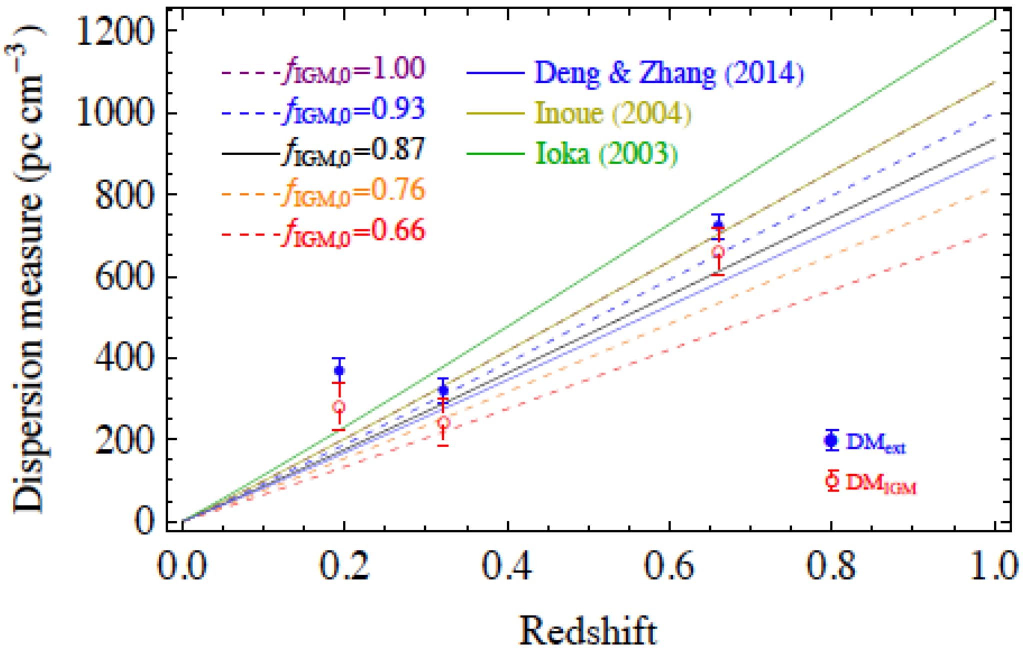
Zhang, 2018, ApJL, 867, L21



Cordes +, 2016, ApJ

FRBs: Observational properties

- True redshifts for three localized FRBs:
  - FRB 121102: z ~ 0.19 (Tendulkar et al. 2017)
  - FRB 180924: z ~ 0.32 (Bannister et al. 2019)
  - FRB 190523: z ~ 0.66 (Ravi et al. 2019)



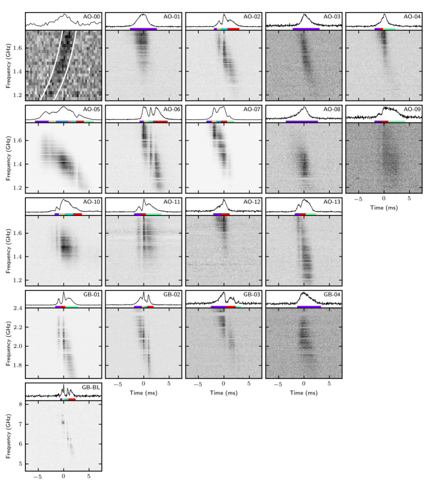
$$z \sim \mathrm{DM_{IGM}}/855\mathrm{pc\ cm^{-3}}$$

Credit: Z. Li

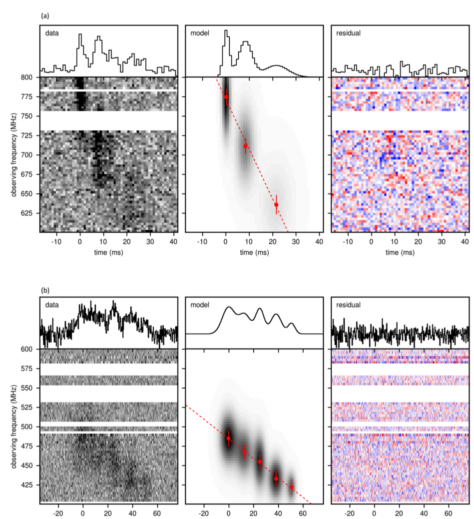
See also Adam Deller’s talk
Ken Nagamine’s poster (theoretical)

FRBs: Observational properties

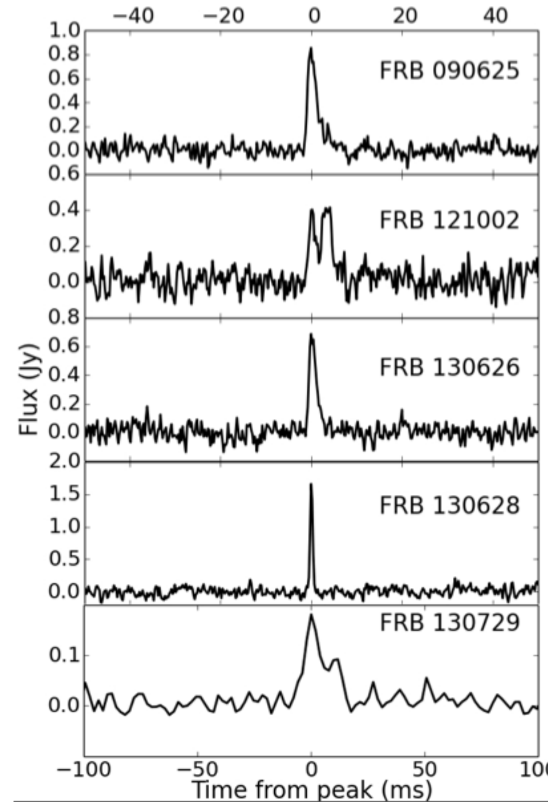
- High brightness temperature (coherent emission)
- $$T_b \simeq \frac{S_{\nu,p} D_A^2}{2\pi k(\nu w)^2} = (1.2 \times 10^{36}\ \mathrm{K}) \left(\frac{D_A}{10^{28}\ \mathrm{cm}}\right)^2 \frac{S_{\nu,p}}{\mathrm{Jy}} \left(\frac{\nu}{\mathrm{GHz}}\right)^{-2} \left(\frac{w}{\mathrm{ms}}\right)^{-2}$$
- Typical frequency (400 MHz to 8 GHz)
- Spectral index: -10 top +14 (FRB 121102)
- Internal structure & scattering tail
- Frequency downdrifting



FRB 121102



FRB 180814.J0422+73

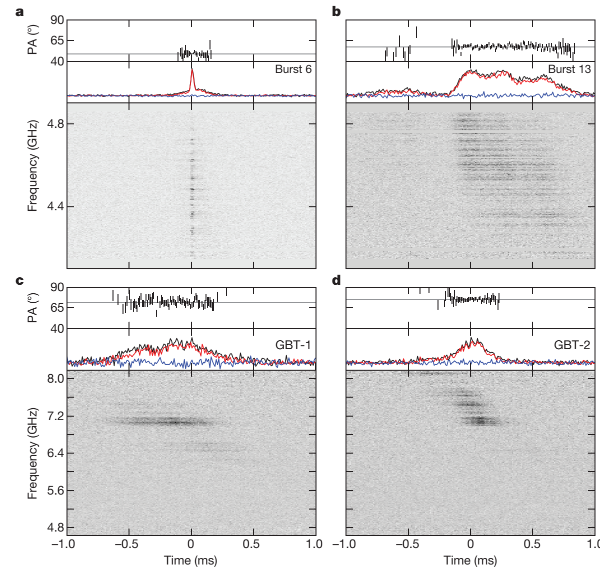


Champion et al. 2016

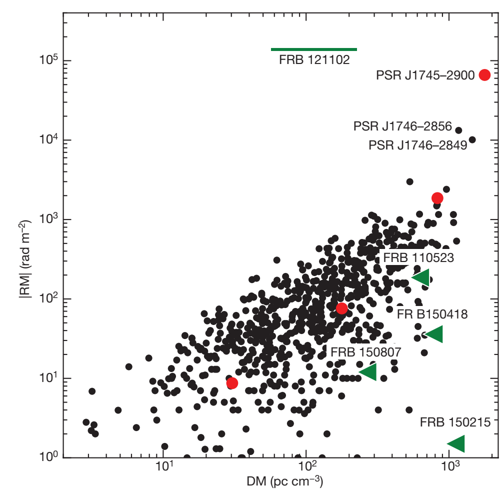
Hessels et al. 2019
Amiri et al. 2019

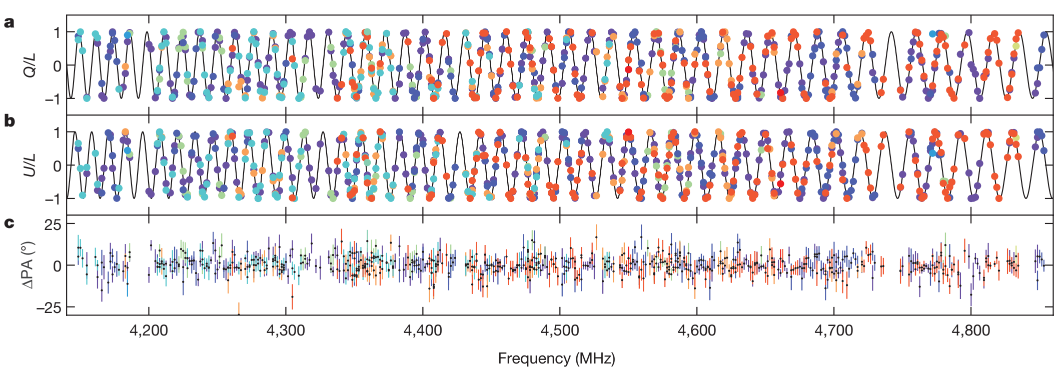
FRBs: Observational properties

- Mixed polarization properties:
- ~100% linear polarization for some, low polarization degree for some others
- Some have circular polarization, some not
- Constant polarization angle in each burst (FRB 121102)
- large and variable rotation measure (RM) for FRB 121102, regular or low RM for some others



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



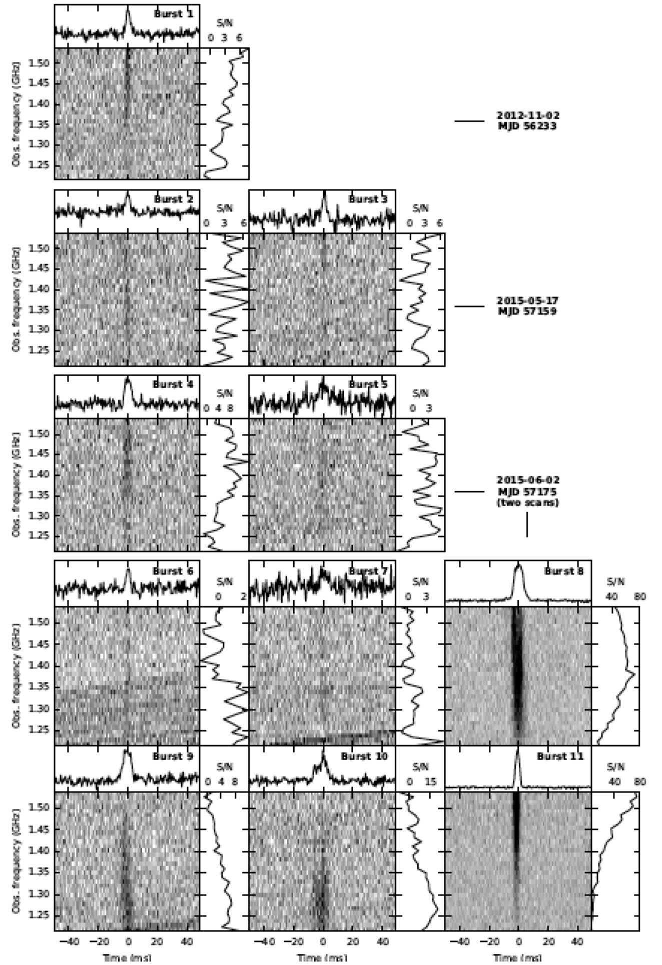


Michilli et al. 2017

Repetition:
At least a fraction of FRB sources repeat

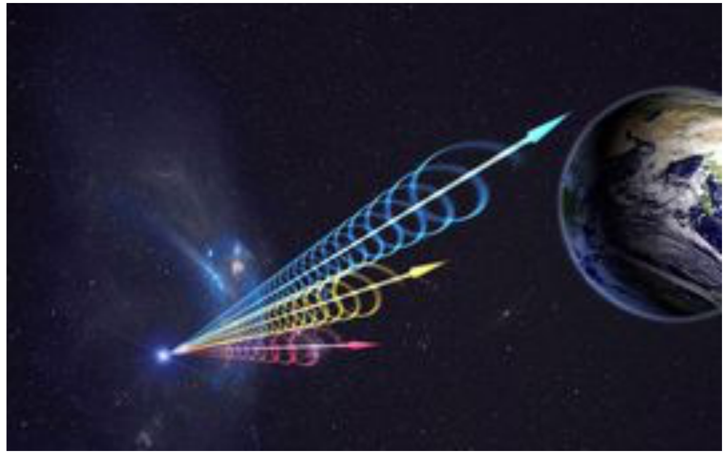
- 2016, First repeater: FRB 121102 (Arecibo)
- 2018, Second repeater: FRB 180814.J0422+73 (CHIME)
- 2019, (at least) 8 new repeaters from CHIME
- 2019, ASKAP bright burst (FRB 171019) followed by faint bursts detected by GBT
- 2019, FAST repeater(s)

- Repeatings FRBs are no longer news



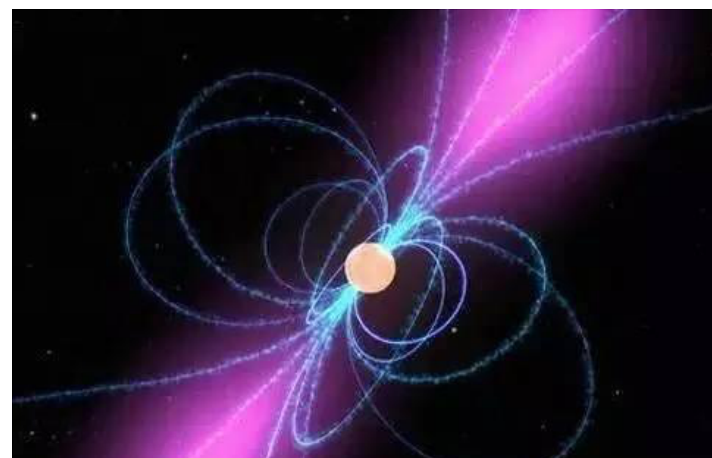
Spitler et al. 2016

Relatives of FRBs



FRBs

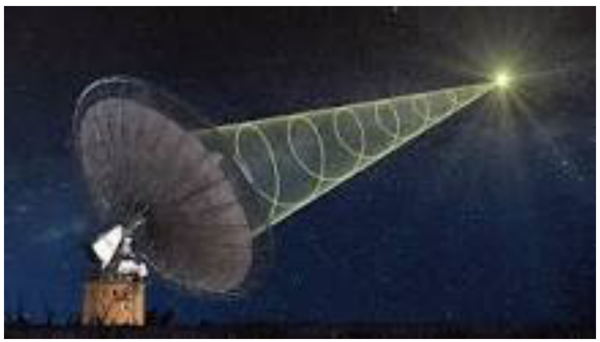
GRBs



radio pulsars

FRBs vs. GRBs

- Physical connection??
- Cultural connection between the two fields



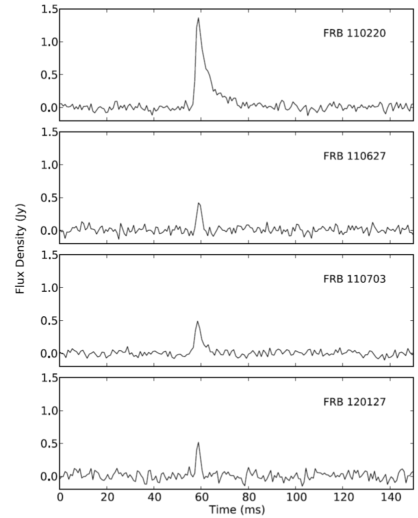
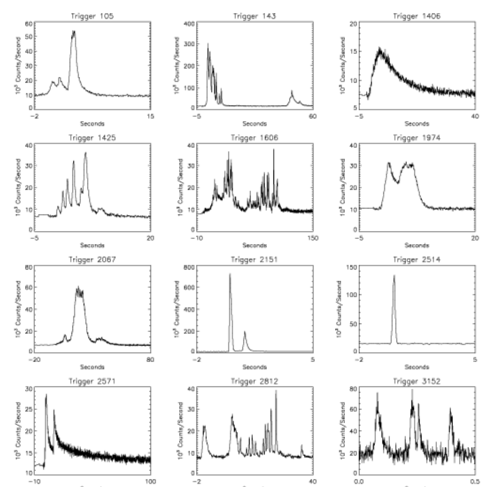


Fig. 1. The frequency-integrated flux densities for the four FRBs. The time resolutions match the level of dispersive smearing in the central frequency channel (0.8, 0.6, 0.9, and 0.5 milliseconds, respectively).



FRBs vs. GRBs

	GRBs	FRBs
Step one: Are they astrophysical?	1967 – 1973	2007 – 2015
Step two: Where are they (distance)?	1973 – 1997 – 2004 (Afterglow counterpart, host galaxy)	2016 (VLBI localization of first repeater, direct localizations with ASKAP, host galaxy)
Step three: What make them?	1998 – 2017 (SN Ic, GW)	??? (young magnetars? pulsars? massive black holes? …)

Observationally driven
Healthy dialog between observers and theorists

What may make them?

(An incomplete list, no particular order)
Platts et al. (2018) for full list

Repeating:

- Supergiant radio pulses (Cordes & Wasserman 2015; Connor et al. 2015; Pen & Connor 2015)
- Magnetar giant flare radio bursts (Popov et al. 2007, 2013; Kulkarni et al. 2014; Katz 2015)
- NS-Asteroid collisions (Geng & Huang 2015; Dai et al. 2016)
- WD accretion (Gu et al. 2016)
- Flaring stars (Loeb et al. 2013; Maoz et al. 2015)
- AGN induced plasma instability (Romero et al. 2016)
- Young magnetar powered bursts (Murase et al. 2016; Metzger et al. 2017)
- Cosmic combs (Zhang 2017)
- Bremsstrahlung / synchrotron / curvature maser (Romero et al. 2016; Ghisellini 2017; Waxman 2017; Beloborodov 2017)
- Instability within pulsar magnetosphere (Philippov, Katz)

Catastrophic:

- Collapses of supra-massive neutron stars to black holes (thousands to million years later after birth, or in a small fraction hundreds/thousands of seconds after birth), ejecting "magnetic hair" (Falcke & Rezzolla 2013; Zhang 2014)
- Magnetospheric activity after NS-NS mergers (Totani 2013)
- Unipolar inductor in NS-NS mergers (Piro 2012; Wang et al. 2016)
- Mergers of binary white dwarfs (Kashiyama et al. 2013)
- BH-BH mergers (charged) (Zhang 2016; Liebling & Palenzuela 2016)
- Kerr-Newman BH instability (Liu et al. 2016)
- Cosmic sparks from superconducting strings (Vachaspati 2008; Yu et al. 2014)
- Evaporation of primordial black holes (Rees 1977; Keane et al. 2012)
- White holes (Barrau et al. 2014; Haggard)
- Axion miniclusters, axion stars (Tkachev 2015; Iwazaki 2015)
- Quark Nova (Shand et al. 2015)
- Dark matter-induced collapse of NSs (Fuller & Ott 2015)
- Higgs portals to pulsar collapse (Bramante & Elahi 2015)
- charged CBC in general, plunging BH-NS mergers (Zhang 2019)
- ……

Lessons from GRBs

- Discovered in late 1960s
- More than 100 models
- "The only feature that all but one (and perhaps all) of the very many proposed models have in common is that they will not be the explanation of gamma-ray bursts"
  - Malvin Ruderman (1975)
- The same may be stated for FRB models — right now > 50 models

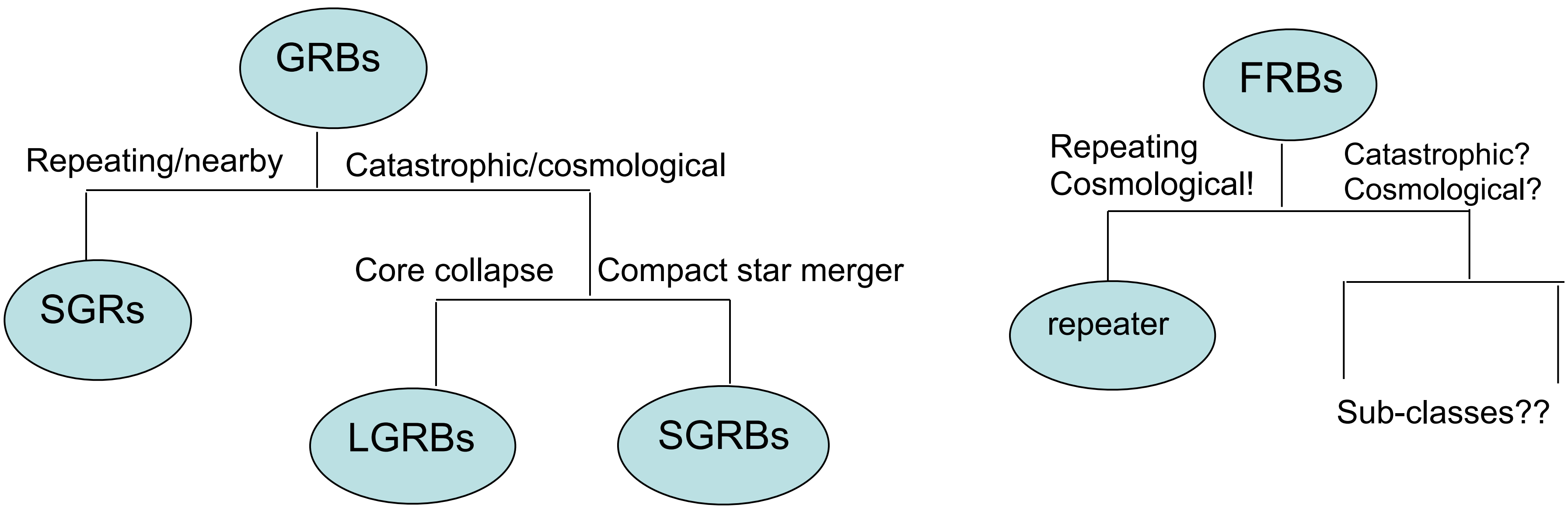
Table 1

#	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
1.	Colgate	1968	CJPhys, 46, S476	ST		COS	SN shocks stellar surface in distant galaxy
2.	Colgate	1974	ApJ, 187, 333	ST		COS	Type II SN shock brem, inv Comp scat at stellar surface
3.	Stecker et al.	1973	Nature, 245, PS70	ST		DISK	Stellar superflare from nearby star
4.	Stecker et al.	1973	Nature, 245, PS70	WD		DISK	Superflare from nearby WD
5.	Harwit et al.	1973	ApJ, 186, L37	NS	COM	DISK	Relic comet perturbed to collide with old galactic NS
6.	Lamb et al.	1973	Nature, 246, PS52	WD	ST	DISK	Accretion onto WD from flare in companion
7.	Lamb et al.	1973	Nature, 246, PS52	NS	ST	DISK	Accretion onto NS from flare in companion
8.	Lamb et al.	1973	Nature, 246, PS52	BH	ST	DISK	Accretion onto BH from flare in companion
9.	Zwicky	1974	Ap & SS, 28, 111	NS		HALO	NS chunk contained by external pressure escapes, explodes
10.	Grindlay et al.	1974	ApJ, 187, L93	DG		SOL	Relativistic iron dust grain up-scatters solar radiation
11.	Brecher et al.	1974	ApJ, 187, L97	ST		DISK	Directed stellar flare on nearby star
12.	Schlovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Schlovskii	1974	SovAstron, 18, 390	NS	COM	DISK	Comet from system's cloud strikes NS
14.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST		COS	Absorption of neutrino emission from SN in stellar envelope
15.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST	SN	COS	Thermal emission when small star heated by SN shock wave
16.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	NS		COS	Ejected matter from NS explodes
17.	Pacini et al.	1974	Nature, 251, 399	NS		DISK	NS crustal starquake glitch; should time coincide with GRB
18.	Narlikar et al.	1974	Nature, 251, 590	WH		COS	White hole emits spectrum that softens with time
19.	Tsygan	1975	A&A, 44, 21	NS		HALO	NS corequake excites vibrations, changing E & B fields
20.	Chanmugam	1974	ApJ, 193, L75	WD		DISK	Convection inside WD with high B field produces flare
21.	Prilutski et al.	1975	Ap & SS, 34, 395	AGN	ST	COS	Collapse of supermassive body in nucleus of active galaxy
22.	Narlikar et al.	1975	Ap & SS, 35, 321	WH		COS	WH excites synchrotron emission, inverse Compton scattering
23.	Piran et al.	1975	Nature, 256, 112	BH		DISK	Inv Comp scat deep in ergosphere of fast rotating, accreting BH
24.	Fabian et al.	1976	Ap & SS, 42, 77	NS		DISK	NS crustquake shocks NS surface
25.	Chanmugam	1976	Ap & SS, 42, 83	WD		DISK	Magnetic WD suffers MHD instabilities, flares
26.	Mullan	1976	ApJ, 208, 199	WD		DISK	Thermal radiation from flare near magnetic WD
27.	Woosley et al.	1976	Nature, 263, 101	NS		DISK	Carbon detonation from accreted matter onto NS
28.	Lamb et al.	1977	ApJ, 217, 197	NS		DISK	Mag grating of accret disk around NS causes sudden accretion
29.	Piran et al.	1977	ApJ, 214, 268	BH		DISK	Instability in accretion onto rapidly rotating BH
30.	Dasgupta	1979	Ap & SS, 63, 517	DG		SOL	Charged intergal rel dust grain enters sol sys, breaks up
31.	Tsygan	1980	A&A, 87, 224	WD		DISK	WD surface nuclear burst causes chromospheric flares
32.	Tsygan	1980	A&A, 87, 224	NS		DISK	NS surface nuclear burst causes chromospheric flares
33.	Ramaty et al.	1981	Ap & SS, 75, 193	NS		DISK	NS vibrations heat atm to pair produce, annihilate, synch cool
34.	Newman et al.	1980	ApJ, 242, 319	NS	AST	DISK	Asteroid from interstellar medium hits NS
35.	Ramaty et al.	1980	Nature, 287, 122	NS		HALO	NS core quake caused by phase transition, vibrations
36.	Howard et al.	1981	ApJ, 249, 302	NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp
37.	Mitrofanov et al.	1981	Ap & SS, 77, 469	NS		DISK	Helium flash cooled by MHD waves in NS outer layers
38.	Colgate et al.	1981	ApJ, 248, 771	NS	AST	DISK	Asteroid hits NS, tidally disrupts, heated, expelled along B lines
39.	van Buren	1981	ApJ, 249, 297	NS	AST	DISK	Asteroid enters NS B field, dragged to surface collision
40.	Kuznetsov	1982	CosRes, 20, 72	MG		SOL	Magnetic reconnection at heliopause
41.	Katz	1982	ApJ, 260, 371	NS		DISK	NS flares from pair plasma confined in NS magnetosphere
42.	Woosley et al.	1982	ApJ, 258, 716	NS		DISK	Magnetic reconnection after NS surface He flash
43.	Fryxell et al.	1982	ApJ, 258, 733	NS		DISK	He fusion runaway on NS B-pole helium lake
44.	Hameury et al.	1982	A&A, 111, 242	NS		DISK	e- capture triggers H flash triggers He flash on NS surface
45.	Mitrofanov et al	1982	MNRAS, 200, 1033	NS		DISK	B induced cyclo res in rad absorp giving rel e-s, inv C scat
46.	Fenimore et al.	1982	Nature, 297, 665	NS		DISK	BB X-rays inv Comp scat by hotter overlying plasma
47.	Lipunov et al.	1982	Ap & SS, 85, 459	NS	ISM	DISK	ISM matter accum at NS magnetopause then suddenly accretes
48.	Baan	1982	ApJ, 261, L71	WD		HALO	Nonexplosive collapse of WD into rotating, cooling NS
49.	Ventura et al.	1983	Nature, 301, 491	NS	ST	DISK	NS accretion from low mass binary companion
50.	Bisnovatyi- et al.	1983	Ap & SS, 89, 447	NS		DISK	Neutron rich elements to NS surface with quake, undergo fission
51.	Bisnovatyi- et al.	1984	SovAstron, 28, 62	NS		DISK	Thermonuclear explosion beneath NS surface
52.	Ellison et al.	1983	A&A, 128, 102	NS		HALO	NS corequake + uneven heating yield SGR pulsations
53.	Hameury et al.	1983	A&A, 128, 369	NS		DISK	B field contains matter on NS cap allowing fusion
54.	Bonazzola et al.	1984	A&A, 136, 89	NS		DISK	NS surface nuc explosion causes small scale B reconnection

Nemiroff, 1994, Comments on Astrophysics, 17, 189

118 models

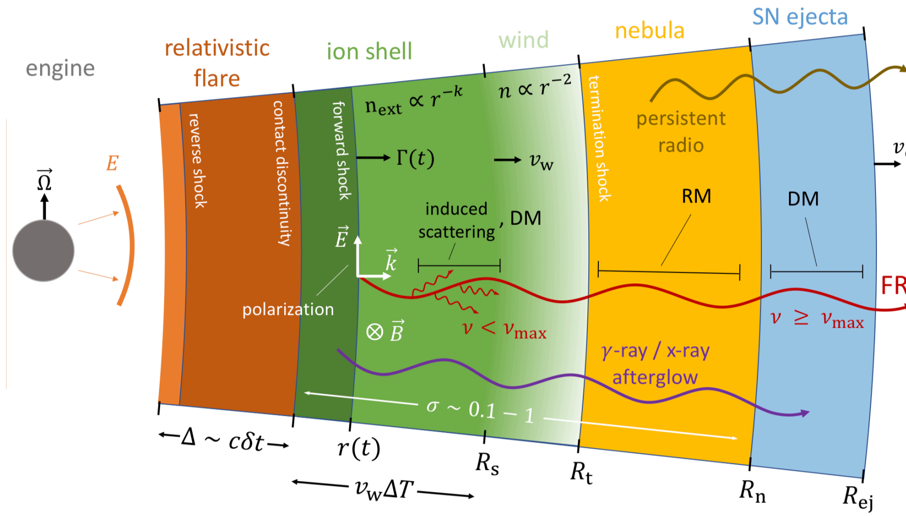
Multiple progenitor systems?



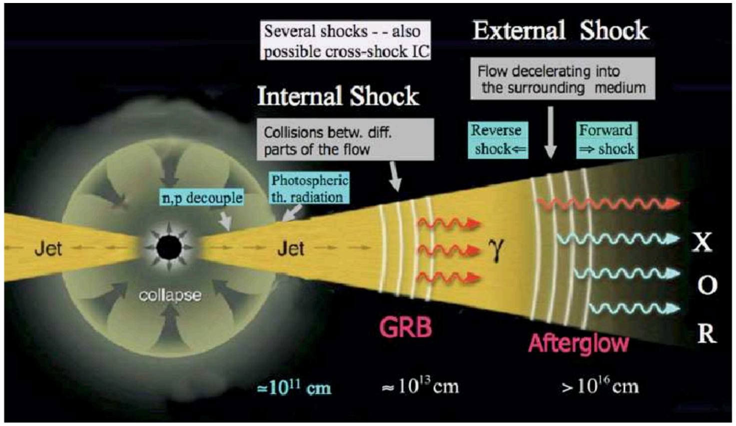
Known observationally-defined transients have multiple progenitors (SNe & GRBs)

Lessons from GRBs

- Relativistic outflow
- Internal & external shocks
- Some ideas (not observationally confirmed) on coherent radio emission
  - Synchrotron masers

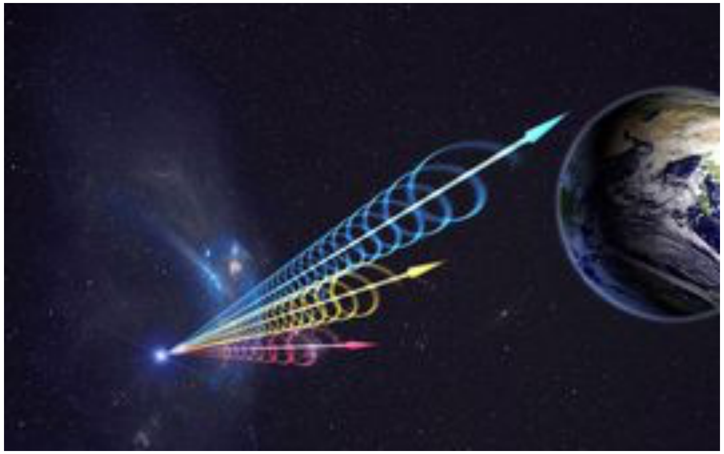


Metzger et al. 2019



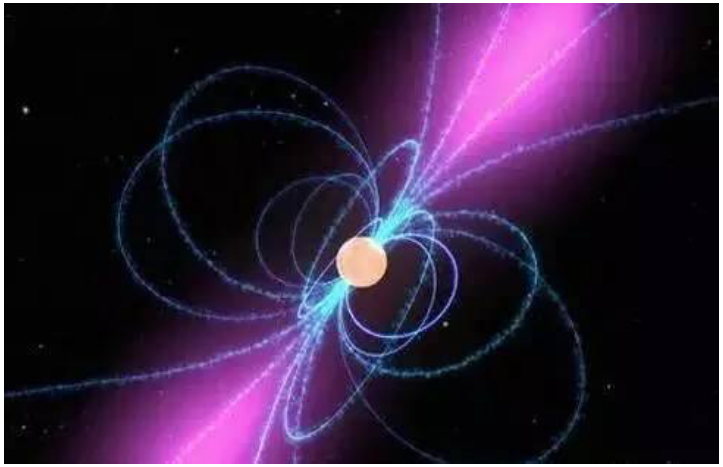
Meszaros 2001

Relatives of FRBs



FRBs

GRBs

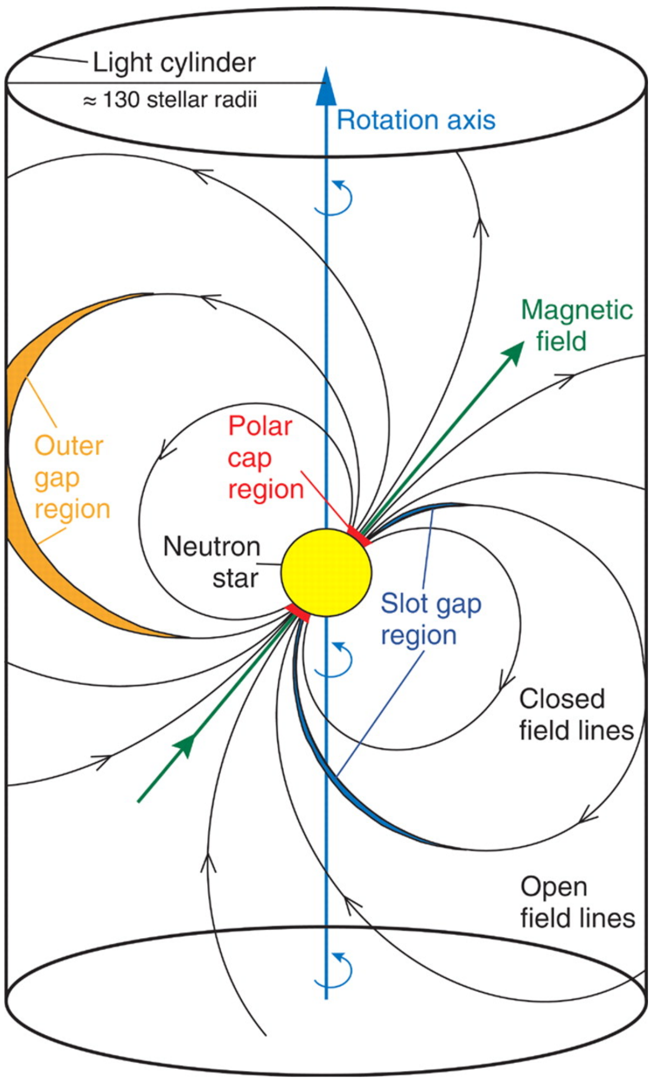


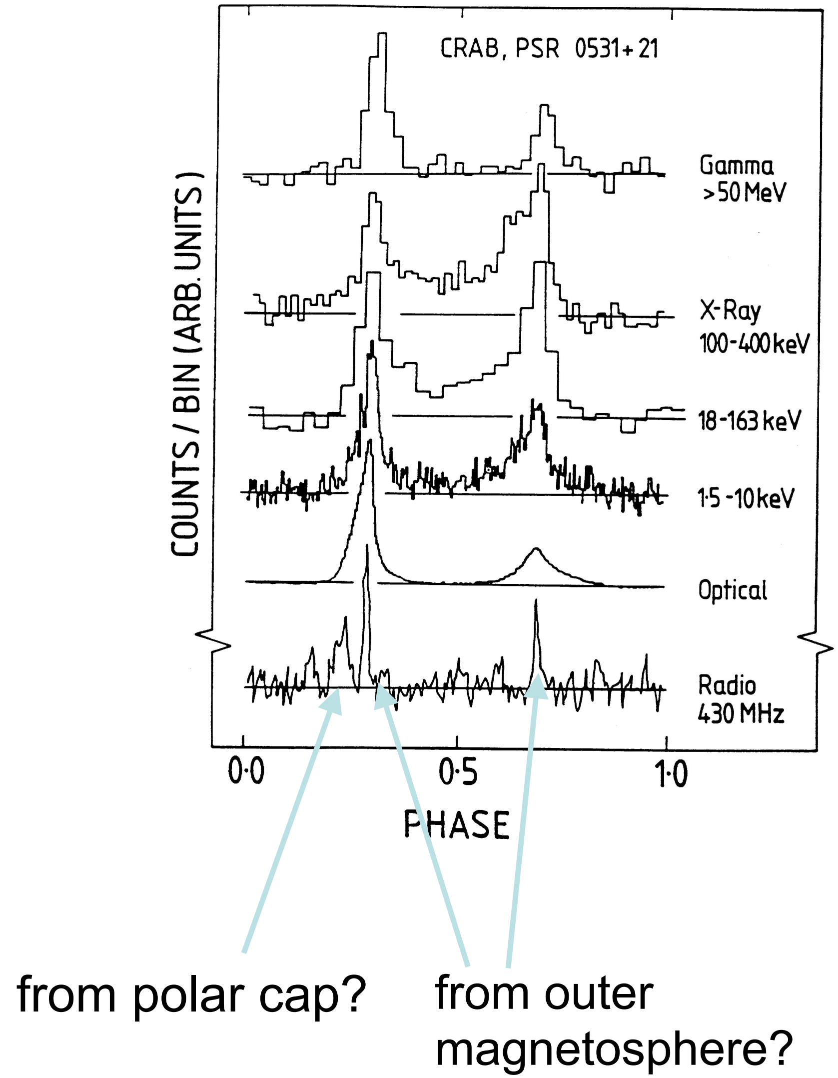
radio pulsars

Lessons from radio pulsars

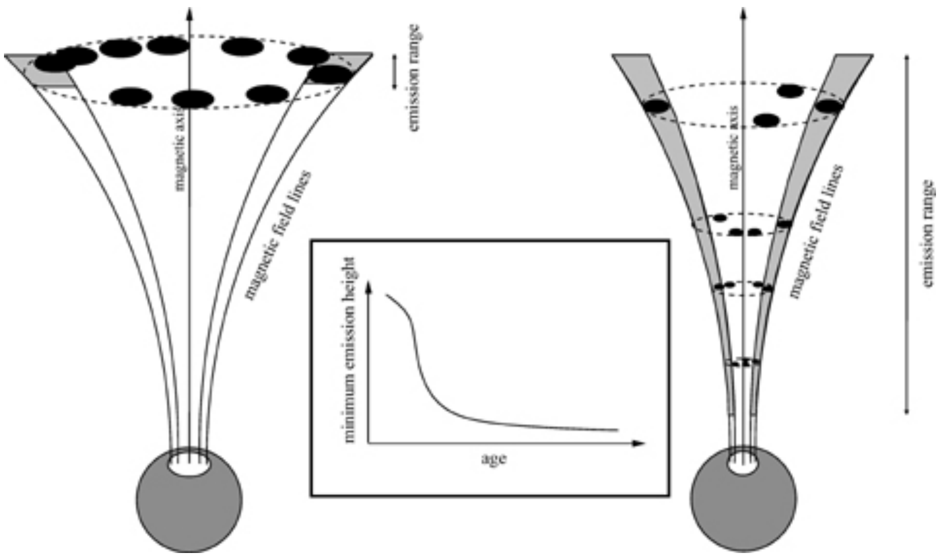
- Pulsar radio emission has $T_b \sim 10^{25}$ -10^{30} K, second highest brightness temperature in the universe
- Theoretical ideas to produce coherent pulsar radio emission (magnetospheric)
  - Bunching (antenna)
  - Maser (collective plasma effect, negative absorption…)
- Observationally there are at least two ways to produce pulsar radio emission in magnetosphere
  - Polar cap region (bunching?)
  - Near light cylinder (maser?)

Crab pulsar radio emission





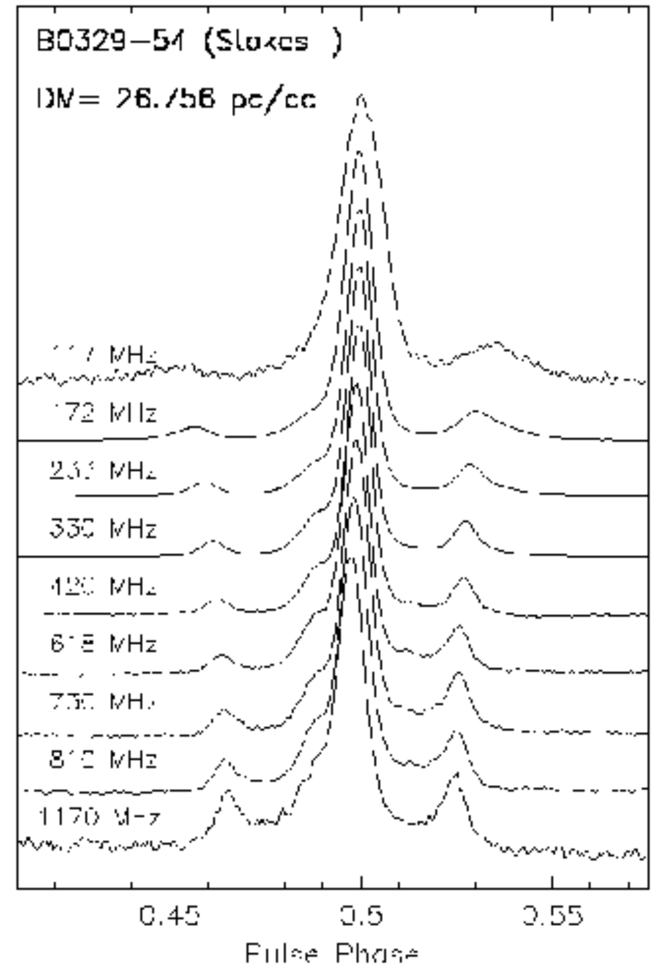
Normal radio pulsars



young pulsars
(Crab like)

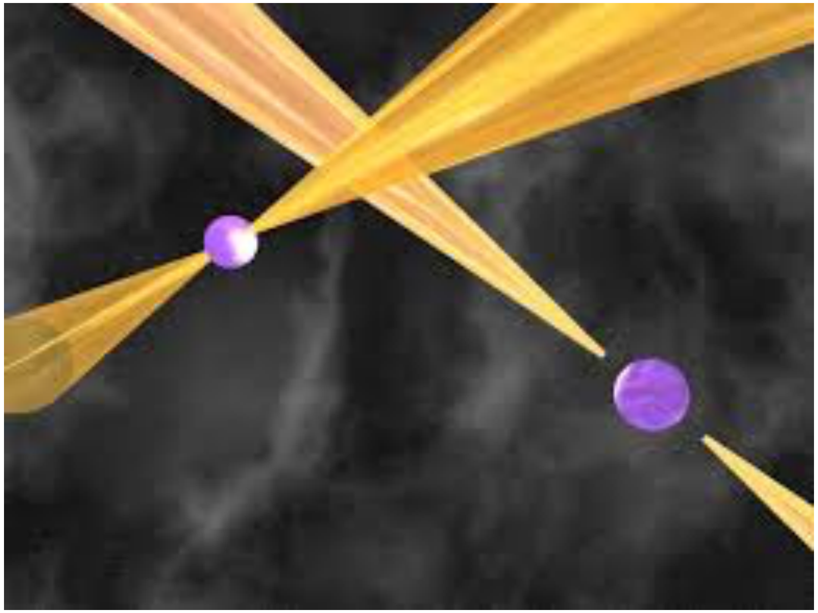
old pulsars

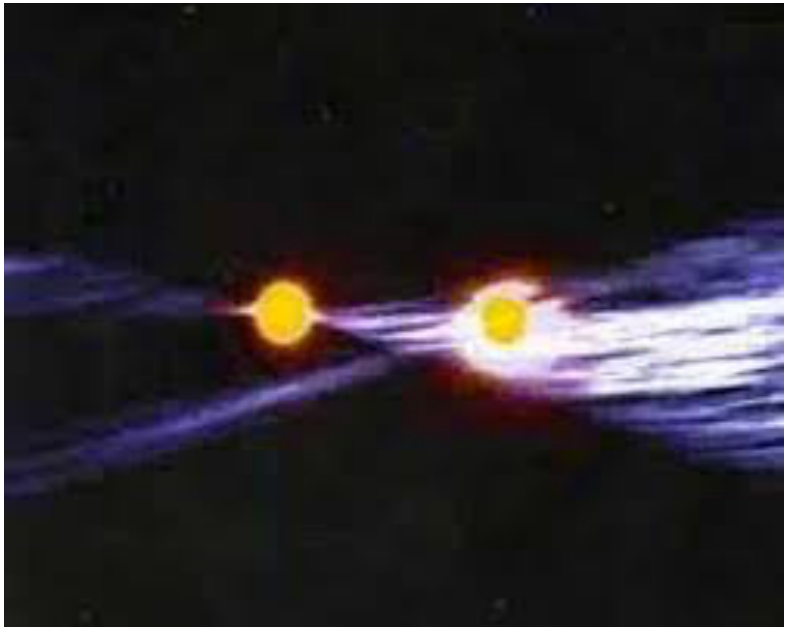
Karastergiou & Johnson (2007)



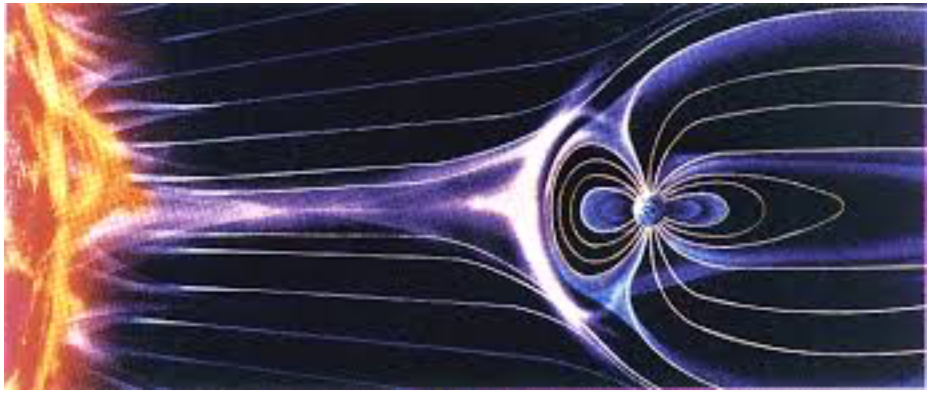
Radius-to-frequency mapping

A third possibility:
The double pulsars: J0737-3039A & B



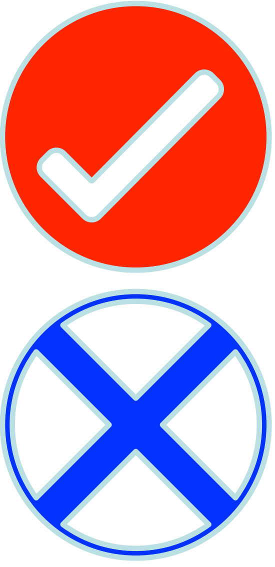


Pulsar A's wind re-shape B's magnetosphere



Lessons from pulsars: Bottom line

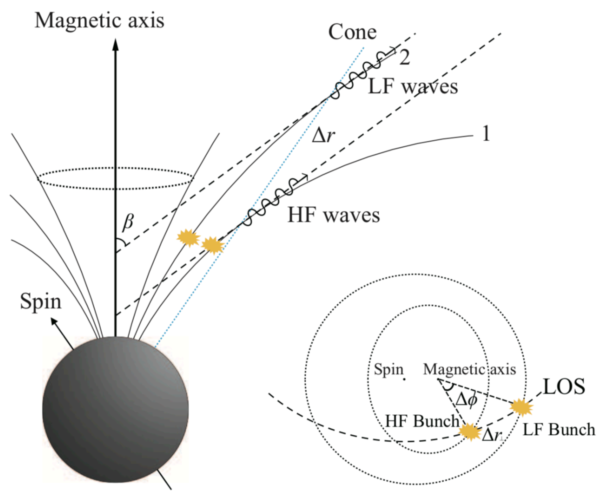
- Emission is made "bottom-up", not "top-down"
- All related to magnetospheres
- Energy power
  - spin-down power
  - magnetic energy power
  - kinetic energy power
  - accretion power

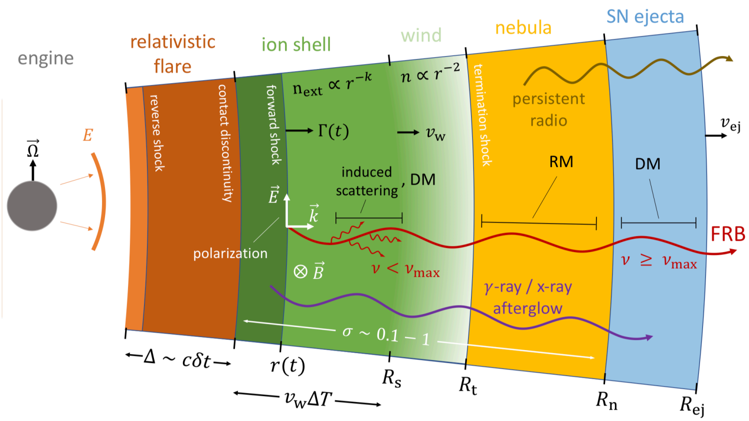


Radiation Mechanisms

Coherent mechanisms

- Pulsar-like (magnetosphere)
  - Coherent curvature radiation by bunches (Katz 2016; Kumar et al. 2017; Yang & Zhang 2018)
  - Collective plasma effect (plasma maser) (Lyutikov 2019)
  - Vacuum maser
- GRB-like (far from magnetosphere)
  - Plasma synchrotron maser (I): low B (Waxman 2017)
  - Plasma synchrotron maser (II): ordered B, $\sigma \sim 1$ (Lyubarski 2014; Plotnikov & Sironi 2019; Metzger et al. 2019; Beloborodov 2019)
  - Vacuum synchrotron maser (Ghisellini 2017)





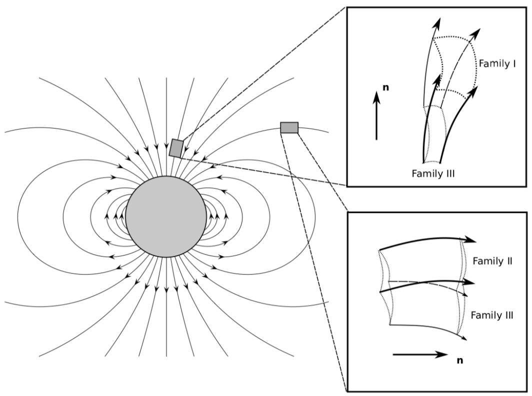
Lu & Kumar (2018) for a critical analysis of these models

Score card of radiation models

	Pulsar-like models			GRB-like models		
	Bunching curvature radiation	Plasma maser	Vacuum maser	Plasma maser I	Plasma maser II	Vacuum maser
T_B	Y	N	N	N?	N?	N?
frequency	Y	Y	Y	Y	Y	Y
narrow spectrum	N?	Y?	N?	Y	N?	N
down drifting	Y	Y?	Y?	N?	Y?	N?
100% polarization	Y	Y	Y	N	Y	Y
low polarization	N?	N?	N?	Y	N	N
circular polarization diversity	Y?	Y?	Y?	N	N	N
theoretical issues	Y	Y	Y	Y	Y	Y

Coherent radiation by bunches

Yang & Zhang, 2018, ApJ, 868, 31



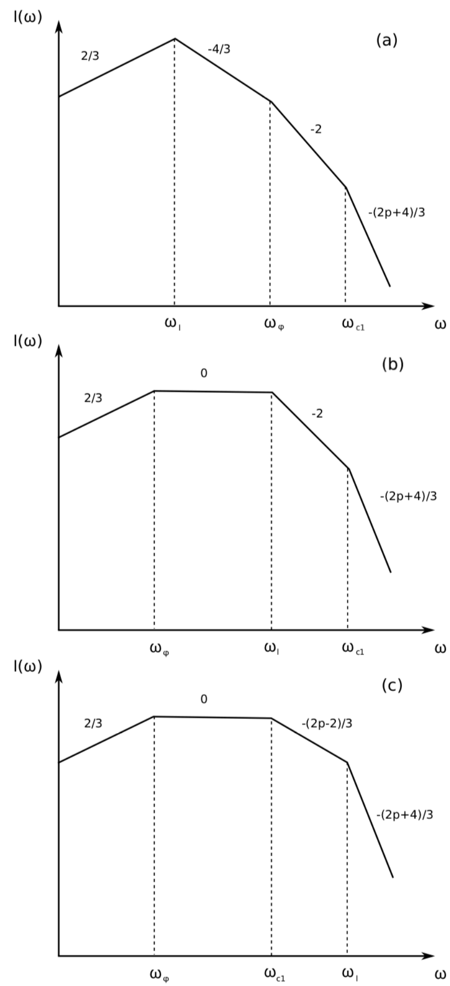


FIG. 11.— The spectra of the coherent curvature radiation from a three-dimensional bunch: (a) the spectrum with $\omega_l \ll \omega_\varphi \ll \omega_{c1}$; (b) the spectrum with $\omega_\varphi \ll \omega_l \ll \omega_{c1}$; (c) the spectrum with $\omega_\varphi \ll \omega_{c1} \ll \omega_l$.

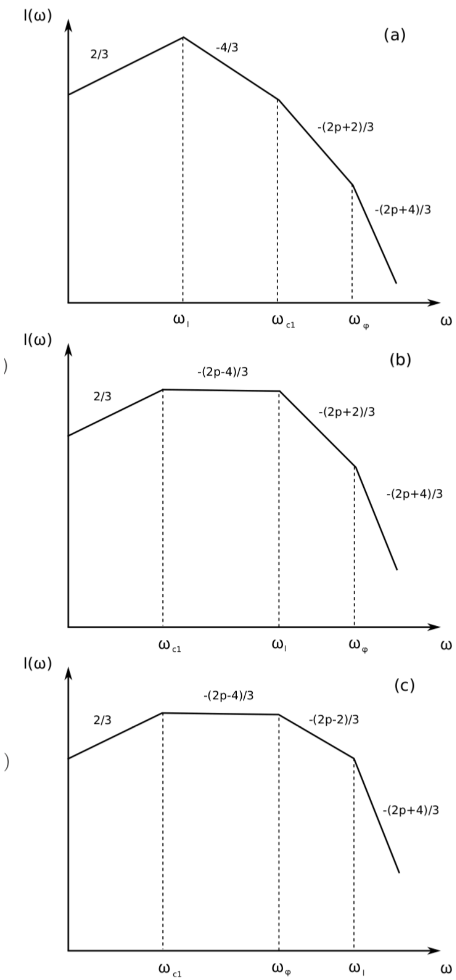


FIG. 12.— The spectra of the coherent curvature radiation from a three-dimensional bunch: (a) the spectrum with $\omega_l \ll \omega_{c1} \ll \omega_\varphi$; (b) the spectrum with $\omega_{c1} \ll \omega_l \ll \omega_\varphi$; (c) the spectrum with $\omega_{c1} \ll \omega_\varphi \ll \omega_l$.

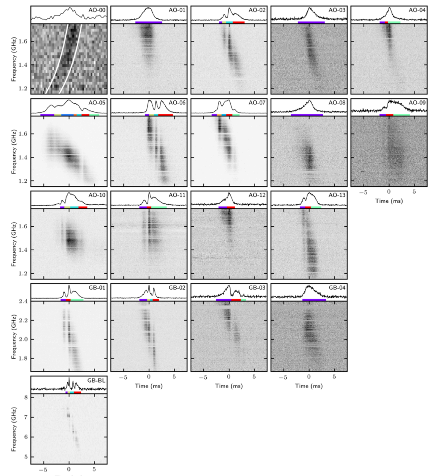
- Broken power law spectrum
- Depends on three characteristic frequencies

  $\omega_c \quad \omega_l \quad \omega_\varphi$
- From open field lines! (field lines flare out)

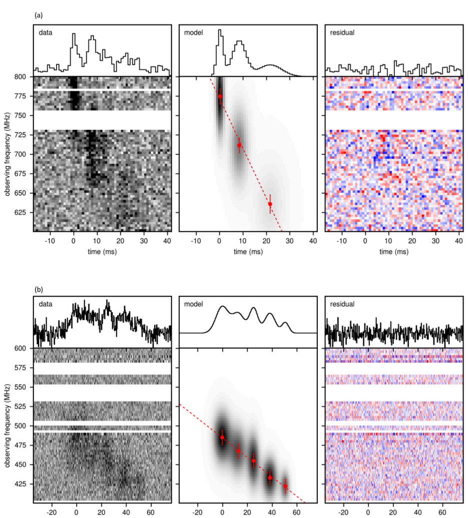
See other constraints by Kumar et al. (2017)

Time-frequency down-drifting: evidence of magnetospheric radiation in open field line regions

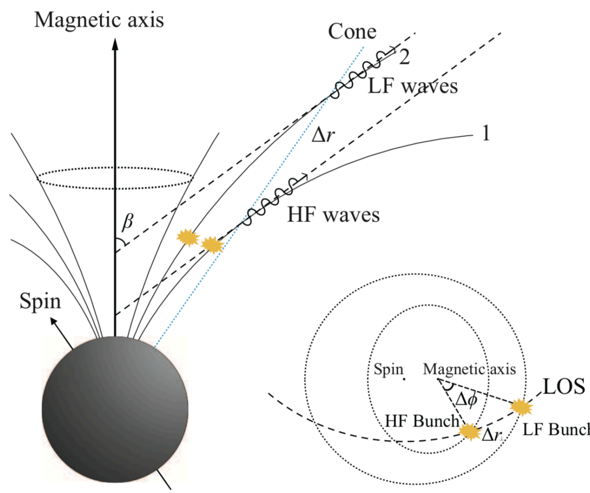
Wang et al., 2019, ApJL, 876, L15

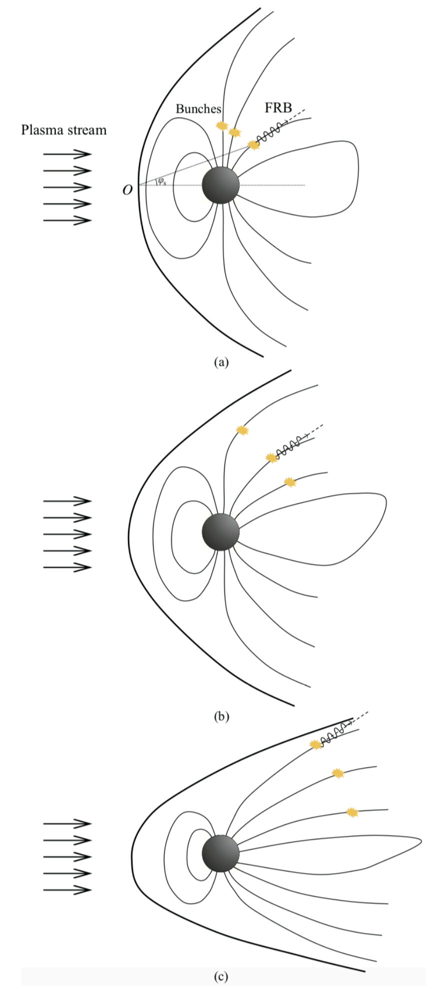


FRB 121102
Hessels et al., 2018



FRB 180814.J0422+73
Amiri et al. 2019





Lyutikov 2019 for the similar idea

Source Models I: Repeating (non-catastrophic) models

Possible energy powers

- Intrinsic power
  - Spin-down power
  - Magnetic power
- Extrinsic power
  - Gravitational power
  - Kinetic power

Possible sources

- Neutron star models
  - Intrinsic models (reconnection, star quake, instability, "flashing", etc)
    - Young pulsars
    - Old magnetars
    - young magnetars
  - Extrinsic models
    - NS accretion models (accretion, comets & asteroids)
    - Cosmic comb (interaction)
- Non-neutron star models (not discussed)
  - AGNs
  - Accreting white dwarfs
  - Exotic models (cosmic strings, macroscopic magnetic dipole, etc.)

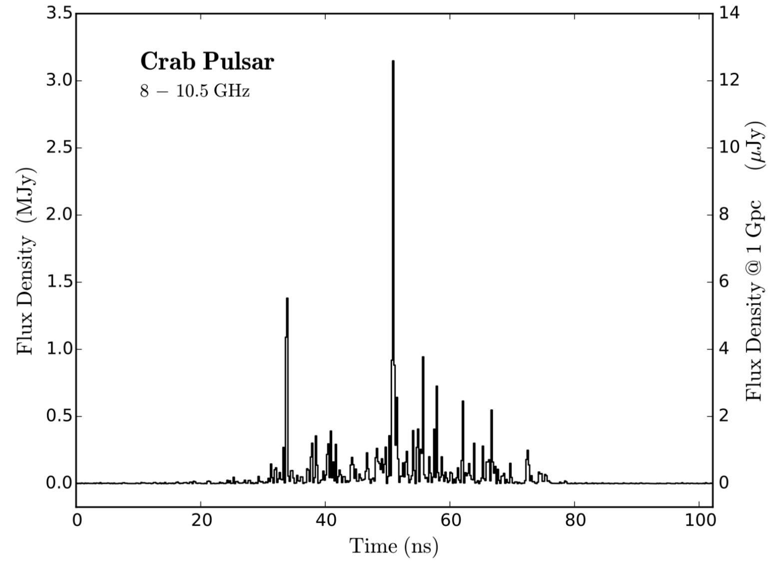
Best bet: Intrinsic pulsar/magnetar models

- Pros/features:
  - Spindown or magnetically powered
  - Not disruptive, known giant pulses (young pulsars) and magnetar giant flares (old magnetars)
- Cons:
  - Drawbacks of known populations (young pulsars & old magnetars)
  - Promise of the imaginary population (young magnetars) not fulfilled

Young pulsar models

(Cordes & Wasserman 2016; Conor et al. 2016)

- Motivations:
  - Nano-shots in Crab?
  - Most familiar (but not understood) mechanism
- Issues:
  - Requires extreme stretching of parameters ("ERB", "non-cosmological")
  - Cosmological origin disfavors it unless they are from young magnetars with ~100% efficiency

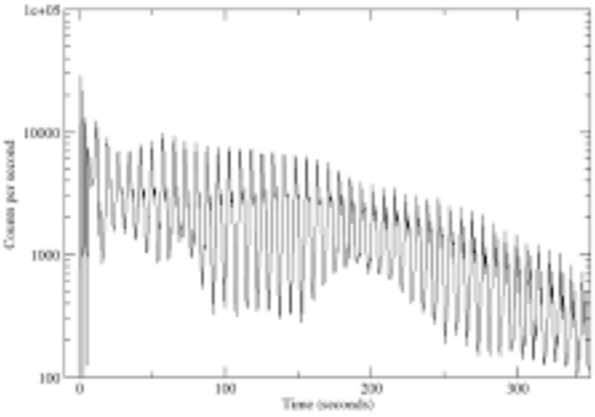


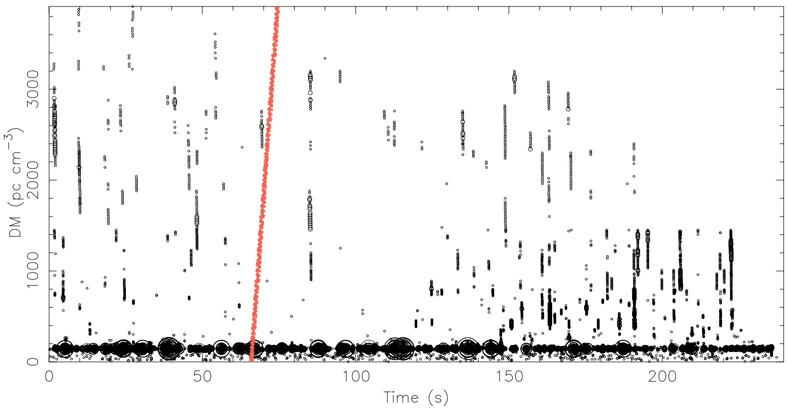
Cordes & Wasserman 2016

Magnetar giant flare models

(Popov et al. 2007, 2013; Kulkarni et al. 2014; Katz 2015)

- Motivations:
  - Magnetars produce giant flares with a short hard gamma-ray peak
  - There could be radio emission associated with it
- Issues:
  - Constraints from SGR 1806-20

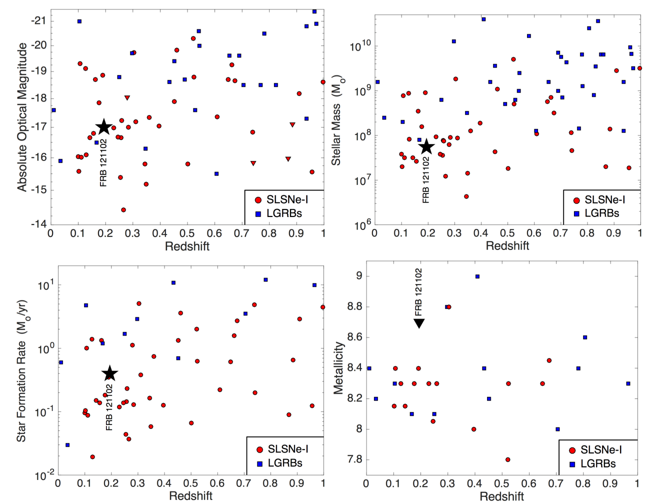


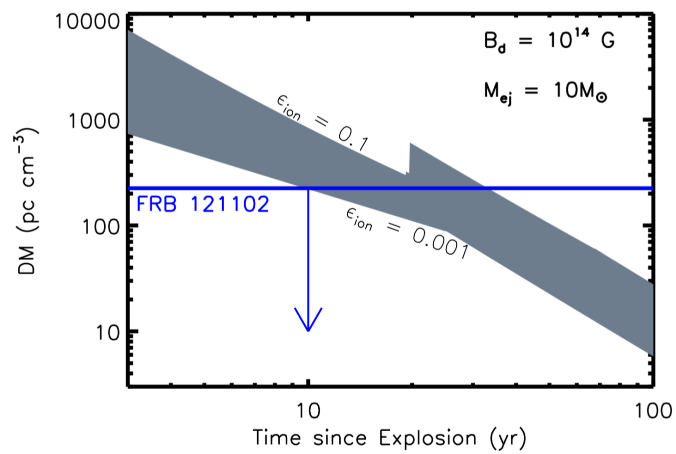


Tendulkar et al. (2016)

Young magnetar models

- Motivations (Murase et al,. 2016; Metzger et al. 2017):
  - Star-forming galaxy of FRB 121102 is analogous to those of long GRBs and SLSNe
  - Young magnetars have high spindown luminosity and enough magnetic energy to power the repeating bursts
- Issues:
  - Cannot be too old — otherwise the spindown luminosity is not large enough
  - Cannot be too young — otherwise radio waves cannot escape (free-free absorption) and DM would show evolution over several years (no evolution was observed)

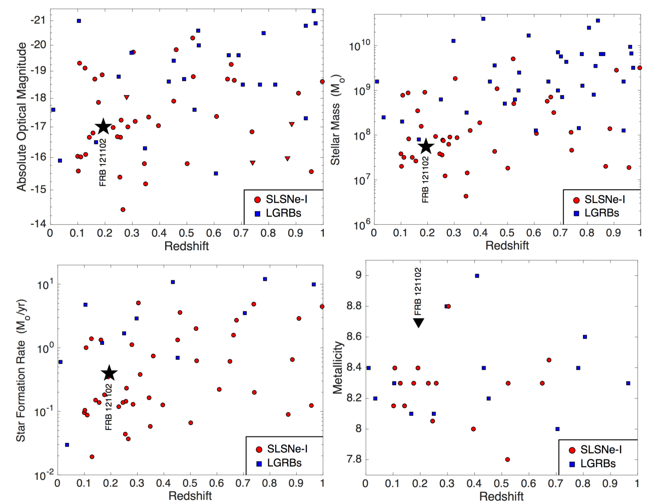




Metzger et al. 2017

Young magnetar bandwagon: Fact or wishful imagination?

- **FRB hosts should be similar to those of long GRBs and SLSNe** (Metzger et al. 2017)
  - Fact: No. Most are in old environment
  - WI: They are from magnetars made from NS-NS mergers (Margalit et al. 2019)
- **One should detect FRBs from LGRB & SLSNe remnants** (Metzger et al. 2017)
  - Fact: So far no (Men et al. 2019; Law et al. 2019)
  - WI: They form persistent radio sources similar to FRB 121102, FRBs should come someday
- **FRBs should have large RMs** (Margalit & Metzger 2018)
  - Fact: Except FRB 121102, others not
  - WI: FRB 121102 is a repeater. Repeaters should have large RM
- **Repeating FRBs should have long RMs** (Metzger et al. 2019)
  - Fact: Except FRB 121102, others not
  - WI: FRB 121102 is a young magnetar, others are old



All the predictions of this model have failed so far!

When should one seriously consider other possibilities?

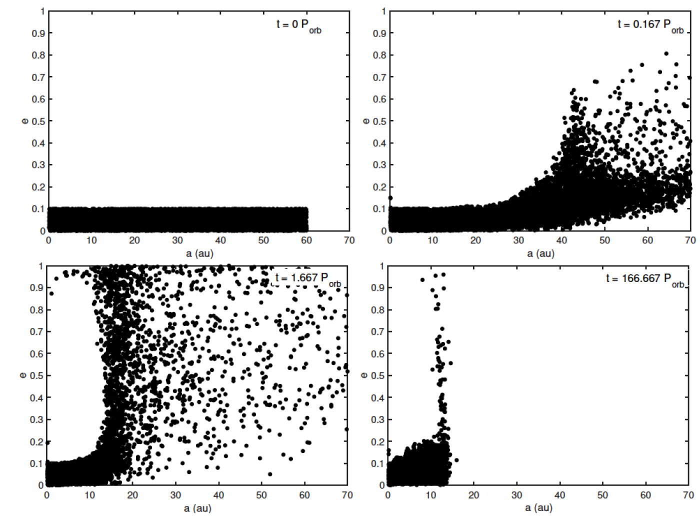
Also Adam Deller's talk

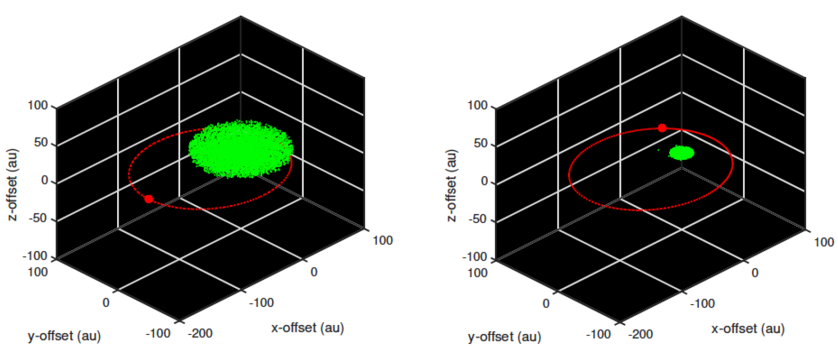
Extrinsic pulsar/magnetar models

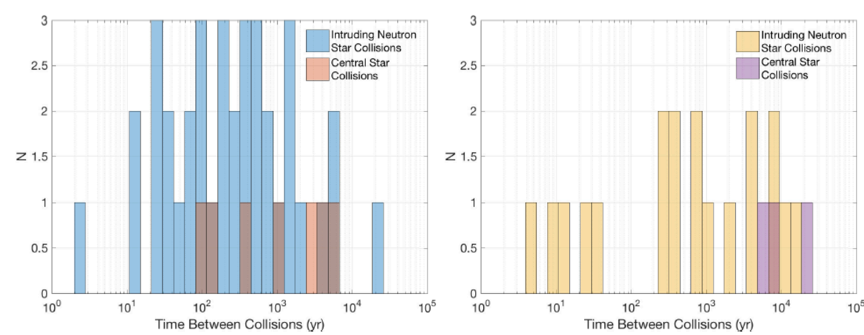
- Gravitationally powered
  - Accretion-induced instabilities
  - Comet/asteroid collisions
- Kinetically powered
  - Interaction between an external wind (“stream”) with a pulsar magnetosphere (cosmic string)

One specific model: NS - asteroids/comets collisions

- Several authors suggested such collisions as sources of FRBs (Geng & Huang 2015; Dai et al. 2016; Bagchi 2017)
  - If the model turns out correct, can probe extragalactic planetary systems
  - General issue of accretion models
- N-body simulations of collision rate suggest extreme physical conditions to reproduce the observed repetition rate (Smallwood, Martin & Zhang, 2019, MNRAS)







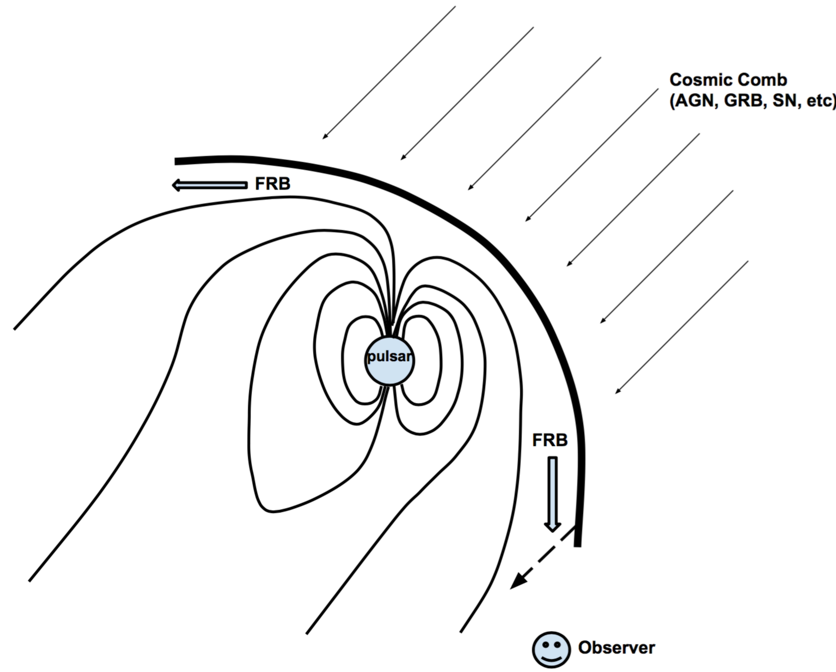
Smallwood et al. (2019, MNRAS)

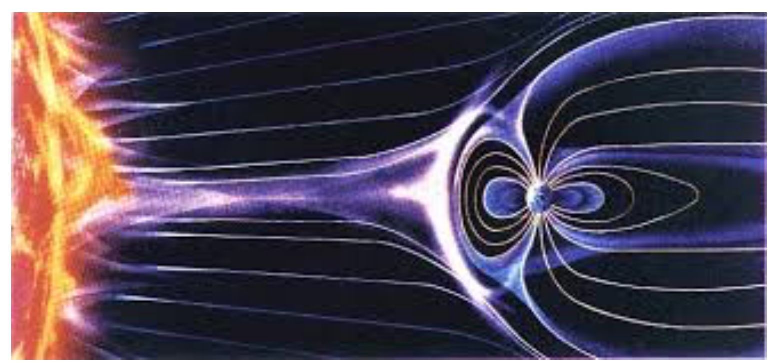
Rate: the belt needs to be 4 orders of magnitude denser than Kuiper belt even under most favorable conditions

Cosmic combs

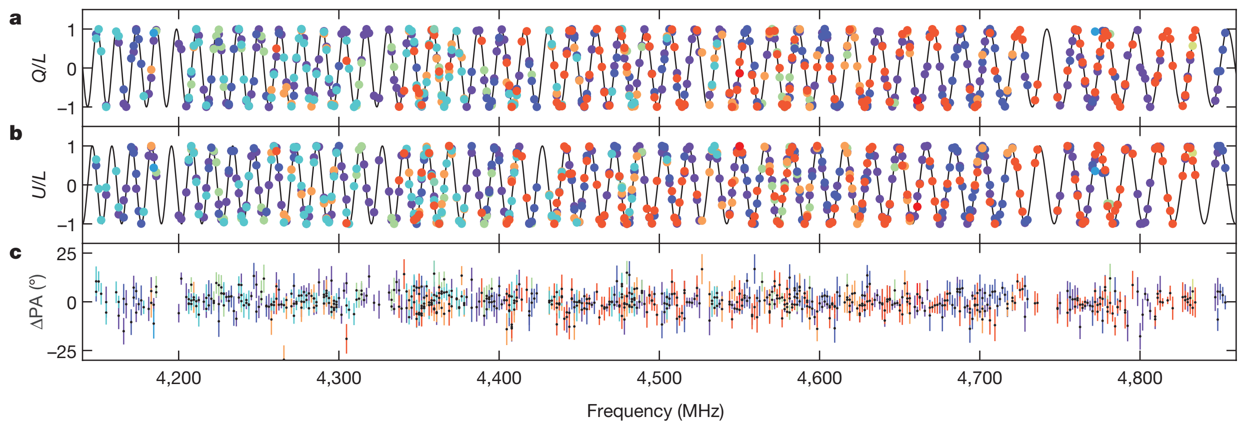
Zhang (2017, ApJL, 836, L32)

- Condition: ram pressure > magnetic pressure (energy is from an external source)
- Source of comb: AGN, GRB, SN, TDE, companion …
- Motivation: a unified model
  - FRB 150418: combed by an AGN
  - FRB 131104: combed by a GRB
  - Repeater: "marginally" combed by an unsteady nebula wind

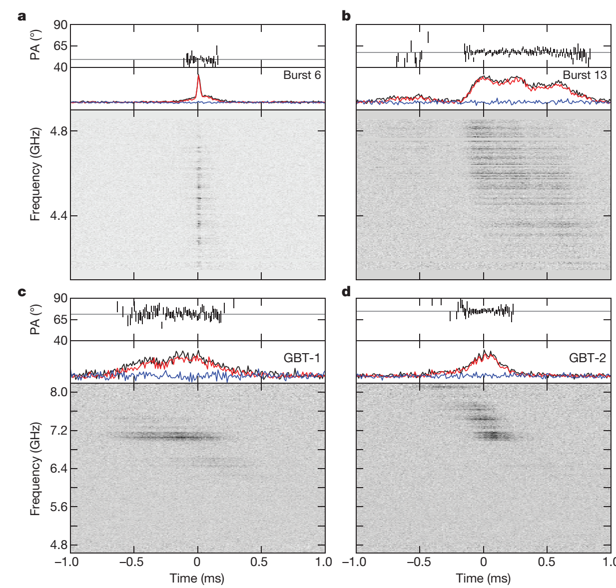




Clues from rotation measure (RM) data



- RM as large as $+1.46 \times 10^5$ radian per square meter, seen only near super-massive black holes
- Vary by ~10% in 7 months
- ~100% linear polarization
- Polarization angle constant in each burst, varies among bursts



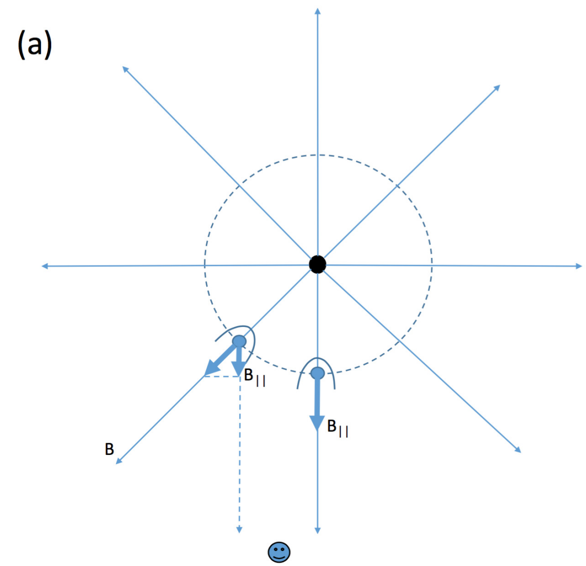
$$\mathrm{RM} = \frac{e^3}{2\pi m^2 c^4} \int_0^d n_e(s) B_{||}(s)\, \mathrm{d}s$$

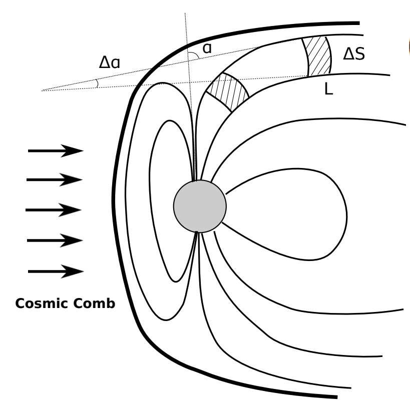
Michilli et al. 2018, Nature, 553, 182

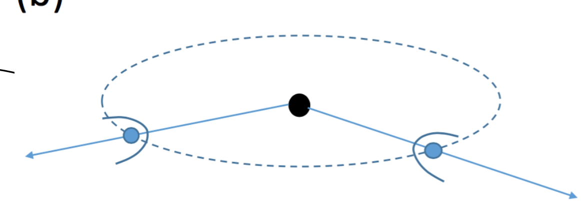
FRB 121102: Marginal Combing by a supermassive BH

- Interpretations
  - Large and variable RM
  - 100% linear polarization: curvature radiation (like pulsars)
  - Constant polarization degree (magnetic field line near straight)
  - Repetition and temporal structure (marginal combing)
  - Non-varying DM (not at center)

- Falsifiable predictions:
  - RM will go up again (orbital periodic motion)
  - PA orbital periodic variation







Zhang (2018, ApJL, 854, L21)

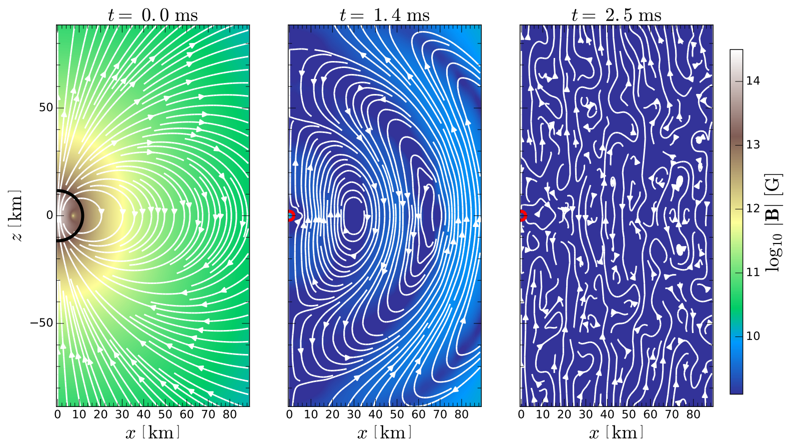
Source Models 2: Non-repeating (catastrophic) models

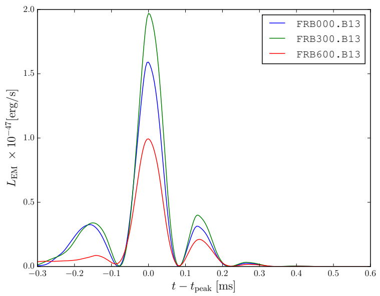
Disclaimer:
1. These FRBs may not exist at all. (Adam Deller)
2. If exist, they only comprise a small fraction of the observed FRBs (e.g. Ravi 2019)

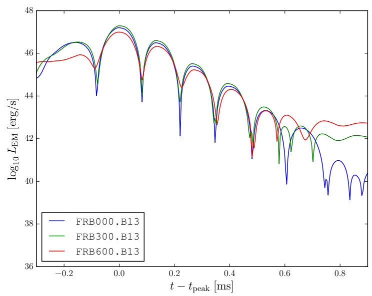
Blitzars

Falcke & Rezzolla (2014); Most et al. (2018)

- Features:
  - Supramassive NS collapses, ejecting magnetosphere
  - Right duration
- Pros:
  - Inside out
  - A more violent version of pulsar magnetosphere “sparking”
  - Magnetic energy power, not subject to constraint of spindown luminosity
- Cons:
  - Not a known phenomenon before
  - Not repeating



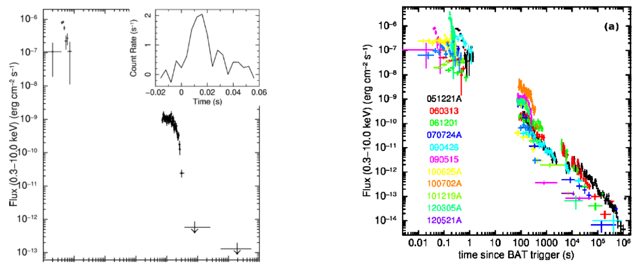




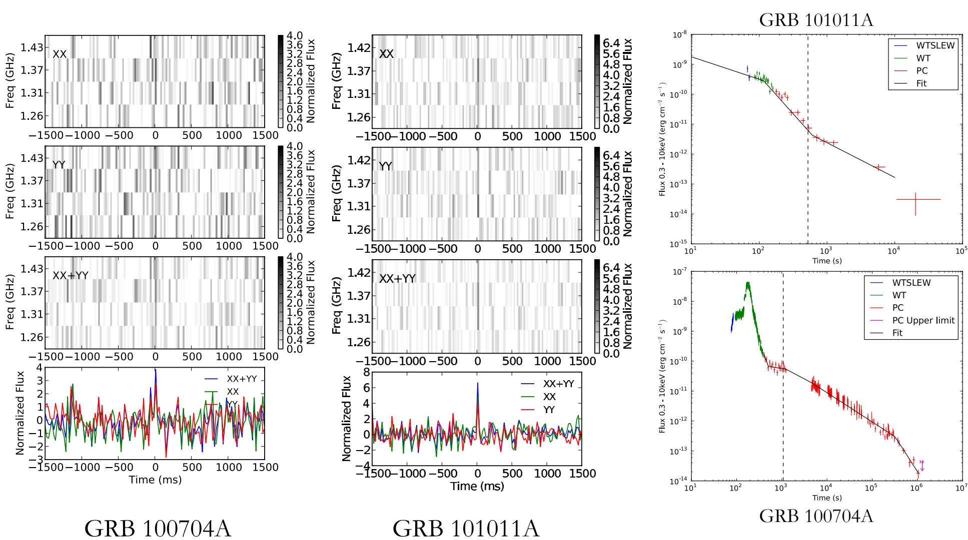
Blitzar FRB following a GRB?

Zhang (2014)

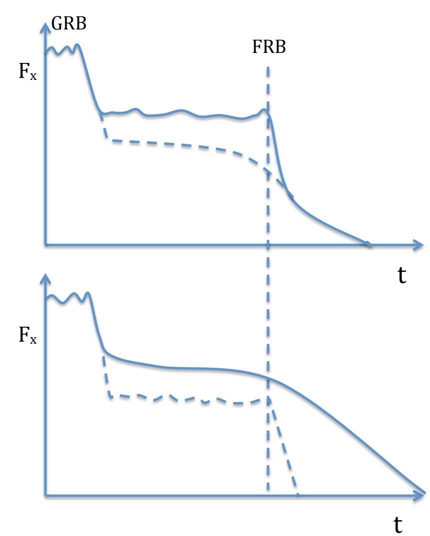
- Signature of supramassive neutron star collapse seen in some GRBs, especially short GRBs
- Dedicated search needed



Rawlinson et al. 2010, 2013



Bannister, Murphy, Gaensler & Reynolds, 2012, ApJ, 757, 38

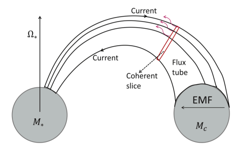


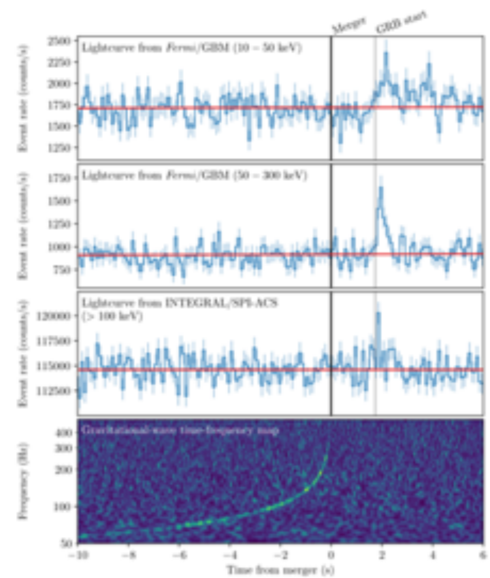
Zhang, 2014, ApJ, 780, L21

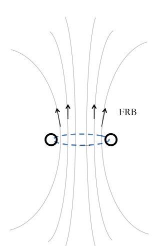
Compact star Coalescences (CBCs)

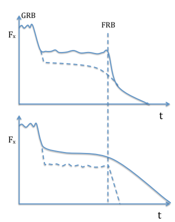
Totani; Zhang; Piro; Wang et al.; Liebling & Palenzuela; Liu et al.

- Significance: GW associations!
- Variations:
  - Post-merger synchronization of the magnetosphere (NS-NS mergers only)
  - Unipolar induction (NS-NS and possibly NS-BH mergers
  - Charged compact binary coalescence (cCBC) (NS-NS, NS-BH, BH-BH mergers)
  - Post-merger blitzar
- Pros:
  - Inside out
  - Some brief EM signal should accompany these events
- Cons:
  - Not repeating
  - Event rate not high enough (only a small fraction of FRBs at most)



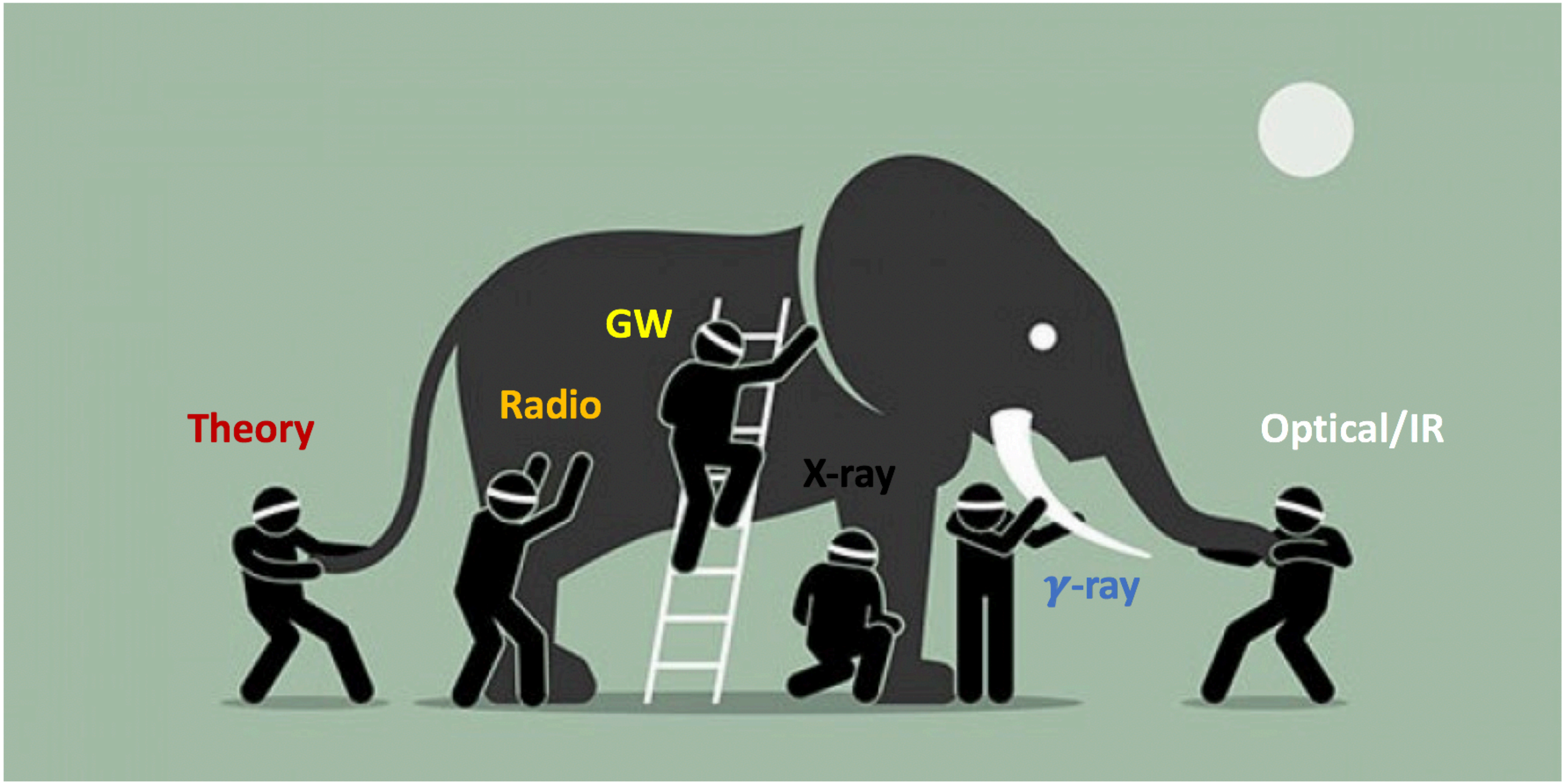






Zhang, 2014, ApJ, 780, L21

Picking apart the wreckage of a merger

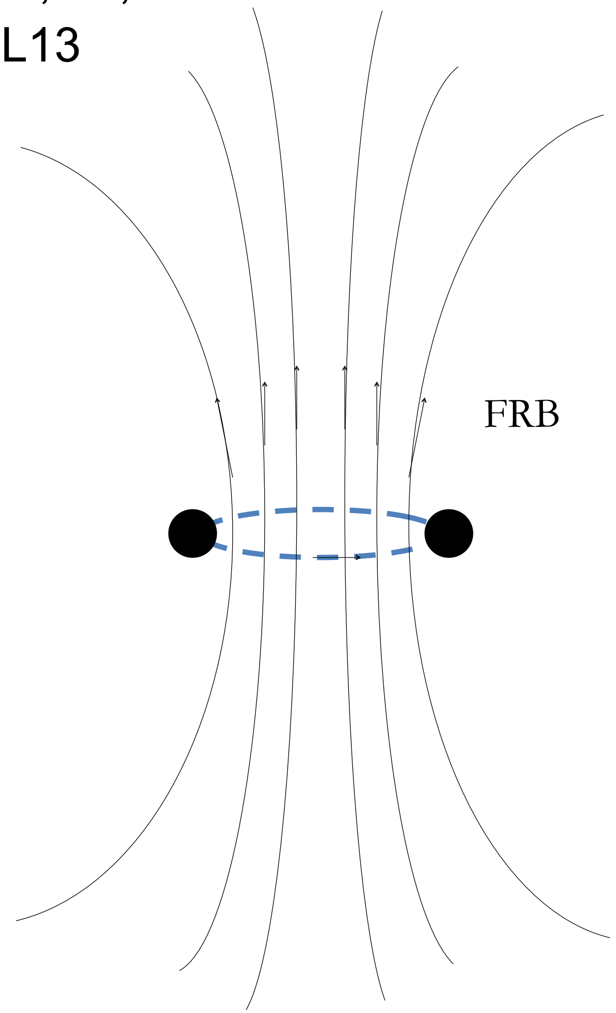


Credit: Adam Deller

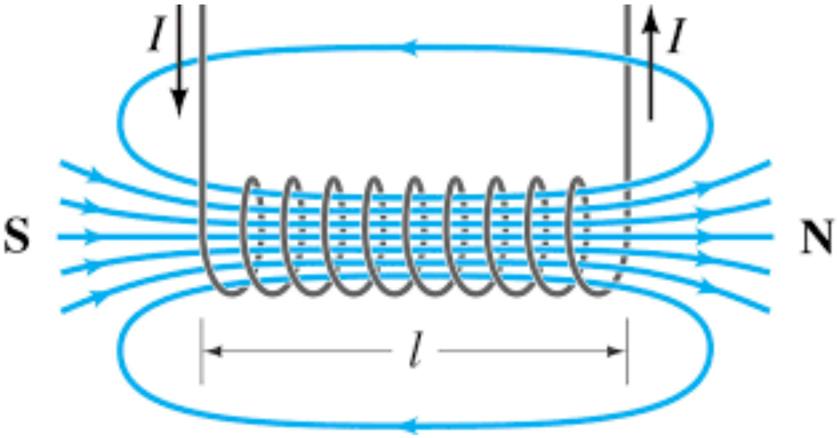
Charged Compact Binary Coalescence (cCBC)

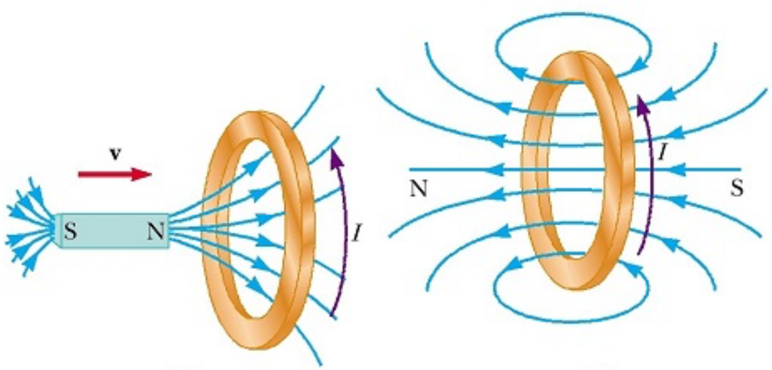
Zhang, 2016, ApJ, 827, L31;
Zhang, 2019, ApJ, 873, L9;
Dai, 2019, ApJ, 873, L13

- General picture:
  - As long as one of the member in cCBC is charged, one can have a brief EM signal rapidly increases at the time of coalescence
  - A macroscopic pulsar, bottom up
  - Quite generic, applies to NS-NS, NS-BH, BH-BH mergers
- FRB or not, something should happen. Strength depends on amount of charge



cCBC physics





(a) (b)

1. $\nabla \cdot \mathbf{D} = \rho_V$
2. $\nabla \cdot \mathbf{B} = 0$
3. $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
4. $\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$

High school E&M

General theory of charged CBC signal

Zhang, 2019, ApJ, 873, L9

Arbitrary mass and charge for the two members:

$$(m_1, \hat{q}_1) \text{ and } (m_2, \hat{q}_2) \qquad \hat{q}_i \equiv Q_i / Q_{c,i}$$

$$Q_{c,i} \equiv 2\sqrt{G} m_i, \qquad i = 1, 2$$

Gravitational wave radiation:

$$L_{\rm GW} = \frac{1}{5}\frac{c^5}{G}\left(\frac{r_s(M_h)}{a}\right)^5 f(e)$$
$$= \frac{1}{5}\frac{c^5}{G}\left(\frac{r_s(M_r)}{a}\right)^2 \left(\frac{r_s(M)}{a}\right)^3 f(e),$$

$$\frac{c^5}{G} \simeq 3.6 \times 10^{59} \text{ erg s}^{-1}$$

Electric dipole radiation:

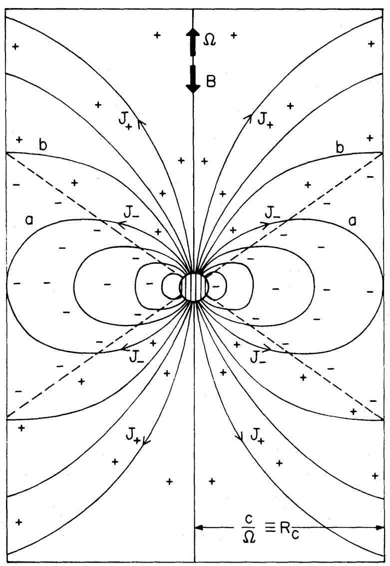
$$L_{\rm e,dip} = \frac{1}{6}\frac{c^5}{G}(\hat{q}_1^2 + \hat{q}_2^2)\left(\frac{r_s(m_1)}{a}\right)^2 \left(\frac{r_s(m_2)}{a}\right)^2. \quad (11)$$

$$E_{\rm e,dip} = \int_a^{a_{\rm min}} da \frac{L_{\rm e,dip}}{\dot{a}}$$
$$= \frac{5}{24}\ln\left(\frac{a}{a_{\rm min}}\right)(\hat{q}_1^2 + \hat{q}_2^2) M_r c^2, \qquad (13)$$

General theory of charged CBC signal

Zhang, 2019, ApJ, 873, L9

Spinning magnets are charged! Certainly NSs are charged. BHs may be also charged.

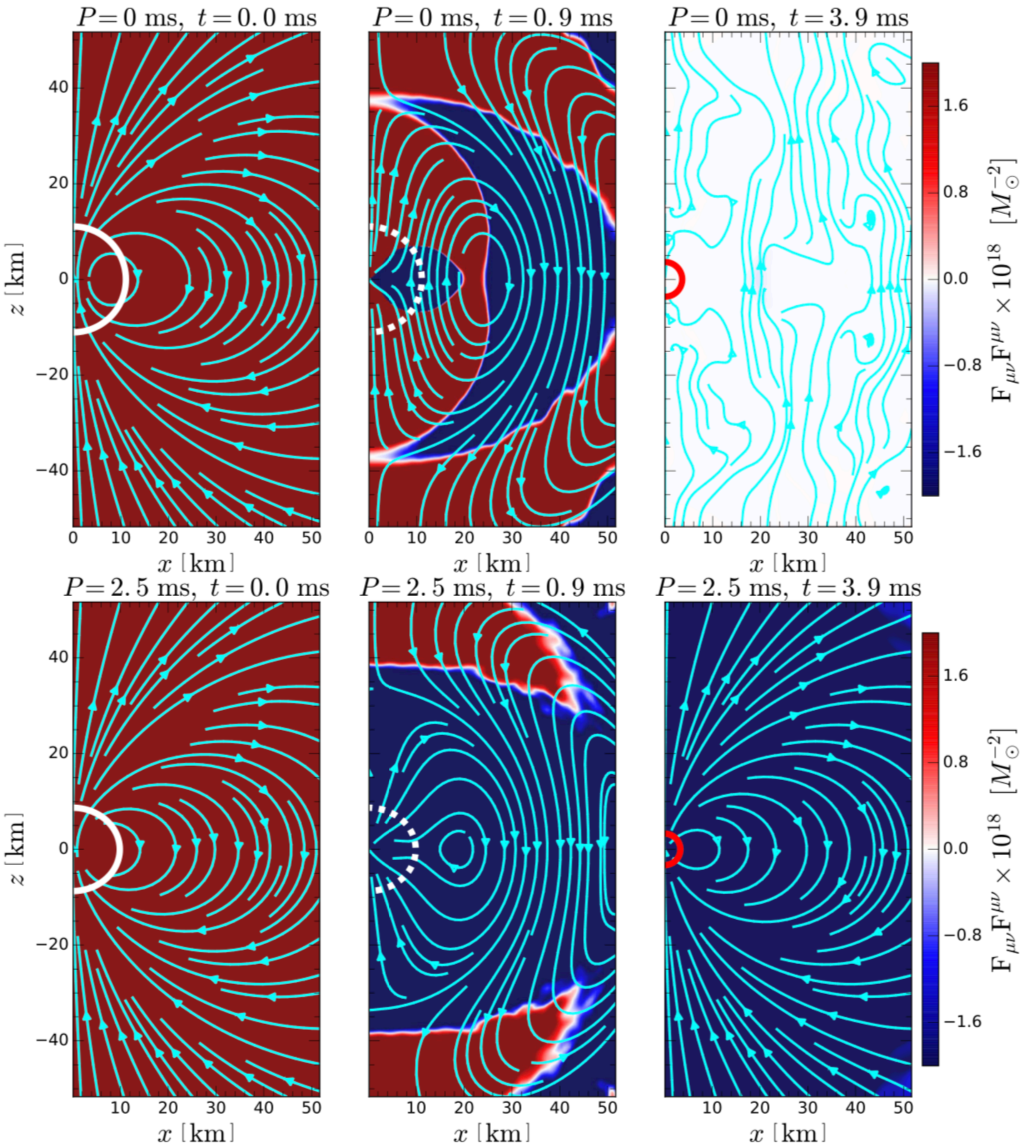


$$
\begin{aligned}
Q_{\rm mag} &= 4\pi \int_R^r \int_0^{\pi/2} -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi c} r^2 d\theta dr \\
&= \int_R^r \frac{1}{r} dr \int_0^{\pi/2} \frac{2\Omega\mu_*}{c} \cos\theta \sqrt{1+3\cos^2\theta} d\theta \\
&= \ln\left(\frac{r}{R}\right) \frac{\Omega\mu_*}{c} \left(1 + \frac{4\sqrt{3}}{9}\pi\right), \\
&= \ln\left(\frac{r}{R}\right) \frac{\Omega B_p R^3}{c} \left(\frac{1}{2} + \frac{2\sqrt{3}}{9}\pi\right), \qquad (23)
\end{aligned}
$$

$$
\hat{q}_{\rm NS} \simeq \frac{3\Omega B_p R^3}{2c\sqrt{GM}} = (4.4\times 10^{-7}) B_{13} P_{-2}^{-1} R_6^3 M_{1.4}^{-1}. \qquad (24)
$$

Formation of charged BHs

(Nathanail, Most & Rezzolla, 2017, MNRAS)

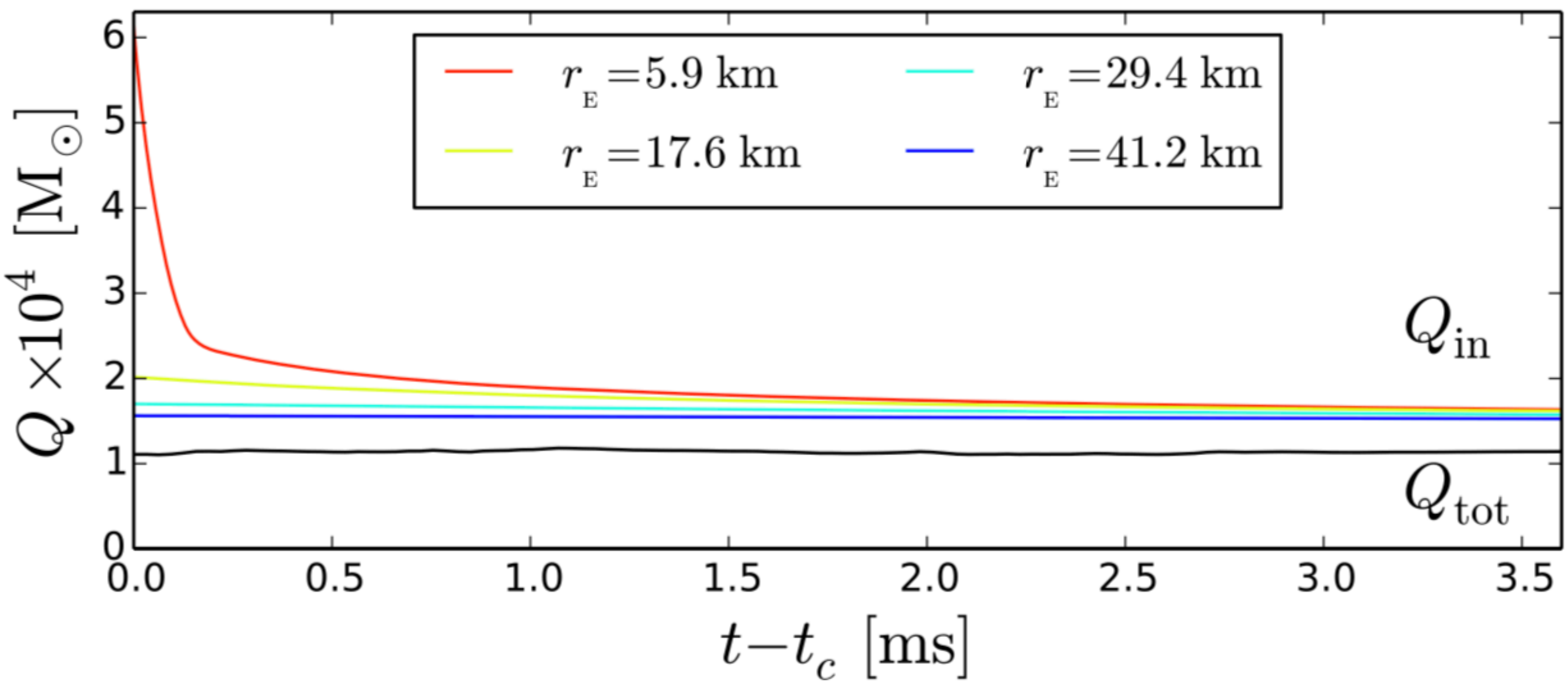


A non-spinning NS collapses to a Schwarzschild BH

$$F_{\mu\nu}F^{\mu\nu} \simeq 0$$

A spinning NS collapses to a Kerr-Newman BH

$$F_{\mu\nu}F^{\mu\nu} < 0$$

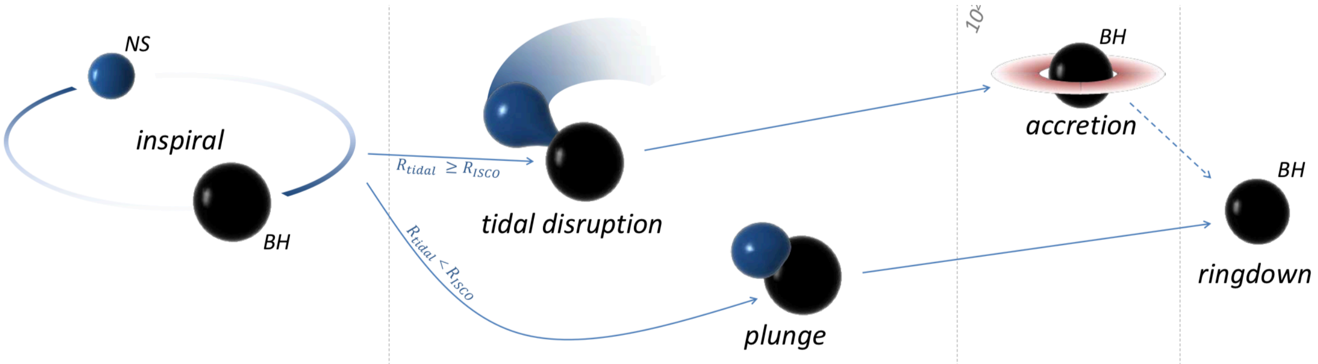


Charge tends to stay constant after the collapse is complete

Nathanail, Most & Rezzolla (2017)

Plunging BH-NS mergers

Zhang, 2019, ApJ, 873, L9



Bartos et al. (2013)

$$
\begin{aligned}
L_{\rm e,dip,max} &= (5.0 \times 10^{42}\ {\rm erg\ s^{-1}})\ \hat{q}_{-7}^2, \\
E_{\rm e,dip} &= (1.0 \times 10^{40}\ {\rm erg})\ \hat{q}_{-7}^2, \\
L_{\rm B,dip,max} &= (1.7 \times 10^{38}\ {\rm erg\ s^{-1}})\ \hat{q}_{-7}^2, \\
E_{\rm B,dip} &= (1.2 \times 10^{34}\ {\rm erg})\ \hat{q}_{-7}^2. \qquad (25)
\end{aligned}
$$

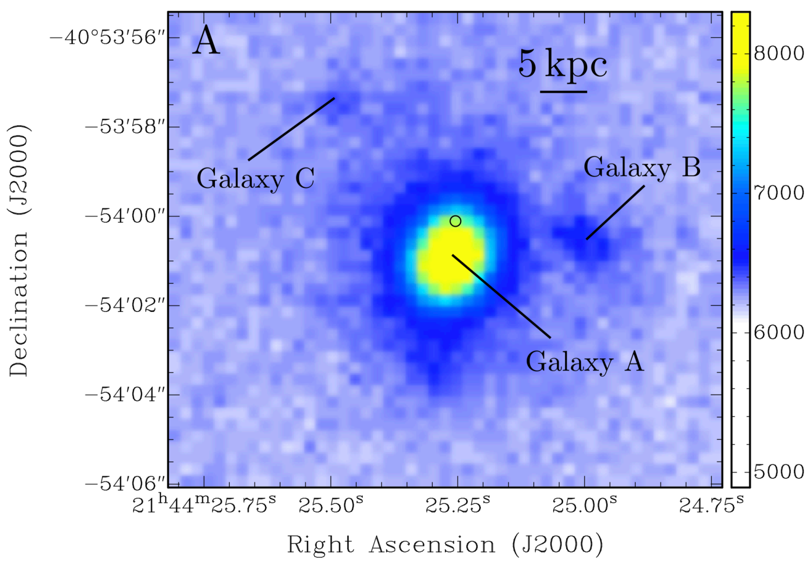
FRB if the NS is Crab-like?

Search for coincident associations (temporal and spatial) of FRBs with CBCs of all kinds (especially plunging BH-NS and BH-BH mergers) will constrain amount of charges in NSs and BHs

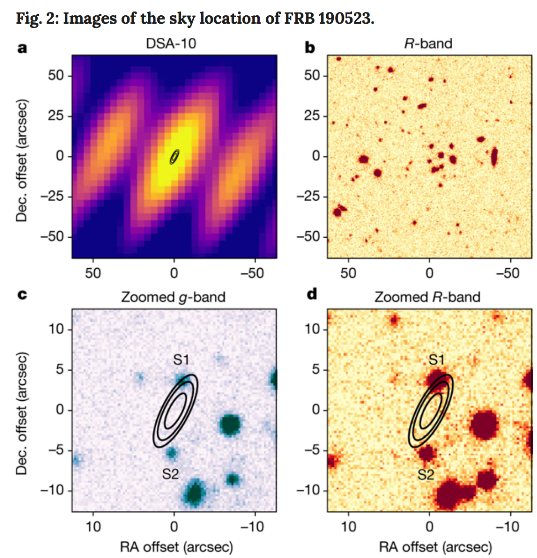
With the possibility of BIG discovery

Do magnetars from NS-NS mergers make the majority of FRBs?

Margalit, Berger & Metzger (2019)



Bannister et al. 2019

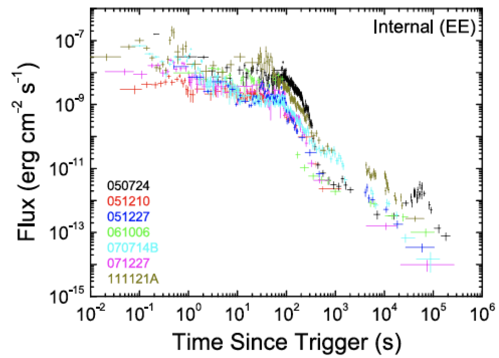


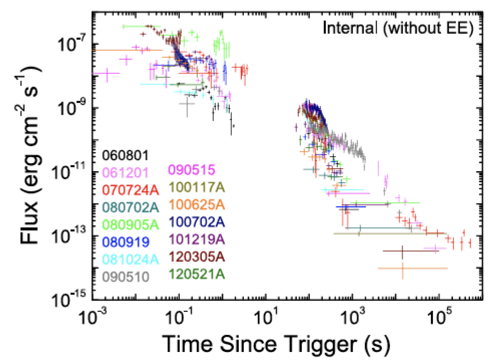
Ravi et al. 2019

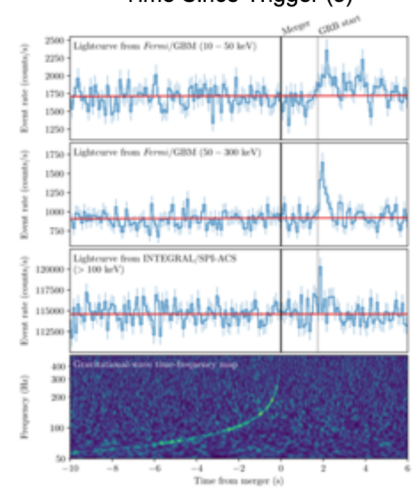
Fulfill the prediction of Francois Foucart

M_{TOV} controversy

- The HMNS/BH : SMNS: SNS proportion:
- ~ 0.4 : 0.3 : 0.3
  - Gao, Zhang & Lü (2016, PRD)
  - $M_{\mathrm{TOV}} \sim (2.3 - 2.4) M_\odot$
  - Good to interpret short GRB X-ray plateau data
- (0.32-0.67) : (0.18-0.68) : (<0.03)
  - Margalit & Metzger (2019, ApJL)
  - $M_{\mathrm{TOV}} = 2.17 M_\odot$
  - Assumes that the merger product of GW170817/GRB 170817A is a HMNS which collapses to a BH shortly afterwards







Ben cannot be right on both counts

- NS-NS merger remnants are sources of most FRBs (Margalit et al. 2019)
- In order to have the SGRB-like hosts out number the LGRB-like hosts, most NS-NS mergers need to produce stable neutron stars

- The merger product of GW170817 is a black hole (Margalit & Metzger 2017)
- The fraction of stable NS remnants is <0.03 (Margalit & Metzger 2019). Not enough to produce the relative ratio between FRBs with SGRB-like and LGRB-like environments

Summary

- The FRB field is exciting, emerging field. A lot of fun!
- FRB mystery is being solved, mostly by observers, with theoretical insights from the field of GRBs and pulsars.
- It will take a long time to constrain and eliminate the large amount of models (both radiation models and source models), even though some progress has been made
- The leading young magnetar model has not fulfilled the promise of giving correct predictions, even though most of the community are still wishfully expecting the next prediction becomes true.
- The possibility that a small fraction of FRBs are related to CBCs is not impossible. It will be profound if it turns out to be the case.