Pre-/post-dictions for

Counterparts of FRBs

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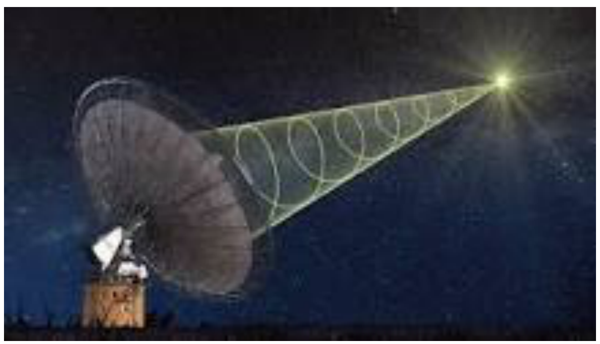
FRBs vs. GRBs

- Physical connection??
- Social/cultural connection between the two fields



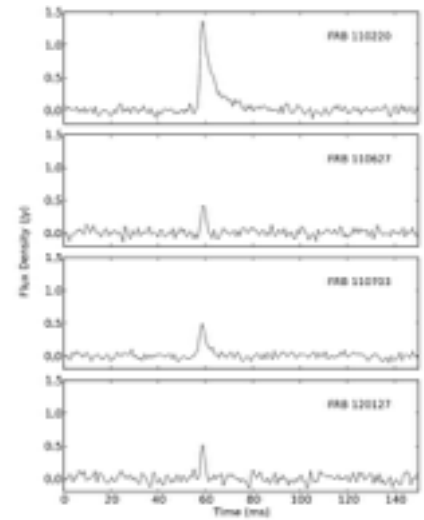
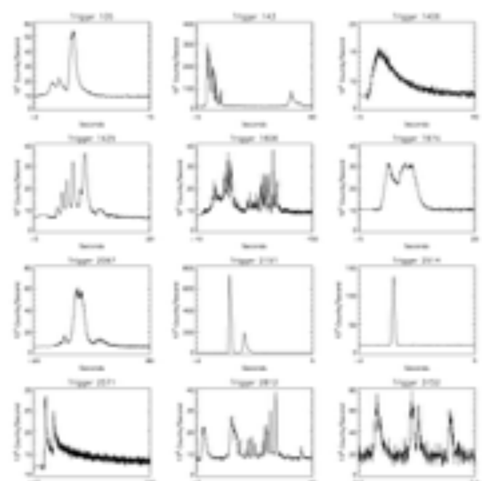


Fig. 1. The frequency-integrated flux densities for the four FRBs. The time resolutions match the level of dispersive smearing in the central frequency channel (0.8, 0.6, 0.9, and 0.5 milliseconds, respectively).



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 (Persistent radio source, host galaxy)
Step three: What make them?	1998 – ??? (SN Ic, GW?)	??? (AGN? GRB? magnetar-powered nebula?)

Observationally driven
Healthy dialog between observers and theorists

What may make them?

(An incomplete list, no particular order)

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)
- Instability within pulsar magnetosphere (Philippov's talk)

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)

……

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

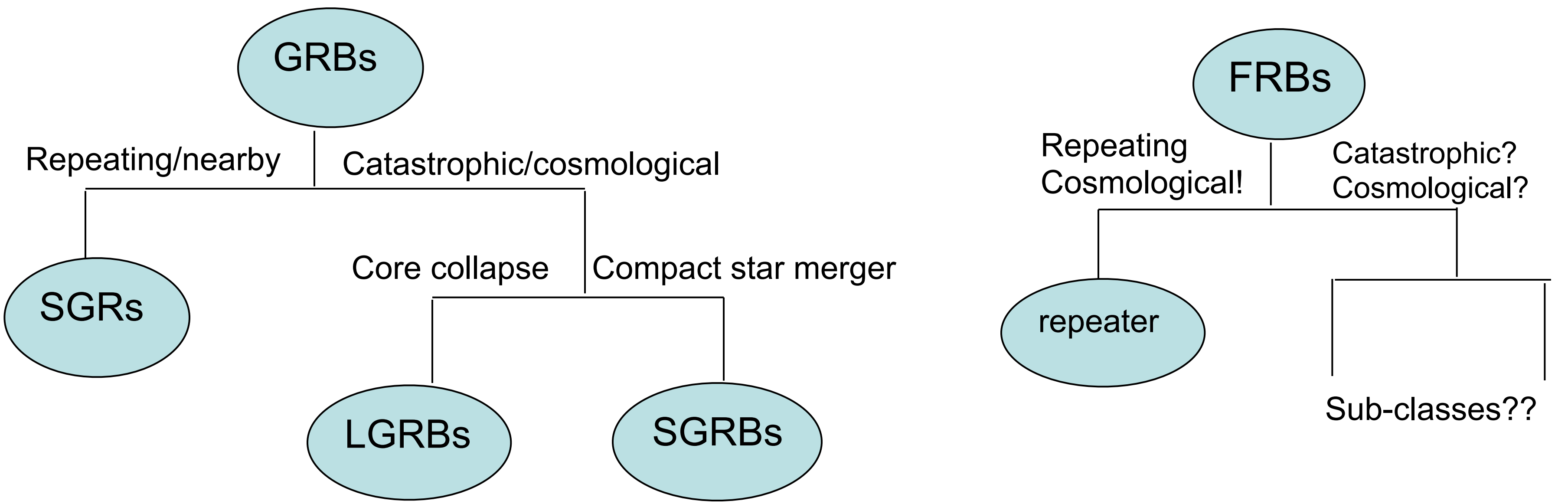
Table 1

#	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.	Schklovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Schklovskii	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 cycle 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

128 models

Multiple progenitor systems?



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

Following discussion not limited to repeating models

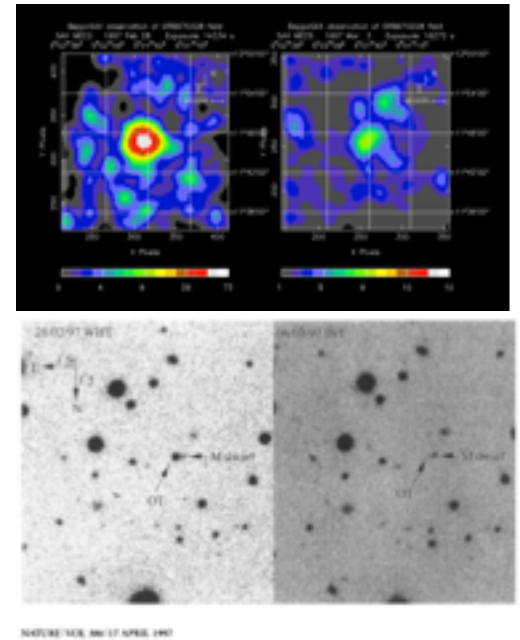
Plan

- Model-independent (parameter-dependent) predictions
  - Afterglow
  - Prompt emission in other wavelengths
- Model-specific predictions
  - Models without bright counterparts
  - Models with bright counterparts: SGR giant flare, GRB, SN, AGN, GW?
- Data
  - FRB 150418
  - FRB 131104
  - The repeater FRB 121102
- Latest ideas
  - Young magnetar?
  - Cosmic combs?

Model-independent (parameter-dependent) Predictions

Afterglow

- Any “explosion” would leave behind an afterglow through interaction between the ejecta and ambient medium
- Relativistic ejecta have brighter afterglows. Both FRBs and GRBs are relativistic
- However, isotropic emission energy differs by 12-13 orders of magnitudes!



GRB afterglow

$$F_{\nu,max} = (7.7 \text{ mJy}) \ (p+0.12)(1+z)^{3/2}\epsilon_{B,-2}^{1/2}E_{52}A_* D_{L,28}^{-2} t_d^{-1/2}$$

$$\nu_m = (4.0 \times 10^{14} \text{ Hz}) \ (p-0.69)(1+z)^{1/2}\epsilon_{B,-2}^{1/2}[\epsilon_e g(p)]^2 E_{52}^{1/2} t_d^{-3/2}$$

Detectable only if FRBs have very low efficiency in radio, so that a much larger energy kinetic energy is released to drive a bright afterglow

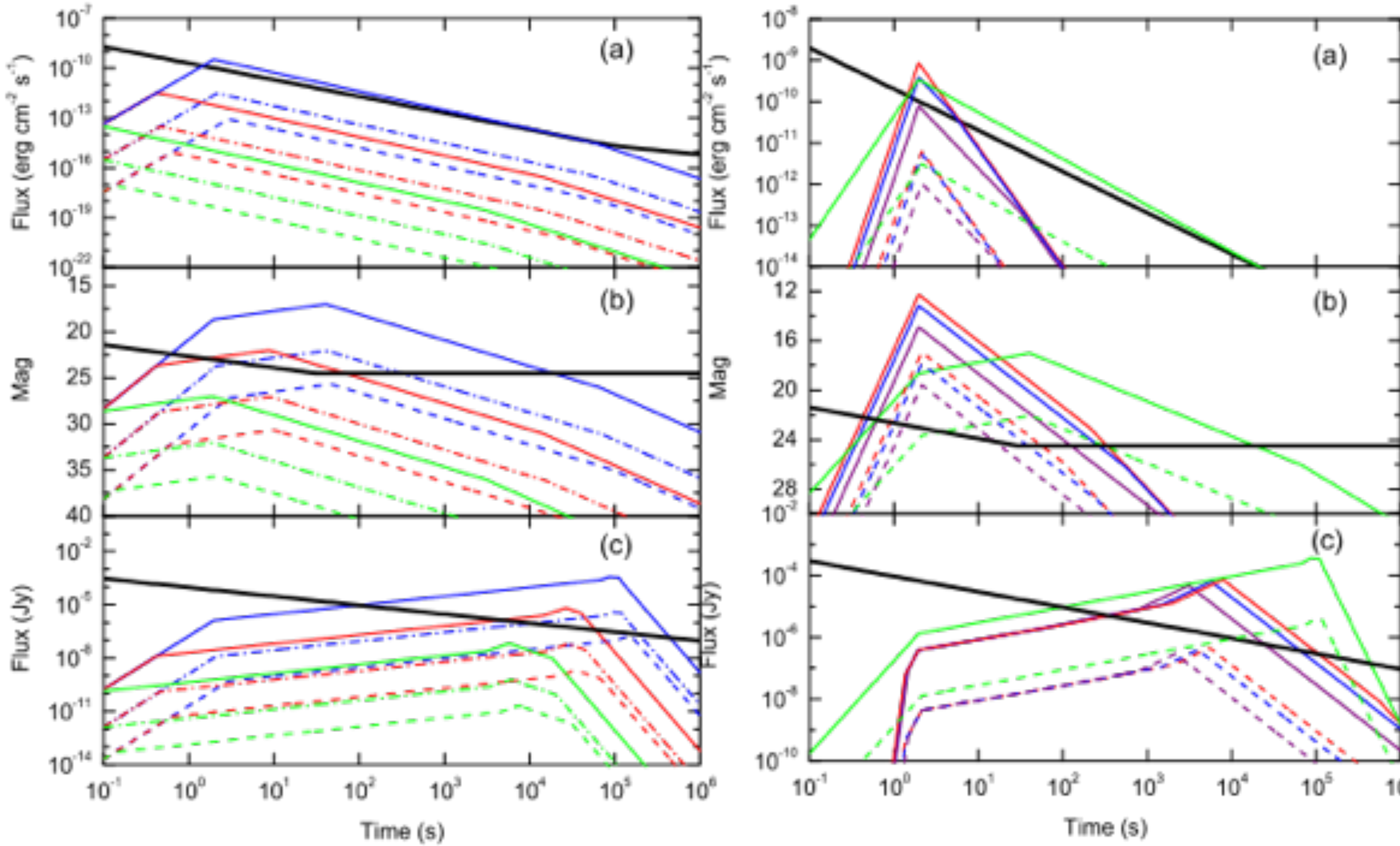
FRB Afterglows

(Yi, Gao & Zhang 2014, ApJL, 792, L21)

X-rays (XRT)

Optical (LSST)

Radio (EVLA)

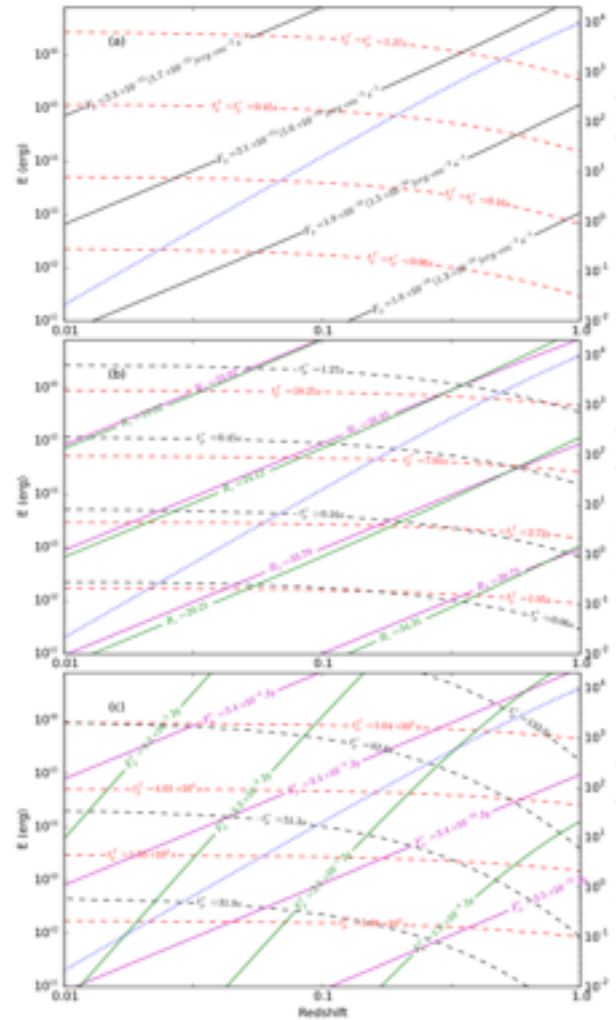


$E = 10^{47}$ (blue), 10^{45} (red), 10^{43} (green)
$z = 0.5$ (dashed), 0.1 (dash-dotted), 0.01 (solid)

Reverse vs. forward shock

FRB Afterglows

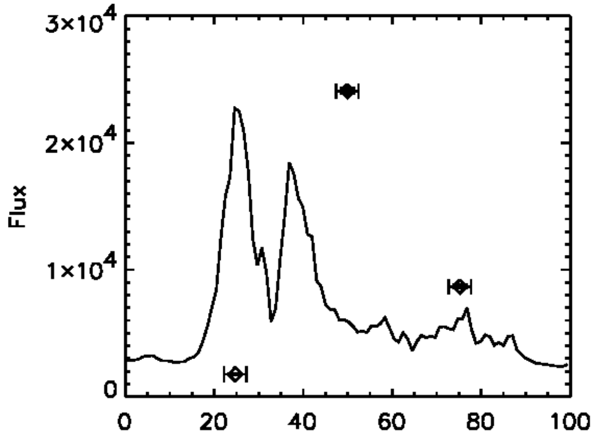
- Very faint!
- Observational strategy:
  - Rapid follow-up may not help much.
  - Wide field telescopes (X-rays and optical) may help
  - Best shot: deep follow-up observations in radio. However, much fainter than the steady nebula observed from the repeater.

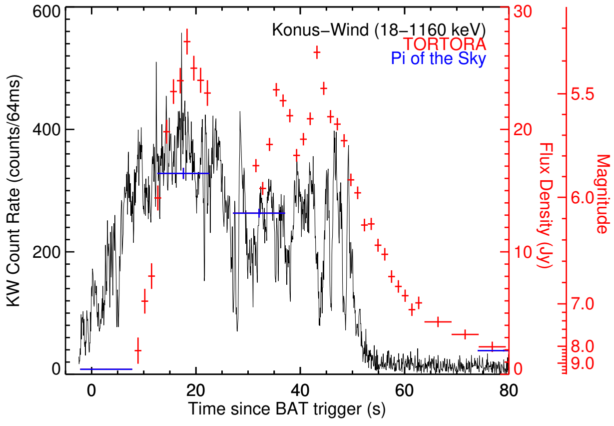


Prompt emission in optical?

(guess rather than prediction)

- No reliable prediction on optical emission (radio emission is coherent)
- Keep searching
- There might be a lot of fast optical bursts - may or may not related to FRBs.





GRB prompt optical emission

Model-specific Predictions

Models likely without a bright counterpart

- Pulsar nano-shots
- Pulsar magnetospheric instabilities
- Blitzars with a long delay (e.g. thousands of years after formation of supramassive NS)
- ……

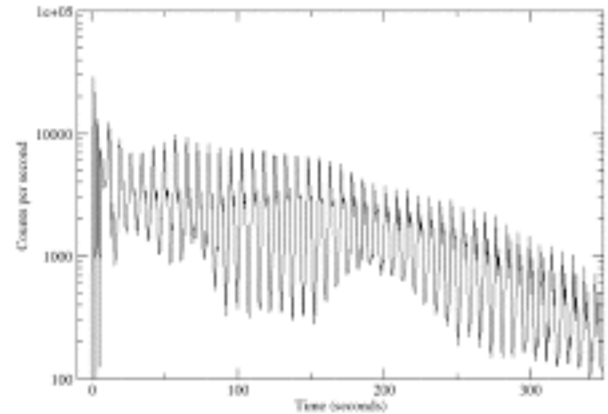
Models likely with a counterpart

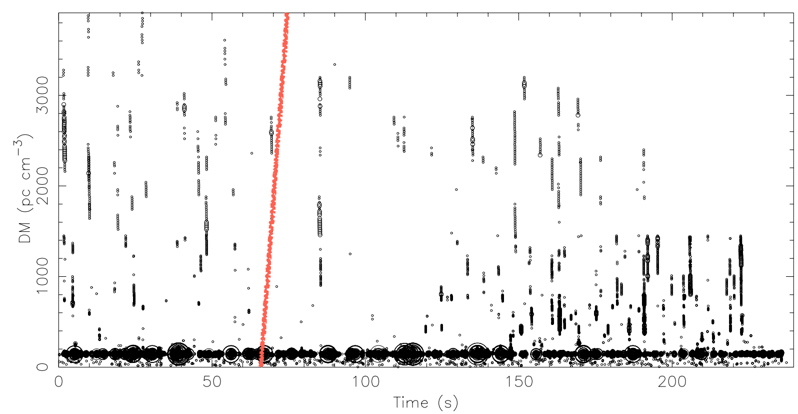
- FRB - SGR giant flare connection?
- FRB - GRB connection?
- FRB - SN connection?
- FRB - GW connection?

FRB - Magnetar giant flare connection?

Popov et al.; Kulkarni et al. Katz; …

- Short-hard spike detectable as short GRBs out to ~ 70 Mpc (non-detectable at z=0.193 unless flares are more energetic)
- No dispersed radio emission for SGR 1806-20



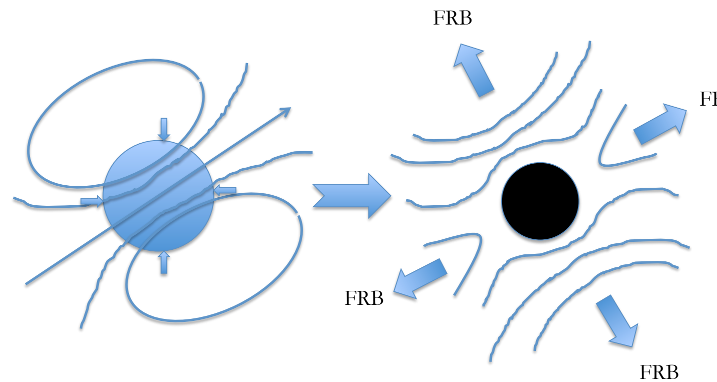


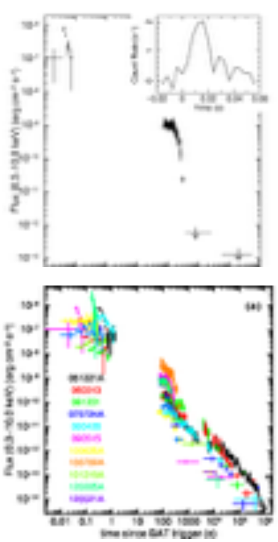
Tendulkar et al. (2016)

FRB - GRB connection?

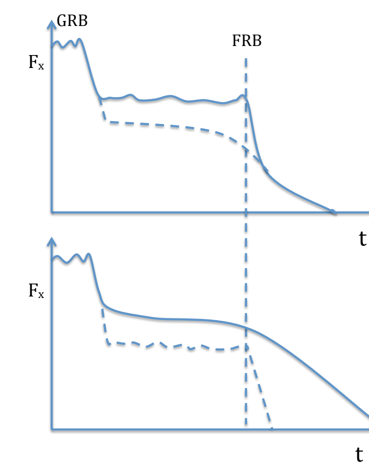
Zhang (2014); Murase et al. (2016); Dai et al. (2016)

- Blitzar in GRB
  - Supra-massive NSs as GRB engine
  - Collapse 100-10000 s after the burst
  - ~ 30% short GRBs have magnetar collapsing signature ~ 300 s after the bursts
- NS - NS mergers
  - Pre-merger unipolar induction (Piro 2012; Wang et al. 2016)
  - Charged compact star mergers (Zhang 2016)





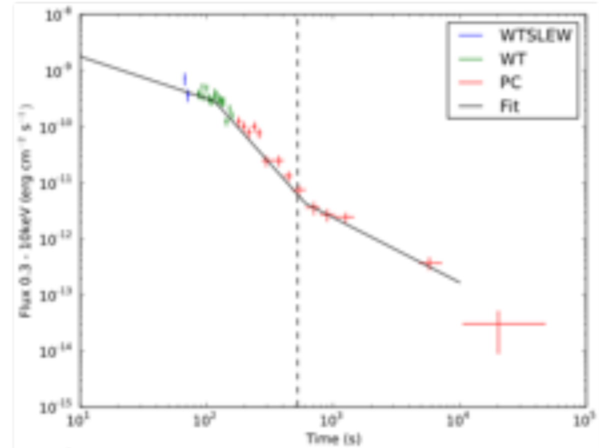
Rawlinson et al. 2010, 2013

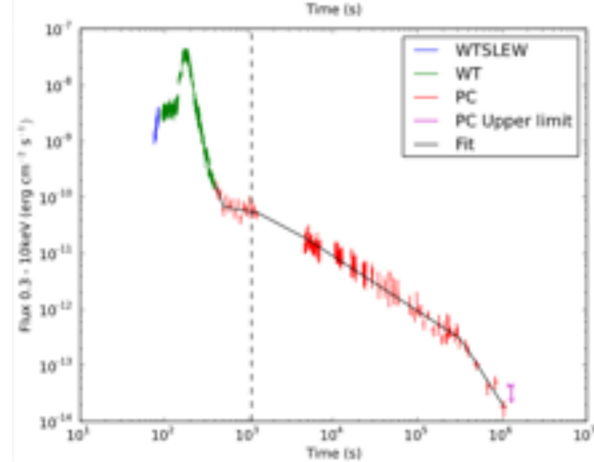


Zhang, 2014, ApJ, 780, L21

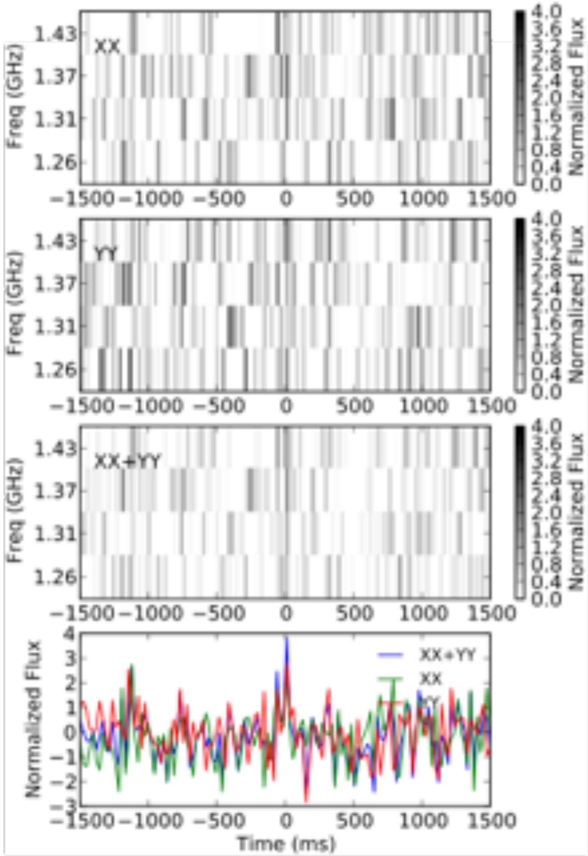
Early search

GRB 101011A

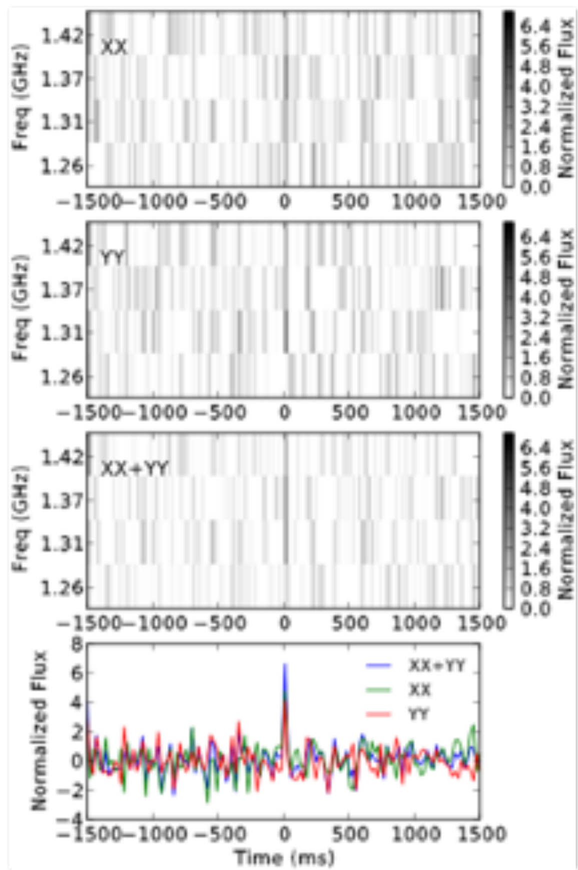




GRB 100704A



GRB 100704A

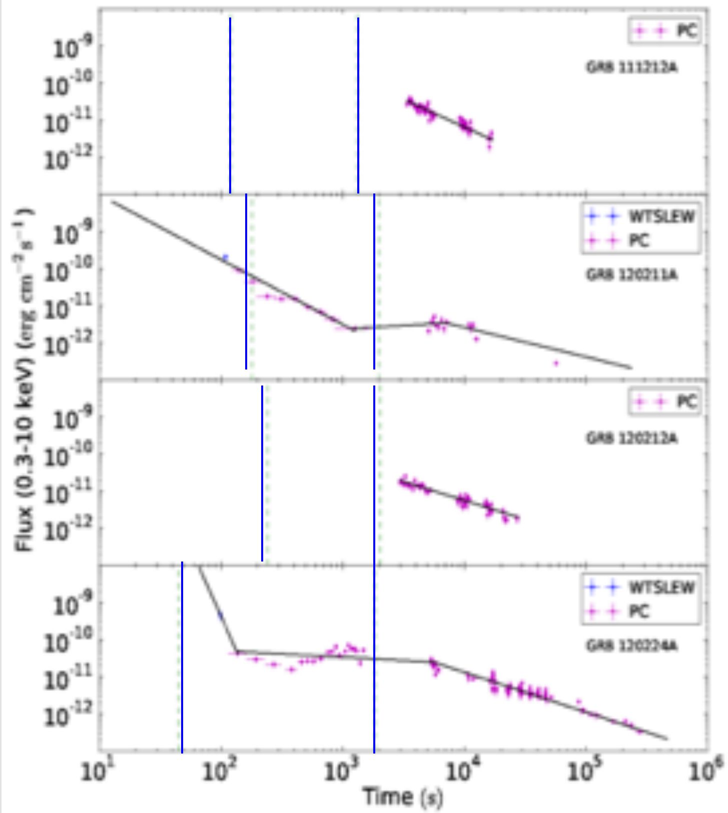


GRB 101011A

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

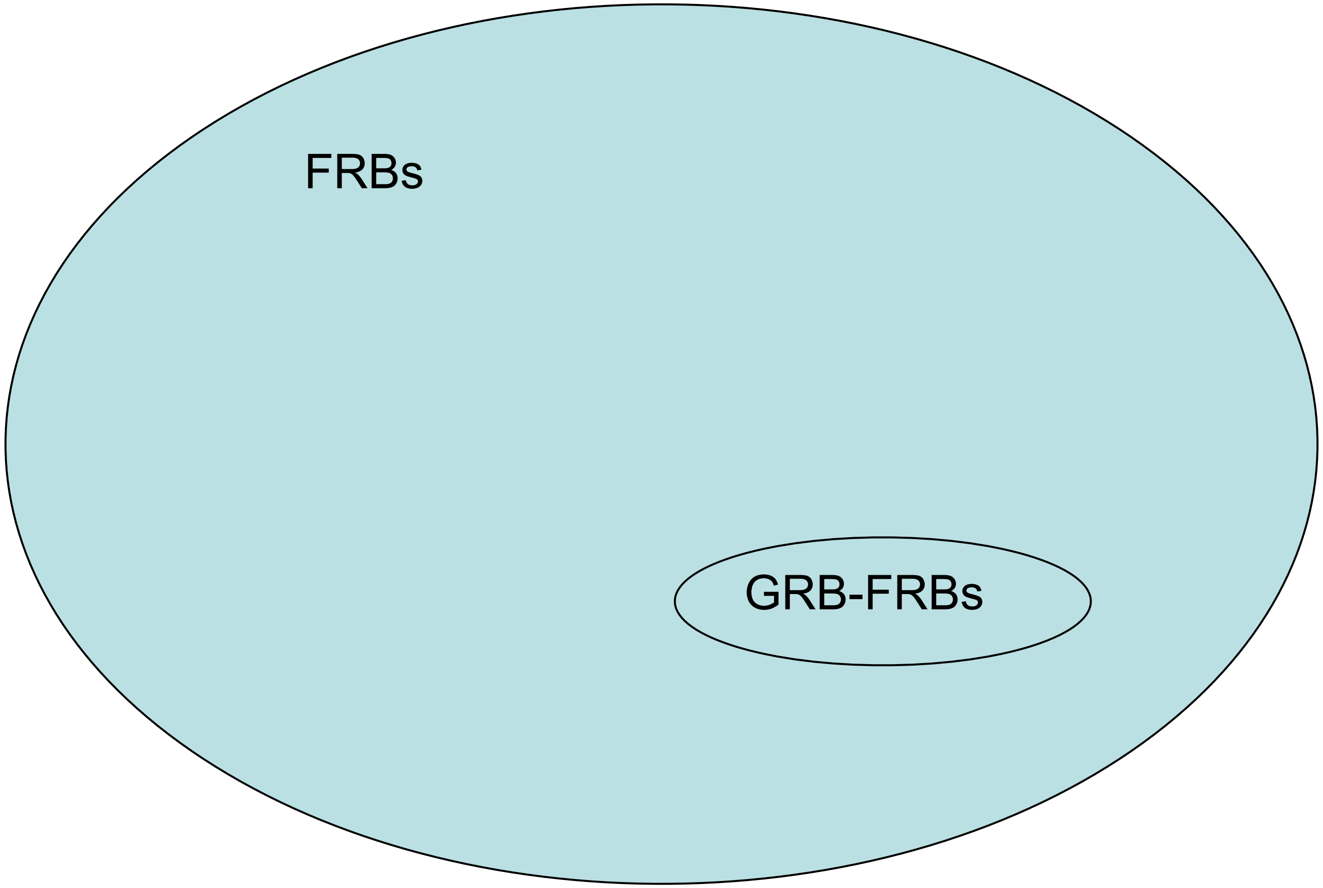
Search for an FRB in a right GRB at a right time

- Non detections in several more GRBs
- Non-detection is norm. To detect an FRB following a GRB, one needs to have
  - Right GRB (not a BH nor a stable magnetar)
  - At the right time (not before or after collapse)
  - With a bright enough flux (~Jy at z~0.5-1?)
- Rapid slew, continuous monitoring highly desired
- Especially 300 s after short GRBs!

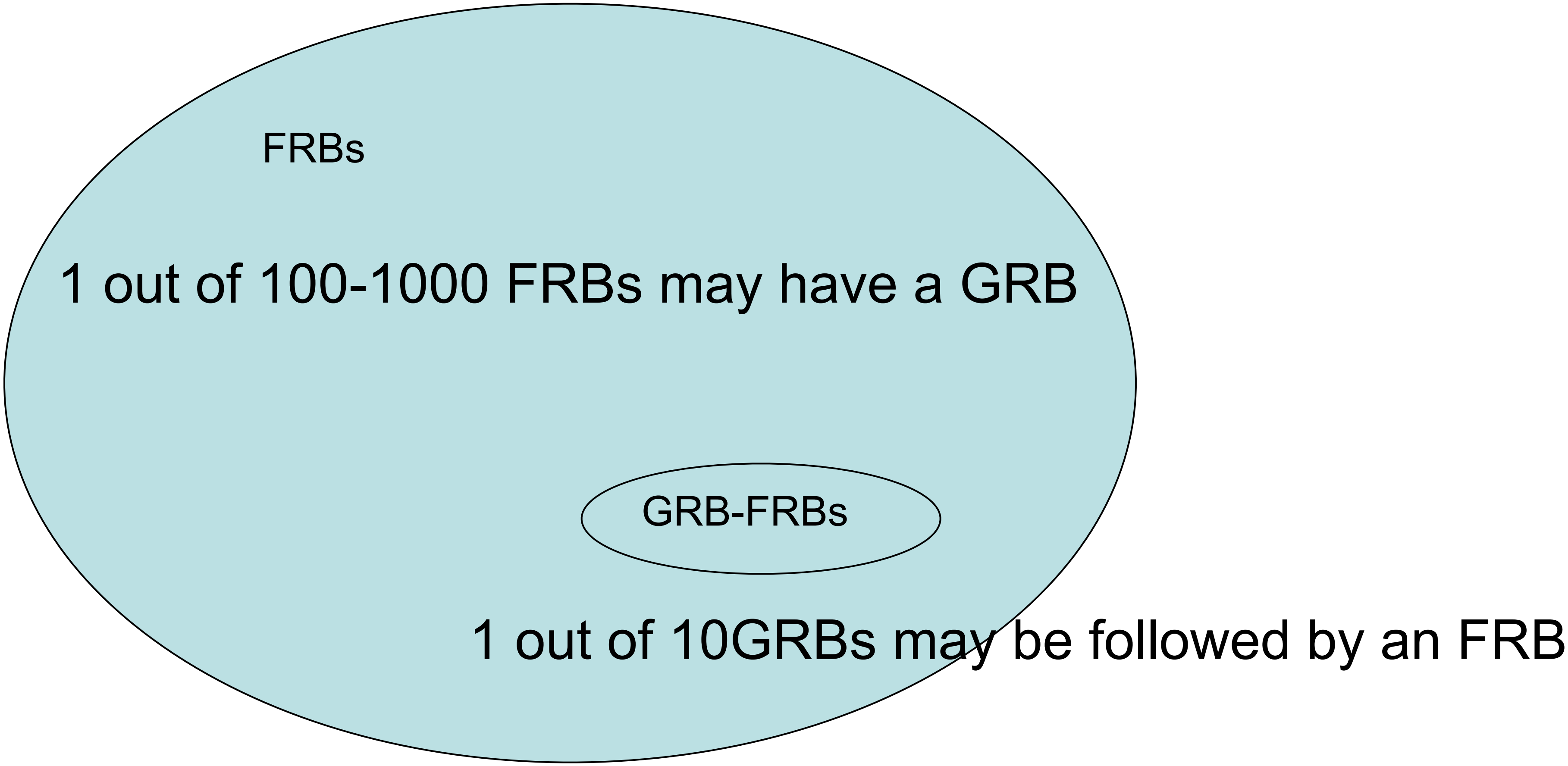


Palaniswamy et al., 2014, ApJ, 790, 63

FRB - GRB rates



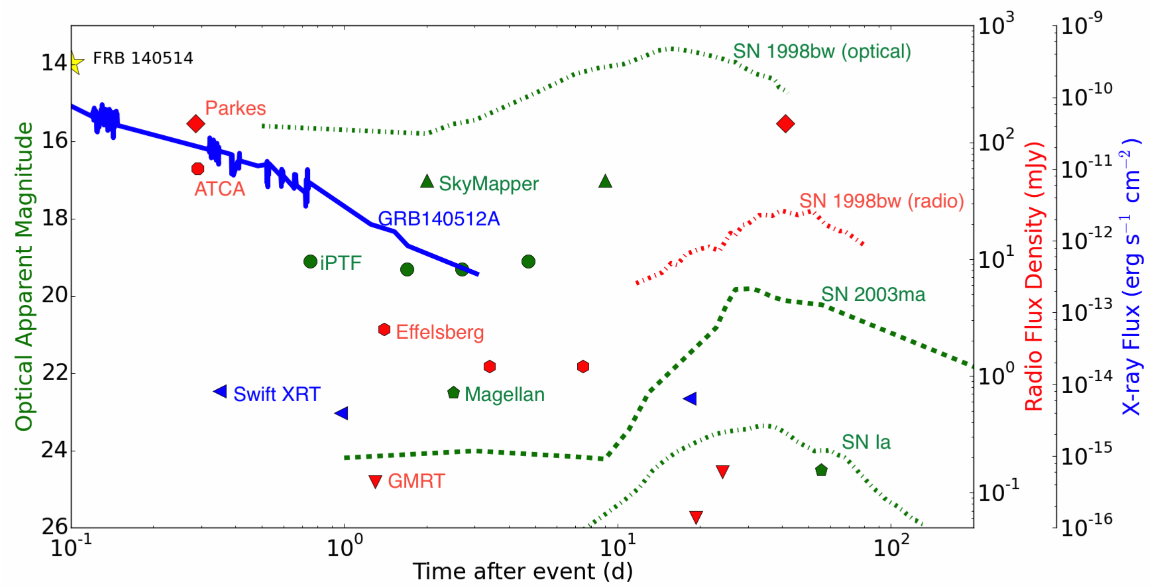
FRB - GRB rates



FRB - SN connection?

Kashiyama et al. (2013)

- WD - WD merger making a Type Ia SN - ruled out in large parameter space
- Importance of real-time follow-up



Petroff et al. (2015)

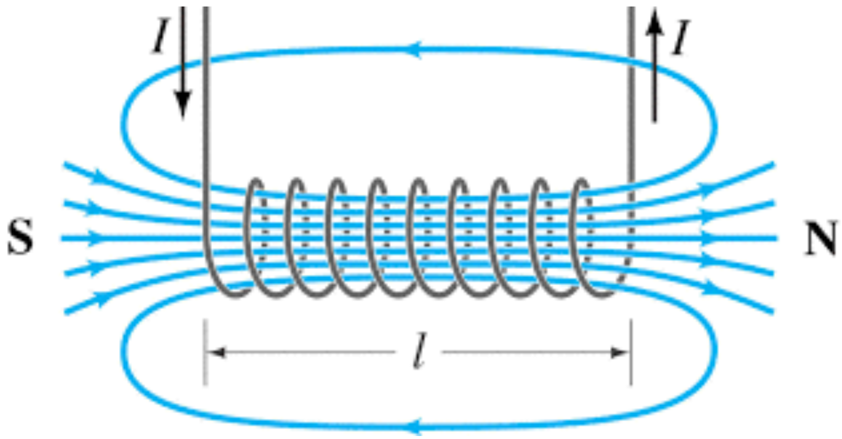
FRB - GW connection?

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

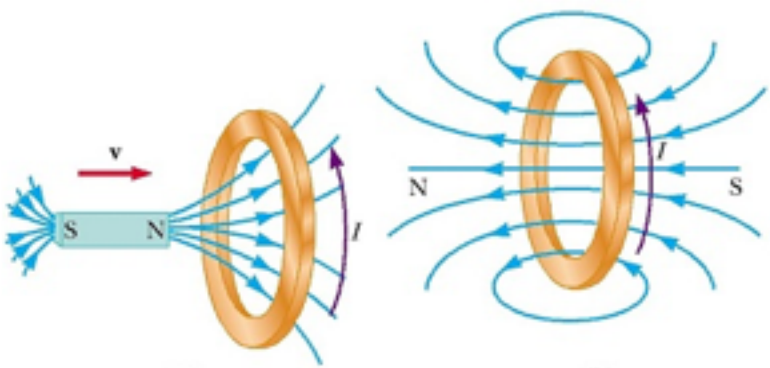
- Post-merger synchronization of the magnetosphere (NS-NS mergers only)
- Unipolar induction (NS-NS and possibly NS-BH mergers
- Pre-merger magnetospheric activities of mergers with at least one charged member (NS-NS, NS-BH, BH-BH mergers)

Charged BH merger model

(Zhang, ApJ, 827, L31)



$$\nabla \cdot E = 4\pi\rho$$
$$\nabla \cdot B = 0$$
$$\nabla \times E = -\frac{1}{c}\frac{\partial B}{\partial t}$$
$$\nabla \times B = \frac{4\pi}{c}J + \frac{1}{c}\frac{\partial E}{\partial t}$$



(a) (b)

Maxwell Equations

High school AP Physics E&M

Charged BH merger model

(Zhang, ApJ, 827, L31)

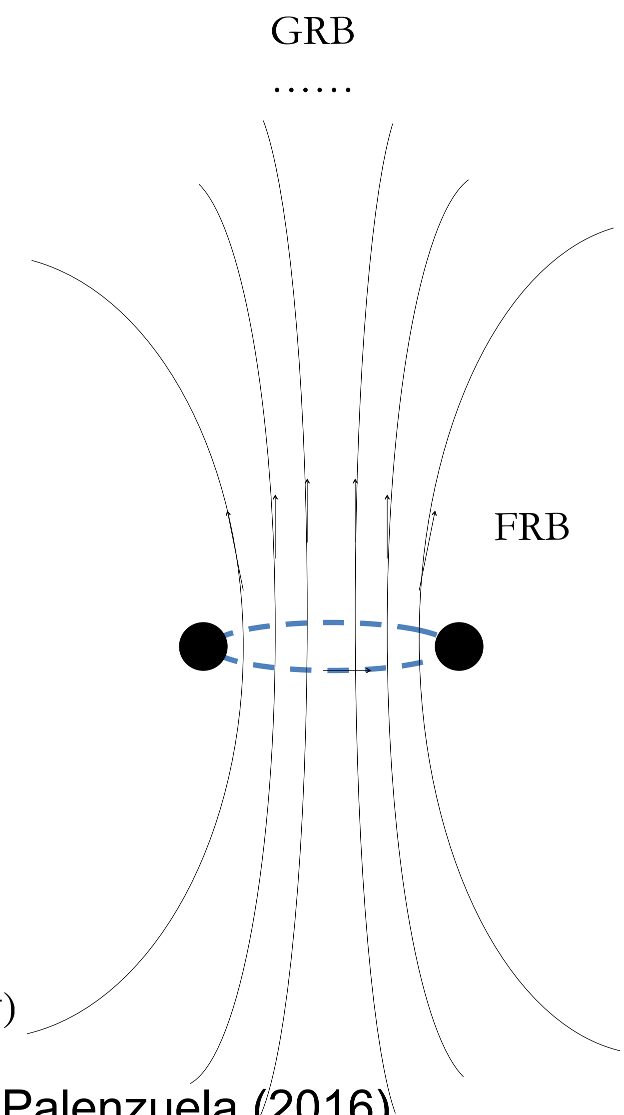
$$\mu = \frac{\pi I (a/2)^2}{c} = \frac{\sqrt{2GMa}Q}{4c} = \frac{\sqrt{2}G^{3/2}M^2}{c^2}\hat{q}\hat{a}^{1/2}$$
$$= (1.1 \times 10^{33}\ \mathrm{G\ cm^3}) \left(\frac{M}{10M_\odot}\right)^2 \hat{q}_{-4}\hat{a}^{1/2},$$

$$L_w \simeq \frac{2\ddot{\mu}^2}{3c^3} \simeq \frac{49}{120000}\frac{c^5}{G}\hat{q}^2\hat{a}^{-15}$$
$$\simeq (1.5 \times 10^{48}\ \mathrm{erg\ s^{-1}})\hat{q}_{-4}^2\hat{a}^{-15},$$

$$L_w \sim 0.4\hat{q}^2 L_{\rm GW}\hat{a}^{-10}.$$

$$Q = \hat{q}Q_c, \qquad \frac{da}{dt} = -\frac{2}{5}\frac{c}{\hat{a}^3}$$

$$Q_c \equiv 2\sqrt{G}M = (1.0 \times 10^{31}\ \mathrm{e.s.u.})\left(\frac{M}{10M_\odot}\right)$$



Can produce Fast radio bursts (FRBs) and short GRBs

$\hat{q} \sim (10^{-9}–10^{-8})$ $\qquad$ $\hat{q} \sim (10^{-5}–10^{-4})$

See also GR simulations by Liebling & Palenzuela (2016)

Merger & FRB rate

- BH-BH merger event rate density (Abbott et al. 2016)

$$(9 - 240)\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

- FRB event rate density

$$\dot{\rho}_{\mathrm{FRB}} = \frac{365\dot{N}_{\mathrm{FRB}}}{(4\pi/3)D_z^3} \simeq (5.7\times10^3\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}) \times \left(\frac{D_z}{3.4\ \mathrm{Gpc}}\right)^{-3}\left(\frac{\dot{N}_{\mathrm{FRB}}}{2500}\right),$$

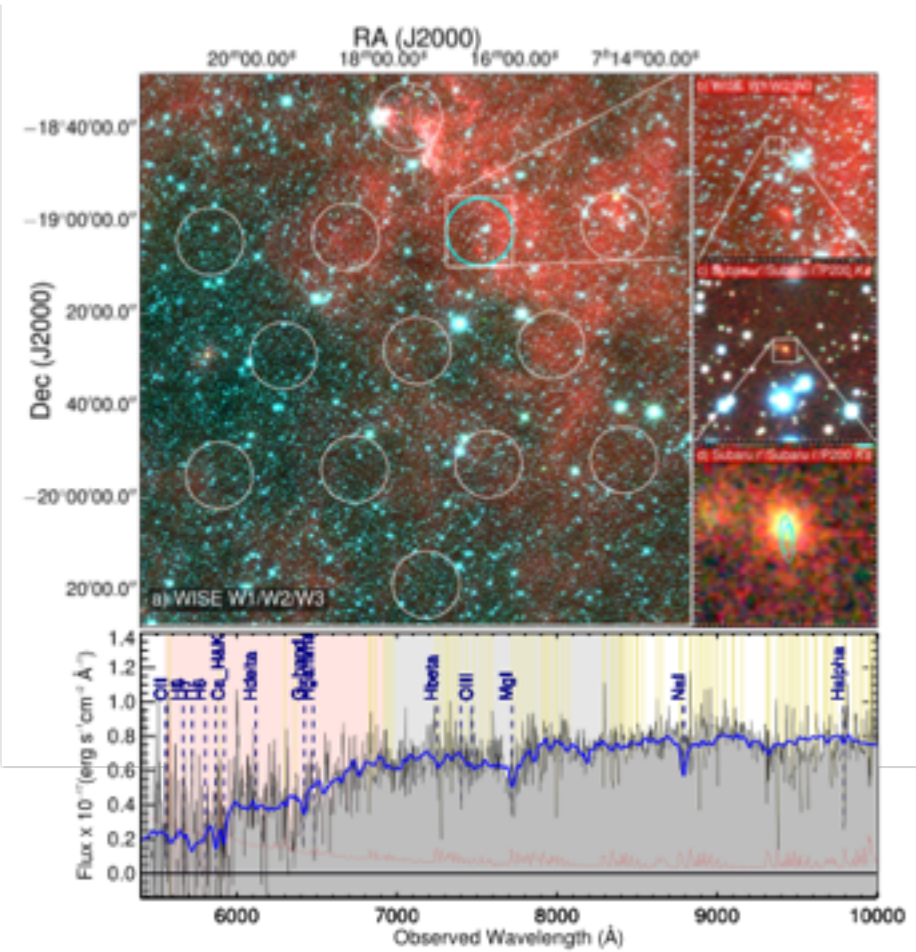
- Adding NS-NS, NS-BH mergers, may account for a good fraction of FRBs

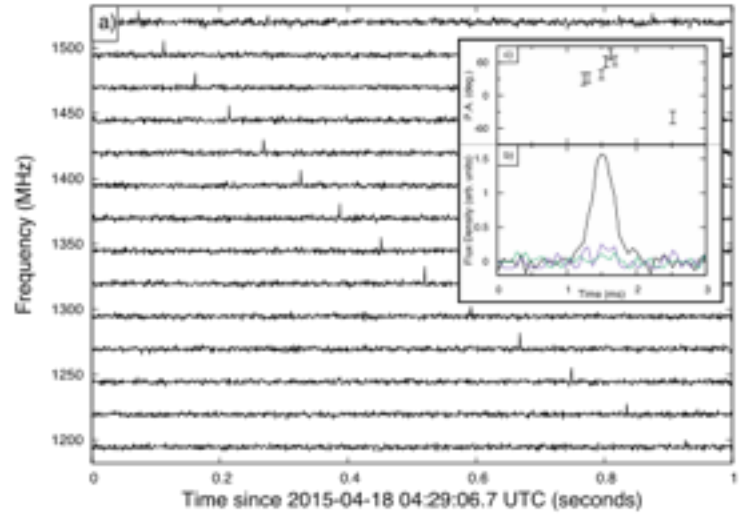
What do data tell us?

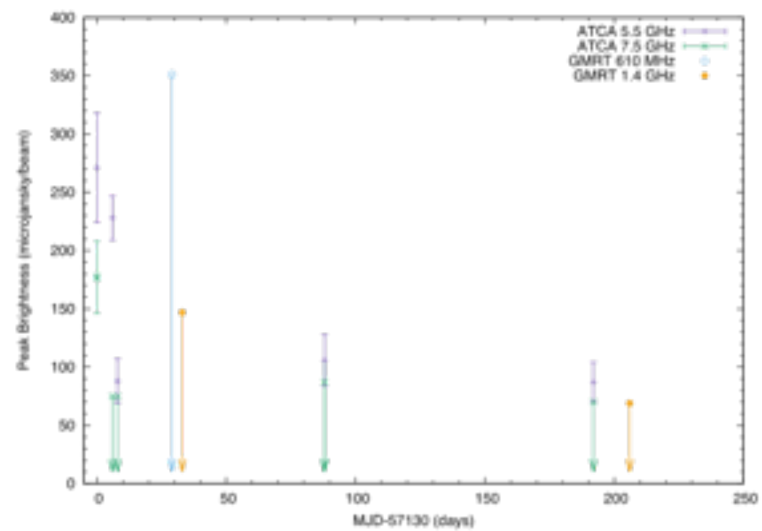
Any counterpart discovered?

FRB 150418

(Keane et al. 2016, Nature)







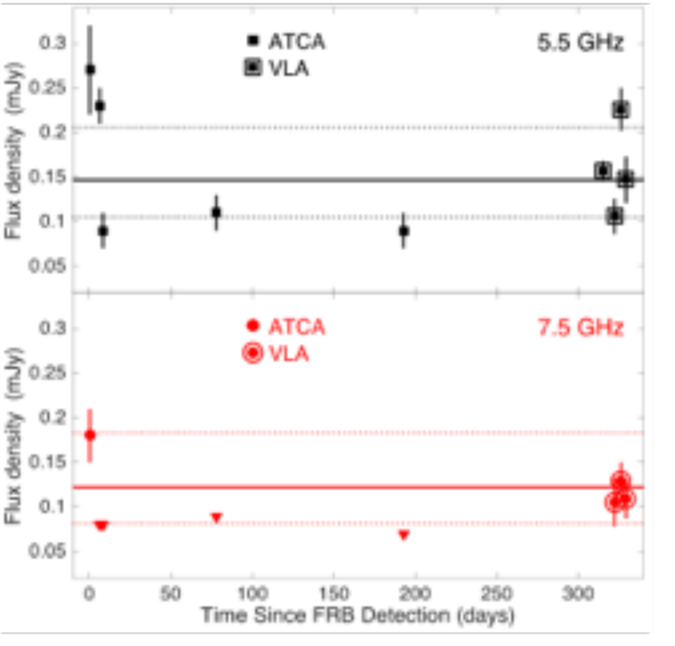
z = 0.492

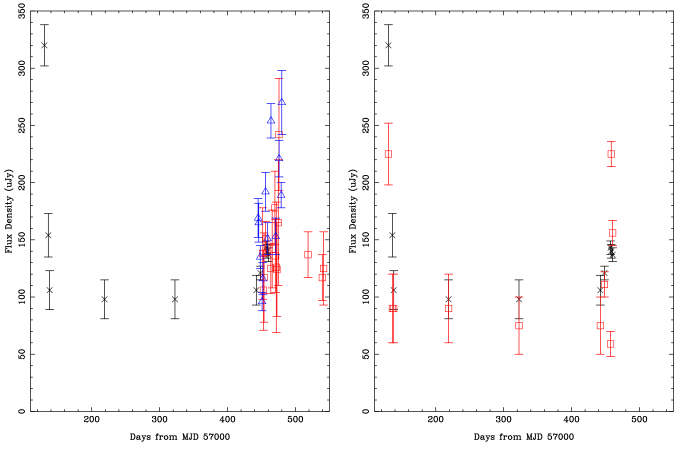
If afterglow, energy is comparable to a GRB!

Flaring AGN - connection to FRB?

- Re-brightened to the original level (Williams & Berger 2016; Vedanthem et al. 2016; Johnston et al. 2016)
- AGN flare or scintillation?
- An unrelated background source or is there a connection between the AGN and the FRB?

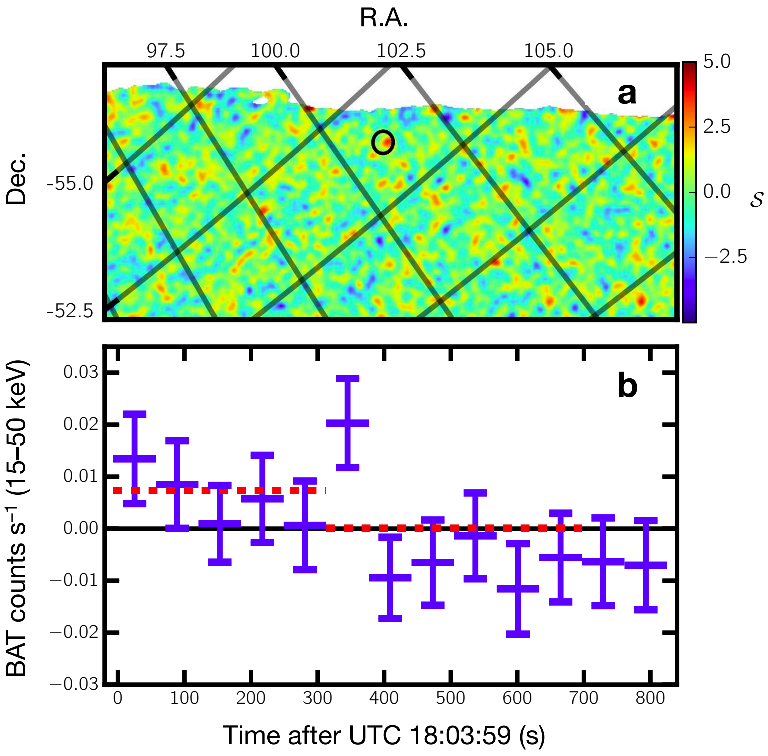
- Low probability of having the bright flare coincides with FRB both in space and in time (Li & Zhang 2016)

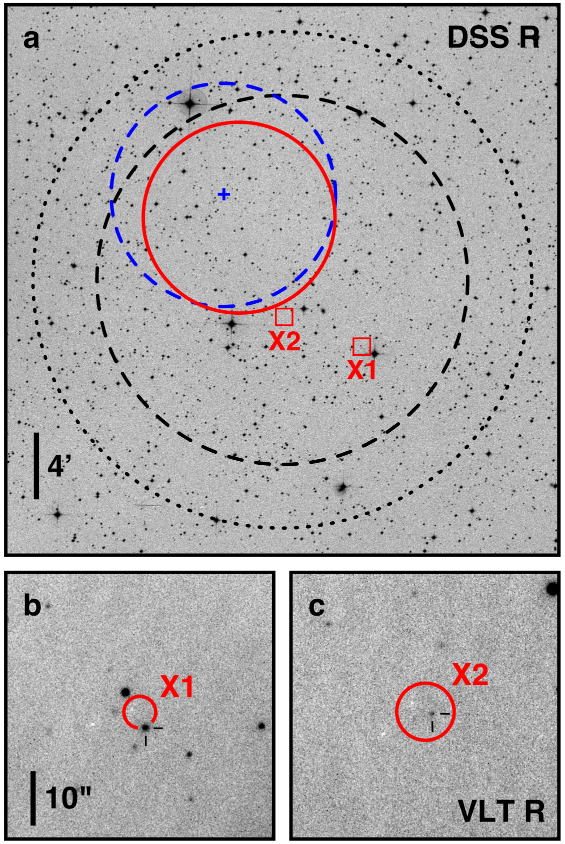




FRB 131104 - Swift J0644.5-5111

(DeLaunay et al. 2016, ApJL; Murase et al. 2017, ApJL)

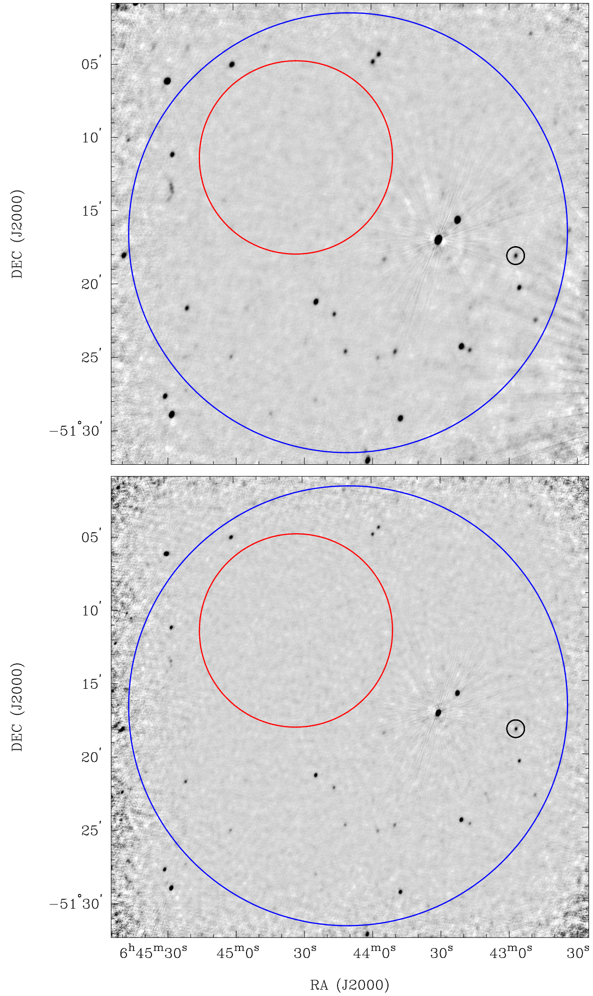




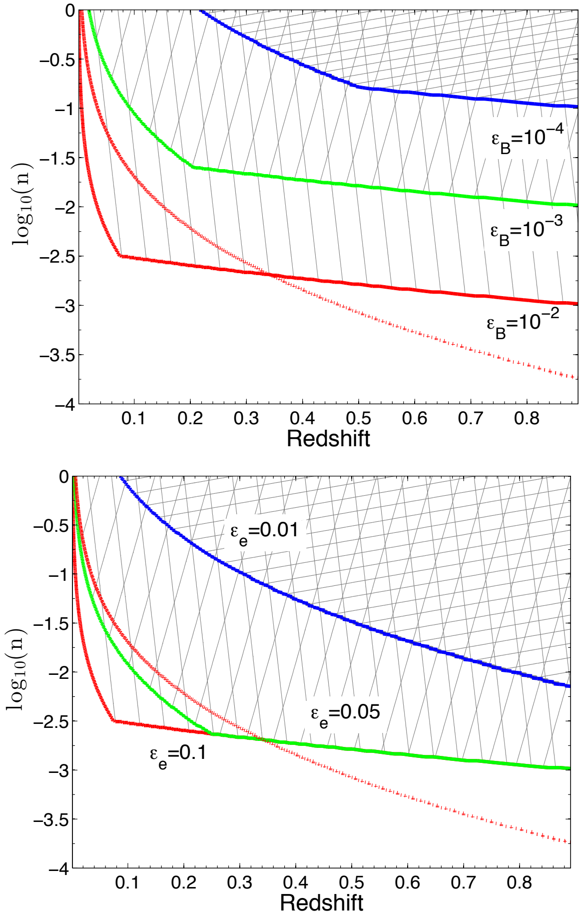
A faint GRB association? 4.2σ

FRB 131104 - Swift J0644.5-5111
No radio afterglow

(Shannon & Ravi; Murase et al.; Gao & Zhang; Dai et al.)

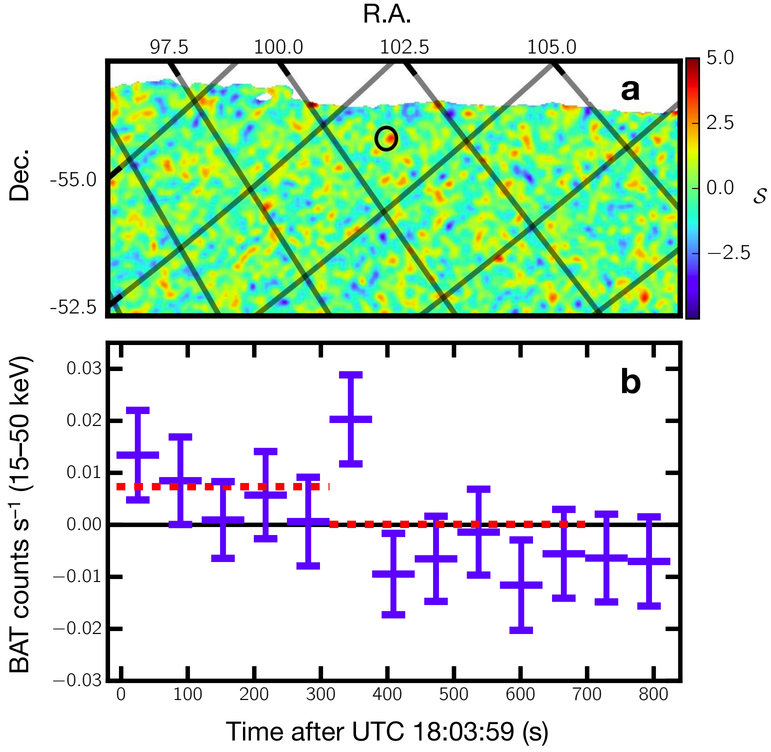


Shannon & Ravi 2016



Gao & Zhang 2017

Does it make sense?



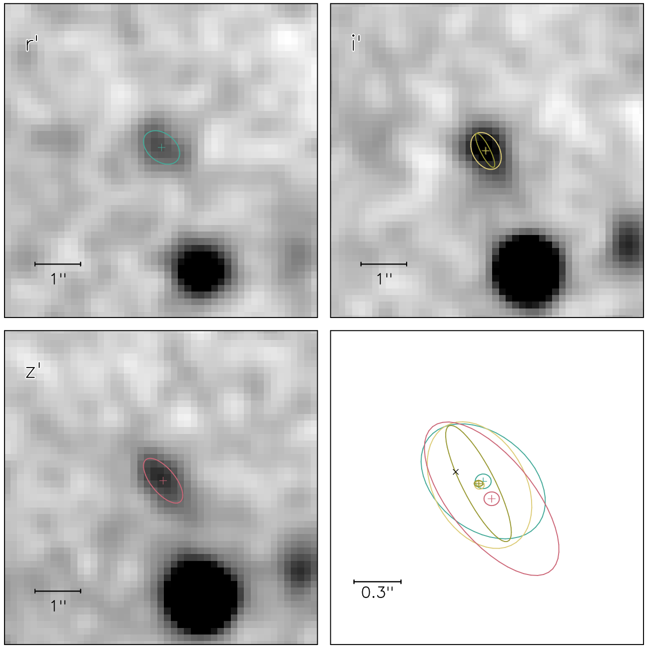
- Not exactly.
- Model predictions:
  - Either FRB after the GRB (blitzar scenario)
  - or FRB before the GRB (merger scenario)
- Data:
  - GRB started at least 7 s before the FRB

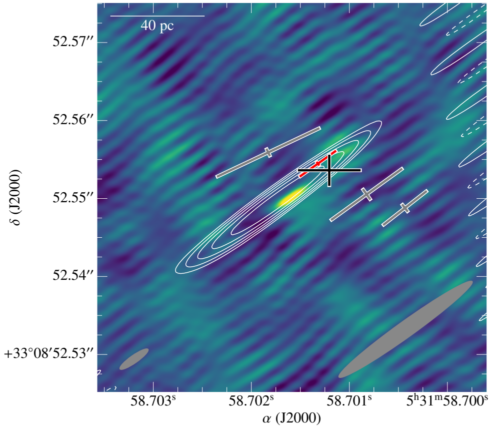
The repeater FRB 121102

Chatterjee et al.; Marcote et al.; Tendulkar et al.

- Located in a star forming galaxy
- Associated with a steady radio source

- What is the relationship between the radio source and FRBs?



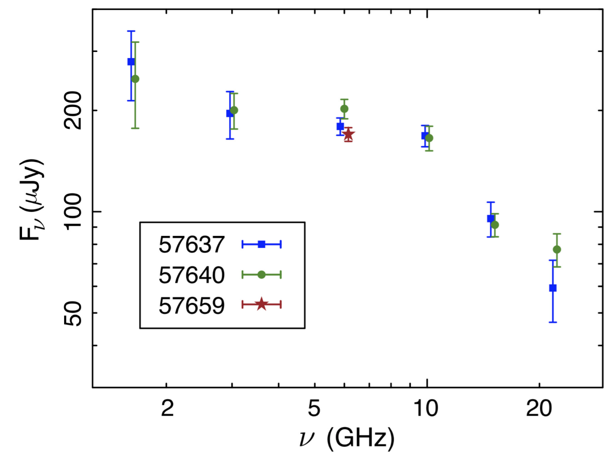


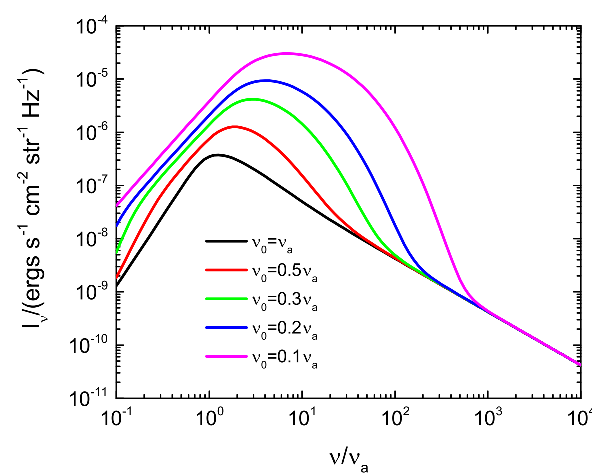
Latest ideas

Magnetar-powered FRBs in a nebula

Yang et al. (2016); Murase et al. (2016); Metzger et al. (2017)

- A magnetar powers both the nebula and FRBs?
- Preceded by a long GRB or super-luminous SN? - A connection with GRB and SN?
- Synchrotron heating of the nebula by FRBs?
- Issue: No evolution of DM for the repeater



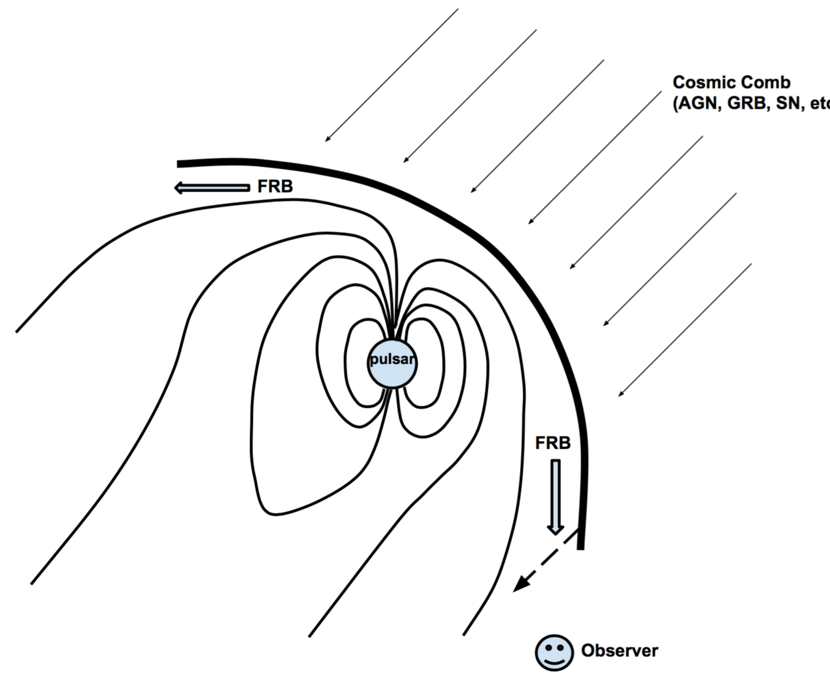


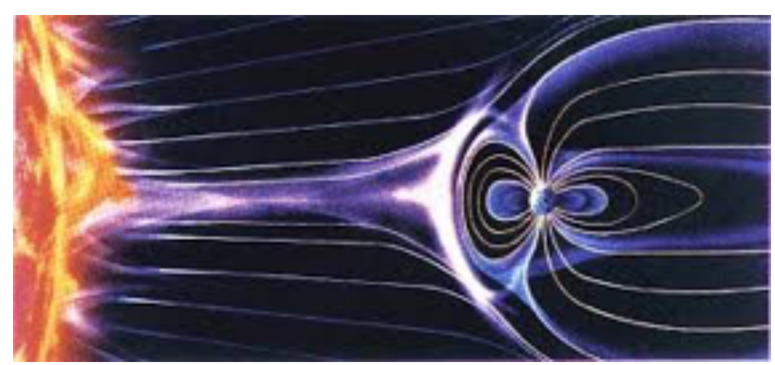
Yang et al. 2016, ApJL, 819, L12

Cosmic combs

Zhang (2017, ApJL, arXiv:1701.04094)

- Condition: ram pressure > magnetic pressure
- Source of comb: AGN, GRB, SN, TDE, companion …
- A unified model
  - FRB 150418: combed by an AGN
  - FRB 131104: combed by a GRB
  - Repeater: “marginally” combed by an unsteady nebula wind

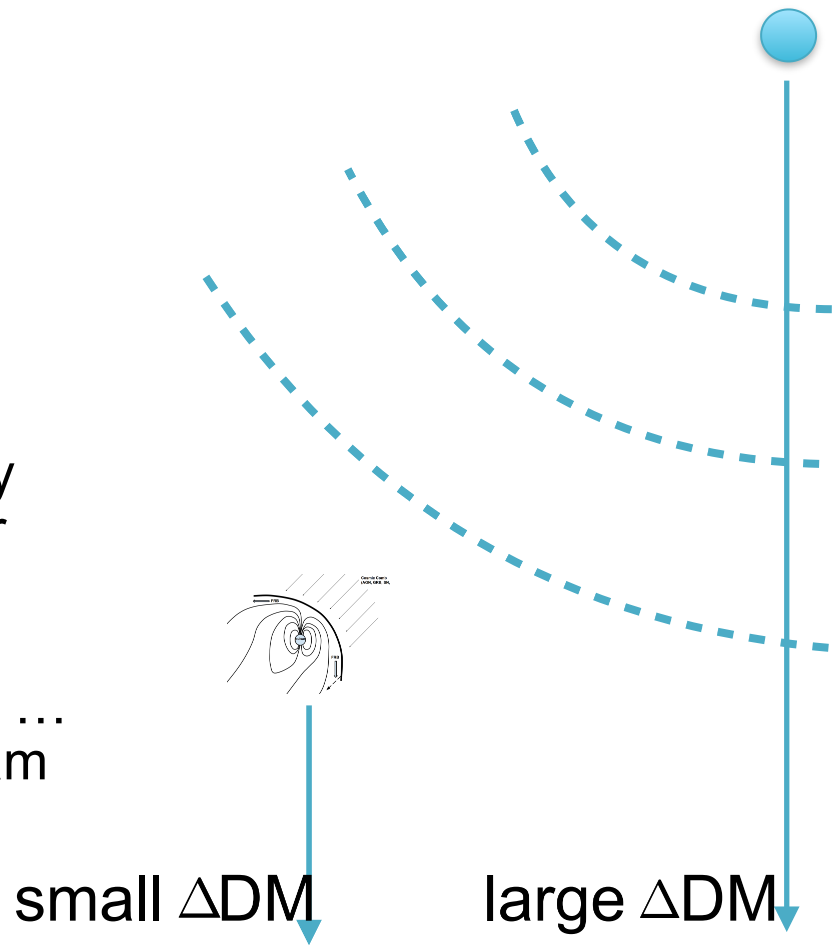




Cosmic combs

Zhang (2017, ApJL, arXiv:1701.04094)

- Advantages:
  - Additional energy source other than spindown and magnetic energy: kinetic energy of the stream
  - Can repeat or not
  - Insignificant DM evolution
- Predictions
  - FRB 150418: may (or may not) repeat during another AGN flare
  - Association of FRBs with AGNs, GRBs, SNe, TDEs … anything produces a stream
  - Or no association at all (a companion comb)



Conclusions

- FRB counterparts would reveal their progenitor(s)
- Model-independent and model-specific predictions (none realized)
- Some counterparts (or counterpart candidates) detected. Observations are perplexing and inconsistent
- Continue multi-wavelength, multi-messenger observations!
- Don’t over-estimate the creativity of Nature, but don’t under-estimate it, either!