# Cosmological Fast Radio Bursts from Binary White Dwarf Mergers

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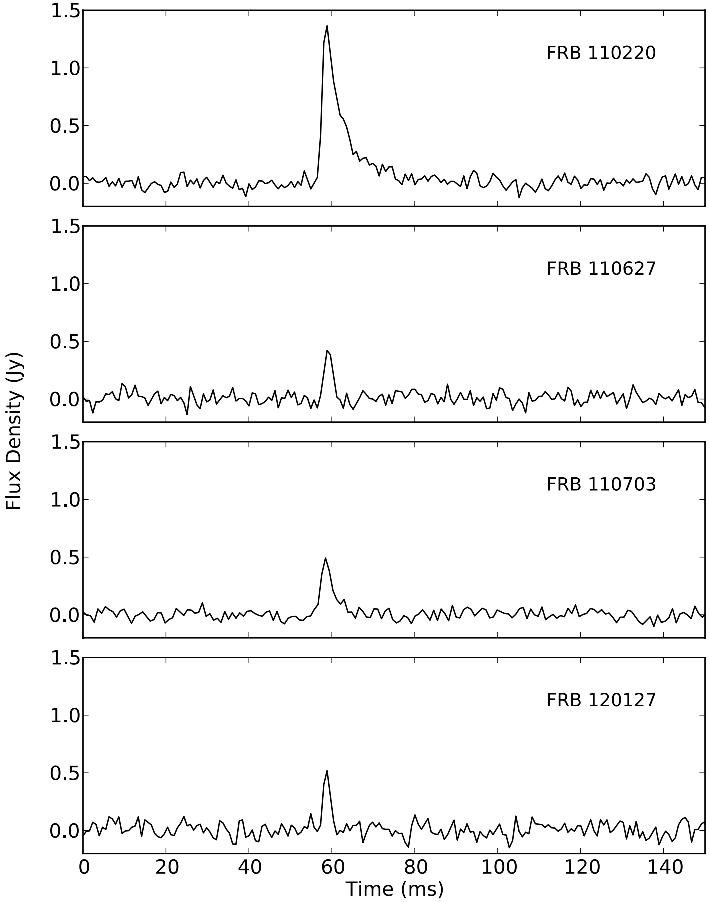
2. Possible Origins
   - Binary White Dwarf Merger Scenario
3. Future Prospects

# 1. Cosmological(?) Fast Radio Bursts

# Fast Radio Bursts

Parks 64m "High Transient Radio Universe" survey
High latitude (-70 deg < b < -30 deg)

Thornton+13



$$\nu \sim 1.4 \text{ GHz}$$

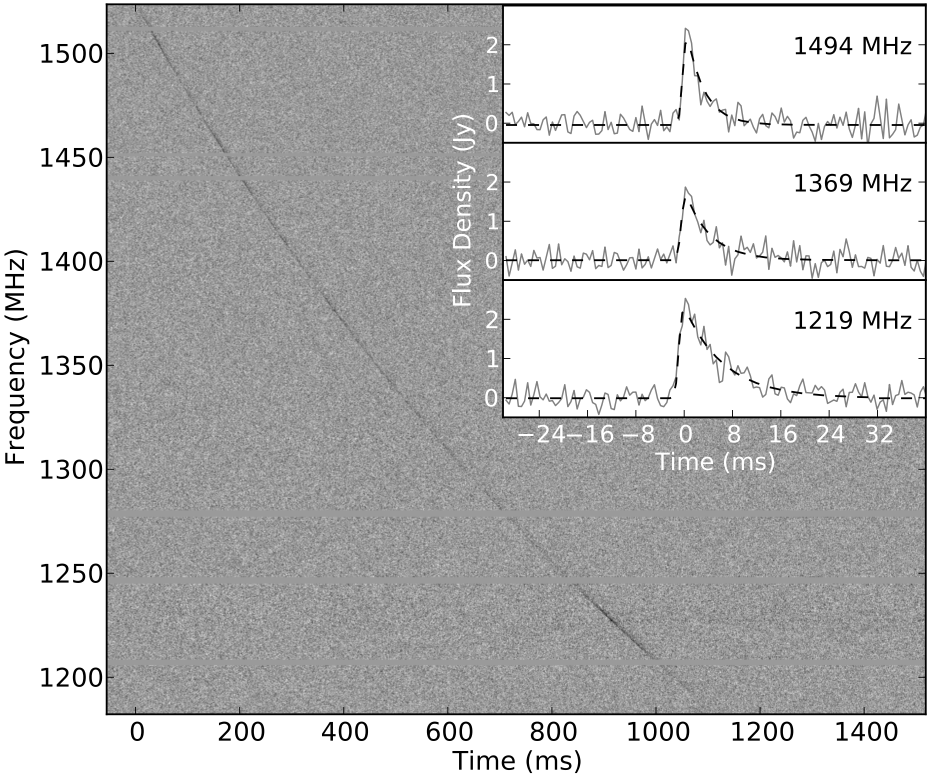
$$S_\nu \sim 0.4\text{-}1.3 \text{ Jy}$$

$$\Delta t < 5 \text{ ms}$$

# Fast Radio Bursts

Parks 64m “High Transient Radio Universe” survey
High latitude (-70 deg < b < -30 deg)

Thornton+13

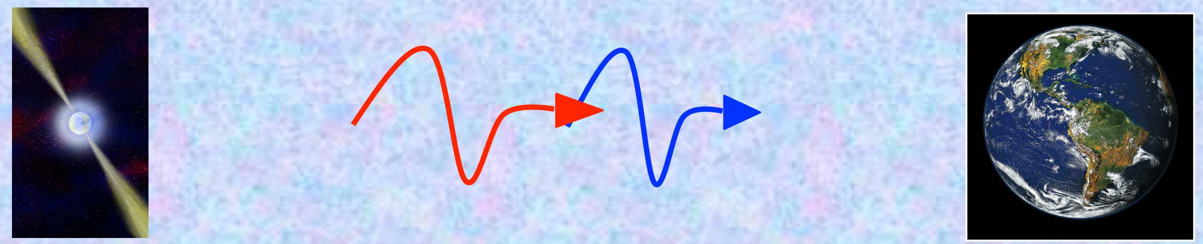


$\fallingdotseq \nu^{-2}$ arrival time pulse sweep

Only detected in a single beam

# Radio Dispersion

Dispersion relation in ionized media $\omega^2 = k^2c^2 + \omega_{pe}^2 \quad \omega_{pe} = \sqrt{\frac{4\pi n_e e^2}{m_e}}$

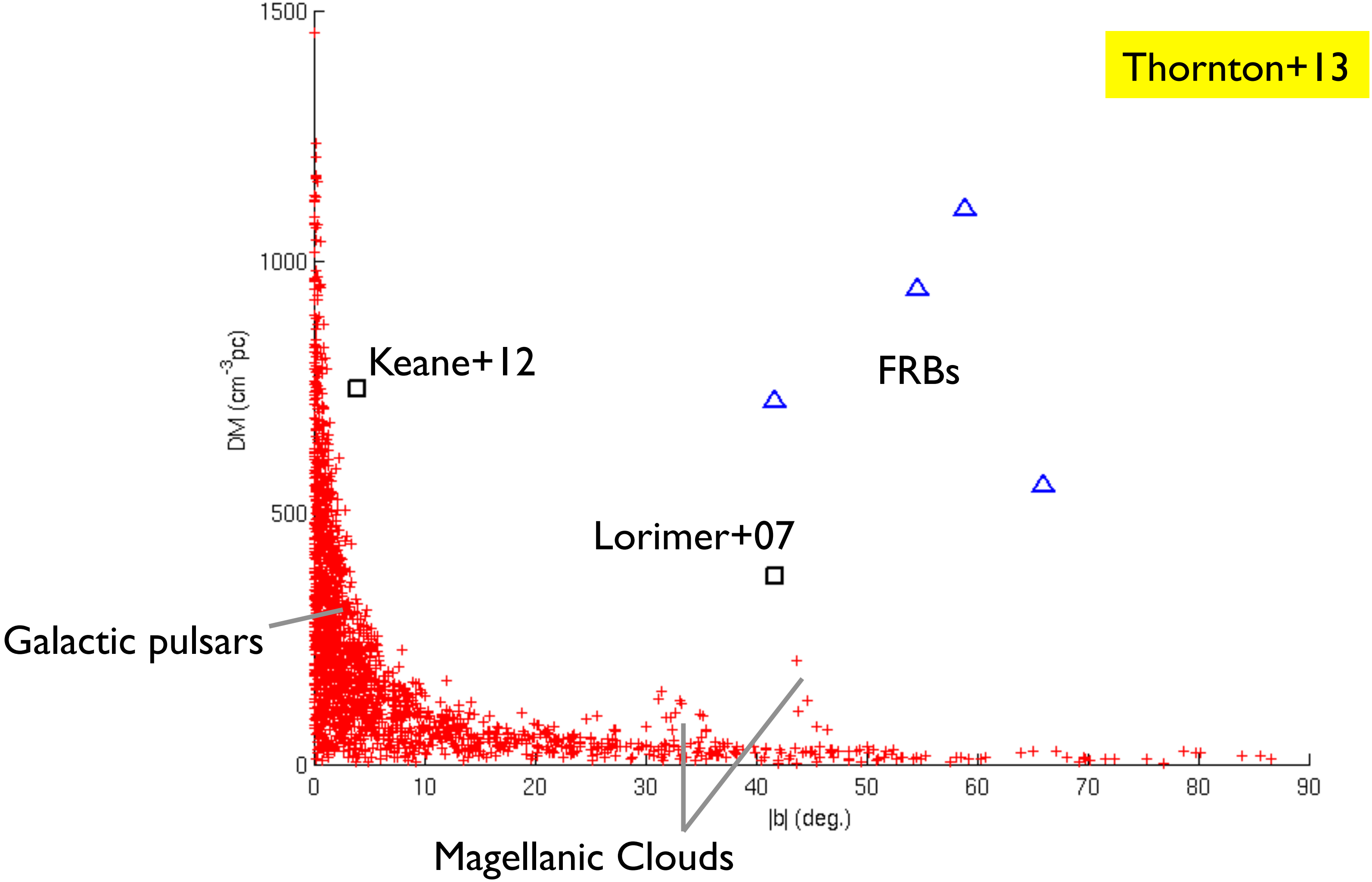


arrival time: $T = \int^L \left(\frac{\partial \omega}{\partial k}\right)^{-1} ds \sim \frac{L}{c} + \frac{2e^2}{m_e c}\frac{1}{\nu^2}\boxed{\int^L n_e ds}$

$\equiv DM$

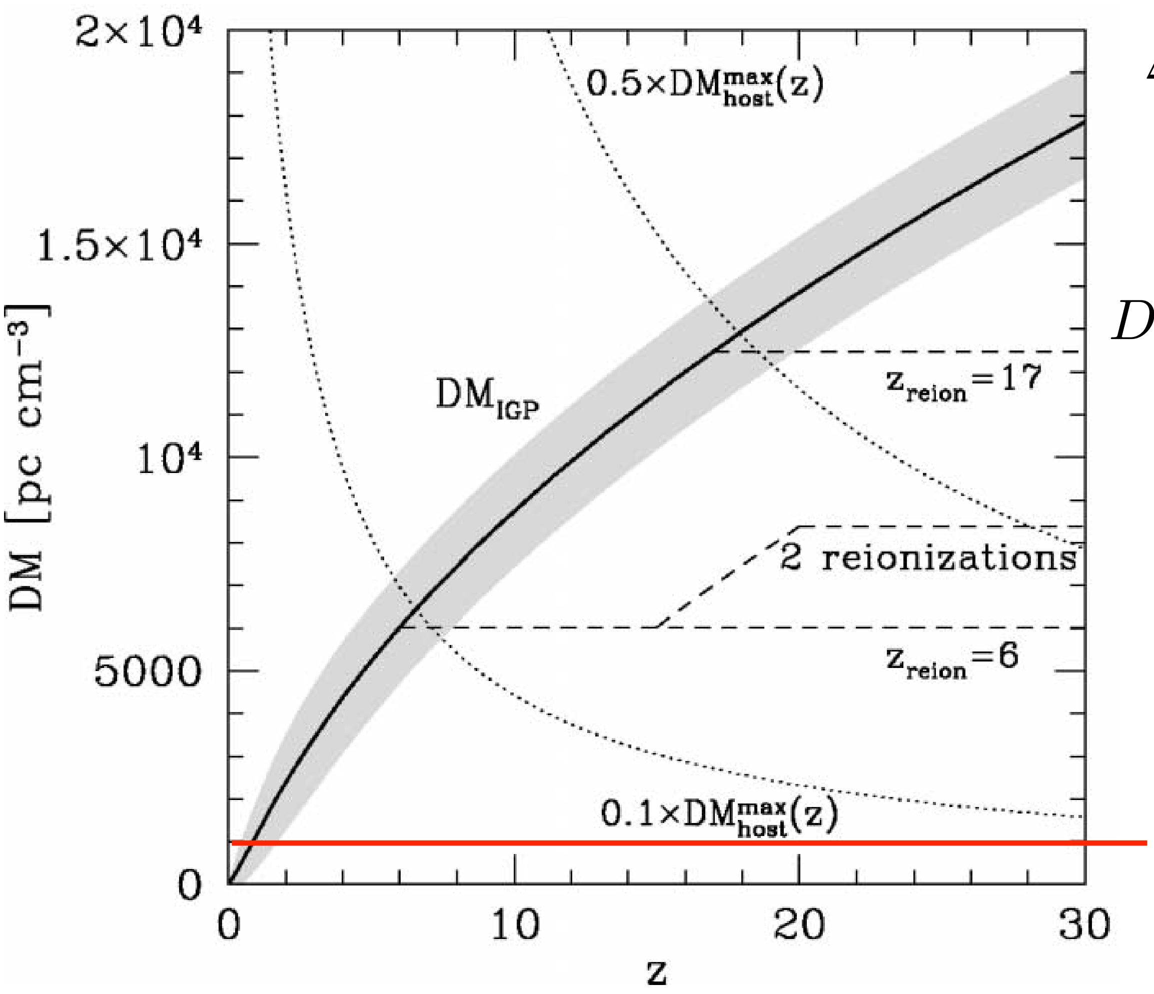
$$\Delta T \sim 4.2 \text{ s} \left(\frac{\nu}{\text{GHz}}\right)^{-2}\left(\frac{DM}{10^3 \text{ cm}^{-3} \text{ pc}}\right)$$

# Galactic Dispersion



# Intergalactic Dispersion

Ioka 03; Inoue 04



$$\Delta t = \int_0^z dz \frac{dt}{dz} \frac{1}{2} \frac{(1+z)\nu_{pe}^2}{[(1+z)\nu]^2}$$

$$\Downarrow$$

$$DM_{IGM} = n_{e,0} \frac{c}{H_0} \times \int_0^z \frac{(1+z)dz}{[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}}$$

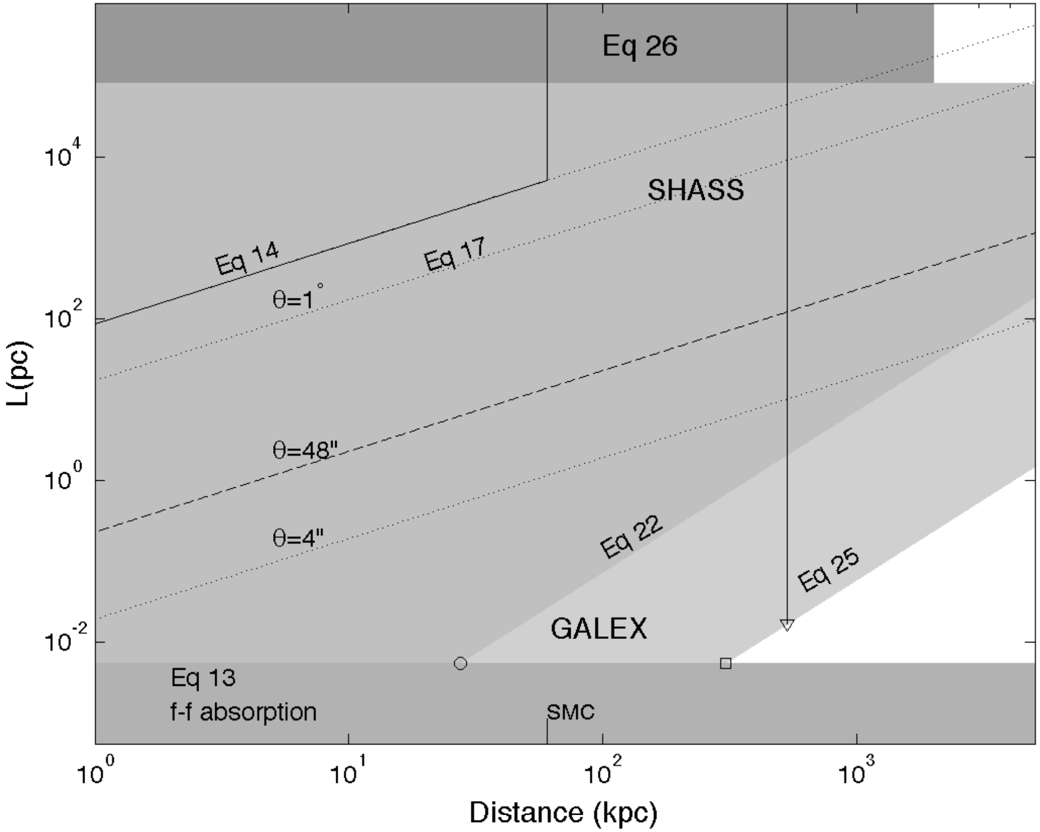
(including missing baryons)

$$DM \sim 10^3 \ \mathrm{cm}^{-3} \ \mathrm{pc}$$
$$@z \sim 1$$

# Lower limits on the distances

No direct feature from the ionized region

⇒ constraints on the size ($L$) and the distance ($d$)



The sources are extragalactic,

or

The dispersions are intrinsic.

c.f. "Perytons"

Kulkani+14

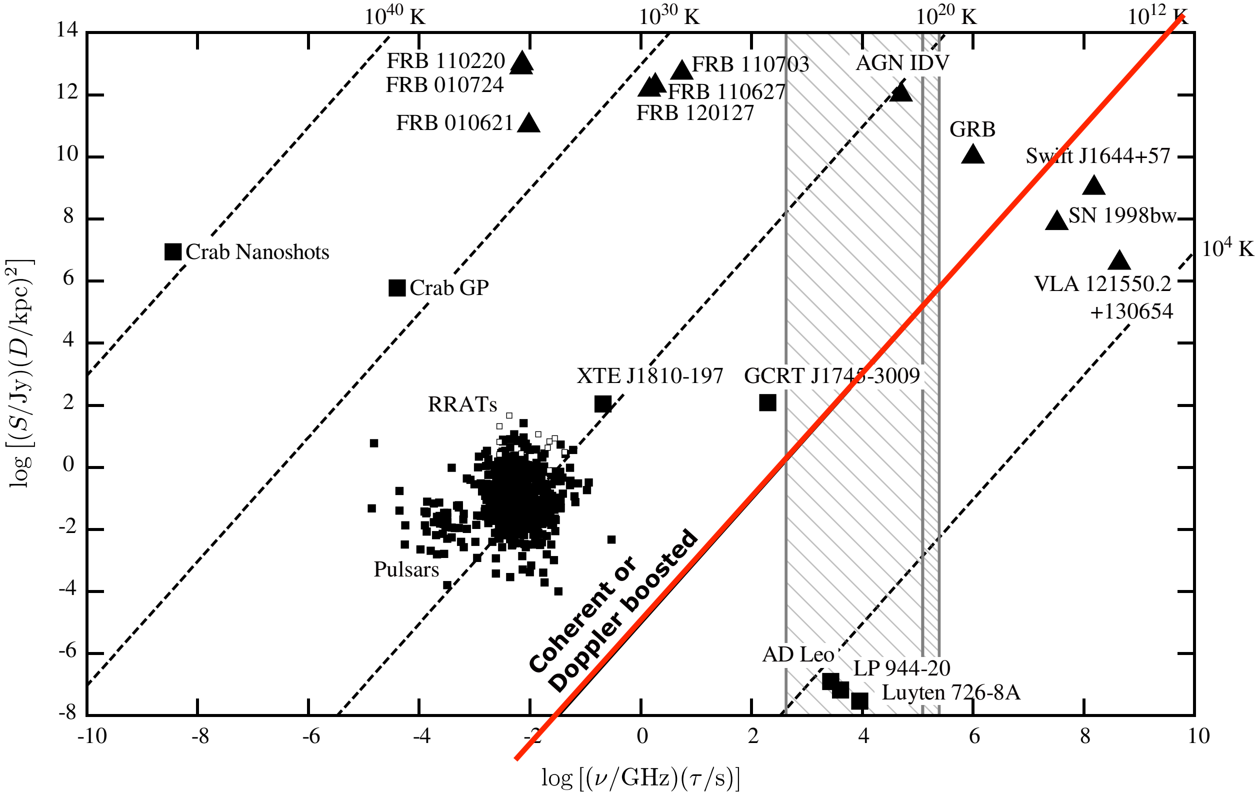
# If cosmological …

# Event rate

Thornton+13

- Observing 4078 $\mathrm{deg}^2$ (0.098 sky) for 270 s
  $\Rightarrow R_{\mathrm{FRB}}(F \sim 3$ Jy ms$) \sim 10^4\ \mathrm{sky}^{-1}\ \mathrm{day}^{-1}$
- Lorimer burst (FRB 010724)
  $\Rightarrow R(F \sim 150$ Jy ms$) = 225\ \mathrm{sky}^{-1}\ \mathrm{day}^{-1}$
  consistent with $N \propto F^{-3/2}$
- **$R_{\mathrm{FRB}} \sim 10^{-3}\ \mathrm{yr}^{-1}\ \mathrm{gal}^{-1}$**
  c.f. $R_{\mathrm{CCSN}} \sim 10^{-2}\ \mathrm{yr}^{-1}\ \mathrm{gal}^{-1}$
  $R_{\mathrm{NS\text{-}NS}} \sim R_{\mathrm{GRB}} \sim 10^{-5}\ \mathrm{yr}^{-1}\ \mathrm{gal}^{-1}$

# Brightness Temperature



Aoki+14

$$T_B \sim 6\times 10^{33}\ \mathrm{K}$$
$$\times S_{\mathrm{Jy}}\nu_{\mathrm{GHz}}^{-2}\delta t_{\mathrm{ms}}^{-2}\Gamma^{-3}d_{L,\mathrm{Gpc}}^{2}$$

⇒

coherent emission

unless $\Gamma > 10^7$

# Cosmological FRBs

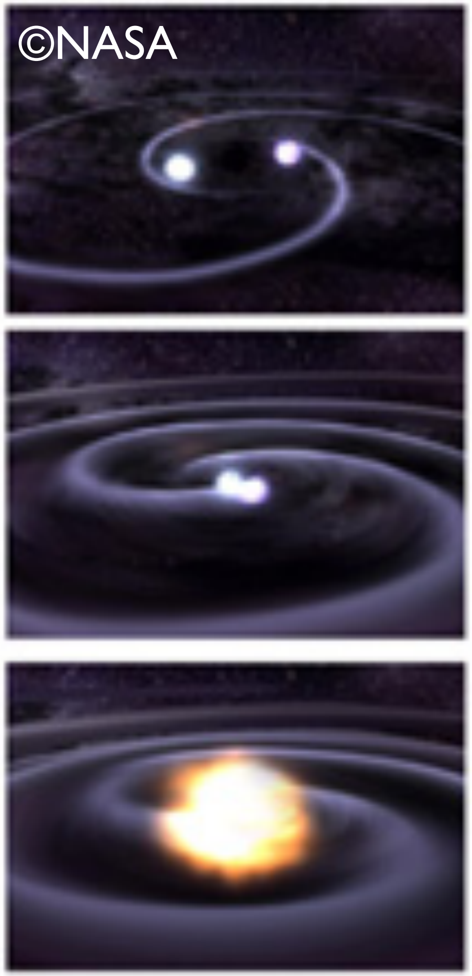
- $DM = 500\text{-}1000\ cm^{-3}\ pc \longrightarrow z = 0.5\text{-}1,\ d_L \sim 2\text{-}6\ Gpc$
- $\Delta t < 5\ ms \longrightarrow c\Delta t < 1500\,(1+z)^{-1}\ km$
- $S_\nu \sim Jy \longrightarrow E_{iso} \sim 10^{38\text{-}40}\ erg$
- $\sim 10^4\ day^{-1} sky^{-1} \longrightarrow \sim 10^{-3}\ yr^{-1} gal^{-1} \sim 0.1 \times R_{CCSN}$
- Coherent emission
- No repeated burst so far
- No counterpart so far

# 2. Possible Origins

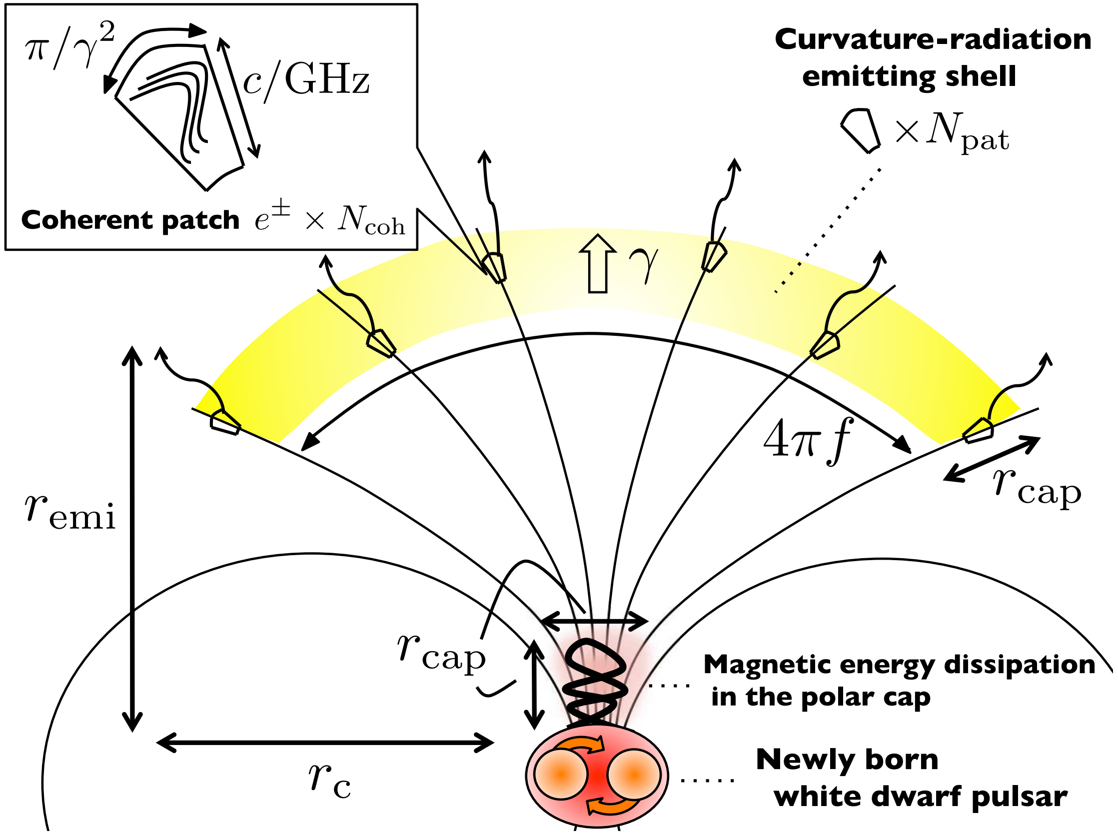
# Possible Origins

- Galactic
  - Rotating radio transients
  - Flaring stars Loeb+13
- Extragalactic
  - Giant pulse from young pulsars
  - Magnetar giant flares Popov&Postnov 08; Thornton+13
  - Supernovae into nearby stars Calgate+71,75; Egorov&Postnov 08
  - Core-collapses of hypermassive NSs Falcke&Rezzolla 13; Zhang 13
  - Binary NS mergers Hansen&Lyutikov+01; Totani 13
  - Binary WD mergers KK, Ioka, Meszaros 13
  - Evaporations of BHs Rees 77; Blandford 77; Kavic+08; Keane+12
  - Superconducting cosmic strings Cai+12

# Binary White Dwarf Mergers?



KK,Ioka,Meszaros,13



# Energetics

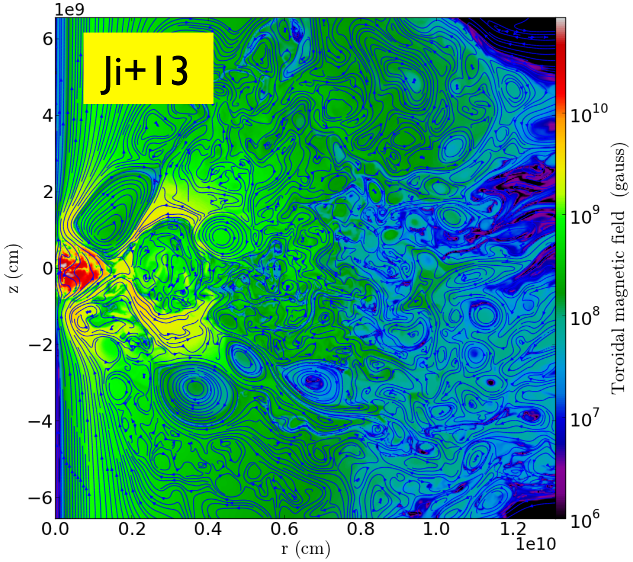
WD-WD merger → differential rotation → B amplification

$$E_{max} \approx \frac{GM^2}{R}$$

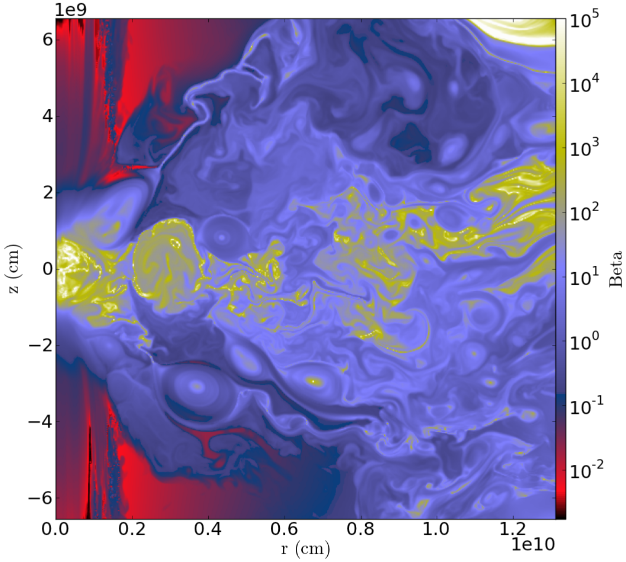
$$\sim 10^{50}\ \mathrm{erg}\ M_0^2 R_{8.7}^{-1}$$

$$\Omega \approx \frac{v}{r} \sim 1\ \mathrm{s}^{-1}\ r_{8.7}^{-3/2}$$

$$B_{max} \gtrsim 10^{11}\ \mathrm{G}$$



(c) Magnetic Field



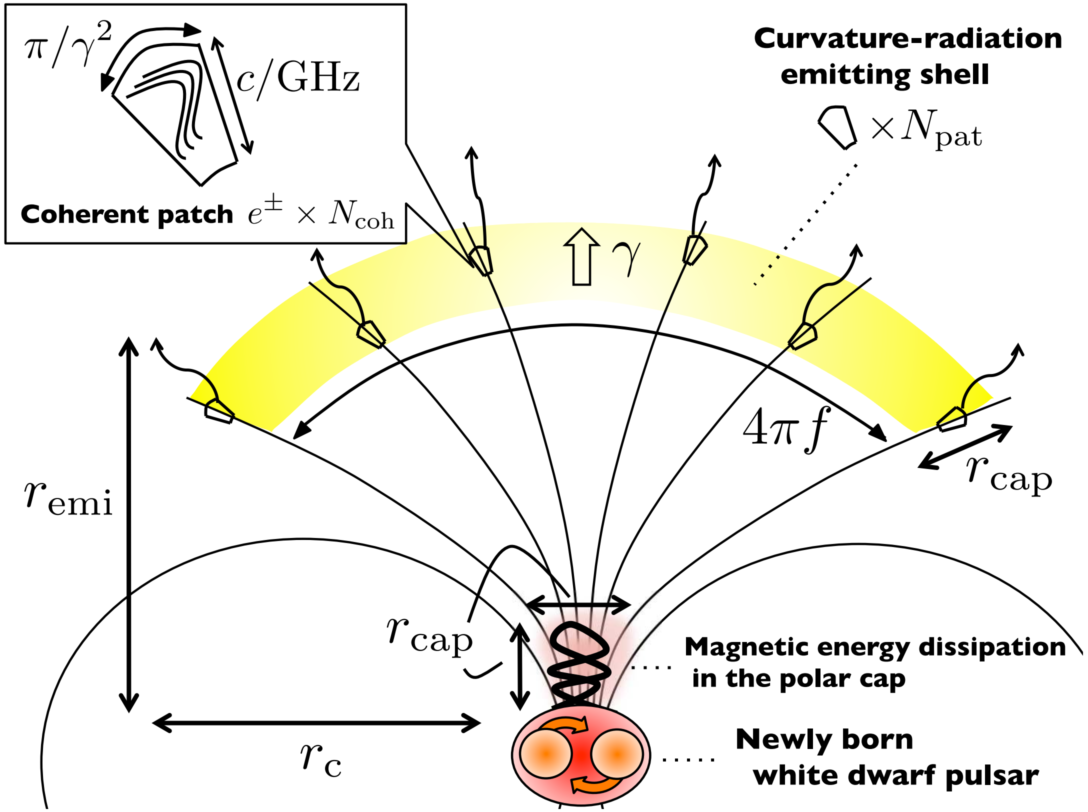
(d) log $\beta$

$$E_B \approx \frac{B^2}{8\pi} \times \frac{4\pi r^3}{3} \sim 2 \times 10^{43}\ \mathrm{erg}\ B_9^2 r_{8.7}^3$$

c.f. $B_{obs,max} \sim 10^9\ \mathrm{G}$ Kawka+07; Kepler+13

# Timescale

WD-WD merger → differential rotation → B amplification
→ B dissipation in the polar cap → injection of e± bunches



$$r_{cap} \approx r\left(\frac{r\Omega}{c}\right)^{1/2}$$

$$\sim 6.7 \times 10^{7}\ \mathrm{cm}\ r_{8.7}^{3/2}\Omega_0^{1/2}$$

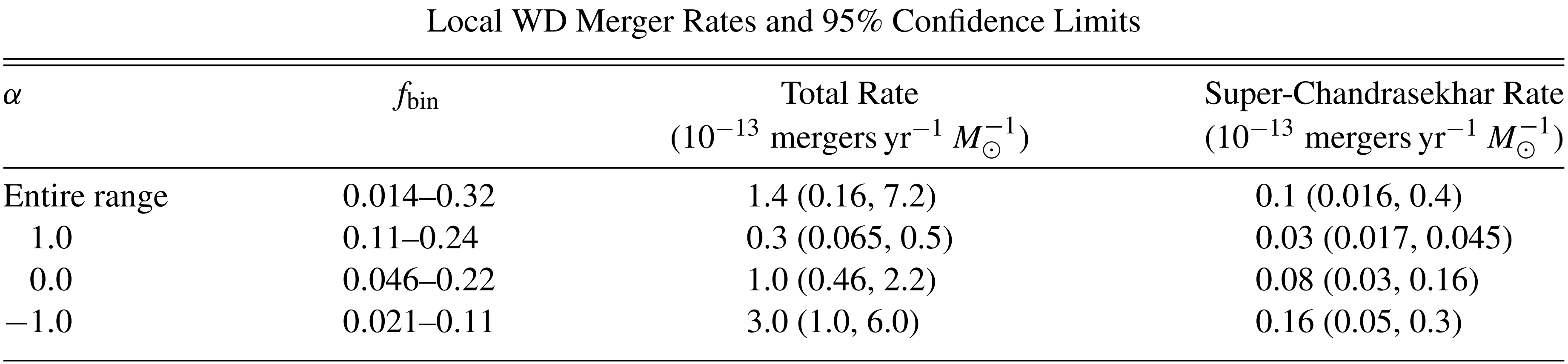
$$\frac{r_{cap}}{c} \sim 2.3\ \mathrm{ms}\ r_{8.7}^{3/2}\Omega_0^{1/2}$$

# Event Rate

e.g., Badenes&Maoz 12

Radial velocity distribution of ~ 4000 WDs in SDSS

→ separation distribution ( $\alpha$ ) & binary fraction ($f_{bin}$)



Local WD Merger Rates and 95% Confidence Limits

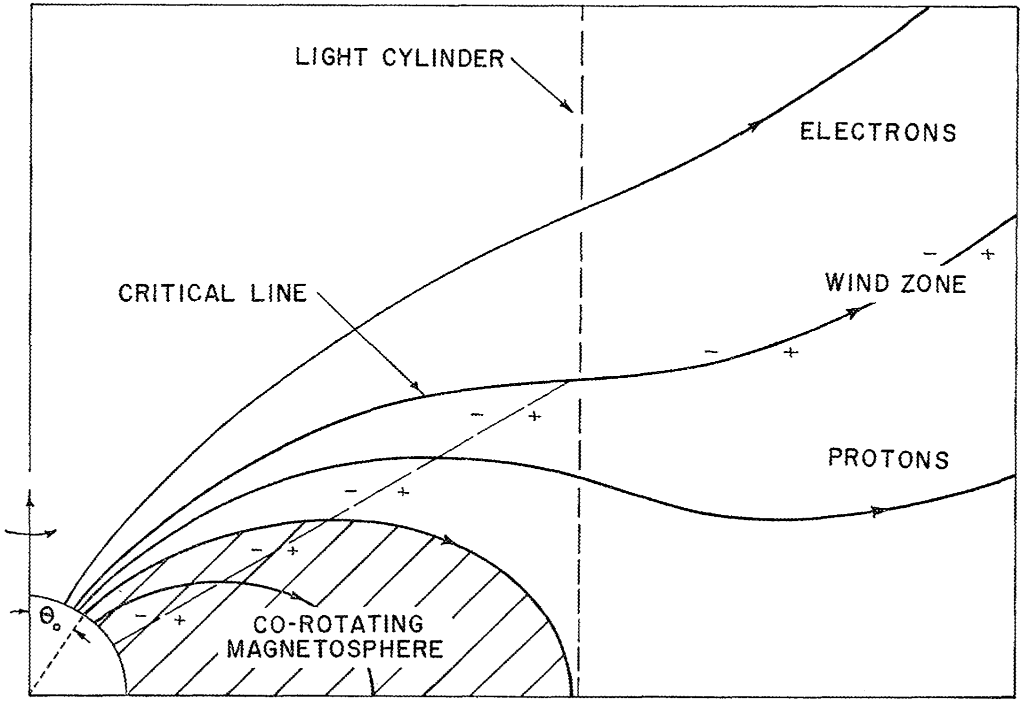
| $\alpha$ | $f_{\rm bin}$ | Total Rate<br>($10^{-13}$ mergers yr$^{-1}$ $M_\odot^{-1}$) | Super-Chandrasekhar Rate<br>($10^{-13}$ mergers yr$^{-1}$ $M_\odot^{-1}$) |
|---|---|---|---|
| Entire range | 0.014–0.32 | 1.4 (0.16, 7.2) | 0.1 (0.016, 0.4) |
| 1.0 | 0.11–0.24 | 0.3 (0.065, 0.5) | 0.03 (0.017, 0.045) |
| 0.0 | 0.046–0.22 | 1.0 (0.46, 2.2) | 0.08 (0.03, 0.16) |
| −1.0 | 0.021–0.11 | 3.0 (1.0, 6.0) | 0.16 (0.05, 0.3) |

$$\mathcal{R}_{WD-WD} \sim 10^{-2}\text{-}10^{-3}\ \mathrm{yr}^{-1}\mathrm{gal}^{-1}$$

# Relativistic e± Bunch Formation

An huge E field along with the open B field

$$\Phi_{max} \approx \frac{B\Omega^2 r^3}{2c^2} \sim 2.5 \times 10^{16} \text{ Volt } B_9 \Omega_0^2 r_{8.7}^3$$



e± pair avalanche

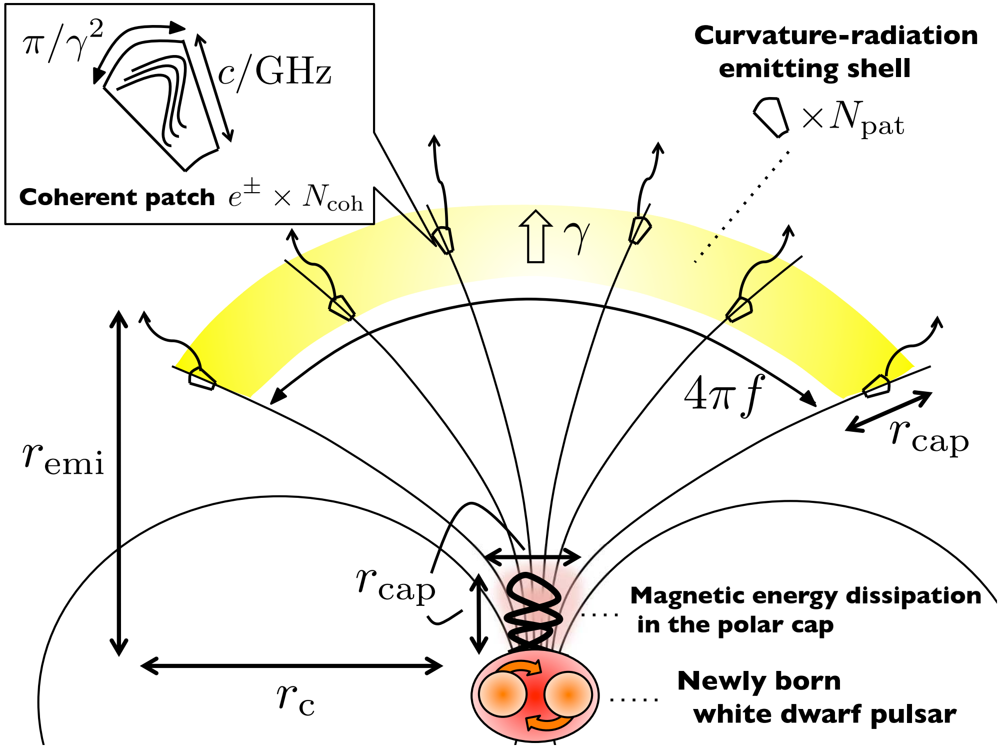
+

acceleration

KK,Ioka,Kawanaka11

# Curvature Radiation

WD-WD merger → differential rotation → B amplification
→ B dissipation in the polar cap → injection of e± bunches
→ Coherent curvature radiation



$$r_{emi} \approx r_c \lesssim r_{lc}$$

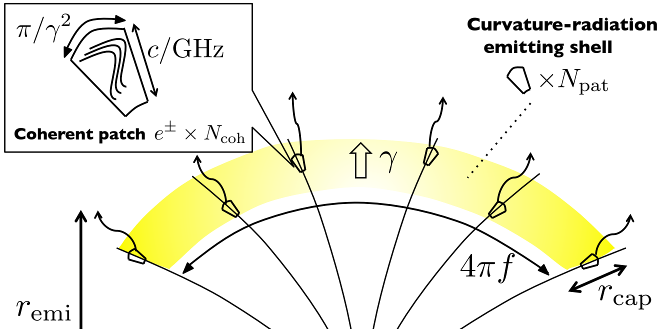
$$\sim 3 \times 10^{10}\ \mathrm{cm}\ r_{8.7}^{3/2}$$

$$\nu_c \approx \gamma^3 \frac{3c}{4\pi r_c}$$

$$\sim 0.72\ \mathrm{GHz}\ \gamma_3^3 r_{c,10}^{-1}$$

$$\gamma \geq 1100\ \nu_9^{1/3} r_{c,10}^{1/3}$$

# Luminosity



$$L_{tot} \approx (P_c N_{coh}^2) \times N_{pat}$$

$$P_c \approx \frac{2\gamma e^2 c}{3 r_c^2} \sim 5 \times 10^{-17}\ \mathrm{erg\ s^{-1}}\ \gamma_3^4 r_{c,10}^{-2}$$

$$N_{coh} \approx n_e \times V_{coh} \approx n_e \times \frac{4}{\gamma^2} r_{emi}^2 \frac{c}{\nu_c} \sim n_e \times 2 \times 10^{16}\ \mathrm{cm^3} \gamma_3{}^{-5} r_{c,10} r_{emi,10}^2$$

$$N_{pat} \approx \frac{V_{emi}}{V_{coh}} \approx \frac{4\pi f r_{emi}^2 r_{cap}}{V_{coh}} \sim \frac{9 \times 10^{28}}{V_{coh}}\ \mathrm{cm^3}\ f r_{emi,10}^2 r_{cap,7.8}$$

$$L_{tot} \sim 4 \times 10^{42}\ \mathrm{erg\ s^{-1}}\ f n_{e,7} \gamma_3{}^{-1} r_{c,10}^{-1} r_{emi,10}^4 r_{cap,7.8}$$

# Electron density

- ✓ Luminosity condition

$$n_e \sim 2 \times 10^7 \ \mathrm{cm}^{-3} \ L_{43}^{1/2} \gamma_3^{1/2} r_{c,10}^{1/2} r_{emi,10}^{-2} r_{cap,7.8}^{-1/2}$$

- ✓ Plasma cutoff limit

$$\nu_c \geq \nu_{pe} \approx \frac{\gamma}{2\pi} \left( \frac{4\pi n_e' e^2}{m_e} \right)^{1/2}, \quad n_e' = \frac{n_e}{\gamma}$$

$$n_e \leq 0.6 \times 10^7 \ \mathrm{cm}^{-3} \ \gamma_3^5 r_{c,10}^{-2}$$

- ✓ Required multiplicity

$$\kappa_{GJ} = \frac{n_e}{n_{GJ}} = \frac{n_e}{B_{emi}\Omega/2\pi ce} \sim 8 \times 10^3 \ n_{e,7} B_{emi,5}^{-1} \Omega_0^{-1}$$

Comparable to young NS pulsars

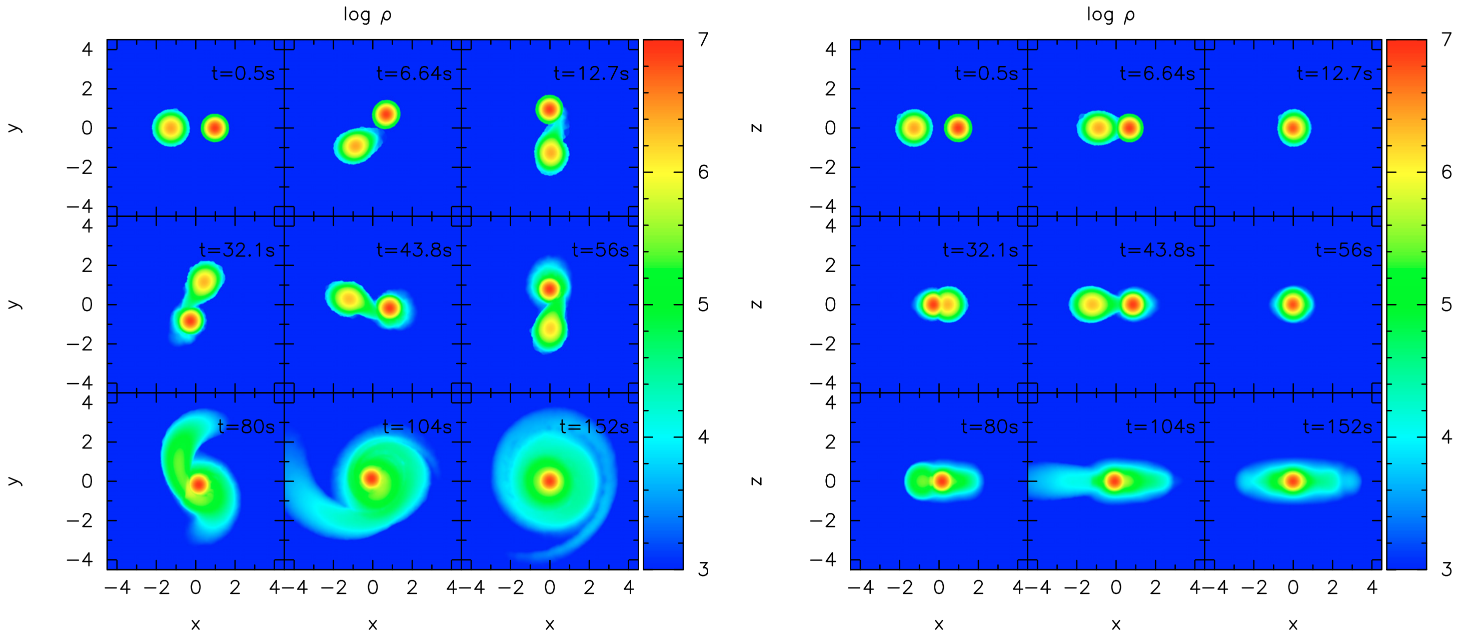
# Binary WD Merger Scenario

- ☑ Energetics
- ☑ Timescale
- ☑ Event rate
- ☑ Emission mechanism

$$\left( \begin{array}{l} \text{Coherent curvature emission with} \\ \quad \gamma \sim 10^{3\text{-}4} \text{ and } \kappa_{GJ} \lesssim 10^4 \end{array} \right)$$

# Counterparts

- Supernova Ia (double degenerate model)
- X-ray debris disk **Loren-Aguilar+09** **KK, Ioka, Meszaros 13**
  - $L_x < 10^{47}$ erg/s for ~100 s → Swift for nearby FRBs



- Magnetically powered optical transient **Beloborodov 14**

# Summary

- Fast Radio Bursts
  - If cosmological

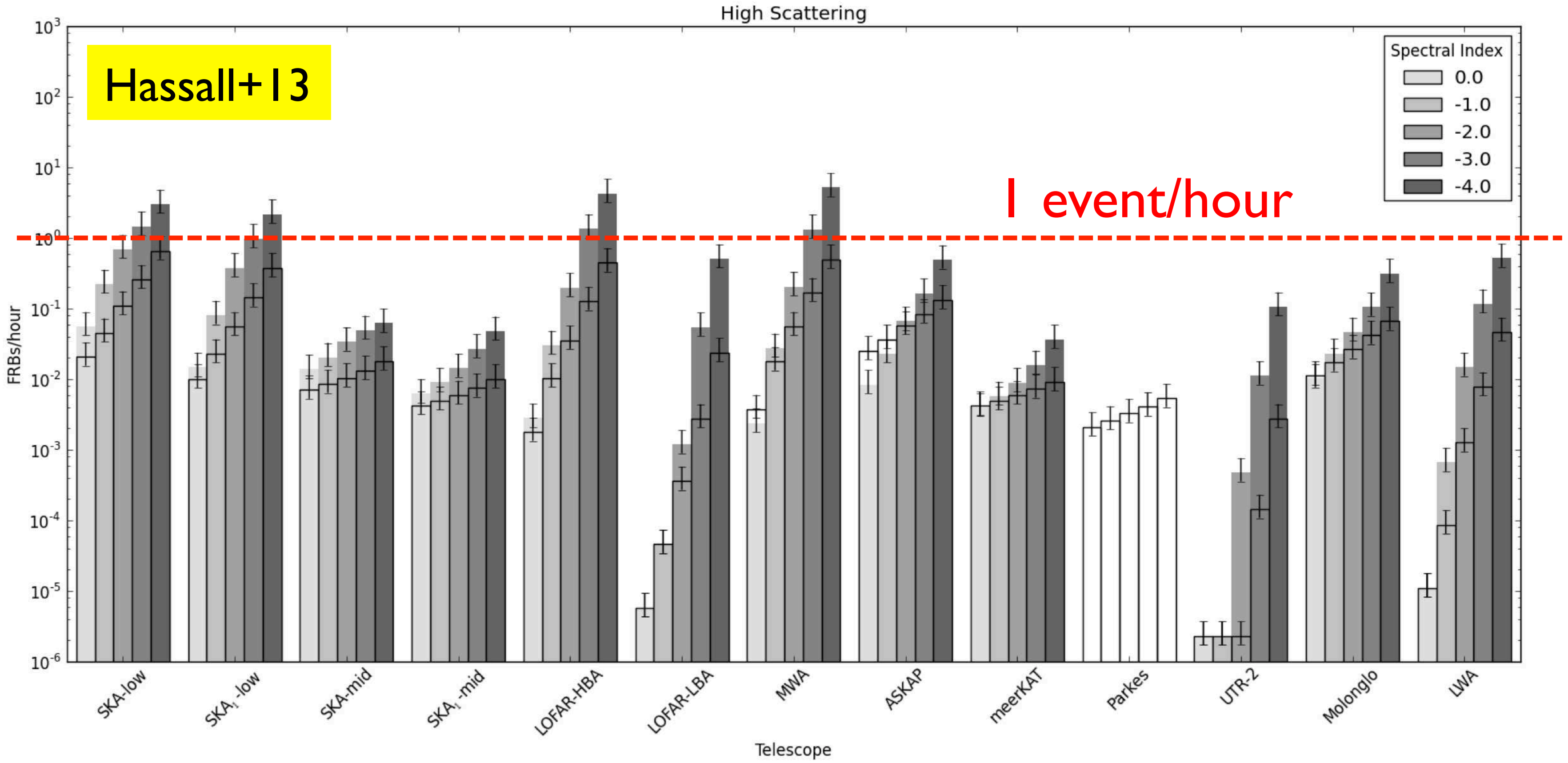
    high event rate ~ $10^4$ $\mathrm{yr}^{-1}$ $\mathrm{gal}^{-1}$ coherent bursts
  - Possible scenarios

    magnetar giant flares, binary white dwarf mergers, etc
- Perytons
- Multi-messenger observations
  - lower frequency radio
  - counterpart search
- FRB cosmology

# Appendix

# 2. Future Observations

# Expected Detection Rate



Hassall+13

1 event/hour

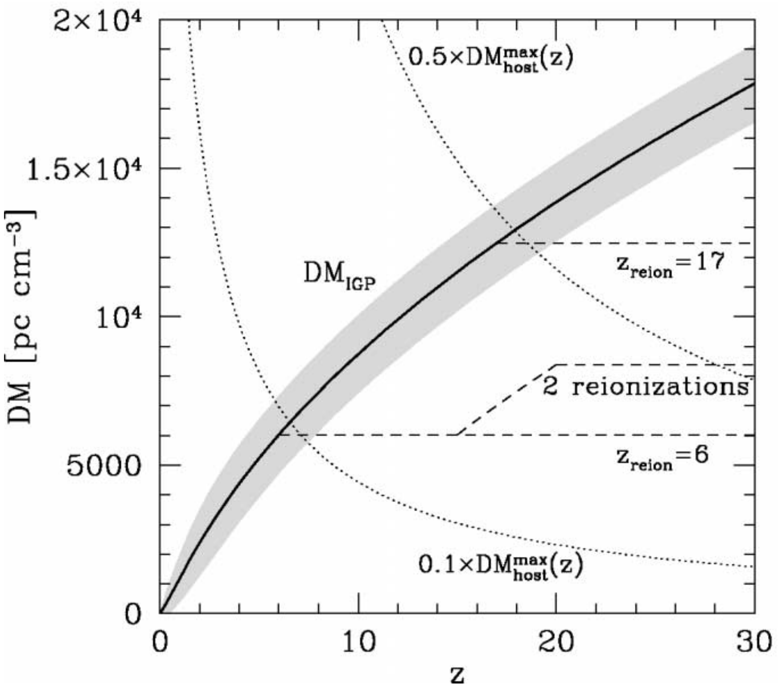
**Figure 2.** Expected number of FRBs per hour for various observatories in the high-scattering simulations. The coloured bars show the number of FRBs detectable in imaging surveys, assuming different spectral indices of: 0.0 (white), -1.0, -2.0, -3.0 and -4.0 (darkest grey). The number of FRBs detectable in beamformed surveys are indicated by the bars with a solid black outline. The DM range used was $0 - 6000$ pc cm$^{-3}$.

# FRB Cosmology

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

$$+$$

$$d_L = \frac{c(1+z)}{H_0}\int_0^z \frac{dz}{[\Omega_m(1+z)^3+\Omega_\Lambda]^{1/2}}$$



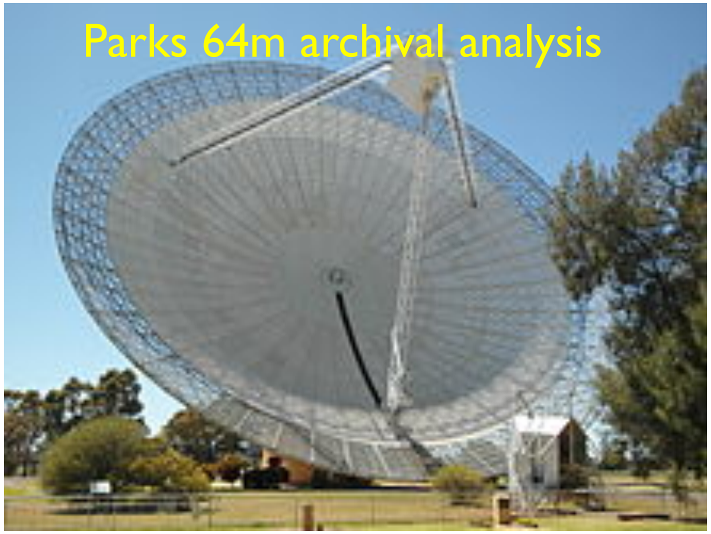
- Reionization
- Missing baryon
- Dark energy, cosmological parameters, etc

McQuinn 13; Deng & Zhang 14; Kalkarni+14

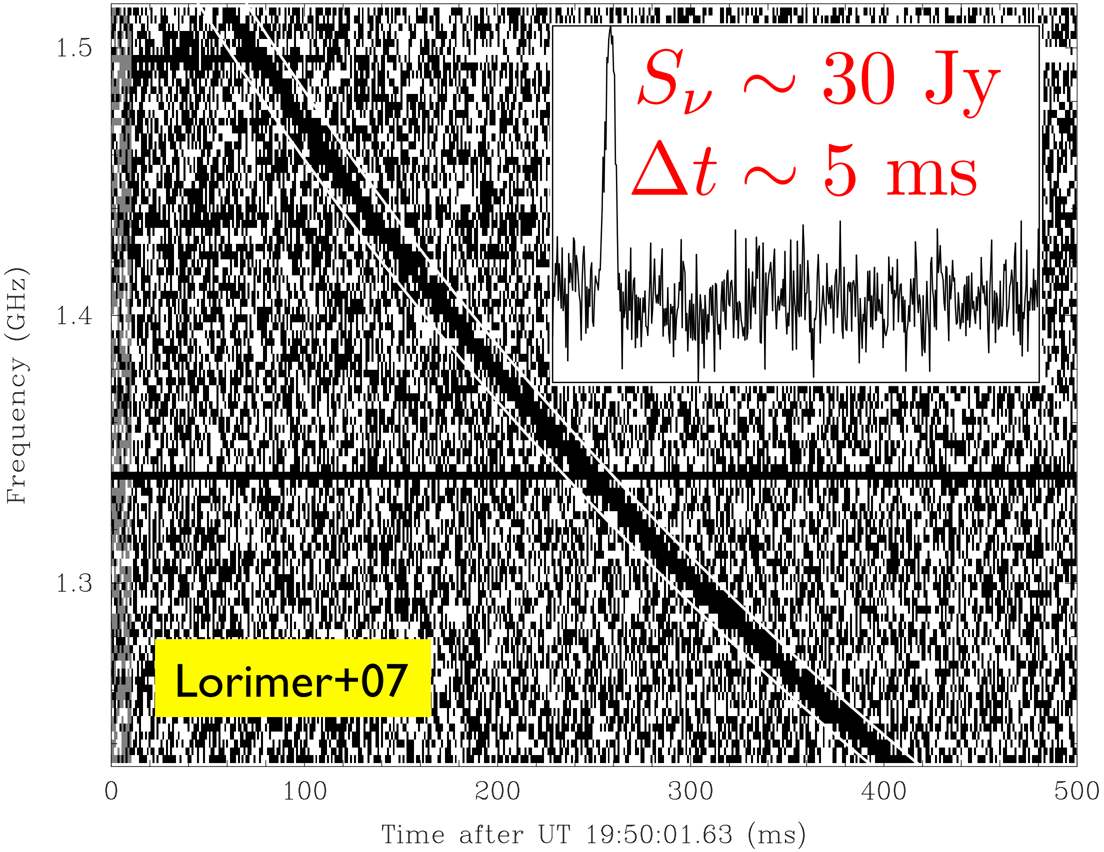
# Multi-messenger observations

- Lower frequencies with larger FOV
- Optical, X-ray, and gamma-ray counterparts?
- GW and neutrino counterparts?

# Lorimer Burst, Sparker, FRB 010724

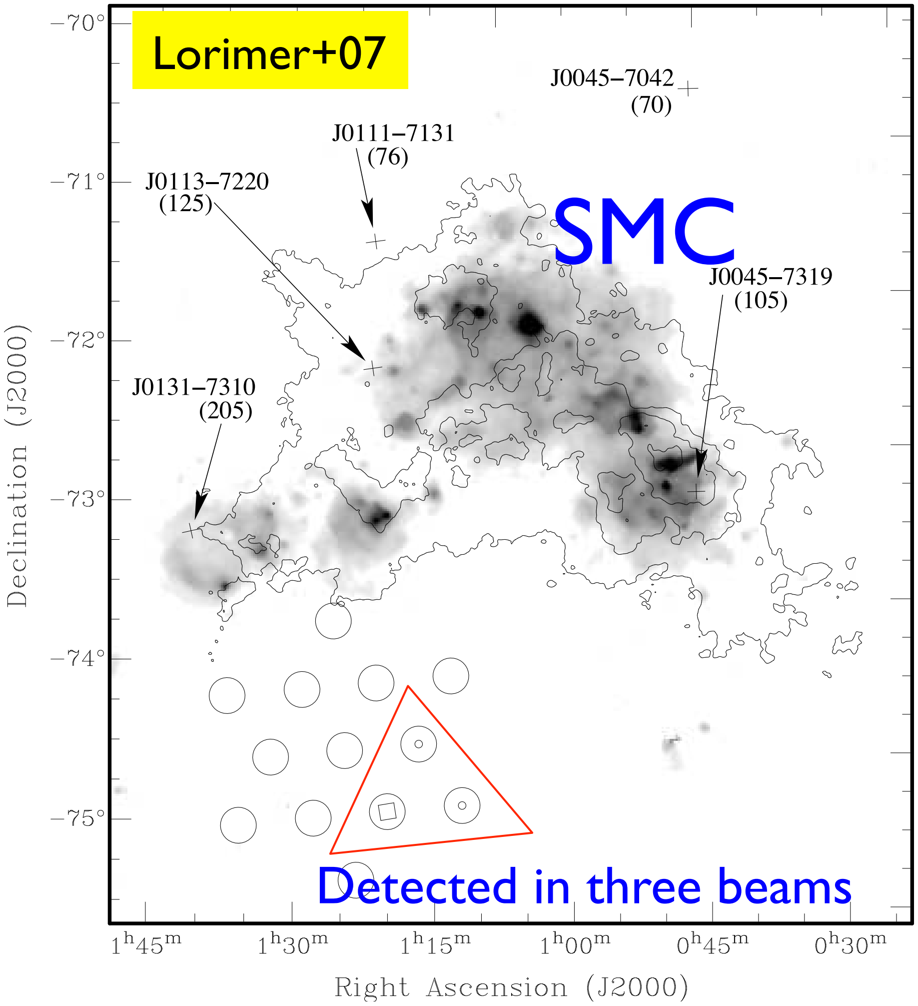


$\nu \sim 1.4$ GHz



≒ $\nu^{-2}$ arrival time pulse sweep

# Lorimer Burst, Sparker, FRB 010724



Detected in three beams

$$DM \sim 375\ \mathrm{cm}^{-3}\mathrm{pc}$$

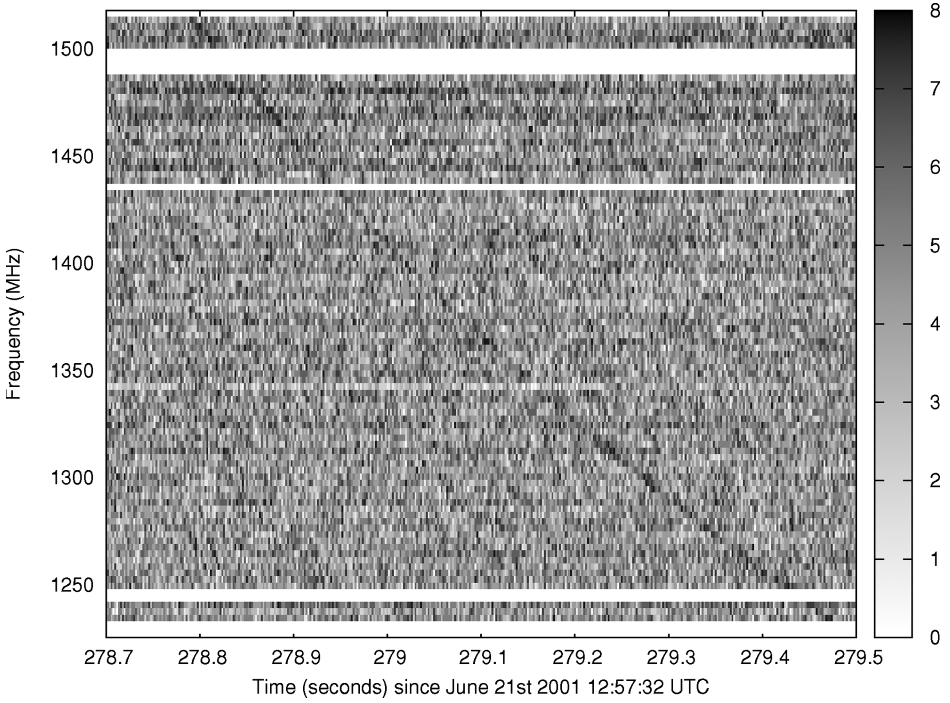
$$\updownarrow$$

$$DM_{MW} \sim 25\ \mathrm{cm}^{-3}\mathrm{pc}$$

$$DM_{SMC} \sim 50\ \mathrm{cm}^{-3}\mathrm{pc}$$

# Keane Burst, FRB 010621

- The Parkes Multi-beam Pulsar Survey
- 288 MHz band centered on ~1.4 GHz
- Detected in a single beam
- 13:02:10.795 UTC
- S/N ~ 16.3
- DM = 746±1 cm$^{-3}$
- Peak flux ~ 0.4 Jy
- Pulse width ~ 7.8 ms
- No counterpart
- No repeated bursts



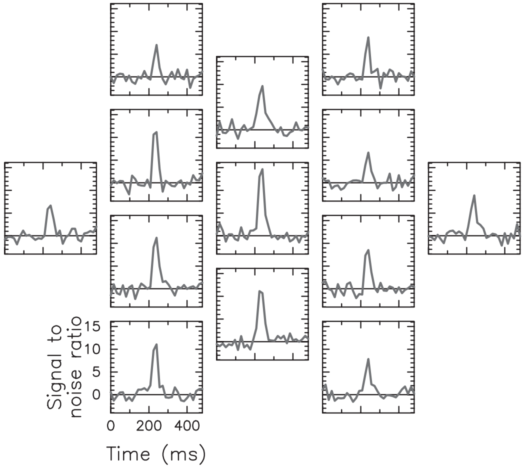
Keane+11

# Terrestrial?

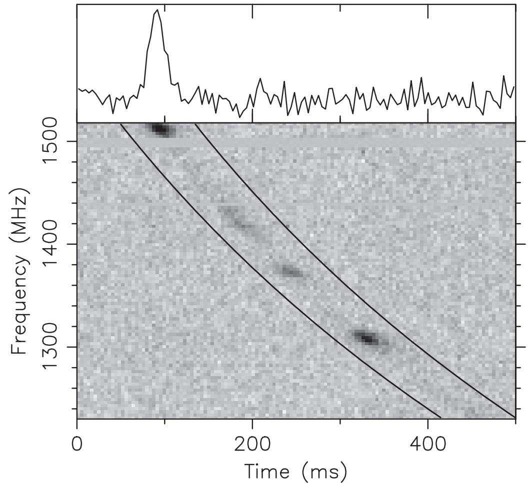
Burke-Spolaor+11; Kocz+12

“Perytons”

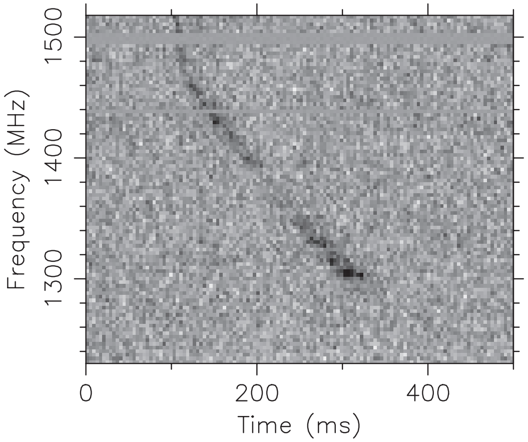
- ✓ Hit all 13 receivers
- ✓ Temporal distributions (UTC range 0-3)
- ✓ Some show $\sim\nu^{-2}$ dispersion (some not)



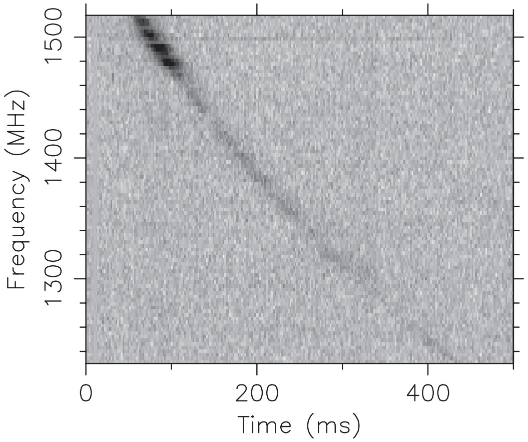
(a) Peryton 08 in 13 beams



(b) Peryton 08



(c) Peryton 06



(d) Peryton 15

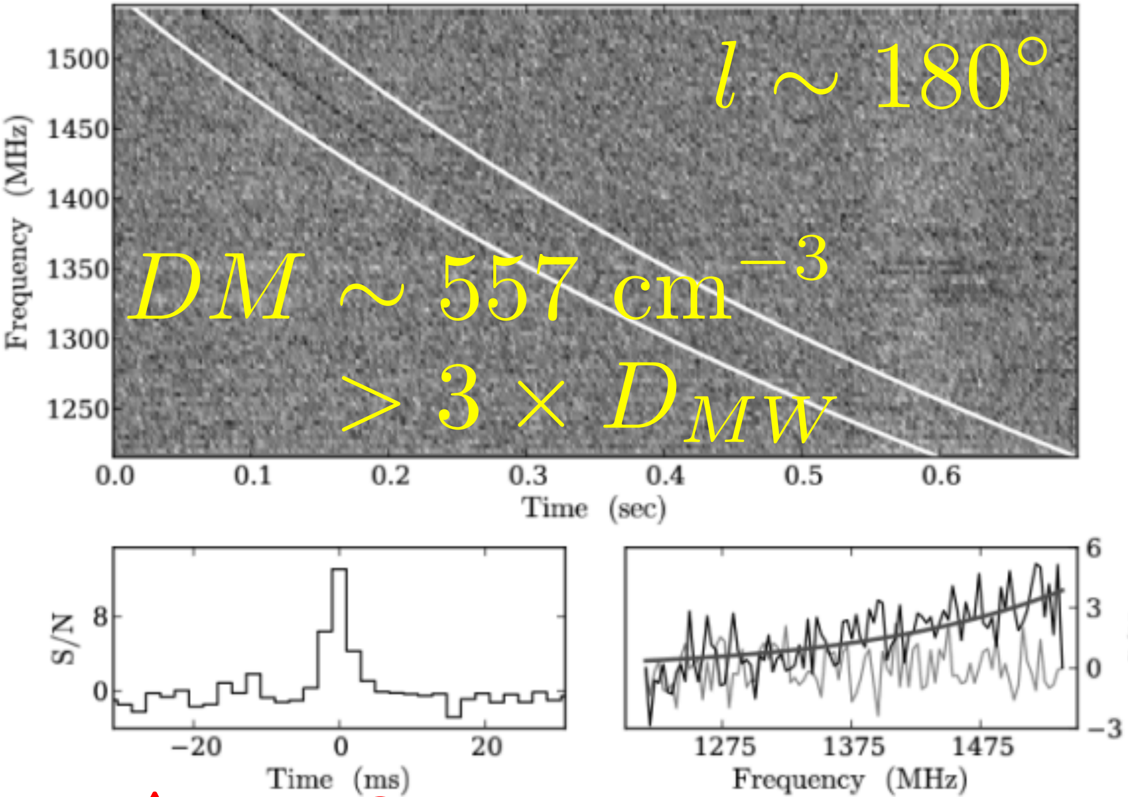
# FRBs ≠ Perytons?

- FRBs are detected in a single beam.
- Perytons have $\Delta t \sim$ 30-50 ms, which is ~10 times larger than FRBs.
- Perytons have symmetric, but some FRBs have an exponential tail.
- Perytons have DM ~ 200-400 $\mathrm{cm^{-3}pc}$, which is smaller than 4 FRBs.
- Atmospheric emissions at different heights?
  - Perytons < 10 km < Lorimer burst < FRBs

Kulkani+14

# Arecibo Detects FRB 121102

Pulsar ALFA survey targeting low latitude (|b| < 5 deg) **Spitler+14**



$\nu \sim 1.4 \text{ GHz}$

Hit a single beam (maybe a sidelobe)

$\Delta t \sim 3 \text{ ms}$

# Coherent radio emissions with GRBs?

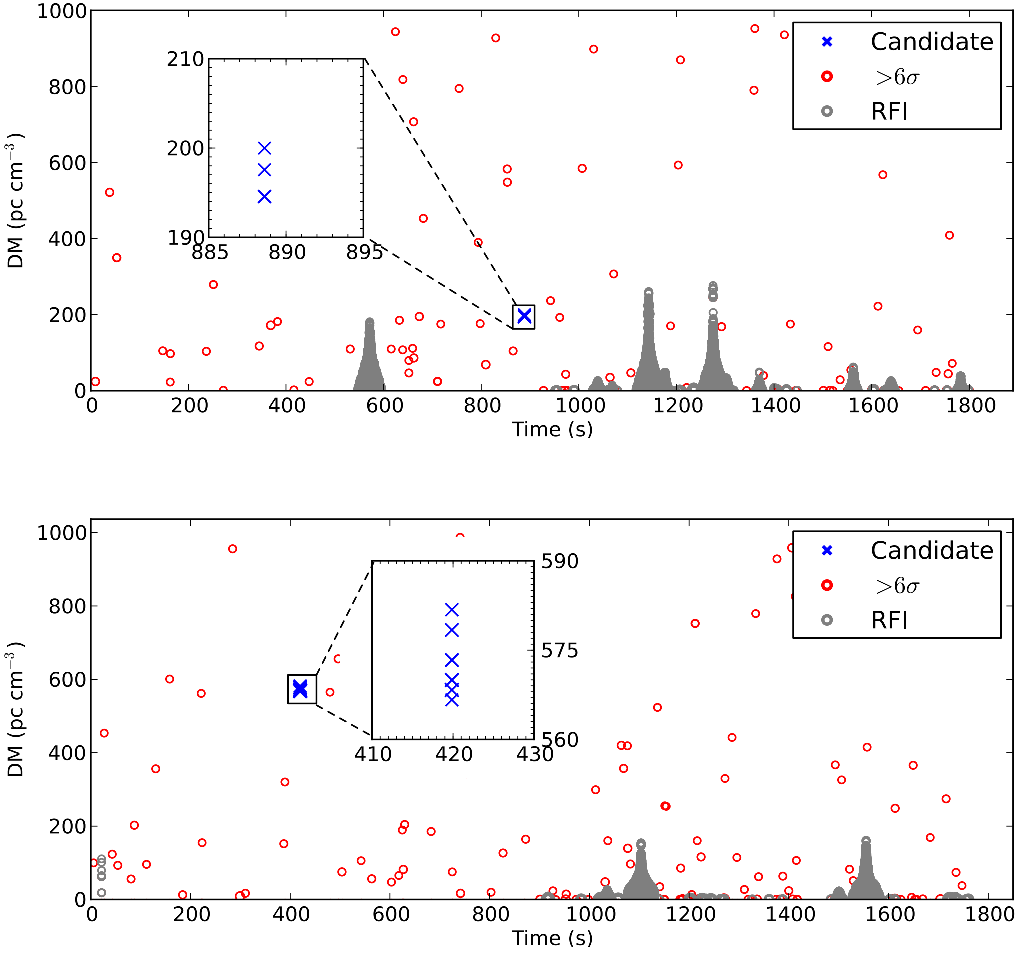


**Figure 2.** DM vs. time for the two GRBs with single-pulse candidates. Single-pulse detections with a significance $\geq 6\sigma$ appear as circles in this plot, with the size proportional to the S/N. The detections are color coded according to their classification by the friends-of-friends algorithm as candidates (blue), false positives (red) and RFI (grey). Top panel: GRB 100704A with a single pulse candidate 1076 seconds after the GRB at a DM of 195 pc cm$^{-3}$, with a significance of 6.2$\sigma$ and width of 6 ms. Bottom panel: GRB 101011A with a single pulse candidate 524 seconds after the GRB at a DM of 570 pc cm$^{-3}$, with a significance of 6.6$\sigma$ and width of 25 ms. The time origin of these plots is the time that the telescope first arrived on source ($T_{\mathrm{on}}$). For clarity, DMs from 1000 pc cm$^{-3}$ are not shown.

Baninister+12

# Host Galaxy

Thornton+13

- Galactic center: DM > 700 $cm^{-3}$ pc
  - – $W \propto D_{obs} D_{scr} / (D_{obs} + D_{scr})^2$
  - – If $D_{scr} << D_{obs}$, it locates at the galactic center
- Elliptical host: low DW
- Spiral host: DM > 700 $cm^{-3}$ pc  
  if I > 87 deg (5 %)
- Intervening galaxy: P < 5%

# Coherent emission

- Emission from N particles

$$P_{tot} = |\sum_{k=1}^{N} E_k e^{i\phi_k}|^2$$

$$= \sum_{k=1}^{N} |E_k|^2 + \sum_{k\neq j} E_k E_j e^{-i(\phi_k - \phi_j)}$$

$$= PN + P\sum_{k\neq j} e^{-i(\phi_k - \phi_j)}$$

$$n^{-1/3} > \lambda \ \rightarrow P_{tot} = PN$$ incoherent

$$n^{-1/3} < \lambda \ \rightarrow P_{tot} = PN^2$$ **coherent**

# Induced Compton

Melrose 71; Wilson & Rees 78; Lyubarsky 08

Compton scattering is enhanced by coherent photons

$$\frac{\partial n(\nu,\boldsymbol{\Omega})}{\partial t} + c(\boldsymbol{\Omega}\cdot\nabla)n(\nu,\boldsymbol{\Omega}) = \frac{3\sigma_{\mathrm{T}}}{8\pi} N \frac{h}{m_e c} n(\nu,\boldsymbol{\Omega}) \times \int (\boldsymbol{e}\cdot\boldsymbol{e}_1)^2 (1-\boldsymbol{\Omega}\cdot\boldsymbol{\Omega}_1) \frac{\partial \nu^2 n(\nu,\boldsymbol{\Omega}_1)}{\partial \nu} d\boldsymbol{\Omega}_1 ,$$

- ✓ induced Compton limit

$$\gamma \geq 2000\ r_{c,10}^{3/14} r_{emi,10}^{3/14} n_{e,7}^{3/14}$$

# Free-Free Absorption

Kulkani+14

$\tau_{\rm ff} \sim 5 \Rightarrow$ 1.2-1.5 GHz can be strongly affected.

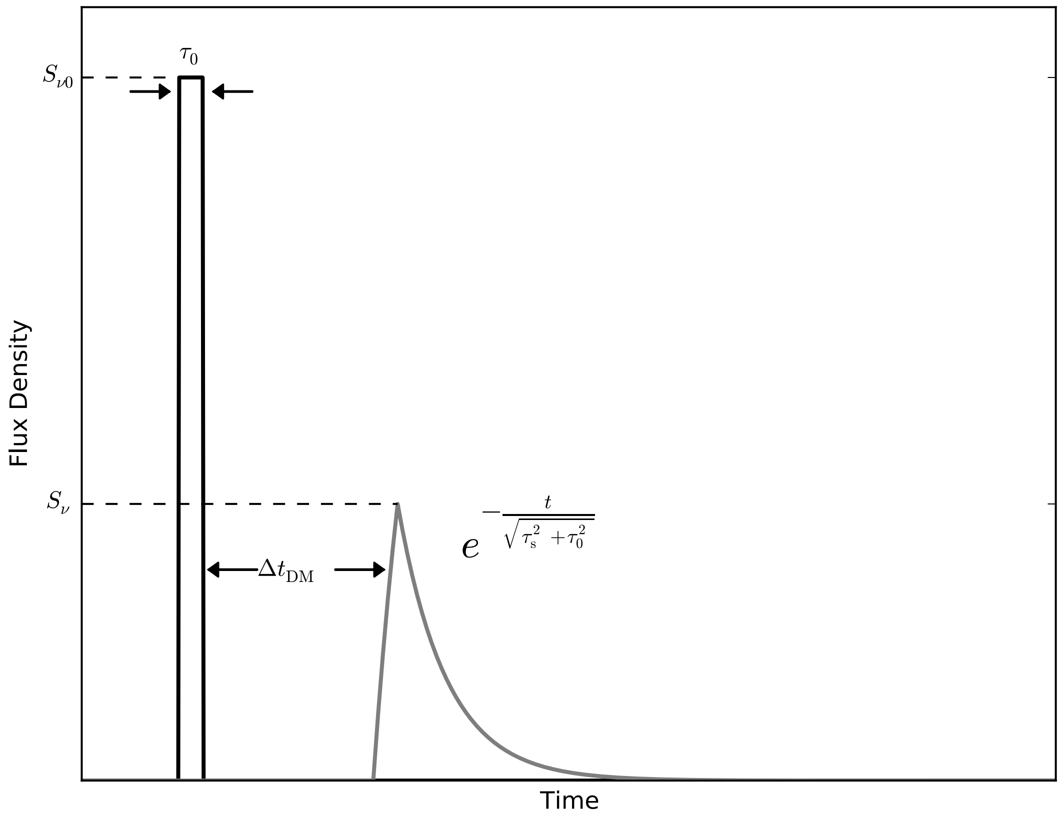
- ✓ Hot ionized nebula

$$\tau_{ff} \sim 2.7 \left(\frac{DM}{325\ \mathrm{cm}^{-3}\ \mathrm{pc}}\right) \left(\frac{\nu}{1.4\ \mathrm{GHz}}\right)^{2.1} \left(\frac{T_e}{8000\ \mathrm{K}}\right)^{-1.35} \left(\frac{l}{0.01\ \mathrm{pc}}\right)^{-1}$$

- ✓ Stellar wind

$$\tau_{ff} \sim 1.9 \left(\frac{\dot{M}}{10^{-5}\ M_{\odot}\mathrm{yr}^{-1}}\right)^{2} \left(\frac{v_w}{10^{8}\ \mathrm{cm\ s}^{-1}}\right)^{-2} \left(\frac{l}{10^{15}\ \mathrm{cm}}\right)^{-3}$$

# Propagation effect



**Hassall+13**

$$\Delta t_{\rm DM} = \frac{\rm DM}{2.410 \times 10^{-4} \nu^2}$$

$$\log \tau_{\rm s} = 2.12 + 0.154 \log({\rm DM}) + 1.07 (\log {\rm DM})^2 - 3.86 \log \nu$$

$$S_\nu = \frac{\mathcal{F}}{\sqrt{\tau_0^2 + \tau_{\rm s}^2}}$$

$$\text{if } \tau_s \gtrsim \tau_0$$

$$S_\nu \propto \tau_s^{-1} \propto \nu^{3.86}$$

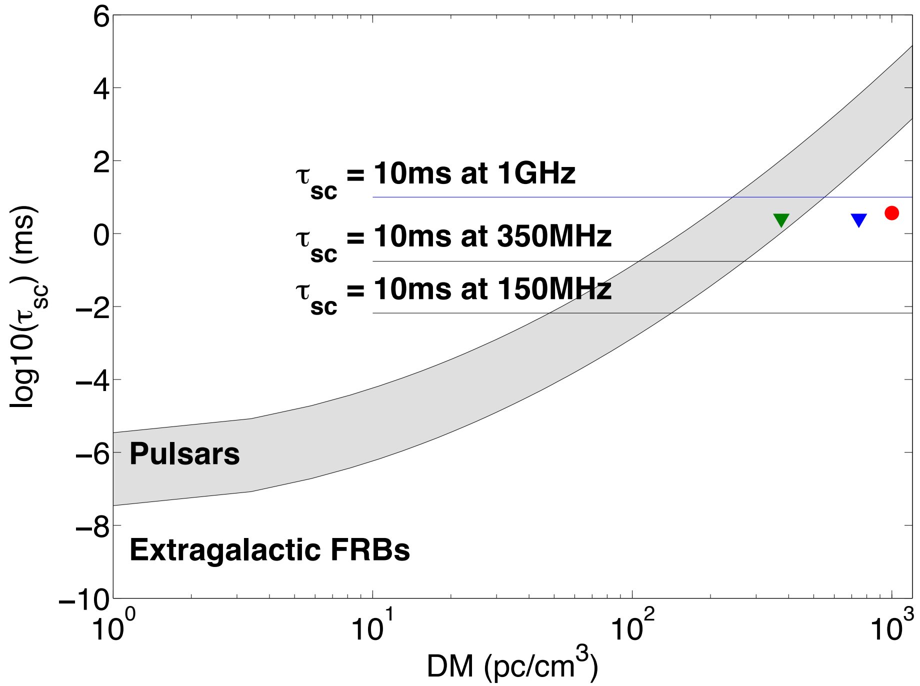


**Figure 1.** Scattering time at 1 GHz versus dispersion measure showing the radio pulsars (adapted from Bhat et al. 2004) along with current scattering constraints on FRBs. The green and blue triangles indicate the scattering timescale upper limits of 1 ms at 1.4 GHz for the FRBs discussed in Lorimer et al. (2007) and Keane et al. (2012), scaled to 1 GHz. The red circle indicates the scattering timescale of 1 ms scaled to 1 GHz measured for one of the FRBs discussed in Thornton et al. (2013). The other FRBs, with DMs of 944, 723, and 553 cm$^{-3}$ pc have scattering timescale upper limits of 1 ms.

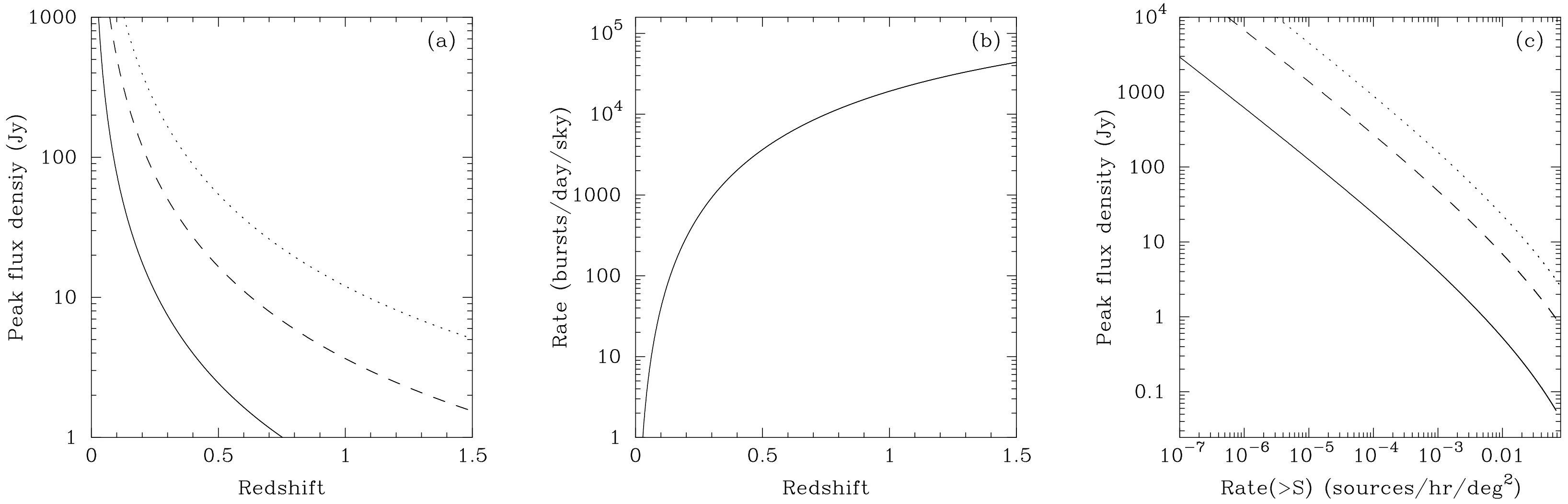
Lorimer+13

# Low (frequency) is More (Events)?

Lorimer+13

"The scattering effects at lower radio frequency are less than previously thought."

Even z > 0.5 events can be detectable in surveys below 1 GHz

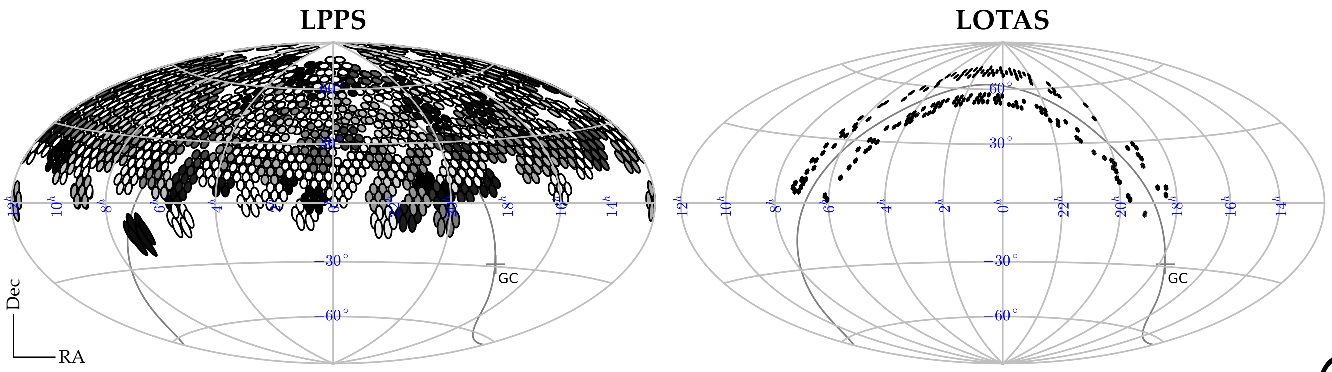


Sources may already be present in 350-MHz surveys with the GBT.

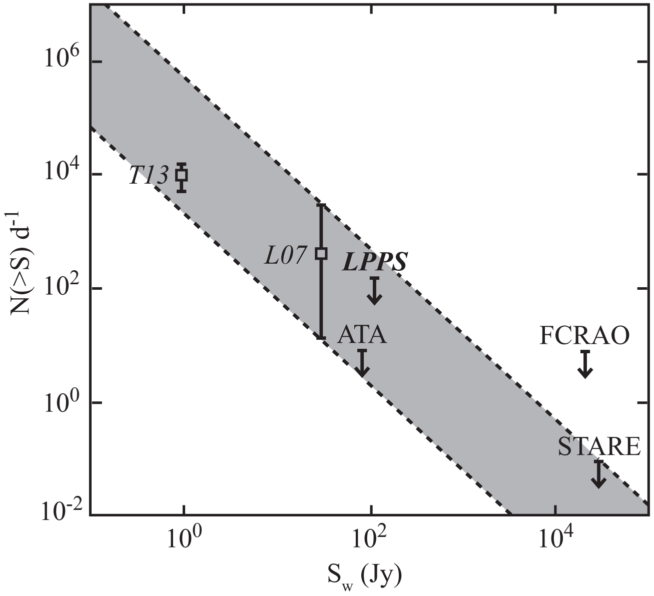
Surveys at 150 MHz with 30 deg$^2$ FoV could detect 1 event/hr above 30 Jy…

# LOFAR non-detection

Coenen+14



@~140 MHz



Stay tuned…

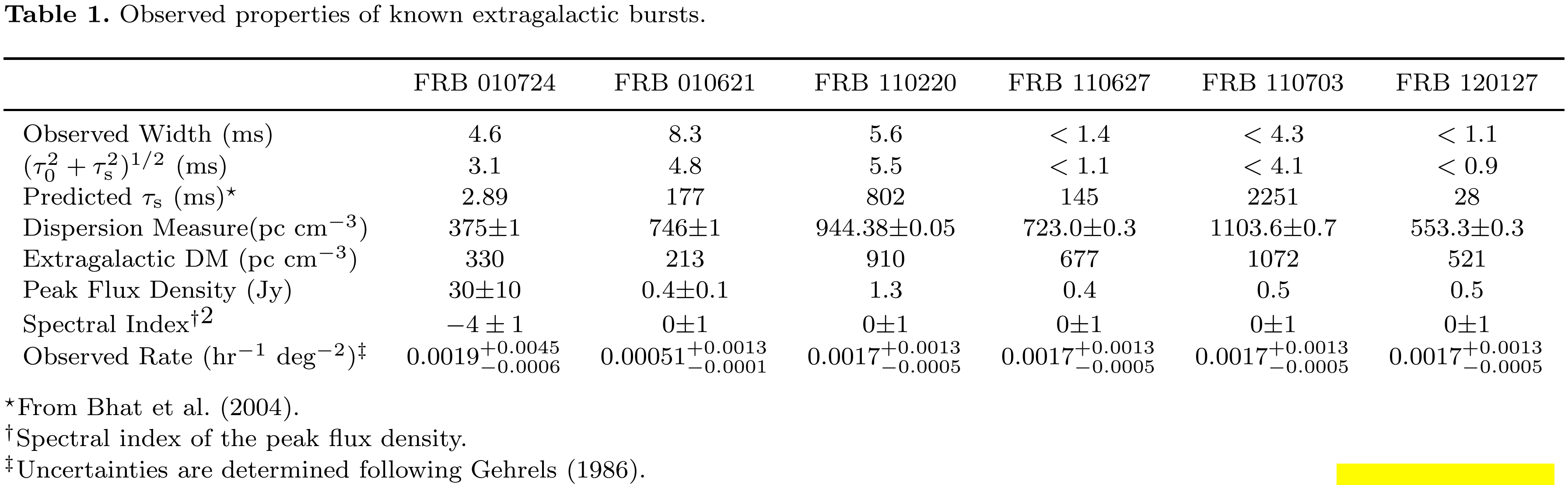


**Table 1.** Observed properties of known extragalactic bursts.

| | FRB 010724 | FRB 010621 | FRB 110220 | FRB 110627 | FRB 110703 | FRB 120127 |
|---|---|---|---|---|---|---|
| Observed Width (ms) | 4.6 | 8.3 | 5.6 | $< 1.4$ | $< 4.3$ | $< 1.1$ |
| $(\tau_0^2 + \tau_s^2)^{1/2}$ (ms) | 3.1 | 4.8 | 5.5 | $< 1.1$ | $< 4.1$ | $< 0.9$ |
| Predicted $\tau_s$ (ms)[⋆] | 2.89 | 177 | 802 | 145 | 2251 | 28 |
| Dispersion Measure(pc $\mathrm{cm}^{-3}$) | 375±1 | 746±1 | 944.38±0.05 | 723.0±0.3 | 1103.6±0.7 | 553.3±0.3 |
| Extragalactic DM (pc $\mathrm{cm}^{-3}$) | 330 | 213 | 910 | 677 | 1072 | 521 |
| Peak Flux Density (Jy) | 30±10 | 0.4±0.1 | 1.3 | 0.4 | 0.5 | 0.5 |
| Spectral Index[†][2] | $-4 \pm 1$ | 0±1 | 0±1 | 0±1 | 0±1 | 0±1 |
| Observed Rate ($\mathrm{hr}^{-1}$ $\mathrm{deg}^{-2}$)[‡] | $0.0019^{+0.0045}_{-0.0006}$ | $0.00051^{+0.0013}_{-0.0001}$ | $0.0017^{+0.0013}_{-0.0005}$ | $0.0017^{+0.0013}_{-0.0005}$ | $0.0017^{+0.0013}_{-0.0005}$ | $0.0017^{+0.0013}_{-0.0005}$ |

[⋆] From Bhat et al. (2004).

[†] Spectral index of the peak flux density.

[‡] Uncertainties are determined following Gehrels (1986).

Hassall+13

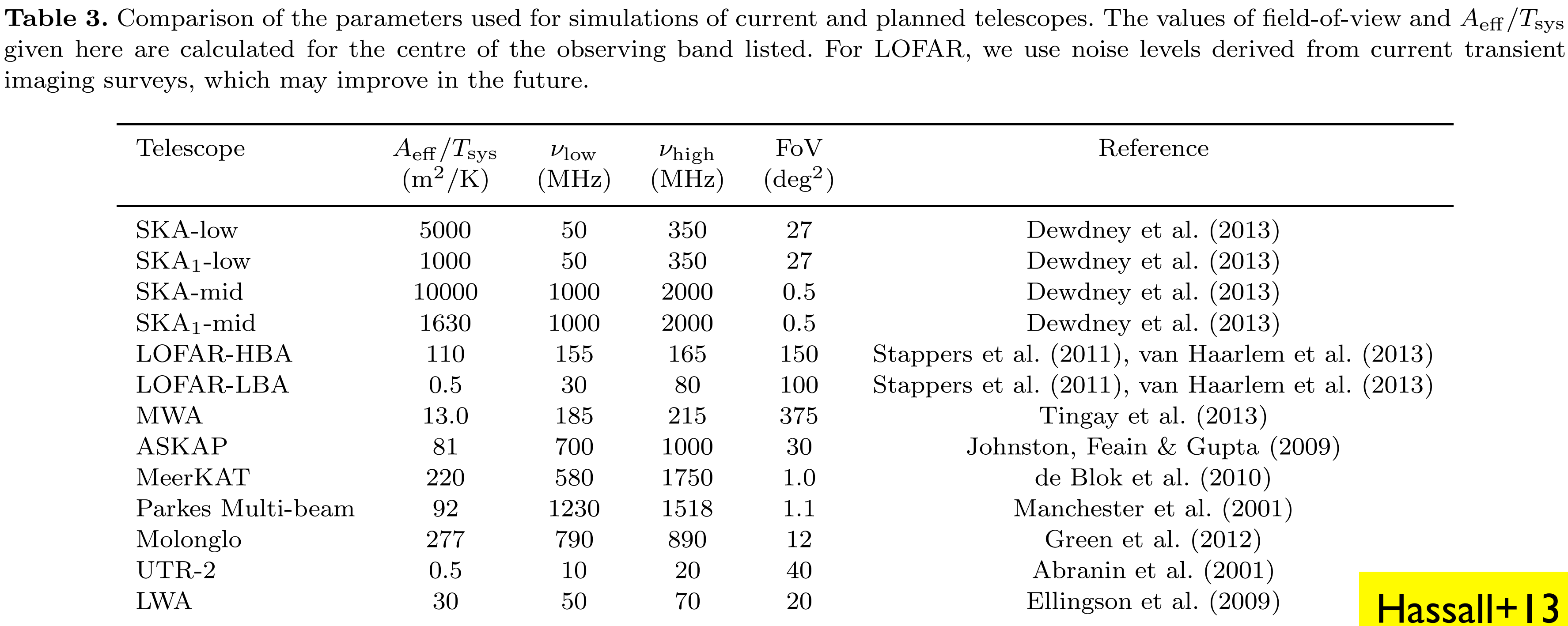


**Table 3.** Comparison of the parameters used for simulations of current and planned telescopes. The values of field-of-view and $A_{\mathrm{eff}}/T_{\mathrm{sys}}$ given here are calculated for the centre of the observing band listed. For LOFAR, we use noise levels derived from current transient imaging surveys, which may improve in the future.

| Telescope | $A_{\mathrm{eff}}/T_{\mathrm{sys}}$ ($\mathrm{m}^2$/K) | $\nu_{\mathrm{low}}$ (MHz) | $\nu_{\mathrm{high}}$ (MHz) | FoV ($\mathrm{deg}^2$) | Reference |
|---|---|---|---|---|---|
| SKA-low | 5000 | 50 | 350 | 27 | Dewdney et al. (2013) |
| $\mathrm{SKA}_1$-low | 1000 | 50 | 350 | 27 | Dewdney et al. (2013) |
| SKA-mid | 10000 | 1000 | 2000 | 0.5 | Dewdney et al. (2013) |
| $\mathrm{SKA}_1$-mid | 1630 | 1000 | 2000 | 0.5 | Dewdney et al. (2013) |
| LOFAR-HBA | 110 | 155 | 165 | 150 | Stappers et al. (2011), van Haarlem et al. (2013) |
| LOFAR-LBA | 0.5 | 30 | 80 | 100 | Stappers et al. (2011), van Haarlem et al. (2013) |
| MWA | 13.0 | 185 | 215 | 375 | Tingay et al. (2013) |
| ASKAP | 81 | 700 | 1000 | 30 | Johnston, Feain & Gupta (2009) |
| MeerKAT | 220 | 580 | 1750 | 1.0 | de Blok et al. (2010) |
| Parkes Multi-beam | 92 | 1230 | 1518 | 1.1 | Manchester et al. (2001) |
| Molonglo | 277 | 790 | 890 | 12 | Green et al. (2012) |
| UTR-2 | 0.5 | 10 | 20 | 40 | Abranin et al. (2001) |
| LWA | 30 | 50 | 70 | 20 | Ellingson et al. (2009) |

Hassall+13

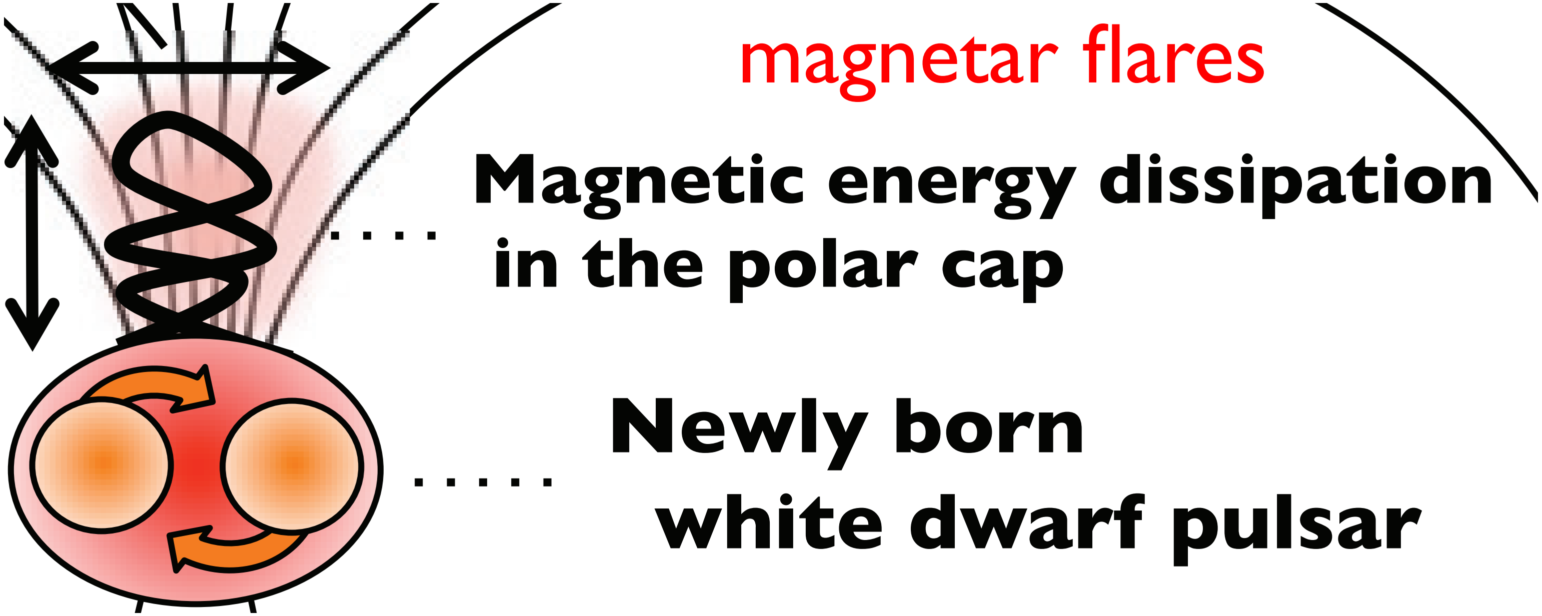
# Energy Injection

The spin-down luminosity is not enough.

$$L_{sd} \approx \frac{B^2 r^6 \Omega^4}{c^3} \sim 1.7 \times 10^{38}\ \mathrm{erg\ s^{-1}}\ B_9^2 r_{8.7}^6 \Omega_0^4 \ll 10^{43}\ \mathrm{erg\ s^{-1}}$$

cf. solar flares

magnetar flares



**Magnetic energy dissipation in the polar cap**

**Newly born white dwarf pulsar**

# Magnetized White Dwarfs

Mt. Stromlo Observatory
H-rich DA WD
Zeeman splitting

Kawka+07