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Gamma-ray Constraints on Electromagnetic Counterparts of Fast Radio Bursts

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"A blind search for prompt gamma-ray counterparts of fast radio bursts with *Fermi*-LAT data"

Yamasaki et al. 2016 (arXiv:1604.03077, MNRAS in press)

Outline

1. General features of FRBs
2. Motivation, Data & Search algorithm
3. Results & Discussion
4. Implications for FRBs
5. Summary
6. Current work

The Dawn of FRB Astronomy (2007-)

- Fast radio burst (FRB) was first discovered by Lorimer (2007) through pulsar search. **FRB 010724**
- FRBs are further confirmed with a considerable sample (**17 FRBs** at the moment, i.e., Thornton et al. 2013; Keane et al. 2011 & 2016; Burke-Spolaor & Bannister 2014; Spitler et al. 2014 &2016; ;Champion et al. 2015; Ravi et al. 2015).

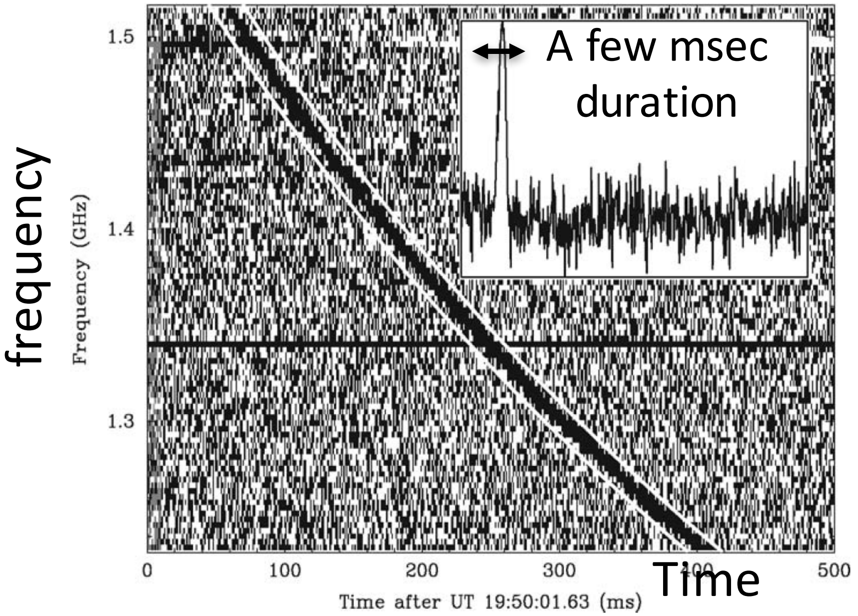


Fig. 2. Frequency evolution and integrated pulse shape of the radio burst. The survey data, collected on 24 August 2001, are shown here as a two-dimensional "waterfall plot" of intensity as a function of radio frequency versus time. The dispersion is clearly seen as a quadratic sweep across the frequency band, with broadening toward lower frequencies. From a measurement of the pulse delay across the receiver band, we used standard pulsar timing techniques and determined the DM to be 375 ± 1 cm^{-3} pc. The two white lines separated by 15 ms that bound the pulse show the expected behavior for the cold-plasma dispersion law assuming a DM of 375 cm^{-3} pc. The horizontal line at ~1.34 GHz is an artifact in the data caused by a malfunctioning frequency channel. This plot is for one of the offset beams in which the digitizers were not saturated. By splitting the data into four frequency subbands, we have measured both the half-power pulse width and flux density spectrum over the observing bandwidth. Accounting for pulse broadening due to known instrumental effects, we determine a frequency scaling relationship for the observed width $W = 4.6$ ms $(f/1.4\ \mathrm{GHz})^{-4.8 \pm 0.4}$, where f is the observing frequency. A power-law fit to the mean flux densities obtained in each subband yields a spectral index of -4 ± 1. The inset shows the total-power signal after a dispersive delay correction assuming a DM of 375 cm^{-3} pc and a reference frequency of 1.5165 GHz. The time axis on the inner figure also spans the range 0 to 500 ms.

Fast Radio Bursts

- Duration $\delta t \sim$ a few milliseconds

  Indicates compact objects : $r_{\mathrm{FRB}} \sim c\delta t \sim 3 \times 10^{7}\,\mathrm{cm}(\delta t / ms)$

- Flux density ~ a few Jy at ~ GHz

  Coherent emissions :

  $$T_B = \frac{10^{36}\,\mathrm{K}}{\Gamma^2}\left(\frac{S_\nu}{\mathrm{Jy}}\right)\left(\frac{d}{\mathrm{Gpc}}\right)^2\left(\frac{\nu}{\mathrm{GHz}}\right)^{-2}\left(\frac{\delta t}{\mathrm{ms}}\right)^{-2}$$ (Luan & Goldreich 2014)

  Even at ~kpc , T_B is still high (10^{12} K : upper limit of astrophysical sources)

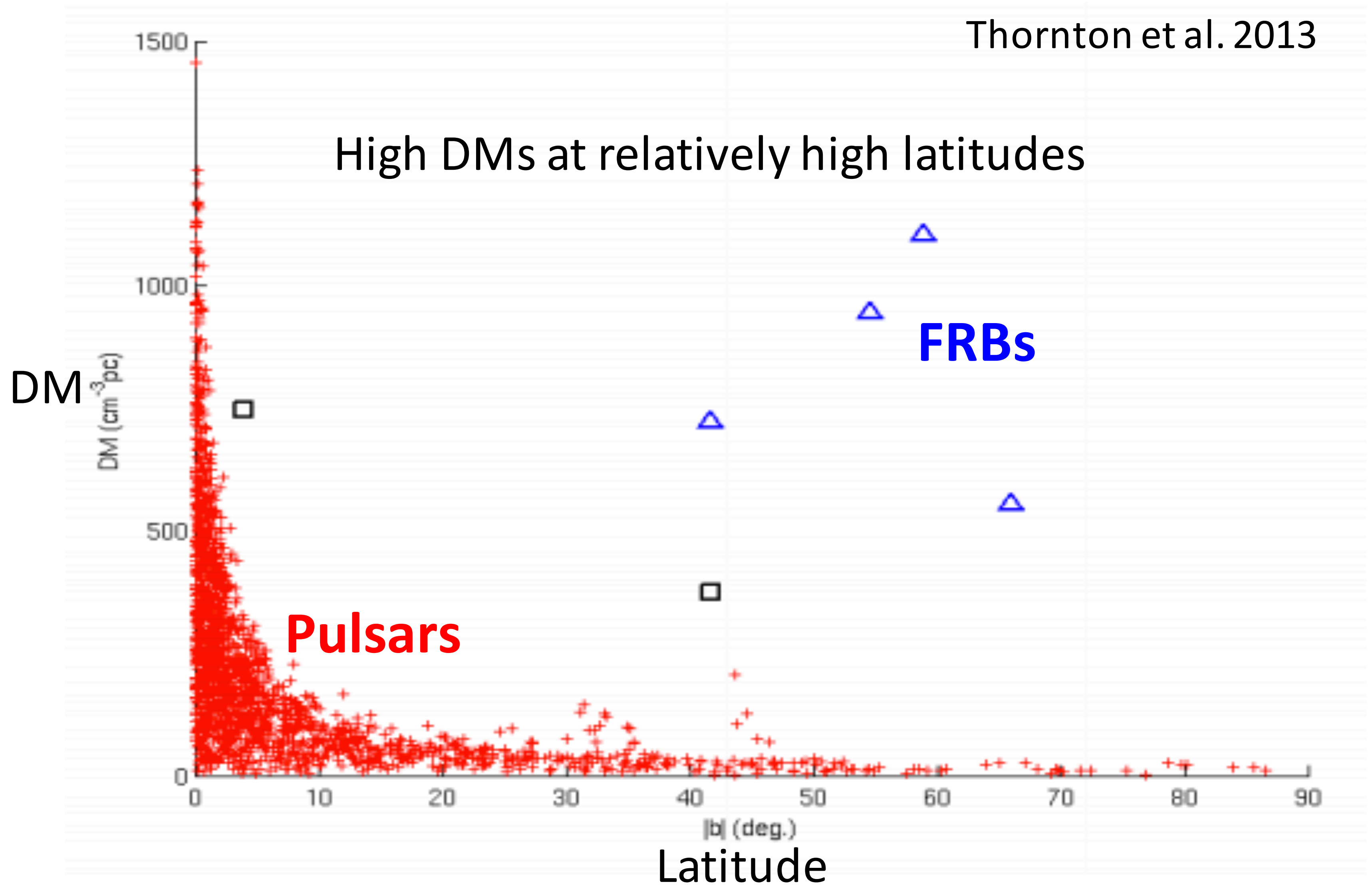
- Anomalously high Dispersion Measure (DM) (375-1500 pc/cm^3)

  Propagating through the ionized ISM:

  $$\text{Time delay} \propto \mathrm{DM} \times \nu^{-2}$$

  $$\text{Pulse width} \propto \nu^{-4}$$

Comological origin? (DM-b plot)



Fast Radio Bursts

- Cosmological Distances

  High DM values suggest $z = 0.2\text{–}1.3$ → indicating cosmoloical origin

  (if dilation occurs by propagation through ISM)

- Event rate : $10^4\,/\,\mathrm{sky}\,/\,\mathrm{day}$ or $\sim 10^{-3}\,\mathrm{gal}^{-1}\mathrm{yr}^{-1}$
  - Event rate of GRBs : $\sim 10^{-6}\,\mathrm{gal}^{-1}\mathrm{yr}^{-1}$
  - Event rate of core-collapse SNe : $\sim 10^{-2}\,\mathrm{gal}^{-1}\mathrm{yr}^{-1}$

- No counterparts so far in other wavelength (except for FRB150428)

- Constraints on prompt high energy emission
  - 10-100 keV : $(\nu F_\nu)_{Soft-\gamma} / (\nu F_\nu)_{\mathrm{radio}} < 10^8\text{–}10^{10}$ (Tendulkar+16, Murase+16)
  - 1-100 GeV : $(\nu F_\nu)_{Hard-\gamma} / (\nu F_\nu)_{\mathrm{radio}} < 10^8$ (Yamasaki+16, this work)

Recent observations (Totani-san's talk)

- Keane+16
  - ATCA detected ~6 day radio afterglow associated with FRB150428
  - A host galaxy was found in Subaru i' band image for the first time
  - The host galaxy of FRB150428 is elliptical (hence not star-forming)
    → progenitor = old stellar population (i.e. NS-NS merger, etc..)

    … but currently, its association under debate (AGN activity?)

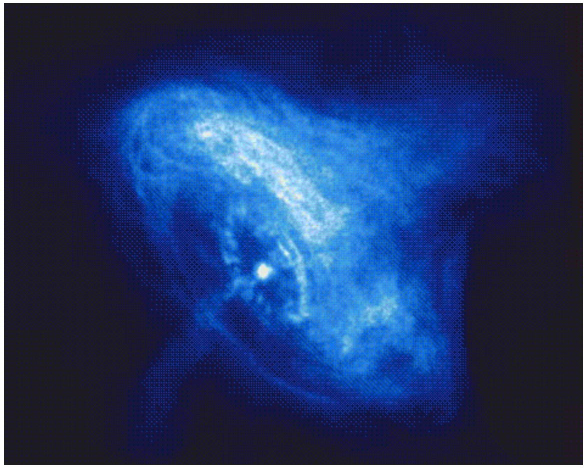
- Spitler+16 & Scholtz+16
  - Arecibo FRB (FRB121102) repeats 17 times total
  - All DMs consistent with a single value (~559 pc/cm^3)
    → prgenitor = super-giant pulses from young pulsars or magnetars ?
  - No prompt X-ray emission detected

→ All FRBs repeat ? At least two populations ?

Leading Progenitor Models

FRB 121102 (Arecibo/GBT)

Repeatable

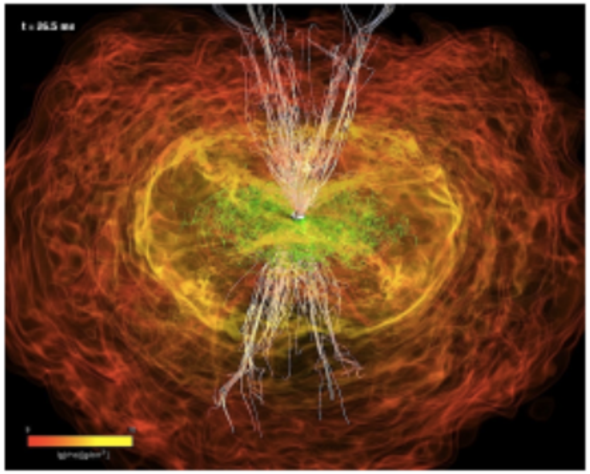


(Image Credit: NASA/CXC/SAO)

- Pulsar emissions
- SGR (Magnetar) flares
- Asteroids collision with NS

FRB150428 (Parkes)

Catastrophic (One-off)



(Rezzolla et al. 2011)

- NS-NS (BH) merger
- HMNS collapse
- WD-WD merger
- BH-BH merger

Possible site of gamma-ray emissions

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Motivations

- Whatever the progentor is, it is reasonable to expect corresponding ms-duration high-energy radiations at the onset of FRBs

- No association with X-ray (*Swift*-BAT) and gamma-ray (*Fermi*-GBM) emission detected yet

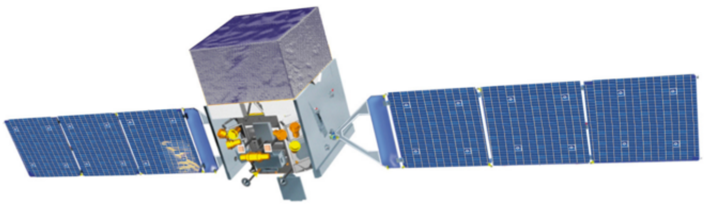
  → Use *Fermi*-LAT Pass7Rep (1-100 GeV, 2008-2015) all-sky data

- Radio telescopes finding FRBs at cosmological distances have narrower field-of-views (~ 15 arcmin beam size for Parkes) than *Fermi*-LAT

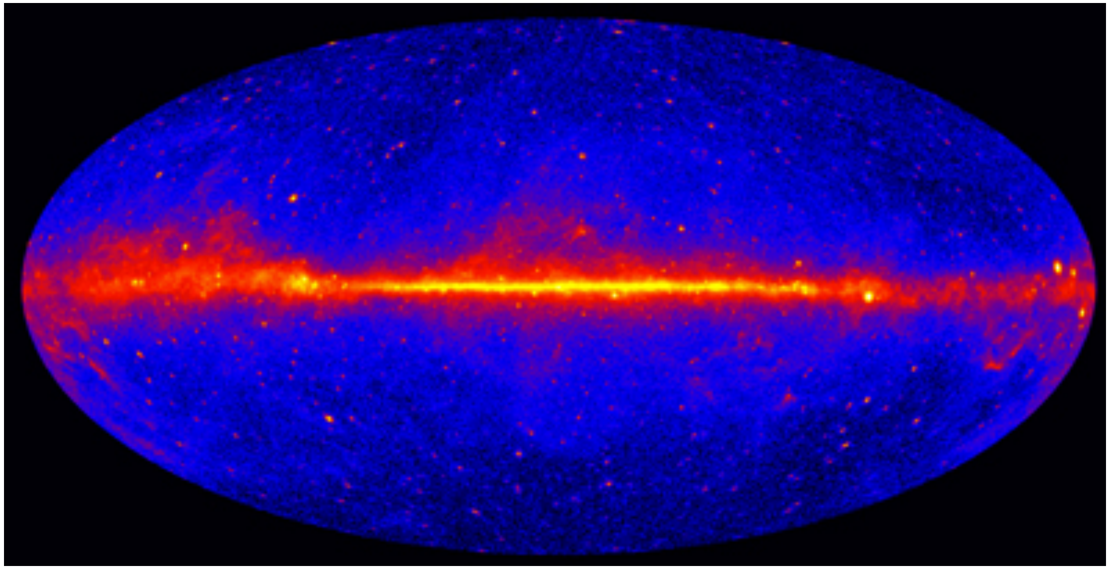
  → Rather than examining the *Fermi*-LAT data at known FRB locations (z=0.5-1.0), we search for ms-duration gamma-ray flashes from nearby potential FRBs (z<0.02)

Fermi-LAT (Large Area Telescope)

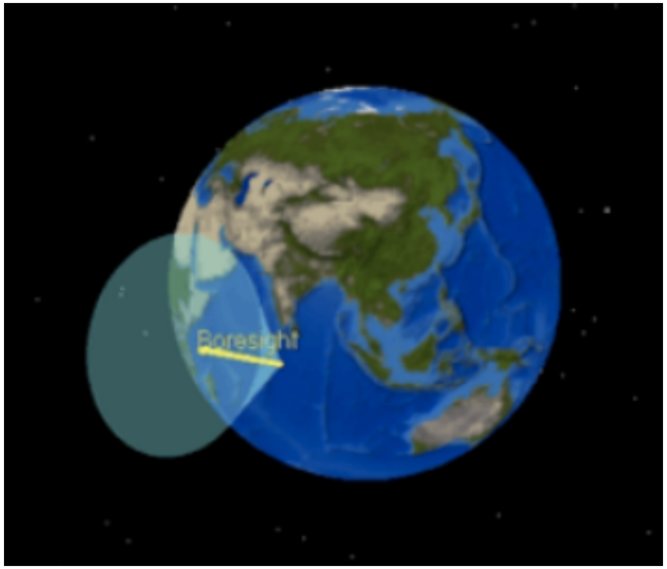
- Effective area: 8000 cm^2
- Energy Range: 20MeV-300GeV
- Angular resolution: 0.8 deg @1GeV
- Pair-conversion telescope ($\gamma \rightarrow e^+ + e^-$)



(Image Credit: NASA)

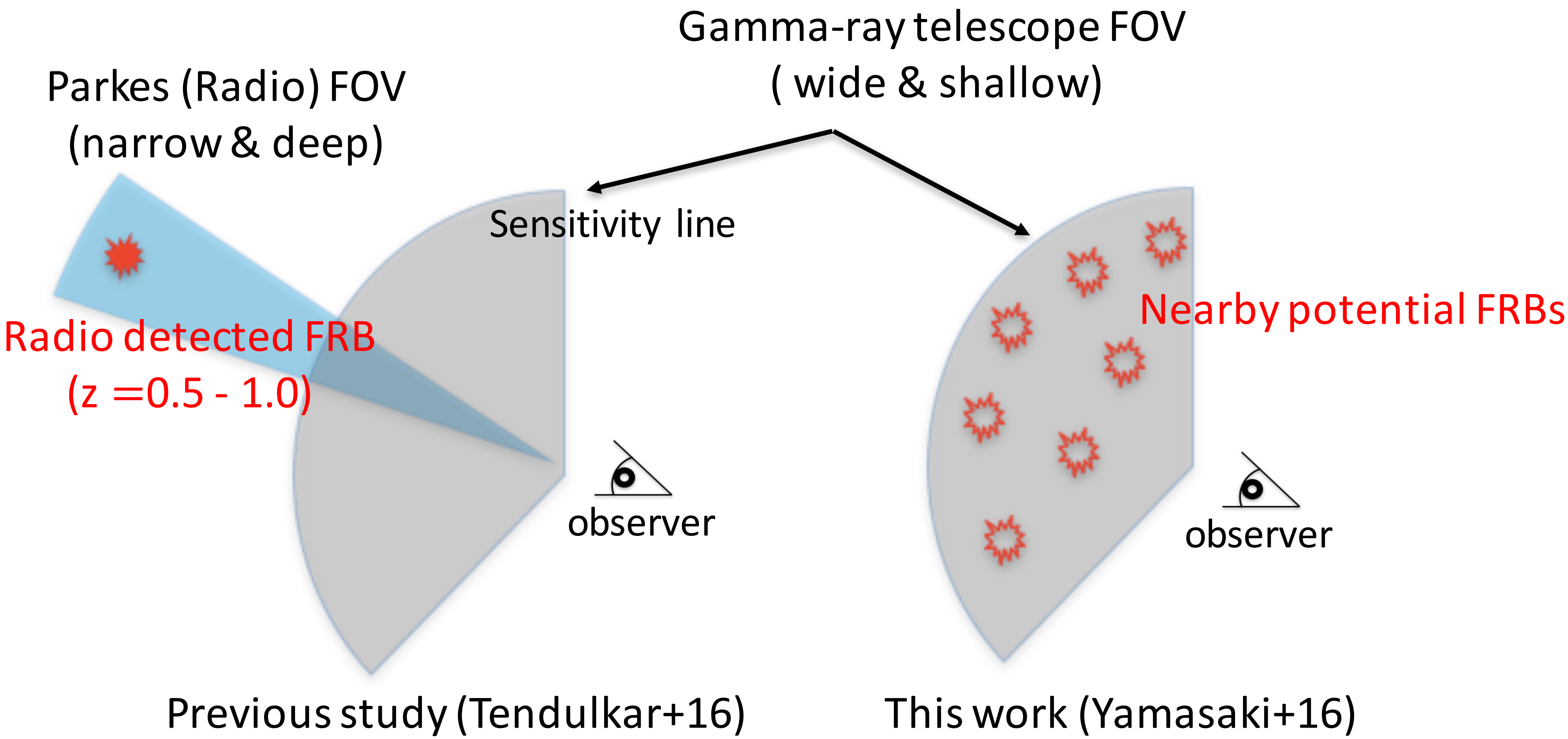


Resolved gamma-ray sky (0.1-300 GeV)



Wide field of view (~ 2.4 sr)

Schematic Picture



→ We improve the detection sensitivity by a factor of $\gtrsim 100$

Data & Search Algorithm

- Time span: 6.8 years from July 31, 2008 (UTC) to June 18, 2015 (UTC), the total amount of good time intervals is 79% of this.
- Photon data: “P7SOURCE” (smaller contamination)
- Energy Range: 1-100 GeV (Initially we used 30MeV-300GeV which turned out to include large backgroud contamination)
- Search time window : Δt = 1, 2, 5, and 10 ms are tried.
- We consider a reference γ-ray event, and other γ-ray events are searched within 2° radius from the reference in the time interval of Δt starting from the reference event.

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Results

Table 1. The number of detected MGF candidates (N_{obs}^{2ph} and N_{obs}^{3ph} for $N_{ph} = 2$ and 3, respectively). 'No cut' is the result of our blind search for MGFs without any event cut. The '1st cut' is to remove MGF candidates associated with GRB 090519. The '2nd cut' is the result after removing MGF events that are caused by nearby bright sources [brighter than a photon flux of 4×10^{-9} photons cm^{-2} s^{-1} (1 GeV $< E <$ 100 GeV) with angular separation less than 2°0]. The '3rd cut' is removing regions close to the Galactic disc ($|b| < 20°$). The expected numbers of false events caused by the Poisson statistics of the diffuse gamma-ray background flux are shown as N_{pred}^{2ph} in the 2nd and 3rd cut results.

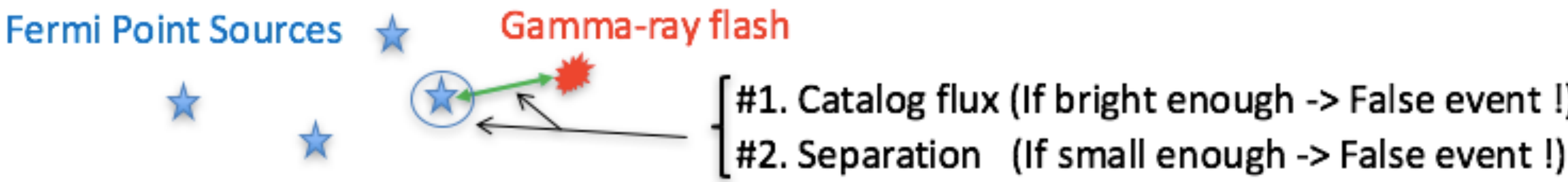
Cuts	No cut		1st cut		2nd cut		3rd cut	
f_{sky}[a]	1.0		1.0		0.96		0.68	
Time Windows	N_{obs}^{2ph}	N_{obs}^{3ph}	N_{obs}^{2ph}	N_{obs}^{3ph}	N_{obs}^{2ph} (N_{pred}^{2ph})	N_{obs}^{3ph}	N_{obs}^{2ph} (N_{pred}^{2ph})	N_{obs}^{3ph}
$\Delta t = 1$ ms	17	0	14	0	1 (2.7)	0	0 (1.2×10^{-1})	0
$\Delta t = 2$ ms	33	0	29	0	4 (5.3)	0	0 (2.3×10^{-1})	0
$\Delta t = 5$ ms	68	1	62	0	17 (13)	0	0 (5.8×10^{-1})	0
$\Delta t = 10$ ms	133	1	127	0	38 (27)	0	0 (1.0)	0

Note. [a]The remaining sky fraction after each event cut.

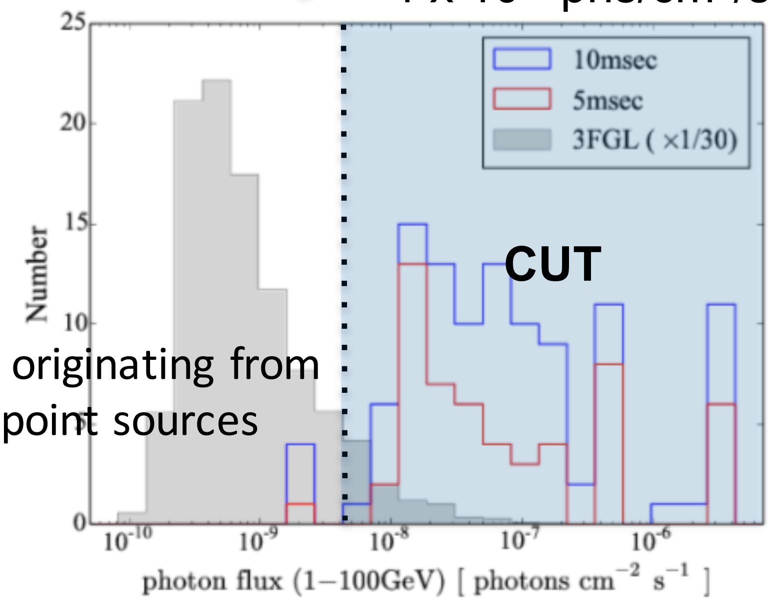
- ~100 flash candidates are detected
- Are they genuine? or false event ?

→ We examined the significance of these events

False Events from bright point sources



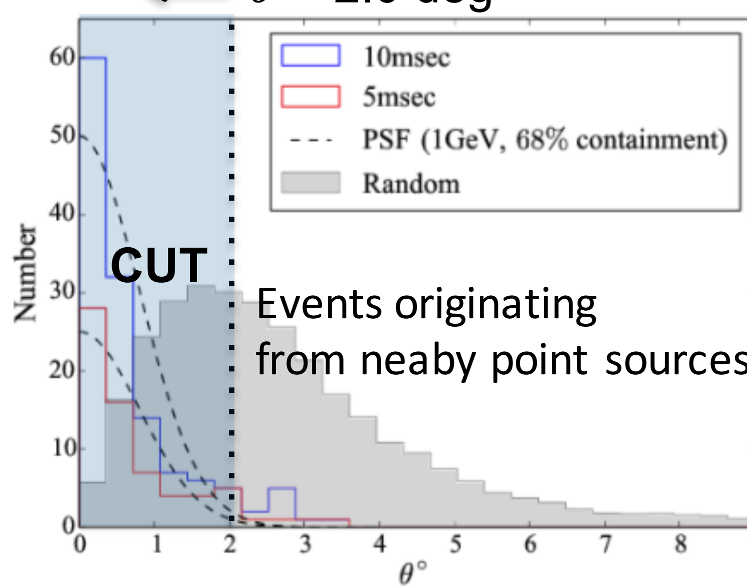
→ > 4 x 10^{-9} phs/cm^2/s



Events originating from bright point sources

#1. The photon flux distribution of the nearest point source to each event

← θ < 2.0 deg



Events originating from neaby point sources

#2. Angular separation distribution from each event to the nearest point source

False Events from diffuse background

- After removing events from bright steady point sources, we found no flash events at |b|>20°
- The expected number of events from the diffuse background (black) can account for the remaining flash events at |b|< 20° (grey)
- We used this final result (no ganmma-ray flash events at |b|>20°, remaining sky fraction~ 0.68) to set an upper-limit on the flux of ms-scale gamma-ray flashes

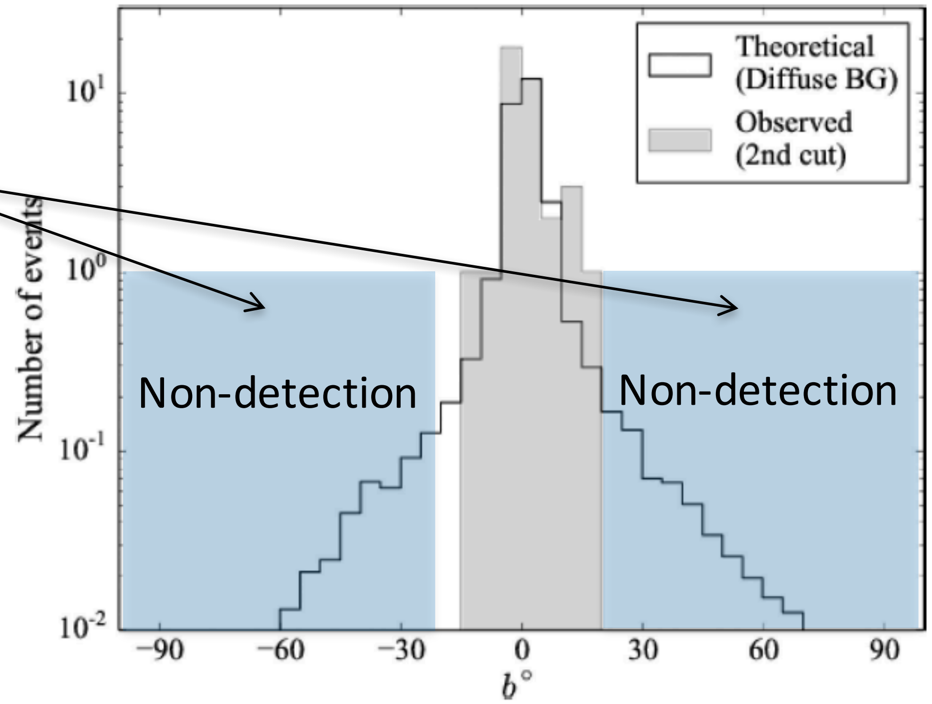


Figure 3. The Galactic latitude distribution of the MGF candidates with $N_{\rm ph} = 2$ and $\Delta t = 10$ ms after the 2nd cut (grey histogram). The expected distribution from the Poisson statistics of the diffuse gamma-ray background is shown as solid histogram.

Galactic latitude distribution of remaining events (N_{photon} = 2, Δt = 10 ms)

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Upper-limit on gamma-ray/radio flux ratio

- The Standard candle approximation: we define gamma-ray to radio luminosity ratio in the rest-frame of an FRB as

$$\xi \equiv \frac{(\nu L_\nu)_\gamma}{(\nu L_\nu)_r}$$

(ξ : the key parameter in our analysis)

- We assume that ξ is the same for all FRBs, and that FRBs have a power-law gamma-ray spectrum with a photon spectral index Γ (here we take Γ = 2)

- The maximum redshift of detection ($z_{\rm max}(\xi, T_i, \Omega_j)$) is determined by :

$$N_\gamma = \Delta t \int_{1\ \rm GeV}^{100\ \rm GeV} d\epsilon_{\rm obs}\ A_{\rm eff}(T_i, \Omega_j) \frac{{\rm d}F_\gamma(\epsilon_{\rm obs}; z, \xi)}{{\rm d}\epsilon_{\rm obs}}$$

Number of observed γ-ray flashes (< 2) within Δt

Duration (3ms)

Effective area of LAT

Differential γ-ray flux of an FRB

- Volumetric FRB rate evolution is included as $\Phi_{\rm FRB}(z, \beta) = \Phi_0(1 + z)^\beta$

- The upper-limit on ξ (2-sigma) is derived for β = 0-4 by solving

$$N_{\rm MGF}^{\rm tot}(\xi) = 3.09$$

w/ $N_{\rm MGF}(T_i, \Omega_j) = \mathcal{R}_{\rm FRB}[0, z_{\rm max}; \beta] \frac{\Delta\Omega_j}{4\pi} T_{\rm exp}(T_i)$

Number of FRBs in $z < z_{\rm max}$

Direction (for j-th sky grid)

Exposure time (for i-th time bin)

Number of detectable γ-ray flashes from FRBs (for i-th time bin and j-th sky direction)

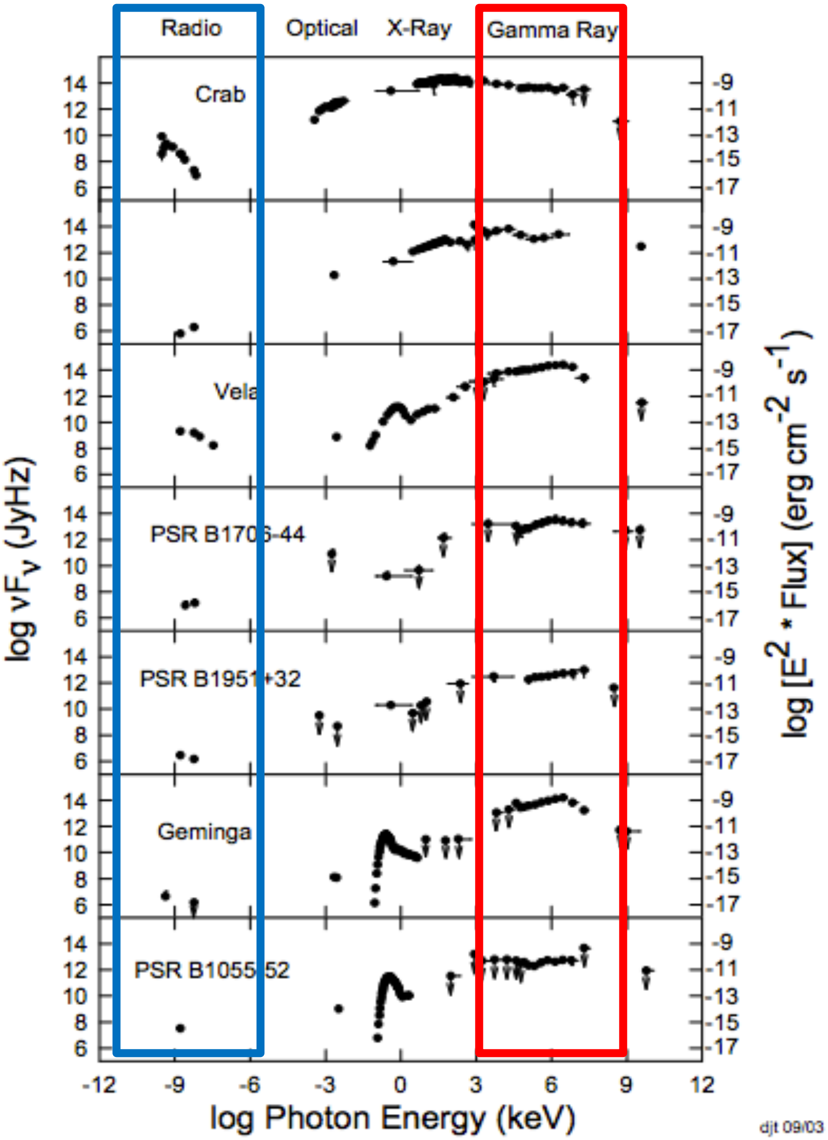
Result

Table 2. The 2σ upper limits on gamma-ray to radio flux ratio (ξ) for $\beta = 0$–4. The normalization of the volumetric FRB rate at $z = 0$ (Φ_0) is also shown. FRB duration is assumed to be $\Delta t = 3$ ms.

β	Φ_0 (Gpc^{-3} yr^{-1})	ξ ($\equiv (\nu L_\nu)_\gamma / (\nu L_\nu)_r$)
0	$1.2^{+1.5}_{-0.8} \times 10^4$	$<4.2^{+2.4}_{-1.7} \times 10^7$
1	$7.4^{+9.4}_{-4.7} \times 10^3$	$<5.2^{+4.3}_{-2.0} \times 10^7$
2	$4.5^{+5.7}_{-2.9} \times 10^3$	$<7.0^{+5.0}_{-2.8} \times 10^7$
3	$2.7^{+3.5}_{-1.7} \times 10^3$	$<9.2^{+7.8}_{-3.8} \times 10^7$
4	$1.6^{+2.1}_{-1.0} \times 10^3$	$<1.2^{+1.2}_{-0.4} \times 10^8$

$\xi \lesssim (4.2 - 12)\times 10^7$ (@GeV band, this work)

Our limit on ξ is stronger than that obtained from non-detection of radio-detected FRBs by *Fermi*-LAT (typically $\xi \lesssim 4 \times 10^{10}$)

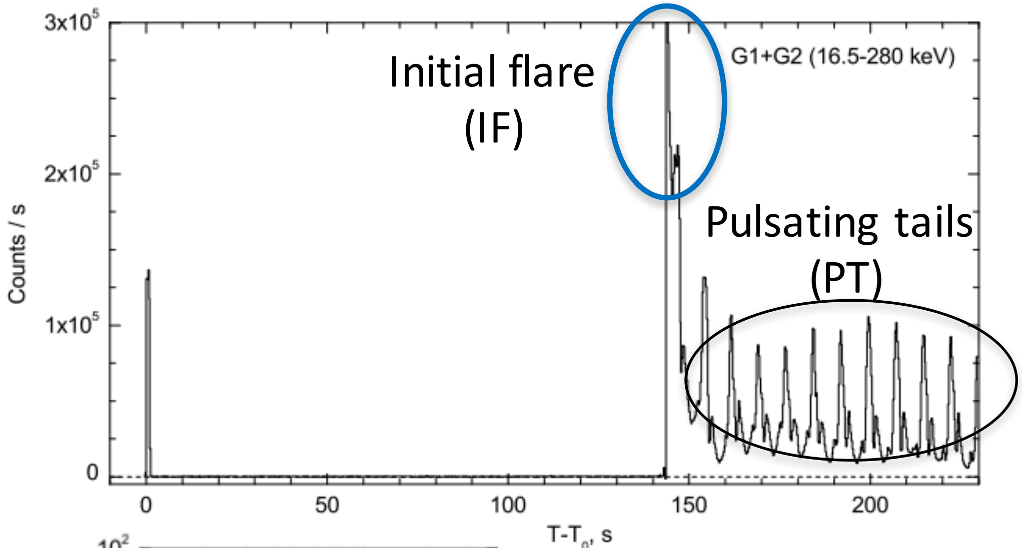


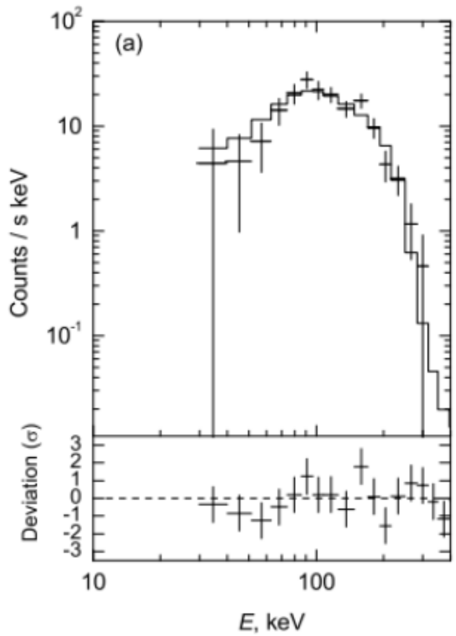
Thompson, D. J. 2004a, in IAU Symp. 218

The multi-wavelength spectra of typical gamma-ray pulsars

- Typically $\xi = 10^6 - 10^8$
- Some young pulsars exhibit $\xi < 10^4$
- ξ of pulsars are distributed in a wide range($\xi_{PSR} = 10^4 - 10^8$), and our result ($\xi \lesssim 10^8$) does not exclude a possibility that FRBs have a similar GeV gamma-ray to radio flux ratio to pulsars

SGR 1806-20 (magnetar) flares in Dec 2004





The SED of Initial flare

~10 – 100 keV observation only

- The brightest gamma-ray event but non-detection in the radio band:
  $(\nu F\nu)_{radio} < 1.1$ MJy (Tendulkar+16)

- Gamma-ray : ~keV observation only
  → We estimate the GeV flux of IF using PT's SED:
  $(\nu F\nu)_{Hard-\gamma} \sim 0.51$ erg cm^{-2} s^{-1}

- The lower-limit on ξ for SGR is derived as : $\xi_{SGR} \gtrsim 10^{7.5}$

- This is marginally consistent with our limit : $\xi \lesssim (4.2-12)\times 10^{7}$

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Summary

- We searched ms-scale gamma-ray flashes in the 7-yr Fermi-LAT data, motivated by the possible gamma-ray counterpart to FRBs
  - About 100 flash candidates are detected
  - After careful event cuts, the remaining events at low lat. regions ($|b| < 20°$) are consistent with the statistical flukes originating from diffuse gamma-ray background
  - No ms-scale (Δt <10 ms) gamma-ray flashes found at high lat. regions ($|b|>20°$, sky fraction~0.68)

- Considering the z-evolution of FRB rate density, we set upper bounds on GeV gamma-ray to radio flux ratio ($\equiv \xi$) of FRBs : $\xi \lesssim (4.2 - 12)\times 10^{7}$

  - ξ of pulsars : $\xi_{PSR} = 10^4 - 10^8$ → we cannot exclude that FRBs have similar values of ξ to pulsars in general
  - ξ of a magnetar(SGR 1806-20) : $\xi_{SGR} \gtrsim 10^{7.5}$ → the upper bound on the radio flux for SGR 1806-20 is marginally consistent with our limit of ξ

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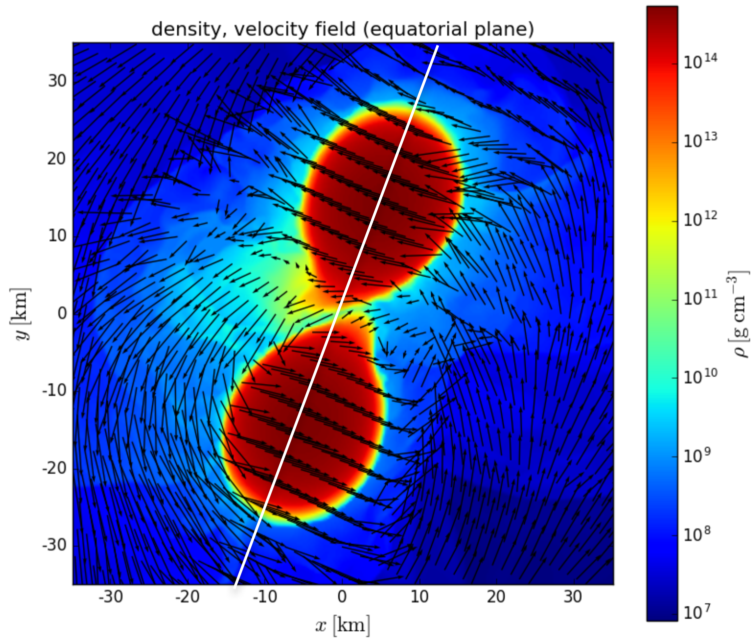
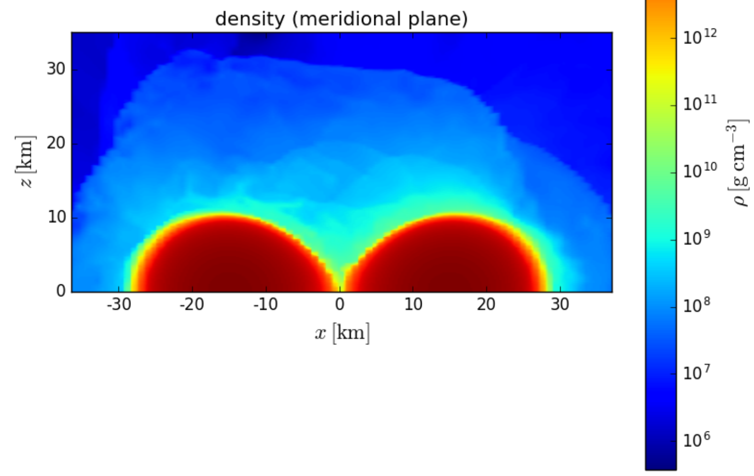
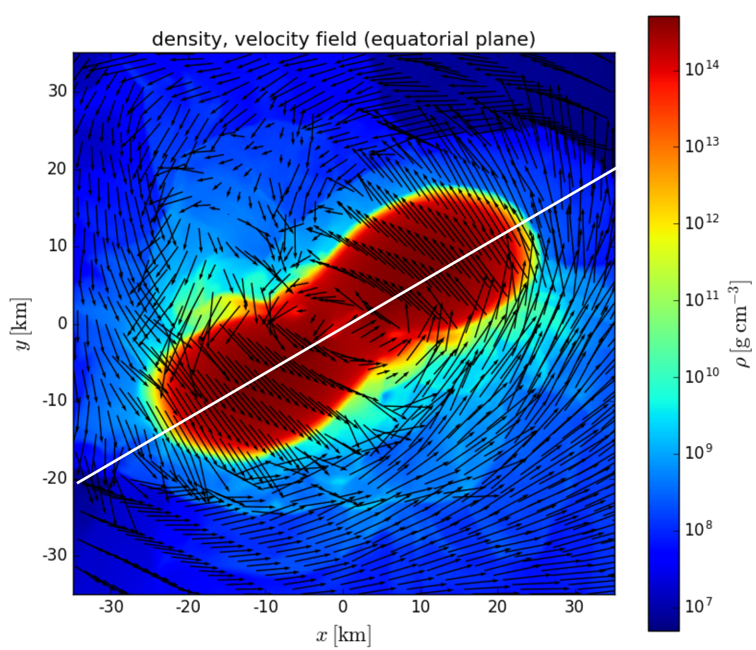
Testing binary NS merger model for FRBs

- Binary NS mergers are possible origin of FRBs (e.g. Totani 2013, Zhang+2016, Wang +2016)
- The emission mechanism producing coherent radio emission is unclear
  (Magnetic dipolar emission, curvature radiation, synchrotron, Inverse Compton…)
- Theoretical studies predict possible electromagnetic emissions during insipral phase (prior to merger)
  (e.g. Hansen & Lyutikov 2000, Lai 2012, Wang+2016)
- Using binary NS merger simulation data (K.Kiuchi, M.Shibata), we test proposed scenarios and consider a realistic model for FRBs if possible

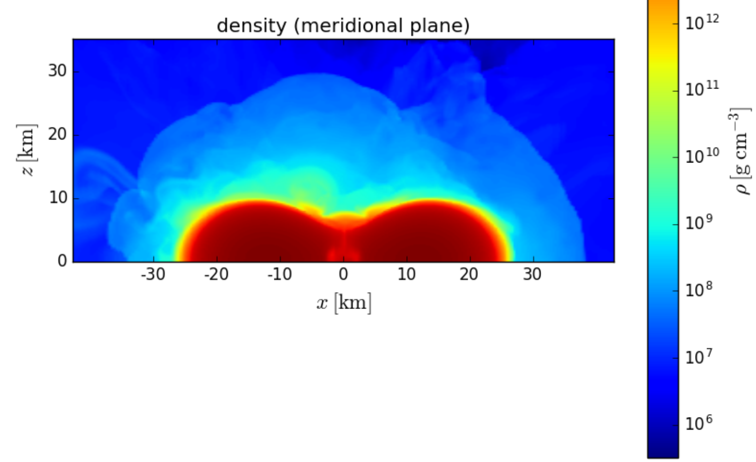


$t = t_{mrg} - 1.4$ ms (i = 22)



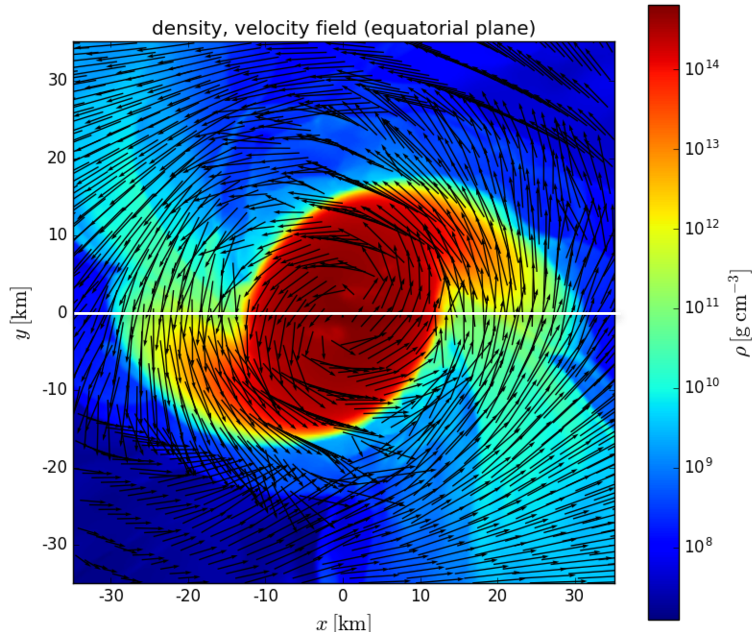


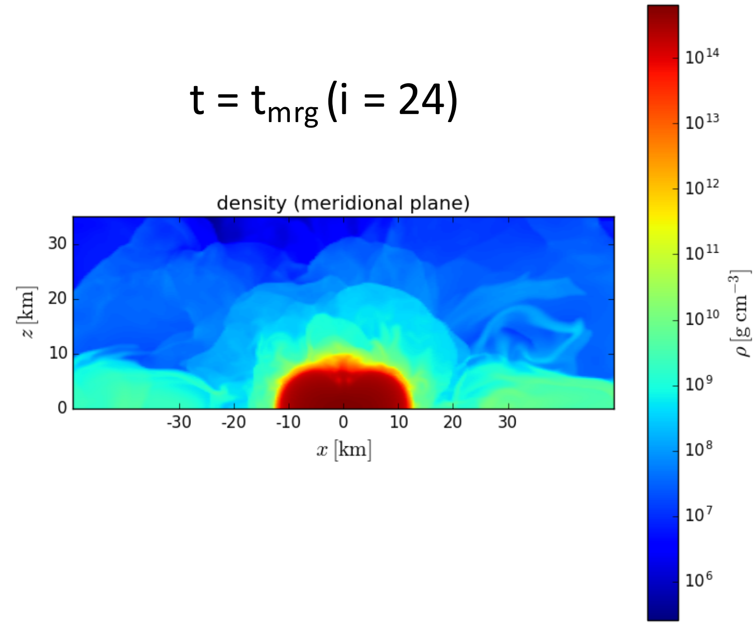
$t = t_{mrg} - 0.7$ ms (i = 23)



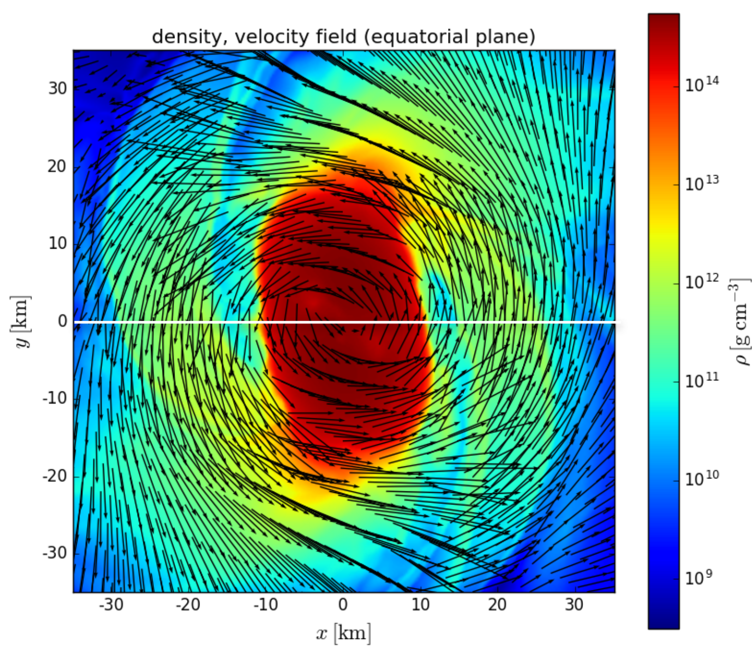
H4 EOS, 1.35 M_{SUN} – 1.35 M_{SUN}

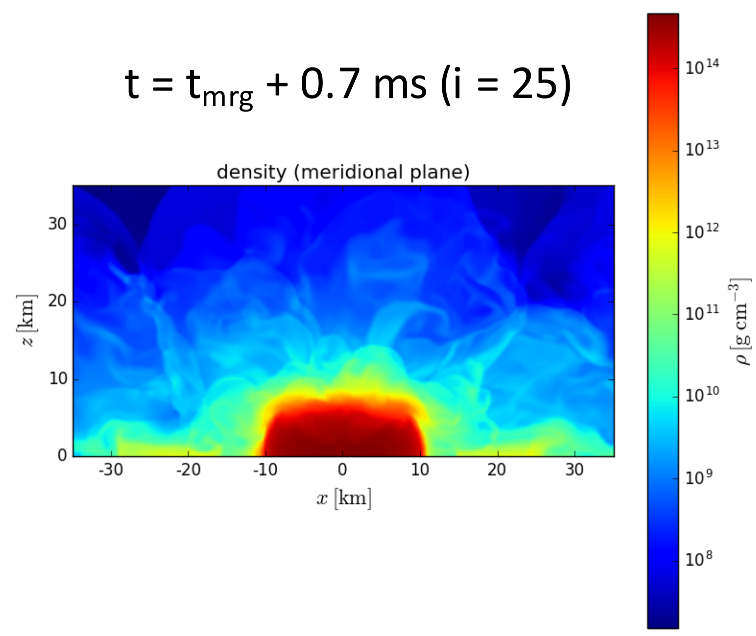
t = t_{mrg} (i = 24)





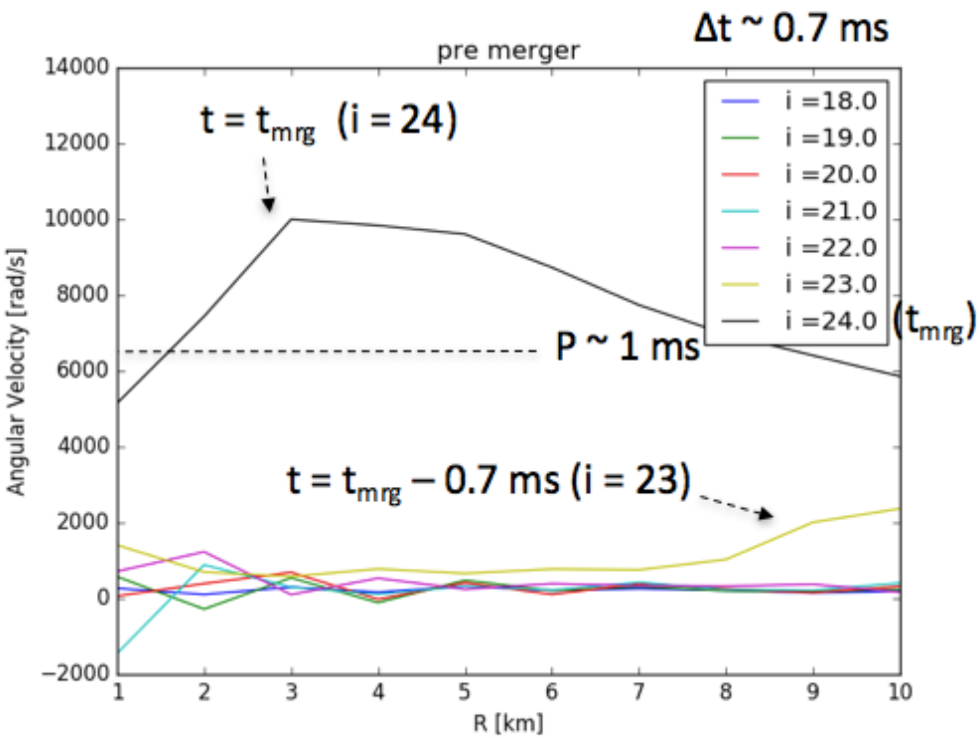
t = t_{mrg} + 0.7 ms (i = 25)





H4 EOS, 1.35 M_{SUN} – 1.35 M_{SUN}

Angular velocity evolution
(before merger t_{mrg} - 4.2 ms < t < t_{mrg})



$$F_\nu = \frac{1}{\nu_{\rm obs}} \frac{\epsilon_r |\dot{E}|}{4\pi D_{\rm lum}^2} = 0.02 \left(\frac{\epsilon_r}{10^{-4}}\right) \left(\frac{D_{\rm lum}}{4.6 \text{ Gpc}}\right)^{-2} \times \left(\frac{B}{10^{12.5} \text{ G}}\right)^2 \left(\frac{R}{10 \text{ km}}\right)^6 \left(\frac{P}{0.5 \text{ msec}}\right)^{-4} \text{Jy}$$

(Totani 2013)

The angular velocity enhanced by a factor of ~3-10 in the last 0.7ms before merger

Open questions:

- How energy is extracted from the spin and orbital motion of inspiral NS ?
- Is coherent emission possible ?
- The magnetospheric environment (density, opacity…)