Constraining the Age of a Magnetar Possibly Associated with FRB 121102

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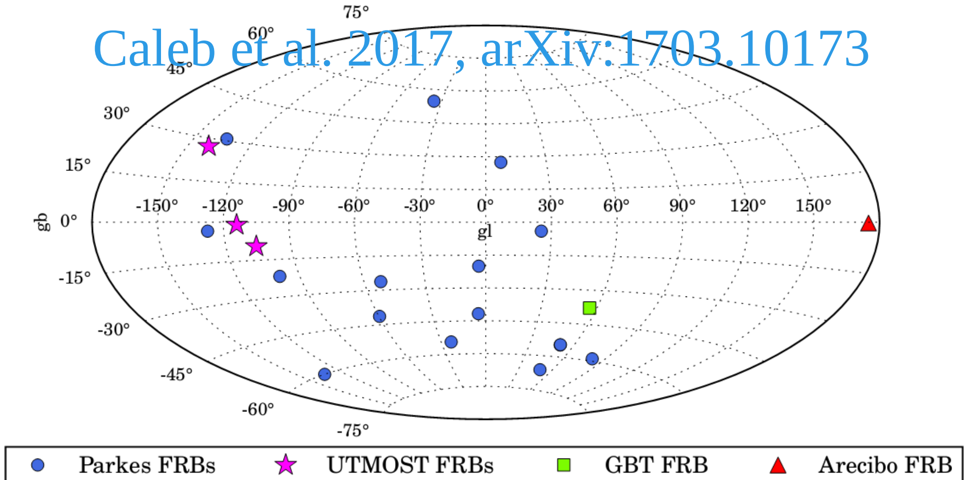
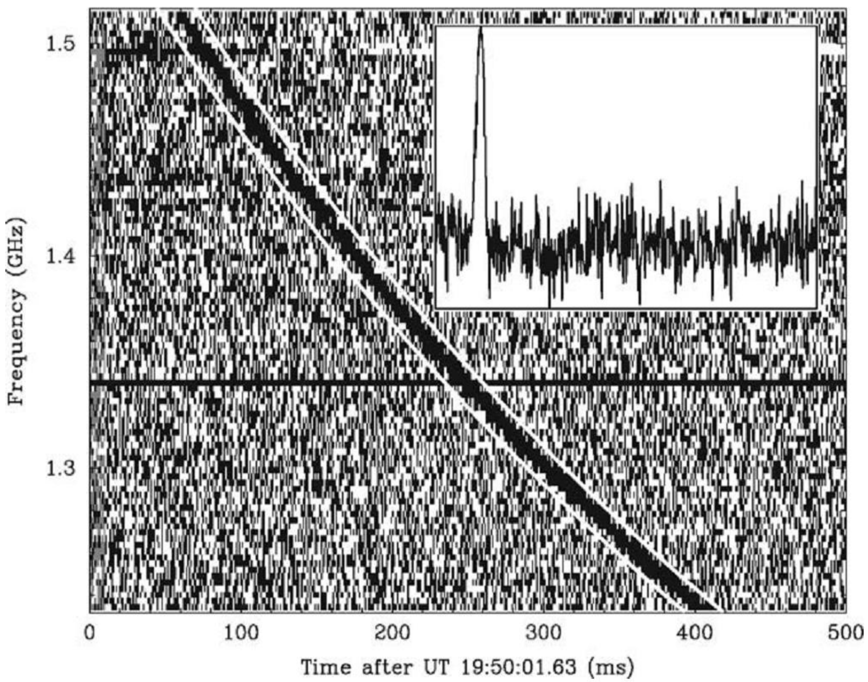
Fast Radio Bursts

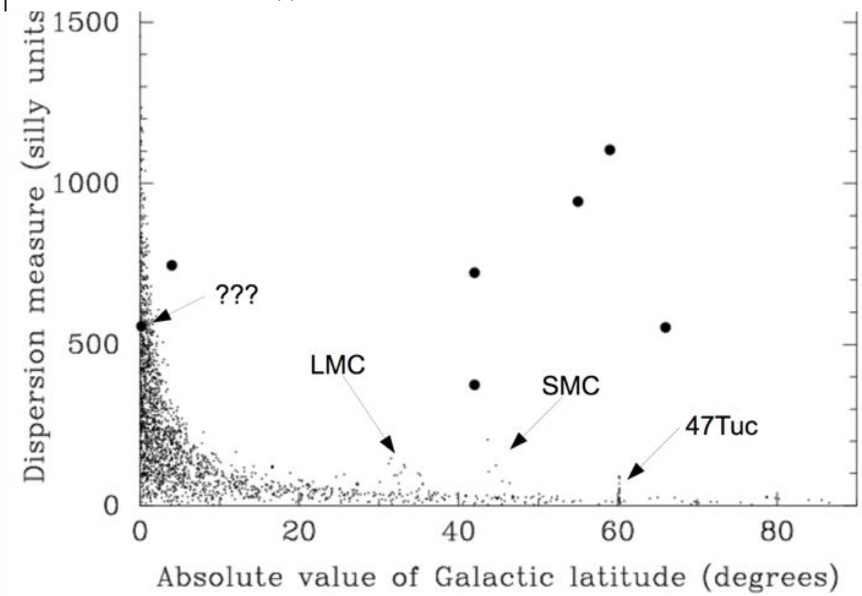
$$\Delta t = \frac{e^2}{2\pi m_e c}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right) \mathrm{DM}$$

Caleb et al. 2017, arXiv:1703.10173



Lorimer et al. 2007, Science, 318, 7





Thornton et al. 2013, Science, 341, 53

Models: Catastrophic Collapses/ Mergers of Compact Star Systems

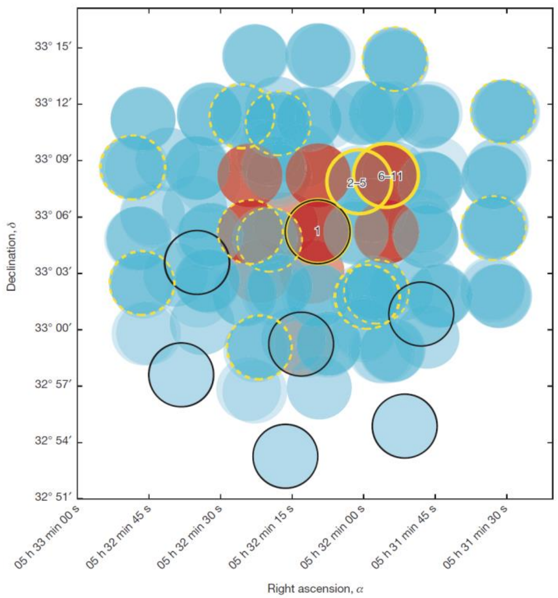
- Collapses of supramassive neutron stars to black holes at several thousand to millions of years old (Falcke & Rezzolla 2014) or at birth (Zhang 2014);
- Inspiral or mergers of double neutron stars (Totani 2013 ; Wang et al. 2016);
- Mergers of binary white dwarfs (Kashiyama et al. 2013);
- Mergers of charged black holes (Zhang 2016);
- Collisions of asteroids/ comets with neutron stars (Geng & Huang 2015) .

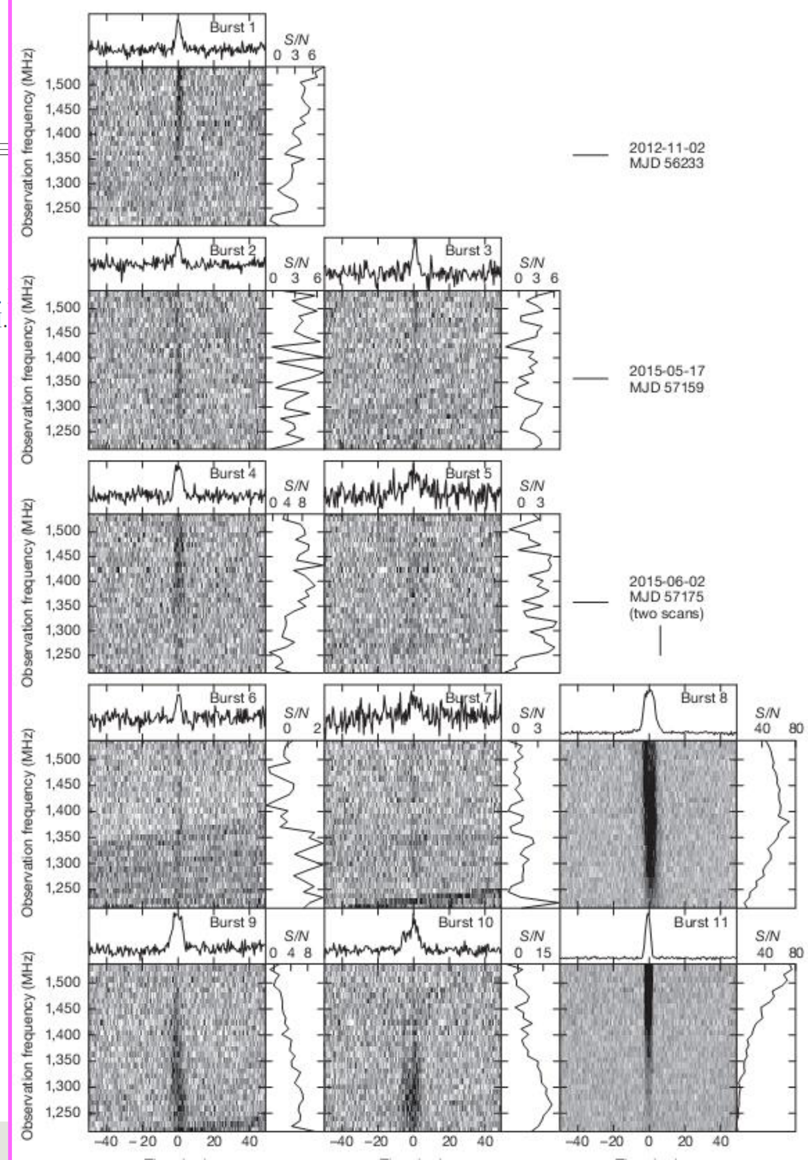
Repeating FRB 121102

LETTER

A repeating fast radio burst

L. G. Spitler[1], P. Scholz[2], J. W. T. Hessels[3,4], S. Bogdanov[5], A. Brazier[6,7], F. Camilo[5,8], S. Chatterjee[6], J. J. Deneva[10], R. D. Ferdman[2], P. C. C. Freire[1], V. M. Kaspi[2], P. Lazarus[1], R. Lynch[11,12], E. C. Madsen[2], M. S. M. Ransom[13], A. Seymour[14], I. H. Stairs[2,15], B. W. Stappers[16], J. van Leeuwen[3,4] & W. W. Zhu[1]

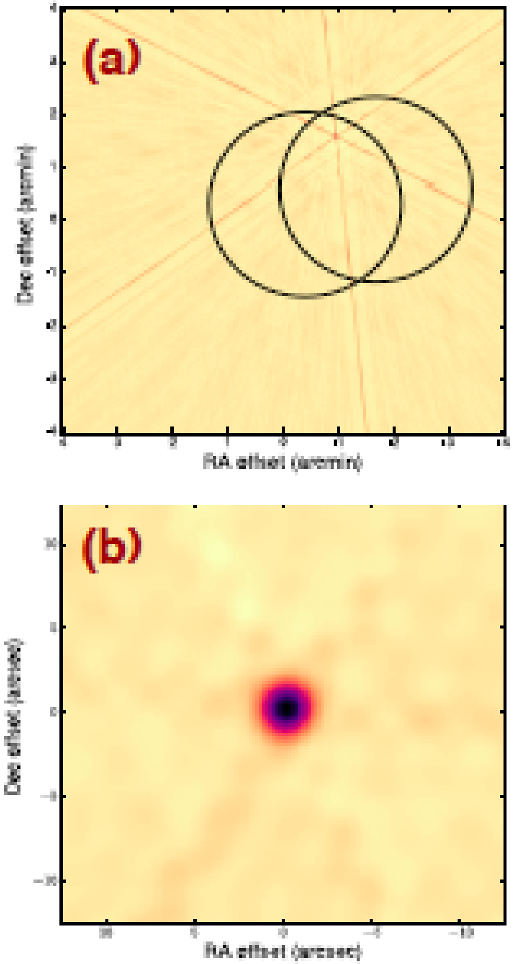




Spitler et al. 2016, Nature, 531, 202

Localization of FRB 121102

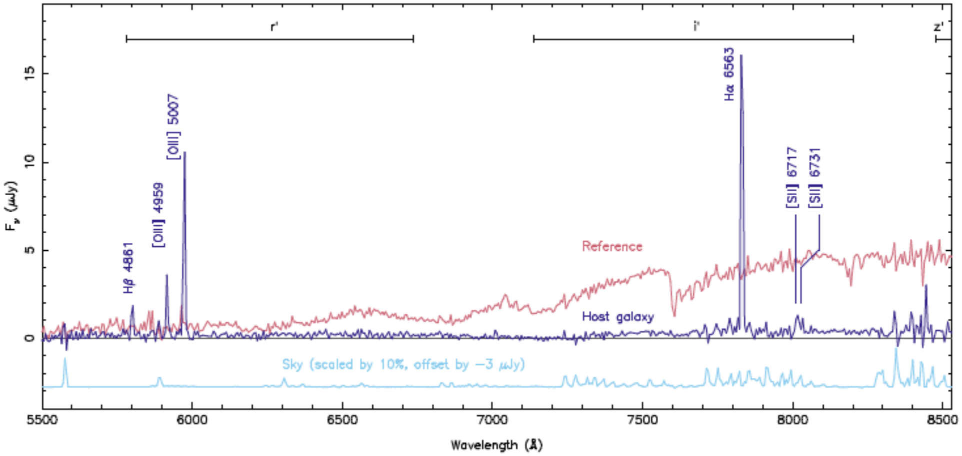
➢ **A 100-milliarcsecond localization of FRB 121102 by VLA**



- (a) A 5-ms dispersion-corrected dirty image shows a burst from FRB 121102 at MJD 57633.67986367 (2016 Sep 02). The approximate localization uncertainty from previous Arecibo detections9 (30 beam FWHM) is shown with overlapping circles.
- (b) A zoomed in portion of the above image, de-convolved and recentered on the detection, showing the 0.100 localization of the burst.

Chatterjee et al. 2017, Nature, 541, 58

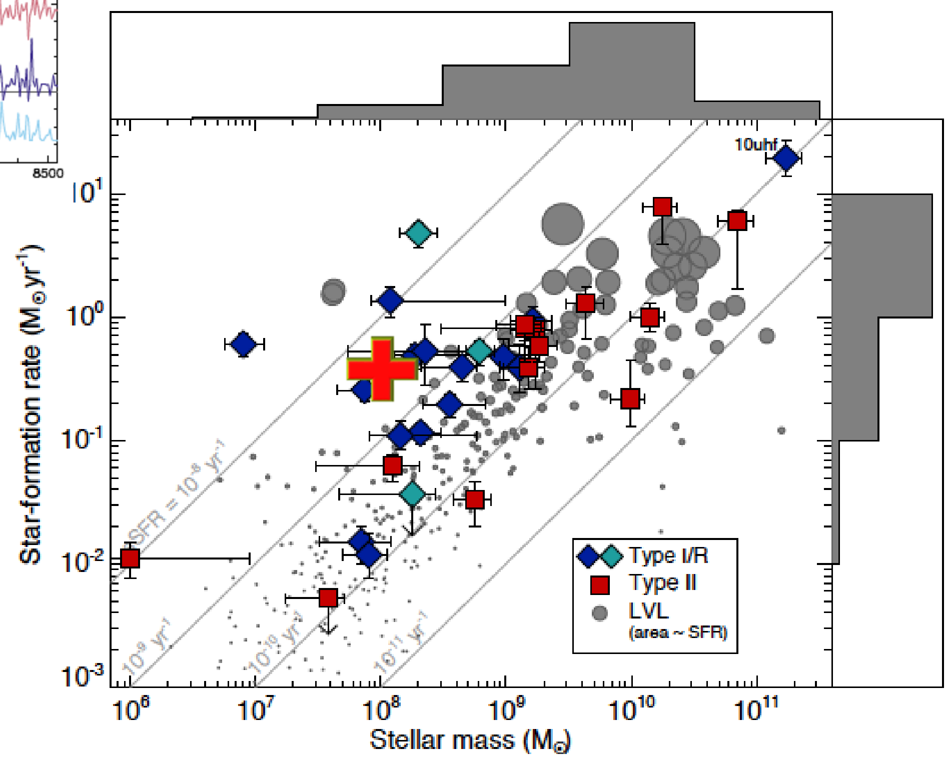
Host Galaxy of FRB 121102



Tendulkar et al. 2017, ApJL, 834, L7

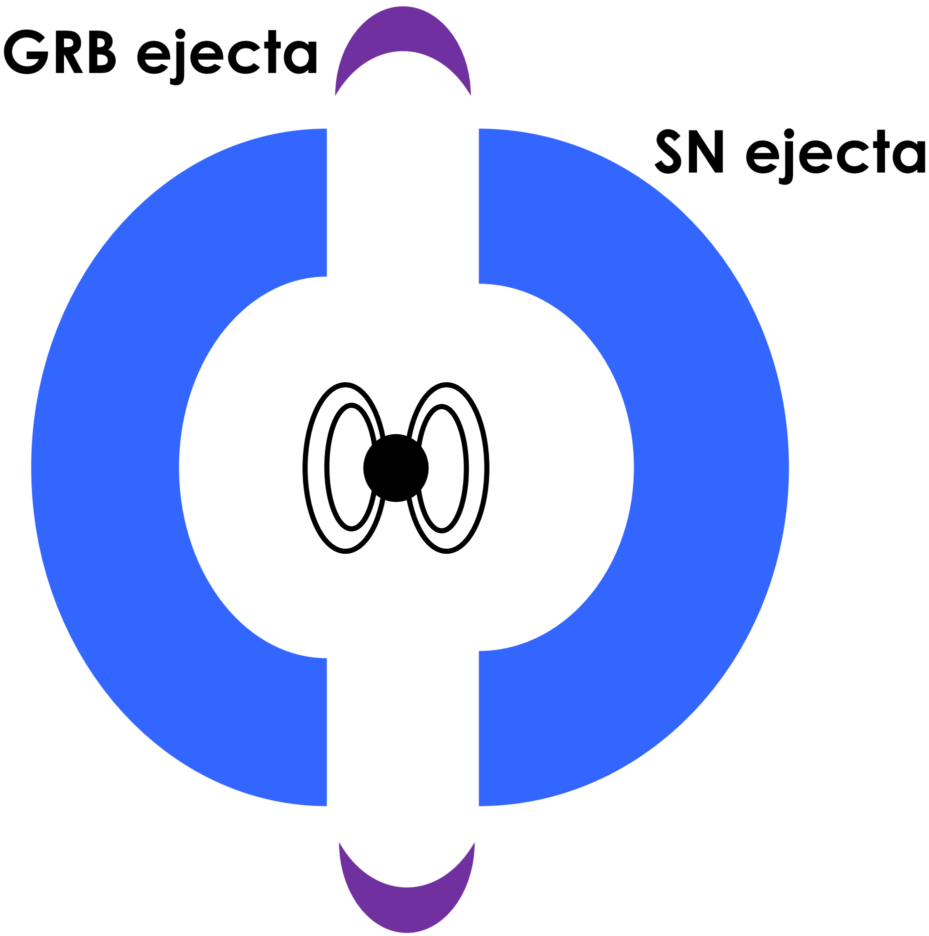
- A low-metallicity, star-forming, $m_{r'}$=25.1 AB mag dwarf galaxy at a redshift of $z = 0.19273(8)$, ~1 Gpc.

- This host has a diameter~4 kpc, a stellar mass of M^{*}~(4–7)$\times 10^{7} M_{sun}$, an SFR of ~0.4M_{sun} yr^{-1}, and a substantial host DM≤ 324 pc cm^{-3}.

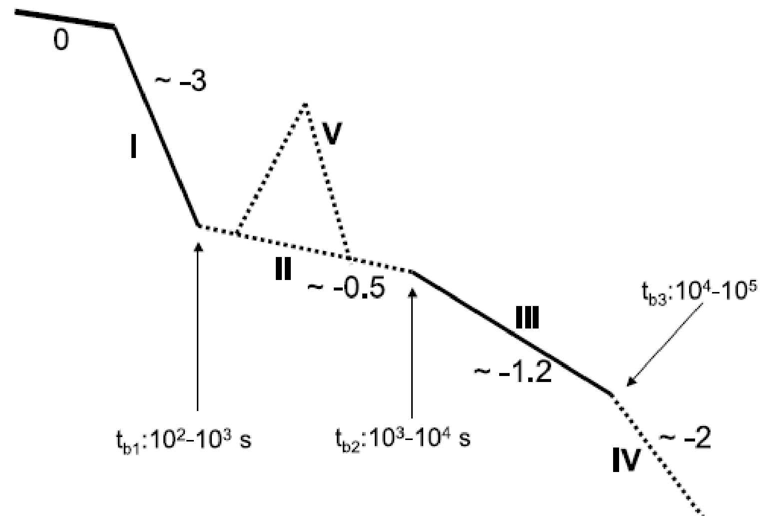


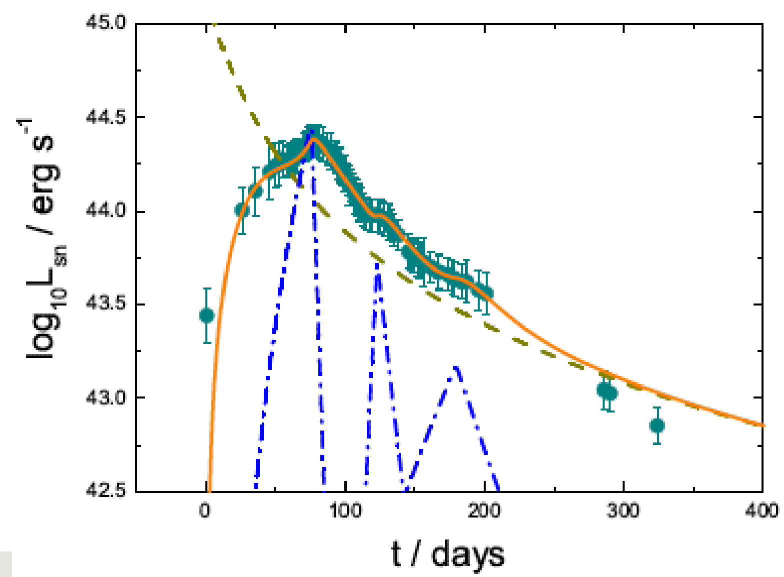
Perley et al. 2016, ApJ, 830, 13

Long GRBs and Type I SLSNe



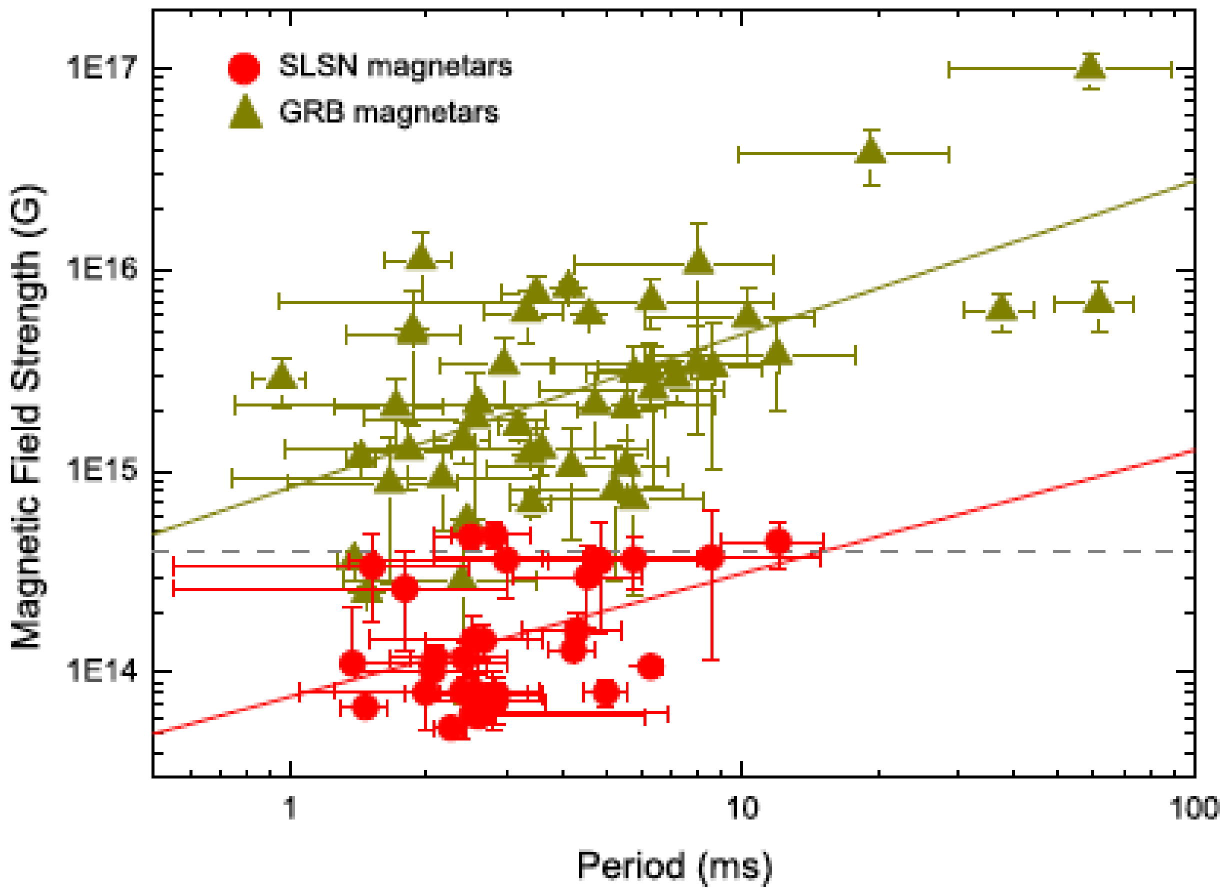
Millisecond Magnetar Engine





Long GRBs and Type I SLSNe

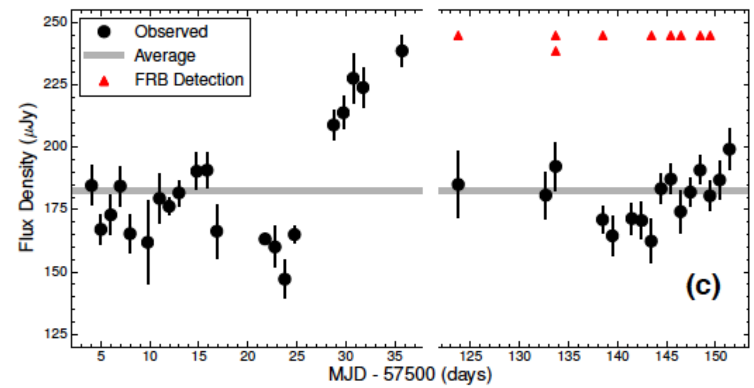
Millisecond Magnetar Engine

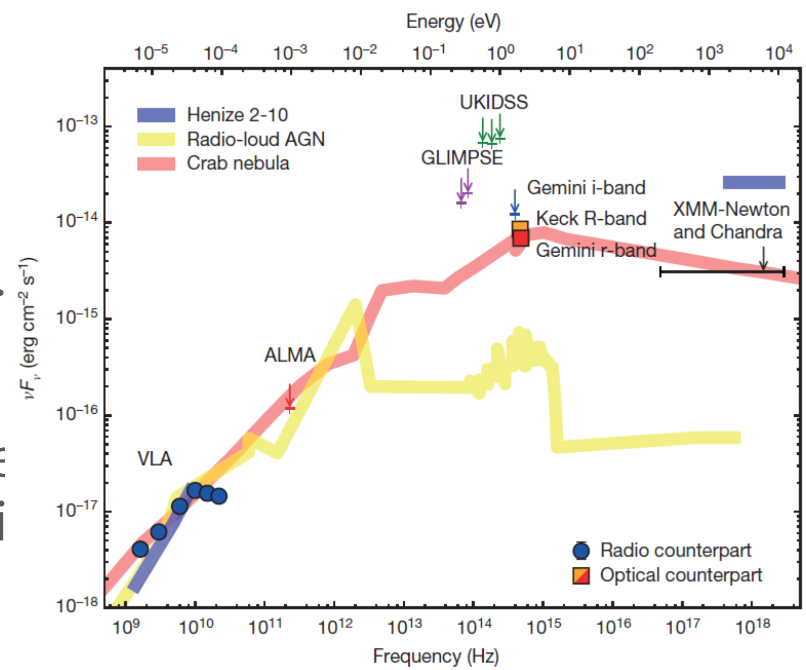


Yu et al. 2017, ApJ, 840, 12

Persistent Radio Counterpart

- A faint 180 uJy persistent radio source with a continuum spectrum that is consistent with non-thermal emission.
- The flux density of the persistent radio source varies by tens of percent on day timescales, and very long baseline radio interferometry yields an angular size less than 1.7 milliarcseconds.
- A counterpart to FRB 121102 is detected in archival Keck image at RAB =24.9 mag and in Gemini GMOS r-band image at rAB = 25.1 mag

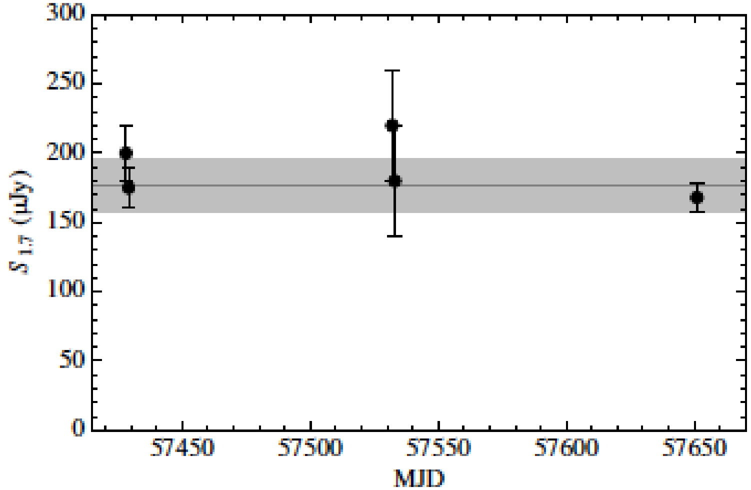


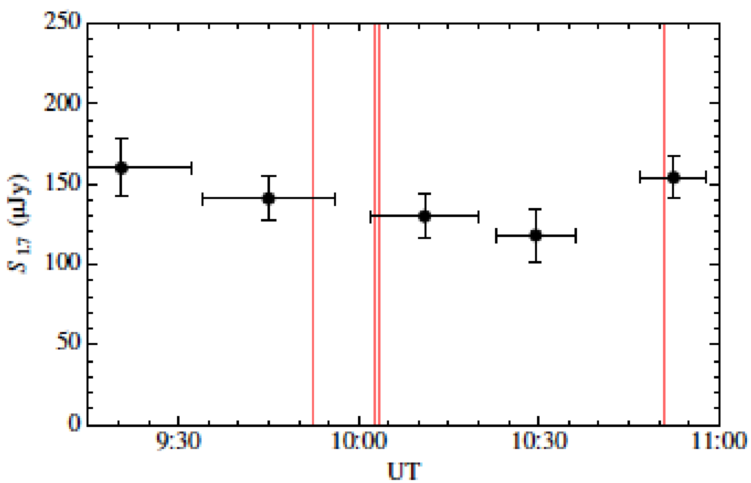


Chatterjee et al. 2017, Nature, 541, 58

Persistent Radio Counterpart

- the European VLBI Network and the 305-m Arecibo telescope





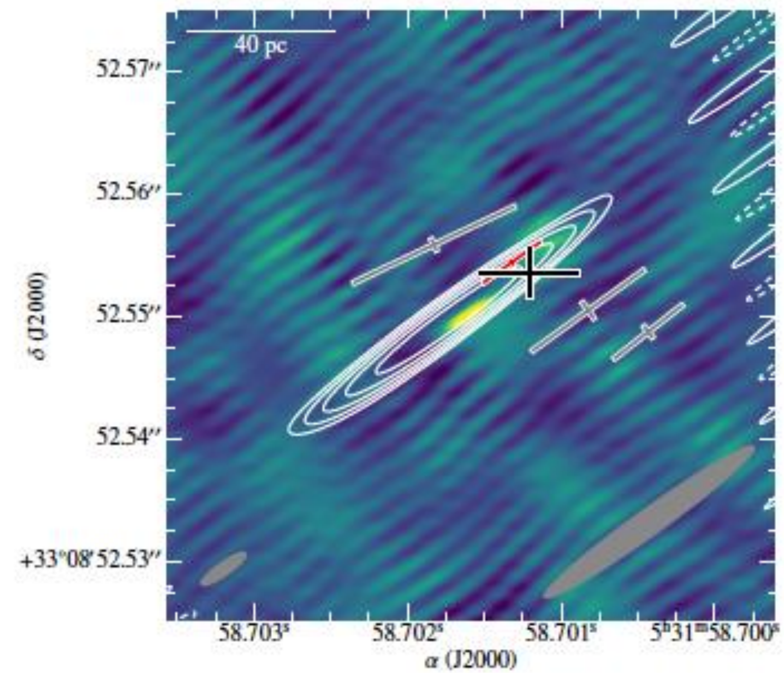
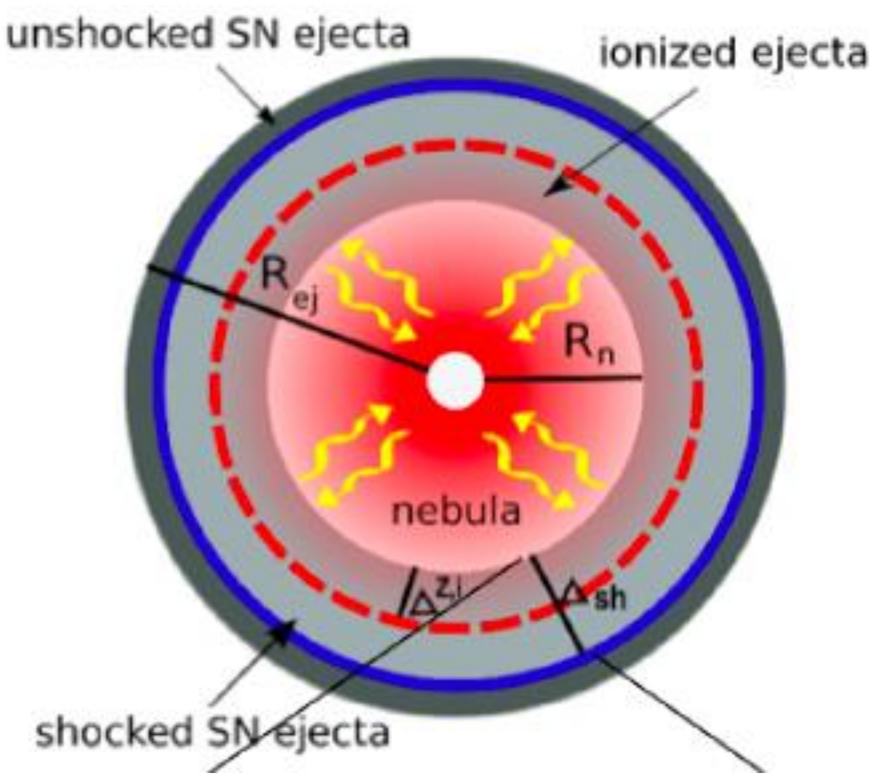


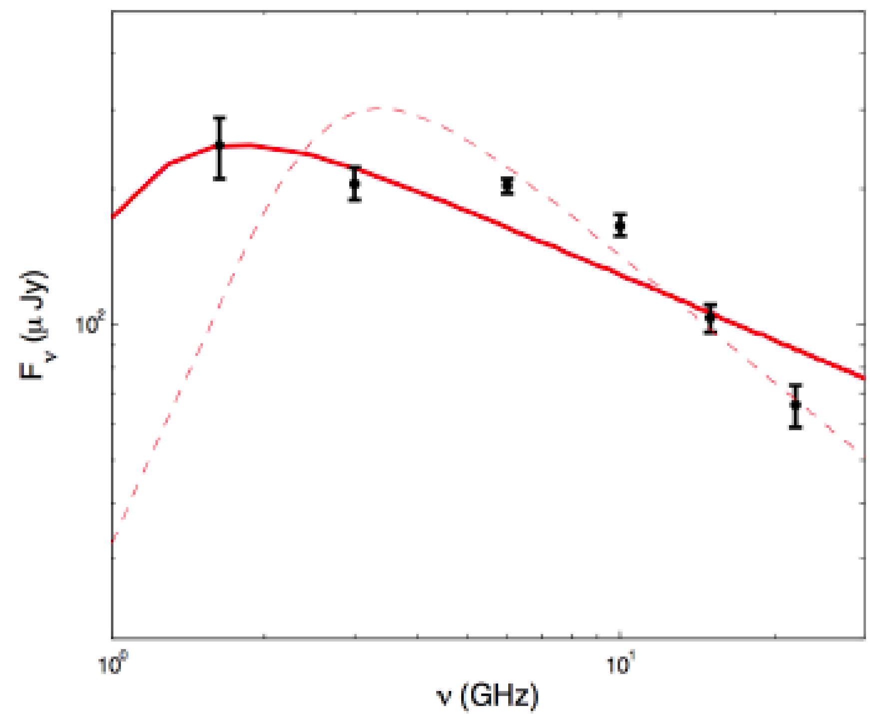
Figure 1. EVN image of the persistent source at 1.7 GHz (white contours) together with the localization of the strongest burst (red cross), the other three observed bursts (gray crosses), and the position obtained after averaging all four bursts detected on 2016 Sep 20 (black cross). Contours

≤0.2mas (~0.7 pc) separation to FRB.

Marcote et al. 2017, ApJL, 834, L8

Persistent Radio Counterpart





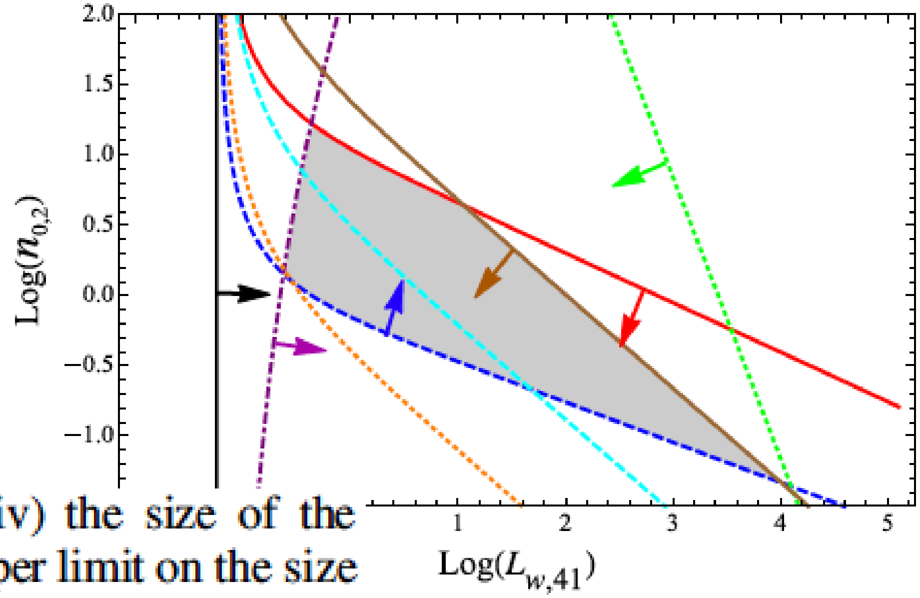
$$F_\nu \approx \frac{L_{\rm sd}}{8\pi D^2 \nu_{\rm max}} \left(\frac{\nu}{\nu_{\rm max}}\right)^{-0.25}$$

$$\approx 200\,\mu{\rm Jy}\,\nu_{\rm GHz}^{-0.25} \left(\frac{\nu_{\rm max}}{10^{12}\,{\rm Hz}}\right)^{-0.75} B_{14}^{-2} t_1^{-2}$$

Metzger et al. 2017, ApJ, in press
Kashiyama & Murase, 2017, ApJL, 839, L3

Persistent Radio Counterpart

$$\frac{d}{dt}\left[R_p^2 \frac{d}{dt}\left(M_{sw}\frac{dR_p}{dt}\right)\right] = R_p L_w.$$



The other requirements are as follows: (iv) the size of the PWN should be smaller than the observed upper limit on the size of the persistent radio source (Marcote et al. 2017), $R_p \lesssim 0.7$ pc; (v) the radius of the termination shock, R_t, must be much smaller than the radius of the contact discontinuity, R_p, in order for our PWN scenario to be self-consistent; (vi) the DM contributed from the shocked medium should be smaller than the estimated host-galaxy DM (Cao et al. 2017; Tendulkar et al. 2017; Yang

Dai et al., 2017, ApJL, 838, L7

Persistent Radio Counterpart

- By considering that the luminosity of the wind emission is ultimately determined by the spin-down luminosity of the magnetar, it is convenient to simply require the spin-down luminosity to be higher than the luminosity of the steady radio emission

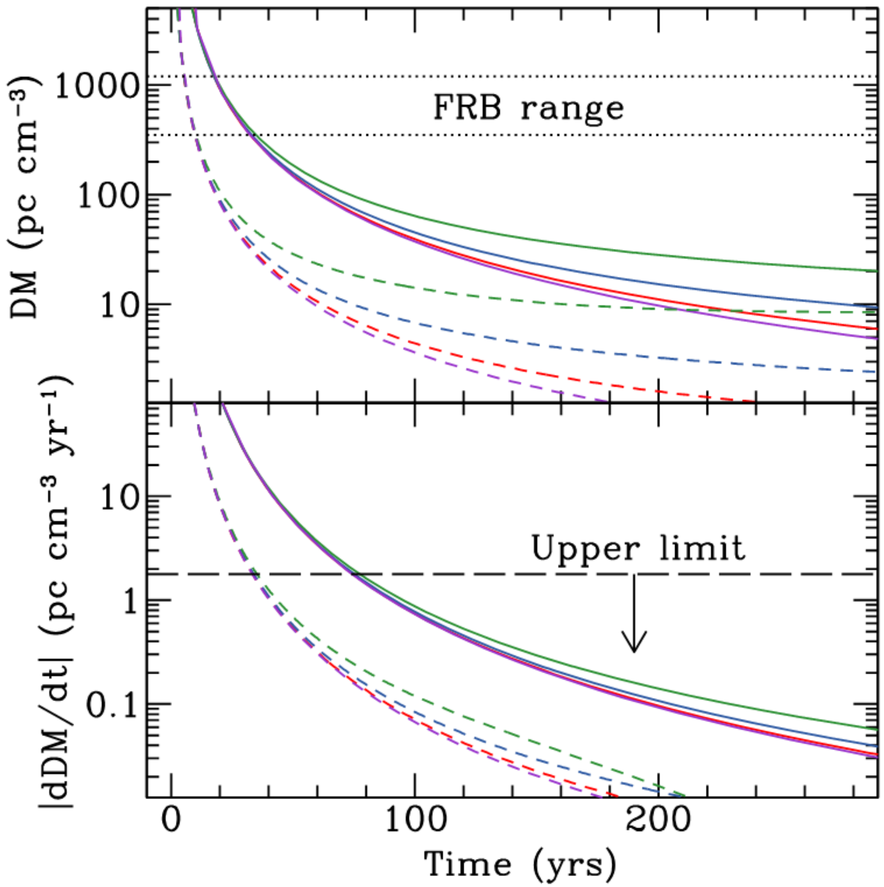
$$L_{\rm sd} > L_{\rm radio} = 3 \times 10^{38}\ {\rm erg\ s^{-1}}.$$

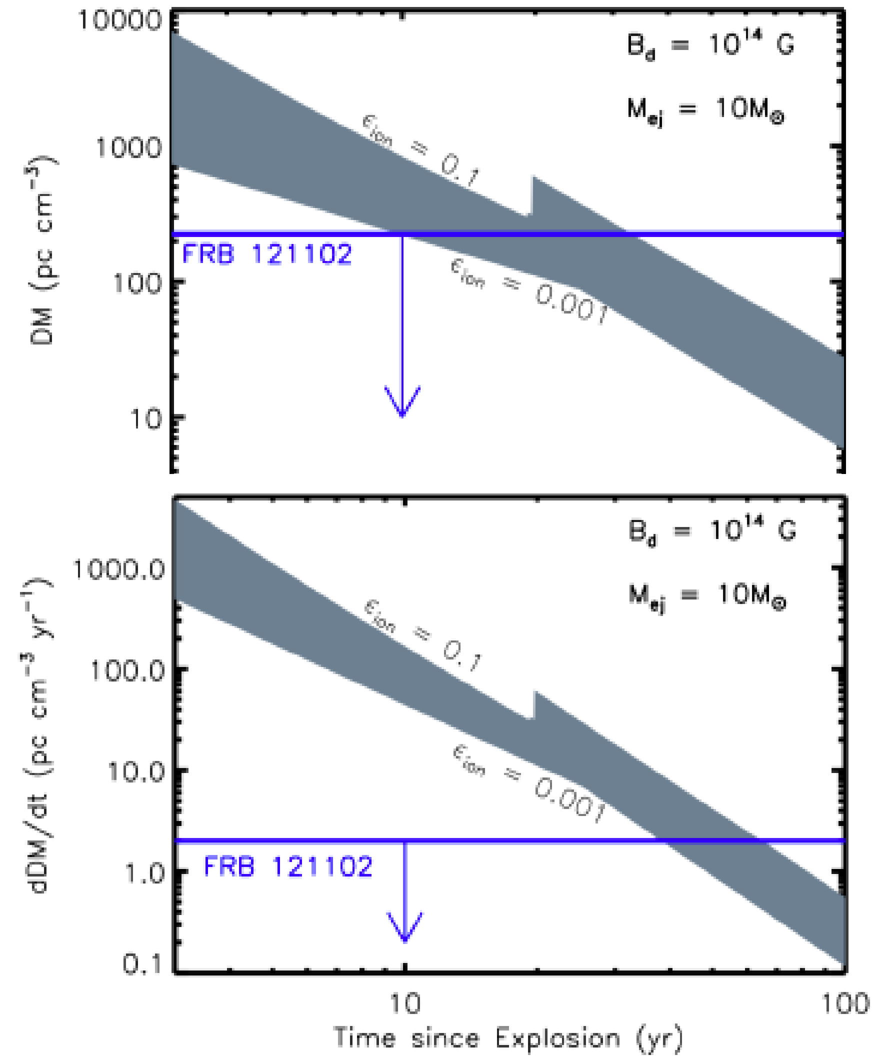
$$P < 134 B_{\rm p,14}^{1/2}\ {\rm ms}$$

$$t_{\rm age} < 116 B_{\rm p,14}^{-1}\ {\rm years}.$$

Cao et al 2017, ApJL, 839, L20

DM contributed by SN ejecta





Piro 2016, ApJL, 824, L32

Metzger et al. 2017, arXiv:1701.02370

Local DM of FRB 121102

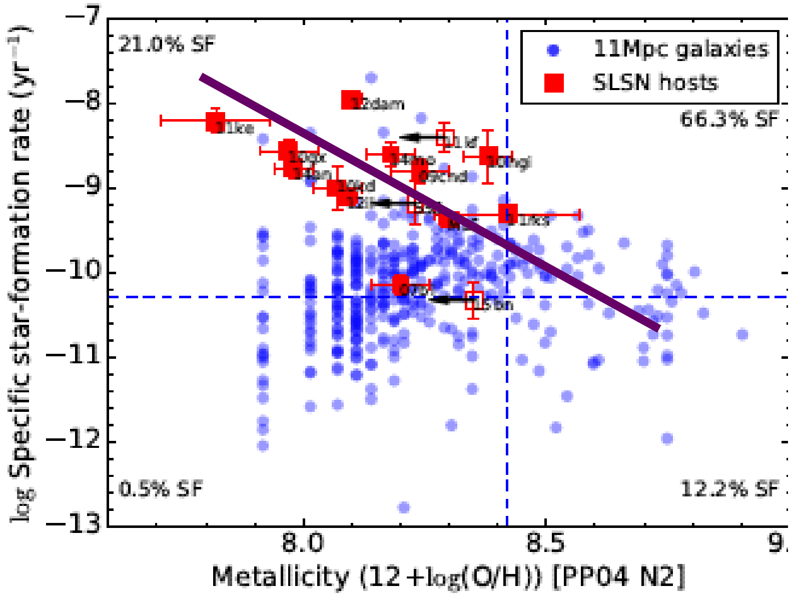
$$\mathrm{DM_{total}} = 558\ \mathrm{pc\ cm^{-3}}$$

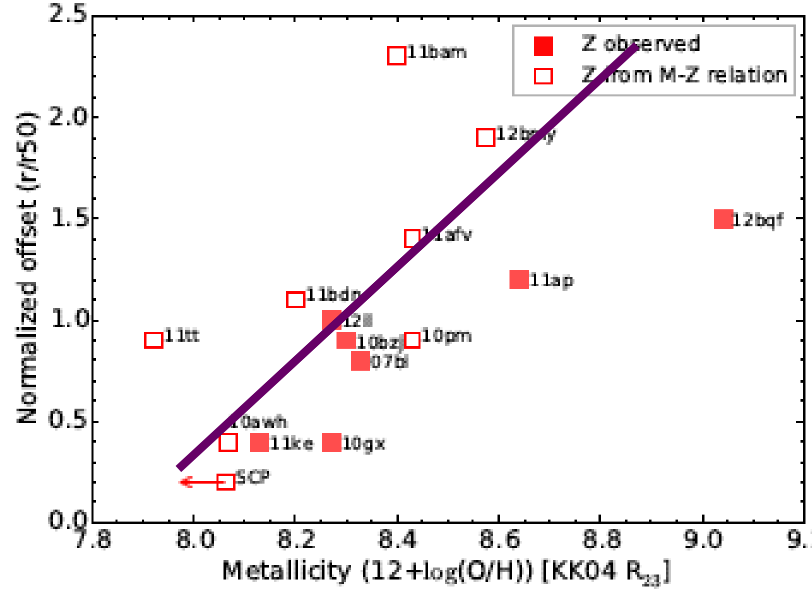
Tendulkar et al. 2017, ApJL, 834, L7

$$55 \lesssim (\mathrm{DM_{host}} + \mathrm{DM_{src}}) \lesssim 225\ \mathrm{pc\ cm^{-3}}.$$

$$\mathrm{DM_{host}} \approx 324\ \mathrm{pc\ cm^{-3}} \left[\frac{4 d_{\mathrm{kpc}} f}{\zeta(1+\epsilon^2)}\right]^{1/2}$$

Chen et al. 2016, arXiv:1605.04925





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Our Analysis

$$\mathrm{SFR}/M_* \sim (5-10)\mathrm{Gyr^{-1}}$$

For SL

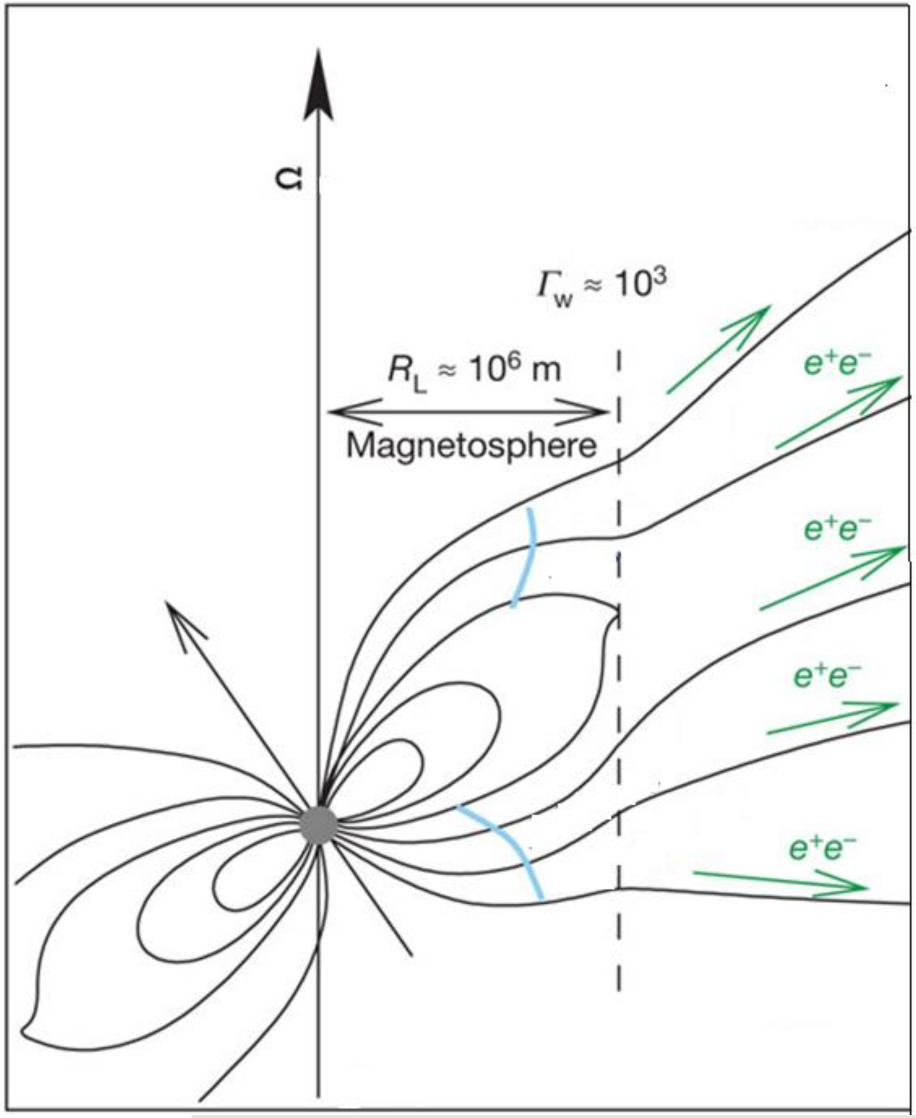
$\log_{10}$

$\frac{r_{\mathrm{off}}}{r_{\frac{1}{2}}} =$

The DM contribution leaving to the FRB source including the magnetar wind and the supernova remnant is very limited!

$$d_{\mathrm{FRB}}/d \sim (r_{\frac{1}{2}} - r_{\mathrm{off}})/r_{\frac{1}{2}} \sim 0.26$$

Electron-Positron Wind of a Magnetar



$$n_{GJ}(r) \approx (\Omega B_p / 2\pi c e)(r/R)^{-3}$$

$$\dot{N}_w \approx 4\pi r_L^2 \mu_{\pm} n_{GJ}(r_L) c$$

$$n_w(r) \approx \frac{\dot{N}_w}{4\pi r^2 c} = \mu_{\pm} n_{GJ}(r_L) \left(\frac{r}{r_L}\right)^{-2}.$$

Cao et al 2017, ApJL, 839, L20

Constraints on the wind

Plasma Frequency

$$\nu_p(r) = \frac{\mu_\pm^{1/2}\Gamma_L^{1/2}}{1+z}\left[\frac{e^2}{\pi m_e} n_{GJ}(r_L)\right]^{1/2}\left(\frac{r}{r_L}\right)^{-5/6}.$$

$$\nu_p(r_L) = 1.5 \times 10^4 \mu_\pm^{1/3} B_{p,14}^{2/3} P_{-3}^{-7/3}\ \mathrm{GHz},$$

$$P > 61 \mu_\pm^{1/7} B_{p,14}^{2/7}\ \mathrm{ms}.$$

$$t_{age} > 24 \mu_\pm^{2/7} B_{p,14}^{-10/7}\ \mathrm{years},$$

Dispersion Measure

$$\mathrm{DM_w} = \frac{1}{(1+z)}\int_{r_L} 2\Gamma(r)\cdot n_w(r)dr$$

$$= \frac{3\Gamma_L \mu_\pm n_{GJ}(r_L) r_L}{(1+z)}$$

$$= 1.5 \times 10^7 \mu_\pm^{2/3} B_{p,14}^{4/3} P_{-3}^{-11/3}\ \mathrm{pc\ cm^{-3}}.$$

$$P > 90 \mu_\pm^{2/11} B_{p,14}^{4/11} \mathrm{DM}_{w,up}^{-3/11}\ \mathrm{ms},$$

$$t_{age} > 53 \mu_\pm^{4/11} B_{p,14}^{-14/11} \mathrm{DM}_{w,up}^{-6/11}\ \mathrm{years}.$$

$$t_{age} > 0.7 f_{ion,-1}^{1/3}\left(\frac{M_{ej}}{10 M_\odot}\right)^{1/3} v_{ej,9}^{-1}\ \mathrm{years},$$

$$t_{age} > 215 f_{ion,-1}^{1/2}\left(\frac{M_{ej}}{10 M_\odot}\right)^{1/2} v_{ej,9}^{-1} \mathrm{DM}_{ej,up}^{-1/2}\ \mathrm{years},$$

Constraints on the wind

Cao et al 2017, ApJL, 839, L20

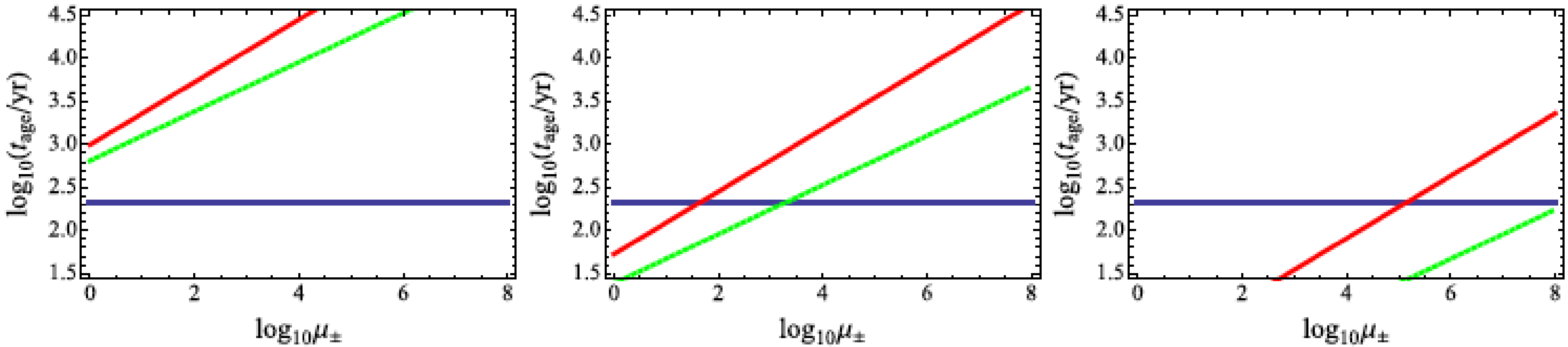


Figure 1. Lower limits on the magnetar age that are obtained by constraining the wind plasma frequency (dotted green line), the wind DM contribution (solid red line), and the DM contribution of supernova ejecta (dashed blue line), where a putative upper limit on the DM of the FRB source is taken as $DM_{src,up} = 1$ pc cm^{-3}. The panels from left to right correspond to magnetic fields of 10^{13} G, 10^{14} G, and 10^{15} G, respectively.

$$t_{age} > 24\mu_\pm^{2/7} B_{p,14}^{-10/7} \text{ years},$$

$$t_{age} > 53\mu_\pm^{4/11} B_{p,14}^{-14/11} DM_{w,up}^{-6/11} \text{ years}.$$

$$t_{age} > 0.7 f_{ion,-1}^{1/3} \left(\frac{M_{ej}}{10M_\odot}\right)^{1/3} v_{ej,9}^{-1} \text{ years},$$

$$t_{age} > 215 f_{ion,-1}^{1/2} \left(\frac{M_{ej}}{10M_\odot}\right)^{1/2} v_{ej,9}^{-1} DM_{ej,up}^{-1/2} \text{ years},$$

Constraints on magnetar Parameters

- To make the lower and upper limits of the magnetar age consistent with each other

$$B_{\rm p,14} > 0.06\mu_{\pm}^{4/3}{\rm DM}_{\rm w,up}^{-2}$$

$$B_{\rm p,14} < 0.5{\rm DM}_{\rm ej,up}^{1/2}$$

$$\mu_{\pm} < 5.5{\rm DM}_{\rm w,up}^{3/2}{\rm DM}_{\rm ej,up}^{3/8}.$$

- For a putative DM_{src,up} ~ 5 pc cm^- 3 , mu ~ 100 , and a relatively low magnetic field of Bp ~ 10^14 G , all of the limits on the age can reach a consensus at the age of about ~ 100 years.

Cao et al 2017, ApJL, 839, L20

Conclusions

- If FRB 121102 and its persistent radio counterpart is powered by the spin-down of a young magnetar, the age of the magnetar should be around 100 years.
- The DM contributed by the magnetar and the possible supernova ejecta is probably on the order of a few pc cm^- 3 .
- The magnetic field strength of the magnetar is more likely associated with SLSNe than long GRBs.
- The electron-positron multiplicity is not very much higher than unity at the light cylinder radius.

Cao et al 2017, ApJL, 839, L20

Possible Energy Source of the FRB

- **Rotational Energy**: FRBs could be analogical to giant pulses that are powered by the spin-down of a magnetar (Cordes & Wasserman 2016).

$$L_{\rm sd} = 5 \times 10^{46} B_{14}^2 P_{\rm ms}^{-4} \left(1 + \frac{t}{t_{\rm sd}}\right)^{-2} \,{\rm erg\,s^{-1}}$$
$$\underset{t \gg t_{\rm sd}}{\approx} 8 \times 10^{40} B_{14}^{-2} t_1^{-2} \,{\rm erg\,s^{-1}},$$

$t_{\rm age} < 9(L_{\rm FRB}/10^{41}\ {\rm erg\ s^{-1}})^{-1} B_{\rm p,14}^{-1}$ years (Metzger et al. 2017),

- **Magnetic Energy:** giant fl ares of soft gamma-ray repeaters (Popov & Postnov 2010; Lyubarsky 2014) .

- **Gravitational Energy:** repeated material captures by magnetars from an asteroid belt (Dai et al. 2016) or white dwarf campanion (Gu et al. 2016).

- **Kinetic Energy:** pulsars suddenly " combed" by a nearby strong plasma stream (Zhang 2017) .

Cao et al 2017, ApJL, 839, L20

Possible Energy Source of the FRB

- **Rotational Energy:** we propose that the energy release of an FRB is connected with a glitch-like process (Cao et al. 2017)

$$\Delta E \sim E_{\rm iso} = 2 \times 10^{39} \ {\rm erg}.$$

$$\Delta E = \frac{1}{2} I \Omega^2 - \frac{1}{2} I (\Omega - \Delta\Omega)^2 \approx I \Omega \Delta\Omega.$$

- Observations of Galactic pulsars usually found

$$\Delta\Omega / \Omega \sim 10^{-9}\text{–}10^{-6}$$

for their glitches, and the current maximum value can be as large as 10^−5 (Yuan et al. 2010 ; Manchester & Hobbs 2011) .

$$E_{\rm rot} \gg (10^5\text{–}10^9) E_{\rm iso},$$

$$t_{\rm age} \ll (67\text{–}6.7 \times 10^5) B_{\rm p,14}^{-2} \ {\rm years}.$$

Cao et al 2017, ApJL, 839, L20