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# *Workshop on Perspectives on the Extragalactic Frontier: from Astrophysics to Fundamental Physics*

**TRIESTE – Adriatico Guest House – 06 May 2016**

# Fast Radio Bursts (FRBs)

**Andrea Possenti**

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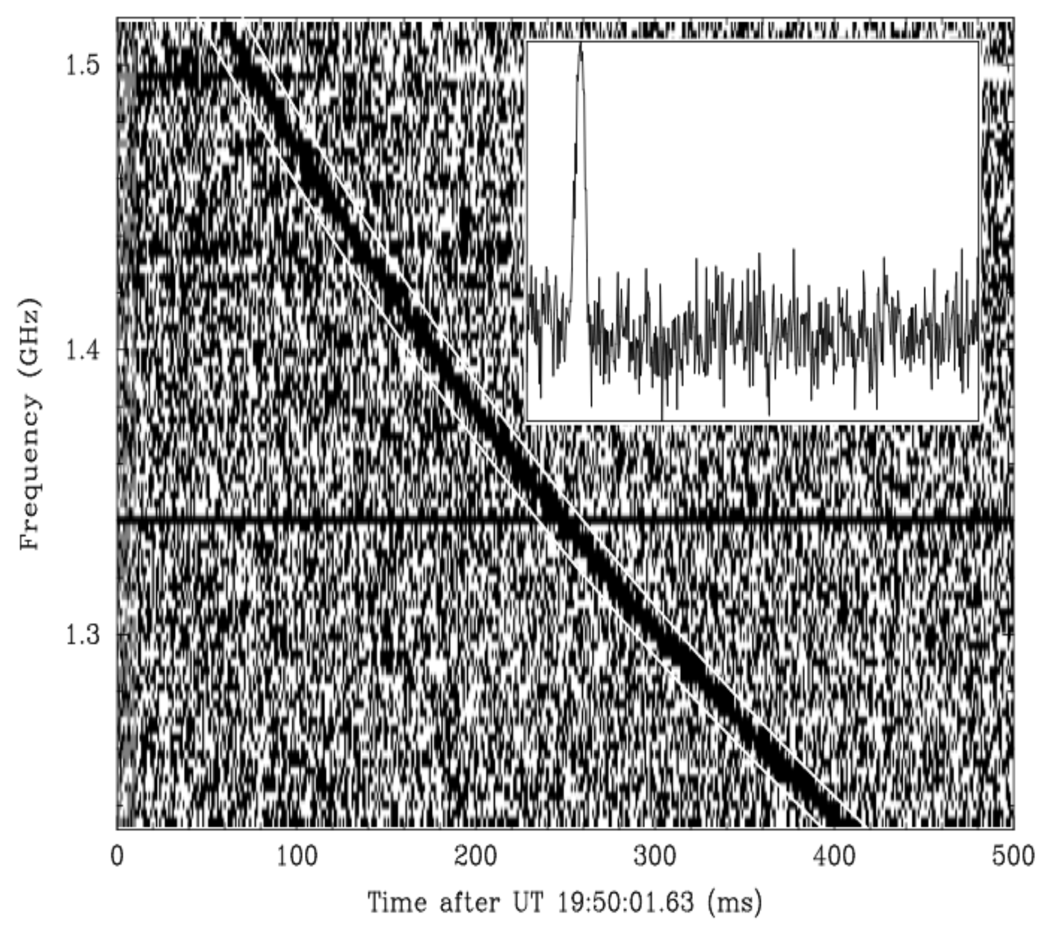
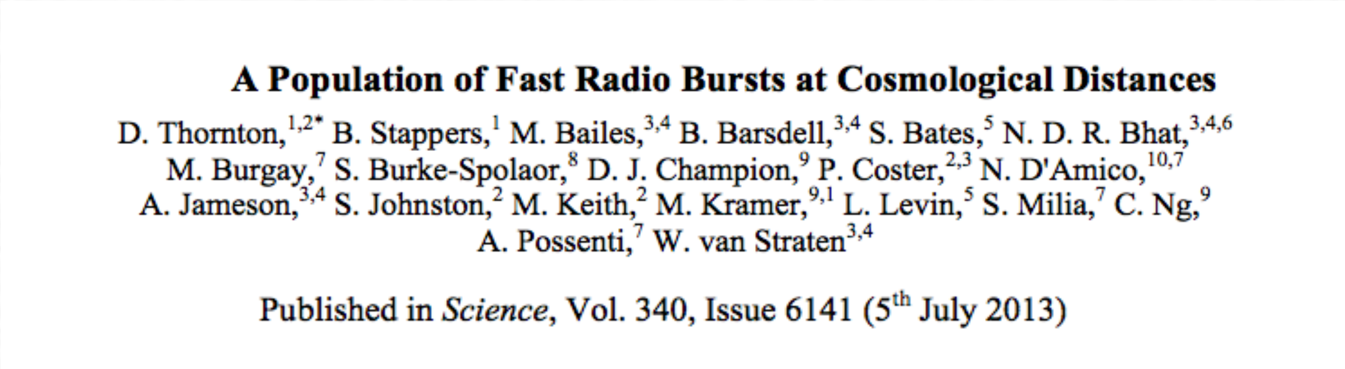
# *A surprising (and skeptically acknowledged) event*



[Lorimer et al- 2007 ]

**First case of detection of an extragalactic (?) dispersed radio burst**

# *The discovery of a Population of Fast Radio Bursts at Parkes*



**A Population of Fast Radio Bursts at Cosmological Distances**

D. Thornton,[1,2*] B. Stappers,[1] M. Bailes,[3,4] B. Barsdell,[3,4] S. Bates,[5] N. D. R. Bhat,[3,4,6]
M. Burgay,[7] S. Burke-Spolaor,[8] D. J. Champion,[9] P. Coster,[2,3] N. D'Amico,[10,7]
A. Jameson,[3,4] S. Johnston,[2] M. Keith,[2] M. Kramer,[9,1] L. Levin,[5] S. Milia,[7] C. Ng,[9]
A. Possenti,[7] W. van Straten[3,4]

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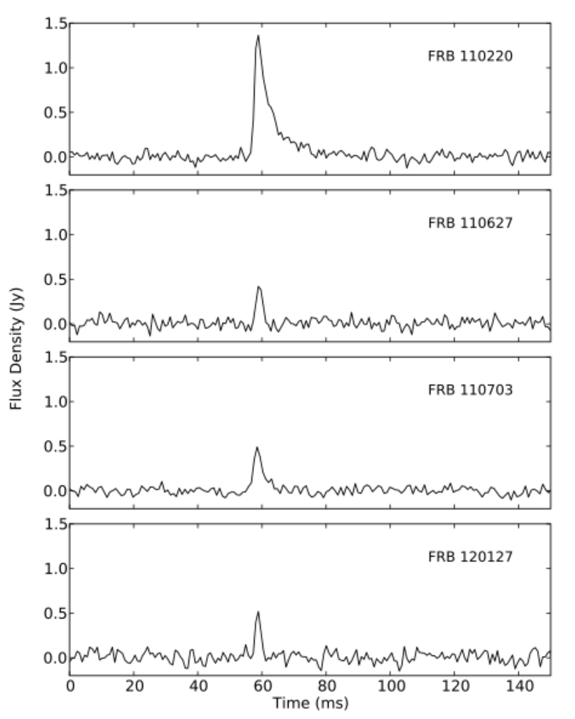
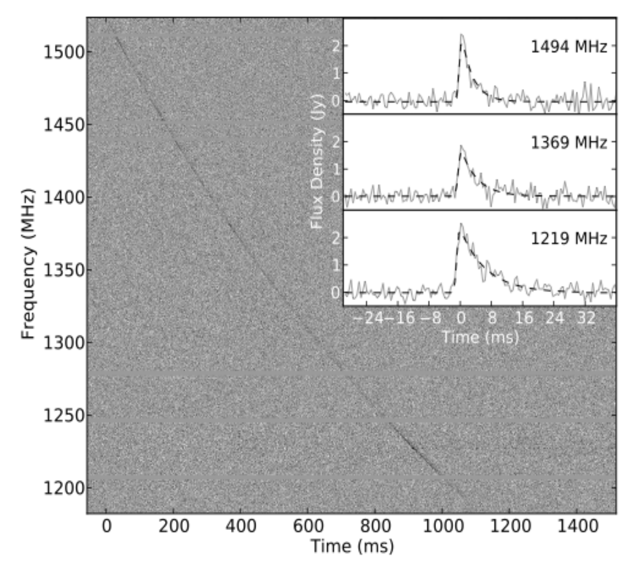
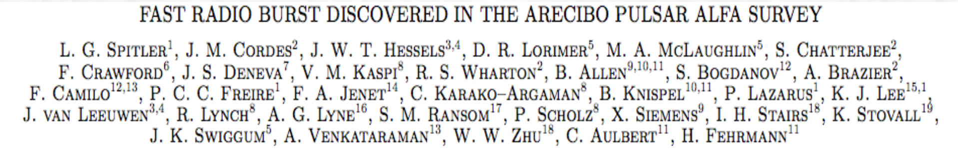




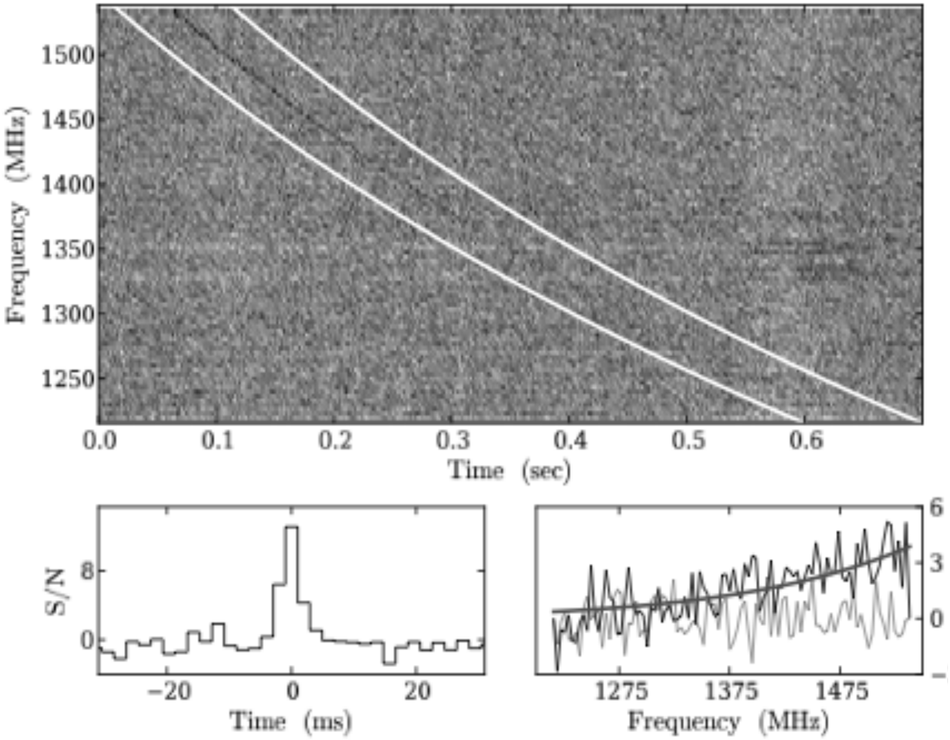
**Clear signature of a signal undergoing "scattering" in FRB110220**

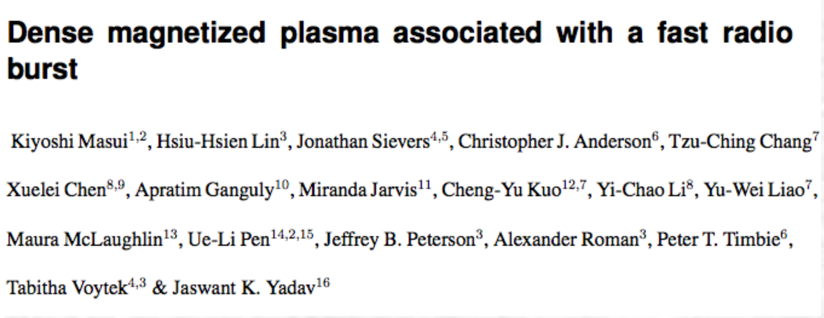
# … and shortly after at Arecibo at 1.4 GHz and GBT at 0.8 GHz



FAST RADIO BURST DISCOVERED IN THE ARECIBO PULSAR ALFA SURVEY

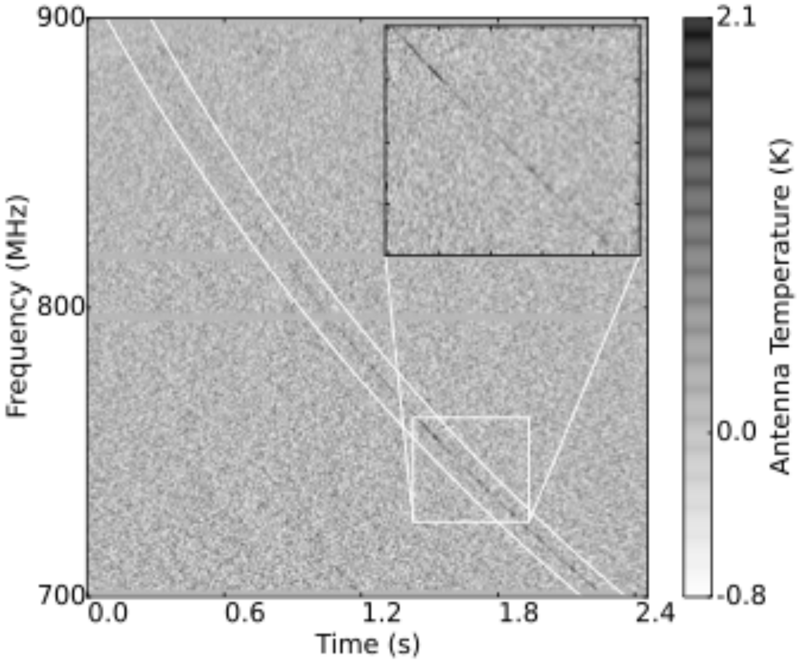
L. G. Spitler[1], J. M. Cordes[2], J. W. T. Hessels[3,4], D. R. Lorimer[5], M. A. McLaughlin[5], S. Chatterjee[2], F. Crawford[6], J. S. Deneva[7], V. M. Kaspi[8], R. S. Wharton[2], B. Allen[9,10,11], S. Bogdanov[12], A. Brazier[2], F. Camilo[12,13], P. C. C. Freire[1], F. A. Jenet[14], C. Karako–Argaman[8], B. Knispel[10,11], P. Lazarus[1], K. J. Lee[15,1], J. van Leeuwen[3,4], R. Lynch[8], A. G. Lyne[16], S. M. Ransom[17], P. Scholz[8], X. Siemens[9], I. H. Stairs[18], K. Stovall[19], J. K. Swiggum[5], A. Venkataraman[13], W. W. Zhu[18], C. Aulbert[11], H. Fehrmann[11]





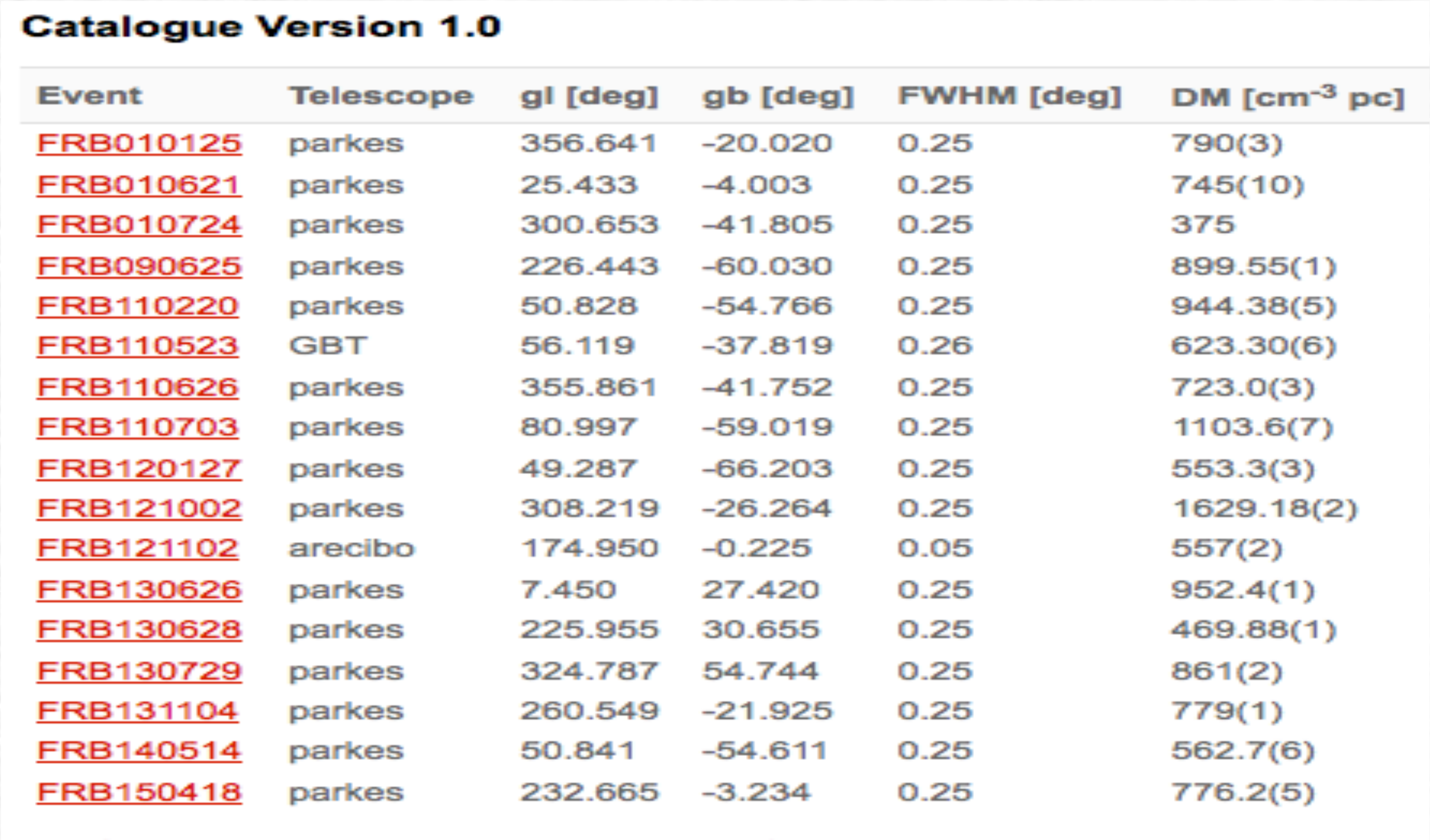
**Dense magnetized plasma associated with a fast radio burst**

Kiyoshi Masui[1,2], Hsiu-Hsien Lin[3], Jonathan Sievers[4,5], Christopher J. Anderson[6], Tzu-Ching Chang[7] Xuelei Chen[8,9], Apratim Ganguly[10], Miranda Jarvis[11], Cheng-Yu Kuo[12,7], Yi-Chao Li[8], Yu-Wei Liao[7], Maura McLaughlin[13], Ue-Li Pen[14,2,15], Jeffrey B. Peterson[3], Alexander Roman[3], Peter T. Timbie[6], Tabitha Voytek[4,3] & Jaswant K. Yadav[16]



# The official catalog of published FRBs

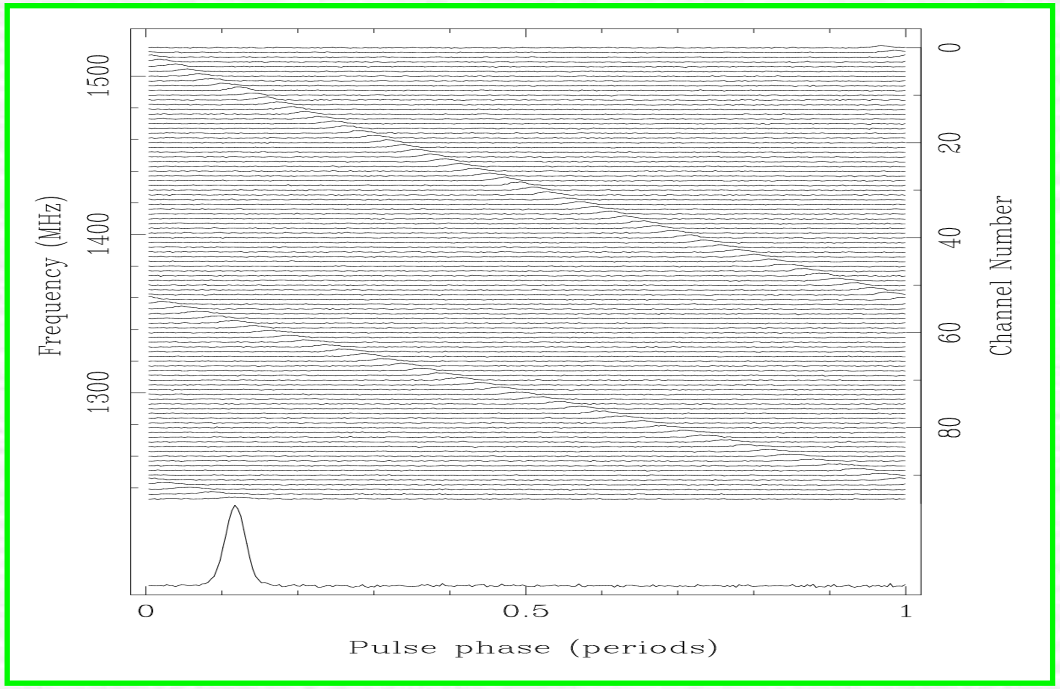
It is located at http://astronomy.swin.edu.au/pulsar/frbcat



**Catalogue Version 1.0**

| Event | Telescope | gl [deg] | gb [deg] | FWHM [deg] | DM [cm$^{-3}$ pc] |
|---|---|---|---|---|---|
| FRB010125 | parkes | 356.641 | -20.020 | 0.25 | 790(3) |
| FRB010621 | parkes | 25.433 | -4.003 | 0.25 | 745(10) |
| FRB010724 | parkes | 300.653 | -41.805 | 0.25 | 375 |
| FRB090625 | parkes | 226.443 | -60.030 | 0.25 | 899.55(1) |
| FRB110220 | parkes | 50.828 | -54.766 | 0.25 | 944.38(5) |
| FRB110523 | GBT | 56.119 | -37.819 | 0.26 | 623.30(6) |
| FRB110626 | parkes | 355.861 | -41.752 | 0.25 | 723.0(3) |
| FRB110703 | parkes | 80.997 | -59.019 | 0.25 | 1103.6(7) |
| FRB120127 | parkes | 49.287 | -66.203 | 0.25 | 553.3(3) |
| FRB121002 | parkes | 308.219 | -26.264 | 0.25 | 1629.18(2) |
| FRB121102 | arecibo | 174.950 | -0.225 | 0.05 | 557(2) |
| FRB130626 | parkes | 7.450 | 27.420 | 0.25 | 952.4(1) |
| FRB130628 | parkes | 225.955 | 30.655 | 0.25 | 469.88(1) |
| FRB130729 | parkes | 324.787 | 54.744 | 0.25 | 861(2) |
| FRB131104 | parkes | 260.549 | -21.925 | 0.25 | 779(1) |
| FRB140514 | parkes | 50.841 | -54.611 | 0.25 | 562.7(6) |
| FRB150418 | parkes | 232.665 | -3.234 | 0.25 | 776.2(5) |

# *The impact of a cold ionized plasma on a radio signal*



$$DM = \int_0^d n_e \, ds$$

$t_1 - t_\infty = 4.15$ ms $DM$ (GHz/ $\nu_1$ )$^2$

$DM = 1000$ pc/cm$^3$

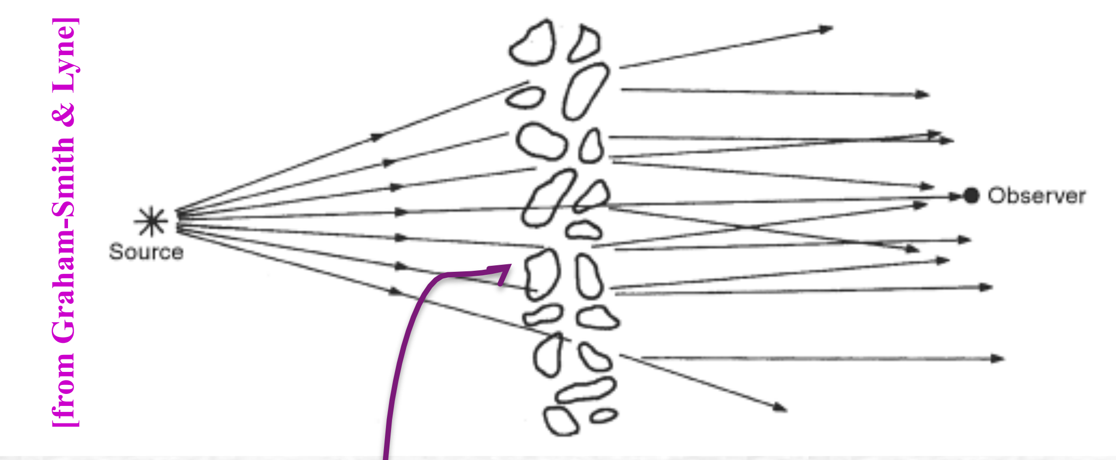
@ 1.4 GHz → $t_1 - t_\infty = 2.1$ s

@ 0.8 GHz → $t_1 - t_\infty = 6.5$ s

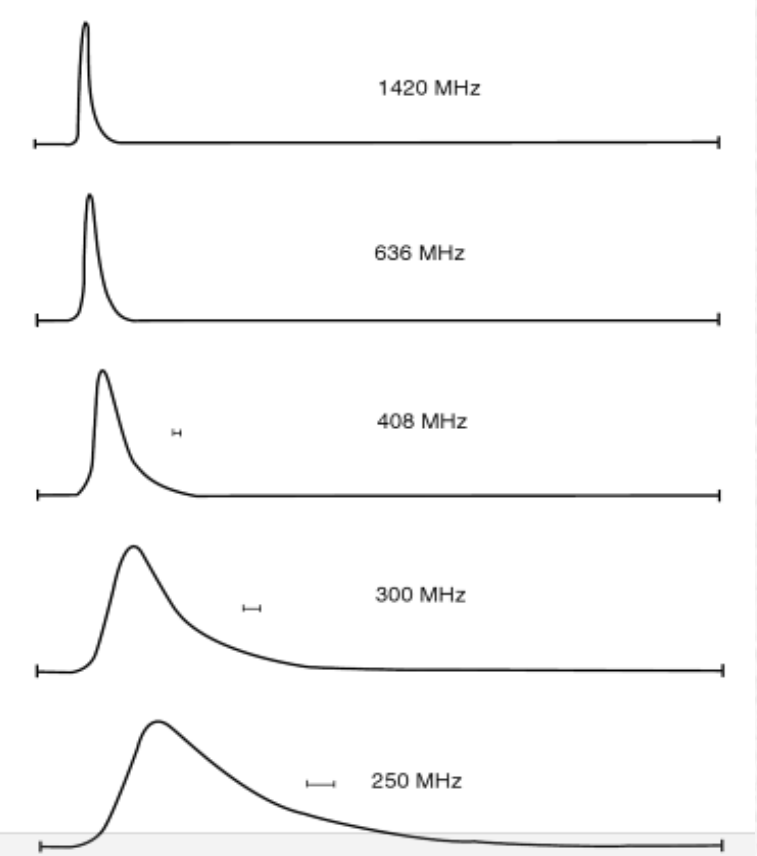
@ 0.1 GHz → $t_1 - t_\infty = 415$ s

# *The impact of a thin screen of inhomogeneous plasma on a radio signal*

[from Graham-Smith & Lyne]



**in-homogeneities in the plasma**



**For a Kolmogorov spectrum of in-homogeneities, the scattering time $\tau_{SCATT}$ , i.e. the e-folding time of the asymmetrical exponential tail, scales as**

$$\tau_{SCATT} \cong \nu^{-4.4}$$

# *Summary of basic observational features*

## The so far observed parameters are:

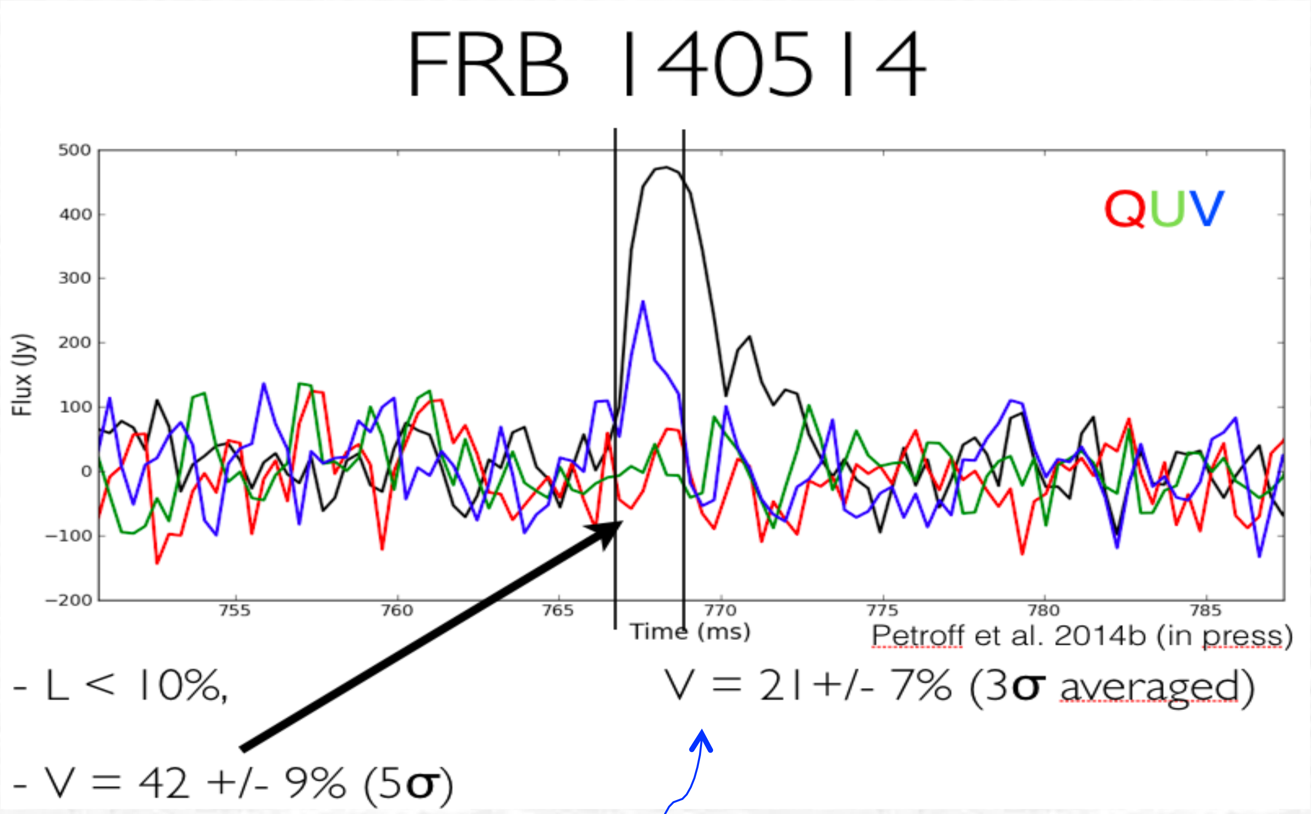
[Thornton et al 2013, Spitler et al 2014, Masui et al 2015, Keane et al 2016, Champion et al 2016, FRB public catalog]

- Burst of ≈ millisecond duration
- Dispersion measure DM > few × $DM_{MW}$ (the expected Milky-Way contribution)
- Dispersion delay consistent with $\nu^{-2}$: e,g. : $\nu^{-2.003\pm0.006}$ : $\nu^{-2.000\pm0.006}$ : $\nu^{-1.998\pm0.003}$
- When measurable, scattering time compatible with Kolmogorov: e.g. $\nu^{-4.8\pm0.4}$ : $\nu^{-4.0\pm0.4}$ : $\nu^{-3.6\pm1.4}$
- Peak Flux density at 1.4 GHz ≈ 0.1-10 Jansky
- Fluence at 1.4 GHz ≈ 0.1-10 Jansky * ms

# *The polarization properties of the FRBs*

**FRB 140514 (from Parkes @ 1.4 GHz) showed significant CIRCULAR polarization but negligible LINEAR polarization**

[Petroff et al 2015a]



Petroff et al. 2014b (in press)

- $L < 10\%$,

- $V = 42 \pm 9\%$ ($5\sigma$)

$V = 21 \pm 7\%$ ($3\sigma$ averaged)

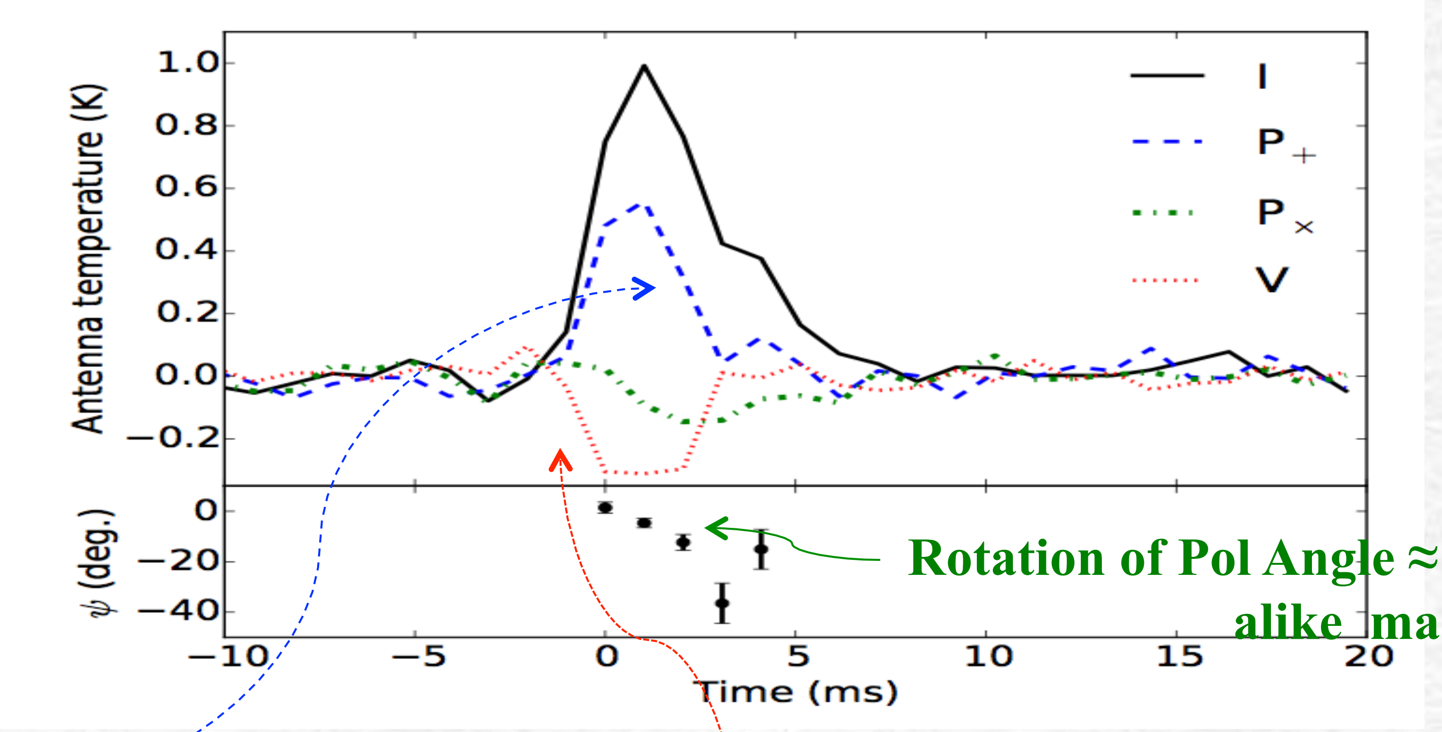
**Linear Pol**

**V = Circular Pol**

# *The polarization properties of the FRBs*

**FRB 110523 (from Green Bank @ 0.8 GHz) showed unsignificant (or instrumental CIRCULAR polarization but significant LINEAR polarization**

[Masui et al. 2016]



**Rotation of Pol Angle ≈ 15°/ms alike many psrs**

**Linear Pol ≈ 40%**

**V = Circular Pol ≈ 20%** **(but likely instrumental)**

# Implications of the polarization seen in FRB110523

**Ionized gas in a magnetized_ medium causes left-hand circularly polarized radio waves to arrive at the Earth with a delay compared to right-hand circularly polarized waves: the associated differential phase rotation (called Faraday rotation) is dependent on both density $n_e$ and los magnetic field $B_{||}$ and is quantified by the ROTATION MEASURE RM**

Faraday Rotation: $\Delta\psi_{Far} = \int_0^d (k_{\rm R} - k_{\rm L})\,{\rm d}l = \frac{e^3}{\pi m_e^2 c^2 \nu^2}\int_0^d n_e B_{||}\,{\rm d}l$

Rotation Measure: $\Delta\psi_{PPA} = {\rm RM}\,\lambda^2$ with $\Delta\psi_{PPA} = \frac{1}{2}\Delta\psi_{Far}$

$${\rm RM} = \frac{e^3}{2\pi m_e^2 c^4}\int_0^d n_e B_{||}\,{\rm d}l$$

$$\langle B_{||}\rangle = \frac{\int_0^d n_e B_{||}\,{\rm d}l}{\int_0^d n_e\,{\rm d}l} = 1.23\,\mu{\rm G}\left(\frac{\rm RM}{\rm rad\ m^{-2}}\right)\left(\frac{\rm DM}{\rm cm^{-3}\ pc}\right)^{-1}$$

[Masui et al. 2016]

**For FRB 110523:**

**RM = -186.1±1.4 rad/m$^2$** [MW contributes ≈ 18±13 rad/m$^2$, IGM≈ 0±6 rad/m$^2$ ]

**DM = 623.30±0.06 pc/cm$^3$**

**<B$_{||}$> = 0.38 μG** (likely local to the FRB site) [cf ≈ 10 μG in spirals]

**Rotation measure scaling consistent with $\lambda^{1.7\pm0.2}$**

# *The surprisingly high rate ...*

**From combining all the Parkes surveys:**

**[3÷10] × $10^3$ sky/day [Champion et al 2016] for fluence > 0.13-5.9 Jy * ms**

**[1.3÷9.6] × $10^3$ sky/day [Rane et al 2015] for fluence > 4.0 Jy * ms**

**≈ 2800 sky/day [Keane & Petroff 2015] for fluence > 2.0 Jy * ms
where Parkes survey are basically "complete"**

**all the calculations predict:**

**rate at 1.4 GHz ≈ $10^{-2}$ ÷ $10^{-3}$ a year in a MilkyWay-like gal**

# *Observational constraints about sky distribution*

**From combining all the Parkes surveys:**

[Petroff et al 2014] [Bourke-Spolaor & Bannister 2014][Champion et al 2016 ]

**the observed rate at high galactic latitudes is ≈ 6 times higher than the observed rate at low galactic latitudes**

**[Keane et al 2016 in prep]**

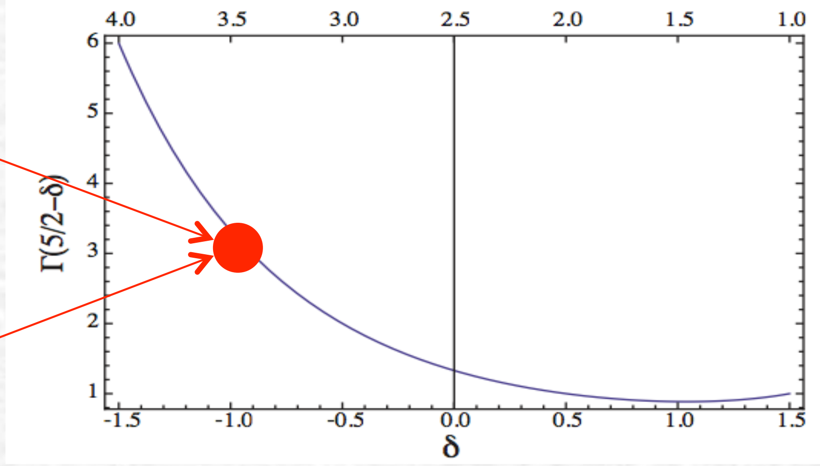
**If the FRBs are isotropically distributed (e.g. cosmological)**

**Overestimate of the rate by a factor ≈ 3 (or more if logN-logS is very steep)**

+

**Enhancement of the detectability at high galactic latitudes due to diffractive scintillation (it implies $S_{\nu,FRB} = \nu^{-3.5}$)**

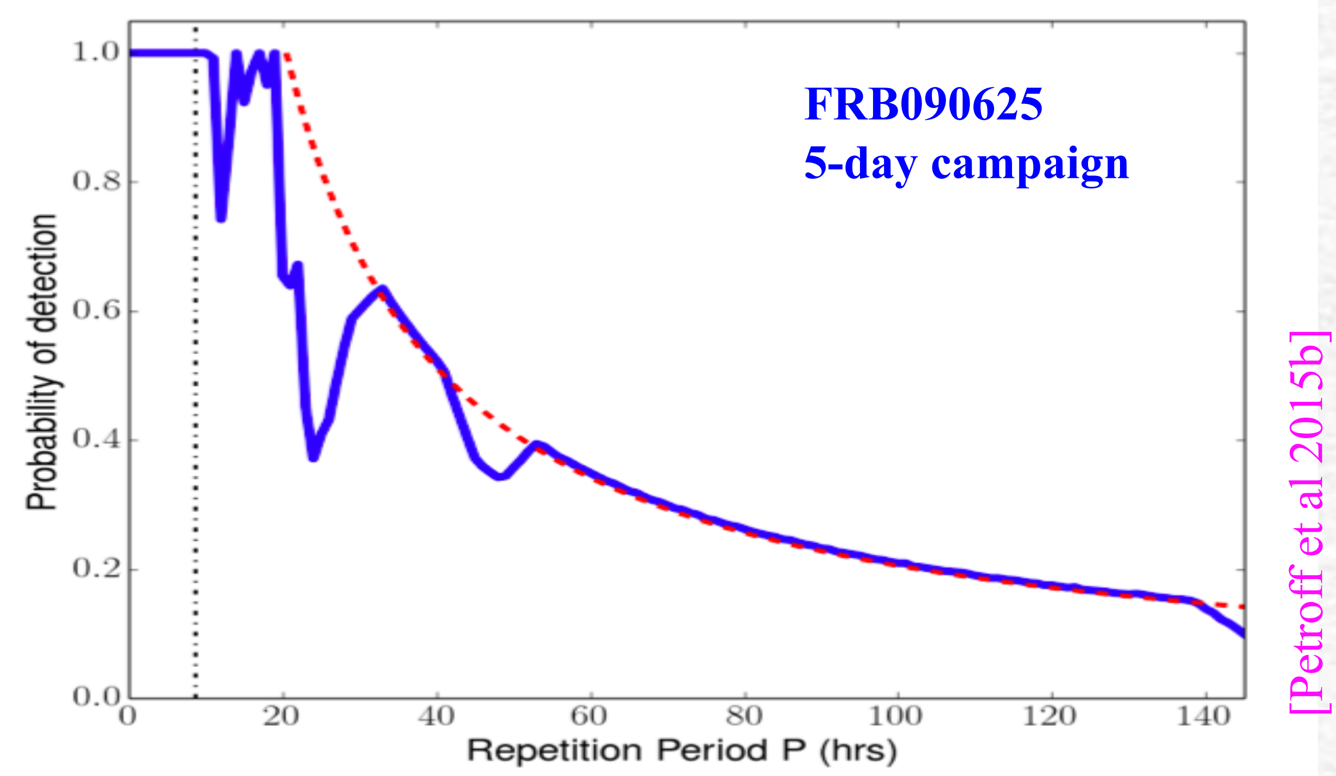
**[Macquart & Johnston 2015]**



# *Limits on repeatability...*

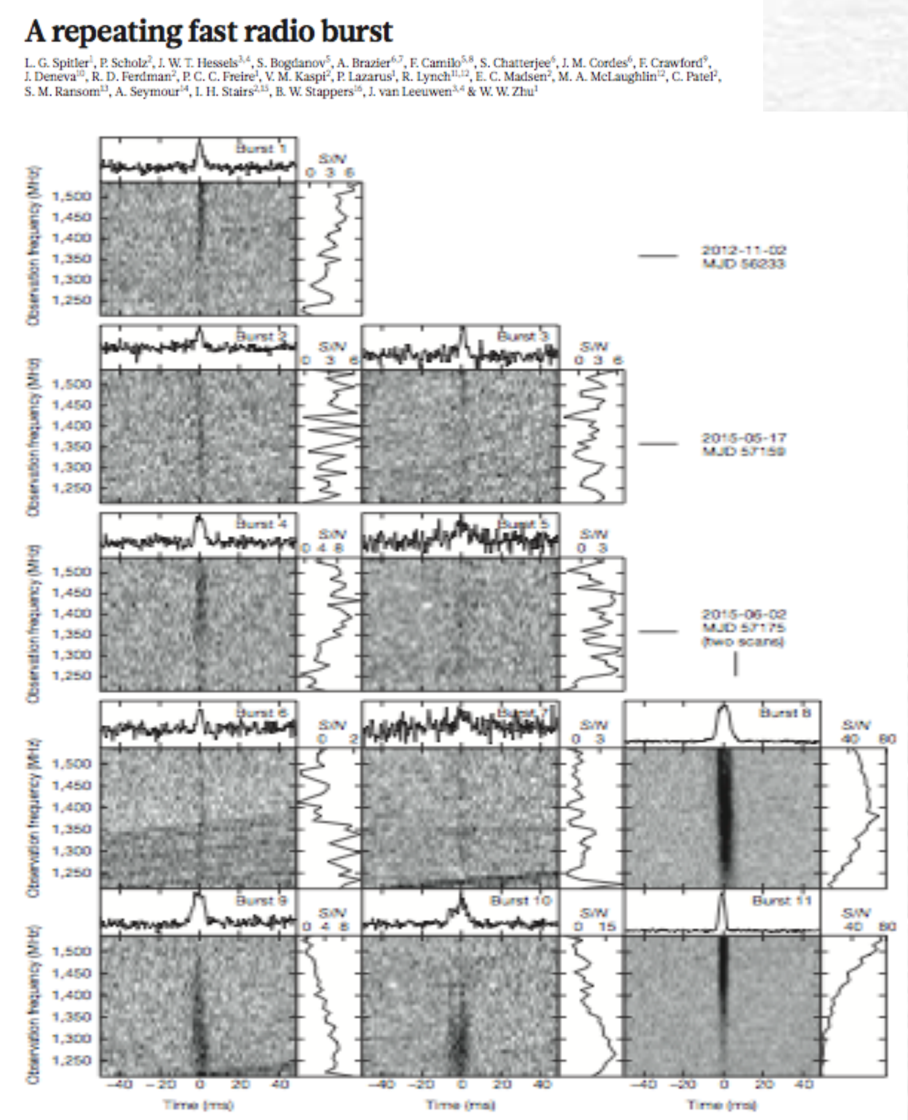
A dedicated survey consisted of 110 hours over 6 months dedicated to re-observing the fields of 8 known FRBs [Petroff et al 2015b]

**No repeat emission was detected from an FRB during this time**



[Petroff et al 2015b]

# ... *but for FRB121102*



**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. M. Cordes[6], F. Crawford[9], 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. A. McLaughlin[12], C. Patel[2], 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]

Follow-up pointings with Arecibo (1.4 GHz) and Green Bank (2.0 GHz) telescope toward the position of FRB121102 [Spitler et al. 2015] ...

**seen to repeat**

[Spitler et al. 2016]

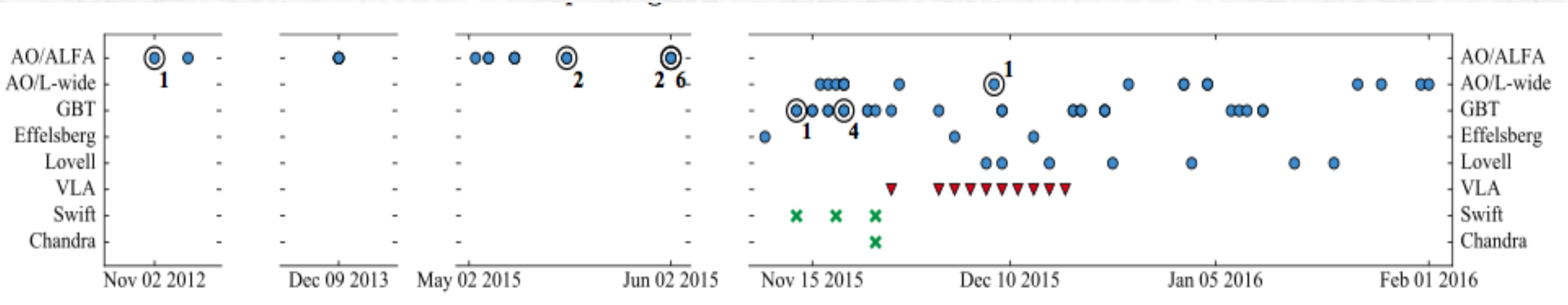
The **repeating** bursts are **resolved** in time: i.e. intrinsic timescale of ≈ ms

vs

often **unresolved** Parkes FRBs, **never seen** so far **to repeat** [Keane et al. 2016]

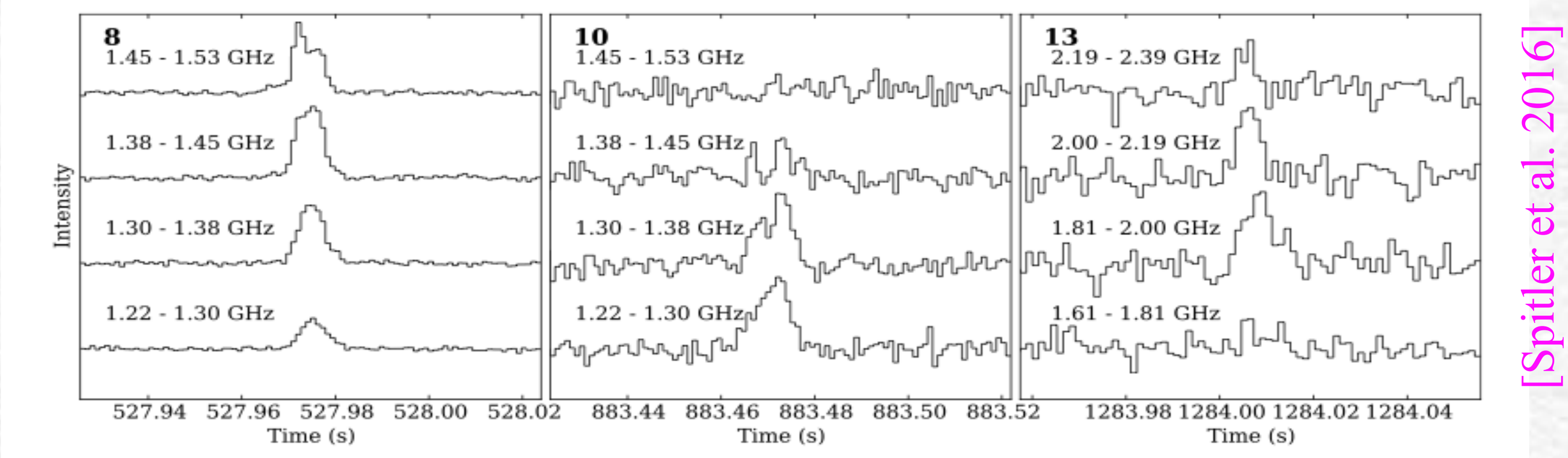
# *Some features of FRB121102*

The **bursts** (encircled in the image below) seem coming **in trains**



[Scholz et al. 2016]

The **spectral index (S ≈ $\nu^\alpha$)** of the bursts **varies wildly** from α= -10 to α= +14



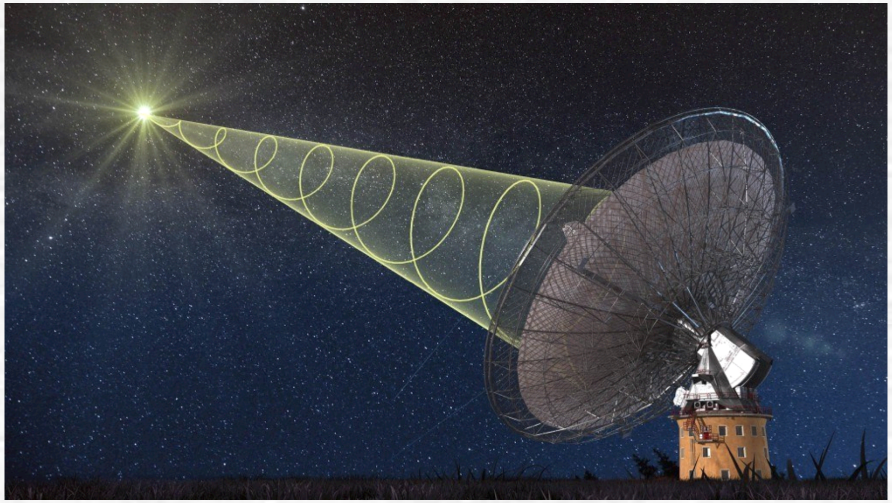
[Spitler et al. 2016]

# *The two major (plus one implicit) questions ...*

① **What is the nature of the FRBs ?**

② **How can we use them ?**

**The answers are expected to be somehow linked to each other and strongly interlaced with an**



③ **independent determination of the distance**

# *General considerations on distance and nature*

Kulkarni et al (2014) provided a wide **review of possibilities, from local radio interferences to high *z* cosmological sources**

**General statements:**

1. The FRBs **have to be extra-galactic** , provided that the frequency dependent arrival time is a result of propagation through cold plasma [Kulkarni et al 2014]

2. Suitable progenitor models are those which have an **ultra-clean emitting region** and, in addition, a **low density circum-stellar medium** so that external absorption is not significant. This means, almost always, that the free-free optical depth should not be large (for usual parameters, the plasma frequency is usually well below the GHz band) [Kulkarni et al 2014]

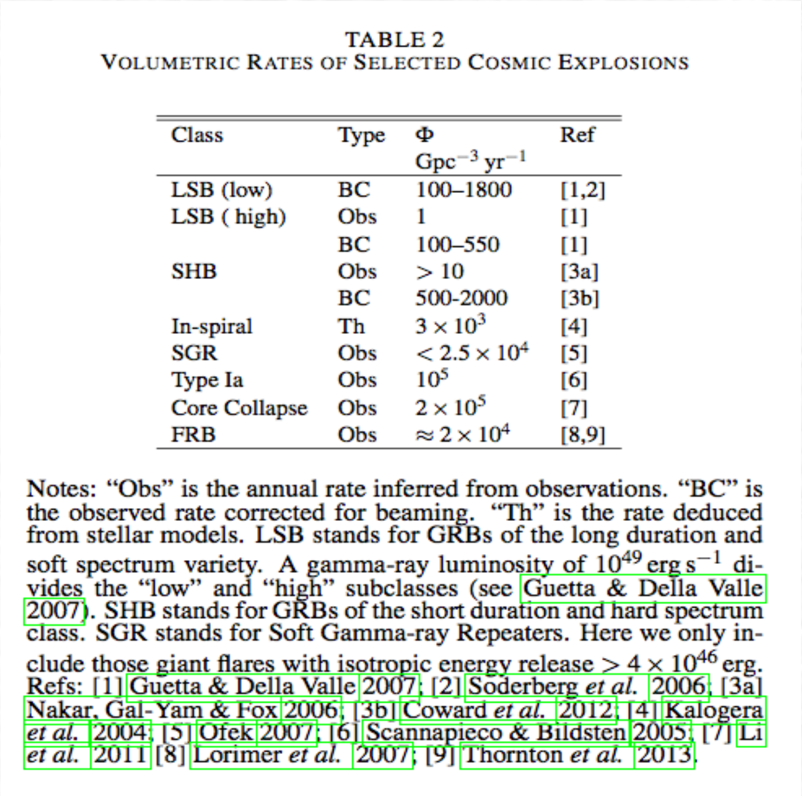


TABLE 2

VOLUMETRIC RATES OF SELECTED COSMIC EXPLOSIONS

| Class | Type | $\Phi$ $\mathrm{Gpc^{-3}\,yr^{-1}}$ | Ref |
|---|---|---|---|
| LSB (low) | BC | 100–1800 | [1,2] |
| LSB ( high) | Obs | 1 | [1] |
| | BC | 100–550 | [1] |
| SHB | Obs | $> 10$ | [3a] |
| | BC | 500-2000 | [3b] |
| In-spiral | Th | $3 \times 10^3$ | [4] |
| SGR | Obs | $< 2.5 \times 10^4$ | [5] |
| Type Ia | Obs | $10^5$ | [6] |
| Core Collapse | Obs | $2 \times 10^5$ | [7] |
| FRB | Obs | $\approx 2 \times 10^4$ | [8,9] |

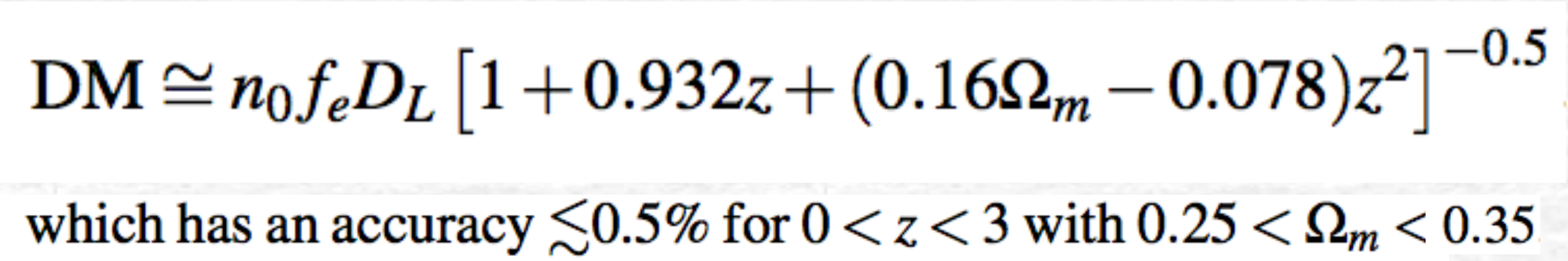
Notes: "Obs" is the annual rate inferred from observations. "BC" is the observed rate corrected for beaming. "Th" is the rate deduced from stellar models. LSB stands for GRBs of the long duration and soft spectrum variety. A gamma-ray luminosity of $10^{49}$ erg $\mathrm{s}^{-1}$ divides the "low" and "high" subclasses (see Guetta & Della Valle 2007). SHB stands for GRBs of the short duration and hard spectrum class. SGR stands for Soft Gamma-ray Repeaters. Here we only include those giant flares with isotropic energy release $> 4 \times 10^{46}$ erg. Refs: [1] Guetta & Della Valle 2007; [2] Soderberg *et al.* 2006; [3a] Nakar, Gal-Yam & Fox 2006; [3b] Coward *et al.* 2012; [4] Kalogera *et al.* 2004; [5] Ofek 2007; [6] Scannapieco & Bildsten 2005; [7] Li *et al.* 2011 [8] Lorimer *et al.* 2007; [9] Thornton *et al.* 2013.

# *Distance from the dispersion delay*

If the frequency dependent arrival time of the FRBs is due to dispersion in a cold plasma, it is possible to use the observed Dispersion Measure DM for constraining the distance of the source.

Building up on pioneering works of [Ioka 2003] and [Inoue 2004], one can write the relation between **DM**, the distance of Luminosity **$D_L$**, the red-shift $z$, the matter density parameter in the universe $\Omega_m$, the mean number density $n_0$ of nucleons at $z=0$ and $f_e \approx 0.88$ at low red-shift

[Zheng et al. 2014]



$$\mathrm{DM} \cong n_0 f_e D_L \left[1 + 0.932z + (0.16\Omega_m - 0.078)z^2\right]^{-0.5}$$

which has an accuracy $\lesssim 0.5\%$ for $0 < z < 3$ with $0.25 < \Omega_m < 0.35$

# *Derived observational features for cosmological FRBs*

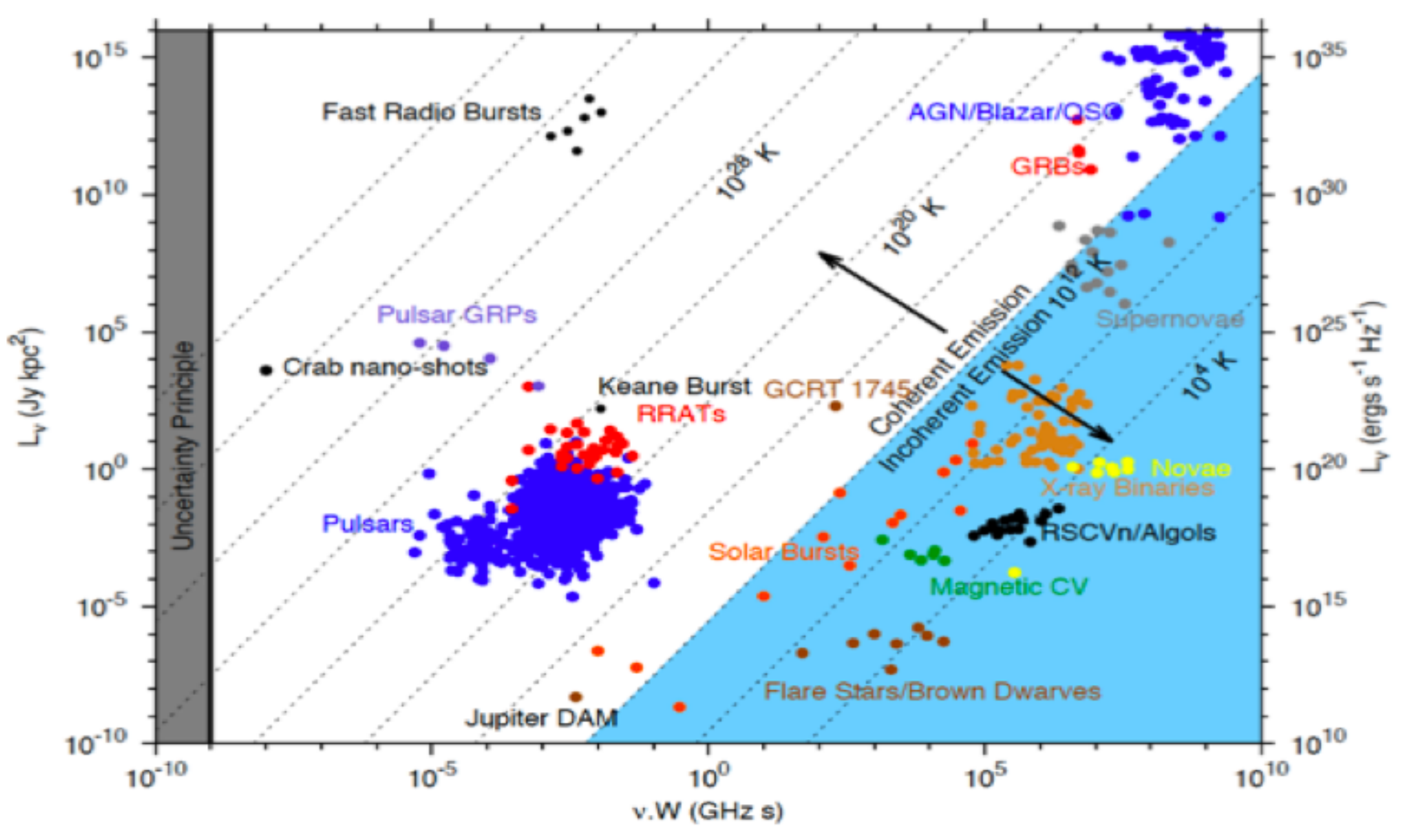
**Given the so far observed parameters:**

- Burst of ≈ millisecond duration
- Dispersion measure > few x the expected Milky Way contribution
- Dispersion delay consistent with $\nu^{-2}$
- When measurable, scattering time consistent with Kolmogorov spectral index, $\nu^{-4.4}$
- Peak Flux density at 1.4 GHz ≈ 0.1-10 Jansky

**Assuming that the extra-DM is mainly due to the Inter Galactic Medium, one can derive the following additional parameters:**

- **Red-shift** $0.2 < z < 1.0$ (IGM from [Ioka 2003;Inoue 2004])
- **Co-moving distance** $1 < D\ (\mathrm{Gpc}) < 3$
- **Isotropic emitted energy** $10^{38} < E_{iso}\ (\mathrm{erg}) < 10^{40}$
- **Brightness temperature** $10^{33} < T\ (\mathrm{K}) < 10^{36}$

# *… whence, coherent emission required*



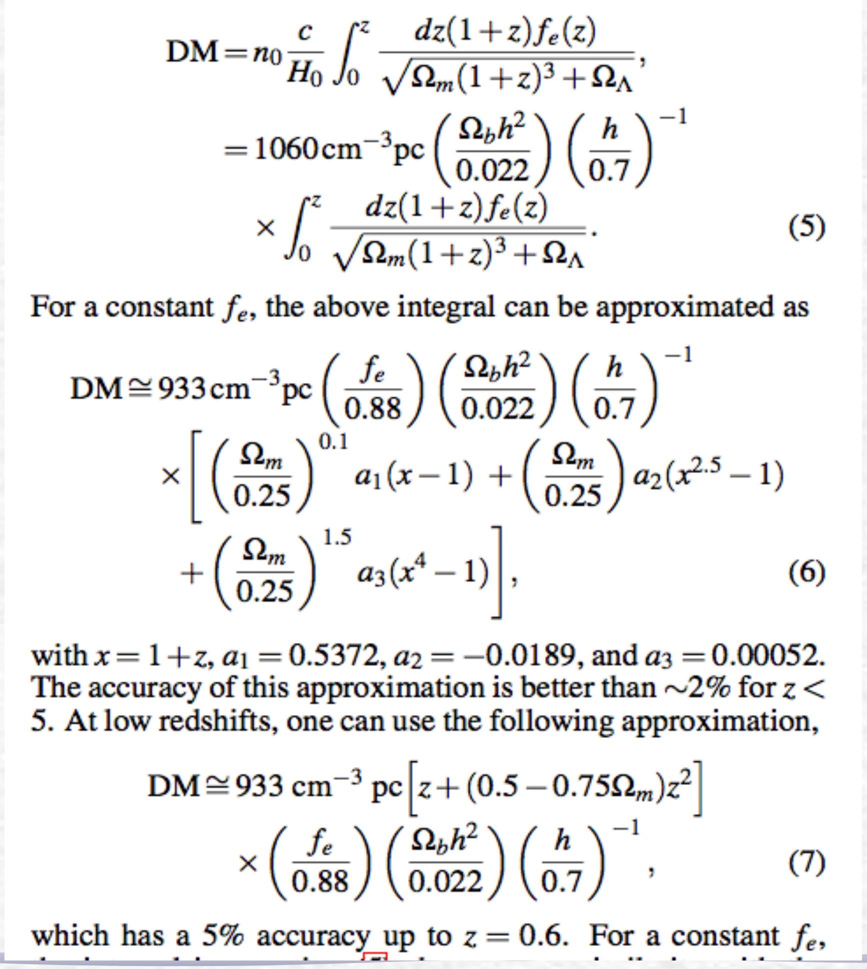
[ Pietka et al. 2015]

**The radio transient "phase space"**

# *... if truly cosmological and independent z ...*

- The first measurement of the **average density of the ionized component of the Inter Galactic Medium** along 1000+ lines of sight

[Zheng et al. 2014]



$$\mathrm{DM} = n_0 \frac{c}{H_0} \int_0^z \frac{dz(1+z)f_e(z)}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}},$$
$$= 1060\,\mathrm{cm}^{-3}\mathrm{pc}\left(\frac{\Omega_b h^2}{0.022}\right)\left(\frac{h}{0.7}\right)^{-1} \times \int_0^z \frac{dz(1+z)f_e(z)}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}. \quad (5)$$

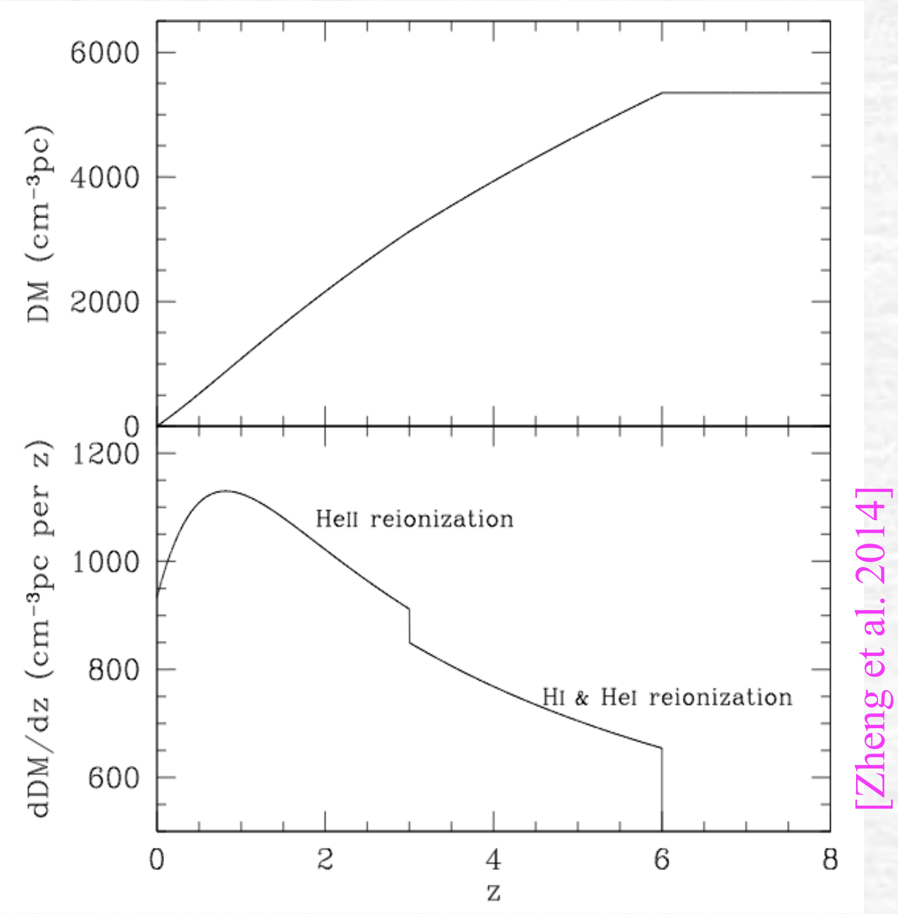
For a constant $f_e$, the above integral can be approximated as

$$\mathrm{DM} \cong 933\,\mathrm{cm}^{-3}\mathrm{pc}\left(\frac{f_e}{0.88}\right)\left(\frac{\Omega_b h^2}{0.022}\right)\left(\frac{h}{0.7}\right)^{-1} \times \left[\left(\frac{\Omega_m}{0.25}\right)^{0.1} a_1(x-1) + \left(\frac{\Omega_m}{0.25}\right) a_2(x^{2.5}-1) + \left(\frac{\Omega_m}{0.25}\right)^{1.5} a_3(x^4-1)\right], \quad (6)$$

with $x = 1+z$, $a_1 = 0.5372$, $a_2 = -0.0189$, and $a_3 = 0.00052$. The accuracy of this approximation is better than $\sim$2% for $z <$ 5. At low redshifts, one can use the following approximation,

$$\mathrm{DM} \cong 933\,\mathrm{cm}^{-3}\,\mathrm{pc}\left[z + (0.5-0.75\Omega_m)z^2\right] \times \left(\frac{f_e}{0.88}\right)\left(\frac{\Omega_b h^2}{0.022}\right)\left(\frac{h}{0.7}\right)^{-1}, \quad (7)$$

which has a 5% accuracy up to $z = 0.6$. For a constant $f_e$,



[Zheng et al. 2014]

# *… if truly cosmological and independent z …*

✧ With a series of **independent** ***z*** **determinations** (from the identification of the source at other wavelengths), one could

- **measure the missing baryonic matter in the Universe** [e.g. through the investigations of galactic halos at 0.2-2 virial radii [MacQuinn 2014]] ;

- **weight baryons in the IGM** [Deng & Zhang 2014] ;

- **constrain the EoS of the "dark energy"** [Gao et al 2014; Zhou et al 2014] ;

- **probe the era of Helium re-ionization at $z \approx 3$** [Zheng et al. 2014] ;

- **put constraints to fundamental quantities and laws** [Wei et al 2015] ;

- **put limits to the existence of floating MACHO-like objects** in the IGM via gravitational lensing (better with > 5 GHz observations) [Zheng et al. 2014]

- **3D clustering of the electrons in the Universe**, with > 10000 FRBs, even without red.shift [Masui & Sigurdson 2015]

- **put limits to the fraction of "dark matter" in MACHO of $>20M_\odot$** via counting the number of echoes due to gravitational lensing [Munoz et al 2016]

# *Interpretations: astrophysical modeling*

Bursts from **corona of very nearby flare stars** [Loeb et al. 2013]. Ruled out, since, in the high $e^-$ density of these stars ($n_e \approx 10^{10}$ cm$^{-3}$), the $\nu^{-2}$ trend is not correct (!) [e.g. Tuntsov 2014, Dennison 2014]

**Asteroid/Planet/WD magnetosphere interaction with the wind from a orbited pulsar/NS** [Mottez & Zarka 2014] Events should repeat (almost regularly at the pace of the orbital period)

**Core Collapse SuperNovae,** [Thornton et al 2013] Energetics works (with $10^{-6}$ radio efficiency) . Compatible with 10% of the CCSN. But CCSN have not a clean enough environment (?) [Kulkarni et al 2014]

**Binary WD merger to highly magnetic rapidly spinning WD** [Kashiyama et al 2013] Not a clean enough environment (?)

**Binary Neutron Star merger; short hard GRBs** [Keane et al. 2012, Totani et al 2013, Zhang et al 2014] Troubles with rate (far too low), red-shift distribution, or (for supramassive NS to BH collapse) not clean enough environment (?) [Kulkarni et al 2014] Also, recent [Palaniswamy et al. 2014] prompt (≈ 140 sec) searches for FRBs following 5 GRB events gave negative answers

…

# Interpretations: exotic sources modeling

**Evaporating primordial BH** [Keane et al 2012] Low freq radio emission from a relativistic shock in a magnetized medium surrounding the BH [Rees 1977] Not enough energy (?)

**BH to WH quantum transition** [Haggard & Rovelli 2014]. For a BH of $\approx 1.2\times10^{23}$ kg, a strong explosion in a small region should emit a signal with a $\lambda$ of the order of the size of the region or somehow larger leading to an electromagnetic signal emitted at $\lambda \approx 0.02$ cm [ Barrau, Rovelli & Vidotto 2014]. Energy is enough to explain the observations, but predicted $\lambda <<$ observed wavelength ( $\approx 20$ cm)

**Collisions btw axion stars and neutron stars** [Iwazaki 2014] The bursts are emitted in the atmosphere of the neutron stars. The observed frequencies of the bursts are given by the axion mass $m_a$ such as $m_a/2\pi \simeq 1.4$ GHz $[m_a/(6 \times 10^{-6}\text{eV})]$. From the radio freq and event rate, one can determine both the mass of the axion (apparently compatible with cosmological constraints [Kim & Carosi 2010], and the mass $\approx 10^{-11}\,M_\odot$ of the axion star

**Explosive decay of axion miniclusters** [Tkachev 2014] Assuming that in early-Universe scenarios a significant fraction of the mass density of the Universe may be in the form of axion miniclusters of mass $\approx 10^{-12}\,M_\odot$ , FRB can be matched in a explosive model with maser emission mechanism in radio and hence a **small expected emission bandwidth**

**Superconducting cosmic string (SCS) loops** [Cai et al. 2012] **oscillating in cosmic magnetic fields** [Yu et al 2014] A SCS moving through the cosmic magnetic fields. Energetic works and the red-shift distribution ($z < 1$) of the seen FRBs can be well accounted for... No clear evidence for the existence of SCS and why not also higher $z$ events?

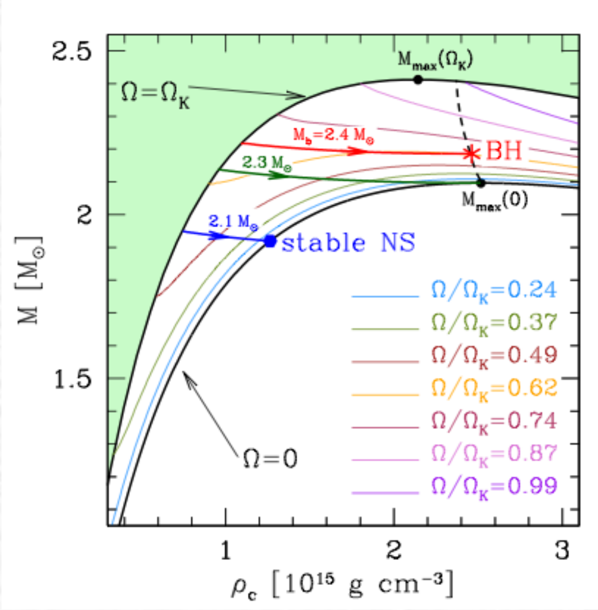
# *Interpretations: the blizar model*

[Falcke & Rezzolla 2014] from an original scenario of [Vietri & Stella 2000 ]

Collapse to BH of a **isolated** NS just above $M_{TOV}$ due to its slow down in a rarefied environment. Magnetosphere ejected with a radio-only event [Dionysopoulou et al 2013] likely with highly polarized curvature emission having rather flat spectrum.

Energetic works and rate gives 10% of the Core-Collapse SN rate, about right. Cleaning the ambient requires typically $10^3$-$10^6$ yr

Too many young pulsars, too energy (not seen) in SNR, too high IR emission (?) [Kulkarni et al 2014]



Formation of isolated stellar-mass BHs, invisible by GW-detectors since the GW emission is small.
The ring-down of the event horizon could be visible in the radio emission of a blitzar as a succession of exponentially decaying sub-ms pulses

# *Interpretations: a magnetar Giant Flare*

[Popov & Postnov 2007, Thornton et al 2013]

Energetic works (with $10^{-6}$ radio efficiency) and rate about right for Magnetars. Compatible with a clean enough environment [Kulkarni et al 14]

Radio emission results from **synchrotron maser mechanism** from relativistic, magnetized shocks formed via the interaction of the magnetic pulse with the plasma within the nebula inflated by the magnetar wind within the surrounding medium.
A **scattering tail** appears when the medium is highly turbulent at the interface btw the plerion and star forming molecular clouds.

Expected to be **repeatable over decade-long timescale**

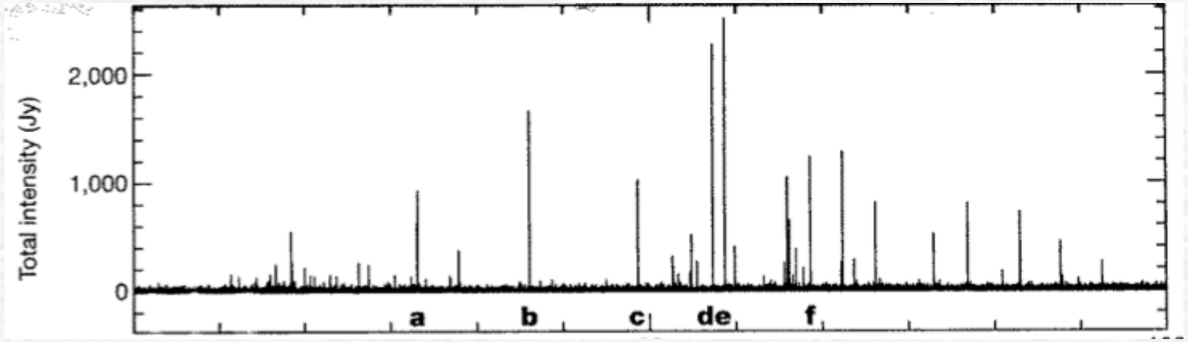
Also [Lyubarsky 2014] indicates that **a strong detectable TeV ms-burst** should be associated to these events and visible by Cerenkov detector up to ≈100 Mpc

Also GWs from Giant/Hyper Flares……. [Israel, Stella …. 2005]

# *Interpretations: Hyper Pulses from extra-galactic NSs*

[Cordes & Wasserman 2016]

If sources are at cosmological distances, **only a few pulses per NS can account for the estimated rate of ERBs**. The number of pulses required per NS scales inversely as the population volume, but even for substantially closer populations, the pulse rate is still too low to expect any repeats.



The largest single giant pulse observed to date from the Crab pulsar [Hankins & Eilek 2007] could only be detected within the Local Group at a flux density ≈1 Jy. However, the brightest giant pulse emitted during the entire lifetime of the pulsar could have been bright enough to have been visible at distances ~ 15 − 300 Mpc. Strong gravitational lensing by stars may contribute to the rate of detectable bursts if the source population extends to $z \approx 1$.

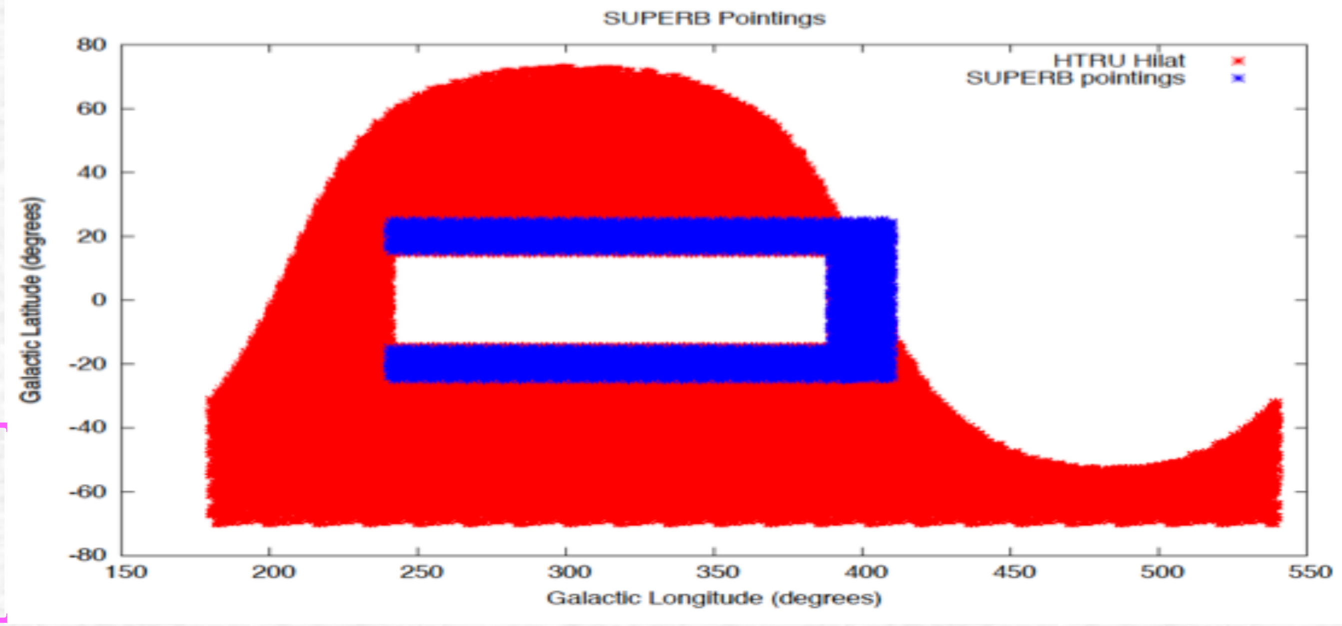
FRBs **will repeat only very rarely**, so that from an observational standpoint, no repeats are needed over time scales of years or decades

The NS birth rate is approximately equal to the rate of core-collapse supernovae (CCSNae).

# *The SUPERB attack*

**SU**rvey for **P**ulsars and **E**xtragalactic **R**adio **B**ursts ***(Project P858 @ Parkes, PI: Keane)***

≈ **3000 hours** of Parkes observations. 9 min for each obs. Begun on 23 April 2014



[© Keane]

Expected yield: **~10 FRBs** + 110 ‘slow’ PSRs (excl RRATs) + 20 MSPs,

# *SUPERB aim and partners*

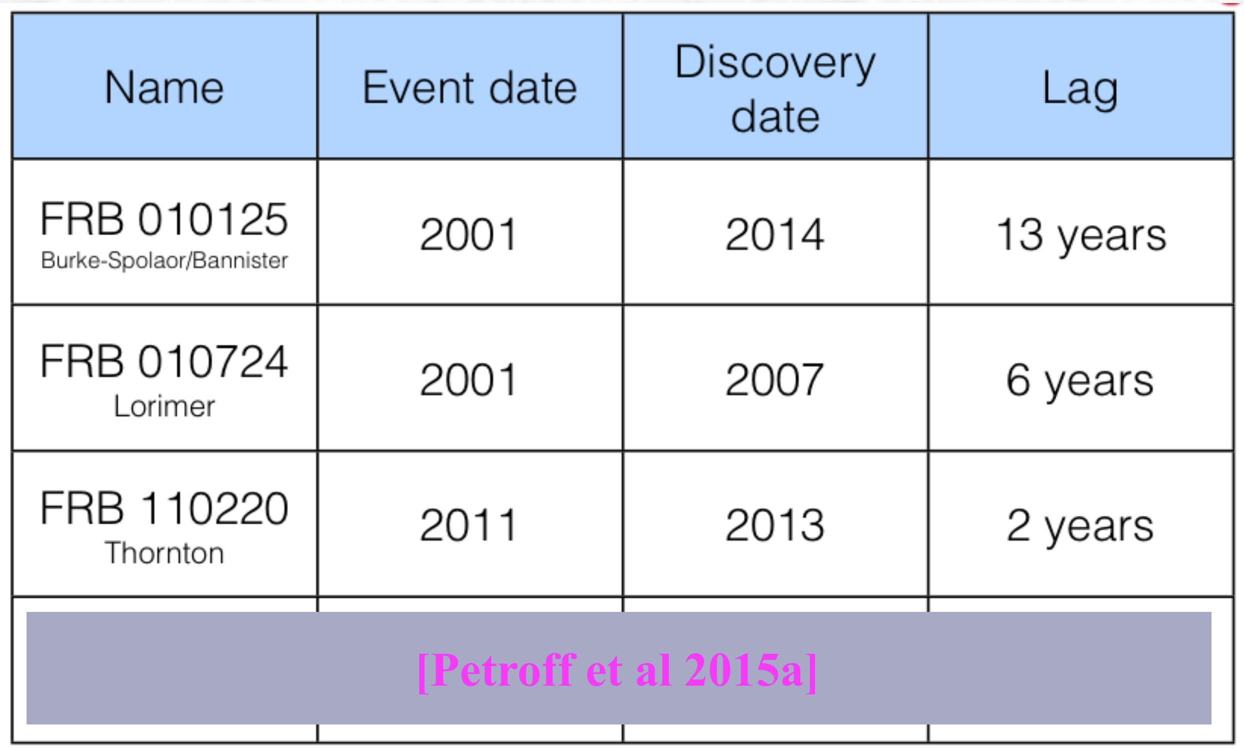
## Most ambitious aim: detecting the counterpart of a FRB in another band of the electromagnetic spectrum !

- Swinburne University of Technology (Australia)
- University of Manchester (UK)
- Cagliari Astronomical Observatory (Italy)
- ATNF (Australia)
- MPIfR (Germany)

# *The new capabilities of SUPERB: prompt alert & full polarization data*

Data are processed with 2 pipelines: the **F**(ast) & the **T**(horough) ones

The **FRB search is done** in RAM **“live”** thus leading to real time discoveries, with **full Stokes data** saved on disk and **multi-λ alerts**

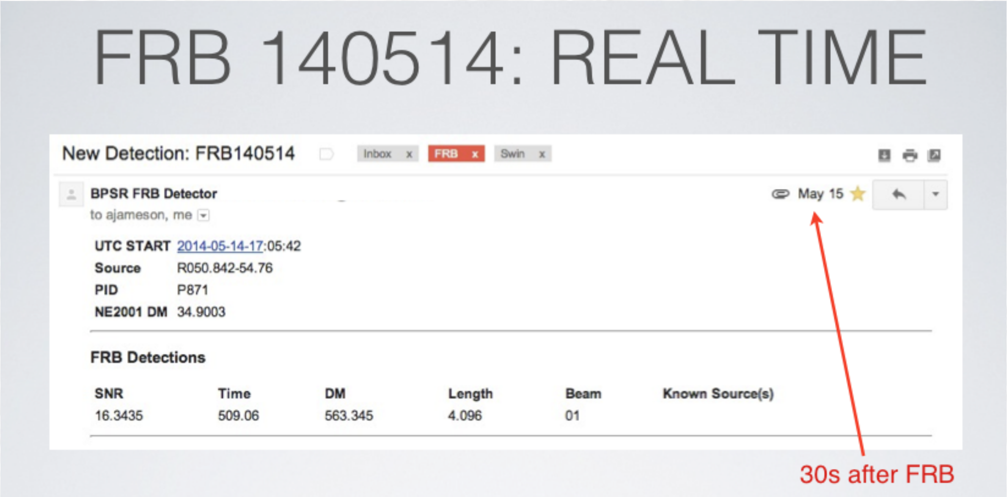


| Name | Event date | Discovery date | Lag |
|---|---|---|---|
| FRB 010125<br>Burke-Spolaor/Bannister | 2001 | 2014 | 13 years |
| FRB 010724<br>Lorimer | 2001 | 2007 | 6 years |
| FRB 110220<br>Thornton | 2011 | 2013 | 2 years |

[Petroff et al 2015a]

[© Petroff]

# *The first "real time" FRB: 14 may 2014*



## FRB 140514: REAL TIME

New Detection: FRB140514

**BPSR FRB Detector**
to ajameson, me

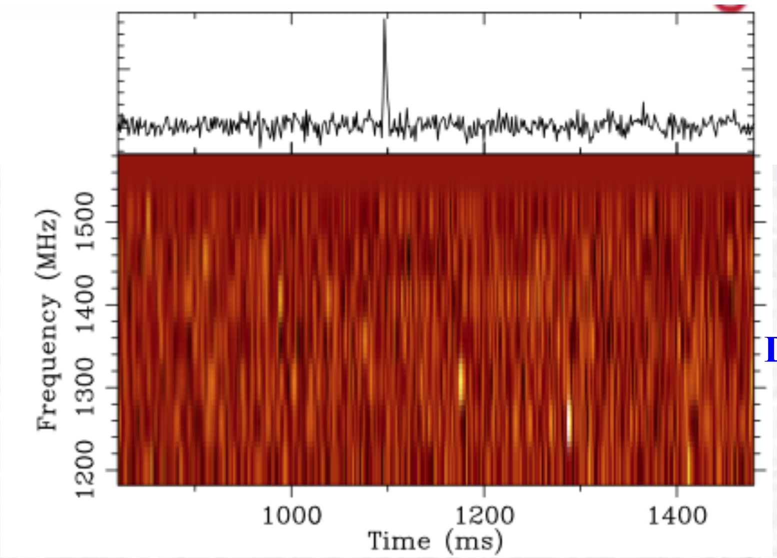
**UTC START** 2014-05-14-17:05:42
**Source** R050.842-54.76
**PID** P871
**NE2001 DM** 34.9003

**FRB Detections**

| SNR | Time | DM | Length | Beam | Known Source(s) |
|---|---|---|---|---|---|
| 16.3435 | 509.06 | 563.345 | 4.096 | 01 | |

30s after FRB

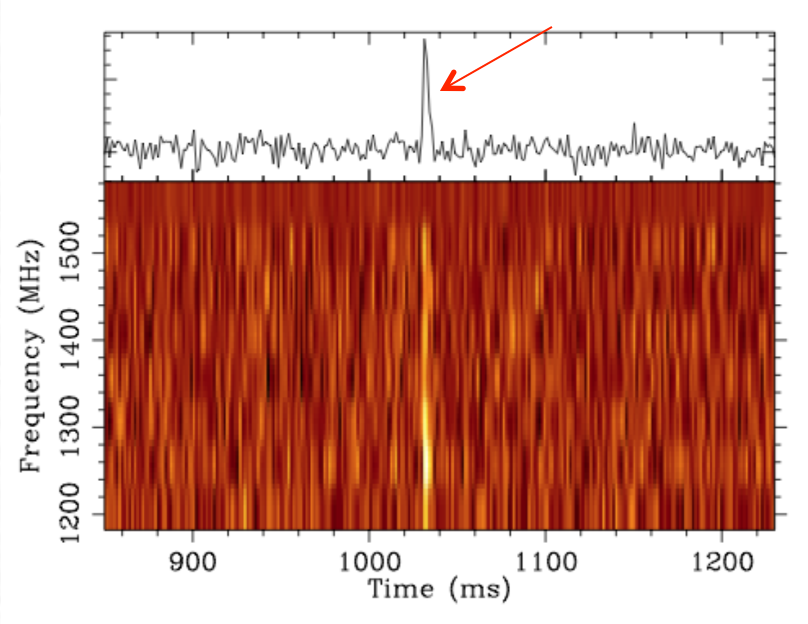
[Petroff et al 2015a]



**Dedispersed**

DM = 563 pc $cm^{-3}$

**Pulse width ≈ 3 ms**



# *The new capabilities of SUPERB: prompt follow-up*

## Radio commensal follow-ups

**Molonglo** will shadow Parkes for every SUPERB observation

Also obtained 42 hours to shadow Parkes pointings with **GMRT** in fast imaging mode
(led by R. Bhat)

## Rapid and not-so-rapid Optical and X-ray ToO/Napa follow-ups

Thai 2.4m + ULTRASPEC

Liverpool/Faulkes
Telescope modified
GRB system Gemini

Magellan, DECam

VLT, NOT, TNG

SWIFT

- 12 telescopes total

# *follow-up partners*

SWINBURNE UNIVERSITY OF TECHNOLOGY

CAASTRO
ARC CENTRE OF EXCELLENCE FOR ALL-SKY ASTROPHYSICS

NCRA • TIFR

MANCHESTER 1824

Australian National University

MPE

Goddard SPACE FLIGHT CENTER

CSIRO

E. Petroff[1,2,3], M. Bailes[1,3], E. D. Barr[1,3], N. D. R. Bhat[3,4], F. Bian[5,6], S. Burke-Spolaor[7], M. Caleb[6,1,3], D. Champion[8], P. Chandra[9], G. Da Costa[6], C. Delvaux[10], C. Flynn[1], N. Gehrels[11], J. Greiner[10], A. Jameson[1], S. Johnston[2], M. M. Kasliwal[12], E. F. Keane[1,3], S. Keller[6], M. Kramer[8,13], D. Malesani[14], J. S. Mulchaey[12], C. Ng[8], E. Ofek[15], D. A. Perley[16], A. Possenti[17], B. Schmidt[6], Y. Shen[12], B. Stappers[13], P. Tisserand[6], W. van Straten[1,3], C. Wolf[6]

JPL

Dark Cosmology Centre

CARNEGIE OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON

ICRAR

Max-Planck-Institut für Radioastronomie

ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS
INAF

Curtin University

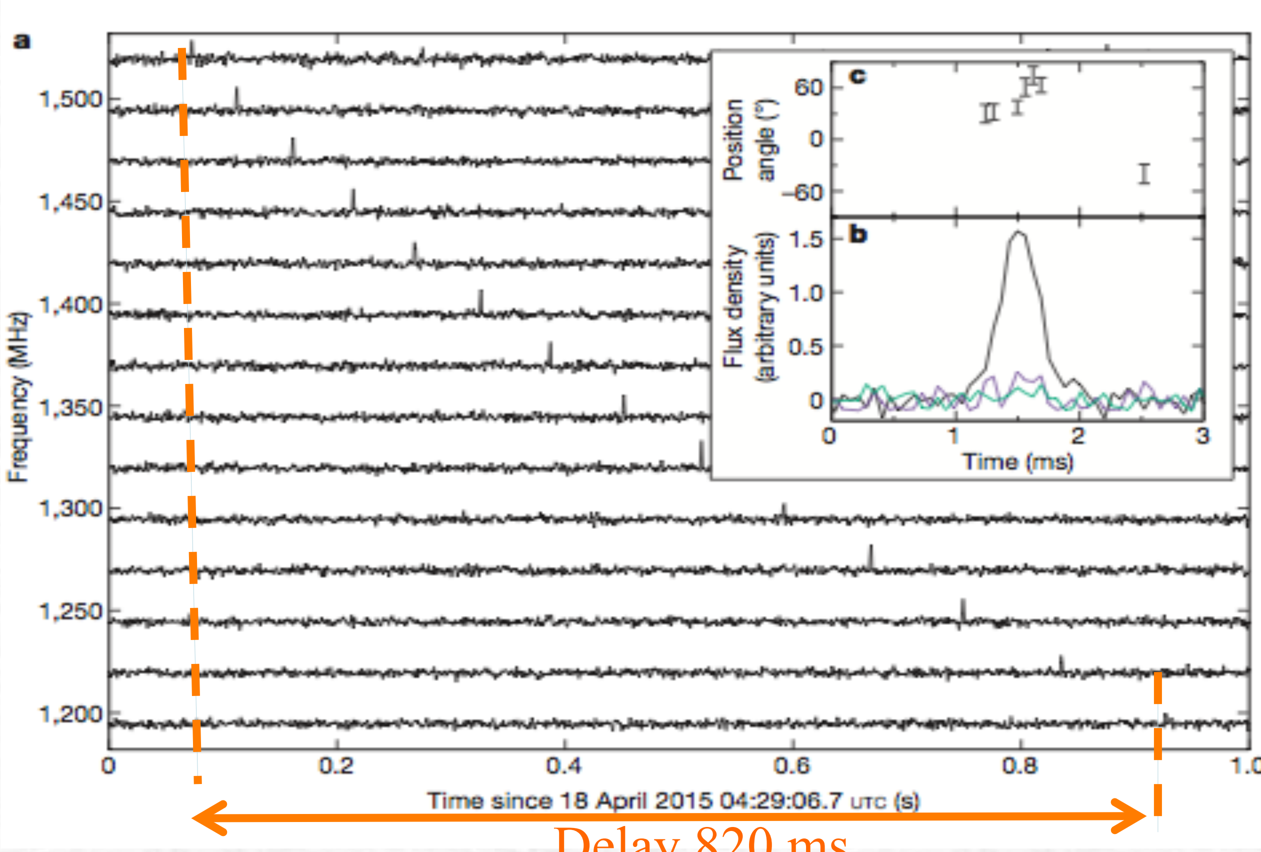
# *FRB150418: a Rosetta stone ?*

# *Replay : Step ONE*

18 April 2015: The discovery of the FRB at Parkes

DM = 776 pc/cm$^3$, unresolved 0.8 ms-wide pulse

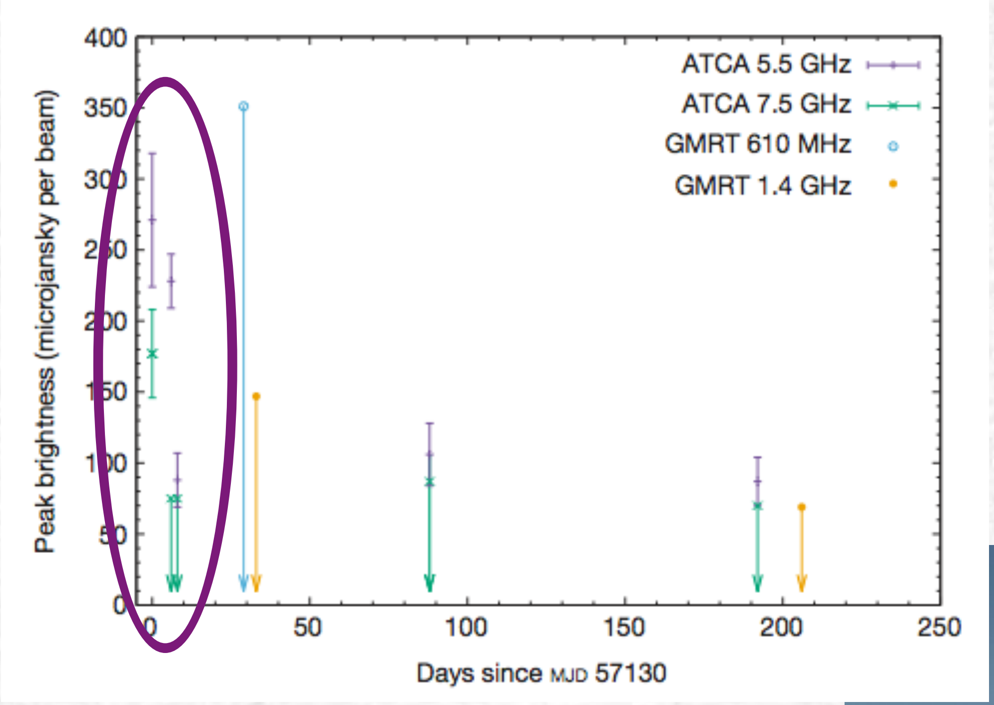
Flux at peak = 2.2 Jy, ≈10% linear pol, no circ pol, no RM determined



[Keane et al. 2016]

Delay 820 ms

# *Replay : Step TWO*



[Keane et al. 2016]

Observed a **fading** radio source in the uncertainty beam of the Parkes detection: **pinpointed the position** and seen **a 3x flux variation** in about 1 week

Atca: 6 x 22m antennas

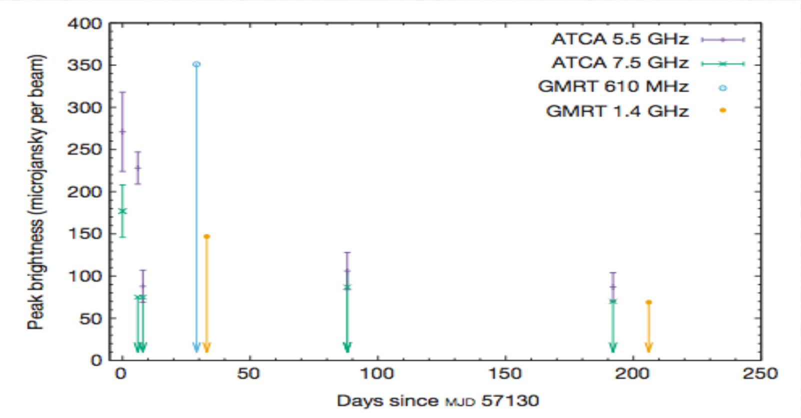
Radio interferometry with ATCA **less than 2 hours after** the detection at Parkes

# *Replay : Step TWO (some stats)*

Probability of serendipitously finding a 3x varying (in < 1 week) transient radio source

< **7 %** from ATCA surveys at 5.5 GHz [Bell et al 2015]
< **0.1 %** from VLA survey at 2-4 GHz [Mooley et al. 2016]

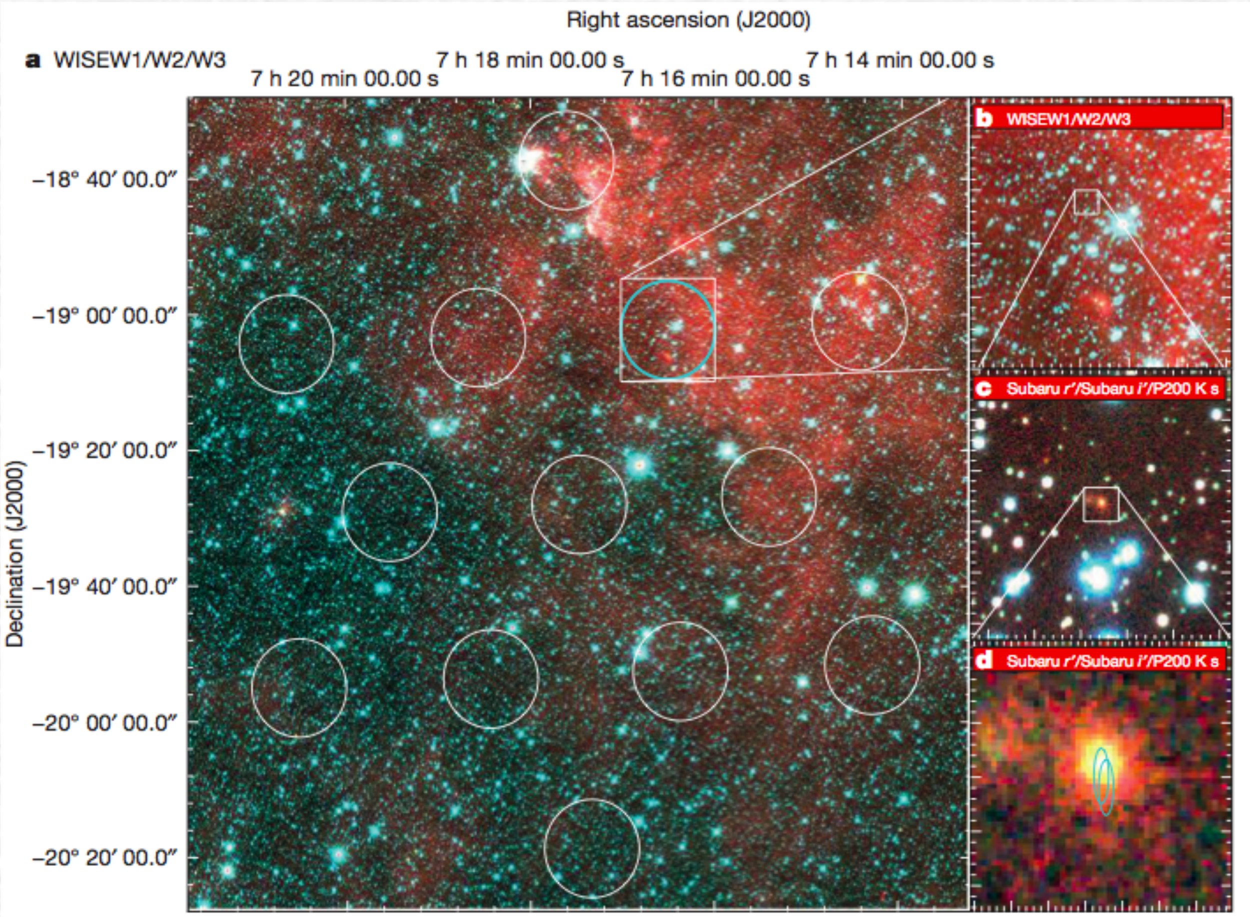
With 5 epoch data it appeared to be settled down to a steady level, then classified as a transient



If additional data will demonstrate it varies up-and-down, one has to consider the statistic of radio variable sources

**Poorly known stats at 100 μJy level**
Using stats from brighter samples
the chance probability becomes < **1.6 %**
(at 95% c.l.)

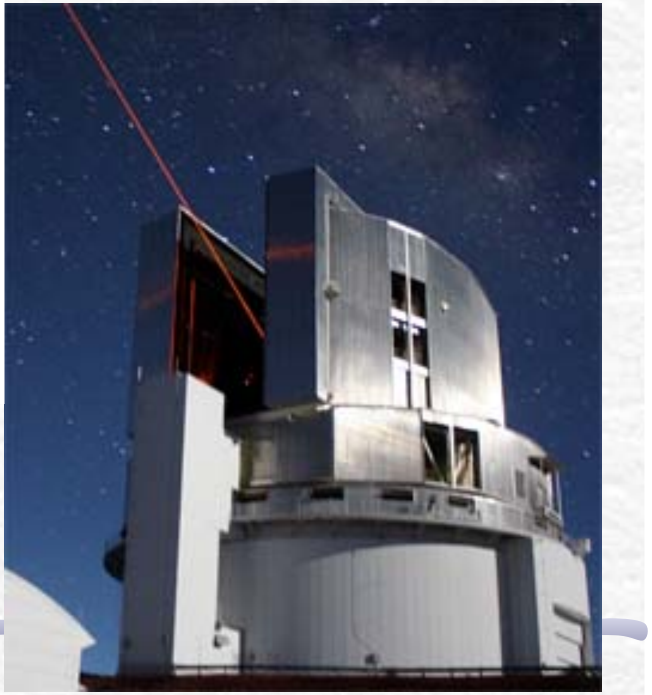
# *Replay : Step THREE*



[Keane et al. 2016]

Detected an elliptical galaxy at the position of the fading source

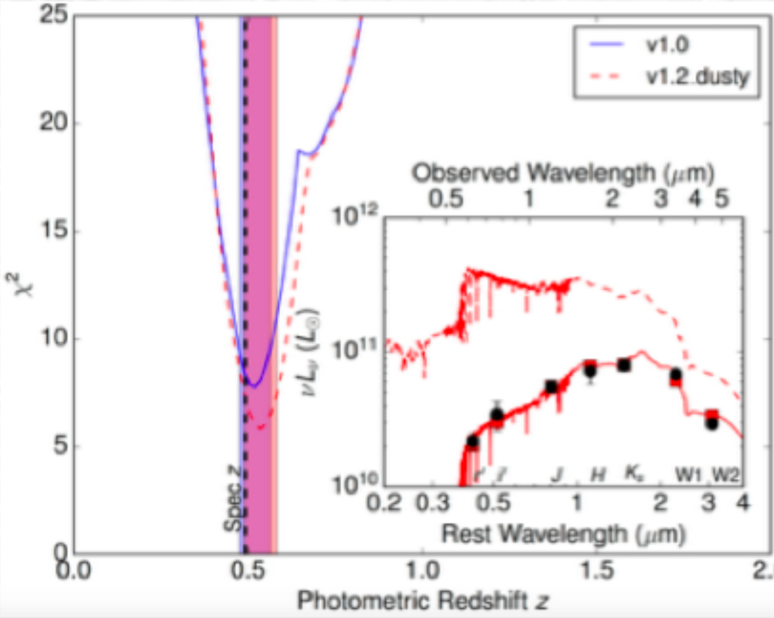
8.2 m telescope at Mauna Kea site

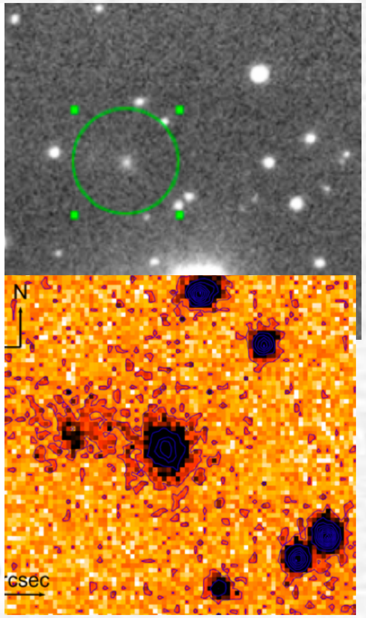


Run optical observations with Subaru 1 and 2 days after the detection of the FRB and then again about 6 months later

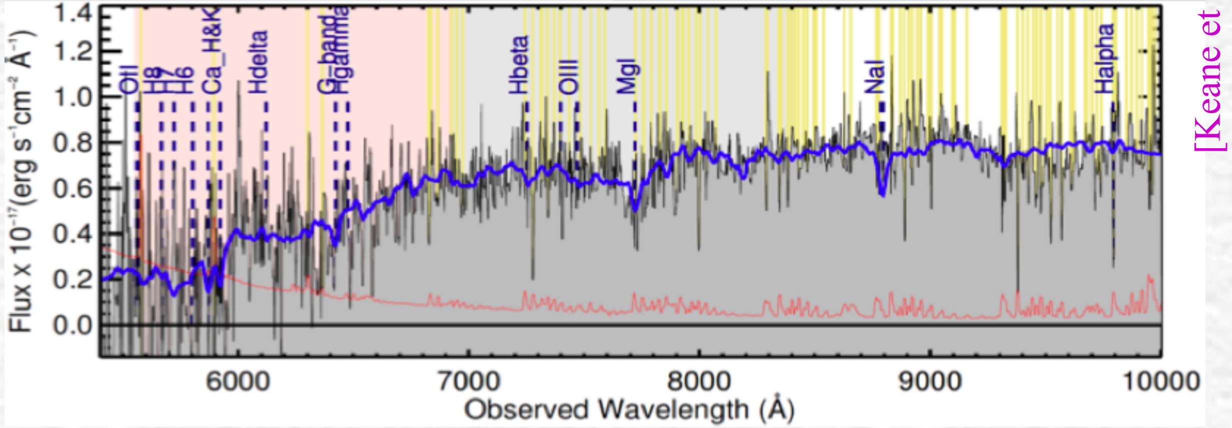
# Replay: Step THREE *(photometry & spectroscopy)*

First obtained a photometric red-shift
**$z = 0.52 \pm 0.04$**



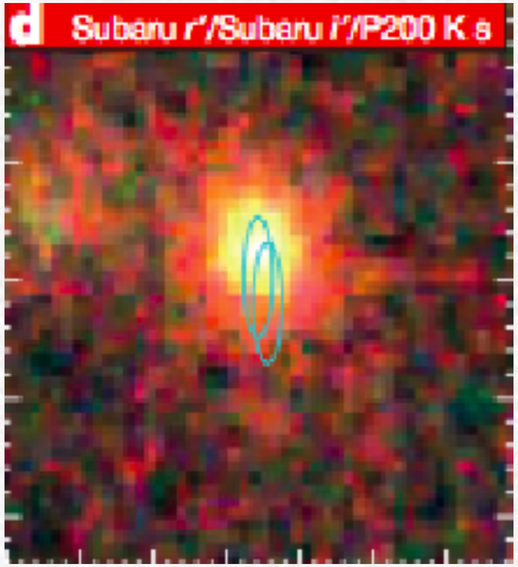


Then obtained a spectroscopic red-shift
**$z = 0.492 \pm 0.008$**



[Keane et al. 2016]

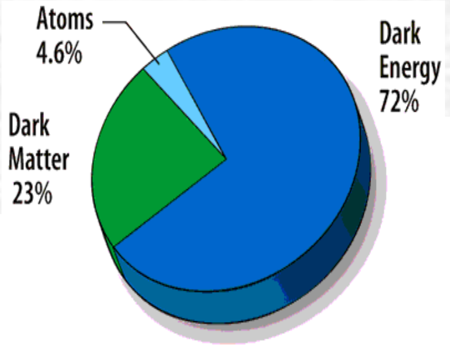
# *Weighting the mass along the line-of-sight*



From **red-shift $z$** (via optical obs) and **dispersion delay $\mathrm{DM}_{\mathrm{IGM}}$** (via radio obs), for each given set of cosmological parameters $H_0$ , $\Omega_m$ and $\Omega_\Lambda$, plus the fraction of ionized atoms $f_e$ , one can get the baryon density along the line of sight $\boldsymbol{\Omega_{IGM}}$

$$\mathrm{DM}_{\mathrm{IGM}} = \frac{3cH_0\Omega_{\mathrm{IGM}}}{8\pi G m_{\mathrm{p}}} \int_0^z \frac{(1+z')f_{\mathrm{e}}(z')\mathrm{d}z'}{[(1+z')^3\Omega_{\mathrm{m}}+\Omega_\Lambda]^{0.5}}$$

It turns out $\boldsymbol{\Omega_{IGM}} = 4.9\ \% \pm 1.3\ \%$



In agreement with WMAP and other indirect determinations for ΛCDM cosmologies

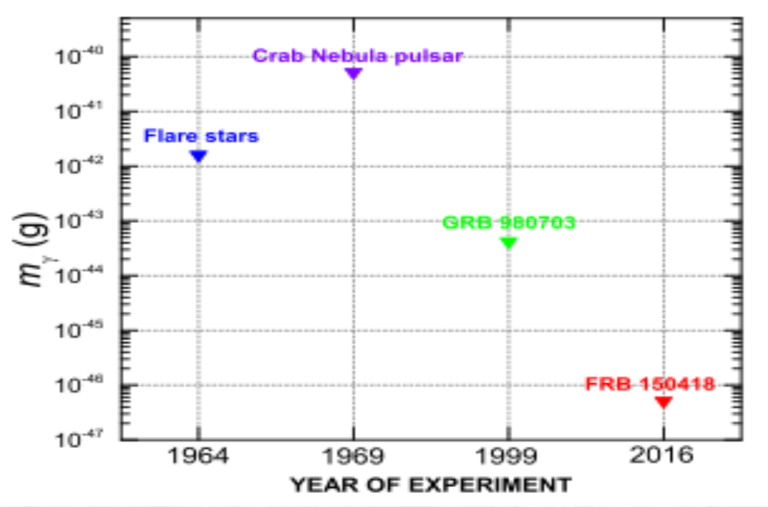
**So far, only 50% of the baryonic mass had been directly observed (i.e. the missing baryons issue)**

# *Immediate additional insights from FRB 150418*

Upper limit to the **mass of the photons** [Wu et al 2016]

$m_\gamma < 5.26 \times 10^{-47}$ g

[$10^3$ better than previous astrophysical constraints]

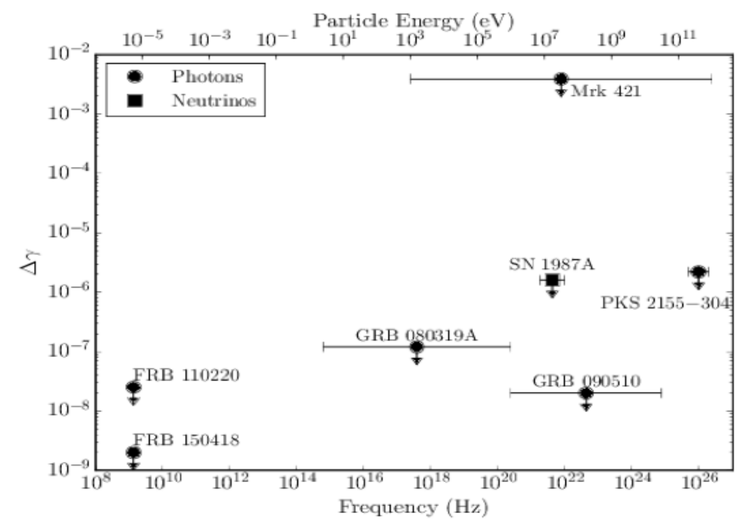


Upper limit to deviations to the **Einstein Equivalence Principle**

[Wei et al 2015; Tingay & Kaplan 2016]

$\Delta\gamma < 1\text{-}2 \times 10^{-9}$

[$10^4$ better than previous astrophysical constraints on the PN-par $\gamma$ (=1 for GR)]



# *Got some answer ... but new questions arose, and plenty ...*

- Is the fading source seen by ATCA really associated to the FRB 150418 ?

  Temporal coincidence supports the association [Li & Zhang 2016]

  Accounting for intrinsic AGN variability questions the connexion [ Williams & Berger 2016]

  Extrinsic effects – like scintillation – maybe responsible for the flux variations [Akiyama & Johnson 2016]

- Are FRBs catastrophic or highly energetic but repeating events

- Are there multiple classes of FRBs (*à la* GRBs) ?

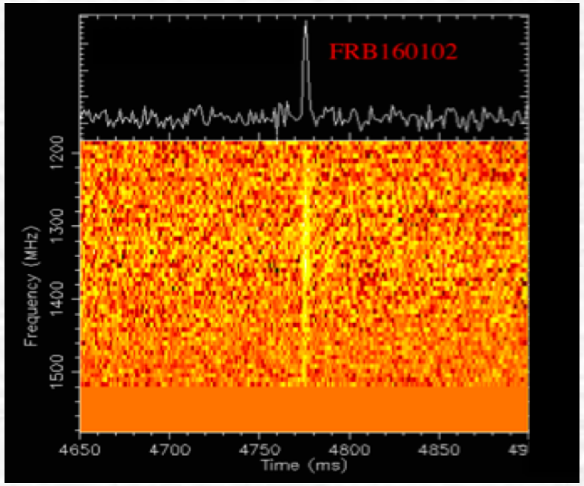
- ... ?

# … the unofficial count …

- FRB010724 Lorimer Burst (Lorimer et al. 2007)
- FRB010621 possibly galactic (Keane et al. 2010)
- 4 from HTRU-high (Thornton et al 2013)
- 5 more from HTRU-high (Champion et al 2016, submitted)
- FRB011025 in PKS archival data (Burke-Spolaor et al 2014)
- FRB121102 from Arecibo PALFA (Spitler et al 2014)
- FRB131104 from PKS (Ravi et al 2014)
- FRB140514 from PKS live! (Petroff et al. 2014)
- FRB110523 from GBT at 800 MHz (Masui et al. 2015)
- FRB150418 from PKS with optical counterpart (Keane et al 2016)
- 1 from PKS in August 2015
- 3 from SUPERB on late 2015 (at intermediate latitudes)
- 2 at Molonglo early in 2016 at 800 MHz
- Few rumors of other …

Total ~**25** and counting

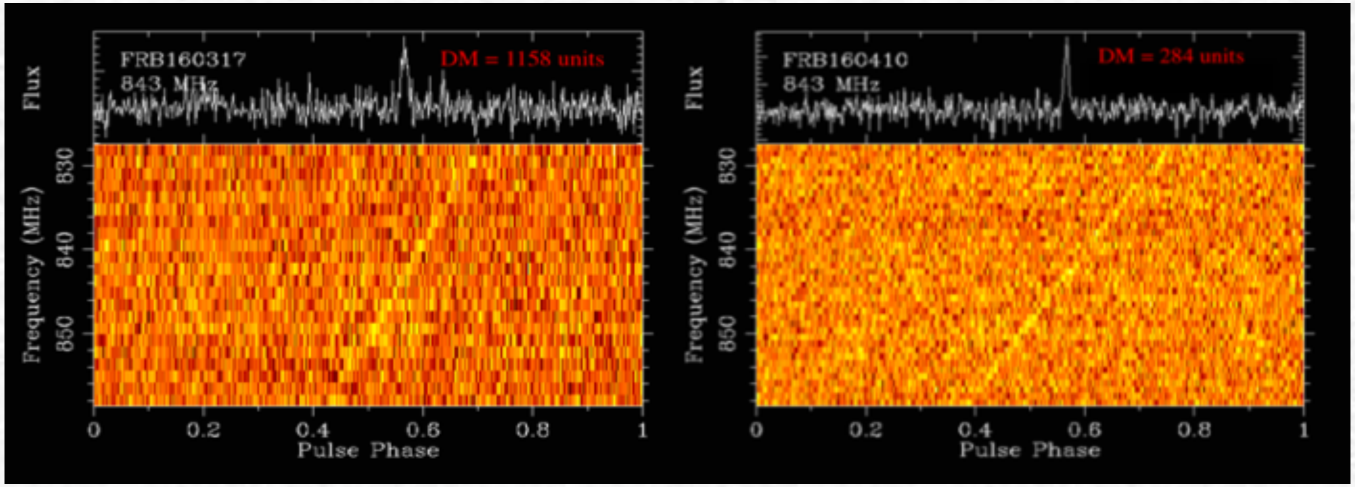
# *… with some new remarkable cases …*



From SUPERB

FRB160201 became the new record-holder of the highest DM = 2593 pc cm$^{-3}$

which implies a red-shift z ≈ 2, i.e. distance ≈ 10 Gly



The first two FRBs observed with a "transit" telescope: localized them in at least one coord

# ... stay tuned ...

# THANKS !