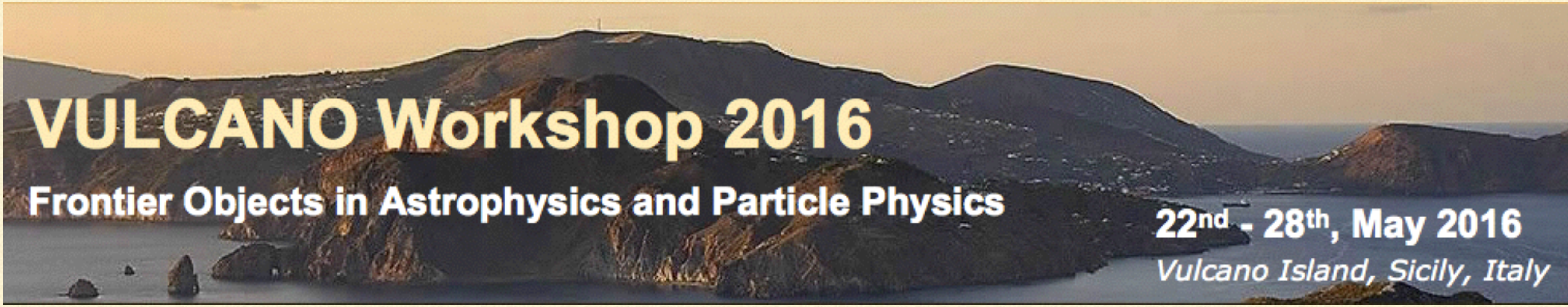


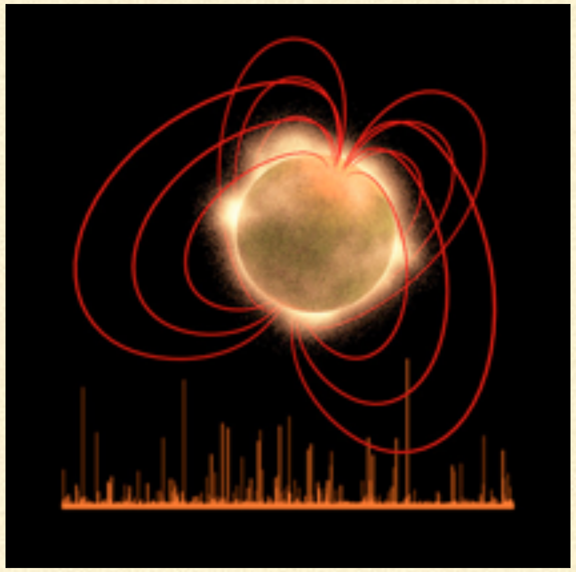
Fast Radio Bursts

Marta Burgay

INAF OAC Osservatorio Astronomico di Cagliari

Transient Radio Sky at ms-timescales

Giant pulses
from young PSRs

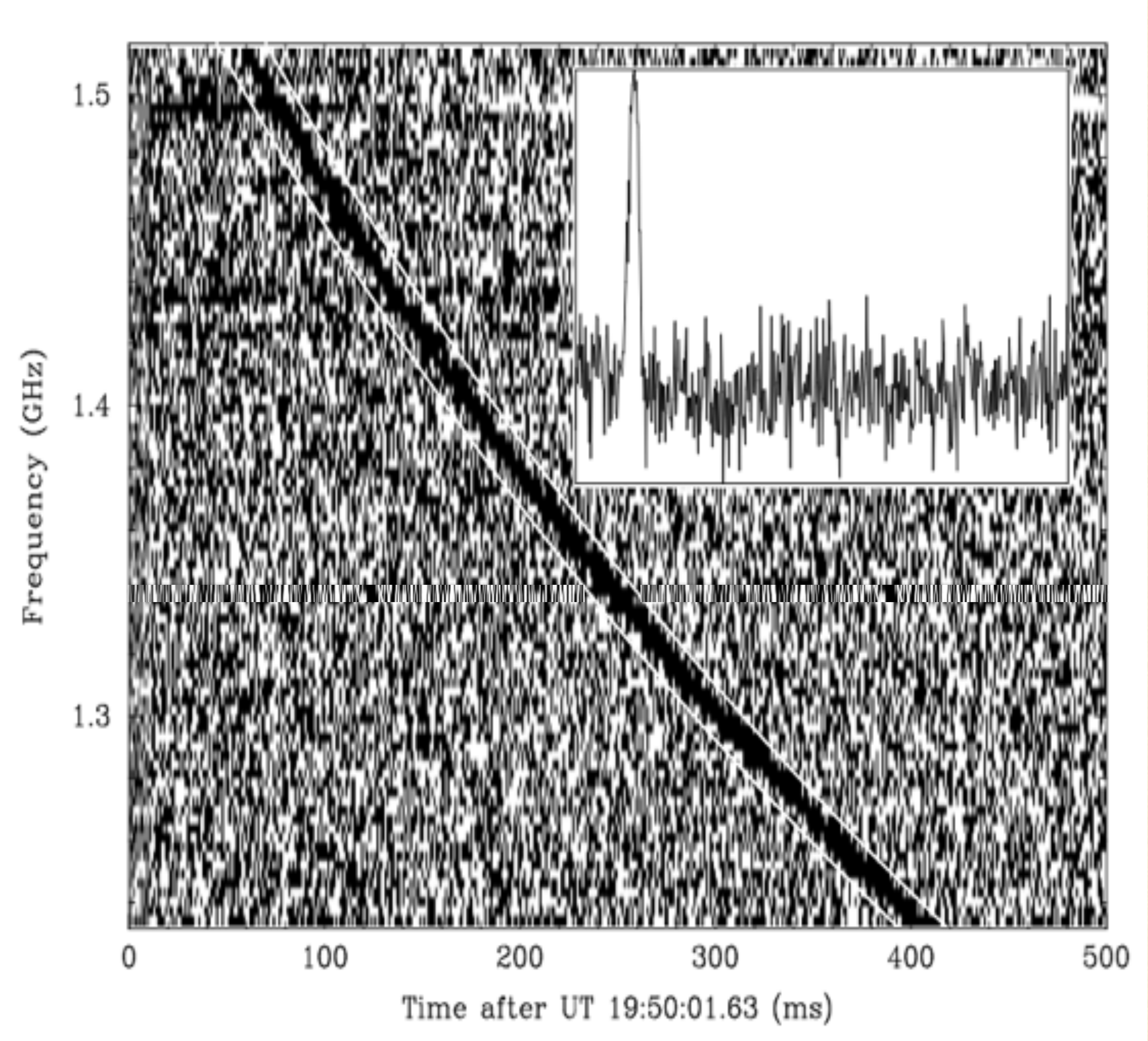


Transient
magnetars

Rotating RAdio
Transients (RRATs)

Radio pulses emitted by rotating galactic NSs

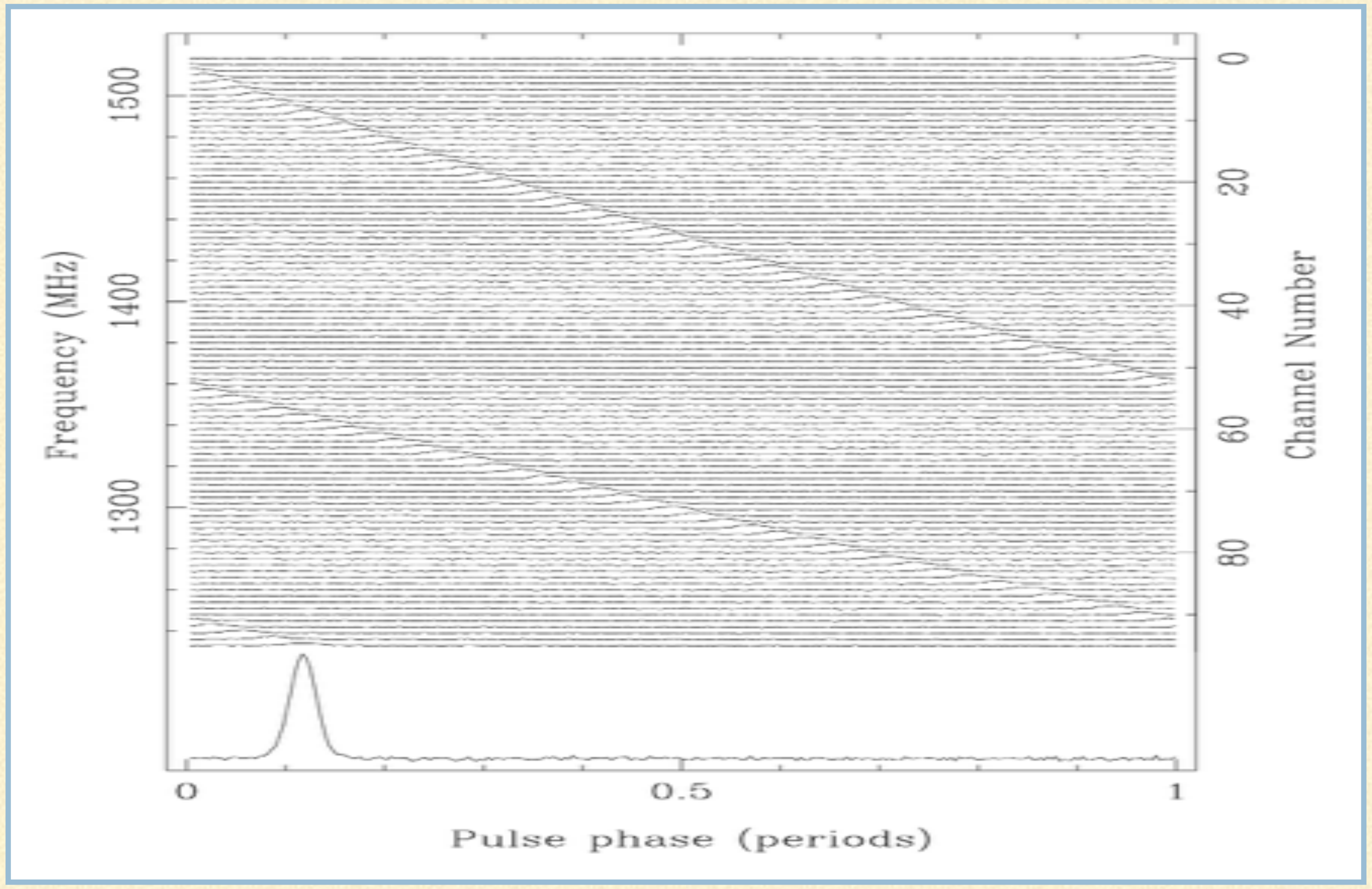
A SURPRISING (AND SKEPTICALLY ACKNOWLEDGED) EVENT



Lorimer et al 2007

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

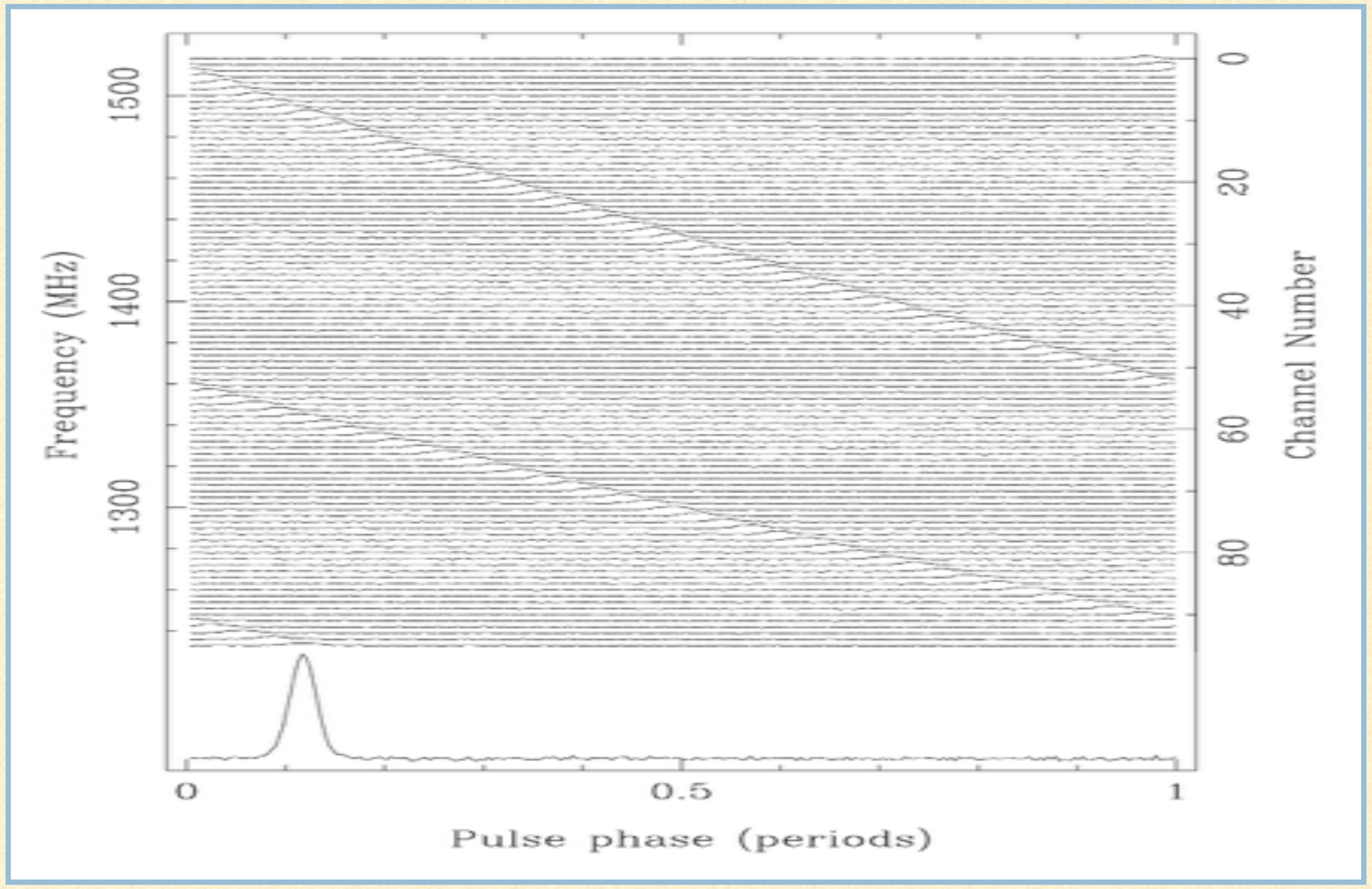
The impact of a cold ionised plasma on a radio signal



$$t_\nu - t_\infty = 4.15 \text{ ms DM } (\text{GHz}/\nu)^2$$

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

The impact of a cold ionised plasma on a radio signal



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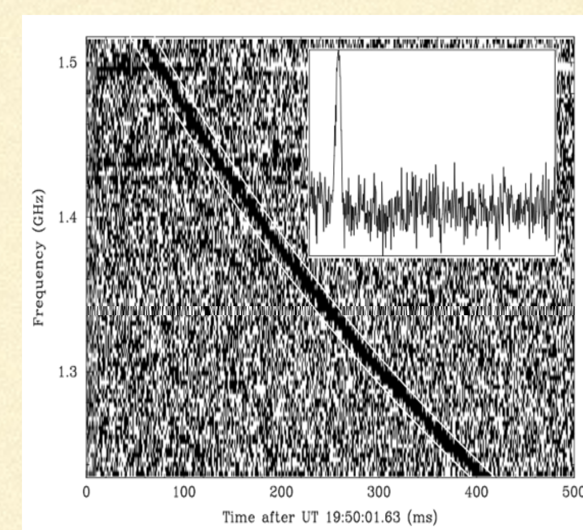
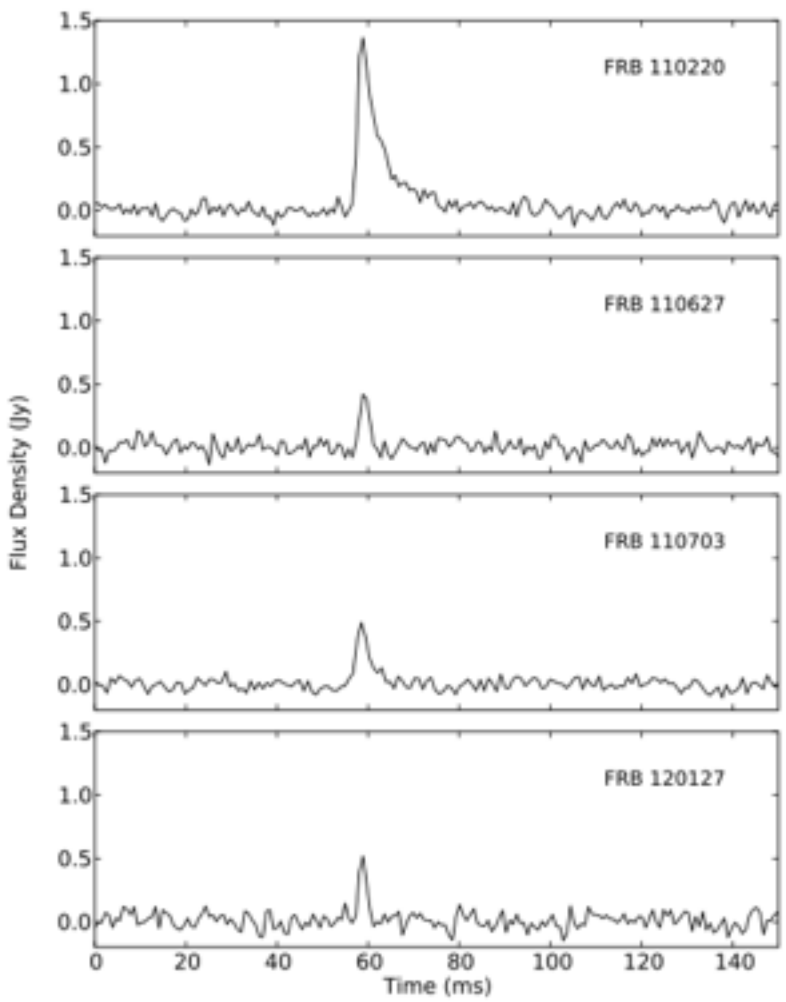


THE DISCOVERY OF A POPULATION OF FAST RADIO BURSTS AT PARKES

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]

Published in *Science*, Vol. 340, Issue 6141 (5th July 2013)



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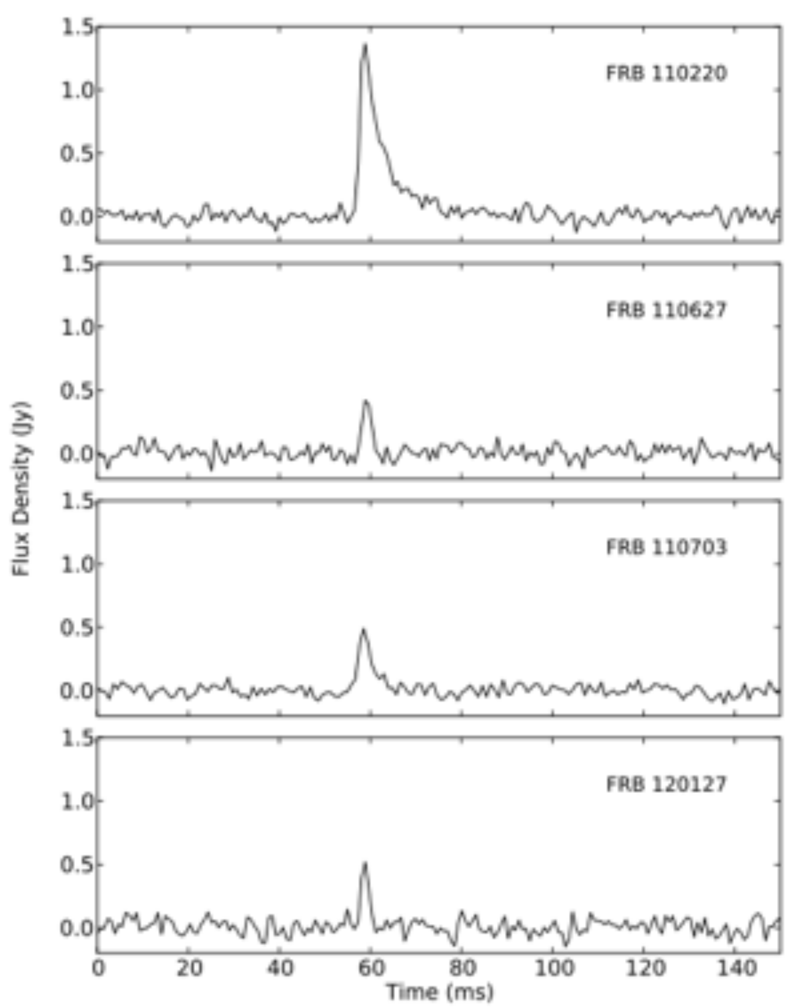
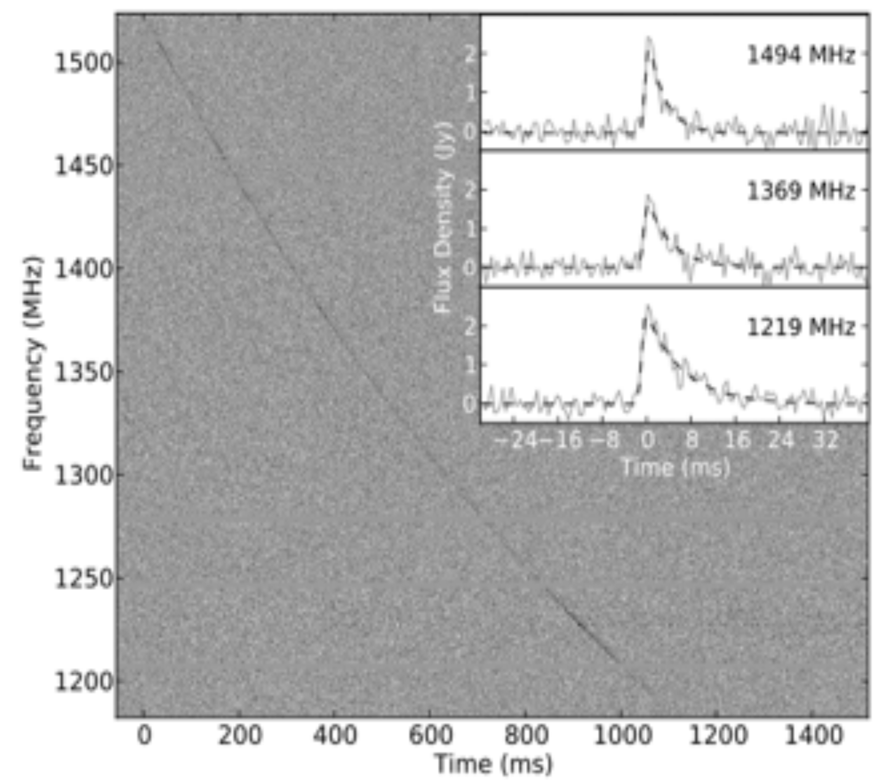




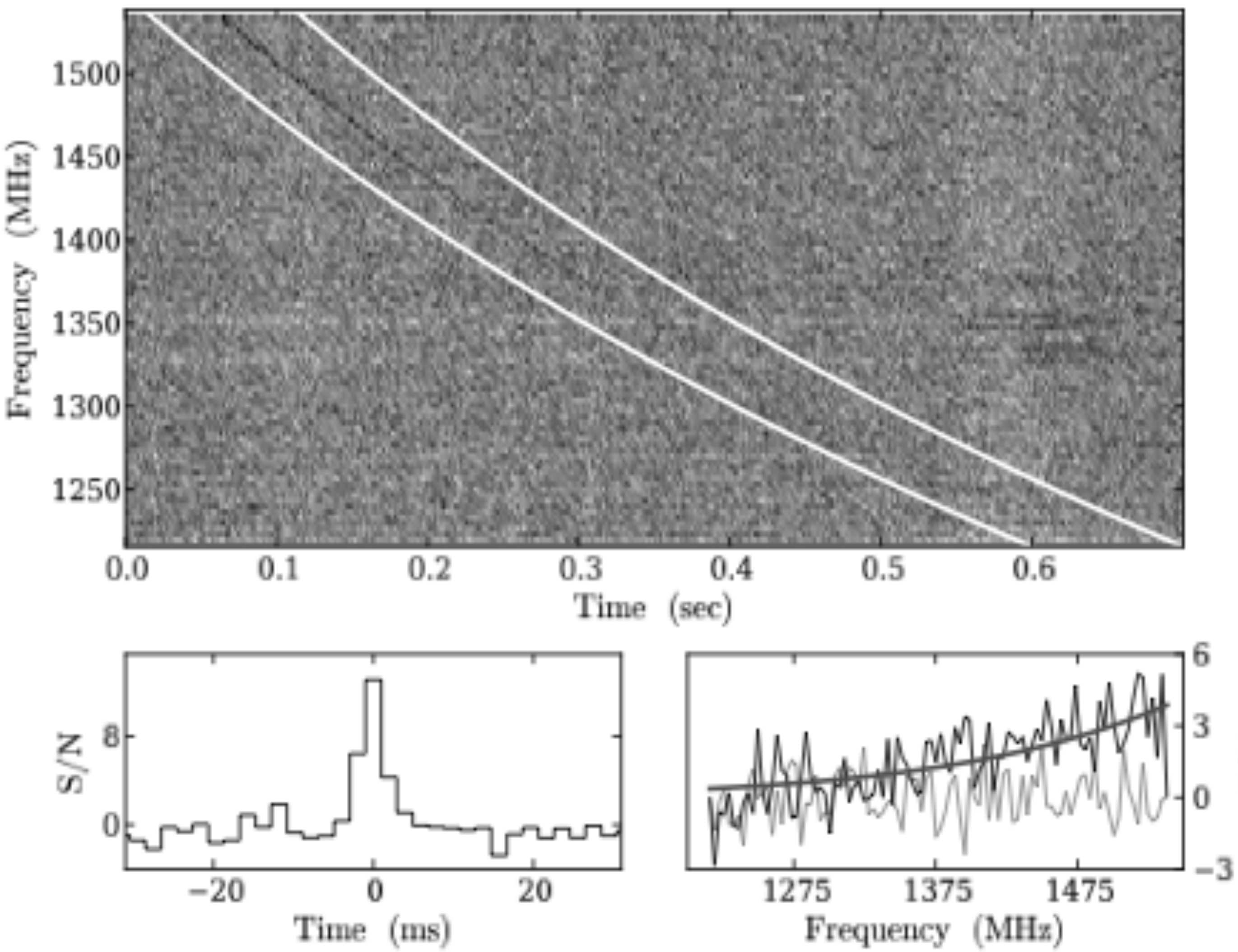
Clear signature of a signal undergoing "scattering" in FRB110220

FRBs at other telescopes and frequencies

FAST RADIO BURST DISCOVERED IN THE ARECIBO PULSAR ALFA SURVEY

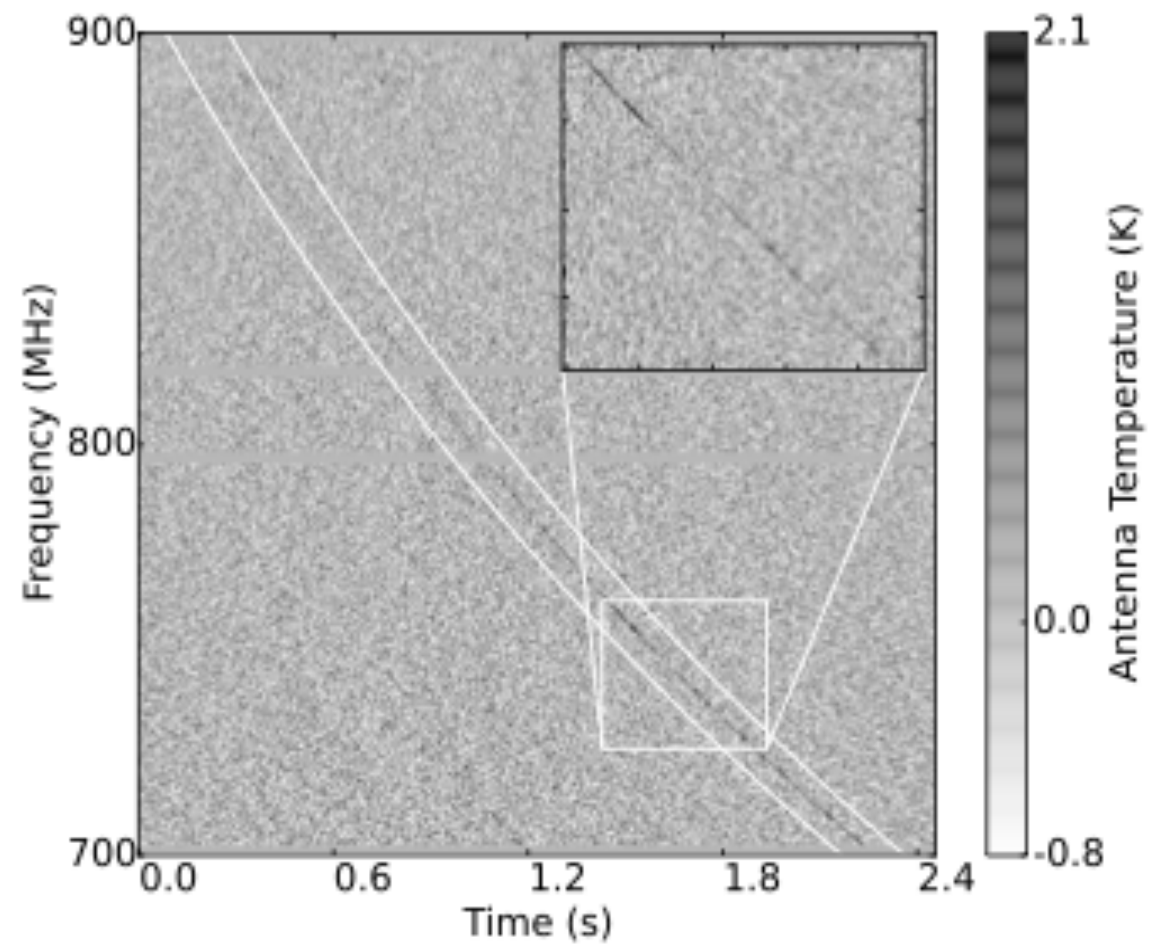
L. G. Spitler[1], J. M. Cordes[2], J. W. T. Hessels[3,4], D. R. Lorimer[5], M. A. McLaughlin[5], S. Chatterjee[2], F. Crawford[6], J. S. Deneva[7], V. M. Kaspi[8], R. S. Wharton[2], B. Allen[9,10,11], S. Bogdanov[12], A. Brazier[2], F. Camilo[12,13], P. C. C. Freire[1], F. A. Jenet[14], C. Karako–Argaman[8], 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]

Draft version April 14, 2014



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 CATALOGUE OF PUBLISHED FRBS

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)

http://www.astronomy.swin.edu.au/pulsar/frbcat/

SUMMARY OF BASIC OBSERVATIONAL FEATURES

- Burst of $\approx$ millisecond duration
- Dispersion measure DM $>$ few $\times$ DM_{MW} (the expected Milky-Way contribution)
- Dispersion delay consistent with ν^{-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 $\approx$ 0.1-10 Jansky
- Fluence at 1.4 GHz $\approx$ 0.1-10 Jansky $*$ ms

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

FRBs Event Rates

Combining all Parkes surveys:

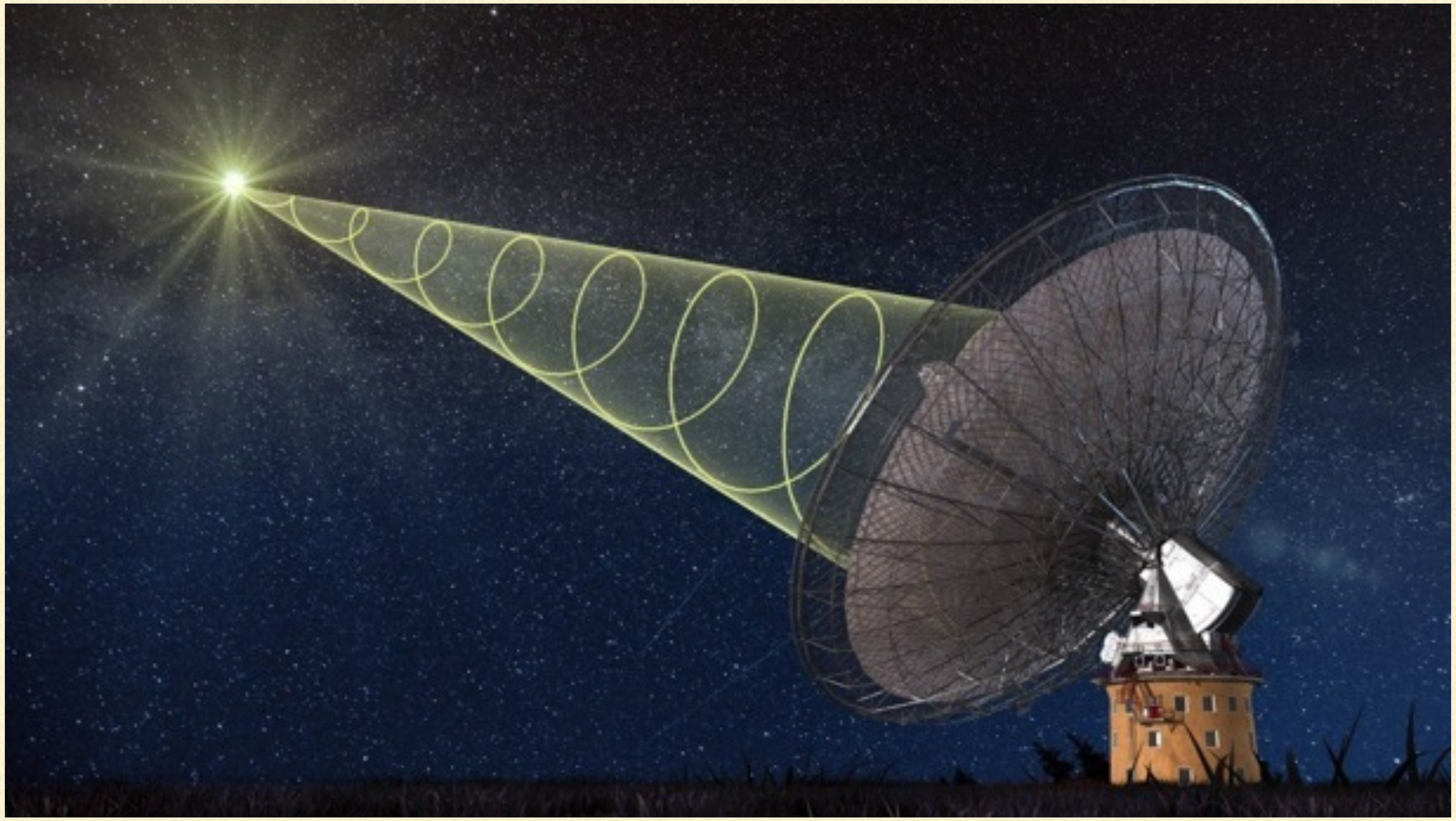
- $[3 \div 10] \times 10^3$ sky/day [Champion et al 2016] for fluence > 0.13-5.9 Jy $*$ ms
- $[1.3 \div 9.6] \times 10^3$ sky/day [Rane et al 2015] for fluence > 4.0 Jy $*$ ms
- $\approx$ 2800 sky/day [Keane & Petroff 2015] for fluence > 2.0 Jy $*$ ms
  where Parkes survey are basically "complete"

All calculations predict:
rate at 1.4 GHz $\approx 10^{-2} \div 10^{-3}$ per year in a MilkyWay-like galaxy

Open Questions

What is the nature of the FRBs ?

How can we use them ?

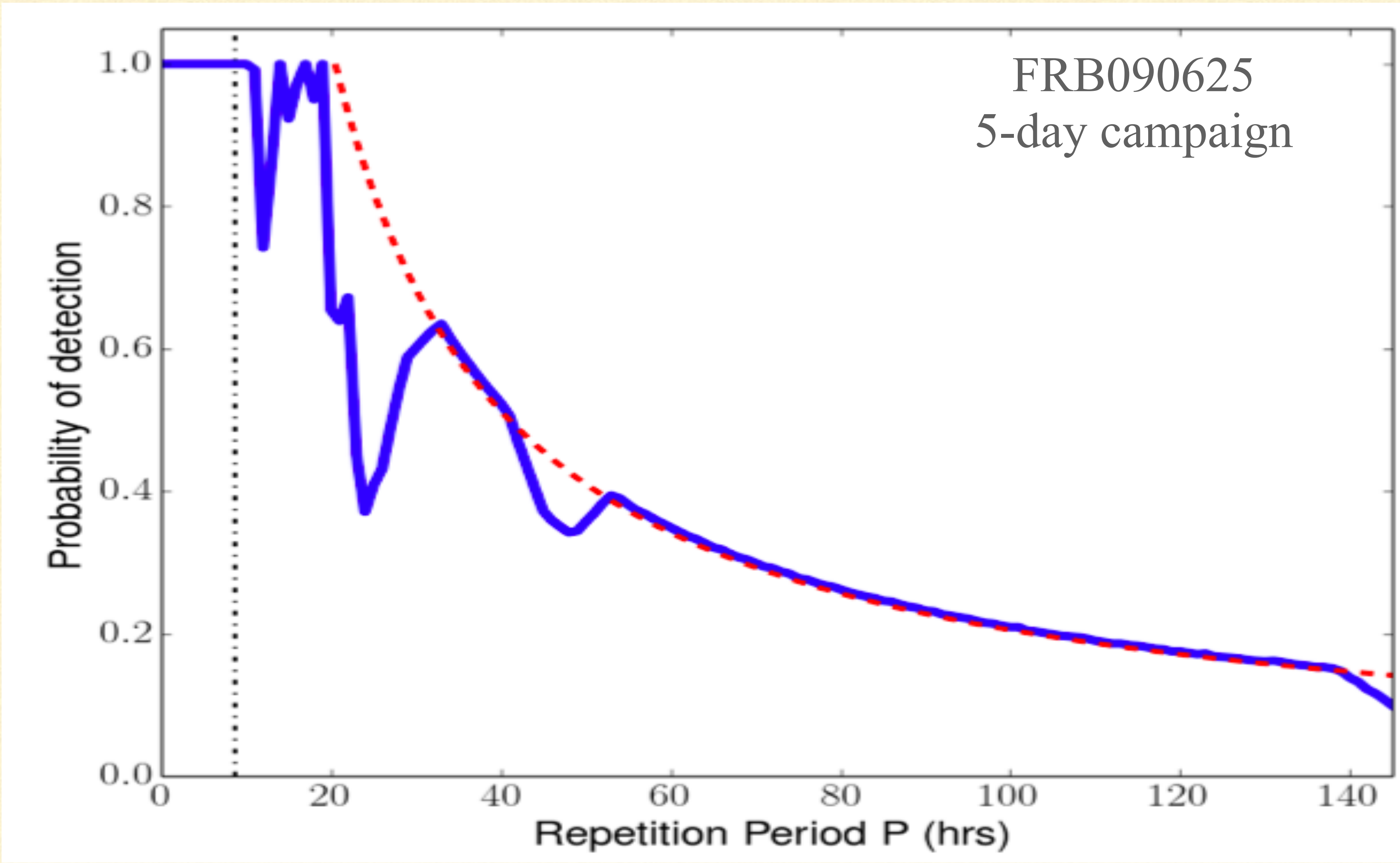


FRB MODELS

- Bursts from corona of very nearby flare stars [Loeb et al. 2013]
- Asteroid/Planet/WD magnetosphere interaction with the wind from a orbited pulsar/NS [Mottez & Zarka 2014]
- Core Collapse SuperNovae, [Thornton et al 2013]
- Binary WD merger to highly magnetic rapidly spinning WD [Kashiyama et al 2013]
- Binary Neutron Star merger; short hard GRBs [Keane et al. 2012, Totani et al 2013, Zhang et al 2014]
- Evaporating primordial BH [Keane et al 2012]
- BH to WH quantum transition [Haggard & Rovelli 2014]
- Collisions btw axion stars and neutron stars [Iwazaki 2014]
- Explosive decay of axion miniclusters [Tkachev 2014]
- Superconducting cosmic string (SCS) loops [Cai et al. 2012] oscillating in cosmic magnetic fields [Yu et al 2014]
- Blitzar: Collapse to BH of a supramassive NS [Falcke & Rezzolla 2014] from an original scenario of [Vietri & Stella 2000]
- Magnetar giant flares [Popov & Postnov 2010, Thornton et al 2013]
- Hyper Pulses from extra-galactic NSs [Cordes & Wasserman 2016]

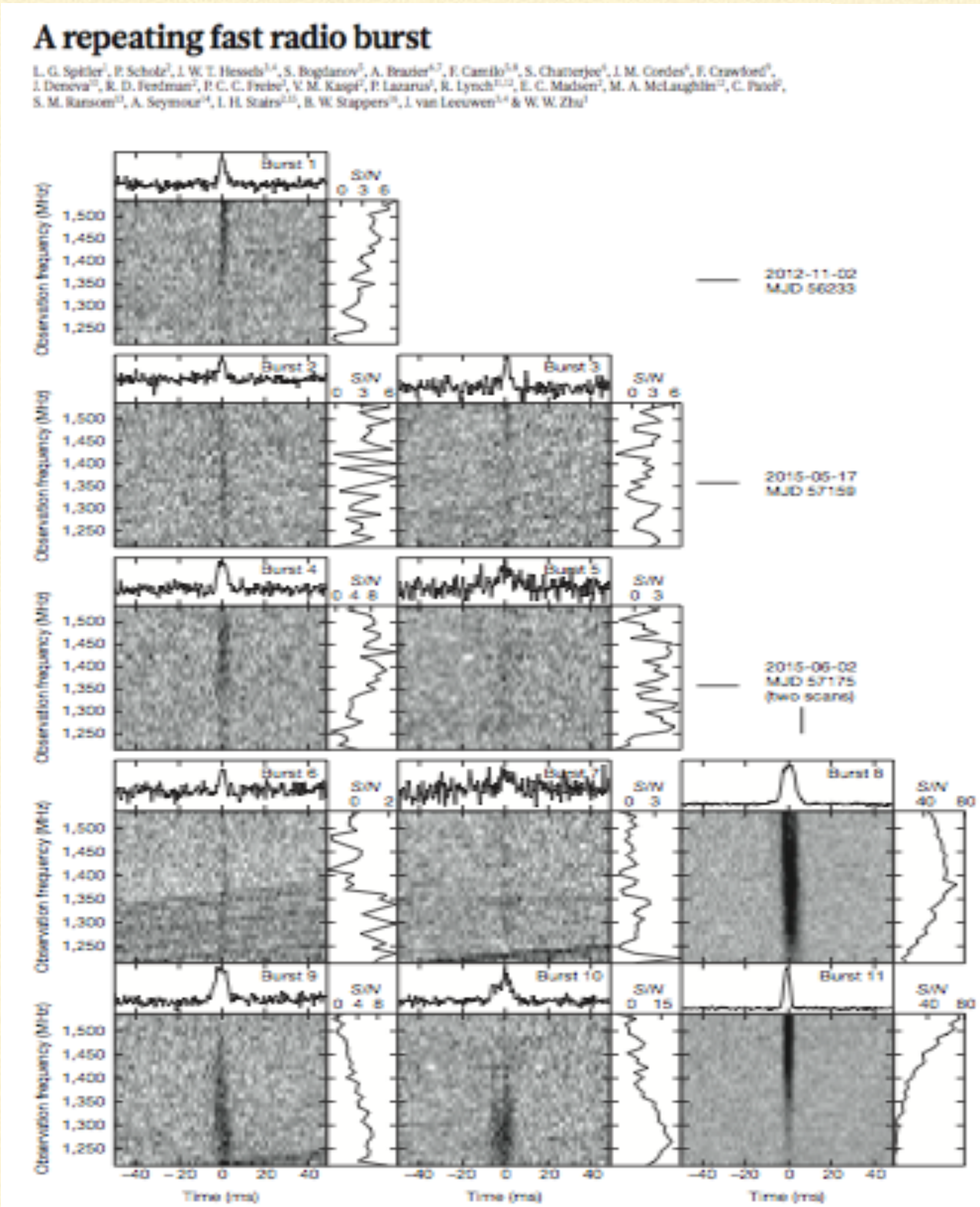
Limits on Repeatability…

A survey of 110 hours over 6 months dedicated to re-observing the fields of 8 known FRBs
No repeat emission was detected from an FRB during this time



[Petroff et al 2015b]

… BUT FOR FRB121102



Follow-up pointings with Arecibo (1.4 GHz) and Green Bank (2.0 GHz) telescope toward the position of FRB121102 [Spitler et al. 2014]

seen to repeat!
[Spitler et al. 2016]

The repeating bursts are resolved in time:
i.e. intrinsic timescale of $\approx$ ms
vs
often unresolved Parkes FRBs, never seen (so far) to repeat [Keane et al. 2016]

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 to constrain the distance of the source.

Building up on pioneering works of [Ioka 2003] and [Inoue 2004], one can write the relation between DM, the Luminosity Distance DL , the red-shift z, the matter density parameter in the universe Ω_m, the mean number density n_0 of nucleons at z=0 and fe ≈ 0.88 at low red-shift

[Zheng et al. 2014]

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

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

Derived Features for Cosmological FRBs

Given the observed parameters

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 $1 < D$ (Gpc) < 3
- Isotropic emitted energy $10^{38} < E_{iso}$ (erg) $< 10^{40}$
- Brightness temperature $10^{33} < T$ (K) $< 10^{36}$

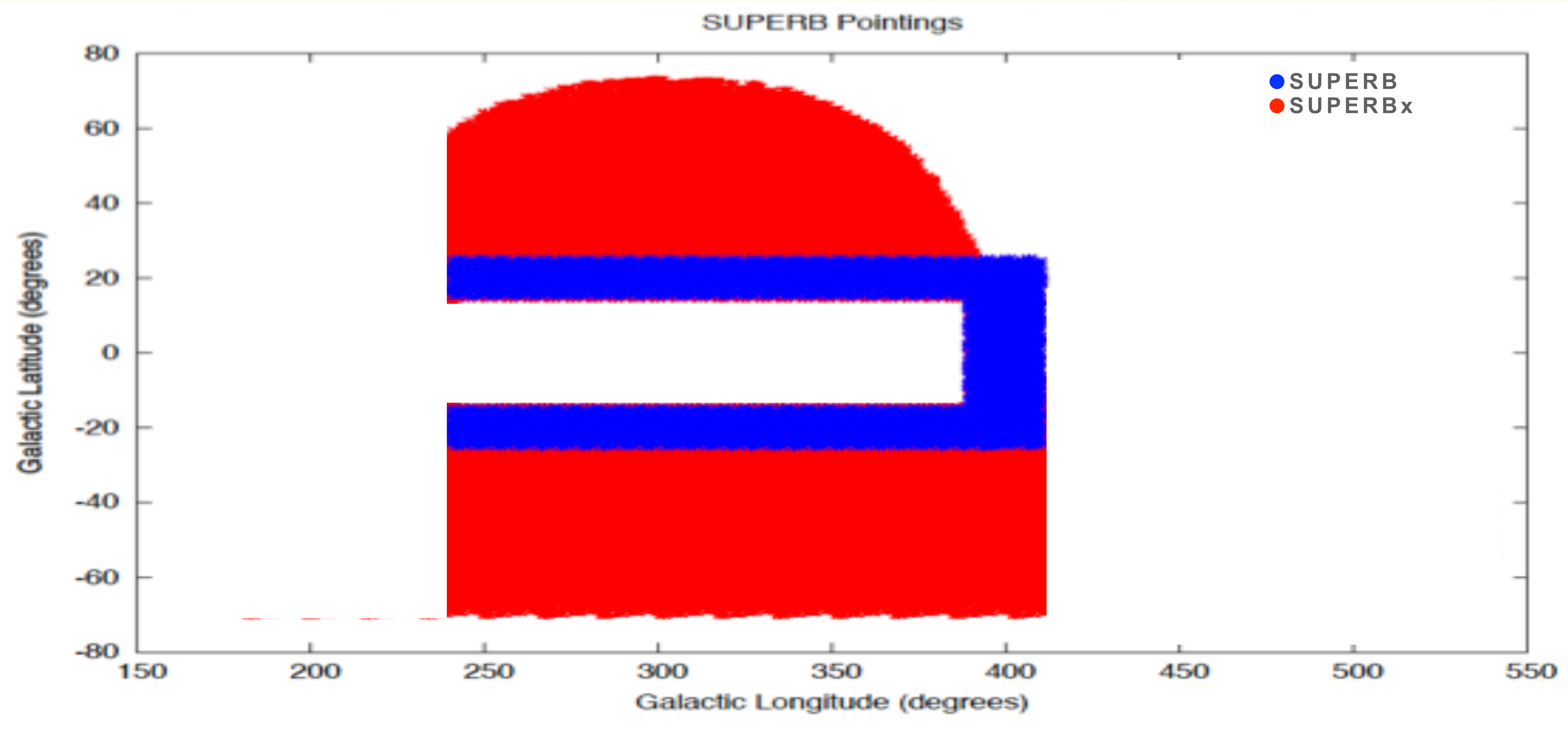
FRBs as Cosmological probes

If cosmological, with a series of independent z determinations (from the identification of the source at other wavelengths), one could

- measure the density of the ionised component of the IGM [Zheng et al. 2014]
- measure the missing baryonic matter in the Universe [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-ionisation 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 [Zheng et al. 2014]
- 3D clustering of the electrons in the Universe, with > 10000 FRBs, even without redshift [Masui & Sigurdson 2015]
- put limits to the fraction of "dark matter" in MACHO of $>20 M_{\odot}$ via counting the number of echoes due to gravitational lensing [Munoz et al 2016]

SUPERB: SOLVING FRBS' MYSTERY

SUrvey for Pulsars and Extragalactic Radio Bursts
≈ 3000 hours of Parkes observations. 9 min for each obs. Begun on 23 April 2014



[© Keane]

Expected yield: ~10 FRBs (+ few tens of PSRs and MSPs)

SUPERB

Main 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)

SUPERB LIVE!

The FRB search is done in RAM “live” thus leading to real time discoveries

SUPERB LIVE!

The FRB search is done in RAM "live" thus leading to real time discoveries

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

[Petroff et al 2015a]

SUPERB LIVE!

The FRB search is done in RAM “live” thus leading to real time discoveries

Name	Event date	Discovery date	Lag
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FRB 010724 Lorimer	2001	2007	6 years
FRB 110220 Thornton	2011	2013	2 years
FRB 140514 Petroff	14 May, 2014 17:14:11 UT	14 May, 2014 17:14:30 UT	20 seconds

[Petroff et al 2015a]

A trigger e-mail il sent to partners who signed an LoI with SUPERB to start multi-wavelength follow-up

SUPERB FOLLOW-UP & SHADOWING

SUPERB FOLLOW-UP & SHADOWING

GMRT shadowed 42 hrs of Parkes pointings in fast imaging mode

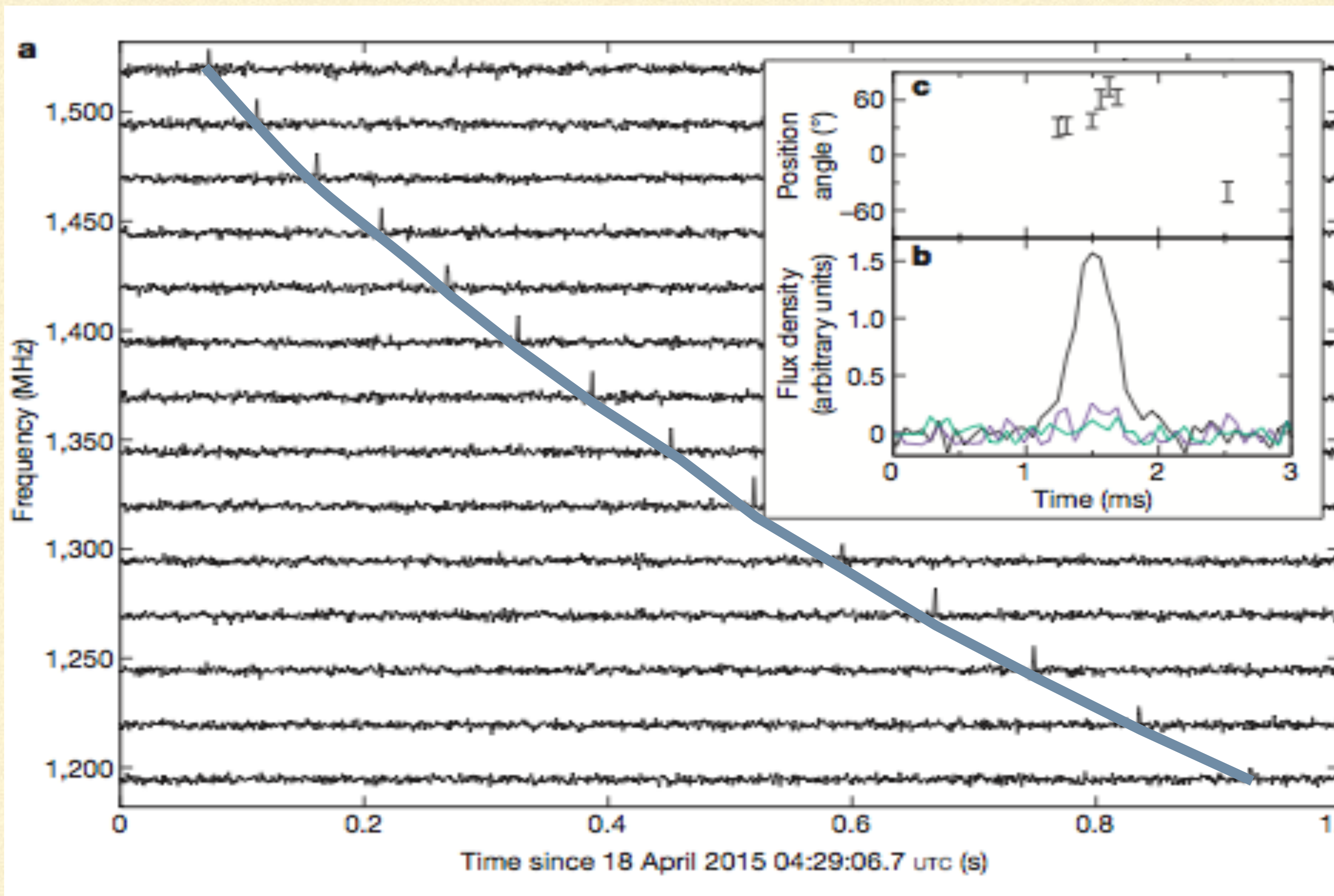
SUPERB follow-up & shadowing

GMRT shadowed 42 hrs of Parkes pointings in fast imaging mode

Molonglo will shadow Parkes for every SUPERB observation

FRB150418: A ROSETTA STONE ?

DM = 776 pc/cm3, 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]

FRB150418: A ROSETTA STONE ?

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

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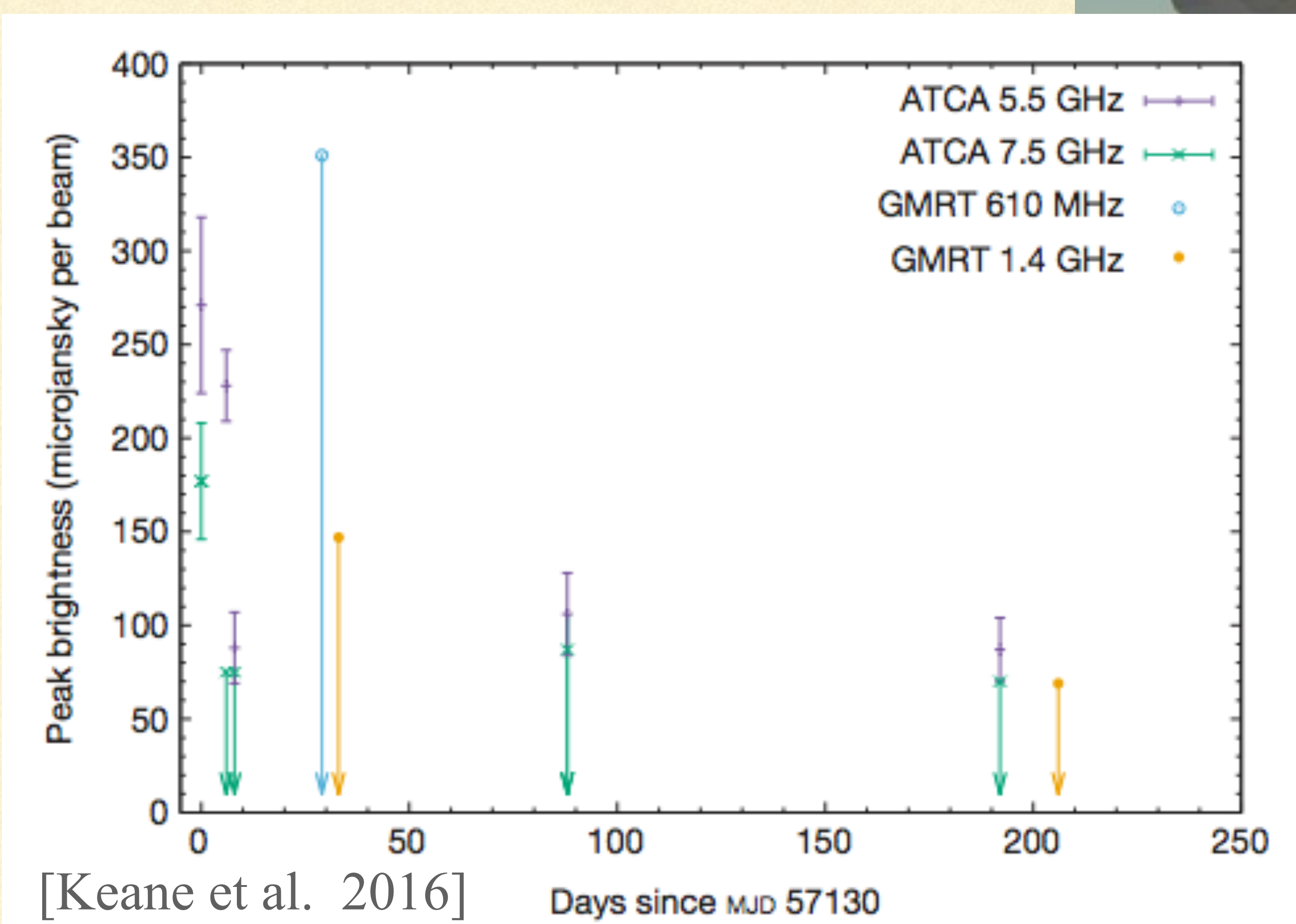

[Keane et al. 2016]

Observed a fading radio source in the uncertainty beam of the Parkes detection that showed a 3x flux variation in about 1 week

FRB150418: 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]

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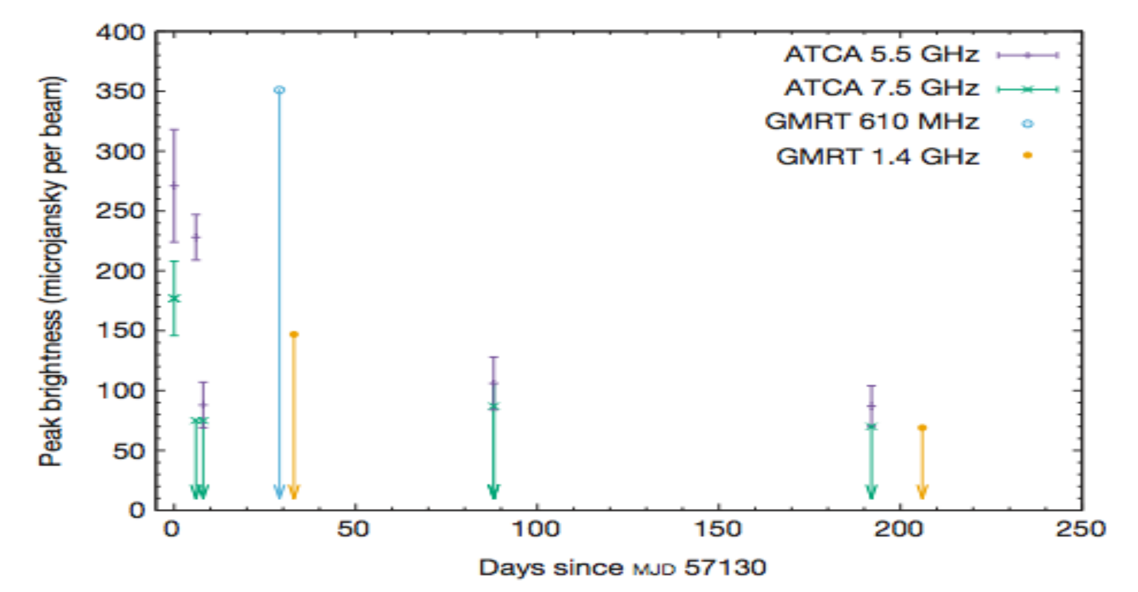
With 5 epoch data it appeared to be settled down to a steady level, then classified as a *transient*



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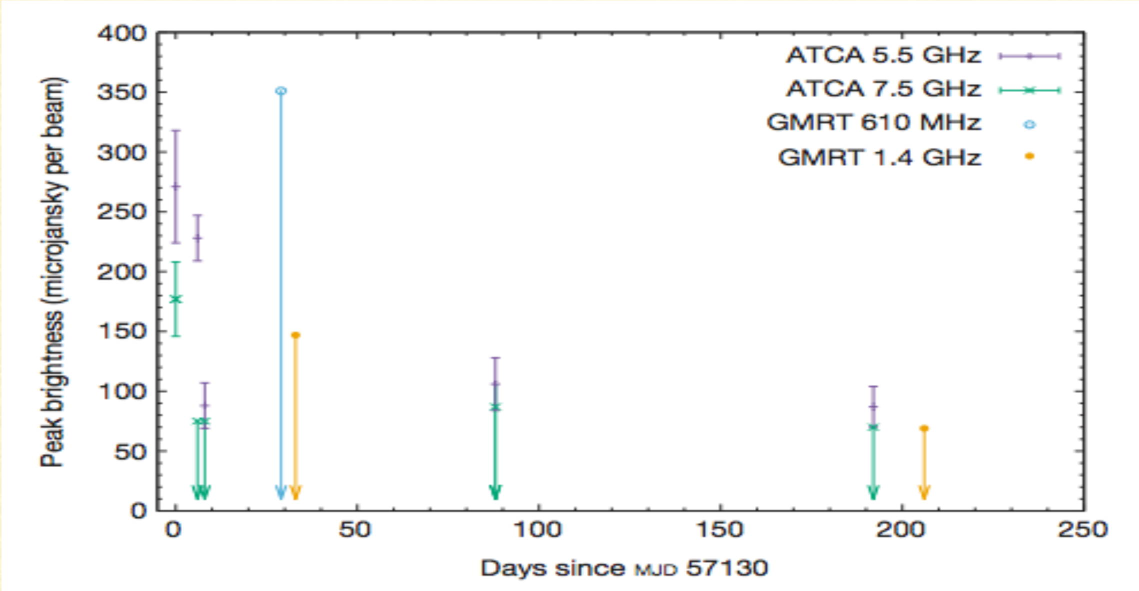
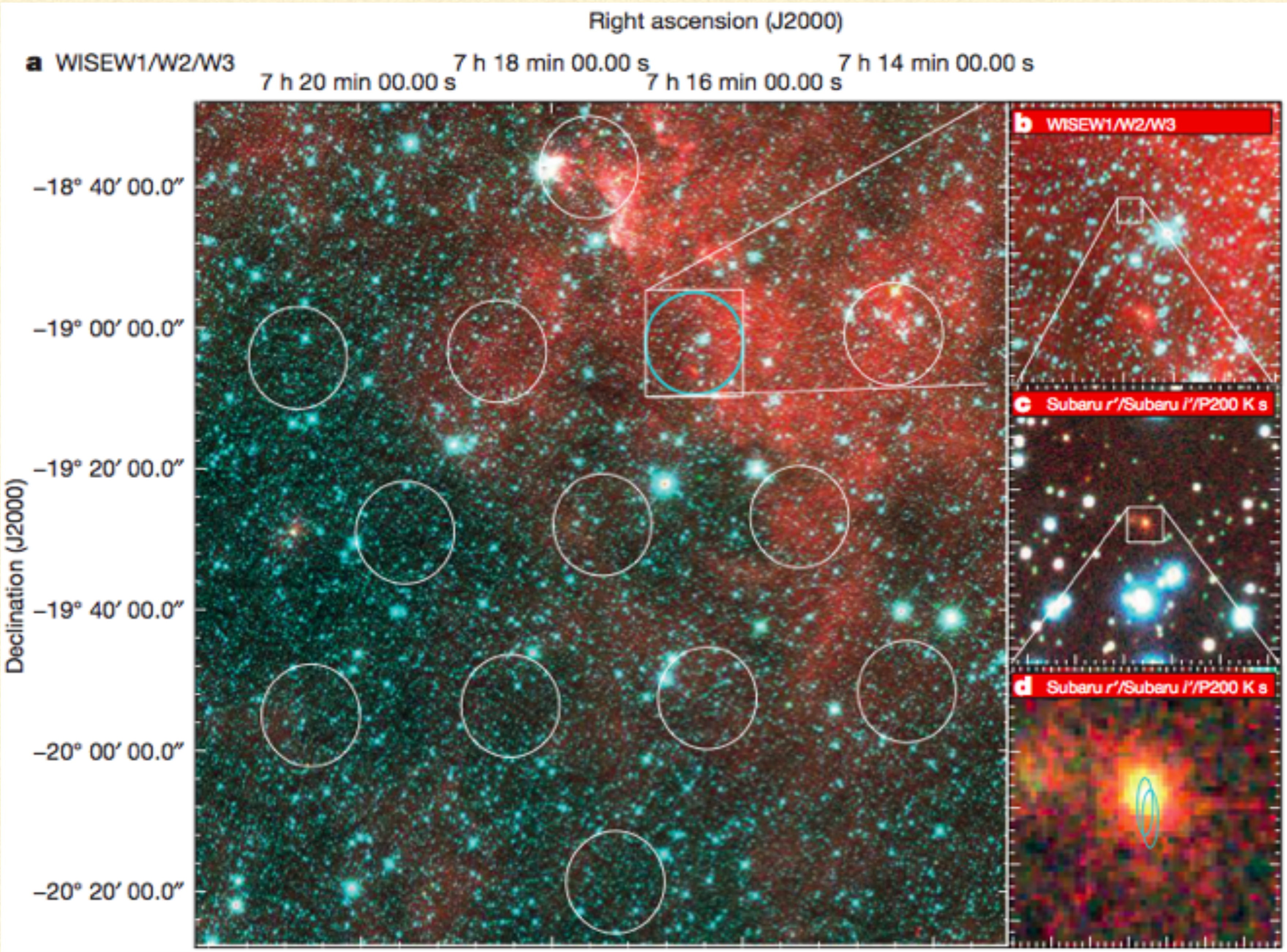


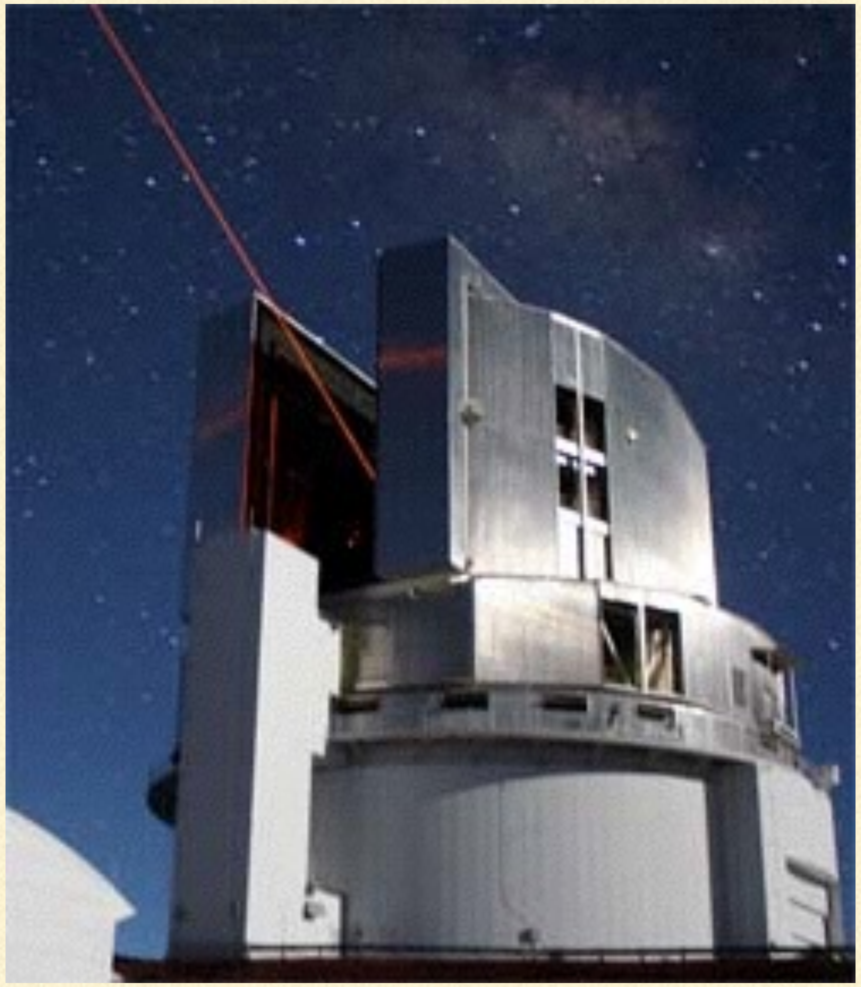
Additional data seem to show that flux varies up-and-down: one has to consider the statistic of radio *variable* sources → Poorly known stats at 100 μJy level
Using stats from brighter samples
the chance probability becomes < 1.6 % (at 95% c.l.)

FRB150418: A Rosetta stone ?



[Keane et al. 2016]

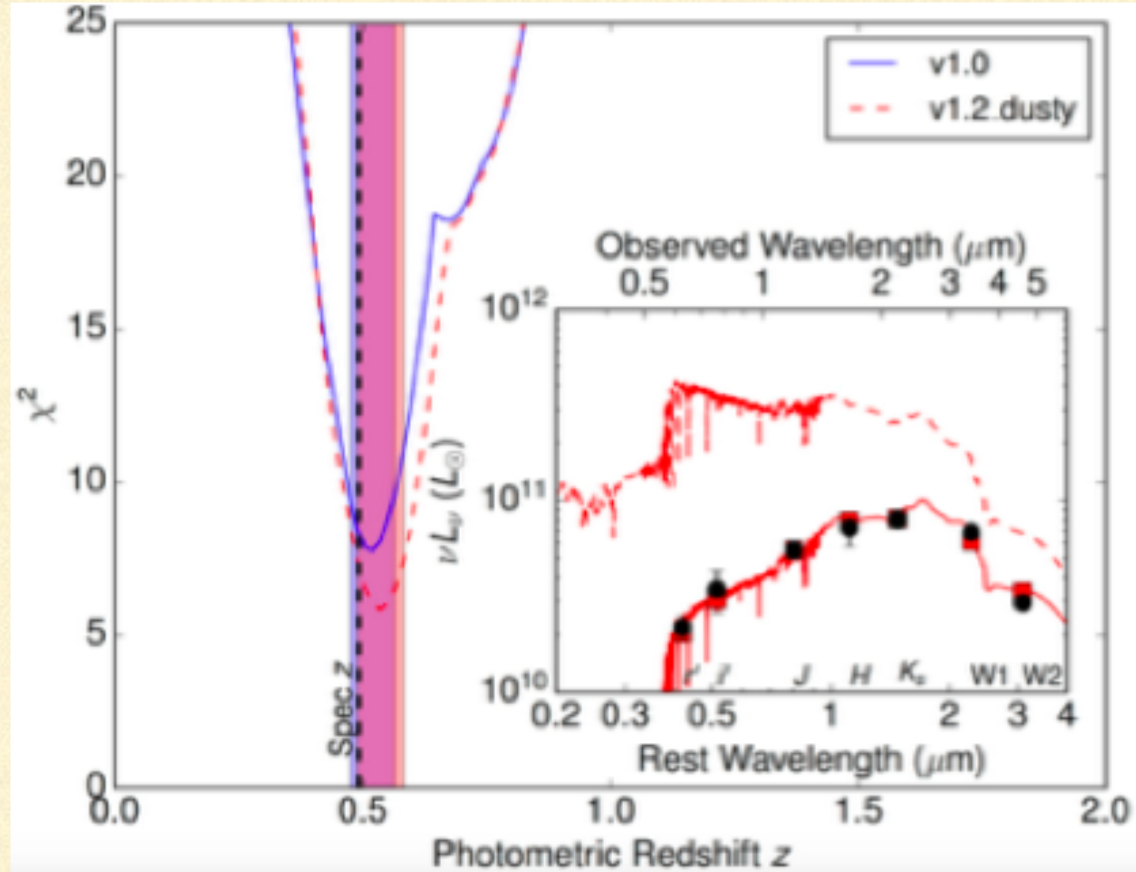
Detected an elliptical galaxy at the position of the fading source

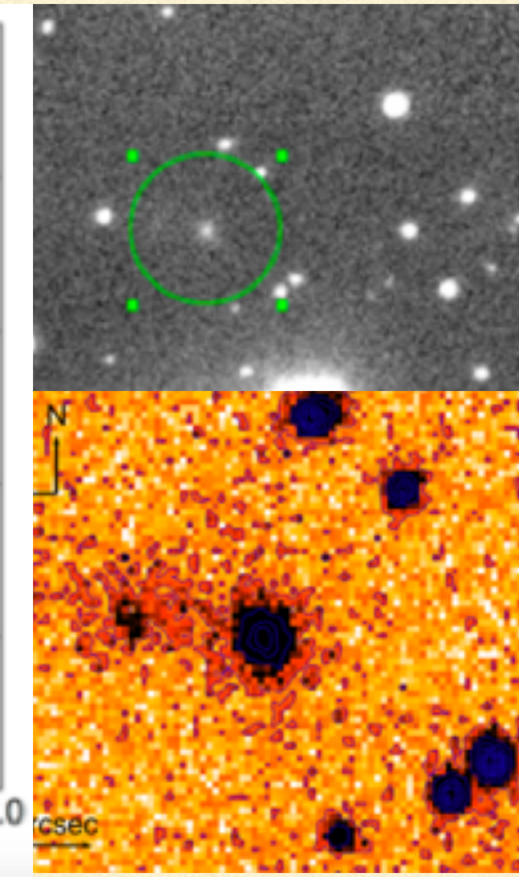


Performed optical observations with Subaru, 1 and 2 days after the detection of the FRB and again ~6 months later

FRB150418: A ROSETTA STONE ?

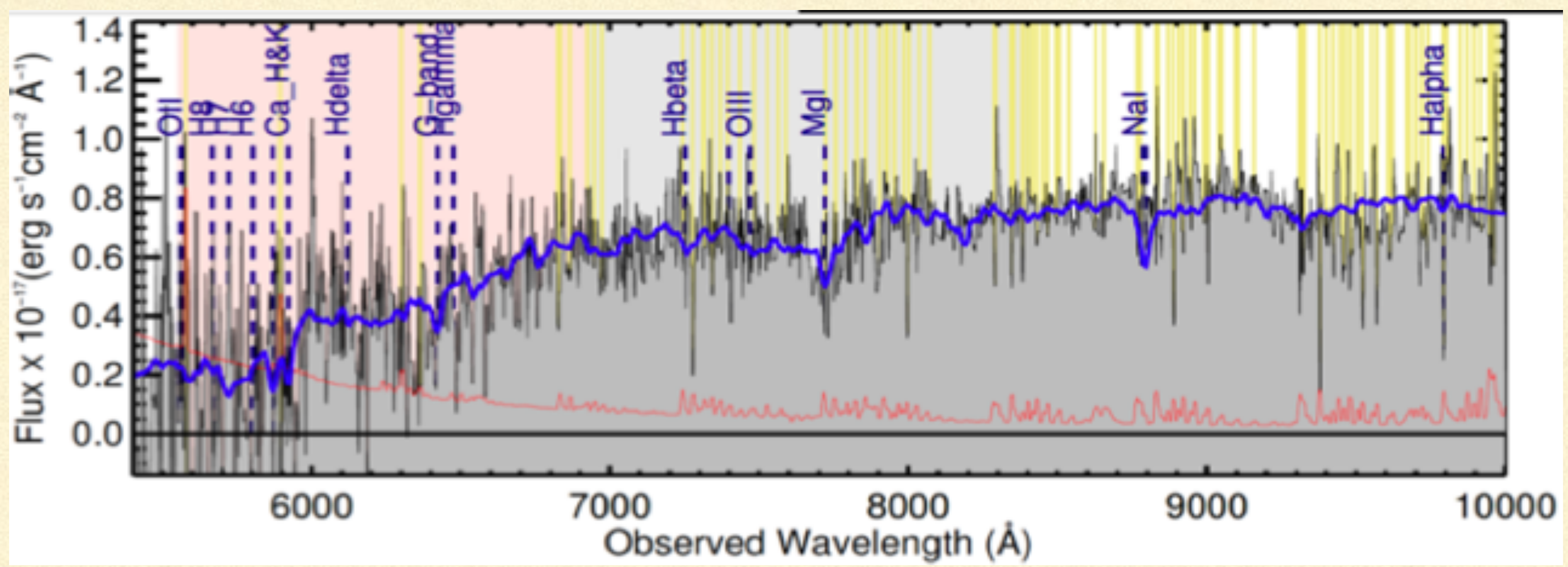
Photometric red-shift
z = 0.52±0.04



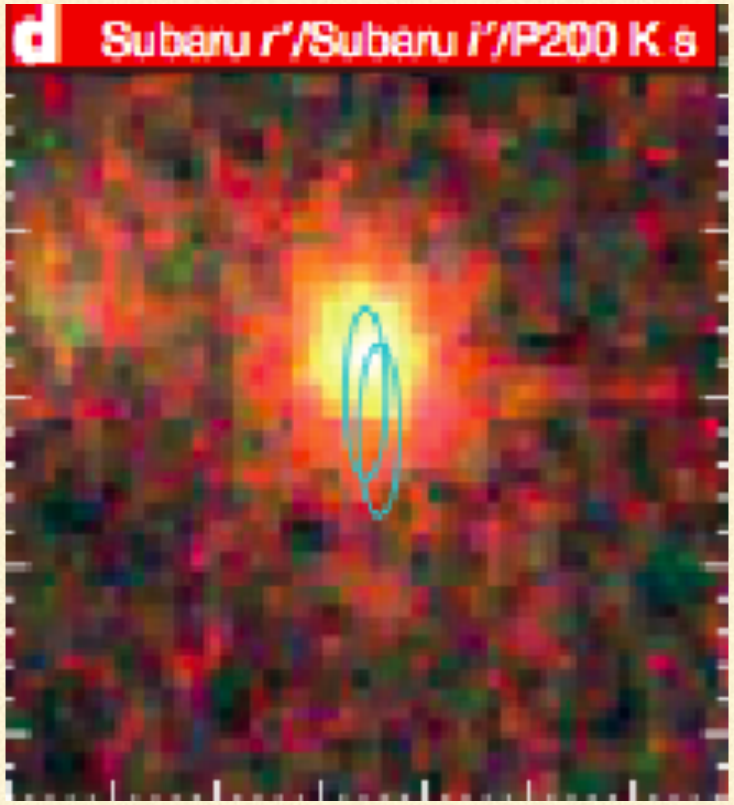


[Keane et al. 2016]

Spectroscopic red-shift
z = 0.492±0.008



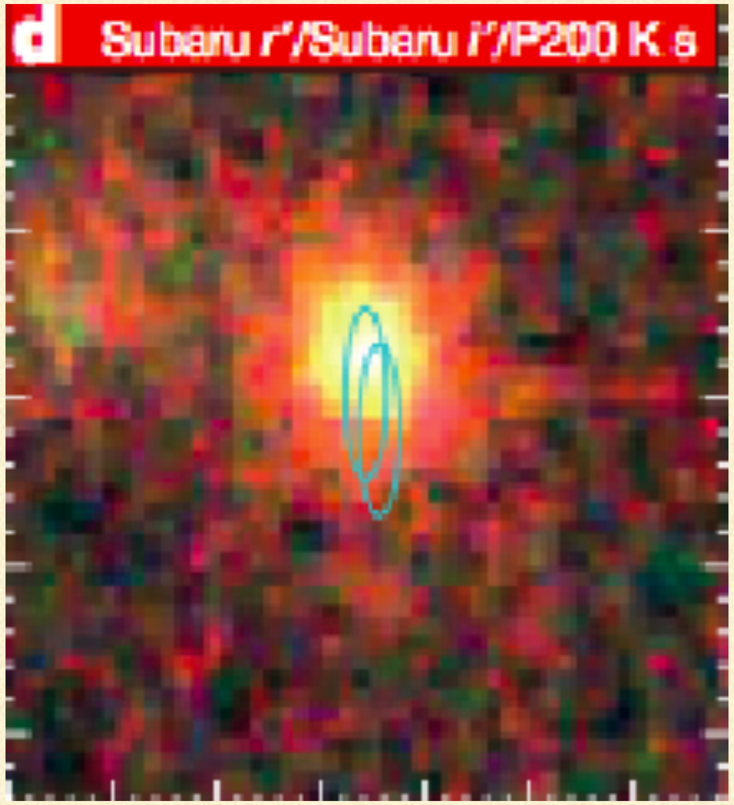
WEIGHTING THE MASS ALONG THE LINE-OF-SIGHT



From z and DM_{IGM}, for each given set of cosmological parameters H_0 , Ω_m and Ω_Λ, plus the fraction of ionized atoms f_e , one can get the baryon density along the line of sight Ω_{IGM}

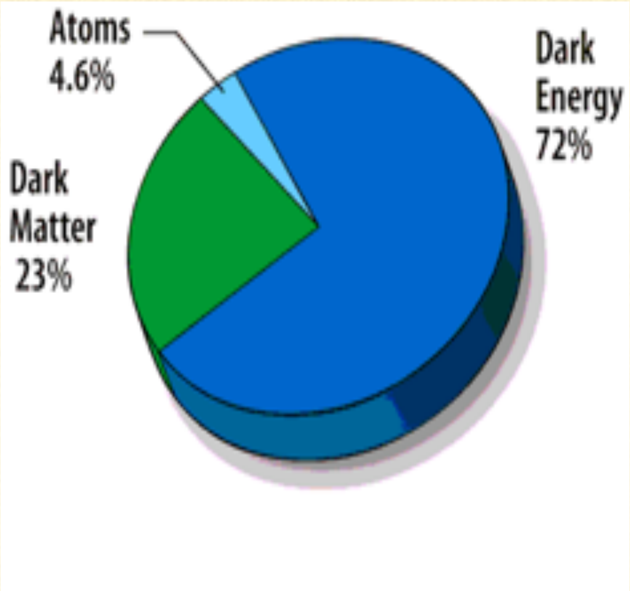
$$\mathrm{DM}_{\mathrm{IGM}} = \frac{3cH_0\Omega_{\mathrm{IGM}}}{8\pi G m_{\mathrm{p}}} \int_0^z \frac{(1+z')f_{\mathrm{e}}(z')\mathrm{d}z'}{[(1+z')^3\Omega_{\mathrm{m}} + \Omega_\Lambda]^{0.5}}$$

WEIGHTING THE MASS ALONG THE LINE-OF-SIGHT



From z and DM_{IGM}, for each given set of cosmological parameters H_0 , Ω_m and Ω_Λ, plus the fraction of ionized atoms f_e , one can get the baryon density along the line of sight Ω_{IGM}

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



Ω_{IGM} = 4.9 % ± 1.3 %

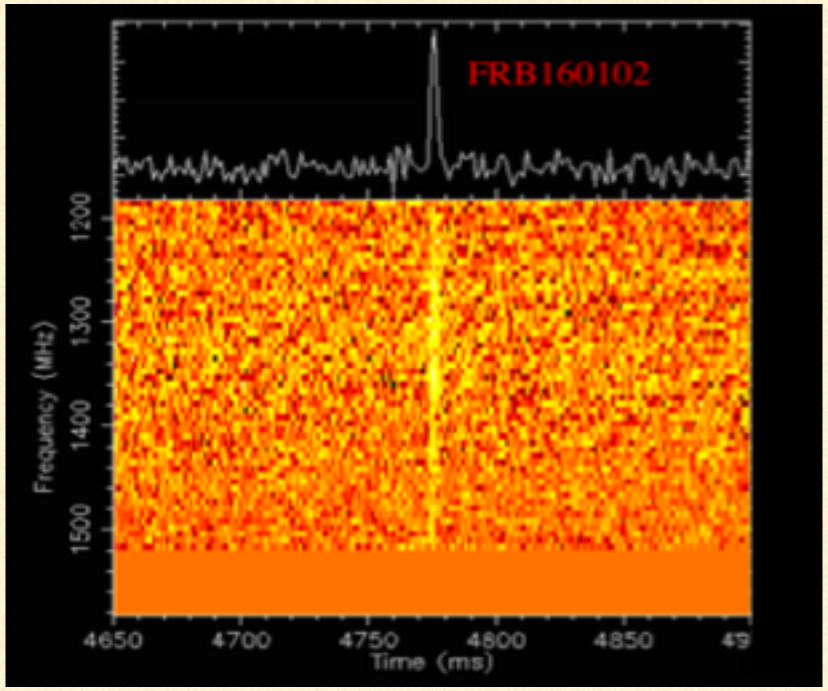
In agreement with WMAP and other indirect determinations for ΛCDM cosmologies

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

We've got some answer ... but also lots of new questions...

- Is the fading source seen by ATCA really associated to FRB150418 ?
    - Temporal coincidence supports the association [Li & Zhang 2016]
    - Accounting for intrinsic AGN variability, the connection becomes questionable [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) ?
- ... ?

NEW FRBS



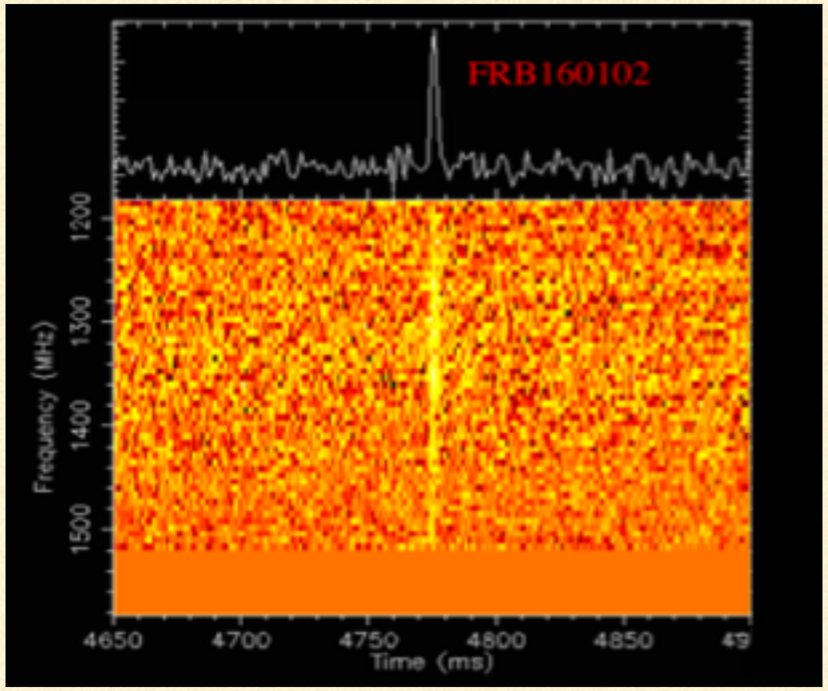
From SUPERB:

FRB160102

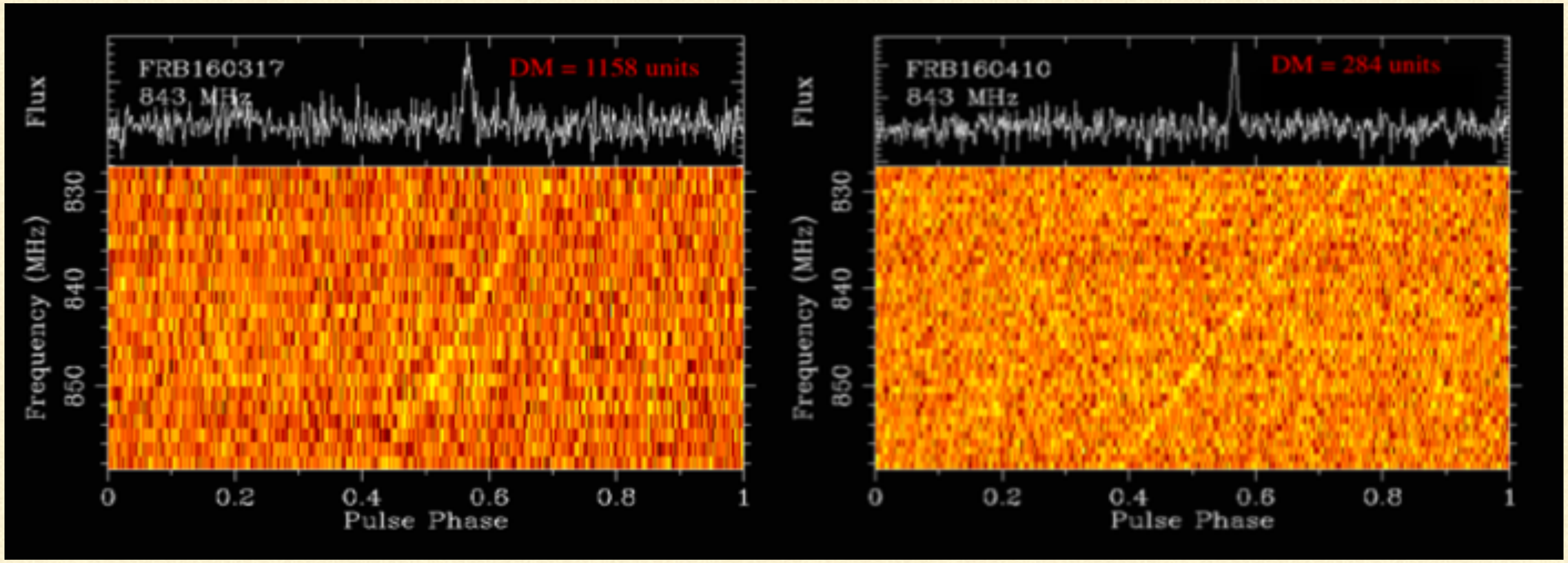
highest DM = 2593 pc cm^{-3}

implying a red-shift $z \approx 2$

NEW FRBS



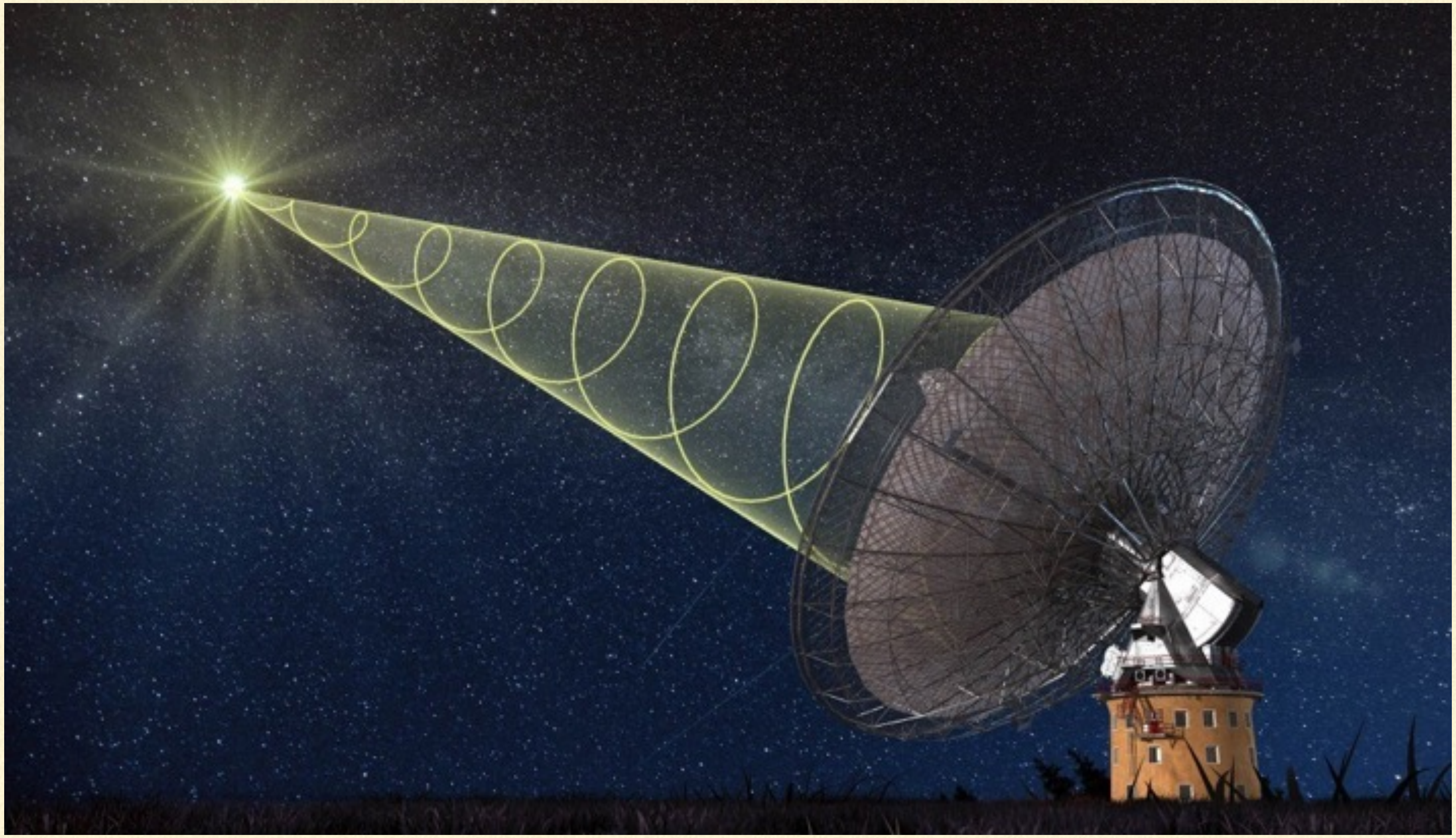
From SUPERB:
FRB160102
highest DM = 2593 pc cm^{-3}
implying a red-shift $z \approx 2$



The first two FRBs
observed with a
transit telescope:
localised in
at least one coord

... STAY TUNED ...

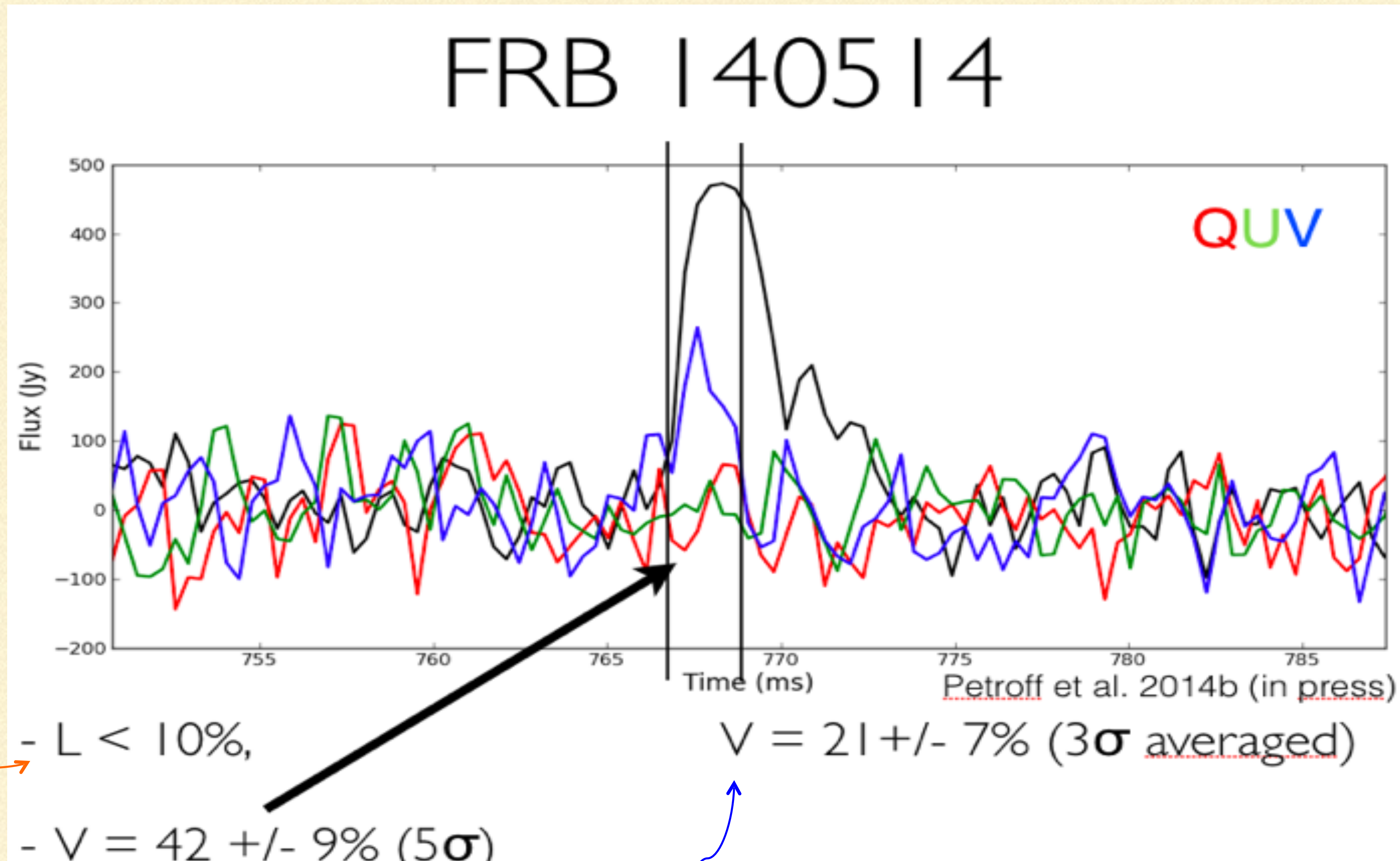
THANKS !



POLARISATION PROPERTIES OF FRBS

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

[Petroff et al 2015a]



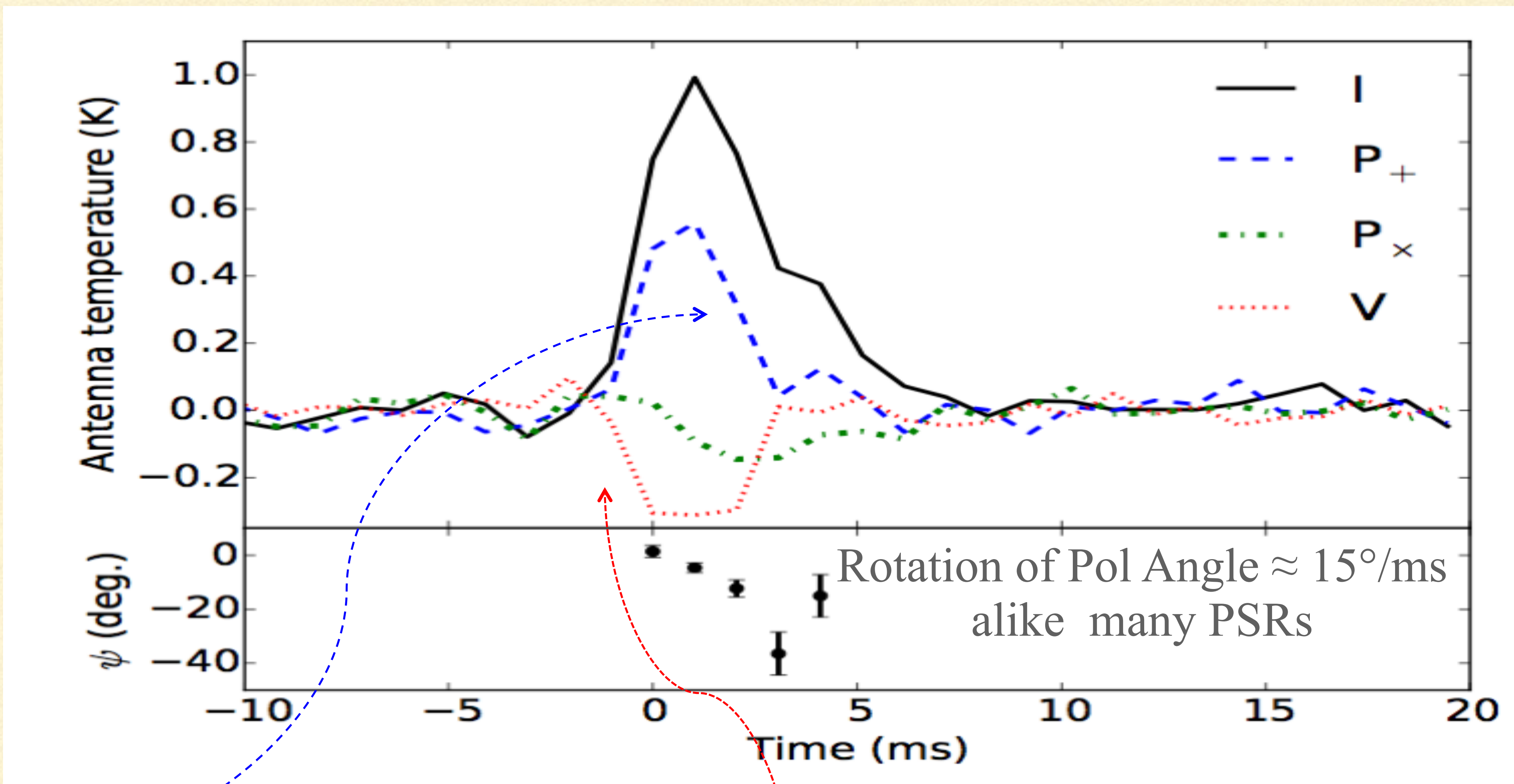
Linear Pol

V = Circular Pol

Polarisation properties of FRBs

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

[Masui et al. 2016]



Linear Pol ≈ 40%

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

Implications of the polarisation in FRB110523

Ionised gas in a magnetised 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: $\Delta\psi_{Far} = \int_0^d (k_R - k_L)dl = \frac{e^3}{\pi m_e^2 c^2 \nu^2} \int_0^d n_e B_{||} dl$

Rotation Measure: $\Delta\psi_{PPA} = \mathrm{RM}\ \lambda^2$

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

with $\Delta\psi_{PPA} = ½\ \Delta\psi_{Far}$

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

For FRB 110523:

RM = -186.1±1.4 rad/m2 [MW contributes ≈ 18±13 rad/m2, IGM≈ 0±6 rad/m2]

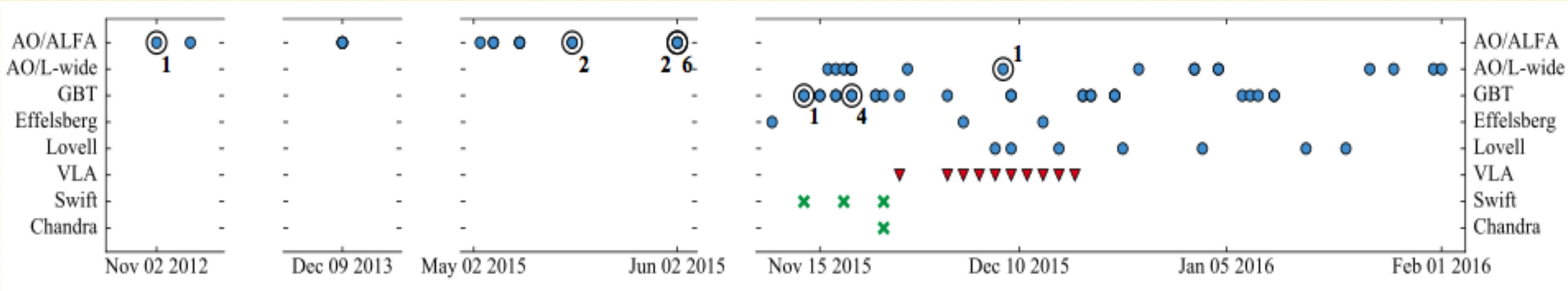
DM = 623.30±0.06 pc/cm3

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

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

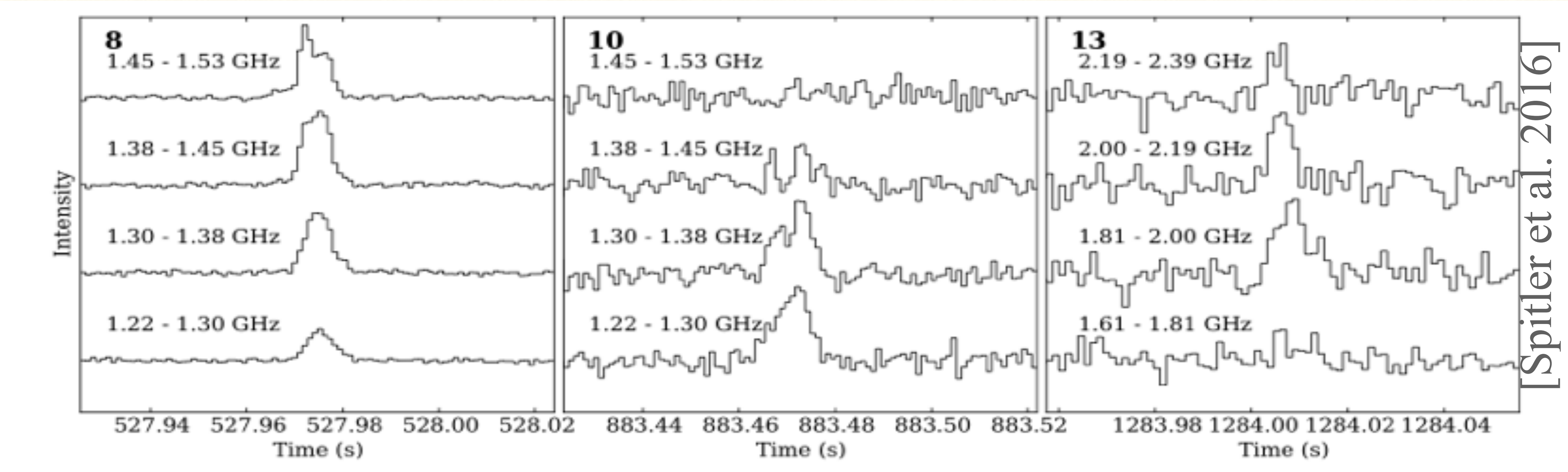
[Masui et al. 2016]

FRB121102 Features



[Scholz et al. 2016]

The bursts seem coming in trains



[Spitler et al. 2016]

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

Sky Distribution

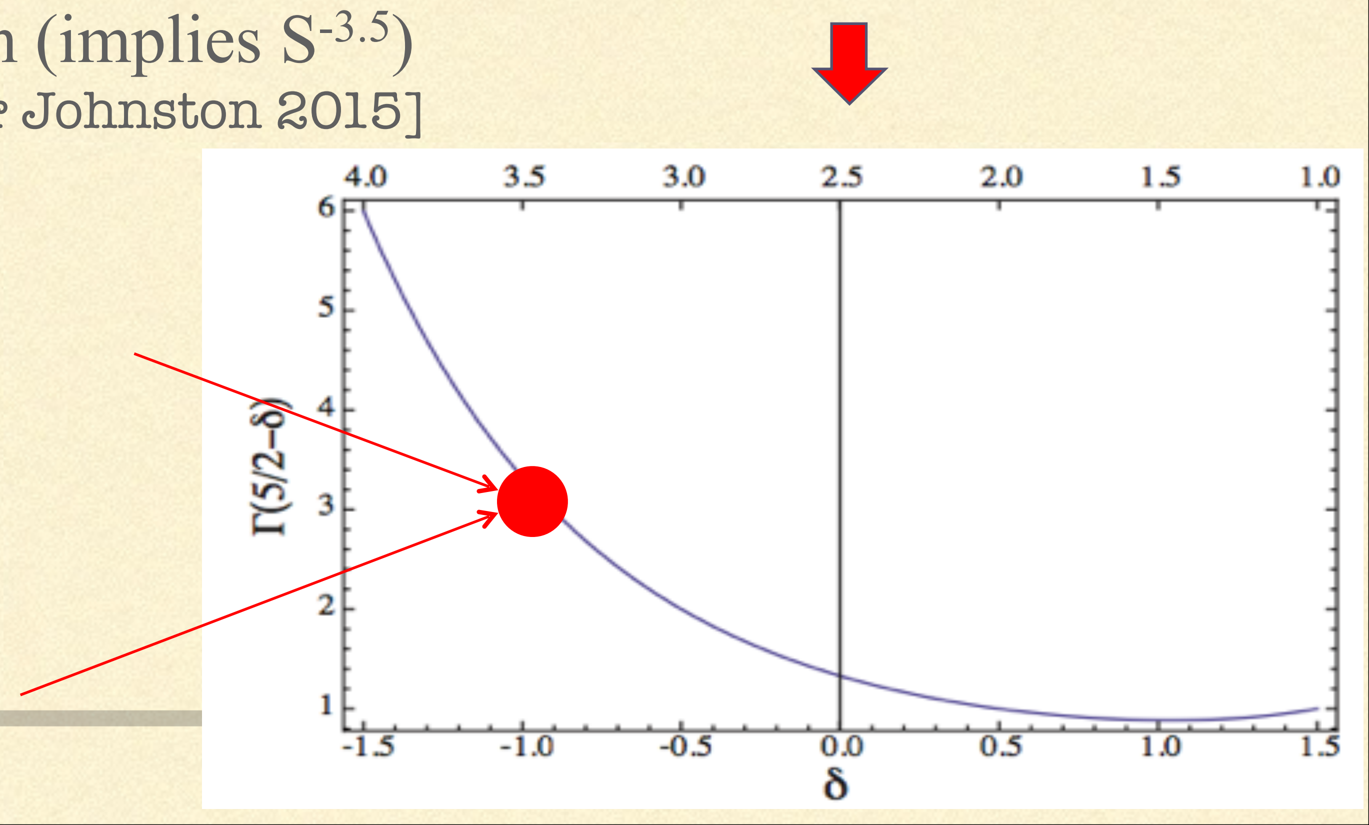
Combining all Parkes surveys,

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

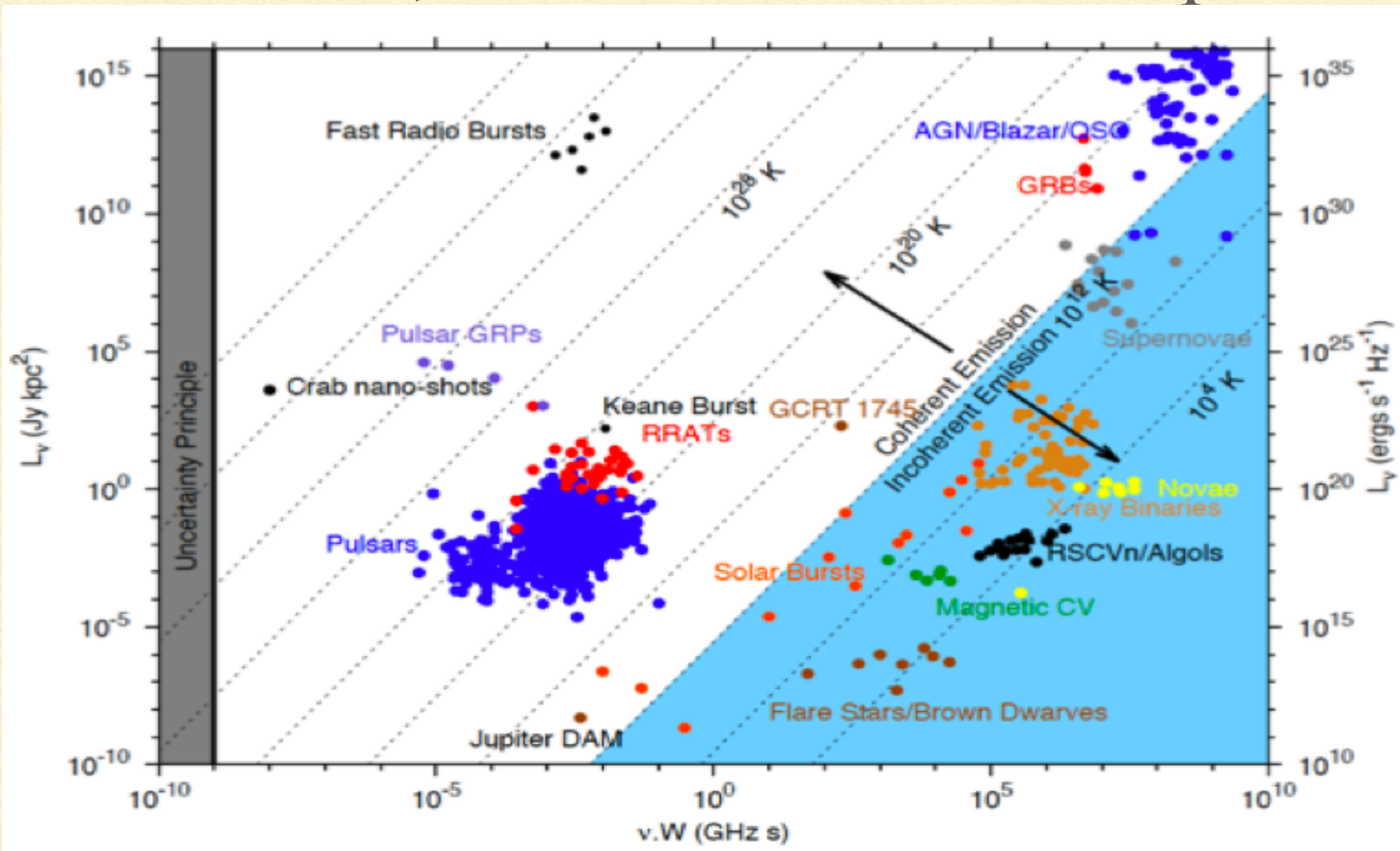
[Petroff et al 2014; Bourke-Spolaor & Bannister 2014; Champion et al 2016; Keane et al 2016 in prep]

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 (implies $S^{-3.5}$)
[Macquart & Johnston 2015]



... whence, coherent emission required



The radio transient “phase space”

[Pietka et al. 2015]

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

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)

TABLE 2
VOLUMETRIC RATES OF SELECTED COSMIC EXPLOSIONS

Class	Type	Φ $\mathrm{Gpc^{-3}\,yr^{-1}}$	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	3×10^3	[4]
SGR	Obs	$< 2.5 \times 10^4$	[5]
Type Ia	Obs	10^5	[6]
Core Collapse	Obs	2×10^5	[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 $10^{49}\,\mathrm{erg\,s^{-1}}$ 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.

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 (ne ≈ 10^{10} cm^{-3}), the ν^{-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 λ 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 λ << observed wavelength (≈ 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 ma such as $ma/2\pi \simeq 1.4$ GHz $[ma/(6 \times 10-6eV)]$. 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 ≈10−11 M⊙ of the axion star

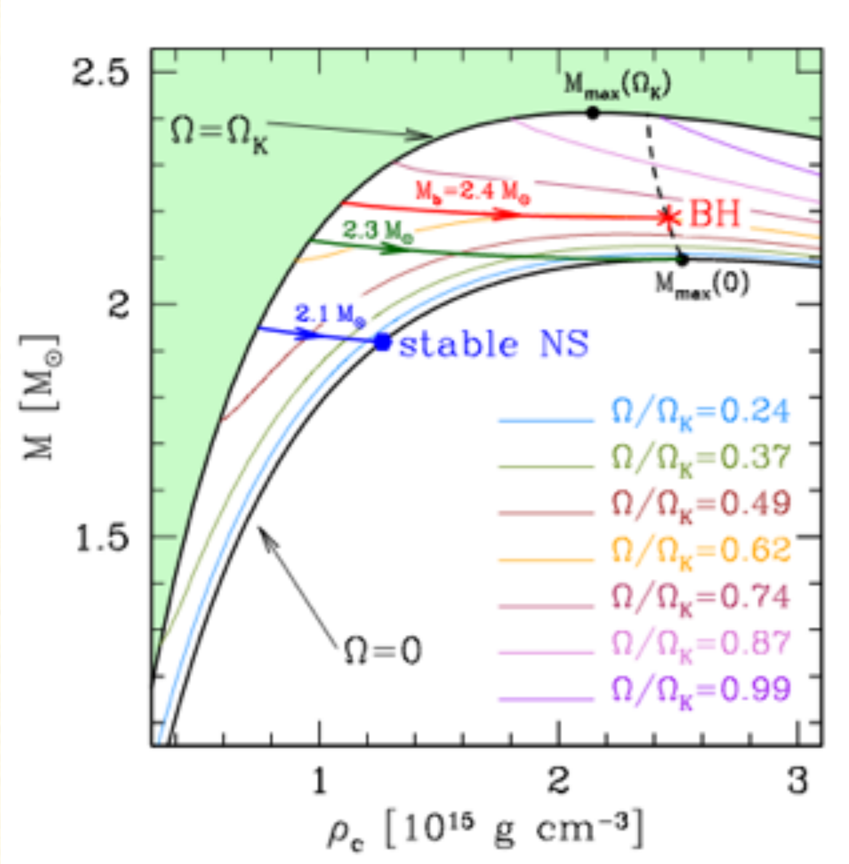
Explosive decay of axion miniclusters [Tkachev 2014] Assuming that in early-Universe scenarios a significant fraction of the mass density of the Universe may be in the form of axion miniclusters of mass ≈ 10−12 M⊙ , FRB can be matched in a explosive model with maser emission mechanism in radio and hence 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 MTOV 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 103-106 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.

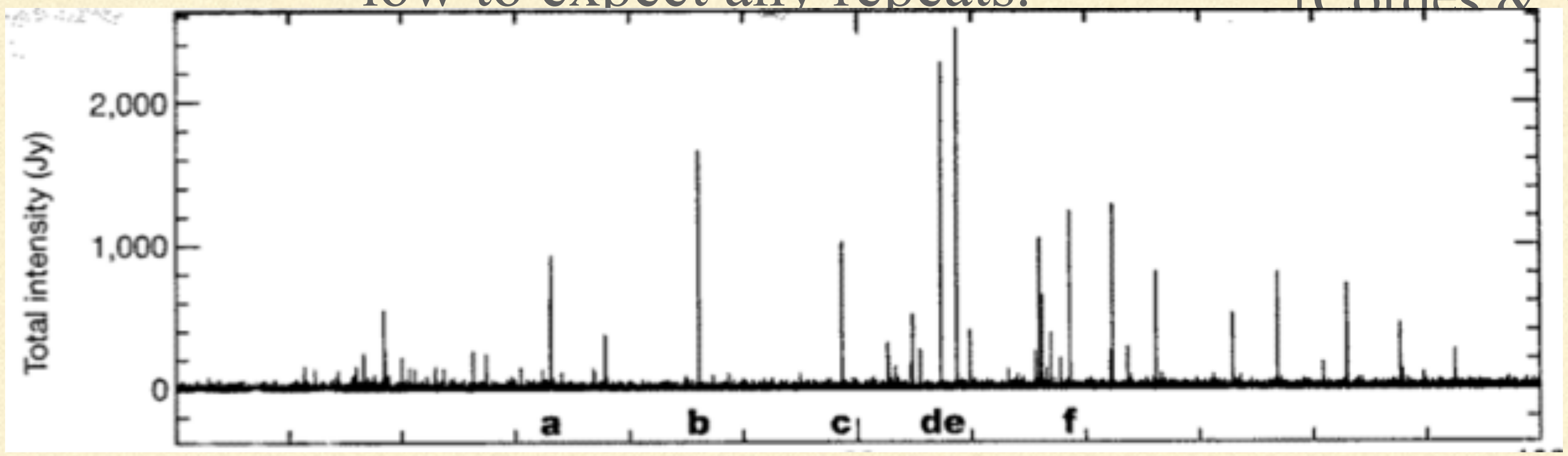
Expected to be repeatable over decade-long timescale

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

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. [Cordes & Wasserman 2016]



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 ≈ 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).

... 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]

$$\mathrm{DM} = n_0 \frac{c}{H_0} \int_0^z \frac{dz(1+z)f_e(z)}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}},$$

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

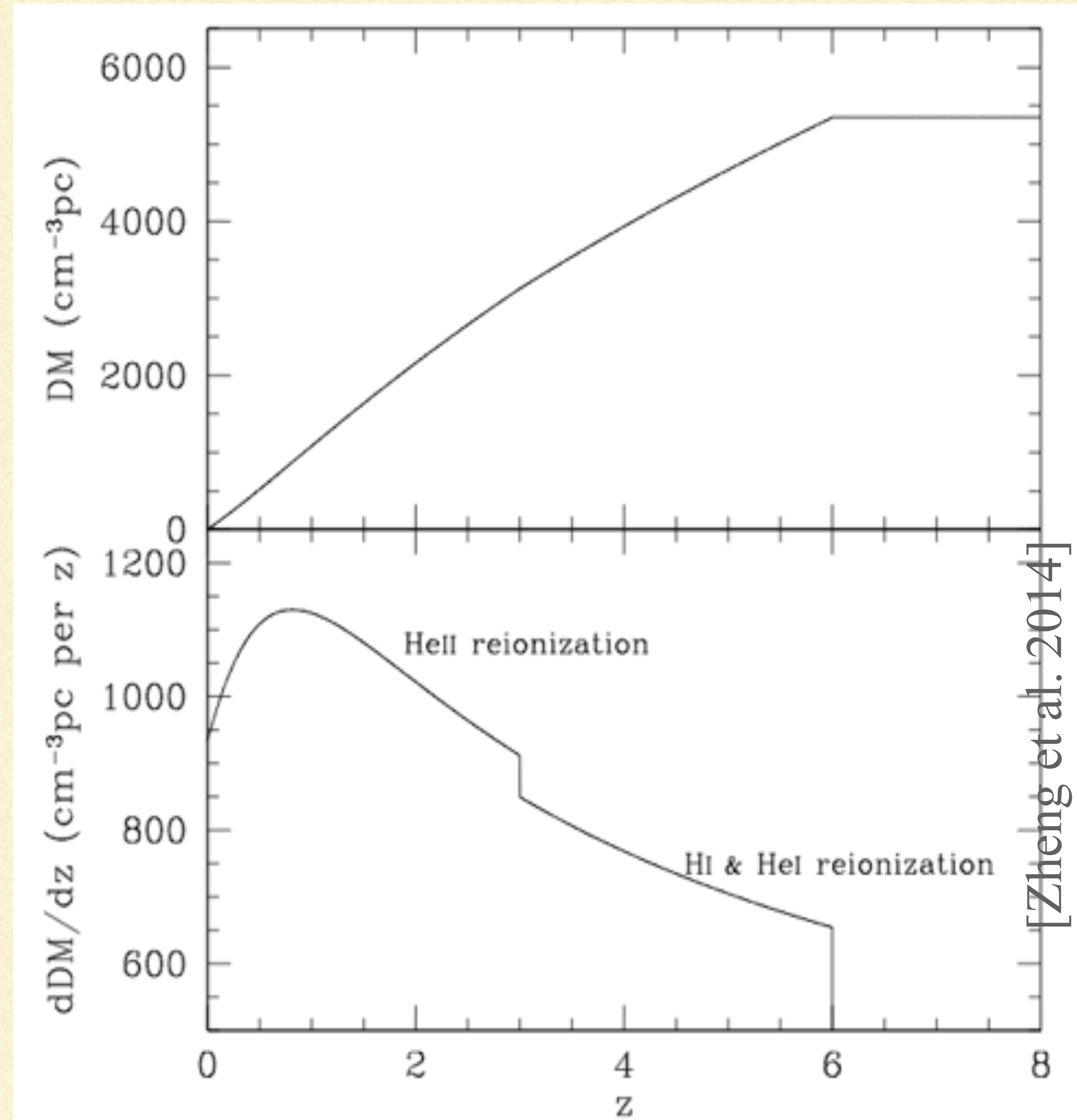
For a constant f_e, the above integral can be approximated as

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

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 ~2% for $z < 5$. At low redshifts, one can use the following approximation,

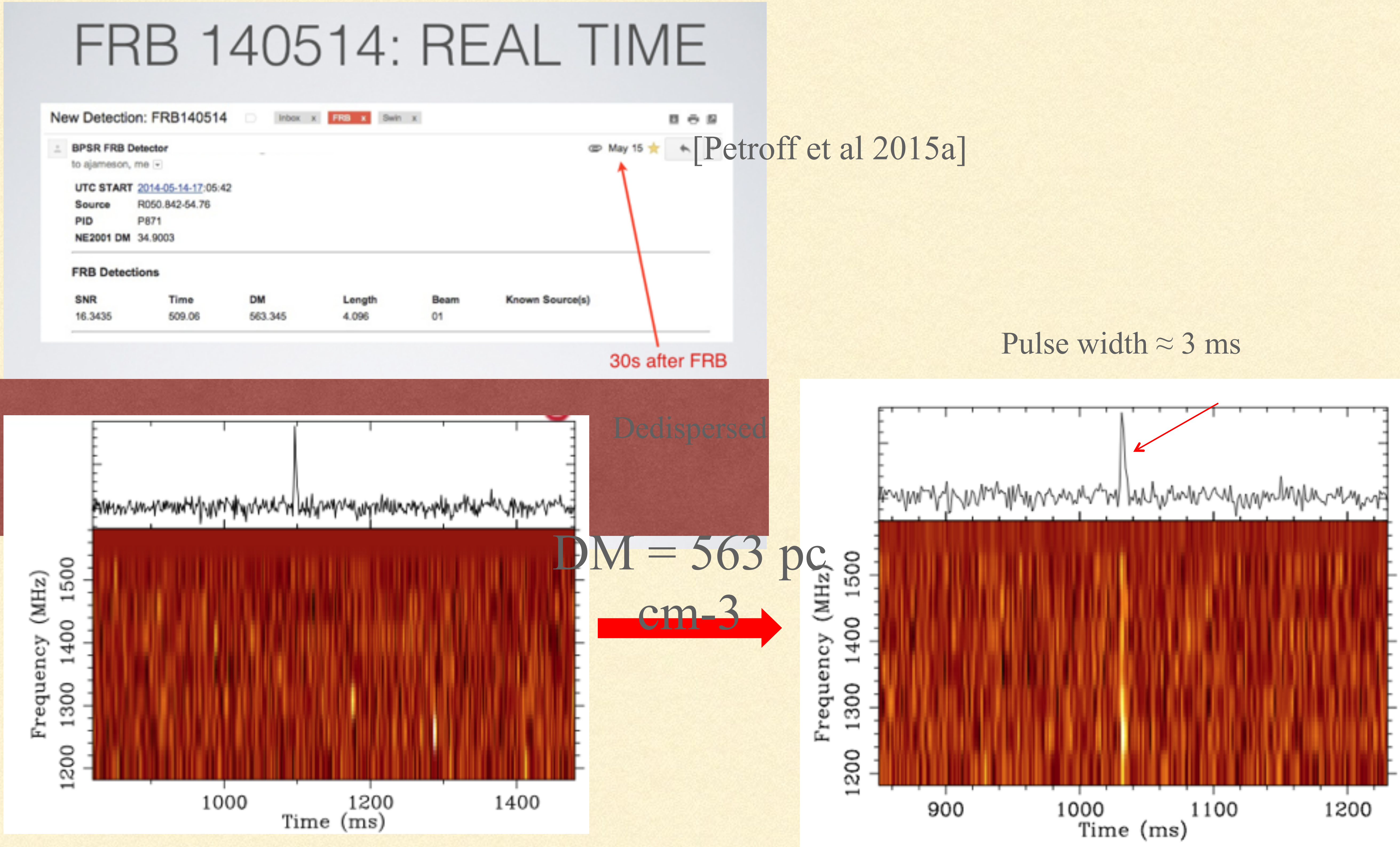
$$\mathrm{DM} \cong 933\ \mathrm{cm}^{-3}\ \mathrm{pc}\left[z + (0.5 - 0.75\Omega_m)z^2\right] \times \left(\frac{f_e}{0.88}\right)\left(\frac{\Omega_b h^2}{0.022}\right)\left(\frac{h}{0.7}\right)^{-1}, \quad (7)$$

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



[Zheng et al. 2014]

The first "real time" FRB: 14 may 2014



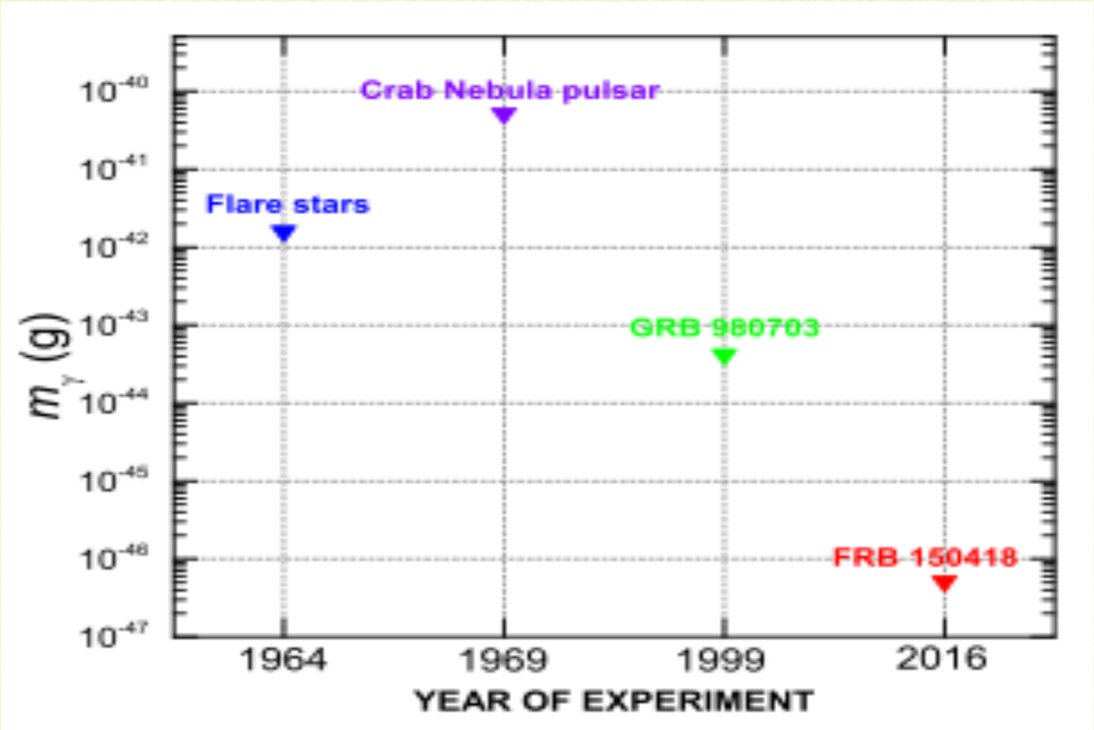
[Petroff et al 2015a]

Pulse width ≈ 3 ms

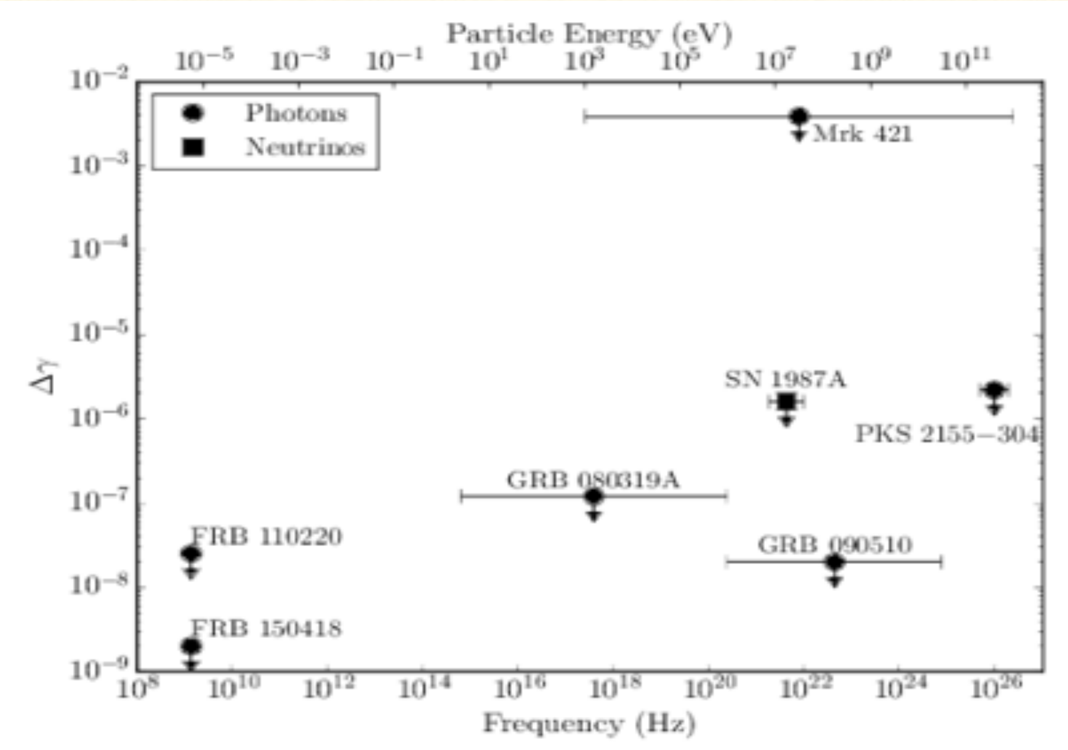
DM = 563 pc cm-3

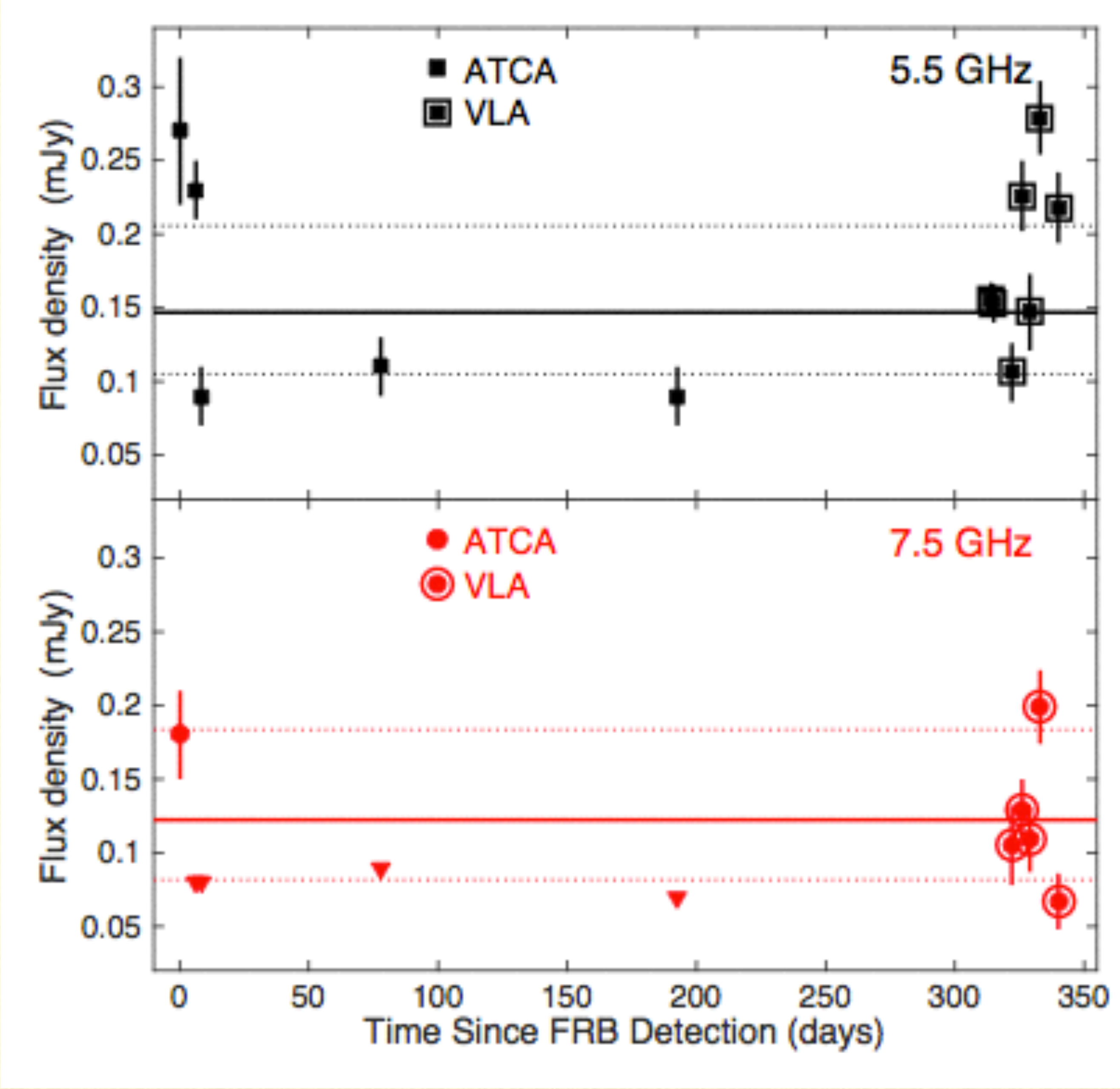
ADDITIONAL INSIGHTS FROM FRB150418

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 γ (=1 for GR)]





ATCA
VLA
5.5 GHz
Flux density (mJy)
0.3
0.25
0.2
0.15
0.1
0.05
ATCA
VLA
7.5 GHz
Flux density (mJy)
0.3
0.25
0.2
0.15
0.1
0.05
0
50
100
150
200
250
300
350
Time Since FRB Detection (days)