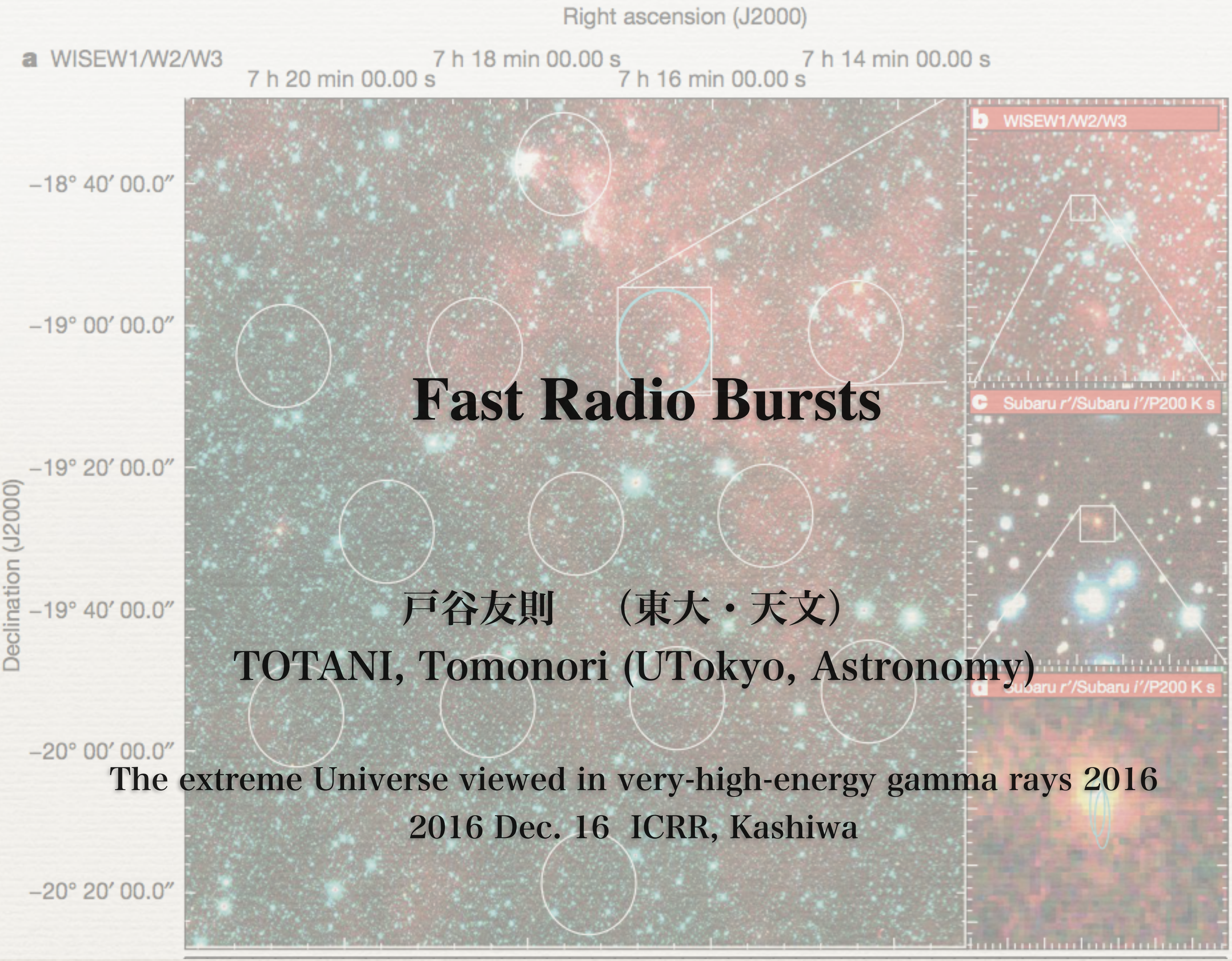


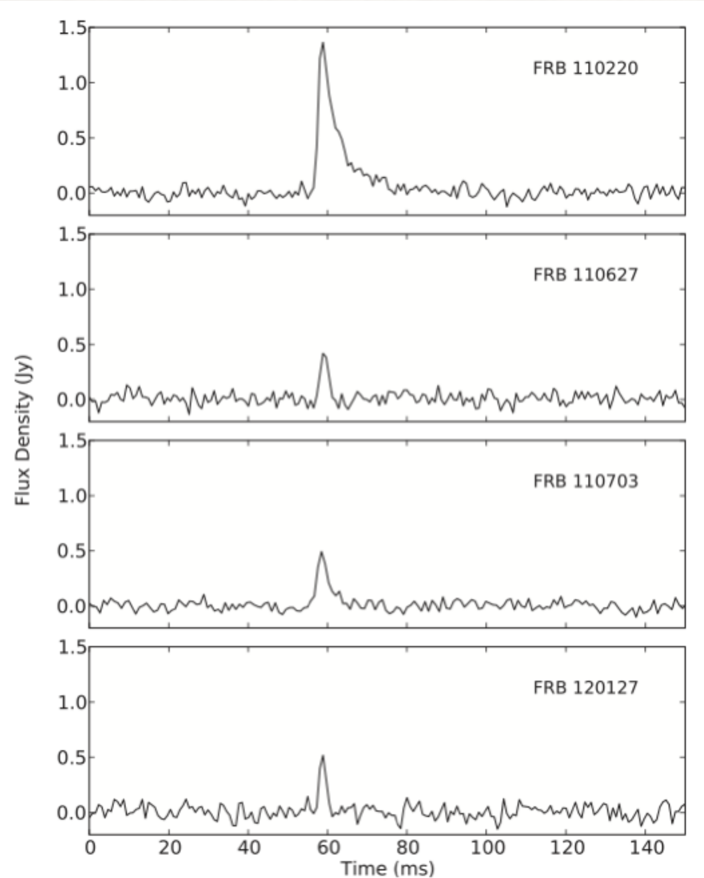
Fast Radio Bursts

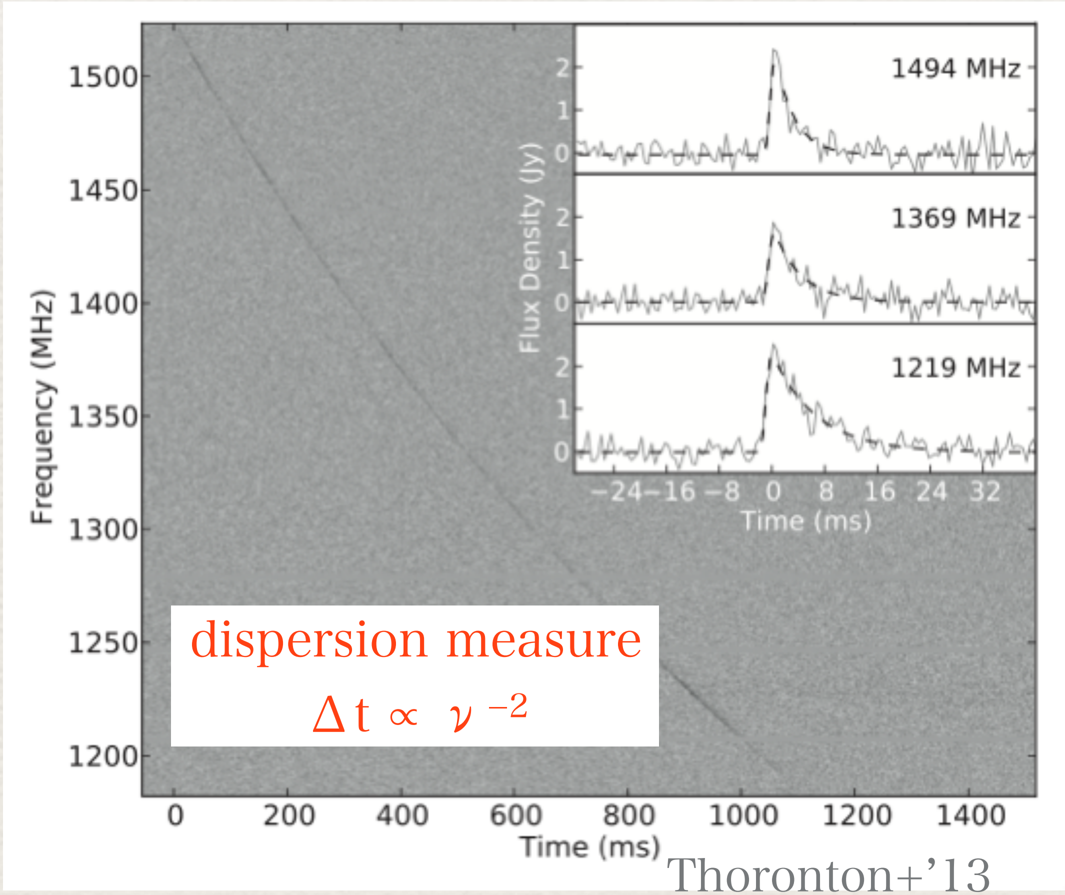
戸谷友則　（東大・天文）
TOTANI, Tomonori (UTokyo, Astronomy)

The extreme Universe viewed in very-high-energy gamma rays 2016
2016 Dec. 16 ICRR, Kashiwa

Fast Radio Bursts: A New Transient Population at Cosmological Distances

- four events discovered by Thornton et al. (2013) at high galactic latitudes
  - the first one event reported by Lorimer et al. (2007)
- ~Jy level flux at GHz frequency
- intrinsic pulse width <~ 1 msec (observed width broadened by scattering)
- event rate ~ $10^{3\text{-}4}$ /sky /day
- dispersion measure (DM) detected

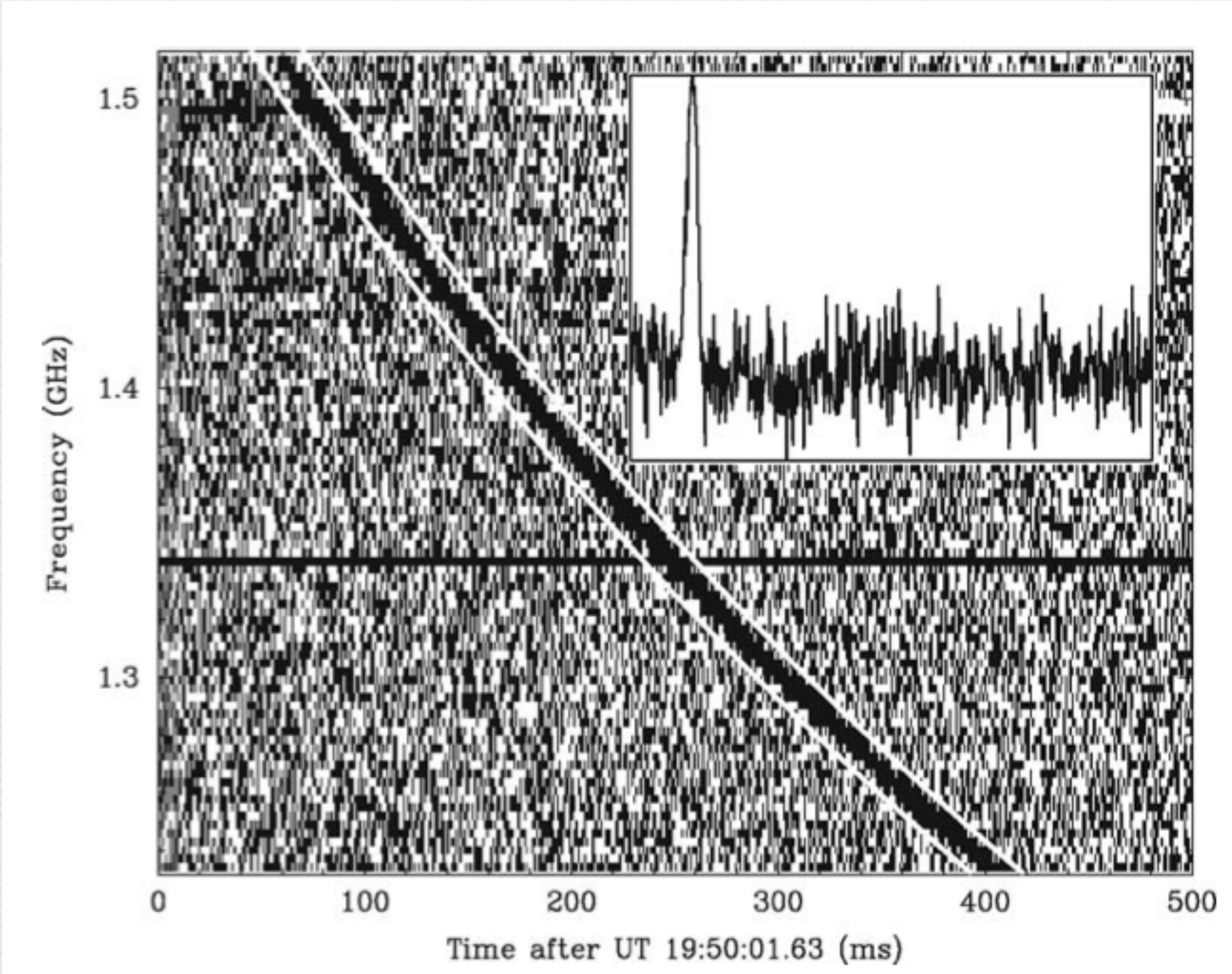




Thoronton+'13

the Lorimer burst

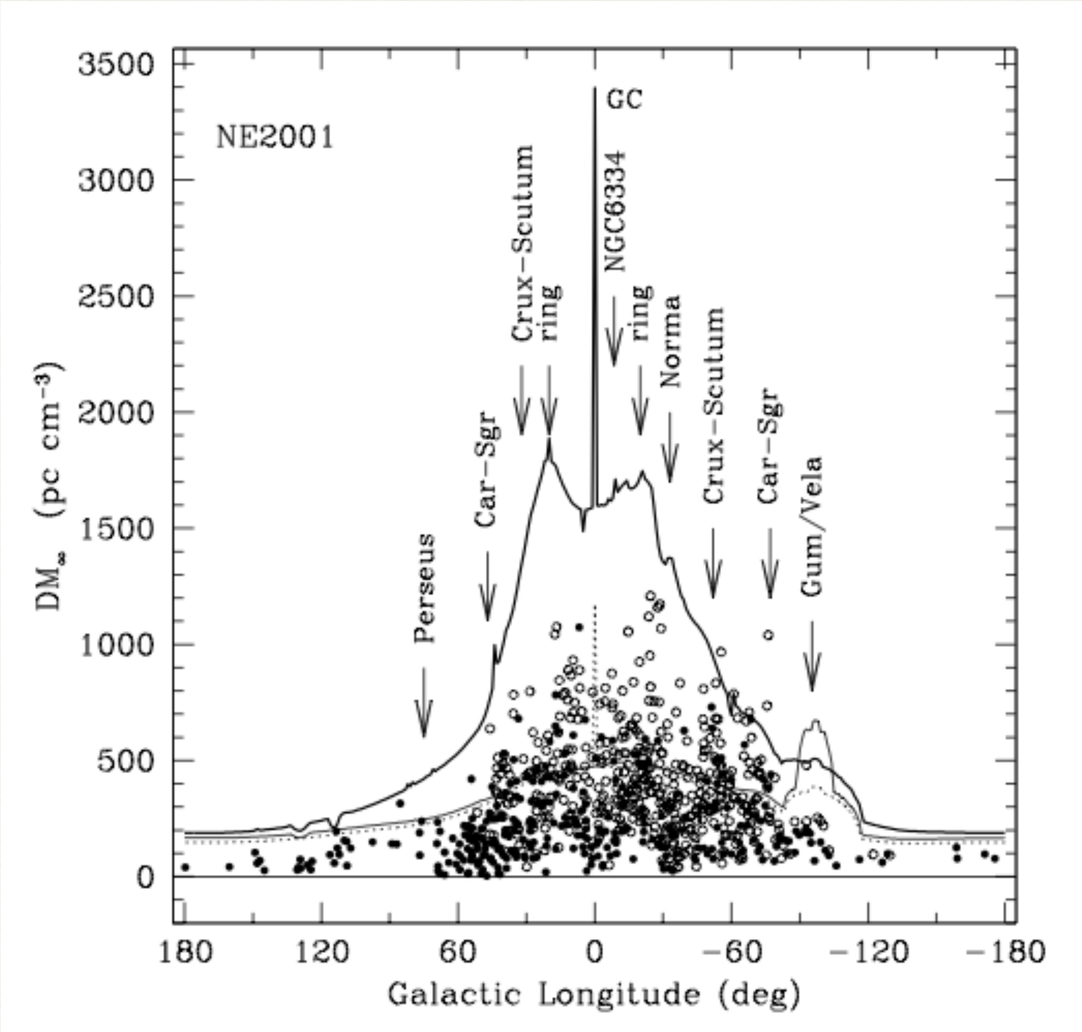
- the first discovery of FRB, detected in 2001
- reported by Lorimer+ ’07
- very bright, z <~ 0.2 (DM_E ~ 350 cm^{-3} pc after MW subtracted)
- “godfather” of FRBs



Godfather of CTA Japan?

large DMs! a cosmological origin?

- FRB's DM = $\int n_e dl$ ~ 500-1000 cm^{-3} pc!
  - too large to explain by DM in the Galaxy



Cordes+ '02
heavy solid: b=0
thin solid: b=5 deg
dotted: b=-5 deg

large DMs! a cosmological origin?

- extragalactic DM in reionized universe
  - DM ~ 1000 cm^{-3} pc at z=1
  - Ioka '03, Inoue '04
- dispersion measure indicates z ~ 0.5-1
- ~ 10^4 /sky /day ~ 4×10^4 yr^{-1} Gpc^{-3} (z < 1, ⟨z⟩ =0.75)

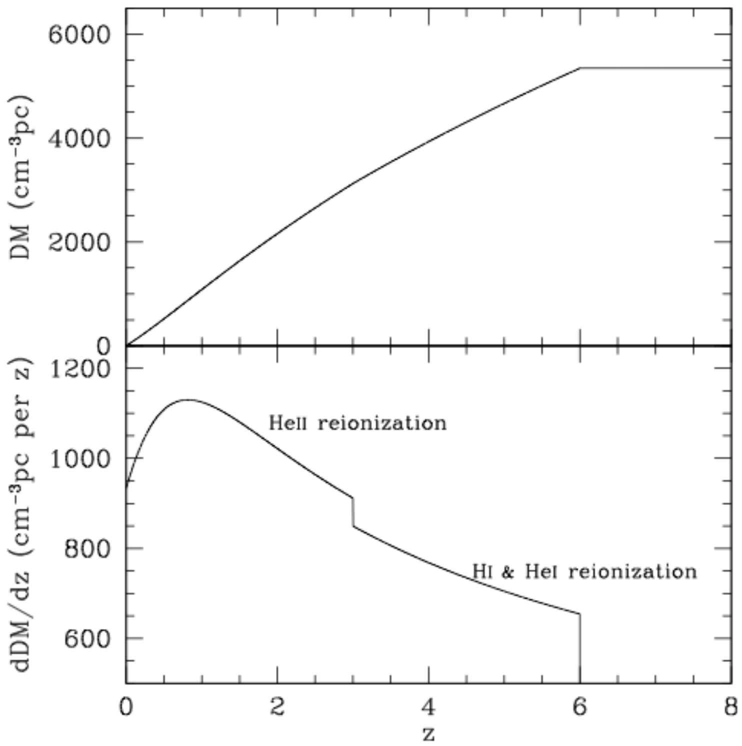
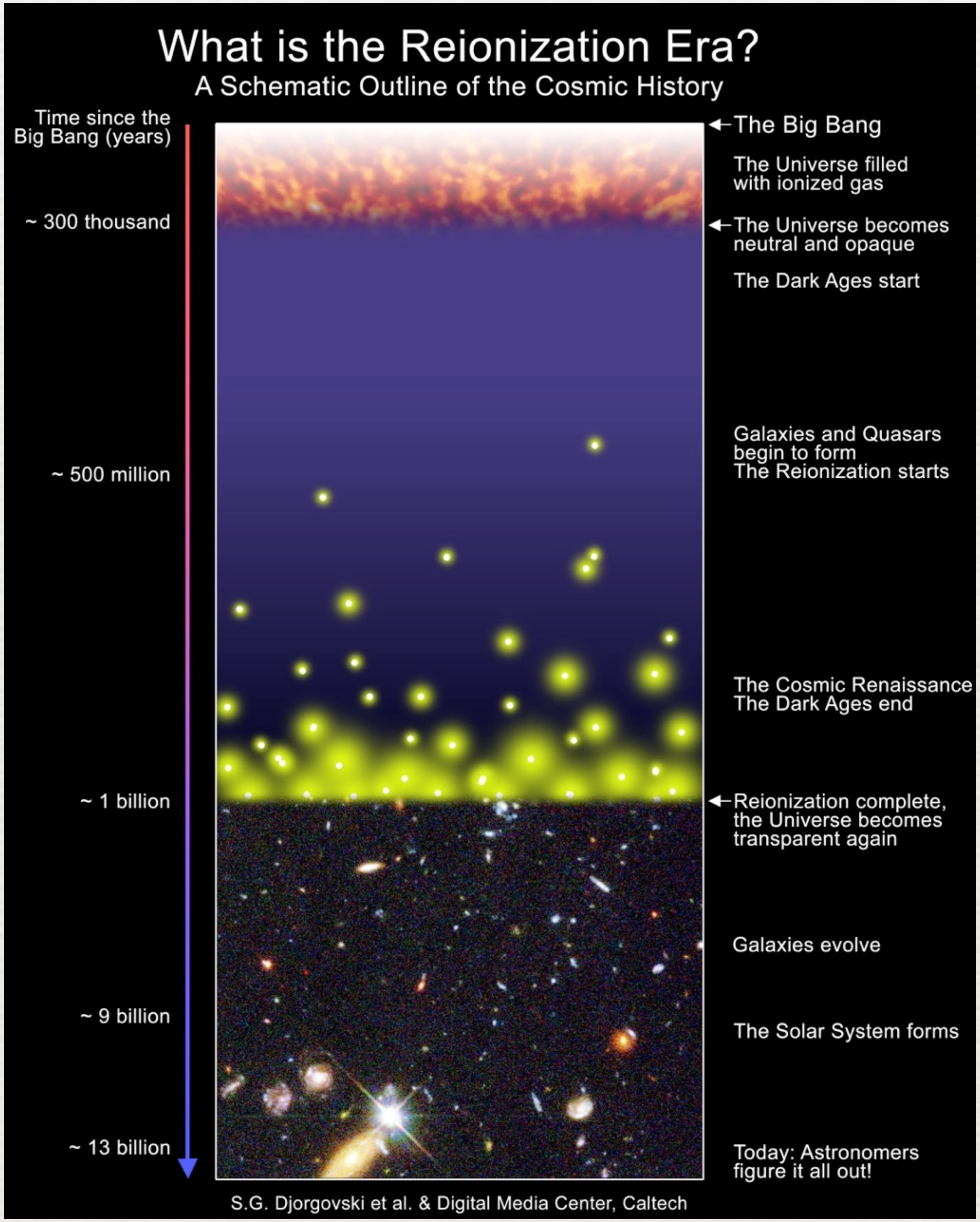


Figure 1. Illustration of using dispersion measure to probe the epoch of reionization of He II. Top and bottom panels show DM and its derivative as a function of redshift, respectively. A sharp H I and He I reionization at $z \sim 6$ and a sharp He II reionization at $z \sim 3$ are assumed.



	FRB 110220	FRB 110627	FRB 110703	FRB 120127
Beam right ascension (J2000)	$22^h\ 34^m$	$21^h\ 03^m$	$23^h\ 30^m$	$23^h\ 15^m$
Beam declination (J2000)	$-12°\ 24'$	$-44°\ 44'$	$-02°\ 52'$	$-18°\ 25'$
Galactic latitude, b (°)	−54.7	−41.7	−59.0	−66.2
Galactic longitude, l (°)	+50.8	+355.8	+81.0	+49.2
UTC (dd/mm/yyyy hh:mm:ss.sss)	20/02/2011 01:55:48.957	27/06/2011 21:33:17.474	03/07/2011 18:59:40.591	27/01/2012 08:11:21.723
DM (cm^{-3} pc)	944.38 ± 0.05	723.0 ± 0.3	1103.6 ± 0.7	553.3 ± 0.3
DM_E (cm^{-3} pc)	910	677	1072	521
Redshift, z (DM_{Host} = 100 cm^{-3} pc)	0.81	0.61	0.96	0.45
Co-moving distance, D (Gpc) at z	2.8	2.2	3.2	1.7
Dispersion index, α	-2.003 ± 0.006	–	-2.000 ± 0.006	–
Scattering index, β	-4.0 ± 0.4	–	–	–
Observed width at 1.3 GHz, W (ms)	5.6 ± 0.1	<1.4	<4.3	<1.1
SNR	49	11	16	11
Minimum peak flux density S_ν(Jy)	1.3	0.4	0.5	0.5
Fluence at 1.3 GHz, F (Jy ms)	8.0	0.7	1.8	0.6
$S_\nu D^2$ ($\times 10^{12}$ Jy kpc^2)	10.2	1.9	5.1	1.4
Energy released, E (J)	$\sim 10^{33}$	$\sim 10^{31}$	$\sim 10^{32}$	$\sim 10^{31}$

Proposed Scenarios for FRBs

- magneter/SGR giant flares (Popov+'07; Thornton+'13)
- delayed collapse of hyper massive neutron stars (Falcke+'13)
- binary neutron star merger (Totani+'13)
- binary white dwarf merger (Kashiyama, Ioka+'13)
- flares of nearby stars (Loeb+'13)
- giant pulse from young pulsars (Connor+'16, Lyutikov+'16)
- …

FRBs from NS-NS mergers

TT 2013, PASJ, 65, L12

- FRB rate is consistent with estimates for NS-NS mergers
  - but marginally at the high end of the plausible NS-NS merger rate range
  - FRB radio emission cannot be strongly beamed
  - GW from NS-NS should be detected soon

- predicted radio flux is at the same order with FRBs, if
  - dipole with B ~ 10^{12} G and r ~ 10 km
  - rotation period ~ msec
  - similar (radio luminosity)/(magnetic breaking energy loss) to isolated radio pulsars (~10^{-4})

$$\dot{E} = -6.2 \times 10^{45} \left(\frac{B}{10^{12.5}\,\mathrm{G}}\right)^2 \left(\frac{R}{10\,\mathrm{km}}\right)^6 \times \left(\frac{P}{0.5\,\mathrm{ms}}\right)^{-4} \mathrm{erg\ s^{-1}}\ .$$

$$F_\nu = \frac{1}{\nu_{\mathrm{obs}}} \frac{\epsilon_{\mathrm{r}} |\dot{E}|}{4\pi D_{\mathrm{lum}}^2} = 0.02 \left(\frac{\epsilon_{\mathrm{r}}}{10^{-4}}\right) \left(\frac{D_{\mathrm{lum}}}{4.6\,\mathrm{Gpc}}\right)^{-2} \times \left(\frac{B}{10^{12.5}\,\mathrm{G}}\right)^2 \left(\frac{R}{10\,\mathrm{km}}\right)^6 \left(\frac{P}{0.5\,\mathrm{ms}}\right)^{-4} \mathrm{Jy}\ .$$

- short duration (msec) is naturally expected

Table 1. Rate statement terminology.

Abbreviation	Rate statement	Physical significance
R_{max}, $\dot{N}_{\mathrm{max}}$ [a]	Upper limit	Rates should be no higher than ...
R_{high}, $\dot{N}_{\mathrm{high}}$	Plausible optimistic estimate	Rates could reasonably be as high as ...
R_{re}, $\dot{N}_{\mathrm{re}}$	Realistic estimate	Rates are likely to be ...
R_{low}, $\dot{N}_{\mathrm{low}}$	Plausible pessimistic estimate	Rates could reasonably be as low as ...

[a] The symbols R_{max}, R_{high}, etc, refer to rates per galaxy; the symbols $\dot{N}_{\mathrm{max}}$, $\dot{N}_{\mathrm{high}}$, etc, refer to detection rates.

Table 2. Compact binary coalescence rates per Milky Way Equivalent Galaxy per Myr.

Source	R_{low}	R_{re}	R_{high}	R_{max}
NS–NS (MWEG^{-1} Myr^{-1})	1 [1] [a]	100 [1] [b]	1000 [1] [c]	4000 [16] [d]
NS–BH (MWEG^{-1} Myr^{-1})	0.05 [18] [e]	3 [18] [f]	100 [18] [g]	
BH–BH (MWEG^{-1} Myr^{-1})	0.01 [14] [h]	0.4 [14] [i]	30 [14] [j]	
IMRI into IMBH (GC^{-1} Gyr^{-1})			3 [19] [k]	20 [19] [l]
IMBH-IMBH (GC^{-1} Gyr^{-1})			0.007 [20] [m]	0.07 [20] [n]

Table 4. Compact binary coalescence rates per Mpc^3 per Myr[a].

Source	R_{low}	R_{re}	R_{high}	R_{max}
NS–NS (Mpc^{-3} Myr^{-1})	0.01 [1]	1 [1]	10 [1]	50 [16]
NS–BH (Mpc^{-3} Myr^{-1})	6×10^{-4} [18]	0.03 [18]	1 [18]	
BH–BH (Mpc^{-3} Myr^{-1})	1×10^{-4} [14]	0.005 [14]	0.3 [14]	

Abadie+'10

FRB event rate vs others

- Hassal+'13

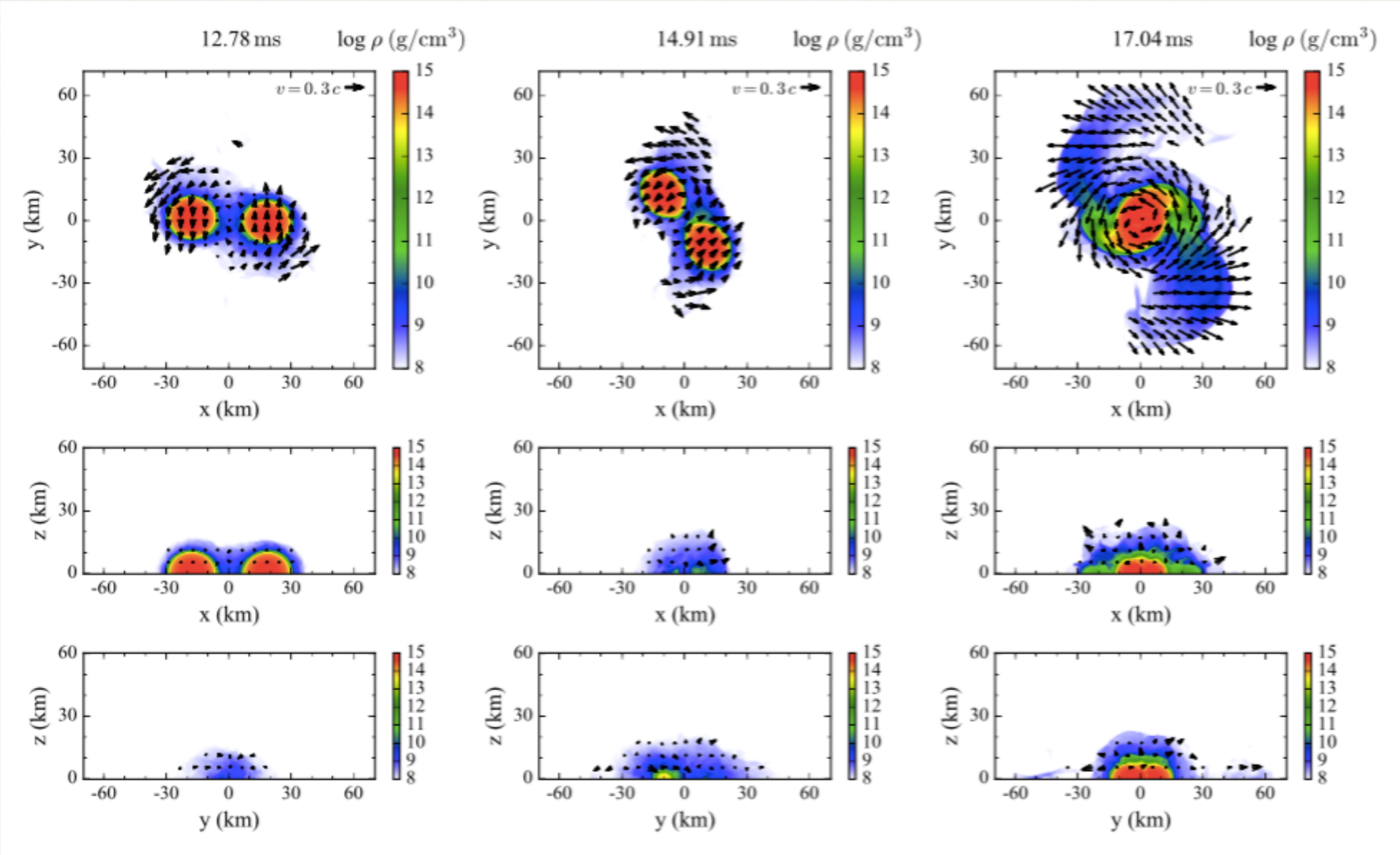
Table 2. Comparison of transient rates.

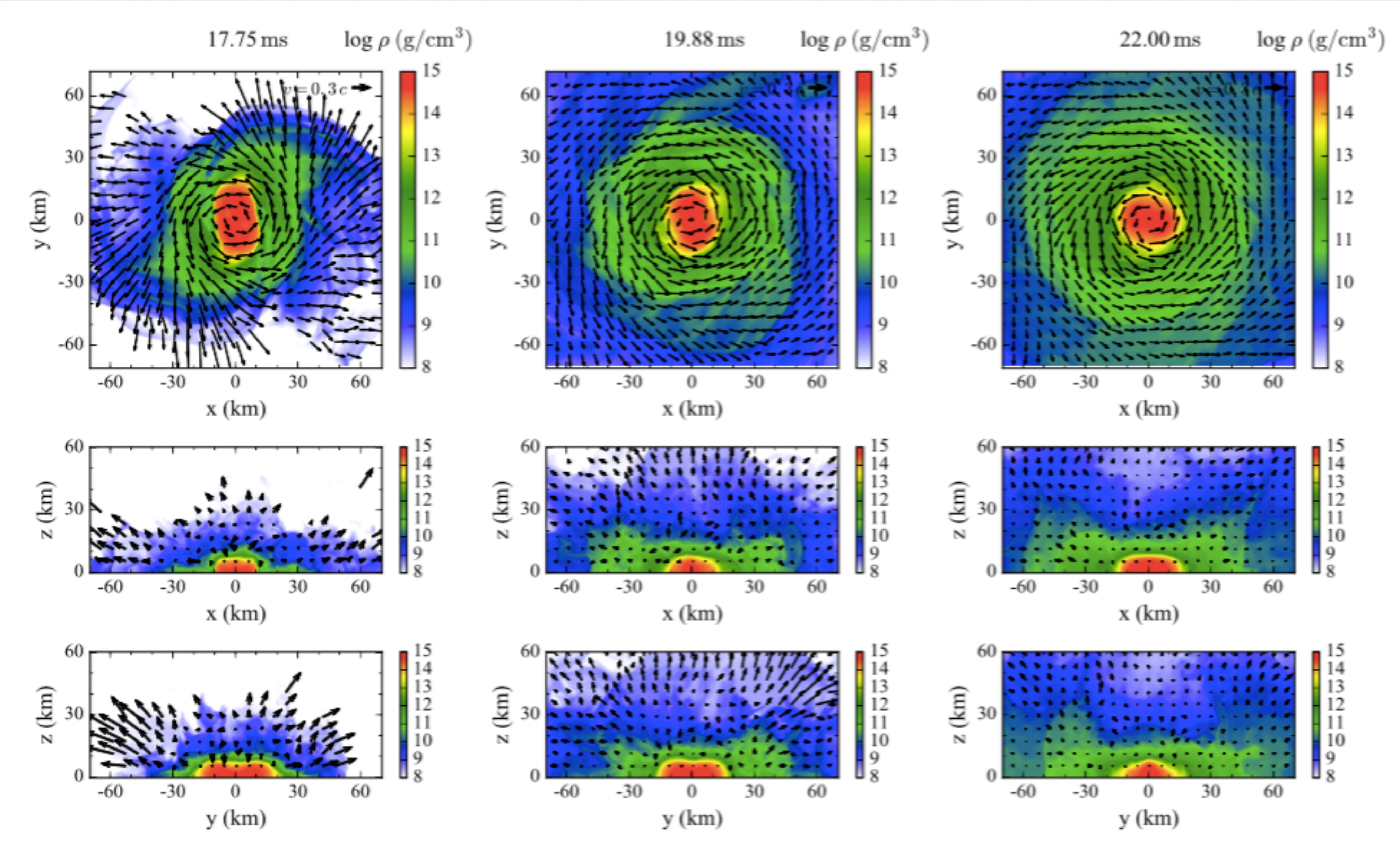
Object	Rate[a] (Gpc^{-3} d^{-1})	Reference
FRBs (high scattering)	51^{+31}_{-14}	This work
FRBs (no scattering)	$5.3^{+3.1}_{-1.4}$	This work
Short GRBs	~0.3–3	Fong et al. (2012)
NS mergers	~0.3–30	Abadie et al. (2010)
CC supernovae	~200–2000	Li et al. (2011)

[a]The rates given here are 'local' ($z < 1$), but the true rates depend on redshift. They should be treated as order of magnitude estimates.

NS-NS merger ejecta and radio emission

- $10^{-3} \sim 10^{-2}\ M_\odot$ ejecta are expected from merger
- no radio emission if they are absorbed by thick ejecta?

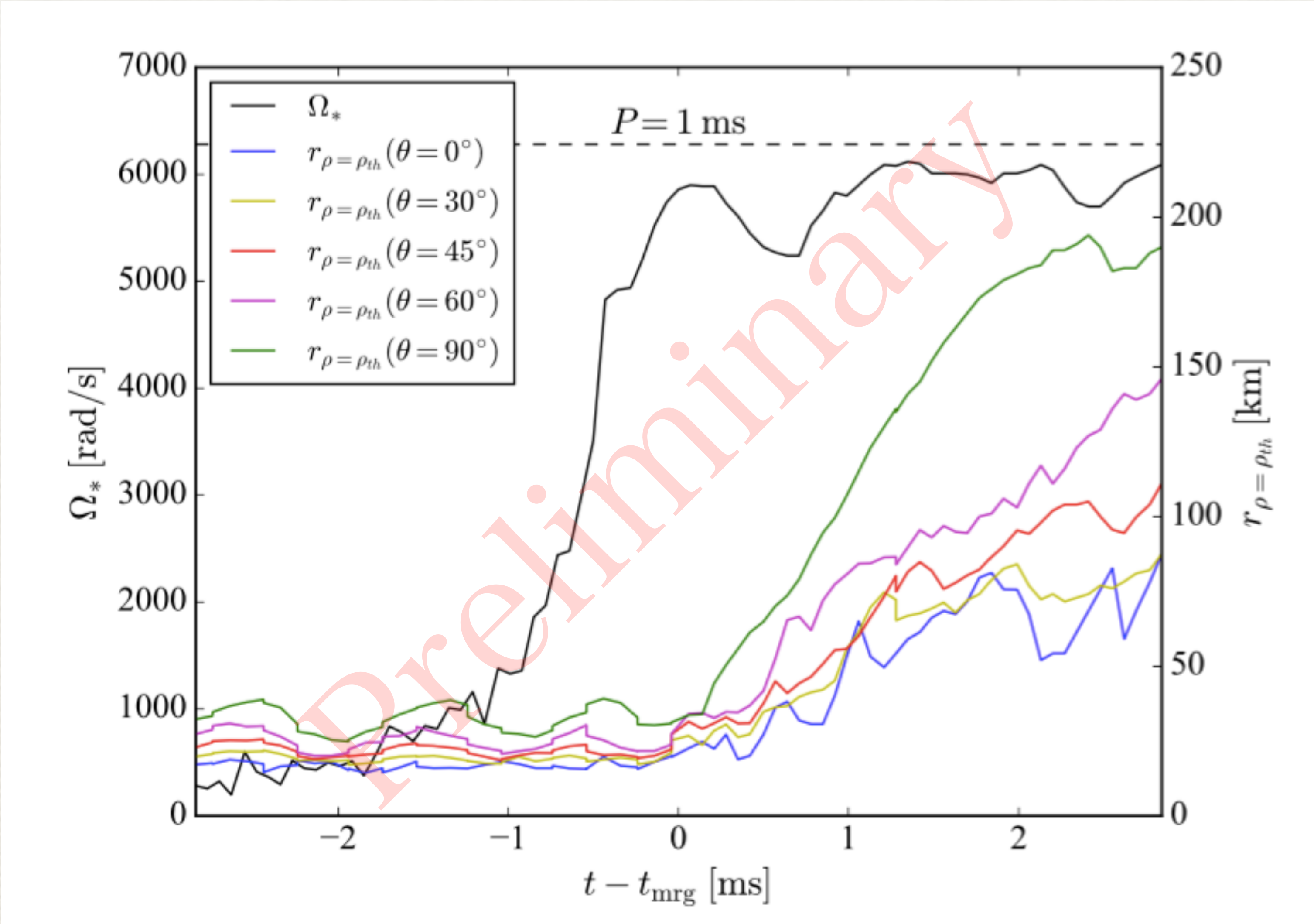




17.75 ms
19.88 ms
22.00 ms
log ρ (g/cm^3)
$v = 0.3c$
x (km)
y (km)
z (km)

magnetic dipole radiation vs. ejecta formation

- work in progress (S. Yamasaki, TT, K. Kiuchi, M. Shibata)



FRB 150418: identification of host galaxy and redshift measurement

Keane+'16, Nature, 530, 453

LETTER

doi:10.1038/nature17140

The host galaxy of a fast radio burst

E. F. Keane[1,2,3], S. Johnston[4], S. Bhandari[2,3], E. Barr[2], N. D. R. Bhat[3,5], M. Burgay[6], M. Caleb[2,3,7], C. Flynn[2,3], A. Jameson[2,3], M. Kramer[8,9], E. Petroff[2,3,4], A. Possenti[6], W. van Straten[2], M. Bailes[2,3], S. Burke-Spolaor[10], R. P. Eatough[8], B. W. Stappers[9], T. Totani[11], M. Honma[12,13], H. Furusawa[12], T. Hattori[14], T. Morokuma[15,16], Y. Niino[12], H. Sugai[16], T. Terai[14], N. Tominaga[16,17], S. Yamasaki[11], N. Yasuda[16], R. Allen[2], J. Cooke[2,3], J. Jencson[18], M. M. Kasliwal[18], D. L. Kaplan[19], S. J. Tingay[3,5], A. Williams[5], R. Wayth[3,5], P. Chandra[20], D. Perrodin[6], M. Berezina[8], M. Mickaliger[9] & C. Bassa[21]

In recent years, millisecond-duration radio signals originating in distant galaxies appear to have been discovered in the so-called fast radio bursts[1–9]. These signals are dispersed according to a precise physical law and this dispersion is a key observable quantity, which, in tandem with a redshift measurement, can be used for fundamental physical investigations[10,11]. Every fast radio burst has a dispersion measurement, but none before now have had a redshift measurement, because of the difficulty in pinpointing their celestial coordinates. Here we report the discovery of a fast radio burst and the identification of a fading radio transient lasting ∼6 days after the event, which we use to identify the host galaxy; we measure the galaxy's redshift to be $z = 0.492 \pm 0.008$. The dispersion measure and redshift, in combination, provide a direct measurement of the cosmic density of ionized baryons in the intergalactic medium of $\Omega_{IGM} = 4.9 \pm 1.3$ per cent, in agreement with the expectation from the Wilkinson Microwave Anisotropy Probe[12], and including all

Upon detection of FRB 150418 at Parkes, a network of telescopes was triggered across a wide range of wavelengths (see Methods). Beginning two hours after the FRB, observations with the Australia Telescope Compact Array (ATCA) were carried out at 5.5 GHz and 7.5 GHz, identifying two variable compact sources. One of the variable sources is consistent with a GHz-peaked-spectrum source, with a positive spectral index, as previously identified in observations at these frequencies[16]. The other variable source (right ascension, RA 07 h 16 min 34.6 s; declination, dec. −19° 00′ 40″), offset by 1.944 arcmin from the centre of the Parkes beam, was seen at 5.5 GHz at a brightness of 0.27(5) mJy per beam just 2 h after the FRB. The source was then seen to fade over subsequent epochs, settling at a brightness of ∼0.09(2) mJy per beam (Fig. 2). The source is also seen at 7.5 GHz at 0.18(3) mJy per beam in the first epoch but subsequently not detected. These observations indicate a ∼6-day transient with a negative spectral index; we obtain $\alpha = -1.37$ in the first epoch, for a power-law spectrum of the form

FRB 150418: identification of host galaxy and redshift measurement

Keane+'16, Nature, 530, 453

- discovered by SUPERB team using Parkes Telescope
- time: 2015 Apr. 18 04:29UTC
- Galactic coordinate: l = 232 deg, b = −3.2 deg
- Galactic extinction $A_V = 5.1$
- observed DM: 776.2 cm^{-3} pc
  - Milky Way DM: 188.5 cm^{-3} pc
- linear/circular polarization 8.5±1.5% / < 4.5%
  - in contrast to the Green-Bank FRB (Masui+'15)
- alert sent out to world-wide follow-up partners within a few hours
- Parkes beam FWHM diameter 14.1 arcmin

Follow-up by Subaru/S-Cam & ATCA

- Subaru/Suprime-Cam
  - Apr. 19, 20 , ~06:00 UTC (1 & 2 days after FRB)
  - r', i' bands
  - integration time ~1000 s per band
  - no particularly interesting object showing 1 day variability
    - many variable Galactic stars

- ATCA (Australia Telescope Compact Array)
  - starting ~2 hours after FRB
  - 5.5 and 7.5 GHz
  - two variable sources
    - one is showing positive spectral index
      - $F_\nu \propto \nu^{\alpha}$, $\alpha > 0$
      - looks like a compact blazar with synchrotron self absorption
      - not peculiar in past radio surveys
    - another source showing negative index $\alpha = -1.37$
      - such sources hardly show variability

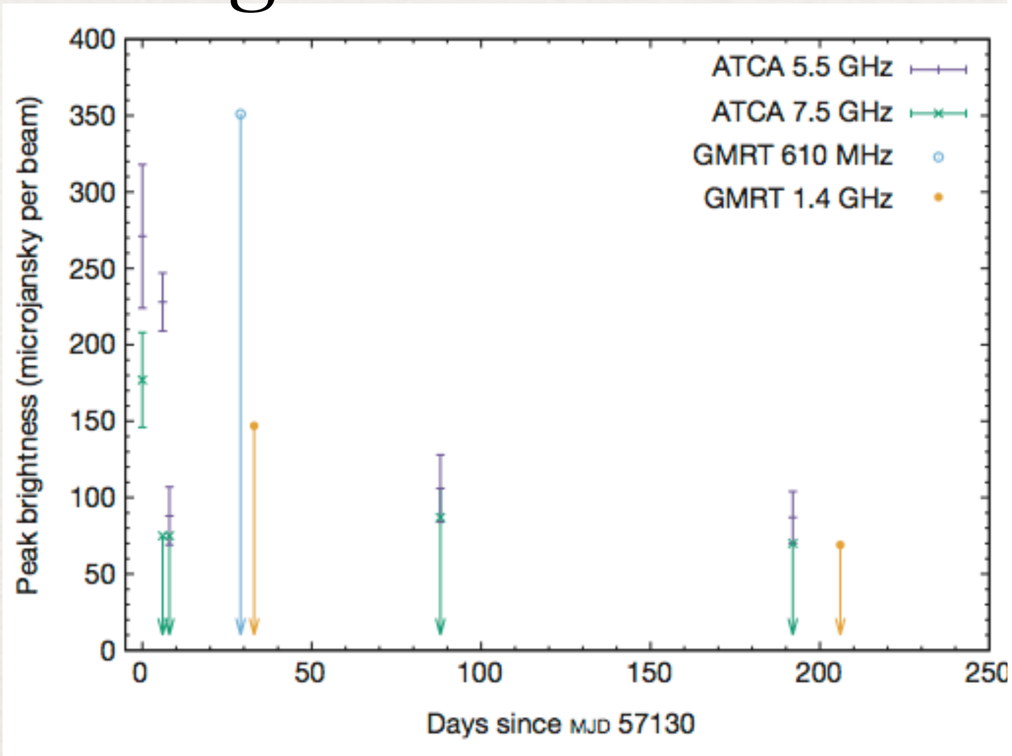
fading radio afterglow

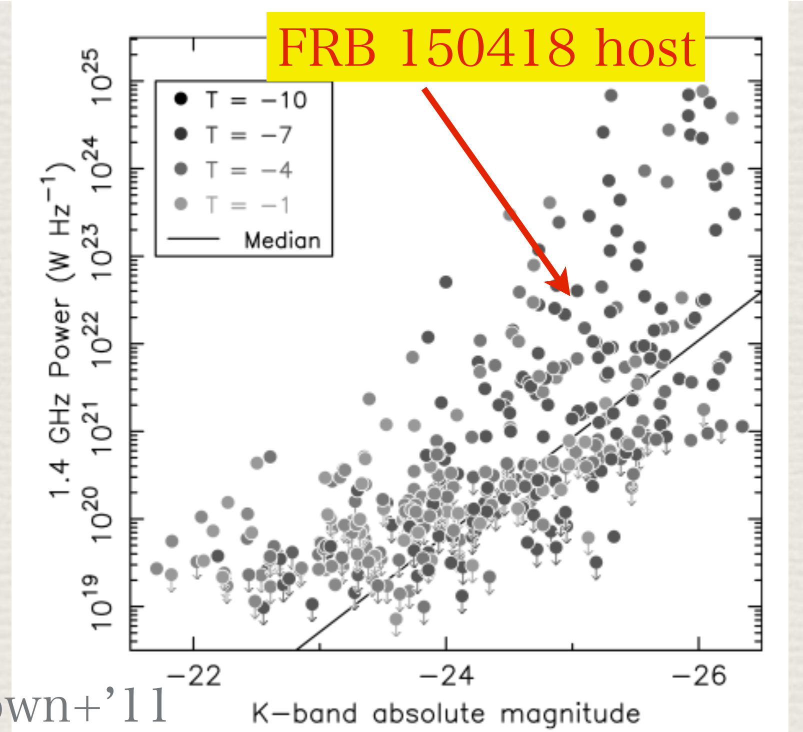
- detectable in 5.5 GHz for 6 days, factor of 3 decline at 8 days from FRB
  - detection in 7.5 GHz only in the first epoch (2 hr from FRB)

- constant flux after that for ~200 days
  - likely to be persistent flux (AGN or SF)
    - typical for this type of galaxy
  - perhaps yr-long afterglow?
    - yr-scale radio afterglow known for GRBs

- chance probability
  - from ATCA data at the same frequency
    - < 6% (past data not so large)
  - VLA survey (Mooley+'16) → 0.1-1%
    - transient, or
    - factor ~3 variability in a week

- this source seems to be associated with the FRB

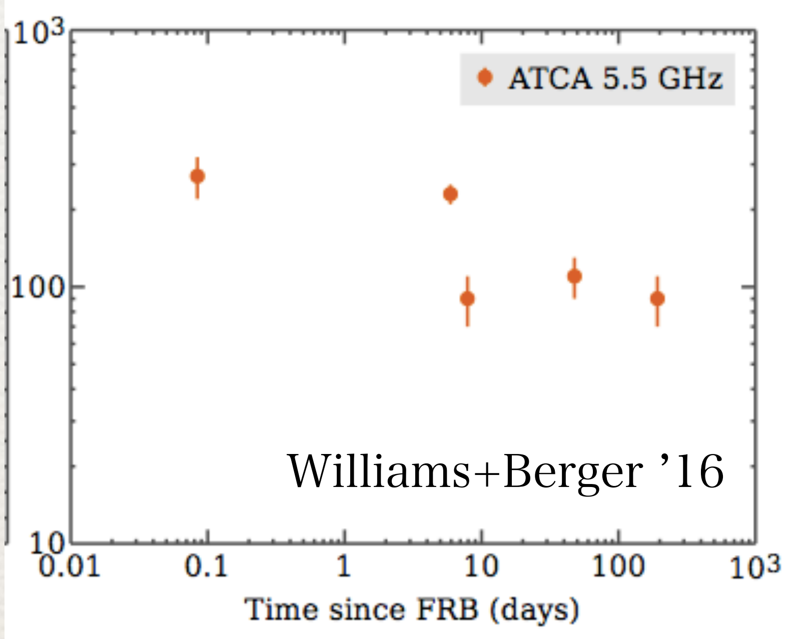


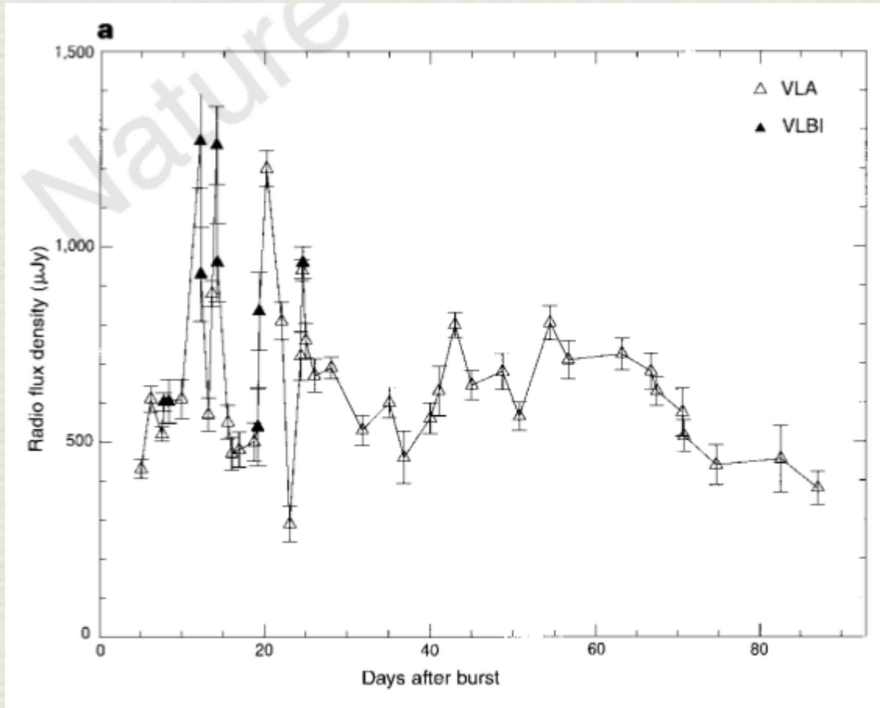


Brown+'11

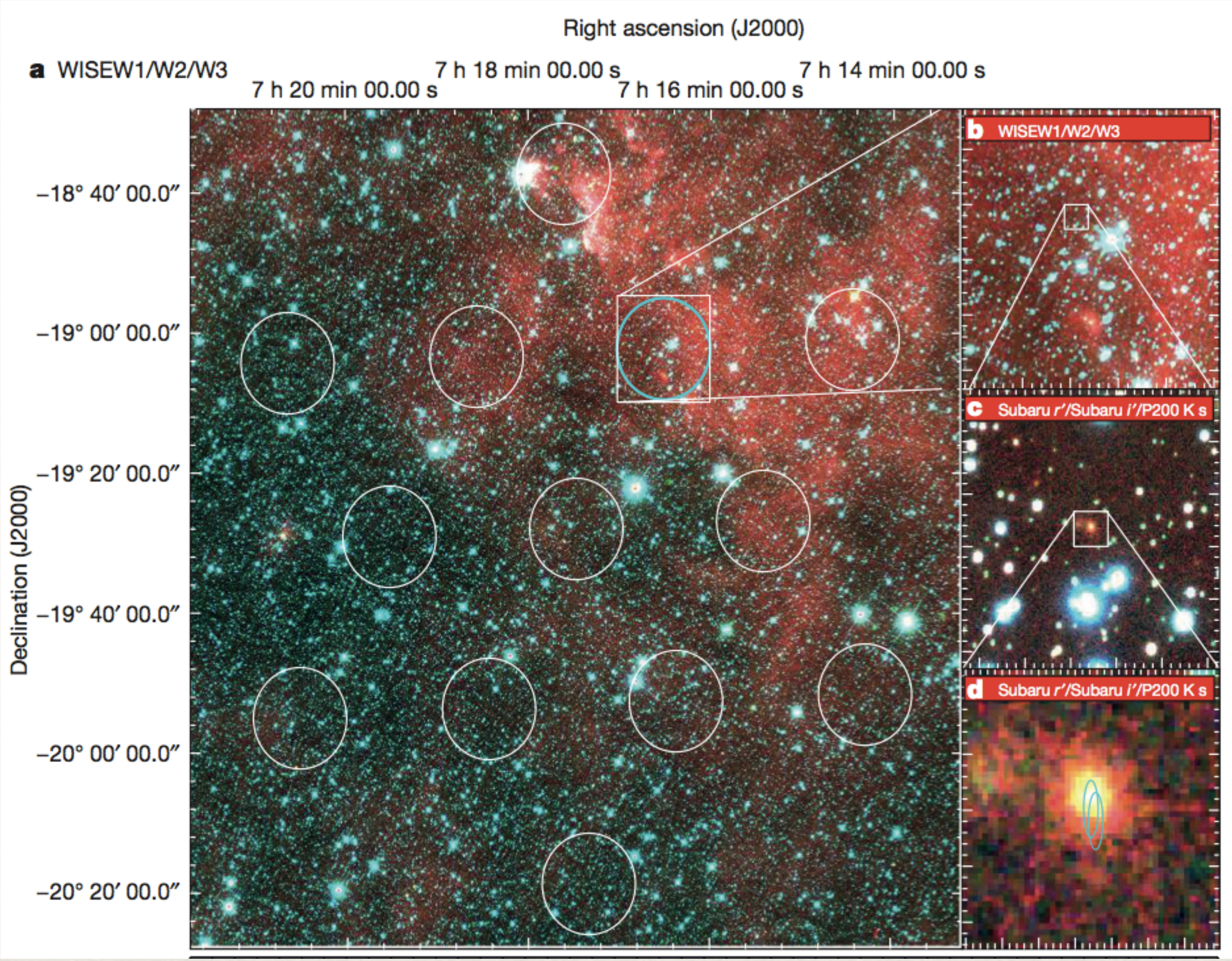
FRB 150418 radio afterglow vs. GRBs

- the observed radio flux is similar to GRB radio afterglows
- factor 3 flux decrease at day 6→8
- spectral index $\alpha = -1.37$
- inconsistent with GRB afterglow model?
- But... look GRB 970508
  - strong variability (factor 3) on day scale!
  - α rapidly changes from -1.15 to $+1.61$!
  - looks similar to this FRB
- interstellar scintillation?
  - "diffractive" regime
  - compact source (10^{17}cm for GRB 970508)
  - this FRB is close to Galactic plane





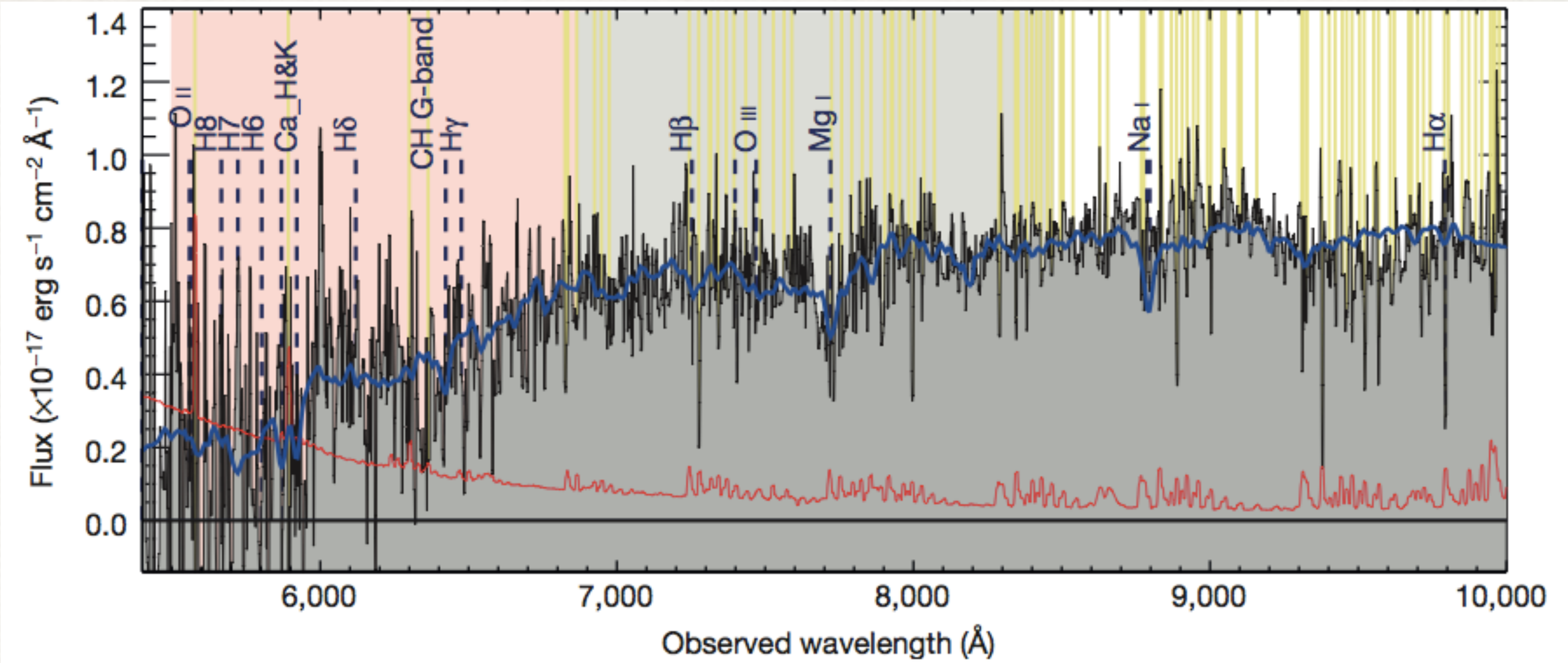
Now check the Subaru Image



- an elliptical galaxy at z~0.5 from morphology and color?

Spectroscopy by Subaru/FOCAS

- good match to an elliptical galaxy template
  - A_V~5 de-reddened to correct Galactic extinction
- z = 0.492±0.008



DM vs. z: implications for missing baryon

- FRB 150418's DM = 776.2 cm^{-3} pc
  - DM (Milky Way) = 189
  - DM (Milky Way halo) = 30
  - a model for elliptical galaxy DM ~ 37
  - DM_{IGM} ~ 776 - 189 - 30 - 37 = 520
  - uncertainty from IGM inhomogeneity ~ 100

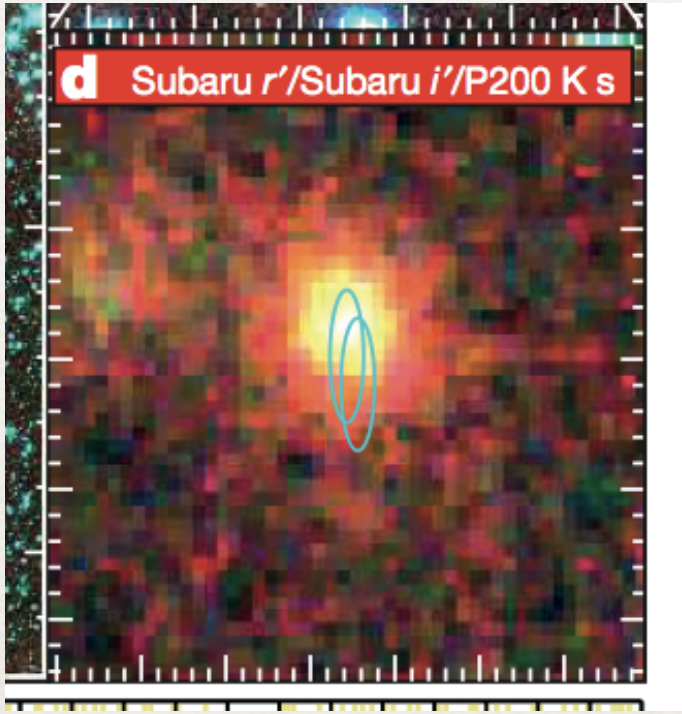
- z = 0.492 to FRB 150418, and from $DM_{IGM} \rightarrow$
  - $\Omega_{IGM} = 0.049 \pm 0.013$
  - assuming wholly ionized IGM, $f_e = n_e/n_{baryon} = 0.88$ (H + ^{4}He)

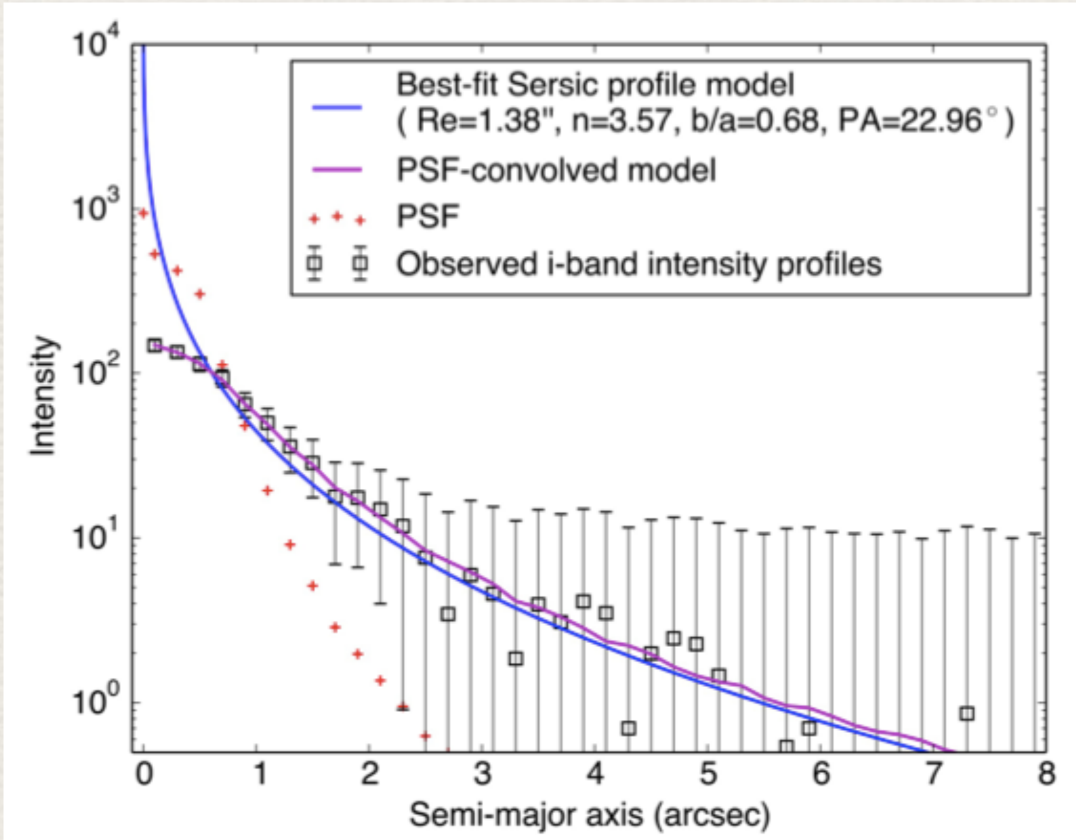
- from WMAP
  - $\Omega_{baryon} = 0.046 \pm 0.002$
  - assuming 10% in galaxies, $\Omega_{IGM} = 0.041 \pm 0.002$

- the missing baryon problem:
  - more than 90% of cosmic baryon is expected to be IGM, but most of them are not yet observed
  - ionized IGM consistent with cosmology now revealed by observation

The host is an elliptical

- good match to the spectral template
- surface brightness profile consistent with the Sersic index n~4 (i.e. de Vaucouleur's law)
- no Hα line → SFR <~ 0.2 M$_\odot$/yr
- like short GRBs, this suggests a connection between FRBs and compact binary mergers (long delay time)





press release movie

NHK やってしまいました

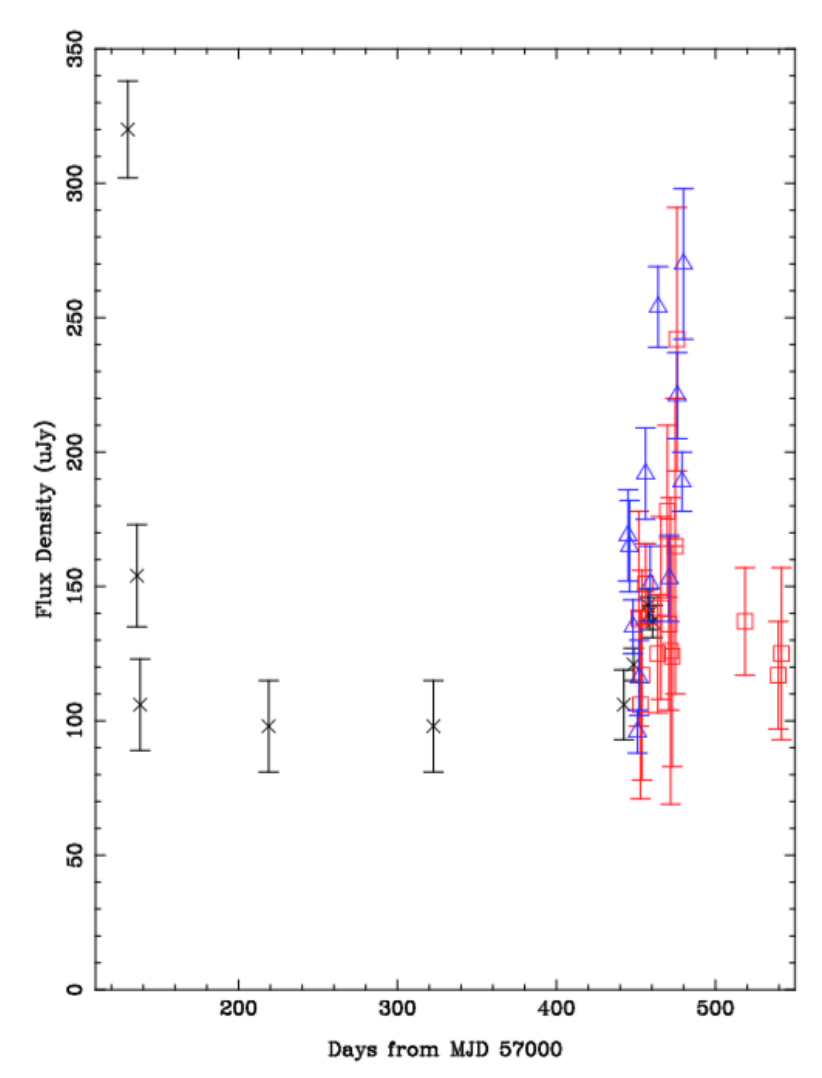
and dispute!

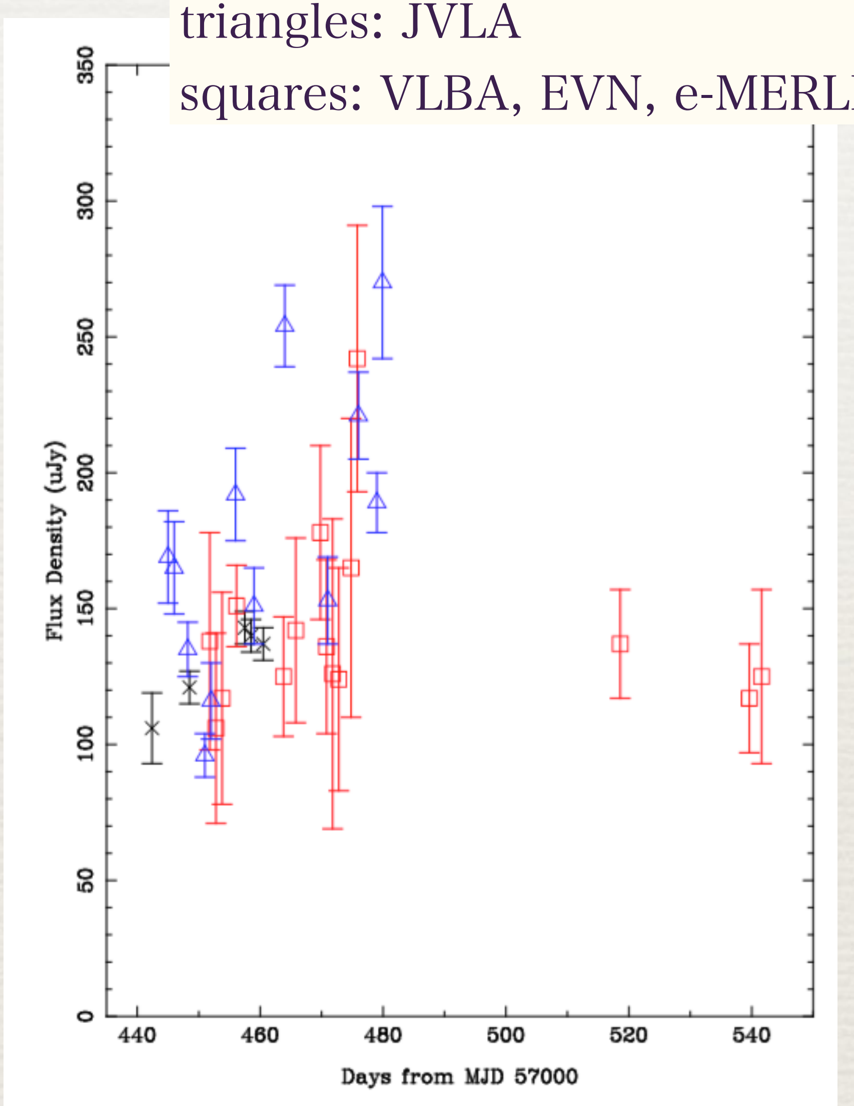
- Williams & Berger '16 claimed:
  - finding a radio transient in a FRB error circle is of order 1
  - the "host galaxy" shows strong radio variability (a factor of 3 in a few days) even 1yr after FRB, according to their own VLA observation
  - they argued that the radio flare reported by Keane+'16 is an AGN flare

- However…
  - their estimate of probability is for radio variability on ~1yr scale
  - Li & Zhang '16 reached the same conclusion with Keane+
    - probability of finding unrelated "strong" variability (a factor of few in a few days) in an FRB error circle should be small
    - based on Ofek+'11 survey data (at low Galactic latitude)
  - there are some other follow-up radio observations of the FRB host galaxy ~1yr after the event, but strong variability is not found

5.5 GHz light curve

crosses: ATCA
triangles: JVLA
squares: VLBA, EVN, e-MERLIN





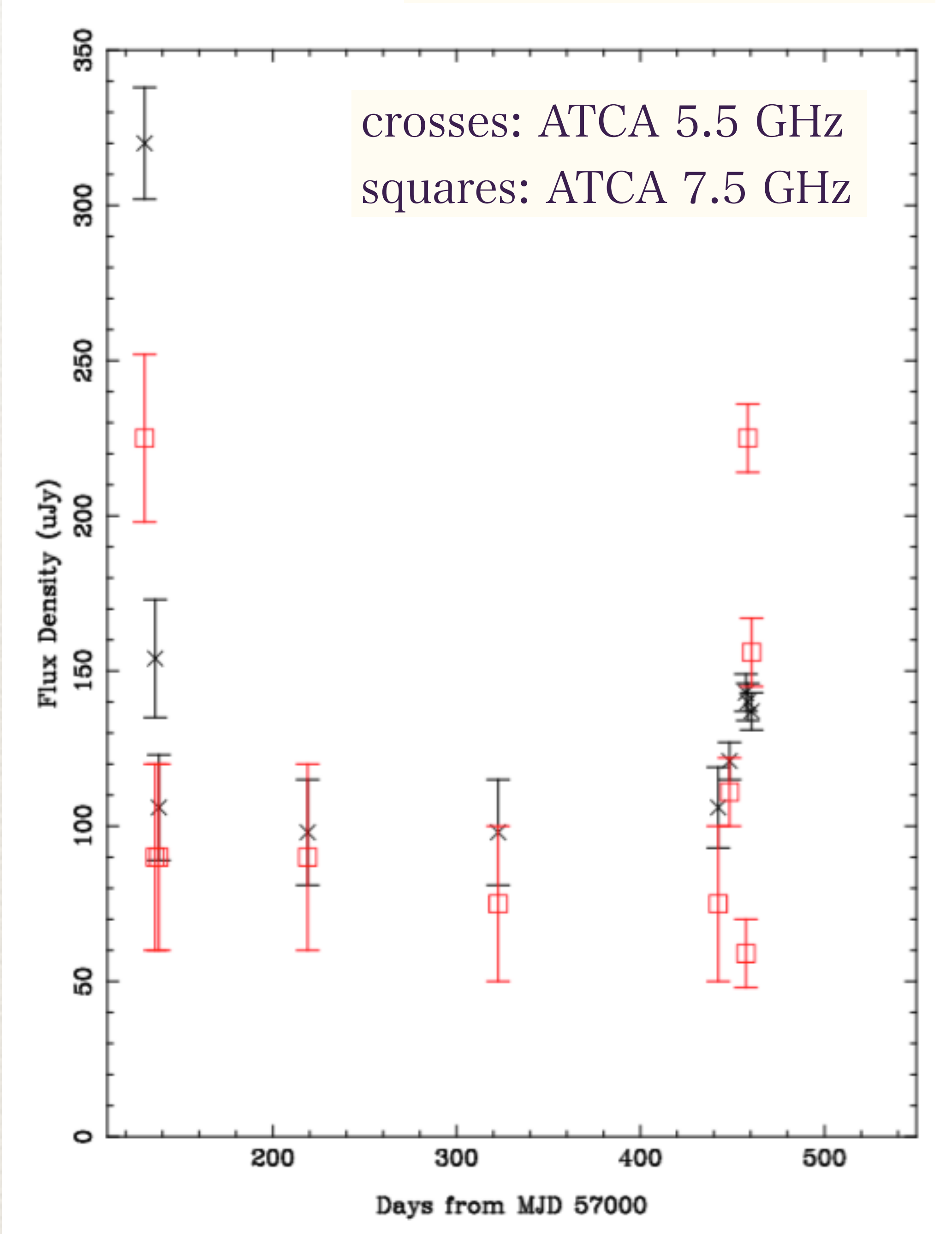
- only JVLA data show flare at ~500 days after FRB
- other data (including VLBI) do not show variability after FRB
- VLBI data reveals steady radio emission at the galactic center → AGN

Johnston+'16

7.5 GHz light curve

- In 7.5 GHz, ATCA データ showing a flare at ~460 days!?
- Still, it seems that a probability that an unrelated flare occurred just after the FRB
- rapid variability implies scintillation, but the fraction of compact AGNs to show scintillation is highly uncertain
  - perhaps contribution from yr-long compact FRB afterglow?
  - at least, FRB would be more compact than AGN
- Anyway, we need data for more FRBs…

Johnston+'16 submitted.



…and further confusing results…

Arecibo FRB is repeating!

- (Spitler+'16)
- DMs are all around 560 pc cm^{-3} (i.e., intervening rather than source)
- spectral index changes from 8.8 to −10.4
- compared with other FRBs, it shows rather long duration (~10 msec), lower luminosity (assuming DM∝distance), different spectrum
  - implying a different population from other FRBs?
- rumor: VLBI determination of the location and host/redshift determination?

Spitler+'16

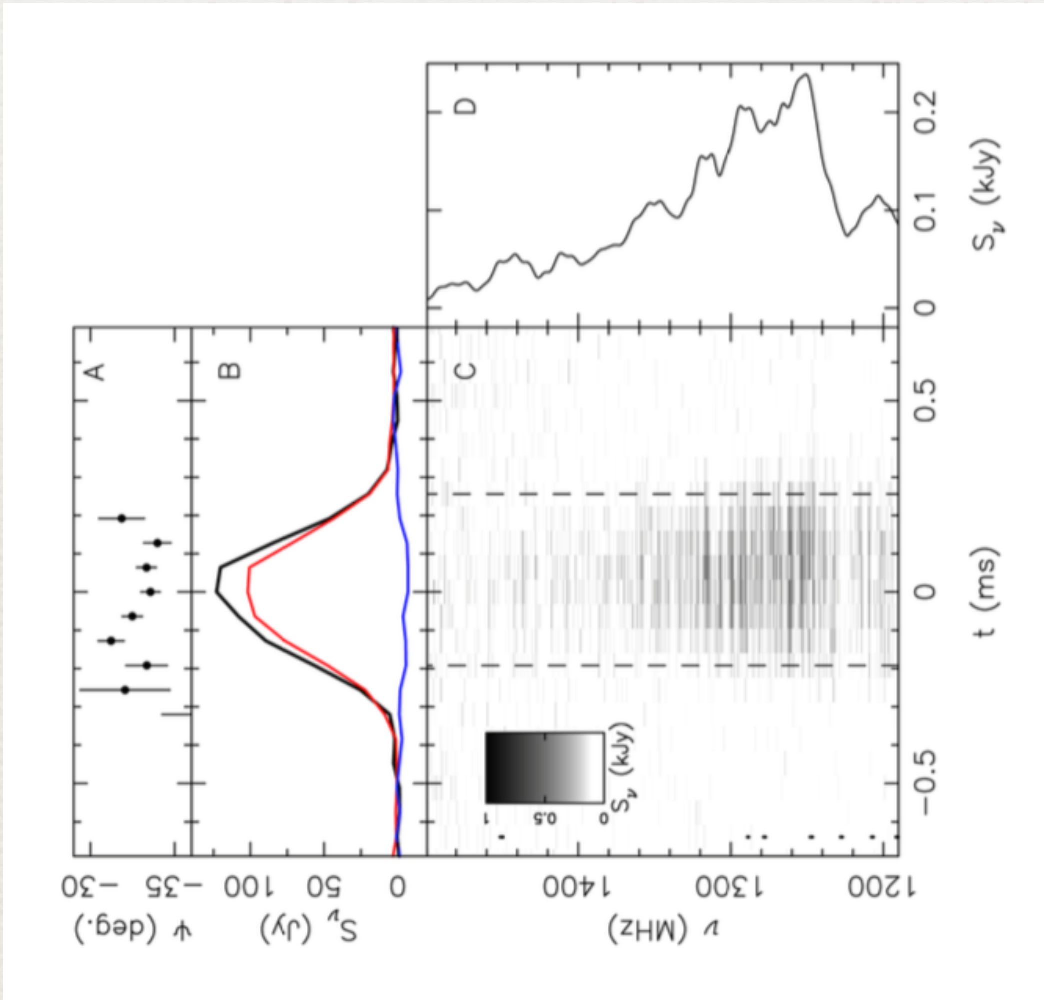
Table 1 | Properties of detected bursts

Burst number	Barycentric peak time (MJD)	Peak flux density (Jy)	Fluence (Jy ms)	Gaussian width (ms)	Spectral index	DM (pc cm^{-3})
1	56233.282837008	0.04	0.1	3.3 ± 0.3	8.8 ± 1.9	$553 \pm 5 \pm 2$
2	57159.737600835	0.03	0.1	3.8 ± 0.4	2.5 ± 1.7	$560 \pm 2 \pm 2$
3	57159.744223619	0.03	0.1	3.3 ± 0.4	0.9 ± 2.0	$566 \pm 5 \pm 2$
4	57175.693143232	0.04	0.2	4.6 ± 0.3	5.8 ± 1.4	$555 \pm 1 \pm 2$
5	57175.699727826	0.02	0.09	8.7 ± 1.5	1.6 ± 2.5	$558 \pm 6 \pm 4$
6	57175.742576706	0.02	0.06	2.8 ± 0.4		$559 \pm 9 \pm 1$
7	57175.742839344	0.02	0.06	6.1 ± 1.4	-3.7 ± 1.8	
8	57175.743510388	0.14	0.9	6.6 ± 0.1		$556.5 \pm 0.7 \pm 3$
9	57175.745665832	0.05	0.3	6.0 ± 0.3	-10.4 ± 1.1	$557.4 \pm 0.7 \pm 3$
10	57175.747624851	0.05	0.2	8.0 ± 0.5		$558.7 \pm 0.9 \pm 4$
11	57175.748287265	0.31	1.0	3.06 ± 0.04	13.6 ± 0.4	$556.5 \pm 0.1 \pm 1$

Uncertainties are the 68% confidence interval, unless otherwise stated. MJD, modified Julian day.
The barycentric peak time is the arrival time corrected to the Solar System barycentre and referenced to infinite frequency (that is, the time delay due to dispersion is removed).
The peak flux density and the fluence are lower limits because it is assumed that the burst is detected at the centre of the beam (that is, with an assumed gain of 10 K Jy^{-1} yielding a system equivalent flux density of 3 Jy). Gaussian widths are the full-width at half-maximum. For the spectral index, bursts 8 and 10 are not well fitted by a power-law model and burst 6 is too corrupted by RFI to include.
Quoted errors on DM are, in order, statistical and systematic (see Methods). The DM for burst 7 was too weak and corrupted by RFI to include.

100 Jy FRB 150807

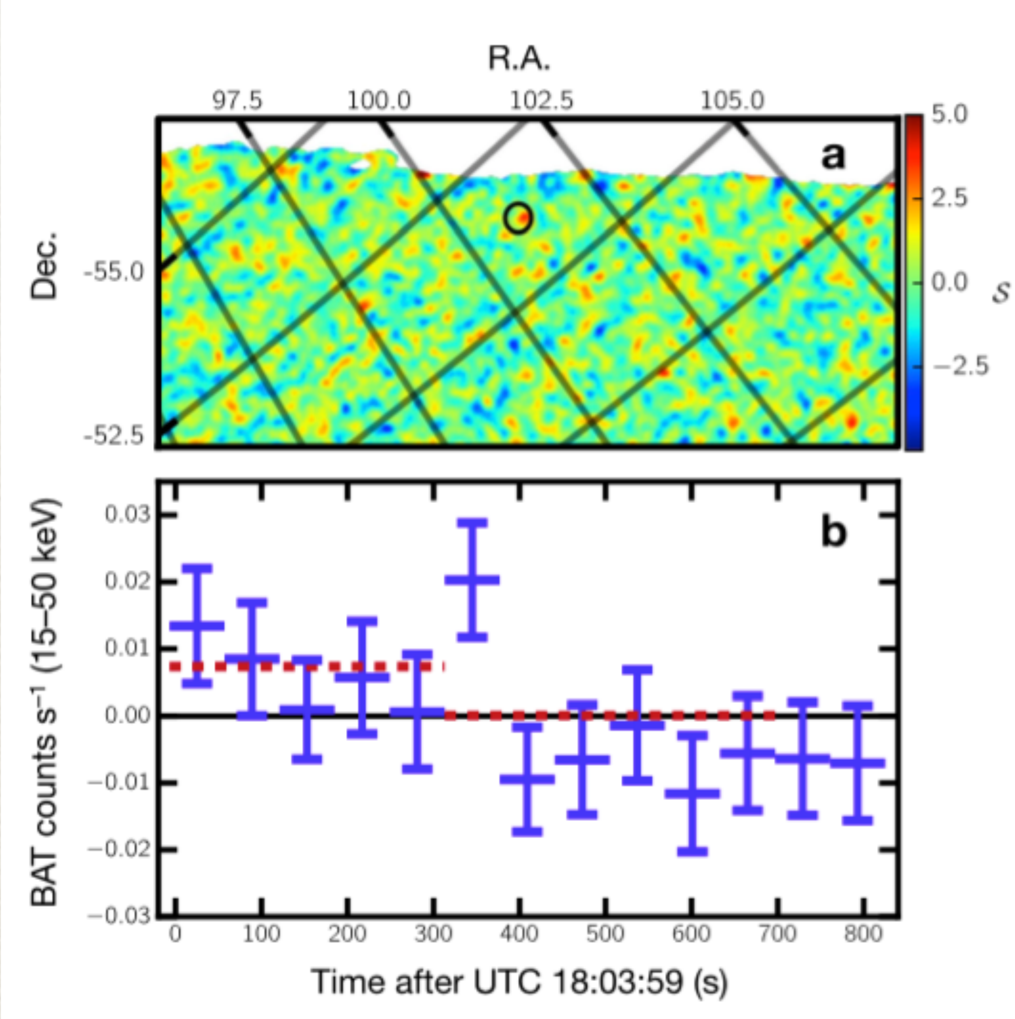
- a very bright (100 Jy!) FRB
- DM = 267 pc cm^{-3}, MW contribution ~ 70, z_{exp} ~ 0.2
- rotation measure 12.0 rad m^{-2} (consistent with fully MW contribution)
    - net extragalactic B field < 21 nG
- low RM indicates negligible magnetization in the circum-burst plasma
    - disfavors young stellar populations / dense star forming regions
    - c.f. large linear polarization (44%) and rotation measure (186 rad m^{-2}) from the Green Bank FRB 110523 (Masui+'15)



Ravi+'16

the Carina FRB 131104

- a FRB in the direction to the Carina dwarf galaxy
- Swift BAT transient associated? (DeLaunay +'16)
  - 3.2 σ
  - $T_{90} > 100$ s
  - E ~ 5 x 10^{51} erg if z ~ 0.55 from DM



the Carina FRB 131104 contd.

- No radio detection for the Swift counterpart (Shannon+'16)
  - upper limit more stringent than typical expectations from GRB afterglow
  - n_{ISM} <~ 10^{-3} cm^{-3} (Dai+'16; Gao+'16; Murase+'16)
  - favoring old stellar populations rather than young star forming regions

- Shannon+'16 reports an interesting variable radio source, peaking near to FRB, whose location is DIFFERENT from the Swift source
  - two optical sources for the radio source

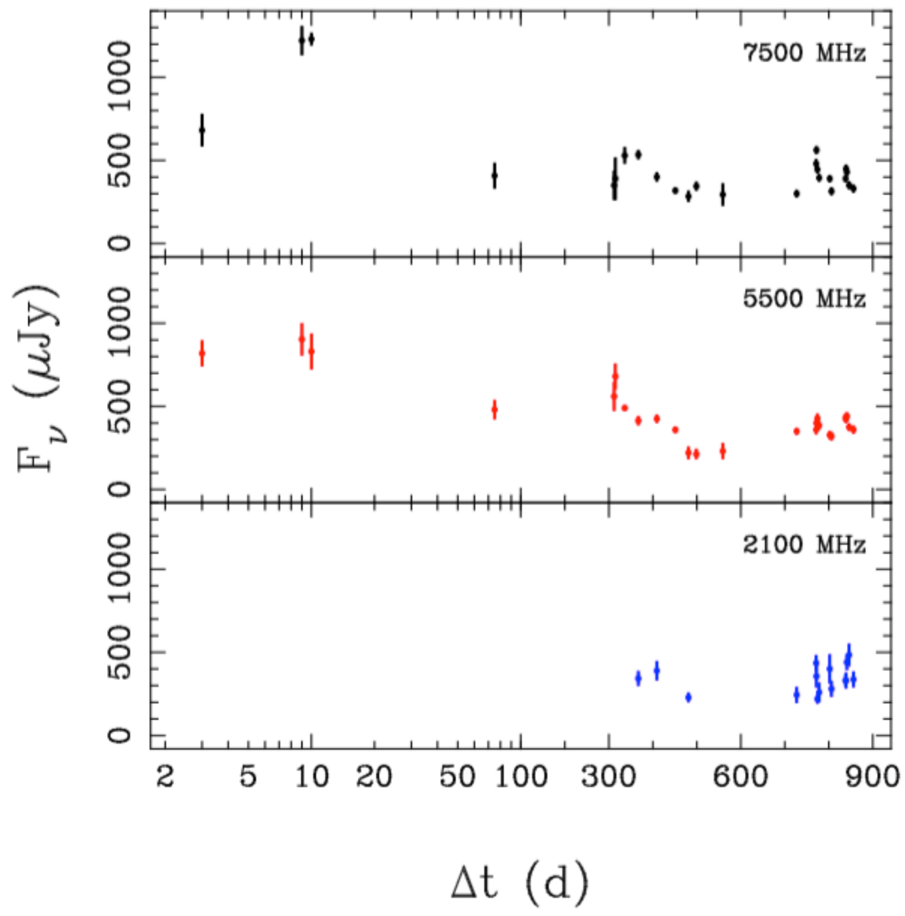


Figure 2. Radio light curve for the variable radio source AT J0642.9−5118. From the lower to upper panels we show the flux density measured in the bands centered at 2.1 GHz, 5.5 GHz, and 7.5 GHz. The x-axis is the time since FRB 131104. For $\Delta t < 100$ d we show the light curve on a logarithmic time axis. For $\Delta t > 100$ d the axis is linear.

the Carina FRB 131104 contd.

- upper-right source coincident to the radio source
- spectrum implies that the upper-right source is an AGN, while the lower-left source is an early type galaxy
  - z = 0.805, 0.888
- FRB comes from an AGN? Just a coincidence? Perhaps FRB radio afterglow?