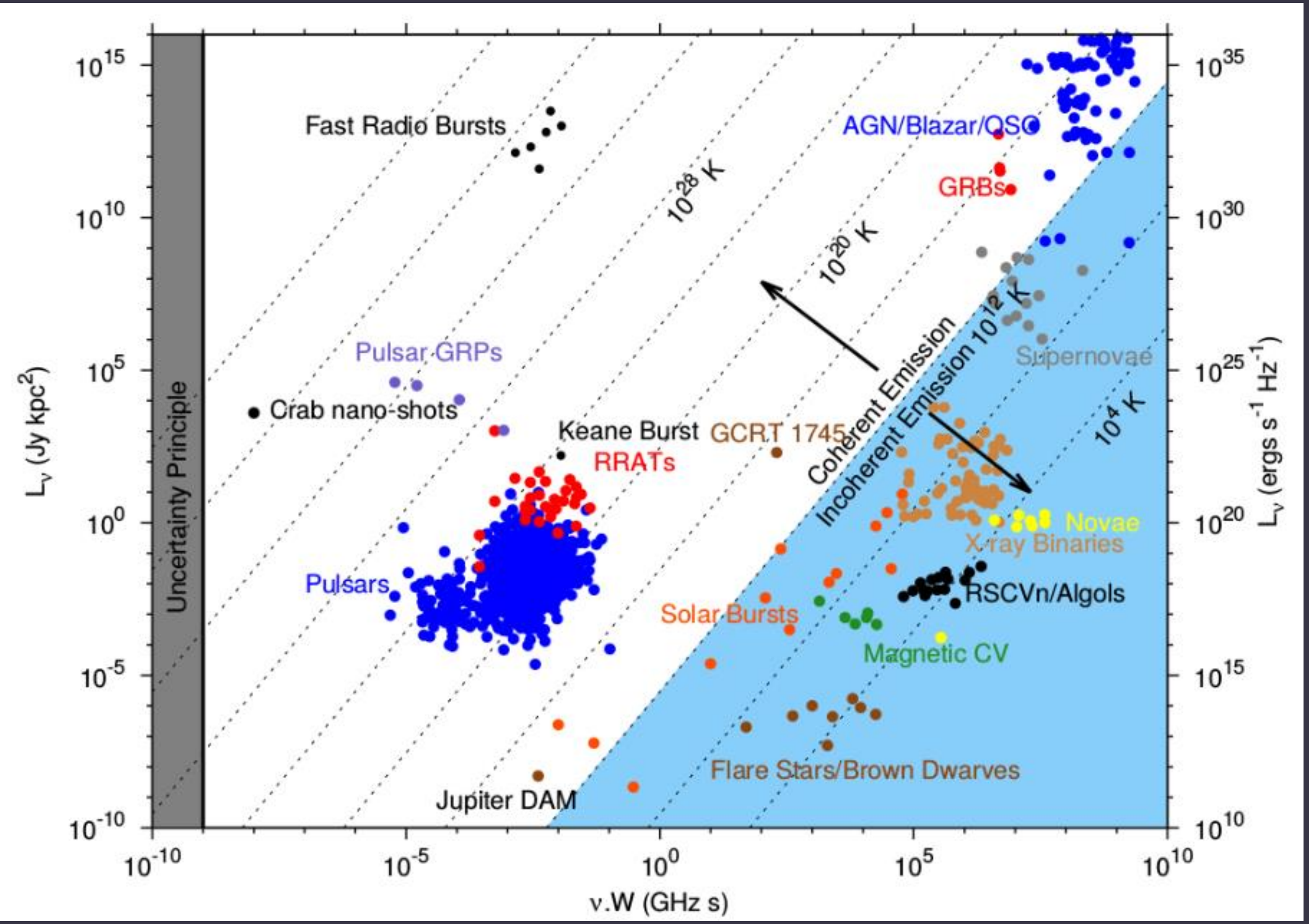
# Fast radio bursts: a new exotic puzzle in astrophysics

SERGEI POPOV (SAI MSU)

See a review Popov, Postnov, Pshirkov in arXiv: 1806.03628. Physics Uspekhi (2018 N10) (and in Russian at ufn.ru)

# Radiotransients




Many different types of transient sources are already detected at radio wavelengths.

However, detection of very short and non-repeating flares of unknown sources without identification at other bands is a very complicated task.

Rotating Radio Transients (RRATs) – millisecond radio bursts from neutron stars, - have been identified in 2006.

In 2007 the first example of a new class of millisecond radio transients have been announced: the first extragalactic millisecond radio burst.

1507.00729, 1411.1067

# Brightness temperature

Black-body radiation

$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

Brightness temperature

$$T_b = \frac{h\nu}{k} \ln^{-1}\left(1 + \frac{2h\nu^3}{I_\nu c^2}\right)$$

For $h\nu \ll kT$ we have $T_b = \frac{I_\nu c^2}{2k\nu^2}$

$$2\pi k T_b = \frac{S_\nu D^2}{(W\nu)^2}$$

$W \sim l/c,$

$$T_b \approx 10^{35.8}[\text{K}] \left(\frac{S_\nu}{1\ \text{Ян}}\right) \left(\frac{(D/1\ \text{Гпк})}{(\nu/1\ \text{ГГц})(W/1\ \text{мс})}\right)^2$$

Inverse Compton catastrophe

Inverse-Compton losses
very strongly cool the relativistic electrons
if the source brightness temperature
exceeds $T_b$ ~$10^{12}$ K in the rest frame of the source

see astro-ph/0611667

$$\frac{L_{\text{IC}}}{L_{\text{s}}} = \left(\frac{T_{\text{B}}}{T_{\text{thresh}}}\right)^5 \left[1 + \left(\frac{T_{\text{B}}}{T_{\text{thresh}}}\right)^5\right]$$

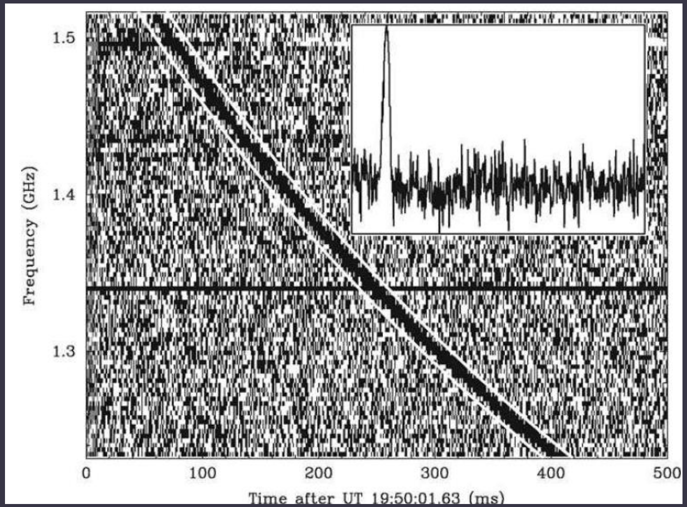
$$\left(\frac{\nu_m}{10^9 Hz}\right)\left(\frac{T_B}{10^{12} K}\right)^5 = 1$$

# Brief history of FRBs

2007 Lorimer et al. The first event announced.
2012 Keane et al. The second event.
2013 Thornton et al. Four events. The story really starts.

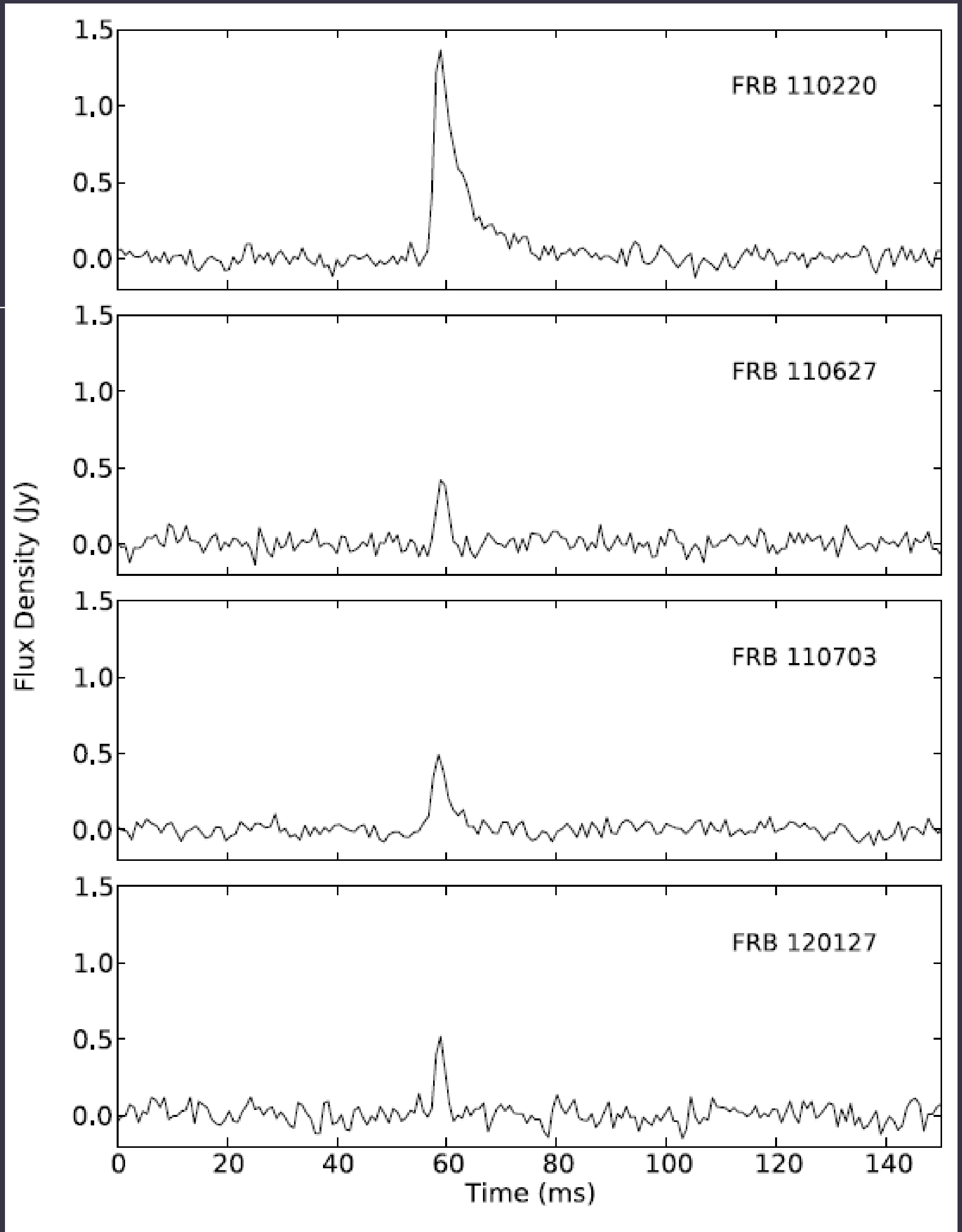
2016 Spitler et al. The first repeating source.
Chatterjee et al. Identification of the host galaxy

Lorimer et al.

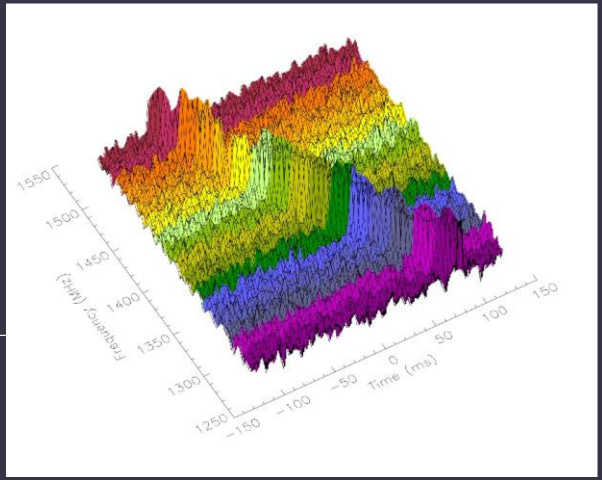



Large dispersion measure points to extragalactic origin.

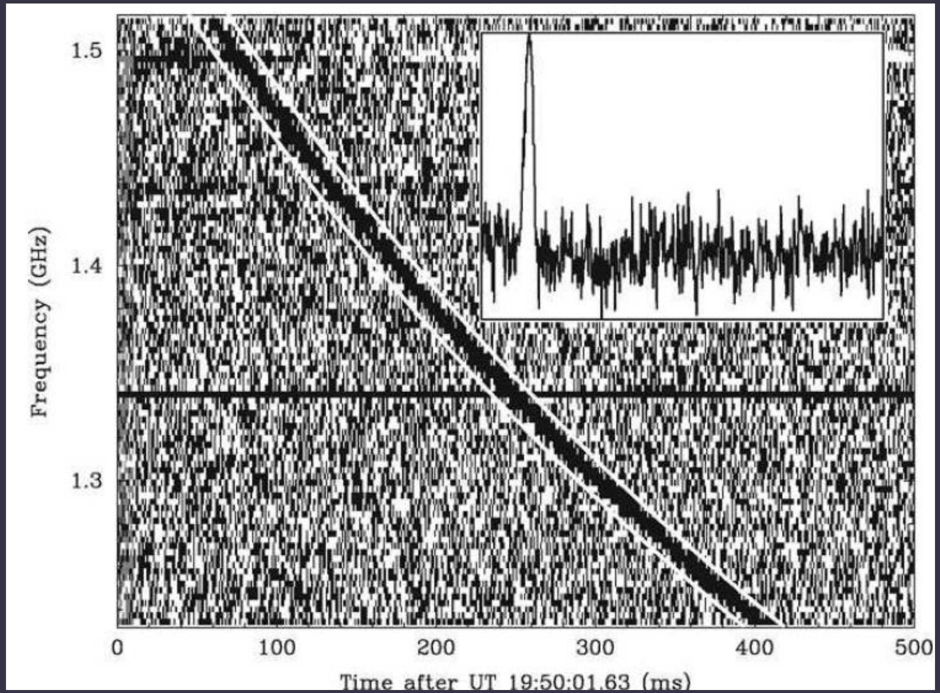
This is supported by isotropic sky distribution and many other considerations.



# Millisecond extragalactic radio bursts




Science 318, 777 (2007)




**Discovered in 2007.**

**Origin - unknown.**

One of the most interesting discoveries in XXI.

No coincident bursts in other wavelengths.

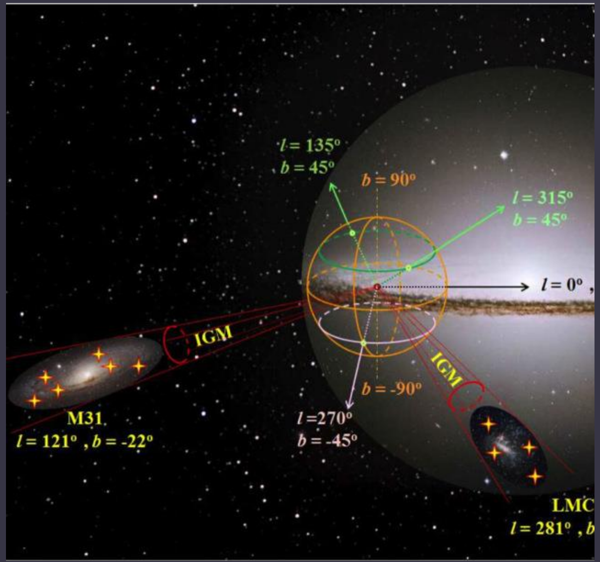
No source identification.

[About the difference between RRATs and FRB see 1512.02513]

Large dispersion measure.
If dispersion is due to intergalactic medium then radio luminosity is ~$10^{43}$ erg/s.

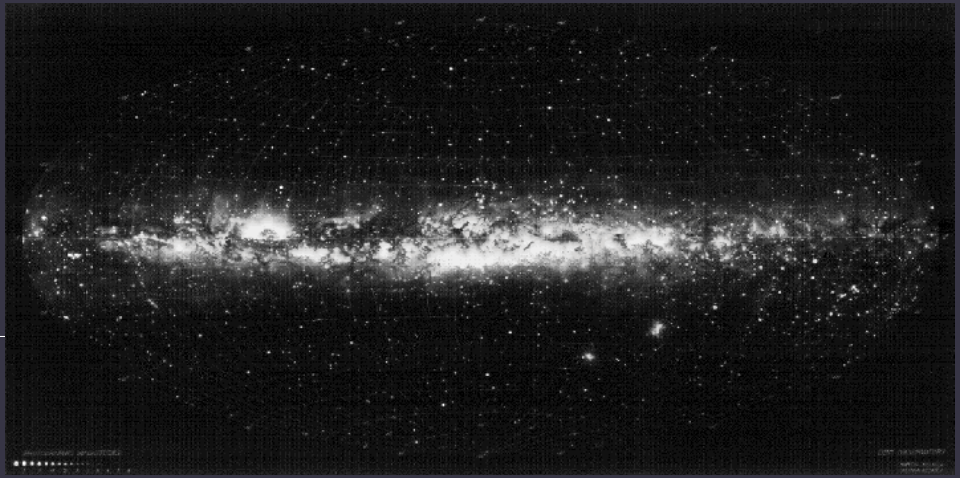
# Dispersion measure

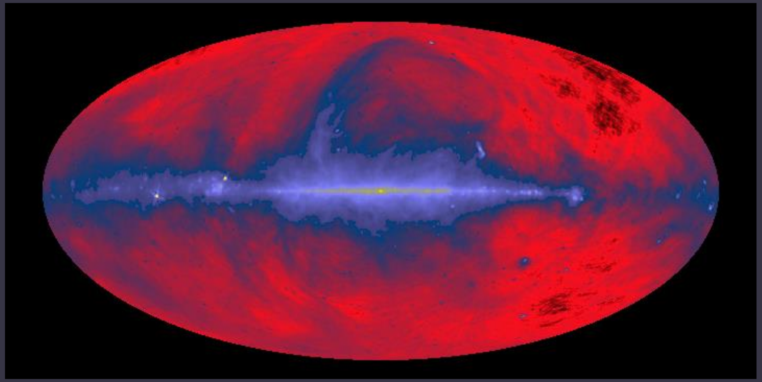
1504.00200

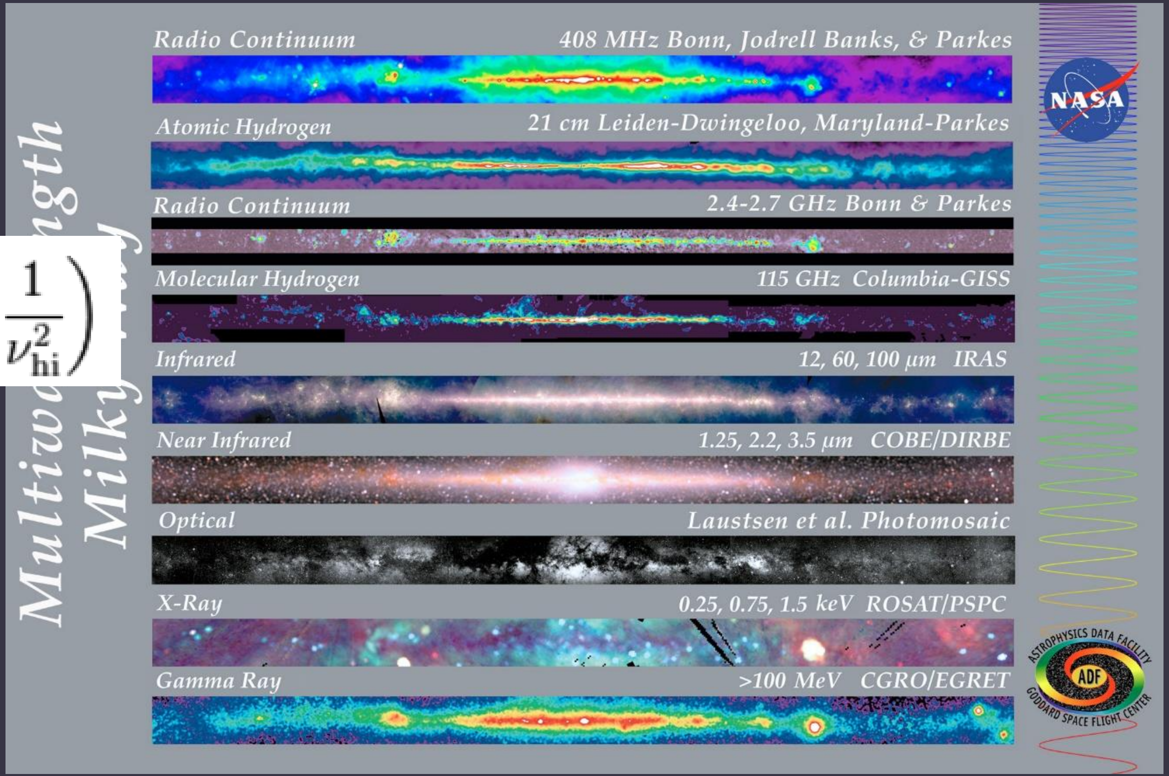



$$t = k_{\rm DM} \times \left(\frac{\rm DM}{\nu^2}\right)$$

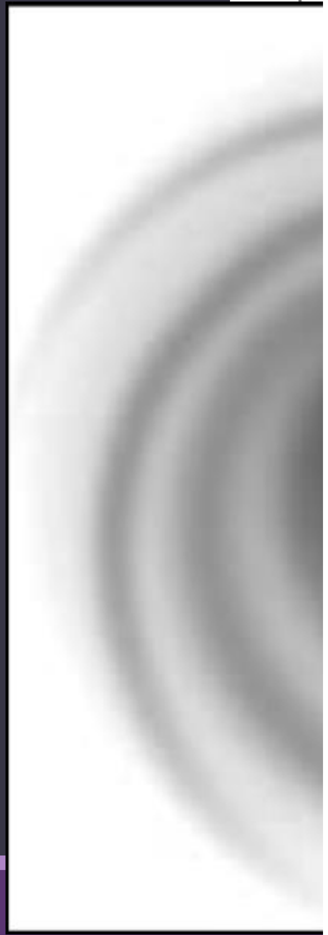
$$\Delta t = k_{\rm DM} \times {\rm DM} \times \left(\frac{1}{\nu_{\rm lo}^2} - \frac{1}{\nu_{\rm hi}^2}\right)$$

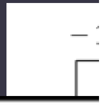







http://www2.astro.psu.edu/users/niel/astro1/slideshows/class29/slides-29.html





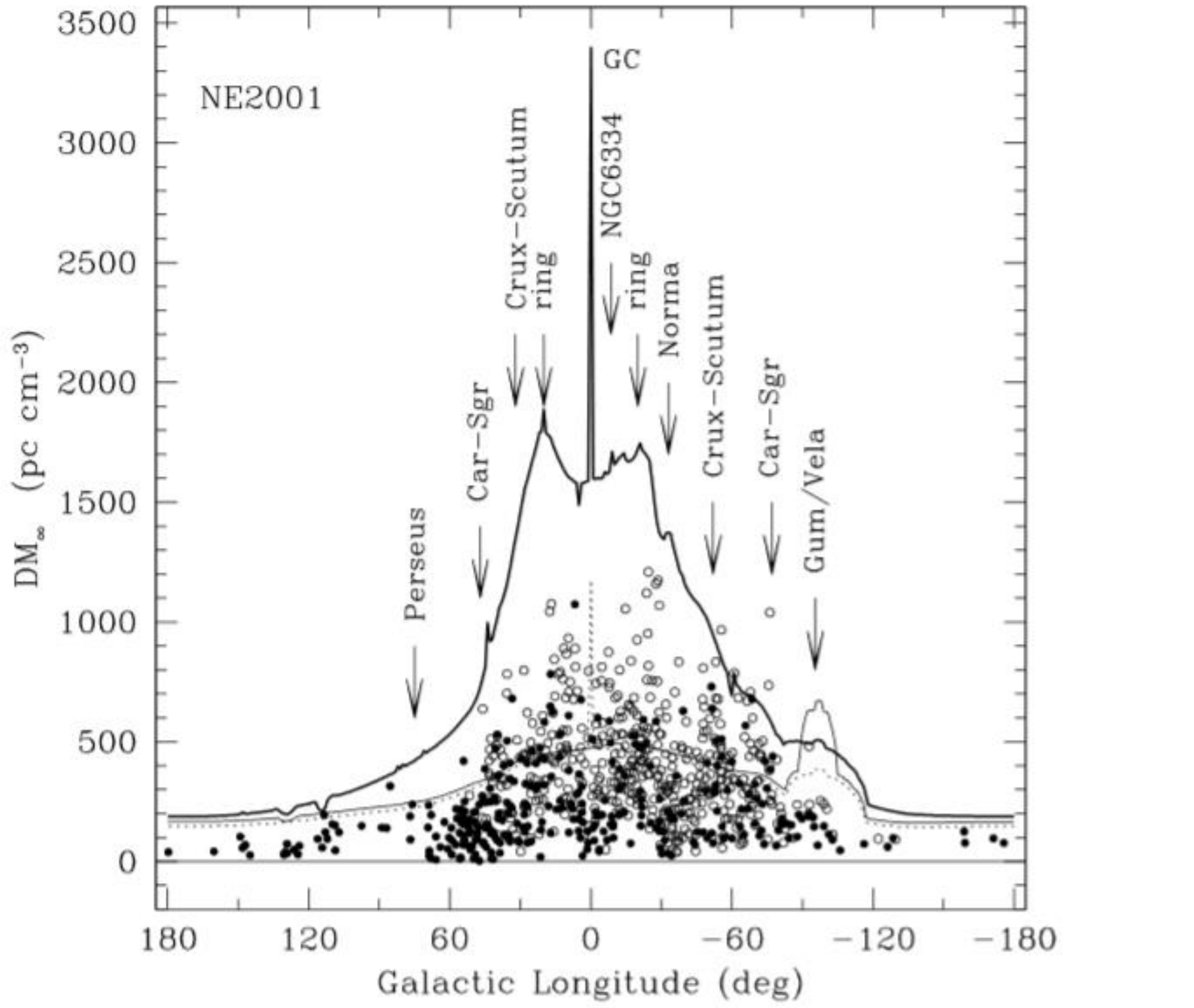
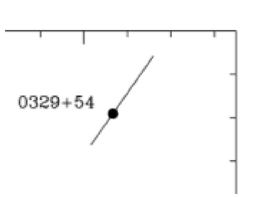
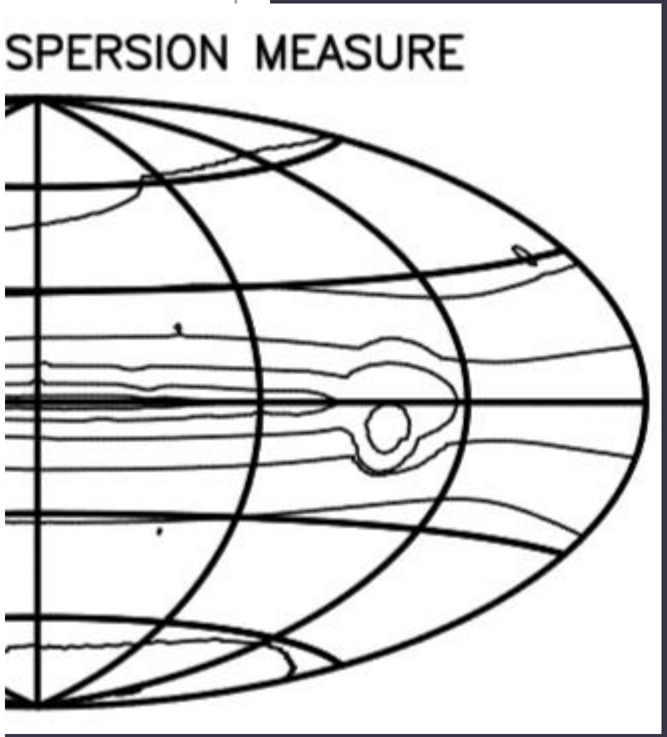


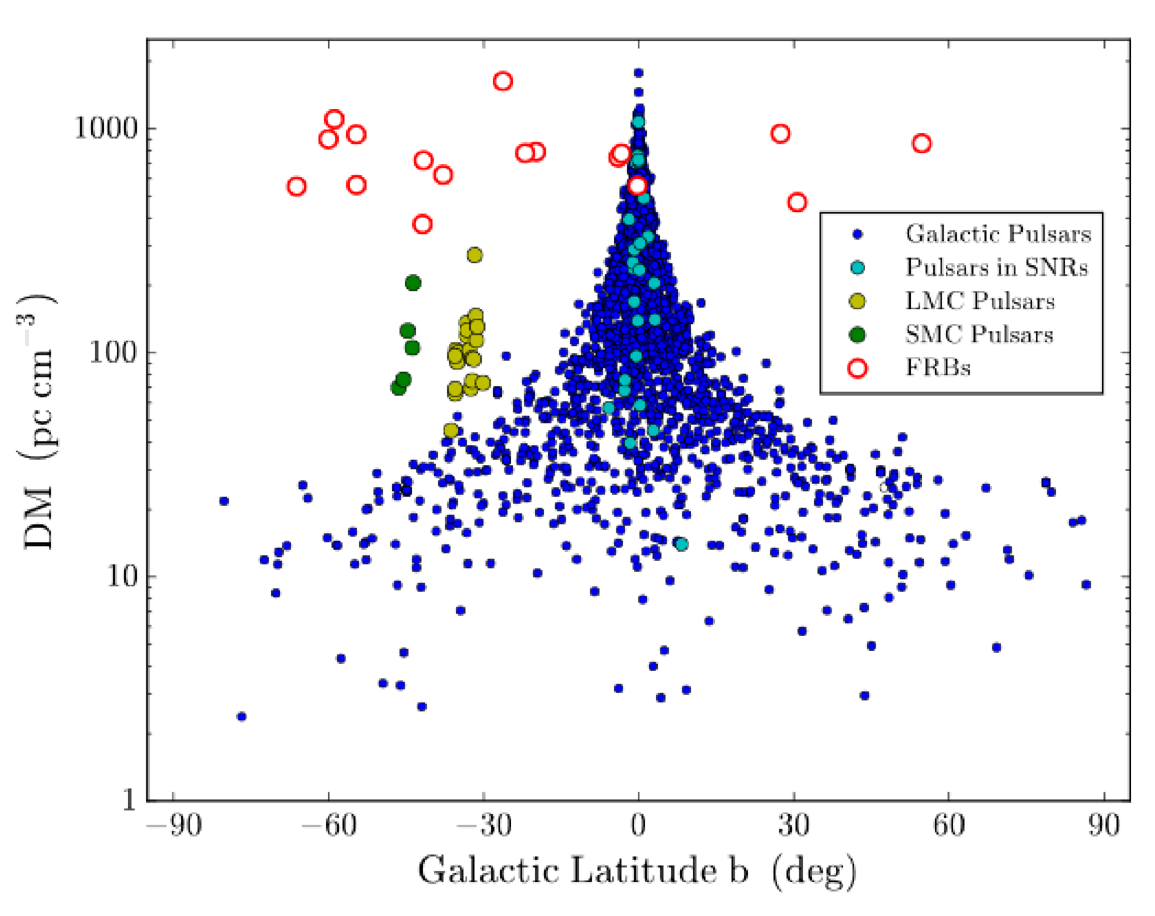

FIG. 11.— Plot of $DM_\infty(\ell, b)$, the maximum DM obtained by integrating the NE2001 model. Heavy solid line: $b = 0°$.




astro-ph/0207156

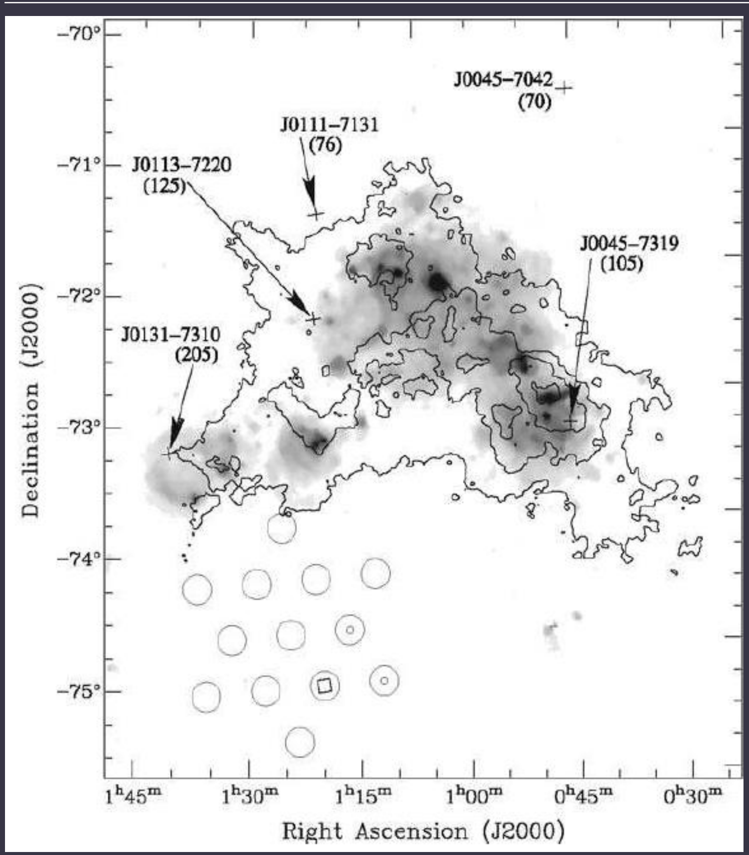
# Comparison with radio pulsars




1605.05890

# The first event

Science 318, 777 (2007)




Discovered at Parkes
by Duncan Liromer et al.

~30-40 Jy, < 5 msec.

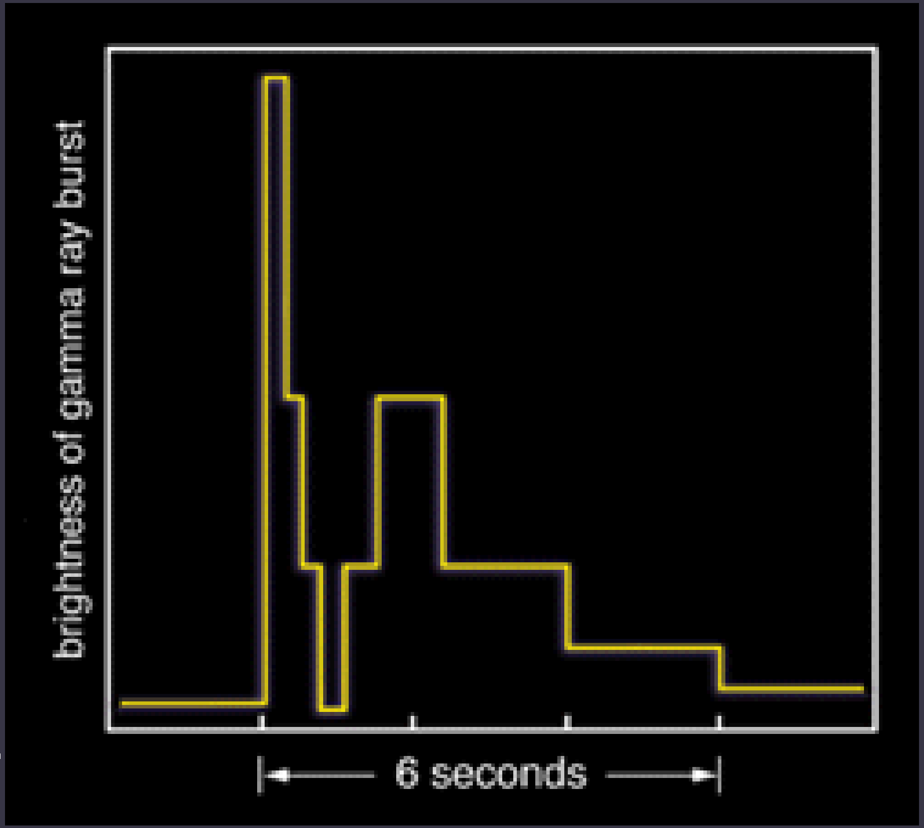
3 degrees from
Small Magellanic cloud

$$\mathcal{L} = 1.3 \times 10^{41} \text{erg/s} \left(\frac{S_\nu}{1\ \text{Jy}}\right)\left(\frac{\Delta\nu}{1.4\ \text{GHz}}\right)\left(\frac{\Omega}{1\ \text{sr}}\right)\left(\frac{D}{1\ \text{Gpc}}\right)^2.$$

# History repeating? GRB2.0?

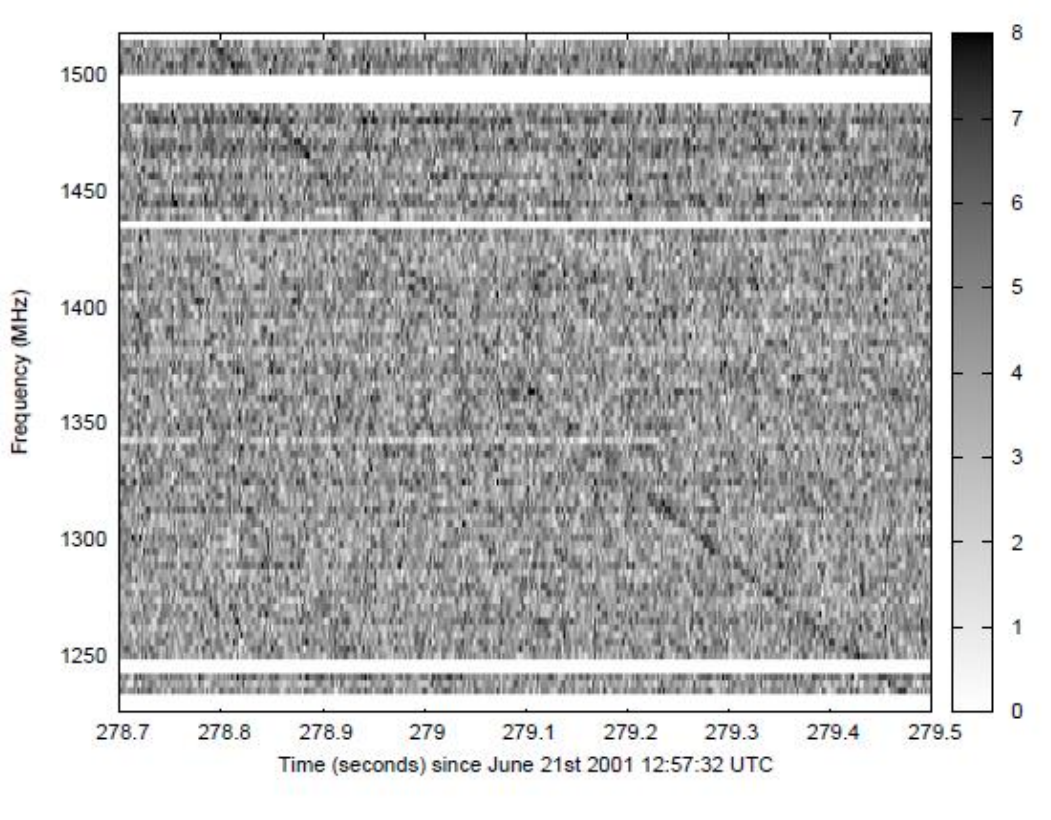
At the end of 1960s cosmic gamma-ray bursts have been discovered.
They have been a mystery f
or ~30 years as there were
no counterparts at other wavelengths.

Only at the end of 1990s
a burst was simultaneously
observed in X-rays.
This allowed to measure
coordinates precisely enough,
and thus to identify the source.



# The second event?

1206.4135




In the Galactic plane.

Hypothesis:
black hole evaporation!

Radio bursts from evaporating black holes have been predicted long ago.

Curiously, this prediction played a role in developing the WiFi technology.

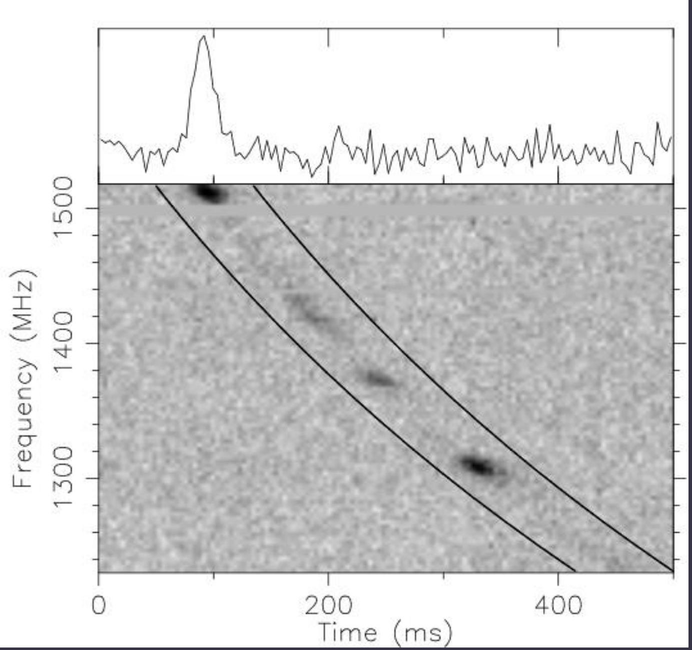
But such bursts can be detected only from small distances <few hundred pc.

The event was somehow different from the Lorimer burst due to its position in the sky,

# Perytons

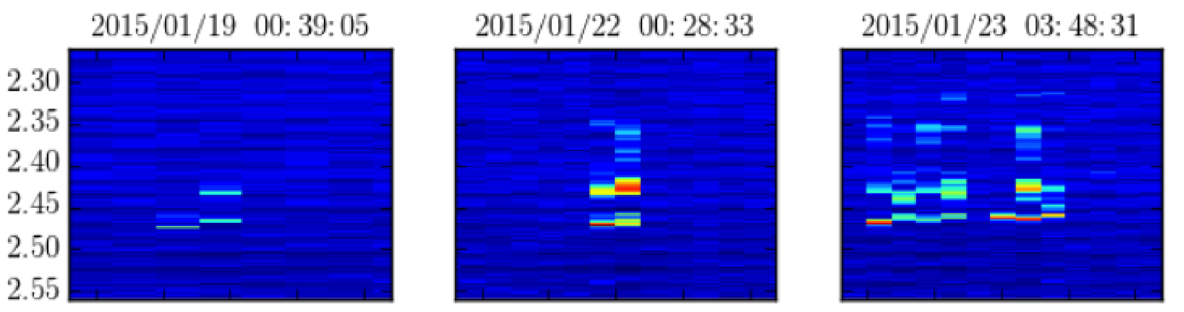
Perytons were discovered few years after identification of FRBs.
Their properties suggested that sources are near-by,
at most within the Earth magnetosphere.
Still in many respects they are similar to FRBs.

1009.5392




They were observed mainly in working hours.

Up to 2015 about half-hundred of such events have been detected. All at Parkes.




Solution came out
to be unexpected.
A new monitoring system
helped to find it.

# Doubts

Discovery of perytons somehow brought the Lorimer burst into doubt.

Note, that FRBs were discovered only in the archival data.

Digging in many archives for several years didn’t produce any results – no new examples of FRBs.

http://www.onex.in/images/doubts.jpg

Even theoreticians stayed quiet …..

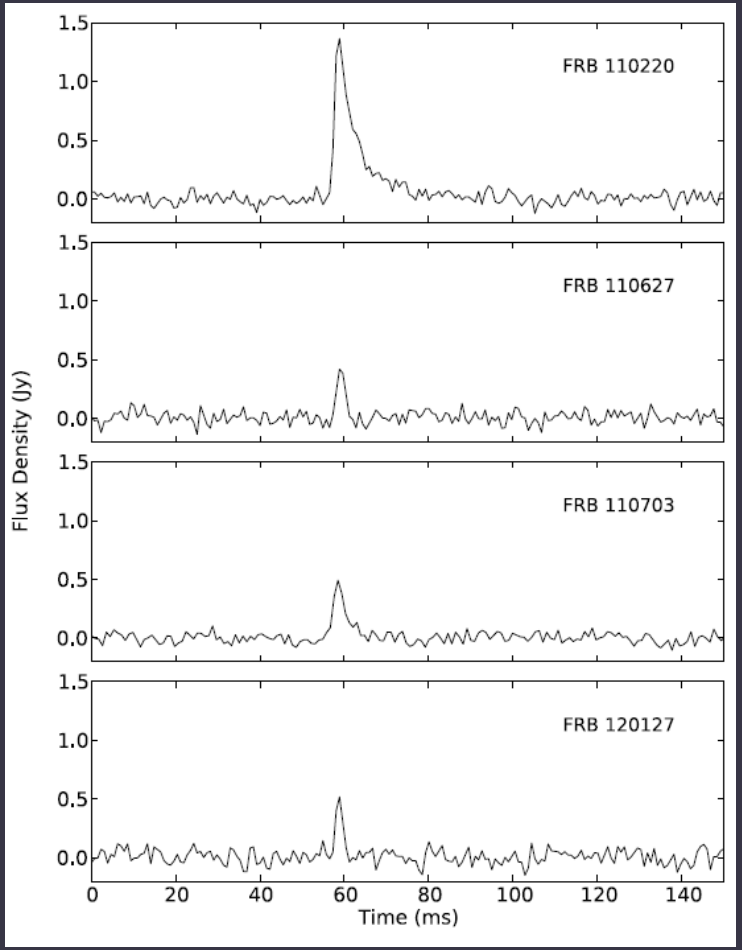
# Millisecond radio bursts – definite at last

2007 The first burst.
2011 Perytons. Doubts
2012 The second event. Galactic plane. Unclear.

2013 – Four more!

Rate ~few thousand per sky per day confirmed

A new type of astronomical phenomena
with unknown origin is established.

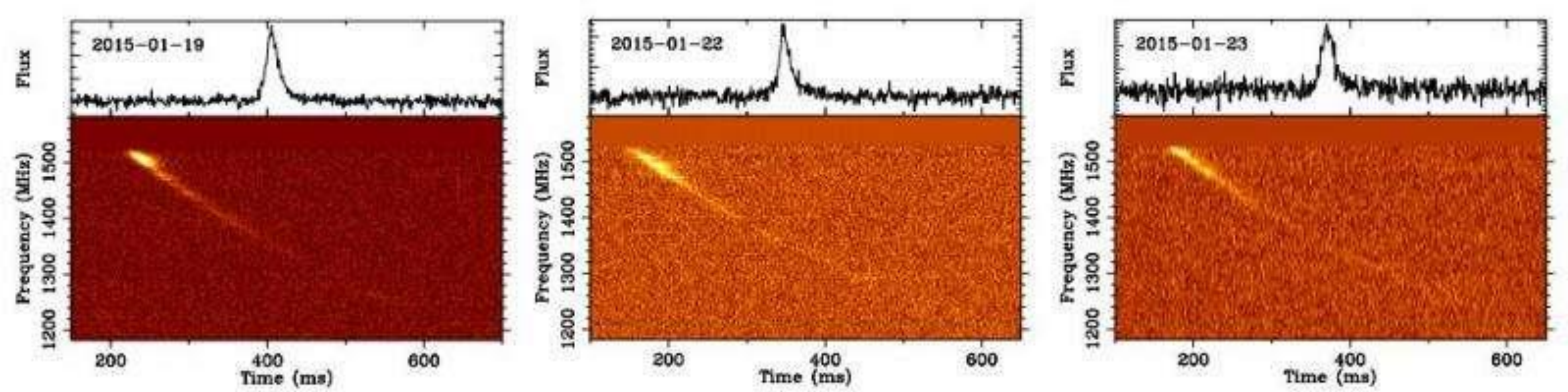



In this paper the final notation –
Fast Radio Bursts – was proposed.

1307.1628

# Perytons come from microwave ovens

1504.02165

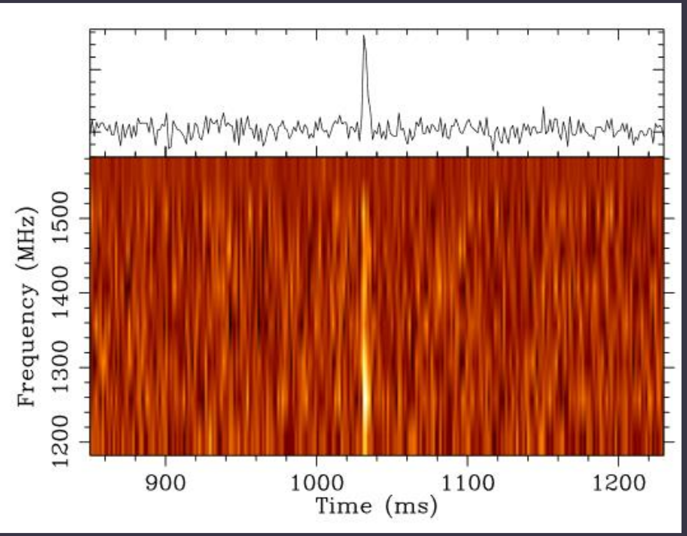




Studies showed that perytons are generated when an oven is opened before it stops. The signal is detected only at particular positions of the telescope. Identification of these signals demonstrated that known FRBs are real astronomical sources.

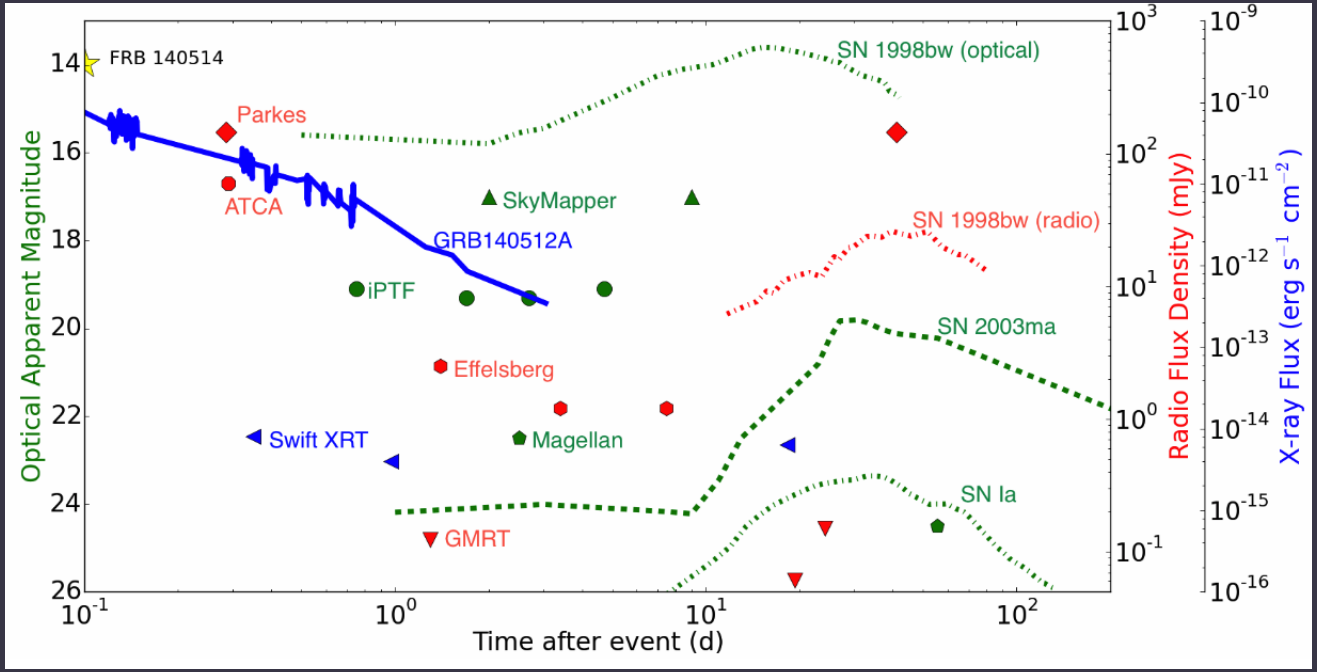
# The first burst detected in real time

1412.0342




In may 2014 for the first time a burst was detected in real time.
This allowed to trigger searches of an afterglow in other energy ranges.

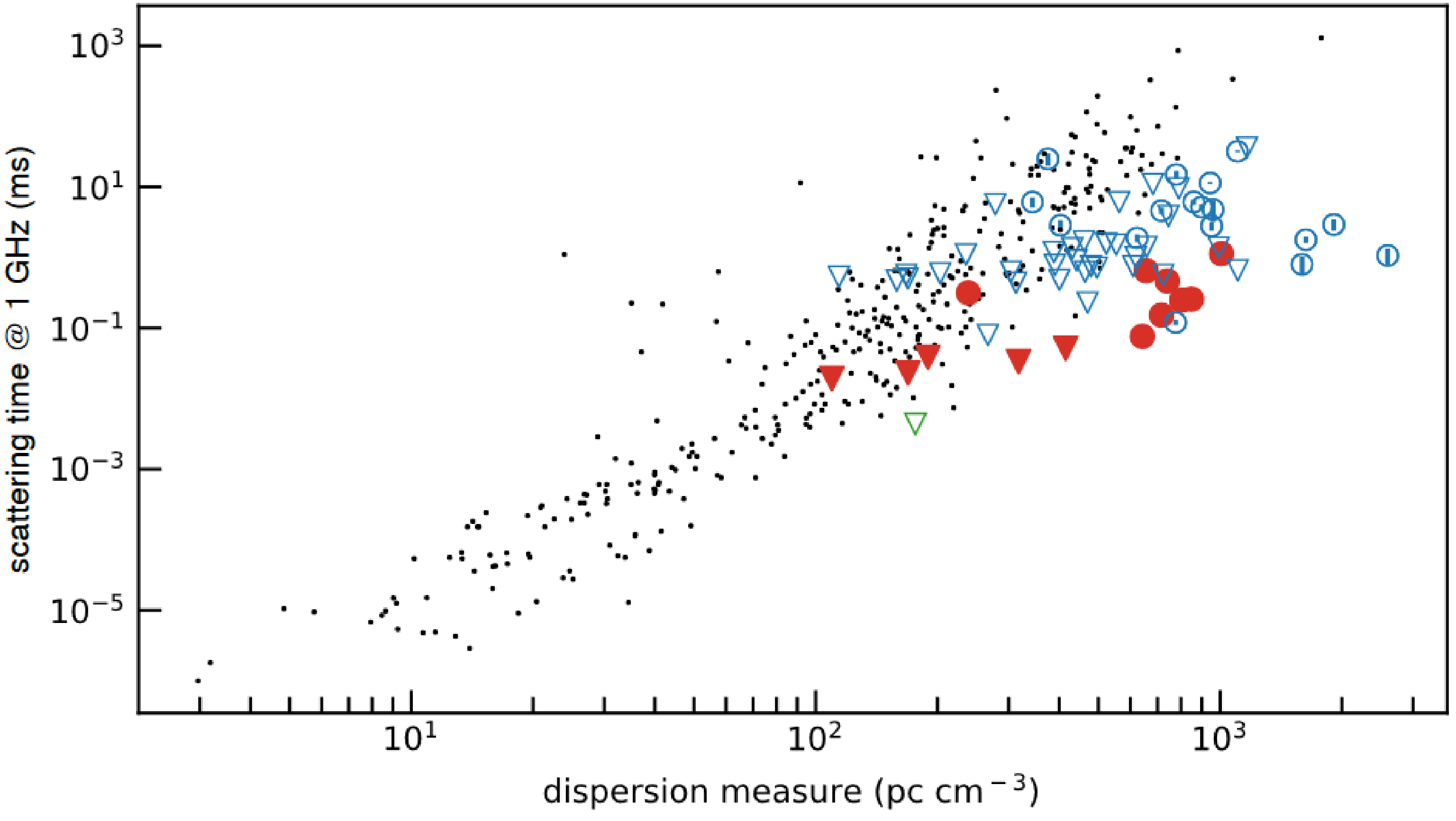
Absence of any transients at other wavelengths closed the models of a SN and a GRB as a soiurce of FRBs.



# CHIME results

13 FRBs at ~400 MHz

| FRB | Width (ms) | DM (pc cm$^{-3}$) |
|---|---|---|
| 180725.J0613+67 | $0.31^{+0.08}_{-0.07}$ | $715.98^{+0.02}_{-0.01}$ |
| 180727.J1311+26 | $0.78 \pm 0.16$ | $642.07 \pm 0.03$ |
| 180729.J1316+55 | $0.12 \pm 0.01$ | $109.610 \pm 0.002$ |
| 180729.J0558+56 | $< 0.08$ | $317.37 \pm 0.01$ |
| 180730.J0353+87 | $0.42 \pm 0.04$ | $849.047 \pm 0.002$ |
| 180801.J2130+72 | $0.51 \pm 0.09$ | $656.20 \pm 0.03$ |
| 180806.J1515+75 | $< 0.69$ | $739.98 \pm 0.03$ |
| 180810.J0646+34 | $< 0.27$ | $414.95 \pm 0.02$ |
| 180810.J1159+83 | $0.28 \pm 0.03$ | $169.134 \pm 0.002$ |
| 180812.J0112+80 | $1.25^{+0.49}_{-0.47}$ | $802.57 \pm 0.04$ |
| 180814.J1554+74 | $< 0.18$ | $238.32 \pm 0.01$ |
| **180814.J0422+73** | $2.6 \pm 0.2$ | $189.38 \pm 0.09$ |
| 180817.J1533+42 | $< 0.37$ | $1006.840 \pm 0.002$ |



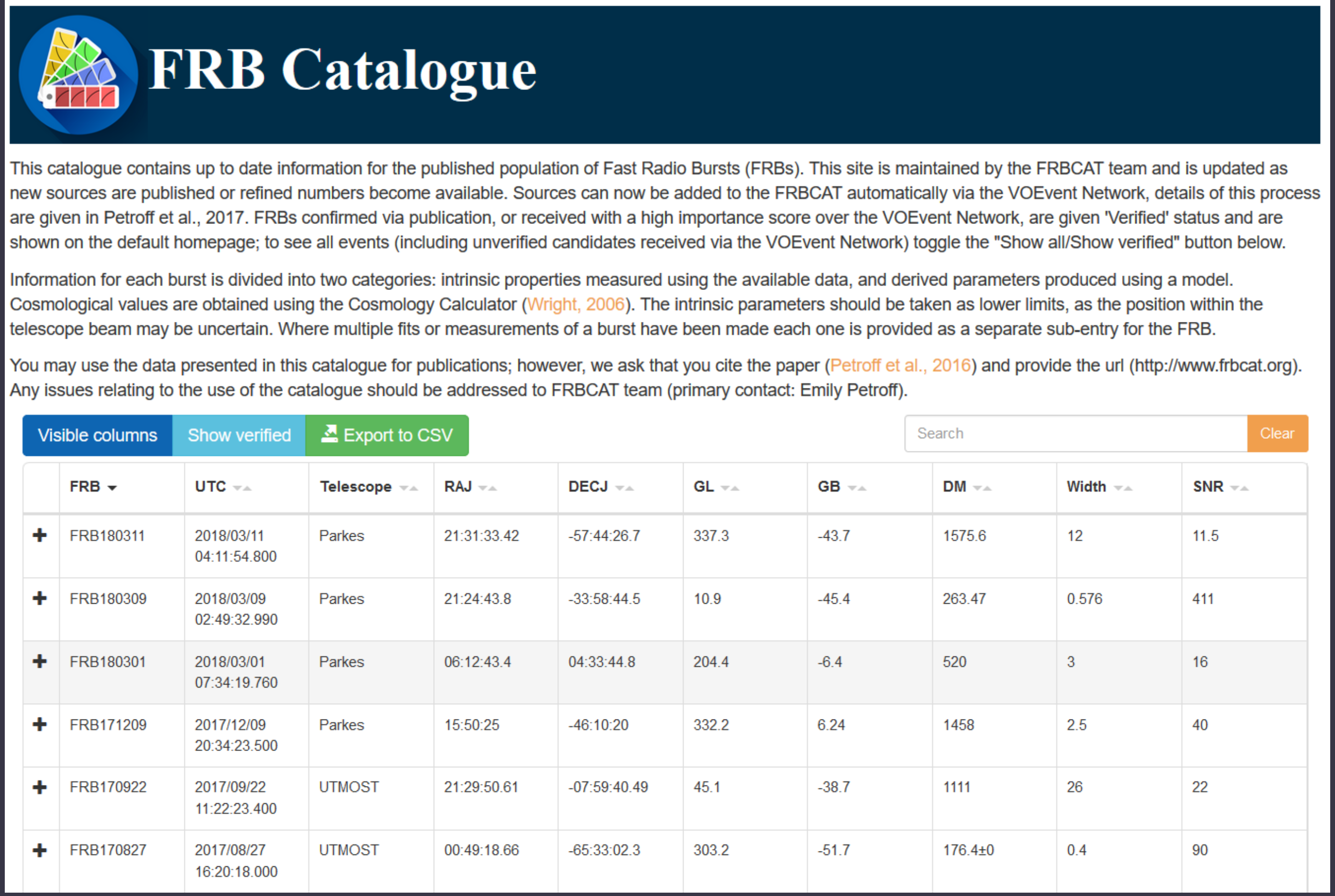
# Catalogue

109 FRBs
(several repeaters)

Parkes - 27
UTMOST – 9
ASKAP – 28
CHIME - 30
GBT – 1
DSA-10 - 1
Arecibo – 2
Pushchino – 11 (?)

Several bursts are known,
but not yet included in the list.

Rate: several thousands
per day per sky



# FRB Catalogue

This catalogue contains up to date information for the published population of Fast Radio Bursts (FRBs). This site is maintained by the FRBCAT team and is updated as new sources are published or refined numbers become available. Sources can now be added to the FRBCAT automatically via the VOEvent Network, details of this process are given in Petroff et al., 2017. FRBs confirmed via publication, or received with a high importance score over the VOEvent Network, are given 'Verified' status and are shown on the default homepage; to see all events (including unverified candidates received via the VOEvent Network) toggle the "Show all/Show verified" button below.

Information for each burst is divided into two categories: intrinsic properties measured using the available data, and derived parameters produced using a model. Cosmological values are obtained using the Cosmology Calculator (Wright, 2006). The intrinsic parameters should be taken as lower limits, as the position within the telescope beam may be uncertain. Where multiple fits or measurements of a burst have been made each one is provided as a separate sub-entry for the FRB.

You may use the data presented in this catalogue for publications; however, we ask that you cite the paper (Petroff et al., 2016) and provide the url (http://www.frbcat.org). Any issues relating to the use of the catalogue should be addressed to FRBCAT team (primary contact: Emily Petroff).

Visible columns | Show verified | Export to CSV | Search | Clear

| | FRB | UTC | Telescope | RAJ | DECJ | GL | GB | DM | Width | SNR |
|---|---|---|---|---|---|---|---|---|---|---|
| + | FRB180311 | 2018/03/11 04:11:54.800 | Parkes | 21:31:33.42 | -57:44:26.7 | 337.3 | -43.7 | 1575.6 | 12 | 11.5 |
| + | FRB180309 | 2018/03/09 02:49:32.990 | Parkes | 21:24:43.8 | -33:58:44.5 | 10.9 | -45.4 | 263.47 | 0.576 | 411 |
| + | FRB180301 | 2018/03/01 07:34:19.760 | Parkes | 06:12:43.4 | 04:33:44.8 | 204.4 | -6.4 | 520 | 3 | 16 |
| + | FRB171209 | 2017/12/09 20:34:23.500 | Parkes | 15:50:25 | -46:10:20 | 332.2 | 6.24 | 1458 | 2.5 | 40 |
| + | FRB170922 | 2017/09/22 11:22:23.400 | UTMOST | 21:29:50.61 | -07:59:40.49 | 45.1 | -38.7 | 1111 | 26 | 22 |
| + | FRB170827 | 2017/08/27 16:20:18.000 | UTMOST | 00:49:18.66 | -65:33:02.3 | 303.2 | -51.7 | 176.4±0 | 0.4 | 90 |

http://frbcat.org/

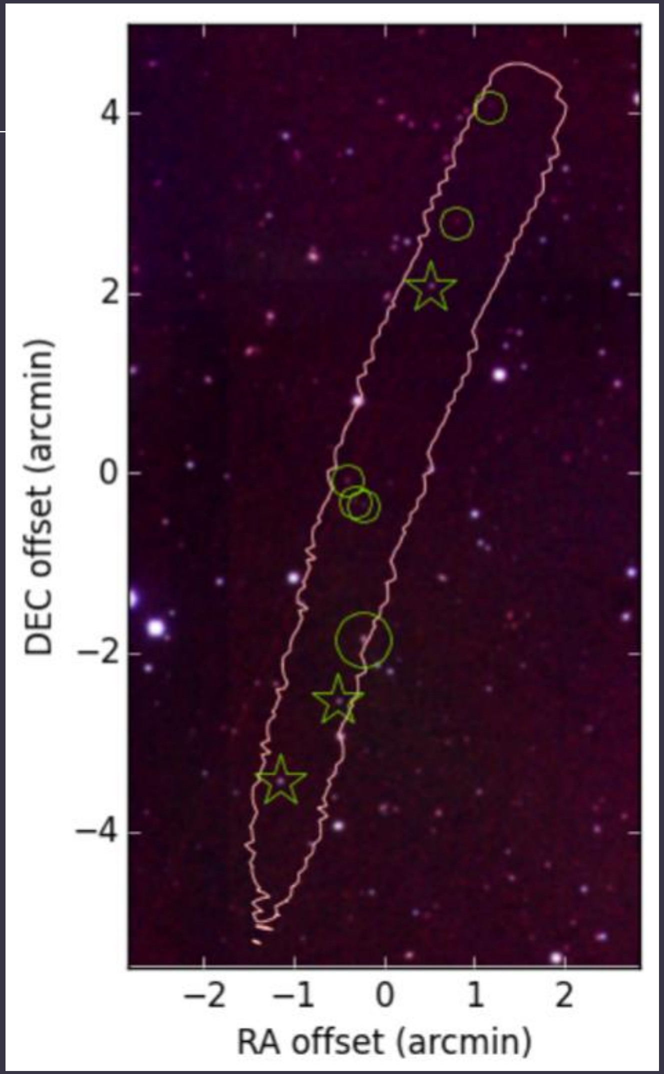
# Bright burst: FRB 150807

120+/-30 Jy
Detected in real time.
Was the brightest till 2018 (now – the second)

No counterparts. No repetitions.

Rotation measure detected.

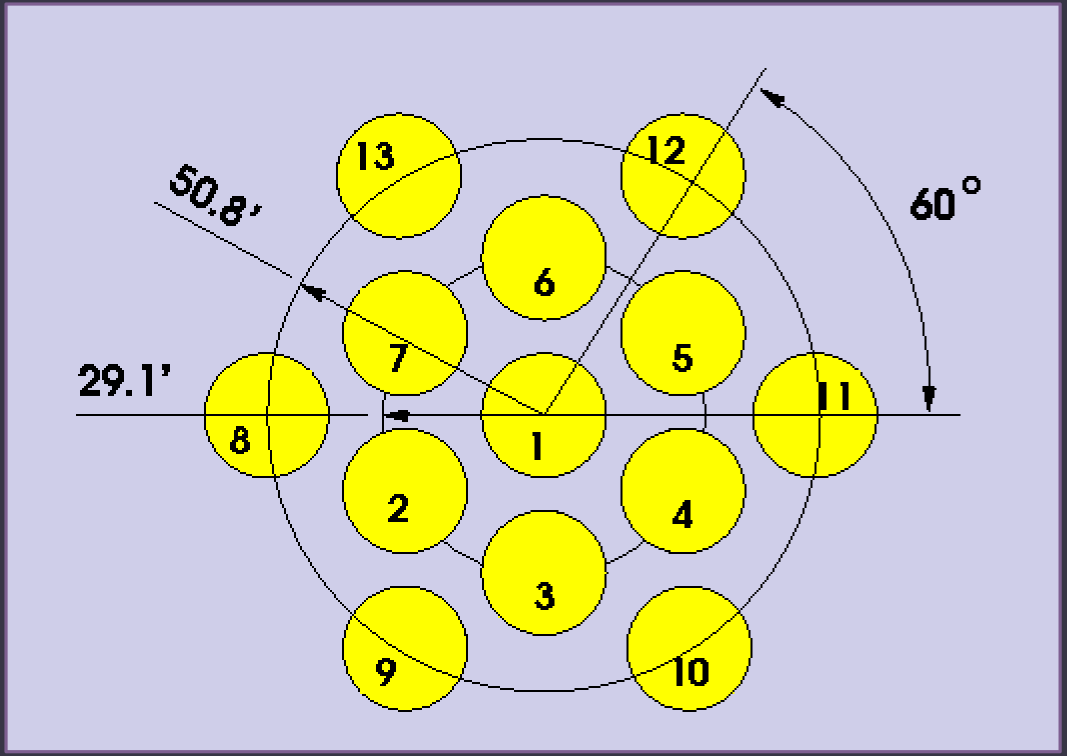
Relatively low DM
(~200 without the Galactic contribution).



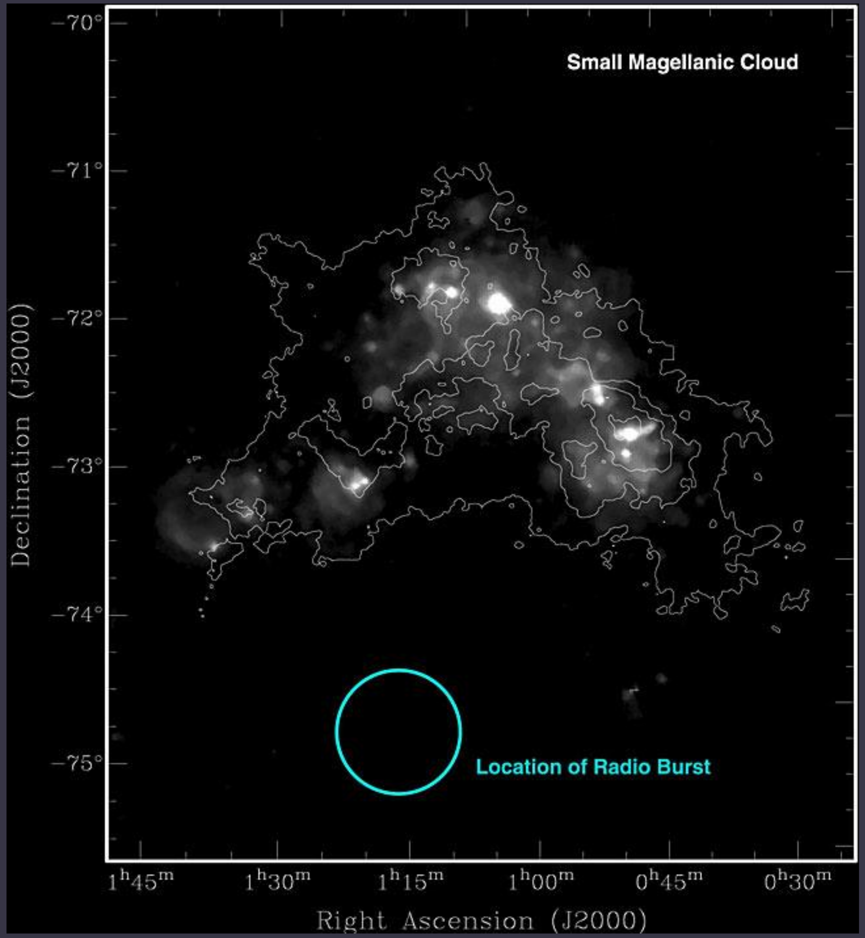

Localization – 9 arcmin

# Localization

Radius of uncertainty circle ~10 arcmin




Usually FRBs are seen just in one beam.



# Repeating bursts

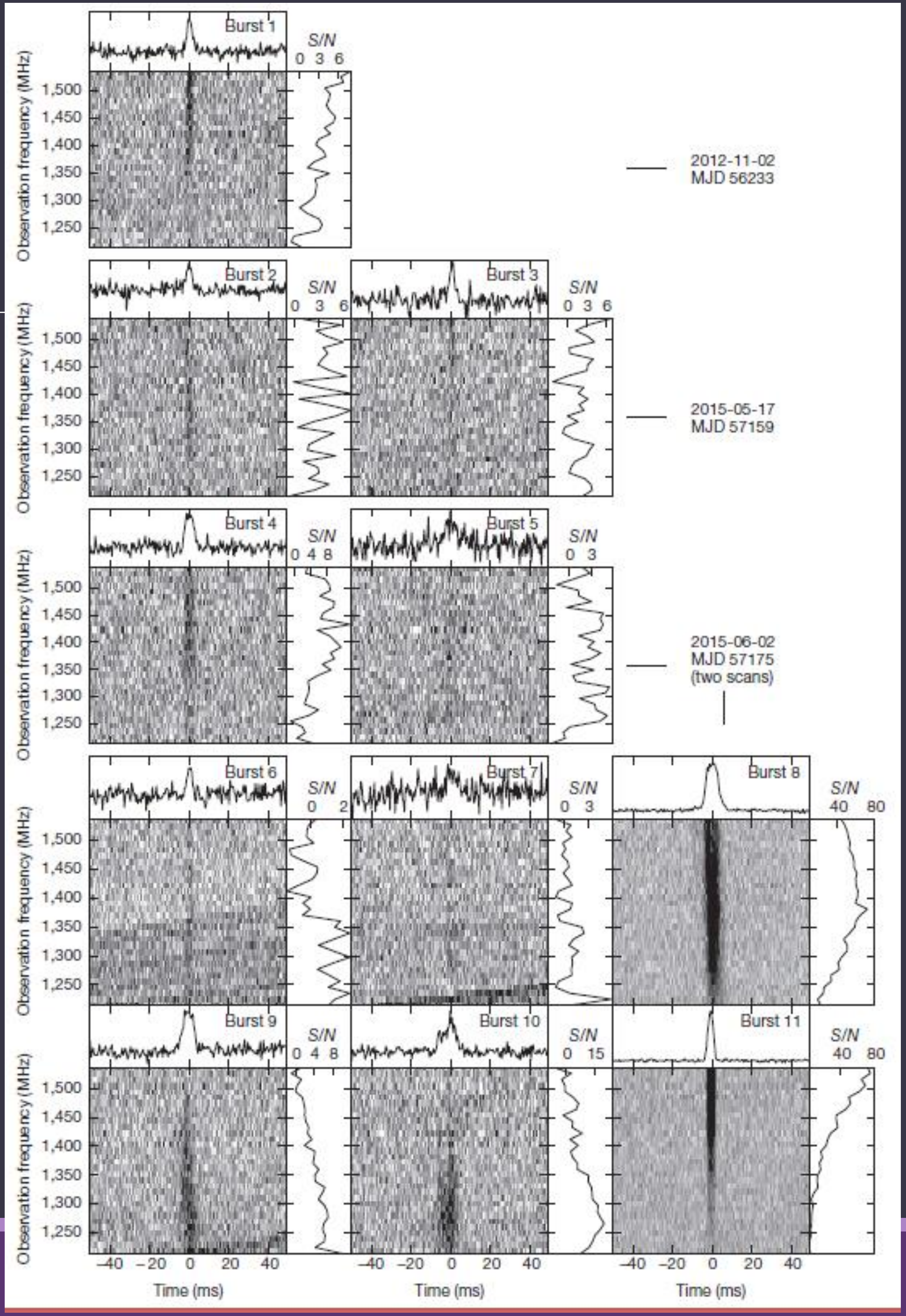
Repeating bursts are detected firstly  from FRB 121102.

The source was found at Arecibo.

Initially 10 events reported.
Rate ~ 3/hour
Weak bursts (<0.02-0.3 Ян)

Variable spectral parameters.

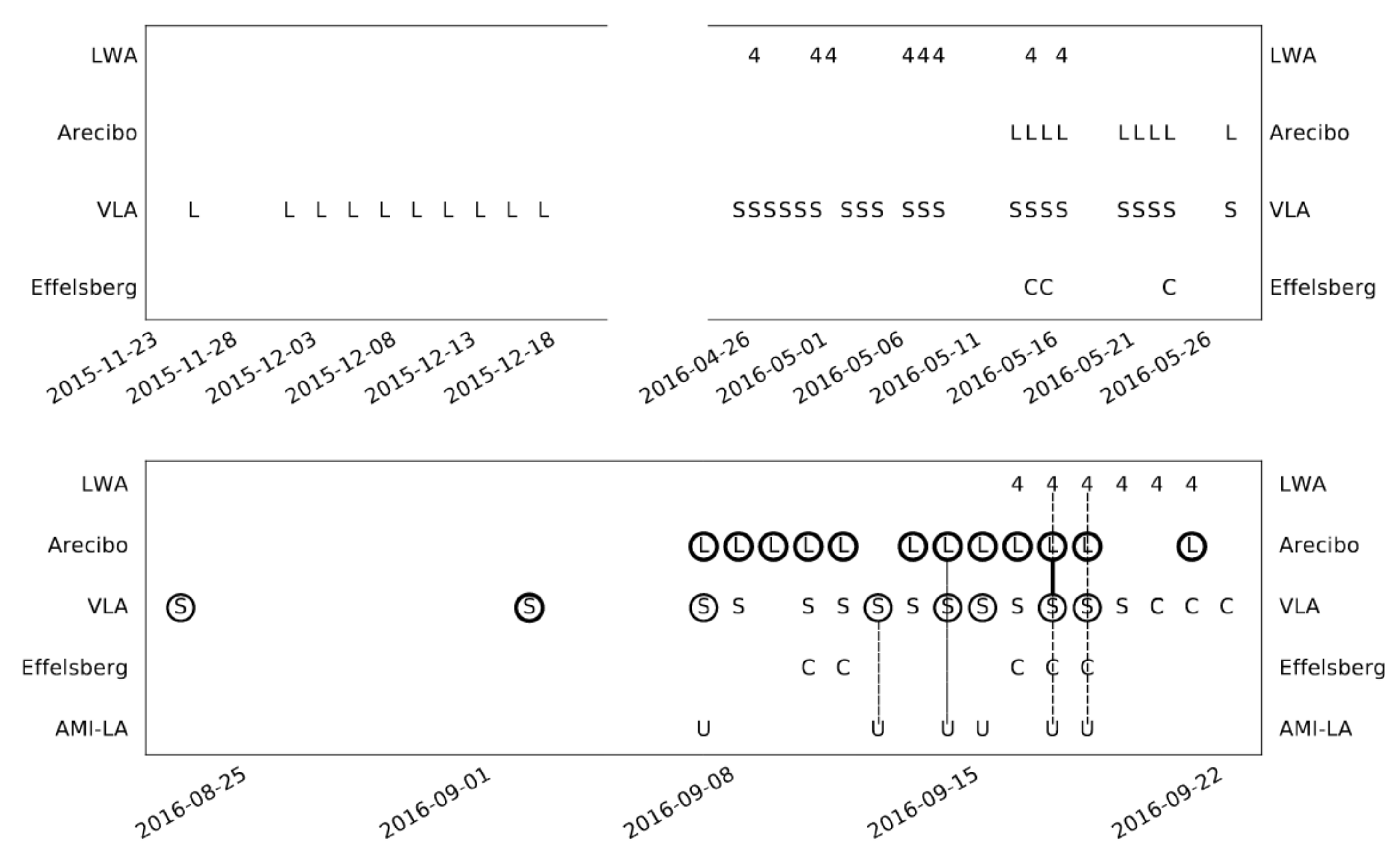
Unclear if it is a unique source,
or it is a close relative of other FRBs.



# VLA, Arecibo and all the rest

During periods of activity rate is few per hour.

Simultaneous detection with Arecibo, VLA and other instruments.

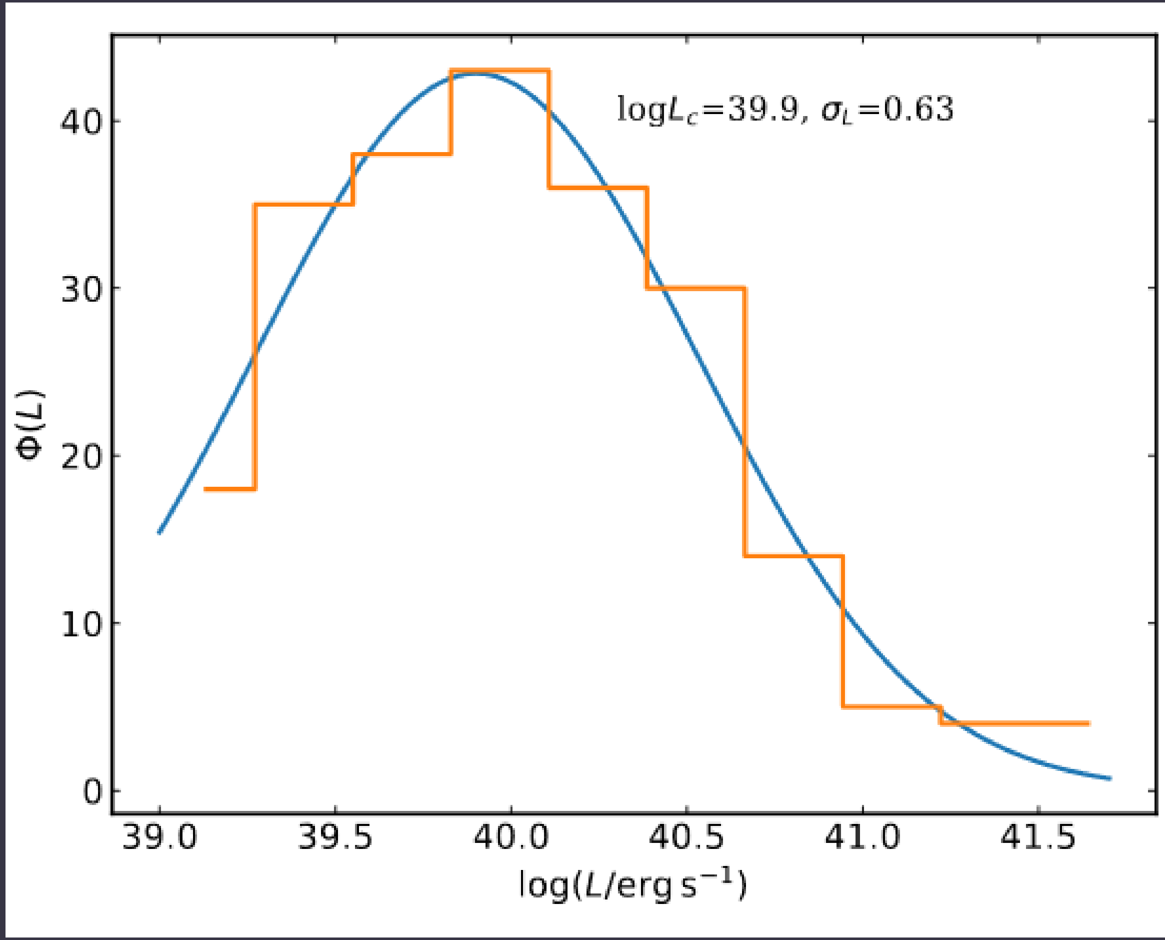



The source is also detected at 4-8 GHz
and polarization is measured (1801.03965).

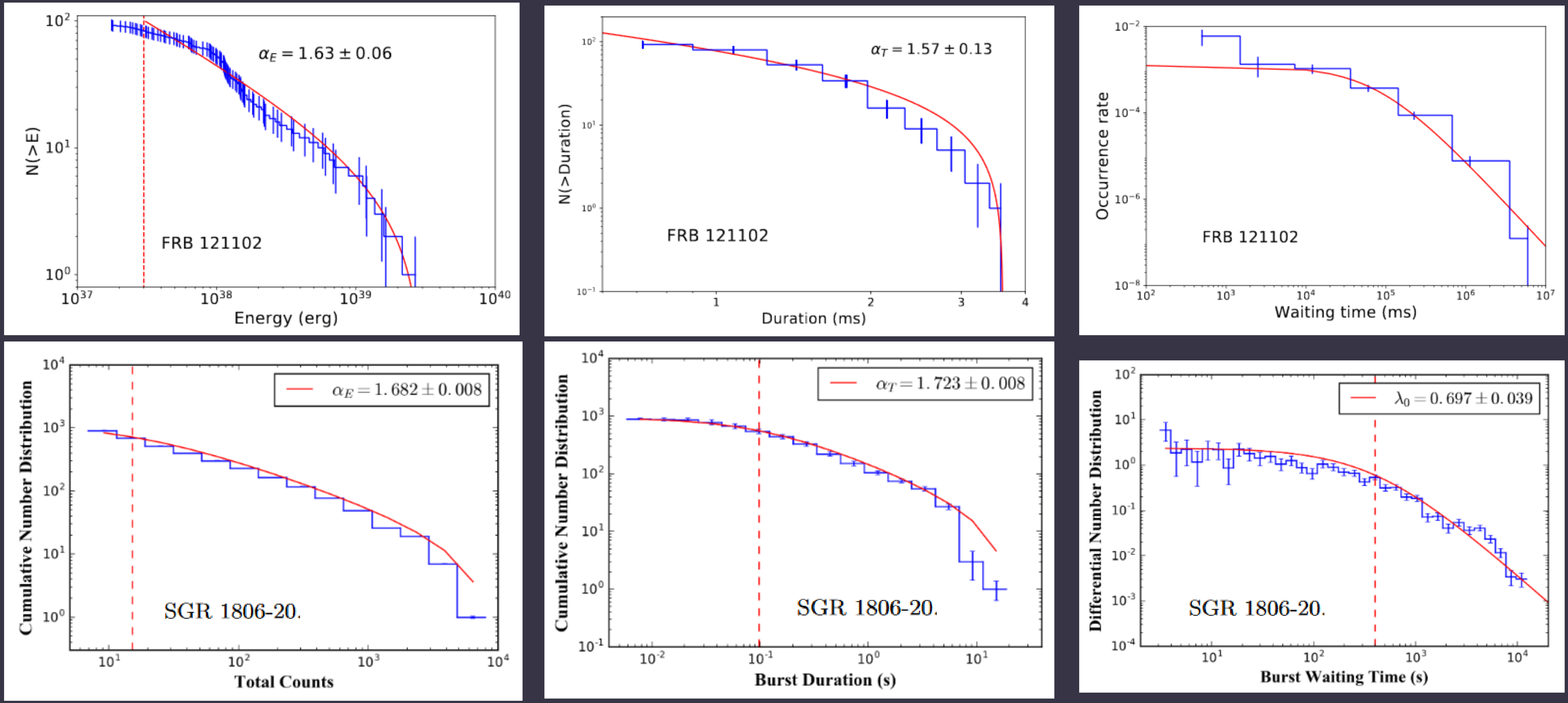
# Luminosity distribution

$$\Phi(L|L_c,\sigma_L)=\frac{1}{\sqrt{2\pi}\sigma_L L}e^{-\frac{1}{2}\left[\log\left(\frac{L}{L_c}\right)/\sigma_L\right]^2}$$

227 bursts used for the plot.



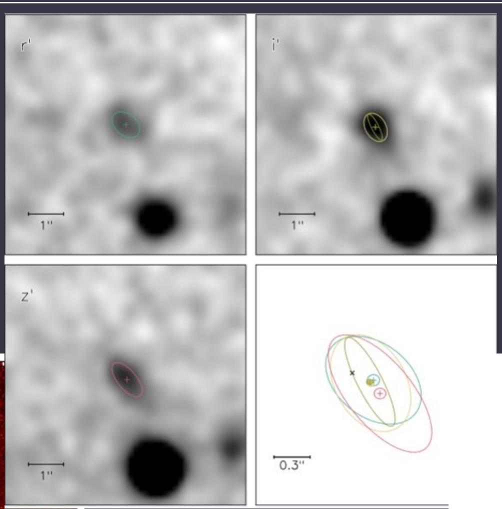
# SGRs vs. FRBs

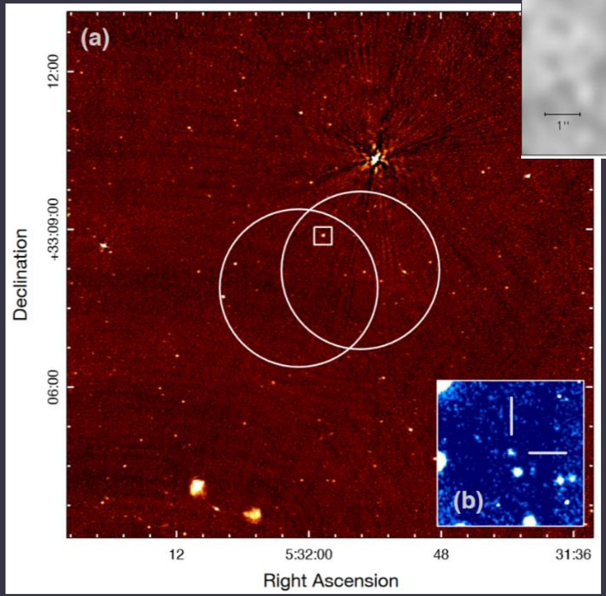


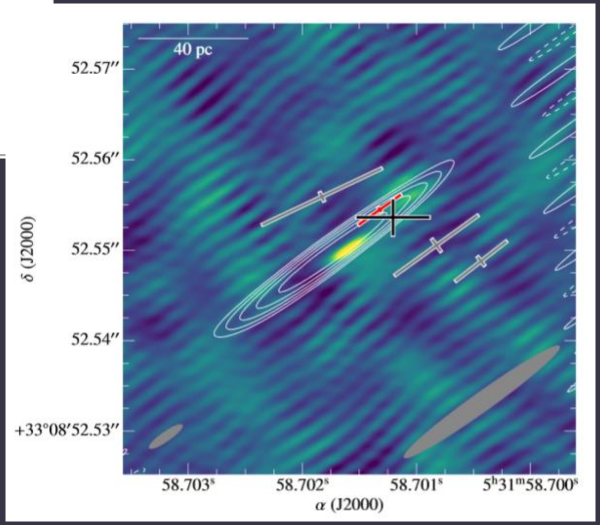

1910.14201

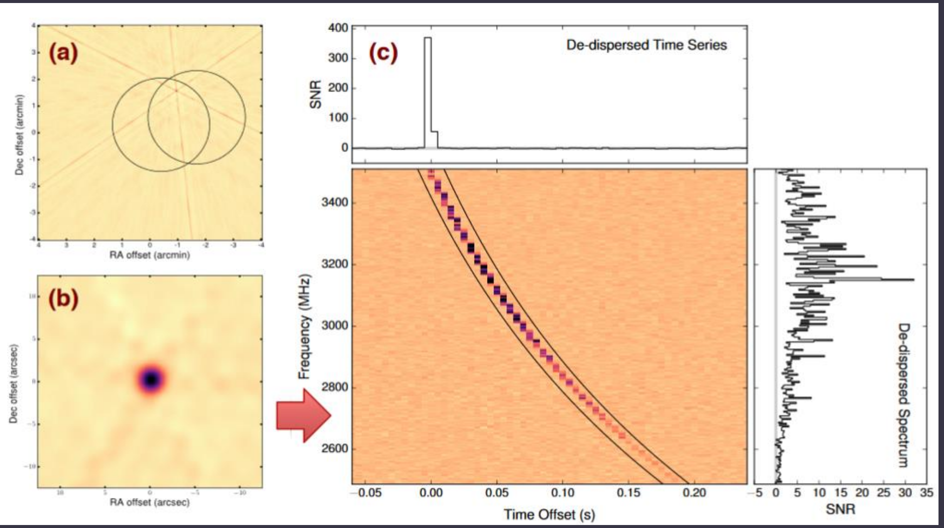
# Host galaxy of the FRB

Thanks to precise localization of FRB 121102
it became possible to identify a host galaxy.
This a dwarf galaxy with high starformation rate
at z~0.2 (~1 Gpc).



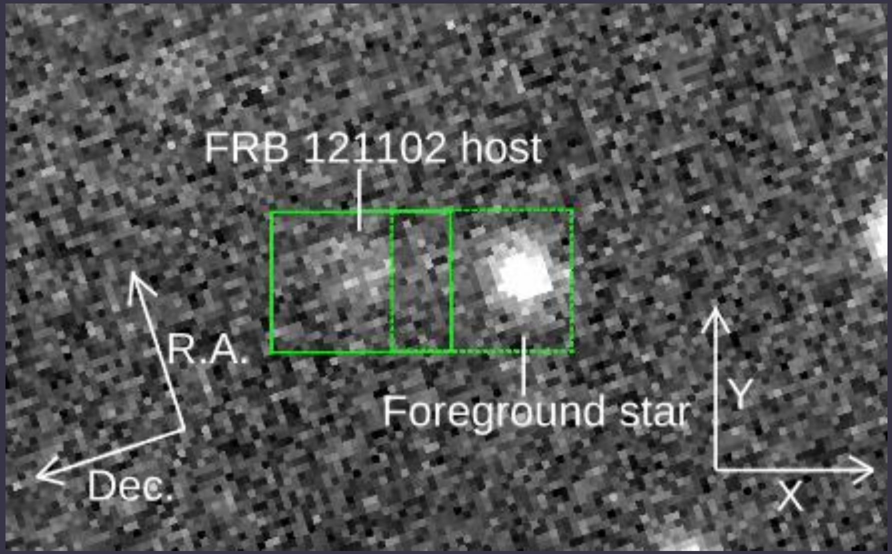



# H-alpha emission in the host galaxy of FRB 121102

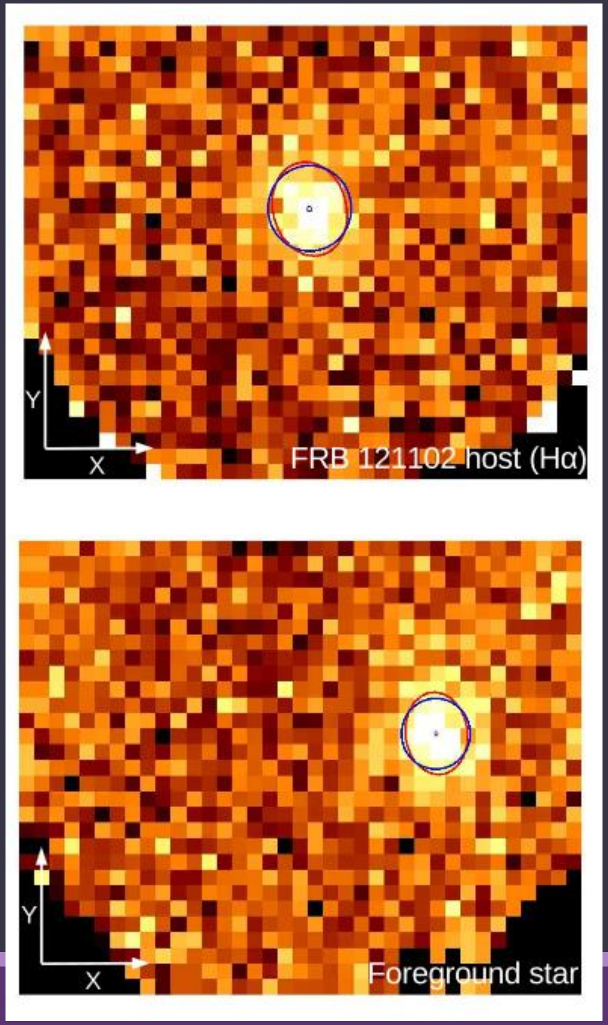
1705.04693




Keck observations.
Rectangles show the areas observed at Subaru.

Coincidence of the FRB position with a H-alpha region is an argument in favour of models involving young neutron stars.

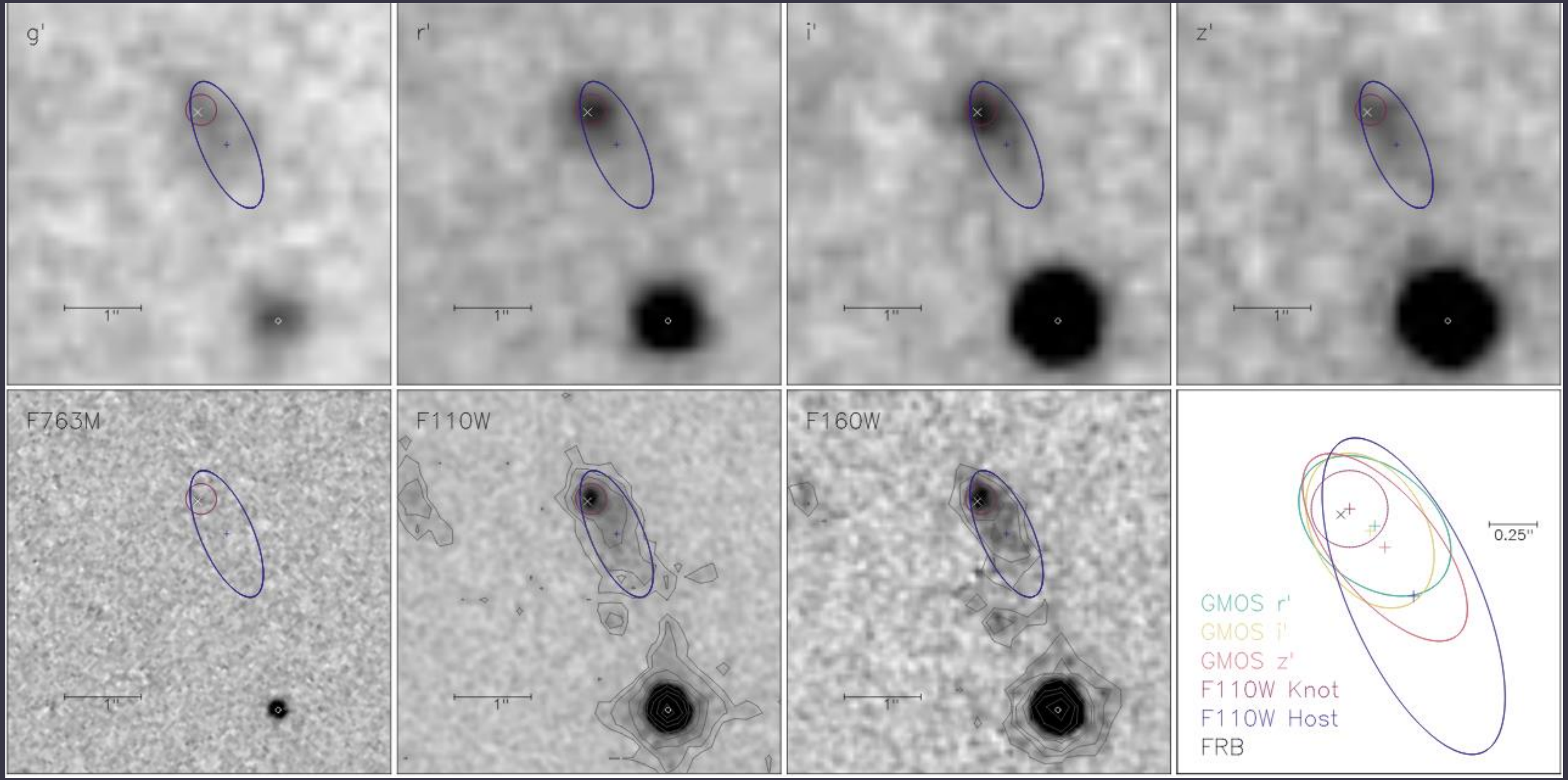
H-alpha region can also contribute to the observed dispersion measure.



# Starformation region and FRB 121102

Gemini, Hubble, Spitzer

Irregular dwarf low mass low metallicity galaxy.

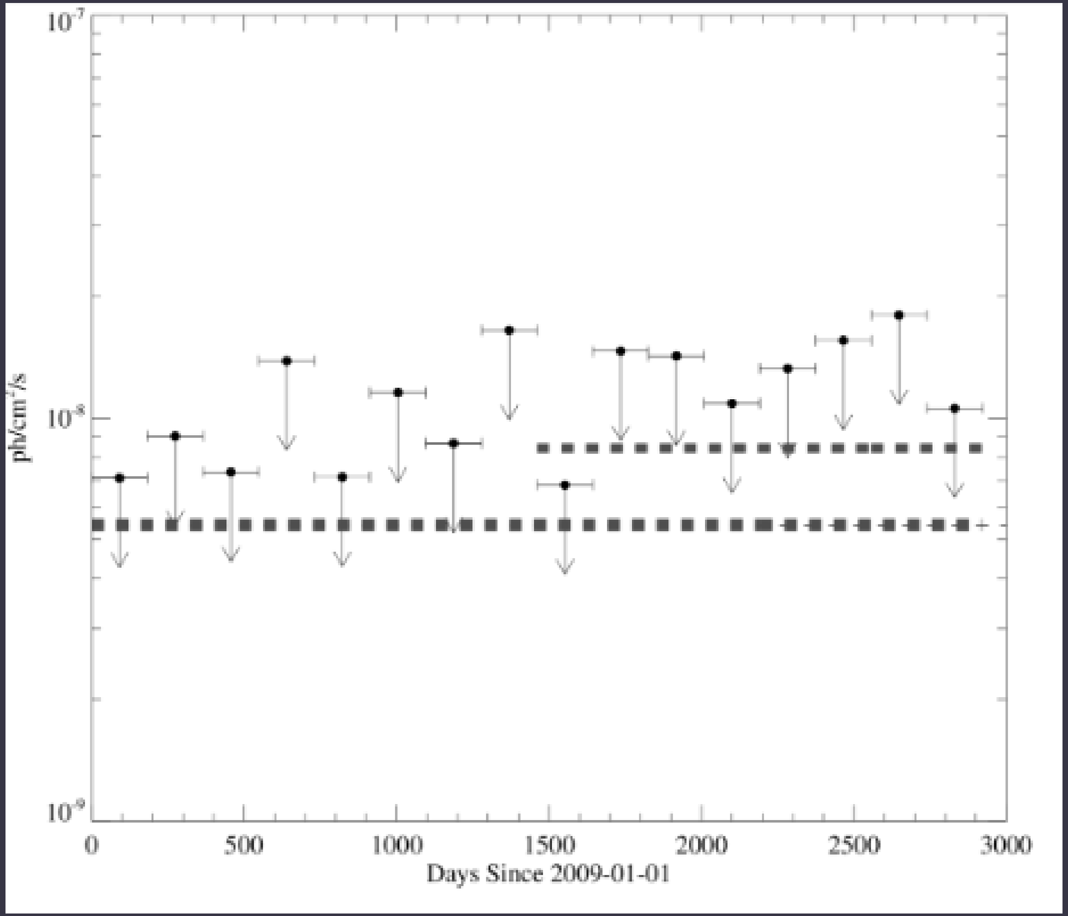



1705.07698

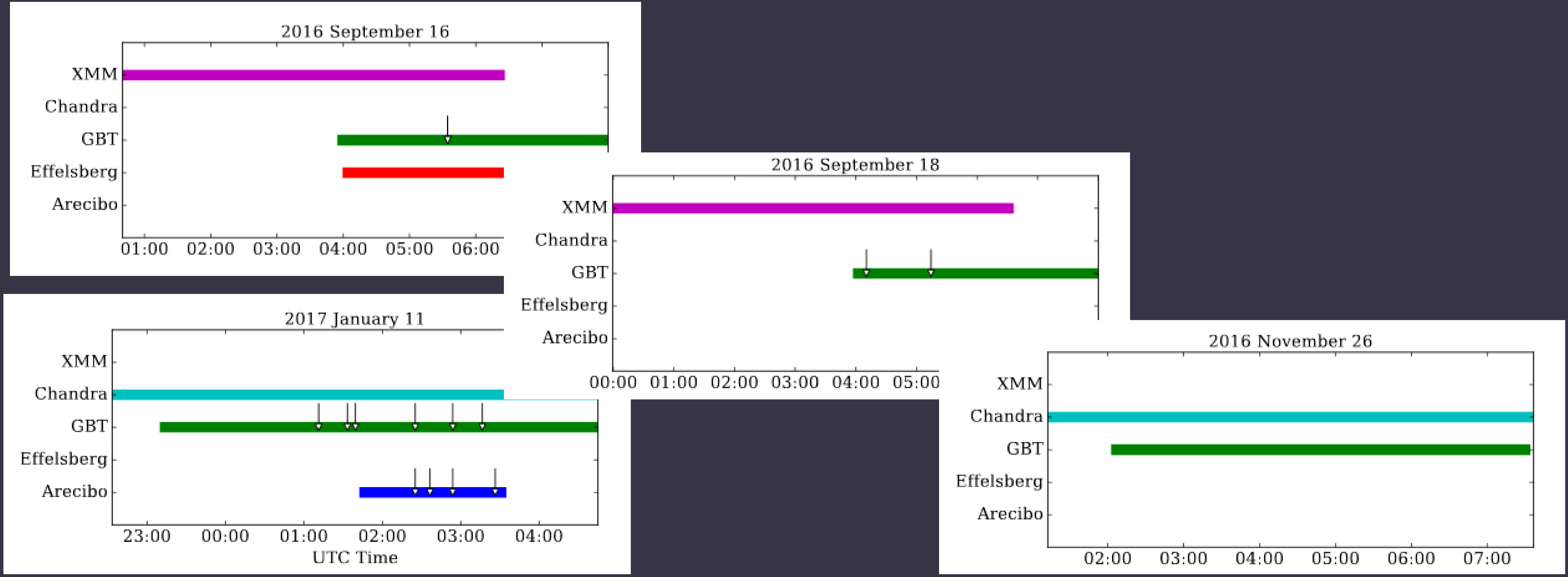
# Fermi limits on the gamma-ray emission of the repeating FRB

Despite many effort no counterparts detected.

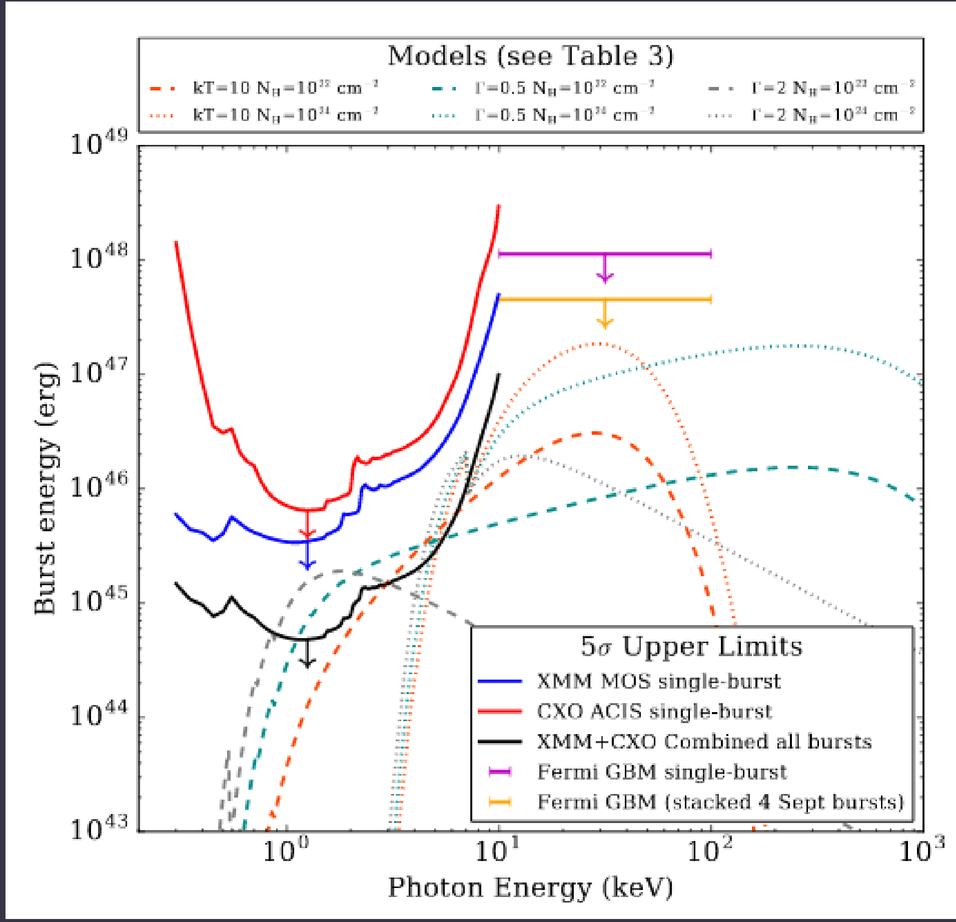
Now simultaneous observations are done also with Integral (Atel 13073, 13075)



# No simultaneous X-ray bursts



# Simultaneous observation in radio and X-rays



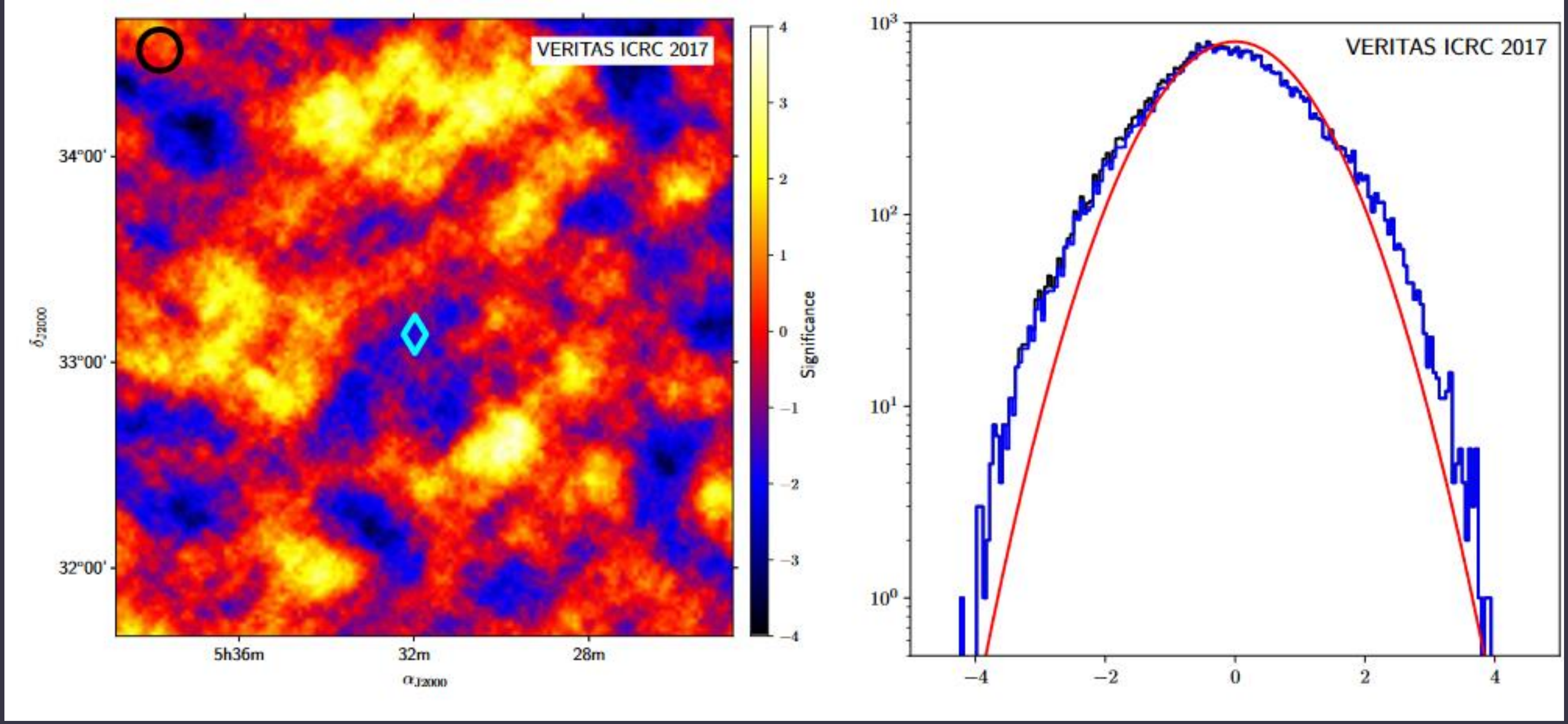

12 radio bursts during ~70 ksec of X-ray observations.
No activity in X-ray detected.

| Model | $N_H$ ($cm^{-2}$) | kT/Γ (keV/-) | Absorbed 0.5–10 keV Fluence Limit ($10^{-11}$ erg $cm^{-2}$) | Unabsorbed 0.5–10 keV Energy Limit[a] ($10^{45}$ erg) | Extrapolated 10 keV–1 MeV Energy Limit[a] ($10^{47}$ erg) |
|---|---|---|---|---|---|
| Blackbody | $10^{22}$ | 10 | 5 | 6 | 2 |
| Blackbody | $10^{24}$ | 10 | 13 | 110 | 30 |
| Cutoff PL | $10^{22}$ | 0.5 | 3 | 4 | 13 |
| Cutoff PL | $10^{24}$ | 0.5 | 11 | 120 | 400 |
| Soft PL | $10^{22}$ | 2 | 1.3 | 3 | 0.04 |
| Soft PL | $10^{24}$ | 2 | 8 | 300 | 40 |

1705.07824

# Observations of FRB 121102 with VERITAS

No signal detected during >10 hours of observational time.
Signal above 1 TeV is expected to be absent due to EBL.

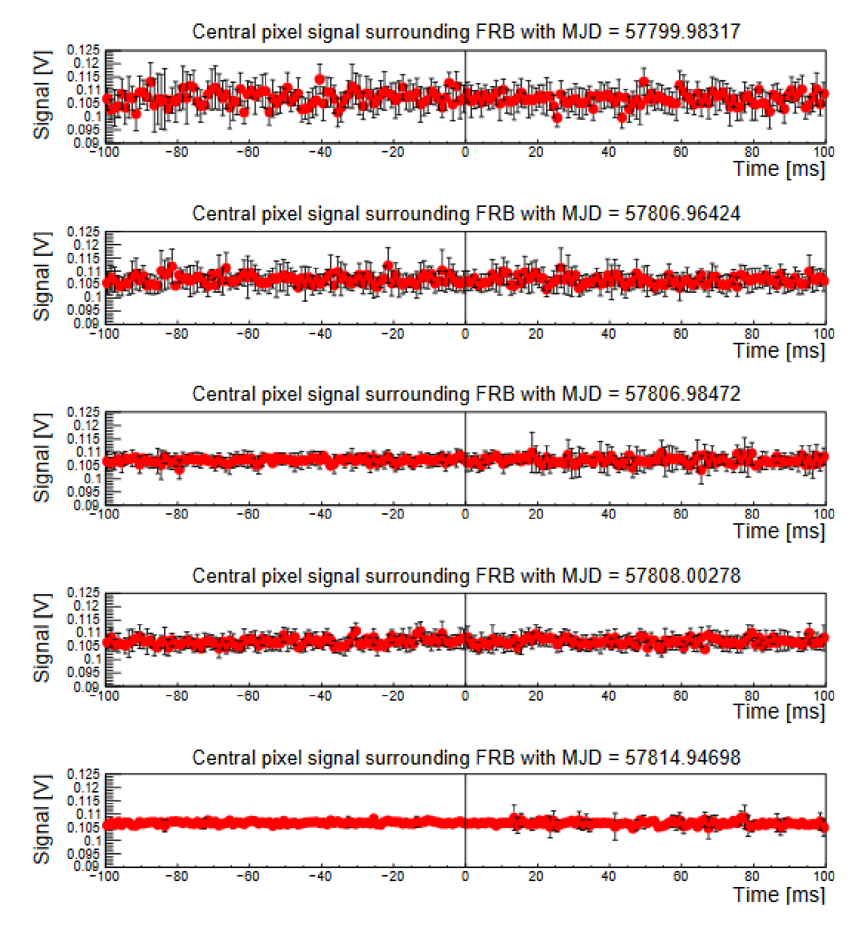



1708.04717

# MAGIC upper limits

Simultaneous observations with Arecibo.

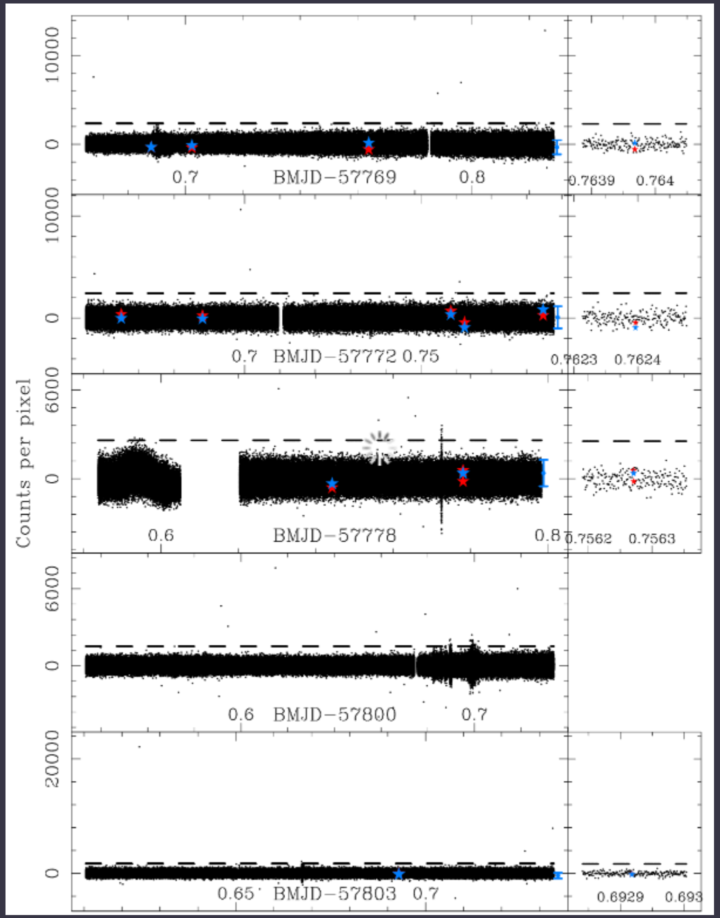
In radio 5 bursts have been detected, and nothing in gamma/optical.



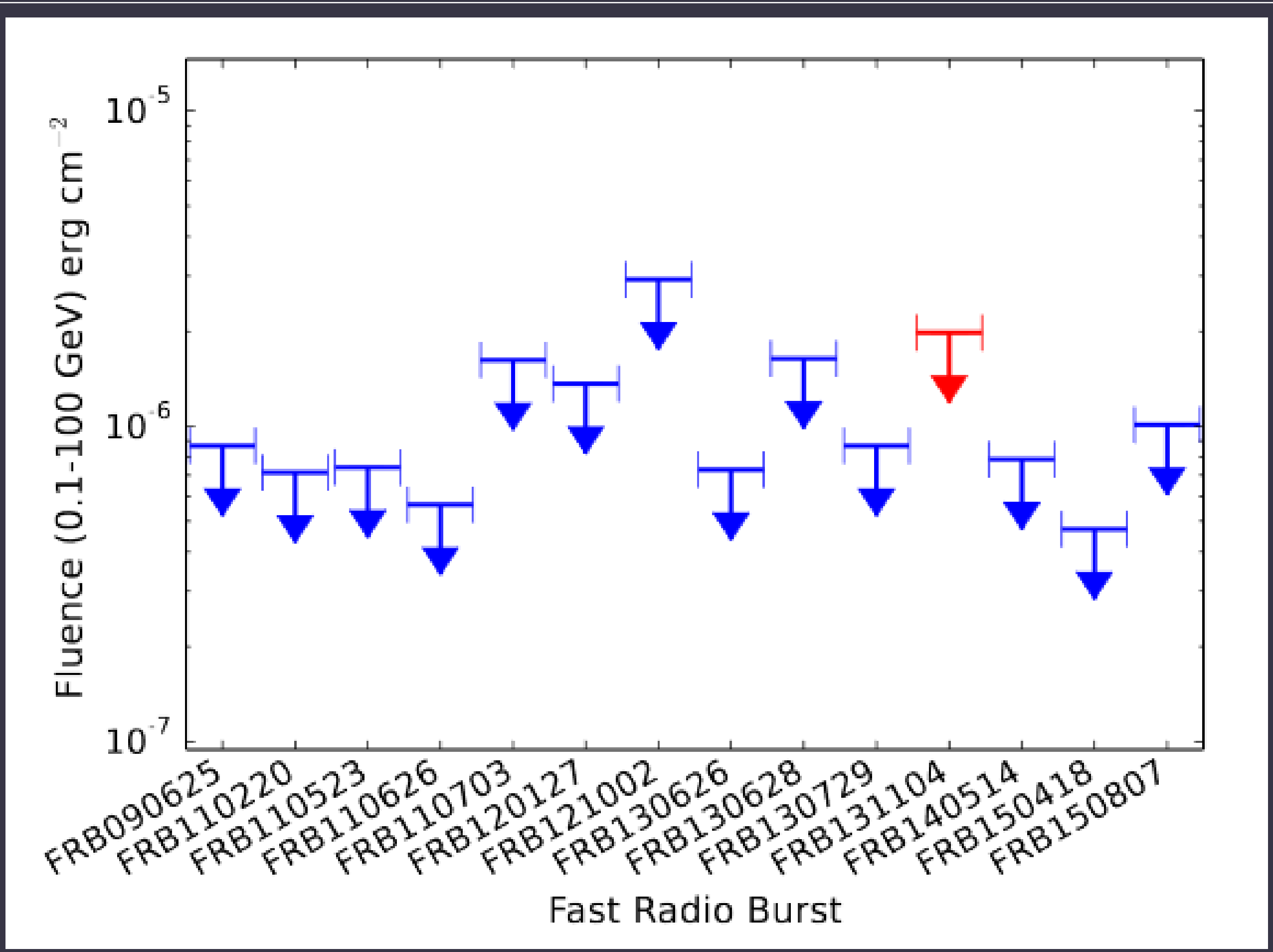

1809.00663 (see some update in 1908.07506)

# No optical flares from FRB121102

Simultaneous observations in radio (Effelsberg)
and optics (2.4-meter telescope).
13 radio bursts detected. Nothing in optics.



# Limits on gamma-emission




Fermi data

# No FRBs from GRB remnants

| GRB name* (yymmdd) | Redshift | RA (h : m : s) | Dec (° : ′ : ″) | $DM_{IGM}$ ($cm^{-3}$ pc) | $DM_{MW}$† ($cm^{-3}$ pc) | Obs. telescope | Obs. time (minutes) | Comments |
|---|---|---|---|---|---|---|---|---|
| 030329 | 0.168 | 10:44:50.00 | +21:31:17.8 | 147 | 17 | Arecibo | 340.7 | LGRB+SN2003dh |
| 130603B | 0.3564 | 11:28:48.16 | +17:04:18.0 | 311 | 29 | Arecibo | 448.8 | short GRB |
| 111225A | 0.297 | 00:52:37.21 | +51:34:19.5 | 259.875 | 118.09 | GBT | 76.5 | LGRB |
| 051109B | 0.08 | 23:01:50.30 | +38:40:46.7 | 70.0 | 71.17 | GBT | 131.3 | LGRB |
| 111005A | 0.013 | 14:53:07.74 | -19:44:08.9 | 11.375 | 51.12 | GBT | 82.5 | LGRB |
| 980425 | 0.0085 | 13:25:41.93 | -26:46:55.7 | 7.43 | 53.59 | GBT | 70.6 | LGRB+SN1998bw |

No bursts in 20 hours. Means that these GRBs did not produce analogues of FRB 121102

1908.10222, see also 1909.11682

# No FRBs from SLSN-I remnants

| Name | Redshift | R.A. (J2000) | Decl. (J2000) | Age (yr) |
|---|---|---|---|---|
| SN 2005ap[a] | 0.283 | 13:01:14:83 | +27:43:32:3 | 9.9 |
| SN 2007bi | 0.127 | 13:19:20:14 | +08:55:43:7 | 9.4 |
| SN 2006oz | 0.396 | 22:08:53:56 | +00:53:50:4 | 8.0 |
| PTF10hgi[c] | 0.098 | 16:37:47:04 | +06:12:32:3 | 6.8 |
| PTF09cnd | 0.258 | 16:12:08:94 | +51:29:16:1 | 6.6 |
| SN 2010kd | 0.101 | 12:08:00:89 | +49:13:32:9 | 6.4 |
| SN 2010gx[b] | 0.23 | 11:25:46:71 | -08:49:41:4 | 6.2 |
| PTF09cwl | 0.349 | 14:49:10:08 | +29:25:11:4 | 6.1 |
| SN 2011ke | 0.143 | 13:50:57:77 | +26:16:42:8 | 5.7 |
| PTF09atu | 0.501 | 16:30:24:55 | +23:38:25:0 | 5.5 |

No FRB detections.

VLA. 3 GHz

Typical observation 0.5 – 1 hour.

PTF10hgi is consistent with the magnetar model.

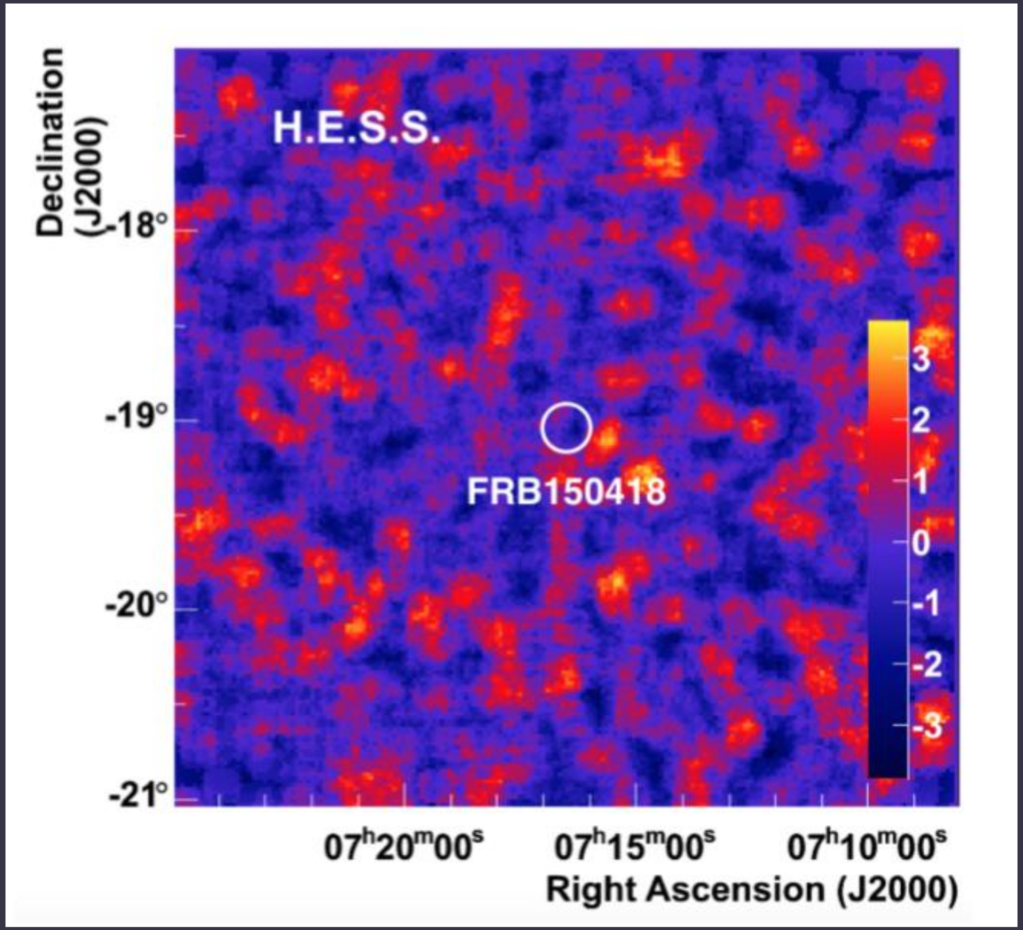
# No FRBs from SGRBs sites

| Source | R.A. (hh:mm:ss) | Dec (dd:mm:ss) | Redshift | Distance (Gpc) | $DM_{gal}$ (pc cm$^{-3}$) | Age (yr) |
|---|---|---|---|---|---|---|
| GRB 050509B | 12:36:14 | +28:59:05 | 0.225 | 1.16 | 19.85 | 12.0 |
| GRB 050709 | 23:01:27 | −38:58:40 | 0.160 | 0.79 | 32.87 | 11.8 |
| GRB 080905A | 19:10:42 | −18:52:49 | 0.122 | 0.59 | 177.57 | 8.6 |
| GRB 130603B | 11:28:48 | +17:04:18 | 0.356 | 1.96 | 29.28 | 3.9 |
| GRB 150101B | 12:32:05 | −10:56:02 | 0.134 | 0.65 | 36.57 | 2.4 |
| GRB 160821B | 18:39:55 | +62:23:31 | 0.160 | 0.79 | 55.54 | 0.1 |

| Source | Telescope | $E_{max}/10^{38}$ (erg) |
|---|---|---|
| GRB 050509B | GBT | 1.38 |
| GRB 050509B | Arecibo | 0.33 |
| GRB 050709 | GBT | 0.60 |
| GRB 080905A | GBT | 0.33 |
| GRB 130603B | GBT | 4.35 |
| GRB 130603B | Arecibo | 1.05 |
| GRB 150101B | GBT | 0.40 |
| GRB 160821B | GBT | 0.60 |

1909.11682

# TeV range observations




H.E.S.S.
FRB 150418

Observations within
15-16 hours after the burst.

~1 hour of observations

No signal.

# X-ray limits from AstroSat

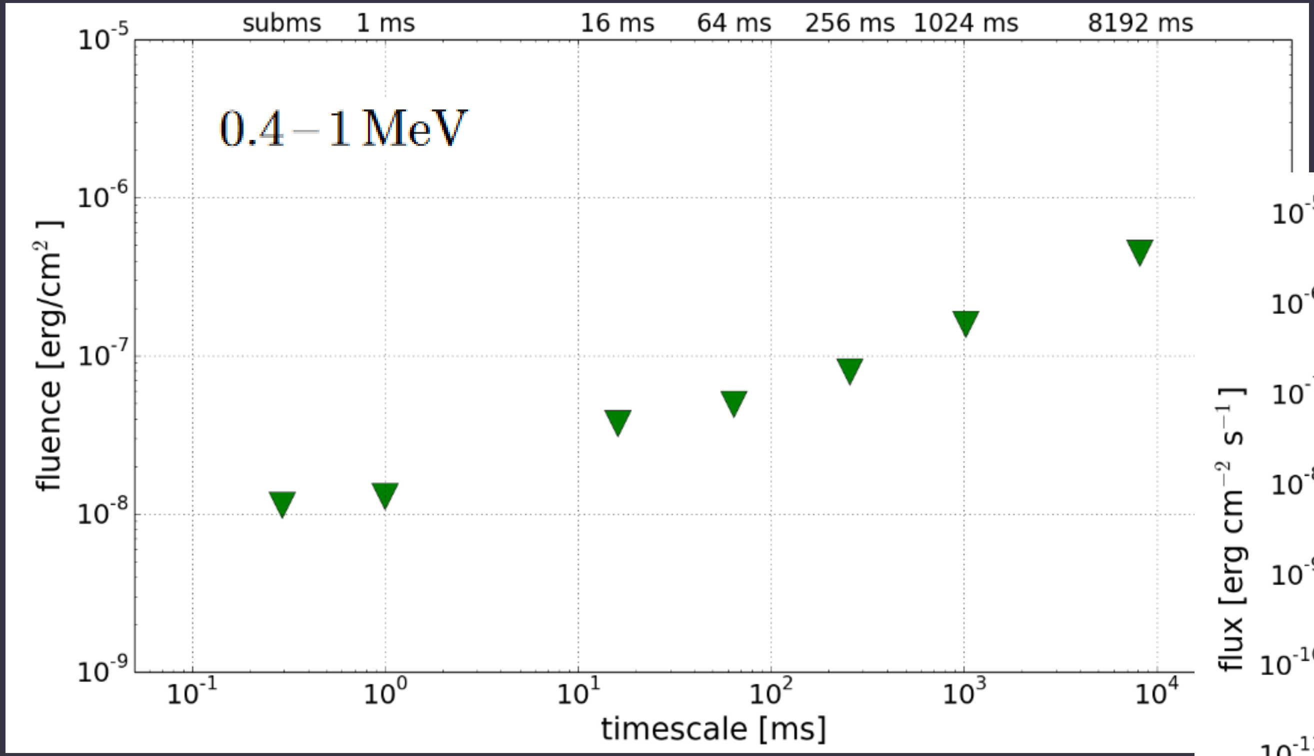
Limits for 41 FRBs

| Name (Reference to original detection) | Radio Flux Density Jy | Radio Fluence Jy-ms | tbin s | $\Gamma_{max}$ | X-ray fluence erg cm$^{-2}$ $\Gamma=-1$ | $\Gamma=\Gamma_{max}$ | $\eta/10^9 = \frac{F_{X-ray}}{F_{Radio}}/10^9$ $\Gamma=-1$ | $\Gamma=\Gamma_{max}$ |
|---|---|---|---|---|---|---|---|---|
| FRB190806 | 3.91 | 46.8 | 0.01 | −1.19 | 1.6e−07 | 1.65e−07 | 0.34 | 0.35 |
| (Gupta et al. 2019a) | | | 0.1 | −1.25 | 3.67e−07 | 3.84e−07 | 0.78 | 0.82 |
| | | | 1.0 | −1.33 | 5.69e−07 | 6.03e−07 | 1.21 | 1.29 |
| FRB190714 | 4.7 | 8.0 | 0.01 | −1.24 | 7.38e−08 | 7.47e−08 | 0.92 | 0.93 |
| (Bhandari et al. 2019) | | | 0.1 | −1.3 | 1.67e−07 | 1.69e−07 | 2.08 | 2.11 |
| | | | 1.0 | −1.38 | 2.72e−07 | 2.76e−07 | 3.4 | 3.45 |
| FRB190711 | 4.1 | 28.0 | 0.01 | −1.16 | 4.33e−07 | 4.44e−07 | 1.55 | 1.59 |
| (Shannon et al. 2019) | | | 0.1 | −1.22 | 9.72e−07 | 1.01e−06 | 3.47 | 3.6 |
| | | | 1.0 | −1.3 | 1.55e−06 | 1.64e−06 | 5.55 | 5.85 |

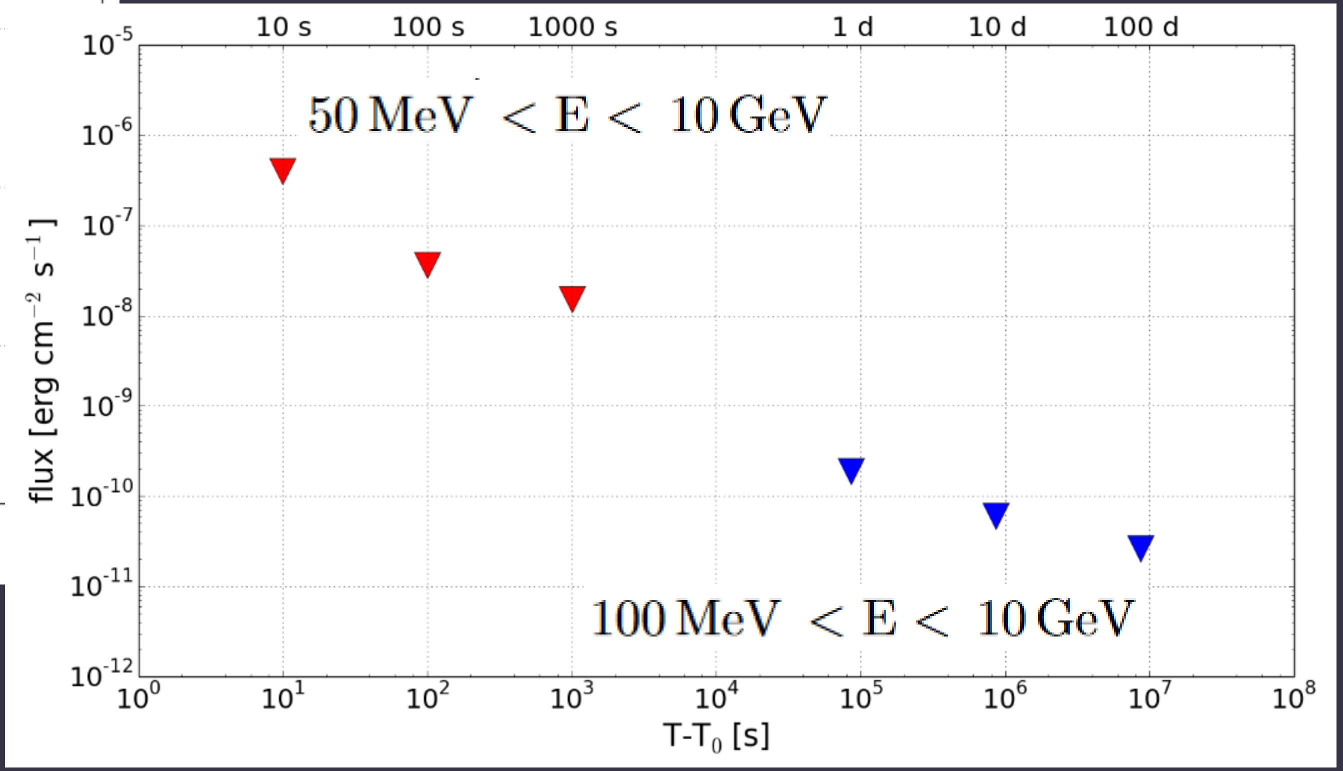
The authors provide Limits for Γ=-1.
They are not very constraining:
fluence <~$10^{-7}$ erg/cm$^2$

1911.00537

# MeV limits from AGILE

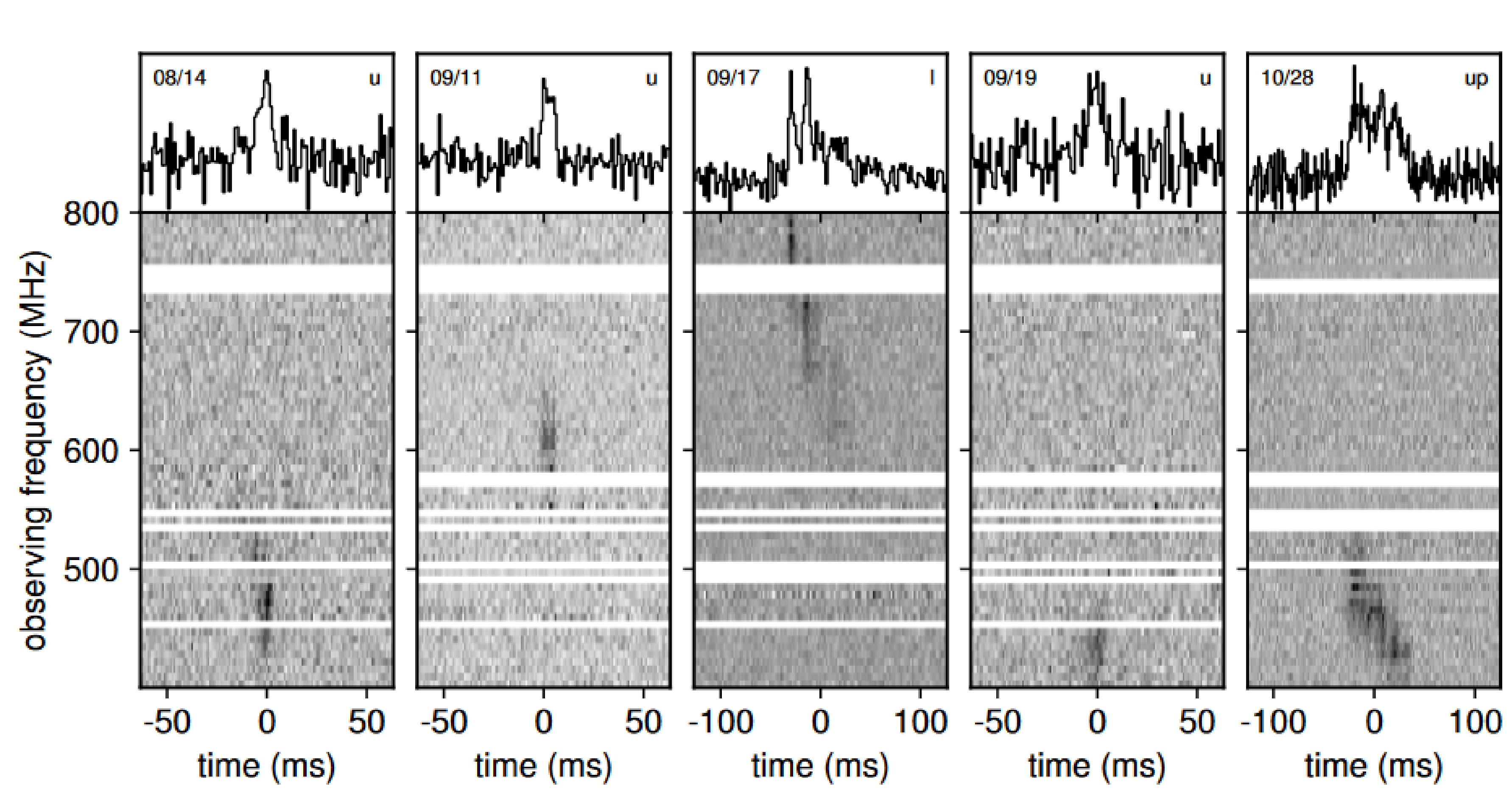



Restrictive only for distances ~100 kpc.



# The second repeater

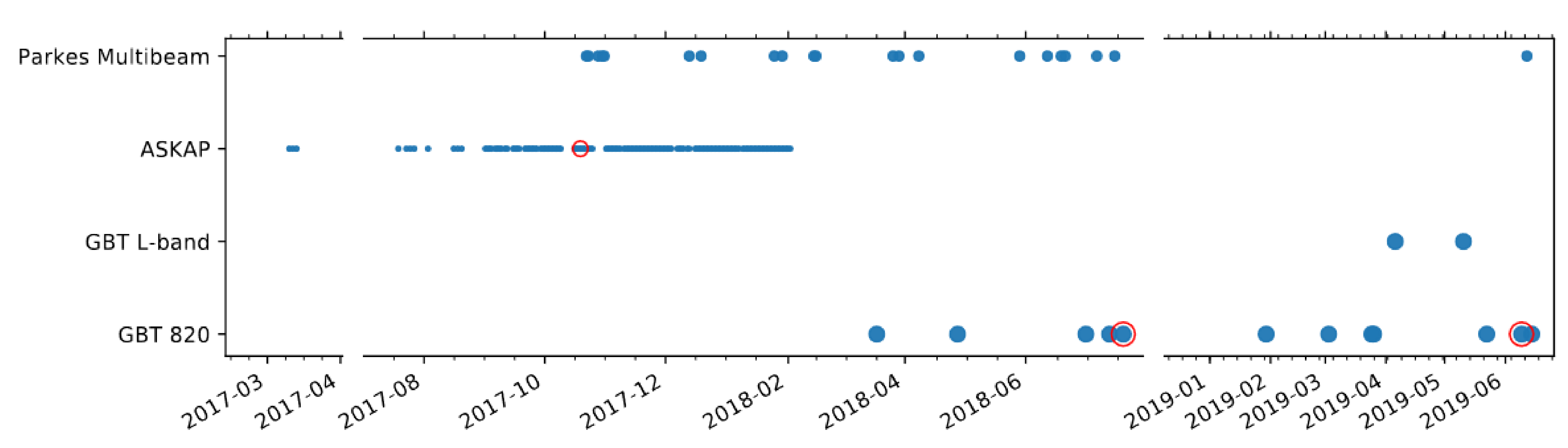
FRB 180814
CHIME



# The third repeater

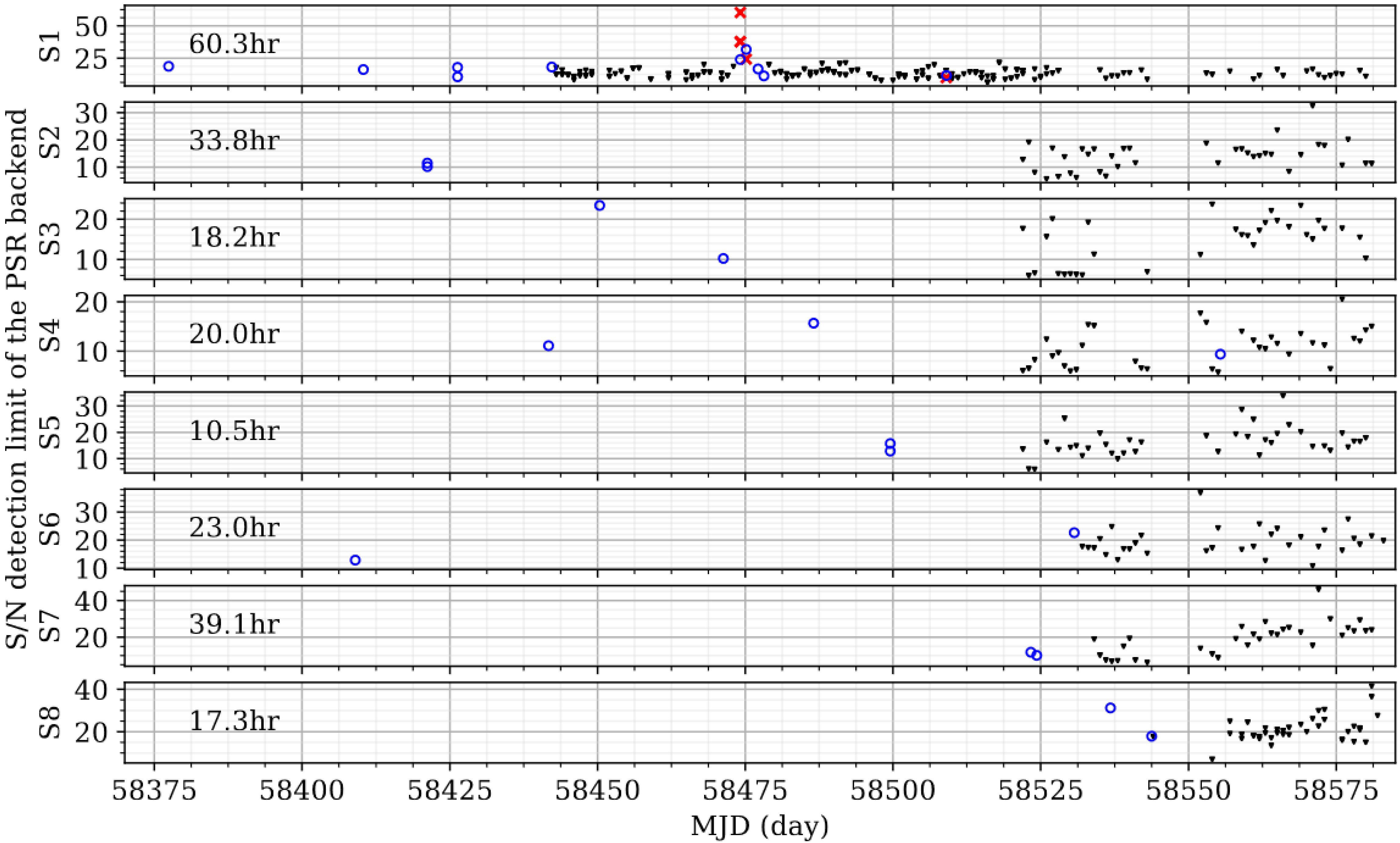
FRB 171019 Discovered by ASKAP.

Two weak bursts detected at ~800MHz by GBT.



# Eight repeaters from CHIME

| Source | Name[a] | R.A.[b] (J2000) | Dec.[b] (J2000) | $l^c$ (deg) | $b^c$ (deg) | DM[d] (pc cm$^{-3}$) | $DM^c_{NE2001}$ (pc cm$^{-3}$) | $DM^c_{YMW16}$ (pc cm$^{-3}$) | $N_{bursts}$ | Exposure[f] (hr, upper / lower) | Completeness[g] (Jy ms) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 180916.J0158+65 | 1h58m±7′ | +65°44′±11′ | 129.7 | 3.7 | 349.2(3) | 200 | 325 | 10 | 23±8 | 4.2 |
| 2 | 181030.J1054+73 | *10h54m±8′* | *+73°44′±26′* | 133.4 | 40.9 | 103.5(3) | 40 | 32 | 2 | 27±14 / 19±11 | ... / 17 |
| 3 | 181128.J0456+63 | *4h56m±11′* | *+63°23′±12′* | 146.6 | 12.4 | 450.5(3) | 112 | 151 | 2 | 16±10 | 4.0 |
| 4 | 181119.J12+65 | 12h42m±3′ | +65°08′±9′ | 124.5 | 52.0 | 364.05(9) | 34 | 26 | 3 | 19±9 | 2.6 |
| | | 12h30m±6′ | +65°06′±12′ | | | | | | | | |
| 5 | 190116.J1249+27 | 12h49m±8′ | +27°09′±14′ | 210.5 | 89.5 | 441(2) | 20 | 20 | 2 | 8±5 | 5.7 |
| 6 | 181017.J1705+68 | *17h05m±12′* | *+68°17′±12′* | 99.2 | 34.8 | 1281.6(4) | 43 | 37 | 2 | 20±11 | 5.6 |
| 7 | 190209.J0937+77 | *9h37m±8′* | *+77°40′±16′* | 134.2 | 34.8 | 425.0(3) | 46 | 39 | 2 | 34±19 / 28±18 | 3.8 / ... |
| 8 | 190222.J2052+69 | 20h52m±10′ | +69°50′±11′ | 104.9 | 15.9 | 460.6(2) | 87 | 101 | 2 | 20±10 | 5.4 |


S/N detection limit of the PSR backend
S1
60.3hr
S2
33.8hr
S3
18.2hr
S4
20.0hr
S5
10.5hr
S6
23.0hr
S7
39.1hr
S8
17.3hr
58375
58400
58425
58450
58475
58500
58525
58550
58575
MJD (day)

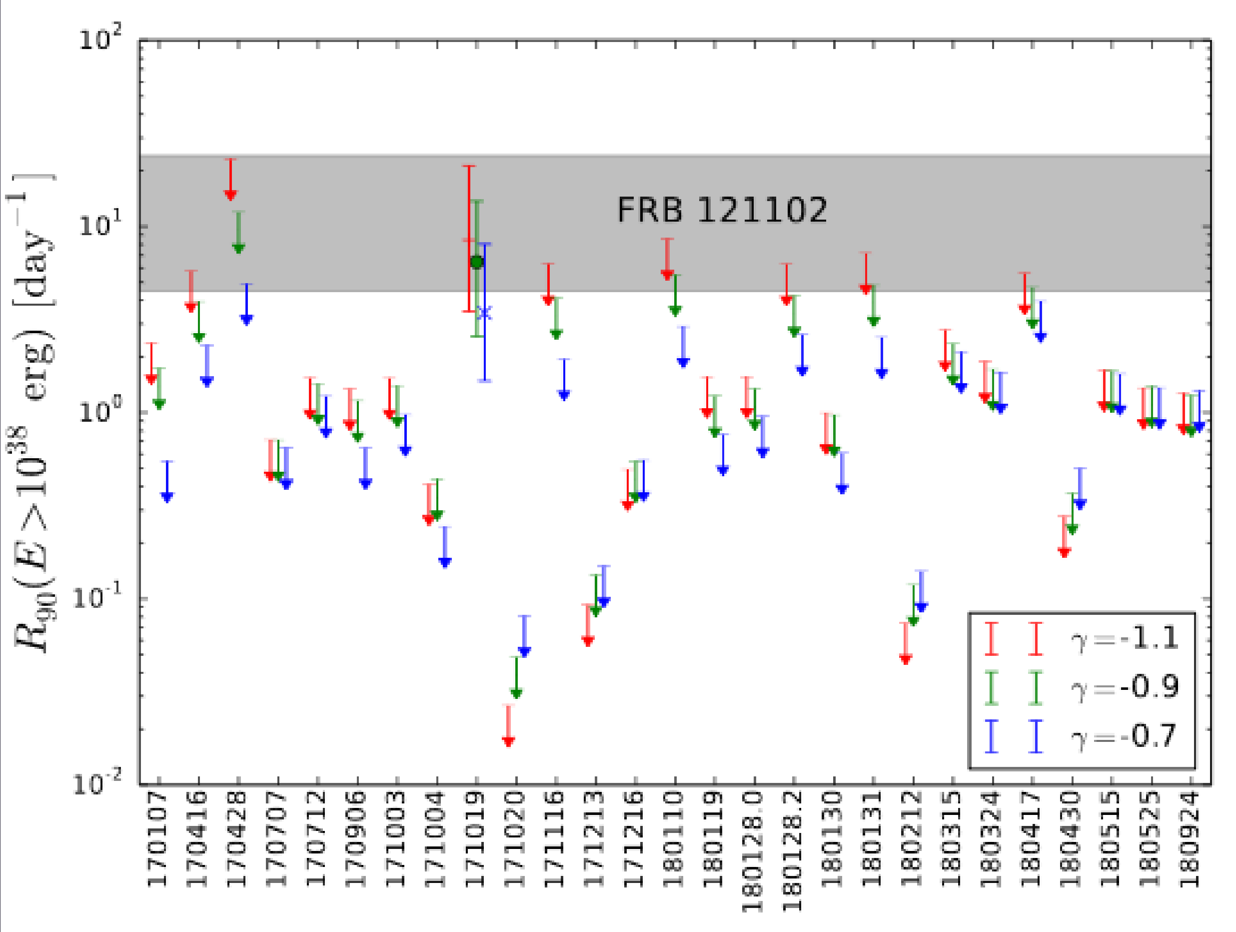
1908.03507

# Which FRB repeat?

$$R(F_{1.3\,\mathrm{GHz}}) = R_0 \left(\frac{F_{1.3\,\mathrm{GHz}}}{1\ \mathrm{Jy\,ms}}\right)^{\gamma},$$

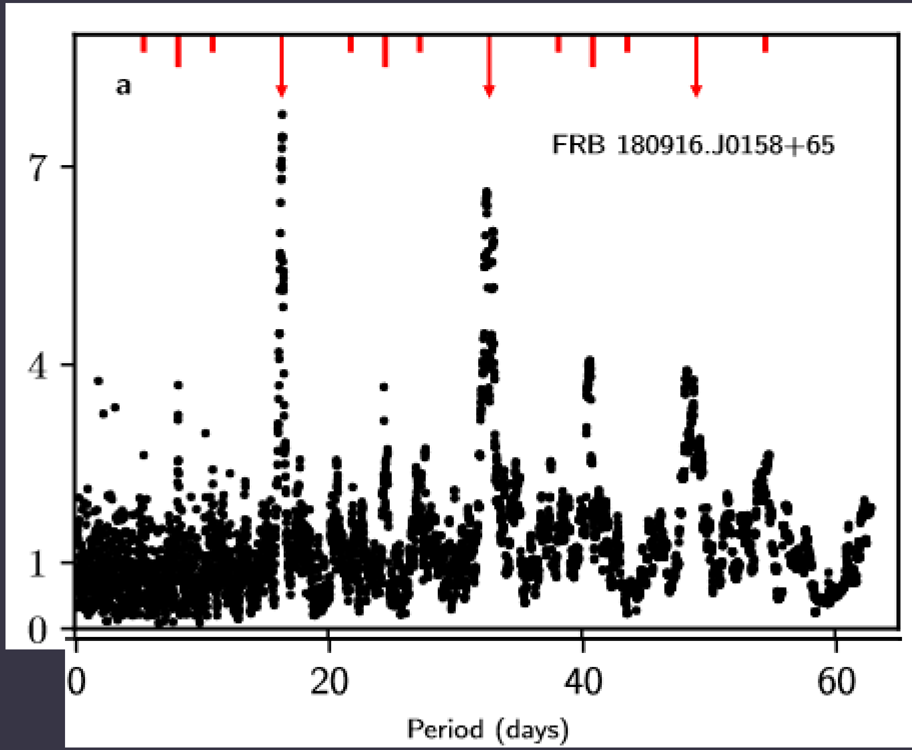
Among 27 FRB discovered by ASKAP and followed by Parkes, only one show repeating bursts.
This puts strong limits on the rate of bursts (if all sources are repeaters).

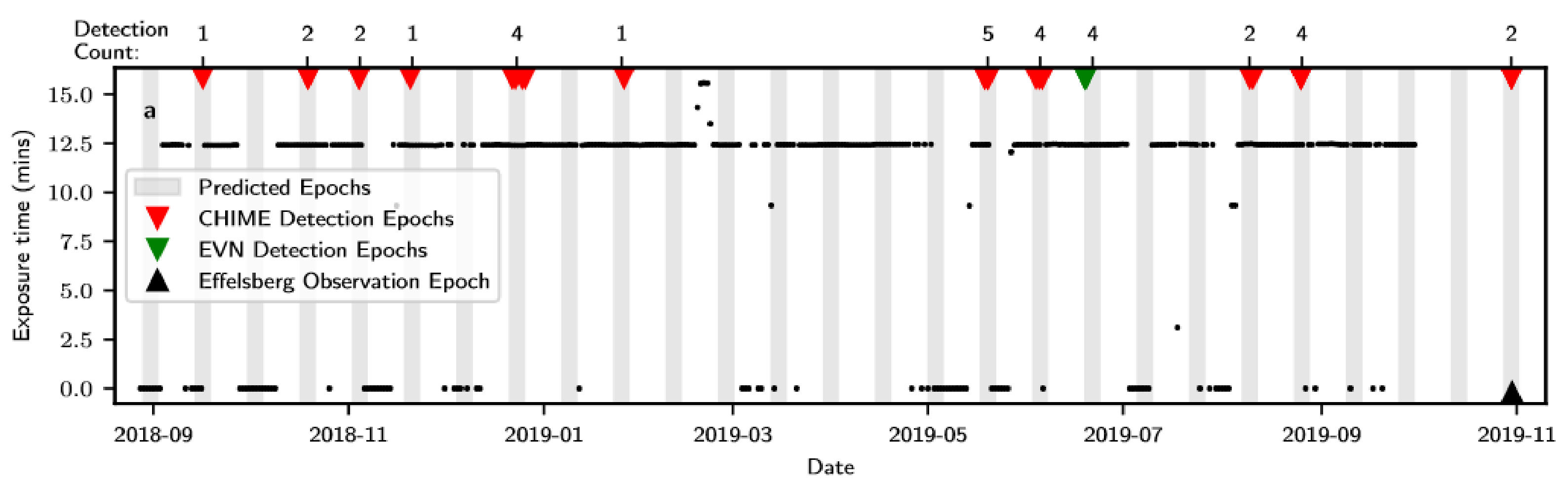
It is shown that FRB 121102 seems to be unique with its high rate.



# Periodicity in FRB bursts

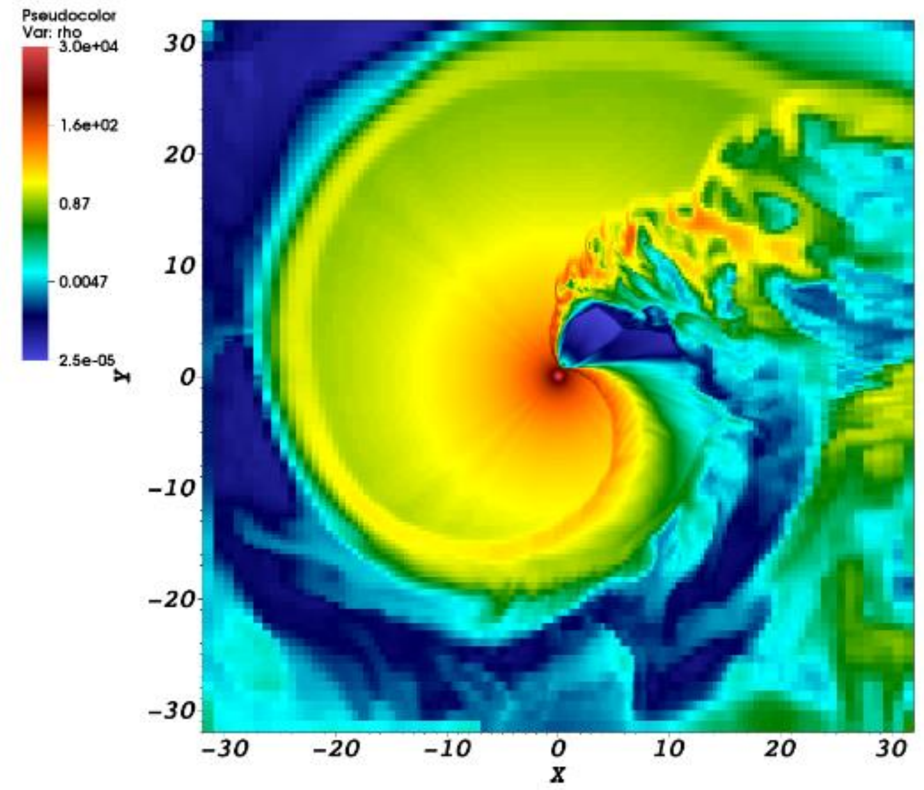
FRB 180916.J0158+65
CHIME (+Effelsberg)

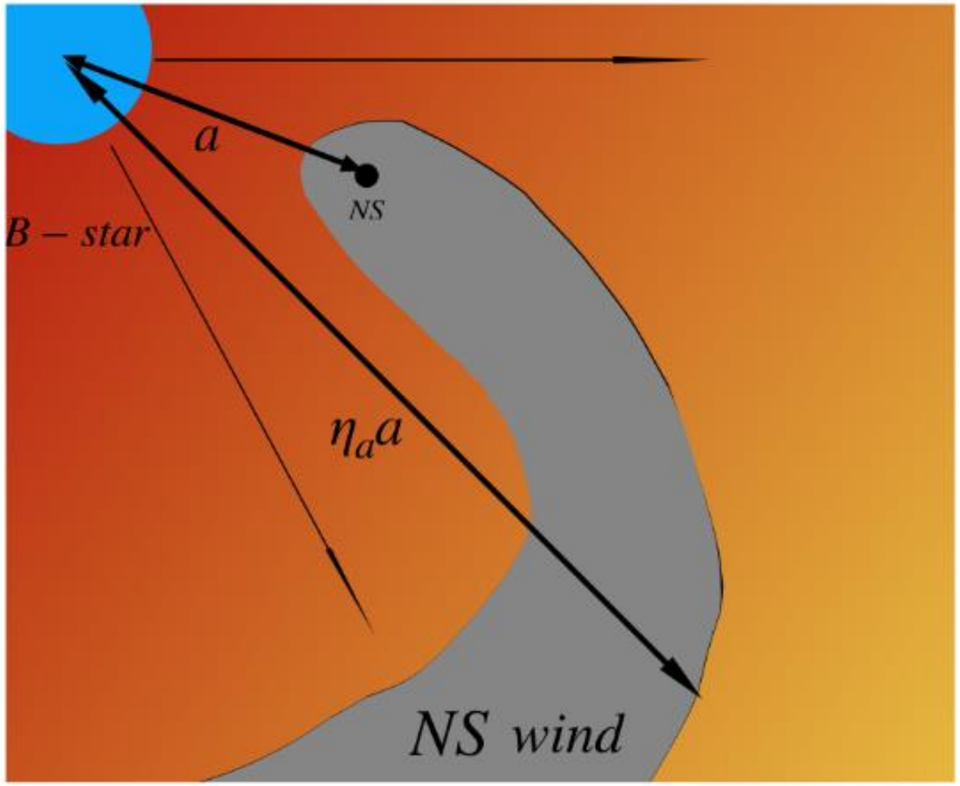



The source is localized in a near-by massive spiral galaxy.
Period ~16.35 days

# A binary system?



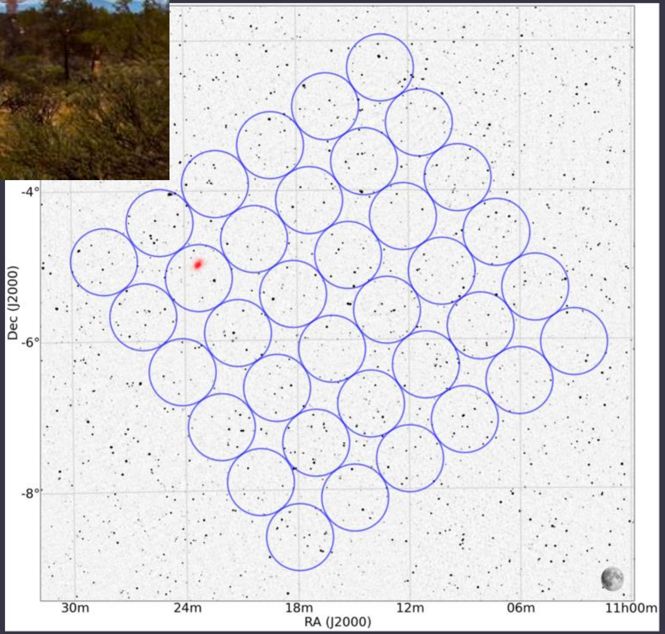



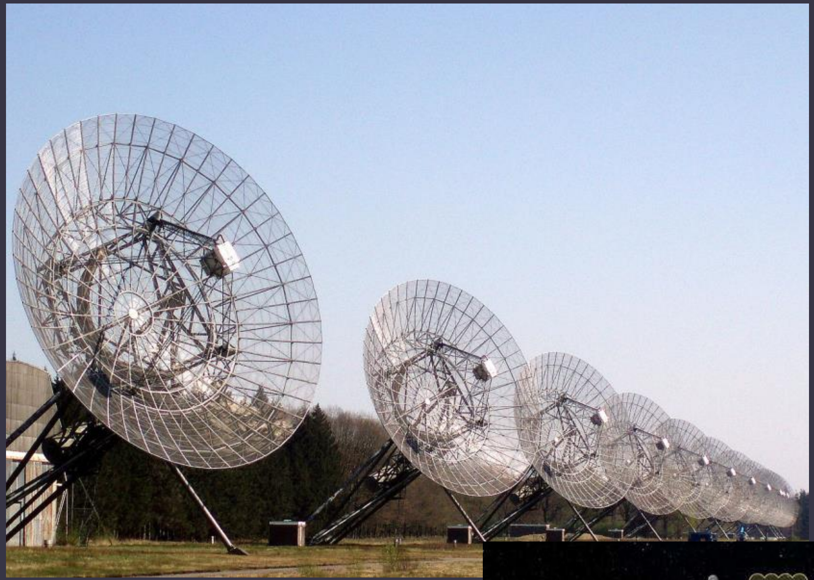
# ASKAP and Apertif

ASKAP

Few bursts per week.
1709.02189

ASKAP reported 20 new FRBs in October 2018
1810.04356

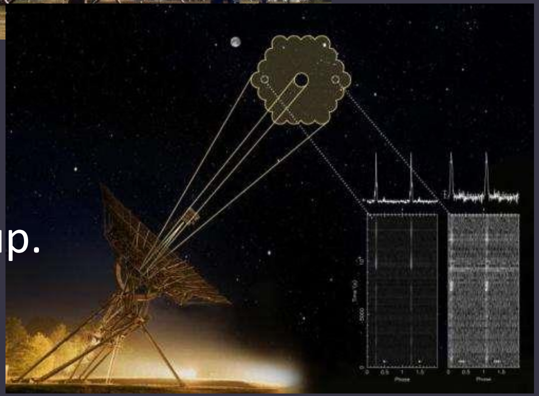


Westerbork

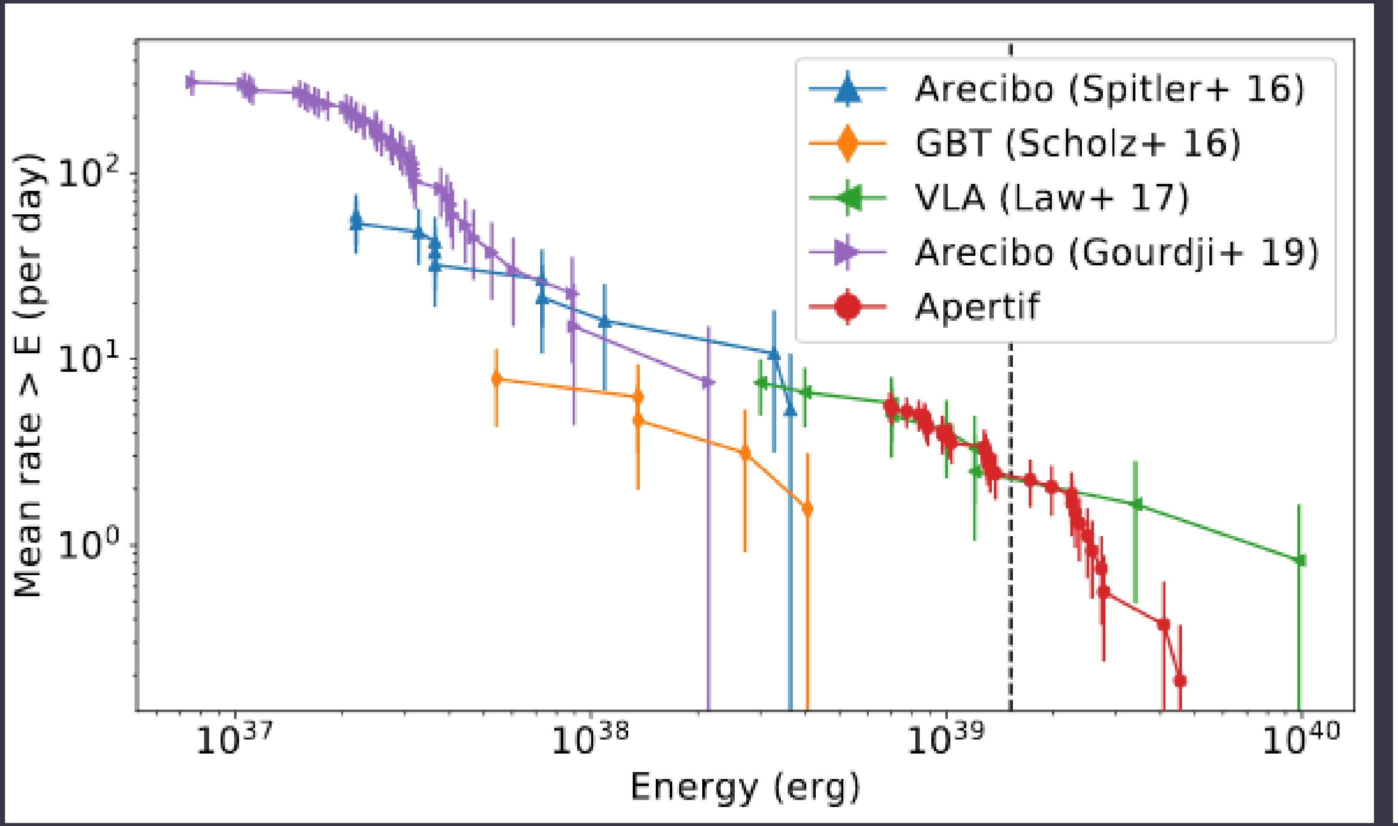
Northern sky.
Doubling the number?
Rapid on-line identification – follow-up.
FRB per week.

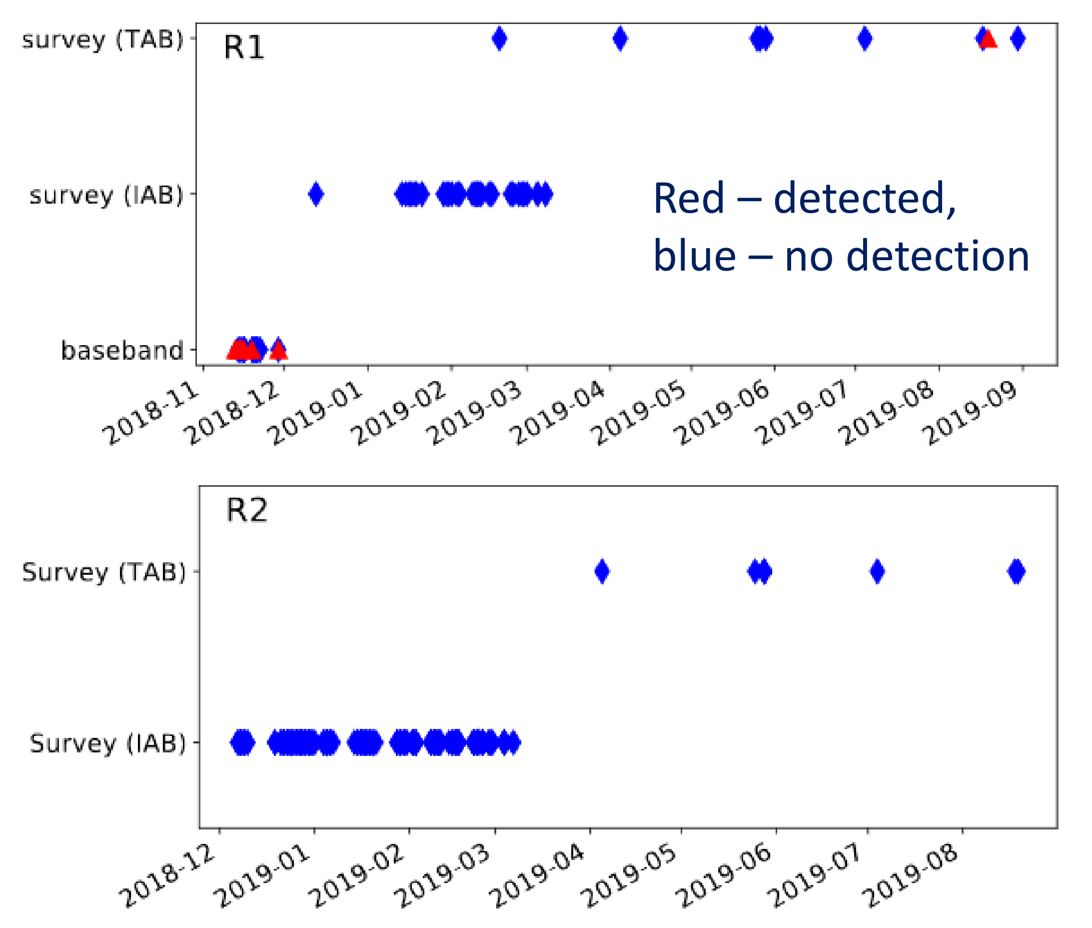
1709.06104



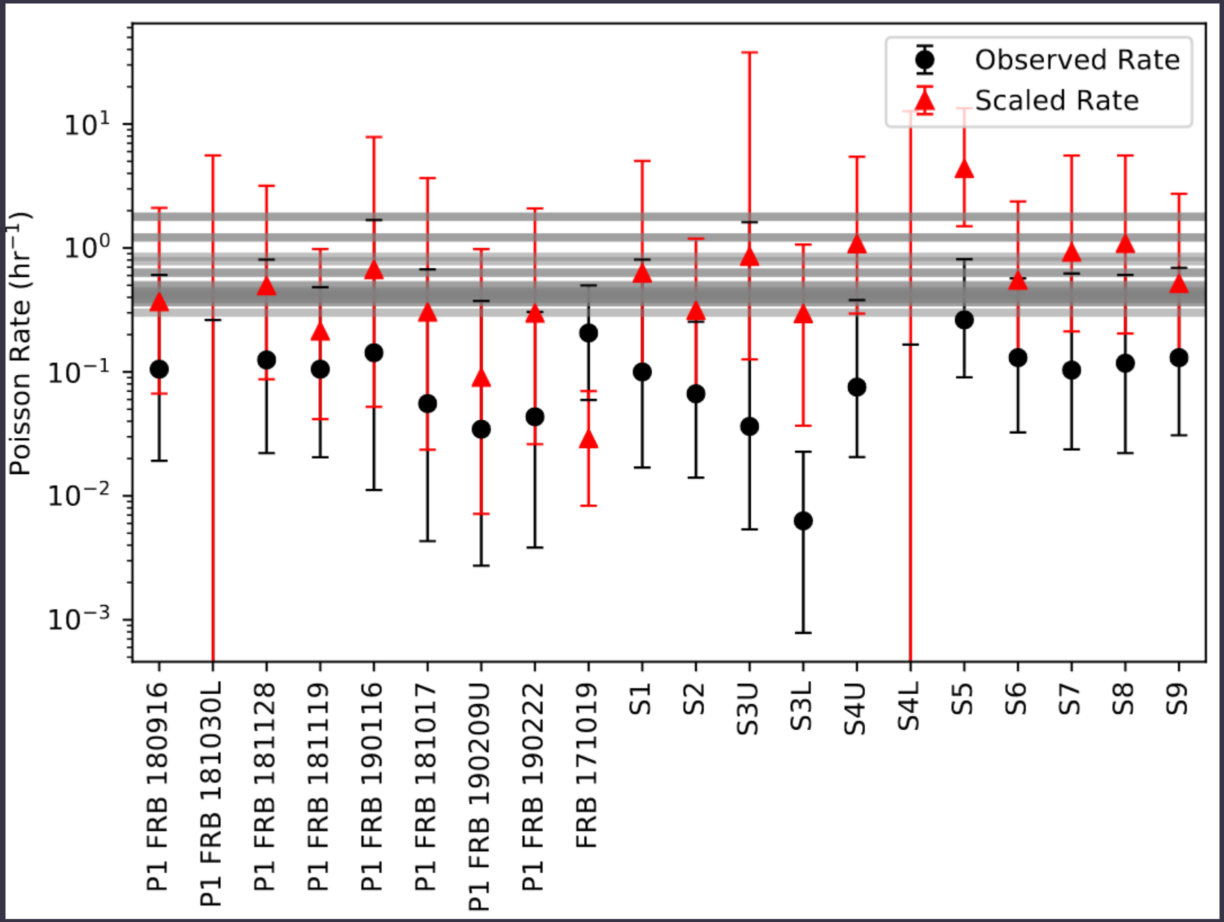
# Repeating bursts at WSRT/Apertif

First results on FRB121102 from this instrument.
30 bursts detected.



# Nine repeaters from CHIME




Aug. 2018 – Sept. 2019
2-5 bursts from each.

Localization ~10’
DM 195-1380

Repeaters have wider pulses.

# Second localization of a FRB

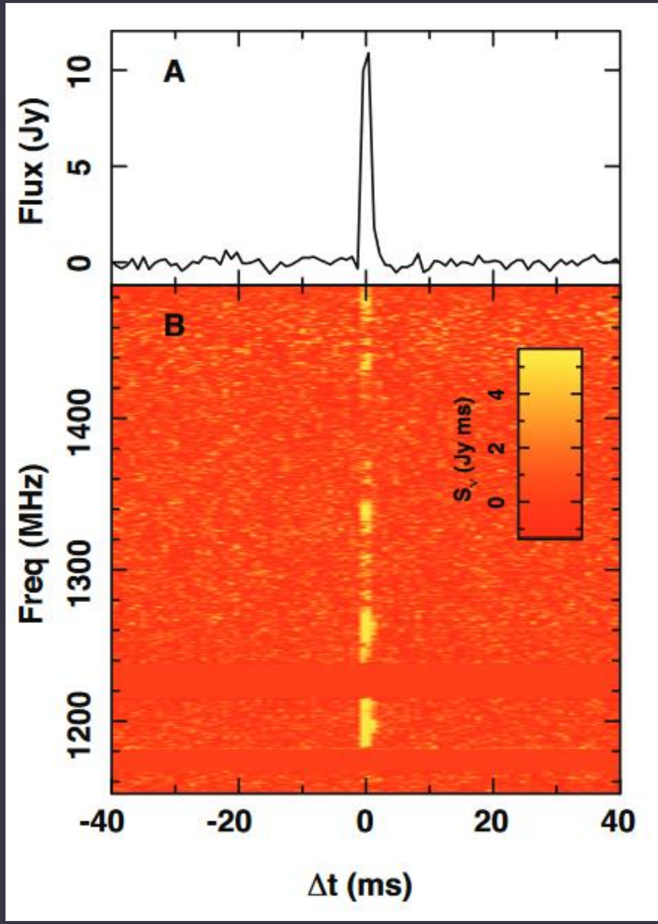
ASKAP

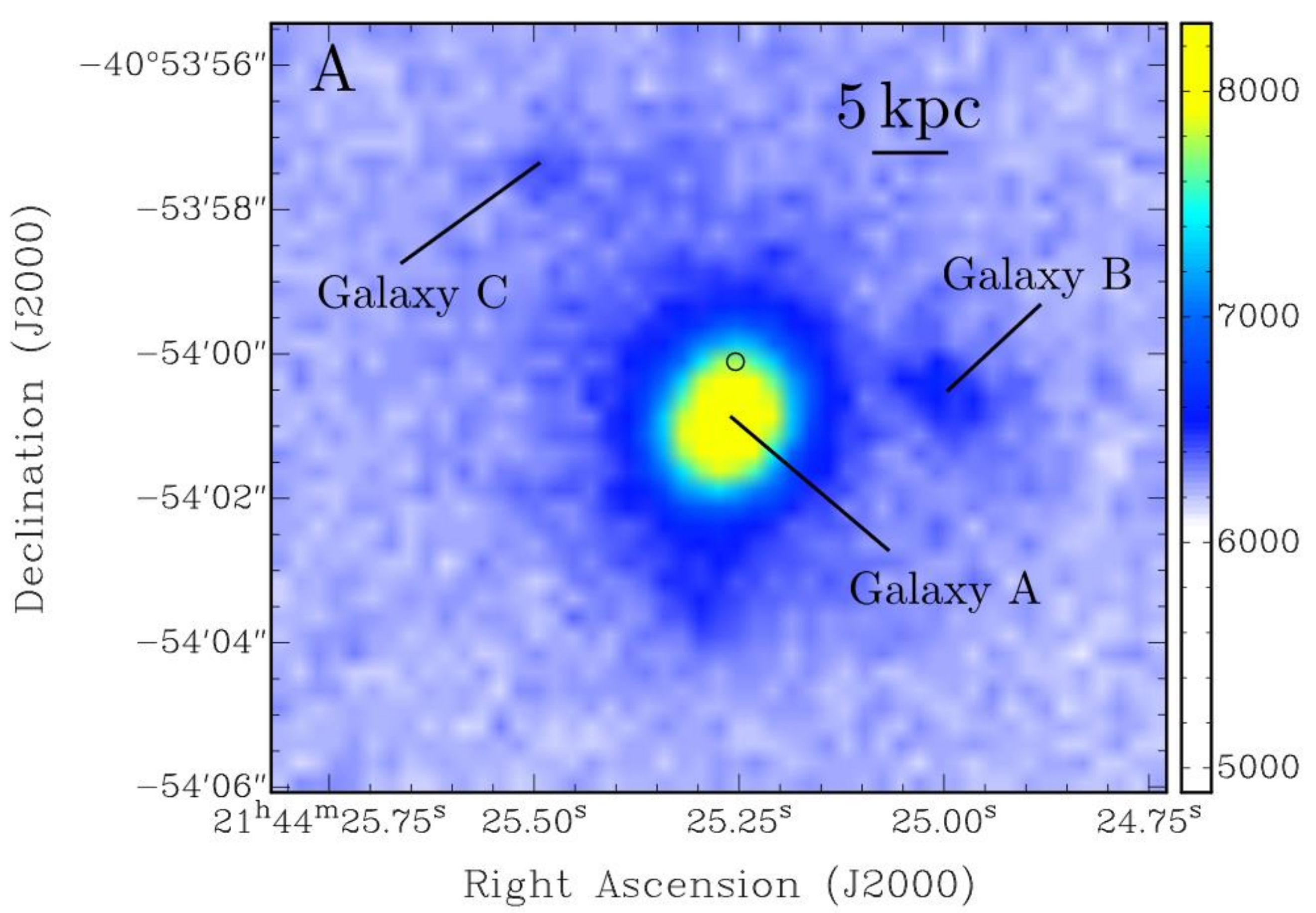
FRB 180924
non-repeating

16 Jy
DM~360
linear polarization
RM~14

Localization
~0.12 arcsec

z=0.32
Massive lenticular
or early-type



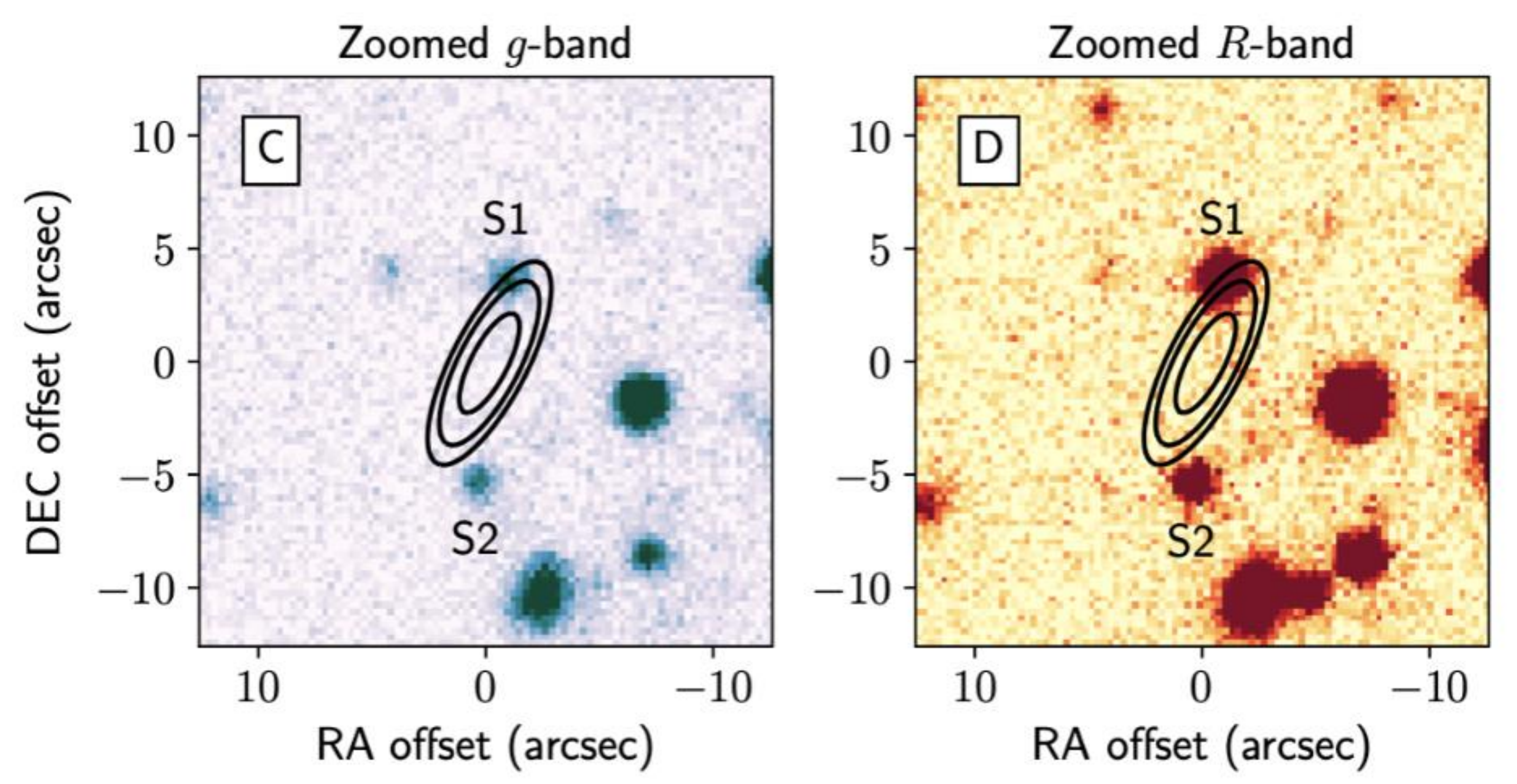
# Third localization

DSA-10 antenna
1.4 GHz

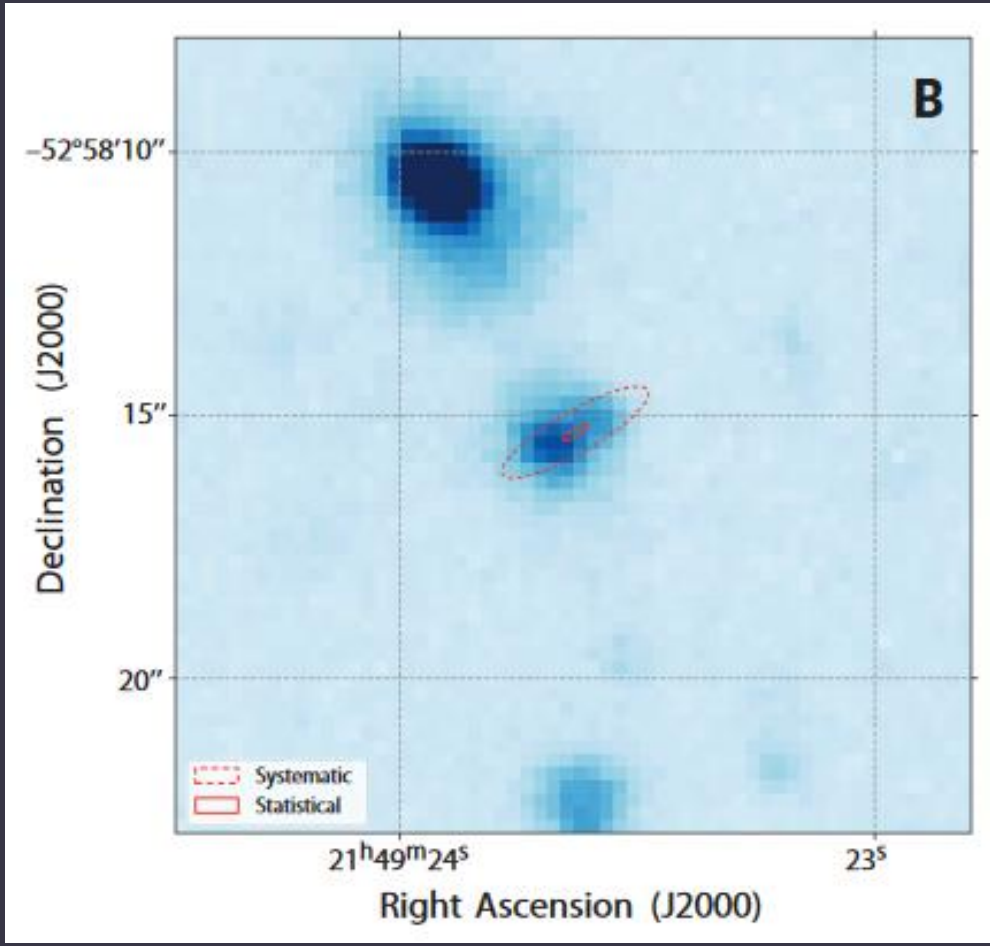
FRB 190523
non-repeating

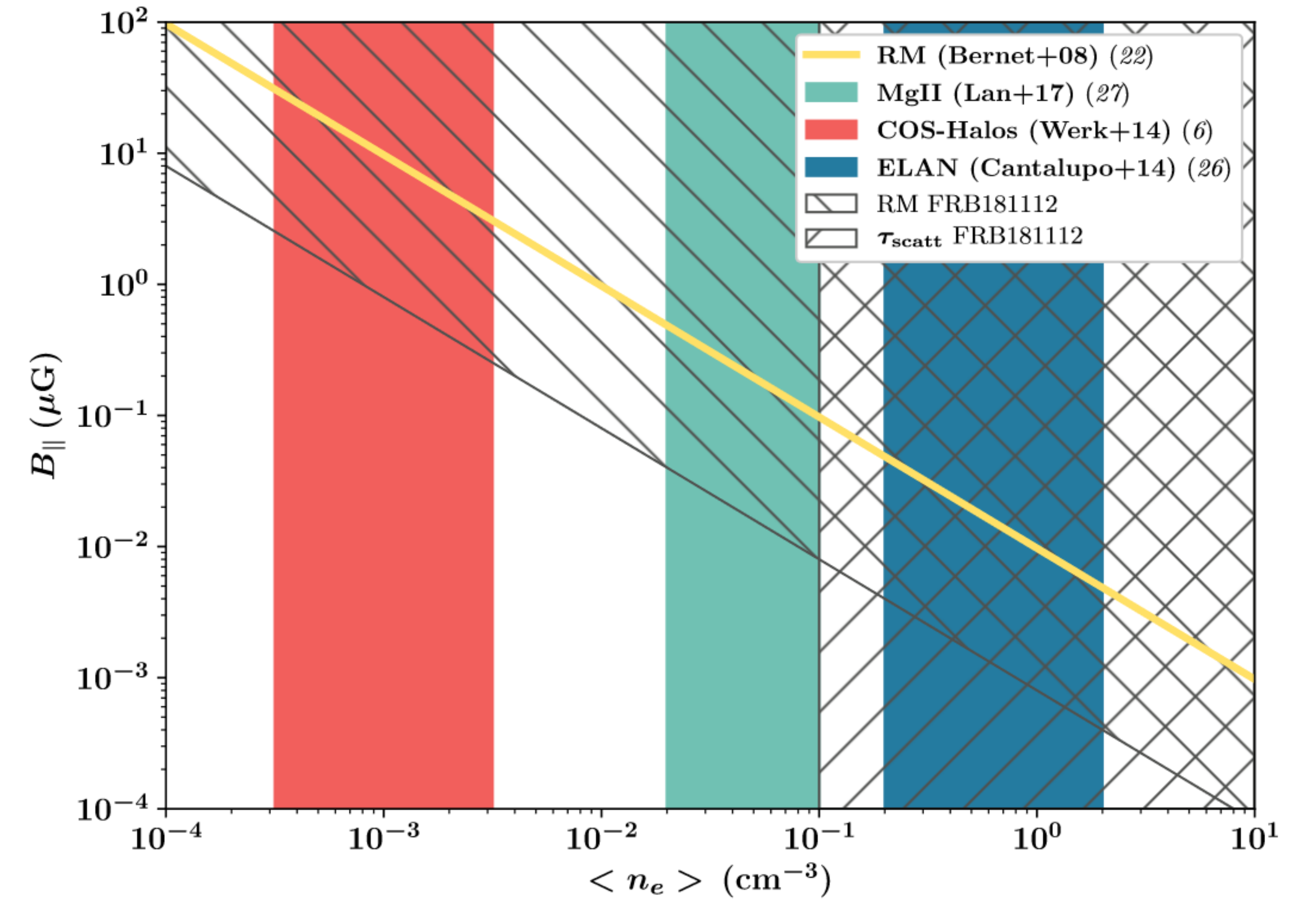
DM=760

Massive galaxy
z=0.66
SFR<~1/3 of Galactic



# Fourth localization and halo probing




1909.11681

# Probing M33 and M31 halos

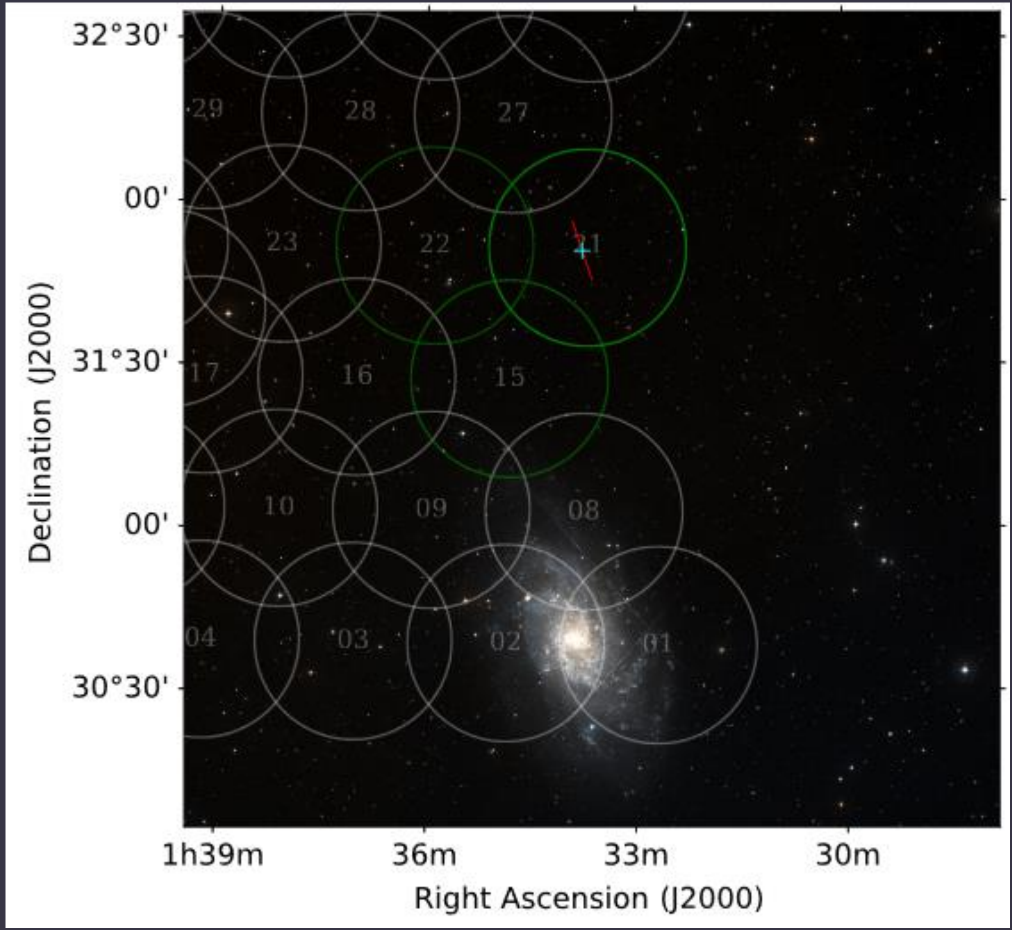
WSRT/Apertif

FRB 19110

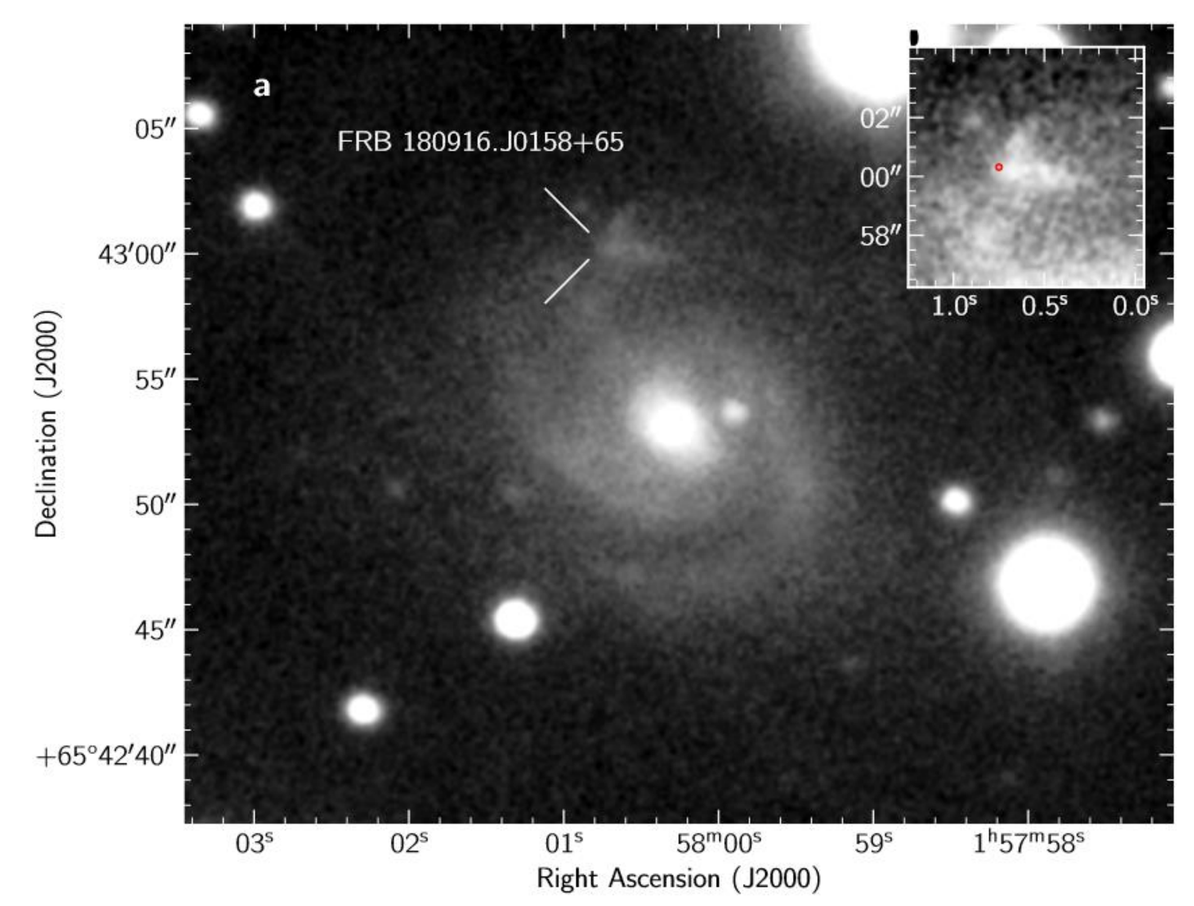
Localization:
3.5’ x 2.5”

18 kpc (1.2 degree)
from M33 center

~10% of DM is due to
M31 and M33



# Fifth localization




FRB180916.J0158+65

Near-by spiral galaxy

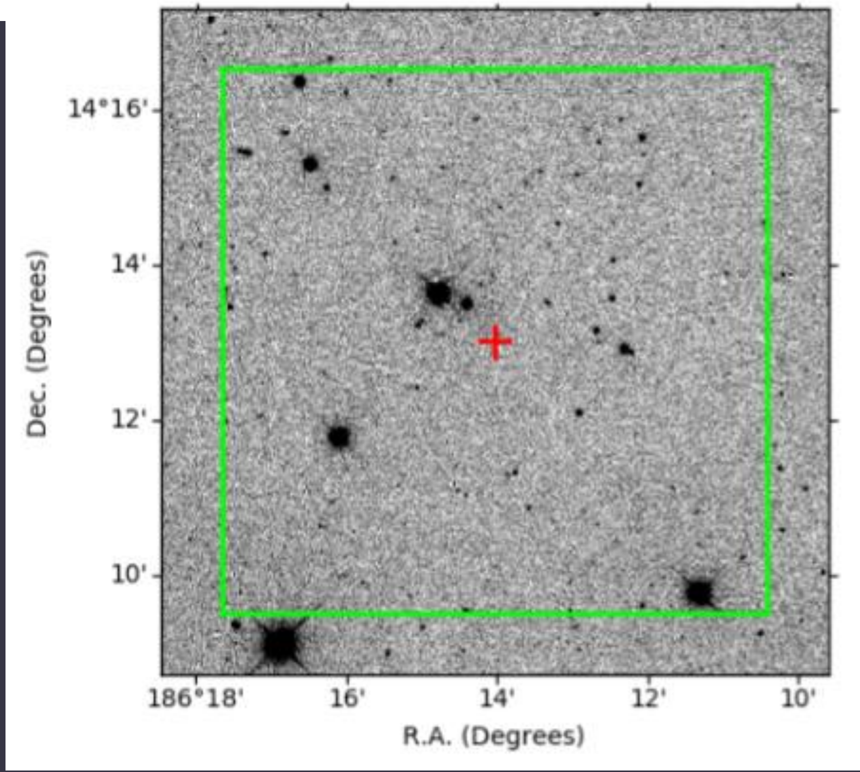
# A fast radio burst in the direction of the Virgo cluster

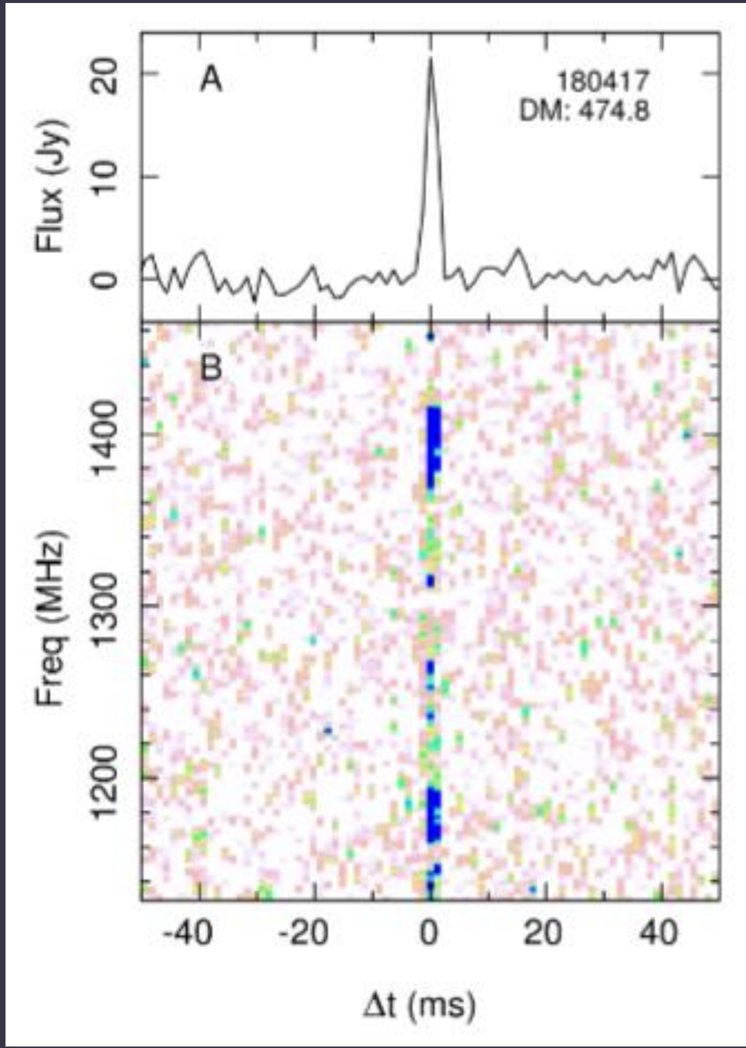
Devansh Agarwal[1,2]*, Duncan R. Lorimer[1,2], Anastasia Fialkov[3,4,5], Keith W. Bannister[6], Ryan M. Shannon[7], Wael Farah[7], Shivani Bhandari[6], Jean-Pierre Macquart[8], Chris Flynn[7], Giuliano Pignata[10,11], Nicolas Tejos[12], Benjamin Gregg[8], Stefan Osłowski[7], Kaustubh Rajwade[9], Mitchell B. Mickaliger[9], Benjamin W. Stappers[9], Di Li[13,14], Weiwei Zhu[13], Lei Qian[13], Youling Yue[13], Pei Wang[13] and Abraham Loeb[15]

FRB 180417
ASKAP

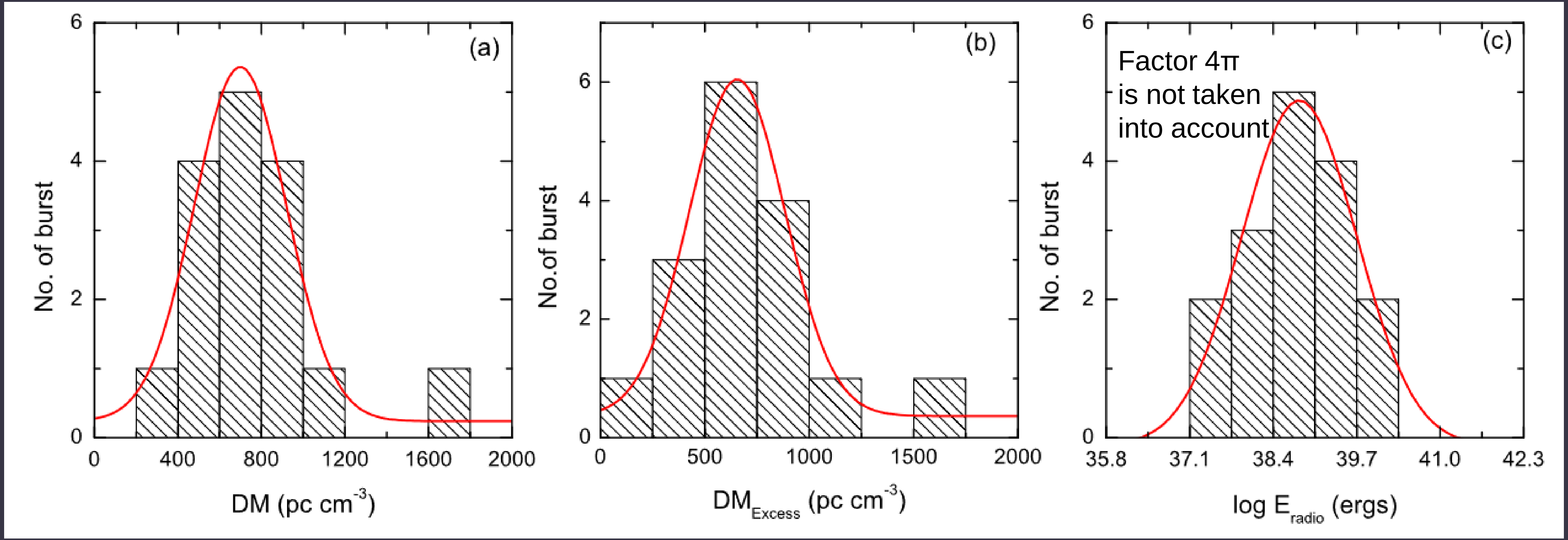
DM 475
Does this mean that
it is a background source?

No optical counterpart



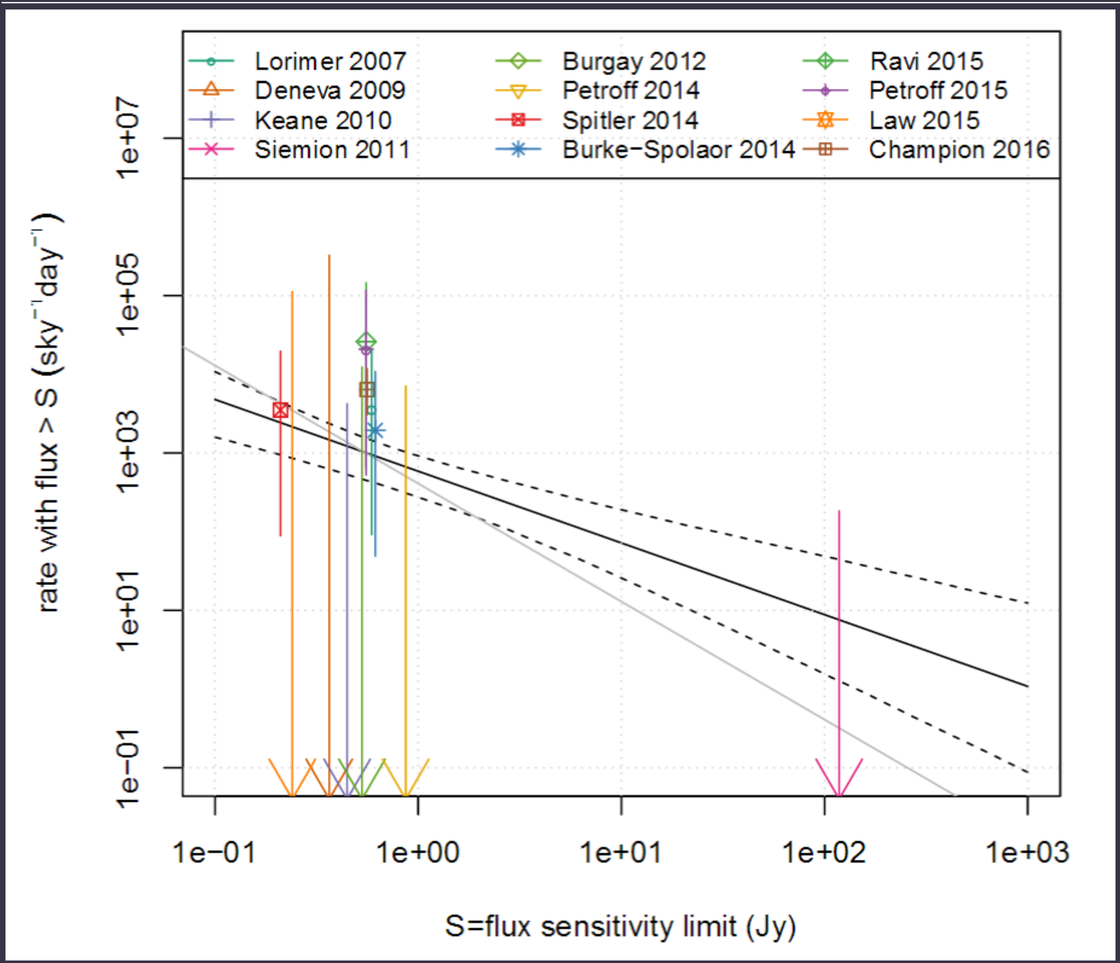
# Statistical properties of FRBs




$$\frac{dN}{dF_{\rm obs}} = (4.4 \pm 0.4) \times 10^3 \, F_{\rm obs}^{-1.18\pm0.15} \, {\rm sky}^{-1} \, {\rm day}^{-1}$$

1602.06099

# More estimates of the rate




Black solid line –
new data.
Dotted lines –
95% uncertainty.

Grey line is plotted under assumption that index is the Log N – Log S distribution is equal to 3/2.

See also 1612.00896

587 per day with flux above 1 Jy.

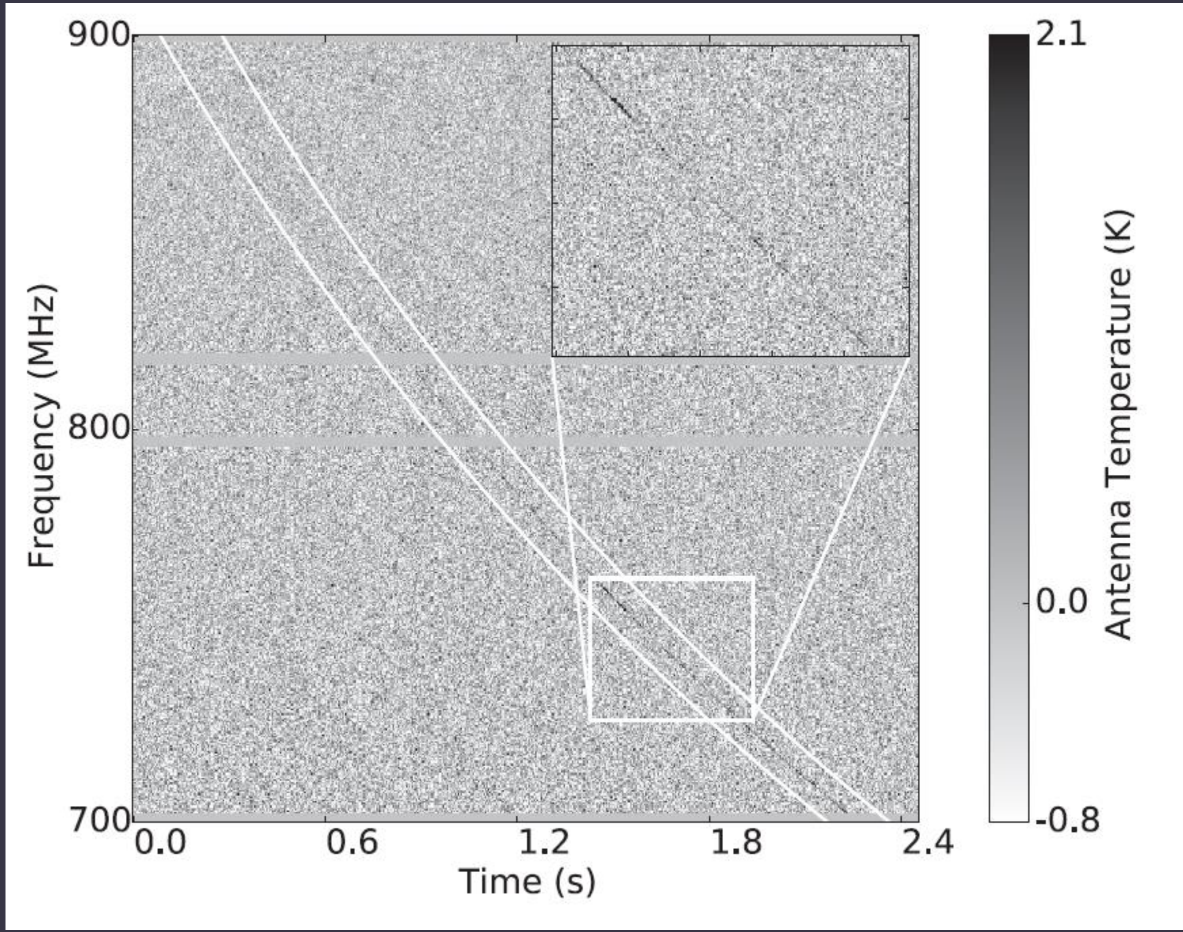
# Polarization of FRB emission

Petroff et al. (1412.0342) detected circular polarization of FRB 140514 at the level ~20%.

Later Masui et al. (2015) detected linear polarization of FRB 110523.

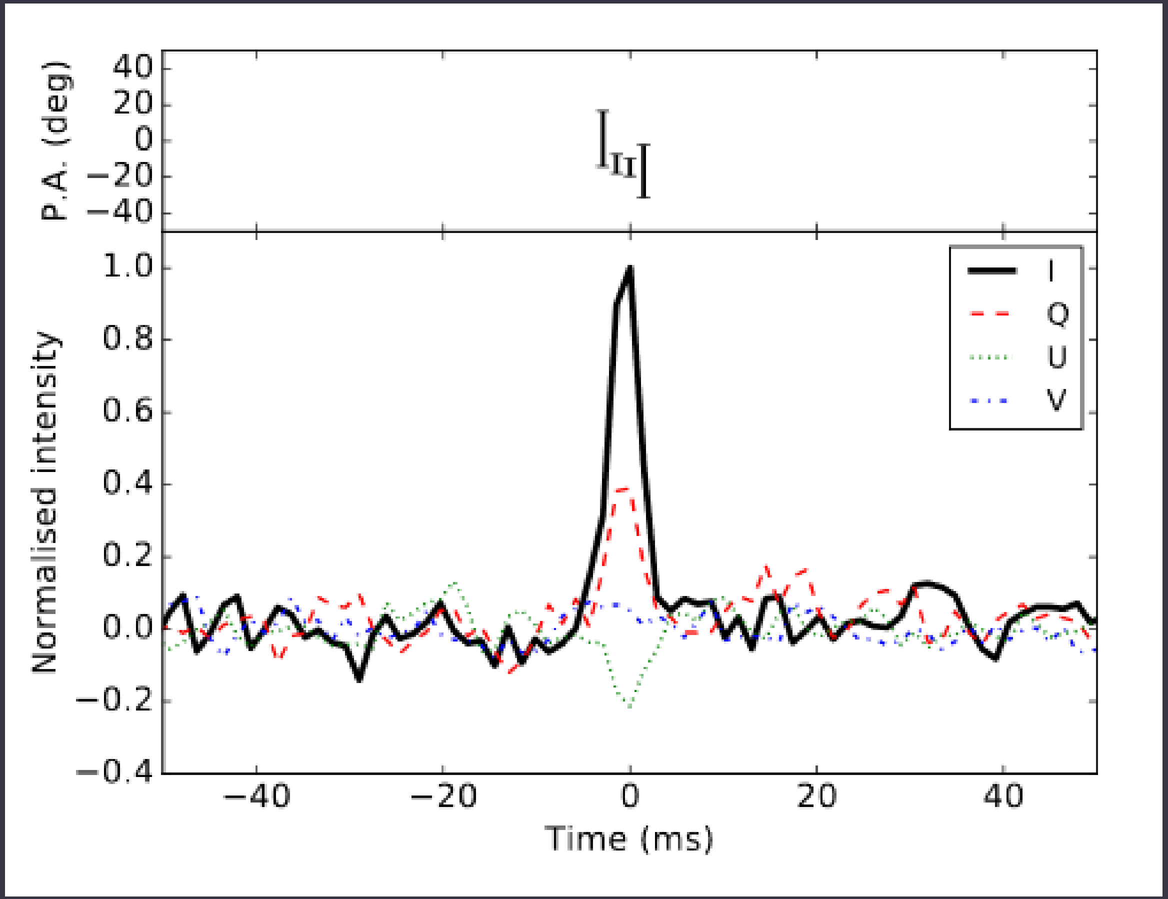
0.38 microGauss

This result fits models with a young NS in a SNR or PWN.




Masui et al. 1512.00529

# Another example



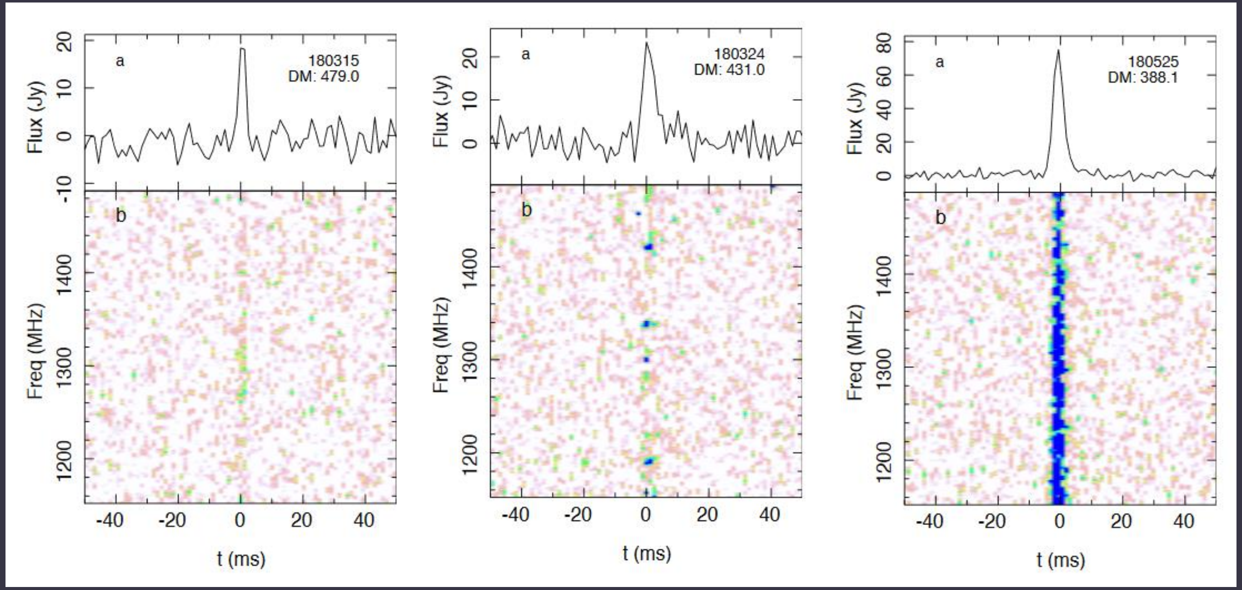

FRB150215
Detected in real time.
No counterparts detected.
Close to the galactic plane.
DM~1100
Flux ~0.7 Jy
Width ~2.8 msec
Linear polarization ~43%
RM~0

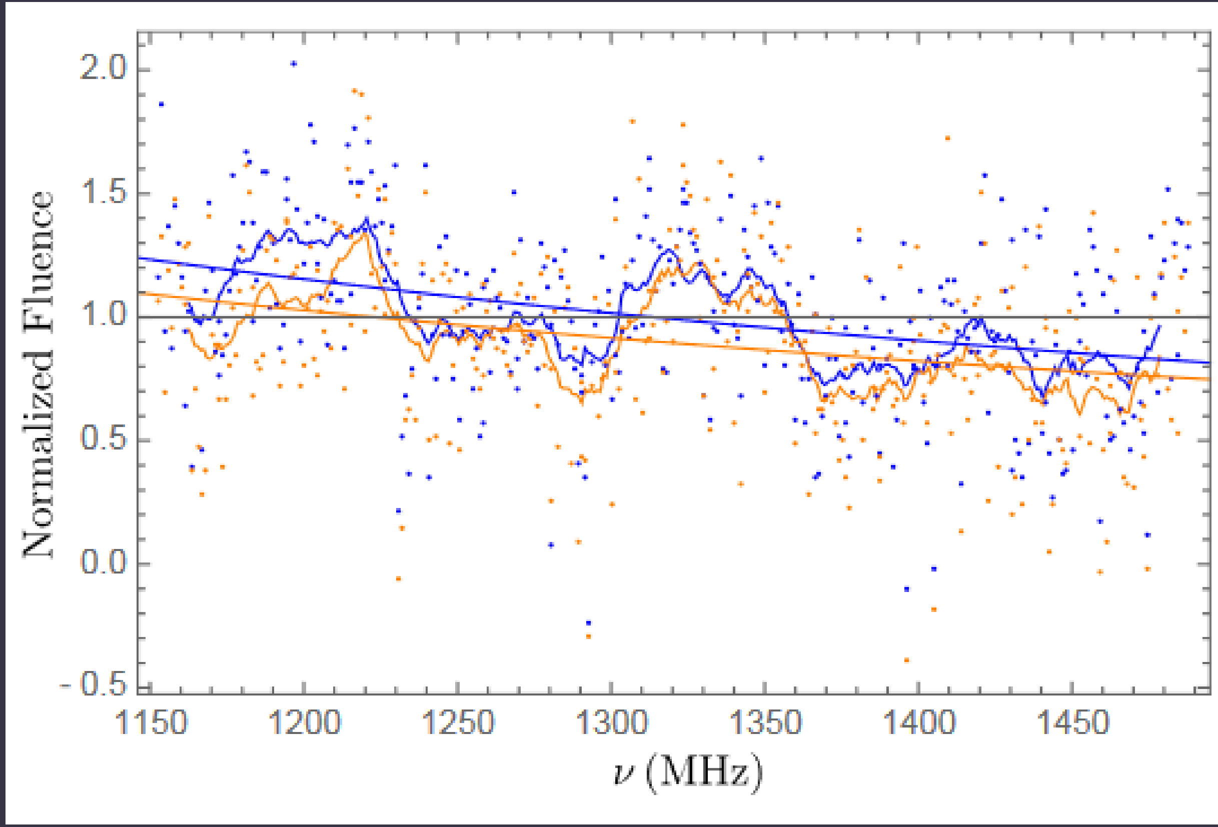
Polarization of the repeating bursts in measured at high frequency 4-8 GHz (1801.03965).

# Spectra

Spectral data for non-repeating bursts are poor.

Data for 23 ASKAP bursts $E(\nu) \sim \nu^{-(1.5-2)}$

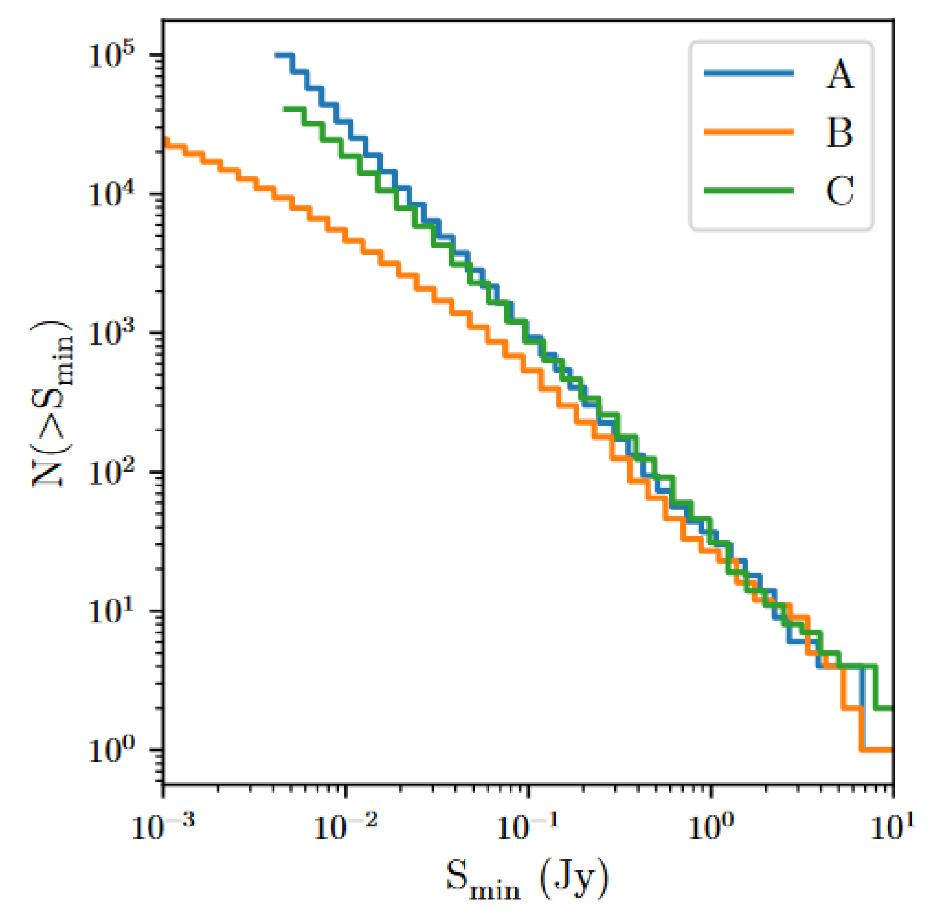



No detection at <200 MHz (1810.04355).
This means that there is a cutoff in spectrum.

# Population synthesis of FRBs

| Parameters | Units | *Default* | *Simple* | *Complex* | *Standard Candles* |
|---|---|---|---|---|---|
| $n_{model}$ | | SFR | $vol_{co}$ | $vol_{co}$ | SFR |
| $H_0$ | km/s/Mpc | 67.74 | 67.74 | 67.74 | 67.74 |
| $\Omega_m$ | | 0.3089 | 0.3089 | 0.3089 | 0.3089 |
| $\Omega_\Lambda$ | | 0.6911 | 0.6911 | 0.6911 | 0.6911 |
| $DM_{host,\ model}$ | | normal | normal | normal | normal |
| $DM_{host,\ \mu}$ | $pc/cm^3$ | 100 | 0 | 100 | 100 |
| $DM_{host,\ \sigma}$ | $pc/cm^3$ | 200 | 0 | 200 | 0 |
| $DM_{igm,\ index}$ | $pc/cm^3$ | 1000 | 0 | 1000 | 1000 |
| $DM_{igm,\ \sigma}$ | $pc/cm^3$ | $0.2DM_{igm,\ index}$ | 0 | $200z$ | $200z$ |
| $DM_{mw,\ model}$ | | NE2001 | zero | NE2001 | NE2001 |
| $\nu_{emission,range}$ | MHz | $10^6$-$10^9$ | $10^6$-$10^9$ | $10^6$-$10^9$ | $10^6$-$10^9$ |
| $L_{bol,\ range}$ | ergs/s | $10^{39}$-$10^{45}$ | $10^{38}$-$10^{38}$ | $10^{39}$-$10^{45}$ | $10^{36}$-$10^{36}$ |
| $L_{bol,\ index}$ | | 0 | 0 | 0 | 0 |
| $\alpha_{in}$ | | $-1.5$ | $-1.5$ | $-1.5$ | $-1.5$ |
| $w_{int,\ model}$ | | Lognormal | Uniform | Lognormal | Uniform |
| $w_{int,\ range}$ | ms | 0.1-10 | 10-10 | - | 1-1 |
| $w_{int,\ \mu}$ | ms | 0.1 | - | 0.1 | - |
| $w_{int,\ \sigma}$ | ms | 0.5 | - | 0.7 | - |
| $\gamma_\mu$ | | $-1.4$ | 0 | $-1.4$ | 0 |
| $\gamma_\sigma$ | | 1 | 0 | 1 | 0 |
| $z_{max}$ | | 2.5 | 0.01 | 2.5 | 2.5 |
| $n_{gen}$ | | - | $10^8$ | $10^8$ | $10^8$ |



# FRBs. Different hypotheses

Millisecond extragalactic radio bursts of that intensity without immediate identification with other bursts have not been predicted by earlier studies.

Since 2007 many hypotheses have been proposed.

A real flow started in late summer of 2013 after the paper by Thornton et al.

- Magnetars
- Super radio pulsars
- Evaporating black holes

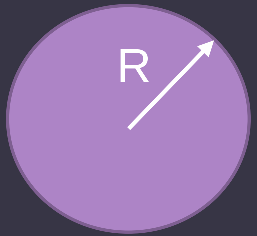
- Coalescing NSs
- Coalescing WDs
- Coalescing NS+BH

- Supramassive NSs
- Deconfinement of a NS
- Axion clouds and NSs

- Cosmic strings
- Charged BHs
- NS collapse

bestiary.ca/

# Neutron stars and exotics



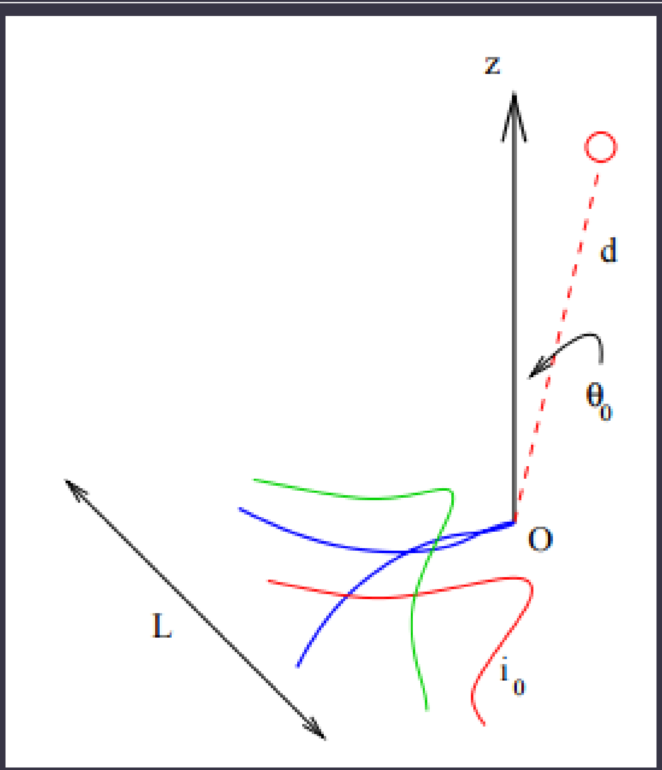

A neutron star has mass ~solar and
radius ~10 km.
This gives free fall velocity $v=(2GM/R)^{1/2}$ ~0.5 c
Free fall time scale t=R/v< 0.1 msec
Thus, it is easy to get very short events.
The same is true for BHs.

Absence of counterparts and, in general, shortage of data allows to propose very exotics scenarios for explanation of Fast Radio Bursts.

In addition, NSs have strong magnetic fields
and they are known sources of strong short radio bursts.

So, model of FRBs can divided into two parts:
neutron stars and exotics.

# Cosmic strings

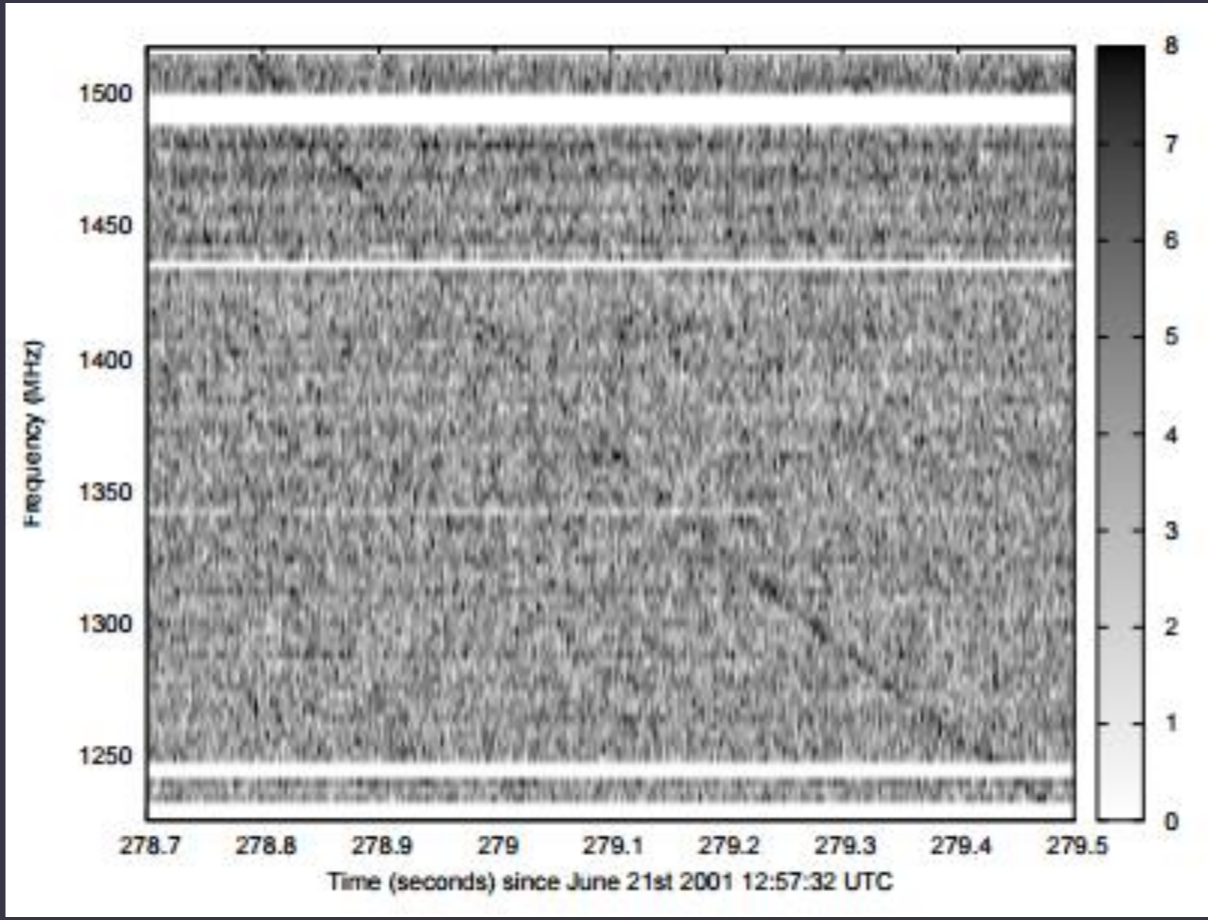



Superconducting strings
Vachaspati 0802.0711

Strings can behave in a peculiar way.
In particular, cusps – where strings are bended,
can be formed, and they can move with superluminal velocity.
Such points on strings might become strong
sources of electro-magnetic radiation.
This is the base of this model of FRBs.

Also, the model of cosmic strings in application to FRBs
Was discussed in several other papers: 1110.1631, 1409.5516, ….

# Primordial black holes




Cannot be extragalactic due to low luminosity.
Might be visible from <~200 pc.

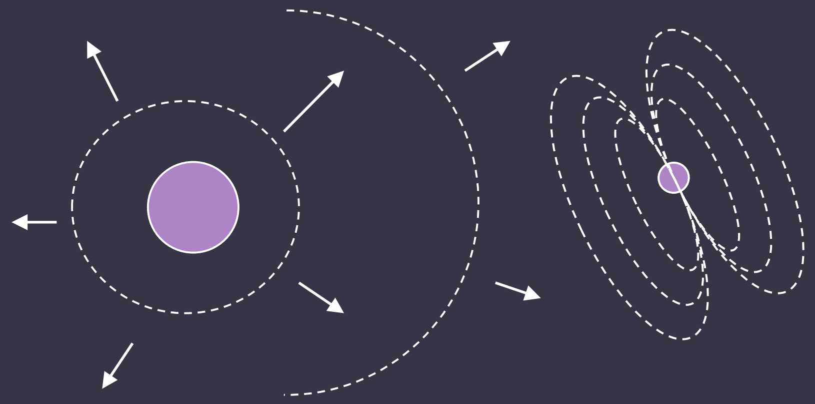
Predicted years ago (Rees 1977).

Evaporation in models with extra-dimensions
can provide larger energy release,
but still distance are not more than ~300 pc.

Can be accompanied by a burst of hard radiation
(if the source is near-by).

Keane et al. 1206.4135

# Supernova and pulsar



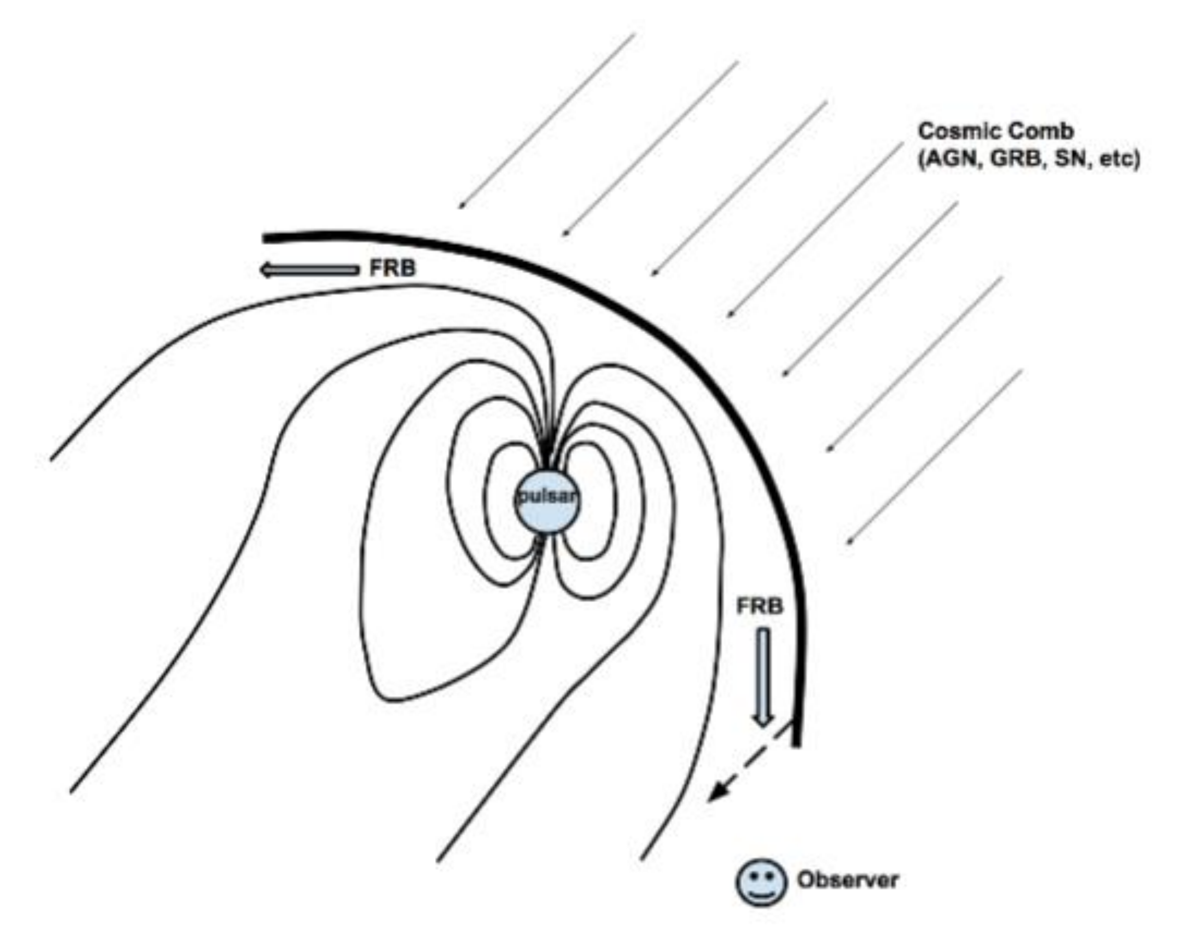
Shock wave after a SN in a close HMXB can interact with the NS magnetosphere forming a magnetotail.

Reconnection in the magnetotail may result in a short radio flare (Egorov, Postnov arXiv: 0810.2219).

So, radio bursts might be always accompanied by a supernova.

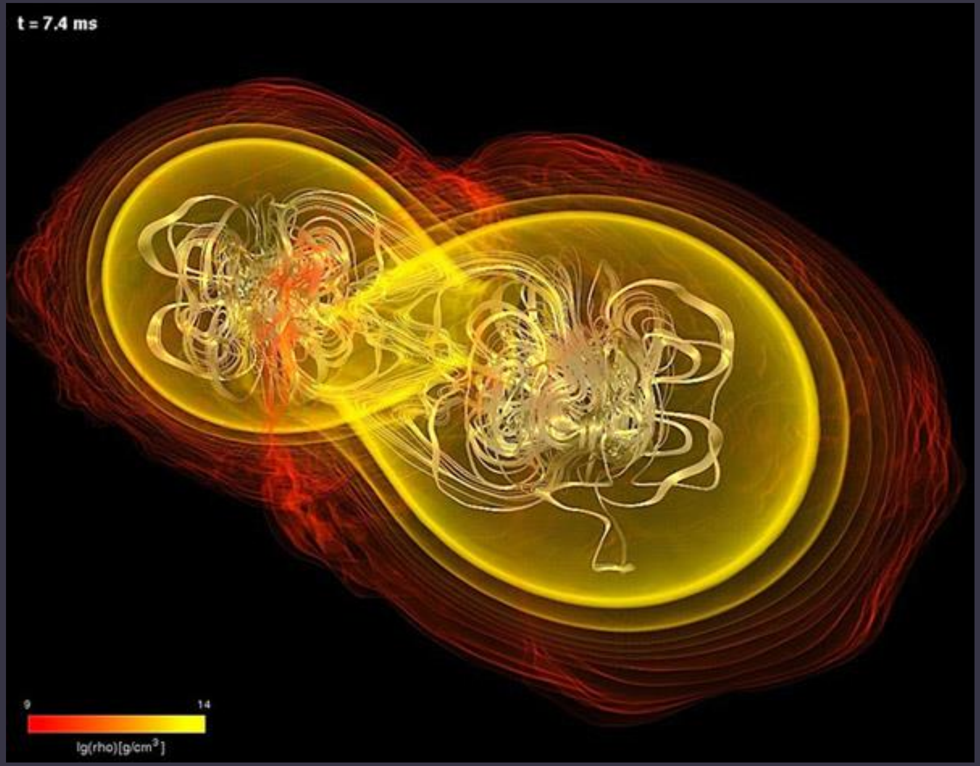
# Cosmic comb model

A radio burst might be coincident with another powerful transient event (AGN flare, GRB, etc.).



# Coalescence of neutron stars

http://www.int.washington.edu/PROGRAMS/14-2a/




There are several scenarios in which strong radio transient appear as a result of neutron star coalescence
(Lipunov, Panchenko; Hansen, Lyutikov; Postnov, Pshirkov).

In application to FRBs the first paper is Totani (1307.4985).

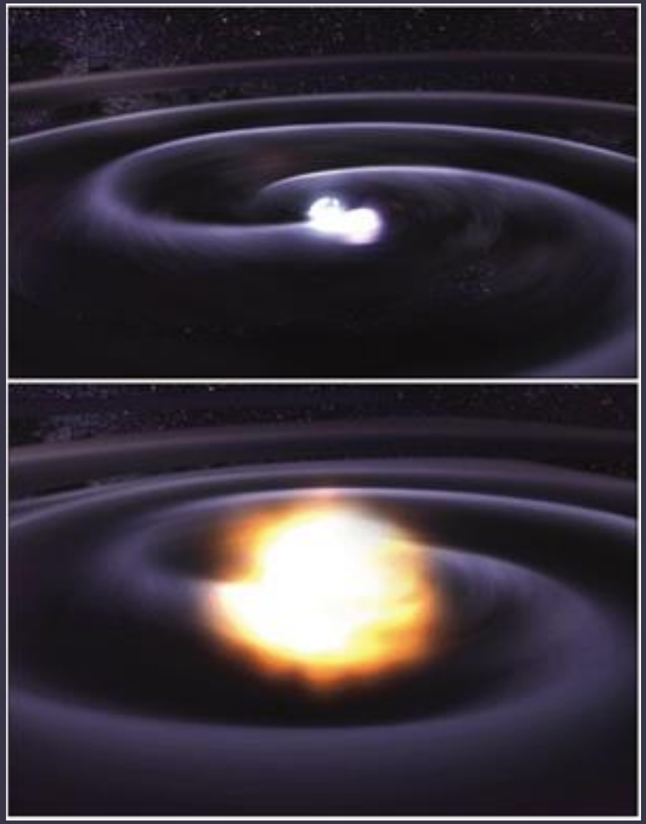
$$\dot{E} = -6.2 \times 10^{45} \left(\frac{B}{10^{12.5}\ \mathrm{G}}\right)^2 \left(\frac{R}{10\ \mathrm{km}}\right)^6 \times \left(\frac{P}{0.5\ \mathrm{msec}}\right)^{-4} \mathrm{erg\ s^{-1}}\ .$$

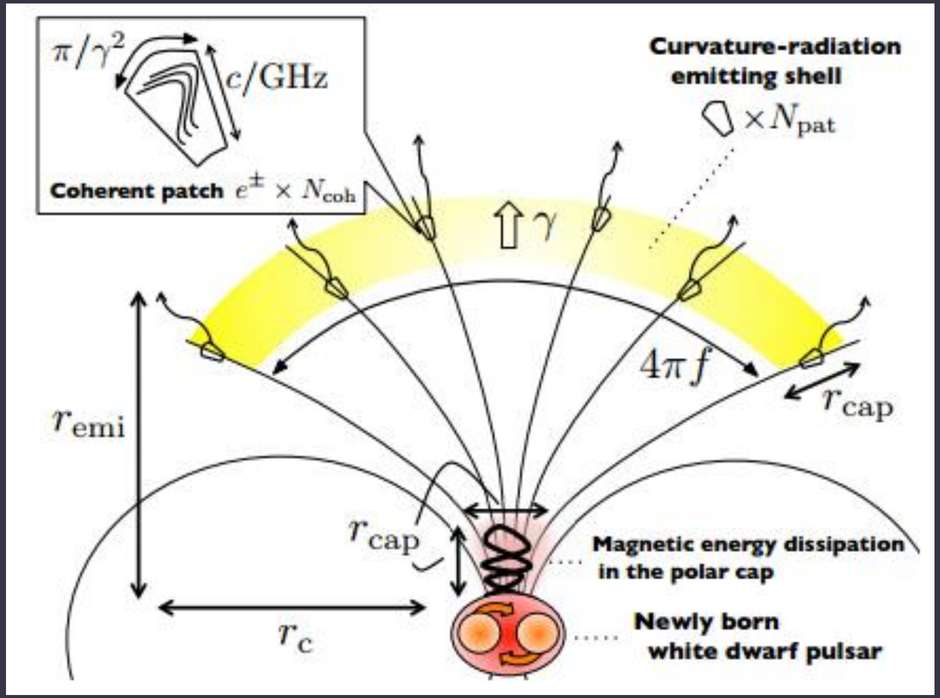
Easy to obtain rapid rotation and strong magnetic field.
But there are many uncertainties.

Might be accompanied by a GW burst.

# White dwarf coalescence

http://cerncourier.com/cws/article/cern/31855





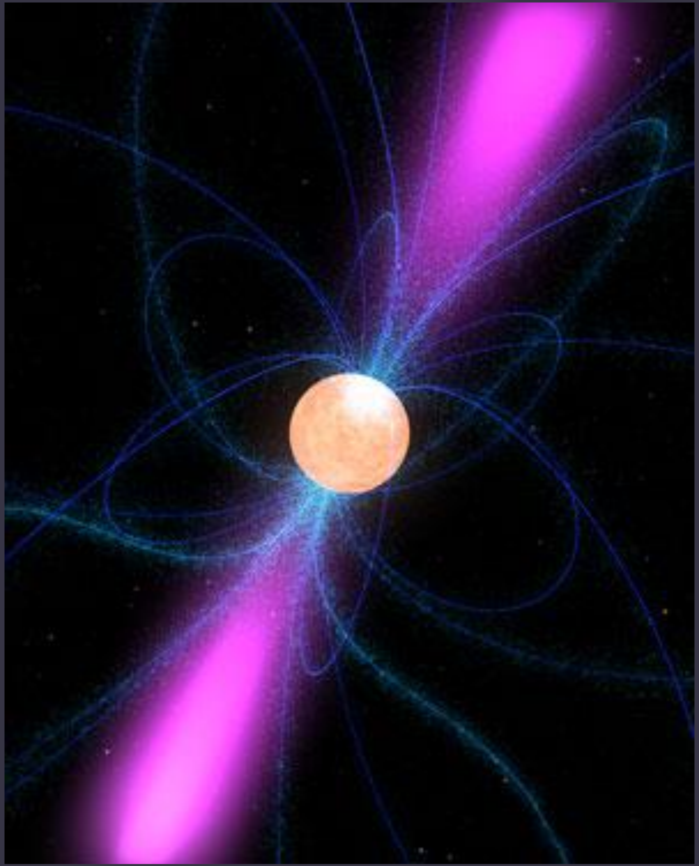

Kashiyama et al. 1307.7708

Energy release is due to magnetic field lines reconnection at the polar cap. This also allows to obtain necessary duration of the burst.

Is accompanied by a SN Ia and, probably, X-ray emission due to fall back.

# Supramassive neutron stars

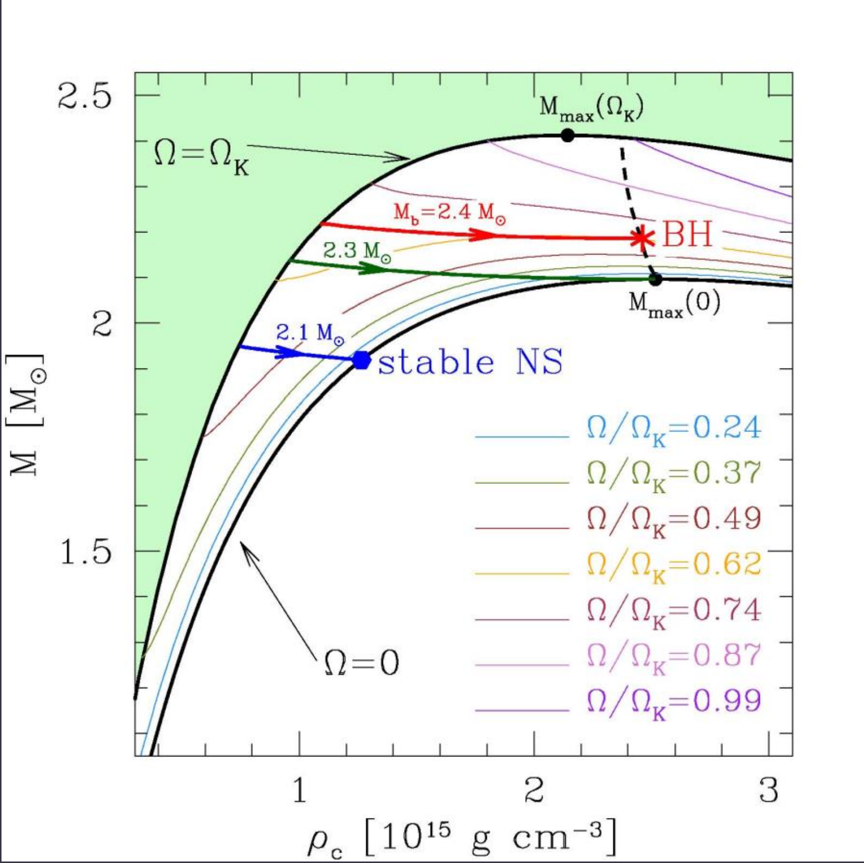
http://www.astro.ru.nl/~falcke/PR/blitzar/



Neutron star can be stable against collapse due to rapid rotation. Such situation can appear after NS-NS coalescence, accretion, or immediately after a NS birth.

Collapse can happen, as it was suggested, thousand years after the NS formation.

Collapse can be accompanied by a SN-like event, short GRB and a GW burst.
Double-peaked events can also appear in this scenario.

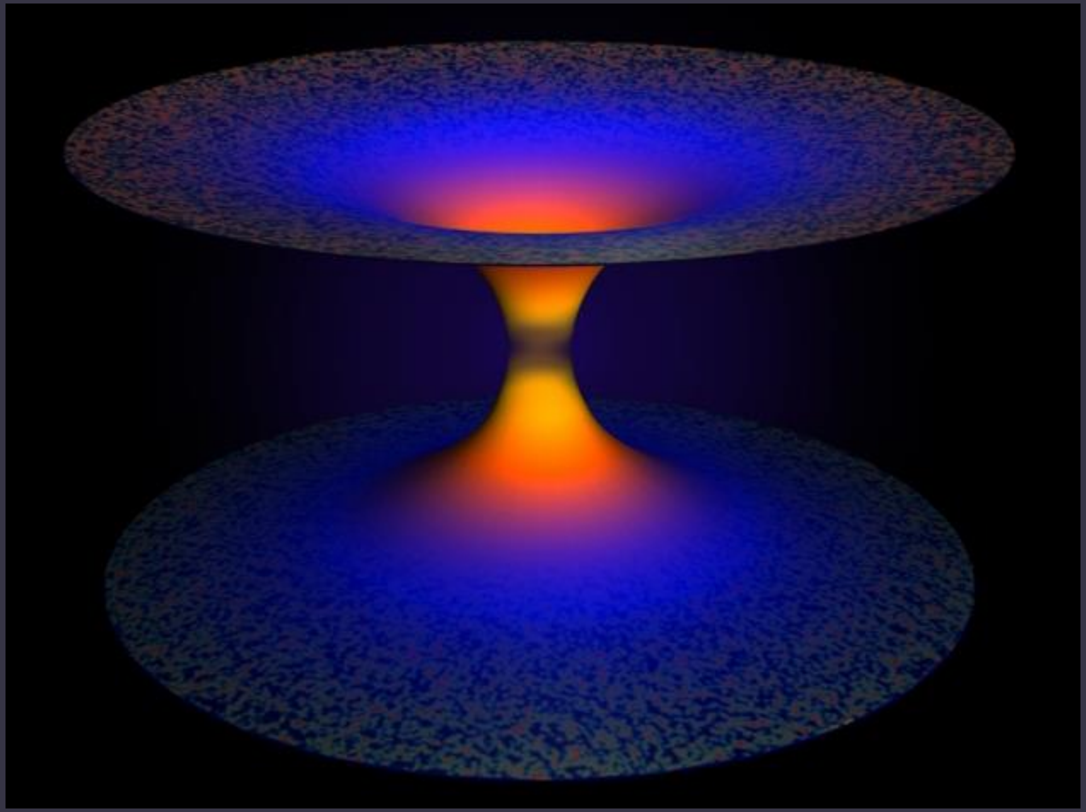



**"blitzar"**

Falcke, Rezzola 1307.1409

# White holes (from black)

http://www.nature.com/news/quantum-bounce-could-make-black-holes-explode-1.15573



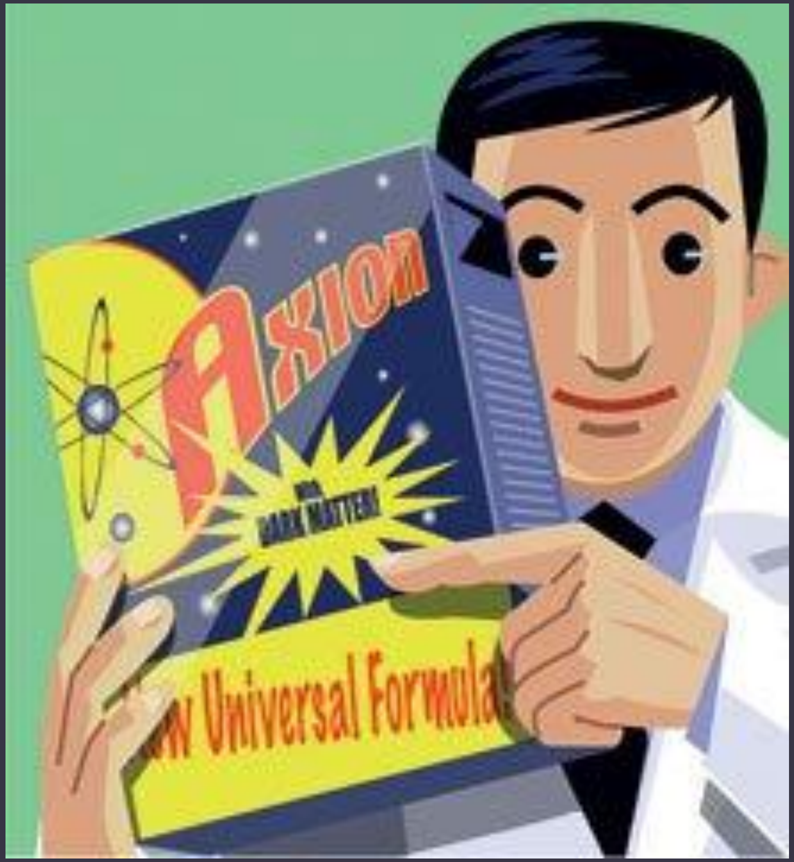
We do not know exactly, how BHs evaporate.
In loop quantum gravity this can include a white hole formation on late stages of the process.

BH evaporation was proposed as a possible explanation for FRBs. In this case a shock wave interacts with external magnetic field.

In the case of a WH formation emission is related to quantum gravity effects.

Initial calculations have not predict radio emission.
But the authors of 1409.4031 suggest that there are many uncertainties in the model, and radio emission is also possible.
Wavelength corresponds to the size of the hole.

# Axions




Axions are dark matter particle candidates
For FRBs axions miniclusters are important.
They are formed in young universe.
Typical mass – similar to a large asteroid.
Typical size – solar radius.

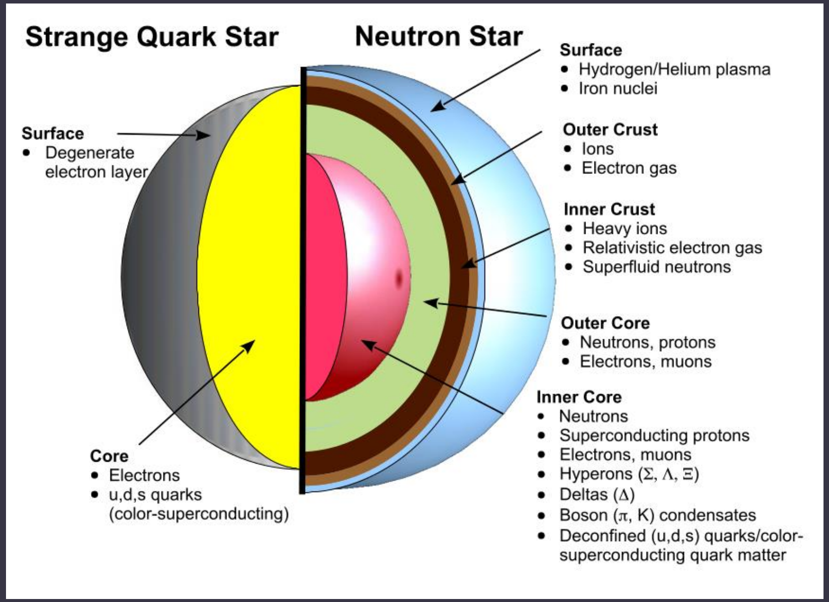
A cluster can be more compact due to formation of Bose-Einstein condensate.
Then, the size can be ~few hundred km, this corresponds to expected size of emitting region in FRB sources (duration multiplied by the velocity of light).
Mass of such compact cluster can be about the mass of the Earth!

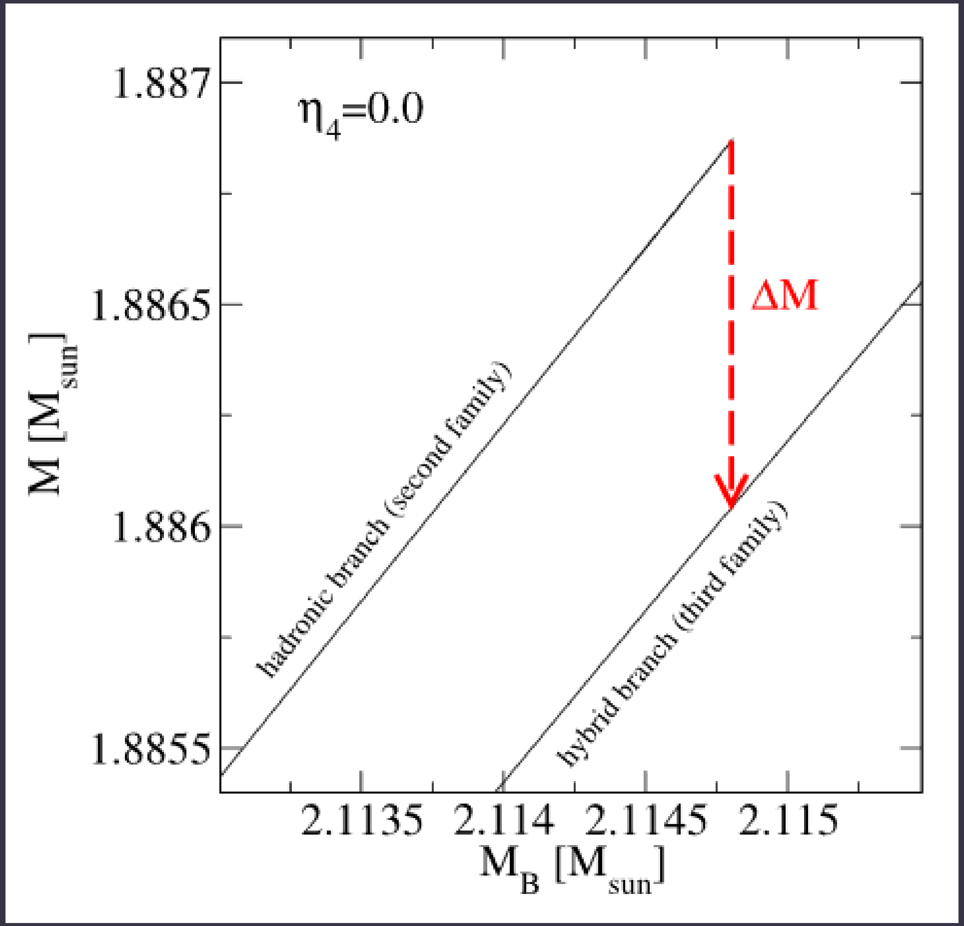
When such cluster flies into a NS magnetosphere then due to the Primakoff effect axions start to be converted into photons.
Thus, a flare of electromagnetic radiation is generated.

1411.3900, 1410.4323, 1512.06245, 1707.04827

# Deconfinement – formation of a quark star

http://astrobites.org



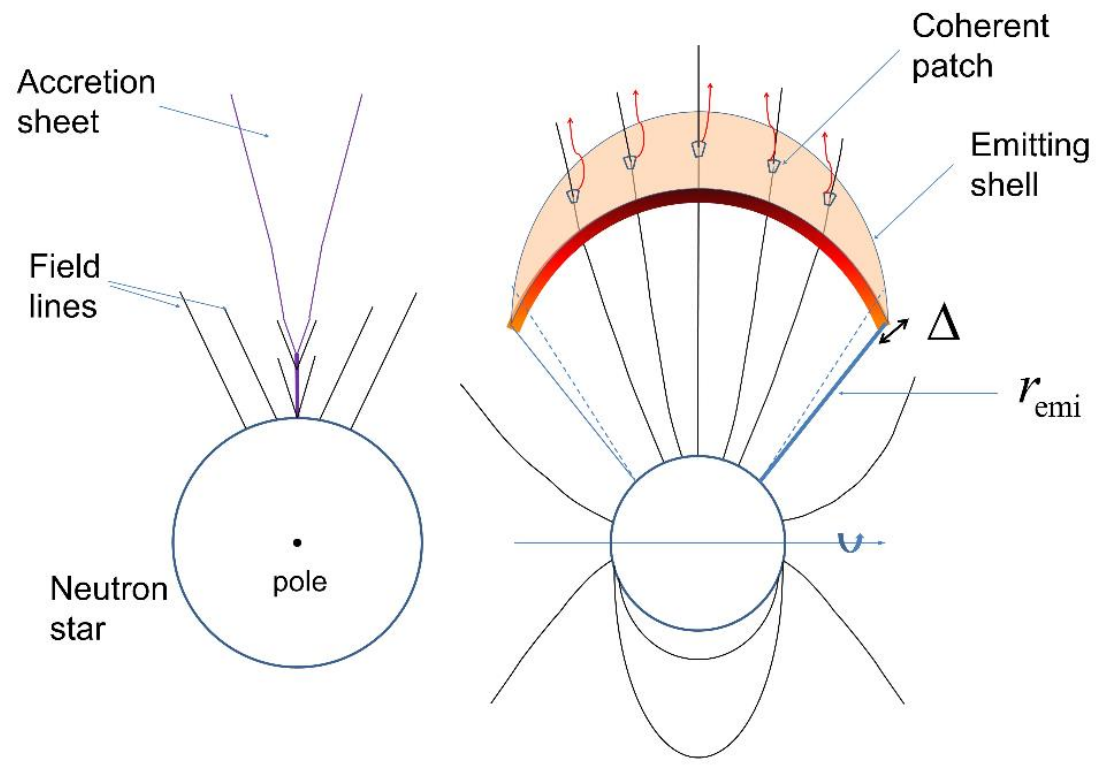

1506.08645

During its evolution the whole NS or its part can experience deconfinement:
normal matter is converted into quarks.
This is accompanied by huge energy release.

Also there attempts to reproduce FRB  in the model of so-called “quark nova” (1505.08147).

# Falling asteroids

1502.05171, see also 1512.06519




For explanation of FRBs researchers actively used mechanisms proposed previously (~30-40 years ago) for cosmic GRBs. Here is one of them.

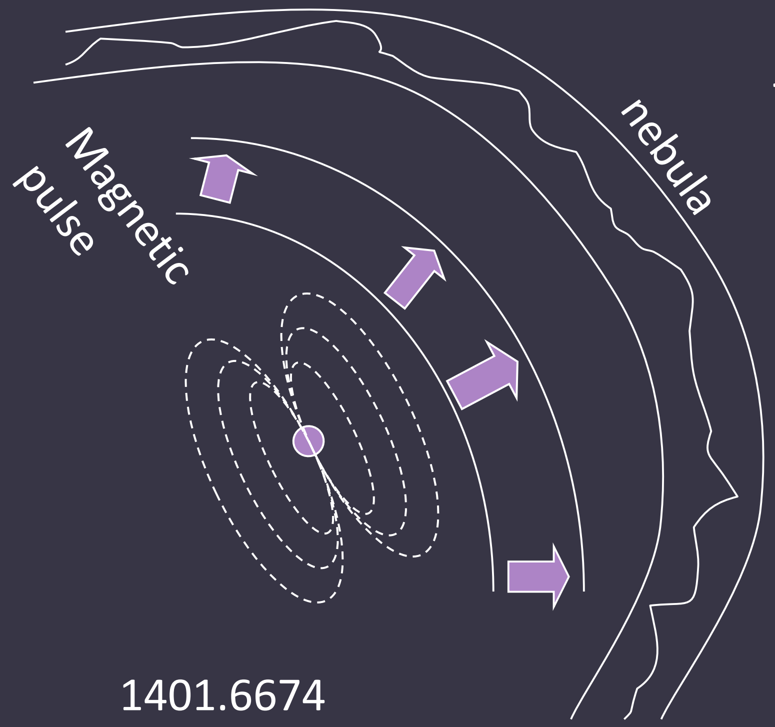
Free-fall time scale in the vicinity of a NS is ~ few msec. Energy release can be explained by potential energy.

After a massive asteroid falls onto a NS an outflowing envelope is formed. This can result in a radio and X-ray flare.

On modification to explain repeating FRBs see 1603.08207.

On evaporation of asteroid by PSRs see 1605.05746.

# Magnetar model




1401.6674

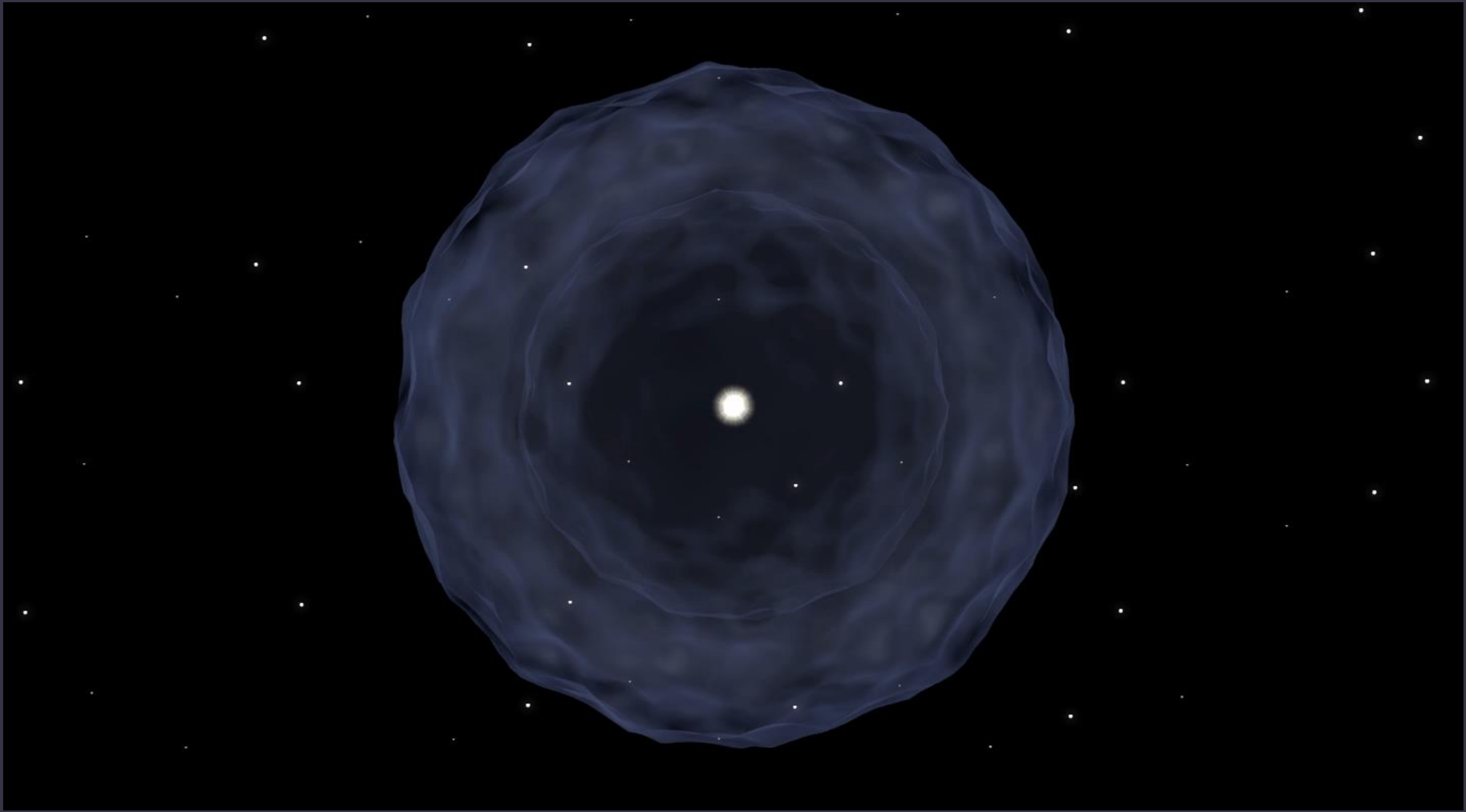
The first idea of possible connection between FRBs and magnetars
has been proposed already in 2007: arXiv 0710.2006.

This hypothesis has been based on rate and energetics considerations, mainly.

*FRB bursts might be related to giant flares of magnetars*

Later this approach was developed by Lyubarsky (2014).

In the model by Lyubarsky the radio burst happens
due to synchrotron maser emission
after interaction between a magnetic pulse after
a giant flare of a magnetar with surrounding nebula.



# Early ideas

Exotics: strings, axions, white holes, etc.

Catastrophic events: SN, GRBs, coalescence, …

Compact objects + smth.: asteroids on NSs, etc.

Mainstream: magnetars and pulsars

# Magnetars or/and Pulsars

**Magnetars**

Giant flares:
Rate
Energetics
Time scale

Typical distances can be ~1 Gpc

Can belong to young population (collapse) or old population (coalescence)

Problems with polarization, but see Beloborodov 2019

Problems with exact emission mechanism

Can repeat.
No counterparts.

**Pulsars**

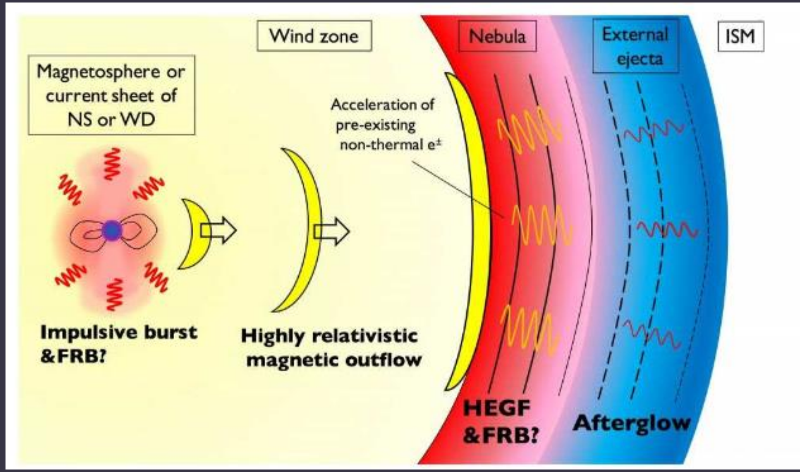
Giant pulses:
Energetics
Time scale

Typical distances might be ~100 Mpc

Might belong to young population

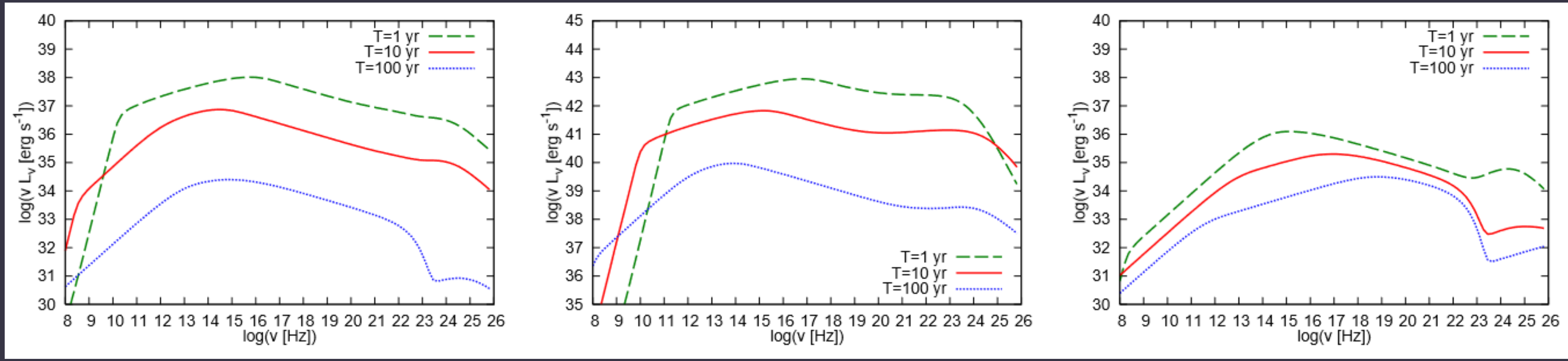
Problems with efficiency (too high, see Lyutikov 2017)

# Nebula emission




The model of a nebular emission
after a huge energy release
in a central source
was developed by several authors.

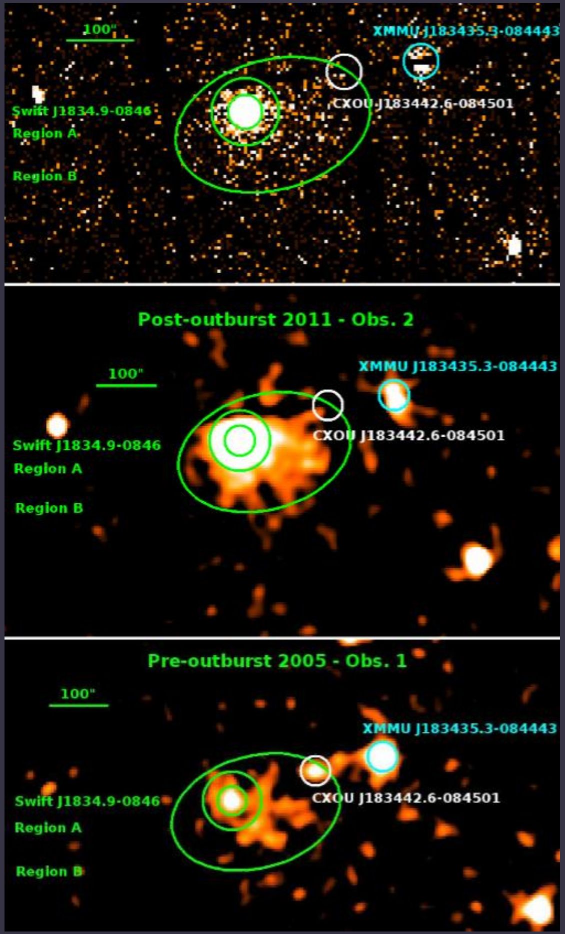
1603.08875



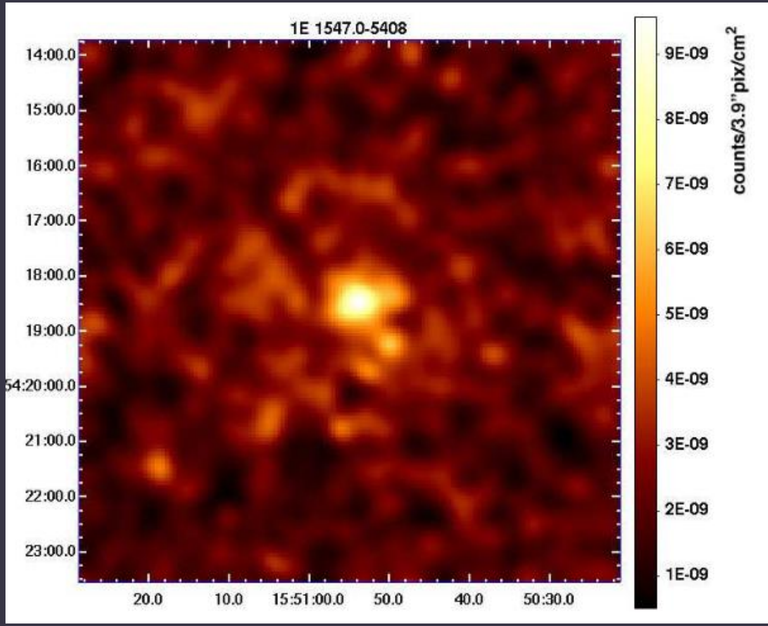

Magnetar RNS MWD

# Nebulae around magnetars

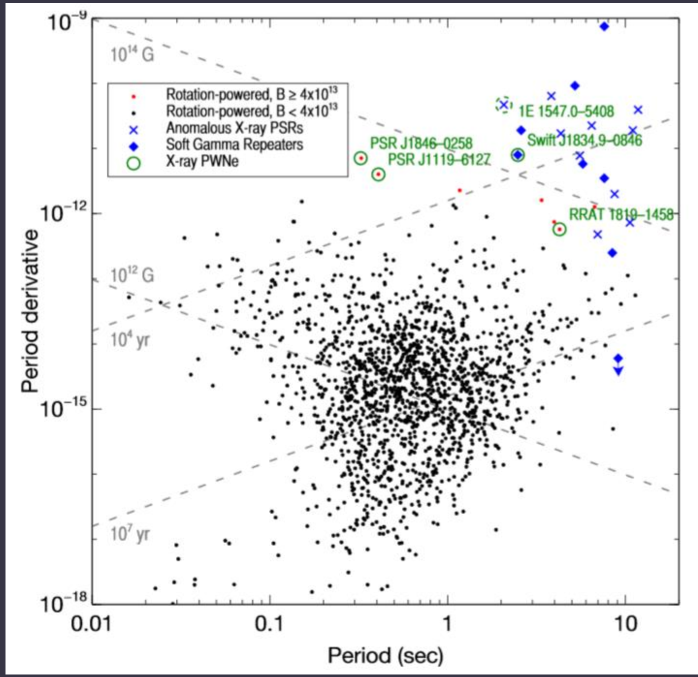
1206.3330. New results in 1604.06472




There are examples of nebulae around magnetars and highly magnetized radio pulsars.

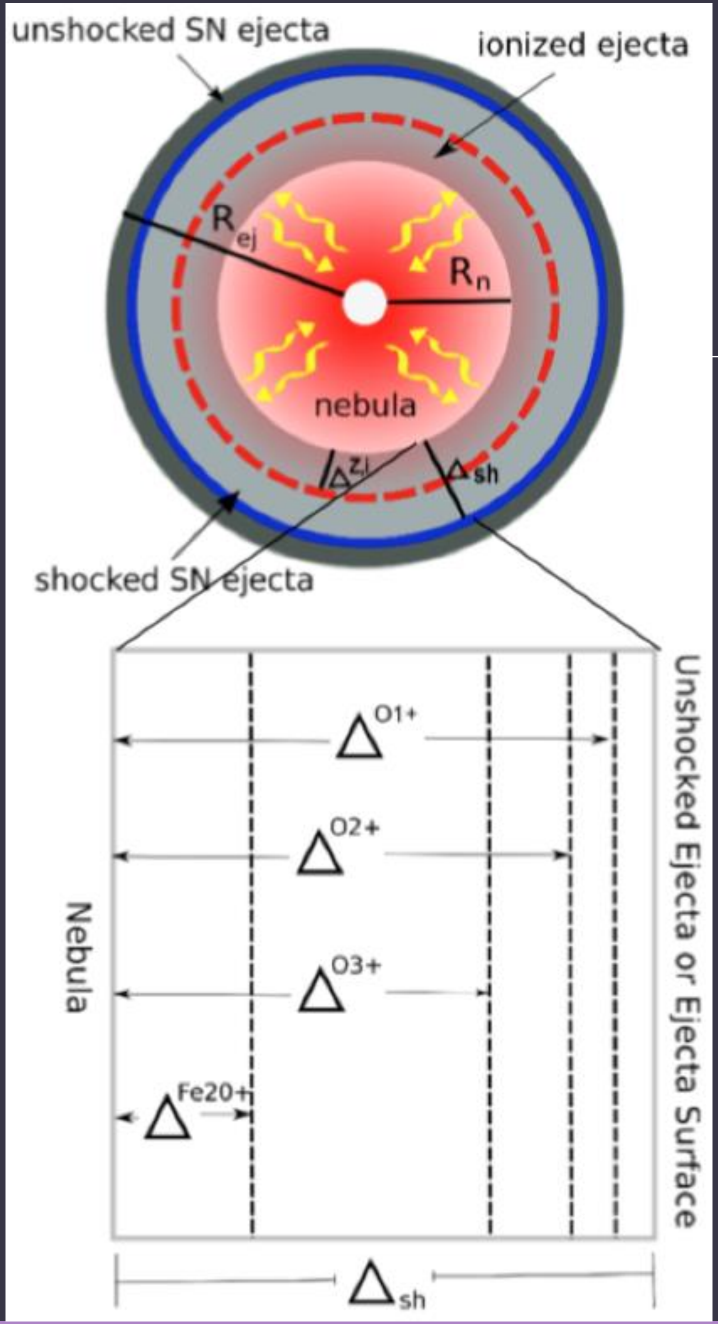



0909.3843




1211.0852

About formation of pulsar nebulae around magnetars see 1606.01391




# Young millisecond magnetar

$$L_{\rm sd} = 5\times10^{46} B_{14}^2 P_{\rm ms}^{-4}\left(1+\frac{t}{t_{\rm sd}}\right)^{-2} {\rm erg\,s^{-1}} \underset{t\gg t_{\rm sd}}{\approx} 8\times10^{40} B_{14}^{-2} t_{10}^{-2}\,{\rm erg\,s^{-1}},$$

$$P = P_0\left(1+\frac{t}{t_{\rm sd}}\right)^{1/2} \underset{t\gg t_{\rm sd}}{\approx} 28\,{\rm ms}\,B_{14} t_{10}^{1/2},$$

$$t_{\rm sd} \simeq 4.7\,{\rm day}\ B_{14}^{-2} P_{\rm ms}^2.$$

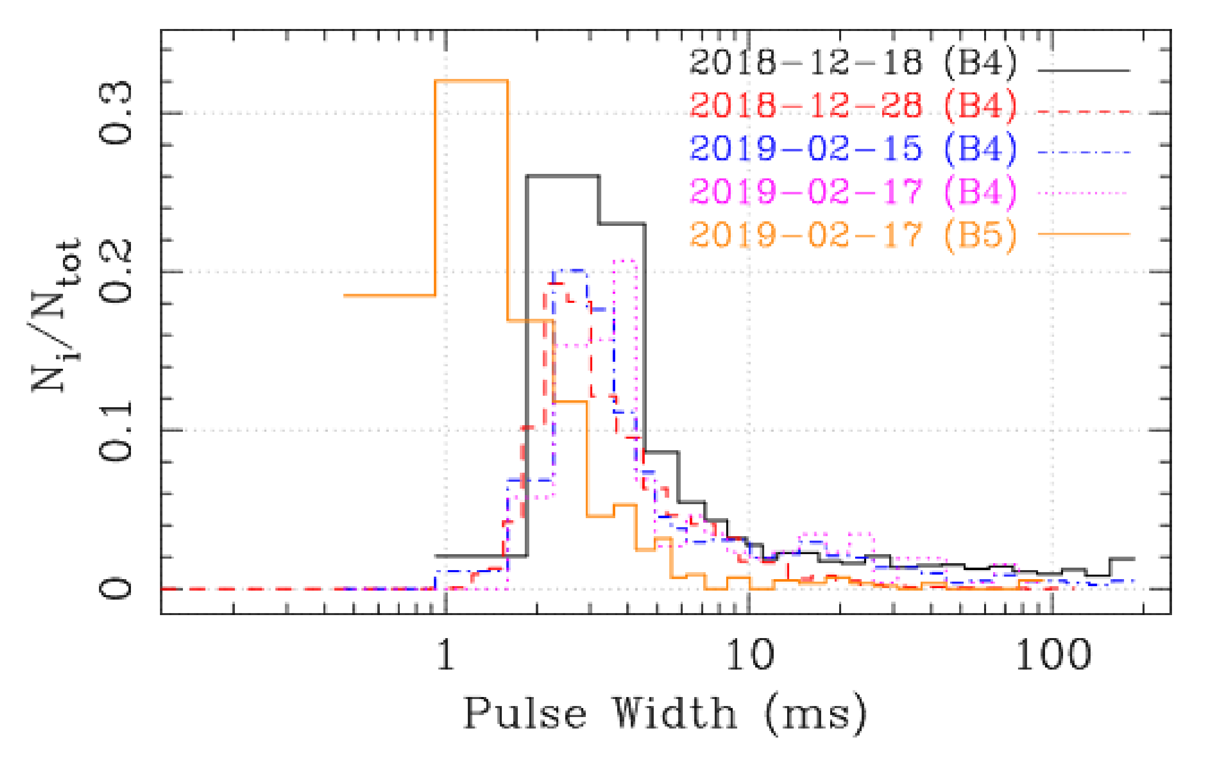
Number of bursts during lifetime of a magnetar

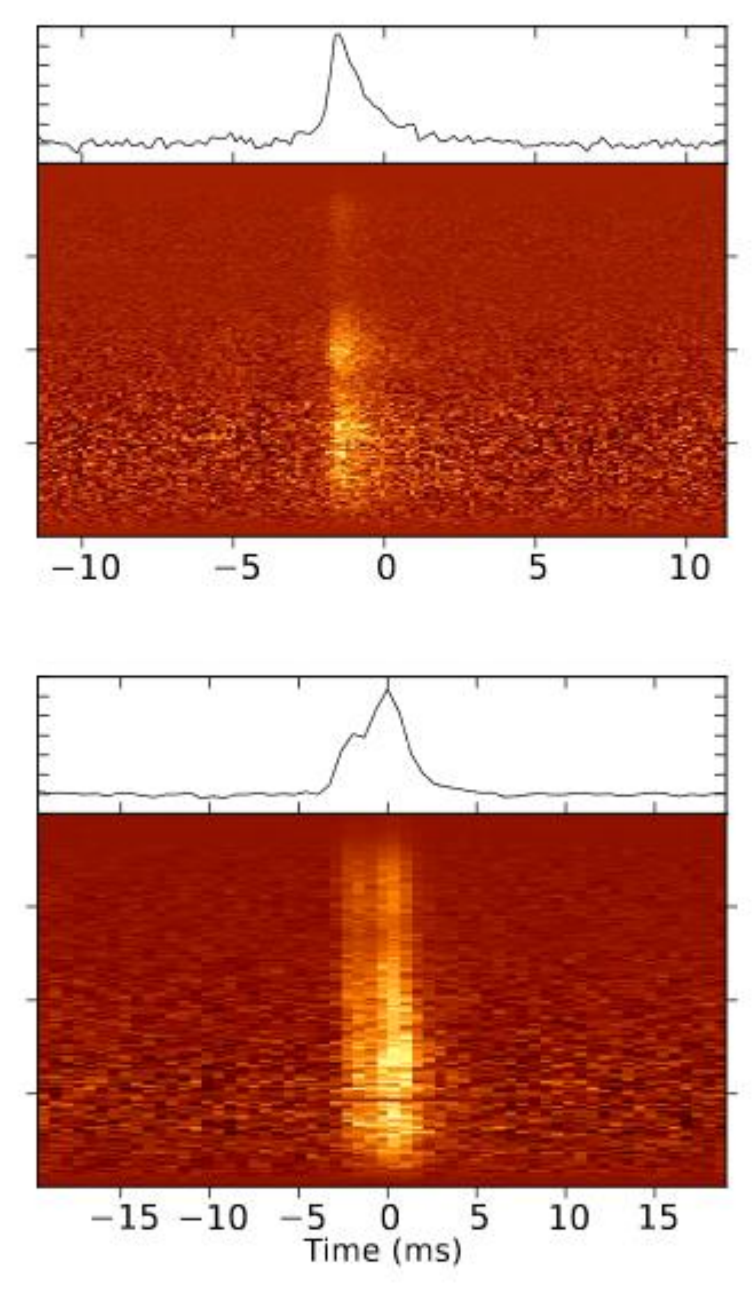
$$N_{\rm FRB} = \frac{E_{\rm B}}{E_{\rm FRB}} \approx 3\times10^2 f_b^{-1}\left(\frac{f_{\rm r}}{10^{-8}}\right)\left(\frac{B_{\rm int}}{10^{16}\,{\rm G}}\right)^2\left(\frac{E_{\rm FRB}}{10^{39}{\rm erg}}\right)^{-1} \quad (5)$$

# Bursts from a magnetar

XTE J1810−197
Second period of activity with radio emission: 2018-2019.

Millisecond scale bursts and spectral properties similar to FRBs.



# Magnetar-based model by Beloborodov

- A magnetar is surrounded by relativistic expanding (cold) wind
- A burst (giant flare) produces a blast wave propagating with large velocity
- A shock appear due to interaction of the blast wave and the wind
- At the shock due to maser mechanism a msec radio burst at ~GHz can be generated

FRBs might be:
- beamed
- polarized

# Wind generation

I. From the inner magnetosphere

$$B(R_\pm) = 10^{13}\,\mathrm{G} = B_\pm.$$

$$I \sim \psi\, c R_\pm B_\pm$$

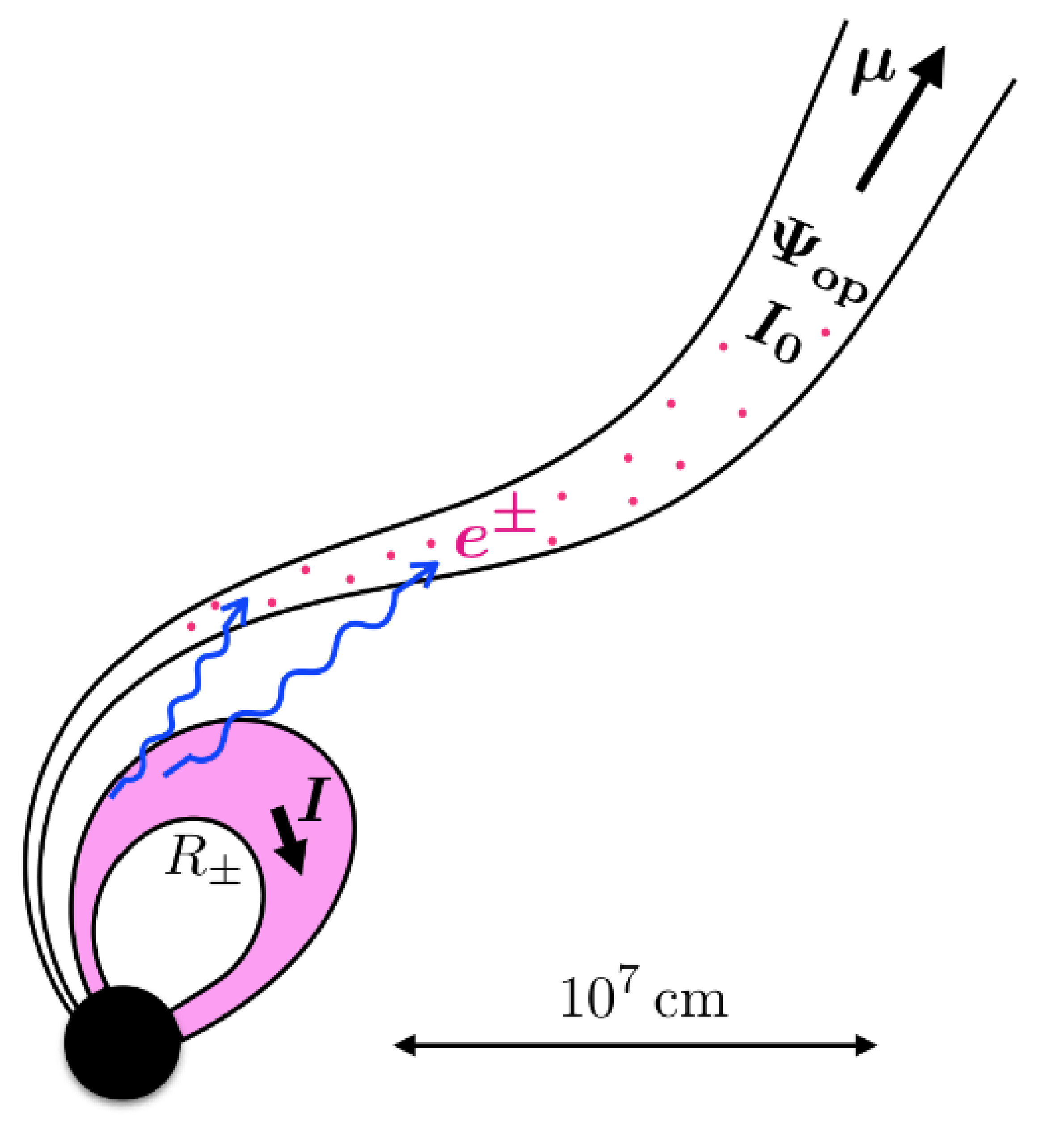
This wind is more favorable for FRB generation.

$$I(R_\pm) \sim \psi (R_{\mathrm{LC}}/R_\pm)^2 I_0$$

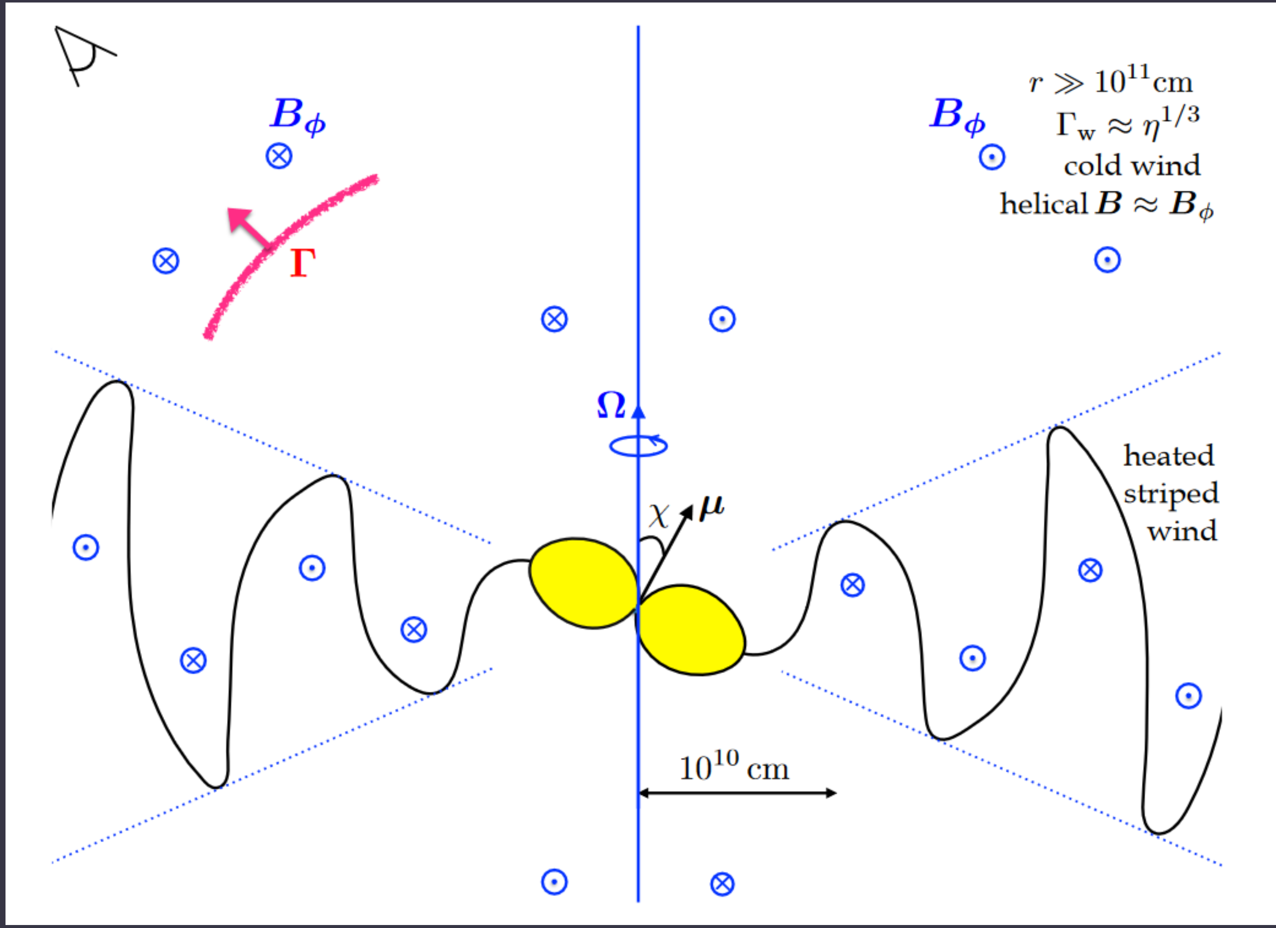
II. From magnetic reconnection

Accelerated particle emit photons, which then are converted into e+/- pairs in the open field line region

Before a giant flare wind is stronger than on average.



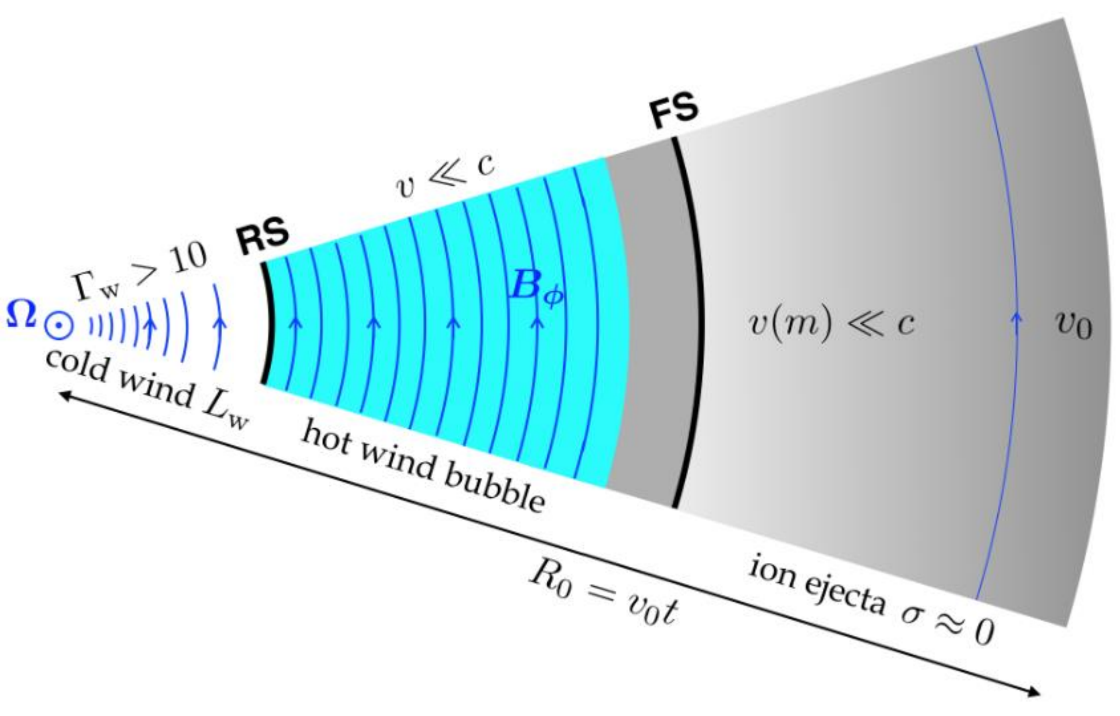
# Different winds around a magnetar

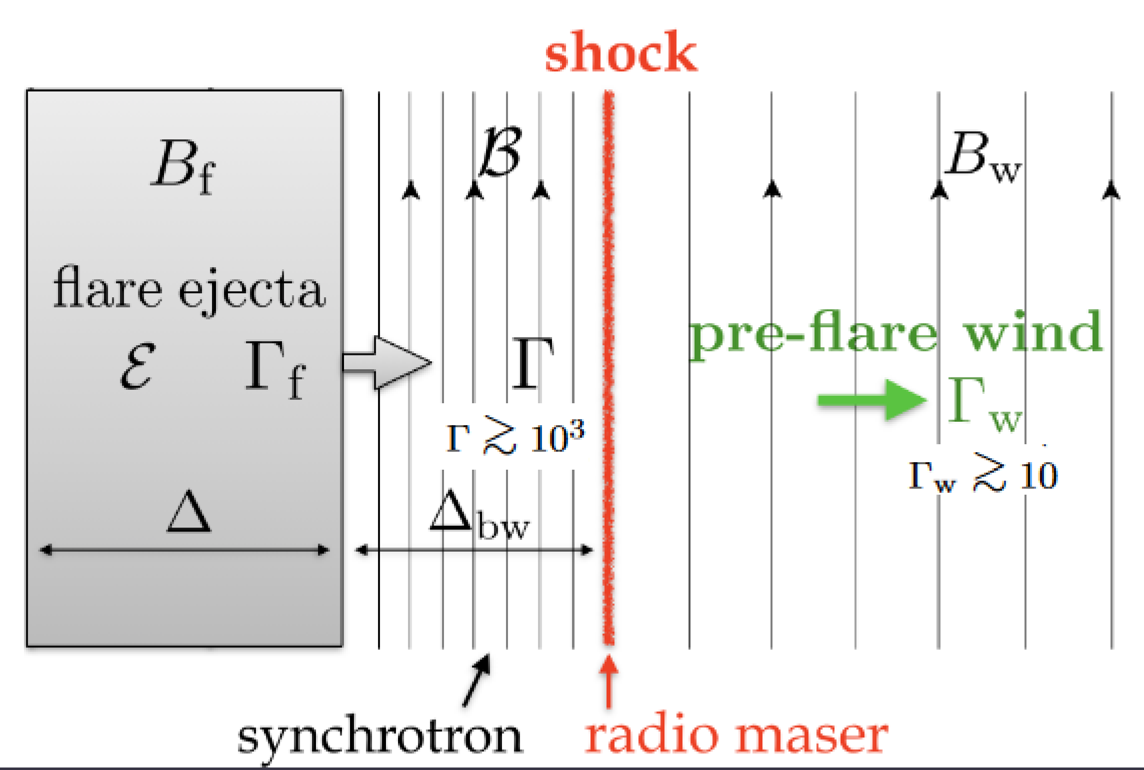



The more probable location of FRB generation is inside the volume filled by the cold helical wind.

1908.07743

# Wind interaction with the tail of ion ejecta




$$\Gamma_f(r) \approx \left(\frac{\eta_f\, r}{\Delta}\right)^{1/3} = 10^5\, r_{13}^{1/3}\, \eta_{f,9}^{1/3}\, \Delta_7^{-1}$$

# FRB parameters

$$\nu_{\rm peak} \sim \frac{e\,\Gamma_{\rm w}\,(2\mathcal{E})^{1/2}}{m_e c\, r^{3/2}} \approx \frac{2.5\ {\rm GHz}}{r_{14}^{3/2}} \left(\frac{\Gamma_{\rm w}}{10}\right) \mathcal{E}_{44}^{1/2}.$$

$$t_{\rm obs}(r) \sim \frac{r}{c\Gamma_{\rm sh}^2} = t_\diamond \times \begin{cases} r/R_\diamond & r < R_\diamond \\ (r/R_\diamond)^2 & r > R_\diamond \end{cases}$$

$$t_\diamond \sim \frac{\tau}{2\sigma_{\rm w}} = \frac{1\ {\rm ms}}{2\sigma_{\rm w}}\,\tau_{-3}.$$

$$\nu_{\rm peak} = \nu_\diamond \times \begin{cases} t_\diamond/t_{\rm obs} & t_{\rm obs} < t_\diamond \\ (t_\diamond/t_{\rm obs})^{3/4} & t_{\rm obs} > t_\diamond \end{cases}$$

$$\nu_\diamond \sim \frac{e\,L_{\rm w}^{3/4}}{2m_e c^{5/2}\,\mathcal{E}^{1/4}\,\tau^{3/4}\,\Gamma_{\rm w}^2} \approx 5.5\,\frac{L_{\rm w,39}^{3/4}}{\mathcal{E}_{44}^{1/4}\,\tau_{-3}^{3/4}} \left(\frac{\Gamma_{\rm w}}{10}\right)^{-2} {\rm GHz}.$$

$$L_{\rm FRB} = \frac{d\mathcal{E}_{\rm FRB}}{dt_{\rm obs}} \sim 2\epsilon\,\frac{\Gamma^4}{\Gamma_{\rm w}^4}\,L_{\rm w}.$$

$$L_{\rm FRB} \sim L_\diamond \times \begin{cases} 1 & t_{\rm obs} < t_\diamond \\ t_\diamond/t_{\rm obs} & t_{\rm obs} > t_\diamond \end{cases}$$

$$L_\diamond \sim \epsilon\,\frac{\mathcal{E}}{\tau} \sim 10^{44}\,\frac{\mathcal{E}_{44}}{\sigma_{\rm w}\,\tau_{-3}}\,\frac{\rm erg}{\rm s}.$$

$$\frac{d\mathcal{E}_{\rm FRB}}{d\ln\nu} \sim \mathcal{E}_\diamond \times \begin{cases} \nu_\diamond/\nu & \nu > \nu_\diamond \\ 1 & \nu < \nu_\diamond \end{cases}$$

$$\mathcal{E}_\diamond \sim L_\diamond t_\diamond \sim \frac{\epsilon\,\mathcal{E}}{\sigma_{\rm w}} \sim 10^{41}\,\sigma_{\rm w}^{-2}\,\mathcal{E}_{44}\ {\rm erg}.$$

Strong linear polarization.
Direction determined by
the magnetar spin axis.

# Wind, shock, blast

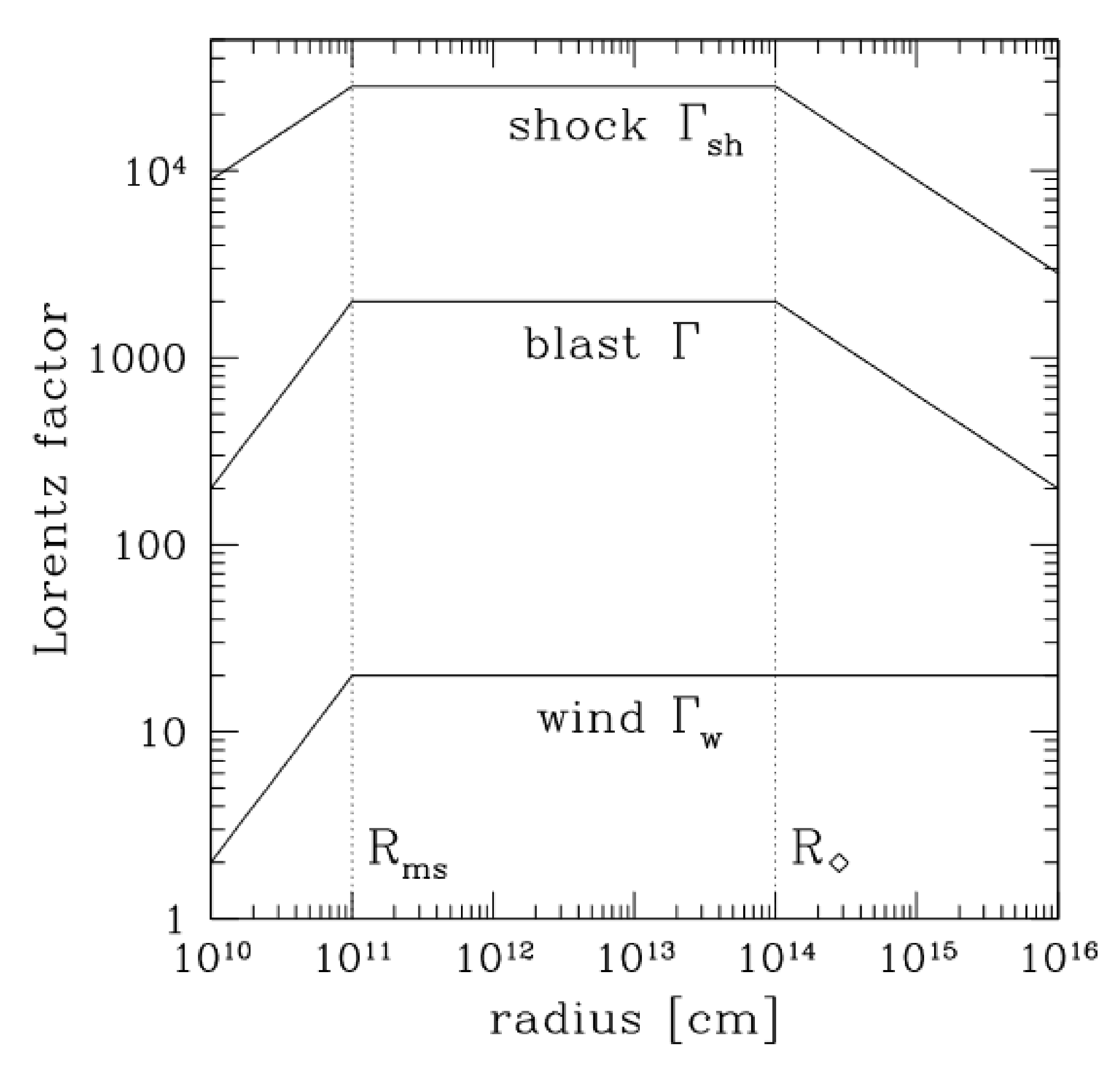
$L_w \approx 10^{39}$ erg/s and $\eta \approx 10^3$

$\mathcal{E} \approx 10^{44}$ erg

$\Gamma_{sh} \approx 2\sigma_w^{1/2}\Gamma$

Three Lorentz factors are shown:
$\Gamma_w$ (the pre-explosion wind), $\Gamma_{sh}$ (the shock),
and Γ (the blast —the hot plasma behind the shock).

~1 s optical flash with E~$10^{44}$ erg can appear,
if the blast wave interacts with the wind bubble
in the tail of a previous burst.
Rate of such transients can be relatively high.
This is synchrotron emission.
In this case – no FRB (no maser emission).



# Death-line for FRBs

In this model
FRBs are due to
short bursts of SGRs.

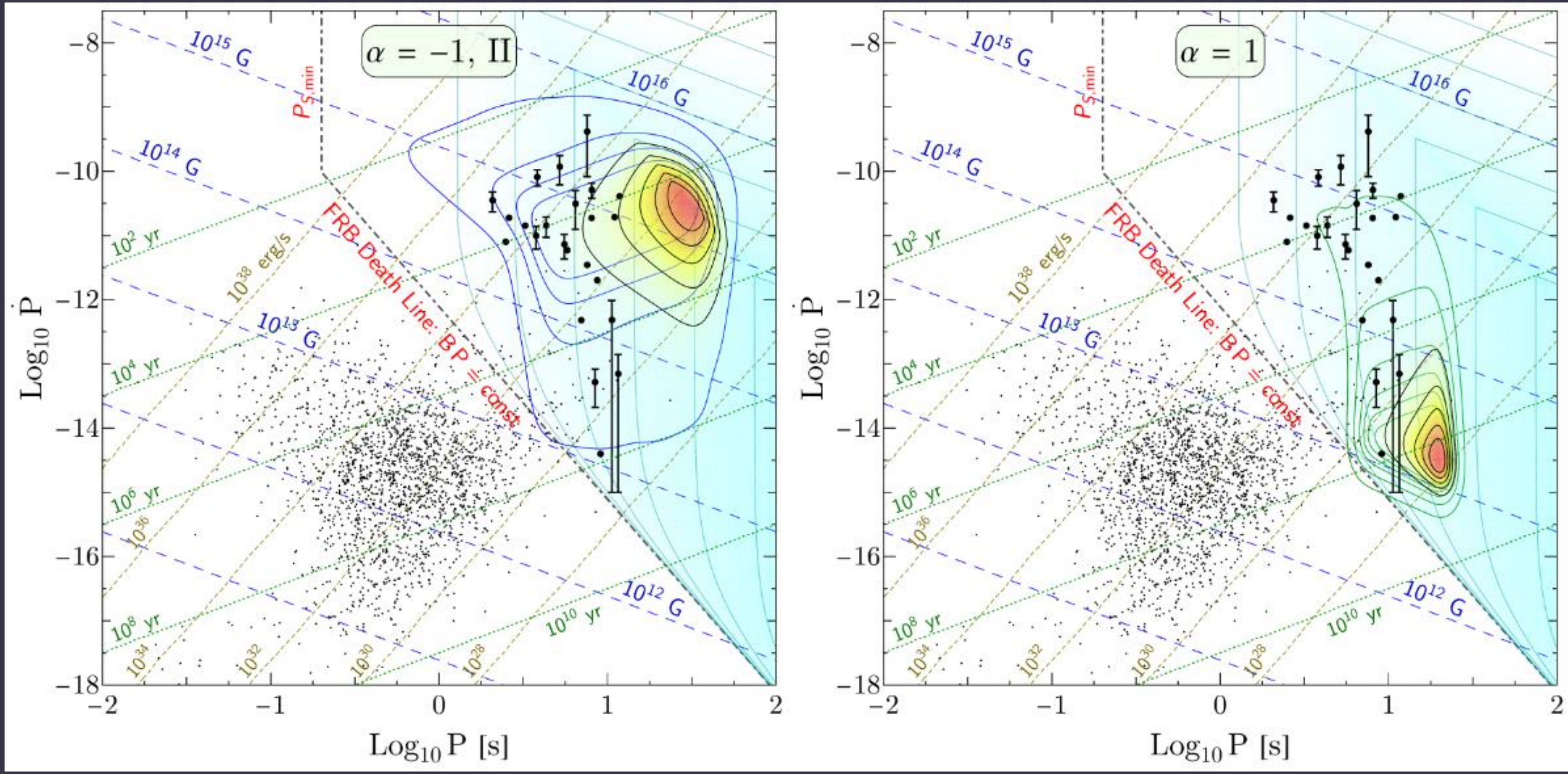
Plasma density
close to surface
must not be very high.

Thus, a condition
for a death-line
can be figured out.

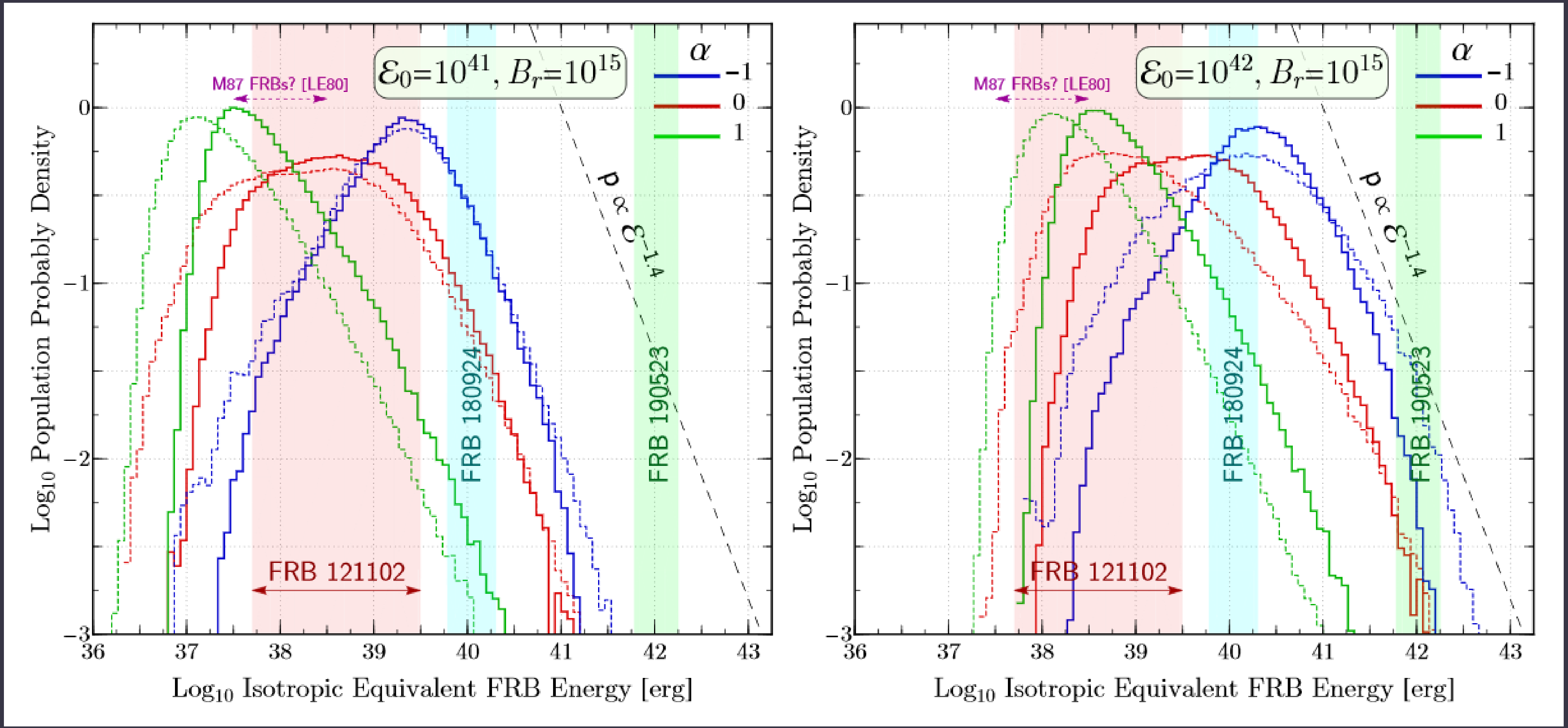
Low-twist model (WT19).

$P \gtrsim 2/(\nu\sigma_{\rm max}) \sim 0.2$ s

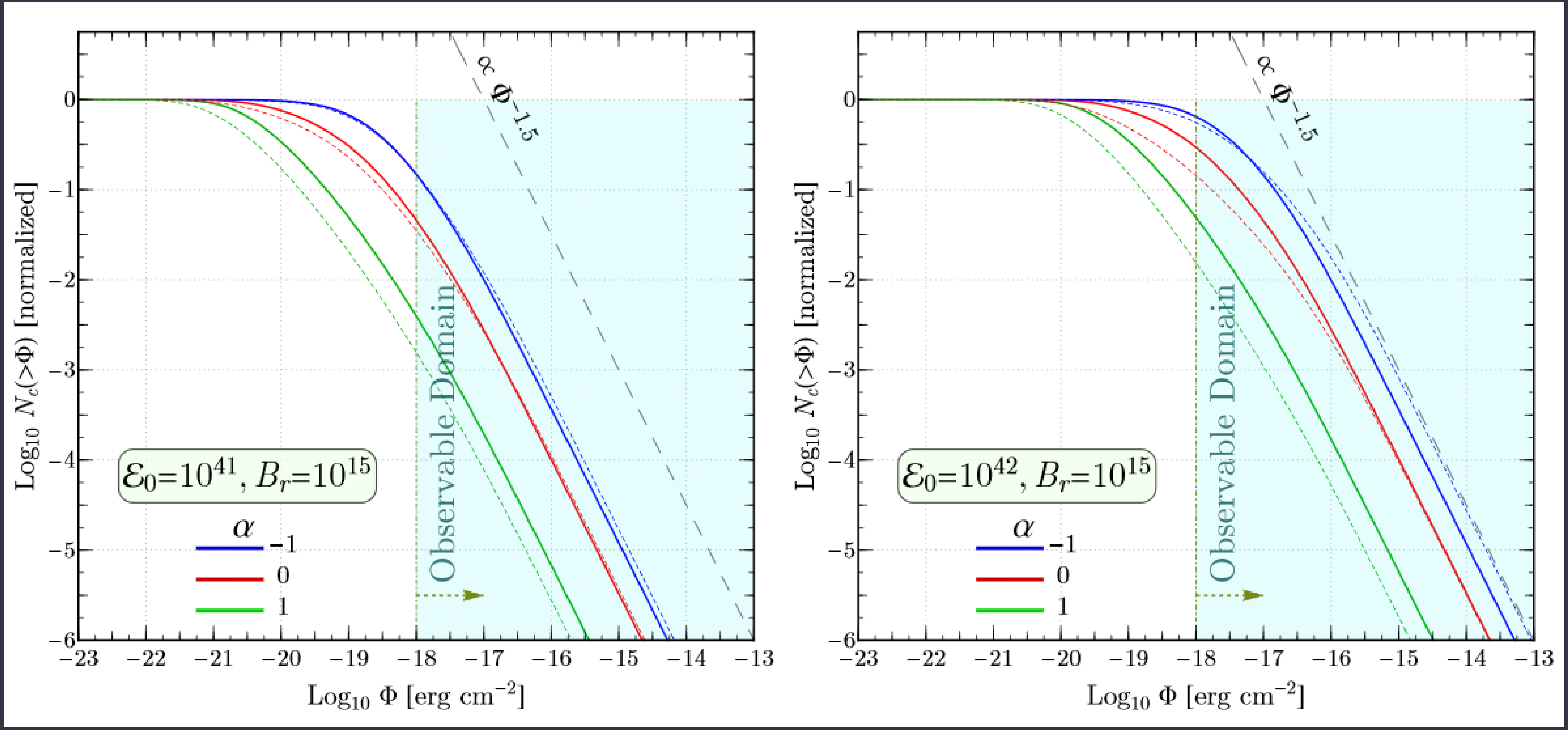
$B\,P \gtrsim 6 \times 10^{13}$ G s



# Energy distribution

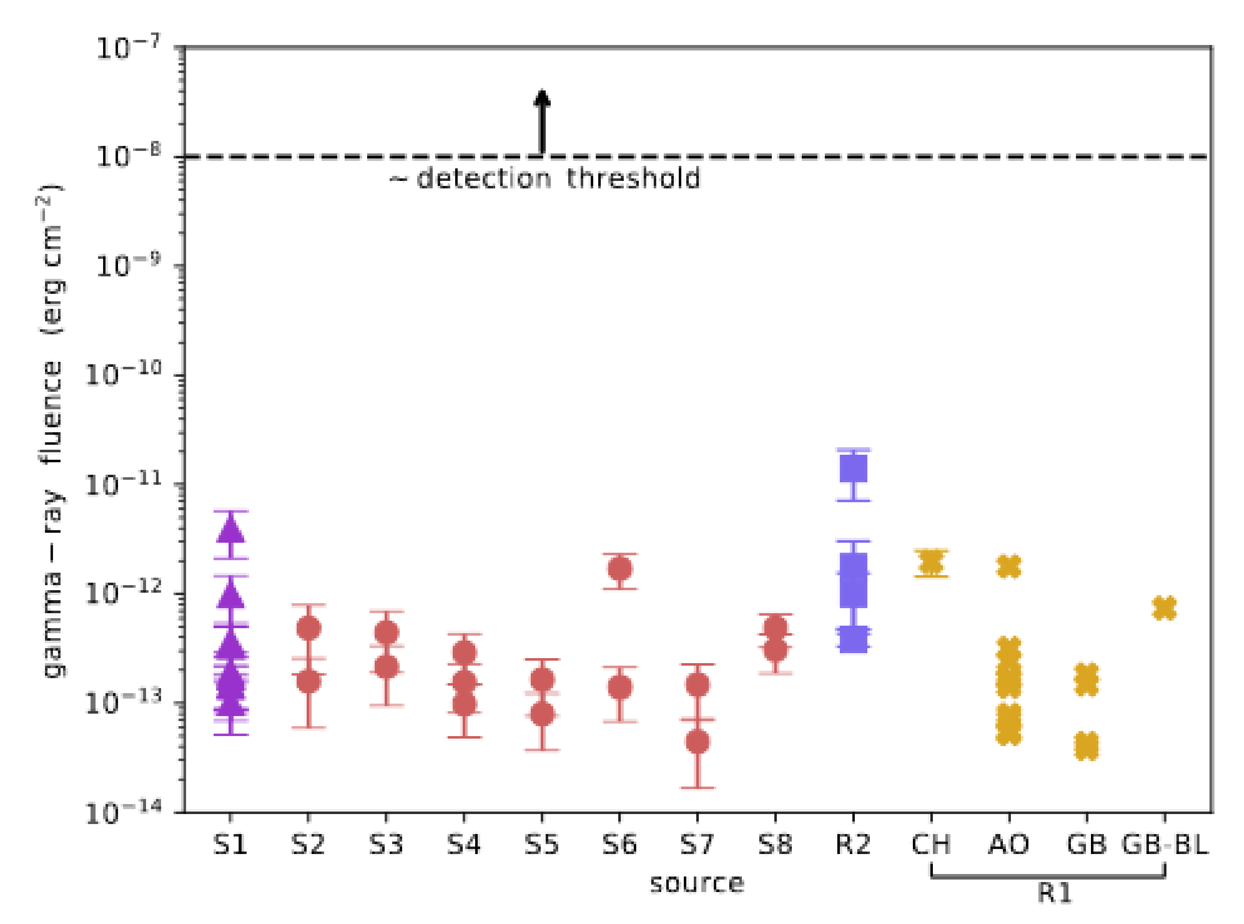


# Log N – log S



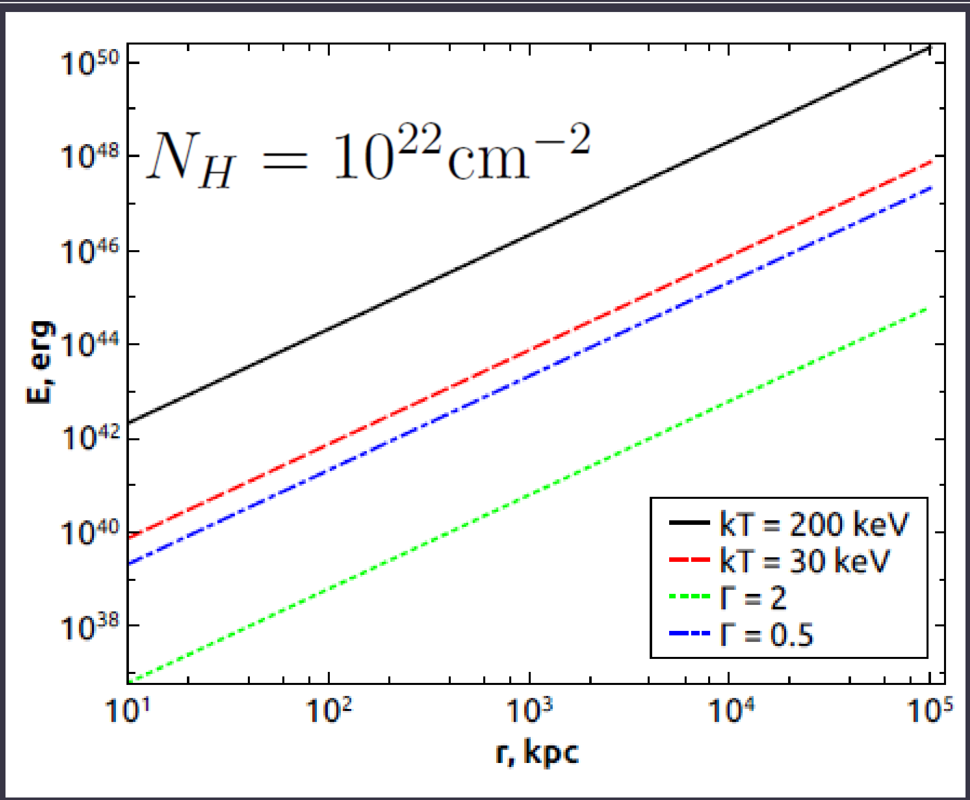
$\propto \Phi^{-1.5}$
Observable Domain
$\mathcal{E}_0$=$10^{41}$, $B_r$=$10^{15}$
$\alpha$
−1
0
1
Log$_{10}$ $N_c(>\Phi)$ [normalized]
Log$_{10}$ $\Phi$ [erg cm$^{-2}$]
$\propto \Phi^{-1.5}$
Observable Domain
$\mathcal{E}_0$=$10^{42}$, $B_r$=$10^{15}$

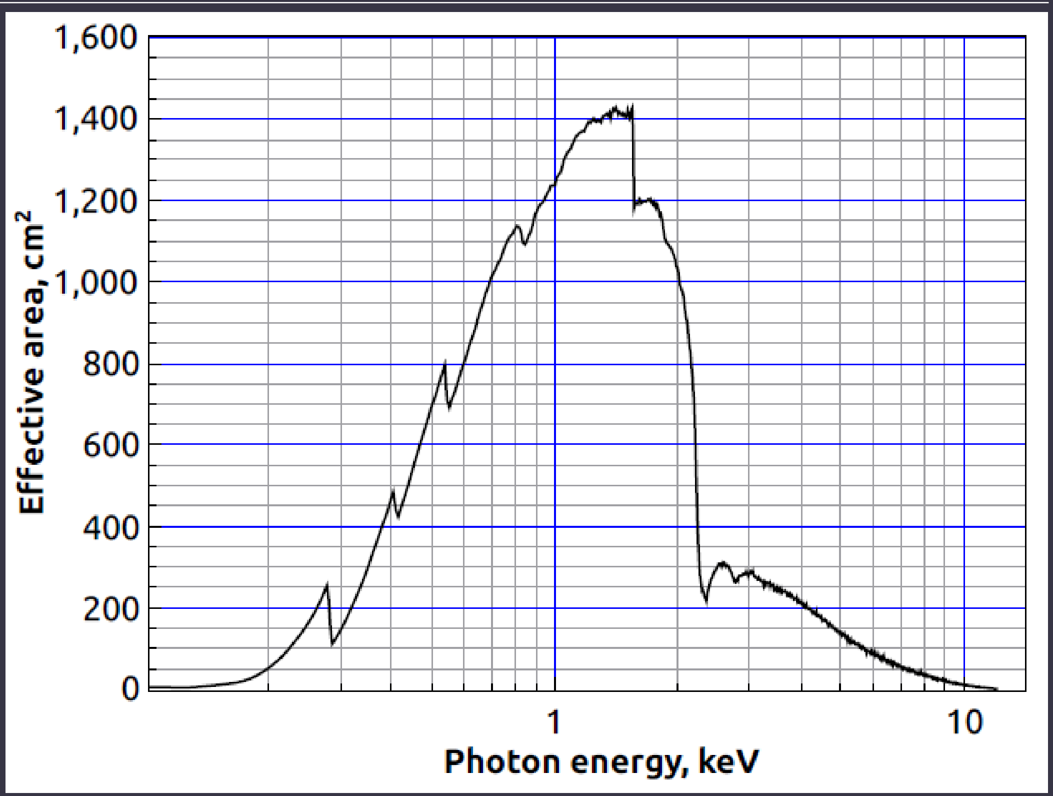
# Predictions for X/γ-ray fluxes




Predictions are made for the repeating FRB 121102 in the framework of the magnetar model.

# FRB with eROSITA?

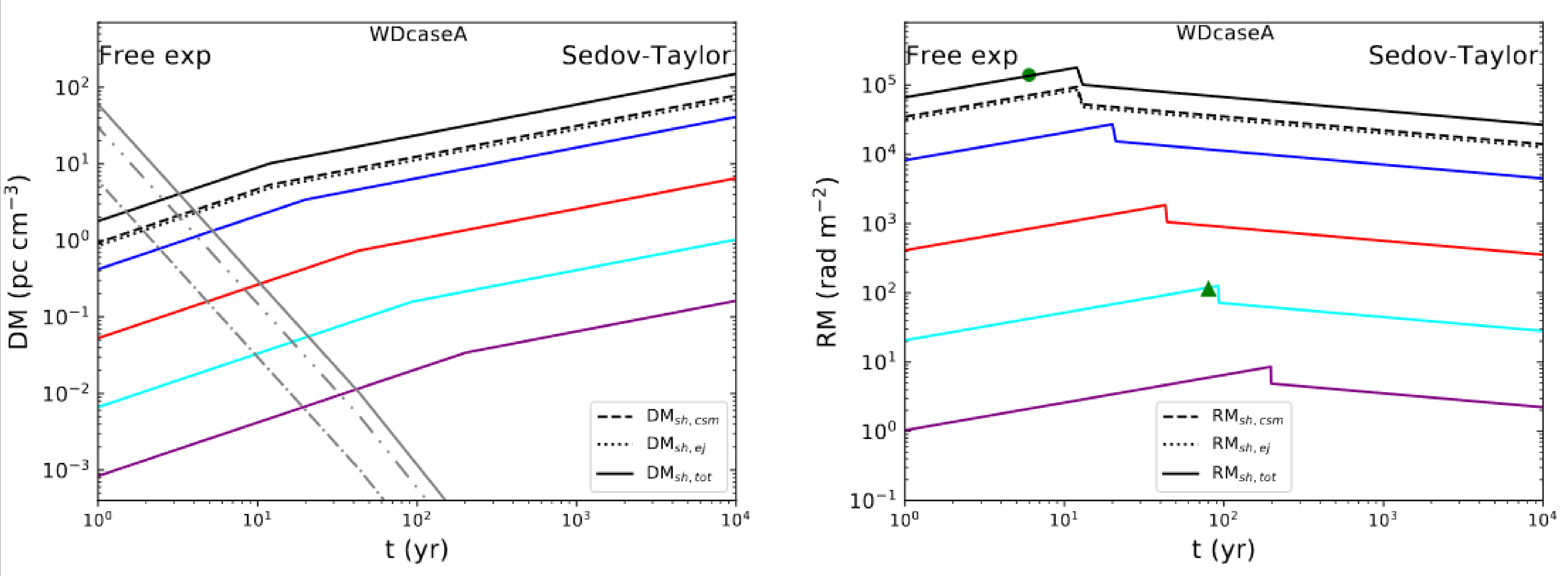



$$N_d = \int_{E_1}^{E_2} \frac{C_p \pi B_E(T,E) E^{-1} e^{-\sigma N_H} S_{eff}(E) dE}{4\pi r^2}.$$

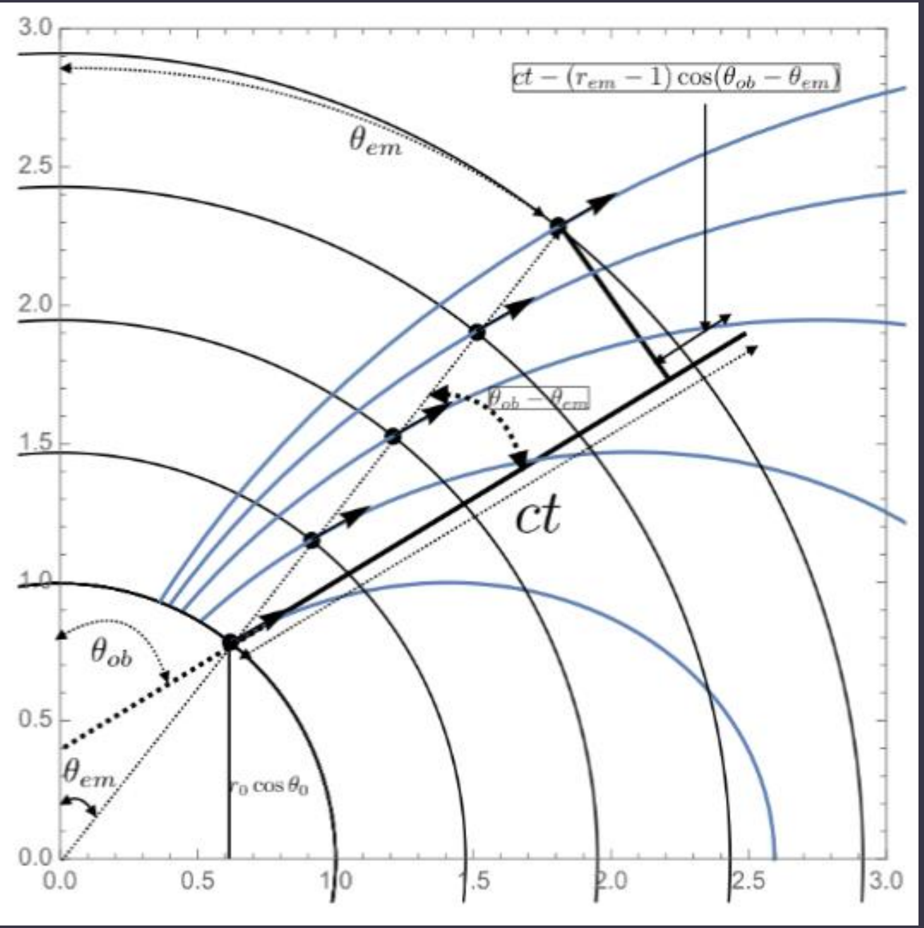
$$N_d = \int_{E_1}^{E_2} \frac{C E^{-\Gamma} e^{-E/E_{cutoff}} e^{-\sigma N_H} S_{eff}(E) dE}{4\pi r^2}.$$

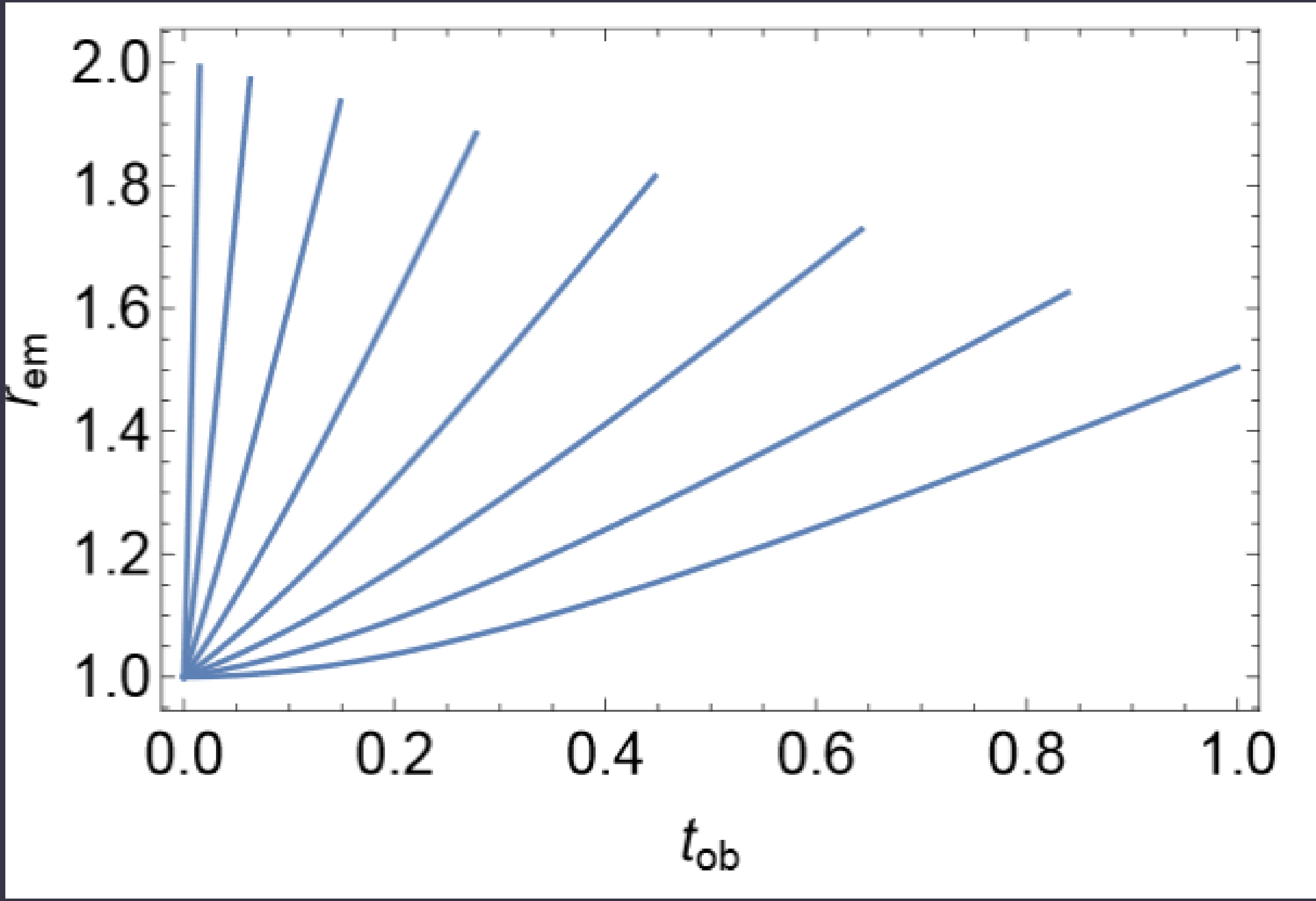
# Coalescence of WD? DM and RM




1912.08287

# Frequency drift

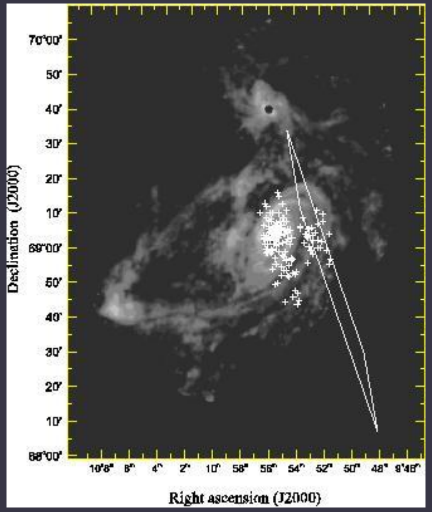


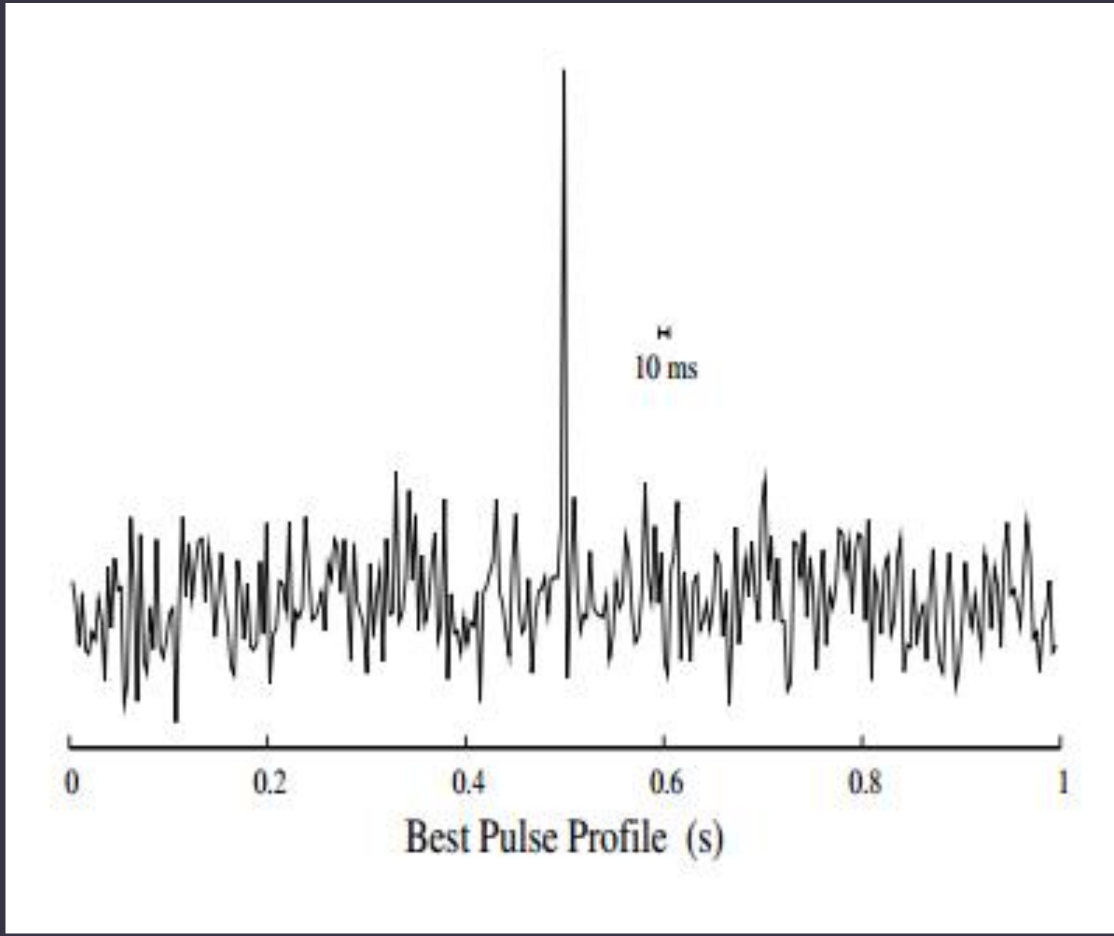
# Radio flares from M31

Rubio-Herrera et al. (2013) discovered millisecond radio bursts from the Andromeda galaxy.

It looks like a scaled version of FRBs.
In the magnetar model such (more frequent) bursts can be related to weaker flares of magnetars.




Note, that Frederiks et al. (2005) proposed a candidate for a giant magnetar flare in M31.

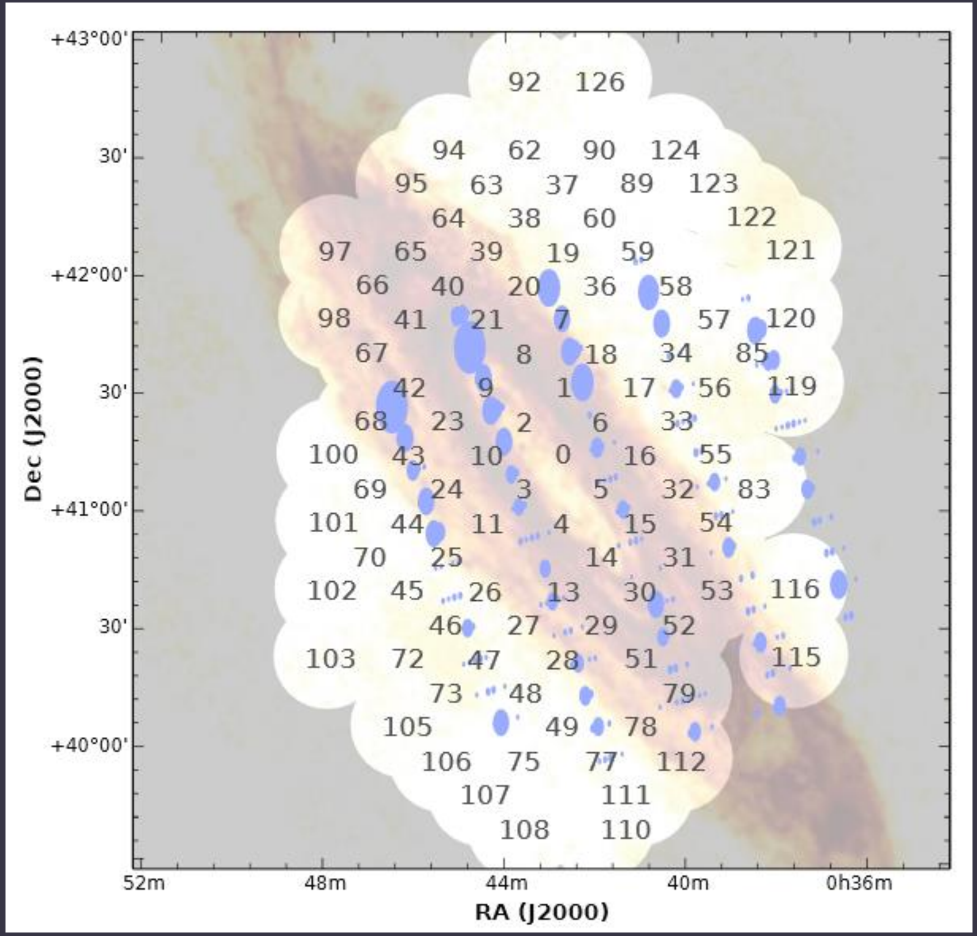


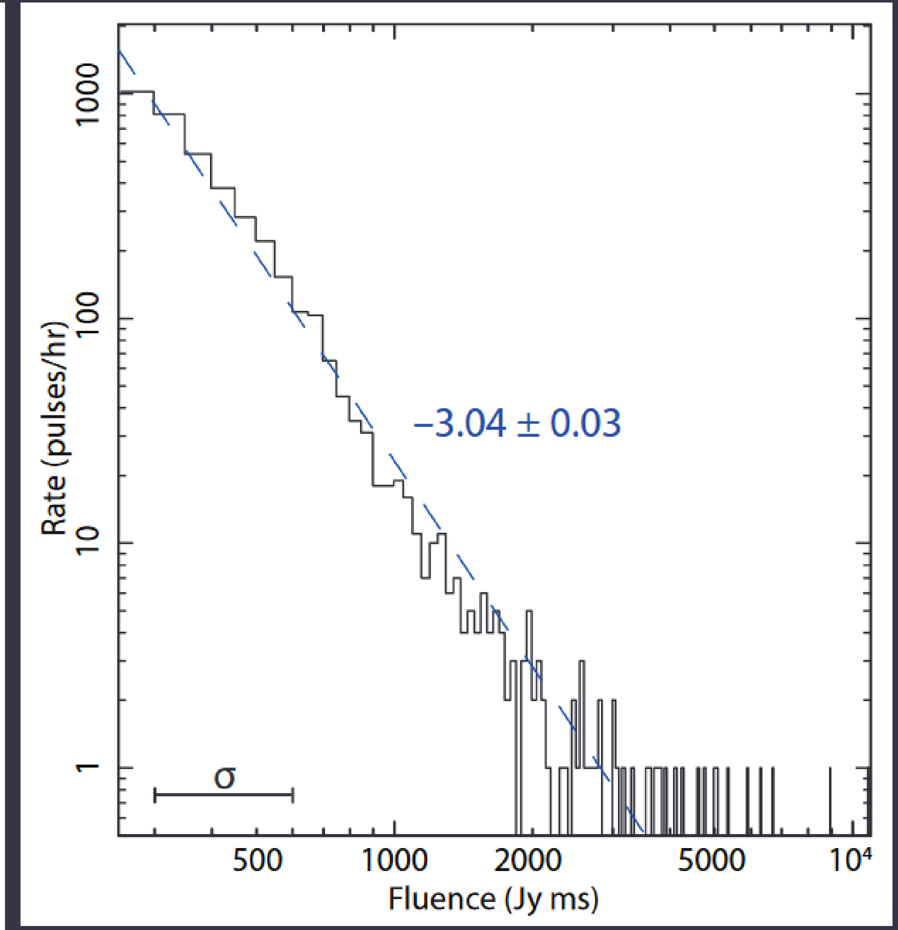
# No giant pulses from M31 at low-freq.

LOFAR observations for 5 hours.

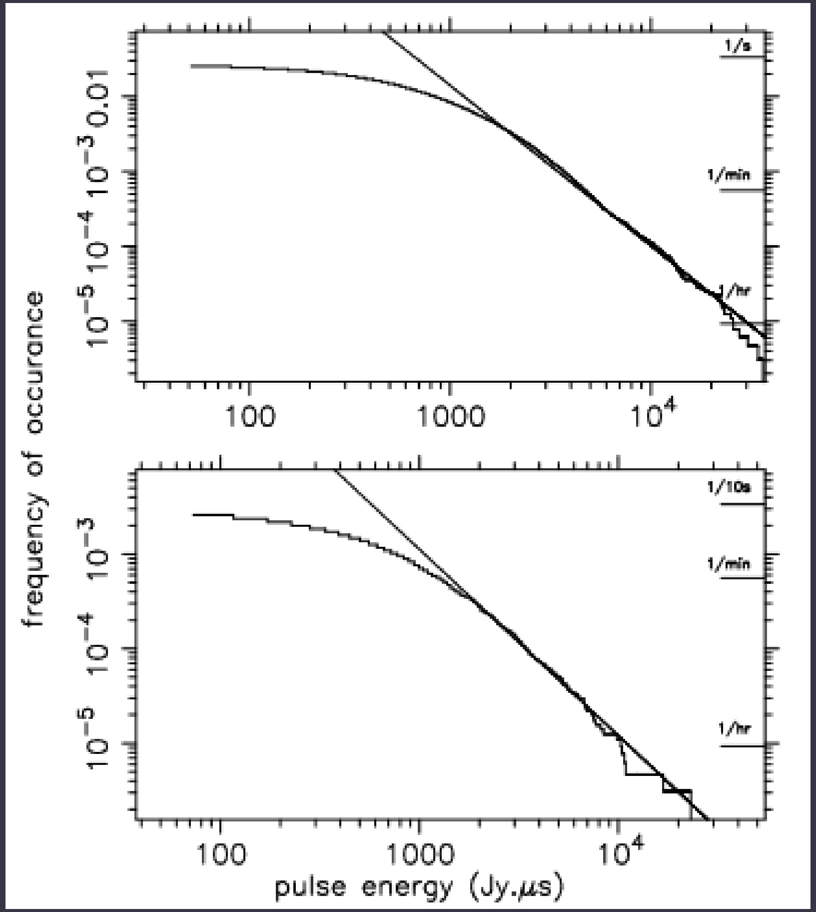
No detected pulsating sources in the Andromeda galaxy.

Crab might be detected with giant pulses, if it emits towards us.



# Radio pulsar model



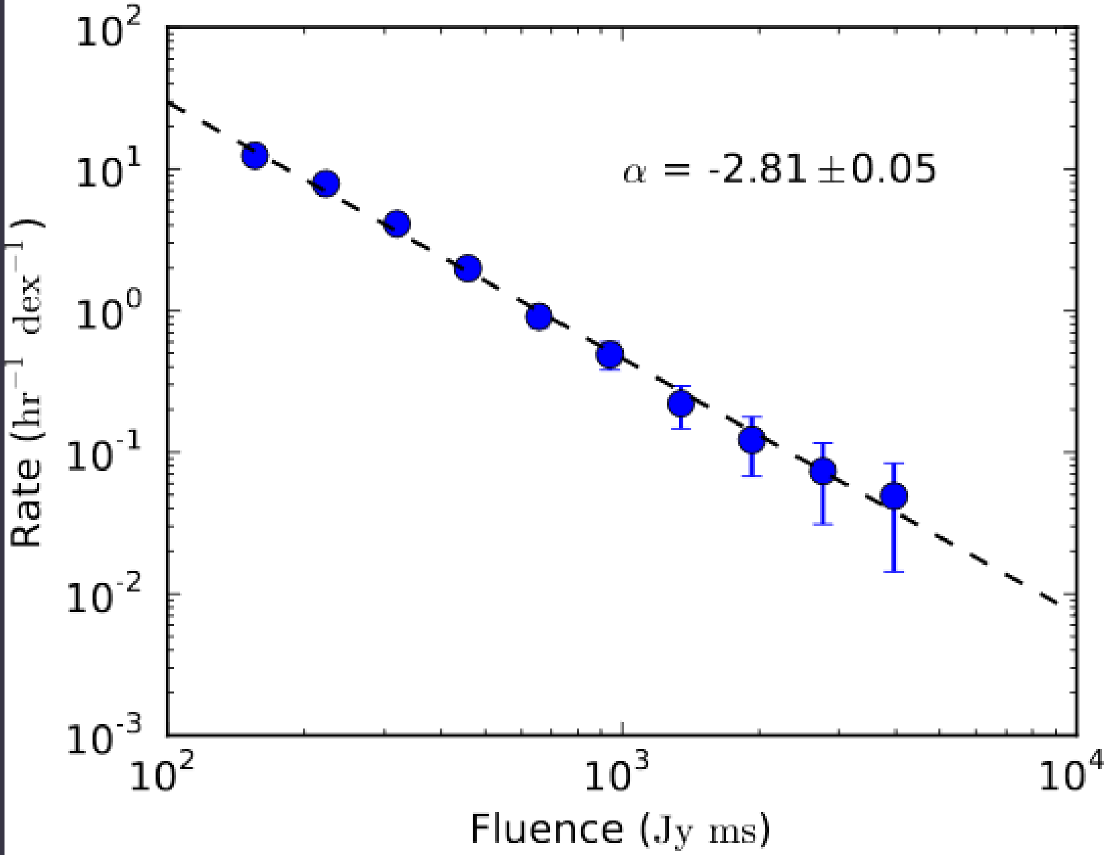

1004.2803

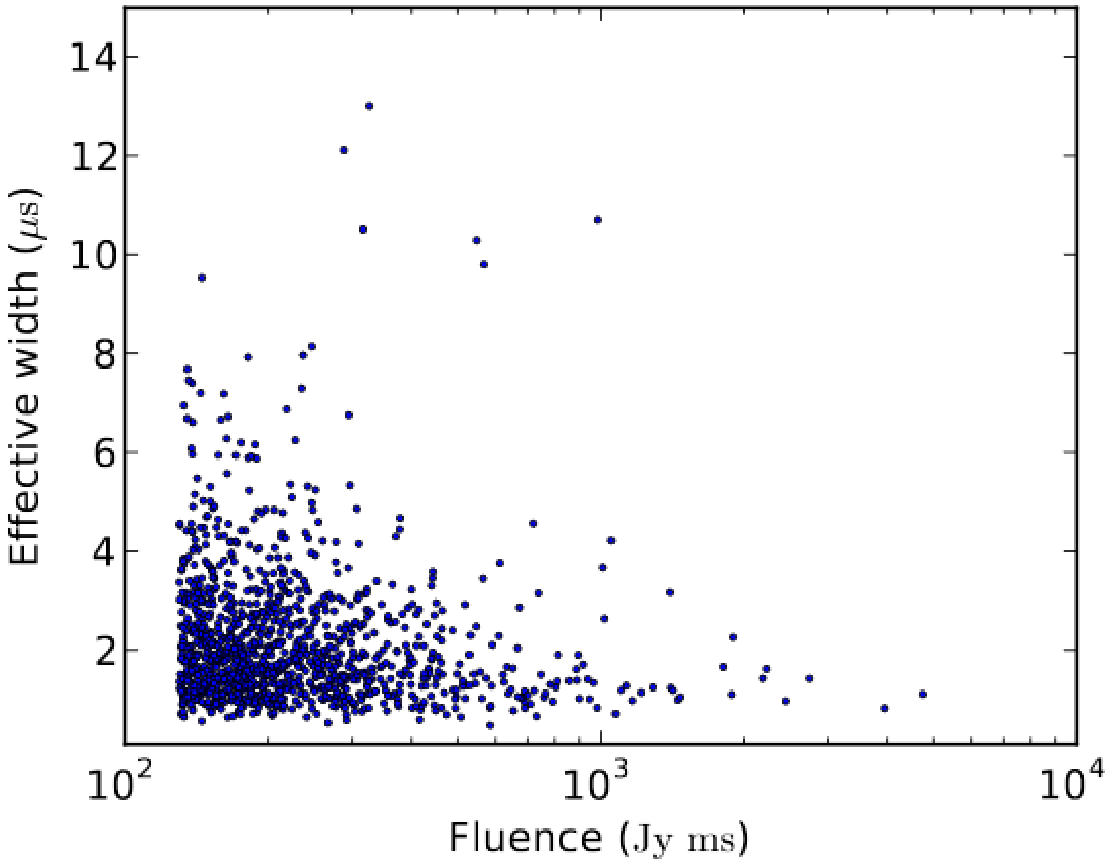
In the case of the Crab pulsar
so-called giant pulses are known.

It has been suggested (1501.00753, 1505.05535) that young pulsars with large Edot can rarely produce much more energetic events.

Scaling allows to reproduce energetics of FRBs.

# Crab supergiant pulses



# FRBs as supergiant pulses

$$\eta = \frac{L_{GP}}{\dot{E}_{\rm Crab}} = \frac{\nu c^3 d_{\rm Crab}^2 S_\nu P_{NS}^4}{4\pi^3 B_{NS}^2 R_{NS}^6} \approx 10^{-2},$$

Estimates are done via scaling of parameters of the Crab. Rather normal magnetic field but rapid rotation formally can explain FRB energetics.

$$L_{FRB} = \eta \dot{E} \rightarrow B_{NS} = \frac{c^{3/2} d \sqrt{(\nu F_\nu)} P_{NS}^2}{2\pi^{3/2} R_{NS}^{3/2} \sqrt{\eta}} = 2 \times 10^{13}\, d_{\rm 100Mpc} F_{\rm 30Jy}^{1/2} \tau_{\rm 5msec}^2 \sqrt{\nu_9} \eta_{-2}^{-1/2}\, {\rm G}.$$

$$\tau_{SD} = \frac{\pi \eta I_{NS}}{d^2 F_\nu \mu P^2} \sim \text{few years.}$$

With magnetic field and spin period it is possible to estimate the characteristic spin-down time.

# Dispersion in a dense supernova remnant

$$\mathrm{DM} \approx \frac{M_{ej}}{m_p r^2}$$

$$r = \sqrt{M_{ej}/m_p}\frac{1}{\sqrt{\mathrm{DM}}} = 0.34\mathrm{pc}\,\sqrt{m_\odot}\mathrm{DM}_{375}^{-1/2}$$

$$\frac{M_{swept}}{M_{ej}} = \sqrt{M_{ej}/m_p}\frac{n_{ISM}}{\mathrm{DM}^{3/2}\mathrm{pc}^{3/2}} = 4.5\times 10^{-4} n_{ISM}\sqrt{m_\odot} \ll 1,$$

$$v_{ej} = \sqrt{\frac{2E_{ej}}{M_{ej}}}.$$

$$t = \frac{M_{ej}}{\sqrt{2\mathrm{DM}E_{ej}m_p}} = 35\mathrm{yrs}\,m_\odot$$

$$\tau = 8\times 10^{-2} n^2 \nu^{-2.1} r T^{-1.35} = 0.05\,\mathrm{DM}_{375}^{5/2} m_\odot^{-1/2}\nu_9^{-2.1}$$

Dispersion in a dense SNR might explain observed DM of FRBs in the model when they are near-by at distances ~100-200 Mpc.

1603.02891

# Burst rate

SN rate ~3 $10^{-4}$ $yr^{-1}$ $Mpc^{-3}$ (Dahlen et al. 2012).
This gives ~1 SN per day in 100 Mpc.
Ages and typical lifetime of our sources ~30-100 years.
Thus, we have ~10 000 – 30 000 sources in 100 Mpc.
The observed rate of FRBs ~3 $10^3$ per day.
Then, each source might give a flare per few days.
If we increase the distance up to 200 Mpc then we can use just 10% of most energetic neutron stars.

Giant pulses of the Crab with fluence 100-200 kJy for Edot increased by factor 100 000
are scaled to flares with the flux ~1 Jy from 100-200 Mpc.

Number of giant pulses depends on flux as ~$S^{-3}$.
For FRBs we then obtain that most bright event might be observed once per few months.

# FRB vs. ULX

For a typical FRB with peak flux $S_{\rm peak} = 1$ Jy we obtain radio luminosity:

$$L_{\rm r} = 1.7 \times 10^{40} (S_{\rm peak}/1\,{\rm Jy})(d/100\,{\rm Mpc})^2\,{\rm erg\,s^{-1}}.$$

Then, rotational energy losses are:

$$\dot{E} = 1.7 \times 10^{42} (S_{\rm peak}/1\,{\rm Jy})(d/100\,{\rm Mpc})^2 (\eta/0.01)^{-1}\,{\rm erg\,s^{-1}}.$$

Using the relation from Possenti et al. we obtain the X-ray luminosity:

$$L_{\rm X} = 1.8 \times 10^{41} (S_{\rm peak}/1\,{\rm Jy})^{1.34} \times$$
$$\times (d/100\,{\rm Mpc})^{2.68} (\eta/0.01)^{-1.34}\,{\rm erg\,s^{-1}}.$$

And so, the X-ray flux is:

$$f_{\rm X} = 1.5 \times 10^{-13} (S_{\rm peak}/1\,{\rm Jy})^{1.34} \times$$
$$\times (d/100\,{\rm Mpc})^{0.68} (\eta/0.01)^{-1.34}\ \ {\rm erg\ \ cm^{-2}\ \ s^{-1}}.$$

For large distances we obtain higher $f_{\rm X}$ for a given $S_{\rm peak}$, for smaller — weaker. If a source with peak flux 1 Jy is at 10 Mpc, then $f_{\rm X} = 3.2 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. Correspondently, for 200 Mpc we have $f_{\rm X} = 2.5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$.

1605.01992

In the model of supergiant pulses
it is natural to expect that
at distances 100-200 Mpc
young energetic PSRs might be
strong X-ray sources, similar to ULXs.

$$L_{\rm X} \approx 2 \times 10^{42} \left(\dot{E}/10^{43}\ {\rm erg\ s^{-1}}\right)^{1.34}\ {\rm erg\ s}^{-1},$$

(Possenti et al. 2002)

Searches for possible counterparts of FRBs
in X-ray in near-by (100-200 Mpc) galaxies
can confirm or falsify the model.

# Rapid evolution: spin (power) and DM

Young neutron stars and their surroundings
are expected to be subjects of rapid evolution
on time scales down to few years.

$$\tau_{SD} = \frac{\pi \eta I_{NS}}{d^2 F_\nu \mu P^2} \sim \text{few years.}$$

This evolution, potentially,
can followed for individual sources.
However, it can also influence global distribution
of parameters of non-repeating FRBs.

$$\mathrm{DM_{SNR}} \approx 30\,\mathrm{pc\,cm^{-3}} \times \left(\frac{\tau}{30\,\mathrm{yrs}}\right)^{-2}$$

Selection effect:
young sources are expected to be more active,
thus, it is easier to detect them as repeaters.

$$\frac{d\mathrm{DM_{SNR}}}{dt} \approx -2\,\mathrm{pc\,cm^{-3}\,yr^{-1}} \times \left(\frac{\tau}{30\,\mathrm{yrs}}\right)^{-3}$$

1909.00004

# Simple constrains on the pulsar model

$$\frac{L_{FRB}}{L_{GP}} \approx 2.5 \times 10^5$$

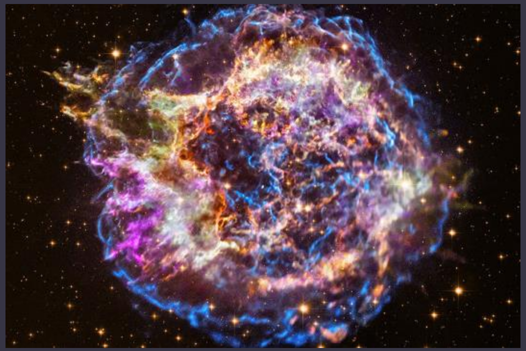
$$\left(\frac{B_{FRB}}{B_{Crab}}\right)\left(\frac{P_{FRB}}{P_{Crab}}\right)^{-2} \approx 500$$

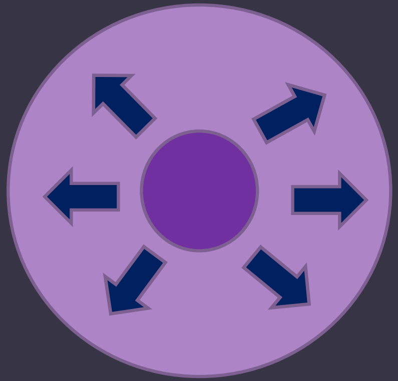
$$\nu F_\nu = \eta \frac{L_{sd}}{4\pi D^2}$$

$$\tau_{SD} = \eta \frac{\pi I_{NS}}{2D^2 \nu F_\nu P_{min}^2} \approx 600\,\eta\,\mathrm{yrs}$$

It is necessary to assume very effective conversion of rotational energy losses to radio emission.

$$\eta \to 1.$$





$$DM \propto t^{-2}$$

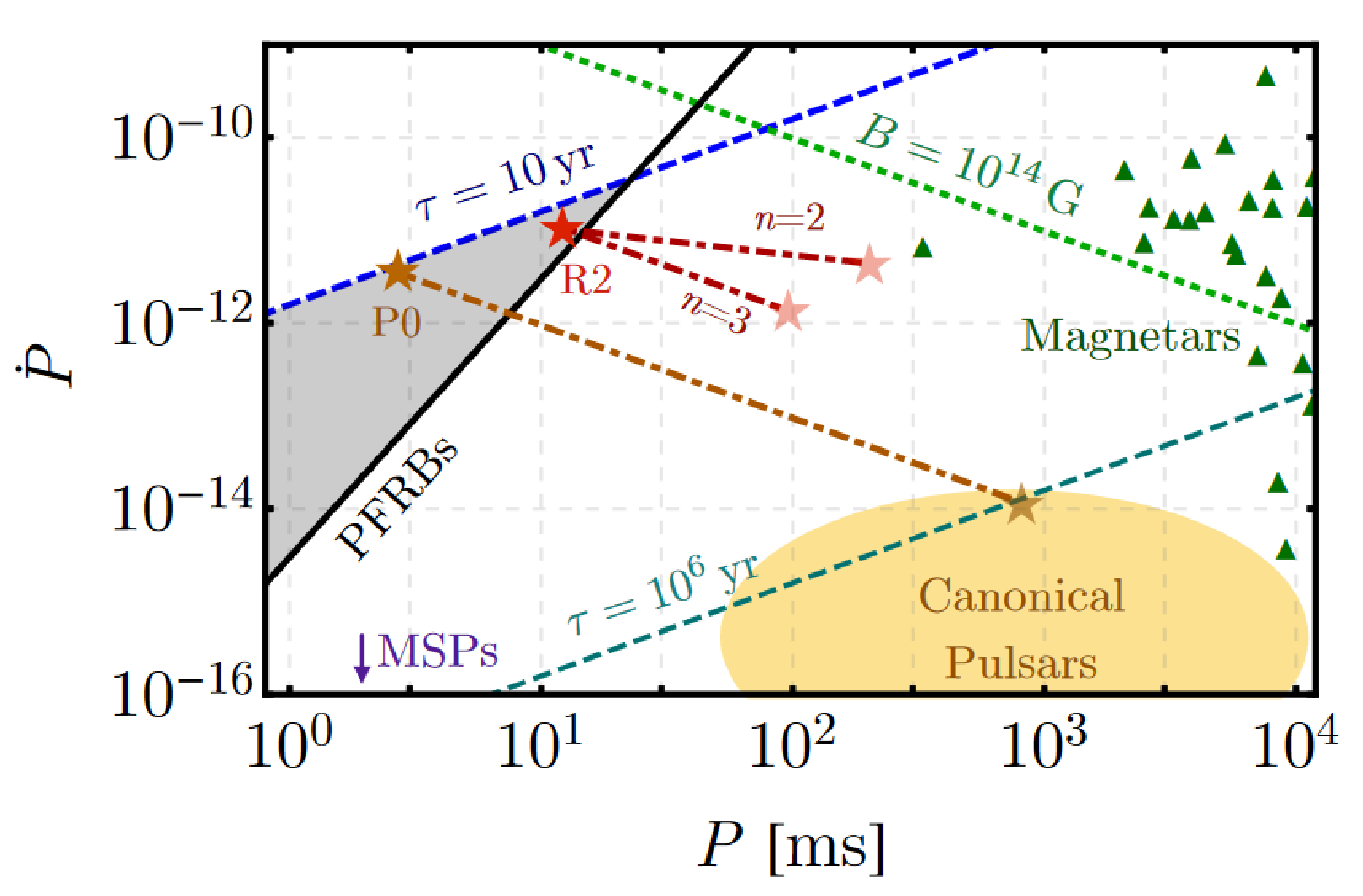
In the pulsar model DM is expected to be changing rapidly.

# Experimentum crusic

I). P and Pdot (in repeating sources or,
less probable, in pulse profile).

II). Relation to older (~10 years at least) SN.

III). Counterparts (X-rays, or may be TeV and optics)




1909.00004

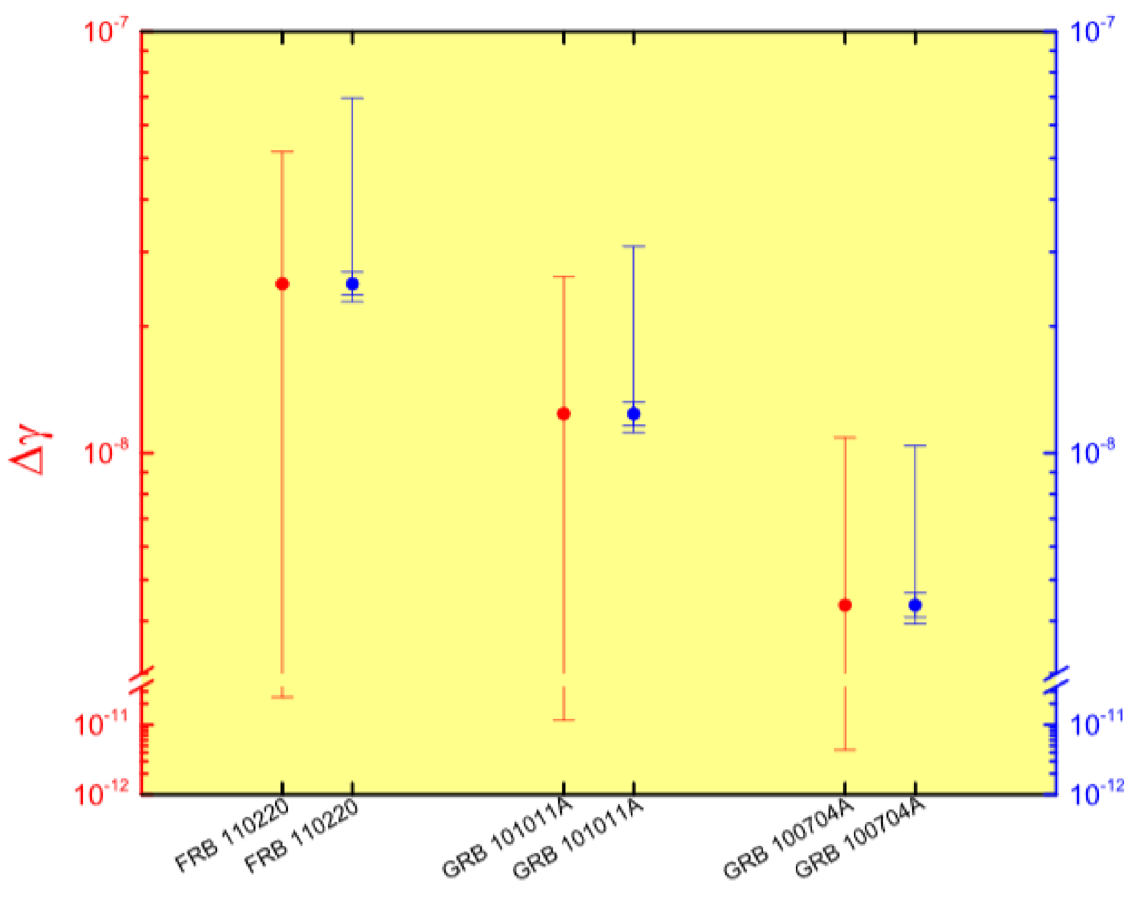
# Current ratings of hypothesis

- Discovery of repeating bursts with high rate provides arguments in favour of the models with supergiant pulses of energetic radio pulsars and activity of young magnetars
- Identification of a dwarf galaxy with high star formation rate as a host galaxy of the source of the repeating burster is a strong argument in favour of models involving young neutron stars.
  However, two other identified host galaxies are much different!
- The first repeater can be a non-typical source
- Altogether, dissipation of magnetic energy seems to be more reliable.

- At the present moment there two promising approaches

- Population of FRBs can be non-uniform, i.e. more than one scenario can realize in Nature

# Test of equivalence principle



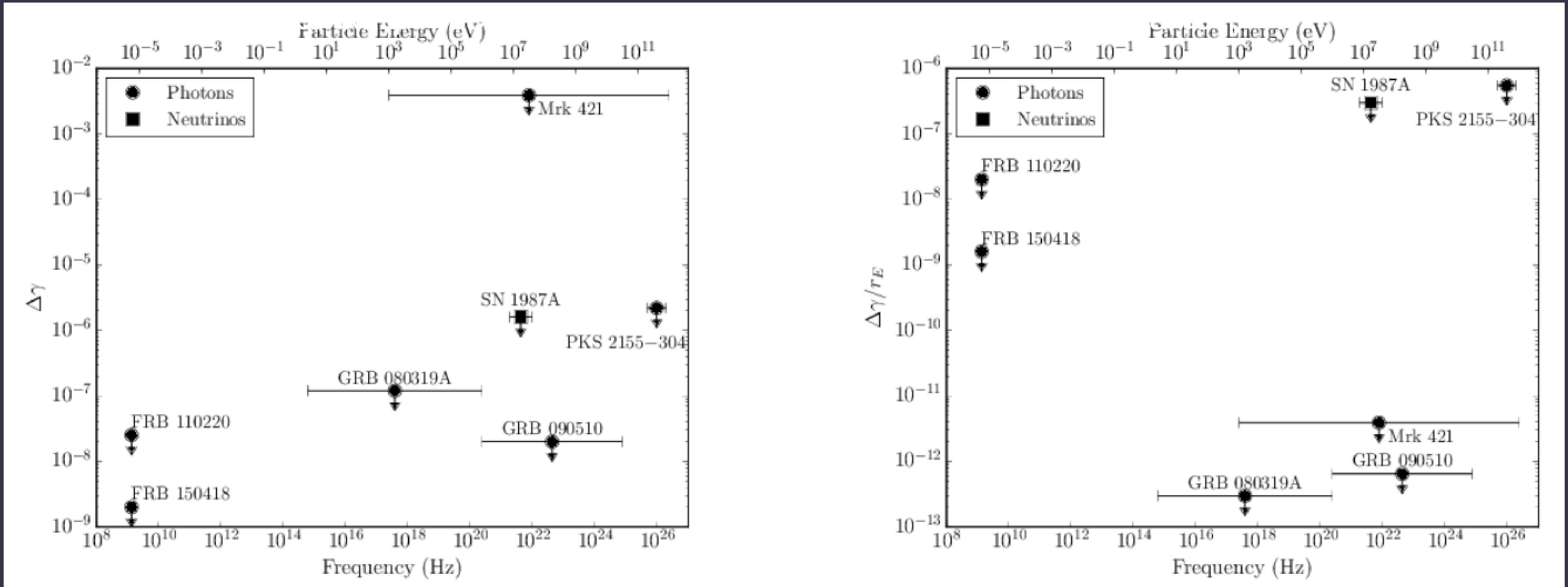

1512.07670

Also FRBs can be used to test Lorentz-invariance, especially, if a FRB is accompanied by a gamma-ray flare.

See also 1509.00150, 1601.04558

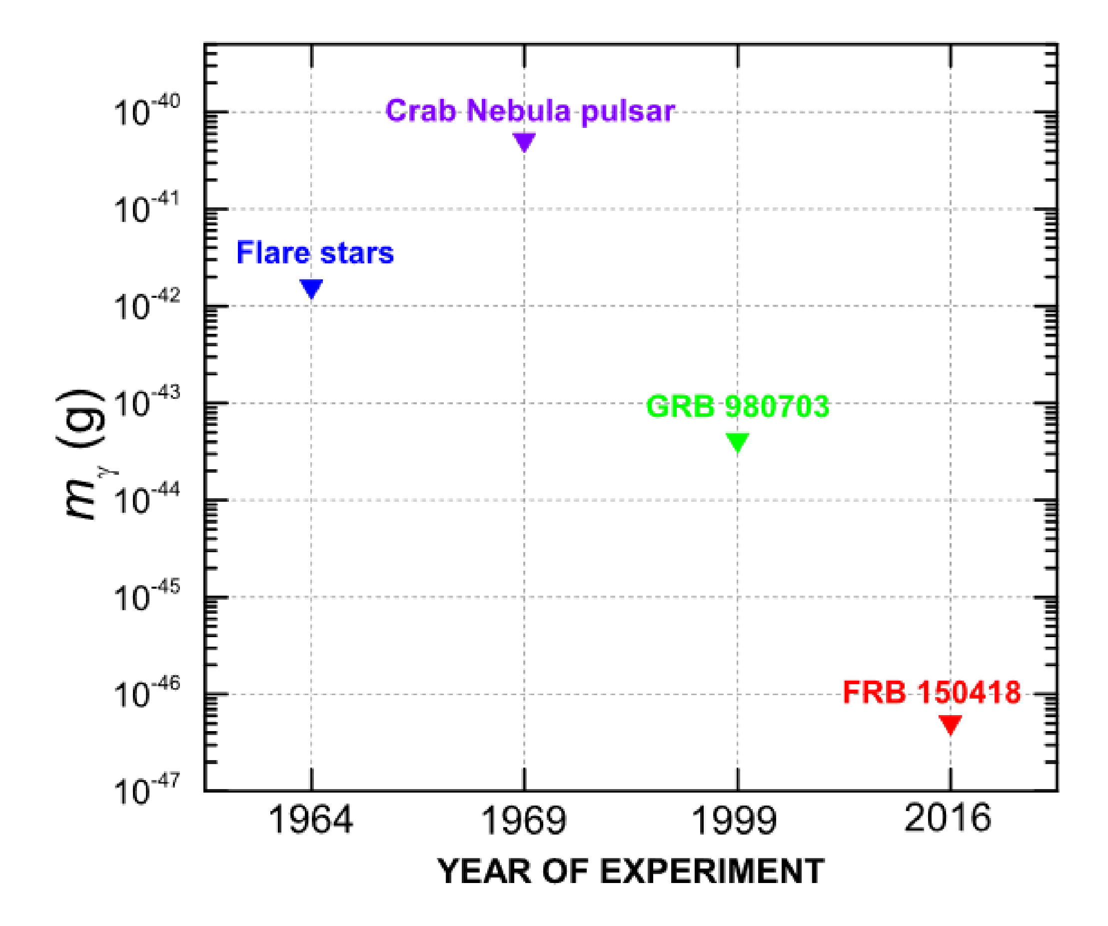
# Improvements on the limit of parameter γ

Independent distance evaluation allows to use FRBs to put constraints on the post-Newtonian parameter γ




1602.07643

# Limits on the photon mass



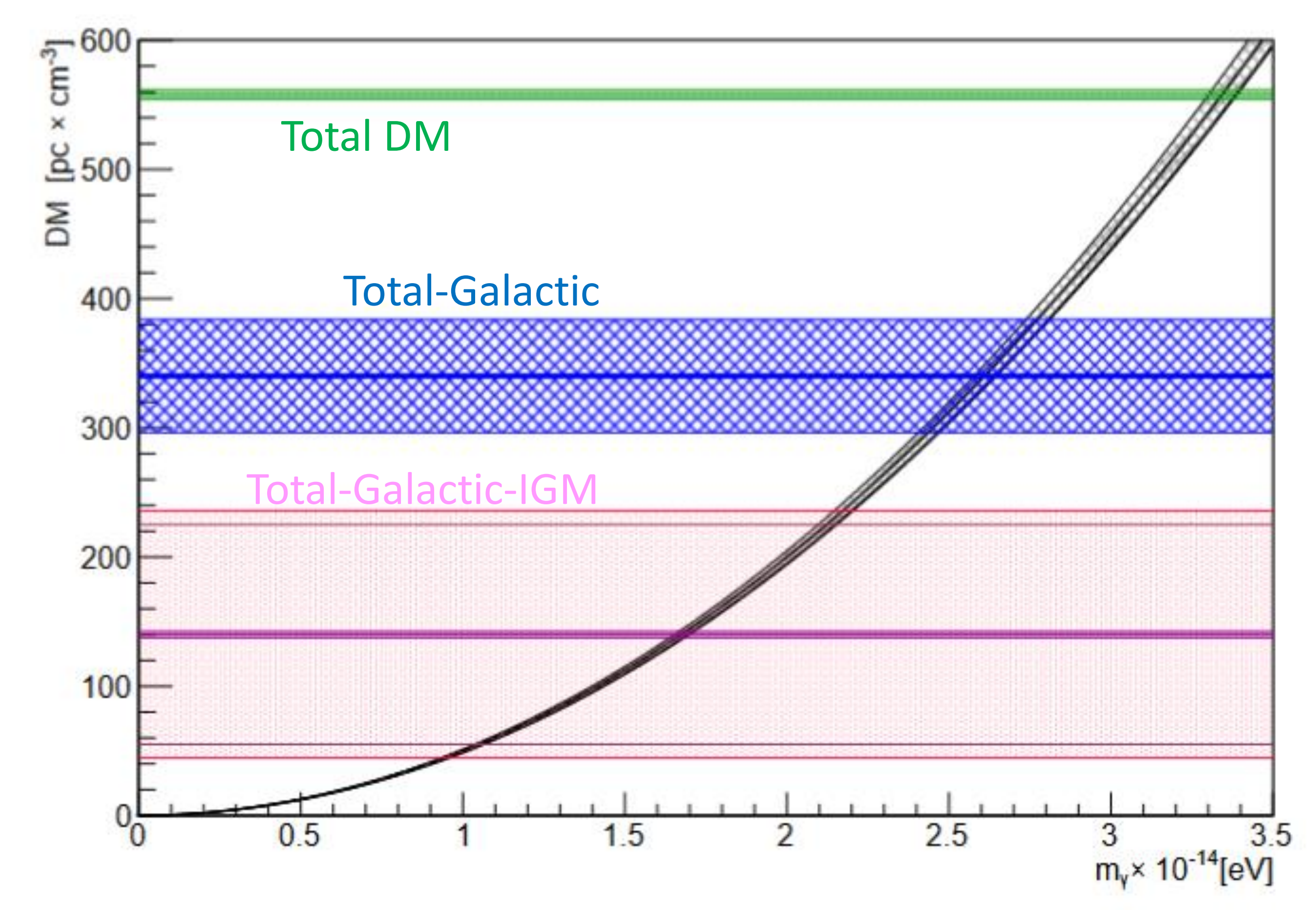

$$m_\gamma = (1.56 \times 10^{-47}\mathrm{g}) \left\{ \frac{\Delta t_{m_\gamma \neq 0}/\mathrm{s}}{\left[\left(\frac{\nu_l}{\mathrm{GHz}}\right)^{-2} - \left(\frac{\nu_h}{\mathrm{GHz}}\right)^{-2}\right] H_1(z)} \right\}^{1/2}$$

Now this result is just of historic interest, as it was shown that association of the source with a proposed host galaxy is spurious.

See also 1602.09135

1602.07835

# New limits on photon mass




FRB121102

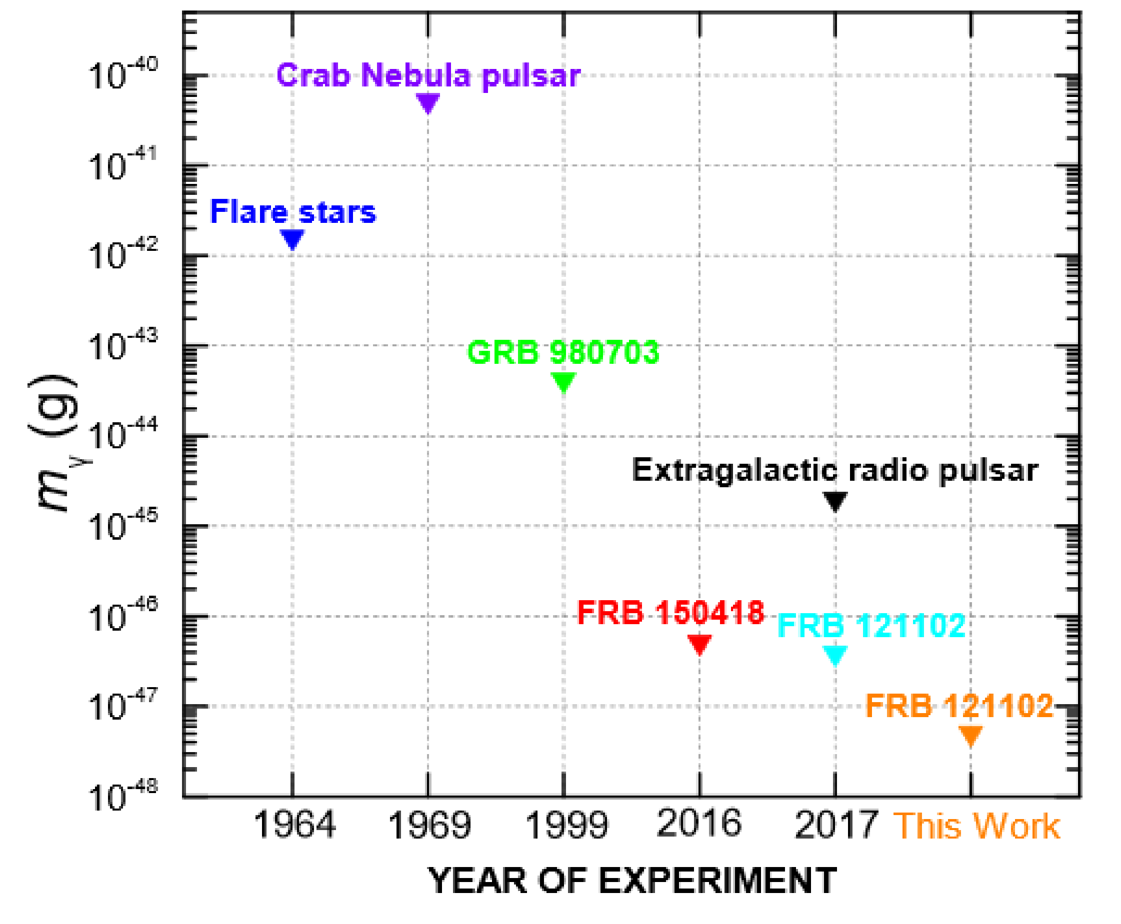
$$\Delta t_{m_\gamma} = \frac{m_\gamma^2}{2H_0} \cdot \left( \frac{1}{E_1^2} - \frac{1}{E_2^2} \right) \cdot H_\gamma(z)$$

$$h = c = 1$$

$$H_\gamma(z) \equiv \int_0^z \frac{dz'}{(1+z')^2 \sqrt{\Omega_\Lambda + (1+z')^3 \Omega_m}} .$$

$$m_\gamma \lesssim 2.2 \times 10^{-14} \text{ eV c}^{-2} \ (3.9 \times 10^{-50} \text{ kg})$$

# More results and better limits




$$m_\gamma = (1.56 \times 10^{-47}\mathrm{g}) \left\{ \frac{\Delta t_{m_\gamma \neq 0}/\mathrm{s}}{\left[ \left(\frac{\nu_l}{\mathrm{GHz}}\right)^{-2} - \left(\frac{\nu_h}{\mathrm{GHz}}\right)^{-2} \right] H_1(z)} \right\}^{1/2}$$

# Future observations



FAST – burst per week

1602.06099

SKA – burst per hour!

1602.05165, 1501.07535

FAST reported it’s first FRB observations in September 2019: ATel 13064. These are bursts of FRB 121102.

# More observations

New system ALFABURST at Arecibo.
1511.04132

Observation at other telescopes, especially for the repeating source.

Attempts to identify something at other wavelengths.


http://astronomy.swin.edu.au/research/utmost/
Burst per week, see 1601.02444

Observations at Parkes with a new monitoring system.

# ASKAP and MeerKAT

# Special projects partly dedicated to FRBs

SUPERB

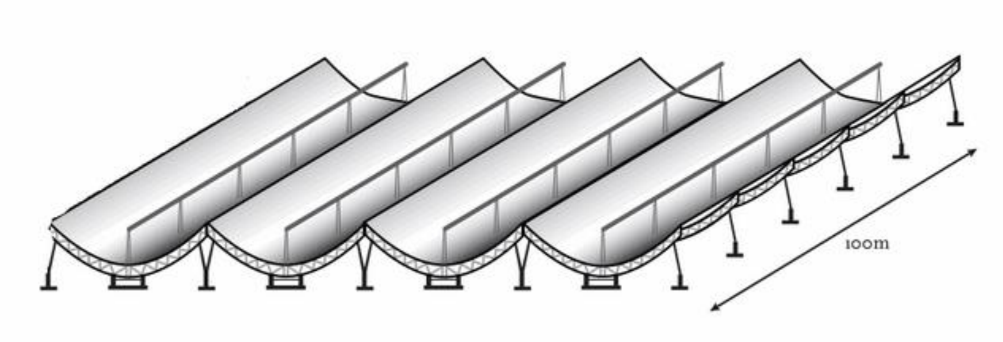
Survey for Pulsars and Extragalactic Radio Bursts

https://sites.google.com/site/publicsuperb/

**CHIME**

The Canadian Hydrogen Intensity Mapping Experiment

http://chime.phas.ubc.ca/



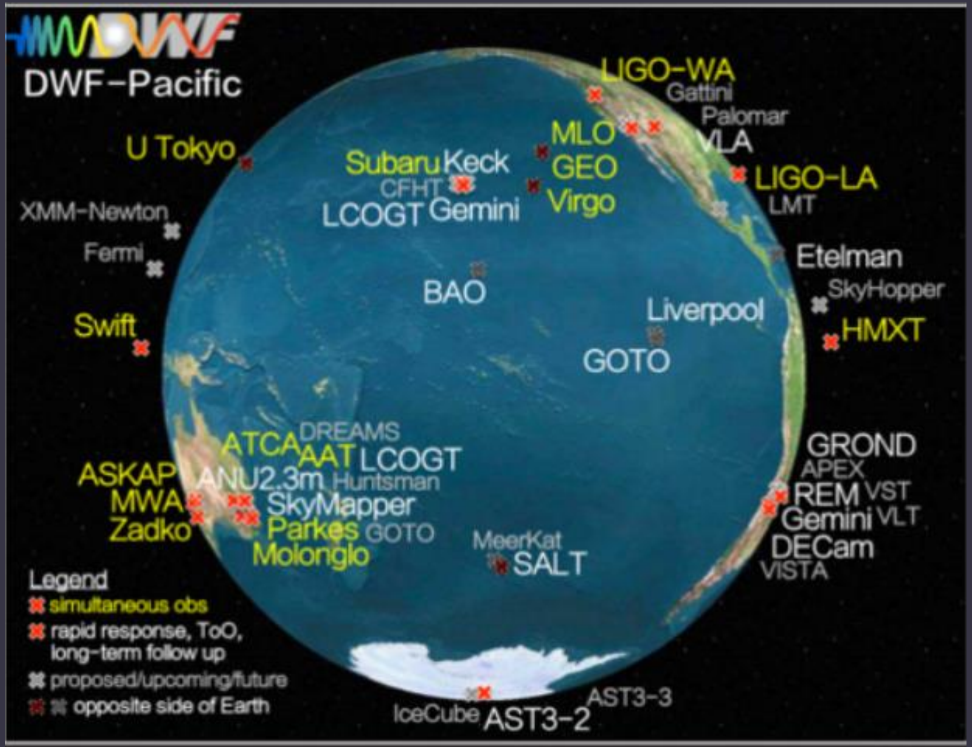

CHIME – burst per day!
1601.02444

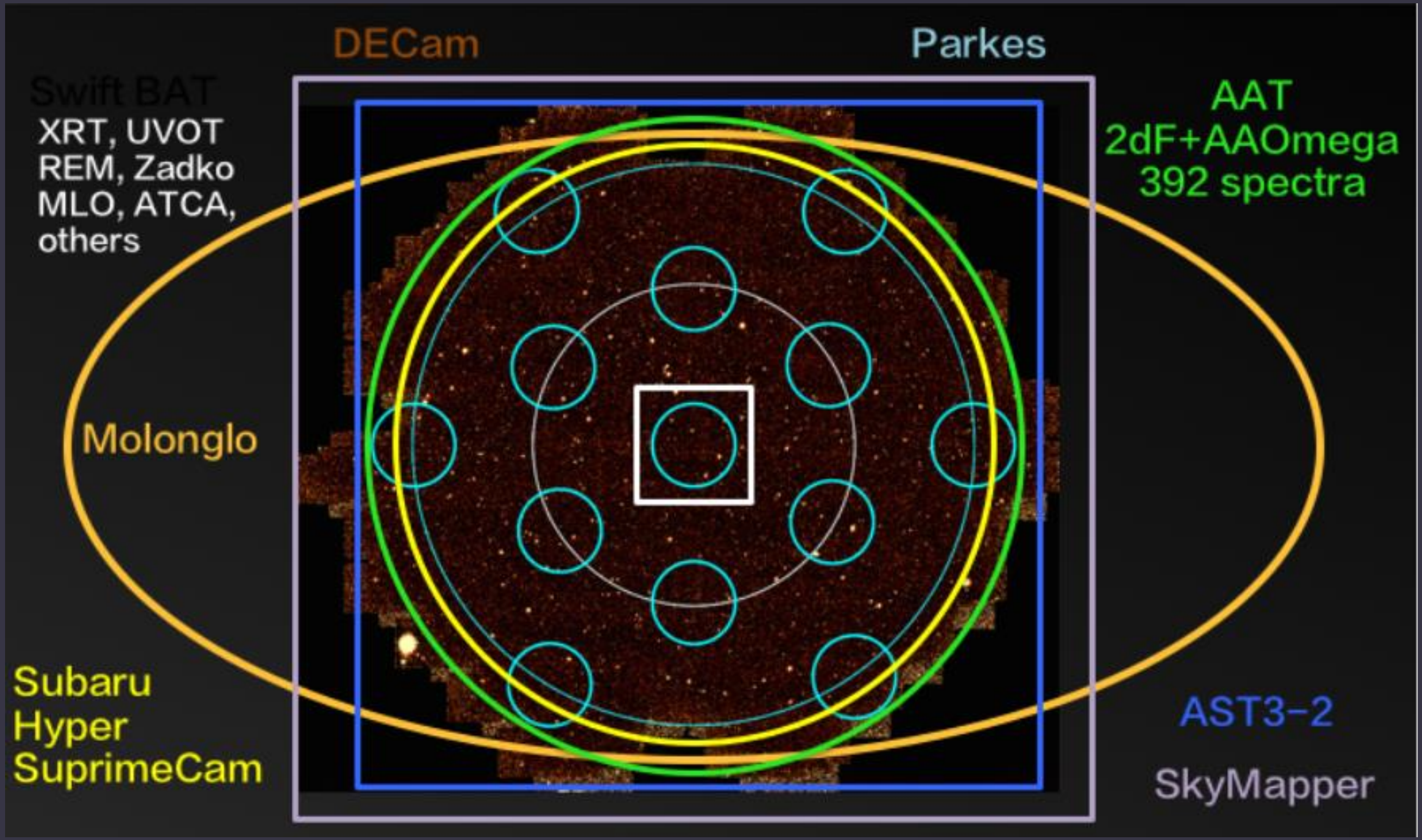
HIRAX.
South variant of CHIME

1607.02059

# Multi-messenger searches

Deeper Wider Faster



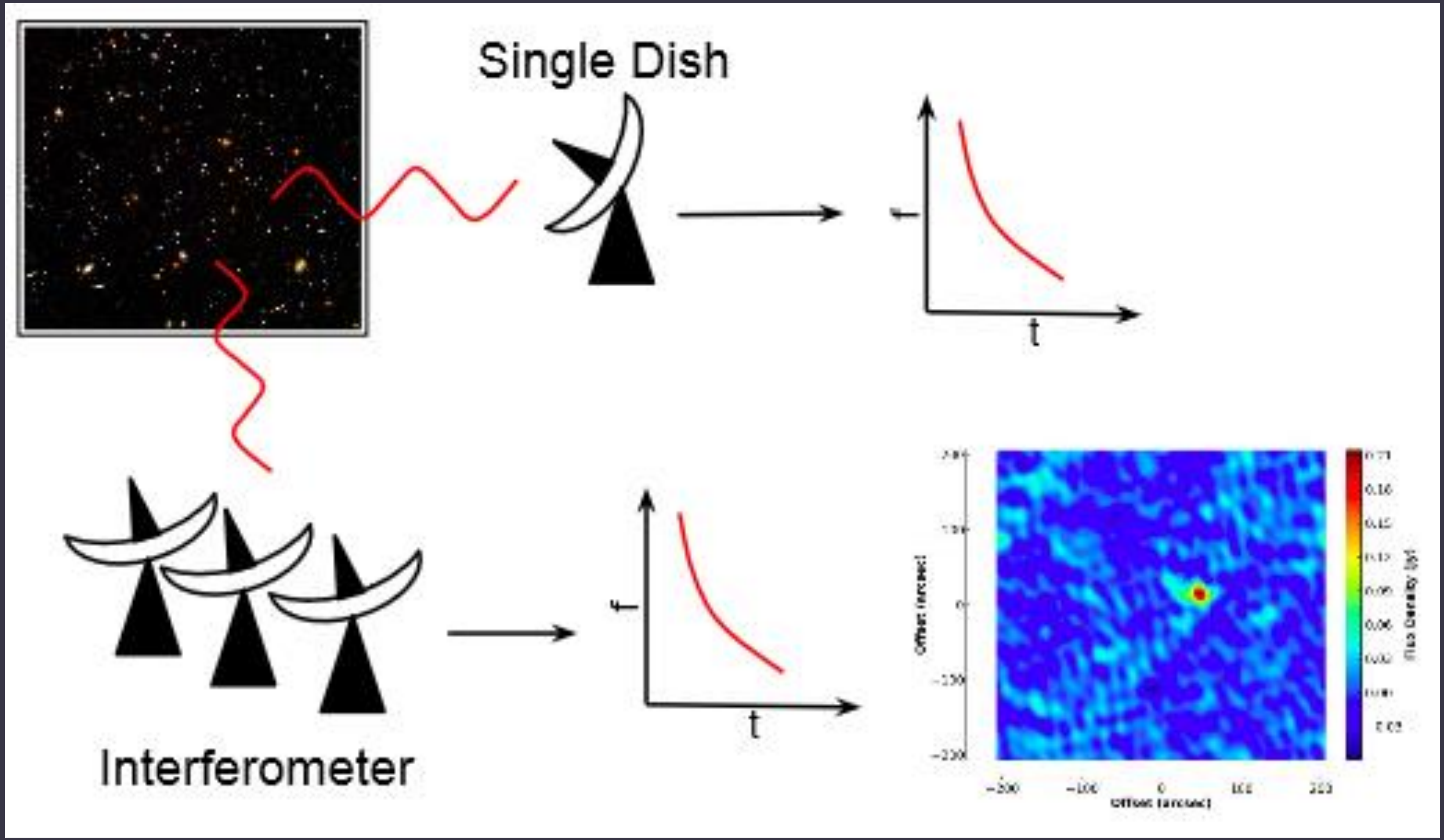



# Realfast: new system on VLA

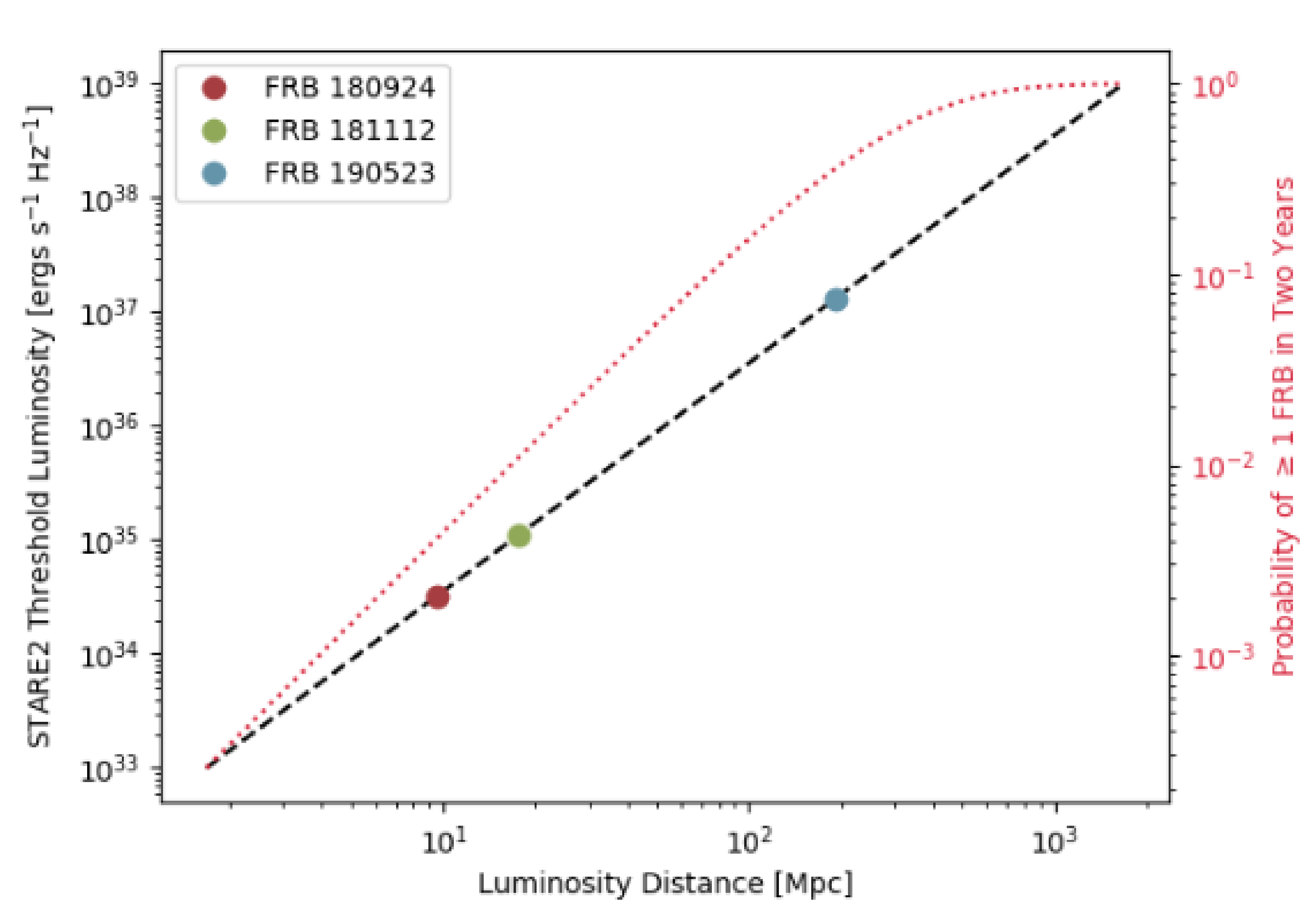
New system for rapid analysis
of fast transients (not only FRBs).

Installed in 2018.

Rapid localization.



# STARE2. Looking for near-by transients




Four stations are planned.
Two are operating, already.

Upper limits for FRBs are available.

2001.05077

# Summary of observations

Main reviews: 1806.03628, 1810.05836,
1906.05878, 1904.07947

In catalogue (01/09/2019) frbcat.org
109 bursts (20 repeaters)
4 localized.

12 with polarization data (11 – linear, 6 – circular)
RM for 6 (+3 consistent with 0 within errors)
Max flux: 160 Jy
DM max: 2600; DM min: 100

58 out of 109 detected at ~1.4 GHz.
10 at ~800-840 MHz (9 at UTMOST, 1 at GBT)
30 at ~600 (CHIME), and 11 (?) at 111 (Puschino)