Fast radio bursts: a new exotic puzzle in astrophysics

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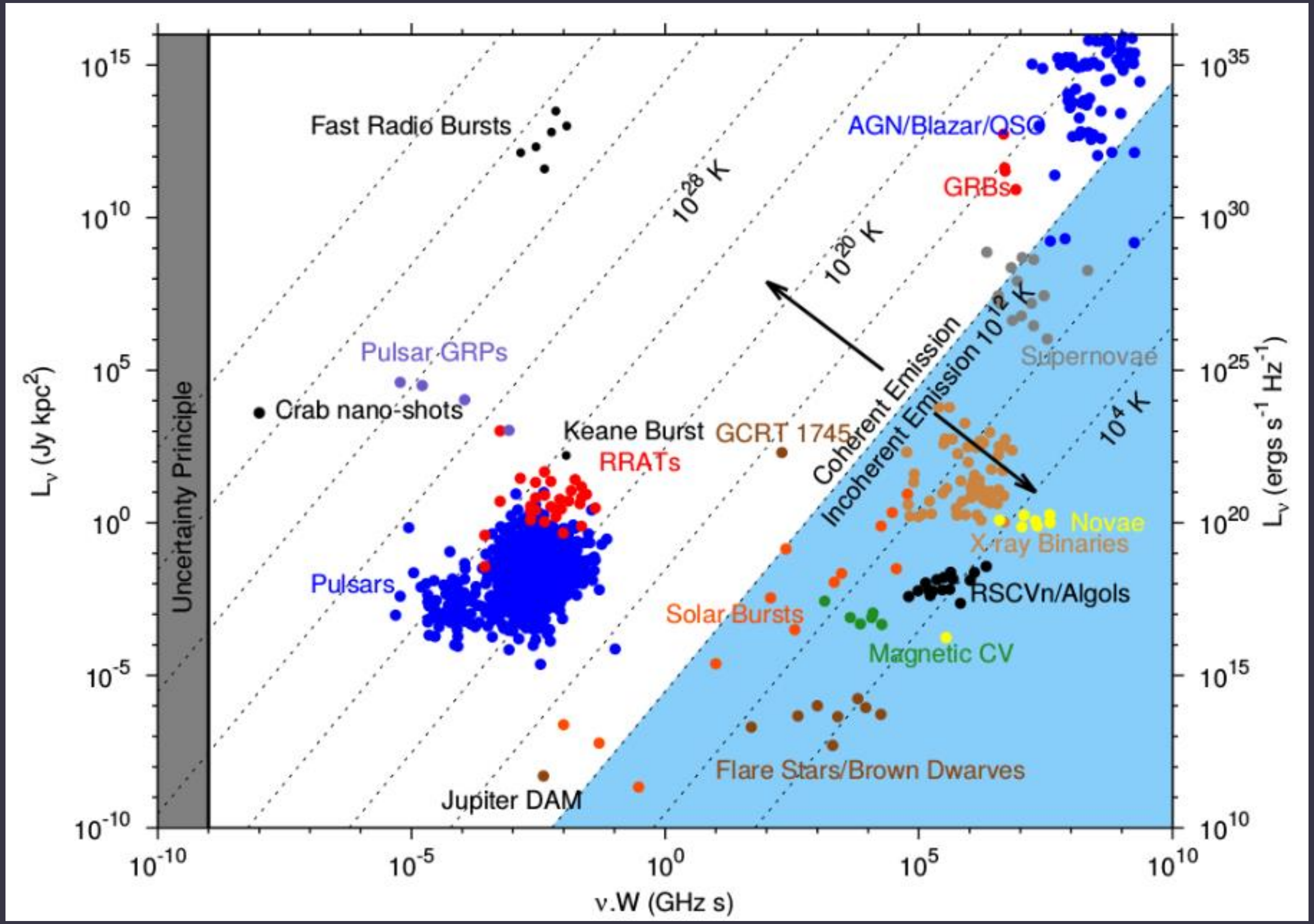
Radiotransients



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.

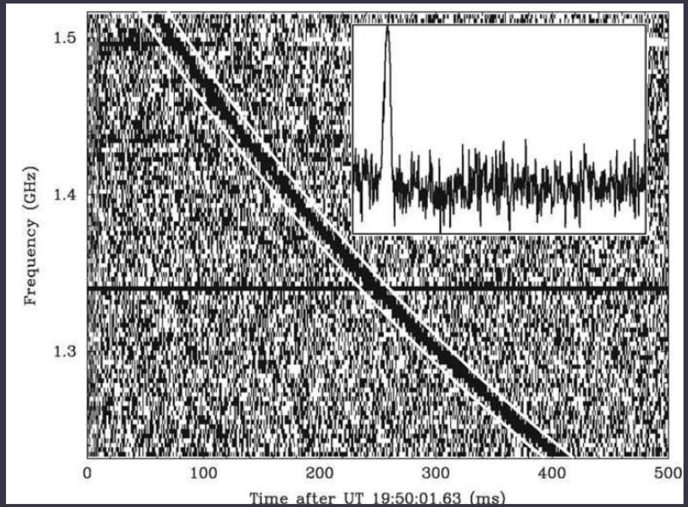
In 2007 the first example of a new class of millisecond radio transients have been announced: the first extragalactic millisecond radio burst.

1507.00729, 1411.1067

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.

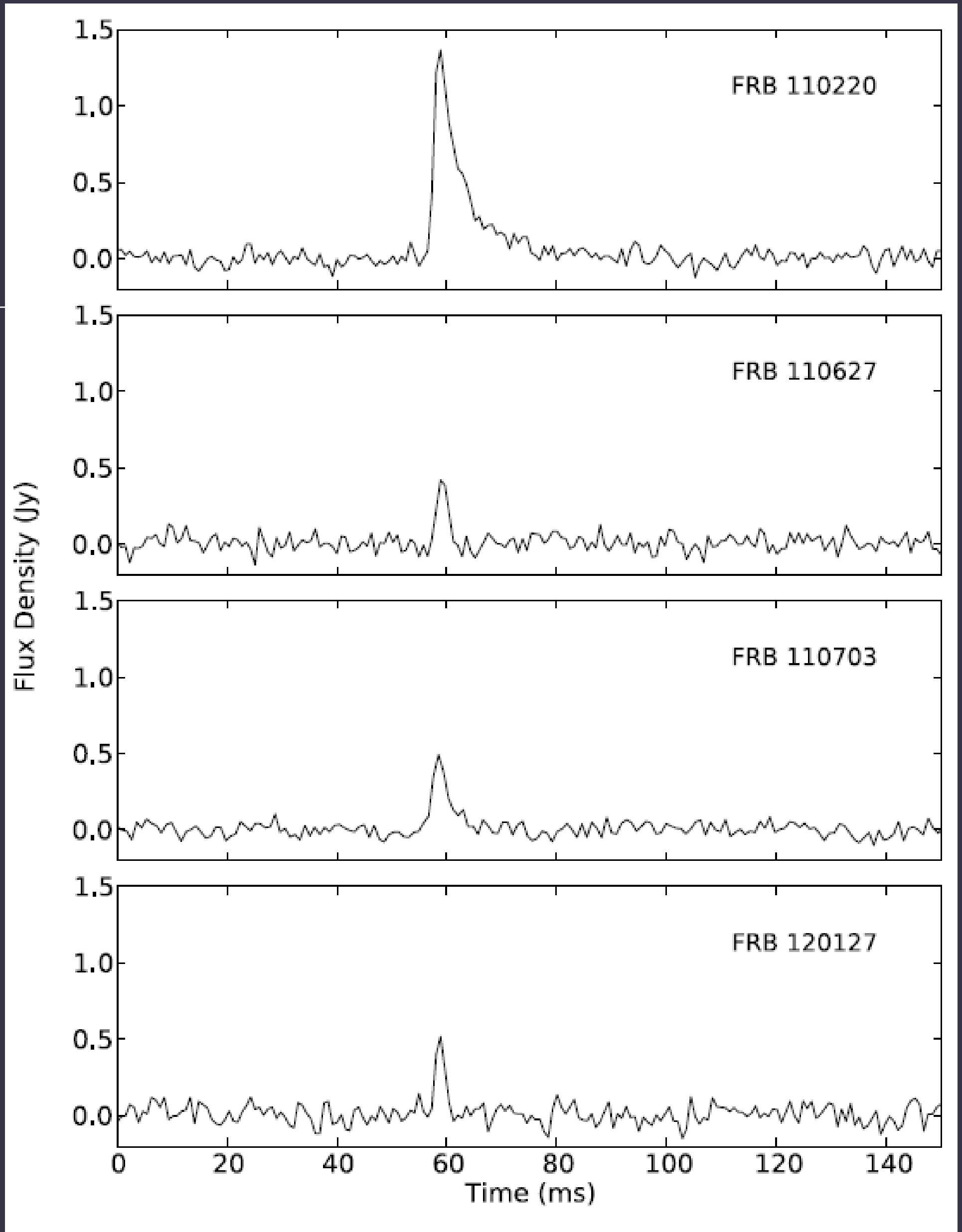
2016 Spitler et al. The first repeating source.
Chatterjee et al. Identification of the host galaxy



Lorimer et al.

Large dispersion measure points to extragalactic origin.

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



1307.1628

Catalogue

23 FRBs

+

one repeater

Rate: several thousands per day per sky

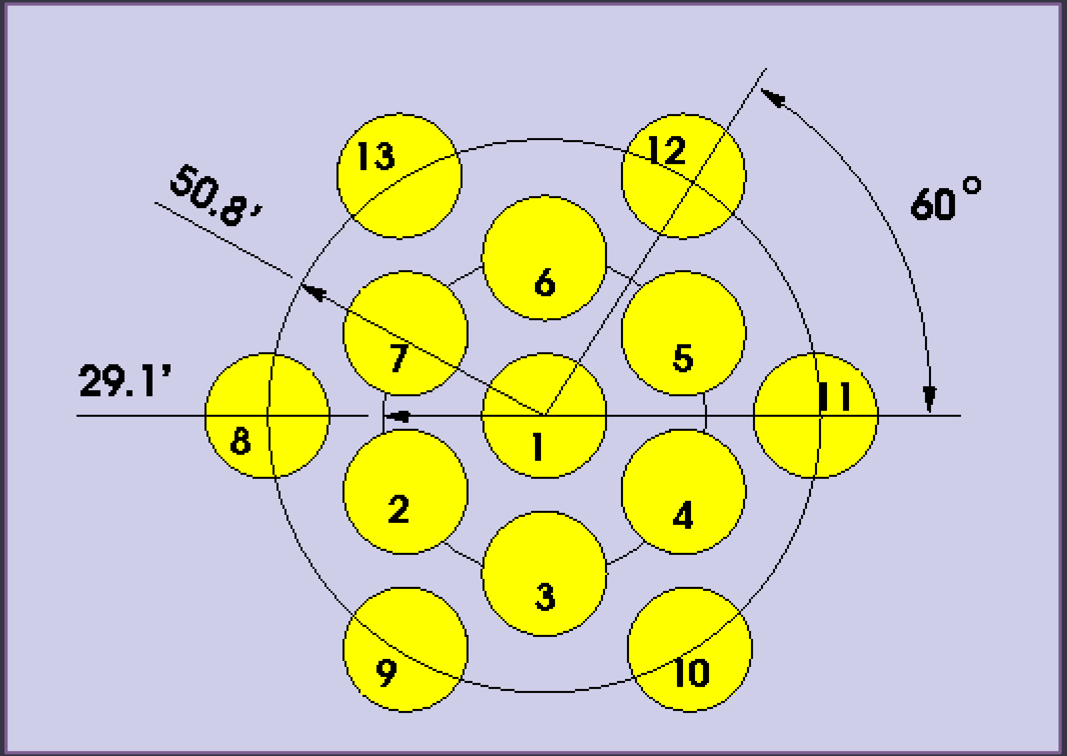
Event	Telescope	gl [deg]	gb [deg]	FWHM [deg]	DM [cm^{-3} pc]	S/N	W_{obs} [ms]	$S_{peak,obs}$ [Jy]	F_{obs} [Jy ms]
FRB010125	parkes	356.641	-20.020	0.25	790(3)	17	$9.40^{+0.20}_{-0.20}$	0.30	2.82
FRB010621	parkes	25.433	-4.003	0.25	745(10)		7.00	0.41	2.87
FRB010724	parkes	300.653	-41.805	0.25	375	23	5.00	$>30.00^{+10.00}_{-10.00}$	>150.00
FRB090625	parkes	226.443	-60.030	0.25	899.55(1)	30	$1.92^{+0.83}_{-0.77}$	$1.14^{+0.42}_{-0.21}$	$2.19^{+2.10}_{-1.12}$
FRB110220	parkes	50.828	-54.766	0.25	944.38(5)	49	$5.60^{+0.10}_{-0.10}$	$1.30^{+0.00}_{-0.00}$	$7.28^{+0.13}_{-0.13}$
FRB110523	GBT	56.119	-37.819	0.26	623.30(6)	42	$1.73^{+0.17}_{-0.17}$	0.60	1.04
FRB110626	parkes	355.861	-41.752	0.25	723.0(3)	11	1.40	0.40	0.56
FRB110703	parkes	80.997	-59.019	0.25	1103.6(7)	16	4.30	0.50	2.15
FRB120127	parkes	49.287	-66.203	0.25	553.3(3)	11	1.10	0.50	0.55
FRB121002	parkes	308.219	-26.264	0.25	1629.18(2)	16	$5.44^{+3.50}_{-1.20}$	$0.43^{+0.33}_{-0.06}$	$2.34^{+4.46}_{-0.77}$
FRB121102	arecibo	174.950	-0.225	0.05	557(2)	14	$3.00^{+0.50}_{-0.50}$	$0.40^{+0.40}_{-0.10}$	$1.20^{+1.60}_{-0.45}$
FRB130626	parkes	7.450	27.420	0.25	952.4(1)	21	$1.98^{+1.20}_{-0.44}$	$0.74^{+0.49}_{-0.11}$	$1.47^{+2.45}_{-0.50}$
FRB130628	parkes	225.955	30.655	0.25	469.88(1)	29	$0.64^{+0.13}_{-0.13}$	$1.91^{+0.29}_{-0.23}$	$1.22^{+0.47}_{-0.37}$
FRB130729	parkes	324.787	54.744	0.25	861(2)	14	$15.61^{+9.98}_{-6.27}$	$0.22^{+0.17}_{-0.05}$	$3.43^{+6.55}_{-1.81}$
FRB131104	parkes	260.549	-21.925	0.25	779(1)	30	2.08	1.12	2.33
FRB140514	parkes	50.841	-54.611	0.25	562.7(6)	16	$2.80^{+3.50}_{-0.70}$	$0.47^{+0.11}_{-0.08}$	$1.32^{+2.34}_{-0.50}$
FRB150215	parkes	24.662	5.280	0.25	1105.6(8)	19	$2.80^{+1.20}_{-0.50}$	$0.70^{+0.28}_{-0.01}$	$1.96^{+1.96}_{-0.37}$
FRB150418	parkes	232.665	-3.234	0.25	776.2(5)	39	$0.83^{+0.25}_{-0.25}$	$2.19^{+0.60}_{-0.30}$	$1.82^{+1.20}_{-0.72}$
FRB150807	parkes	336.709	-54.400	0.25	266.5(1)		$0.35^{+0.05}_{-0.05}$	$128.00^{+5.00}_{-5.00}$	$44.80^{+8.40}_{-7.90}$
FRB160317	UTMOST	246.050	-0.990	0.00	1165(11)	13	$21.00^{+7.00}_{-7.00}$	>3.00	>63.00
FRB160410	UTMOST	220.360	27.190	0.00	278(3)	13	$4.00^{+1.00}_{-1.00}$	>7.00	>28.00
FRB160608	UTMOST	254.110	-9.539	0.00	682(7)	12	$9.00^{+6.00}_{-6.00}$	>4.30	>38.70
FRB170107	ASKAP	266.000	51.400	0.13	609.5(5)	16	2.60	22.30	57.98

1601.03547

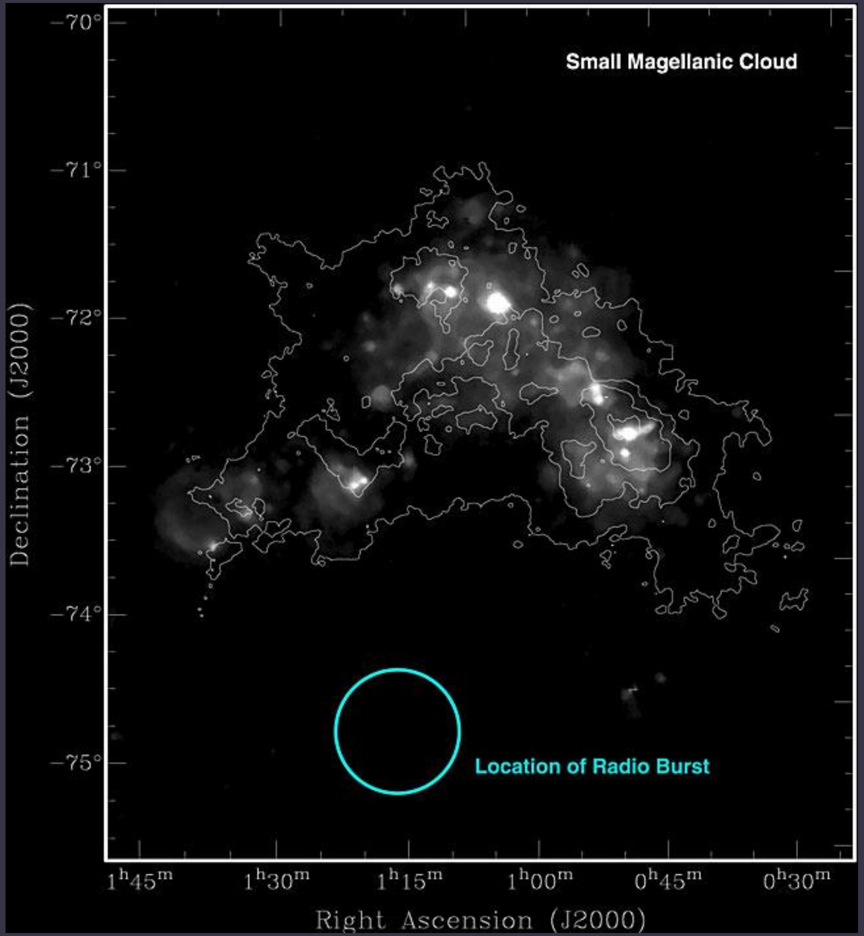
http://www.astronomy.swin.edu.au/pulsar/frbcat/

Localization

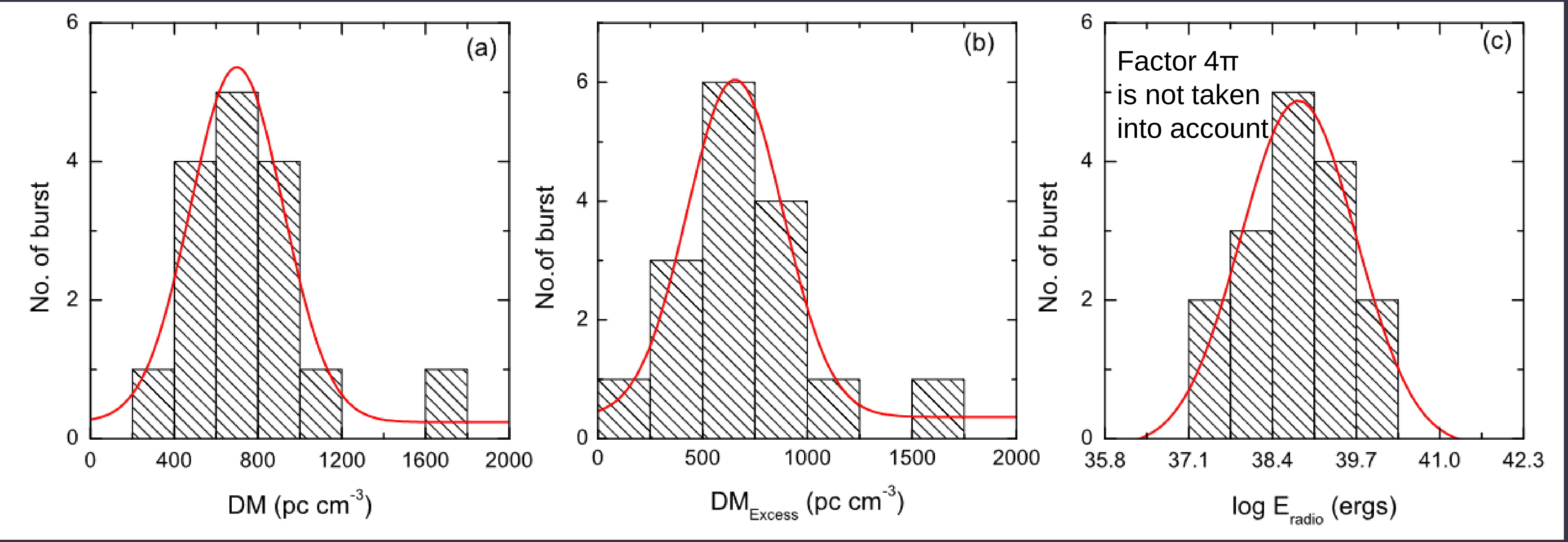
Radius of uncertainty circle ~10 arcmin



Usually FRBs are seen just in one beam.



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

FRBs. Different hypotheses

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

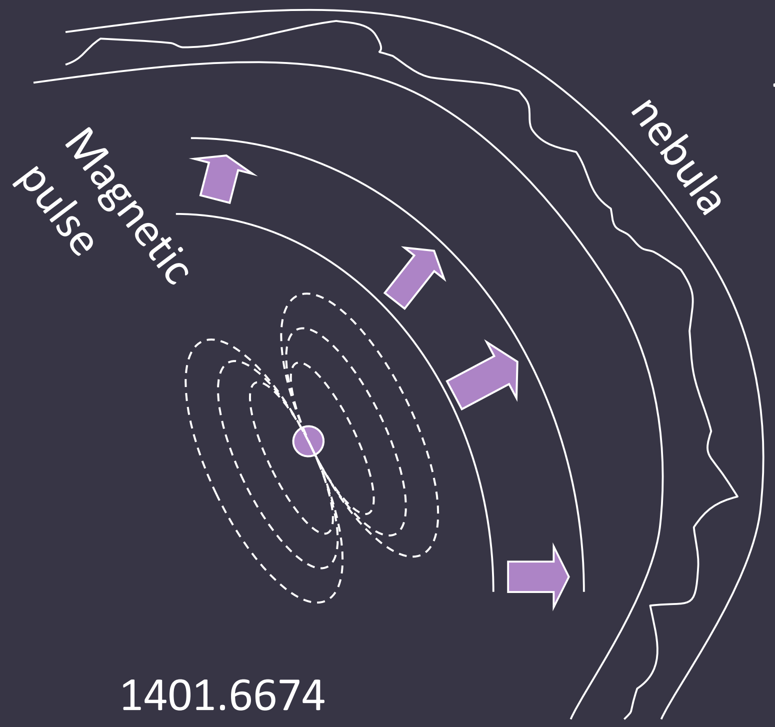
Since 2007 many hypotheses have been proposed.

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/

Magnetar model



1401.6674

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

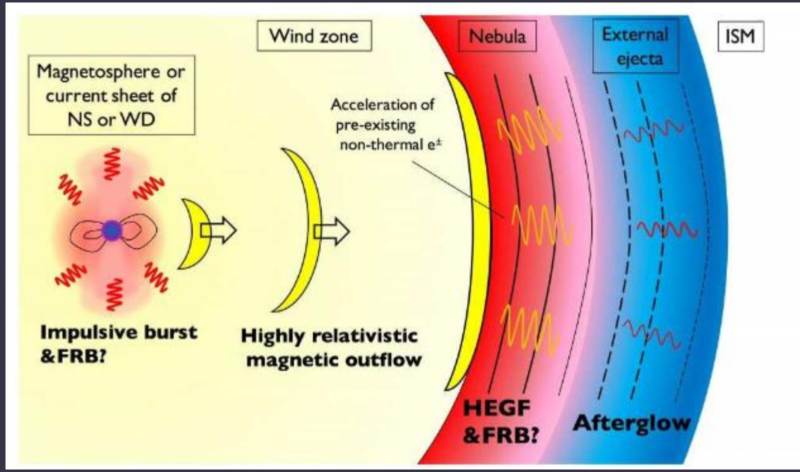
This hypothesis has been based on rate and energetics considerations, mainly.

FRB bursts might be related to giant flares of magnetars

Later this approach was developed by Lyubarsky (2014).

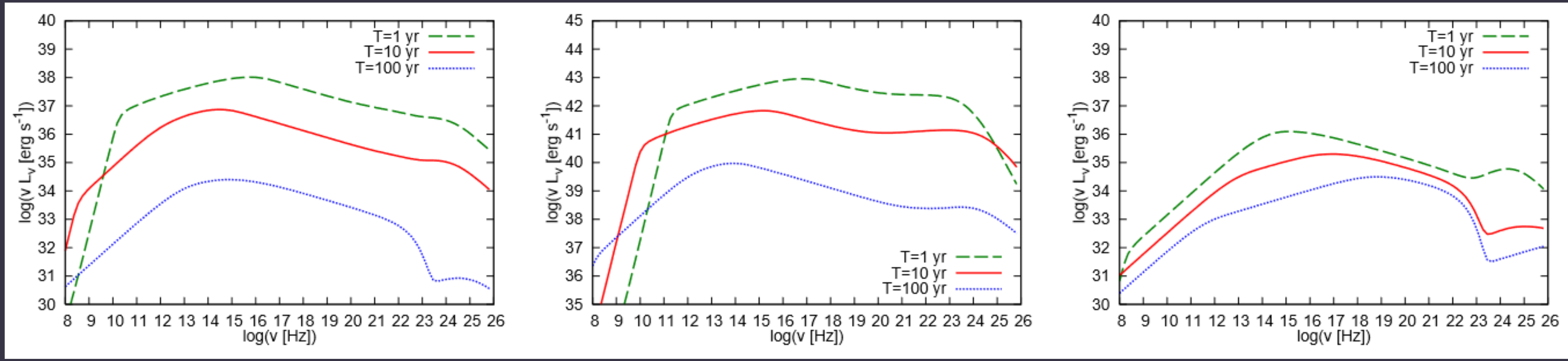
In the model by Lyubarsky the radio burst happens
due to synchrotron maser emission
after interaction between a magnetic pulse after
a giant flare of a magnetar with surrounding nebula.

Nebula emission



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

1603.08875

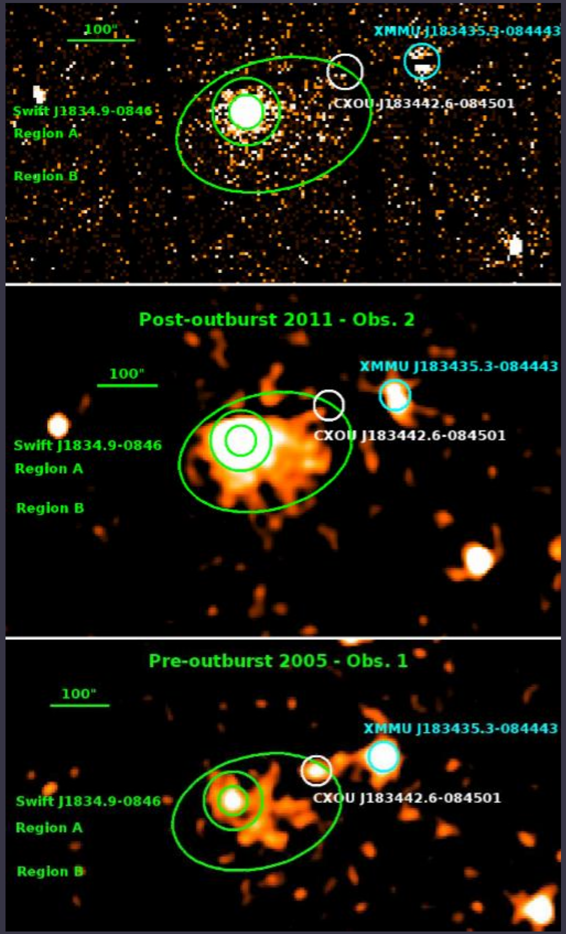


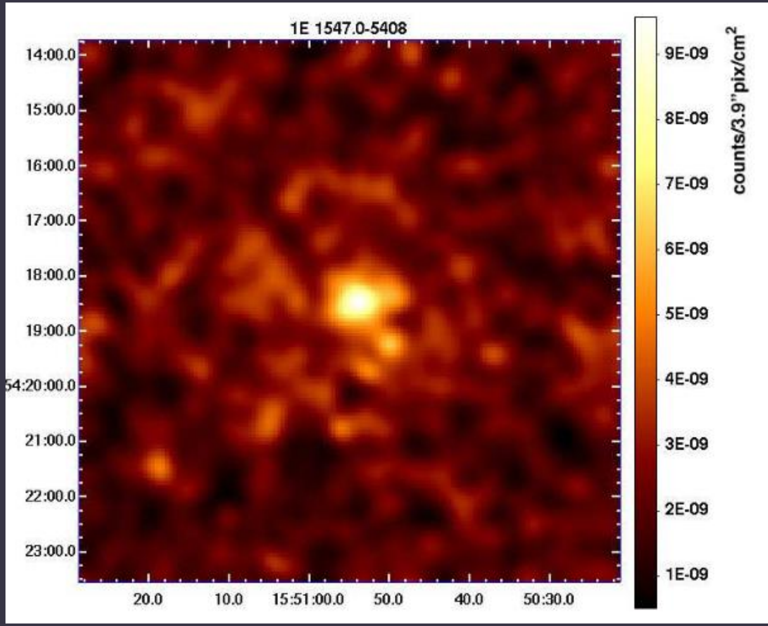
Magnetar RNS MWD

Nebulae around magnetars

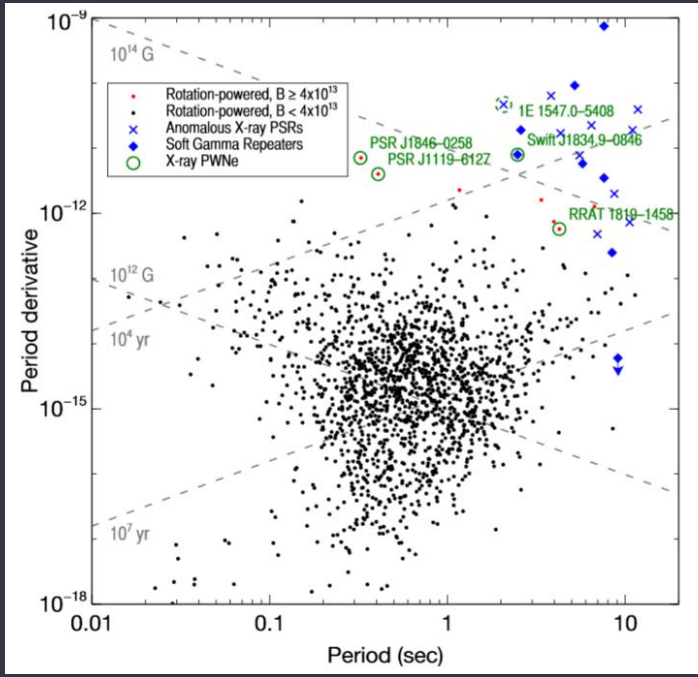
There are examples of nebulae around magnetars and highly magnetized radio pulsars.

1206.3330. New results in 1604.06472





0909.3843



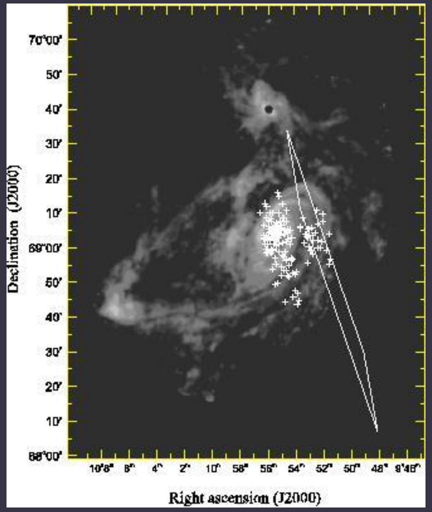
1211.0852

About formation of pulsar nebulae around magnetars see 1606.01391

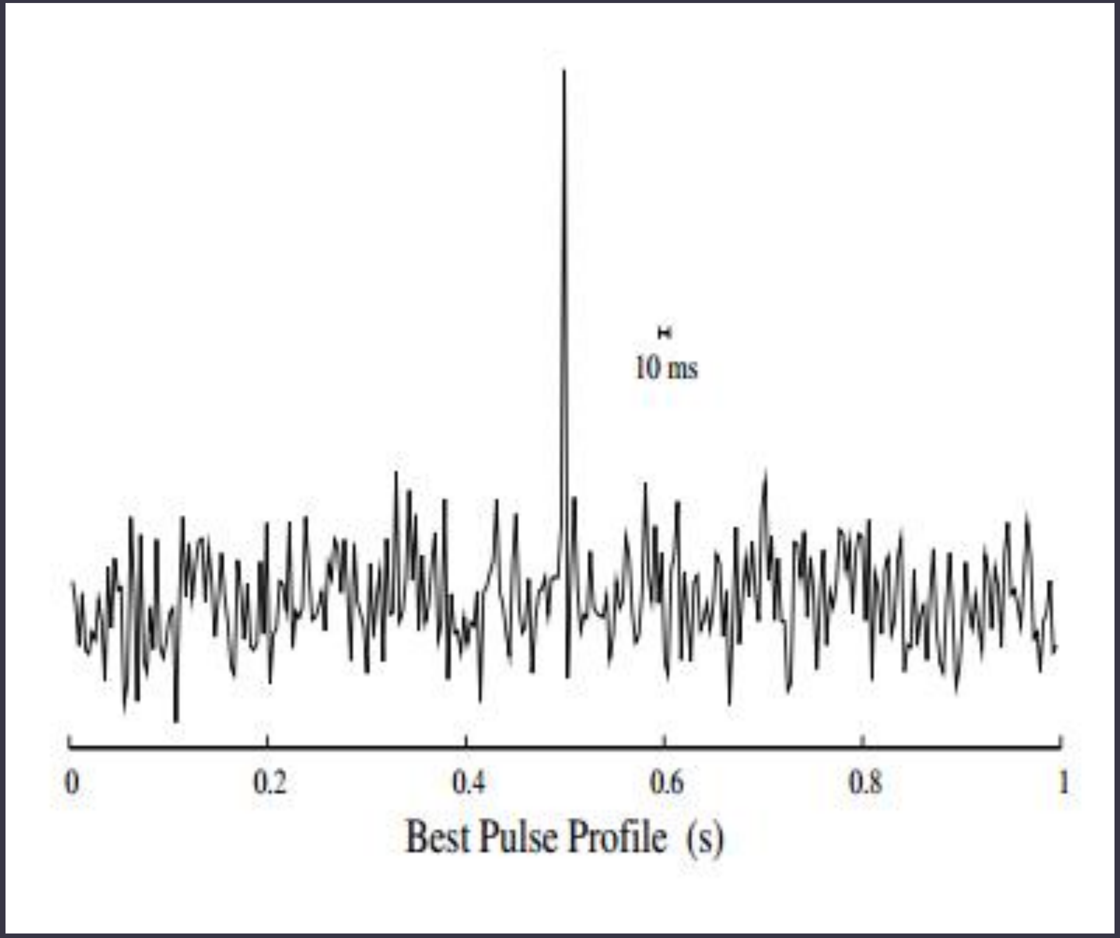
Radio flares from M31

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

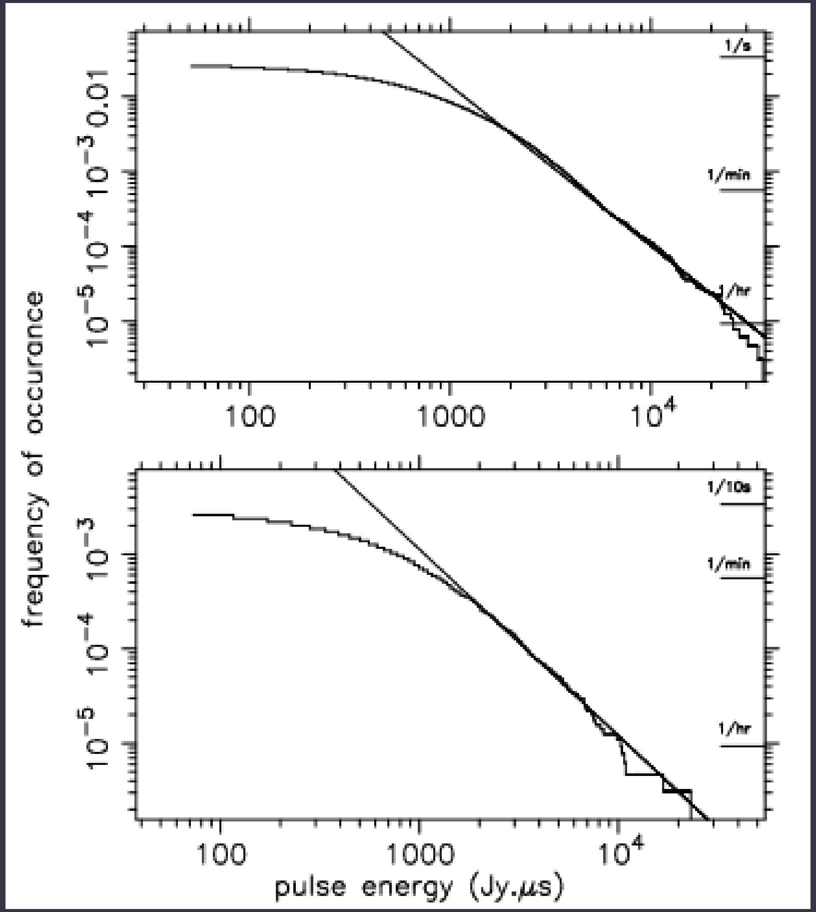
It looks like a scaled version of FRBs.
In the magnetar model such (more frequent) bursts can be related to weaker flares of magnetars.



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



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.

FRBs as supergiant pulses

$$\eta = \frac{L_{GP}}{\dot{E}_{\rm Crab}} = \frac{\nu c^3 d^2_{\rm Crab} S_\nu P^4_{NS}}{4\pi^3 B^2_{NS} R^6_{NS}} \approx 10^{-2},$$

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

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

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

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

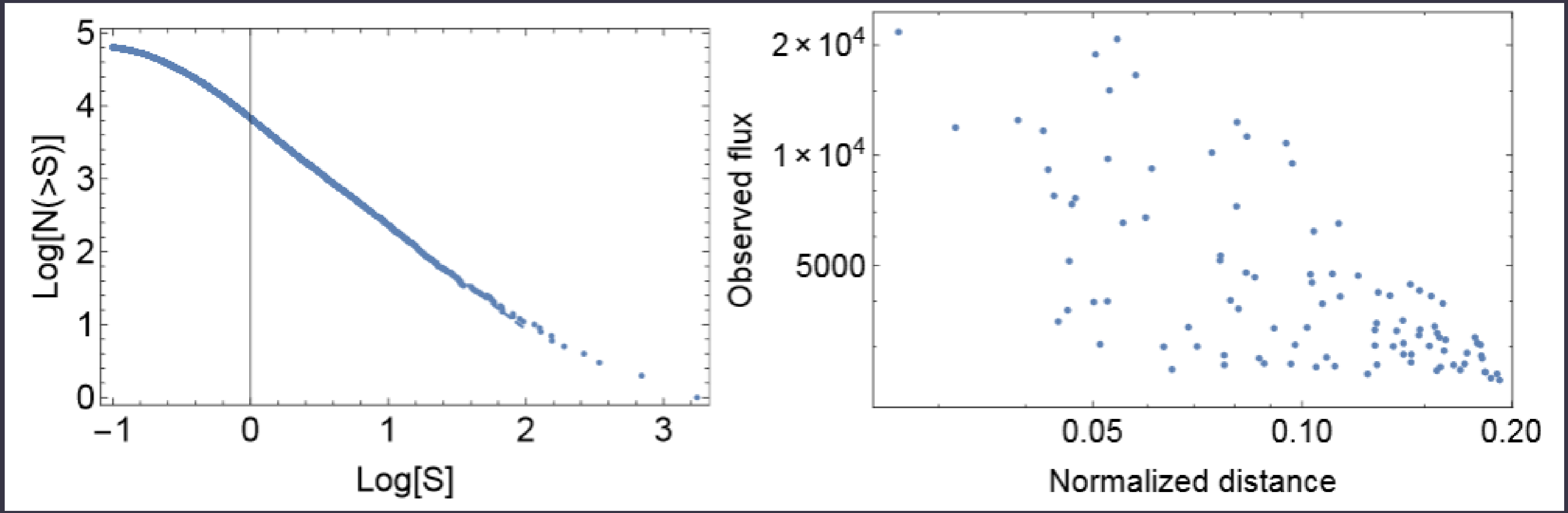
Supergiant pulses of young radio pulsars in dense supernova remnants

Age 30-100 years
Uniform distribution in Edot in logarithmic scale
Absorption of low-frequency radiation in the remnant
Repeating bursts
Bursts are uniformly distributed in distance

$$f(\dot{E}) \propto \frac{\ln(\dot{E}_0/\dot{E})}{\dot{E}^{3/2}}, \beta = 1$$

Steady state solution for magneto-dipole spindown and

$$f_{inj}(\dot{E}) \propto \dot{E}^{-\beta}$$



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 increase by factor 100 000
are scaled to flares with the flux ~1 Jy from 100-200 Mpc.

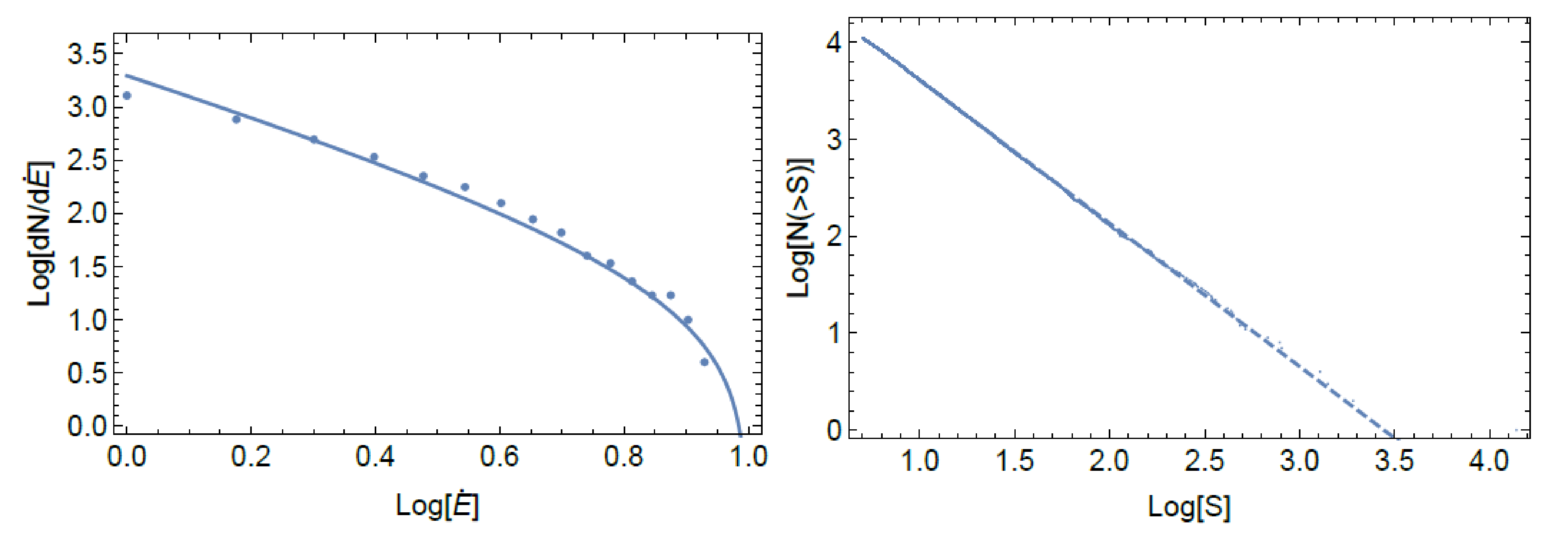
Number of giant pulsars depends on flux as ~S^{-3}.
For FRBs we then obtain that most bright event might be observed once per few months.

Monte Carlo simulations

$f_{inj} \propto \dot{E}^{-1}$

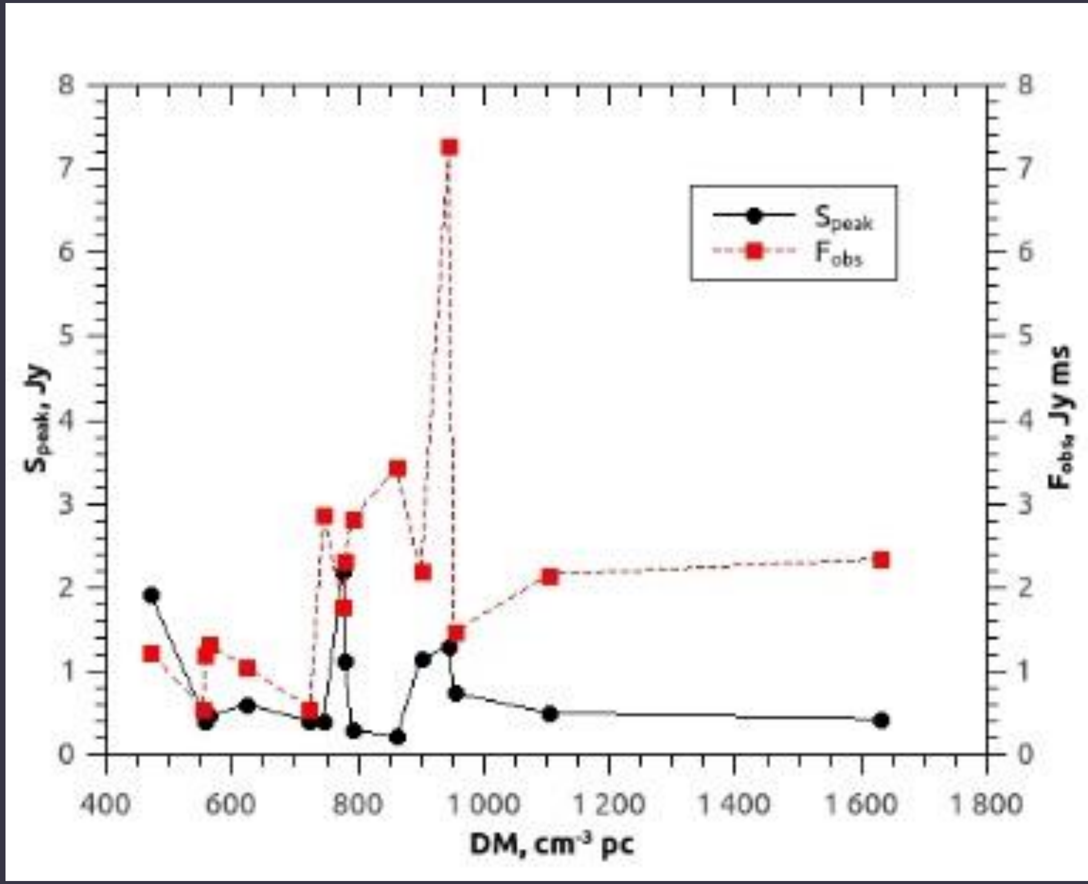
$\partial_t \dot{E} \propto -\dot{E}^{-3/2}$

$S \propto \dot{E}/r^2.$



Distribution in distance and DM

1603.02891



$$S \propto \frac{\dot{E}}{r^2} \propto \dot{E}\, f(\dot{E})^{2/3}$$

$$S \propto \dot{E}^{(1-2\alpha/3)} \propto r^{-2+3/\alpha}$$

$$\dot{E} = \frac{\dot{E}_0}{(1+t/\tau)^2},$$

$$\mathrm{DM} = \frac{M_{ej}^2}{2E_{ej}m_p\tau}\frac{\dot{E}}{(\dot{E}+\dot{E}_0)^2}$$

Dispersion measure does not correlate with fluence or peak luminosity.

This is in correspondence with the model.

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.

Future observations

FAST

SKA

FAST – burst per week

1602.06099

SKA – burst per hour!

1602.05165, 1501.07535

Near future

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.

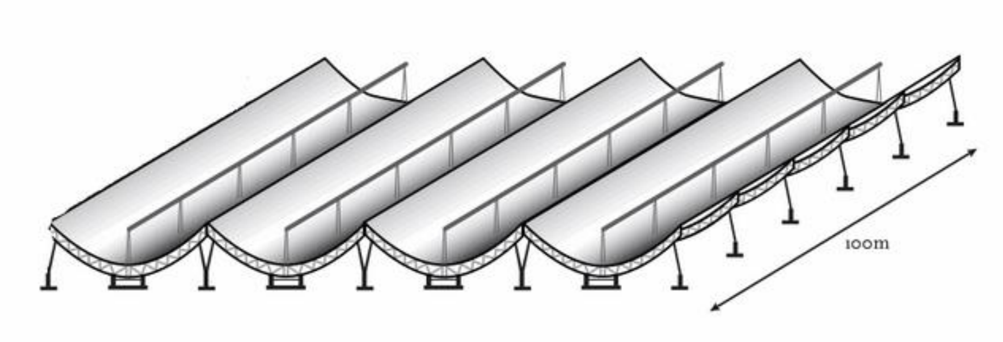
Special projects partly dedicated to FRBs

SUPERB
Survey for Pulsars and Extragalactic Radio Bursts

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

CHIME

The **C**anadian **H**ydrogen **I**ntensity **M**apping **E**xperiment



CHIME – burst per day!
1601.02444

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

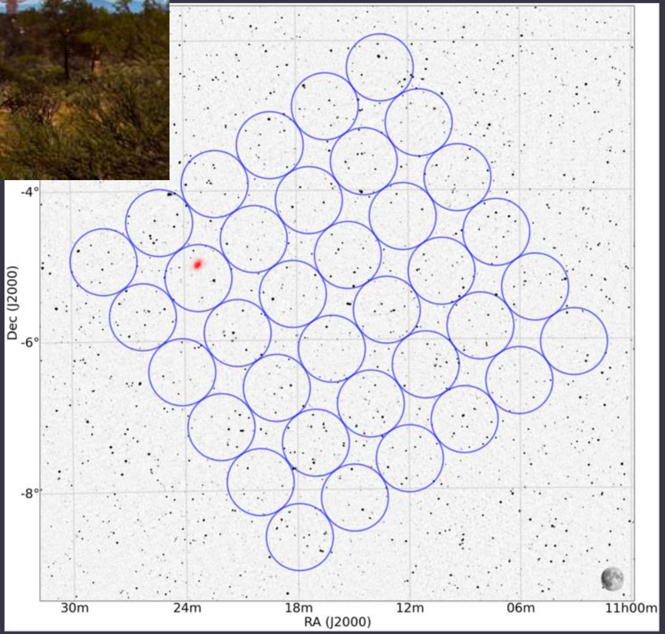
HIRAX.
South variant of CHIME

1607.02059

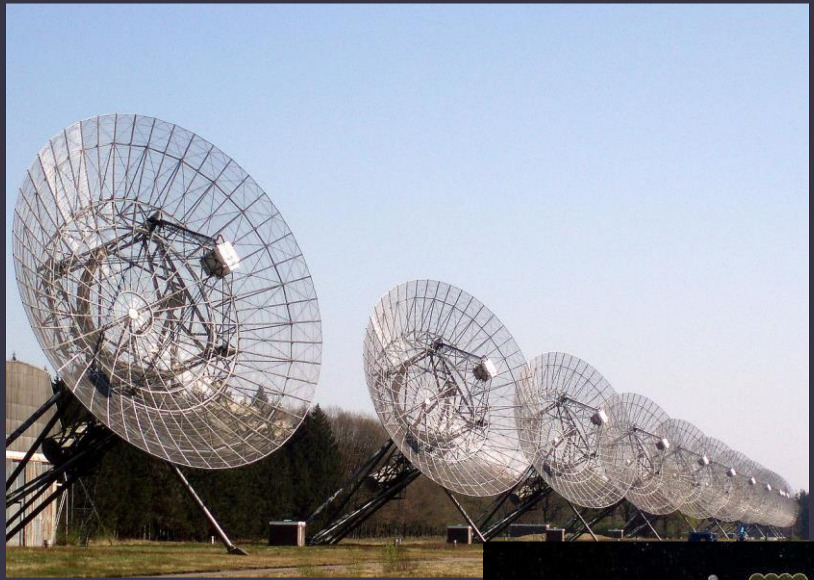
ASKAP and Apertif

ASKAP

Few bursts per week.
1709.02189



Westerbork



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

1709.06104