Fast radio bursts: magnetars, pulsars or what?

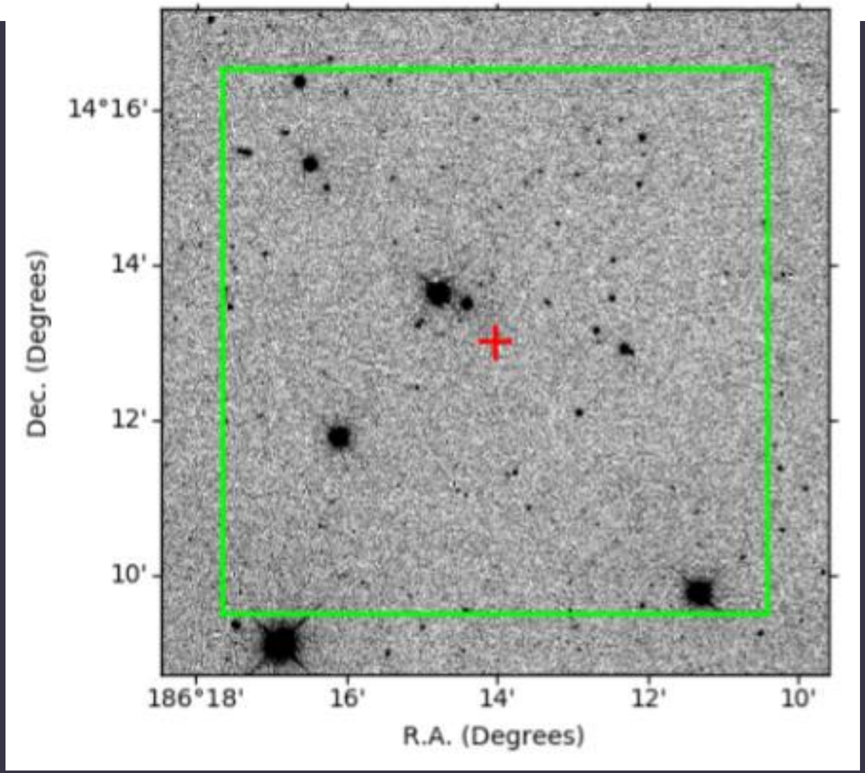
SERGEI POPOV (SAI MSU)

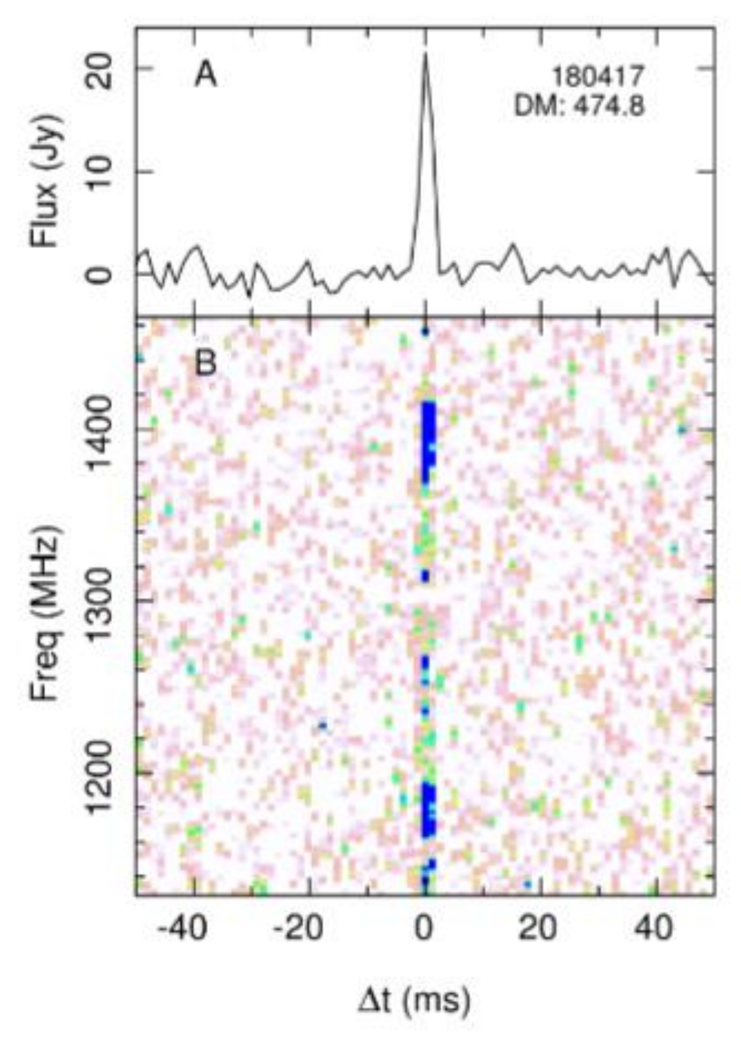
See a review Popov, Postnov, Pshirkov in arXiv: 1806.03628. Physics Uspekhi (2018 N10)

FRB 180417

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]

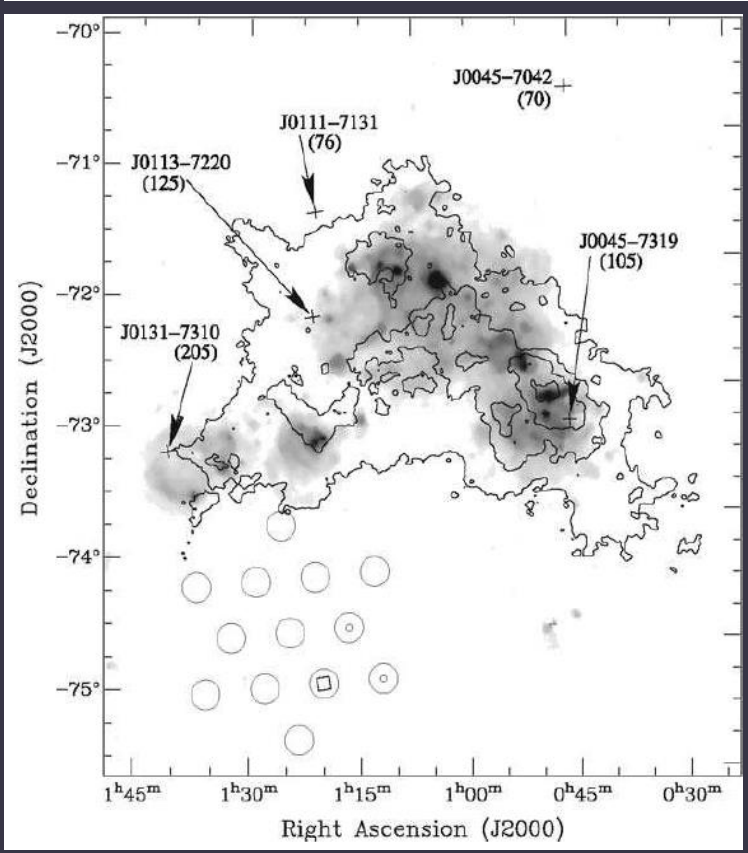




1909.05779

The first event

Science 318, 777 (2007)



Discovered at Parkes
by Duncan Liromer et al.

~30-40 Jy, < 5 msec.

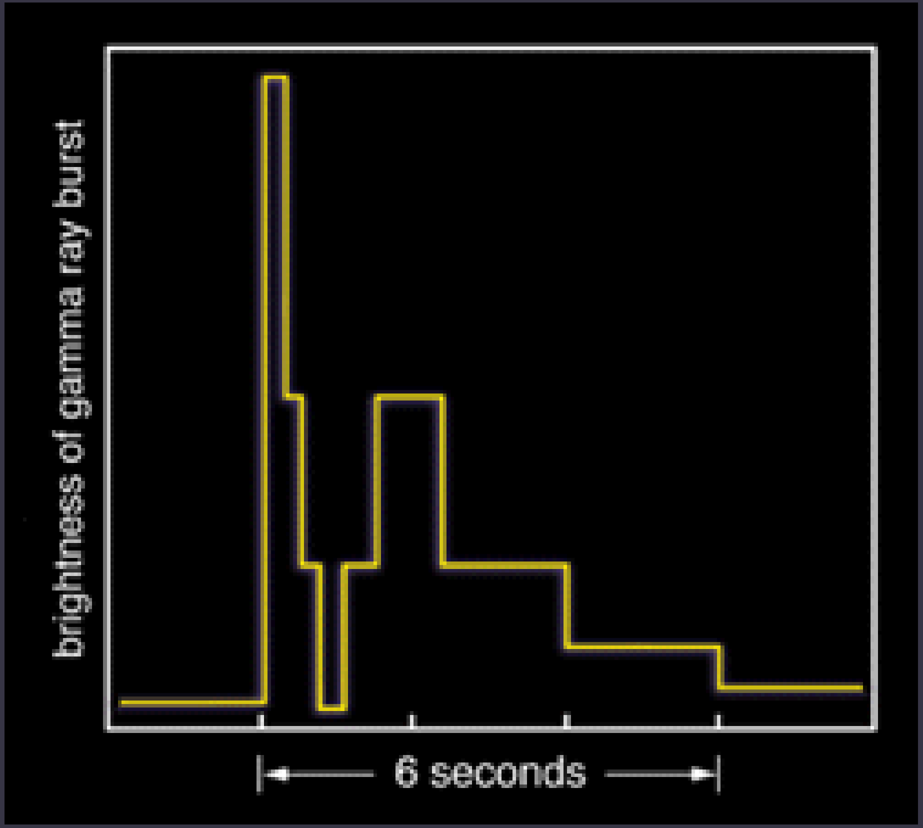
3 degrees from
Small Magellanic cloud

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

1511.02870

History repeating? GRB2.0?

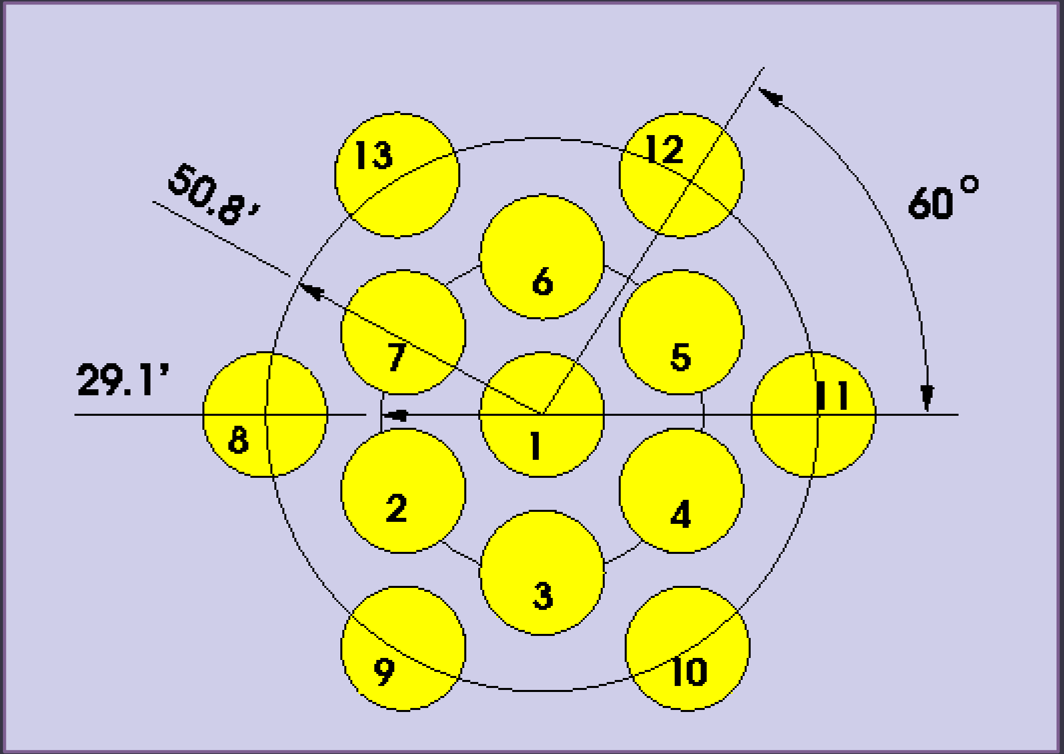
At the end of 1960s cosmic gamma-ray bursts have been discovered.
They have been a mystery f
or ~30 years as there were
no counterparts at other wavelengths.



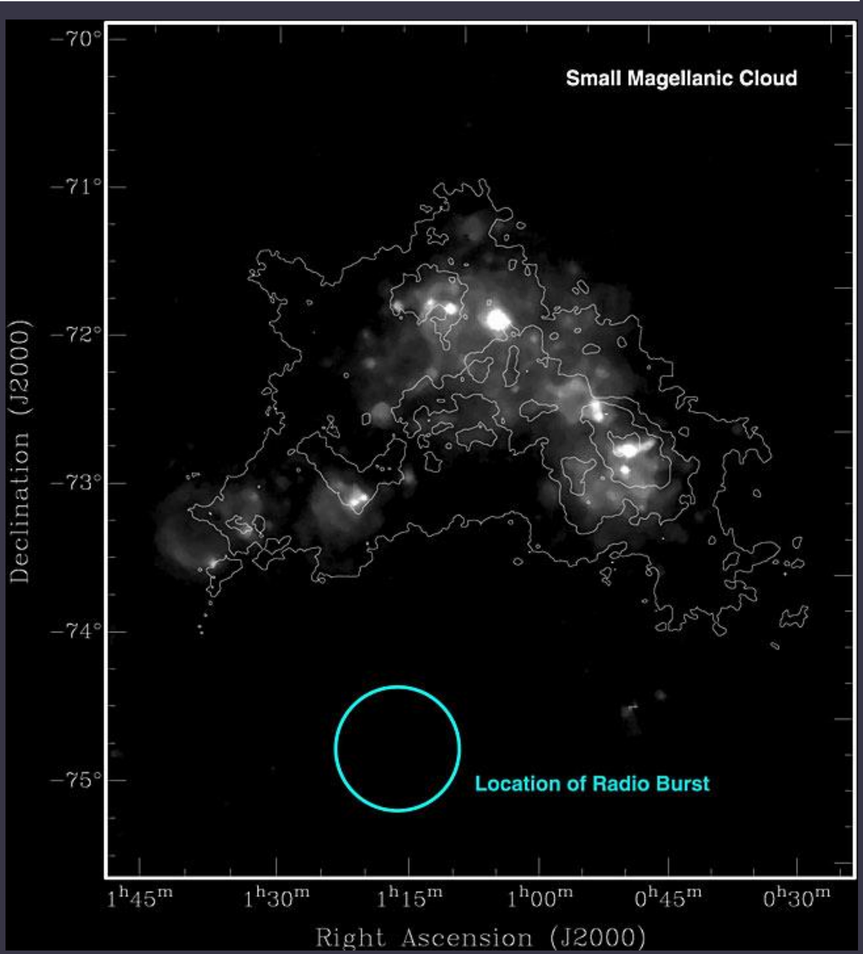
Only at the end of 1990s
a burst was simultaneously
observed in X-rays.
This allowed to measure
coordinates precisely enough,
and thus to identify the source.

Localization

Radius of uncertainty circle ~10 arcmin



Usually FRBs are seen just in one beam.



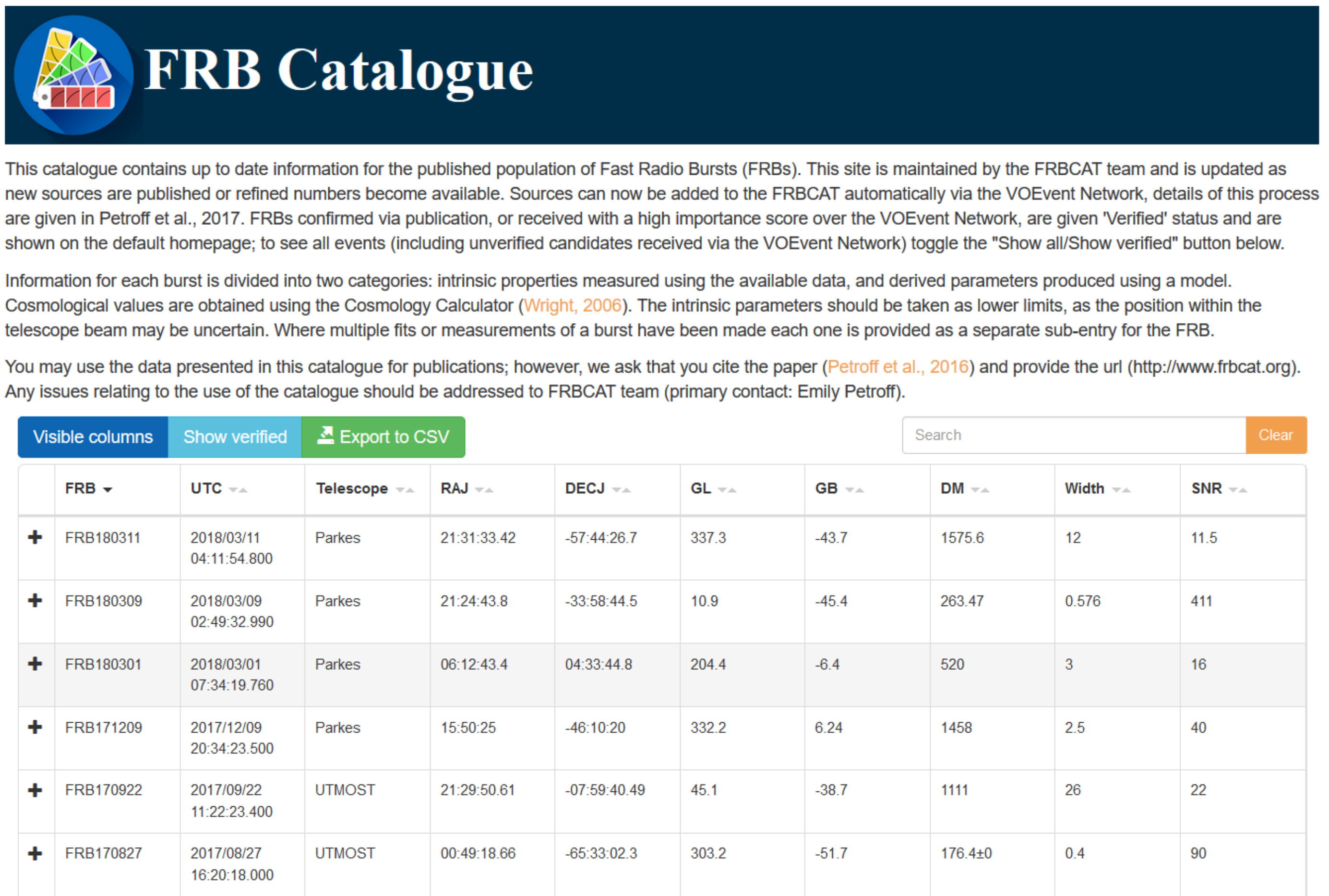
Catalogue

90 FRBs
(~10 repeaters)

Parkes - 27
UTMOST – 9
ASKAP – 26
CHIME - 21
GBT – 1
DSA-10 - 1
Arecibo – 2
Pushchino – 3 (?)

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.

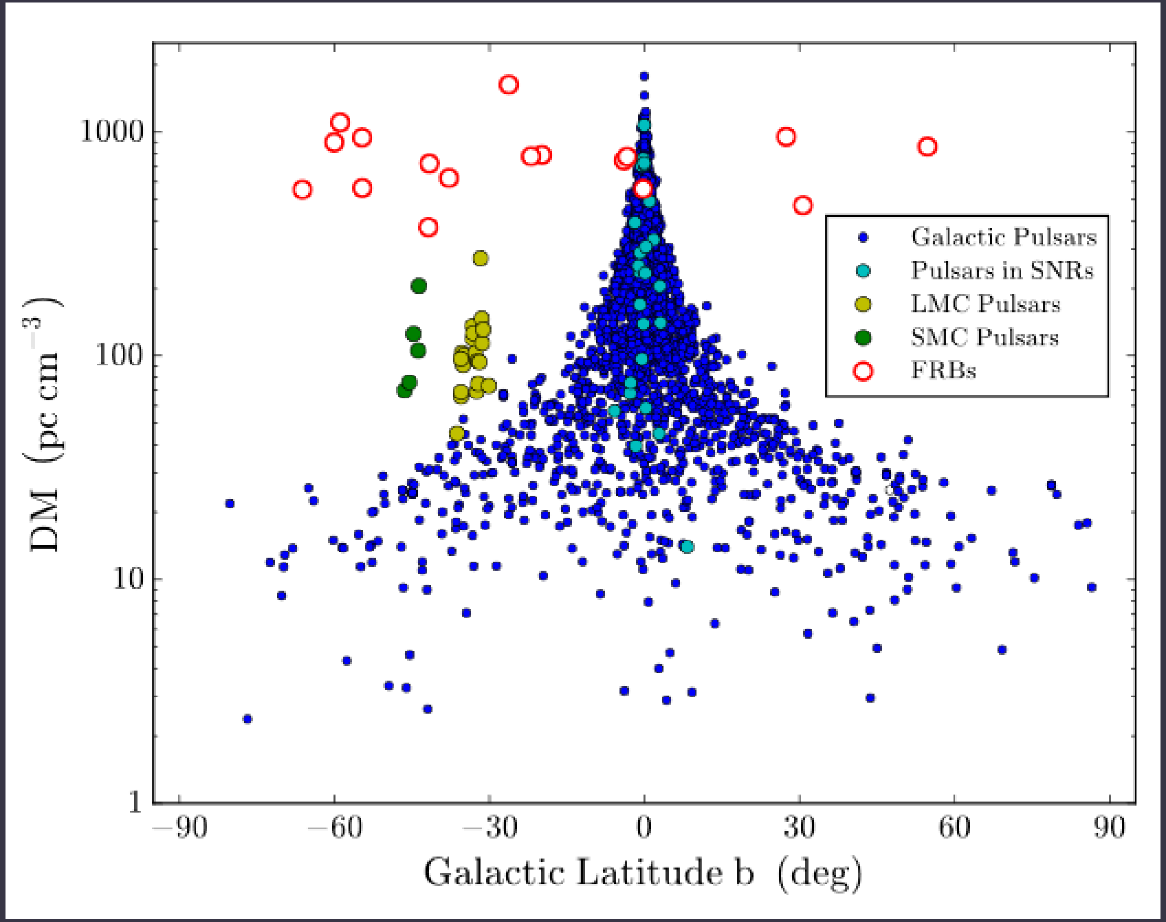
You may use the data presented in this catalogue for publications; however, we ask that you cite the paper (Petroff et al., 2016) and provide the url (http://www.frbcat.org). Any issues relating to the use of the catalogue should be addressed to FRBCAT team (primary contact: Emily Petroff).

	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/

1601.03547

Comparison with radio pulsars



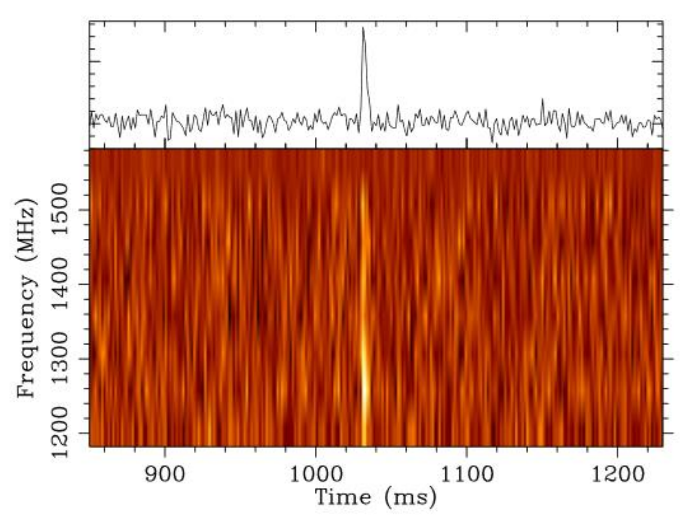
$$\frac{dN}{dF_{\mathrm{obs}}} = (4.4 \pm 0.4) \times 10^3\, F_{\mathrm{obs}}^{-1.18 \pm 0.15}\ \mathrm{sky}^{-1}\ \mathrm{day}^{-1}$$

1602.06099

1605.05890

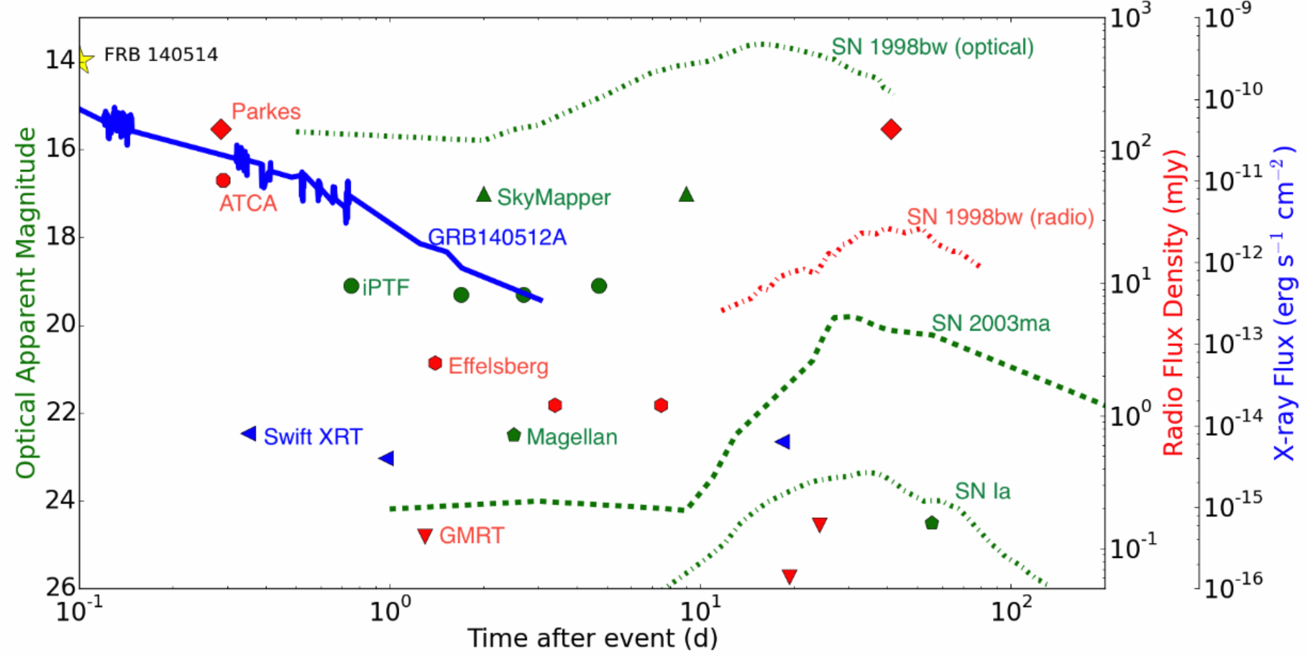
The first burst detected in real time

1412.0342

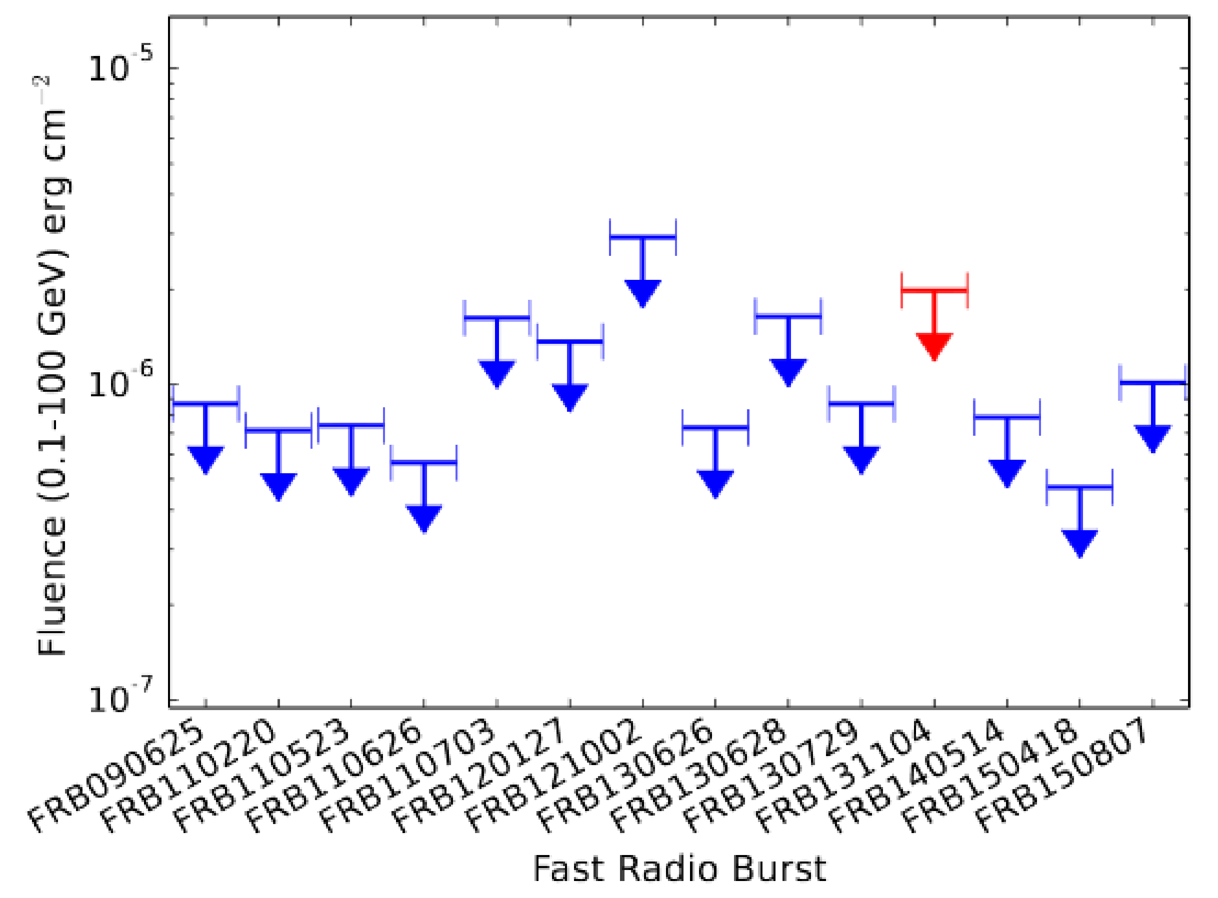


In may 2014 for the first time a burst was detected in real time.
This allowed to trigger searches of an afterglow in other energy ranges.

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



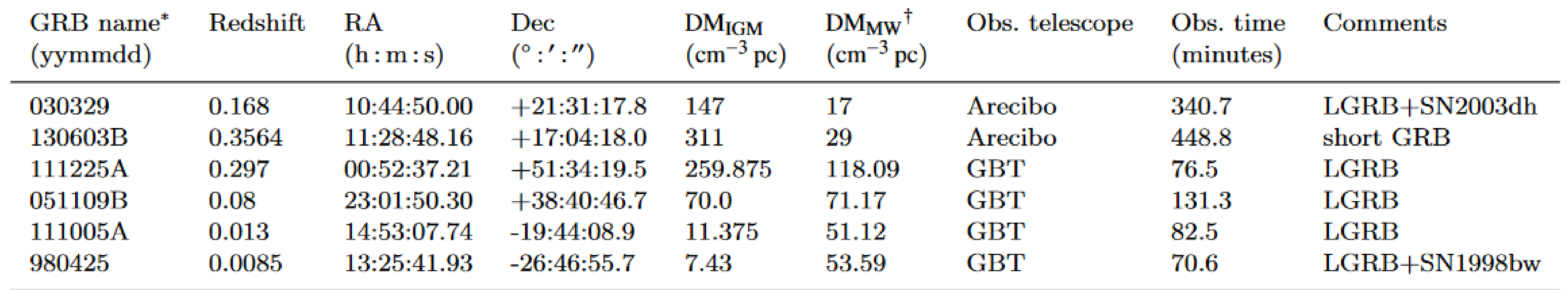
Limits on gamma-emission



Fermi data

1705.03657

No FRBs from GRB remnants

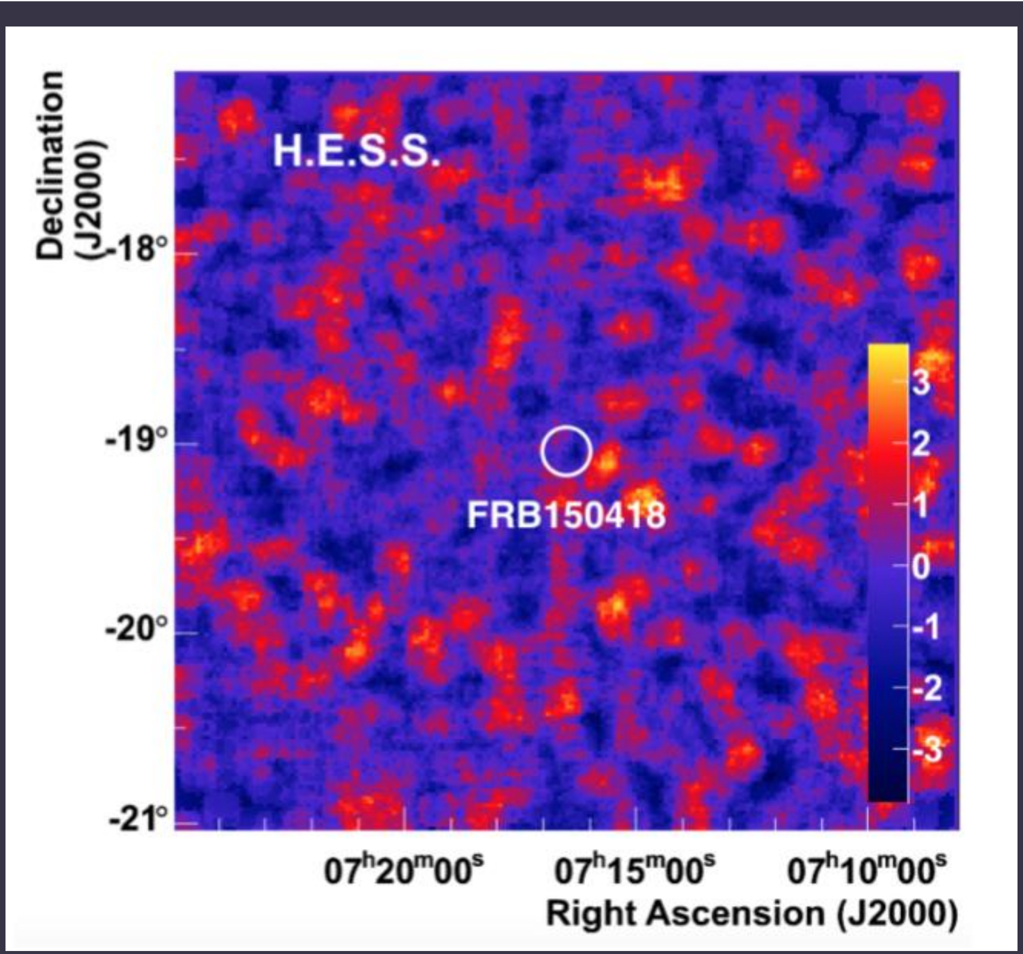


GRB name* (yymmdd)	Redshift	RA (h : m : s)	Dec (° : ′ : ″)	DM_{IGM} (cm^{-3} pc)	$DM_{MW}^{\dagger}$ (cm^{-3} pc)	Obs. telescope	Obs. time (minutes)	Comments
030329	0.168	10:44:50.00	+21:31:17.8	147	17	Arecibo	340.7	LGRB+SN2003dh
130603B	0.3564	11:28:48.16	+17:04:18.0	311	29	Arecibo	448.8	short GRB
111225A	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
(but mind the possibility of beaming!!!)

1908.10222

TeV range observations



H.E.S.S.
FRB 150418

Observations within
15-16 hours after the burst.

~1 hour of observations

No signal.

1611.09209

Repeating bursts

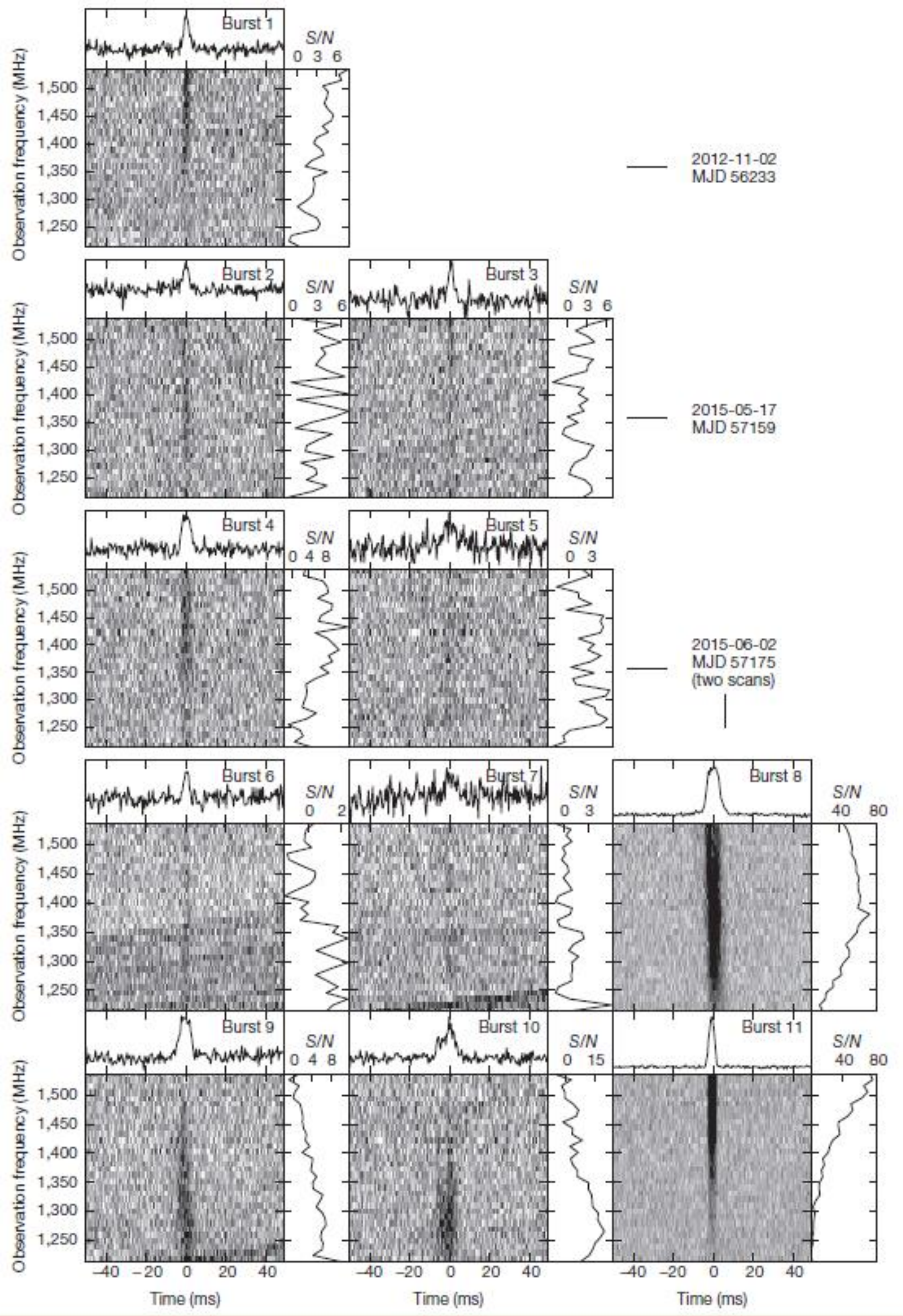
Repeating bursts are detected firstly from FRB 121102.

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.

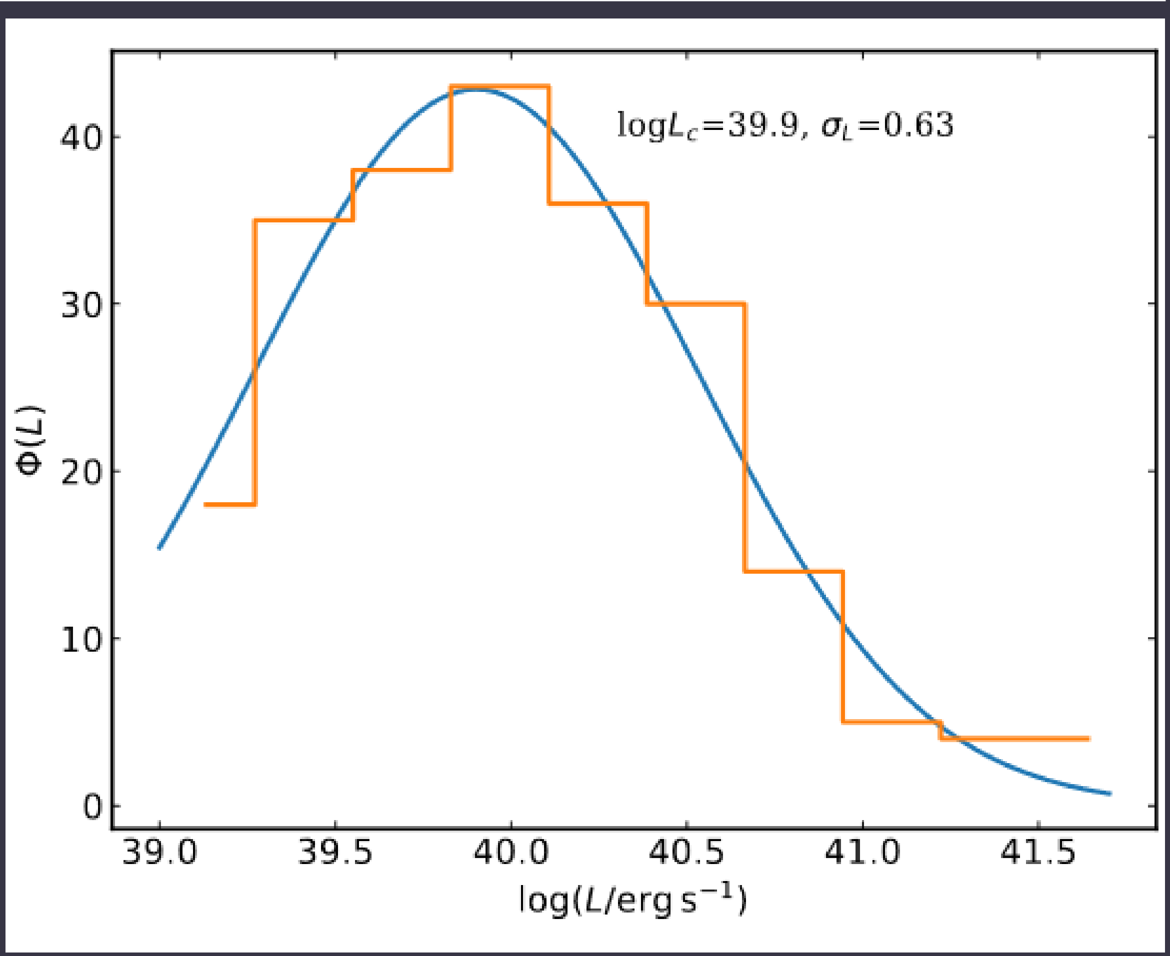


1603.00581

Luminosity distribution for FRB121102

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

227 bursts used for the plot.

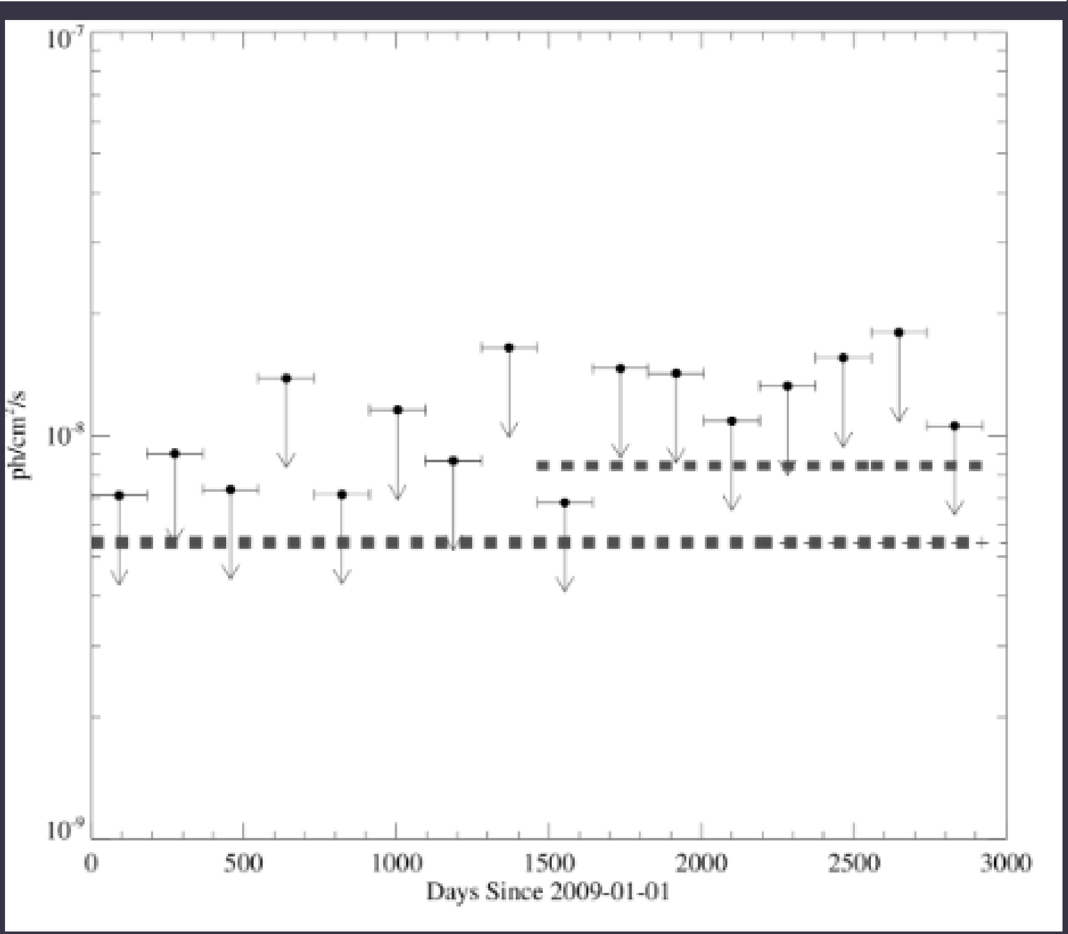


1908.10222

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

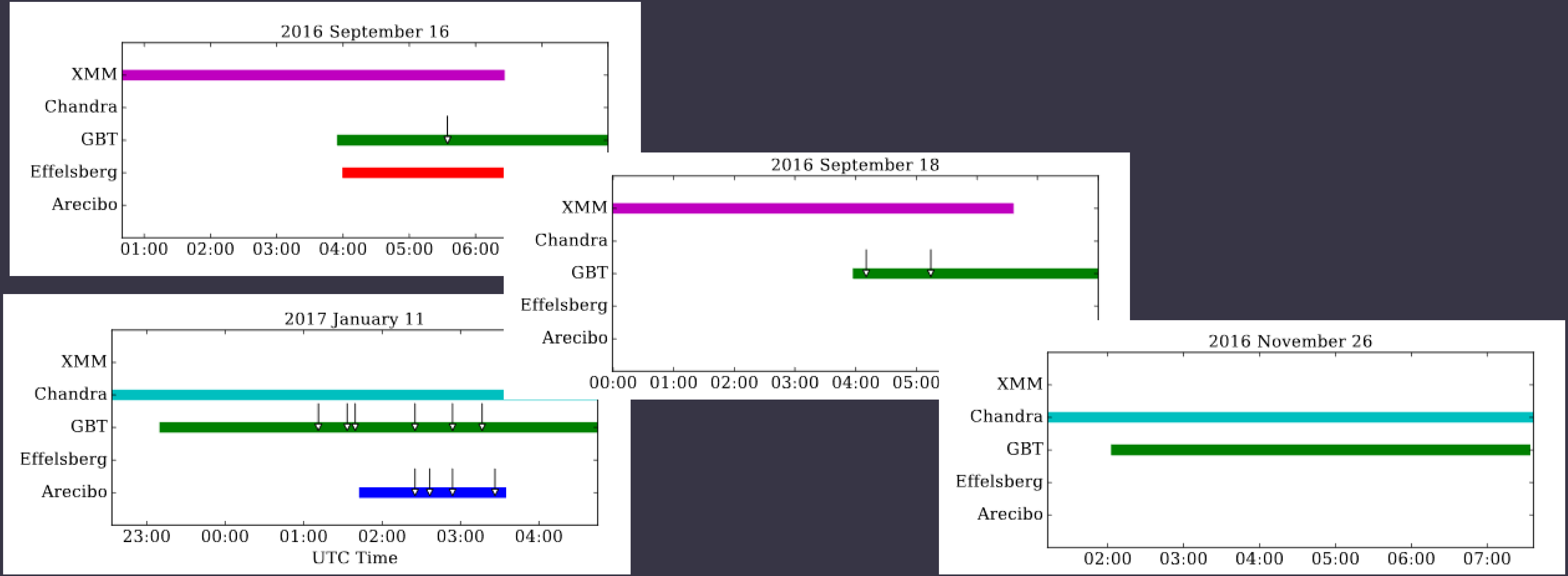
Despite many effort no counterparts detected.

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



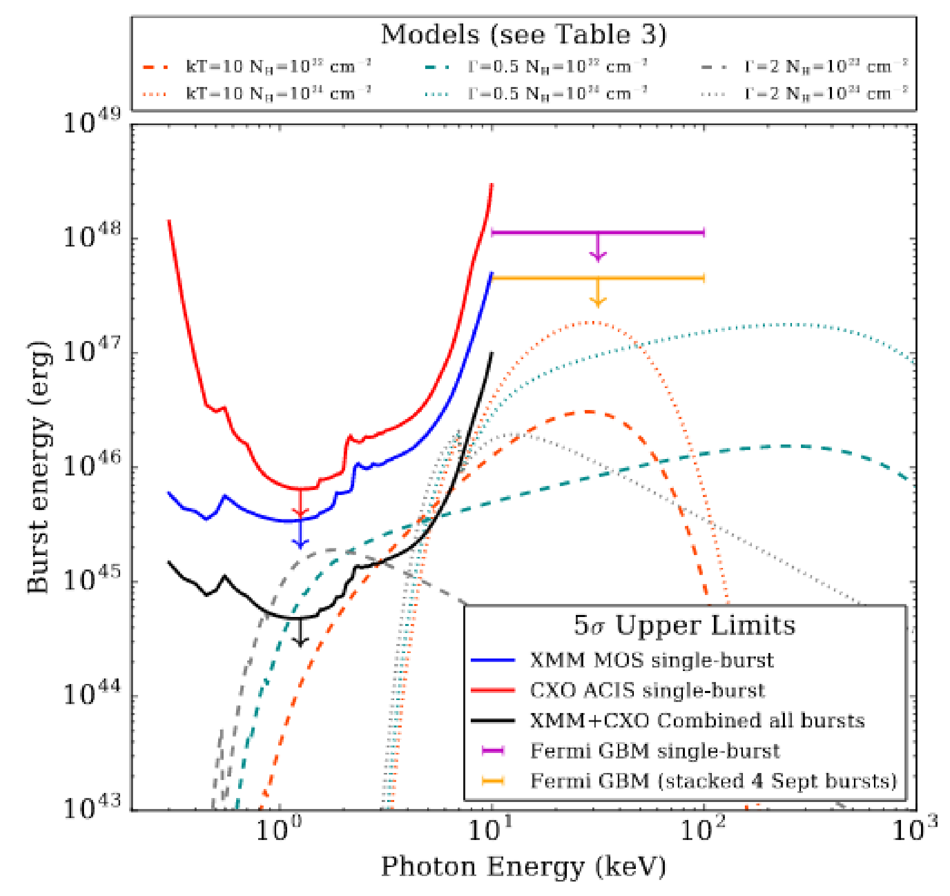
1705.04242

No simultaneous X-ray bursts

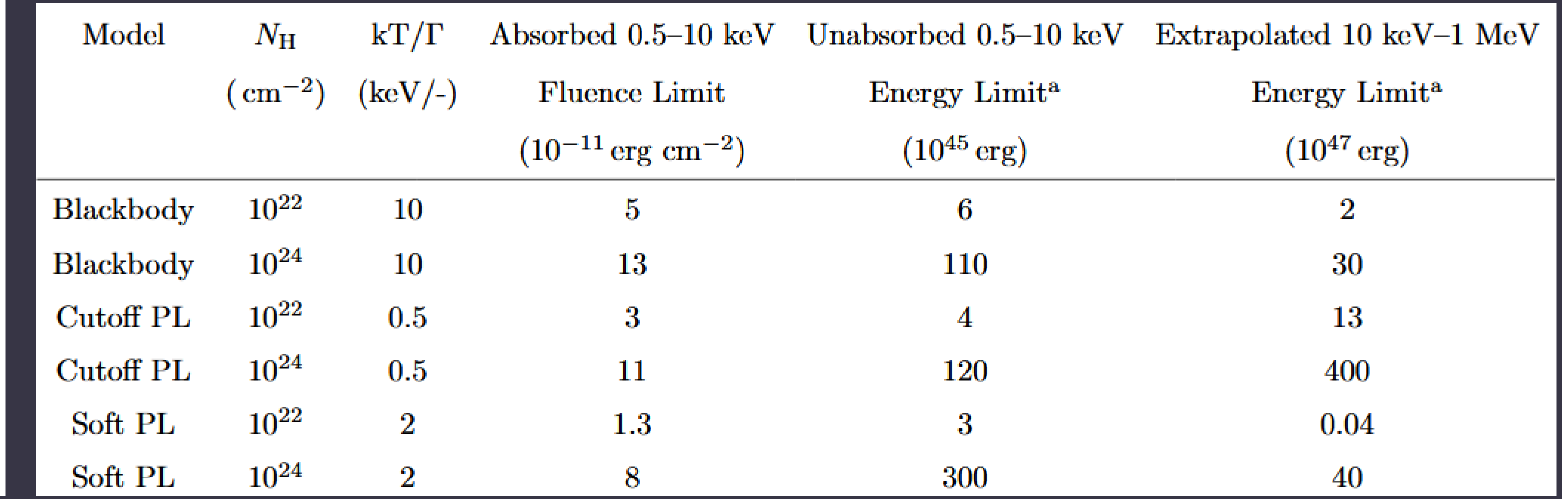


1705.07824

Simultaneous observation in radio and X-rays



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

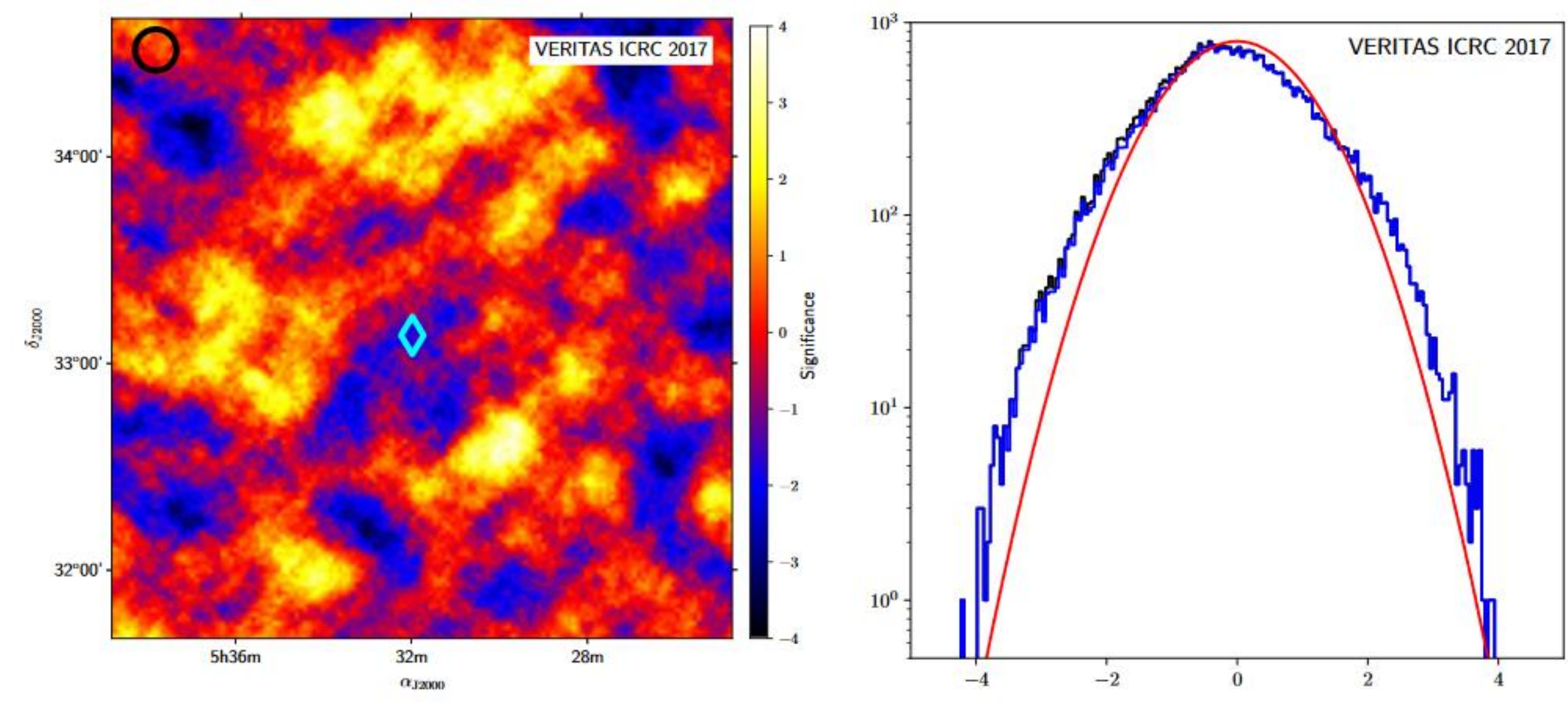


Model	N_H (cm^{-2})	kT/Γ (keV/-)	Absorbed 0.5–10 keV Fluence Limit (10^{-11} erg cm^{-2})	Unabsorbed 0.5–10 keV Energy Limit^a (10^{45} erg)	Extrapolated 10 keV–1 MeV Energy Limit^a (10^{47} erg)
Blackbody	10^{22}	10	5	6	2
Blackbody	10^{24}	10	13	110	30
Cutoff PL	10^{22}	0.5	3	4	13
Cutoff PL	10^{24}	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.

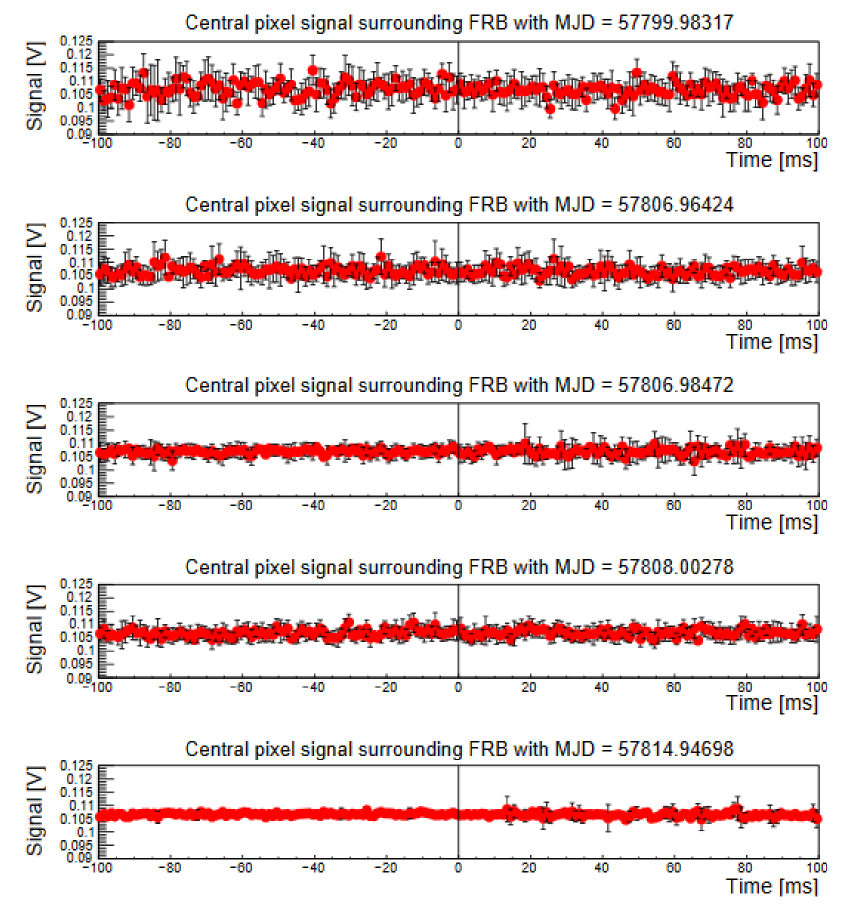


1708.04717

MAGIC upper limits

Simultaneous observations with Arecibo.

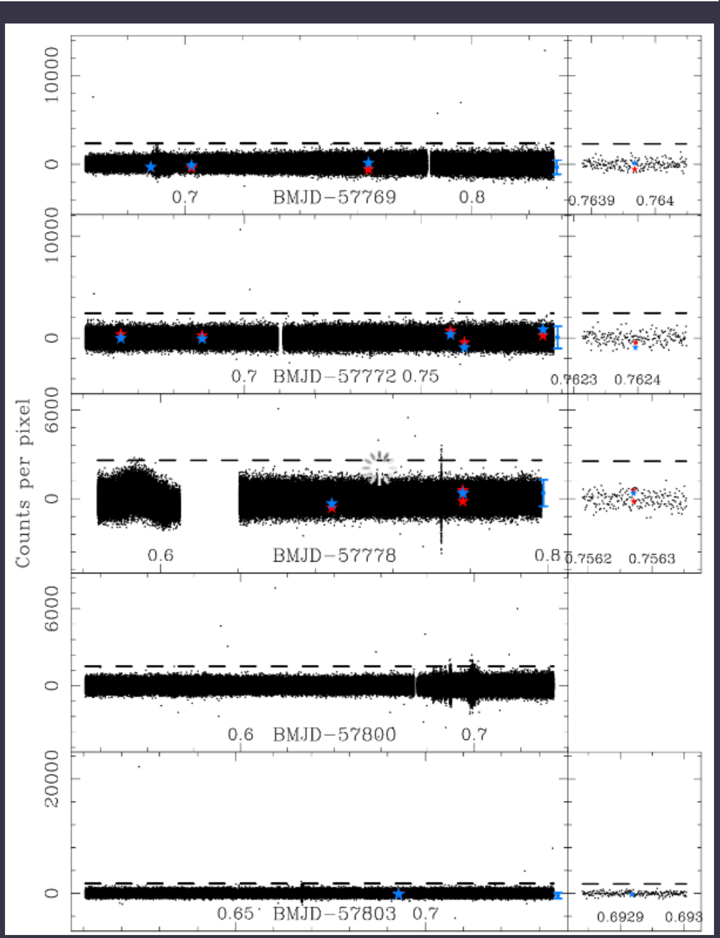
In radio 5 bursts have been detected,
and nothing in gamma/optical.



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.



1708.06156

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.

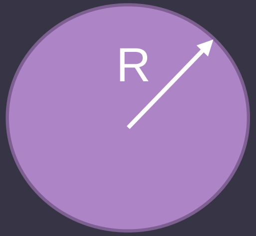
A real flow started in late summer of 2013 after the paper by Thornton et al.

- 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/

See a catalogue of FRB theories in 1810.05836

Neutron stars and exotics



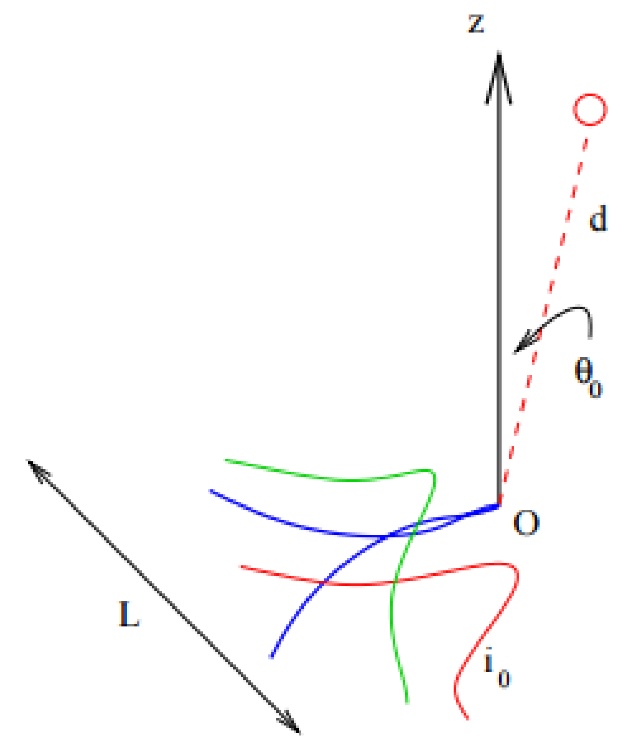
A neutron star has mass ~solar and
radius ~10 km.
This gives free fall velocity $v=(2GM/R)^{1/2}$ ~0.5 c
Free fall time scale $t=R/v< 0.1$ msec
Thus, it is easy to get very short events.
The same is true for BHs.

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

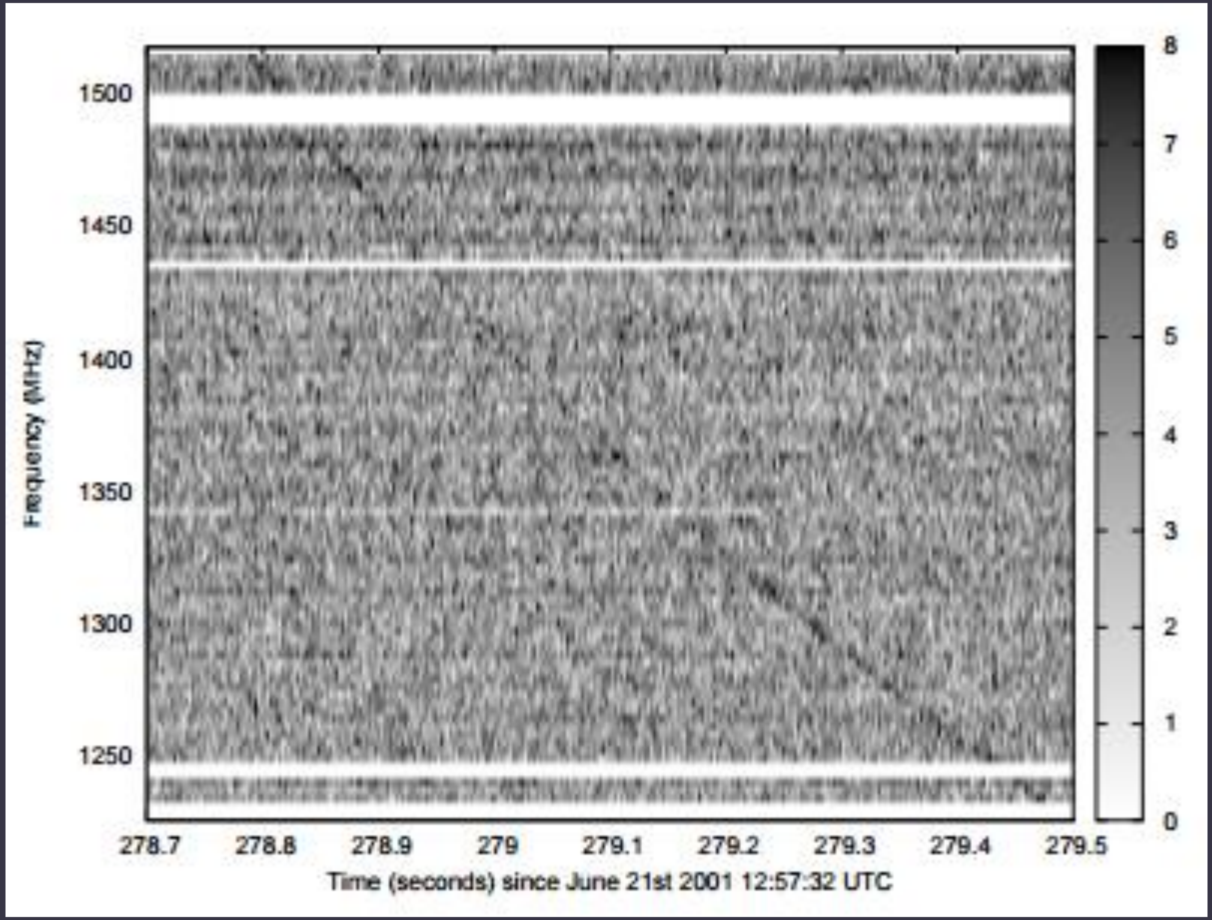


Superconducting strings
Vachaspati 0802.0711

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.

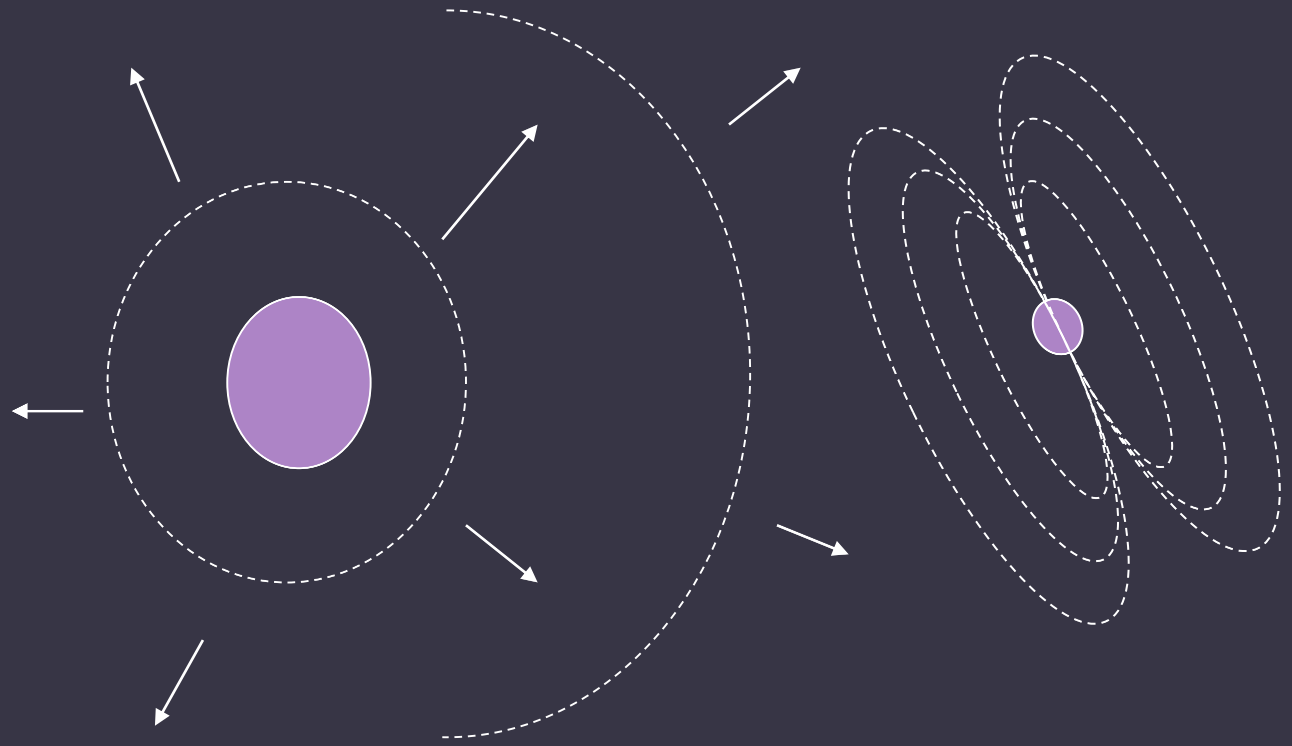
Predicted years ago (Rees 1977).

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



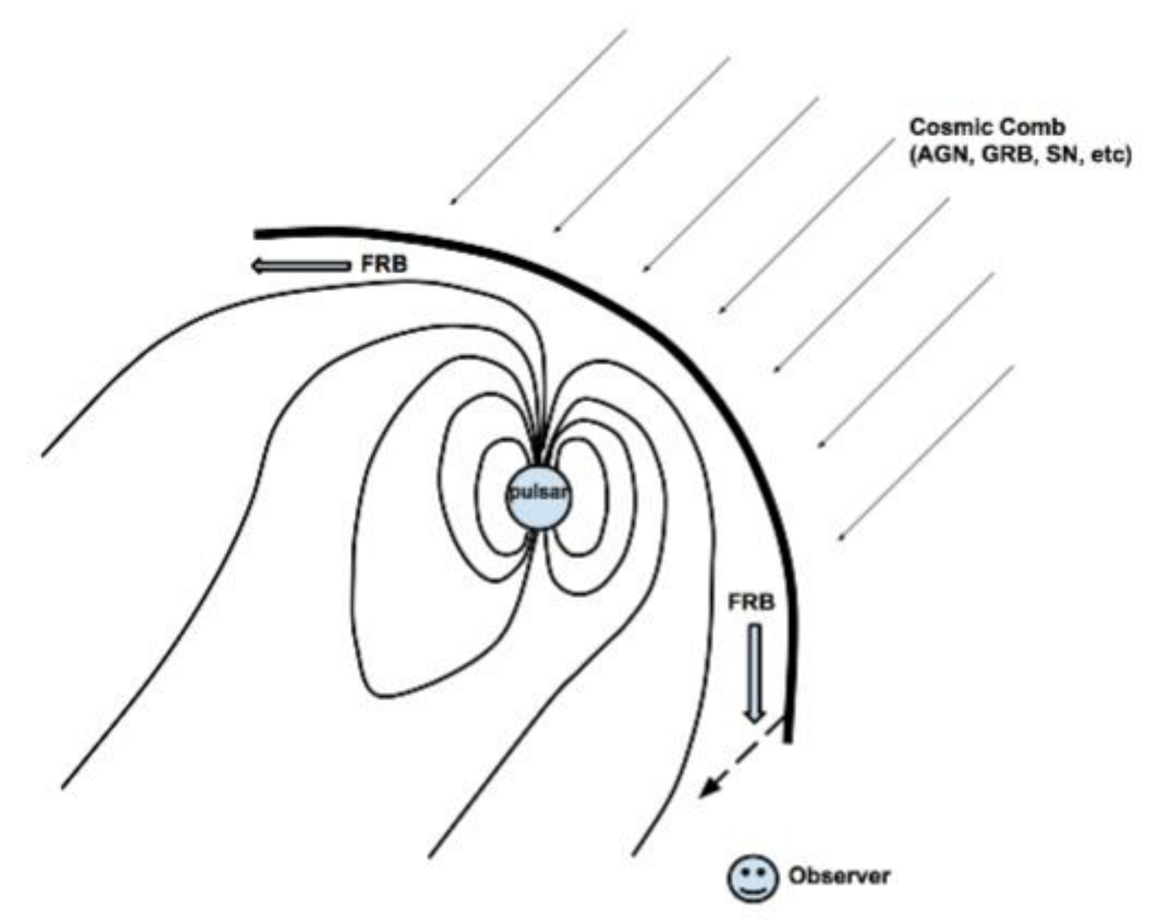
Shock wave after a SN in a close HMXB can interact with the NS magnetosphere forming a magnetotail.

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.

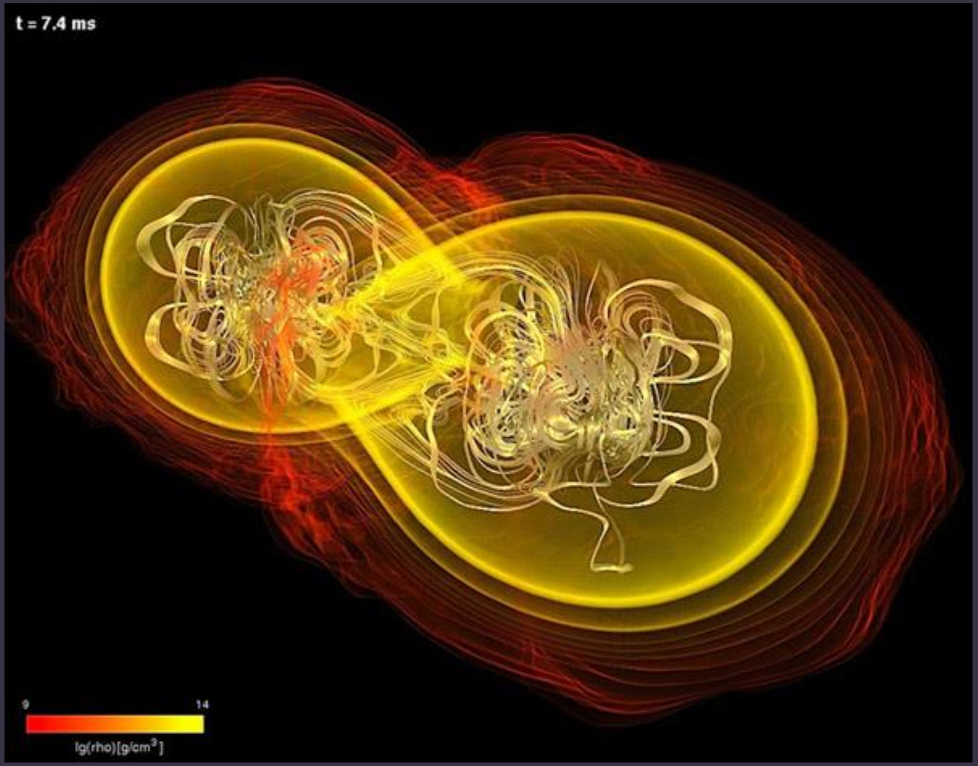
Cosmic comb model

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



1701.04094

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).

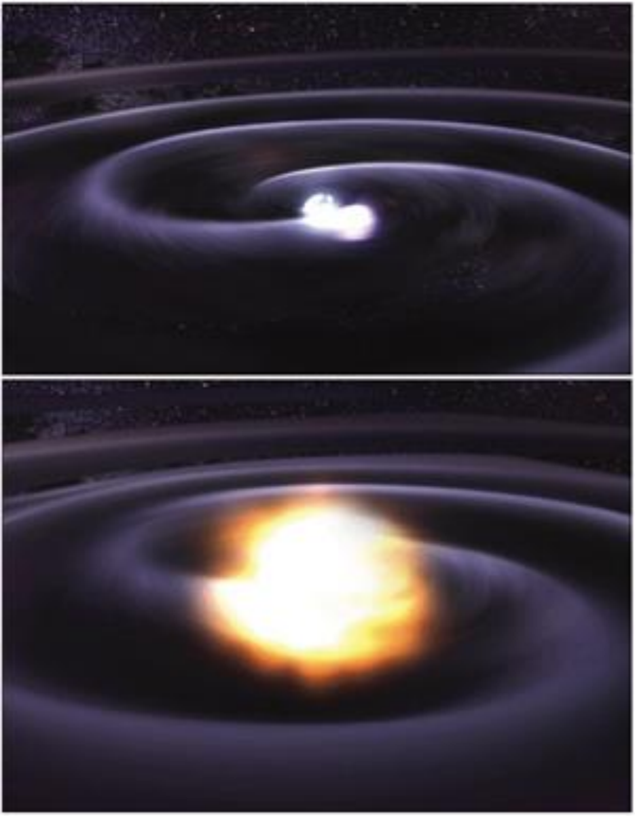
In application to FRBs the first paper is Totani (1307.4985).

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

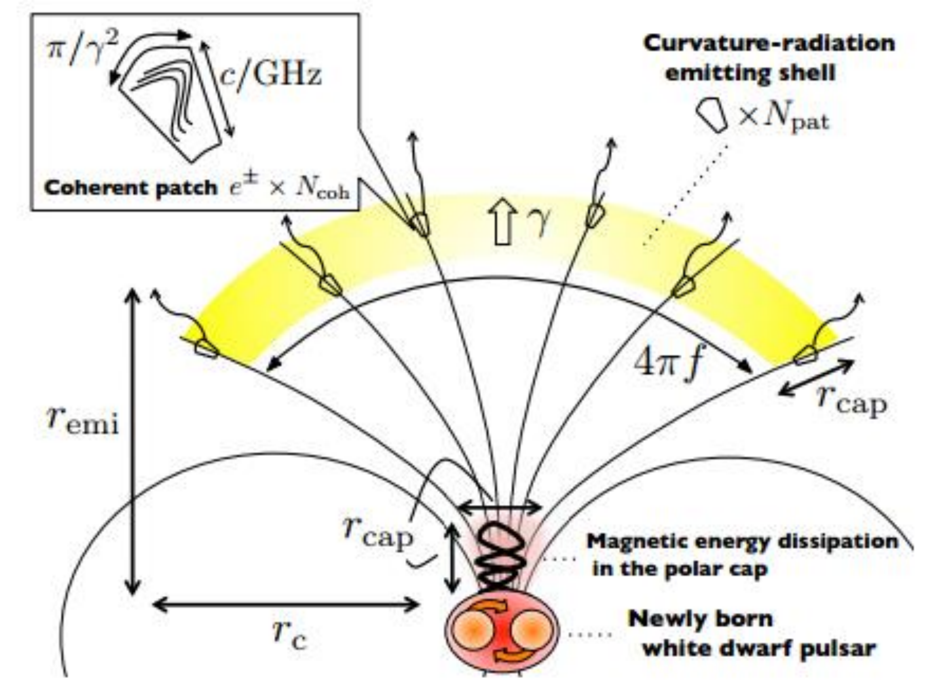
Easy to obtain rapid rotation and strong magnetic field.
But there are many uncertainties.

Might be accompanied by a GW burst.

White dwarf coalescence



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



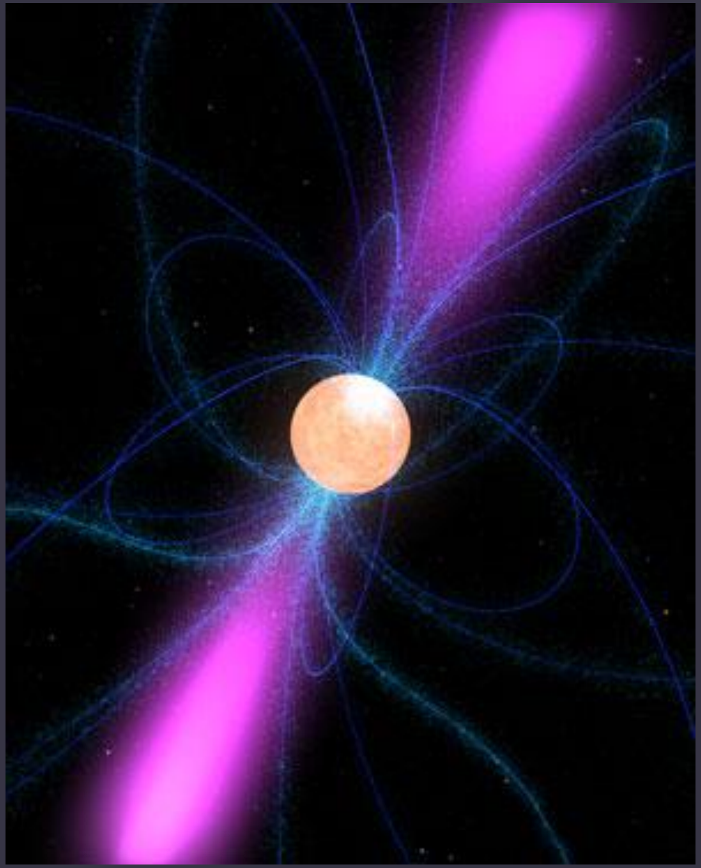
Kashiyama et al. 1307.7708

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

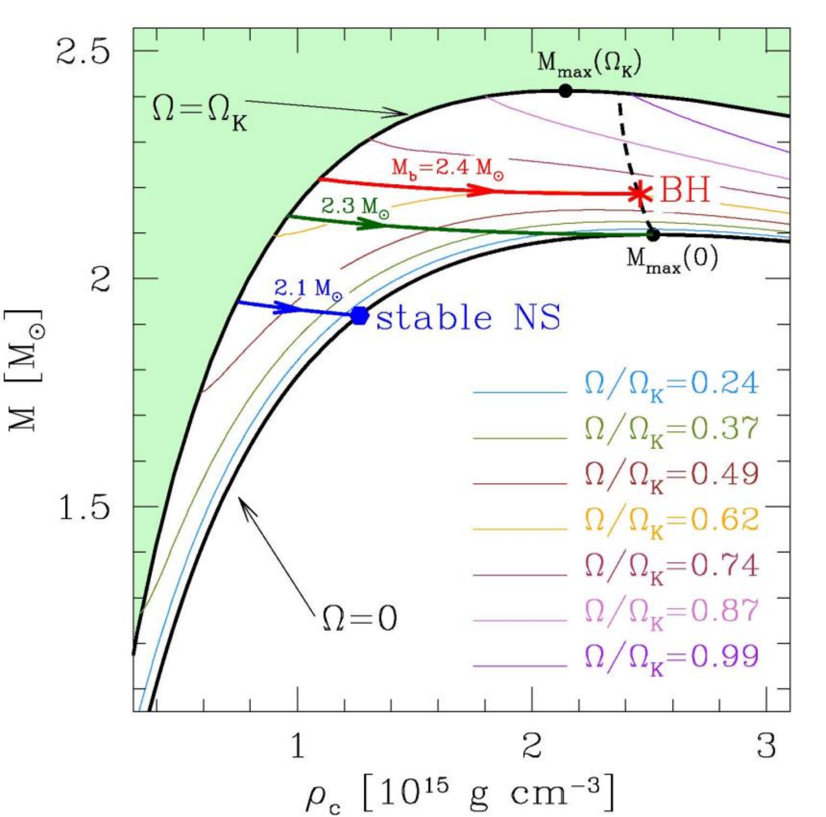
http://www.astro.ru.nl/~falcke/PR/blitzar/



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.

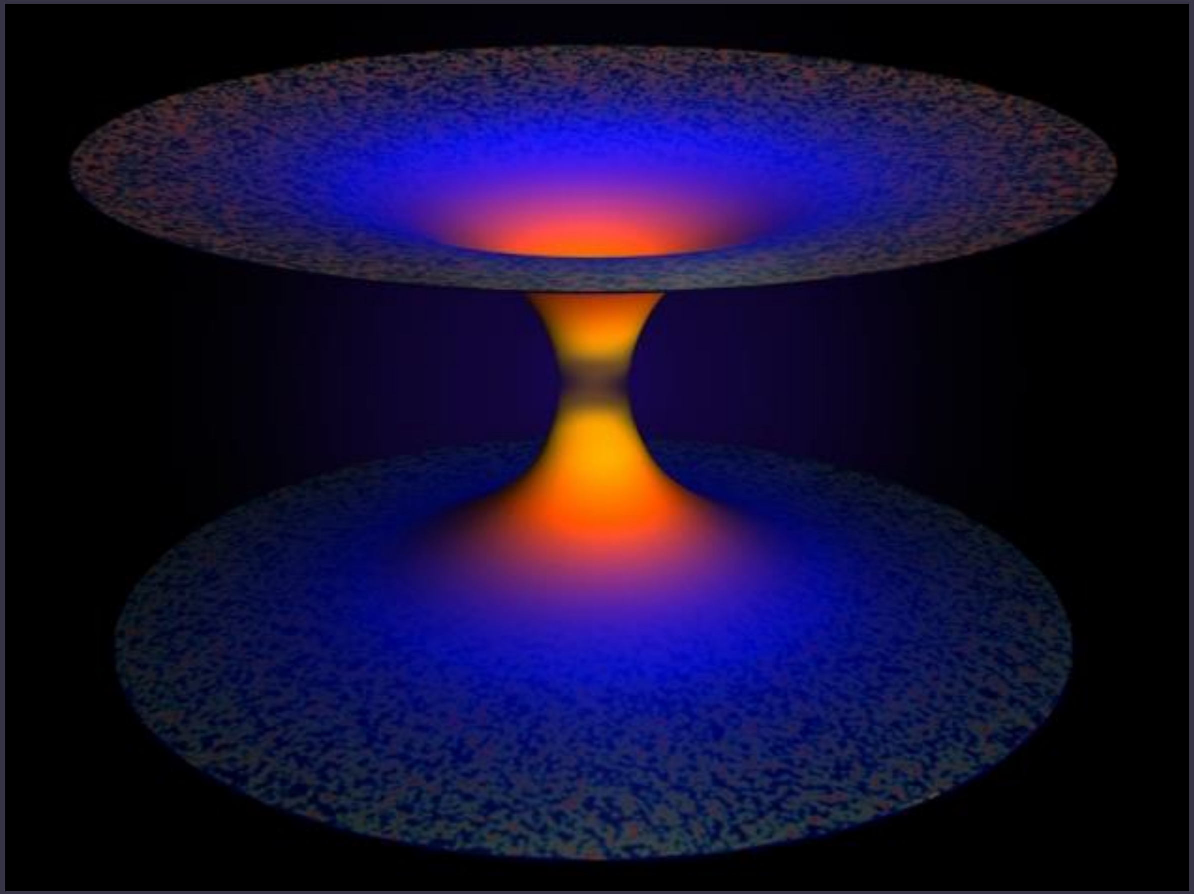
Collapse can be accompanied by a SN-like event, short GRB and a GW burst.
Double-peaked events can also appear in this scenario.



“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.

1409.4031

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.

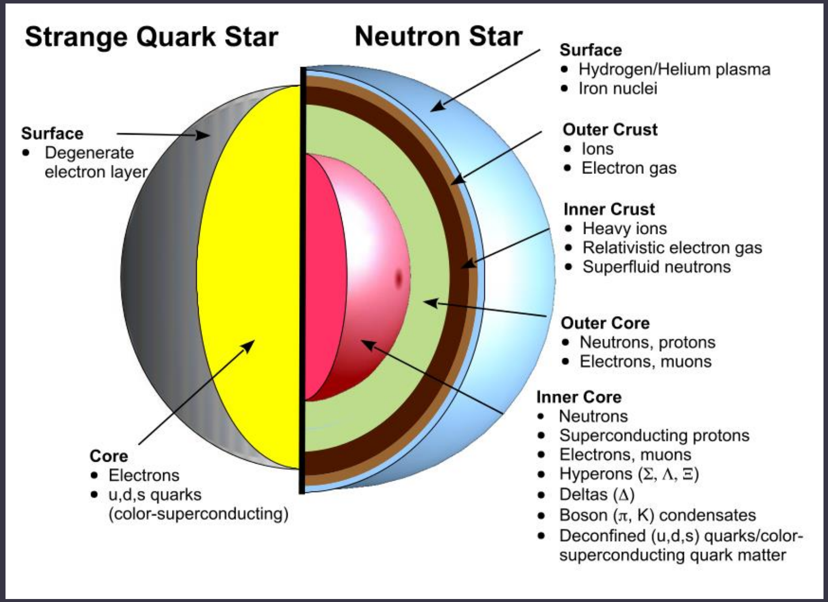
A cluster can be more compact due to formation of Bose-Einstein condensate.
Then, the size can be ~few hundred km, this corresponds to expected size of emitting region in FRB sources (duration multiplied by the velocity of light).
Mass of such compact cluster can be about the mass of the Earth!

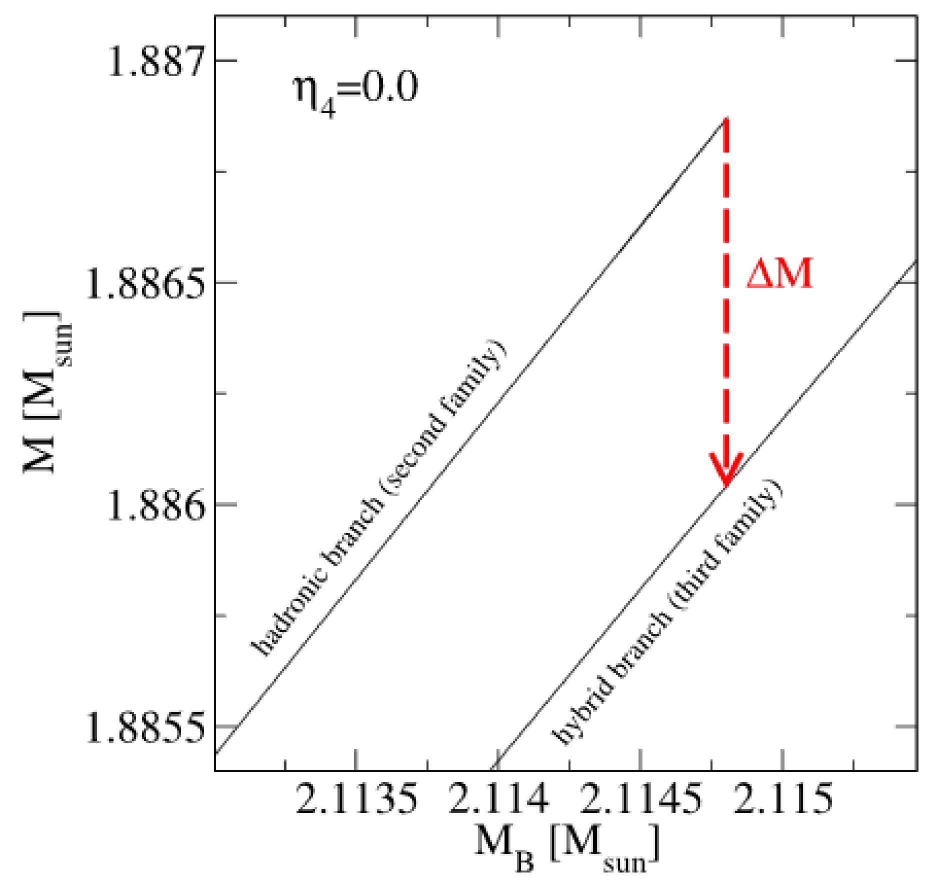
When such cluster flies into a NS magnetosphere then due to the Primakoff effect axions start to be converted into photons.
Thus, a flare of electromagnetic radiation is generated.

1411.3900, 1410.4323, 1512.06245, 1707.04827

Deconfinement – formation of a quark star

http://astrobites.org





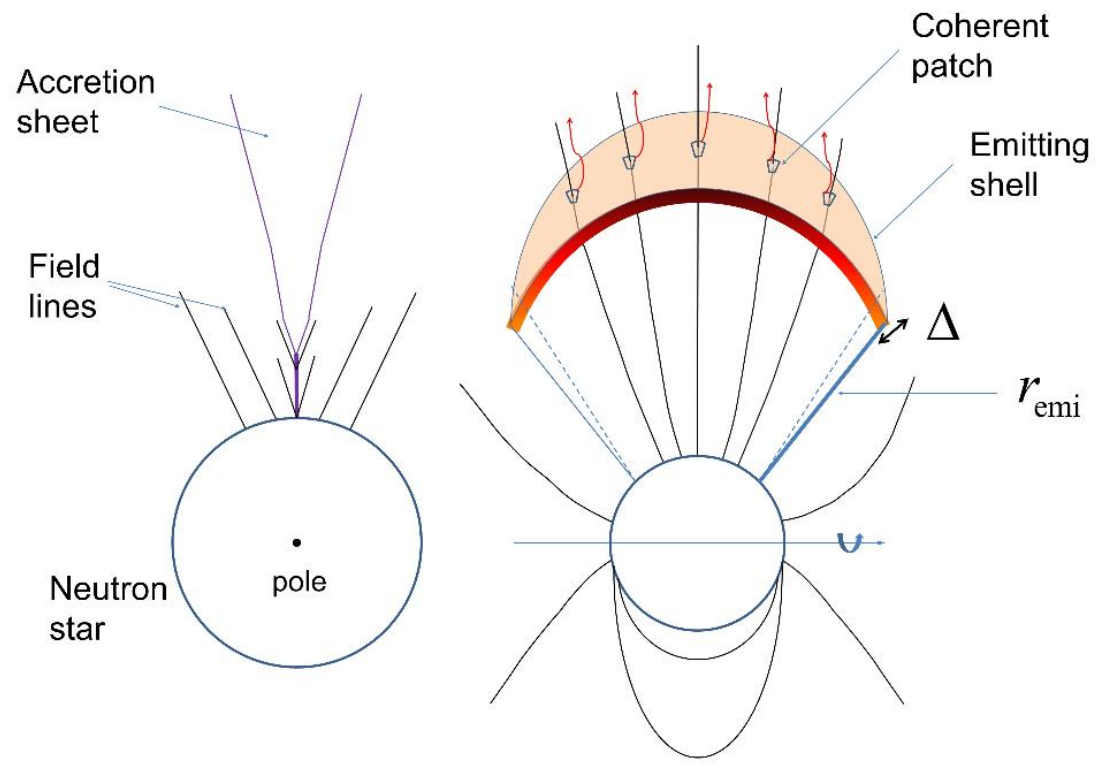
1506.08645

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.

Summary of early ideas

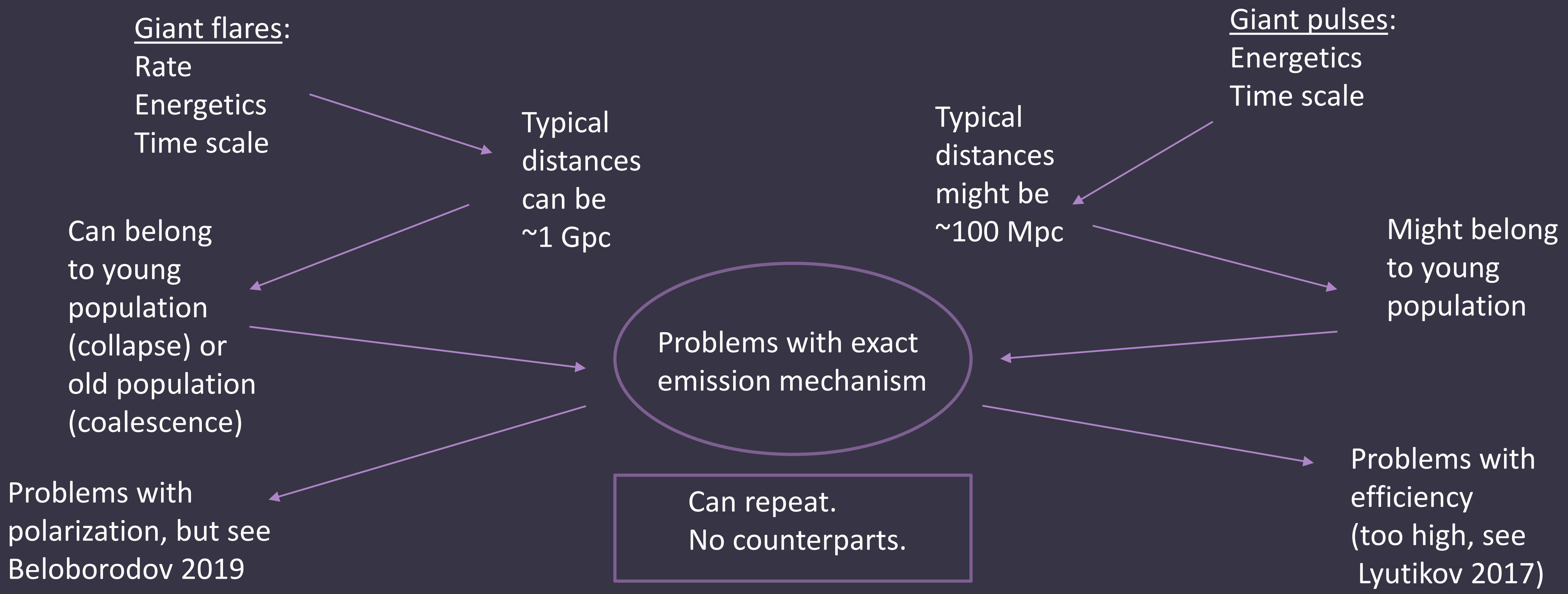
~~Exotics: strings, axions,~~
~~white holes, etc.~~

~~Catastrophic events:~~
~~SN, GRBs, coalescence, …~~

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

Mainstream:
magnetars and pulsars

Magnetars or/and Pulsars



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.

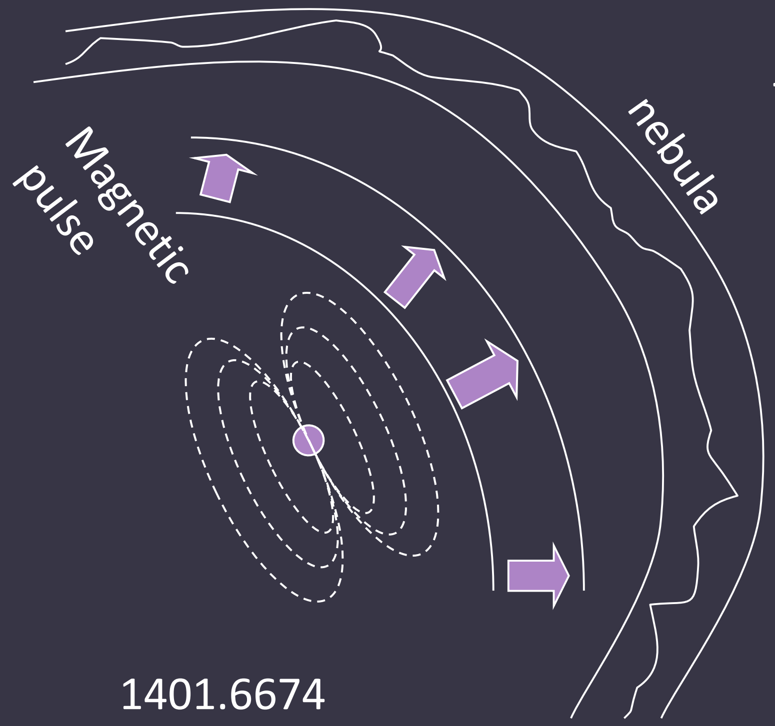
Giant pulses:
Energetics
Time scale

Typical
distances
might be
~100 Mpc

Might belong
to young
population

Problems with
efficiency
(too high, see
Lyutikov 2017)

Magnetar model



1401.6674

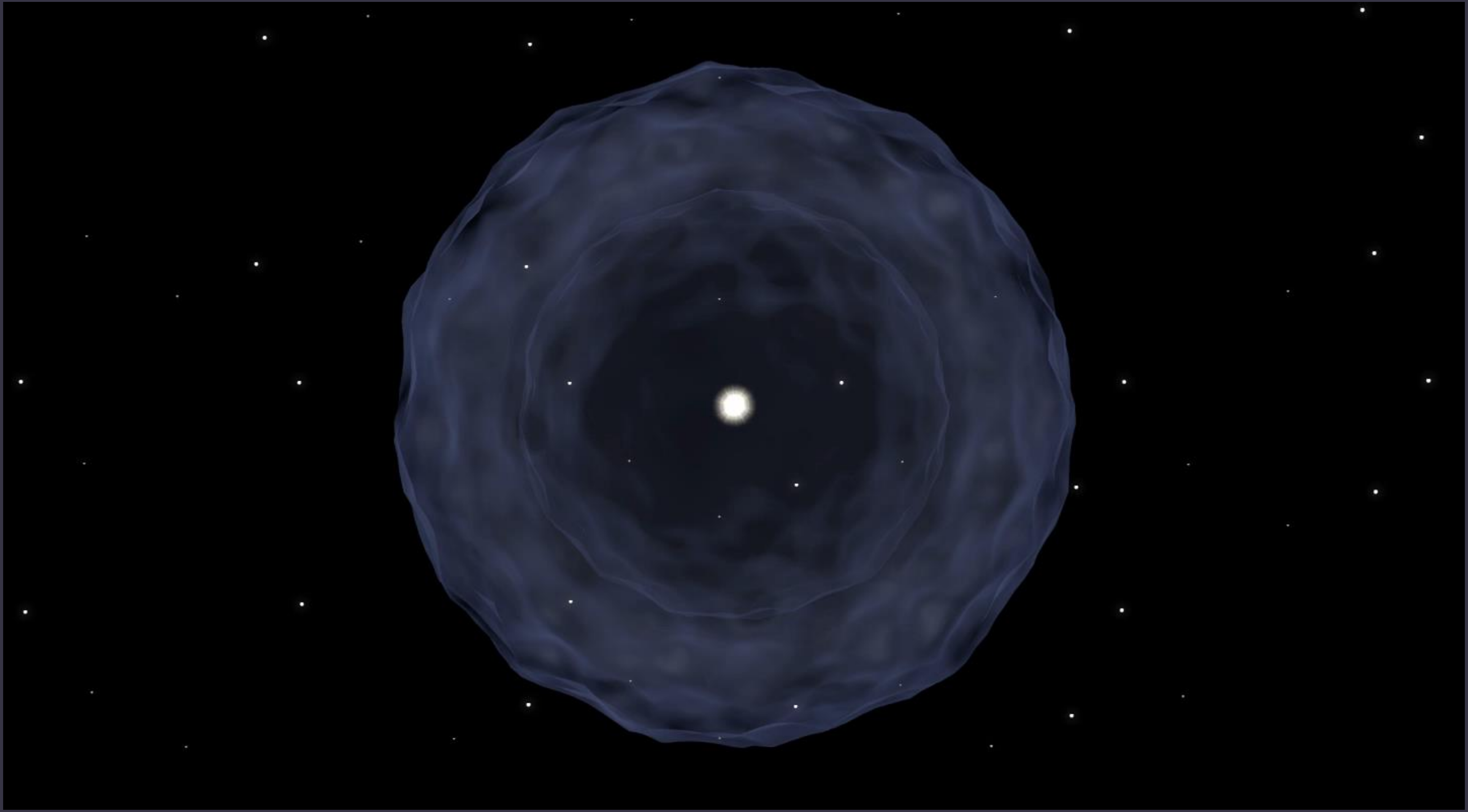
The first idea of possible connection between FRBs and magnetars has been proposed already in 2007: arXiv 0710.2006.

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

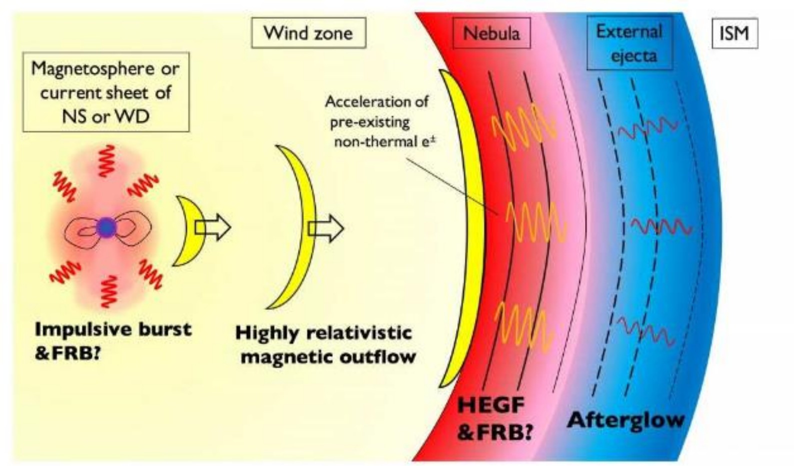
FRB bursts might be related to giant flares of magnetars

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.

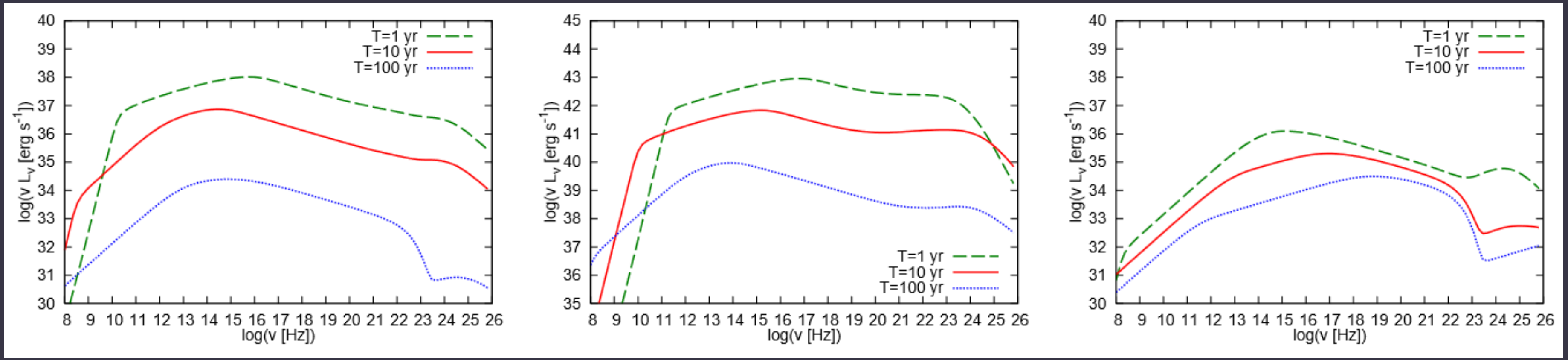


Nebula emission



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

1603.08875



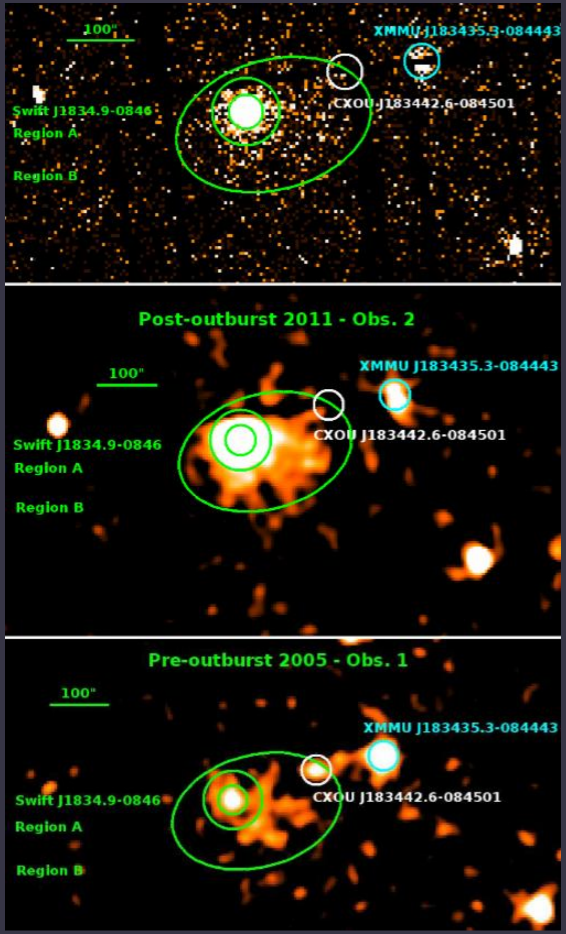
Magnetar

RNS

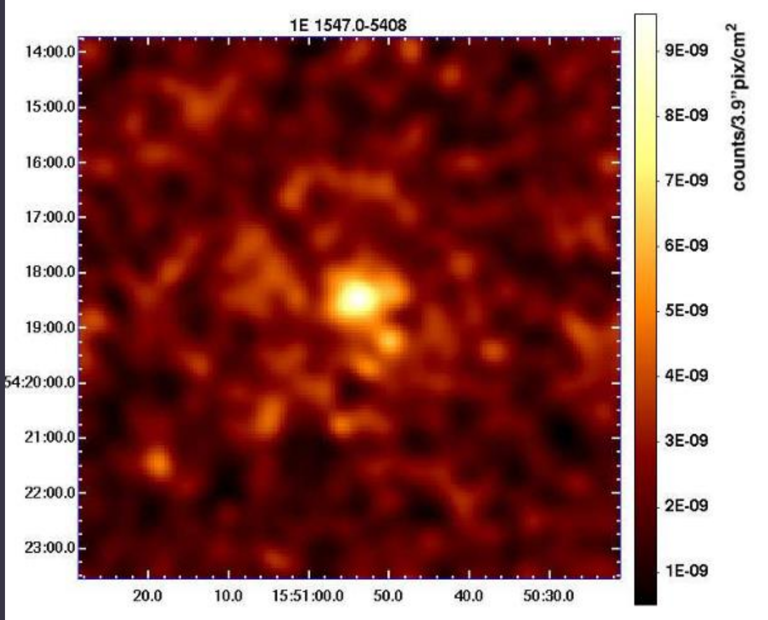
MWD

Nebulae around magnetars

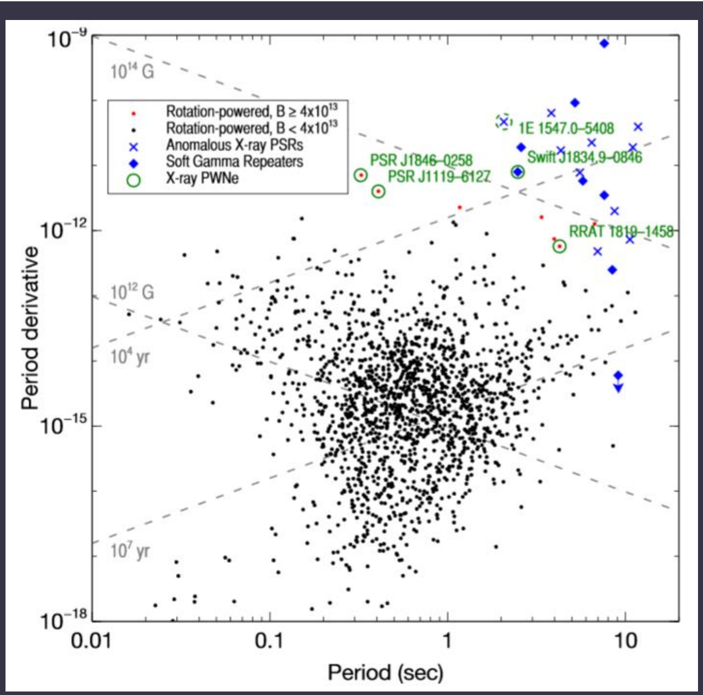
1206.3330. New results in 1604.06472



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

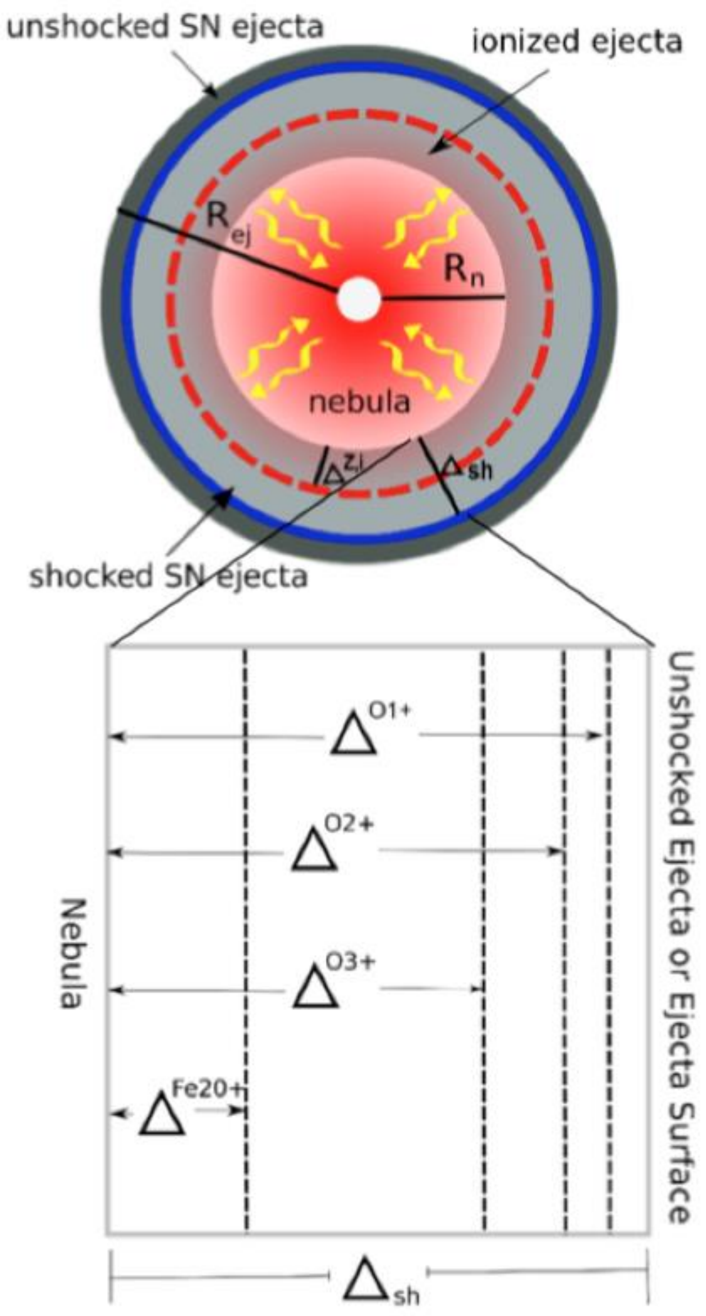


0909.3843



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

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

1701.02370

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

1908.07743

Wind generation

I. From the inner magnetosphere

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

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

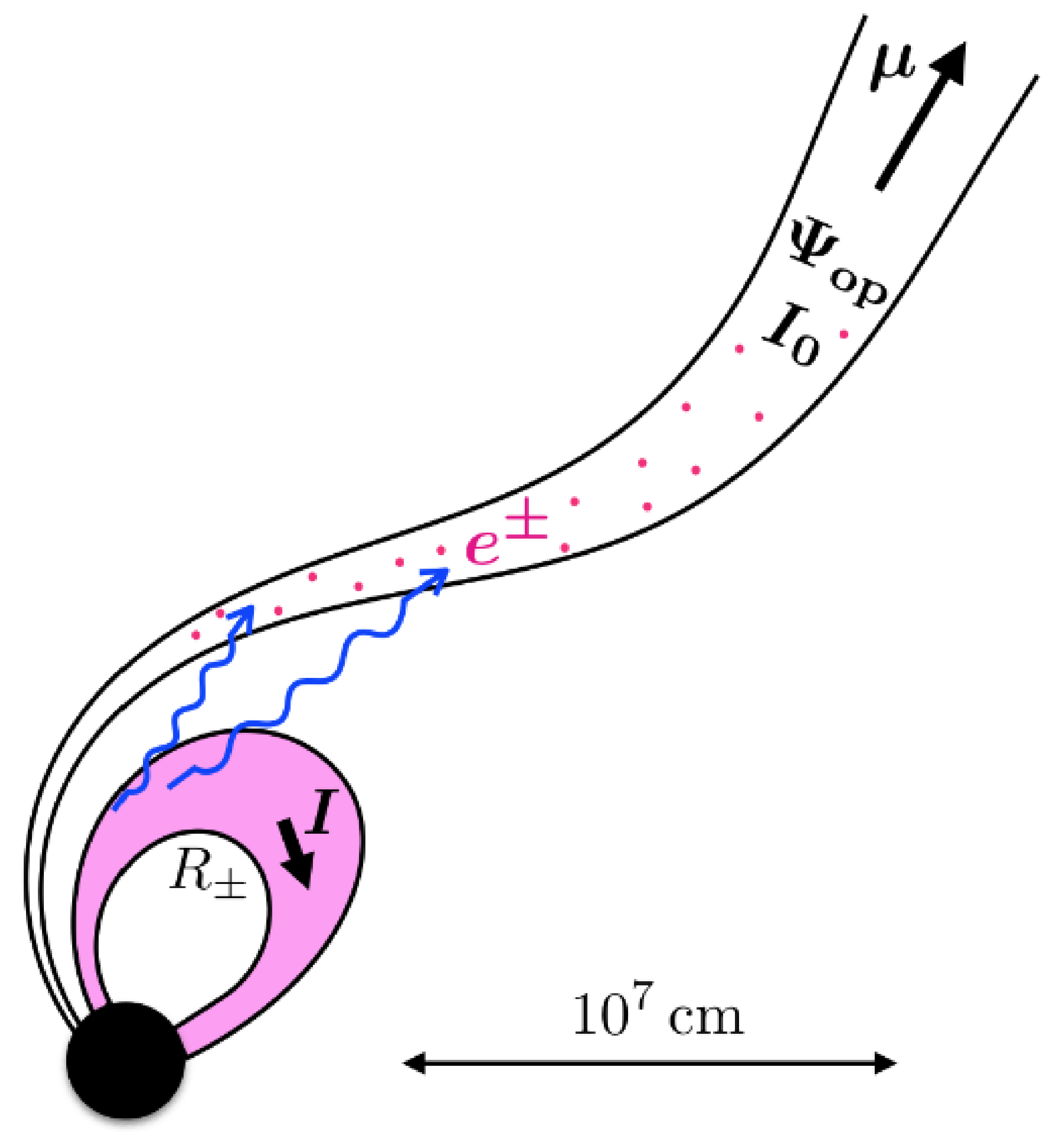
This wind is more favorable for FRB generation.

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

II. From magnetic reconnection

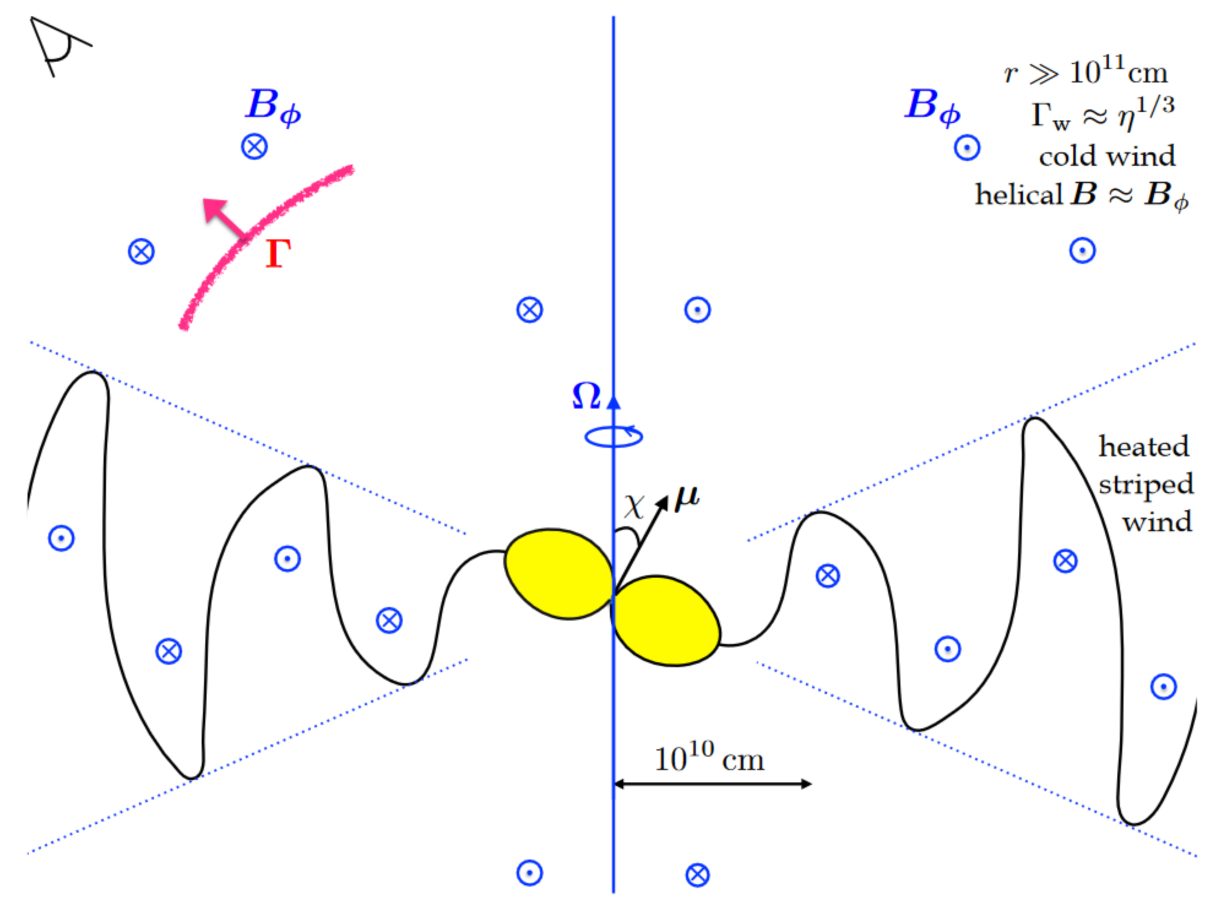
Accelerated particle emit photons, which then are converted into e+/- pairs in the open field line region

Before a giant flare wind is stronger than on average.



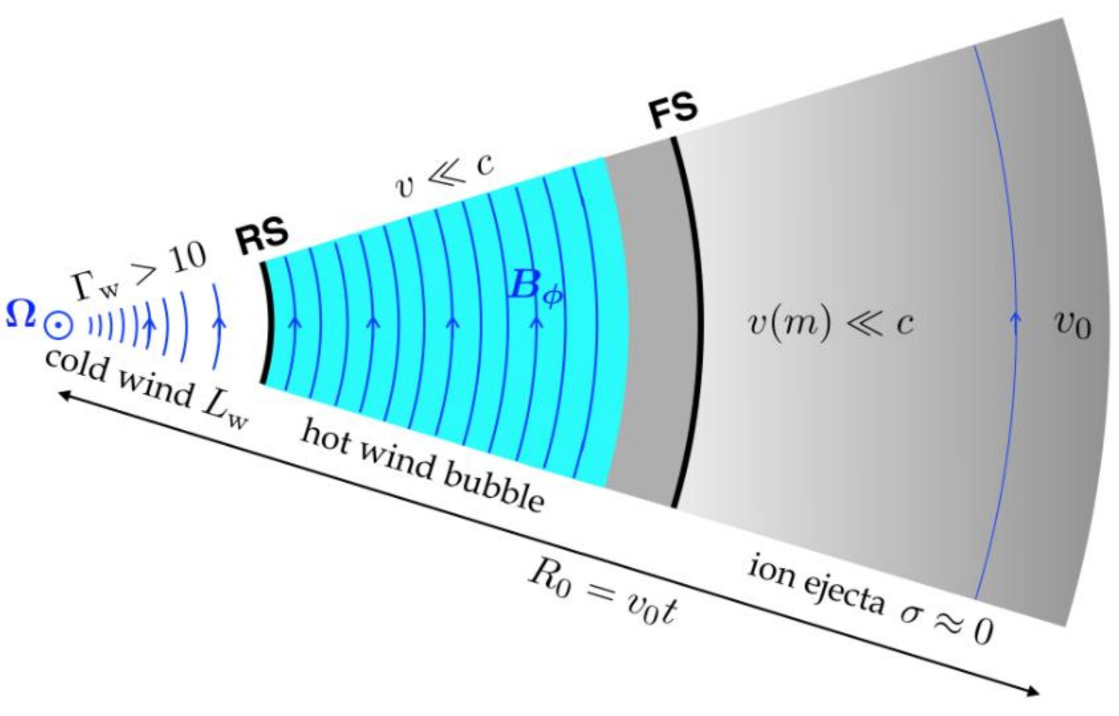
1908.07743

Different winds around a magnetar

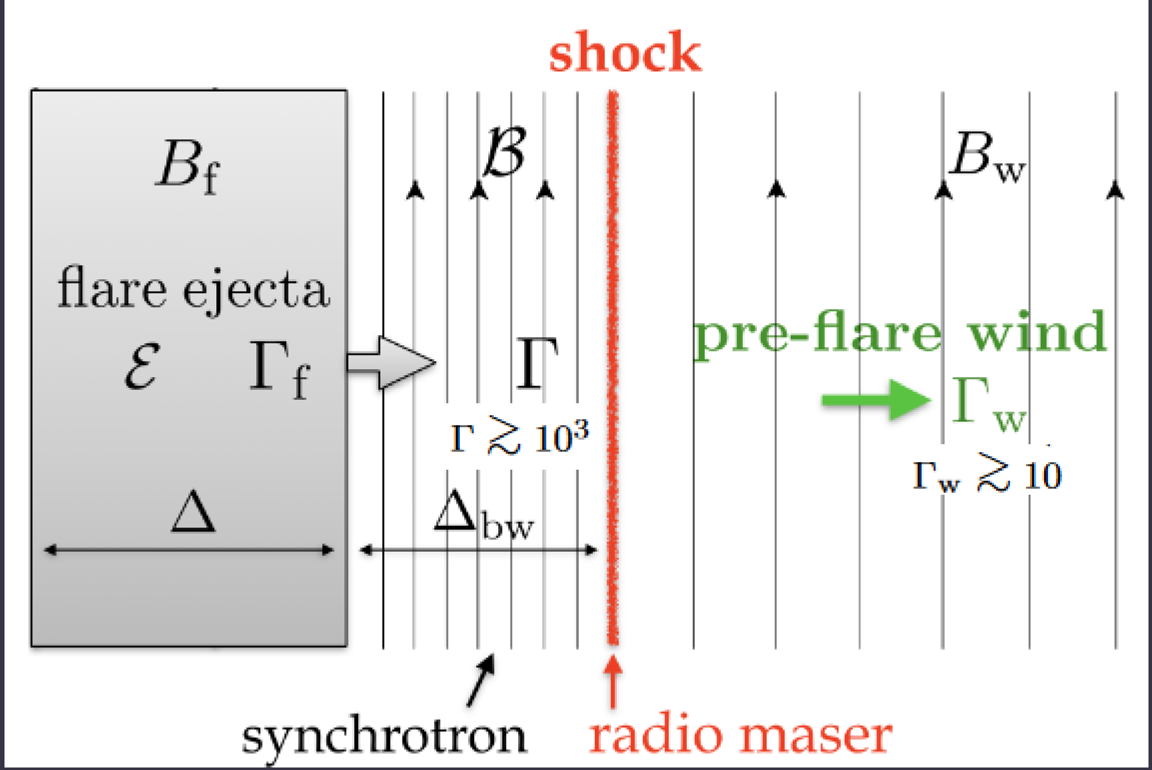


The more probable location of FRB generation is inside the volume filled by the cold helical wind.

Wind interaction with the tail of ion ejecta



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



1908.07743

FRB parameters

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

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

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

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

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

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

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

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

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

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

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

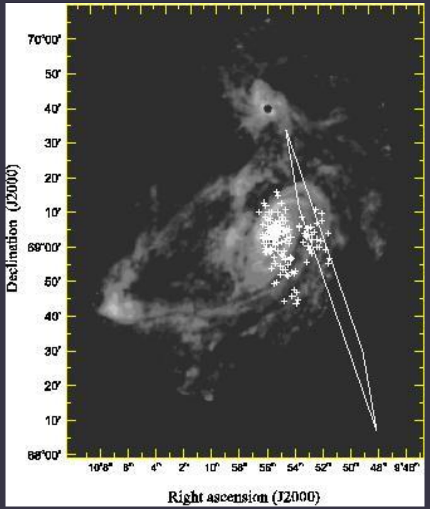
~1 s optical flash with E~10^{44} erg can appear,
if the blast wave interacts with the wind bubble
in the tail of a previous burst.
Rate of such transients can be relatively high.
This is synchrotron emission.
In this case – no FRB (no maser emission).

1908.07743

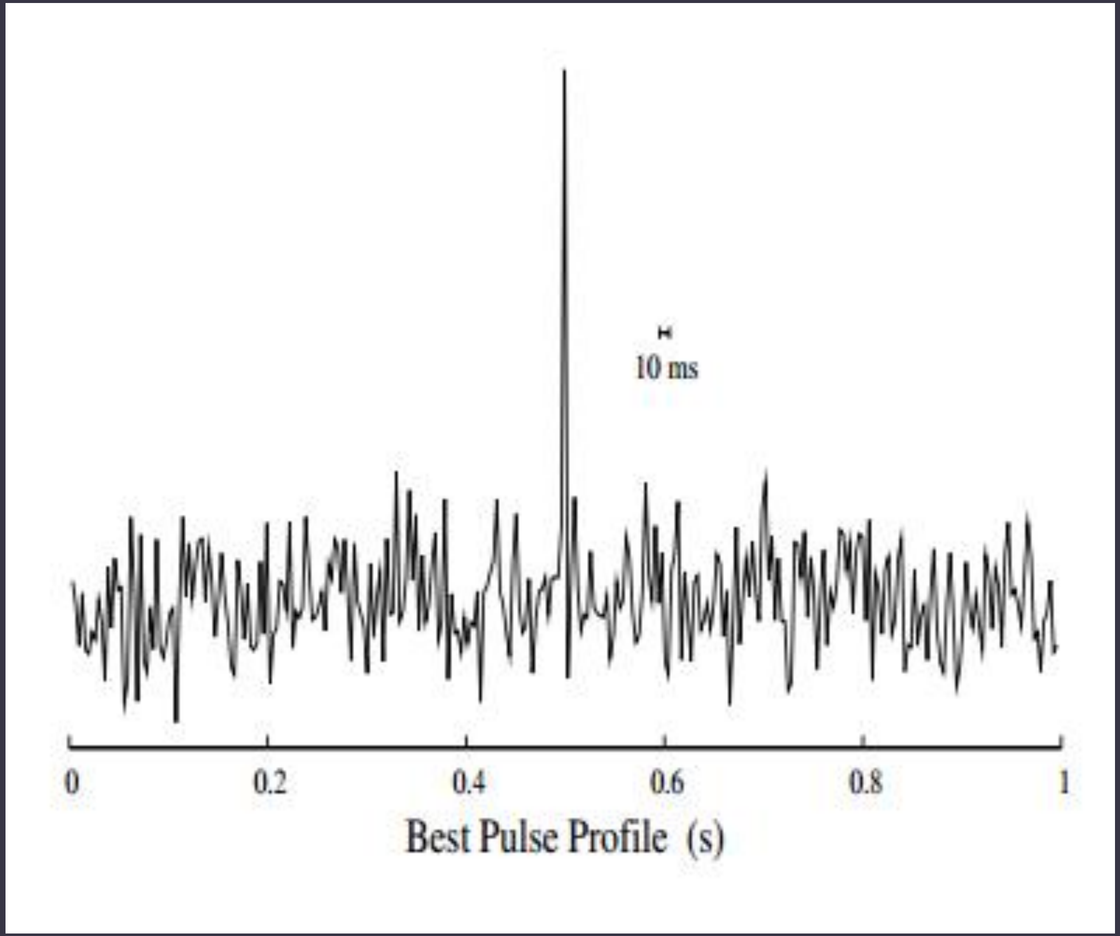
Radio flares from M31

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

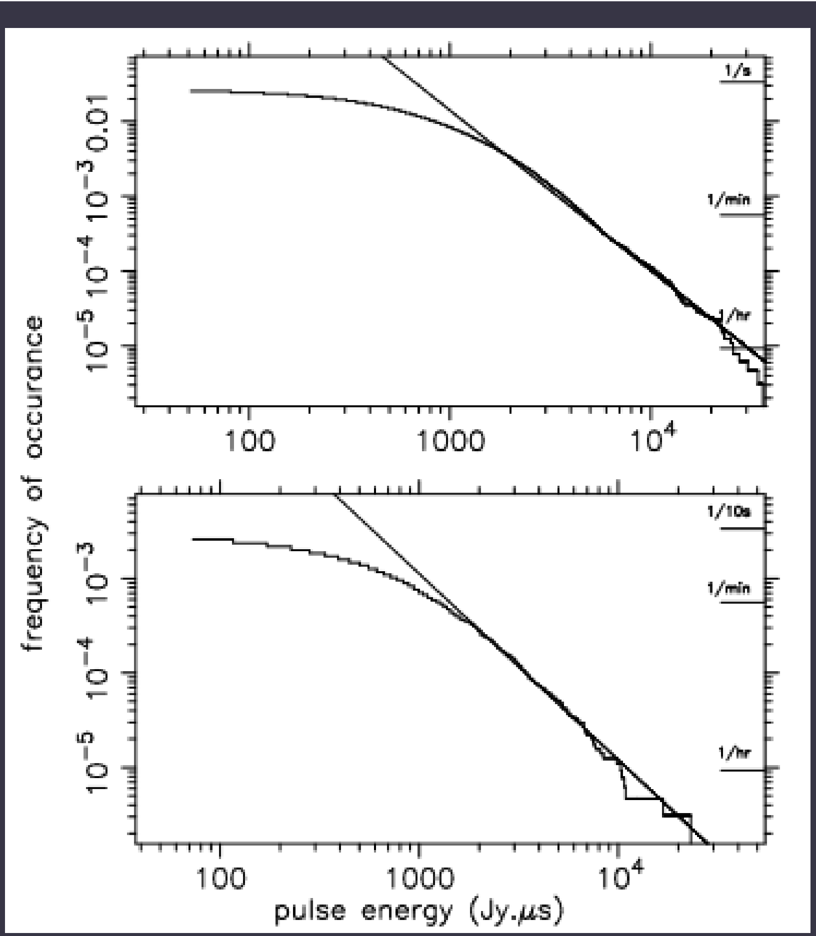
It looks like a scaled version of FRBs.
In the magnetar model such (more frequent) bursts
can be related to weaker flares of magnetars.



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.

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

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

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

1603.02891

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

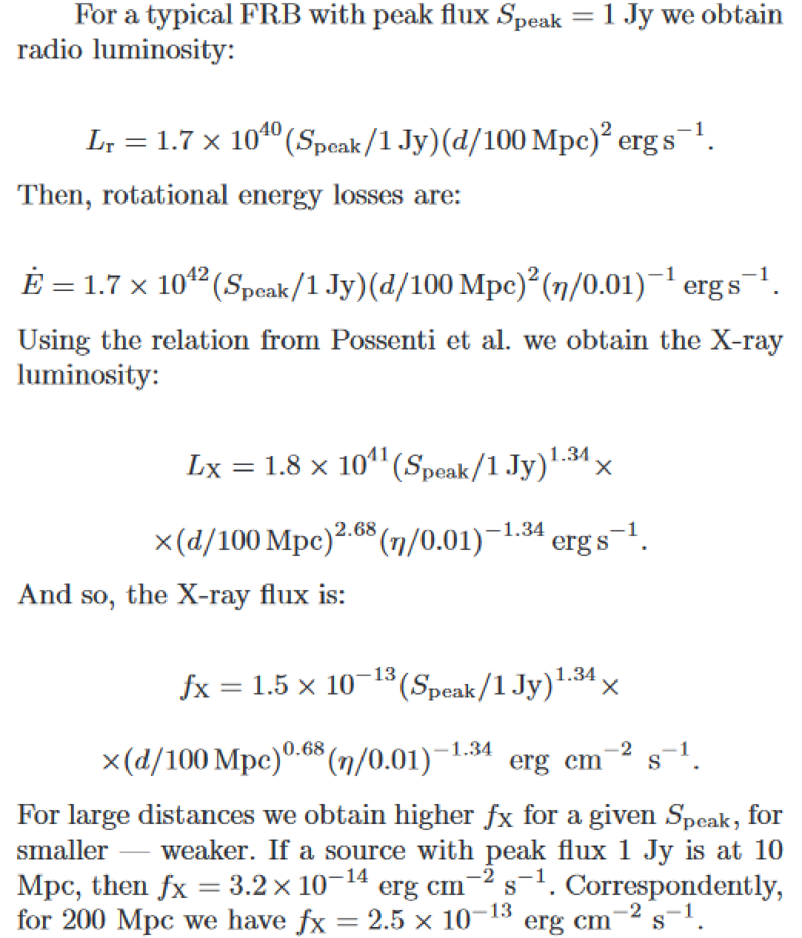
SN rate ~3 10^{-4} yr^{-1} Mpc^{-3} (Dahlen et al. 2012).
This gives ~1 SN per day in 100 Mpc.
Ages and typical lifetime of our sources ~30-100 years.
Thus, we have ~10 000 – 30 000 sources in 100 Mpc.
The observed rate of FRBs ~3 10^3 per day.
Then, each source might give a flare per few days.
If we 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.

1603.02891

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:

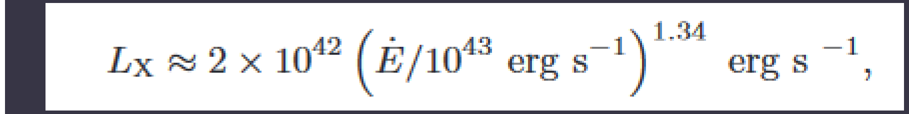
$$f_{\rm X} = 1.5 \times 10^{-13} (S_{\rm peak}/1\,{\rm Jy})^{1.34} \times$$

$$\times (d/100\,{\rm Mpc})^{0.68} (\eta/0.01)^{-1.34}\ \ {\rm erg\ \ cm^{-2}\ \ s^{-1}}.$$

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

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

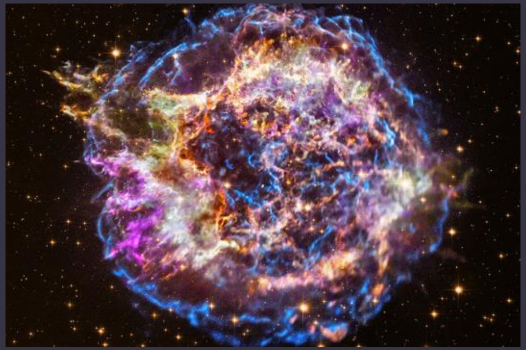
$$\left(\frac{B_{FRB}}{B_{Crab}}\right)\left(\frac{P_{FRB}}{P_{Crab}}\right)^{-2} \approx 500$$

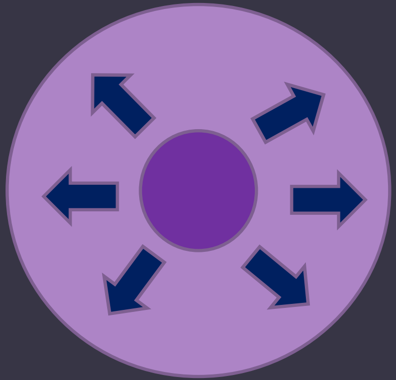
$$\nu F_\nu = \eta \frac{L_{sd}}{4\pi D^2}$$

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

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.

1701.02003

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

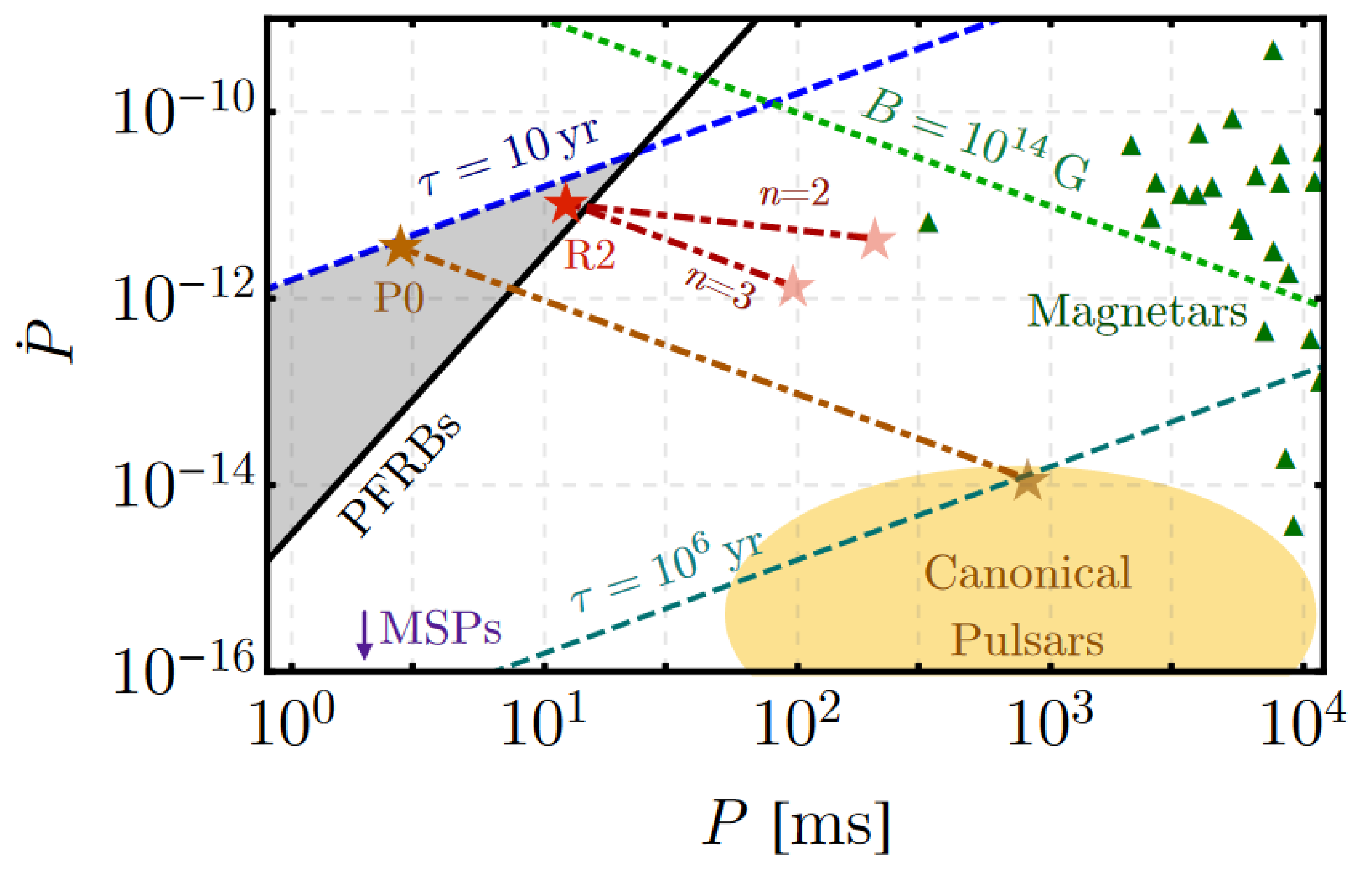
- Population of FRBs can be non-uniform, i.e. more than one scenario can realize in Nature

Experimentum crusic

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

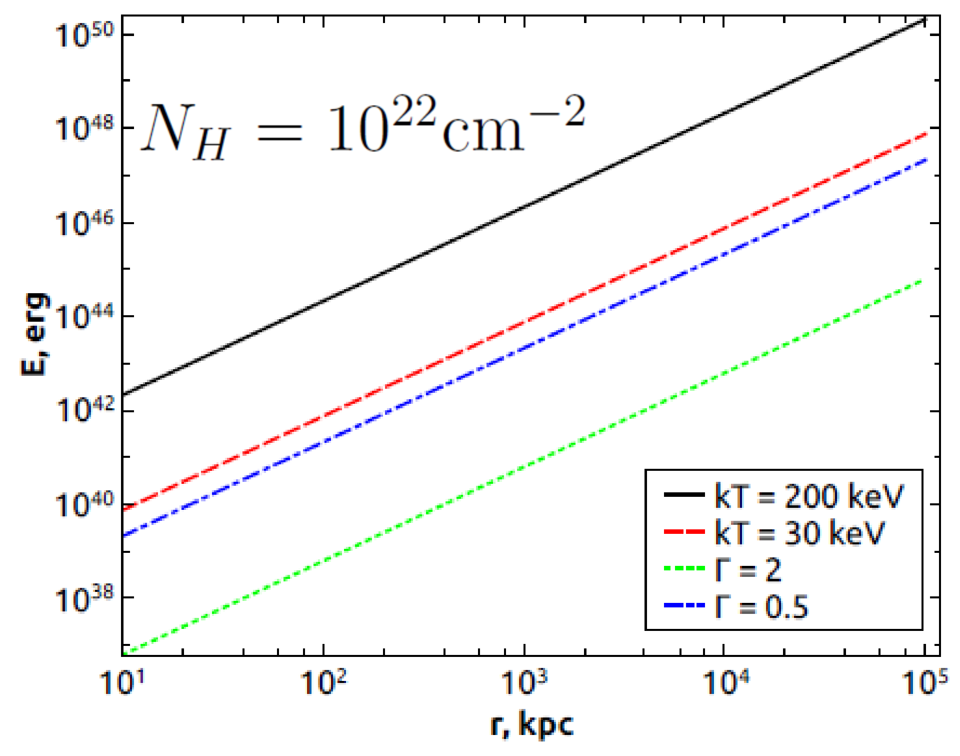
II). Relation to older (~10 years at least) SN.

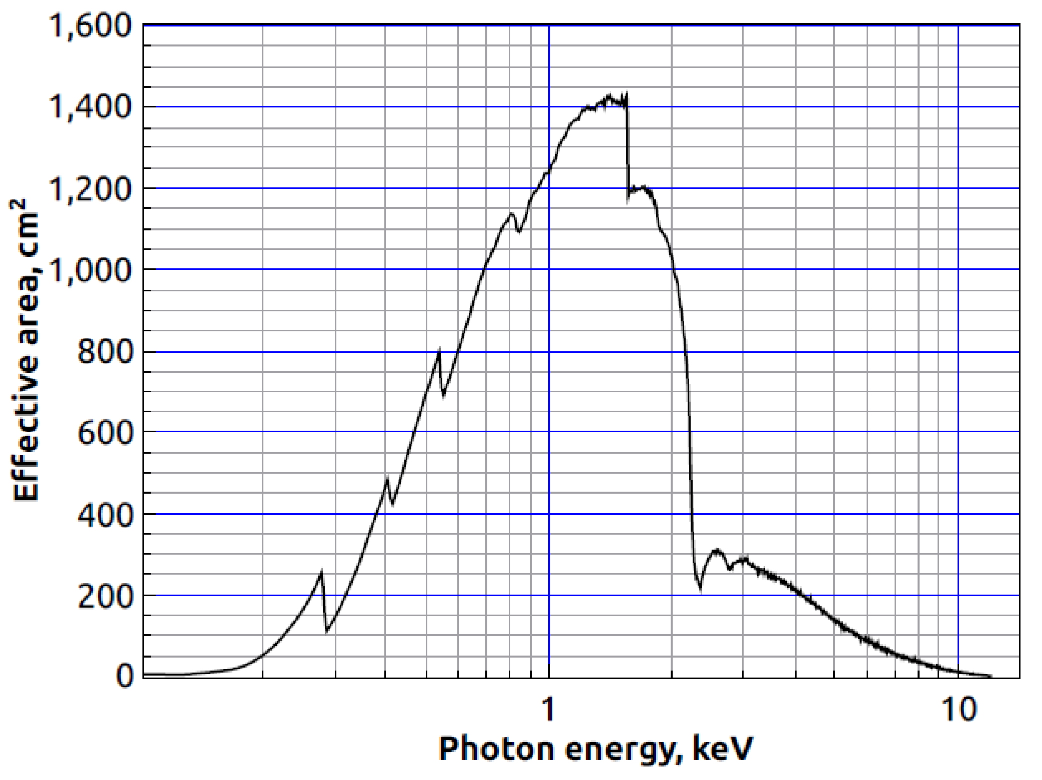
III). Counterparts (X-rays, or may be TeV and optics)



1909.00004

FRB with eROSITA?





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

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

1903.10991

Future observations

FAST – burst per week

1602.06099

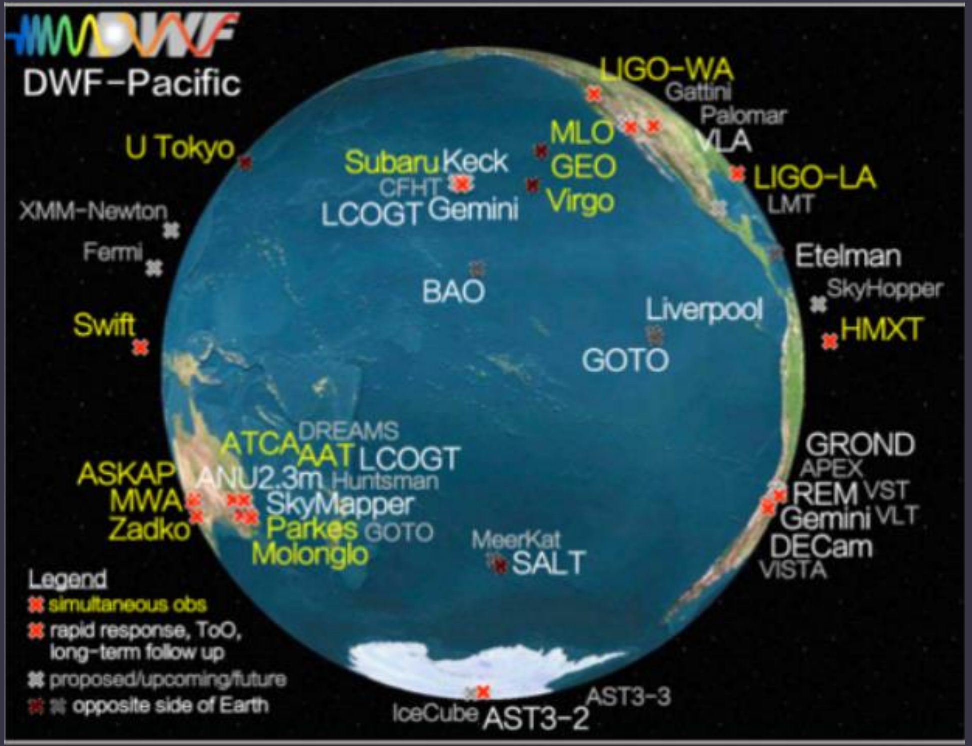
SKA – burst per hour!

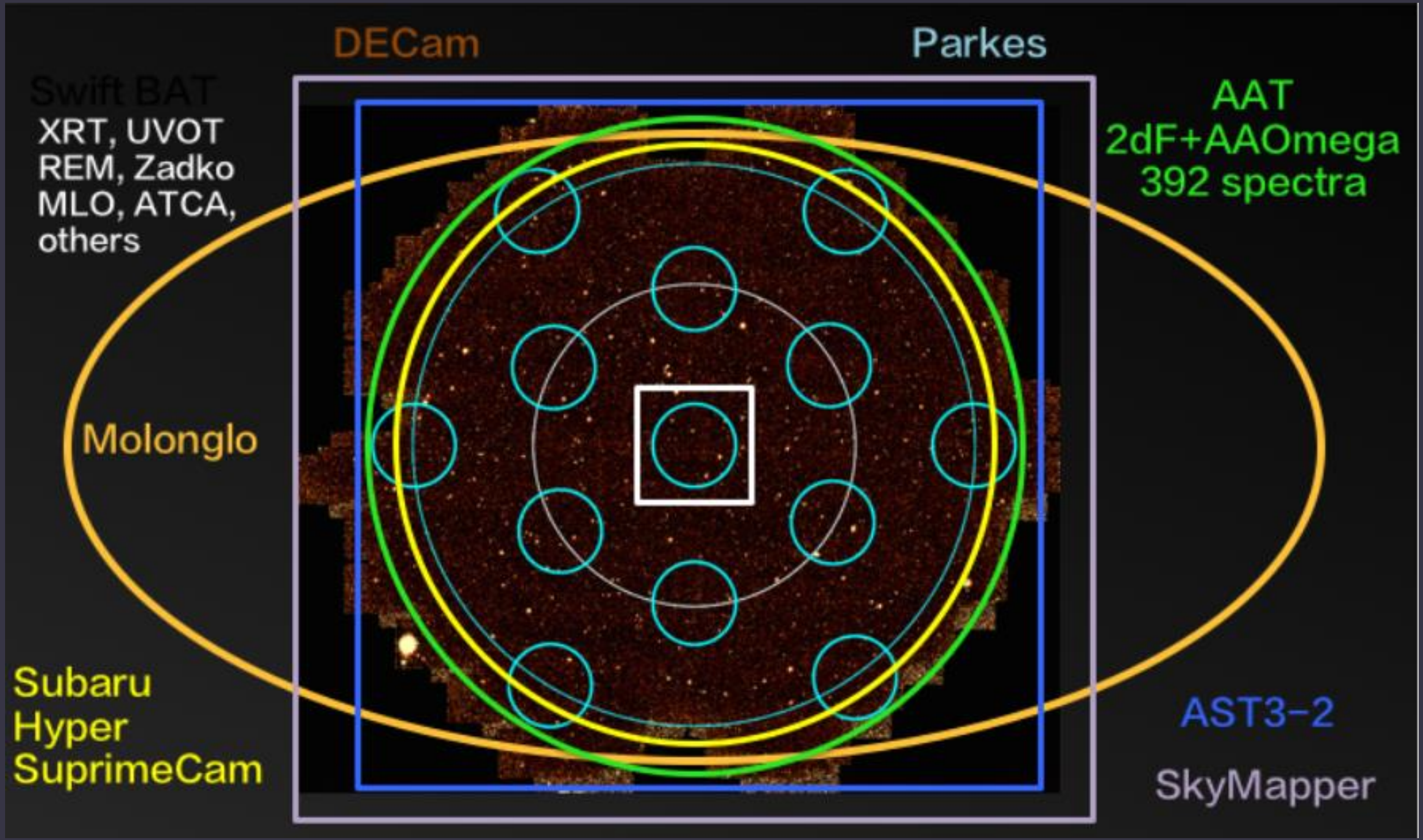
1602.05165, 1501.07535

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

Multi-messenger searches

Deeper Wider Faster





1802.01100

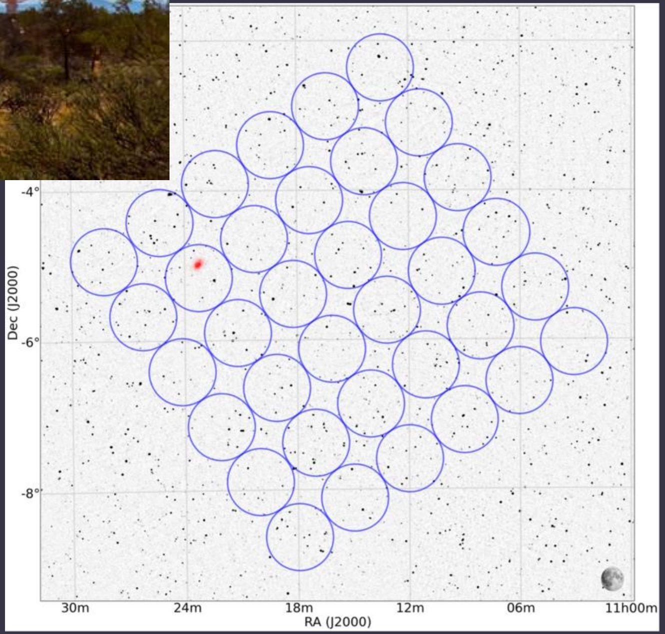
http://dwfprogram.altervista.org/

ASKAP and Apertif

ASKAP

Few bursts per week.
1709.02189

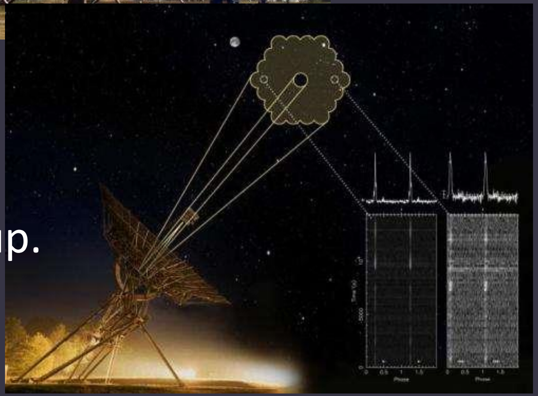
ASKAP reported 20 new FRBs in October 2018
1810.04356



Westerbork

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

1709.06104



Summary of observations

Main reviews: 1806.03628, 1810.05836,
1906.05878, 1904.07947

In catalogue (01/09/2019) frbcat.org
90 bursts (11 repeaters)
3 localized.

9 with polarization data (8 – linear, 6 – circular)
RM for 6 (+3 consistent with 0 within errors)
Max flux: 160 Jy
DM max: 2600; DM min: 100

56 out of 90 detected at ~1.4 GHz.
10 at ~800-840 MHz (9 at UTMOST, 1 at GBT)
21 at ~600 (CHIME), and 3 (?) at 111 (Puschino)