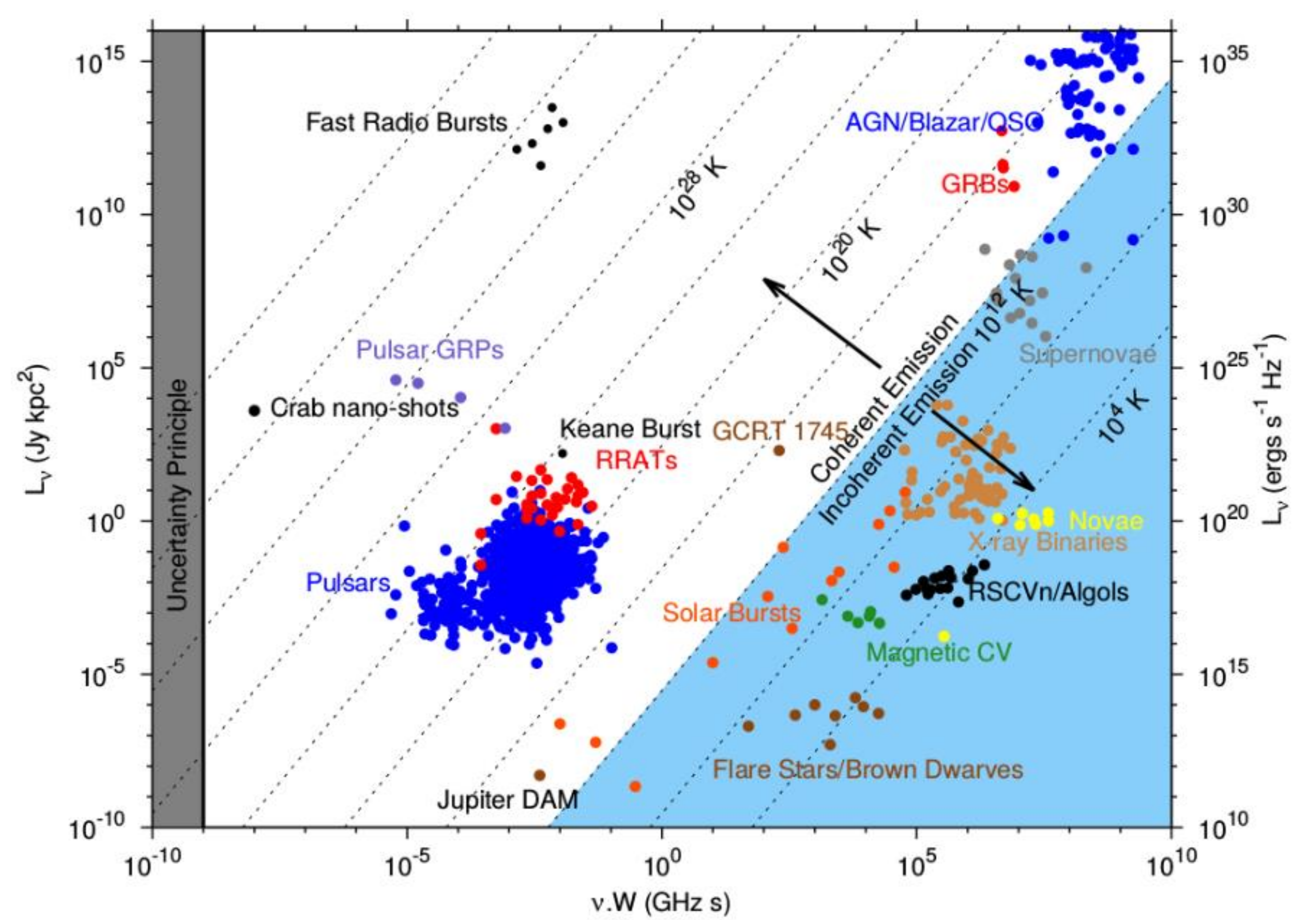
Fast radio bursts: puzzles and fundamental physics

SERGEI POPOV (ICTP, TRIESTE)

Radiotransients



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

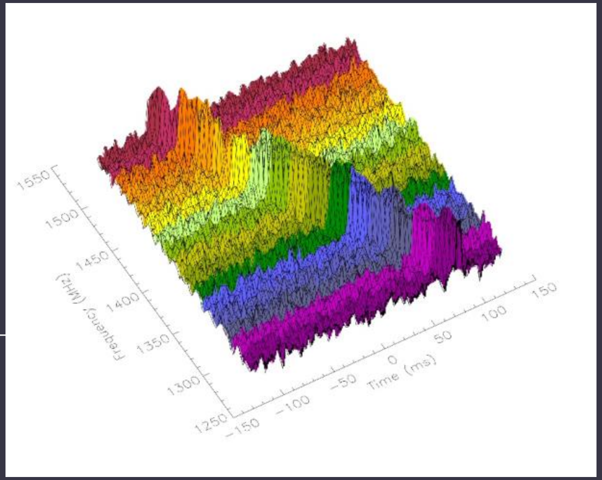
However, detection of very short and non-repeating flares of unknown sources without identification at other bands is a very complicated task.

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

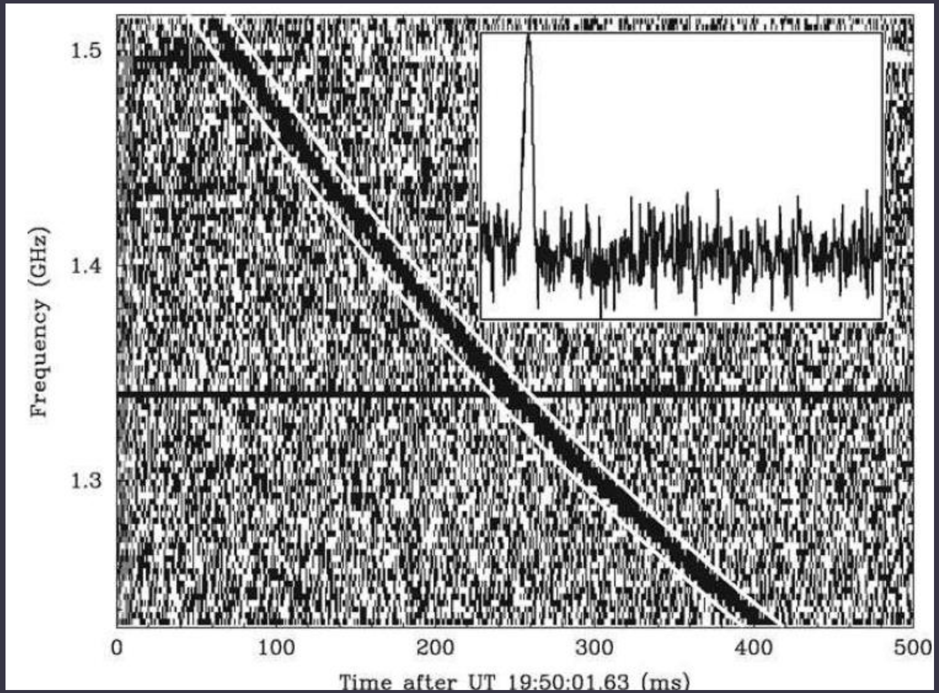
In 2007 the first example of a new class of millisecond radio transients have been announced: the first extragalactic millisecond radio burst.

1507.00729, 1411.1067

Millisecond extragalactic radio bursts



Science 318, 777 (2007)



Discovered in 2007.

Origin - unknown.

One of the most interesting discoveries in the XXIc.

No coincident bursts in other wavelengths.

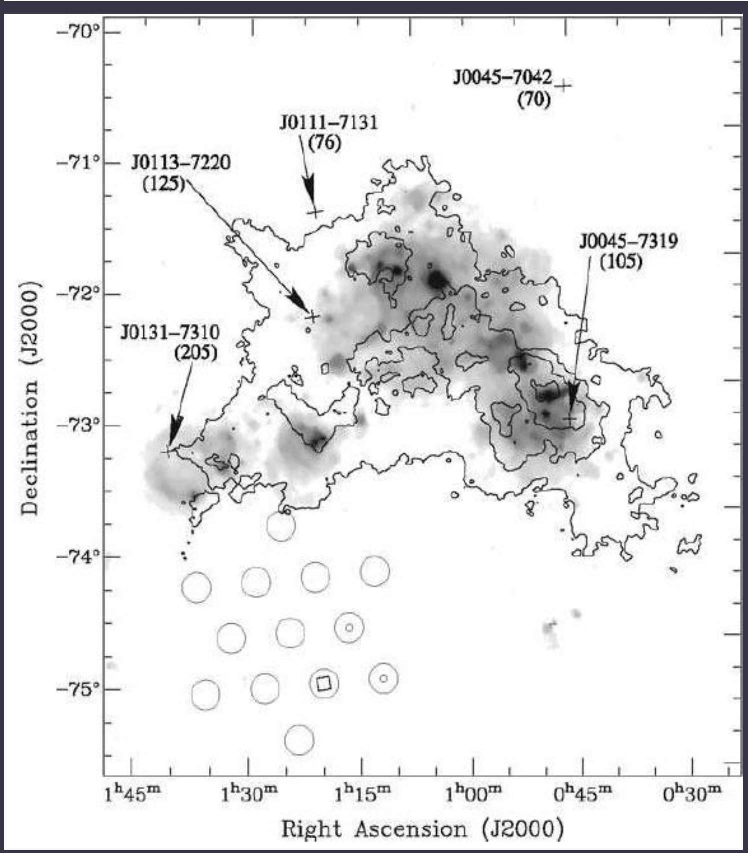
No source identification.

[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.

The first event

Science 318, 777 (2007)



Discovered at Parkes
by Duncan Lorimer 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

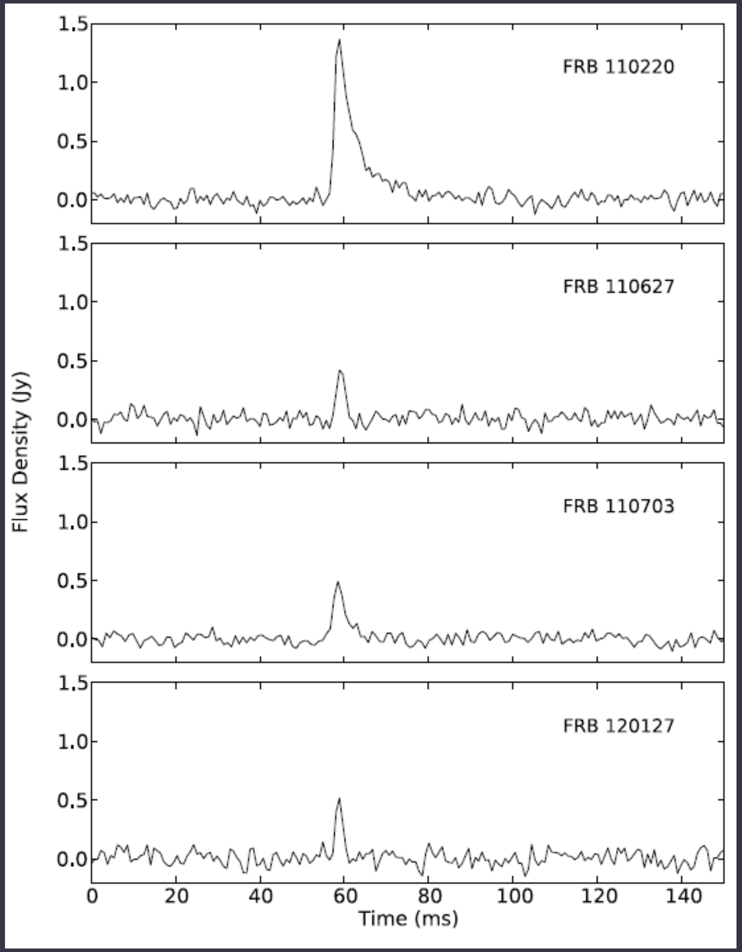
Millisecond radio bursts – definite at last

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

FRBs. Different hypotheses

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

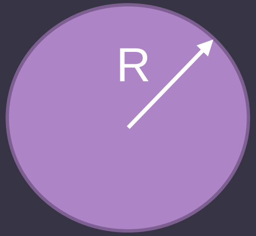
Since 2007 many hypotheses have been proposed.

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



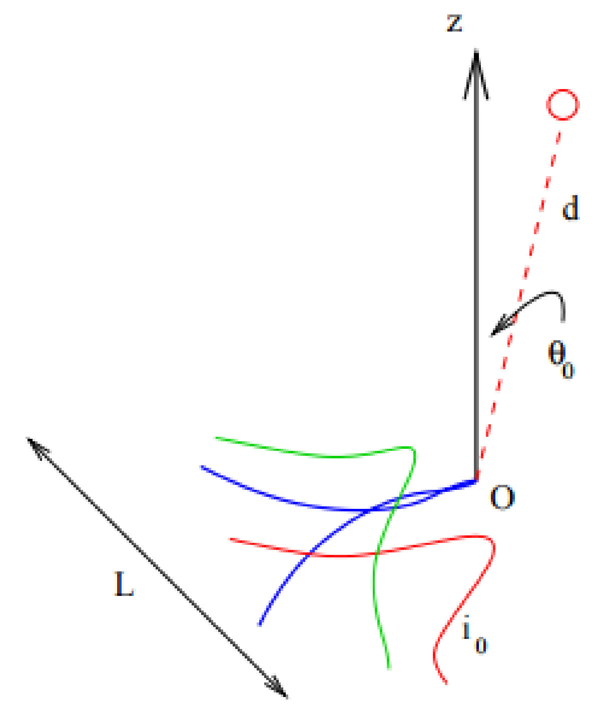
A neutron star has mass ~solar and
radius ~10 km.
This gives free fall velocity $v=(2GM/R)^{1/2}$ ~0.5 c
Free fall time scale $t=R/v< 0.1$ msec
Thus, it is easy to get very short events.
The same is true for BHs.

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

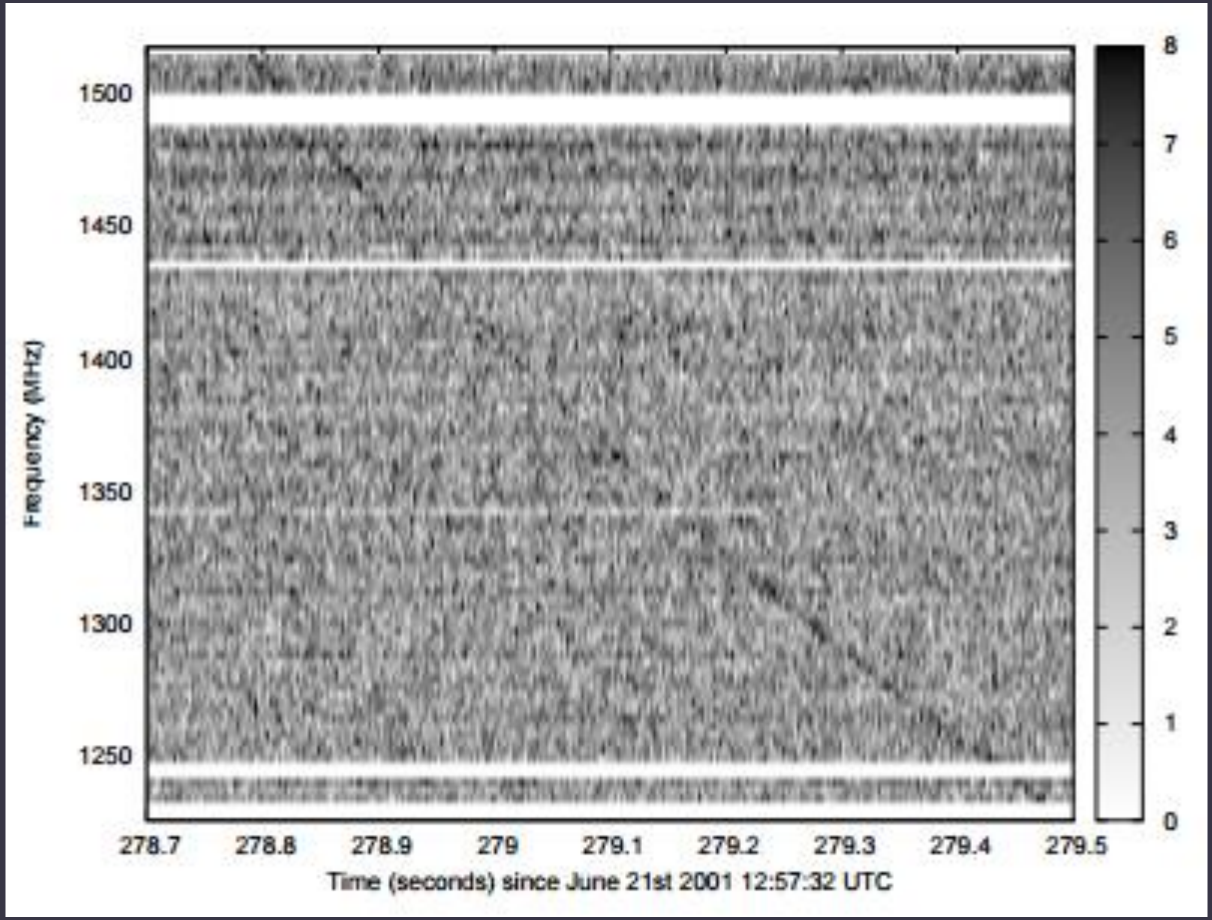


Superconducting strings
Vachaspati 0802.0711

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.

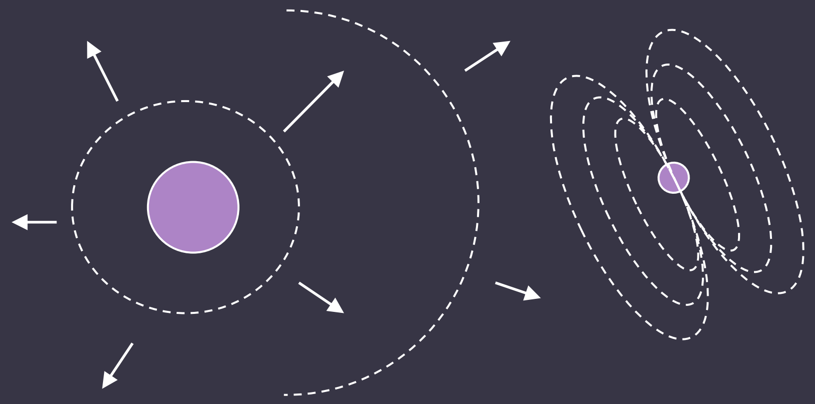
Predicted years ago (Rees 1977).

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

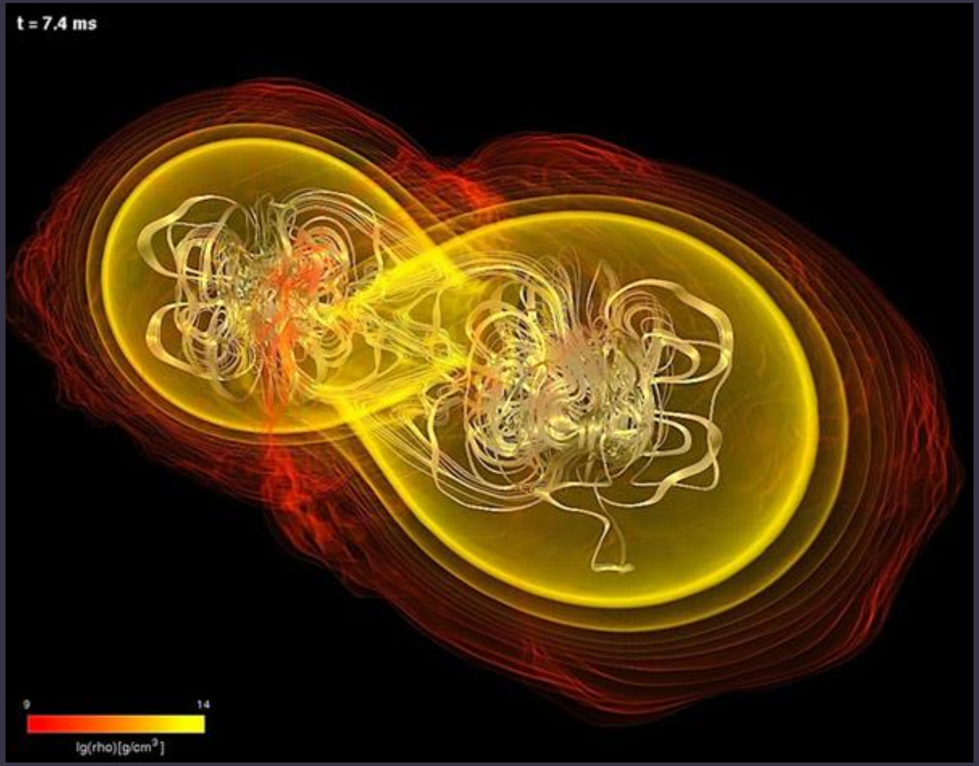


Shock wave after a SN in a close HMXB can interact with the NS magnetosphere forming a magnetotail.

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.

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).

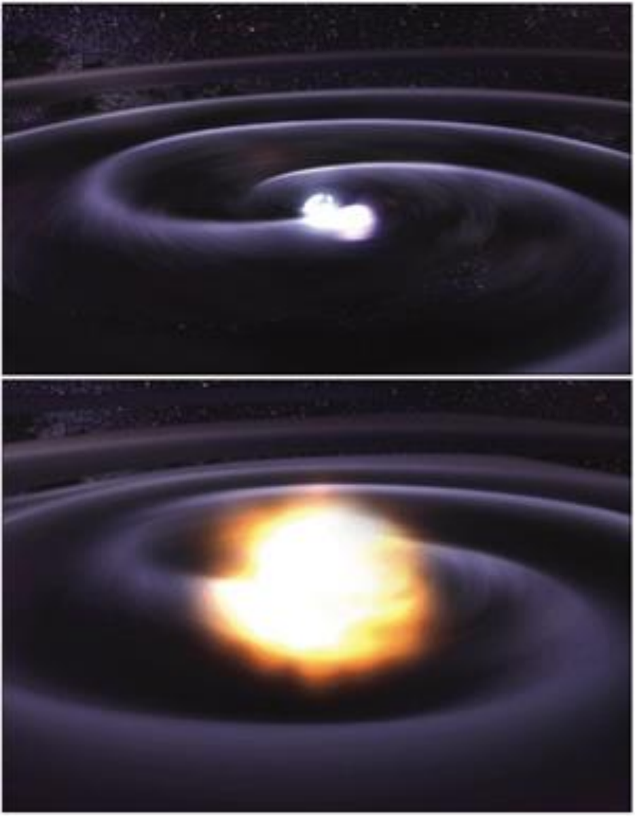
In application to FRBs the first paper is Totani (1307.4985).

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

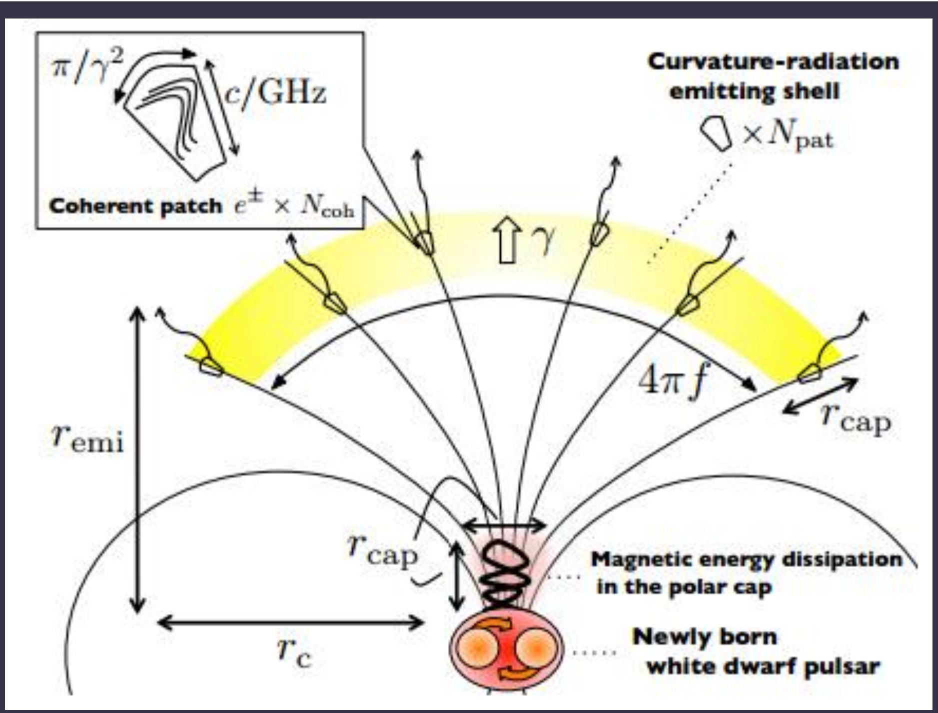
Easy to obtain rapid rotation and strong magnetic field.
But there are many uncertainties.

Might be accompanied by a GW burst.

White dwarf coalescence



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

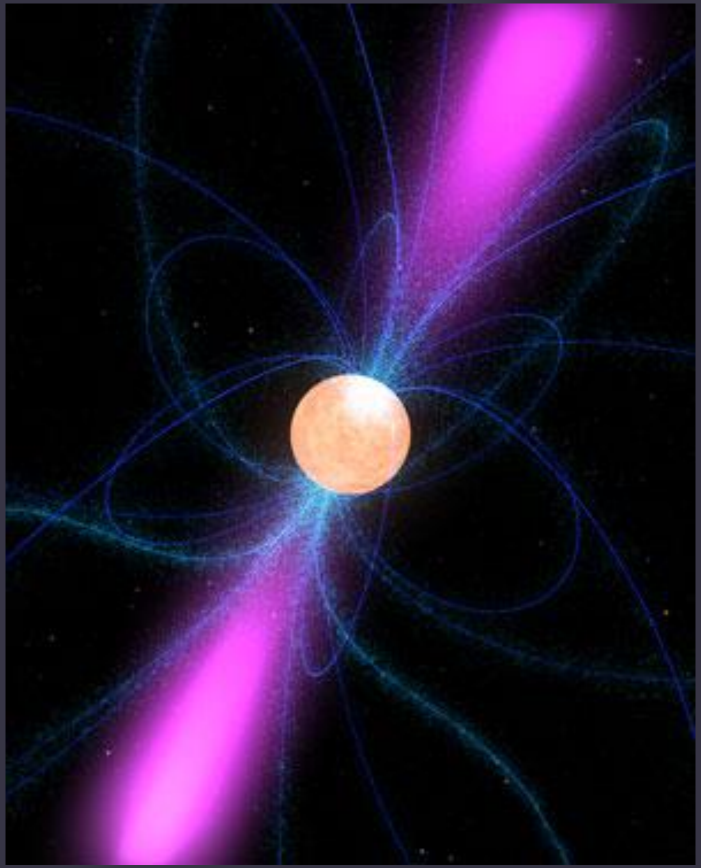


Kashiyama et al. 1307.7708

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

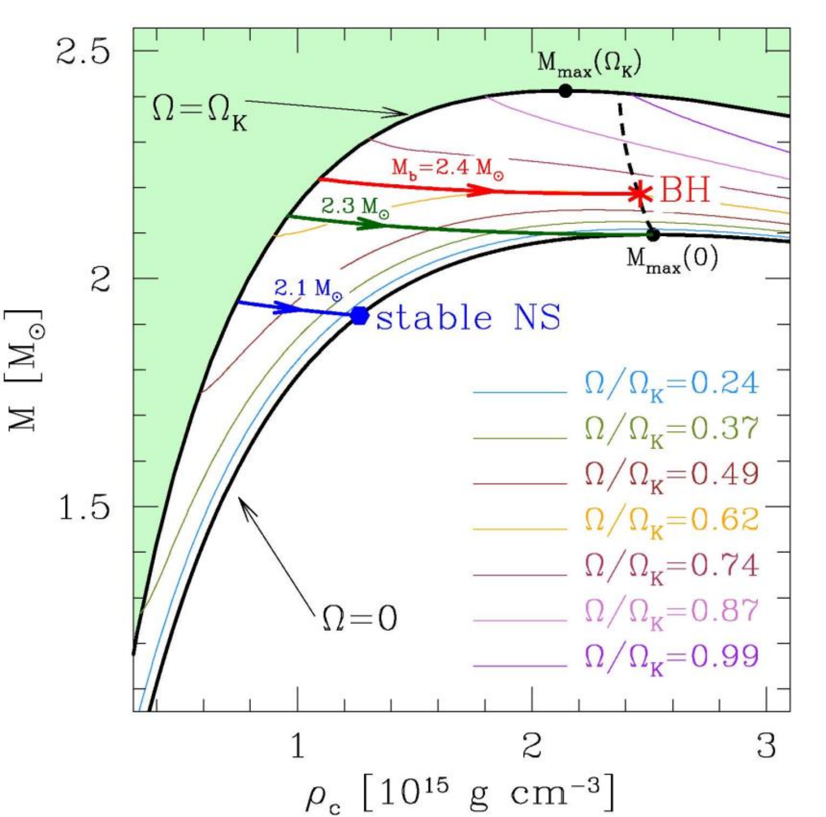


http://www.astro.ru.nl/~falcke/PR/blitzar/

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.

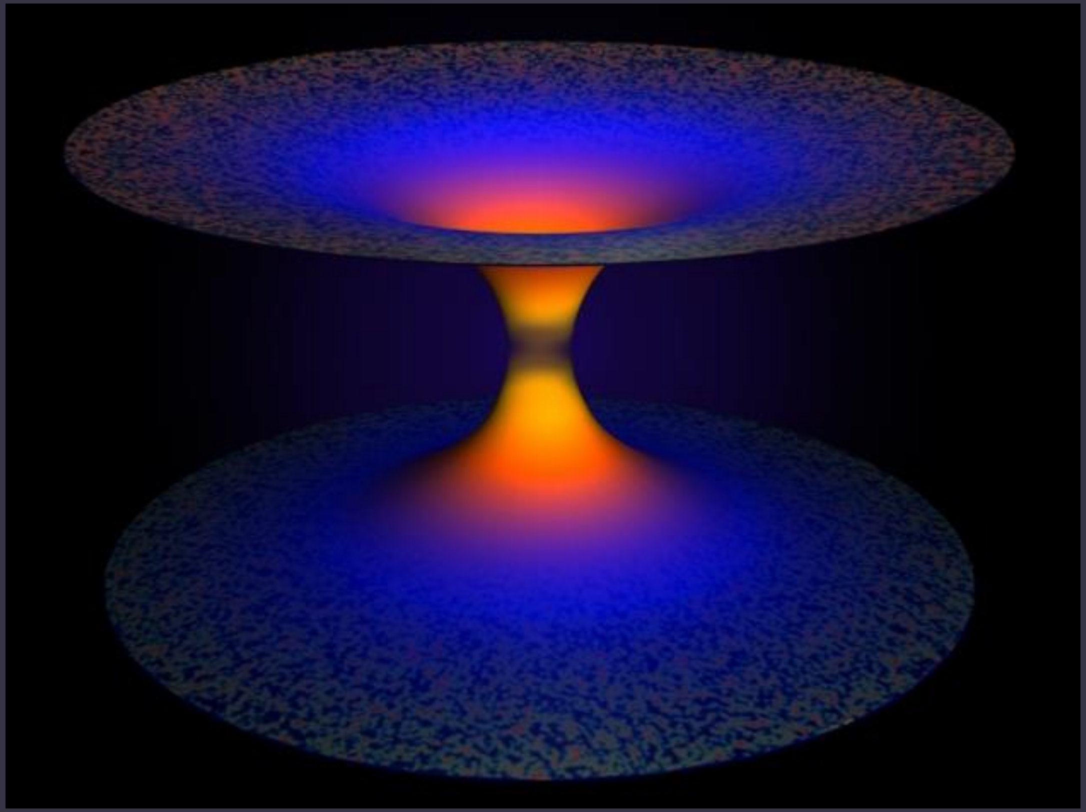
Collapse can be accompanied by a SN-like event, short GRB and a GW burst.
Double-peaked events can also appear in this scenario.



“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.

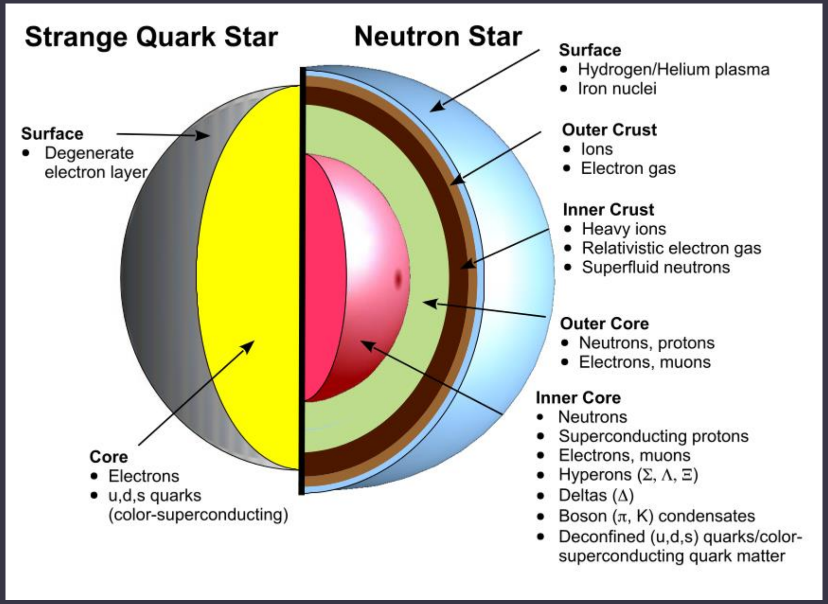
A cluster can be more compact due to formation of Bose-Einstein condensate. Then, the size can be ~few hundred km, this corresponds to expected size of emitting region in FRB sources (duration multiplied by the velocity of light). Mass of such compact cluster can be about the mass of the Earth!

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.

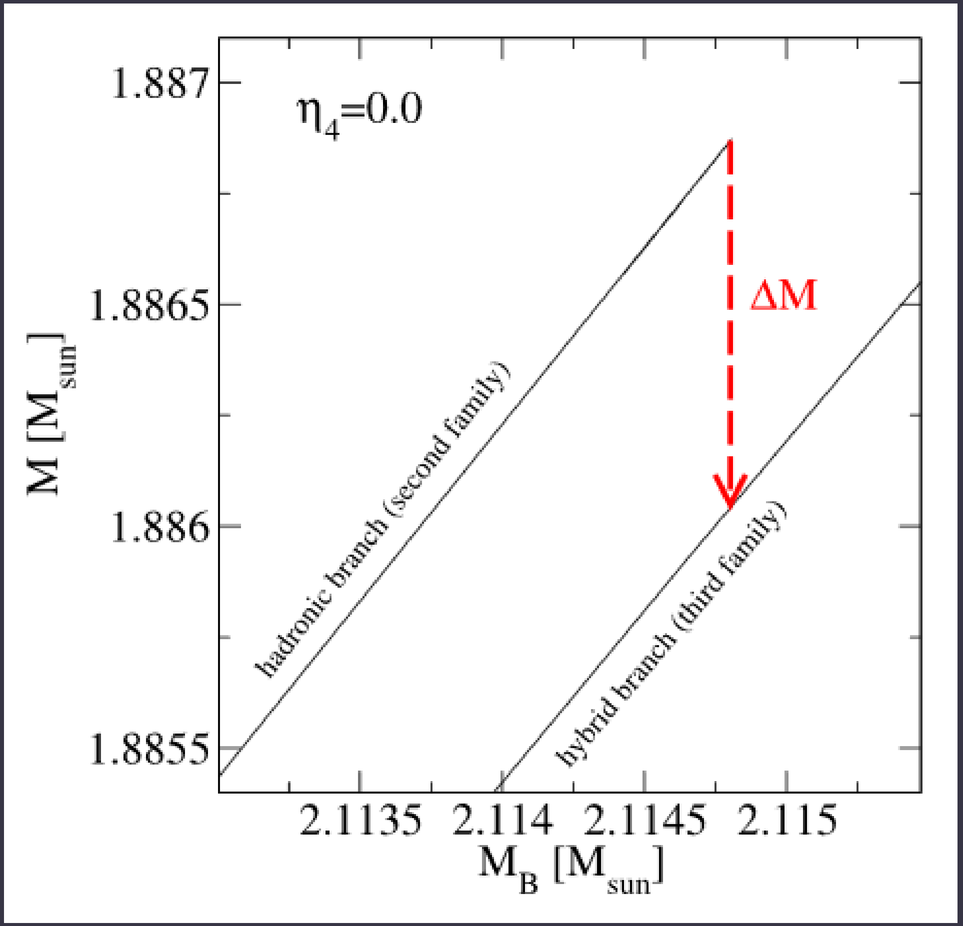
1411.3900, 1410.4323, 1512.06245, 1707.04827

Deconfinement – formation of a quark star

http://astrobites.org



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.

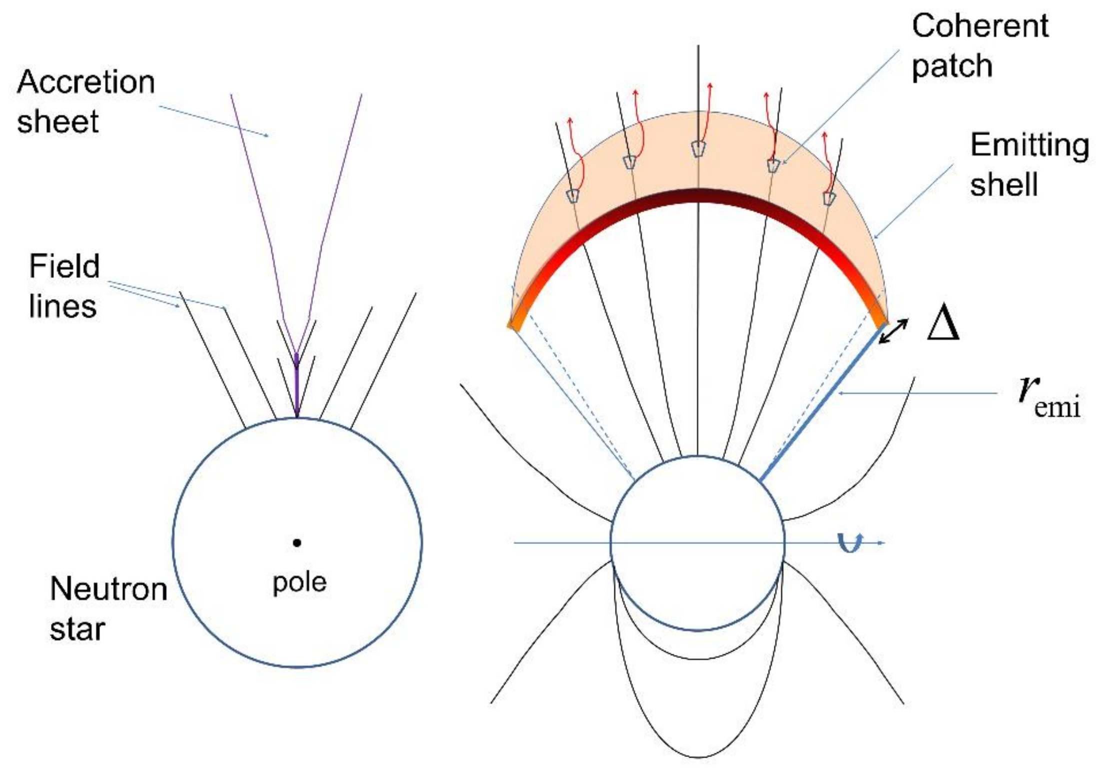


1506.08645

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.

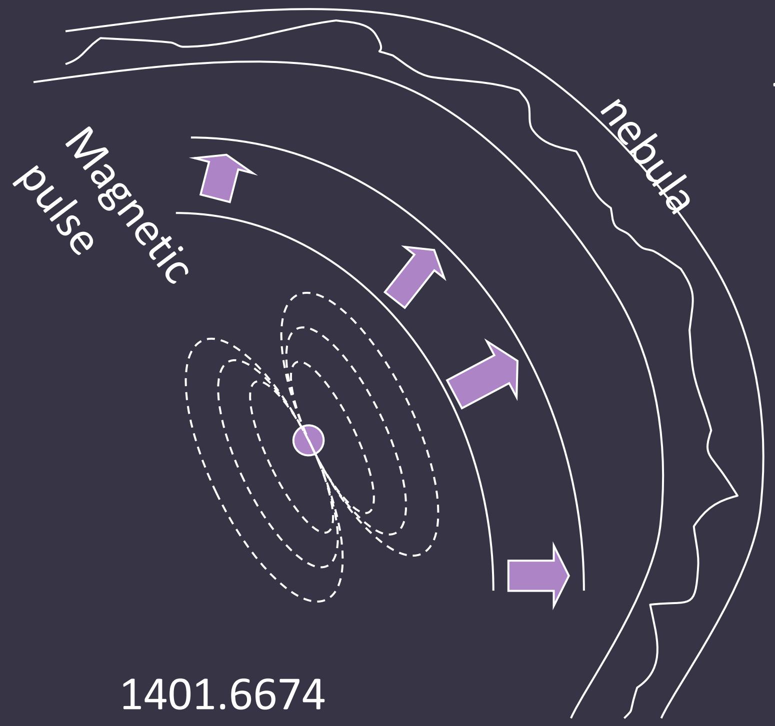
Free-fall time scale in the vicinity of a NS is ~ few msec.
Energy release can be explained by potential energy.

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.

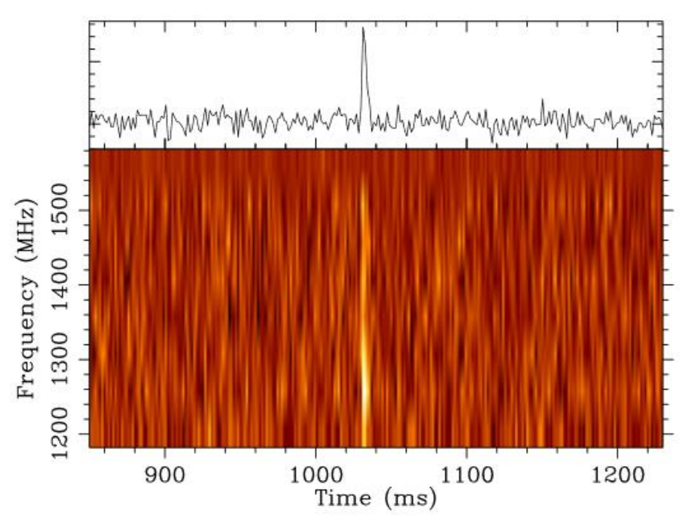
FRB bursts might be related to giant flares of magnetars

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.

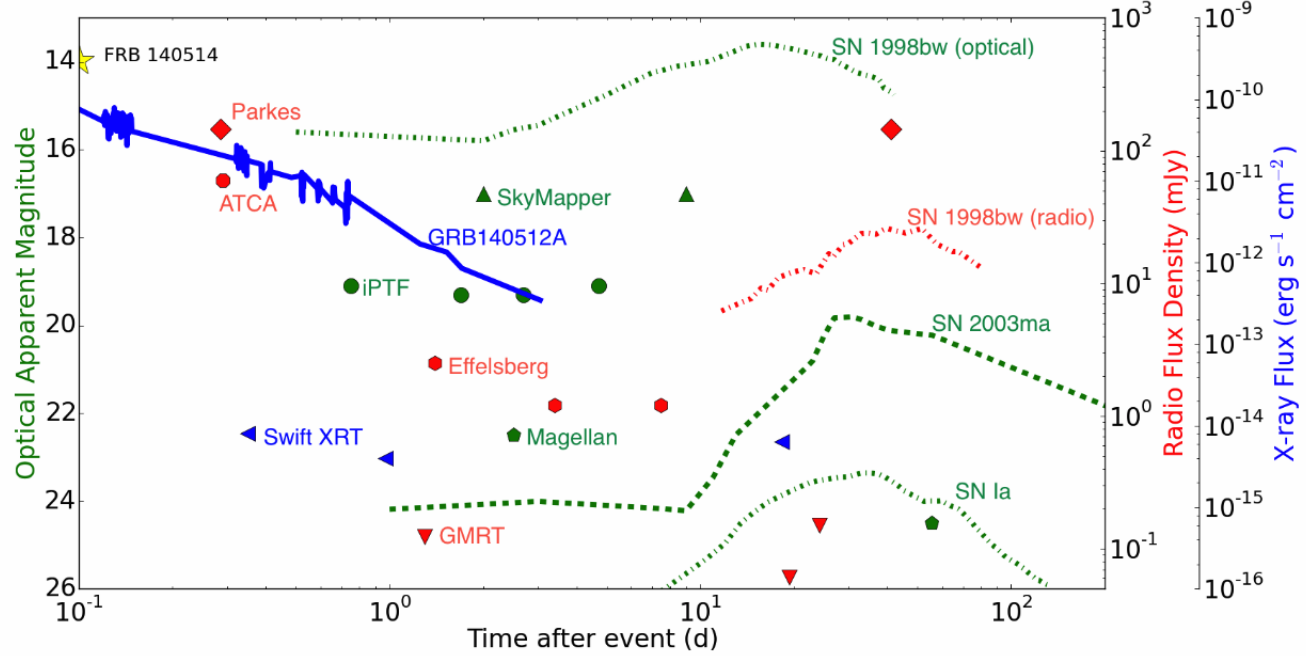
The first burst detected in real time

1412.0342



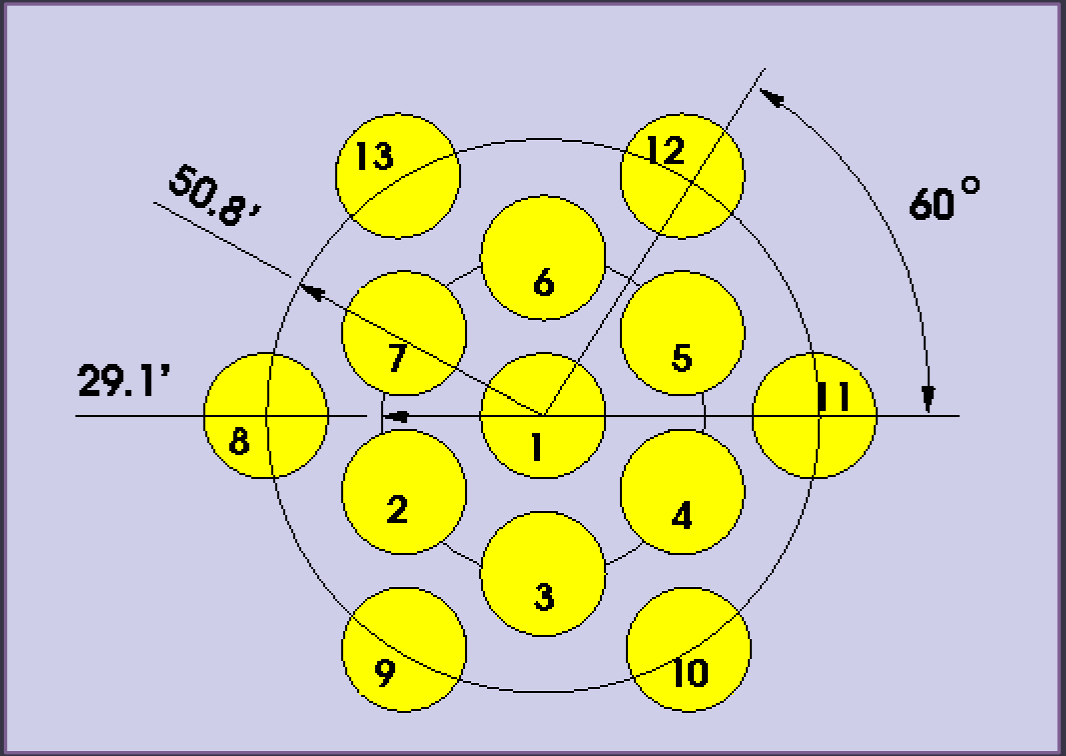
In may 2014 for the first time a burst was detected in real time.
This allowed to trigger searches of an afterglow in other energy ranges.

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

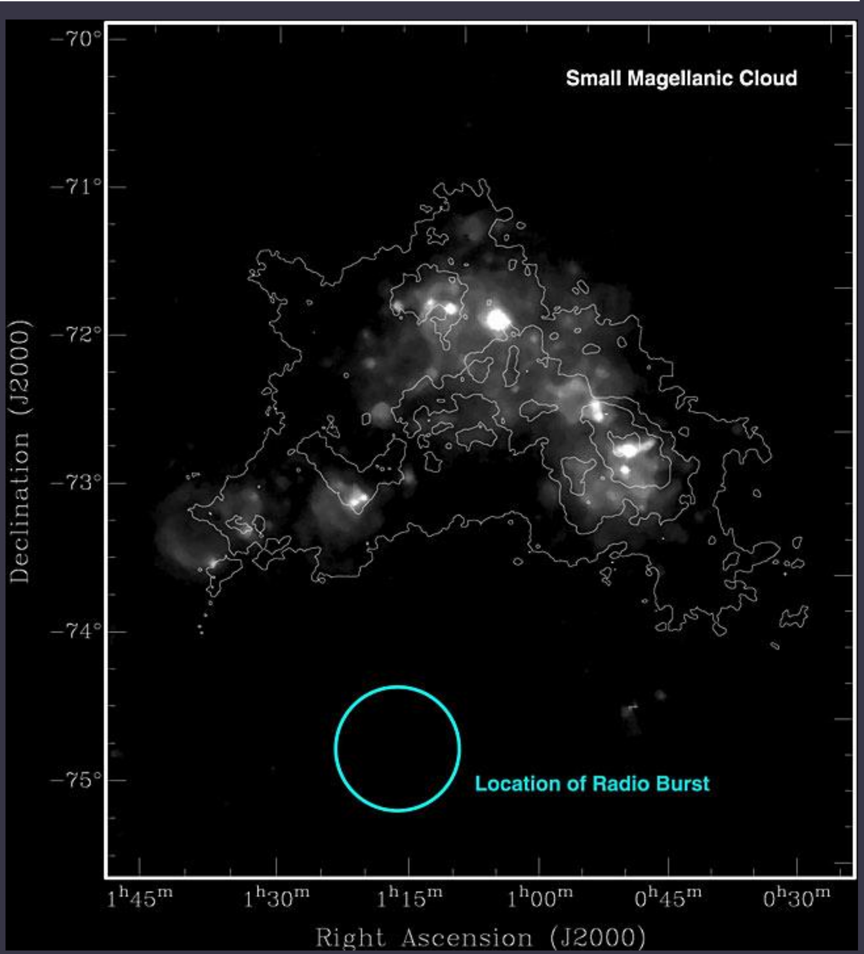


Localization

Radius of uncertainty circle ~10 arcmin



Usually FRBs are seen just in one beam.



Repeating bursts

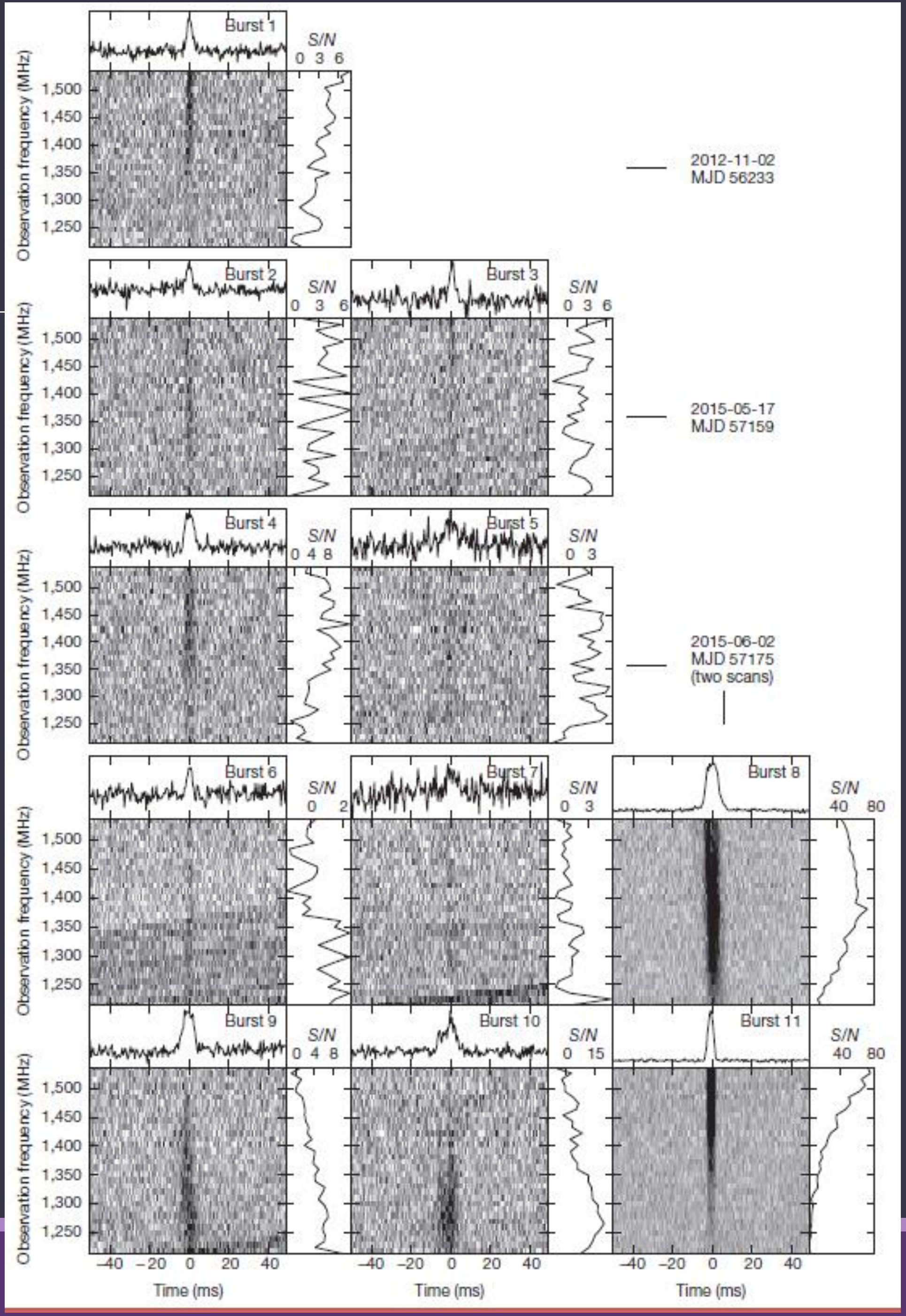
Repeating bursts are detected firstly from FRB 121102.

The source was found at Arecibo.

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

Variable spectral parameters.

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



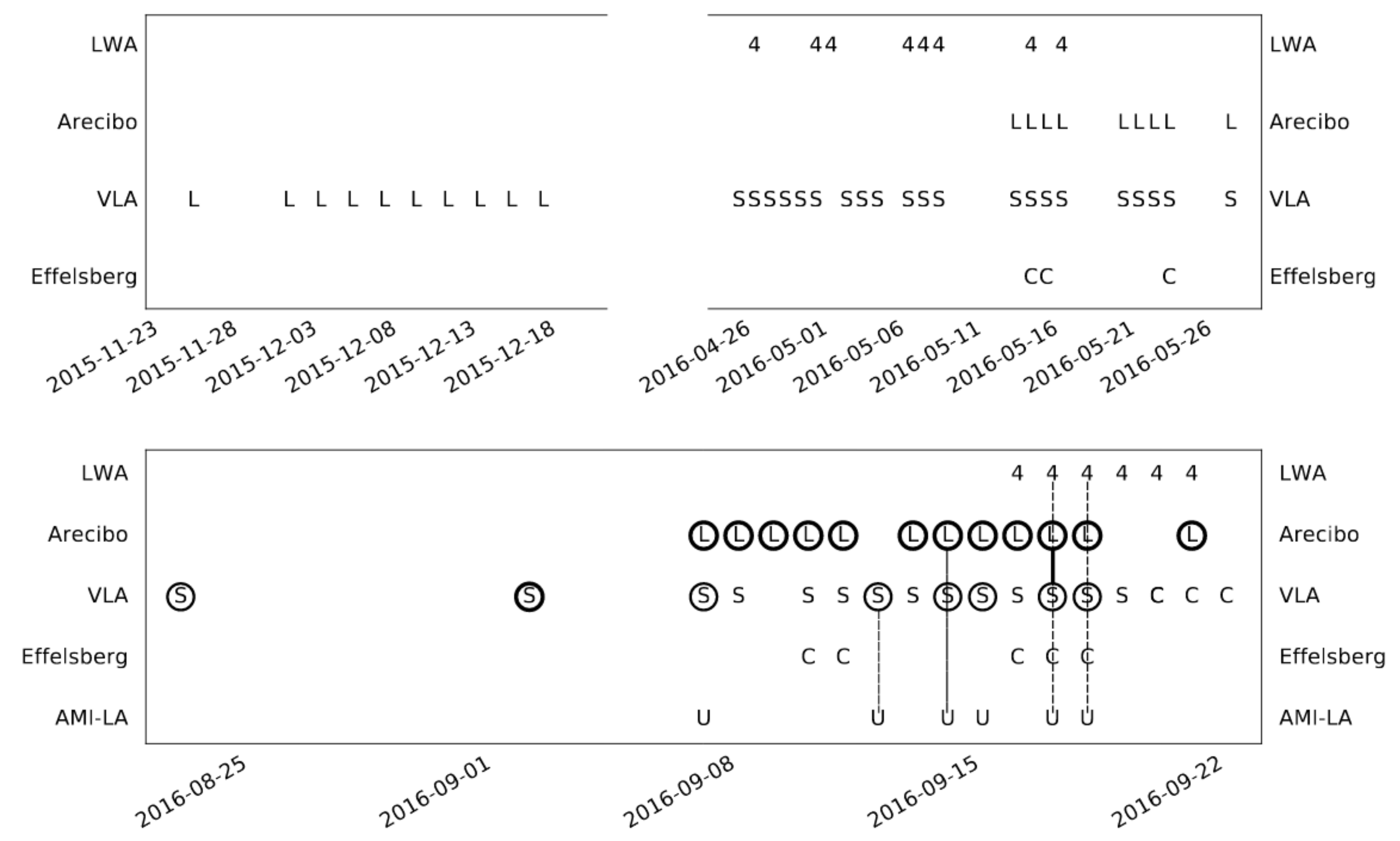
1603.00581

VLA, Arecibo and all the rest

During periods of activity rate is few per hour.

Simultaneous detection with Arecibo, VLA and other instruments.

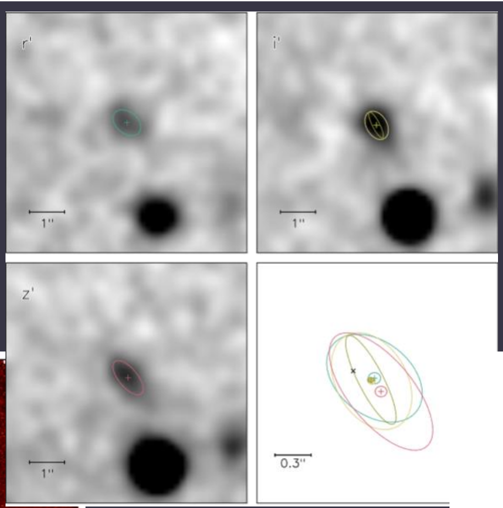
The source is also detected at 4-8 GHz and polarization is measured (1801.03965).

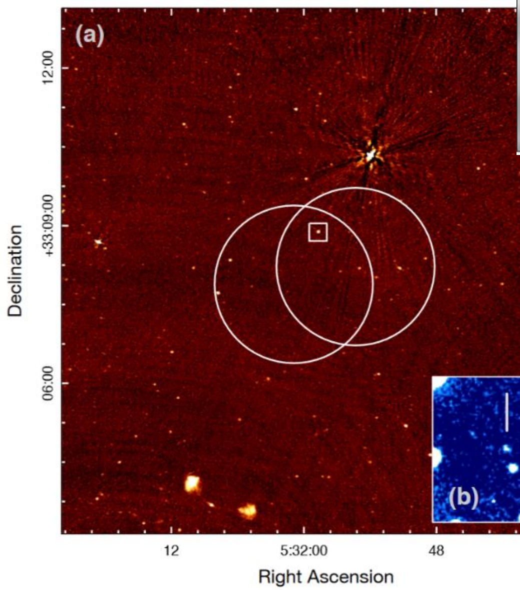


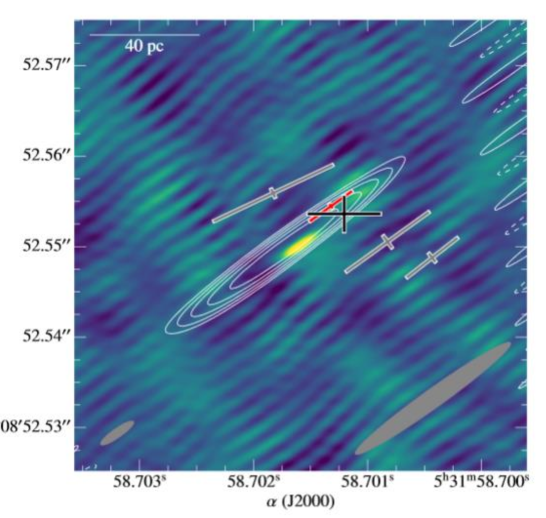
1705.07553

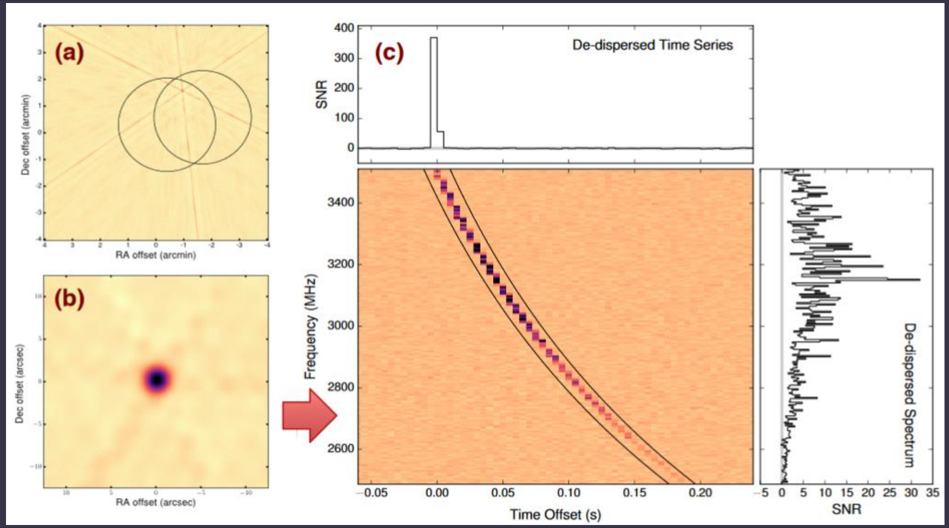
Host galaxy of the FRB

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).





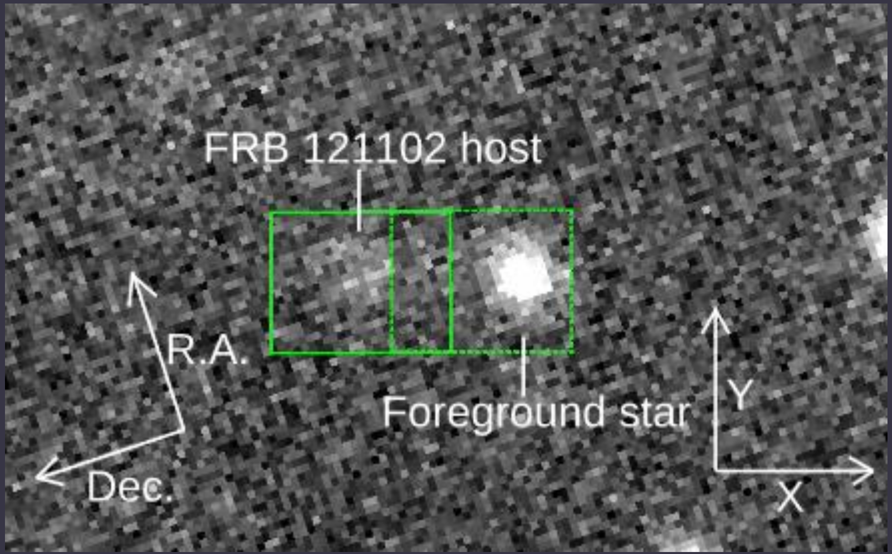




1701.01098, 1701.01099, 1701.01100

H-alpha emission in the host galaxy of FRB 121102

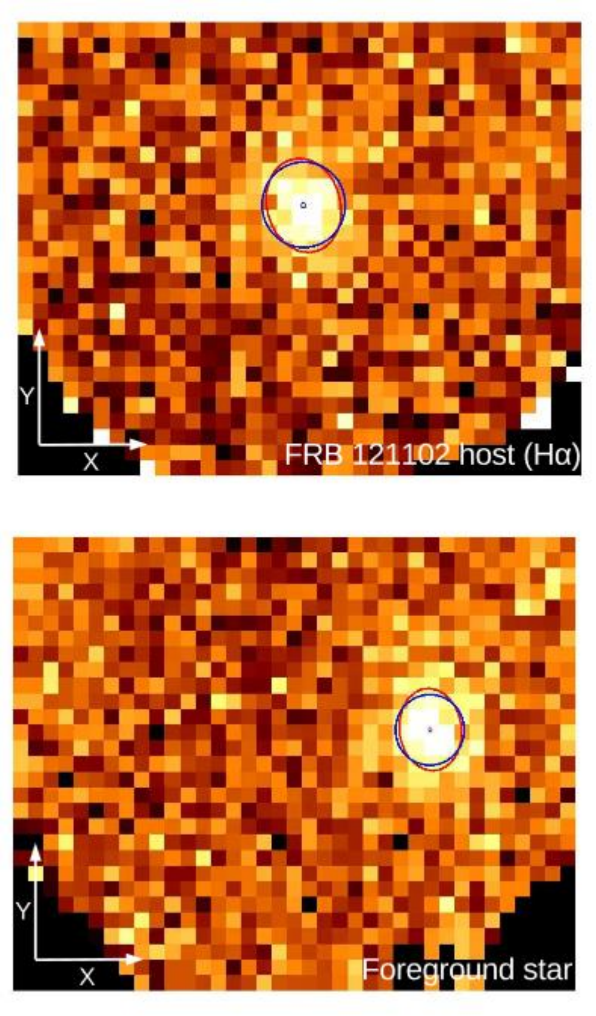
1705.04693



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.



Early ideas

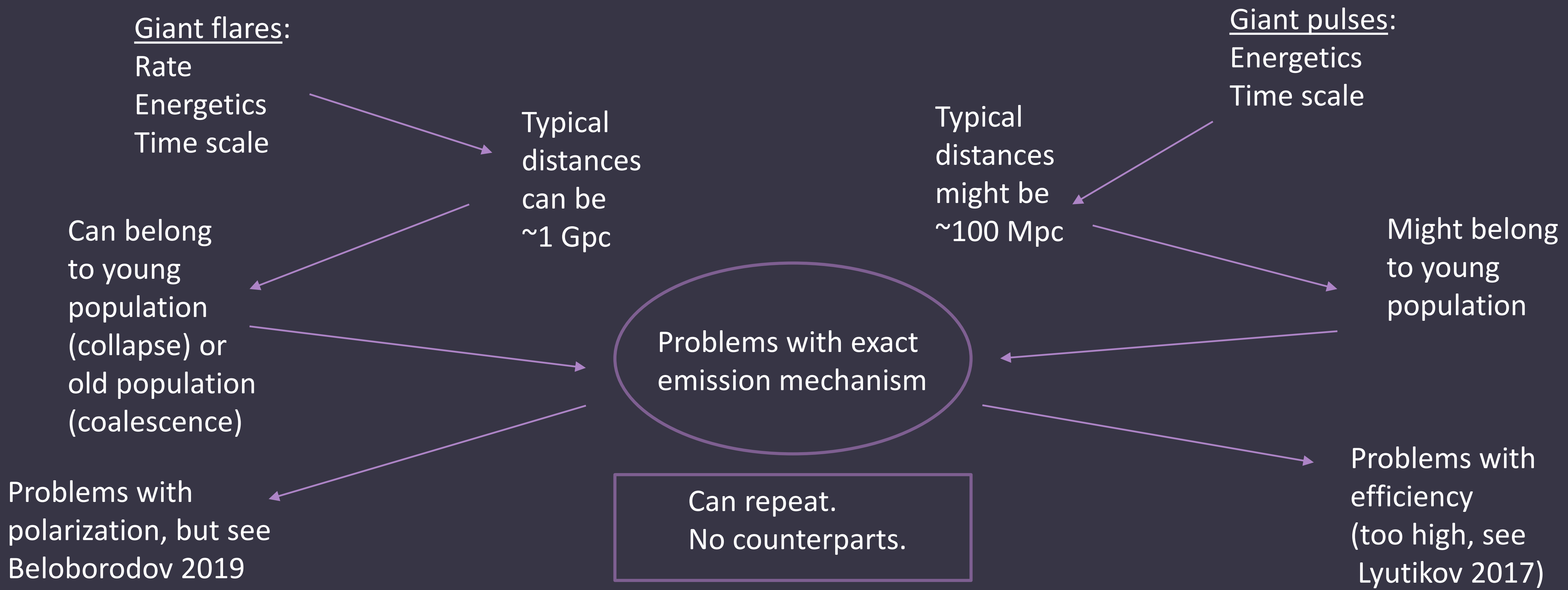
~~Exotics: strings, axions, white holes, etc.~~

~~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

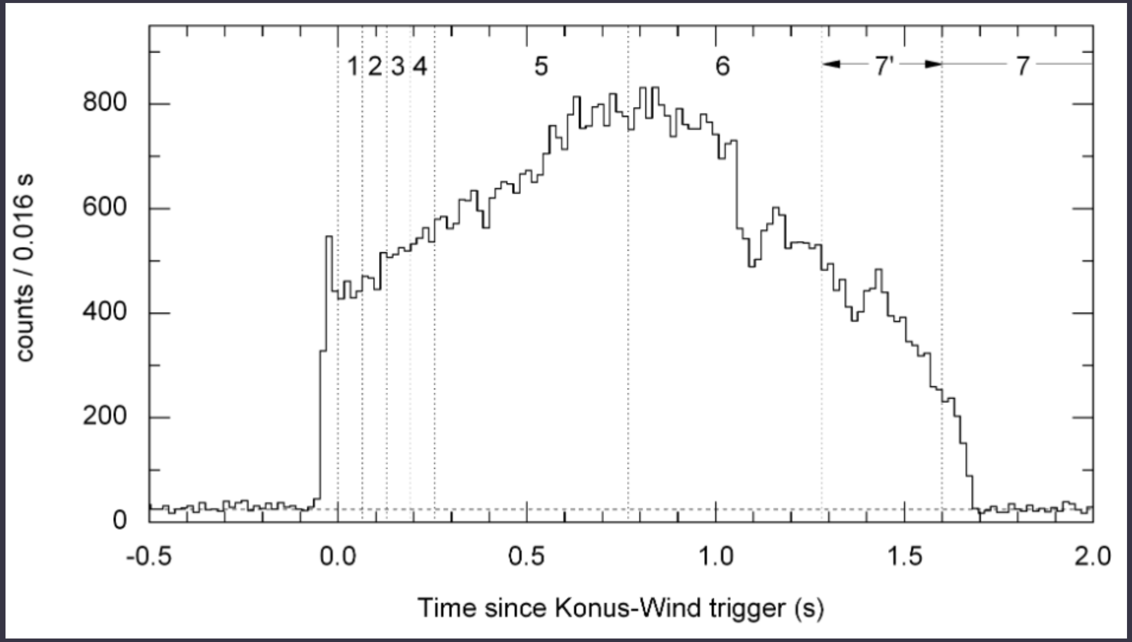
Typical distances might be ~100 Mpc

Might belong to young population

Problems with efficiency (too high, see Lyutikov 2017)

SGR 1935+2154

Discovered in 2014 (see, Israel et al. 2016).
P=3.25 sec
Distance ~7-12 kpc (2005.03517)
Intermediate flare (Kozlova et l. 2016)

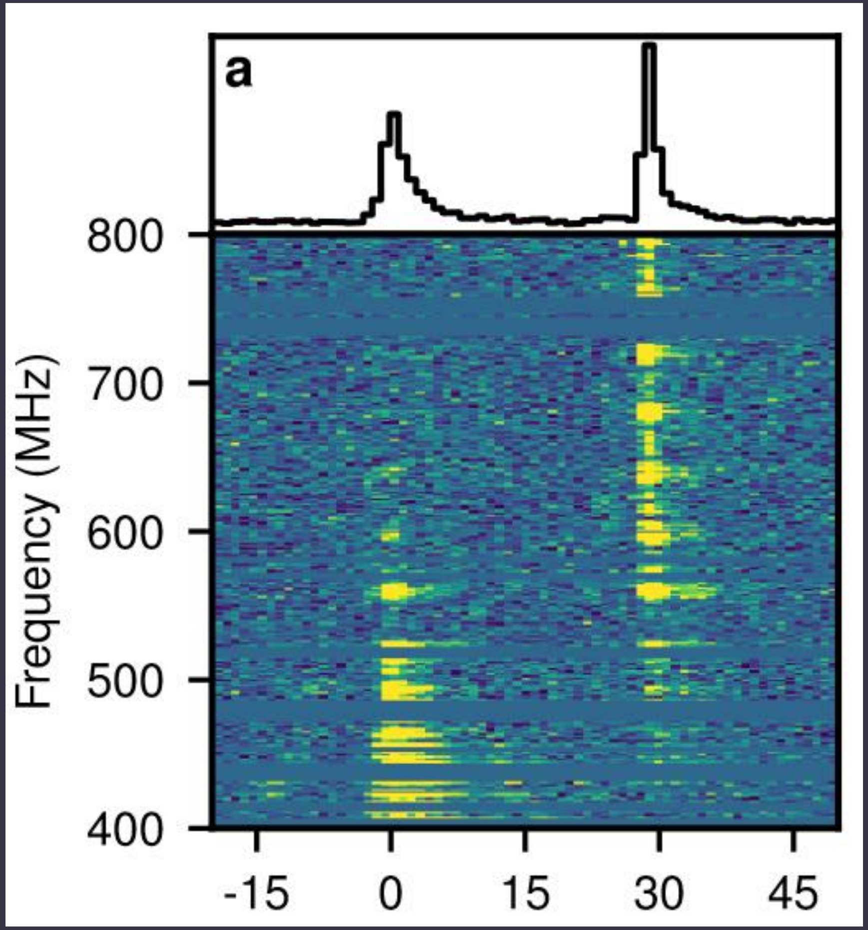


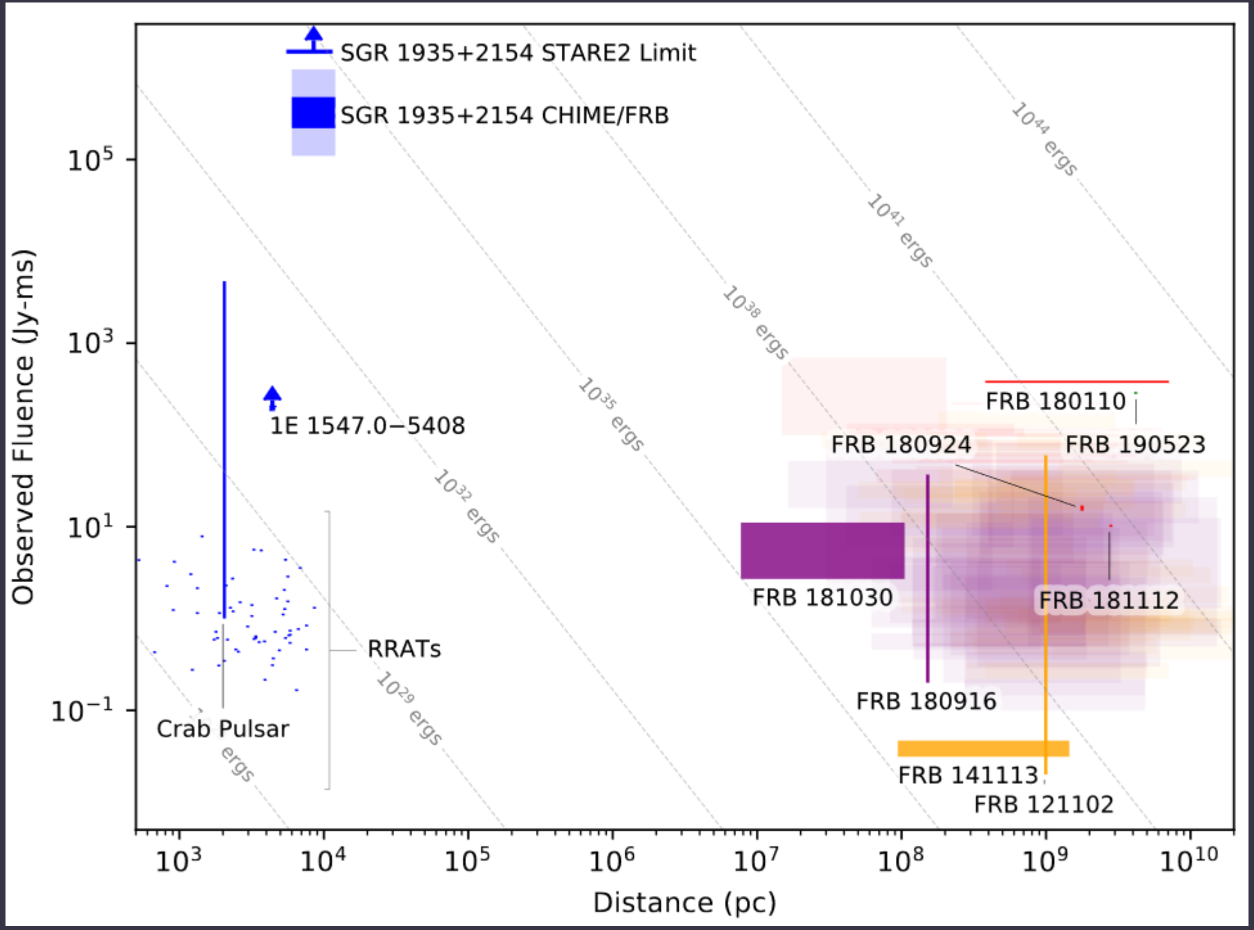
Activated in April 2020.
Finally, on April, 28 2020
A simultaneous burst
in radio and X/gamma
was detected.

Astronomers’ Telegram: 13681-13769

GCN: 27666-27669

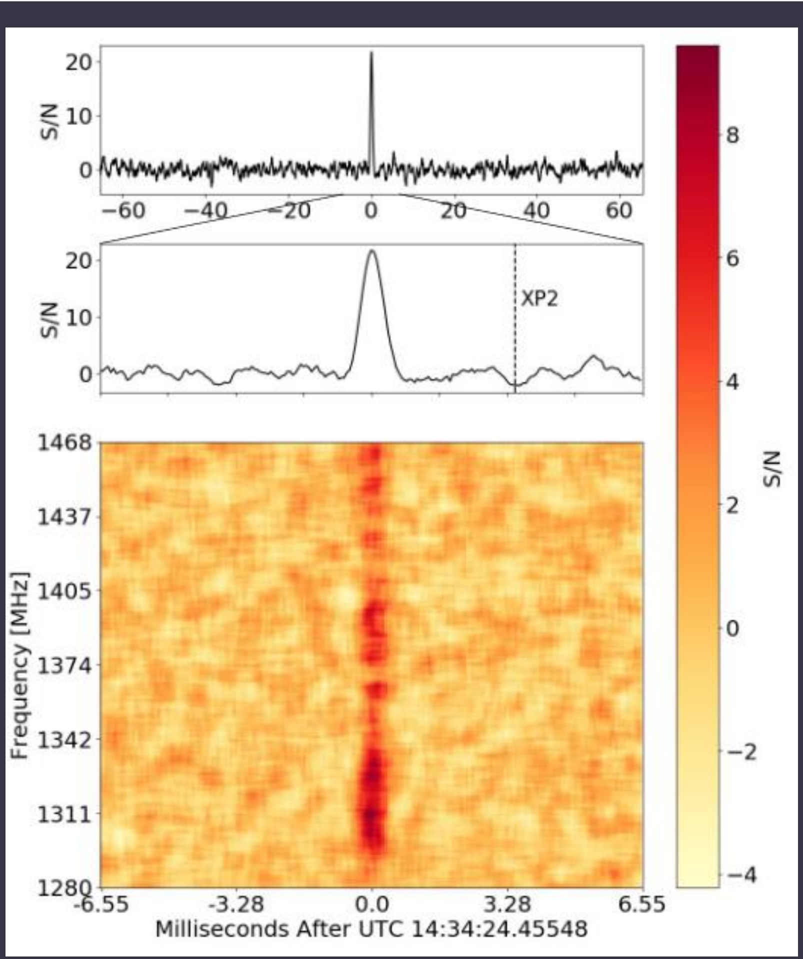
CHIME data

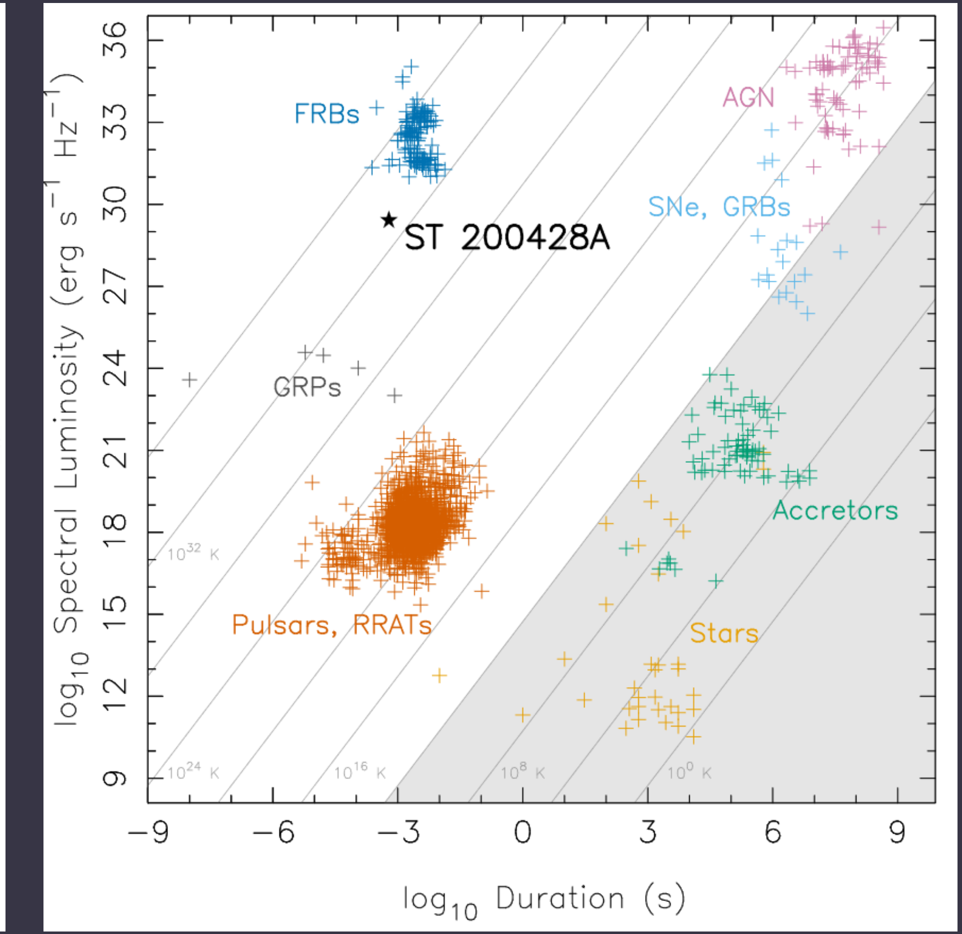




2005.10324

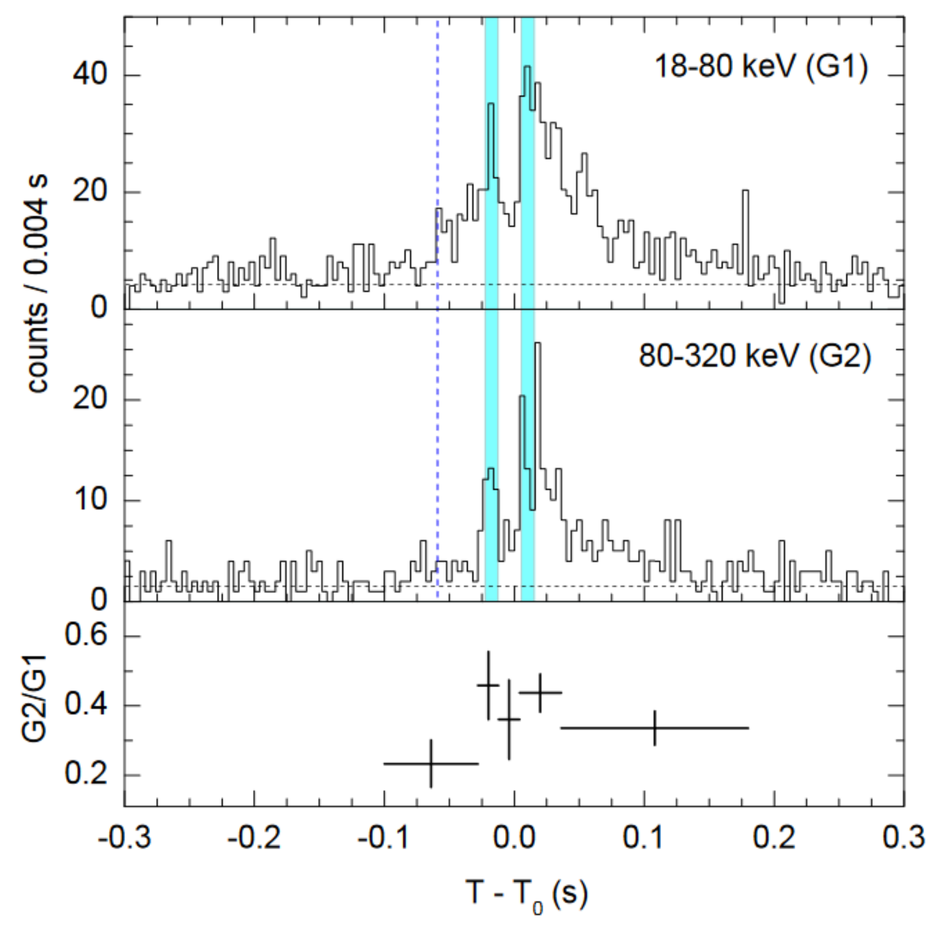
STARE2 data

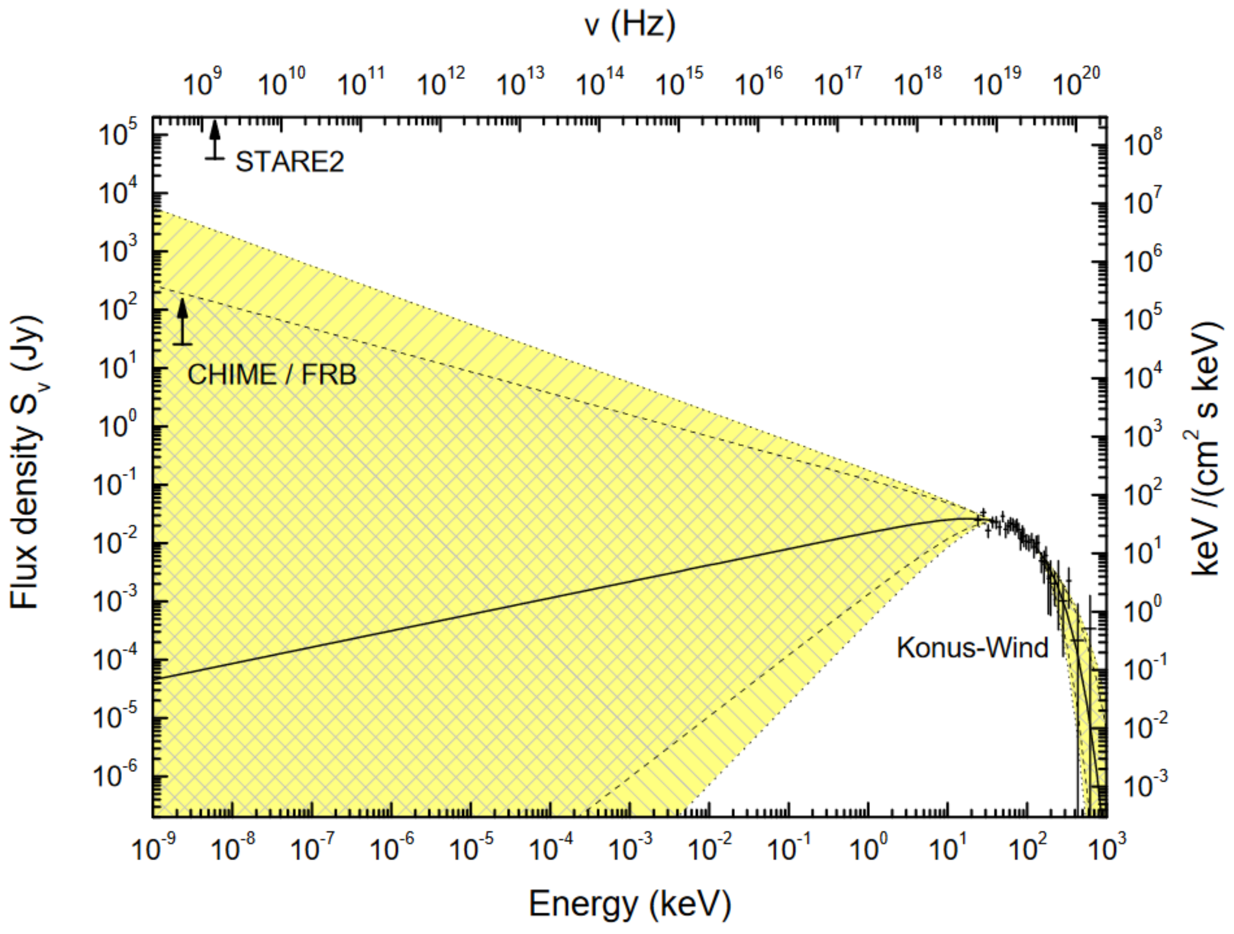




2005.10828

Konus-Wind data

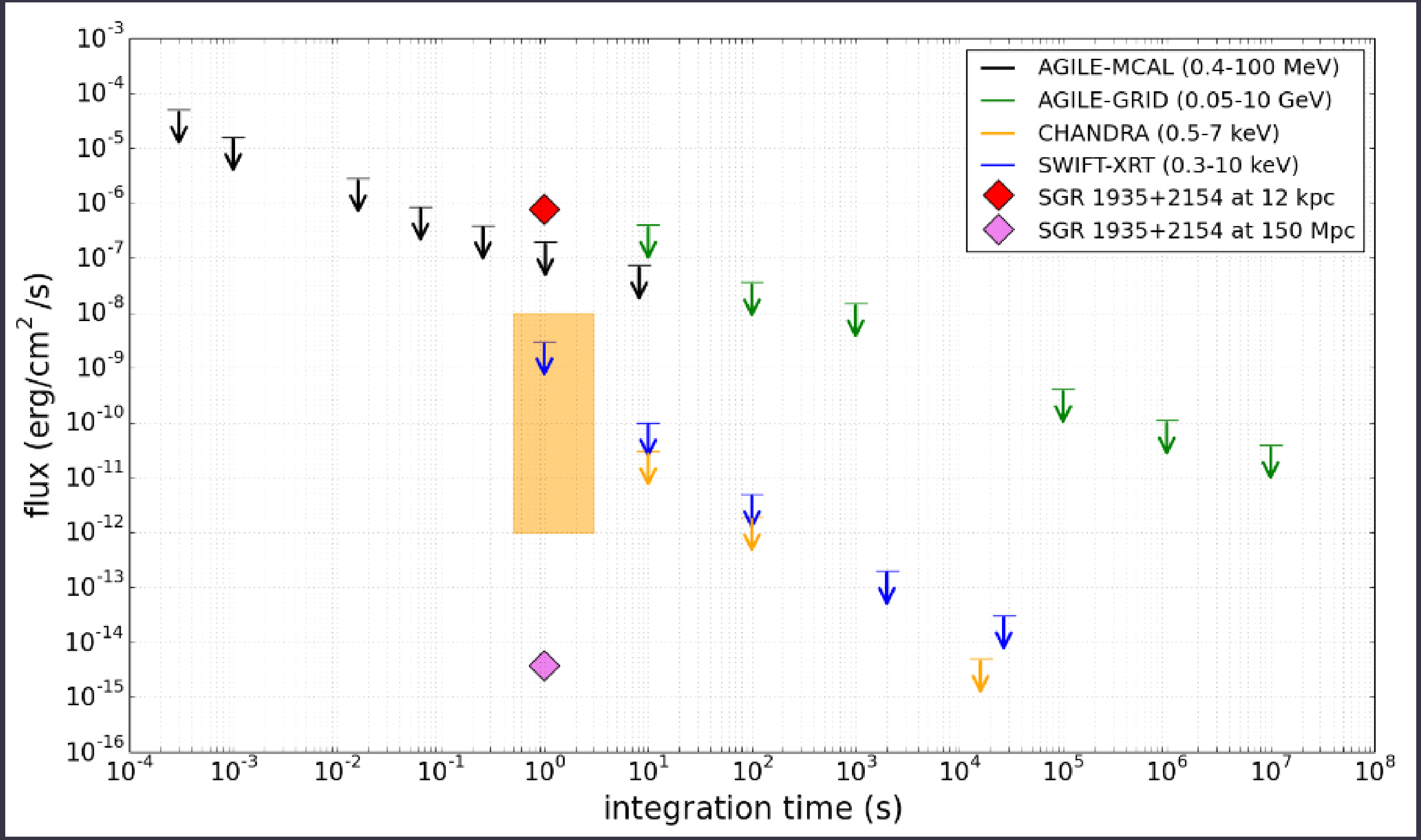




2005.11178

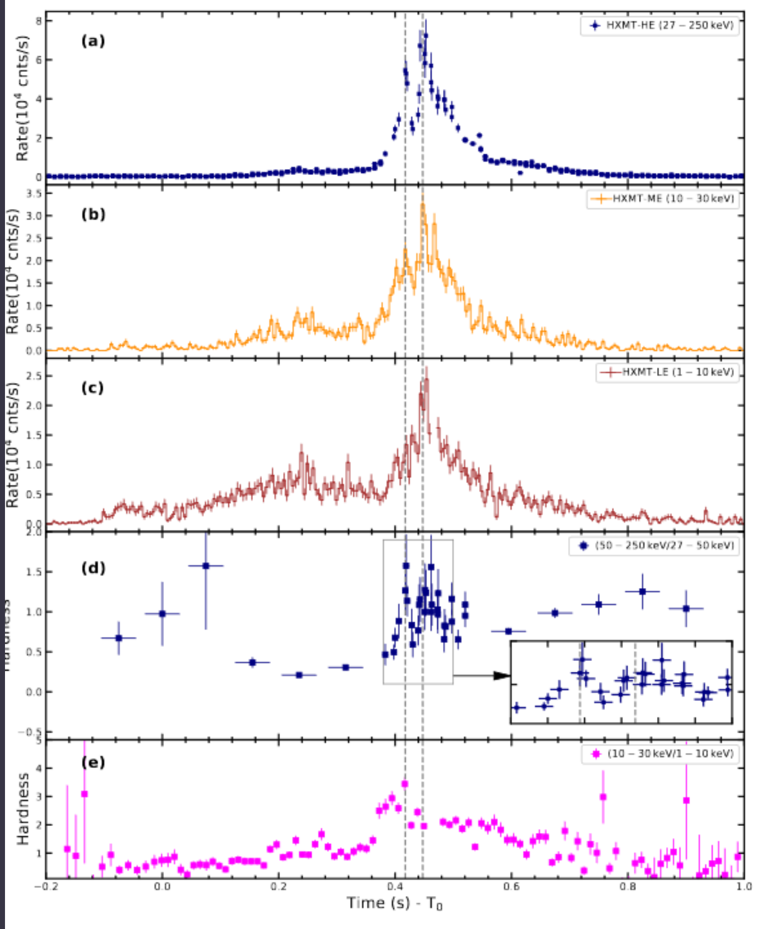
AGILE data

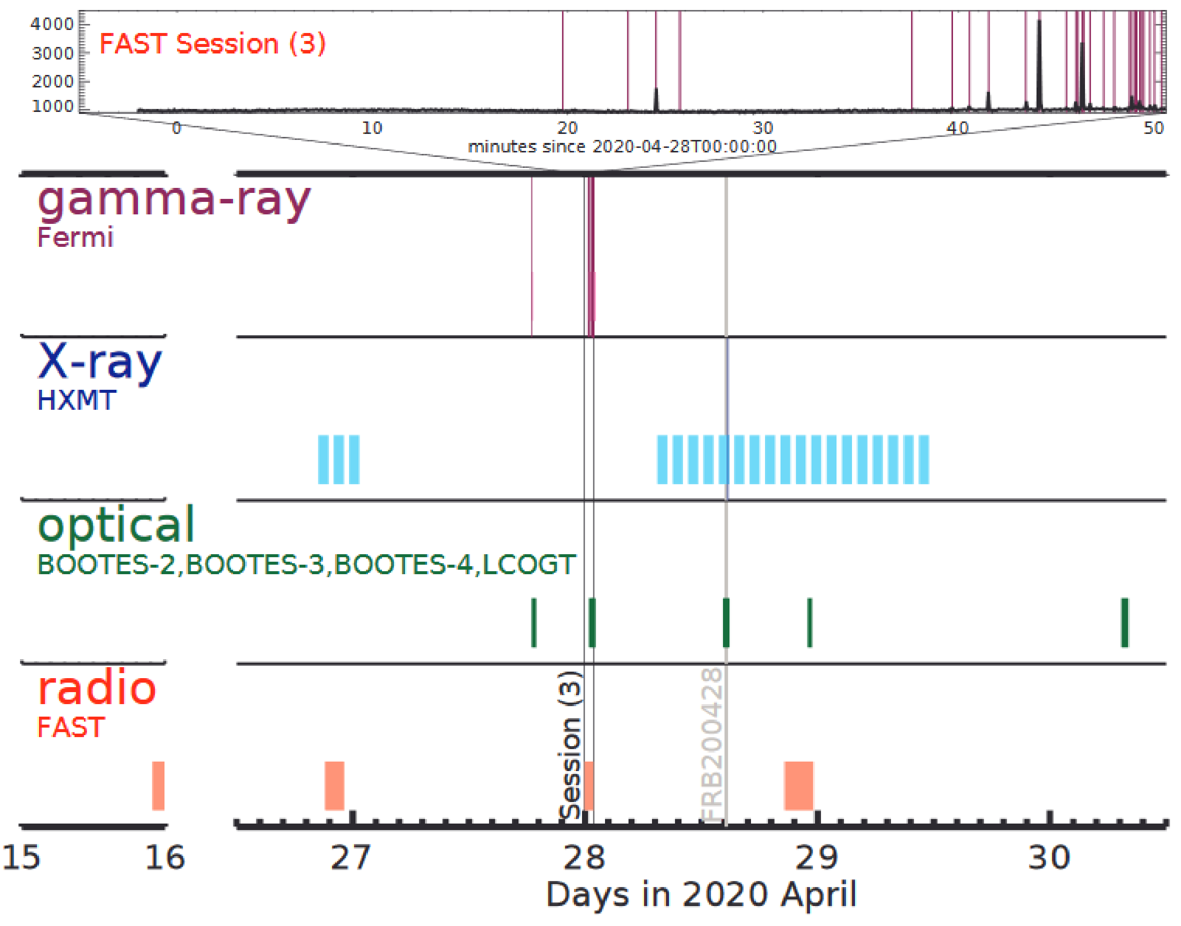
Comparison of SGR 1935 detection with monitoring of the repeating source FRB 180916 (at 149 Mpc)



2005.12164

Insight-HXMT data and FAST

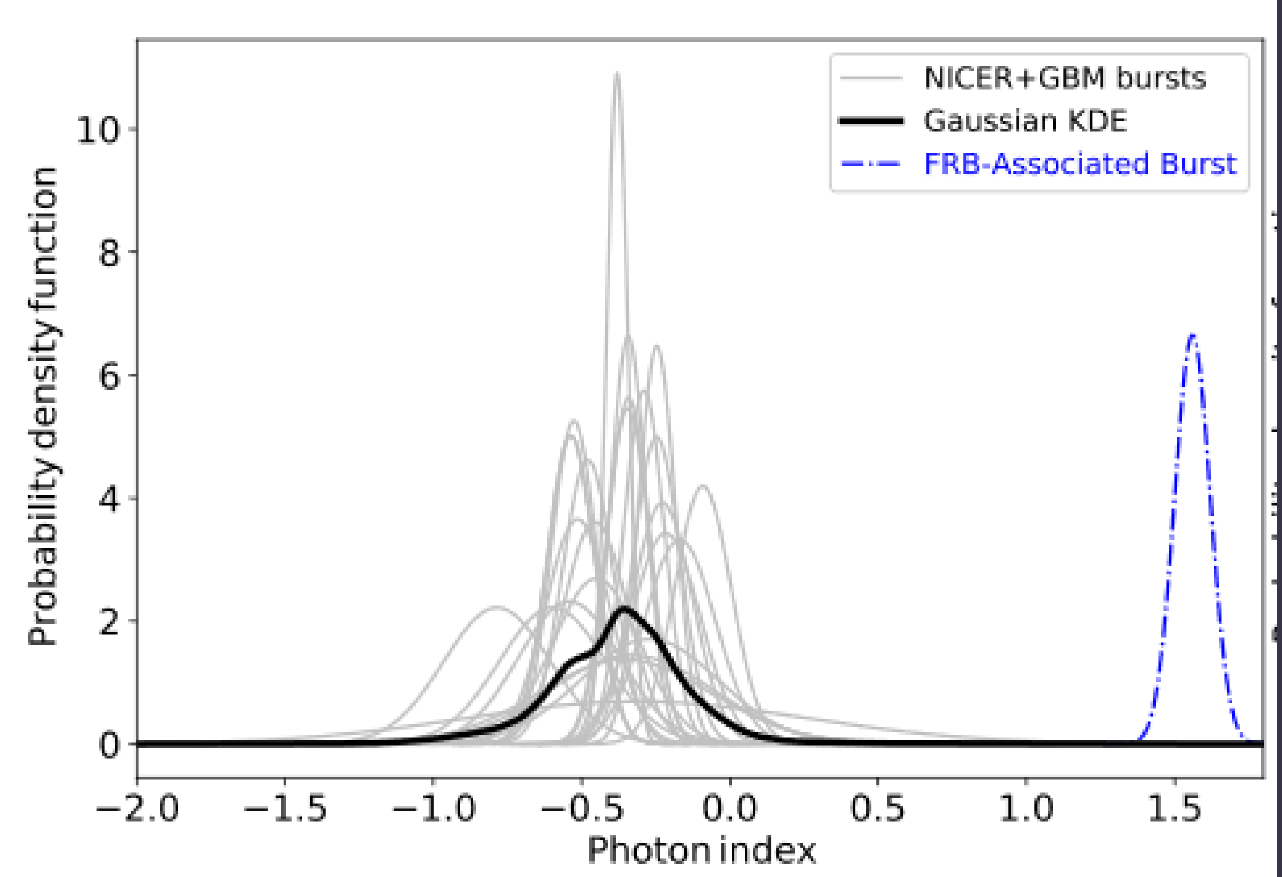


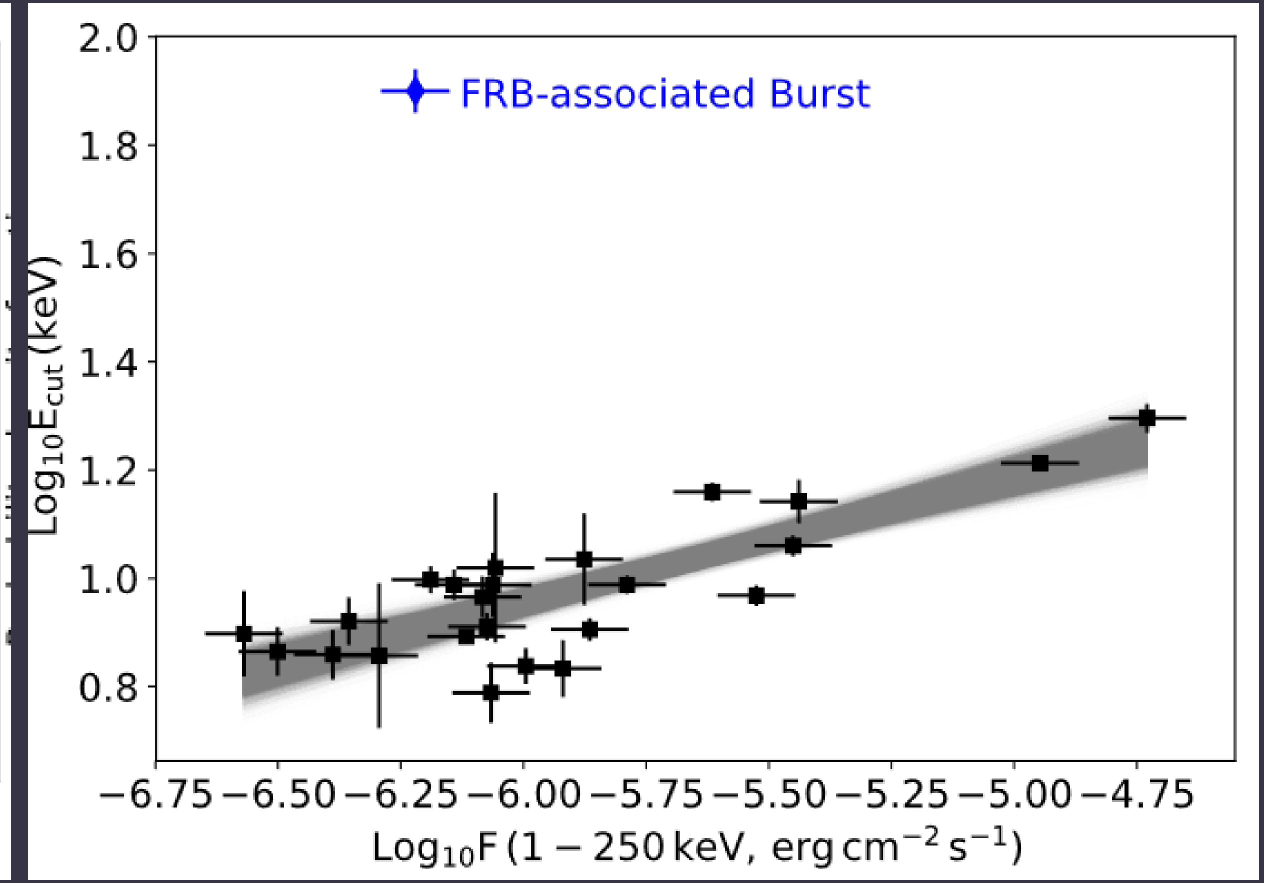


2005.11071, see results of a new data reduction in 2302.00176

2005.11479

FRB associated vs. others





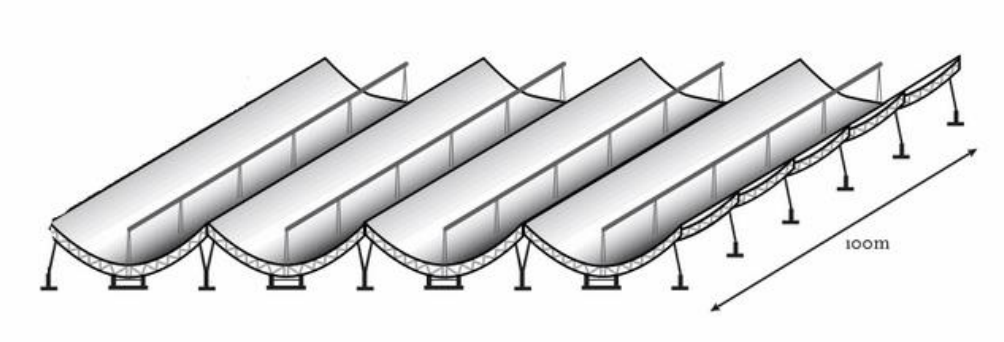
2006.11358

CHIME

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

CHIME

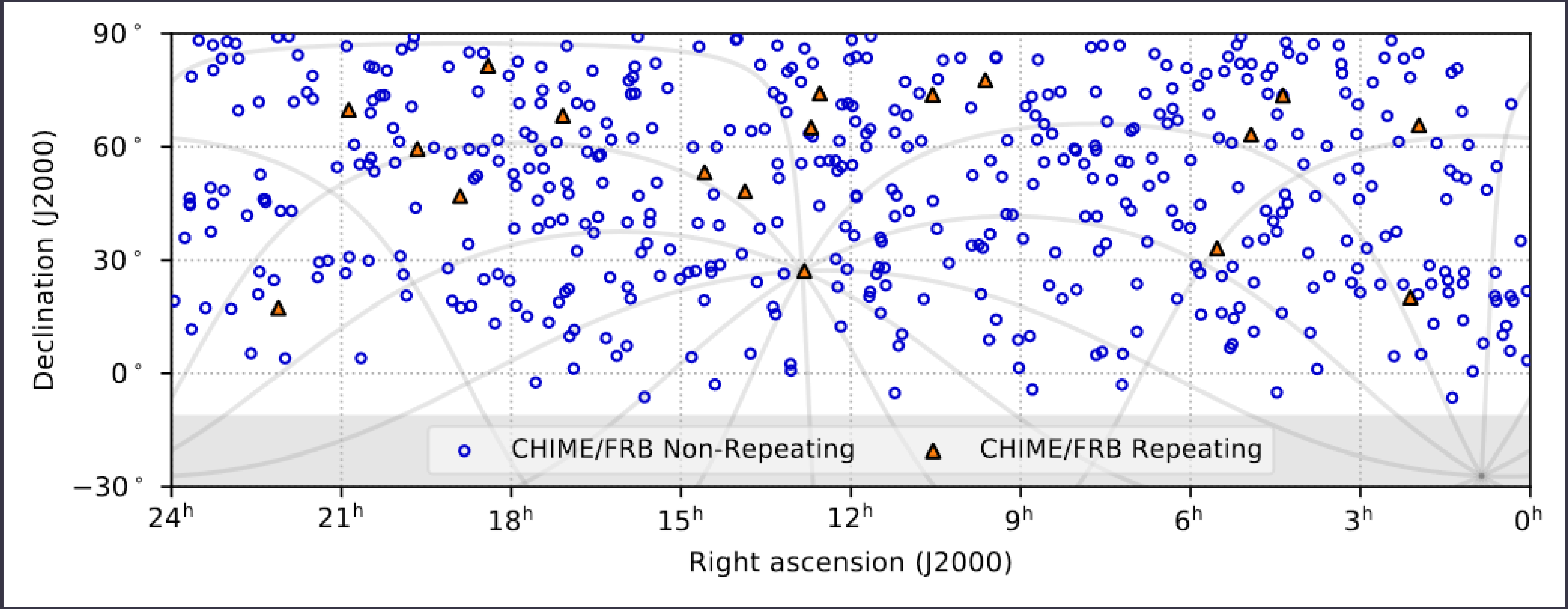
The **C**anadian **H**ydrogen **I**ntensity **M**apping **E**xperiment



CHIME – burst per day!
1601.02444

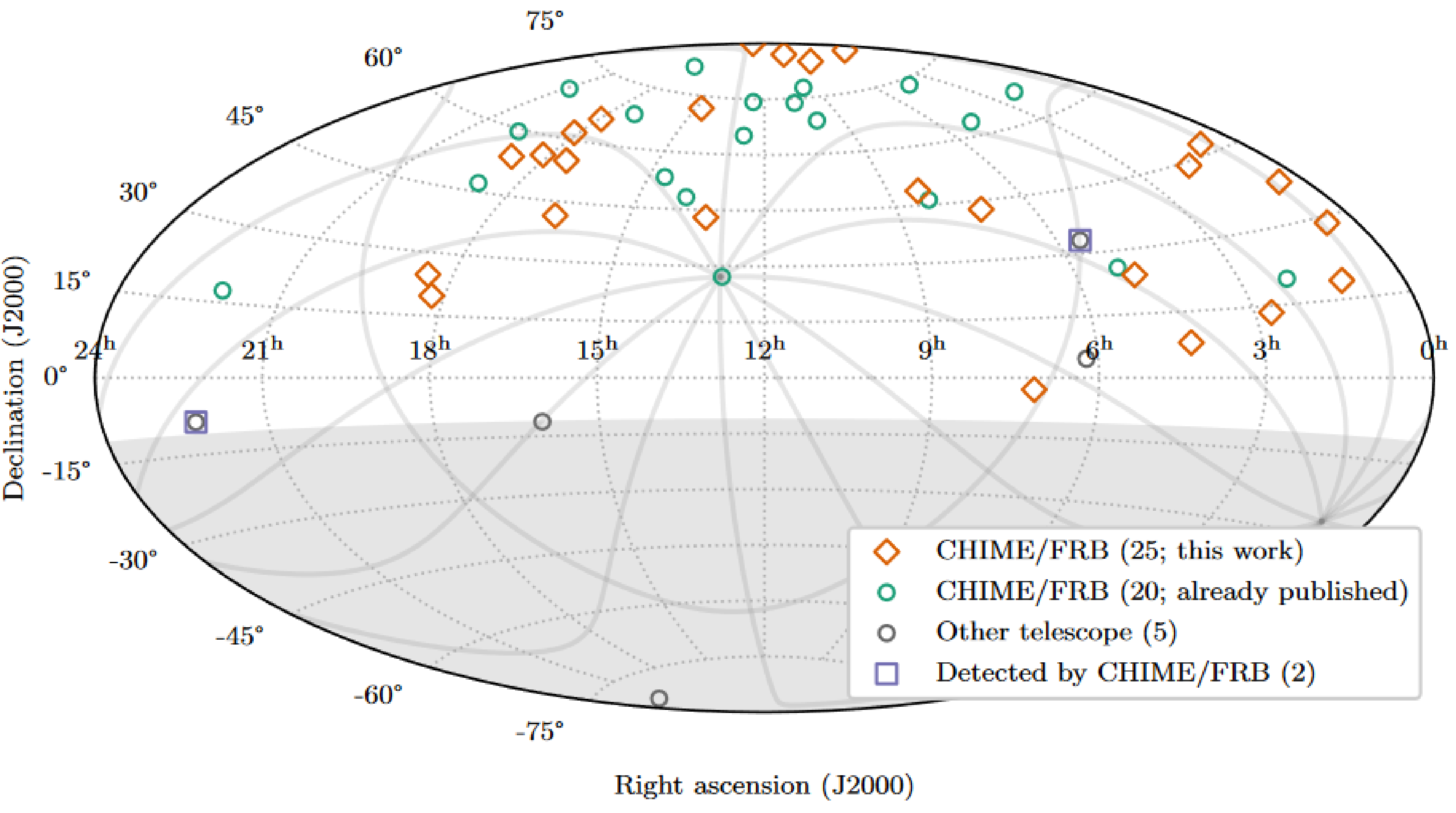
CHIME catalogue

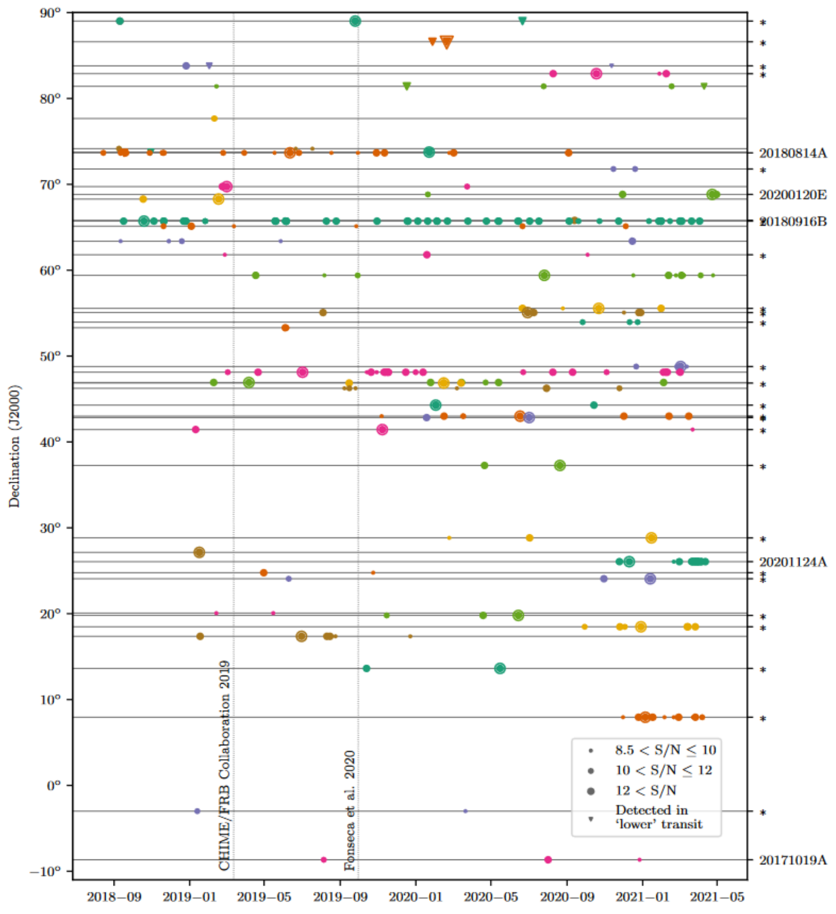
www.chime-frb.ca/catalog



2106.04352

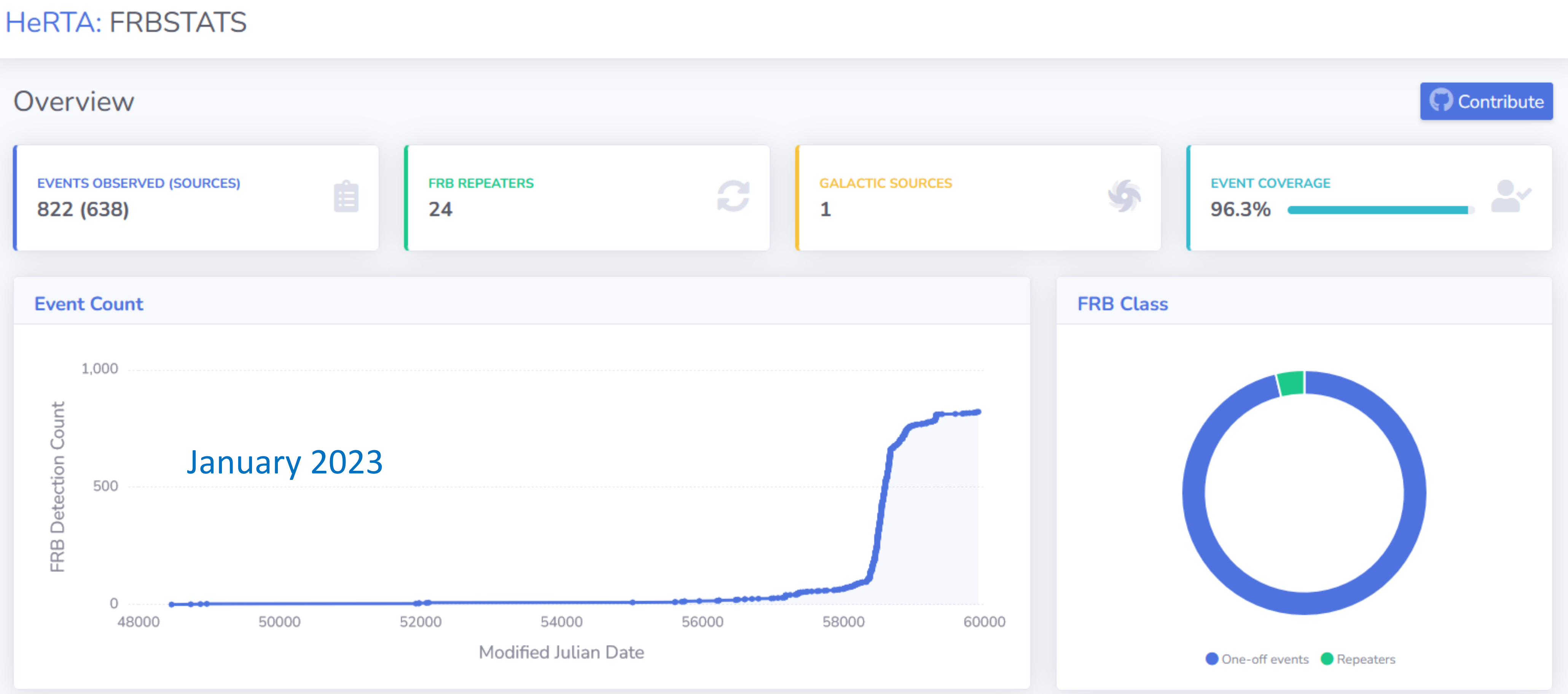
Second large sample of CHIME repeaters





2301.08762

Database



HeRTA: FRBSTATS

Overview

Contribute

EVENTS OBSERVED (SOURCES)
822 (638)

FRB REPEATERS
24

GALACTIC SOURCES
1

EVENT COVERAGE
96.3%

Event Count

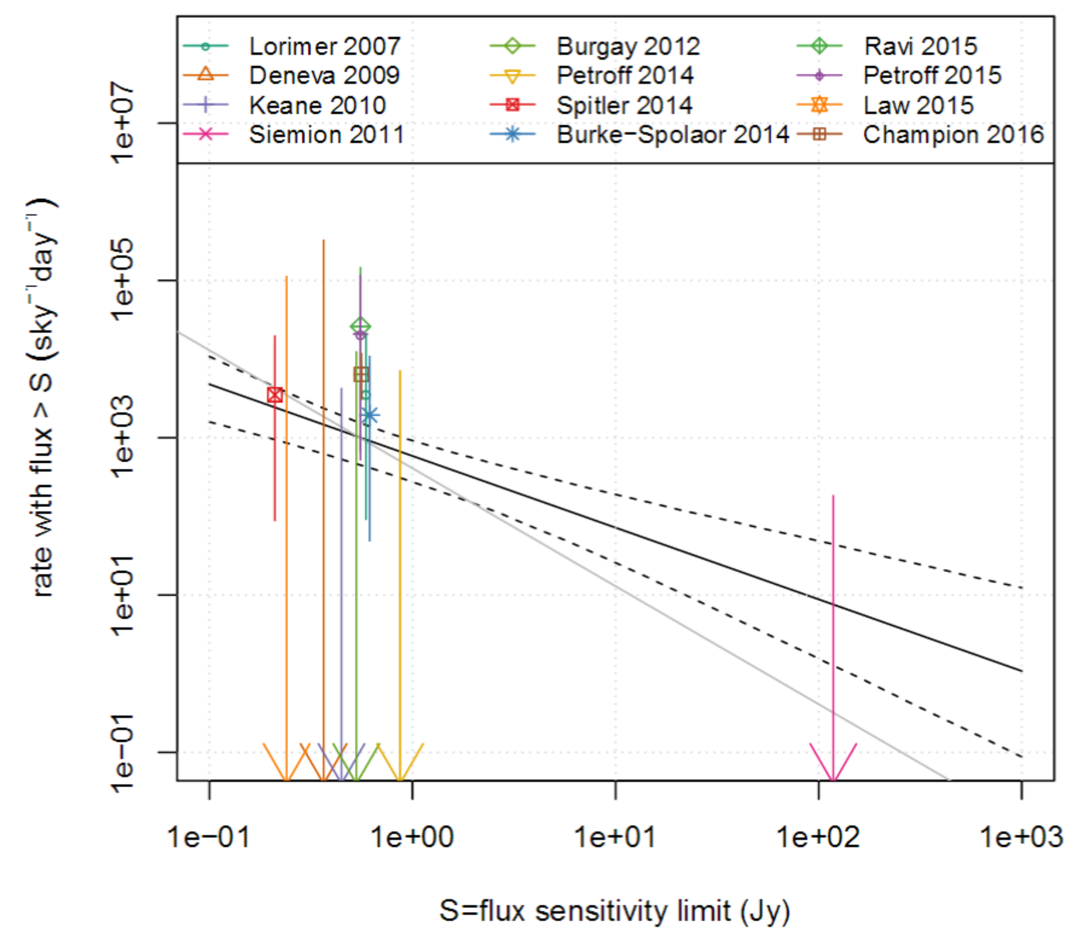
January 2023

FRB Class

2208.03508

https://www.herta-experiment.org/frbstats

Estimates of the rate



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

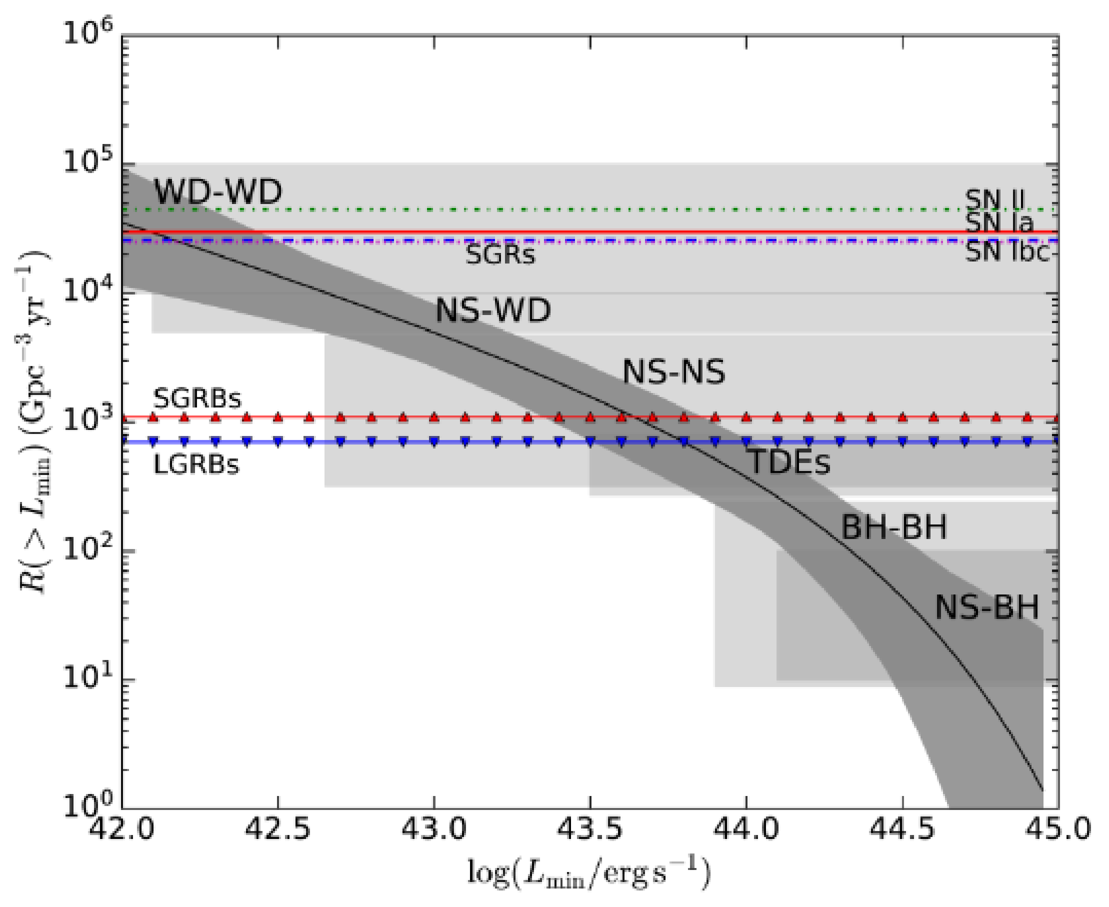
Grey line is plotted under assumption that index is the Log N – Log S distribution is equal to 3/2.

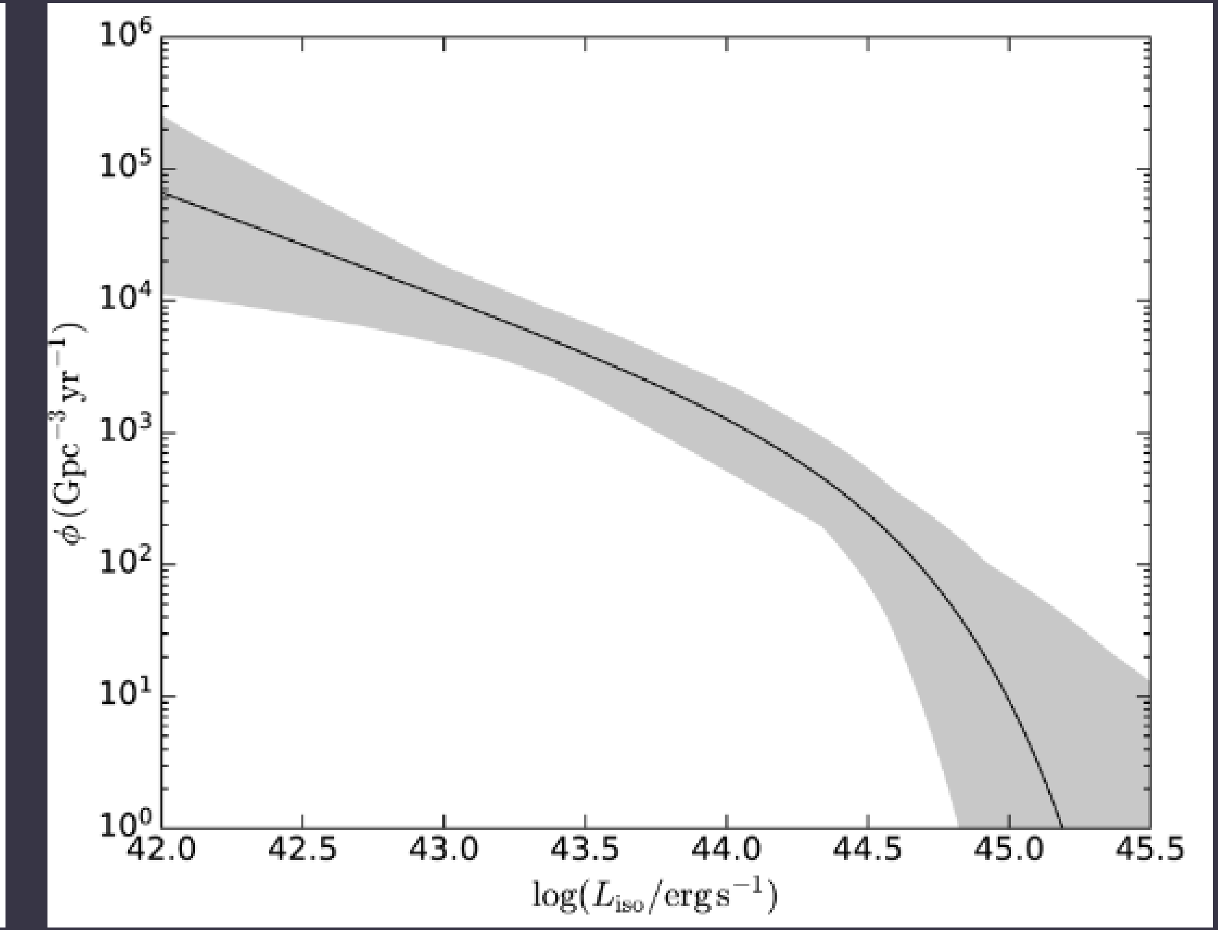
See also 1612.00896

587 per day with flux above 1 Jy.

1611.00458

Rate and luminosity function

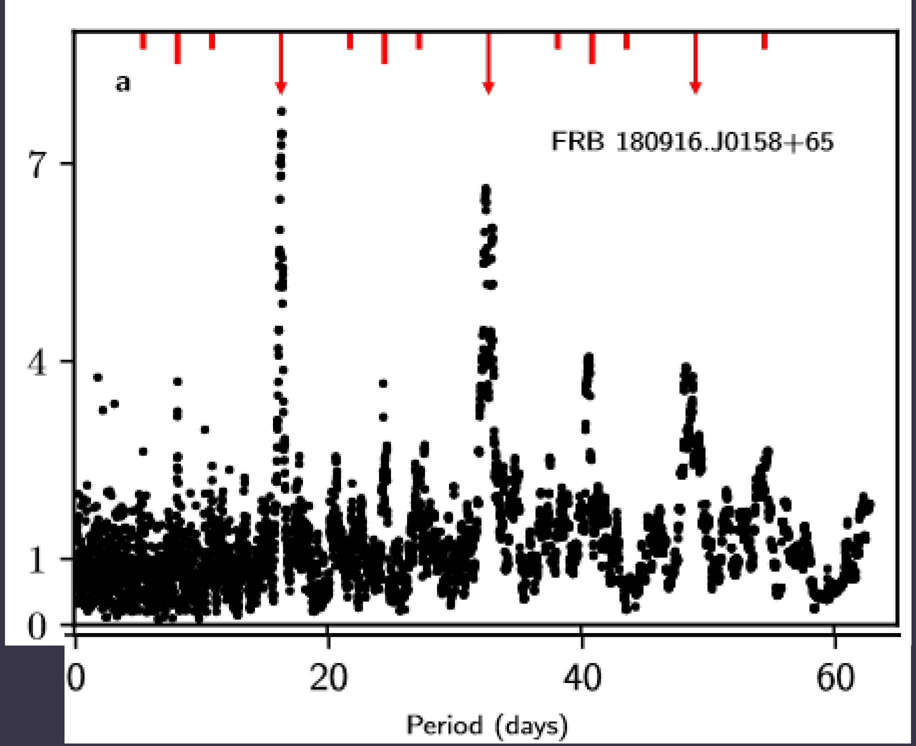


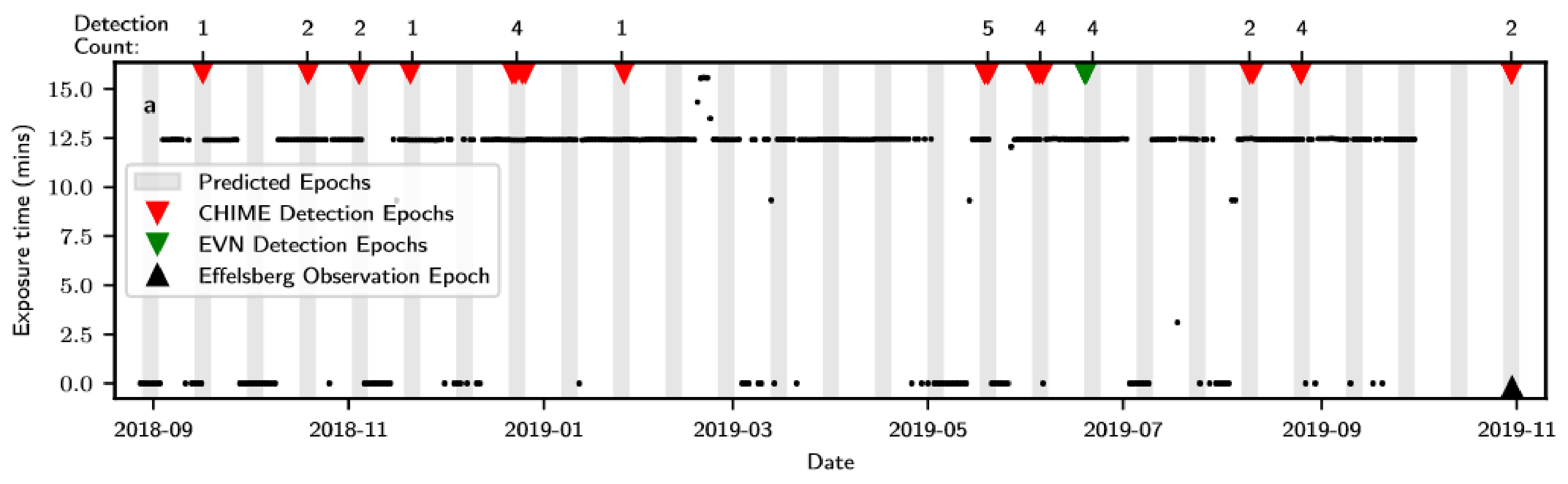


2003.04848

Periodicity in FRB bursts

FRB 180916.J0158+65
CHIME (+Effelsberg)

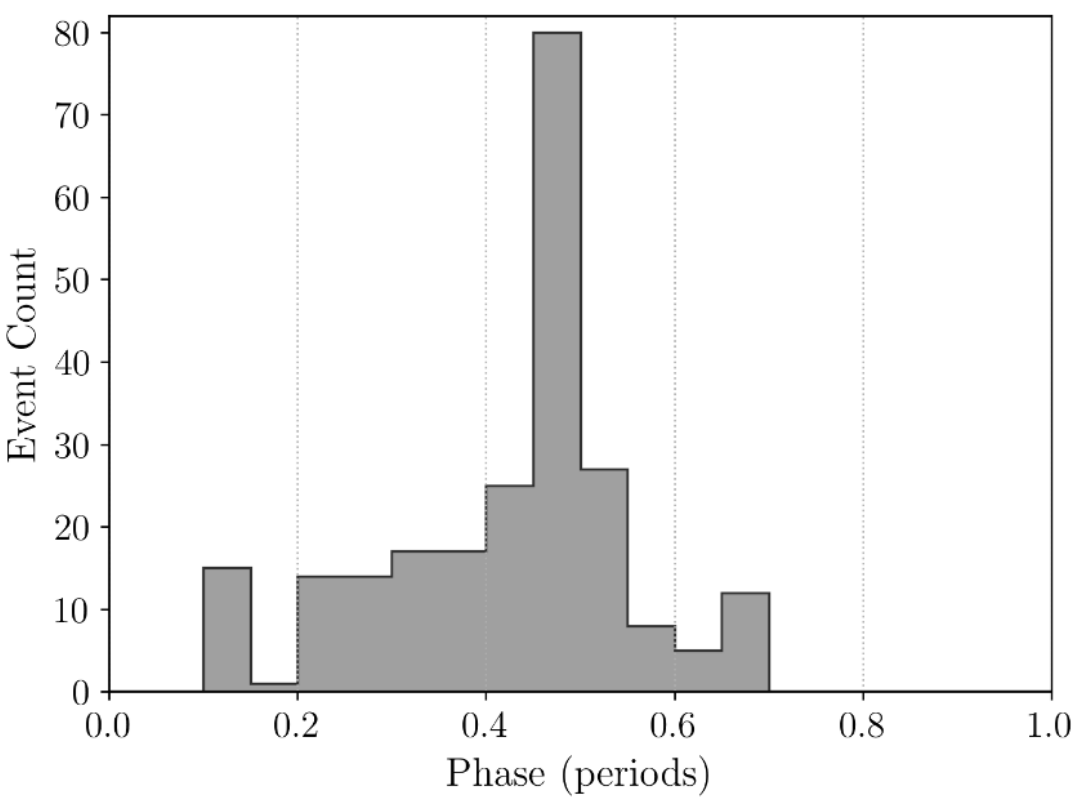


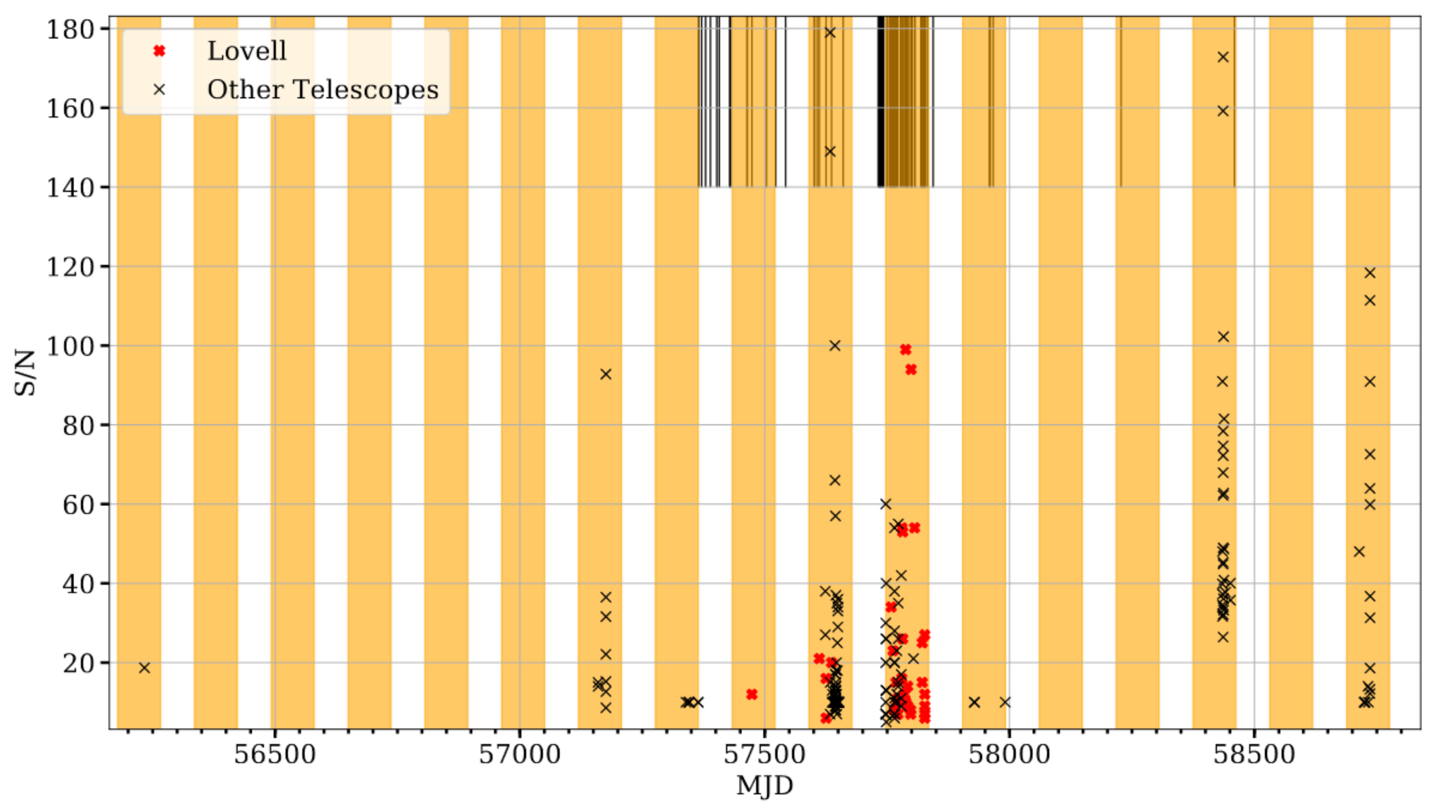


The source is localized in a near-by massive spiral galaxy.
Period ~16.35 days

2001.10275

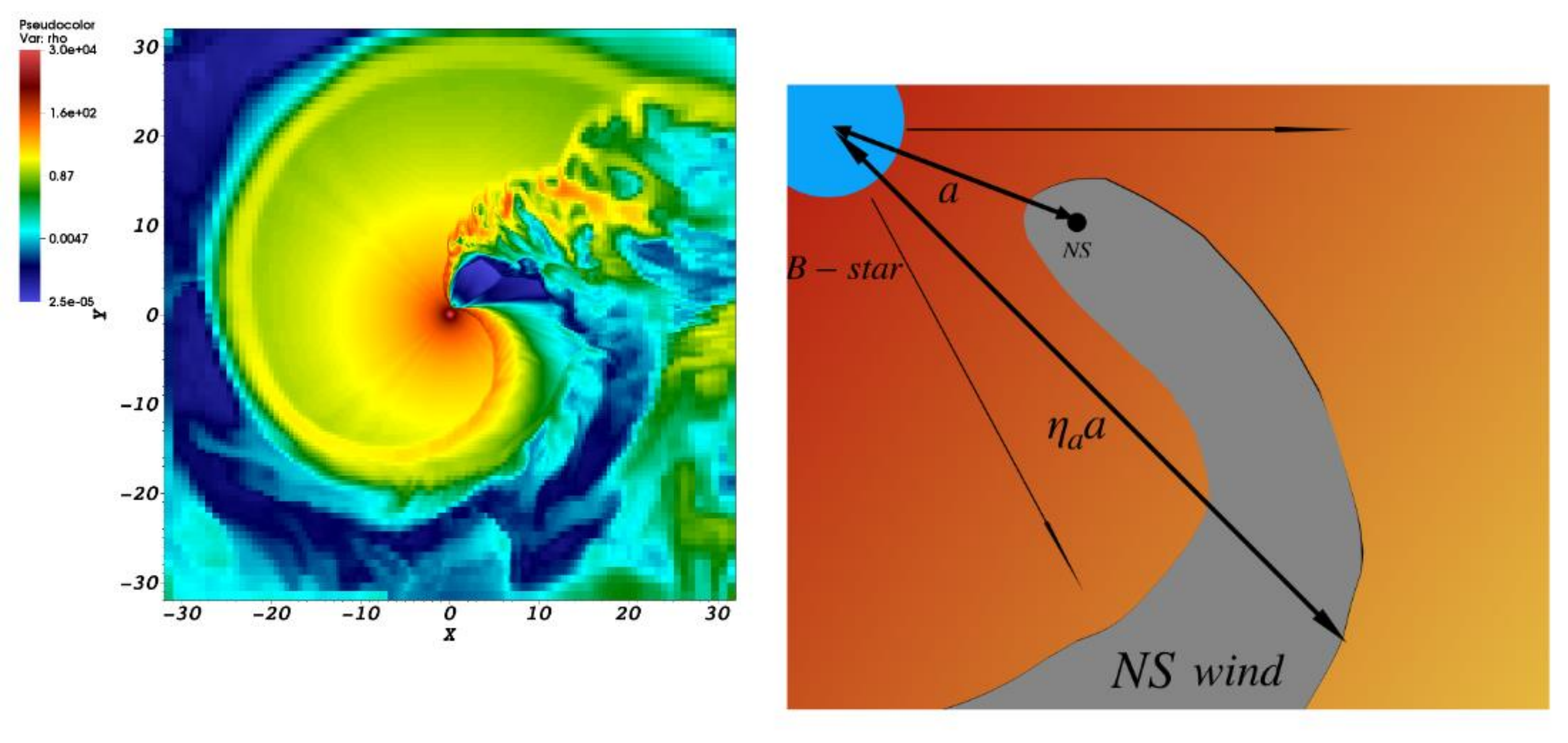
157 day periodicity of FRB 121102





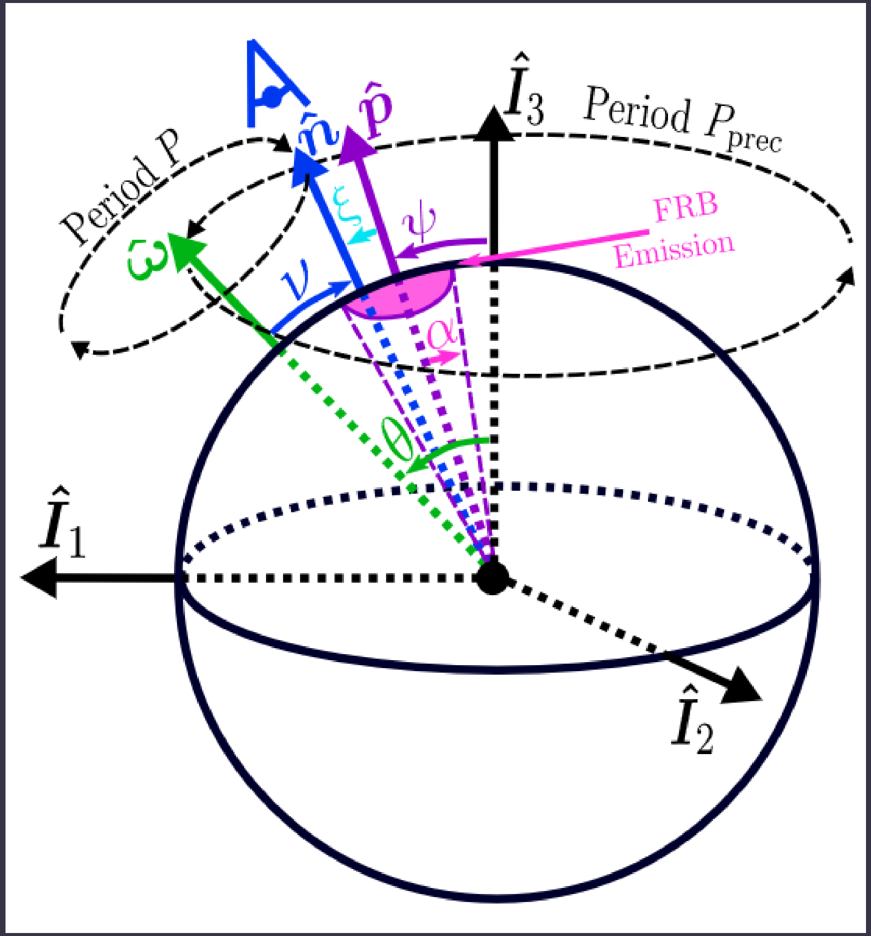
2003.03596, see also 2008.03461

A binary system?



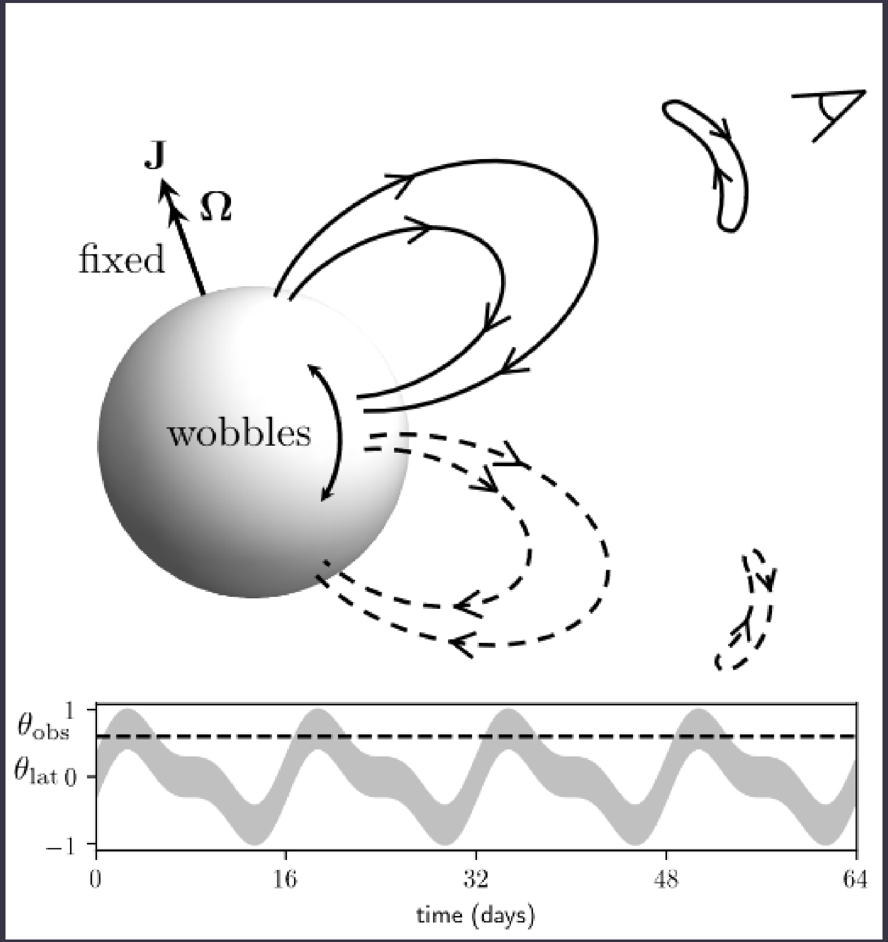
2002.01920

Precession?



Realistic values of oblateness due to strong magnetic field can explain the 16-day precission.

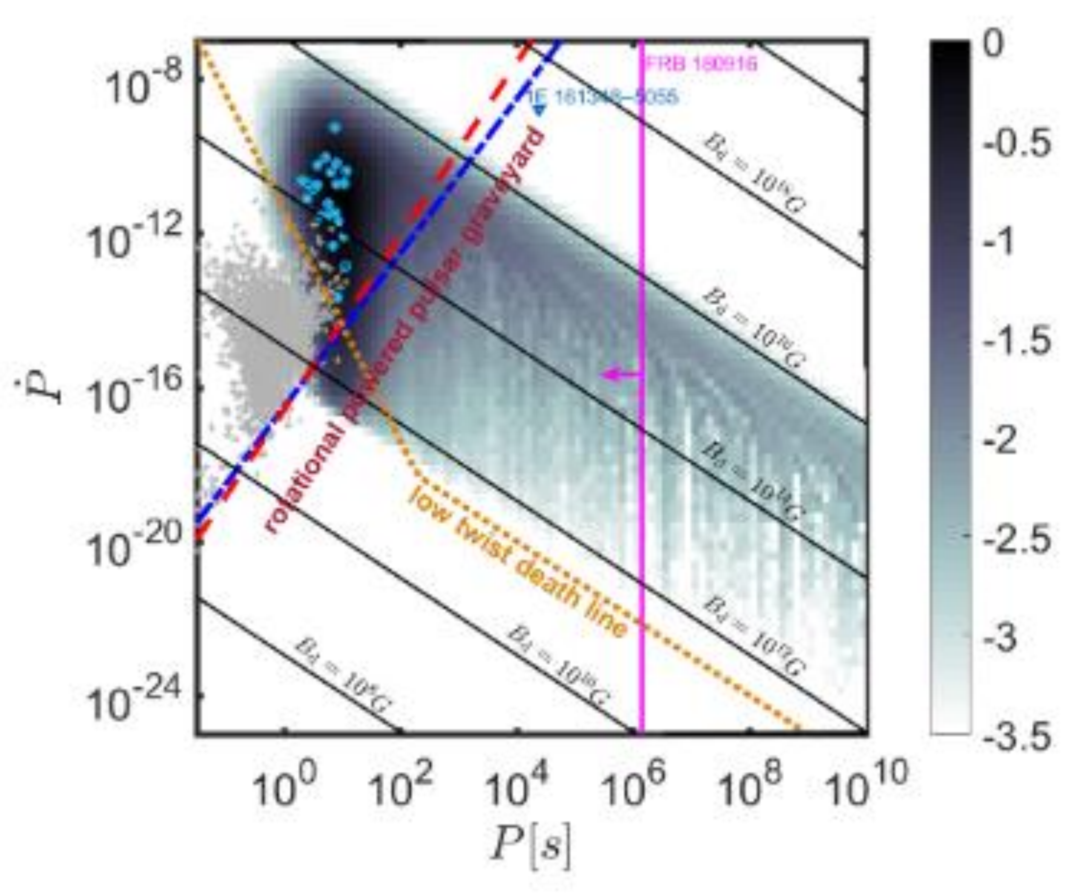
About triaxial precession see 2107.12874, 2107.12911.



2002.05752

2002.04595

Ultra-long spin periods?



E.g., fall-back can help to obtain long spin periods, as in the case of the source in RCW 103 (6.7 hours).
Or, enhanced spin down due to winds can be at work.
Or, kick can help to spin-down the NS.

2003.12509

Second localization of a FRB

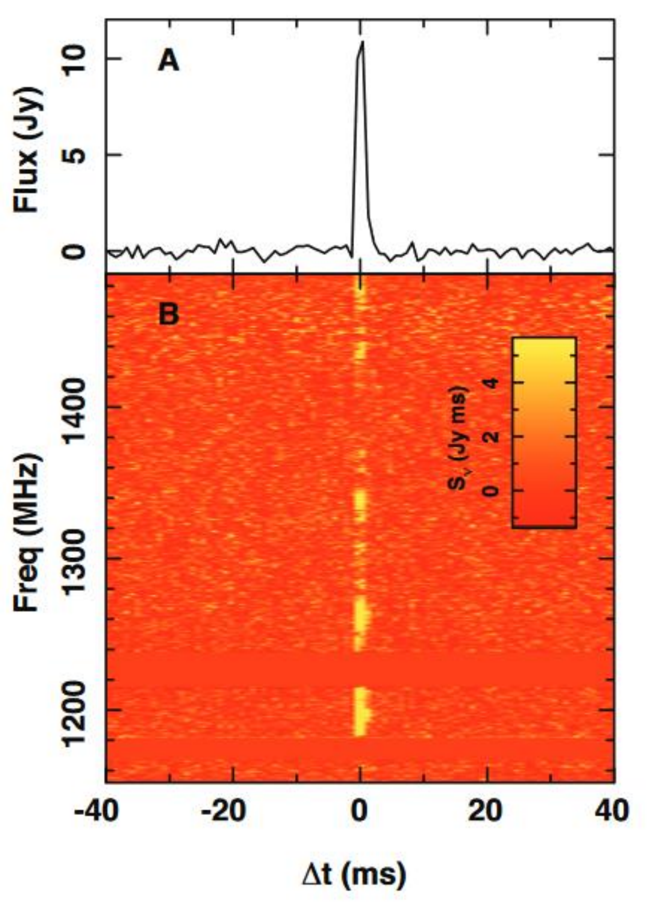
ASKAP

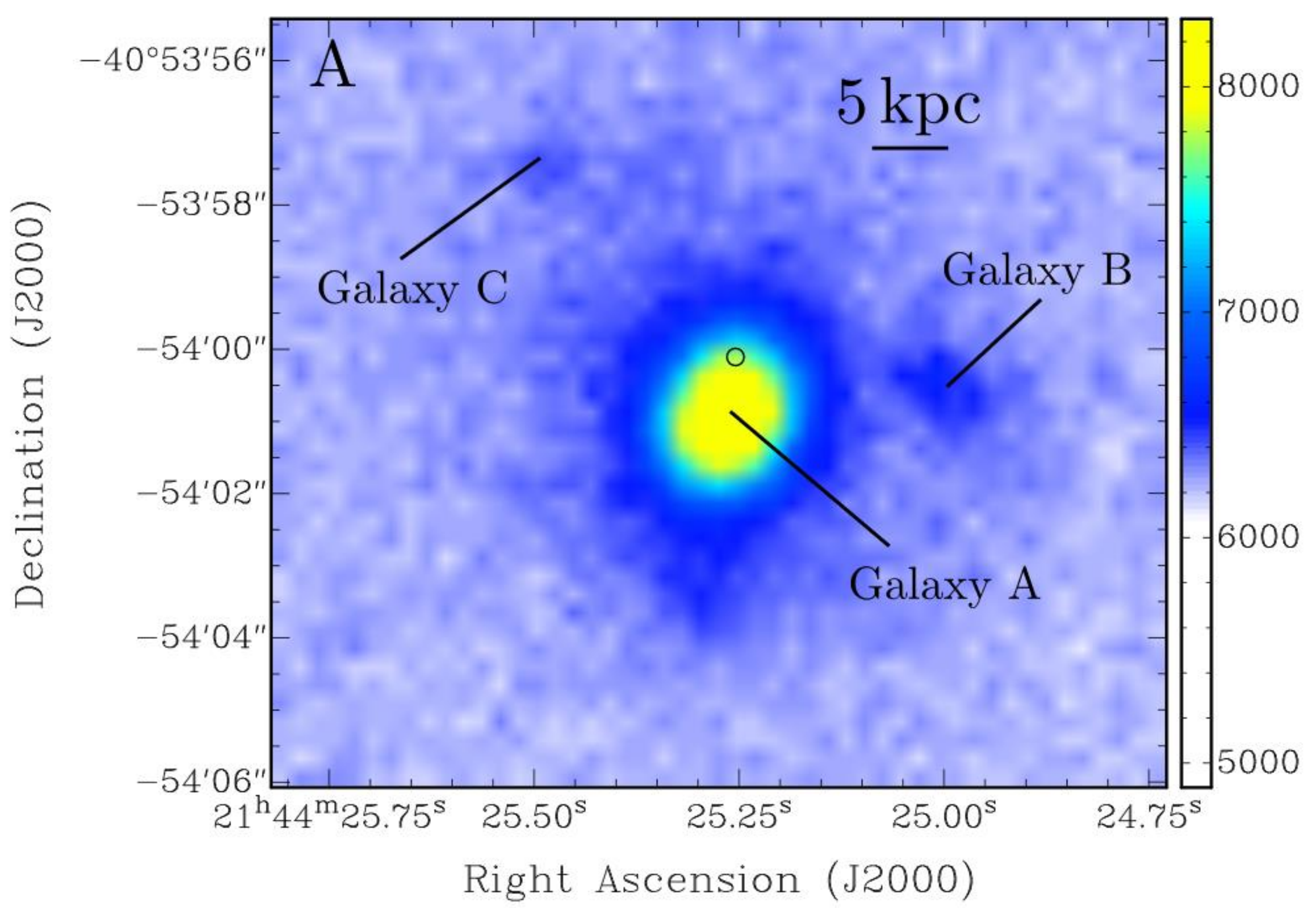
FRB 180924
non-repeating

16 Jy
DM~360
linear polarization
RM~14

Localization
~0.12 arcsec

z=0.32
Massive lenticular
or early-type





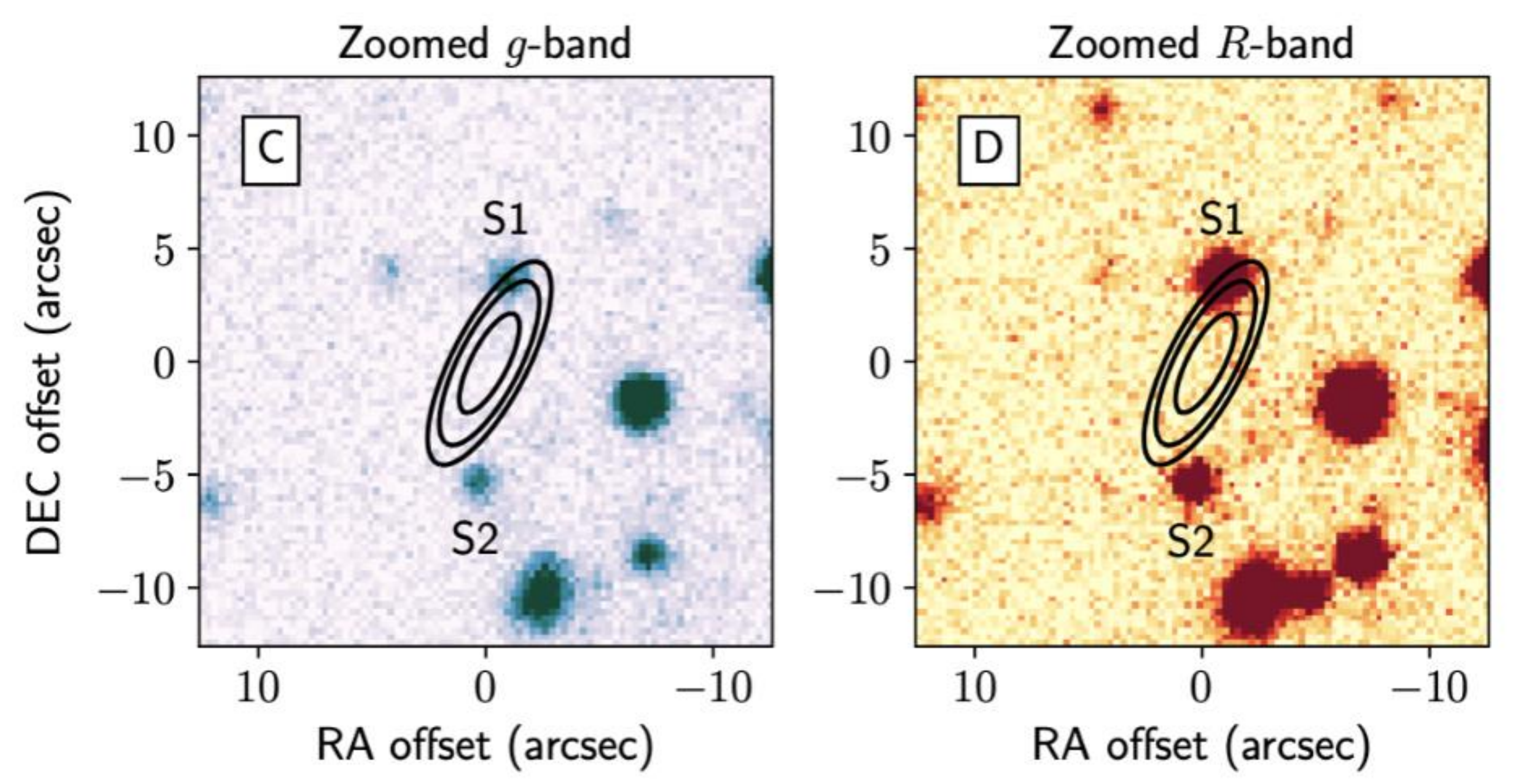
Third localization

DSA-10 antenna
1.4 GHz

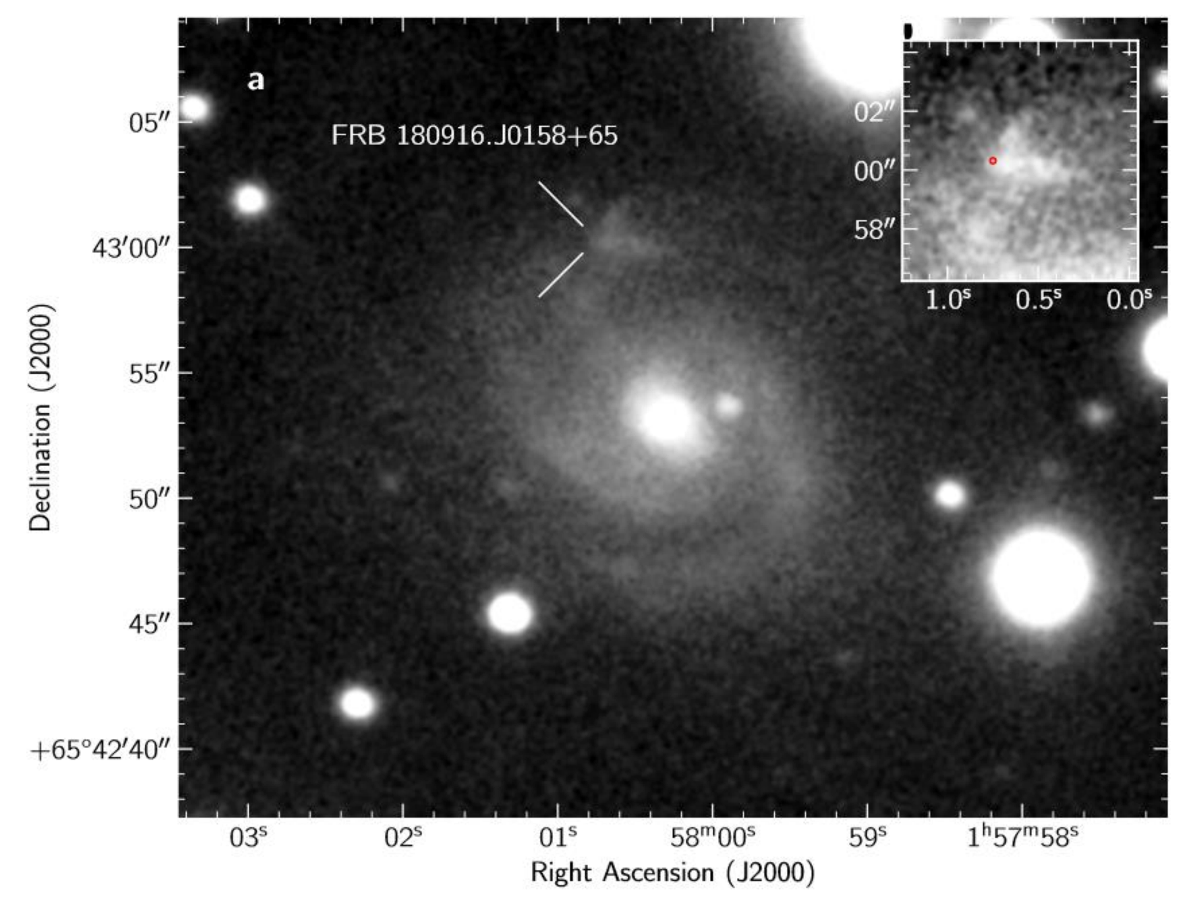
FRB 190523
non-repeating

DM=760

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



Fifth localization



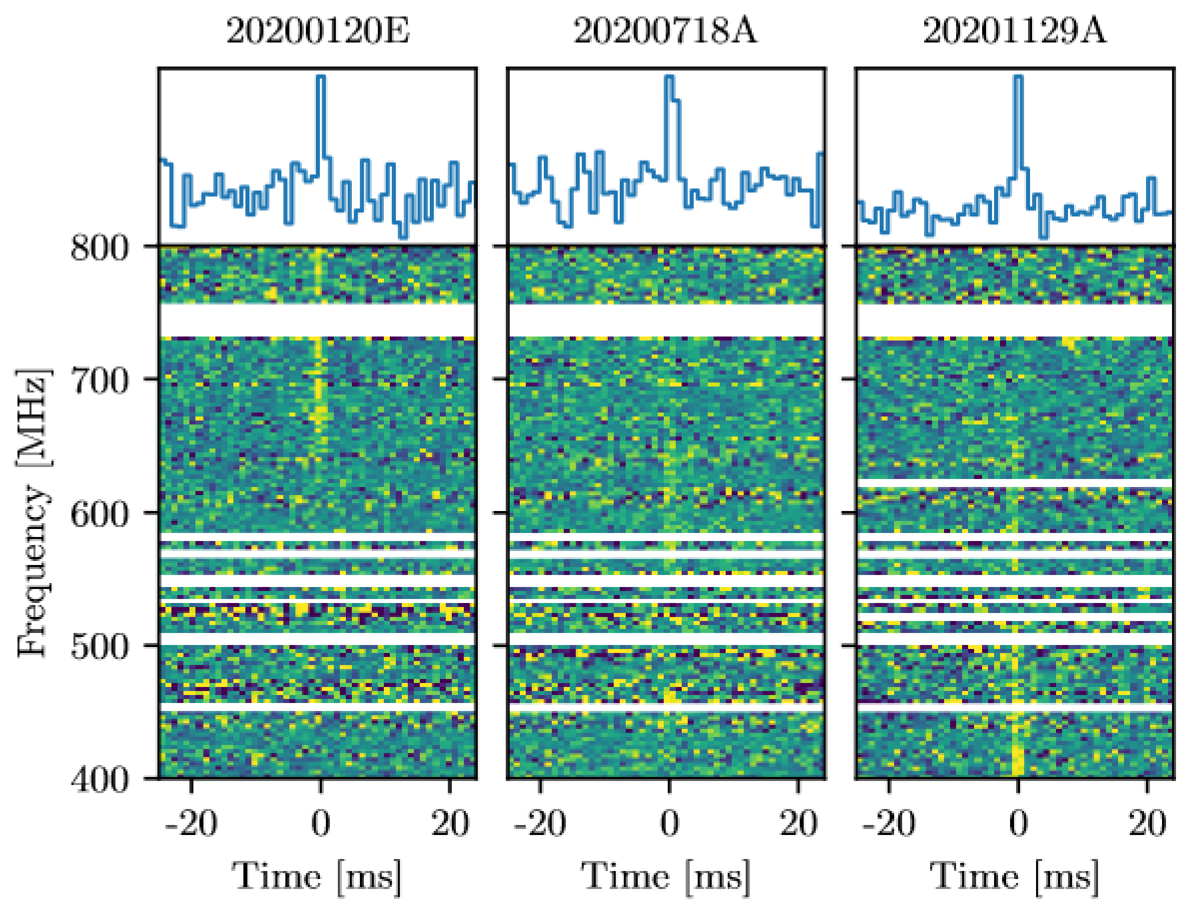
FRB180916.J0158+65
Repeator

Near-by spiral galaxy

See data on the immediate (60 pc) vicinity of the source in 2011.03257

2001.02222

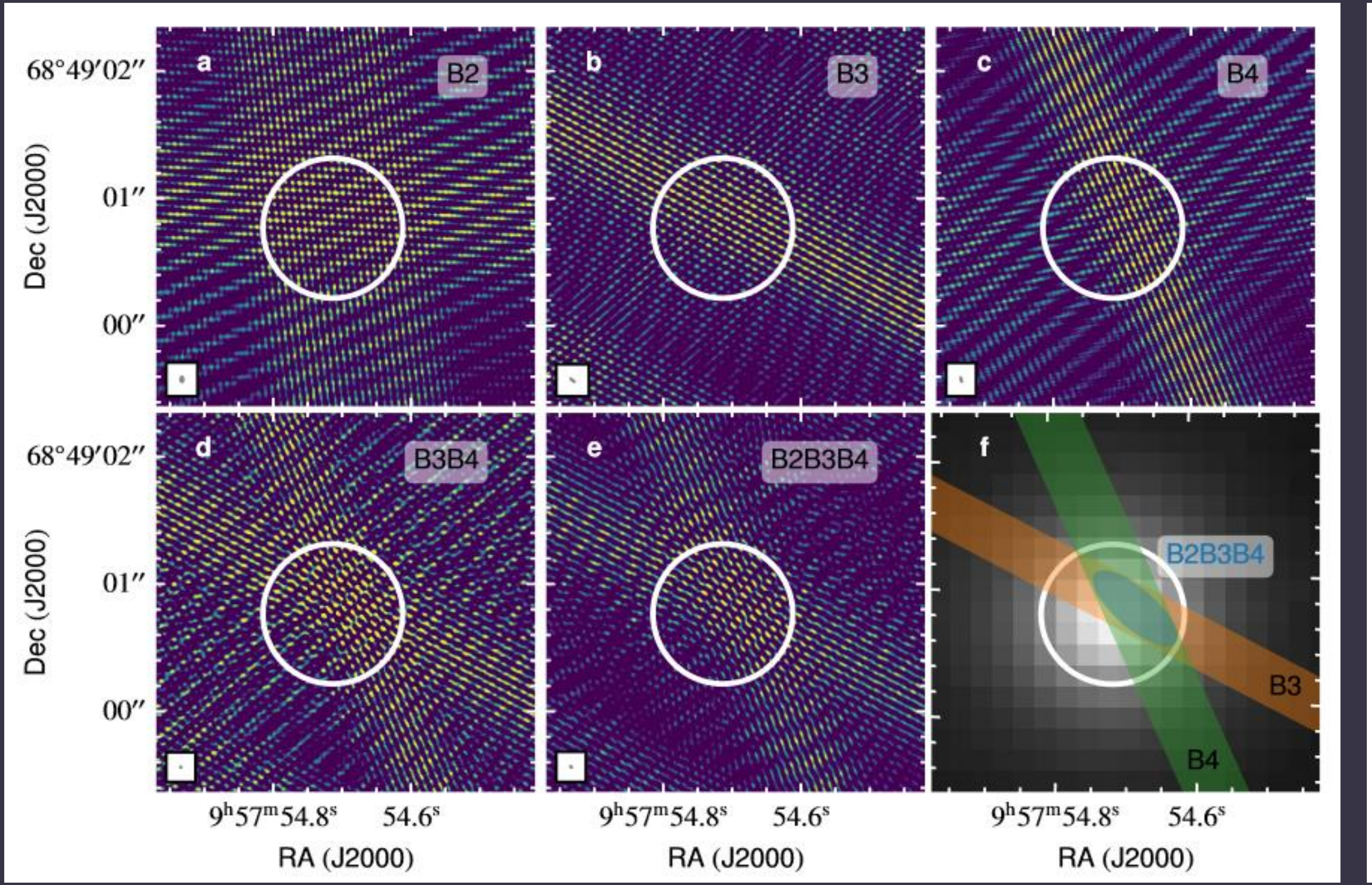
FRB from M81?

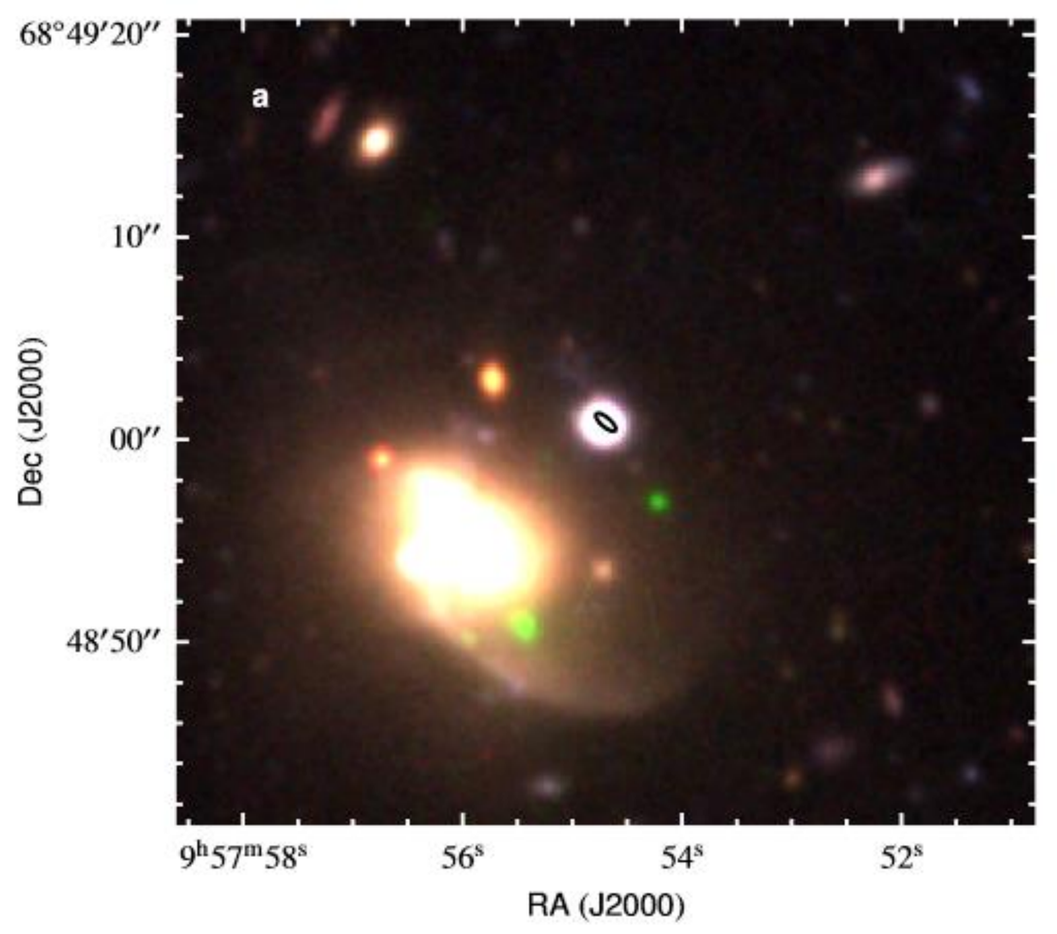


CHIME
Low DM~83

2103.01295

Even a globular cluster in M81?



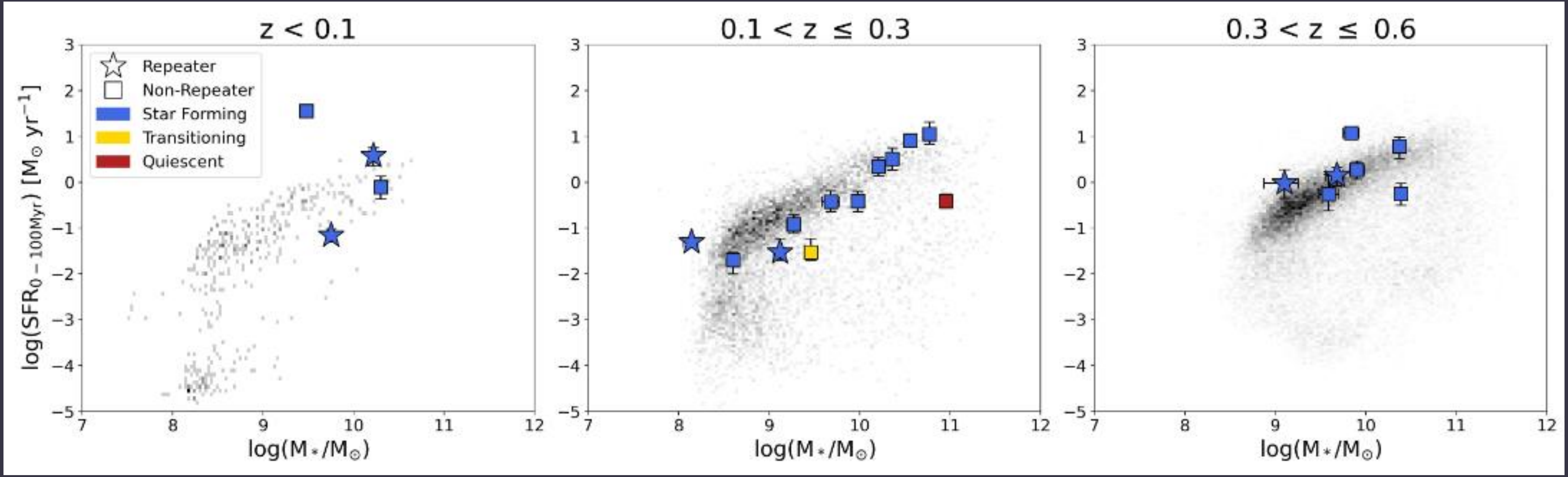


2105.11445

Analysis of 23 hosts

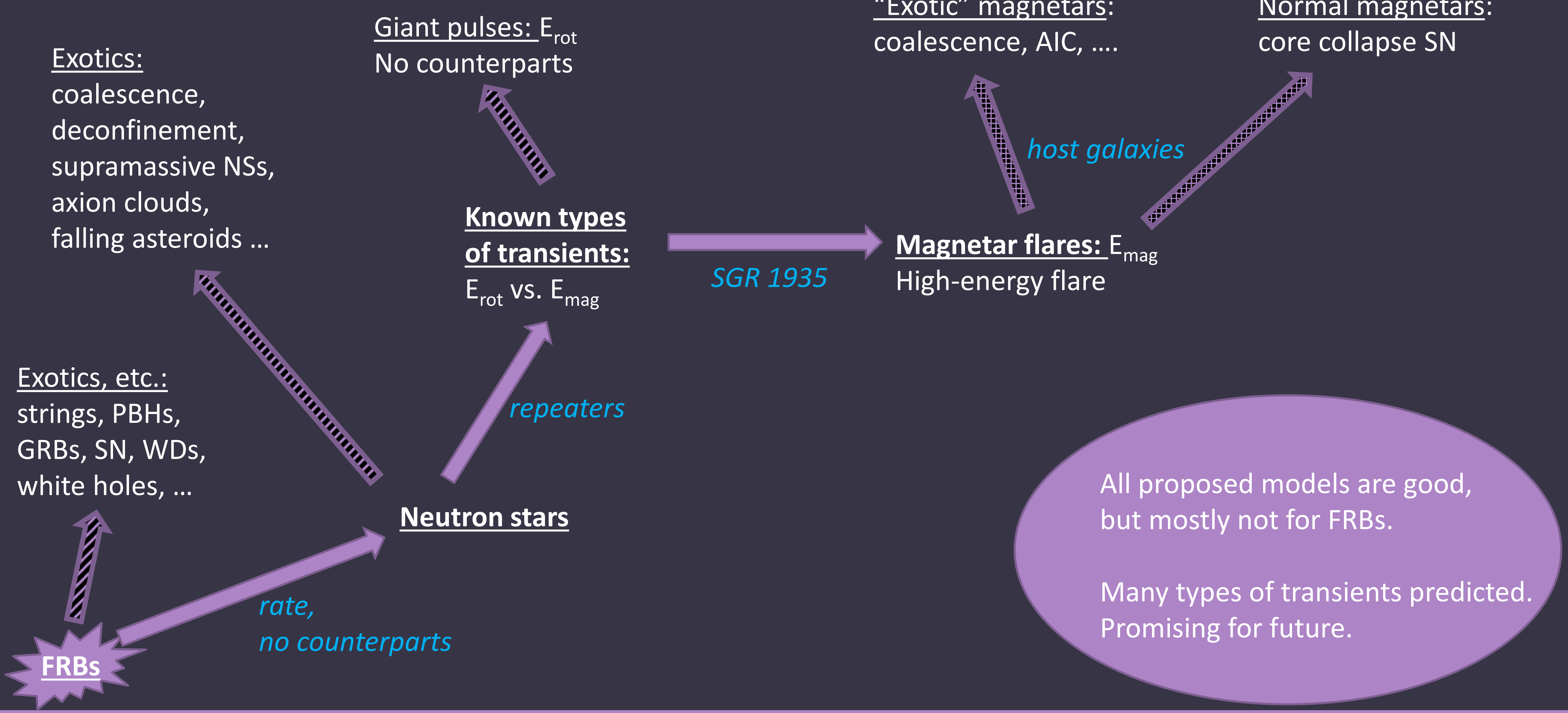
6 repeaters and 17 one-off

21 out of 23 are starforming



2302.05465

Now we know who, we do not know how



Exotics:
coalescence,
deconfinement,
supramassive NSs,
axion clouds,
falling asteroids …

Giant pulses: E_{rot}
No counterparts

"Exotic" magnetars:
coalescence, AIC, ….

Normal magnetars:
core collapse SN

host galaxies

Known types of transients:
E_{rot} vs. E_{mag}

SGR 1935

Magnetar flares: E_{mag}
High-energy flare

Exotics, etc.:
strings, PBHs,
GRBs, SN, WDs,
white holes, …

repeaters

Neutron stars

rate,
no counterparts

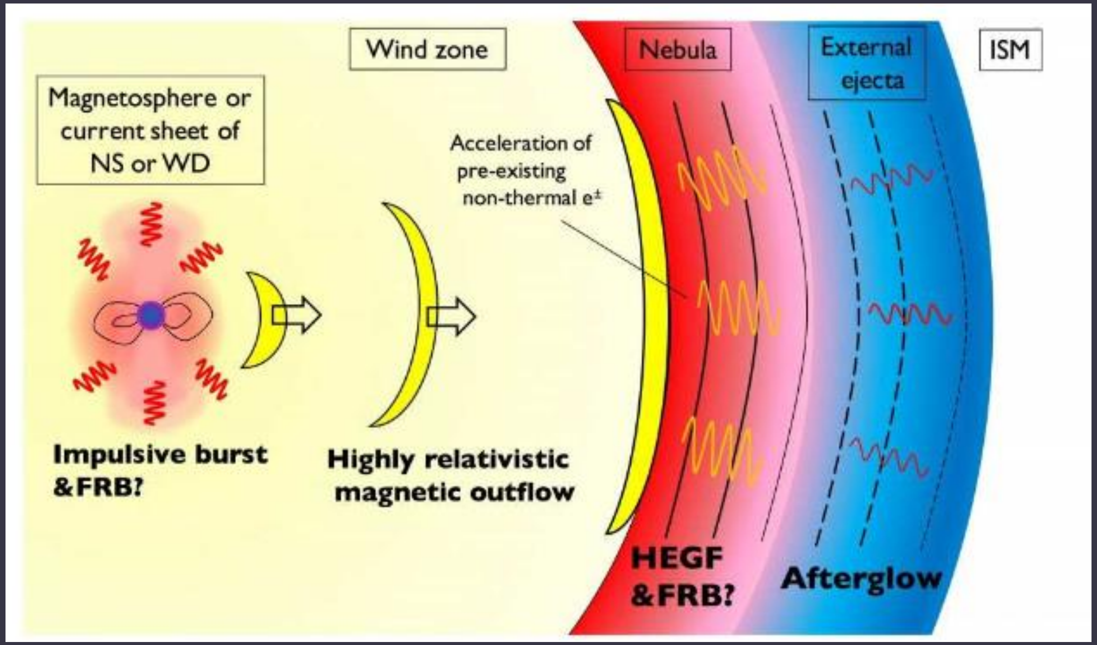
FRBs

All proposed models are good, but mostly not for FRBs.

Many types of transients predicted. Promising for future.

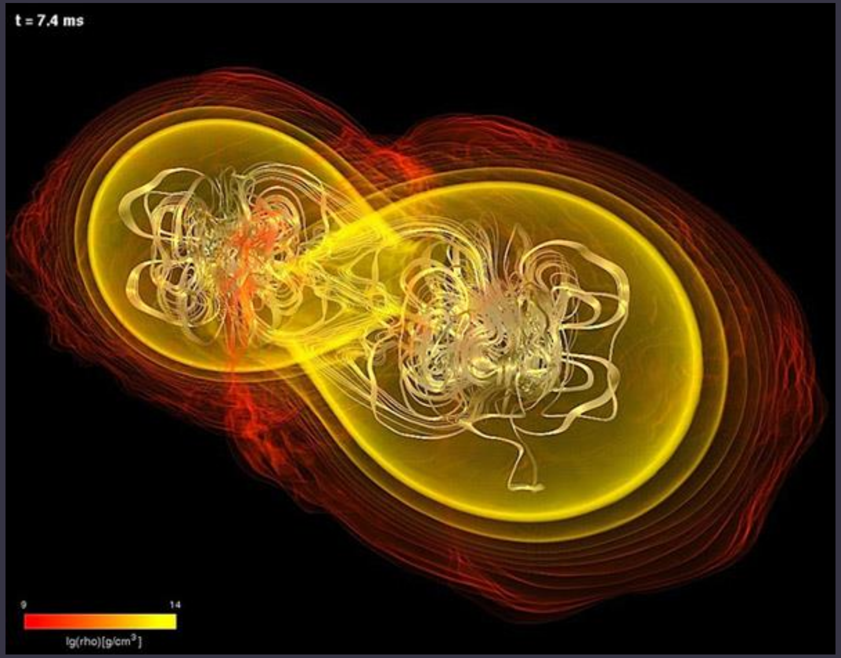
Origin of magnetars

“Normal”:
single core-collapse

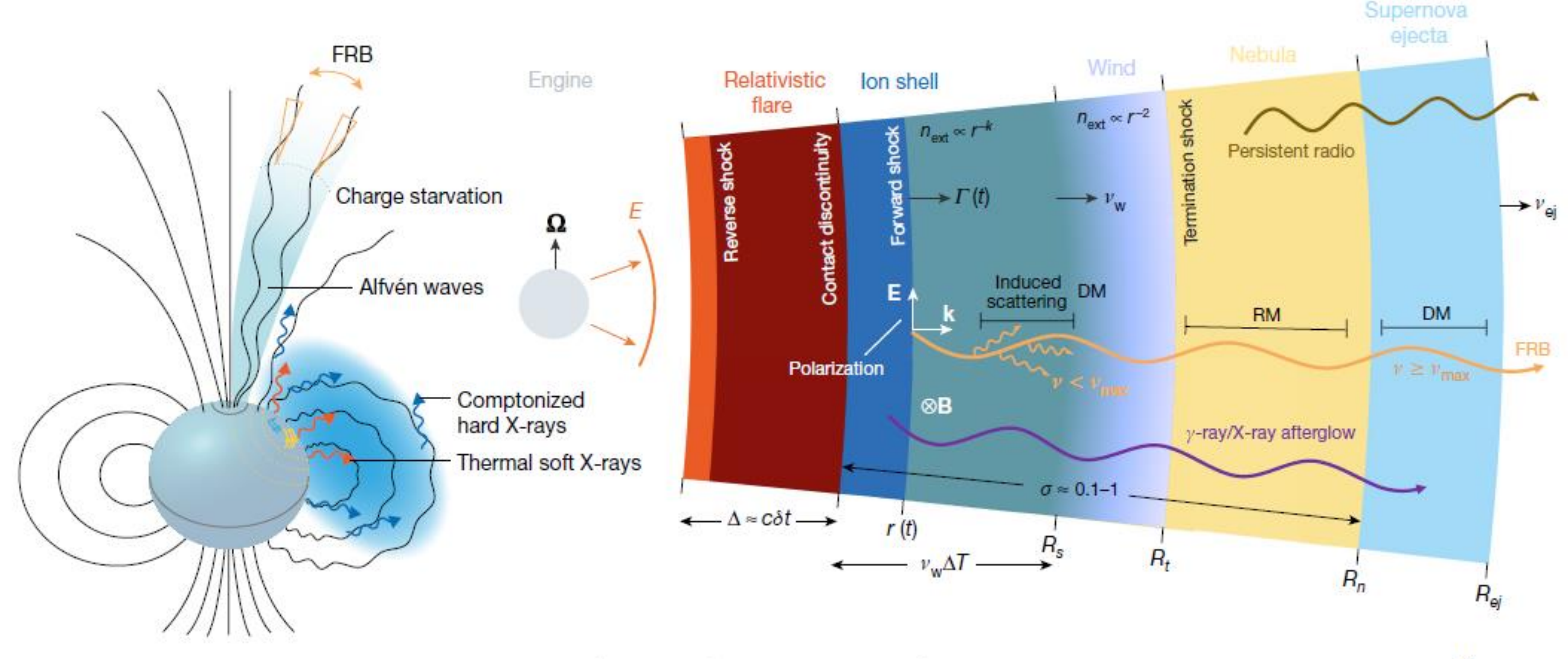


Murase et al. 2016

Coalescence
(NS+NS, NS+WD, WD+WD).

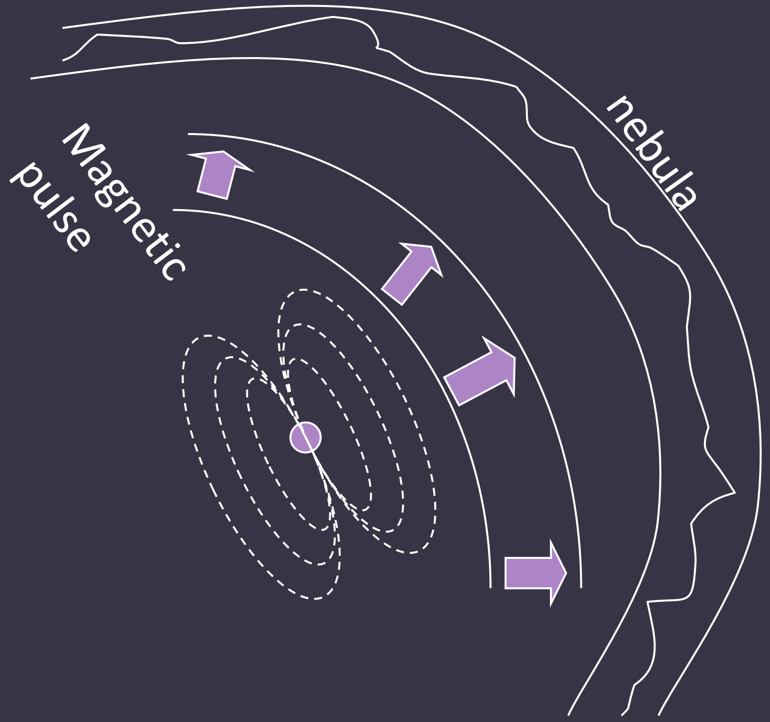


Magnetosphere or outer shocks?



Zhang 2020 (Nature)

Synchrotron maser



Synchrotron maser emission
(Alsop & Arons 1988; Hoshino & Arons 1991).
To obtain high frequency it is necessary to
have a relativistic (magnetized) shock.

In FRB models emission is typically
generated due to interaction with
a nebula at ~10^{13}-10^{16} cm from the NS.

$$\nu = 5 \frac{\zeta}{\sigma_{\rm wind}\gamma^2_{\rm wind}} \frac{\mu_{33}^{3/2}}{L^{1/4}_{\rm pulse,47} P^3 \tau_{\rm ms}} \ {\rm GHz.}$$

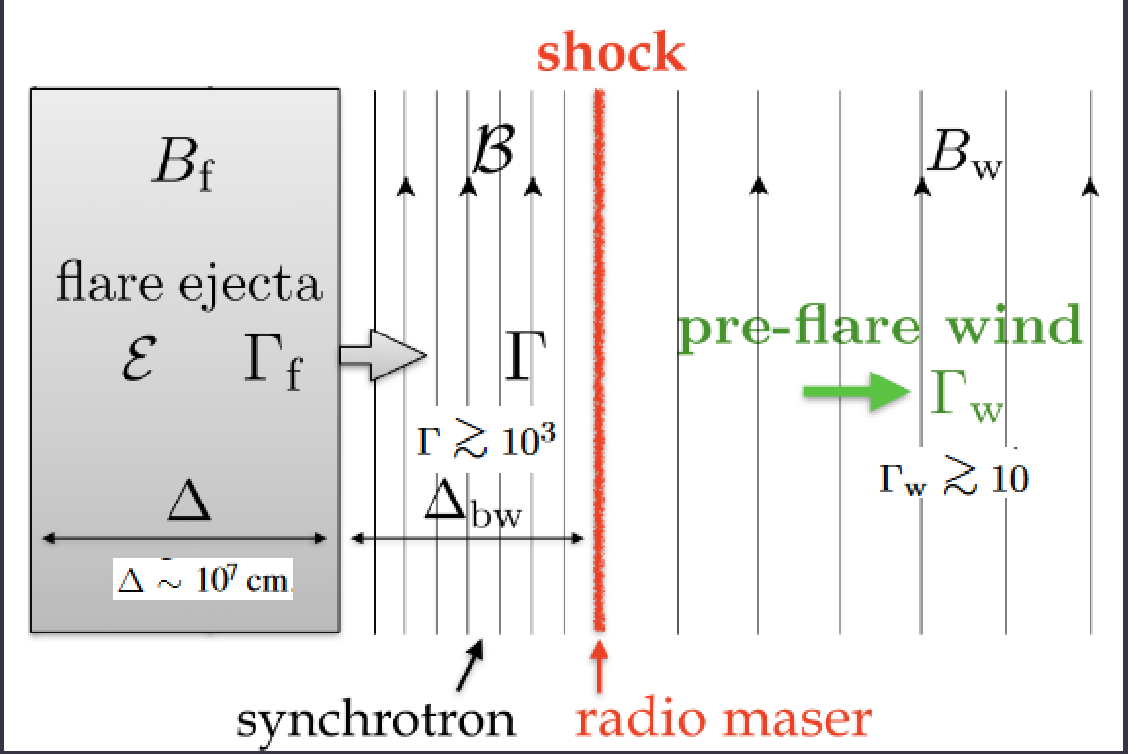
$$\mathcal{E}_{\rm FRB} = \chi\mathcal{E} = 10^{41}\chi_{-3}L_{\rm pulse,47}\tau_{\rm ms}\ {\rm erg.}$$

The first detailed magnetar model
with emission mechanism
was developed by Lyubarsky (2014).

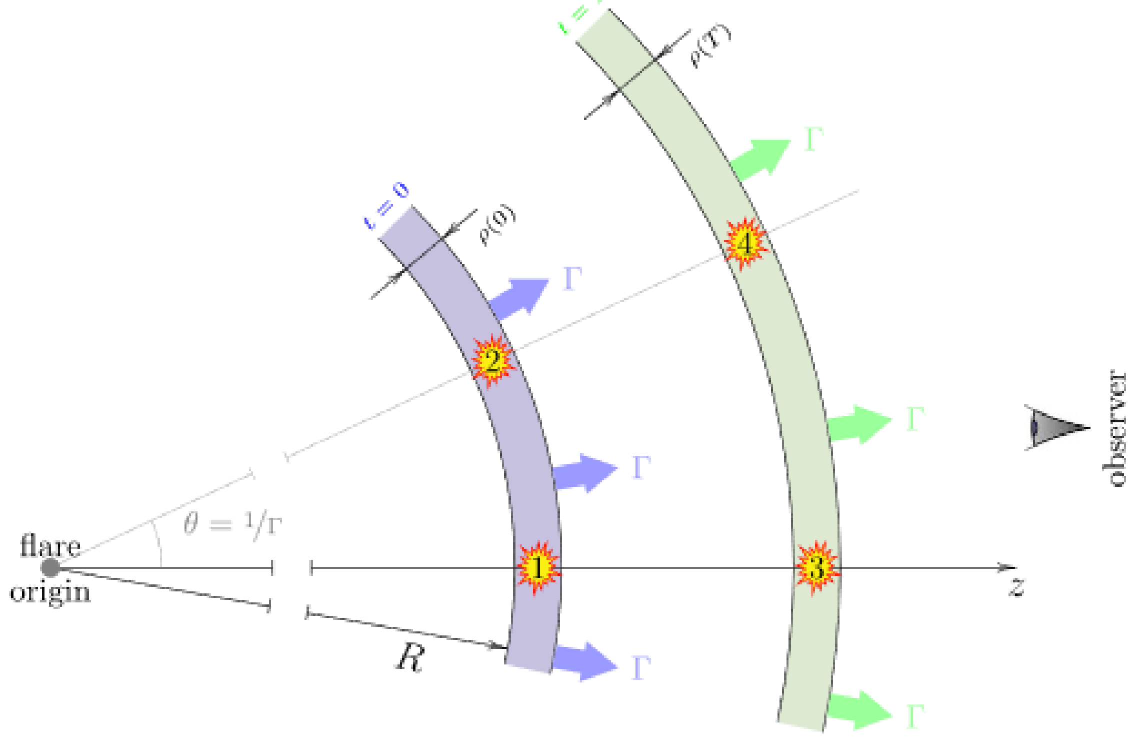
See a review, e.g. in
Lyubarsky 2021

Numerous models with synchrotron masers

A burst produces a blast wave. A shock appears due to interaction of the blast and the wind. At the shock the maser mechanism is operating.



Anisotropic synchrotron maser emission at the reverse shock in the flare's weakly magnetized matter



Beloborodov 2020

Khangulyan et al. 2022

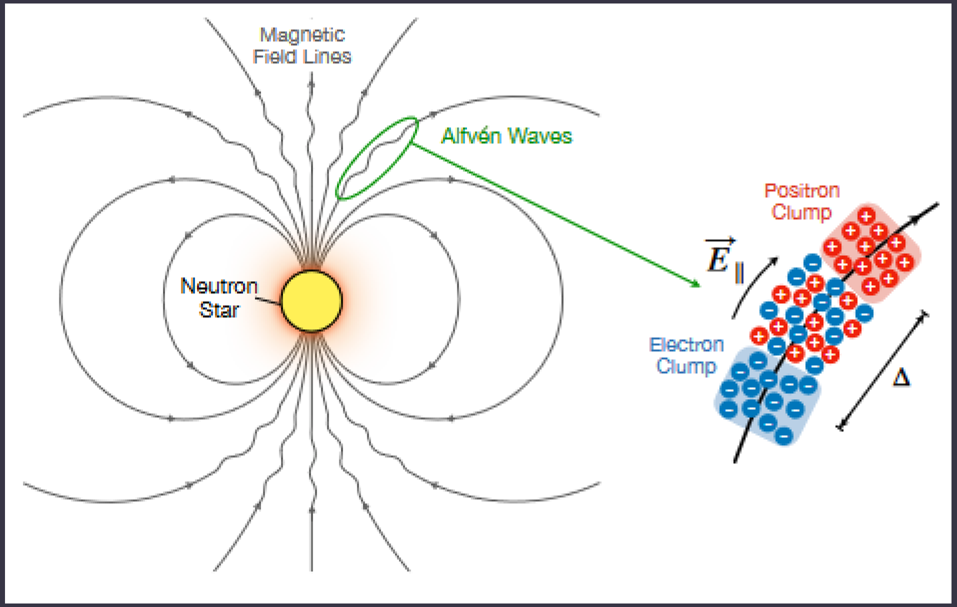
Magnetospheric processes

Perturbations of a NS magnetic field (including reconnection) might result in generation of waves, particle production and acceleration.
At the end, this can produce a burst of radio emission.

Early models were based on analogy with radio pulsars, i.e. rotational energy losses
(Pen & Connor 2015; Cordes & Wasserman 2016).
New models usually assume magnetic energy dissipation.

Magnetospheric models can face difficulties:
- total energy budget (e.g., size of bunches)
- propagation from the inner magnetosphere (external plasma)
- unobserved correlations, e.g. Luminosity-Frequency
- narrow spectra

Electron-positron pairs bunches produce coherent curvature radiation

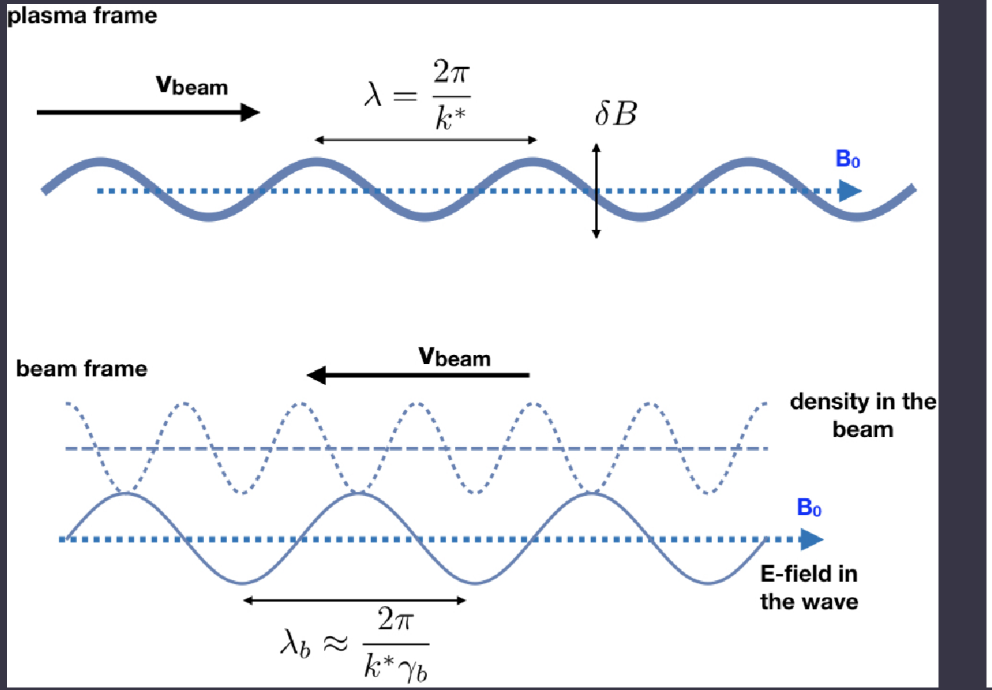


Yang et al. 2020

About early magnetospheric models see e.g. Katz (2014), Kumar et al. (2017).

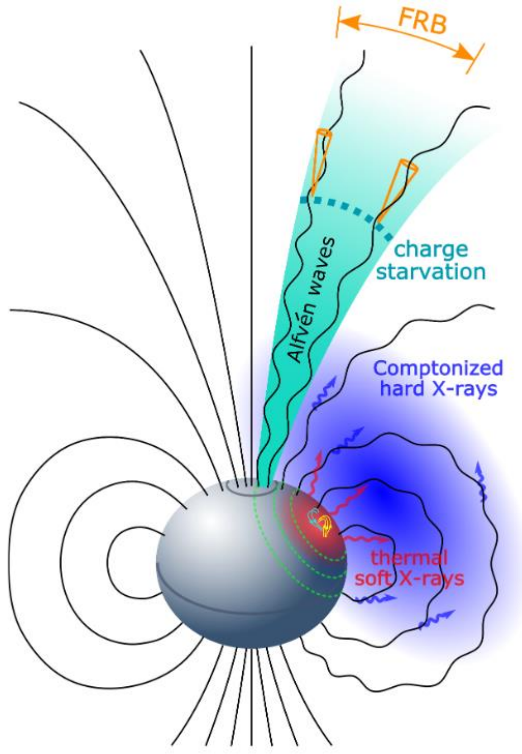
Variety of models: some examples

Free electron laser.
Bunches of particles oscillate and emit coherently



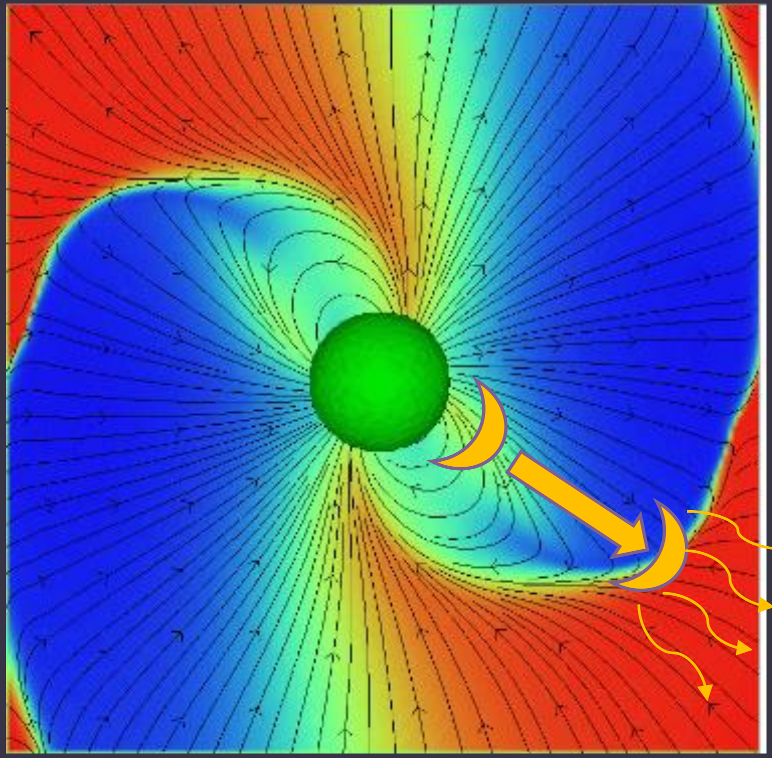
Lyutikov 2020, 2021

Alfven waves+
two-stream instability



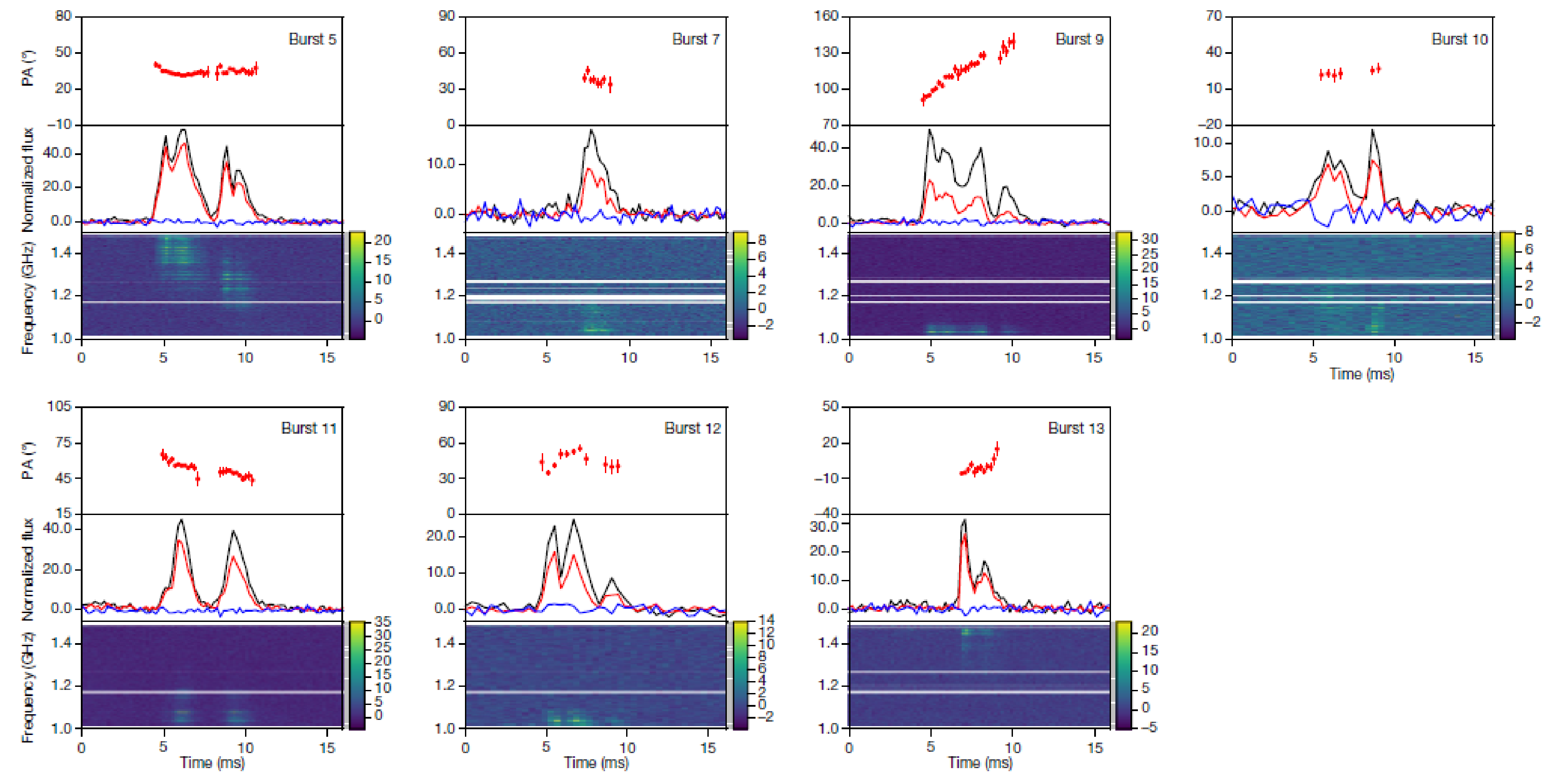
Lu et al. 2020

Relativistic magnetic reconnection
in the outer magnetosphere of the magnetar



Lyubarsky 2020

Polarization variability from burst to burst



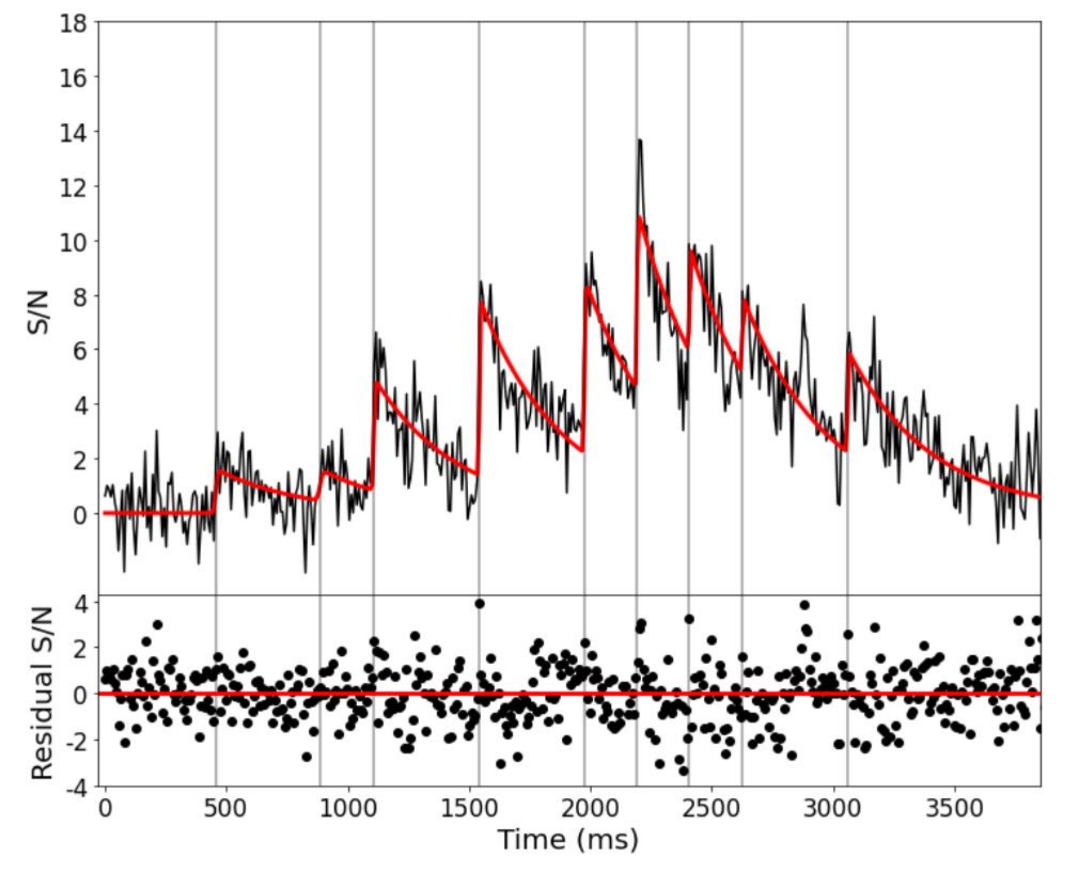
FRB 180301

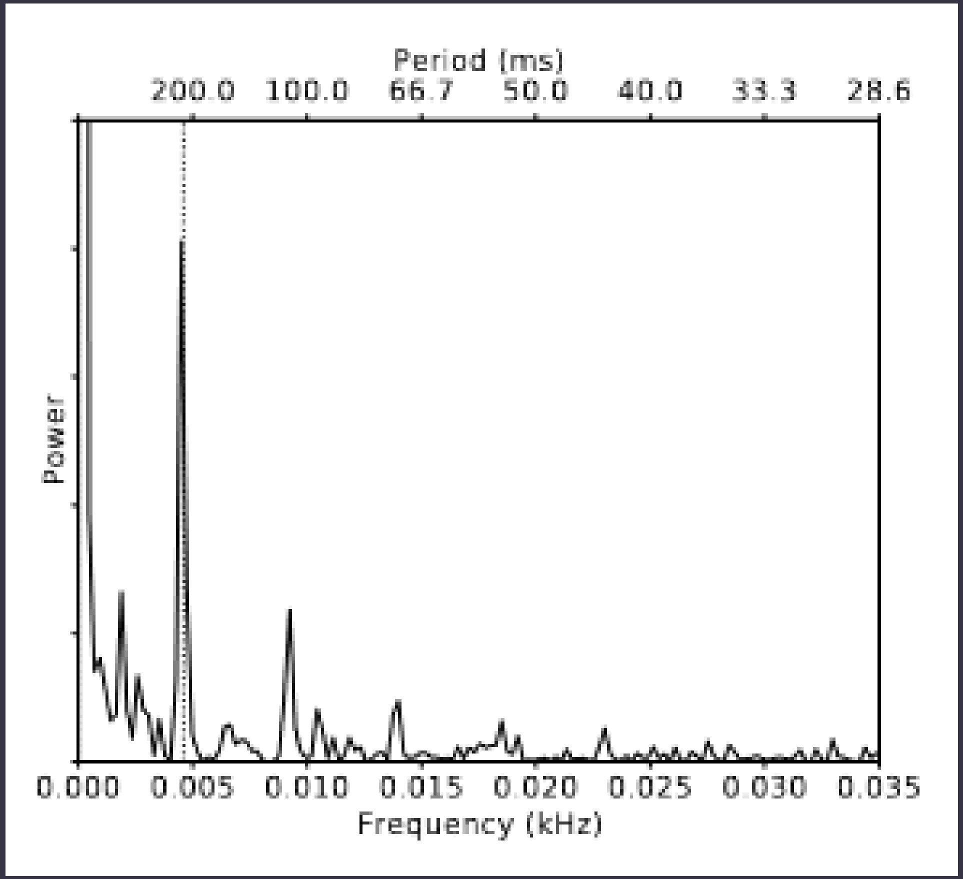
On other hand,
in the case of
FRB 121102
the polarization
angle was stable
for many months
(Michilli et al. 2018)

Luo et al. 2020

Periodicity in the burst structure

CHIME
FRB191221
single burst
217 msec

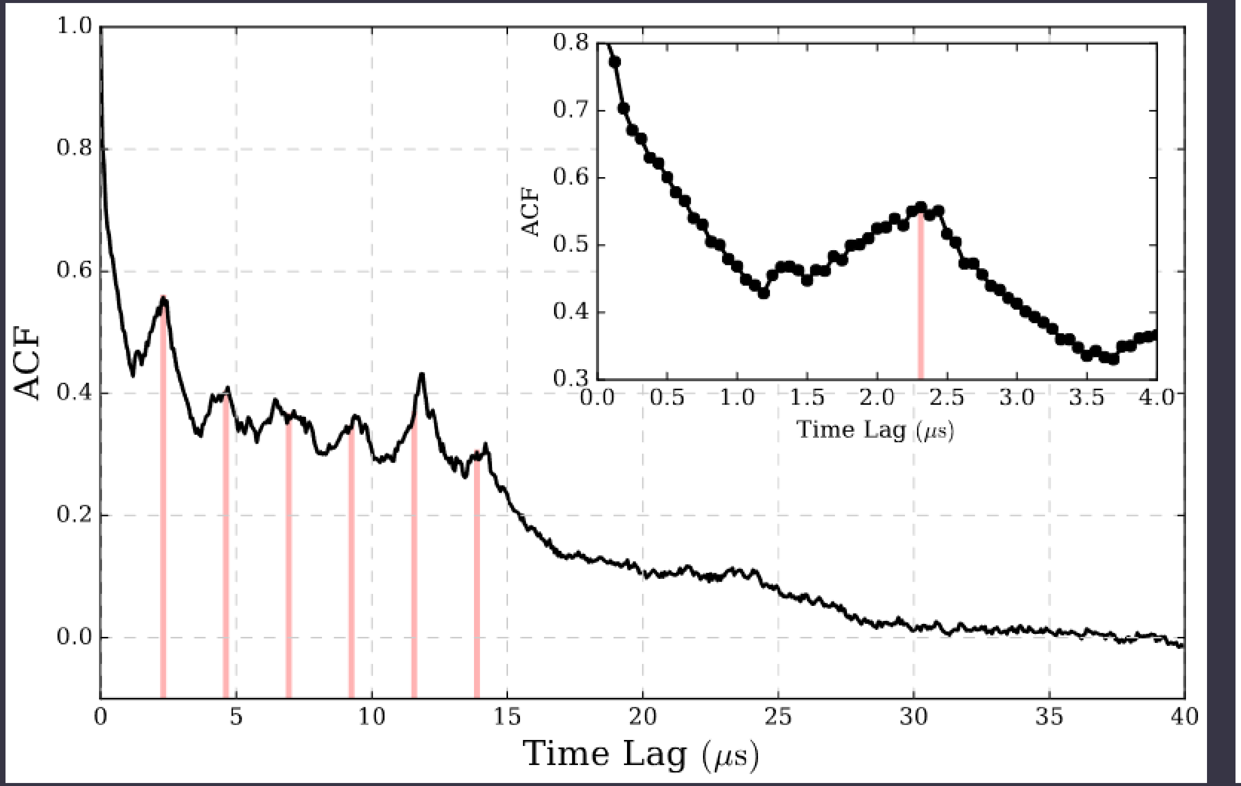


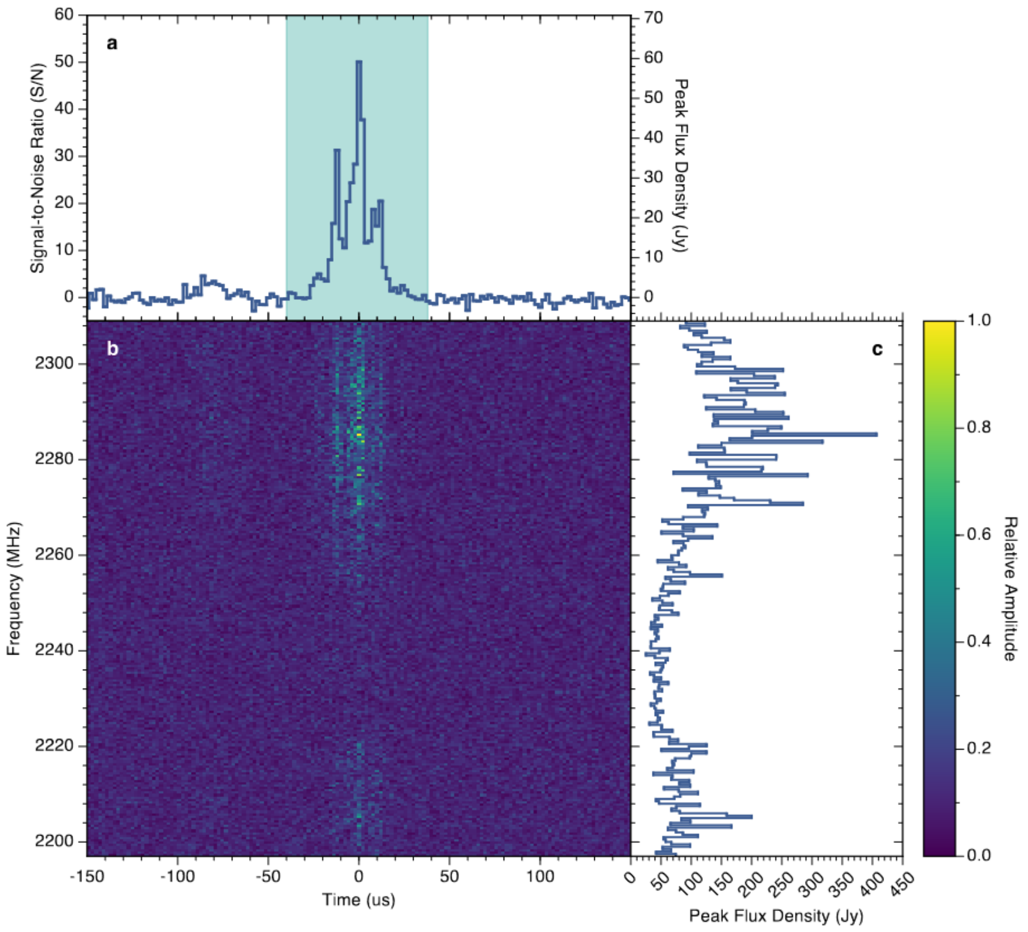


Andersen et al. 2022 Might be a strong argument in favour of magnetospheric models, see 2211.07669

A microsecond periodicity?

FRB 20200120E. The one in a GC in M81
2-3 microsecond structure

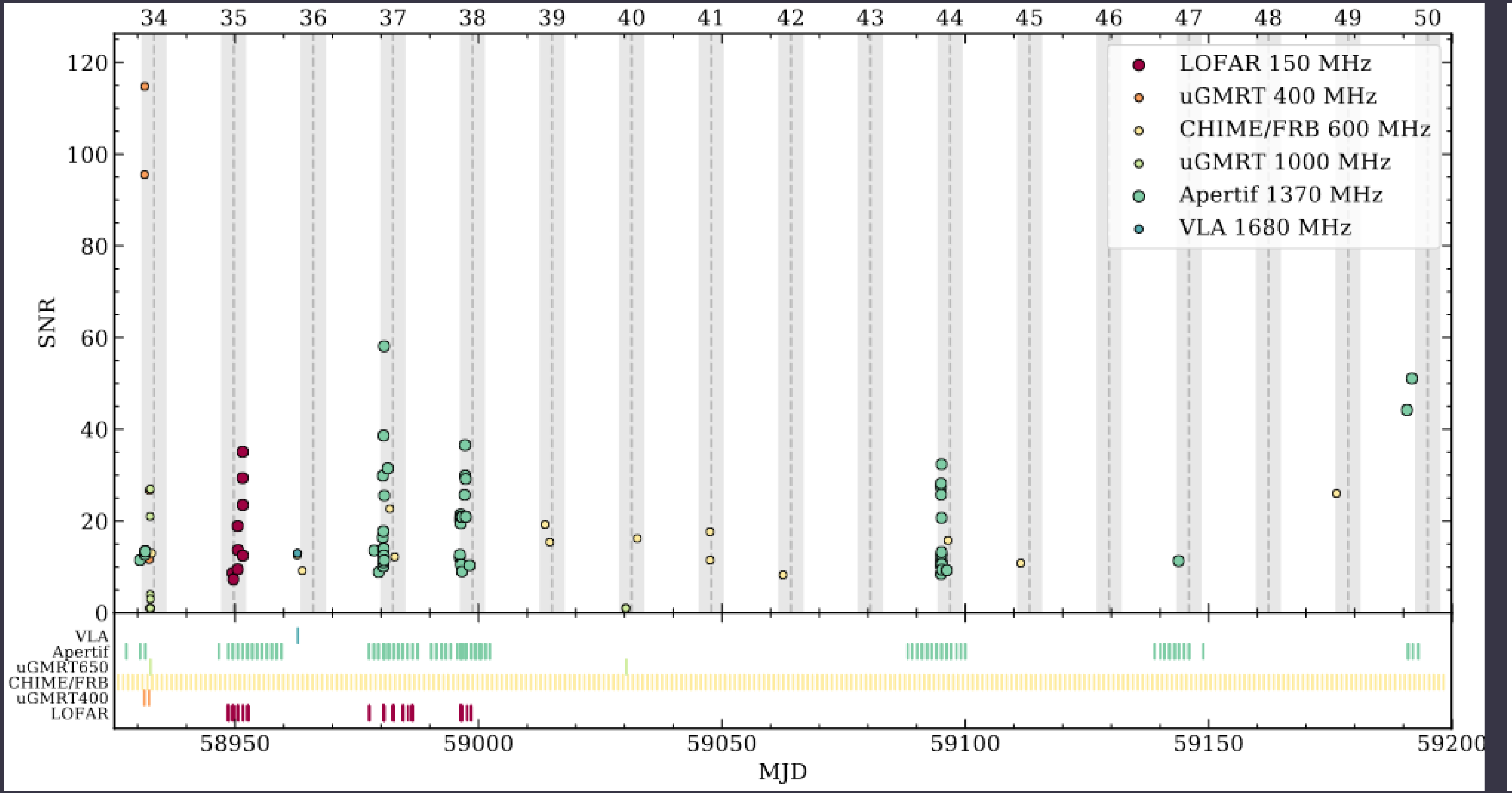




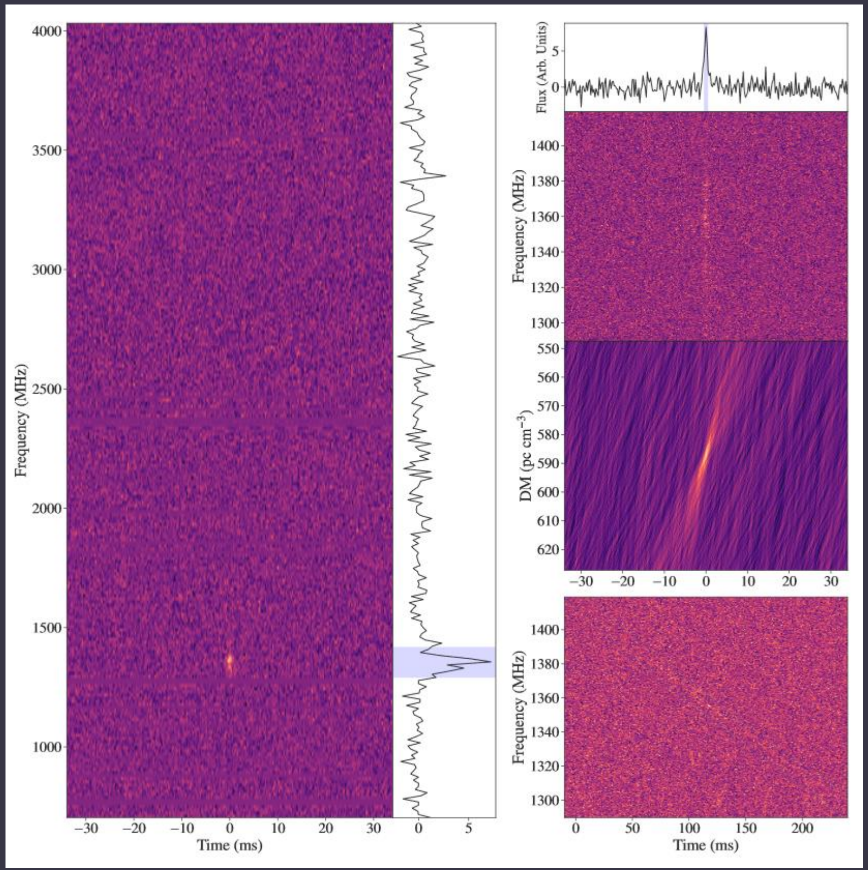
2105.10987

Narrow radio spectra (of repeaters)

No coincident bursts at significantly different frequencies for FRB 20180916B



A very narrow spectra of FRB 20190711A

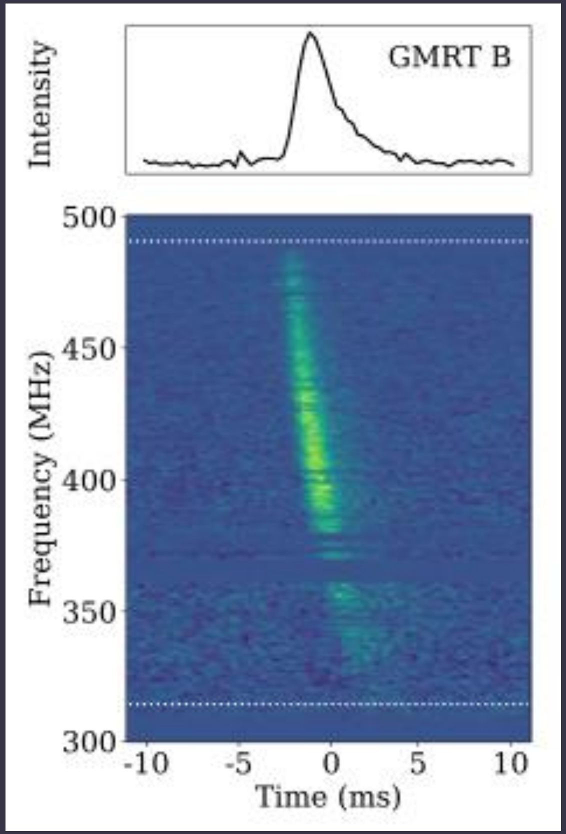


Pastor-Marazuela et al. 2020, see also Sand et al. 2022

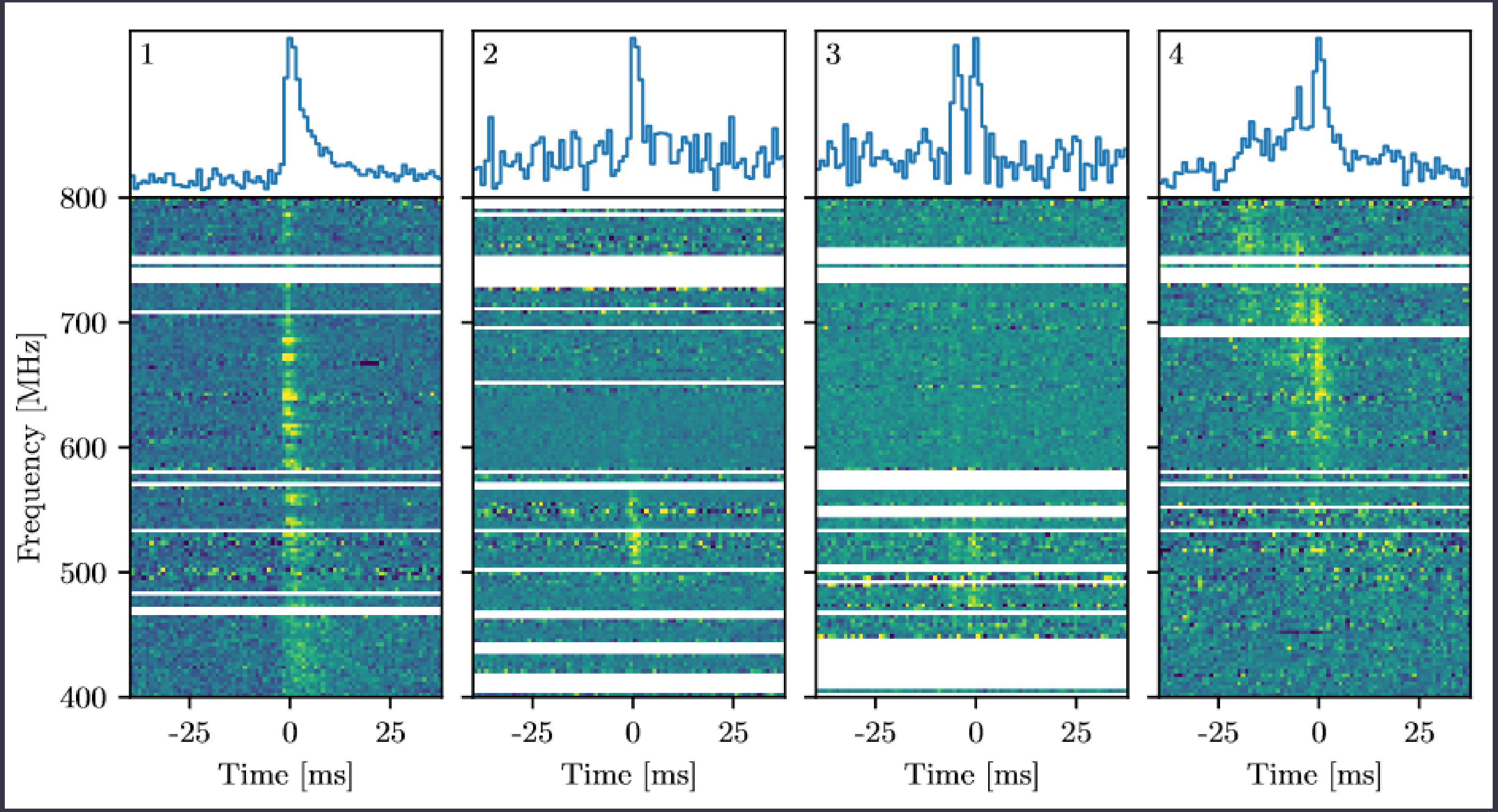
Kumar et al. 2020

Frequency drift

Sad trombone

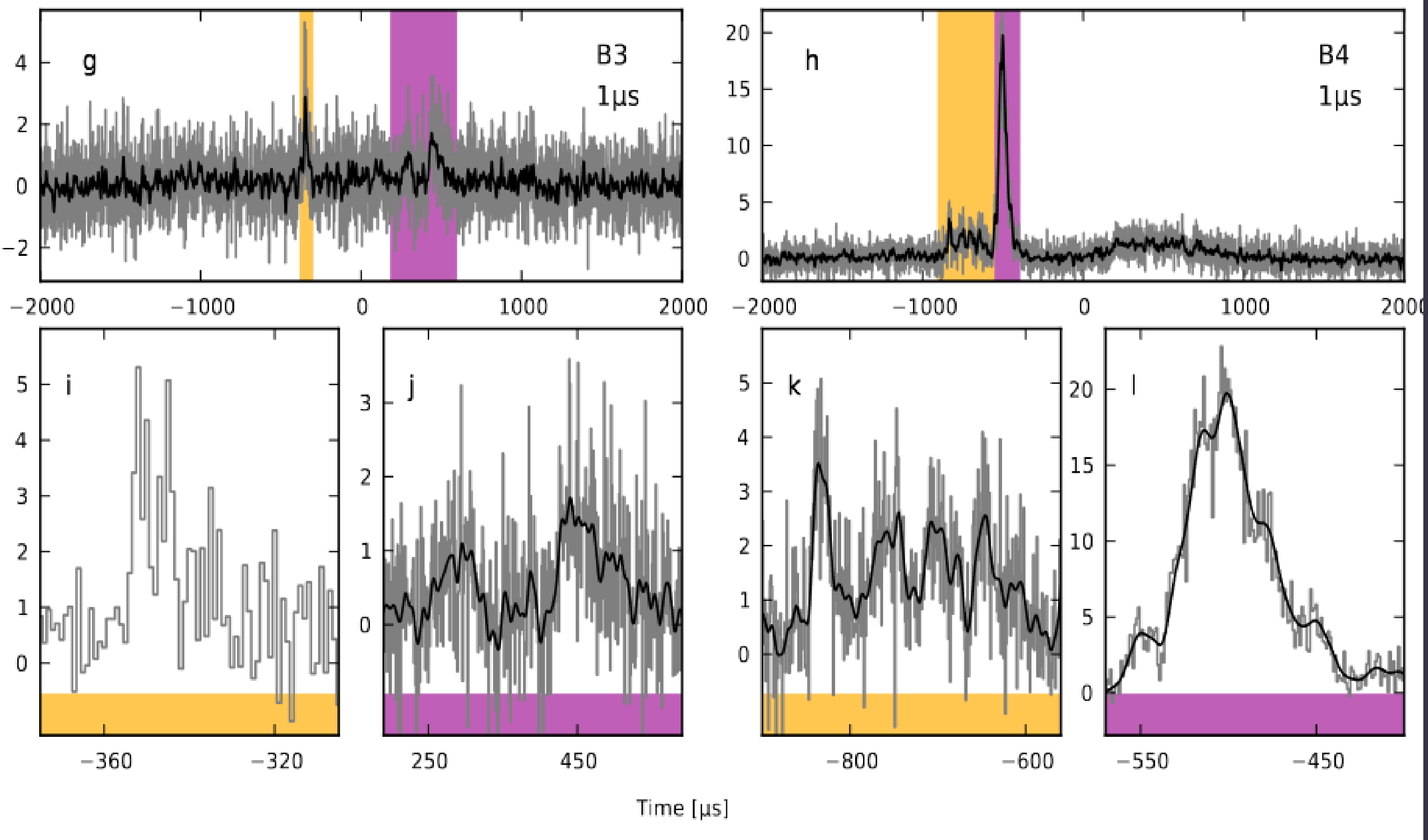


~5% of CHIME bursts demonstrate complex structure downward drifting (Pleunis et al. 2021)



Sand et al. 2020

Rapid variations



FRB 20180916B

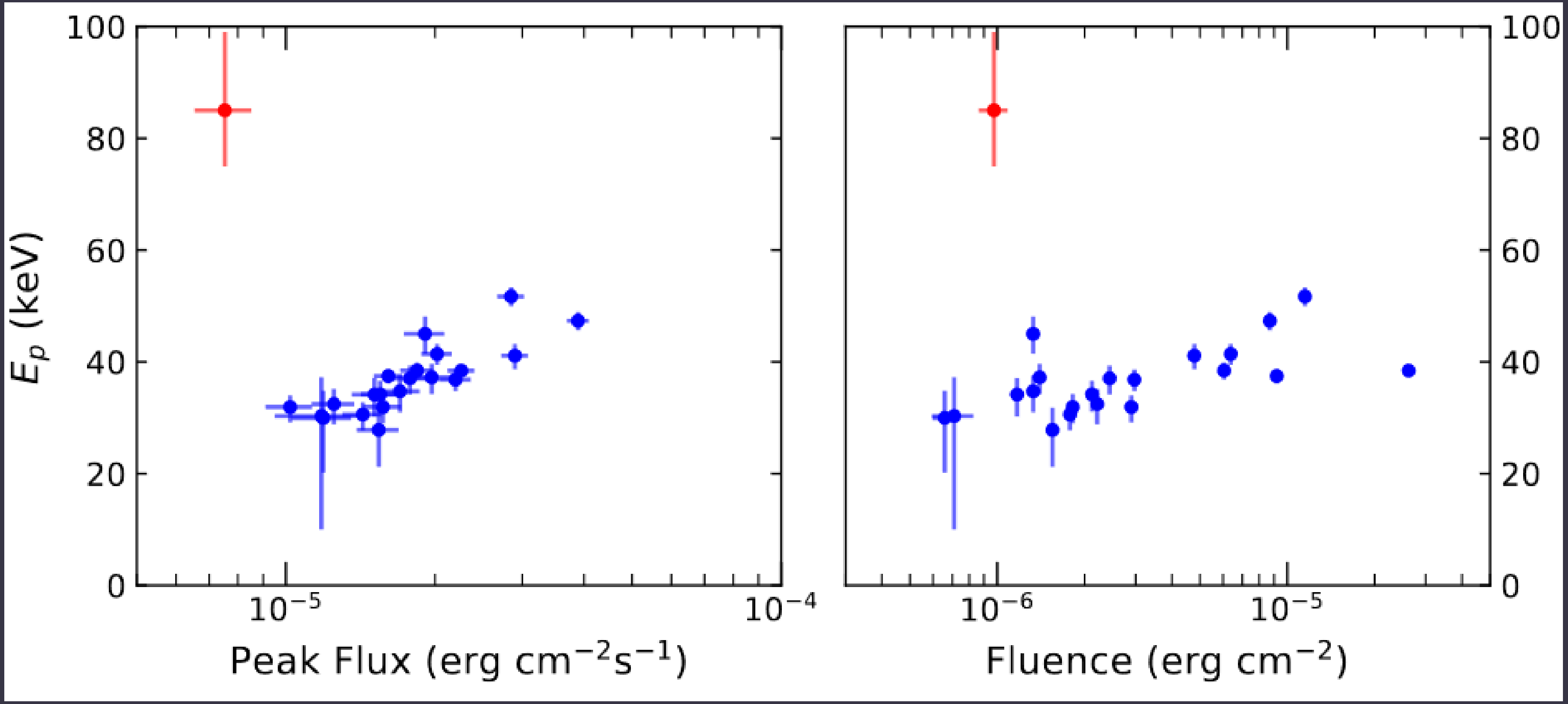
Effelsberg telescope
1.7 GHz

Constant PA
in and between
the bursts
(with slight variations
at the shortest time scale
<100 microseconds).

Single components of bursts
down to 3-4 microseconds.

Nimmo et al. 2021

The Galactic magnetar burst was peculiar



Correlation of
high-energy properties
of the burst with
radio can be
in favour of
magnetospheric models.

But Oct. 2022
bursts may be do not
support the uniqueness
of radio+gamma bursts.

Ridnaia et al. 2021

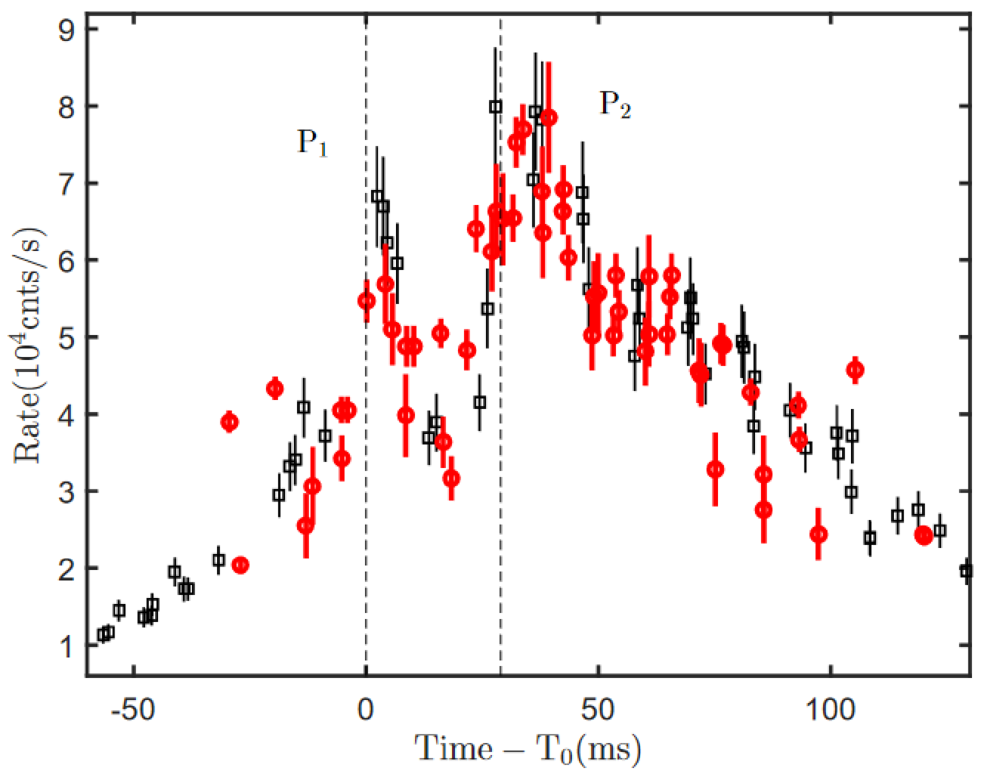
Delay between radio and X/gamma-rays

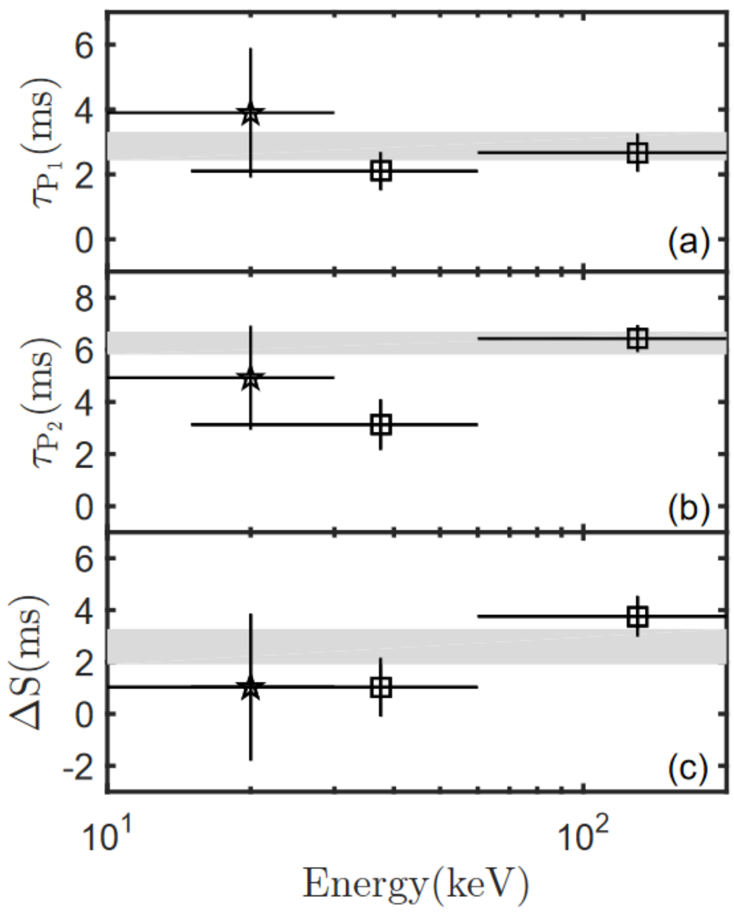
In radio the pulses appear a little bit earlier (Mereghetti et al. 2020; Li et al. 2021).

This peculiarity also can be explained in both frameworks (Lyutikov 2021; Yuan et al. 2020).

Tau_p1 – delay between
X-ray and FRB
for the first pulse

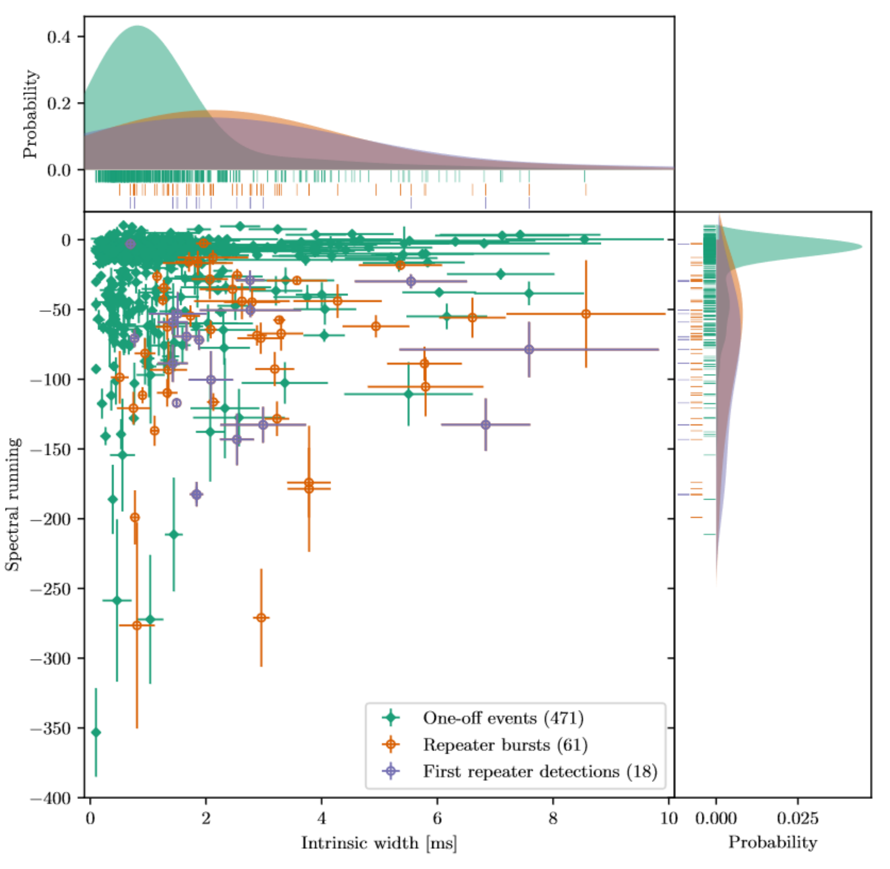
Tau_p2 – delay between
X-ray and FRB
for the secondpulse





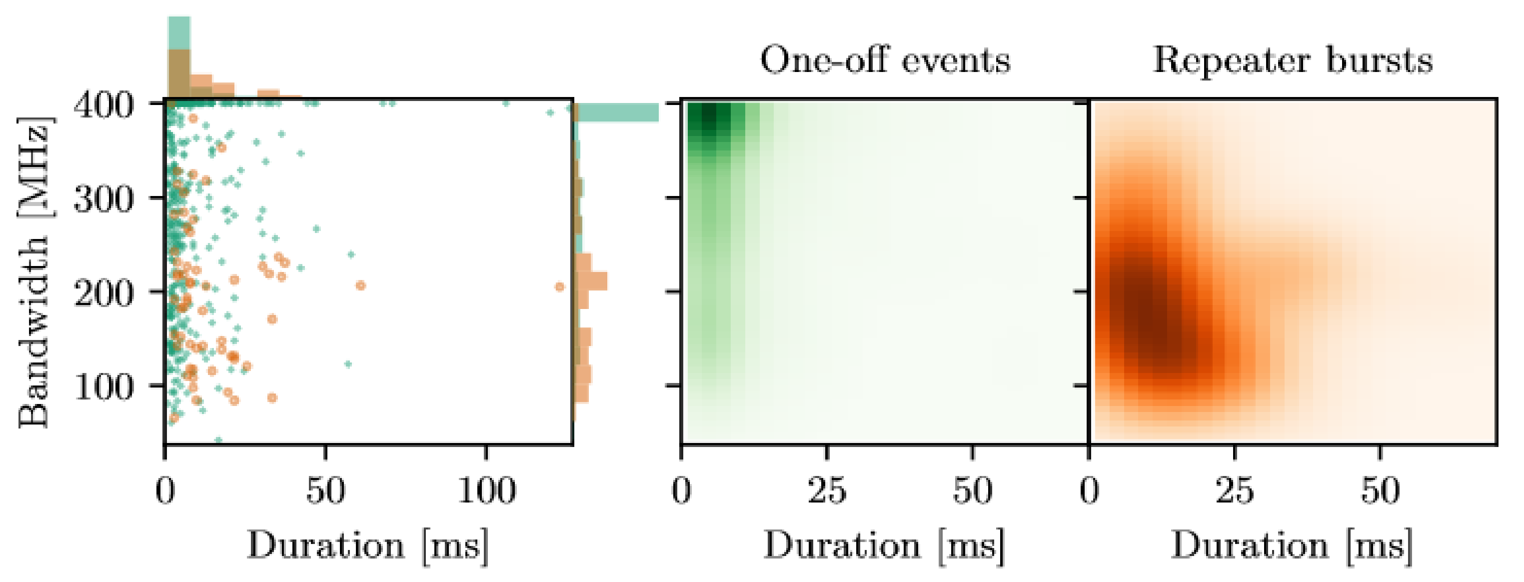
2302.00176

Repeaters vs. (yet?)non-repeaters



$$I(\nu) = A(\nu/\nu_0)^{\gamma+r\ln(\nu/\nu_0)},$$

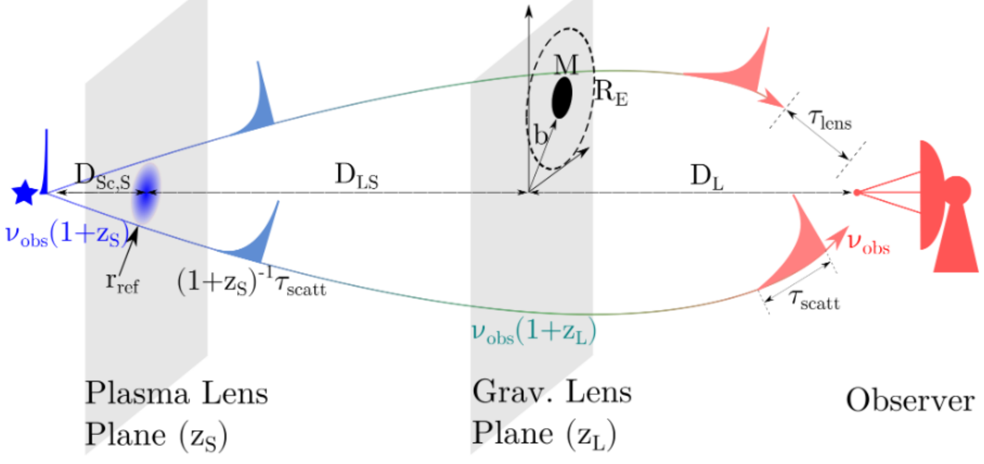
r- spectral running

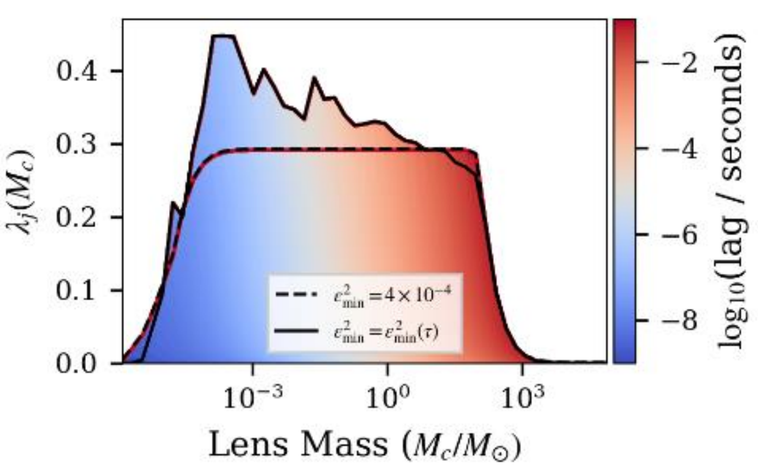


Pleunis et al. 2021

Search for lensing (and PBHs limit)

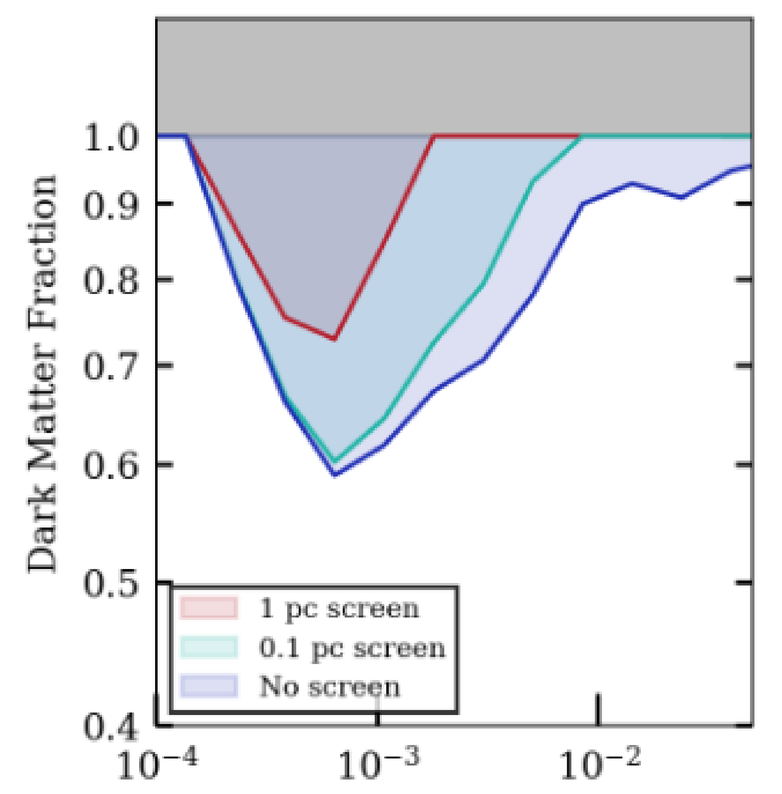
Idea:
direct detection of a second image of the same FRB in the time domain





The expected lensing rate as a function of the lens mass for the sightline toward FRB 20191219F.

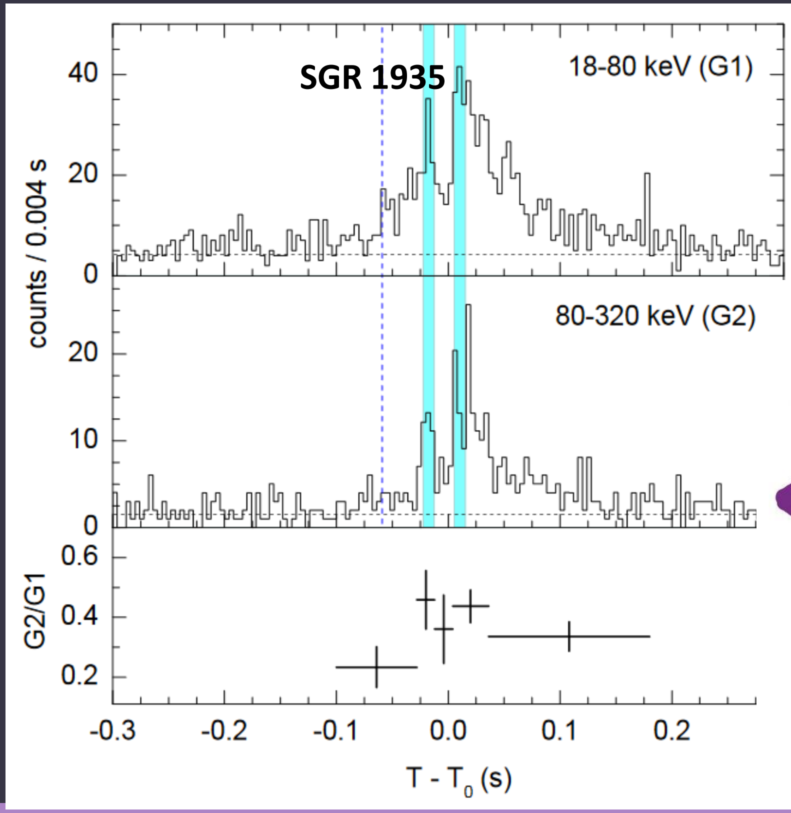
CHIME observation



2204.06001, 2204.06014

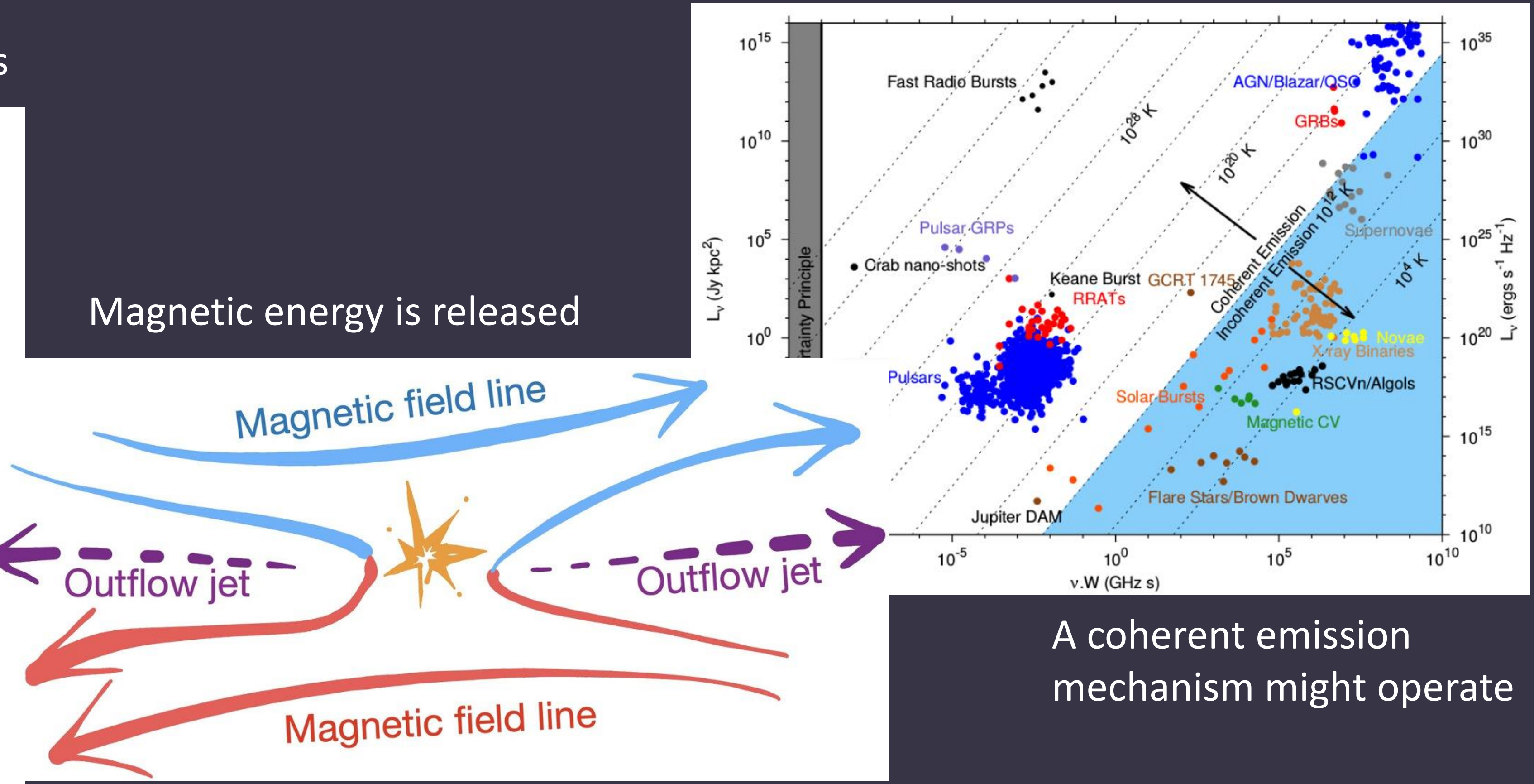
Where do we stand?

FRBs are due to strongly magnetized NSs



Ridnaia et al. 2021

Magnetic energy is released



A coherent emission mechanism might operate

Still, it is not for sure that all FRBs are explained by a single model and that all exotics is ruled out. Review: 2212.03972

Conclusions and hopes

- Magnetars are THE sources
  (small contributions from other types
  of sources are not excluded, yet)
- Two main frameworks are formulated
  (relativistic shocks and magnetospheres)
- Both explain many observed features
- Both have some problems
- Both cannot be proved or falsified, right now

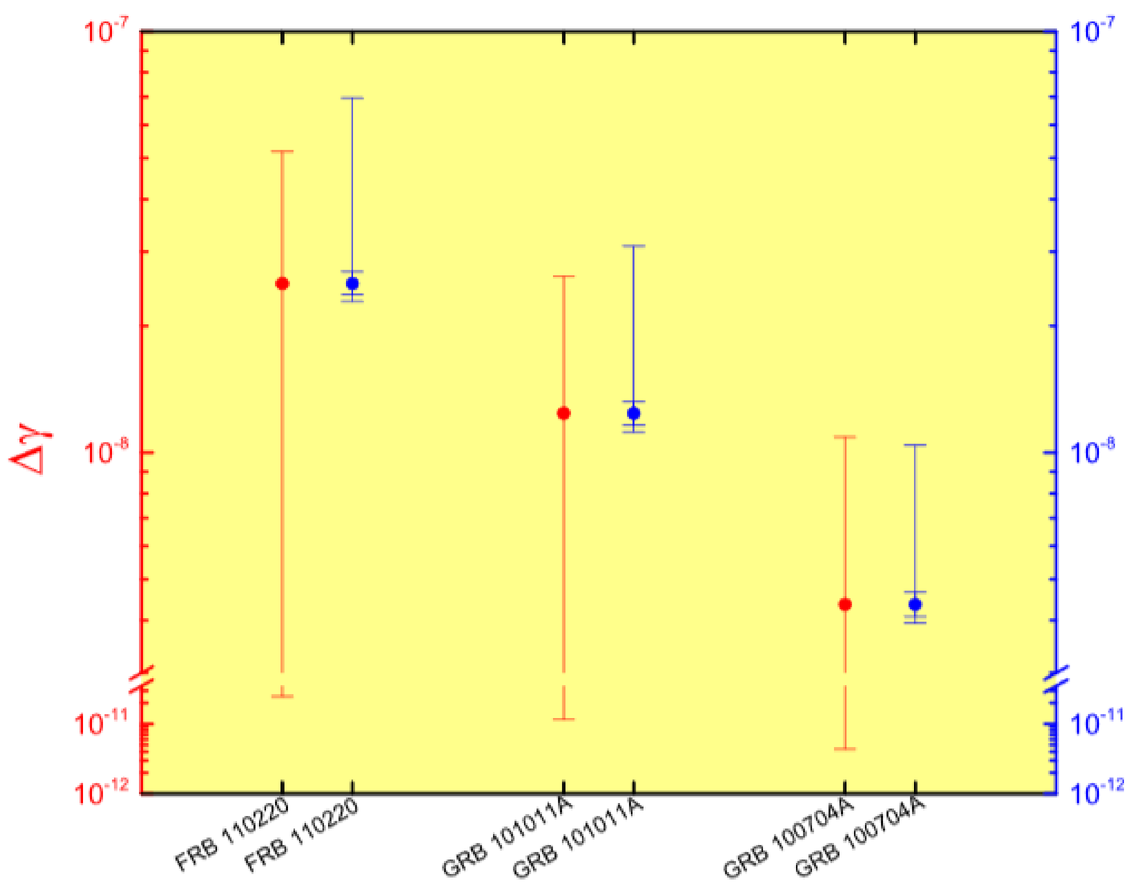
- Differences between repeaters
  and non-repeaters
- Different hosts – different origin

- Counterparts
- Spin periodicity
- More Galactic events
- Delay between hard and radio emission
- Clear differences between events
  from sources of (presumably) different origin

arXiv: 2210.14268

See a set of reviews (Caleb, Keane; Lyubarsky; Nicastro et al.; Pilia) in a special issue on FRBs in *Universe* (2021).

Test of equivalence principle



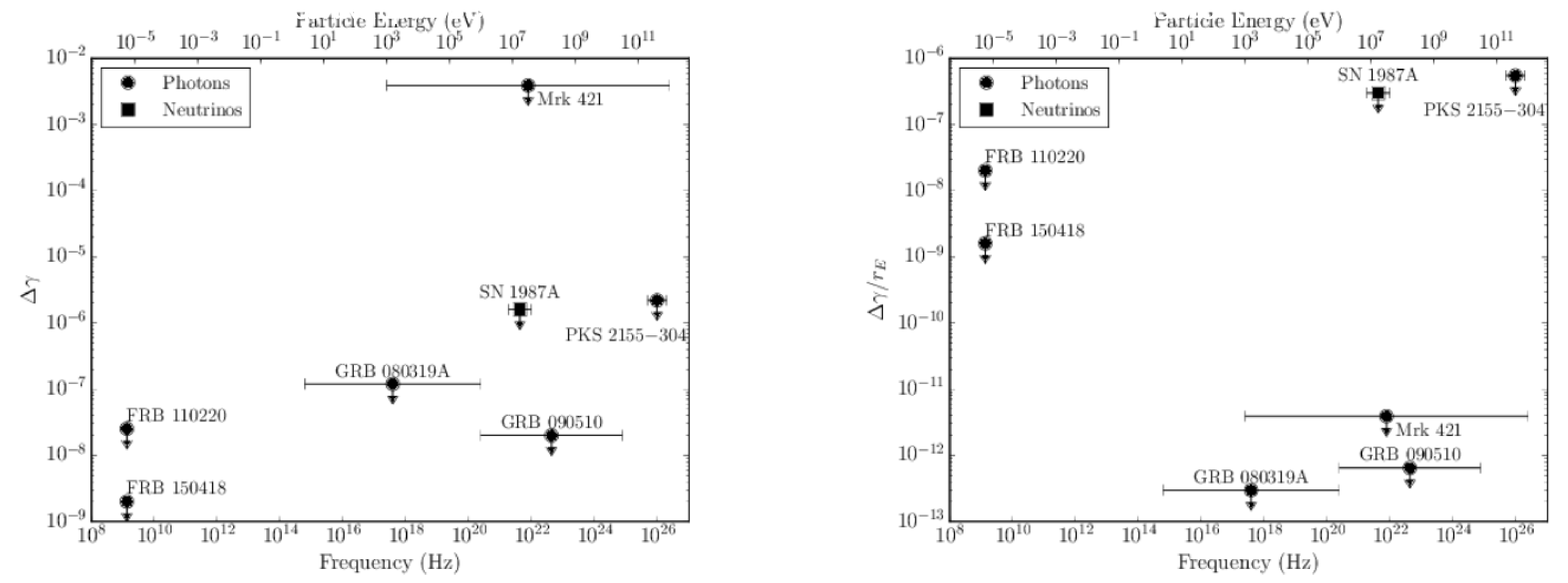
1512.07670

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

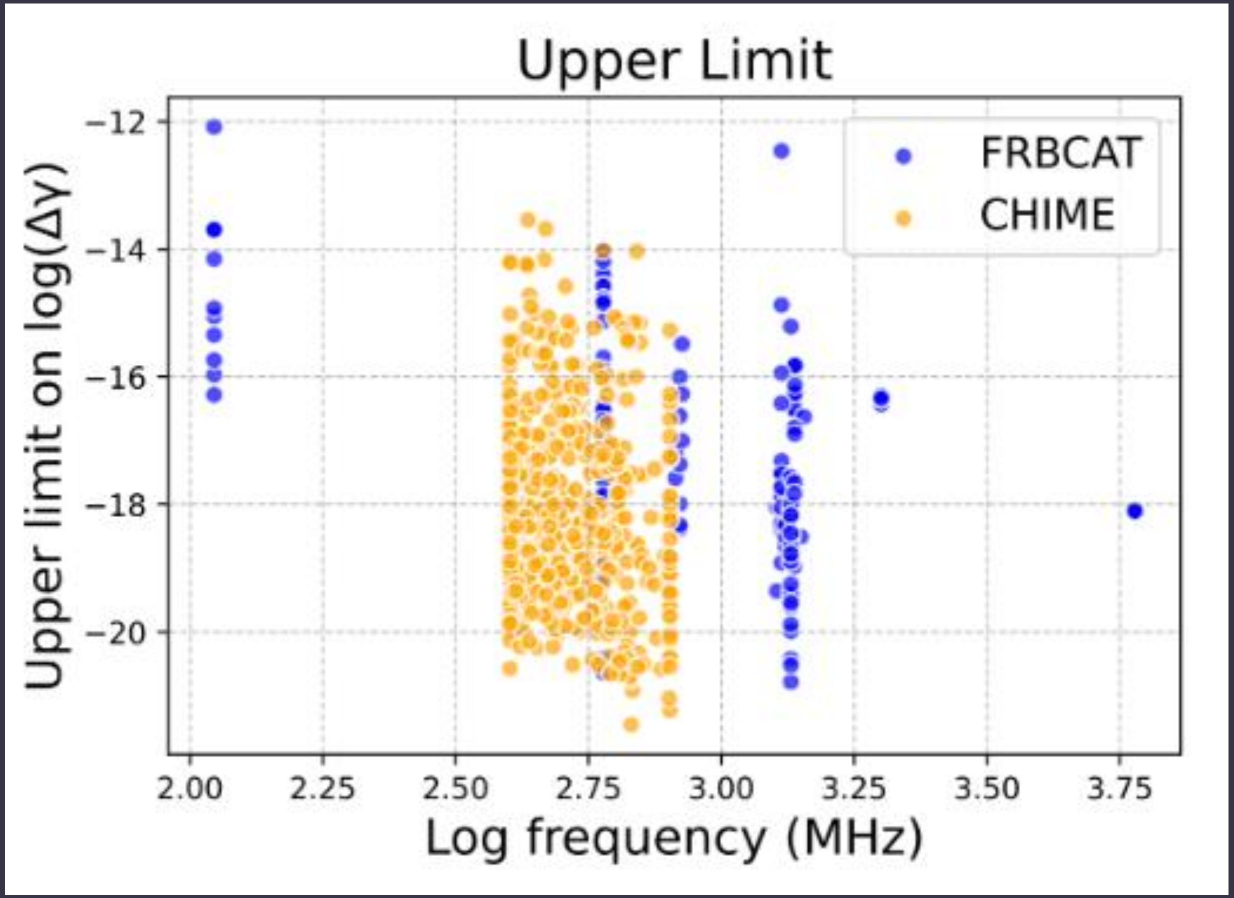
Improvements on the limit of parameter γ

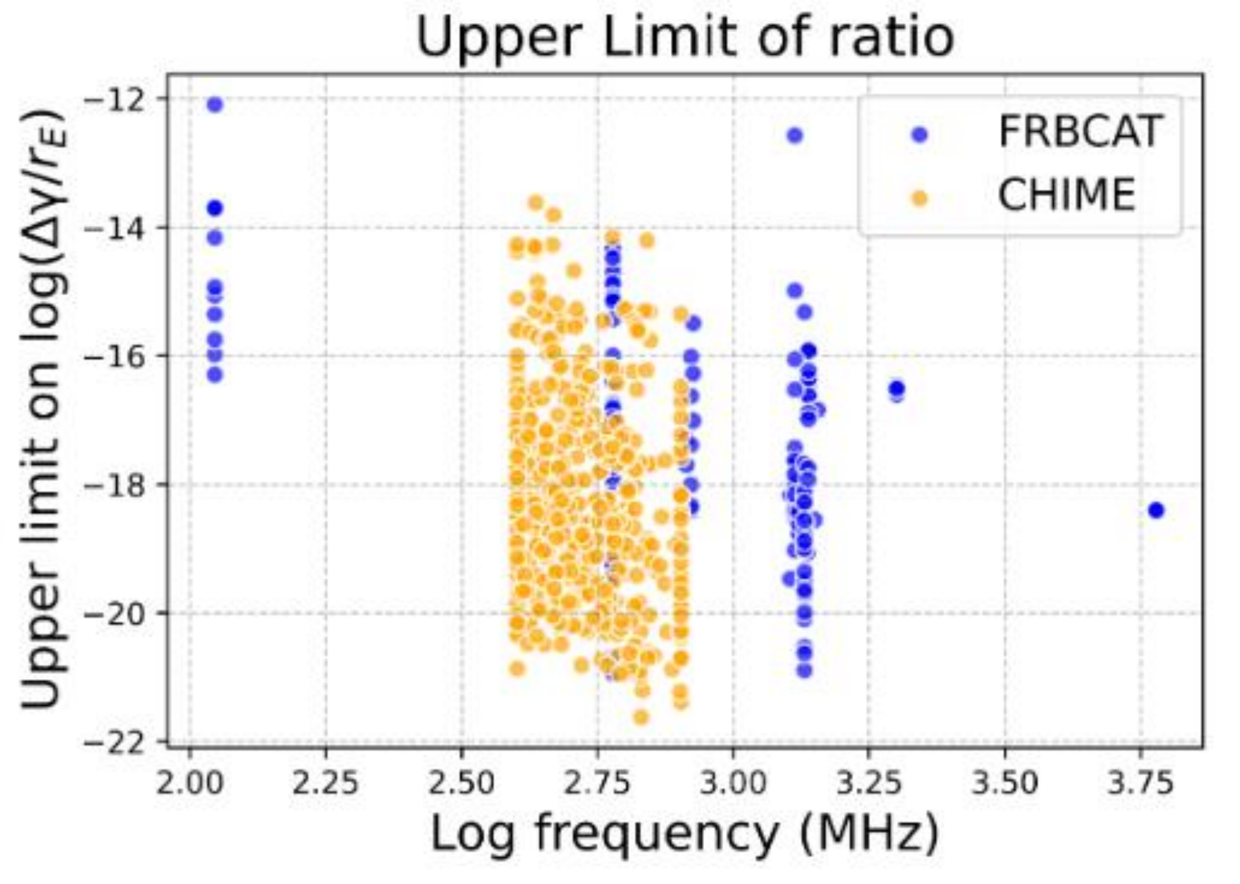
Independent distance evaluation allows to use FRBs to put constraints on the post-Newtonian parameter γ



1602.07643

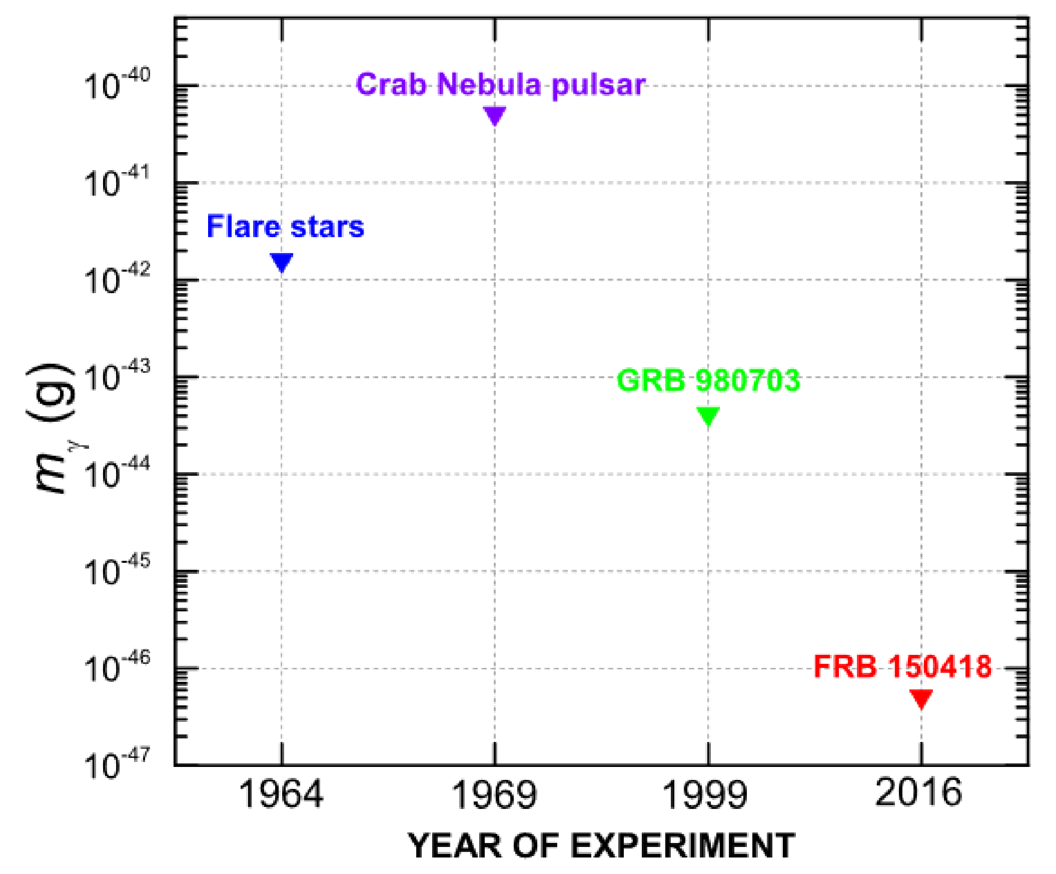
CHIME data and equivalence principle





2111.11451, see also 2111.11447

Limits on the photon mass



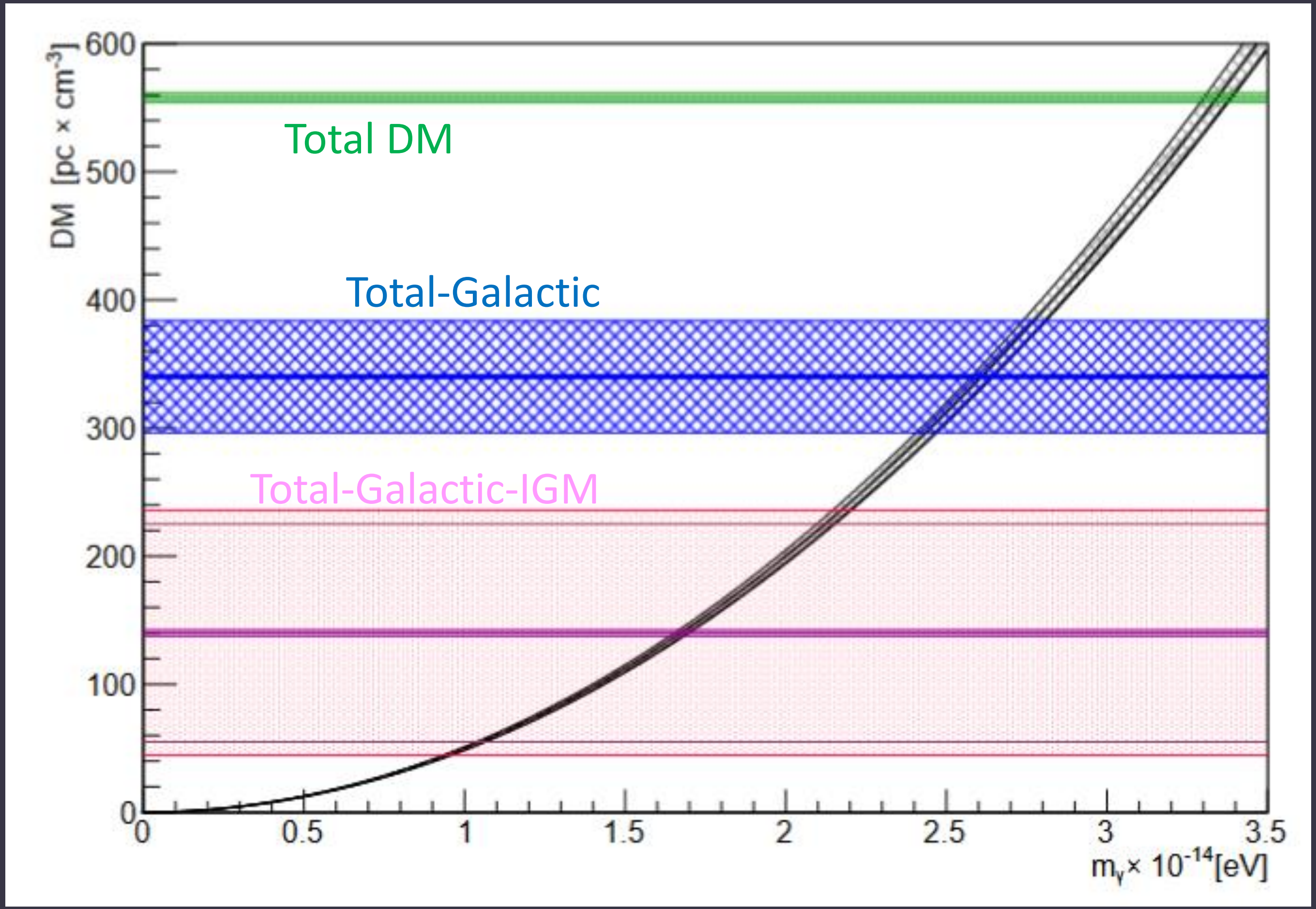
$$m_\gamma = (1.56 \times 10^{-47}\mathrm{g}) \left\{ \frac{\Delta t_{m_\gamma \neq 0}/\mathrm{s}}{\left[\left(\frac{\nu_l}{\mathrm{GHz}}\right)^{-2} - \left(\frac{\nu_h}{\mathrm{GHz}}\right)^{-2} \right] H_1(z)} \right\}^{1/2}$$

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

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

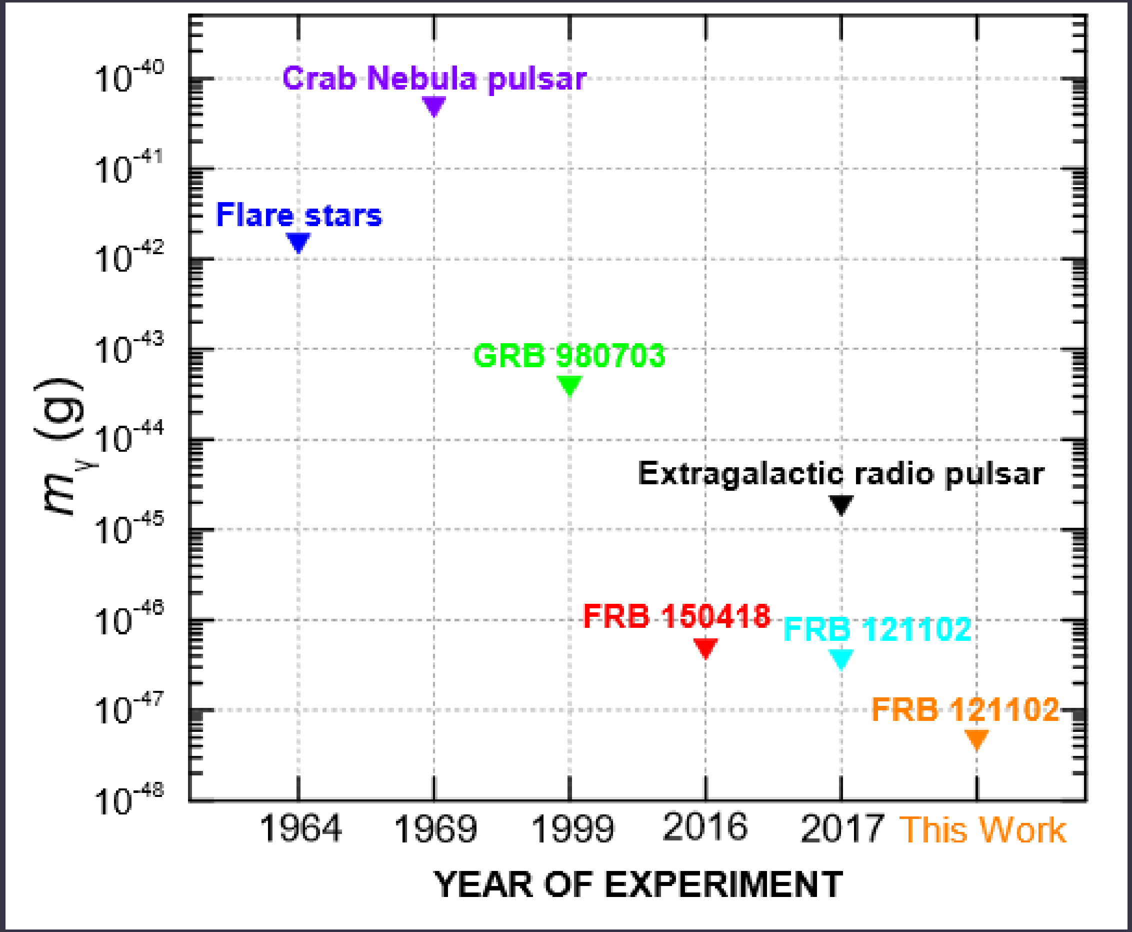
$$h = c = 1$$

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

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

1701.03097

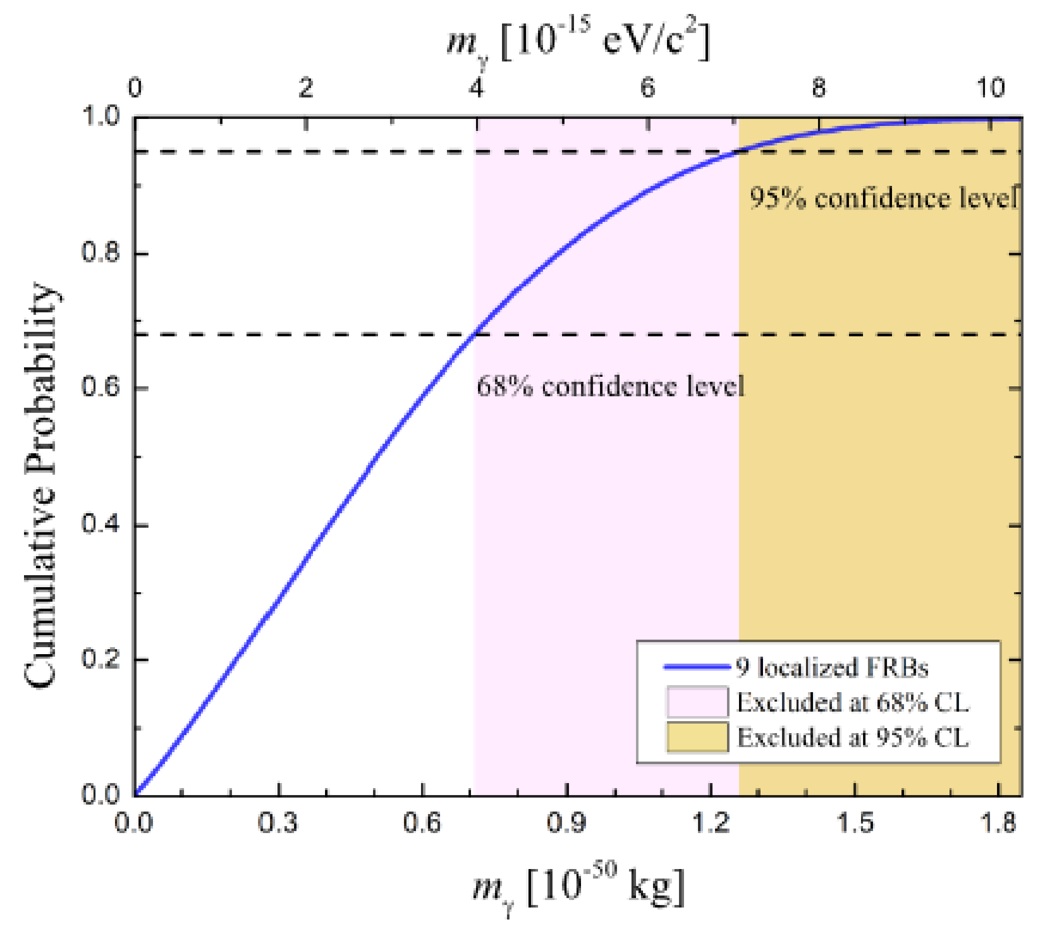
More results and better limits

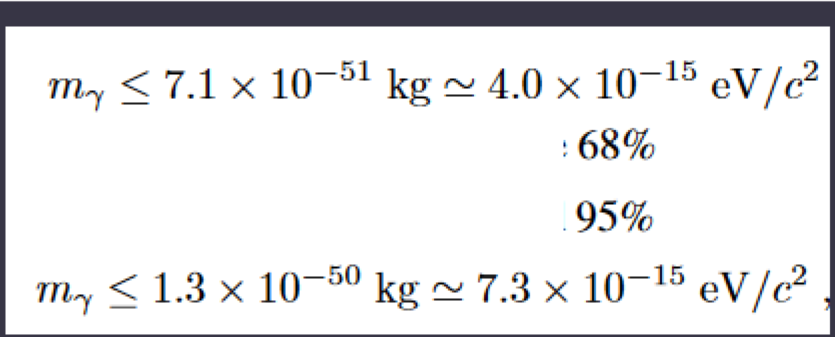


$$m_\gamma = (1.56 \times 10^{-47}\mathrm{g}) \left\{ \frac{\Delta t_{m_\gamma \neq 0}/\mathrm{s}}{\left[\left(\frac{\nu_l}{\mathrm{GHz}}\right)^{-2} - \left(\frac{\nu_h}{\mathrm{GHz}}\right)^{-2}\right] H_1(z)} \right\}^{1/2}$$

1907.00583

Limits with 9 localized bursts





$$m_\gamma \leq 7.1 \times 10^{-51}\ \text{kg} \simeq 4.0 \times 10^{-15}\ \text{eV}/c^2$$

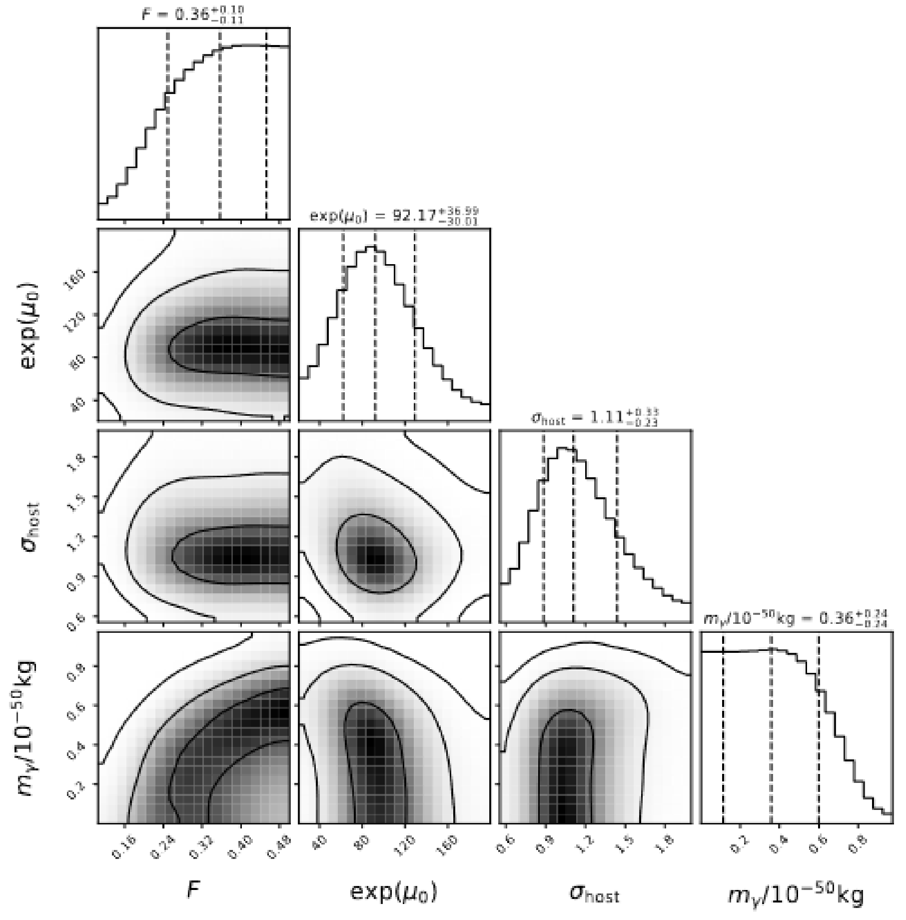
68%

95%

$$m_\gamma \leq 1.3 \times 10^{-50}\ \text{kg} \simeq 7.3 \times 10^{-15}\ \text{eV}/c^2\ ,$$

2006.09680

Photon mass constraint from 17 well-localized FRBs



$$m_\gamma < 4.8 \times 10^{-51}\ \mathrm{kg}.$$

2301.12103