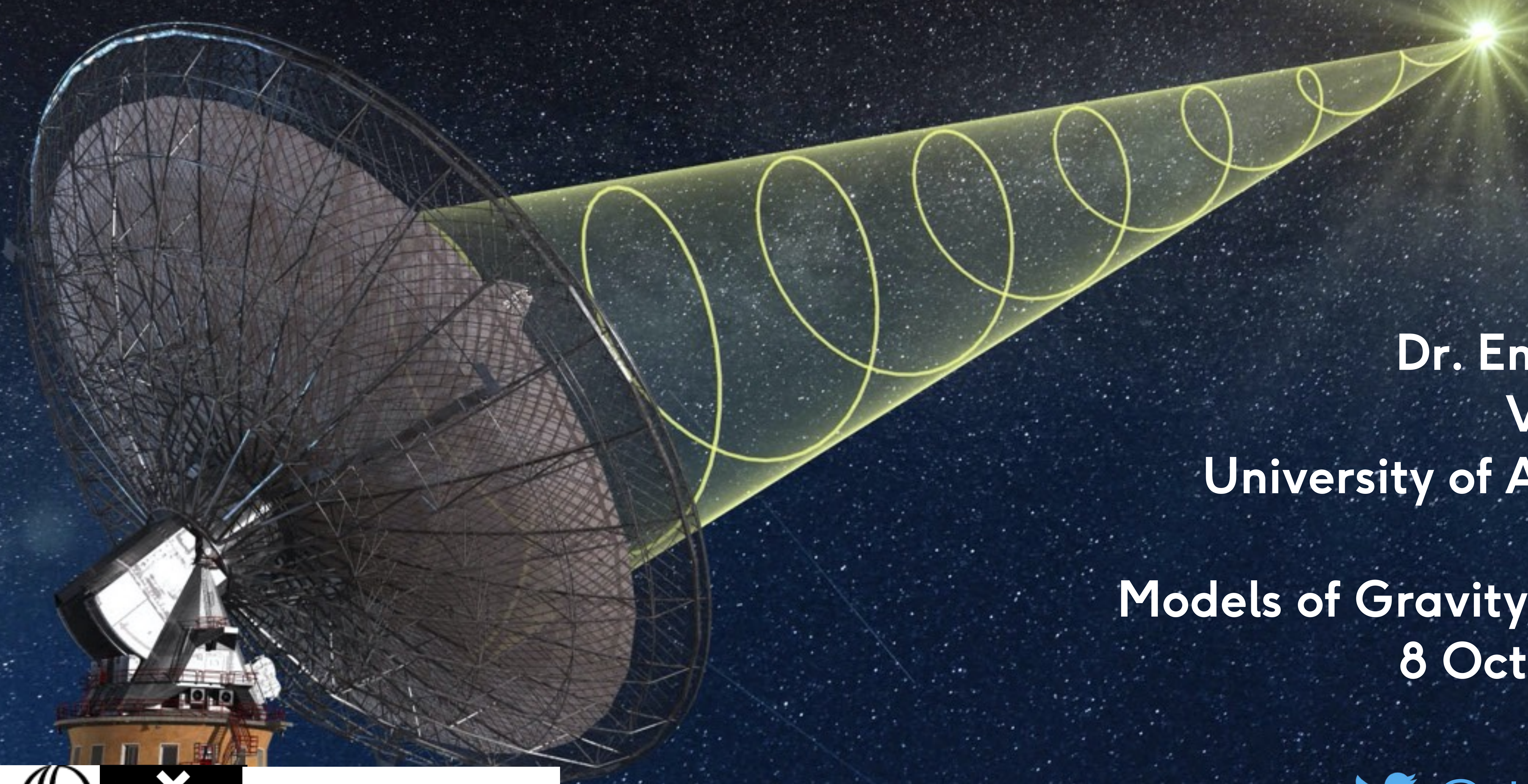
Recent developments in Fast Radio Bursts



Dr. Emily Petroff
Veni Fellow
University of Amsterdam

Models of Gravity Workshop
8 October, 2020

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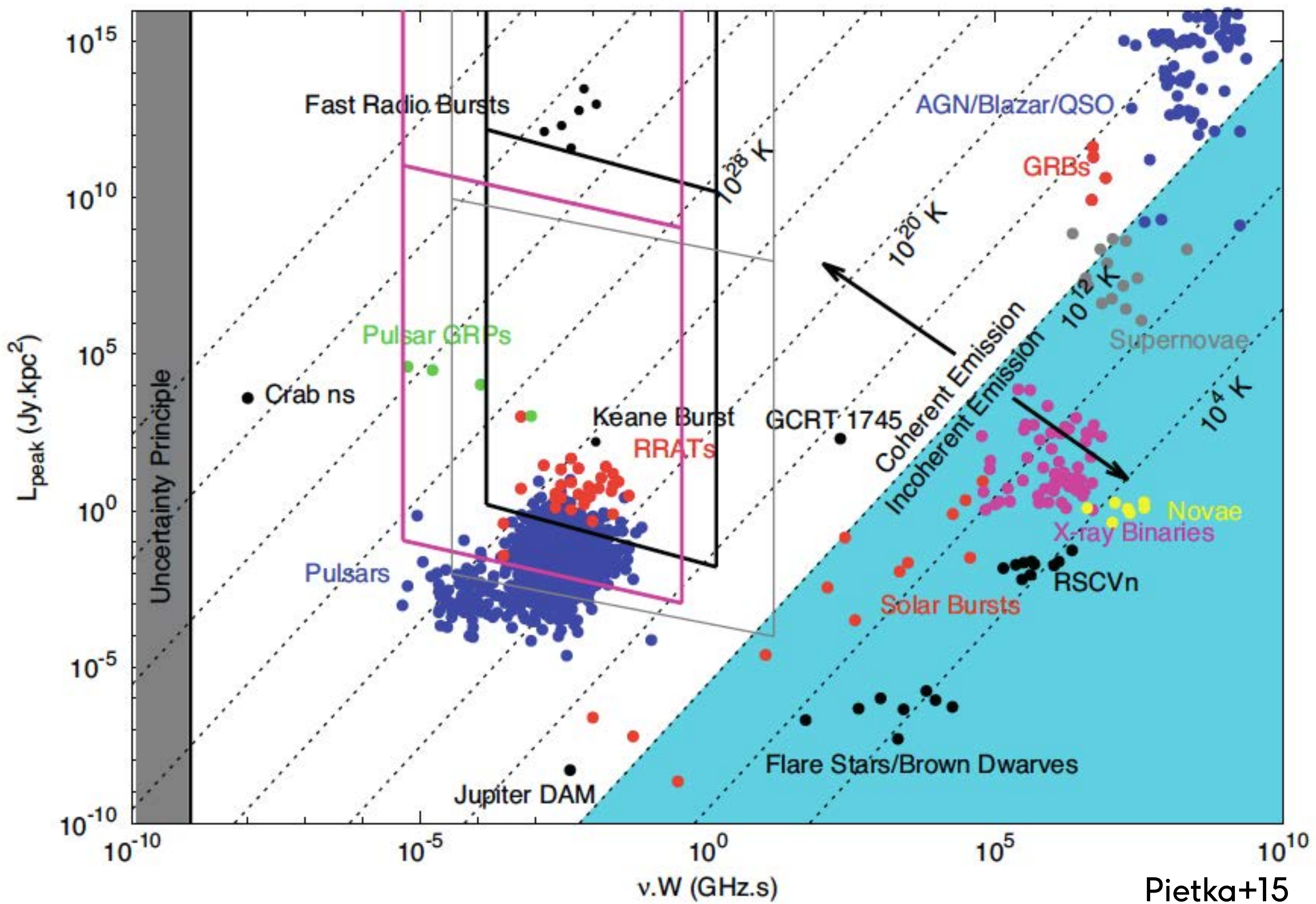
NWO



Fast Radio Bursts
AGN/Blazar/QSO
GRBs
Supernovae
Pulsar GRPs
Crab ns
Keane Burst
RRATs
GCRT 1745
Coherent Emission
Incoherent Emission
Novae
X-ray Binaries
RSCVn
Solar Bursts
Pulsars
Flare Stars/Brown Dwarves
Jupiter DAM
Uncertainty Principle
10^{28} K
10^{20} K
10^{12} K
10^{4} K
L_{peak} (Jy.kpc^2)
ν.W (GHz.s)
10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
10^{-10}
10^{-10}
10^{-5}
10^{0}
10^{5}
10^{10}

Pietka+15

Introduction to Fast Radio Bursts

Bright, short radio pulses

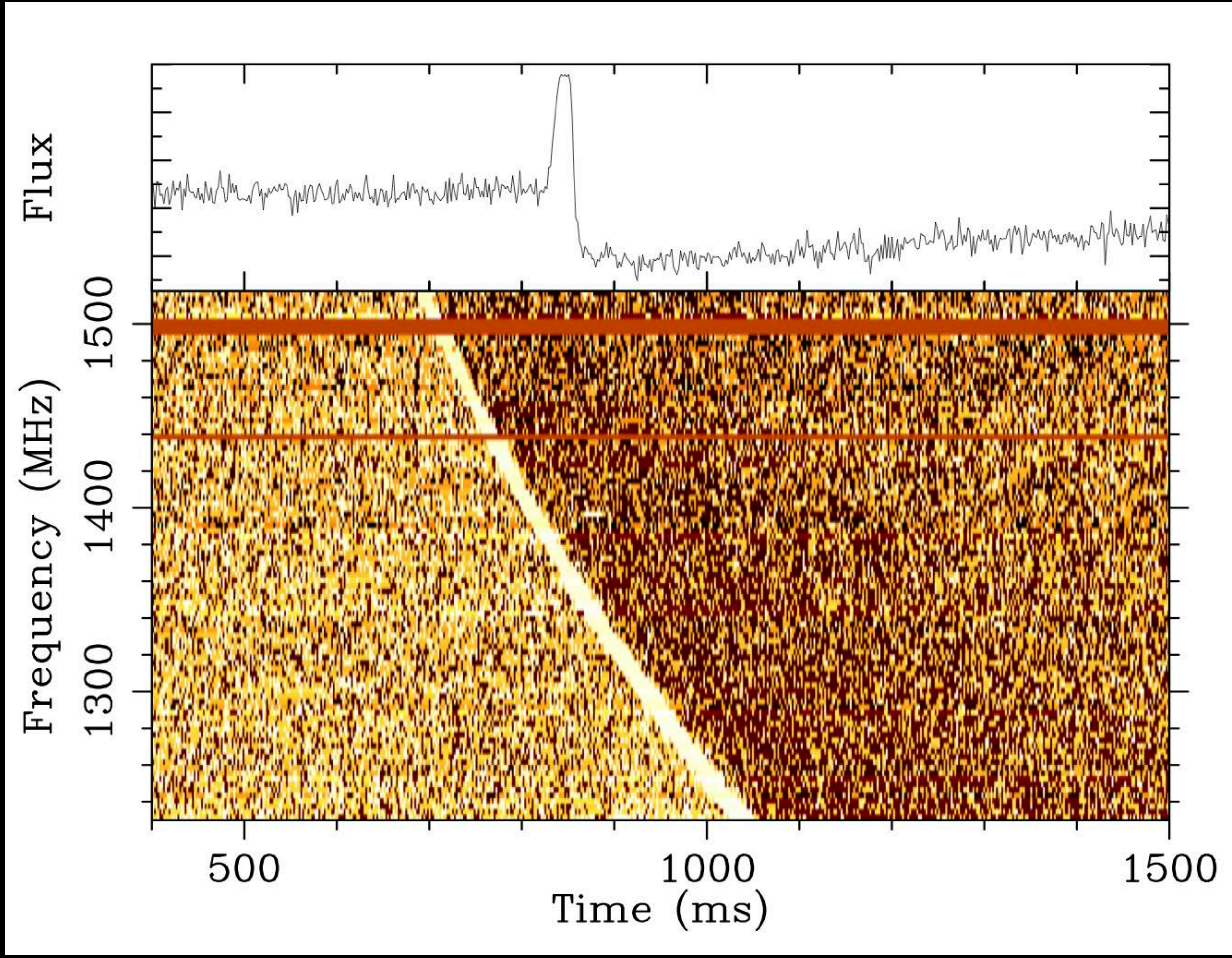
High dispersion measure (DM)

$$DM = \int_0^d n_e \, ds$$

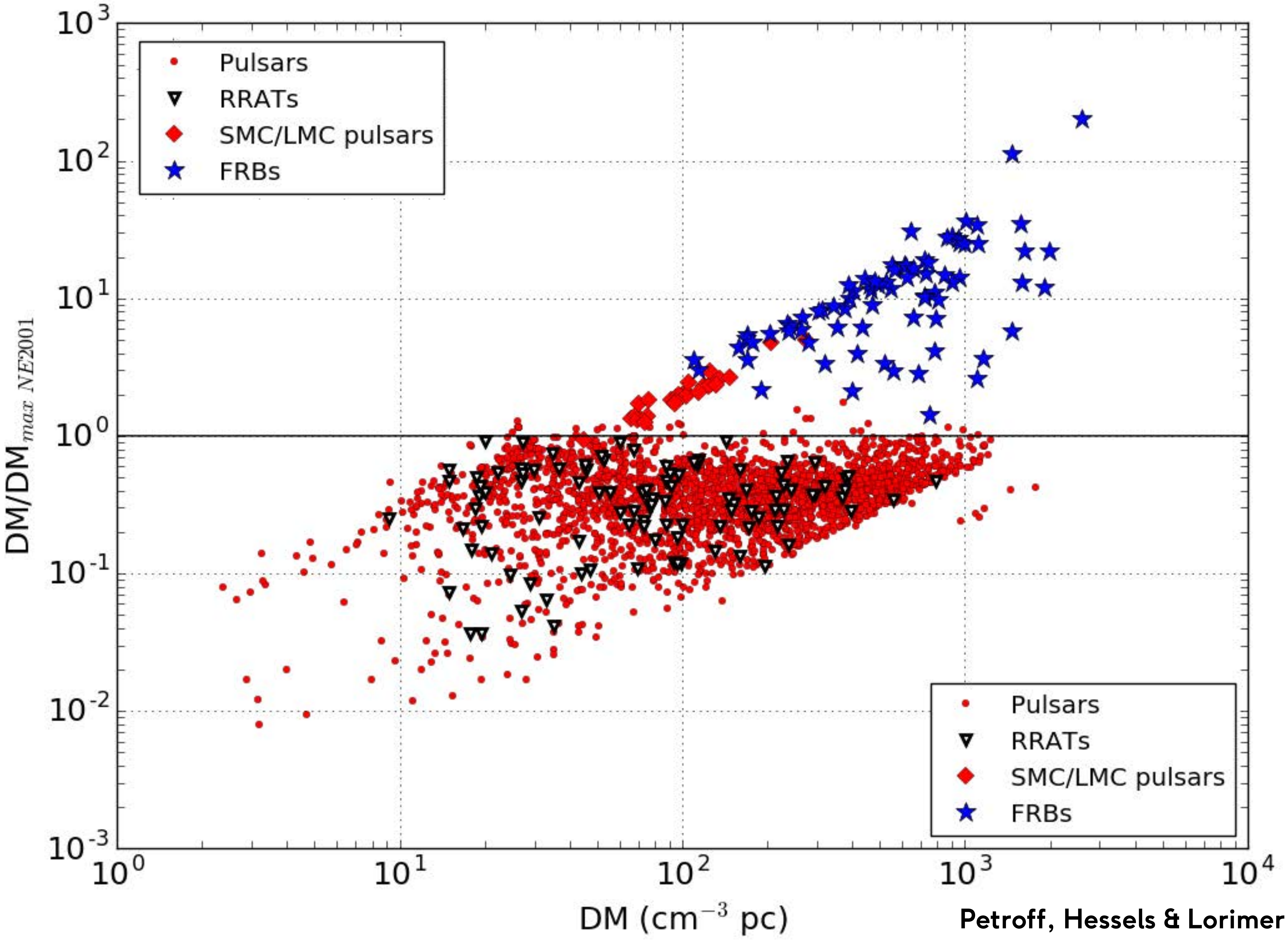
DM(FRB) ~ 10 x DM(MW)

Originate extragalactically

Hugely energetic, relatively common new transients



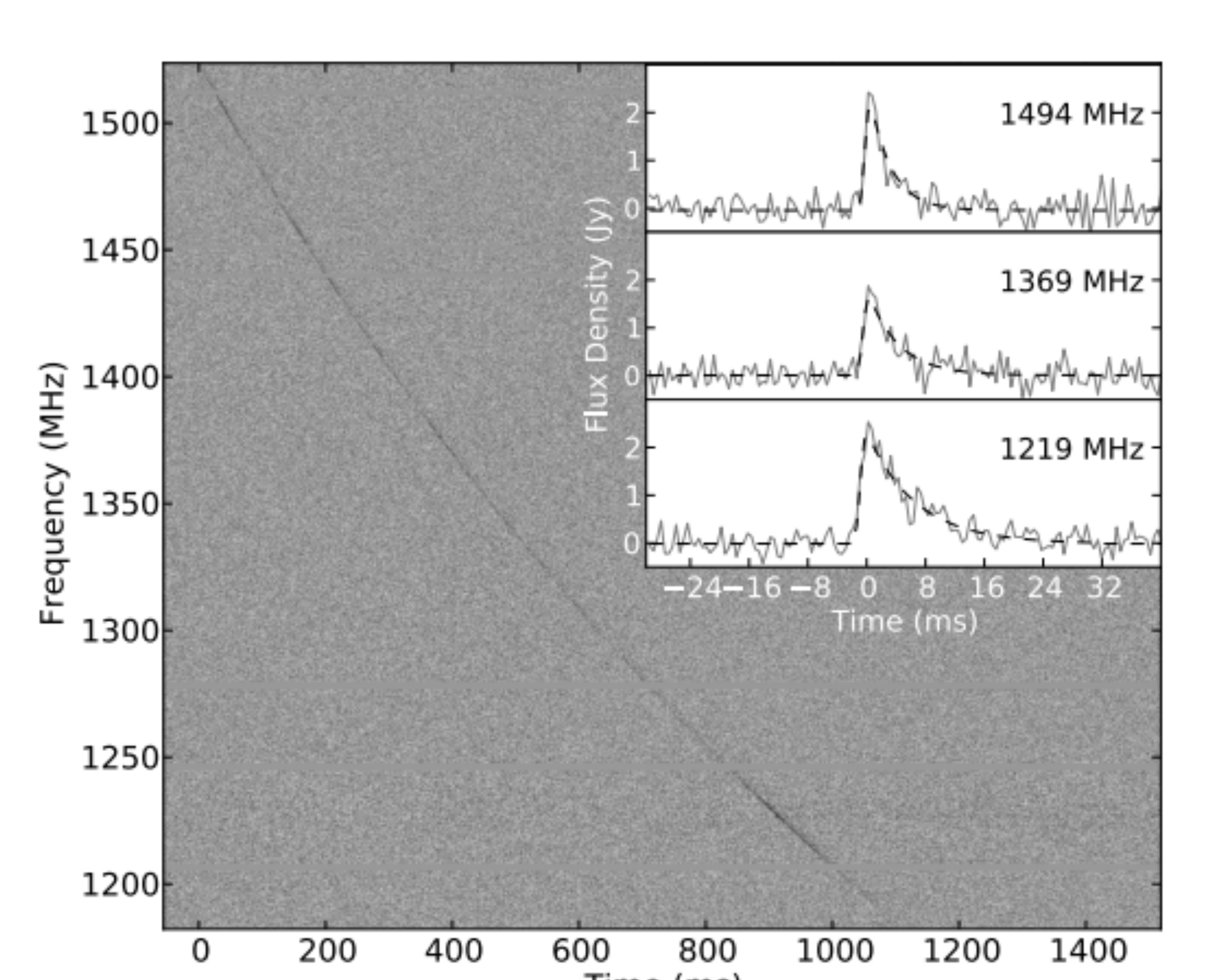
Lorimer et al. 2007



Petroff, Hessels & Lorimer (2019)

Introduction to Fast Radio Bursts

- Some or all excess DM may come from IGM
- Sources outside the Galaxy (at least some are cosmological)
- Rate ~ 5,000 sky^{-1} day^{-1}
- Possible progenitors:
  - GPs from young pulsars
  - Magnetar flares
  - BNS merger
  - NS collapse



Thornton et al. (2013)

Slide credit: Tony Piro

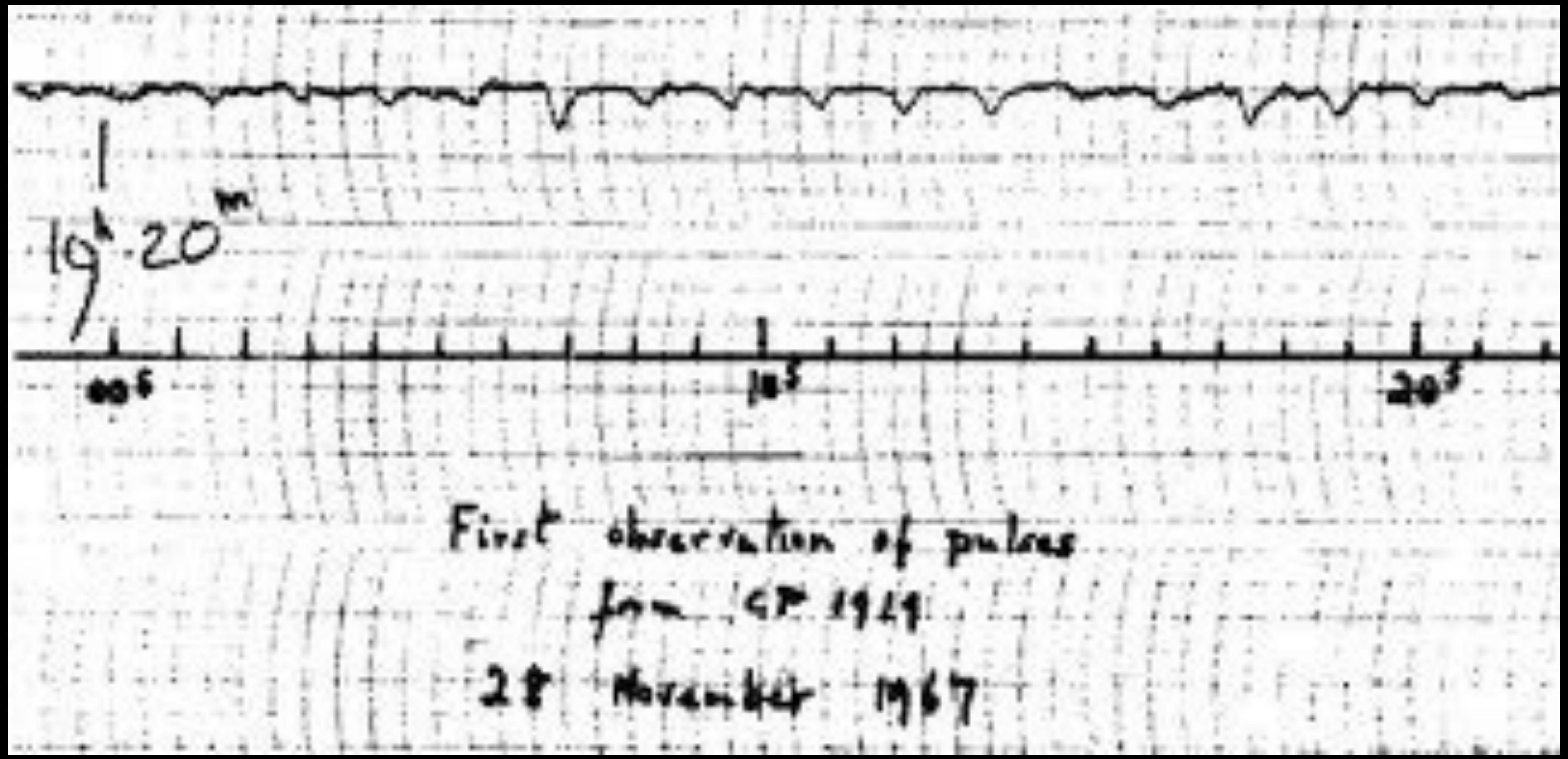
What could FRBs be?

- Neutron stars collapsing to black holes, ejecting "magnetic hair" (Falcke & Rezzolla '14; Zhang '14)
- Merger of charged black holes (Zhang '16; Liu et al. '16; Liebling & Panenzuela '16)
- Magnetospheric activity during neutron star mergers (Totani '13)
- Unipolar inductor in neutron star mergers (Hansen & Lyutikov '01; Piro '12; Wang et al. '16)
- White dwarf mergers (Kashiyama et al. '13)
- Pulses from young neutron stars (Cordes & Wasserman '15; Connor et al. '15; Lyutikov et al. '16; Popov & Pshirkov '16; Kashiyama & Murase '17)
- (Young) Magnetars (Popov et al. '07; Kulkarni et al. '14; Lyubarsky '14; Katz '15; Pen & Connor '15; Lu & Kumar '16; Metger et al. '17; Beloborodov '17; Margarlit & Metzger '18)
- Schwinger instability in young magnetars (Lieu '17)
- Sparks from cosmic strings (Vachaspati '08; Yu et al. '14)
- Evaporating primordial black holes (Rees '77; Keane et al. '12)
- White holes (Barrau et al. '14)
- Flaring stars (Loeb et al. '13; Maoz et al. '15)
- Axion stars (Tkachev '15; Iwazaki '15)
- Asteroids/comets falling onto neutron stars (Geng & Huang '15; Dai et al. '16)
- Quark novae (Chand et al. '15)
- Dark matter-induced collapse of neutron stars (Fuller & Ott '15)
- Higgs portals to pulsar collapse (Bramante & Elahi '15)
- Planets interacting with a pulsar wind (Mottez & Zarka '15)
- Black hole superradiance (Conlon & Herdeiro '17)
- Extragalactic light sails (Lingam & Loeb '17)
- Neutron star-white dwarf binaries (Gu et al. '16)
- Clumpy jets from accreting black holes (Yi et al. '19)
- Black hole interacting with an AGN (Das Gupta & Saini '17; Waxman '17)
- Wandering AGN beam (Katz '17)
- Black hole laser powered by axion superradiant instabilities(Rosa & Kephart '18)
- Starquakes and lightning of pulsars (Wang et al. '18; Song et al. 2017)

www.frbtheorycat.org

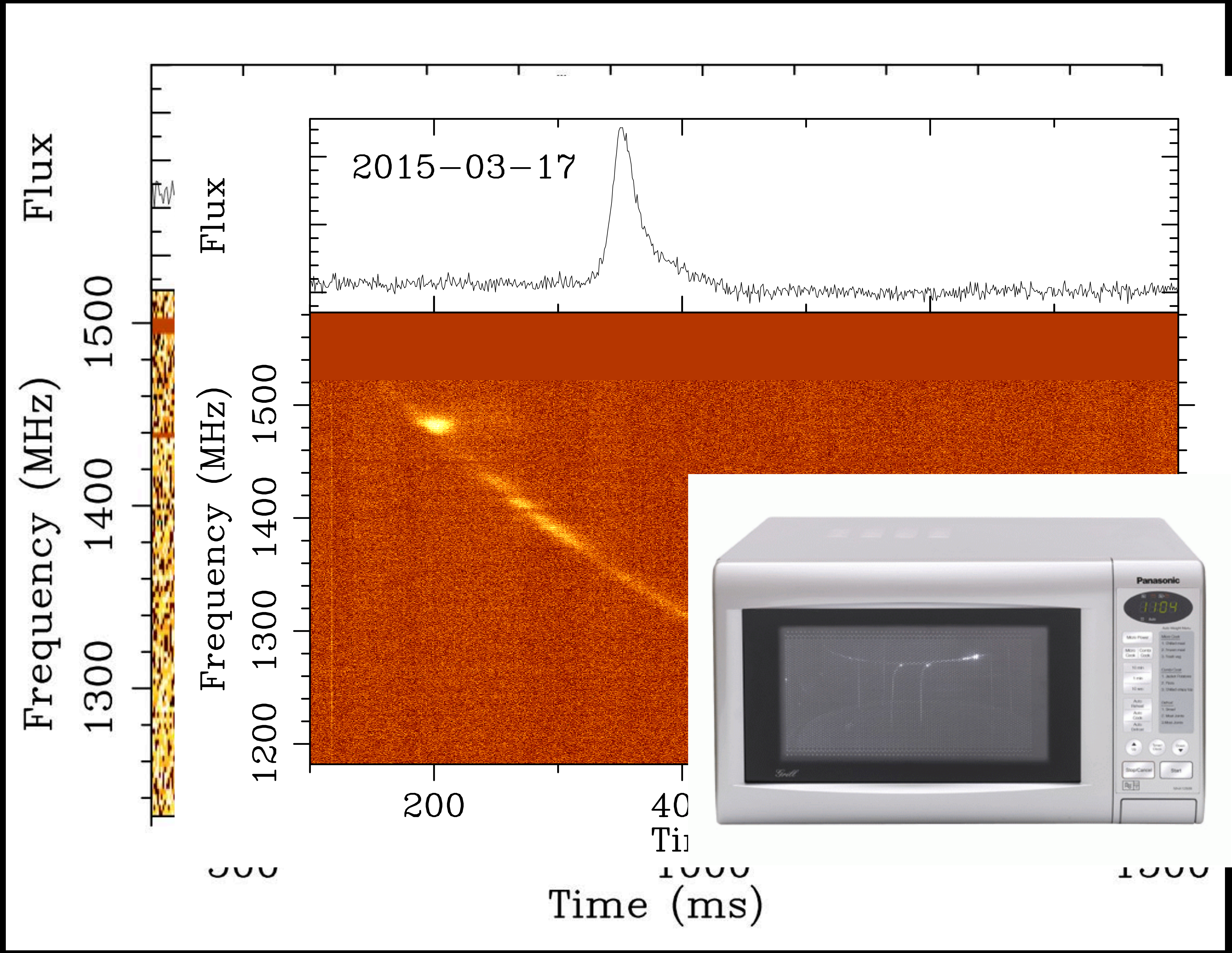
Radio transient history lesson

- Pulsars
- First pulsars found through single pulses
- Move to periodicity searches
- Discovery of RRATs in 2006
- Renewed single pulse searches

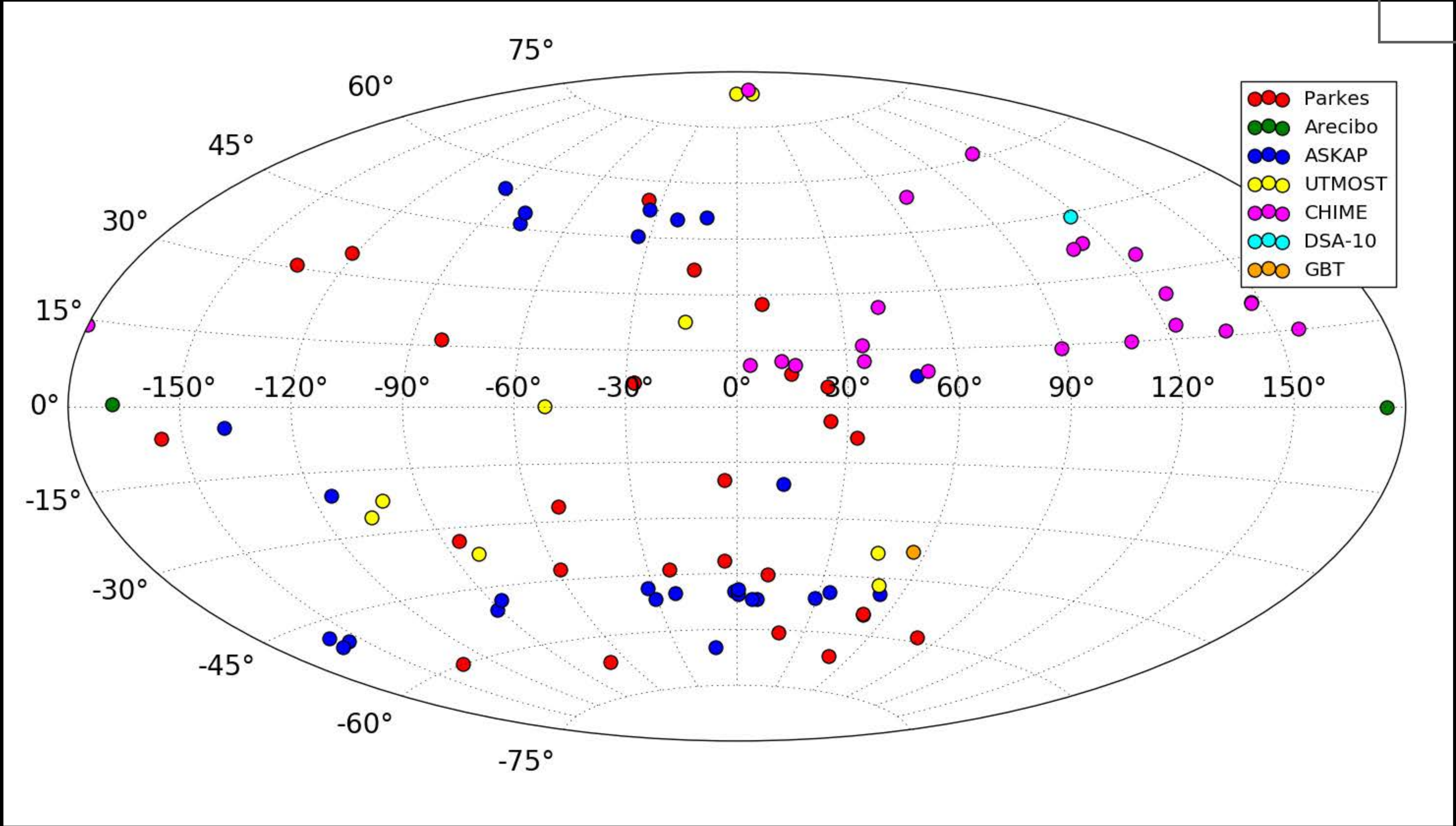


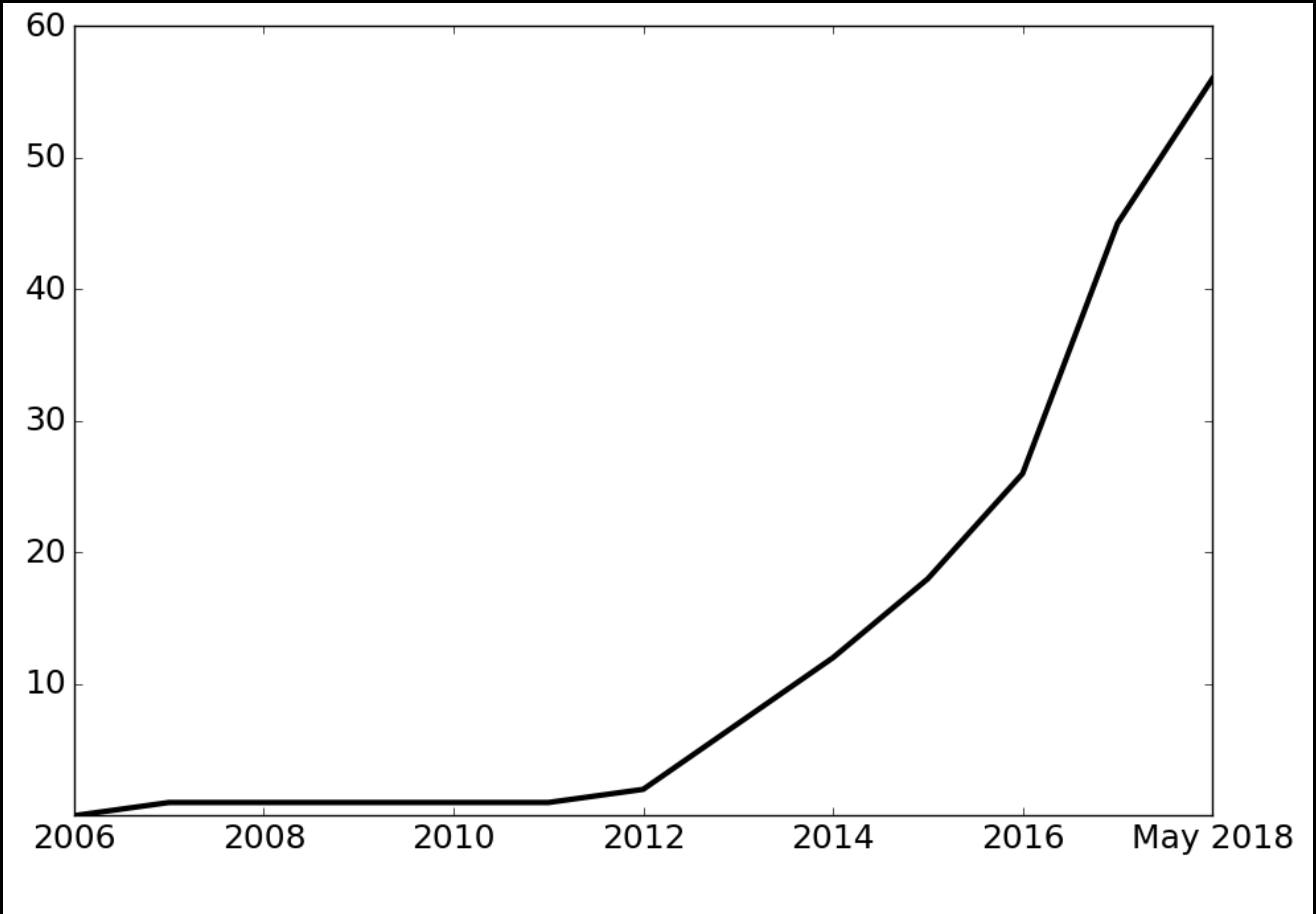
FRB history lesson

- Searches through more parameter space
- 2007: Discovery of Lorimer Burst
- 2010: Concern about strange interference (“perytons”)

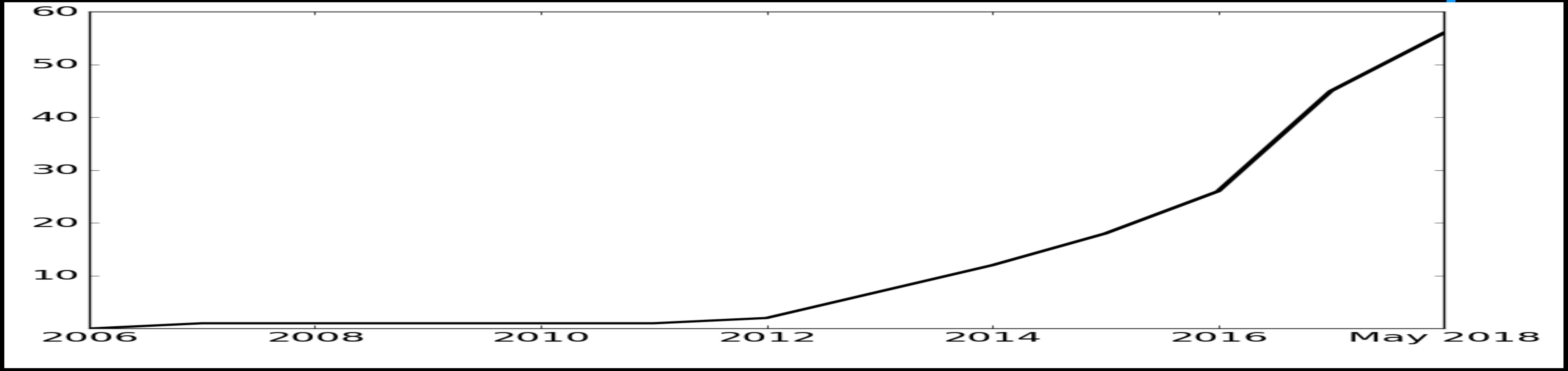


- 120+ published, 7+ telescopes




60
50
40
30
20
10
2006
2008
2010
2012
2014
2016
May 2018

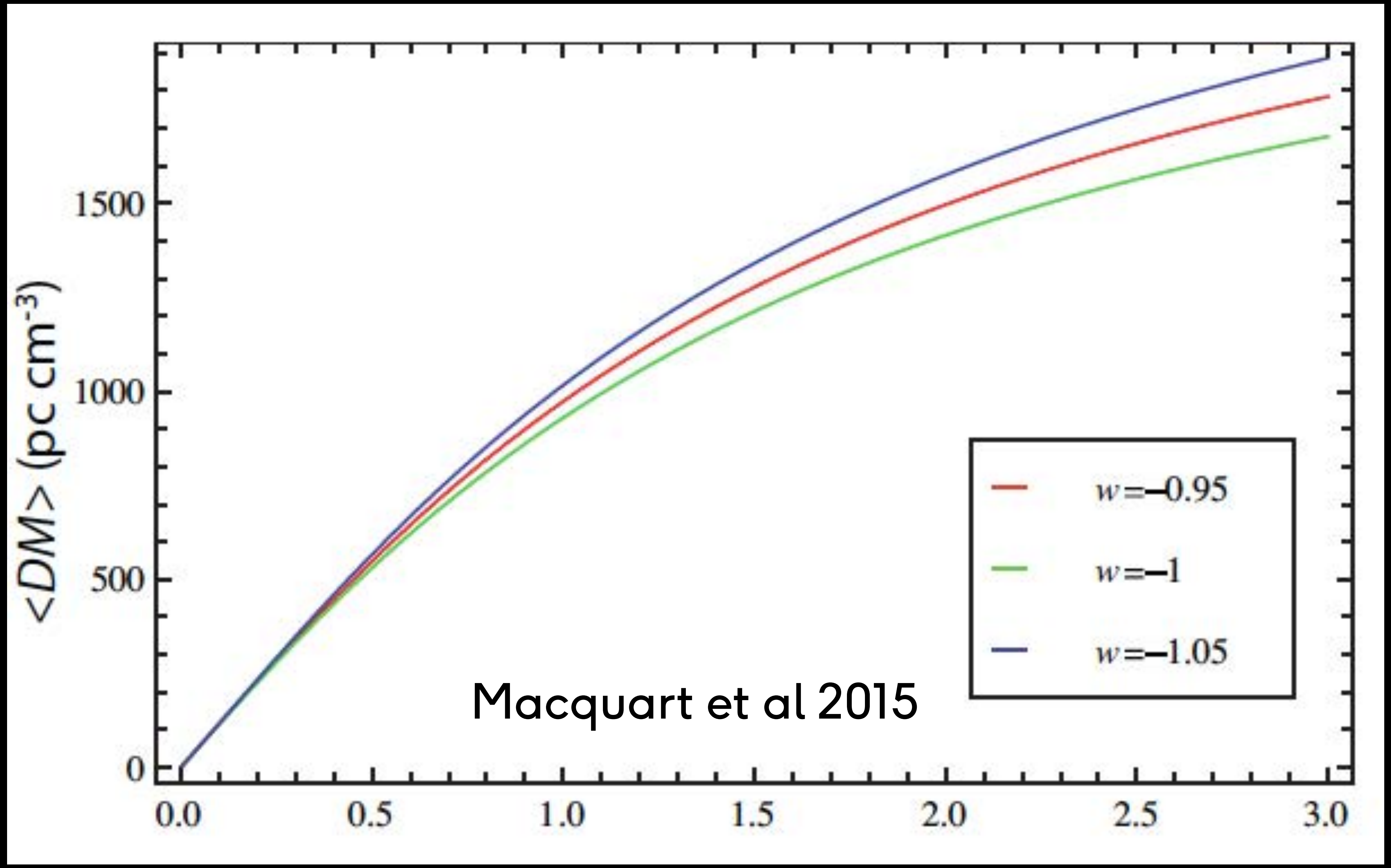
500+

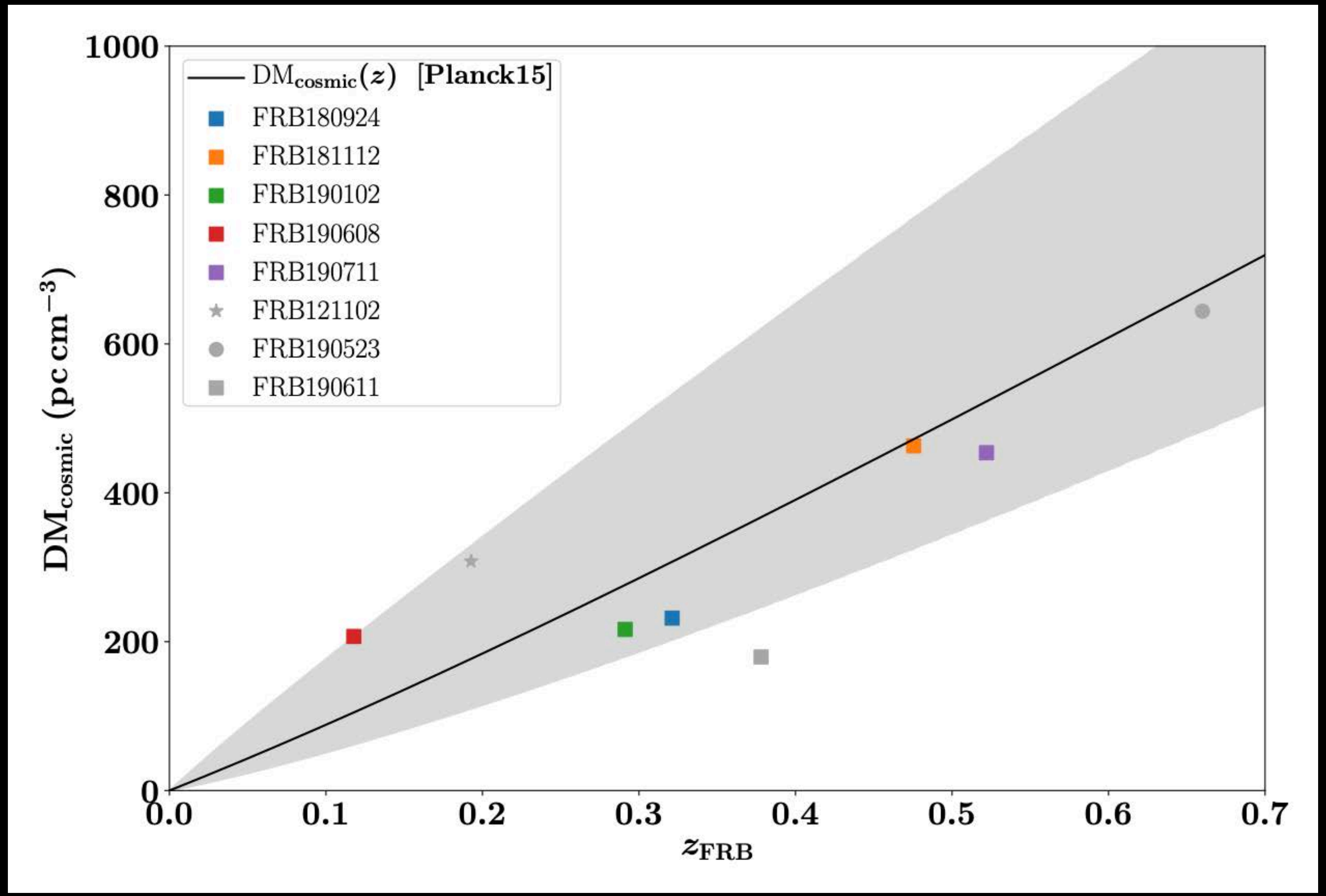


2020

Why are we so excited about FRBs?

- Brand new transients! Extreme physics!
- Use FRBs as probes in interesting cosmological experiments
- Most exciting immediate prospect: probing the baryons in the IGM



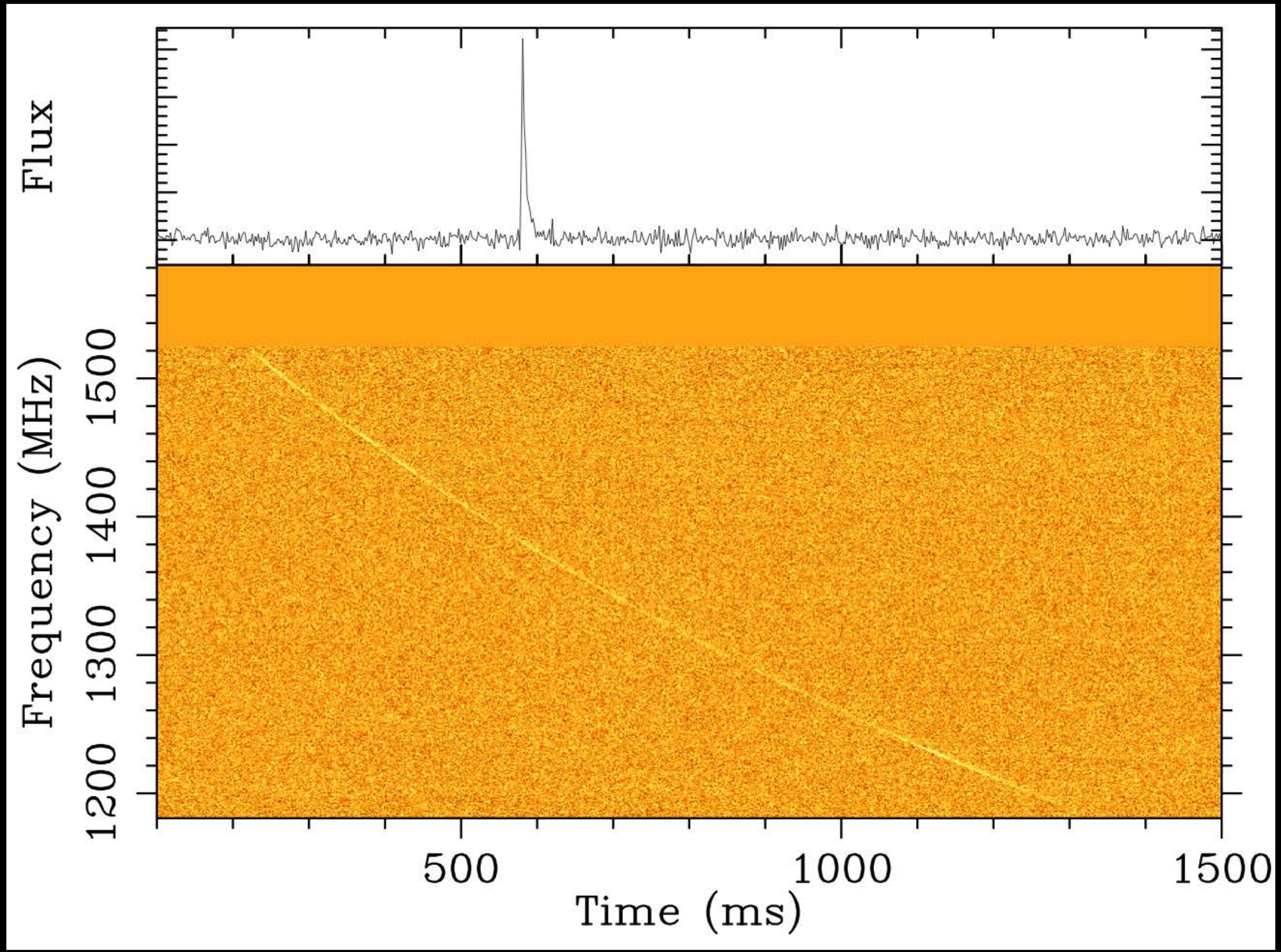


Macquart et al. (2020)

Probing the baryons

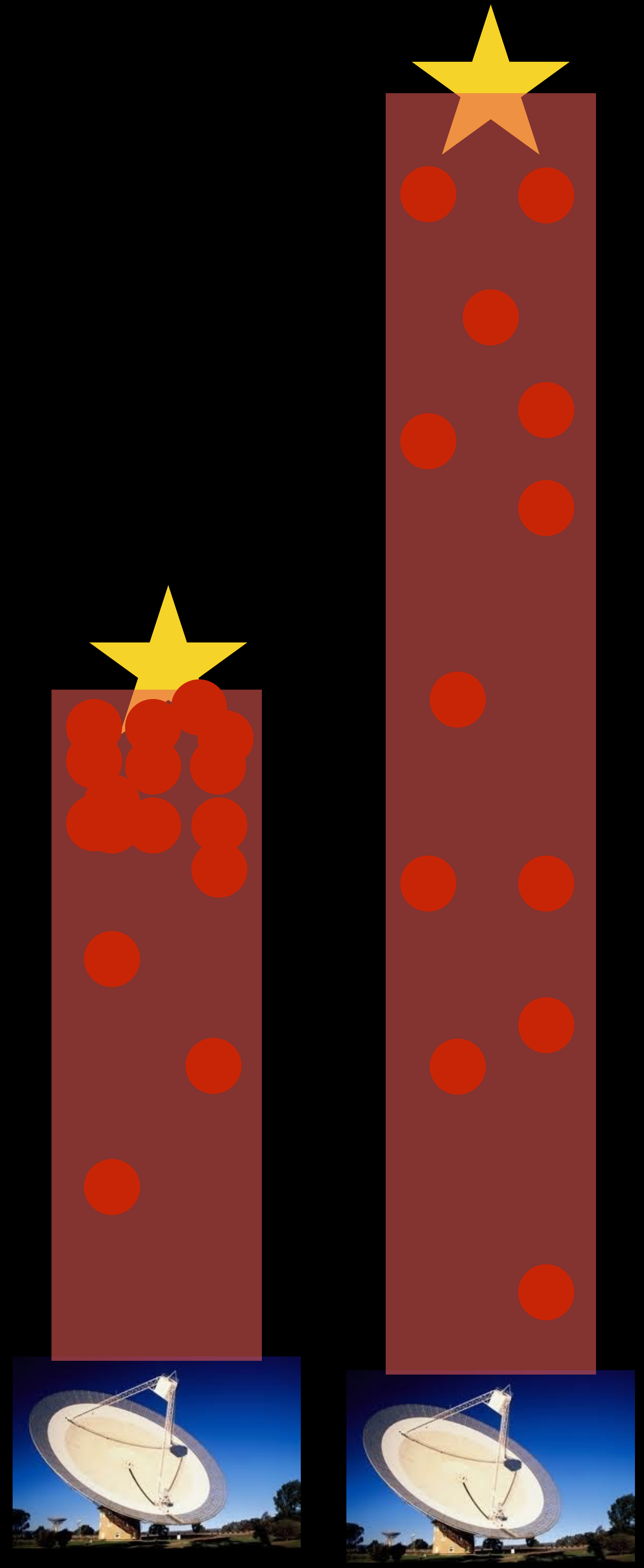
- n_e is the integrated electron column density
- Probing the Warm Ionized Medium along the line of sight
  - ISM
  - IGM
  - intervening halos and CGM
  - host galaxy
  - progenitor region

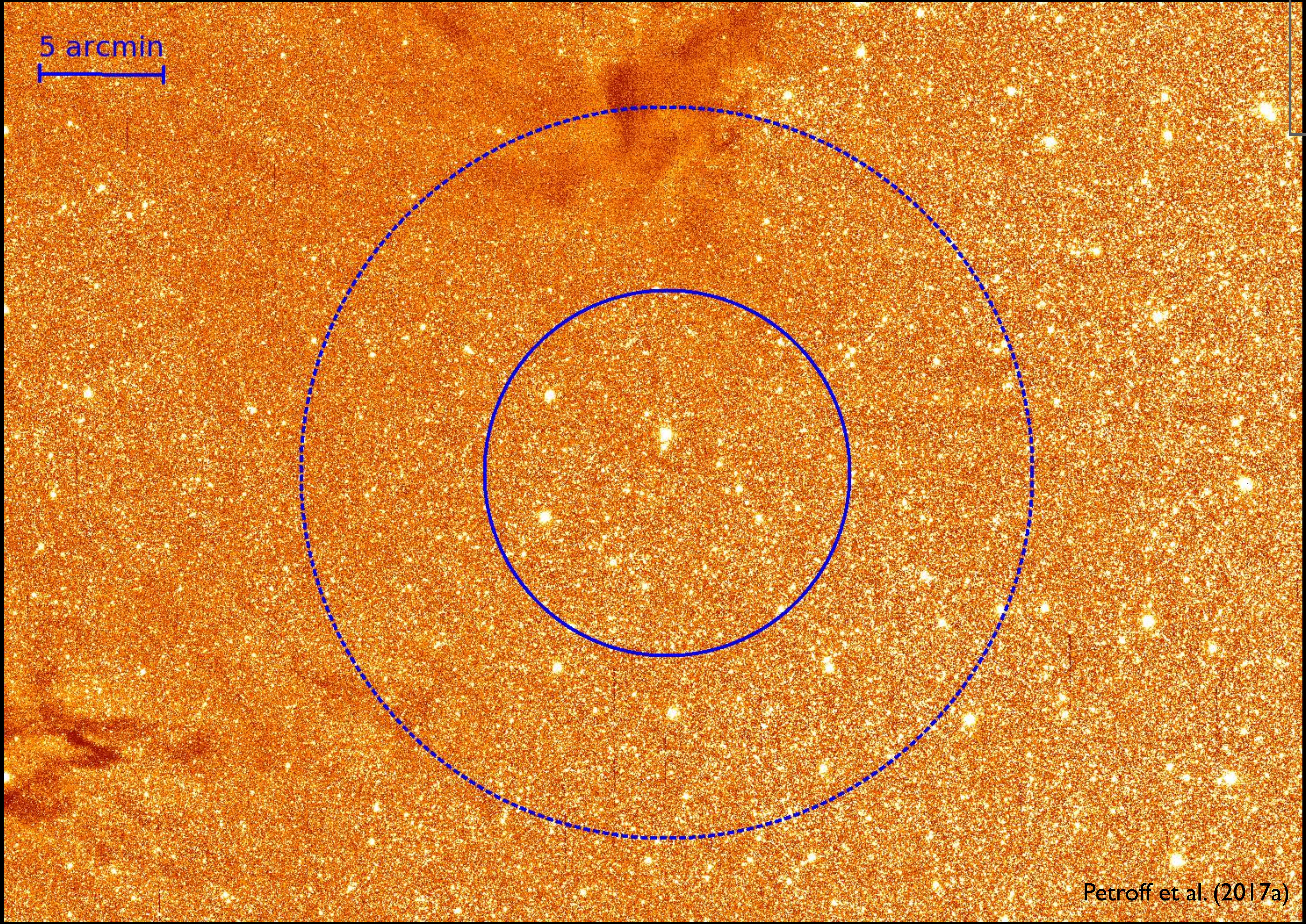
$$DM = \int_0^d n_e \, ds$$



Probing the baryons

$$DM = \int_0^d n_e \, ds$$





Petroff et al. (2017a)

Current priorities

- Find more FRBs
- Study properties - repetition, spectra, luminosity, propagation effects
- Localize FRBs to host galaxies
- Profit?

Fast Radio Bursts

E. Petroff, J.W.T. Hessels & D.R. Lorimer

Received: date / Accepted: date

Abstract The discovery of radio pulsars over a half century ago was a seminal moment in astronomy. It demonstrated the existence of neutron stars, gave a powerful observational tool to study them, and has allowed us to probe strong gravity, dense matter, and the interstellar medium. More recently, pulsar surveys have led to the serendipitous discovery of fast radio bursts (FRBs). While FRBs appear similar to the individual pulses from pulsars, their large dispersive delays suggest that they originate from far outside the Milky Way and hence are many orders-

Outline

Observational progress

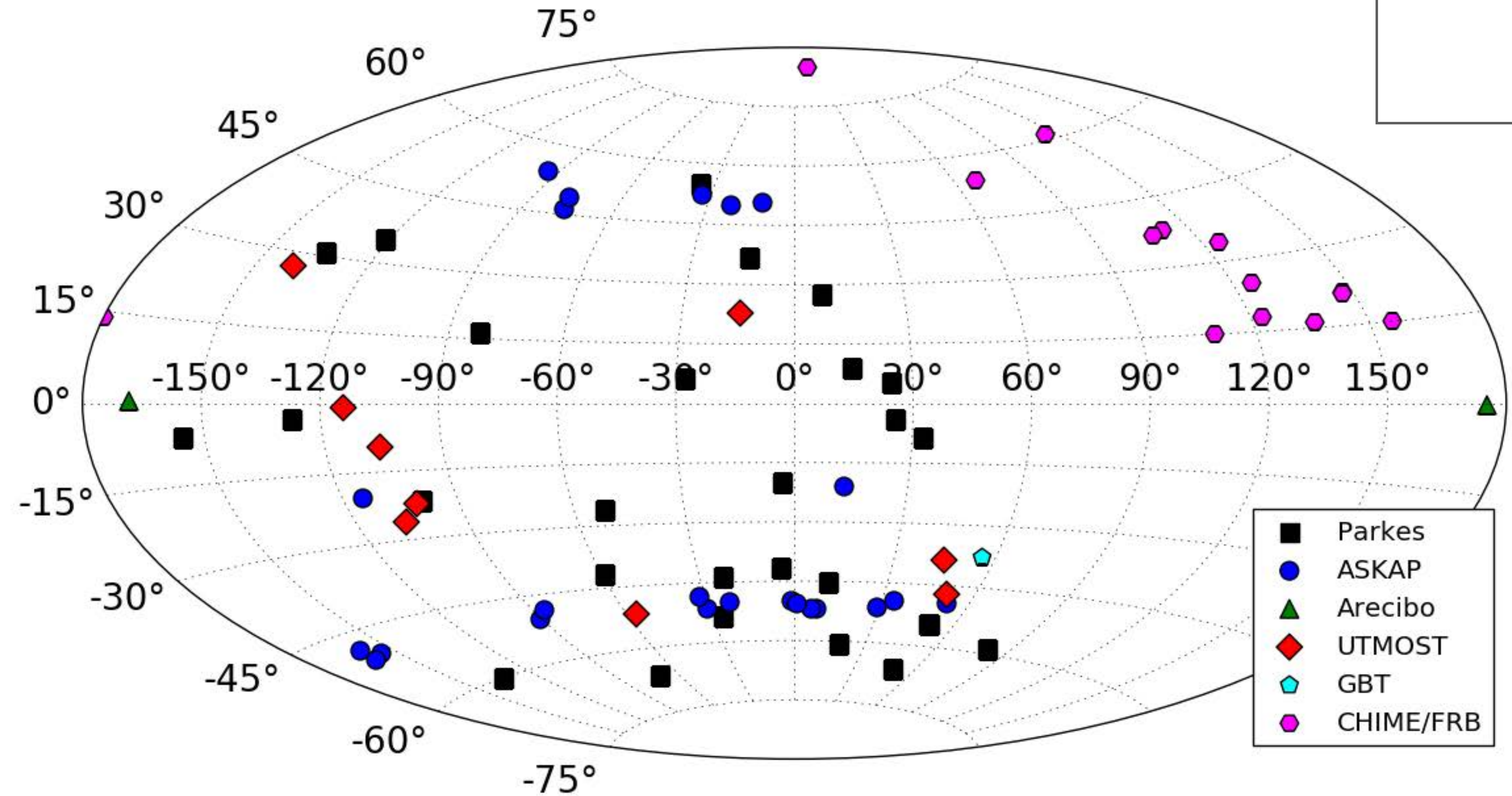
Challenges and open questions

Future prospects

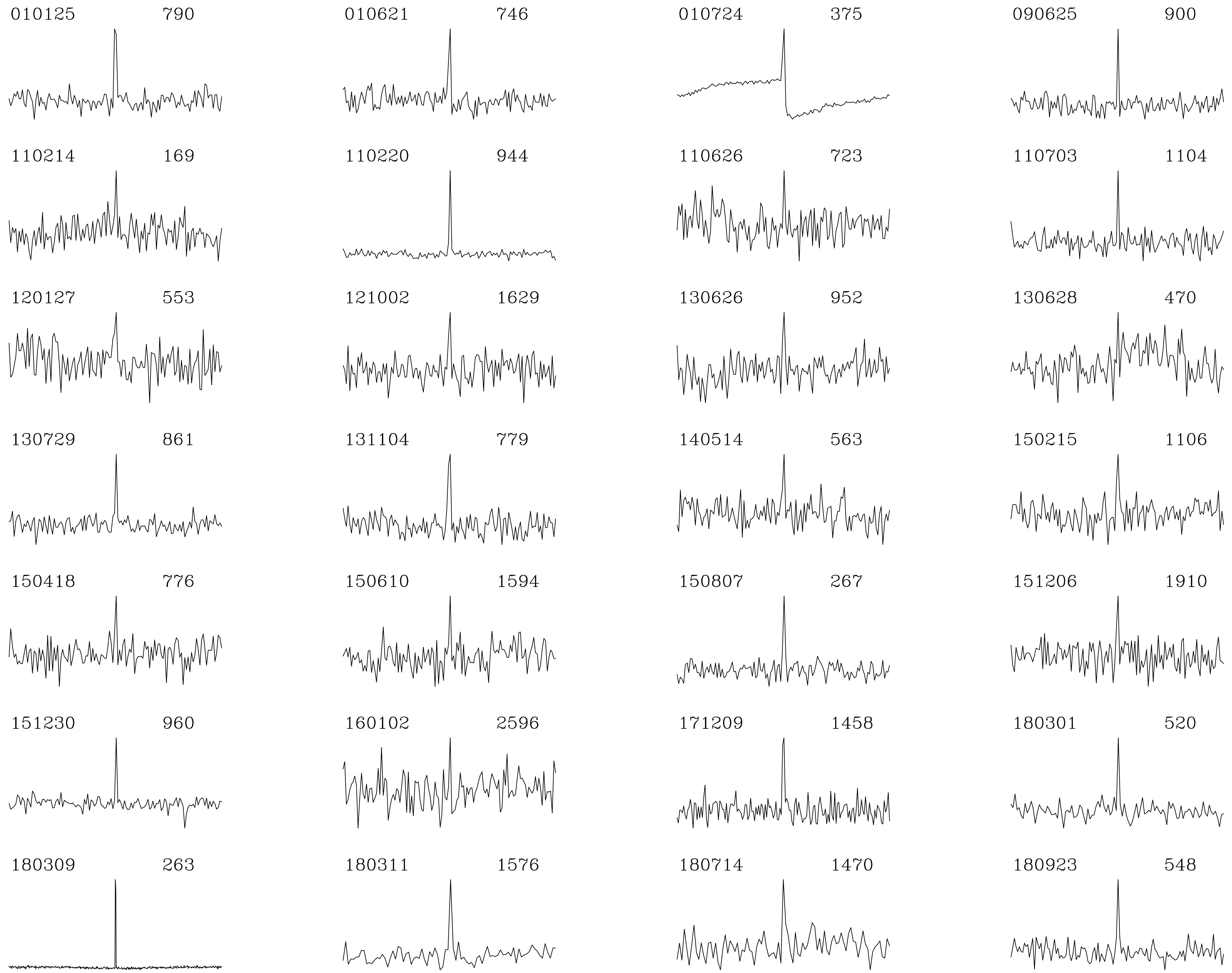
Observational progress

Challenges and open questions

Future prospects



Petroff, Hessels & Lorimer (2019)



Petroff, Hessels & Lorimer (2019)

Measured properties

dispersion measure

$$\mathrm{DM} = \int_0^d n_e \, \mathrm{d}l.$$

pulse width

$$W = \sqrt{W_{\mathrm{int}}^2 + t_{\mathrm{samp}}^2 + \Delta t_{\mathrm{DM}}^2 + \Delta t_{\mathrm{DMerr}}^2 + \tau_{\mathrm{s}}^2},$$

fluence

$$\mathcal{F} = S_{\mathrm{peak}} W_{\mathrm{eq}} = \int_{\mathrm{pulse}} S(t) \, \mathrm{d}t.$$

Derived properties

dispersion measure excess

$$\mathrm{DM_E} = \mathrm{DM} - \mathrm{DM_{MW}} = \mathrm{DM_{IGM}} + \left(\frac{\mathrm{DM_{Host}}}{1+z}\right),$$

dispersion measure of the IGM

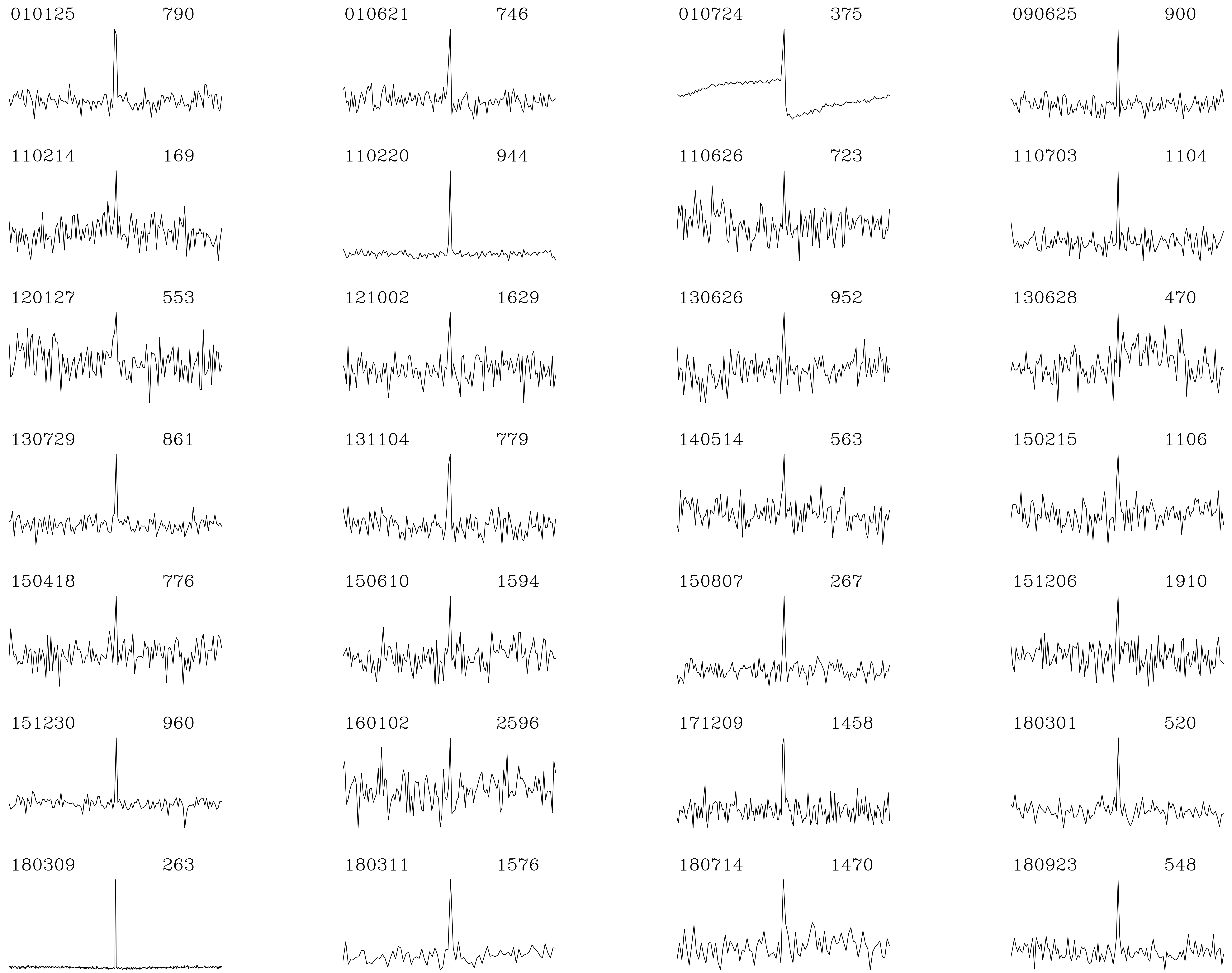
$$\langle \mathrm{DM_{IGM}} \rangle = \int n_{\mathrm{e,IGM}}\, dl = K_{\mathrm{IGM}} \int_0^z \frac{(1+z)x(z)\, dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}},$$

isotropic luminosity

$$L = \frac{4\pi d_L^2 S_\nu \Delta\nu}{(1+z)}.$$

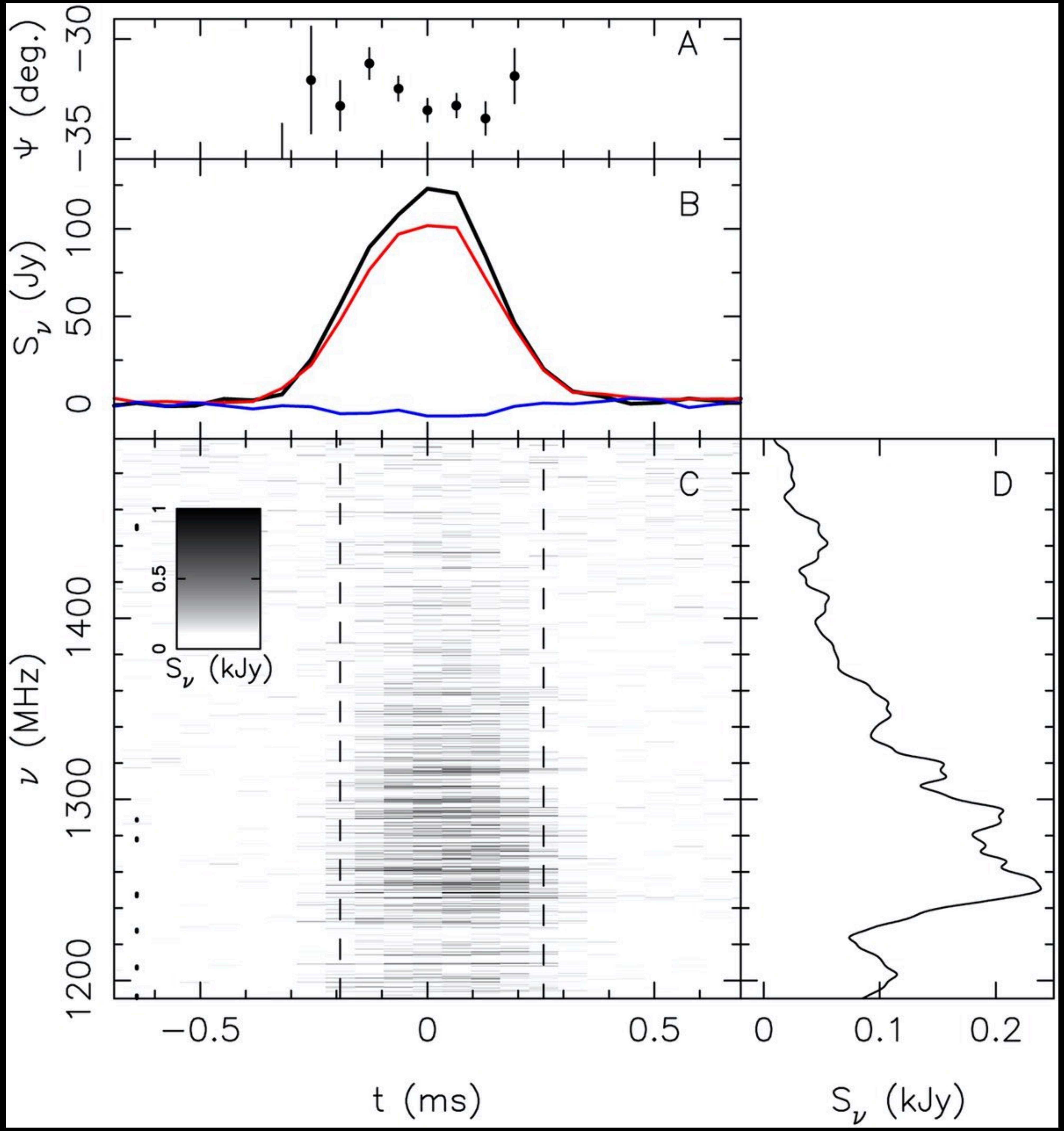
brightness temperature

$$T_{\mathrm{B}} \simeq 10^{36}\ \mathrm{K} \left(\frac{S_{\mathrm{peak}}}{\mathrm{Jy}}\right) \left(\frac{\nu}{\mathrm{GHz}}\right)^{-2} \left(\frac{W}{\mathrm{ms}}\right)^{-2} \left(\frac{d_L}{\mathrm{Gpc}}\right)^{2}.$$



Petroff, Hessels & Lorimer (2019)

Propagation effects

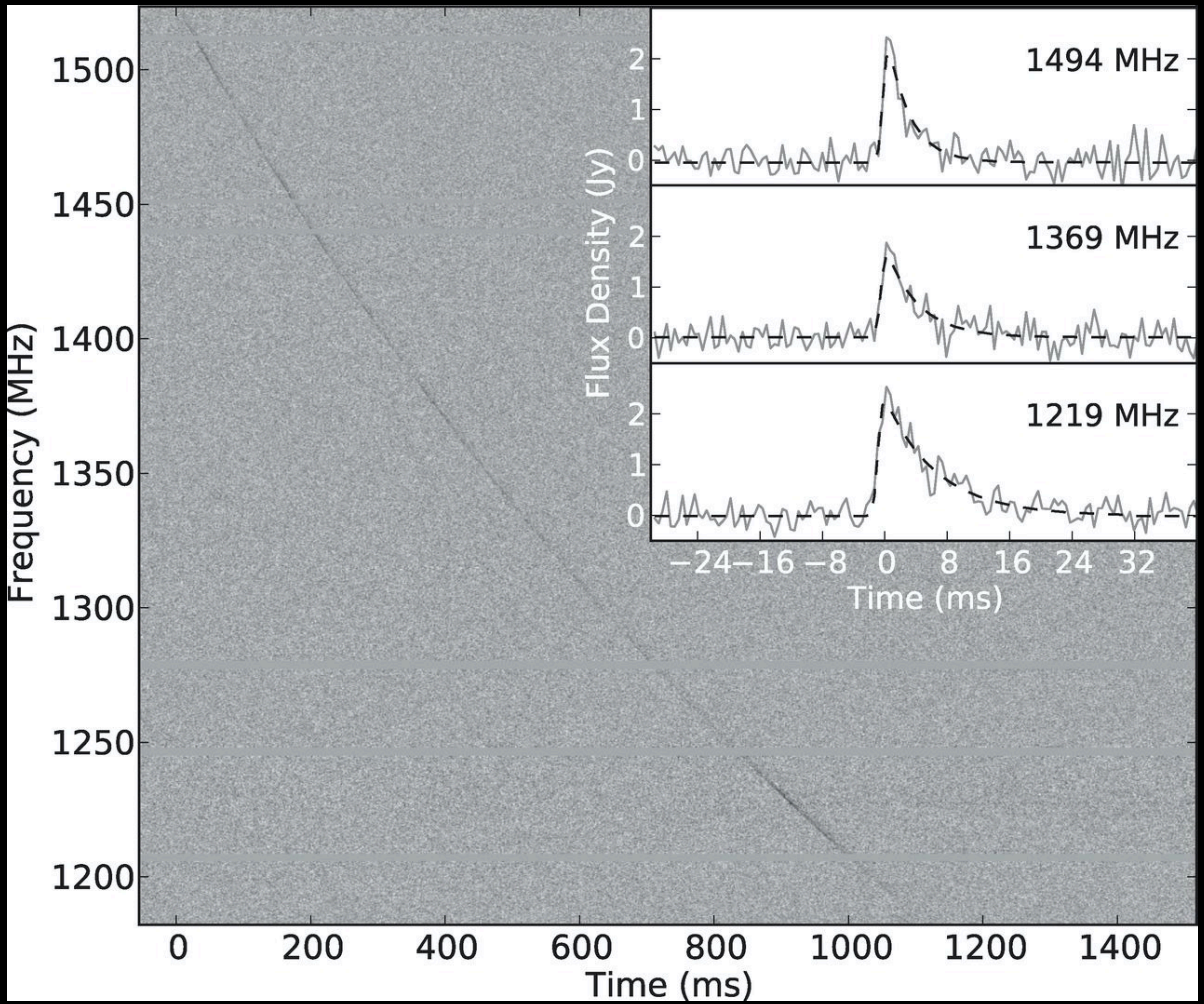


Ravi et al. (2016)

scintillation

$$\Delta\nu_{\rm Scint} \propto \nu^4$$

Propagation effects

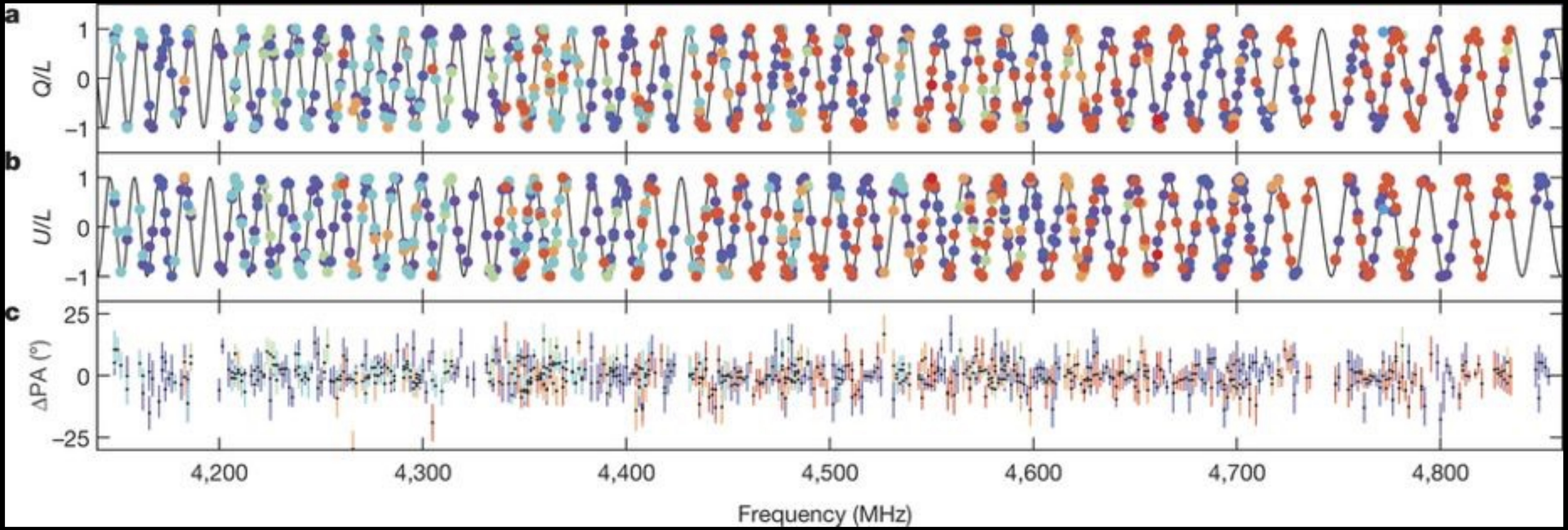


scattering

$$\tau \propto \nu^{-4}.$$

Thornton et al. (2013)

Propagation effects



Michilli et al. (2018)

rotation measure

$$\Theta = \mathrm{RM}\ \lambda^2,$$

$$\mathrm{RM} = -0.81 \int_0^d B(l)_{\|} n_e(l) dl,$$

$$\mathrm{RM_{src}} = \mathrm{RM_{obs}}(1+z)^2$$

Specific FRBs

- FRB 121102 - “The repeater”, “R1”
- CHIME!
- Periodic repetition from FRB180916
- The case of SGR 1935+2154
- The sample of ASKAP Hosts

The repeating FRB

- An FRB that repeats!
  FRB 121102

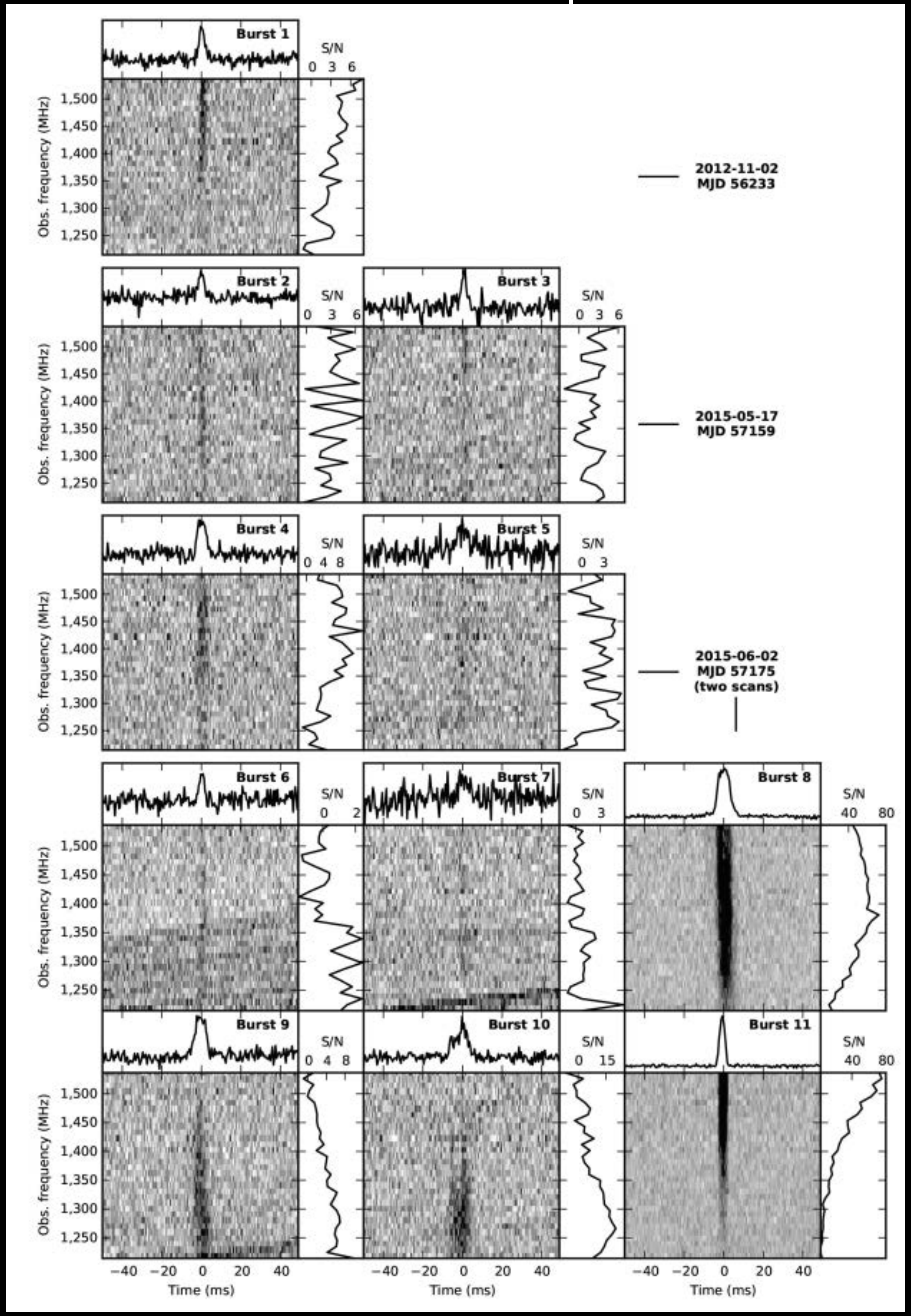
- Found and followed-up with Arecibo

- > 500 pulses found

- Highly clustered in time

- No underlying periodicity**

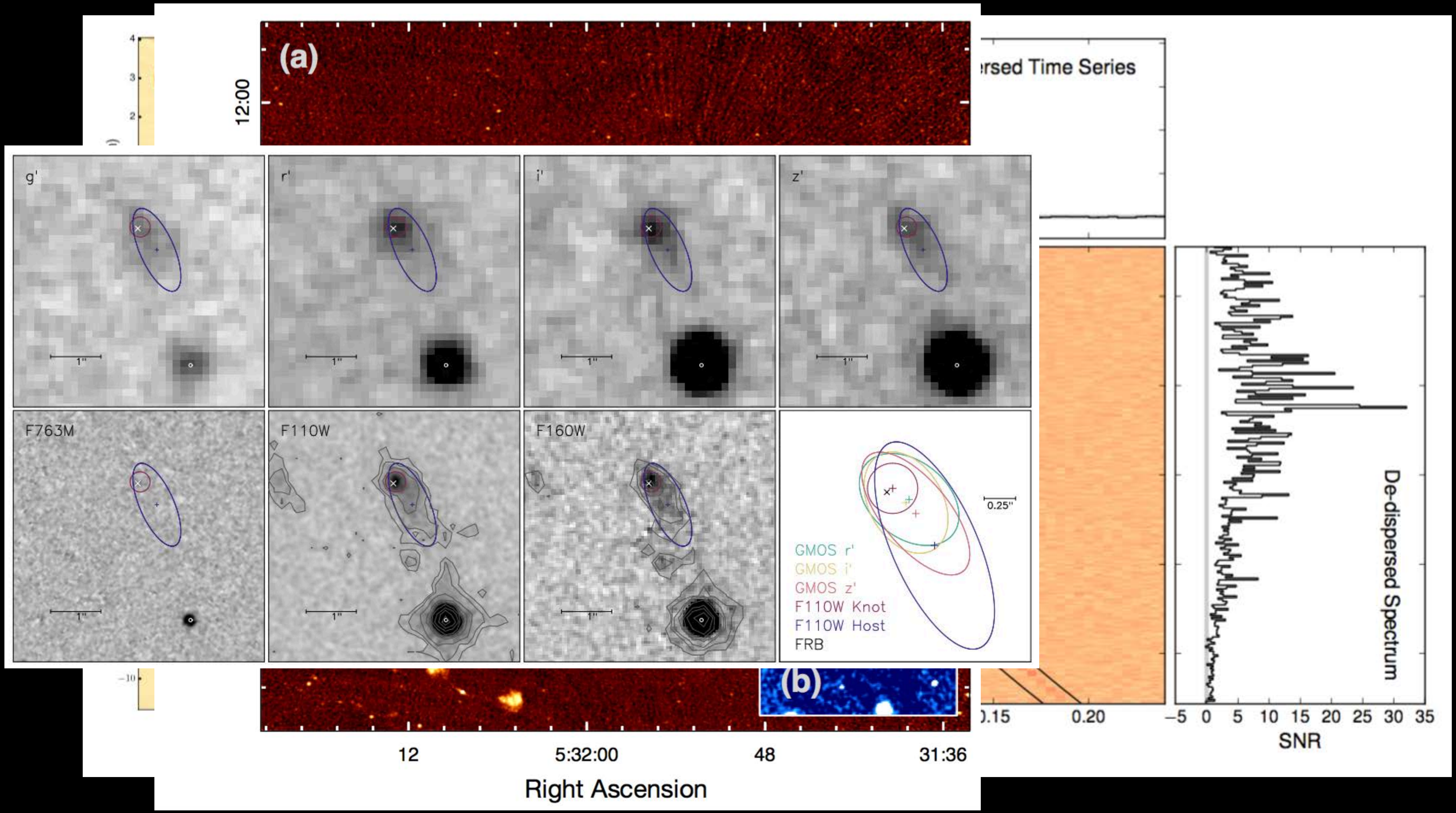
Spitler et al. 2016



The repeating FRB

- Localized through repeating pulses with the VLA
- Localized to a dwarf galaxy
  - $z = 0.19$ (~1 Gpc away)
- Co-located with a persistent radio source
- Possible connection with long GRBs and SLSNe
  - young magnetar in dense PWN?

The first host galaxy

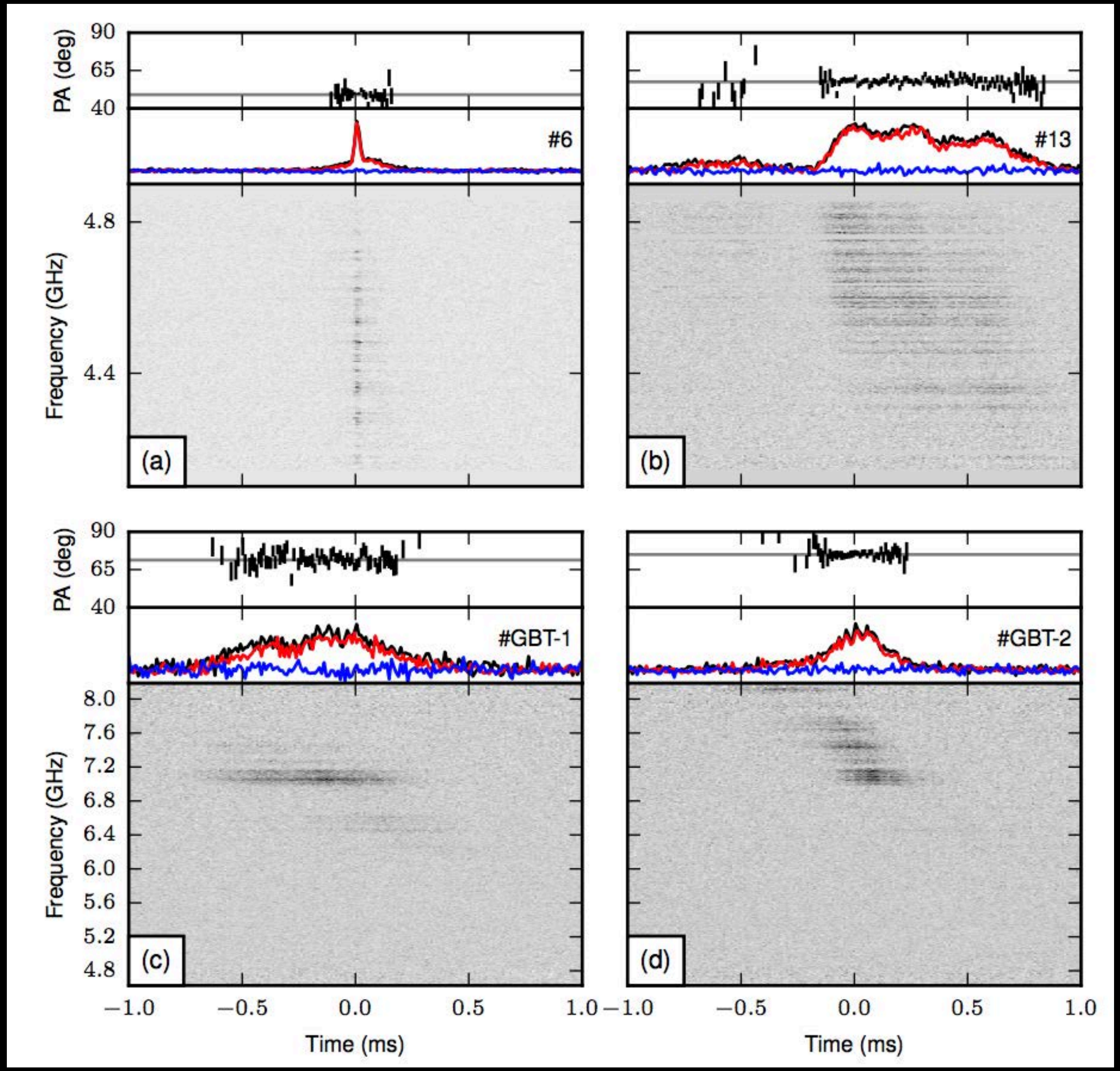


Bassa et al. 2017

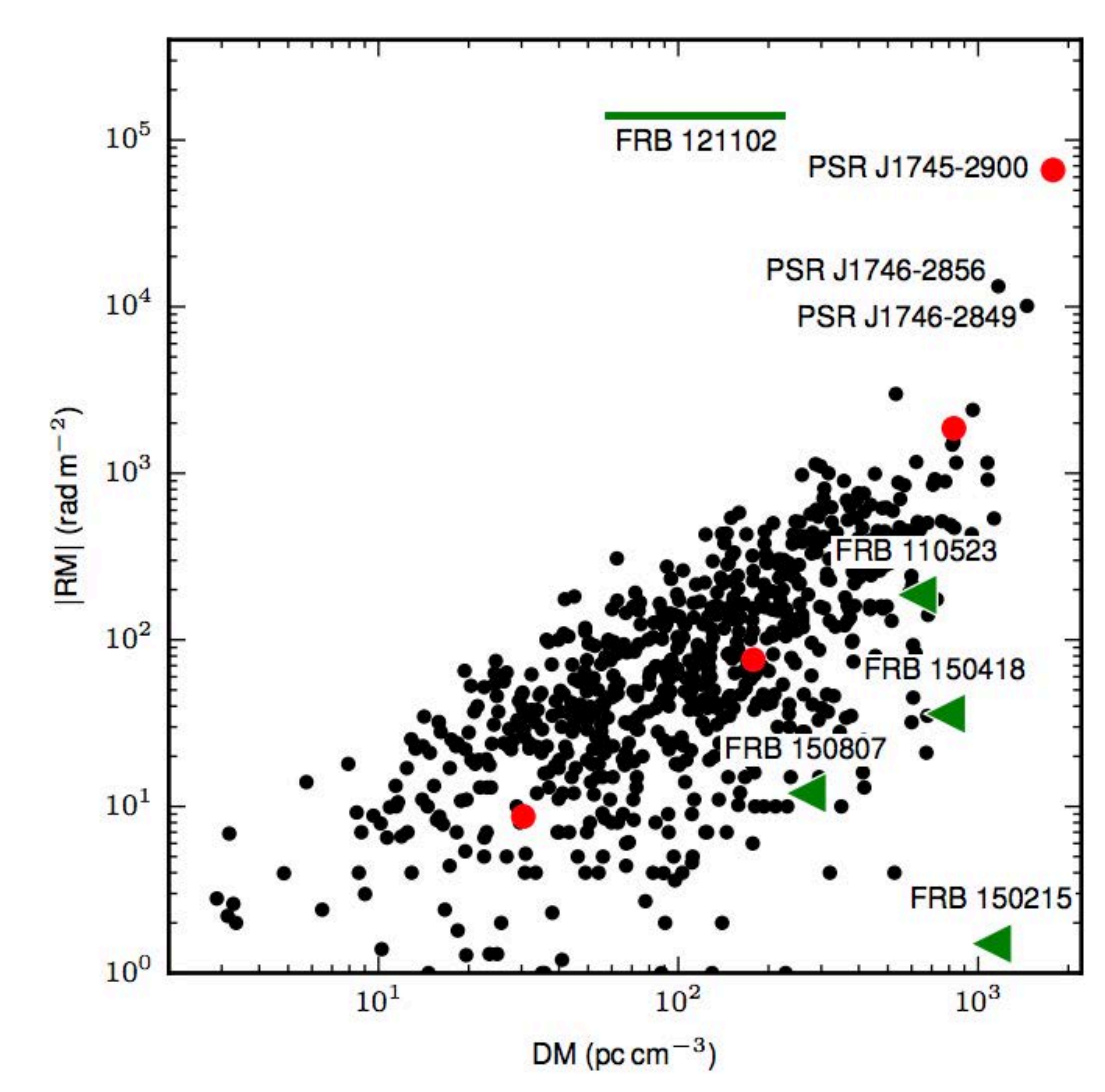
Chatterjee et al. 2017

Tendulkar et al. 2017

FRB 121102 - rotation measure



100% linearly polarized



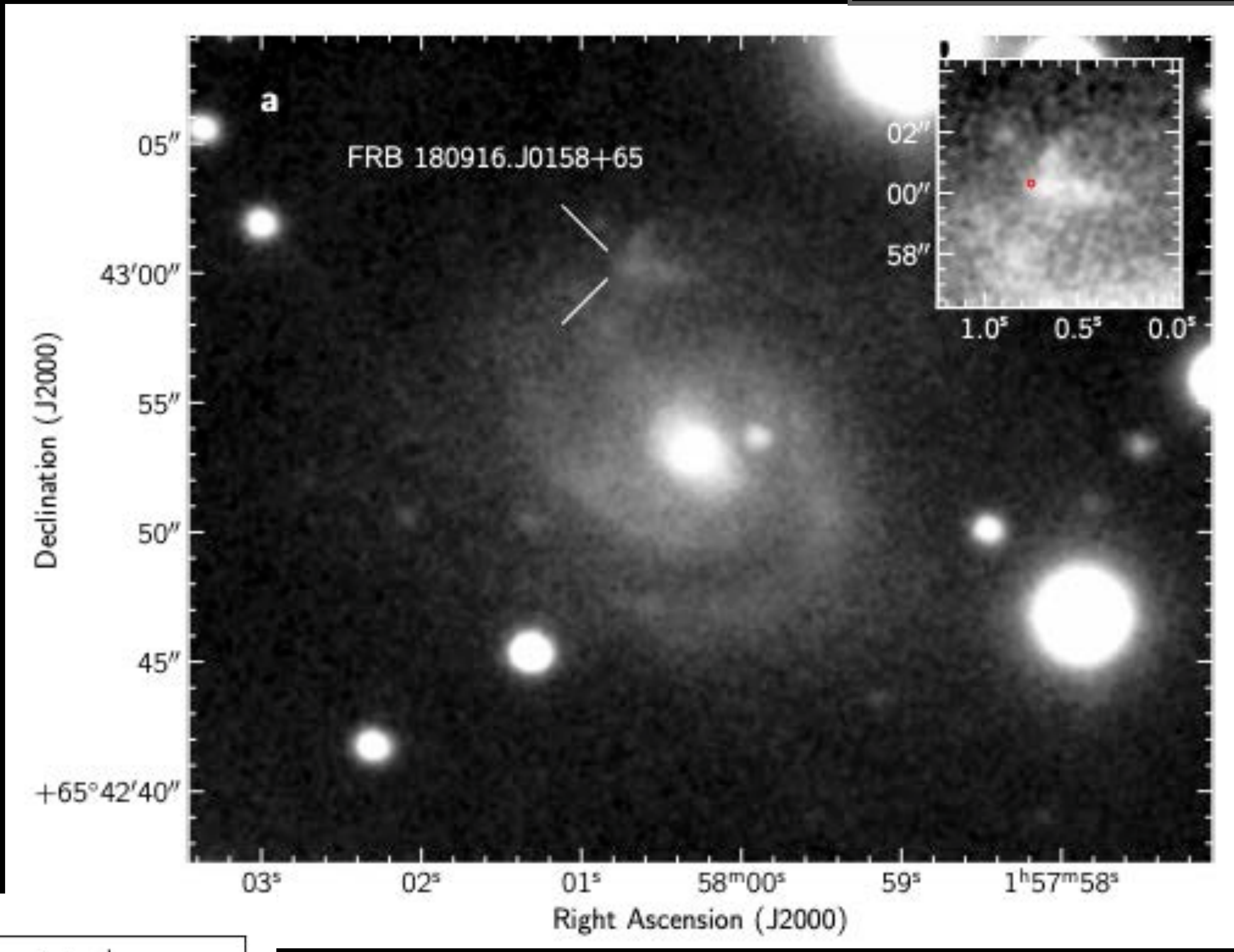
Michilli et al. 2018

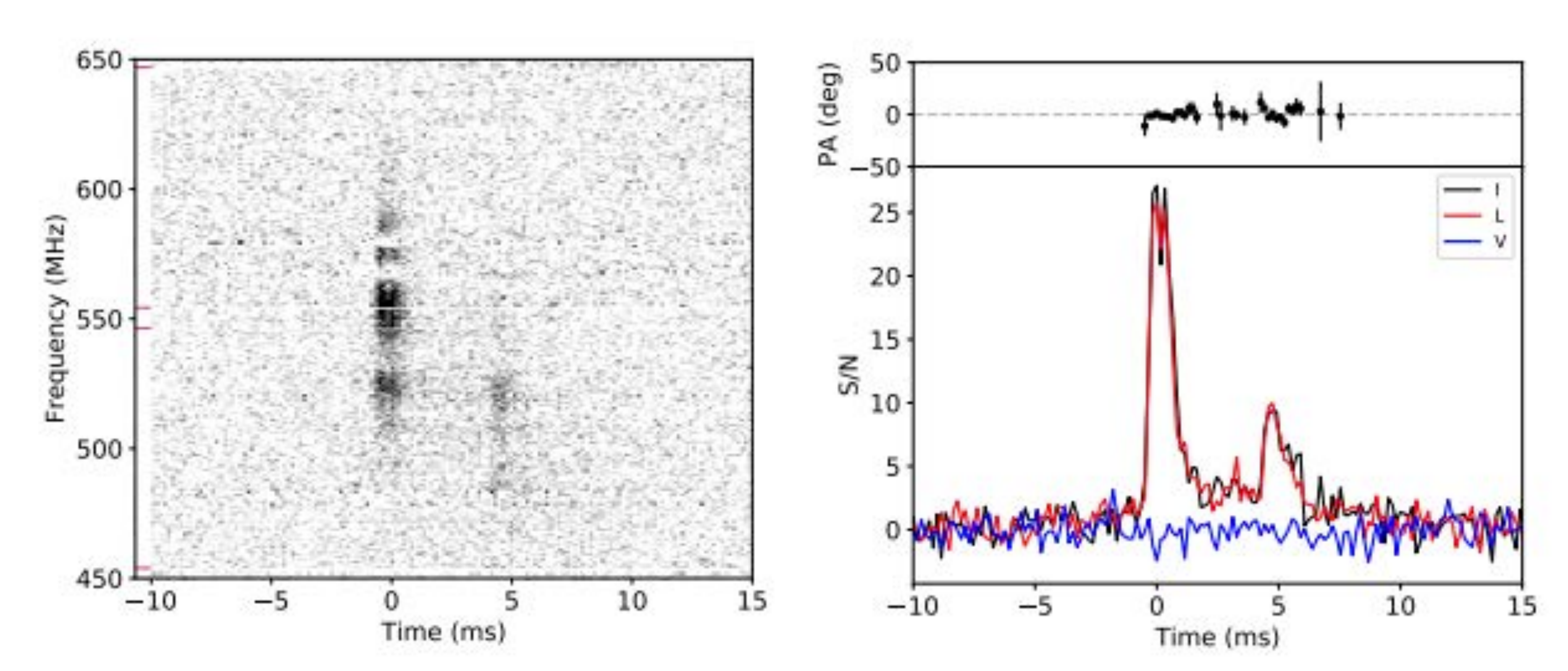
RM = 1.0 x 10^5 rad m^{-2}!!!

$$B_{\|}^{\mathrm{FRB}} = (0.6\text{–}2.4) \times f_{\mathrm{DM}}\ \mathrm{mG}$$

Compare: FRB 180916

- Repeater from CHIME
- FRB 180916.J0158+65 (R3)
- Localized to star forming region in spiral
- Intermediate rotation measure RM = -114 rad m^{-2}

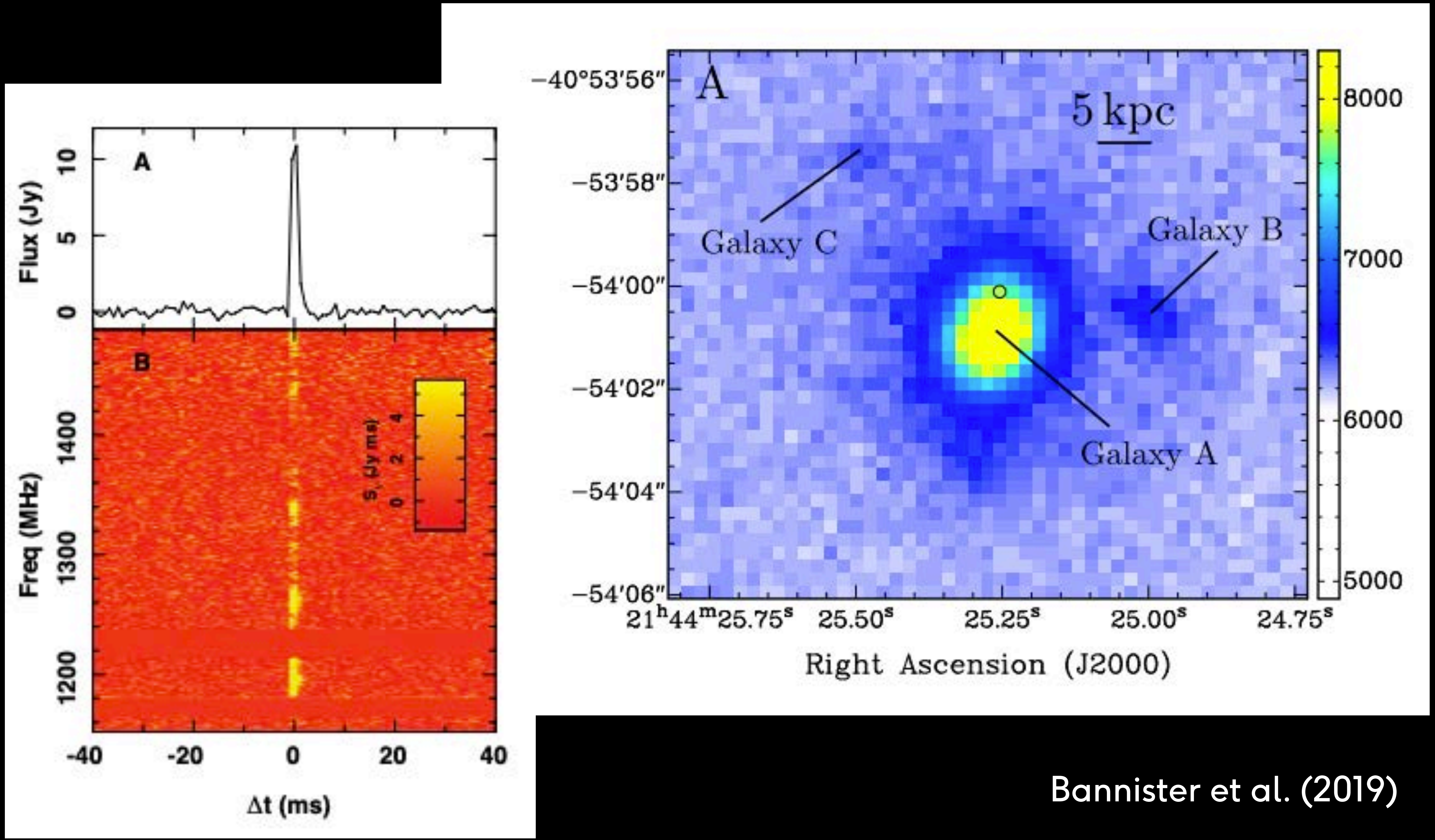




CHIME/FRB Collaboration et al. (2019)
Marcote et al. (2020)

Contrast: FRB 180924

- One-off FRB (so far)
- Localized to outskirts of a massive galaxy
- Low rotation measure RM = 14 rad m^{-2}



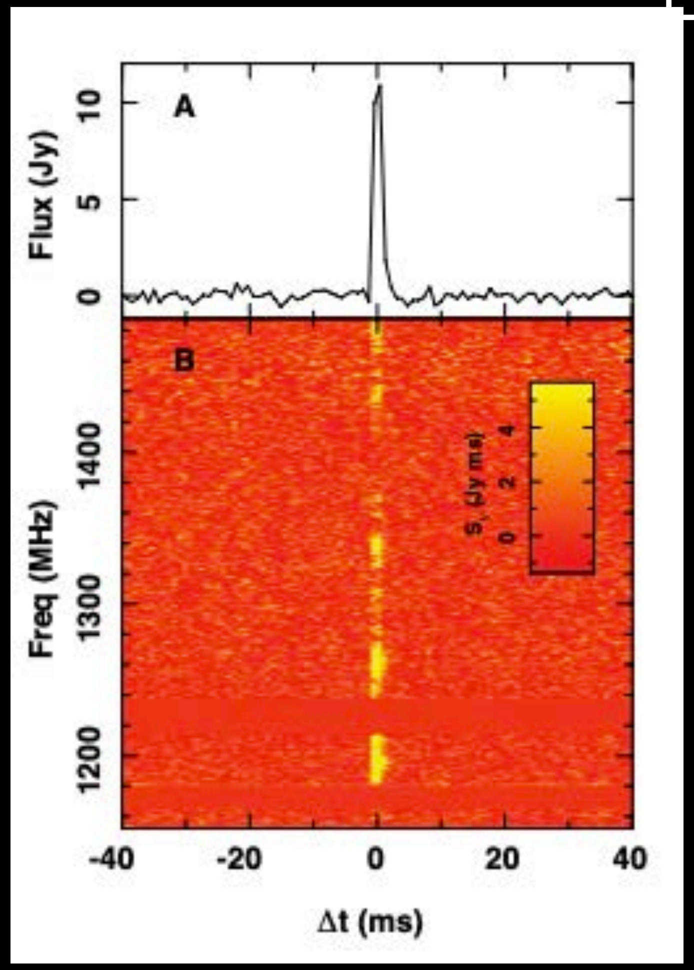
Bannister et al. (2019)

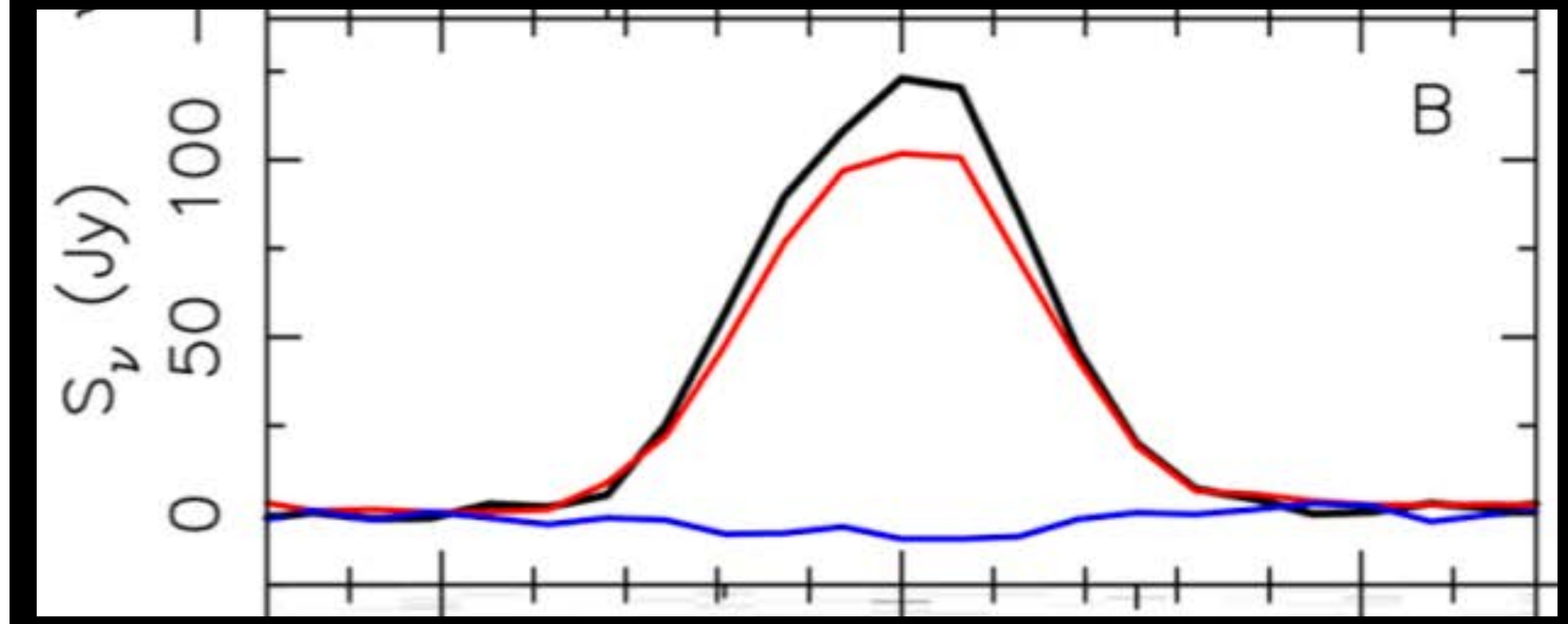
Rotation measure

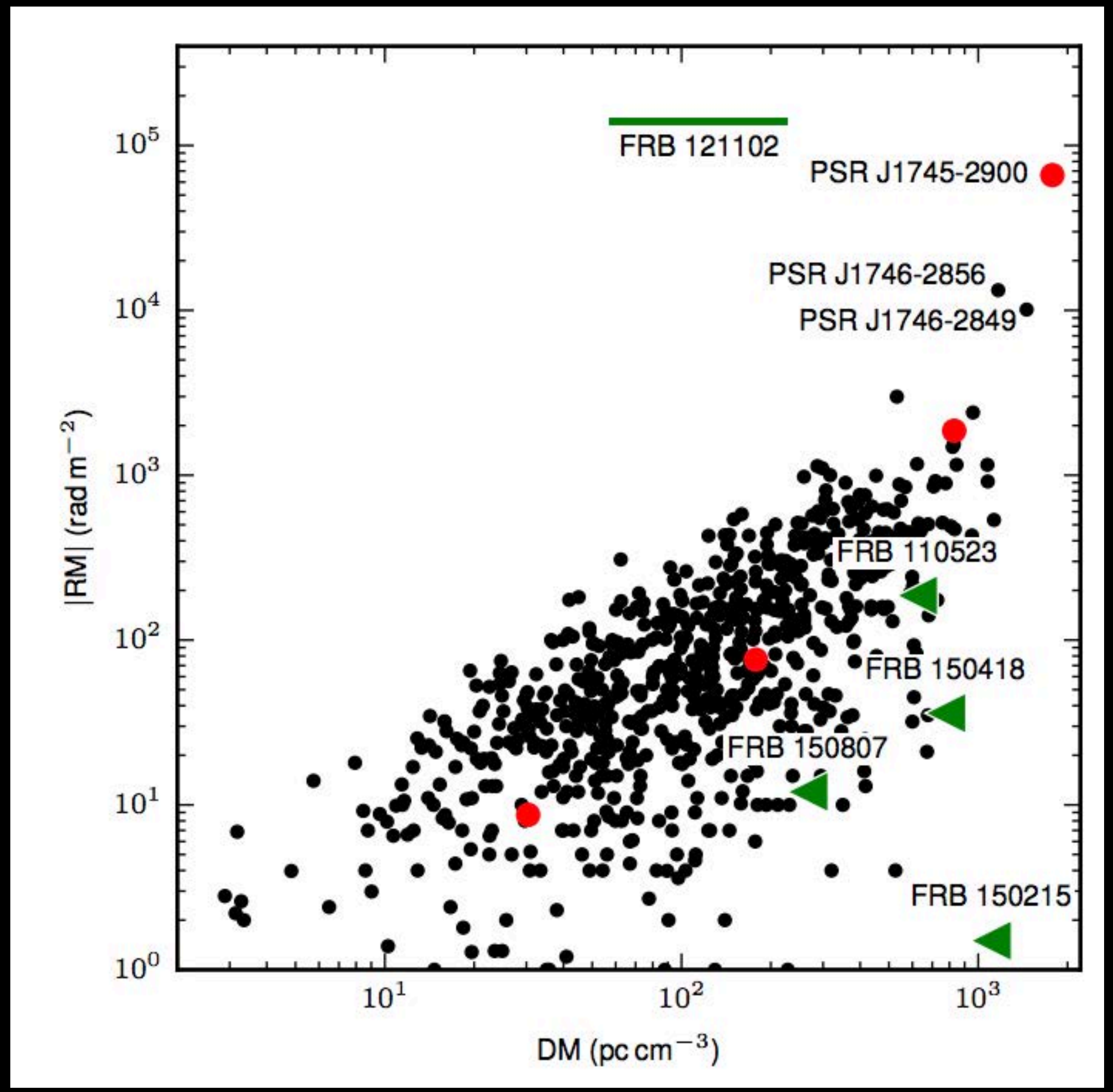
$$\mathrm{RM} = \frac{e^3}{2\pi m_e^2 c^4} \int_0^d n_e B_{\parallel} d\ell$$

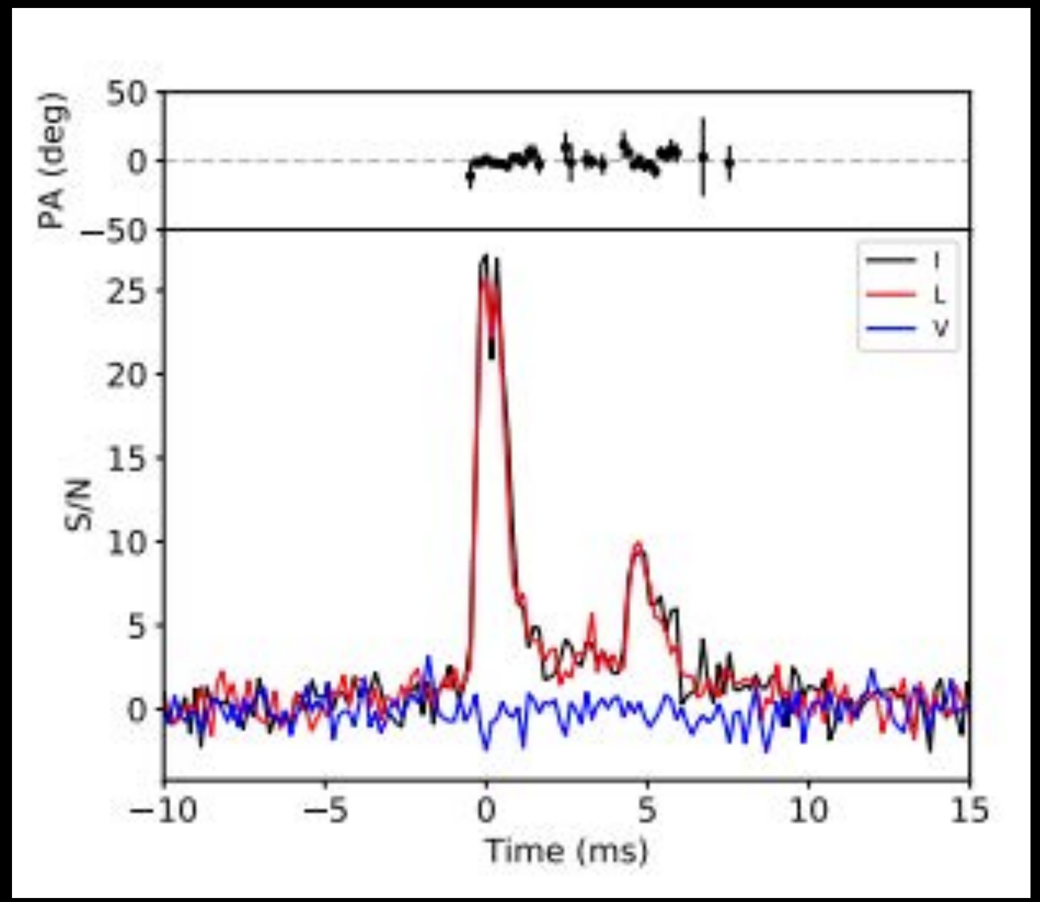
FRB 180924	14 rad m^{-2}
FRB 150807	12 rad m^{-2}

R3	-114 rad m^{-2}
FRB 160102	-220 rad m^{-2}
FRB 121102	10^5 rad m^{-2}









Bannister et al. (2019) Ravi et al. (2016) Michilli et al. (2018)

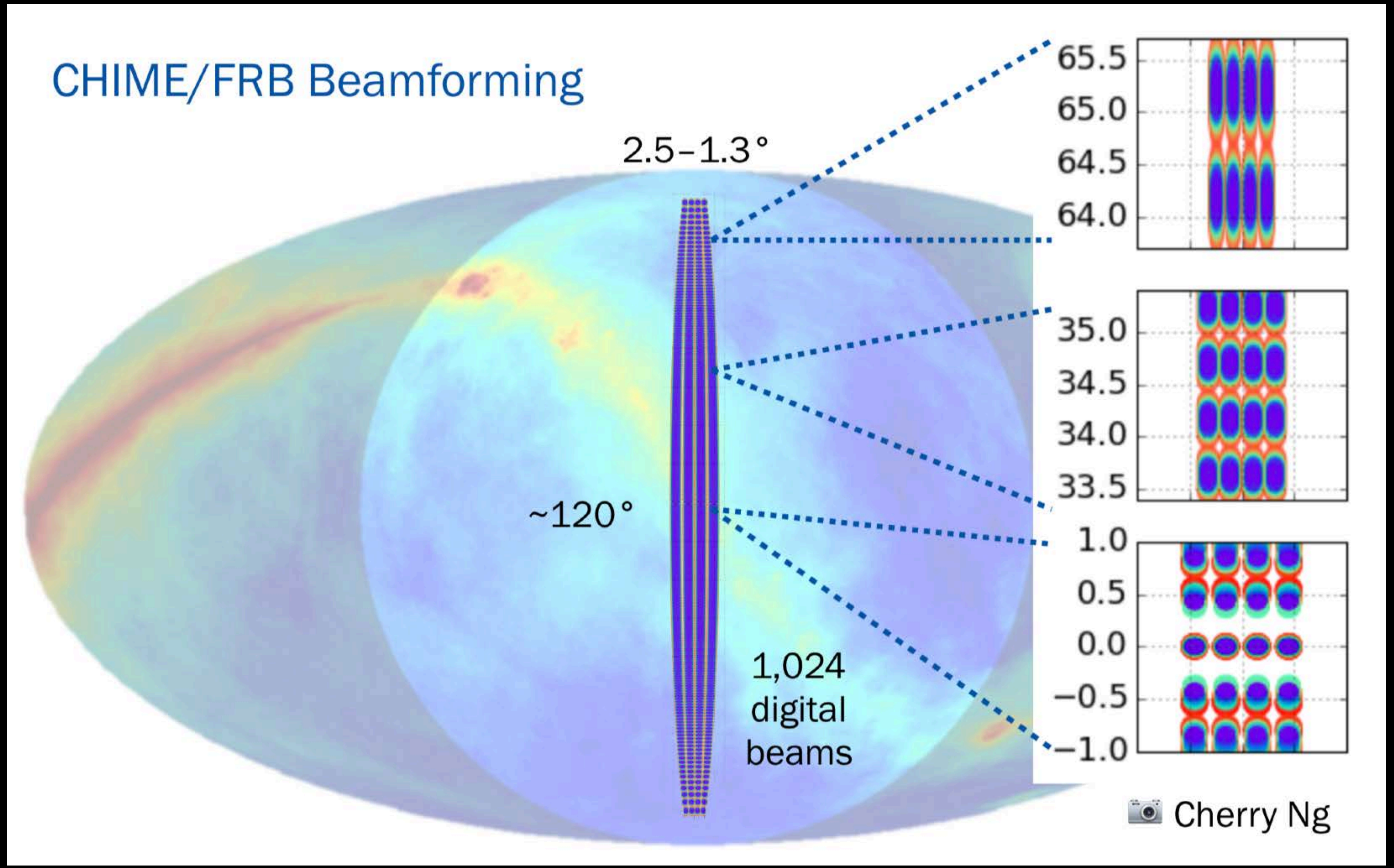
Polarization to Magnetic field

- Two different pictures
- FRBs 180924, other one-offs
  - High fractional linear polarization
  - Low RM consistent with estimates of Galactic foreground
  - No ordered magnetic field in addition to Galactic contribution
- FRBs 121102, R3, others
  - High fractional linear polarization
  - RM much higher than estimated foreground
  - Ordered magnetic field local to progenitor or in host galaxy

RM may give greatest insights into local environment!

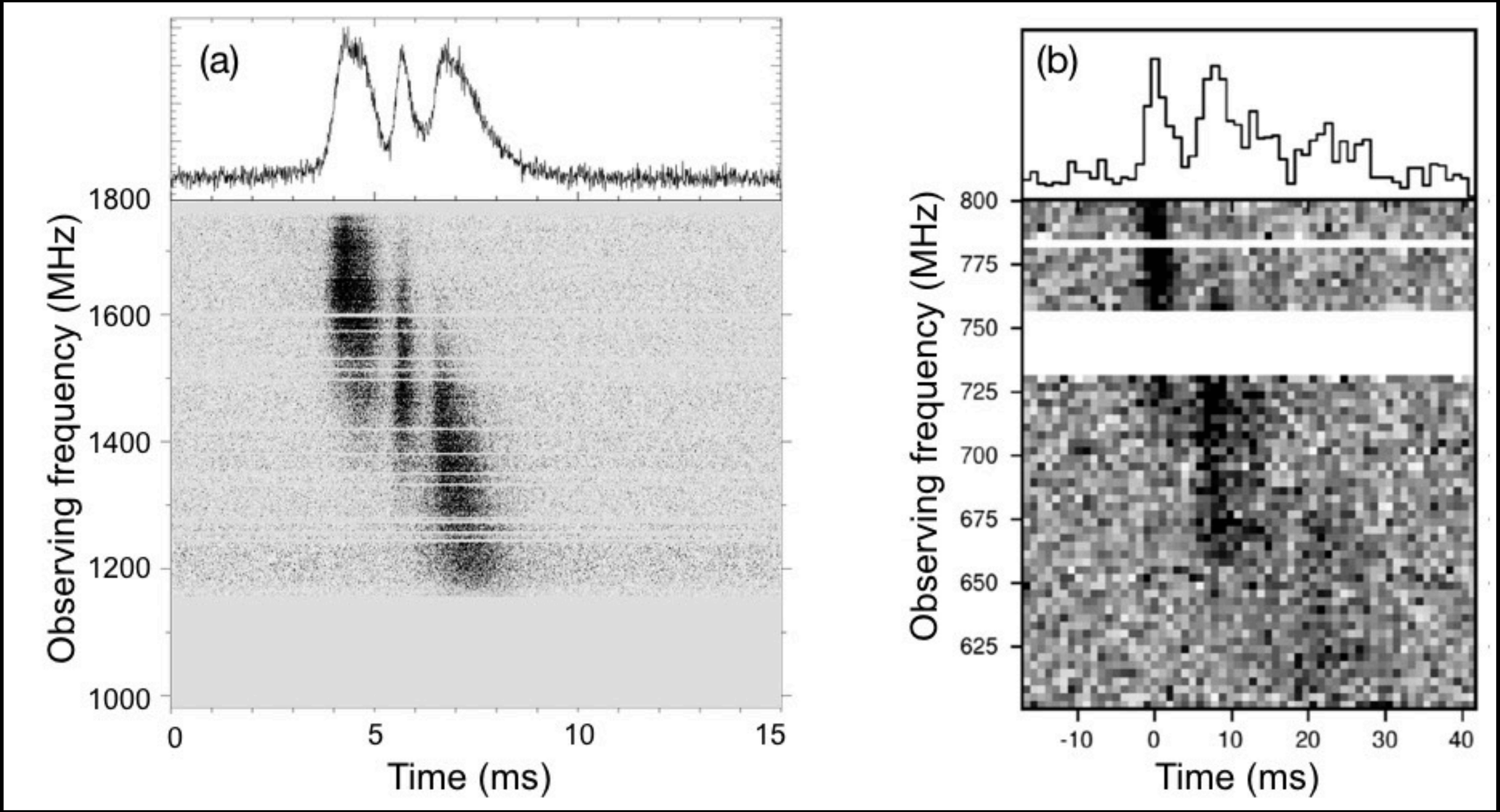
CHIME is turning on

- 400 - 800 MHz
- 250 deg^2
- Transit telescope
- Expected rate: 1-10 FRBs / day



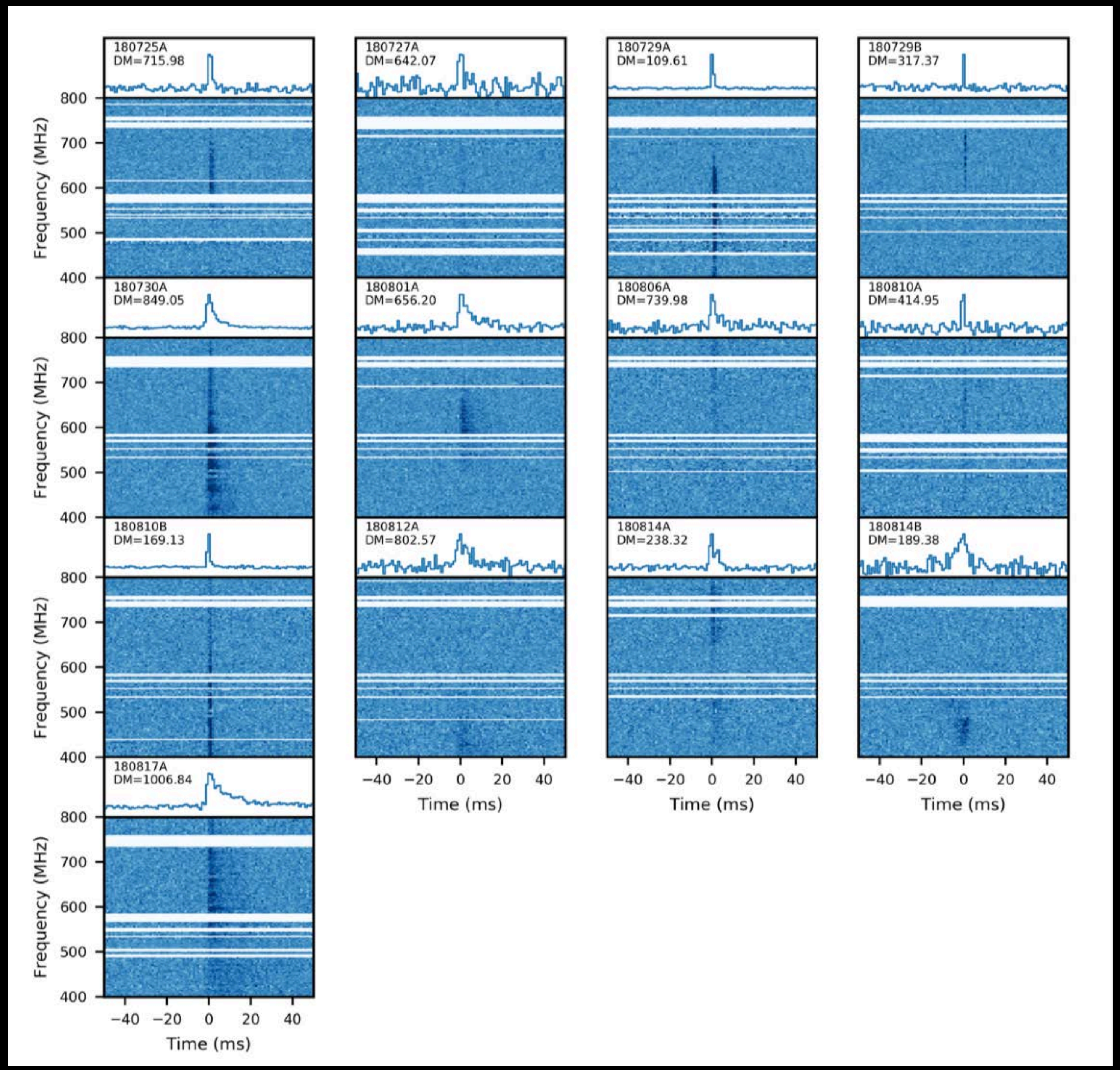
"R1" - Arecibo

"R2" - CHIME



Petroff, Hessels & Lorimer (2019)

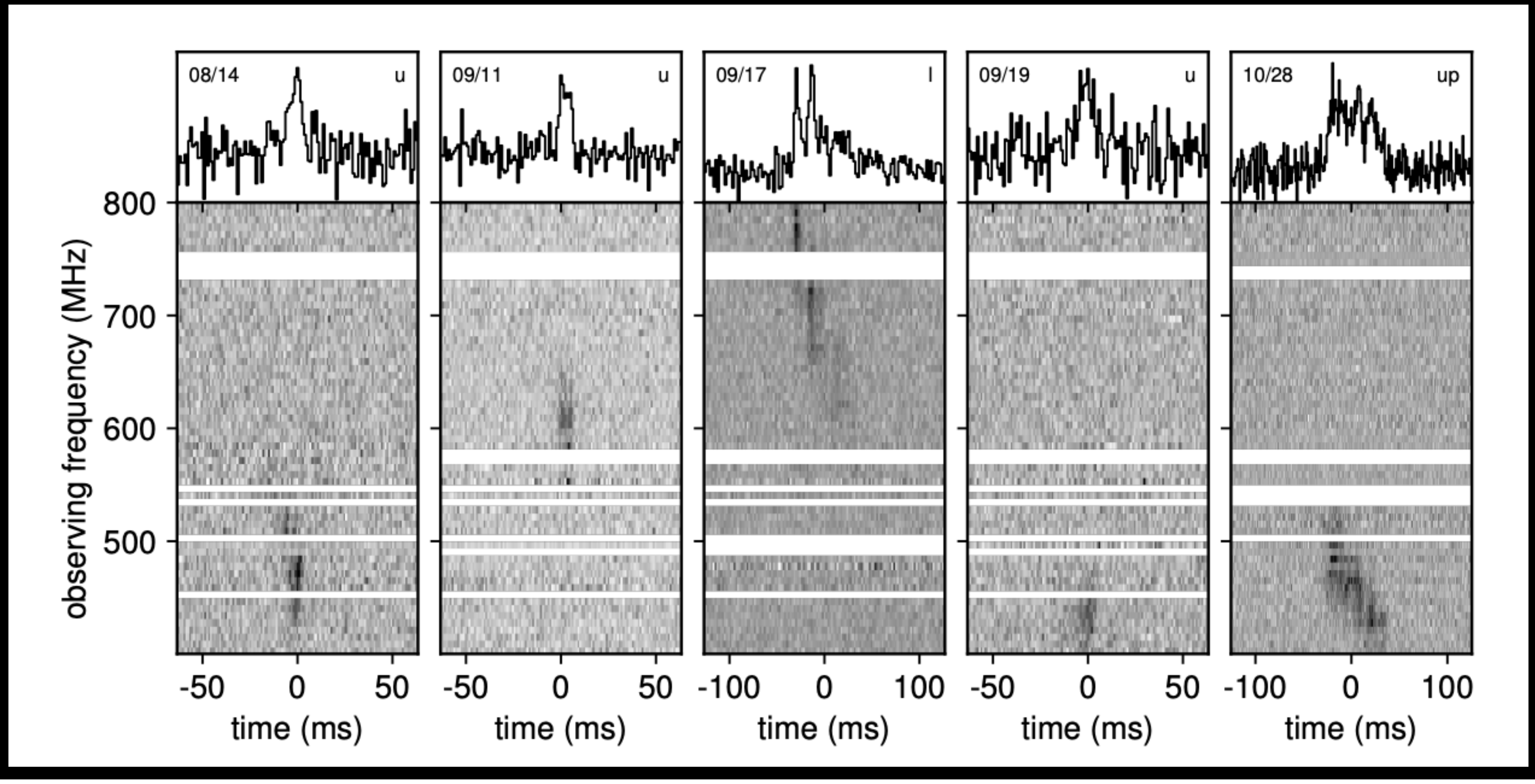
CHIME

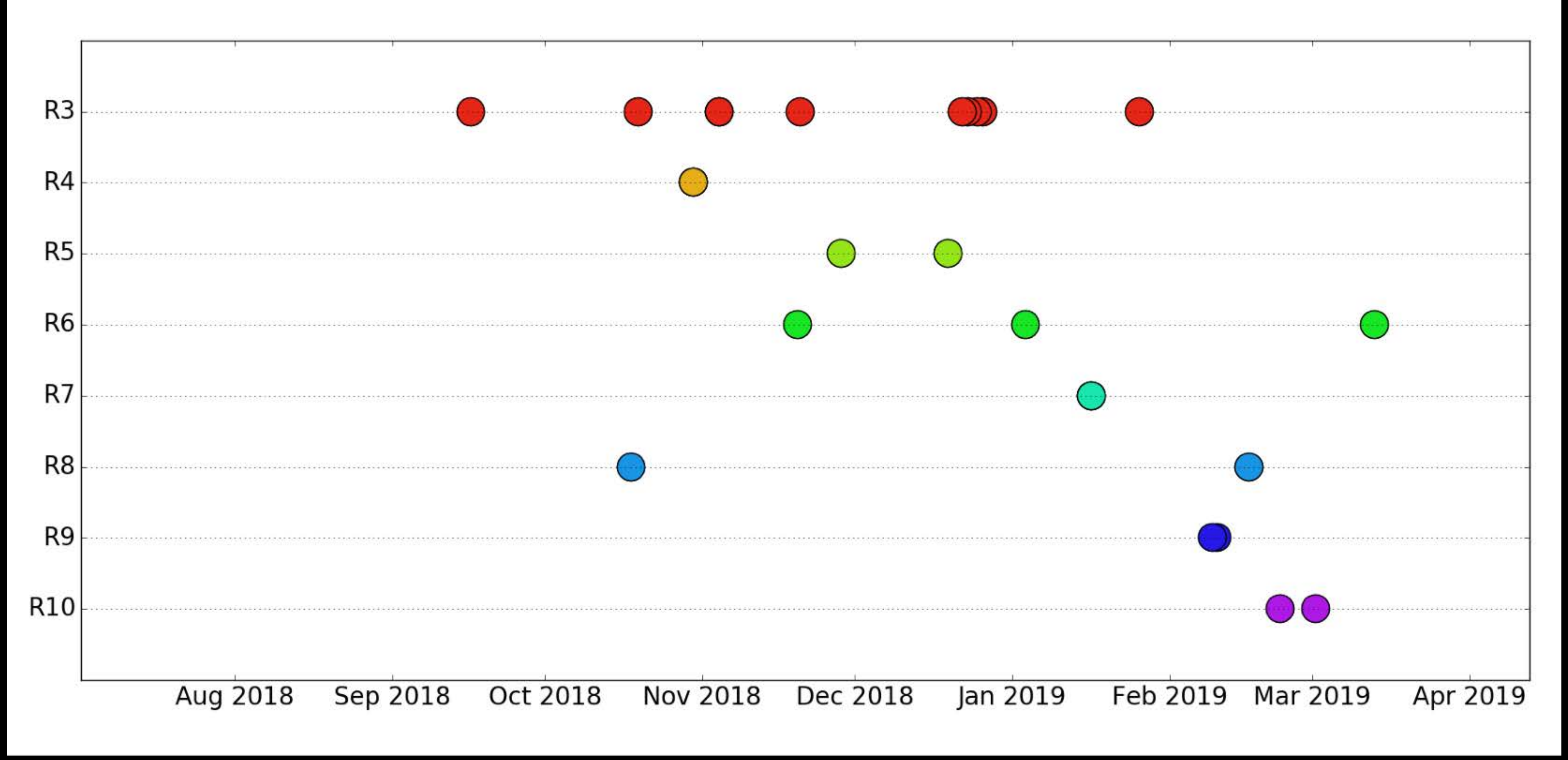


CHIME/FRB Collaboration (2019a)

https://www.chime-frb.ca/repeaters

"R2", CHIME/FRB Collaboration (2019b)

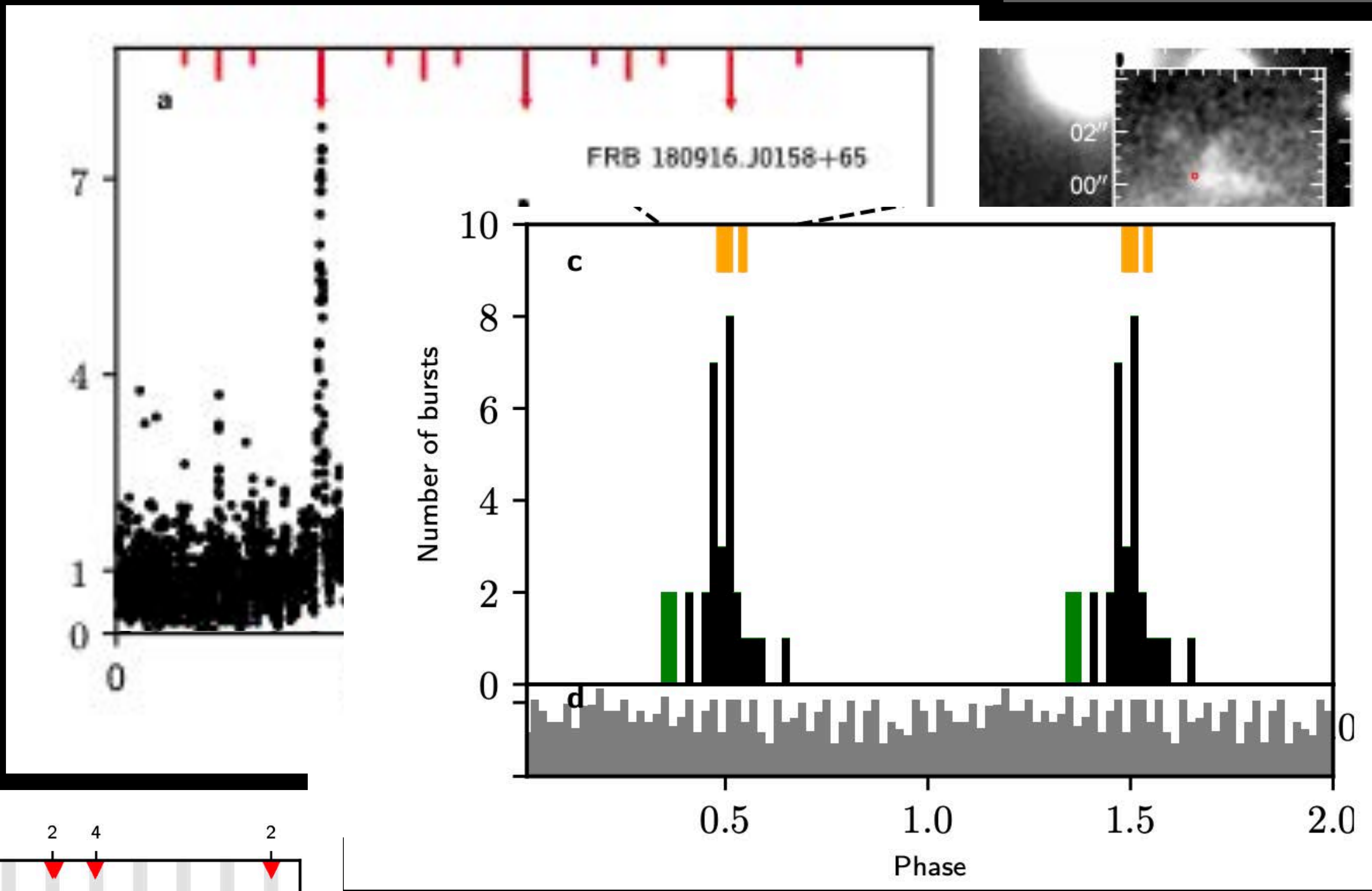


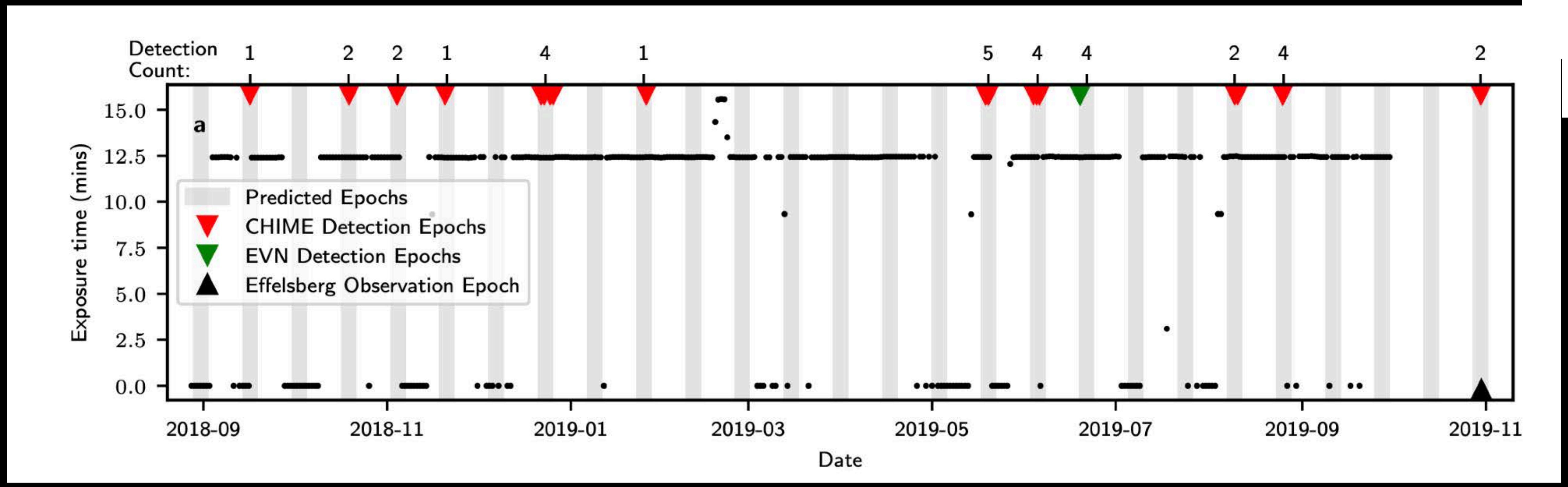


"R3-R10", CHIME/FRB Collaboration (2019c)

First FRB periodicity from CHIME

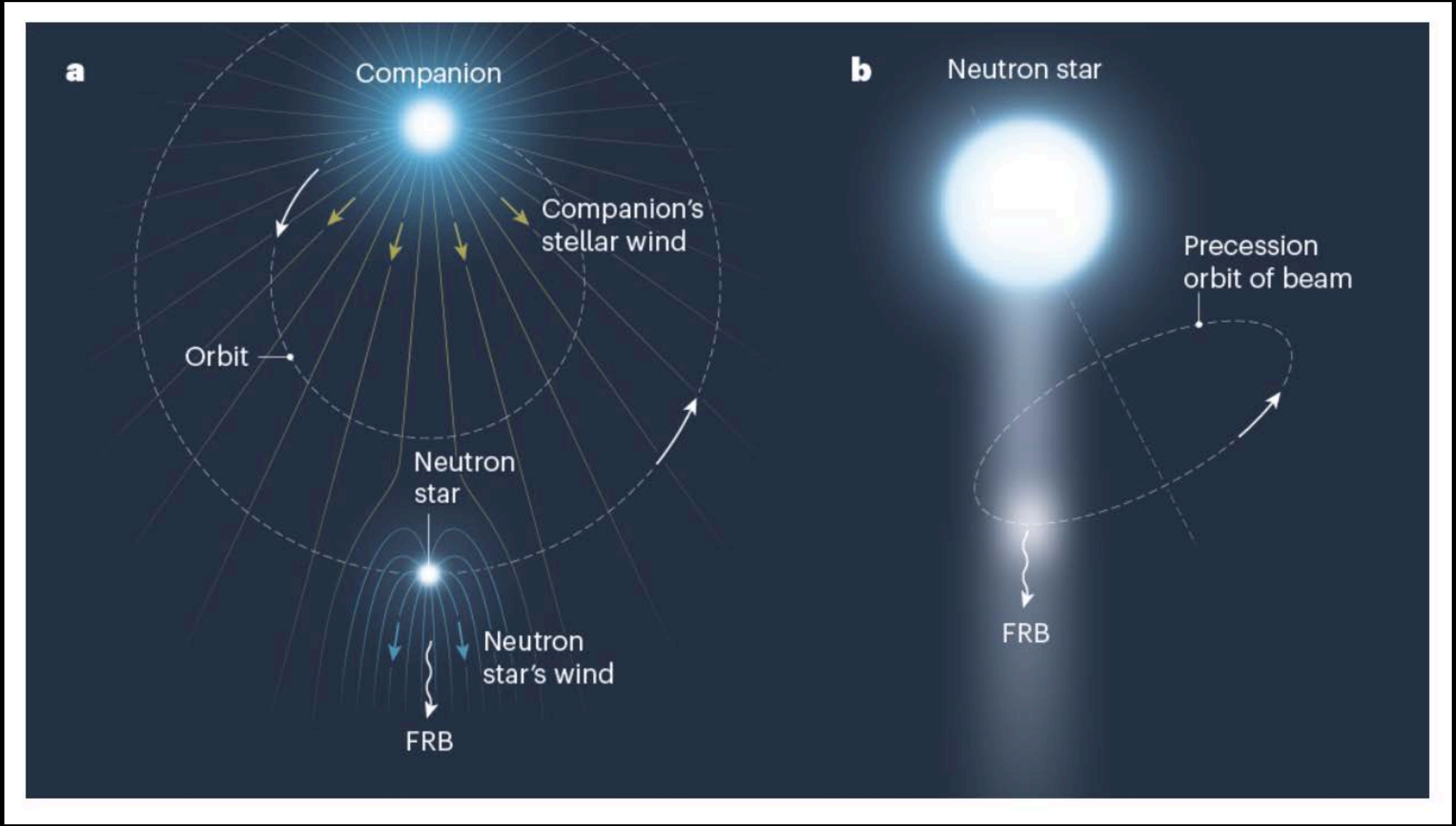
- R3, many pulses now collected by CHIME
- 16.35 day periodicity in activity
- 4 day activity window
- Binary? Precession? Spin period?





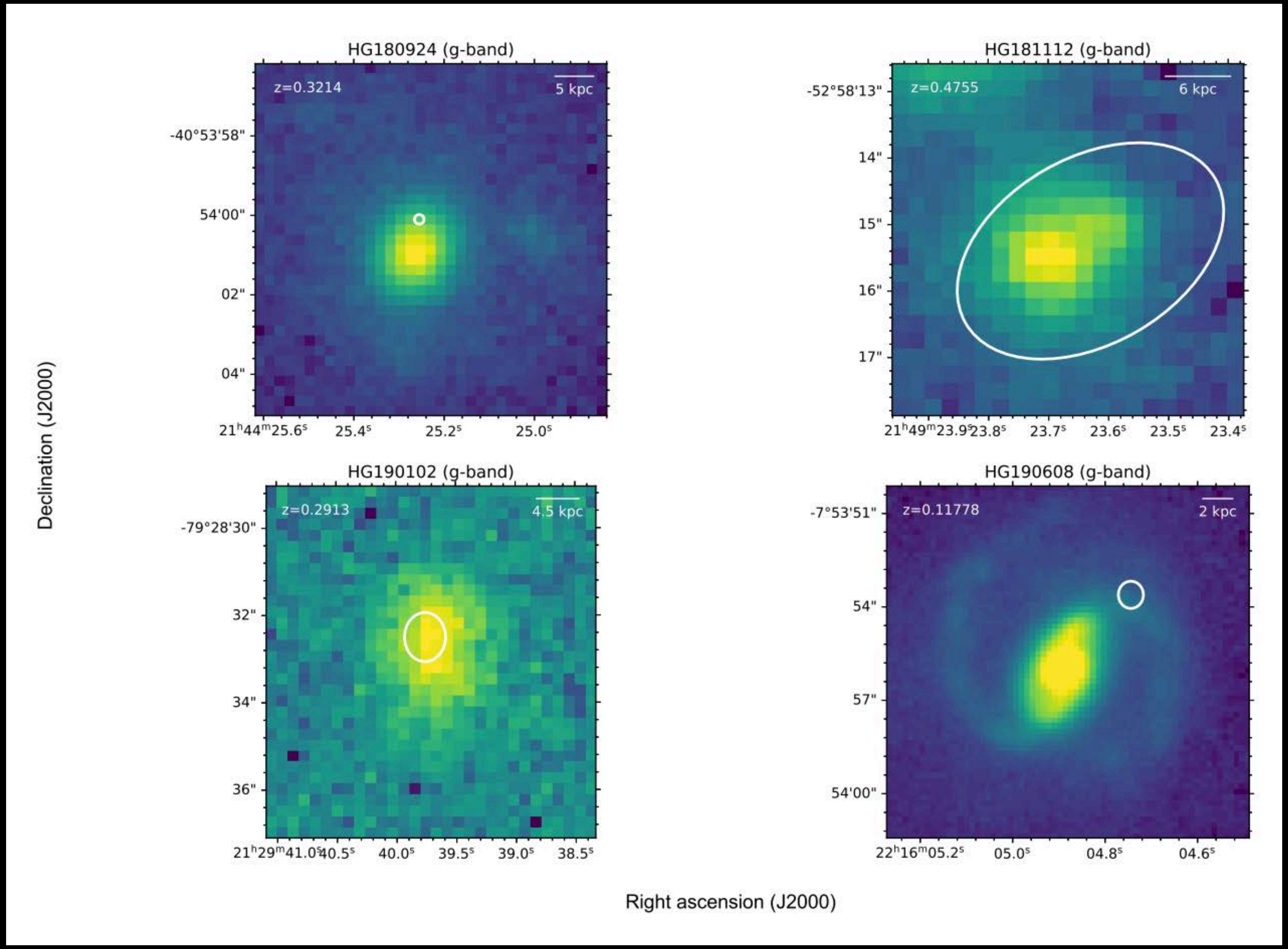
CHIME/FRB Collaboration (2020a)

Compact Objects in tight orbits?

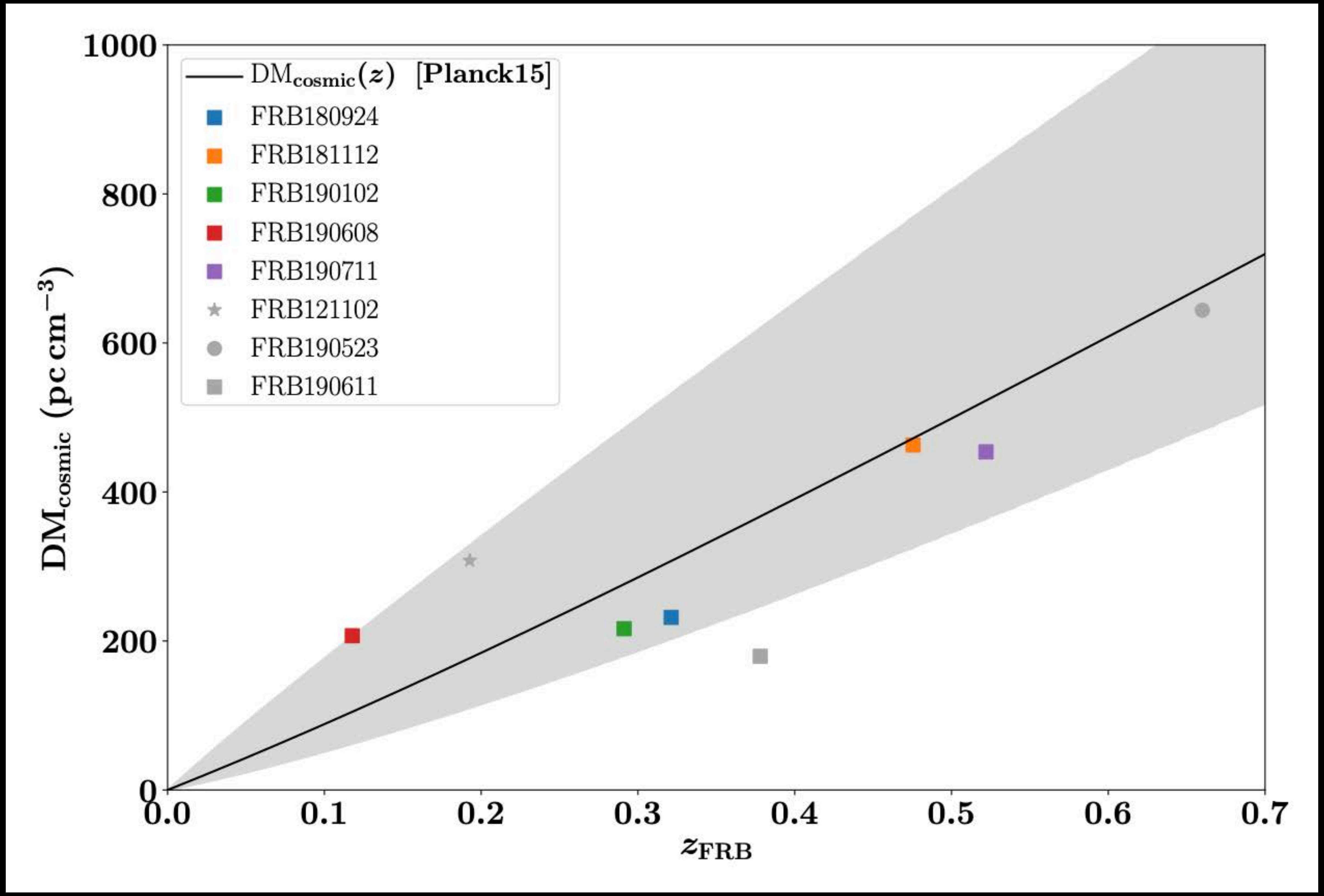


Zhang (2020)

A sample of FRB host galaxies from ASKAP



Bhandari et al. (2020)

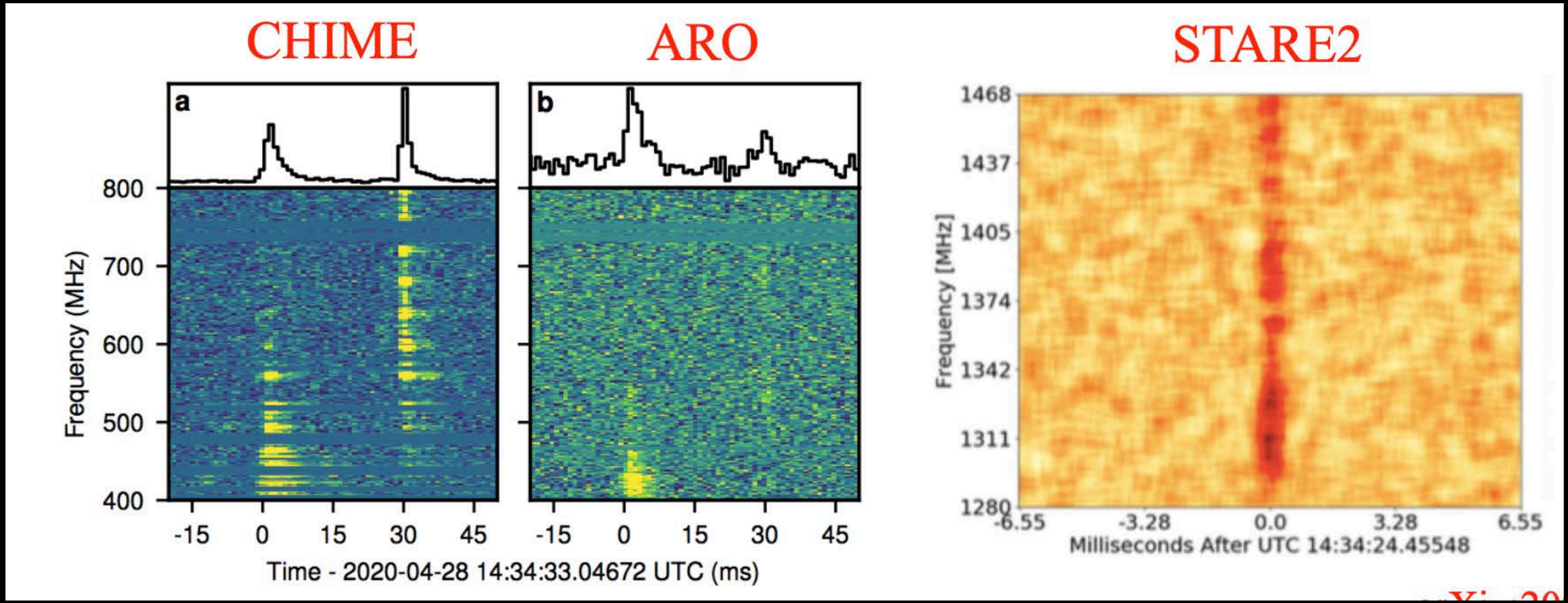


Macquart et al. (2020)

- No unifying property of FRB host galaxy sample (10 galaxies) in recent study from Heintz et al. (2020)

The curious case of SGR 1935+2154

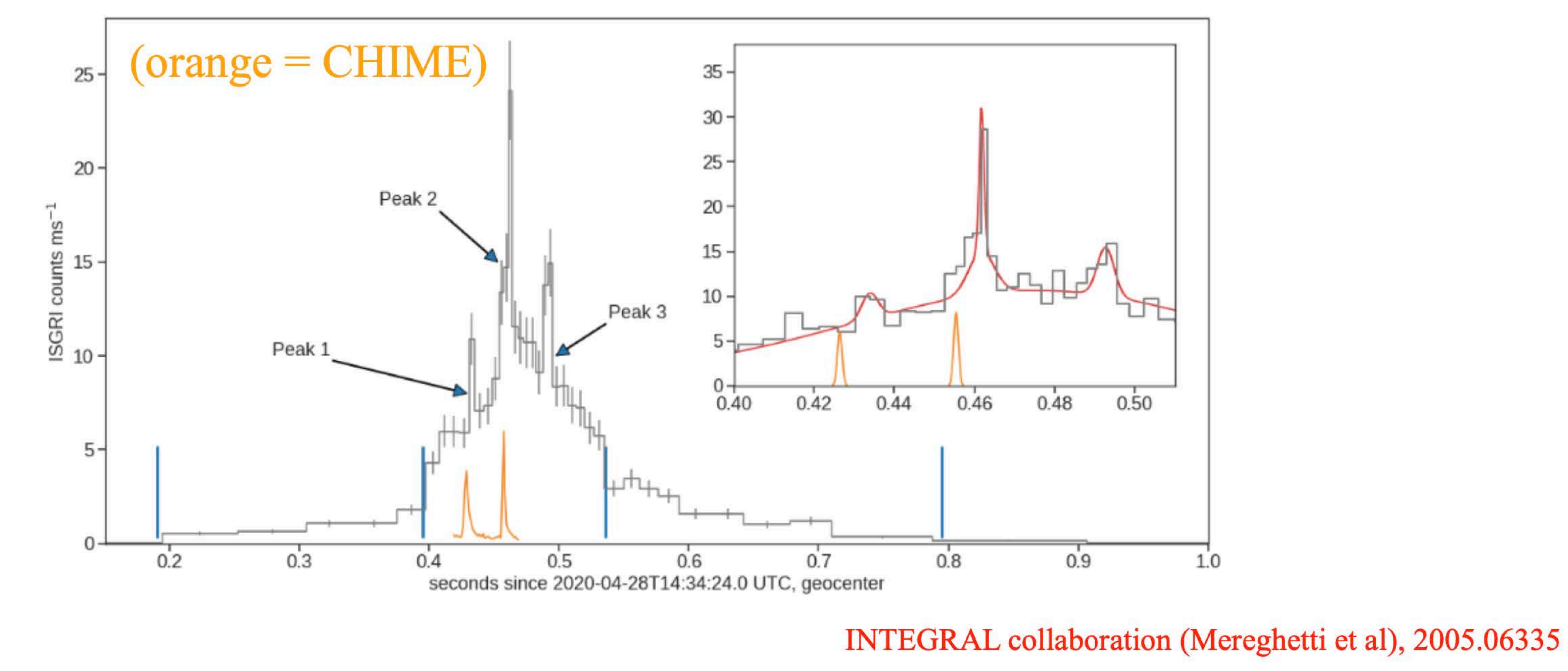
- X-ray burst forest
- ~MJy radio burst CHIME / STARE2
  28 April 2020
- 3 x 10^{34} ergs at CHIME



CHIME/FRB Collaboration (2020c)
Bochenek et al. (2020)

The curious case of SGR 1935+2154

- (Mostly) Coincident X-ray burst
- X-ray trails radio by short time (constraining for theories)
- Subsequent X-ray flares with no radio bursts
- Bursts in NS magnetosphere?

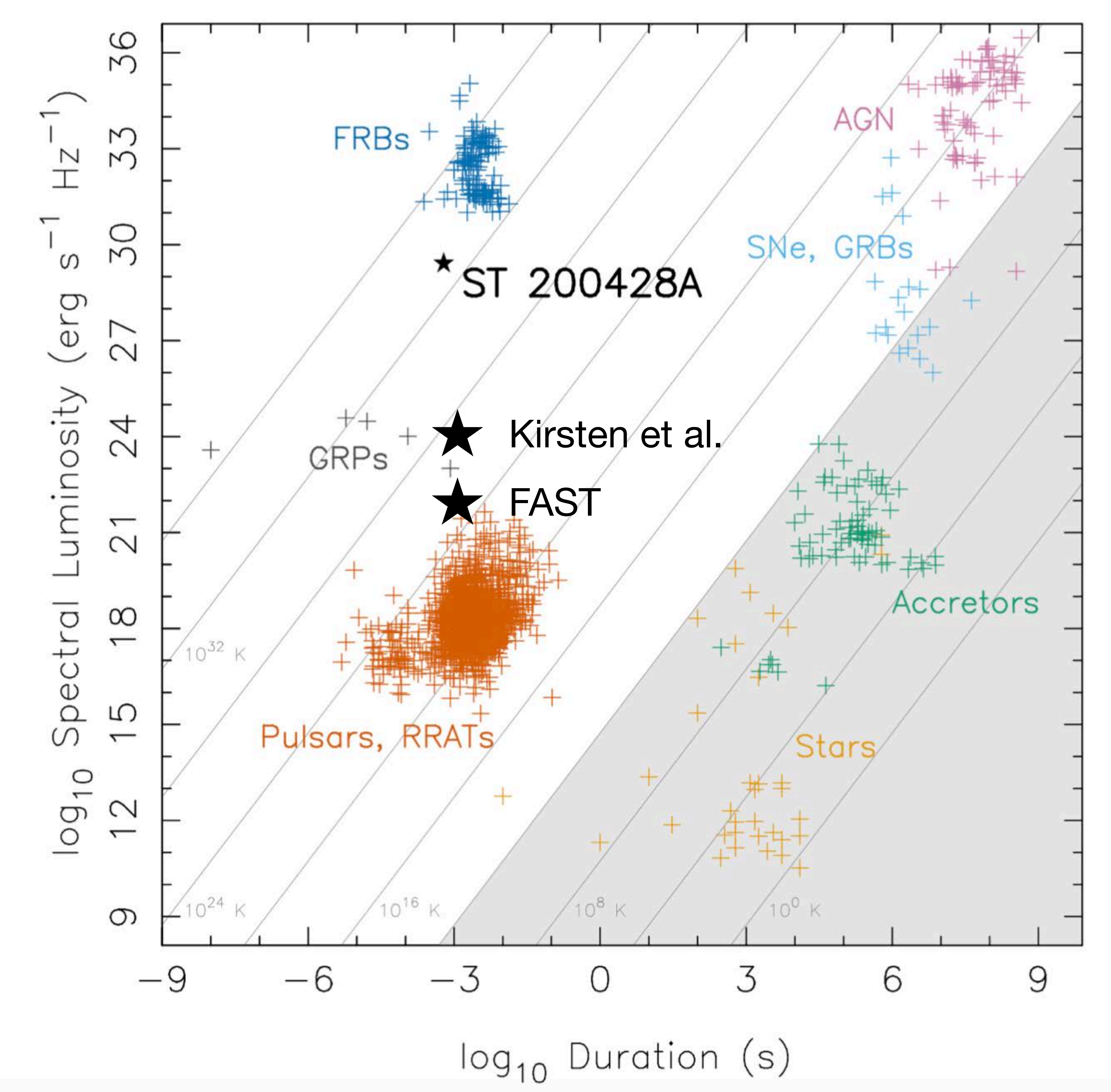


The curious case of SGR 1935+2154

- FAST detected radio burst
  30 April 2020 (60 mJy ms)
  RM = 112 rad m^{-2}
  ATel 13699

- Two more bursts seen by interferometers (~1 Jy ms)
  Kirsten et al. (2020)

- Potential bridge between FRBs and Galactic magnetars



Bochenek et al. (2020)

Observational progress

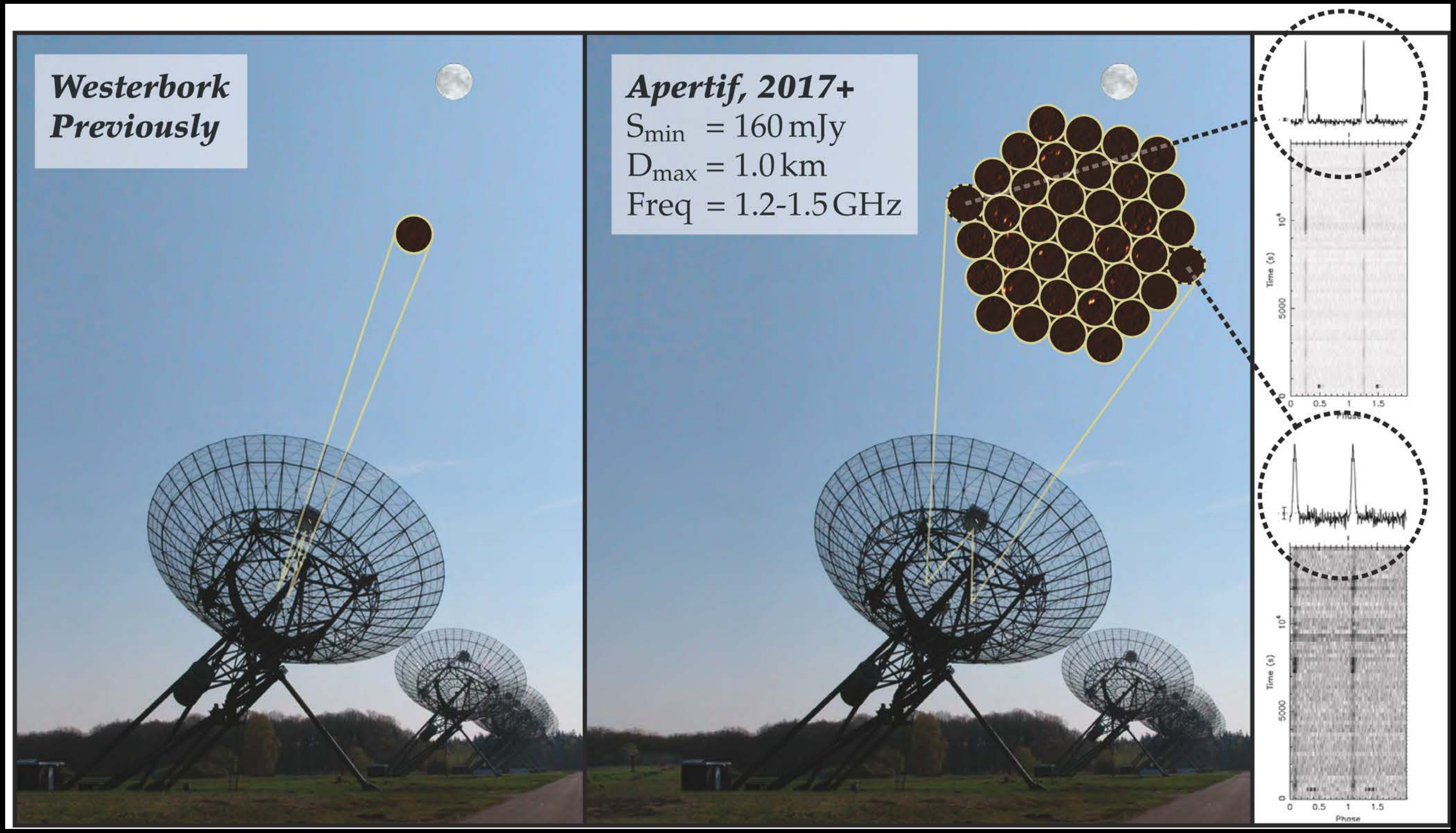
Challenges and open questions

Future prospects

Challenges and open questions

- What fraction of FRBs repeat?
- Are there multiple FRB populations?
- What is the true FRB rate?
- What is the FRB redshift distribution?
- How much of the DM comes from the host galaxy?
- What role does environment play?
- Will we be able to measure the magnetic field of the IGM?
- How useful will FRBs be for cosmology?
- What is the most beneficial way to follow-up new detections?

- Entering the era of wide-field interferometers

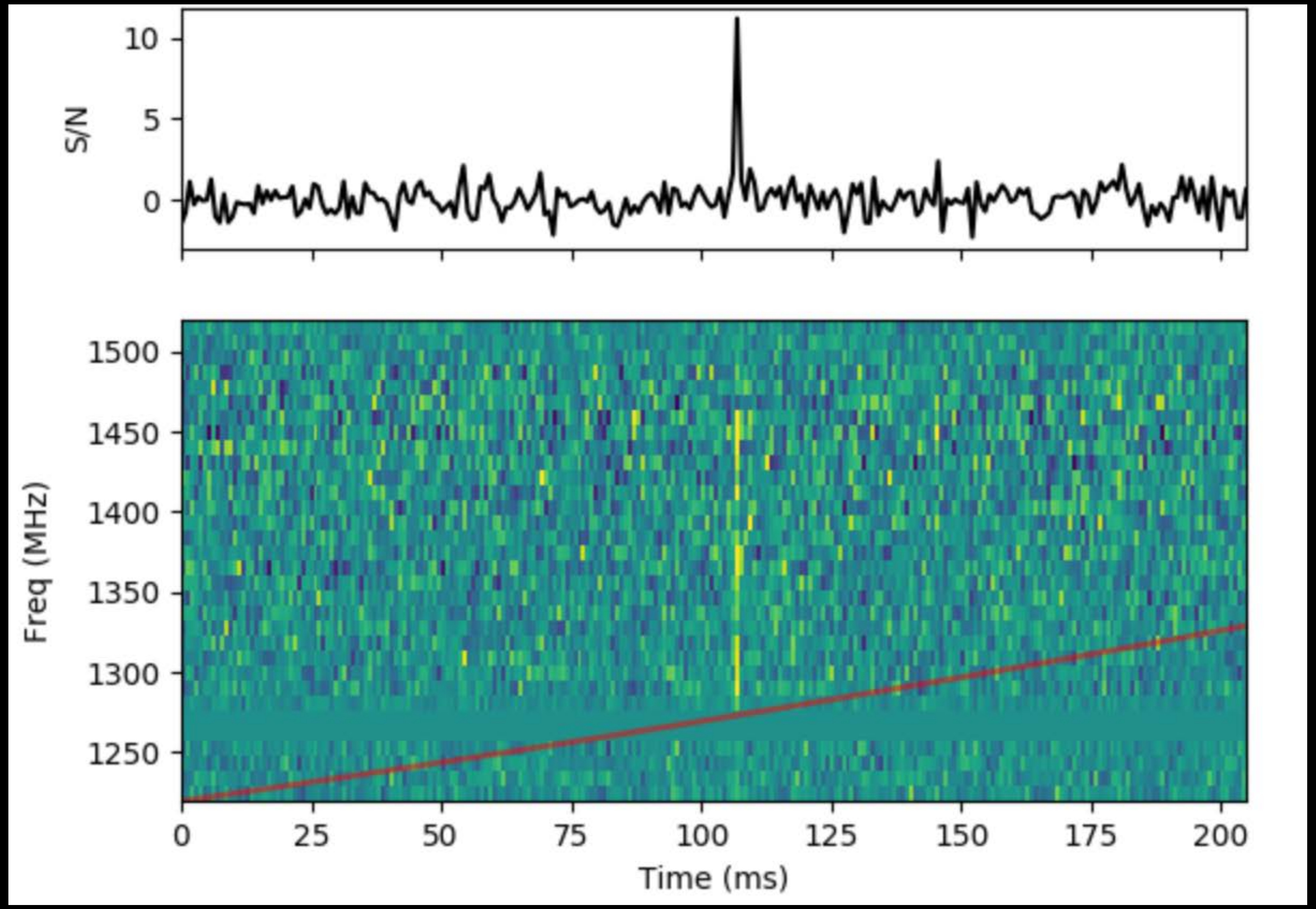


1.4 GHz

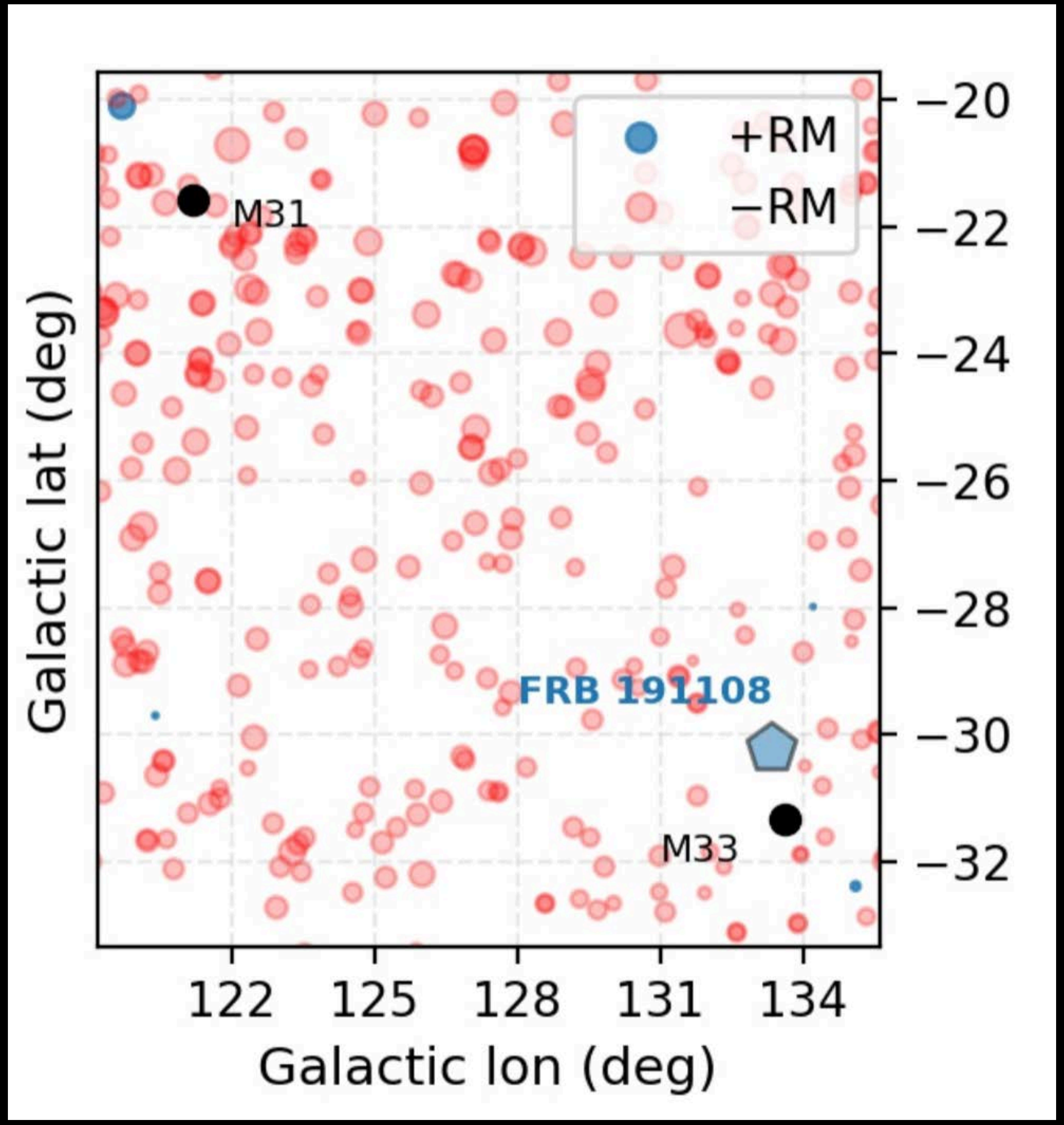
1-5 FRBs per month

150 MHz

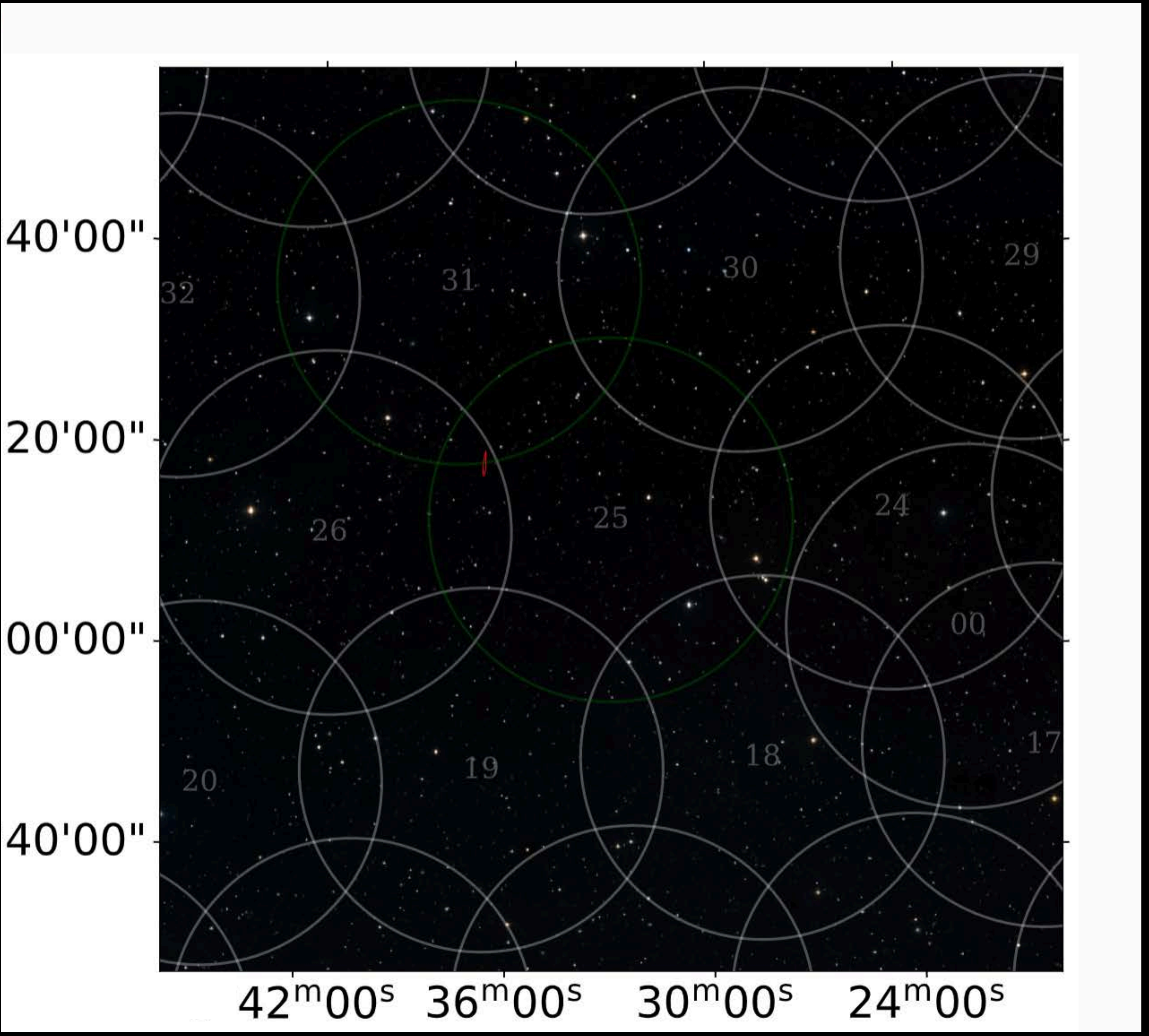
FRBs from Apertif



Real-time pipeline



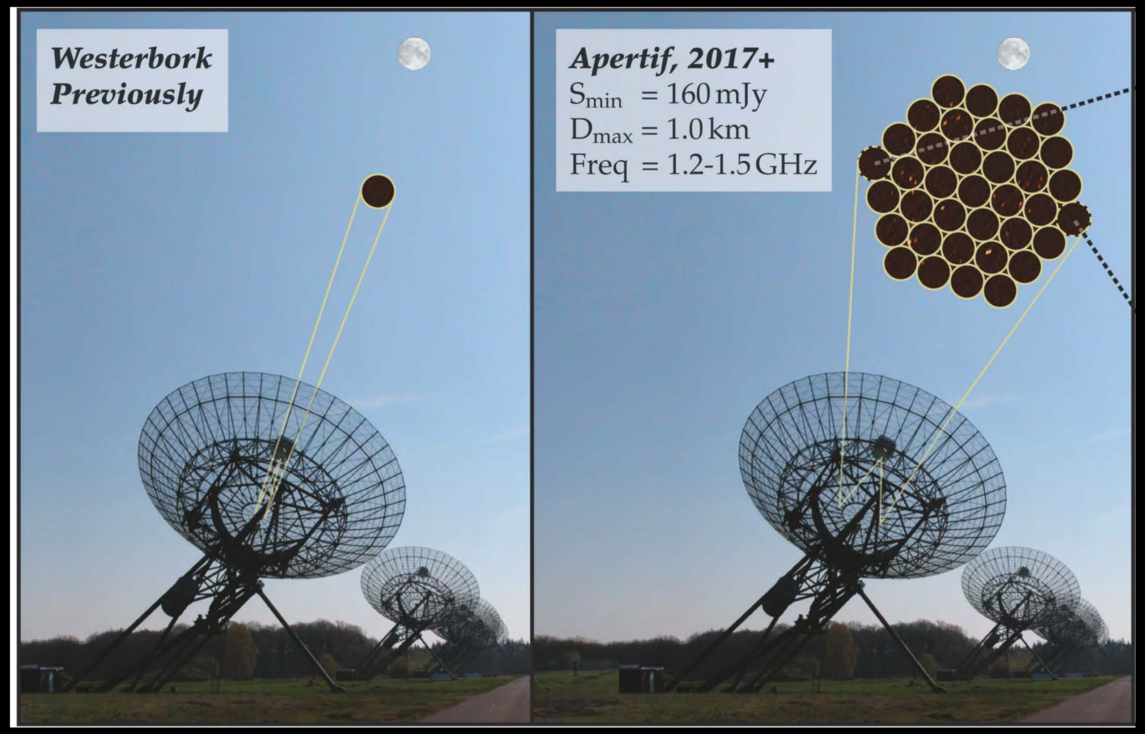
Connor et al. (2020)



Leon Oostrum

hundreds of FRBs

- Entering the era of ~~wide-field interferometers~~



Closing remarks

- 1000s of FRBs will be discovered soon
- Origins unknown despite rapid progress
  - Compact objects, magnetars, pulsars, black holes
- Growing research area
- Localization, polarization, population
- New area of high energy astrophysics
- Watch this space!

Closing remarks

Lots of progress in the past years, still lots to be done!

Thank You!

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