Fast Radio Bursts: an increasingly complex astronomical mystery

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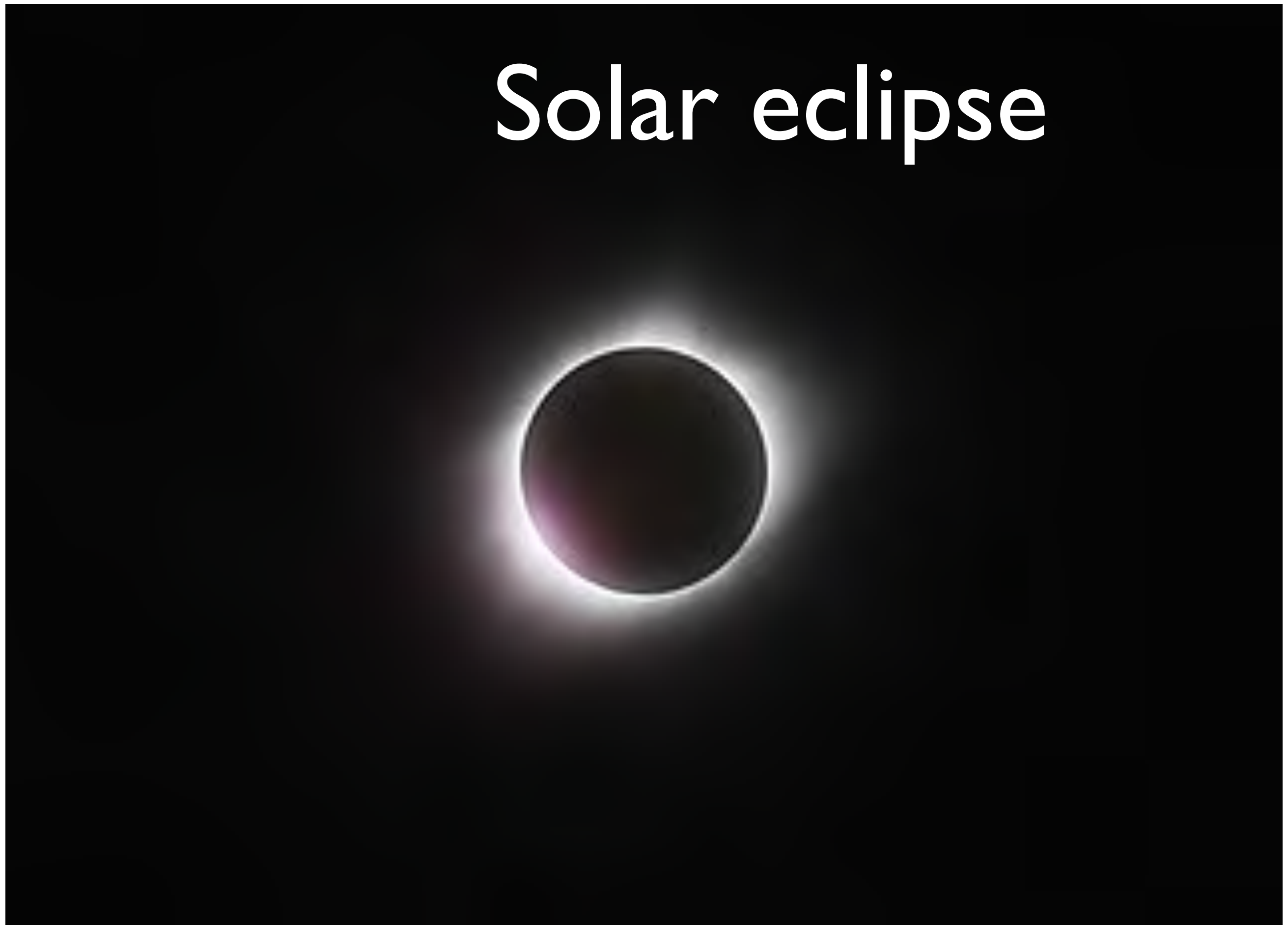
Stockert, Germany


Credit: Ruslan Merzlyakov



Comet

Supernova (1054 n.C.)

Sky mostly empty

Every few seconds, a “star” appears and disappears

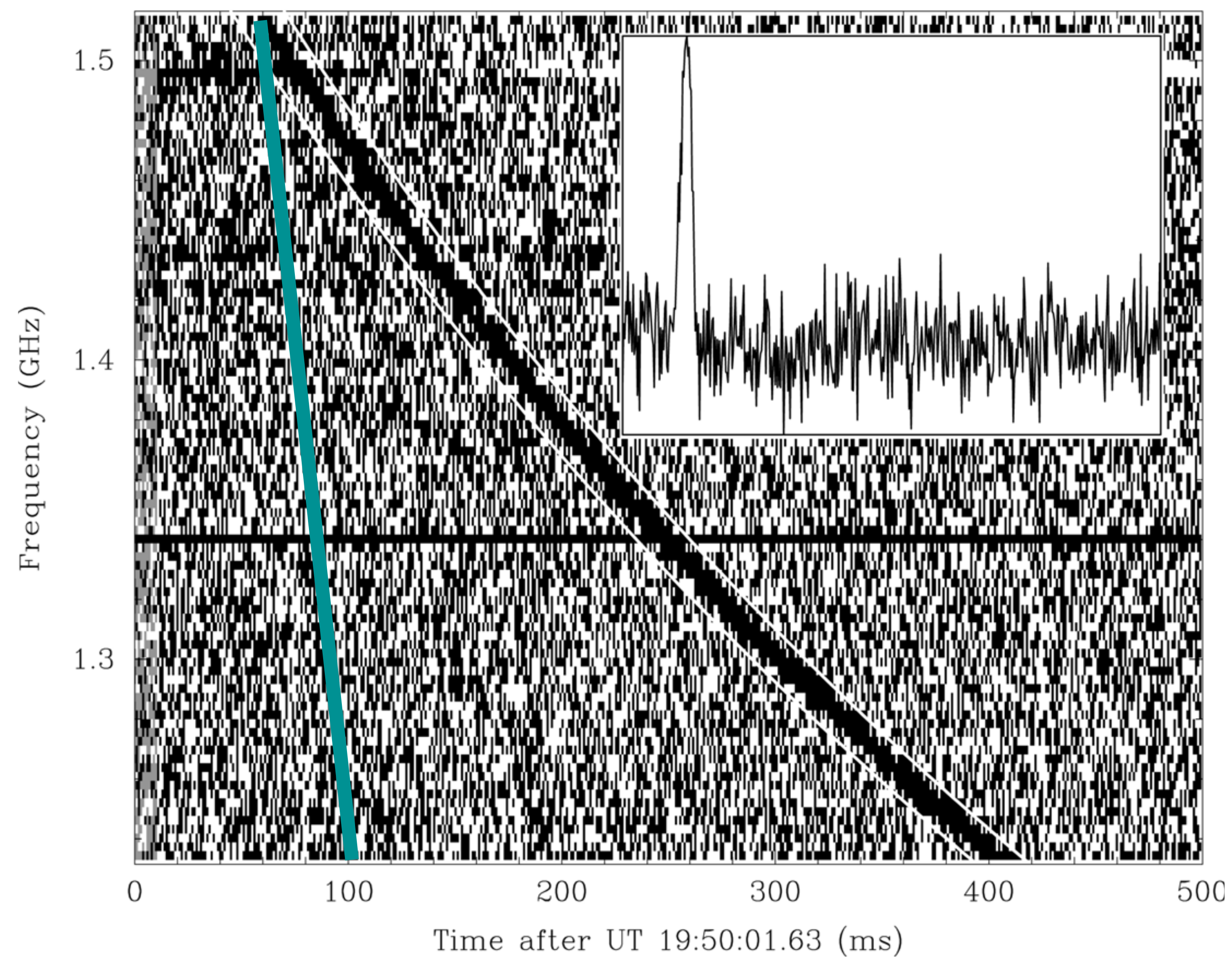
Most sources have only ever been observed once

When a source repeats, it is special

When a source repeats predictably, it is really special

Fast Radio Bursts: observational phenomenon

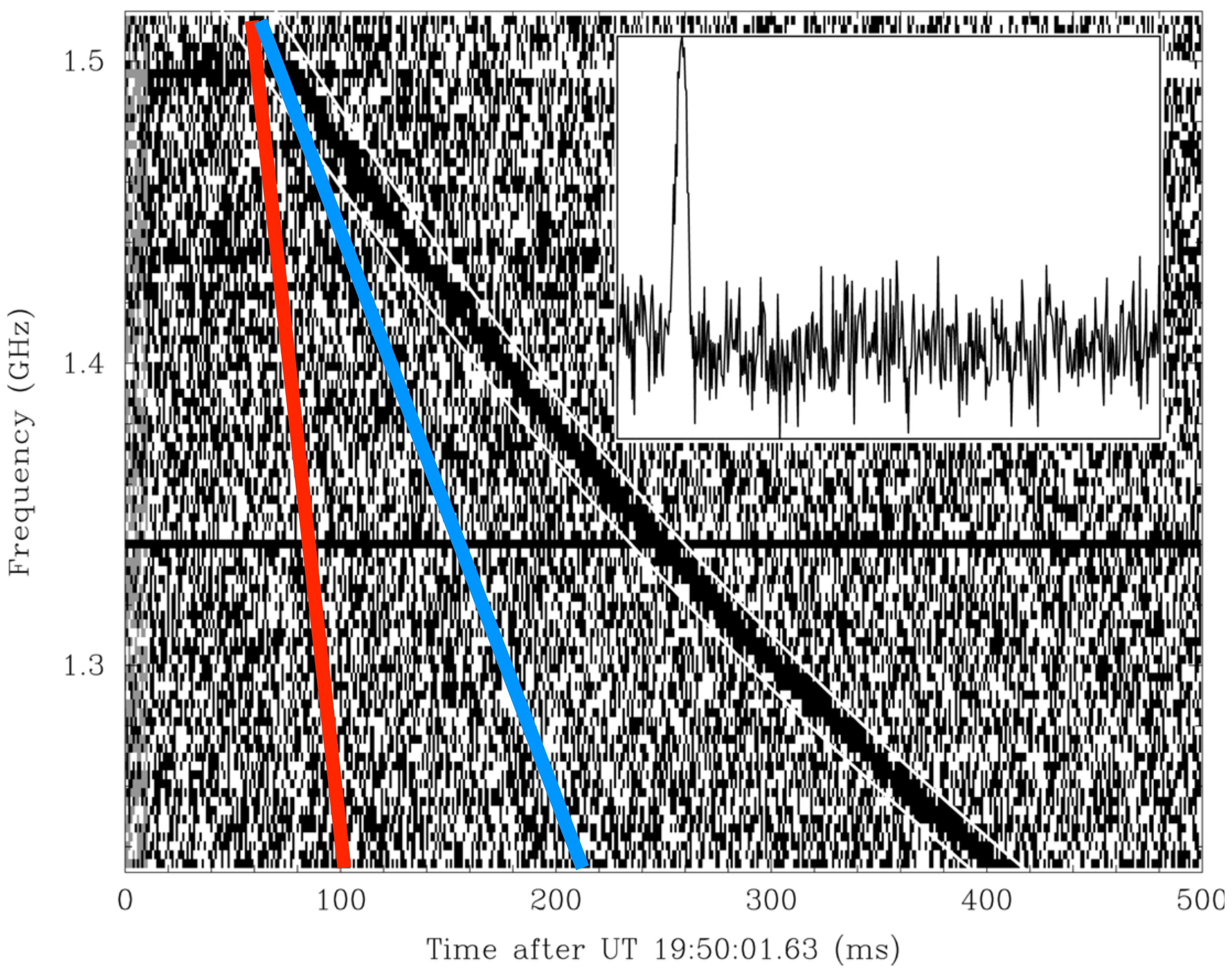
- Luminous, short duration radio flashes
- Extragalactic
- Occur often across the sky
- Subject to dispersion, Faraday rotation, and multipath propagation effects
- Small majority observed as "repeaters"
- Bursting emission only detected in radio



Lorimer et al. *Science*, 2007

Dispersion measure

- Delay between the arrival of a pulse between two reference frequencies
- High DM
  Medium DM
  Low DM
- Unit: pc cm^{-3}
- Correct for it through dedispersion



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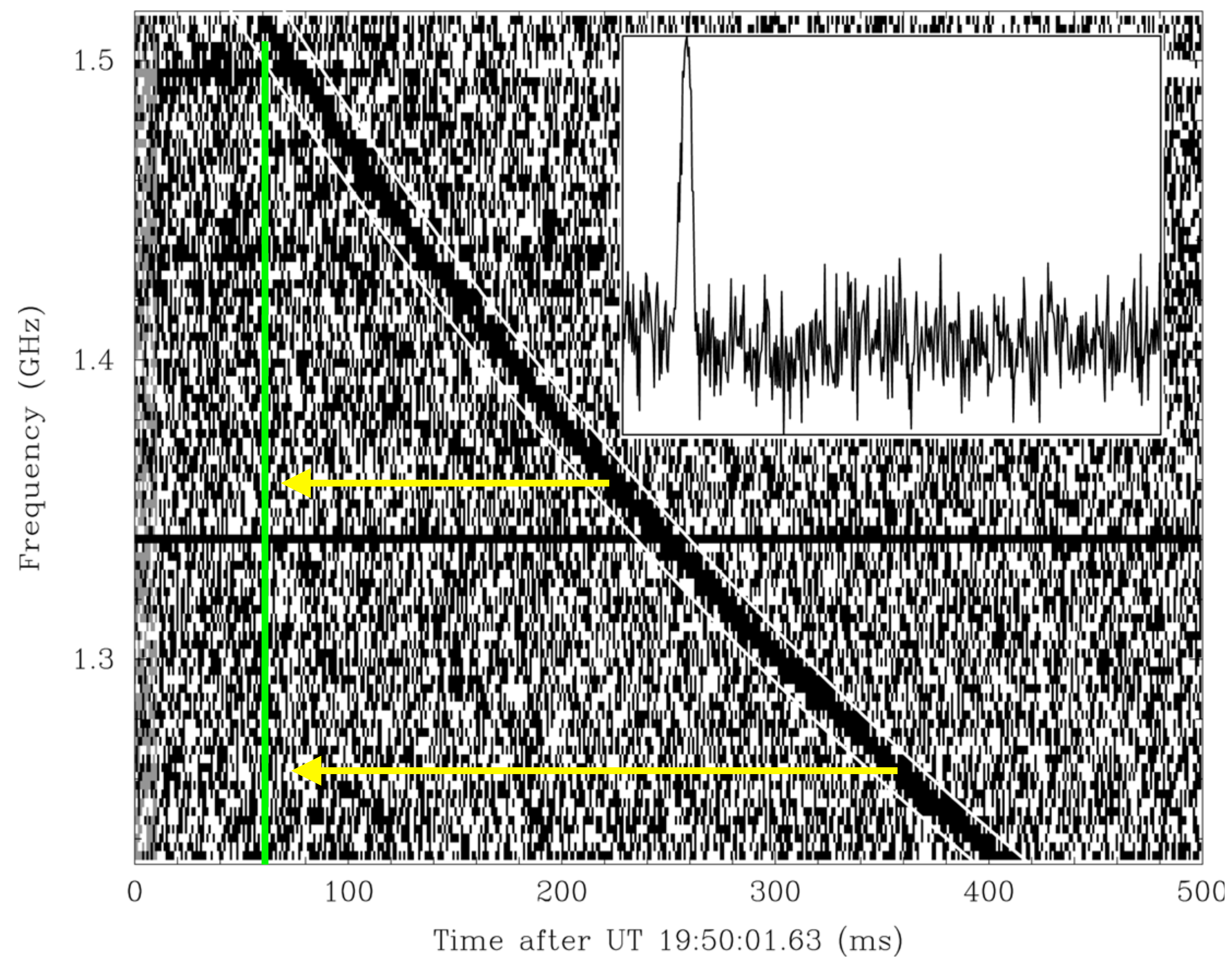
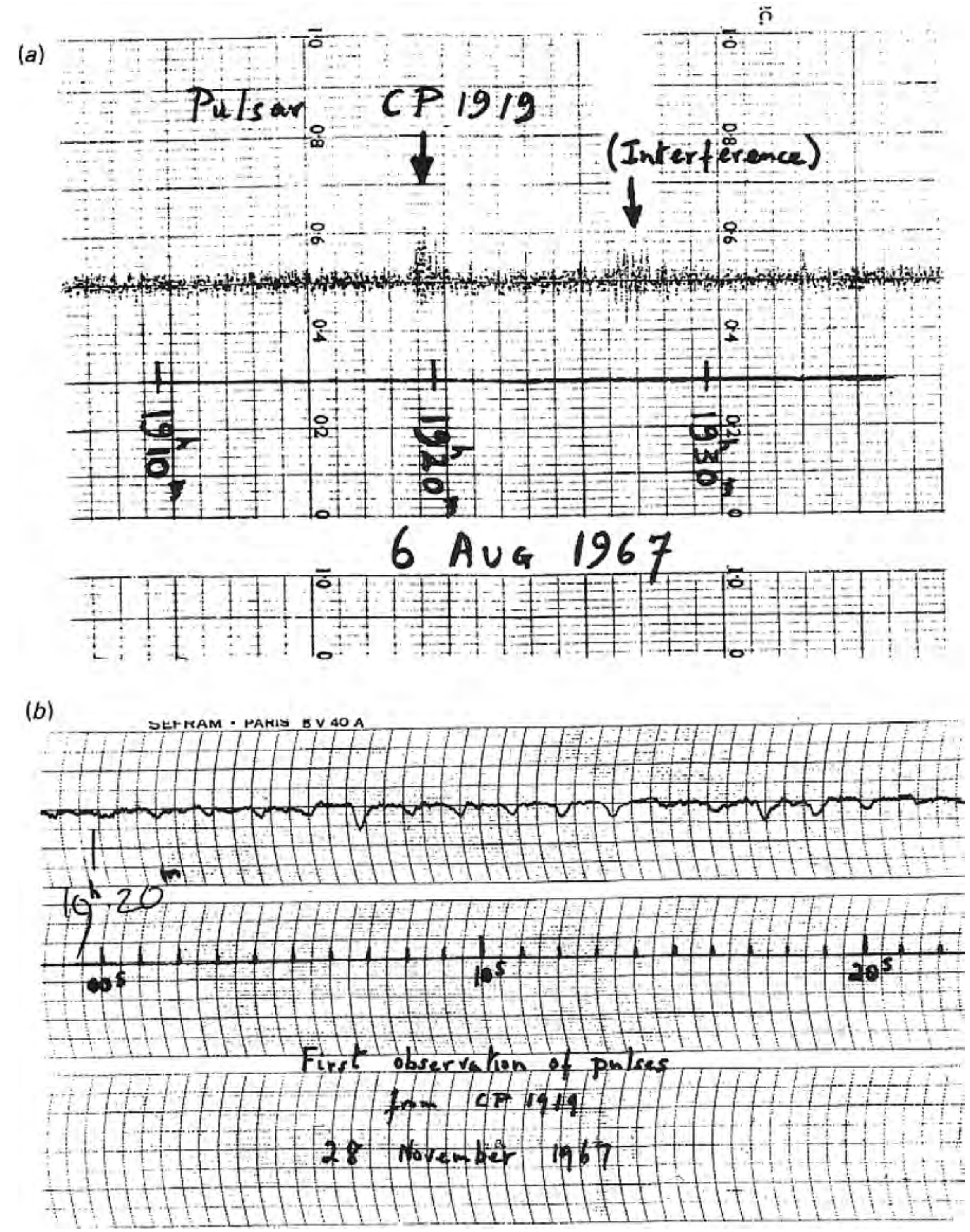


Lorimer et al. *Science*, 2007

Important single pulse discoveries

- The discovery of pulsars was made by detecting bright single pulses as a source passed through the telescope beam
- Once its was realized they are rotating neutron stars, almost all searches by folding the signal



Credit: Jocelyn Bell Burnell & Antony Hewish

In the 1970s, searching for bright, dispersed pulses was trendy

letters to nature

A better way of searching for black-hole explosions?

BLACK holes of $\lesssim 10^{15}$ g evaporate in $\sim 10^{10}$ yr, and eventually annihiliate into a burst of energetic photons and particles[1]. To test this theoretical prediction would be extraordinarily significant for quantum and gravitational physics. There could be $\sim 10^{23}$ 'miniholes' within our Galaxy[2–4]; on the other hand, there may not be any at all. But even if they exist in profusion, how best could we detect black-hole explosions? Attention has been focused on the problem of directly detecting the γ rays, but the prospects seem bleak[3]. The possibility that the particles ejected in the explosion may generate conspicuous effects has hitherto been overlooked. I argue here that collective interaction of electrons and positrons with an ambient interstellar magnetic field can (on some specific assumptions) generate radio bursts powerful enough to be detected from anywhere in our Galaxy, or even beyond. This opens up a more promising perspective on the search.

A conducting sphere, expanding into a uniform magnetic field, will develop surface currents which prevent the field from

Martin Rees, *Nature*, 1977

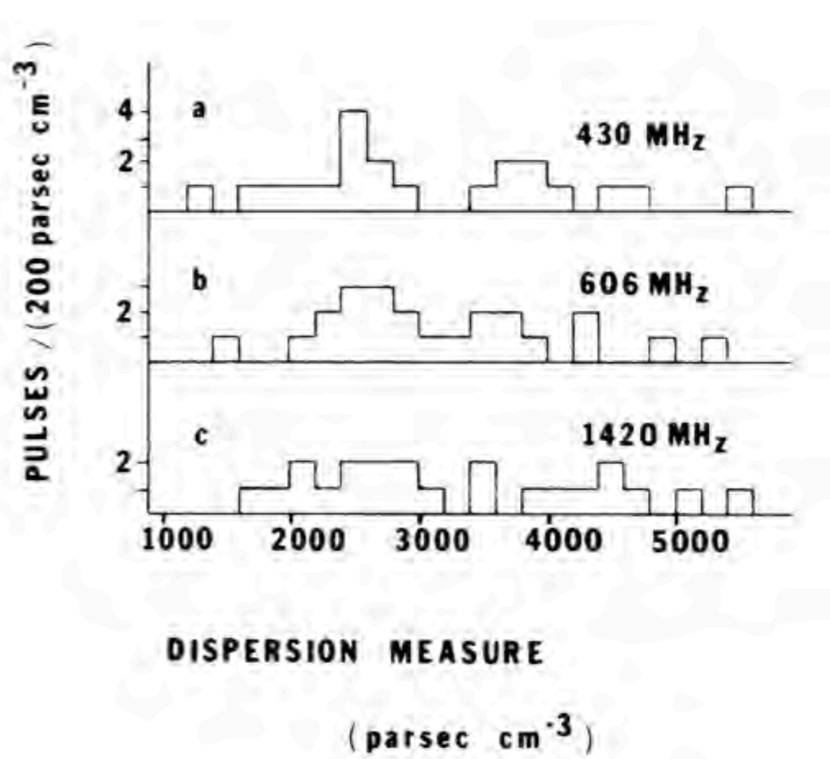
Nature Vol. 277 11 January 1979

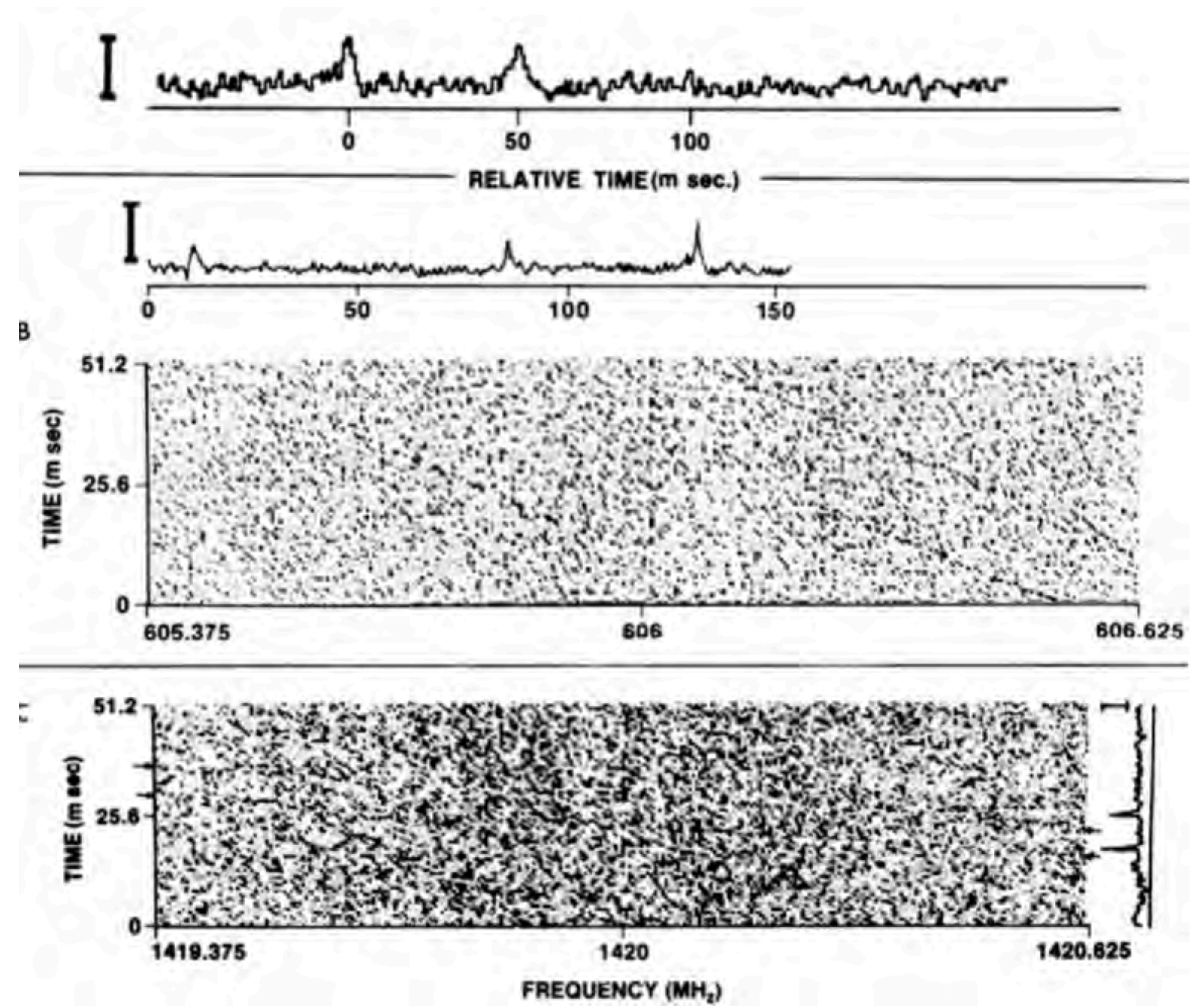
A sensitive search for radio pulses from primordial black holes and distant supernovae

Phinney & Taylor, *Nature*, 1979

Maybe FRBs were discovered earlier?

- Linscott & Erkes 1980
- Arecibo search in M87
- DM = 1000 to 5000 pc/cc
- No bursts found in off-source pointings





Maybe FRBs were discovered earlier?

- Search for radio transients with the Molonglo Observatory Synthesis Telescope
- Unexplained events with durations 1 ms $< \tau <$ 25 ms (DM ~ 25 to 500 pc cc)
- Detection rate ~ 18,000 per sky per day (…a bit high)
- Knowing today's rate, they may have detected a few

Miscellaneous Radio Astronomy

A Search for Transient Events at 843 MHz

S. W. Amy, M. I. Large, *School of Physics, University of Sydney*
A. E. Vaughan, *School of Mathematics, Physics, Computing and Electronics, Macquarie University*

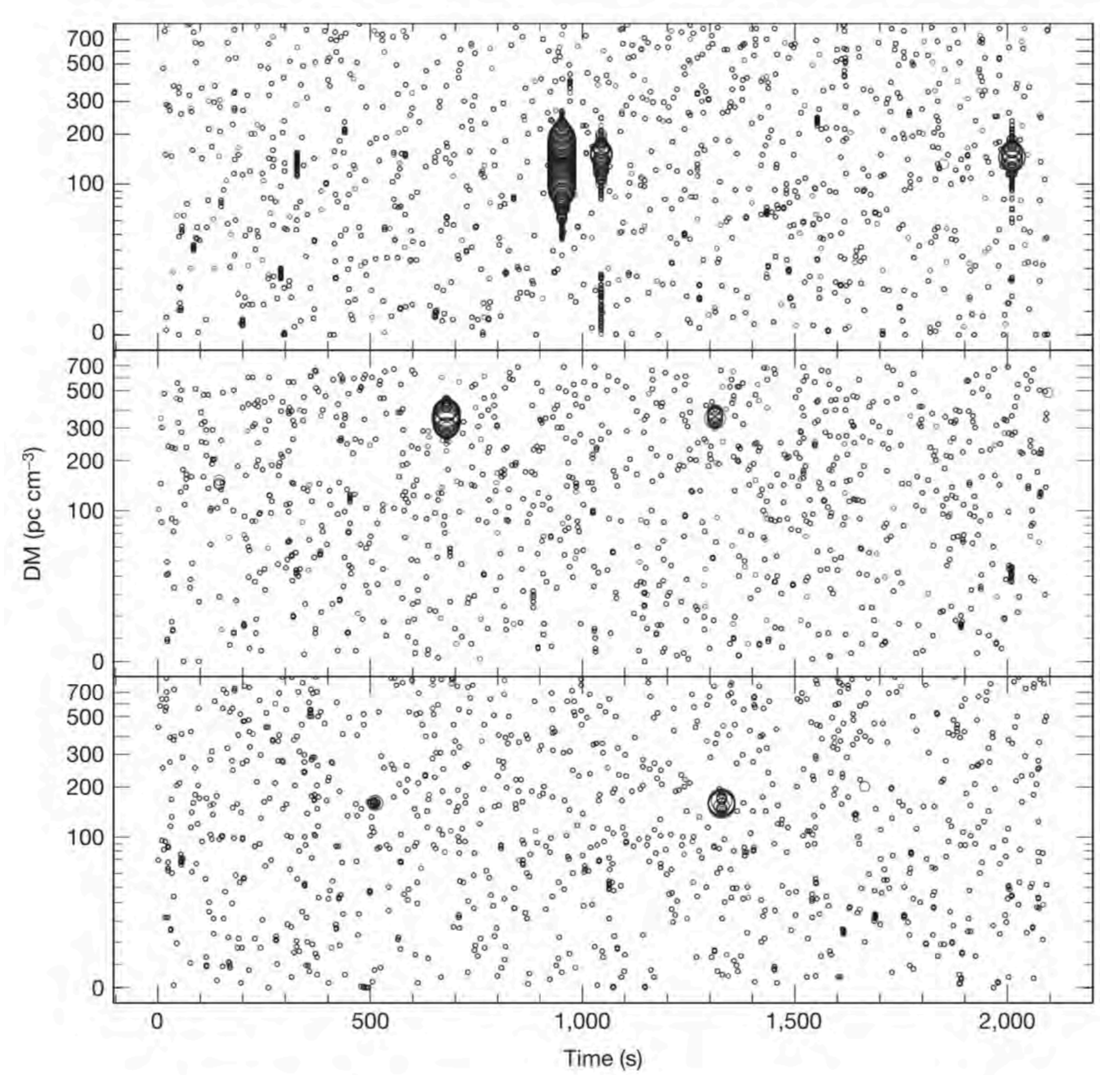
Abstract: The Molonglo Observatory Synthesis Telescope is equipped with a transient event monitoring system which operates during normal synthesis observations. The device is designed to respond to impulsive signals which occur within the passband (843.0 ± 1.5 MHz) with time scales between 0.001 ms and 800 ms. The multiple beam facility of the telescope provides

Single pulse searches of pulsars makes a comeback

Transient radio bursts from rotating neutron stars

M. A. McLaughlin[1], A. G. Lyne[1], D. R. Lorimer[1], M. Kramer[1], A. J. Faulkner[1], R. N. Manchester[2], J. M. Cordes[3], F. Camilo[4], A. Possenti[5], I. H. Stairs[6], G. Hobbs[2], N. D'Amico[5,7], M. Burgay[5] & J. T. O'Brien[1]

- Maura McLaughlin re-started the search for pulsars using single pulse algorithms in the early 2000s.
- Discovered RRATs in 2006 in data from the Parkes 64-m



McLaughlin et al., *Nature*, 2006

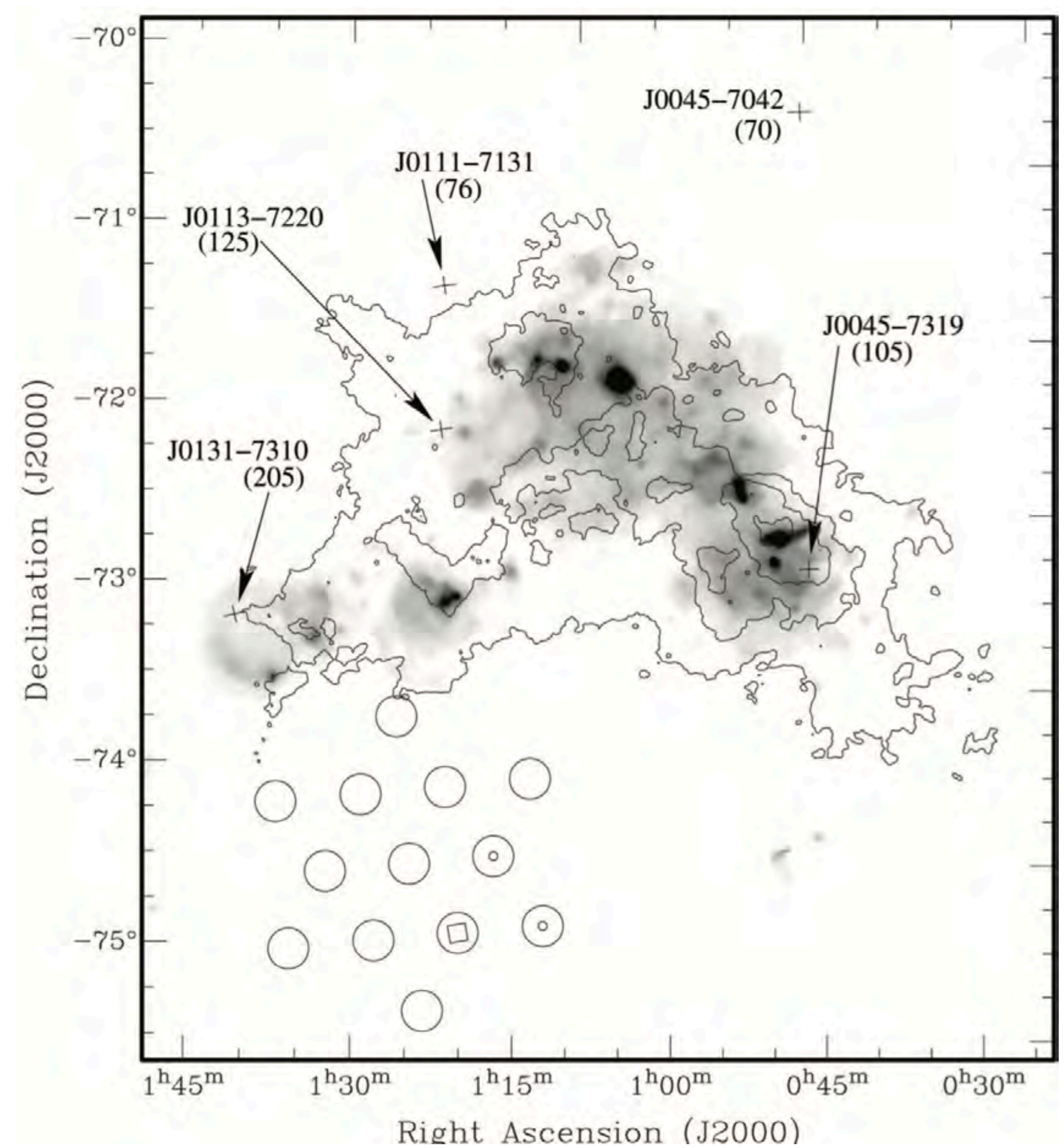
22 years ago…

The Parkes 64-m radio telescope was searching for radio pulsars at 1.4 GHz with a 13-beam feed array…

Credit: CSIRO

Credit: Stephen West

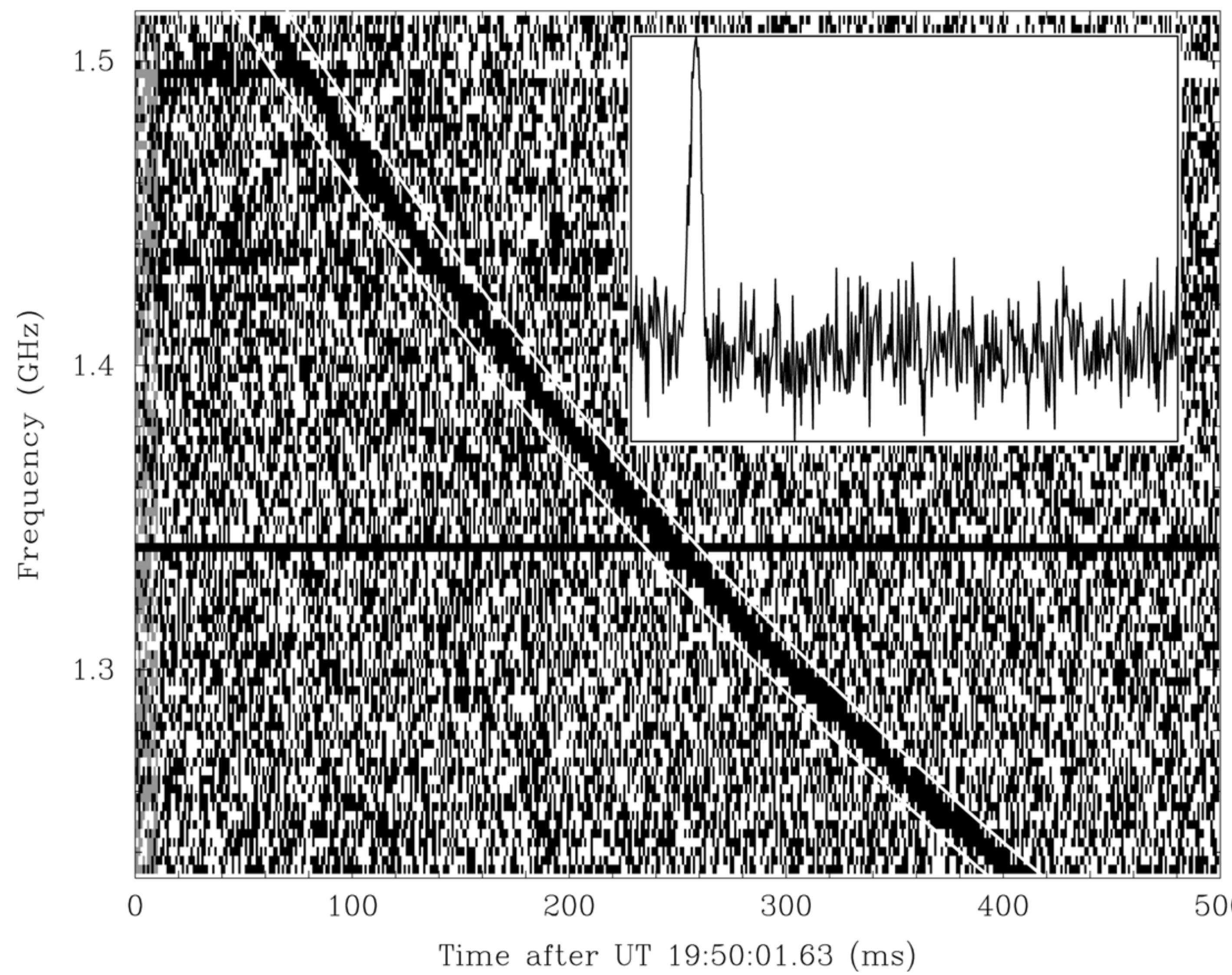
…near the Small Magellanic Cloud



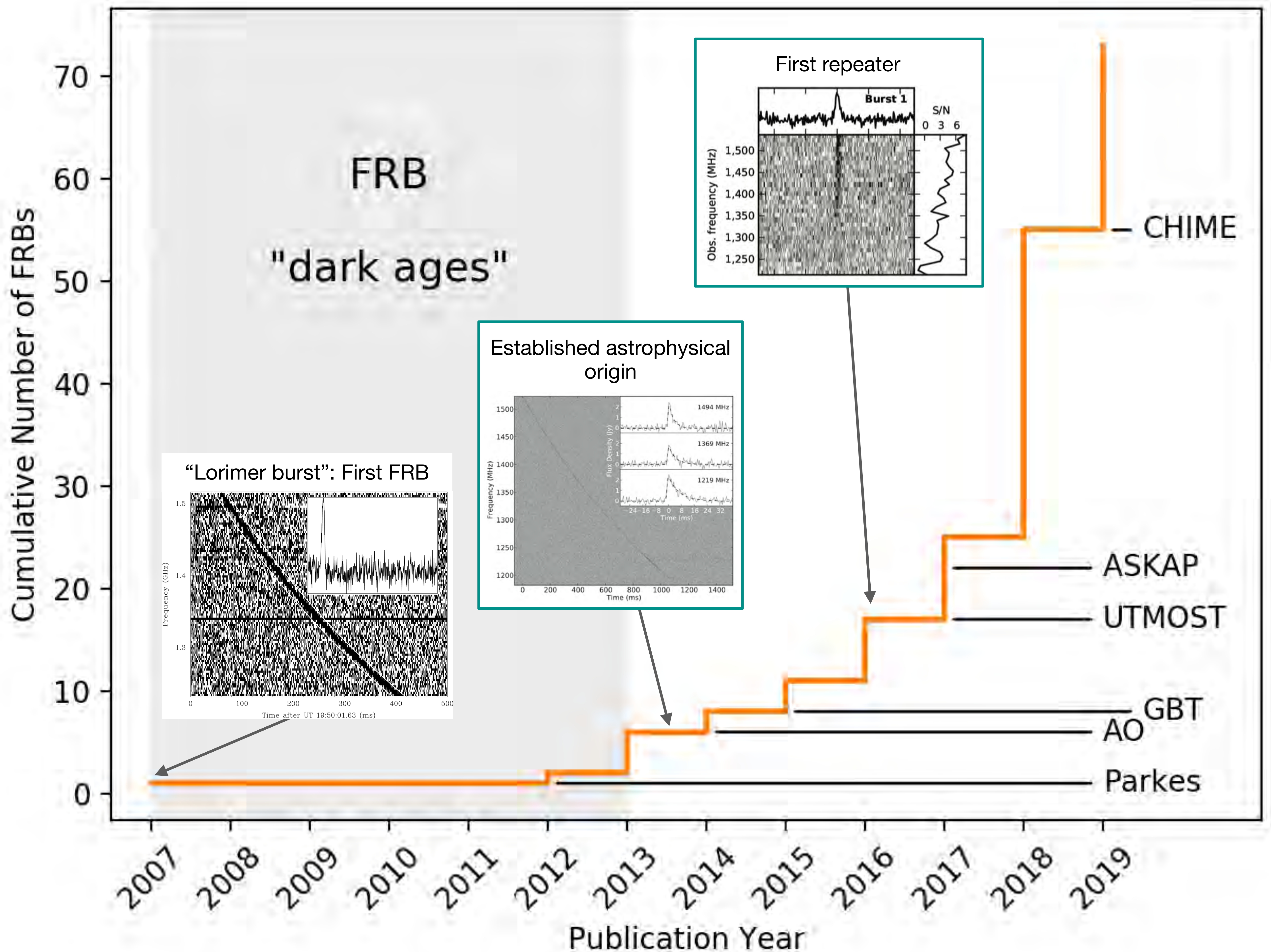
Lorimer et al. *Science*, 2007

The first FRB!

- "Lorimer burst"
- Super bright
  - Saturated the beam that was closest to its position
  - Strange because where are all the fainter ones
- Observed DM ~100 times higher than MW contribution
- The data has since been reprocessed a second, weaker burst was discovered (Zhang et al., MNRAS, 2019)



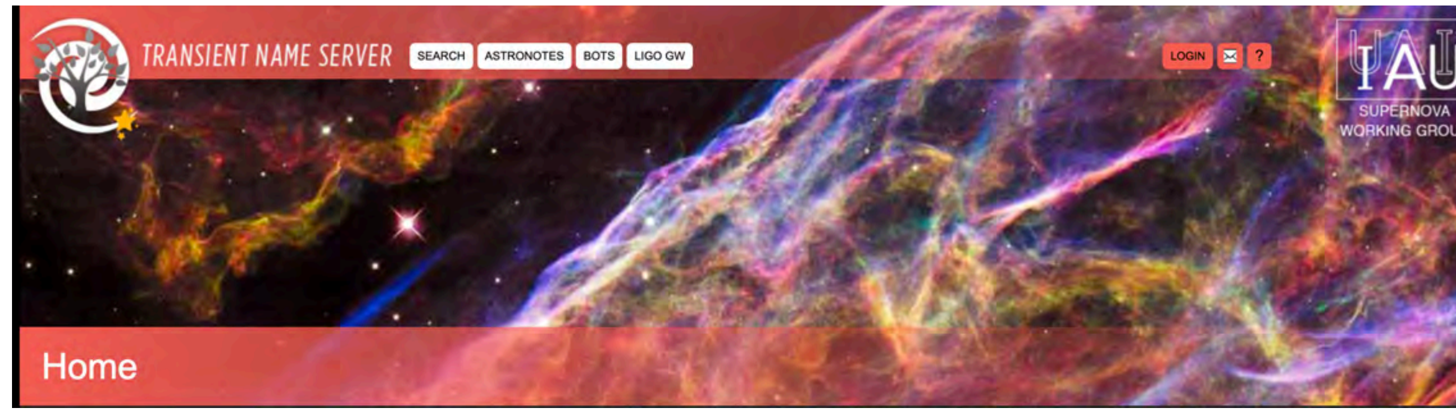
Lorimer et al. *Science*, 2007



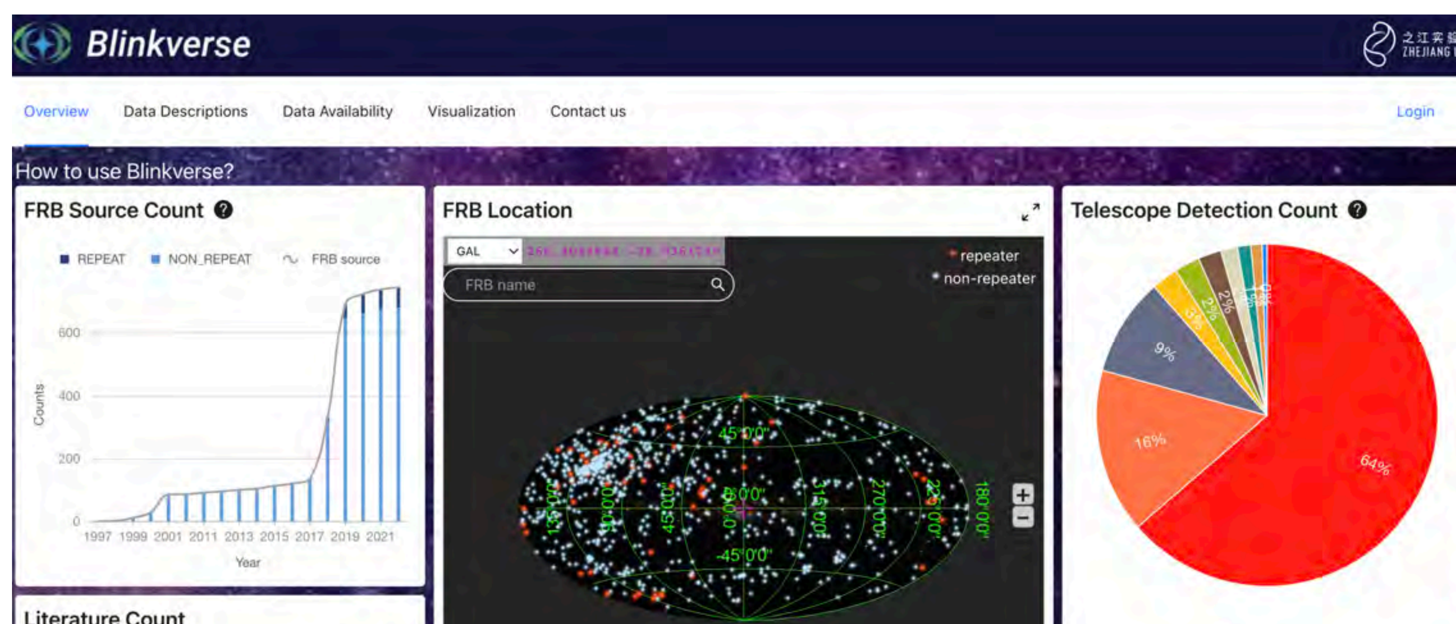
FRB
"dark ages"
"Lorimer burst": First FRB
Established astrophysical origin
First repeater
Burst 1
S/N
Obs. frequency (MHz)
Frequency (MHz)
Flux Density (Jy)
1494 MHz
1369 MHz
1219 MHz
Time (ms)
Time after UT 19:50:01.63 (ms)
Frequency (GHz)
CHIME
ASKAP
UTMOST
GBT
AO
Parkes
Cumulative Number of FRBs
Publication Year
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019

How many FRB sources?

- Published:
  - Total FRBs: 690
    - Repeaters: 51
  - Host galaxies: 39
- Unpublished:
  - Total FRBs: > 4000



Naming (example): FRB 20230916C



First decade: “single dish era”

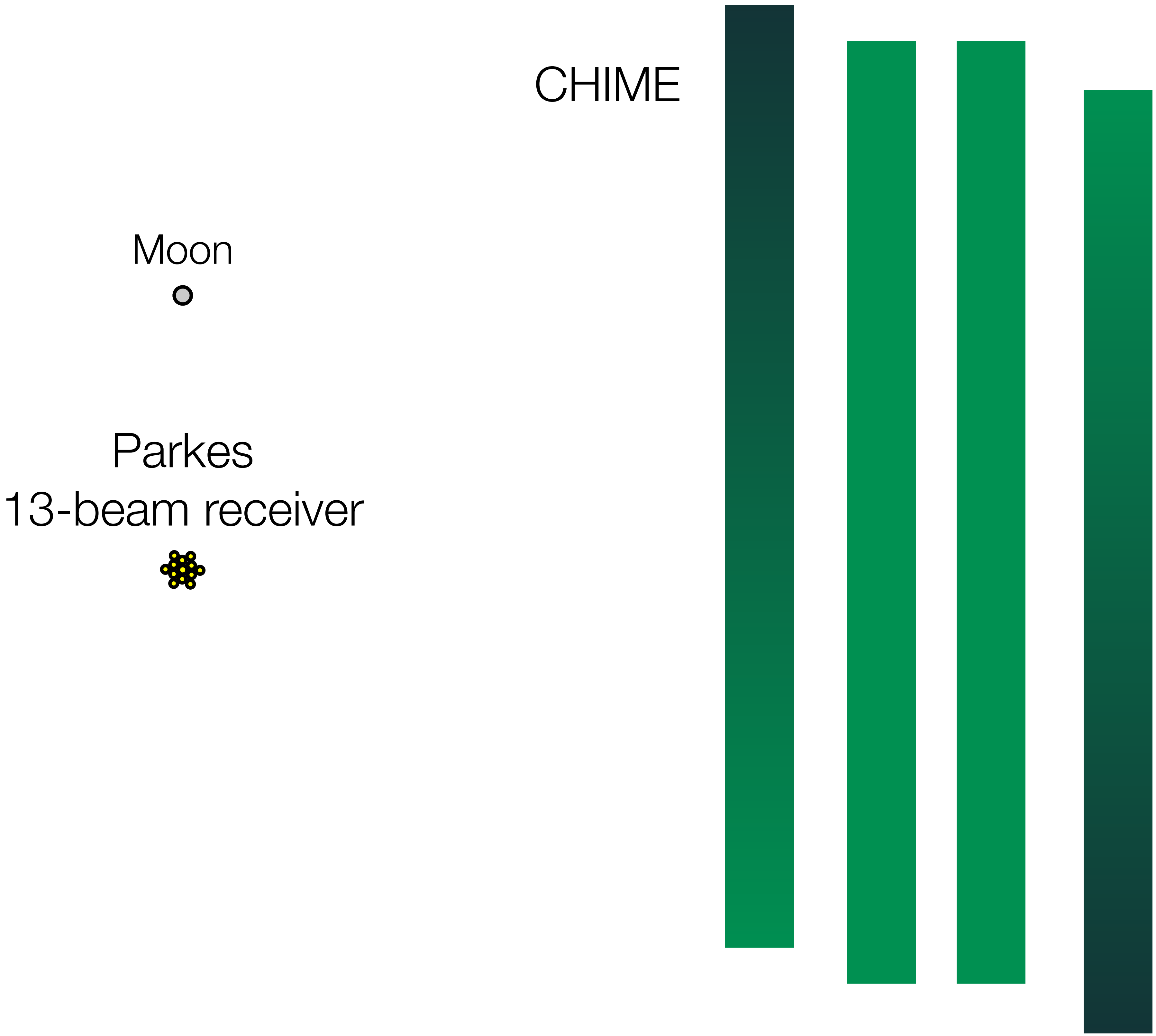
- **Parkes 64-m radio telescope** in NSW, Australia
  - Discovery (Lorimer+2007)
  - Realtime discoveries and multi-wavelength follow-up (Petroff+2015)
  - 20 of 25 FRBs from Parkes
- **Arecibo 305-m radio telescope** in Puerto Rico, USA
  - First non-Parkes discovery (Spitler+2014)
  - First repeating FRB (Spitler+2016)

CHIME/FRB survey

- Canadian Hydrogen Intensity Mapping Experiment
- New telescope built in Penticton, British Columbia, Canada
- Collaboration of many Canadian institutions
- Operates at 400-800 MHz
- Large field-of-view (~250 deg^2)

Image credits: CHIME

FRBs: Field-of-view challenge



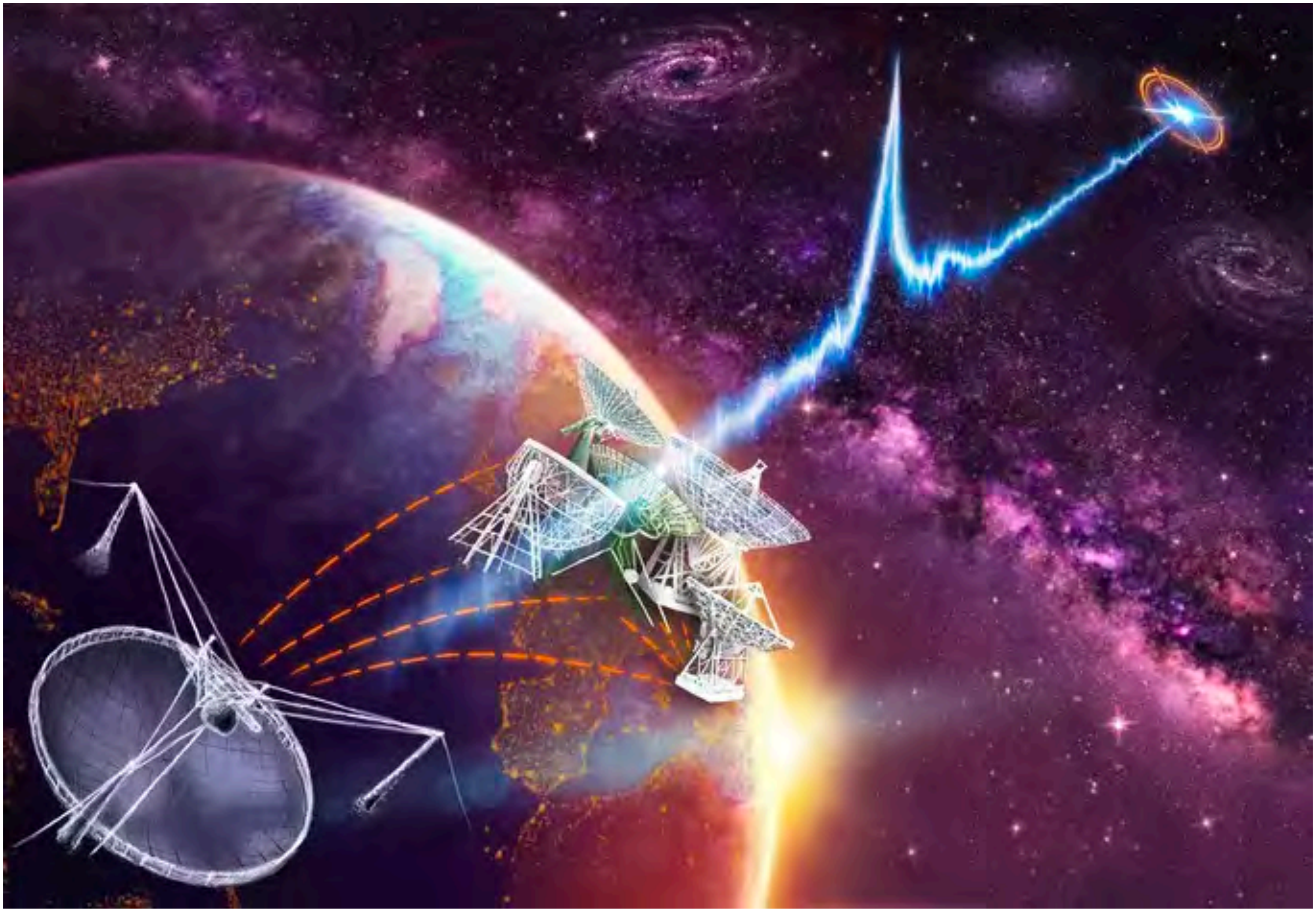
Australian Square Kilometer Array Pathfinder (ASKAP)

- New interferometer built in Western Australia by CSIRO
- 36 antennae with 12 m diameters
- Equipped with 1.4 GHz phased array feeds that form 36 beams
- Reasonably large FoV

Image Credit: CSIRO

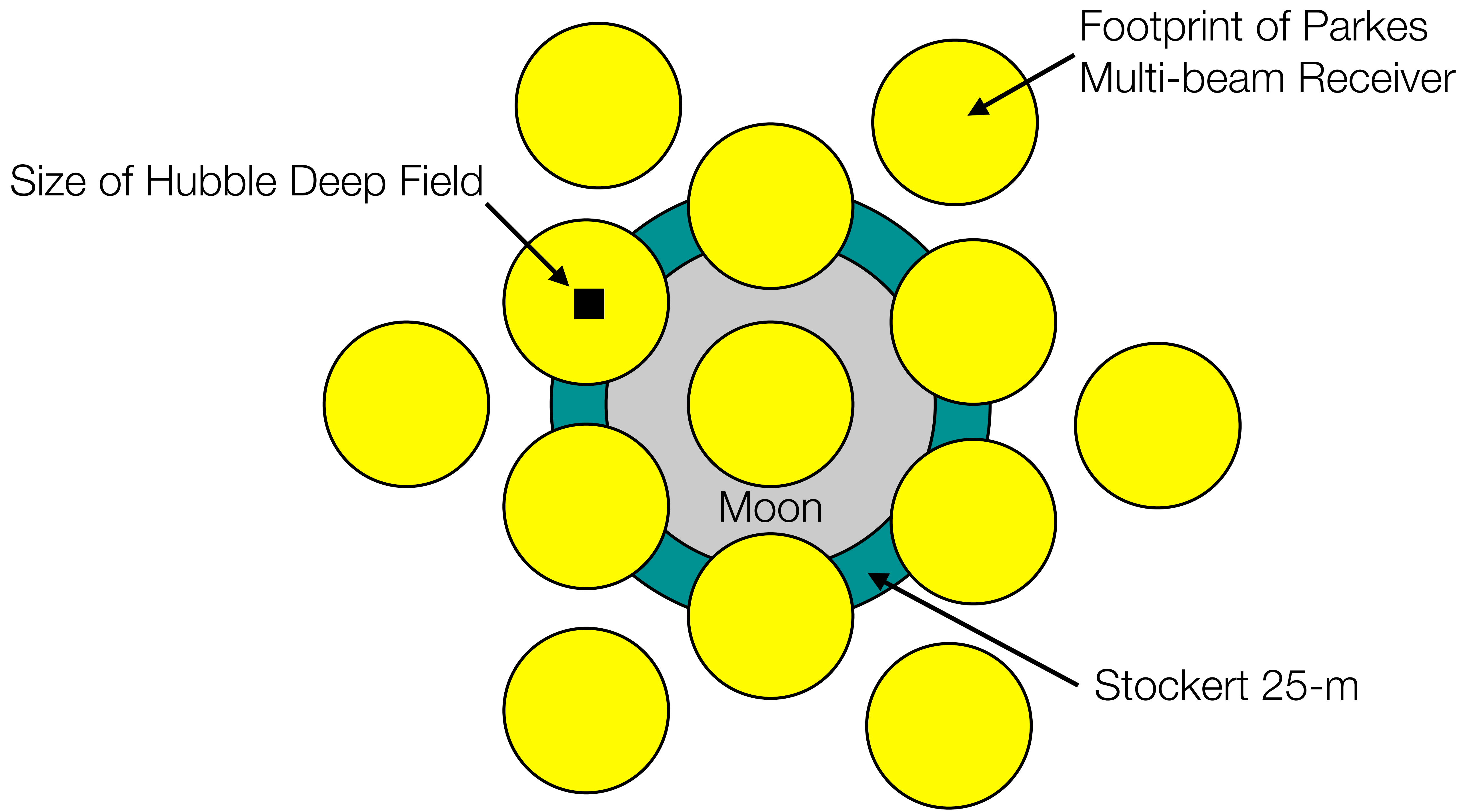
What do we know?	What do we not know?
Extragalactic	The maximum source distance
More energetic than short duration, Galactic radio transients	Maximum possible energy
Some sources have been observed to repeat	Are “one-offs” and repeaters fundamentally different?
Galactic magnetars can produce FRB-like events	Are all repeaters magnetars?
Diverse range of galaxy properties	Are galaxy properties informative?

Prove extragalactic origin: Identify host galaxy



Credit: Danielle Futselaar

FRBs: Localization challenge



FRBs: Localization challenge

Hubble Deep Field

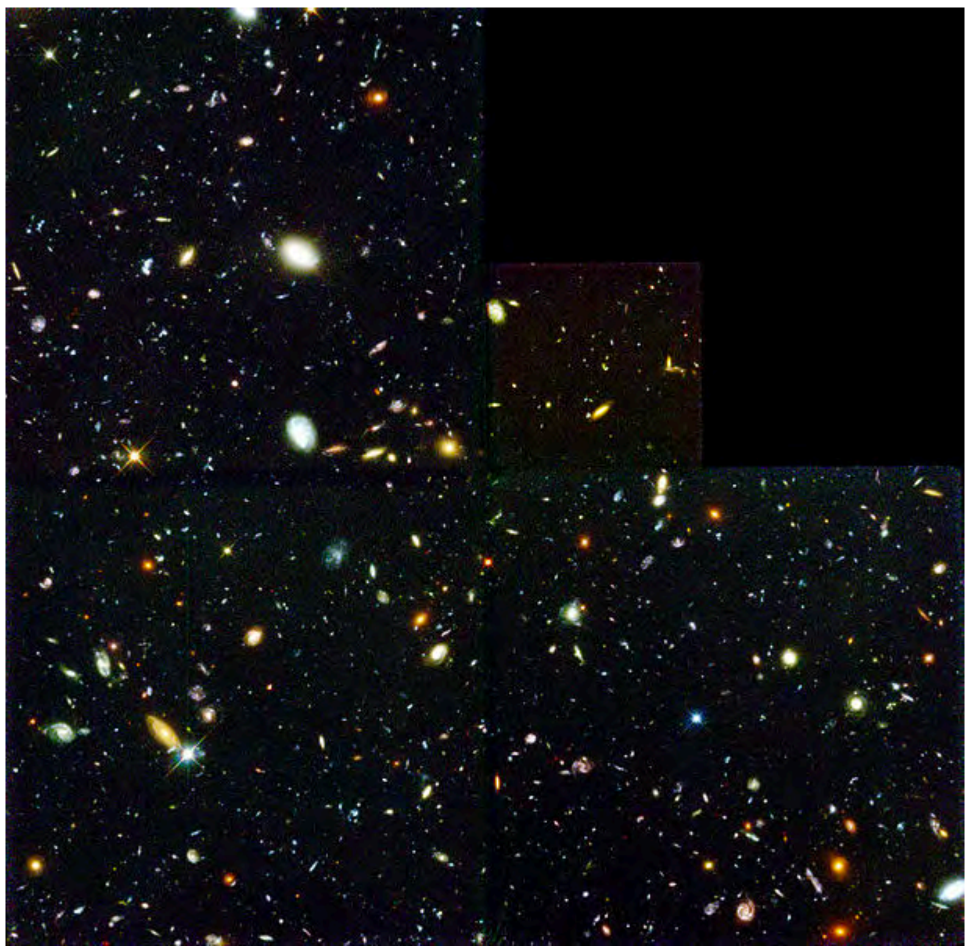
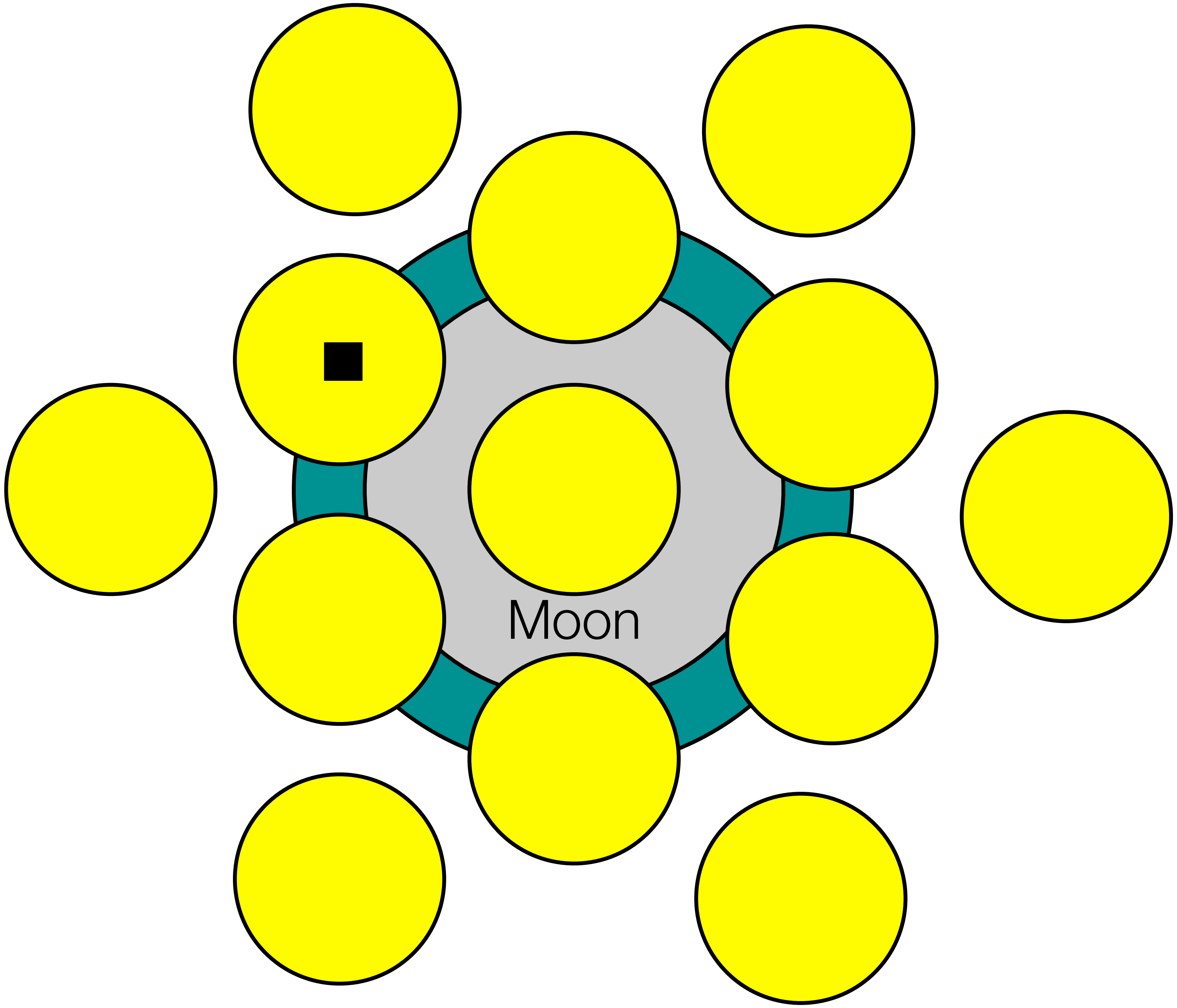


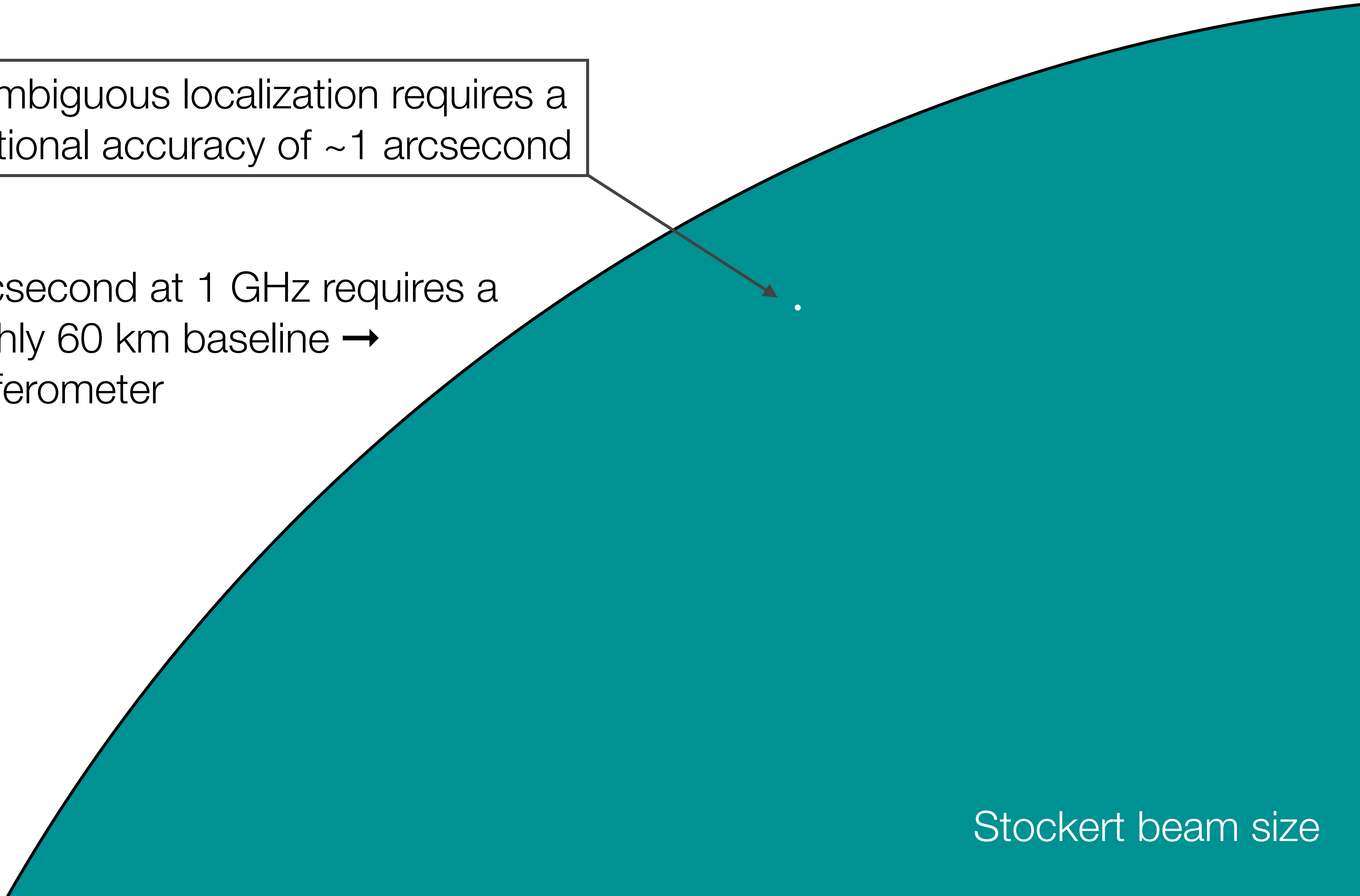
Image Credit: NASA



FRBs: Localization challenge

Unambiguous localization requires a positional accuracy of ~1 arcsecond

1 arcsecond at 1 GHz requires a roughly 60 km baseline ➞ interferometer



Very Large Array (VLA)

First to localize an FRB in follow-up observations.

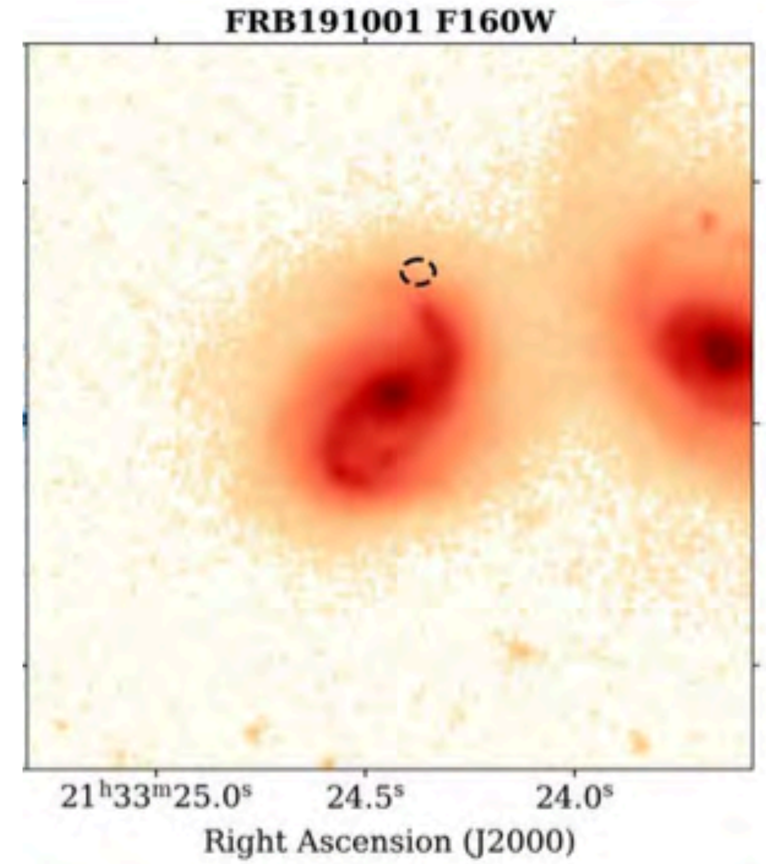
Australian SKA Pathfinder (ASKAP)

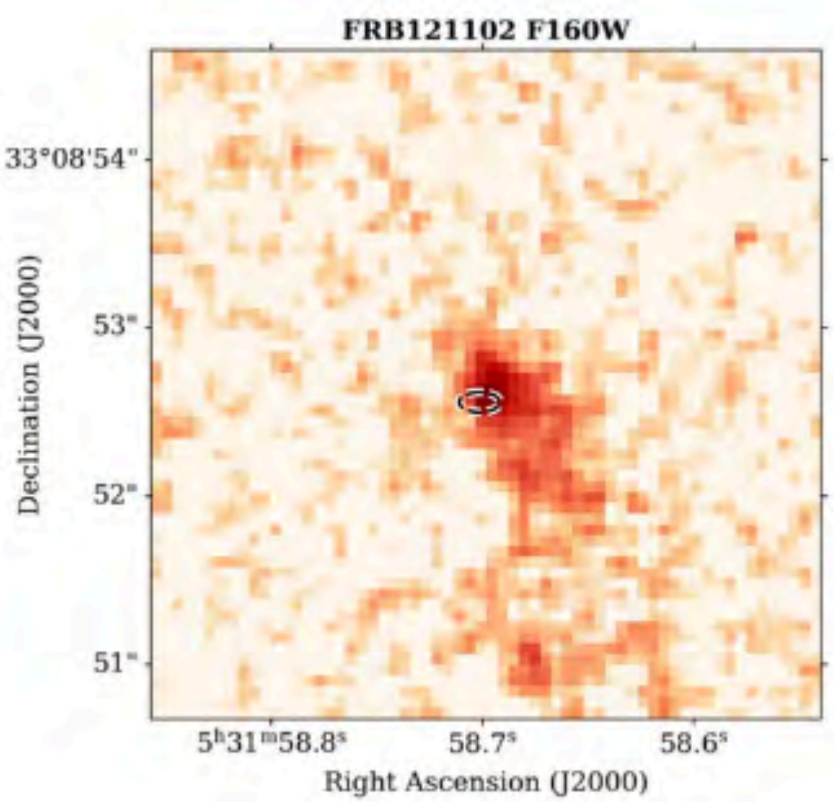
First to localize an FRB upon discovery.

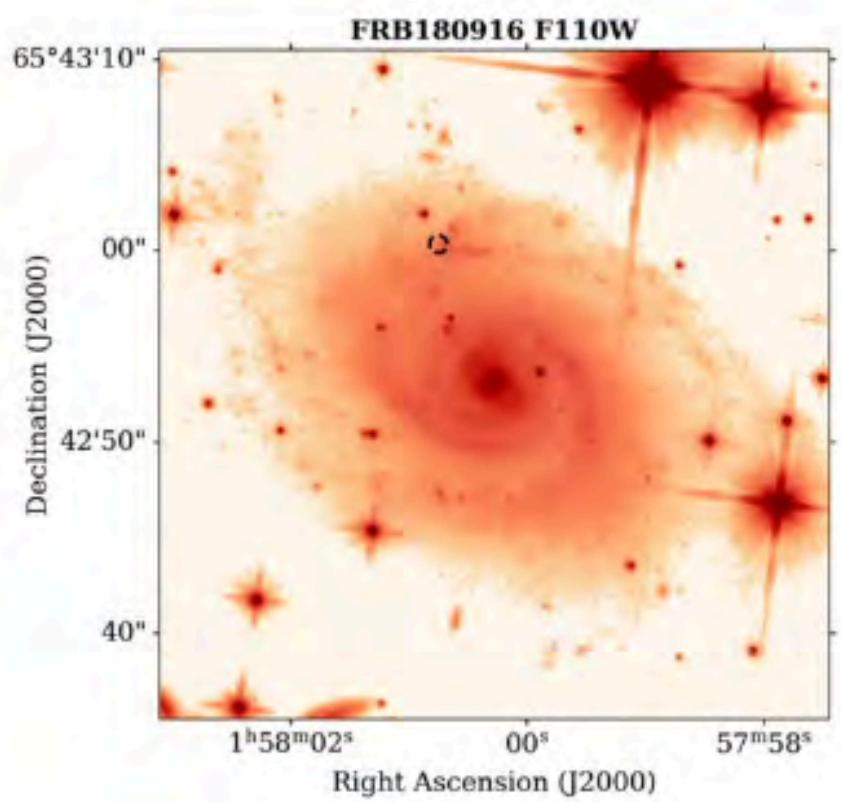
Image Credits:
NRAO/AUI/NSF (left)
CSIRO (right)

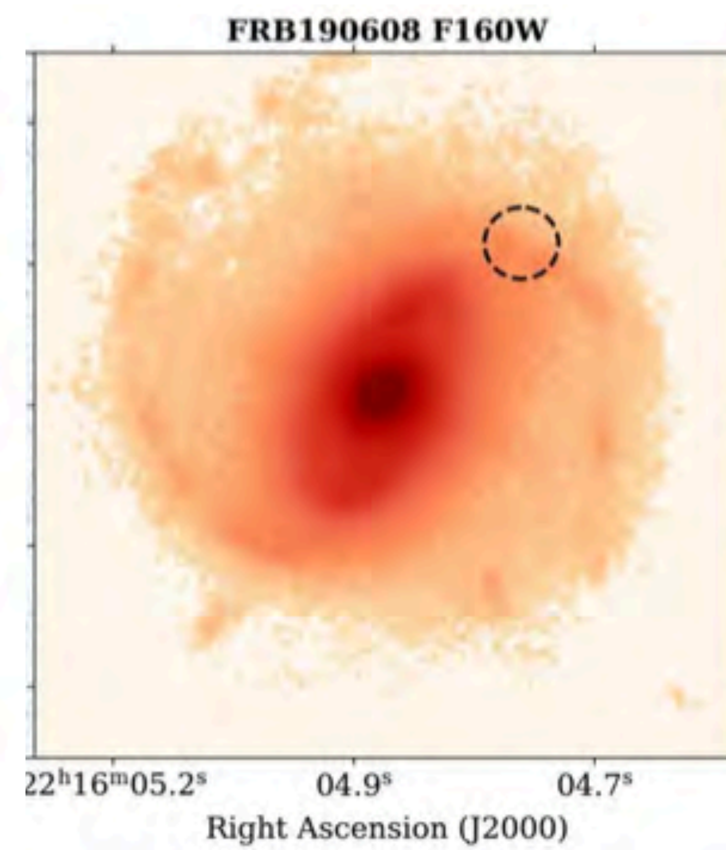
Host galaxies

- Closest localized FRB:
  12 million light years (M81)
- Most distant localized FRB:
  10 billion light years (z=1).









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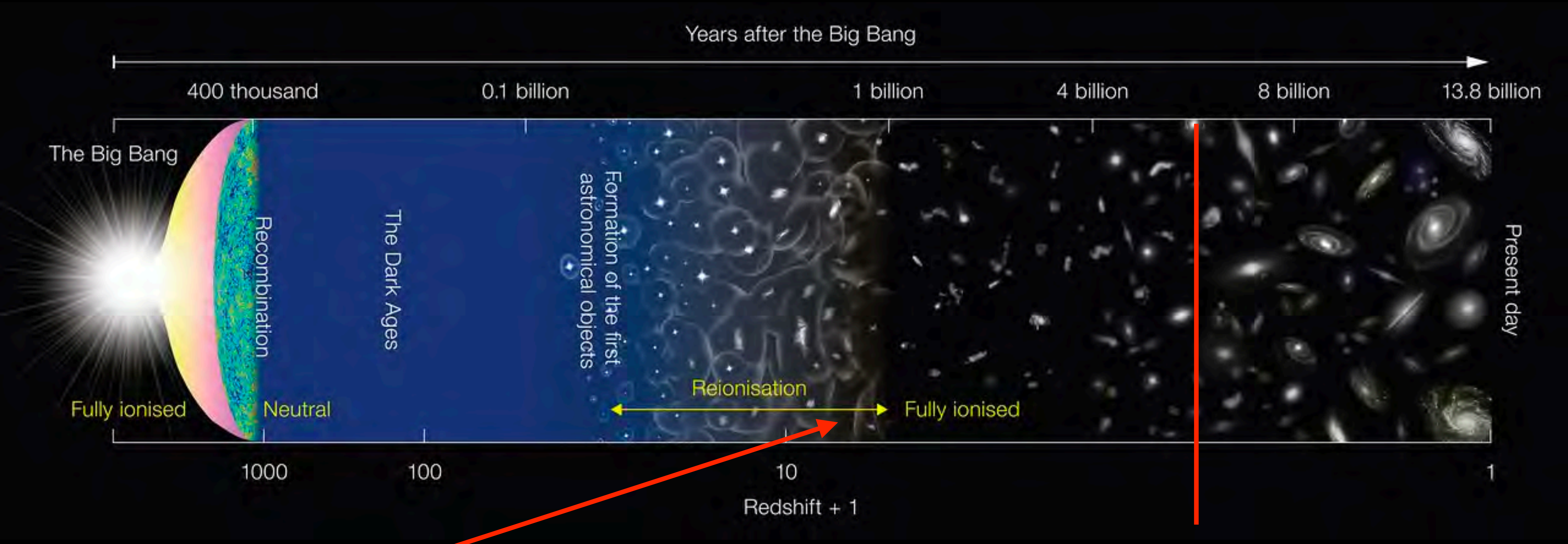
History of the Universe



Most distant localized FRB

Can we detect FRBs here?
Can we observe the host galaxy?
Do the necessary sources exist?

Credit: NAOJ

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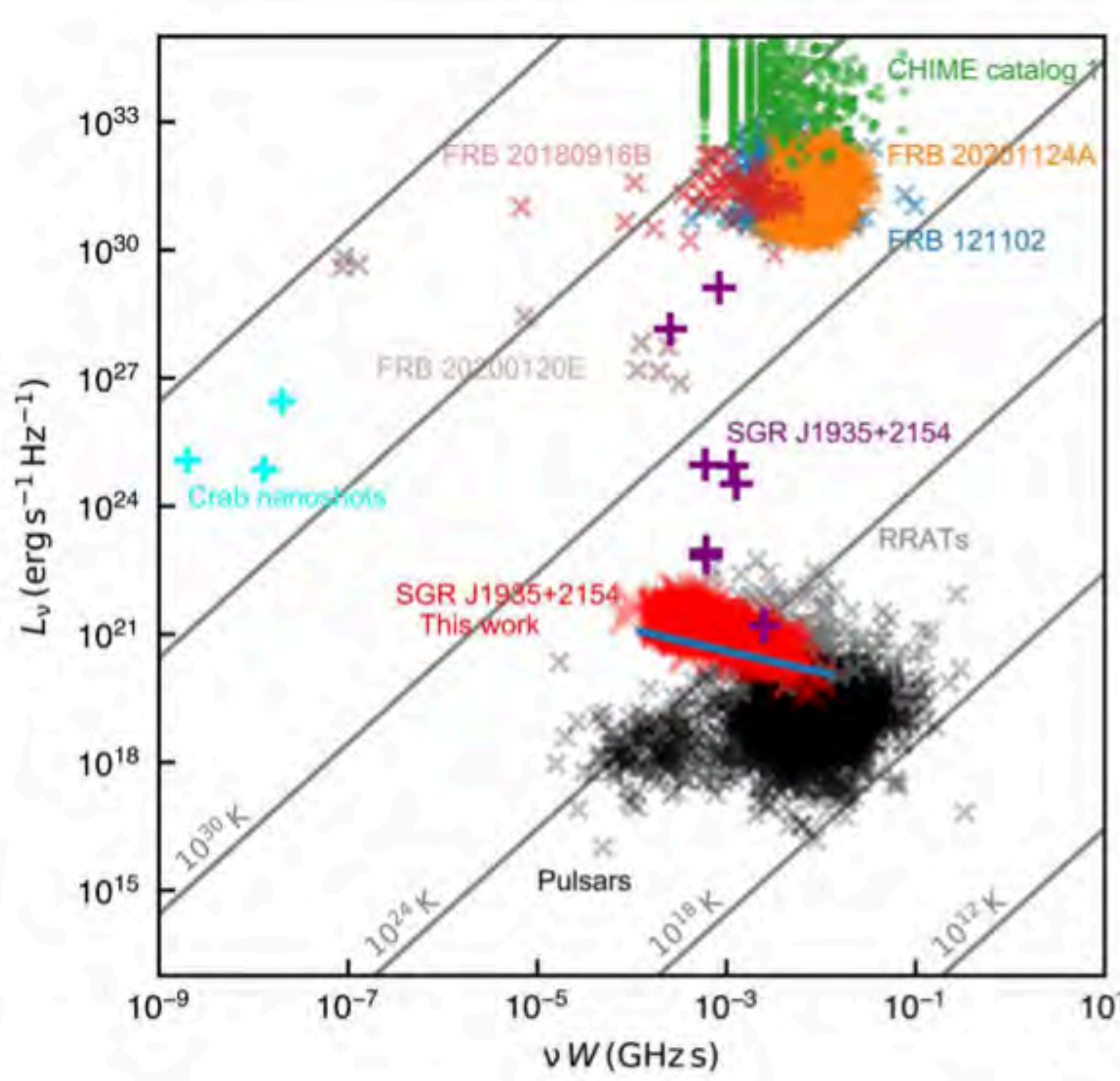
Energetics

- Difference in luminosity between…
  - typical Galactic pulsar emission and typical FRB emission:
    10 orders of magnitude
  - extreme Galactic pulsar emission and typical FRB emission:
    6 orders of magnitude
- Space in between is filling in over the last few years



GJy

MJy

mJy

Zhu et al., Science, 2023

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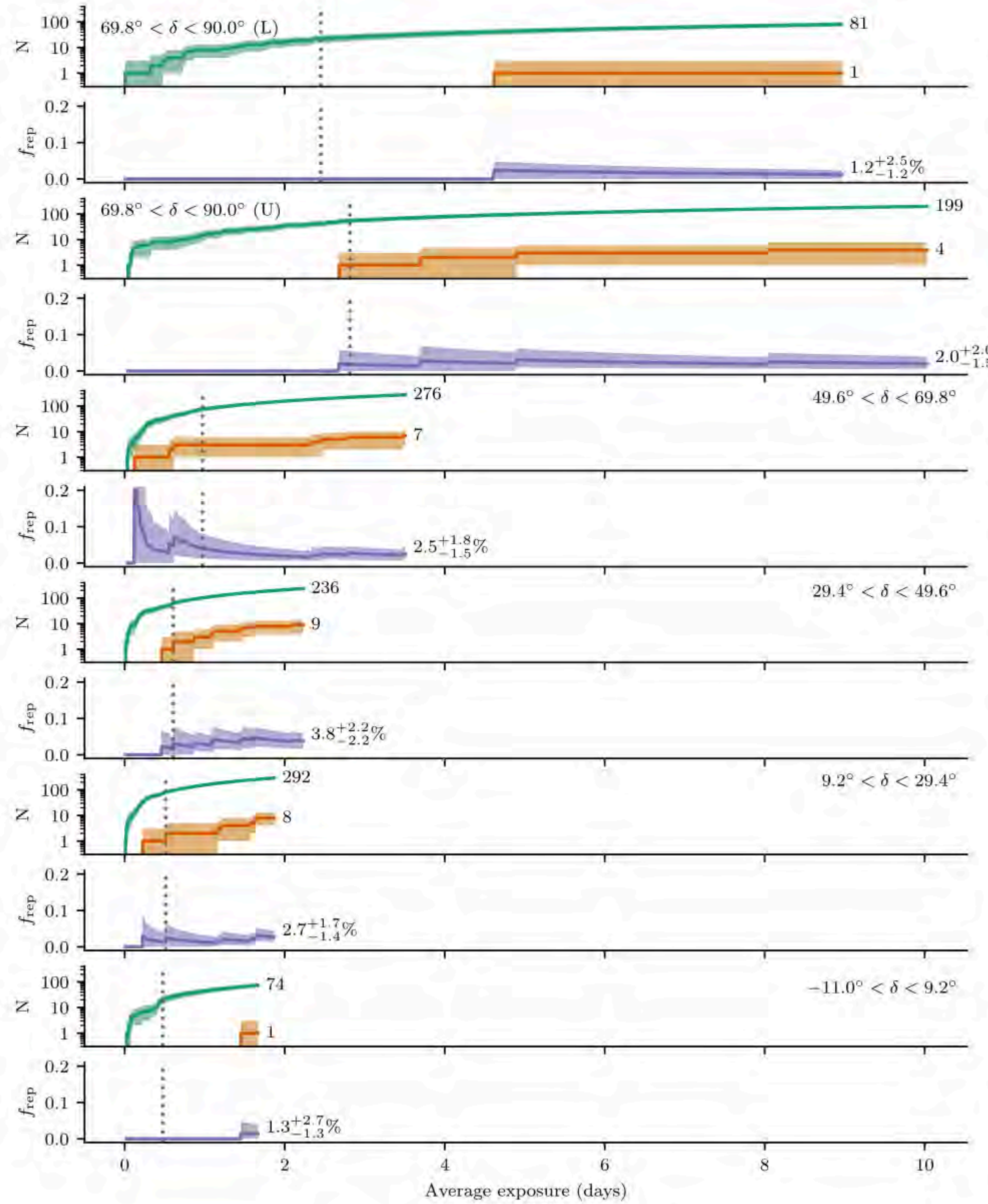
Some sources repeat

- Total: 51*
  - CHIME/FRB
  - Arecibo, FAST, ASKAP, DSA
- Repeater fraction in the CHIME/FRB band (400-800 MHz): 1 - 4 %
- “Stormy” vs “calm”



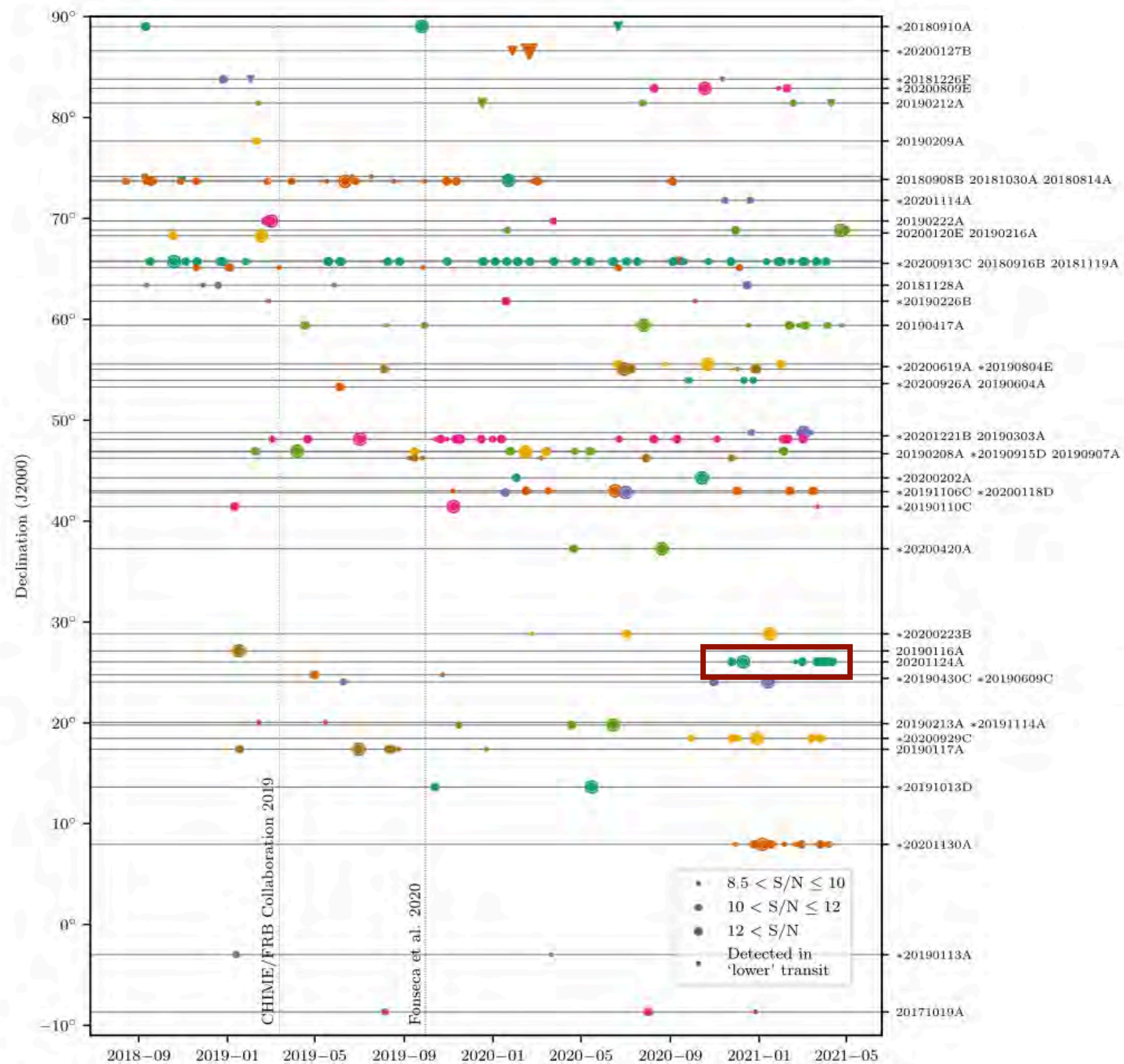
*according to FRB community newsletter

Andersen et al., 2023, ApJ, 947

“Stormy” and “calm” repeaters

- Most FRBs: a handful of bursts detected
- Stormy repeaters:
  - FRB 20121102A
    AO: 220 bursts/hr
  - FRB 20201124A
    FAST: 50 bursts/hr
  - FRB 20220912A
    FAST: 390 bursts/hr
- Warning: our observational data is biased toward active/stormy sources

CHIME/FRB repeaters



Jahns et al., 2023, MNRAS, 519
Xu et al. 2022, Nature, 609
Zhang et al., 2023, submitted

Andersen et al., 2023, ApJ, 947

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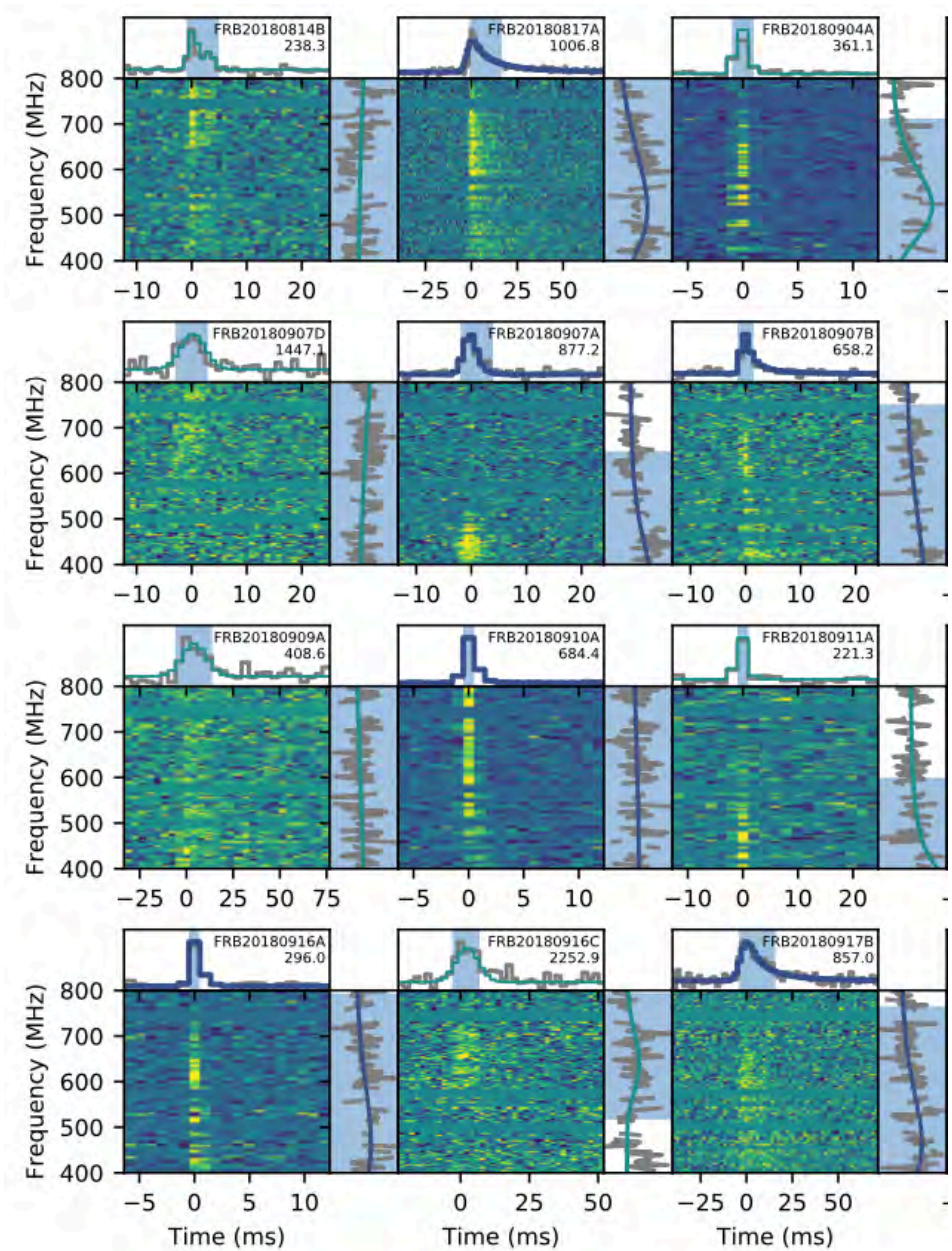
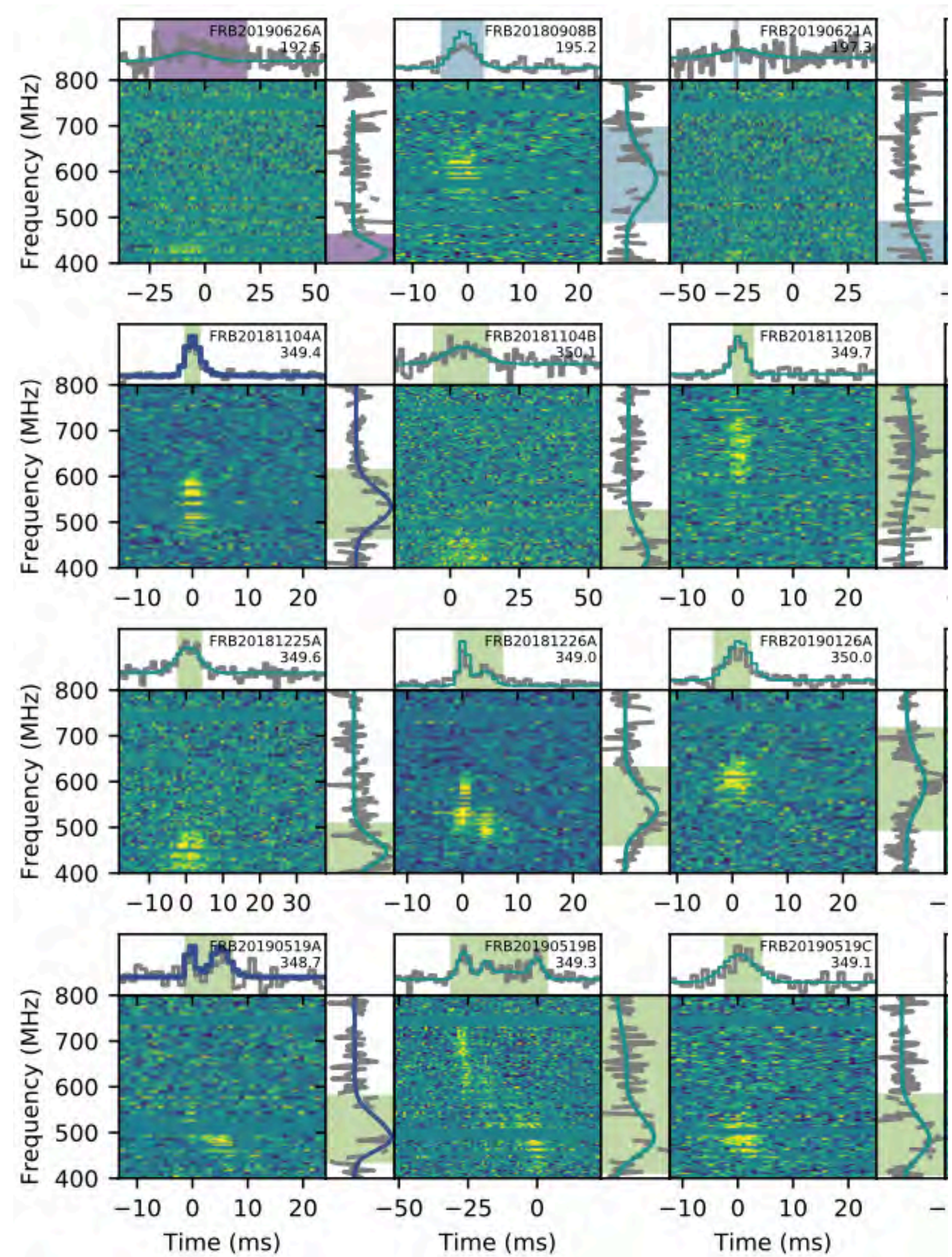
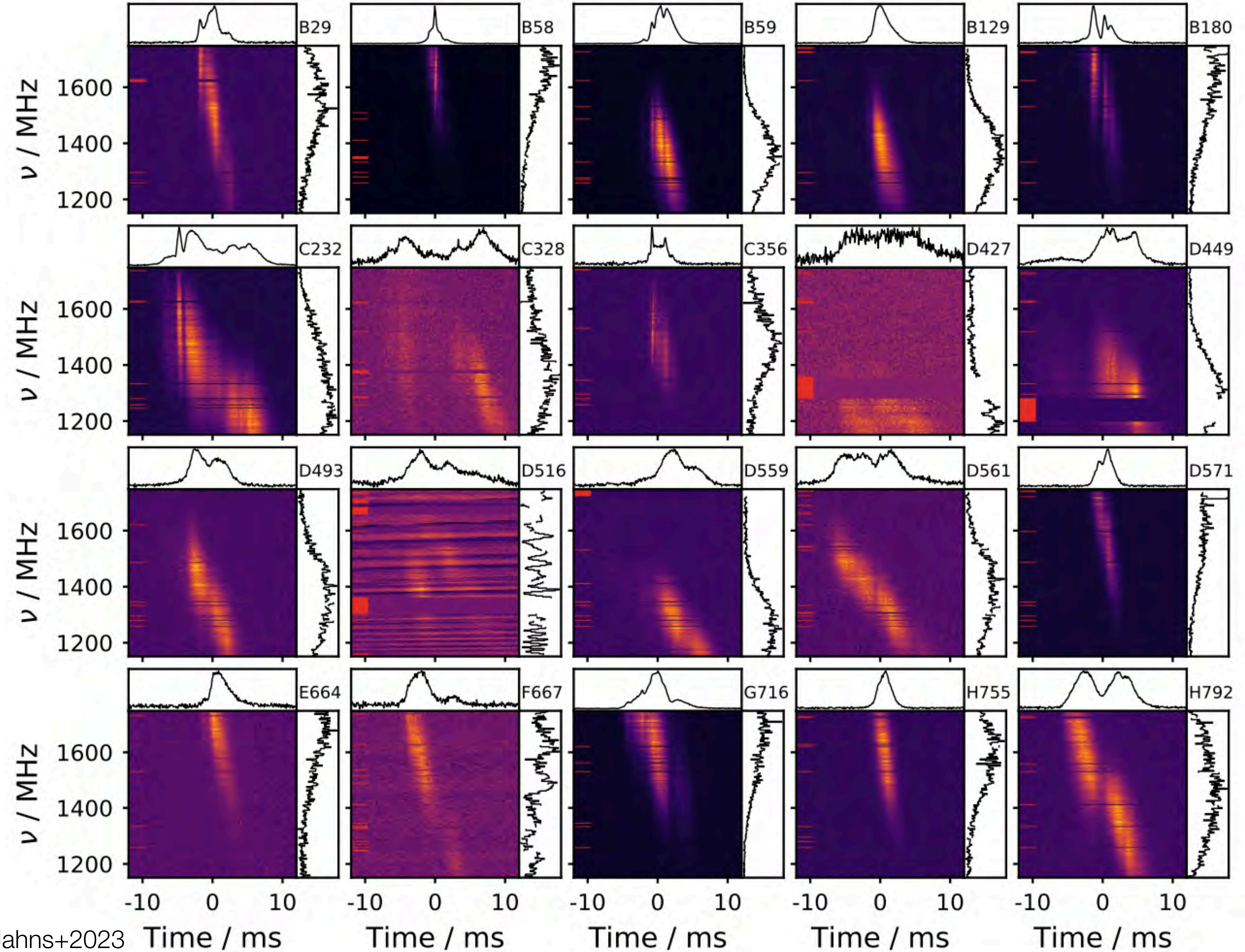
“One-offs”



Repeaters



CHIME/FRB Catalog 1


B29
B58
B59
B129
B180
C232
C328
C356
D427
D449
D493
D516
D559
D561
D571
E664
F667
G716
H755
H792
ν / MHz
1200
1400
1600
Time / ms
-10
0
10

Jahns+2023

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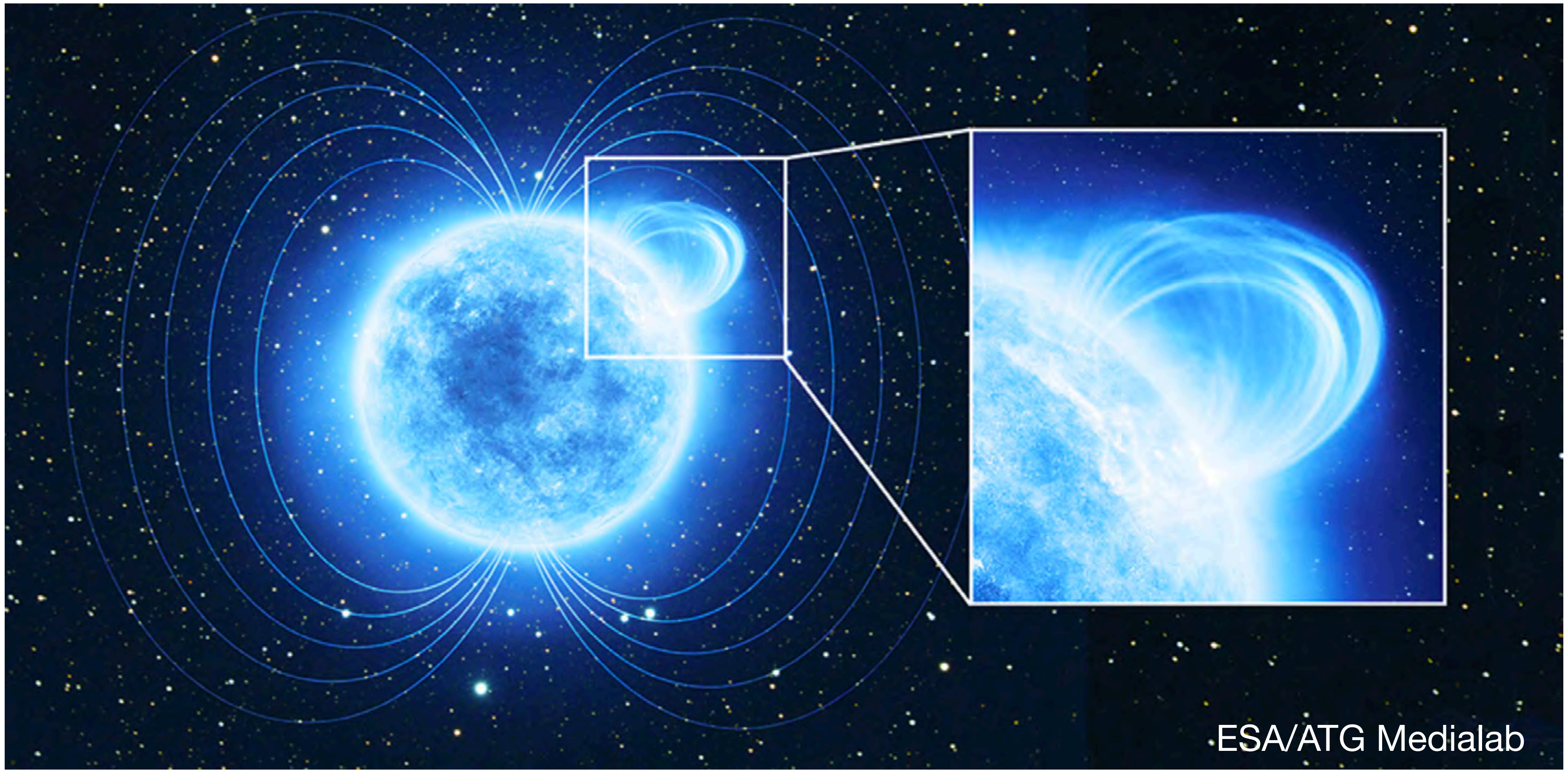
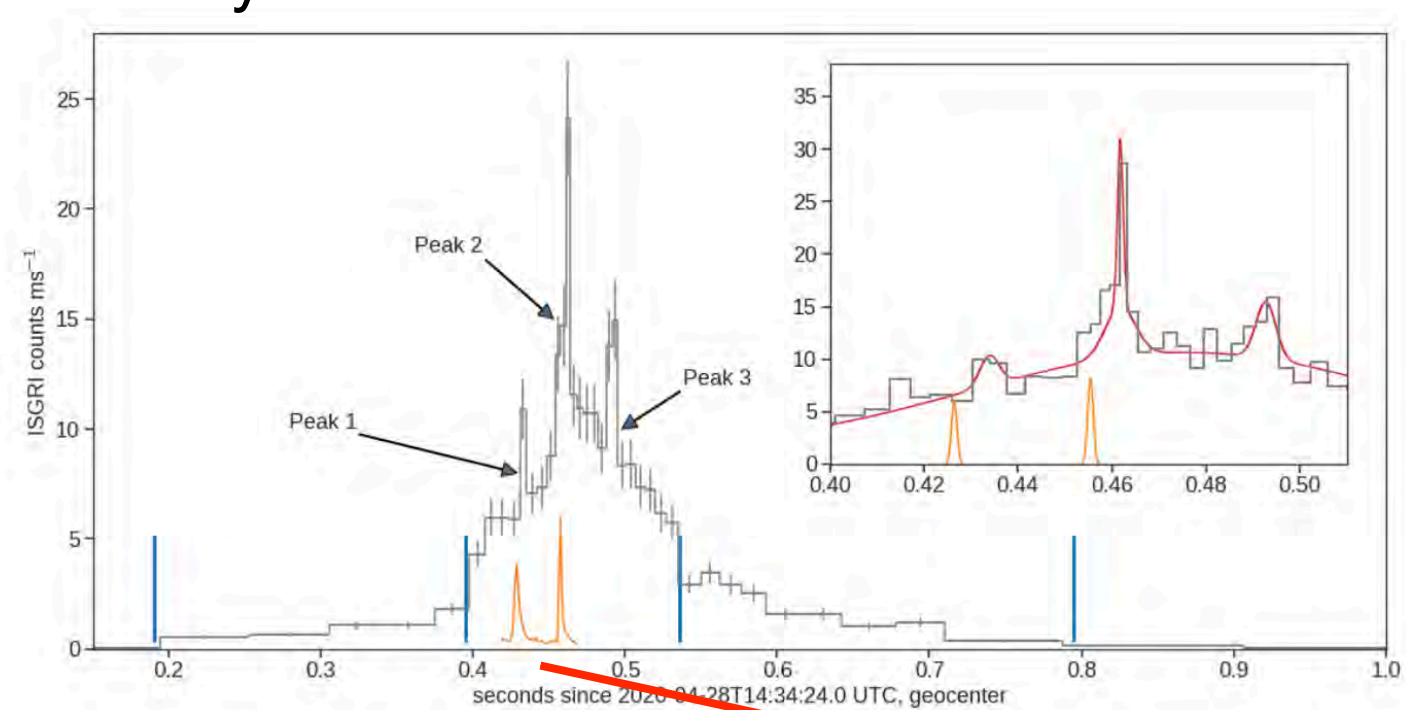
Magnetars

- Neutron stars with strongest magnetic fields
- Highly variable sources, in particular at X-ray wavelengths
- 6 of 30 are also detected as radio pulsars
- SGR 1935+2154: FRB engine in our galaxy?



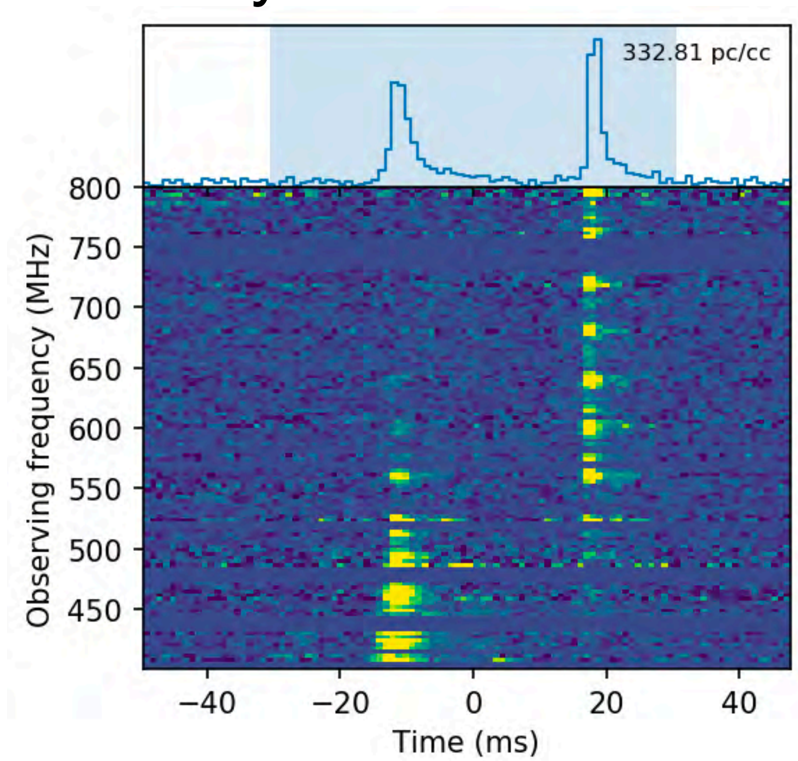
SGR 1935+2154 (aka “1935”)

X-ray bursts



Mereghetti et al. 2020

Radio bursts detected by CHIME/FRB



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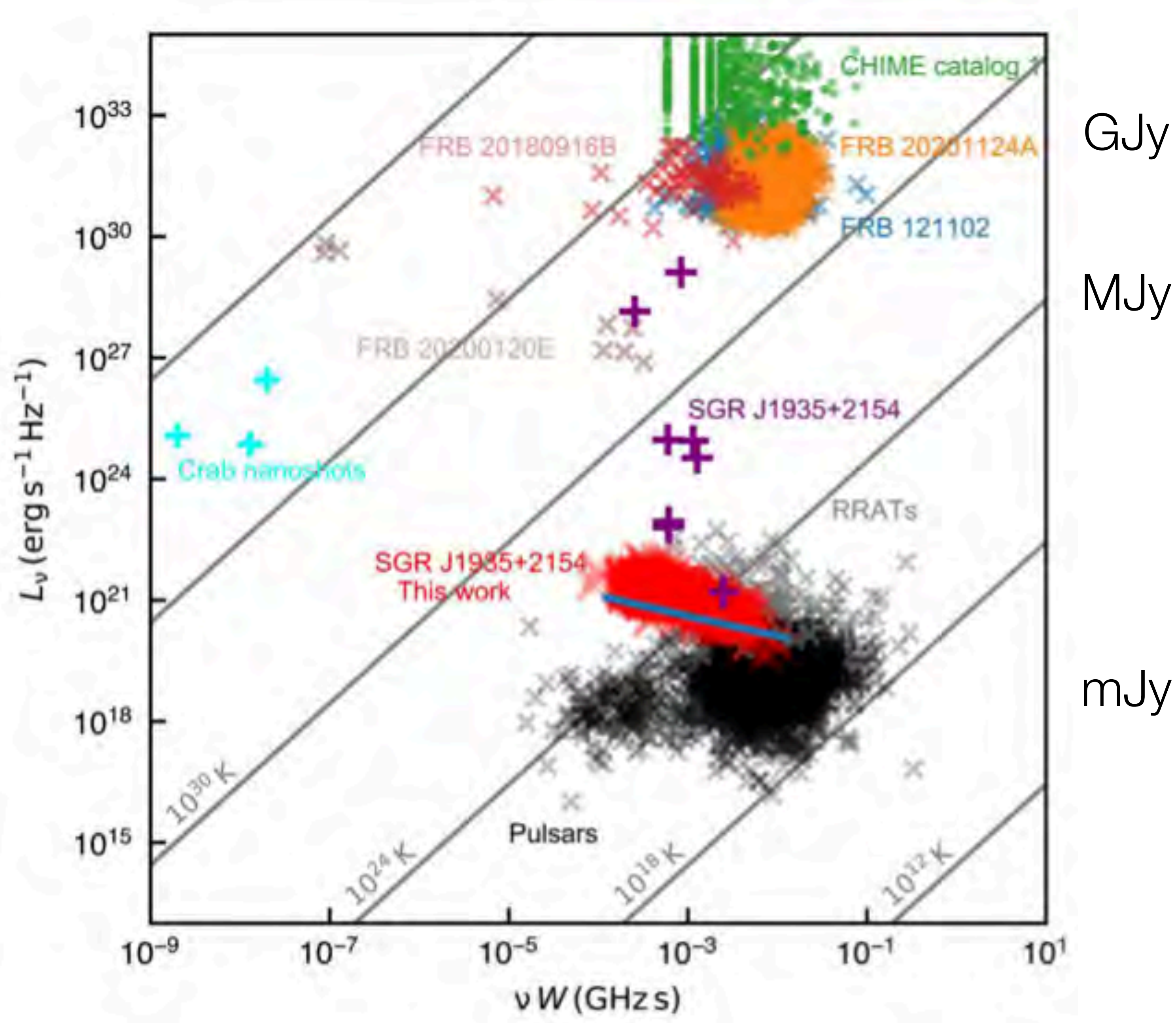

Zhu et al., Science, 2023

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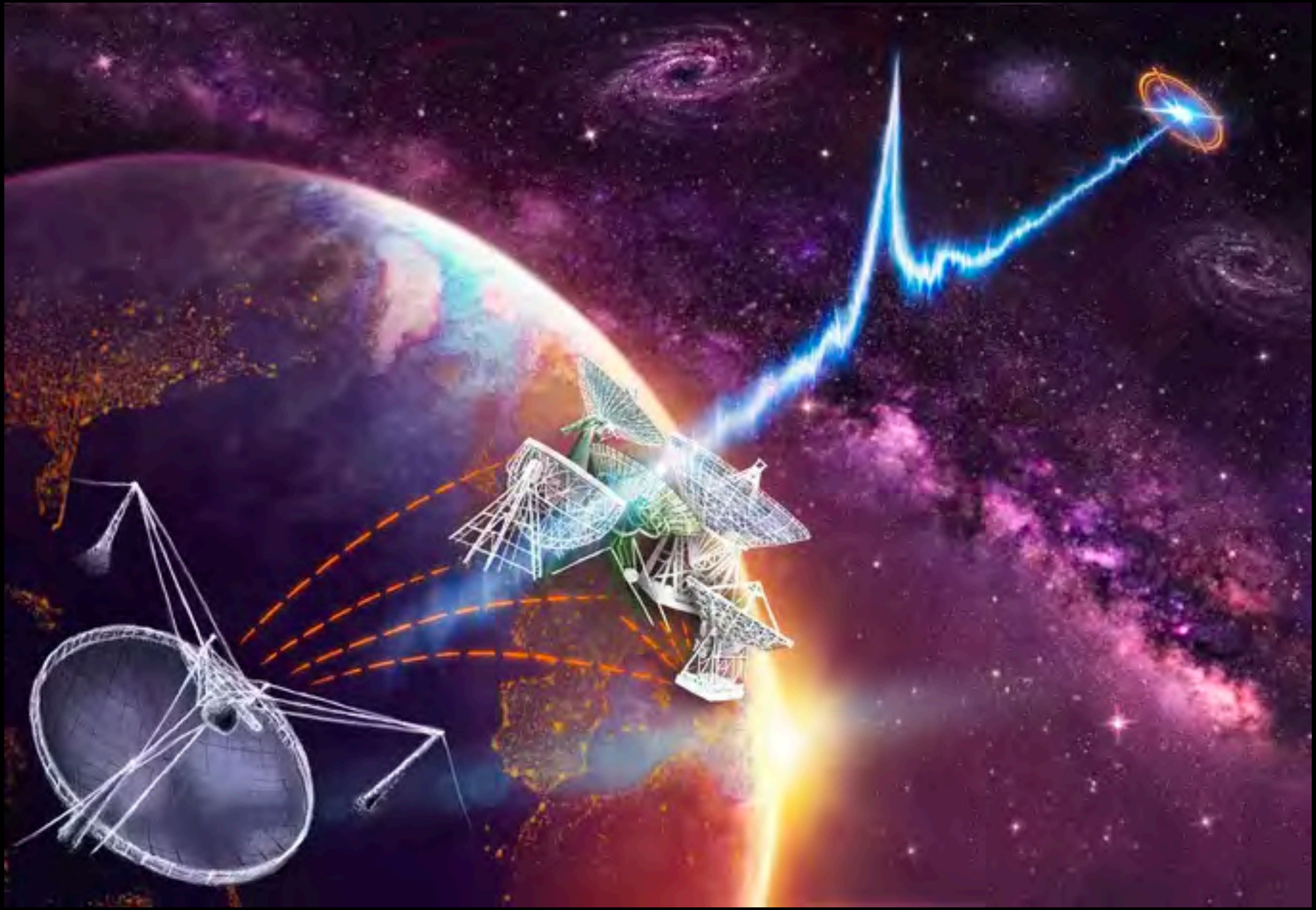
Host galaxies of repeaters

Do we expect magnetars in these galaxies?



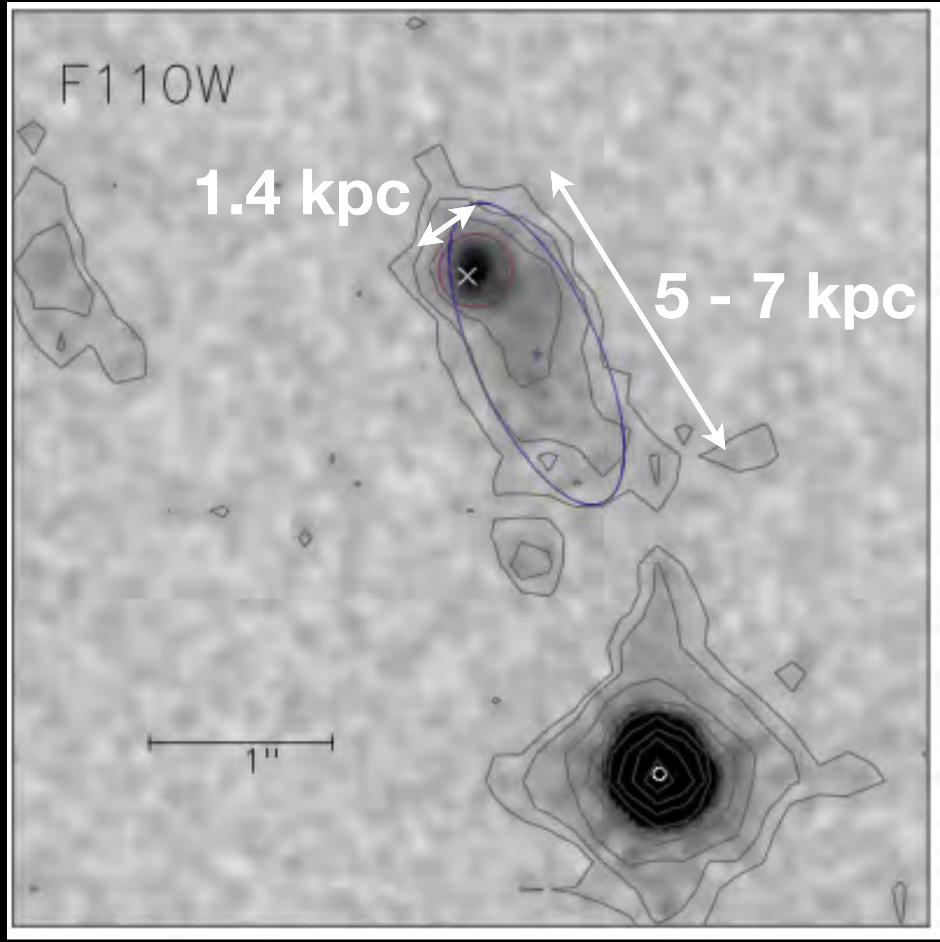
Credit: Danielle Futselaar

(Milky Way: 10^{12} M_{Sun})

Dwarf galaxies

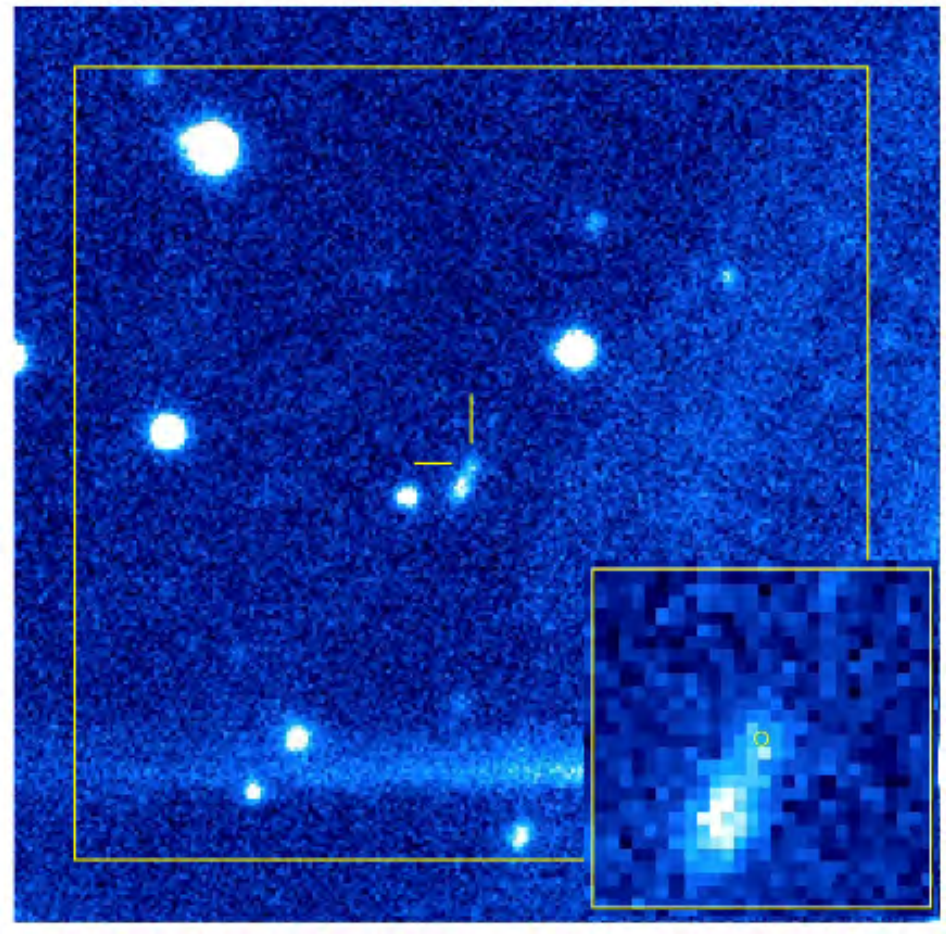
Mass ~ 10^8 M_{Sun}

Host of FRB 20121102A



Marcote et al. 2017

Host of FRB 20190520B



Niu et al. 2022

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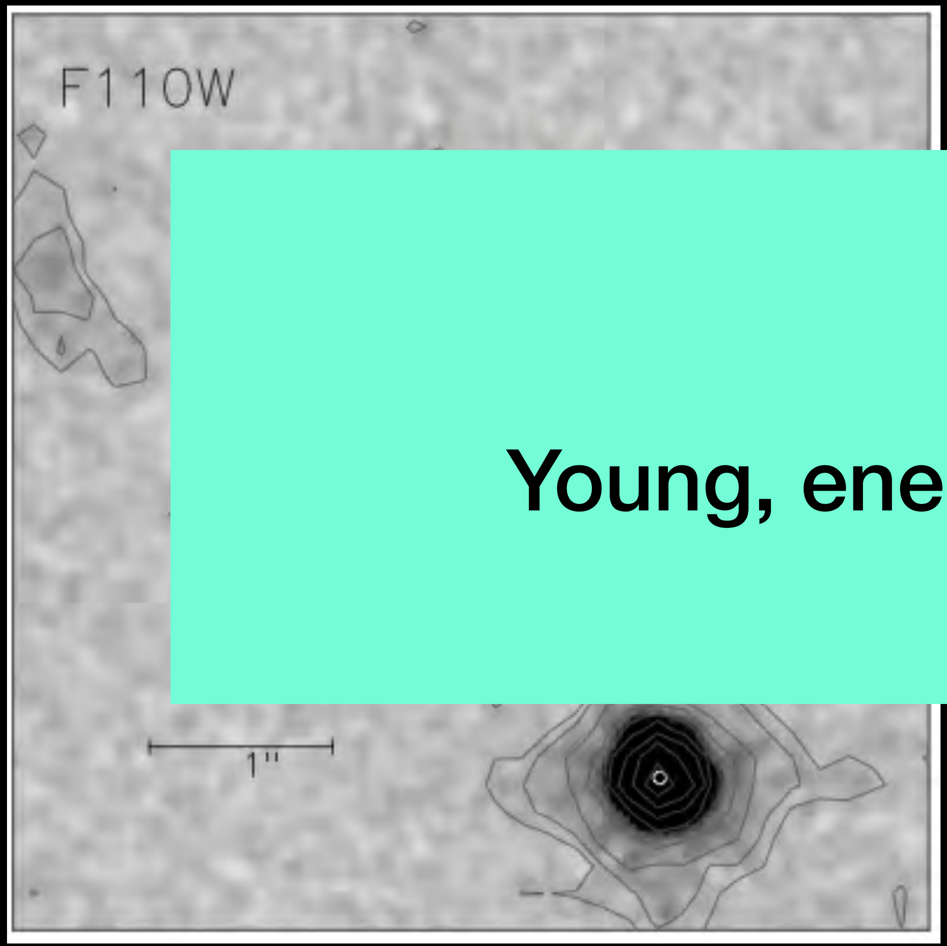
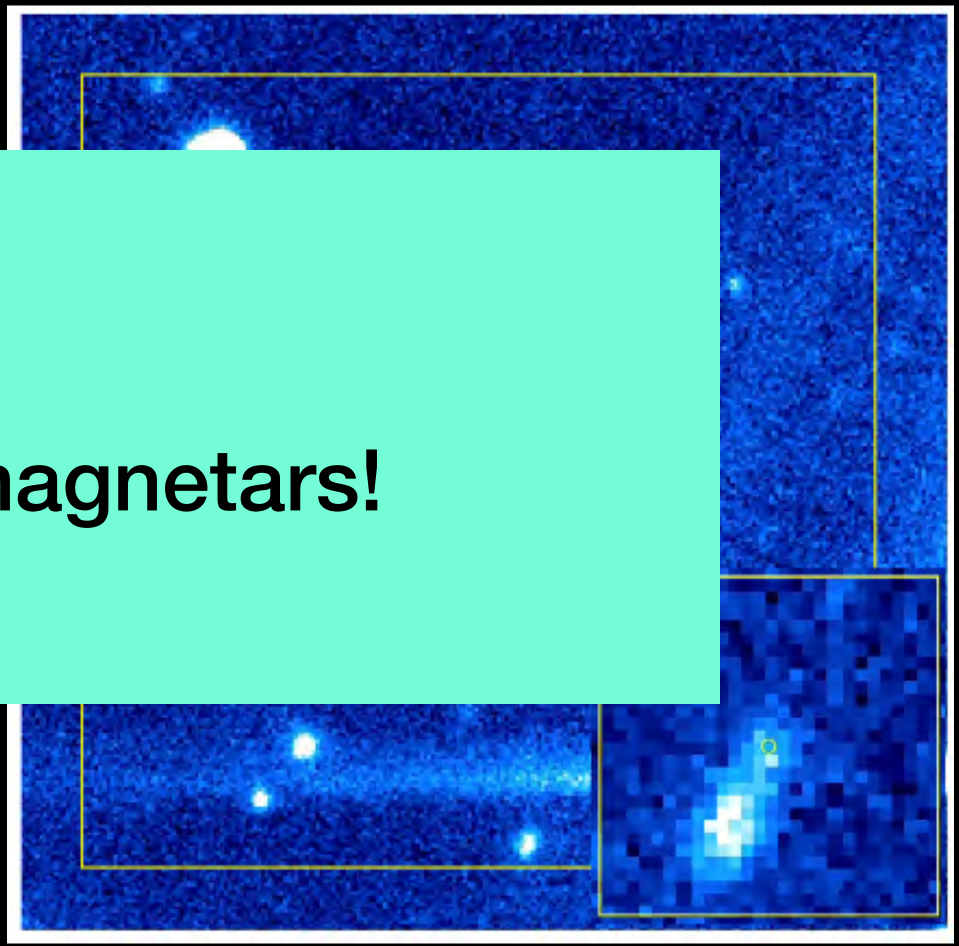


Marcote et al. 2017

Host of FRB 20190520B



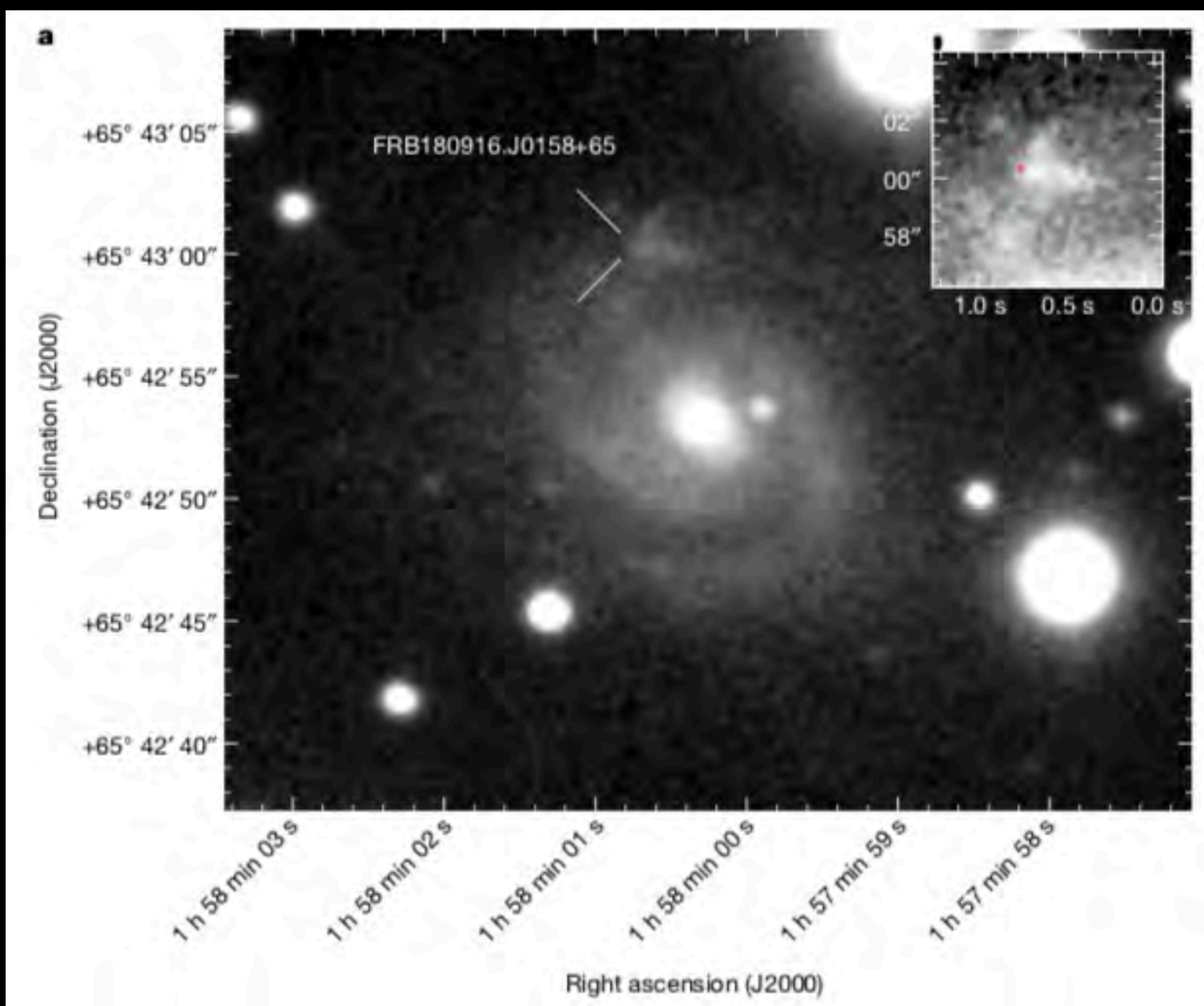
Niu et al. 2022

Yes!
Young, energetic magnetars!

Spiral galaxies

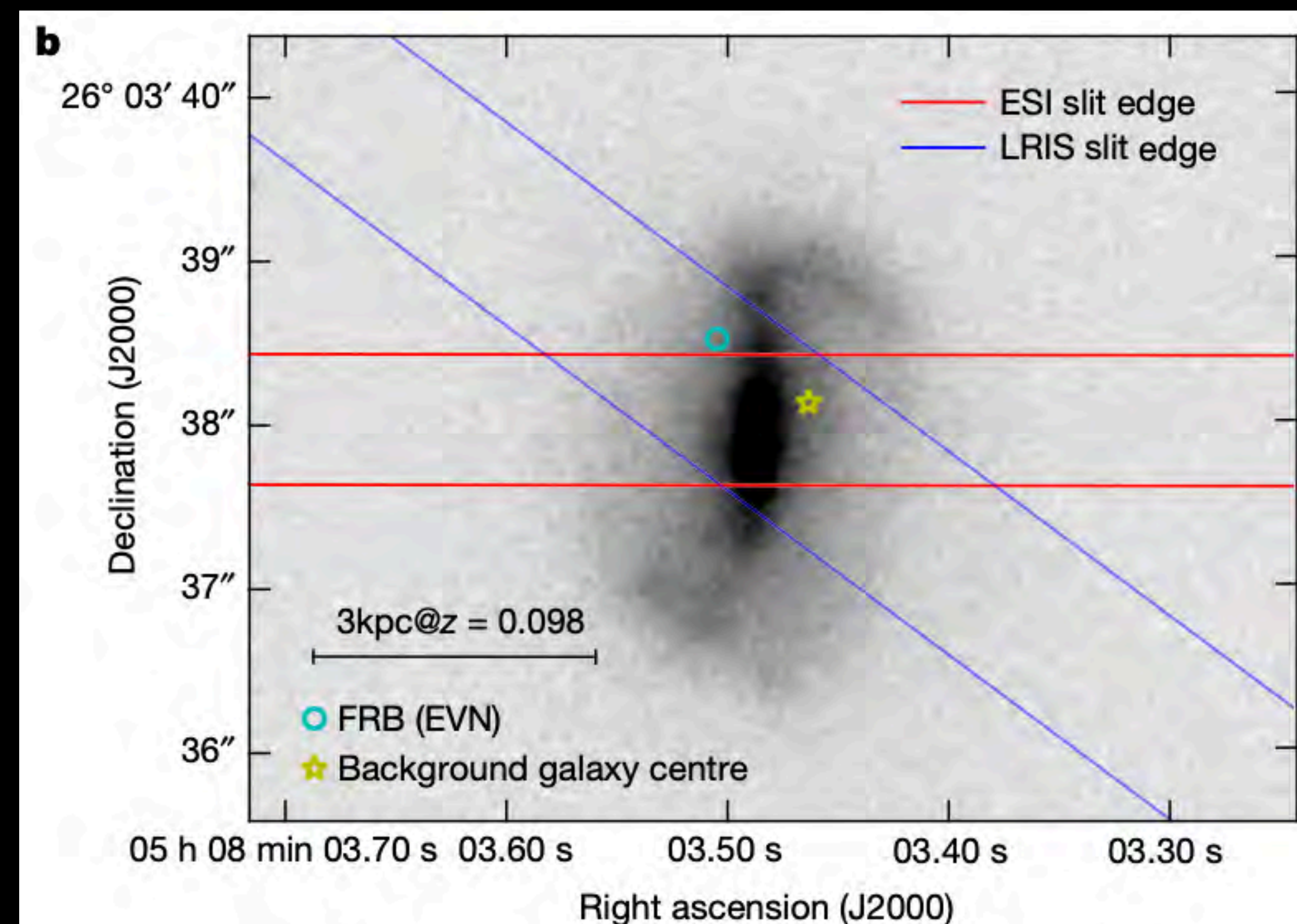
Mass ~ 10^{10} M_{Sun}

Host of FRB 20180916B



Marcote et al. 2020

Host of FRB 20201124A

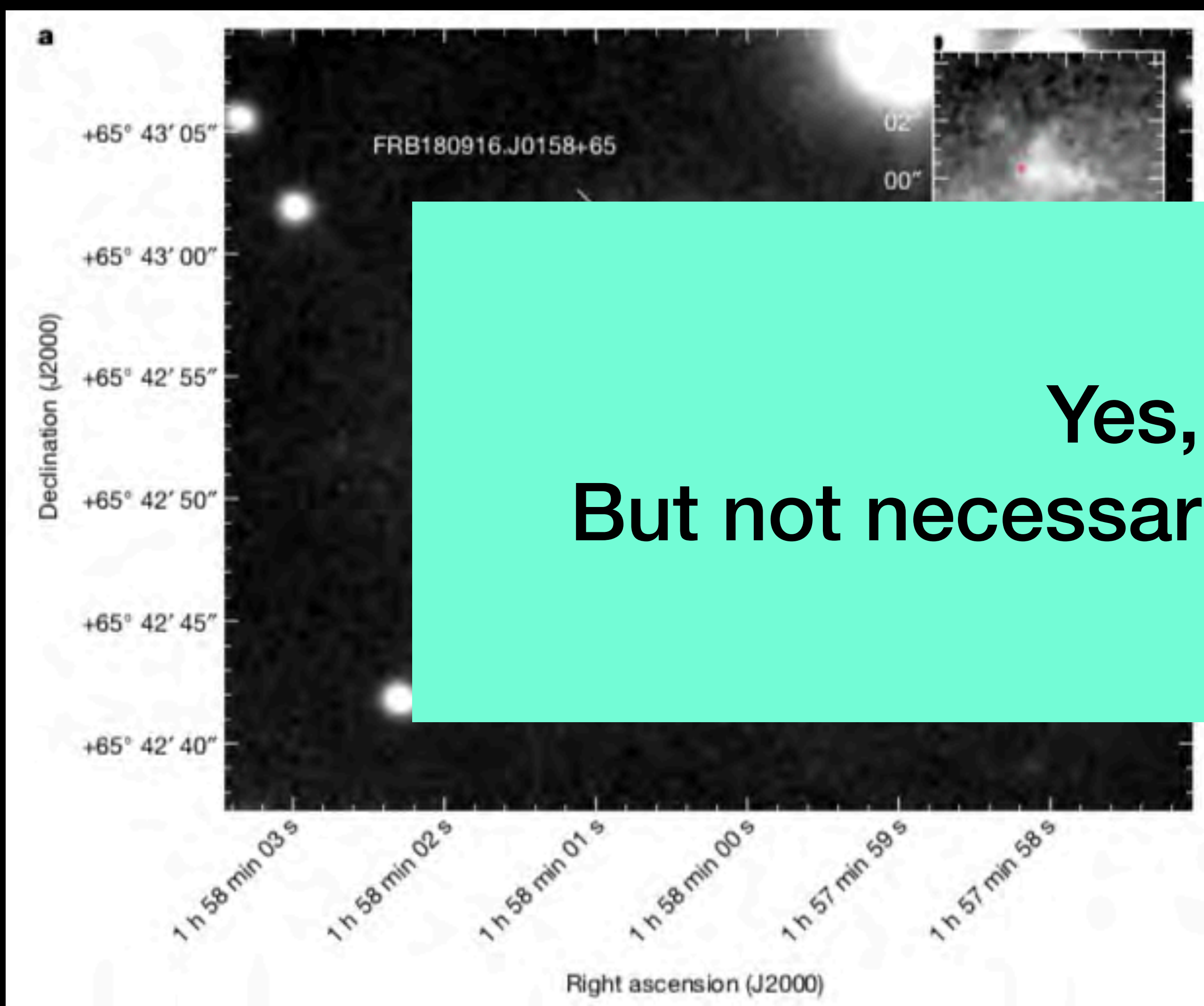


Xu et al. 2022

Spiral galaxies

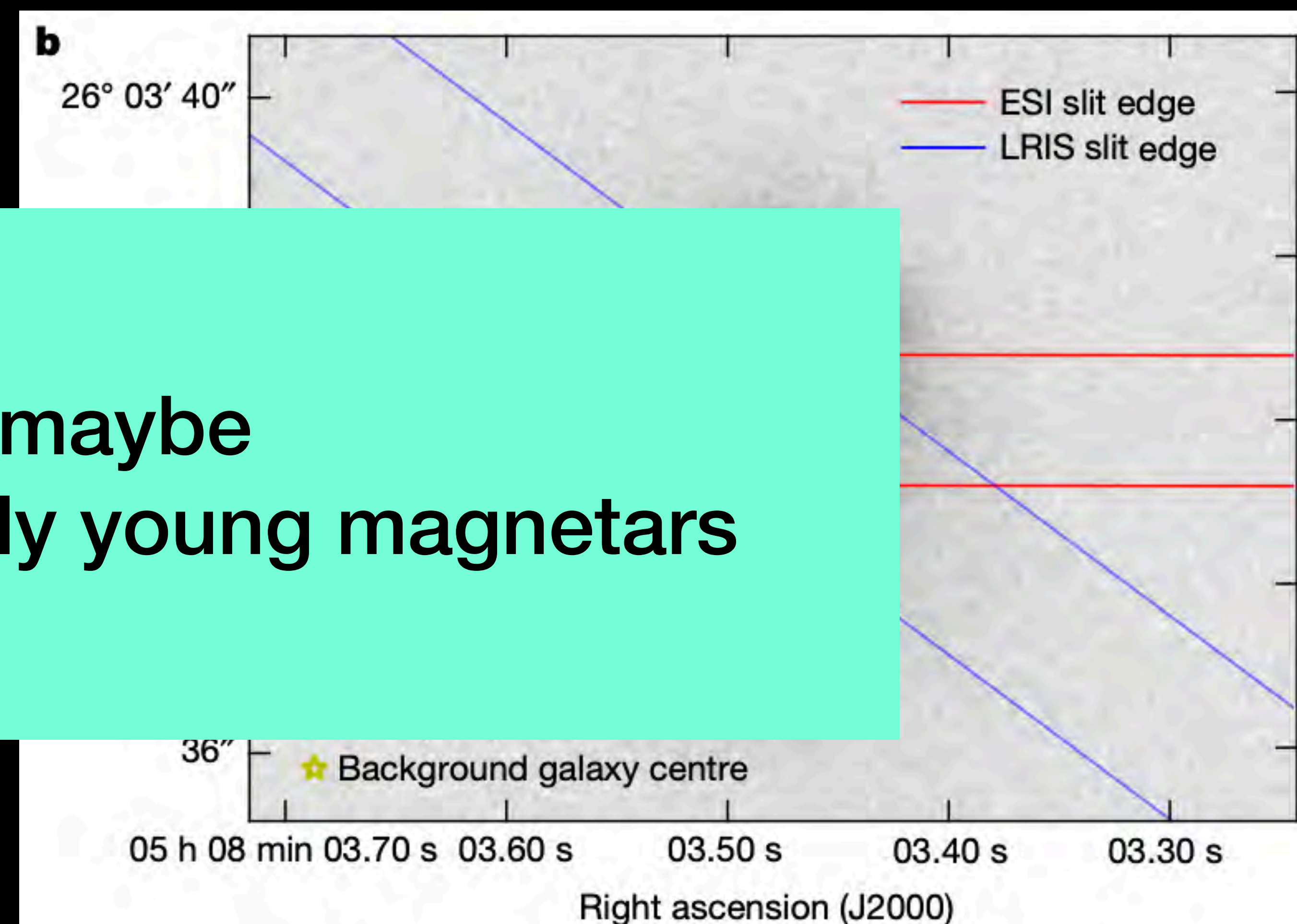
Mass ~ 10^{10} M_{Sun}

Host of FRB 20180916B



Marcote et al. 2020

Host of FRB 20201124A



Xu et al. 2022

Yes, maybe

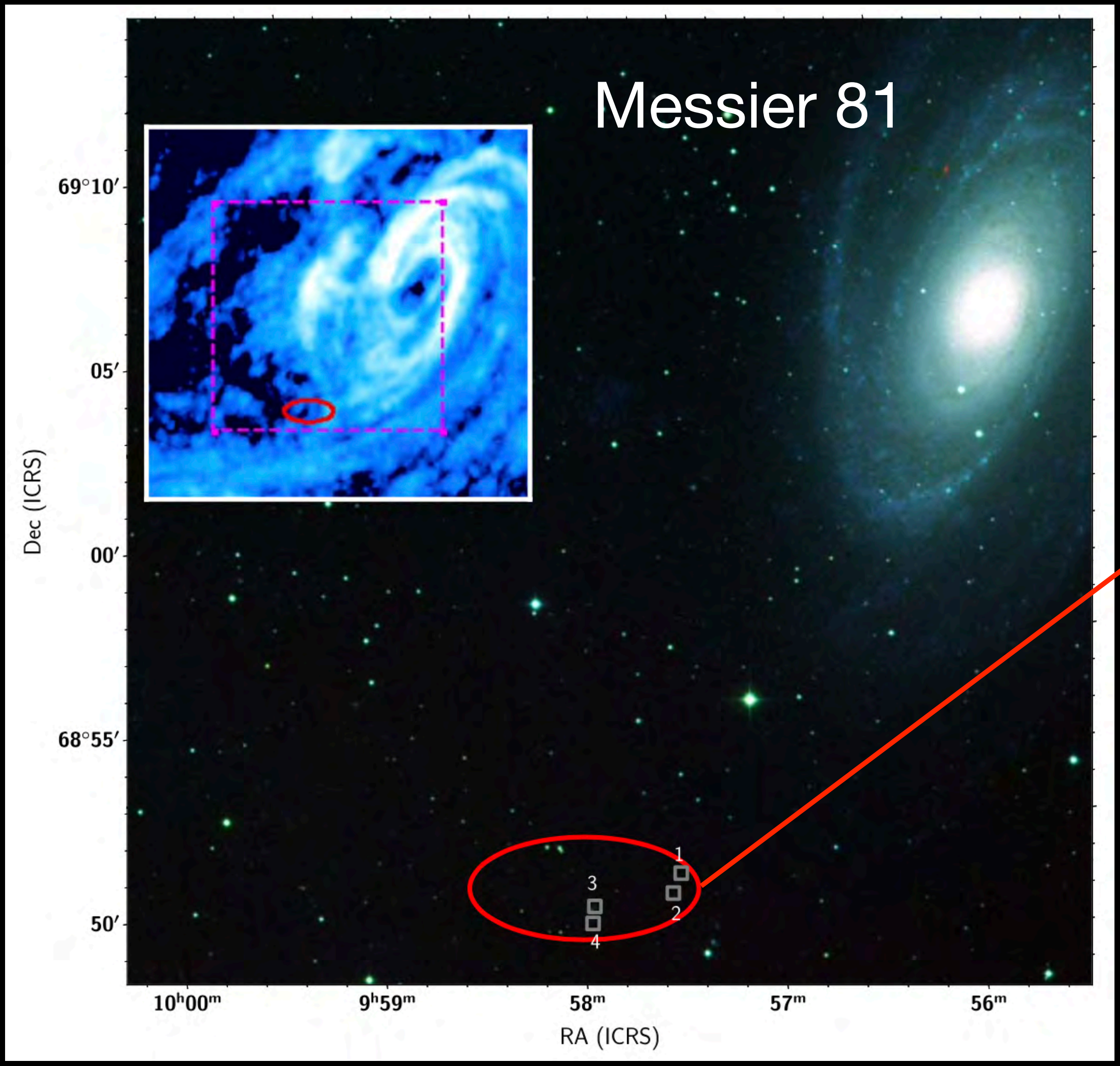
But not necessarily young magnetars

Globular cluster

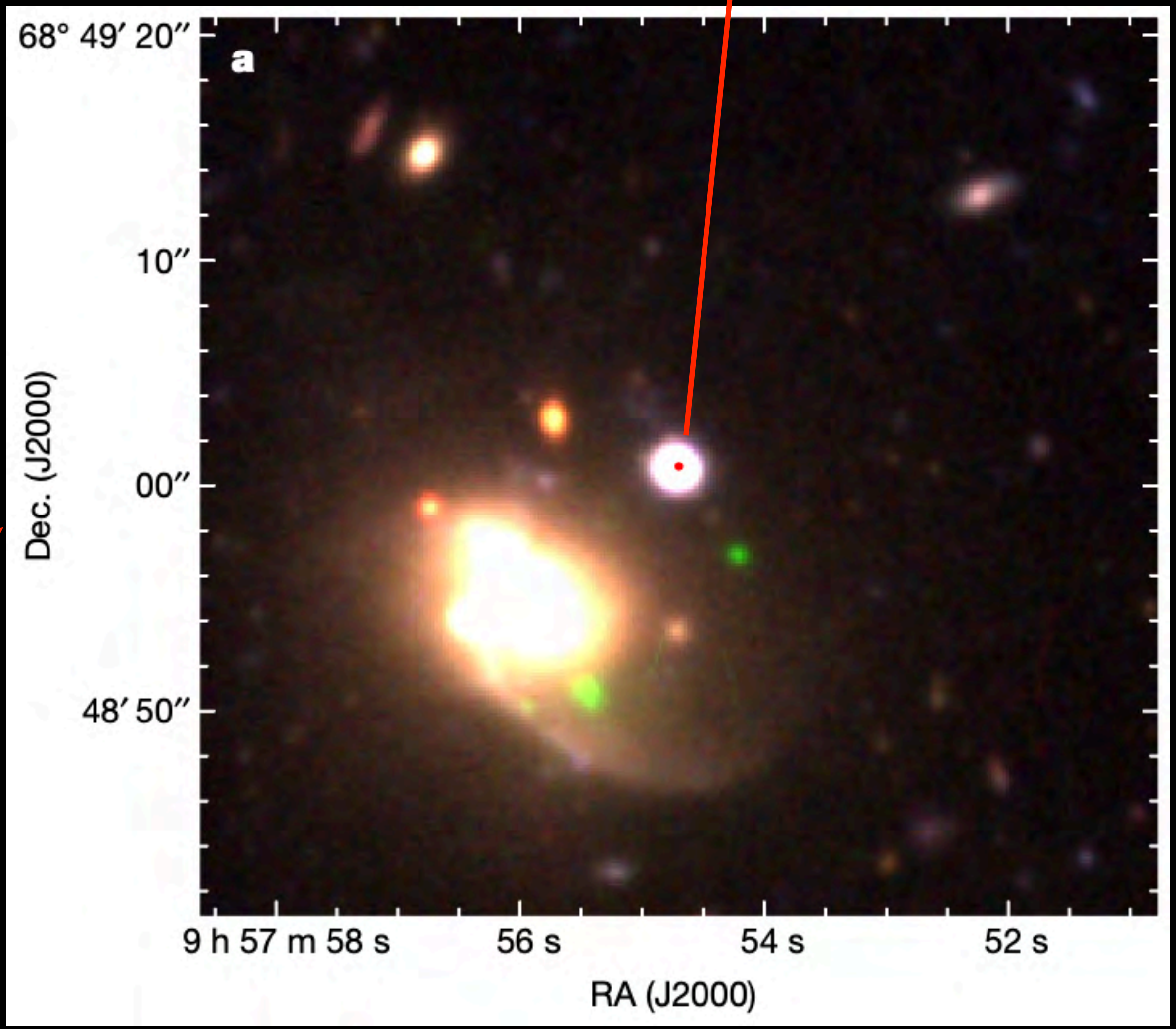
Mass ~ 10^6 M_{Sun}

Messier 13

Host of FRB 20200120E



Bhardwaj et al. 2021



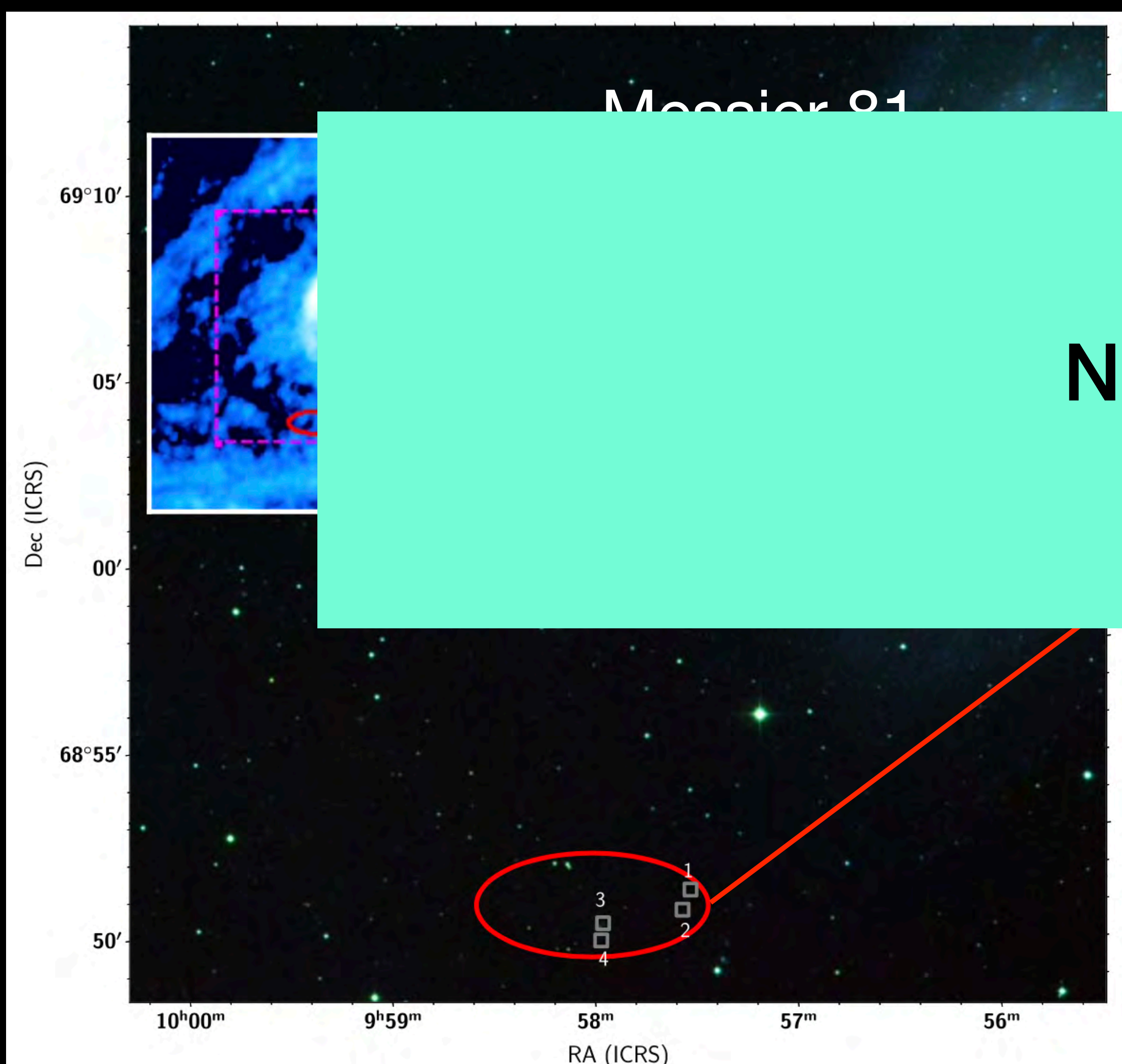
Kirsten et al. 2022

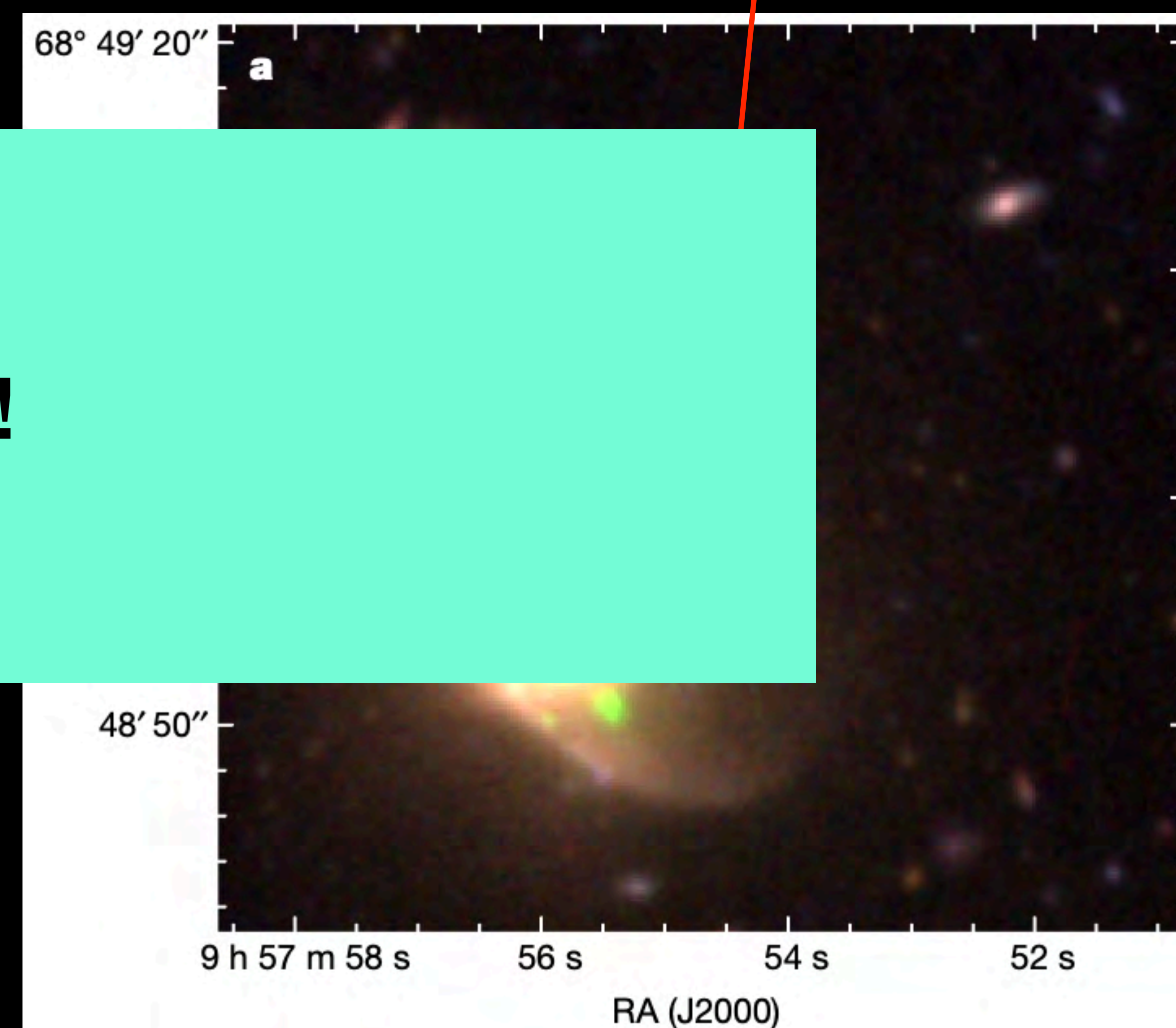
Globular cluster

Mass ~ 10^6 M_{Sun}

Messier 13

Host of FRB 20200120E





Nein!

Kirsten et al. 2022

Bhardwaj et al. 2021

What do we know?	What do we not know?
Extragalactic	The maximum source distance
More energetic than short duration, Galactic radio transients	Maximum possible energy
Some sources have been observed to repeat	Are “one-offs” and repeaters fundamentally different?
Galactic magnetars can produce FRB-like bursts	Are all repeaters magnetars?
Diverse range of galaxy properties	*Are galaxy properties informative?*

Things we kind of know

- Repeaters (all FRBs?) are probably neutron stars
  - In what way are the different from Galactic NSs?
  - Are there different formation channels?
- Balance of evidence is in favor of no fundamental distinction between repeaters and non-repeaters
- FRBs are probes of the intervening interstellar and intergalactic media, Universe expansion, gravitational lensing

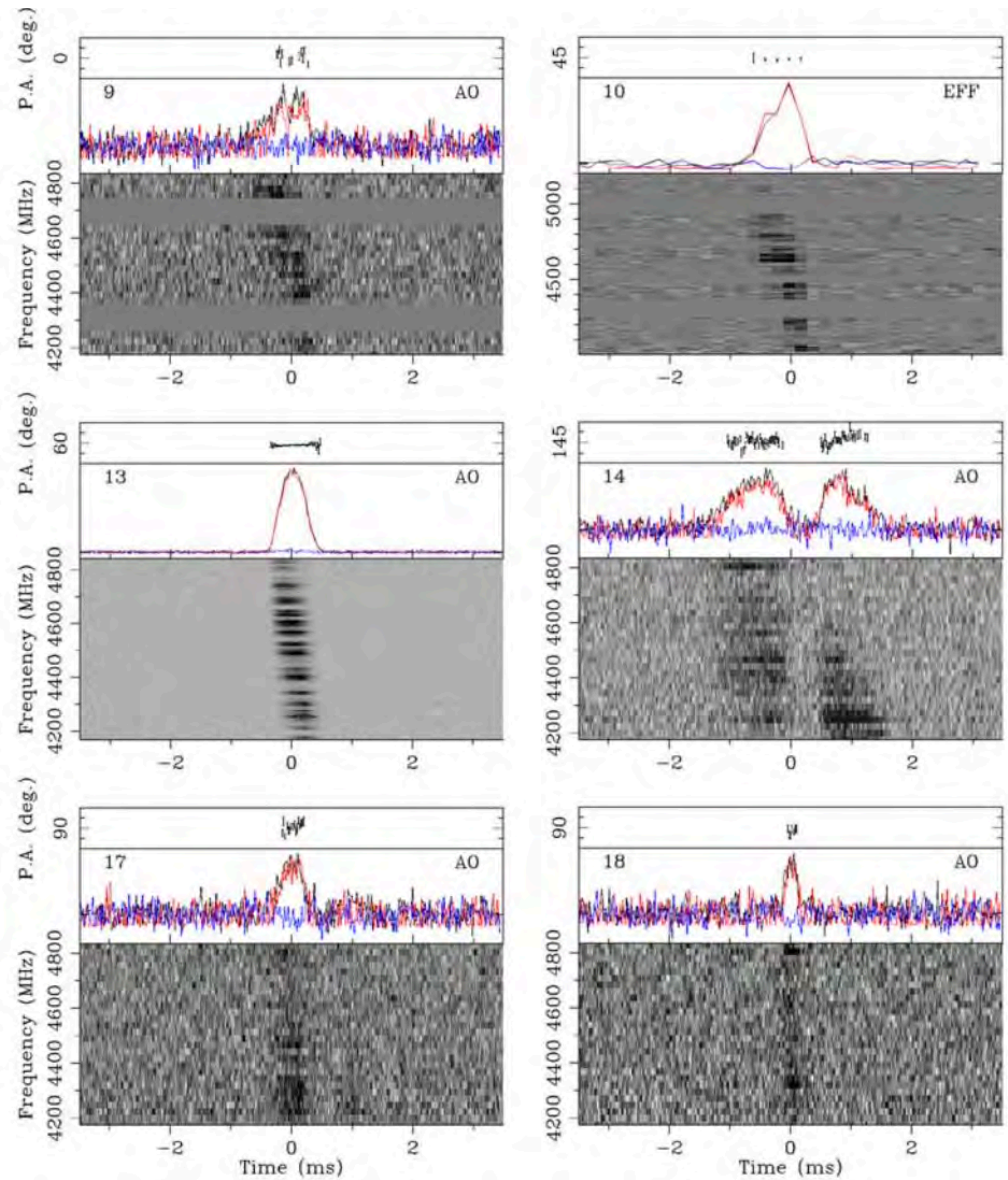
Thank you for your attention

Questions?

Polarization

- Geometry of the magnetic field in the emission region
- “Back in the day” repeaters mostly had…
  - Nearly 100% linear polarization
  - Flat polarization position angle swings
- FRB 20121102A
  FRB 20190816B
  FRB 20200120E
- (Be wary of the first few sources)

FRB 20121102A

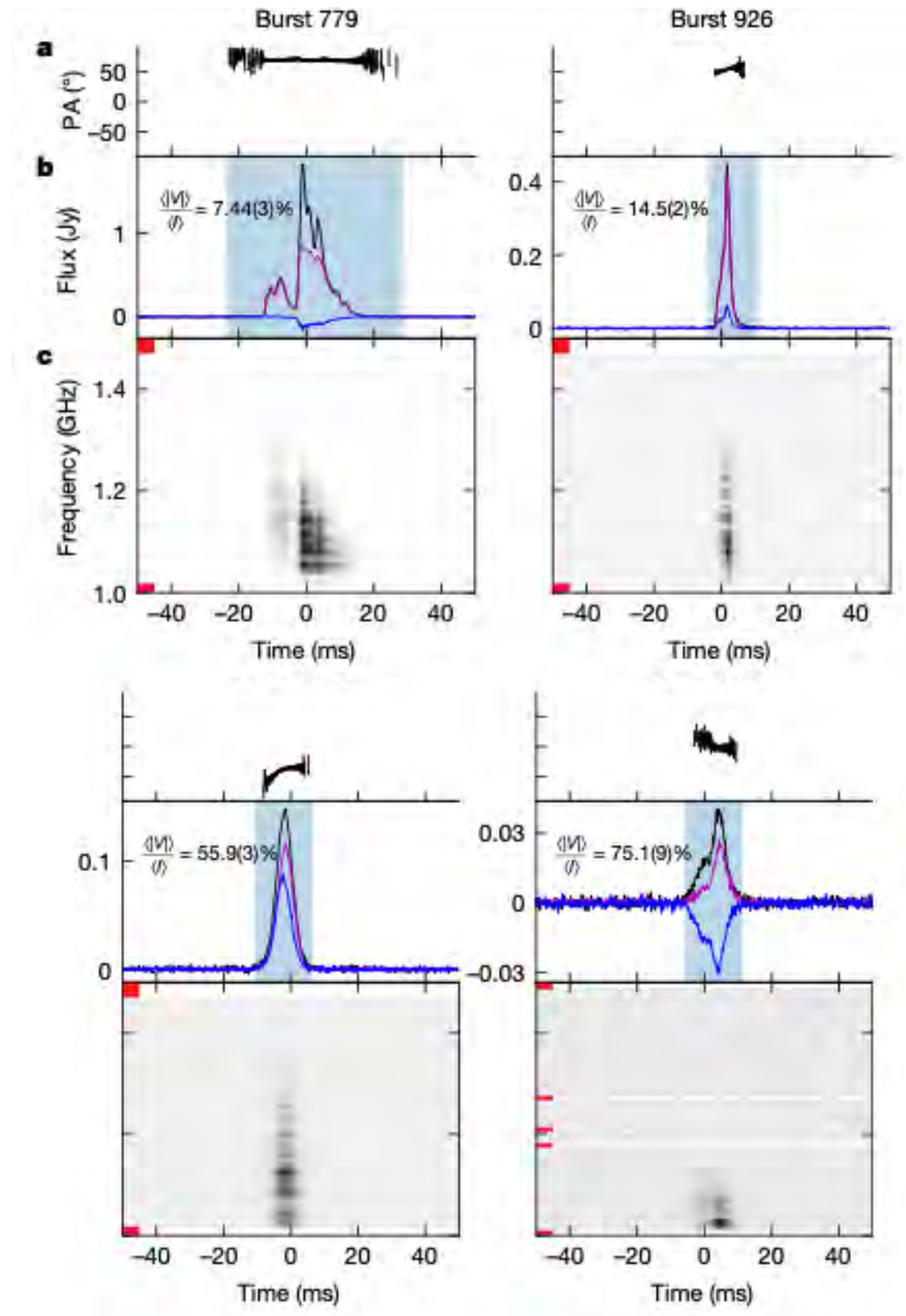


Hilmarsson et al. 2021

Polarization

- Polarization diversity very "pulsar-like" (obs. long enough and you'll see everything)
  - Variable linear fraction
  - Significant and varying circular
  - Pol. position angle swings
- Propagation effects important in some cases
- Stormy repeaters:
  - FRB 20201124A
    FRB 20220912A
- Calm repeaters:
  - See Mckinven et al. 2023, ApJ

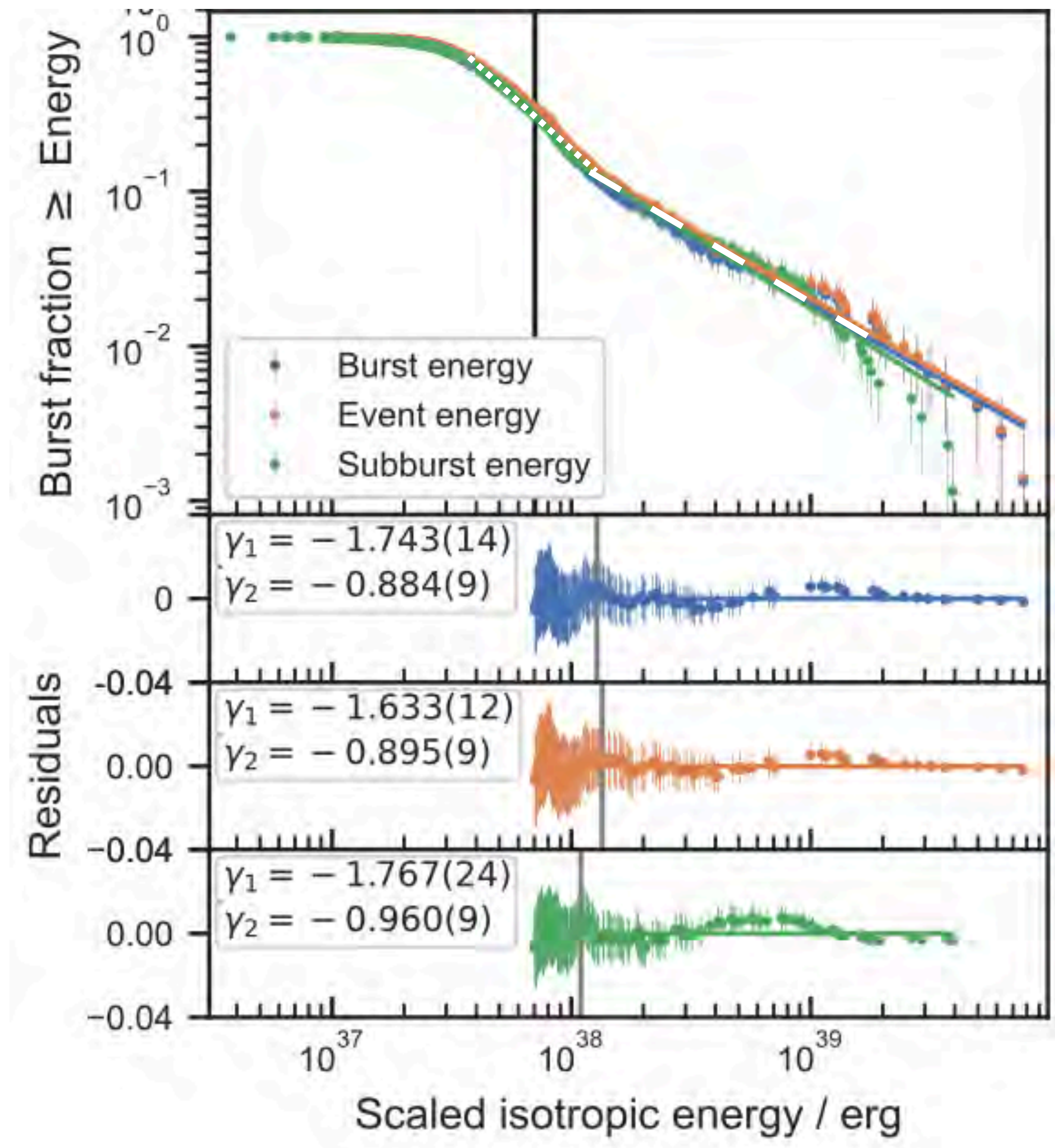
FRB 20201124A



Xu et al. 2022, Nature, 609

Energy distributions

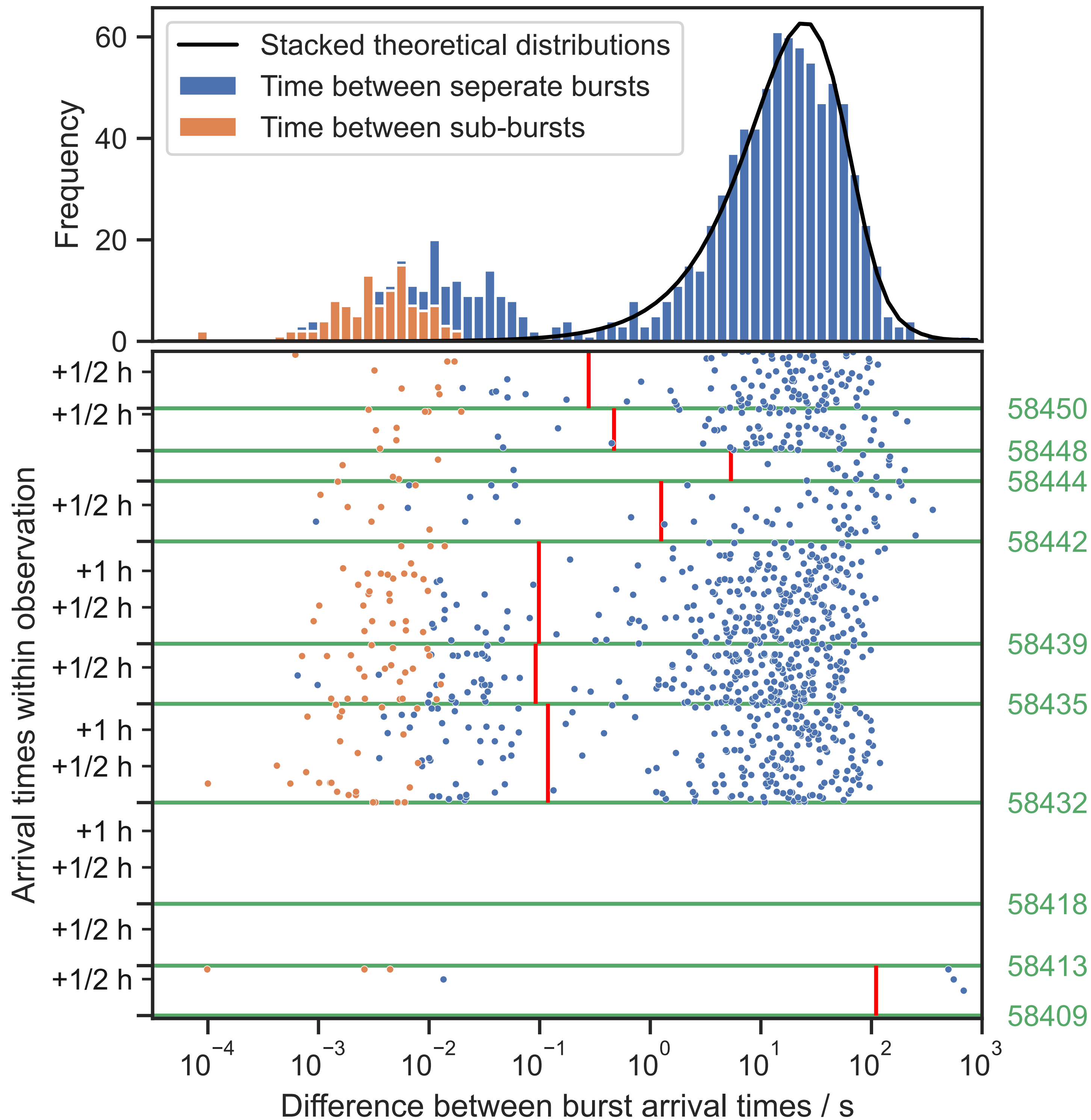
- Goal:
  - Compare to possible Galactic analogs (magnetars, GPs, etc)
- Generally modeled with power laws
- Some distributions “multi-modal”, i.e. require multiple power laws fits



Jahns et al., 2023, MNRAS, 519

Wait times

- Time between consecutive bursts (within a continuous observation)
- Two time scales
  - Long time scale: Poisson rate within the observation(s)
  - Short time scale (1-10 ms): characteristic time of the emission mechanism
- Universally seen in stormy repeaters

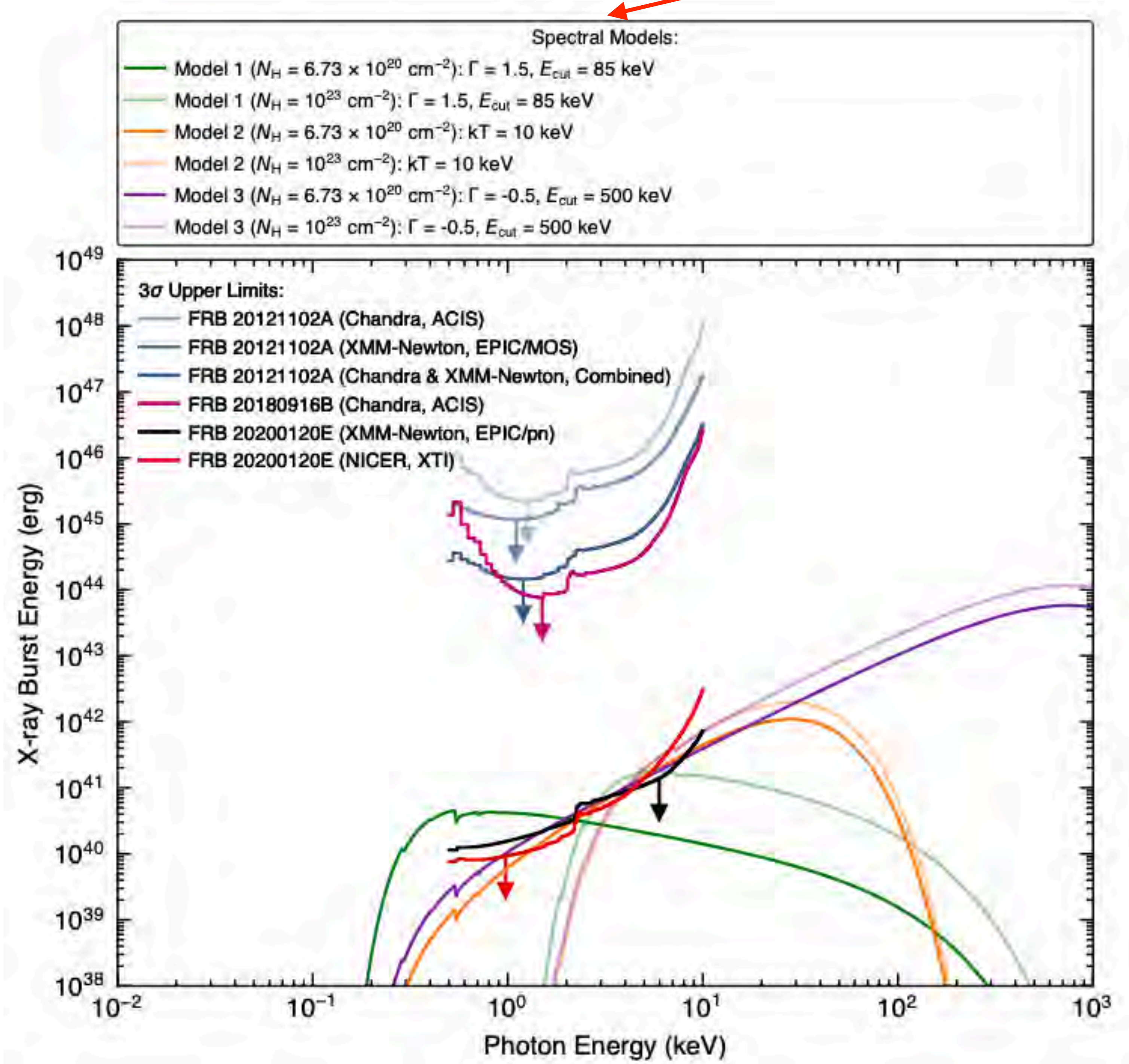


Jahns et al., 2023, MNRAS, 519

Non-radio counterparts

- Persistent emission
  - Two FRBs associated "persistent radio sources" (see Casey Law's talk)
- "Bursty" non-radio emission
  - Searches often focus on times of radio burst detections
  - Other than the FRB-like event associated with SGR 1935+2154, no counterpart found

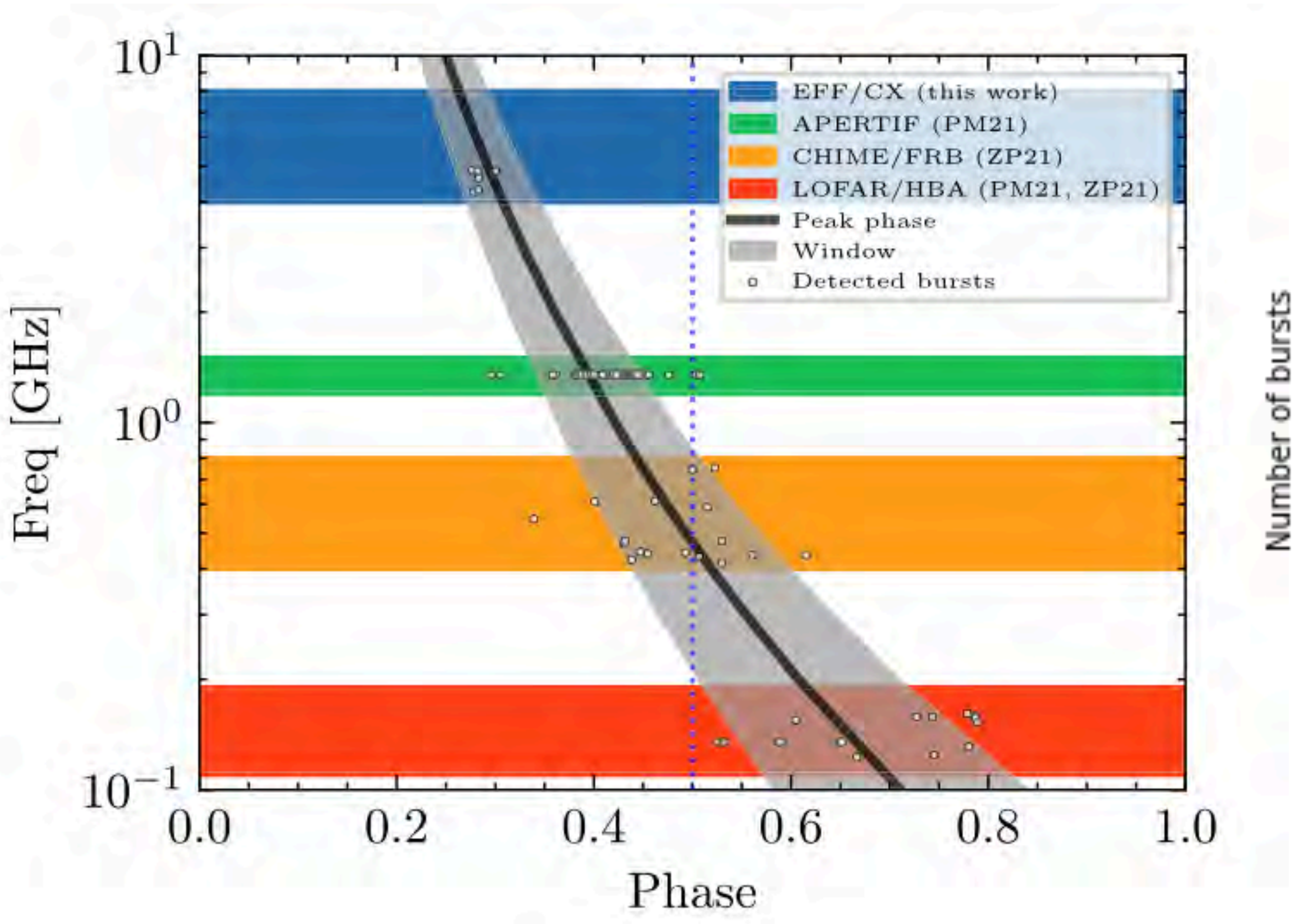
Fiducial spectral models for X-ray emission



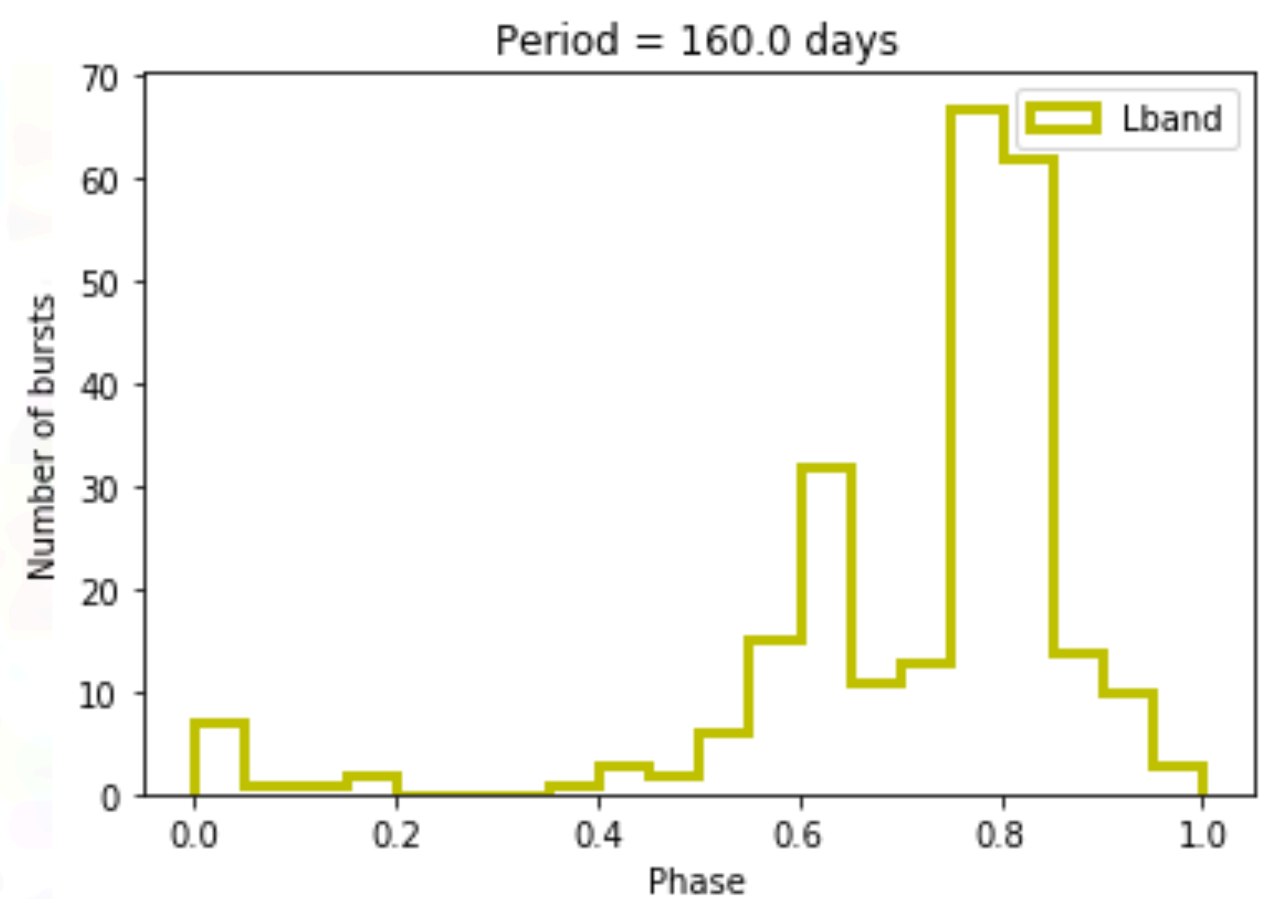
Pearlman et al., 2023, Nature Astronomy, submitted

Activity periods

- FRB 20190816B
  - 16-day period
  - Chromatic window



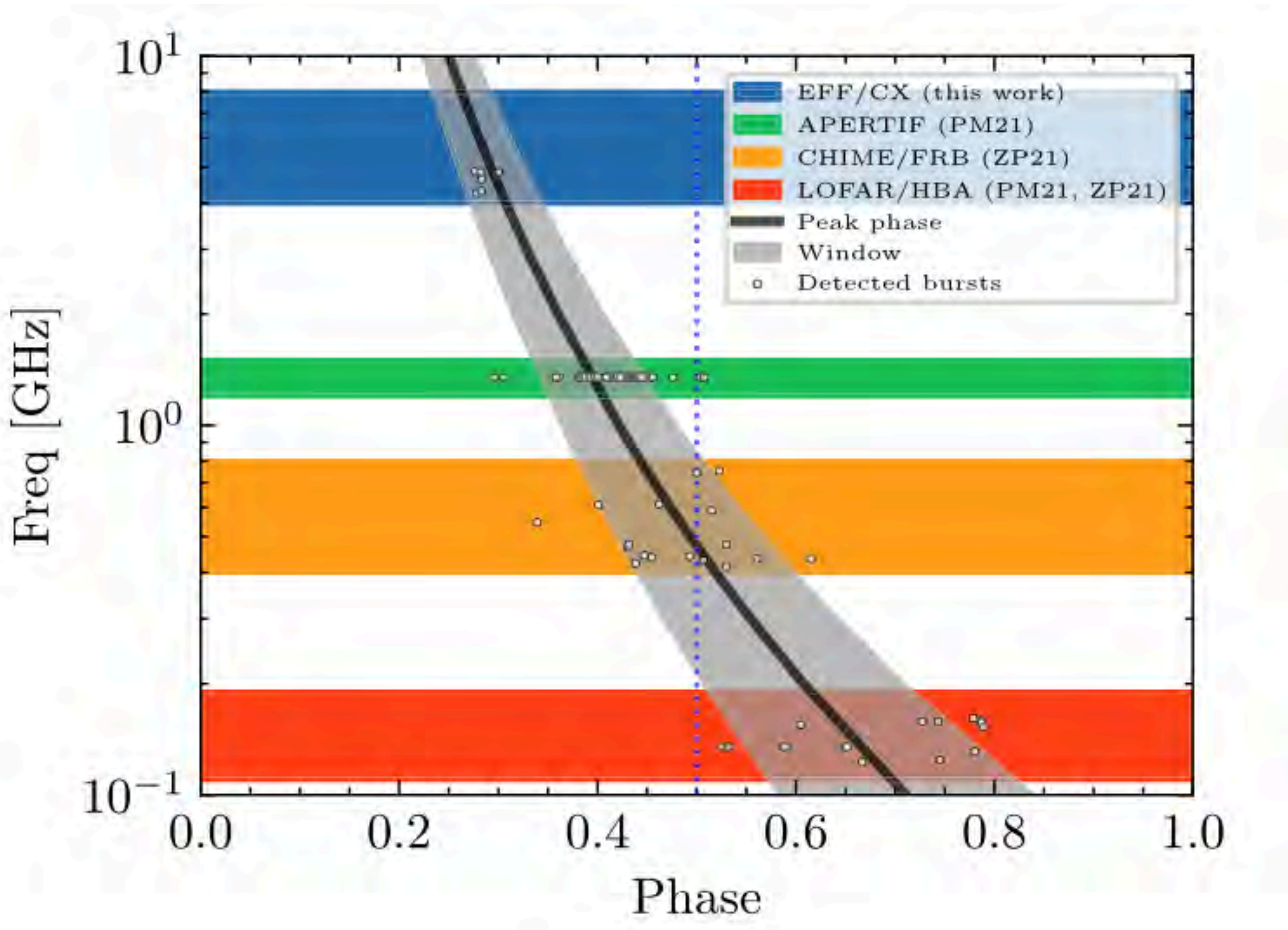
- FRB 20121102A
  - ~160-day period



Bethapudi et al., 2023, MNRAS, 524

Activity periods

- FRB 20190816B
  - 16-day period
  - Chromatic window



Bethapudi et al., 2023, MNRAS, 524

- Particularly “useful” observation
- Models
  - Slow rotating NS
  - Precessing NS
  - Binary system + wind