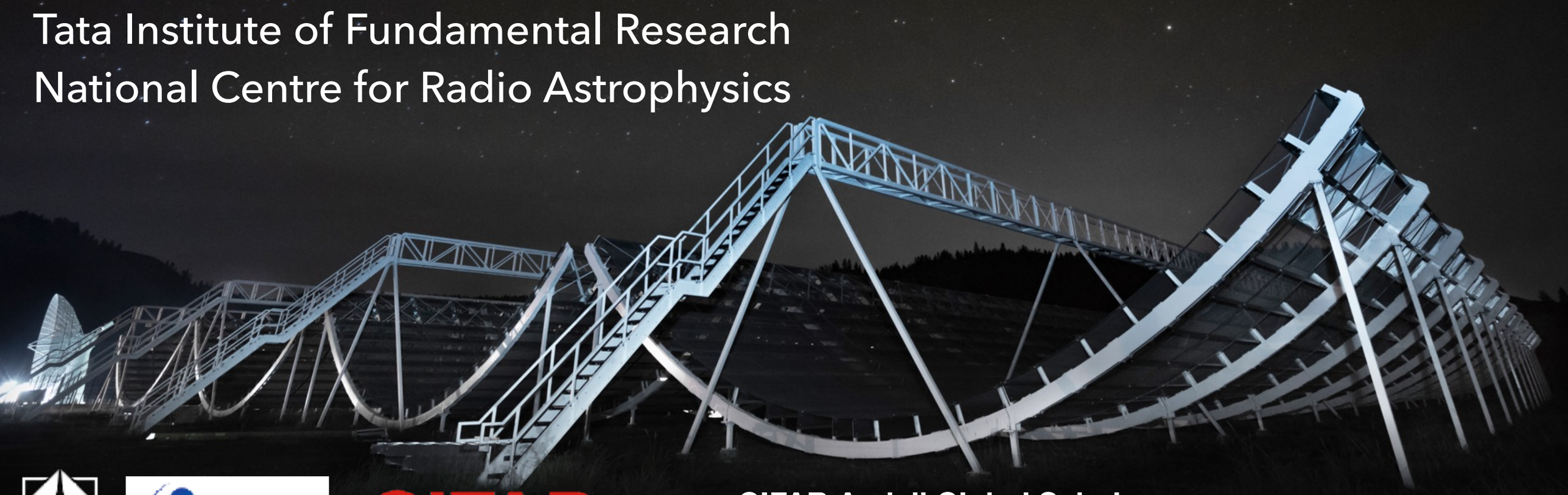
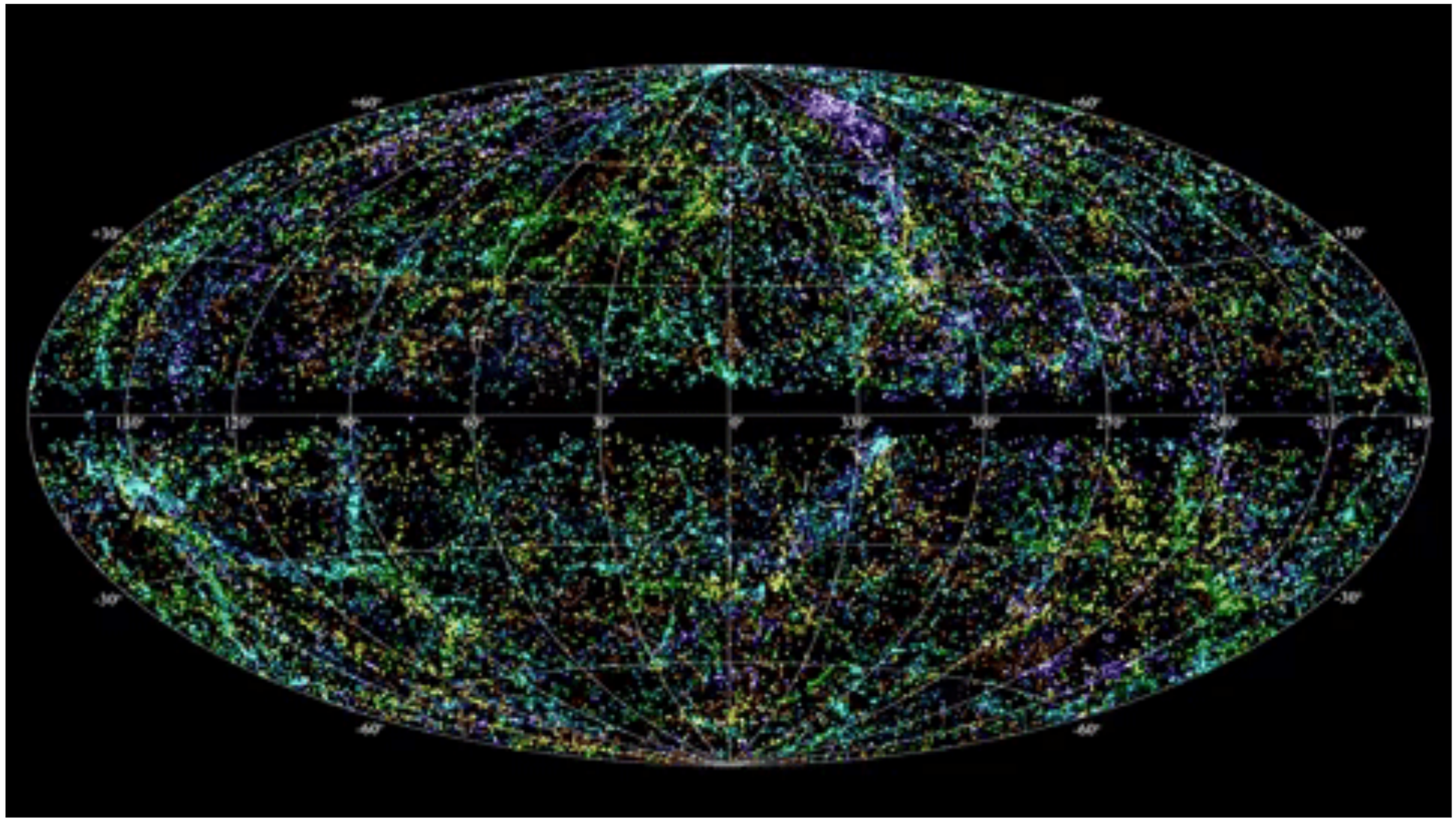
FAST RADIO BURSTS & MULTIWAVELENGTH COUNTERPARTS

Dr. Shriharsh Tendulkar
Tata Institute of Fundamental Research
National Centre for Radio Astrophysics



CIFAR Azrieli Global Scholar,
Gravity & the Extreme Universe Program

ASTROPHYSICAL MYSTERY!



Short + Bright Radio Emission (few repeat!)

$[525 \pm 30\ (\text{stat.})\ ^{+132}_{-141}\ (\text{sys.})]\ \text{sky}^{-1}\ \text{day}^{-1}$

(>5 Jy-ms @ 600 MHz, CHIME/FRB Collaboration+ 2021)

ASTROPHYSICAL MYSTERY!

- Dispersed: arrival time is freq dependent

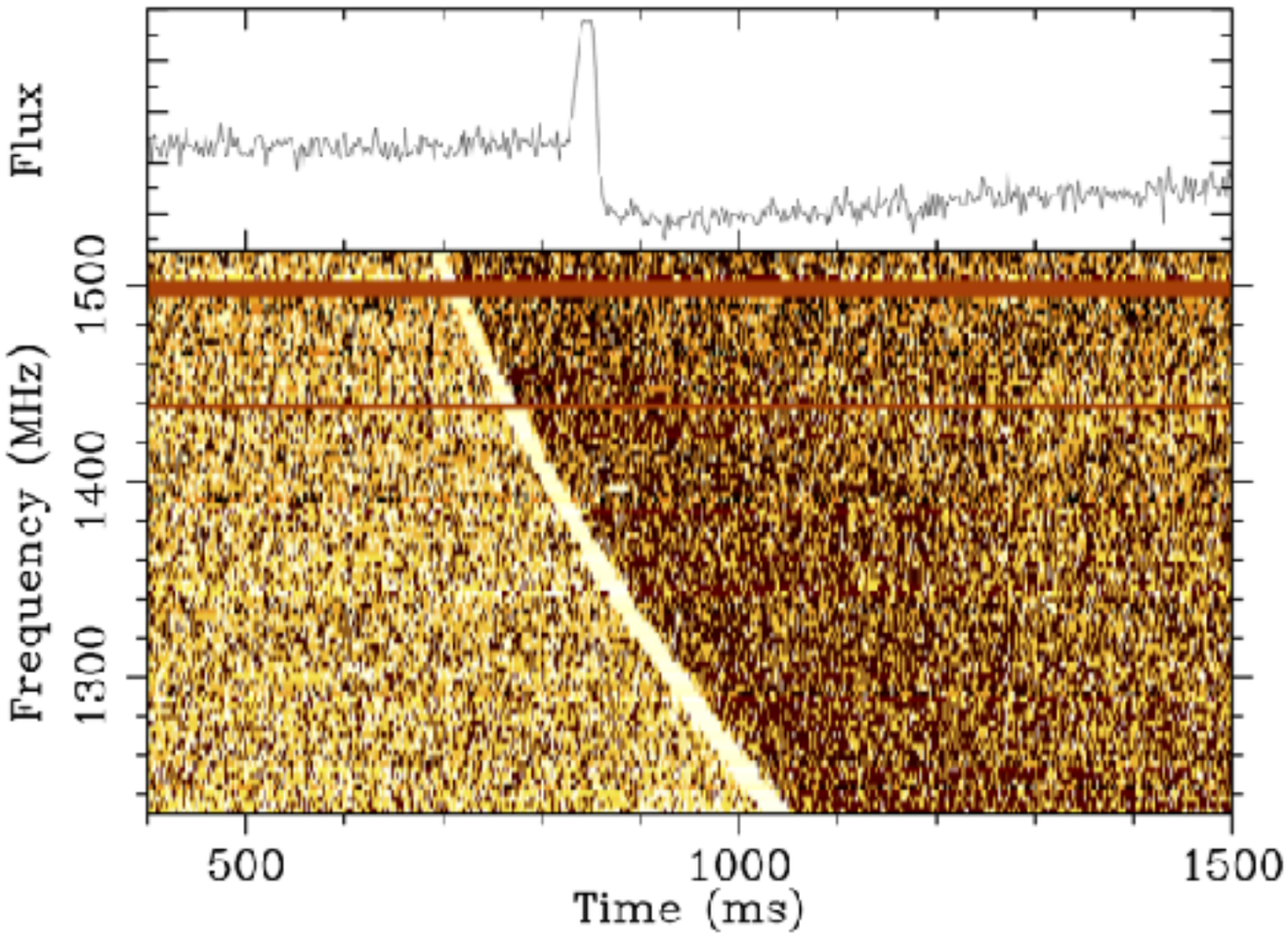
  $t_{arr} \propto DM\ \upsilon^{-2}$

- Dispersion measure

  $DM = \int n_e dl$

- DM not apriori known
  - Computationally expensive search
- Proxy for distance

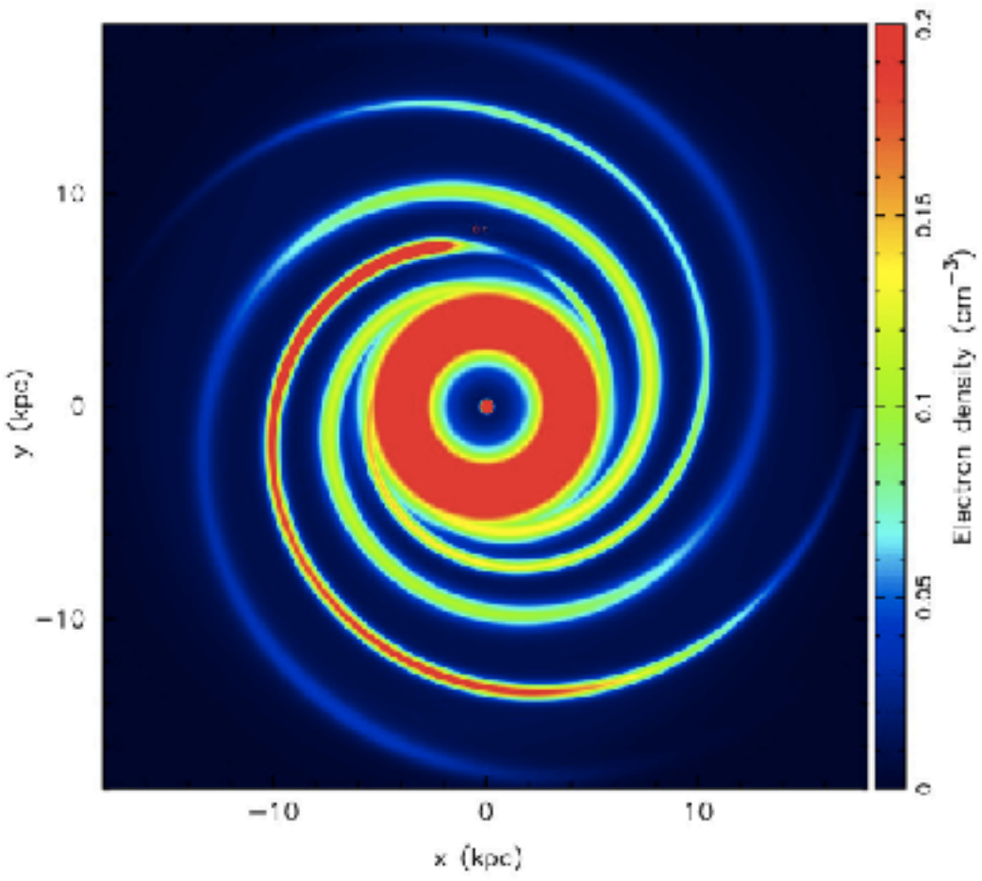
  (after subtracting MW DM)



Lorimer et. al. 2007
(Fig from Petroff et al 2019)

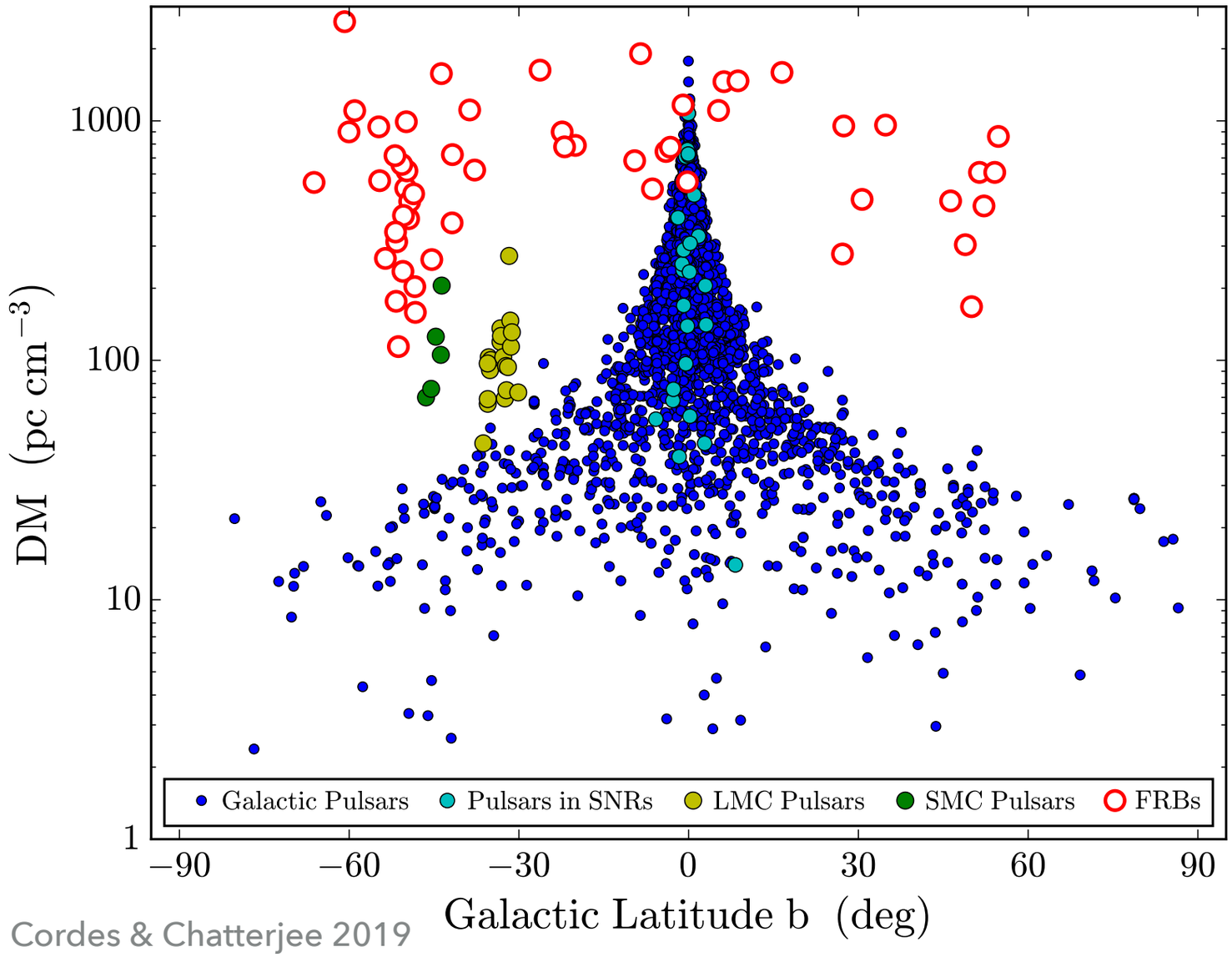
EXTRAGALACTIC LOCATIONS

Electron Distribution in the Milky Way



Yao et al 2017

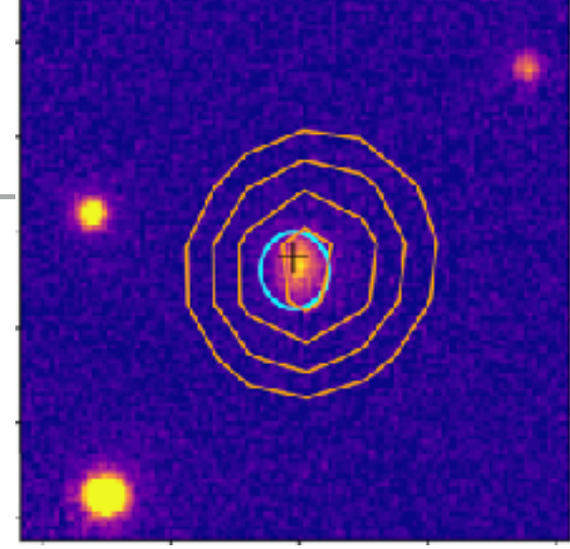
Halpha, continuum radio observations rule out local DM contributions



Cordes & Chatterjee 2019

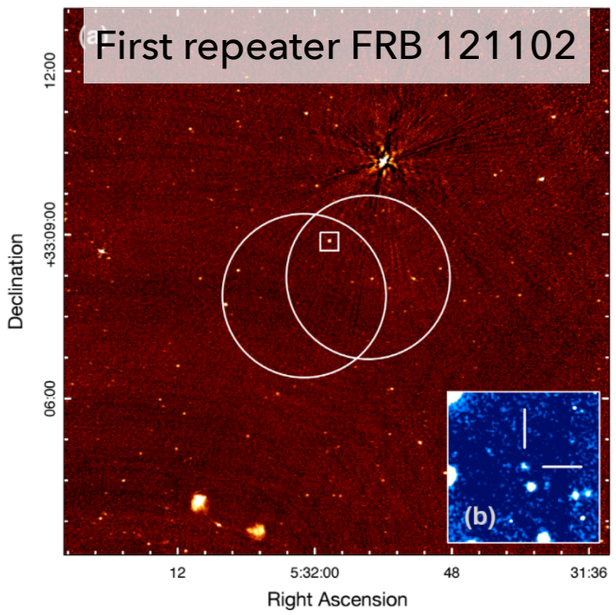
EXTRAGALACTIC LOCATIONS

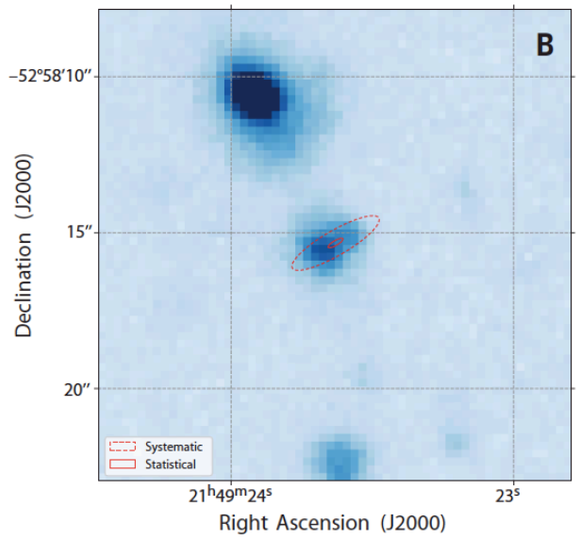
FRB 20201124A
z = 0.098
(Multiple groups)
Fig from Ravi et al 2021



Chatterjee .. SPT et al 2017
Tendulkar et al 2017

z = 0.197



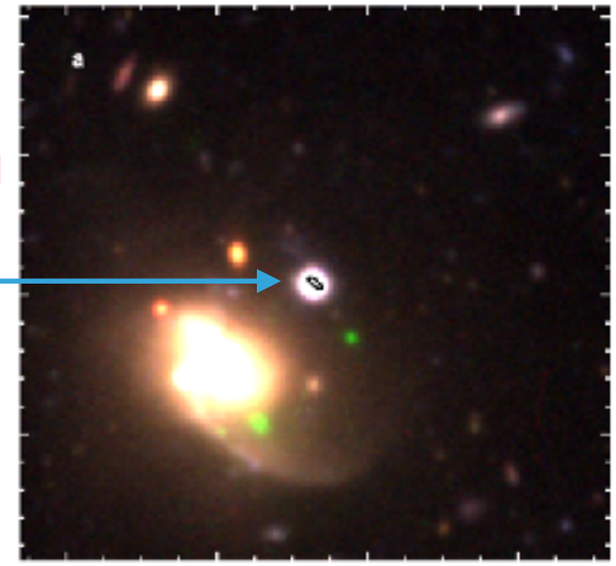


Prochaska et al. 2019

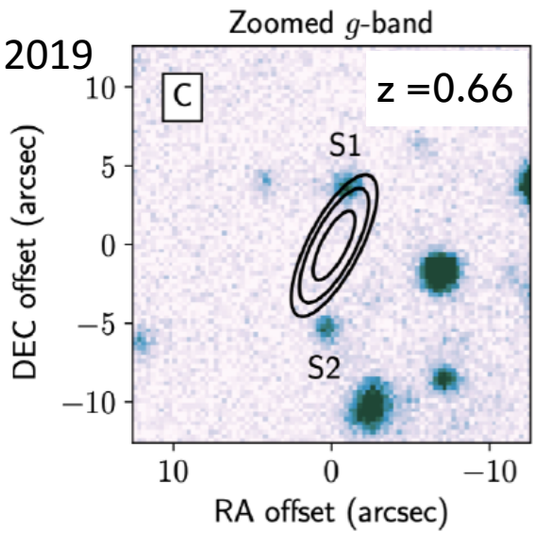
z =0.47

Repeater in a GC in M81

FRB 20200120E
d = 3.6 Mpc
Kirsten .. SPT et al 2022

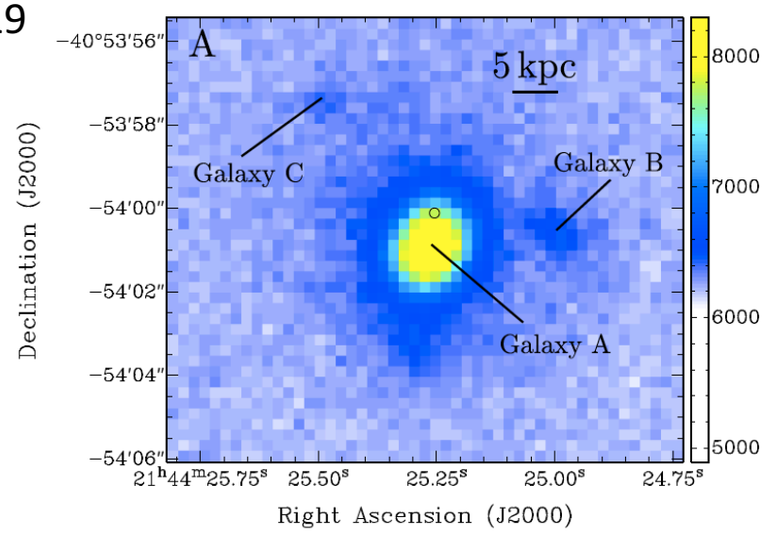


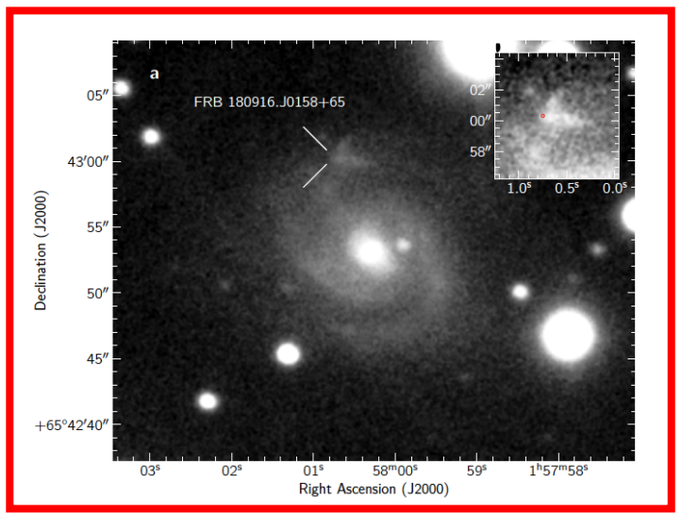
Ravi et al. 2019



Bannister et al. 2019

z = 0.32



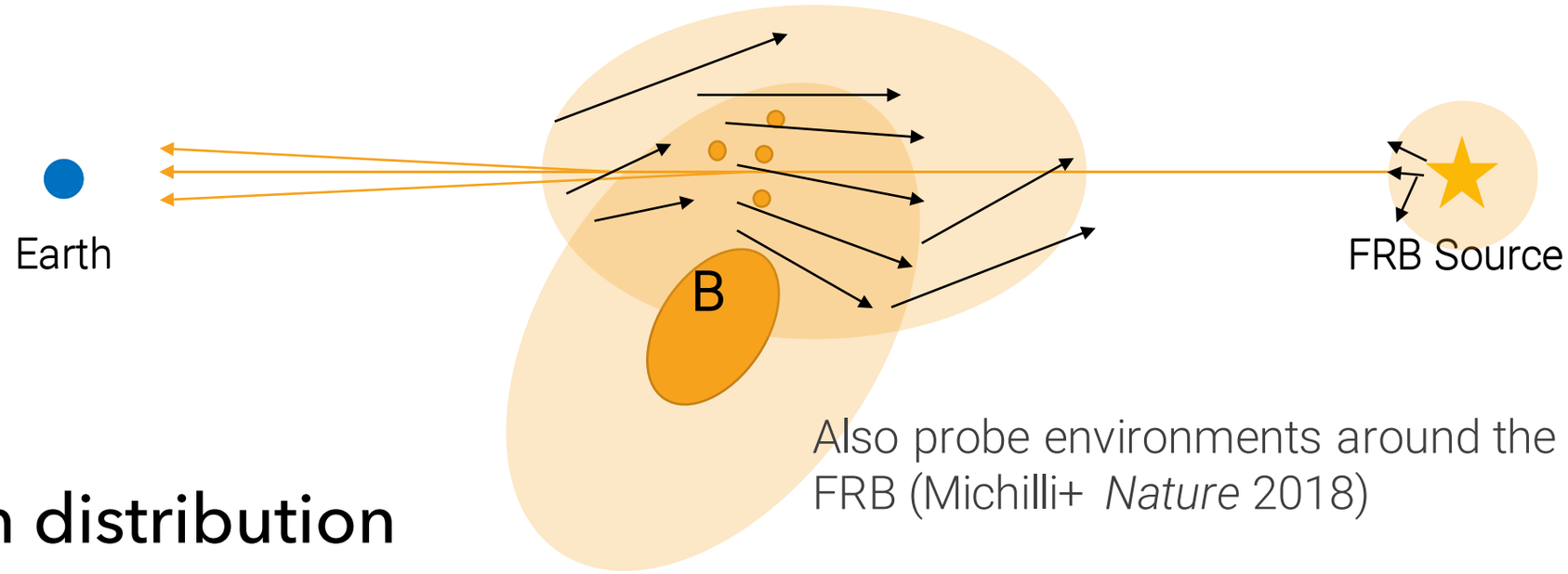


Marcote .. SPT et al 2020

z =0.03 (150 Mpc)

COSMOLOGICAL PROBES

- Polarized radio waves
- Interacts with every electron and B-field



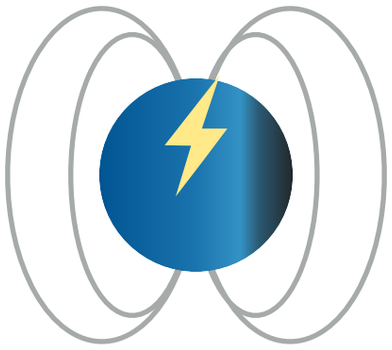
Also probe environments around the FRB (Michilli+ *Nature* 2018)

- Turbulence, baryon distribution
  - Hell reionization at z~3
- Magnetic field distributions
- Gravitational lensing

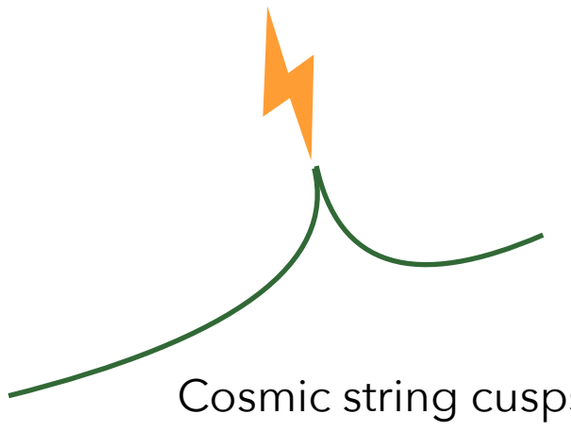
WHAT ARE THEY?

- ~10^{10-12} times brighter than Crab giant pulses
- Magnetar? NS Binary? More exotic?

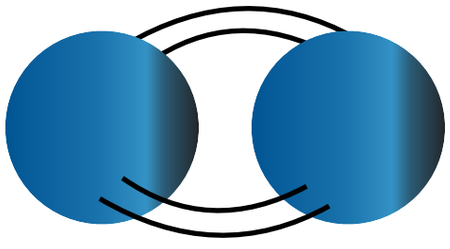
http://frbtheorycat.org Platts .. SPT et al 2019



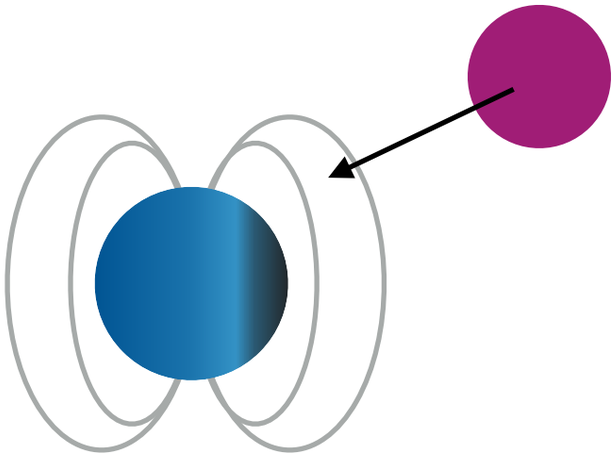
Magnetic field reconnection/ star quake



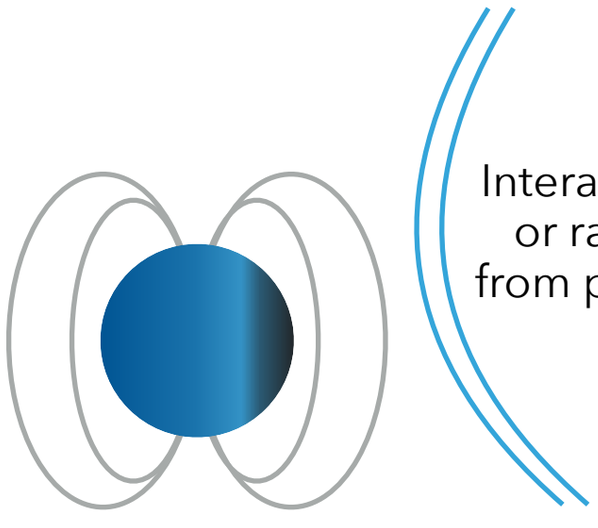
Cosmic string cusps



Merger/Coalescence



Interaction with asteroid/ axion nugget

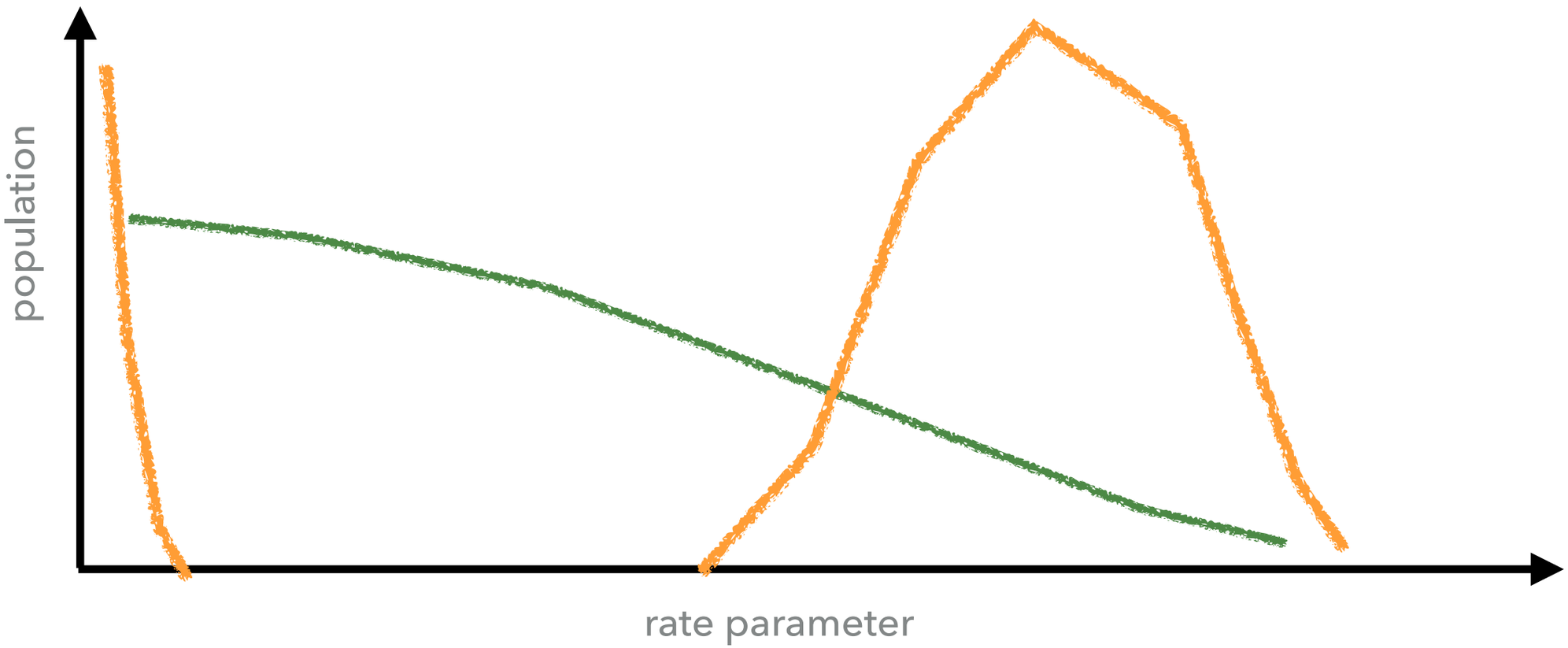


Interaction with winds or radiative shocks from pulsars, OB stars, AGNe

REPEATERS AND NON-REPEATERS

- Some FRBs repeat – same position, almost the same DM
  Most FRBs haven't been seen to repeat
  Despite ~10^1 – 10^3 hrs of obs

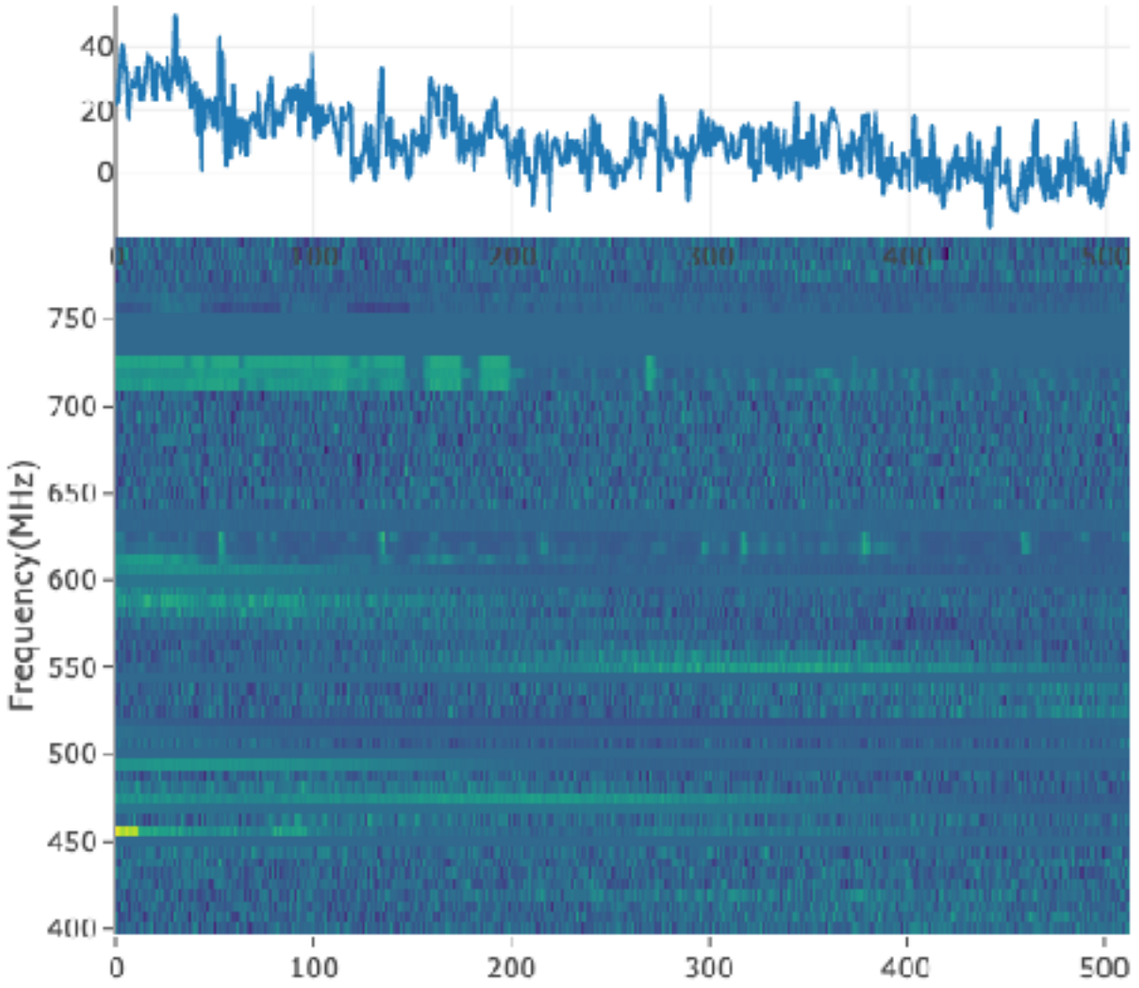
- Are they different populations? or different ends of the same population?

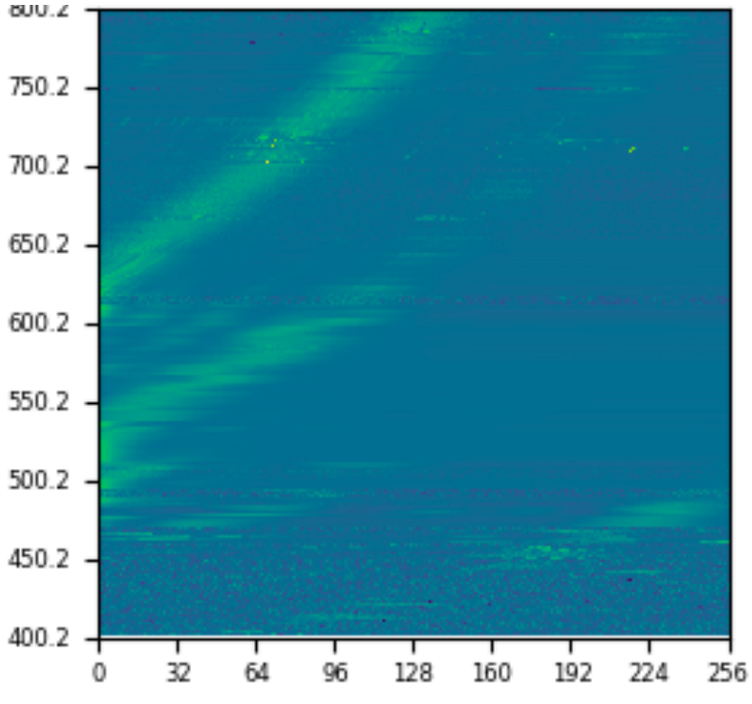


FINDING FRBS

CHALLENGES IN FINDING FRBS

- Millisecond timescales smeared out over 10–20 seconds!
  - Signal dilution by a factor of ~10^4!
- Dedispersion, pulse width, … are not apriori known
  - Large search space
- Radio frequency interference (RFI)
  - Supreme enemy of all radio astronomers



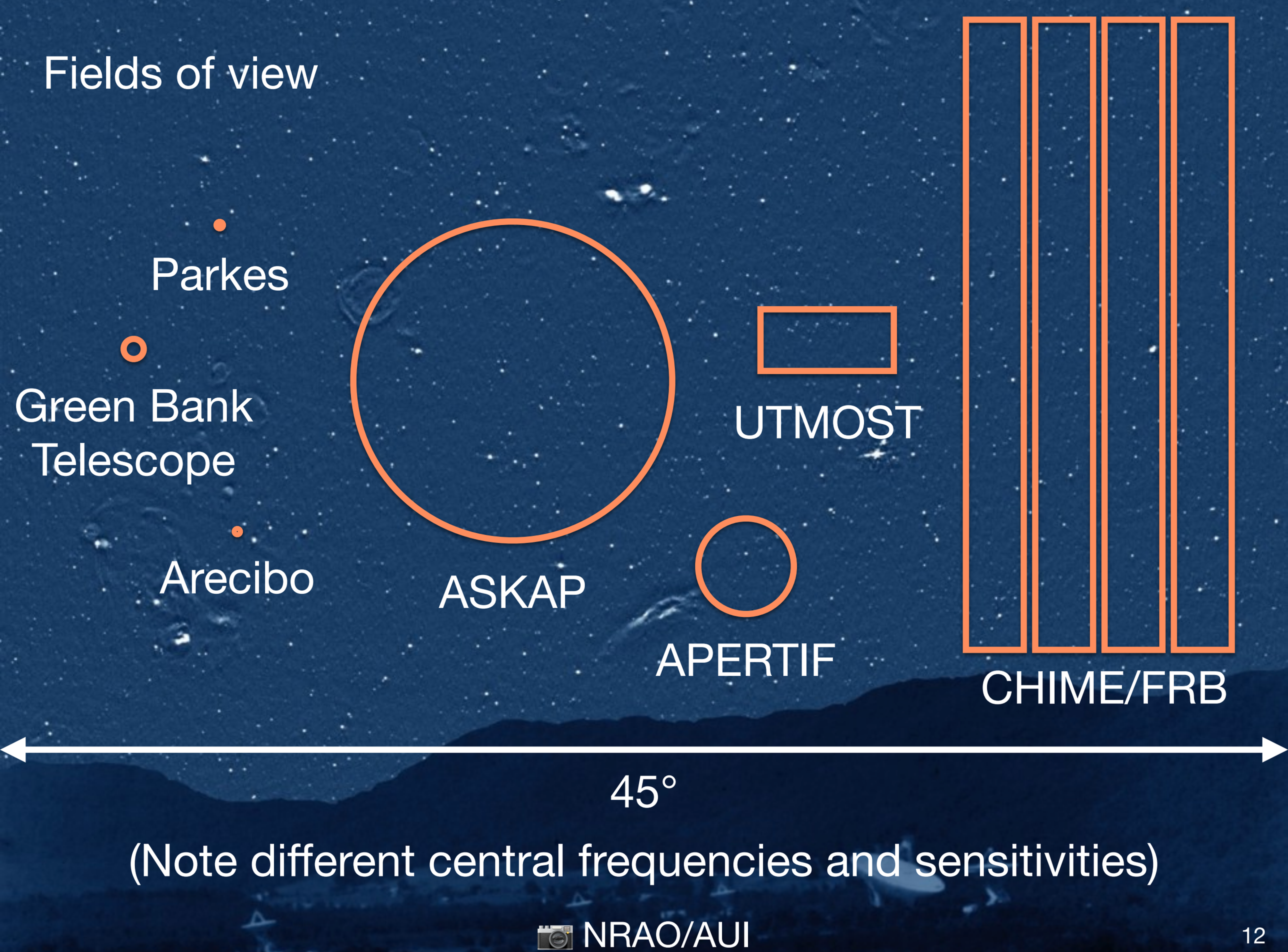


CHIME PARAMETERS

- SKA Pathfinder
- 4 Cylinders - 20m x 100m each
  (like ORT, but flat and stationary)
- 1024 dual-polarization feeds

Bandpass	400 MHz	800 MHz
21 cm Redshift	2.5	0.8
Beam Size	0.52°	0.26°
E-W FoV	2.5°	1.3°
N-S FoV	~100°	
λ	0.75m	37.5cm

Fields of view



(Note different central frequencies and sensitivities)

📷 NRAO/AUI

L0

1 Dish + 1D Interferometry on 256x4 feeds

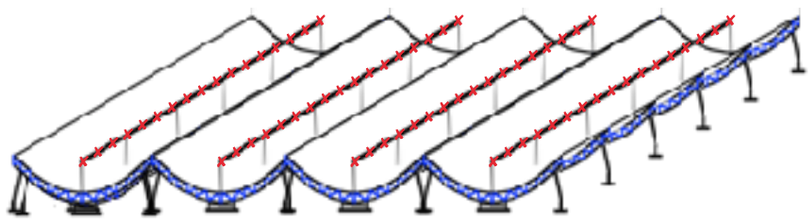
FFT Beam-forming (Tegmark & Zaldarriaga, 2008, 2010)

Hybrid Beam-forming (Cherry Ng et al. 2017, 1702.01748)

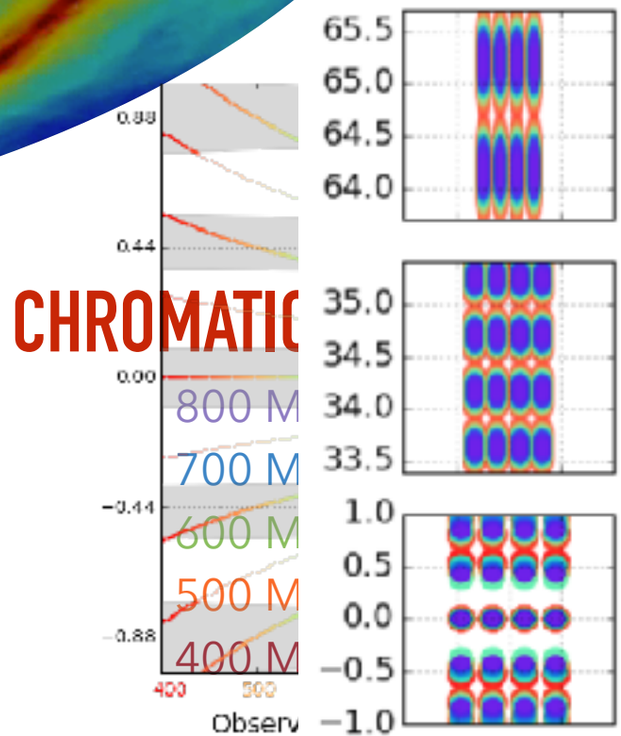
Primary Beam of Single Feed

Hybrid FFT[N-S] for 4 Analogue beam-formed beams [E-W]

Sky Coverage ~250 sq. Degrees



@Cherry Ng



Realtime Backends

Simultaneous observations

CHIME/Cosmology

- Full N^2 visibility matrix
- 10s cadence
- 210 TB/day
- Real time flagging & gain calibration
- Data compression through redundant baselines (1 TB/day)

CHIME/Pulsar

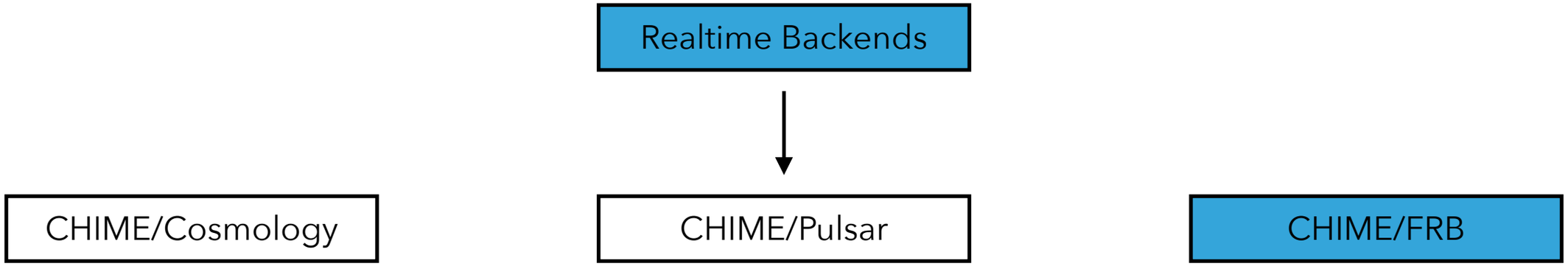
- 10 tracking beams
- Track galactic pulsars daily
- 2.56 μs cadence, 1024 freq. channels, 2 polarizations
- 10 x 6.4 Gbps
- Data compression though folding – 672 GB/day

CHIME/FRB

- 1024 FFT-formed stationary intensity beams
- 0.983 ms cadence
- 16384x 24.4 kHz channels
- 130 Gb/s (intensity)
  800 GB/s (baseband)
- 1.5 PB/day

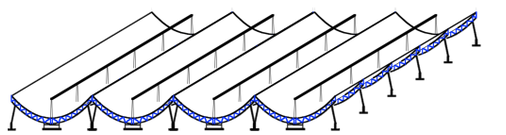
NOTE THE ENORMOUS DATA VOLUMES!

Also new backends coming up – slow pulsar search, slow transient search



L0	FFT Beamforming + Upchannelization
L1	RFI Excision + Incoherent Dedispersion
L2-L3	MultiBeam Analysis + Science Actions
L4	Databases + Offline Processing

WE WILL RETURN TO RFI EXCISION, DEDISPERSION IN DETAIL



Reflector

Analog Receiver Chain

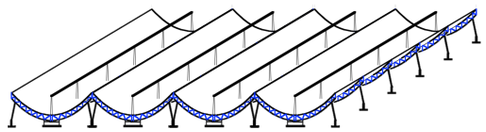
FPGA Channelizer

GPU Correlator

Realtime Backends

Science

Reflector design led by CHIME Team @ UBC



Reflector

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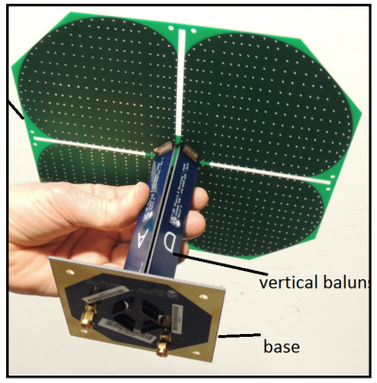
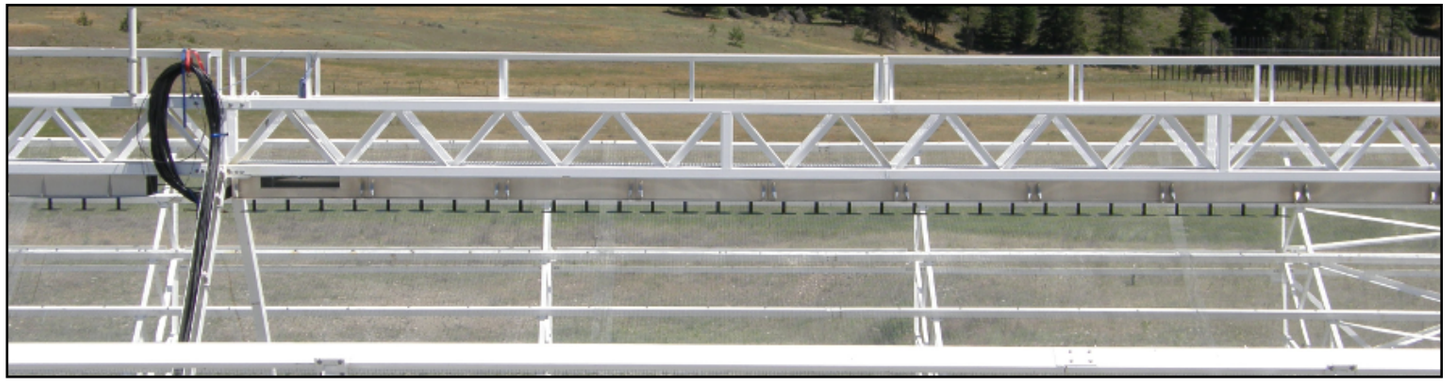
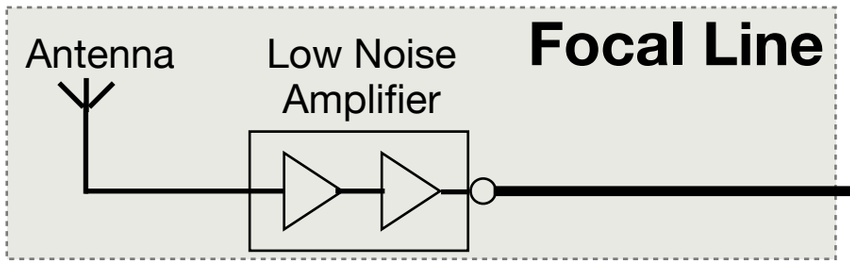
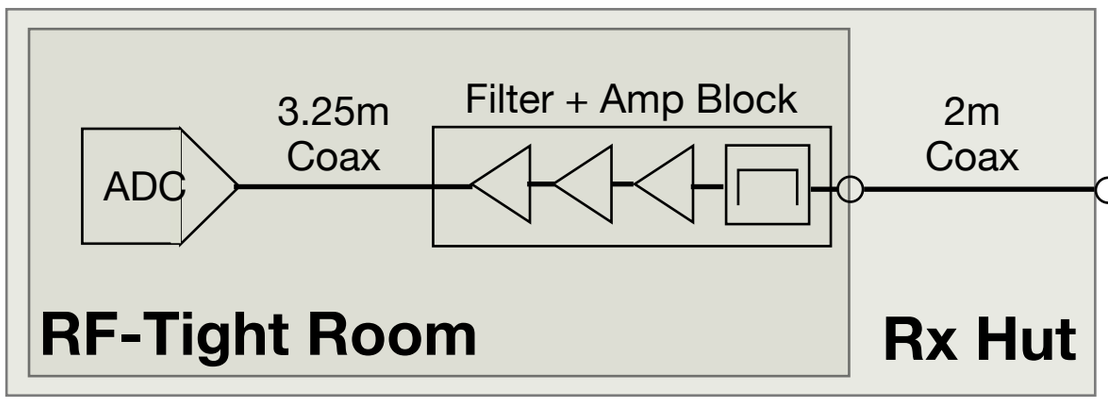
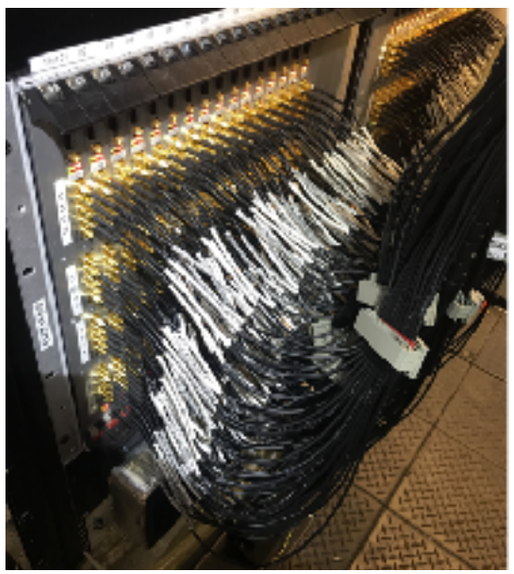
Science

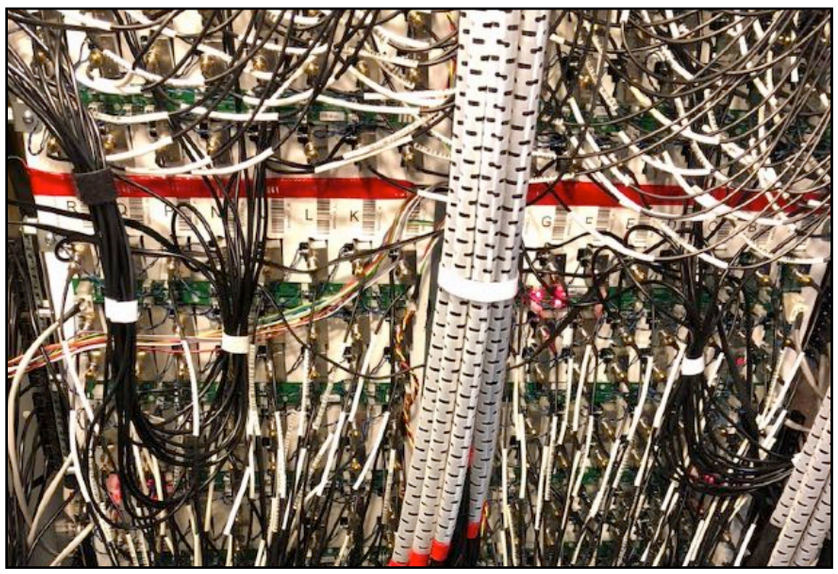


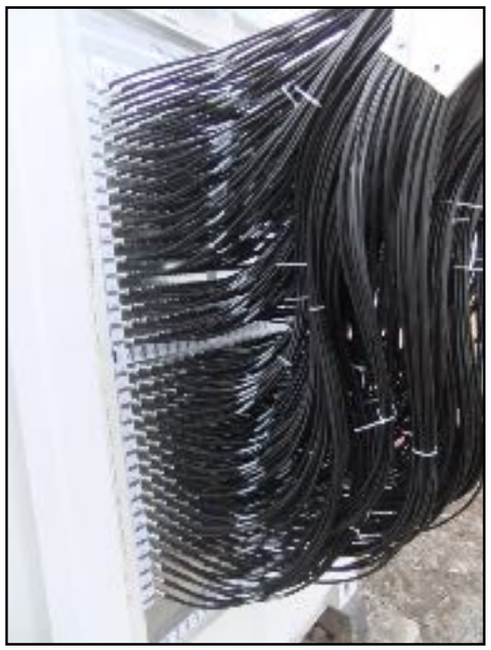


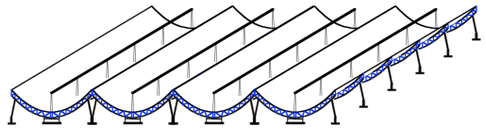












Reflector

Analog Receiver Chain

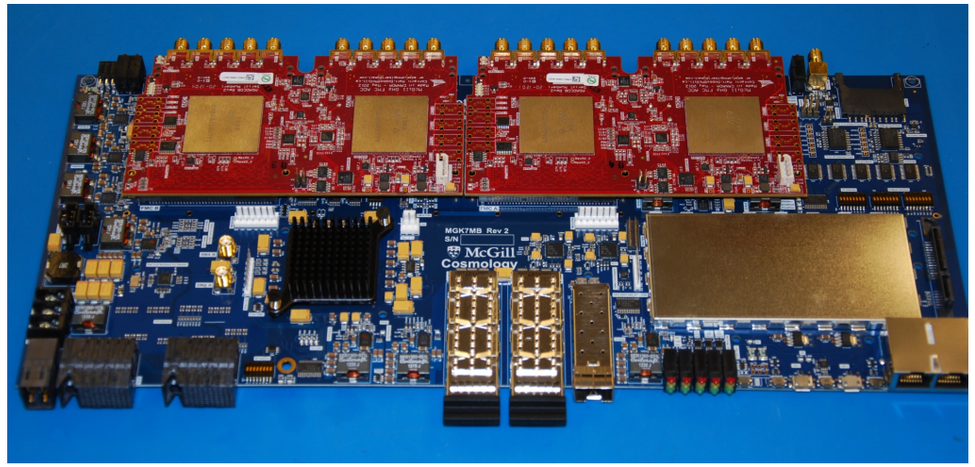
FPGA Channelizer

GPU Correlator

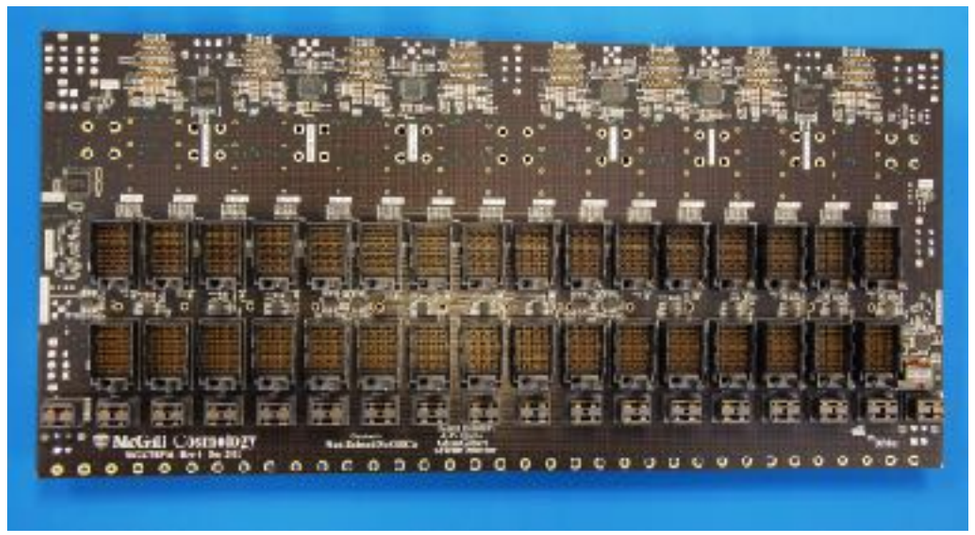
Realtime Backends

Science

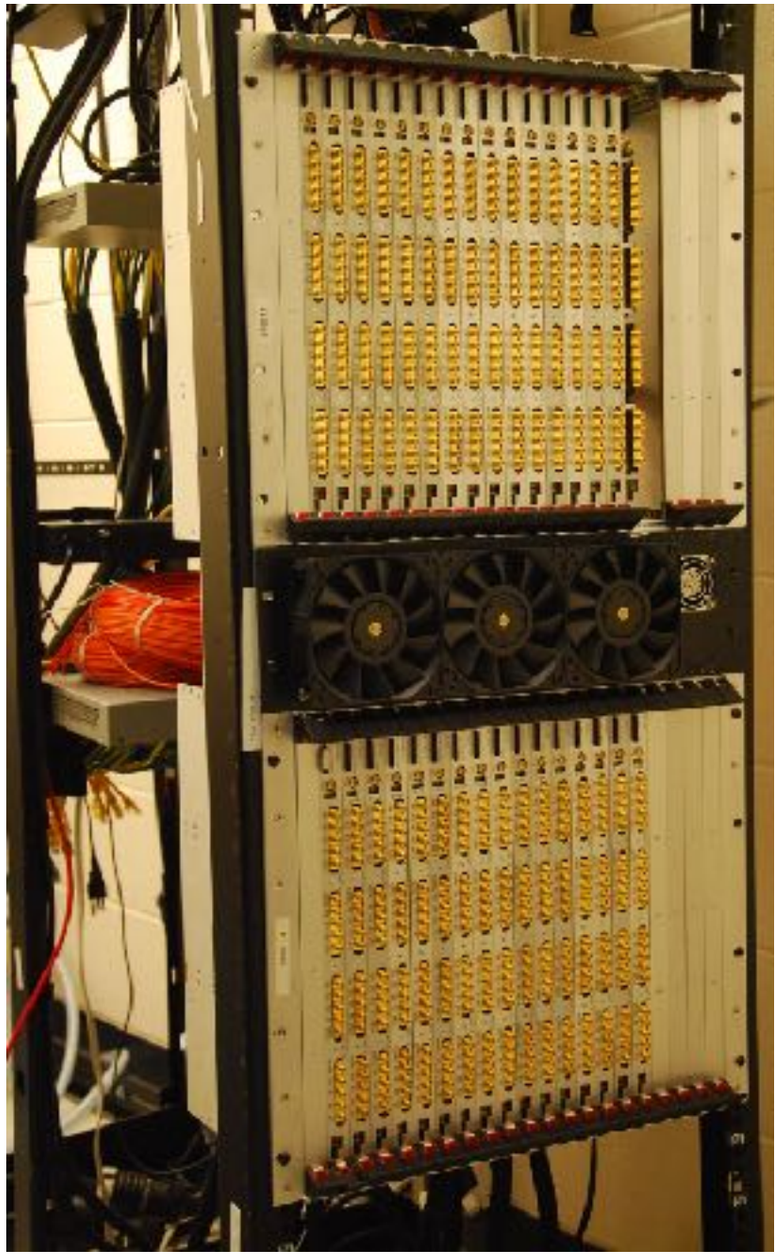
Motherboard - 16 Analog Inputs



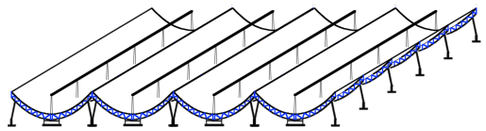
Backplane - 256 Analog Inputs



CHIME Quadrant - 512 Inputs



FPGA Development led by J.F. Cliche under Prof. Matt Dobbs and his team @ McGill



Reflector

Analog Receiver Chain

FPGA Channelizer

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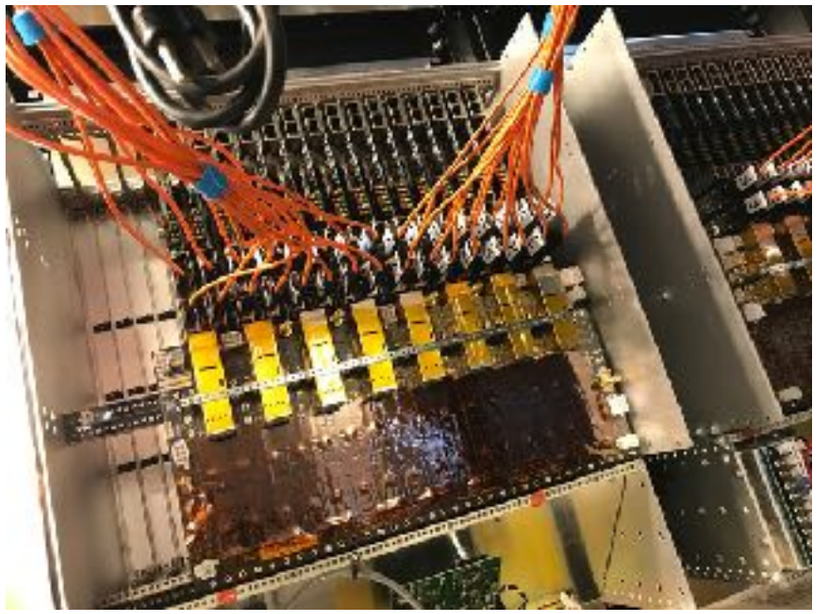
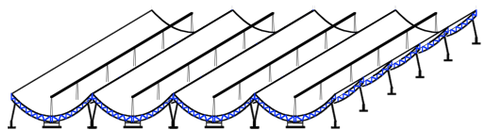
Science





Reflector

↓

Analog Receiver Chain

↓

FPGA Channelizer

↓

GPU Correlator

↓

Realtime Backends

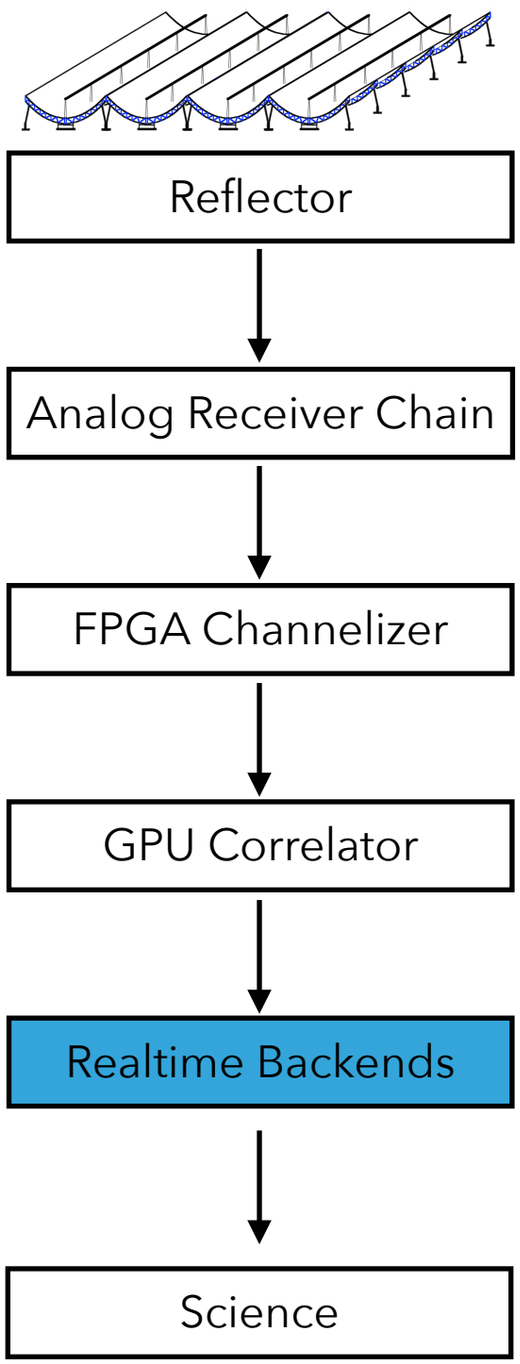
↓

Science

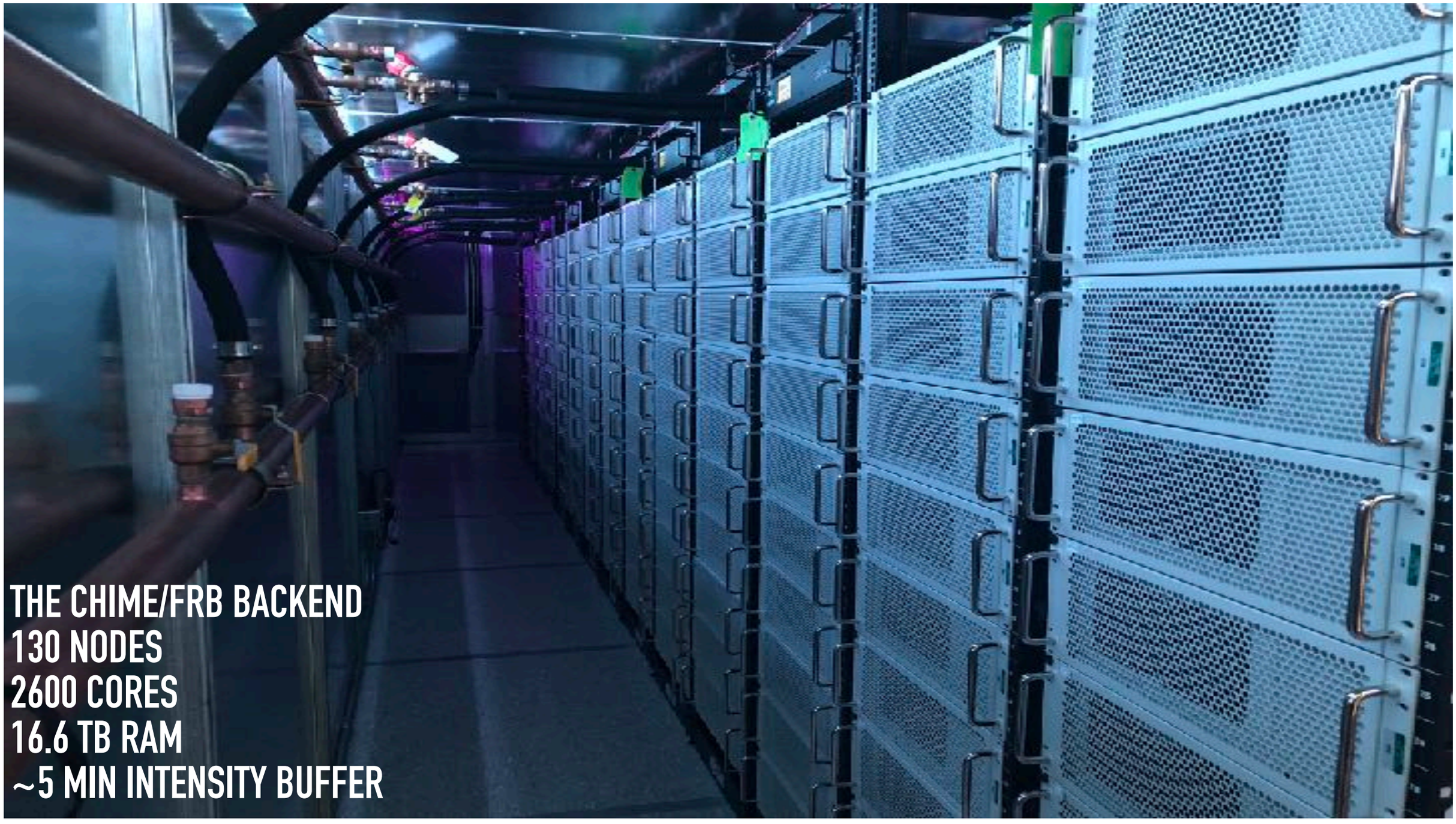
Development lead by Andre Renard with CHIME Team Members under Prof. Keith Vanderline @ UofT

- 256 Nodes w/1024 GPUs + 32.8 TB of RAM
- Processes 800 GB/s & ~40s Baseband Buffer
- Produces data products from all realtime backends

https://github.com/kotekan/kotekan


Reflector
Analog Receiver Chain
FPGA Channelizer
GPU Correlator
Realtime Backends
Science

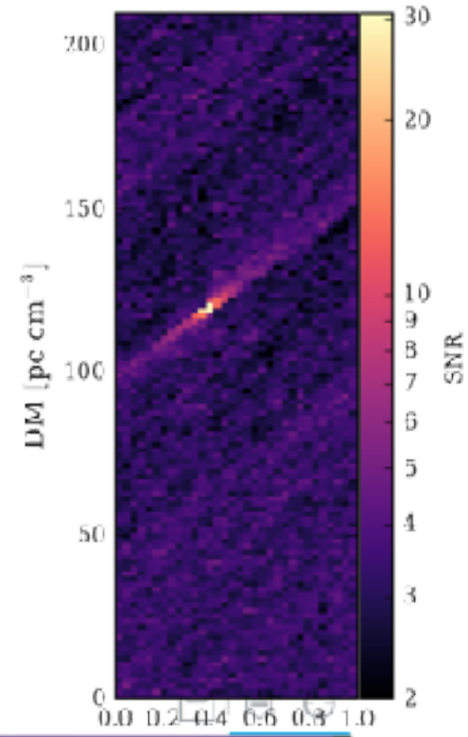
L1

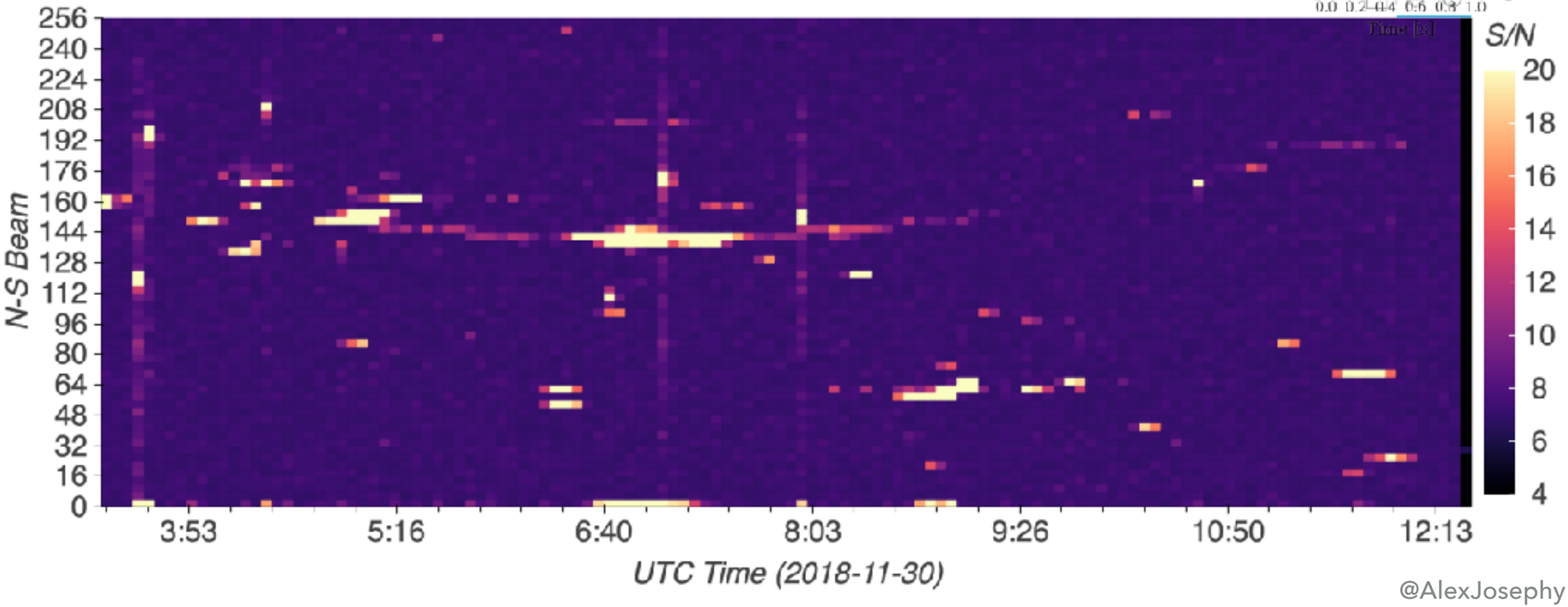

THE CHIME/FRB BACKEND
130 NODES
2600 CORES
16.6 TB RAM
~5 MIN INTENSITY BUFFER

L2-L3

SCIENCE PIPELINE

- Can manage millions of triggers/s
- Find the one trigger which is the FRB!





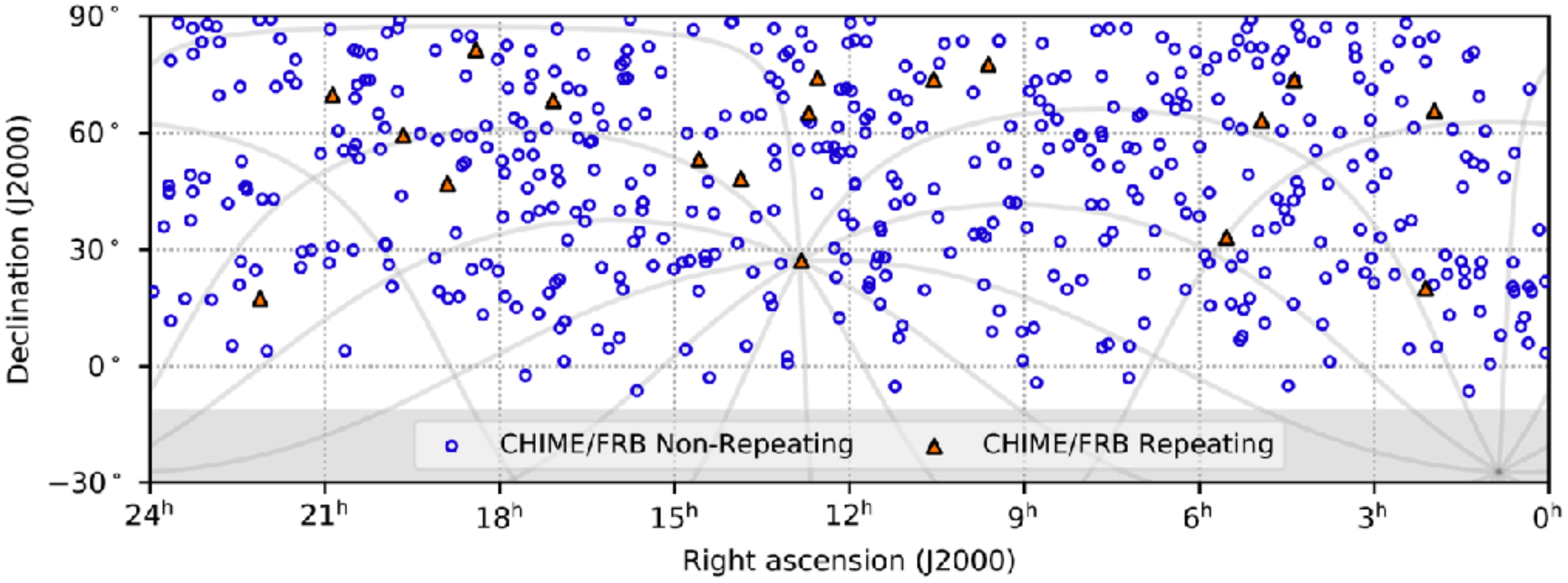
@AlexJosephy

DOING SCIENCE

CHIME FRB CATALOG

Catalog and Data –> https://www.chime-frb.ca/catalog

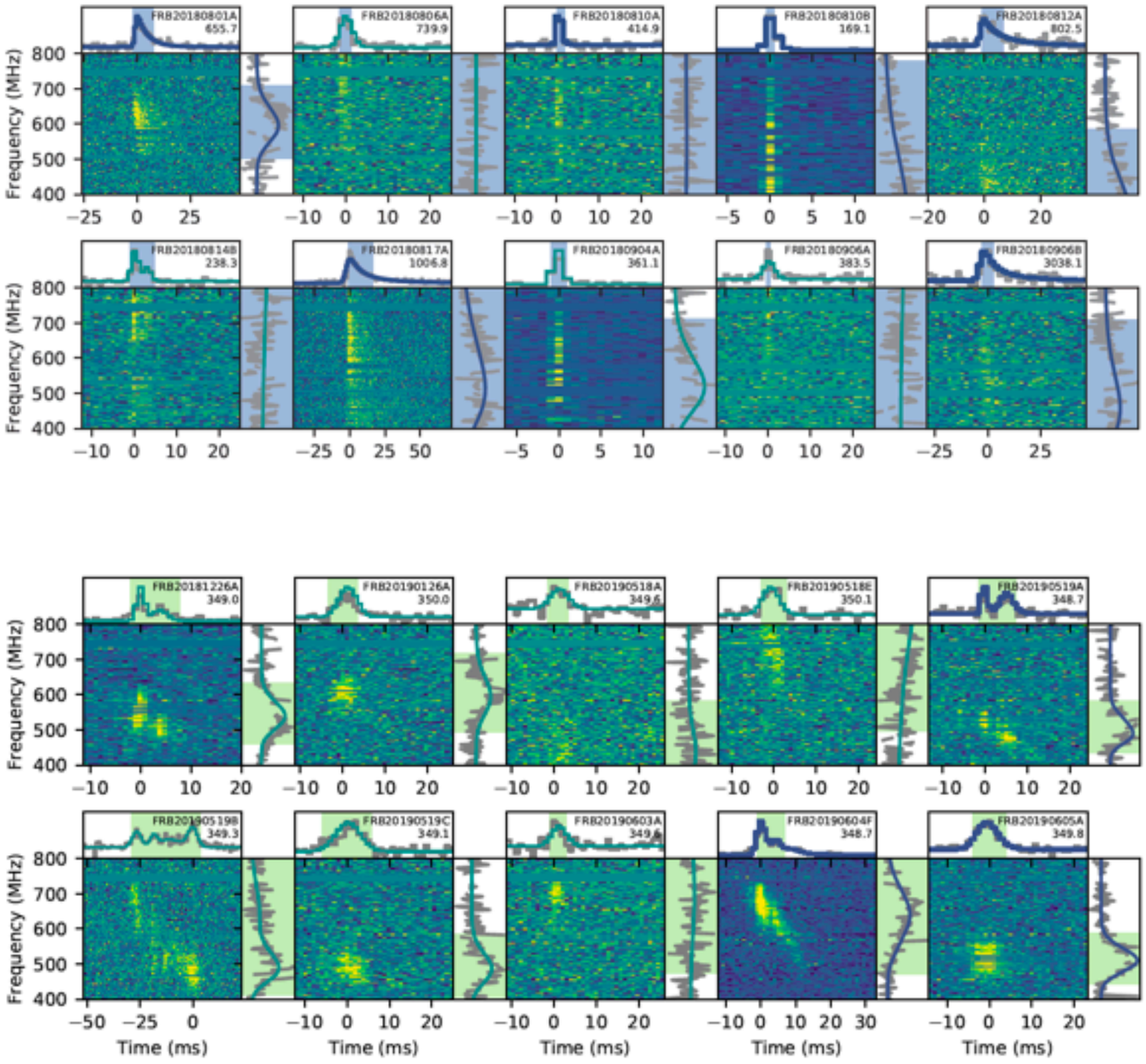
- 535 FRBs characterised from July 2018 – July 2019



CHIME/FRB Collaboration et al (ApJS 2022)

CHIME FRB CATALOG

- Some FRBs are broadband and single component



- Others have multiple components and are narrowband

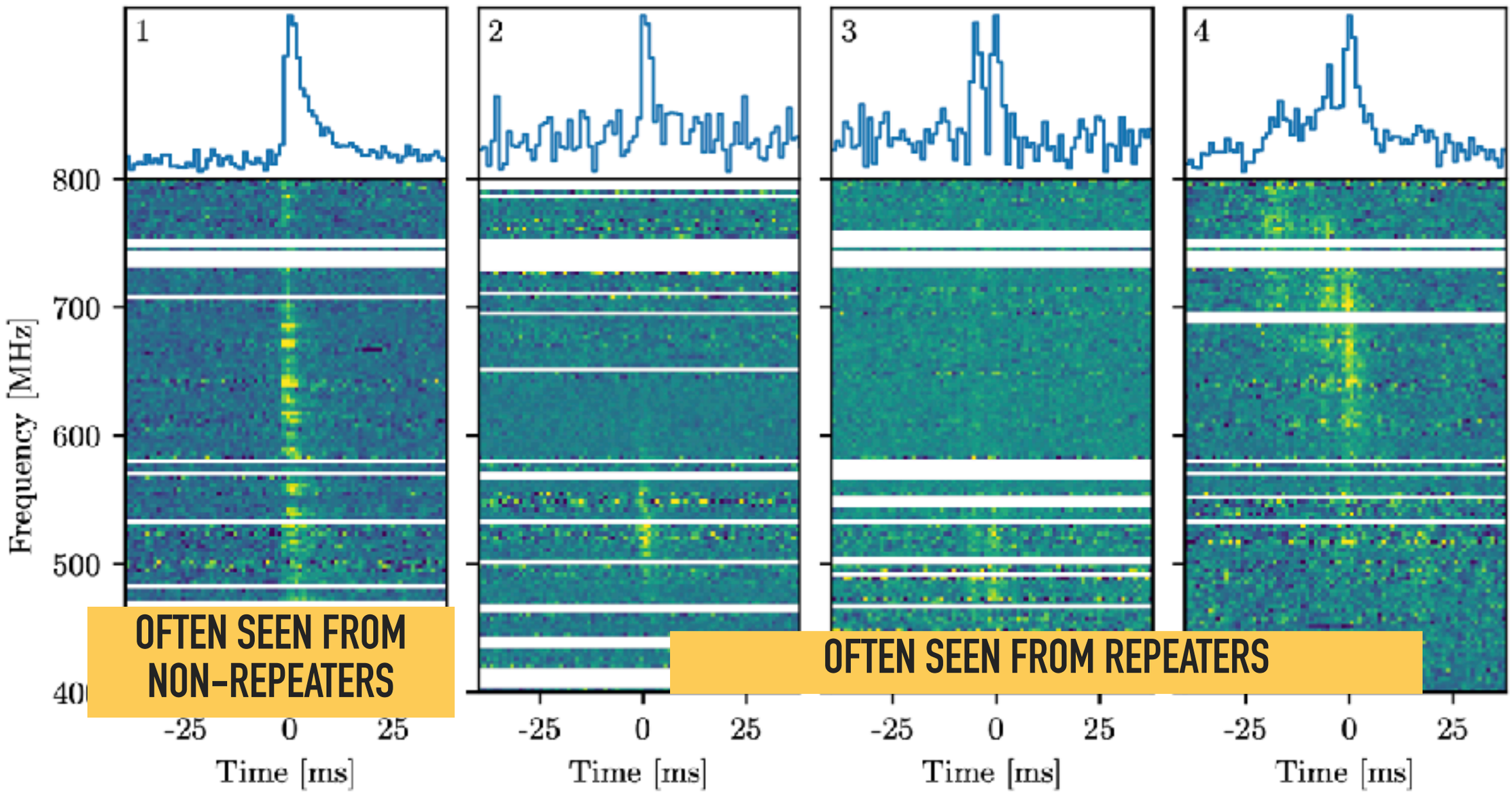
FRB ARCHETYPES

Single component, broadband

Single component, narrowband

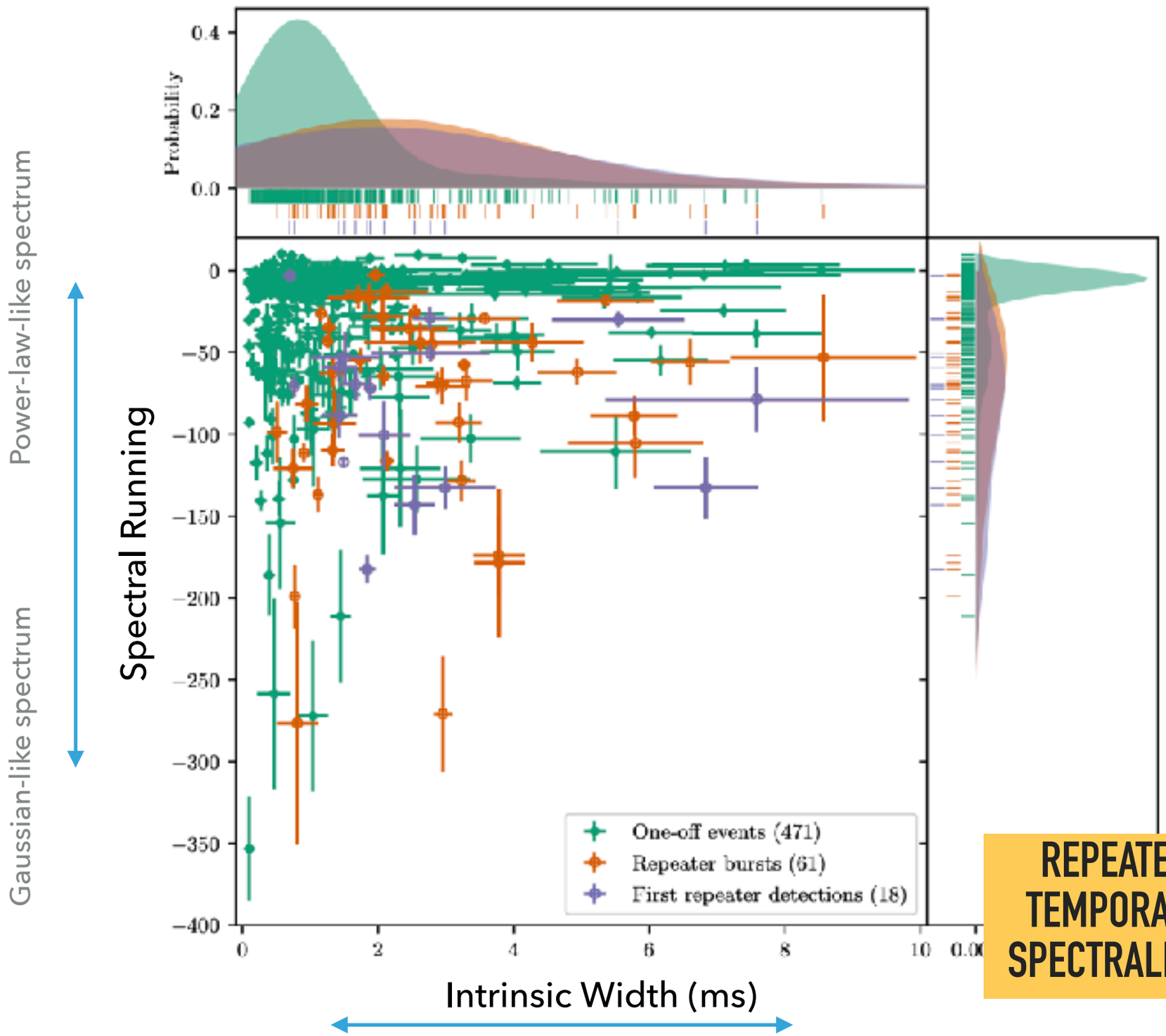
Multiple components similar spectra

Multiple components downward drifting



Beware of beam effects –> see the details

Pleunis et al (2021)



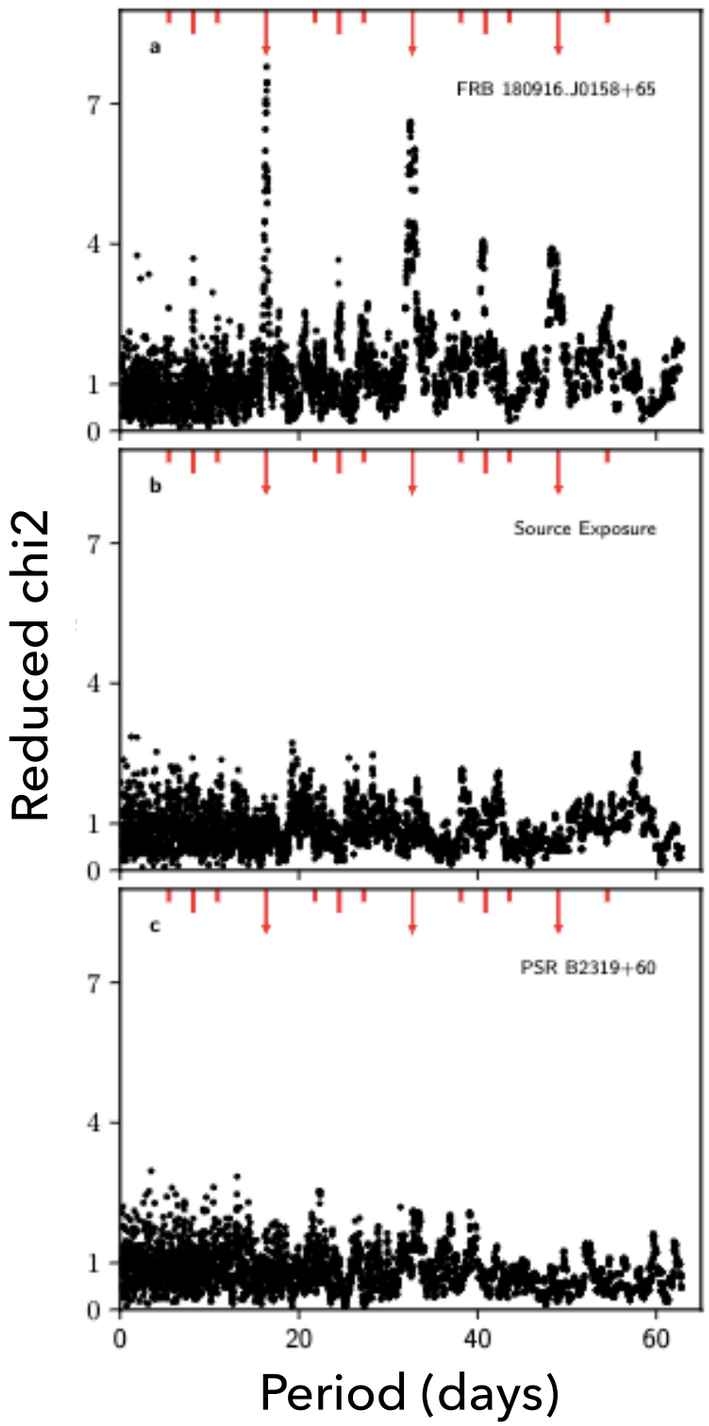
REPEATER BURSTS ARE TEMPORALLY WIDER AND SPECTRALLY NARROWBAND

Pleunis et al (2021)

TWO POPULATIONS?

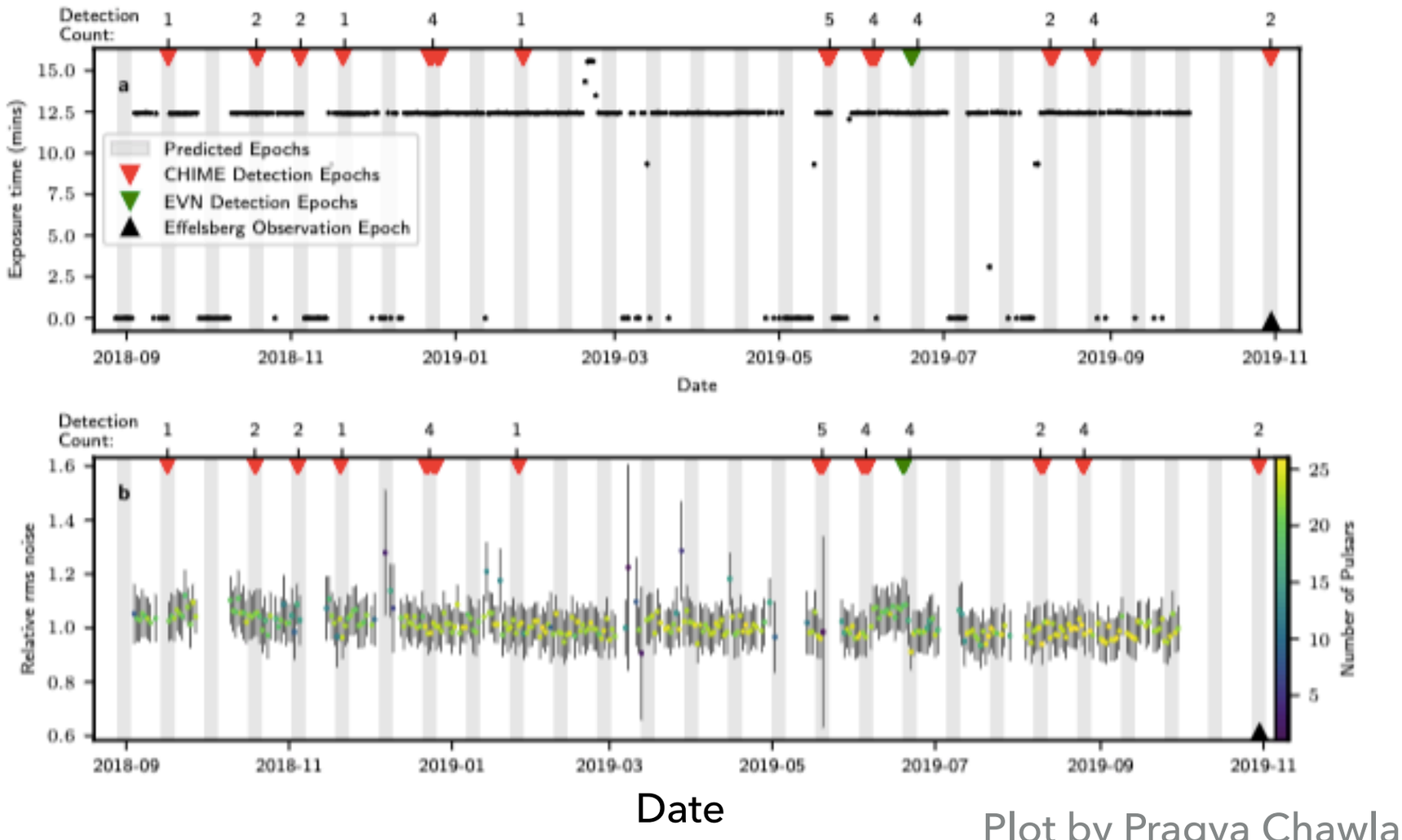
- There are some differences between bursts from repeaters and “as-yet” non-repeaters
- Can burst properties change with repetition rate?
  Rapid repeaters –> complex bursts, Rare repeaters –> simple bursts?
- Can this be propagation or beaming effects?
  Narrower beaming –> rarer repetition –> simple bursts?
- On-going studies with polarisation differences, rates etc…
- Could help guide repeater follow up
  (but avoid biasing catalogs!)

PERIODIC BURST ACTIVITY FROM FRB 180916 (R3)



Plot by Dongzi Li, Hsu-Hsien Lin

CHIME/FRB Collaboration (2020)

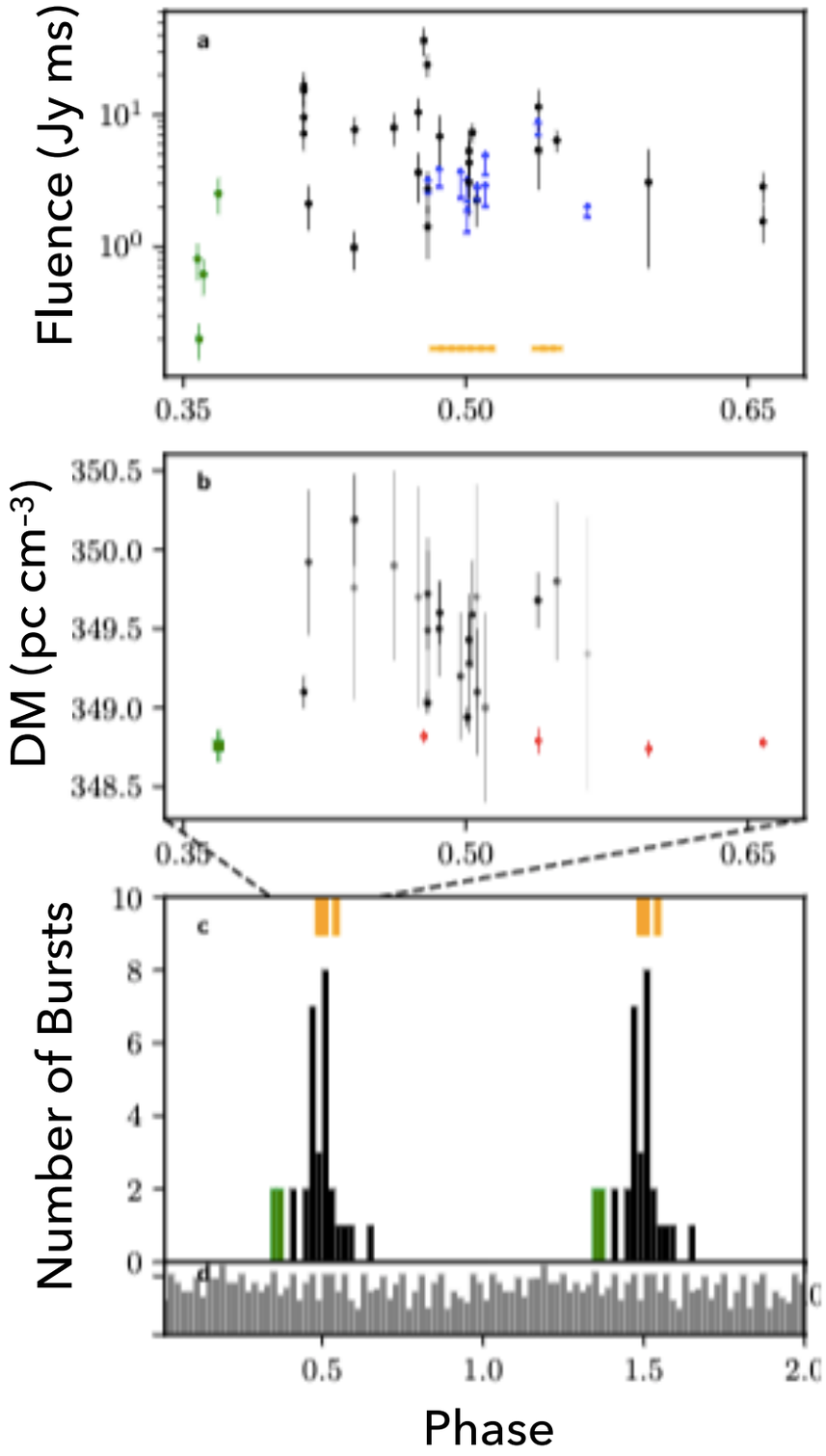


Plot by Pragya Chawla

PERIODIC BURST ACTIVITY

- Source shows activity at 16.35 day period
- Bursts arrive in a 4 day window (at 400-800 MHz)
- Duty cycle is not 100%
- Timescale – rotation? orbit? precession?
  - Is there another underlying periodicity?

FRB 121102 WAS ALSO FOUND TO BE PERIODIC WITH 160-DAY PERIOD
(RAJWADE ET AL 2020, CRUCES ET AL 2020)



Plot by Bridget Anderson, Ziggy Pleunis, Dongzi Li

- First detection of FRBs at 400 MHz (CHIME/FRB Collaboration et al 2018a)
- 17 new repeating FRBs (CHIME/FRB Collaboration et al 2018b, 2019, Fonseca et al 2020)
- 16.35 day periodic activity in FRB 180916 (CHIME/FRB Collaboration et al 2020a)
- A Galactic FRB from SGR 1935+2154 (CHIME/FRB Collaboration et al 2020b)
- Seven new Galactic RRATs and a binary pulsar (Good et al 2020)
- A repeater in M81 at 3.6 Mpc! (Bhardwaj et al 2021, Kirsten et al 2022)

Plus many more off-shoot papers

First catalog paper and related papers on FRB populations published last year

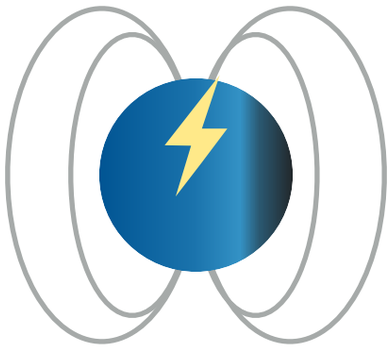
- CHIME/FRB Catalog, rate, logN/logS
- FRB Morphology (Pleunis et al 2021)
- Scattering properties of FRBs (Chawla et al 2021)

- Galactic distribution of FRBs (Josephy et al 2021)
  –> Observed FRB distribution is not affected by the Milky Way
- Cross-correlation of FRBs with galaxy catalogs (Ravandi-Rafiei et al 2021)
  –> FRB positions correlate with haloes in $0.3 \lesssim z \lesssim 0.5$
  –> Small population of FRBs with DM_host ~ 400 pc cm^{-3}

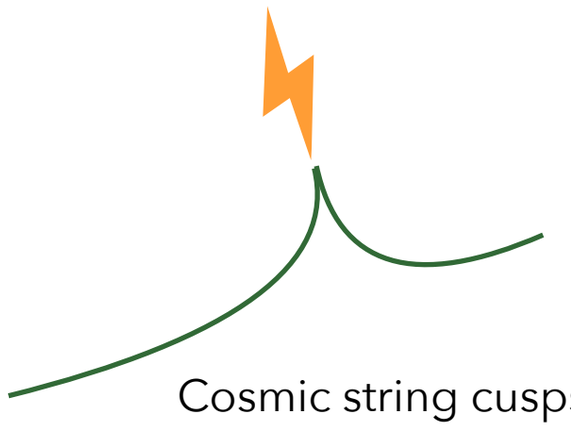
WHAT ARE THEY?

- ~10^{10-12} times brighter than Crab giant pulses
- Magnetar? NS Binary? More exotic?

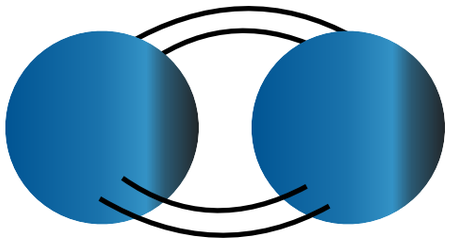
http://frbtheorycat.org Platts .. SPT et al 2019



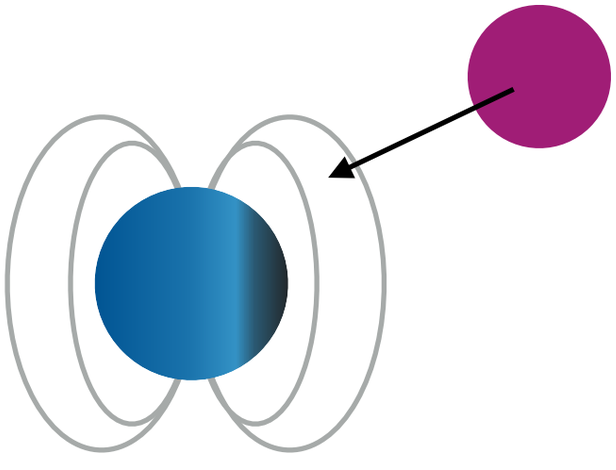
Magnetic field reconnection/ star quake



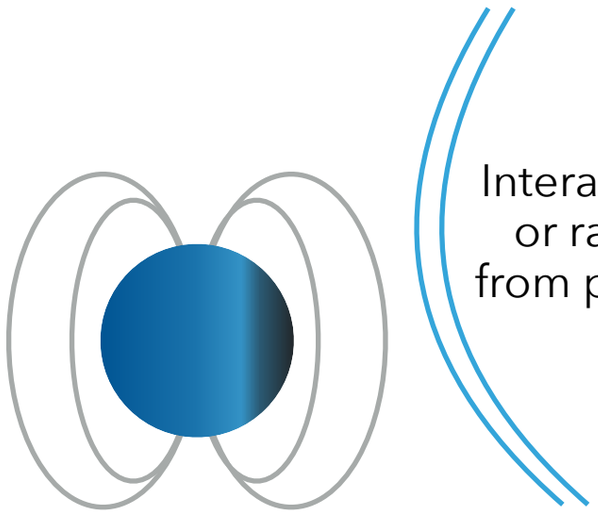
Cosmic string cusps



Merger/Coalescence



Interaction with asteroid/ axion nugget



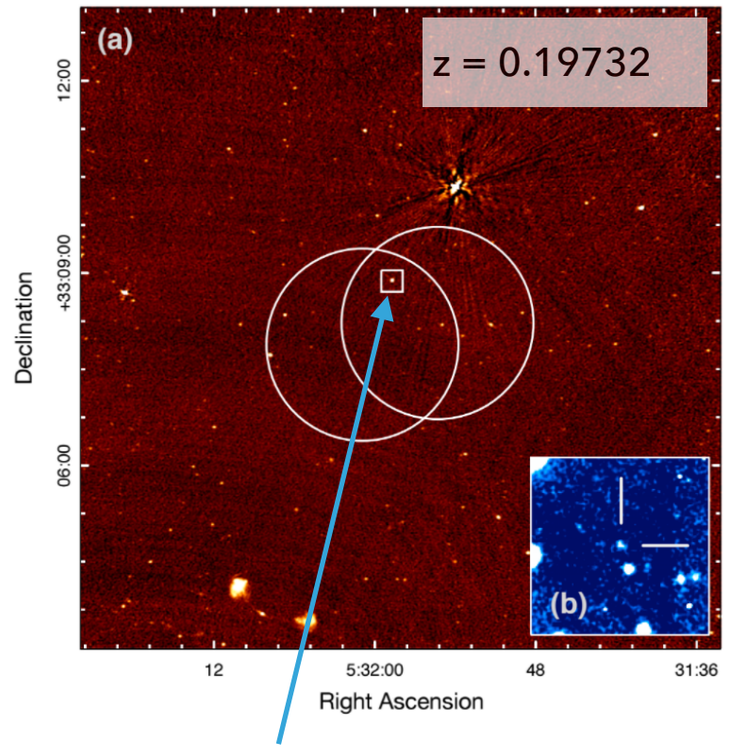
Interaction with winds or radiative shocks from pulsars, OB stars, AGNe

IMPLICATING MAGNETARS

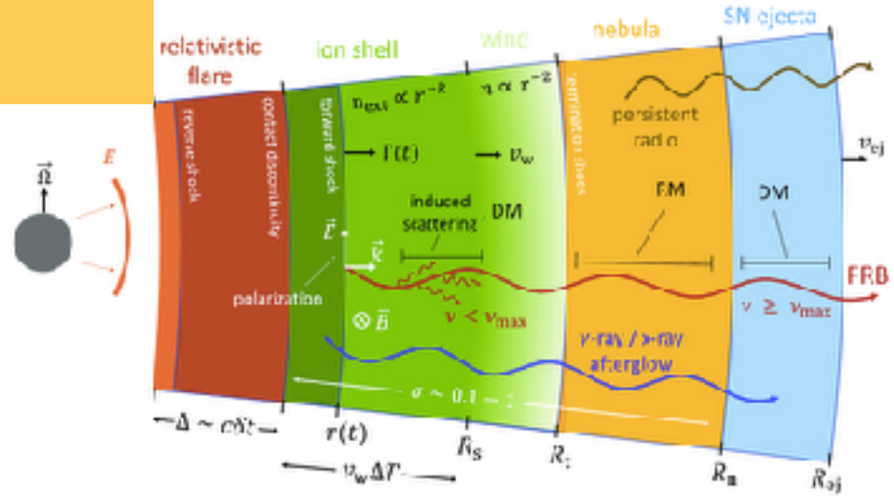
- First repeating FRB in a low metallicity dwarf galaxy
  - Low metallicity –> long GRBs and superluminous supernovae (SLSNe-I)
- Millisecond magnetar model
  - Doesn't v
- 160-day pe
2020)
  - 16.5 day periodic activity in FRB 180916
    CHIME/FRB Collaboration (2020)
- What is this periodicity? We don't know

COULD GALACTIC MAGNETARS GIVE SUCH BURSTS?

Chatterjee .. SPT et al 2017
Tendulkar et al 2017



Co-located with a very bright persistent radio source:
$\nu L\nu \sim 10^{38}\,\mathrm{erg\,s^{-1}}$



Metzger et al (2019), Margalit et al (2018)

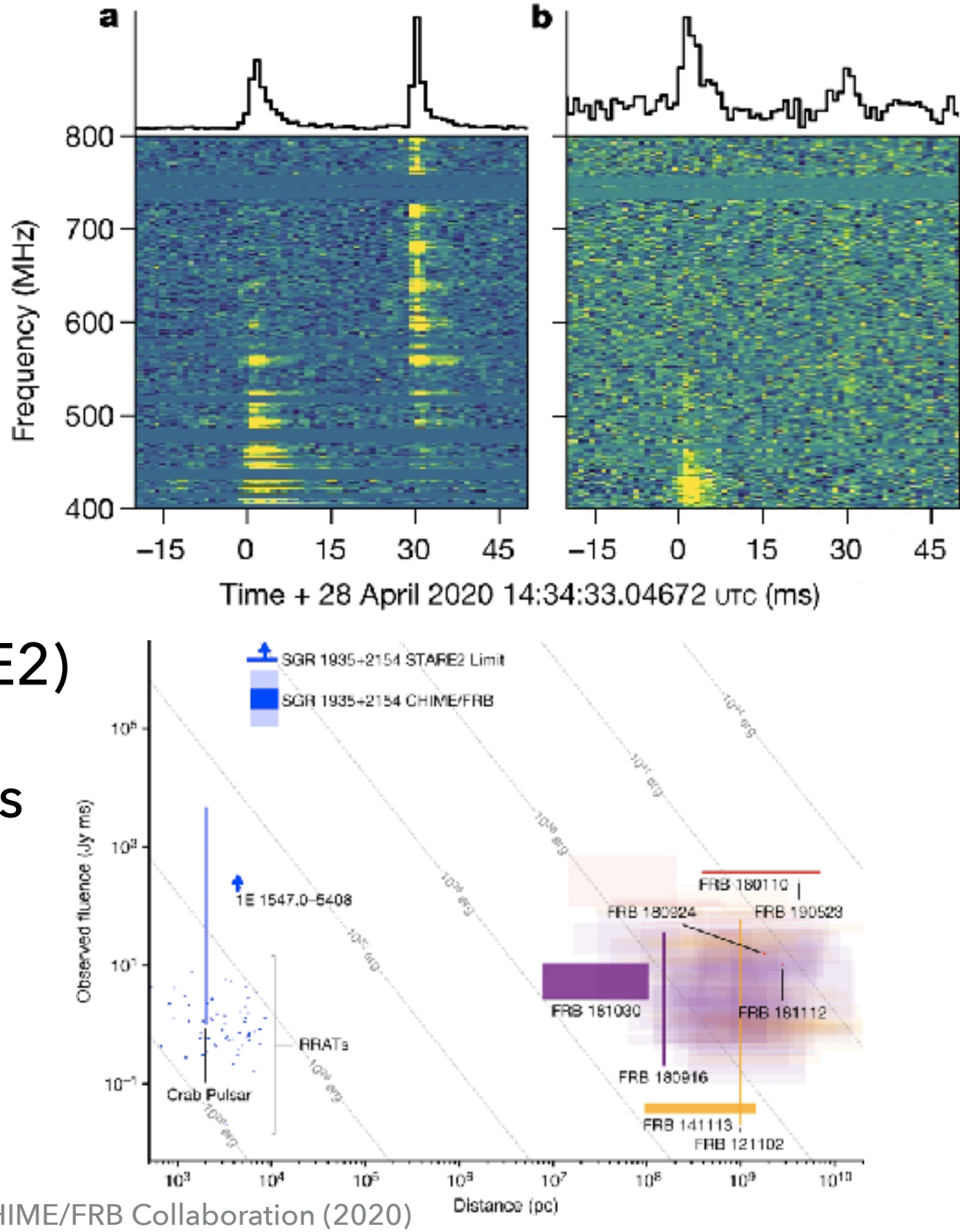
A GALACTIC "FRB"

- Since Nov 2019:
  SGR 1935+2154 active
  X-ray flares/bursts

- 28th April 2020: CHIME/FRB detected a very bright radio burst (also detected by STARE2)

  - Lower end of the energetics (still MJy!)

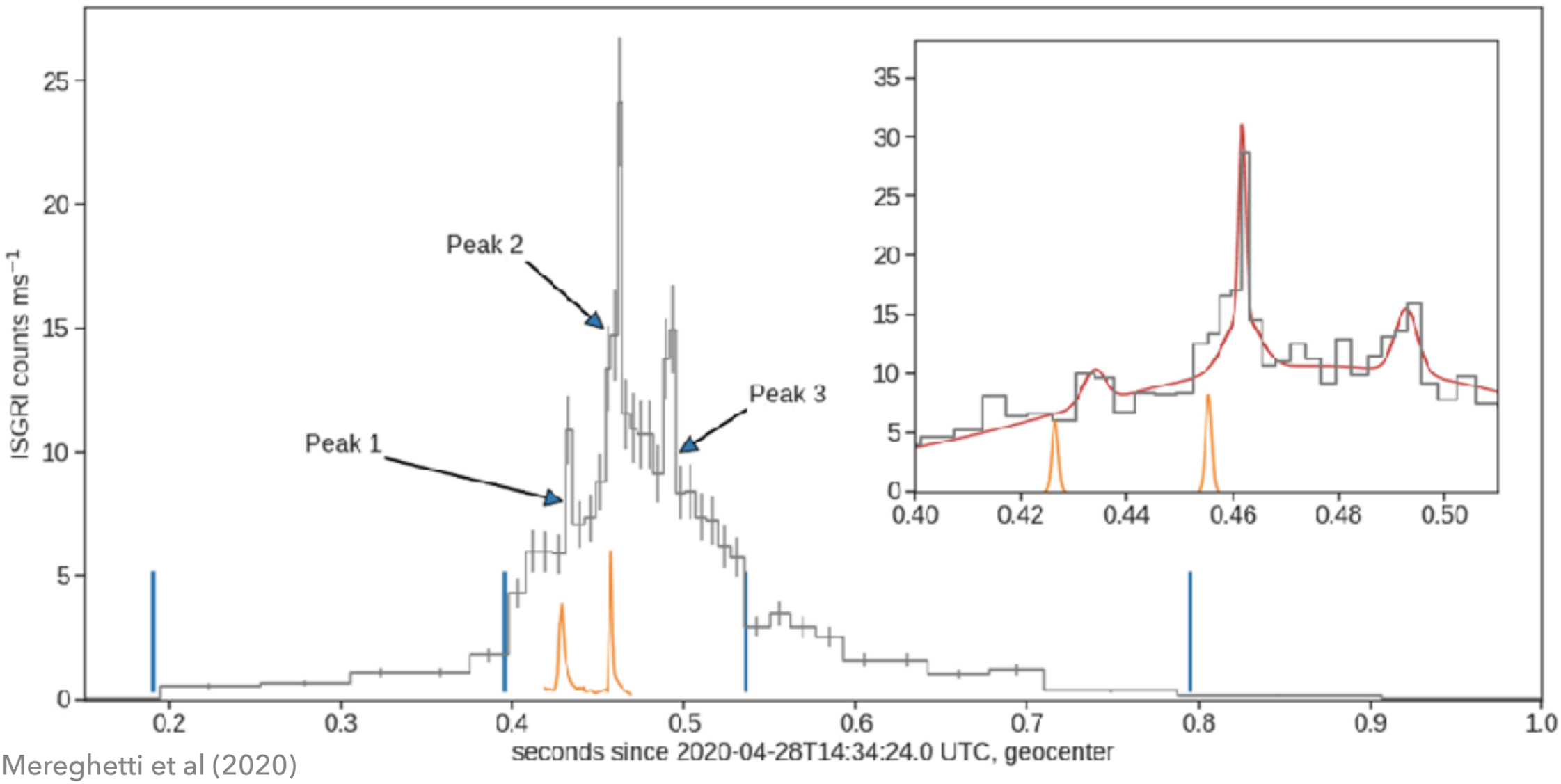
- First FRB from a canonical magnetar



CHIME/FRB Collaboration (2020)

A GALACTIC "FRB"

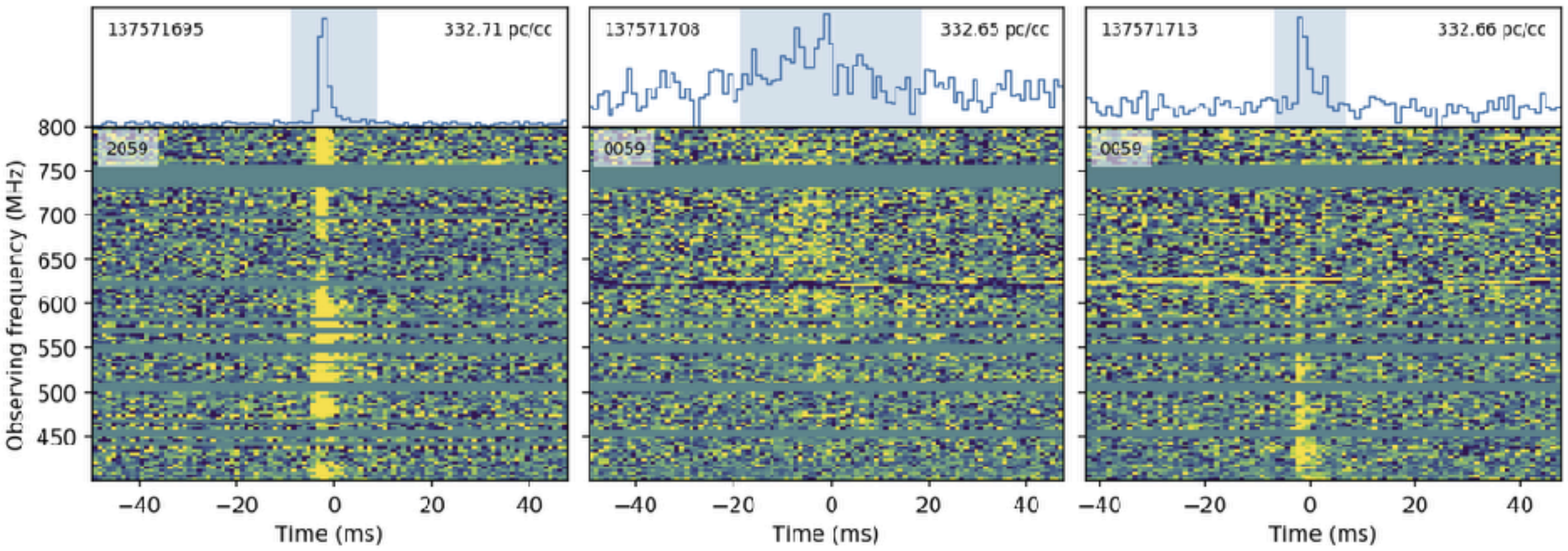
- Multi-peaked 'hard' X-ray burst just after radio



Mereghetti et al (2020)

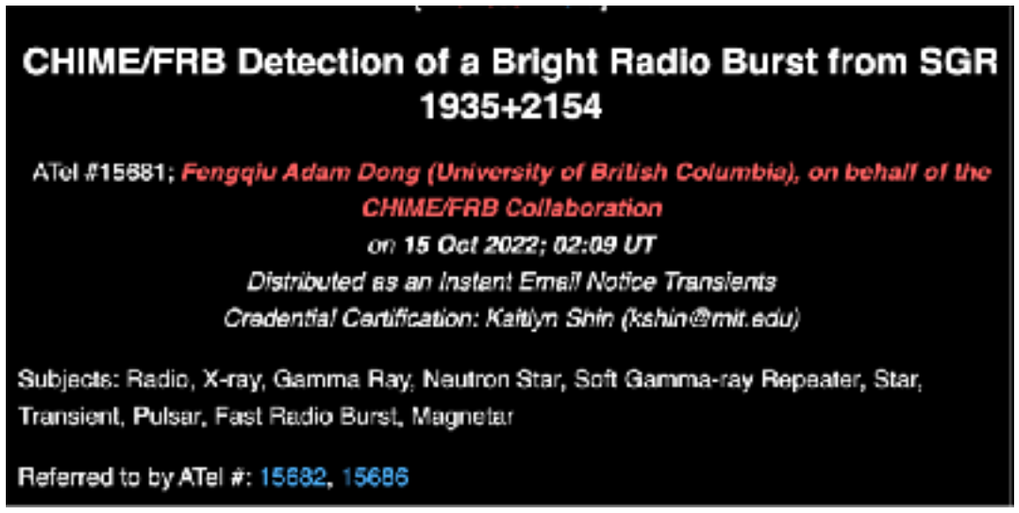
A GALACTIC "FRB"

- Multi-peaked 'hard' X-ray burst just after radio
- BUT – many other X-ray bursts w/o radio (CHIME/FRB Coll 2020, Lin et al 2020)
- Many radio bursts w/o X-ray (CHIME/FRB Coll. 2020, Kirsten et al 2020)



RECENT NEWS

- Another radio + X-ray burst from SGR 1935+2154: 14th Oct 2022

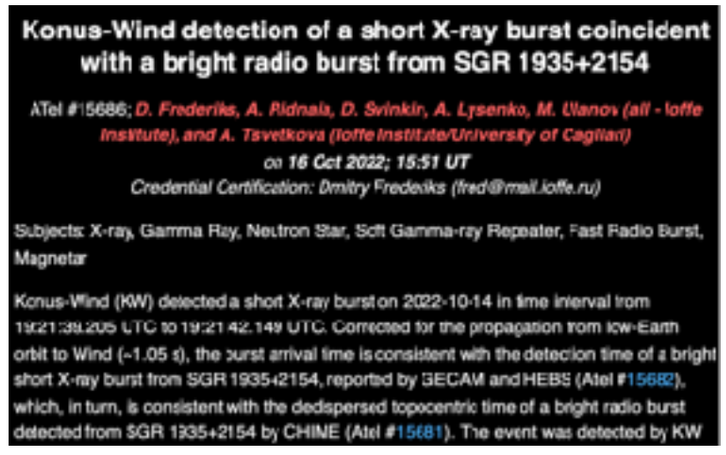


CHIME/FRB Detection of a Bright Radio Burst from SGR 1935+2154

ATel #15881; *Fengqiu Adam Dong (University of British Columbia), on behalf of the CHIME/FRB Collaboration*
on 15 Oct 2022; 02:09 UT
Distributed as an Instant Email Notice Transients
Credential Certification: Kaitlyn Shin (kshin@mit.edu)

Subjects: Radio, X-ray, Gamma Ray, Neutron Star, Soft Gamma-ray Repeater, Star, Transient, Pulsar, Fast Radio Burst, Magnetar

Referred to by ATel #: 15682, 15686



Konus-Wind detection of a short X-ray burst coincident with a bright radio burst from SGR 1935+2154

ATel #15686; *D. Frederiks, A. Ridnaia, D. Svinkin, A. Lysenko, M. Ulanov (all - Ioffe Institute), and A. Tsvetkova (Ioffe Institute/University of Cagliari)*
on 16 Oct 2022; 15:51 UT
Credential Certification: Dmitry Frederiks (fred@mail.ioffe.ru)

Subjects: X-ray, Gamma Ray, Neutron Star, Soft Gamma-ray Repeater, Fast Radio Burst, Magnetar

Konus-Wind (KW) detected a short X-ray burst on 2022-10-14 in time interval from 19:21:39.205 UTC to 19:21:42.149 UTC. Corrected for the propagation from low-Earth orbit to Wind (~1.05 s), the burst arrival time is consistent with the detection time of a bright short X-ray burst from SGR 1935+2154, reported by GECAM and HEBS (Atel #15682), which, in turn, is consistent with the dedispersed topocentric time of a bright radio burst detected from SGR 1935+2154 by CHIME (Atel #15681). The event was detected by KW

GECAM and HEBS detection of a short X-ray burst from SGR J1935+2154 associated with radio burst

ATel #15682; *C. W. Wang, S. L. Xiong, Y. Q. Zhang, J. C. Liu, C. Zheng, W. C. Xue, W. J. Tan, S. L. Xie, Q. B. Yi, Y. Zhao, Y. Wang, C. Cai, S. Xiao, Y. Huang, X. Ma, R. Qiao, P. Wang, X. Y. Zhao, P. Zhang, X. Q. Li, X. Y. Wen, W. X. Pang, L. M. Song, S. J. Zheng, Y. Q. Du, D. Y. Guo, B. Li, X. B. Li, J. Liang, Y. Q. Lu, J. Wang, H. Wu, X. Y. Song, W. H. Yu, Z. Zhang, Z. H. An, P. Y. Feng, M. Gao, K. Gong, X. J. Liu, Y. Q. Liu, X. L. Sun, J. Z. Wang, Y. B. Xu, S. Yang, D. L. Zhang, F. Zhang, C. K. Li, G. Li, J. Y. Liao, G. Chen, F. J. Lu, S. N. Zhang (IHEP) report on behalf of GECAM and HEBS teams:*
on 15 Oct 2022; 06:35 UT
Credential Certification: Yu-Peng Chen (chenyp@ihep.ac.cn)

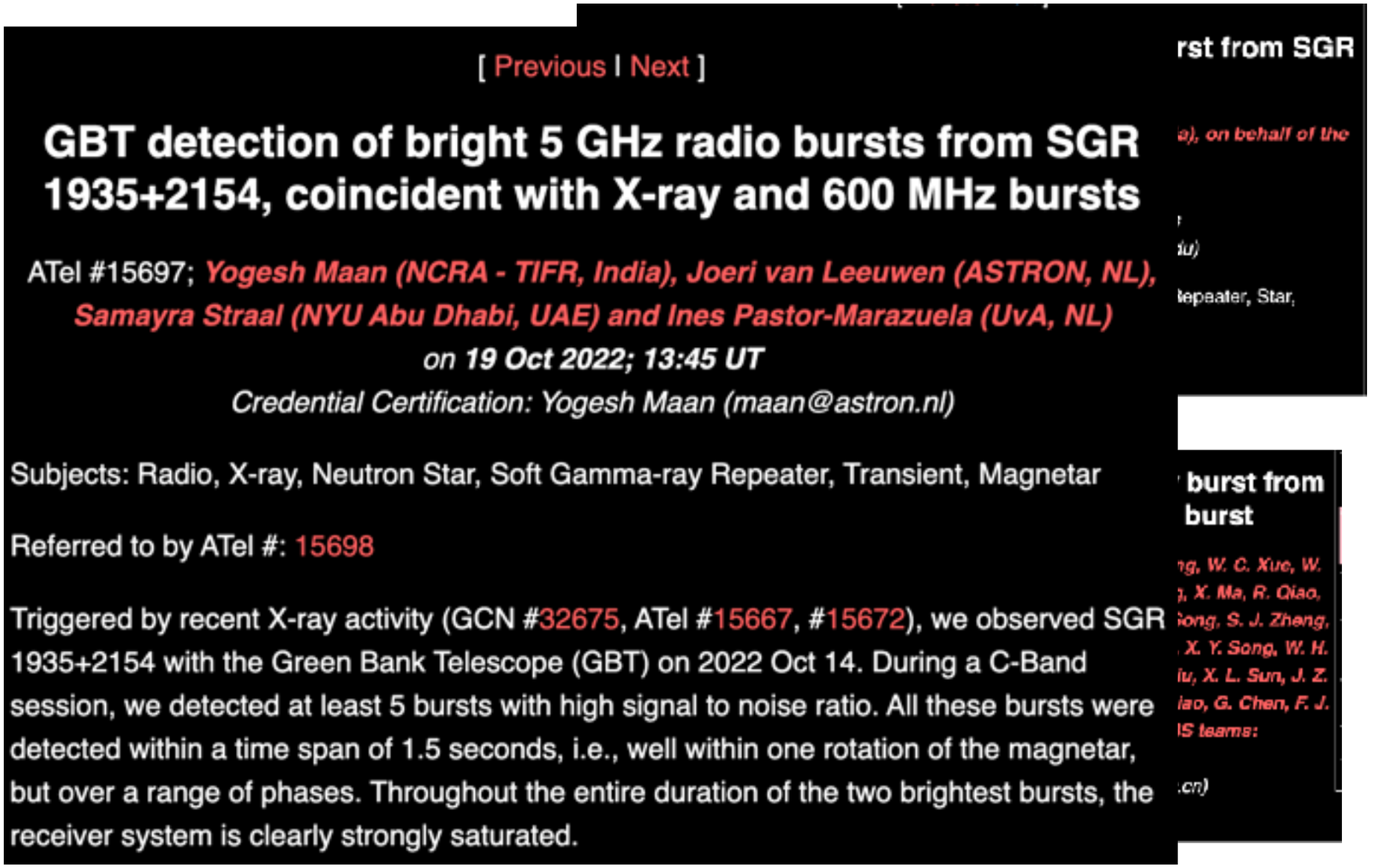
Subjects: Gamma Ray, Gamma-Ray Burst, Neutron Star

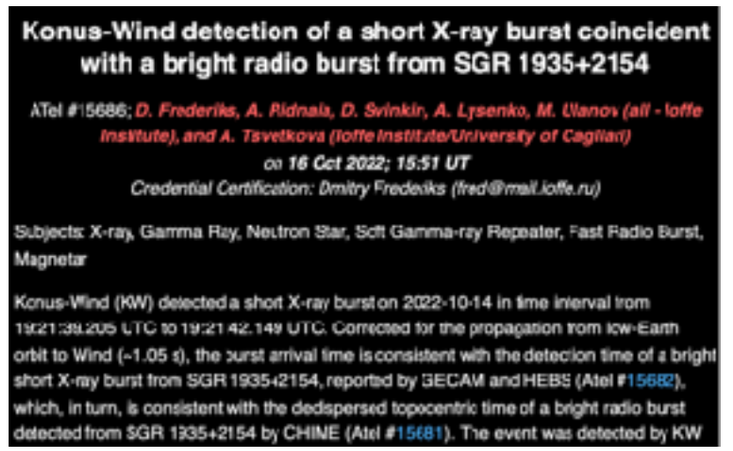
14th October 2022

- Broad spectrum coverage (thermal/non-thermal?)
- Bursts from magnetars in nearby galaxies

RECENT NEWS

- Another radio + X-ray burst from SGR 1935+2154: 14th Oct 2022





14th October 2022

- Broad spectrum coverage (thermal/non-thermal?)
- Bursts from magnetars in nearby galaxies

SO DOES THAT SOLVE ALL OUR PROBLEMS?

- SGR 1935+2154-like magnetars likely don’t explain all FRBs
- The occurrence rate may be consistent with the volumetric rate as a population
- But individual FRBs (repeaters and non-repeaters) have behavior/activity that SGR 1935+2154 (or other magnetars) have not replicated

CURRENT AND NEXT STEPS

- Detecting FRBs is not enough
- Working hard on automated pipelines for characterisation
  - Working on repeater paper 3 and catalog 2.
- VLBI telescopes are built for small field of view

  Cannot find non-repeating FRBs efficiently
- CHIME/FRB building outrigger telescopes

  Get 50 mas localization for every FRB (repeater and non-repeater)
- Aim to get ~1000 localized FRBs every year in 2 years

FRB VOEVENTS

Led by Andrew Zwaniga

- FRB VOEvent stream from CHIME/FRB is now public
- Real-time, low latency (~30 seconds including DM sweep)
- Includes initial information: rough position (~30 arcmin), SNR, DM, quality factors, etc.
- Great for rapid follow up for prompt counterparts

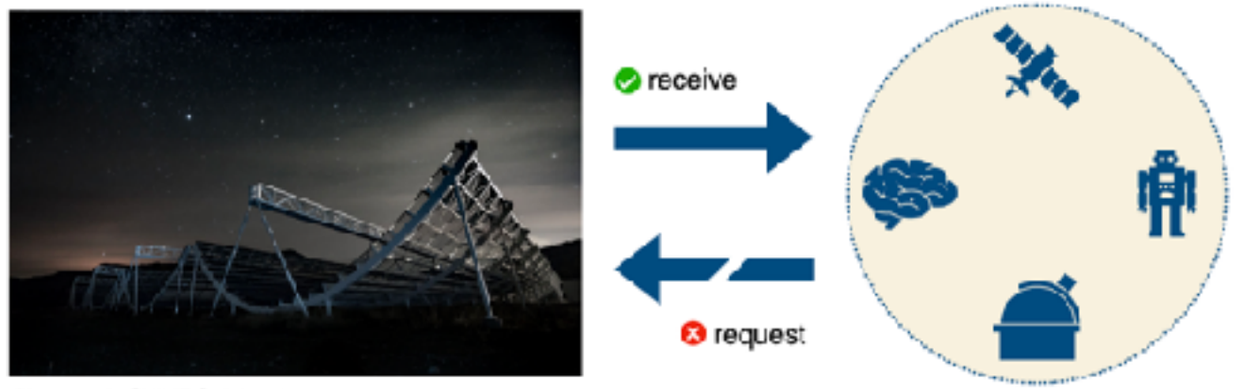


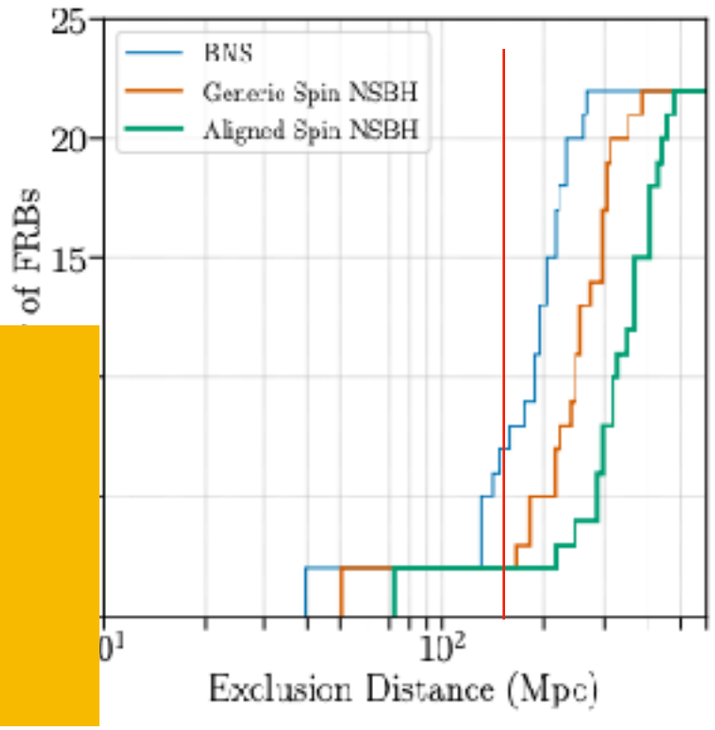
Photo credit: CHIME Collaboration

https://chime-frb-open-data.github.io/voevents/

GRAVITATIONAL WAVES

- Current limits on BNS-like mergers at the CHIME/ FRB catalog 1
  Search range = (–600 s, +120 s)
- Modeled + un
- Future runs wil
  likelihood of d

We need to find the nearest and brightest FRBs (<100 Mpc)

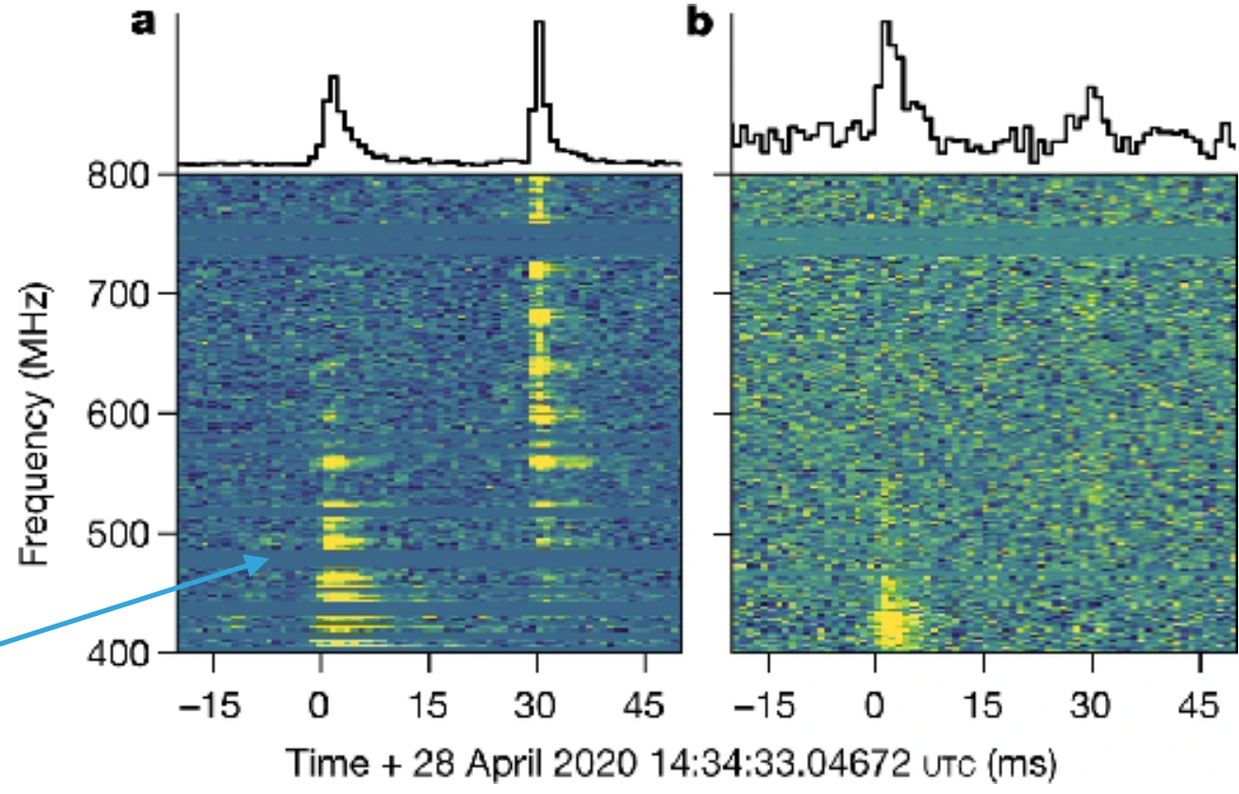


LVK + CHIME/FRB Collaborations (2022)

- Possible association of GW190425z (BNS merger) with FRB 20190425A (2.5 hrs post merger) Moroianu et al (2022)

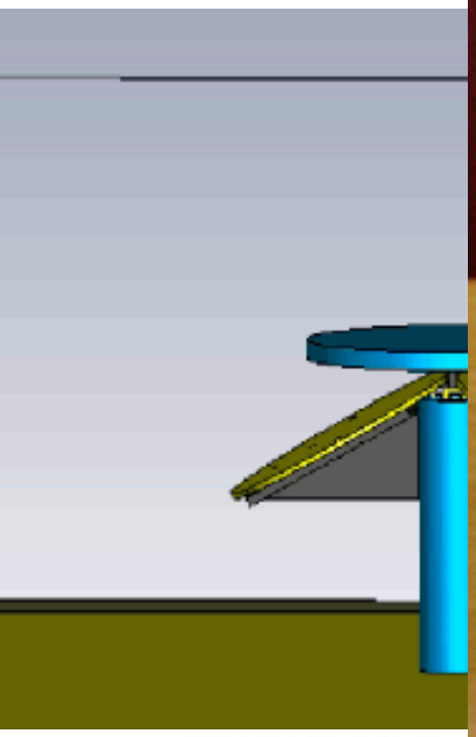
ALL SKY TRANSIENT RADIO ARRAY (ASTRA)

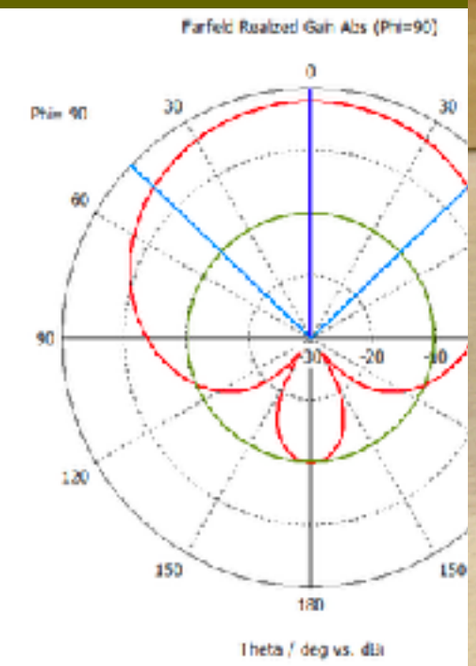
- Nearest and brightest FRBs are key to understanding the origins (Farther FRBs are good as probes)
- Brightest FRBs –> Most likely to have optical, X-ray counterparts (e.g. SGR 1935+2154)
- Also EM/GW counterparts
  LIGO binary NS merger horizon is 200 Mpc
- Need to cast a very wide net

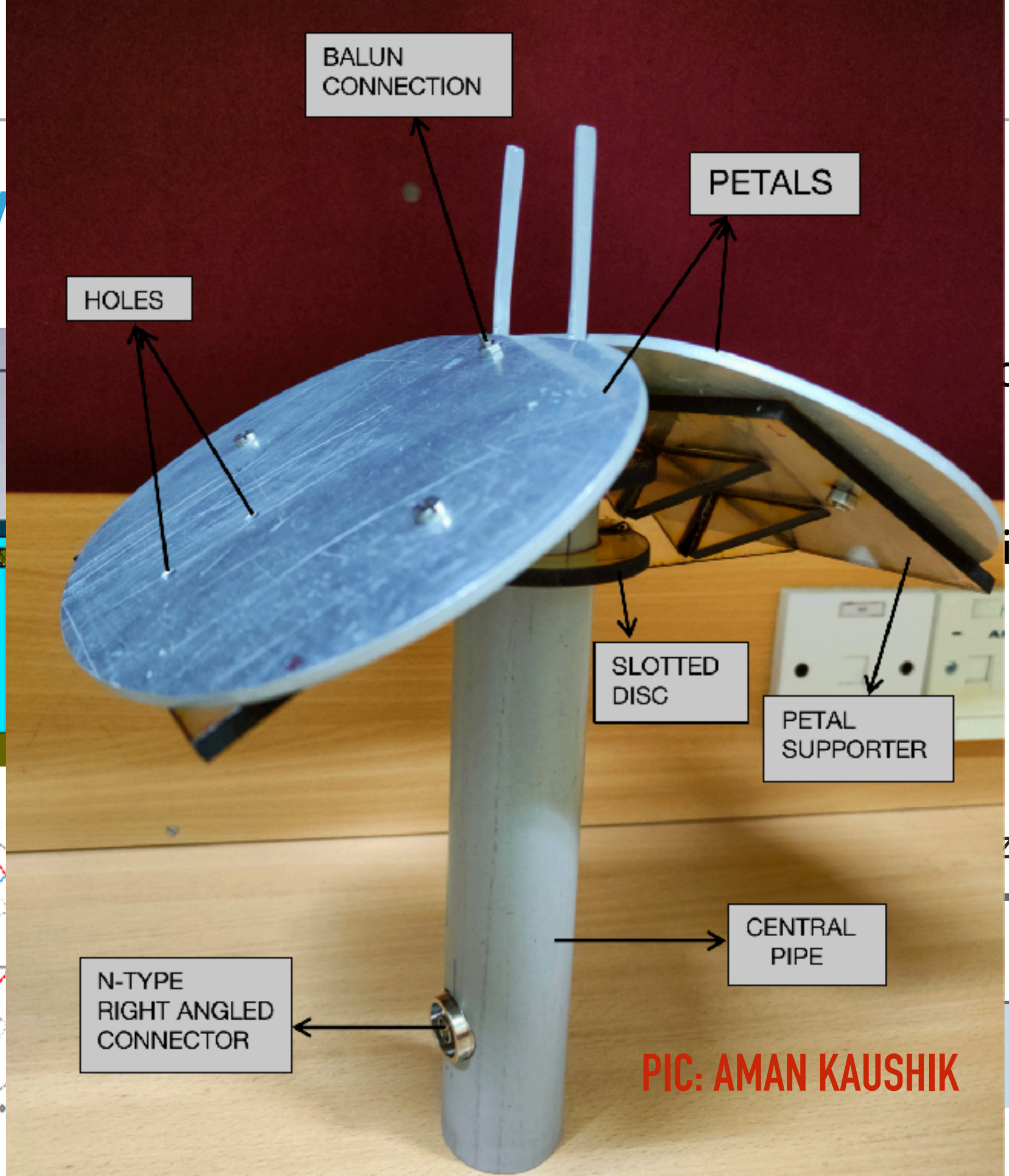


CHIME/FRB sidelobe detection.
Blips caused due to the diffraction lobes

ALL SKY







de

feed

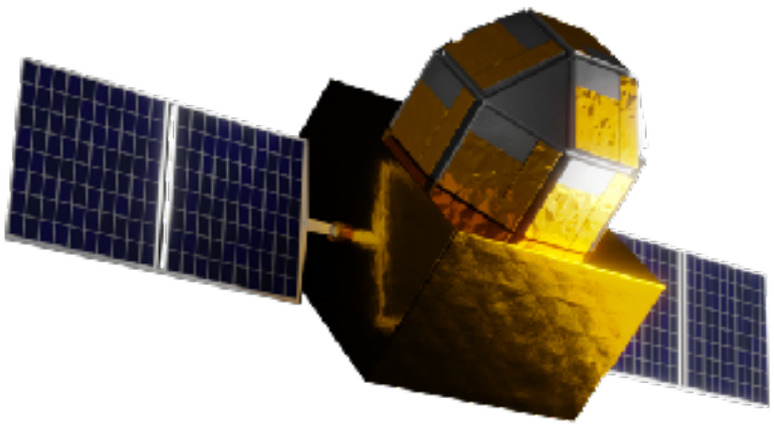
ipun;

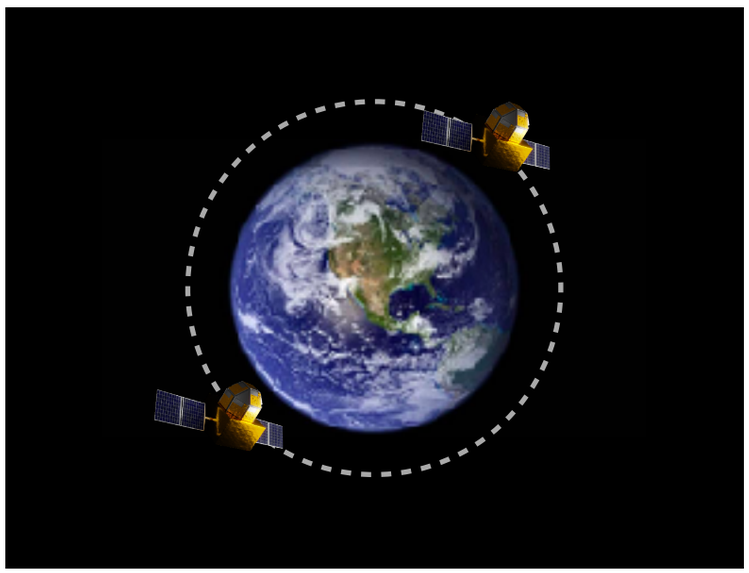
z	800 MHz
	121
	135

IMPROVING X-RAY LIMITS

- Proposed mission from IITB, TIFR, PRL, RRI and ISRO (Phase 1 funded)
- Two satellites with an all-sky view for X-ray transients
- 1keV to 1 MeV coverage; 1300 sq cm at 50 keV
- Helps us find gamma-ray bursts, magnetar flares, FRB counterparts

Daksha ("Alert")





Sensitivity of Swift-BAT, but across the entire sky

CONCLUSIONS AND SUMMARY

- Significant differences between bursts from repeaters and as-yet non-repeaters (but don't necessarily mean astrophysical different channels)
- Some (or most) FRBs could be coming from magnetars
- Multi-wavelength and multimessenger counterparts are urgently needed
- Working on localising FRBs, finding the nearest and brightest ones

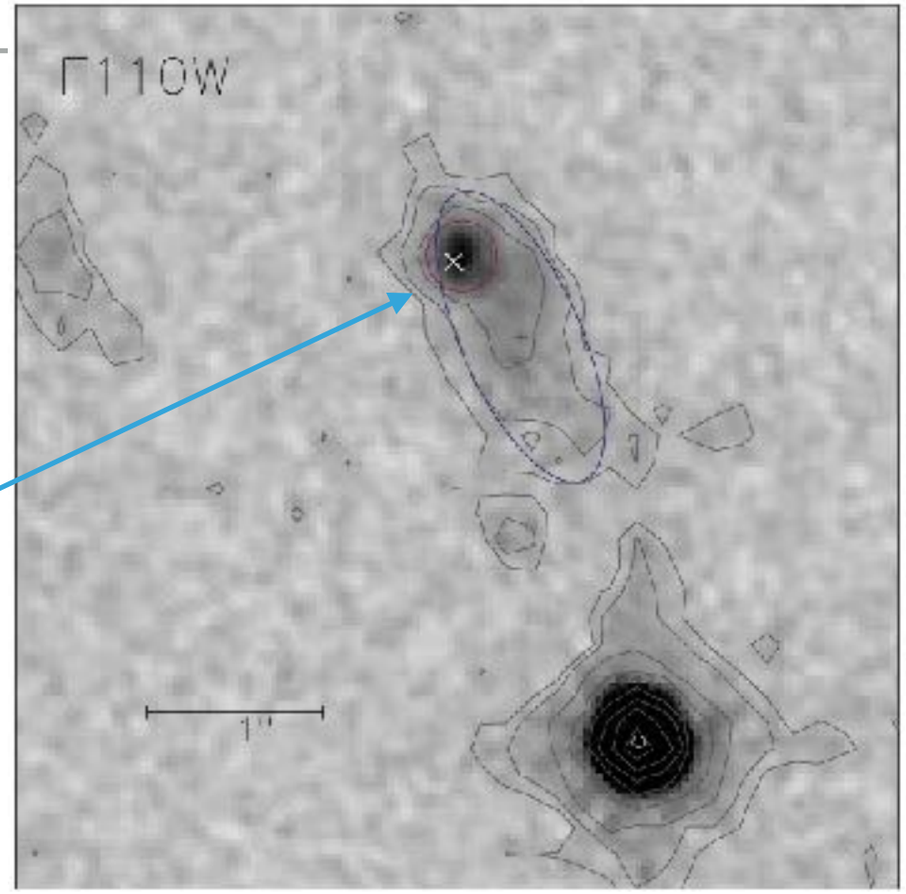
THANK YOU

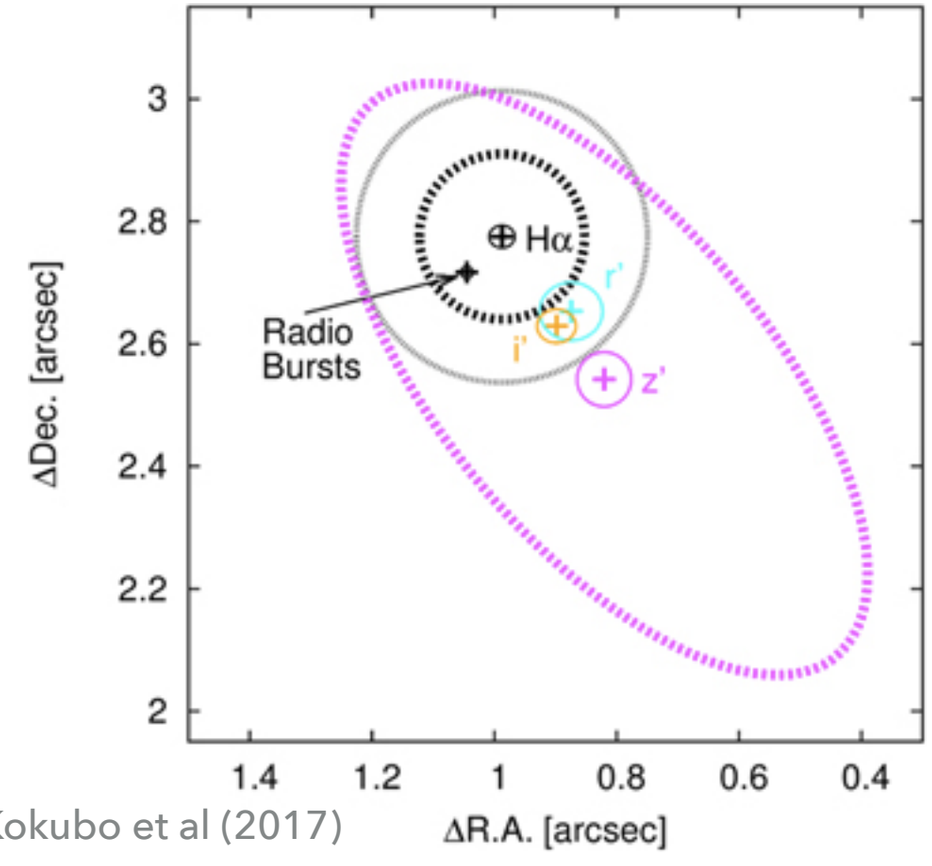
PART 5: THE OUTLOOK

POSITIONAL OFFSET

- VLBI position (5 mas; Marcote...SPT et al 2017)
- Near a star-forming knot in an irregular galaxy (Bassa, SPT et al 2017)
- AO imaging (Kokubo et al 2017)
- 260 pc offset between the peak star forming region

Bassa et al (2017)

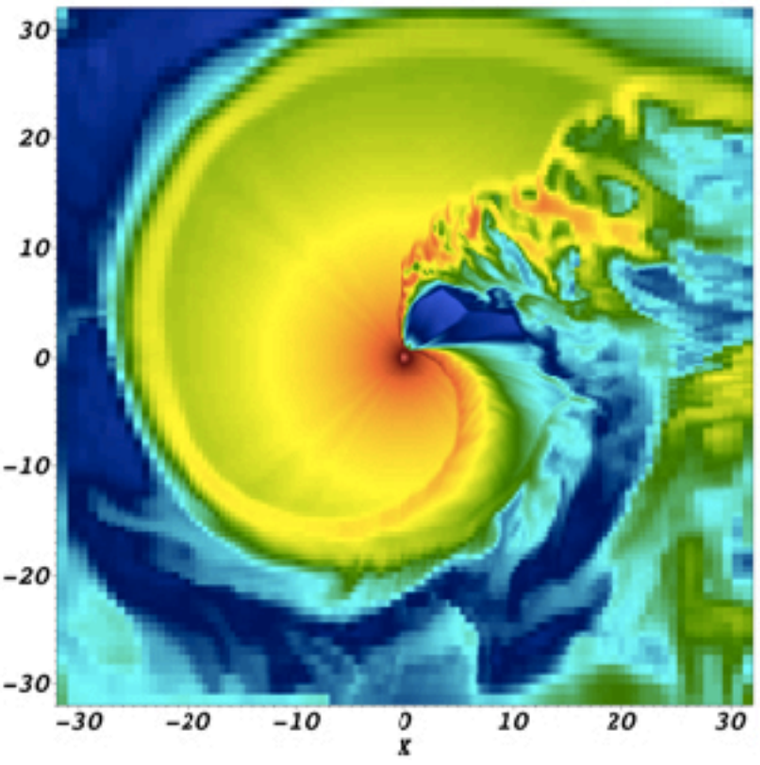


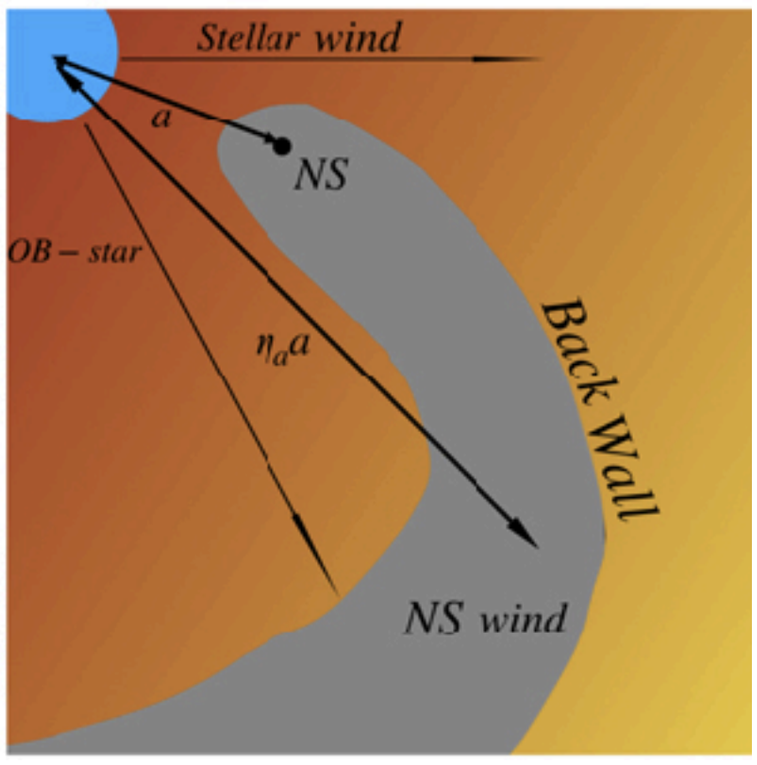


Kokubo et al (2017)

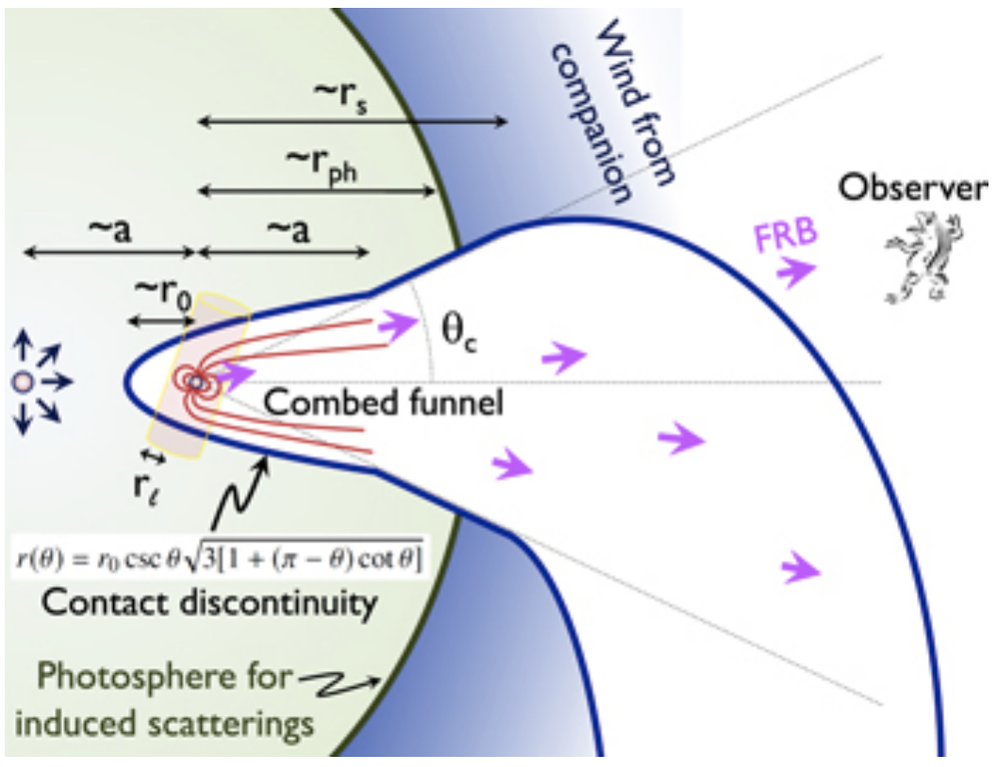
MODELS

Orbital Period





Pulsar in orbit around an OB star: Lyutikov et al (2020).
Simulations from Bosch-Ramon et al. (2015)

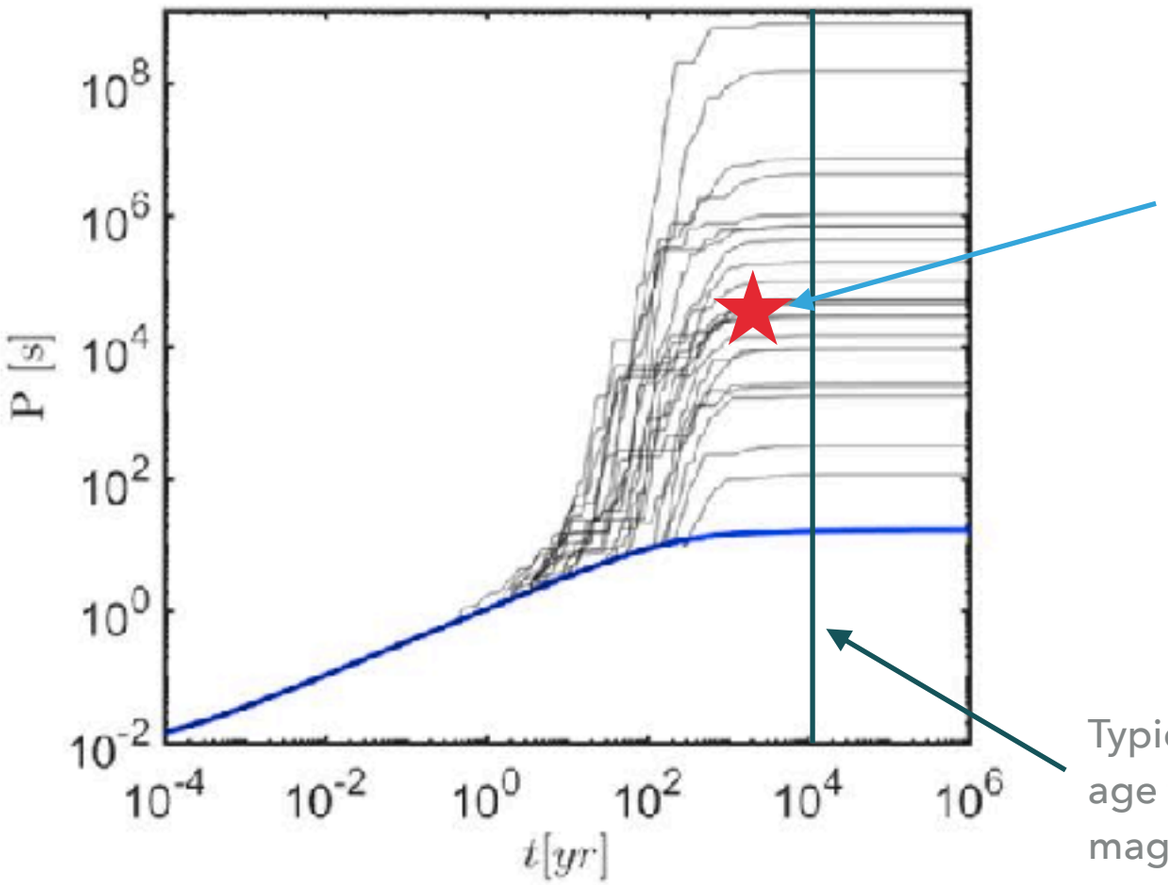


Similar model: Ioka & Zhang(2020).

Certainly possible, HMXBs, Gamma-ray binaries, have few day to 100-day periods

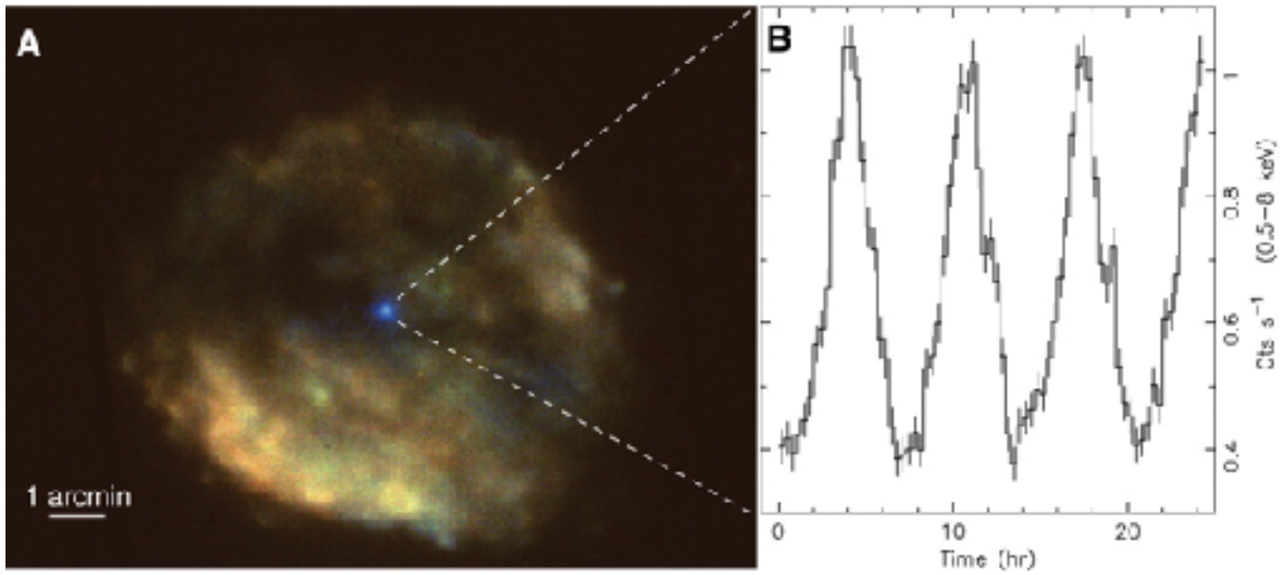
MODELS

Rotation Period of isolated magnetar



Ultra-long period magnetars (Beniamini et al 2020)

Typical active age for Galactic magnetars

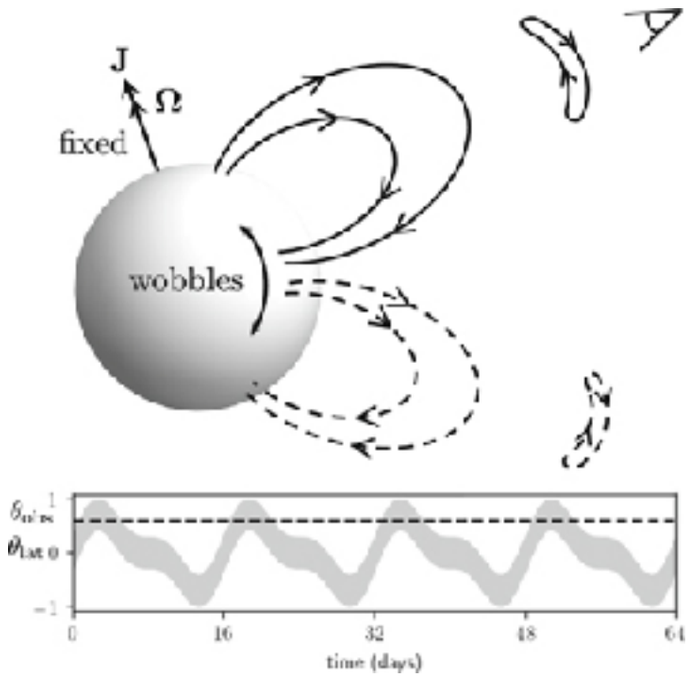


6.67 hr period from 1E161348–5055 (De Luca et al 2006)

Canonical magnetars could slow down soon after birth through a loaded wind

MODELS

Precession Period

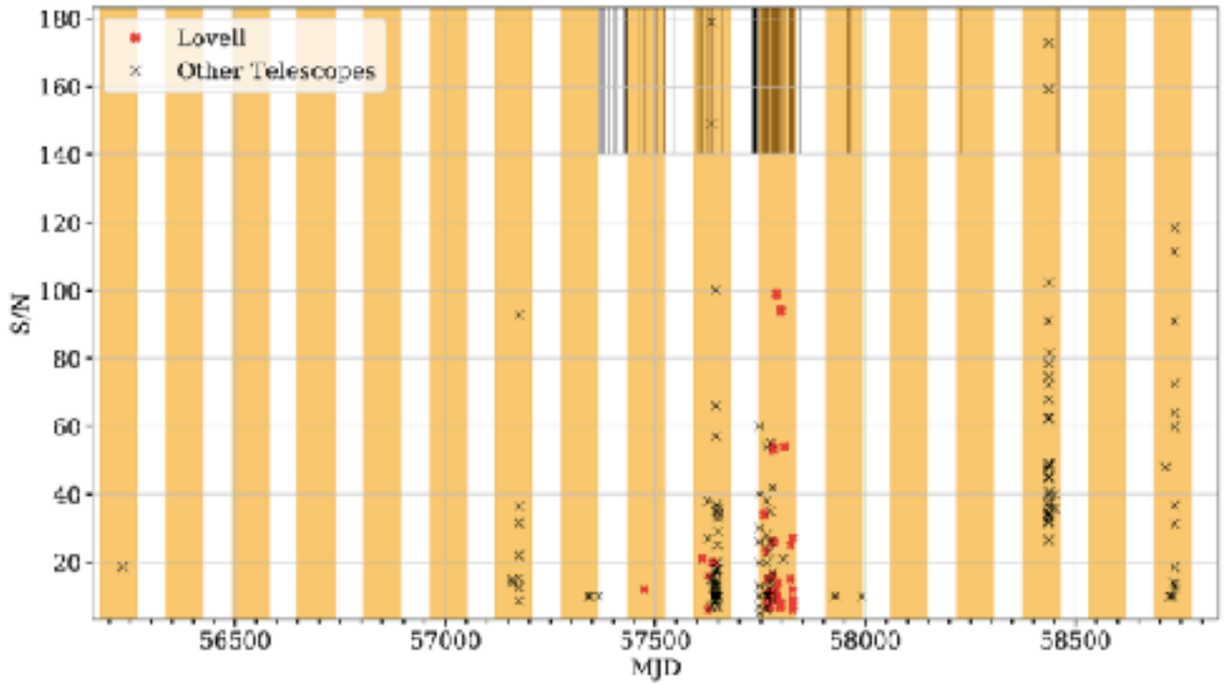


Hyperactive magnetar
with 10^{16} G field
Levin et al (2020)

A very strong magnetic field (10^{16} G) diffuses and causes warps and deformations.

–> Wobbling and precession

PERIODICITY IN FRB 121102 TOO



Rajwade et al 2020

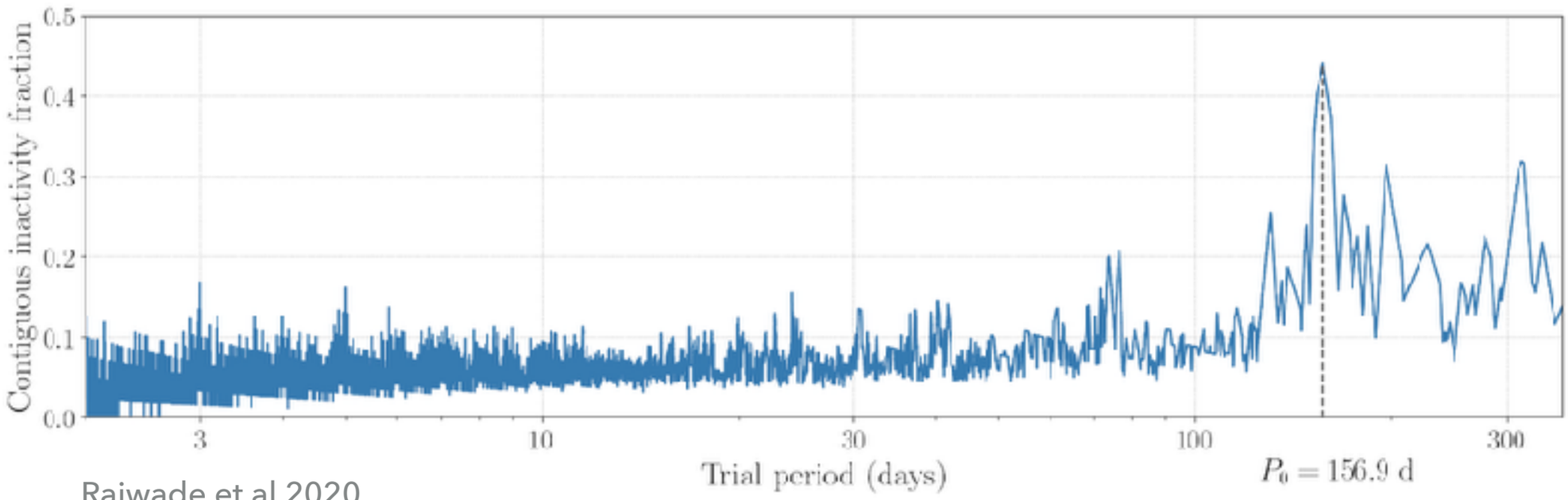
Apparent periodicity of 157 days

(Rajwade et al 2020)

Confirmed: 161+/- 5 days

(Cruces et al 2020)

Really long for rotation!



Rajwade et al 2020

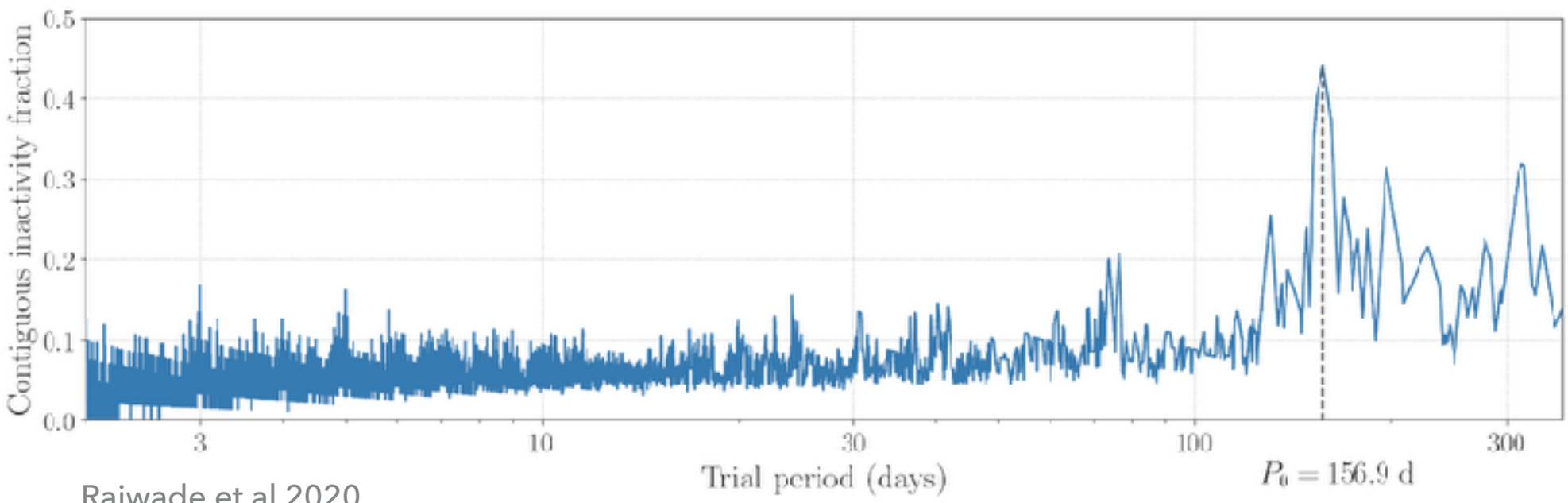
PERIODICITY IN FRB 121102 TOO

161 day period:

Hard to explain for rotation and precession — but achievable through tweaking B-field

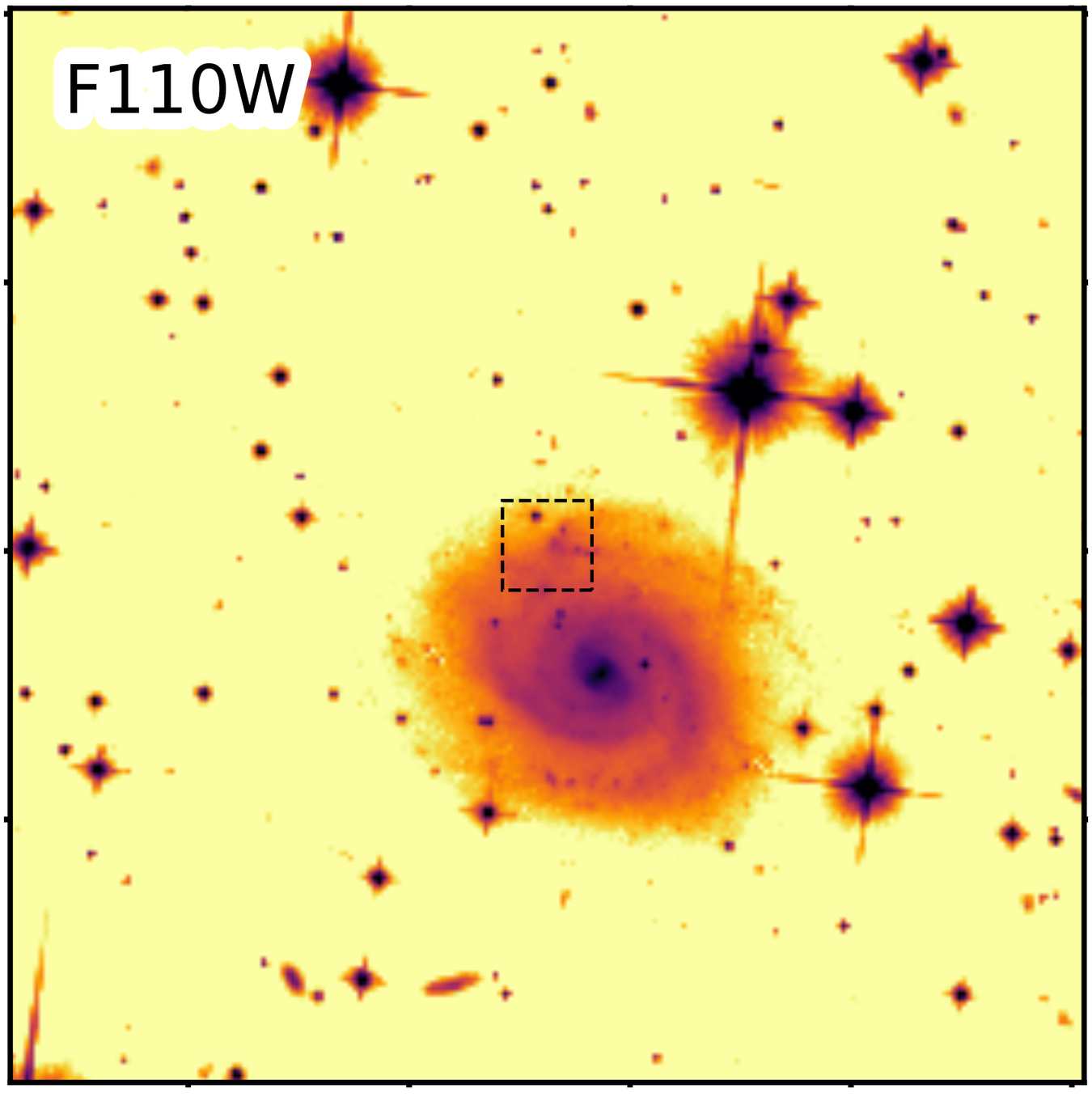
Natural for orbital periods

Rajwade et al 2020



Rajwade et al 2020

IS FRB 180916 A BINARY?



Tendulkar et al (2020), in review

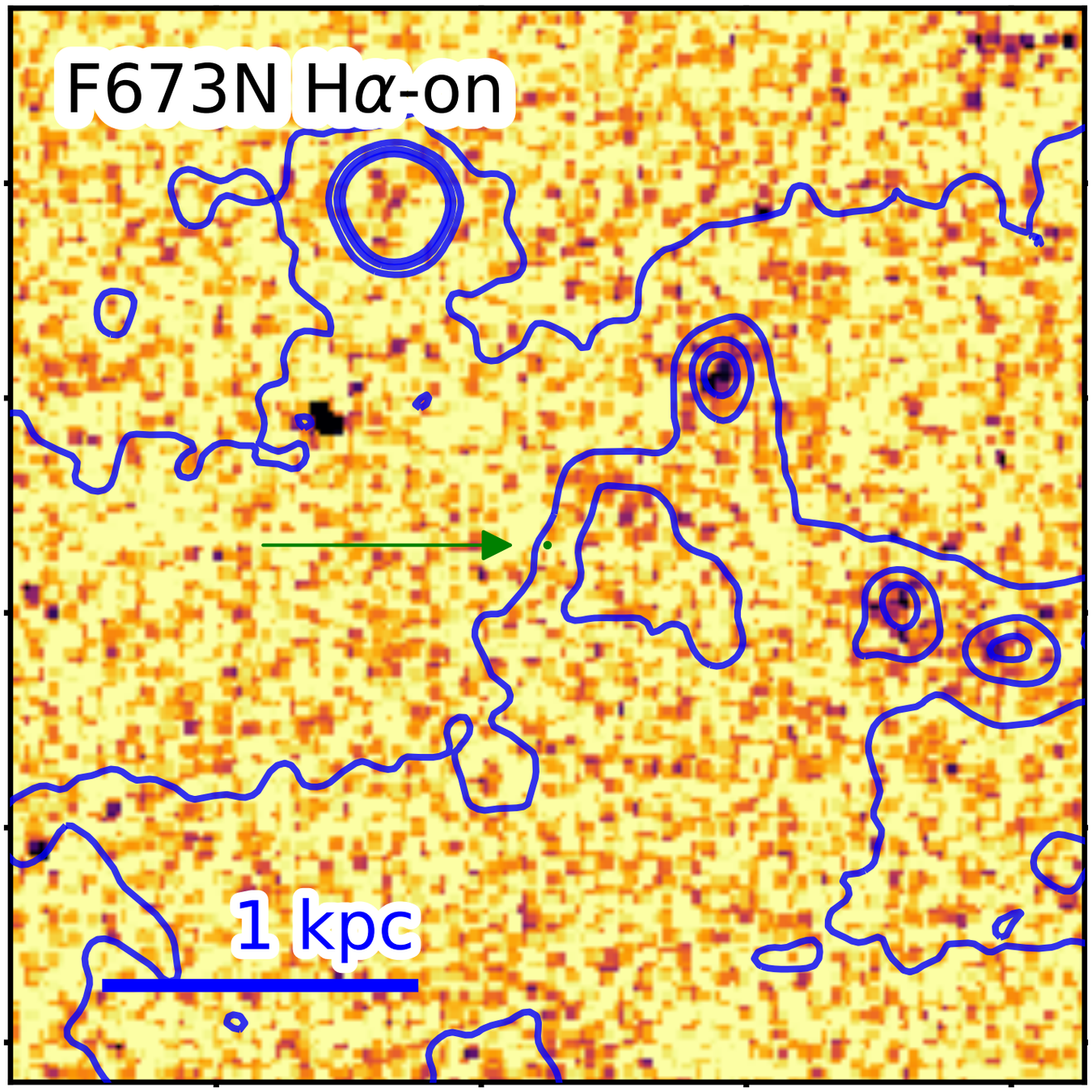
IS FRB 180916 A BINARY?

Halpha traces star-formation rate via young, massive, bright stars

Halpha at the FRB location constrained to 10^{37} erg/s

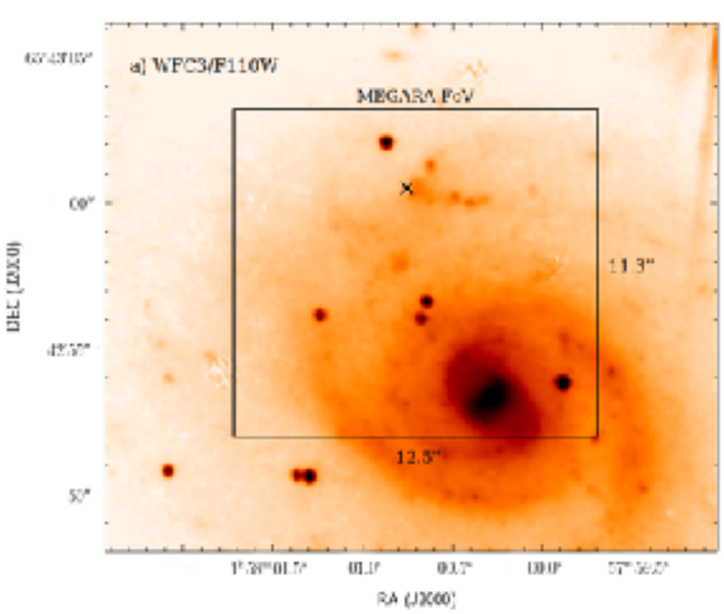
–> SFR < 10^{-4} Msun/year

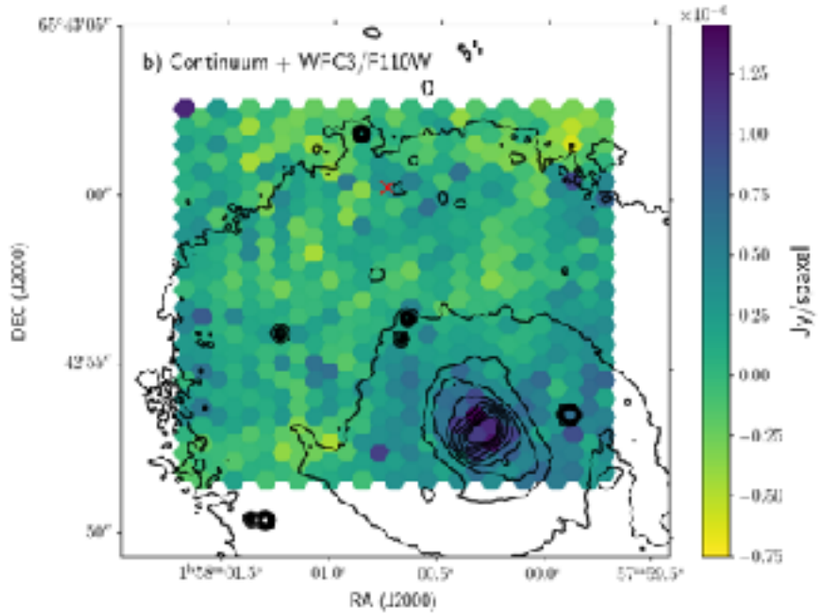
–> Any star > O6V

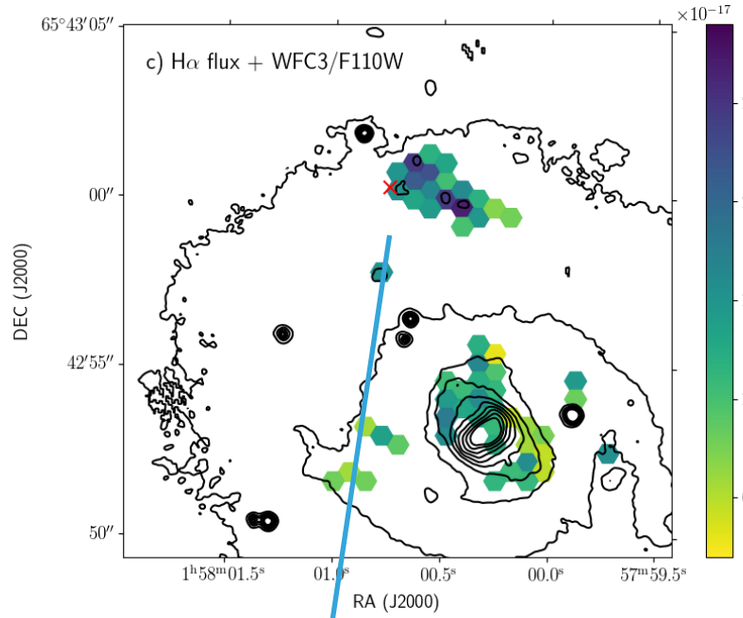


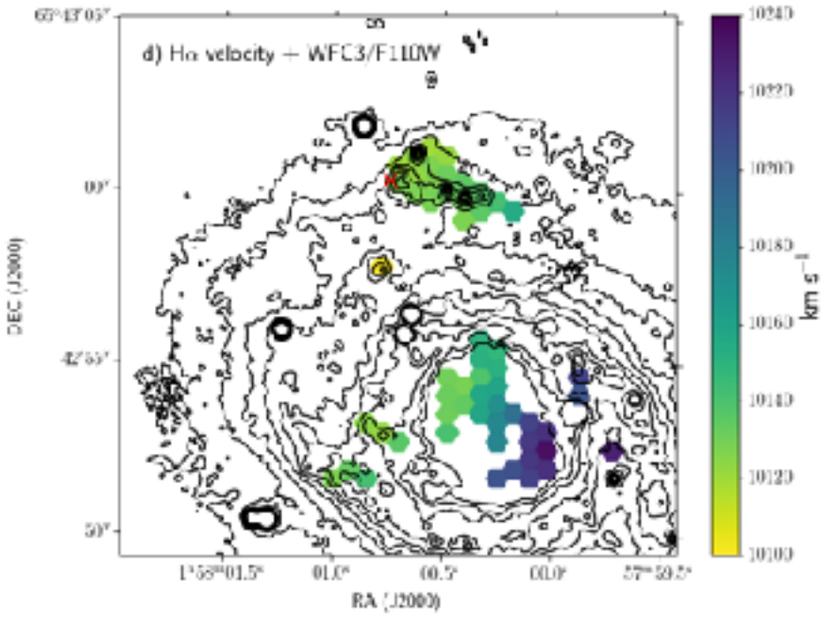
Tendulkar et al (2020), in review

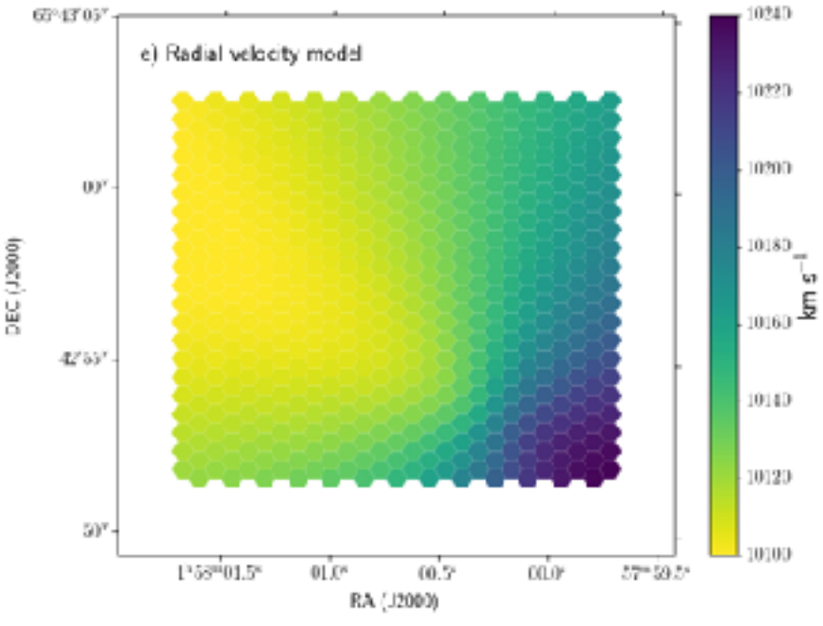
IFU SPECTROSCOPY











V-shaped structure is a part of the spiral arm, not separate satellite galaxy

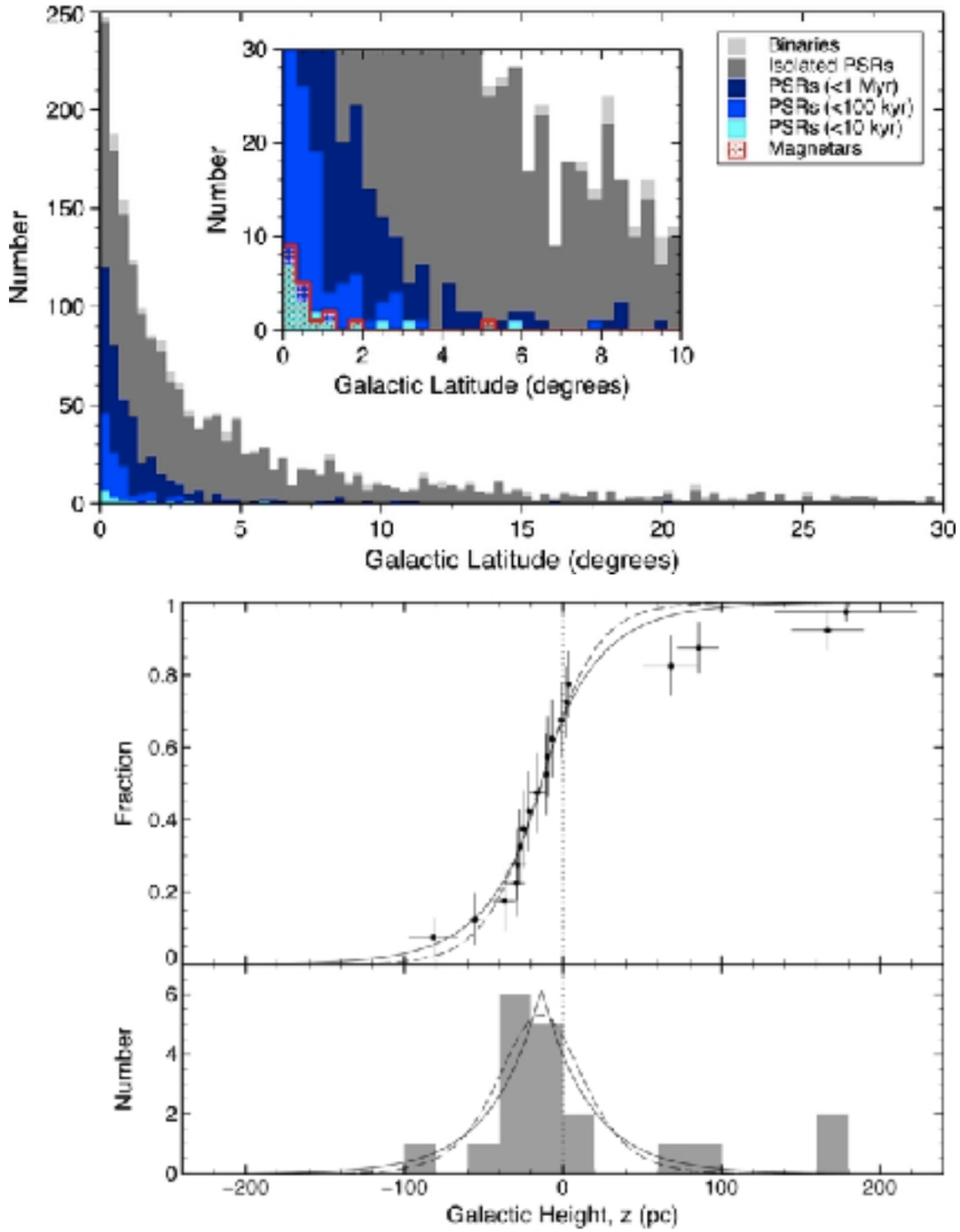
Little star formation at FRB location

WHERE DOES THE 250 PC OFFSET COME FROM?

A 250 pc offset from a star-forming region is significant

Magnetars are young (<10 kyr)
Found near SF regions

Magnetar scale height –>
20-30 pc (little dispersion)



Olausen & Kaspi (2014)

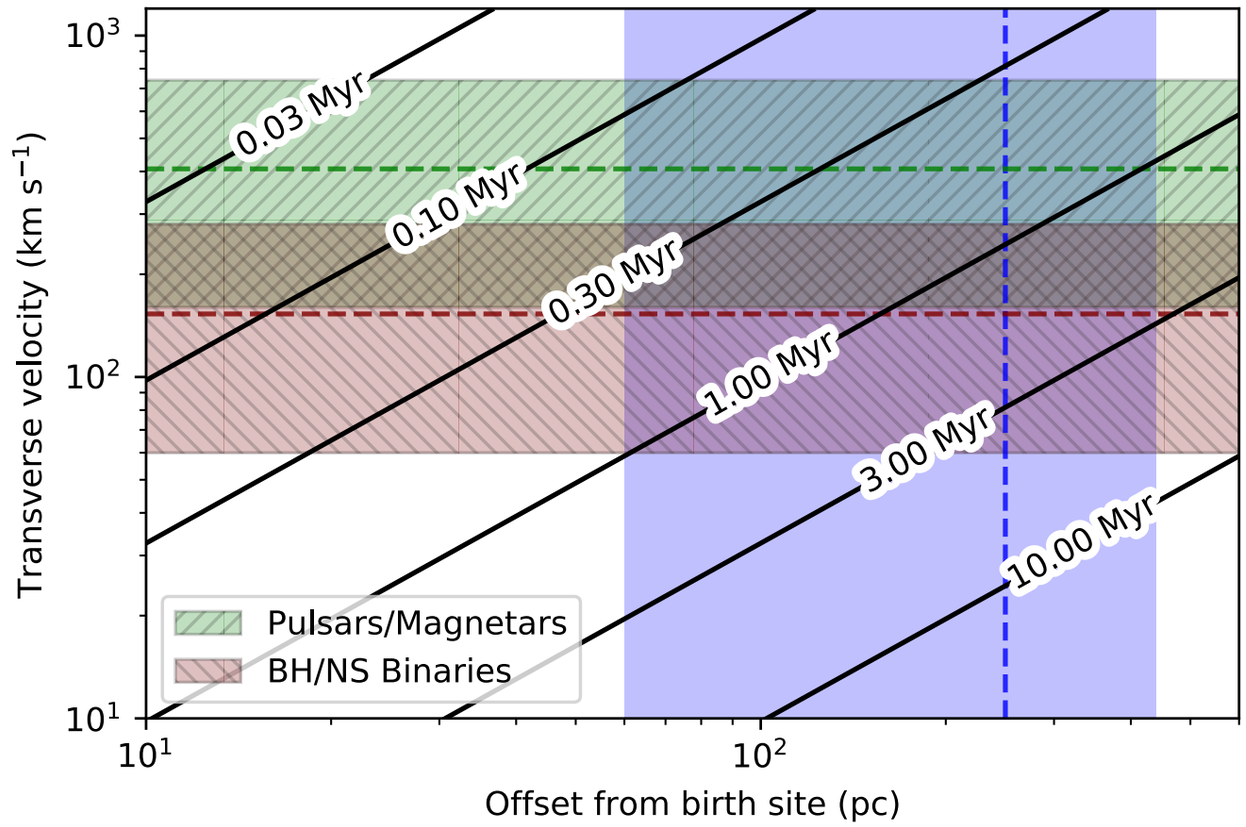
WHERE DOES THE 250 PC OFFSET COME FROM?

A 250 pc offset from a star-forming region is significant

Magnetars are young (<10 kyr)
Found near SF regions

Magnetar scale height –>
20-30 pc (little dispersion)

HMXBs show ~400 pc offsets from nearby SF regions (Bodaghee & Tomsick 2014)



Age is not an issue since activity is driven by the orbit not by the magnetar's flaring

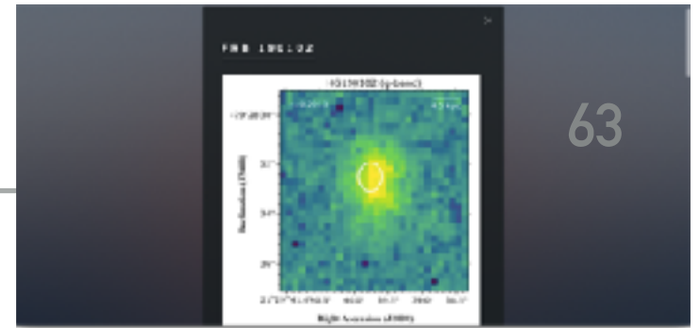
SO WHAT CAN IT BE

- Unlikely to be Galactic magnetar analog unless
  - magnetar formed from a runaway OB star?

    few % of OB stars are ejected at high velocities, live for few Myr, enough time to travel 250 pc
    much lower rate of formation
  - Magnetar formed from alternative mechanisms (AIC?)

    also much lower rate
- Periodicity, position all suggest OB star binary

  late O or early B star (fainter than O6V)

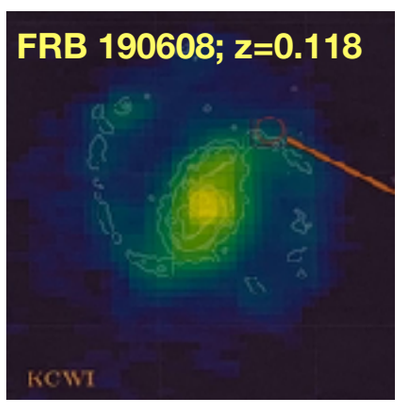


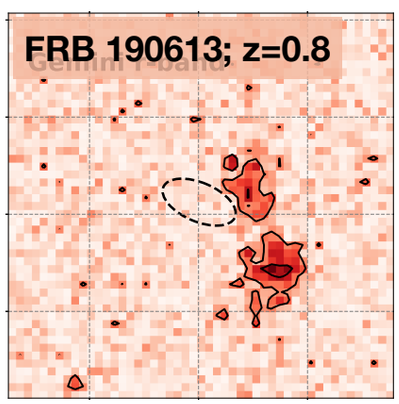
HOST CHARACTERISTICS

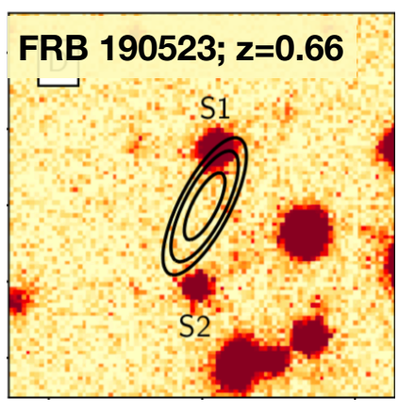
https://frbhosts.org

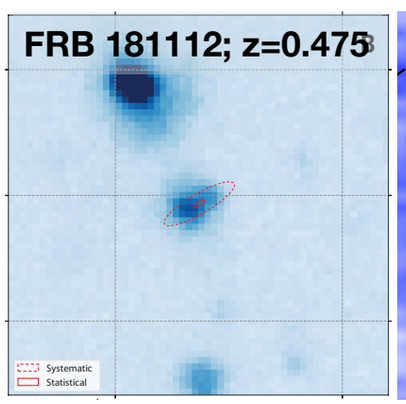
Active/Star-forming ⟷ Quiescent

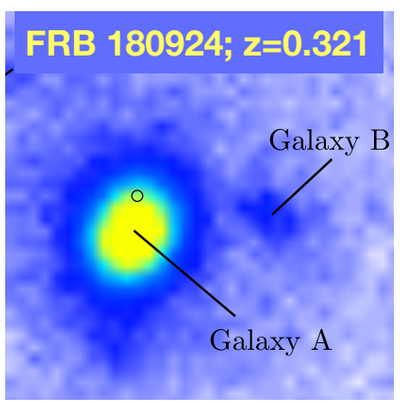
Non-repeaters



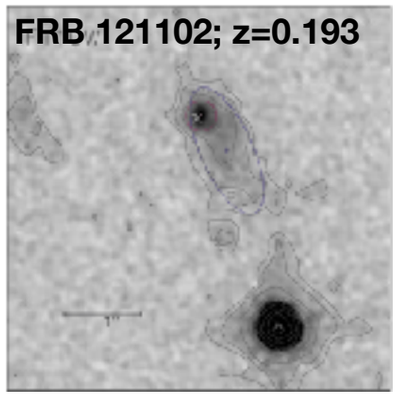


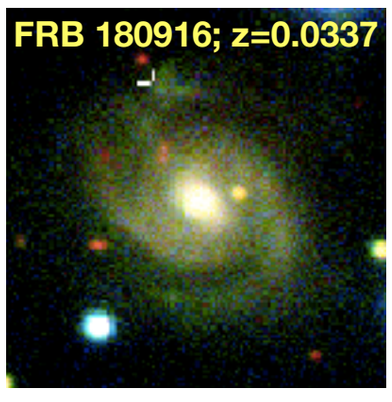


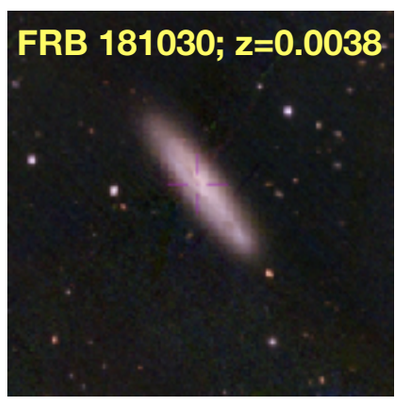




Repeaters





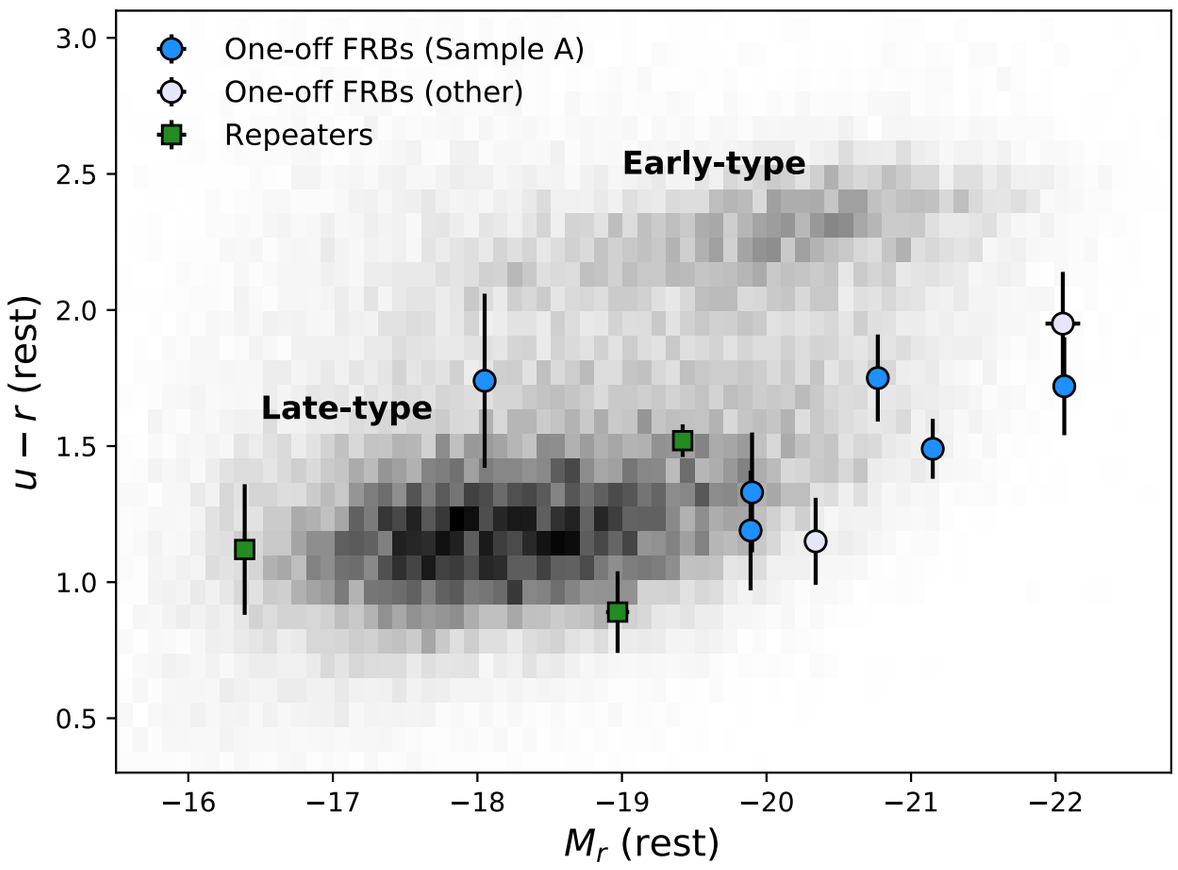


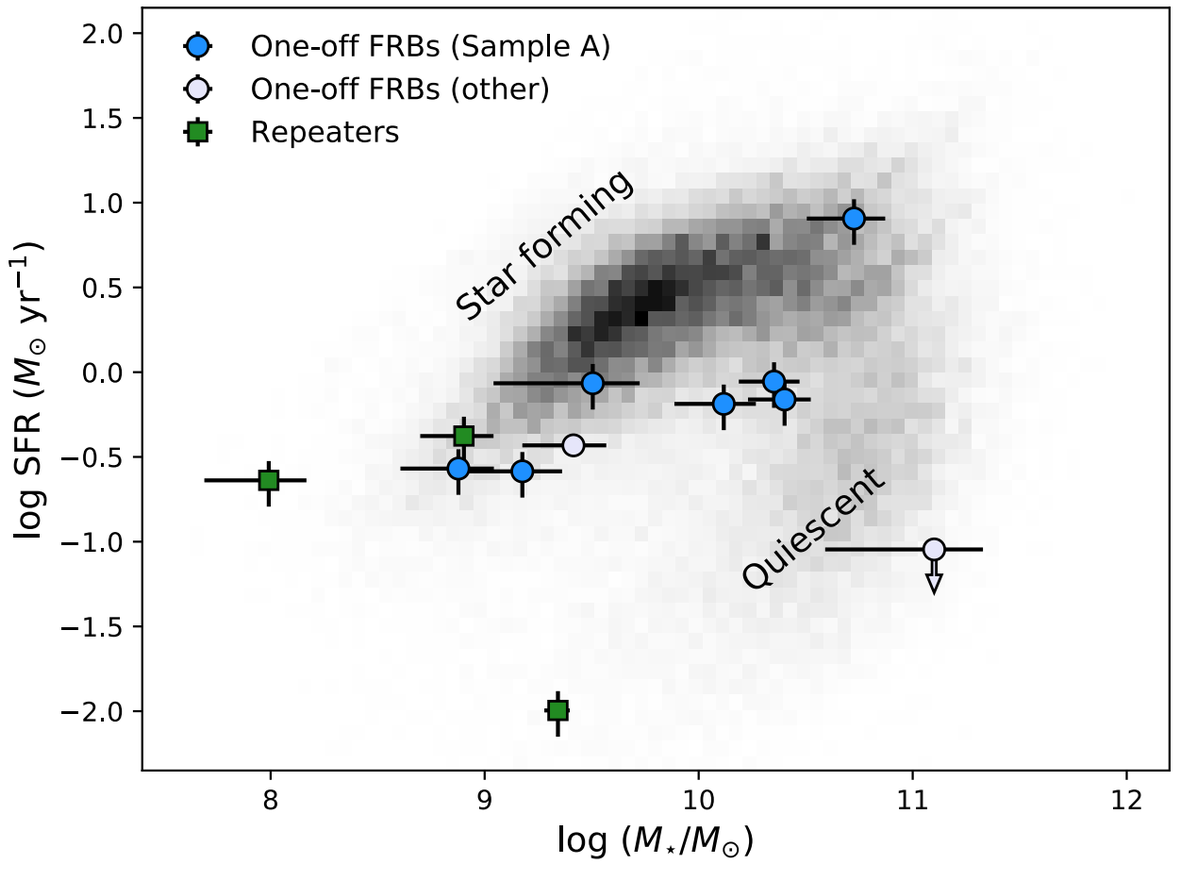
Probabilistic association
(R4 – NGC 3252, 20 Mpc)

References:
FRB 121102 — Chatterjee+ 2017
FRB 180916 — Marcote+ 2020
FRB 190608 — Chittidi+ 2020
FRB 190613 — Law+ 2020 (in review)
FRB 190523 — Ravi+ 2019
FRB 181112 — Prochaska+ 2019
FRB 180924 — Bannister+ 2019

HOST CHARACTERISTICS

Range of host properties, but
repeater hosts are typically lighter





Heintz et al (2020)

IMPORTANCE OF VLBI + HST

- Statistically, FRB host properties are consistent with all Galactic magnetars (Bochenek et al 2020)
- But so are HMXBs
  No difference unless you look very closely
- Similar relation to SFR, stellar mass, even offsets from galaxy centers etc
- Understanding the local environment of FRBs is crucial

FOCUS ON THE NEAREST FRBS

- Even with VLBI and HST, need a sample of the nearest FRBs
  - Also likely to be bright and have X-ray/optical counterparts
- An FRB at z=1 is not useful for understanding mechanisms but is useful for cosmology without needing VLBI
- An FRB at 20 Mpc is the inverse
- CHIME/FRB detecting more and more repeaters, localizing them with VLBI
  Can’t do this for non-repeaters! :(

VLBI FOR NON-REPEATERS

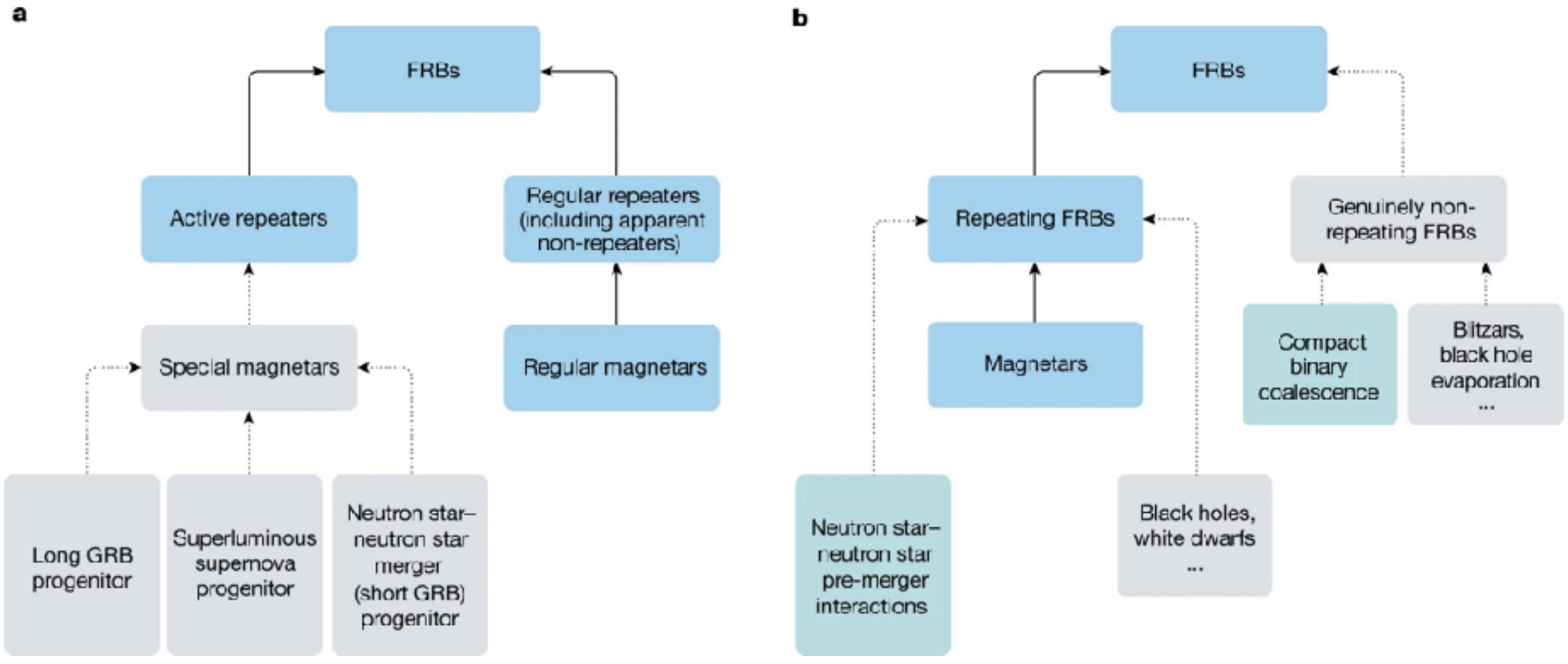
- VLBI telescopes are built for small field of view
  Cannot find non-repeating FRBs efficiently
- CHIME/FRB building outrigger telescopes
  Get 50 mas localization for every FRB (repeater and non-repeater)
- Aim to get ~1000 localized FRBs every year in 2 years!

CONCLUSIONS

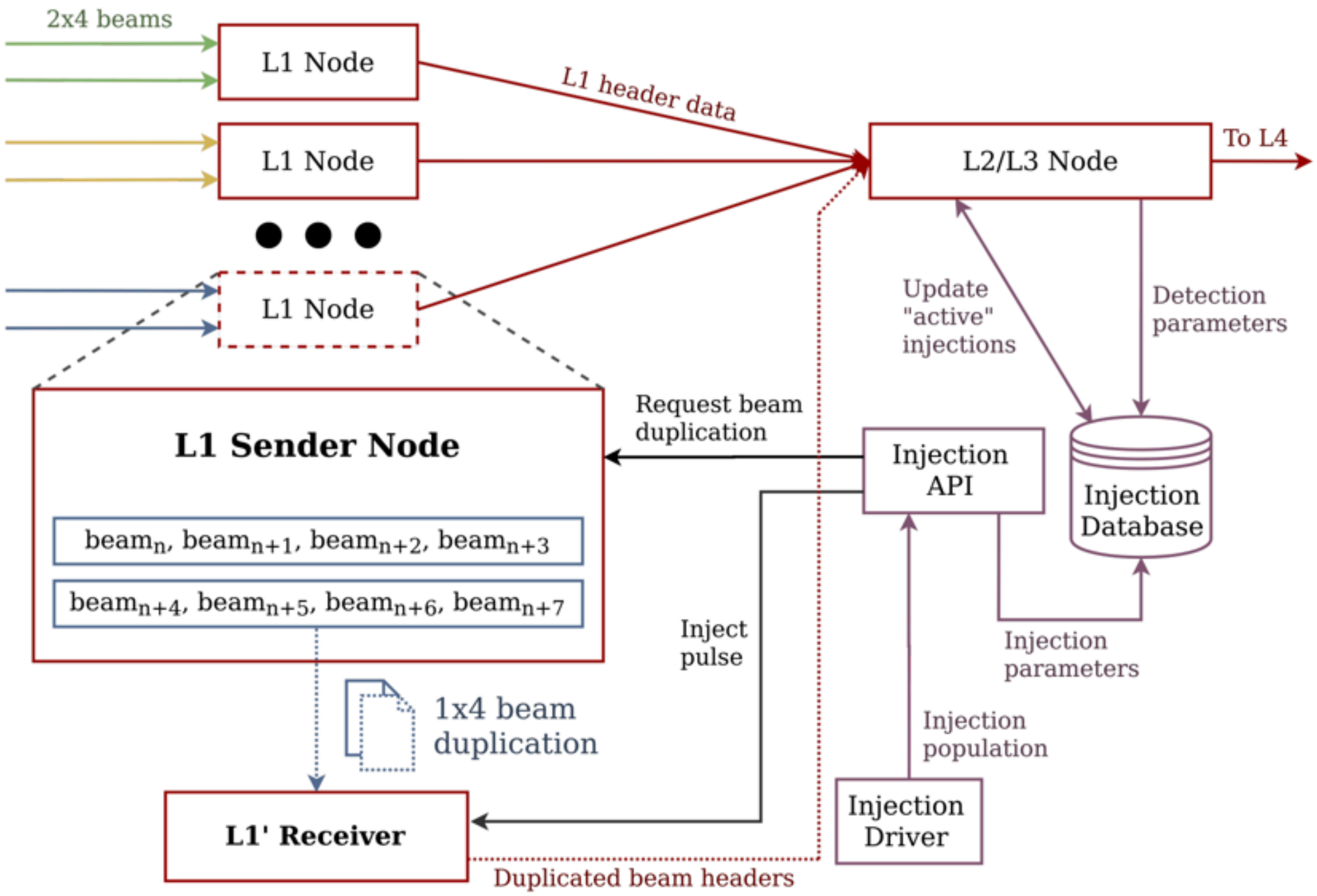
It is not sufficient to know which galaxy an FRB is coming from

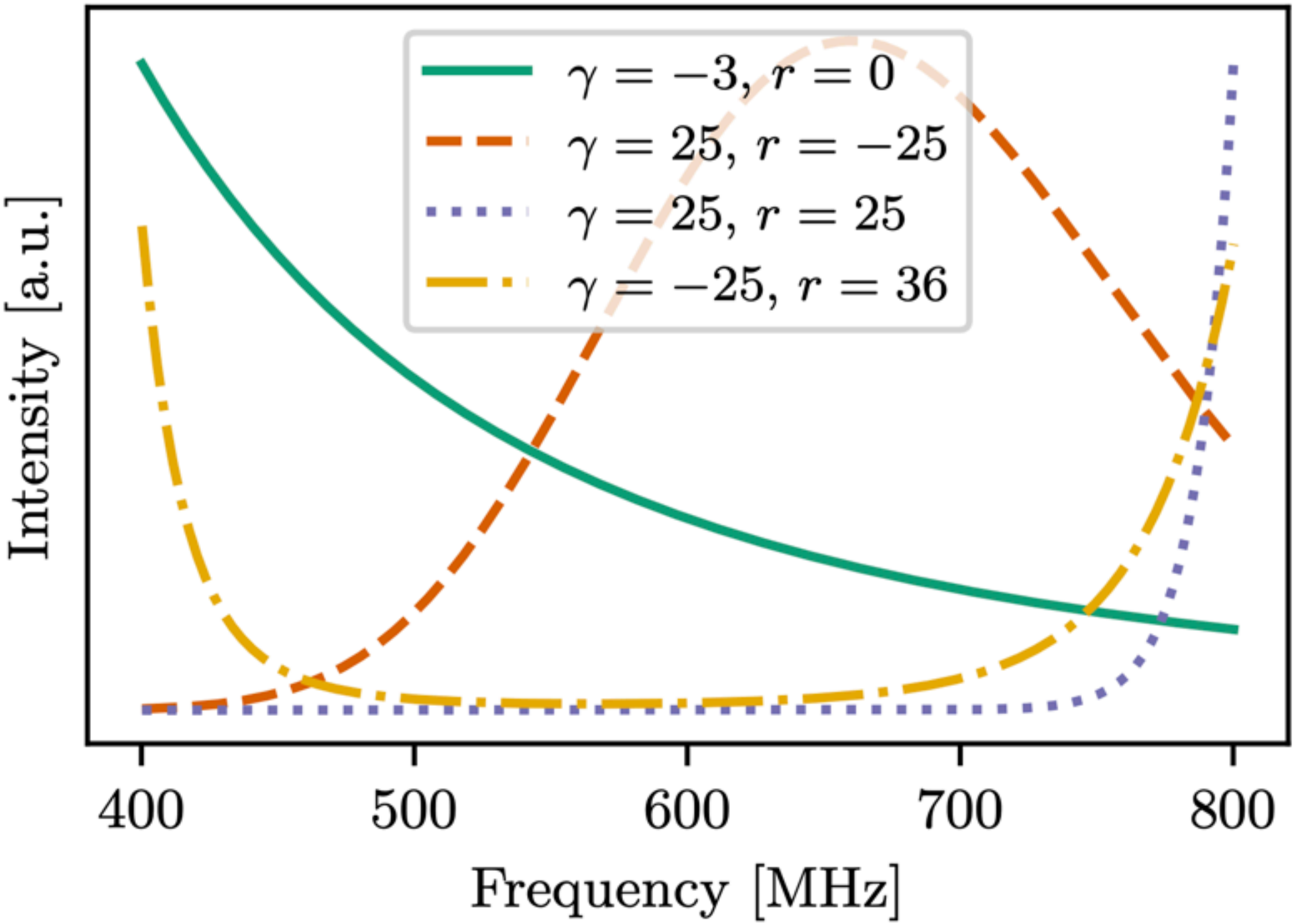
The local environment of FRBs is crucial to understand their astrophysical origins

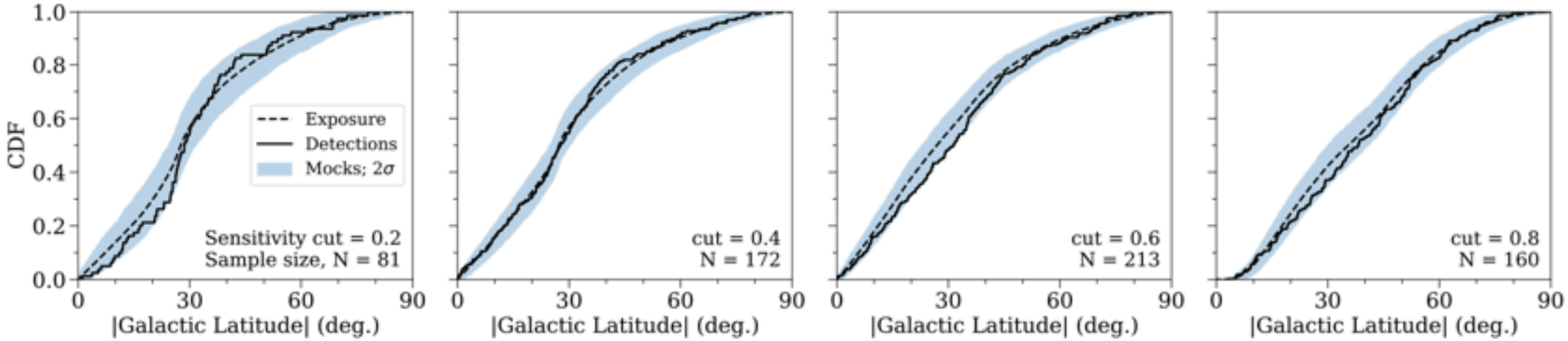
We have to focus on detecting and localizing the *nearest* FRBs

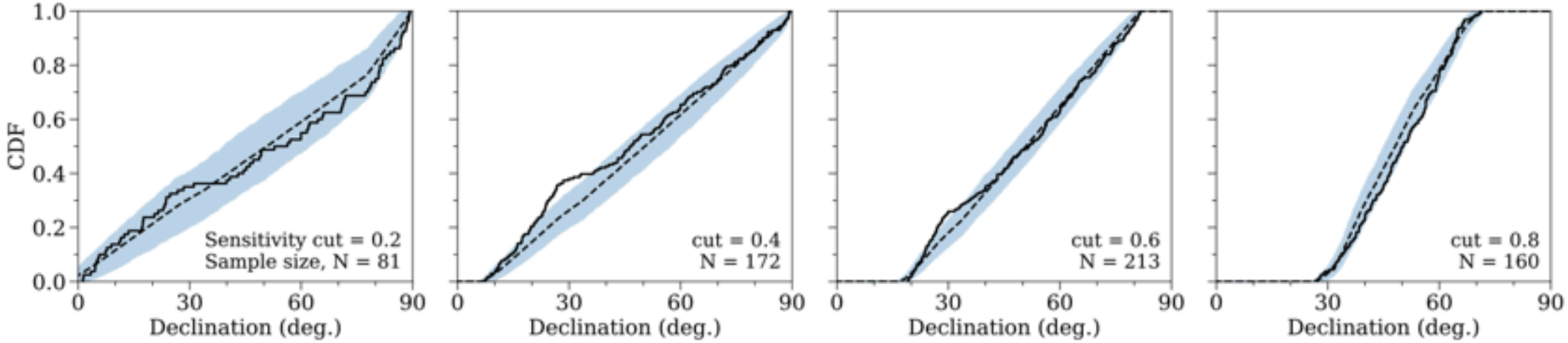


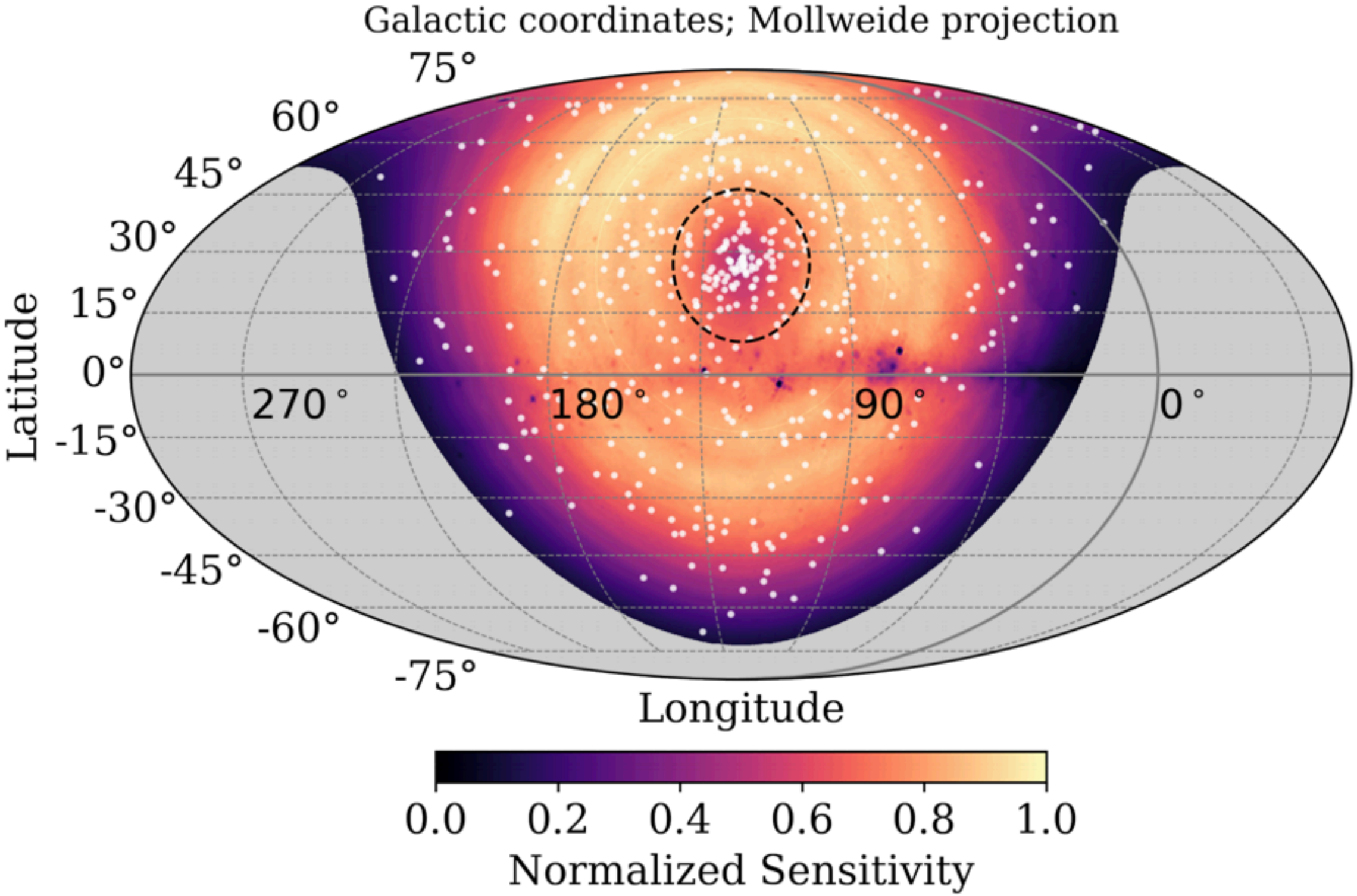
Zhang, B. (2020, Nature review article)

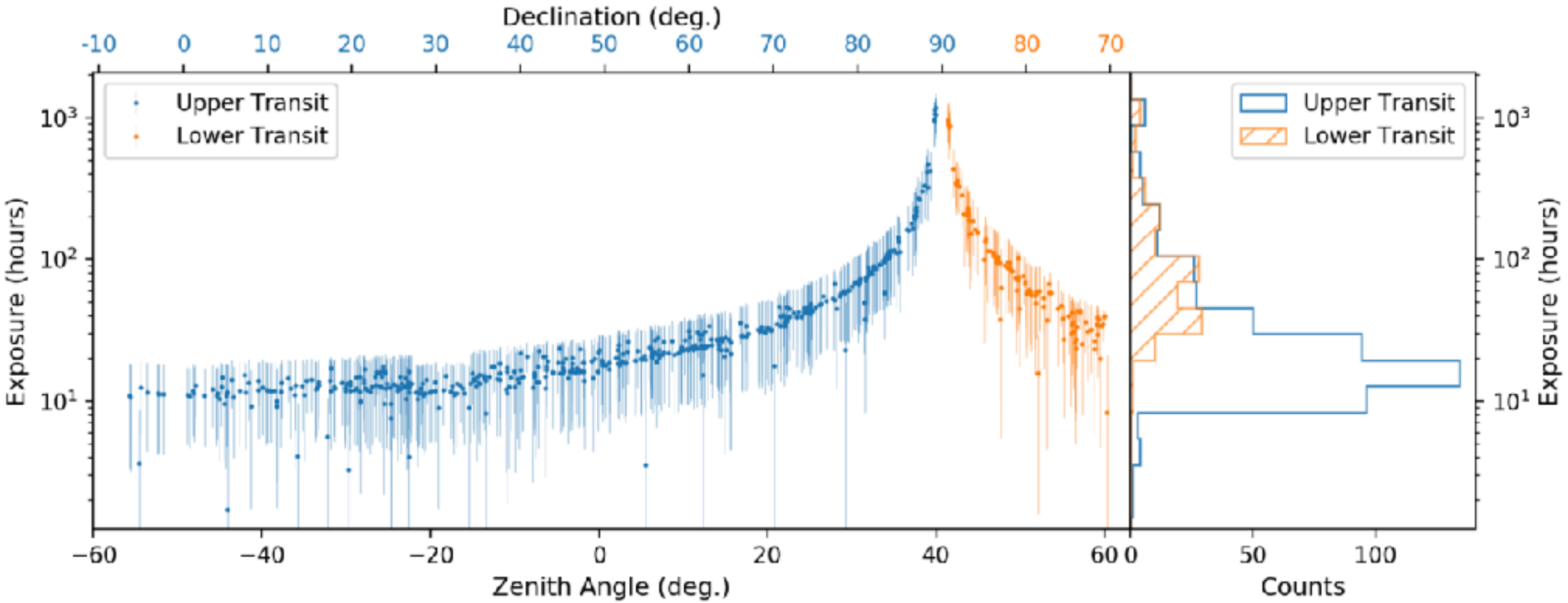

2x4 beams
L1 Node
L1 Node
L1 Node
L1 header data
L2/L3 Node
To L4
Update "active" injections
Detection parameters
L1 Sender Node
beam$_n$, beam$_{n+1}$, beam$_{n+2}$, beam$_{n+3}$
beam$_{n+4}$, beam$_{n+5}$, beam$_{n+6}$, beam$_{n+7}$
Request beam duplication
Injection API
Injection Database
Inject pulse
Injection parameters
Injection population
1x4 beam duplication
L1' Receiver
Injection Driver
Duplicated beam headers


$\gamma = -3, r = 0$
$\gamma = 25, r = -25$
$\gamma = 25, r = 25$
$\gamma = -25, r = 36$
Intensity [a.u.]
400
500
600
700
800
Frequency [MHz]

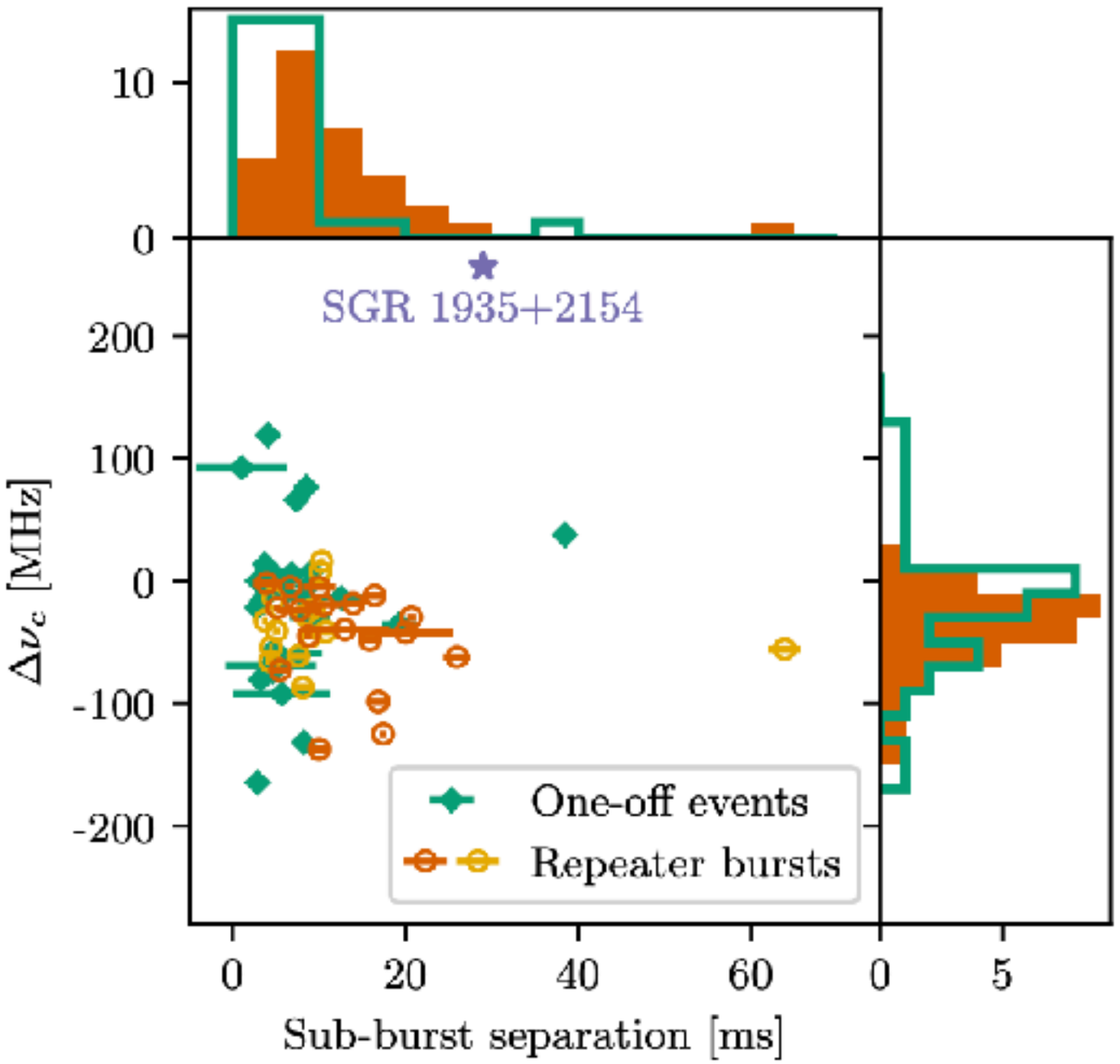

CDF
Exposure
Detections
Mocks; 2σ
Sensitivity cut = 0.2
Sample size, N = 81
cut = 0.4
N = 172
cut = 0.6
N = 213
cut = 0.8
N = 160
|Galactic Latitude| (deg.)


CDF
Sensitivity cut = 0.2
Sample size, N = 81
cut = 0.4
N = 172
cut = 0.6
N = 213
cut = 0.8
N = 160
Declination (deg.)


Galactic coordinates; Mollweide projection
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
Latitude
270°
180°
90°
0°
Longitude
0.0
0.2
0.4
0.6
0.8
1.0
Normalized Sensitivity


Declination (deg.)
-10
0
10
20
30
40
50
60
70
80
90
80
70
Upper Transit
Lower Transit
10^3
10^2
10^1
Exposure (hours)
−60
−40
−20
0
20
40
60
Zenith Angle (deg.)
0
50
100
Counts

DOWNWARD DRIFT VS SEPARATION



ENERGETICS

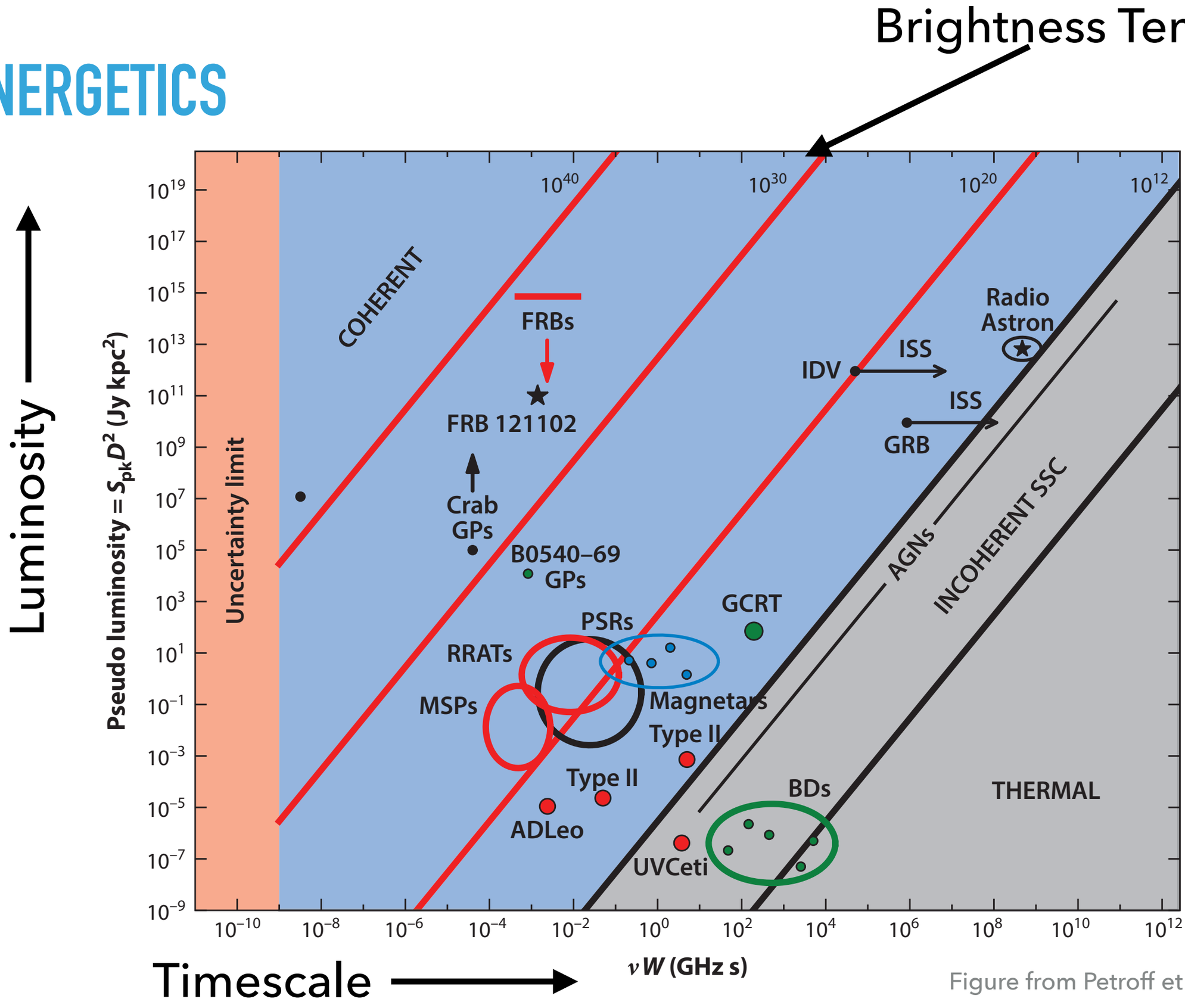


Figure from Petroff et al (2019)

WHAT ARE THEY?

- ~10^{10-12} times brighter than Crab giant pulses

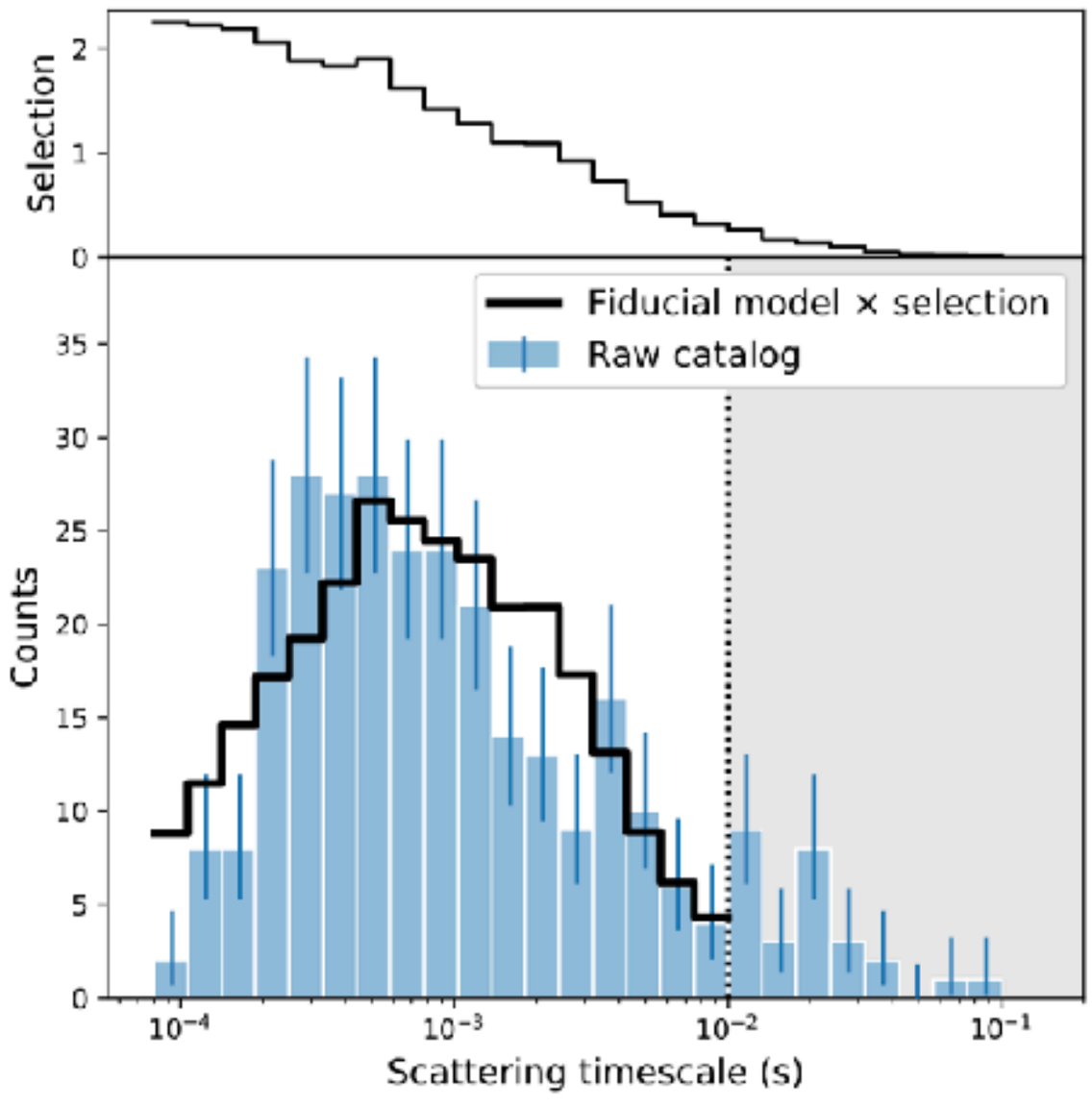
http://frbtheorycat.org Platts .. SPT et al 2019

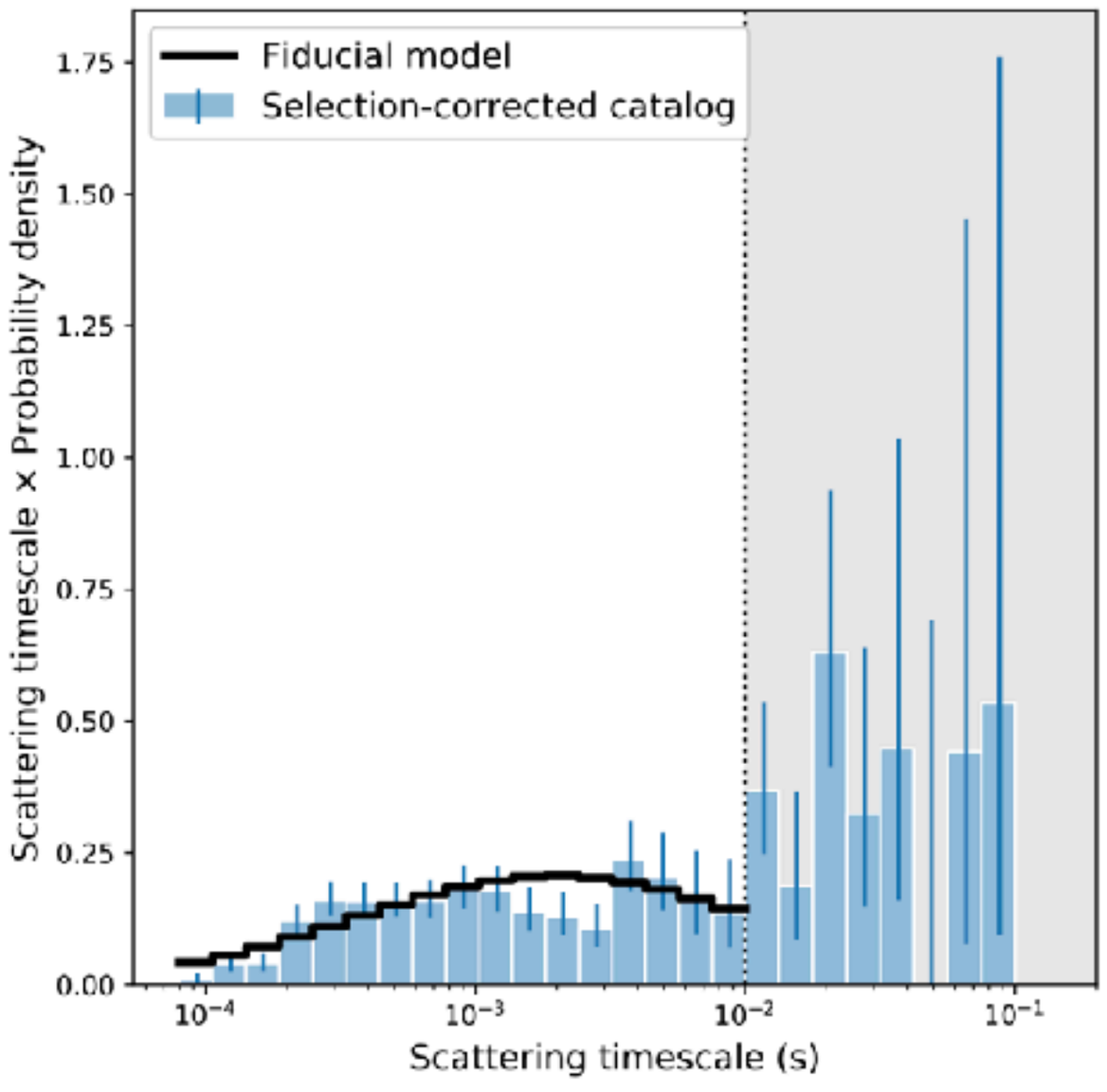
Fuel	→	Engine	→	Transmission
(stores energy)		(sources energy)		(converts energy to EM)
Magnetic Field		Magnetic Reconnection		Synchrotron Radiation
Rotational Energy		Magnetic Acceleration		Curvature Radiation
Kinetic Energy		Shocks		
Gravitational Potential				

PART 4: THE SCATTERING

FRB SCATTERING

- There are many FRBs that are highly scattered!

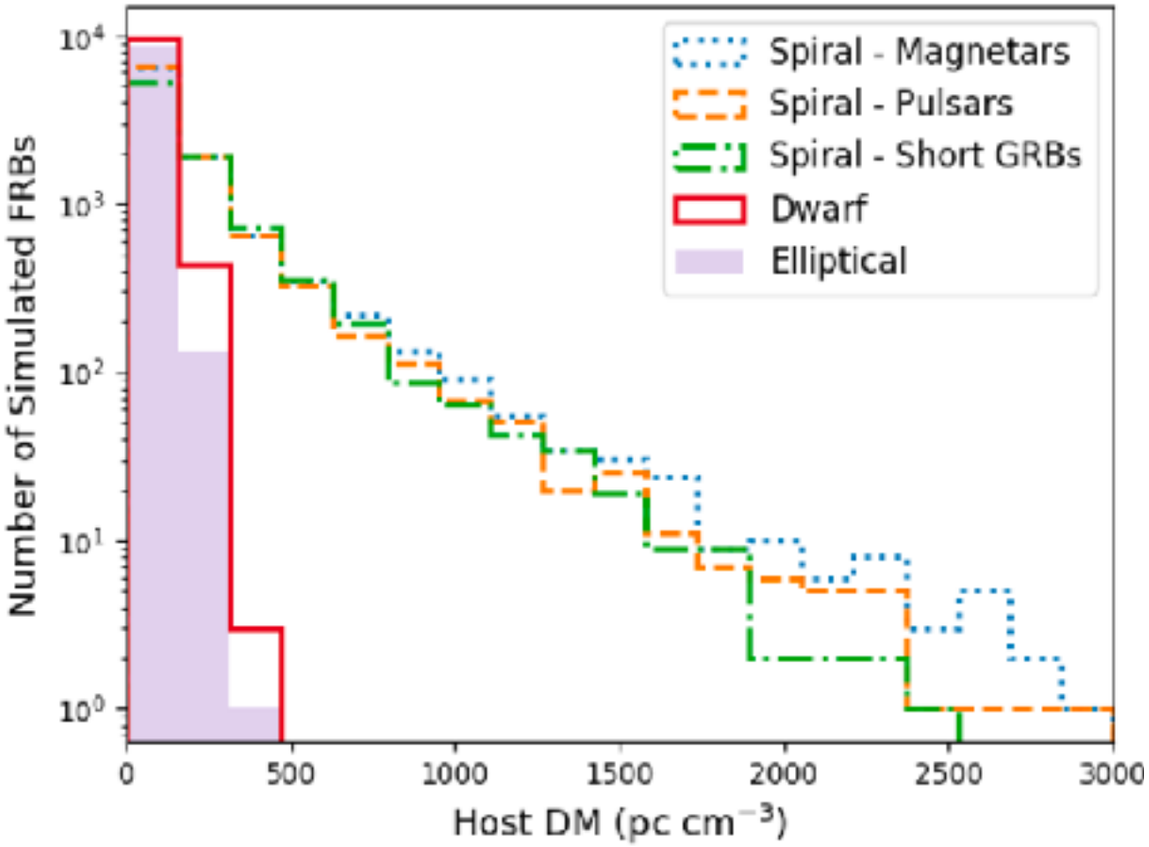


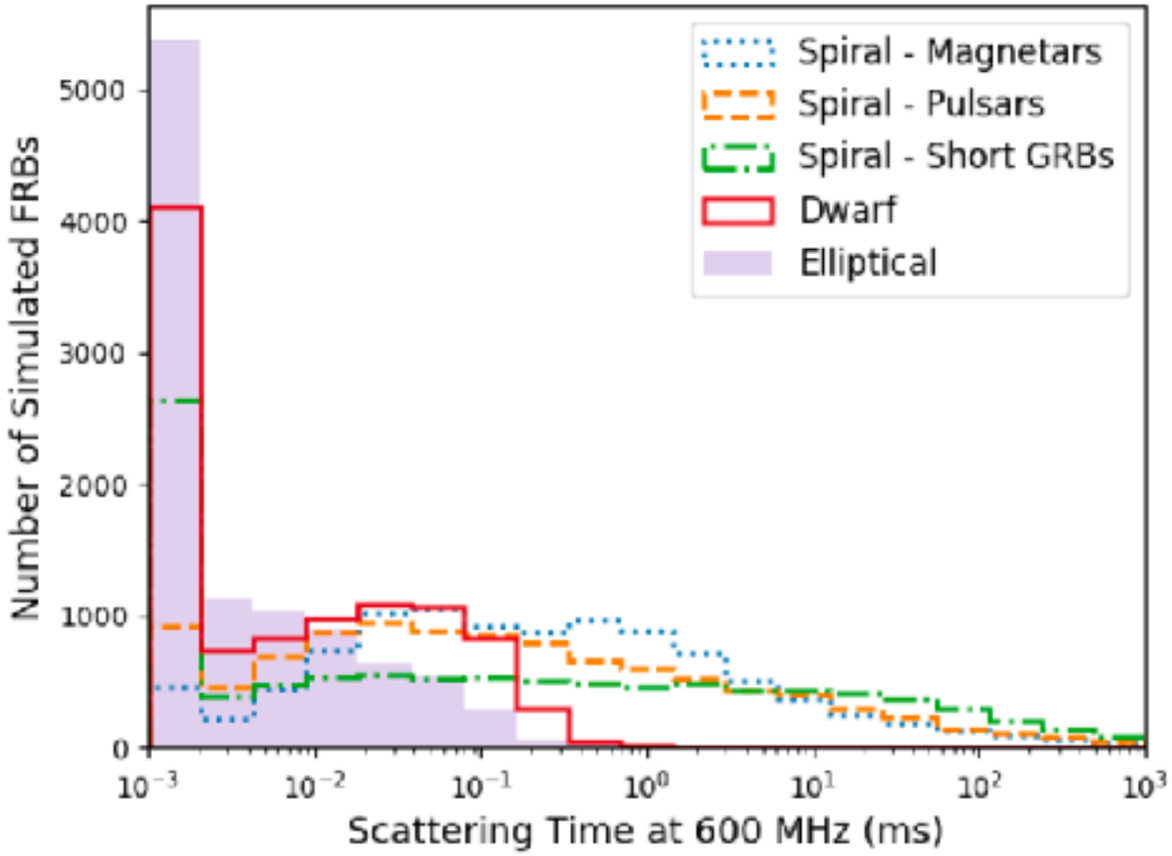


SIMULATING FRB SCATTERING

Chawla P. et al (2021)

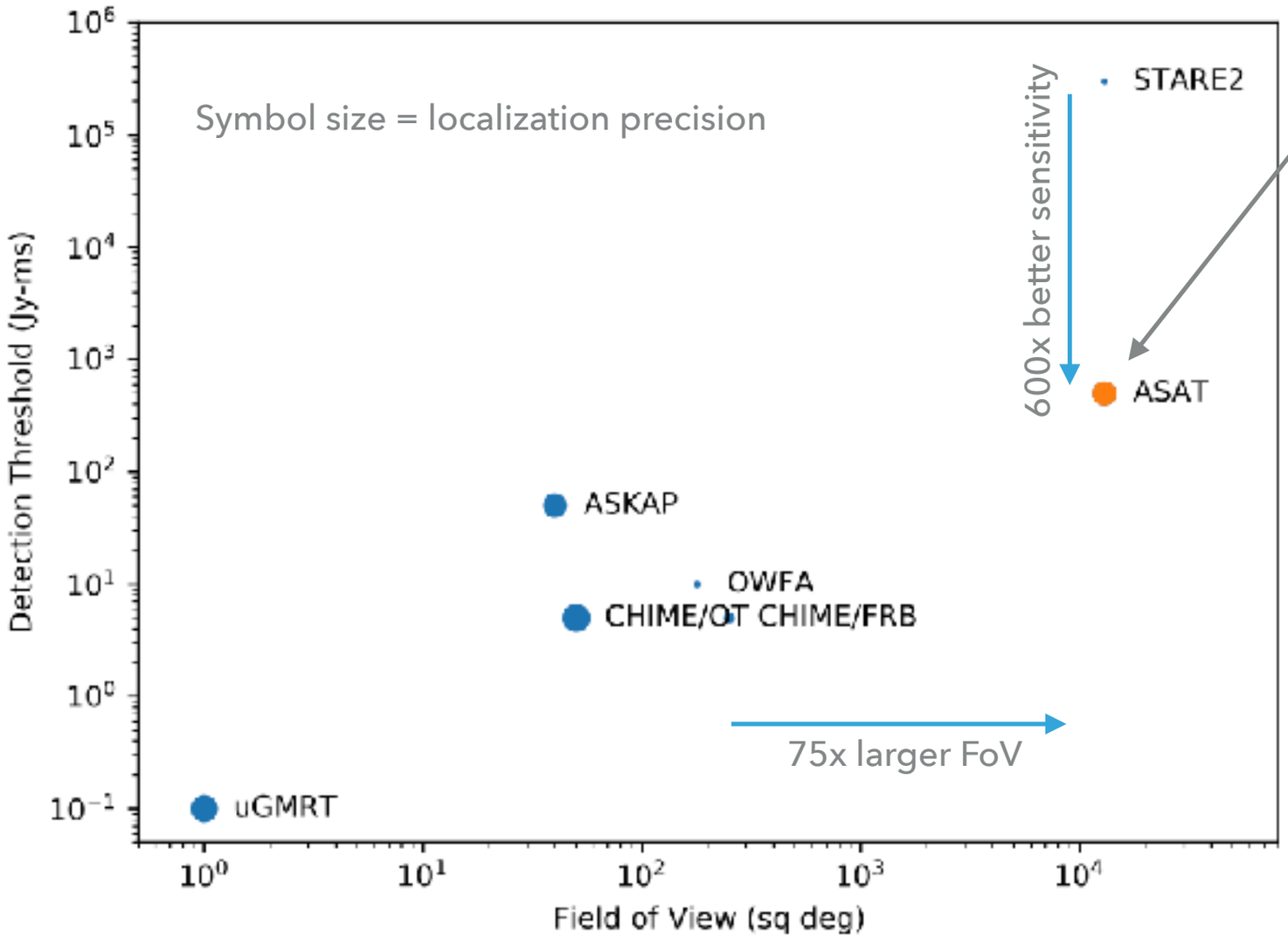
- Build a Universe, populate it with galaxies (spiral, elliptical, dwarf)
- Populate galaxies with FRB sources similar to pulsars, magnetars, SGRBs etc.





PART 2: THE CATALOG

ALL SKY TRANSIENT RADIO ARRAY (ASTRA)

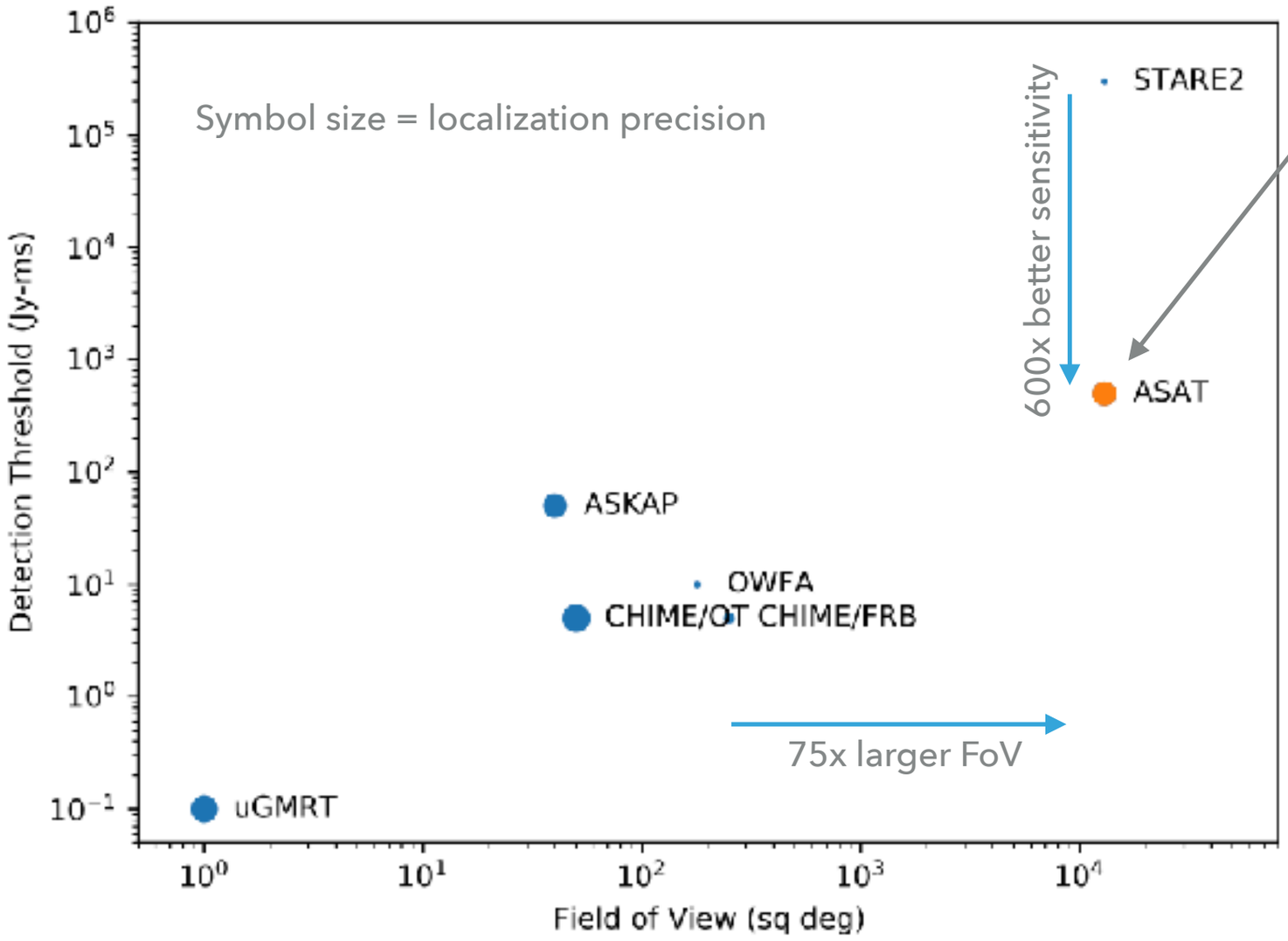


ASTRA

- Array of open feeds between 400–500 MHz
- Multiple stations separated by 10–30 km
- ~15000 sq deg FoV, 500 Jy-ms sensitivity
- Detect 1–2 ultra-bright FRBs per month
- Sub-arcsecond localization
- Also respond to external triggers (LIGO, GCN, Daksha etc)

Pilot project development started at TIFR, NCRA, with help from RRI, ASIAA and other collaborators

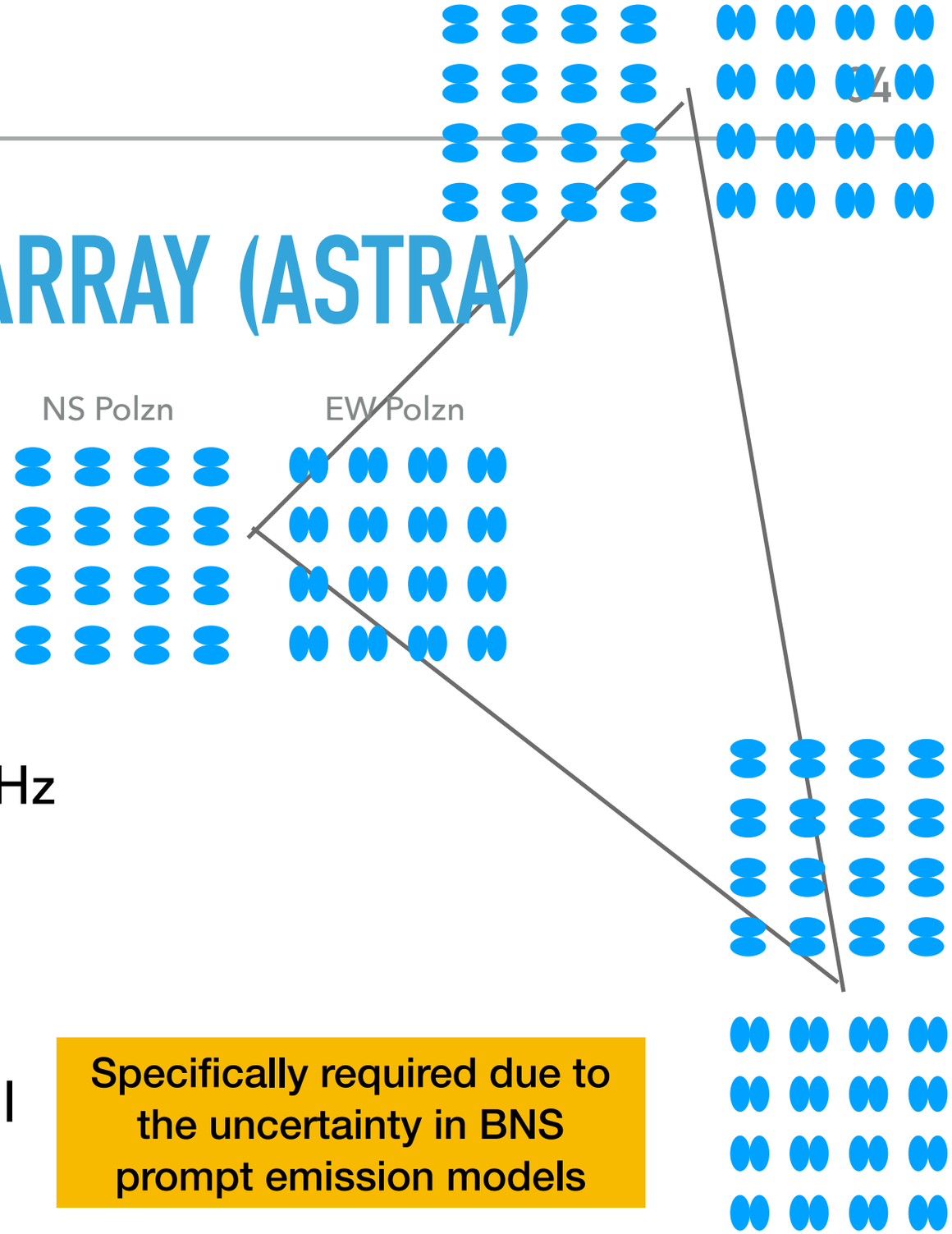
ALL SKY TRANSIENT RADIO ARRAY (ASTRA)



ASTRA

- Needs 2000x signal chains.
- How do we build and deploy inexpensive analog chains?
- How do we digitise and buffer 100 MHz of data?
- Needs new cheaper electronics

ALL SKY TRANSIENT RADIO ARRAY (ASTRA)



- 3 stations (more later)

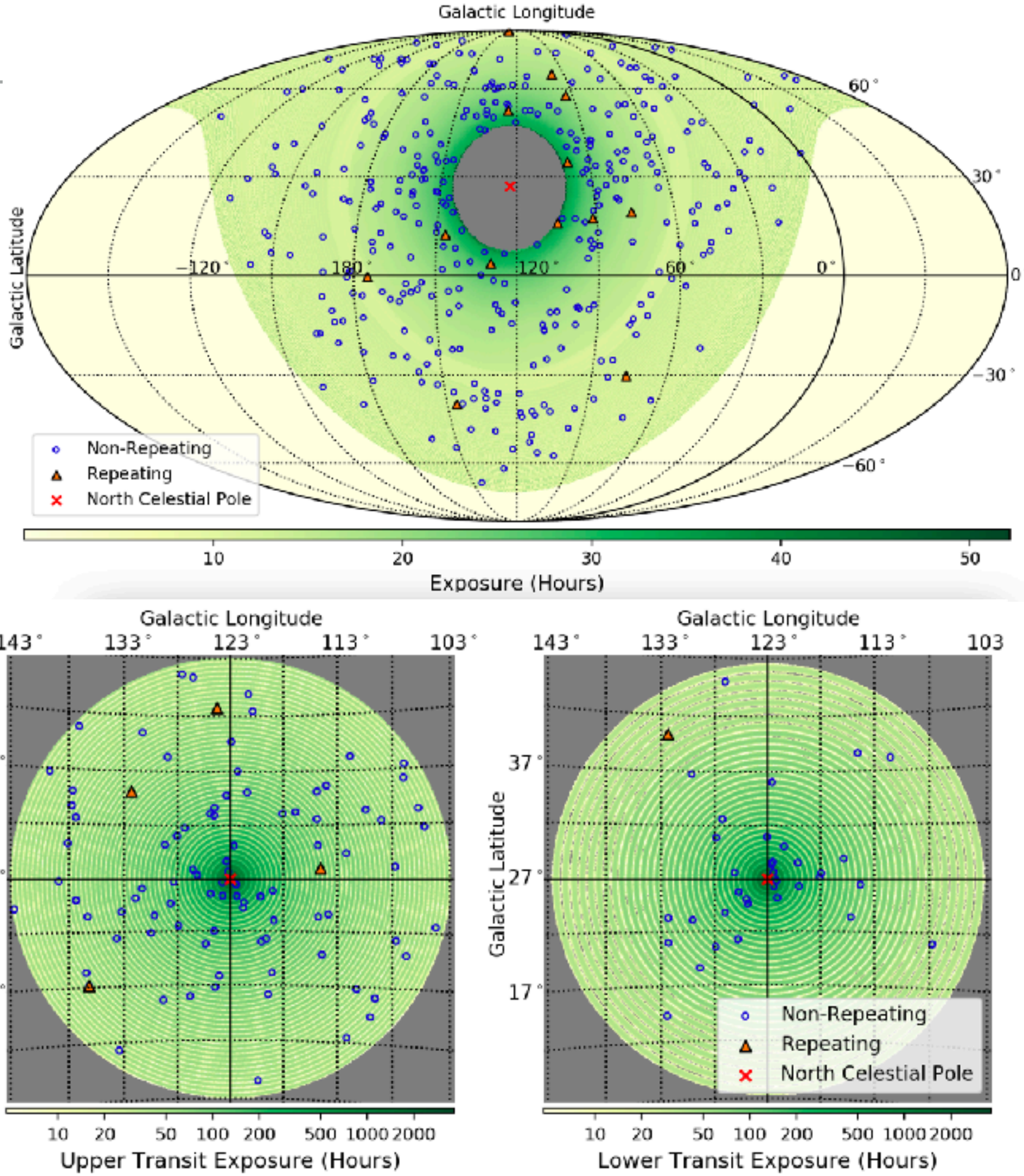
Future expansion possible

- 2 layouts of single polzn dipoles in a grid
- Analog systems designed for 400-800 MHz
- Digital systems designed for 100 MHz (SNAP boards)
- 300s voltage buffer for external + internal triggers
- Trigger on alerts from LVK, Fermi, Daksha

Specifically required due to the uncertainty in BNS prompt emission models

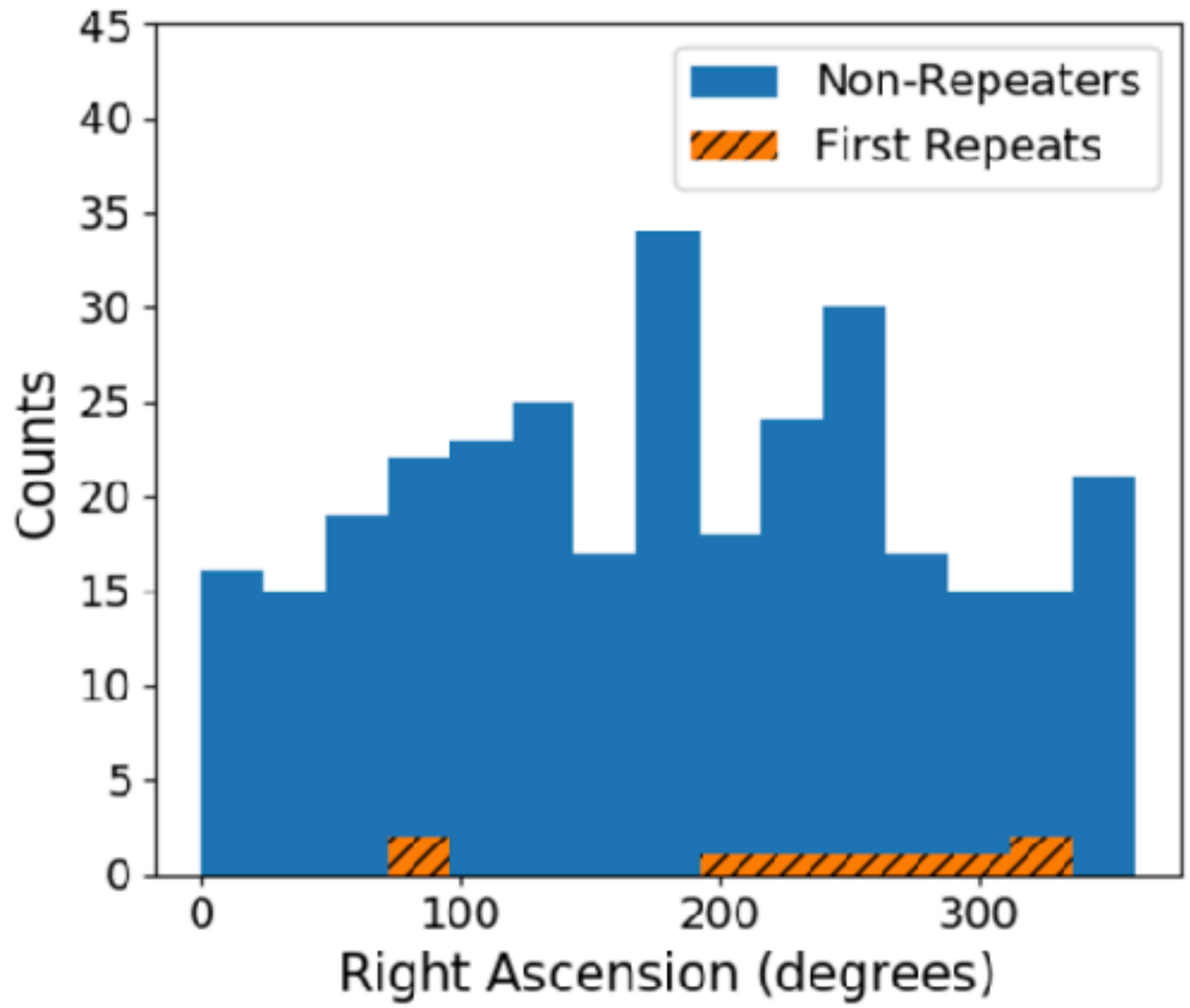
CHIME FRB CATALOG

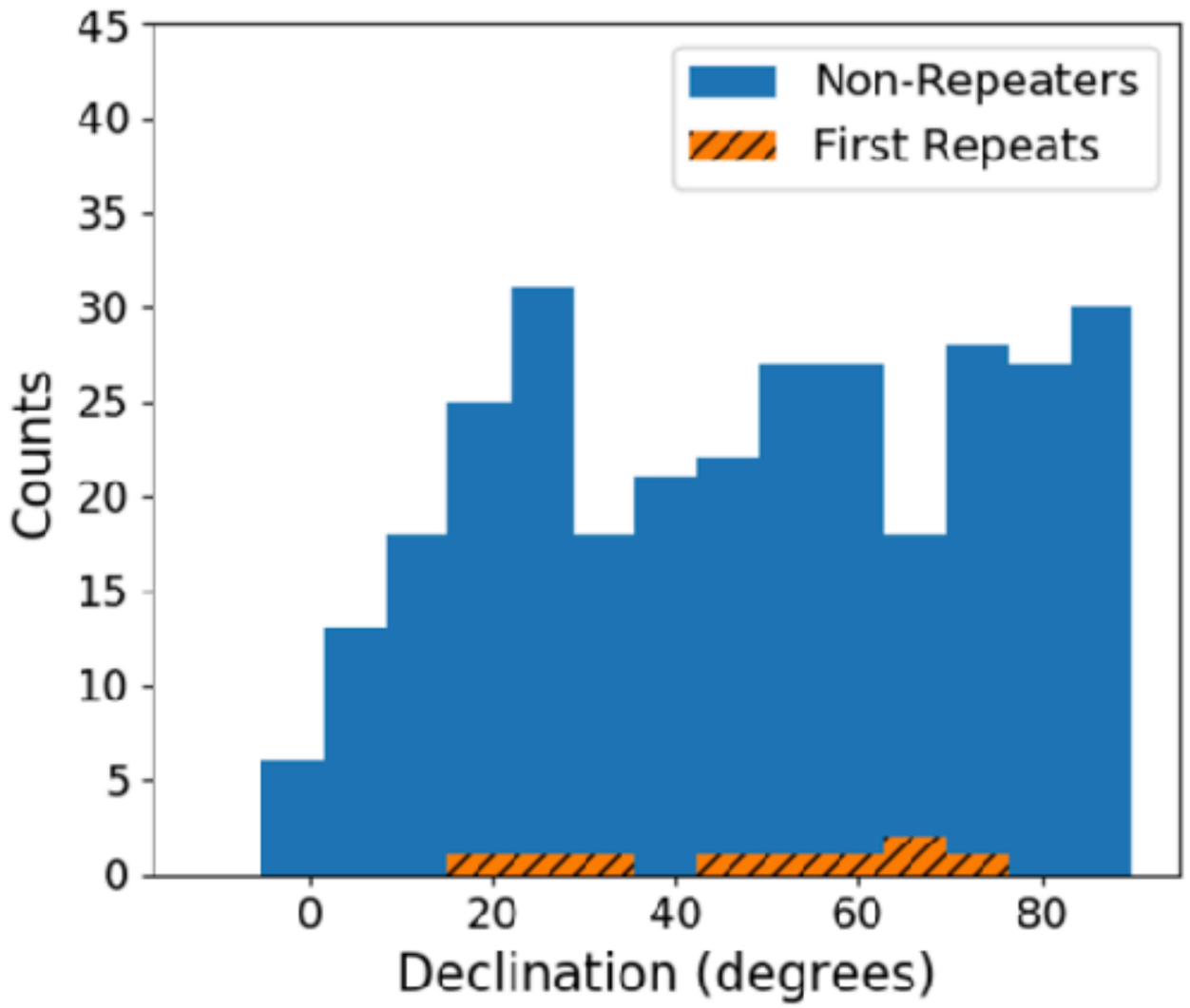
- Wide range of on sky exposure 10–2000 hrs
- Do we see more repeaters with more exposure?
  - Dec distribution of repeaters and non-repeaters are as yet consistent



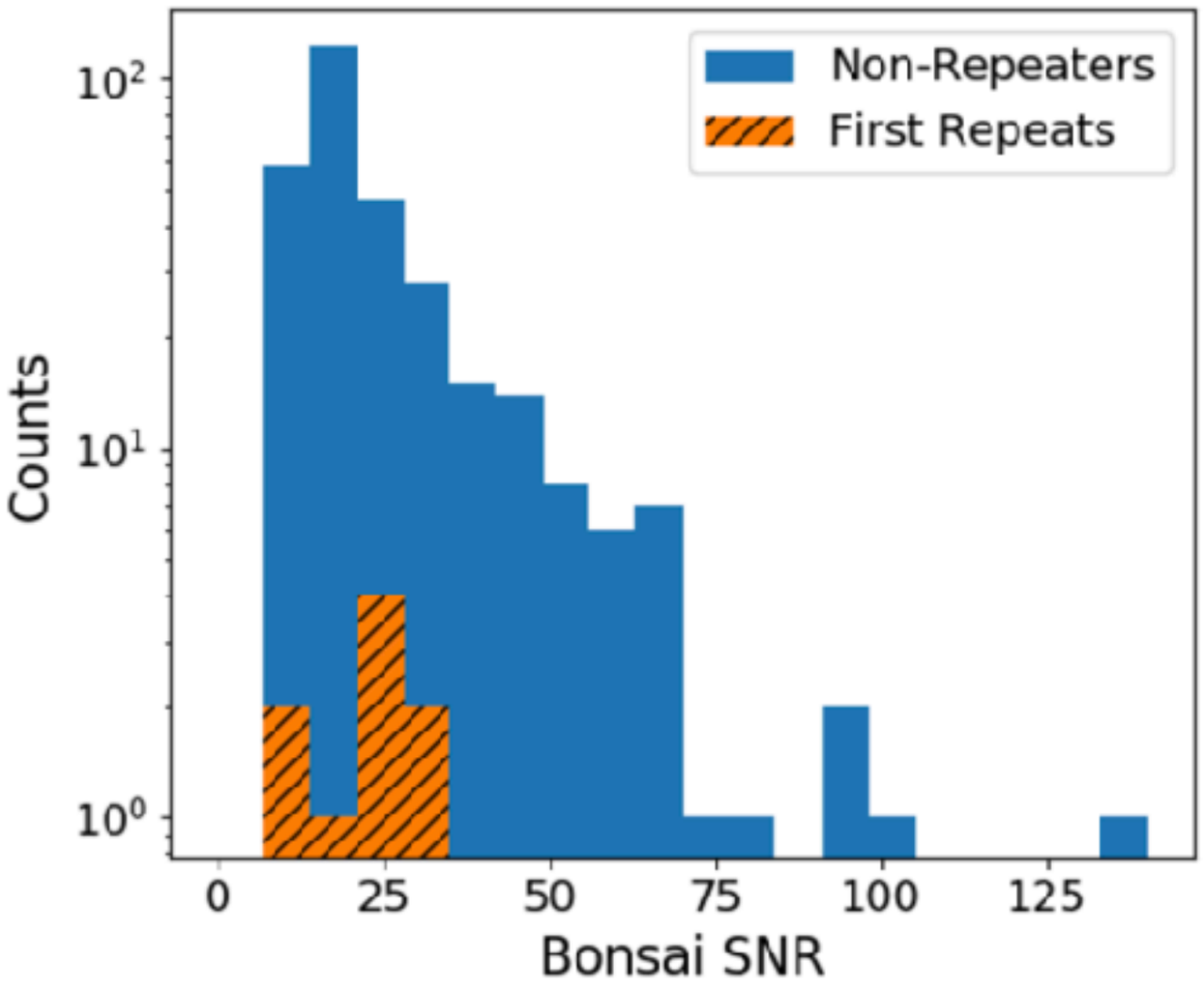
CHIME/FRB Collaboration et al (ApJS 2022)

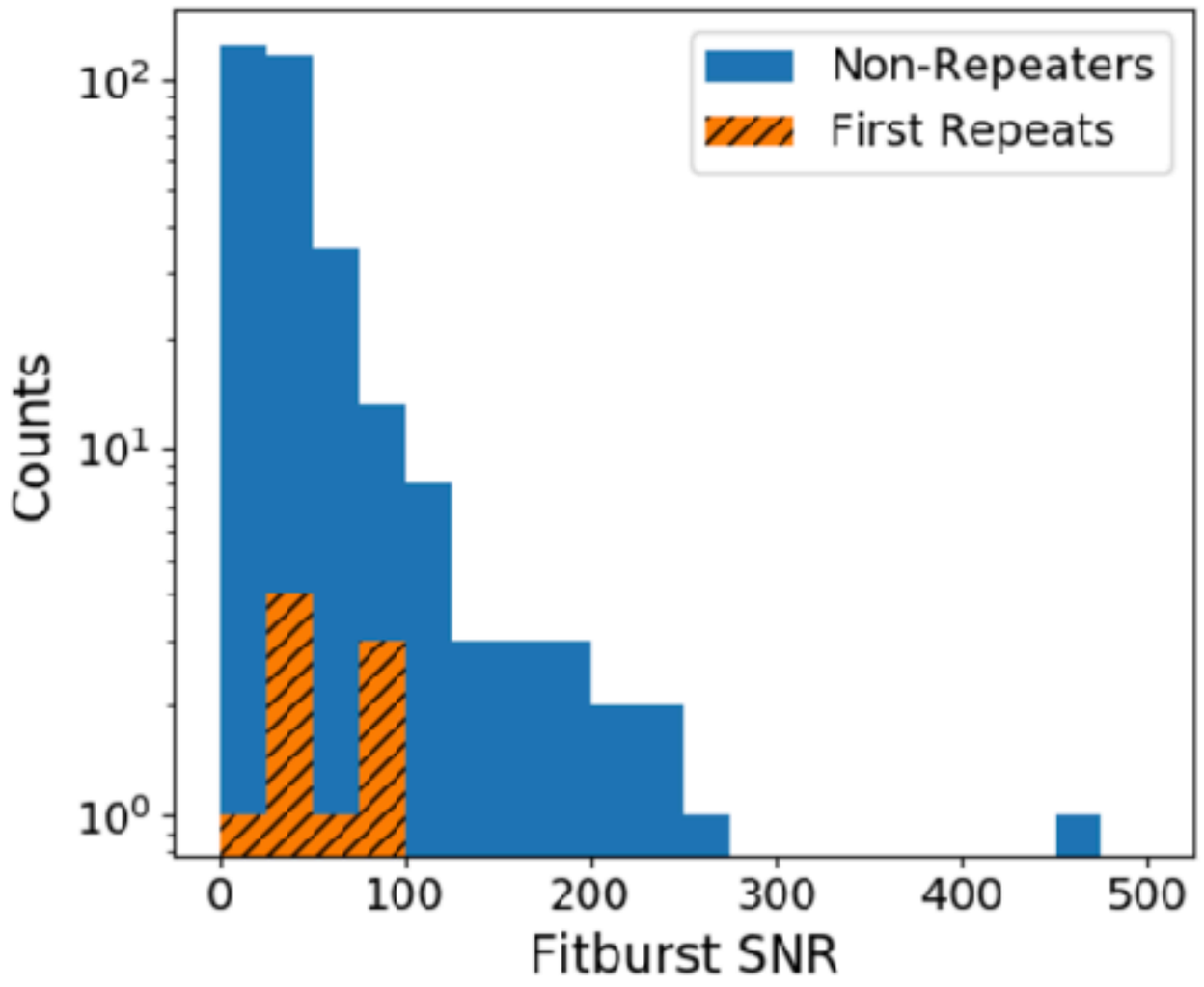
REPEATERS VS NON-REPEATERS





REPEATERS VS NON-REPEATERS

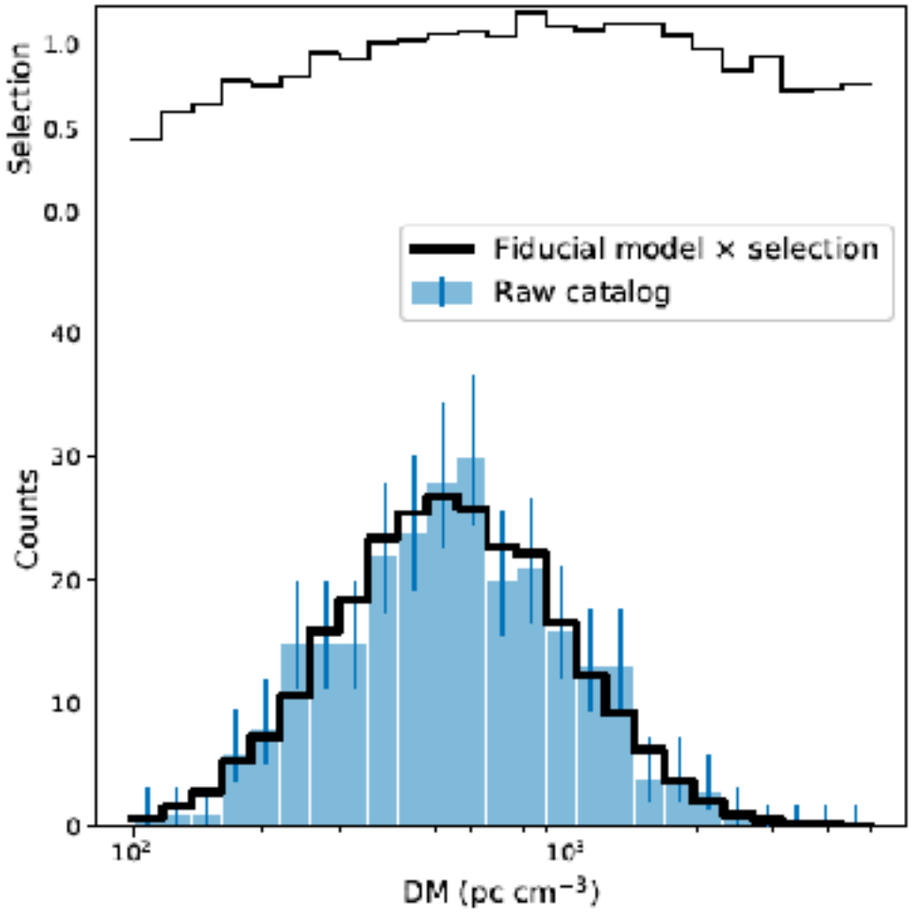


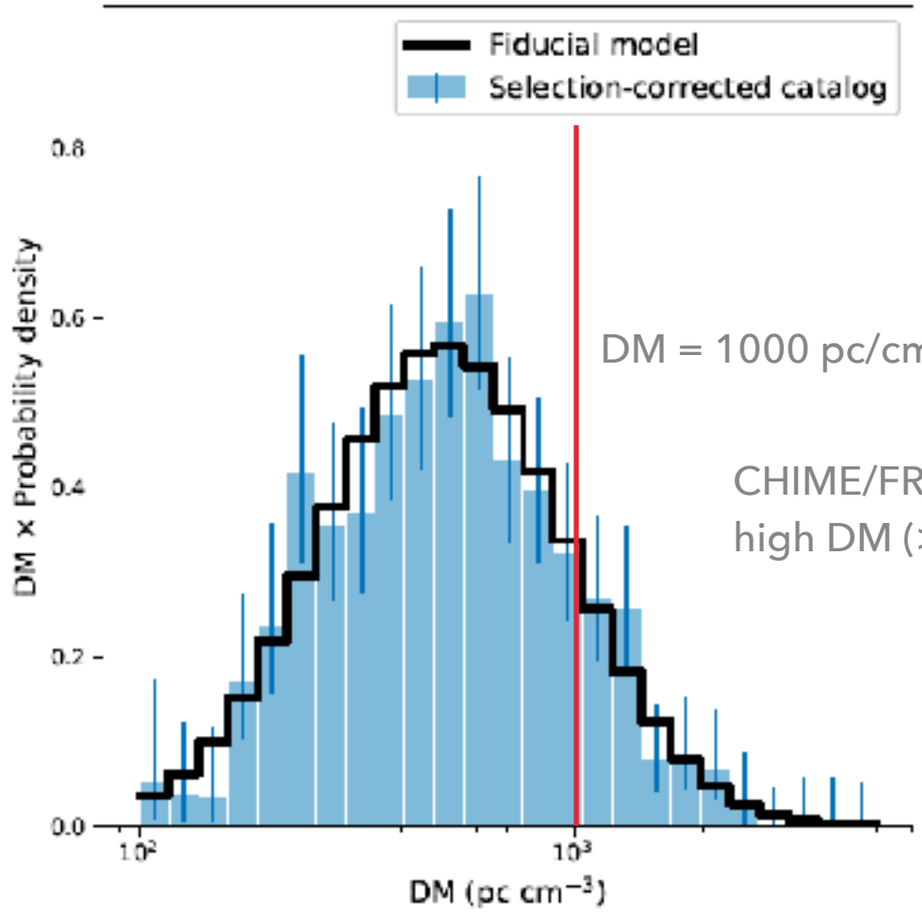


Property	§	Figure No.	p^a_{AD}	p^b_{KS}	p^c_{2DKS}
Right Ascension	5.1	10	0.22	0.24	...
Declination	5.1	10	0.55	0.49	...
DM	5.2	11	0.35	0.33	...
eDM[d]	5.2	11	0.34	0.24	...
`bonsai` SNR	5.3	12	0.65	0.44	...
`fitburst` SNR	5.3	12	0.08	0.26	...
Fluence	5.3	13	0.070	0.066	...
Flux	5.3	13	0.028	0.068	...
2D fluence vs eDM	5.3	...	...	...	0.099
2D flux vs eDM	5.3	...	...	...	0.43
Width[e]	5.4	14	7.3×10^{-5}	5.6×10^{-5}	...
Boxcar width	5.4	14	1.5×10^{-4}	2.2×10^{-4}	...
Bandwidth	5.4	15	1.3×10^{-4}	2.3×10^{-4}	...
Scattering time[e]	5.4	15	0.42	0.32	...
2D scattering time[e] vs eDM	5.4	...	...	...	0.10

USE INJECTIONS TO MEASURE SENSITIVITY

- Characterise sensitivity (detection probability) w.r.t. DM, width, fluence, scattering, sky position –> observationally corrected distributions





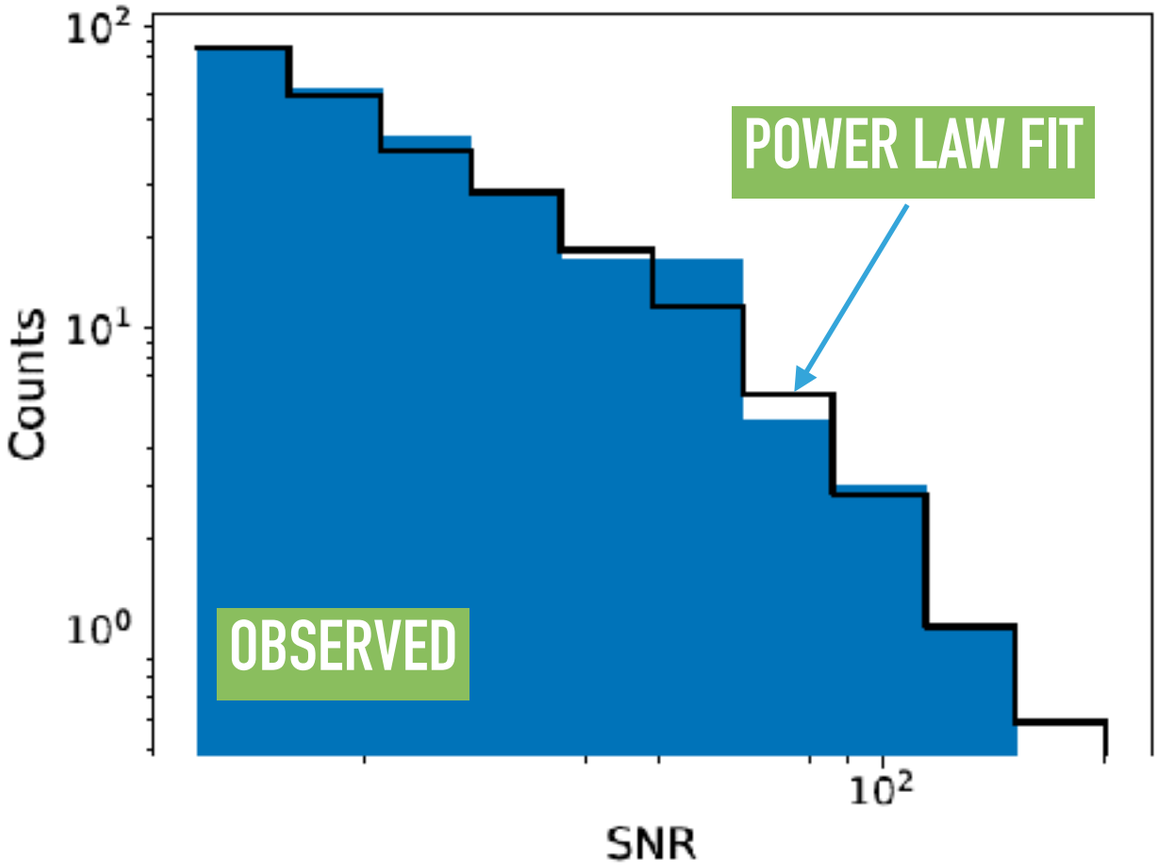
CHIME/FRB rate is low at high DM (>~2000 pc/cm^{-3})

CHIME/FRB Collaboration et al (ApJS 2022)

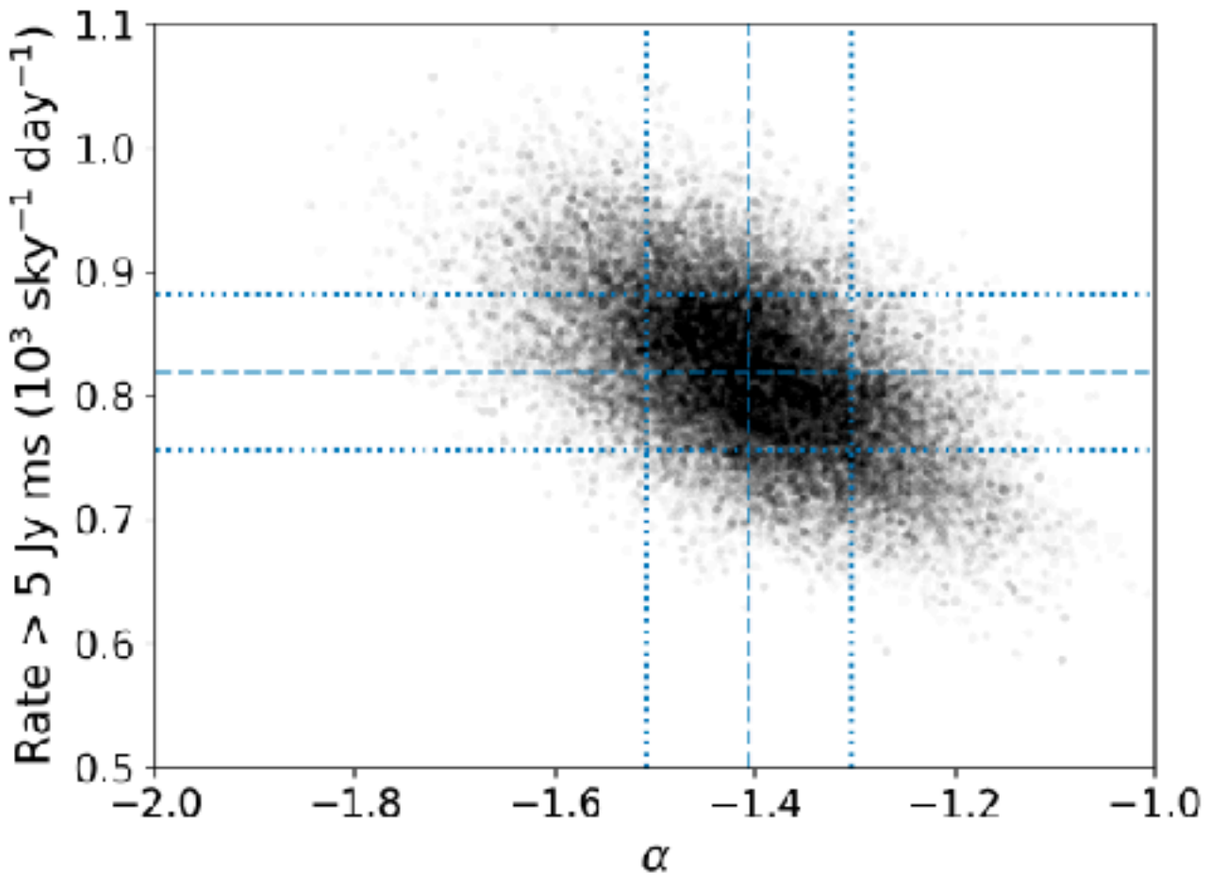
USE INJECTIONS TO MEASURE SENSITIVITY

Beam corrected rate and power law index

$R(>F) \propto F^{\alpha}$



$818 \pm 64\,(\text{stat.})\,^{+220}_{-200}\,(\text{sys.})$ FRBs/sky/day at fluence > 5 Jy-ms at 600 MHz, with scattering time at 600 MHz under 10 ms, and DM above 100 pc cm−3



Consistent with Euclidean value (-1.5) but slight change with DM (steep at high DM)

CHIME/FRB Collaboration et al (ApJS 2022)

PART 3: THE MORPHOLOGY

SIMULATING FRB SCATTERING

Chawla P. et al (2021)

- None of the models fit perfectly, but FRBs with a host offset distribution like that of SGRBs seems to fit best
- Needs additional sources of scattering
  - Circumgalactic medium or
  - Extreme local environments

IT IS REALLY HARD TO REPLICATE THE OBSERVED SCATTERING DISTRIBUTION.

EITHER FRBS ARE IN EXTREME ENVIRONMENTS

OR

WE DON'T UNDERSTAND THE SCATTERING PROPERTIES IN AND AROUND GALAXIES

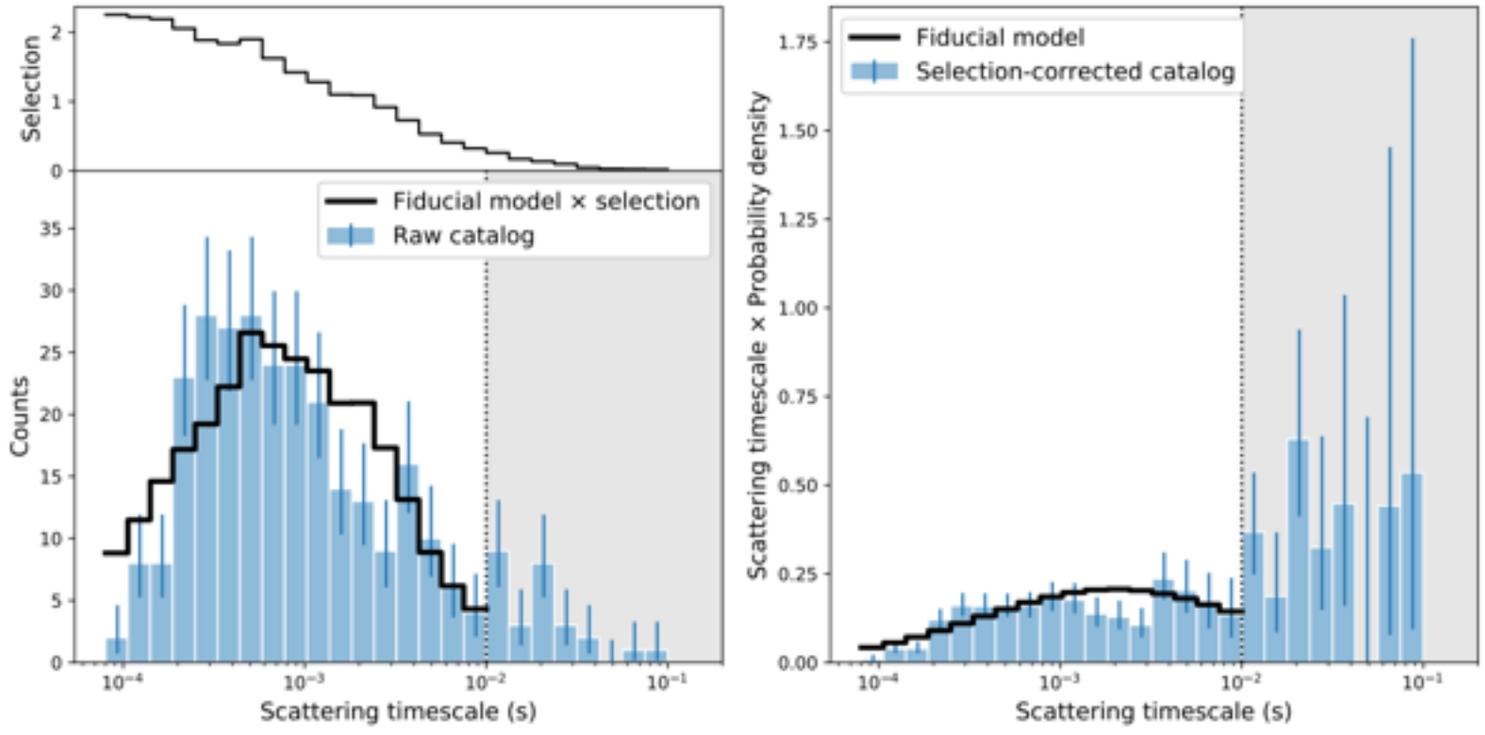
MULTI-SCALE

VERY LOW SENSITIVITY TO BROAD & SCATTERED BURSTS

Inject 10^5 FRBs with different parameters → **CHIME/FRB PIPELINE** → Find which are detected

–> Multi-dimensional selection function

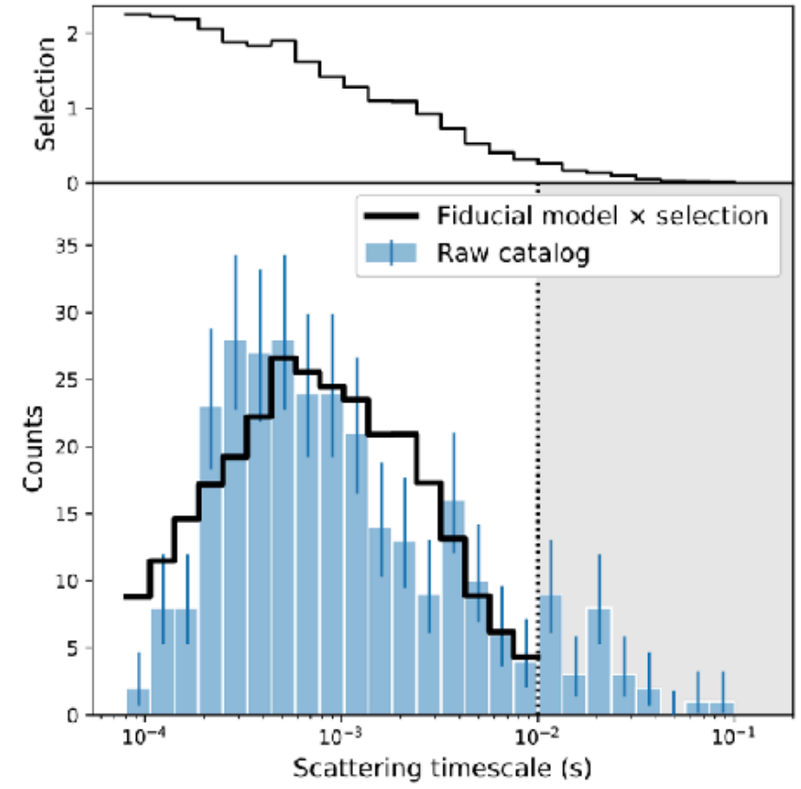
Merryfield, Tendulkar, et al (in review)

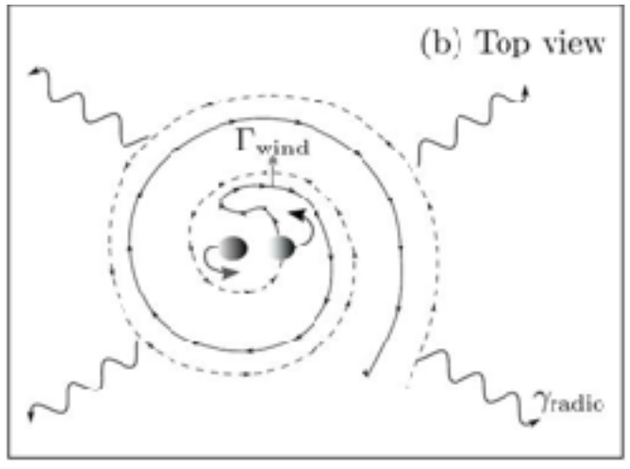


CHIME/FRB Collaboration et al (2021)

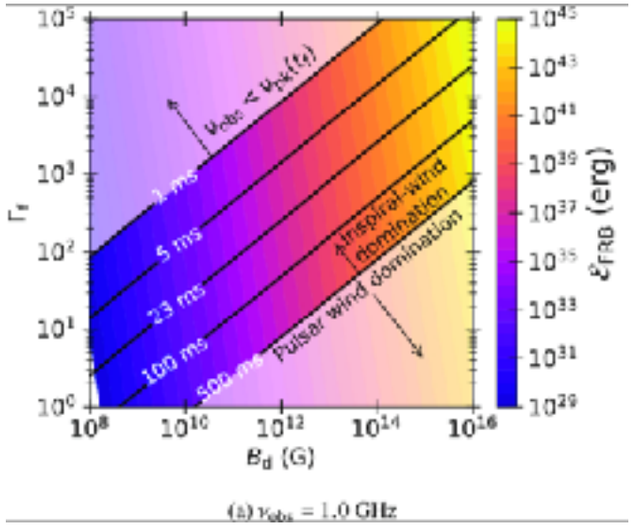
NOT-SO-FAST RADIO BURSTS (NSFRBS)

- CHIME/FRB is not very sensitive to bursts wider than ~30 ms.
  - Scattered FRBs,
  - Possible WD bursts, M-dwarf flares
  - EM counterparts of binary NS mergers
- Separate pipeline searching from ~30 ms – ~5 seconds in timescale
- Unexplored phase space
- Currently building the pipeline, piggybacking on CHIME/Slow Pulsar Search



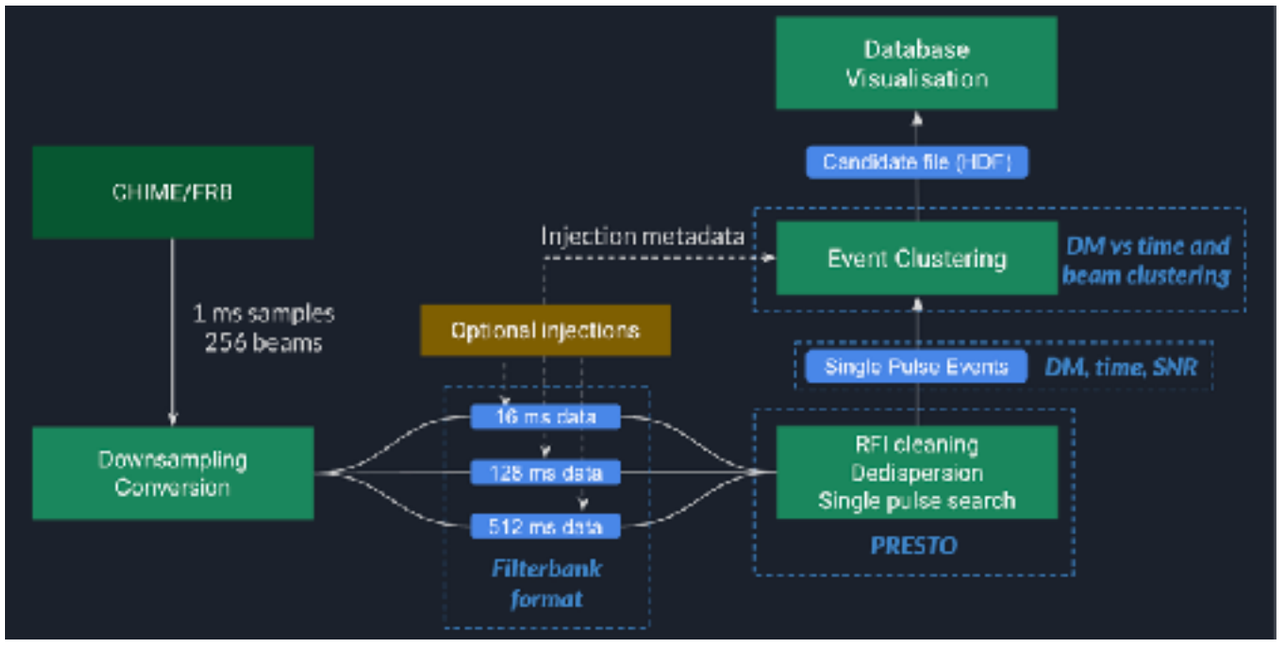


Sridhar & Metzger (2021)



NOT-SO-FAST RADIO BURSTS (NSFRBS)

- Pipeline built and tested at TIFR. Tuning on-going
- Pilot search to be done in the coming months
- 1800 beam-days of data will be copied to TIFR & processed offline

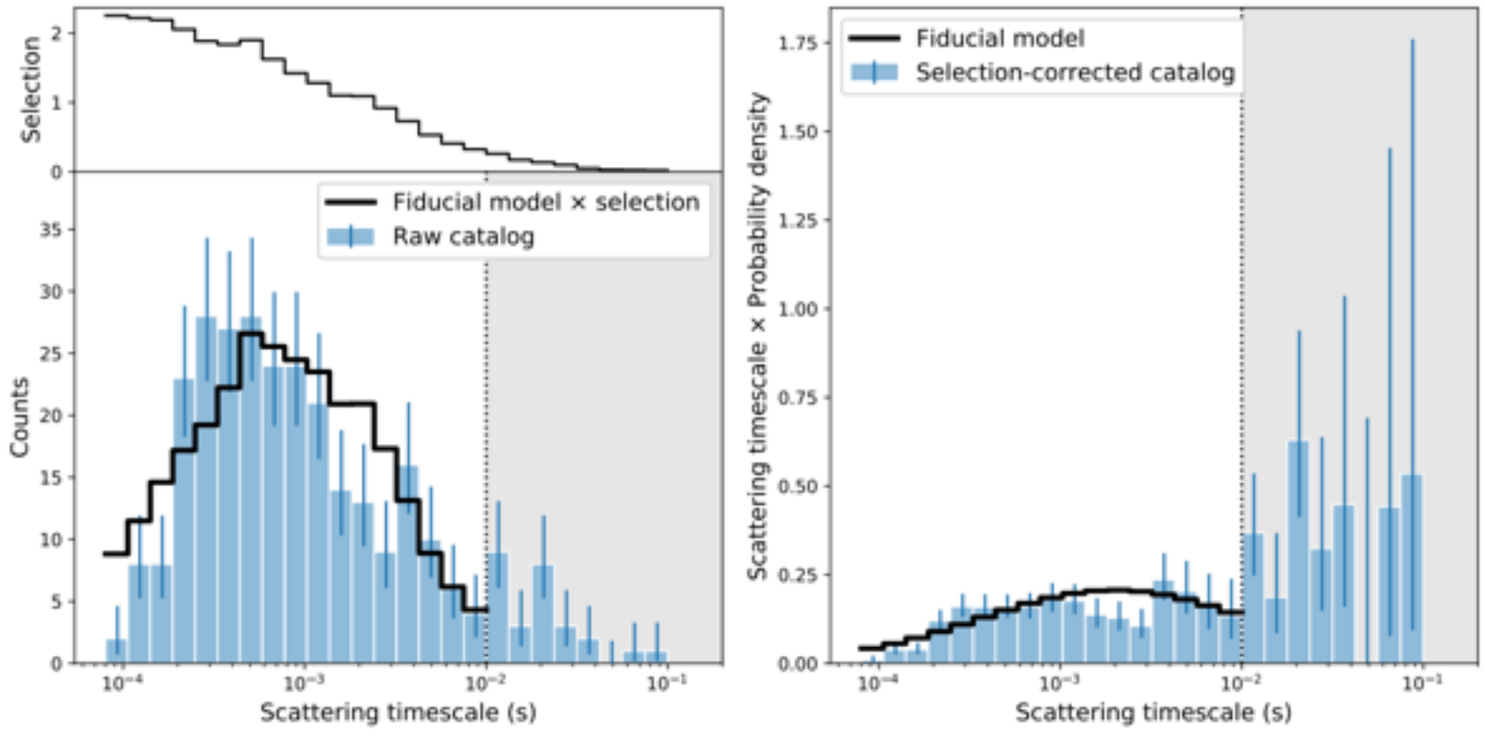


- 18k$ grant from Dunlap Institute (UoT) to put on-site computing (with Z. Pleunis & P. Scholz)

VERY LOW SENSITIVITY TO BROAD & SCATTERED BURSTS

- Using injections to retrain RFI removal ML code
- ~10x improvement in 10-50 ms FRB detection!

Inject 10^5 FRBs with different parameters → **CHIME/FRB PIPELINE** → Find which are detected → –> Multi-dimensional selection function

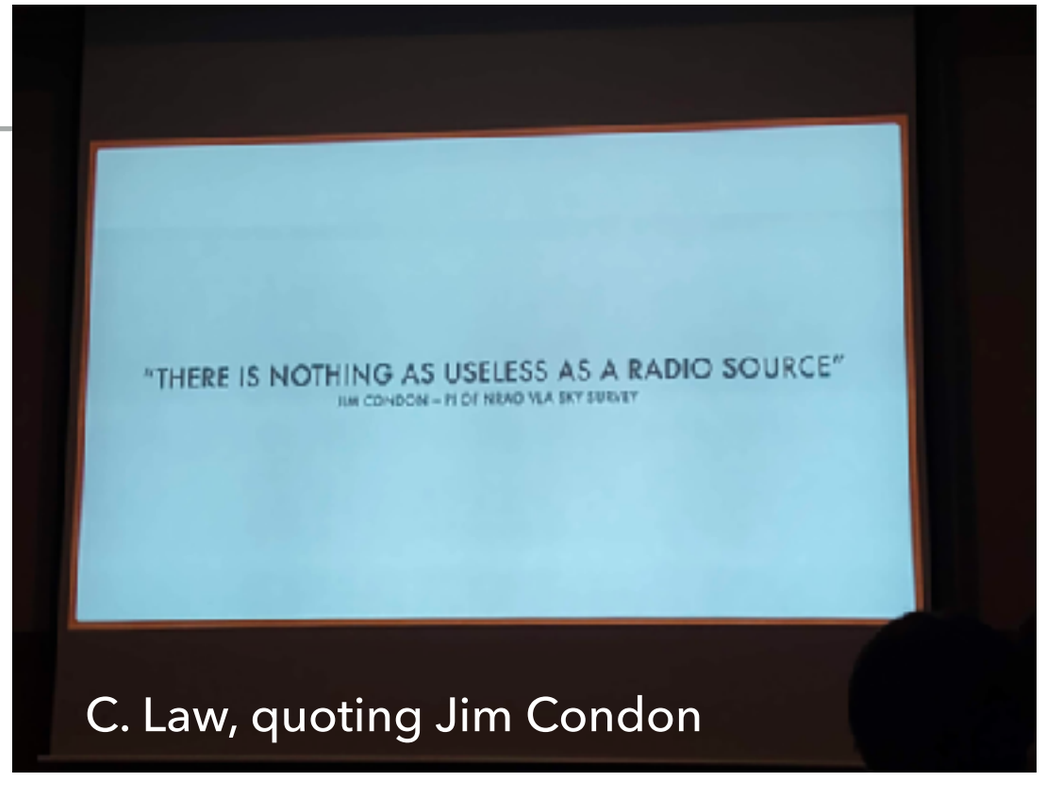


CHIME/FRB Collaboration et al (2021)

MULTI-WAVELENGTH

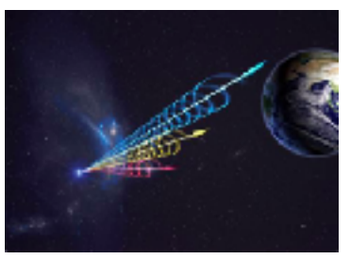
MULTIWAVELENGTH COUNTERPARTS

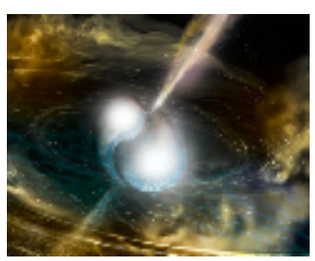
- Radio telescopes are too darn sensitive
  - Detect almost any cosmic blip
  - Not very discerning
- Need more information about the emission processes
- Multi-wavelength/multi-messenger (MWMM) inputs are crucial
- Links different transients together

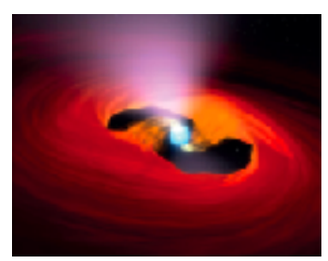


C. Law, quoting Jim Condon

10^{41-44} ergs << 10^{51-52} ergs





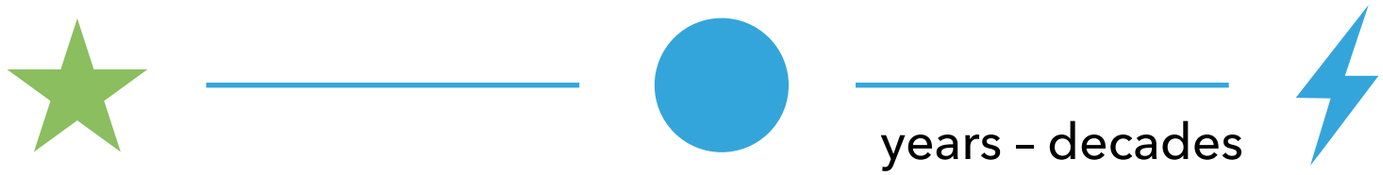


PROMPT VS DELAYED

Harder to find

Cosmic explosion
(GRB, BNS merger, SN, …)

Within a few minutes/hours



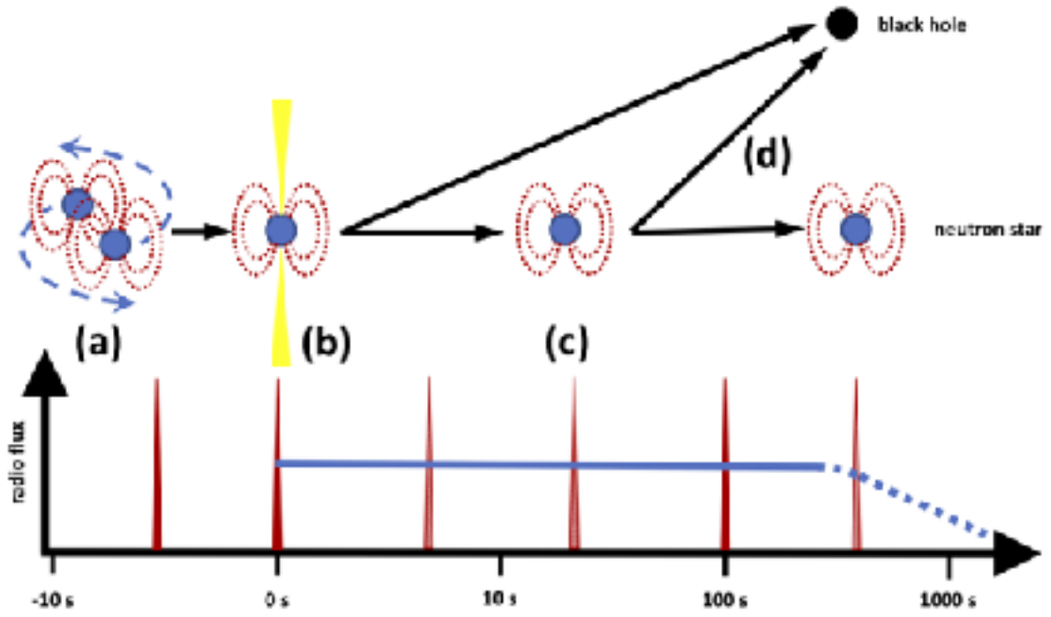
Harder to associate

years – decades

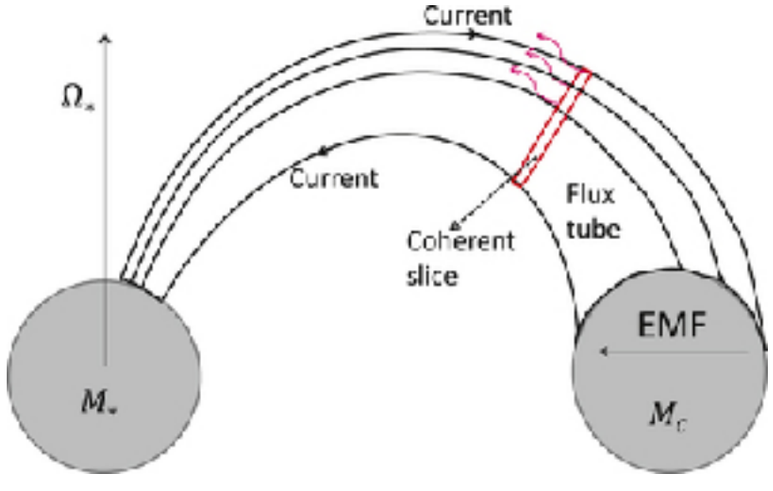
Stable NS (or some remnant)

X-RAYS/GAMMA-RAYS

- Multiple models for FRB - short GRB connection
  - Inspiral phase,
    Actual merger,
    Post merger



Rowlinson et al (2019)



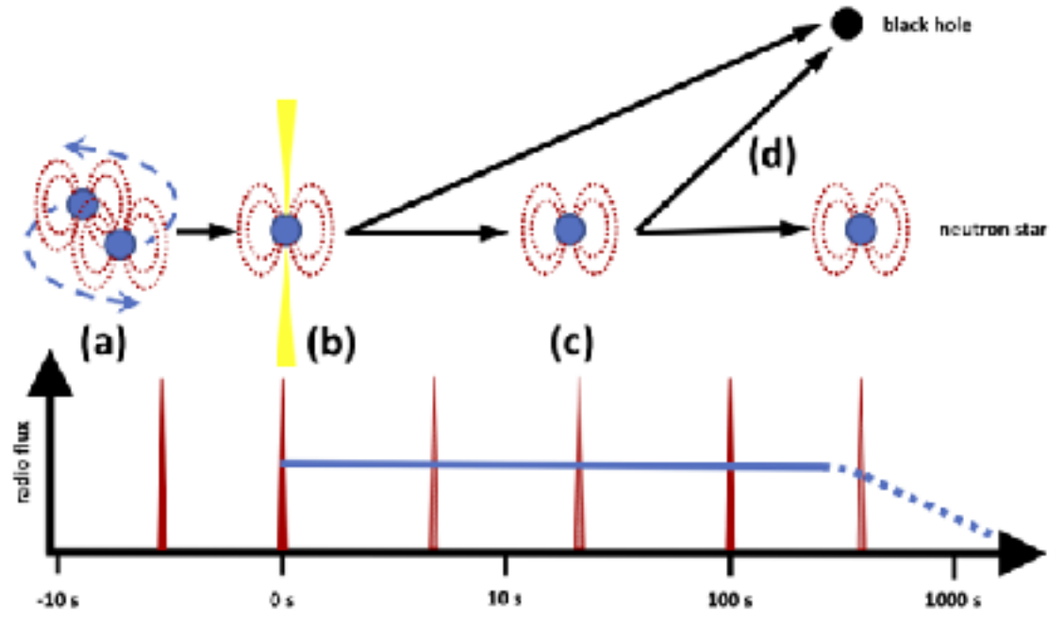
Wang et al (2016)

Take away message:
Lots of different models about when and how FRBs can form — before, during, or after BNS/NSBH mergers.

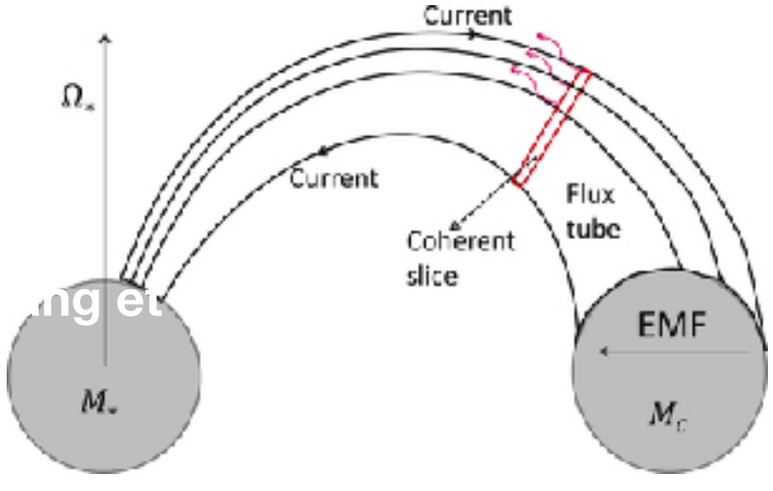
With apologies for incompleteness

X-RAYS/GAMMA-RAYS

- Multiple models for FRB - short GRB connection
  - Inspiral phase,
    Actual merger,
    Post merger



Rowlinson et al (2019)



BUT:

Differential beaming, dirty environments can prevent joint detection of FRBs + GRBs

merger

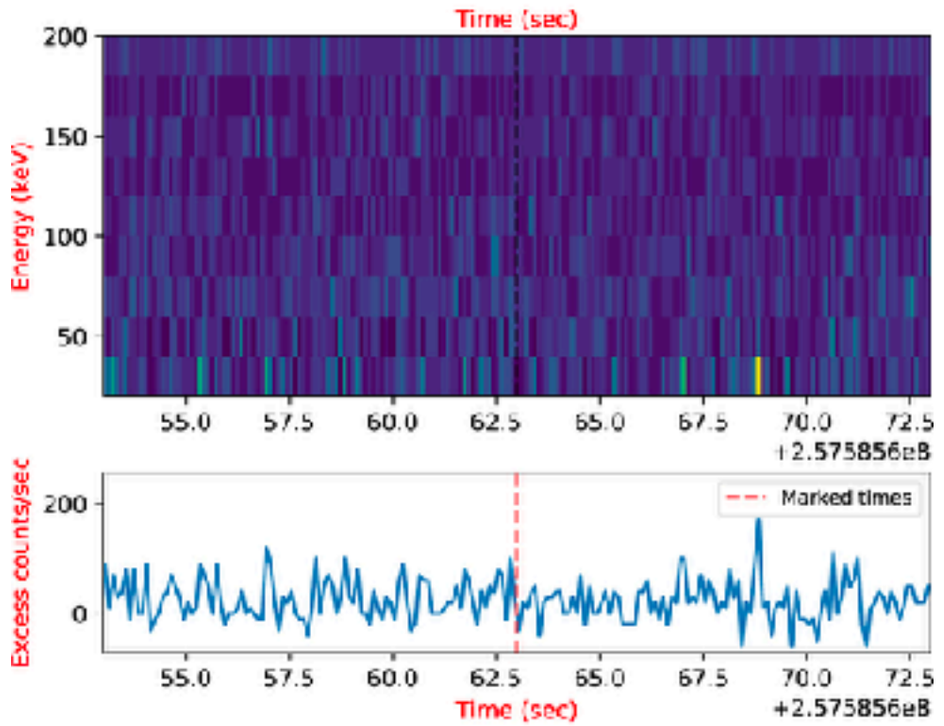
With apologies for incompleteness

FRB-GRB CONNECTION

- Finding prompt X-ray/γ-ray counterparts from all sky monitors
  –> Fluence limits ~10^{-7}–10^{-6} erg/cm^2

- Many observatories – BAT, GBM, Integral, Astrosat – lack of GRB detections gives limits

- Now with VOevents –> rapid response possible –e.g. GUANO (Tohuvavohu et al 2020)



Anumarlapudi, SPT et al (2020)

See more: Yamasaki et al (2016), Gourdji et al (2020), Tian et al (2022), Laha et al (2022)

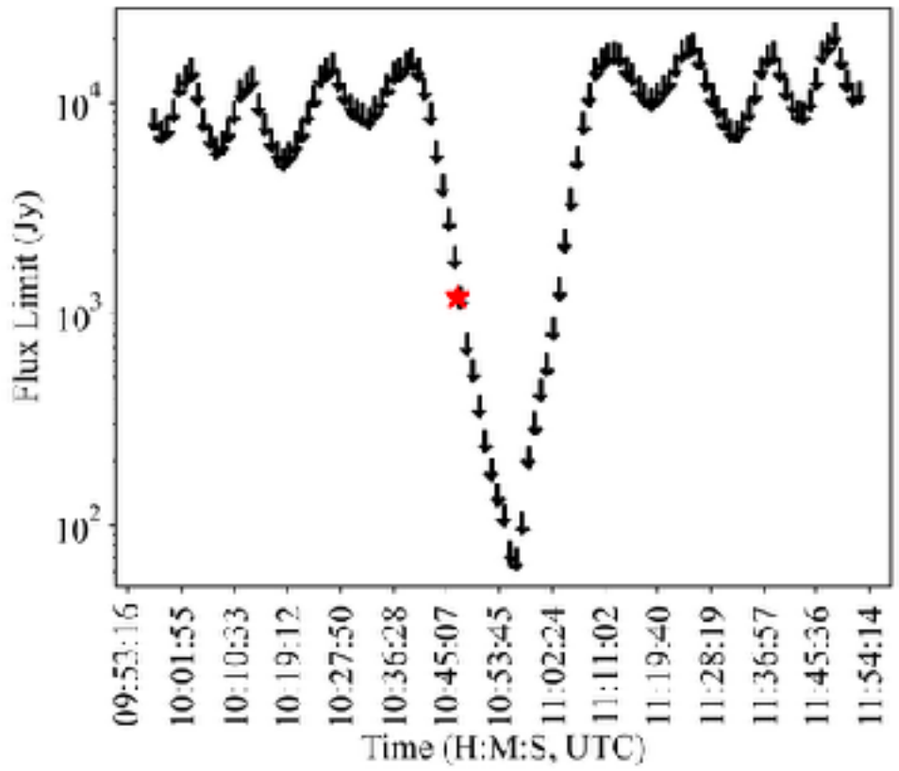
Such limits are not very constraining for most FRBs, but an actual detection is worth the effort!

GRB-FRB CONNECTION

- One can ask the inverse question – given a GRB can we find an FRB?
- Bannister et al (2012), Palaniswamy et al (2014) –> follow up GRBs, few minutes post burst
- Kaplan (2015), Anderson et al (2021), Tian et al (2022) –> MWA/LOFAR electronic beam steering, few seconds latency
- Curtin et al (2022) –> FRB-like limits *before* *(and after)* GRBs

FRB-LIKE EMISSION AT THE TIME OF GRBS

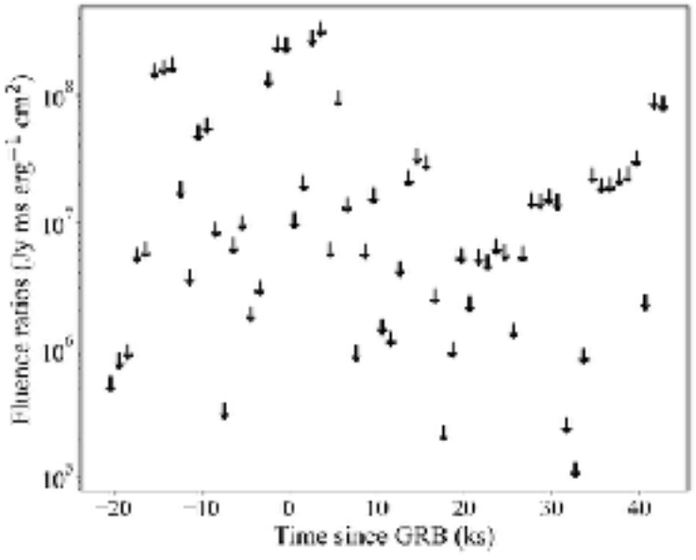
- Search for FRBs before and after GRBs
- 39 well-localised GRBs during CHIME/ FRB's first catalog run
- No coincidences
- Put limits on radio efficiency of SGRBs: ~<10^{-3} – 10^{-4}



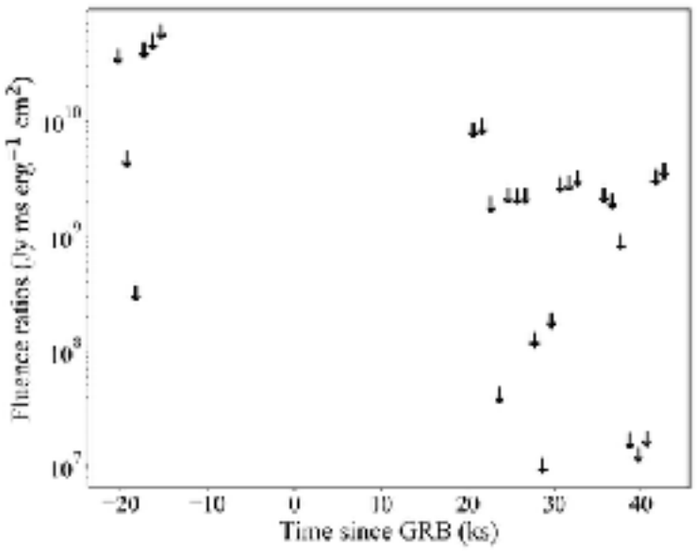
Curtin, A., SPT et al, (in review)

Radio to X-ray Fluence ratios

LGRBS

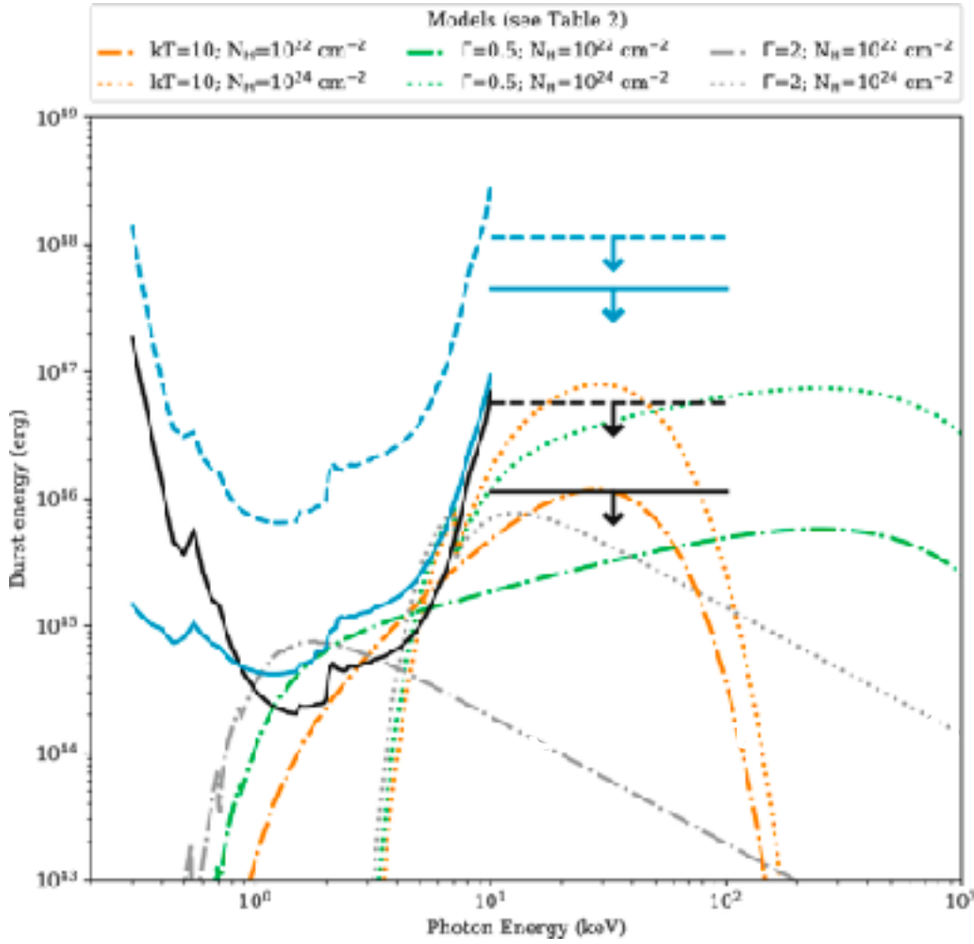


SGRBS



REPEATER – X-RAY CONNECTION

- For repeaters, focused observations are possible
- Simultaneous radio, X-ray also done: Scholz et al (2021) for FRB 20180916B, Scholz et al (2017; FRB 20121102A)
- Fluence limits of ~ 10^{-10}–10^{-9} erg/cm^2
- At 150 Mpc (R3), energy < 10^{45} erg (>> FRB energy)

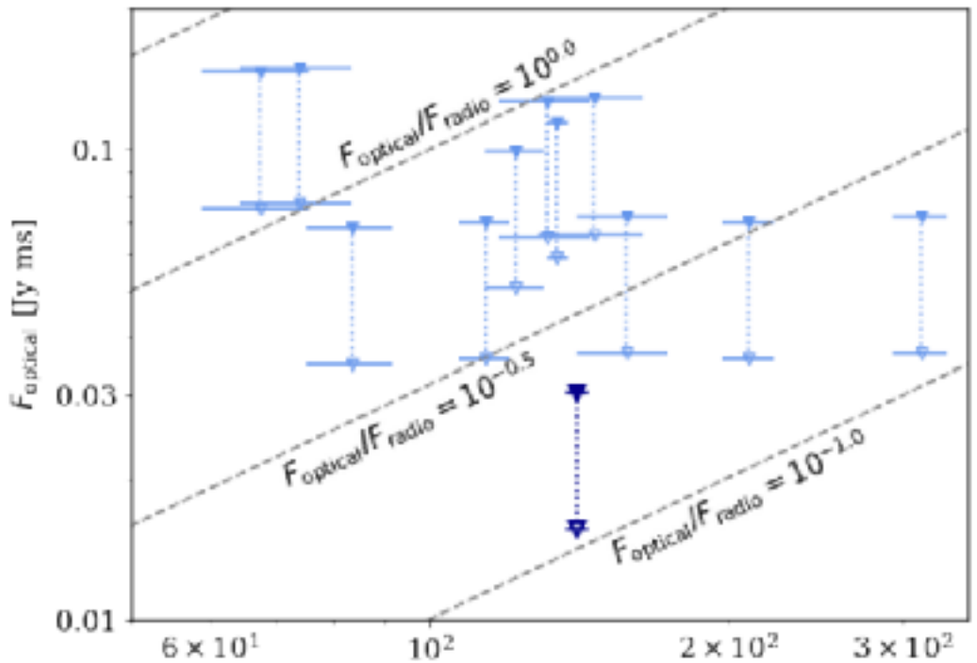


Need nearby repeaters to improve constraints

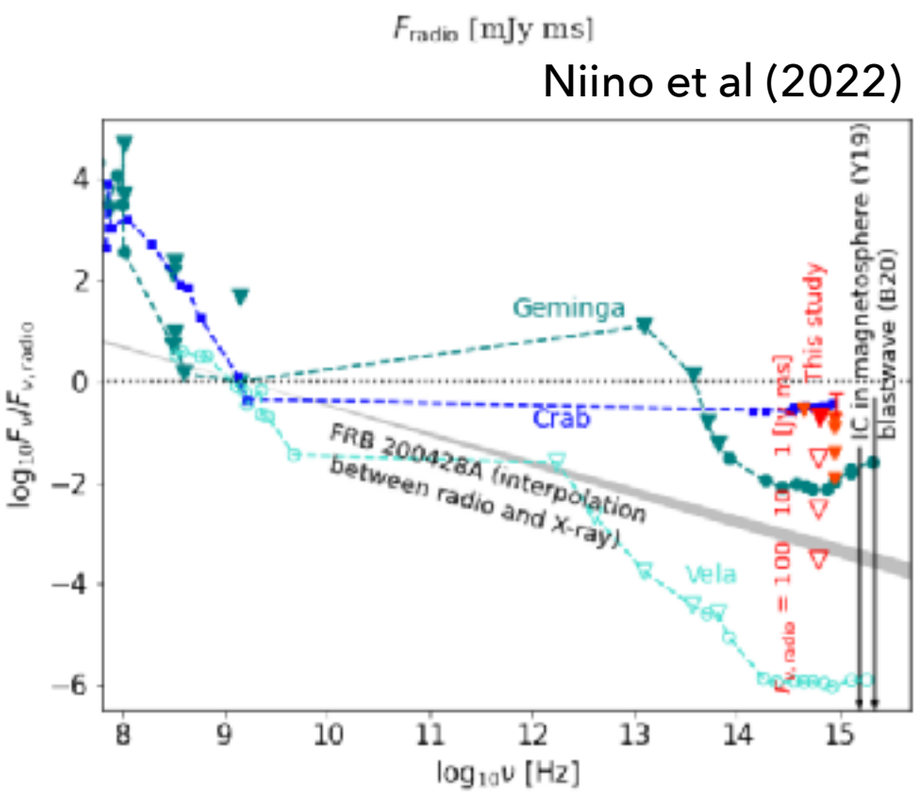
SGR 1806-20 Giant Flare: 10^{47} erg,
SGR 1935+2154 burst: 10^{39} erg (both isotropic)

OPTICAL/IR

- Most efforts on repeaters
  - Focused observations of repeaters:
  - E. g. Hardy et al (2017), MAGIC Coll (2018), Niino et al (2022)
    - Limits of ~ 0.05 Jy ms per burst
    - Not yet constraining, but could be constraining for FRB fluence > 5-10 Jy ms
- Needs specialised high-speed cameras + large telescopes



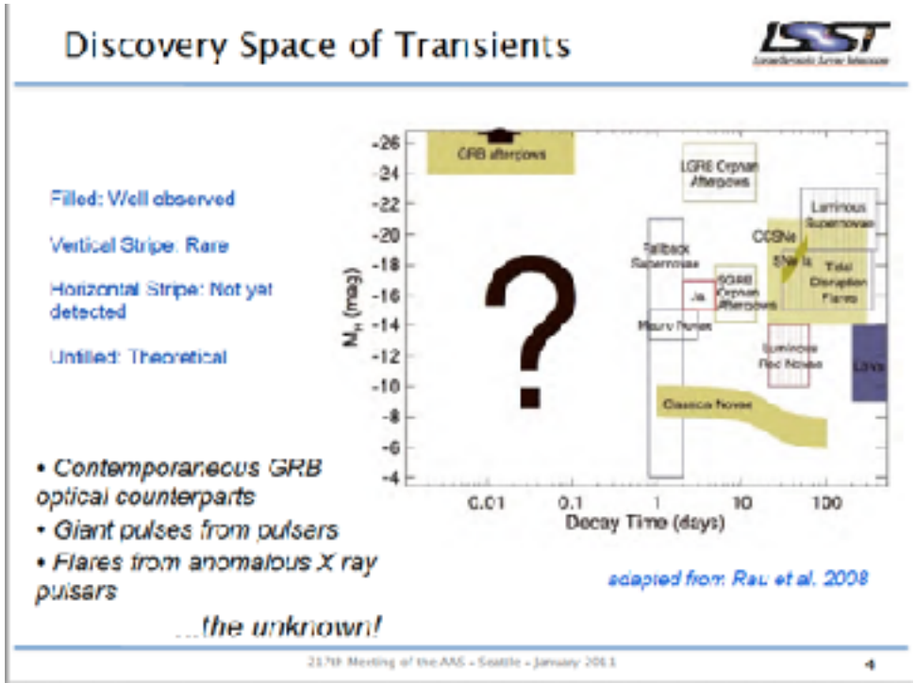
Niino et al (2022)



OPTICAL/IR

- Can we do this with large area surveys? YES!
- DWF – coordinated abs with radio, OIR, X-ray
- Future possibilities – Evryscope/ZTF/Vera Rubin Observatory
- Challenge
  - Integration times of ~10-60 seconds
  - Separating asteroids, satellite glints from single frame transients

Deeper Wider Faster program
Andreoni & Cooke (2018)



Lucianne M. Walkowicz (AAS 2011)

IS FRB 180916 A BINARY?

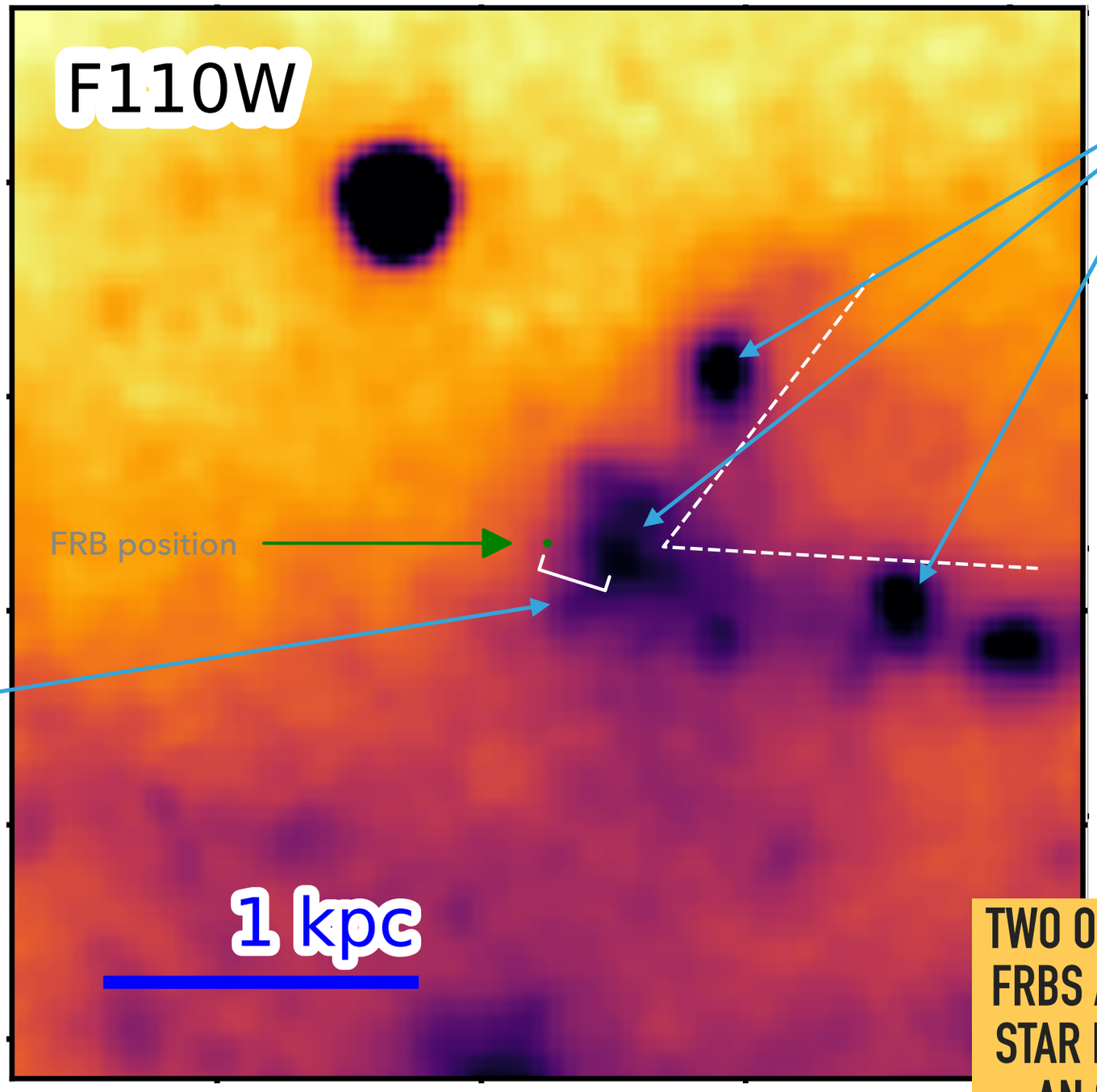
Green circle is 36 mas radius
VLBI error + astrometric error

Resolution of < 60 pc!

Little to no
star-formation
at FRB location

250 pc offset

This offset is much
larger than the scale
height of magnetars,
but similar to that of
X-ray binaries



Similar offset seen in FRB
121102 (Bassa, SPT et al 2017,
Kokubo et al 2017)

TWO OF THE BEST LOCALIZED FRBS ARE ASSOCIATED WITH STAR FORMATION, BUT WITH AN 200–300 PC OFFSET

Tendulkar et al (2021)

OBSERVED RATES

FRBs	10^3/day
GRBs	1/day
Ga… …nd	
Binary NS mergers	1/year (will change in O5)
ULX/HMXB outbursts	10/year

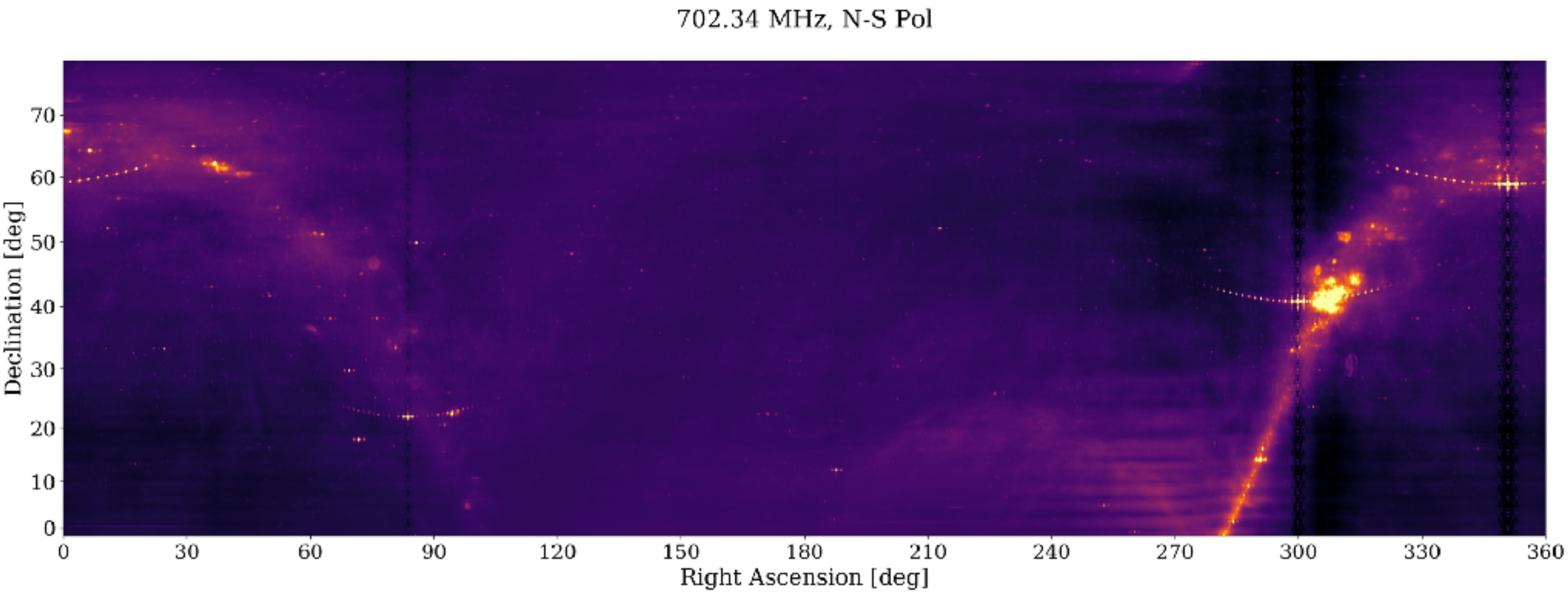
COINCIDENCES ARE RARE.
WE NEED TO FIND A LOT OF TRANSIENTS.

THERE ARE FAR TOO MANY FRBS IN THE SKY

FEW FRBS WILL BE ASSOCIATED WITH OTHER DETECTABLE TRANSIENTS

Realtime Backends

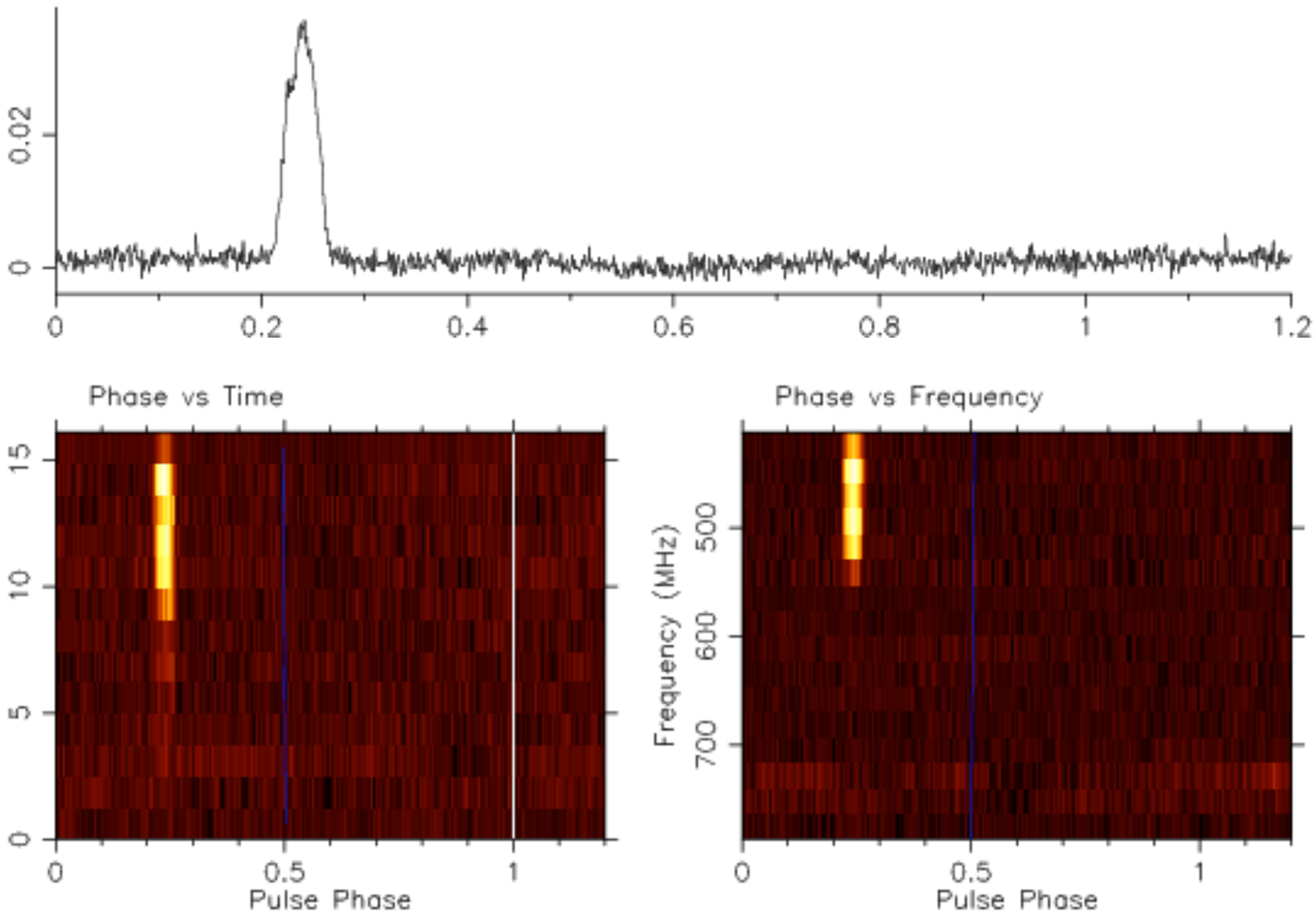
CHIME/Cosmology | CHIME/Pulsar | CHIME/FRB



CHIME Cosmology Dirty Map

Realtime Backends

CHIME/Cosmology | CHIME/Pulsar | CHIME/FRB



Cycle through all the Northern Hemisphere pulsars in ~10 days!