The CHIME telescope

Kendrick Smith (Perimeter Institute)
Edinburgh, January 2023

CHIME collaboration

Lead institutions:

UBC THE UNIVERSITY OF BRITISH COLUMBIA

UNIVERSITY OF TORONTO

McGill

DRAO NRC · CNRC

+ Smaller teams at these institutions:

Yale University LUX ET VERITAS

Carnegie Mellon University

West Virginia University

NRAO

Massachusetts Institute of Technology

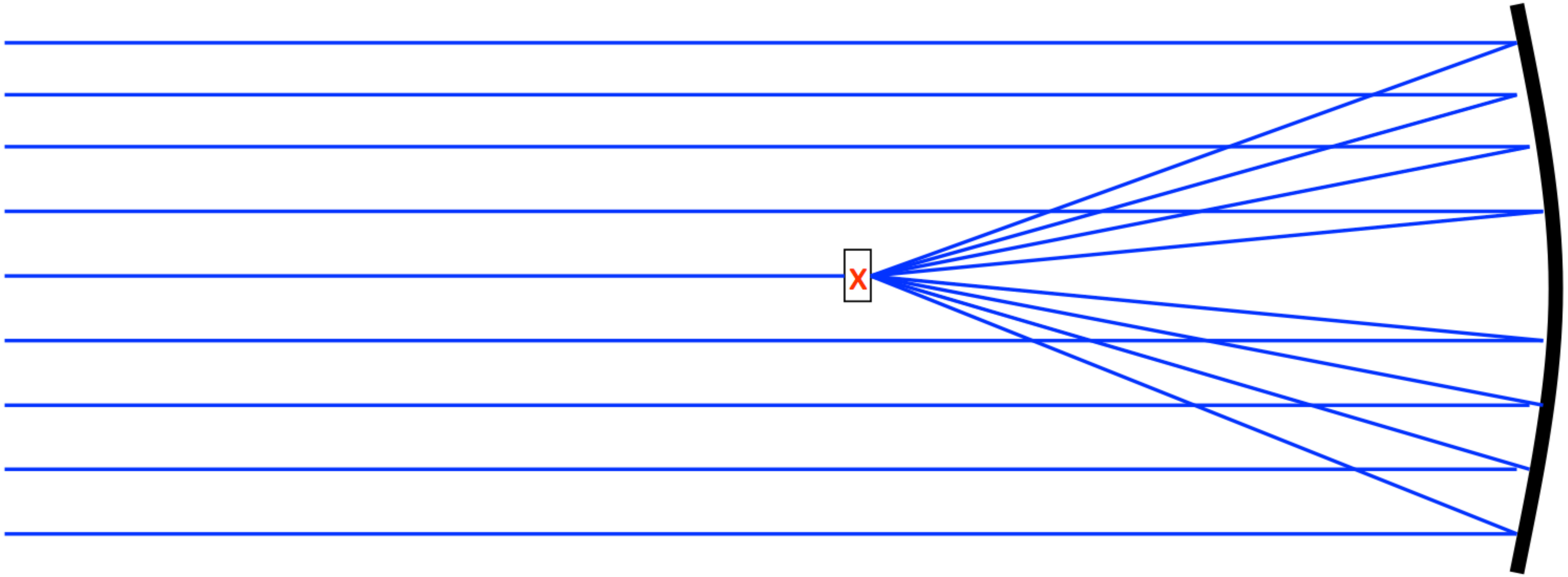
PERIMETER INSTITUTE

1. The CHIME concept: moving difficulty from hardware to software
2. Searching for fast radio bursts with CHIME
3. Two periodic phenomena in FRBs
4. An FRB in the Milky Way
5. A large FRB catalog
6. Coming soon: CHIME outriggers, CHORD

CHIME

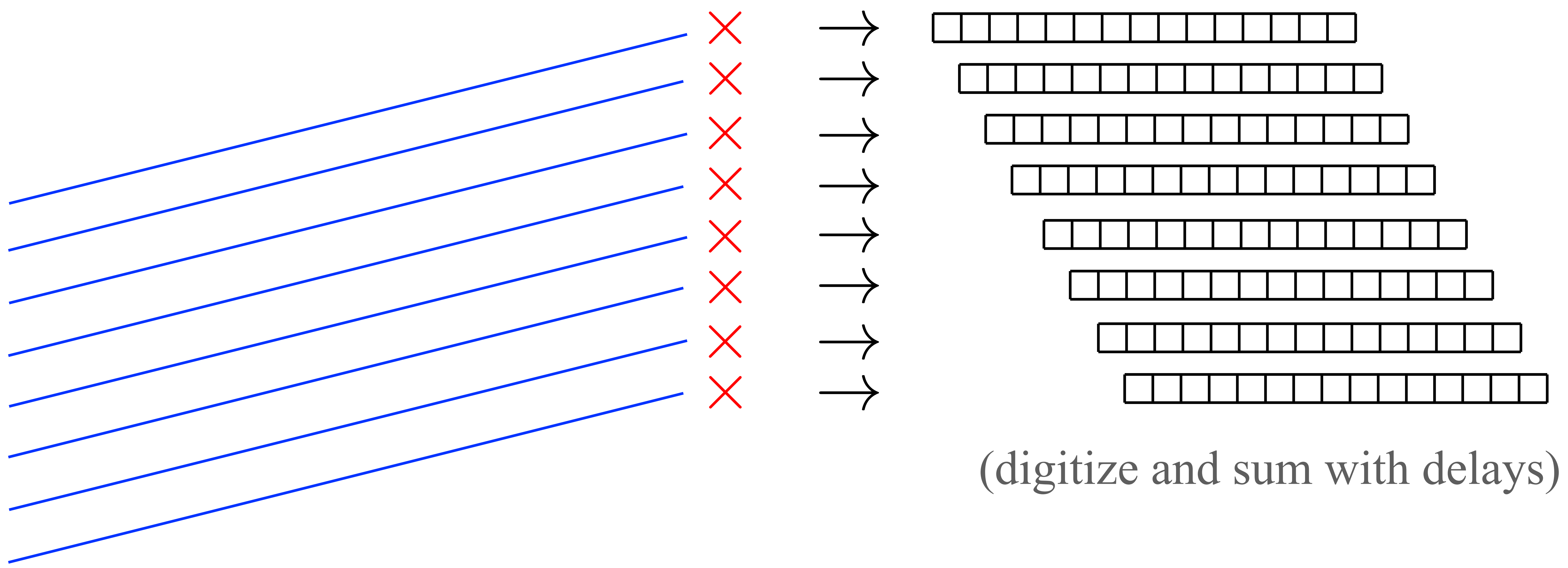
Traditional radio telescope

Single-feed radio telescope



Focuses via physical delays: constructive interference only occurs for a specific direction on the sky

Phased-array interferometer

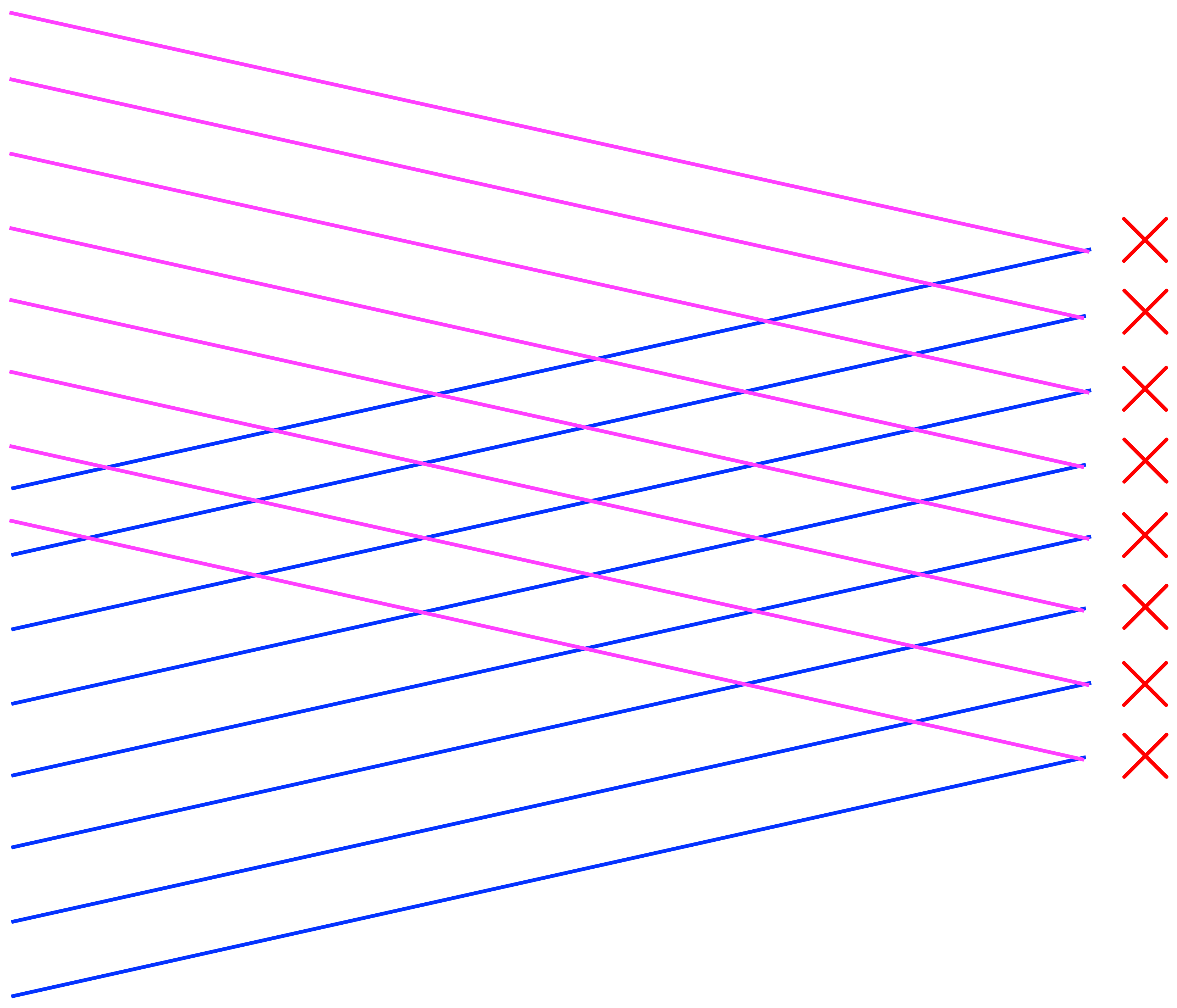


Dish is replaced by an array of antennas whose signals are digitized.

By summing signals with appropriate delays, can simulate the dish in software, and focus on part of the sky.

Can "repoint" telescope by changing delays.

Beamforming interferometer



Copy the digitized signals and repeat the computation N times (in parallel).

Equivalent to N telescopes pointed in different directions.

CHIME

CHIME has a 4 x 256 array of antennas and can form all 1024 independent beams in real time. Raw sensitivity is the same as 1024 single-feed radio telescopes!

80m

Mapping speed

For many purposes, the statistical power of a radio telescope is proportional to its mapping speed:

$$M \approx (\text{Collecting area } A) \times (\text{Number of beams}) \times (\text{Order-one factors})$$

	A	N_{beams}	$M/(10^5 \text{ m}^2)$
Parkes 64m	3200 m²	13	0.41
Green Bank 100m	7850 m²	7	0.55
Arecibo 300m (RIP)	70000 m²	7	4.9
FAST 500m	200000 m²	19	38
CHIME	6400 m²	1024	66


FAST
= CHIME?

The challenge

	A	N_{beams}	$M/(10^5\ \text{m}^2)$
Parkes 64m	3200 m^2	13	0.41
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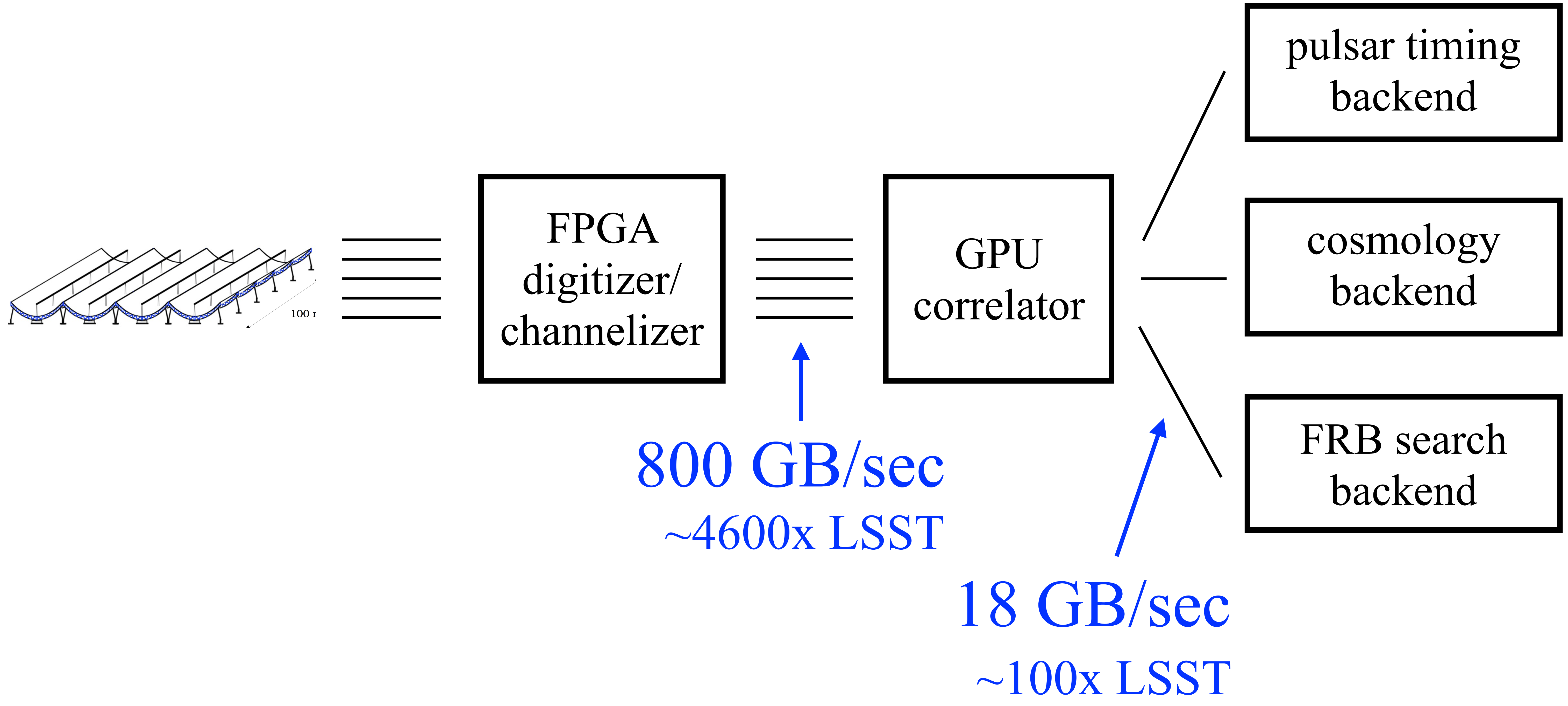
Arecibo 300m (RIP)	70000 m^2	7	4.9
FAST 500m	200000 m^2	19	38
CHIME	6400 m^2	1024	66

In principle, sensitivity is proportional to mapping speed M, but computational cost is proportional to N_{beams} (or worse).

The CHIME design is really a strategy for moving difficulty from hardware to software.

CHIME computing



LSST: 15 TB/day

Pulsar timing backend

- 10 beams (repointable)
- Receives electric field at max resolution

Cosmology backend

- Receives full visibility matrix (2048^2) at low time resolution (10 sec).

FRB search backend

- 1024 beams (fixed)
- Gets intensity in 16384 frequency channels, at 1 ms time resolution.

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FRB mini-introduction (slide 1/3)

An FRB is a radio pulse whose dispersion exceeds the maximum possible contribution from the Milky Way (in models!), suggesting an extragalactic origin.

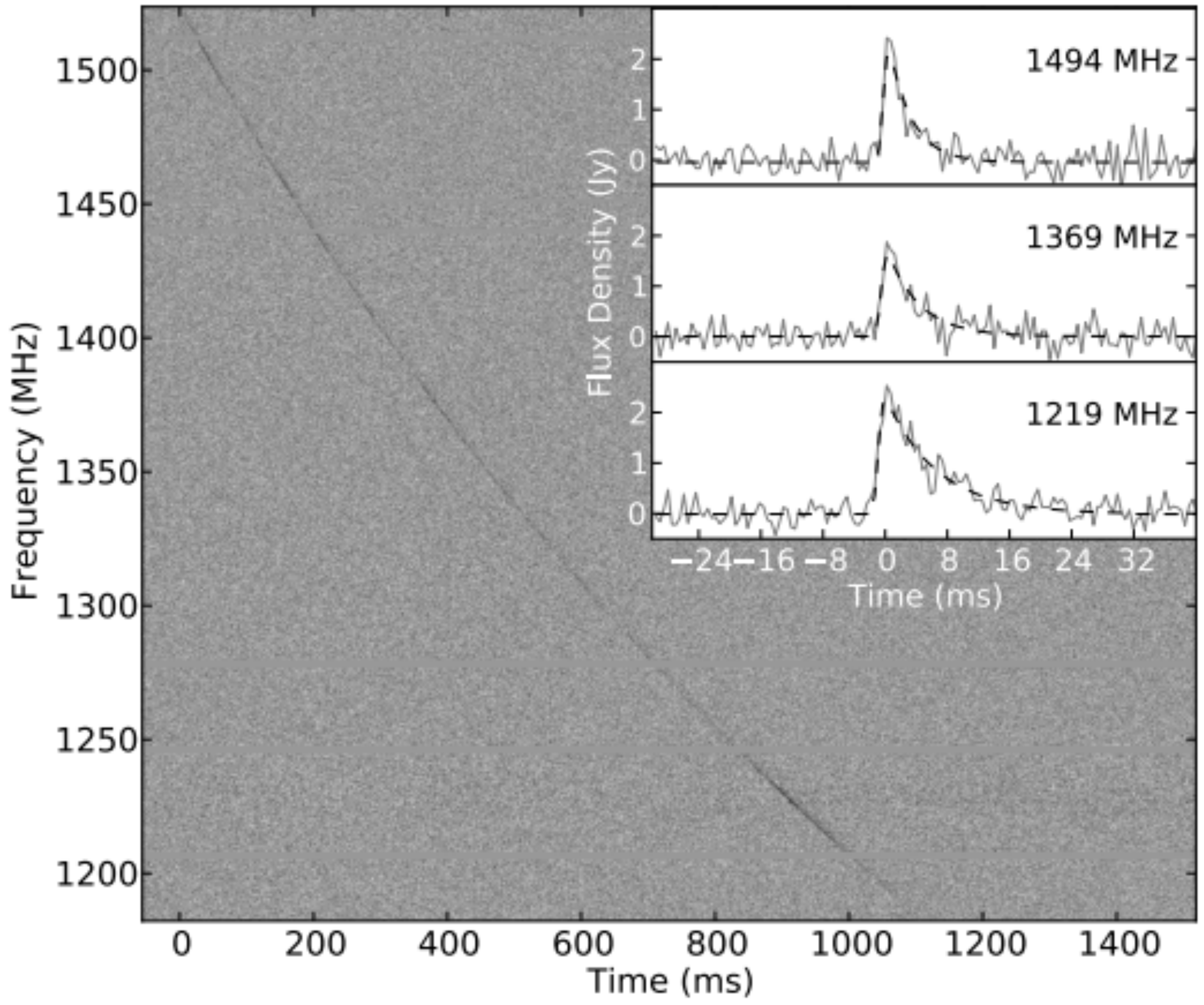
- Dispersion from cold plasma of ionized electrons: (Pulse arrival time) $\propto \nu^{-2}$

- Prefactor is the "dispersion measure":

$$\mathrm{DM} = \int dx\, n_e(x)$$

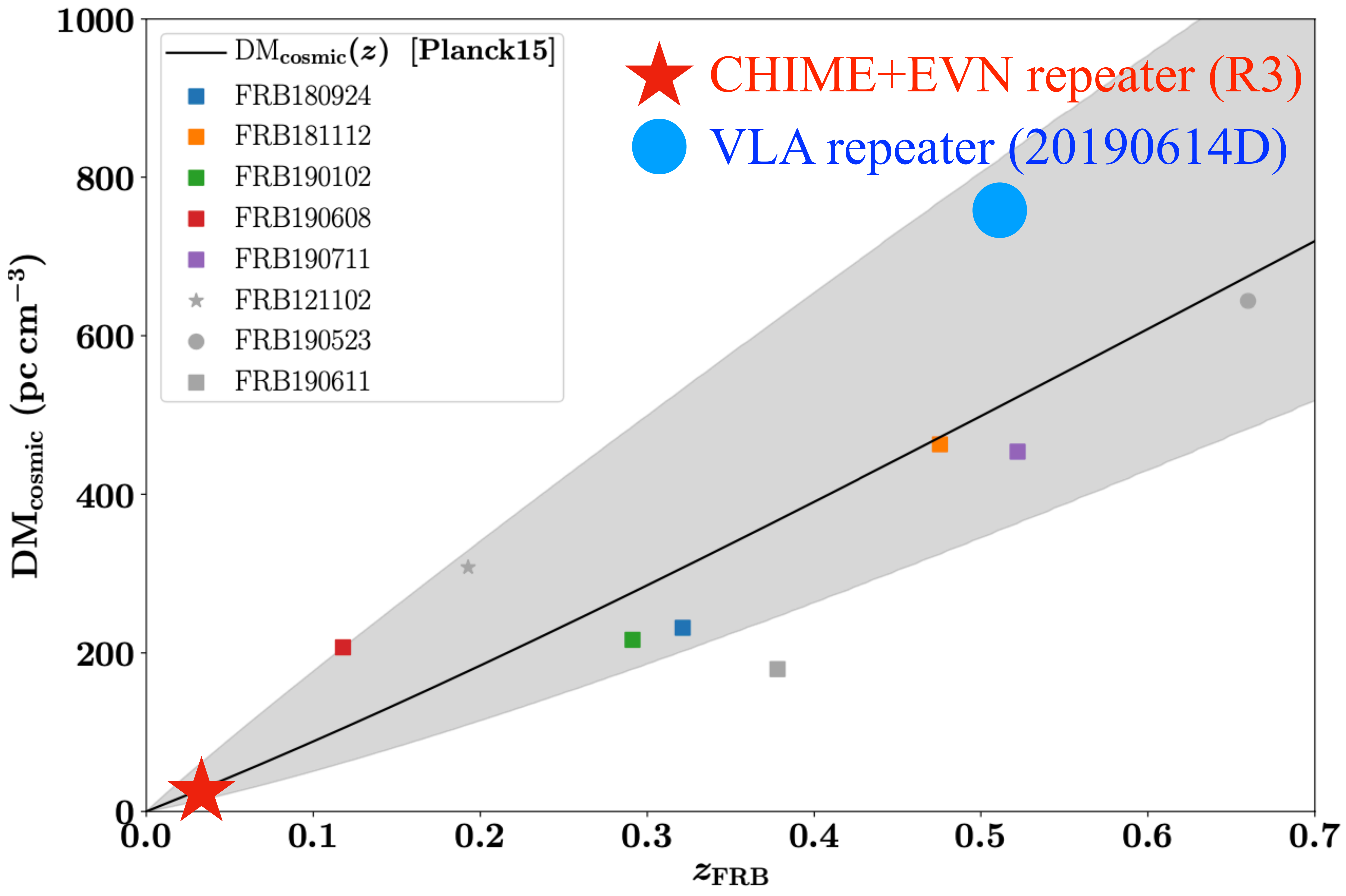
Radio astronomy DM units: pc cm^{-3}.
(DM ~ 500 for a typical FRB.)

- First discovered in 2007! When CHIME started operating, ~30 FRBs had been discovered. (Number is now ~600, of which ~500 were found by CHIME!)



FRB mini-introduction (slide 2/3)

- FRB's don't have redshifts, only DMs.
- However, a few FRBs have been measured with enough angular resolution (~1 arcsec) to associate the FRB with its host galaxy and determine a redshift.
- With ~10 points in the (z, DM) plane, it looks like FRB's are usually cosmological, and DM is a reasonable distance indicator.
- Implication: FRB's are ultra-energetic (~10^5-10^{11} times brighter than known sources in our Galaxy)
- Explaining FRB's has become a central unsolved problem in astrophysics.



"Macquart relation" = "DM-z relation"
Solid line = expected cosmological DM at redshift z

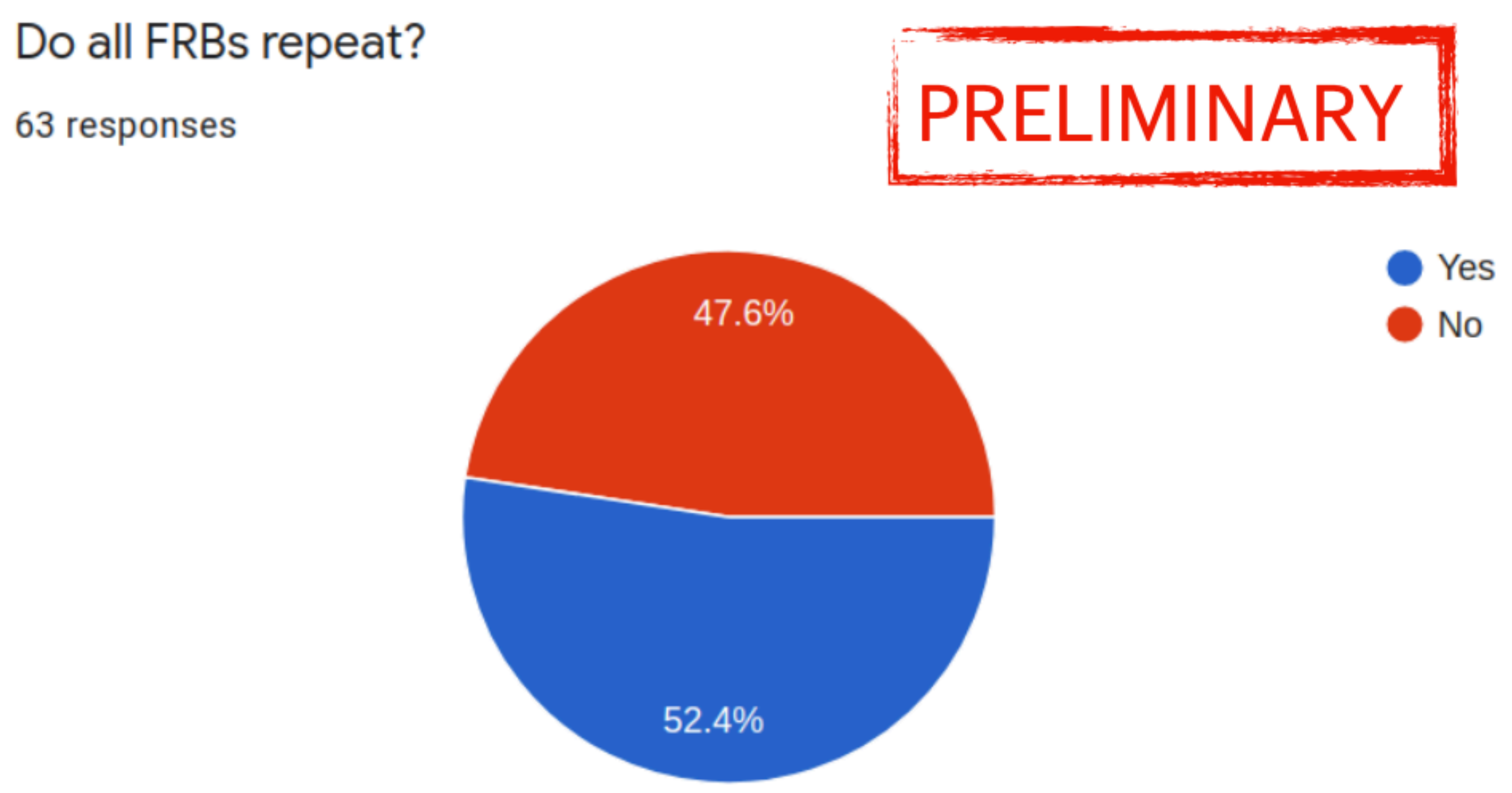
ASKAP (2005.13161)
CHIME+EVN (2001.02222)
DSA (1907.01542)
VLA (2007.02155)

FRB mini-introduction (slide 3/3)

Repeaters: prior to CHIME, one FRB had been observed to repeat. This FRB (now called "R1") was a gold mine of information. In particular, it was the first FRB localized to a host galaxy.

In the first ~year of operation, CHIME found 18 new repeating FRB's, establishing that repetition is a ubiquitous phenomenon! (Since then, 2 more repeaters have been found by other telescopes, and CHIME also has a few dozen unpublished repeaters.)

Open question: do all FRB's repeat, or are repeating and non-repeating FRB's different types of objects?



(poll from FRB2020 online conference)

A Living Theory Catalogue for Fast Radio Bursts

E. Platts[a,*], A. Weltman[a], A. Walters[b,c], S. P. Tendulkar[d], J.E.B. Gordin[a], S. Kandhai[a]

	Progenitor	Mechanism	Emission	Counterparts	Type	References
Merger	NS–NS	Mag. brak.	—	GW, sGRB, afterglow, X-rays, kilonovae	Single	Totani (2013)
		Mag. recon.	Curv.		Both	Wang et al. (2016)
		Mag. flux	—		Both	Dokuchaev and Eroshenko (2017)
	NS–SN	Mag. recon.	—	None	Single	Egorov and Postnov (2009)
	NS–WD	Mag. recon.	Curv.	—	Repeat	Gu et al. (2016)
		Mag. recon.	Curv.	—	Single	Liu (2017)
	WD–WD	Mag. recon.	Curv.	X-rays, SN	Single	Kashiyama et al. (2013)
	WD–BH	Maser	Synch.	X-rays	Single	Li et al. (2018)
	NS–BH	BH battery	—	GWs, X-rays, γ-rays	Single	Mingarelli et al. (2015)
	Pulsar–BH	—	—	GWs	Single	Bhattacharyya (2017)
	KNBH–BH (Inspiral)	Mag. flux	Curv.	GWs, sGRB, radio afterglow	Single	Zhang (2016b)
	KNBH–BH (Magneto.)	Mag. recon.	Curv.	GW, γ-rays, afterglow	Single	Liu et al. (2016)
Collapse	NS to KNBH	Mag. recon.	Curv.	GW, X-ray afterglow & GRB	Single	Falcke and Rezzolla (2014) Punsly and Bini (2016) Zhang (2014)
	NS to SS	β-decay	Synch.	GW, X- & γ-rays	Single	Shand et al. (2016)
	NS to BH	Mag. recon.	Curv.	GW	Single	Fuller and Ott (2015)
	SS Crust	Mag. recon.	Curv.	GW	Single	Zhang et al. (2018)
SNR (Pulsar)	Giant Pulses	Various	Synch./ Curv.	—	Repeat	Keane et al. (2012) Cordes and Wasserman (2016) Connor et al. (2016)
	Schwinger Pairs	Schwinger	Curv.	—	Single	Lieu (2017)
	PWN Shock (NS)	—	Synch.	SN, PWN, X-rays	Single	Murase et al. (2016)
	PWN Shock (MWD)	—	Synch.	SN, X-rays	Single	Murase et al. (2016)
SNR (Mag.)	MWN Shock (Single)	Maser	Synch.	GW, sGRB, radio afterglow, high energy γ-rays	Single	Popov and Postnov (2007) Murase et al. (2016) Lyubarsky (2014)
	MWN Shock (Clustered)	Maser	Synch.	GW, GRB, radio afterglow, high energy γ-rays	Repeat	Beloborodov (2017)
AGN	Jet–Caviton	e^- scatter	Bremsst.	X-rays, GRB, radio	Repeat	Romero et al. (2016)
					Single	Vieyro et al. (2017)
	AGN–KNBH	Maser	Synch.	SN, GW, γ-rays, neutrinos	Repeat	Das Gupta and Saini (2017)
	AGN–SS	e^- oscill.	—	Persistent GWs, GW, thermal rad., γ-rays, neutrinos	Repeat	Das Gupta and Saini (2017)
	Wandering Beam	—	Synch.	AGN emission, X-ray/UV	Repeat	Katz (2017b)
Collision/Interaction	NS & Ast./ Comets	Mag. recon.	Curv.	None	Single	Geng and Huang (2015) Huang and Geng (2016)
	NS & Ast. Belt	e^- stripping	Curv.	γ-rays	Repeat	Dai et al. (2016) ?
	Small Body & Pulsar	Maser	Synch.	None	Repeat	Mottez and Zarka (2014)
	NS & PBH	Mag. recon.	—	GW	Both	Abramowicz and Bejger (2017)
	Axion Star & NS	e^- oscill.	—	None	Single	Iwazaki (2014, 2015a,b) Raby (2016)
	Axion Star & BH	e^- oscill.	—	None	Repeat	Iwazaki (2017)
	Axion Cluster & NS	Maser	Synch.	—	Single	Tkachev (2015)
	Axion Cloud & BH	Laser	Synch.	GWs	Repeat	Rosa and Kephart (2018)
	AQN & NS	Mag. recon.	Curv.	Below IR	Repeat	van Waerbeke and Zhitnitsky (2018)
Other	Starquakes	Mag. recon.	Curv.	GRB, X-rays	Repeat	Wang et al. (2018)
	Variable Stars	Undulator	Synch.	—	Repeat	Song et al. (2017)
	Pulsar Lightning	Electrostatic	Curv.	—	Repeat	Katz (2017a)
	Wandering Beam	—	—	—	Repeat	Katz (2016d)
	Tiny EM Explosions	Thin shell related	Curv.	Higher freq. radio pulse, γ-rays	Repeat	Thompson (2017b,a)
	WHs	—	—	IR emission, γ-rays	Single	Barrau et al. (2014, 2018)
	NS Combing	Mag. recon.	—	Scenario	Both	Zhang (2017, 2018)
	Superconducting Cosmic Strings	Cusp decay	—	GW, neutrinos, cosmic rays, GRBs	Single	Costa et al. (2018)
	Galaxy DSR	DSR	Synch.	—	Both	Houde et al. (2018)
	Alien Light Sails	Artificial transmitter	—	—	Repeat	Lingam and Loeb (2017)
Inviable	Stellar Coronae	N/A	N/A	N/A	N/A	Loeb et al. (2014) Maoz et al. (2015)
	Neutral Cosmic Strings	N/A	N/A	N/A	N/A	Brandenberger et al. (2017)
	Annihilating Mini BHs	N/A	N/A	N/A	N/A	Keane et al. (2012)

Table 1: Tabulated Summary

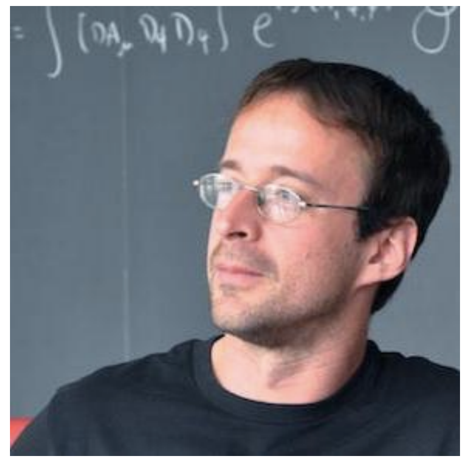
arxiv:1810.05836

“bonsai”: CHIME fast radio burst search software

From 2016-2018, we developed algorithms to search a CHIME-sized dataset for fast radio bursts (FRBs).

The CHIME FRB search software is:

- Orders of magnitude faster than other search software.
- Capable of searching a ~1PB/day(!!) data stream for FRBs in real time
- Near statistically optimal
- Real-time, ~10 second latency
- Includes real-time RFI removal with very low false positive rate



Kendrick Smith

Dustin Lang

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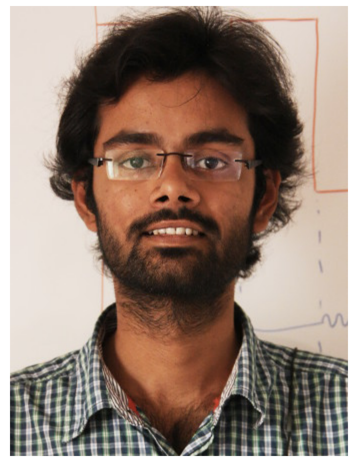
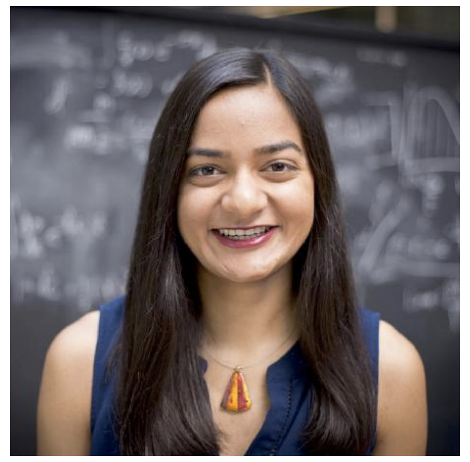


Utkarsh Giri



Maya Burhanpurkar

Alex Roman

nature

Letter | Published: 09 January 2019

Observations of fast radio bursts at frequencies down to 400 megahertz

nature

Letter | Published: 09 January 2019

A second source of repeating fast radio bursts

nature

Article | Published: 17 June 2020

Periodic activity from a fast radio burst source

nature

Article | Published: 04 November 2020

A bright millisecond-duration radio burst from a Galactic magnetar

nature

Article | Published: 06 January 2020

A repeating fast radio burst source localized to a nearby spiral galaxy

nature

Article | Published: 13 July 2022

Sub-second periodicity in a fast radio burst

Science

2020 BREAKTHROUGH OF THE YEAR

RUNNERS-UP

Found: elusive source of fast radio bursts

Everyone loves a good mystery. Take fast radio bursts (FRBs)—short, powerful flashes of radio waves from distant galaxies. For 13 years, they tantalized astronomers keen to understand their origins. One running joke said there were more theories explaining what causes FRBs than there were FRBs. (Currently, astronomers know of more than 100.)

Then, in April, an FRB went off in the Milky Way—close enough that astronomers could examine the scene. The Canadian Hydrogen Intensity Mapping Experiment, a pioneering survey telescope in British Columbia responsible for the discovery of many FRBs, narrowed the source to a small area of sky, which was soon confirmed by the U.S. radio array STARE2. Orbiting observatories sensitive to higher frequencies quickly found that a known magnetar in that part of the sky, called SGR 1935+2154, was acting up at the same time, spewing out bursts of x-rays and gamma rays.

CHIME Fast Radio Burst team to receive 2022 Berkeley Prize

The prize, awarded by the American Astronomical Society, recognizes the landmark detection of fast radio bursts (FRBs) by the CHIME collaboration, including Perimeter researchers.

November 22, 2021

Governor General's Innovation Awards

GOVERNOR GENERAL OF CANADA | CANADA INNOVATION SPACE

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Canadian Hydrogen Intensity Mapping Experiment (CHIME)

NOMINATED BY:
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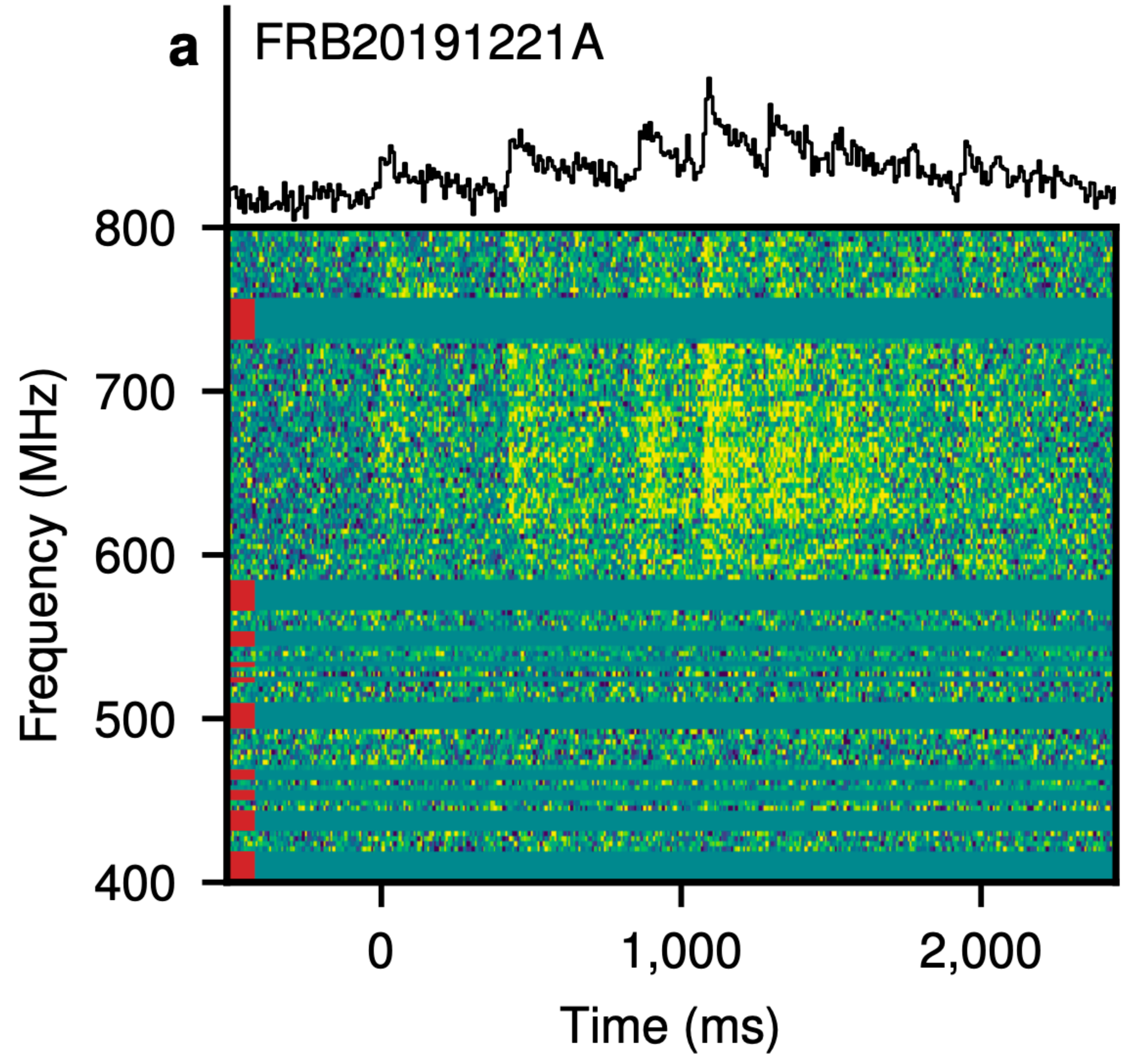
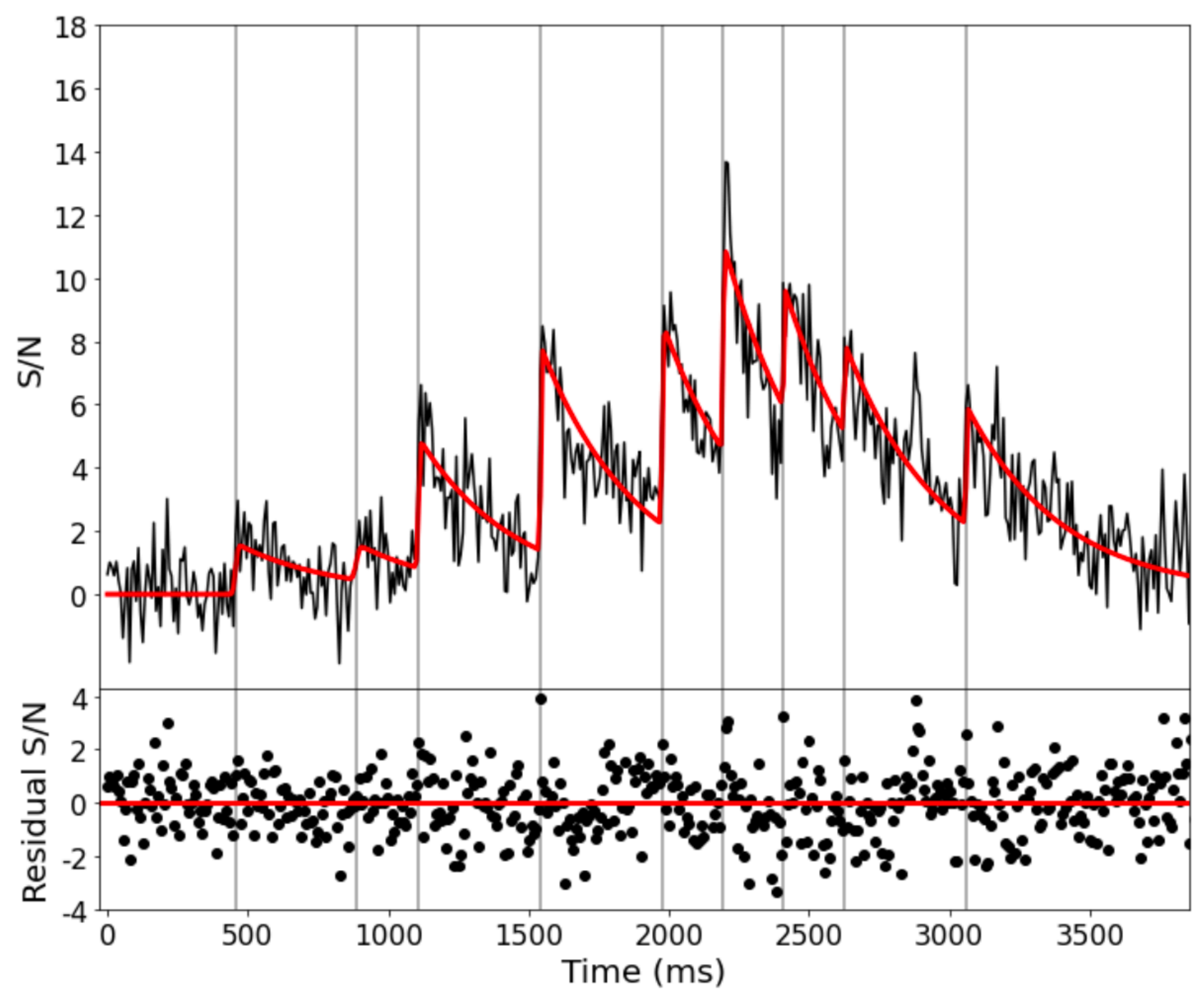
First phenomenon: periodic sub-pulses in an FRB

- A few FRBs show pulse train "microstructure".
- In this example (FRB20191221A), a ~3 second burst of activity can be resolved as a sum of ~9 overlapping pulses.

  (After subtracting a well-motivated model for the pulses, residuals are consistent with noise.)

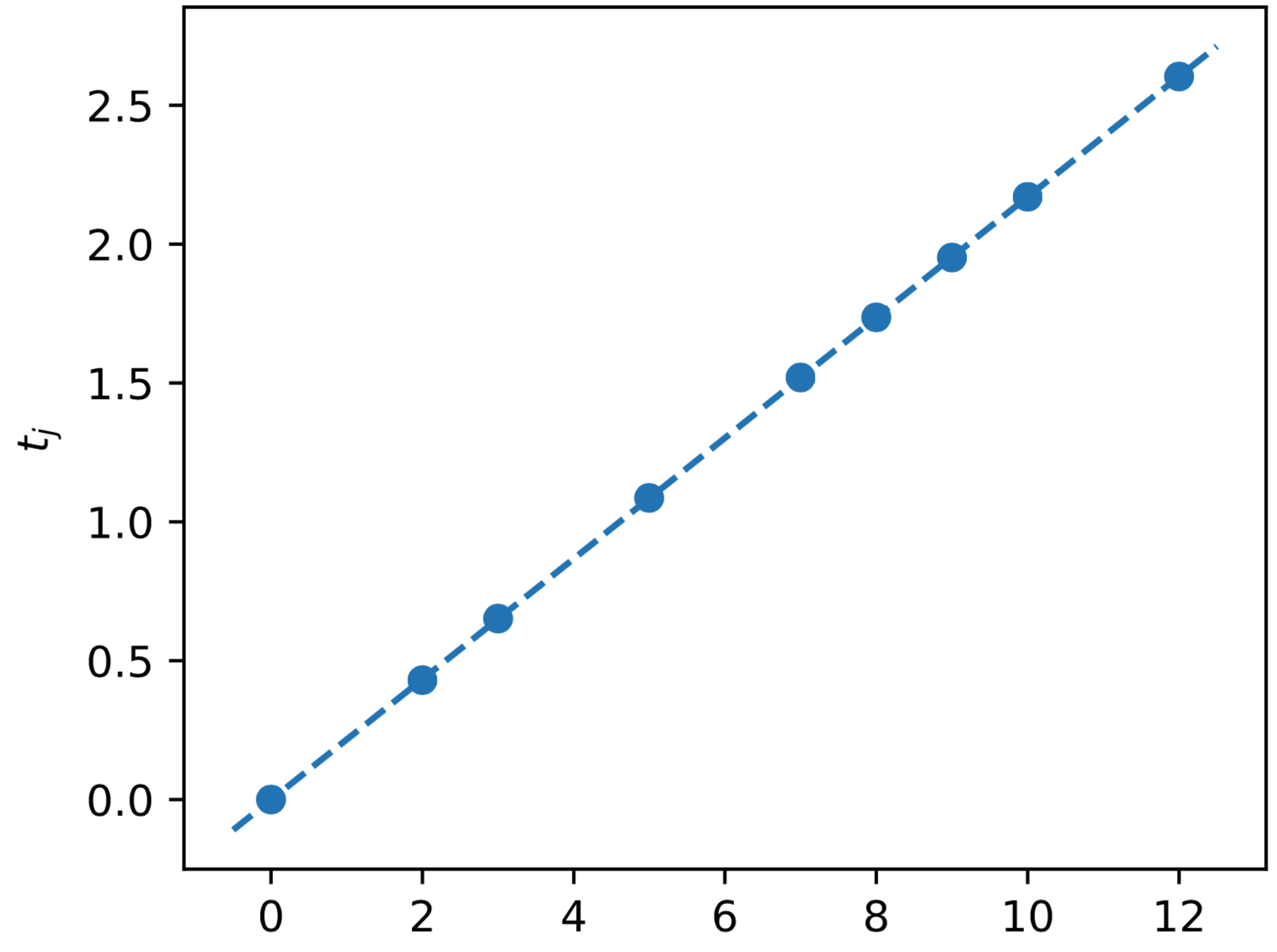


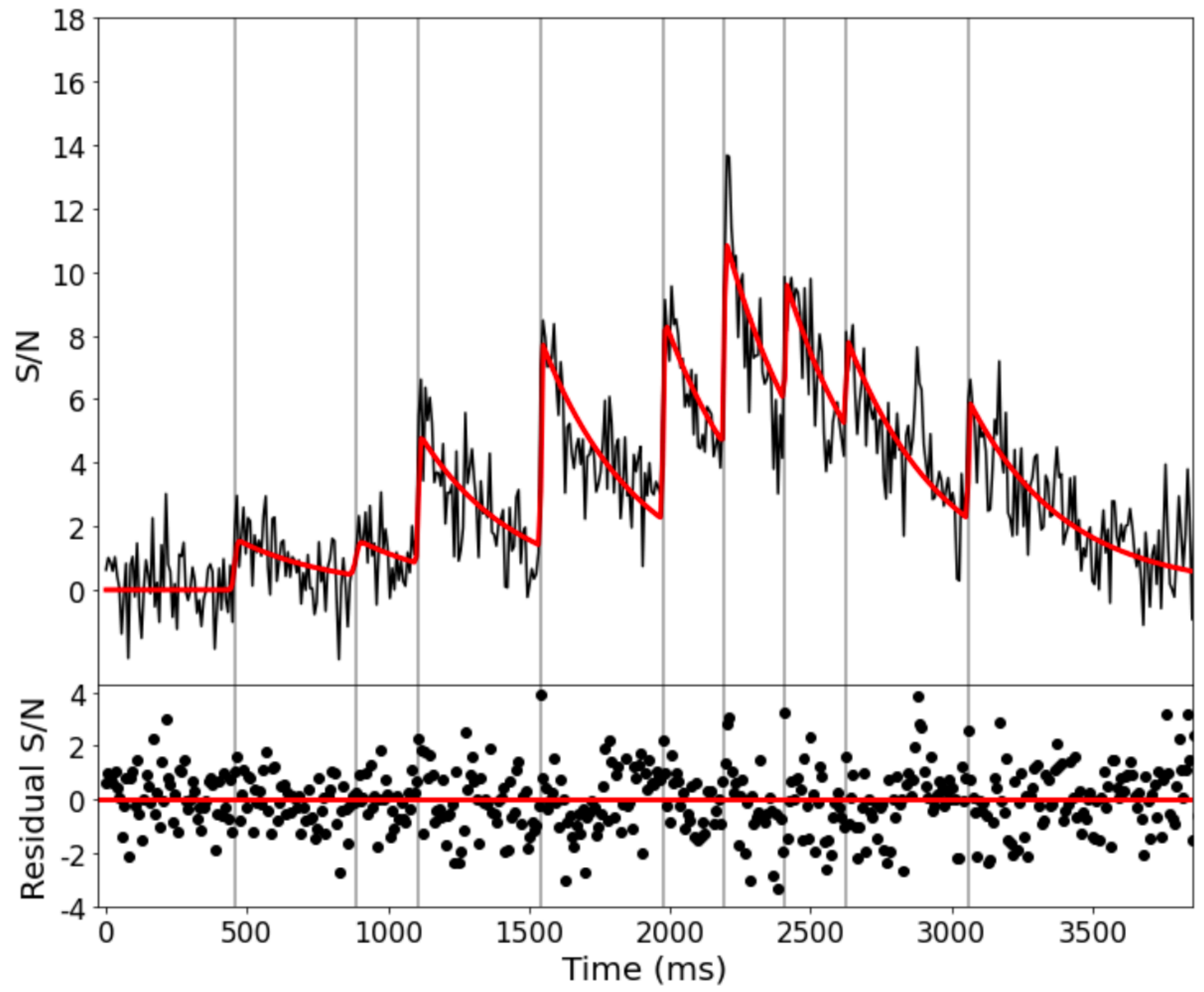


CHIME/FRB collaboration, arxiv:2107.08463

First phenomenon: periodic sub-pulses in an FRB

- We noticed that the arrival times are periodic (with 3 gaps), with best-fit period 217 ms.
- Formal significance is ~6.5σ (p-value 7×10^{-11}), accounting for look-elsewhere effect in period and choice of gaps.
- 217 ms period suggests a neutron star origin.

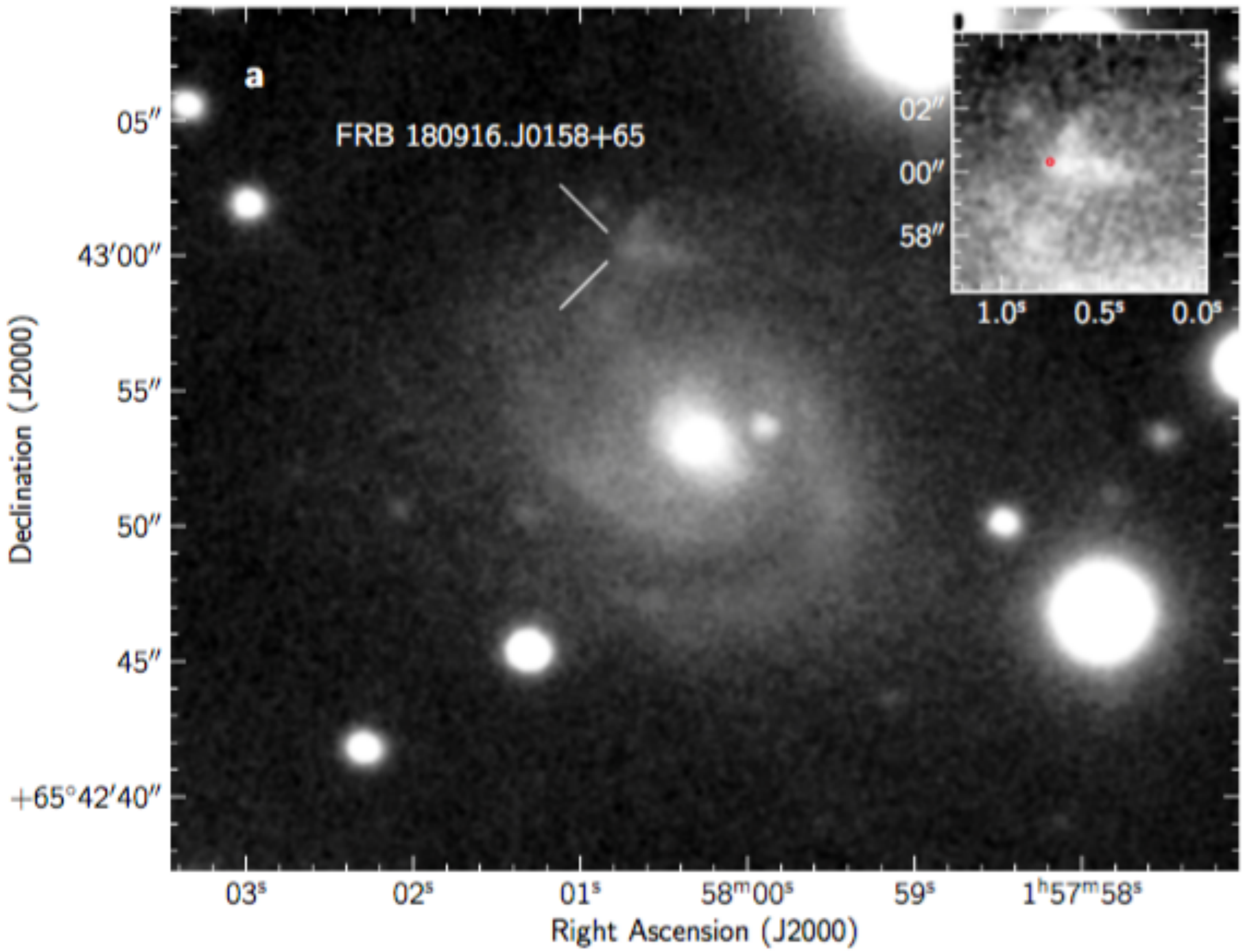




CHIME/FRB collaboration, arxiv:2107.08463

Second phenomenon: periodic activity in an FRB

Source	Name[a]	R.A.[b] (J2000)	Dec.[b] (J2000)	l^c (deg)	b^c (deg)	DM[d] (pc cm^{-3})	DM$^e_{\mathrm{NE2001}}$ (pc cm^{-3})	DM$^e_{\mathrm{YMW16}}$ (pc cm^{-3})	N_{bursts}	Exposure[f] (hr, upper / lower)	Completeness[g] (Jy ms)
1	180916.J0158+65	1h58m±7′	+65°44′±11′	129.7	3.7	349.2(3)	200	325	10	23±8	4.2
2	181030.J1054+73	10h54m±8′	+73°44′±26′	133.4	40.9	103.5(3)	40	32	2	27±14 / 19±11	... / 17
3	181128.J0456+63	4h56m±11′	+63°23′±12′	146.6	12.4	450.5(3)	112	151	2	16±10	4.0
4	181119.J12+65	12h42m±3′ 12h30m±6′	+65°08′±9′ +65°06′±12′	124.5	52.0	364.05(9)	34	26	3	19±9	2.6
5	190116.J1249+27	12h49m±8′	+27°09′±14′	210.5	89.5	441(2)	20	20	2	8±5	5.7
6	181017.J1705+68	17h05m±12′	+68°17′±12′	99.2	34.8	1281.6(4)	43	37	2	20±11	5.6
7	190209.J0937+77	9h37m±8′	+77°40′±16′	134.2	34.8	425.0(3)	46	39	2	34±19 / 28±18	3.8 / ...
8	190222.J2052+69	20h52m±10′	+69°50′±11′	104.9	15.9	460.6(2)	87	101	2	20±10	5.4

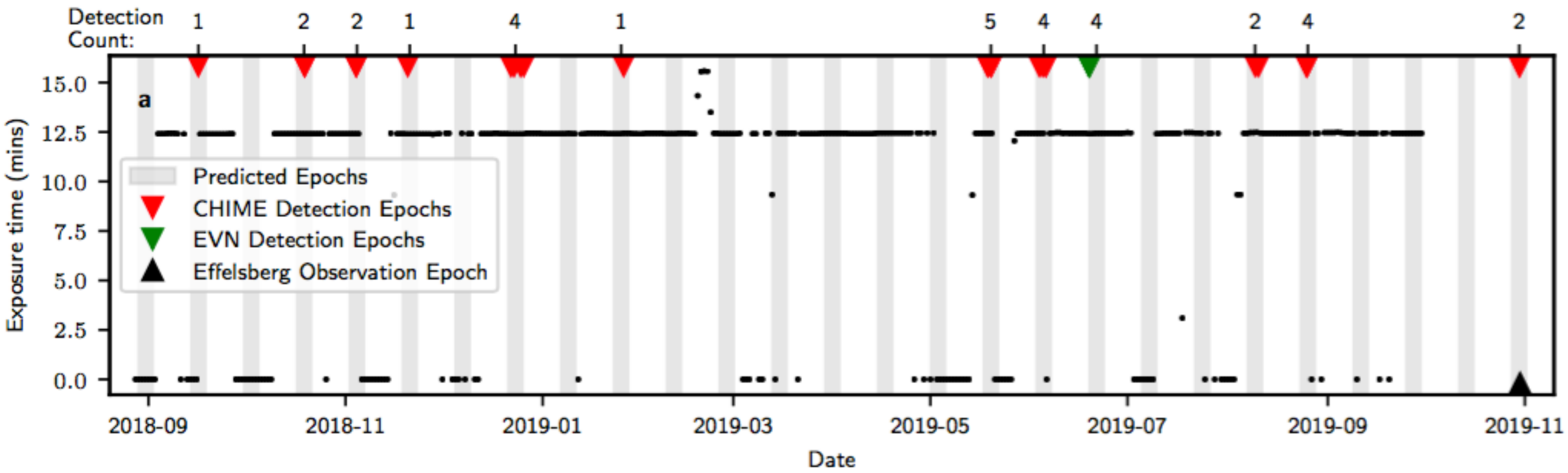


- This repeating FRB ("R3") is the most active repeating FRB in CHIME.
- Discovered with CHIME, then localized to a host galaxy with EVN (European VLBI Network).
- Host is a spiral galaxy at redshift z=0.0337. At the time, this was the closest known FRB.

Nature 577 (2020) 190, arXiv:2001.02222

Second phenomenon: periodic activity in an FRB

- A surprise: R3 is only active in 4-day windows, regularly spaced with period 16.35 days.
- Naturally explained in a neutron star model, as either orbital period (in a binary system) or precession period.



$$\text{p-value} \sim \underbrace{270}\left(\frac{4}{16.35}\right)^{11} \sim (5 \times 10^{-5})$$

Trial factor (# of trial periods × phases)

Nature 582 (2020) 351, arXiv:2001.10275

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An FRB in the Milky Way

- FRBs are much brighter (~10^{36} to 10^{42} ergs) than the brightest pulses ever observed from neutron stars in the Milky Way (~10^{31} ergs). This is why FRBs are a puzzle in the first place!

Nature 587 (2020) 54-58

An FRB in the Milky Way

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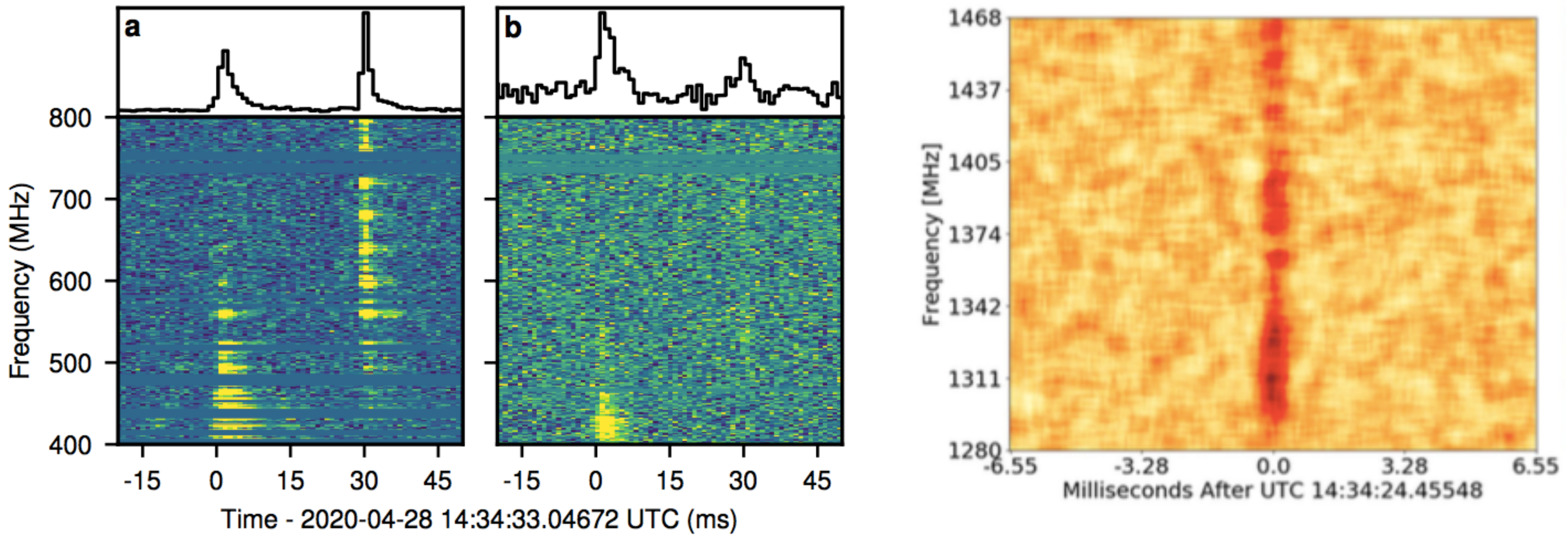
- In April 2020, CHIME observed two pulses from a known magnetar (SGR 1935+2154) with energy (3×10^{34}) ergs! (The first pulse was also seen by ARO; the second pulse was also seen by STARE2 at 1.4 GHz.)

CHIME ARO STARE2



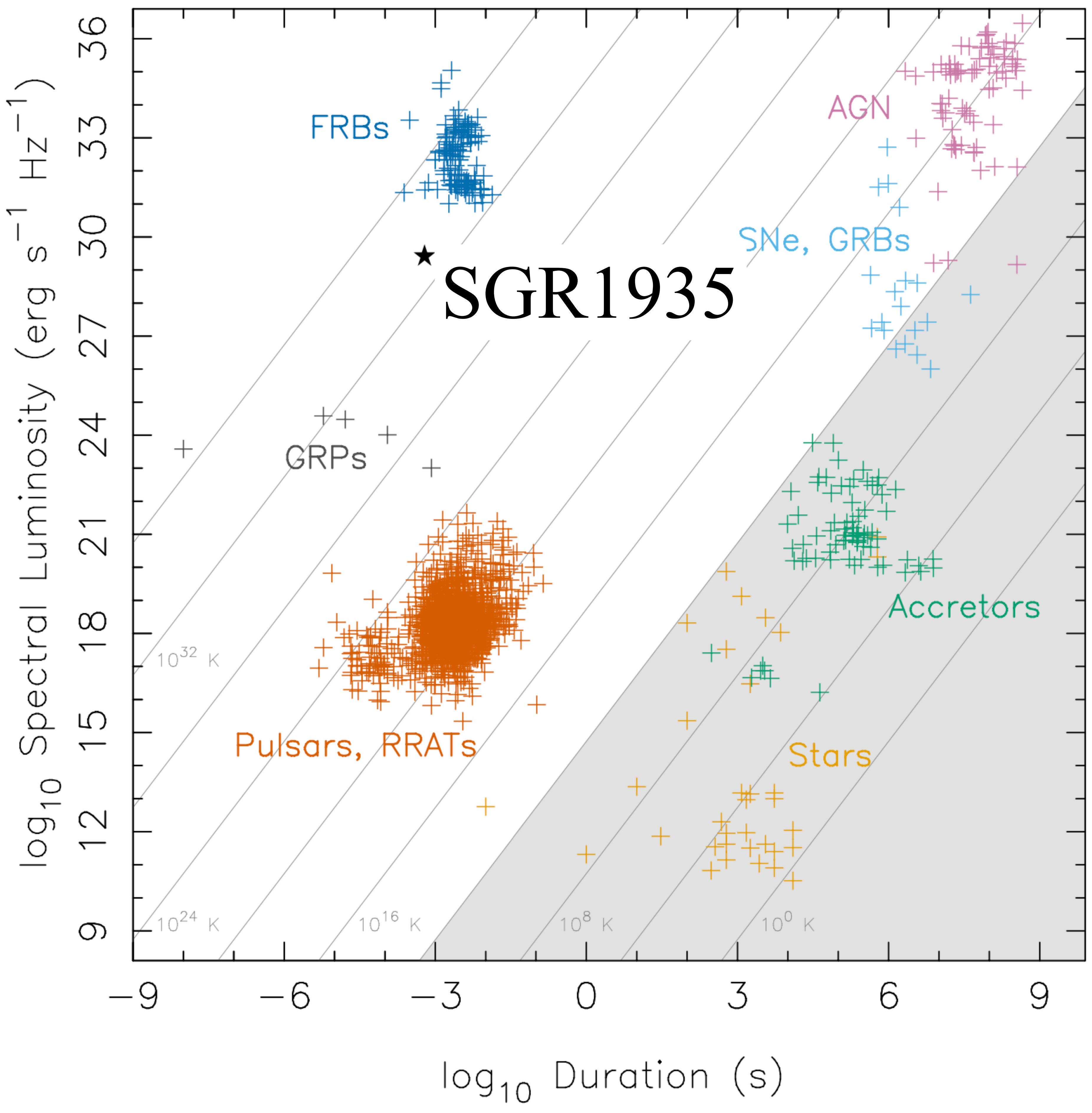
Nature 587 (2020) 54-58

An FRB in the Milky Way

- If this pulse had come from a nearby galaxy, it would be bright enough to qualify as an FRB.
- Implication: at least some FRBs are magnetars!
- It's natural to speculate that all FRBs are magnetars. However, the plot thickens….

Blue = FRBs

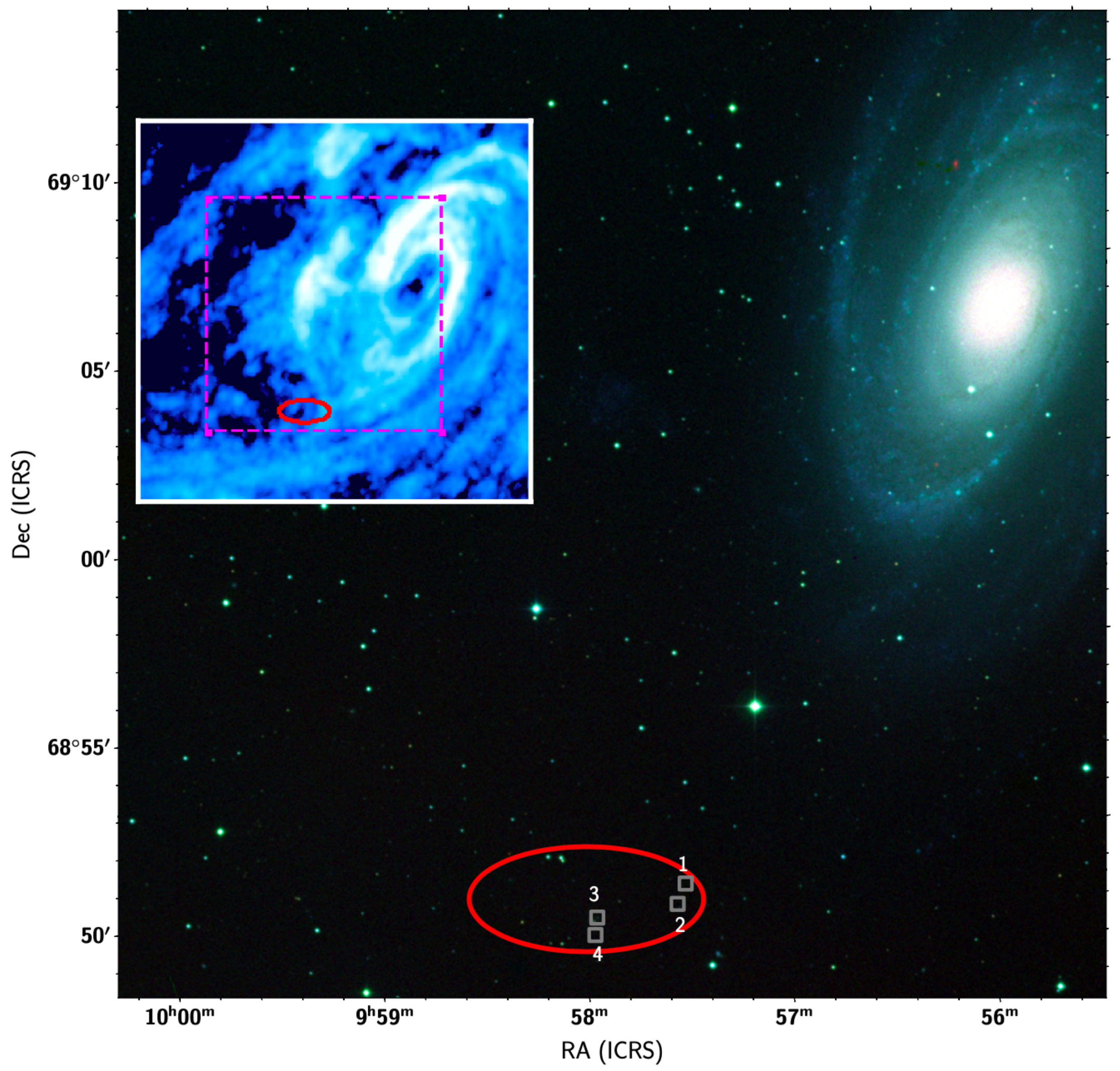
Orange = well-understood Milky Way pulses



Bochenek et al (STARE2)

Another CHIME result: an FRB in an old globular cluster

- FRB 20200120E: repeating FRB discovered in CHIME (3 bursts observed).
- Localized by EVN to old (~10^{10} years) globular cluster near the M81 galaxy (redshift $z \sim 10^{-3}$)
- But, an old globular cluster should have negligible recent star formation. How can there be magnetars?
- Merger-induced collapse may be a viable mechanism (e.g. Kremer et al arXiv:2210.04907).



ars TECHNICA

WELL, THAT'S ODD —

New fast radio burst found in area that shouldn't have any sources

Source narrowed down to a cluster where the stars are too old for bursts.

JOHN TIMMER - 2/24/2022, 5:25 PM

Mysterious Repeating Fast Radio Burst Traced to Very Unexpected Location

SPACE 23 February 2022 By MICHELLE STARR

Bhardwaj et al ApJL (2103.01295)

Kirsten et al 2105.11445

More on the Galactic FRB: comparing X-ray and radio

- Several X-ray telescopes observed X-ray pulses coincident with the radio pulses.
- Arrival time lag $L = t_{radio} - t_{x\text{-}ray}$ is very constraining for models. At the time of the SGR1935 observation, all magnetar FRB models predicted $L \geq 0$ (i.e. radio arrives later).

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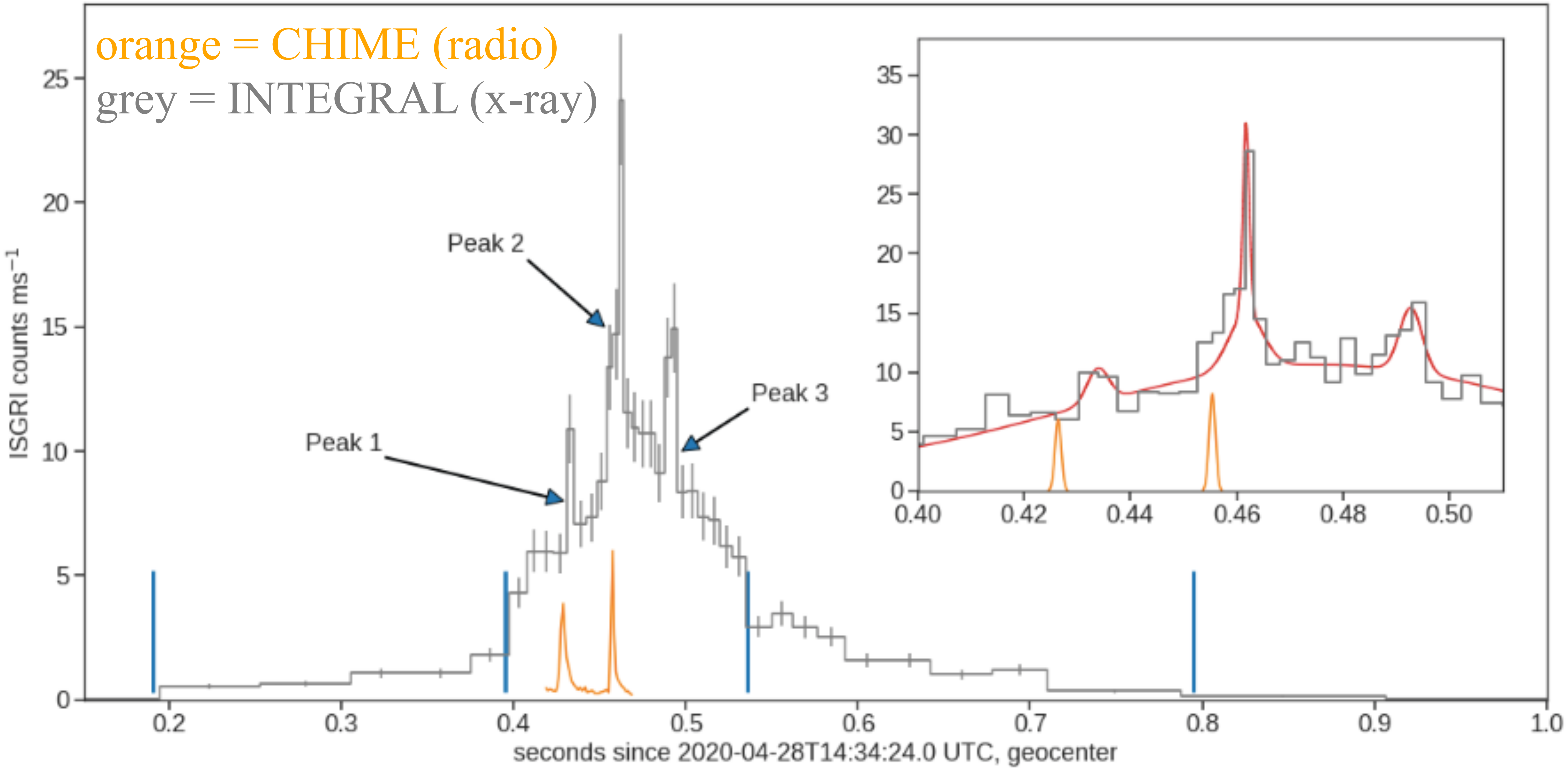
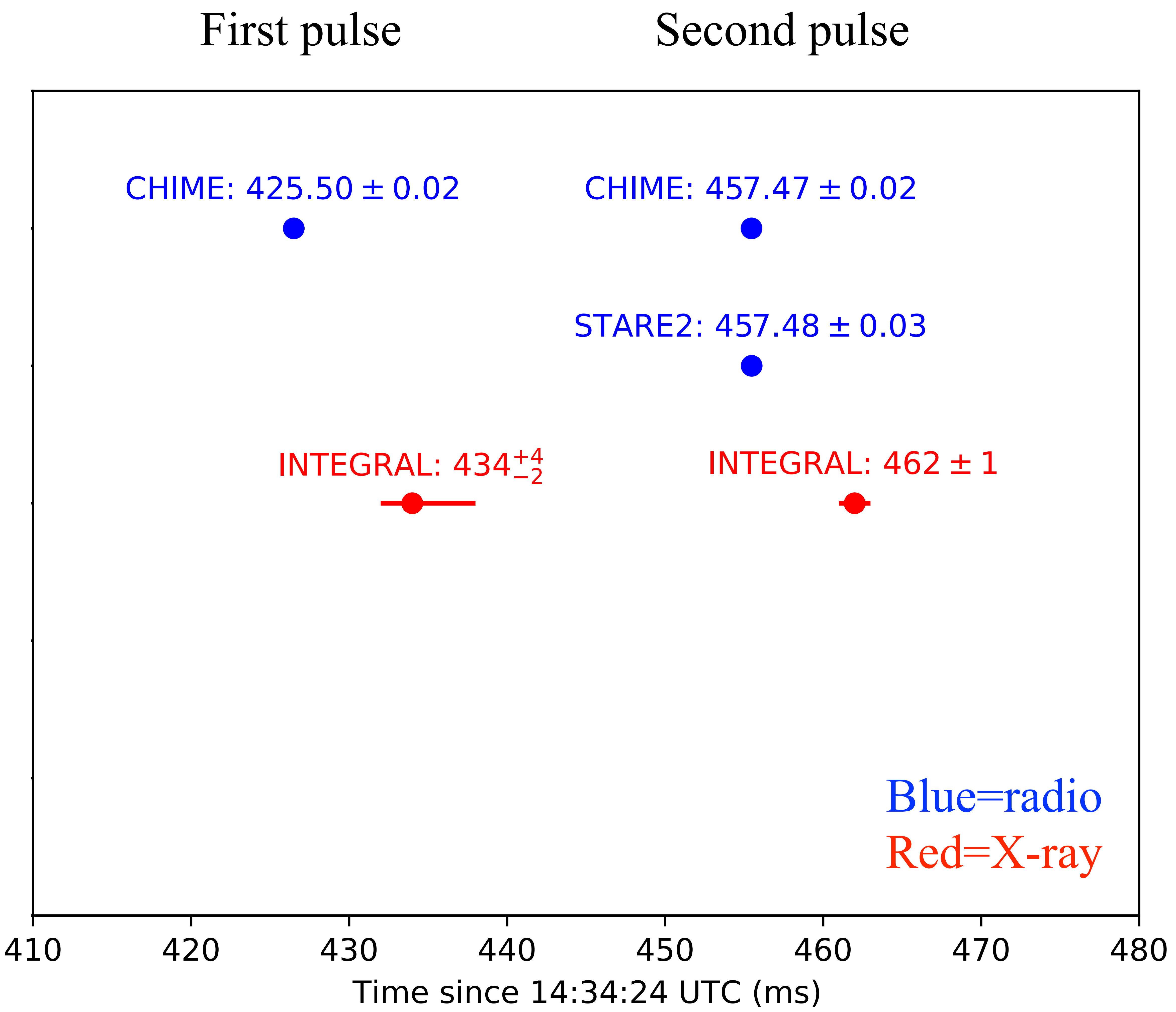
- Arrival time lag $L = t_{radio} - t_{x\text{-}ray}$ is very constraining for models. At the time of the SGR1935 observation, all magnetar FRB models predicted $L \geq 0$ (i.e. radio arrives later).
- The first reported X-ray measurements (INTEGRAL) found $L = (-6.5 \pm 1)$ ms!



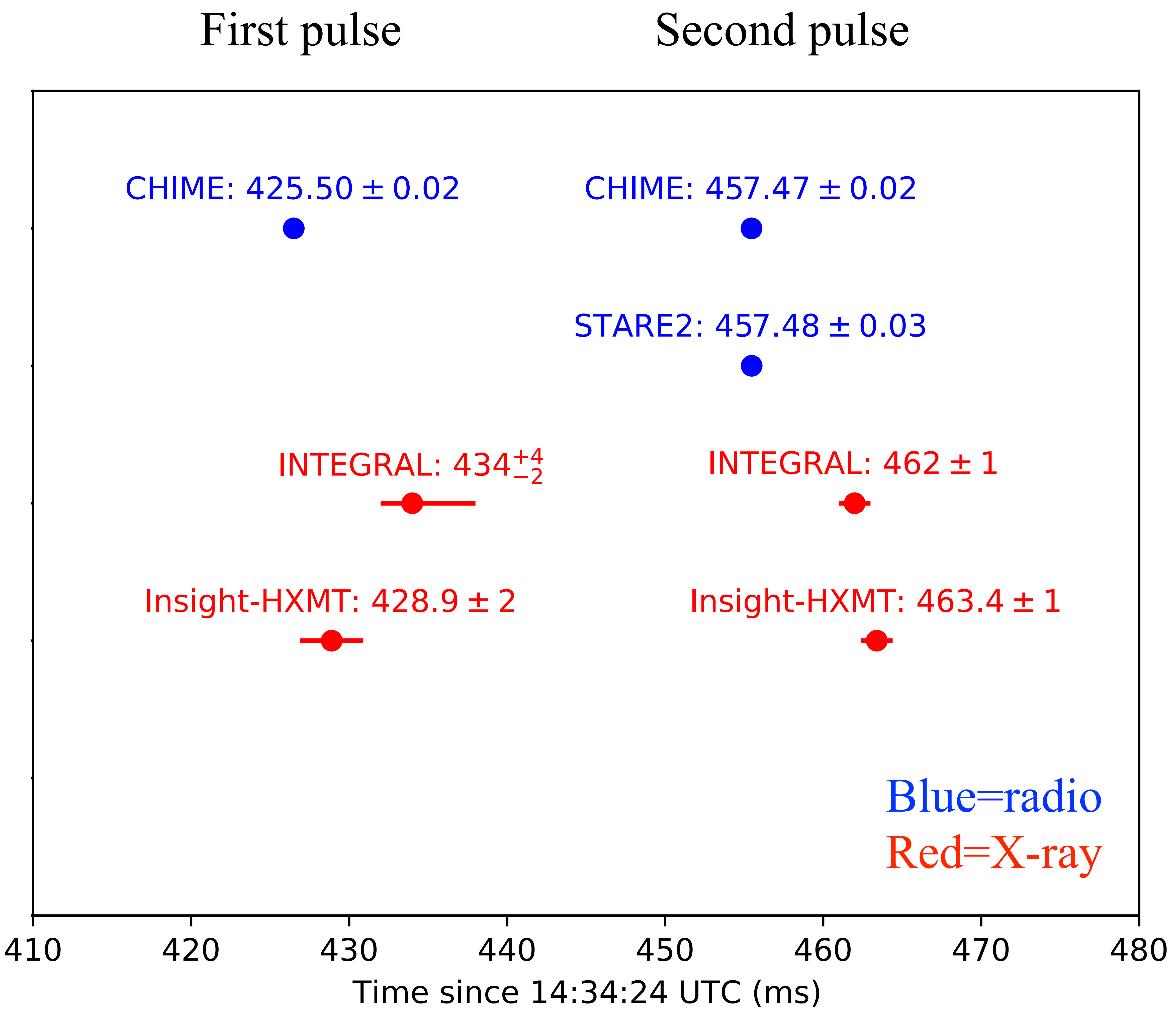
INTEGRAL collaboration (Mereghetti et al), 2005.06335

More on the Galactic FRB: comparing X-ray and radio



- Shortly thereafter, two more X-ray experiments published timings.

More on the Galactic FRB: comparing X-ray and radio



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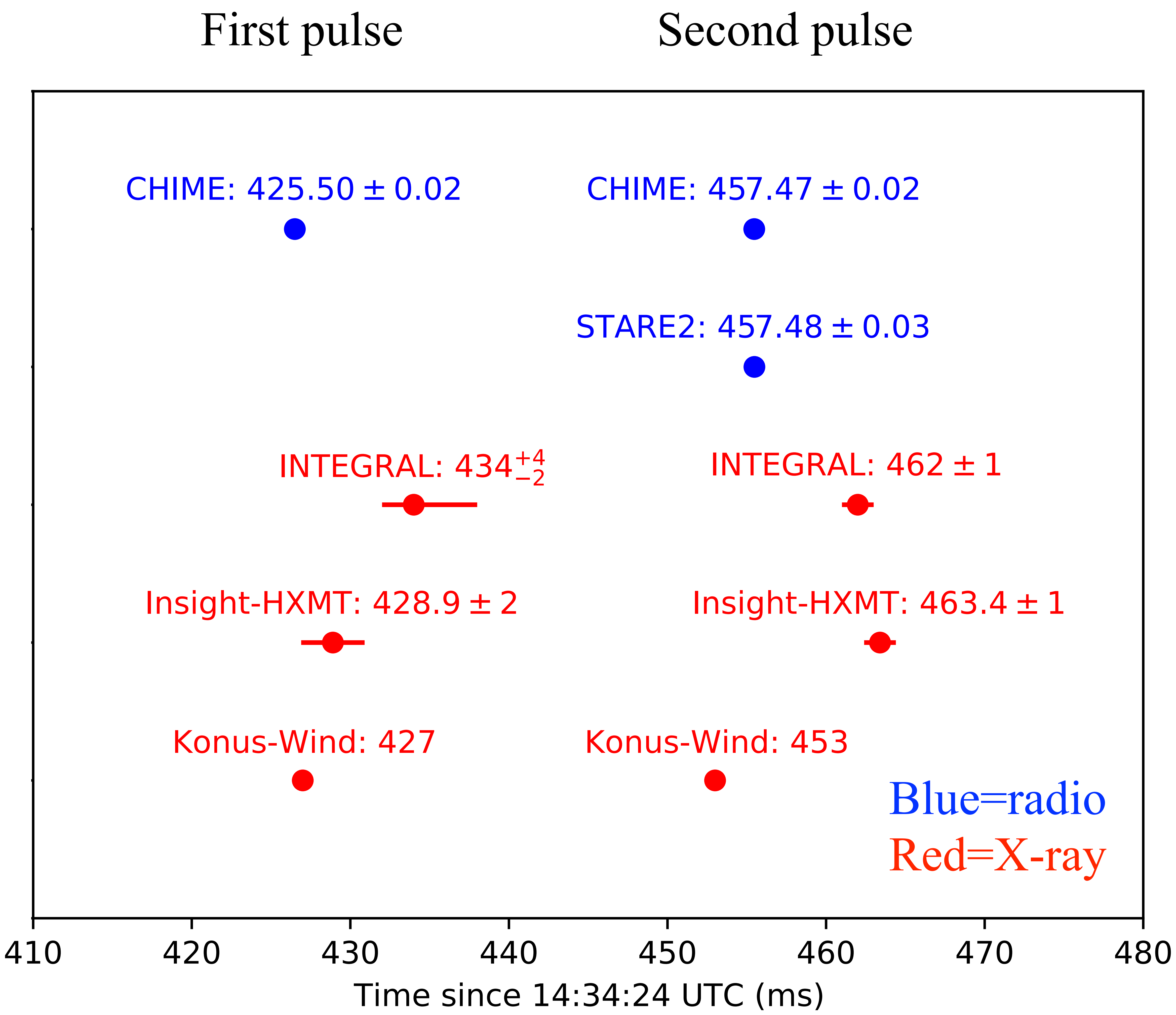

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- Insight-HXMT is consistent with INTEGRAL (chi^2=4.2, dof=2, p=0.12), and increases significance of $L < 0$ to 8.5 sigma.
- Konus-Wind shows no preference for $L < 0$, but doesn't report error bars.

  (For what it's worth, the Konus-Wind instrumental resolution is 2 ms, versus 0.061 ms for INTEGRAL and 1 ms for Insight-HXMT.)

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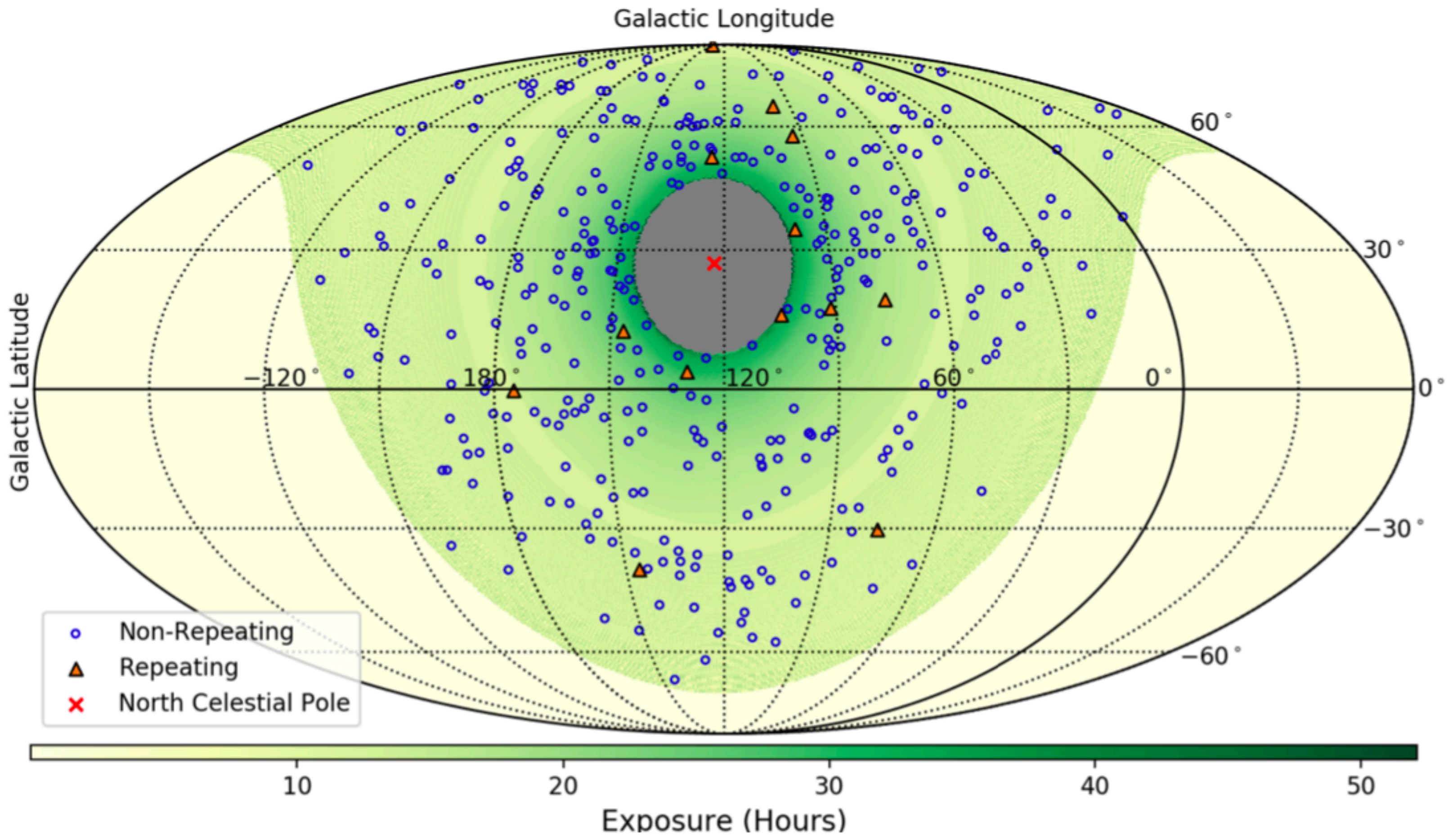
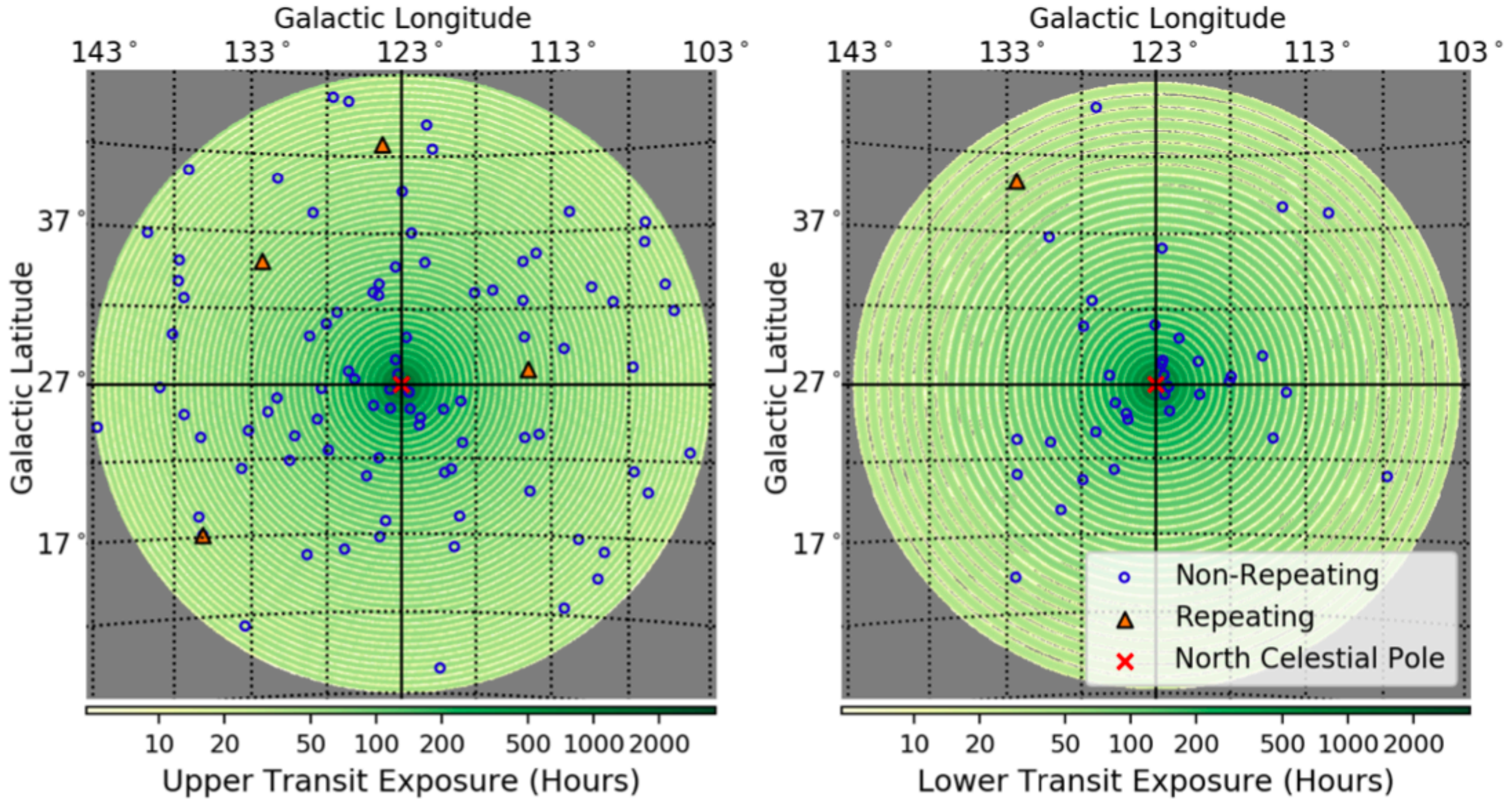
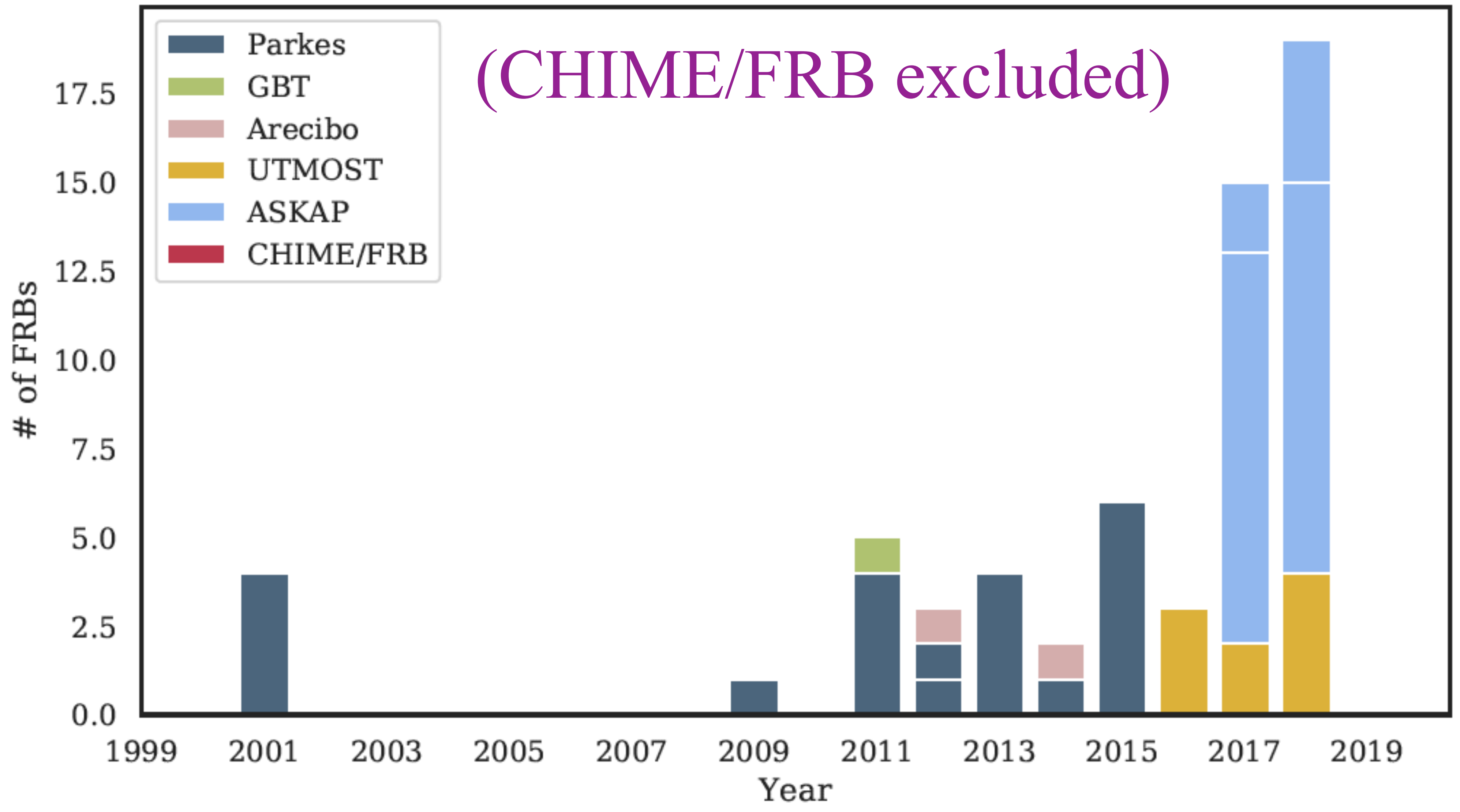
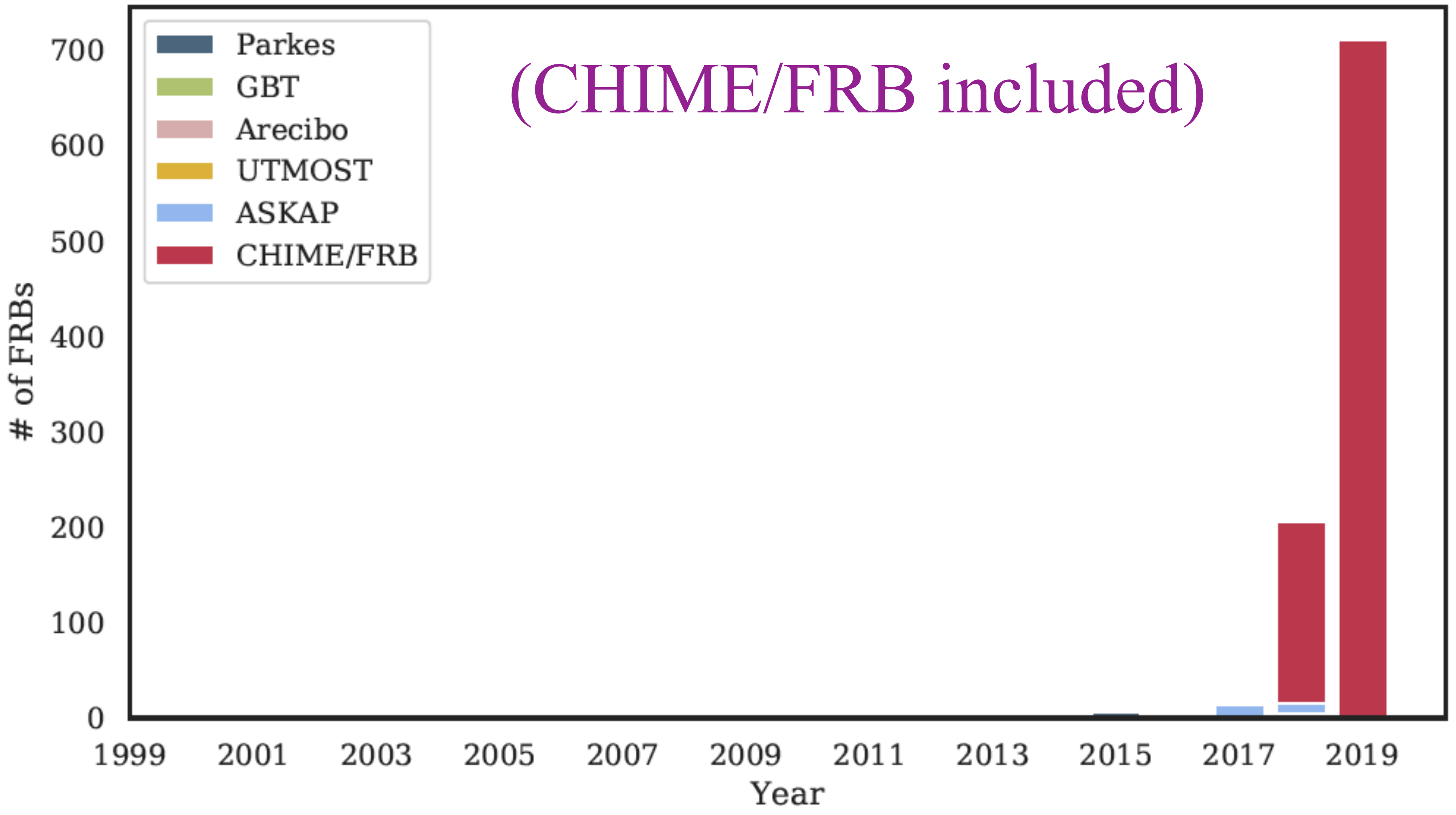
First CHIME FRB catalog

492 total sources, 18 of which are repeaters!





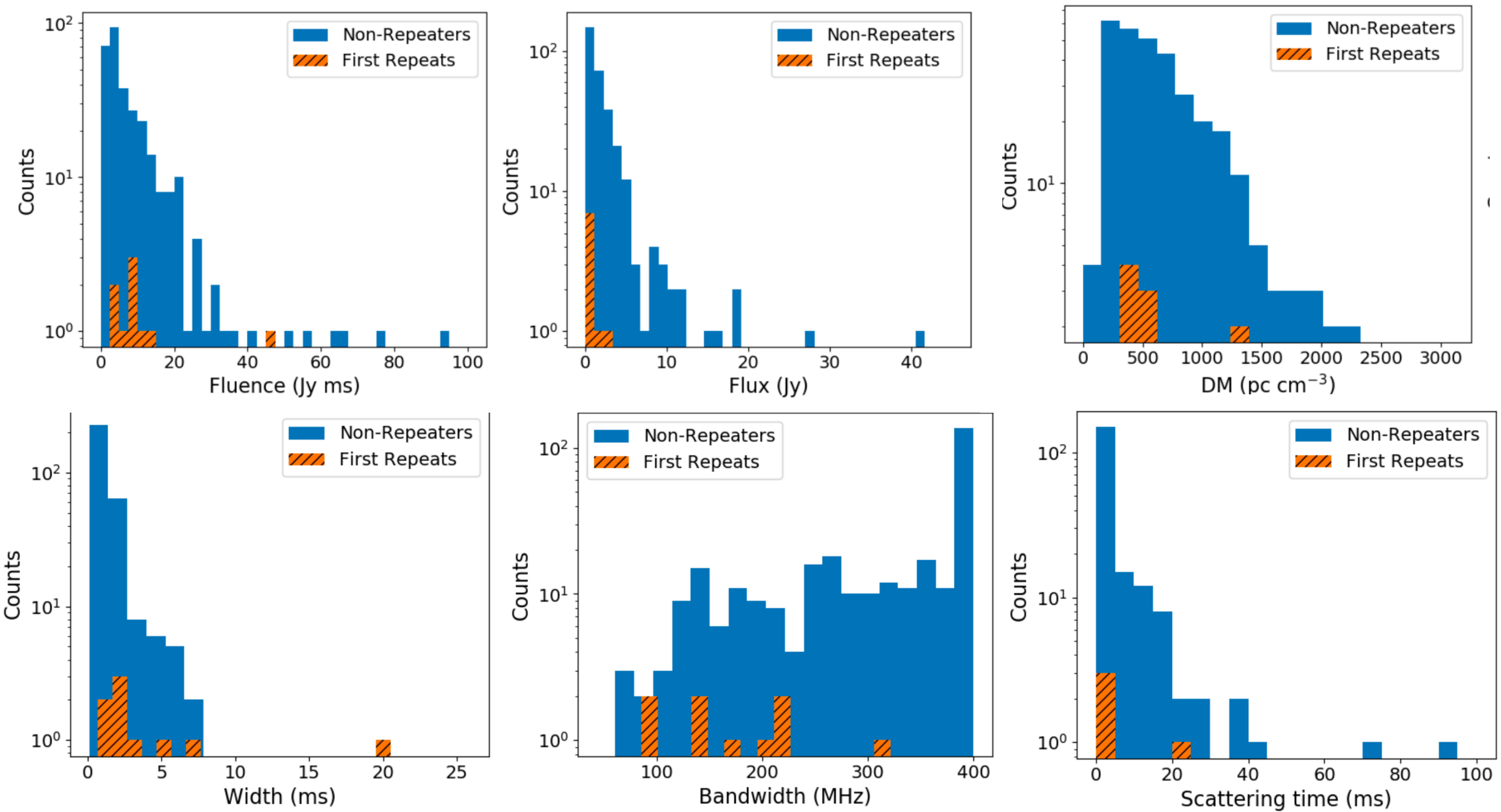




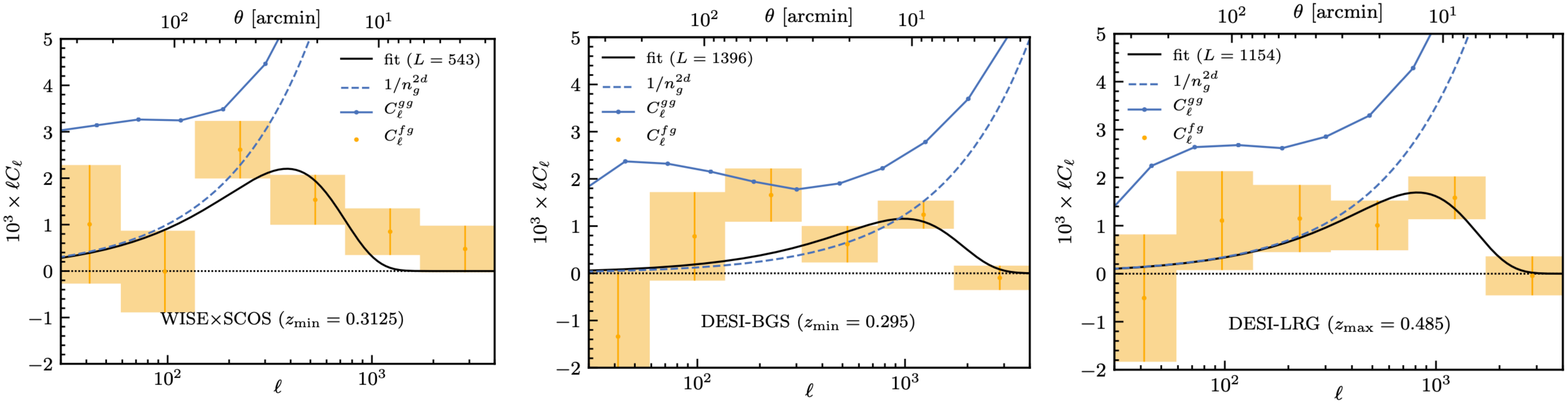
CHIME/FRB collaboration, arxiv:2106.04352, ApJ accepted

First CHIME FRB catalog

- Model parameters for repeating FRBs versus non-repeaters.
  Repeaters have wider pulses and narrower bandwidths, but other parameters are the same (DM, scattering time, flux).



Using FRB-galaxy correlations to learn about FRBs



- CHIME angular resolution is insufficient to associate individual FRBs with individual galaxies.
- By spatially correlating FRBs and galaxies, we see a high significance (5σ) statistical association.
- First evidence for high-DM FRBs (DM ~ 800) at intermediate redshifts (z ~ 0.4), later confirmed by other telescopes.
- Much higher statistical significance coming soon!

Masoud Rafiei-Ravandi

Rafiei-Ravandi et al, ApJ

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Coming soon: CHIME outriggers

CHIME finds FRBs at a very high rate, but has limited angular resolution.

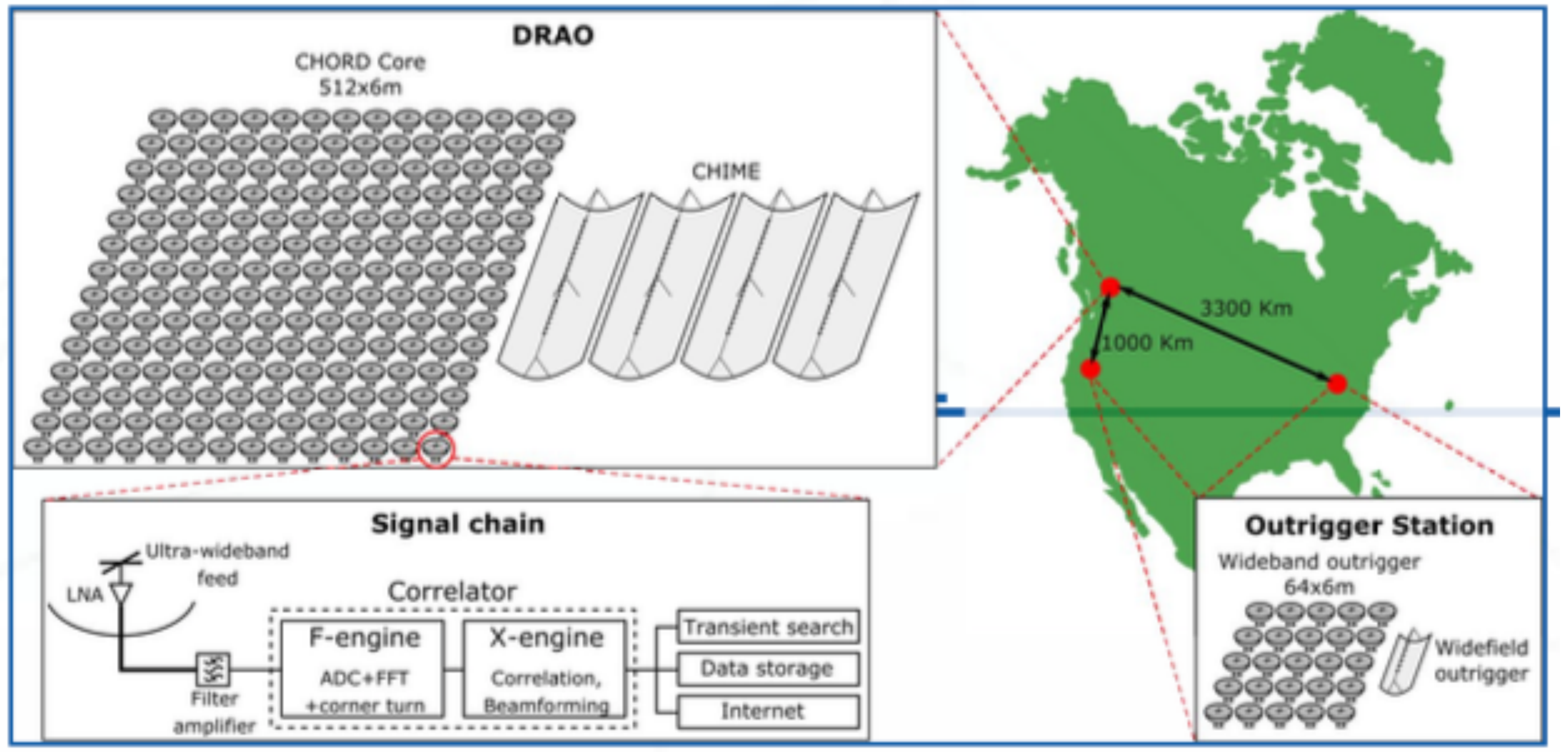
Solution: build outrigger telescopes! (Funded by Moore foundation and NSF.)

- When CHIME core detects an FRB, it tells the outriggers to save voltage data to disk.
- Outriggers do nothing except ring-buffer data, and save to disk on command.
- Later, data can be shipped to computing cluster for VLBI analysis.
- Currently under construction!

Coming soon: CHORD (Canadian successor to CHIME)

New technology under development:

- Wide-band feeds (300-1500 MHz).
- Lower noise, aiming for T_{sys} ~30 K (CHIME is ~50 K).
- Using 512 6-m dishes, total collecting area $(120\ m)^2$.
- Effective mapping speed ~10 times higher than CHIME.
- Outriggers for VLBI resolution.
- "Pathfinder" expected 2023/4, full instrument expected 2025/6.



Concluding thoughts

- For \$20M CAD, you can build the world’s most powerful radio telescope!

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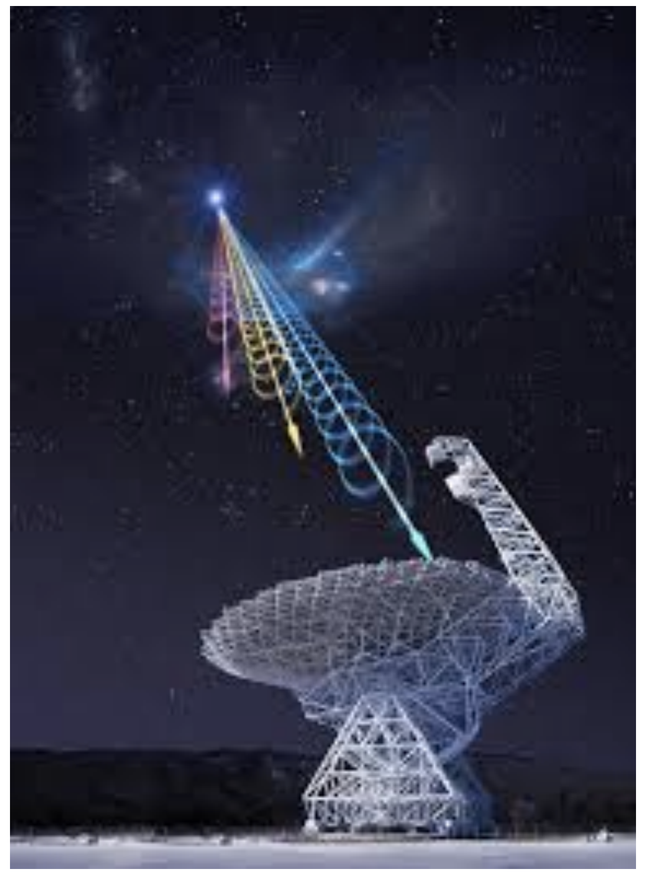
- The beginning of an era in radio astronomy: “large N and clever algorithms”?
- CHIME/CHORD are ambitious steps in this direction. We have made dramatic improvements to certain algorithms in radio astronomy, but more challenges remain.

Concluding thoughts

- For $20M CAD, you can build the world’s most powerful radio telescope!
- … but you will have an immense data rate, and you’ll need to solve extremely hard computing problems.
- The beginning of an era in radio astronomy: “large N and clever algorithms”?
- CHIME/CHORD are ambitious steps in this direction. We have made dramatic improvements to certain algorithms in radio astronomy, but more challenges remain.
- There is a clear path to scaling up CHIME by a factor of ~1000 or so (in mapping speed) in the near future.

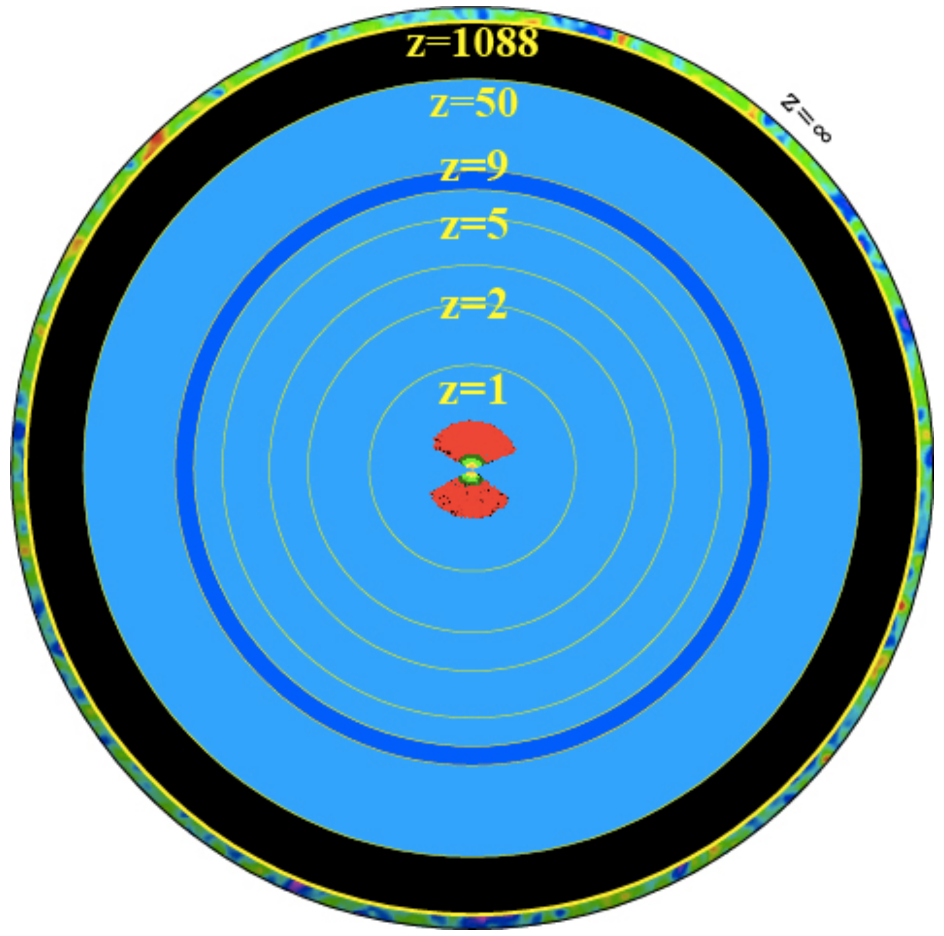
Concluding thoughts

Radio astronomy may be “scaled up” by orders of magnitude in the near future.
The discovery space is huge!



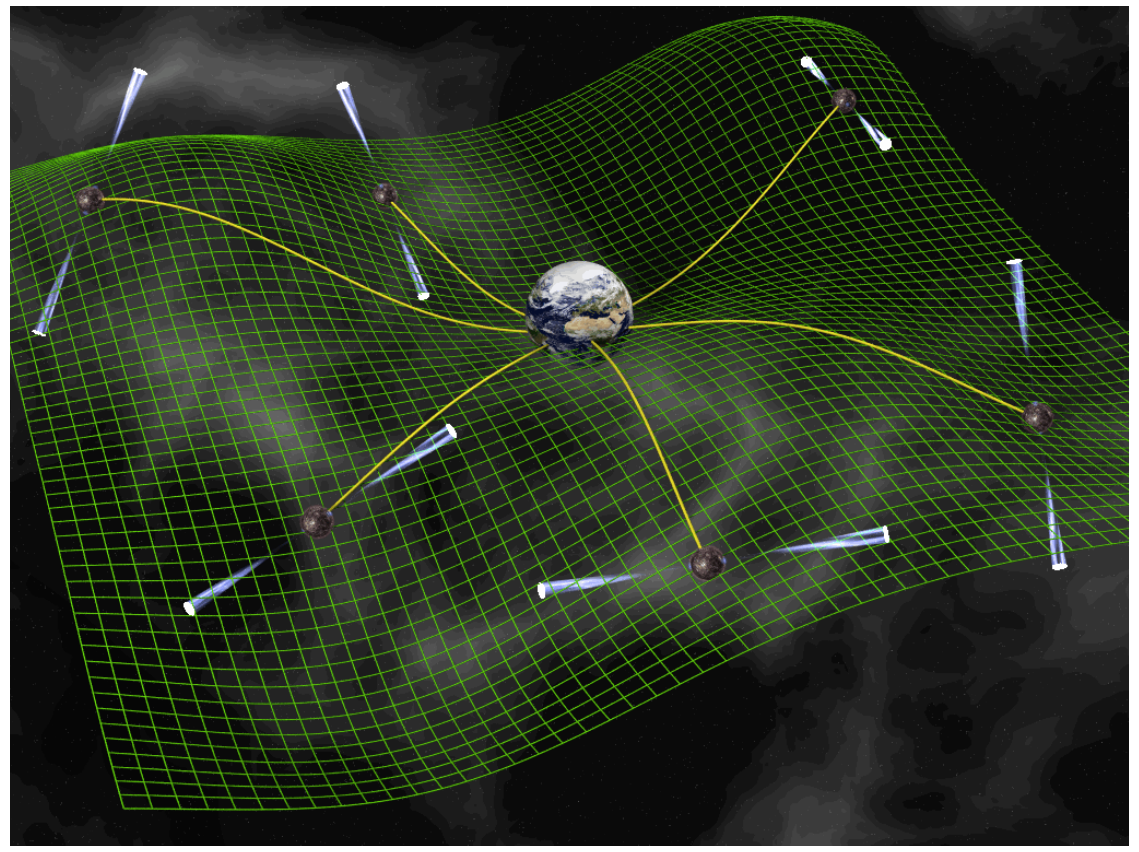
Fast radio bursts:

- what are they?
- potential applications…?



21-cm cosmology:

- 3D “super CMB”
- most powerful way (?) to measure many cosmological parameters (early universe, neutrinos, dark matter, etc.)



Pulsars:

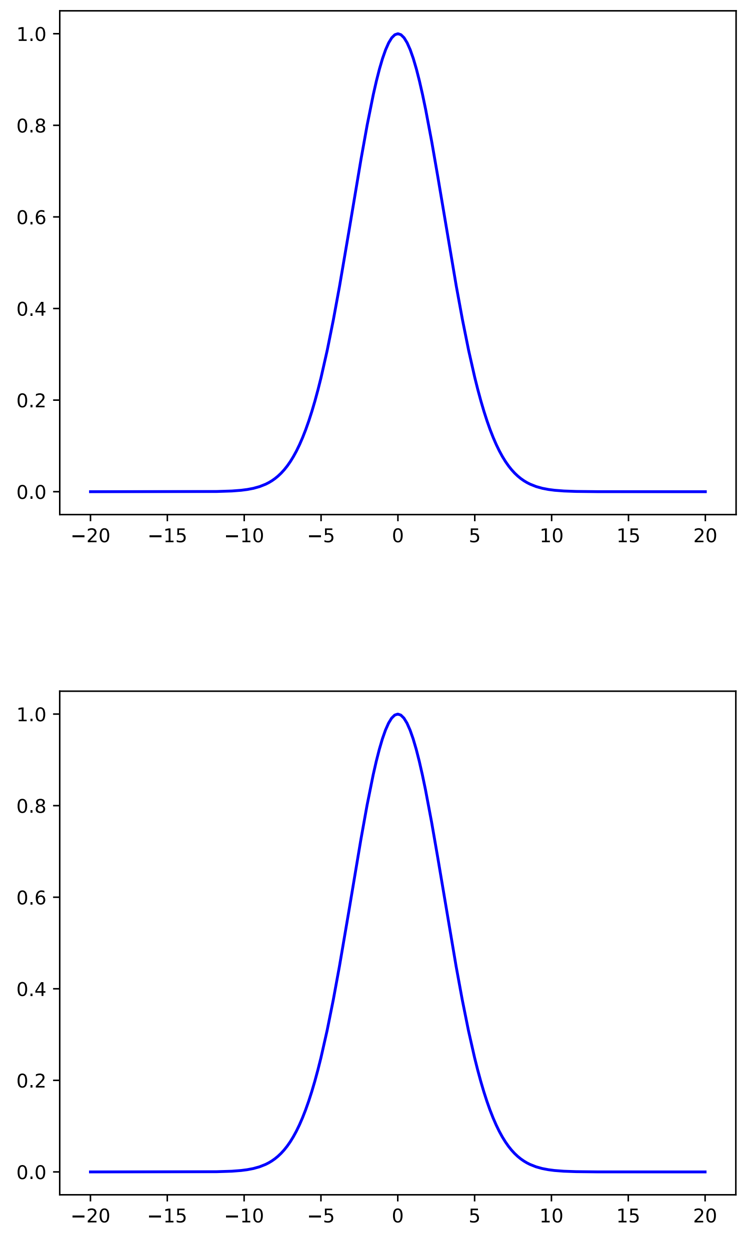
- new tests of GR
- new probe of gravity waves
- rich astrophysics


Thanks!

Two parameters control the pulse width, "scattering time" τ_{600} and "intrinsic width" w

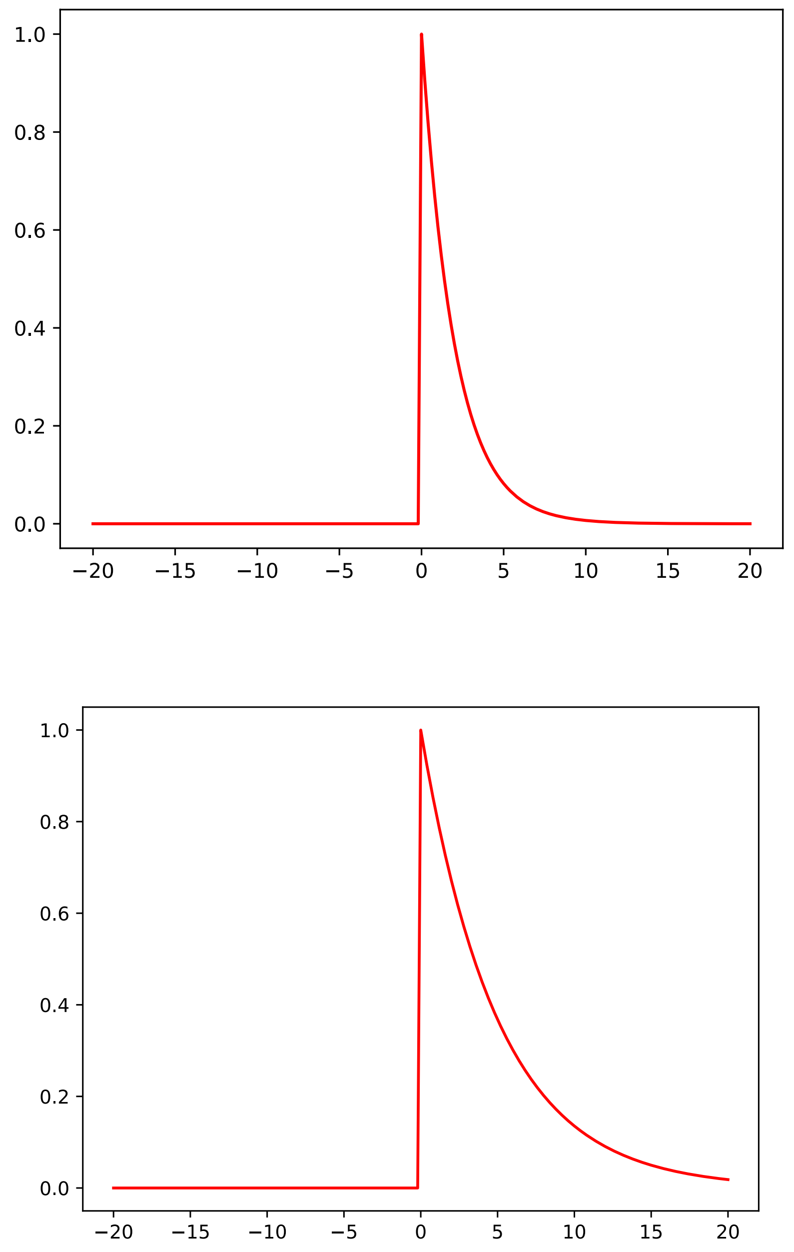
"Intrinsic" profile:

Gaussian, width w frequency-independent

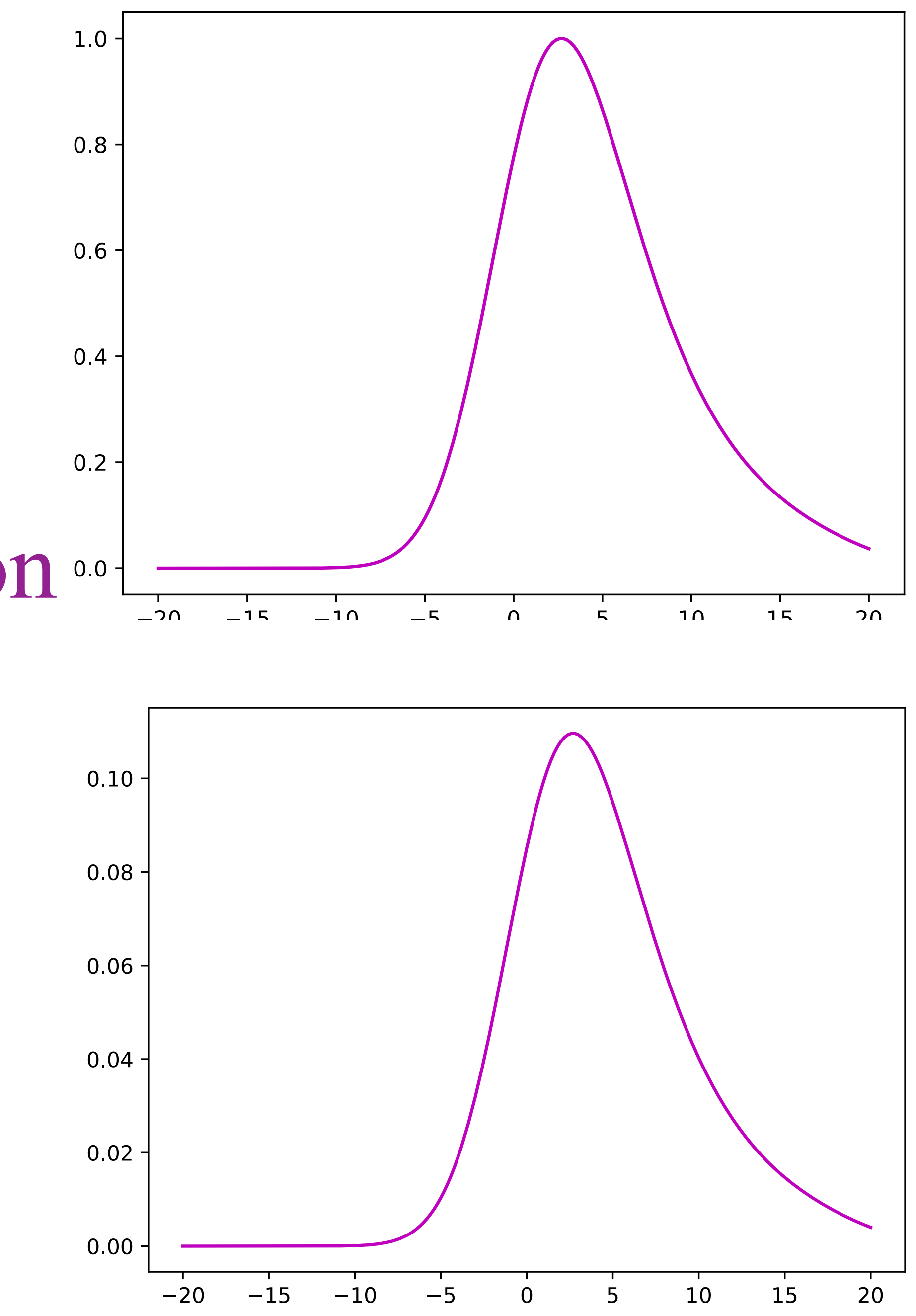


"Scattering" Profile:

Exponential, timescale $= (f/600\text{ MHz})^{-4}$



convolution



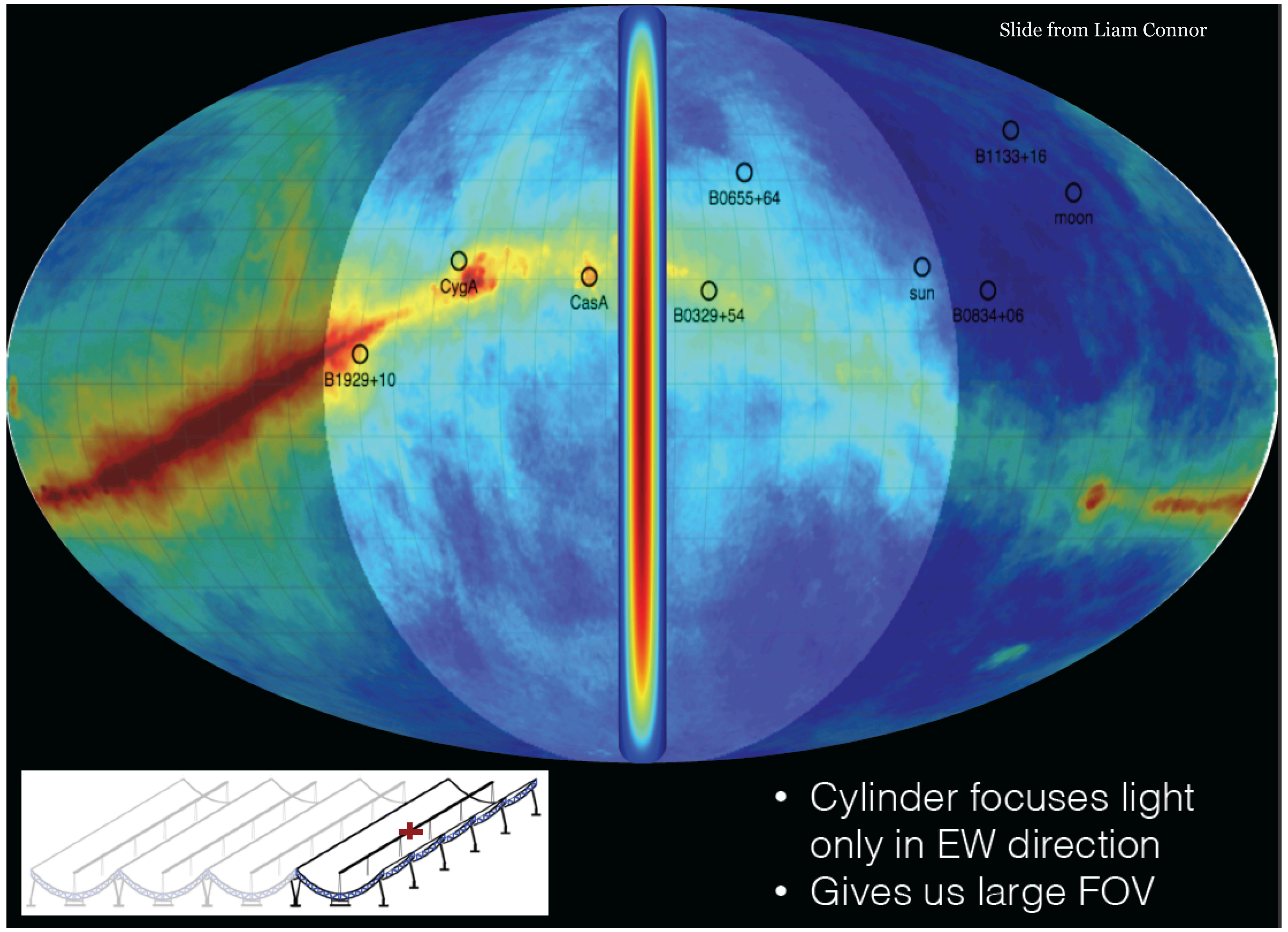
Higher frequency

Lower frequency

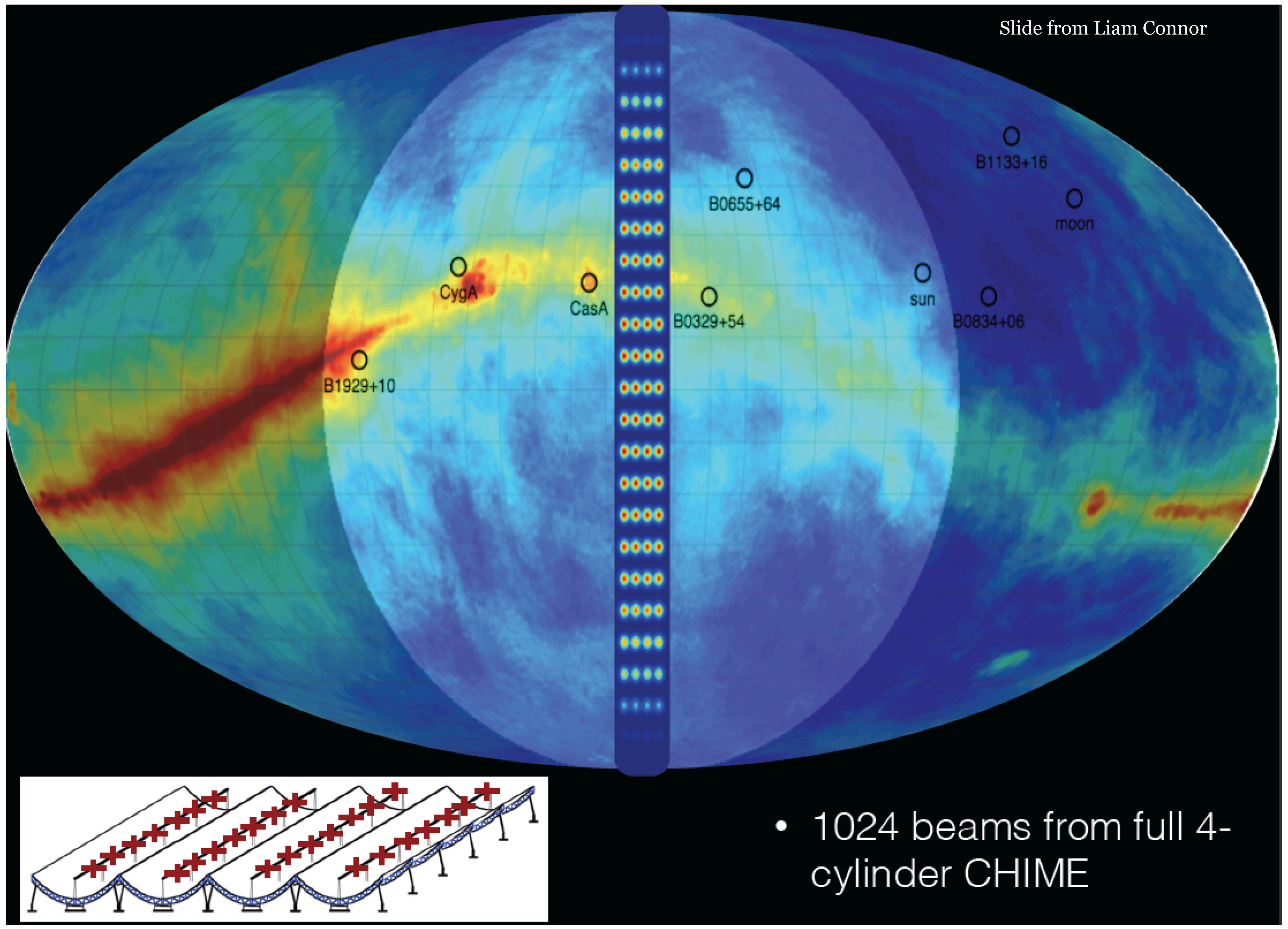
CHIME beamforming, cartoon form

Each antenna sees a narrow strip on the sky ("primary beam").

By beamforming in software as previously described, we can make 1024 "formed" beams with size ~0.3 degree.



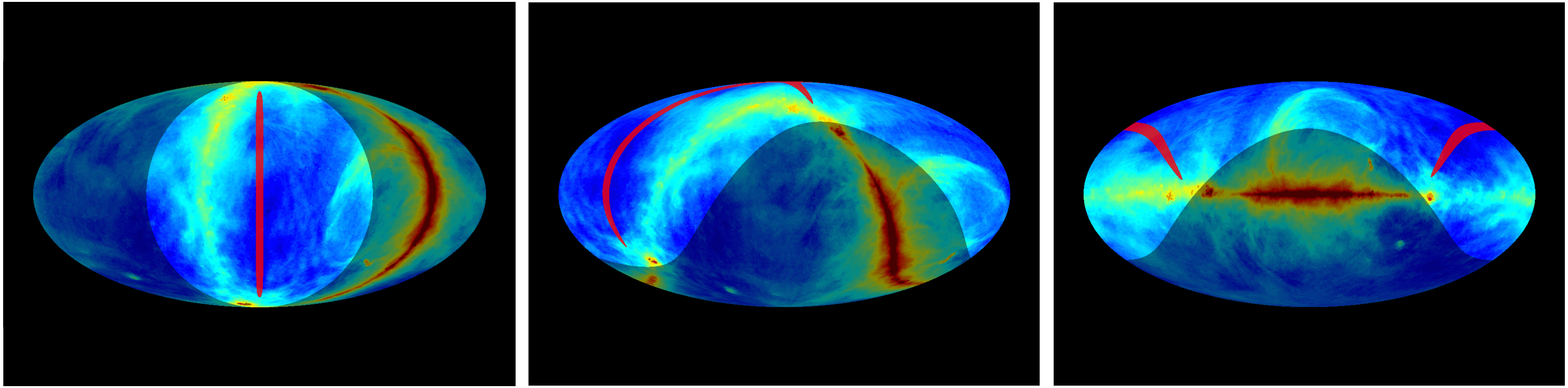
primary beam



formed beams

CHIME beamforming, cartoon form

As the Earth rotates, the primary and formed beams sweep over the sky.



Every 24 hours, we make an image of the sky with 0.3 degree resolution, in frequency range 400-800 MHz.