Fast radio bursts with CHIME

Kendrick Smith (Perimeter Institute)
Berkeley, April 2024

CHIME collaboration

Lead institutions:

THE UNIVERSITY OF BRITISH COLUMBIA

UNIVERSITY OF TORONTO

McGill

DRAO NRC · CNRC

+ Smaller teams at these institutions:

Yale University

Carnegie Mellon University

West Virginia University

NRAO

Massachusetts Institute of Technology

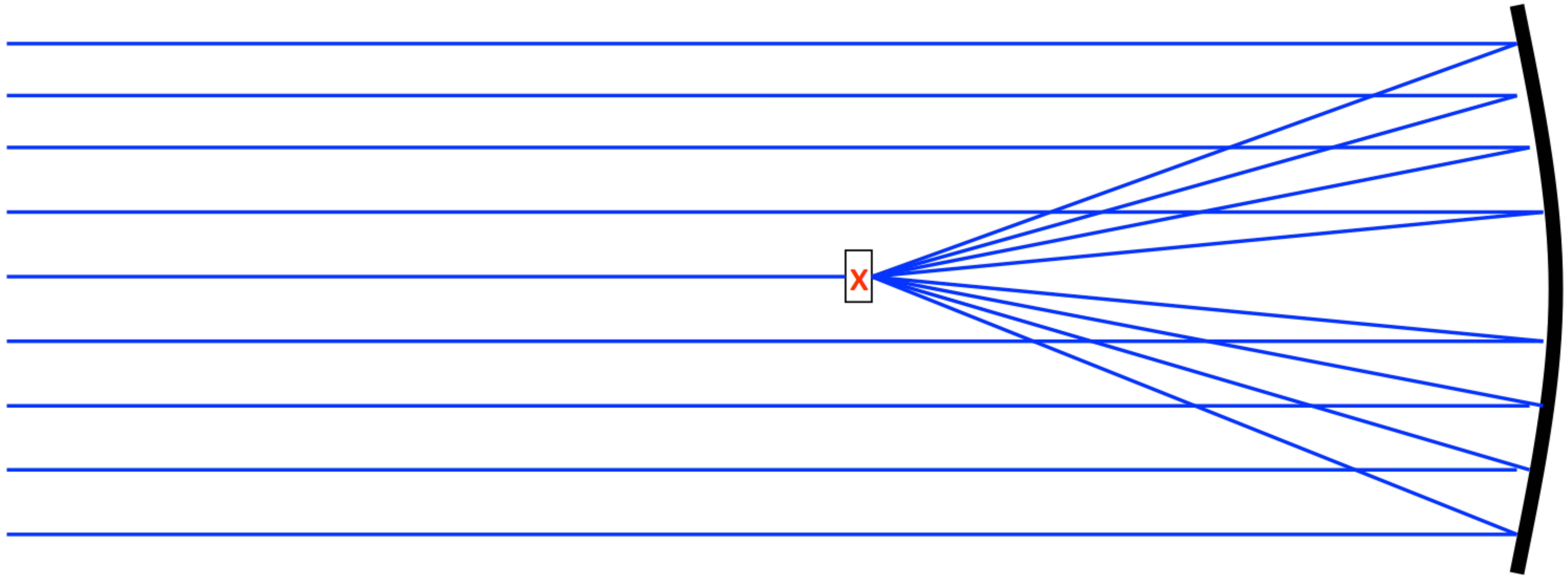
PERIMETER INSTITUTE

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

CHIME

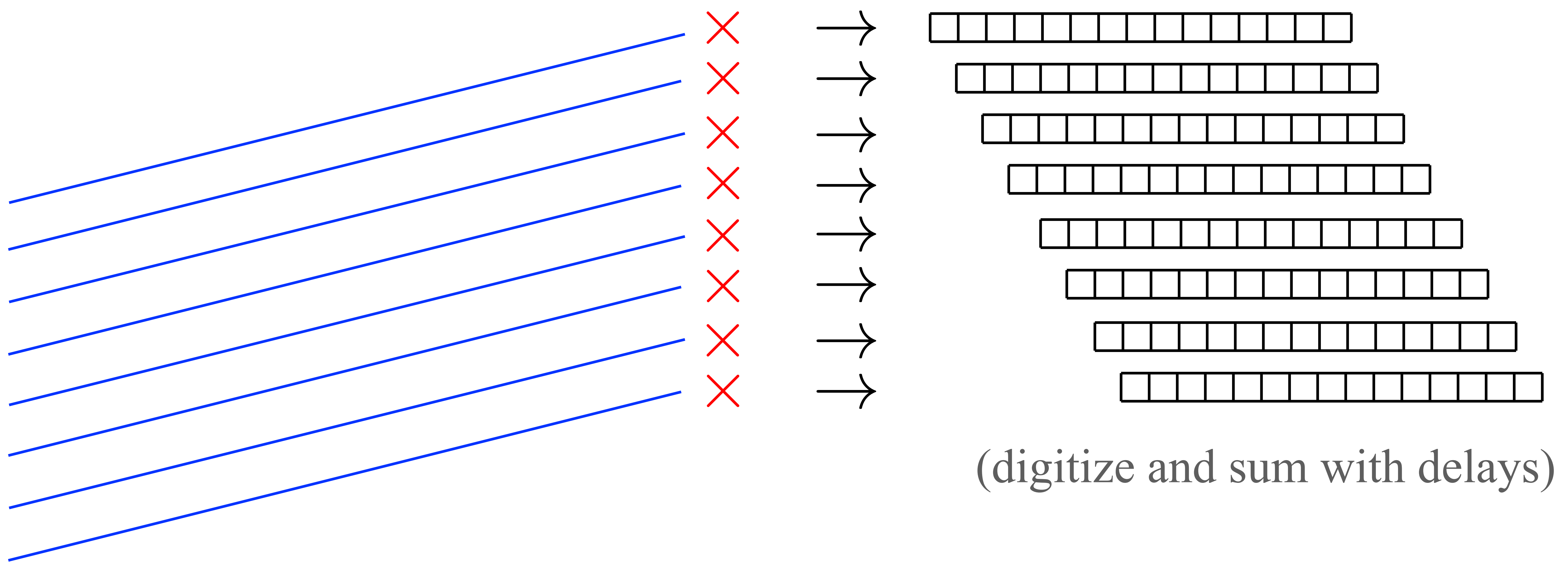
Traditional radio telescope

Single-feed radio telescope



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

Phased-array interferometer

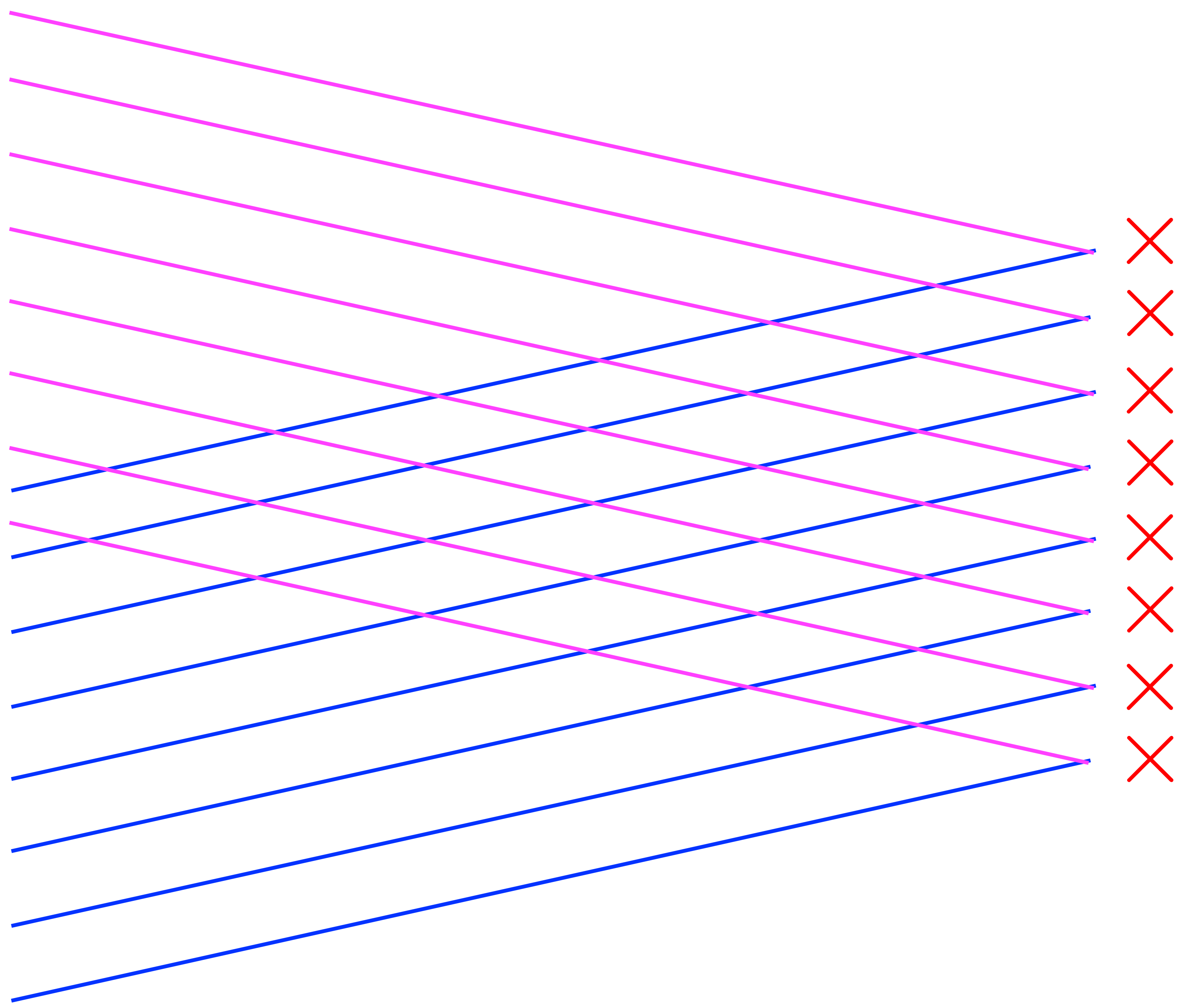


Dish is replaced by an array of antennas whose signals are digitized.

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 m^2	13	0.41
Green Bank 100m	7850 m^2	7	0.55
Arecibo 300m (RIP)	70000 m^2	7	4.9
FAST 500m	200000 m^2	19	38
CHIME	6400 m^2	1024	66


FAST
= CHIME?

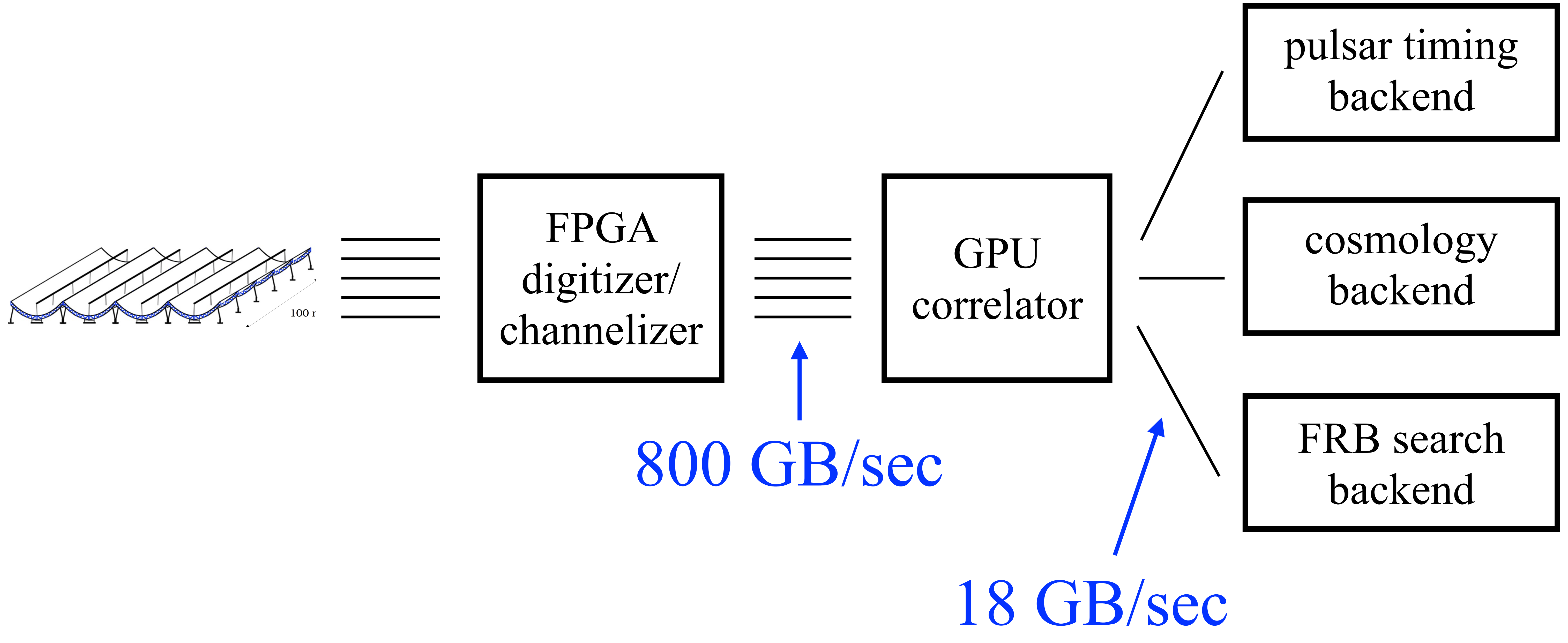
The challenge

	A	N_{beams}	$M/(10^5 \text{ m}^2)$
Parkes 64m	3200 m^2	13	0.41
Green Bank 100m	7850 m^2	7	0.55
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



Pulsar timing backend

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

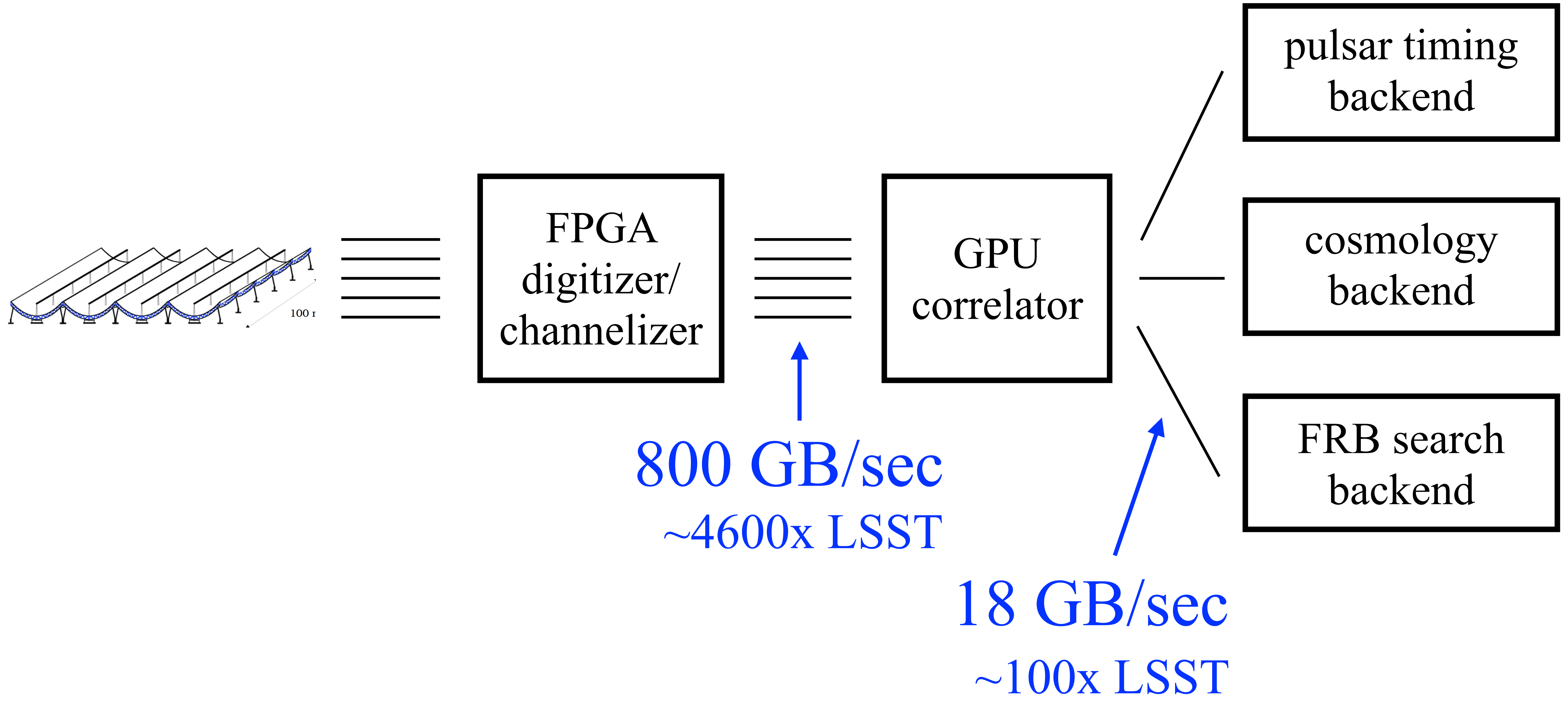
Cosmology backend

- 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.

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.

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

FRB mini-introduction (slide 1/4)

FRBs: a recent astrophysical phenomenon, discovered in 2007.

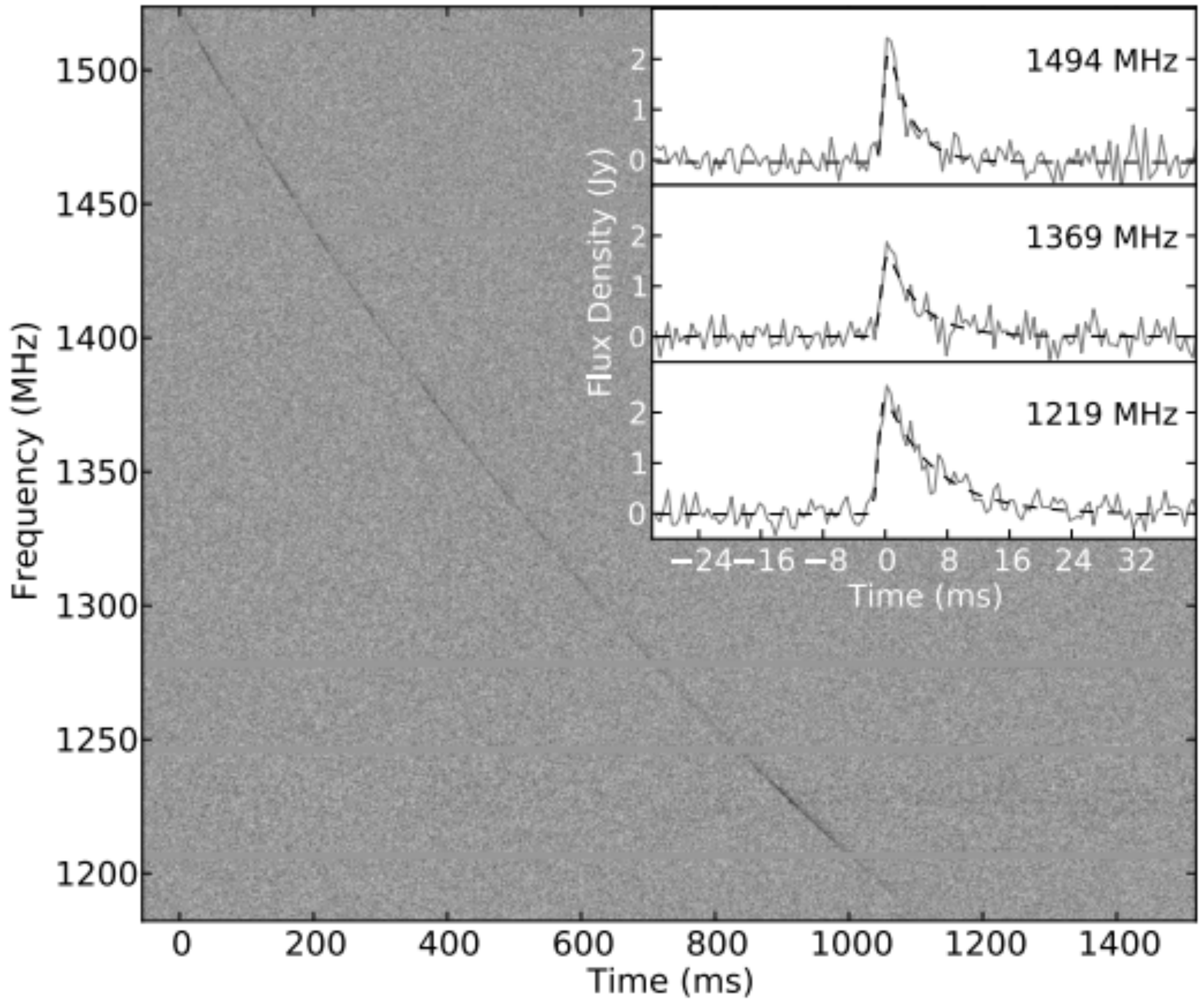
- Recall that when a radio pulse propagates through free electrons, it is dispersed:

$$\text{(Pulse arrival time)} \propto \text{(frequency)}^{-2}$$

- The prefactor (or "dispersion measure" DM) is the electron column density

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

- Defining property of an FRB: observed DM exceeds the total column density of the Milky Way, suggesting an extragalactic origin.



FRB mini-introduction (slide 2/4)

Host galaxies: around ~20 FRBs have been observed with good enough angular resolution to uniquely determine a host galaxy (proving that FRBs are extragalactic).

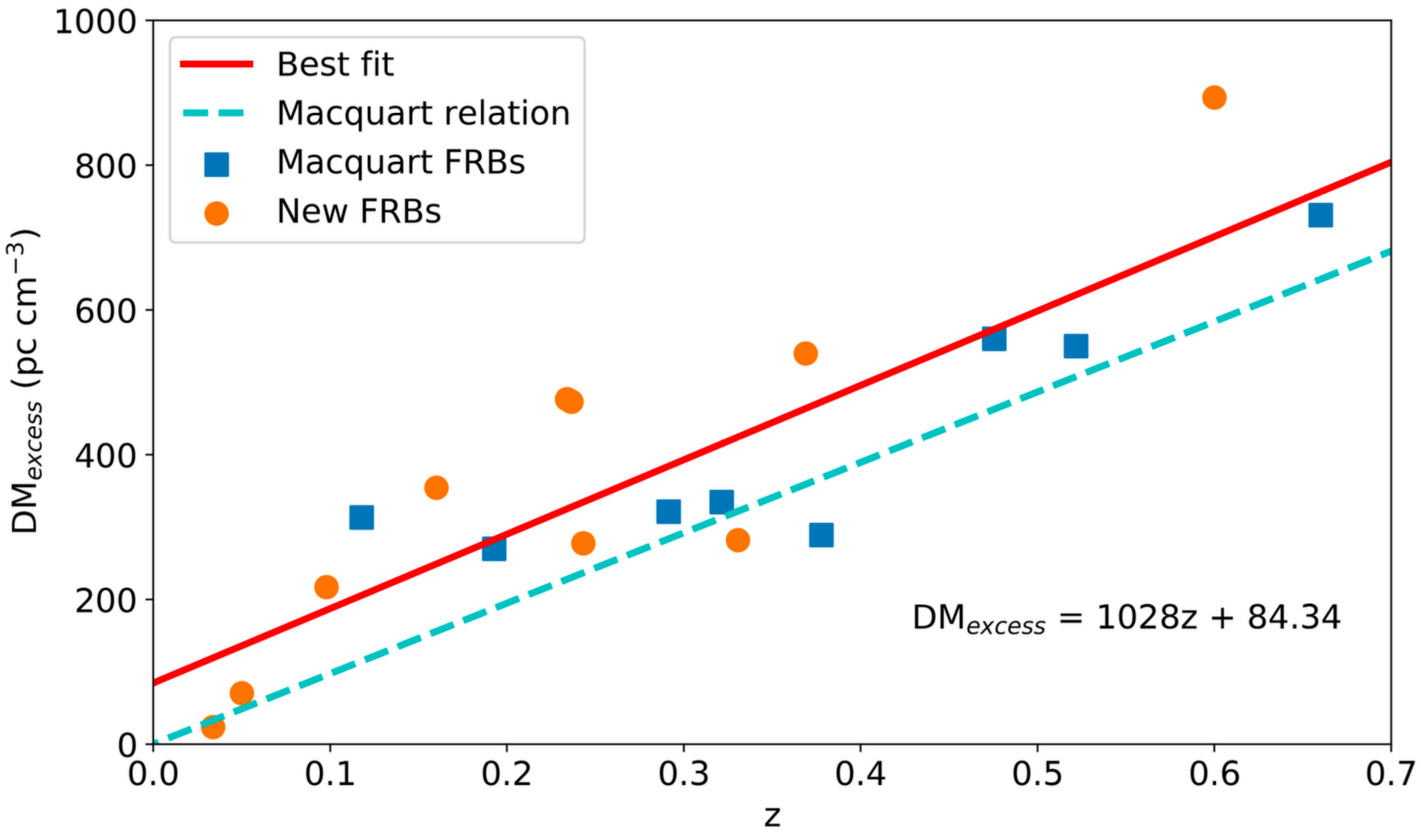
Dissecting the DM:

$$\mathrm{DM} = \mathrm{DM}_{\mathrm{gal}} + \mathrm{DM}_{\mathrm{cosmo}} + \mathrm{DM}_{\mathrm{host}}$$

$\mathrm{DM}_{\mathrm{gal}} =$ Milky Way contribution (can be modelled and subtracted)

$\mathrm{DM}_{\mathrm{cosmo}} = n_{e0} \int dz\, (1+z)/H(z)$ (largest contribution)

$\mathrm{DM}_{\mathrm{host}} =$ FRB-local contribution (acts as "noise" on $\mathrm{DM}_{\mathrm{cosmo}}$)



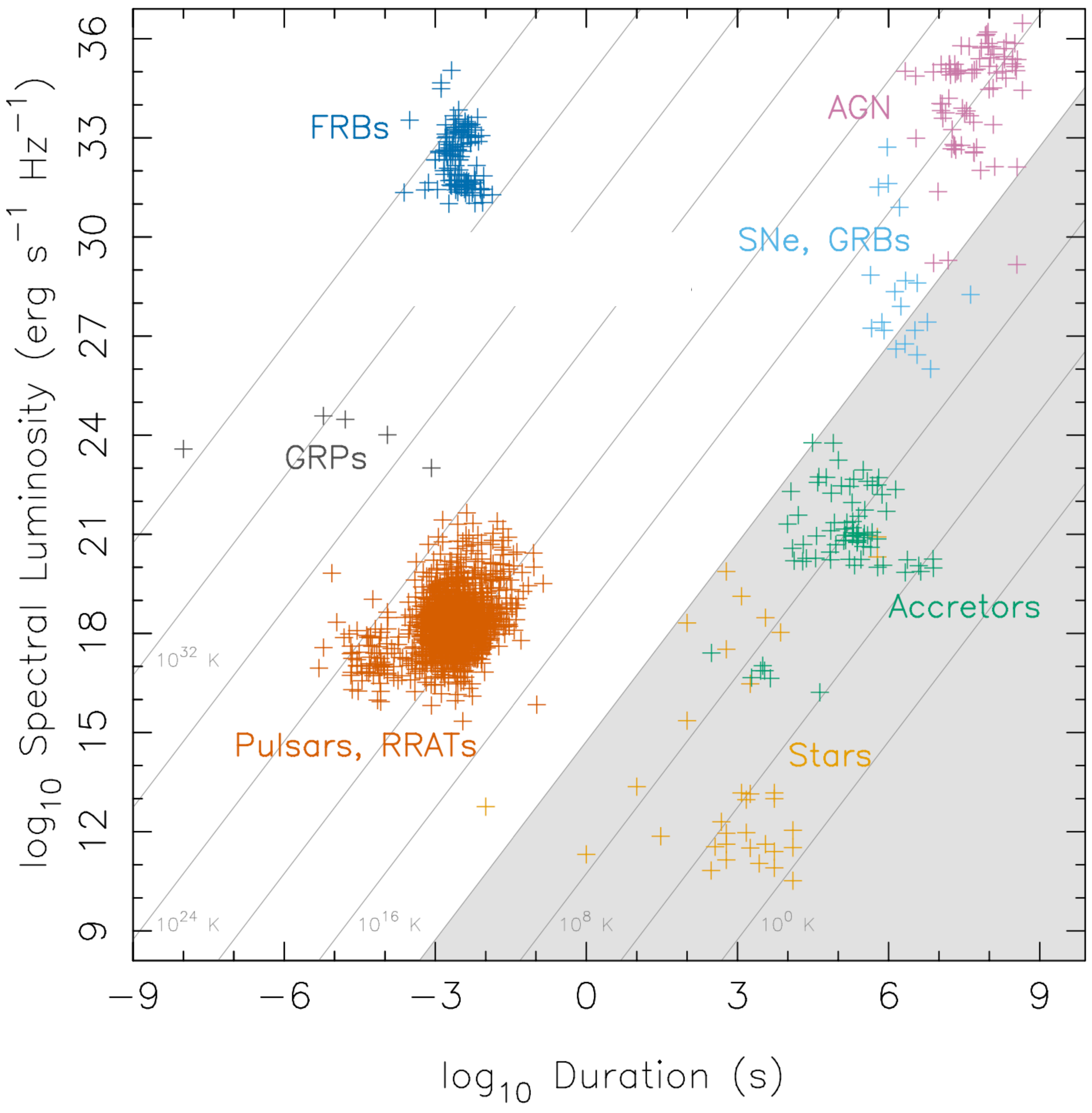
Cui et al 2210.02290

FRB mini-introduction (slide 3/4)

- Implication of comological distances: FRBs are ultra-energetic (~10^5-10^{11} times brighter than known sources in our Galaxy), suggesting a new emission mechanism.
- Explaining FRBs has become a central unsolved problem in astrophysics.
- When CHIME started operating in 2018, only ~30 FRBs were known. (Number is now ~700, around 500 of which have been found by CHIME.)

Blue = FRBs

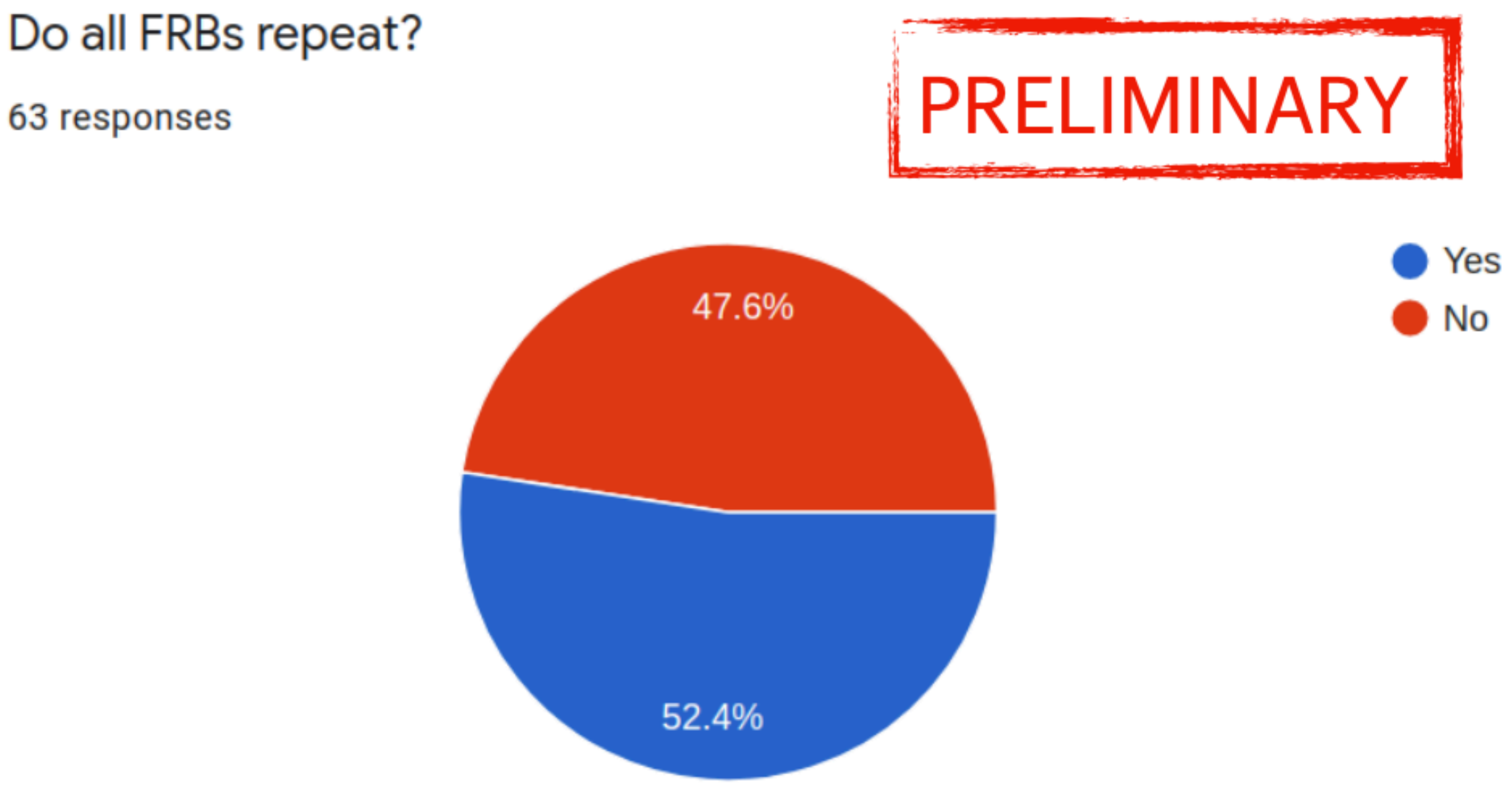
Orange = well-understood Milky Way pulses



Bochenek et al (STARE2)

FRB mini-introduction (slide 4/4)

- Repeating FRBs: prior to CHIME, one FRB had been observed to repeat.
- In the first ~year of operation, CHIME found 18 new repeating FRB's, establishing that repetition is not uncommon.
- 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

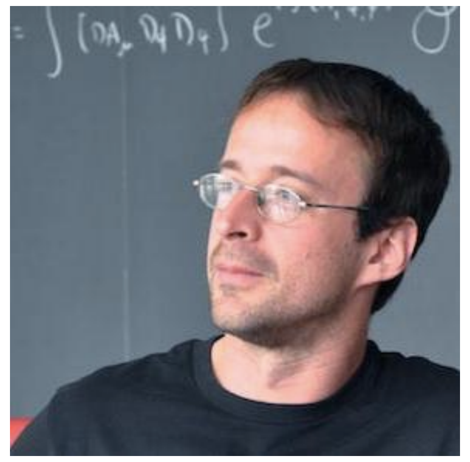
arxiv:1810.05836

“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:

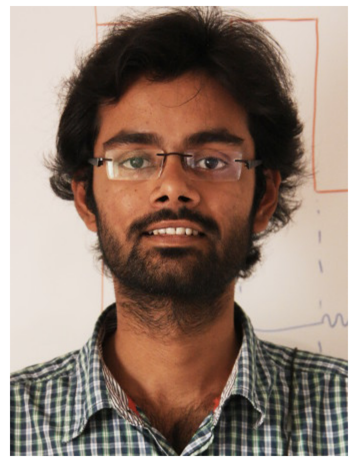
- Orders of magnitude faster than other search software.
- Near statistically optimal
- Real-time, ~10 second latency
- Includes real-time RFI removal with very low false positive rate



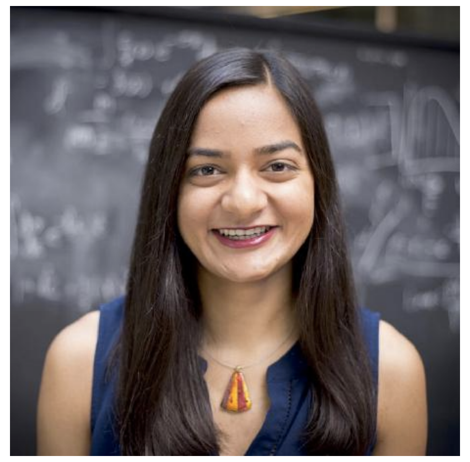
Kendrick Smith

Dustin Lang

Masoud Rafiei-Ravandi



Utkarsh Giri



Maya Burhanpurkar

Alex Roman

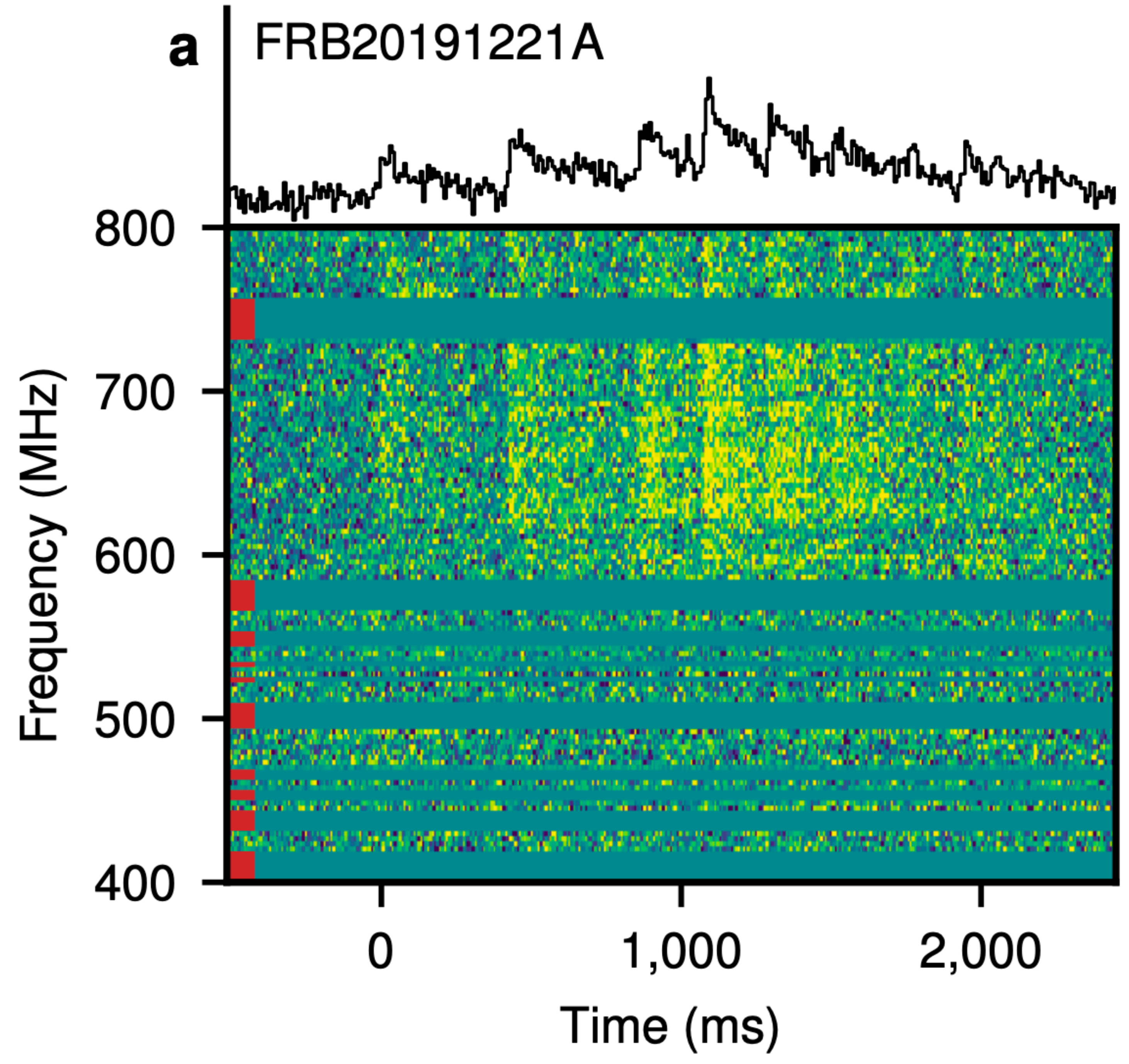
1. The CHIME concept: moving difficulty from hardware to software
2. Searching for fast radio bursts with CHIME
3. Periodic phenomena in FRBs
4. An FRB in the Milky Way
5. A large FRB catalog
6. Coming soon: CHIME outriggers, CHORD

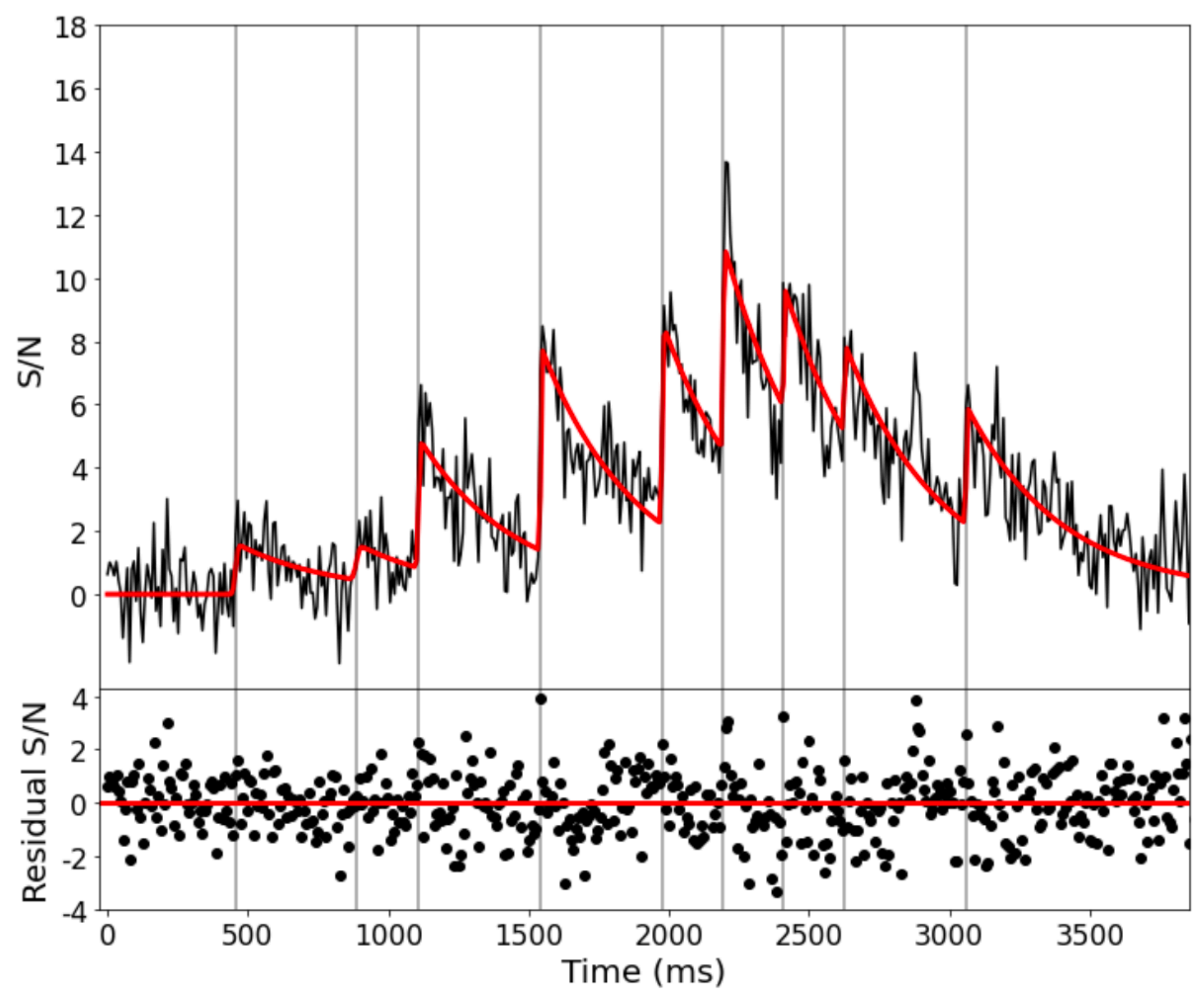
} CHIME FRB "greatest hits" (items 3–5)

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.

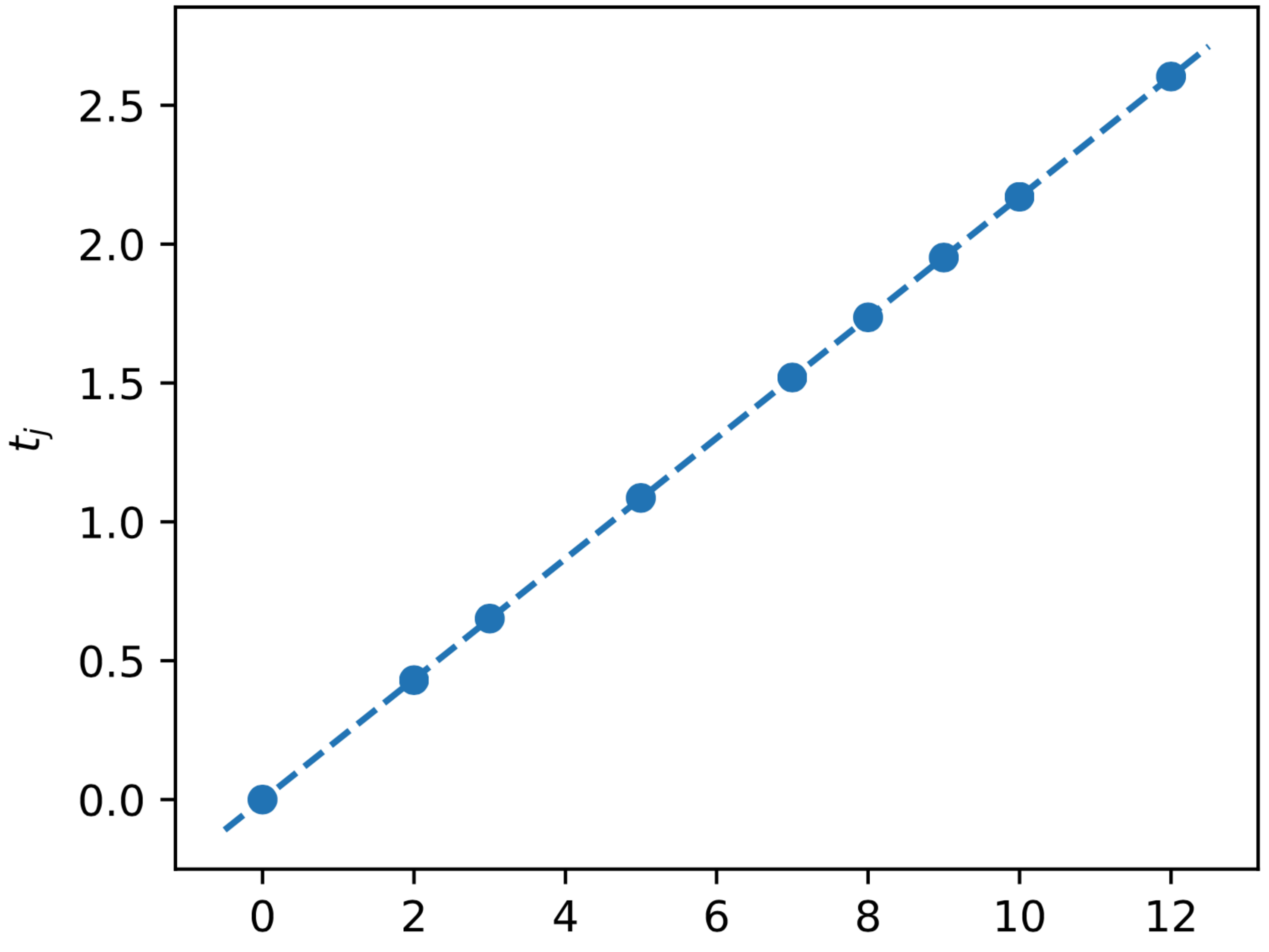
  (After subtracting a well-motivated model for the pulses, residuals are consistent with noise.)



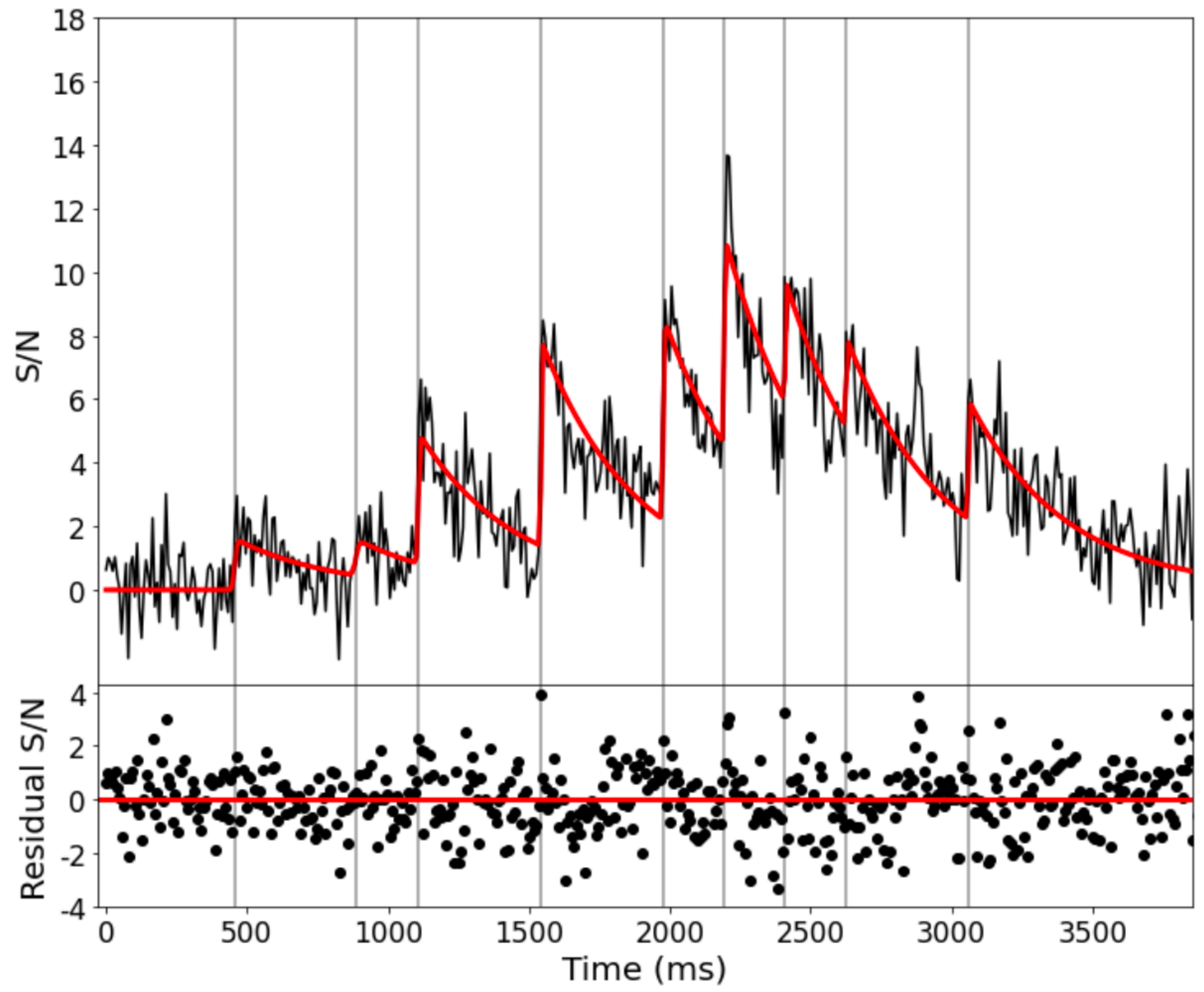


CHIME/FRB collaboration, arxiv:2107.08463

First phenomenon: periodic sub-pulses in an FRB



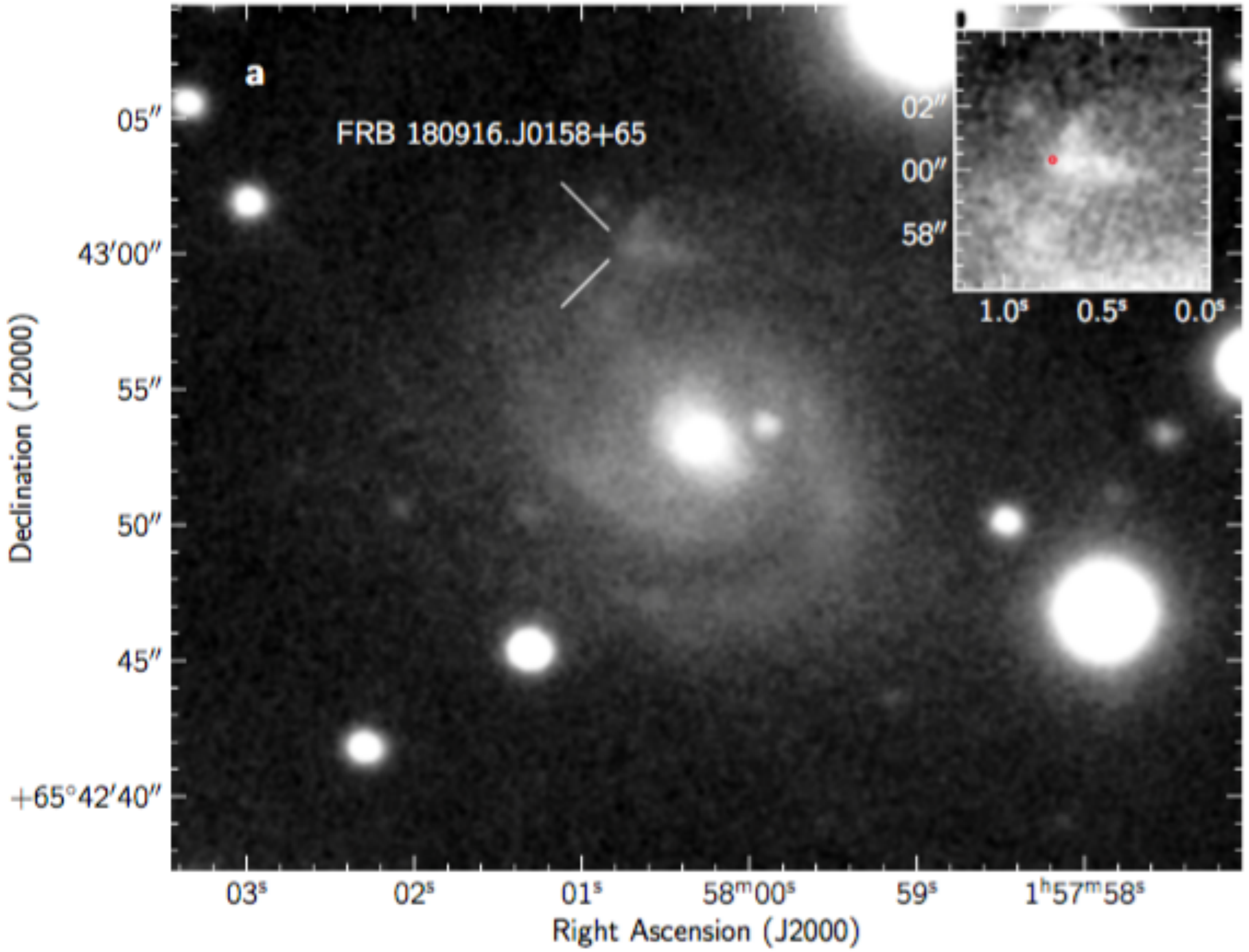
- We noticed that the arrival times are periodic (with 3 gaps), with best-fit period 217 ms.
- Formal significance is ~6.5σ (p-value 7×10^{-11}), accounting for look-elsewhere effect in period and choice of gaps.
- 217 ms period suggests a neutron star origin.



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_{NE2001} (pc cm^{-3})	DM^e_{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

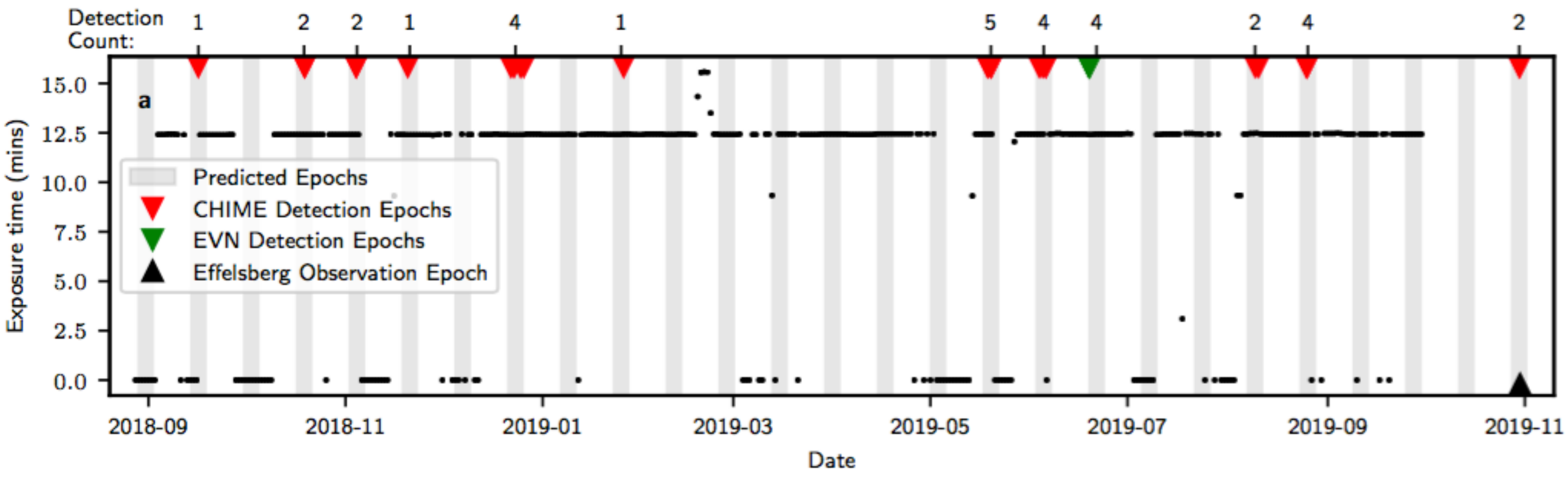


- This repeating FRB (“R3”) is the most active repeating FRB in CHIME.
- Redshift z=0.0337 (EVN + Gemini).
- At the time, this was the closest known FRB.

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.
- Statistical significance was ~4σ after 14 months of data, and has held up since then.
- 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

Second phenomenon: periodic activity in an FRB

- A surprise: R3 is only active in 4-day windows, regularly spaced with period 16.35 days.
- Statistical significance was ~4σ after 14 months of data, and has held up since then.
- Naturally explained in a neutron star model, as either orbital period (in a binary system) or precession period.
- We also observe a secular increase in rotation measure (RM), starting in 2021 (!)

Before showing the plot, I'll pause to define RM.

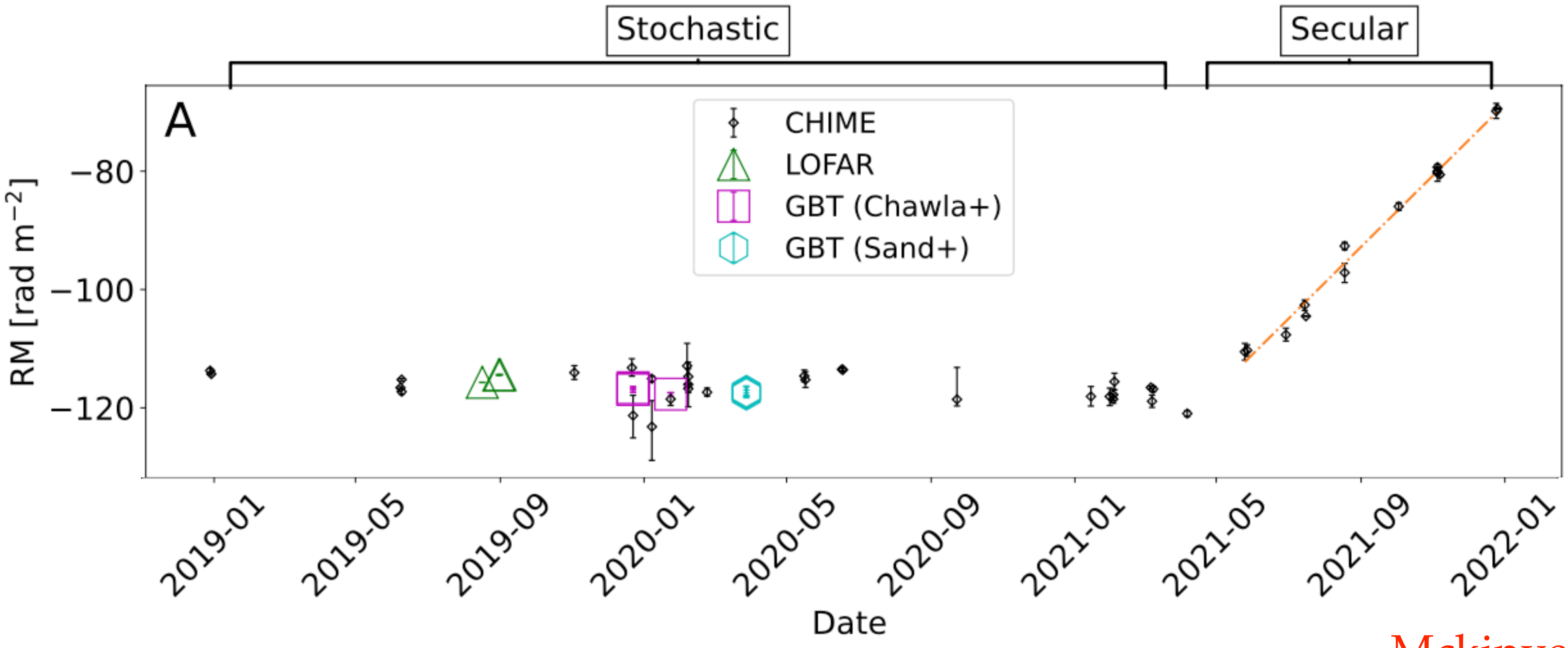
Faraday rotation: a linearly polarized FRB propagating through a magnetic field has frequency-dependent rotation

$$\text{(rotation angle)} = \text{(RM)}\,\lambda^2 \qquad \text{where} \quad \text{RM} \propto \int dx\, n_e(x) B_{||}(x)$$

The "rotation measure" RM probes the magnetic environment along the line-of-sight.

Second phenomenon: periodic activity in an FRB

- A surprise: R3 is only active in 4-day windows, regularly spaced with period 16.35 days.
- Statistical significance was ~4σ after 14 months of data, and has held up since then.
- Naturally explained in a neutron star model, as either orbital period (in a binary system) or precession period.
- We also observe a secular increase in rotation measure (RM), starting in 2021 (!)



Mckinven et al, ApJ 950 (2003) 12

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

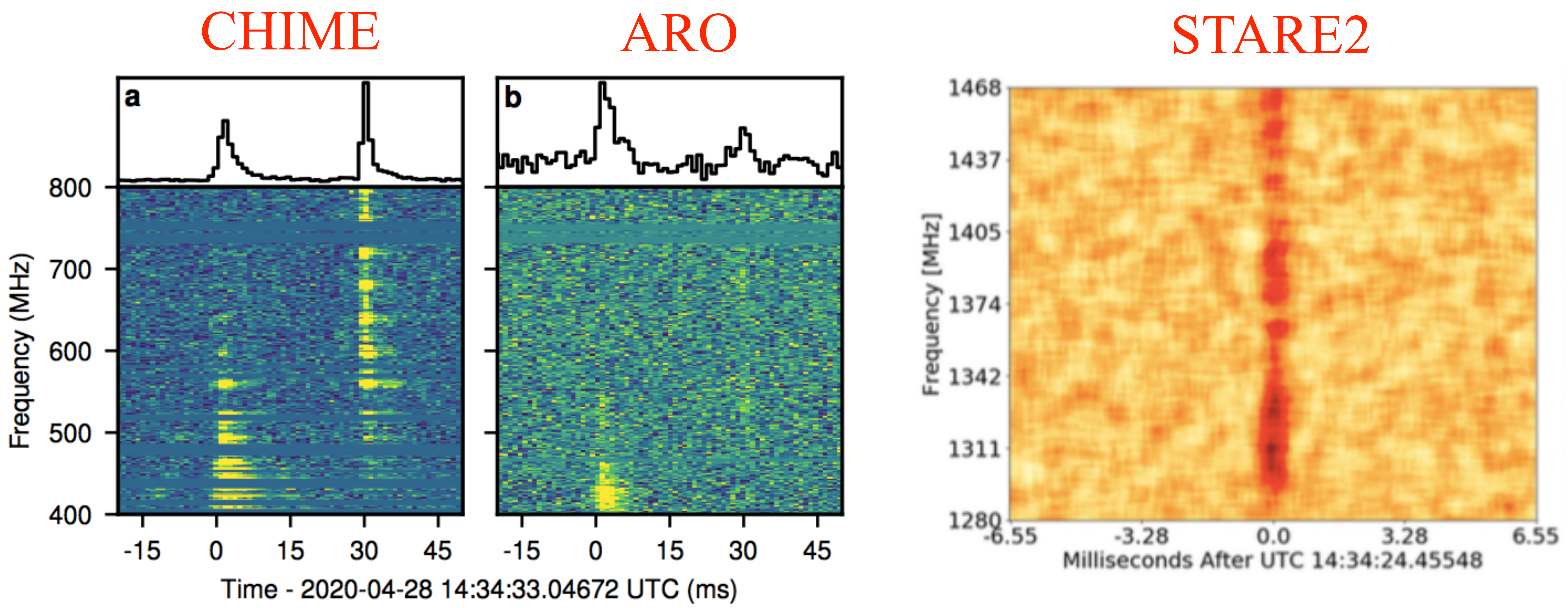
An FRB in the Milky Way

- 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

- 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!
- 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.)



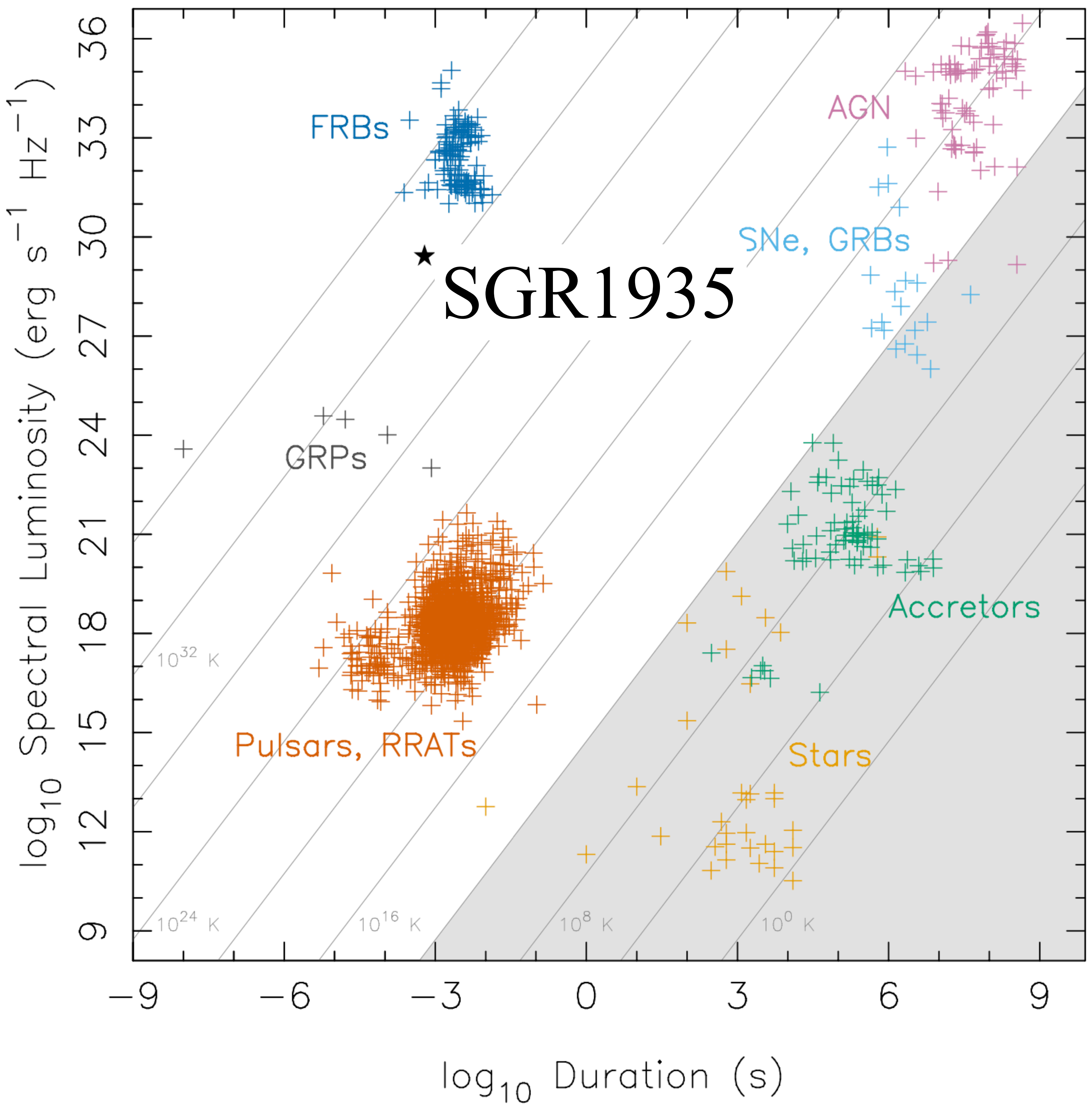
Nature 587 (2020) 54-58

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

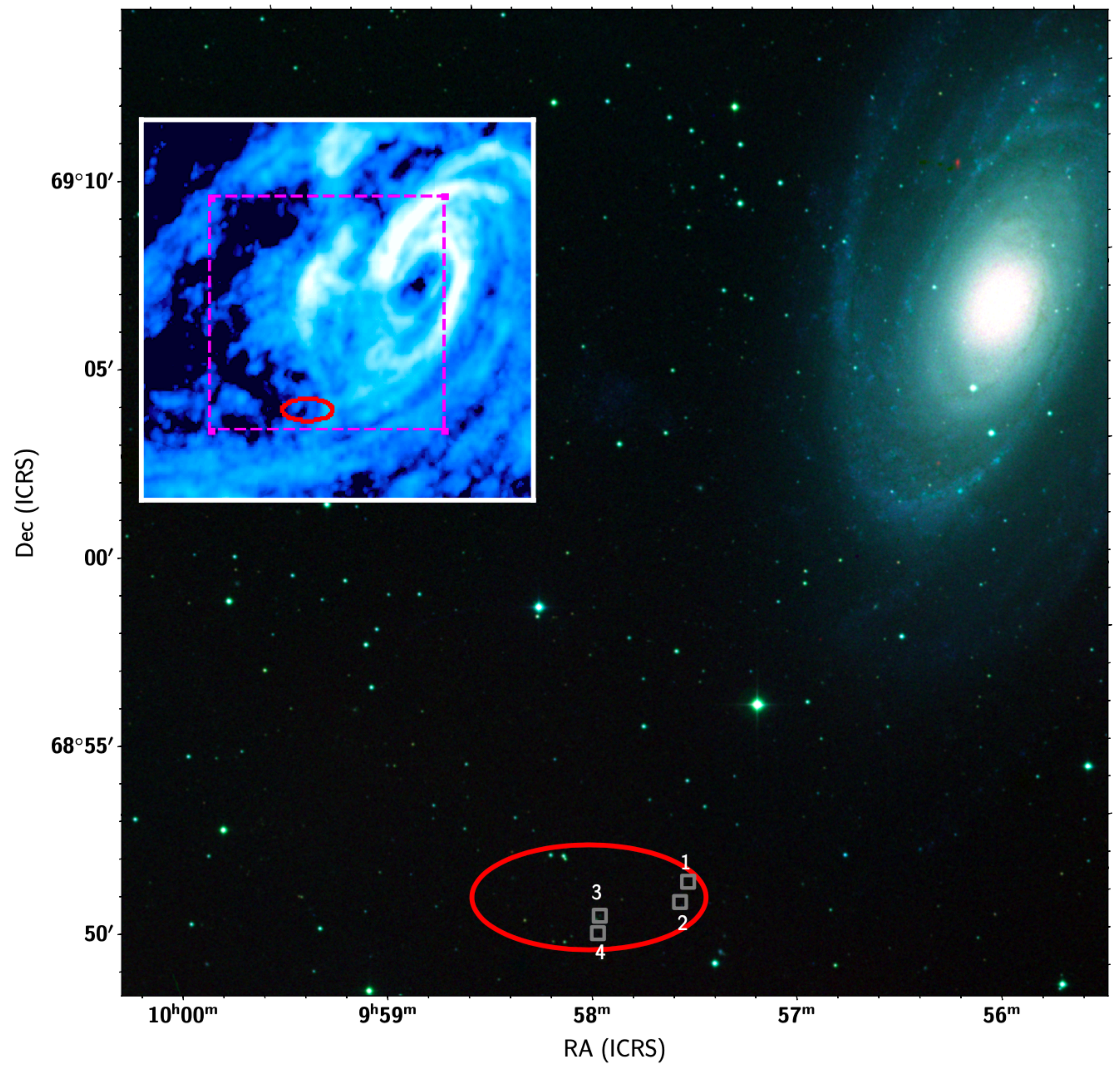
Orange = well-understood Milky Way pulses

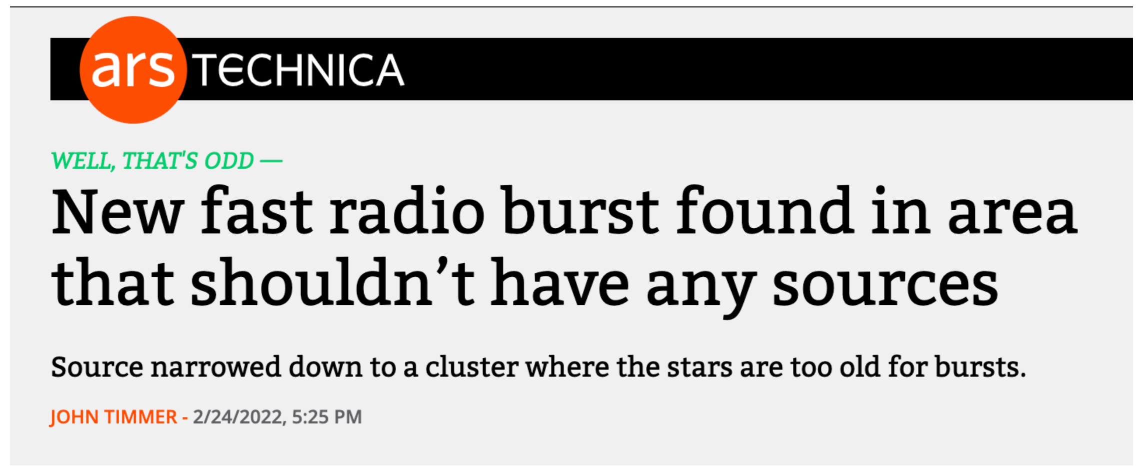


Bochenek et al (STARE2)

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).





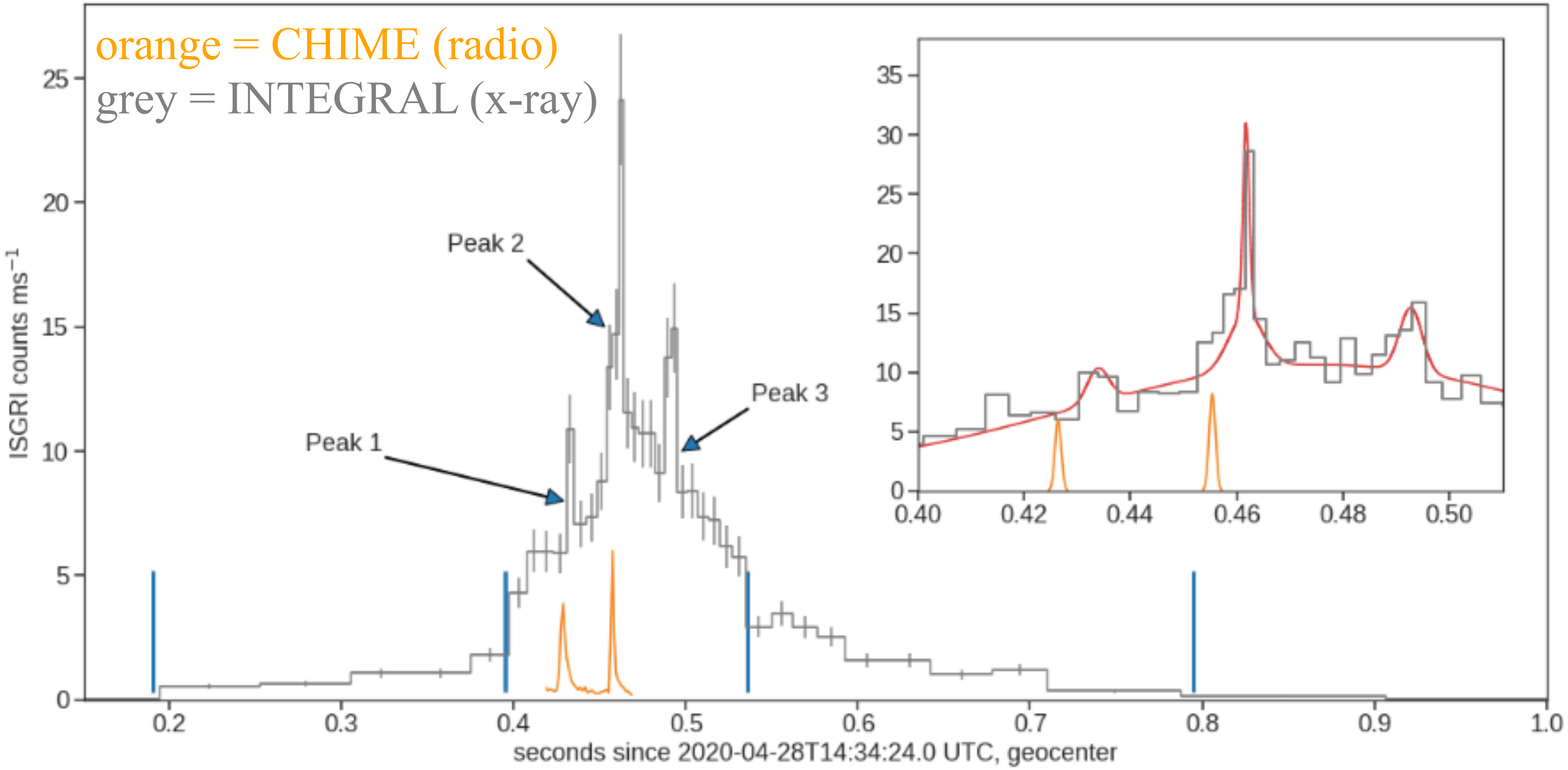
Bhardwaj et al ApJL (2103.01295)
Kirsten et al 2105.11445

An FRB in the Milky Way

- 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. As far as I know, all magnetar FRB models predict $L \geq 0$ (i.e. radio arrives later).

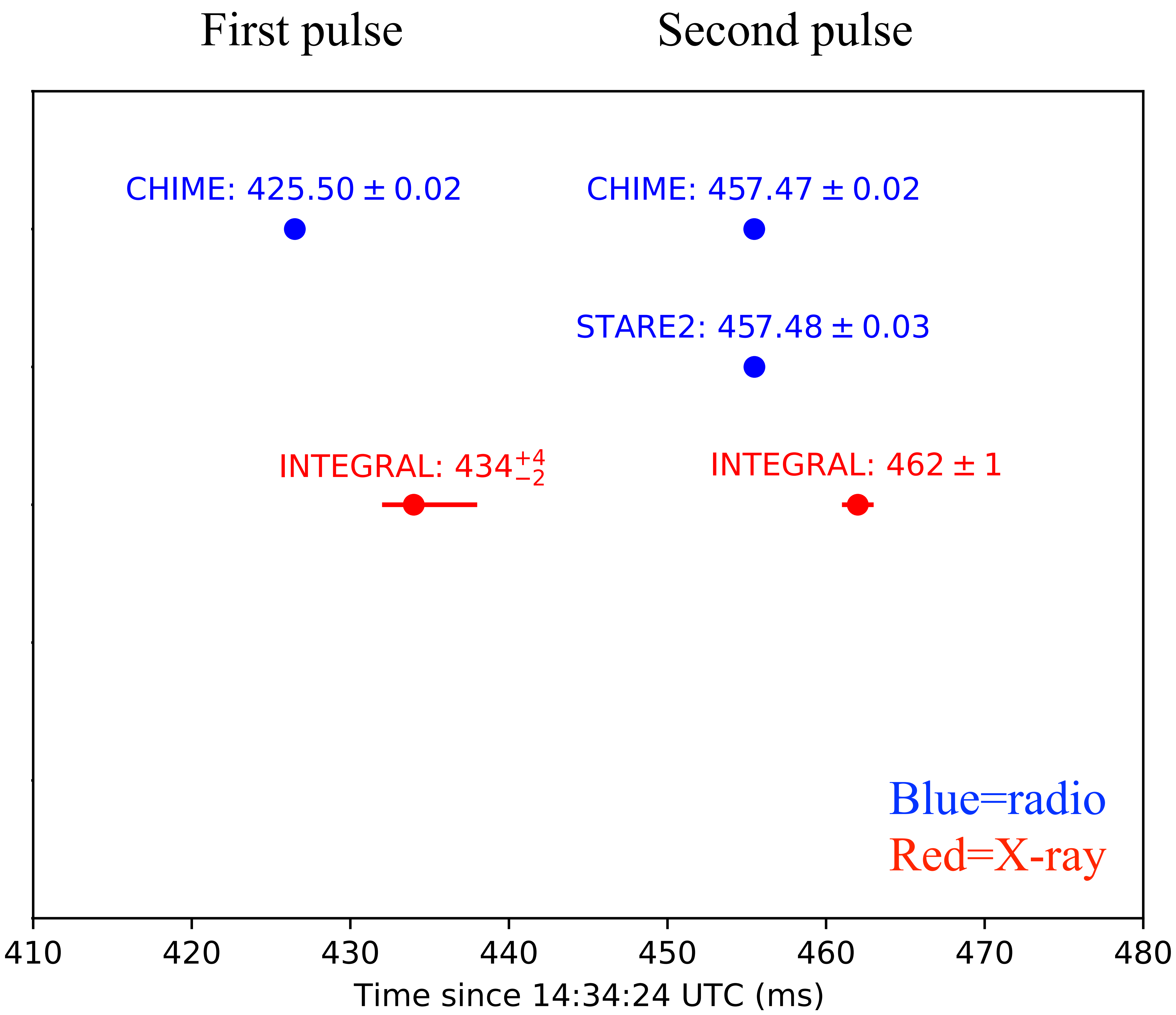
An FRB in the Milky Way

- 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. As far as I know, all magnetar FRB models predict $L \geq 0$ (i.e. radio arrives later).
- The first reported X-ray measurements (INTEGRAL) found $L = (-6.5 \pm 1)$ ms!



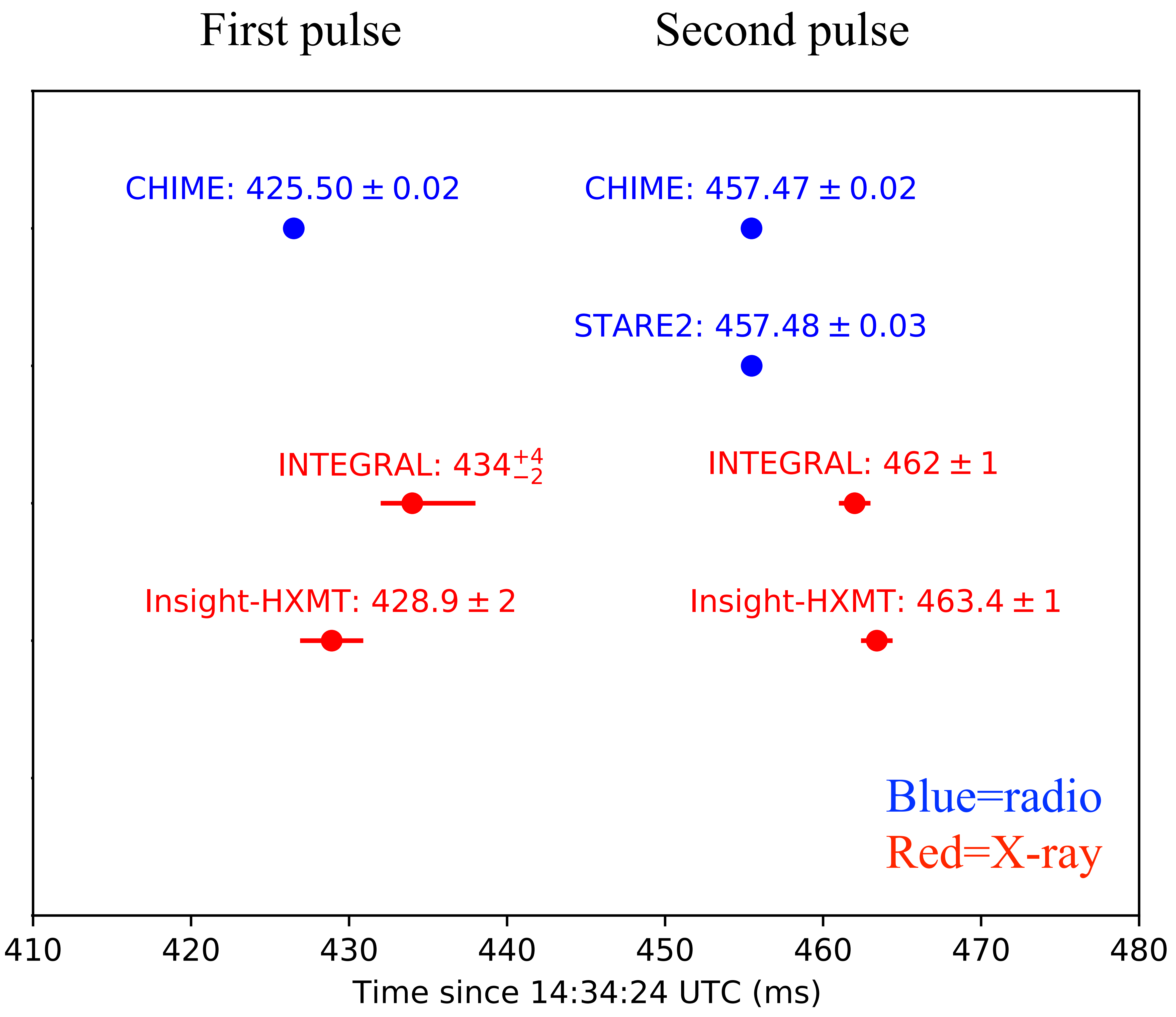
INTEGRAL collaboration (Mereghetti et al), 2005.06335

An FRB in the Milky Way



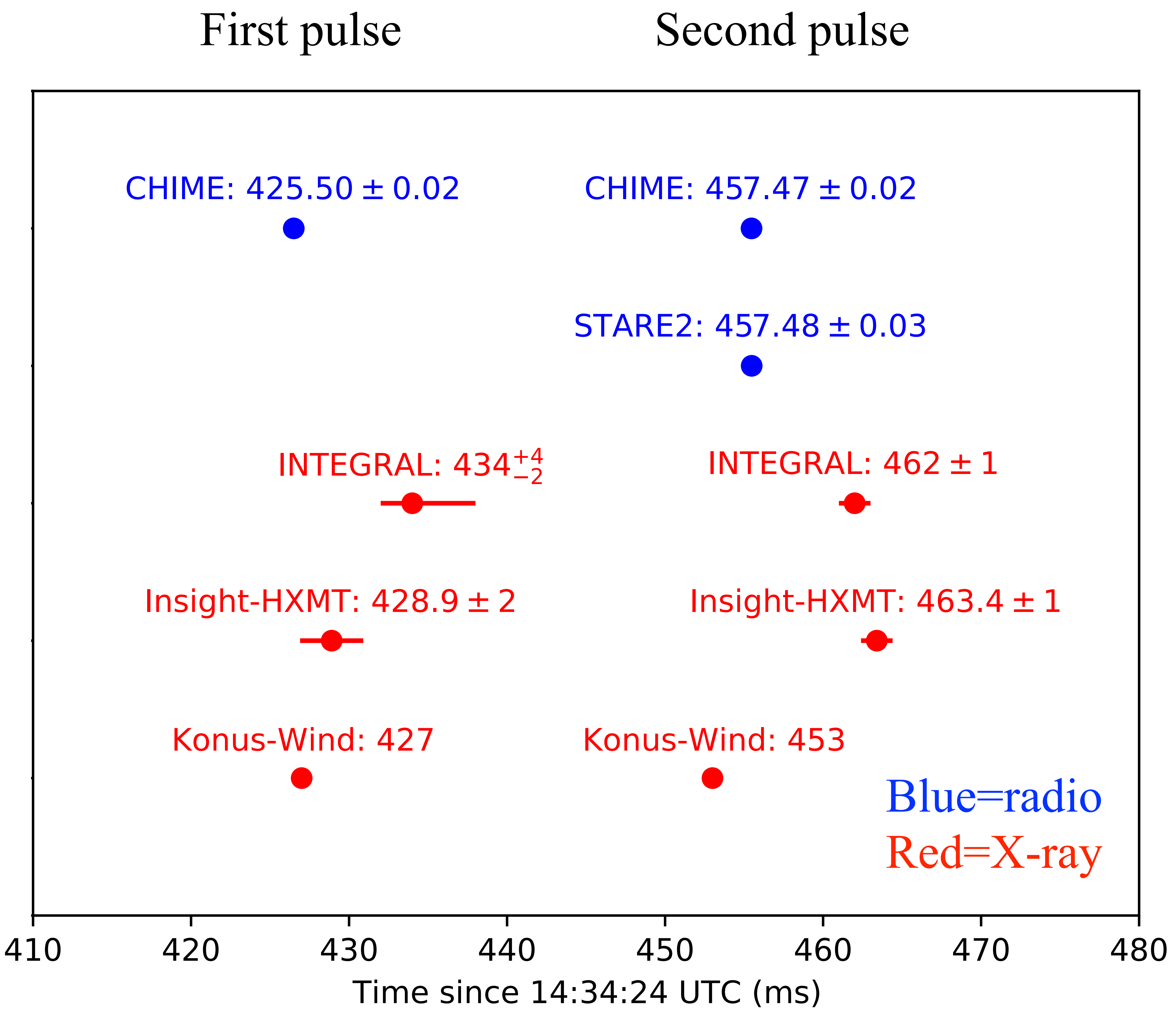
- Shortly thereafter, two more X-ray experiments published timings.

An FRB in the Milky Way



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

An FRB in the Milky Way



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

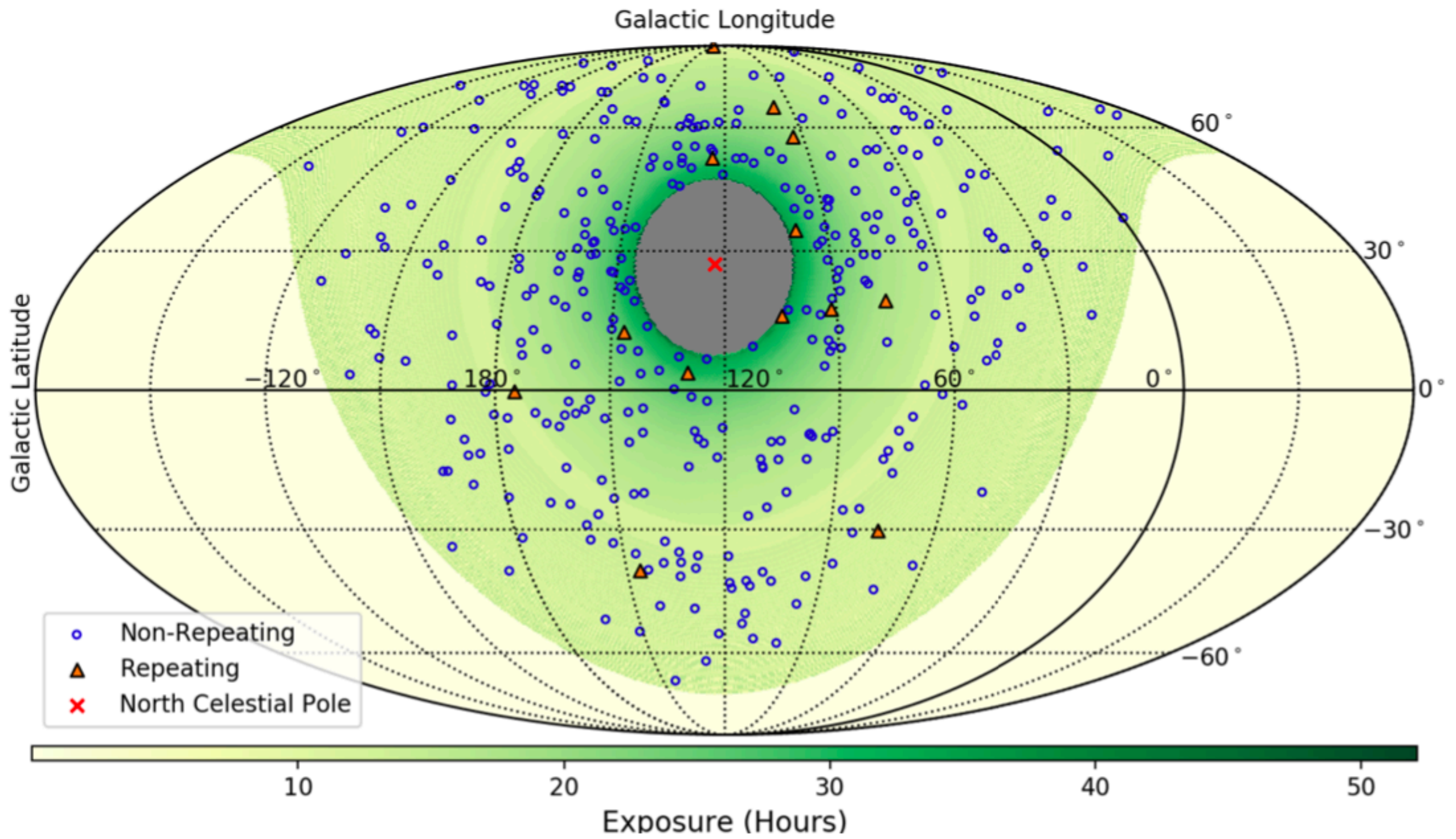
  (For what it's worth, the Konus-Wind instrumental resolution is 2 ms, versus 0.061 ms for INTEGRAL and 1 ms for Insight-HXMT.)

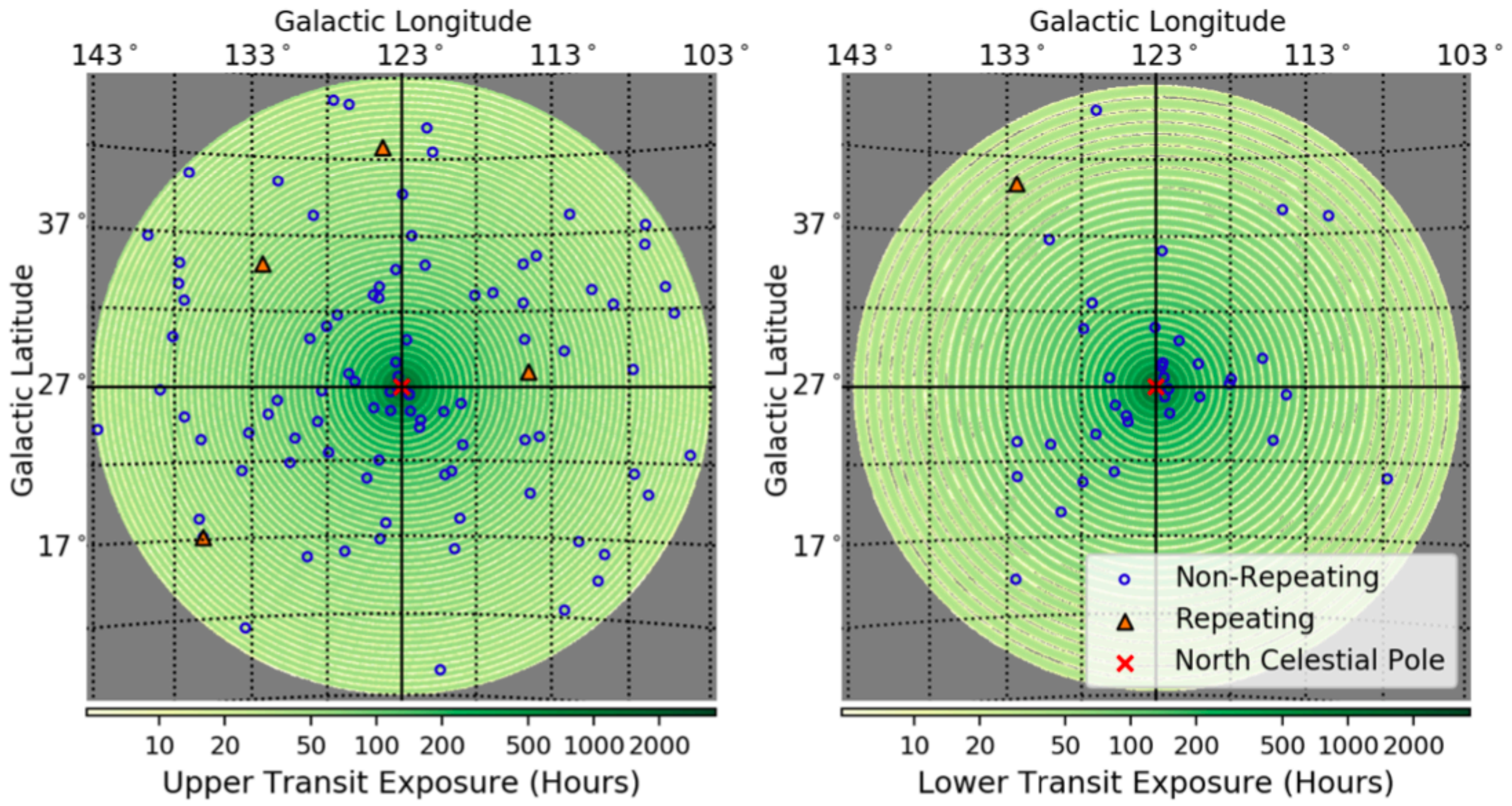
1. The CHIME concept: moving difficulty from hardware to software
2. Searching for fast radio bursts with CHIME
3. Periodic phenomena in FRBs
4. An FRB in the Milky Way
5. A large FRB catalog
6. Coming soon: CHIME outriggers, CHORD

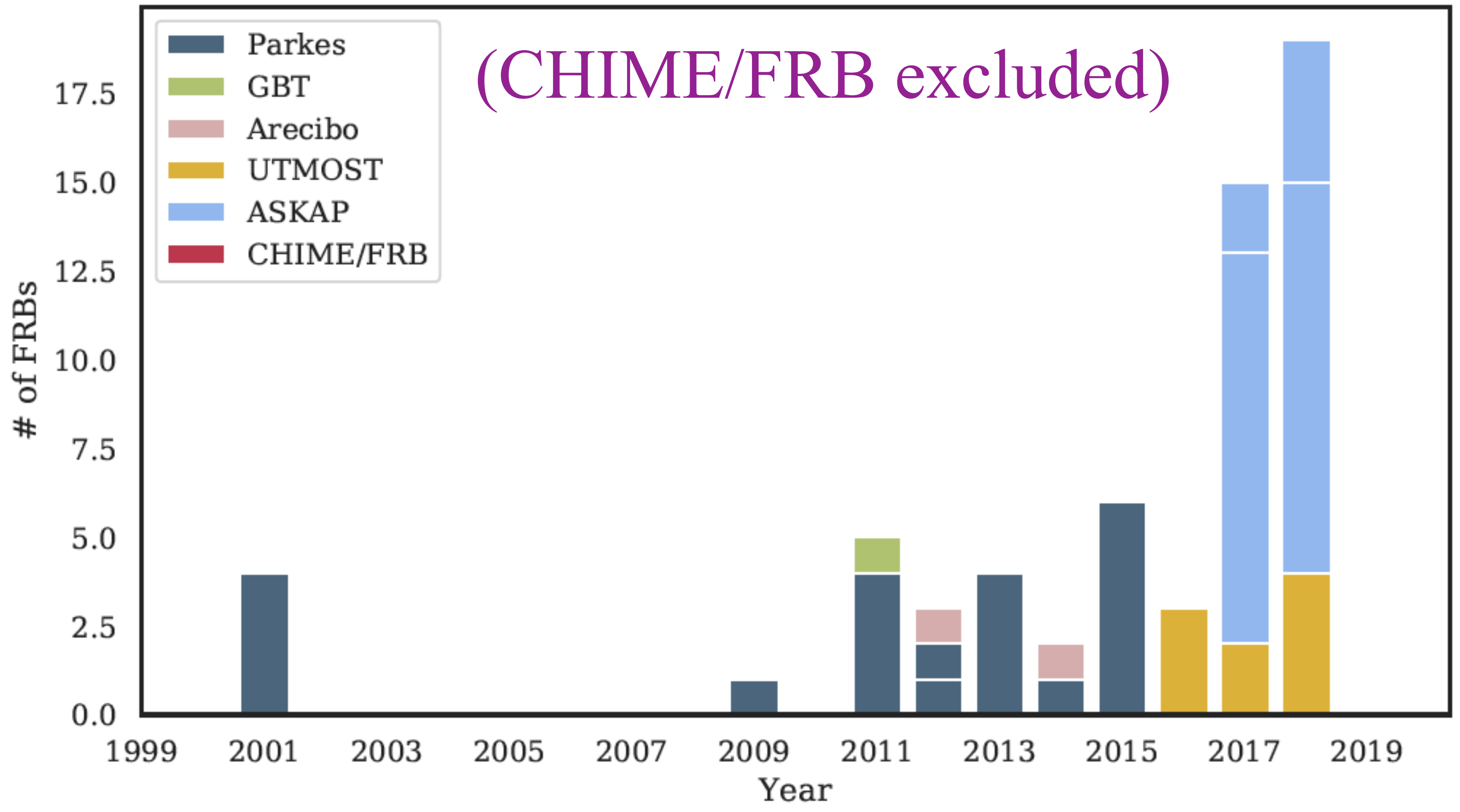
First CHIME FRB catalog

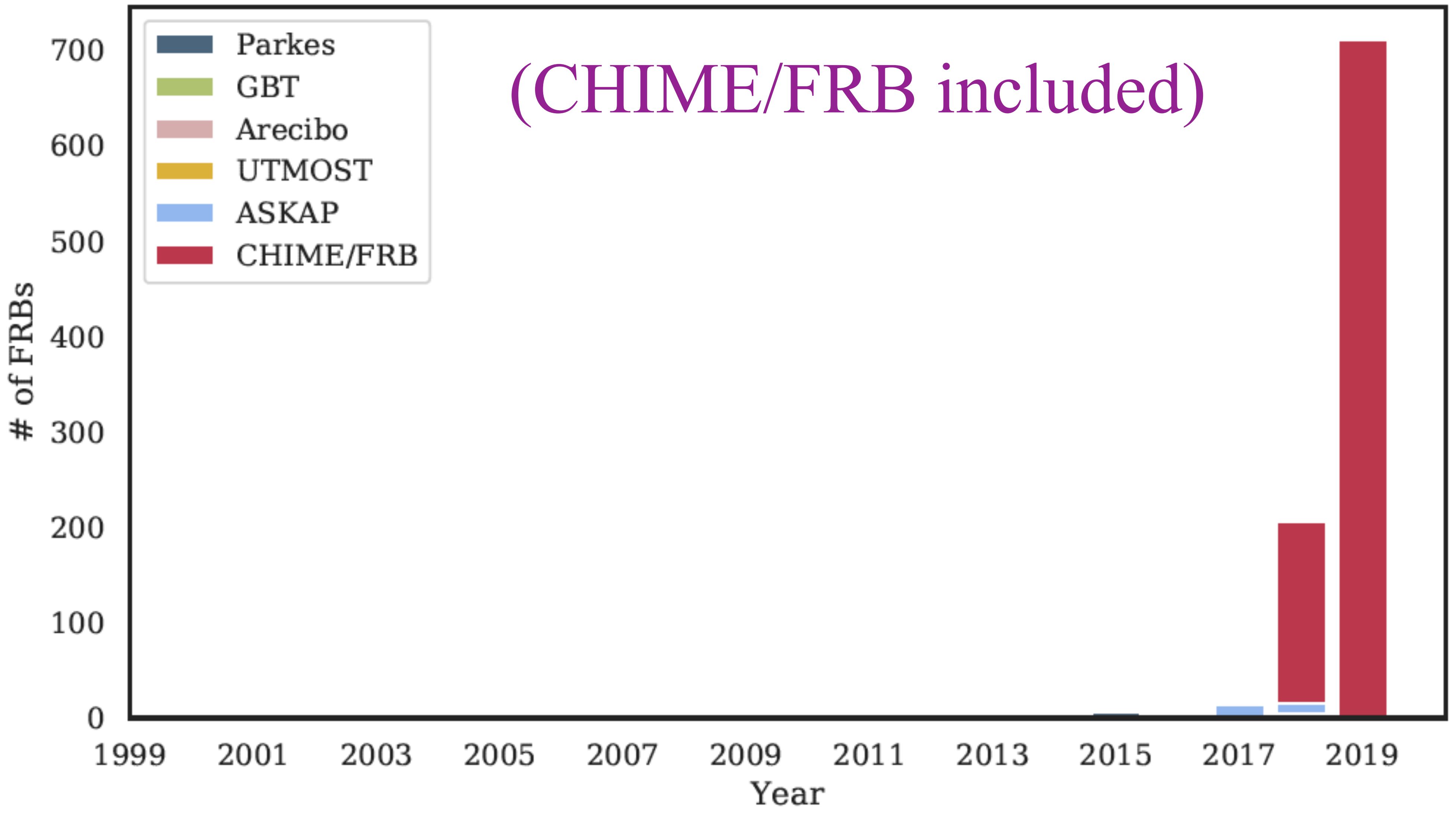
492 total sources, 18 of which are repeaters!

Larger catalogs coming soon (CHIME has found a few thousand FRBs so far.)









CHIME/FRB collaboration, arxiv:2106.04352, ApJ accepted

First CHIME FRB catalog

Main technical challenge: modelling selection function of telescope.
We use a Monte Carlo approach: inject simulated pulses in real search.

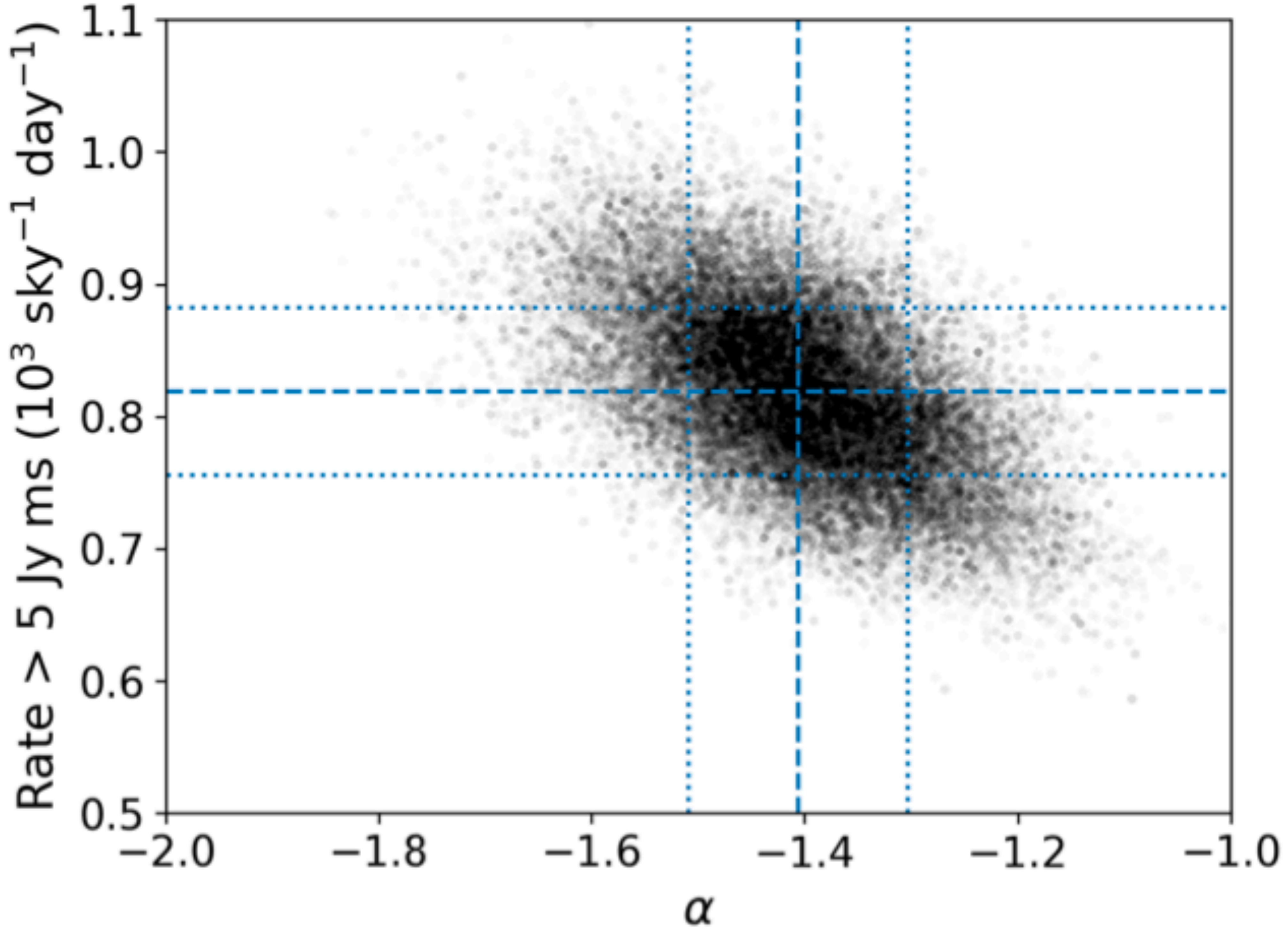
Constraints on overall FRB population:

- FRB luminosity function is consistent with a power law: $N(\geq S) \propto S^{\alpha}$

  Exponent $\alpha = -1.40 \pm 0.11(\text{stat.})^{+0.06}_{-0.09}(\text{sys.})$
  Consistent with Euclidean $\alpha = -3/2$.

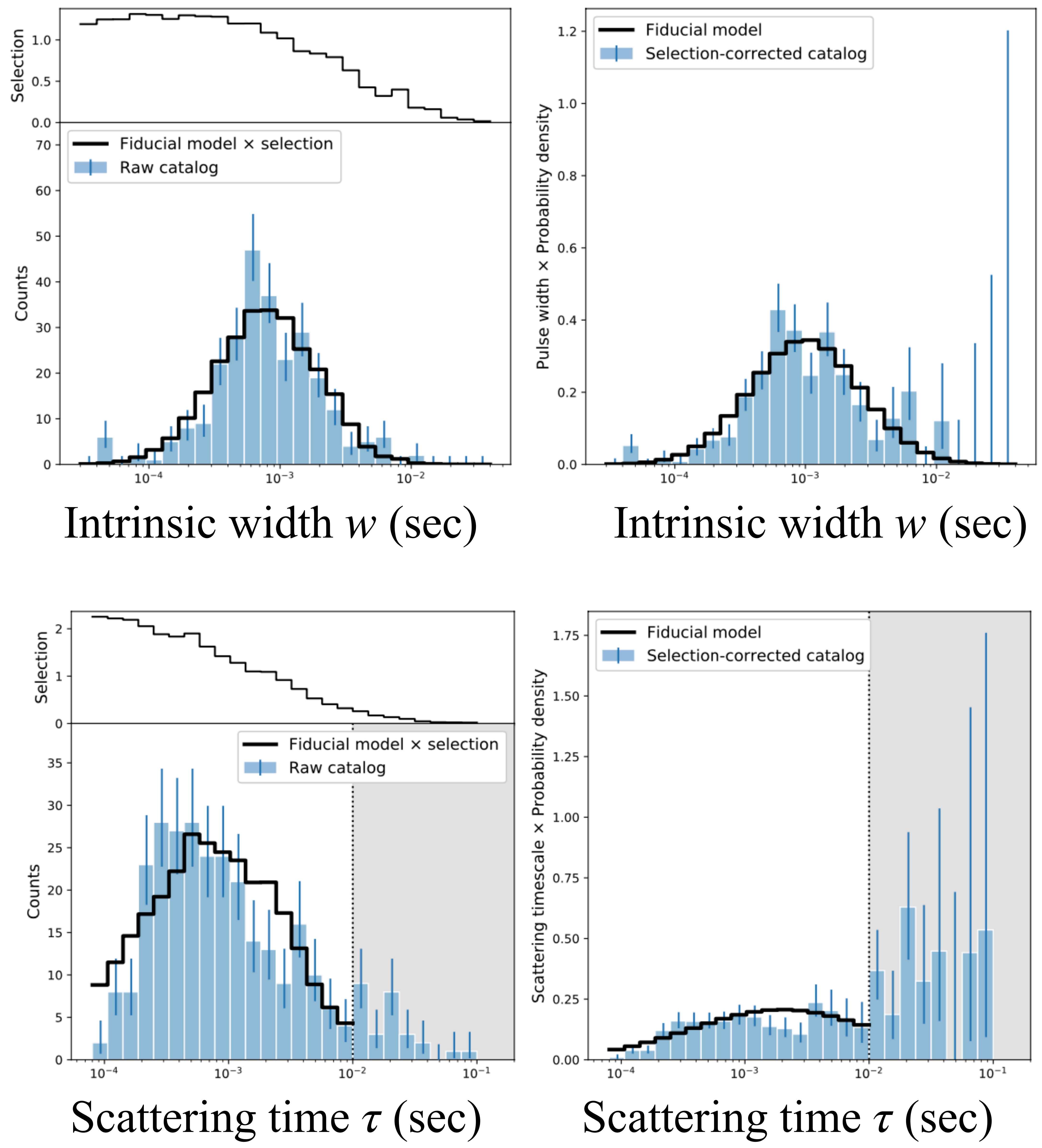
- Total rate $[525 \pm 30(\text{stat.})^{+140}_{-130}(\text{sys.})]\,/\text{sky}\,/\text{day}$

  with cuts: fluence $\geq$ 5 Jy-ms
  DM $\geq$ 100 pc cm^{-3}
  scattering time $\tau_{600} \leq 10$ ms.



CHIME/FRB collaboration, arxiv:2106.04352, ApJ accepted

First CHIME FRB catalog



Constraints on FRB model parameters.

Two examples shown here: intrinsic width w, and scattering time τ.

Technical note: FRB pulse profiles are modelled as convolution of two contributions:

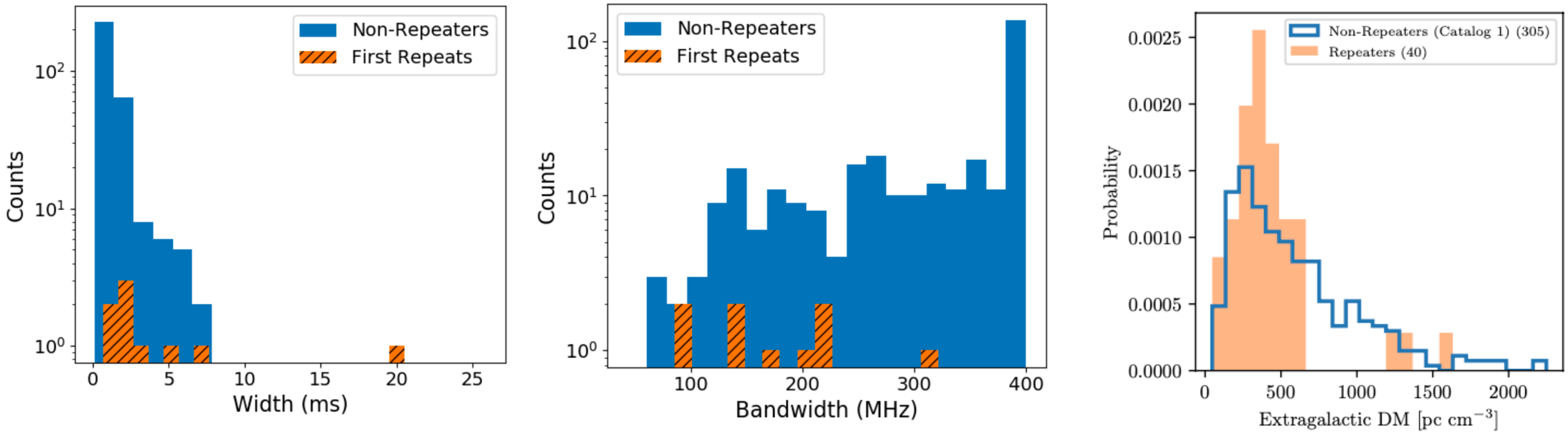
- Gaussian "intrinsic" profile with width w
- Exponential "scattering" profile with width τ

Scattering time τ is an example where the selection function qualitatively changes the interpretation.

CHIME/FRB collaboration, arxiv:2106.04352, ApJ accepted

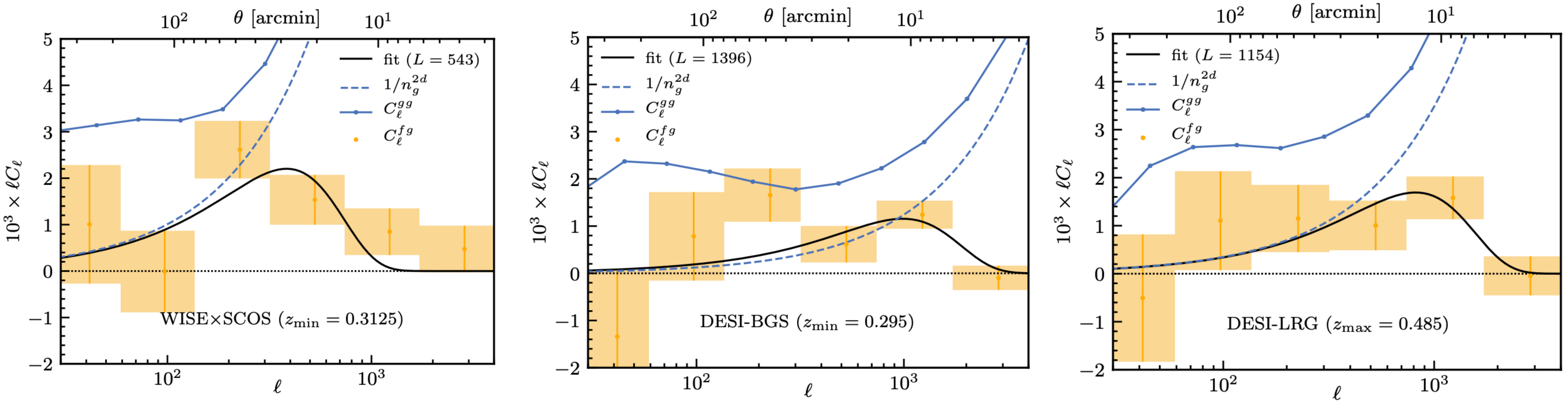
First CHIME FRB catalog

- Repeaters have longer-duration pulses ($p \sim$ few $\times 10^{-5}$) and narrower bandwidths ($p \sim$ few $\times 10^{-8}$) than non-repeaters.
- Tentative evidence that repeaters have higher DM ($p \sim 0.01$).
- Other source properties (brightness, polarization) are consistent between populations.



CHIME/FRB collaboration, ApJS 257 (2021) 59, arXiv:2106.04352
CHIME/FRB collaboration, ApJ accepted, arXiv:2301.08762

Using FRB-galaxy correlations to learn about FRBs

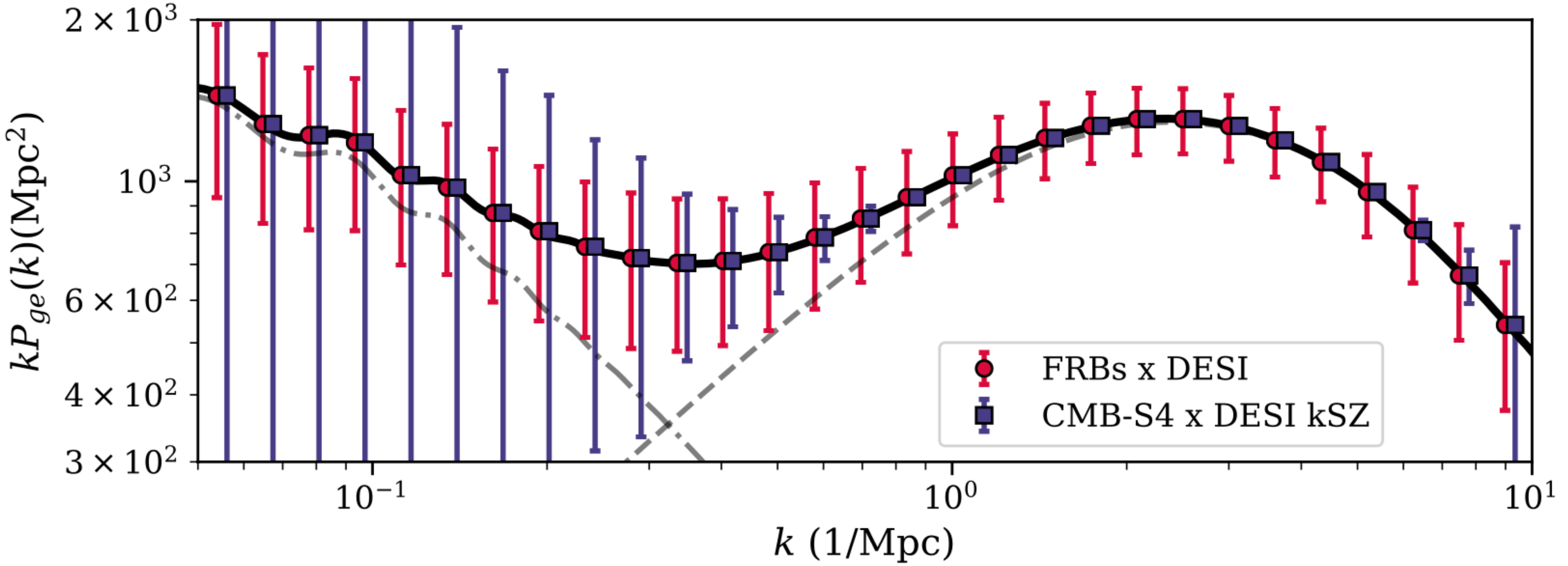


- CHIME angular resolution is insufficient to associate individual FRBs with individual galaxies.
- By spatially correlating FRBs and galaxies, we see a high significance (5σ) statistical association.
- First evidence for high-DM FRBs (DM ~ 800) at intermediate redshifts (z ~ 0.4), later confirmed by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

Masoud Rafiei-Ravandi

Rafiei-Ravandi et al, ApJ

Using FRB-galaxy correlations to learn about FRBs



- Future application: galaxy-electron power spectrum $P_{ge}(k)$, by spatially correlating foreground galaxies with "DM maps" from background FRBs.
- Complementary to kSZ (noise power spectra have different k dependence).
- Can break the optical depth degeneracy in kSZ.
- Measuring $P_{ge}(k)$ is astrophysically interesting and can pin down nuisance parameters for cosmic shear analyses.

Madhavacheril, Battaglia, Smith, Sievers
PRD 100 (2019) 103532.

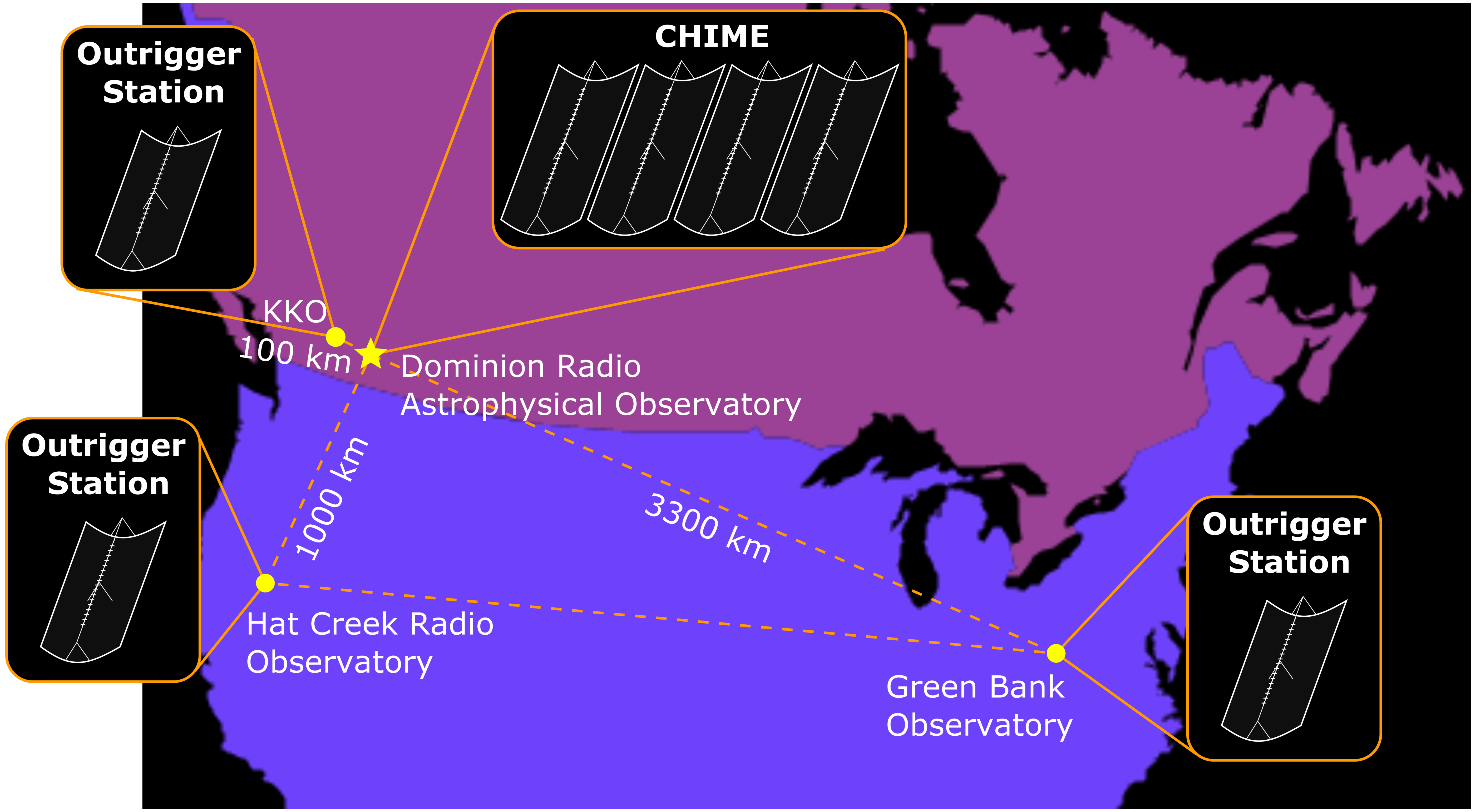
1. The CHIME concept: moving difficulty from hardware to software
2. Searching for fast radio bursts with CHIME
3. Periodic phenomena in FRBs
4. An FRB in the Milky Way
5. A large FRB catalog
6. Coming soon: CHIME outriggers, CHORD

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.

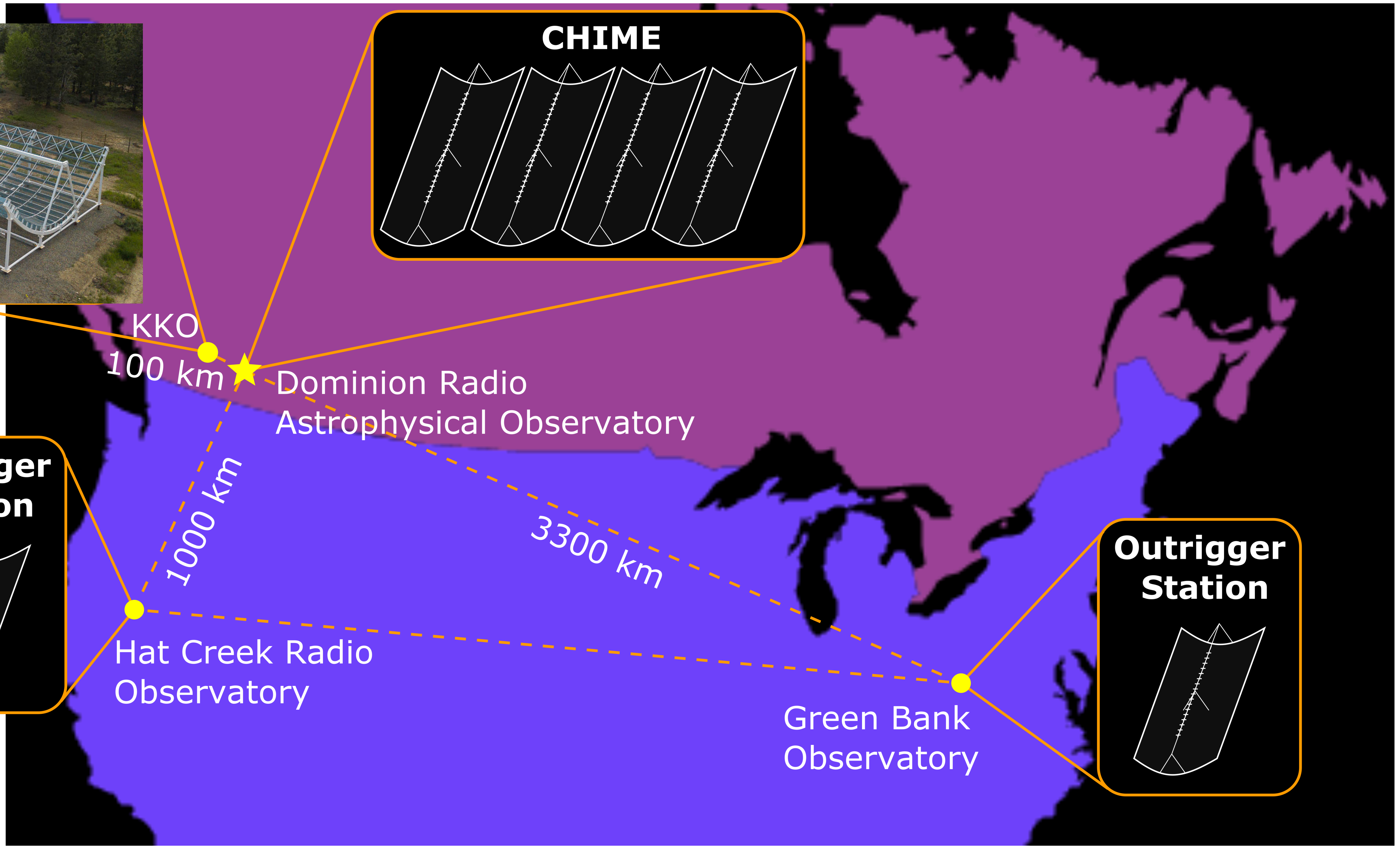


Coming soon: CHIME outriggers

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.

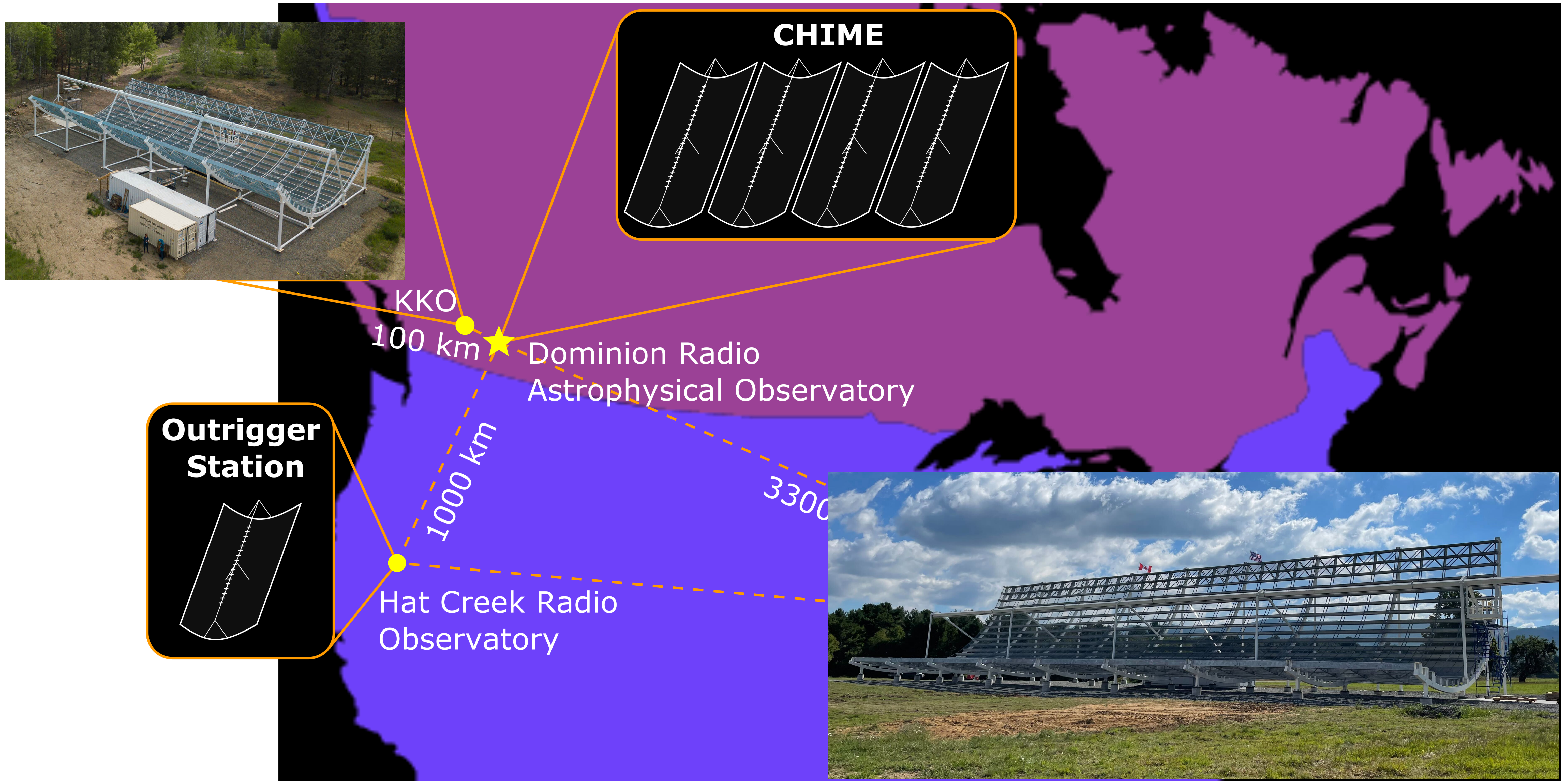


Coming soon: CHIME outriggers

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.

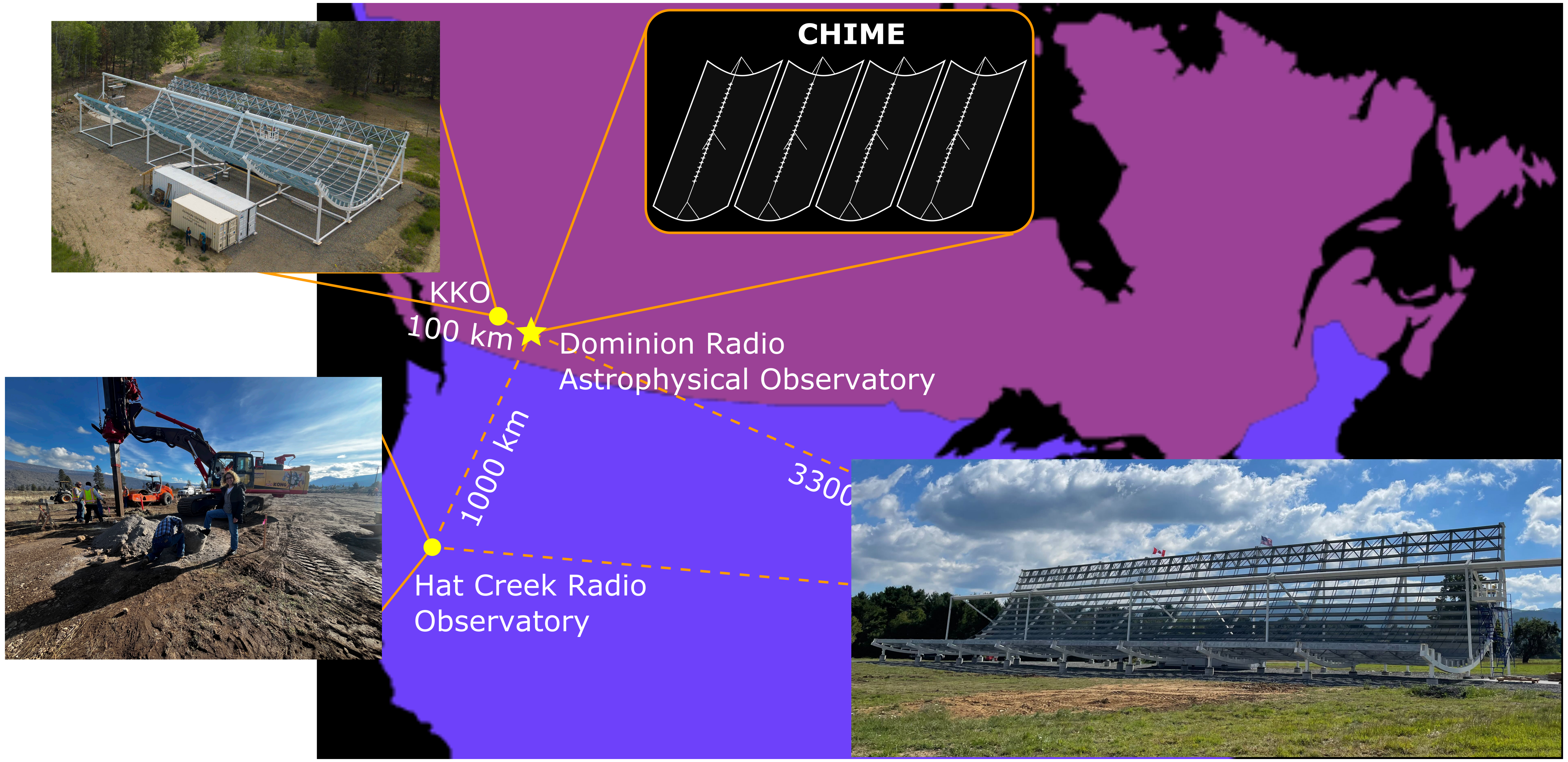


Coming soon: CHIME outriggers

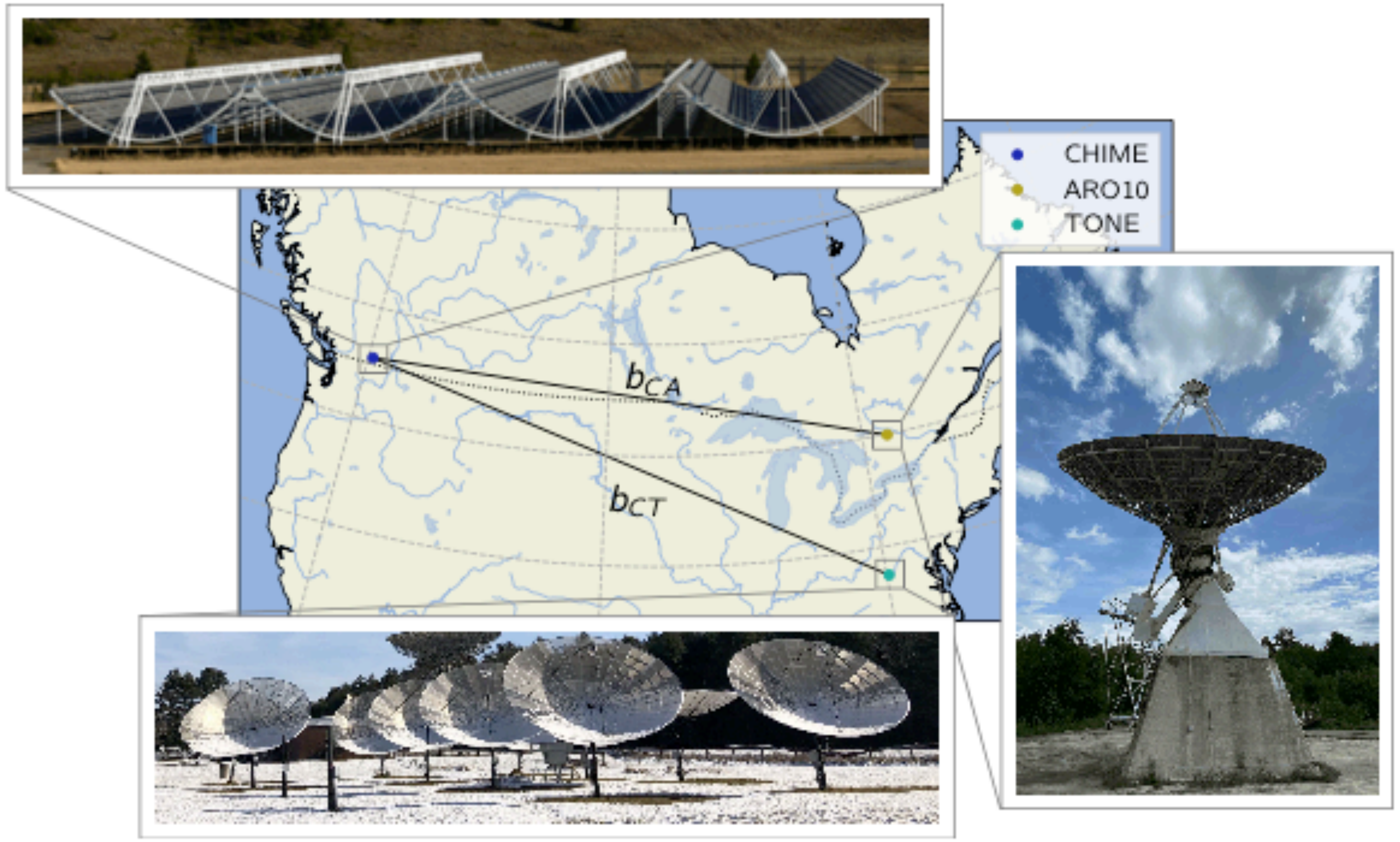
CHIME finds FRBs at a very high rate, but has limited angular resolution.

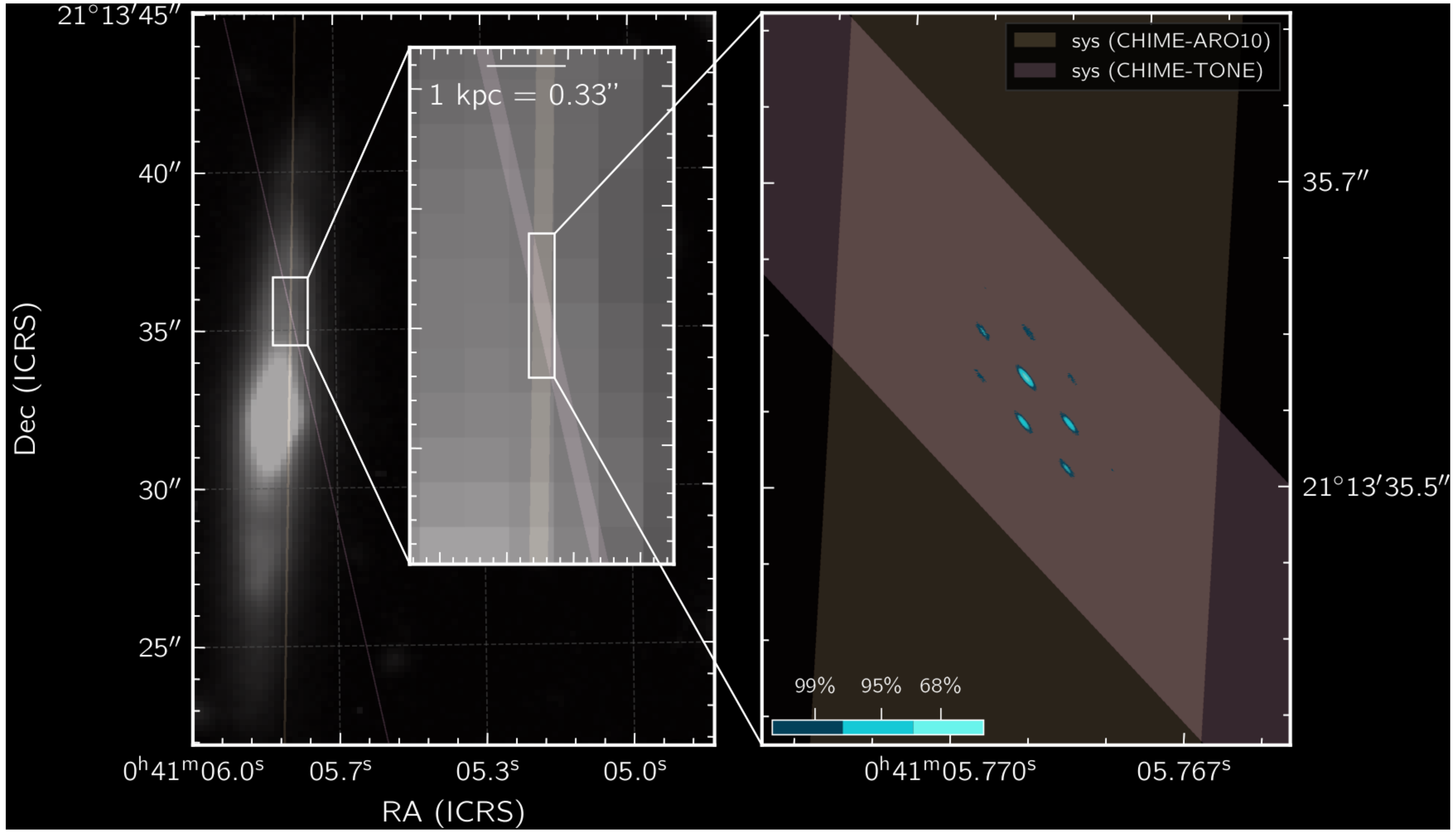
Solution: build outrigger telescopes! (Funded by Moore foundation and NSF.)

- 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.



Proof of concept: an FRB localized to a disk galaxy at z=0.18





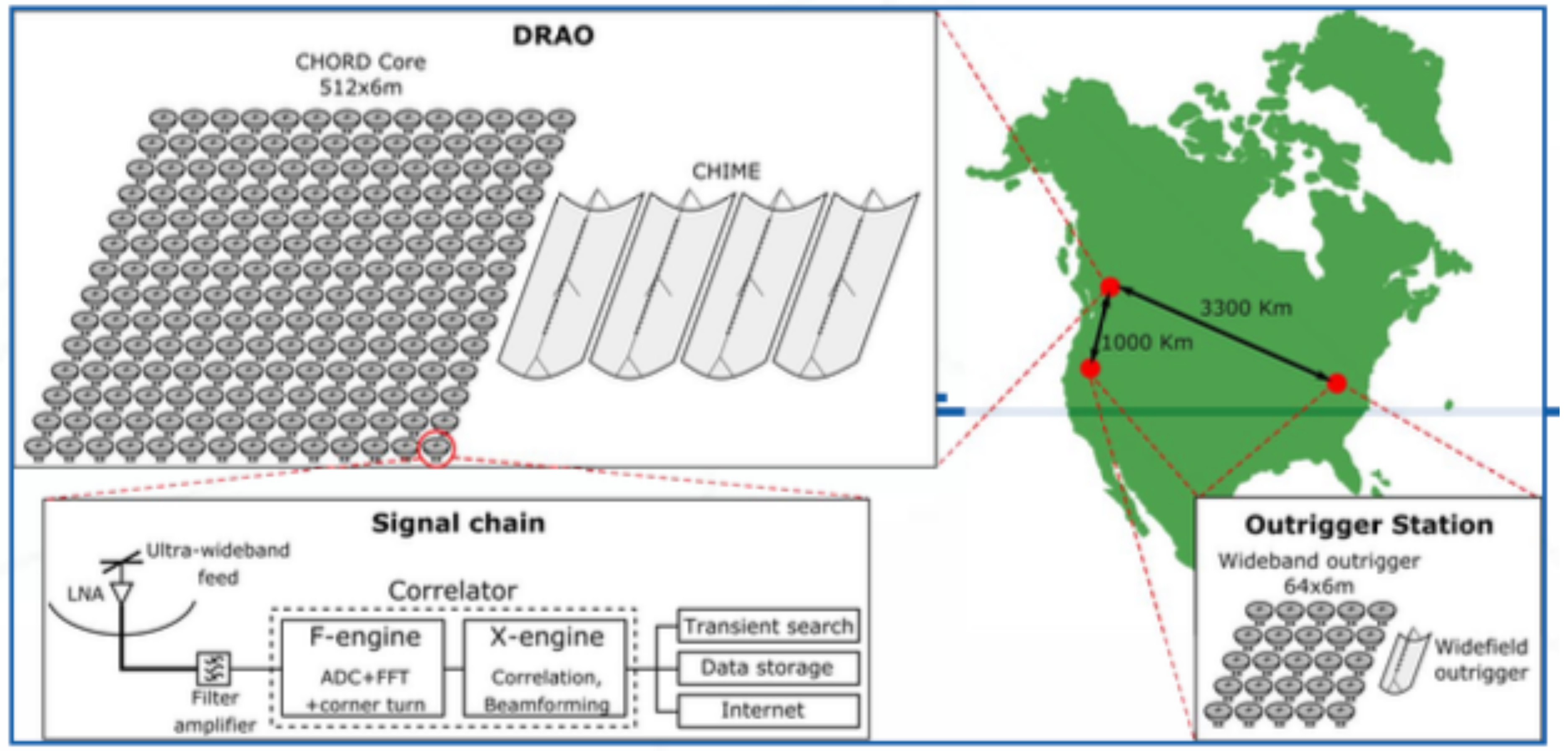
Localization accuracy ~1 arcsec, using ad hoc VLBI network (CHIME + ARO + TONE).
Limited by calibration systematics — hope to get 50 milliarcsec with CHIME outriggers!

Cassanelli et al, arXiv:2307.09502

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 2024/5, full instrument expected 2026.



Concluding thoughts

- For $15M USD, you can build one of the world’s most powerful radio telescopes (!)

Concluding thoughts

- For $15M USD, you can build one of the world's most powerful radio telescopes (!)
- There is a clear path to scaling up CHIME by a factor of ~1000 or so (in mapping speed) in the near future. (CHORD represents the first factor of ~10.)

Concluding thoughts

- For \$15M USD, you can build one of the world's most powerful radio telescopes (!)
- There is a clear path to scaling up CHIME by a factor of ~1000 or so (in mapping speed) in the near future. (CHORD represents the first factor of ~10.)
- The catch: these instruments have immense data rates, and require solving difficult computational problems.

Concluding thoughts

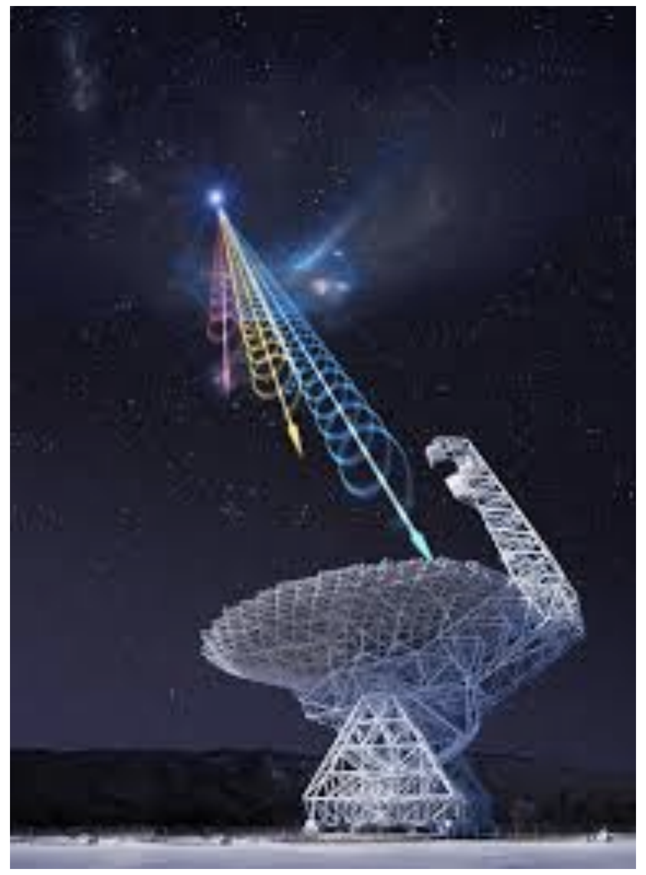
- For \$15M USD, you can build one of the world's most powerful radio telescopes (!)
- There is a clear path to scaling up CHIME by a factor of ~1000 or so (in mapping speed) in the near future. (CHORD represents the first factor of ~10.)
- The catch: these instruments have immense data rates, and require solving difficult computational problems.
- I'm convinced that the future of radio astronomy is "large N and clever algorithms".

Concluding thoughts

- For \$15M USD, you can build one of the world's most powerful radio telescopes (!)
- There is a clear path to scaling up CHIME by a factor of ~1000 or so (in mapping speed) in the near future. (CHORD represents the first factor of ~10.)
- The catch: these instruments have immense data rates, and require solving difficult computational problems.
- I'm convinced that the future of radio astronomy is "large N and clever algorithms".
- CHIME/CHORD are ambitious steps in this direction. We have solved some difficult computational problems (CHIME-scale FRB search!), but more challenges remain.

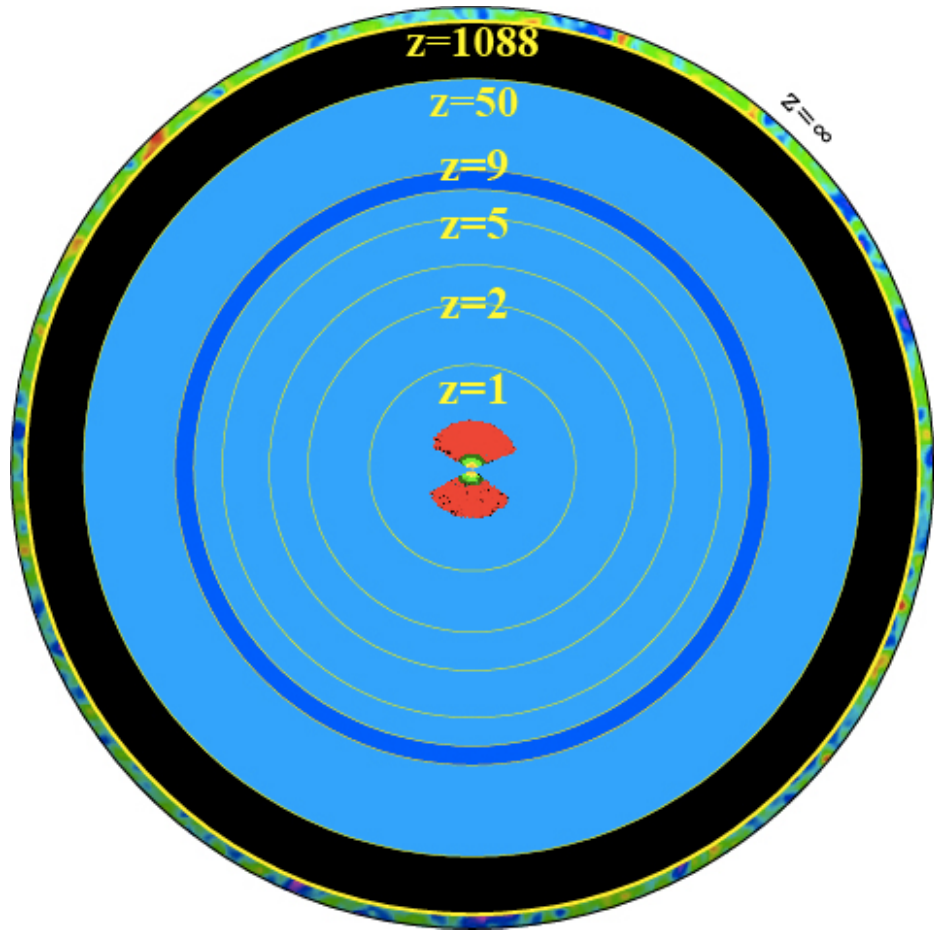
Concluding thoughts

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



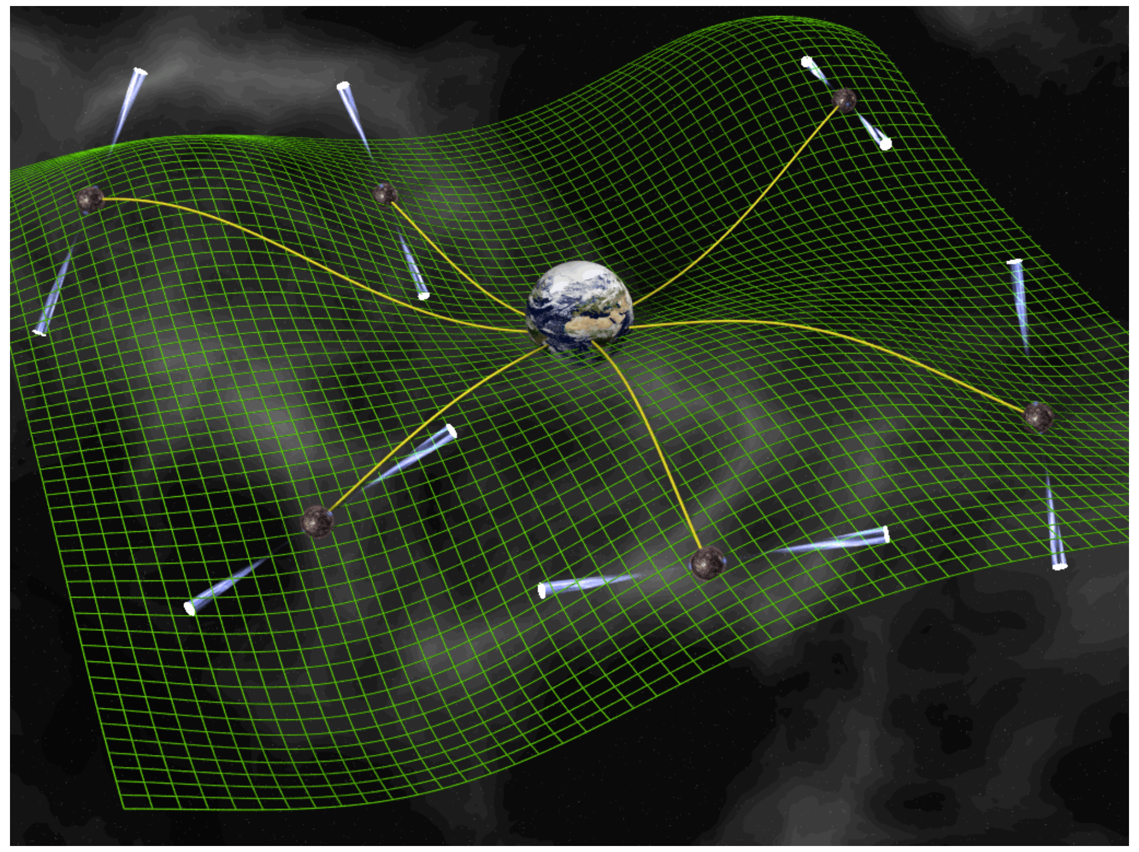
Fast radio bursts:

- 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:

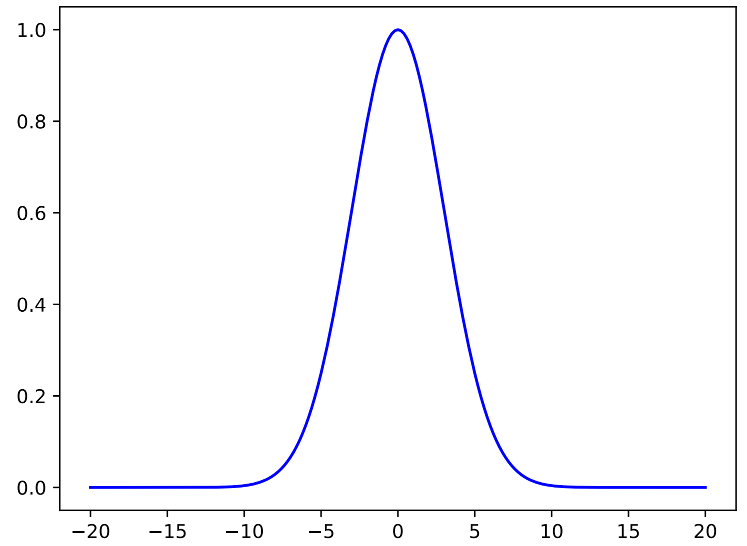
- new tests of GR
- new probe of gravity waves
- rich astrophysics

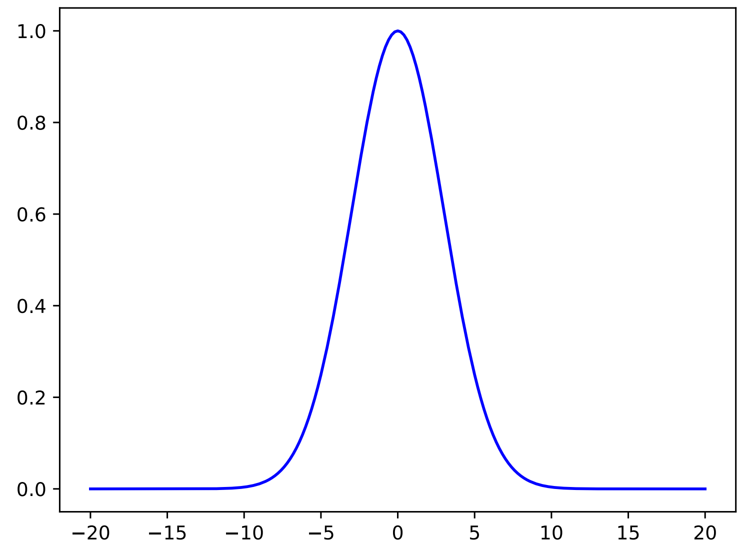
Thanks!

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

“Intrinsic” profile:

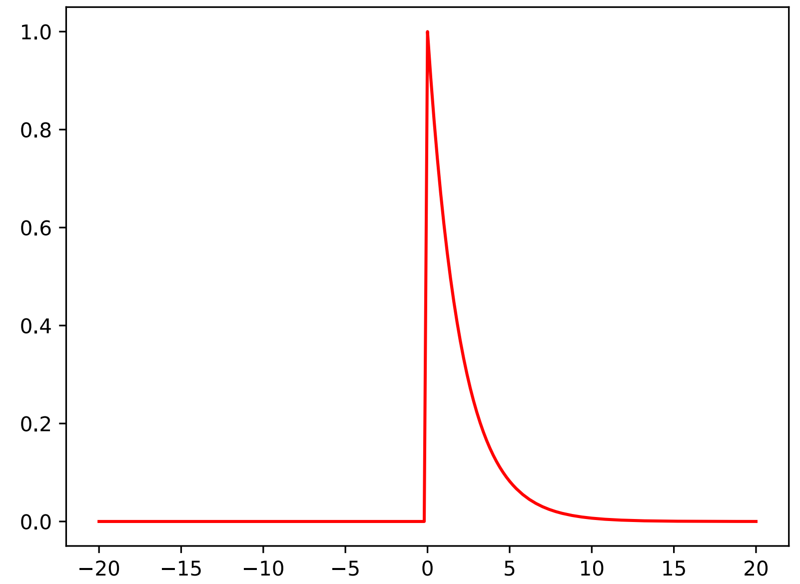
Gaussian, width w frequency-independent

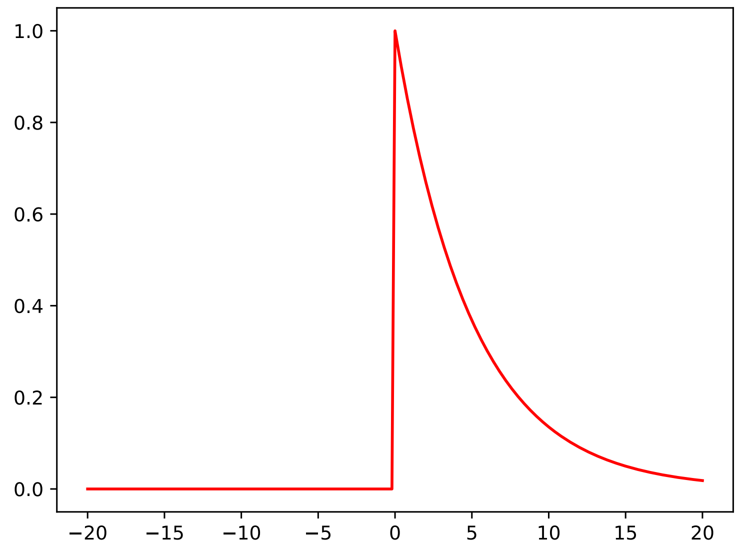




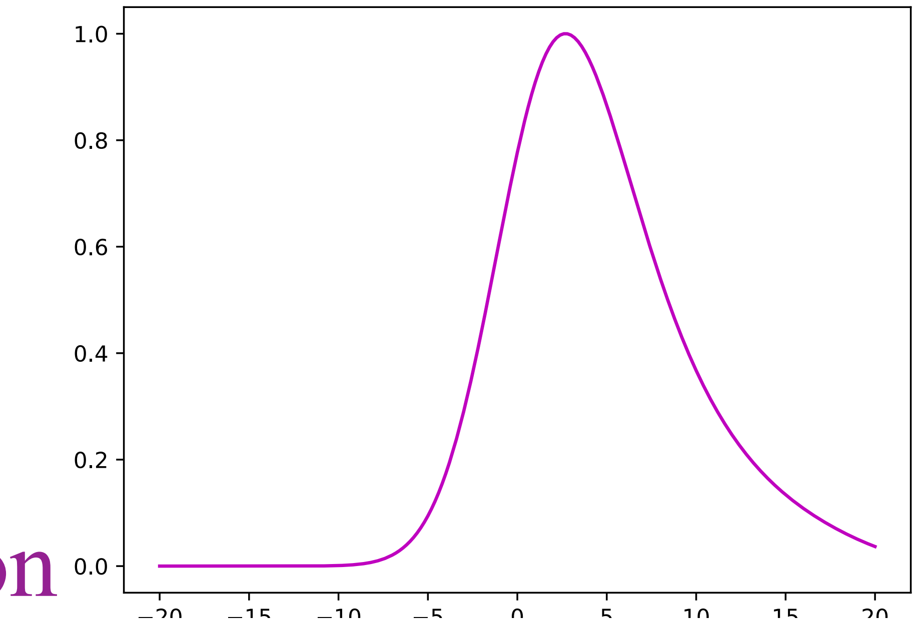
“Scattering” Profile:

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

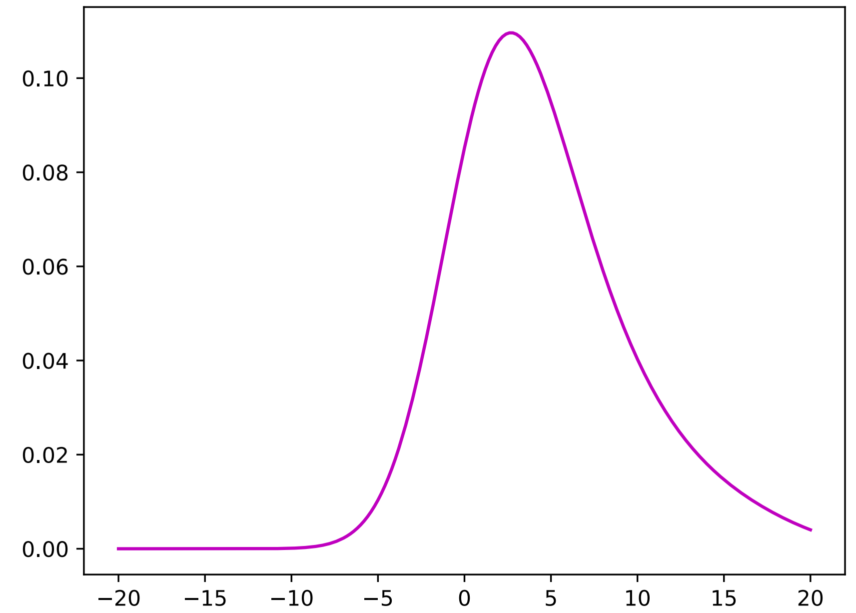




convolution



Higher frequency

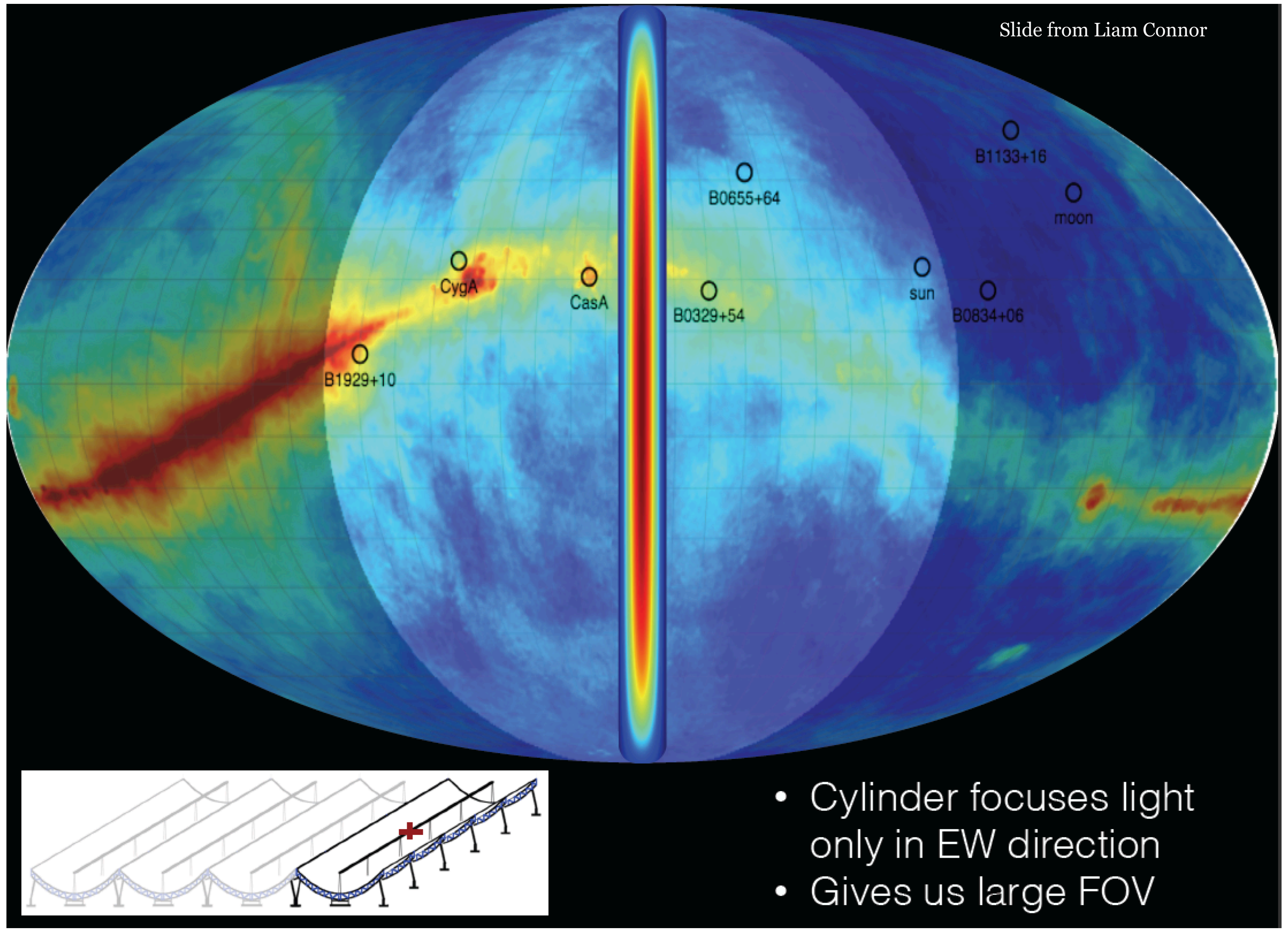


Lower frequency

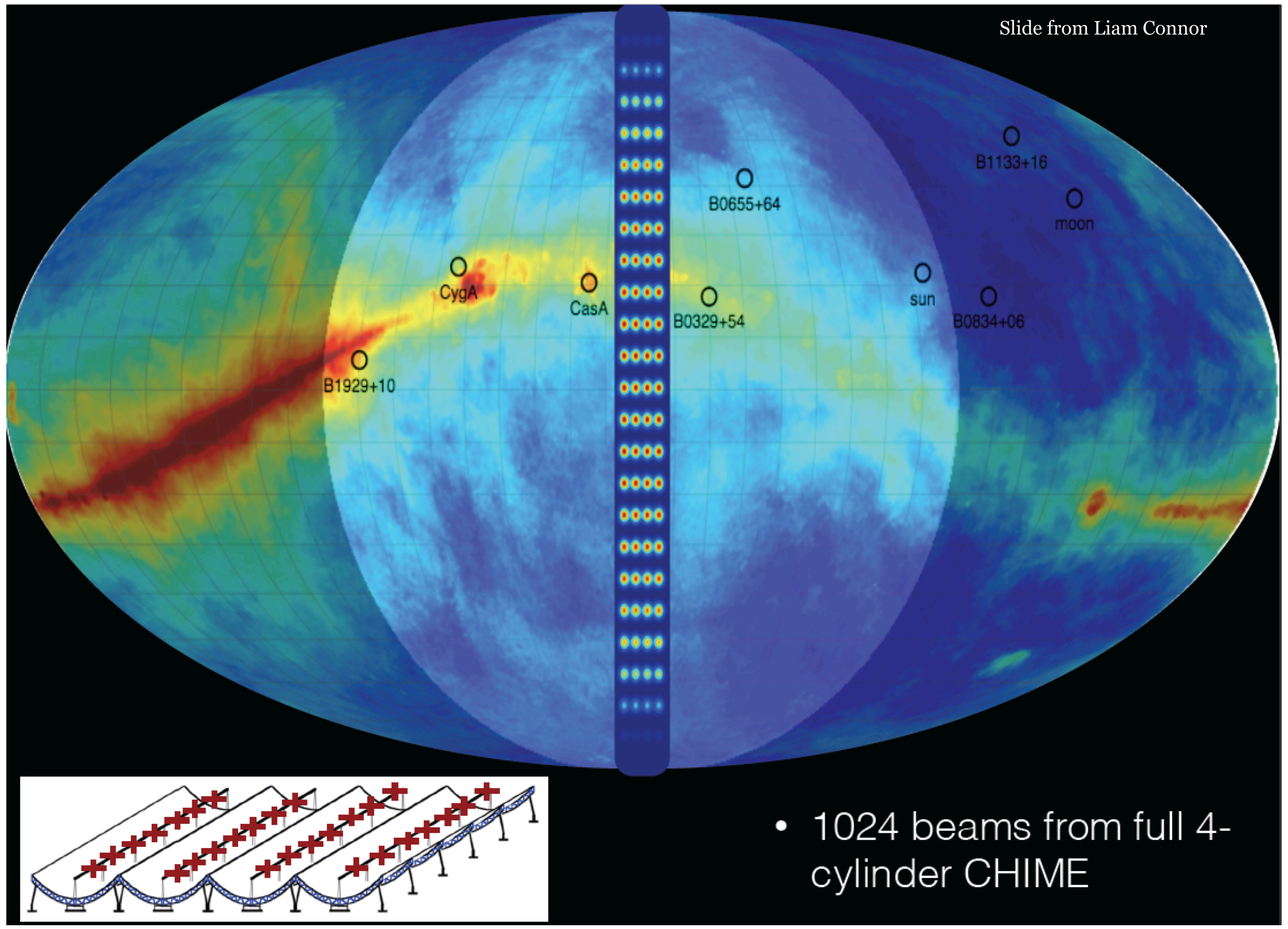
CHIME beamforming, cartoon form

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.



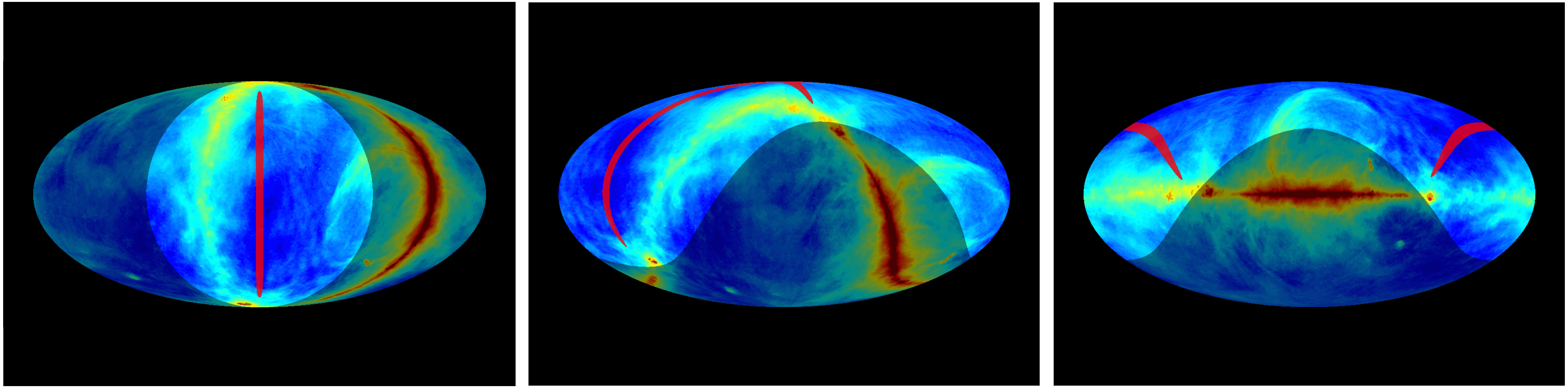
primary beam



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.