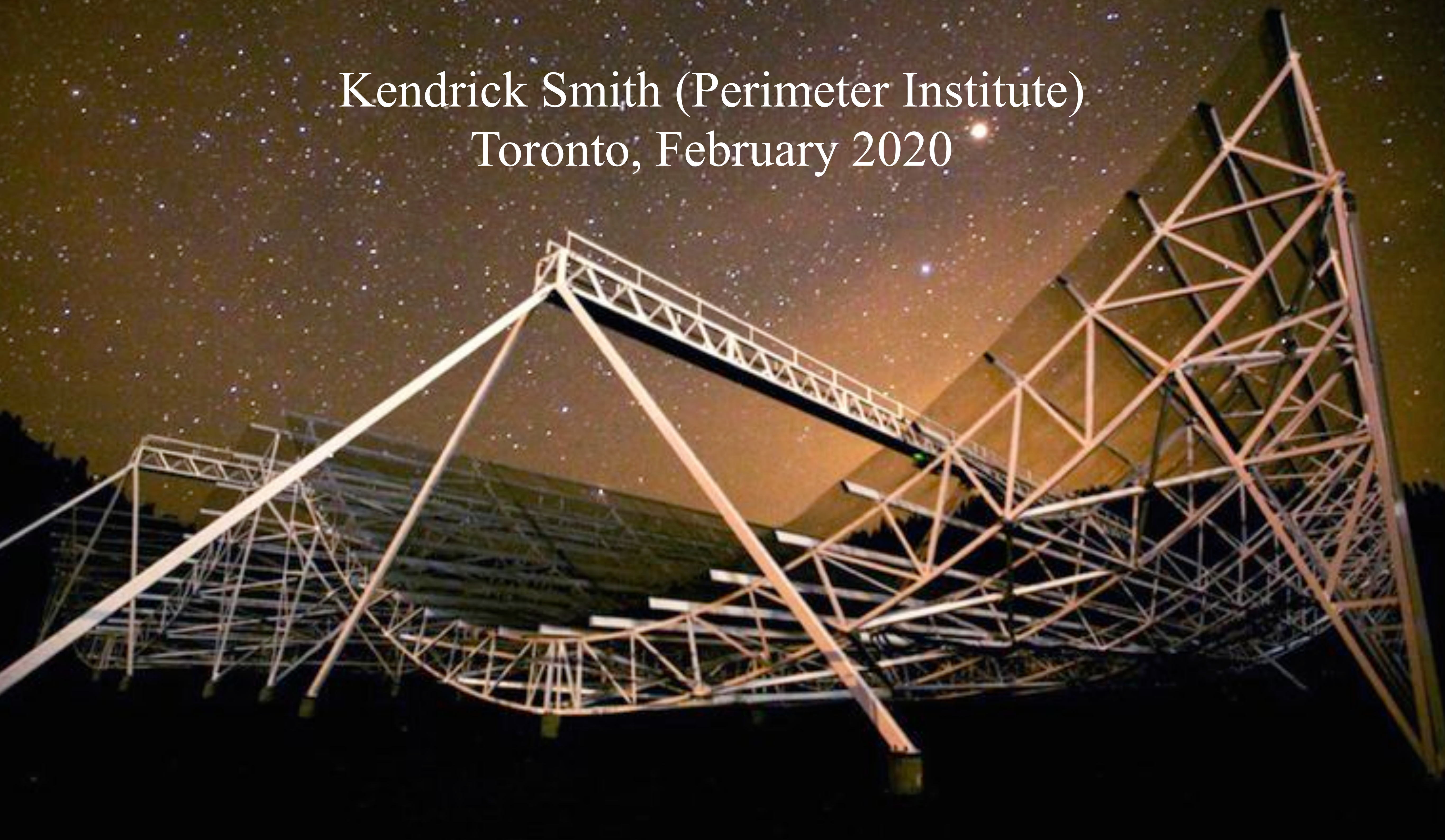
CHIME: The Canadian Hydrogen Intensity Mapping Experiment

Kendrick Smith (Perimeter Institute)

Toronto, February 2020



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
2. Science goals of CHIME
3. Why this is hard
4. FRB science results
5. Concluding thoughts

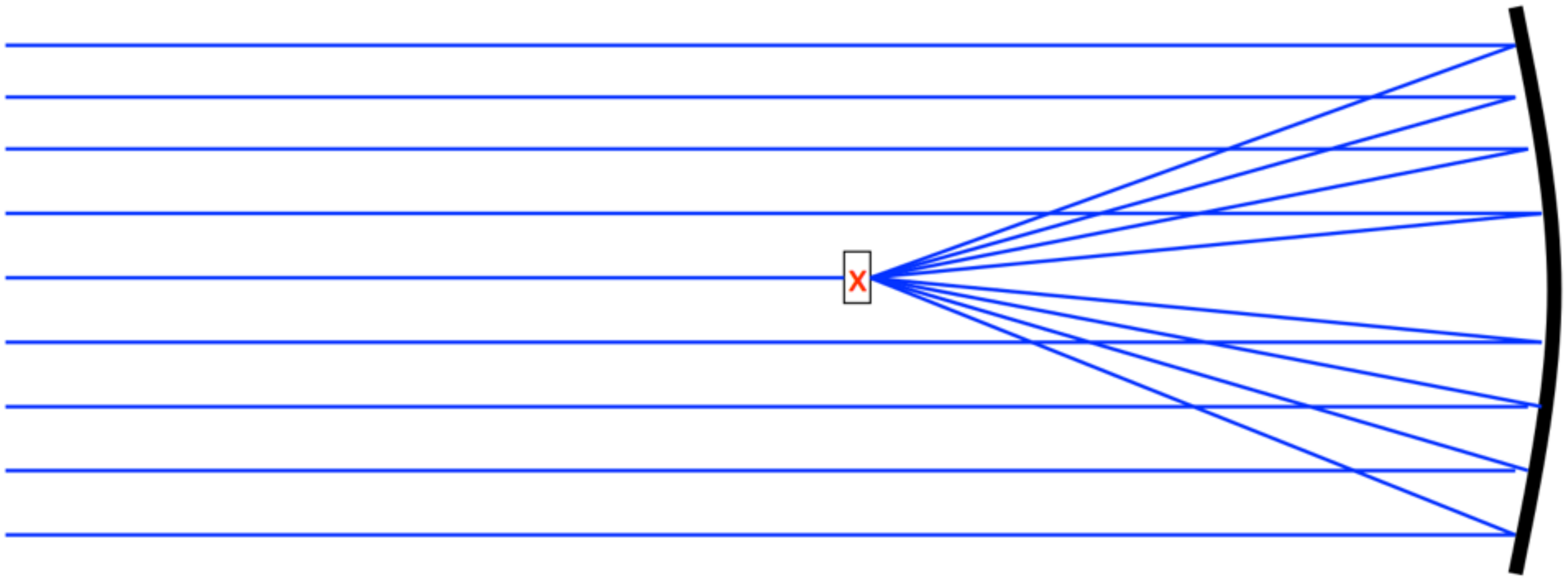
CHIME telescope

- In British Columbia (at DRAO). First new Canadian research telescope in several decades!
- Compact interferometer with no moving parts, uses Earth rotation to survey sky.
- Four cylinders, (4 x 256) dual-polarization feeds, total collecting area $(80\ \mathrm{m})^2$.
- Frequency range 400-800 MHz. Selected for 21-cm cosmology in redshift range $0.8 < z < 2.5$.

CHIME

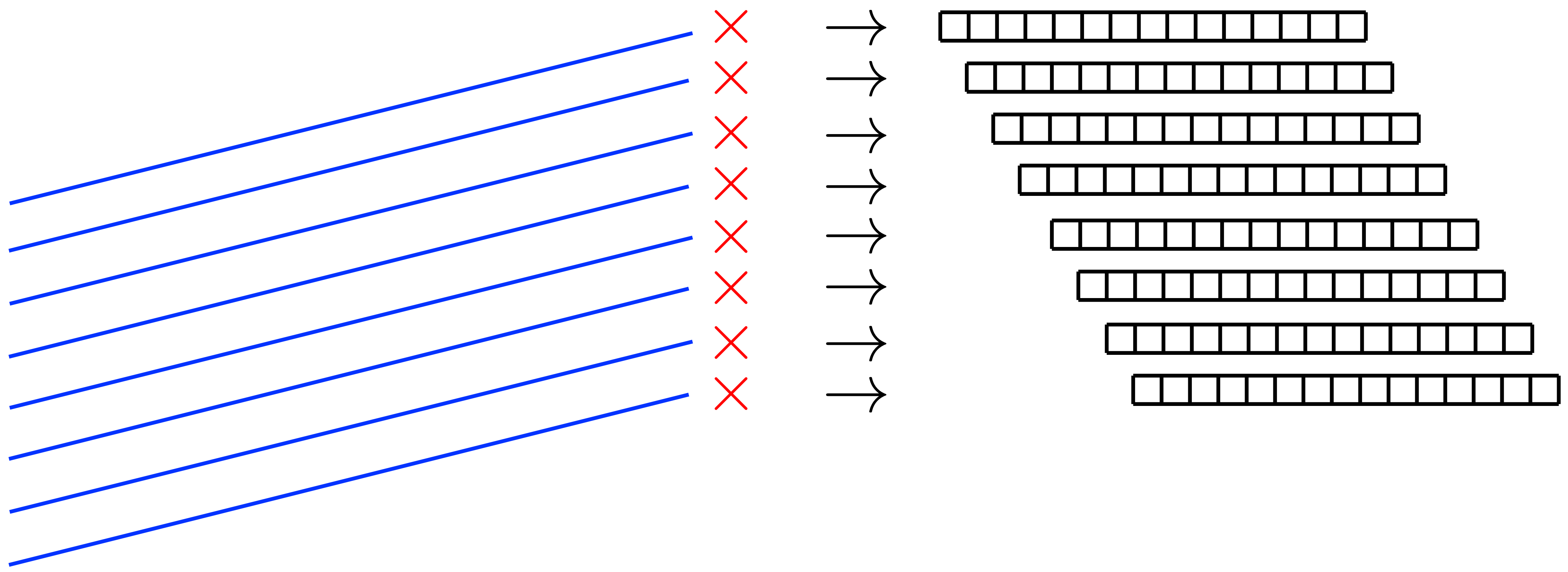
Traditional radio telescope

Single-feed radio telescope



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

Phased-array interferometer

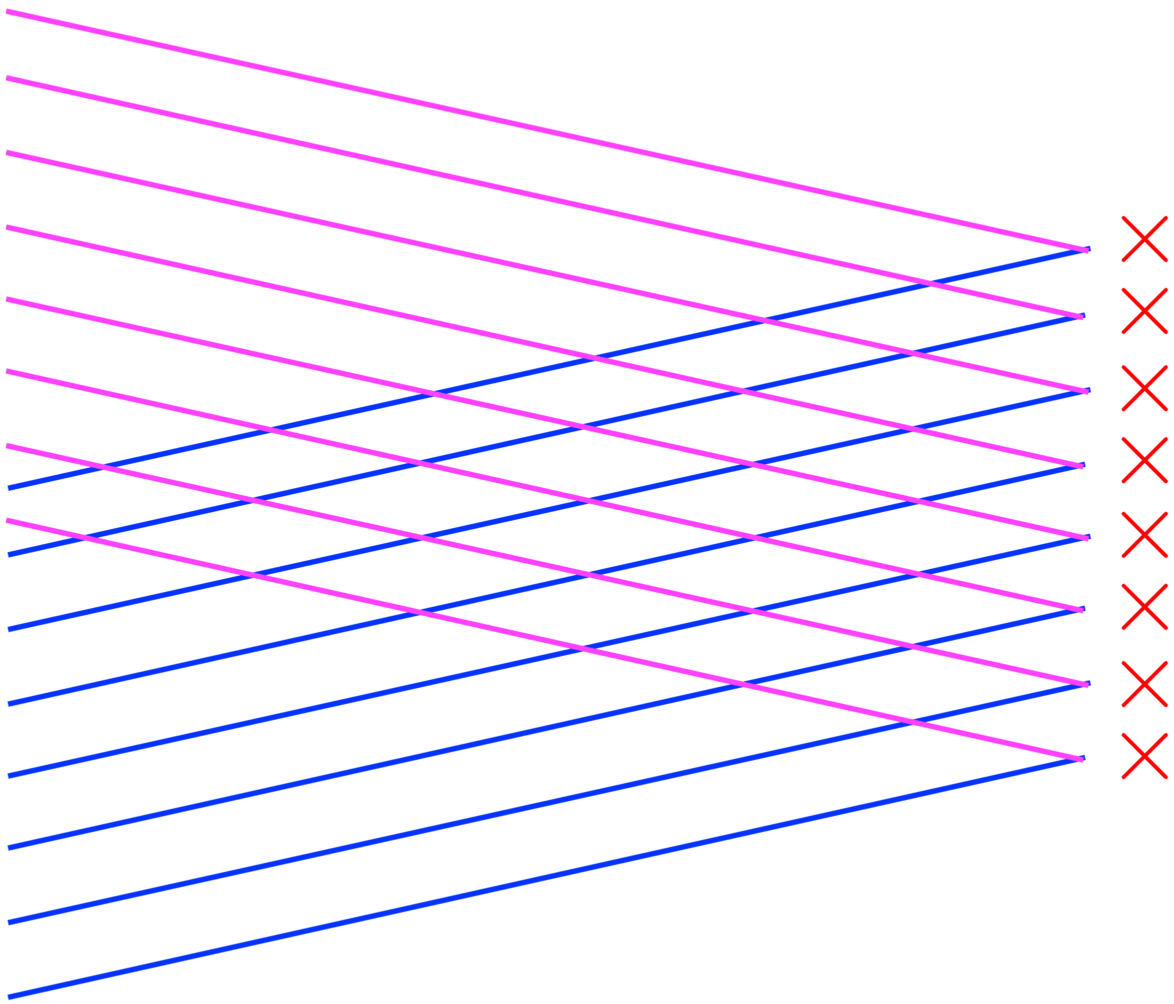


Dish is replaced by an array of antennas whose signals are digitized.

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

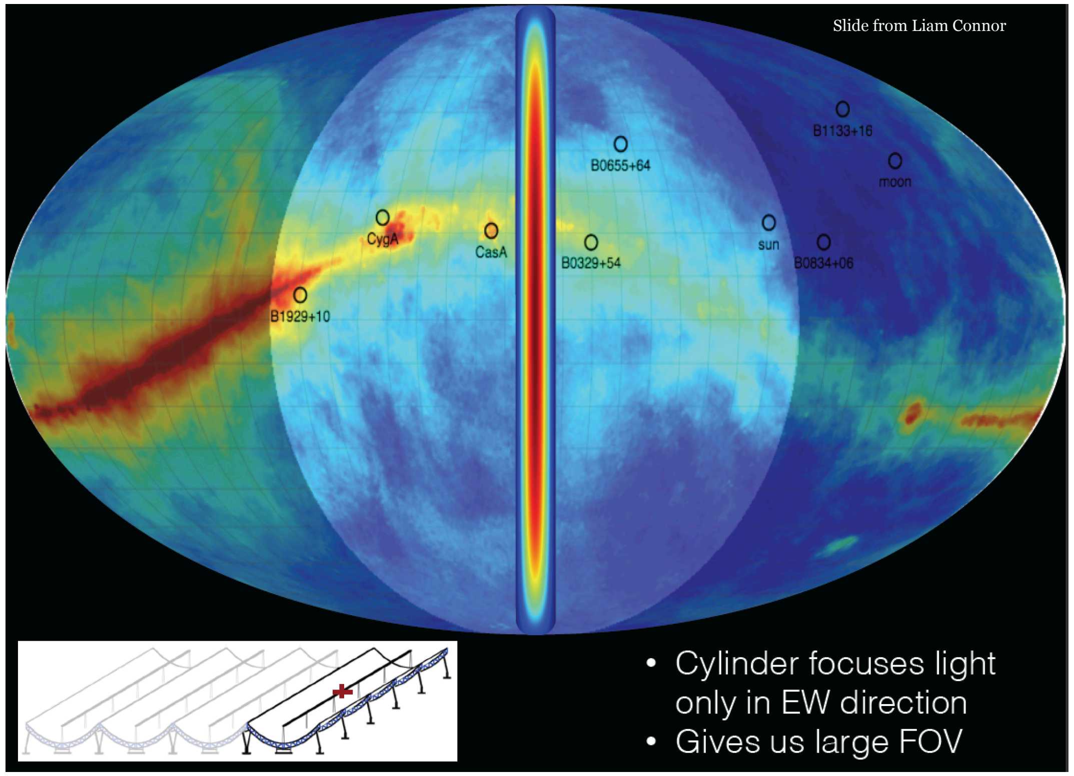
- CHIME has a 4 x 256 array of antennas and can form all 1024 independent beams in real time. Raw sensitivity is the same as 1024 single-feed radio telescopes!

80m

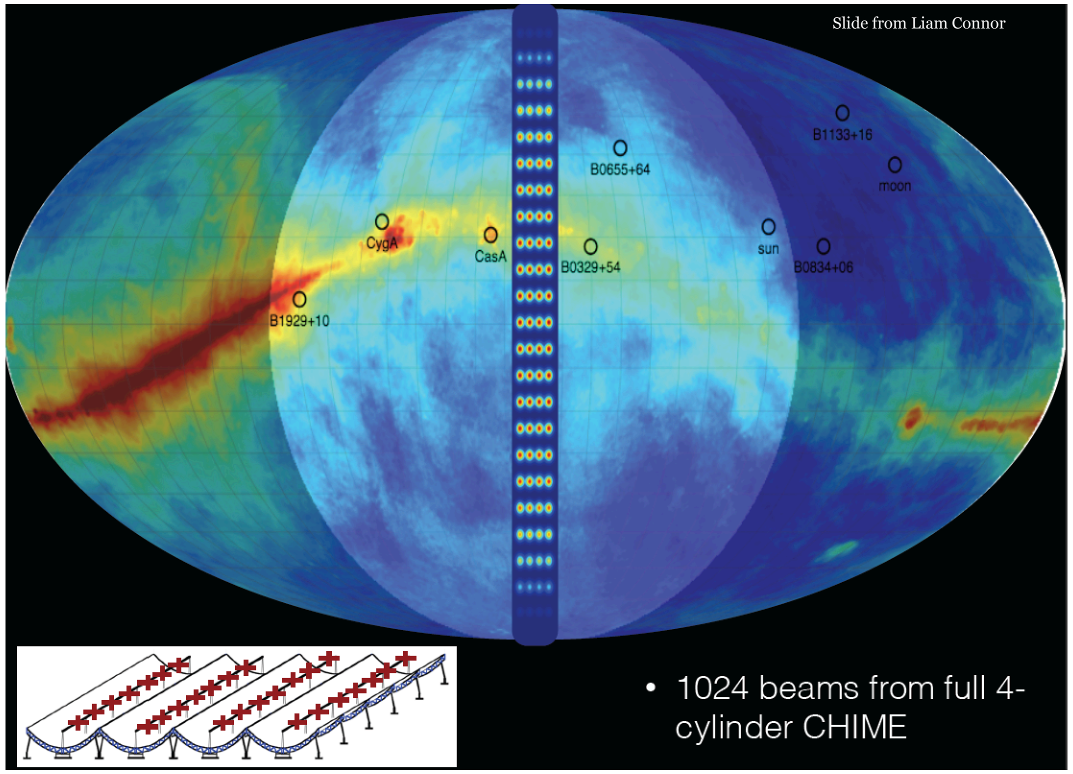
CHIME beamforming, cartoon form

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.



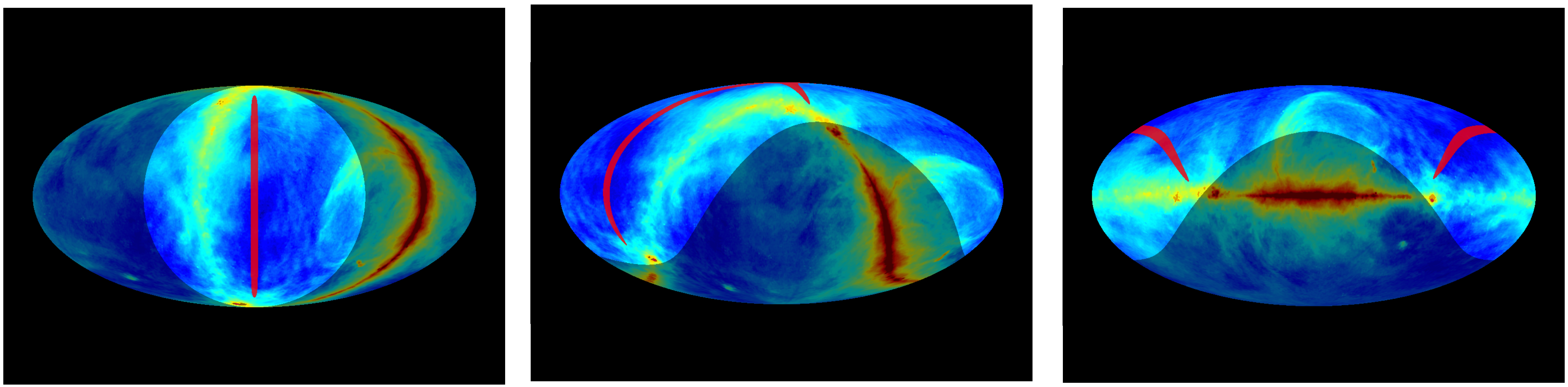
primary beam



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 (= size of formed beams), in frequency range 400-800 MHz.

Mapping speeds (back-of-envelope)

For many purposes, the statistical power of a radio telescope can be quantified by 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	70000 m^2	7	4.9
FAST 500m	200000 m^2	19	38
CHIME	6400 m^2	1024	66

=  CHIME ?!

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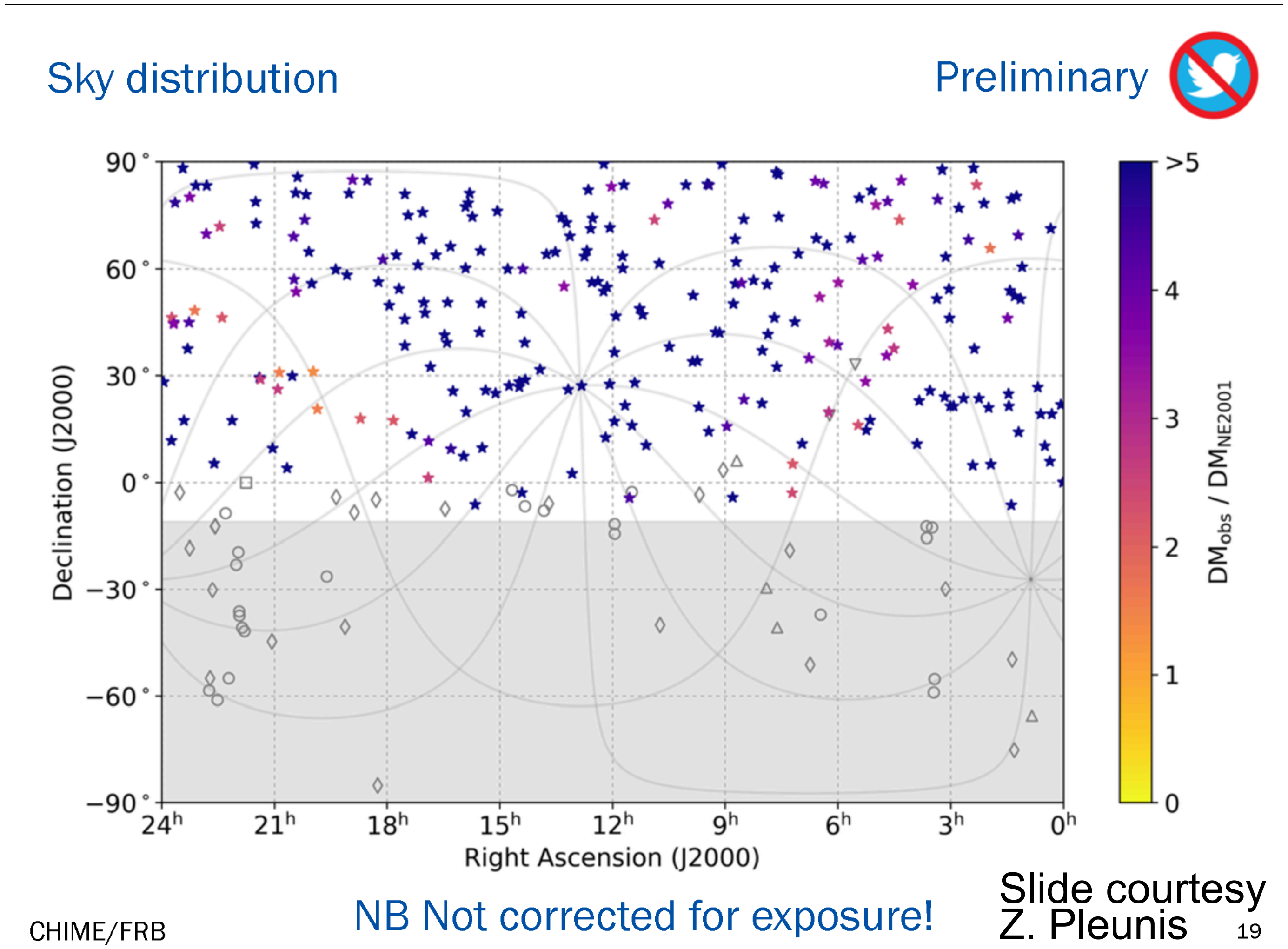
Science goals based on CHIME's high mapping speed

1. Fast radio bursts: CHIME has found ~700 new FRB's! (Total found by all other telescopes combined: 79)



Slide courtesy Z. Pleunis

Science goals based on CHIME's high mapping speed

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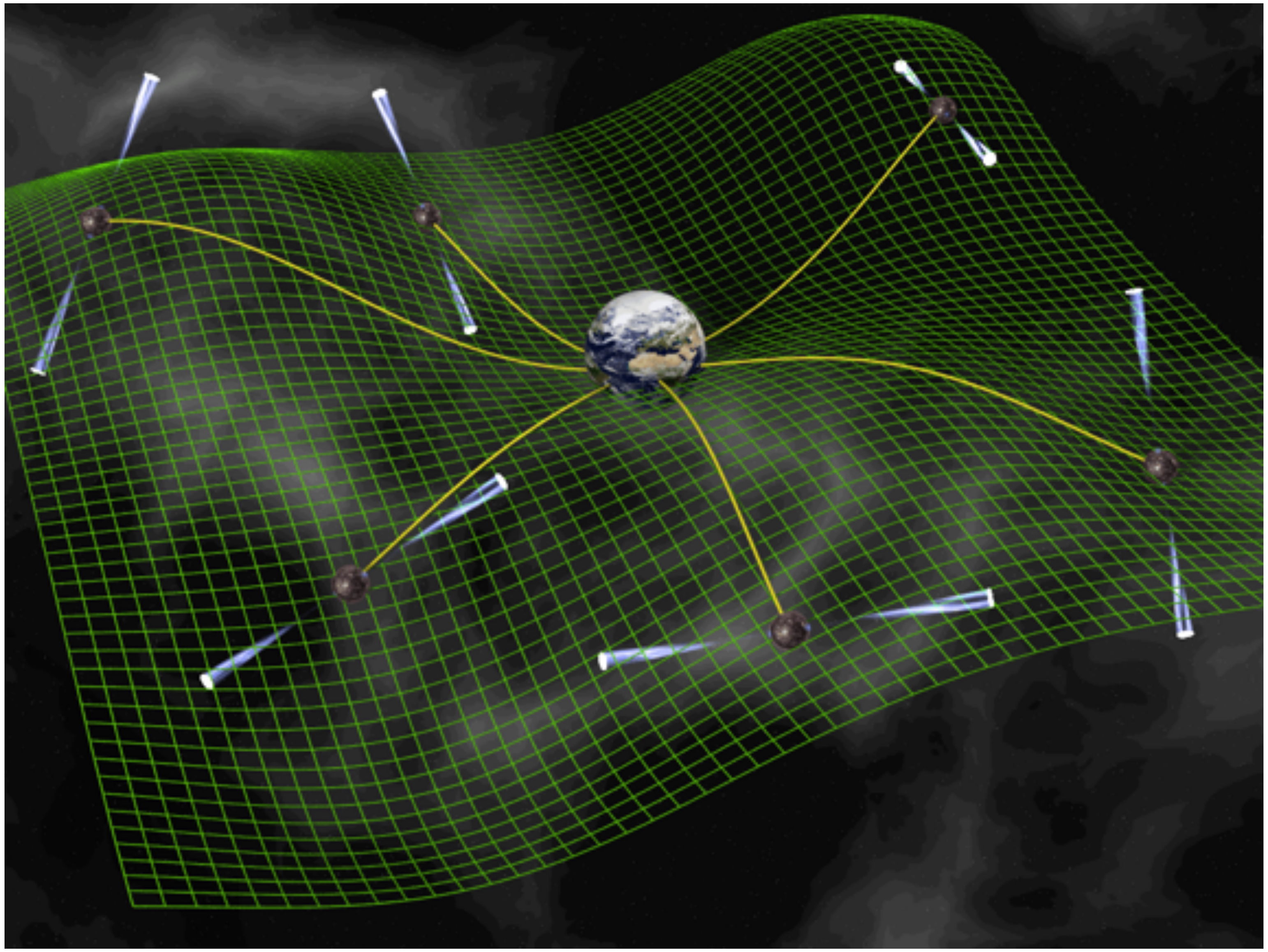
2. Pulsar timing: CHIME is timing almost all known pulsars in the Northern hemisphere.



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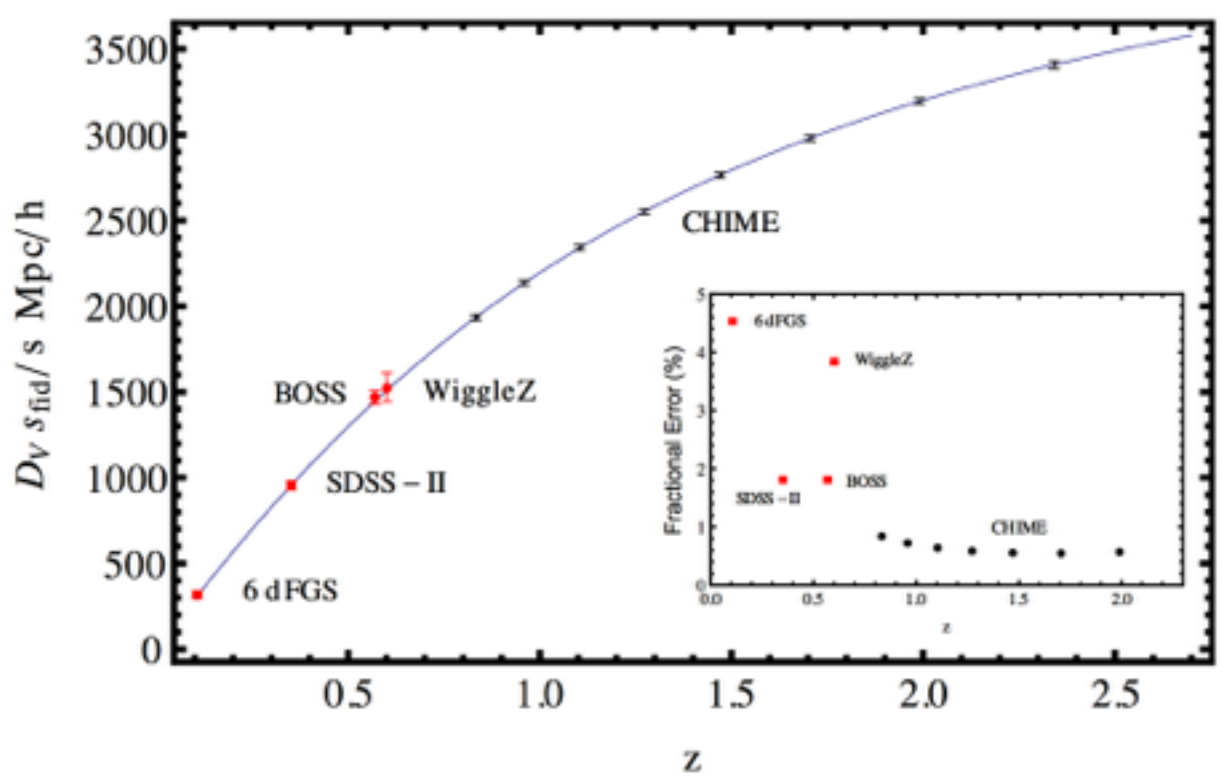
4. Cosmology: CHIME's forecasted BAO measurements are competitive with next-generation LSS surveys.



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CHIME is relatively inexpensive ($15M), and any one of these items would fully justify a larger project.

Too good to be true?

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The challenge

	A	$N_{\rm beams}$	$M/(10^5\ {\rm m}^2)$
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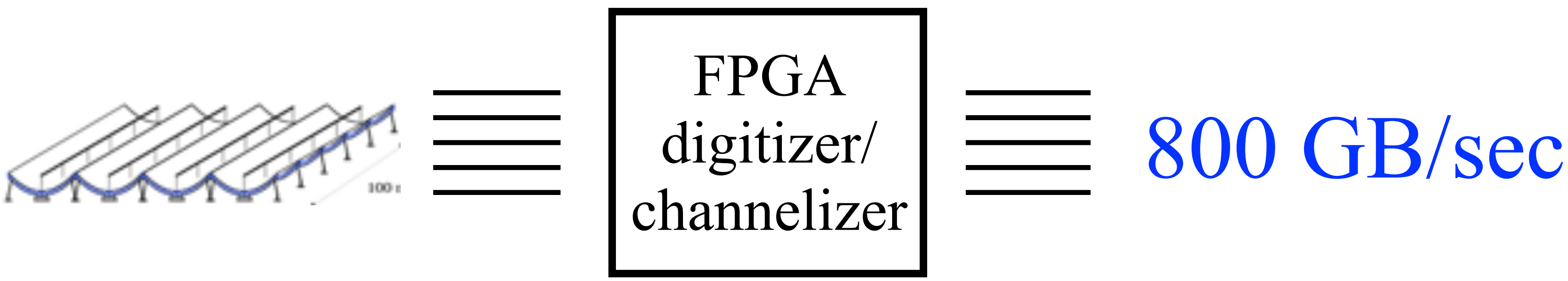
CHIME	6400 m^2	1024	66

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

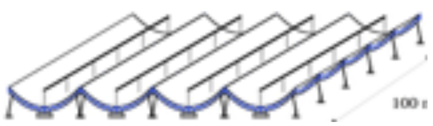
What we have really done is move difficulty from hardware to software.

CHIME computing



- Raw data rate is 800 GB/s = 70 PB/day

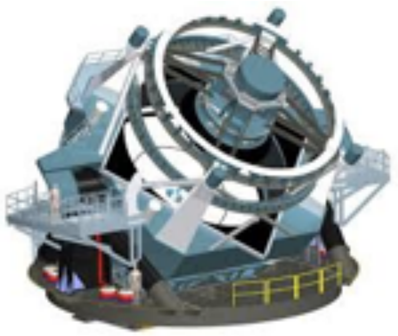
CHIME computing



FPGA
digitizer/
channelizer

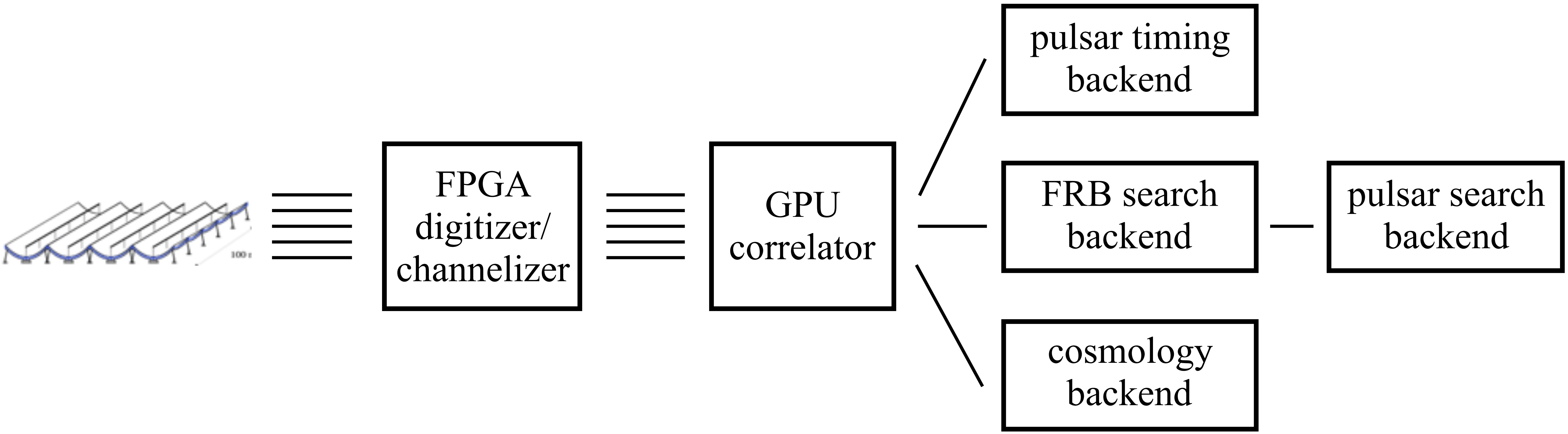
800 GB/sec
(= LSST x 5000)

- Raw data rate is 800 GB/s = 70 PB/day
  = 5000 LSST telescopes!



LSST: 15 TB/day

CHIME computing



- Raw data rate is 800 GB/s = 70 PB/day
- Purpose-built backends receive different data products from the correlator.
- Collectively, CHIME is a large heterogeneous data center / supercomputer.

“bonsai”: CHIME FRB search trigger software

The CHIME FRB search algorithm is:

- orders of magnitude faster than other search software
- near statistically optimal, (for broadband FRB’s!)
- real-time, ~10 second latency
- searches a huge parameter space (e.g. max DM 13000)
- runs on a dedicated 128-node cluster (and searches 1.5 PB/day, a few hundred times larger than any other search)

Kendrick Smith

Dustin Lang

Masoud Rafiei-Ravandi

Utkarsh Giri

Maya Burhanpurkar

Alex Roman

```c
void transpose(float *dst, const float *src, int n)
{
    for (int i = 0; i < n; i++)
        for (int j = 0; j < n; j++)
            dst[i*n+j] = src[j*n+i];
}
```

4 times faster!

```
void transpose_256b(float *dst, const float *src, int n)
{
    for (int i = 0; i < n; i += 8) {
        for (int j = 0; j < n; j += 8) {
            __m256 x0 = _mm256_load_ps(src + j*n + i);
            __m256 x1 = _mm256_load_ps(src + (j+1)*n + i);
            __m256 x2 = _mm256_load_ps(src + (j+2)*n + i);
            __m256 x3 = _mm256_load_ps(src + (j+3)*n + i);
            __m256 x4 = _mm256_load_ps(src + (j+4)*n + i);
            __m256 x5 = _mm256_load_ps(src + (j+5)*n + i);
            __m256 x6 = _mm256_load_ps(src + (j+6)*n + i);
            __m256 x7 = _mm256_load_ps(src + (j+7)*n + i);

            __m256 z0 = _mm256_permute2f128_ps(x0, x4, 0x21);
            x0 = _mm256_blend_ps(x0, z0, 0xf0);
            x4 = _mm256_blend_ps(x4, z0, 0x0f);

            __m256 z1 = _mm256_permute2f128_ps(x1, x5, 0x21);
            x1 = _mm256_blend_ps(x1, z1, 0xf0);
            x5 = _mm256_blend_ps(x5, z1, 0x0f);

            __m256 z2 = _mm256_permute2f128_ps(x2, x6, 0x21);
            x2 = _mm256_blend_ps(x2, z2, 0xf0);
            x6 = _mm256_blend_ps(x6, z2, 0x0f);

            __m256 z3 = _mm256_permute2f128_ps(x3, x7, 0x21);
            x3 = _mm256_blend_ps(x3, z3, 0xf0);
            x7 = _mm256_blend_ps(x7, z3, 0x0f);

            __m256 a0 = _mm256_shuffle_ps(x0, x2, 0x44);
            __m256 a1 = _mm256_shuffle_ps(x1, x3, 0x11);

            x0 = _mm256_blend_ps(a0, a1, 0xaa);
            x1 = _mm256_blend_ps(a0, a1, 0x55);
            x1 = _mm256_permute_ps(x1, 0xb1);

            __m256 a2 = _mm256_shuffle_ps(x0, x2, 0xee);
            __m256 a3 = _mm256_shuffle_ps(x1, x3, 0xbb);

            x2 = _mm256_blend_ps(a2, a3, 0xaa);
            x3 = _mm256_blend_ps(a2, a3, 0x55);
            x3 = _mm256_permute_ps(x3, 0xb1);

            __m256 a4 = _mm256_shuffle_ps(x4, x6, 0x44);
            __m256 a5 = _mm256_shuffle_ps(x5, x7, 0x11);

            x4 = _mm256_blend_ps(a4, a5, 0xaa);
            x5 = _mm256_blend_ps(a4, a5, 0x55);
            x5 = _mm256_permute_ps(x5, 0xb1);

            __m256 a6 = _mm256_shuffle_ps(x4, x6, 0xee);
            __m256 a7 = _mm256_shuffle_ps(x5, x7, 0xbb);

            x6 = _mm256_blend_ps(a6, a7, 0xaa);
            x7 = _mm256_blend_ps(a6, a7, 0x55);
            x7 = _mm256_permute_ps(x7, 0xb1);

            _mm256_store_ps(dst + i*n + j, x0);
            _mm256_store_ps(dst + (i+1)*n + j, x1);
            _mm256_store_ps(dst + (i+2)*n + j, x2);
            _mm256_store_ps(dst + (i+3)*n + j, x3);
            _mm256_store_ps(dst + (i+4)*n + j, x4);
            _mm256_store_ps(dst + (i+5)*n + j, x5);
            _mm256_store_ps(dst + (i+6)*n + j, x6);
            _mm256_store_ps(dst + (i+7)*n + j, x7);
        }
    }
}
```

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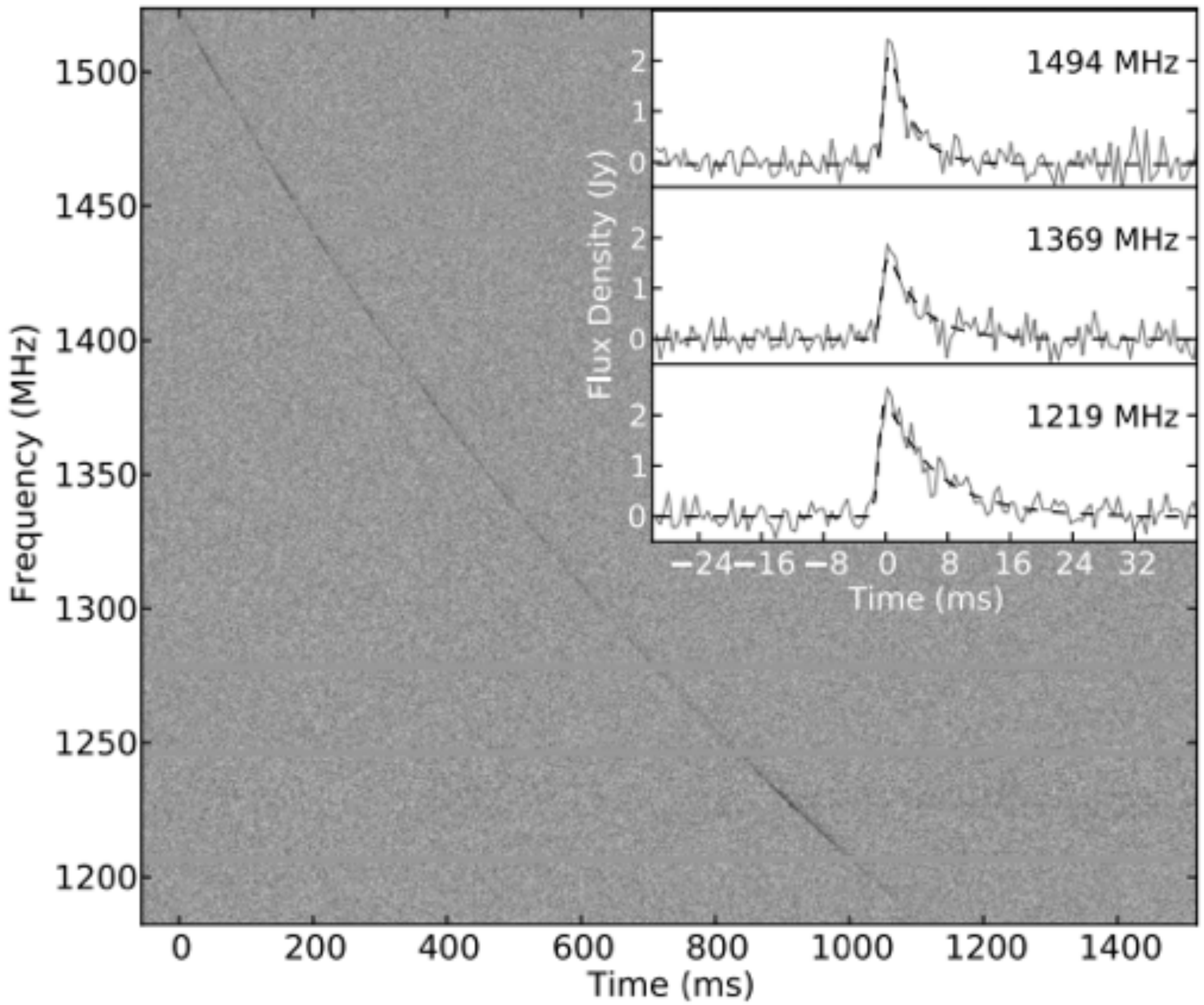
Fast radio bursts (FRB's): an astrophysical mystery

Very occasionally, a bright, short (1 ms) pulse of radio emission is observed with very large dispersion (=frequency-dependent delay).



Fast radio bursts (FRB's): an astrophysical mystery

Very occasionally, a bright, short (1 ms) pulse of radio emission is observed with very large dispersion (=frequency-dependent delay).

The dispersion delay (or "dispersion measure" DM) is proportional to integrated electron density along the line of sight.

$$\mathrm{DM} = \int dr \, \rho_e(r)$$

By definition, FRB's are pulses whose observed DM is greater than the electron density integrated all the way to the edge of the Milky Way, suggesting FRB's are at cosmological distances.

However, when FRB's were first discovered, an alternate hypothesis was that FRB's are in our Galaxy, in local environments with large electron density.

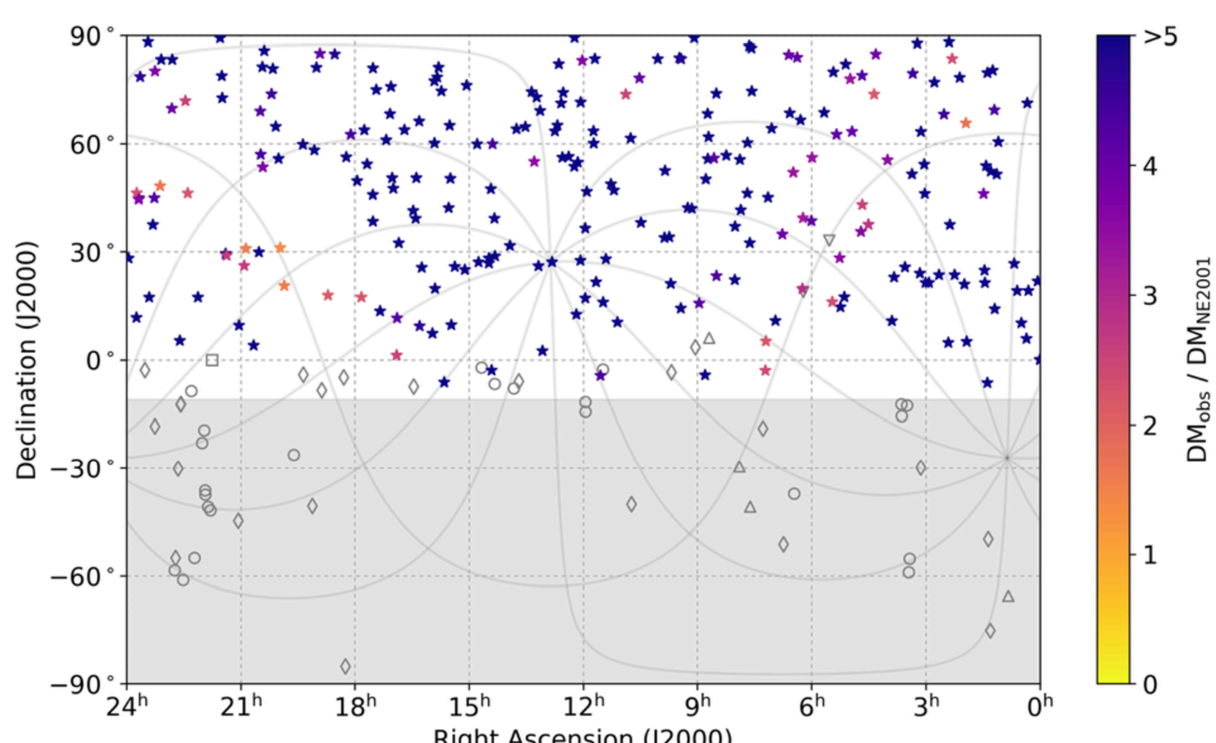
Fast radio bursts (FRB's): an astrophysical mystery

Over time, the cosmological hypothesis proved to be correct:

- Observed sky distribution is isotropic.
- Recently, host galaxies have been determined for a few FRB's, and host galaxy redshifts have all been cosmological.

Sky distribution

Preliminary



CHIME/FRB

NB Not corrected for exposure!

Slide courtesy
Z. Pleunis

Fast radio bursts (FRB's): an astrophysical mystery

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- Observed sky distribution is isotropic.
- Recently, host galaxies have been determined for a few FRB's, and host galaxy redshifts have all been cosmological.

Implication: FRB's are ultra-energetic ($\sim 10^6$ times brighter than the brightest pulses from Galactic pulsars) and frequently occurring ($\sim 10^3$ per day on the whole sky).

Understanding the origin of these pulses has become a central unsolved problem in astrophysics.

Fast radio bursts (FRB's): an astrophysical mystery

Repeaters: prior to CHIME, one FRB (out of ~30 known) had been observed to repeat.

The repeating FRB was a gold mine of information. In particular, it was eventually observed with VLBI (Very Long Baseline Interferometry) telescopes, with sufficient angular resolution to uniquely identify a host galaxy at redshift $z=0.2$.

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

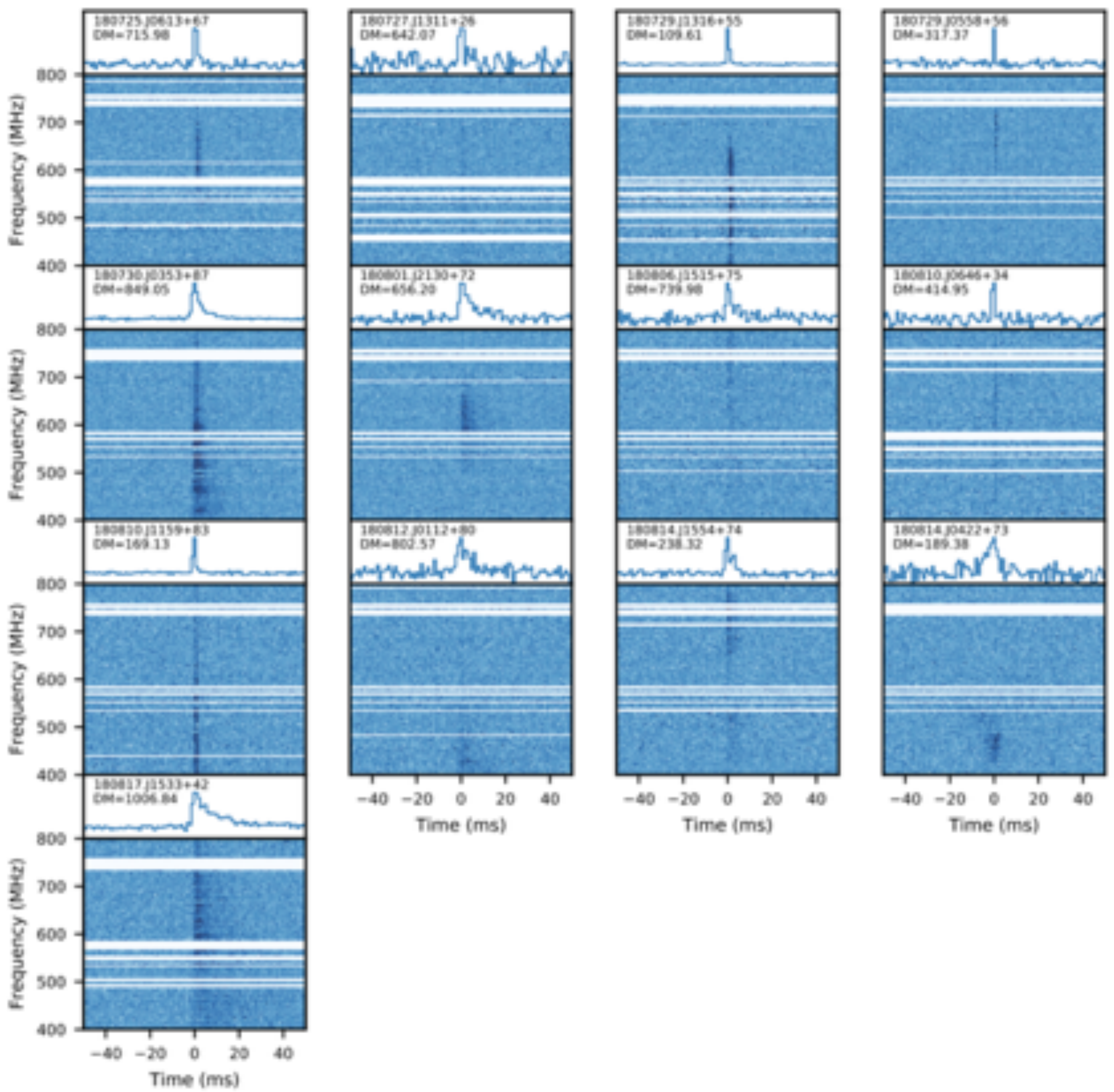
arxiv:1810.05836

CHIME FRB timeline and publications

- August 2018: First FRB detected
  http://www.astronomerstelegram.org/?read=11901
- January 2019 (“Paper 1”): 13 new FRB’s discovered, in first month of commissioning data
  Nature 566 (2019) 230, arXiv:1901.04524
- January 2019 (“Paper 2”): new repeater (“R2”) discovered
  Nature 566 (2019) 235, arXiv:1901.04525
- June 2019 (“Paper 3”): original repeater (“R1”) detected
  ApJL 882 (2019) 18, arXiv:1906.11305
- September 2019 (“Paper 4”): 8 new repeaters discovered, in commissioning data up to March 2019
  ApJL 885 (2019) 24, arXiv:1908.03507
- January 2020 (“Paper 5”): repeating FRB localized to host galaxy
  Nature 577 (2020) 190, arXiv:2001.02222
- January 2020 (“Paper 6”): 9 more repeaters
  ApJL accepted, arXiv:2001.03595.
- January 2020 (“Paper 7”): periodic activity in a repeating FRB (!)
  Nature submitted, arXiv:2001.10275

+ many more in progress!

Paper 1: 13 new FRB's from CHIME



FRB	Width (ms)	DM (pc cm^{-3})	DM_{MW} (pc cm^{-3})	R.A. (hh:mm)	Dec. (dd:mm)	Dec. FWHM (deg)	SNR	τ (ms)
180725.J0613+67	$0.31^{+0.08}_{-0.07}$	$715.98^{+0.02}_{-0.01}$	71, 80	06:13	+67:04	0.34	34.5	$1.18^{+0.13}_{-0.12}$
180727.J1311+26	0.78 ± 0.16	642.07 ± 0.03	21, 20	13:11	+26:26	0.35	14.2	0.6 ± 0.2
180729.J1316+55	0.12 ± 0.01	109.610 ± 0.002	31, 23	13:16	+55:32	…	243.1	< 0.15
180729.J0558+56	< 0.08	317.37 ± 0.01	95, 120	05:58	+56:30	0.32	25.2	< 0.26
180730.J0353+87	0.42 ± 0.04	849.047 ± 0.002	57, 58	03:53	+87:12	0.44	92.4	1.99 ± 0.05
180801.J2130+72	0.51 ± 0.09	656.20 ± 0.03	90, 108	21:30	+72.43	0.35	41.1	5.0 ± 0.3
180806.J1515+75	< 0.69	739.98 ± 0.03	41, 34	15:15	+75.38	0.56	17.5	3.6 ± 0.8
180810.J0646+34	< 0.27	414.95 ± 0.02	104, 140	06:46	+34.52	0.33	17.7	< 0.40
180810.J1159+83	0.28 ± 0.03	169.134 ± 0.002	47, 41	11:59	+83.07	0.38	56.7	< 0.18
180812.J0112+80	$1.25^{+0.09}_{-0.47}$	802.57 ± 0.04	83, 100	01:12	+80:47	0.38	19.8	$1.9^{+0.3}_{-0.4}$
180814.J1554+74	< 0.18	238.32 ± 0.01	41, 35	15:54	+74:01	0.58	29.7	2.4 ± 0.3
180814.J0422+73	2.6 ± 0.2	189.38 ± 0.09	87, 100	04:22	+73:44	0.35	24.0	< 0.40
180817.J1533+42	< 0.37	1006.840 ± 0.002	28, 25	15:33	+42:12	0.32	69.9	8.7 ± 0.2

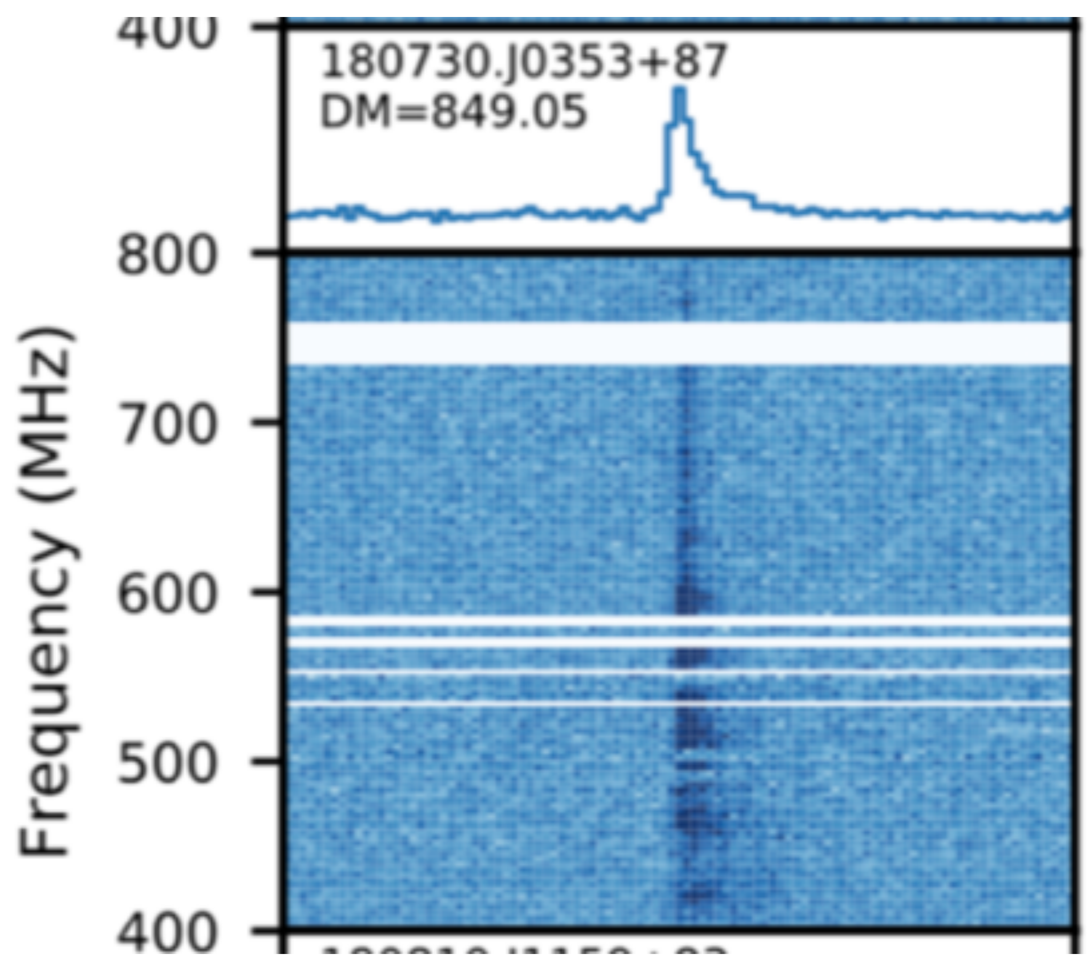
- At lower frequencies than previous FRB observations (400-800 MHz)
- Previously, almost all FRB's were detected at 1.4 GHz, with the exception of a few at ~800 MHz.
- All searches at <~ 200 MHz have been unsuccessful, suggesting a spectral cutoff.
- However, ~half of the CHIME FRB's are bright at 400 MHz.

Nature 566 (2019) 230, arXiv:1901.04524

“Scattering”

If the plasma along the line of sight is turbulent, then multipath propagation (“scattering”) will broaden the pulse in a frequency-dependent way:

$$\text{Width} \propto \nu^{-4}$$



Nature 566 (2019) 230, arXiv:1901.04524

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$$\text{Width} \propto \nu^{-4}$$

Because CHIME is at low frequencies, it gives the best constraints on FRB scattering. Around half of our 13 FRB's are significantly scattered.

FRB	Width (ms)	DM (pc cm^{-3})	DM$_{MW}$ (pc cm^{-3})	R.A. (hh:mm)	Dec. (dd:mm)	Dec. FWHM (deg)	SNR	τ (ms)
180725.J0613+67	$0.31^{+0.08}_{-0.07}$	$715.98^{+0.02}_{-0.01}$	71, 80	06:13	+67:04	0.34	34.5	$1.18^{+0.13}_{-0.12}$
180727.J1311+26	0.78 ± 0.16	642.07 ± 0.03	21, 20	13:11	+26:26	0.35	14.2	0.6 ± 0.2
180729.J1316+55	0.12 ± 0.01	109.610 ± 0.002	31, 23	13:16	+55:32	…	243.1	< 0.15
180729.J0558+56	< 0.08	317.37 ± 0.01	95, 120	05:58	+56:30	0.32	25.2	< 0.26
180730.J0353+87	0.42 ± 0.04	849.047 ± 0.002	57, 58	03:53	+87:12	0.44	92.4	1.99 ± 0.05
180801.J2130+72	0.51 ± 0.09	656.20 ± 0.03	90, 108	21:30	+72.43	0.35	41.1	5.0 ± 0.3
180806.J1515+75	< 0.69	739.98 ± 0.03	41, 34	15:15	+75.38	0.56	17.5	3.6 ± 0.8
180810.J0646+34	< 0.27	414.95 ± 0.02	104, 140	06:46	+34.52	0.33	17.7	< 0.40
180810.J1159+83	0.28 ± 0.03	169.134 ± 0.002	47, 41	11:59	+83.07	0.38	56.7	< 0.18
180812.J0112+80	$1.25^{+0.49}_{-0.47}$	802.57 ± 0.04	83, 100	01:12	+80:47	0.38	19.8	$1.9^{+0.3}_{-0.4}$
180814.J1554+74	< 0.18	238.32 ± 0.01	41, 35	15:54	+74:01	0.58	29.7	2.4 ± 0.3
180814.J0422+73	2.6 ± 0.2	189.38 ± 0.09	87, 100	04:22	+73:44	0.35	24.0	< 0.40
180817.J1533+42	< 0.37	1006.840 ± 0.002	28, 25	15:33	+42:12	0.32	69.9	8.7 ± 0.2

Nature 566 (2019) 230, arXiv:1901.04524

“Scattering”

If the plasma along the line of sight is turbulent, then multipath propagation (“scattering”) will broaden the pulse in a frequency-dependent way:

$$\text{Width} \propto \nu^{-4}$$

Because CHIME is at low frequencies, it gives the best constraints on FRB scattering. Around half of our 13 FRB’s are significantly scattered.

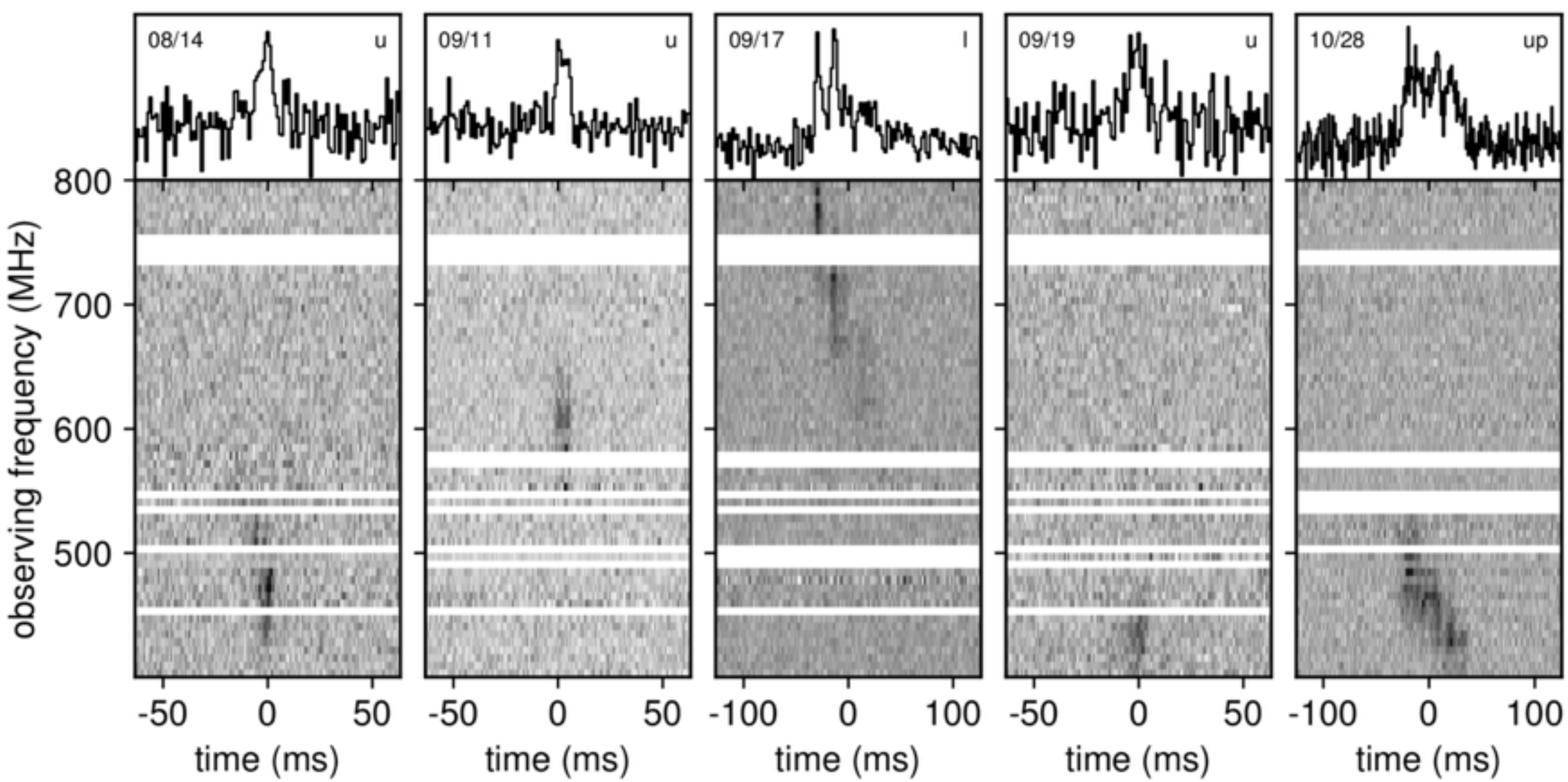
Scattering may arise either from our galaxy, the host galaxy, or the local environment of the FRB (like dispersion!). The level of scattering seen in CHIME is higher than simple models of the host galaxy (+ our galaxy) predict.

Suggests that some scattering/turbulence is local to the FRB.

Nature 566 (2019) 230, arXiv:1901.04524

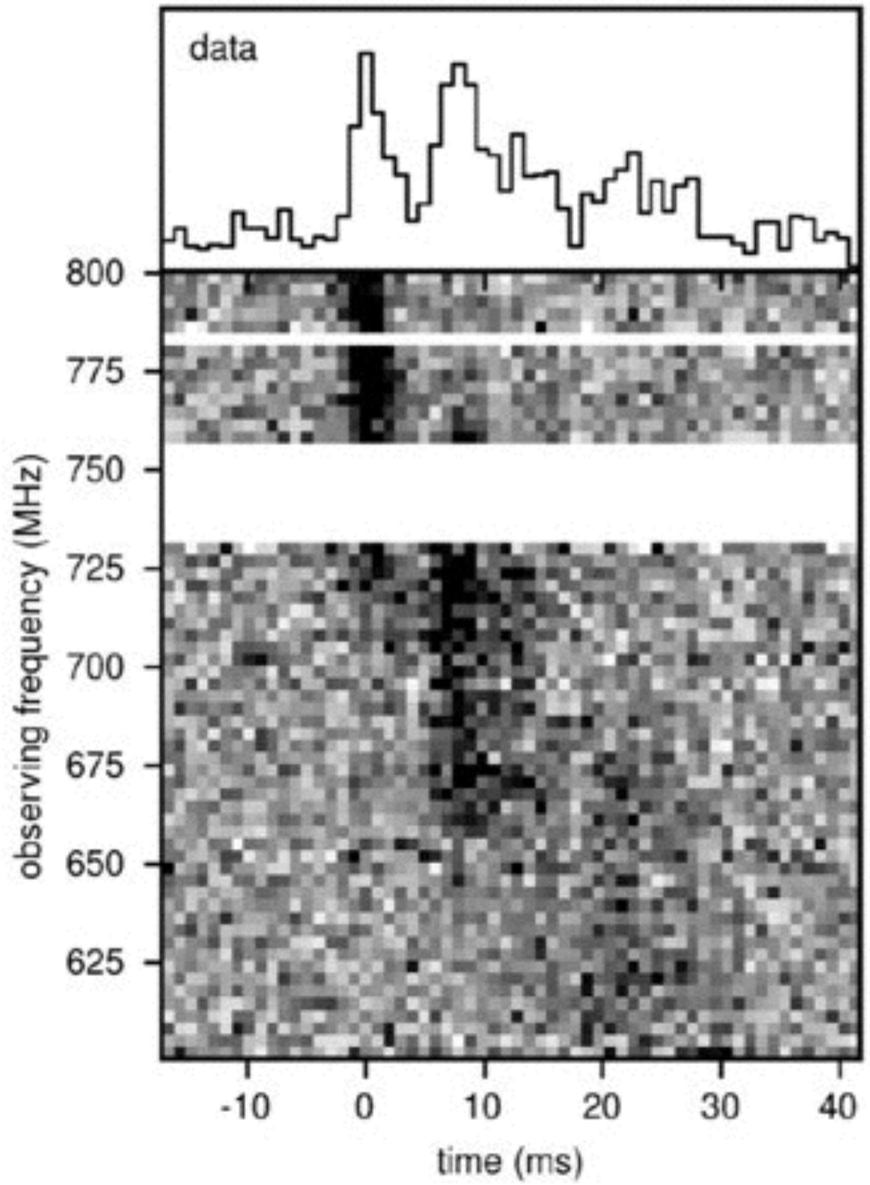
Paper 2: New repeating FRB!

Dispersion measure: DM=189 (max galactic DM ~95 along its line of sight)

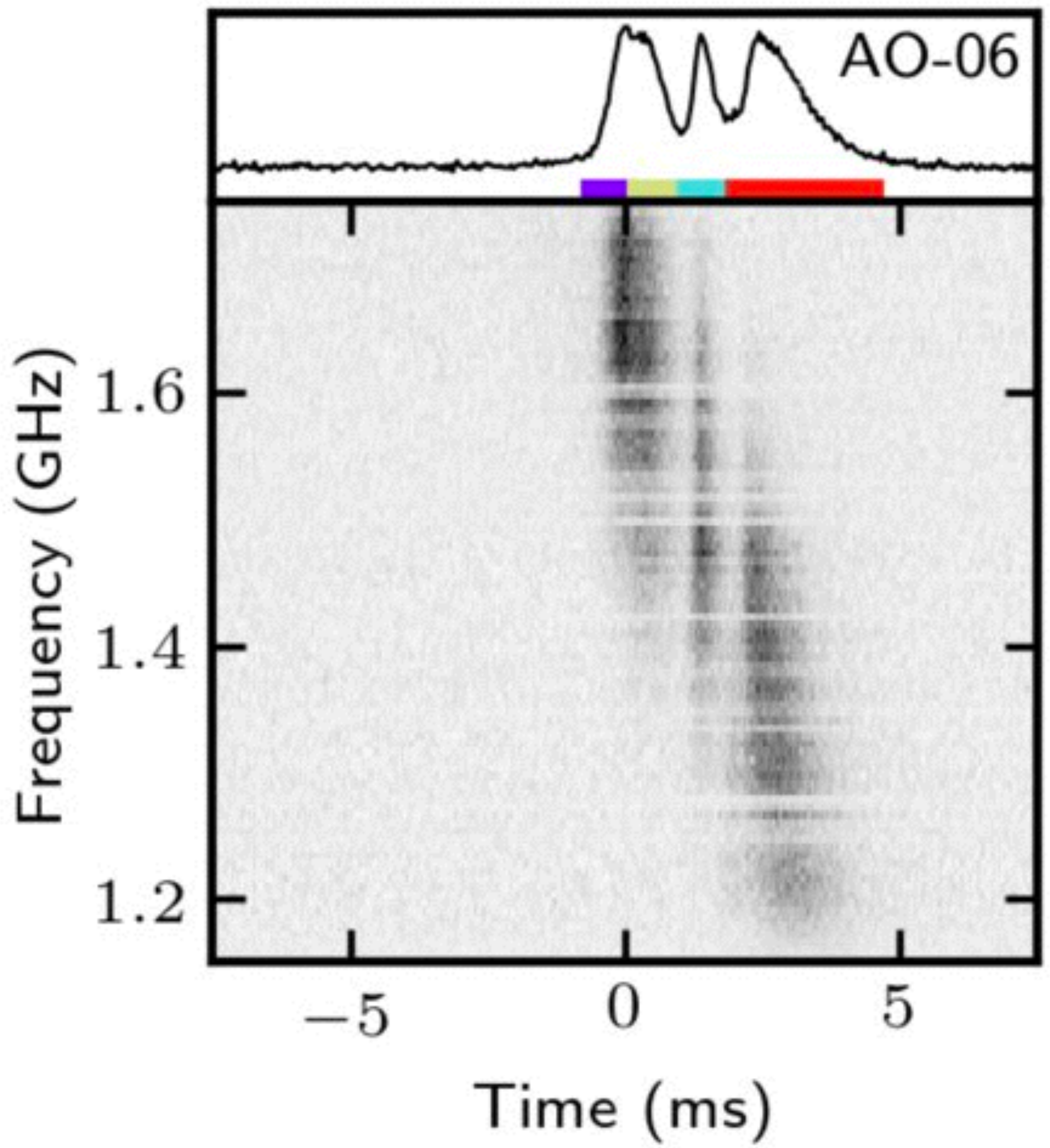


Nature 566 (2019) 235, arXiv:1901.04525

“Downward marching” pulse structure



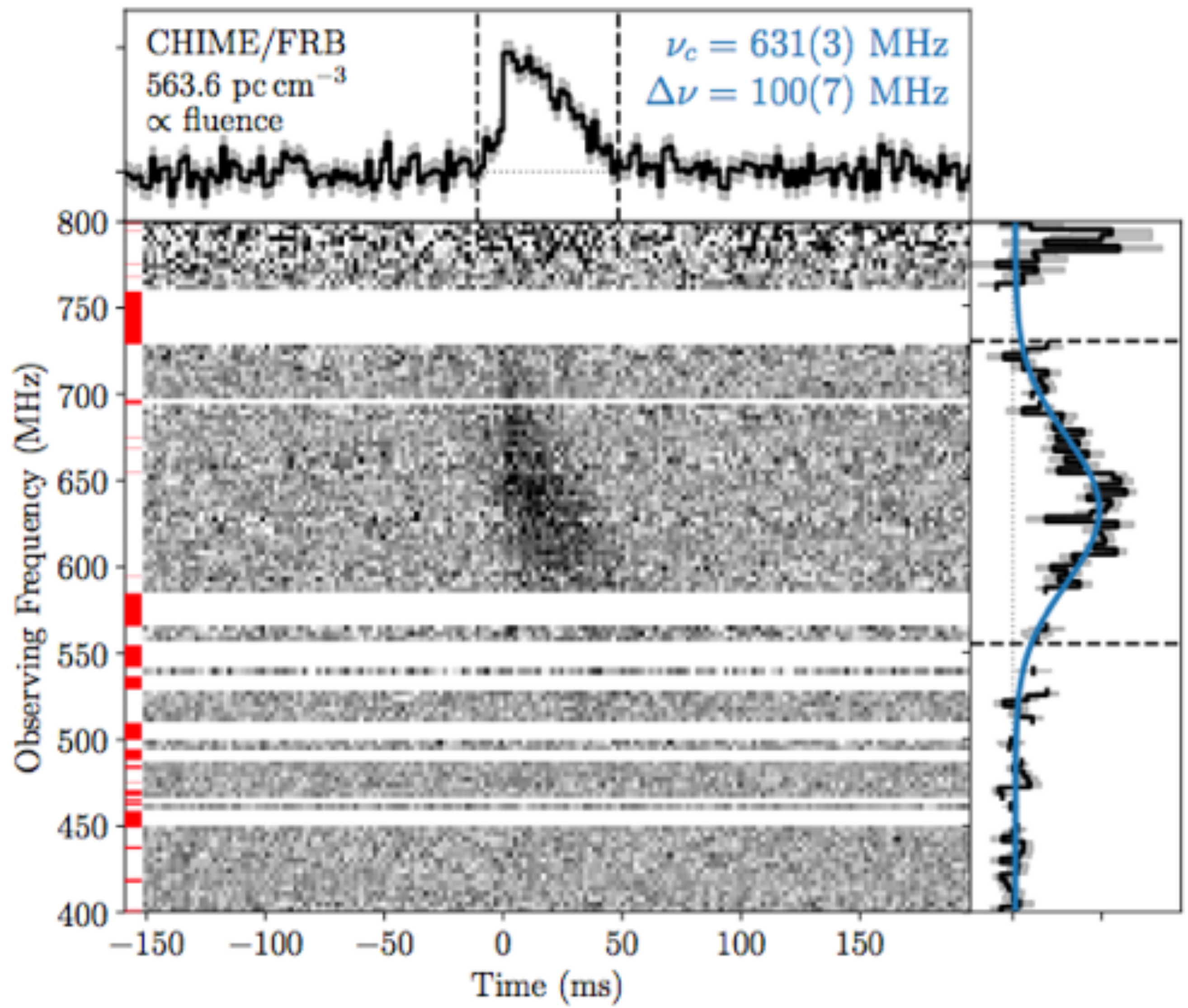
CHIME repeater (R2)



Original repeater (R1)

Nature 566 (2019) 235, arXiv:1901.04525

Paper 3: Original repeater (R1) detected



- Lowest frequency observation to date
- Dispersion measure is ~1% higher than previously reported values

ApJL 882 (2019) 18, arXiv:1906.11305

Paper 4: Eight new repeaters discovered

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

ApJL 885 (2019) 24, arXiv:1908.03507

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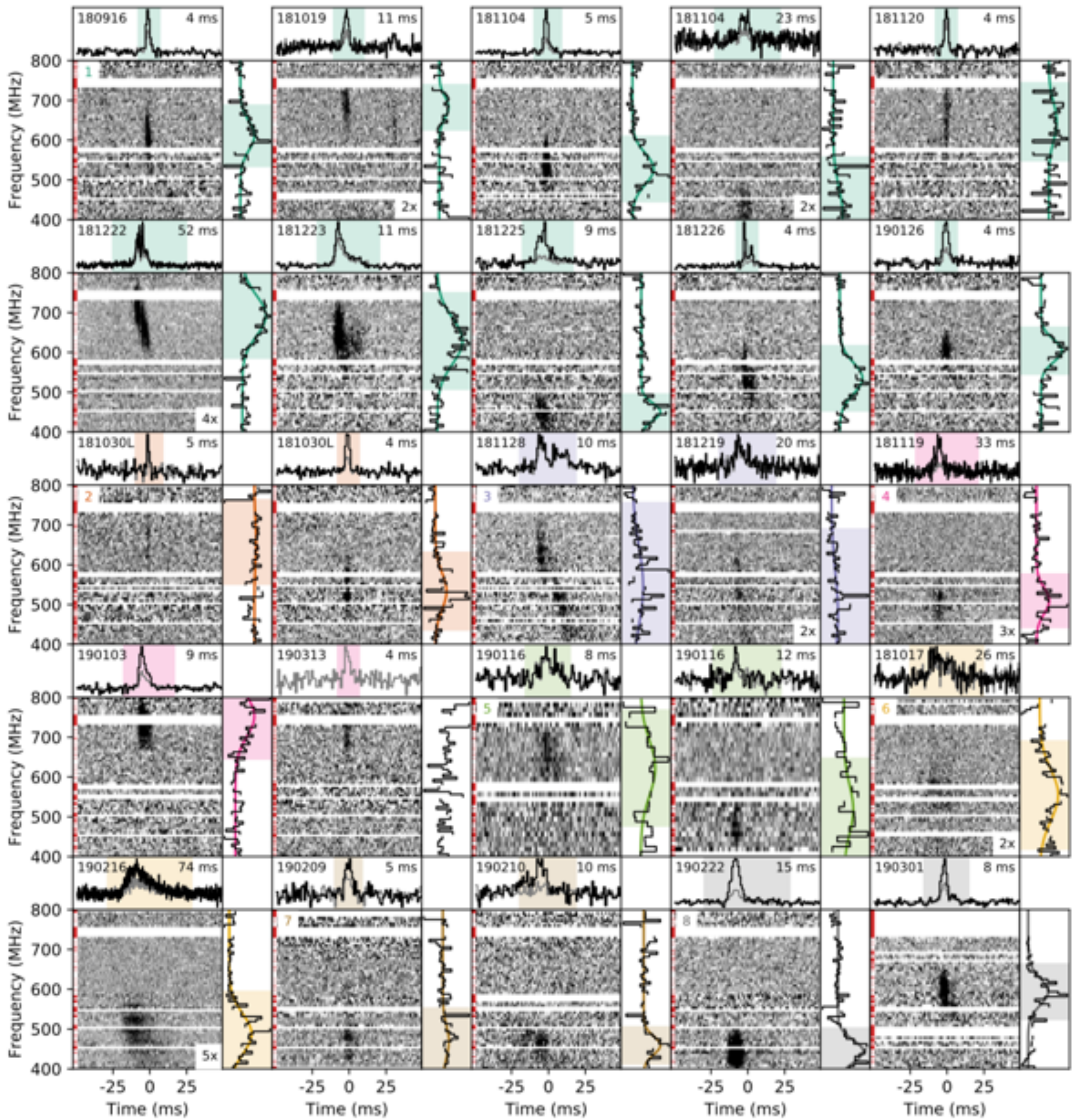
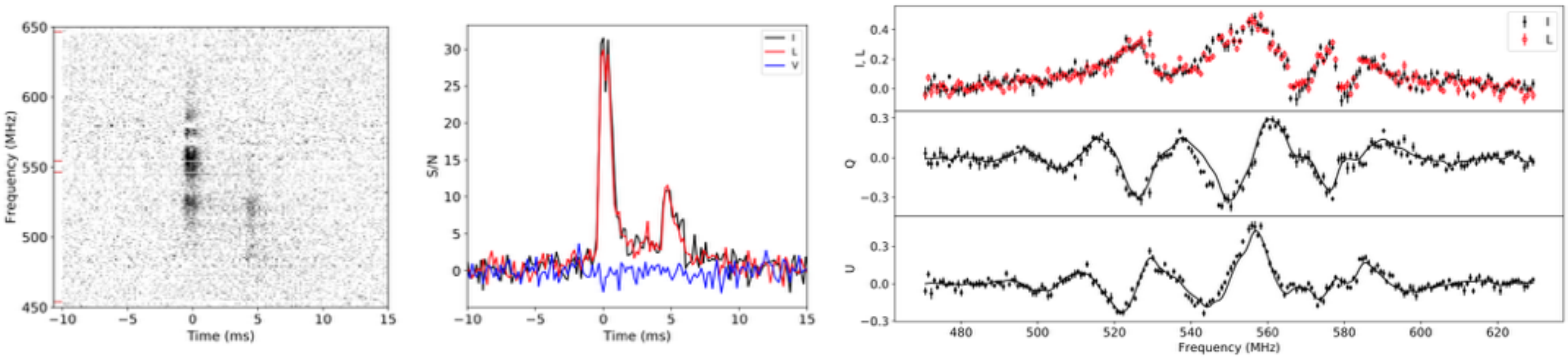


ApJL 885 (2019) 24, arXiv:1908.03507

Baseband (=electric field) data for one event



- Downward-marching structure observed
- Nearly 100% linearly polarized
- Faraday rotation measure is modest (RM = -115 rad m^{-2}) and consistent with contribution from our Galaxy. In contrast to the original repeater, which had a huge RM (~10^5), implying a highly magnetized environment.

ApJL 885 (2019) 24, arXiv:1908.03507

Repeaters have wider pulses

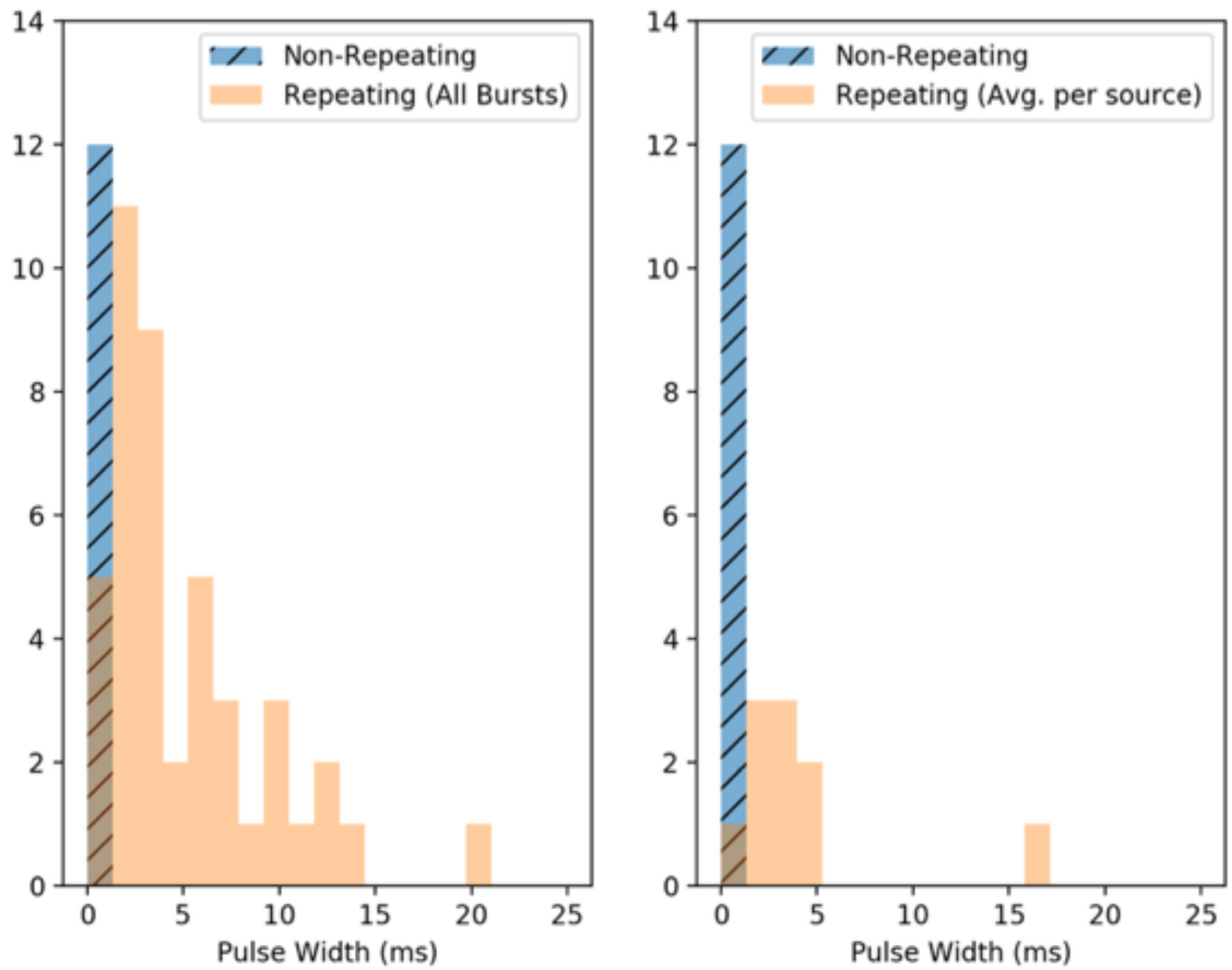
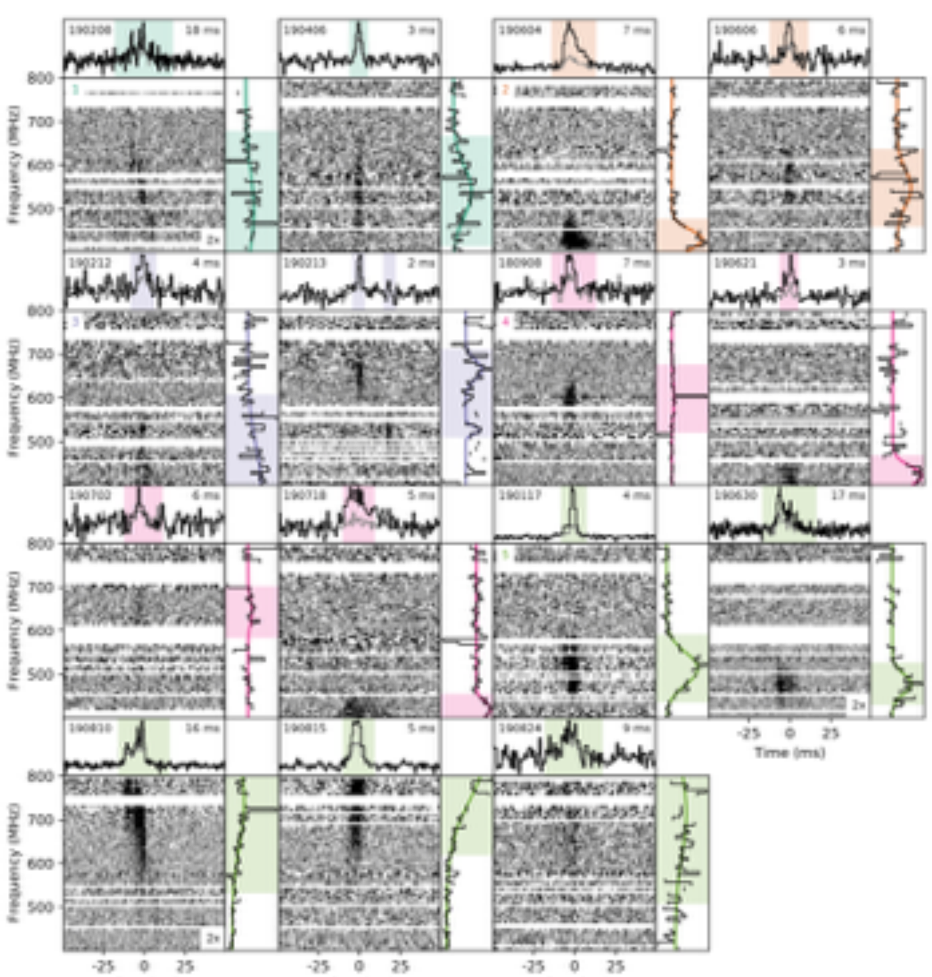


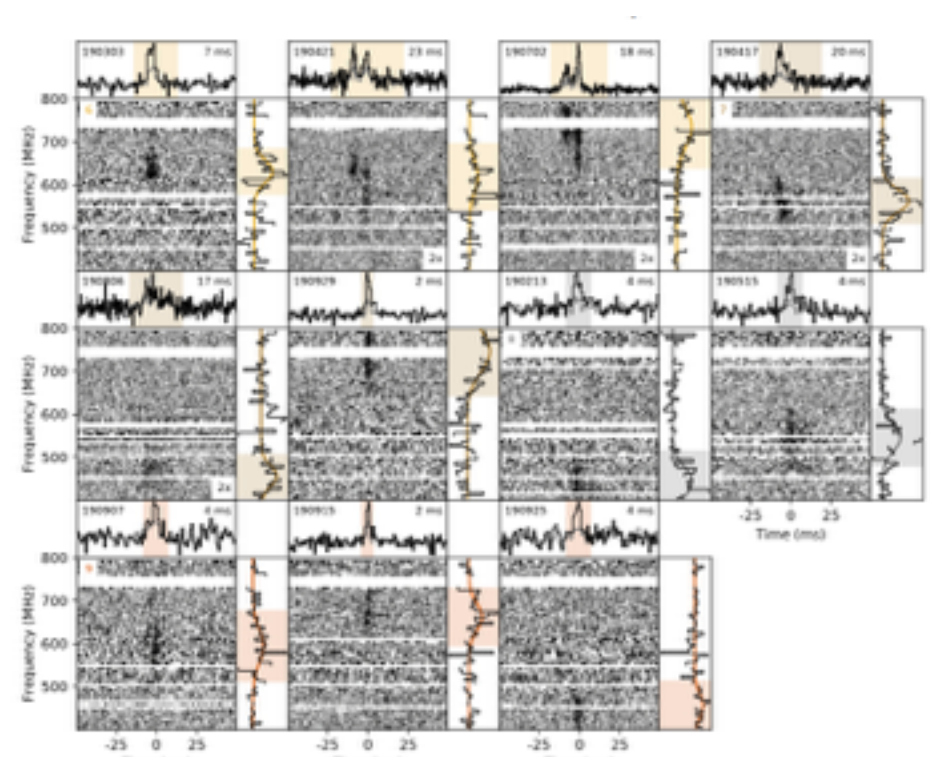
Figure 7. Distribution of intrinsic temporal widths for repeating and non-repeating FRB sources observed in the frequency range of 400–800 MHz. For repeating FRBs, the left panel shows the distribution of widths of the Gaussian spectral components for all bursts from each source while the right panel shows only the weighted average of the widths for each source.

ApJL 885 (2019) 24, arXiv:1908.03507

Paper 6: Nine more repeaters

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	190208.J1855+46	*18h55m±14′*	*+46°58′±15′*	76.8	18.9	580.05(15)	72	66	2	20±14	3.4
2	190604.J1435+53	14h35m±10′	+53°17′±11′	93.8	57.6	552.65(5)	32	24	2	30±11	2.8
3	190212.J18+81	18h24m±15′	+81°26′±10′	113.3	27.8	302(1)	49	44	3[h]	55±52 / 159±11	8.2 / 13
		17h39m±16′	+81°24′±7′	113.5	29.5						
4	180908.J1232+74	12h32m±17′	+74°12′±19′	124.7	42.9	195.6(2)	38	31	4	53±33 / 36±25	5.9 / 18
5	190117.J2207+17	22h07m±8′	+17°23′±15′	76.4	−30.3	393.6(8)	48	40	5	19±8	6.5
6	190303.J1353+48	13h53m±14′	+48°15′±15′	97.5	65.7	222.4(7)	29	22	3	23±12	2.6
7	190417.J1939+59	*19h39m±13′*	*+59°24′±16′*	91.5	17.4	1378.2(2)	78	80	3	29±19	4.3
8	190213.J02+20	02h14m±16′	+20°04′±20′	148.1	−38.7	651.45(5)	43	34	2	17±9	4.4
		02h07m±16′	+20°05′±20′	146.1	−39.4						
9	190907.J08+46	08h09m±11′	+46°16′±14′	173.4	32.3	309.6(2)	53	51	3	23±14	2.5
		08h02m±12′	+46°15′±14′	173.2	31.1						





ApJL accepted, arXiv:2001.03595.

Paper 5: Repeating FRB localized to host galaxy

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)
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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 repeater ("R3") is the most active repeater in CHIME.
It turned out to be a very interesting object!

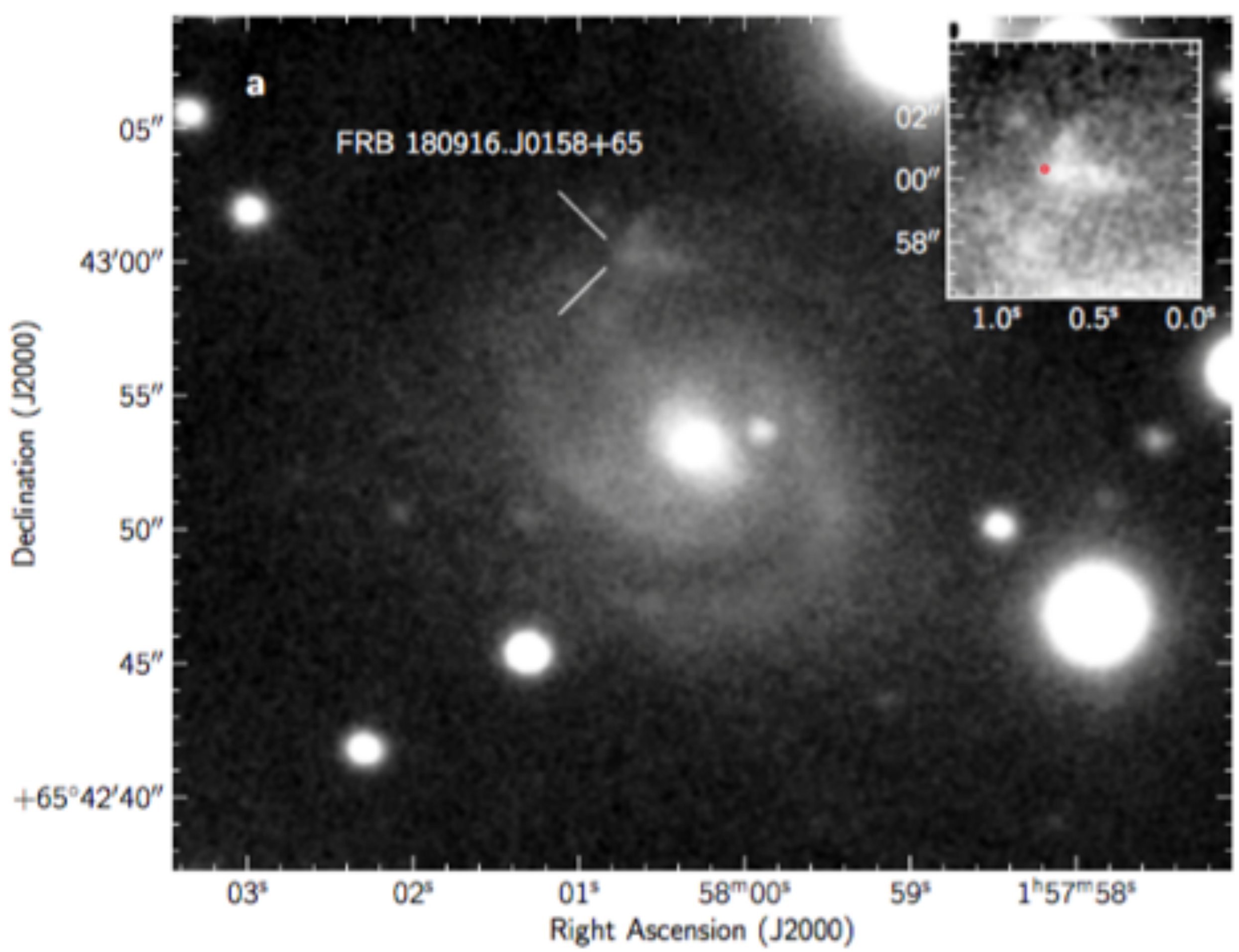
The low excess DM suggests R3 is at low redshift.

However, the CHIME angular resolution is not quite good enough to uniquely identify a host galaxy (even if search is restricted to low-z galaxies).

Nature 577 (2020) 190, arXiv:2001.02222

Paper 5: Repeating FRB localized to host galaxy

We partnered with the EVN (European VLBI Network) to observe R3, and successfully observed 4 pulses in June! EVN resolution allows host galaxy to be determined ($p < 0.01$).

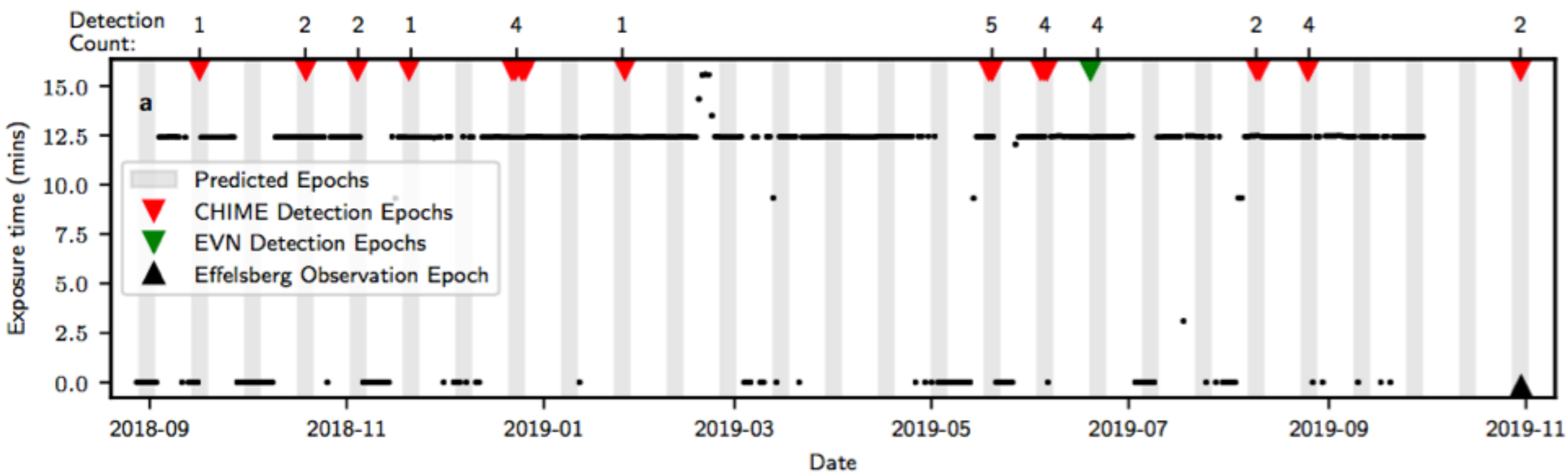


- Spiral galaxy (similar to Milky Way)
- FRB is in star-forming region
- Redshift z=0.0337 (Gemini spectroscopic follow-up).
- Closest FRB so far!

Nature 577 (2020) 190, arXiv:2001.02222

Paper 7: Periodic activity in a repeating FRB

An unexpected surprise: R3 is only active within 4-day windows, regularly spaced with period 16.35 days.



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

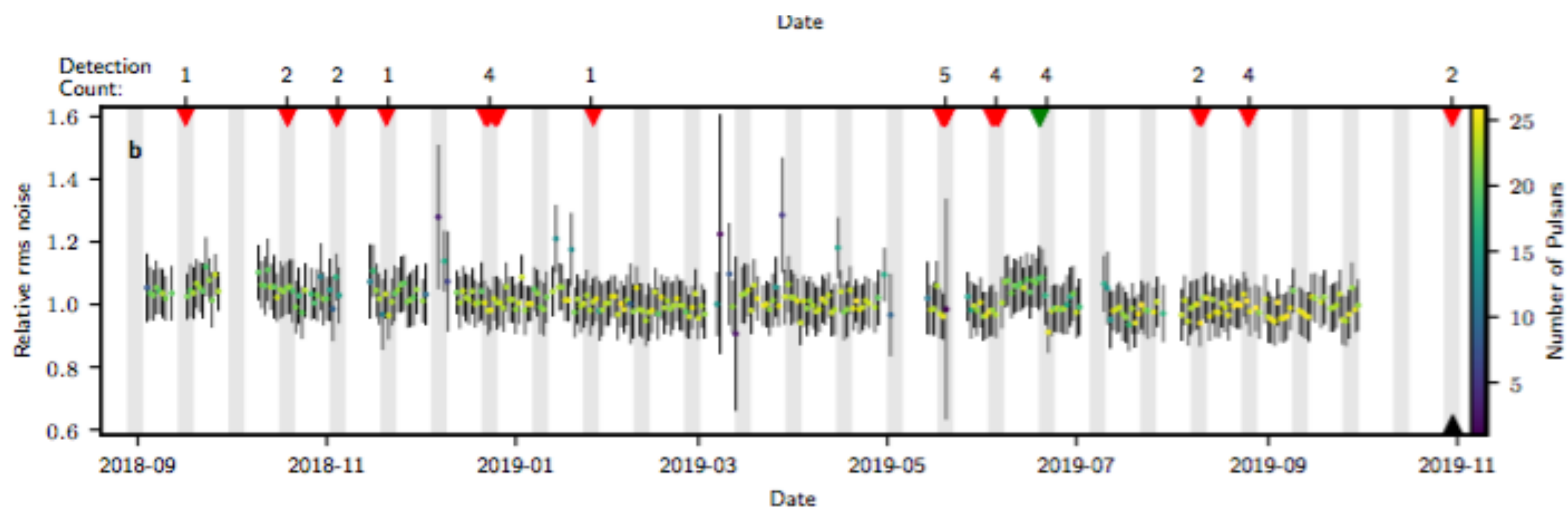
Trial factor (# of periods x phases)

Nature submitted, arXiv:2001.10275

Paper 7: Periodic activity in a repeating FRB

Systematic checks:

- No periodicity observed in exposure, noise level, or number of pulsars detected.



- No spurious periodicity observed in “control” samples constructed by randomly selecting pulses from Galactic pulsars.

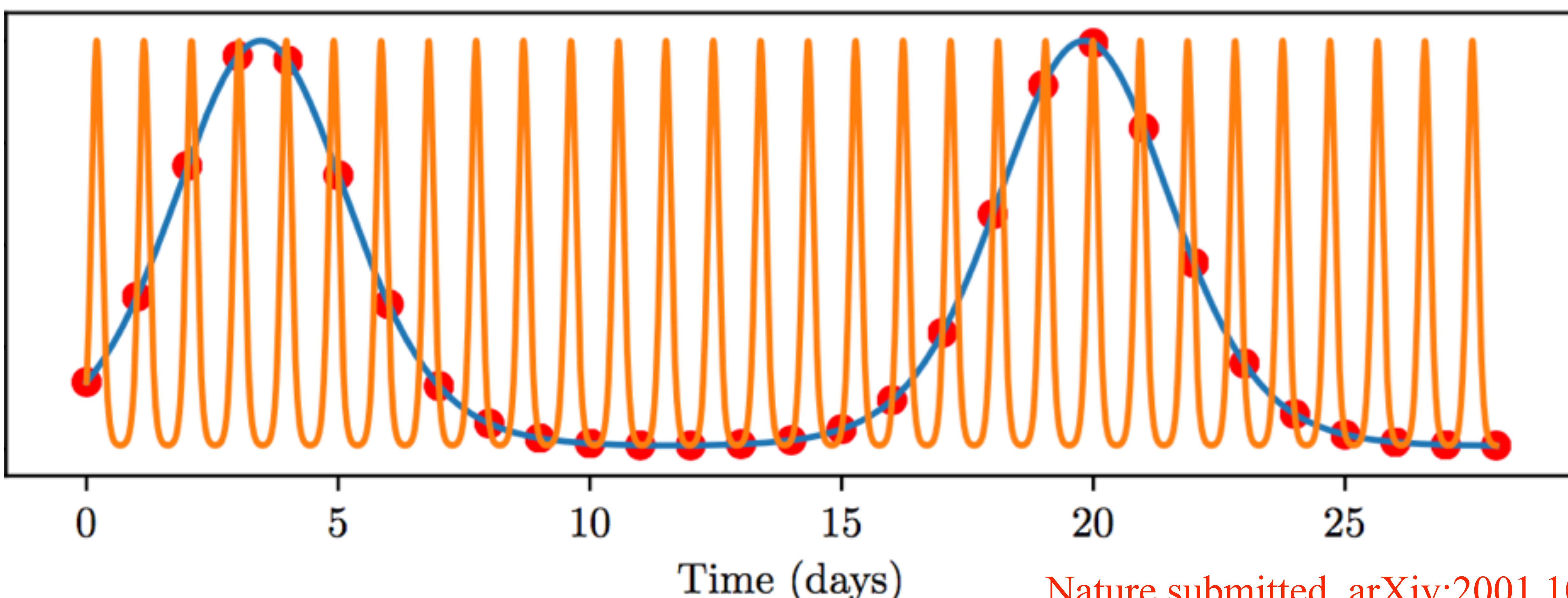
Nature submitted, arXiv:2001.10275

Paper 7: Periodic activity in a repeating FRB

Important note! CHIME observes R3 for 10 minutes per day.

Therefore, the apparent frequency f=1/16.35 could be aliased from a higher frequency. Aliasing occurs whenever a periodic signal is observed with periodic sampling.

Unaliased: $f = (1/16.35)\ \mathrm{day}^{-1}$
Aliased: $f = (1/16.35 + 1)\ \mathrm{day}^{-1}$



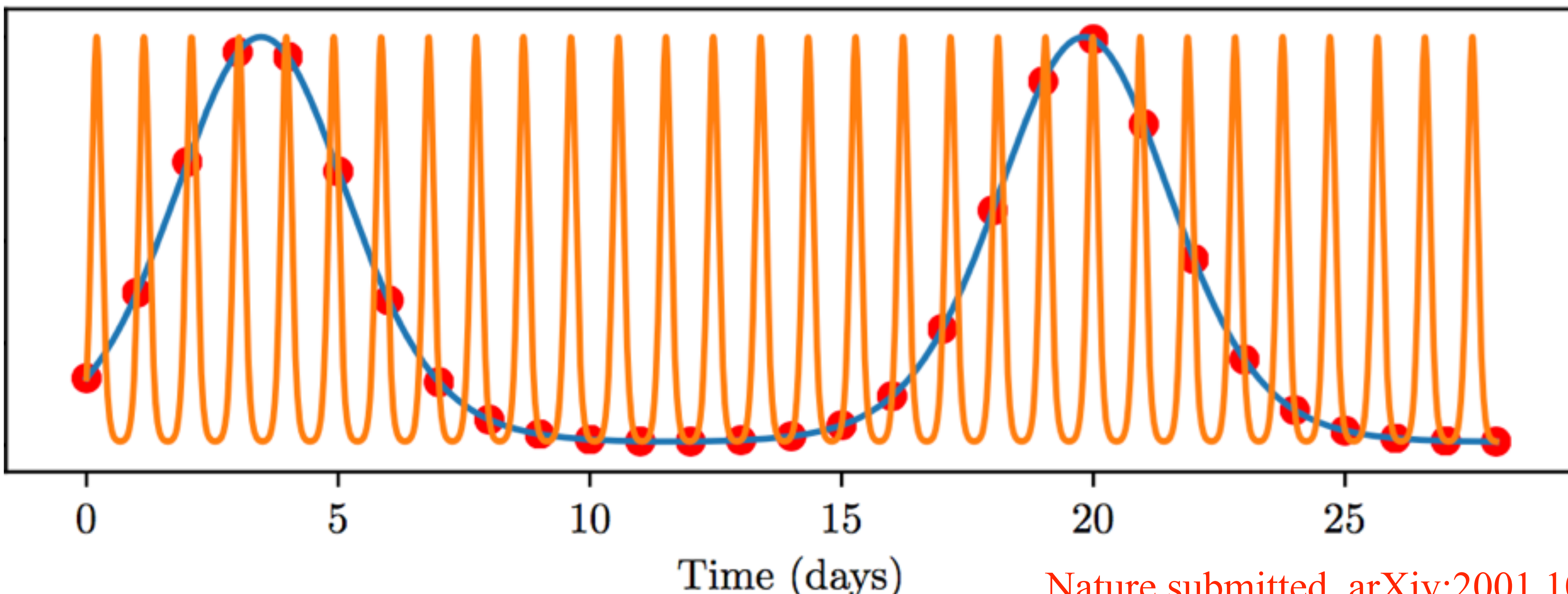
Nature submitted, arXiv:2001.10275

Paper 7: Periodic activity in a repeating FRB

Using CHIME data alone, the following frequencies are allowed:

$$f = \pm \frac{1}{16.35} + N \qquad (N = 0, 1, \cdots, 29)$$

The true period could be anywhere from ~50 minutes to 16 days!
Cannot be narrowed down further using CHIME alone, but a single contiguous observation from another telescope (e.g. GBT) could settle the issue.



Nature submitted, arXiv:2001.10275

1. The CHIME concept
2. Science goals of CHIME
3. Why this is hard
4. FRB science results
5. Concluding thoughts

Concluding thoughts

- For \$15M, you can build the world's most powerful radio telescope!

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- … but you will have an immense data rate, and you'll need to solve extremely hard computing problems.
- CHIME is a testbed for improving radio astronomy algorithms/software, to handle unprecedented data volumes.

Concluding thoughts

- For $15M, 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.
- CHIME is a testbed for improving radio astronomy algorithms/software, to handle unprecedented data volumes.
- If these improvements are successful, there is a clear path to scaling up the CHIME hardware by a factor of ~100 or so (in mapping speed) in the near future.

HIRAX

South African "sister" project to CHIME.

- Array of 1024 dishes (no cylinders)
- Outrigger telescopes for very high resolution!
- In Southern hemisphere (more pulsars)

HIRAX will have ~4 times the collecting area of CHIME, and the same number of beams, so 4 times CHIME mapping speed.

Expanding HIRAX to 2048 dishes would give 16 times CHIME mapping speed.

CHORD: Canadian successor to CHIME

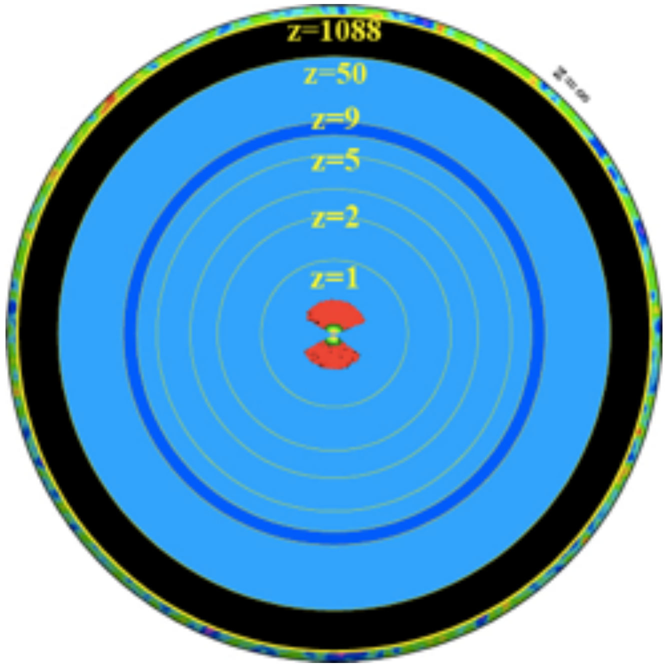
New technology under development (improves effective mapping speed by a factor ~8):

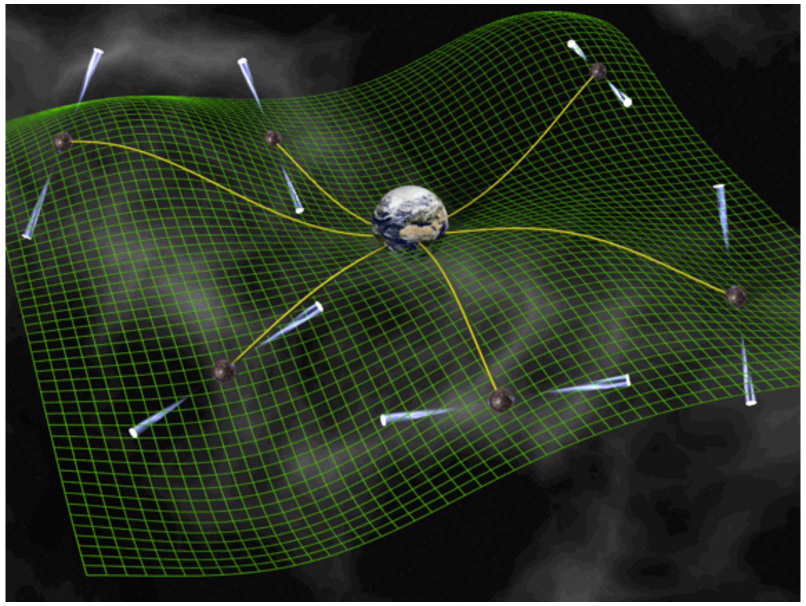
- Wide-band feeds (300-1500 MHz)
- Lower noise, aiming for T_{sys} ~30 K (CHIME is ~50 K)

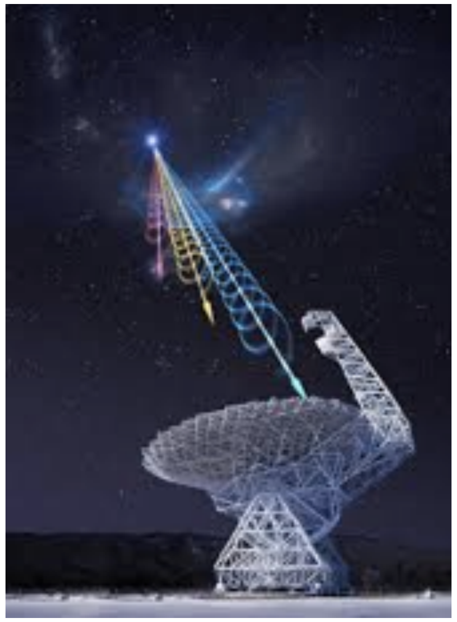
To consist of a large “core” interferometer at DRAO, plus outriggers at other North American locations TBD.

Concluding thoughts

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







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

Fast radio bursts:

- what are they?
- potential applications…?

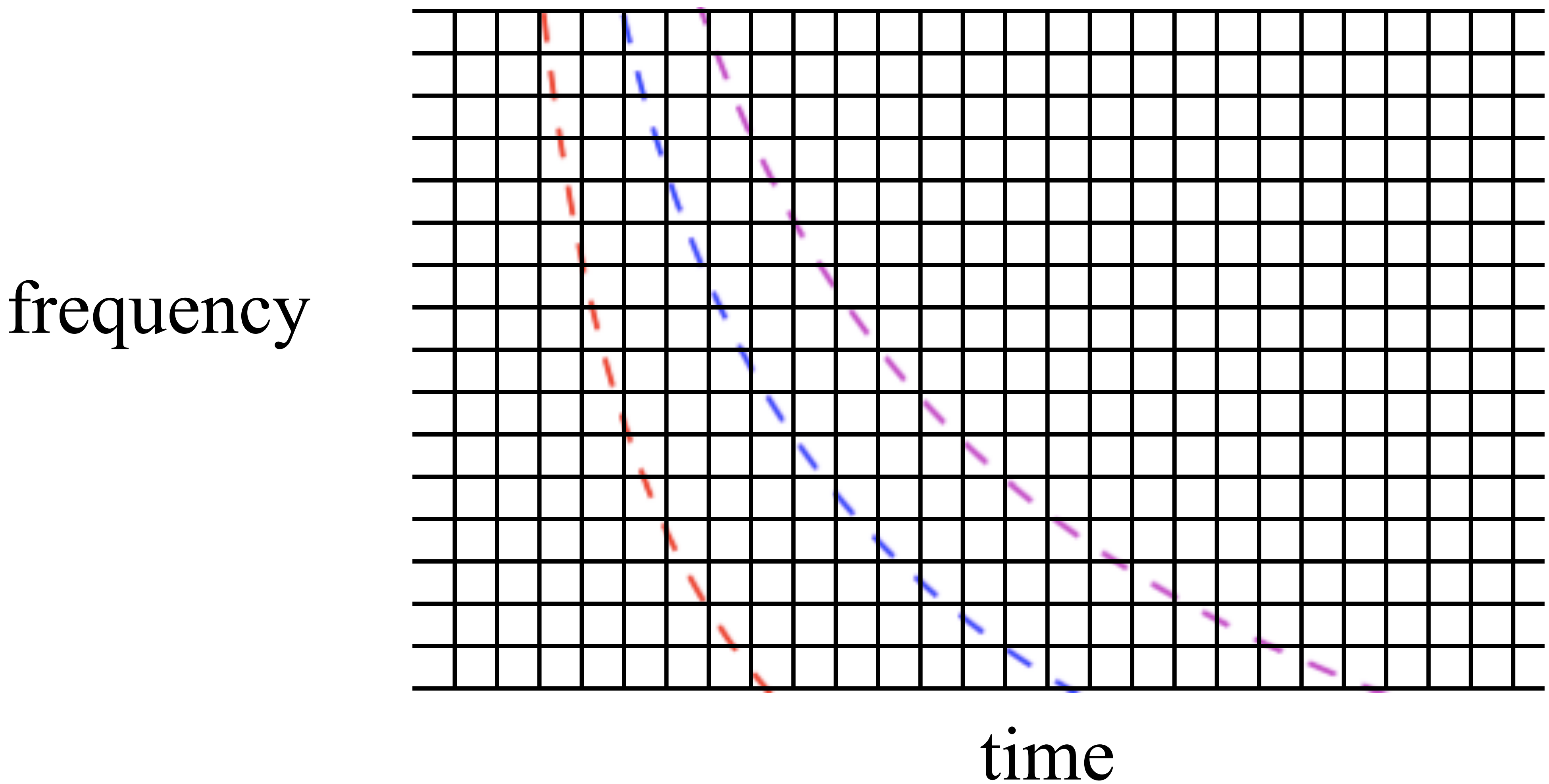

Thanks!

Extra slides (mostly technical)

The FRB search problem

Setting up the problem. The FRB backend incrementally receives a 2D array with (time, frequency) axes. We want to sum over all "tracks" with the shape shown.

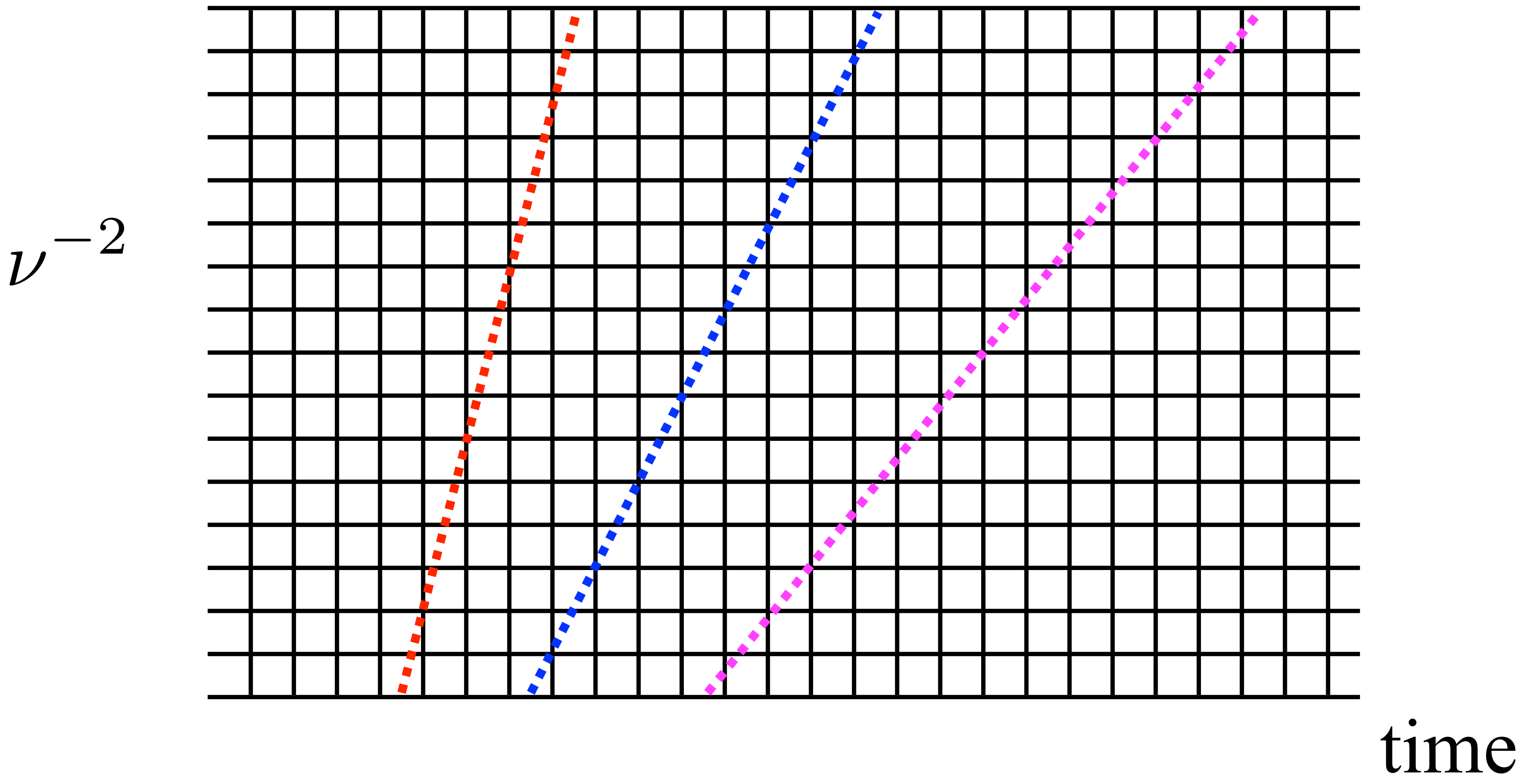
We use a recursive tree algorithm, described in the next few slides.



Tree dedispersion: the basic idea

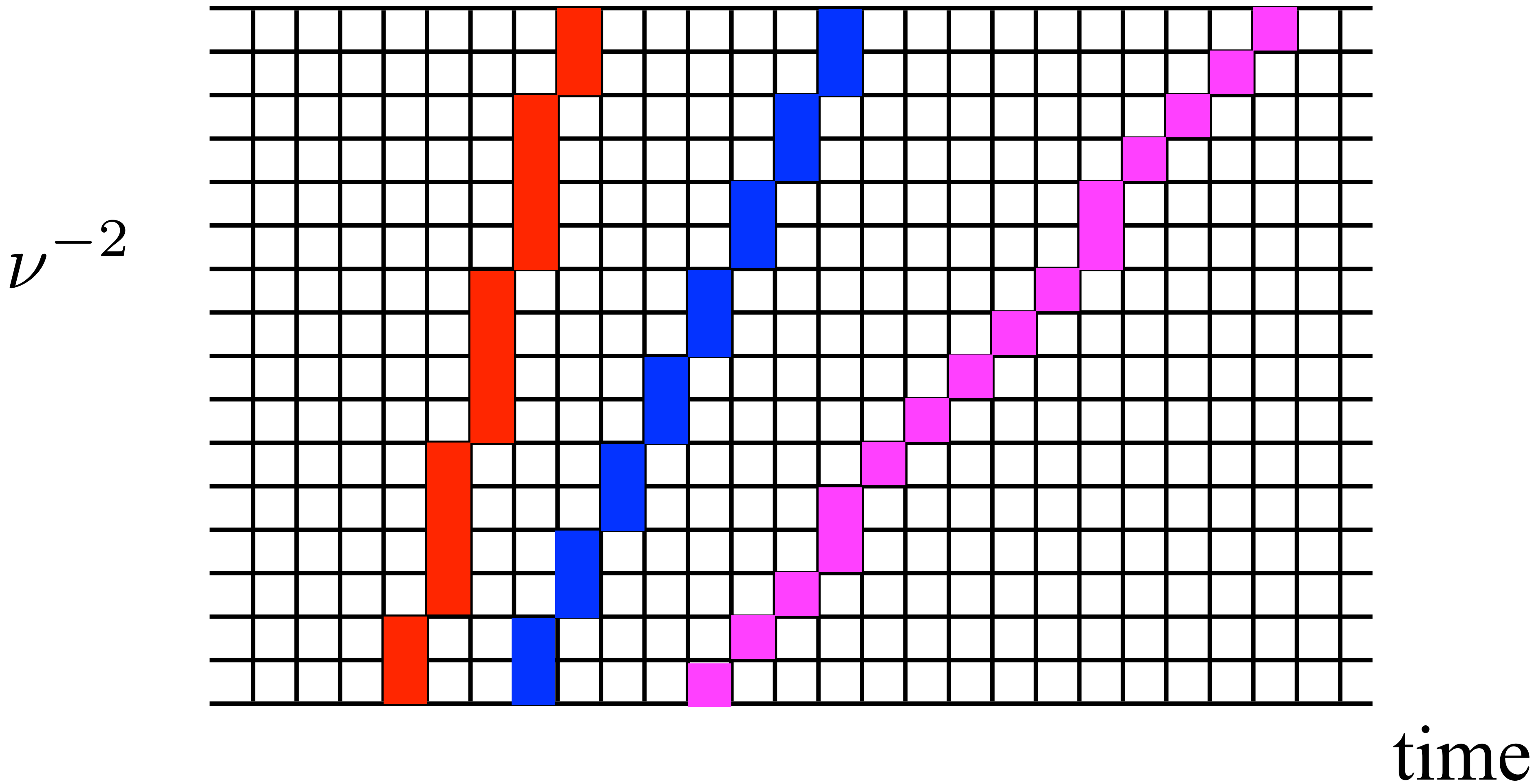
Regrid the input array so that the y-axis corresponds to ν^{-2}, rather than frequency ν.

Then an FRB looks like a straight line. Need a fast algorithm for summing array elements over all straight lines.



Tree dedispersion: the basic idea

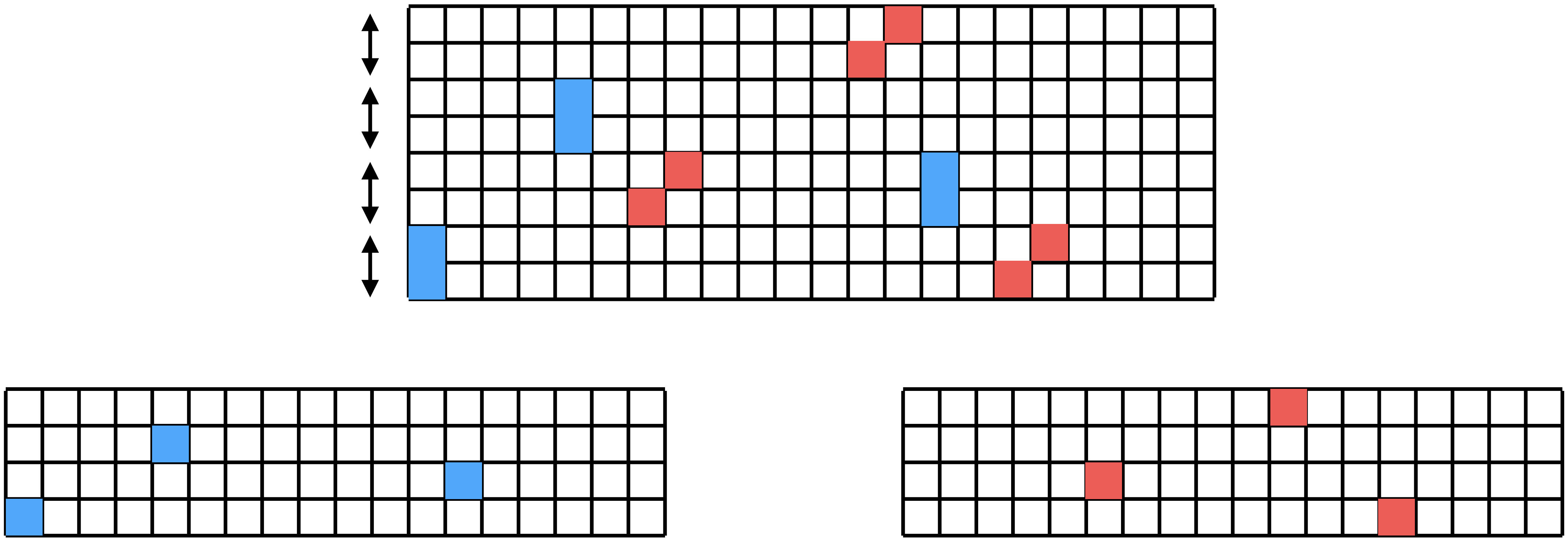
Tree dedispersion will approximate each straight-line track by a jagged sum of samples. The sums are built up recursively as explained in the next few slides.



Tree dedispersion: the basic idea

First iteration: group channels in pairs. Within each pair, we form all "vertical" sums (blue) and "diagonal" sums (red).

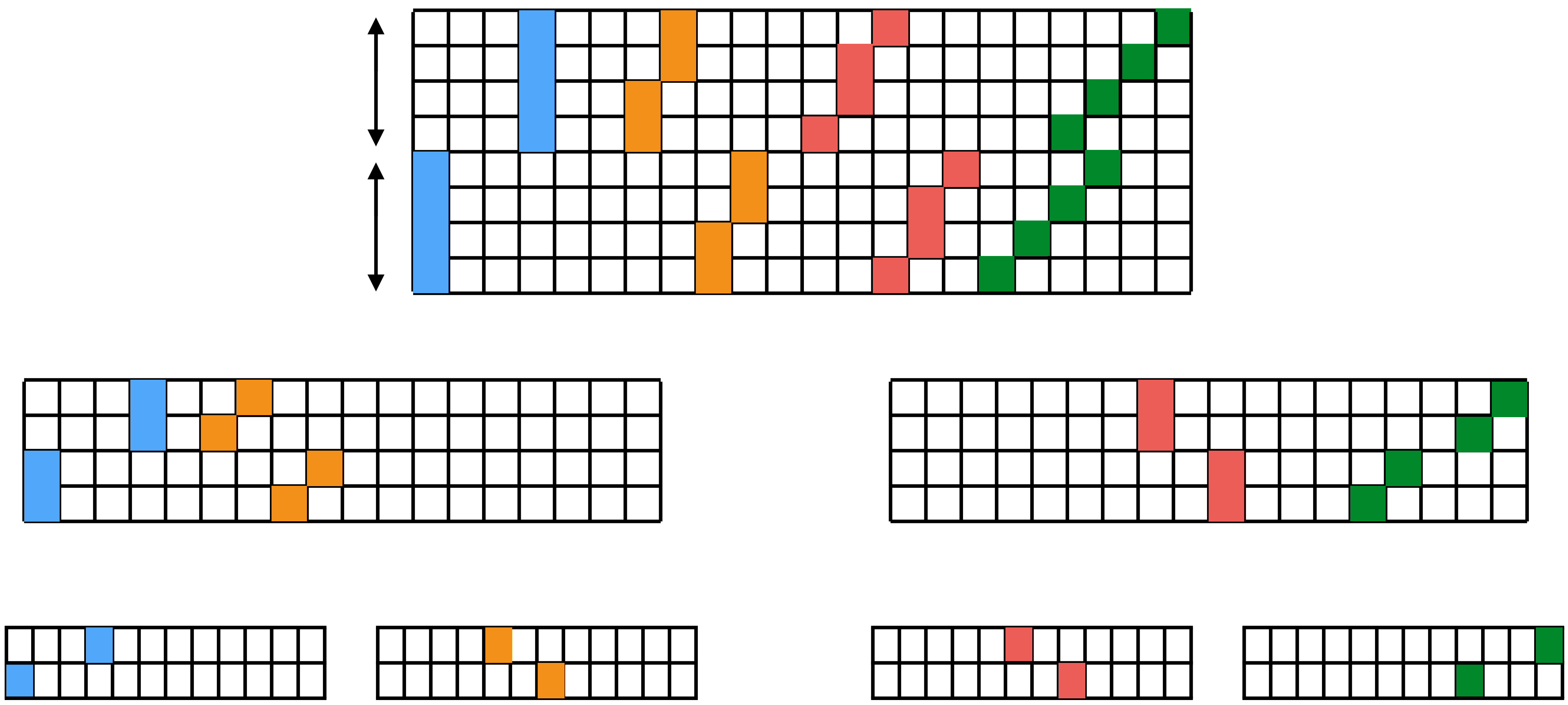
Output is two arrays, each half the size of the input array.



Tree dedispersion: the basic idea

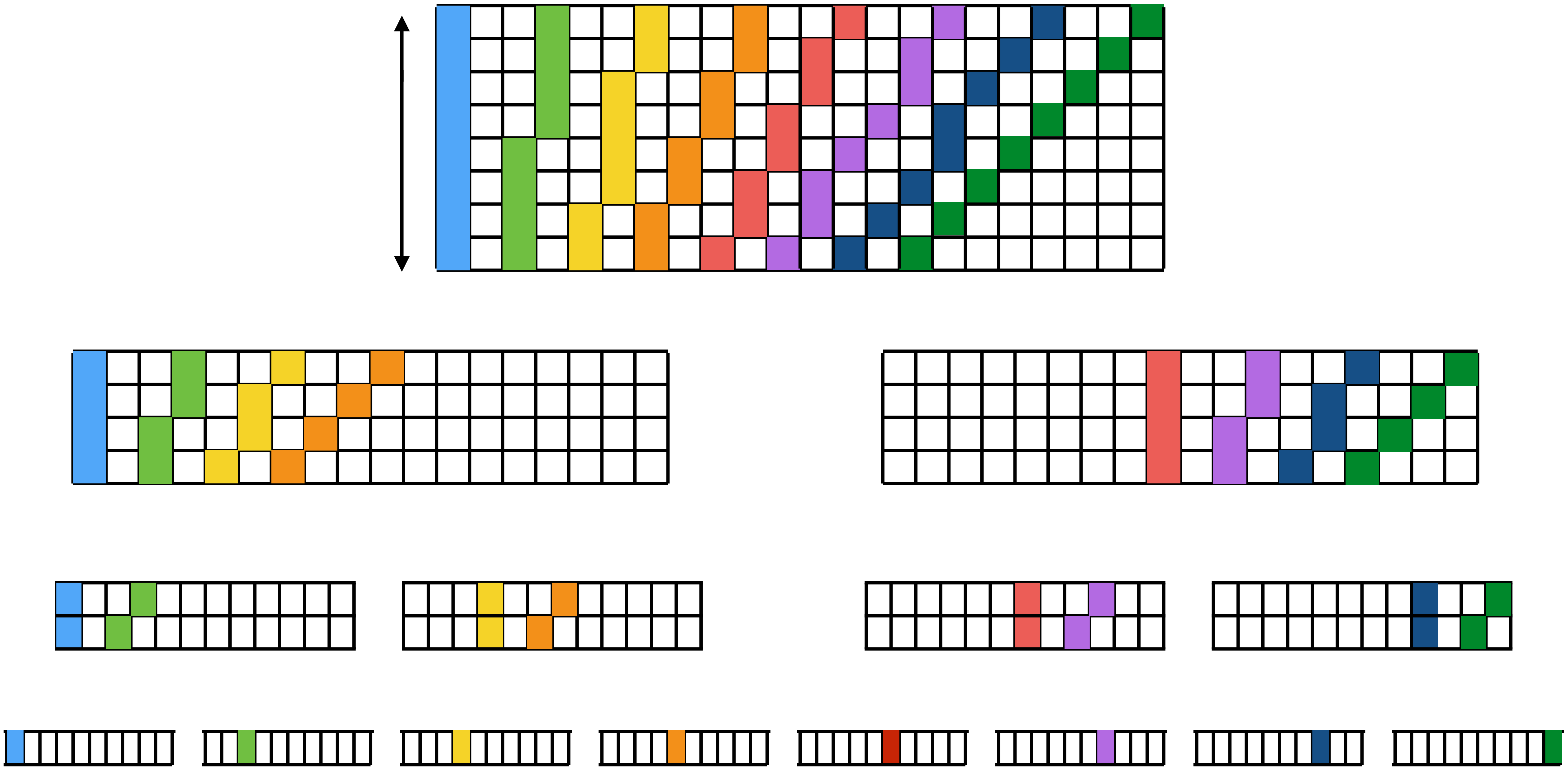
Second iteration: sum pairs into "pairs of pairs".

Frequency channels have now been merged in quadruples.
Within each quadruple, there are four possible sums.

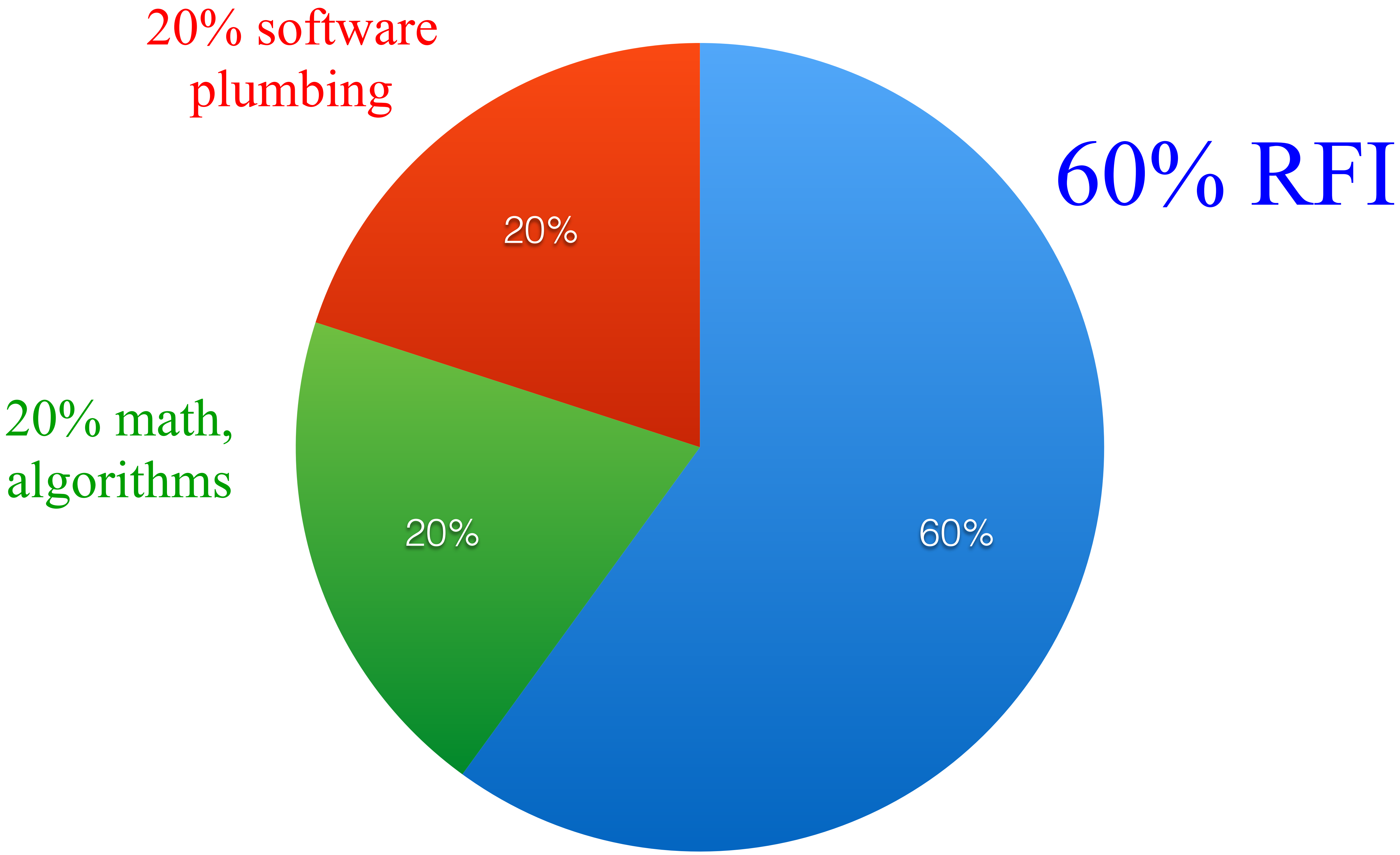


Tree dedispersion: the basic idea

Last iteration: all channels summed.



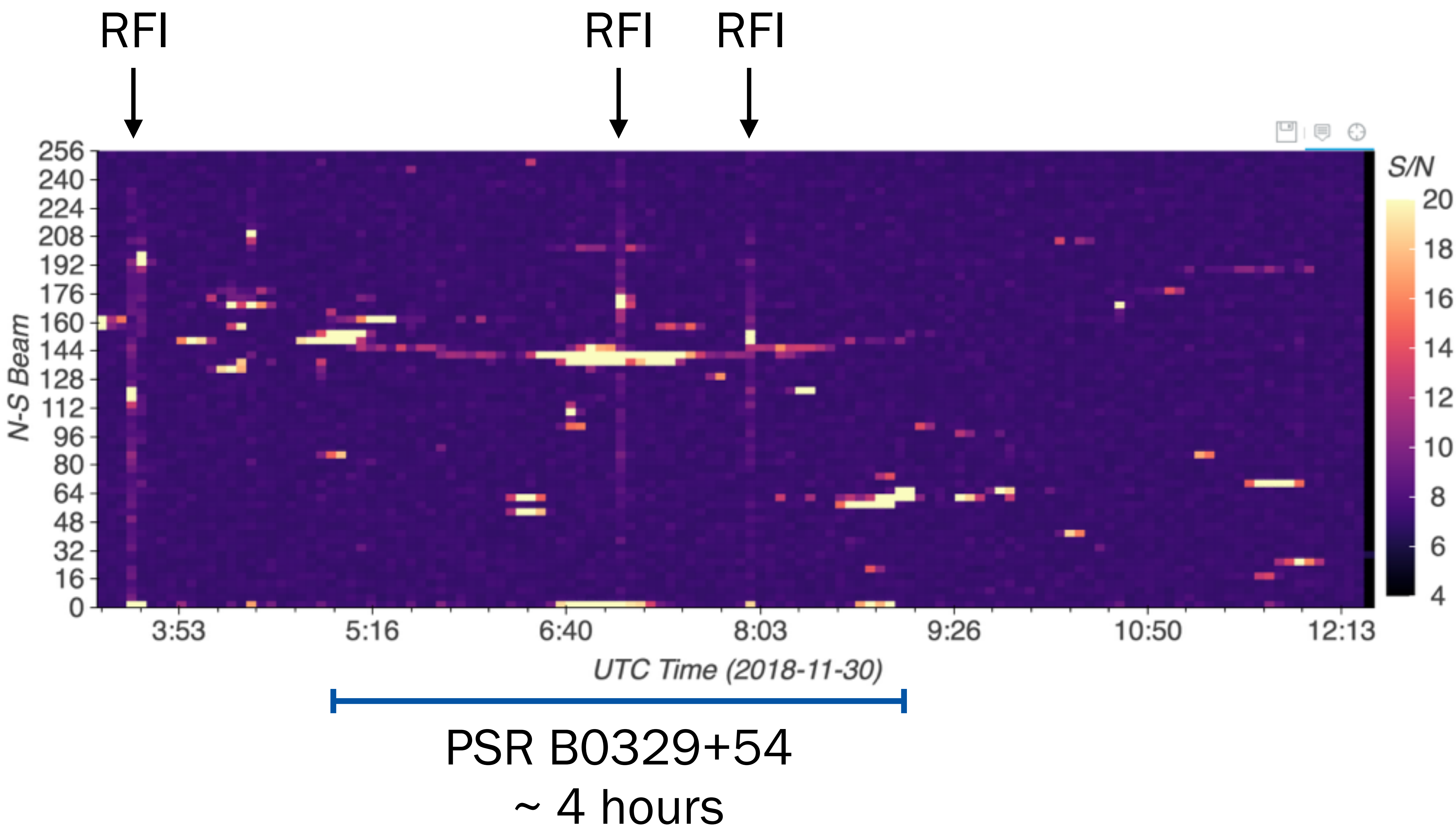
How I spend my time



RFI removal

- For an FRB or pulsar search, the largest instrumental effect (by far!) is radiofrequency interference (RFI), i.e. human-made radio transmissions.
- Main tool for mitigating RFI is masking the data in the (time, frequency) plane, before the FRB search.
- Standard RFI removal software packages do not suffice for CHIME:
    - too slow
    - latency too high
    - false positive rate too high (a few false positives per beam per hour = 10^5 events per day!)

Per-beam triggers after RFI excision, dedispersion and peak finding

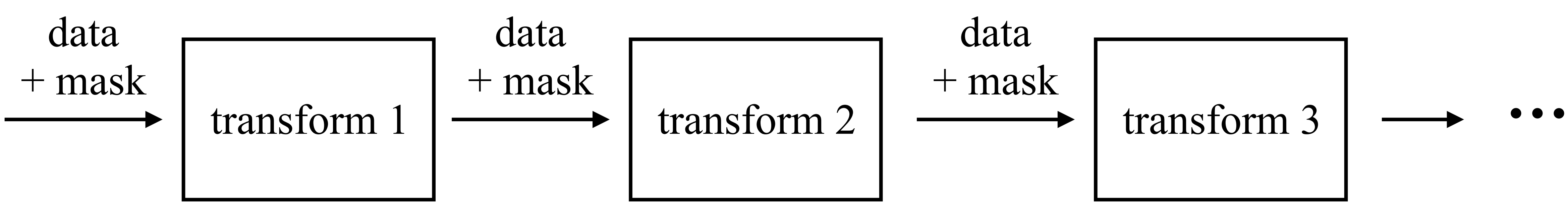


Signal collapsed over 4 East-West beams

Ziggy Pleunis

Our approach to RFI removal

Represent RFI removal as a sequence of “transforms” which operate on the data + mask.



For example:

- Clipping based on intensity
- Clipping based on variance of intensity (voltage “kurtosis”)
- Detrending the data in either time or frequency axis
- Upsampling/downsampling the data/mask

Our key transforms are assembly-language-kernelized, but can be chained together and run from high-level languages (python).

Our approach to RFI removal

Current RFI strategy consists of ~100 transforms!

This iterative approach has proven to be extremely powerful.

```
wi_sub_pipeline(nfreq_out=1024,nds_out=1)
wi_sub_downsampler
        badchannel_mask(mask_path="/data/pathfinder/rfi_masks/rfi_20160705.dat")
        std_dev_clipper(nt_chunk=1024, axis=AXIS_TIME, sigma=3, Df=1, Dt=1, two_pass=1)
        std_dev_clipper(nt_chunk=2048, axis=AXIS_TIME, sigma=3, Df=1, Dt=1, two_pass=1)
        std_dev_clipper(nt_chunk=6144, axis=AXIS_TIME, sigma=3, Df=1, Dt=1, two_pass=1)
        std_dev_clipper(nt_chunk=6144, axis=AXIS_FREQ, sigma=3, Df=1, Dt=1, two_pass=0)
        std_dev_clipper(nt_chunk=6144, axis=AXIS_FREQ, sigma=3, Df=1, Dt=1, two_pass=0)
              ...
        intensity_clipper(nt_chunk=1024, axis=AXIS_FREQ, sigma=5, niter=9, iter_sigma=5, Df=1, Dt=1, two_pass=0)
        intensity_clipper(nt_chunk=1024, axis=AXIS_TIME, sigma=5, niter=9, iter_sigma=5, Df=1, Dt=1, two_pass=0)
        intensity_clipper(nt_chunk=1024, axis=AXIS_NONE, sigma=5, niter=9, iter_sigma=3, Df=2, Dt=16, two_pass=0)
        intensity_clipper(nt_chunk=1024, axis=AXIS_FREQ, sigma=5, niter=9, iter_sigma=3, Df=2, Dt=16, two_pass=0)
        polynomial_detrender(nt_chunk=1024, axis=AXIS_TIME, polydeg=4, epsilon=0.01)
        spline_detrender(nt_chunk=0, axis=AXIS_FREQ, nbins=6, epsilon=0.0003)
        wi_sub_upsampler
    polynomial_detrender(nt_chunk=1024, axis=AXIS_TIME, polydeg=4, epsilon=0.01)
    spline_detrender(nt_chunk=0, axis=AXIS_FREQ, nbins=6, epsilon=0.0003)
```

Masoud Rafiei-Ravandi

2013: CHIME project begins

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New B.C. telescope to make massive 3D map of universe

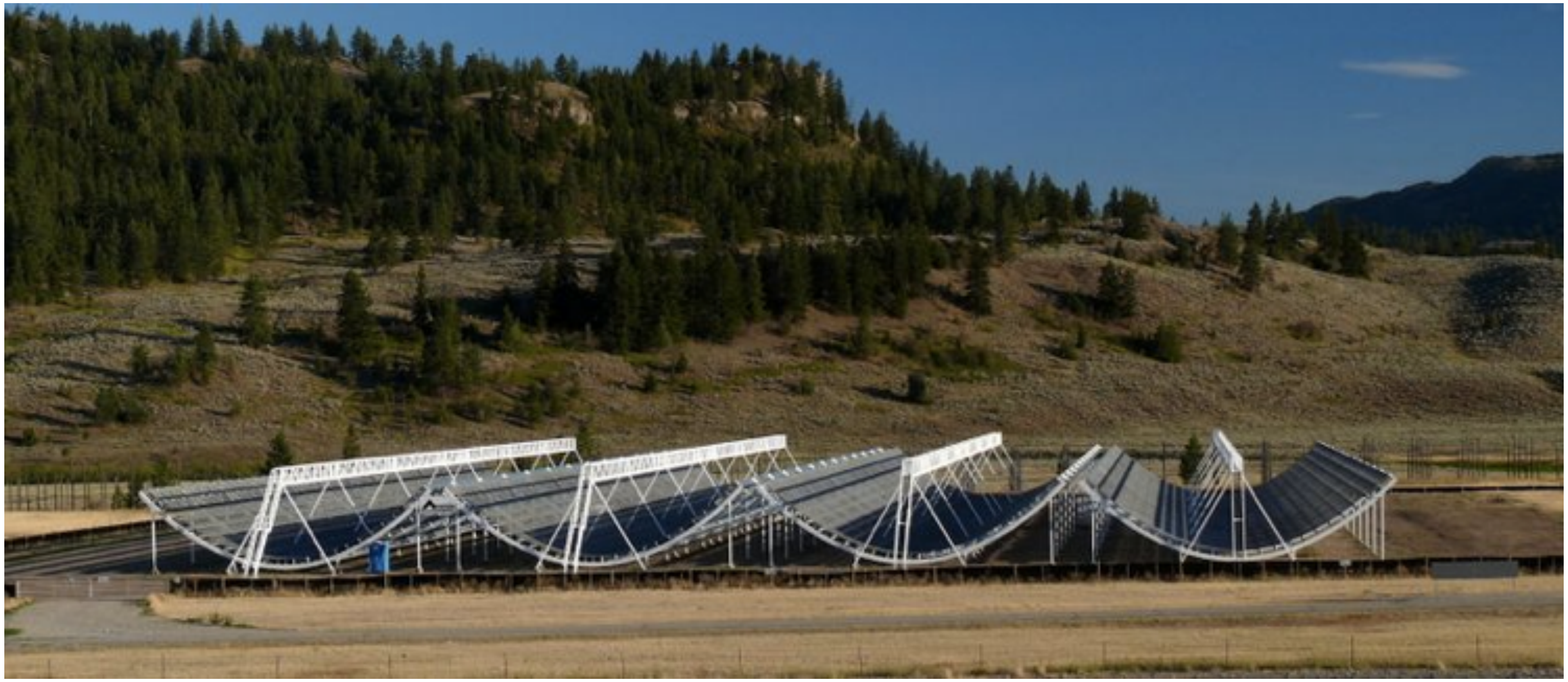
CHIME radio telescope to look 11 billion years into past

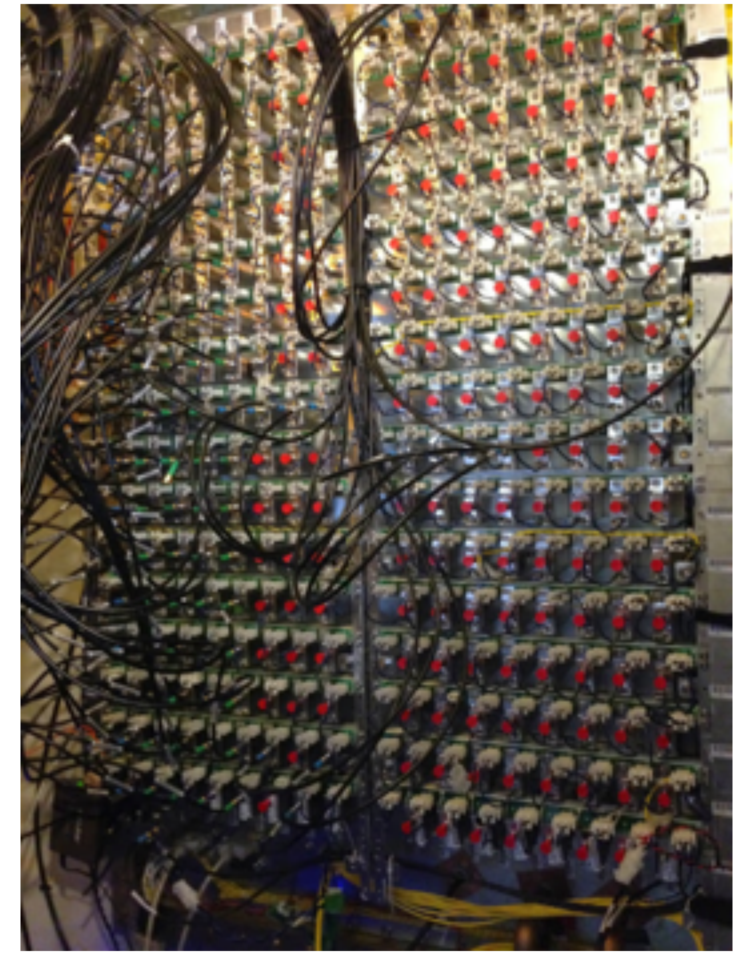
The Canadian Press · Posted: Jan 25, 2013 9:18 AM ET | Last Updated: January 28, 2013

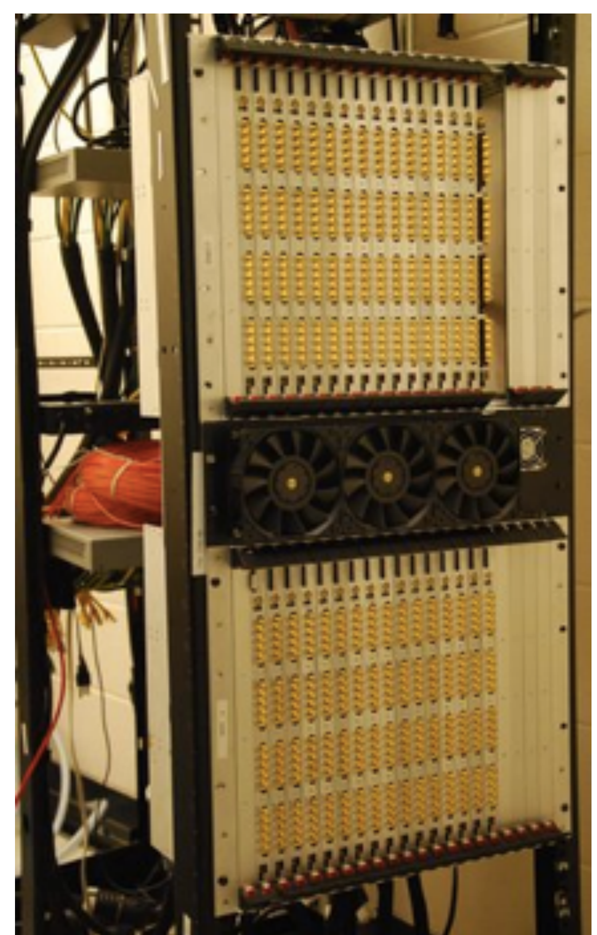
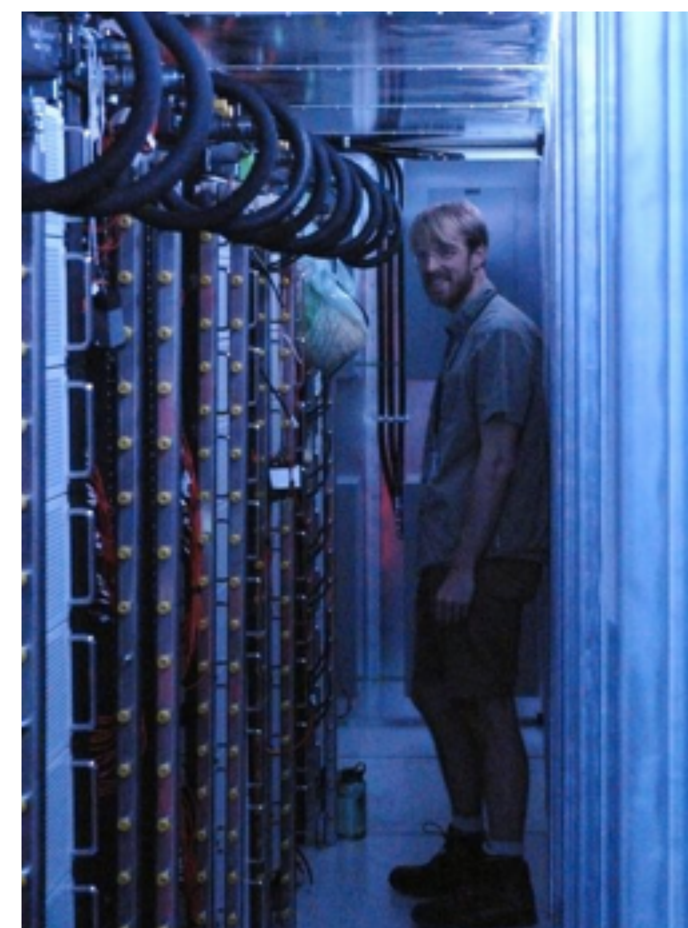
2015: CHIME “pathfinder” (~10% scale version)

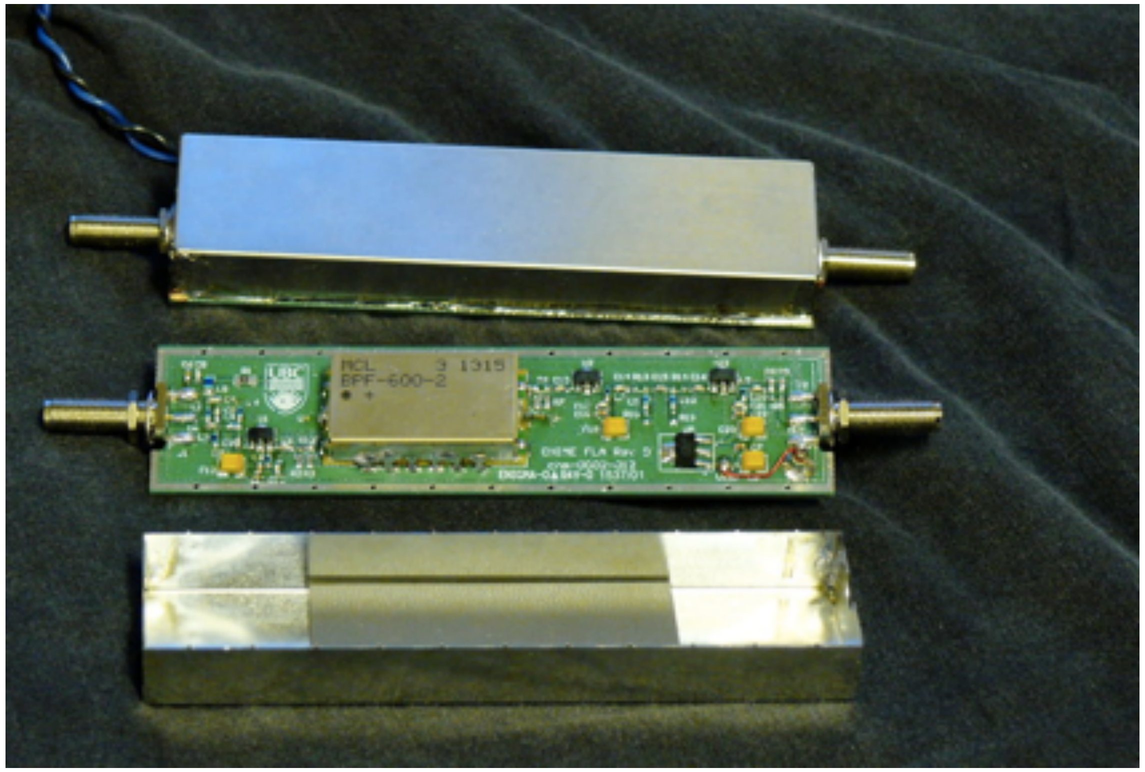
CHIME pathfinder

2017: Full CHIME telescope

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nature

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Bounty includes second known example of a repeating burst.

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Science & Environment

Mysterious radio signals from deep space detected

The New York Times

Broadcasting from Deep Space, a Mysterious Series of Radio Signals

The Canadian Hydrogen Intensity Mapping Experiment, or Chime, a radio telescope array in British Columbia. Soon after it was turned on last summer, it picked up a set of odd radio bursts from deep space. Will Ivy/Alamy Stock Photo

CNN Health + Live TV

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A second mysterious repeating fast radio burst has been detected in space

The Guardian

Alien life

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Repeating bursts of radio waves detected for first time since initial accidental discovery in 2007

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