Title: CHIME: The Canadian Hydrogen Intensity Mapping Experiment

Speakers: Kendrick Smith

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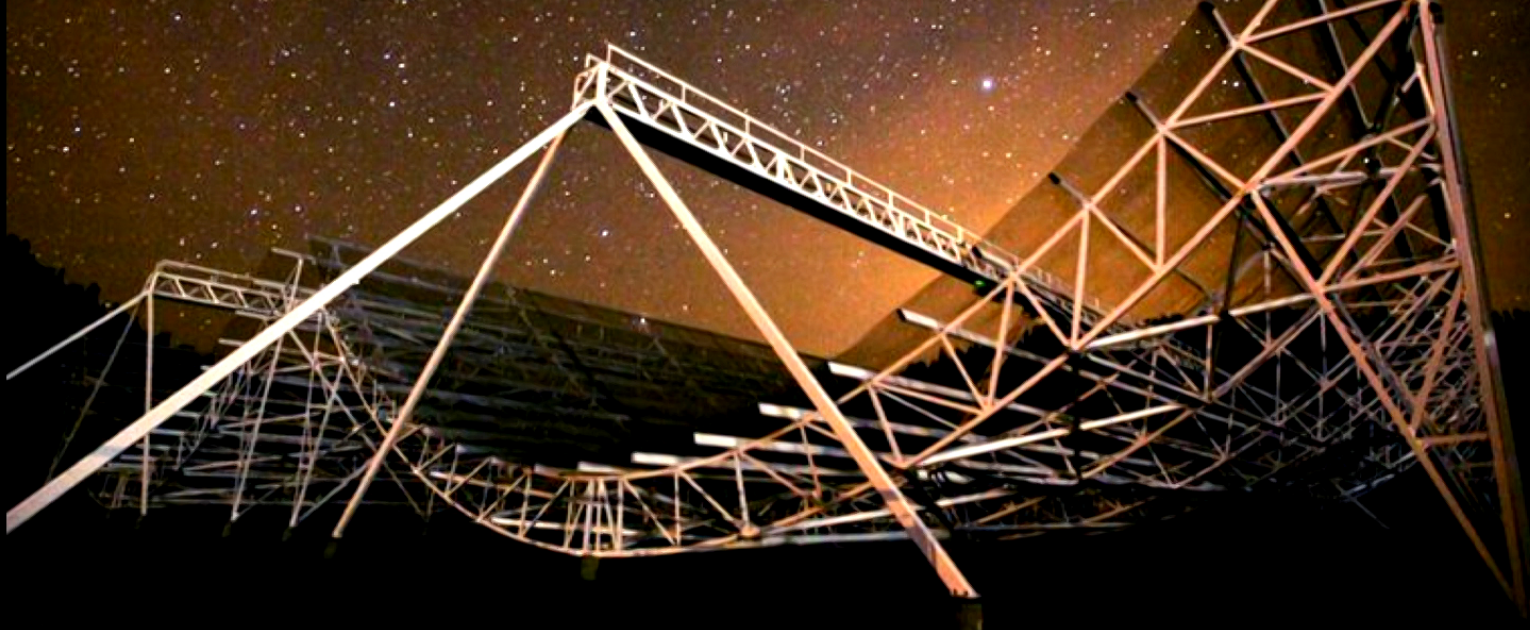
Abstract: CHIME is a new interferometric telescope at radio frequencies 400-800 MHz. The mapping speed (or total statistical power) of CHIME is among the largest of any radio telescope in the world, and the technology powering CHIME could be used to build telescopes which are orders of magnitude more powerful. Recently during precommissioning, CHIME started finding new fast radio bursts (FRB's) at an unprecedented rate, including a new repeating FRB.Understanding the origin of fast radio bursts is a central unsolved problem in astrophysics, and we anticipate that CHIME's statistical power will play an important role in solving it. In this talk, I'll give a status update on CHIME, with emphasis on FRB's.

CHIME: The Canadian Hydrogen Intensity Mapping Experiment

Kendrick Smith (Perimeter Institute)
Perimeter, September 2019



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

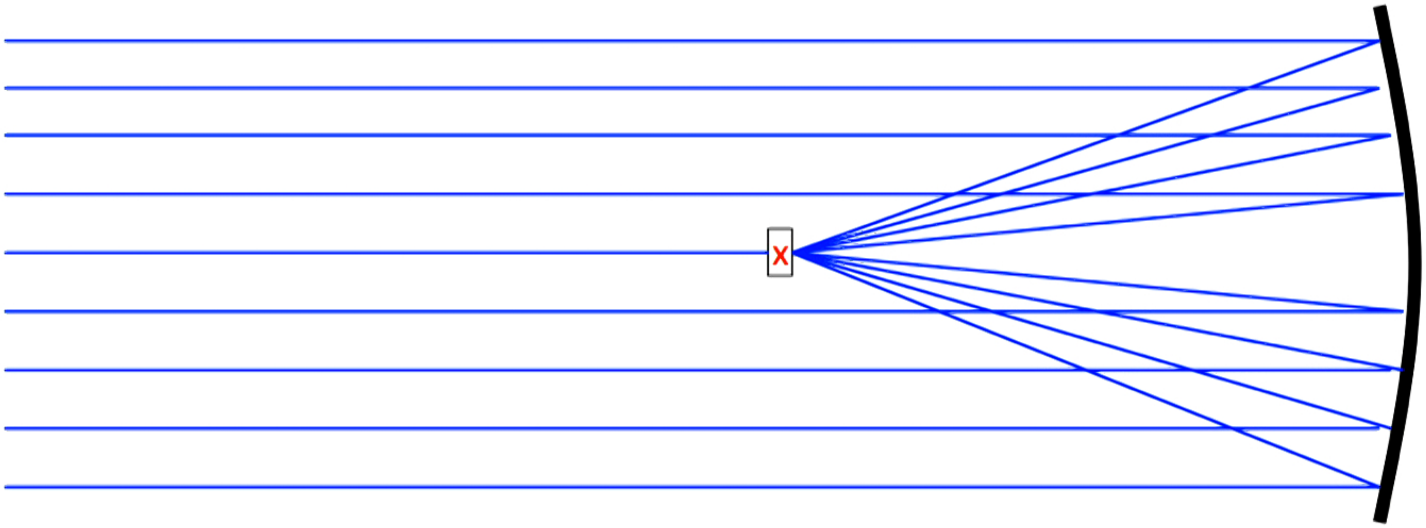
West Virginia University

NRAO

Massachusetts Institute of Technology

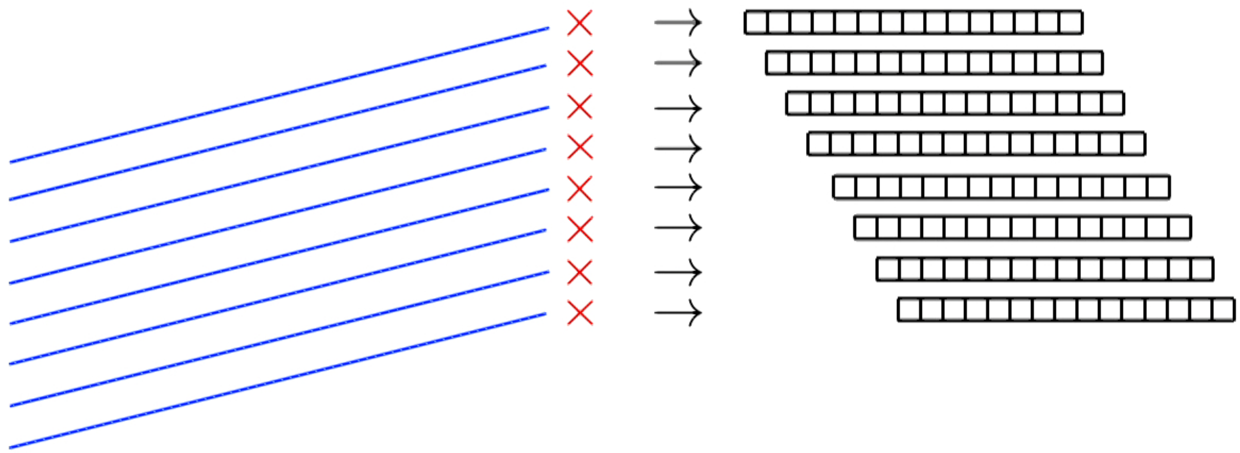
PERIMETER INSTITUTE

Single-feed radio telescope



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

Phased-array interferometer

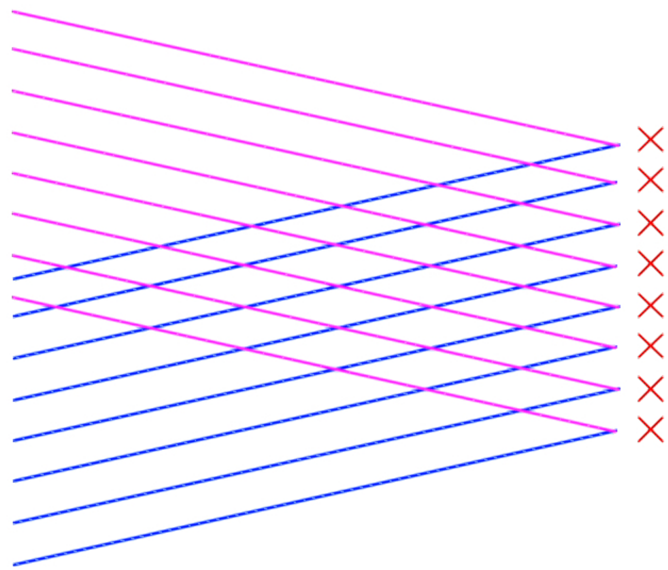


Dish is replaced by an array of antennas whose signals are digitized.

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

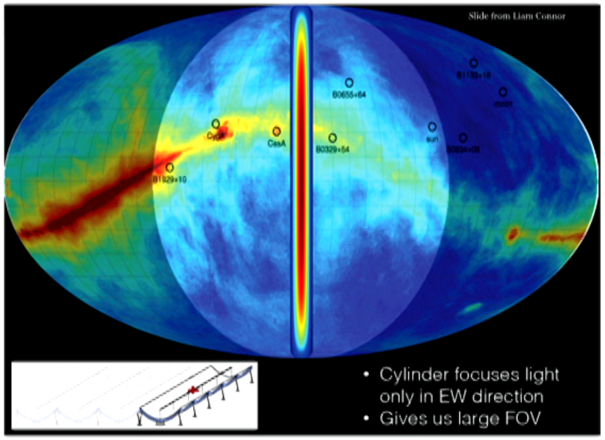
- CHIME has a 4 x 256 array of antennas and can form all 1024 independent beams in real time. Raw sensitivity is the same as 1024 single-feed radio telescopes!

80m

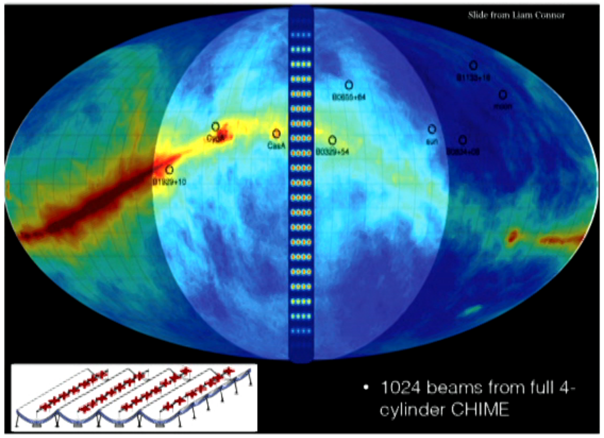
CHIME beamforming, cartoon form

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

Mapping speeds (back-of-envelope)

For many purposes, the statistical power of a radio telescope can be quantified by its mapping speed:

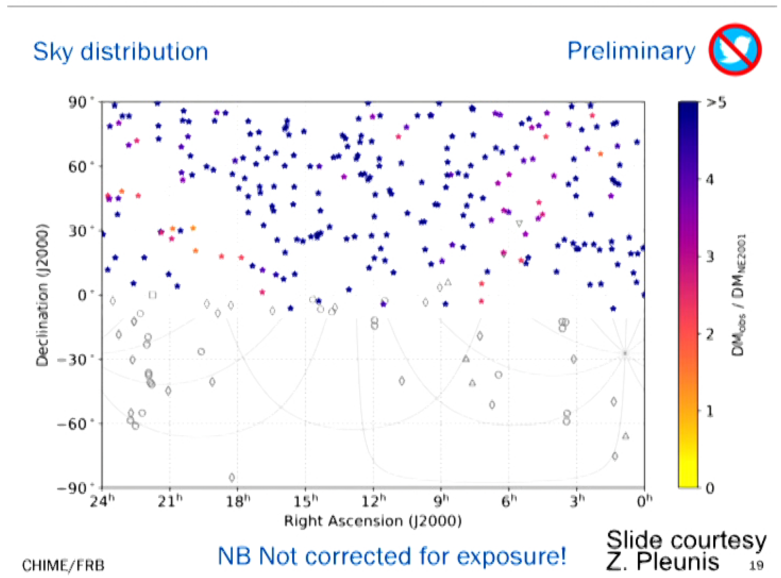
$$M \approx (\text{Collecting area } A) \times (\text{Number of beams}) \times (\text{order-one factors})$$

	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 ?!

Science goals based on CHIME's high mapping speed

1. Fast radio bursts: CHIME has found over 500 new FRB's! (Total found by all other telescopes combined: 52



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Technology & Science

Canadian astronomers discover 2nd mysterious repeating fast radio burst

nature

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Bevy of mysterious fast radio bursts spotted by Canadian telescope

Bounty includes second known example of a repeating burst.

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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

SPACE + SCIENCE

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

The Guardian

Alien life

Mysterious fast radio bursts from deep space 'could be aliens'

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

!!!

Science goals based on CHIME's high mapping speed

1. Fast radio bursts: CHIME has found over 500 new FRB's! (Total found by all other telescopes combined: 52)
2. Pulsar timing: CHIME is timing almost all known pulsars in the Northern hemisphere.
3. Pulsar search: CHIME has enough sensitivity to find thousands of new pulsars.

Science goals based on CHIME's high mapping speed

1. Fast radio bursts: CHIME has found over 500 new FRB's! (Total found by all other telescopes combined: 52)
2. Pulsar timing: CHIME is timing almost all known pulsars in the Northern hemisphere.
3. Pulsar search: CHIME has enough sensitivity to find thousands of new pulsars.
4. Cosmology: CHIME's forecasted BAO measurements are competitive with next-generation LSS surveys.

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

Too good to be true?

The challenge

	A	N_{beams}	$M/(10^5\ \mathrm{m}^2)$
Parkes 64m	3200 m^2	13	0.41
Green Bank 100m	7850 m^2	7	0.55
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CHIME	6400 m^2	1024	66

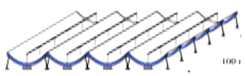
In principle, sensitivity is proportional to mapping speed M, but computational cost is proportional to N_{beams} (or worse).

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



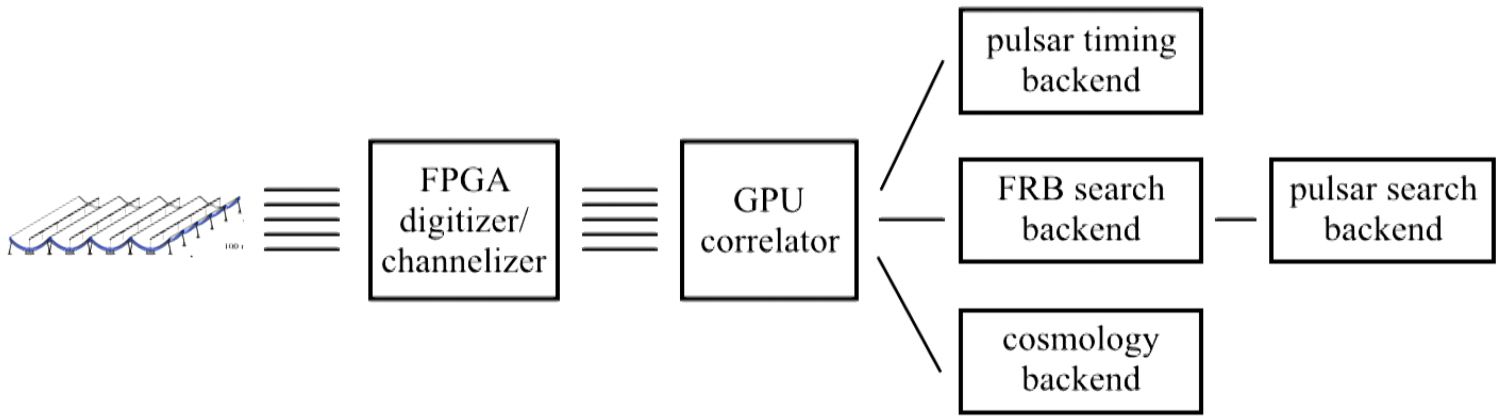
FPGA digitizer/ channelizer

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

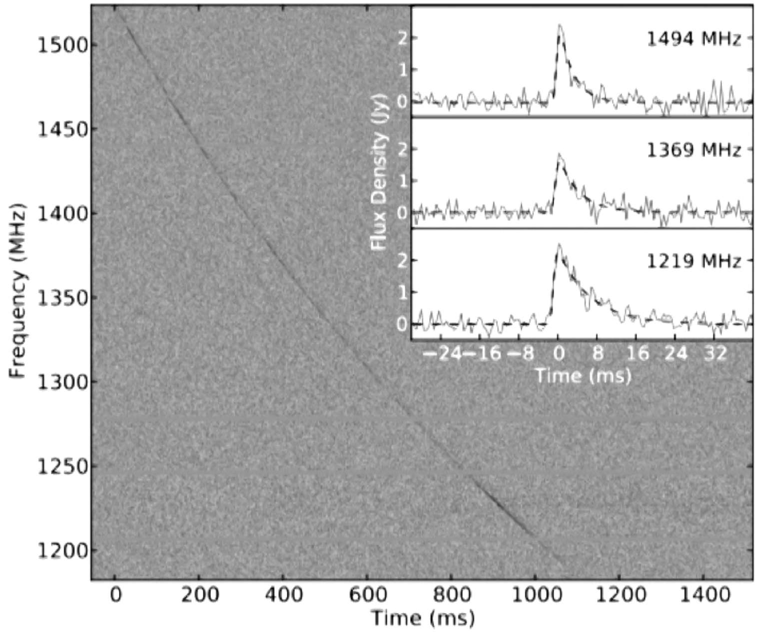


- Raw data rate is 800 GB/s = 70 PB/day
- Purpose-built backends receive different data products from the correlator.
- Collectively, CHIME is a large heterogeneous data center / supercomputer.
- I've mainly been working on the FRB and pulsar search backends, which I'll talk about in more detail.

Fast radio bursts

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).



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

The large implied electron column density (+ isotropic sky distribution) suggests that the pulses originate outside our galaxy.

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

Prior to CHIME, one FRB had been observed to repeat. The repeating FRB was eventually observed with VLBI arrays, with enough angular resolution to identify a host galaxy at z=0.2.

Fast radio bursts

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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)
Invalid	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 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

```
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!

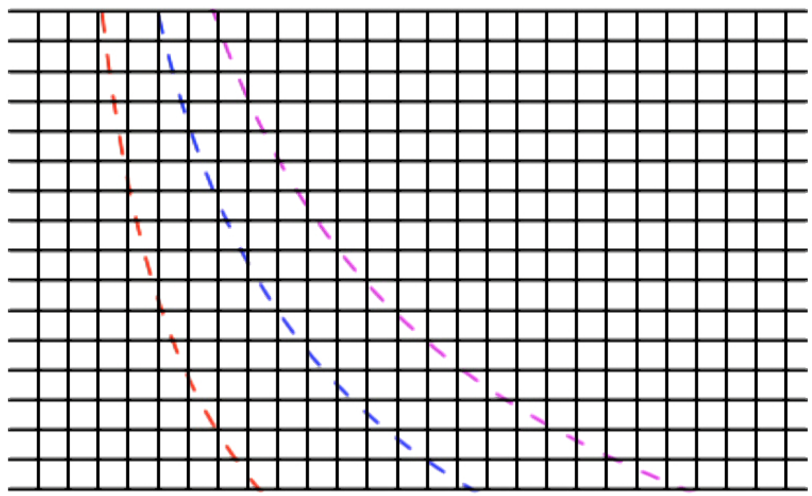
```
void transpose_256b(float *dst, const float *src, int n)
{
    for (int i = 0; i < n; i += 8) {
        for (int j = 0; j < n; j += 8) {
            __m256 x0 = _mm256_load_ps(src + j*n + i);
            __m256 x1 = _mm256_load_ps(src + (j+1)*n + i);
            __m256 x2 = _mm256_load_ps(src + (j+2)*n + 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);
        }
    }
}
```

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.

frequency

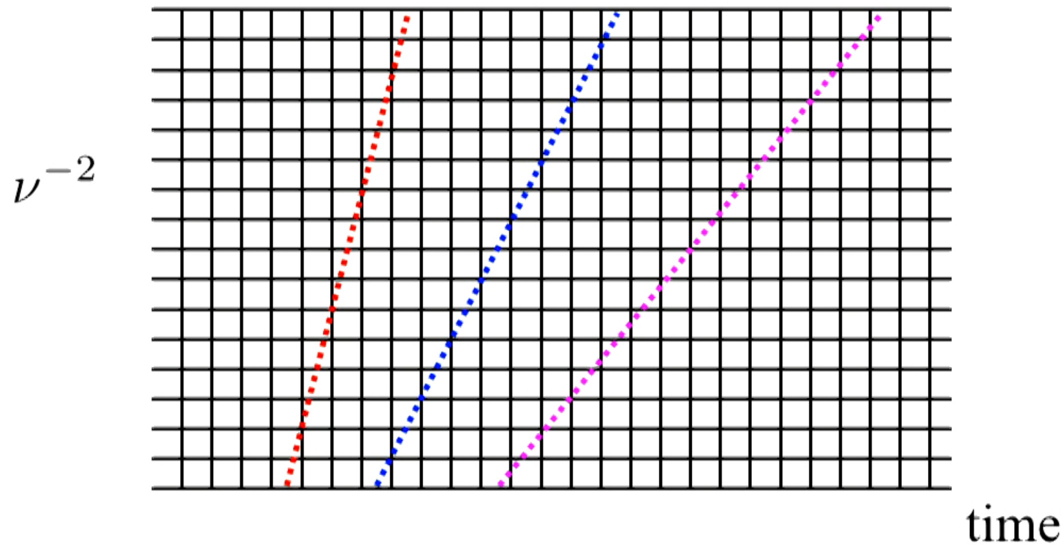


time

Tree dedispersion: the basic idea

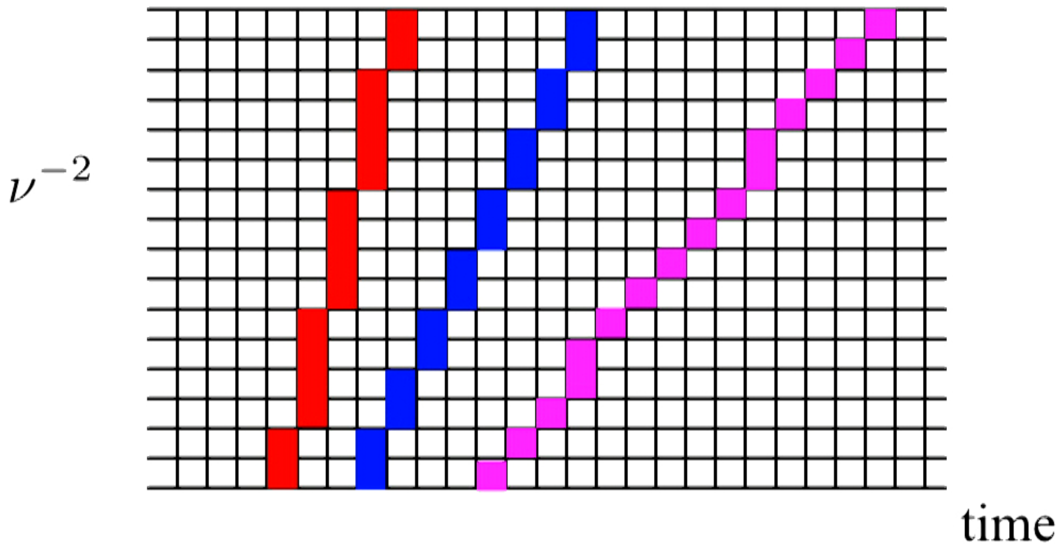
Regrid the input array so that the y-axis corresponds to ν^{-2}, rather than frequency ν.

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

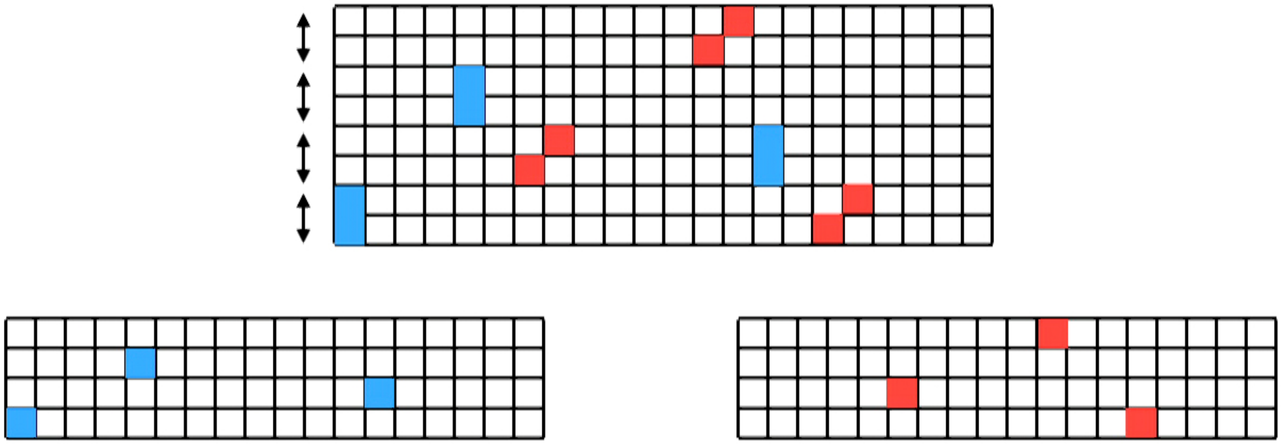
Tree dedispersion will approximate each straight-line track by a jagged sum of samples. The sums are built up recursively as explained in the next few slides.



Tree dedispersion: the basic idea

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

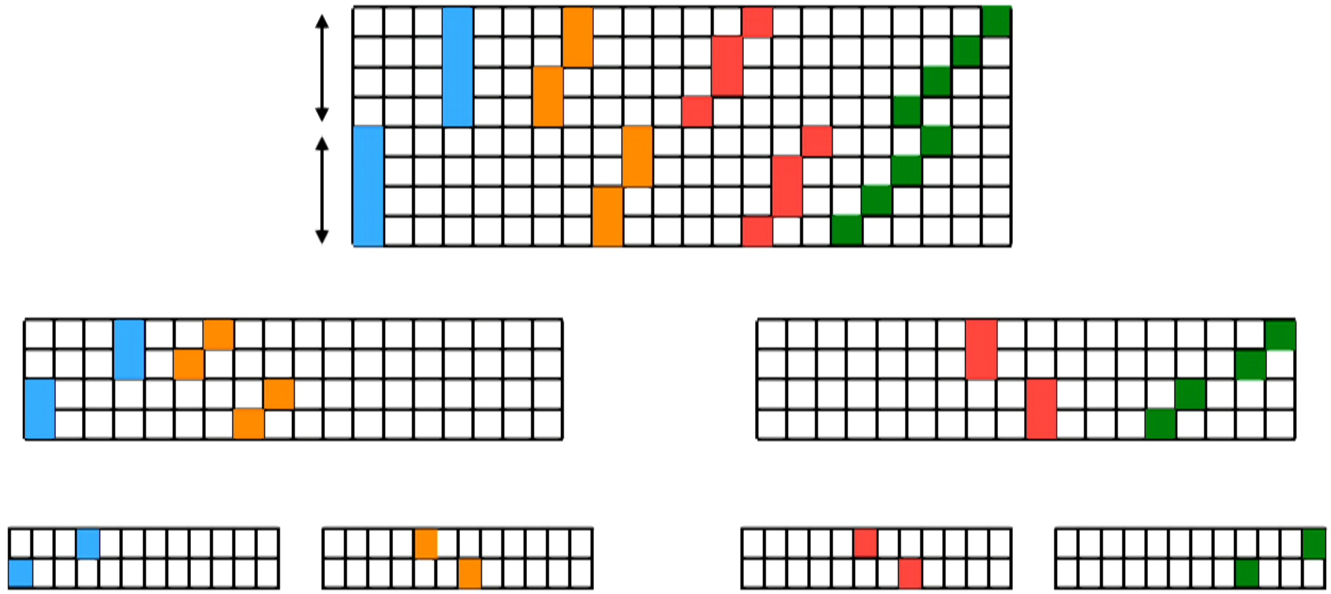
Output is two arrays, each half the size of the input array.



Tree dedispersion: the basic idea

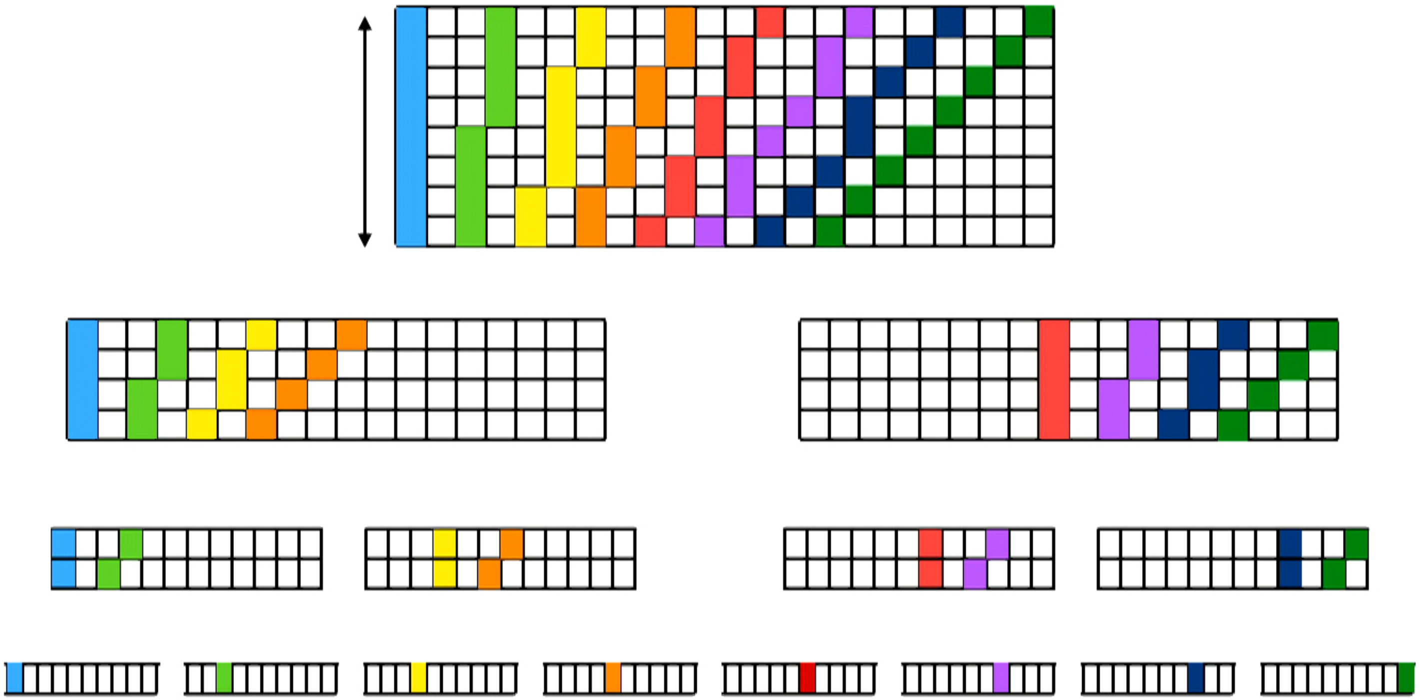
Second iteration: sum pairs into “pairs of pairs”.

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

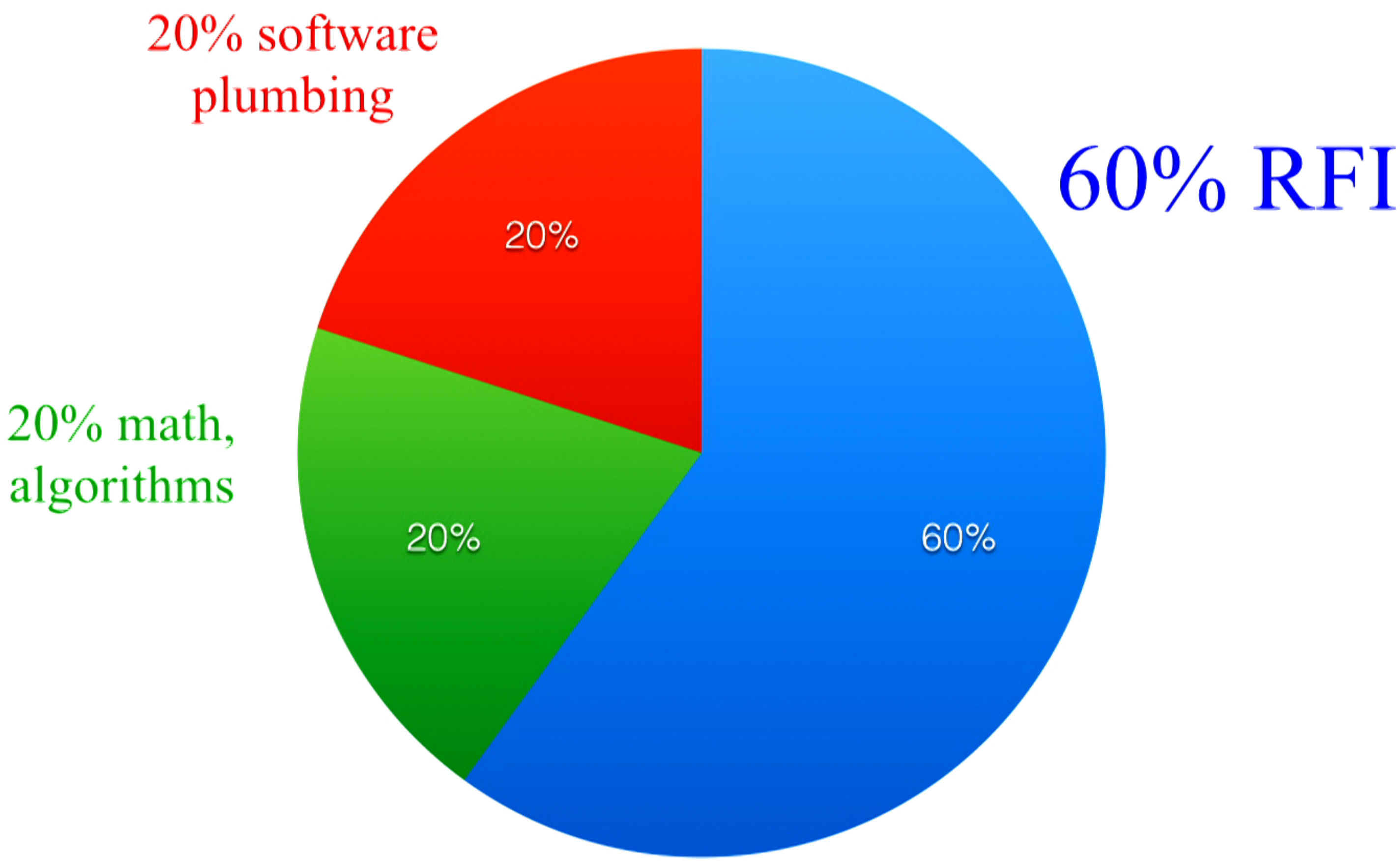


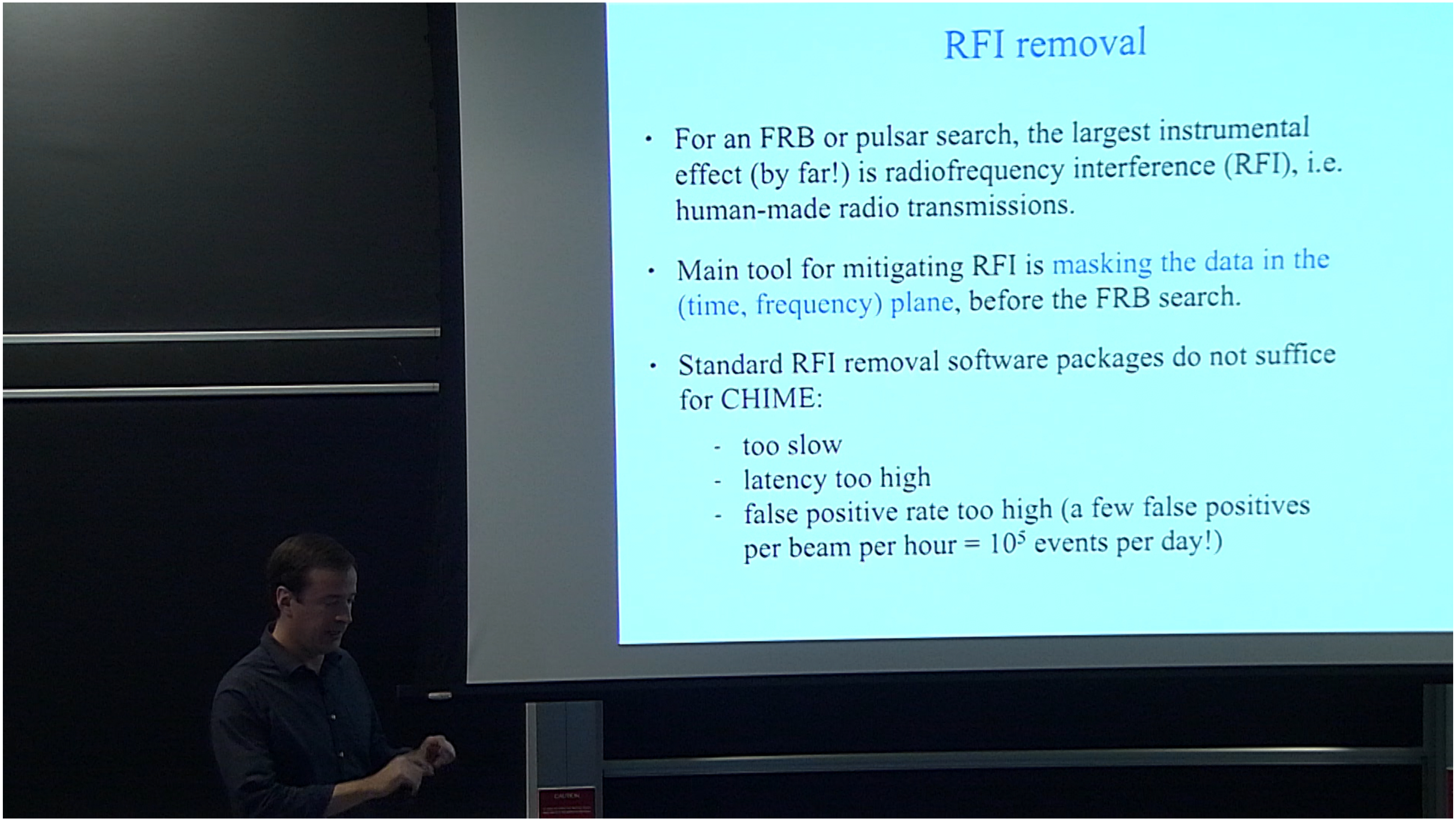
Tree dedispersion: the basic idea

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!)

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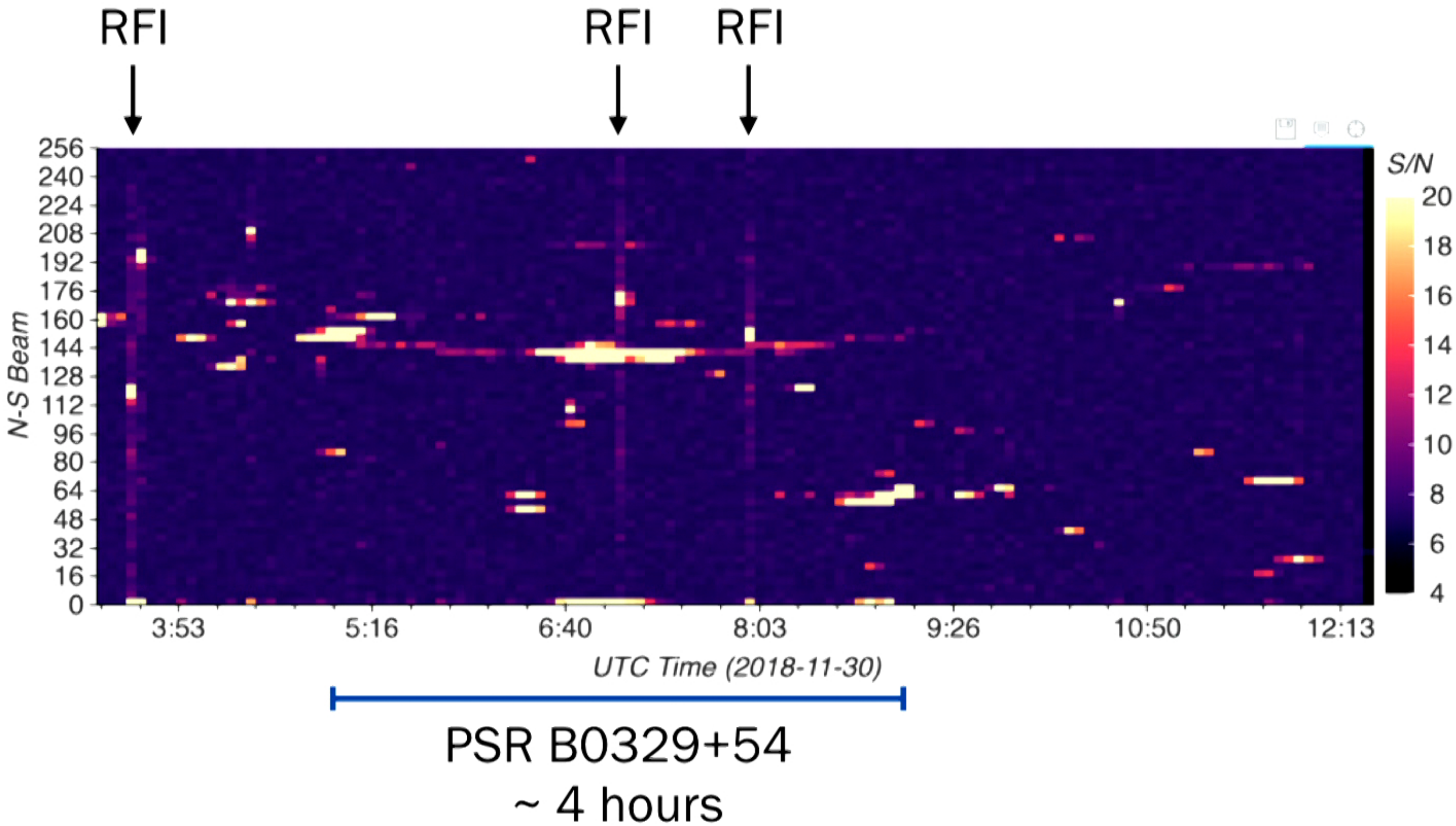
Per-beam triggers after RFI excision, dedispersion and peak finding

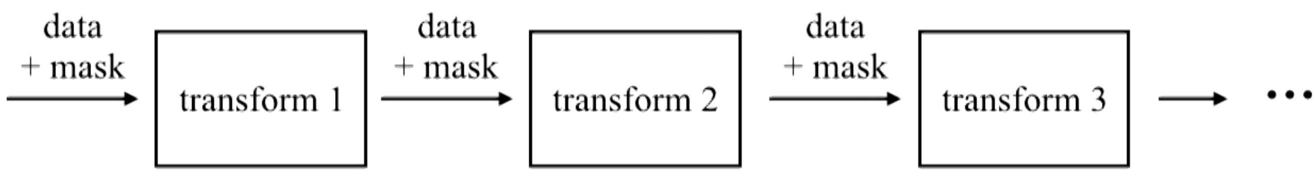


Signal collapsed over 4 East-West beams

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

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

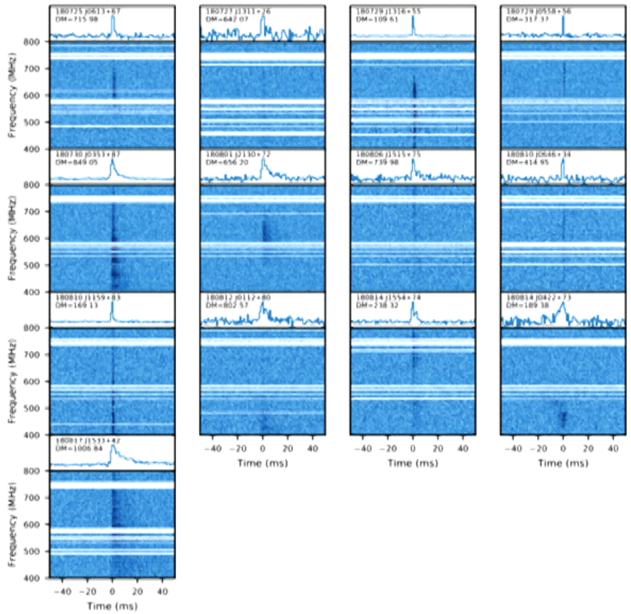
- January 2019 (“Paper 2”): new repeater discovered
  Nature 566 (2019) 235, arXiv:1901.04525

- June 2019 (“Paper 3”): original repeater detected
  ApJL accepted, arXiv:1906.11305

- September 2019 (“Paper 4”): 8 new repeaters discovered, in commissioning data up to March 2019
  ApJL accepted, arXiv:1908.03507

+ many more in progress!

Paper 1: 13 new FRB's from CHIME

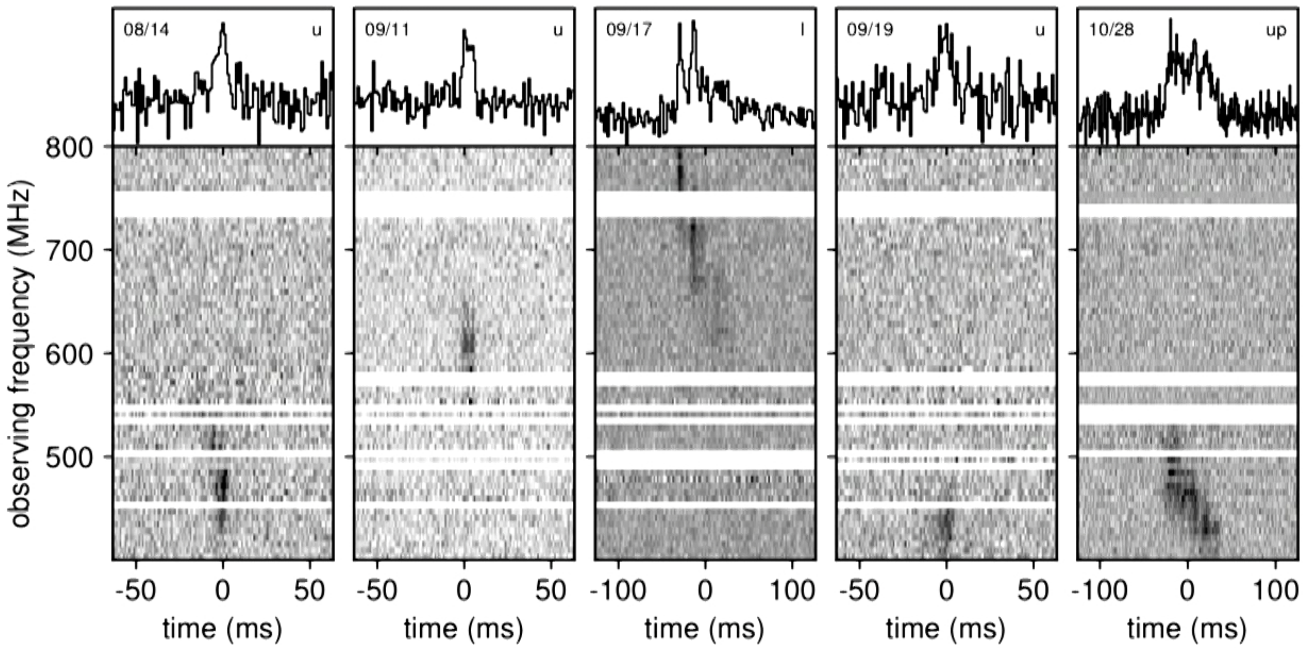


FRB	Width (ms)	DM (pc cm⁻³)	DM[illegible] (pc cm⁻³)	R.A. (hh:mm)	Dec. (dd:mm)	Dec. FWHM (deg)	SNR	τ (ms)
180725.J0613+67	0.31 [illegible]	715.98 [illegible]	71, 80	06:13	+67:04	0.34	34.5	1.18 [illegible]
180727.J1311+26	0.78 ± 0.16	642.07 ± 0.03	21, 20	13:11	+26:26	0.35	14.2	0.6 ± 0.2
180729.J1316+55	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 [illegible]	802.57 ± 0.04	83, 100	01:12	+80:47	0.38	19.8	1.9 [illegible]
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

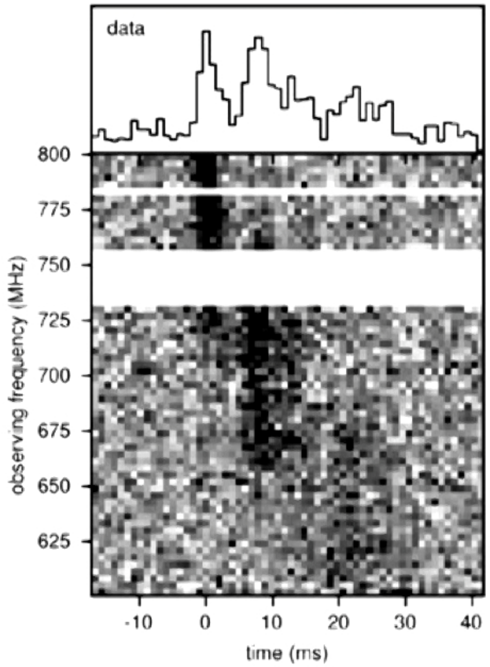
- At lower frequencies than previous FRB observations (400-800 MHz)
- Previously, almost all FRB's were detected at 1.4 GHz, with the exception of a few at ~800 MHz.
- All searches at <~ 200 MHz have been unsuccessful, suggesting a spectral cutoff.
- However, ~half of the CHIME FRB's are bright at 400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

Paper 2: New repeating FRB!

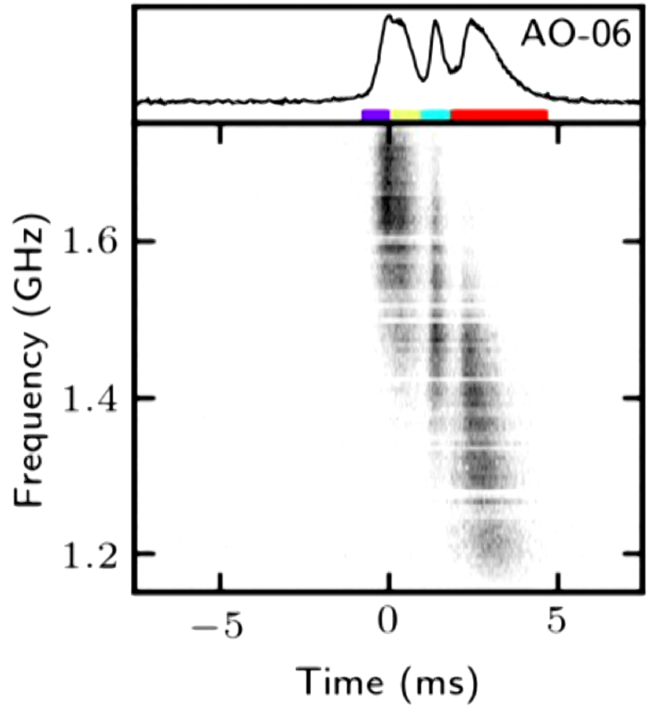
Dispersion measure: DM=189 (max galactic DM ~95 along its line of sight)



“Downward marching” pulse structure

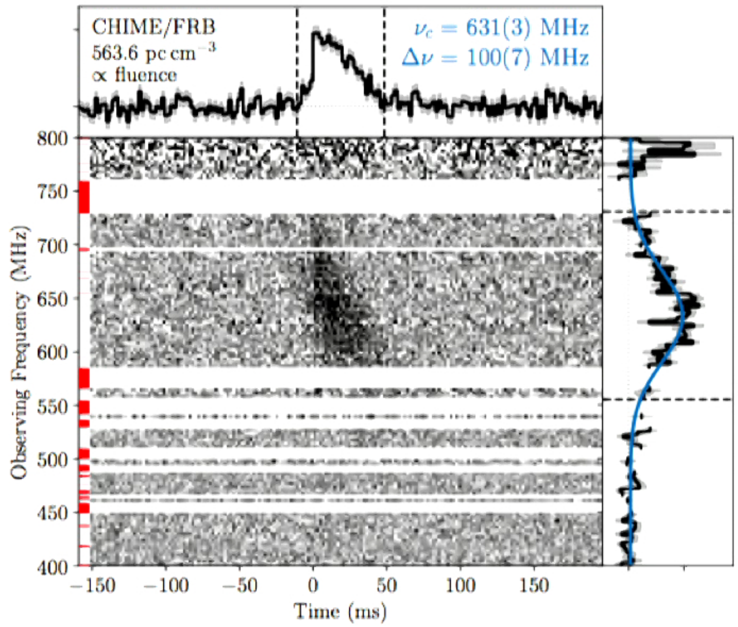


CHIME repeater



Original repeater

Paper 3: Original repeater detected

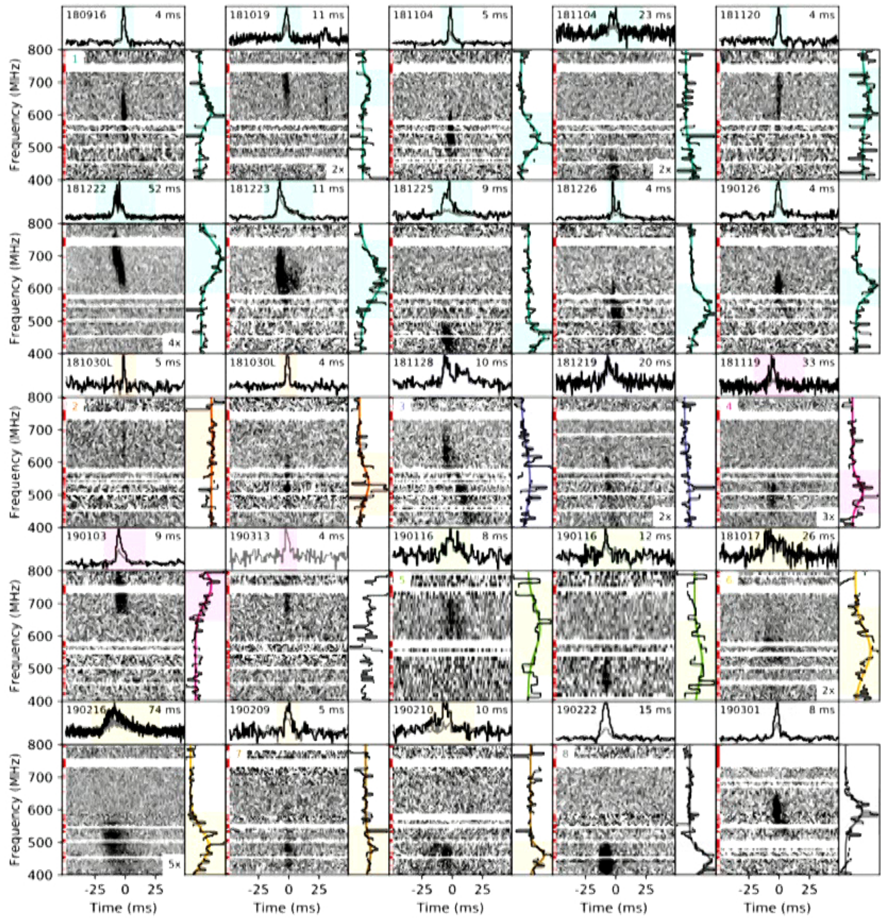


- Lowest frequency observation to date
- Dispersion measure is ~1% higher than previously reported values

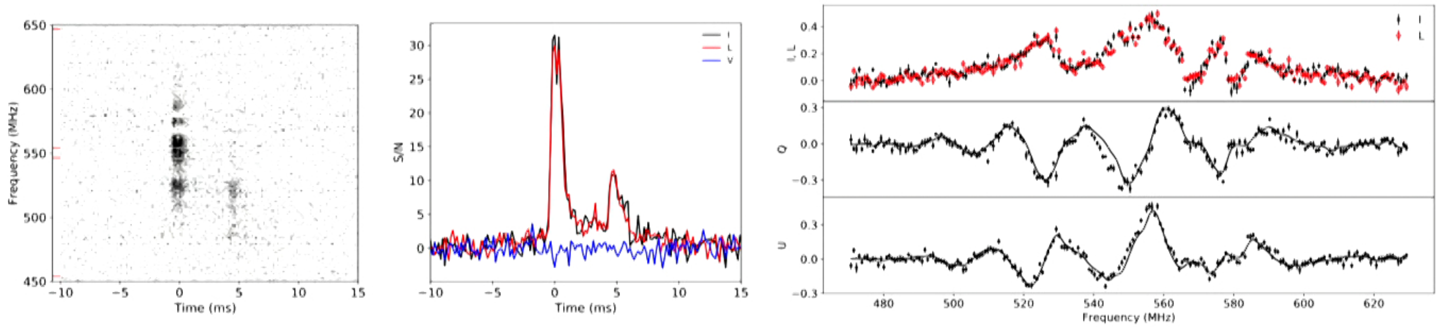
Paper 4: Eight new repeaters discovered

Source	Name[a]	R.A.[b] (J2000)	Dec.[b] (J2000)	l[c] (deg)	b[c] (deg)	DM[d] (pc cm^{-3})	DM$_{\rm NE2001}$[e] (pc cm^{-3})	DM$_{\rm YMW16}$[e] (pc cm^{-3})	N$_{\rm bursts}$	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′	+65°08′±9′	124.5	52.0	364.05(9)	34	26	3	19±9	2.6
		12h30m±6′	+65°06′±12′								
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

Paper 4: Eight new repeaters discovered



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.

Repeaters have wider pulses

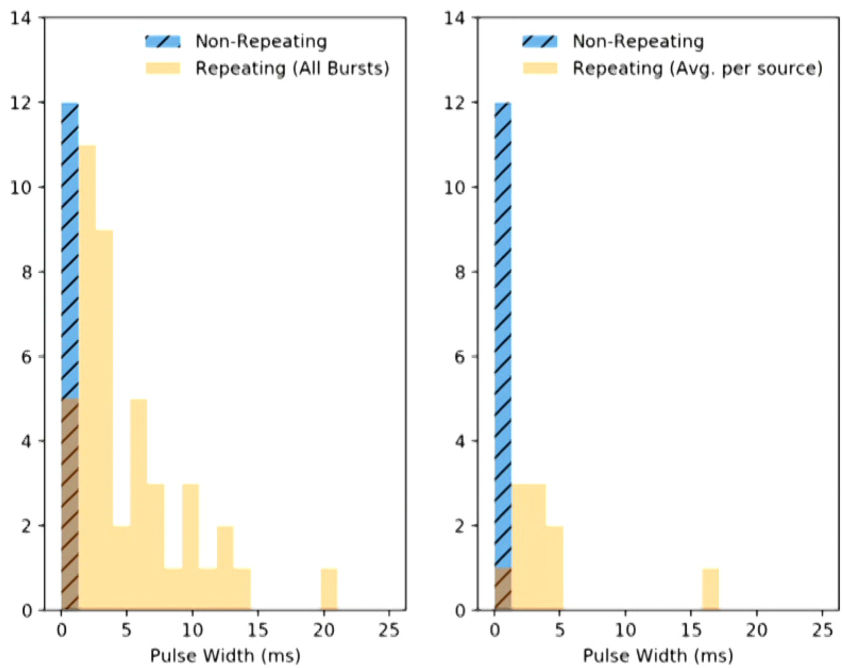


Figure 7. Distribution of intrinsic temporal widths for repeating and non-repeating FRB sources observed in the frequency range of 400–800 MHz. For repeating FRBs, the left panel shows the distribution of widths of the Gaussian spectral components for all bursts from each source while the right panel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

Concluding thoughts

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

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- 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

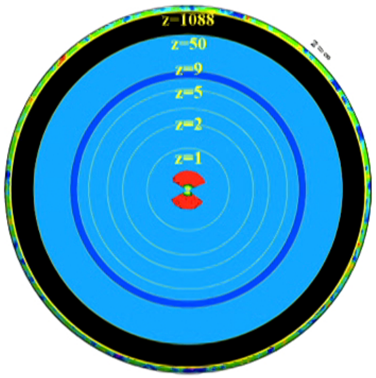
New technology under development (improves effective mapping speed by a factor ~8):

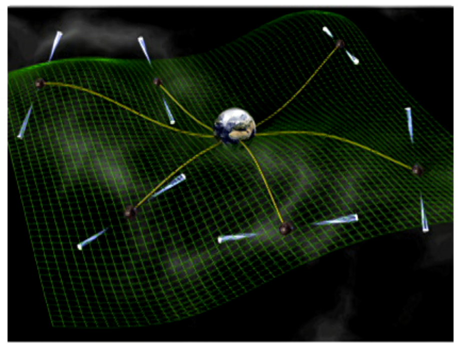
- Wide-band feeds (300-1500 MHz)
- Lower noise, aiming for T_{sys} ~30 K (CHIME is ~50 K)

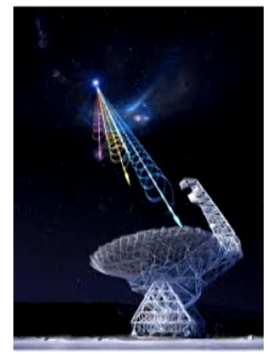
To consist of a large "core" interferometer at DRAO, plus outriggers at other North American locations TBD.

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!