Title: CHIME Telescope

Speakers: Kendrick Smith

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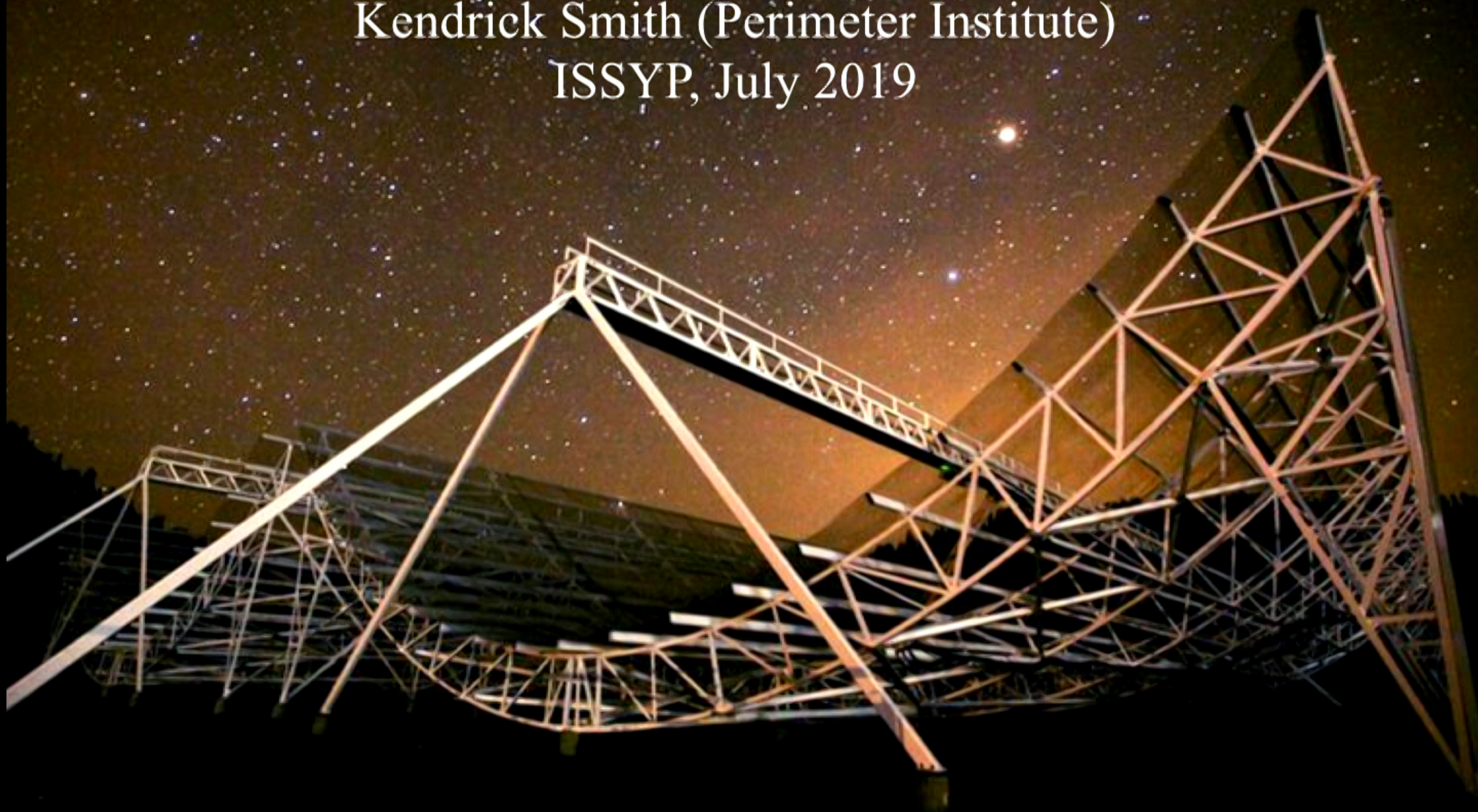
Abstract: Kendick Smith will discuss the CHIME telescope in this talk, which is part of the 2019 International Summer School for Young Physicists.

The CHIME telescope

Kendrick Smith (Perimeter Institute)

ISSYP, July 2019



The CHIME radio telescope

First new Canadian research telescope in 40 years!

CHIME collaboration

Lead institutions:

UBC 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

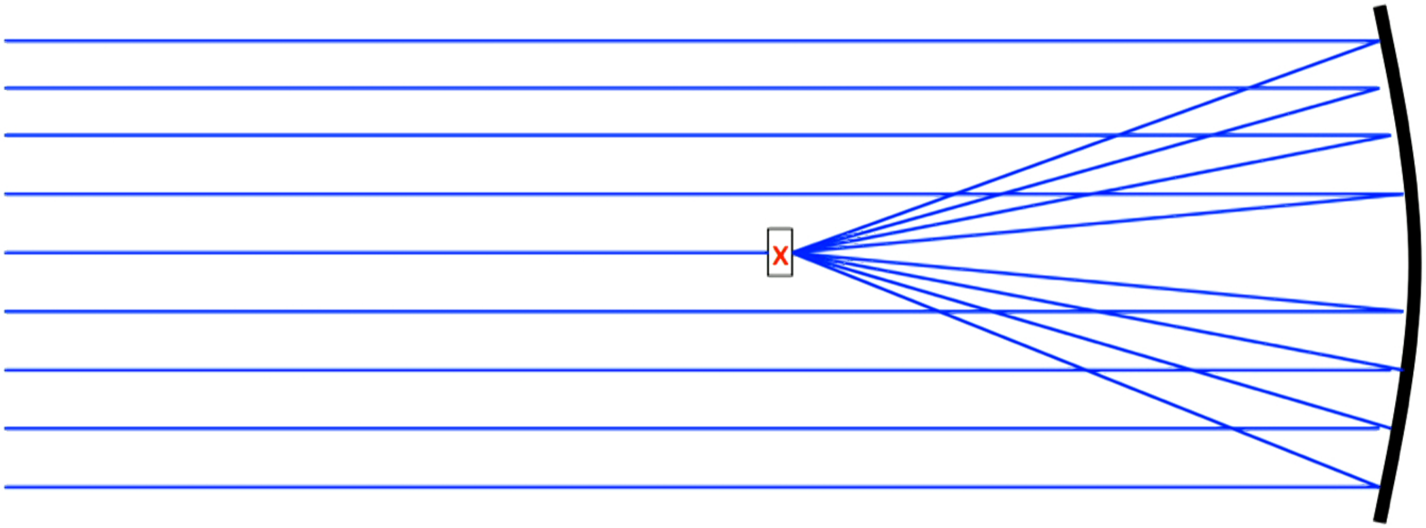
PI PERIMETER INSTITUTE

1. The CHIME concept
2. CHIME science goals
3. Computational challenges
4. The real-time CHIME FRB pipeline
5. CHIME FRB results
6. Concluding thoughts

CHIME

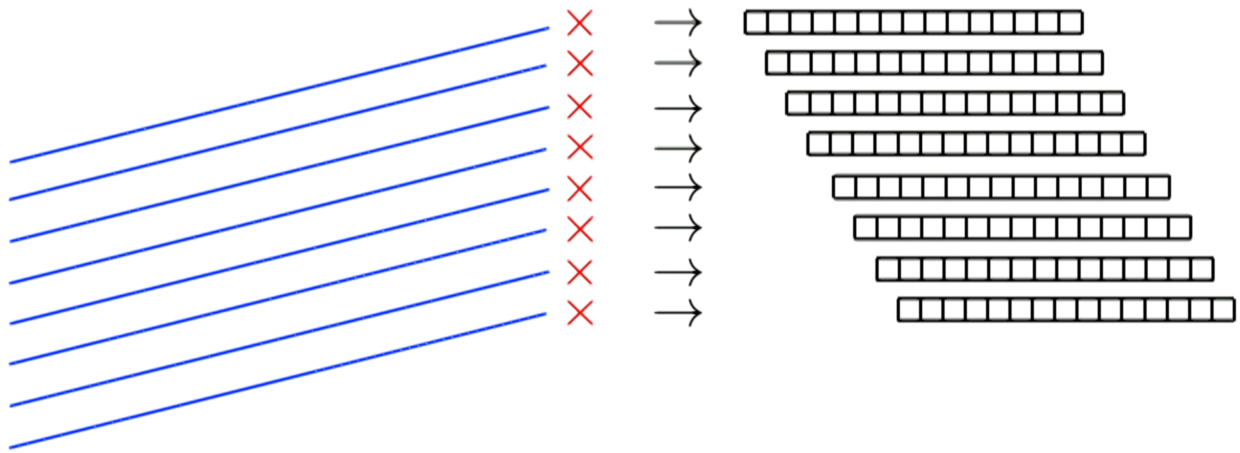
Traditional radio telescope

Single-feed telescope



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

Phased-array interferometer

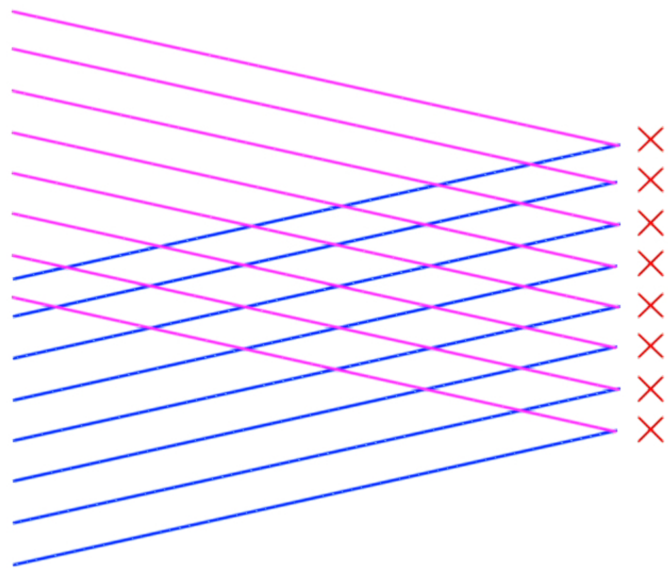


Dish is replaced by an array of antennas whose signals are digitized.

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

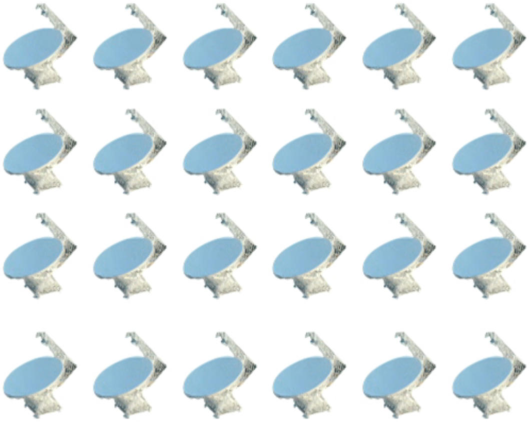


Copy the digitized signals and repeat the computation N times (in parallel). Equivalent to N telescopes pointed in different directions.

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!

=

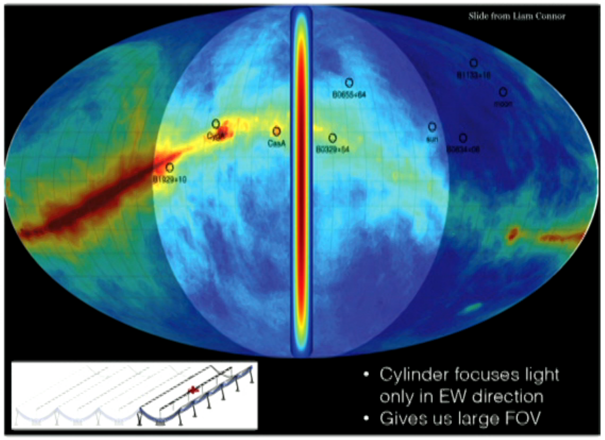


(+ 1000 more!)

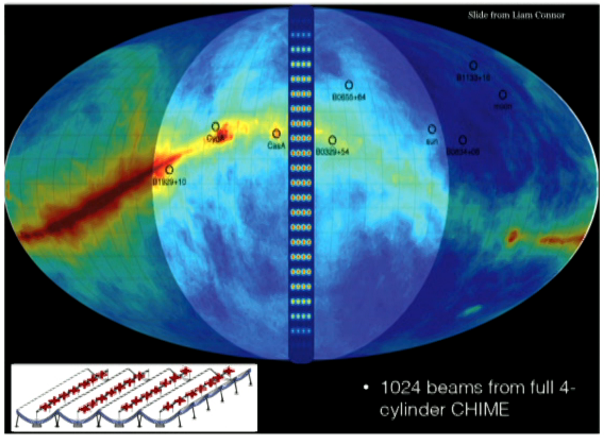
CHIME beamforming, cartoon form

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.



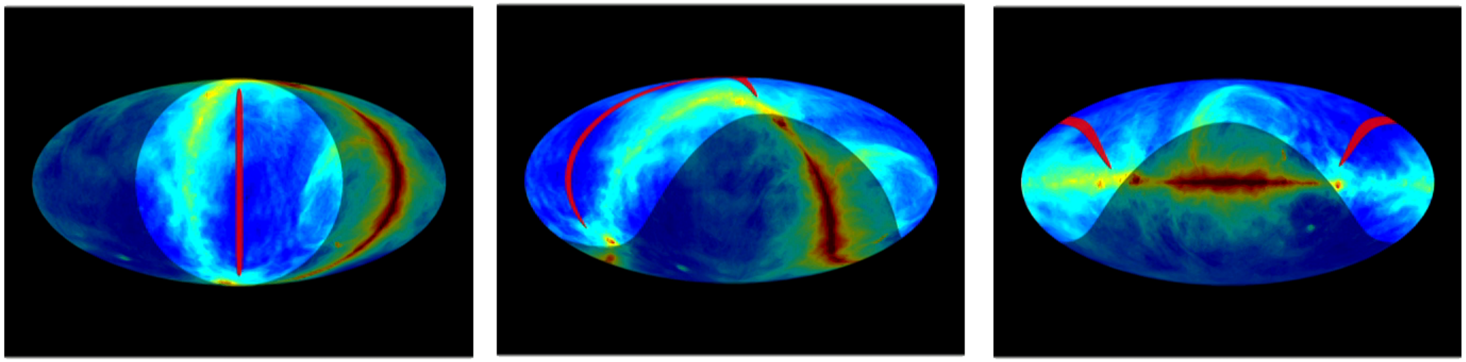
primary beam



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

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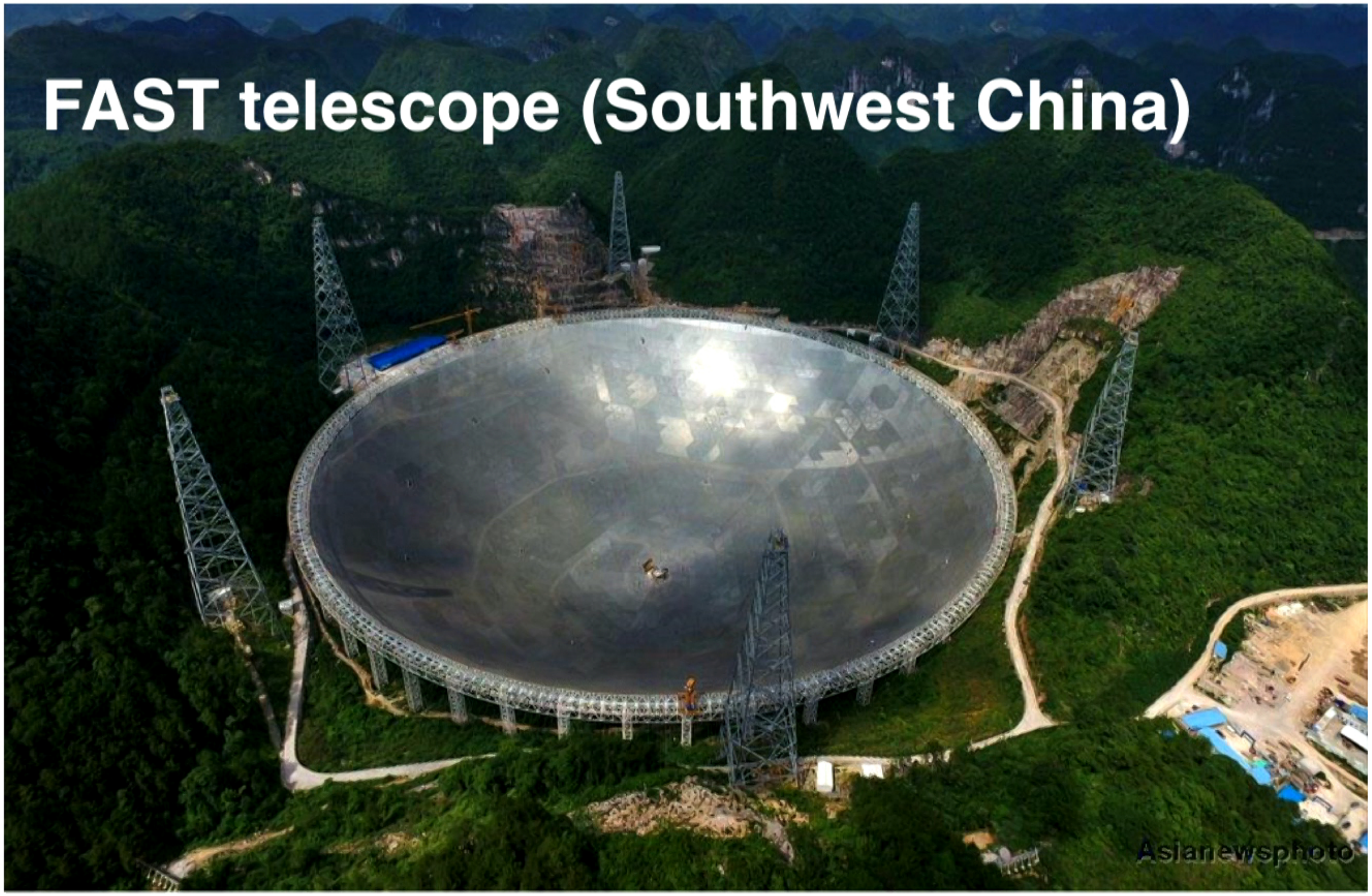

=  CHIME ?!

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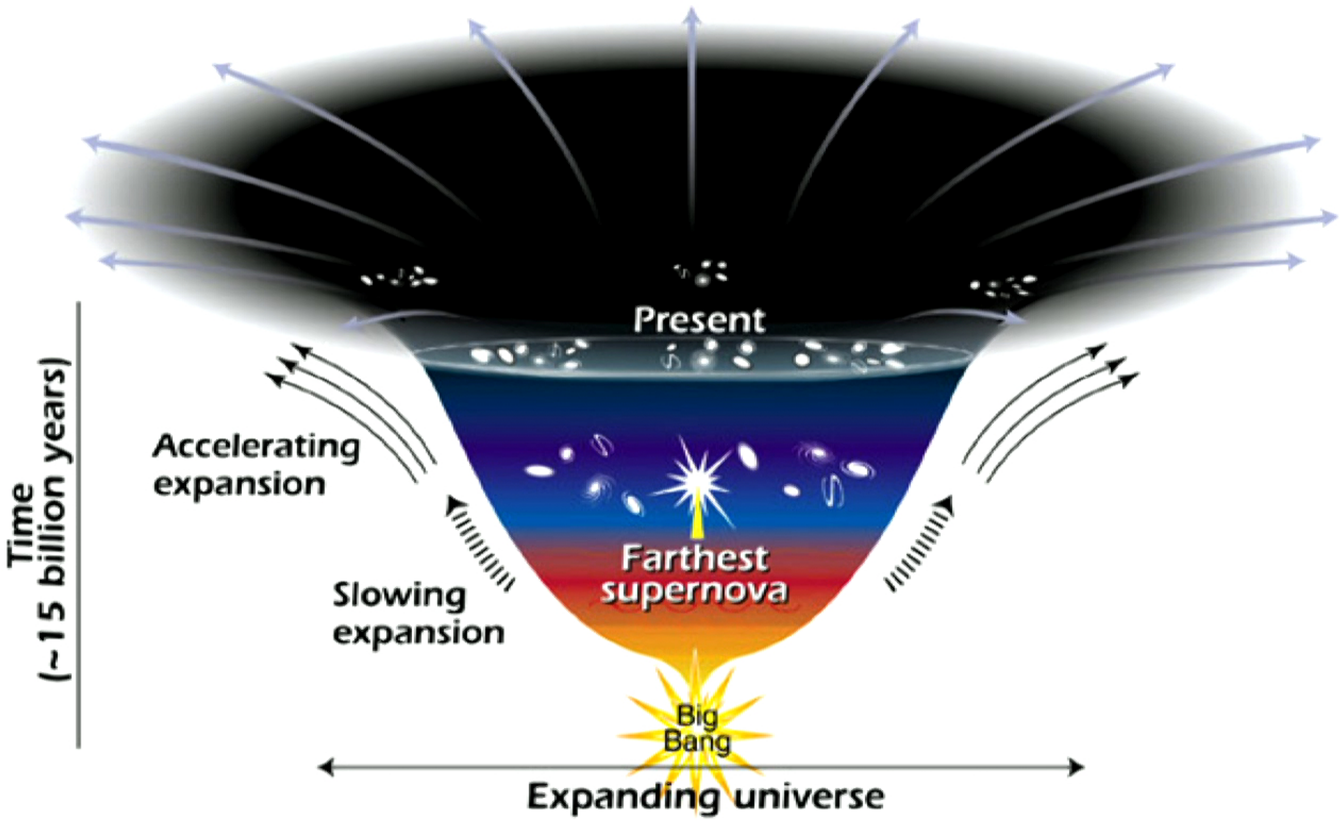
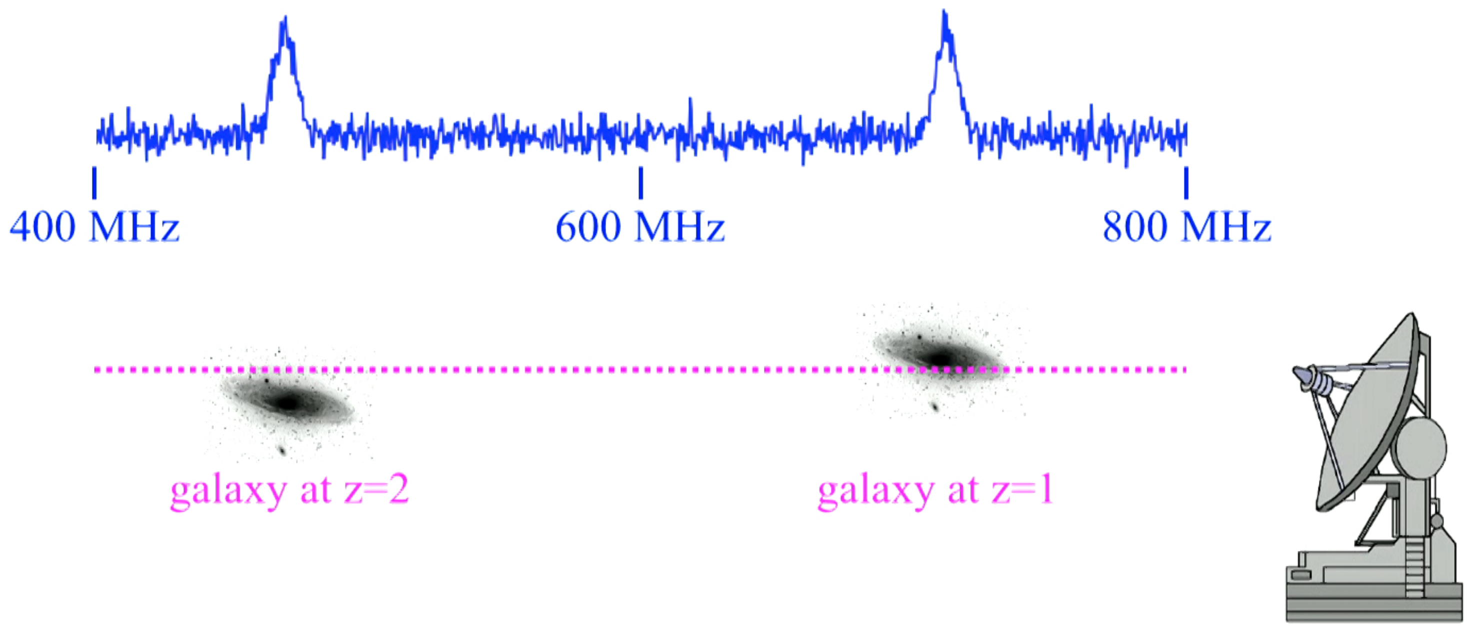
Science goal 1/3: What is dark energy?



21-cm cosmology

CHIME constrains cosmology by making a 3D map of neutral hydrogen on cosmological scales, via the 21-cm spectral line.

First consider the frequency spectrum of a single line-of-sight. Can be interpreted as a 1D noisy map, in the radial direction.



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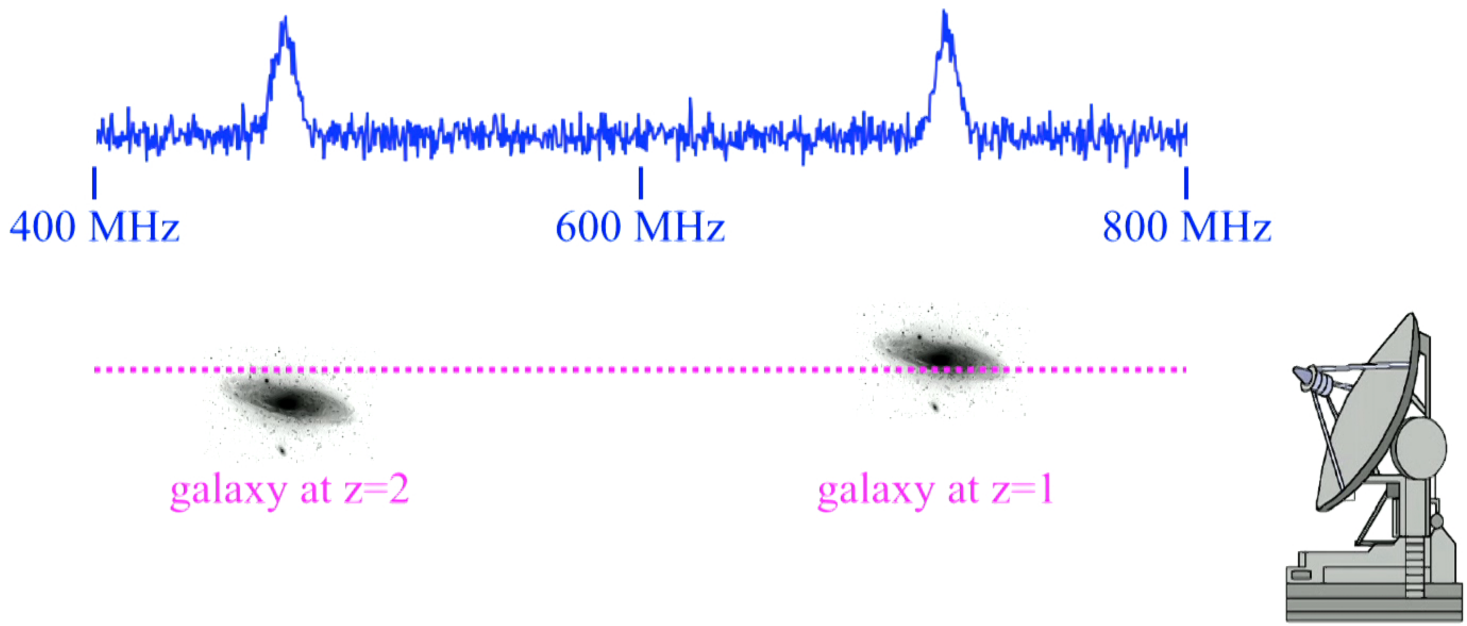

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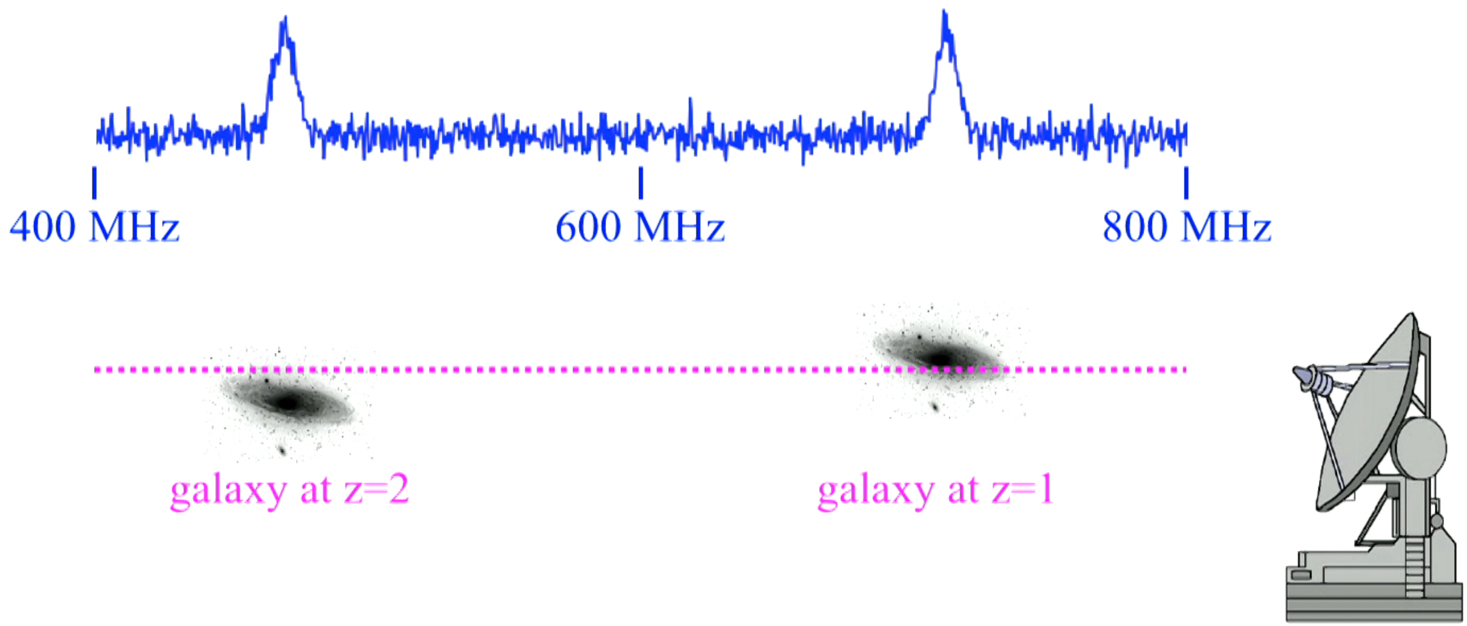
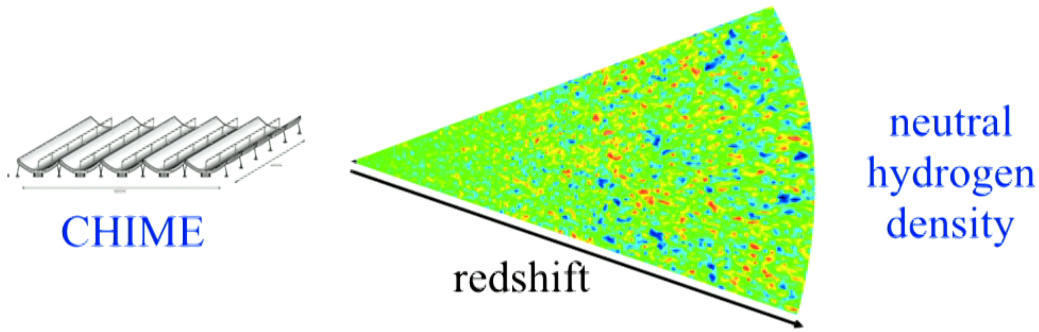


21-cm cosmology

CHIME measures a 1D spectrum at each 2D sky location (θ, ϕ). Get a 3D map of neutral hydrogen in the universe. (Individual galaxies are not resolved.)



Through statistical analysis of this map, the expansion history can be reconstructed. (This is not supposed to be obvious! Uses a statistical effect called "baryon acoustic oscillations" which would take a few slides to explain.)

21-cm cosmology

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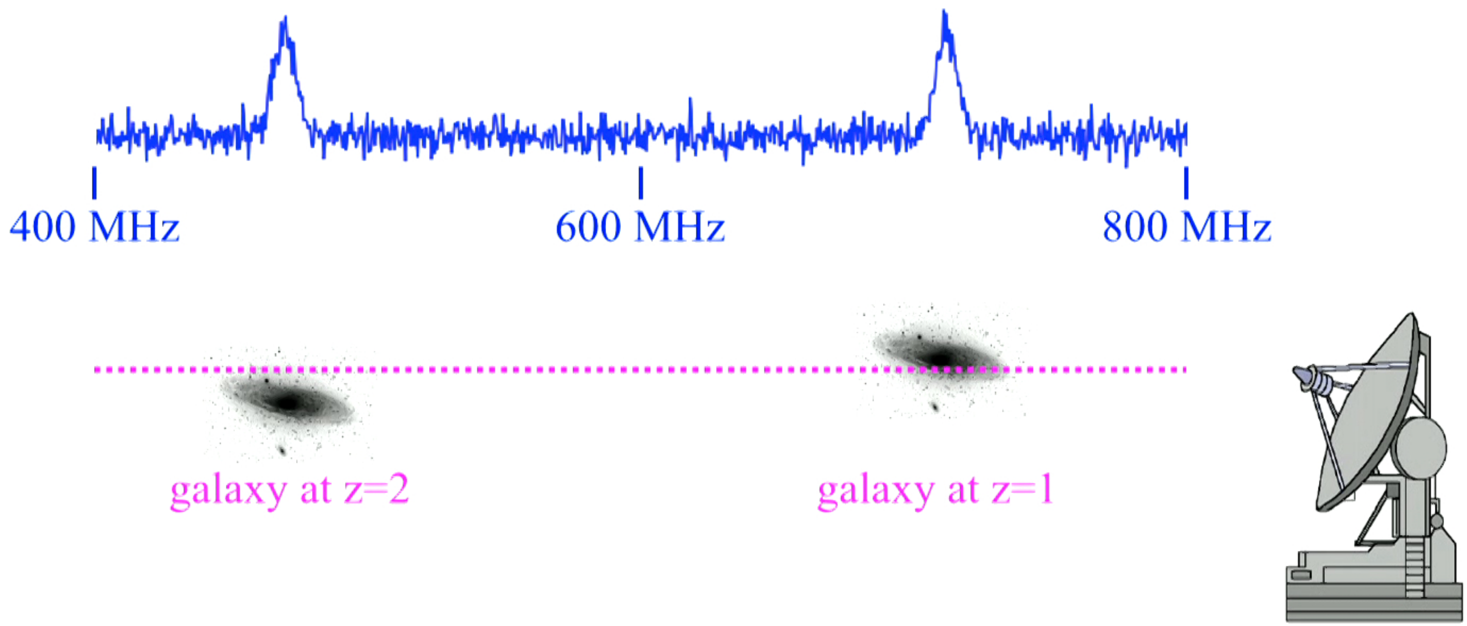
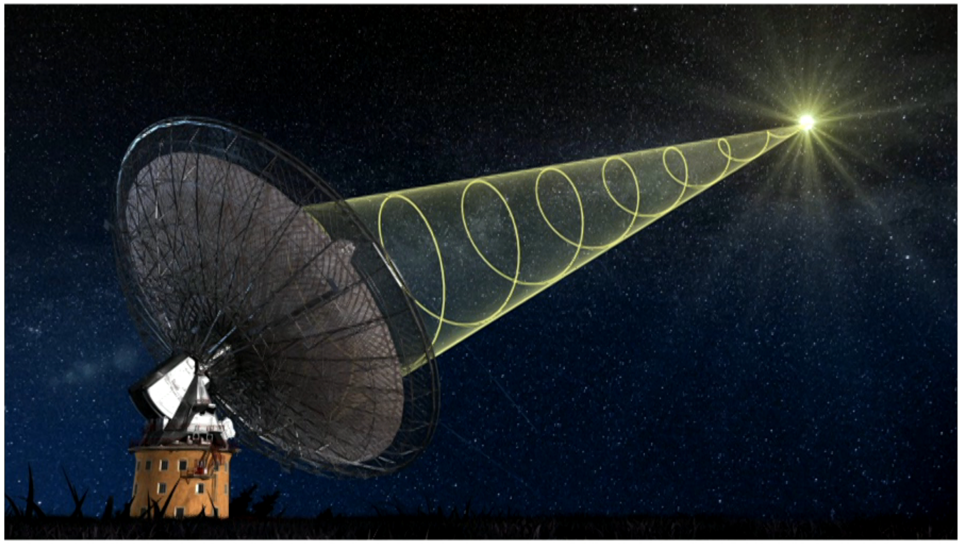
First consider the frequency spectrum of a single line-of-sight. Can be interpreted as a 1D noisy map, in the radial direction.



Science goal 2/3: What are fast radio bursts?

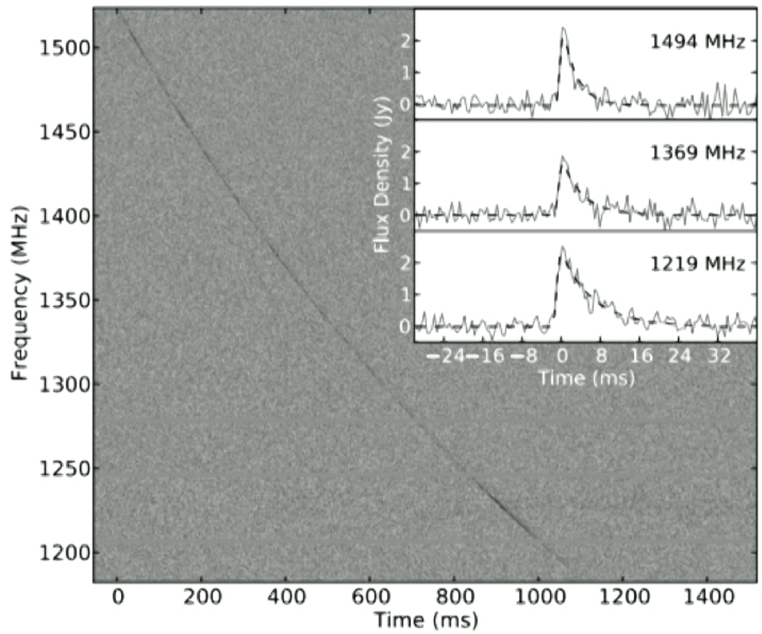
Fast radio bursts: a phenomenon we can't explain. Very occasionally, we see an intense pulse of radio waves from billions of light years away.



Fast radio bursts

FRB's are dispersed: arrival time of the pulse depends on radio frequency. (Delay is proportional to f^{-2}.)

This dispersion relation arises if the pulse has passed through a plasma of free electrons before reaching us.



Fast radio bursts

FRB's are dispersed: arrival time of the pulse depends on radio frequency. (Delay is proportional to f^{-2}.)

This dispersion relation arises if the pulse has passed through a plasma of free electrons before reaching us.

FRB's have very large dispersion, suggesting that the pulse originated at cosmological distances, far outside our galaxy.

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

Due to its high mapping speed, we anticipated that CHIME will discover significantly more FRB's than all other radio telescopes combined (!)

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

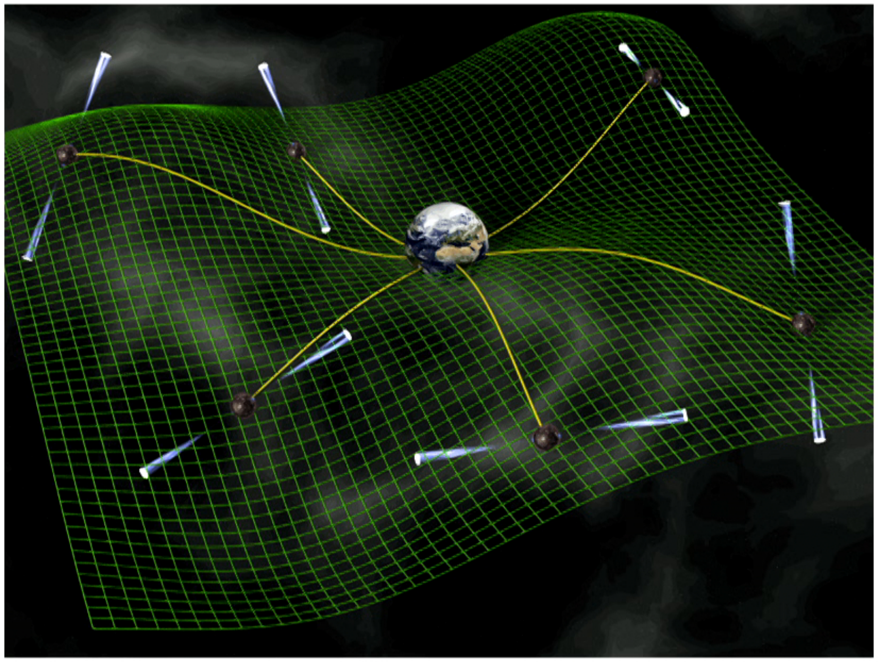
arxiv:1810.05836

Science goal 3/3: Finding new pulsars

A pulsar is a rapidly spinning neutron star with a narrow beam. We see pulses at regular intervals, when the beam sweeps over the Earth.

CHIME will be incredibly powerful for finding new pulsars.

The most exciting application: gravitational wave astronomy!
A new way to learn about black holes.



CHIME forecasts: summary

- Due to its high mapping speed, CHIME has amazing forecasts in several areas (cosmology, fast radio bursts, pulsar science).
- CHIME is relatively inexpensive ($15M), and any one of these forecasts would fully justify a larger project.
- Too good to be true?

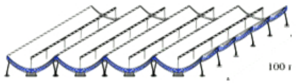
The challenge

	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	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).

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

CHIME computing



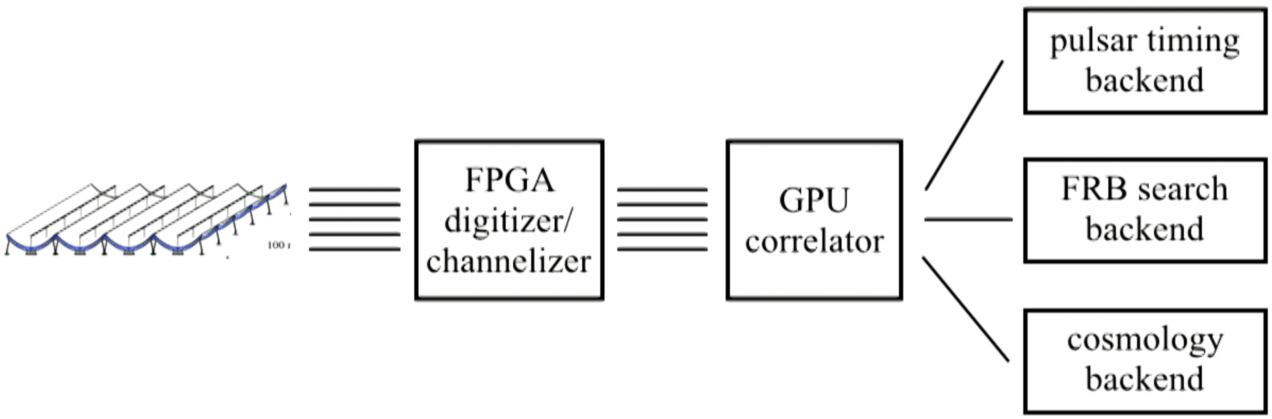
FPGA digitizer/ channelizer

800 GB/sec

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

- Similar to total cell phone traffic in North America
- A few percent of the global internet

CHIME computing



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

- Similar to total cell phone traffic in North America
- A few percent of the global internet

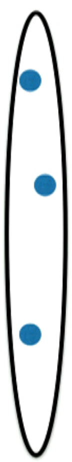
Each box in the diagram is a large supercomputer!

Each backend asks the correlator for a different data stream over the network.

CHIME computing

Each backend asks the correlator for a different data stream over the network. For example:

"Pulsar timing backend"

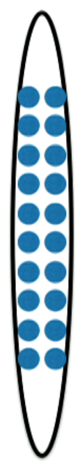


receives digitized electric field

with nanosecond sampling

at 10 specified sky locations

"FRB backend"



receives intensity, obtained from electric field by time-downsampling and polarization-averaging

with millisecond sampling

at a regular array of 1024 sky locations

CHIME computing

The computational challenges are immense!

For example, the FRB search (this is what I worked on):

- Is ~200 times larger (in data volume) than any previously performed FRB search.
- Requires separating FRB's from RFI (human-made radio signals) at ~1000 times the previous best accuracy.
- Must be done in real time, while the data is in a moving window (only a tiny fraction of the data can ever be saved to disk).
- Must build supercomputer from scratch on a modest budget with limited infrastructure.

=  CHIME?

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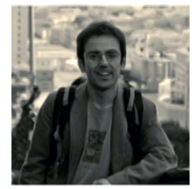
“bonsai”: CHIME FRB search software

The CHIME FRB search algorithm is:

- orders of magnitude faster than other search software
- near statistically optimal
- real-time, (few-second) latency
- runs on a dedicated 2560-core cluster, searches 1.5 PB/day

Kendrick Smith

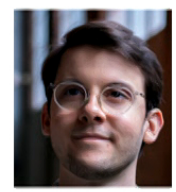
Dustin Lang



Masoud Rafiei-Ravandi

Utkarsh Giri

Maya Burhanpurkar



Alex Roman

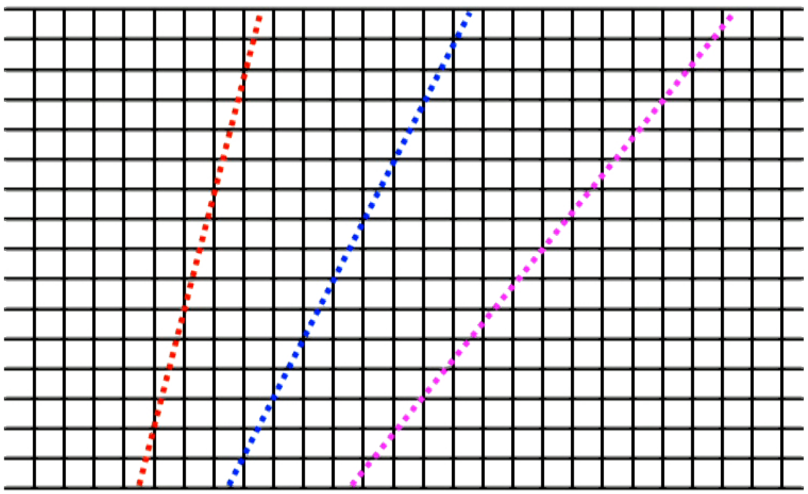
```
void transpose(float *dst, const float *src, int n)
{
    for (int i = 0; i < n; i++)
        for (int j = 0; j < n; j++)
            dst[i*n+j] = src[j*n+i];
}
```

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);
        }
    }
}
```

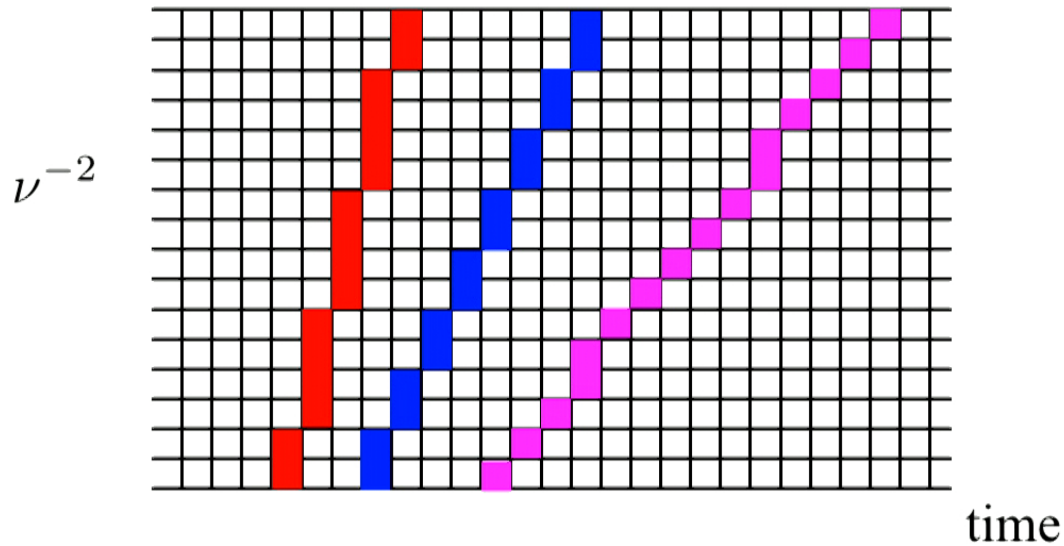
New search algorithms

The basic idea is shown by the following slides. Suppose we have a 2D array of numbers and we want to sum over all straight lines as shown.



New search algorithms

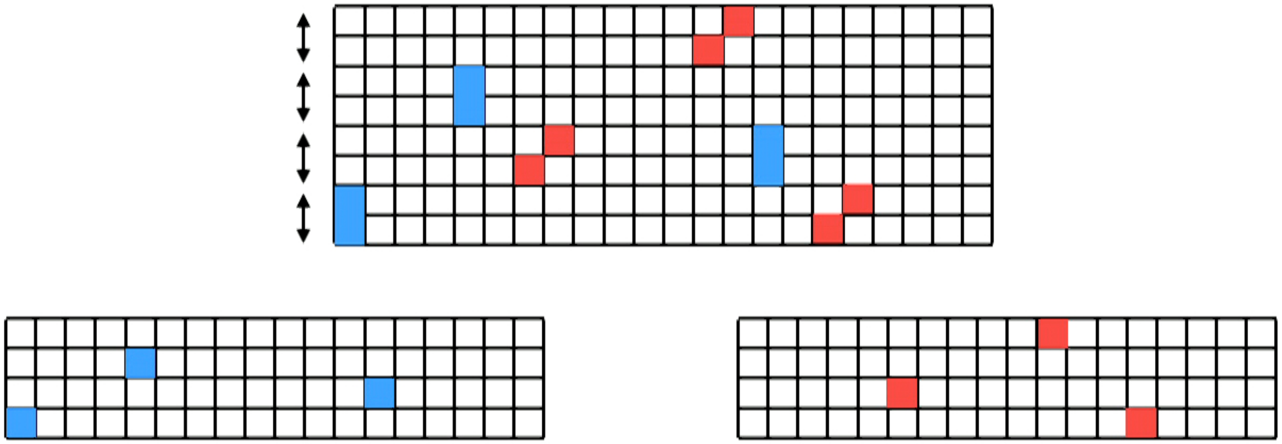
Our algorithm ends up approximating each straight-line track by a jagged sum of samples. The sums are built up recursively as explained in the next few slides.



New search algorithms

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.



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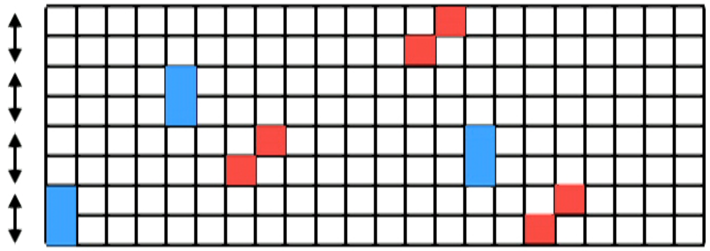
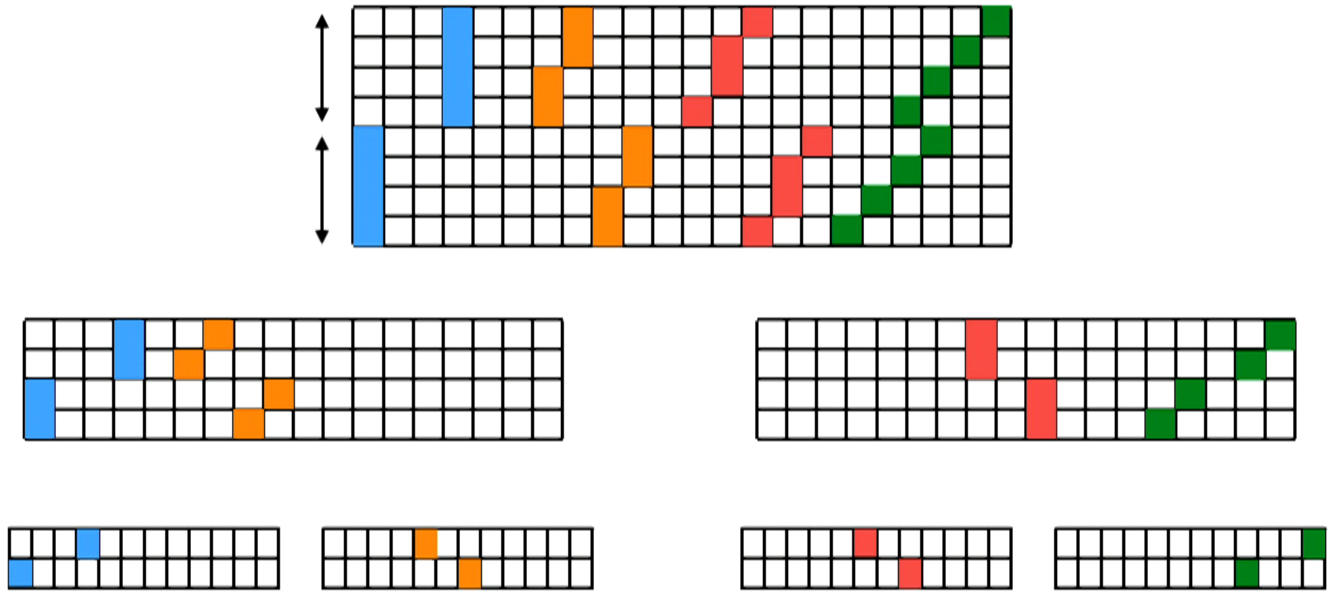


New search algorithms

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

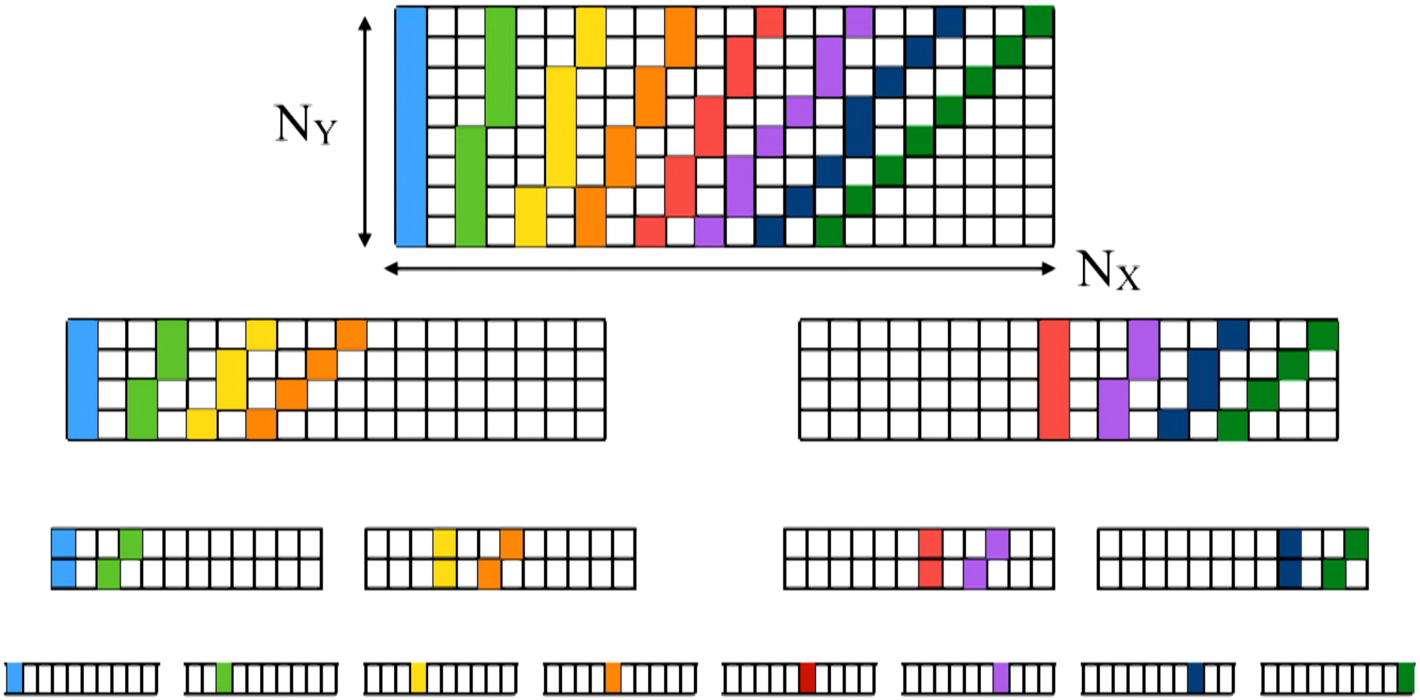
Frequency channels have now been merged in quadruples. Within each quadruple, there are four possible sums.



New search algorithms

Last iteration: all channels summed.

Computational cost of tree algorithm is proportional to $N_X N_Y \log(N_Y)$. A "brute force" algorithm would be $N_X N_Y^2$.



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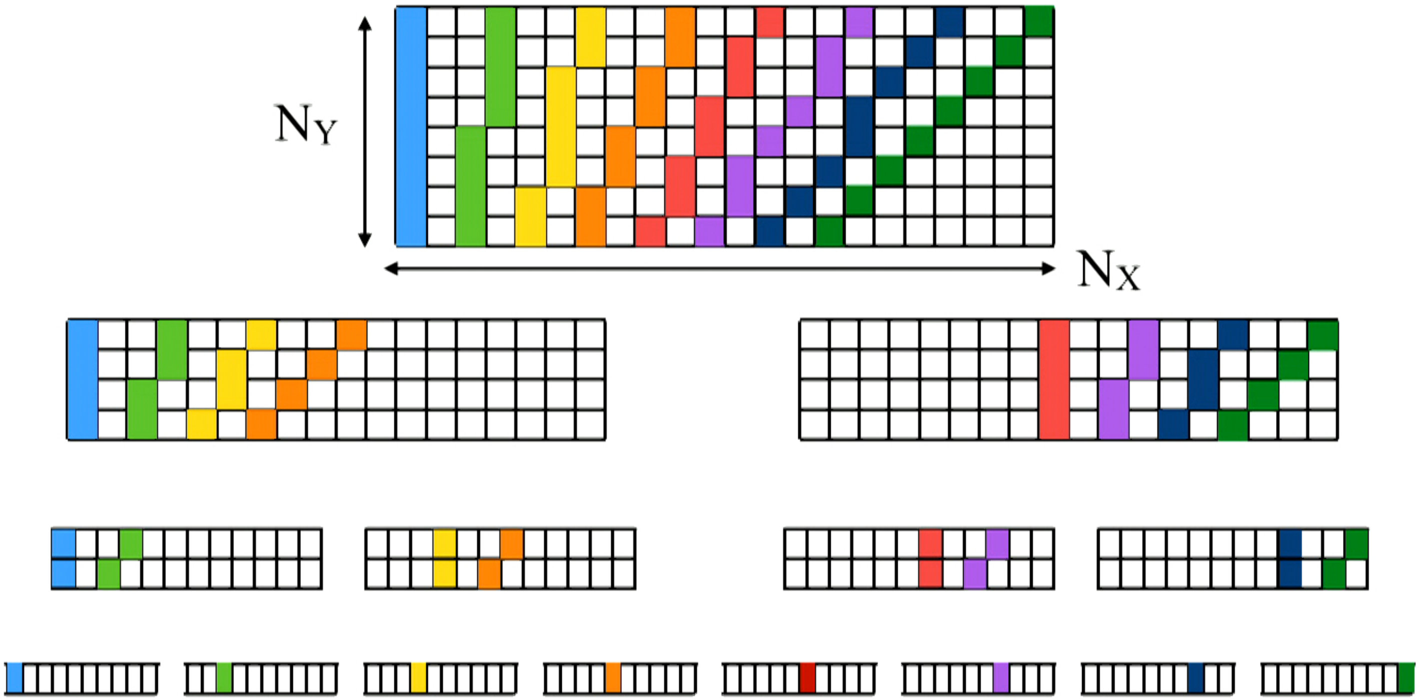

1. The CHIME concept
2. CHIME science goals
3. Computational challenges
4. The real-time CHIME FRB pipeline
5. CHIME FRB results
6. Concluding thoughts

2013: CHIME project begins

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

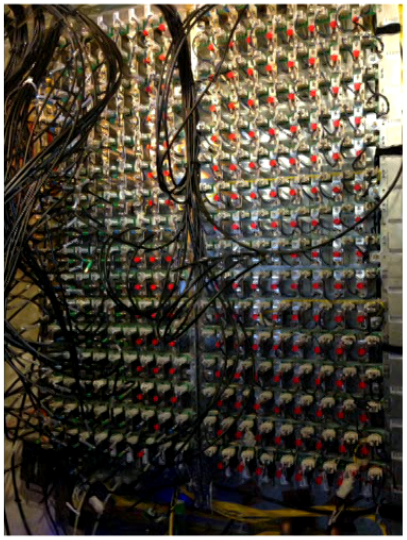
CHIME radio telescope to look 11 billion years into past

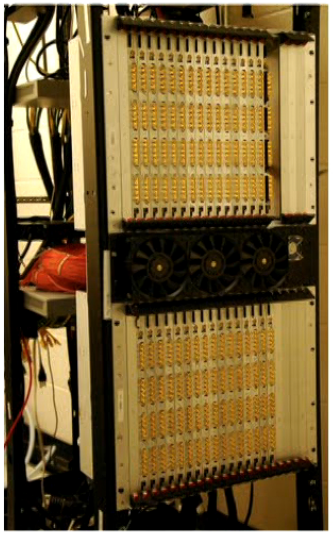
The Canadian Press · Posted: Jan 25, 2013 9:18 AM ET | Last Updated: January 28, 2013

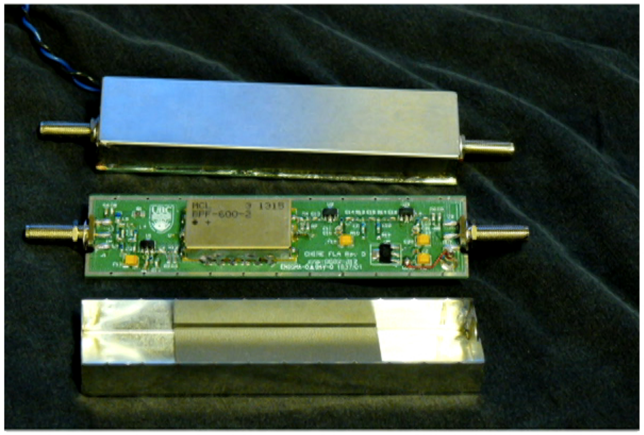
2015: CHIME "pathfinder" (~10% scale)

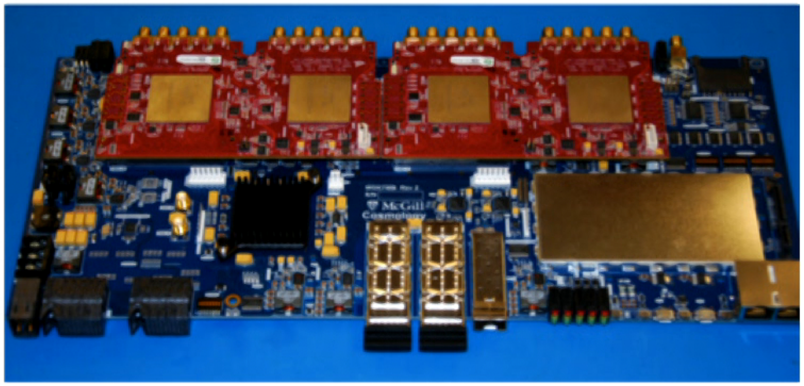
CHIME pathfinder

2017: Full CHIME telescope






850W / node
(50Gop/W)

25 July 2018: First FRB detected with CHIME!

First detection of fast radio bursts between 400 and 800 MHz by CHIME/FRB

ATel #11901; ***P. J. Boyle (McGill University) for the CHIME/FRB Collaboration***
*on **1 Aug 2018; 01:12 UT***
Credential Certification: Patrick Boyle (patrick.boyle@mcgill.ca)

Subjects: Radio, Fast Radio Burst

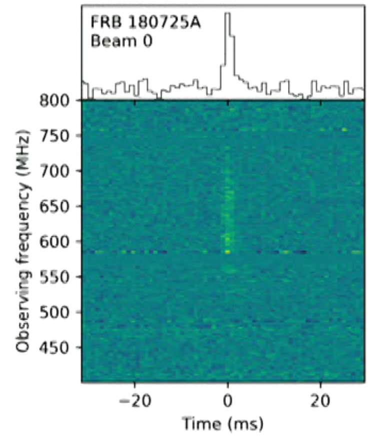
Tweet | Recommend 246

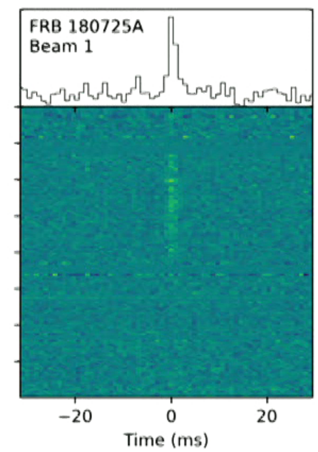
The Canadian Hydrogen Intensity Mapping Experiment (CHIME; www.chime-experiment.ca) is a transit radio telescope consisting of four 20m x 100m cylindrical reflectors oriented North/South, plus a powerful F-X correlator, located at the Dominion Radio Astrophysical Observatory near Penticton, British Columbia, Canada. The CHIME Fast Radio Burst (FRB) Project (CHIME/FRB Collaboration, ApJ, in press, arXiv:1803.11235) forms 1024 independent stationary intensity beams with 1-ms time sampling and 16k frequency channels over a range of 400 - 800 MHz. CHIME/FRB is a uniquely fast survey instrument that can search for FRBs over an instantaneous field of view of ~200 square degrees in real time.

During its ongoing commissioning CHIME/FRB detected FRB 180725A on 2018 July 25 at 17:59:43.115 UTC (topocentric, at 400 MHz). The automated pipeline triggered the recording to disk of ~20 seconds of buffered raw intensity data around the time of the FRB. The event had an approximate width of 2 ms and was found at dispersion measure 716.6 pc/cm^3 with a signal-to-noise ratio S/N ~20.6 in one beam and 19.4 in a neighbouring beam. The centres of these, approximately 0.5 deg wide and circular beams, were at RA, Dec = (06:13:54.7, +67:04:00.1; J2000) and RA, Dec = (06:12:53.1, +67:03:59.1; J2000). However, precise localisation of the source and a flux estimate await further commissioning and calibration. The expected maximum Galactic line-of-sight dispersion measure in the source's direction is 69 pc/cm^3 (from the NE2001 model) or 81 pc/cm^3 (from the YMW16 model). The observed DM is far in excess of these values, even after accounting for the systematic uncertainties in the Galactic-DM models, confirming the identification of this event as an FRB. The event is clearly detected at frequencies as low as 580 MHz and represents the first detection of an FRB at radio frequencies below 700 MHz.

The de-dispersed frequency versus time plots for both beams can be found at the link below. Some frequency channels with terrestrial radio frequency interference have been zero-weighted. We do not find compelling evidence of scattering in the burst profile, and we caution against over-interpreting the band-limited structure of the pulse spectrum, as the data have not been corrected for frequency-dependent beam sensitivity. Further observations to search for repeated bursts at all wavelengths are encouraged.

Link to plot: FRB 180725A 'http://chime-experiment.ca/figures/chimefrb_1st_event.pdf'





http://www.astronomerstelegram.org/?read=11901

Late Aug 2018: 13 new FRB's discovered

(Total number found by all other telescopes: 52)

nature
International journal of science

Letter | Published: 09 January 2019

This is an unedited manuscript that has been accepted for publication. Nature Research are providing this early version of the manuscript as a service to our customers. The manuscript will undergo copyediting, typesetting and a proof review before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers apply.

Observations of fast radio bursts at frequencies down to 400 megahertz

The CHIME/FRB Collaboration

Nature (2019) | Download Citation

arxiv:1901.04524

nature
International journal of science

Letter | Published: 09 January 2019

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A second source of repeating fast radio bursts

The CHIME/FRB Collaboration

Nature (2019) | Download Citation

arxiv:1901.04525

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Technology & Science

Canadian astronomers discover 2nd mysterious repeating fast radio burst

nature

NEWS · 07 JANUARY 2019

CORRECTION 07 JANUARY 2019

Bevy of mysterious fast radio bursts spotted by Canadian telescope

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

SPACE + SCIENCE

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

The Guardian

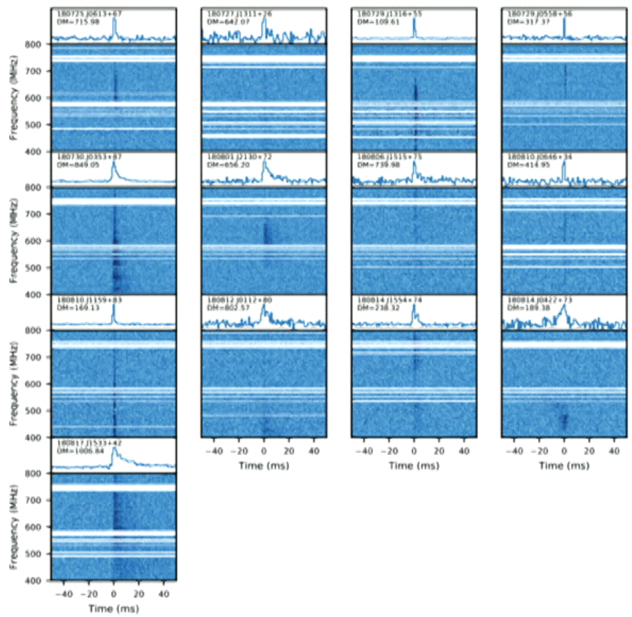
Alien life

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

!!!

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	$1.25^{+0.49}_{-0.47}$	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

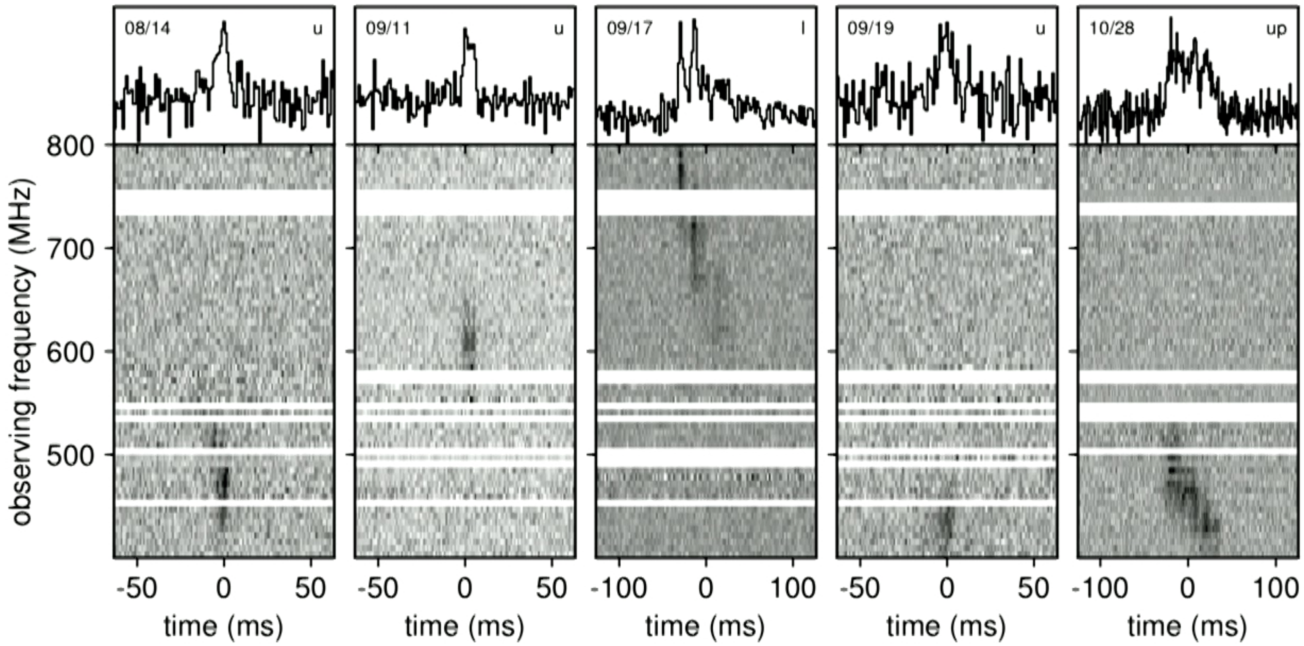
- At lower frequencies than previous FRB observations (400-800 MHz)
- Previously, almost all FRB's were detected at 1.4 GHz, with the exception of a few at ~800 MHz.
- All searches at <~ 200 MHz have been unsuccessful, suggesting a spectral cutoff.
- However, ~half of the CHIME FRB's are bright at 400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

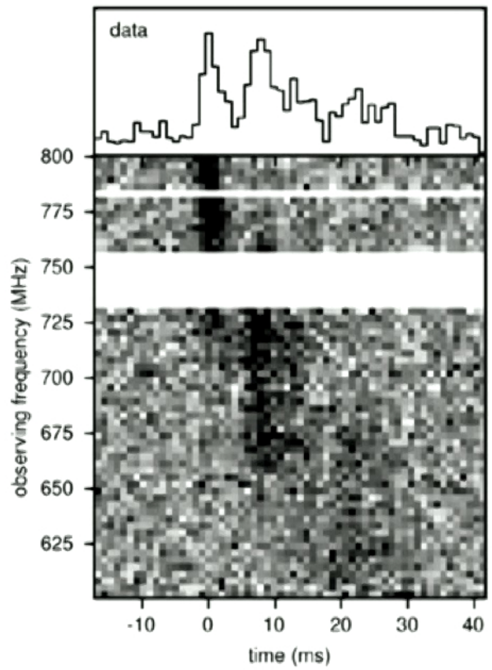
New repeating FRB!

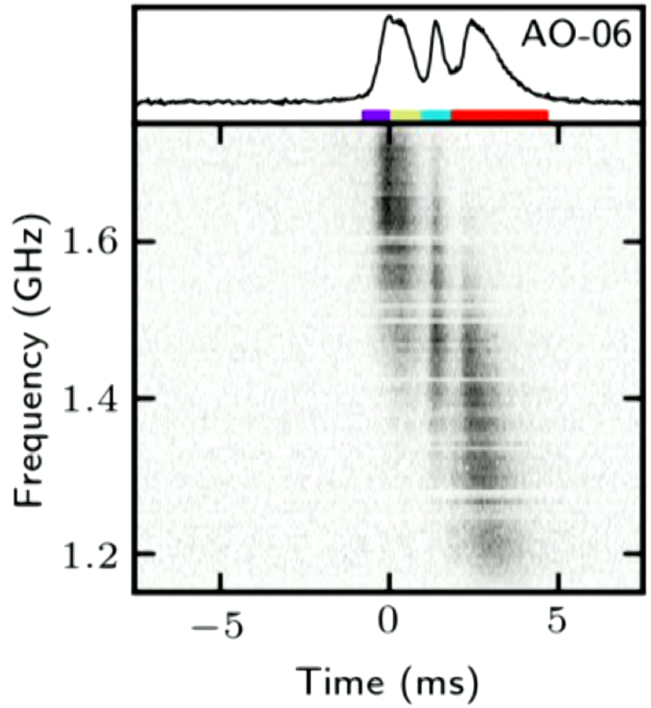
- Before CHIME, 52 FRB's had been discovered, including one repeating FRB (now called R1).
- R1 is much better studied than the non-repeating FRB's (for example, the host galaxy has been determined).
- R1 was found relatively early, but no other FRB had ever been observed to repeat, despite a lot of telescope time spent observing locations of previously found FRB's.

New repeating FRB!

We found a second repeating FRB (R2):







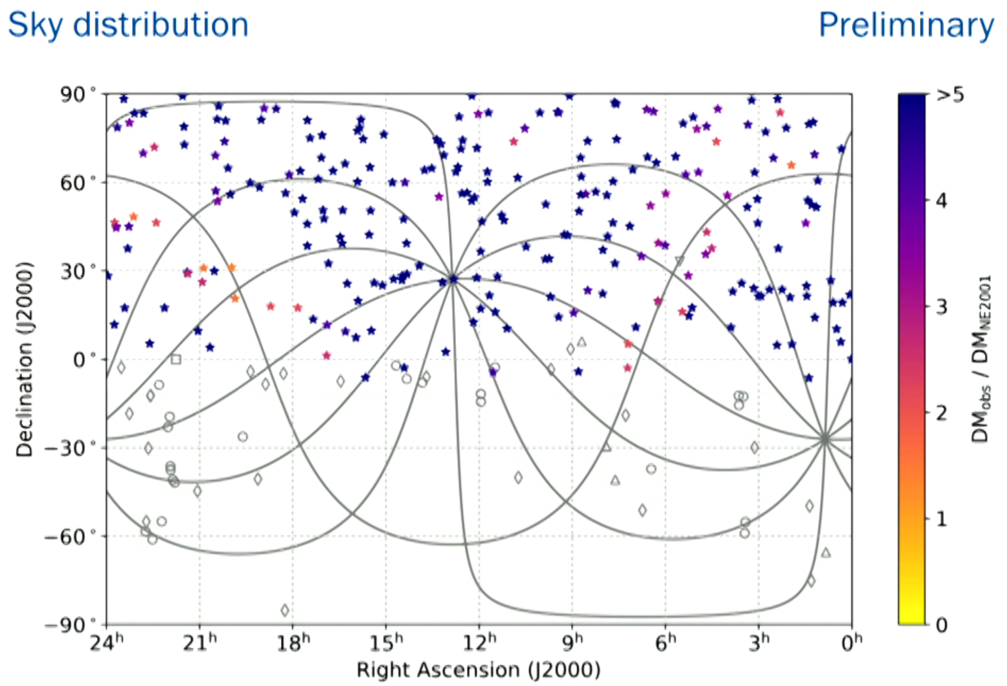
CHIME repeater (R2)

"The" repeater (R1)

2019: Current status

2019: Current status

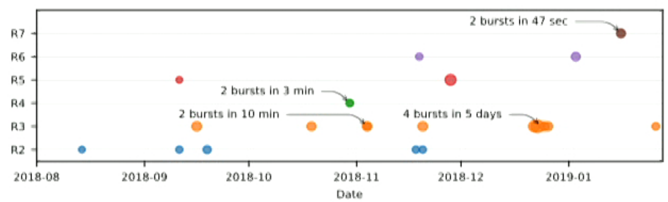
- As of today (July 2019) we have found over 500 fast radio bursts.

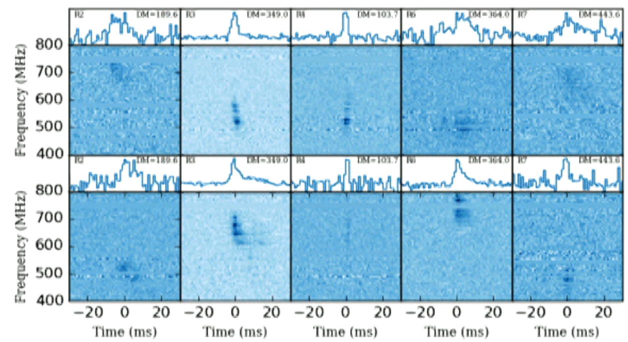


2019: Current status

- As of today (July 2019) we have found over 500 fast radio bursts.
- Multiple repeating FRB's

Name	DM	DM_{excess}	# bursts	SNR Range	First Burst	Last Burst	Notes
	($pc\,cm^{-3}$)				(dd-mm-yyyy)		
R2	189.6	80–100	7	9–13	14-08-2018	20-11-2018	
R3	349	50–150	10	10–32	16-09-2018	26-01-2019	10 m separation for 2 bursts
R4	102	60–70	2	10–11	30-10-2018	30-10-2018	3 m separation
R5	450	310–350	2	9–23	11-09-2018	28-11-2018	
R6	365.55	330–340	2	11–16	19-11-2018	03-01-2019	
R7	446.43	420	2	13–16	16-01-2019	16-01-2019	47 s separation





(table not up-to-date)

2019: Current status

- As of today (July 2019) we have found over 500 fast radio bursts.
- Multiple repeating FRB's
- Many analysis papers in progress, to appear starting in the next few weeks, and continuing for a few years (I hope!)

=  CHIME? Yes for FRB's!

1. The CHIME concept
2. CHIME science goals
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Concluding thoughts

- The CHIME "software telescope" design achieves tremendous sensitivity, at a small fraction of the cost of a traditional radio telescope.

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- … BUT, it has an immense data rate, and achieving this sensitivity depends on solving hard computing problems.

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- The CHIME "software telescope" design achieves tremendous sensitivity, at a small fraction of the cost of a traditional radio telescope
- … BUT, it has an immense data rate, and achieving this sensitivity depends on solving hard computing problems.
- We have succeeded in doing this for the FRB search problem! For other problems (pulsar search, cosmology) we are currently working on it.
- We hope that CHIME is the first step toward a new, more powerful way of doing radio astronomy. What's next?

Concluding thoughts

- We plan to build "outrigger" telescopes (smaller, far away versions of CHIME). Exact number and location TBD.
- Can increase angular resolution by a factor ~10^5!
- More than enough to tell which galaxy an FRB is in, which is very informative.

HIRAX

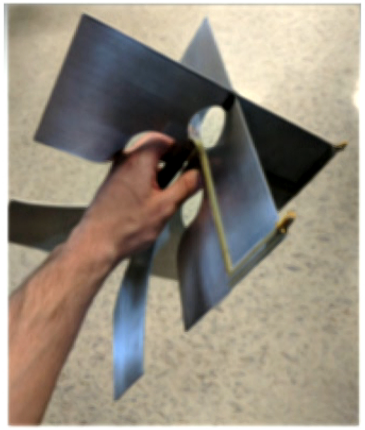
South African "sister" project to CHIME.

- Array of 1024 dishes (no cylinders)
- Outrigger telescopes for 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.

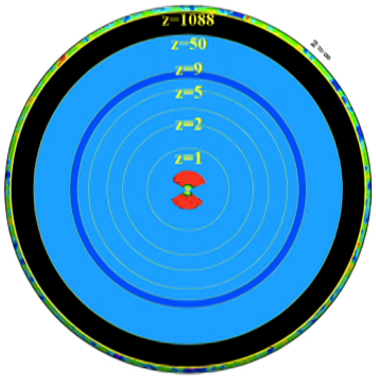
Expanding HIRAX to 2048 dishes would give 16 times CHIME mapping speed.

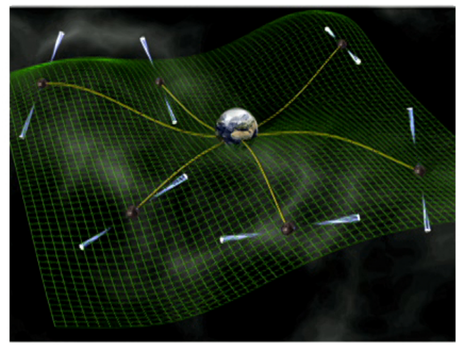
CHORD: a 10x version of CHIME (2022?)

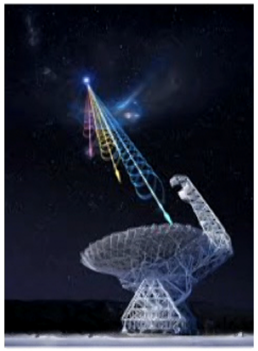


Concluding thoughts

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!