Title: FRB science results from CHIME

Speakers: Kendrick Smith

Series: Colloquium

Date: November 03, 2021 - 2:00 PM

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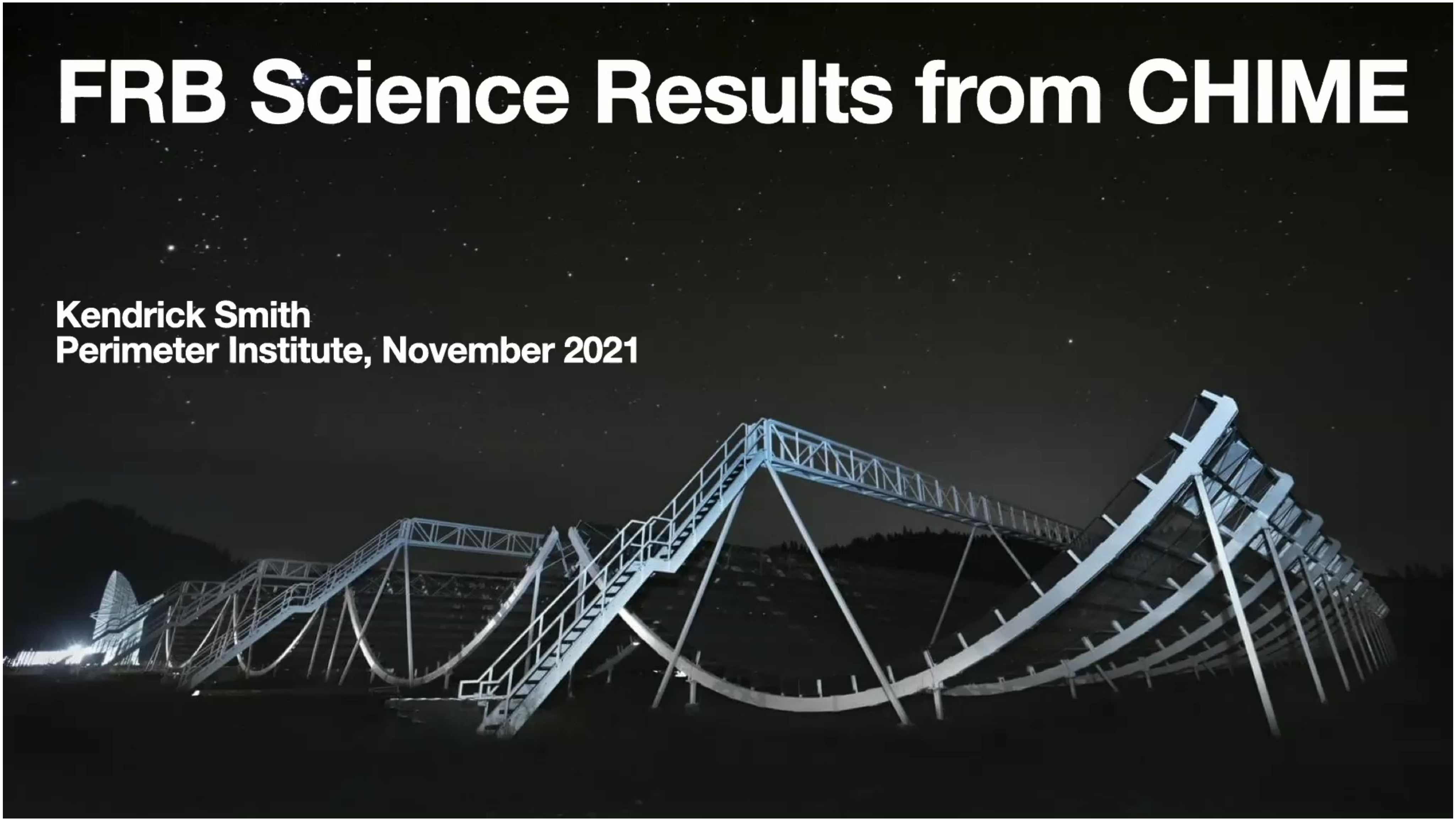
Abstract: Fast radio bursts (FRB's) are a recently discovered, poorly understood class of transient event, and understanding their origin has become a central problem in astrophysics. I will present FRB science results from CHIME, a new interferometric telescope at radio frequencies 400-800 MHz. In the 3 years since first light, CHIME has found ~20 times more FRB's than all other telescopes combined, including ~60 new repeating FRB's, the first repeating FRB with periodic activity, a giant pulse from a Galactic magnetar which may be an FRB in our own galaxy, and millisecond periodicity in FRB sub-pulses. These results were made possible by new algorithms which can be used to build radio telescopes orders of magnitude more powerful than CHIME. I will briefly describe two upcoming projects: outrigger telescopes for CHIME (starting 2022) and CHORD, a new telescope with ~10 times the CHIME mapping speed (starting 2024).

Zoom Link: https://pitp.zoom.us/j/93798160318?pwd=Z3ZlNTRNRXV5MkQ5cUJhU09sVFpOdz09



FRB Science Results from CHIME

Kendrick Smith
Perimeter Institute, November 2021

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

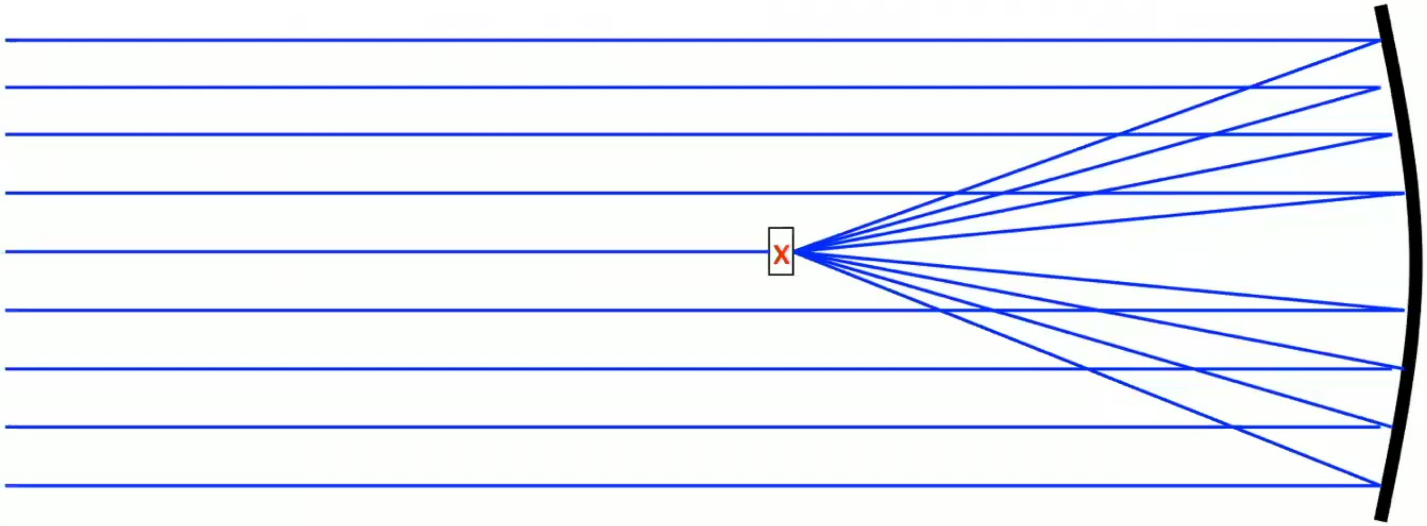
CHIME telescope

- 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 at $0.8 < z < 2.5$.)
- CHIME has many science goals, but almost all of our science results so far are related to fast radio bursts (FRB's). In this talk, I'll focus on FRB science.

CHIME

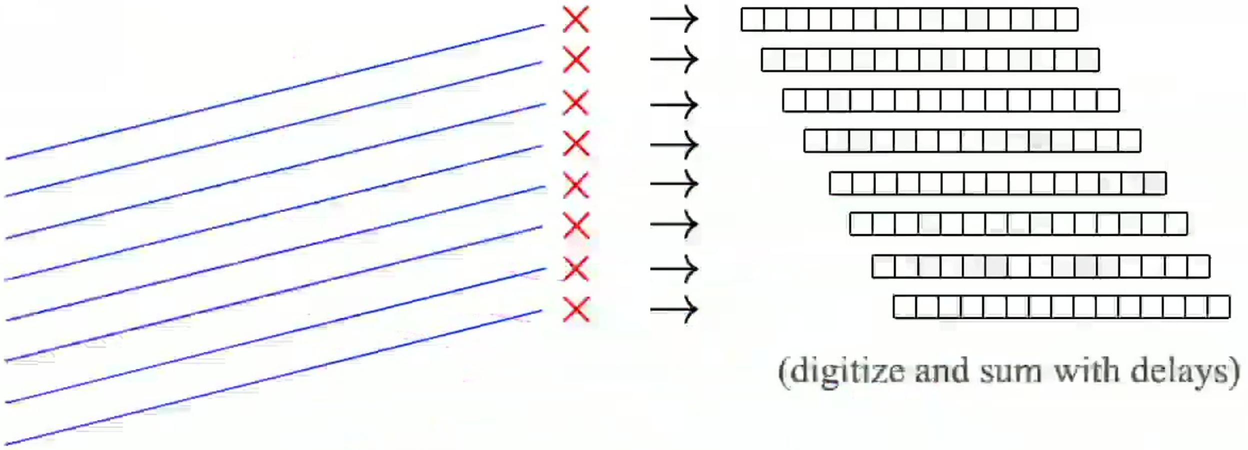
Traditional radio telescope

Single-feed radio telescope



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

Phased-array interferometer



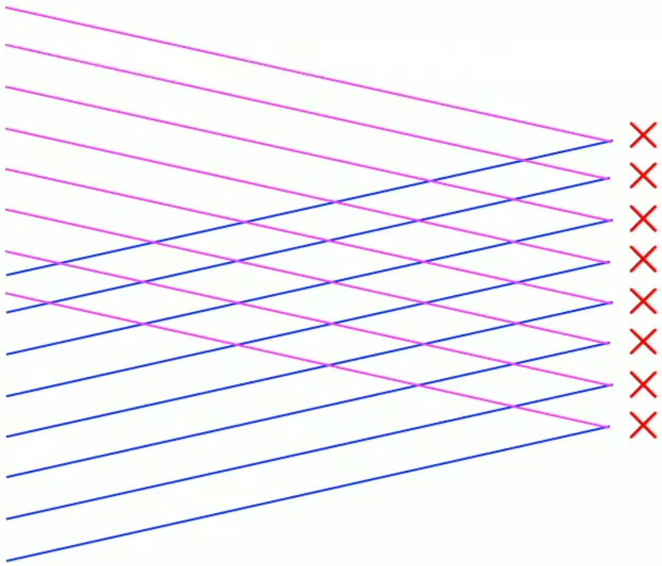
(digitize and sum with delays)

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

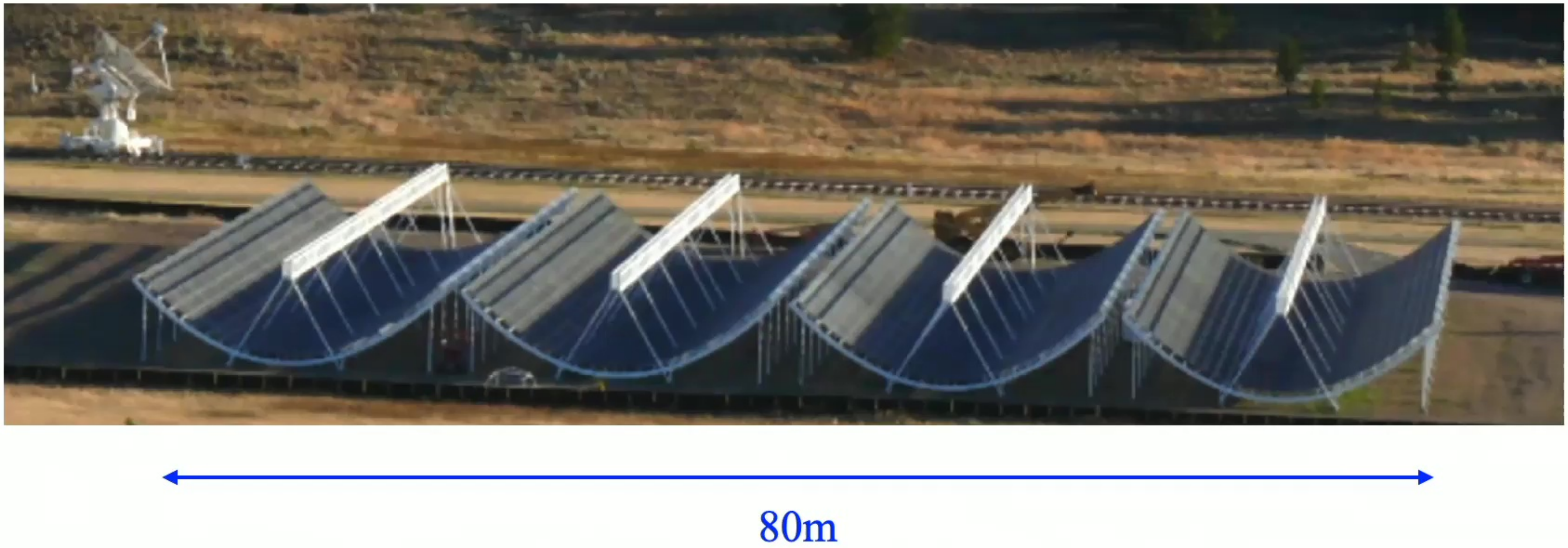


Copy the digitized signals and repeat the computation N times (in parallel).

Equivalent to N telescopes pointed in different directions.

CHIME

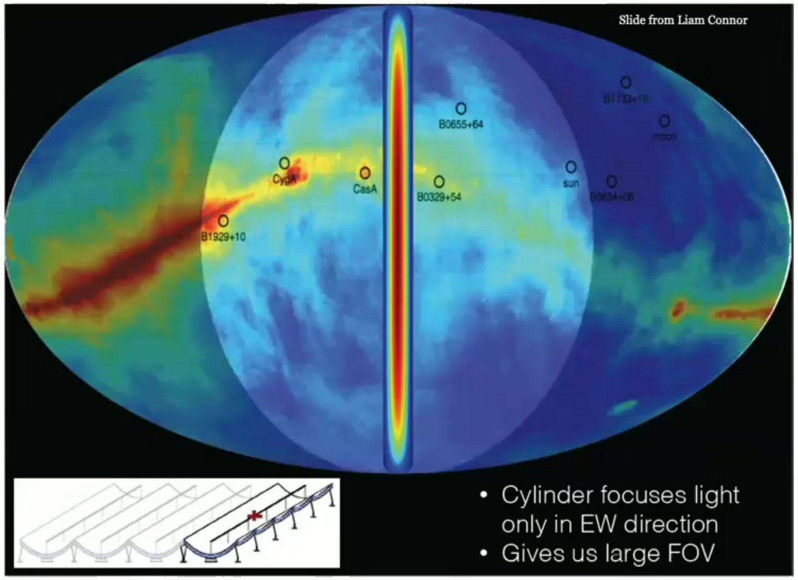
CHIME has a 4 x 256 array of antennas and can form all 1024 independent beams in real time. Raw sensitivity is the same as 1024 single-feed radio telescopes!



CHIME beamforming, cartoon form

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

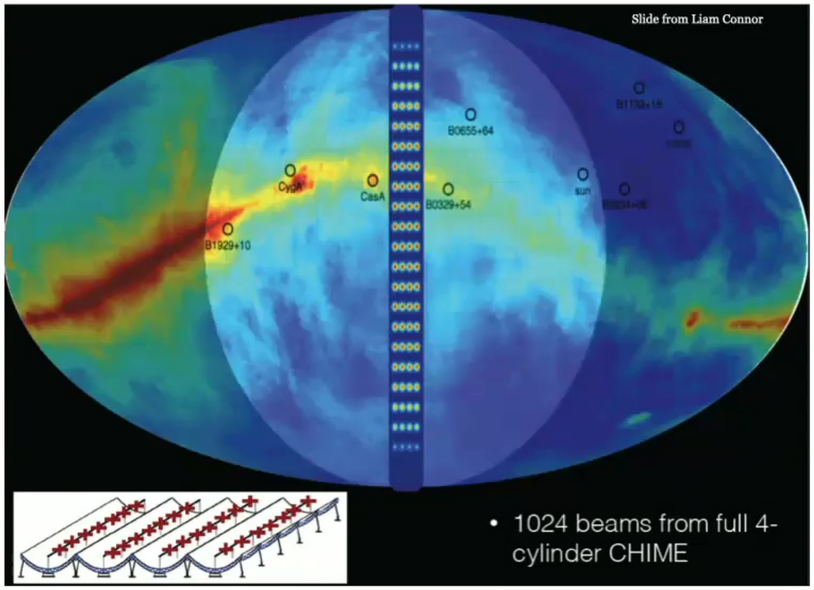
By beamforming in software as previously described, we can make 1024 "formed" beams with size ~0.3 degree.



Slide from Liam Connor

- Cylinder focuses light only in EW direction
- Gives us large FOV

primary beam



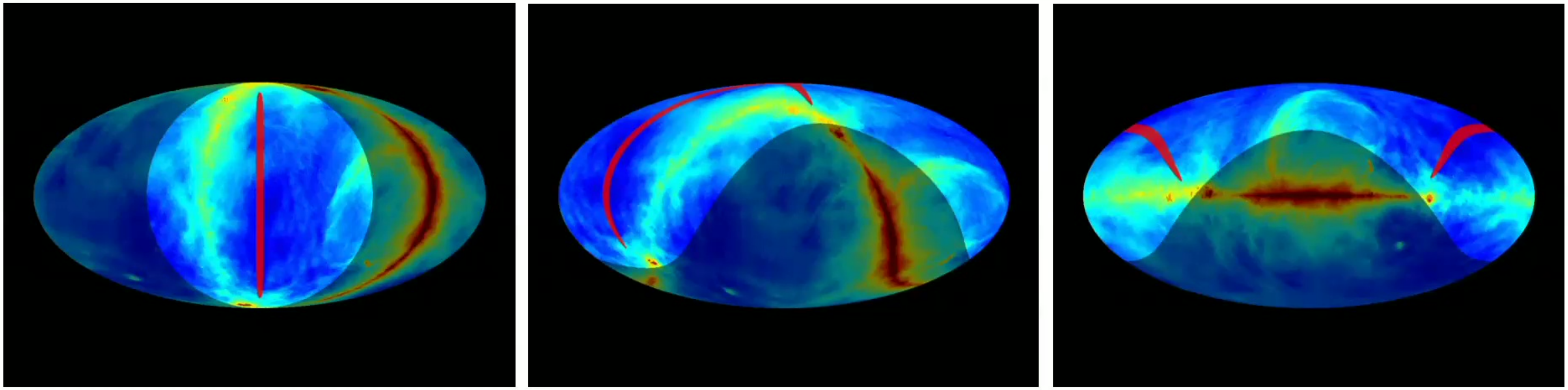
Slide from Liam Connor

- 1024 beams from full 4-cylinder CHIME

formed beams

CHIME beamforming, cartoon form

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



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

Mapping speed

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

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

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

FAST

= CHIME?

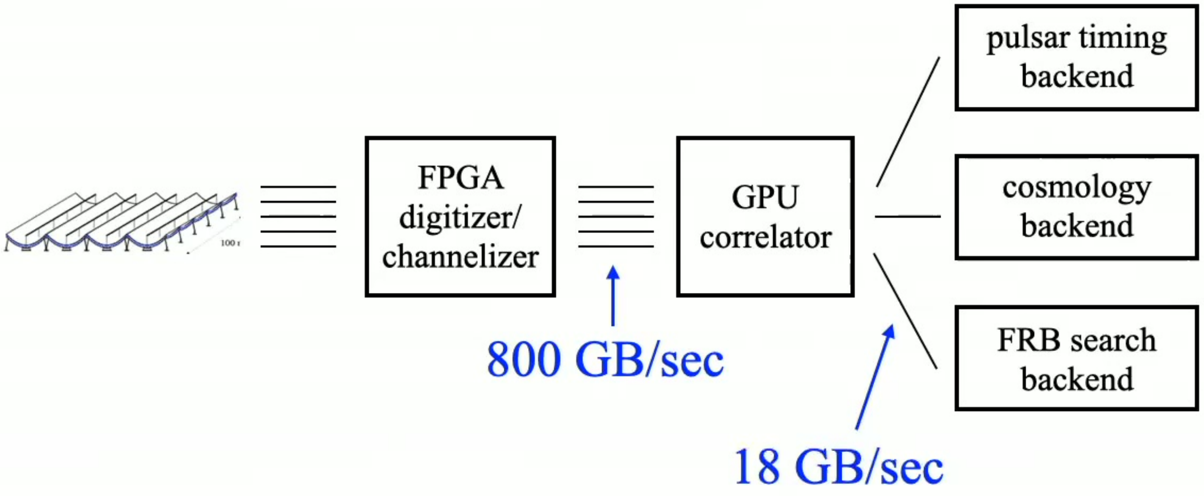
The challenge

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

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

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

CHIME computing



FPGA digitizer/ channelizer

GPU correlator

pulsar timing backend

cosmology backend

FRB search backend

800 GB/sec

18 GB/sec

Pulsar timing backend

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

Cosmology backend

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

FRB search backend

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

“bonsai”: CHIME fast radio burst search software

The CHIME FRB search algorithm is:

- Orders of magnitude faster than other search software. (But at CHIME data volume, still needs a ~2000-core cluster!)
- Near statistically optimal
- Real-time, ~10 second latency
- Includes real-time RFI removal with very low false positive rate

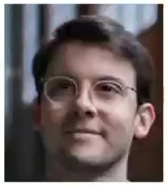

Kendrick
Smith


Dustin
Lang

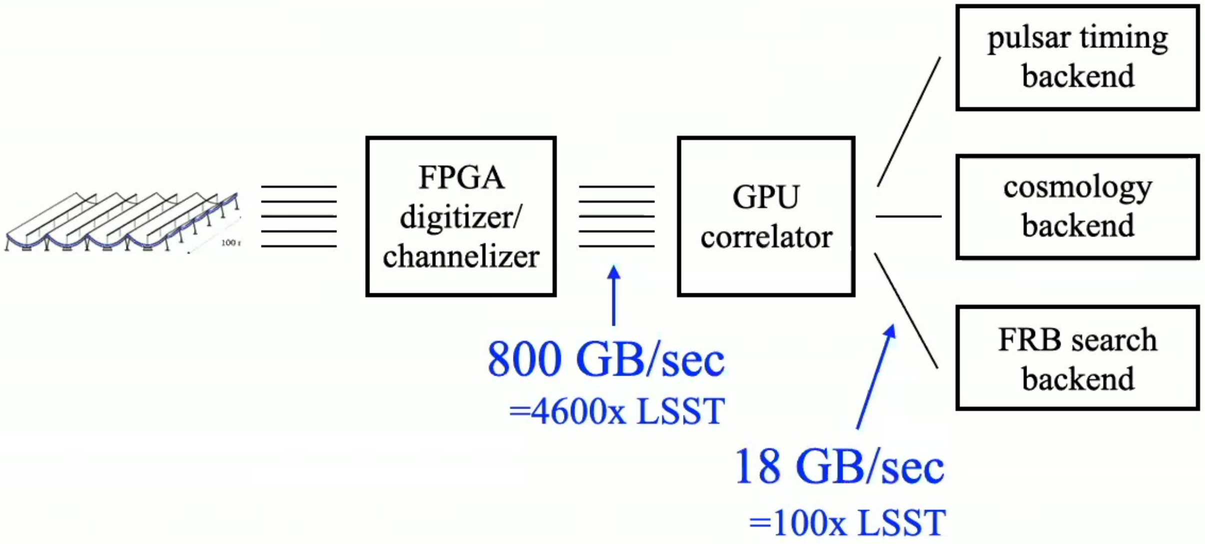

Masoud
Rafiei-Ravandi


Utkarsh
Giri


Maya
Burhanpurkar


Alex
Roman

CHIME computing



FPGA digitizer/ channelizer

GPU correlator

pulsar timing backend

cosmology backend

FRB search backend

800 GB/sec

=4600x LSST

18 GB/sec

=100x LSST

Pulsar timing backend

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

Cosmology backend

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

FRB search backend

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

LSST: 15 TB/day

“bonsai”: CHIME fast radio burst search software

The CHIME FRB search algorithm is:

- Orders of magnitude faster than other search software. (But at CHIME data volume, still needs a ~2000-core cluster!)
- Near statistically optimal
- Real-time, ~10 second latency
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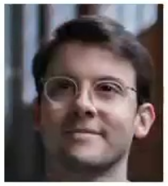
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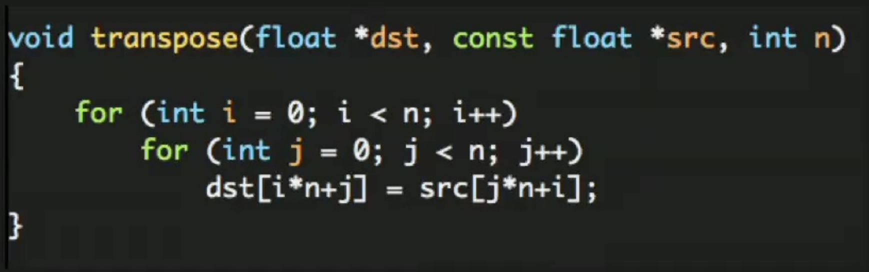
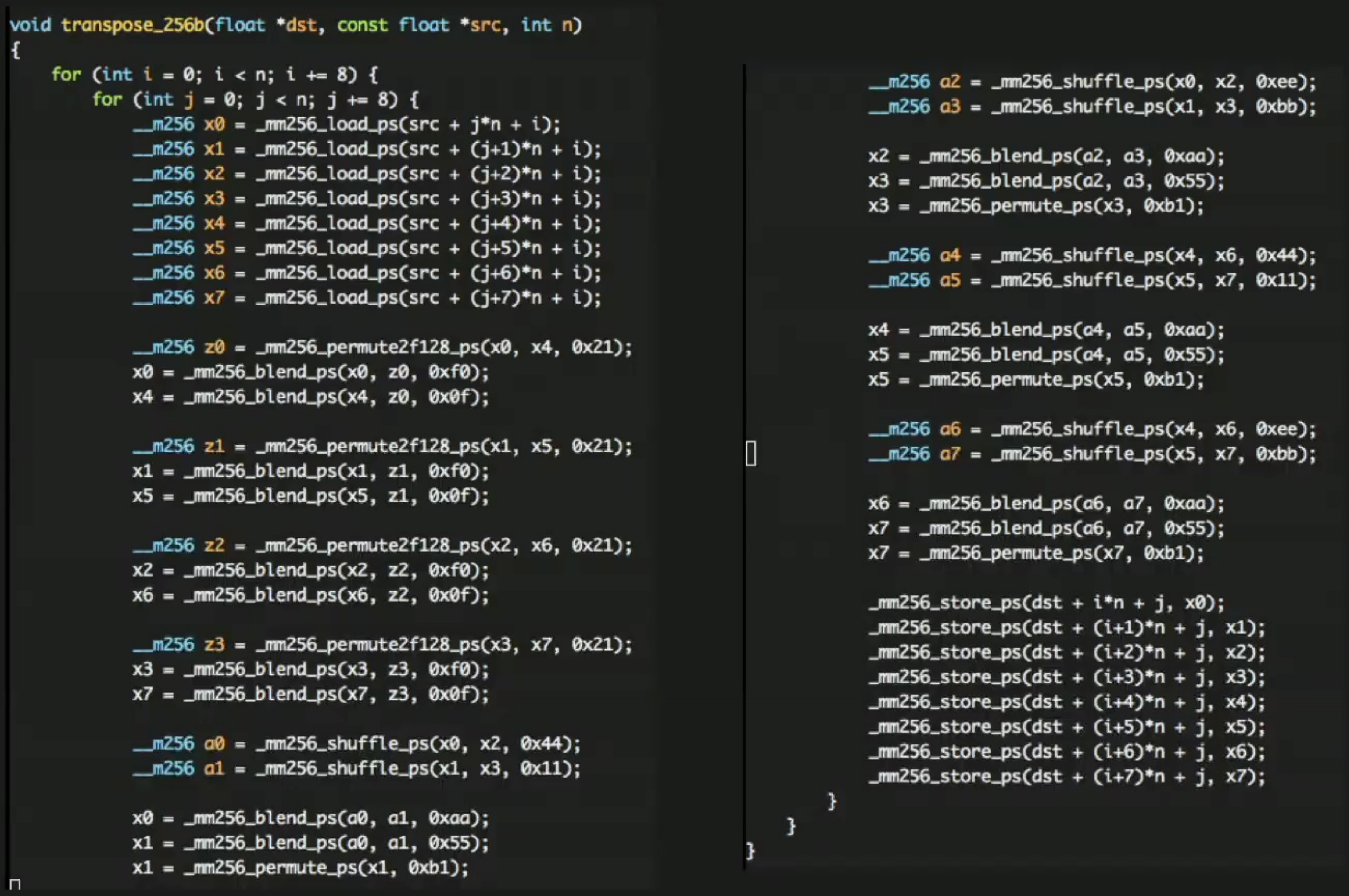


```c
void transpose(float *dst, const float *src, int n)
{
    for (int i = 0; i < n; i++)
        for (int j = 0; j < n; j++)
            dst[i*n+j] = src[j*n+i];
}
```

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);
        }
    }
}
```

FRB mini-introduction

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

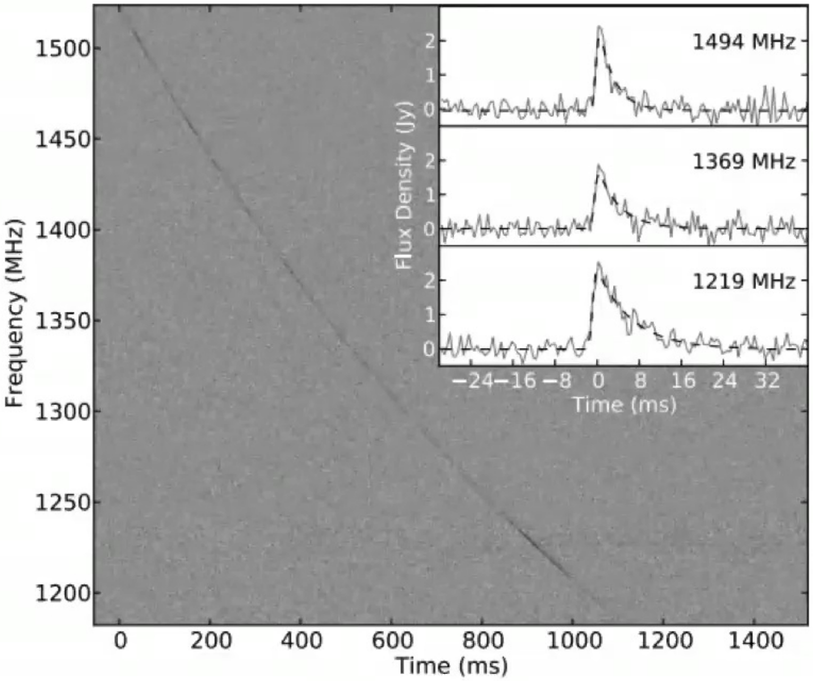
- Dispersion from cold plasma of ionized electrons: (Pulse arrival time) $\propto \nu^{-2}$

- Prefactor is the "dispersion measure":

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

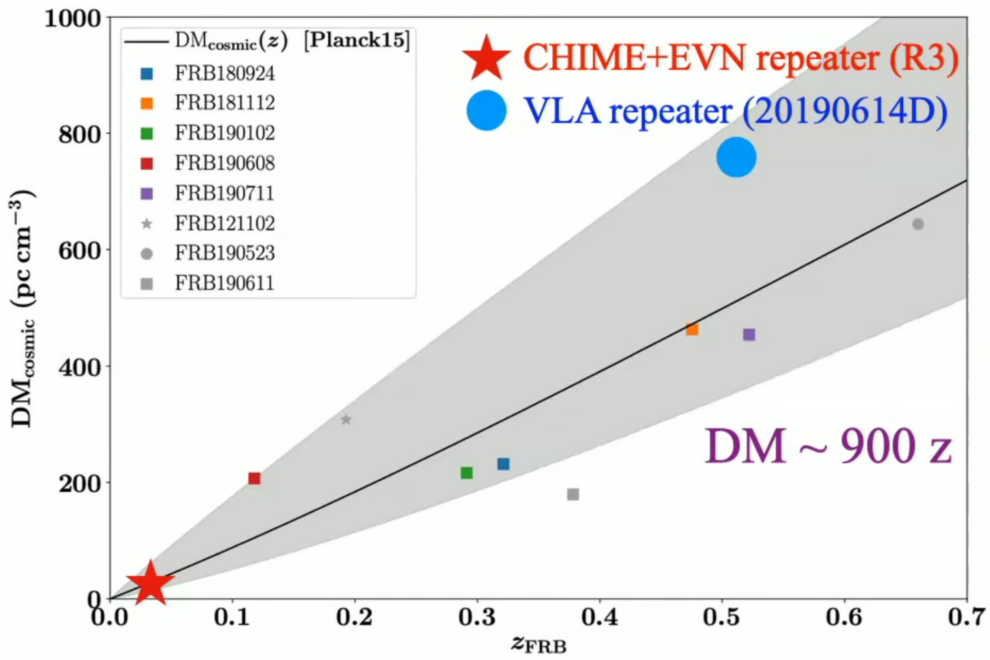
  Radio astronomy DM units: pc cm^{-3}.
  (DM ~ 500 for a typical FRB.)

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



FRB mini-introduction

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



★ CHIME+EVN repeater (R3)

● VLA repeater (20190614D)

DM ~ 900 z

Note: model for DM of (Milky Way + host galaxy) has been subtracted.

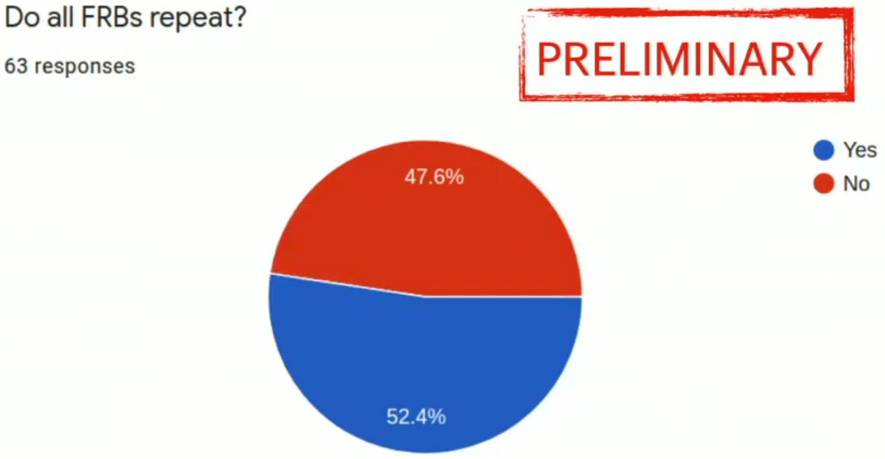
ASKAP (2005.13161)
CHIME+EVN (2001.02222)
DSA (1907.01542)
VLA (2007.02155)

FRB mini-introduction

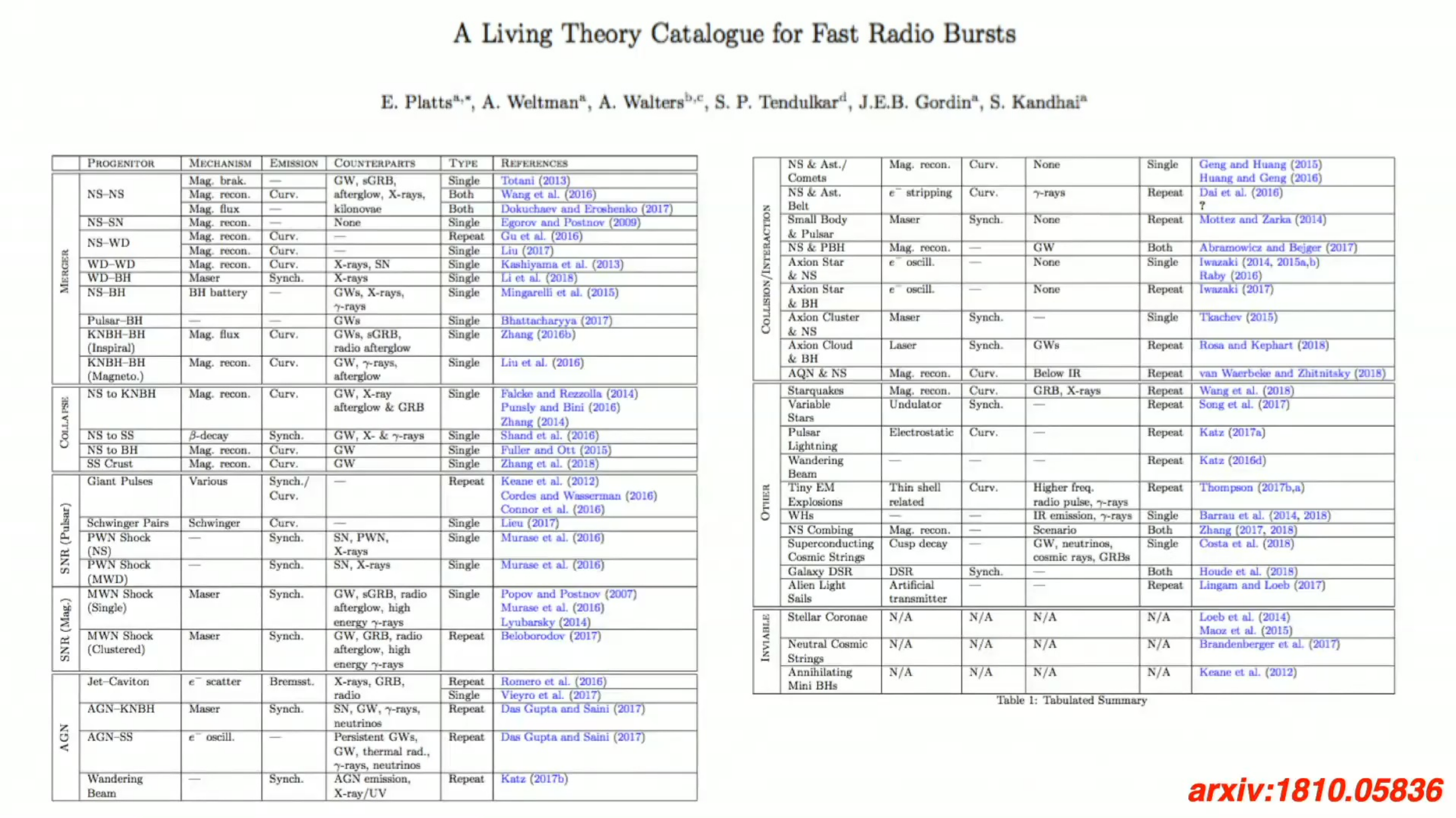
Repeaters: prior to CHIME, one FRB had been observed to repeat. This FRB (now called “R1”) was a gold mine of information. In particular, it was the first FRB localized to a host galaxy.

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

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



(poll from FRB2020 online conference)



A Living Theory Catalogue for Fast Radio Bursts

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

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

Table 1: Tabulated Summary

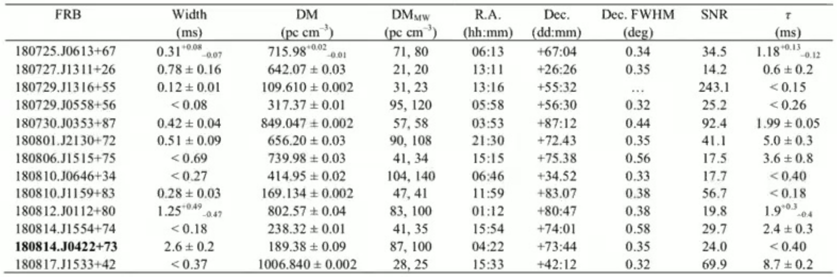
arxiv:1810.05836

FRB science highlights from CHIME

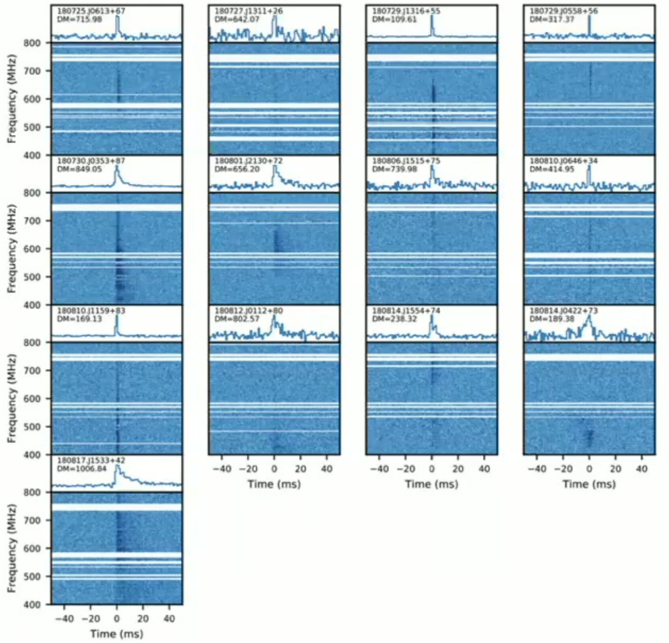
1. FRBs are common at low frequencies
2. Repeating FRBs are common
3. R3: a nearby FRB with periodic activity
4. Giant pulse from galactic magnetar SGR 1935
5. First CHIME FRB catalog
6. FRB-galaxy statistical correlations
7. Millisecond periodicity in a pulse train from an FRB
8. Coming soon: CHIME outriggers, CHORD

13 FRB’s discovered, in first month of commissioning data

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



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



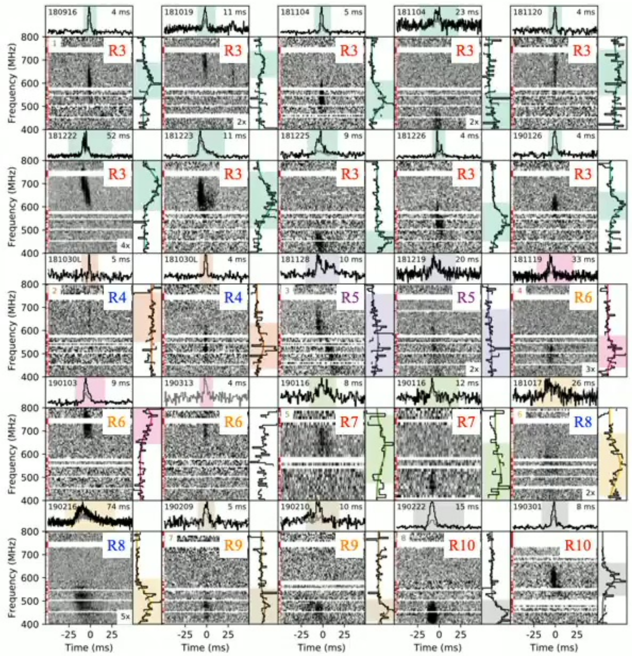
Nature 566 (2019) 230, arXiv:1901.04524

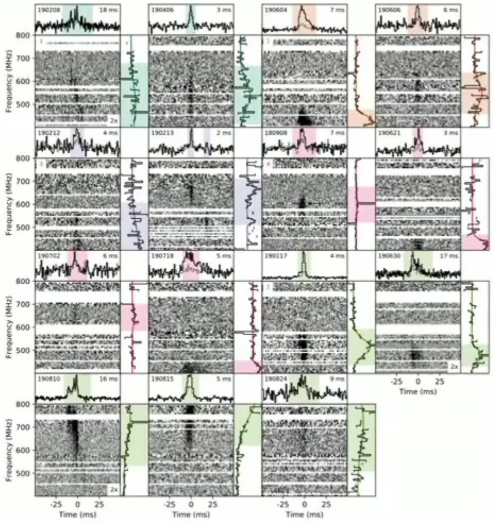
(Note: here and in subsequent slides, FRBs are shown dedispersed.)

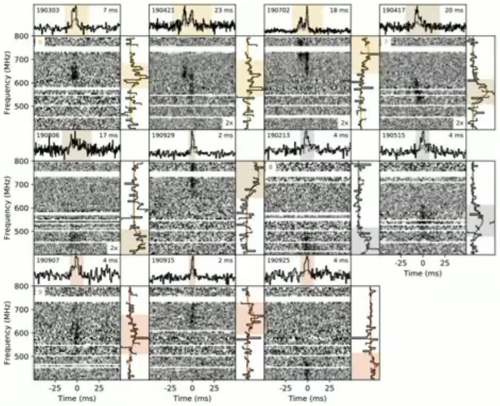
18 repeating FRB’s discovered with CHIME

	R.A.^{b} (J2000)	Dec.^{b} (J2000)	l^c (deg)	b^c (deg)	DM^d (pc cm^{-3})	DM$^e_{\rm NE2001}$ (pc cm^{-3})	DM$^e_{\rm YMW16}$ (pc cm^{-3})	N$_{\rm bursts}$	Exposure^f (hr, upper / lower)	Completeness^g (Jy ms)
R3	1h58m±7′	+65°44′±11′	129.7	3.7	349.2(3)	200	325	10	23±8	4.2
R4	*10h54m±8′*	*+73°44′±26′*	133.4	40.9	103.5(3)	40	32	2	27±14 / 19±11	... / 17
R5	*4h56m±11′*	*+63°23′±12′*	146.6	12.4	450.5(3)	112	151	2	16±10	4.0
R6	12h42m±3′	+65°08′±9′	124.5	52.0	364.05(9)	34	26	3	19±9	2.6
	12h30m±6′	+65°06′±12′								
R7	12h49m±8′	+27°09′±14′	210.5	89.5	441(2)	20	20	2	8±5	5.7
R8	*17h05m±12′*	*+68°17′±12′*	99.2	34.8	1281.6(4)	43	37	2	20±11	5.6
R9	*9h37m±8′*	*+77°40′±16′*	134.2	34.8	425.0(3)	46	39	2	34±19 / 28±18	3.8 / ...
R10	20h52m±10′	+69°50′±11′	104.9	15.9	460.6(2)	87	101	2	20±10	5.4

	R.A.^{b} (J2000)	Dec.^{b} (J2000)	l^c (deg)	b^c (deg)	DM^d (pc cm^{-3})	DM$^e_{\rm NE2001}$ (pc cm^{-3})	DM$^e_{\rm YMW16}$ (pc cm^{-3})	N$_{\rm bursts}$	Exposure^f (hr, upper / lower)	Completeness^g (Jy ms)
R11	*18h55m±14′*	*+46°58′±15′*	76.8	18.9	580.05(15)	72	66	2	20±14	3.4
R12	14h35m±10′	+53°17′±11′	93.8	57.6	552.65(5)	32	24	2	30±11	2.8
R13	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						
R14	12h32m±17′	+74°12′±19′	124.7	42.9	195.6(2)	38	31	4	53±33 / 36±25	5.9 / 18
R15	22h07m±8′	+17°23′±15′	76.4	−30.3	393.6(8)	48	40	5	19±8	6.5
R16	13h53m±14′	+48°15′±15′	97.5	65.7	222.4(7)	29	22	3	23±12	2.6
R17	*19h39m±13′*	*+59°24′±16′*	91.5	17.4	1378.2(2)	78	80	3	29±19	4.3
R18	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						
R19	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						

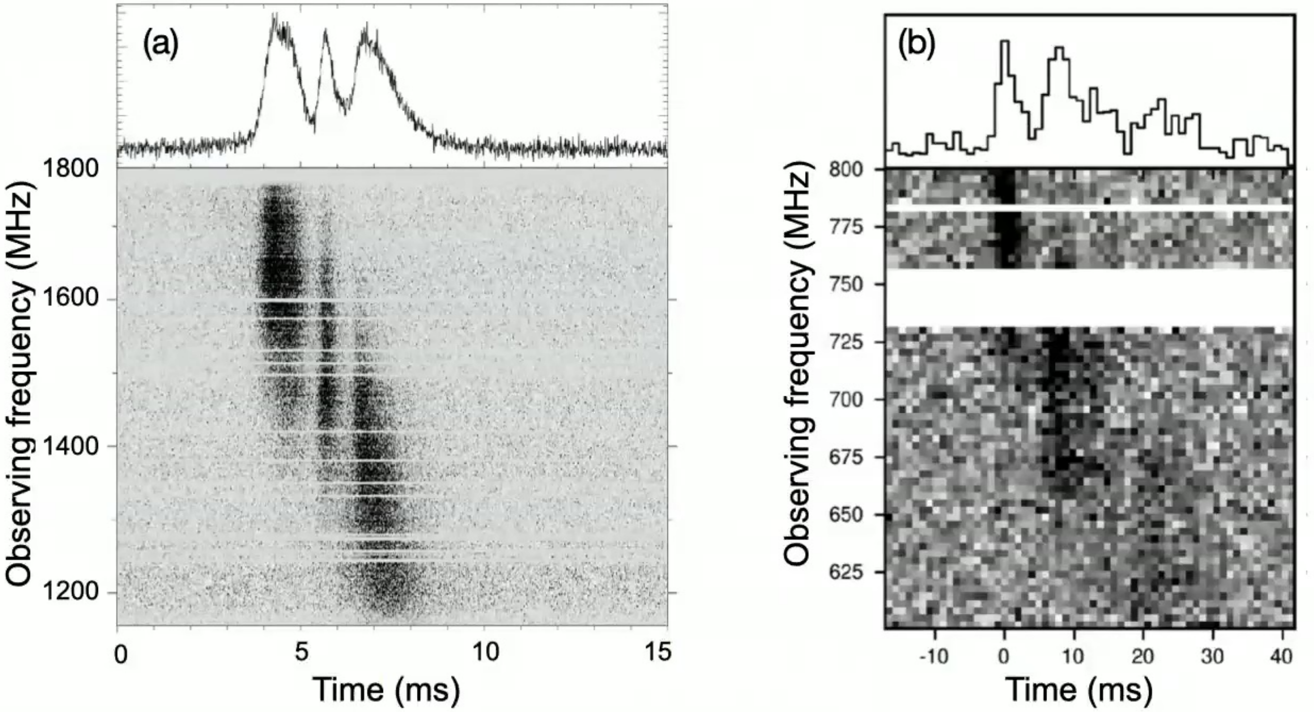






Nature 566 (2019) 235, arXiv:1901.04525
ApJL 885 (2019) 24, arXiv:1908.03507
ApJL accepted, arXiv:2001.03595.

“Downward marching” pulse structure observed in many repeaters



Original repeater (R1)

CHIME repeater (R2)

Nature 566 (2019) 235, arXiv:1901.04525

FRB science highlights from CHIME

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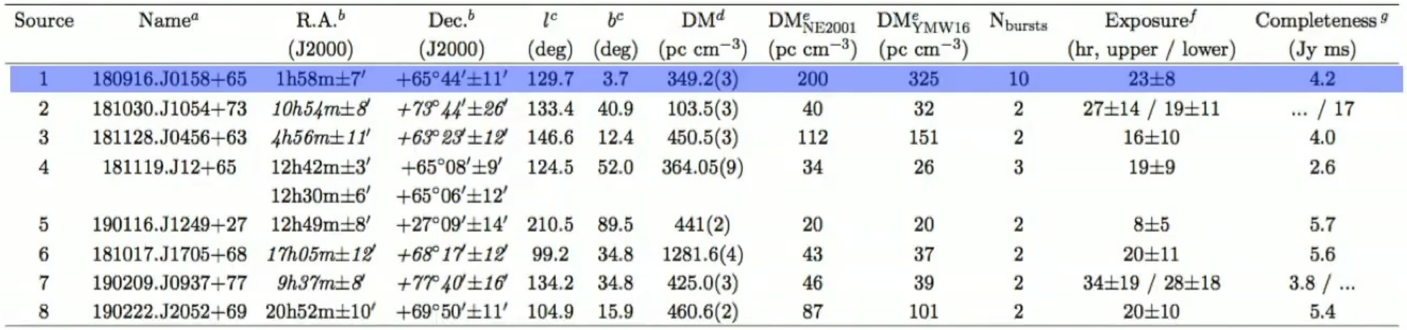
R3: a nearby FRB with periodic activity



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

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

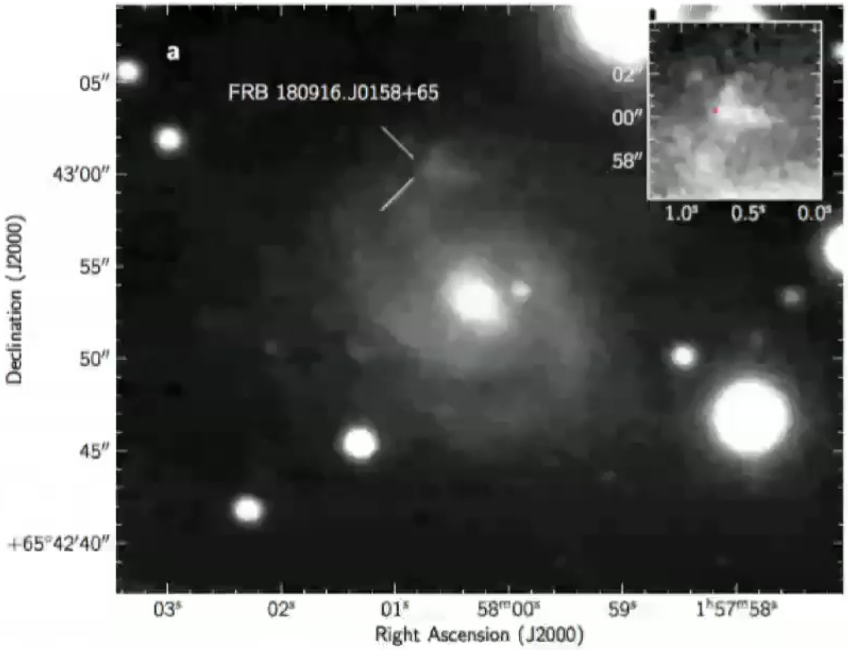
The low excess DM suggests R3 is at low redshift.

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

R3: a nearby FRB with periodic activity

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



$$\mathrm{RA} = 01^h58^m00.7502^s \pm 2.3\ \mathrm{mas}$$

$$\mathrm{Dec} = 65°43'00.3152'' \pm 2.3\ \mathrm{mas}$$

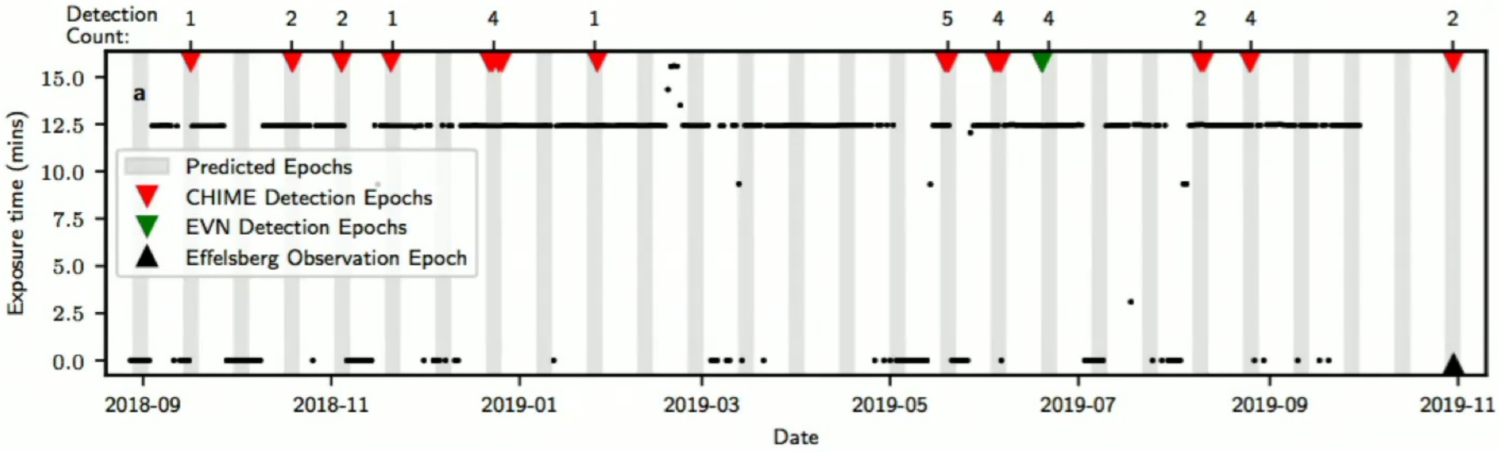
- Spiral galaxy (similar to Milky Way)
- FRB is in star-forming region
- Redshift z=0.0337 (Gemini spectroscopic follow-up).

Nature 577 (2020) 190, arXiv:2001.02222

R3: a nearby FRB with periodic activity

A surprise: R3 is only active within 4-day windows, regularly spaced with period 16.35 days.(*)

$$\text{p-value} \sim \underbrace{270}_{\text{Trial factor (\# of periods x phases)}} \left(\frac{4}{16.35}\right)^{11} \sim (5 \times 10^{-5})$$



(*) CHIME observations allow aliased periods, later ruled out by Apertif (Pastor-Marazuela et al, 2012.08348)

Nature 582 (2020) 351, arXiv:2001.10275

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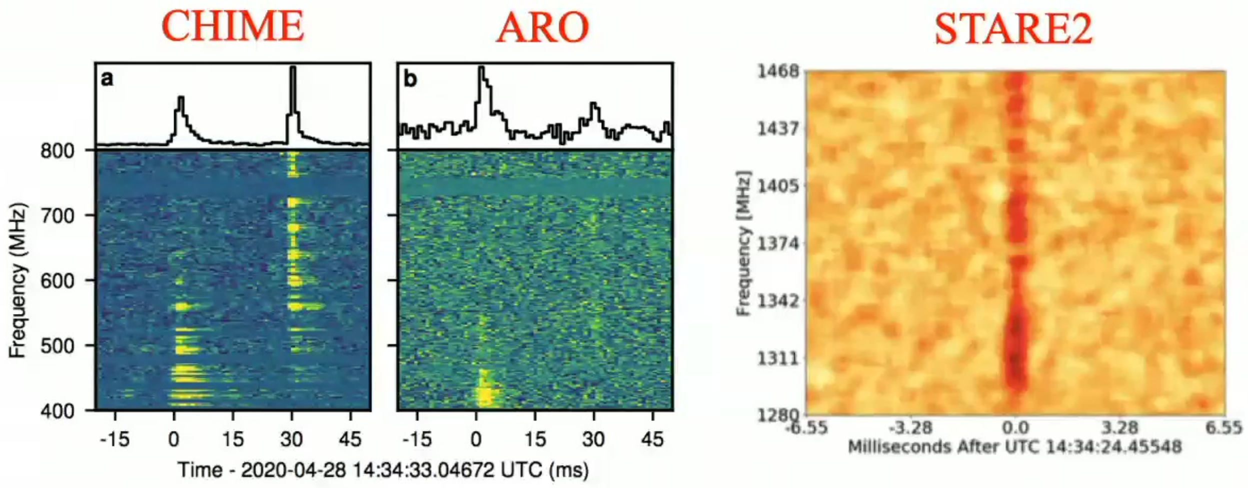
Giant pulse from galactic magnetar SGR 1935

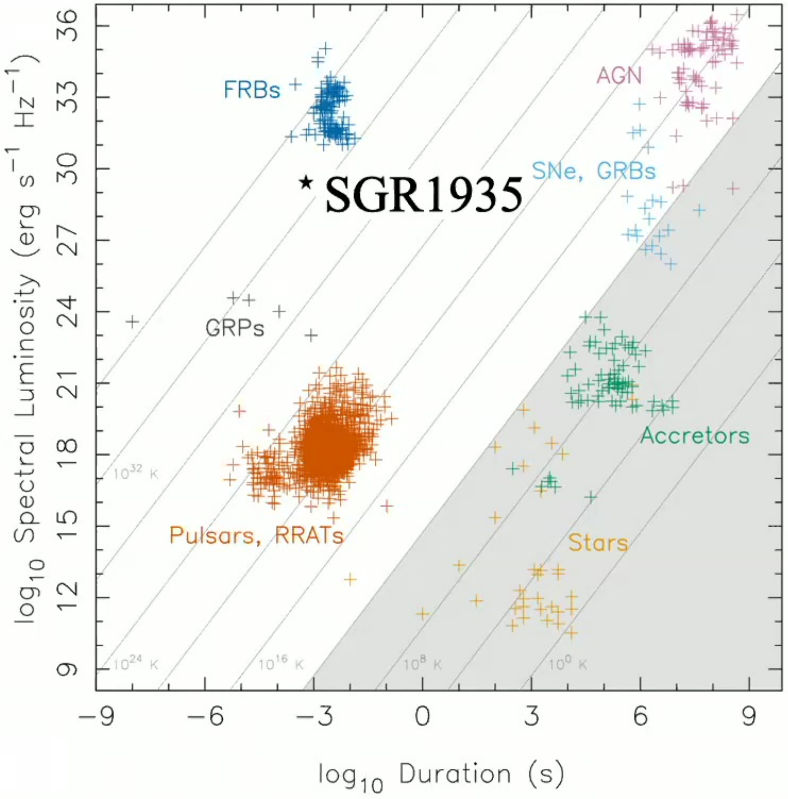
- FRB’s are much brighter (~10^{36} to 10^{42} ergs) than the brightest pulses ever observed from neutron stars in the Milky Way (~10^{31} ergs). This is why FRB’s are a puzzle in the first place!
- In April 2020, CHIME observed two pulses from a known magnetar (SGR 1935+2154) with energy (3 x 10^{34}) ergs! (The first pulse was also seen by ARO; the second pulse was also seen by STARE2 at 1.4 GHz.)



Nature 587 (2020) 54-58

Giant pulse from galactic magnetar SGR 1935

Closes most of the energy gap between galactic pulses and FRB’s!



Bochenek et al (STARE2)

Giant pulse from galactic magnetar SGR 1935

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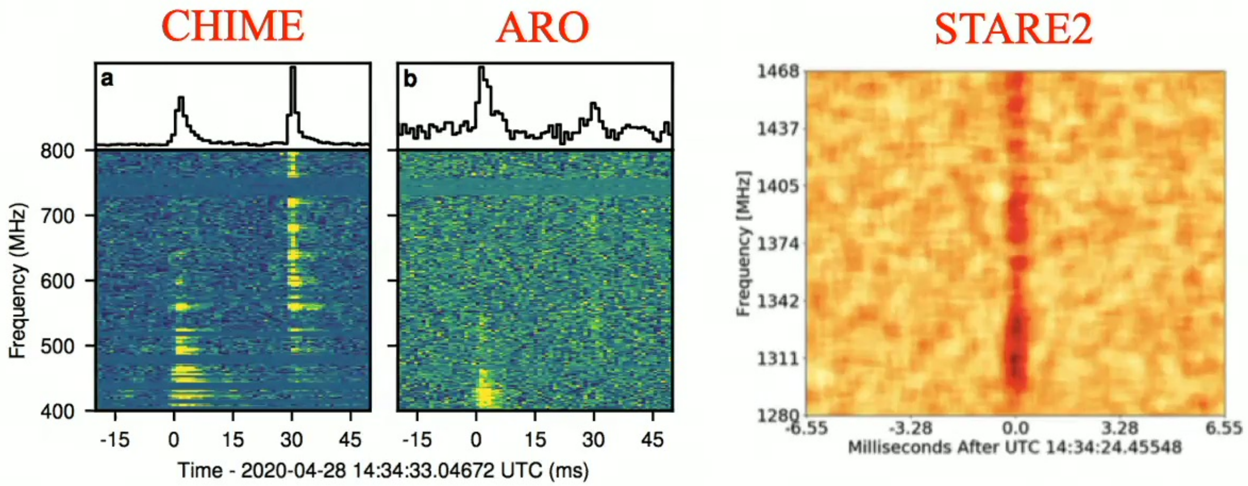

Nature 587 (2020) 54-58

Giant pulse from galactic magnetar SGR 1935

- Several X-ray telescopes observed X-ray pulses coincident with the radio pulses.
- Arrival time lag $L = t_{\text{radio}} - t_{\text{x-ray}}$ is very constraining for models. As far as I know, all magnetar FRB models predict $L \geq 0$ (i.e. radio arrives later).

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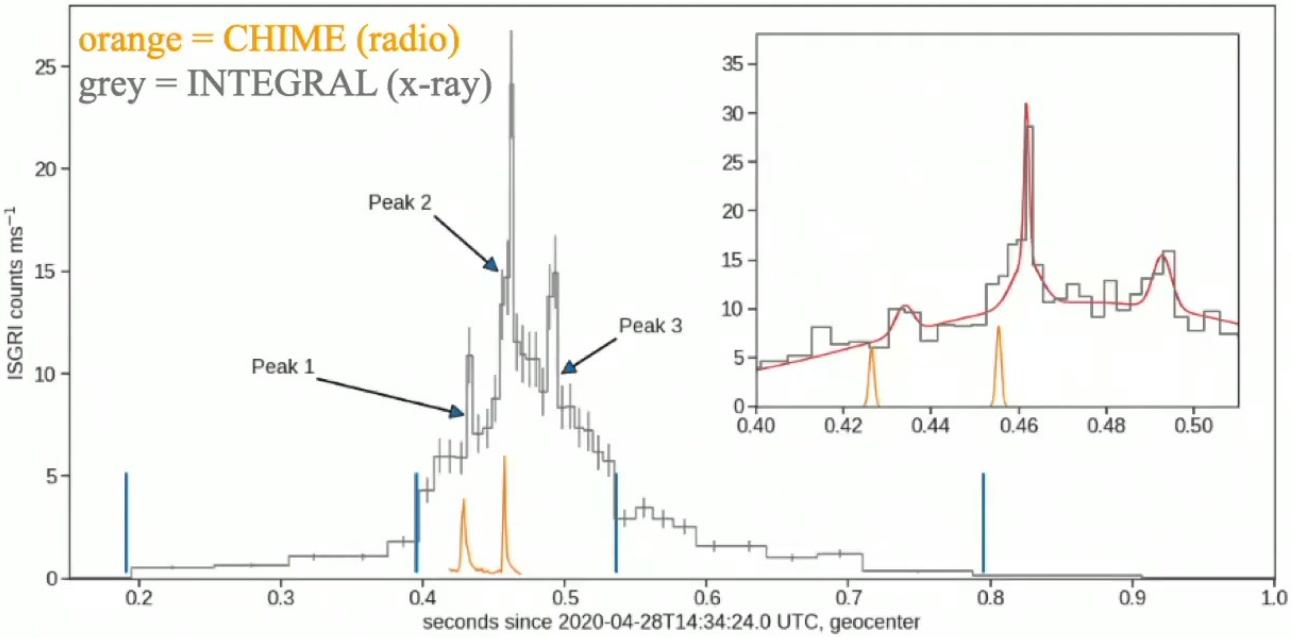
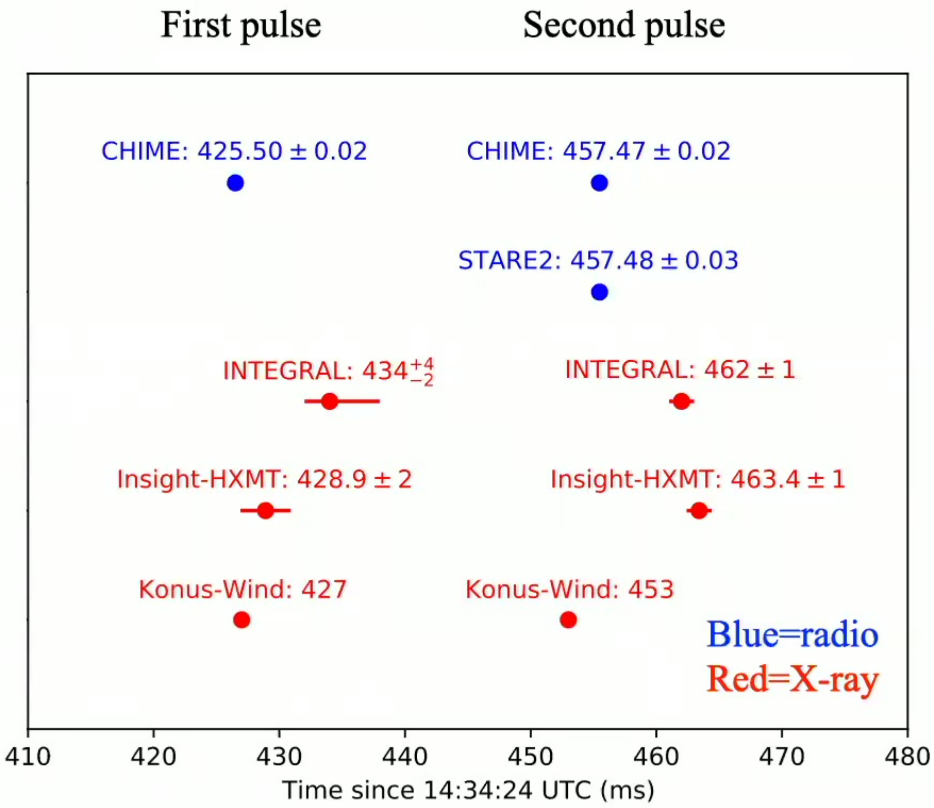
- The first reported X-ray measurements (INTEGRAL) found $L = (-6.5 \pm 1)$ ms!



INTEGRAL collaboration (Mereghetti et al), 2005.06335

Giant pulse from galactic magnetar SGR 1935



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

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

Giant pulse from galactic magnetar SGR 1935

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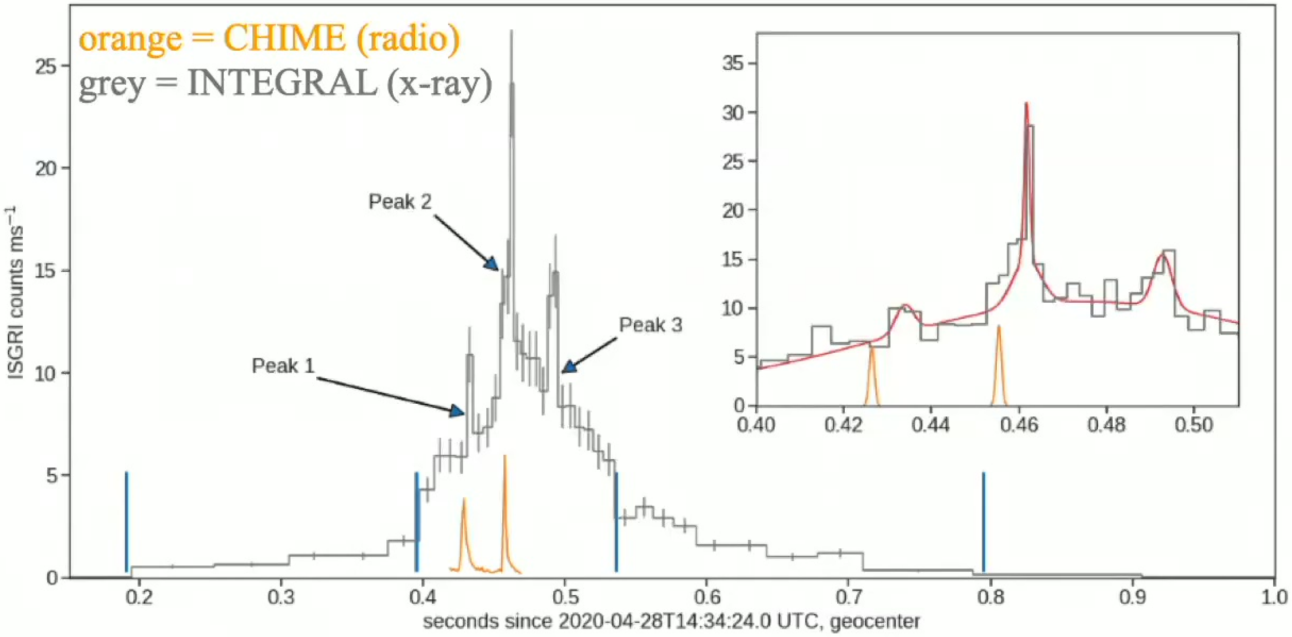

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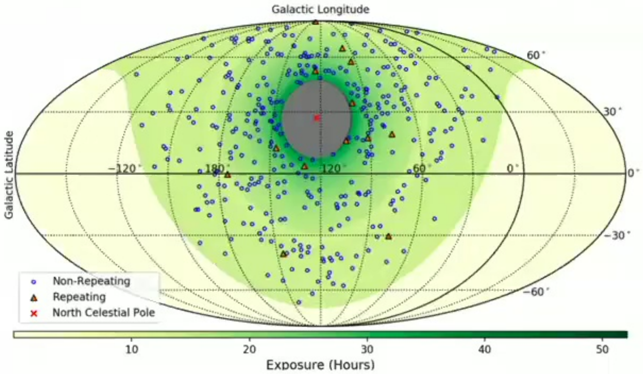
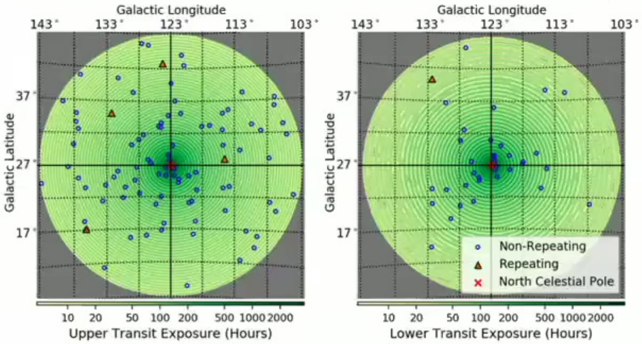
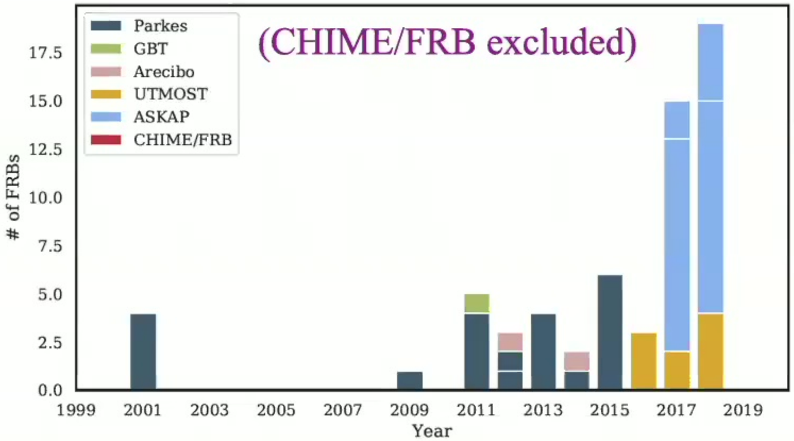
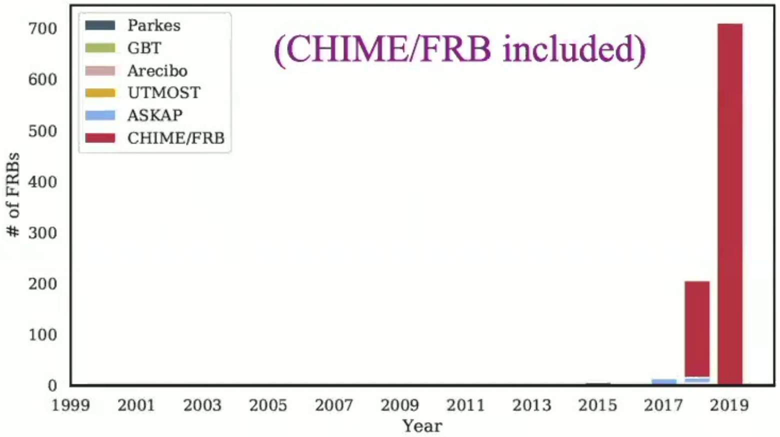
First CHIME FRB catalog

- 492 total sources, 18 of which are repeaters!





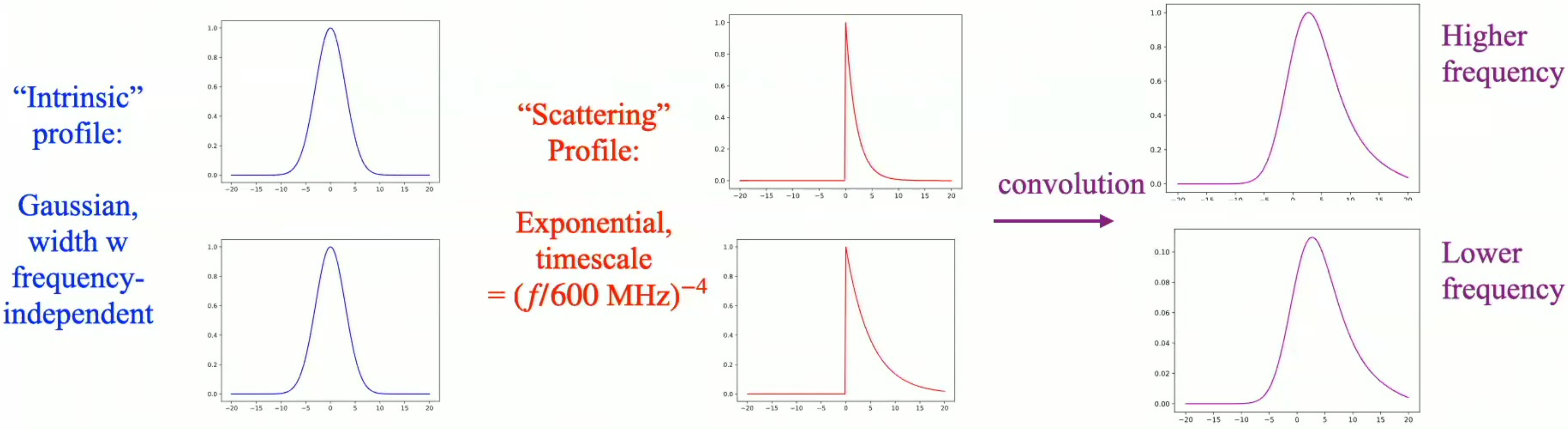




CHIME/FRB collaboration, arxiv:2106.04352, ApJ accepted

First CHIME FRB catalog

- 492 total sources, 18 of which are repeaters!
- Main technical challenge: modelling selection function of telescope.
  Monte Carlo approach: inject simulated pulses in real search (with real RFI, etc.)
- Population statistics for many FRB parameters (flux, frequency spectrum, DM, scattering time, intrinsic width).
- Note: two parameters control the pulse width, “scattering time” τ_{600} and “intrinsic width” w



“Intrinsic” profile:

Gaussian, width w frequency-independent

“Scattering” Profile:

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

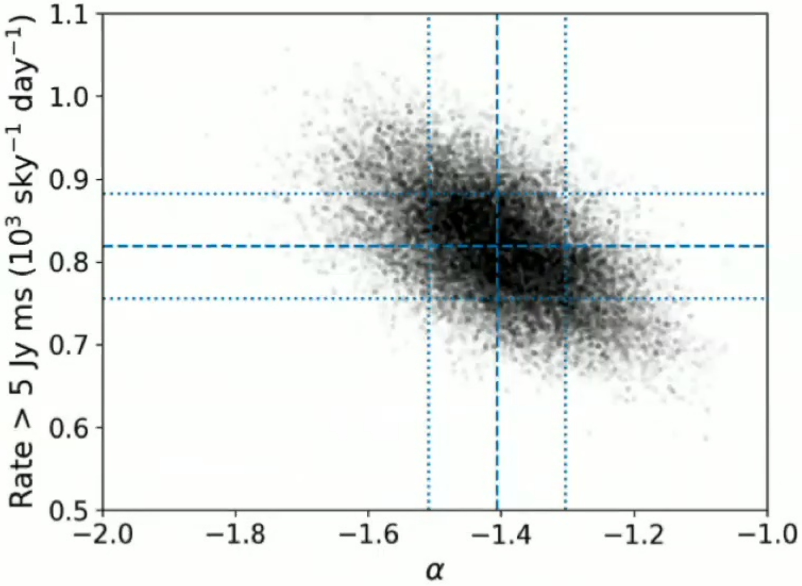
convolution

Higher frequency

Lower frequency

First CHIME FRB catalog

- FRB luminosity function is consistent with a power law: $N(\geq S) \propto S^{\alpha}$
  Exponent is $\alpha = -1.40 \pm 0.011(\mathrm{stat.})^{+0.060}_{-0.085}(\mathrm{sys.})$, consistent with Euclidean $\alpha = -3/2$.
- Overall sky rate $[818 \pm 64(\mathrm{stat.})^{+220}_{-200}(\mathrm{sys.})]$ /sky /day
  with fluence ≥ 5 Jy-ms, DM ≥ 100 pc cm^{-3}, scattering time $\tau_{600} \leq 10$ ms.



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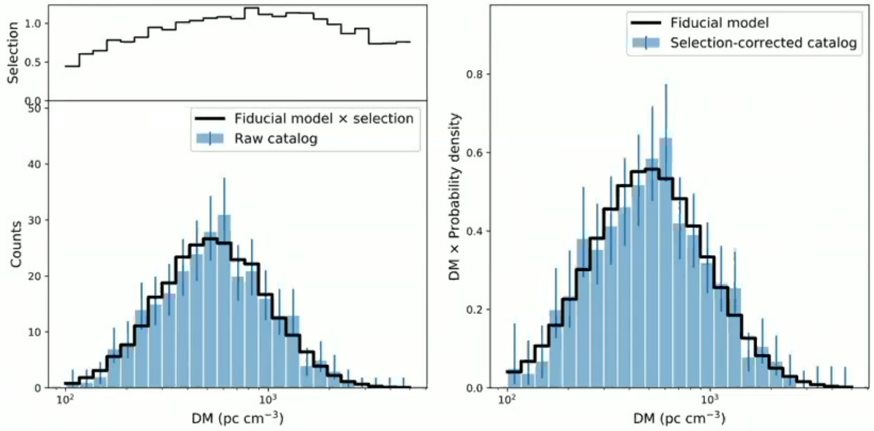
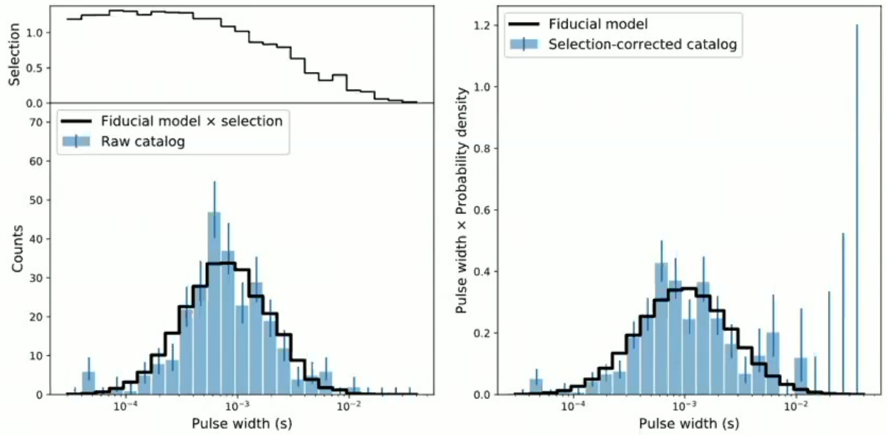
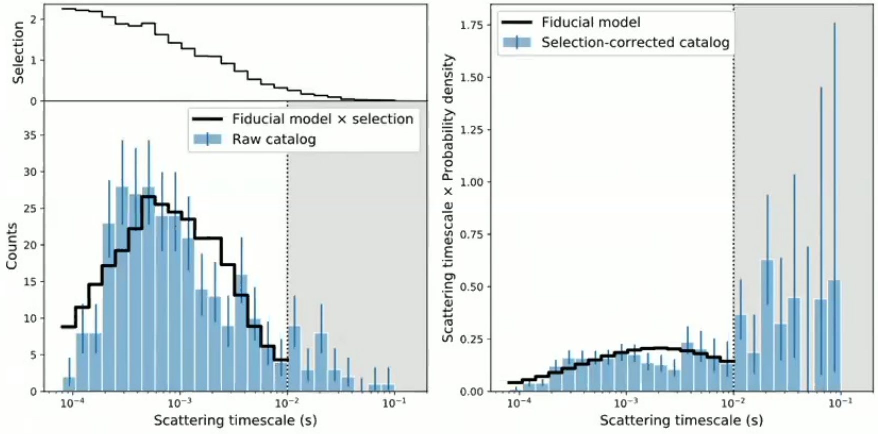


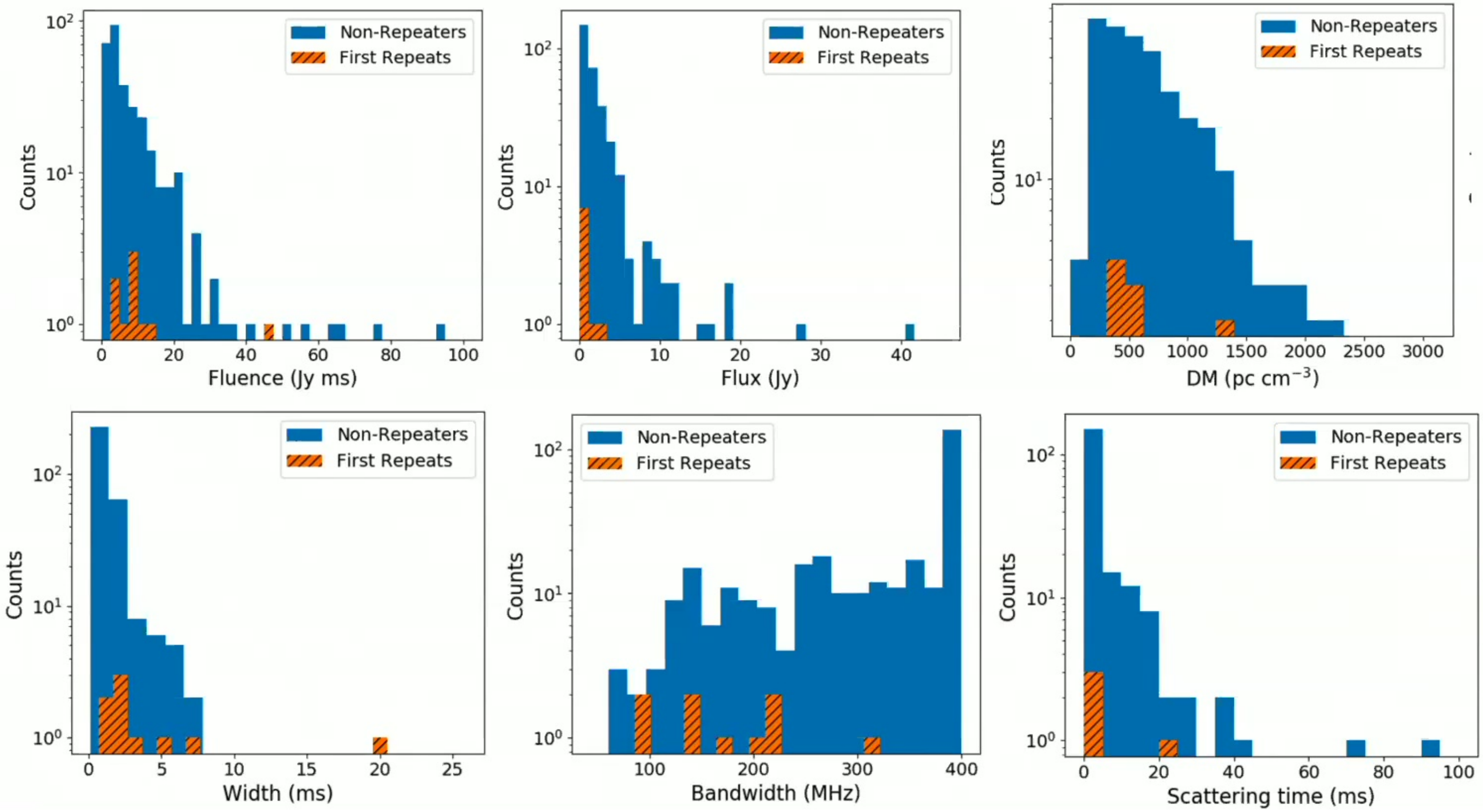




CHIME/FRB collaboration, arxiv:2106.04352, ApJ accepted

First CHIME FRB catalog

- Repeating FRB’s have wider pulses and narrower bandwidths than non-repeating FRBs, but other parameters are the same (DM, scattering time, flux).



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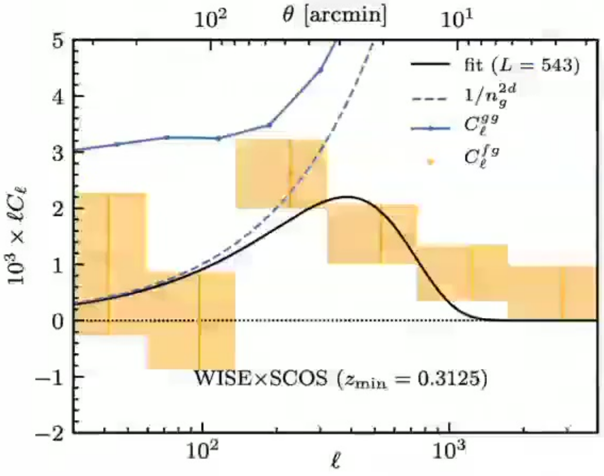
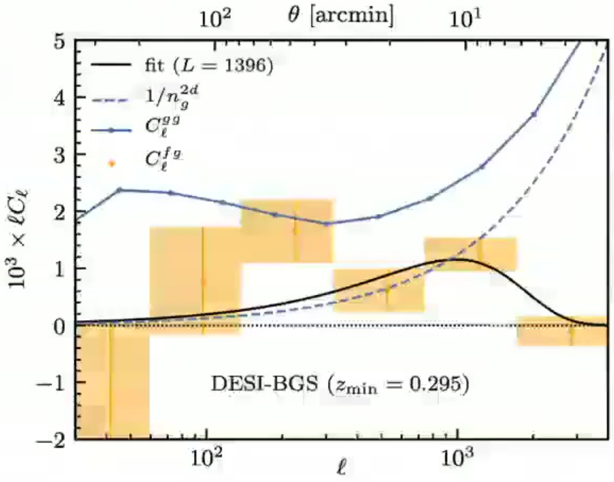
FRB-galaxy statistical correlations

- CHIME does not (usually!) have enough angular resolution to associate individual FRBs with host galaxies. However, we can try to associate FRBs with galaxies statistically, by spatially correlating the FRB/galaxy catalogs (i.e. computing cross power spectrum C_l^{fg}).
- We get statistically significant cross-correlations in galaxy redshift range $0.3 \lesssim z \lesssim 0.5$, with three galaxy catalogs: WISExSCOS, DESI-BGS, and DESI-LRG.

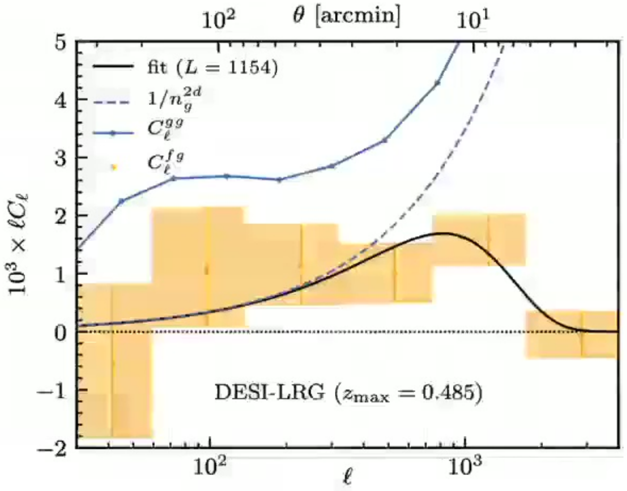
WISExSCOS ($p = 3 \times 10^{-5}$)



DESI-BGS ($p = 3 \times 10^{-4}$)



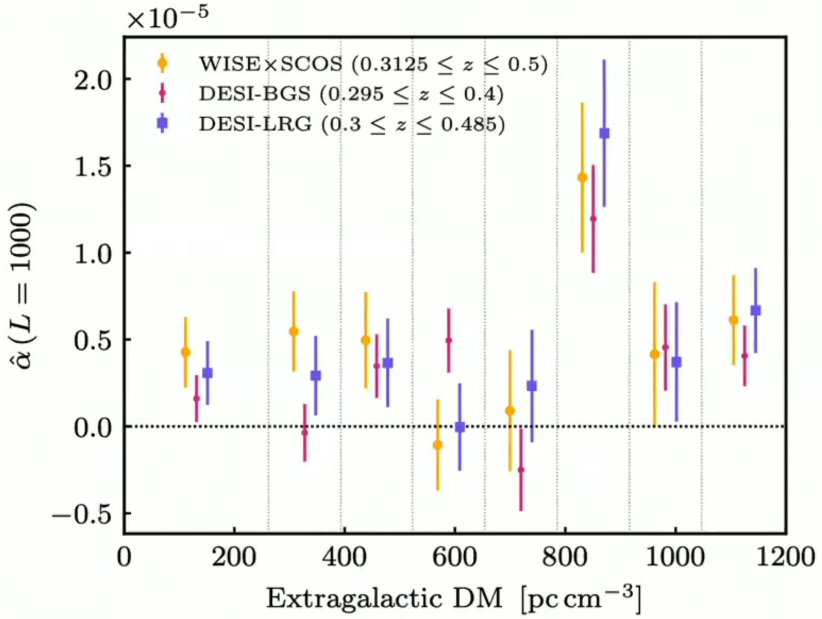
DESI-LRG ($p = 4 \times 10^{-4}$)



Rafiei-Ravandi et al, arxiv:2106.04354, ApJ accepted

FRB-galaxy statistical correlations

- A puzzle: dependence of FRB-galaxy correlation on FRB dispersion measure.
- A large correlation is seen between z~0.4 galaxies, and DM~800 FRBs. Surprising, since cosmic DM at z=0.4 is only ~400.
- One interpretation: population of FRBs with large host DM (~400). Such a population has not been observed in direct associations, but could easily have been missed so far due to small number statistics.
- Another possibility: apparent correlation between foreground galaxies and background FRBs, due to strong lensing (gravitational or plasma)?

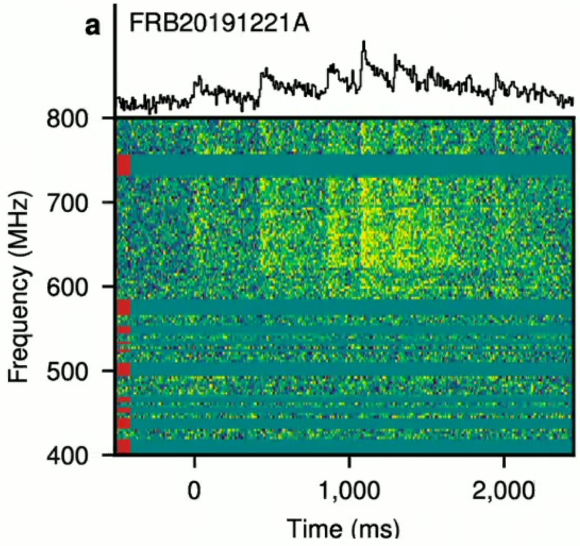


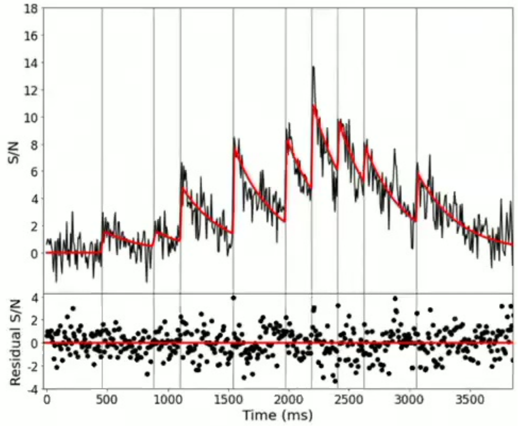
Rafiei-Ravandi et al, arxiv:2106.04354, ApJ accepted

Millisecond periodicity in a pulse train from an FRB

- A few FRBs show pulse train “microstructure”.
- In this example (FRB20191221A), a ~3 second burst of activity can be resolved as a sum of ~9 pulses.
- We model each pulse as a narrow (~4 ms) Gaussian, convolved with a wide (~340 ms at 600 MHz) scattering tail.
- This model is a good fit (after subtracting summed pulses, residuals are consistent with noise).
- This FRB is not a repeater in CHIME (in the 2 years since discovery).

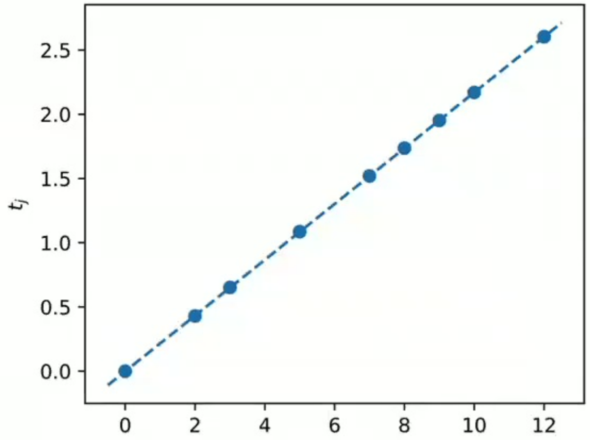
CHIME/FRB collaboration, arxiv:2107.08463

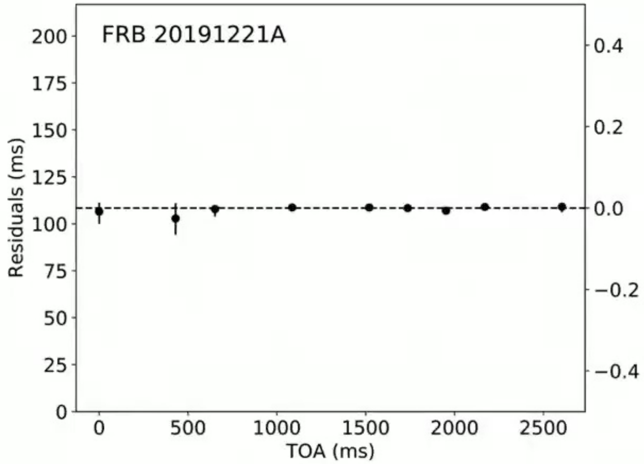




Millisecond periodicity in a pulse train from an FRB

- We noticed that the arrival times are periodic (with 3 gaps), with best-fit period 217 ms.
- Formal significance is ~6.5σ (p-value 7×10^{-11}), accounting for look-elsewhere effect in period and choice of gaps.
- Not a repeating FRB in CHIME.
- 217 ms period suggests a neutron star origin.





CHIME/FRB collaboration, arxiv:2107.08463

FRB science highlights from CHIME

1. FRBs are common at low frequencies
2. Repeating FRBs are common
3. R3: a nearby FRB with periodic activity
4. Giant pulse from galactic magnetar SGR 1935
5. First CHIME FRB catalog
6. FRB-galaxy statistical correlations
7. Millisecond periodicity in a pulse train from an FRB
8. Coming soon: CHIME outriggers, CHORD

Coming soon: CHIME outriggers

CHIME finds FRB's at a very high rate, but has limited angular resolution.

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

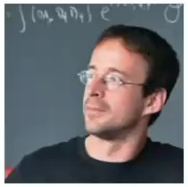
- When CHIME core detects an FRB, it tells the outriggers to save voltage data to disk.
- Outriggers do nothing except ring-buffer data, and save to disk on command.
- Later, data can be shipped to computing cluster for VLBI analysis.
- Expected sometime in 2022.

Coming soon: CHORD (Canadian successor to CHIME)

New technology under development:

- Wide-band feeds (300-1500 MHz).
- Lower noise, aiming for T_{sys} ~30 K (CHIME is ~50 K).
- Using 512 6-m dishes, total collecting area $(120\text{ m})^2$.
- Effective mapping speed ~8 times higher than CHIME.
- Outriggers for VLBI resolution.
- “Pathfinder” expected mid-2023, full instrument expected 2024/5.

Perimeter collaborators


Kendrick Smith


Dustin Lang

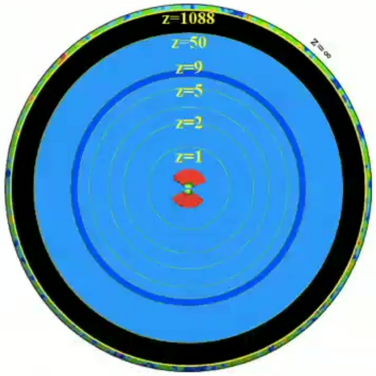

Erik Schnetter

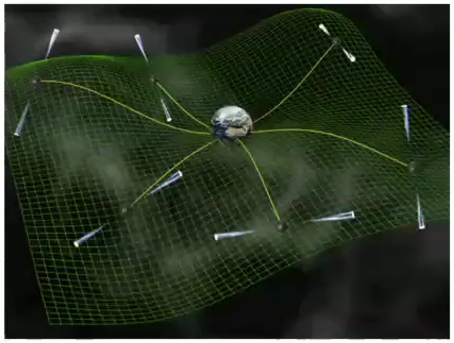
Concluding thoughts

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

Concluding thoughts

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





Fast radio bursts:

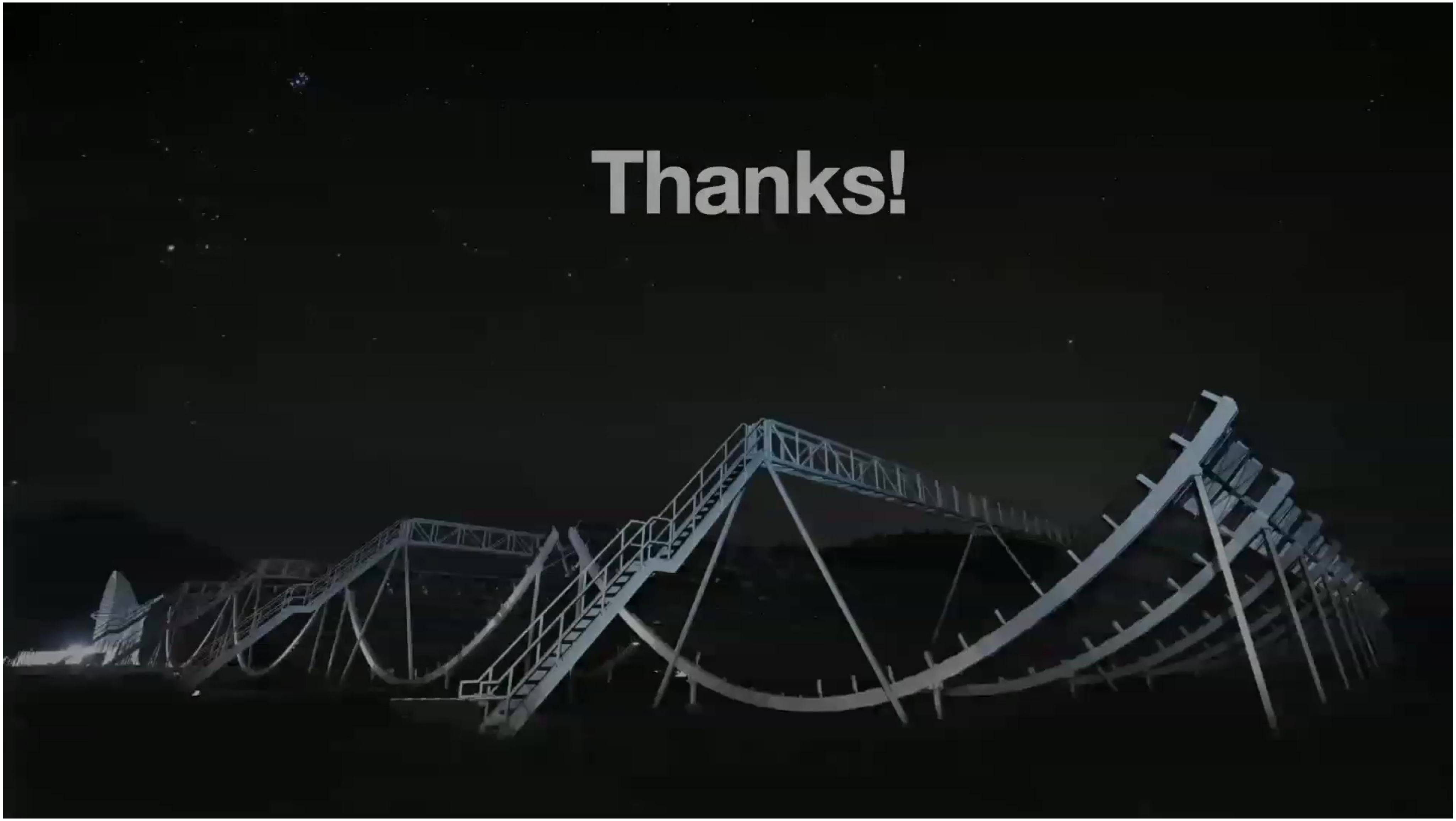
- what are they?
- potential applications…?

21-cm cosmology:

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

Pulsars:

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


Thanks!