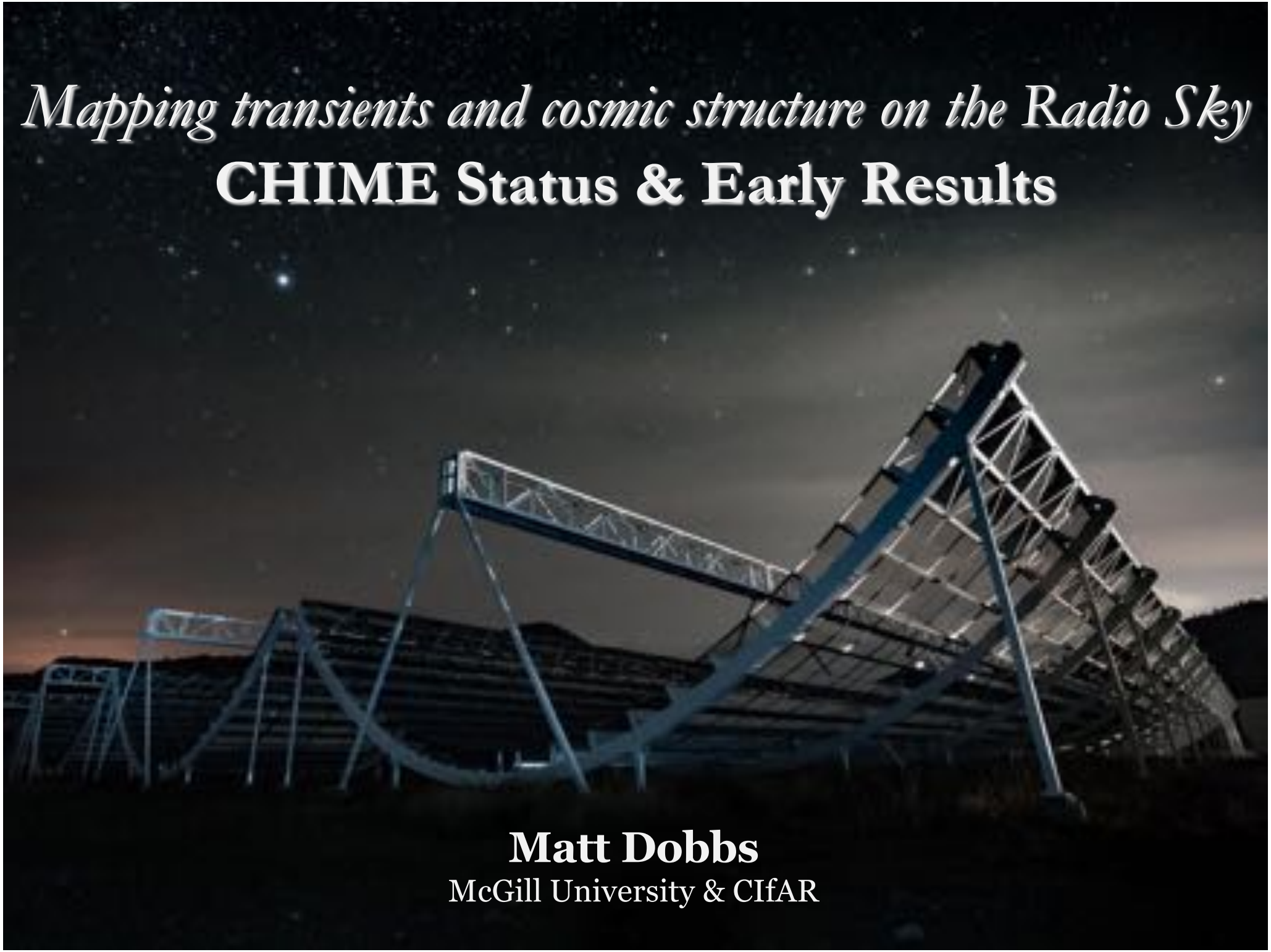


Mapping transients and cosmic structure on the Radio Sky

CHIME Status & Early Results

Matt Dobbs
McGill University & CIfAR

CHIME Collaboration

a collaboration between

Dominion Radio Astrophysical Observatory

McGill

THE UNIVERSITY OF BRITISH COLUMBIA

UNIVERSITY OF TORONTO

with partners at

Yale University

West Virginia University

Massachusetts Institute of Technology

PERIMETER INSTITUTE

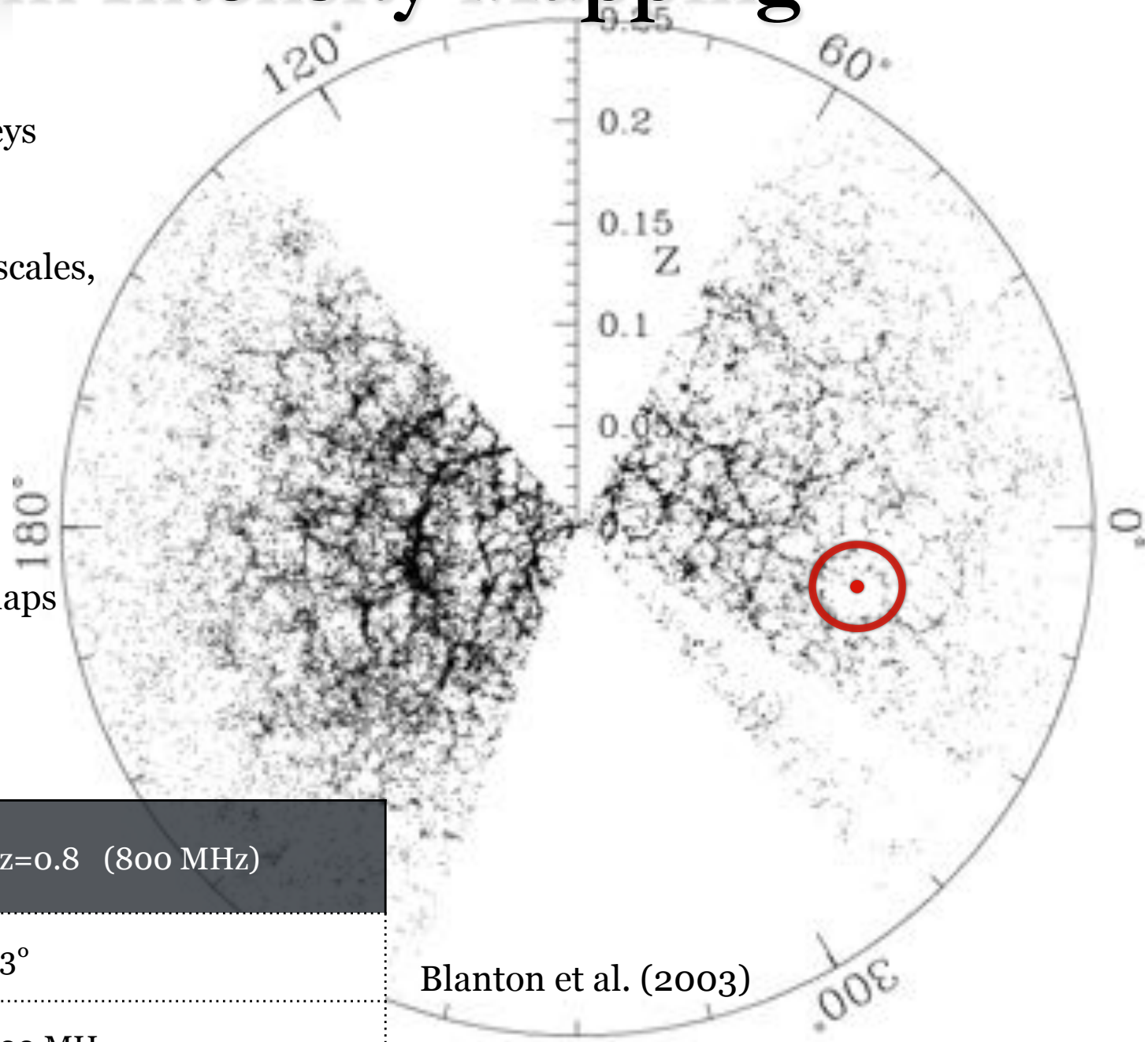
NRAO

More info at our website at: www.chime-experiment.ca

21cm Intensity Mapping

- Spectroscopic galaxy surveys expensive,
  difficult at high-z
- Interested in much larger scales, do not need to resolve individual galaxies

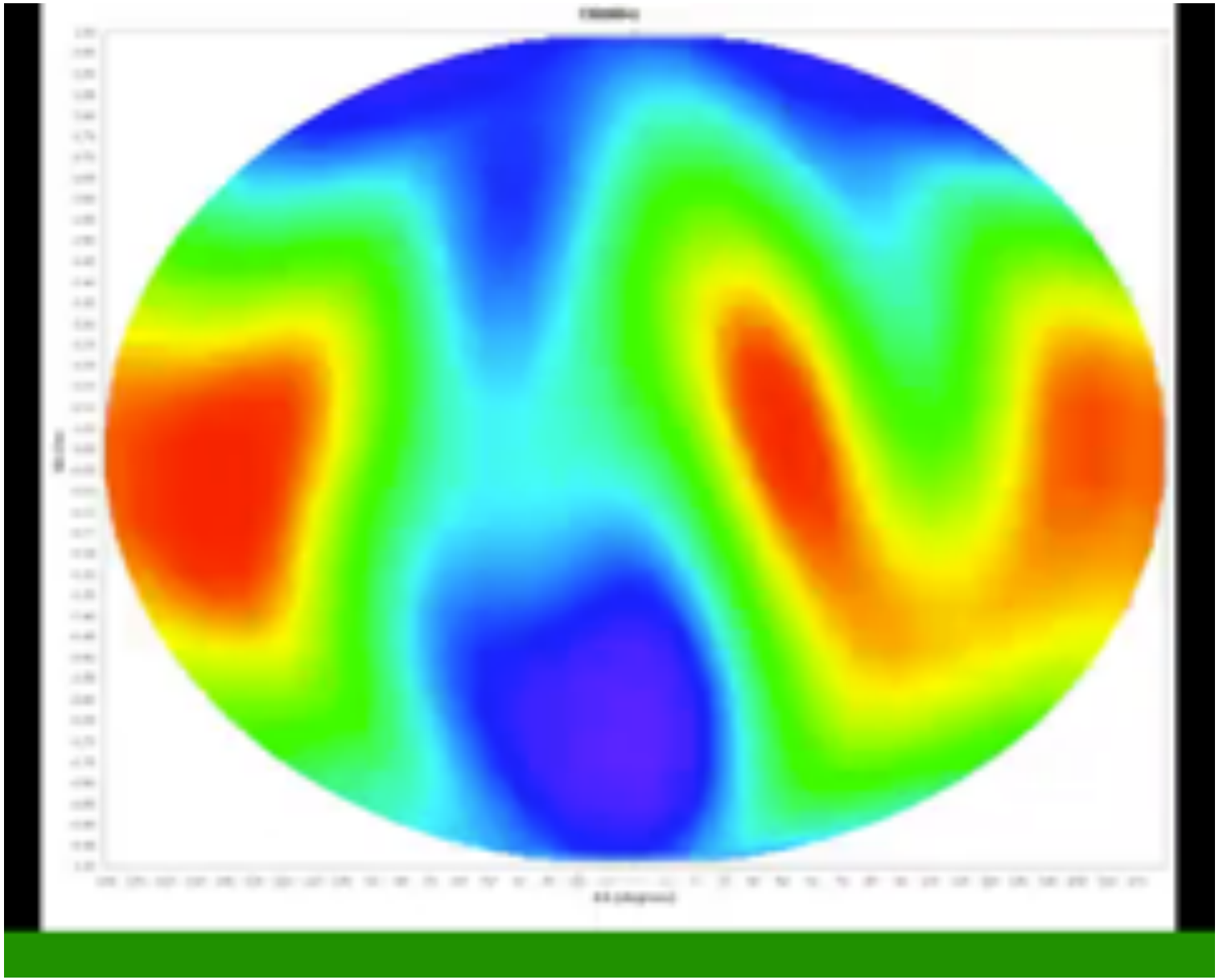
- Instead, measure the aggregate 21 cm emission from neutral hydrogen
  - Observing frequency maps to redshift slice
  - Probe "redshift desert" (1.4 < z < 2.5)



Blanton et al. (2003)

Observable	z=2.5 (400 MHz)	z=0.8 (800 MHz)
$\Delta\theta_{BAO}(z) = r_s/D_M($	1.35°	3°
$\Delta z_{BAO}(z) = r_s H(z)$	12 MHz	20 MHz

Cosmic Sound
Start: z=0.01
End: z=0.62



Observables:

- $\Delta\theta_{\rm BAO}(z) = r_s/D_A(z)$
- $\Delta z_{\rm BAO}(z) = r_s H(z)/c$

Simulation Video: Nick Gnedin & Dave McGinnis (Fermilab),

Cosmic Surveys

SDSS-II
- 2.2 Gpc^3

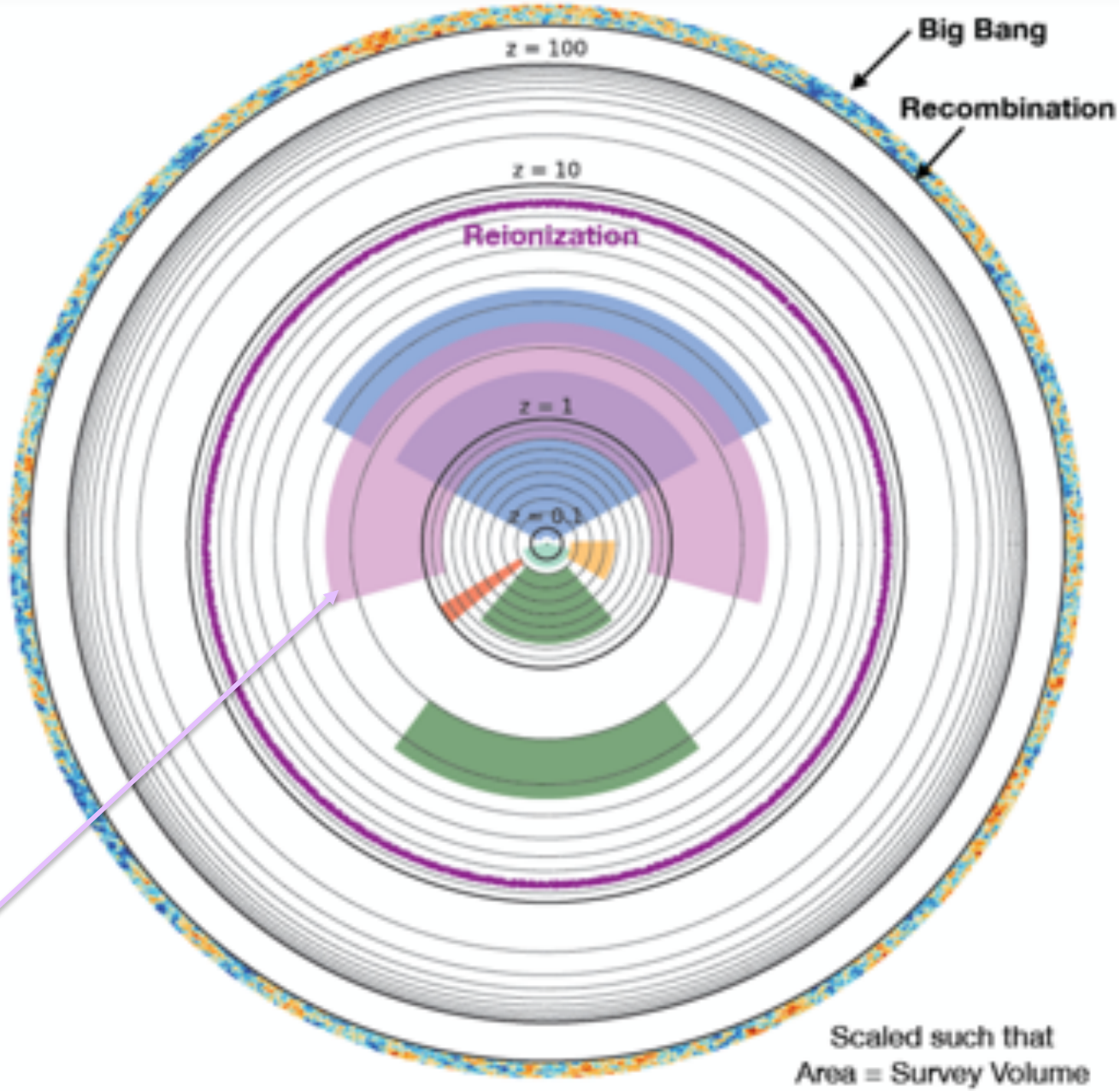
6dFGS
- 0.4 Gpc^3

WiggleZ
- 3.8 Gpc^3

BOSS
- LRG: 20 Gpc^3
- Lyα: 150 Gpc^3

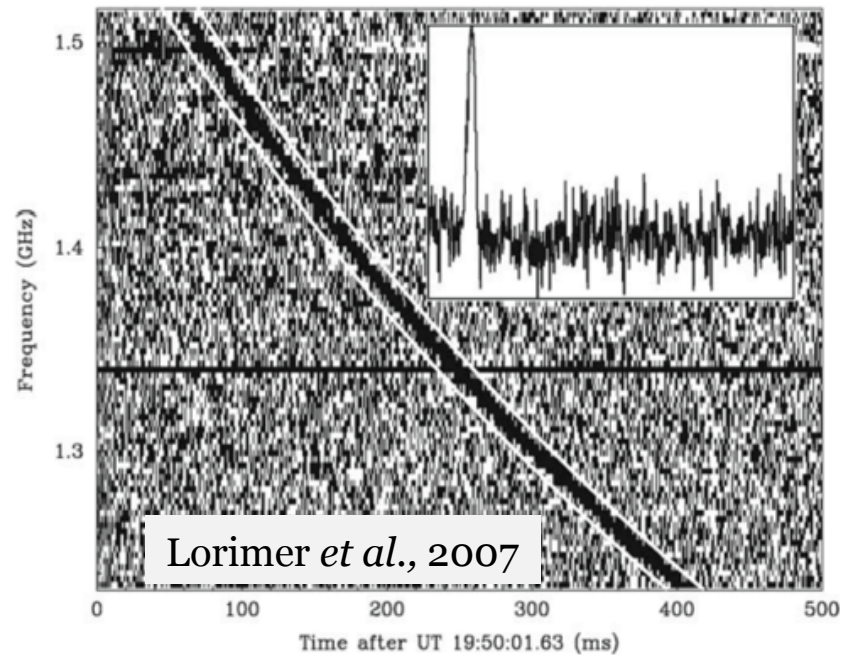
DESI (2019 - 2024)
- LRG/ELG: 140 Gpc^3
- Lyα: 230 Gpc^3

CHIME (2018 - 2023)
- 470 Gpc^3



(Figure from Seth Siegel)

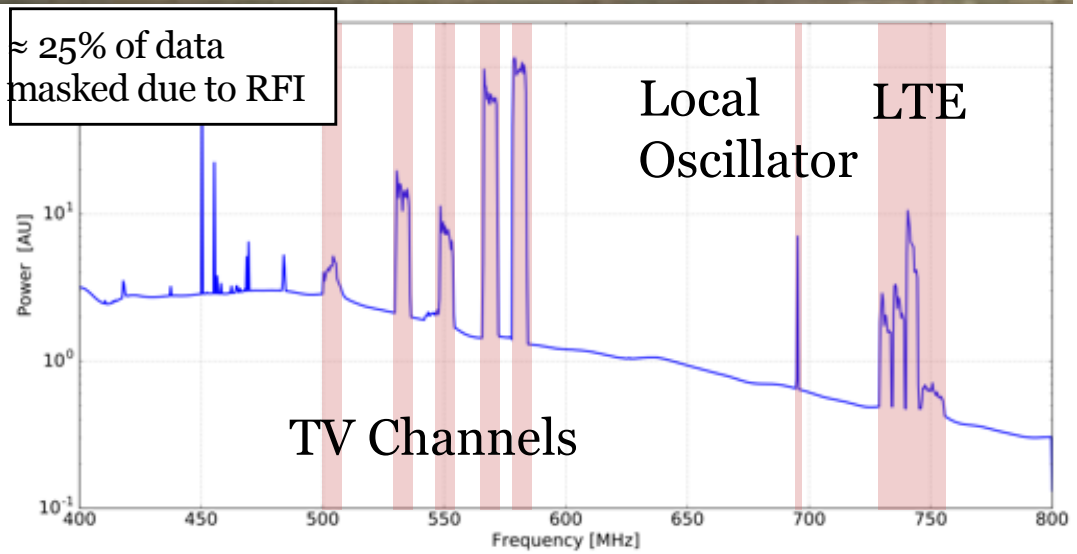
Fast Radio Bursts



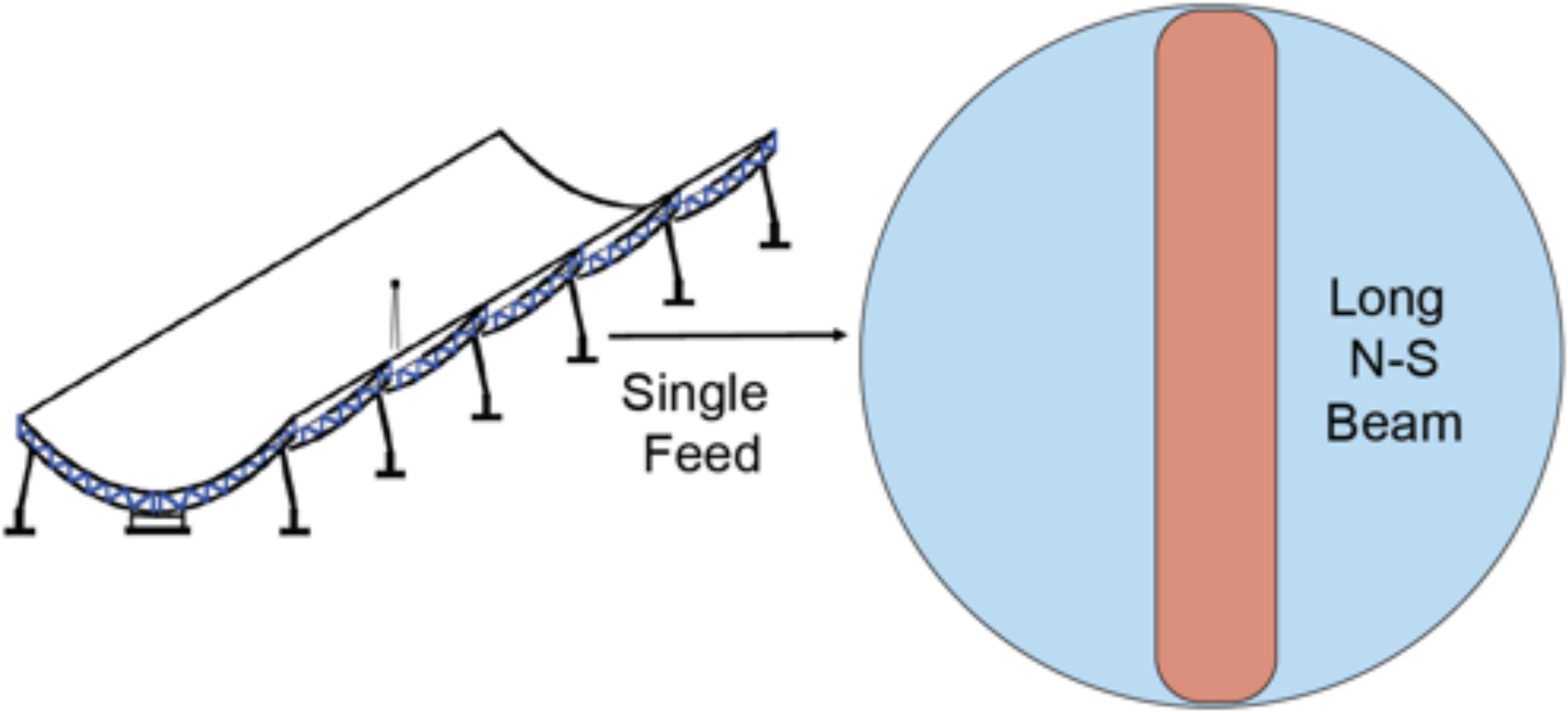
- Bright — Jansky flux density
- High dispersion – cosmological distance
- Compact – millisecond duration

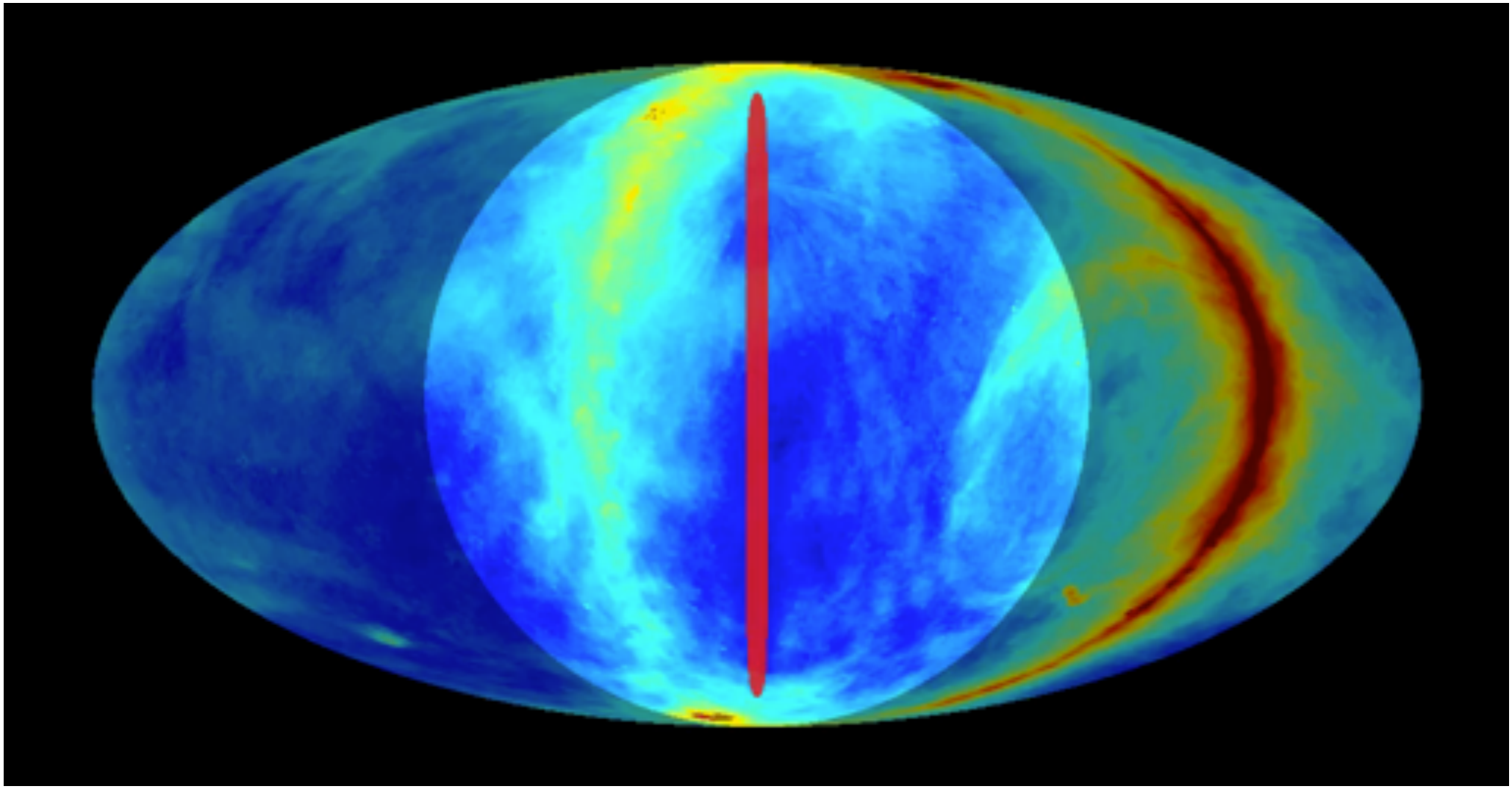
- ~Thousand per sky per day
- Models too numerous to list.
- Ideas for why FRBs can(not) be used at cosmological probes – too numerous to list.

Dominion Radio Astrophysical Observatory

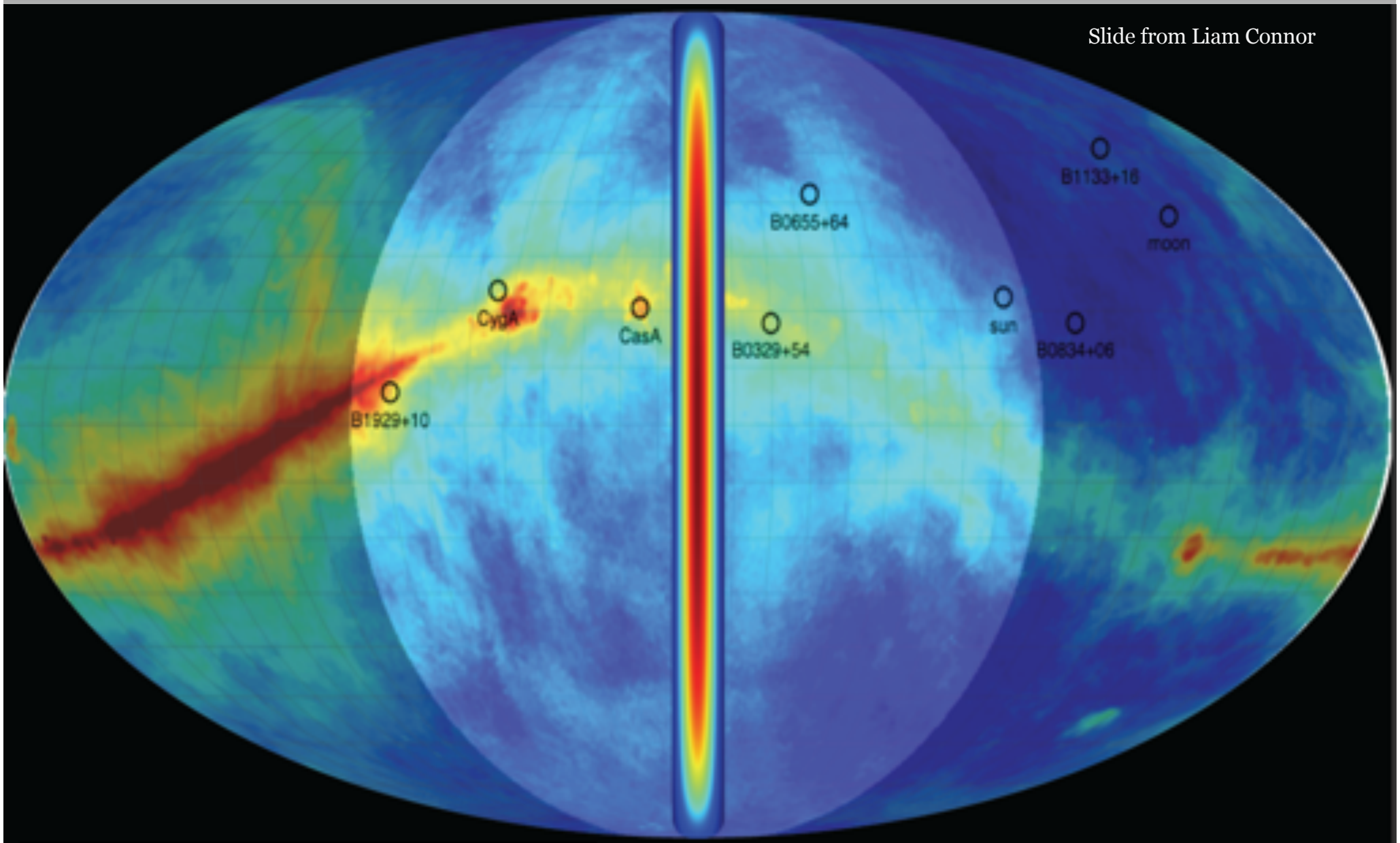


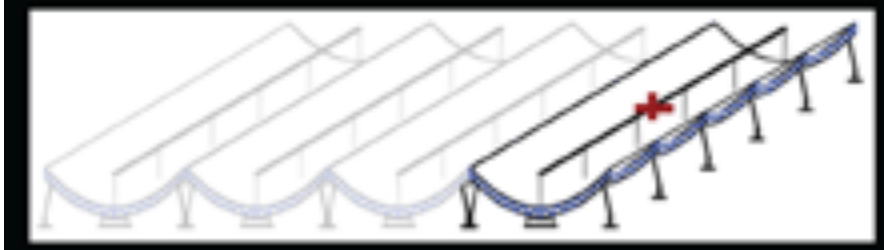
Cylinder Antenna





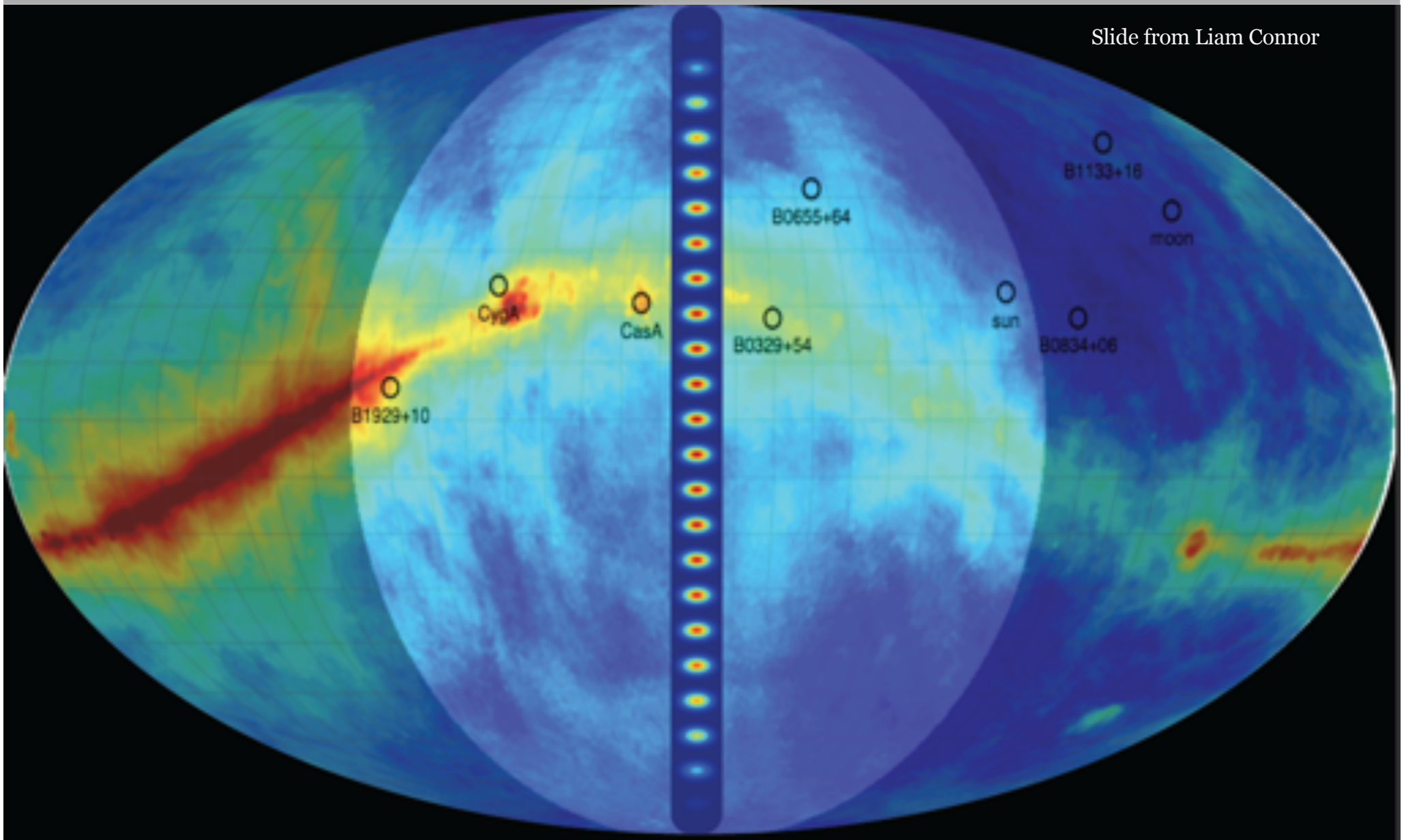
Slide from Liam Connor

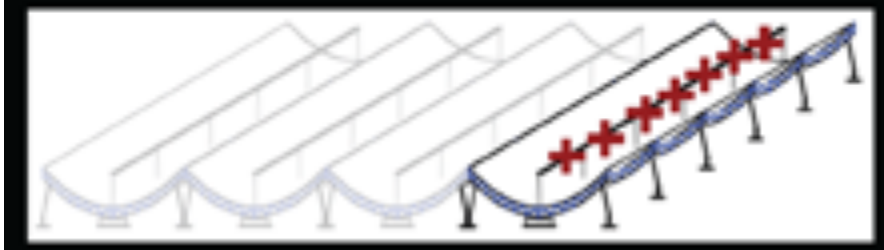




- Cylinder focuses light only in EW direction
- Gives us large FOV

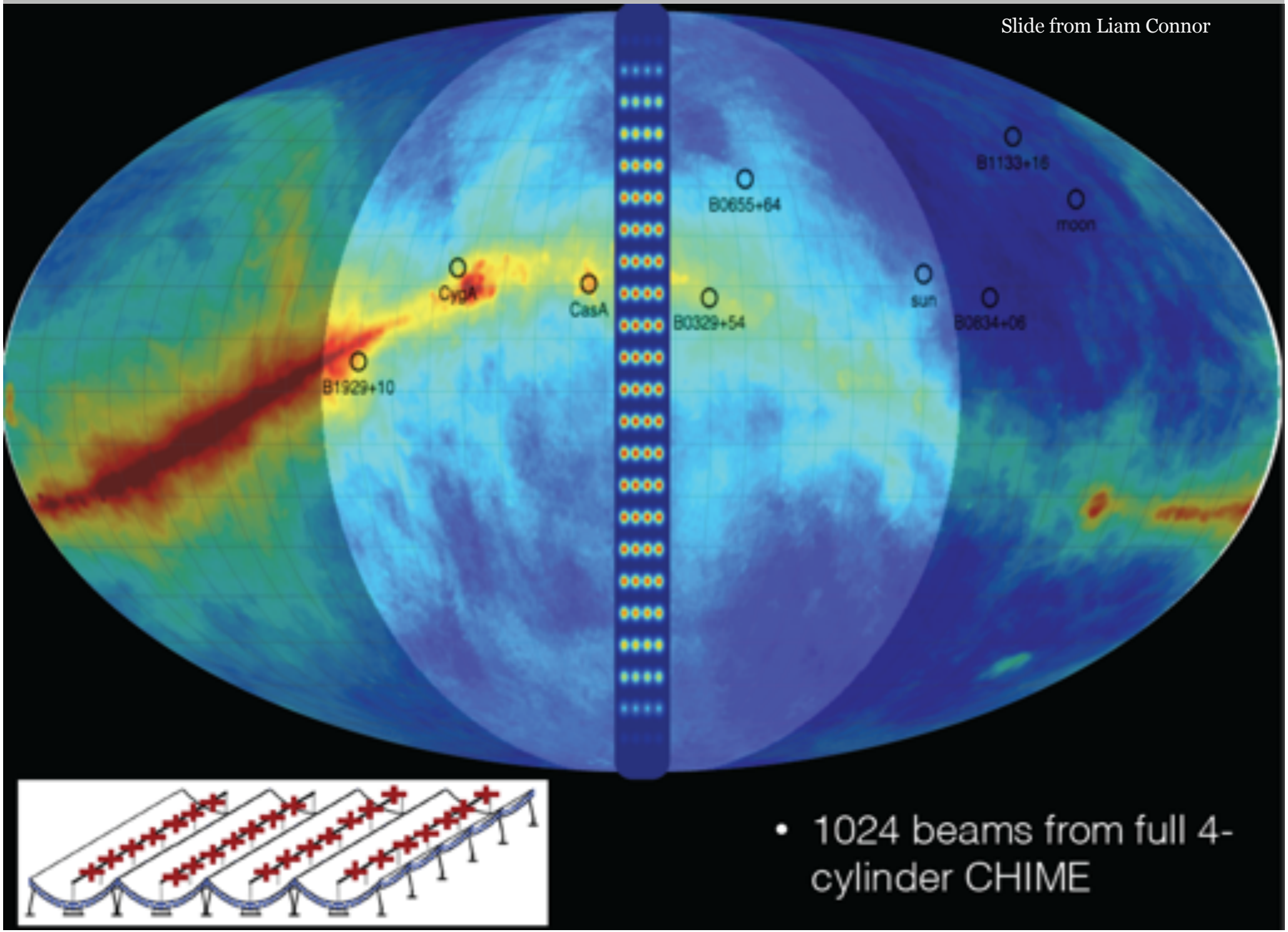
Slide from Liam Connor





- FFT telescope in NS direction
- 256 beams per cylinder

Slide from Liam Connor



Cylindrical Transit Interferometer

$\mathcal{E} \longleftrightarrow \mathcal{W}$

Movie by Peter Klagge

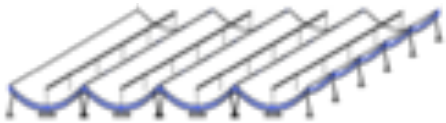
CHIME Science Objectives

chime

Hydrogen Intensity Mapping	Fast Radio Bursts	Pulsar Timing
Measure baryon acoustic oscillations in the distribution of neutral hydrogen between z = 0.8 - 2.5.	Detect large sample of FRBs.	Provide near daily timing data on all northern hemisphere pulsars.
Constrain dark energy.	Constrain properties and origins of FRBs.	Expand NANOGrav timing data set and add ISM information.

Analog Receiver Chain

(PhD: Meiling Deng)



Reflector

↓

Analog Receiver Chain

↓

FPGA Digitizer / Channelizer

↓

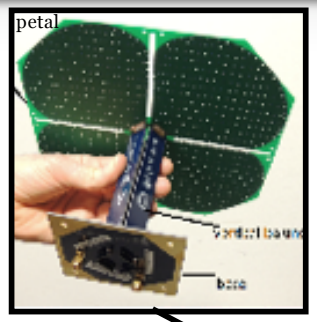
GPU Correlator

↓

Real-time Backends

↓

Disk



Antenna

Low Noise Amplifier

Focal Line

50m Coax

ADC

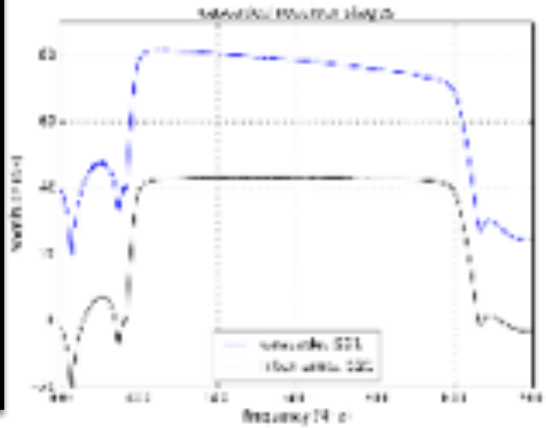
3.25m Coax

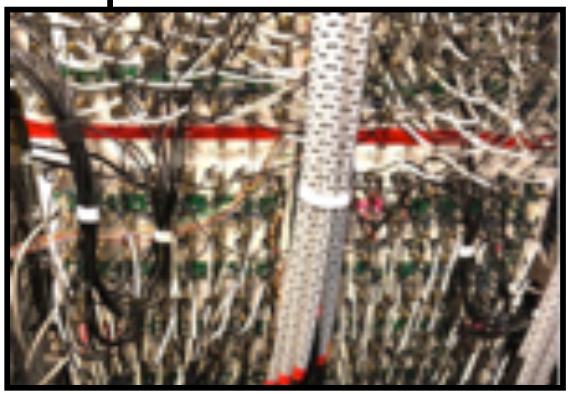
Filter + Amp Block

2m Coax

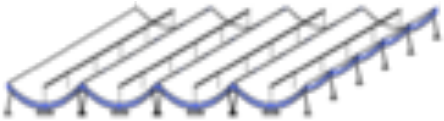
RF-Tight Room

Rx Hut





FPGA Digitizer and Channelizer (F-Engine)



Reflector

↓

Analog Receiver Chain

↓

FPGA Digitizer / Channelizer

↓

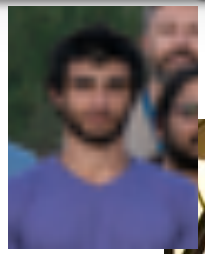
GPU Correlator

↓

Real-time Backends

↓

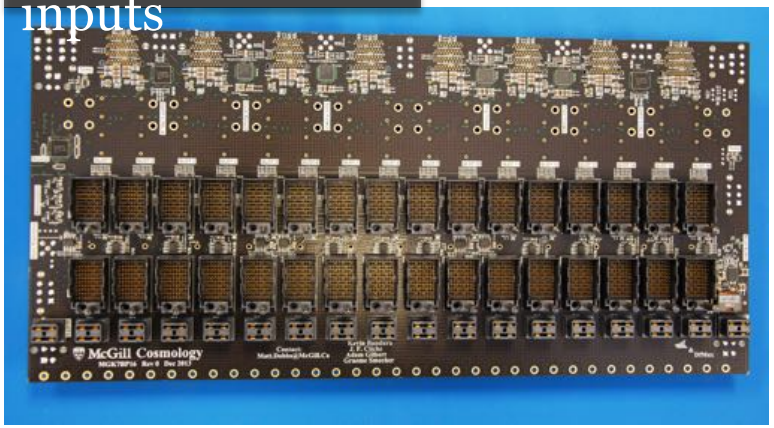
Disk

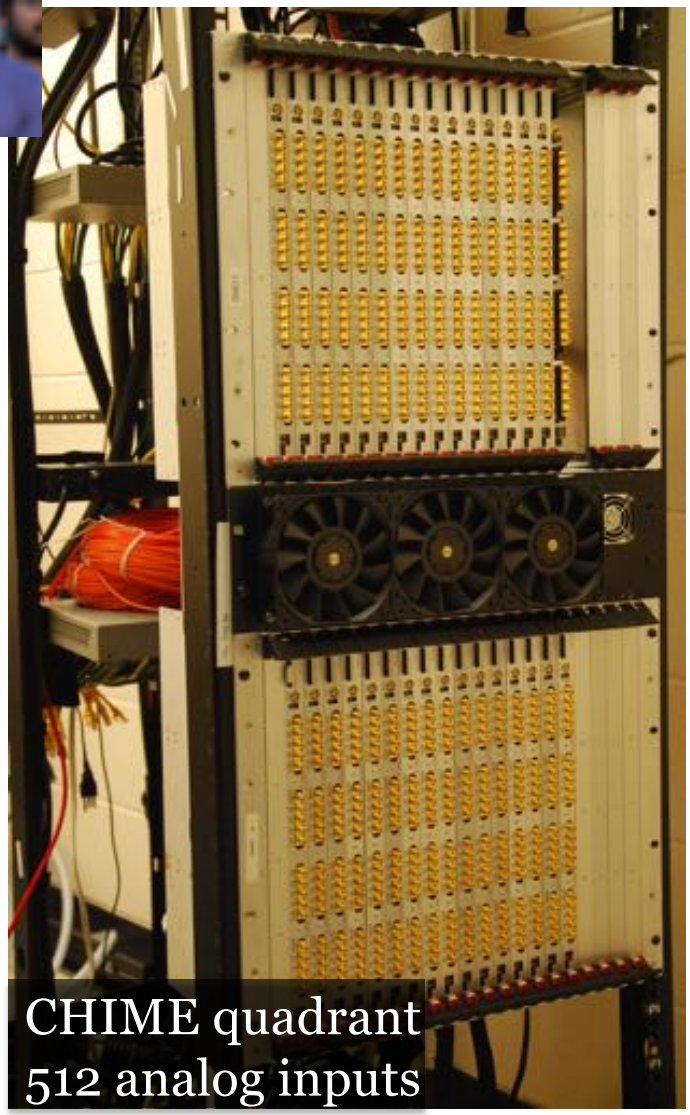


(PhD: Juan Mena)

Motherboard
16 analog inputs

Backplane
256 analog inputs



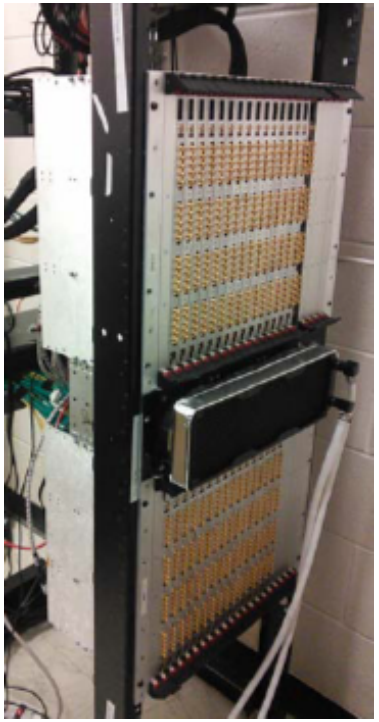


CHIME quadrant
512 analog inputs

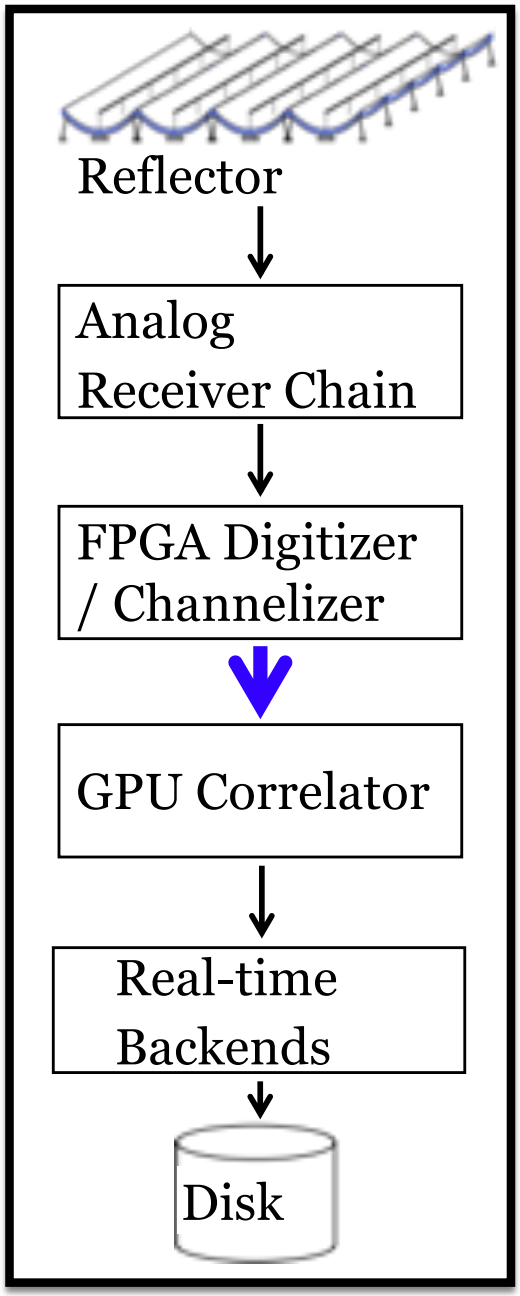
Bandura et al. 2016, JAI

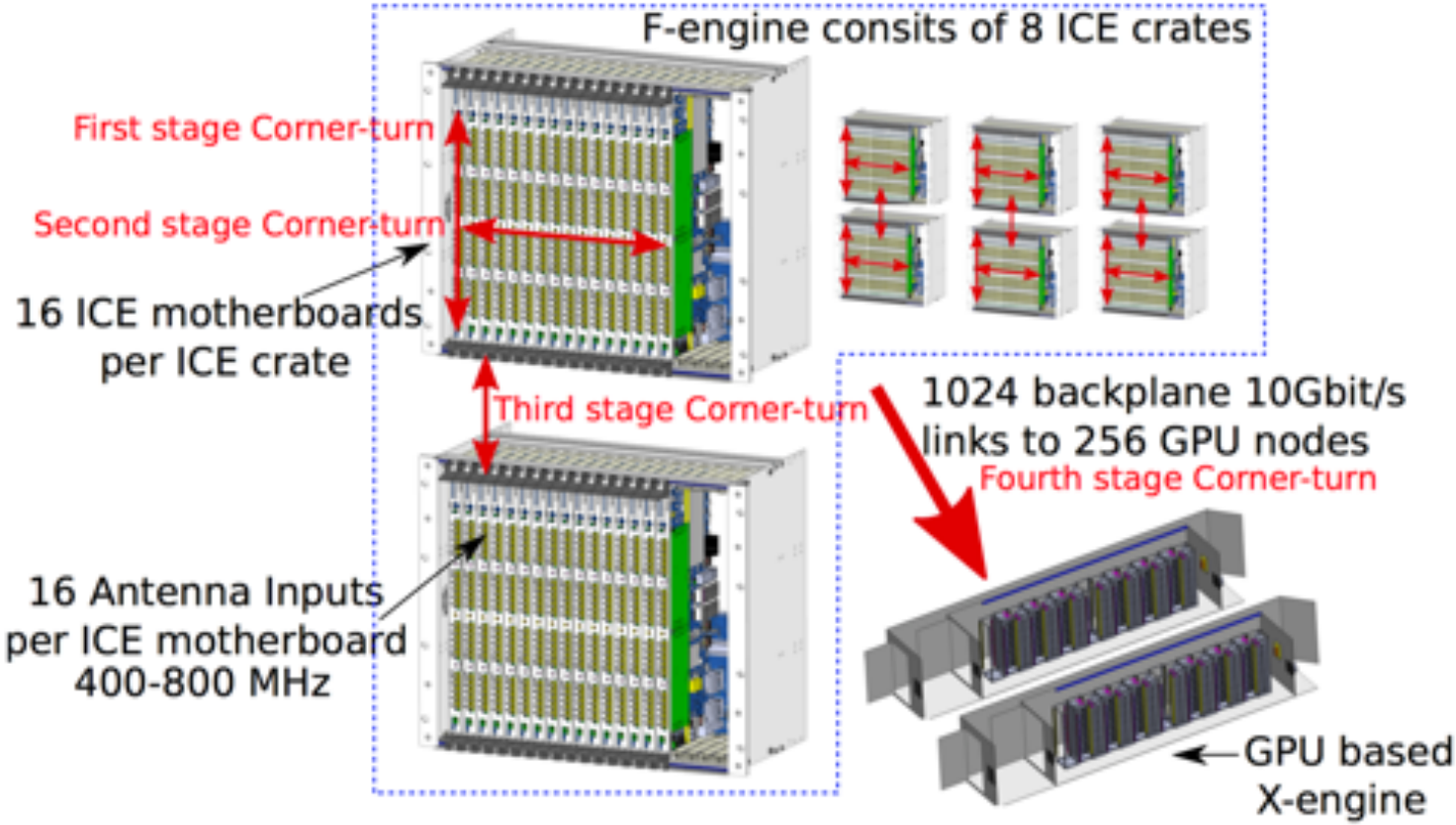
ICE: Scalable FPGA-system for Astronomical Instrumentation

- Radio
  - CHIME
  - HIRAX
  - "Suitcase" Interferometer
- TES Readout
  - POLARBEAR / Simons Array
  - South Pole Telescope 3g
- Designed for KIDs readout compatibility.



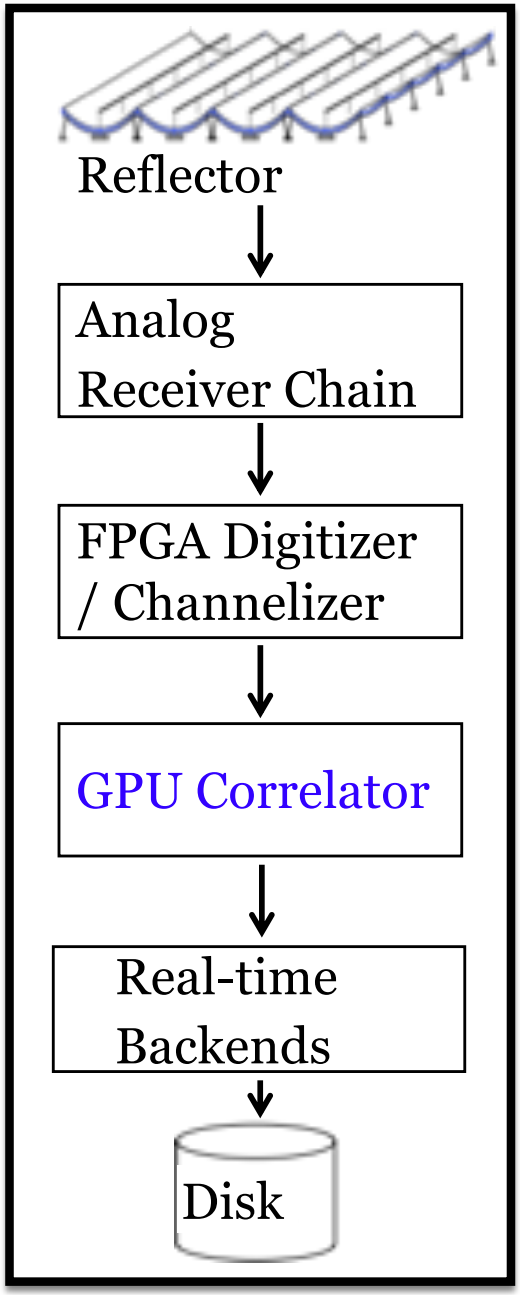
10 Gbit/s Link over Optical Fiber (x1024)

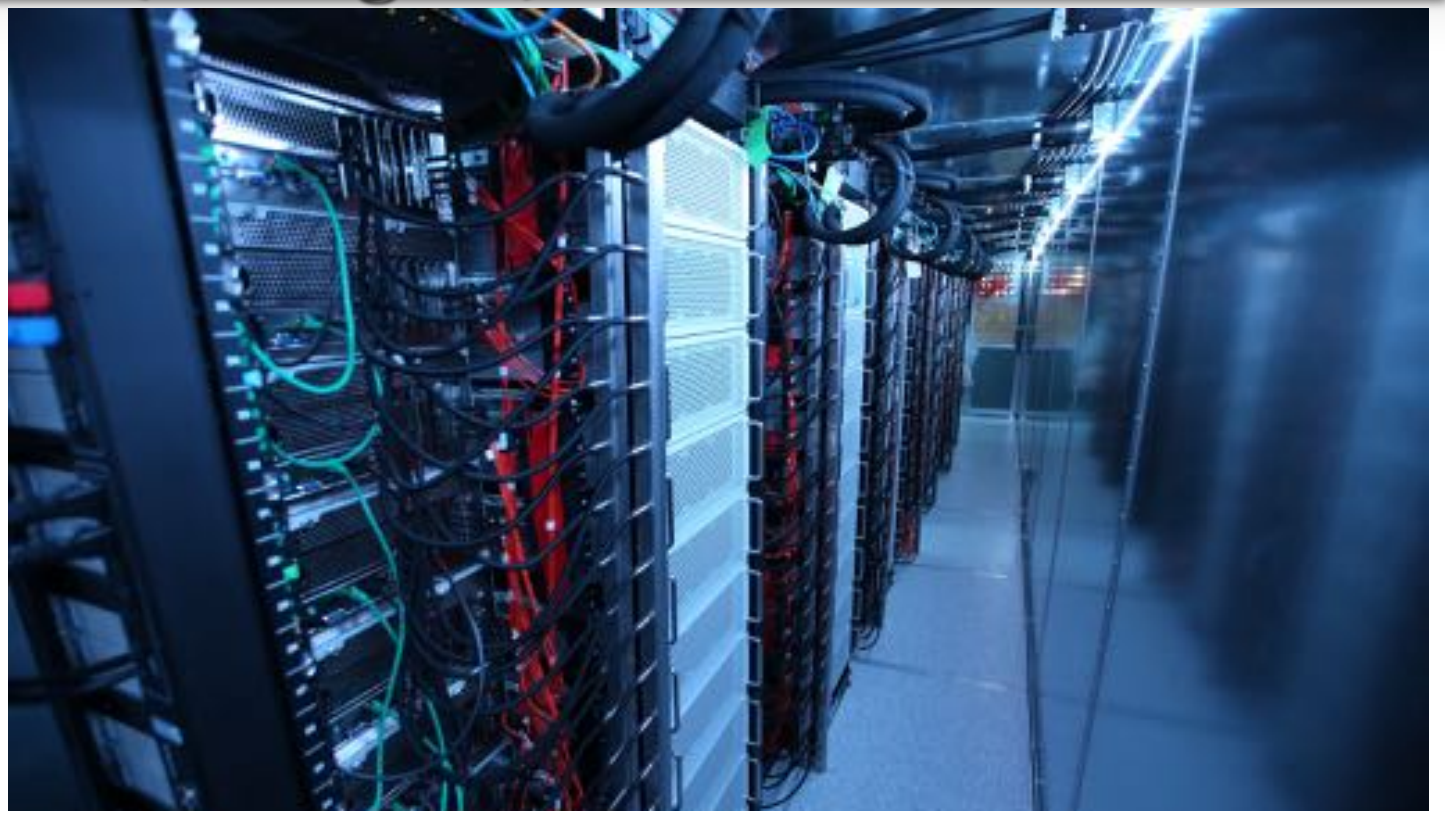




Realtime data rate: 13 terabits/second
70 Pbyte/day = **5kLSST**

GPU Correlator (X-Engine)





CHIME in a Nutshell

Full CHIME Layout		
Structure	4 cylinders, 100m x 20m each	
Bandwidth	400-800 MHz	*Digitize 8bits at 800 MSPS*
Number Feeds/cylinder	256 dual pol feeds per cylinder (2048 digitizers total)	~31cm spacing
Frequency Channels	512 frequency channels, 781 kHz wide (1.28 μs)	(for cosmology, you can channelize further!)
Data Rate	$2N_{FEEDS}$ x 6.4 Gbit/s = 13.8 TeraBit/s	

Observing Frequency	**400 MHz**	**to**	**800 MHz**
Wavelength	75 cm		37 cm
21cm Redshift	z=2.5 *(11 Gyr ago)*		z=0.8 *(7 Gyr ago)*
Beam Size	0.52°		0.26°
E-W FoV	2.5°	*10 → 45 Mpc resolution*	1.3°
N-S FoV	-60° to +60°		
Time/pixel/day	10min, 14min, 24hrs equator, 45deg, ncp		5min, 7min, 24hrs equator, 45deg, ncp
Receiver Noise Temperature	50k		
Flux Conversion	~2K / Jy		
Daily Sensitivity	~50 μJy / pixel		
Final Survey	~1.5 μJy/pixel		
	(Approximate – for planning purposes only)		

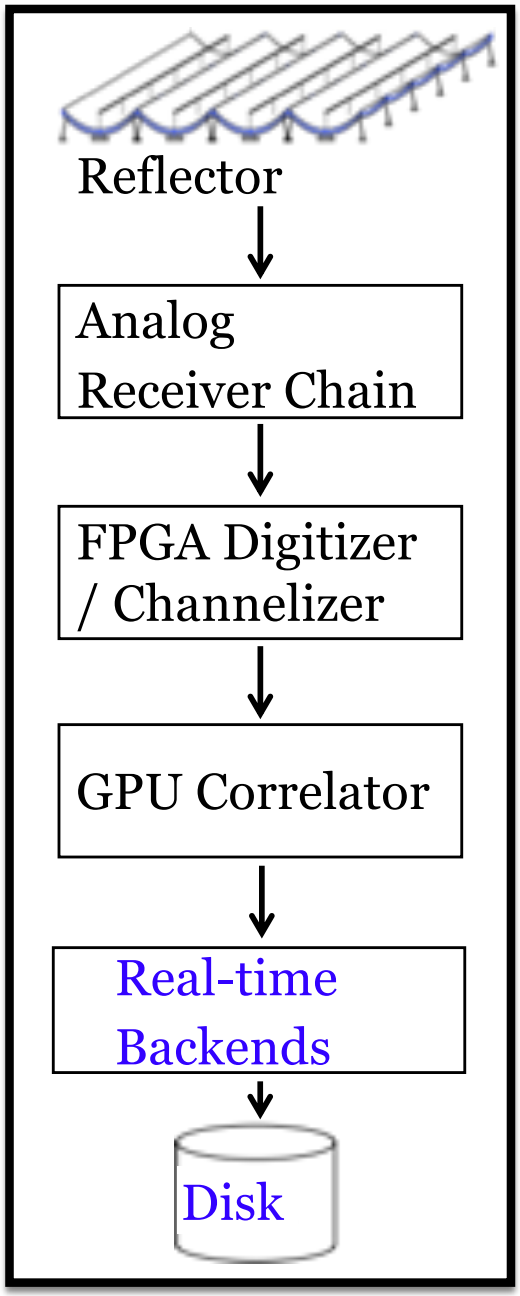
Timeline

- First light, Sept 2017
- FRB pre-commissioning July 2018
- FRB Ops Oct 2018 – now.
- Funded for 5 years ops.

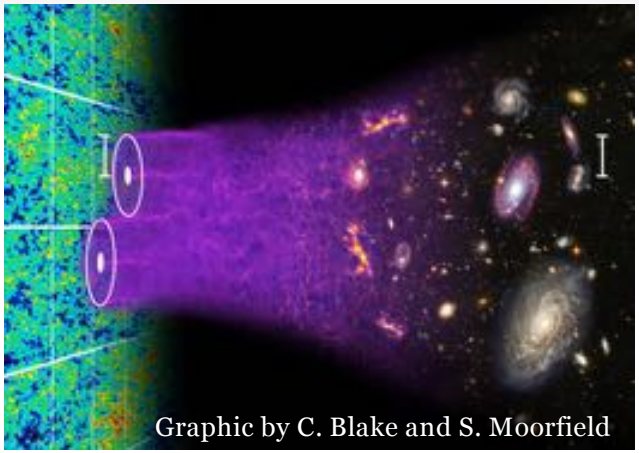
Cost: ~$16M CAD = $12M USD

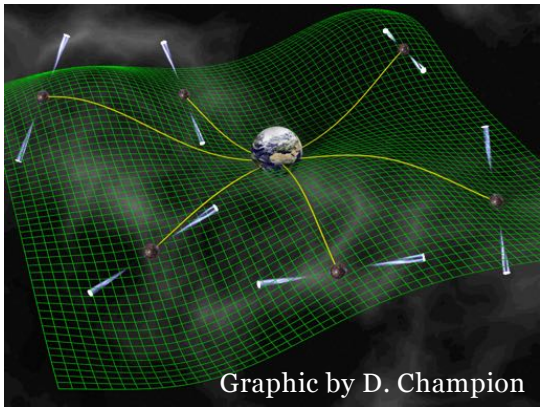
More info at our website at: www.chime-experiment.ca

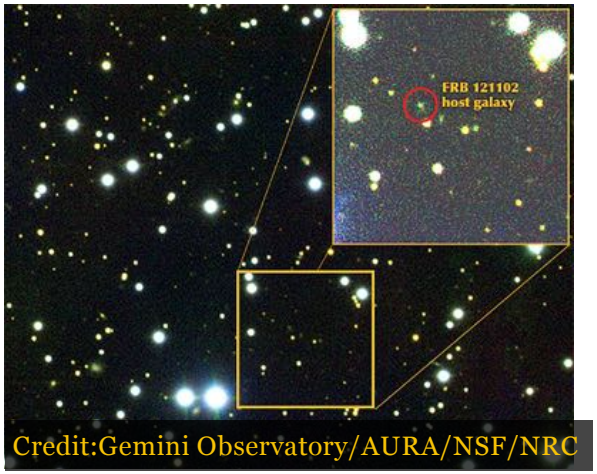
Backends



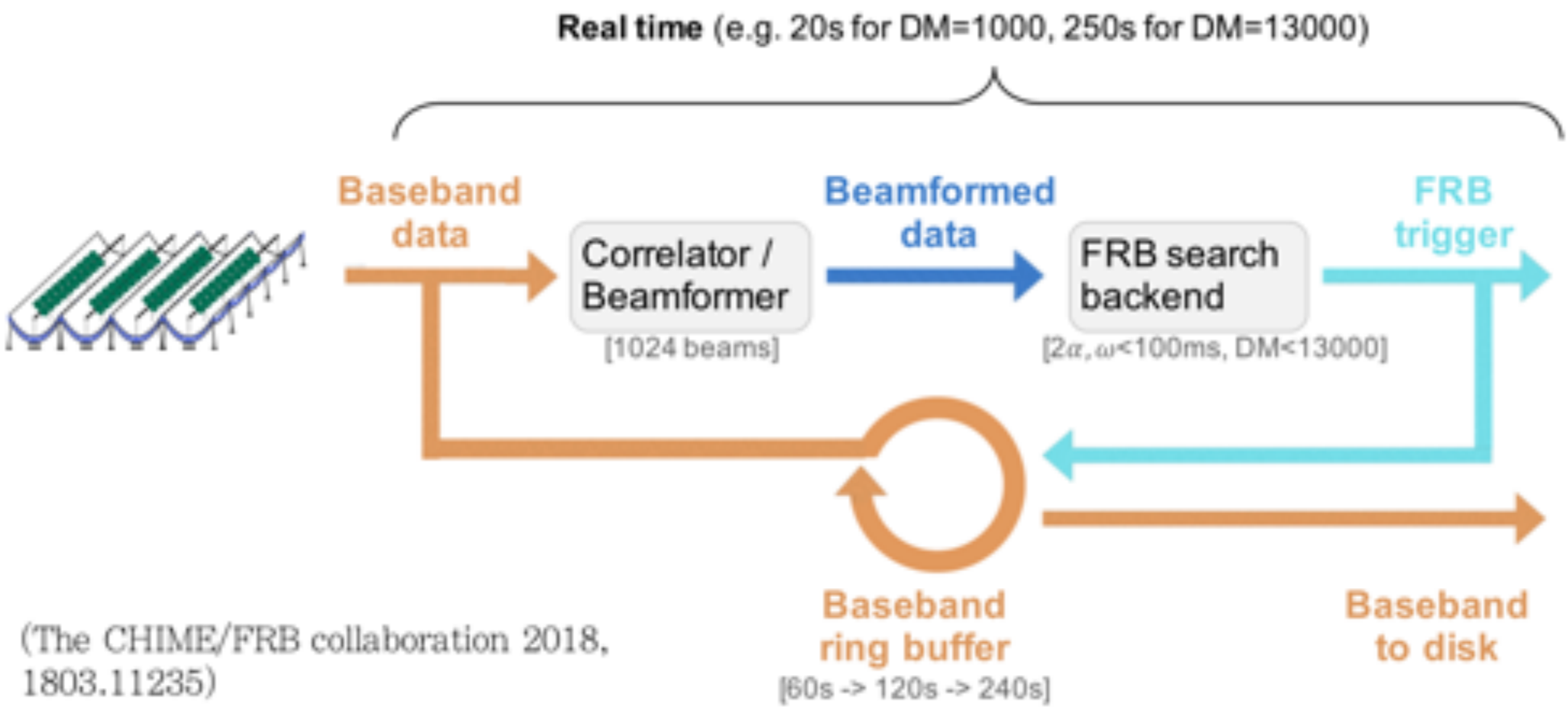
- Cosmology
  - Full N^2 visibility matrix
  - 10 sec cadence
  - 210 TB/day
  - Real time flagging and gain calibration
  - Data compression through redundant baselines (few TB/day)
- Pulsar timing
  - 10 steerable beams
  - 2.56 μs cadence
- Fast Radio Burst
  - 1024 stationary beams
  - 1 msec cadence
  - 16k frequency bins


Graphic by C. Blake and S. Moorfield


Graphic by D. Champion

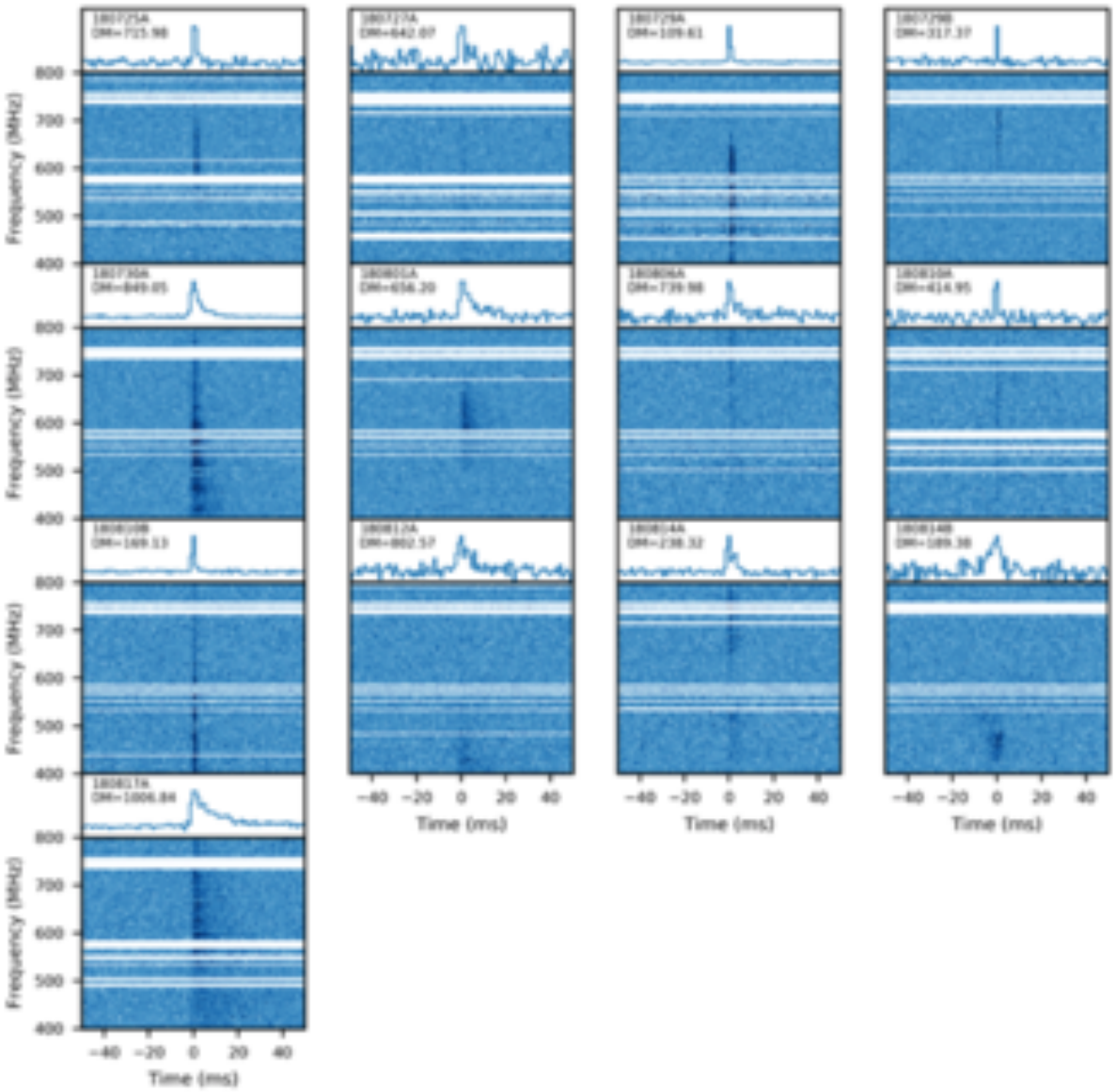


Credit:Gemini Observatory/AURA/NSF/NRC

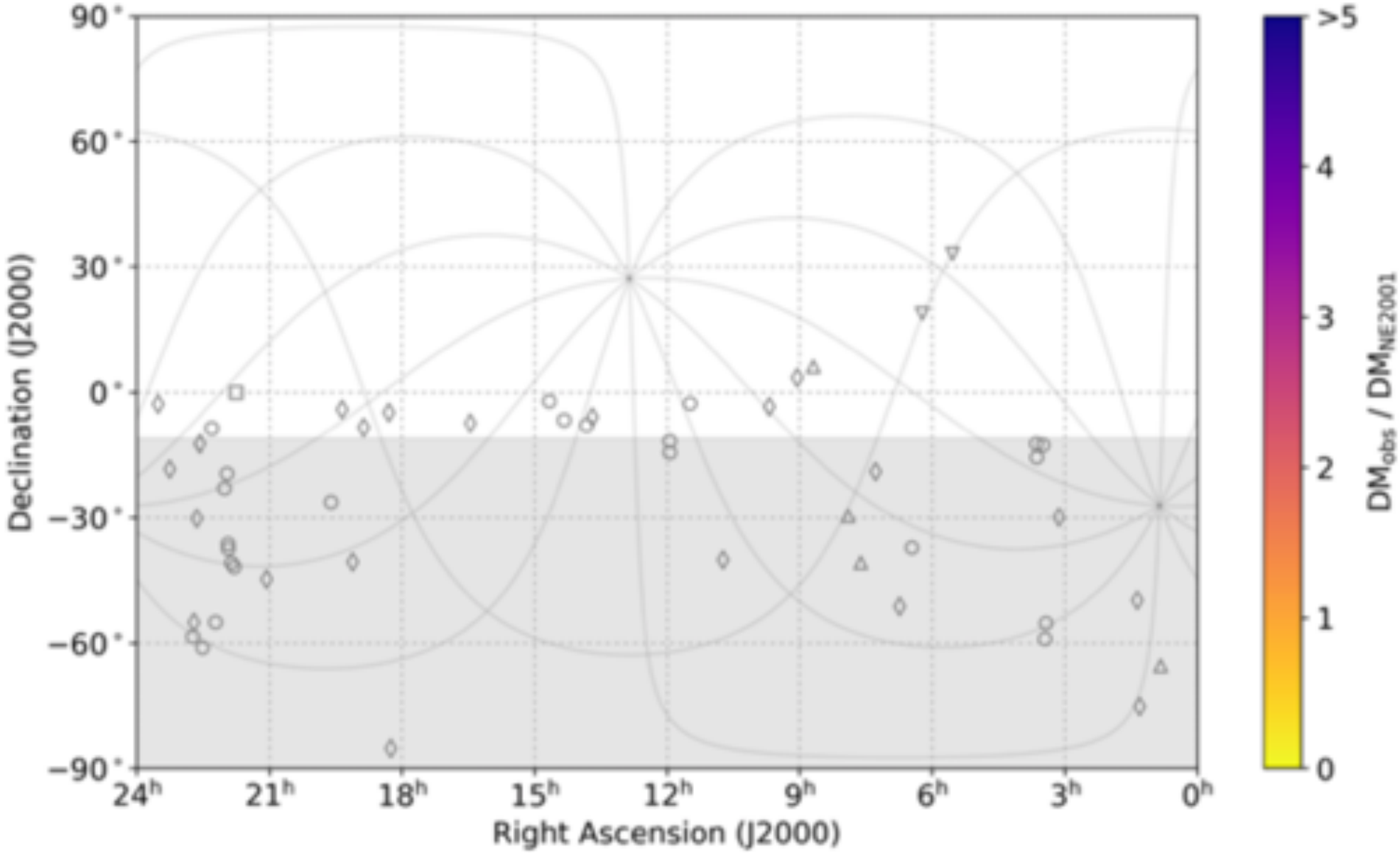


(The CHIME/FRB collaboration 2018, 1803.11235)

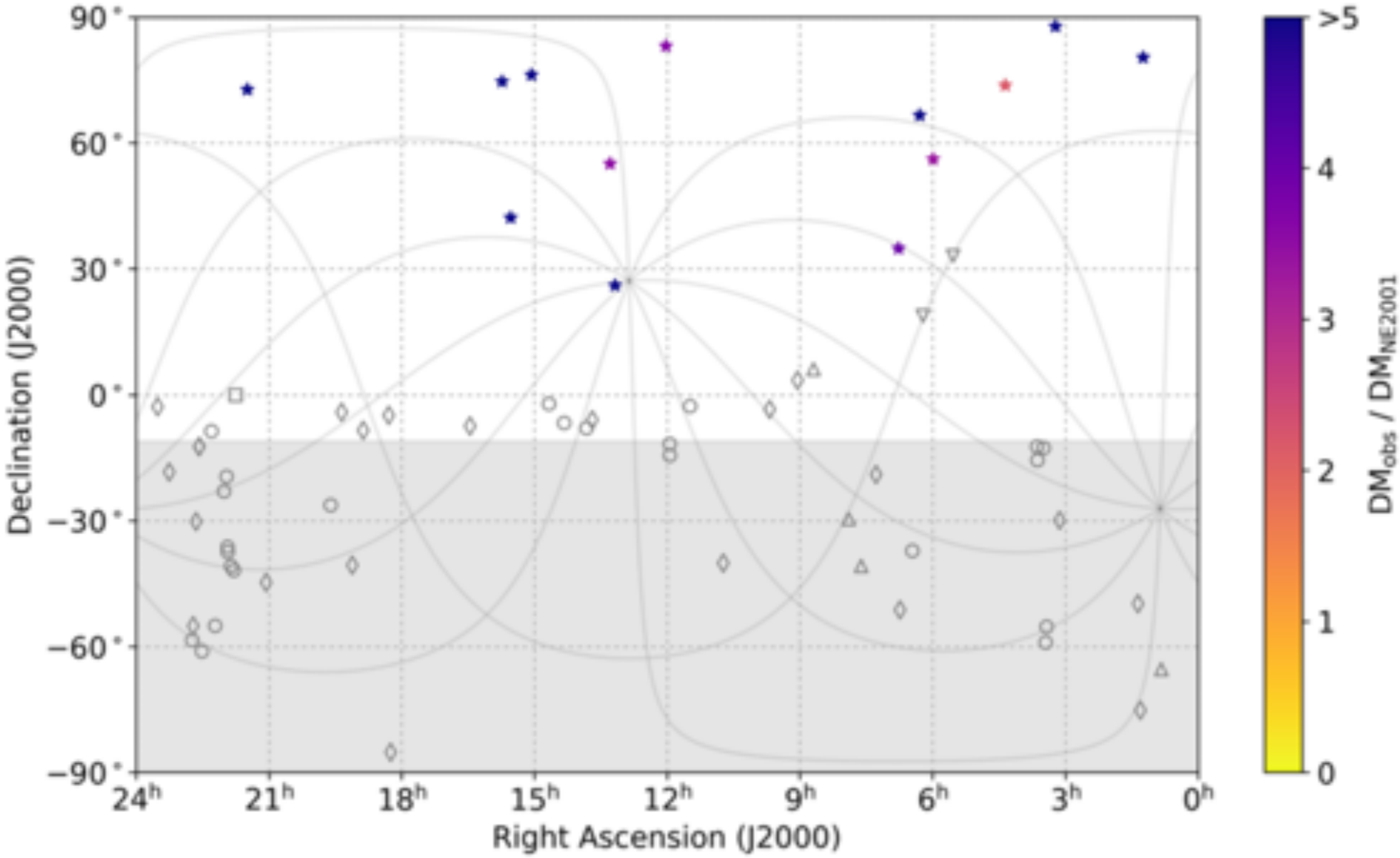
Detection of FRBs Down to 400 MHz



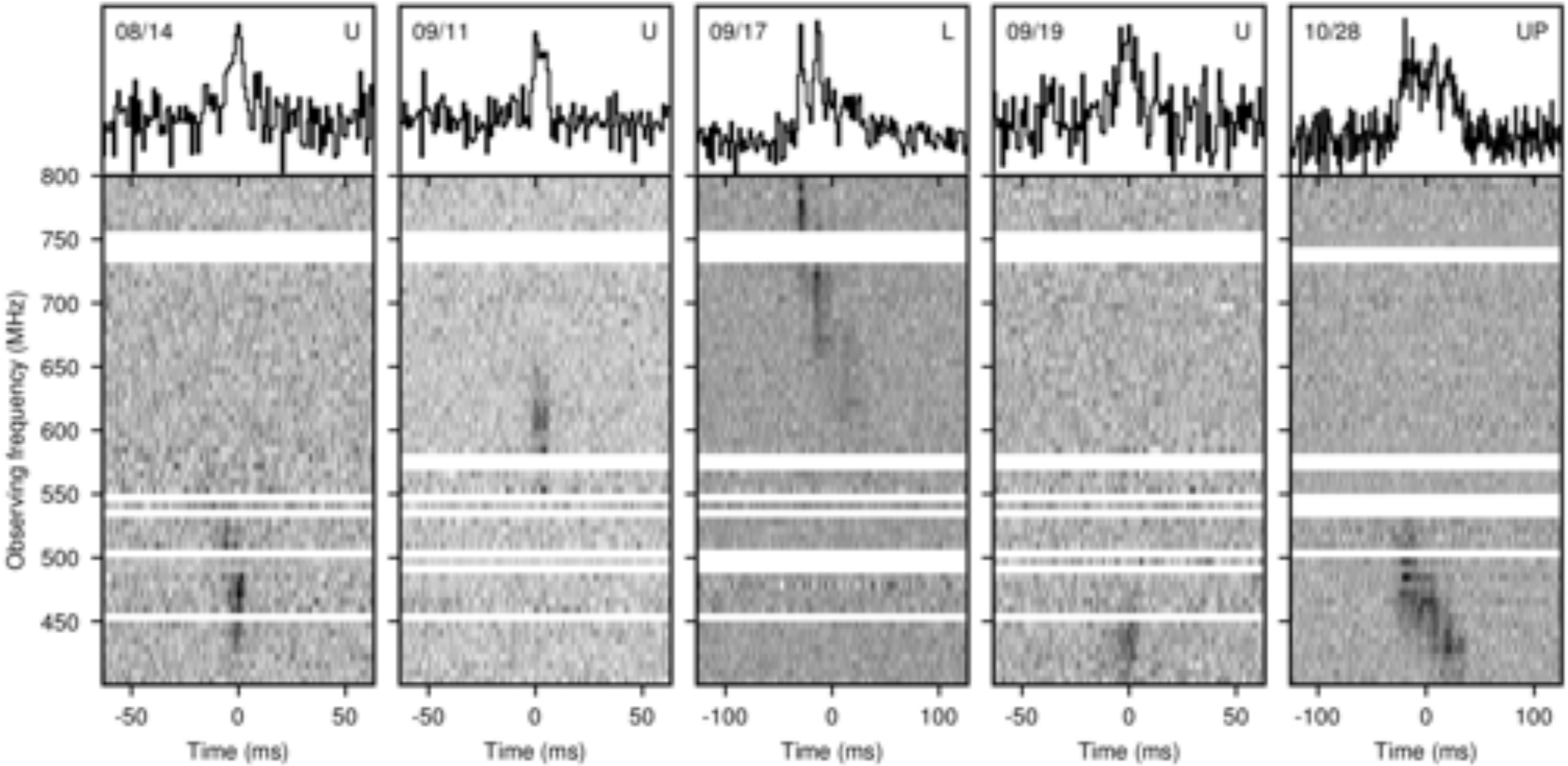
Published FRBs at CHIME/FRB Turn on (July 24,2018)



13 Published CHIME FRBs (Sept 1, 2018)



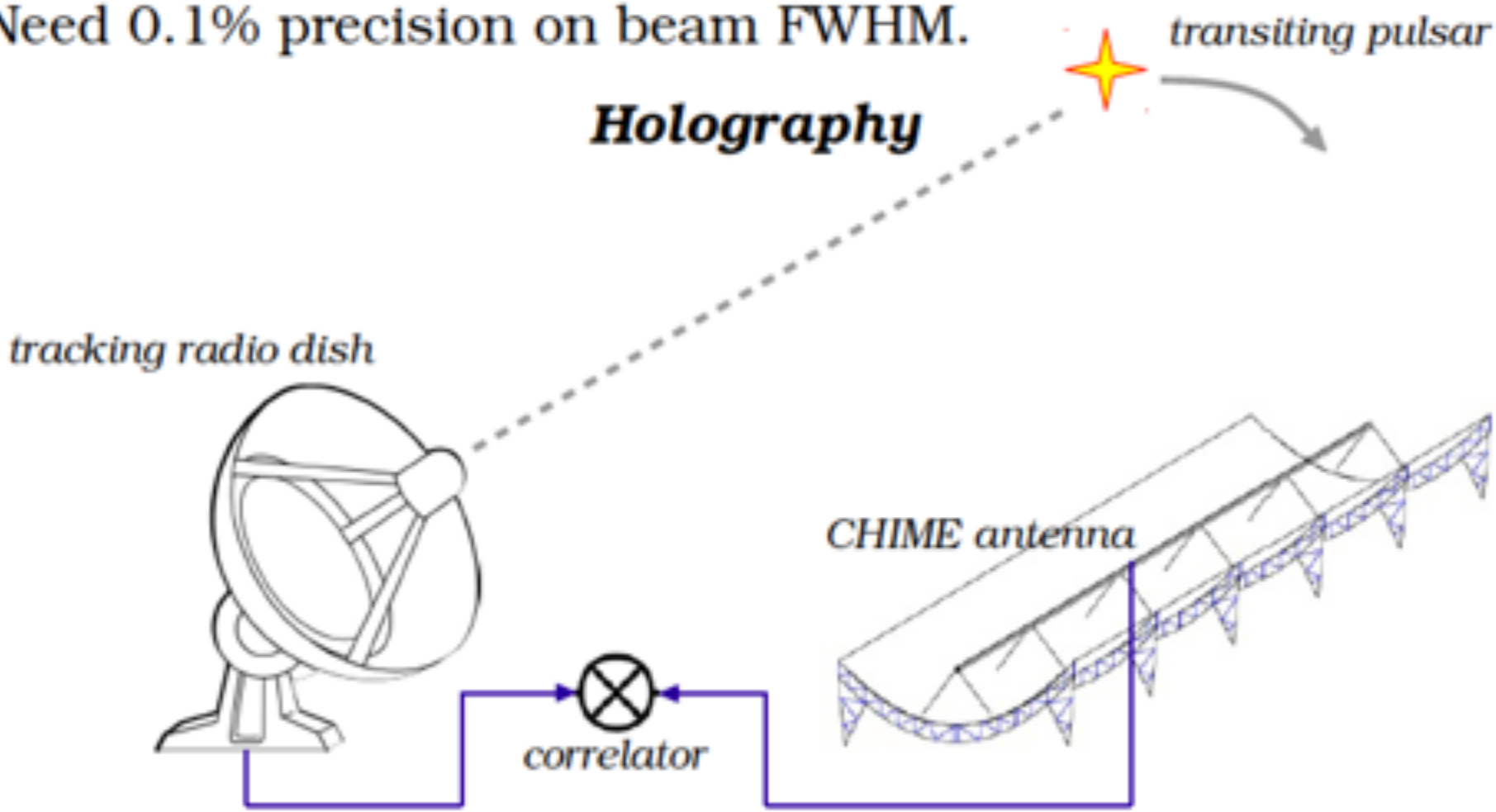
CHIME REPEATER – R2



Team Emphasis now: Calibration

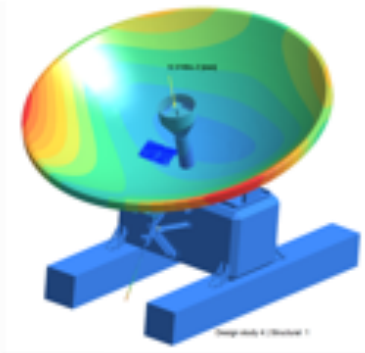
Beams

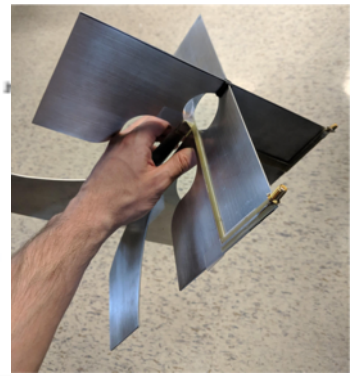
- Beam pattern changes with frequency → beam uncertainties will mix spatial and frequency modes.
- Need 0.1% precision on beam FWHM.

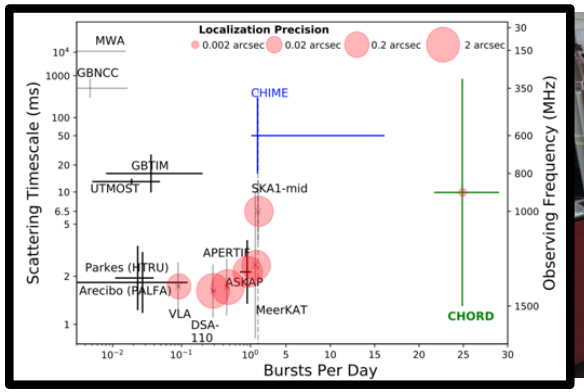


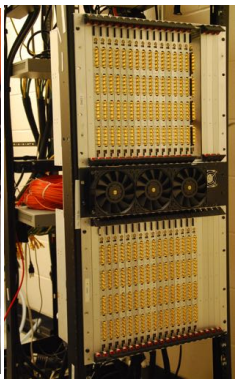
FRB Localization and CHORD

The Canadian Hydrogen Observatory and Radio Transient Detector









UNIVERSITY OF TORONTO

McGill UNIVERSITY

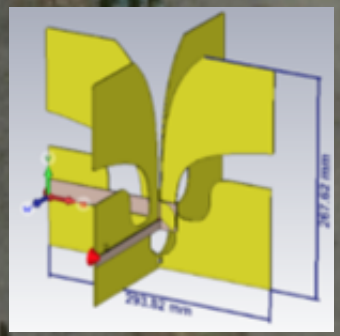
Canada NRC·CNRC

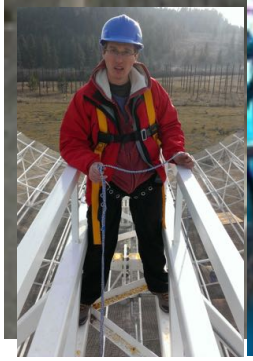
PERIMETER INSTITUTE

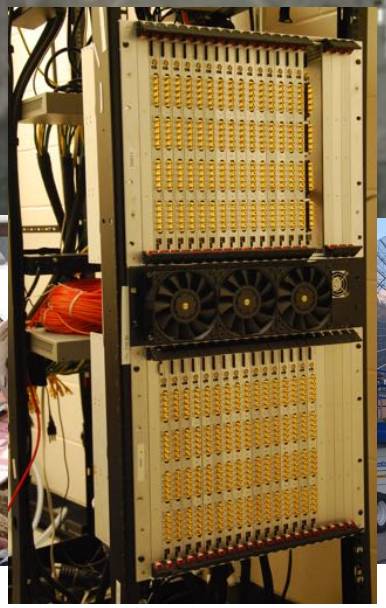
UNIVERSITY OF CALGARY

CHORD Building Blocks

Precision Machine







CHORD Key Science

Fast Radio Bursts	Fundamental Physics	Distribution of Matter in the Universe
• FRB localization (to the galaxy and within the galaxy), informing progenitor scenarios. • FRB Cosmology, e.g. `missing baryons' • Reionization history via high-redshift FRBs • Origin and evolution of cosmic magnetism via polarization	• Discovery of keystone pulsar systems for tests of gravity. • Small-scale matter power spectrum for constraints on neutrinos and other light degrees of freedom.	• A billion pixels in HI intensity mapping. • BAO: broadband power spectrum measurements. • Test—rather than assume—models of how HI traces matter. • 10^7 unresolved HI galaxies

Philosophy: designed and built as a focused transient & 21cm experiment, AND include the ***software/ pipeline/ database/ governance*** infrastructure to make data products available for all applicable science.

Outrigger & CHORD Overview

VLBI Outriggers

- Stage 1: widefield outriggers, FoV matched to CHIME
  - Emphasize *rapid timescale*.
  - 100 and 1000s km baselines
  - milliarcsecond localization
- Stage 2: broadband precision dishes to match compact array

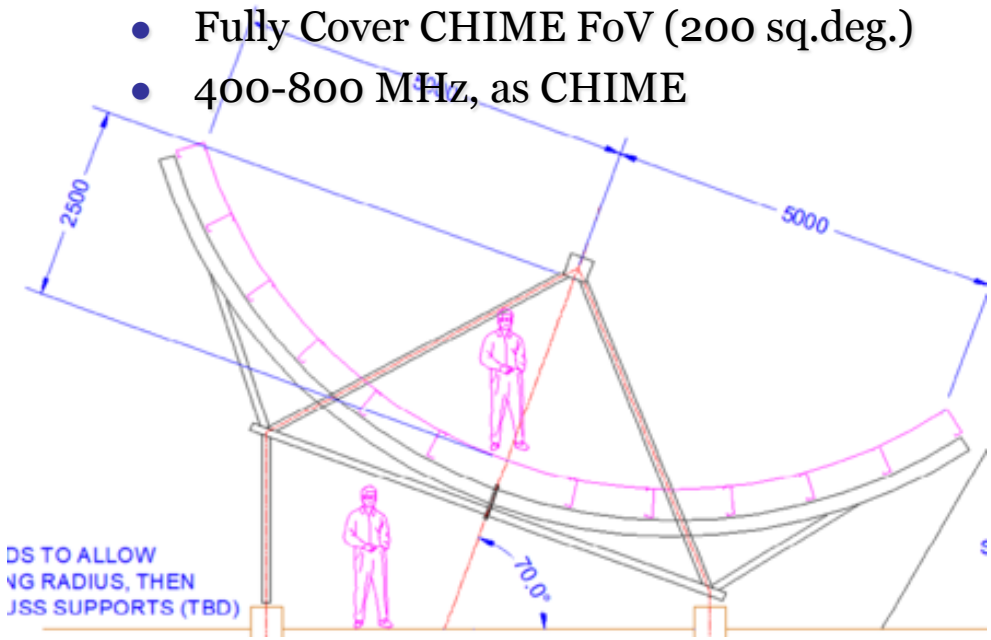
Precision Compact Array

- 512 x 6m composite dishes
  - 15,000 m2
  - Compact configuration
  - DRAO Site
- 300-1500 MHz broadband feeds
- 30K System Temperature

FRB Localization Outriggers

Planning/Prototype funding from Moore Foundation kick-starting this time-critical development.

- Phase 1: Wide-field Outriggers
  - 30m-long x 10-wide cylinders (baseline)
  - Fully Cover CHIME FoV (200 sq.deg.)
  - 400-800 MHz, as CHIME

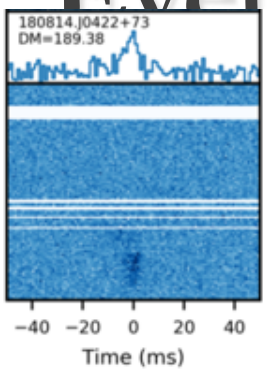


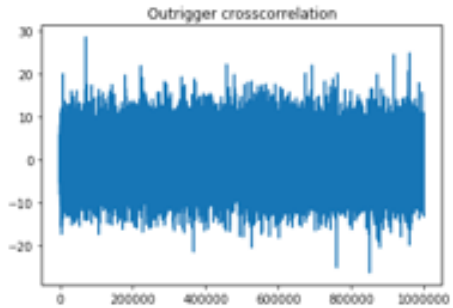
- Phase 2: Precision wide-band dishes
  - Match compact array FoV.
  - Composite Dishes
  - 300-1500 GHz

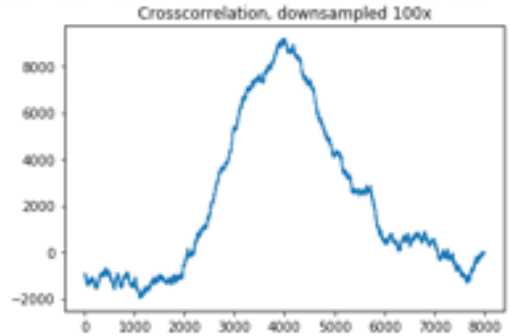
Localization:

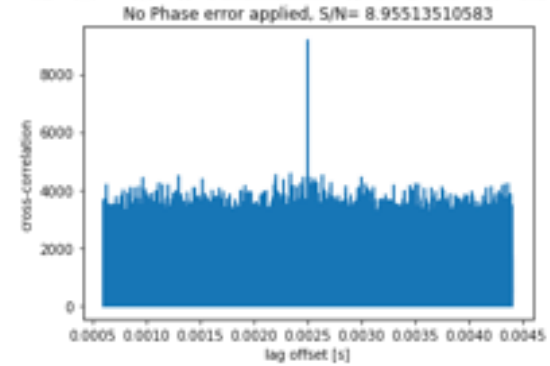
- Arcsecond: Host galaxies
  - distances
  - cosmology
- mas: location within host galaxies
  - Local environments (→ disentangle local & line-of-sight effects)

Event Reconstruction and Localization



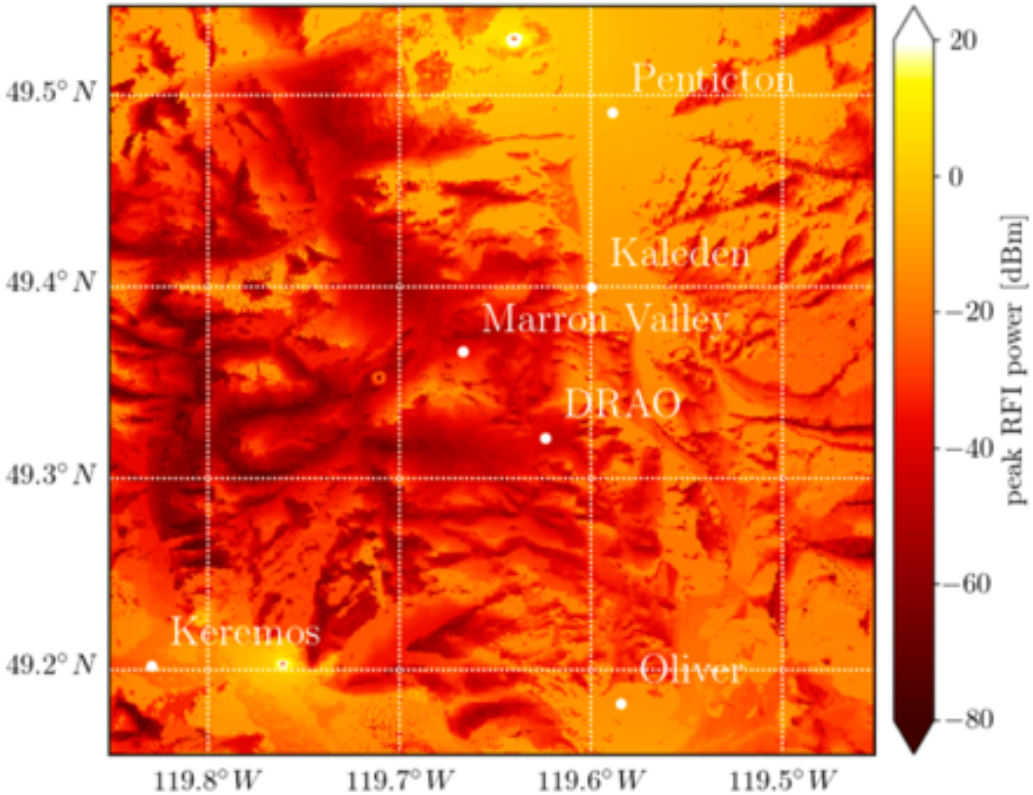






- Trigger with Core Array
  - Baseband dumped at all stations.
  - After beam-forming and de-dispersion → data = 1 Mbyte per ms per station
- Characterize event with high S/N core signal
  - Measure event bandwidth, DM, and best localization (S/N boost)
- Outrigger:
  - VLBI Calibrator in large FoV synchronizes clocks (really, it *is* the clock)
  - De-disperse, beam-form to best localization → data = 1 Mbyte per ms per station
- Perform time-lag correlation → precise measure of time offset

Site Selection



- Being optimized now: localization sims, site logistics, RFI, politics.
- 1 @ 100 km baseline (early prototype)
- 2 @ 1000s km baseline
- Milliarcsecond FRB localizations
  - e.g., ARO= 3074 km → 25 mas

Gavin Noble: New software package implementing Longley/Rice model for radio transmission loss over irregular terrain Integrated with RFI licences and satellite terrain.

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Fast Radio Bursts

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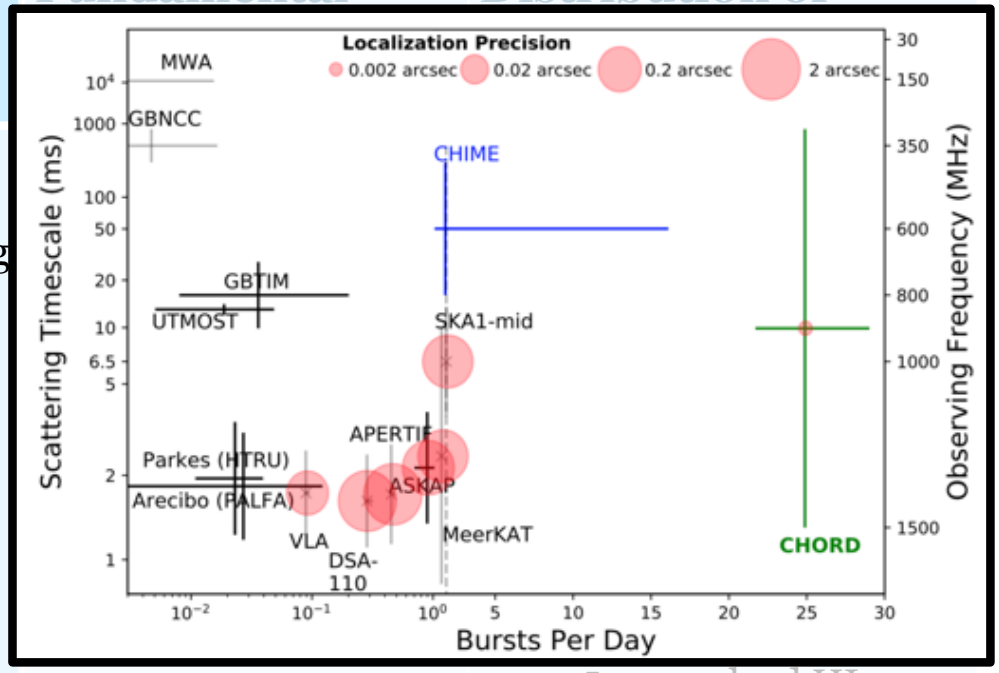
Fundamental

Distribution of

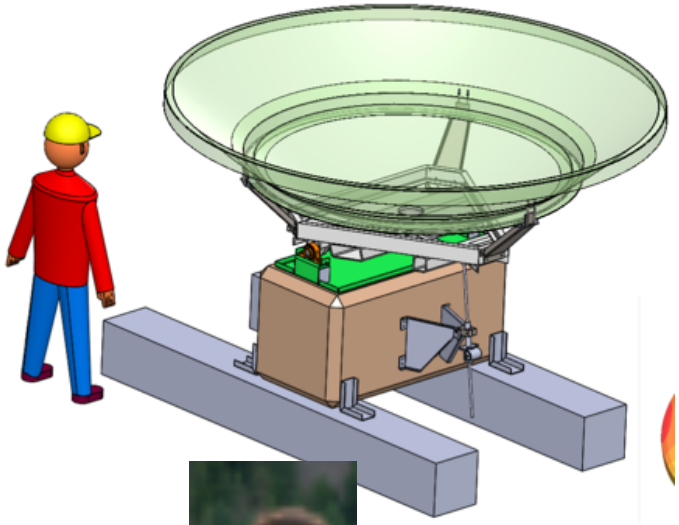


- 10^7 unresolved HI galaxies

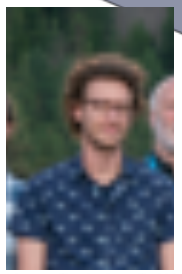
Key Technology: Precision Dishes

D3A: ***Deep Dish Development Array***
(DRAO, McGill, UofT)

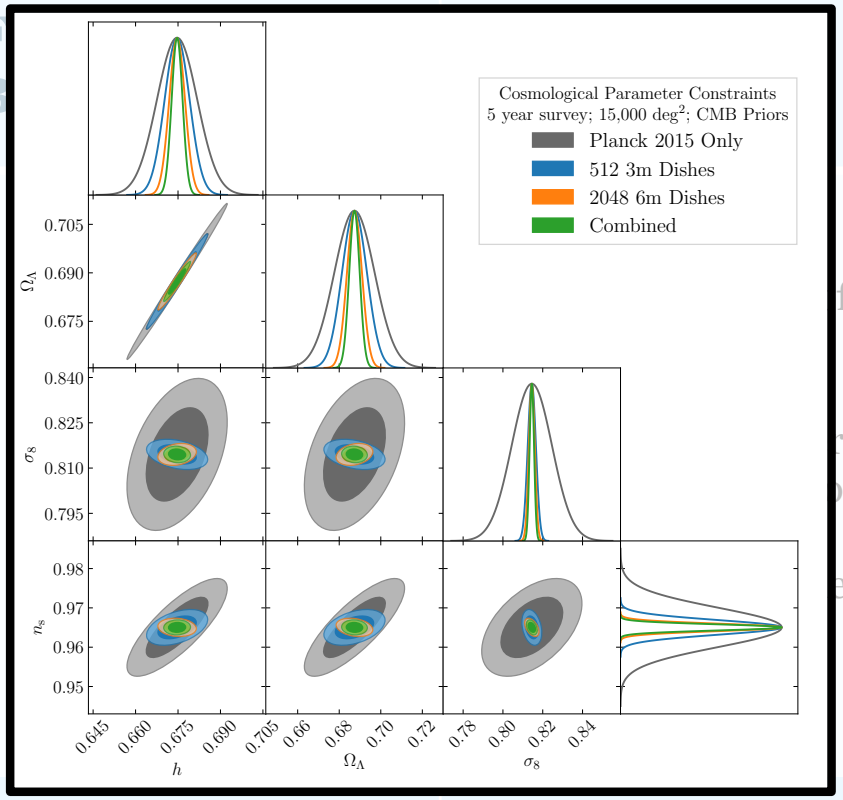
- Focus on beam precision/redundancy for 21cm calibration.
- Composite fiberglass dishes built on-site at DRAO.
- f 0.25 → feed sits below dish rim
- lambda/200 surface precision – demonstrating on sky now.
- Same cost/collecting area as CHIME.
- Developing feed support and mount structures



(DRAO: Mohammed Islam, Richard Hellyer, Gordon Lacy
McGill: Cynthia Chiang, MD, Simon Tartakovsky, **Dallas Wulf**)



CHORD Key Science

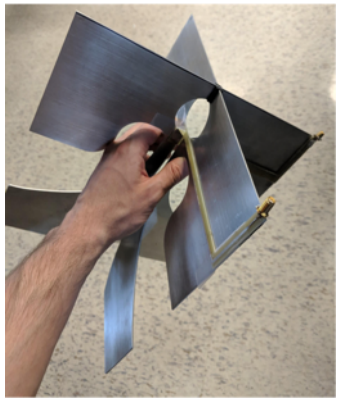


Jon Sievers, Devon Crichton

Distribution of Matter in the Universe

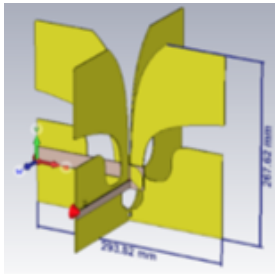
- A billion pixels in HI intensity mapping.
- BAO: broadband power spectrum measurements.
- Test—rather than assume—models of how HI traces matter.
- 10^7 unresolved HI galaxies

Key Technology: Wide-band Feed



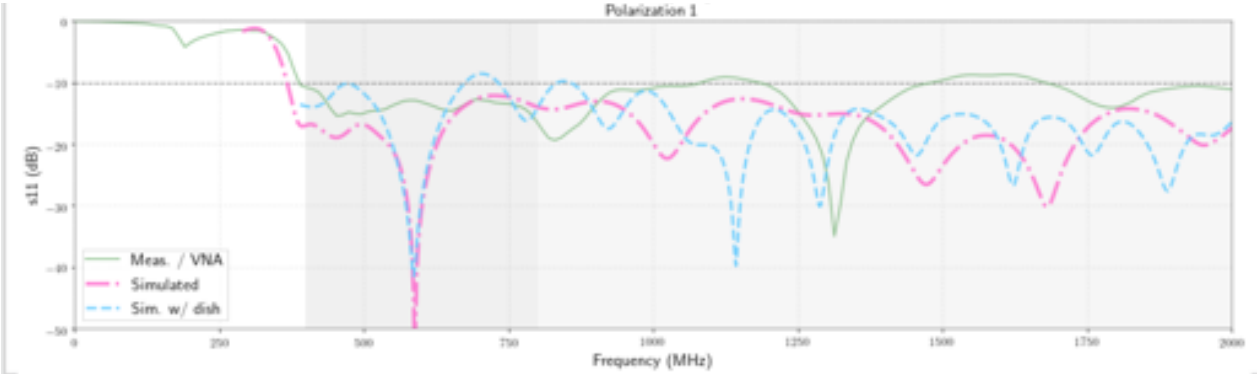
D3A: ***Deep Dish Development Array*** (DRAO, McGill, UofT)

- Low return loss < -10 dB across 300-1500 MHz
- Laser-cut Vivaldi-like geometry – low cost and excellent dish illumination.
- Coupled to low-noise (~15K across band), wide-band amplifier
- Goal: T_sys = 30K across band (integrated UWB)

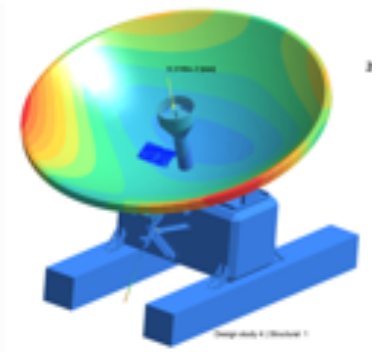


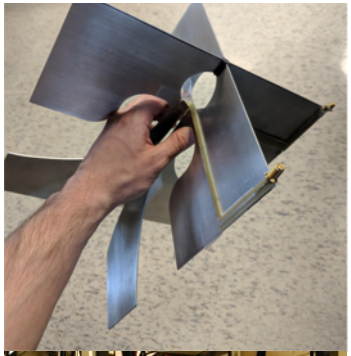
- Prototyping / developing symmetric feed support.

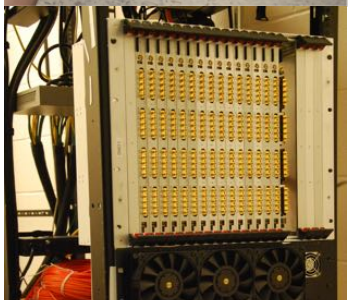
(Toronto: Vincent Mackay, Keith Vanderlinde)



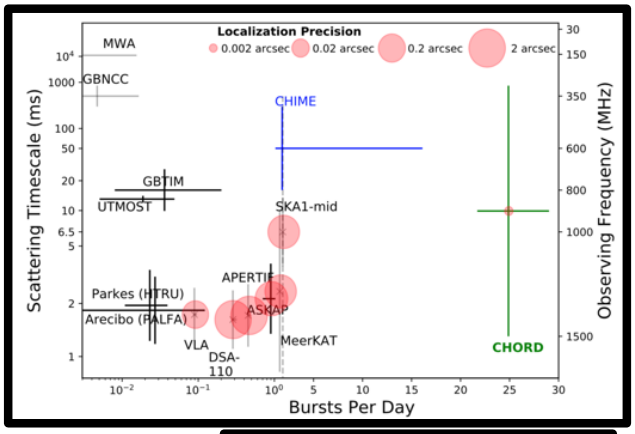
CHORD Timeline

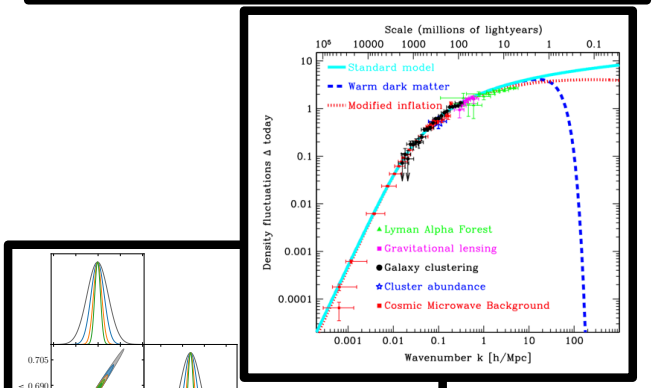


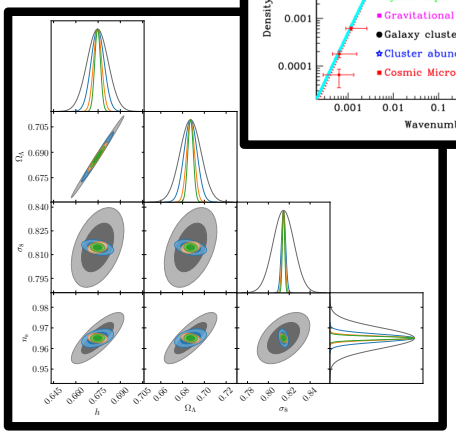




- Year 1: outrigger design, engineering and build first prototype station.
- Jan 2020: Submit CHORD proposal to CFI ($22M)
- Mid-2020: build 1000 km stations
  - 2021: First light for Phase 1 Outriggers
- 2021: CFI Funding available, design and engineering
- 2022: Phase 2 Outrigger and Core construction.
  - Late 2023: First light for Phase 2 Outrigger and Core construction.







Conclusions

- CHIME is demonstrating the incredible science reach of a small, dedicated experiment with a modest budget.
- FRB science has become a data rich endeavor – we continue to yield surprizes – there is room for innovation amongst model builders who continue to enjoy considerable freedom.
  - Precision localization is next vanguard for the field.
- Intensity Mapping requires a precision understanding of the instrument – this is still far from being statistics limited.