Title: A Synoptic View of Fast Radio Bursts with CHIME

Speakers: Kiyoshi Masui

Series: Cosmology & Gravitation

Date: March 28, 2023 - 1:00 PM

URL: https://pirsa.org/23030119

Abstract: For more than a decade, enigmatic extragalactic flashes called fast radio bursts (FRBs) have defied a definitive explanation for their origin. In addition, the unique properties of FRBs make them promising probes of both cosmology and the distribution of gas on intergalactic scales. The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is the only radio telescope capable of instantaneously observing hundreds of square degrees with the sensitivity of a 100-meter scale aperture. As a result, its transient search instrument, CHIME/FRB, has detected thousands of FRBs, increasing the known sample by an order of magnitude. I will give an overview of CHIME/FRB's most recent results, where observations of particular sources and statistical analyses of the FRB population are starting to reveal the nature of this mysterious phenomenon. I will then describe an effort to augment CHIME/FRB's capabilities by adding Outrigger telescopes, which will be located across North America and will precisely localize FRB sources using very long baseline interferometry. The resulting large sample of localized FRBs will allow for detailed measurements of the large-scale distribution of baryons in the universe, providing precise constraints on feedback processes in galaxy evolution.

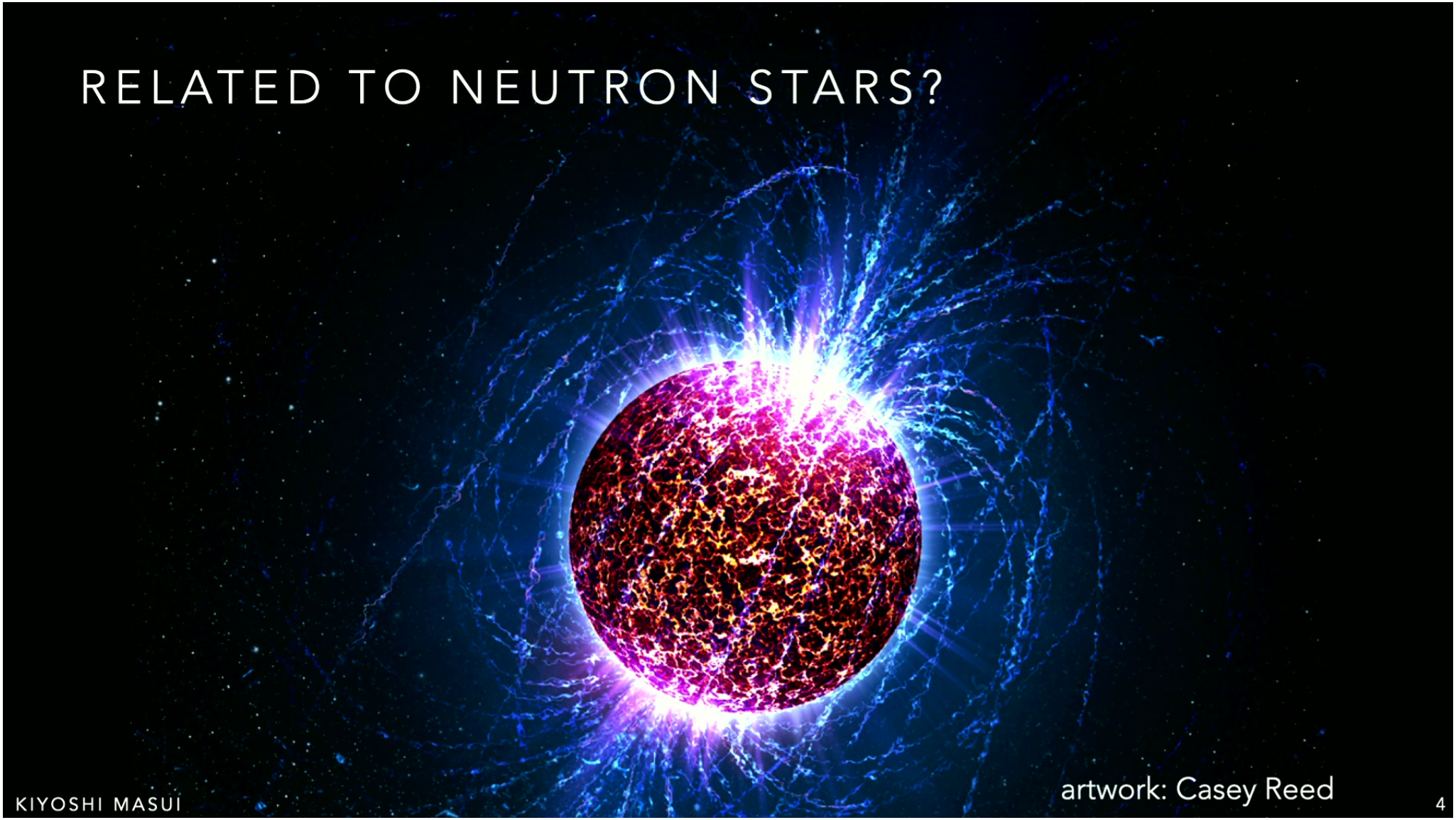
Zoom link: https://pitp.zoom.us/j/93157775112?pwd=bzZDMVc3VnF1WHZzeVlLOTdDZmtQQT09


KIYOSHI MASUI
A SYNOPTIC VIEW OF FAST RADIO BURSTS WITH CHIME
PERIMETER INSTITUTE COSMOLOGY & GRAVITATION SEMINAR
MARCH 28, 2023
Masui Synoptic Radio Lab

FAST RADIO BURSTS

- Single radio flashes that are:
- Brief (~ milliseconds)
- Broad band (observed from 0.2 to 8 GHz)
- Bright, ~1 - 100 Jy (1 Jy = 10^{-26} W/m^2/Hz)
- Cosmologically distant, but typically poorly localized

RELATED TO NEUTRON STARS?



artwork: Casey Reed

DISPERSION

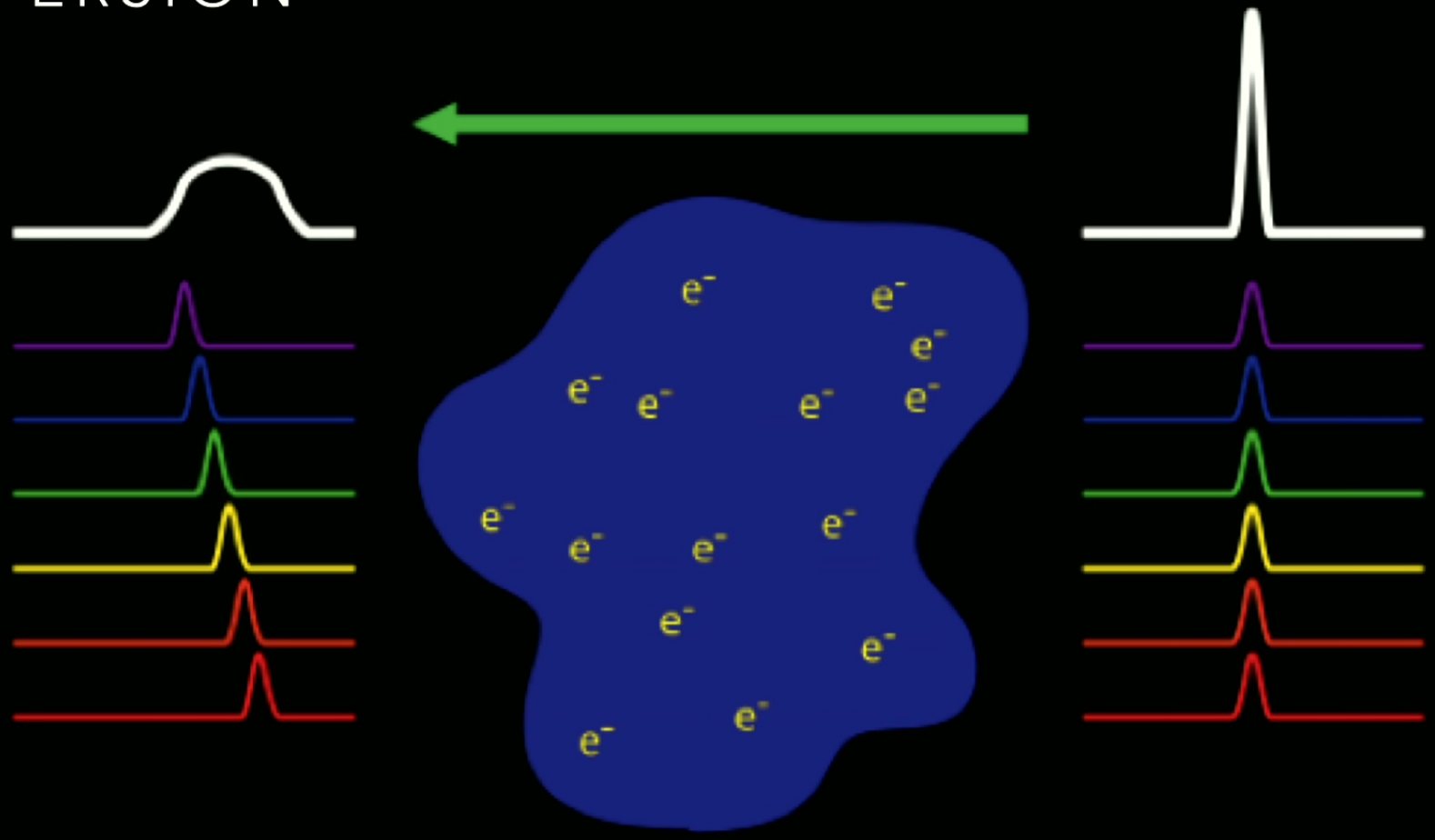
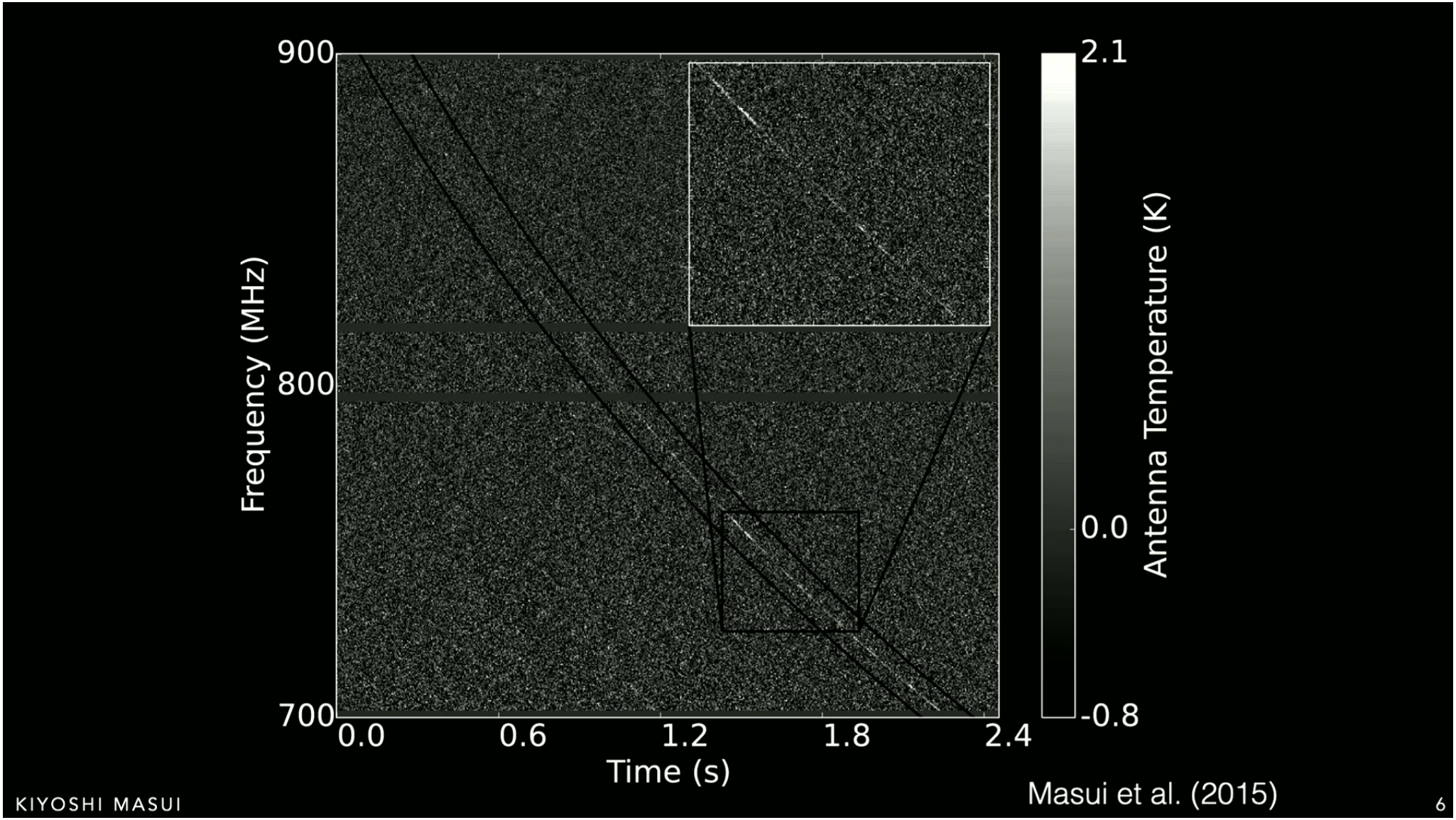


image: Erik Madsen


900
800
700
Frequency (MHz)
0.0
0.6
1.2
1.8
2.4
Time (s)
2.1
0.0
-0.8
Antenna Temperature (K)
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Masui et al. (2015)
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DISPERSION

$$t_d \propto \mathrm{DM}\,\lambda^2$$

$$\mathrm{DM} = \int_{\mathrm{src}}^{\mathrm{obs}} n_e \vec{ds}$$

$$[\mathrm{DM}] = \mathrm{pc/cm^3}$$

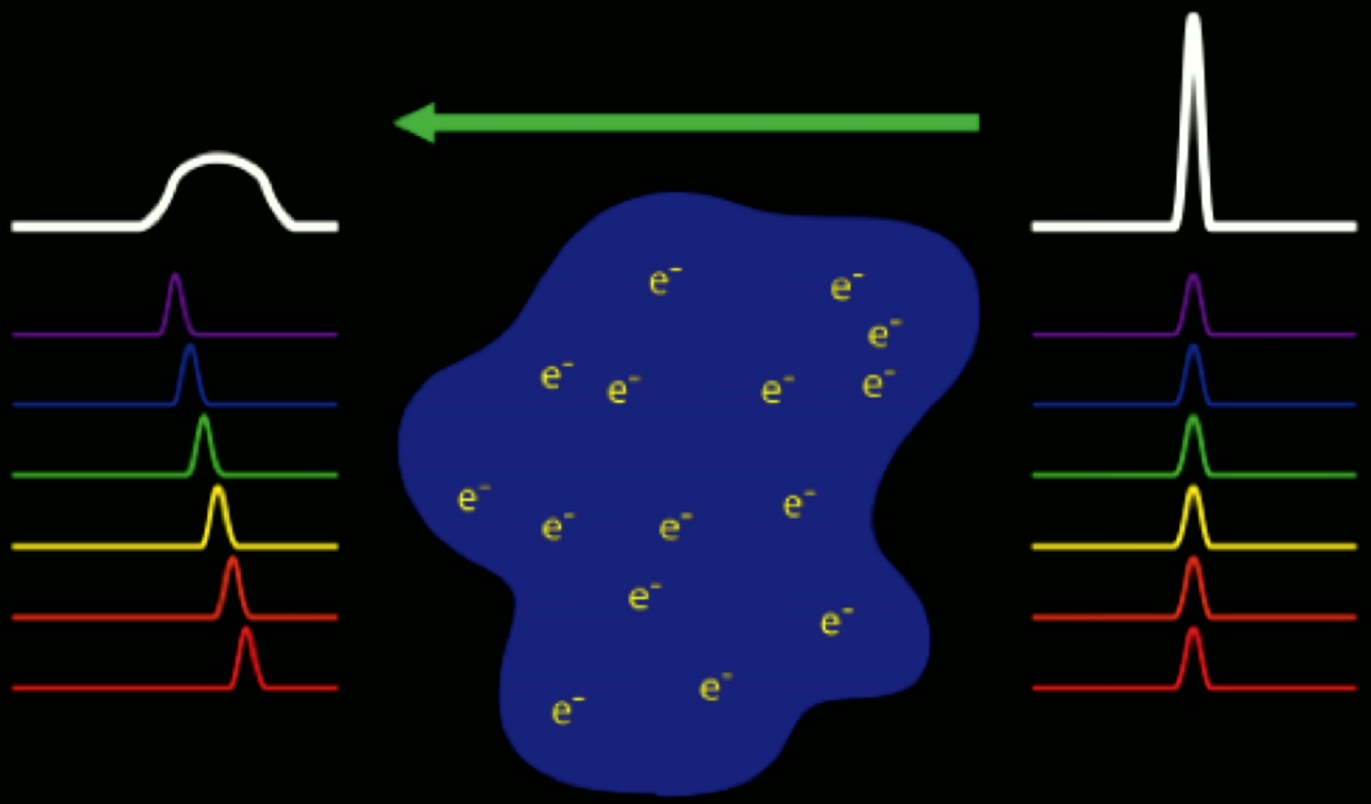
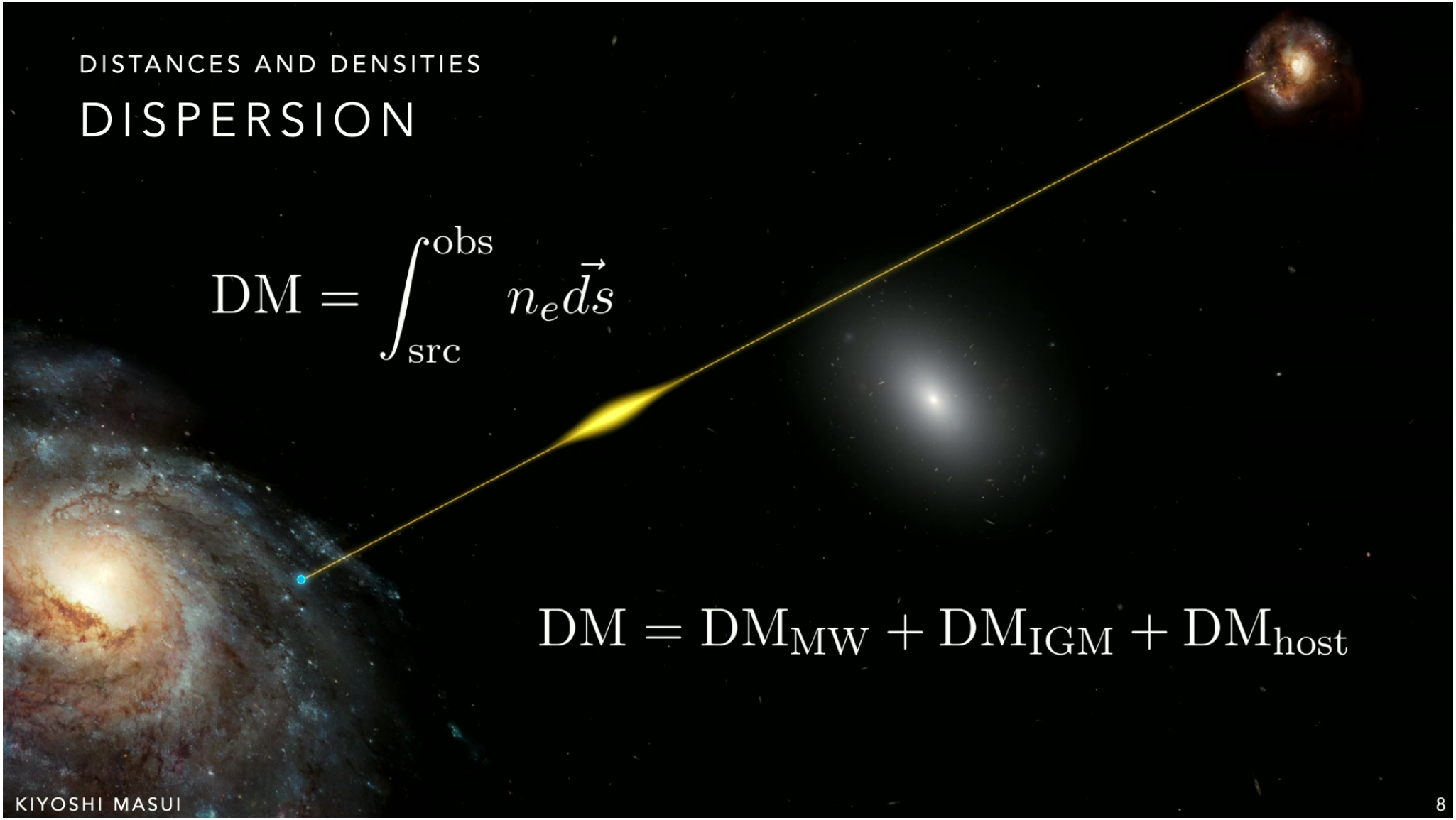


image: Erik Madsen


DISTANCES AND DENSITIES
DISPERSION
$\mathrm{DM} = \int_{\mathrm{src}}^{\mathrm{obs}} n_e d\vec{s}$
$\mathrm{DM} = \mathrm{DM}_{\mathrm{MW}} + \mathrm{DM}_{\mathrm{IGM}} + \mathrm{DM}_{\mathrm{host}}$
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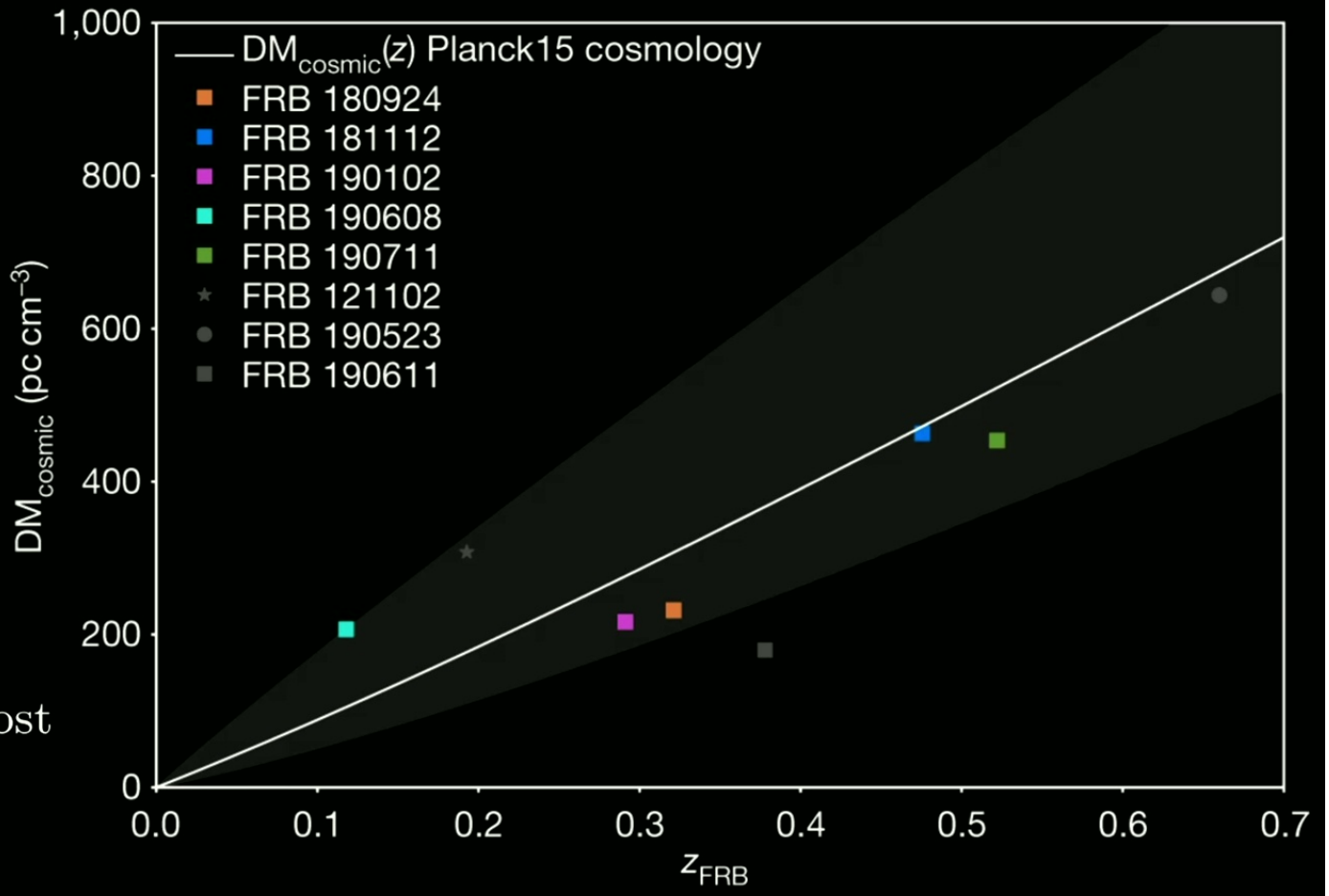
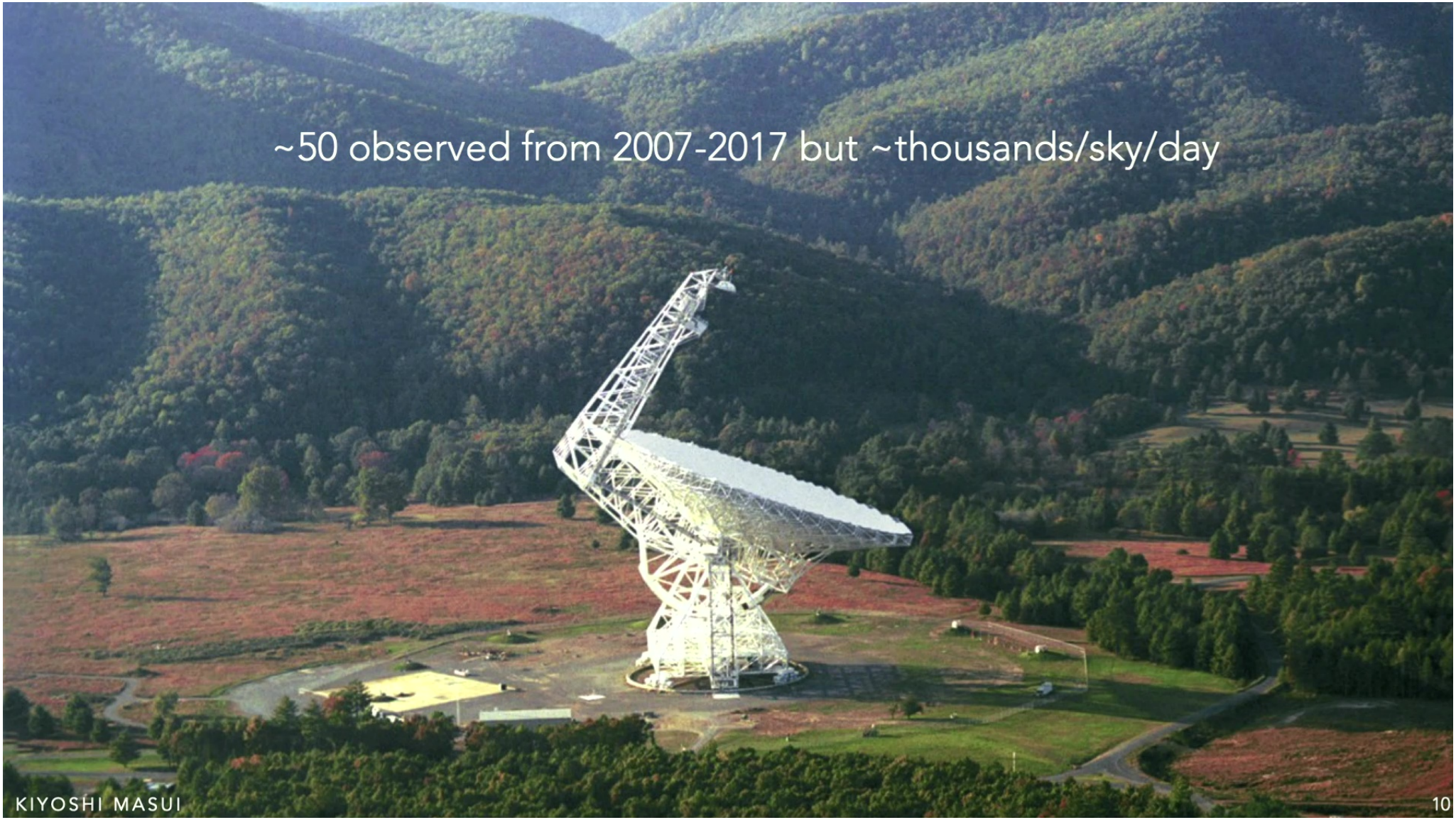
DM VS Z

MACQUART RELATION

$$\mathrm{DM} = \mathrm{DM_{MW}} + \mathrm{DM_{IGM}} + \mathrm{DM_{host}}$$




~50 observed from 2007-2017 but ~thousands/sky/day
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TO UNDERSTAND THESE THINGS

We need a larger sample

TO GET A BIGGER SAMPLE WE NEED

A new kind of radio telescope

WHAT LIMITS THESE?

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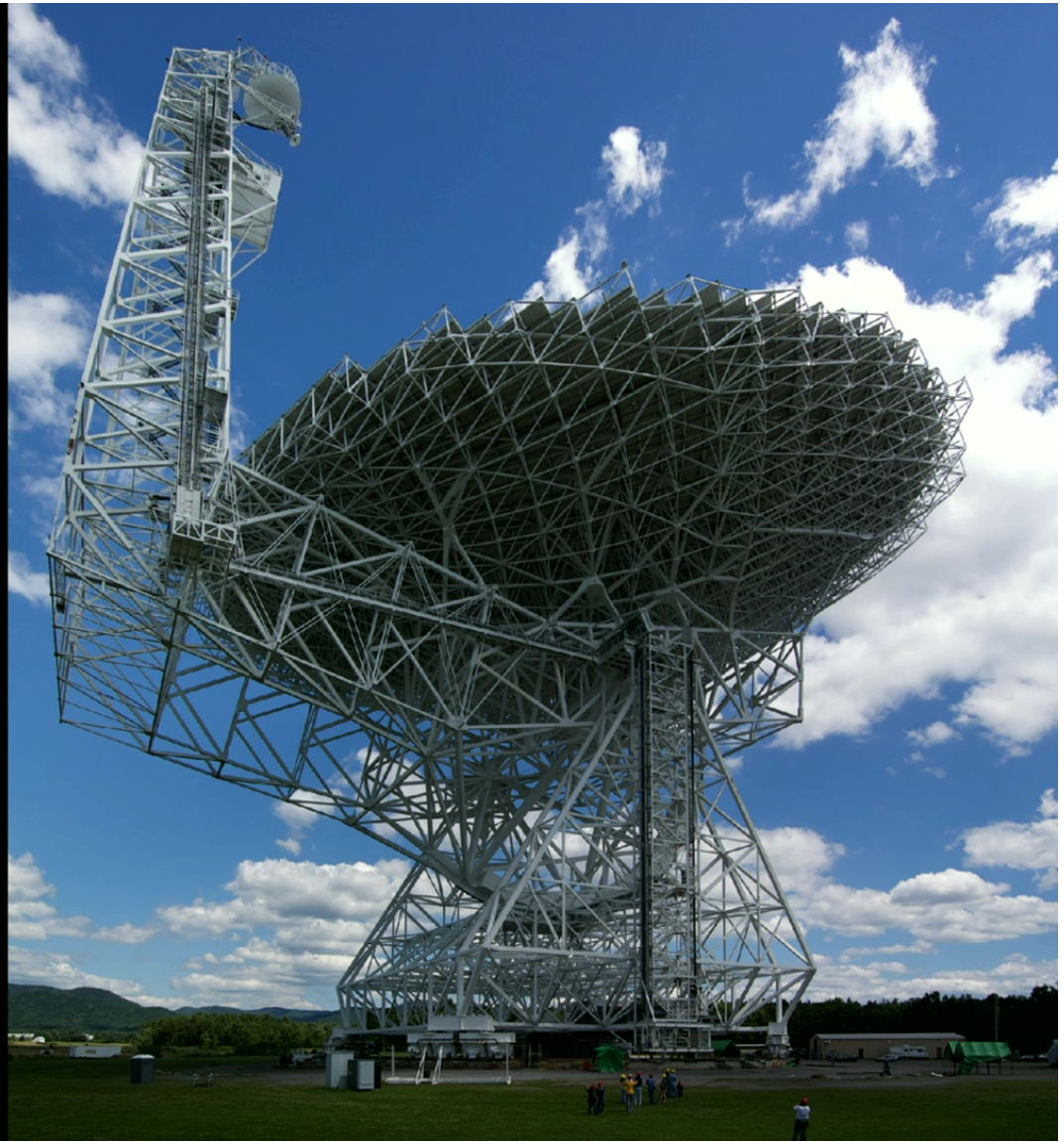

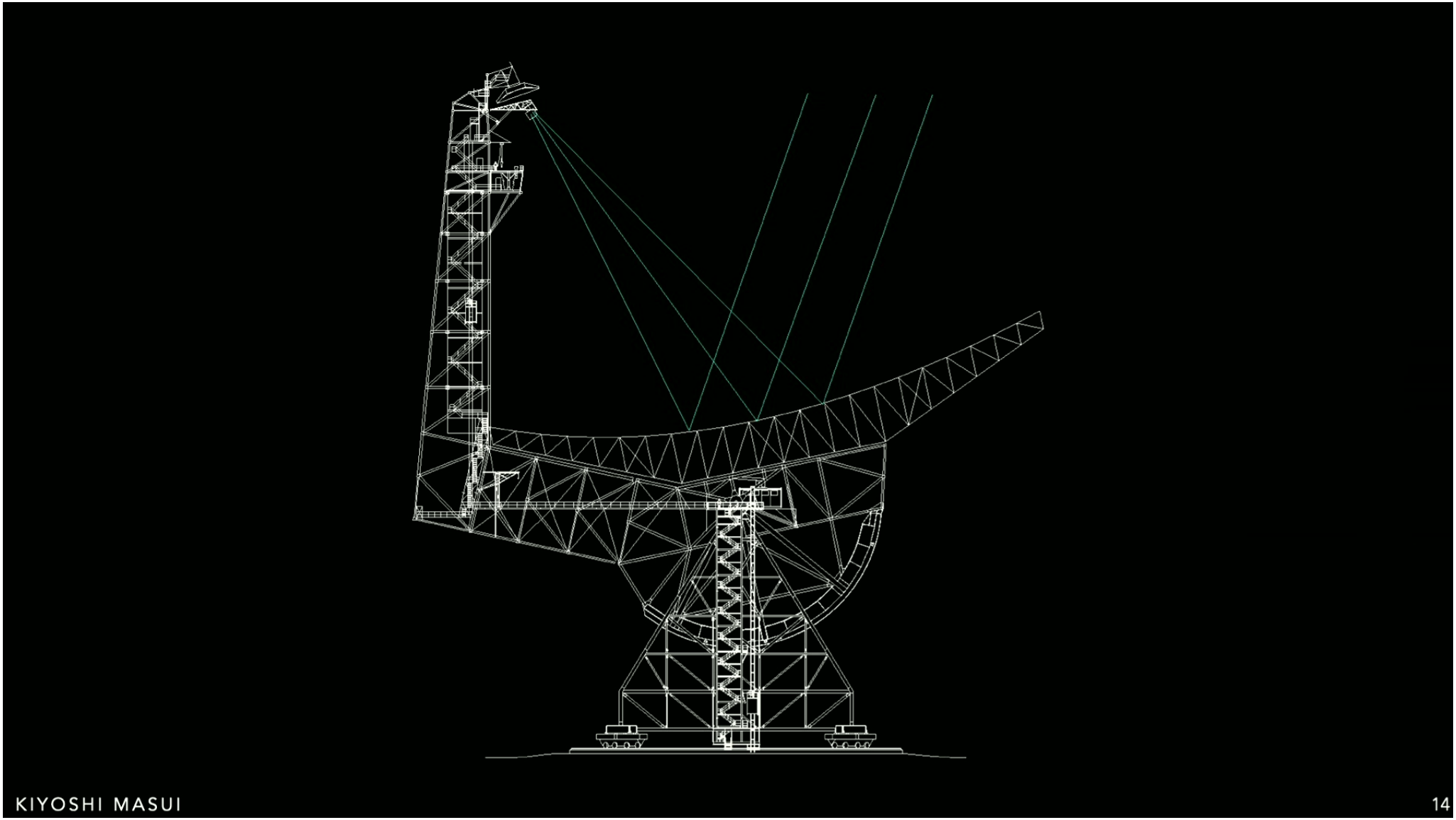
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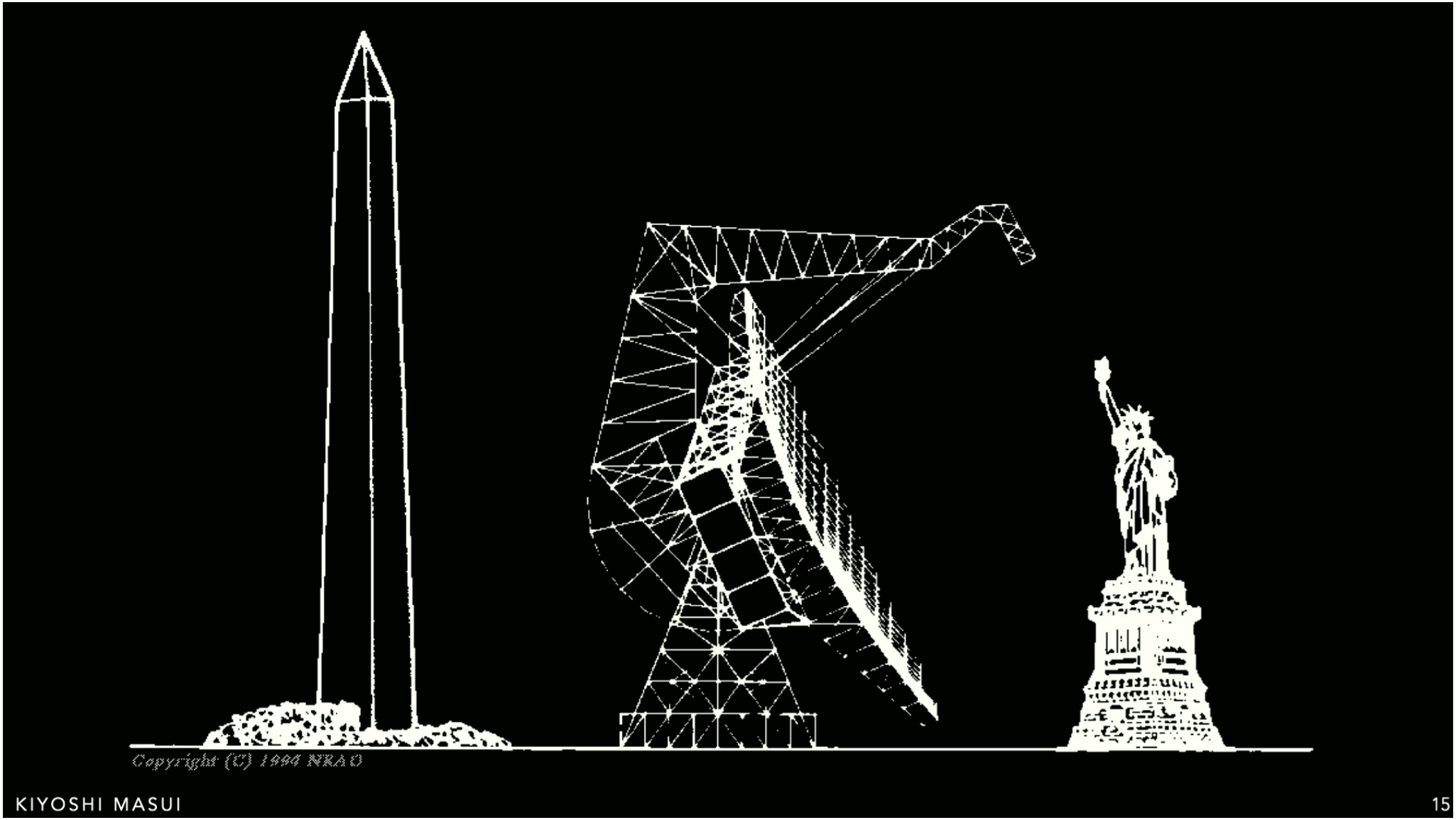

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NEW TECHNOLOGY

WHAT HAS CHANGED?

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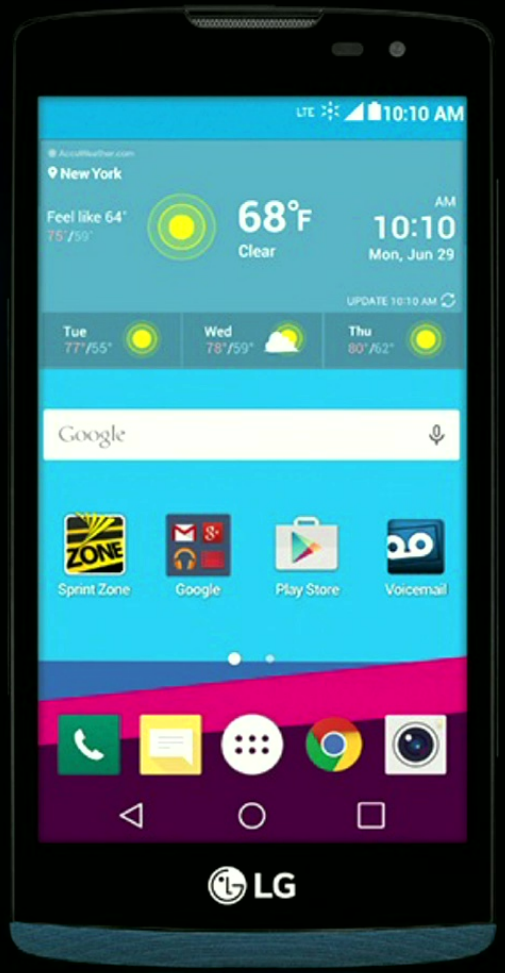

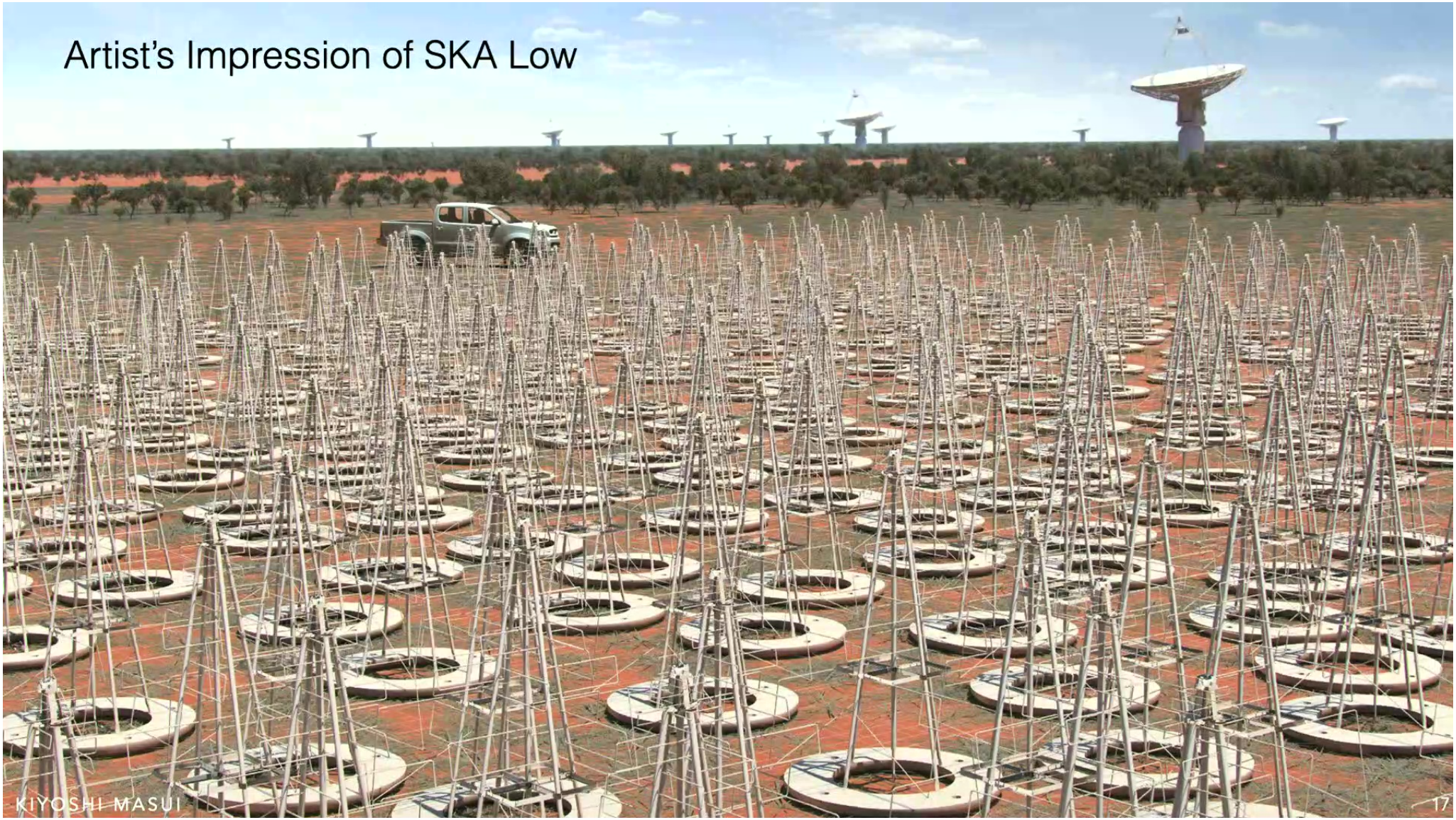
Artist's Impression of SKA Low
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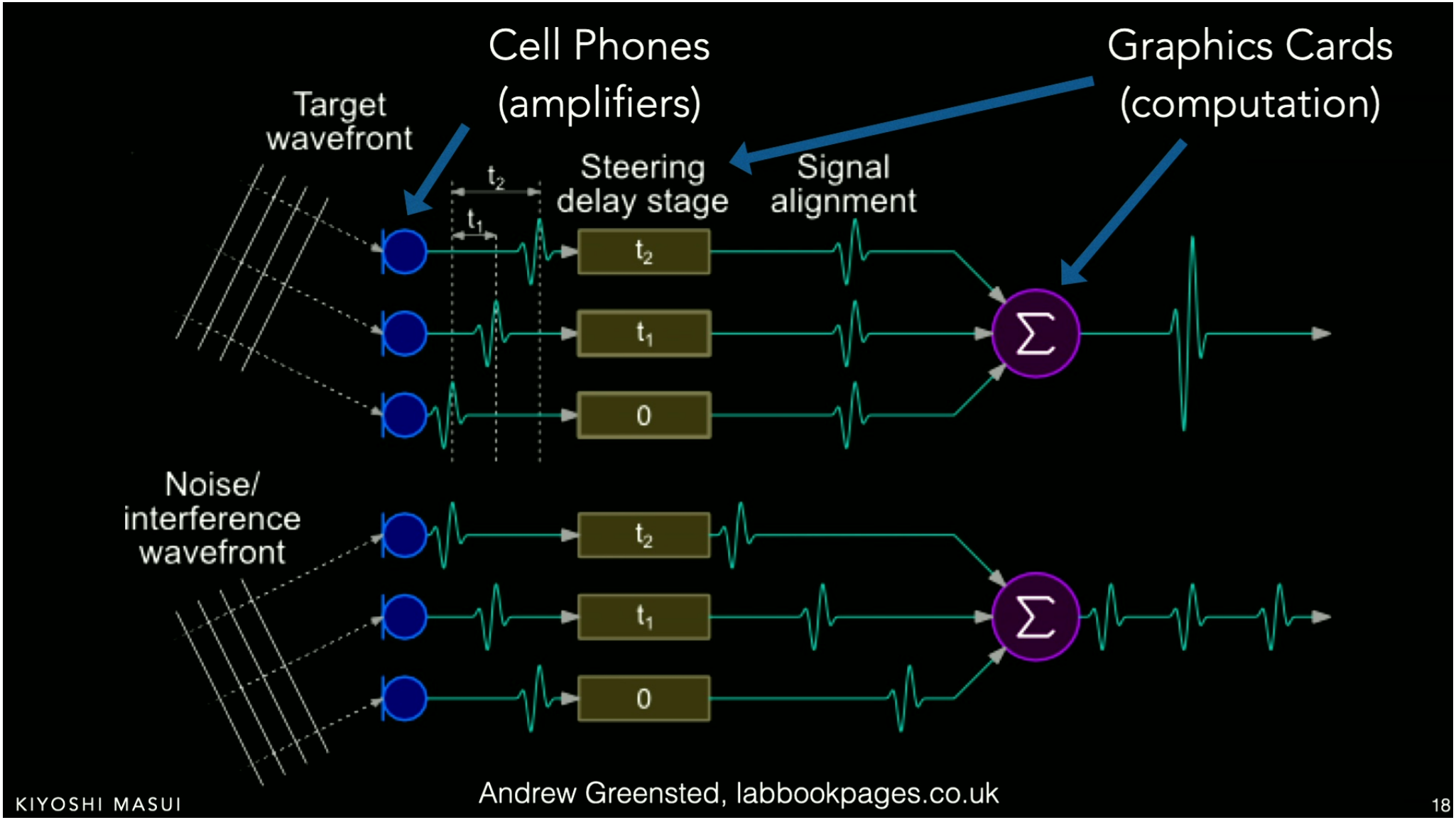
Cell Phones
(amplifiers)
Graphics Cards
(computation)
Target
wavefront
Steering
delay stage
Signal
alignment
t_2
t_1
t_2
t_1
0
Noise/
interference
wavefront
t_2
t_1
0
Σ
Σ
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Andrew Greensted, labbookpages.co.uk
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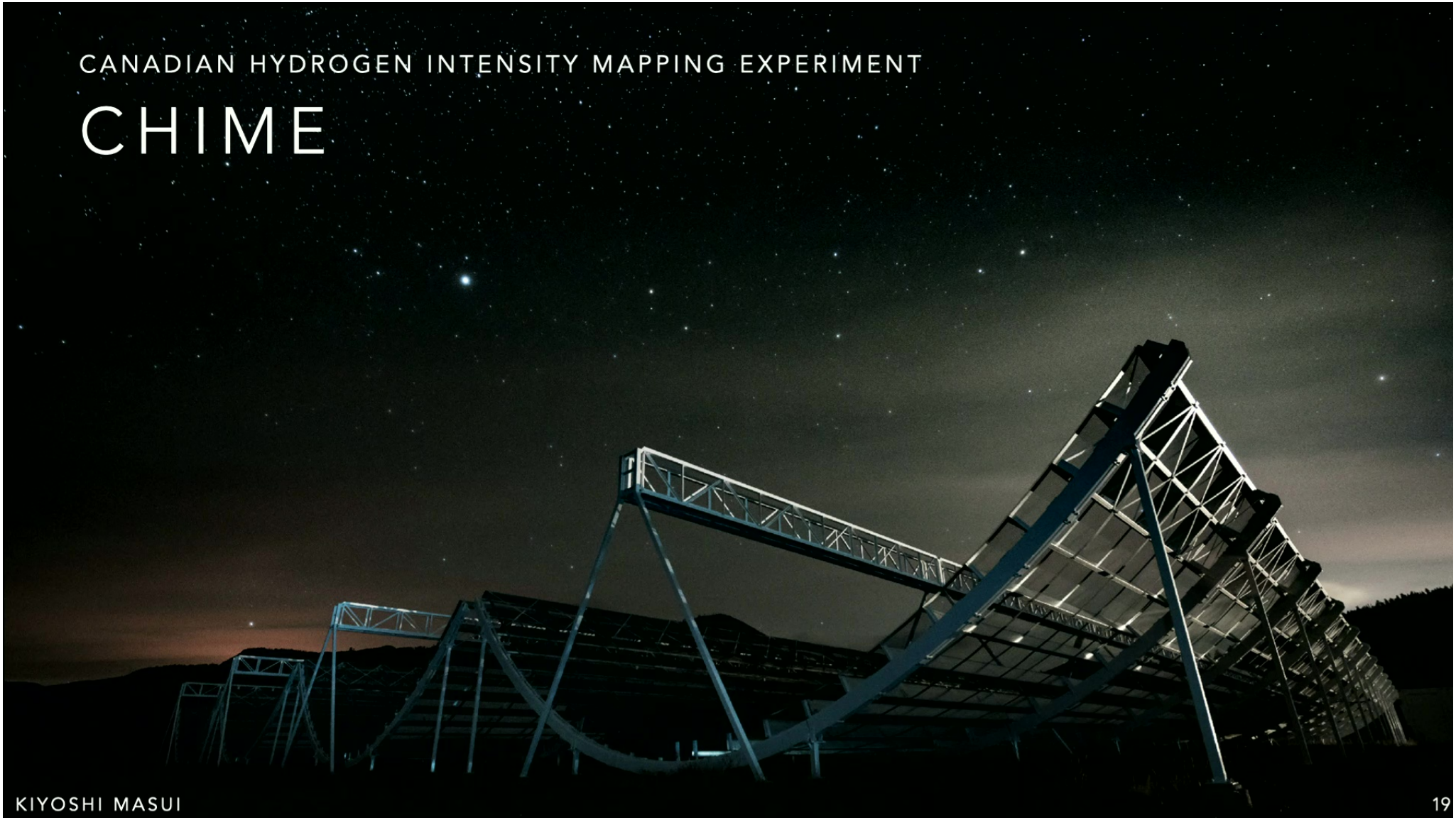
CANADIAN HYDROGEN INTENSITY MAPPING EXPERIMENT
CHIME
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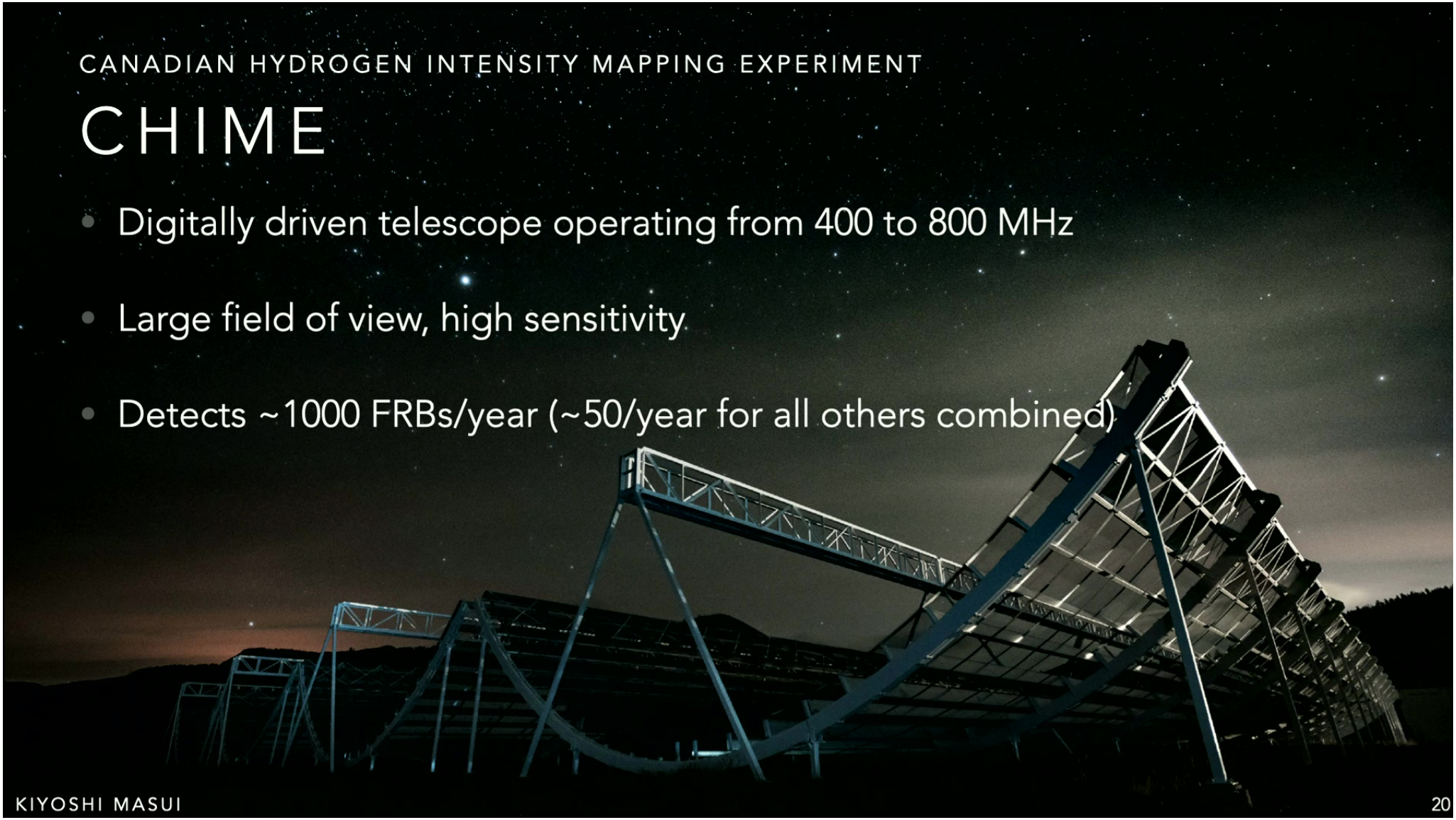
CANADIAN HYDROGEN INTENSITY MAPPING EXPERIMENT
CHIME
Digitally driven telescope operating from 400 to 800 MHz
Large field of view, high sensitivity
Detects ~1000 FRBs/year (~50/year for all others combined)
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McGill
Canada
NRC·CNRC
UBC
PERIMETER INSTITUTE
chime
NRAO
Yale
NCRA • TIFR
Massachusetts Institute of Technology
WestVirginiaUniversity.
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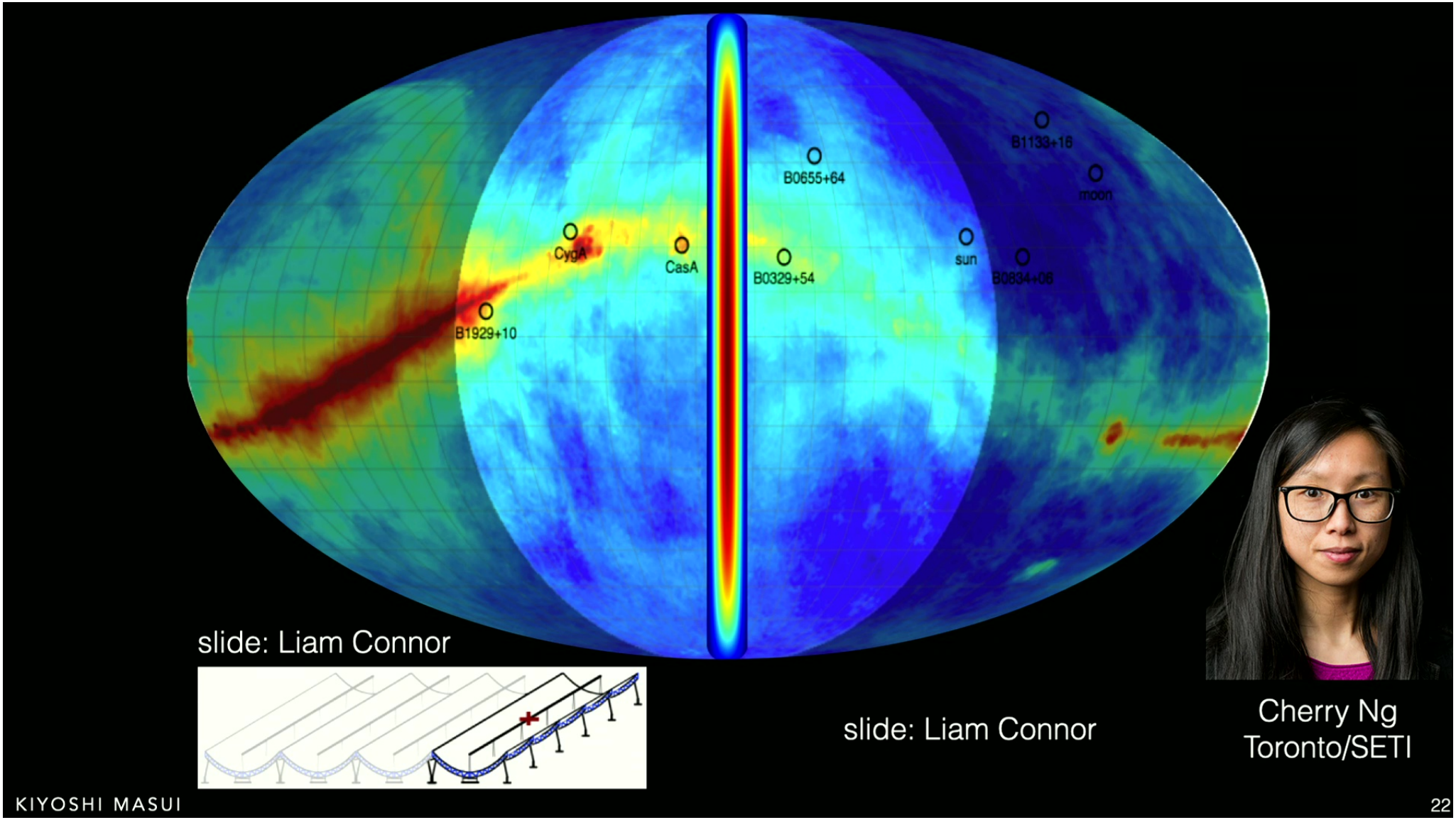
B1133+16
B0655+64
moon
CygA
CasA
B0329+54
sun
B0834+06
B1929+10
slide: Liam Connor
slide: Liam Connor
Cherry Ng
Toronto/SETI
KIYOSHI MASUI
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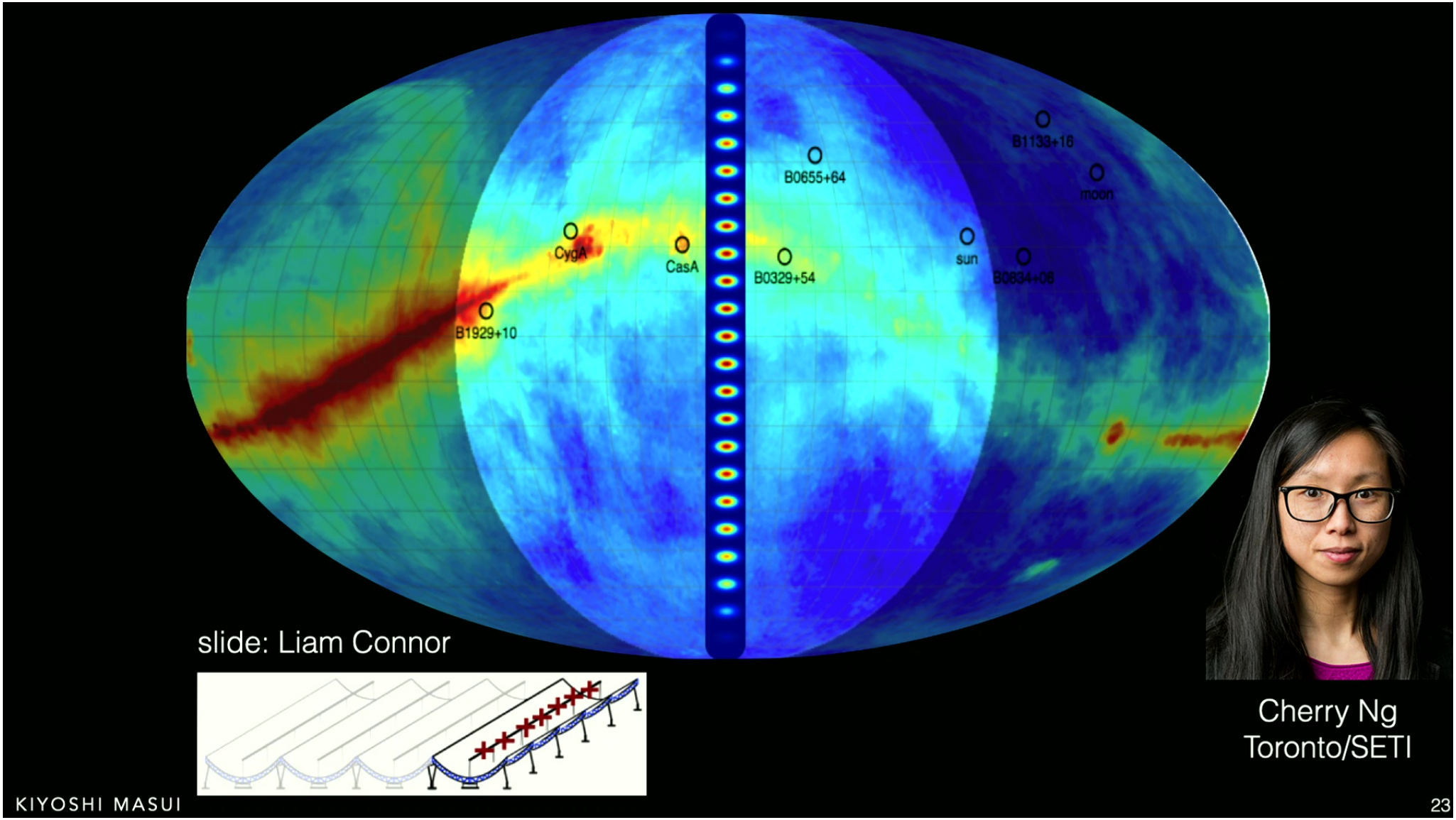
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sun
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slide: Liam Connor
Cherry Ng
Toronto/SETI
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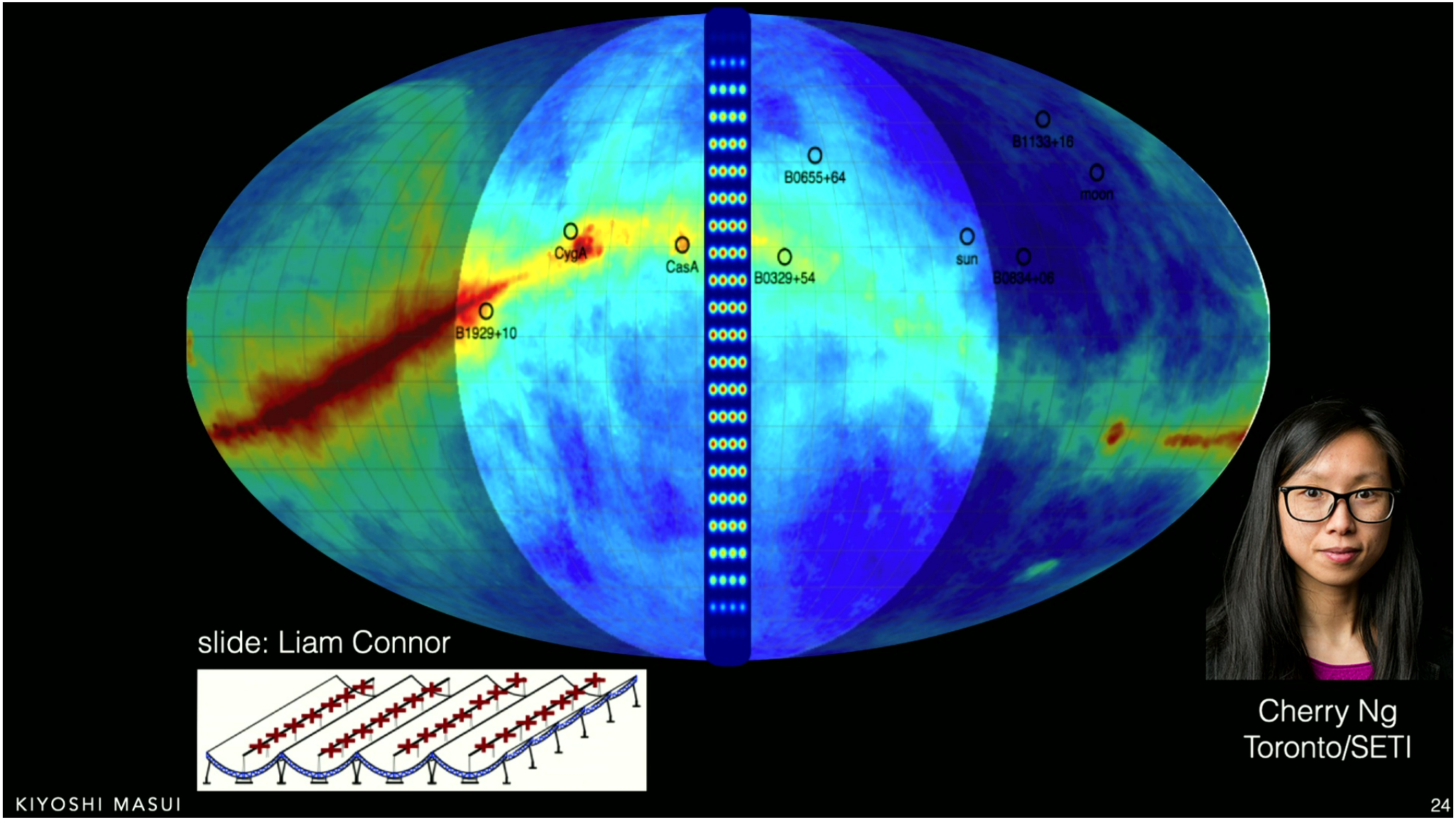
B1133+16
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B0329+54
sun
B0834+06
B1929+10
slide: Liam Connor
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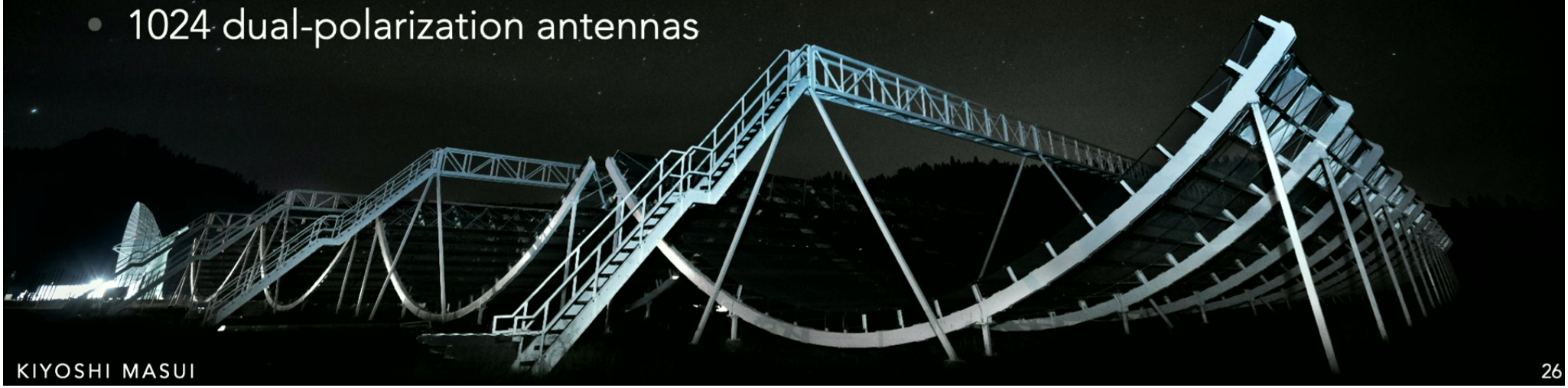
CHIME TELESCOPE

- At Dominion Radio Astrophysical Observatory, Penticton, BC
- 400 - 800 MHz band
- 80m x 80m total aperture, ~ 0.5 degree resolution
- 1024 dual-polarization antennas




DIGITALLY
DRIVEN
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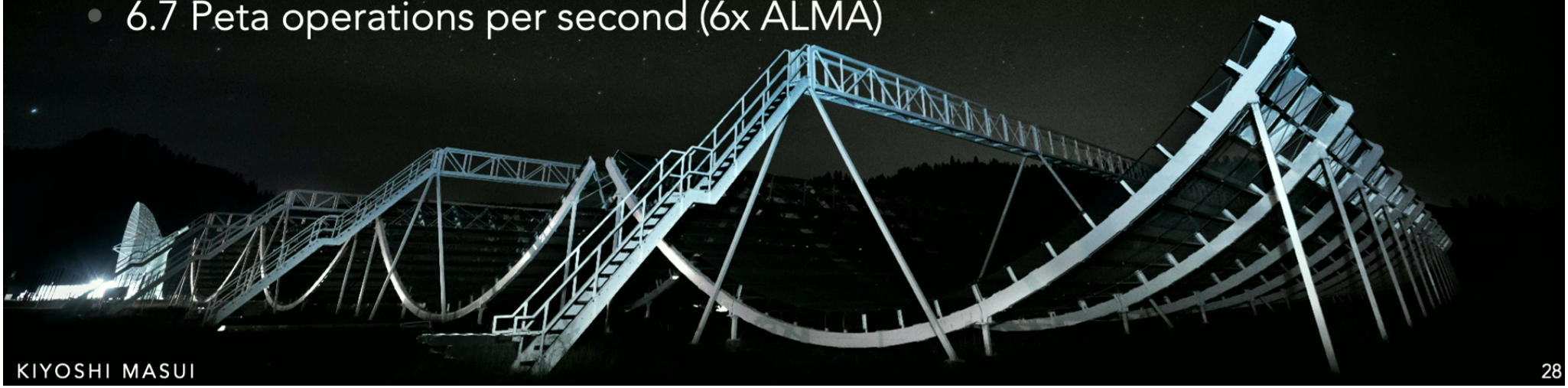
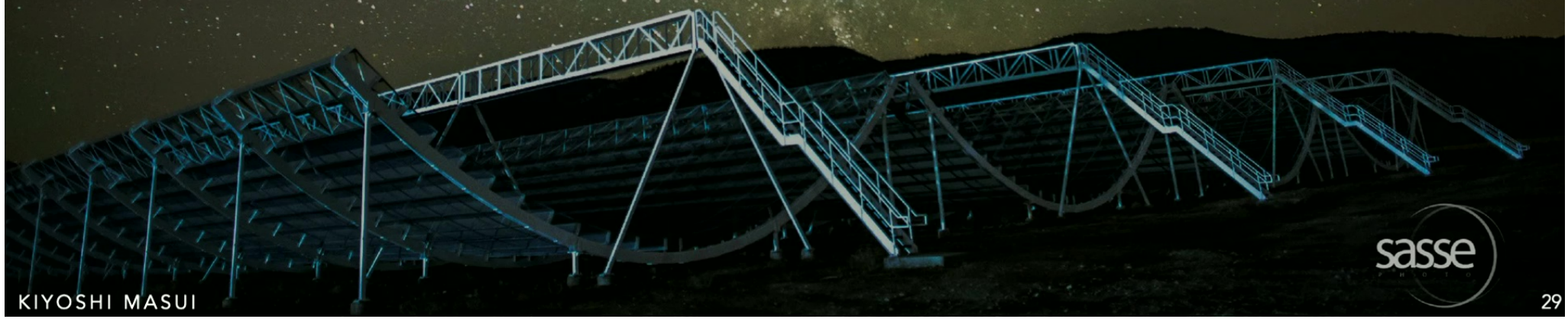
CHIME CORRELATOR

- 2048 ADCs/correlation inputs on 128 FPGA boards
- 6.6 Tbps baseband data
- 256 node cluster, each with 4 GPUs
- 6.7 Peta operations per second (6x ALMA)



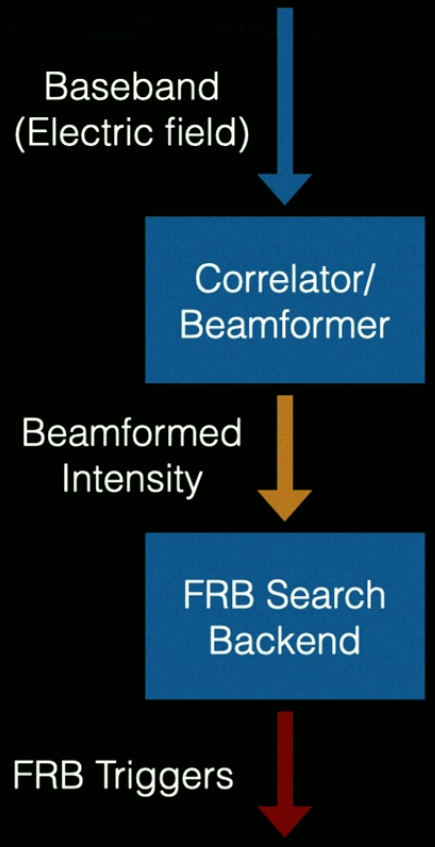
COMMENSALITY

- CHIME 'points' digitally, and data can be copied
- Correlator can feeds backends for multiple commensal surveys:
  - 21 cm intensity mapping
  - Fast radio burst (FRB) search
  - 21 cm absorption system search
  - Multiplexed pulsar timing
  - Slow pulsar search



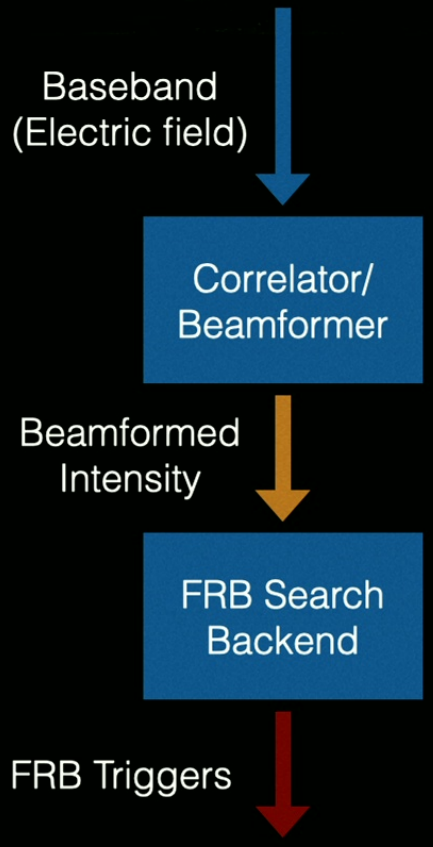
FRB SEARCH PIPELINE

- 1k formed beams
- 16k spectral frequencies from 400 to 800 MHz
- 1 ms sampling
- Processed by a 128 node CPU cluster
- Search in real time, can't afford to store

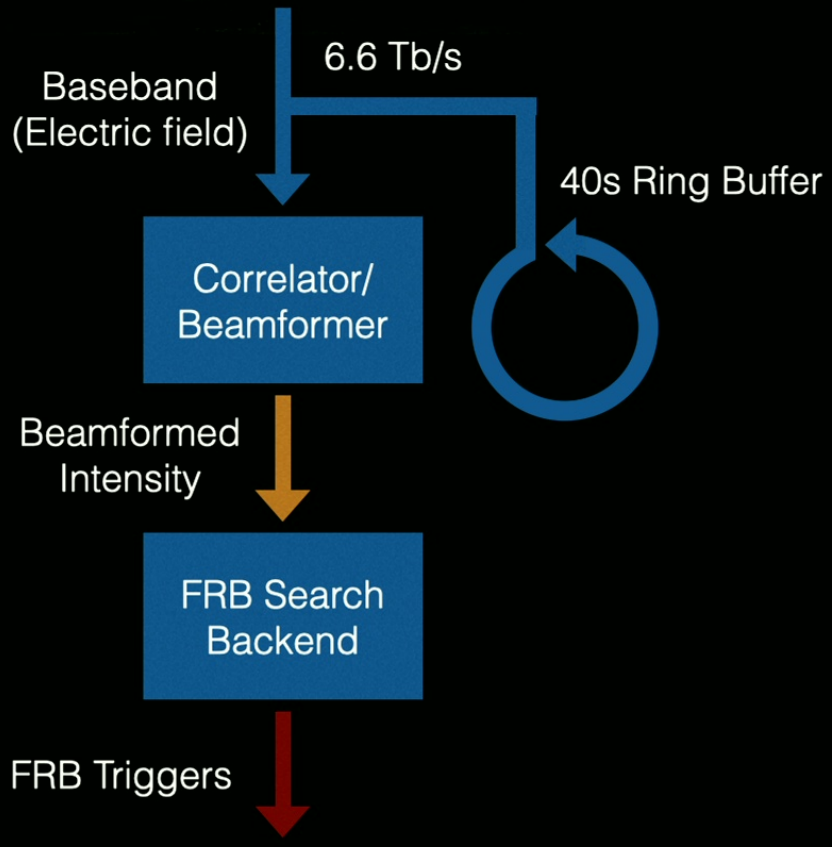


LIMITATIONS OF REAL-TIME SYSTEM

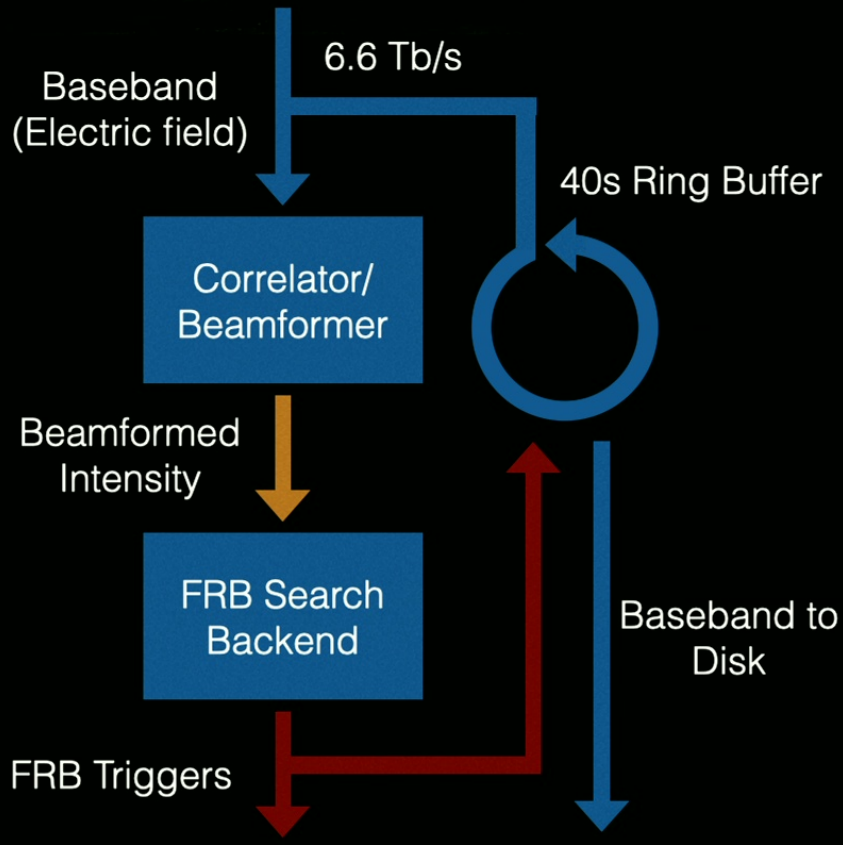
- No polarization sensitivity
- Limited time (1ms) and spectral (16k) resolution
- Limited ability to localize events (~0.25 degrees)



TRIGGERED BASEBAND RECORDING SYSTEM

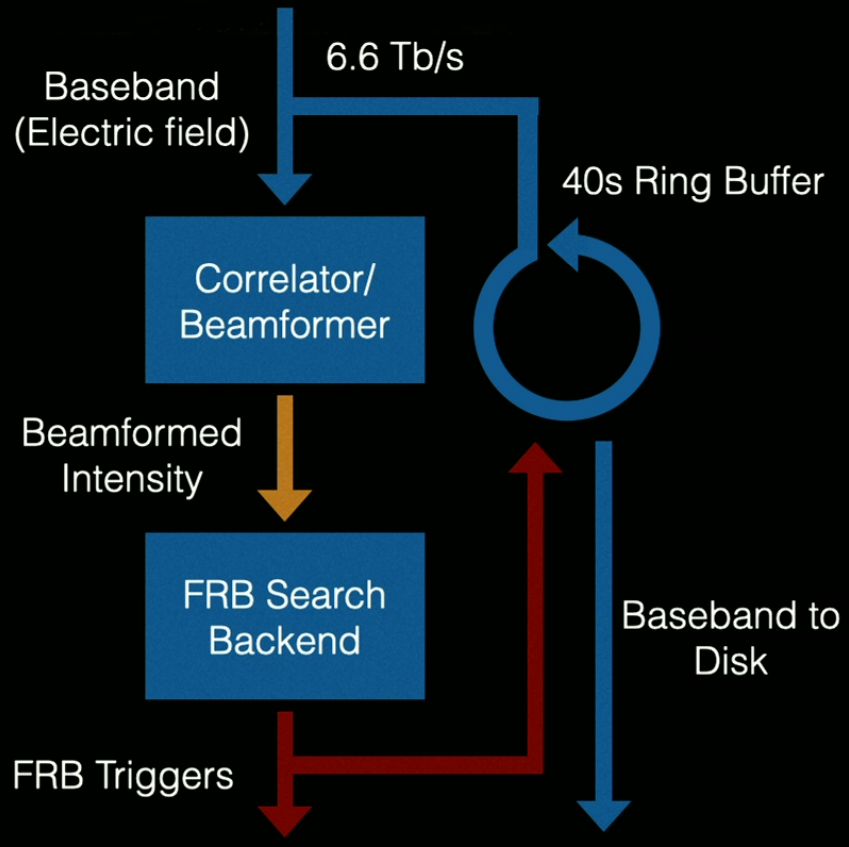


TRIGGERED BASEBAND RECORDING SYSTEM



TRIGGERED BASEBAND RECORDING SYSTEM

- Completely lossless
- Polarization sensitive
- Uncertainty principle limited resolution
  $\Delta t \Delta f > 1$
- Can repoint (dither) the beamformer offline for ~1′ localization



PROGRESS ON PROGENITORS

Detection at low frequencies
CHIME/FRB Collaboration 2019, Nature, arXiv:1901.04524

Subpopulation of sources that emit repeat bursts
CHIME/FRB Collaboration 2019, Nature, arXiv:1901.04525
CHIME/FRB Collaboration 2019, ApJL, arXiv:1908.03507

A repeater that is active on a 16-day period
CHIME/FRB Collaboration 2020, Nature, arXiv:2001.10275

An FRB with 100 ms quasi-periodicity
CHIME/FRB Collaboration 2022, Nature, arXiv:2107.08463

A repeater near a star-forming region of a nearby galaxy
Marcote et al. 2020, Nature, arXiv:2001.02222

A repeater in a globular cluster in M81
Kirsten et al. 2022, Nature, arXiv:2105.11445

A fast radio burst emitted from a Galactic magnetar
CHIME/FRB Collaboration 2020, Nature, arXiv:2005.10324

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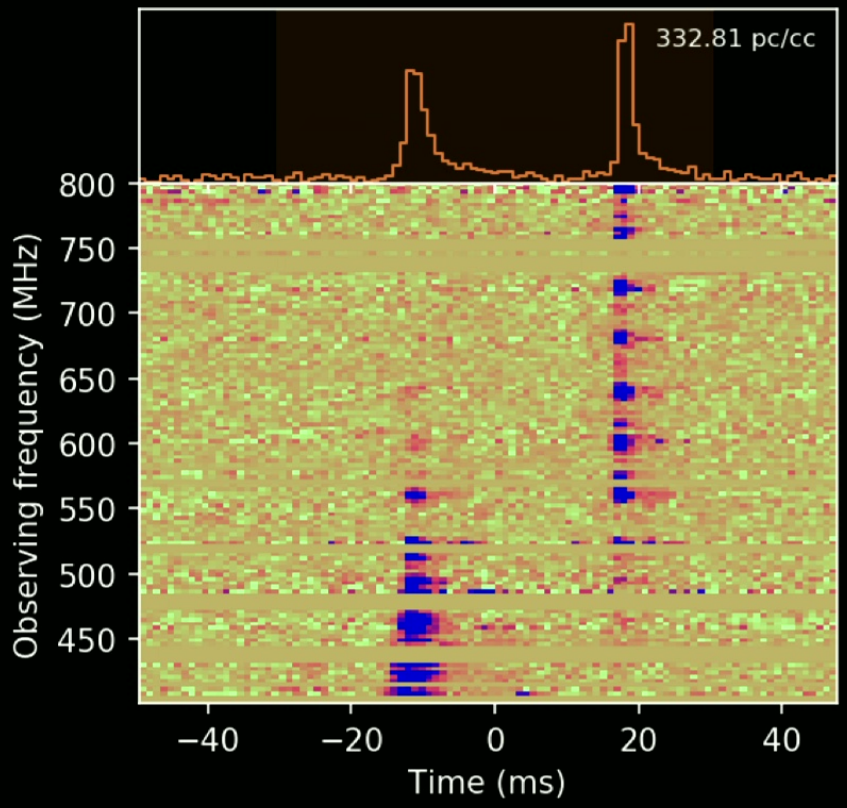
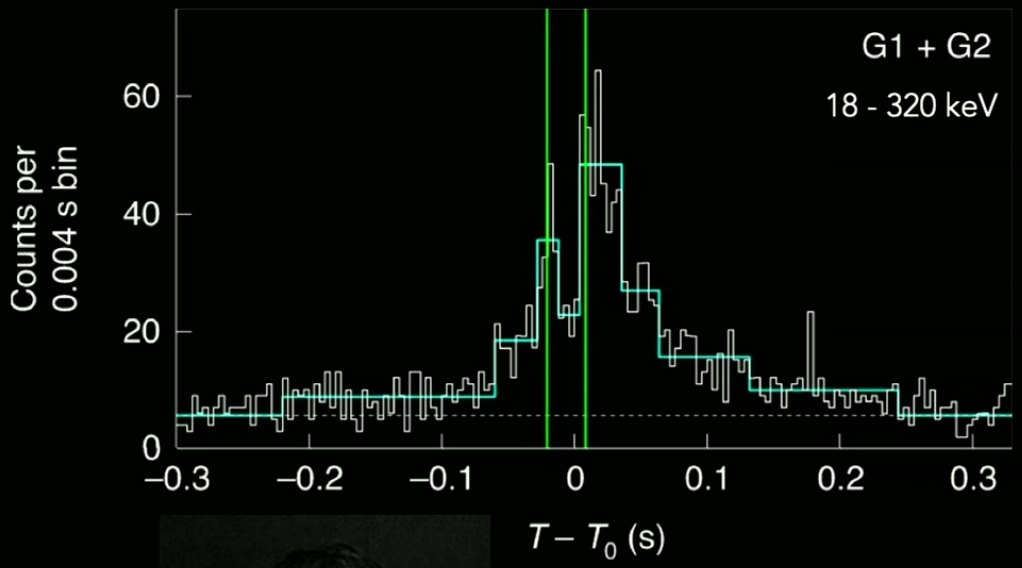
FRB FROM GALACTIC SOURCE SGR1935+2154

CHIME/FRB



Simultaneous X-rays (Konus-Wind)



Paul Scholz
U Toronto

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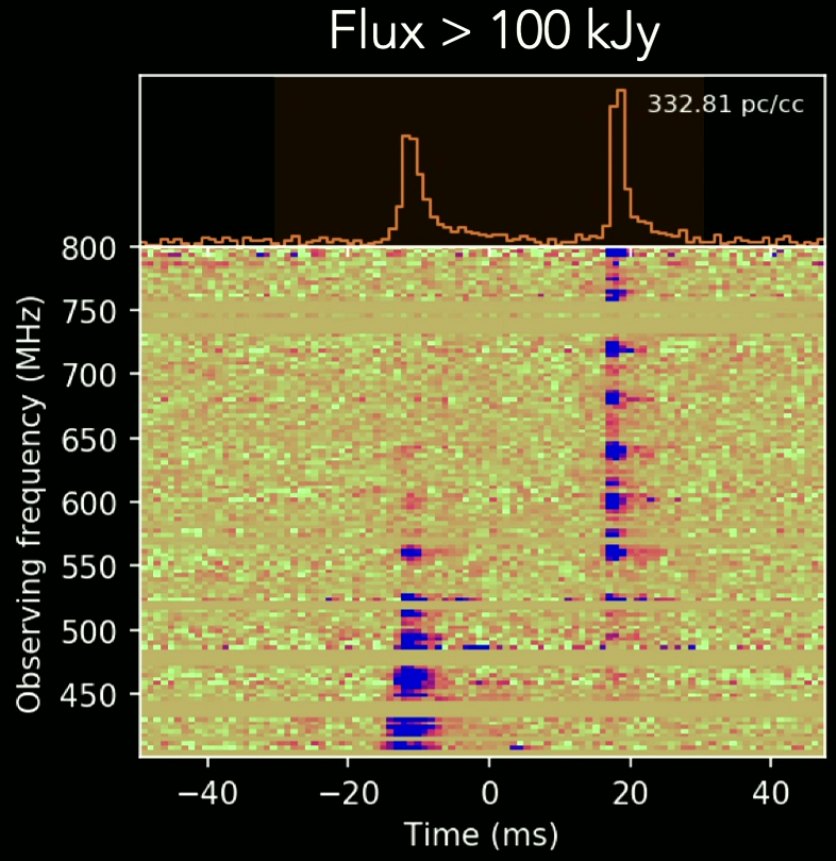
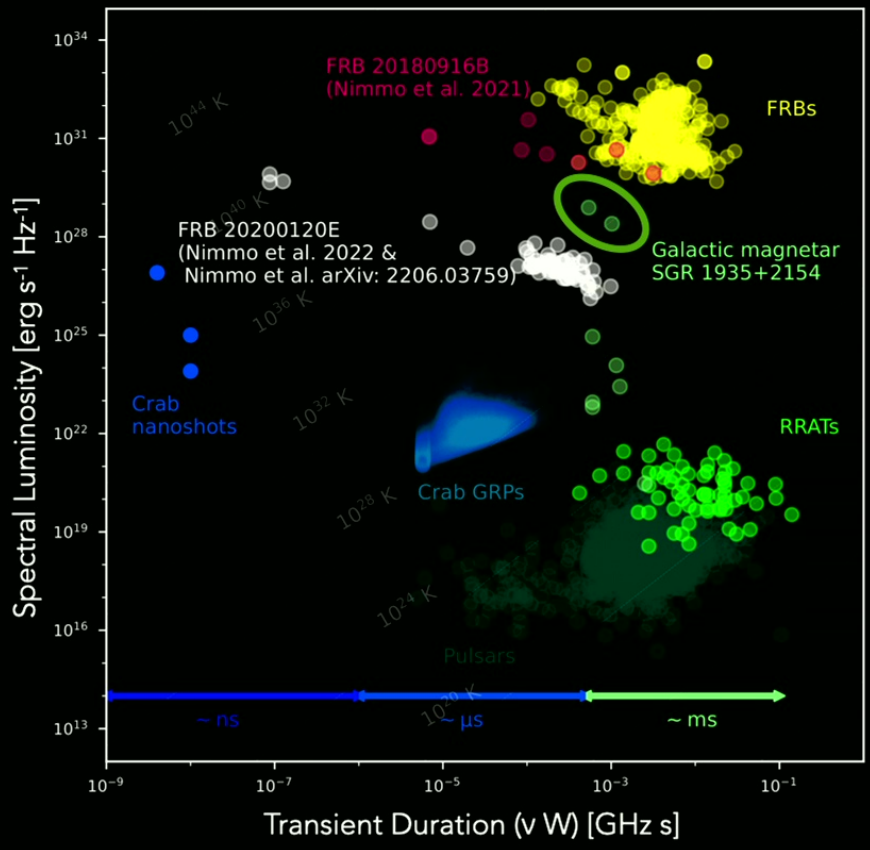
SGR RADIO BURST WAS FRB-LIKE





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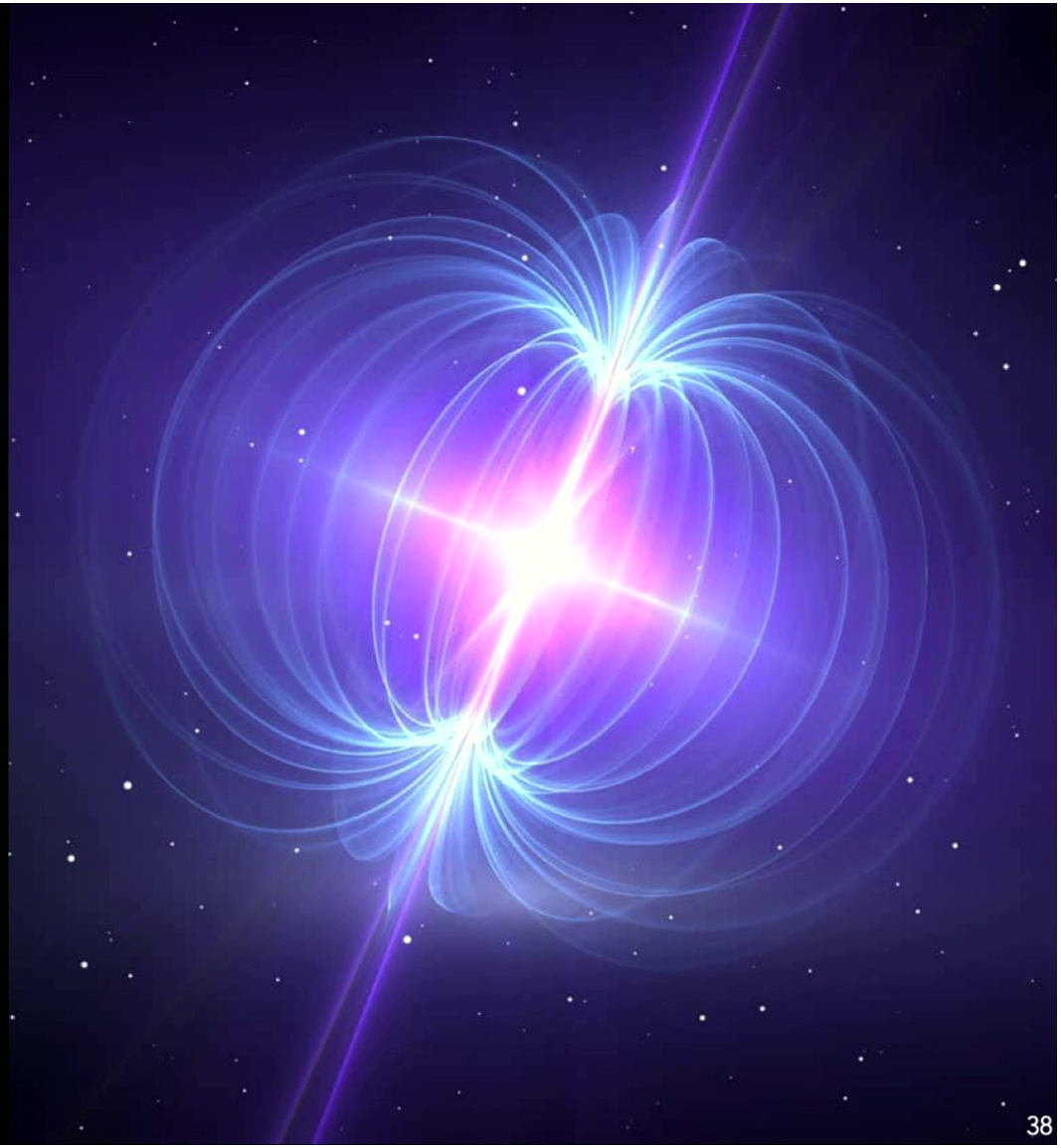
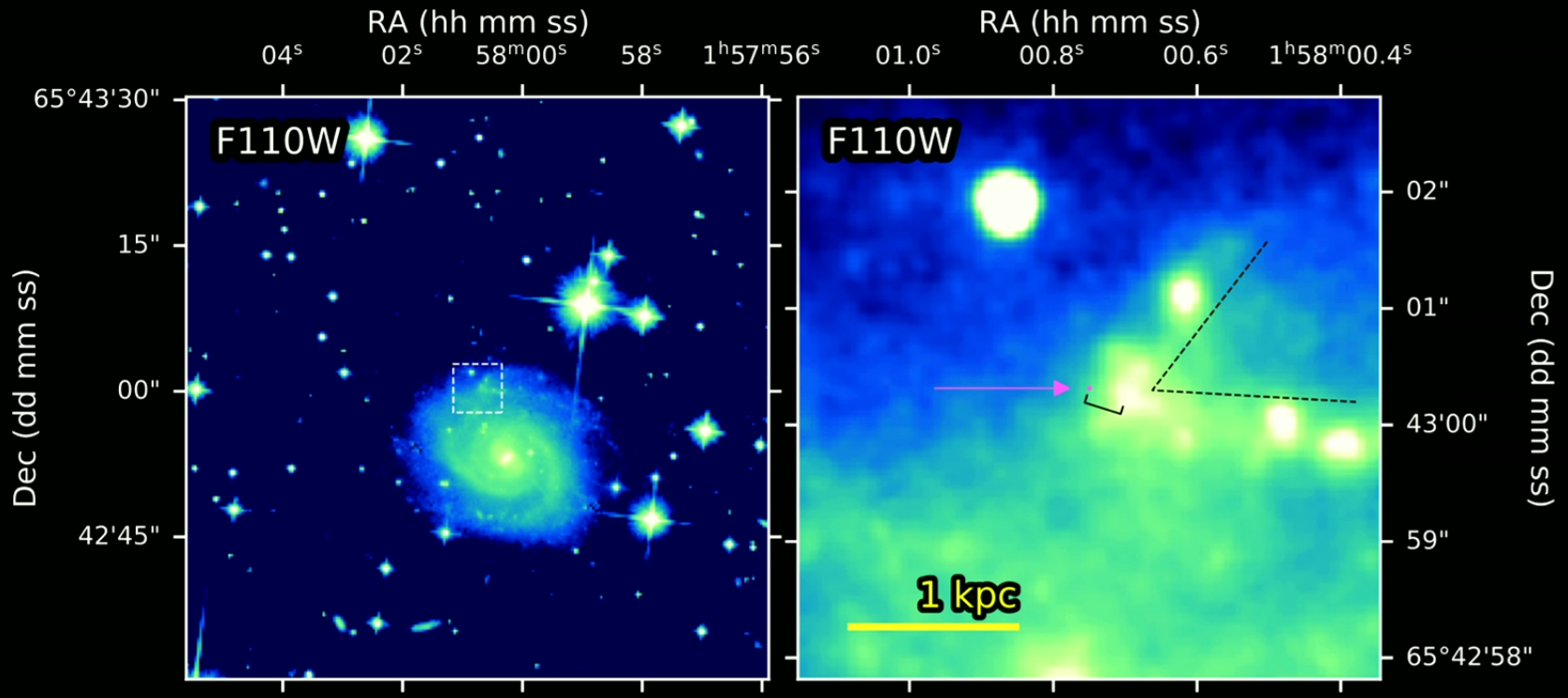
(MOST) CLUES POINT TO MAGNETARS

- Young neutron stars powered by energy stored in extremely strong magnetic fields
- Favored sources because of:
  - Direct association (SGR 1935+2154)
  - Energetics
  - Short time scales
  - Association with star formation
  - Periodic activity from binary orbit or precession



SOURCE ENVIRONMENTS OF REPEATERS

FRB 20180916 (R3)



z = 0.034 spiral galaxy

Marcote et al. 2020, Nature

60 pc from a star forming region

Tendulkar et al. 2021

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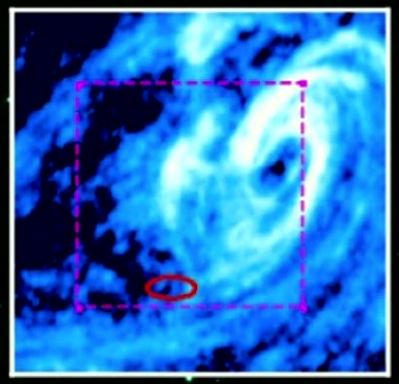
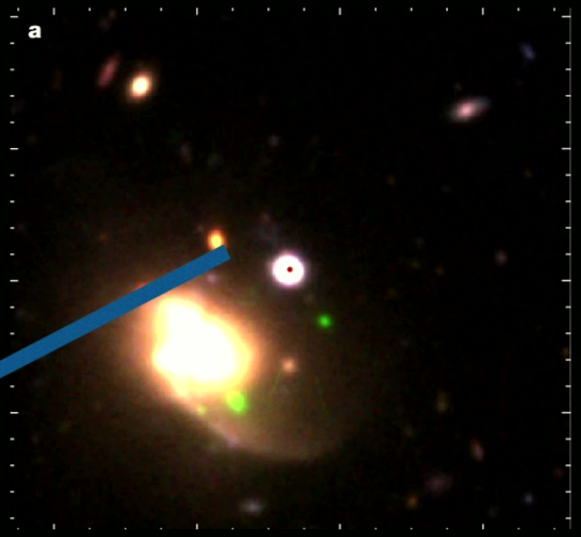
SOURCE ENVIRONMENTS OF REPEATERS



Outskirts of M81
Bhardwaj et al. 2021

FRB 20200120E



An M81 halo globular cluster!
Kristin et al. 2022, Nature

Mohit Bhardwaj
Carnegie Mellon

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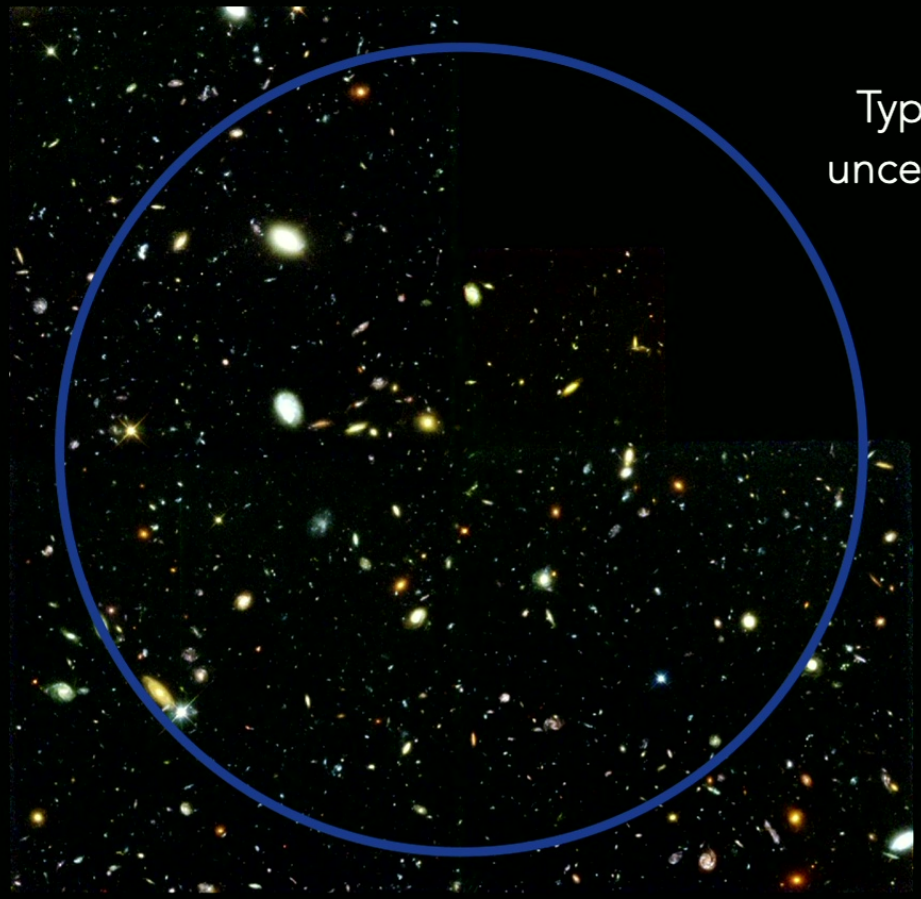
Evidence from source localizations/environments mixed on magnetar hypothesis

But only a few data points…

NEXT INSTRUMENT

CHIME/FRB VLBI OUTRIGGERS

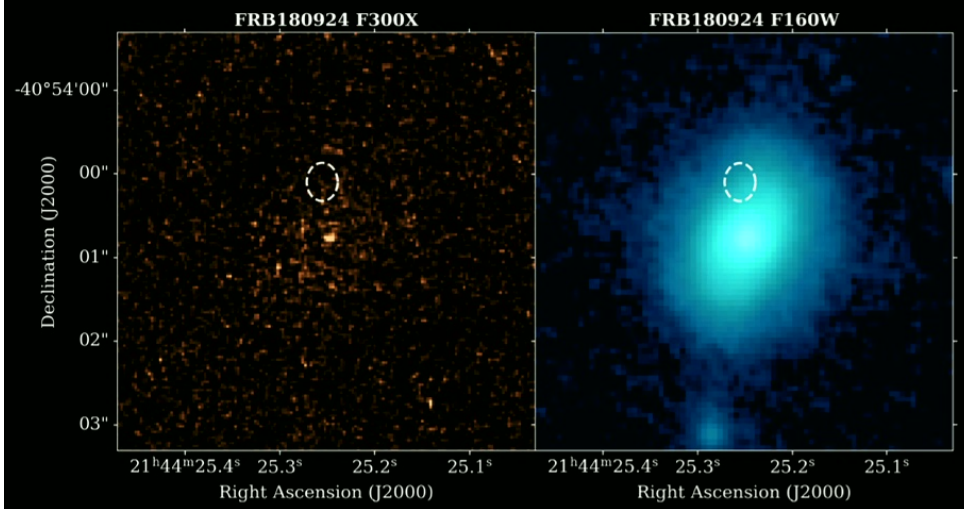
CHIME'S WEAKNESS: RESOLUTION



Typical localization
uncertainty ~1 arcmin

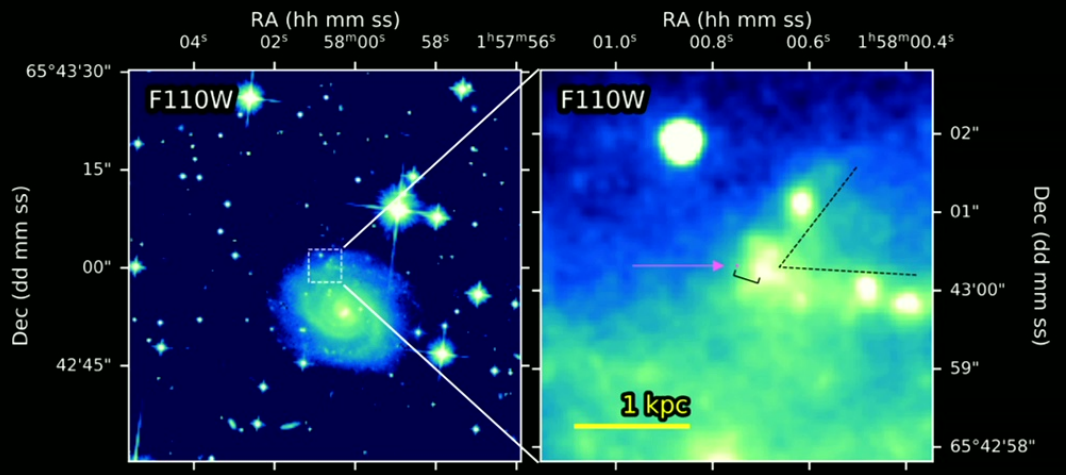
TWO TYPES OF LOCALIZATION

Traditional interferometry
~1 arcsecond



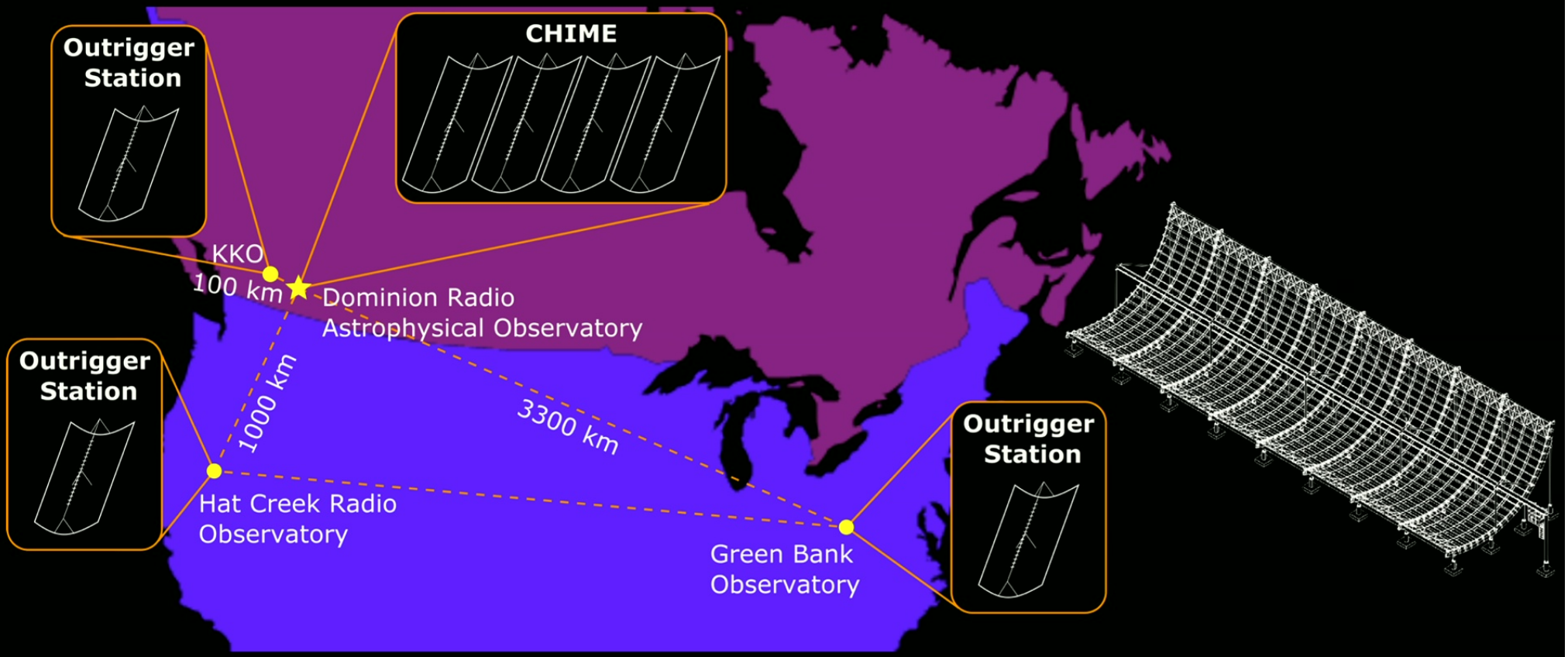
Mannings et al. 2021

VLBI
~milliarcsecond

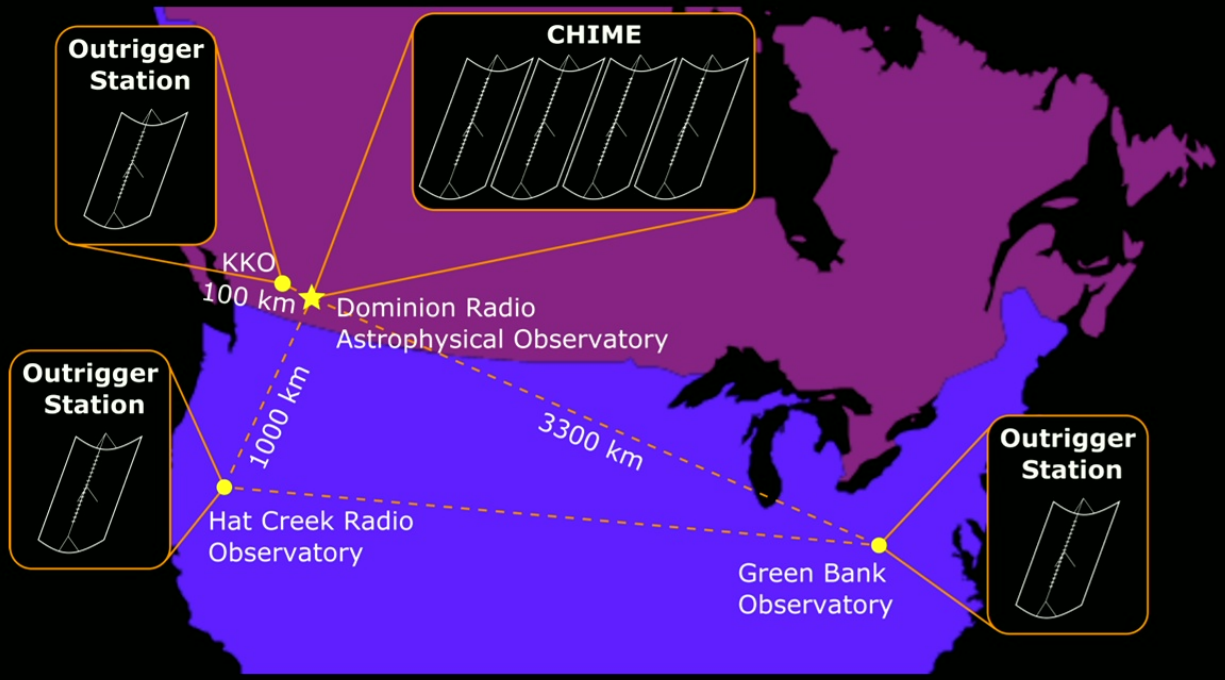


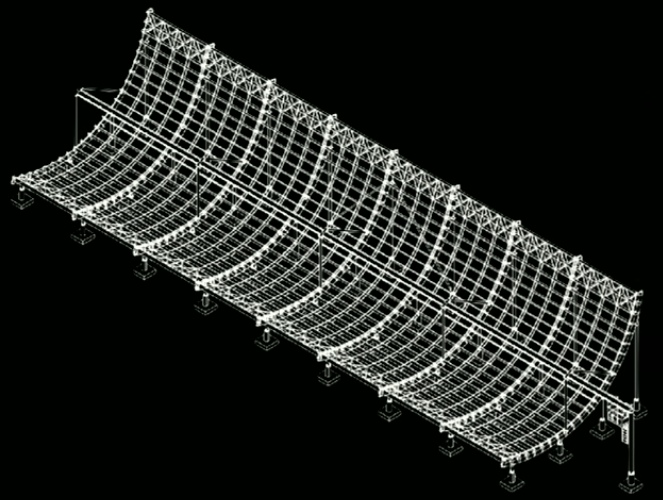
Tendulkar et al. 2021

CHIME/FRB VLBI OUTRIGGERS



CHIME/FRB VLBI OUTRIGGERS





- Each outrigger about 1/8 CHIME collecting area
- "Rolled" reflectors but otherwise nearly identical optical, analog, and digital systems

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GOAL:

Localize Every CHIME-Detected FRB (few thousand) to < 50 mas

THE CHALLENGE:

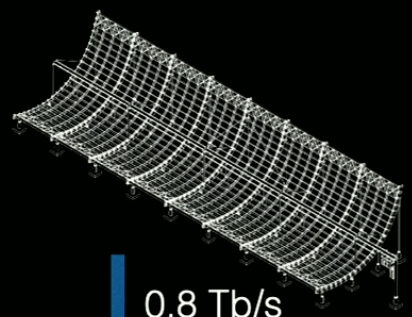
We don’t know where or when our VLBI target is

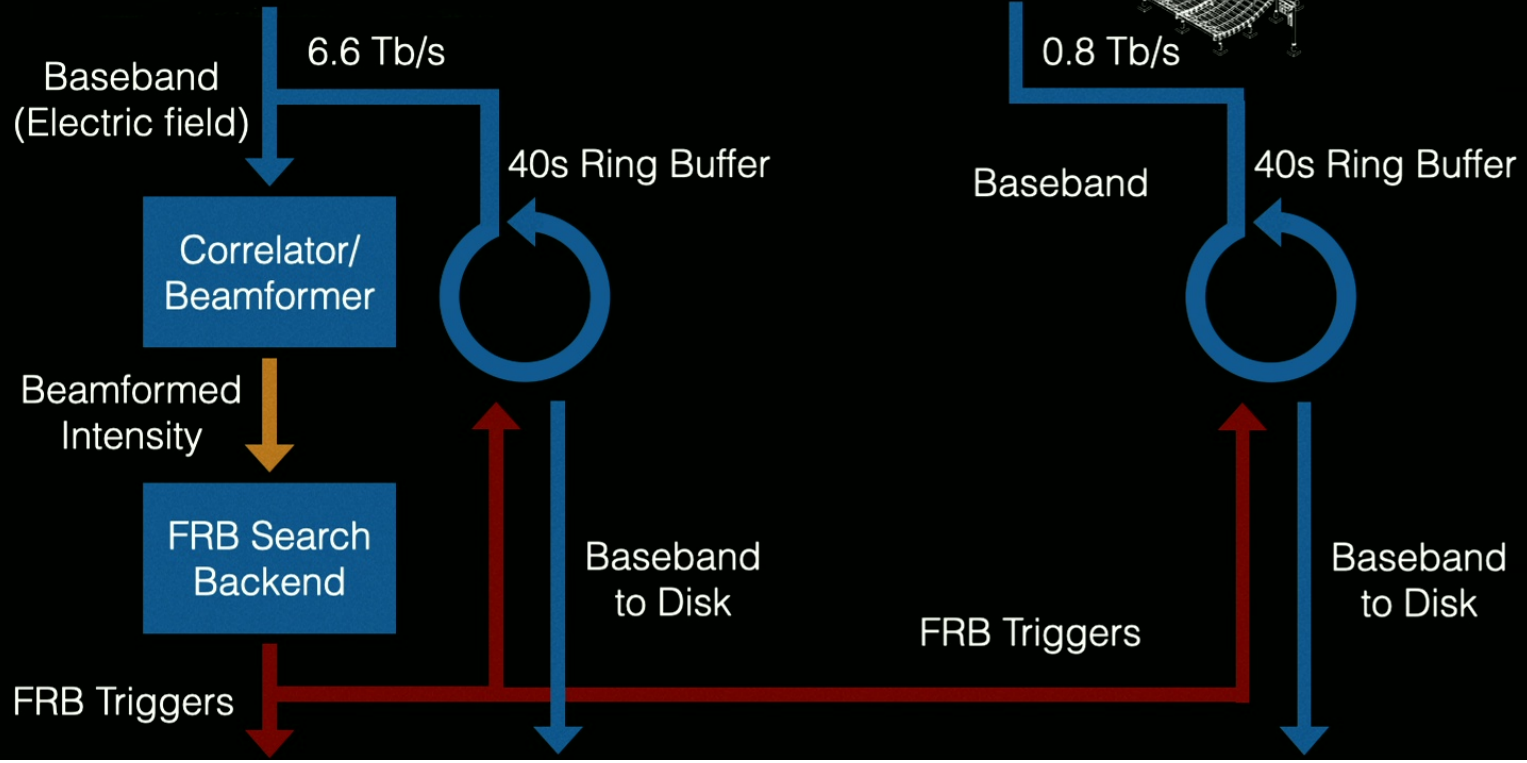
CHALLENGES FOR

SYNOPTIC TRANSIENT VLBI

- Data rate for phase-preserving data:
  - fundamental scaling ~ FOV * Collecting area * Bandwidth
  - CHIME data rate 100x EHT station
- Calibration (clock synchronization and the ionosphere):
  - Don’t know when or where on the sky to calibrate
  - Need an always-ready calibration solution

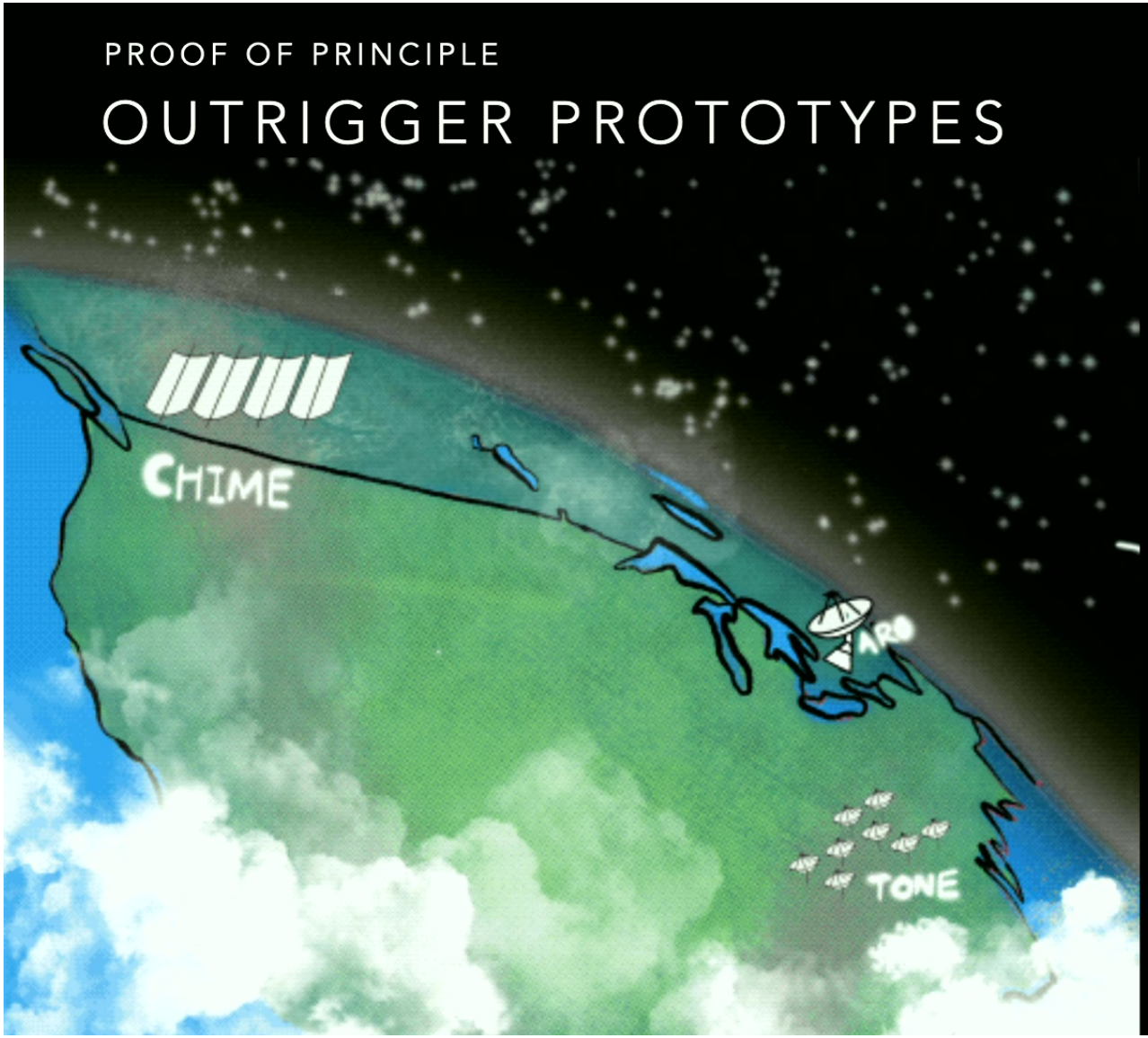
VLBI TRIGGERING AND RECORDING





PROOF OF PRINCIPLE

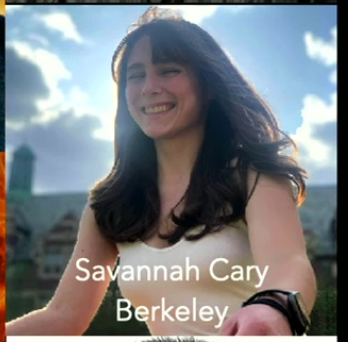
OUTRIGGER PROTOTYPES

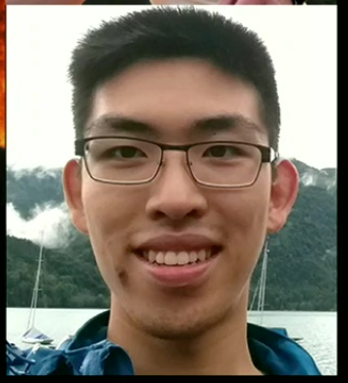



Pranav Sanghavi
Yale


Tomas Cassanelli
U Chile


Juan Mena-Parra
U Toronto

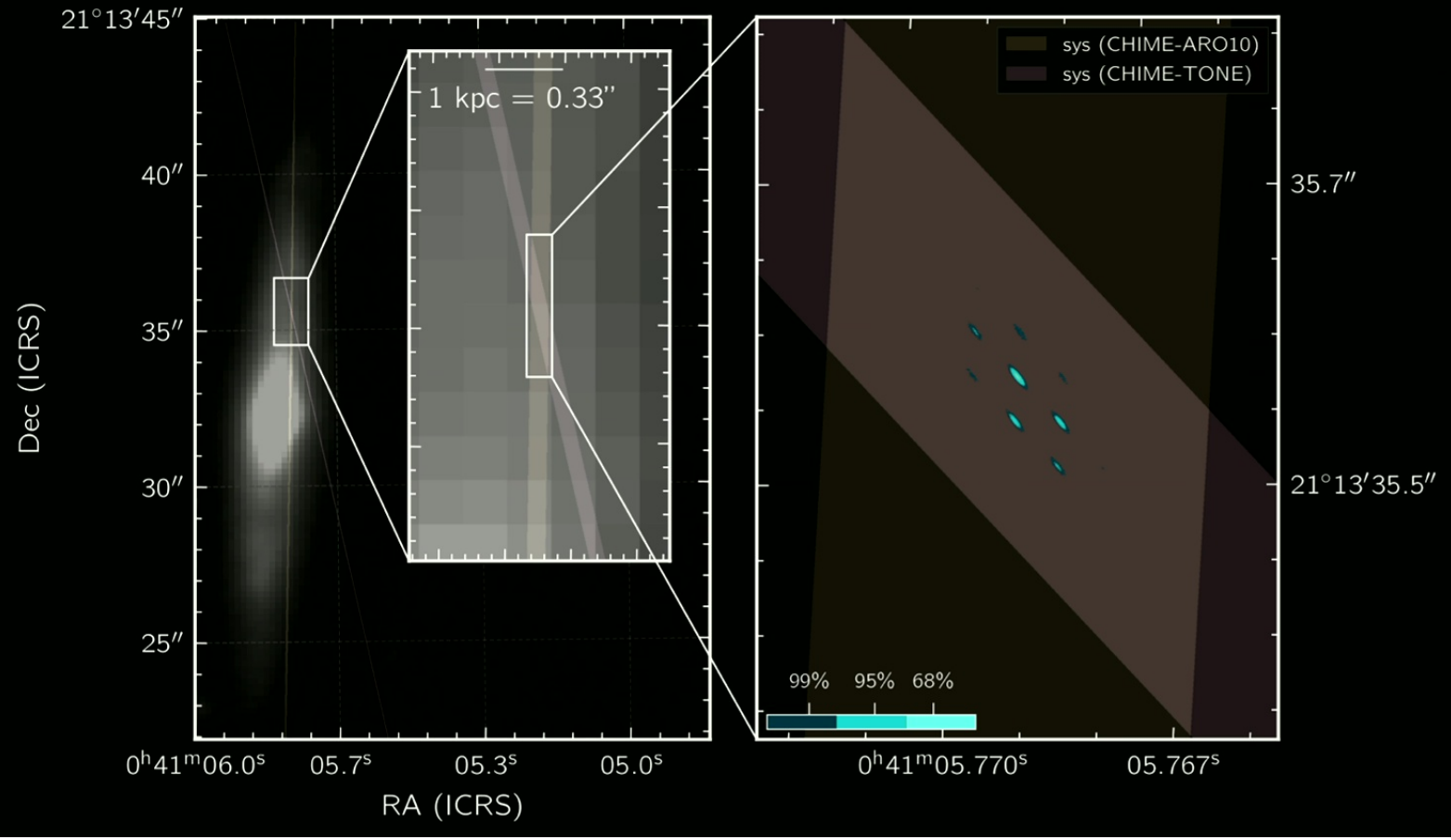

Savannah Cary
Berkeley


Calvin Leung
MIT

Art: Pranav Sanghavi

VLBI LOCALIZATION AT DETECTION

TO AN EDGE-ON Z=0.18 DISK




HAPPENING NOW IN BC
k’niʔatn k’l̓stk’masqt Outrigger (KKO)
Name was a generous gift from the
Upper Similkameen Indian Band.
Listening device for outer space
Photo: NRC
53


HAPPENING NOW IN GREEN BANK
Photo: Kevin Bandura
54

STARTING IN A FEW MONTHS:

Thousands of FRBs, with DMs, localizations, host galaxies, redshifts

HOW TO USE FRBS AS

COSMOLOGICAL PROBES

DISPERSION FOR LARGE-SCALE STRUCTURE

Counts every free electron along line of sight (baryons ~90% ionized)

$$t_d \propto \mathrm{DM}\,\lambda^2$$

$$\mathrm{DM} = \int_{\mathrm{src}}^{\mathrm{obs}} n_e \vec{ds}$$

$$[\mathrm{DM}] = \mathrm{pc/cm^3}$$

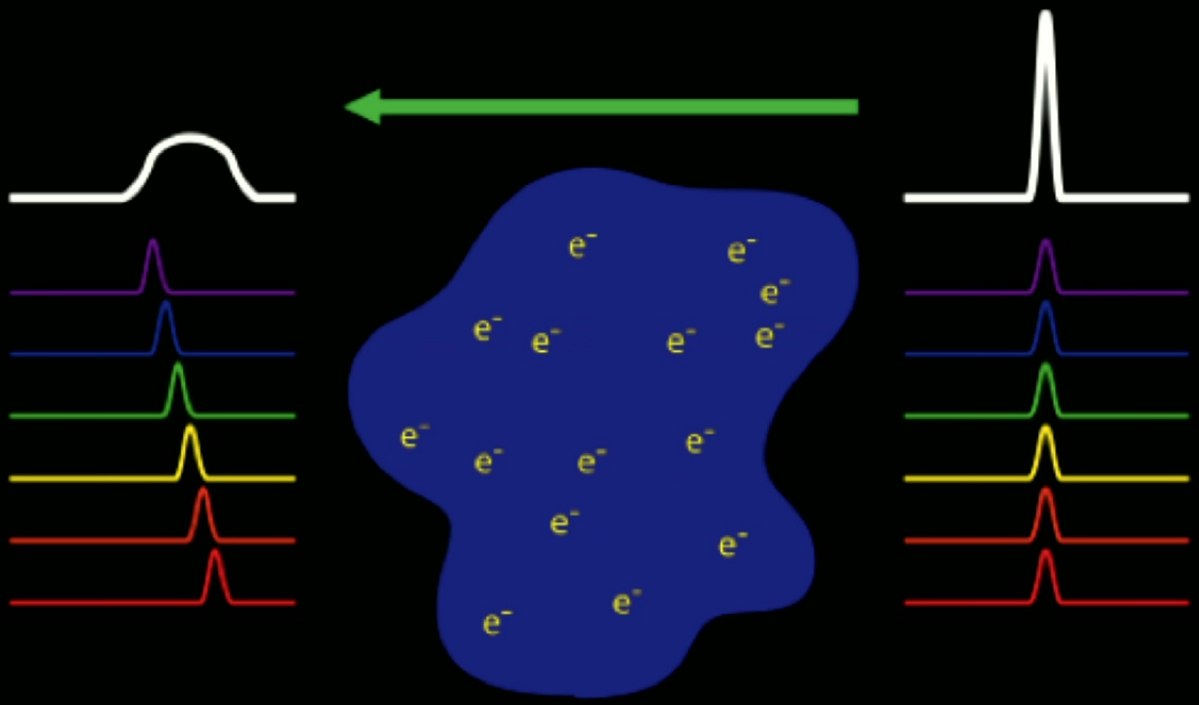
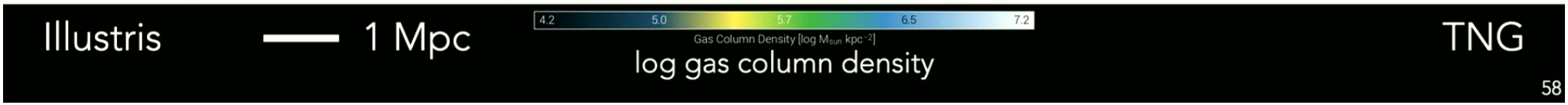
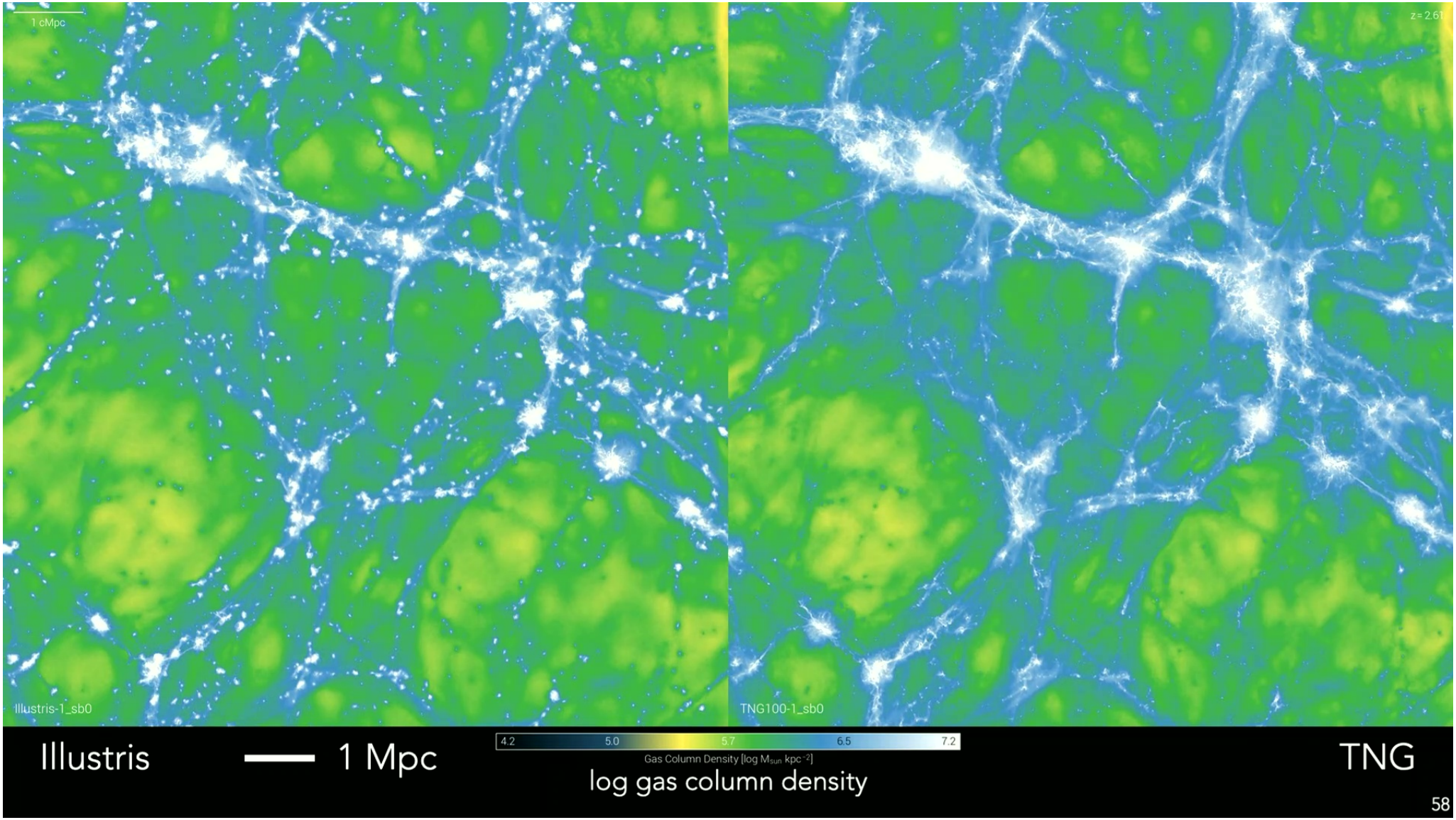


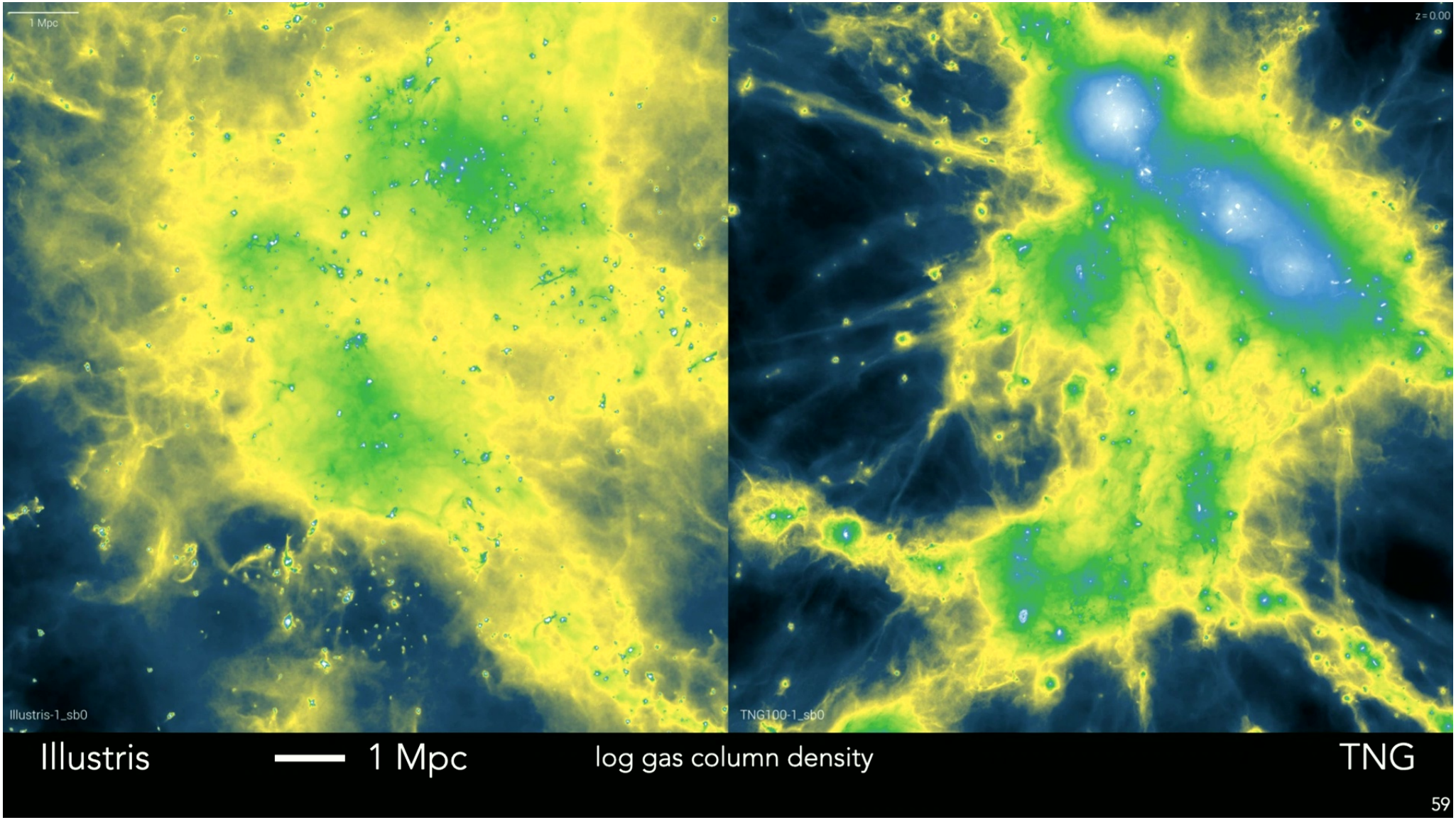
image: Erik Madsen



log gas column density

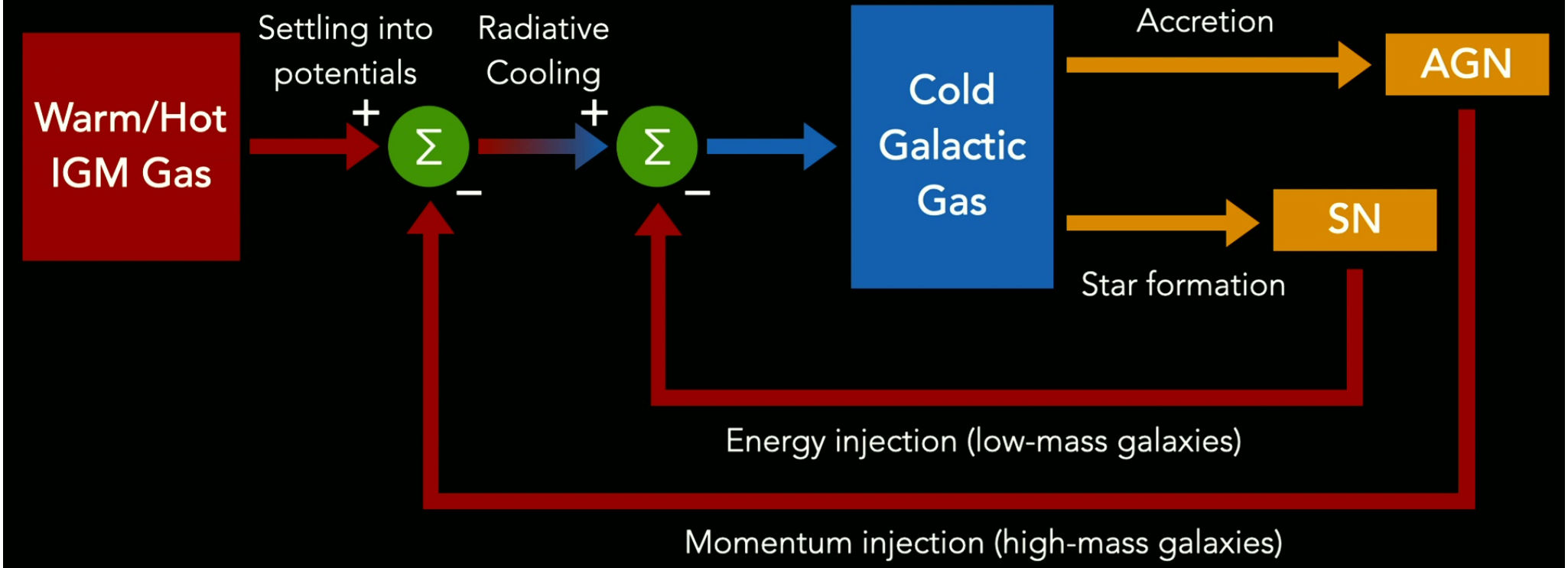
58


1 cMpc
z = 2.61
Illustris-1_sb0
TNG100-1_sb0
Illustris
1 Mpc
4.2
5.0
5.7
6.5
7.2
Gas Column Density [log M_{sun} kpc^{-2}]
log gas column density
TNG
58


1 Mpc
z = 0.00
Illustris-1_sb0
TNG100-1_sb0
Illustris
1 Mpc
log gas column density
TNG
59

WHAT IS

FEEDBACK IN GALAXY FORMATION

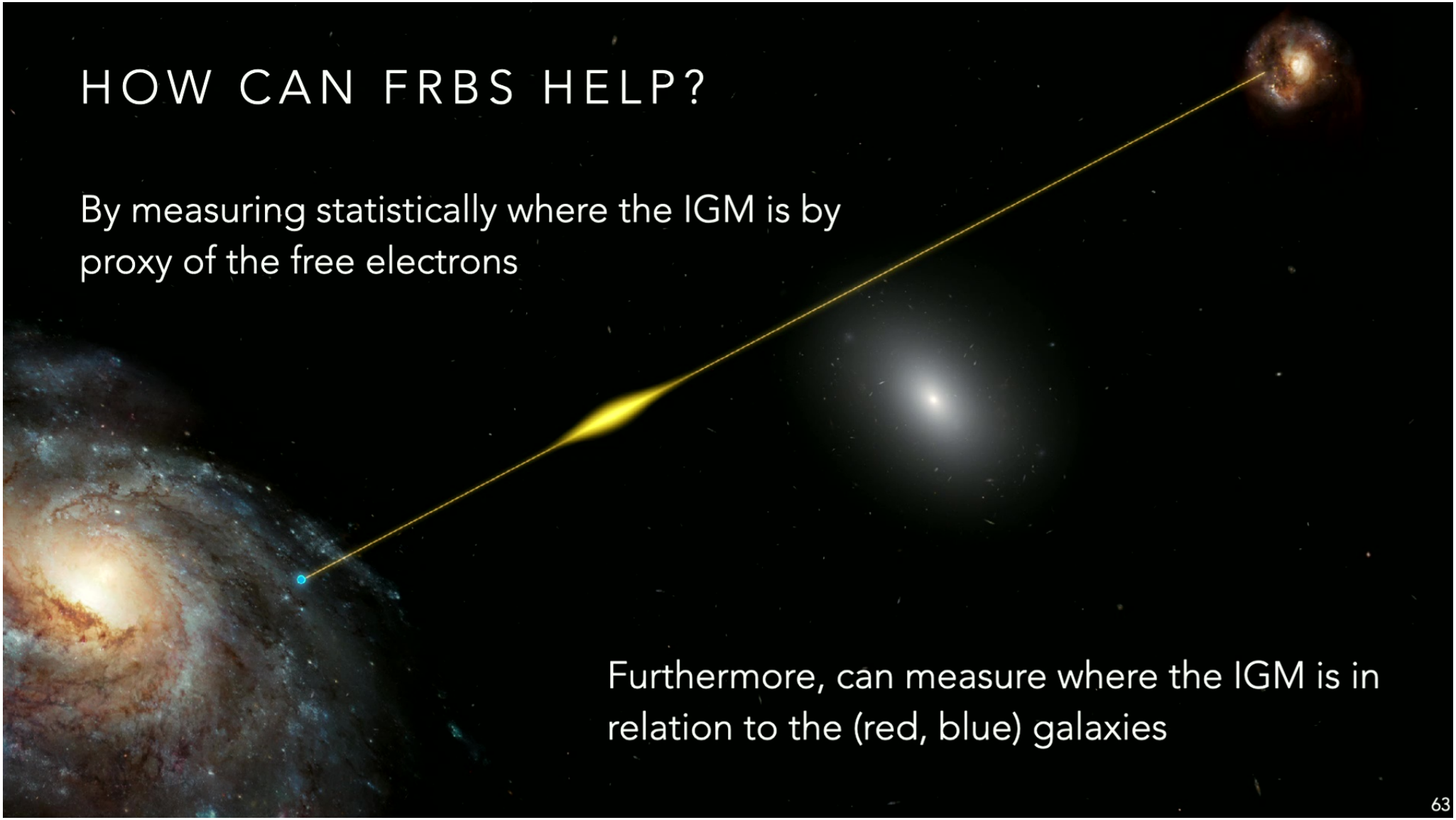


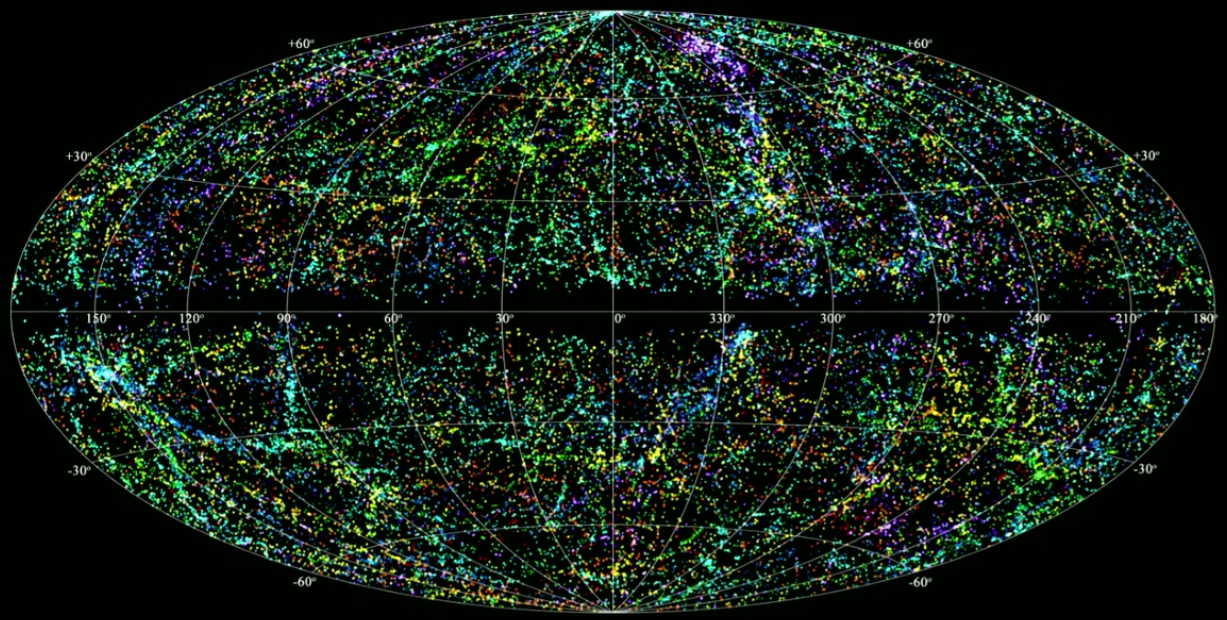
WHY IS FEEDBACK POORLY CONSTRAINED?

- Feedback disrupts cooling of the IGM
- Starves galaxies of the cold gas that feeds star formation
- But can only observe galaxy/stars/cold gas - secondary results of feedback
- Not the direct result, the IGM itself

ASIDE: THE MISSING BARYON PROBLEM

- This *is* the missing baryon problem:
  - IGM contains most of the baryons
  - Cannot be observed, cannot be reliably simulated
  - So we don’t know precisely where in the IGM they are


HOW CAN FRBS HELP?
By measuring statistically where the IGM is by proxy of the free electrons
Furthermore, can measure where the IGM is in relation to the (red, blue) galaxies
63



DM map
and galaxy map

Spherical harmonic
transform

Cross correlate

$C_l^{\mathrm{DM},g}$

$P_{eg}(k)$

Analysis proposed by Madhavacheril, Battaglia, Smith, and Sievers, 2019

WHY COSMOLOGY NEEDS THIS

- Measuring electrons breaks a key degeneracy in the CMB kinematic Sunyaev–Zeldovich (KSZ) effect (Madhavacheril et al. 2019)
- The IGM contaminates weak gravitational lensing (Nicola et al 2022):
  - IGM is 14% of the matter, power spectrum is order-unity uncertain
  - Unless we understand feedback, can't do percent-level measurements of dark matter (and thus dark energy)
- Baryons interact gravitationally with dark matter making it hard to tease out dark matter physics from structure formation

CONCLUSIONS

- Fast radio bursts are a mysterious high-energy phenomena, originating from compact objects
- CHIME is discovering thousands, understanding population - magnetar progenitor favored but evidence mixed
- VLBI Outriggers here soon, providing localizations, redshifts
- FRB data will (finally) measure the large-scale baryon distribution, solving a key uncertainty in large-scale structure formation and cosmology