KIYOSHI MASUI

A SYNOPTIC VIEW OF FAST TRANSIENTS WITH CHIME AND RUBIN

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SLAC - FEBRUARY 28, 2023

MIT | Masui Synoptic Radio Lab

WHAT ARE

FAST RADIO BURSTS

artwork: Jingchuan Yu, Beijing Planetarium

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)
- Few percent are repeating sources, majority are one-offs
- Cosmologically distant, but typically poorly localized

RELATED TO NEUTRON STARS?

artwork: Casey Reed

DISPERSION

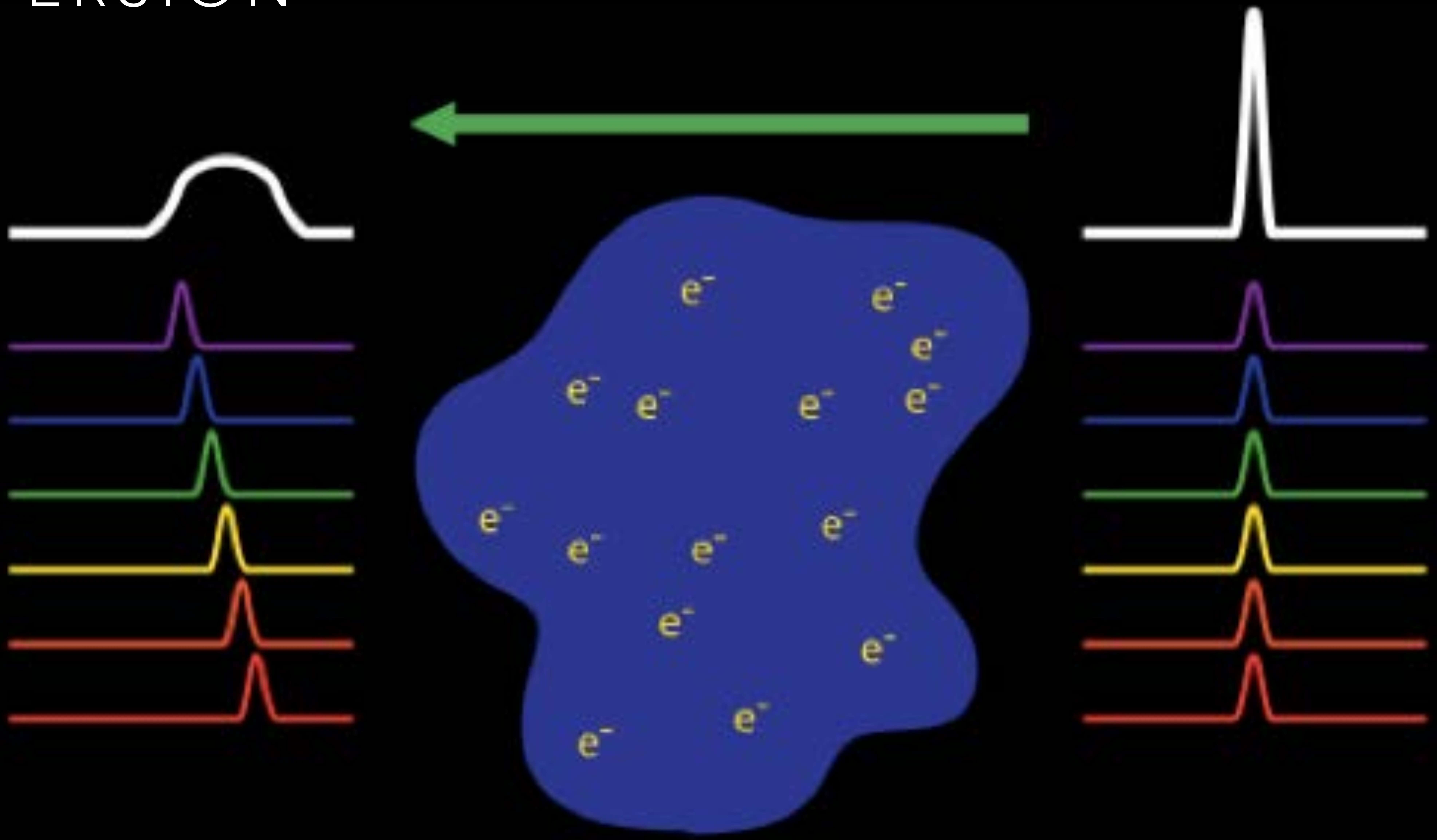
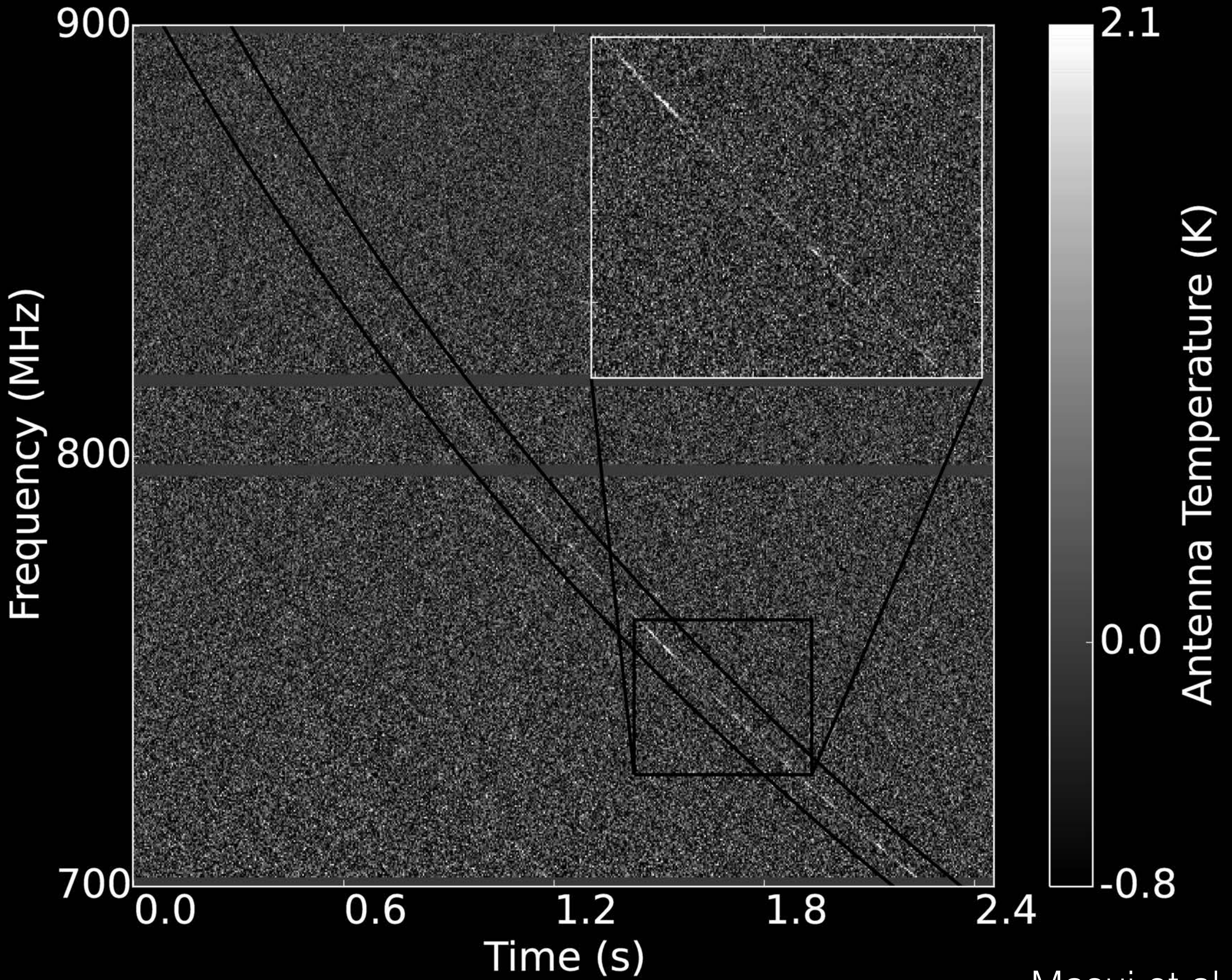


image: Erik Madsen



Masui et al. (2015)

DISPERSION

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

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

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

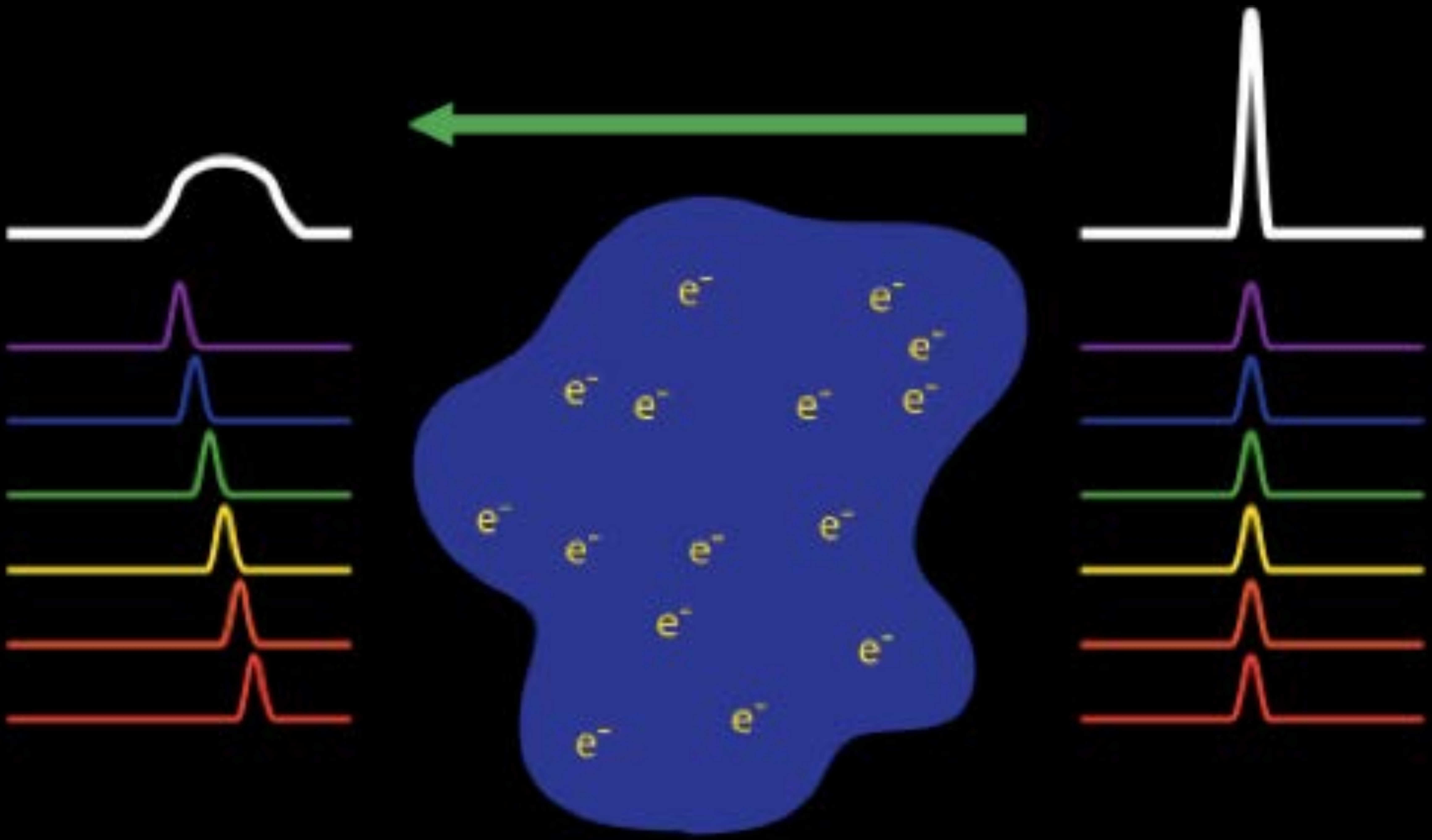


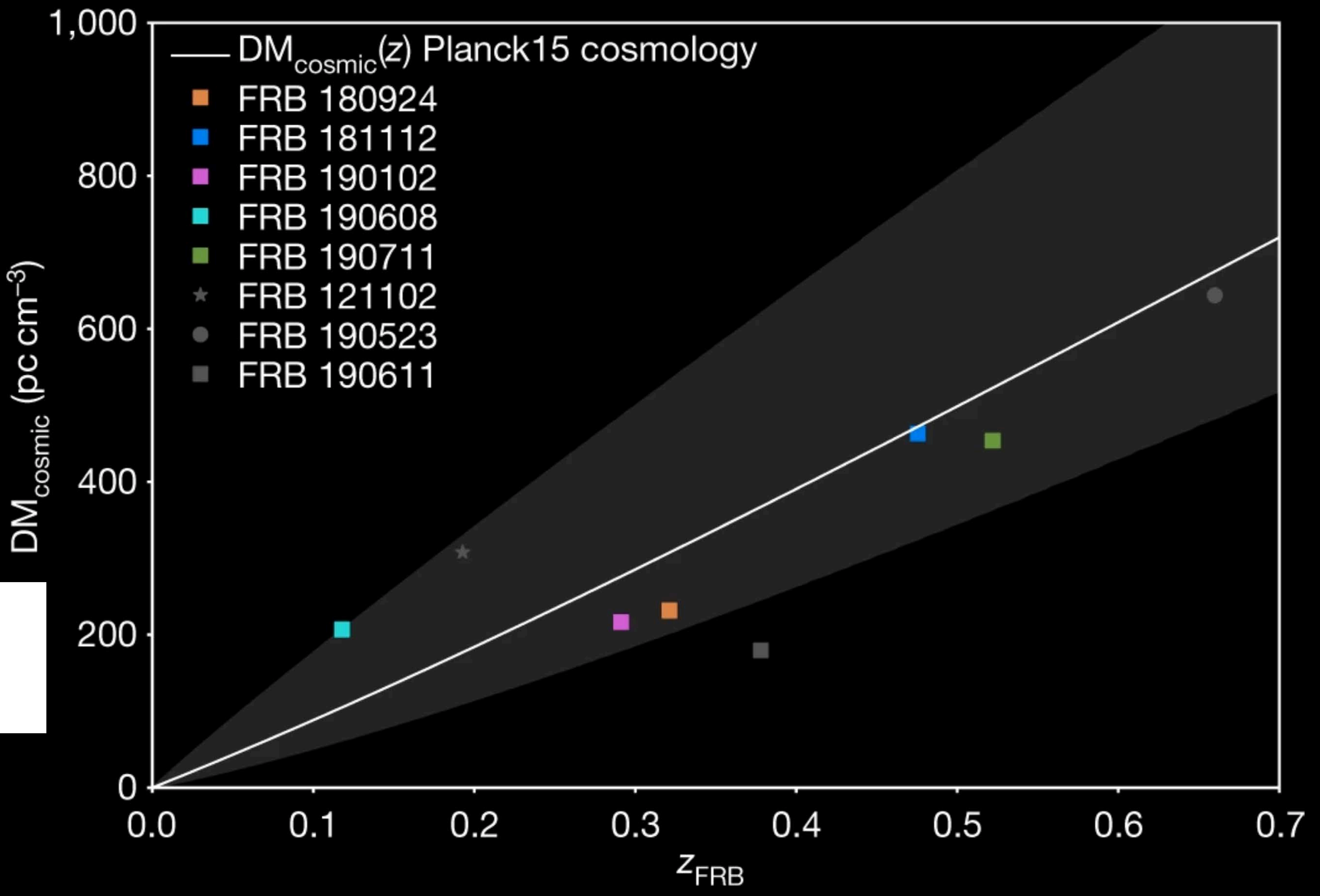
image: Erik Madsen

DISPERSION

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

DM VS Z

MACQUART RELATION



~50 observed from 2007-2017 but ~thousands/sky/day

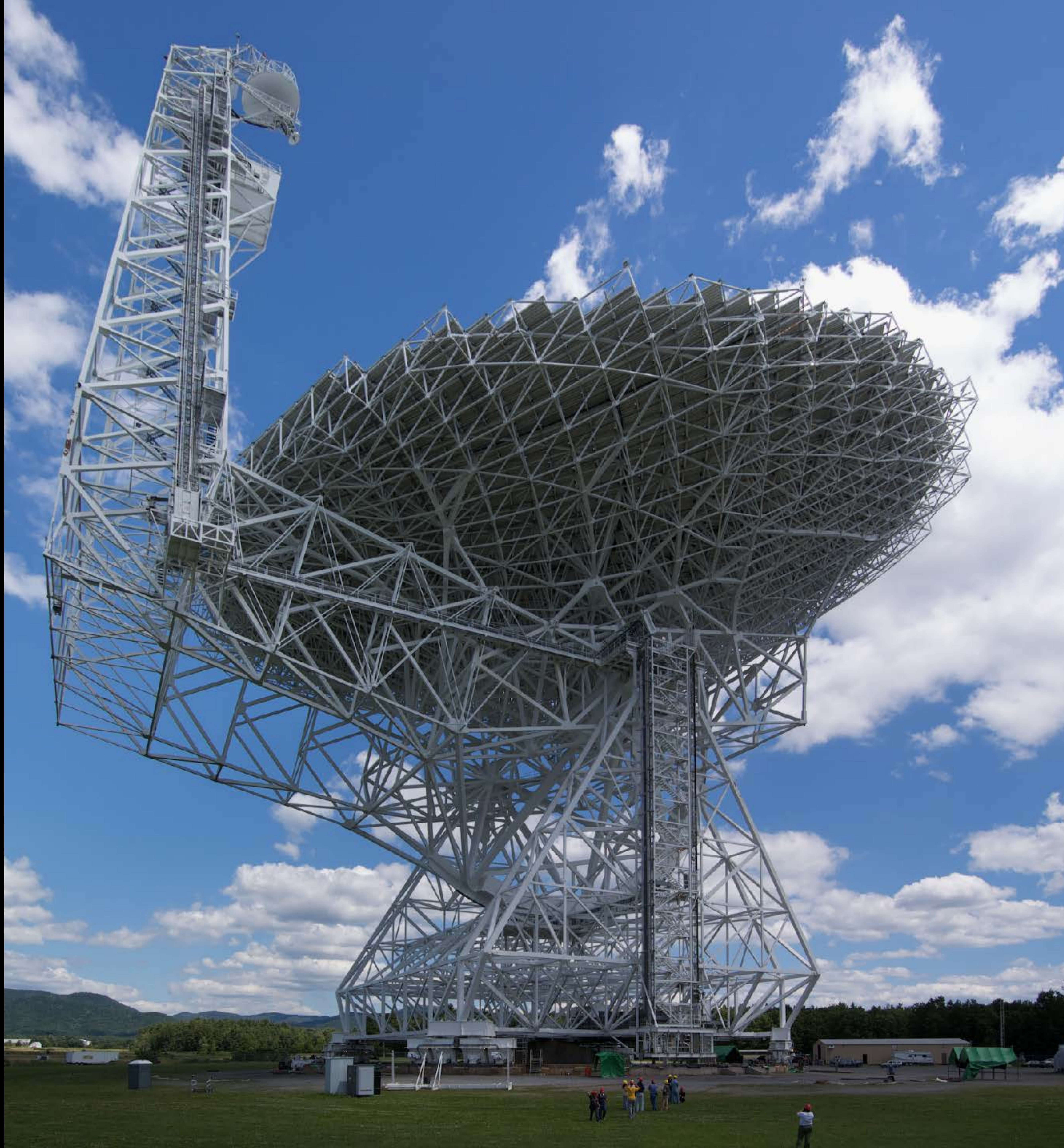
TO UNDERSTAND THESE THINGS

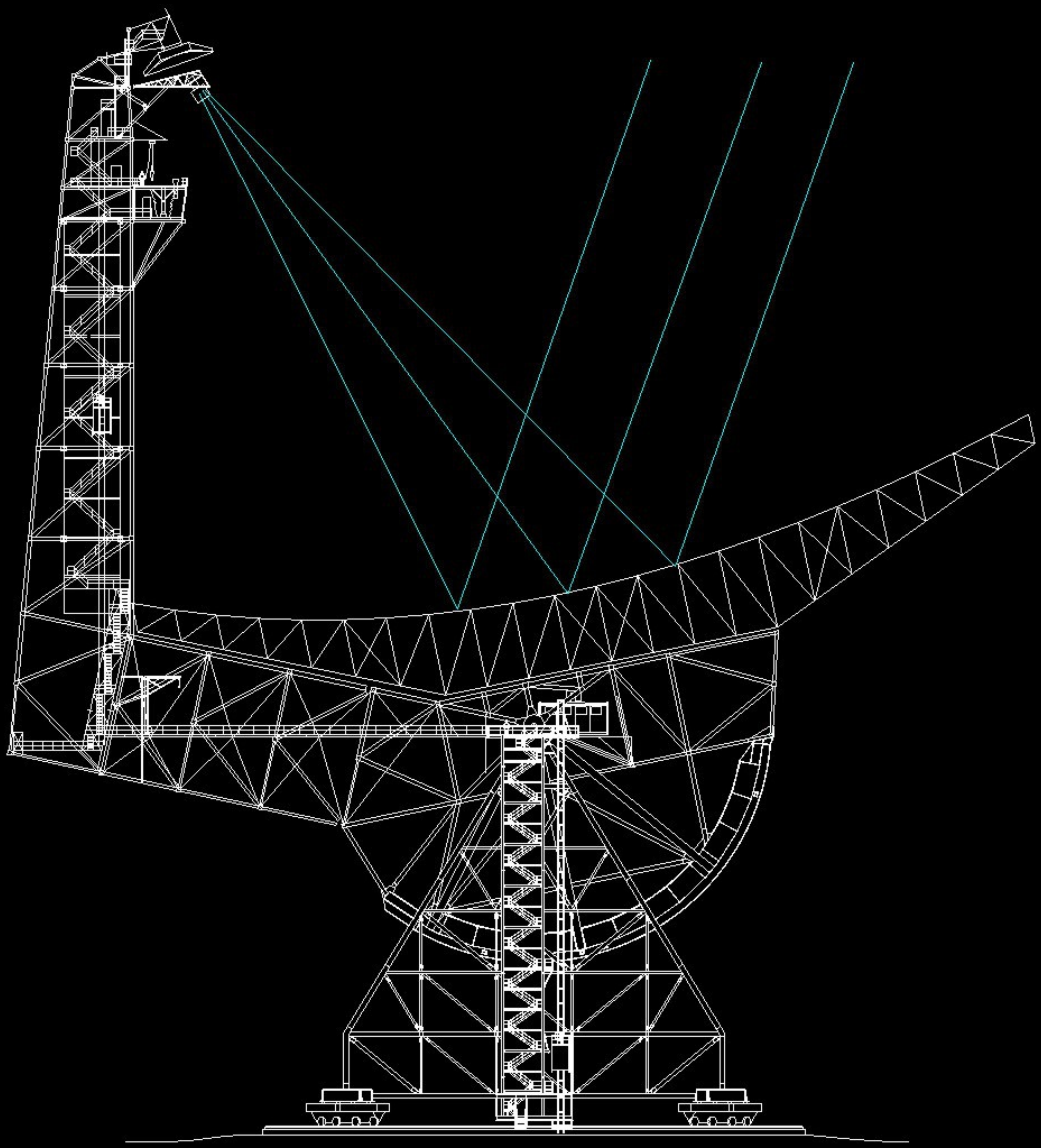
We need a larger sample

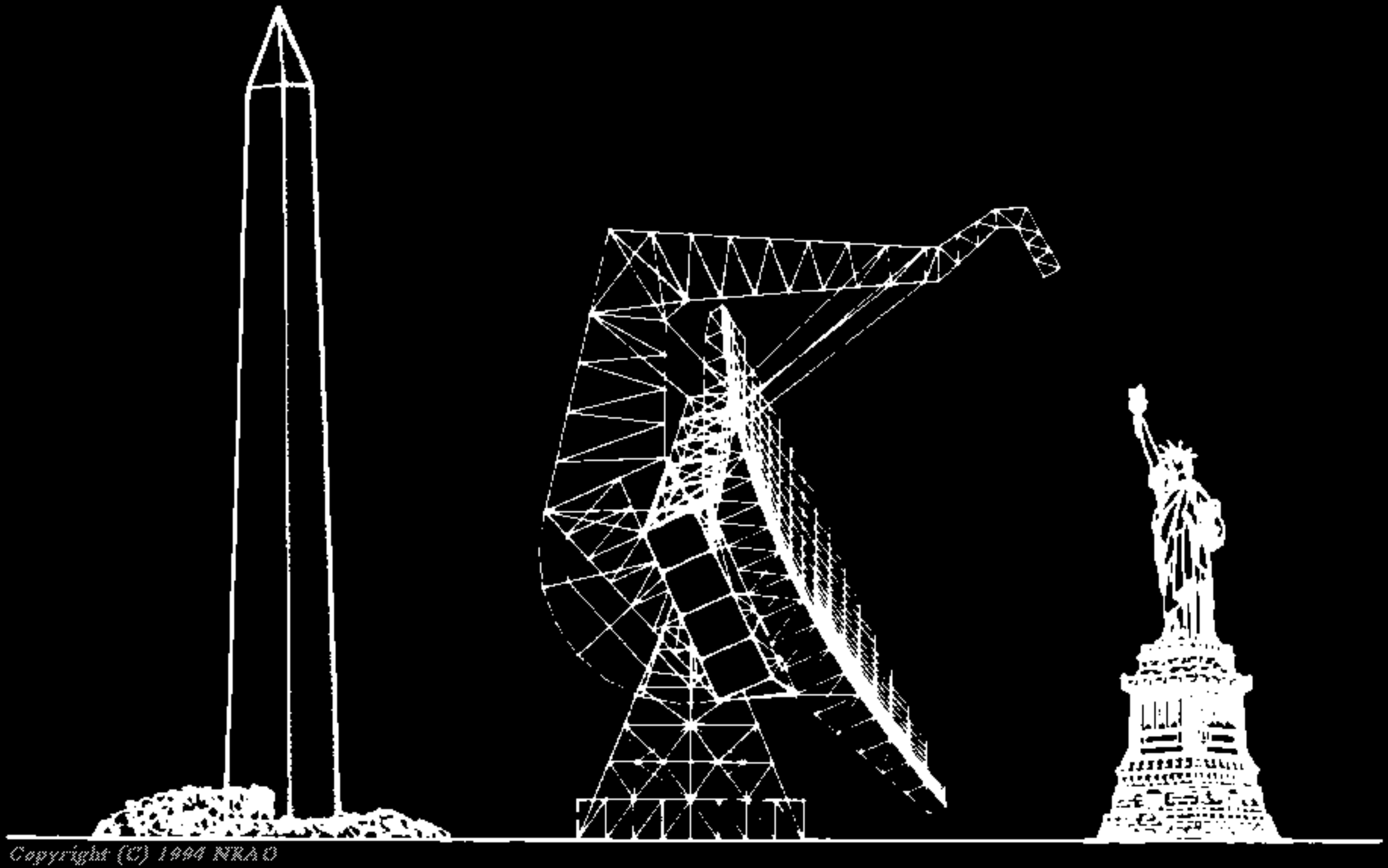
TO GET A BIGGER SAMPLE WE NEED

A new kind of radio telescope

WHAT LIMITS THESE?

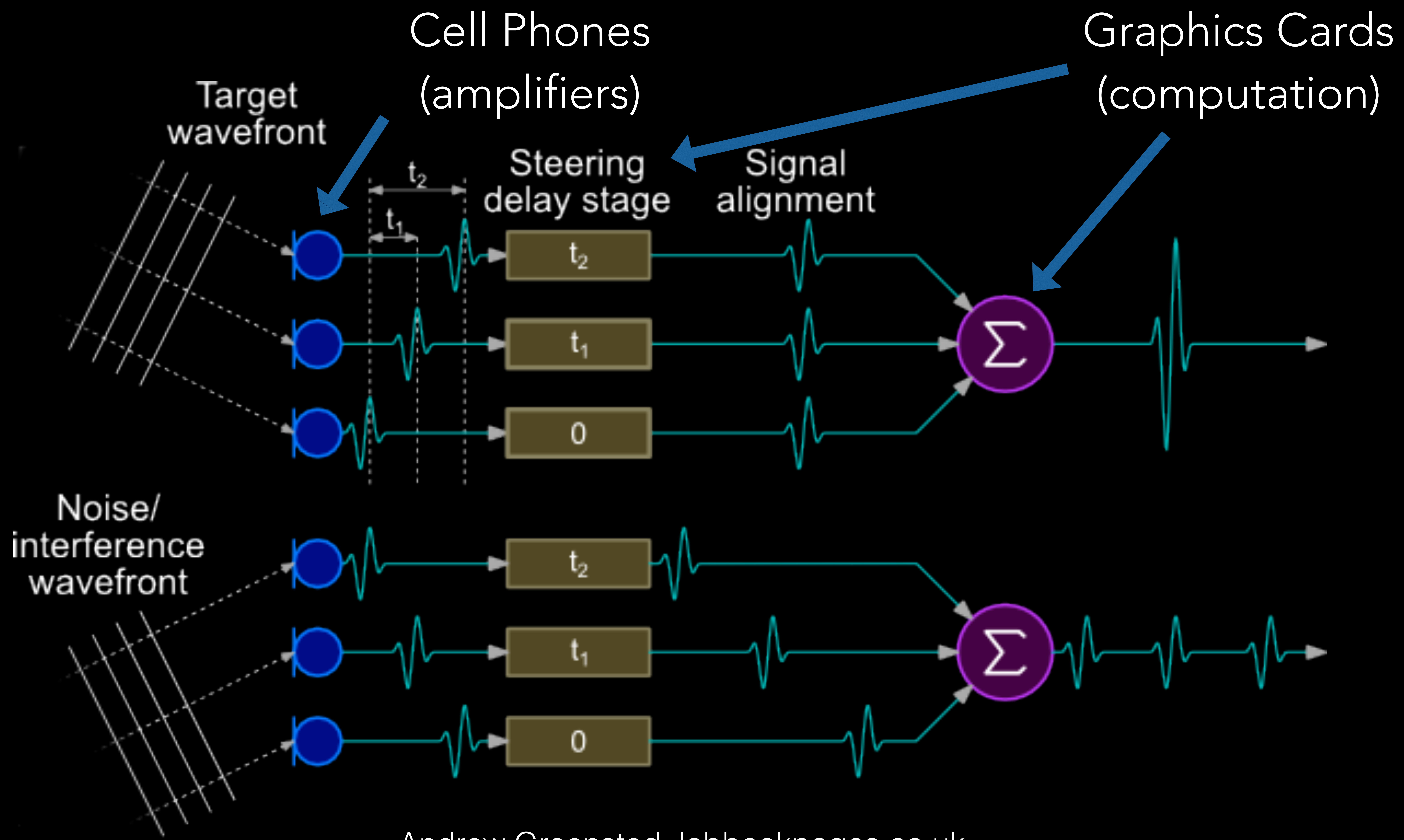





Copyright (C) 1994 NRAO

WHAT HAS CHANGED?

Artist’s Impression of SKA Low



Andrew Greensted, labbookpages.co.uk

CANADIAN HYDROGEN INTENSITY MAPPING EXPERIMENT

CHIME

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)

UNIVERSITY OF TORONTO

McGill

Canada

NRC·CNRC

UBC

PERIMETER INSTITUTE

chime

NRAO

Yale

NCRA • TIFR

Massachusetts Institute of Technology

West Virginia University

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

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- Slow pulsar search

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

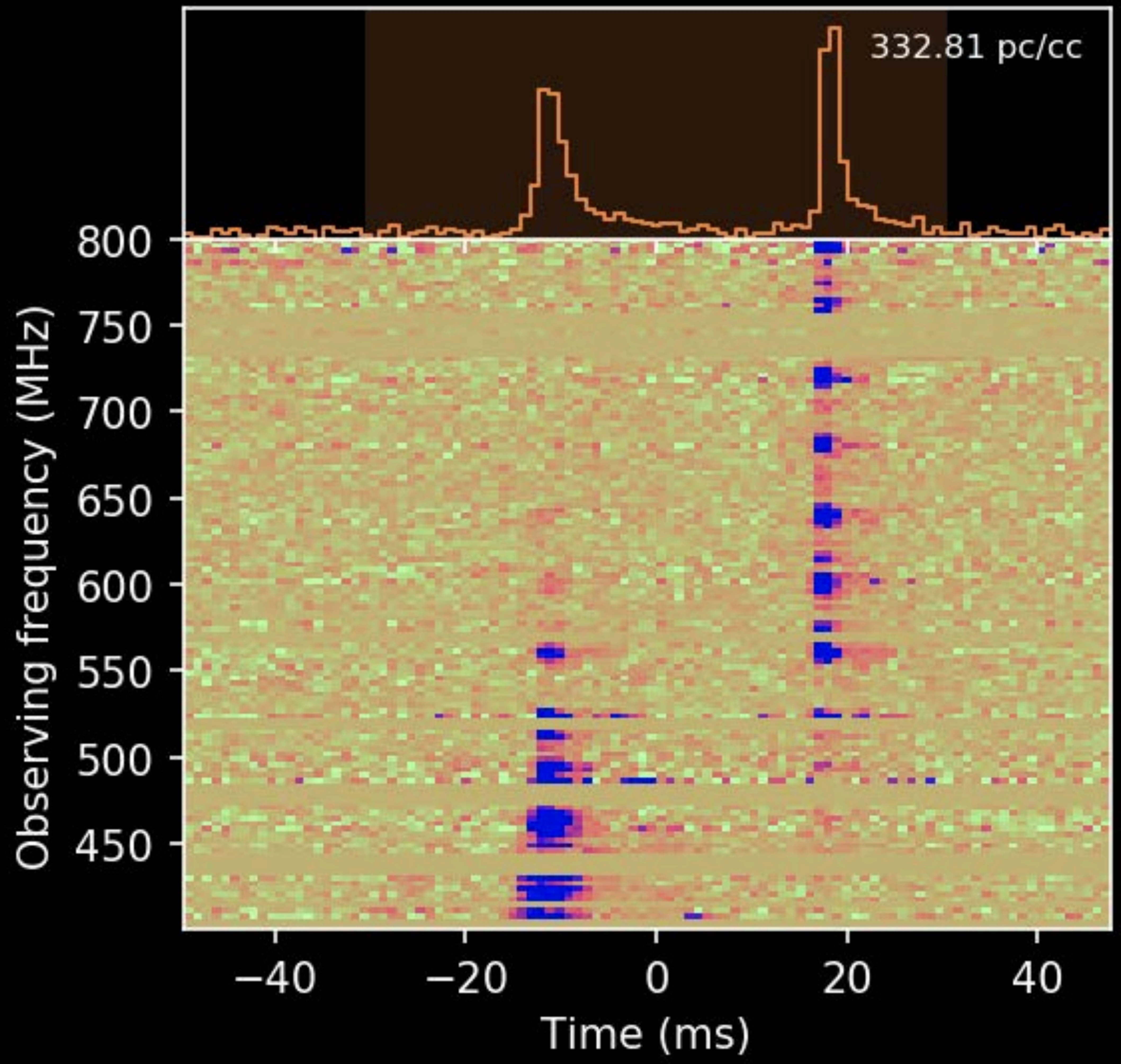
A repeater near a star-forming region of a nearby galaxy
Marcote et al. 2020, Nature, arXiv:2001.02222

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

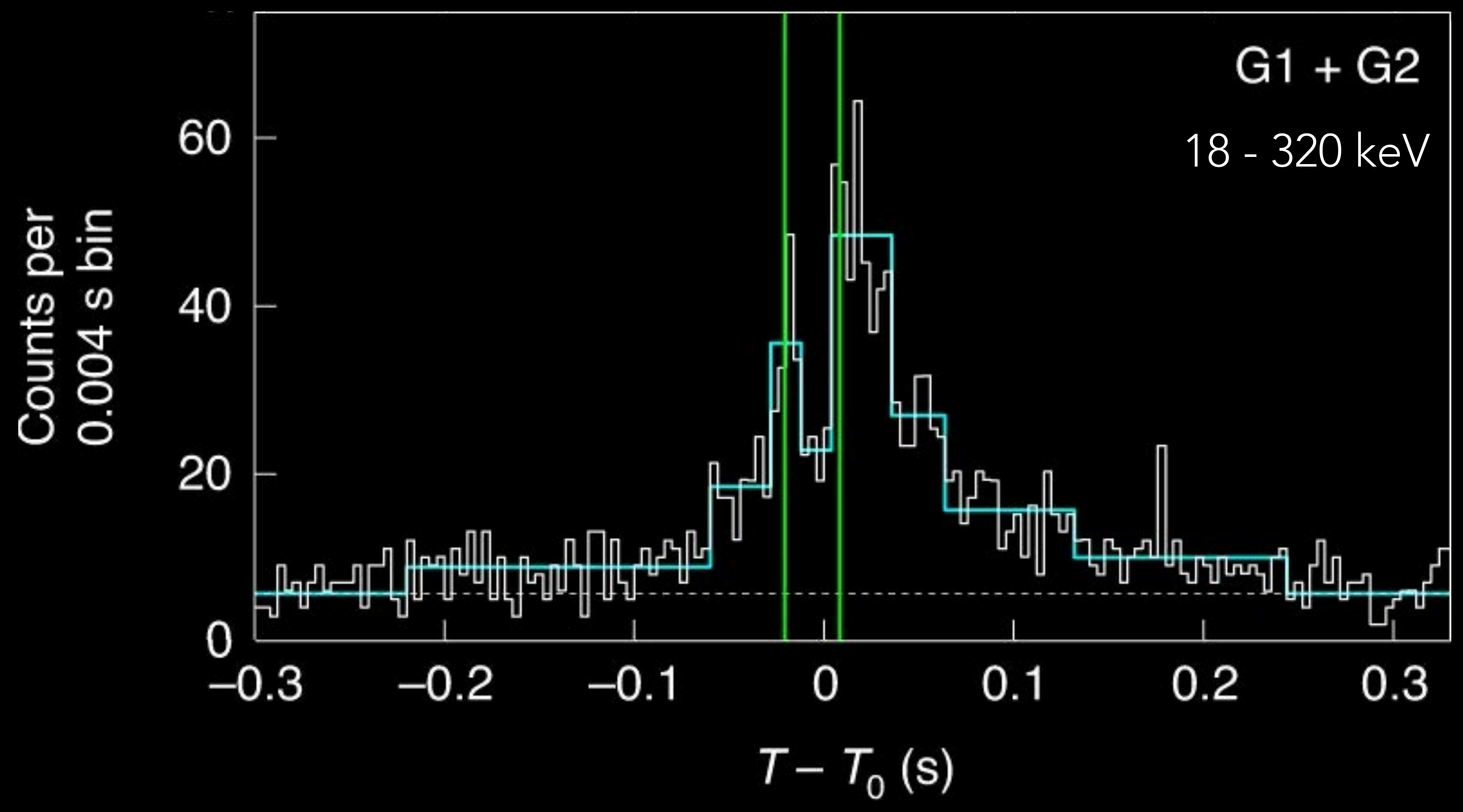
A fast radio burst emitted from a Galactic magnetar
CHIME/FRB Collaboration 2020, Nature, arXiv:2005.10324

FRB FROM GALACTIC SOURCE SGR1935+2154

CHIME/FRB

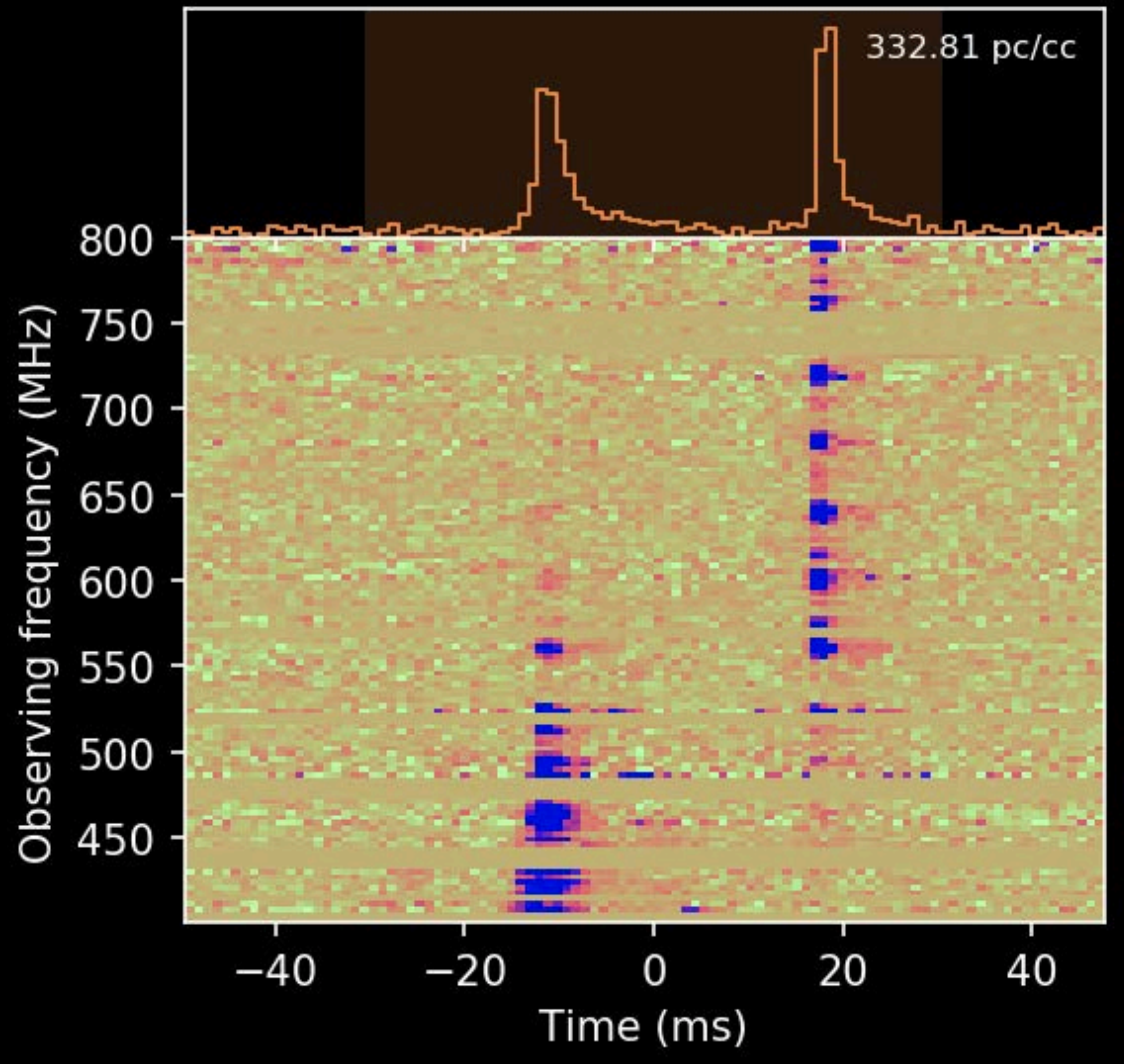


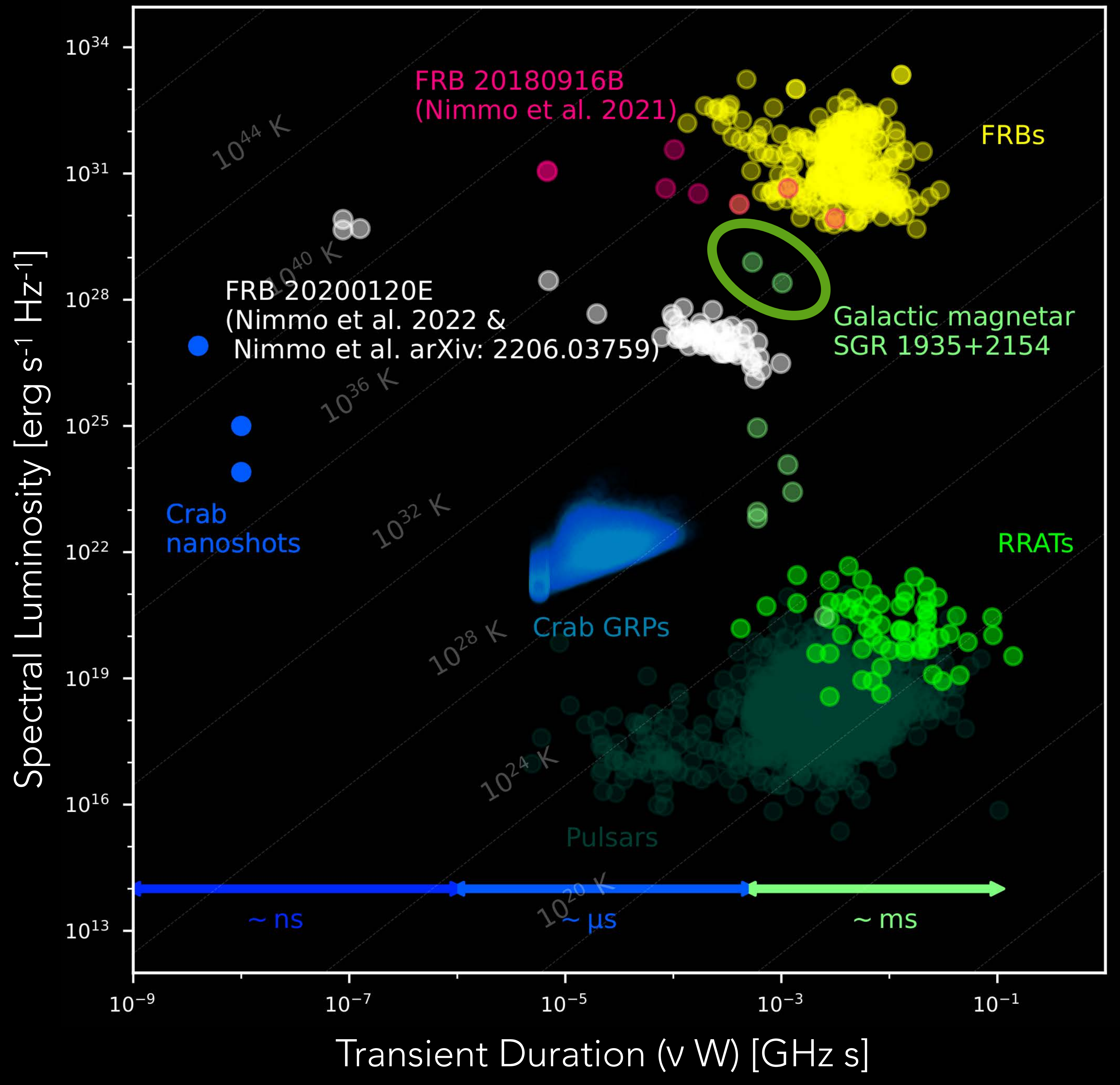
Simultaneous X-rays (Konus-Wind)



SGR RADIO BURST WAS FRB-LIKE

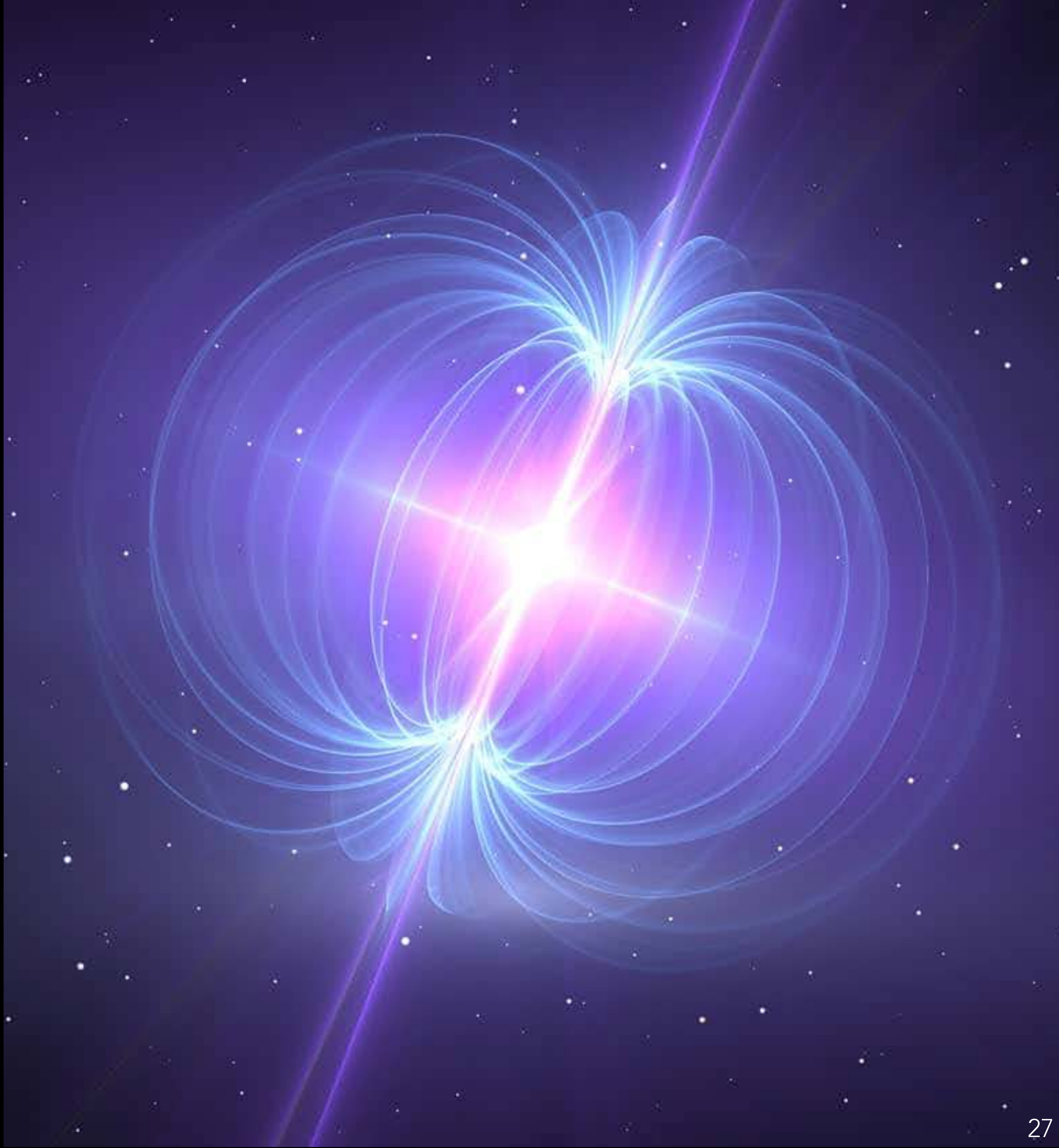
Flux > 100 kJy





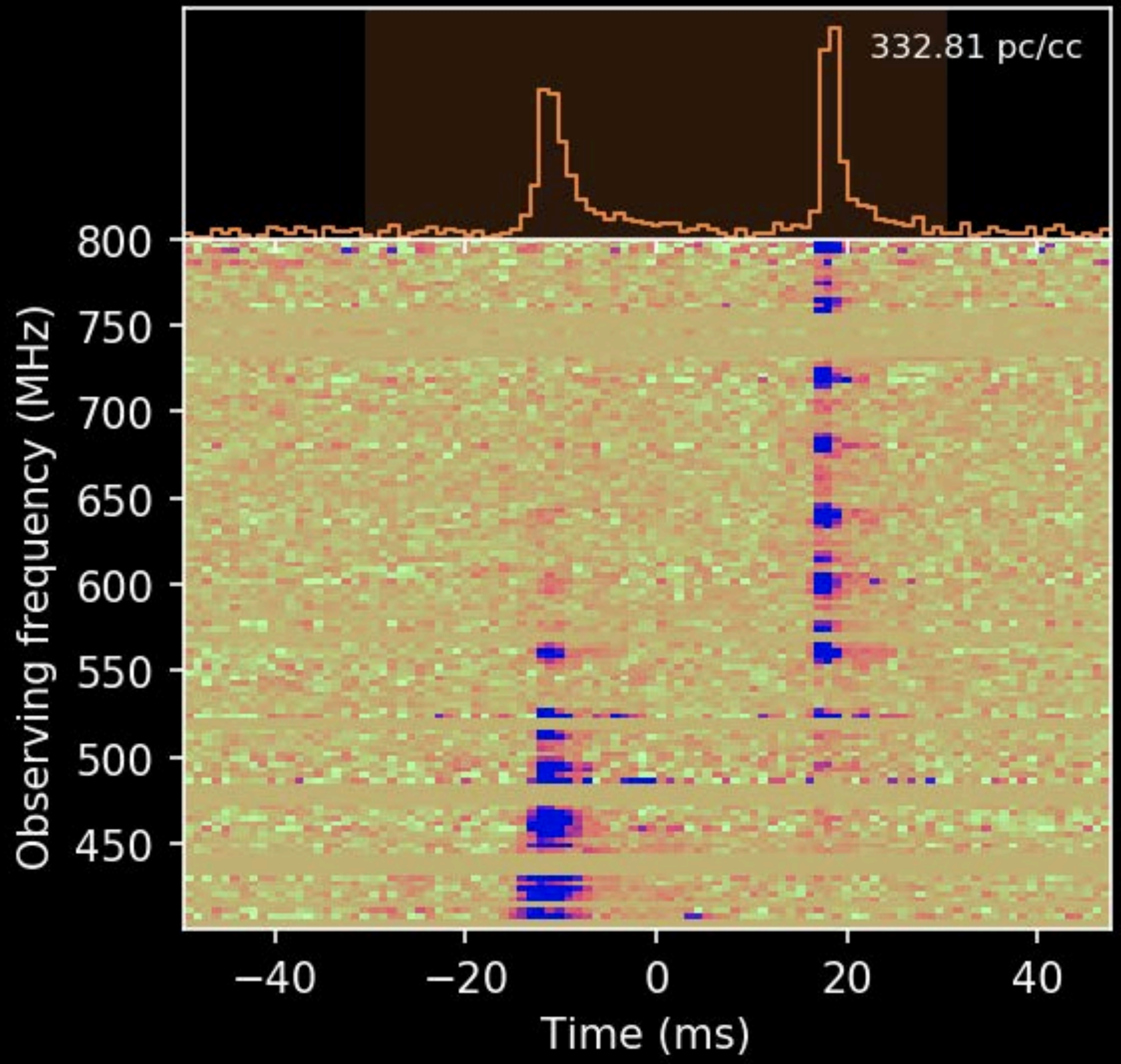
(MOST) CLUES POINT TO MAGNETARS

- 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



ASIDE: FAST OPTICAL BURSTS?

CHIME/FRB



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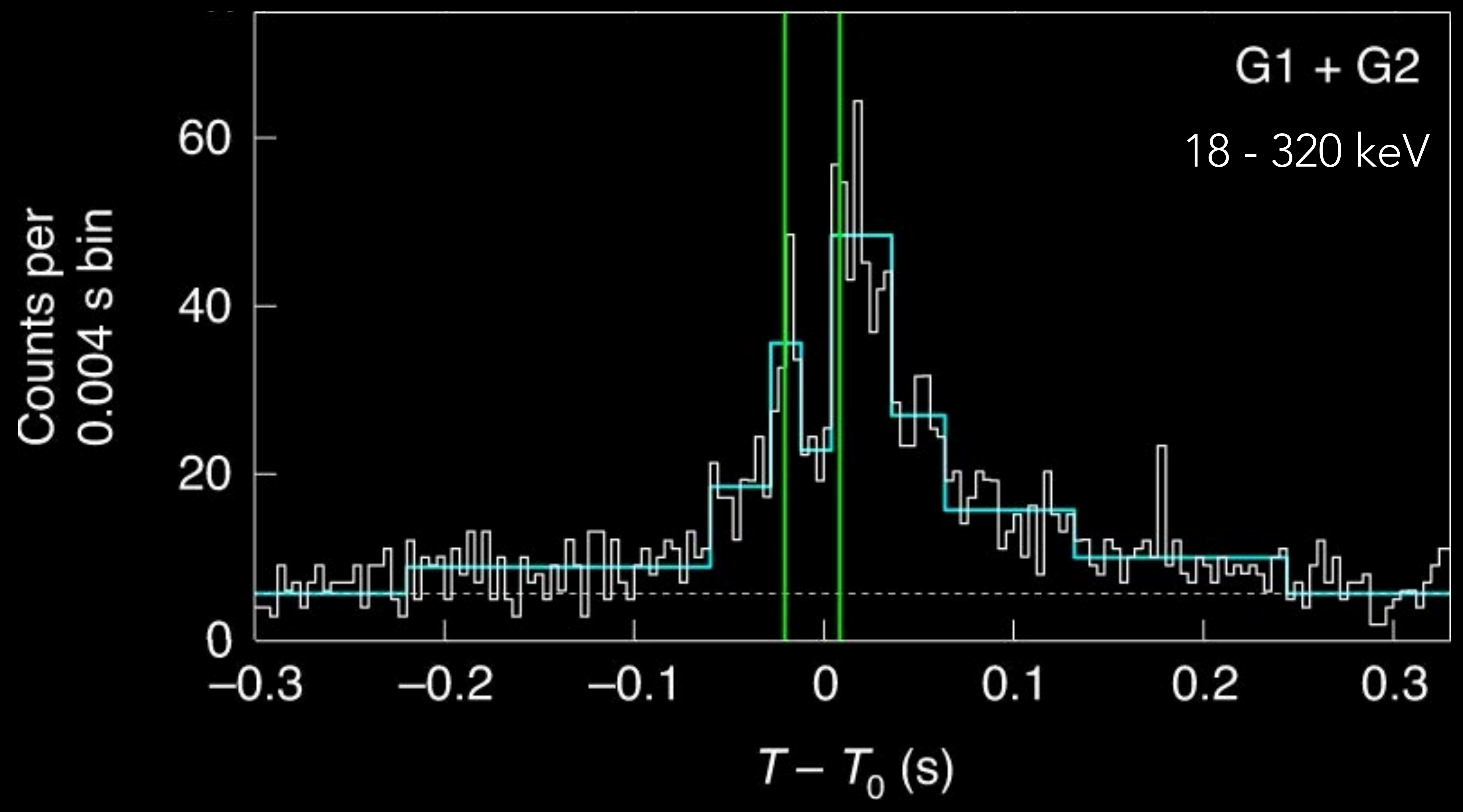
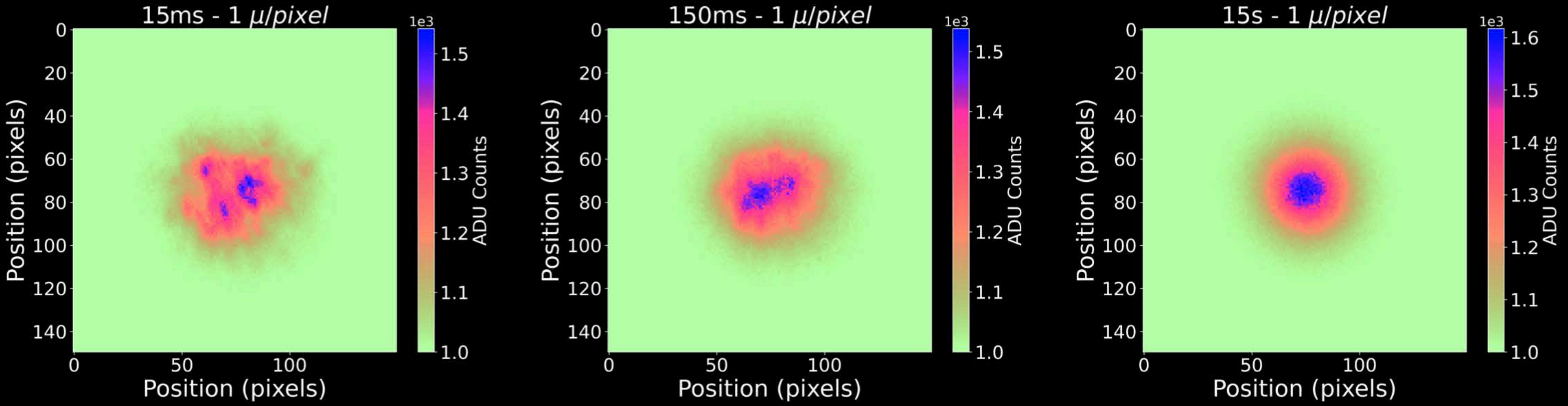


RUBIN THE LEADING BLIND FOB SURVEY

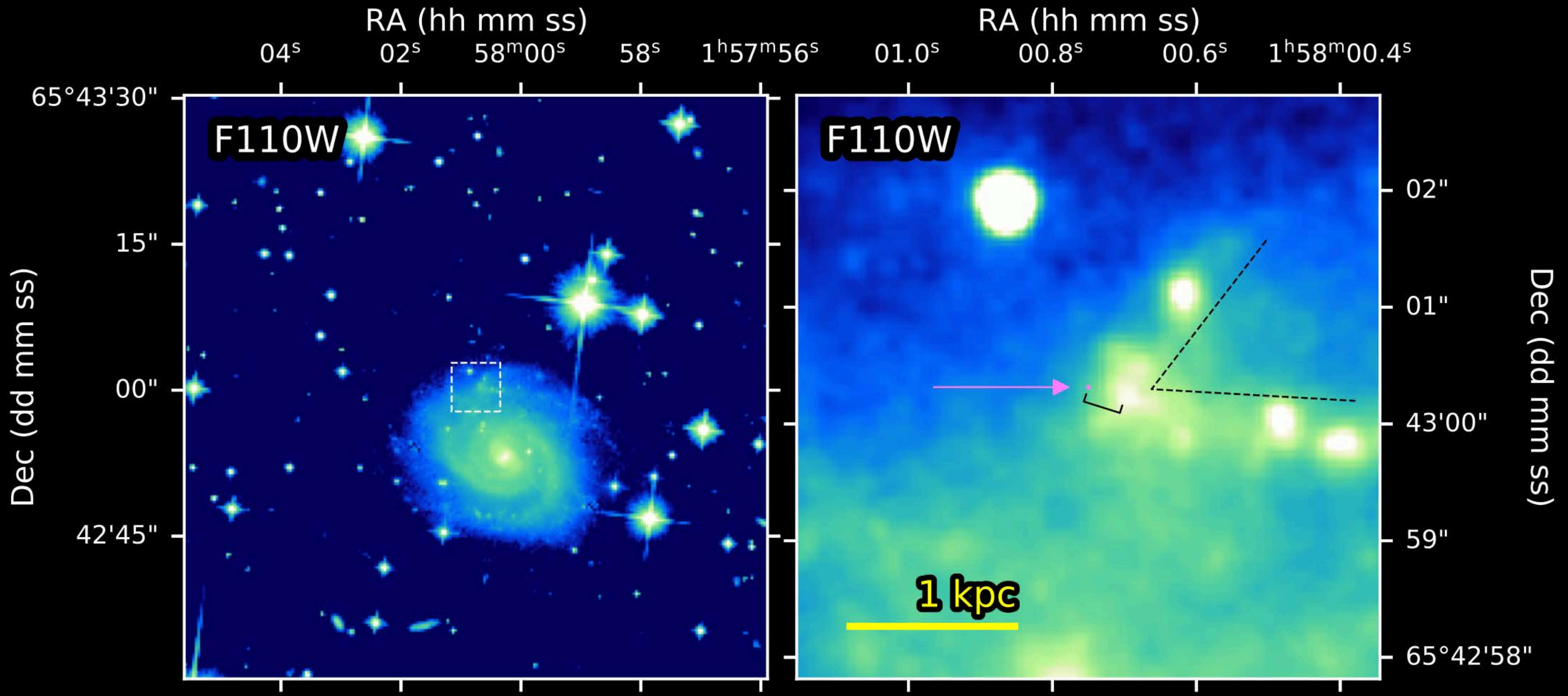
- Rubin's 15s + 15s sequential exposures opens the "fast" discovery space
- Still pay 15s / 1ms in extra background, but Rubin wins by etendue

Guillem Megias Homar, Meyers, Kahn, 2023



SOURCE ENVIRONMENTS OF REPEATERS

FRB 20180916 (R3)



z = 0.034 spiral galaxy

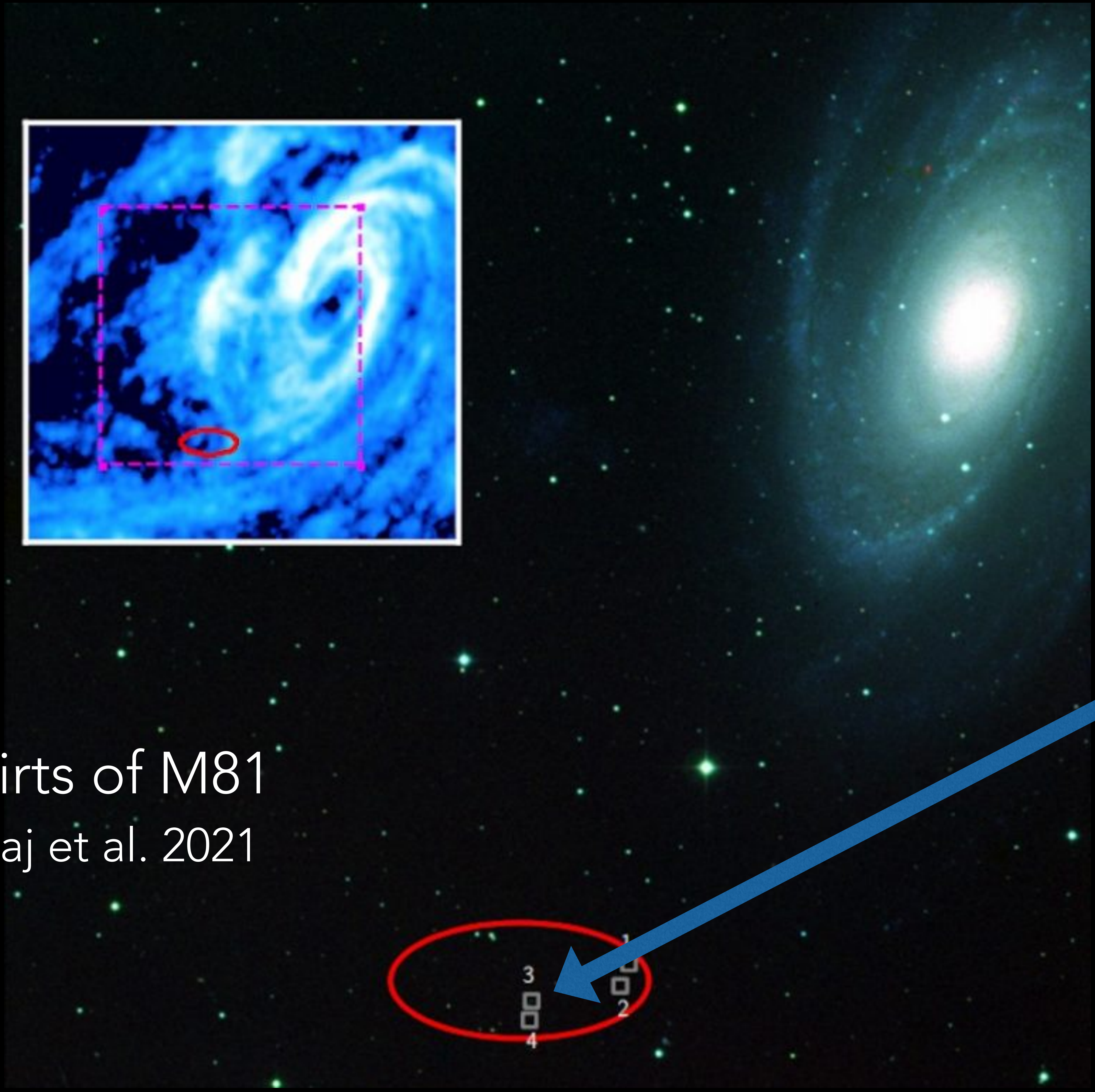
Marcote et al. 2020, Nature

60 pc from a star forming region

Tendulkar et al. 2021

SOURCE ENVIRONMENTS OF REPEATERS

FRB 20200120E



Outskirts of M81

Bhardwaj et al. 2021

An M81 halo globular cluster!

Kristin et al. 2022, Nature

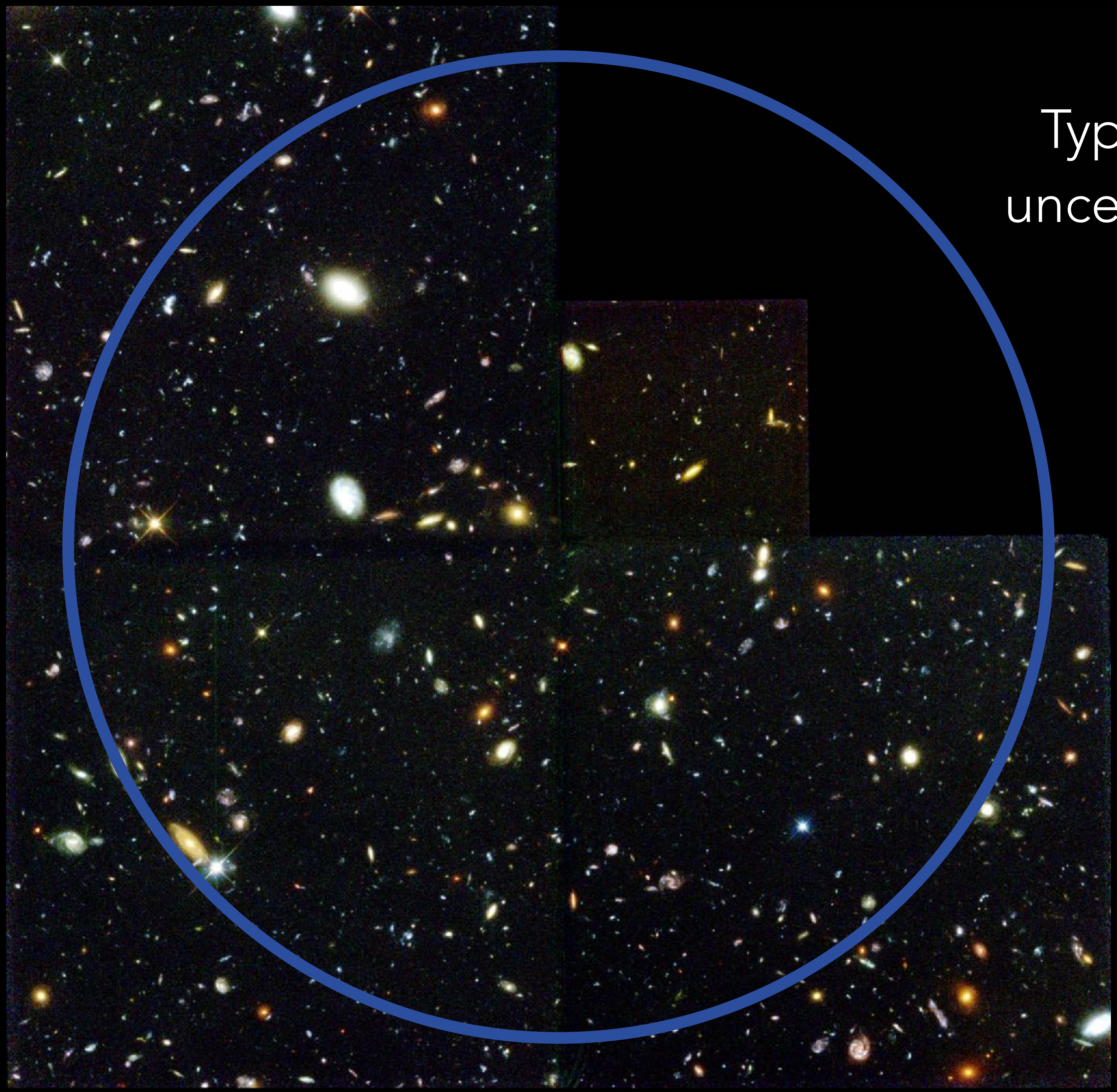
Evidence from source localizations/environments mixed on magnetar hypothesis

But only a few data points…

NEXT INSTRUMENT

CHIME/FRB VLBI OUTRIGGERS

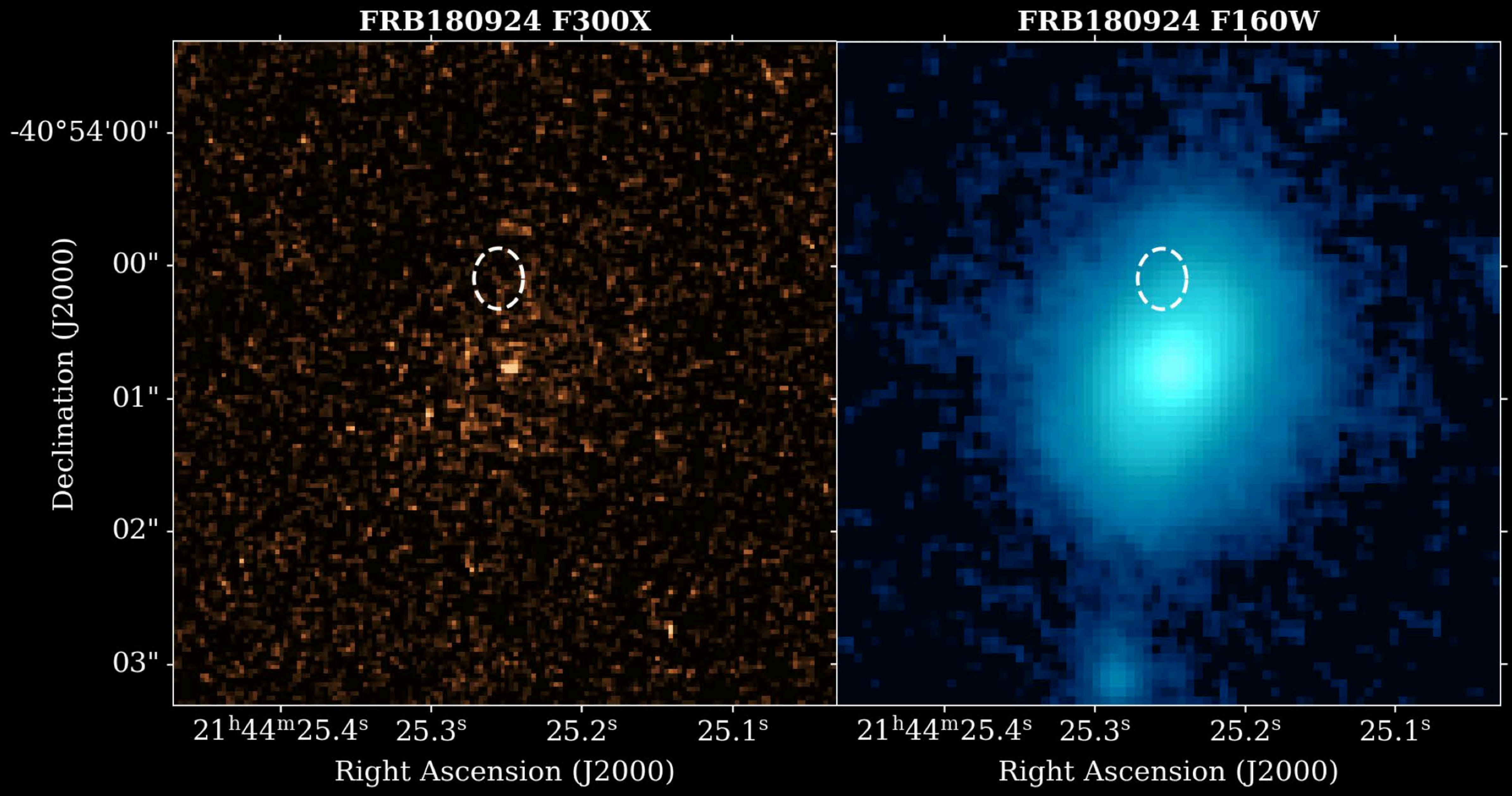
CHIME'S WEAKNESS: RESOLUTION



Typical localization uncertainty ~1 arcmin

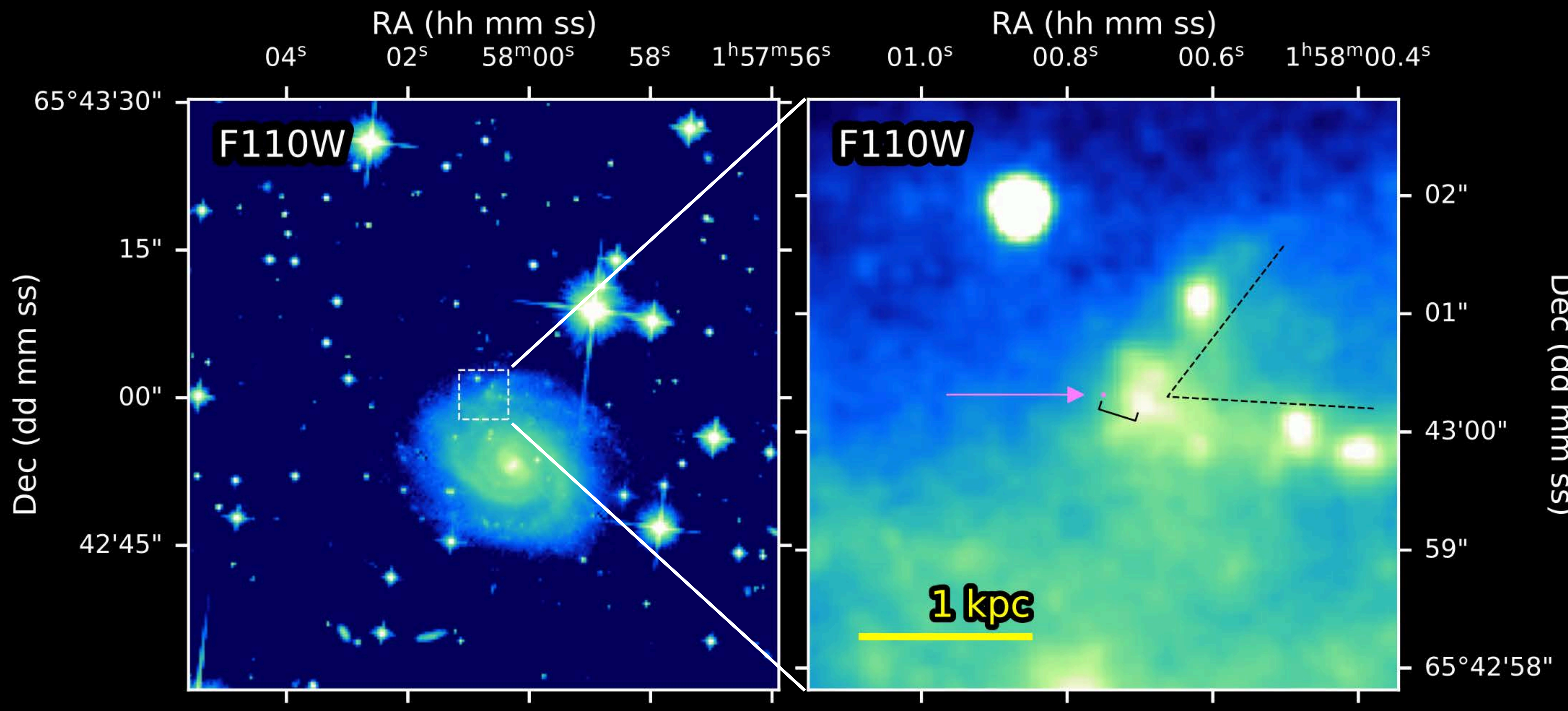
TWO TYPES OF LOCALIZATION

Traditional interferometry
~1 arcsecond



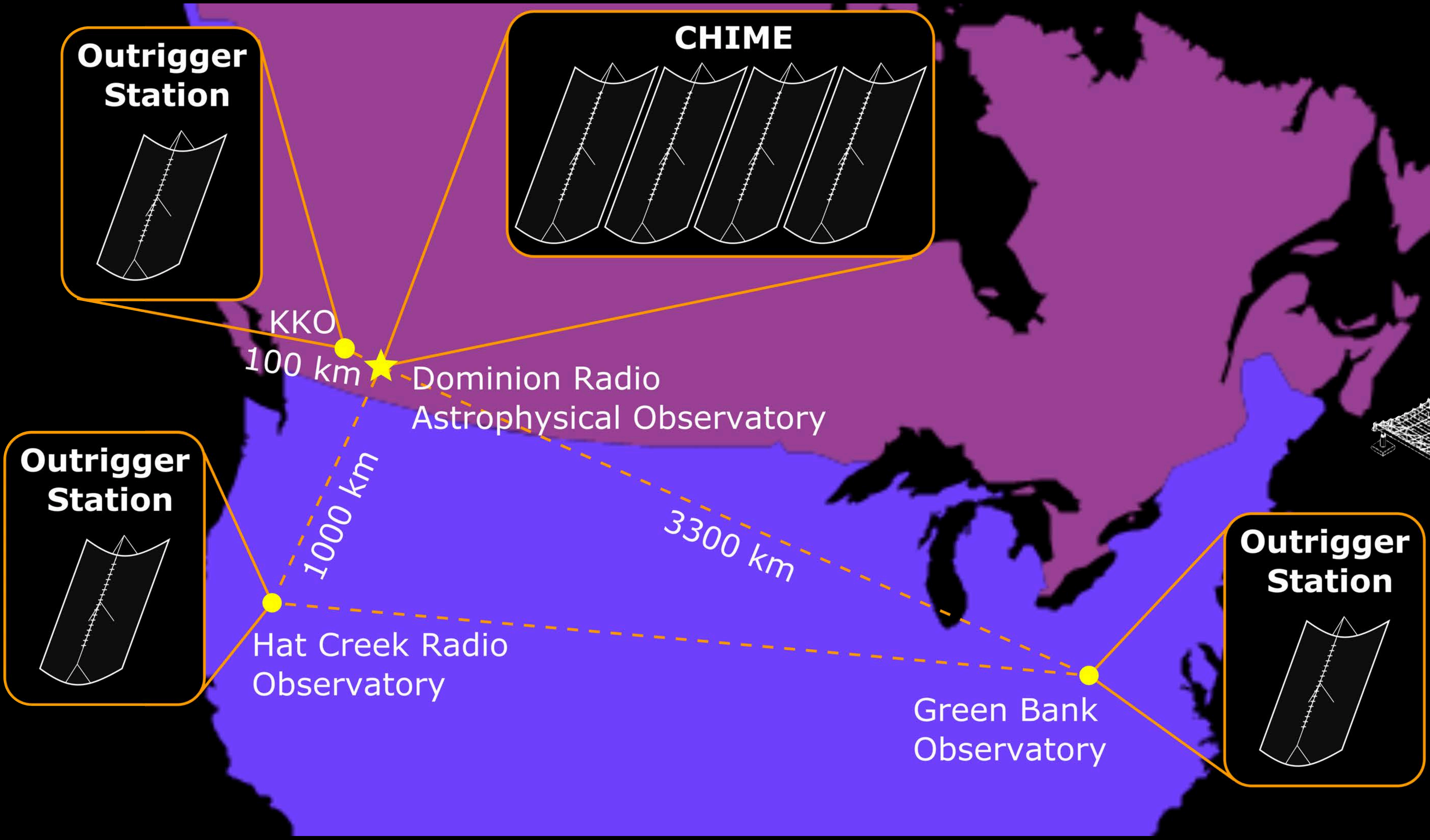
Mannings et al. 2021

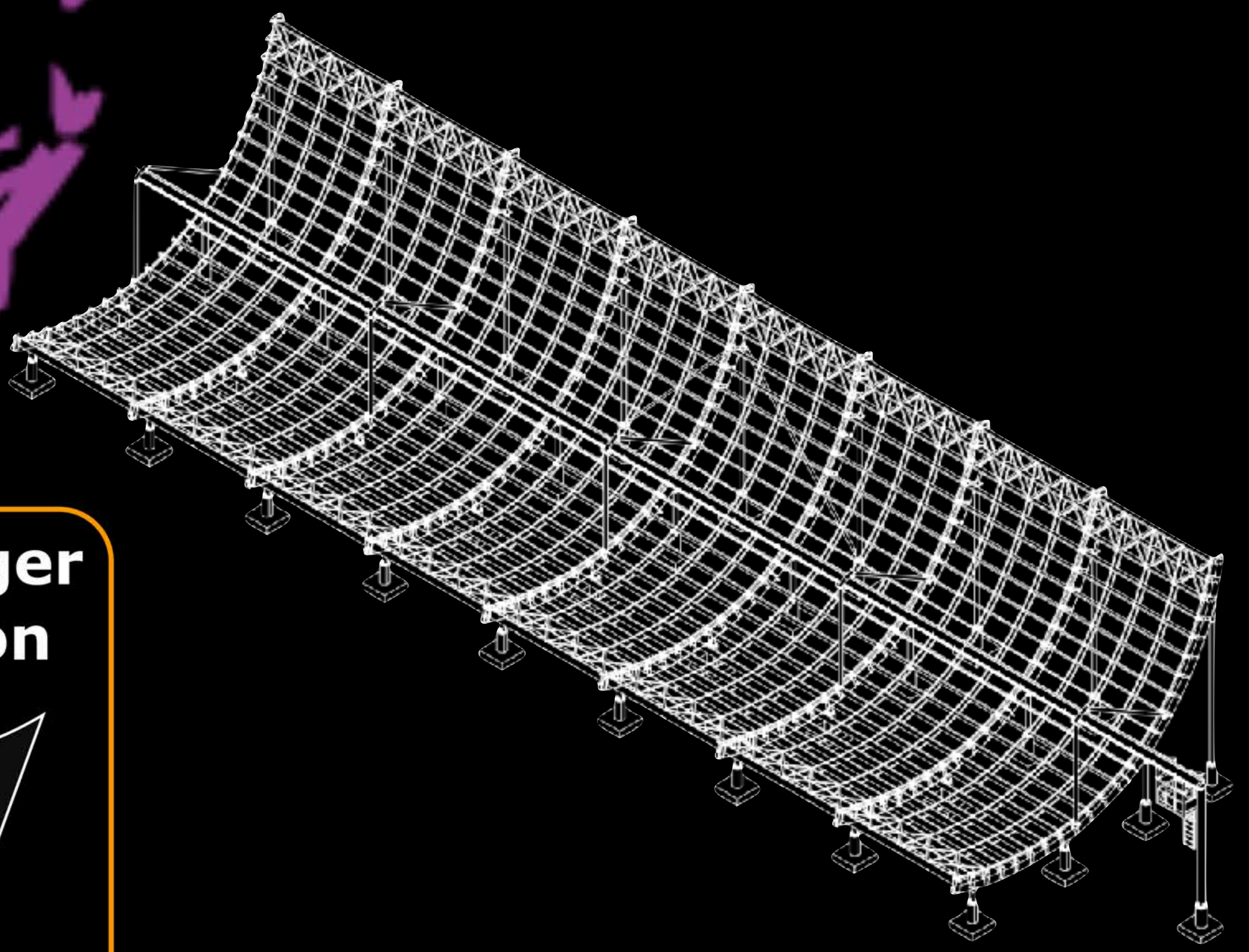
VLBI
~milliarcsecond



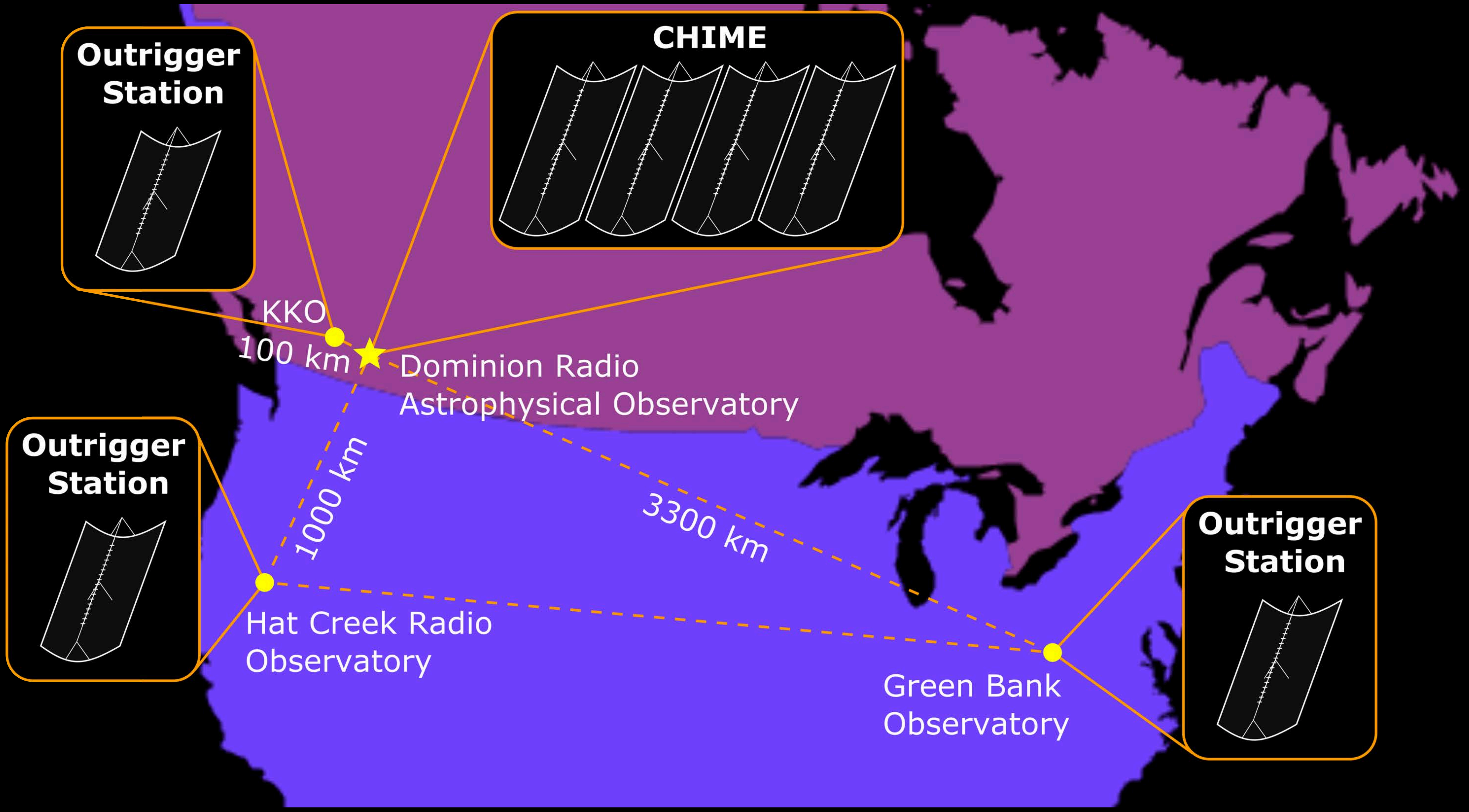
Tendulkar et al. 2021

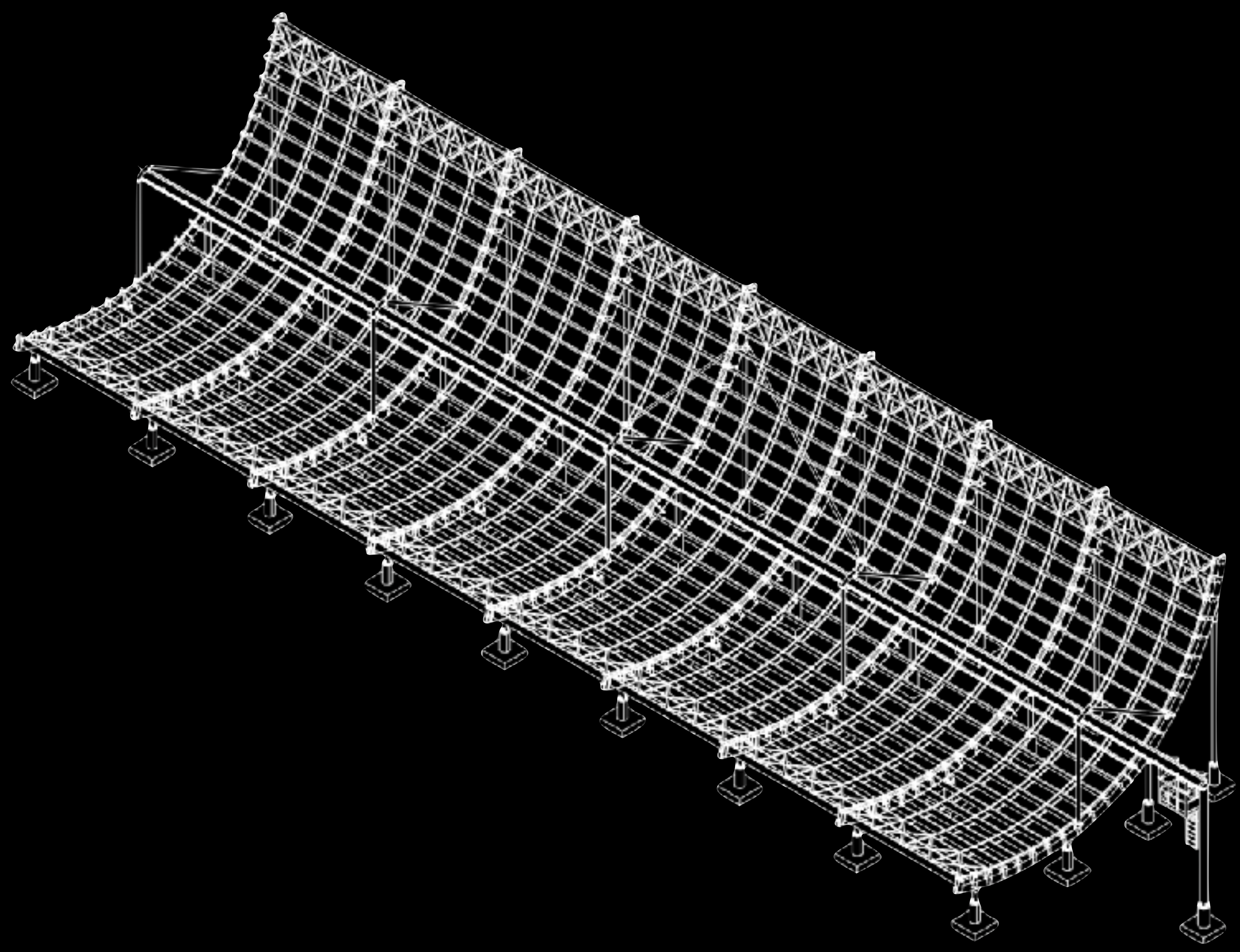
CHIME/FRB VLBI OUTRIGGERS





CHIME/FRB VLBI OUTRIGGERS





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

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

HAPPENING NOW IN BC

k’niʔatn k’l‿stk’masqt Outrigger (KKO)
Name kindly offered by the Upper Similkameen Indian Band
Listening device for outer space

Photo: NRC

HAPPENING NOW IN GREEN BANK

Photo: Kevin Bandura

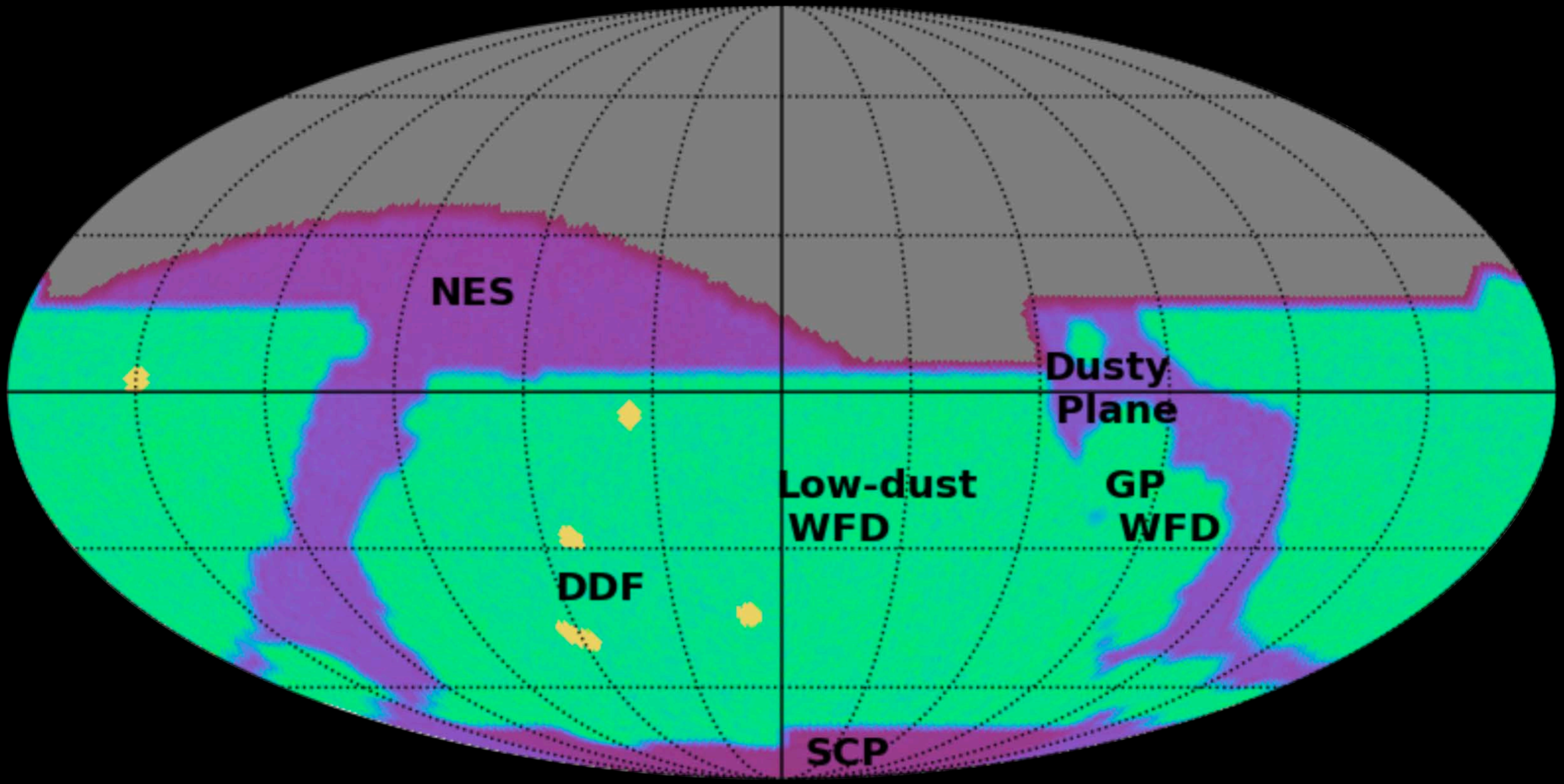
STARTING IN A FEW MONTHS:

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

Rubin will be critical to understanding source environments

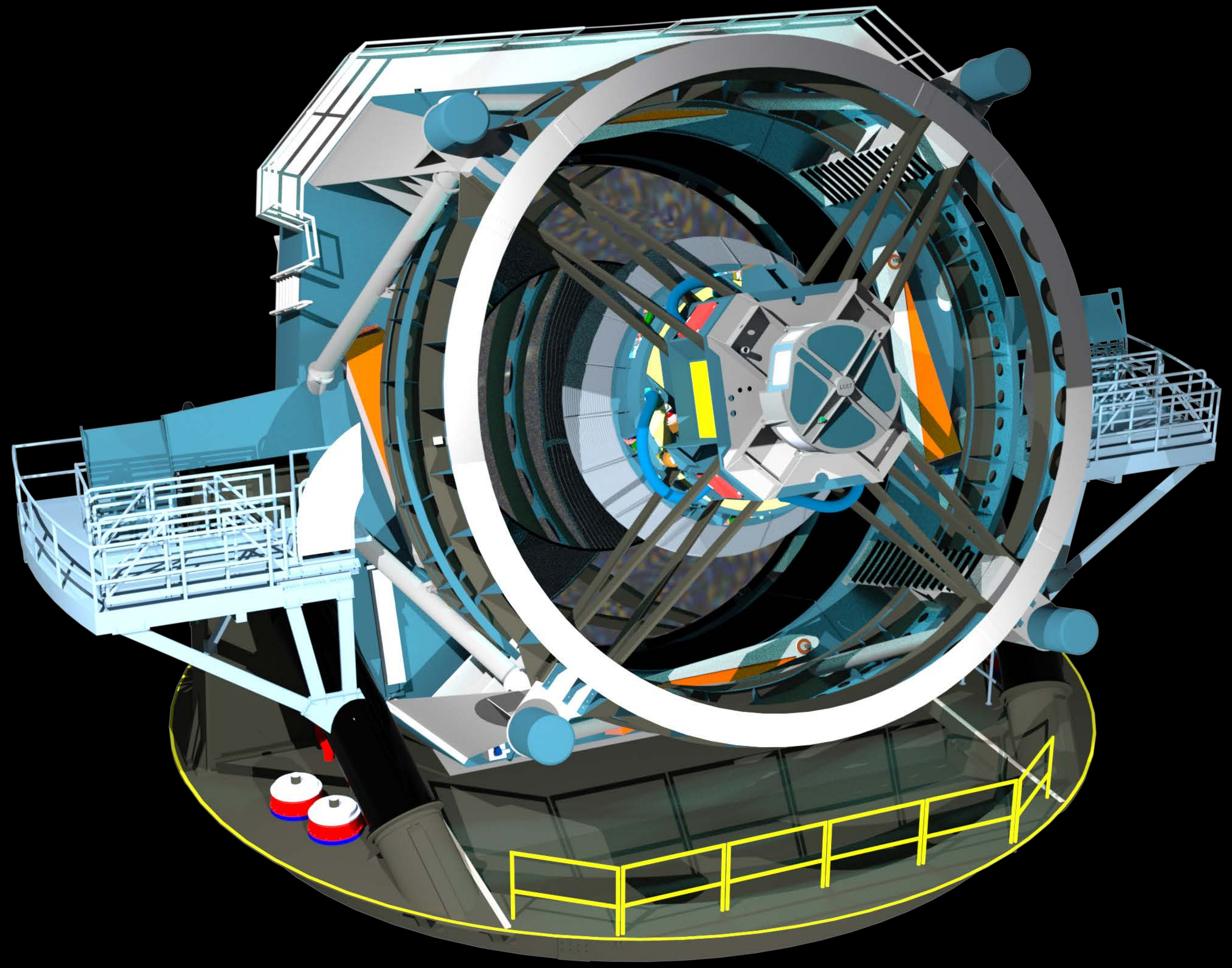
RUBIN IMAGING OF FRB HOSTS/ENVIRONMENTS

- 50 mas localizations only useful with deep colorful imaging with good seeing
- LSST and CHIME have ~4000 sq. deg. of sky overlap: hundreds of FRBs



FRBS IN THE LSST FOOTPRINT WILL HAVE:

- Deepest imaging for identifying faint (dwarf) hosts
- Most reliable host photo-z's
- Deepest images with excellent seeing for associating sources with substructures
- Six filter photometry for measuring source environment properties



WITH CHIME, CHIME/FRB OUTRIGGERS, AND RUBIN

We will know everything there is to know about FRB source environments

HOW TO USE FRBS AS

COSMOLOGICAL PROBES

DISPERSION FOR LARGE-SCALE STRUCTURE

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

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

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

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

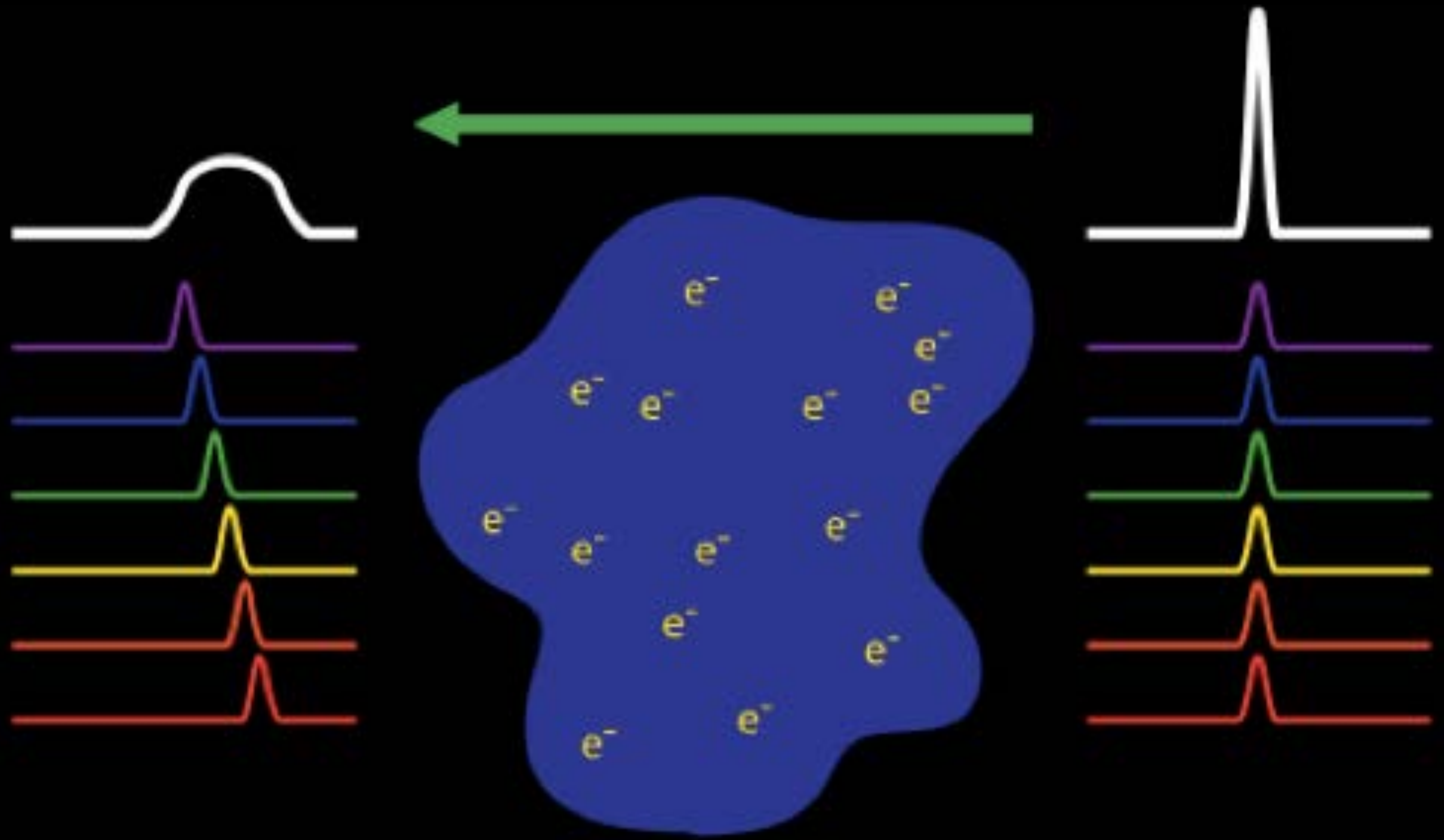


image: Erik Madsen

Illustris 1 Mpc log gas column density TNG

WHY ARE BARYONS SO POORLY CONSTRAINED

- Supernova and AGN feedback processes in galaxy formation are complex
- Single AGN can throw a baryon ~ megaparsecs
- 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

A CRUCIAL INPUT TO RUBIN WEAK LENSING

- The IGM contaminates weak gravitational lensing (Nicola et al. 2022)
- IGM is 14% of the matter, power spectrum is order-of-magnitude uncertain on Mpc scales
- Lensing entangles spatial scales through line-of-sight integral
- Unless we understand feedback, can’t do percent-level measurements of dark matter/dark energy
- With external (FRB) measurement of baryon-CDM cross-power, can interpret lensing on much smaller scales

CHIME AND RUBIN WILL WORK TOGETHER FOR THIS MEASUREMENT

- Most complete sample of photo-z's for both FRB hosts, foreground galaxies to cross-correlate
- Speculatively - could cross-correlate FRB DM with lensing mass, measure matter-baryon cross-power

OTHER REASONS COSMOLOGY NEEDS THIS

- Baryons interact gravitationally with dark matter making it hard to tease out dark matter physics from structure formation

- Measuring electrons breaks a key degeneracy in the CMB kinematic Sunyaev–Zeldovich (KSZ) effect (Madhavacheril et al. 2019)

CONCLUSIONS

- Fast radio bursts are a mysterious high-energy phenomena; from CHIME, magnetar progenitor favored but evidence mixed
- VLBI Outriggers and Rubin imaging/photometry will soon provide localizations, redshifts, and source environments
- FRBs and Rubin data will (finally) measure the large-scale baryon distribution, solving a key uncertainty in large-scale structure formation, decontaminating lensing from baryons