New Opportunities: Line Intensity Mapping

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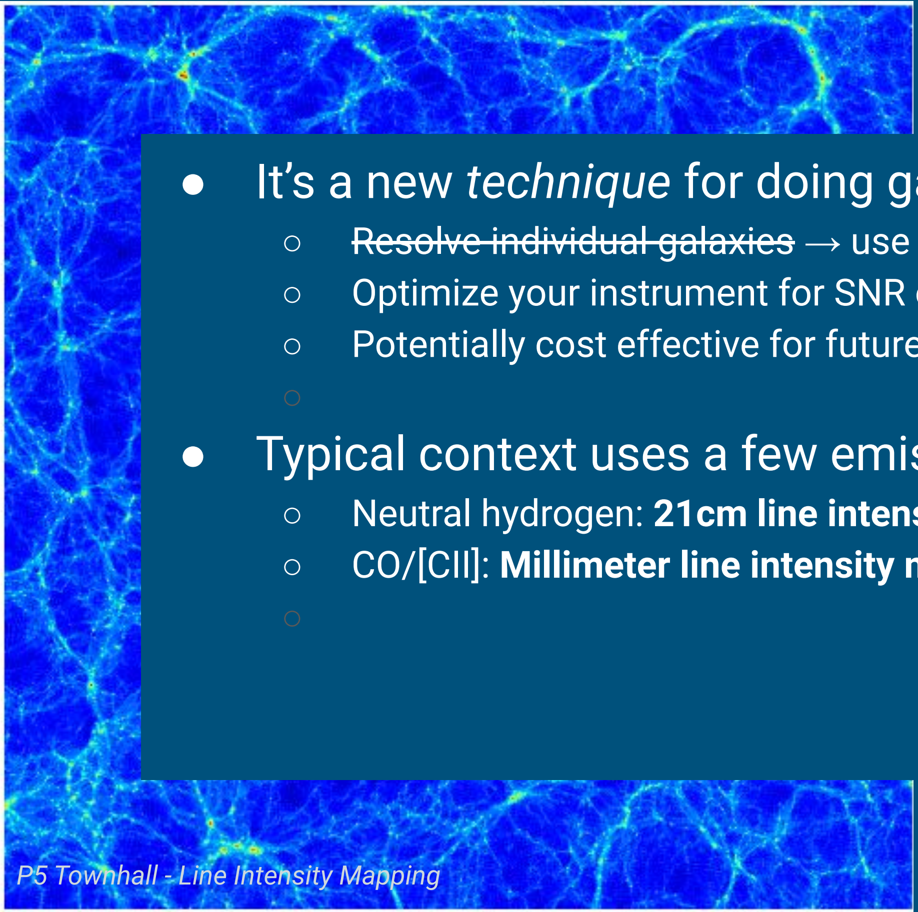
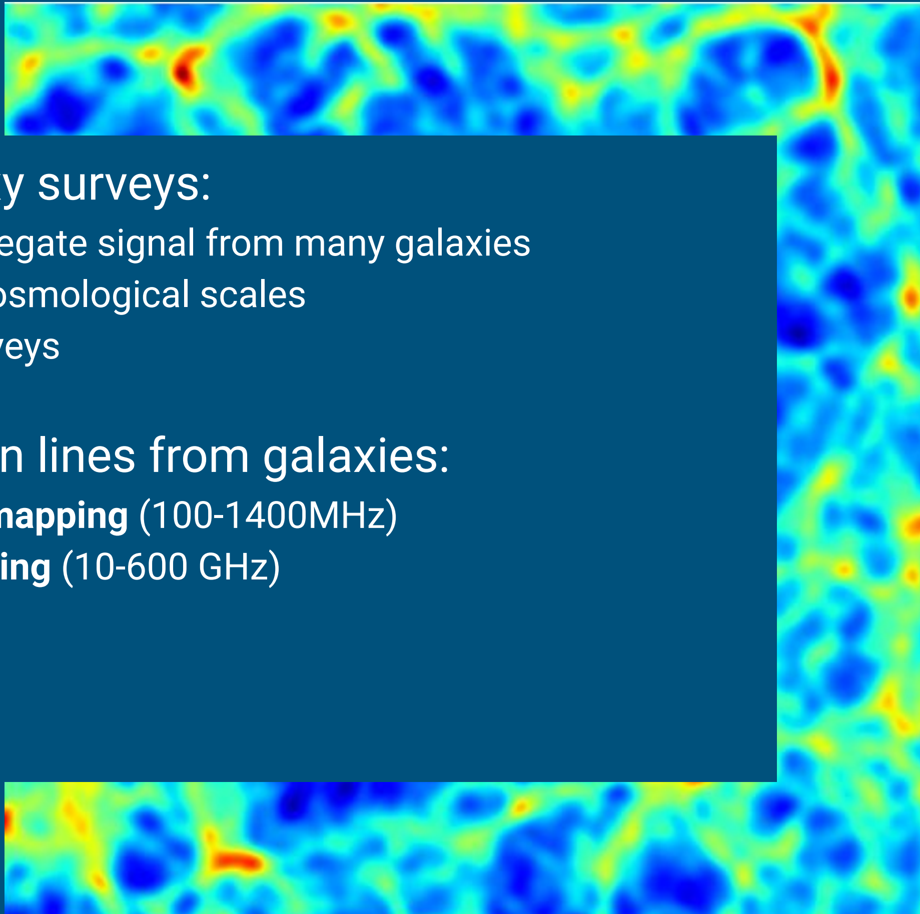
With assist from Anze Slosar, Kirit Karkare, Adrian Liu, Sourabh Paul
Yale University
P5 Townhall - Feb 23, 2023

What is Line Intensity Mapping?





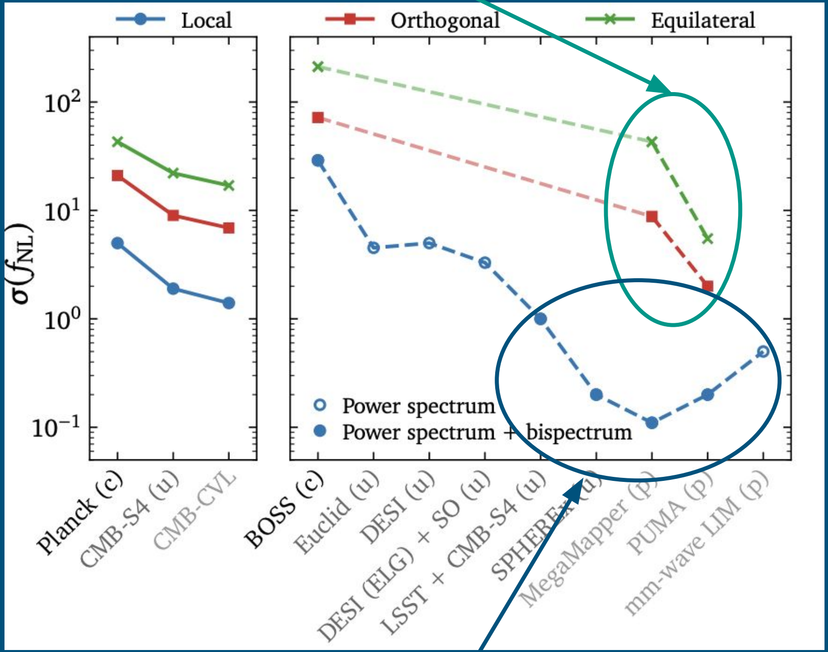
- It's a new *technique* for doing galaxy surveys:
  - ~~Resolve individual galaxies~~ → use aggregate signal from many galaxies
  - Optimize your instrument for SNR on cosmological scales
  - Potentially cost effective for future surveys
- Typical context uses a few emission lines from galaxies:
  - Neutral hydrogen: **21cm line intensity mapping** (100-1400MHz)
  - CO/[CII]: **Millimeter line intensity mapping** (10-600 GHz)

Science Targets:

Snowmass #4: Understand Cosmic Acceleration (dark energy + inflation)

- Expansion history
- Inflation: Inflationary theories can be described in terms of a few parameters
  - **Spectroscopic surveys** measure $\mathbf{f_{NL}}$
  - **CMB-S4** measures **r**
  - In combination, explores the range of single-field + multi-field Inflation

Probe self-interactions; detection of equilateral without orthogonal is an indication of the quantum origin of structure



Discover or rule out single/multi-field inflation

More statistics

How do we improve our statistics?

Higher redshift (further in the past)

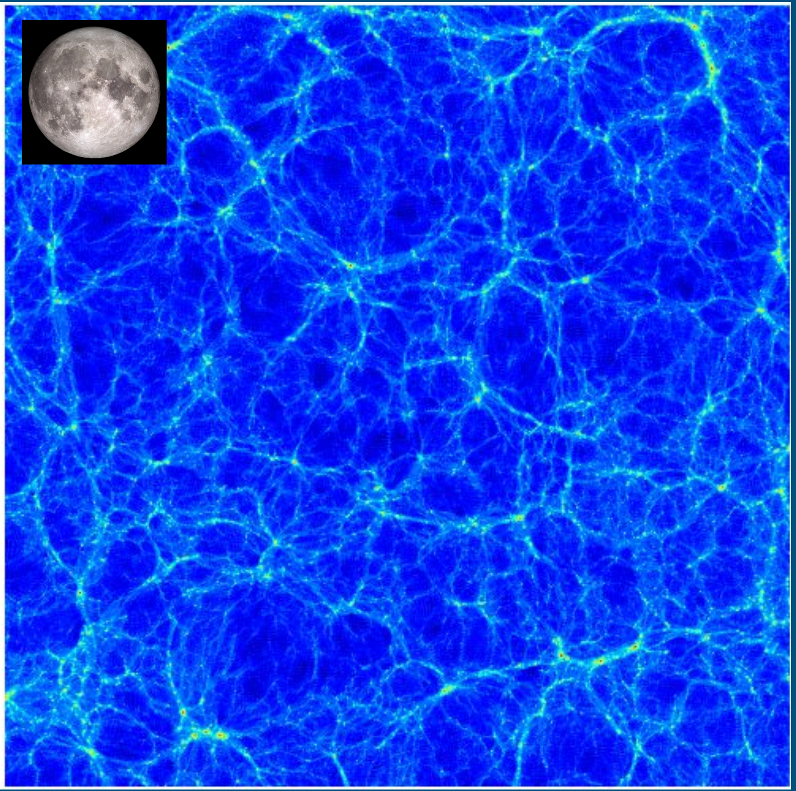
- Lots of **volume** (this is just expansion)
- More **linear** (gravity hasn't complicated things)

Put SNR where its most useful

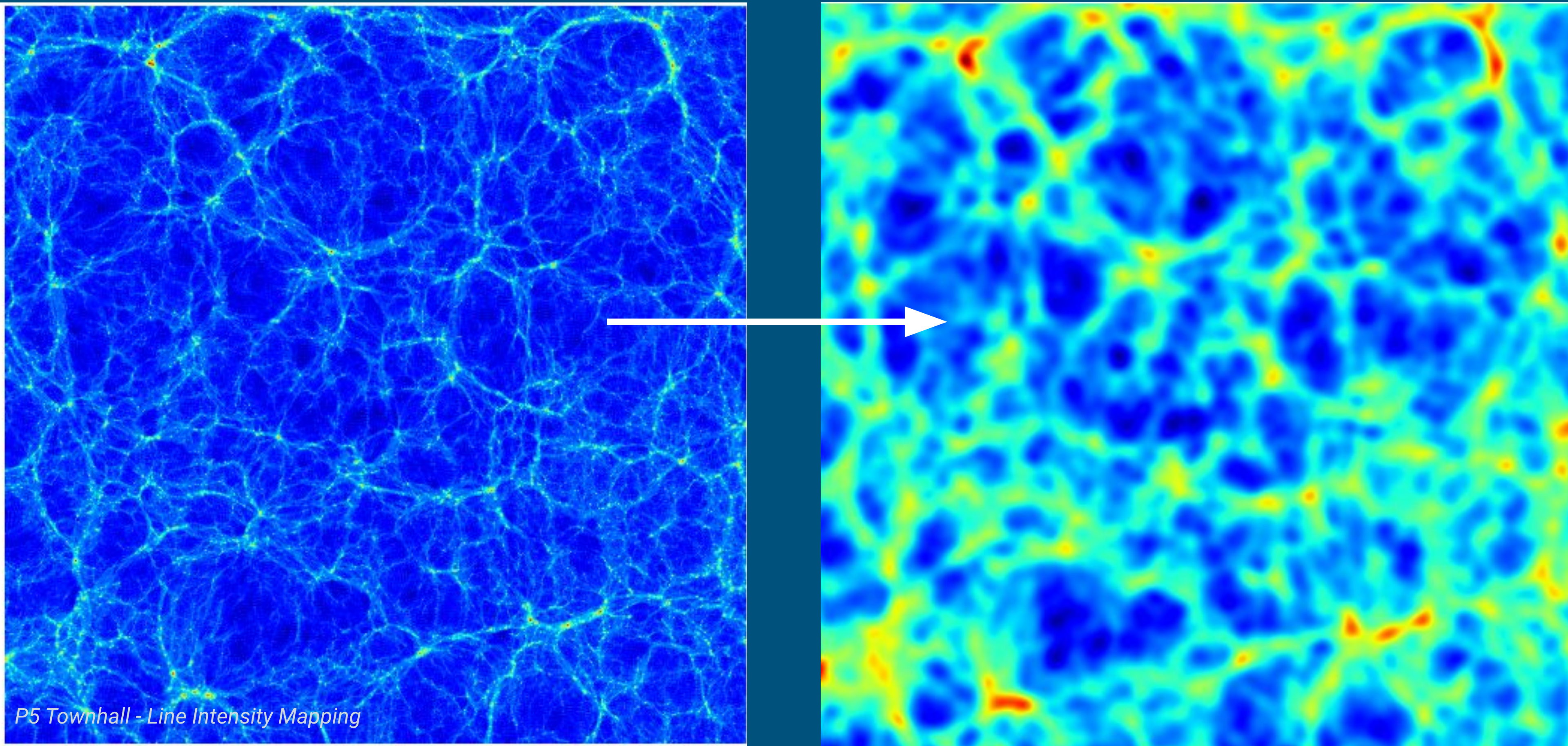
- Most cosmological information comes from scales that are ~the size of the moon

Compared to optical spectroscopic surveys:

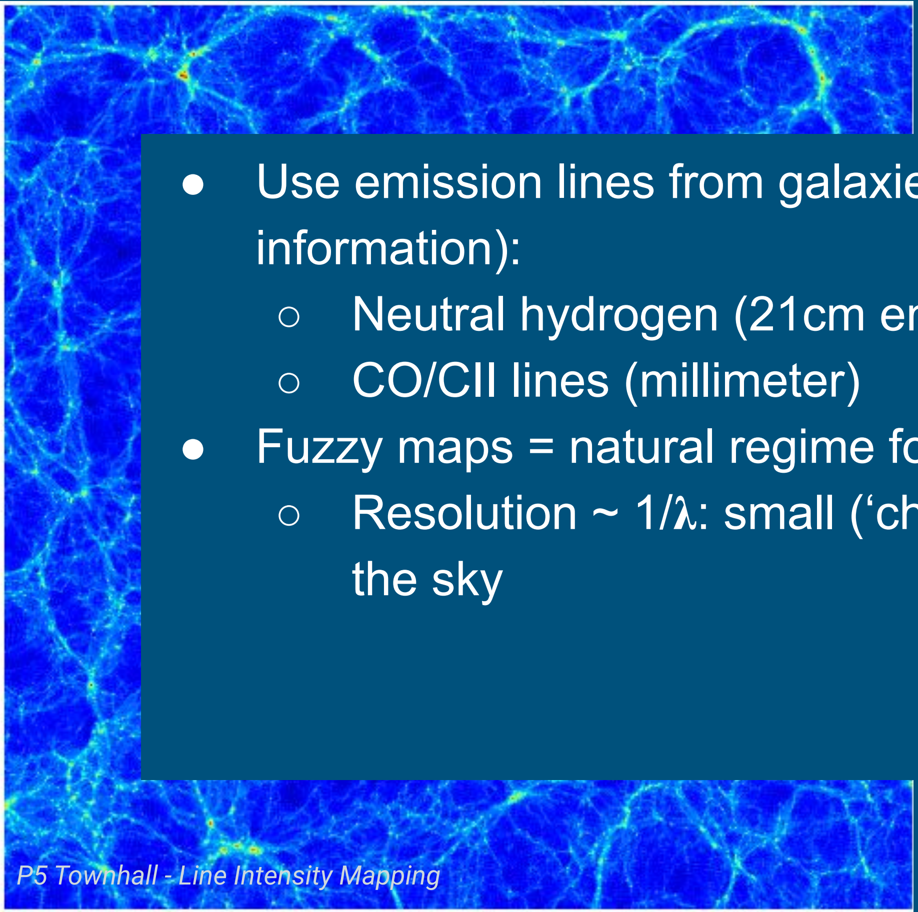
- *Cons:* lose some modes, cannot slice & dice the galaxy sample
- *Pros:* can potentially sample individual modes with much higher fidelity (shot noise largely negligible), see aggregate emission

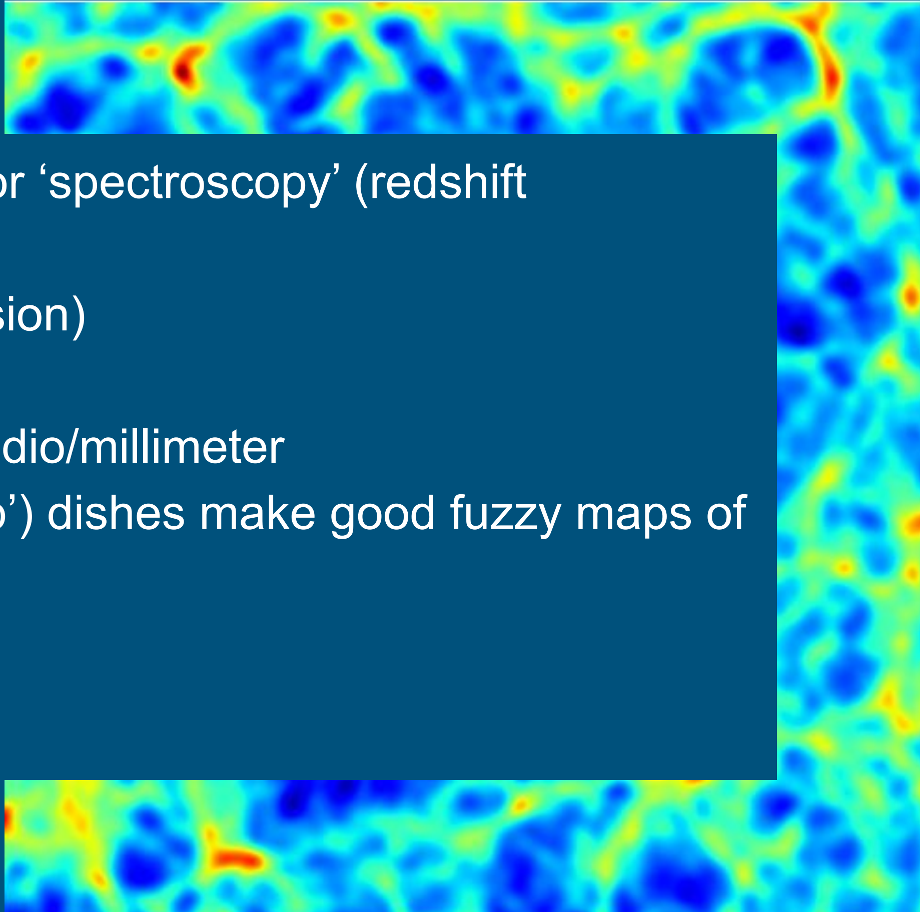


We want **fuzzy**, **‘spectroscopic’** maps of the sky out to **high redshift**



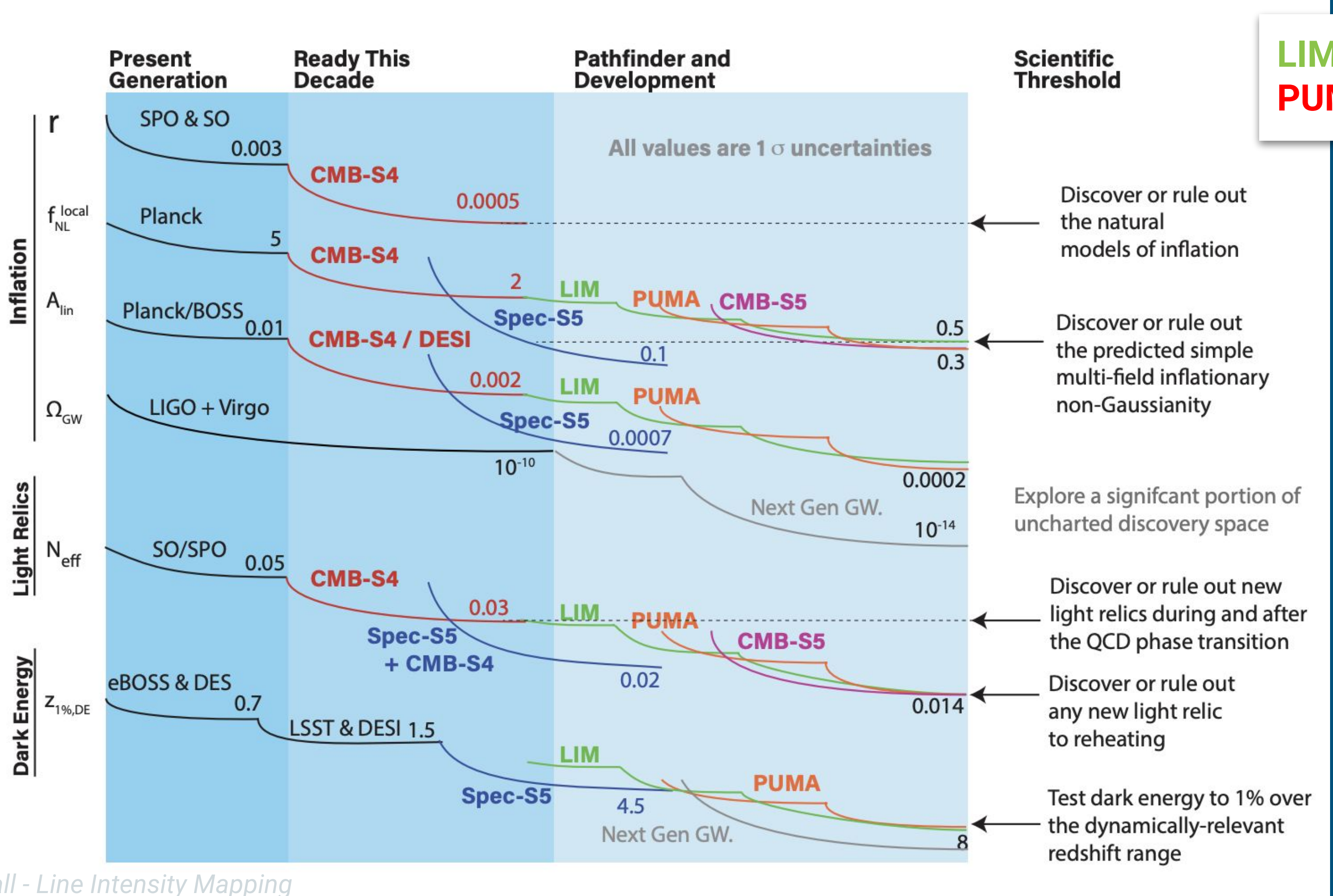
Fuzzy ‘spectroscopic’ maps of the sky = radio wheelhouse





- Use emission lines from galaxies for ‘spectroscopy’ (redshift information):
  - Neutral hydrogen (21cm emission)
  - CO/CII lines (millimeter)
- Fuzzy maps = natural regime for radio/millimeter
  - Resolution ~ $1/\lambda$: small (‘cheap’) dishes make good fuzzy maps of the sky

Projections: Cosmic Frontier summary



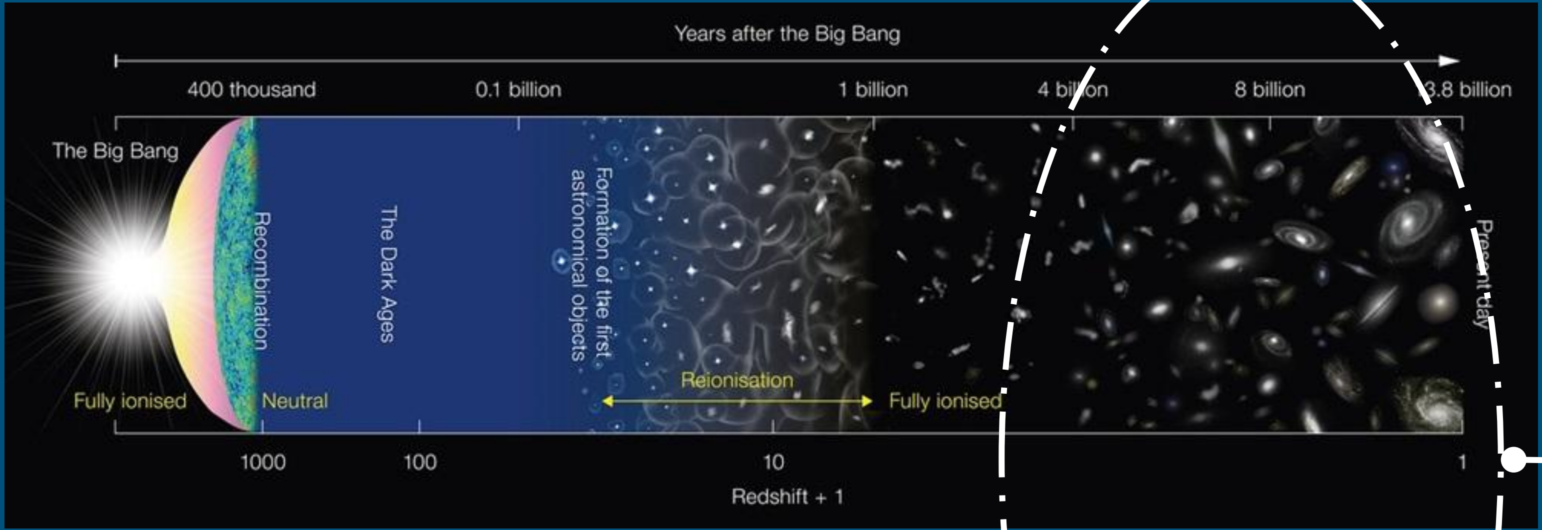
LIM=millimeter
PUMA=21cm

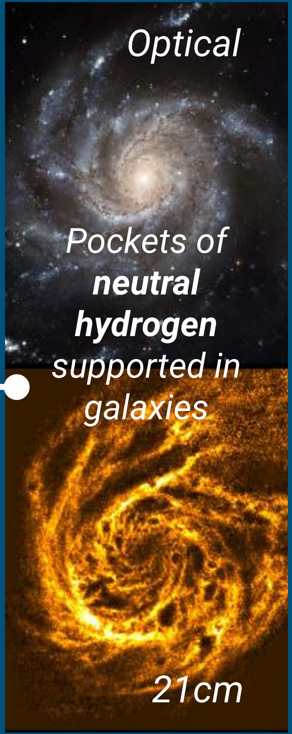
table from Snowmass CF4 report

Technical challenges are articulated in HEP Instrumentation Basic Research Needs Report

21cm LIM

21cm Cosmology





Dark Ages
20 < z < 150

λ ~ 4-30 m
ν ~ 10-70 MHz

Pristine primordial density field

Epoch of Reionization
6 < z < 20

λ ~ 1-4 m
ν ~ 70-200 MHz

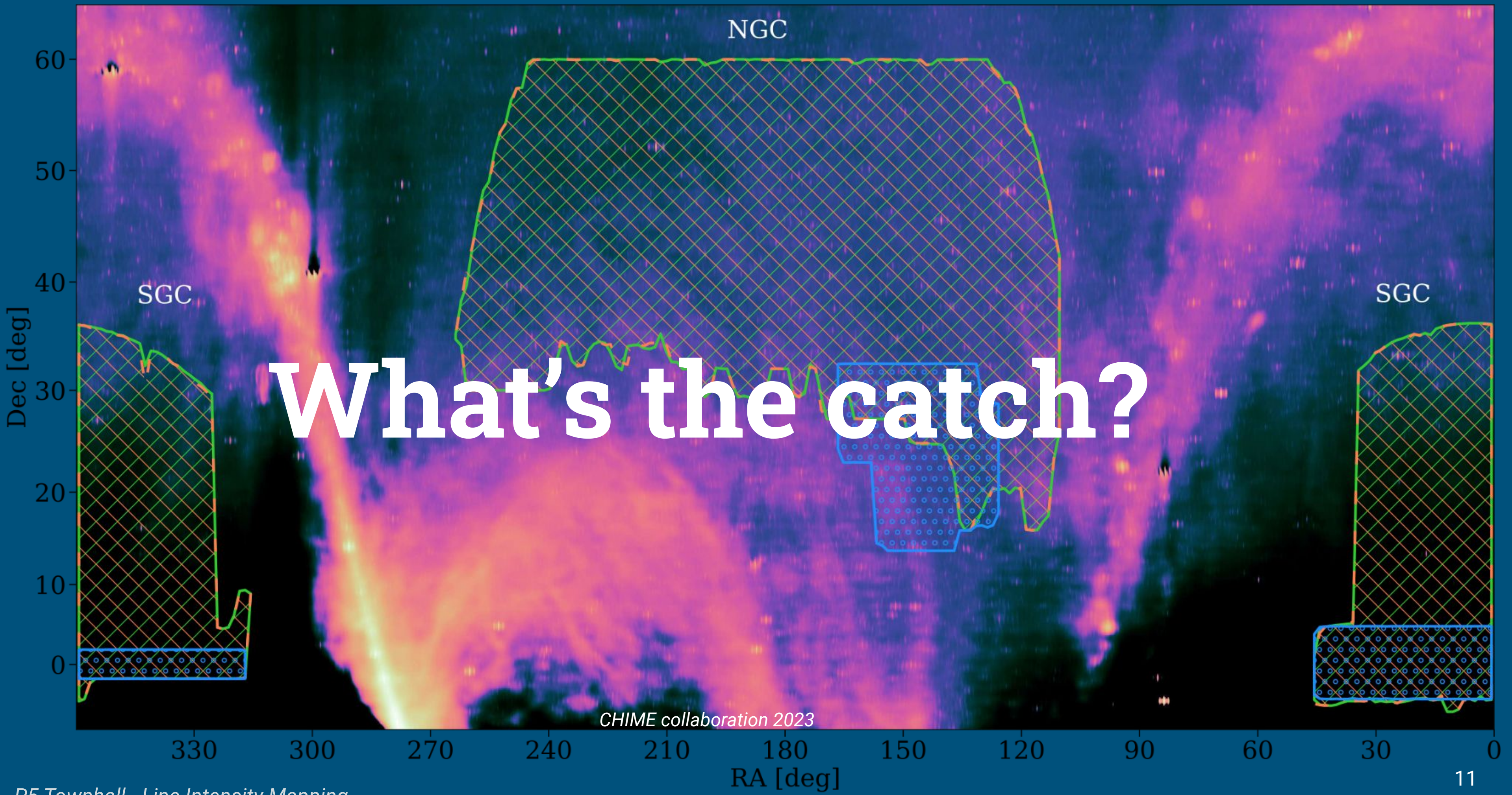
Astrophysics: First stars/galaxies (non-DOE science)

Low redshift
z < 6

λ ~ 21cm - 1m
ν ~ 200-1420 MHz

Radio galaxy survey possible here

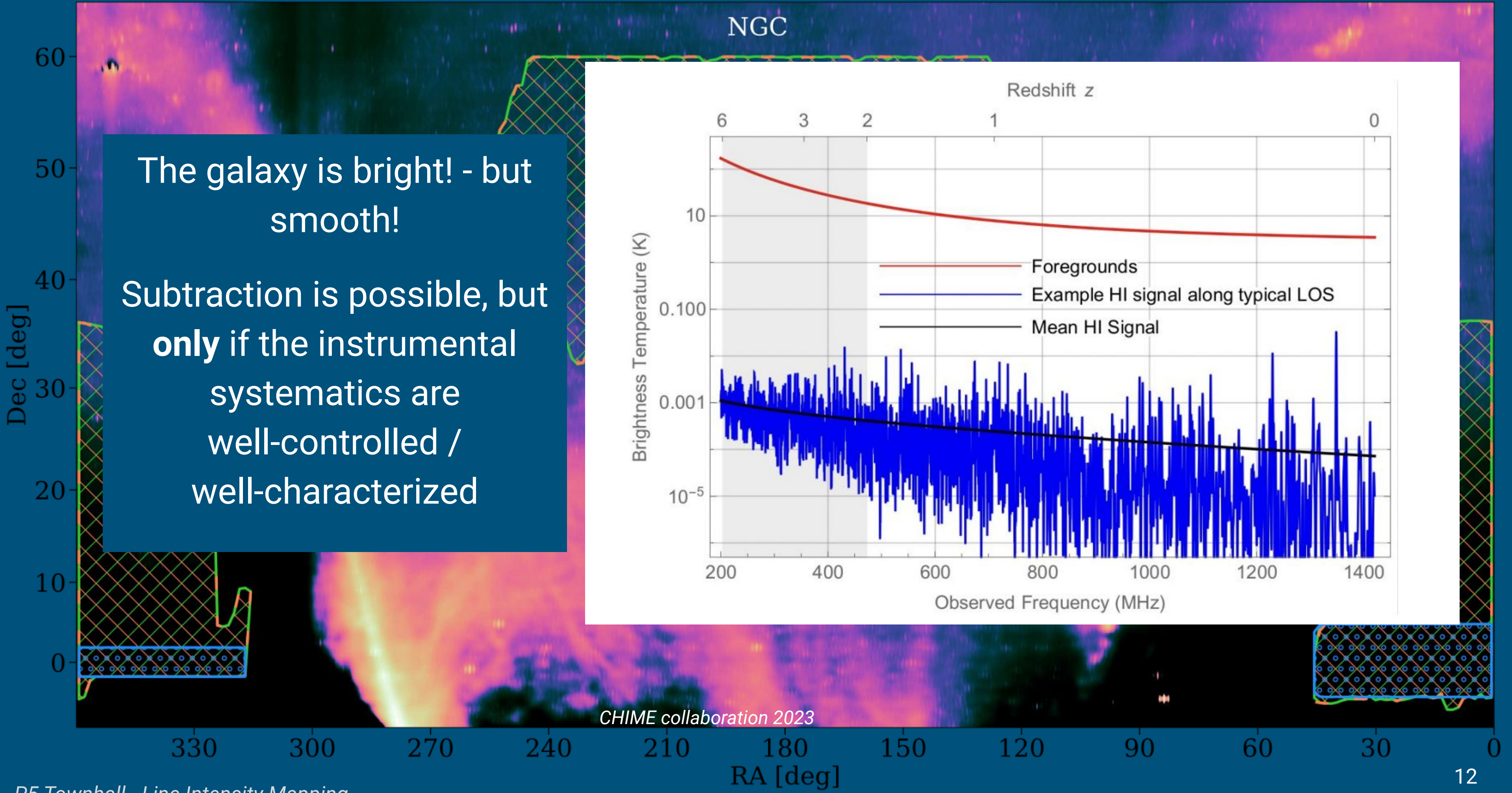
What's the catch?



CHIME collaboration 2023

The galaxy is bright! - but smooth!

Subtraction is possible, but **only** if the instrumental systematics are well-controlled / well-characterized

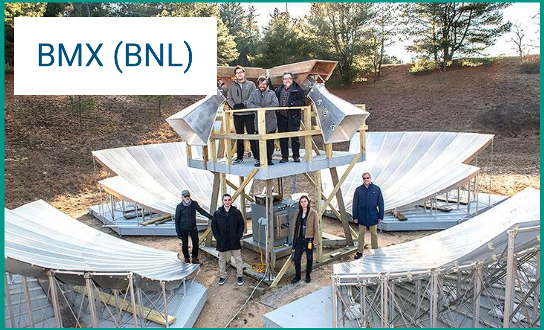


CHIME collaboration 2023

21cm current landscape

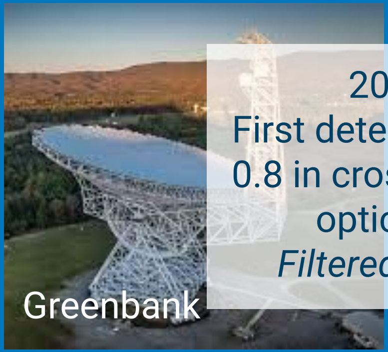
'Traditional' Radio telescopes

Dedicated ongoing experiments

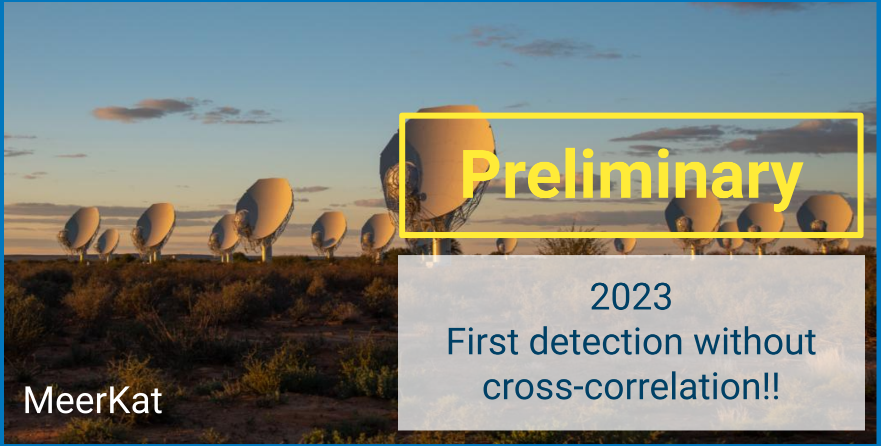


Results! (0.3<z<2.5)

'Traditional' Radio telescopes

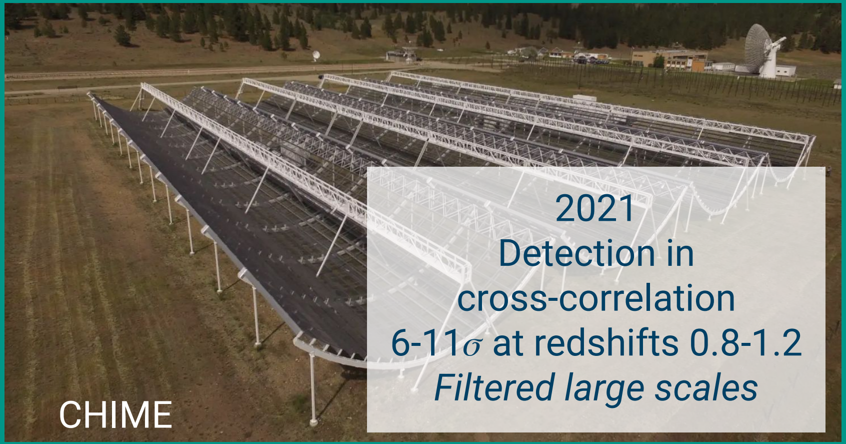


2009/2013
First detection at redshift 0.8 in cross-correlation w optical surveys
Filtered large scales

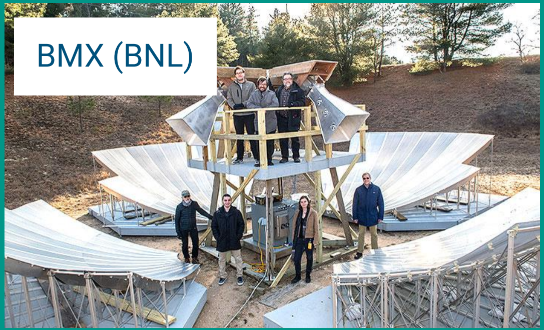


2023
First detection without cross-correlation!!

Dedicated ongoing experiments

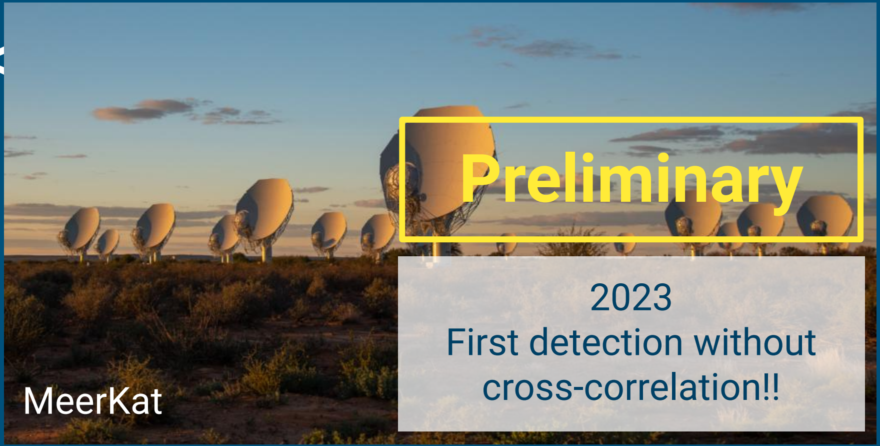


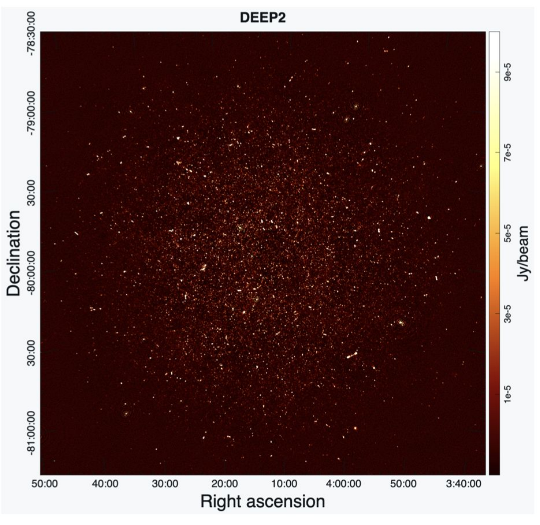
2021
Detection in cross-correlation
6-11σ at redshifts 0.8-1.2
Filtered large scales

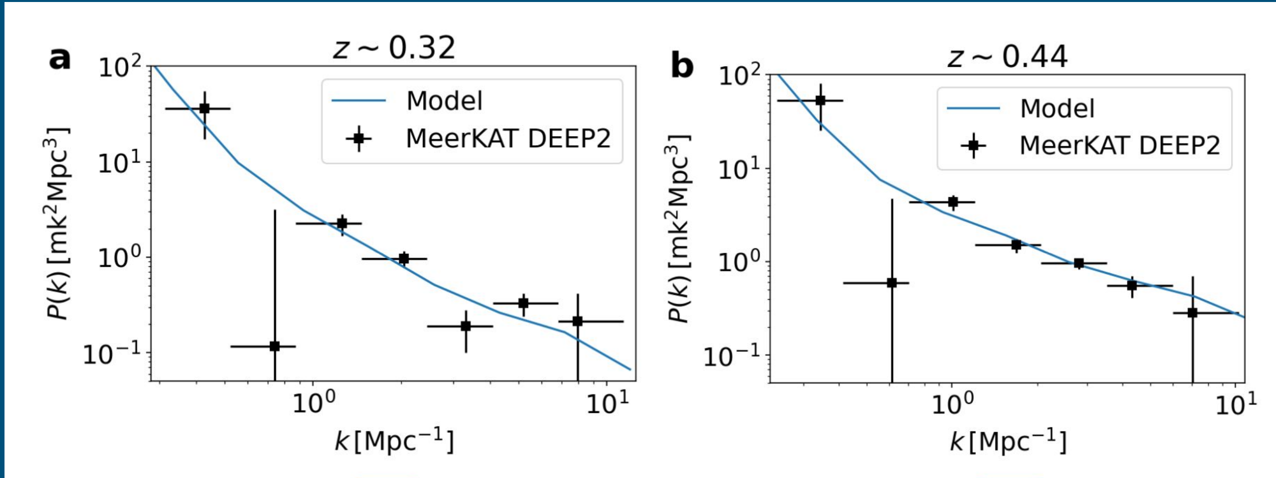


Results! (0.3<

Special thanks to
Sourabh Paul for slide



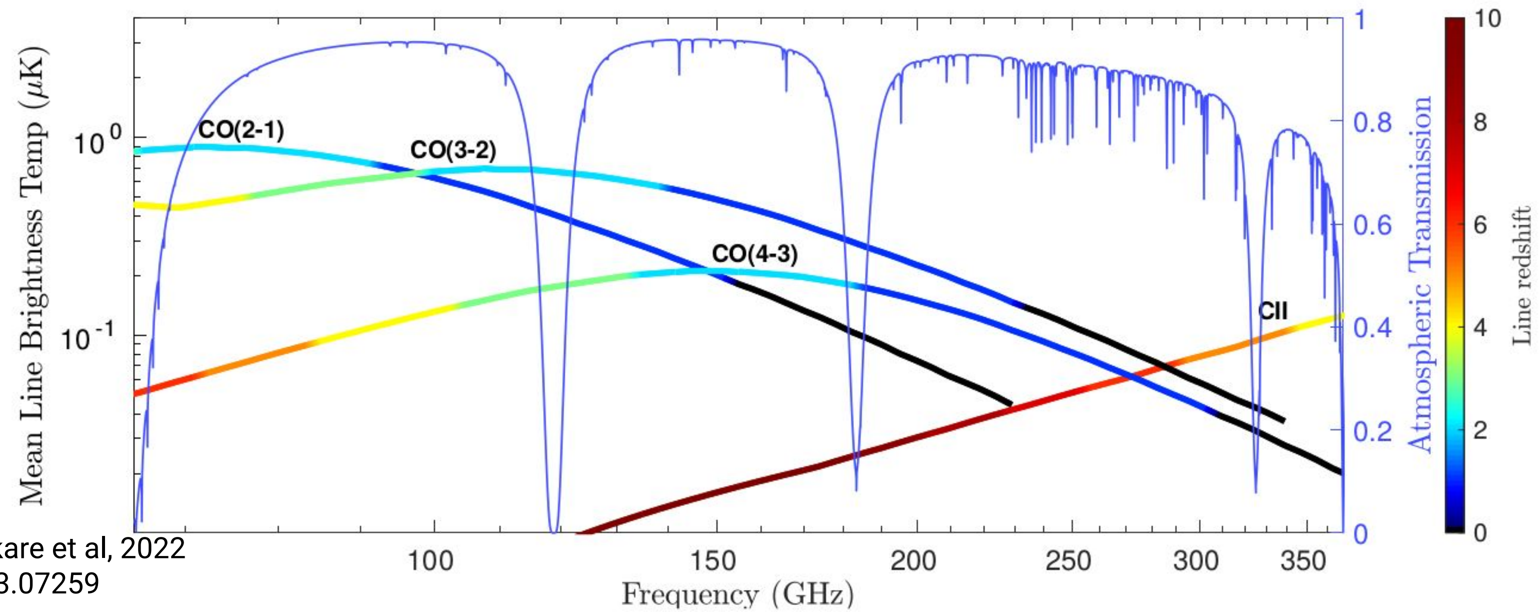




Paul et al 2023
Arxiv 2301.11943

mm LIM

Millimeter Line Intensity Mapping



Karkare et al, 2022
2203.07259

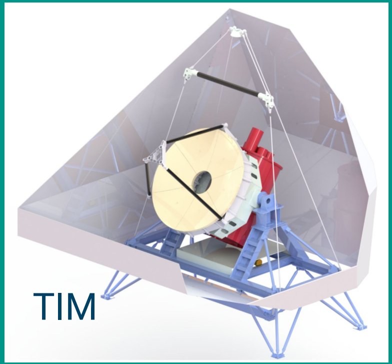
- CO and CII live in galaxies/dust and trace Large Scale Structure
- Redshifted emission in far-IR is observable from the ground in the millimeter
- Instruments covering ‘standard’ ground-based CMB frequencies (80-300 GHz) could detect CO and [CII] from **0<z<10**

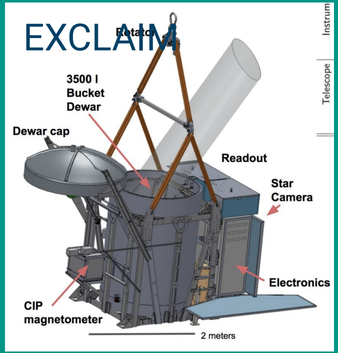
‘Just’ need to add spectroscopy to CMB telescopes!

Current status

Retrofit ‘Traditional’ mm-wave telescopes

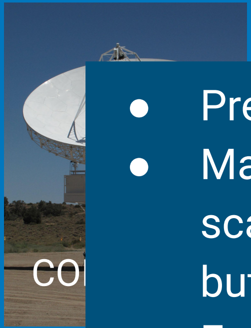
Dedicated experiments

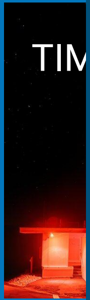




Current status

Retrofit ‘Traditional’ mm-wave telescopes





Dedicated experiments

- Preliminary detections of CO at small scales, and [CII] in cross-correlation
- Many pathfinder experiments in progress, targeting a variety of redshifts and scales are on the verge of detecting the high-redshift CO/[CII] power spectra, but much more sensitive instruments are needed.
- Expect:
  - Higher significance detections in the near-term
  - Resulting in refined models and projections

What’s next?

What's next? - 21cm

Future experiments

Packed Ultra-Wideband Mapping Array (PUMA)

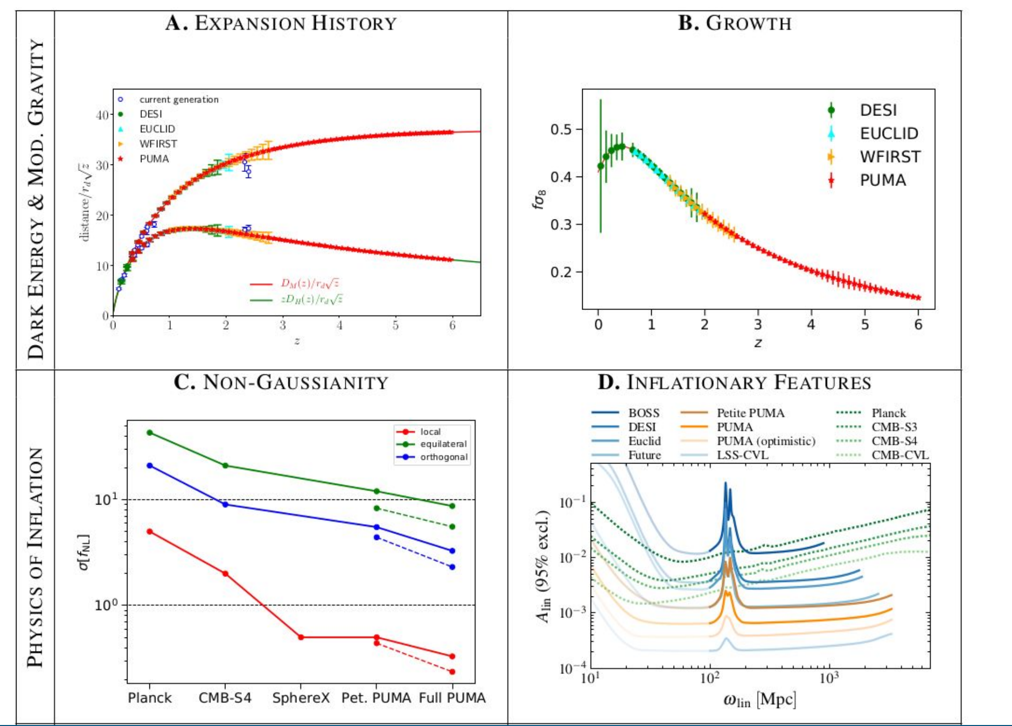
PUMA is

- **Packed**: Dishes close together for maximum sensitivity at scales of interest,
- **Ultra wide-band:** Employing latest in RF technology advances driven by telecom industry,

PUMA is **not**:

- Shovel-ready.
- Technical challenges: calibration, stability, and cost-effective manufacturing of reflectors need to be developed

4 exciting science goals relevant to DOE HEP



More here: 1810.09572 1907.12559 2002.05072

Pathfinding Development

- Small-scale R&D development projects (~$1 mil):
  - cost-effective, low-power electronics
  - beam calibration methodology
  - analysis and simulation
- Join existing projects as junior partner (~$20M):
  - DSA-2000, HIRAX, CHORD
  - work with existing data
  - help with relevant instrument upgrades

Decadal 2020 RFI outlined a clear development plan with costing model

Pathfinding phase

		FULL			PETITE		
Phase	Years	U.S. Federal ($M)	Non-federal ($M)	Total ($M)	U.S. Federal ($M)	Non-federal ($M)	Total ($M)
R&D	FY 21-24	15.0	5.0	20.0	15.0	5.0	20.0
Final design and site acquisition	FY 25-26	8.0	2.0	10.0	8.0	2.0	10.0
Construction and commissioning	FY 27-34	313.2	16.5	329.7	52.3	2.8	55.0
Operations	FY 34-38	89.0	9.9	98.9	14.9	1.7	16.5
Science	FY 35-38	103.9	34.6	138.5	17.3	5.8	23.1
TOTAL	FY 21-38	**529.1**	**68.0**	**597.1**	**107.5**	**17.2**	**124.7**

Full experiments:
Scientific Flagships
at $100M - $1B
(caveats: at the time, a particular config.)

Costing model details: 1810.09572 1907.12559 2002.05072

What's next - mm LIM

Spec-hrs	Example	Time-scale
10^5	TIME, CCAT-p, SPT-SLIM	2022
10^6	TIME-EXT	2025
10^7	SPT-like 1 tube	2028
10^8	SPT-like 7 tubes	2031
10^9	CMB-S4-like 85 tubes	2037

On-chip spectroscopy is an enabling technology - SPT-SLIM and EXCLAIM will be the first demonstrations in the next few years.

Deploying large-format on-chip spectrometer focal planes **at existing CMB facilities** is a natural path towards realizing the required sensitivity.

Pathfinding

21cm

- Support R&D projects in DOE ecosystem to develop (~$1mil grants):
  - low-power, low cost radio electronics synergistic with other fields
  - calibration methodology and hardware
  - analysis and simulation techniques
- Consider DOE involvement in existing synergistic experiments (~ $20M)
  - DSA-2000
  - HIRAX
  - CHORD

Millimeter (CO/[CII])

- Support pathfinder experiments
  - Operate + analysis of small arrays on existing telescopes (~few $M)
- Develop:
  - on-chip mm-wave spectrometers with increased density and resolving power
  - low-cost multiplexer readout electronics
  - Calibration methodology and analysis
- Consider DOE involvement in existing synergistic experiments
  - Multi-year observations w full FOV SPT-like pathfinder (~$10M)

Take-home message

Intensity mapping is a new way to think about galaxy surveys. Can enable amazing science at high redshift

21cm

- Require dedicated experiments to push to cosmological scales
  - Technology benefits from commoditization/ongoing instruments
  - Calibration is primary challenge: can be overcome with sufficient development and testing
  - Analysis benefits from synergies between all 21cm arrays (low redshift, EoR, dark ages)
- Short term, opportunities for meaningful advances at modest investments
- Long-term, 21cm is a good match to DOE institutional strengths

Millimeter (CO/[CII])

- Require dedicated experiments to push to cosmological scales.
  - Current instruments are sensitivity starved
  - High-density from On-chip spectroscopy particular promising, using techniques developed for CMB
- Can re-use CMB telescopes
- Foregrounds easier: interloper lines instead of diffuse galaxy, but discrimination has not been applied to real data
- Development of the large-format on-chip spectrometer focal planes builds on the CMB detector & readout capabilities in the DOE-HEP labs

Backup

Pathfinding Development

mm LIM

Spec-hrs	Example	Time-scale
10^5	TIME, CCAT-p, SPT-SLIM	2022
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10^9	CMB-S4-like 85 tubes	2037

- ~$1M
- ~$10M
- ~$100M

Pathfinding Development

Decadal 2020 RFI outlined a clear development plan with costing model

Name	Description	Purpose	Timeline
PUP-2	A pair of 6m dishes on a ~30 m E-W baseline	• Perform the basic checks of the system, obtain first fringes and auto-correlation transits • Validate antenna design • Independently measure and characterise the two beams • Measure beam stability as function of pointing, temperature, humidity, etc	2020-2022
PUP-6	Six dishes in a packed cluster at PUMA configuration	• Measure dish cross-talk and shadowing • Measure dish-to-dish variations and manufacturing tolerances • Validate pointing tolerances	2022-2023
PUP-20	20 dishes in a packed cluster at PUMA configuration	• Measure cross-talk and coupling between dishes in the "continuum limit" • Continue measuring beam variations, tolerances with larger sample • Validate final model for components that describe dish-to-dish beam variations	2023-2024

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Full experiments:
Smaller array (Petite)
Full array

More here: 1810.09572 1907.12559 2002.05072

Pathfinding

21cm

- Support pathfinder experiments (< $10M)
  - PUMA pathfinder experiments (PUP)
  - Funding for analysis and upgrade for BMX at BNL
- Consider DOE involvement in existing synergistic experiments (<$30M)
  - DSA-2000: NSF radio imager that nominally reaches z~1, recommended by Decadal
  - HIRAX

Millimeter (CO/[CII])

- Support pathfinder experiments
  - Operate + analysis of small arrays on existing telescopes (~few $M)
- Consider DOE involvement in existing synergistic experiments
  - Multi-year observations w full FOV SPT-like pathfinder (~$10M)

Pathfinding Development

21cm

- Development of low-power, low cost radio electronics synergistic with other fields
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- Development of on-chip mm-wave spectrometers with increased density and resolving power
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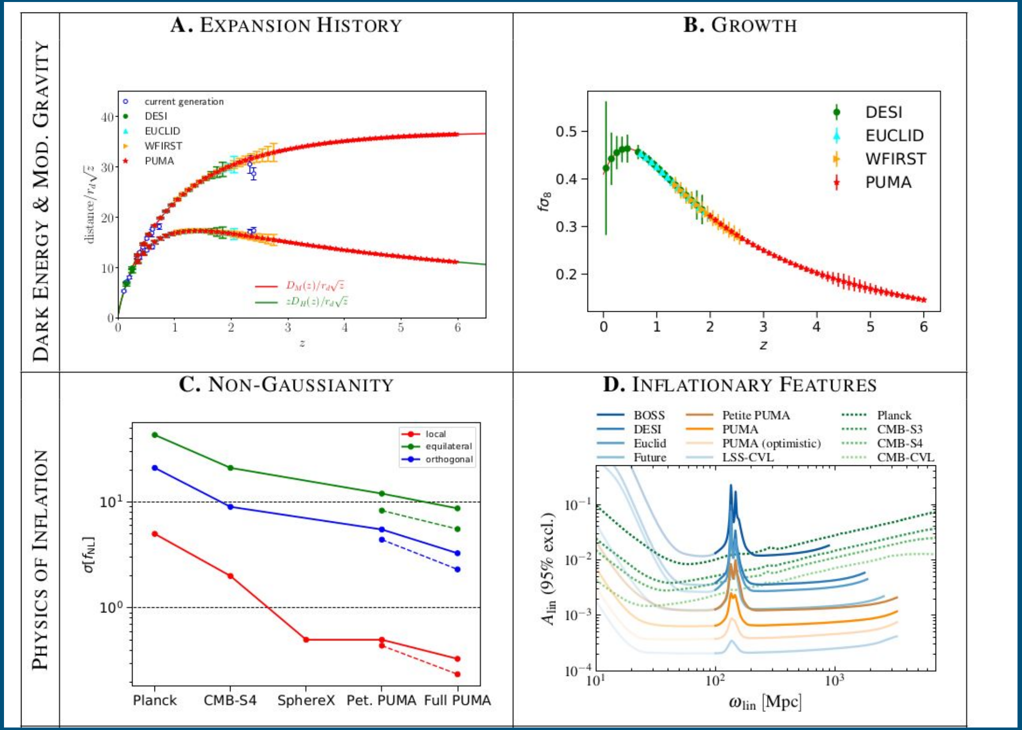
Packed Ultra-Wideband Mapping Array (PUMA)

4 exciting science goals relevant to DOE HEP

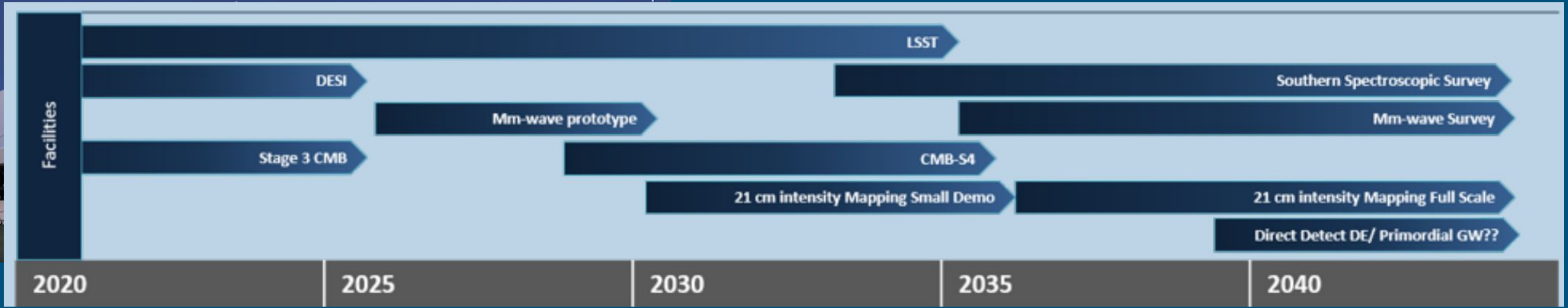


PUMA is

- **Packed**: Dishes close together for maximum sensitivity at scales of interest,
- **Ultra wide-band:** Employing latest in RF technology advances driven by telecom industry,
- **Mapping:** Maps large-scale structure in the Universe,
- **Array:** A software/hardware radio telescope.

More here: 1810.09572 1907.12559 2002.05072

Packed Ultra-Wideband Mapping Array (PUMA)



PUMA pathfinding plan

- **PUMA is not shovel ready**
- Technical challenges: calibration, stability, and cost-effective manufacturing of reflectors need to be developed
- Decadal 2020 RFI outlined a clear development plan
- Will benefit enormously from commodization of radio and compute technology (eg RFSocs)
- Working towards establishing seed funding from agencies to follow this plan

BRN report envisioned start of small demo observations in 2030

PUMA Proto-collaboration:

- Tremendous Arrays Workshop (2018)
- Cosmic Visions 21cm Working group report (2018),
- Astro 2020 Decadal Survey Submissions (2019),
- Snowmass 2021 Letters of Interest,
- First (remote) collaboration meeting in Summer 2020,
- Will continue operating in semi-formal mode for the foreseeable future.

Pathfinding Development

21cm

- Costing model developed for 2019 Decadal Survey based on:
  - cost data from existing experiments
  - trends in cost evolution for commodity RF hardware
  - problem size scaling
  - assumptions about foreign partners, etc
- Indicative of the cost of cosmologically interesting experiment: $100-$600 mil

		FULL			PETITE		
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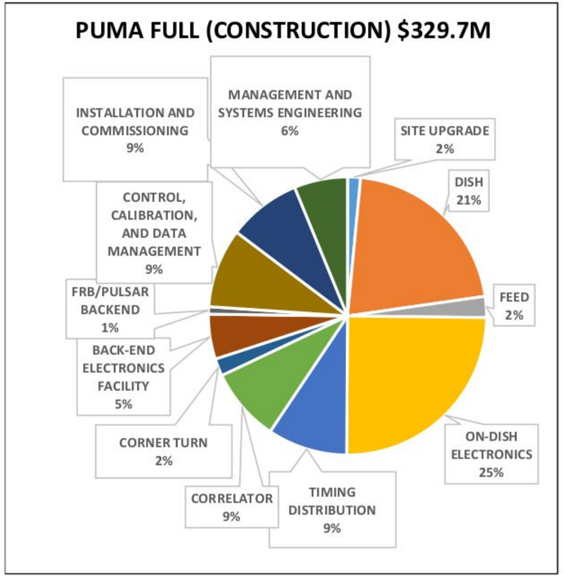
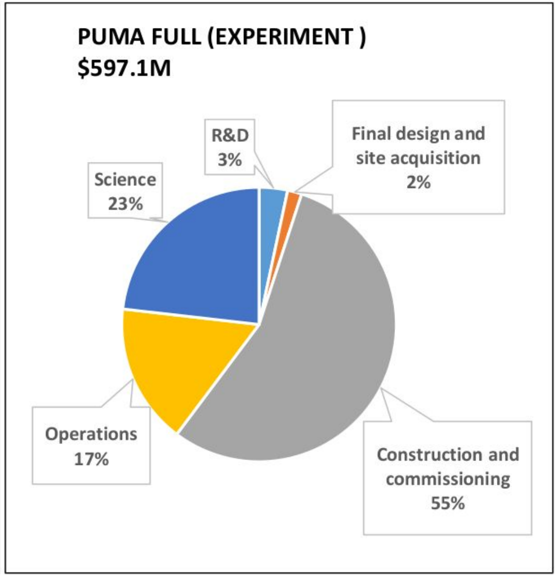




Costing

Phase	PUMA-5K				PUMA-32K			
	Years	U.S. Federal ($M)	Non-federal ($M)	Total ($M)	Years	U.S. Federal ($M)	Non-federal ($M)	Total ($M)
R&D	FY 21-24	22.5	7.5	30.0	FY 21-25	26.3	8.8	35.0
Final design and site acquisition	FY 25-26	8.0	2.0	10.0	FY 26-27	8.0	2.0	10.0
Construction and commissioning	FY 27-30	55.9	2.9	58.8	FY 28-33	354.7	18.7	373.4
Operations	FY 34-30	15.9	1.8	17.7	FY 34-38	100.8	11.2	112.0
Science	FY 31-35	12.4	4.1	16.5	FY35-38	78.4	26.1	104.5
TOTAL	FY 21-35	**114.6**	**18.3**	**133.0**	FY 21-38	**568.2**	**66.8**	**634.9**

Figure 15: Summary costs for PUMA-5K and PUMA-32K.

PUMA-5K:

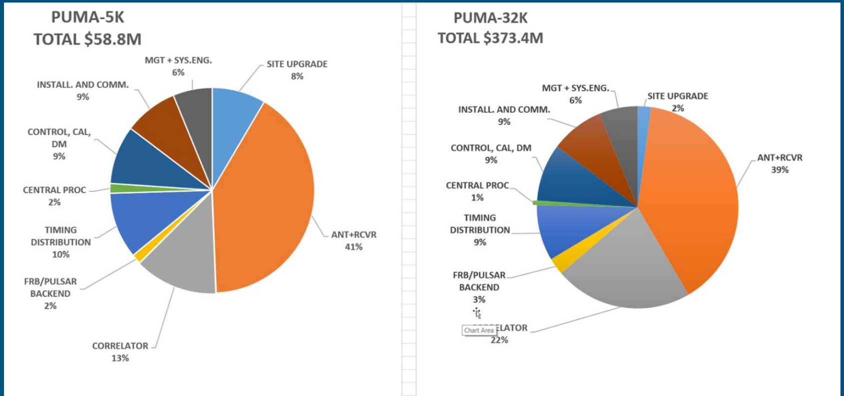
- Equivalent to 600 million galaxies for 55/125m USD

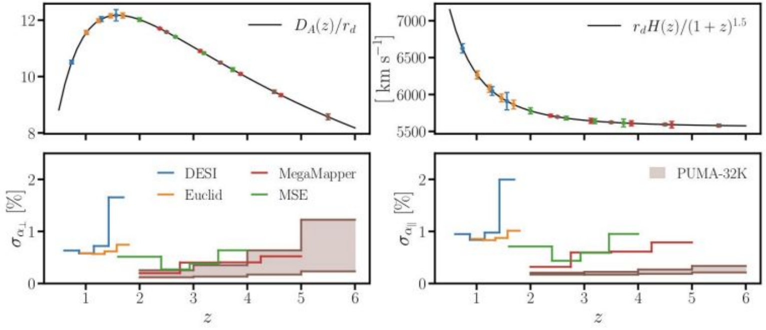
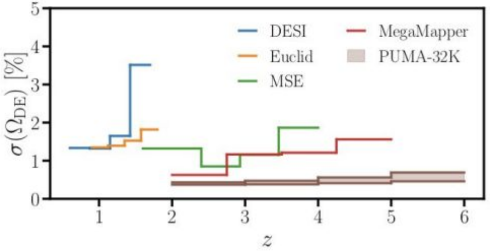
PUMA-32K:

- Equivalent to 2.9 billion galaxies for 330/600 m USD

R&D required:

- 5 mil / year starting FY21




$D_A(z)/r_d$
$r_d H(z)/(1+z)^{1.5}$
$[\mathrm{km\ s^{-1}}]$
$\sigma_{\alpha_\perp}$ [%]
$\sigma_{\alpha_\parallel}$ [%]
DESI
Euclid
MegaMapper
MSE
PUMA-32K
z

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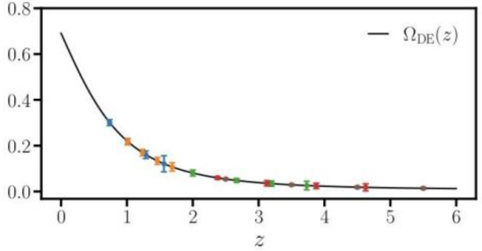
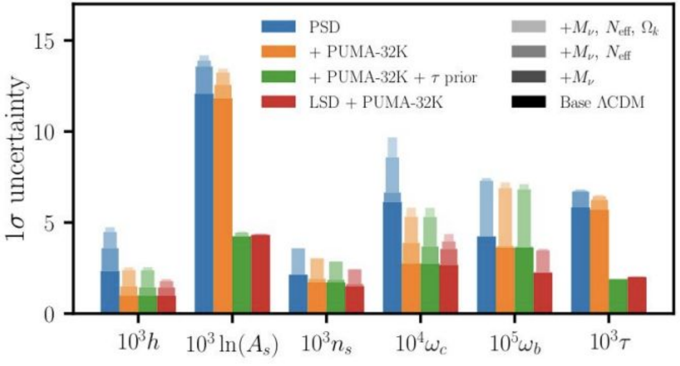
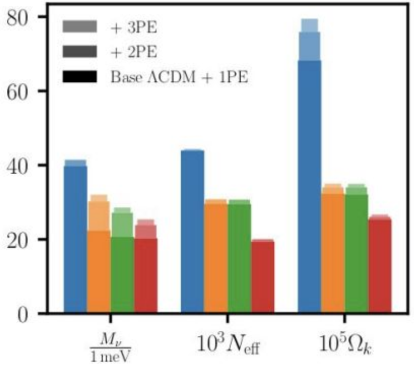
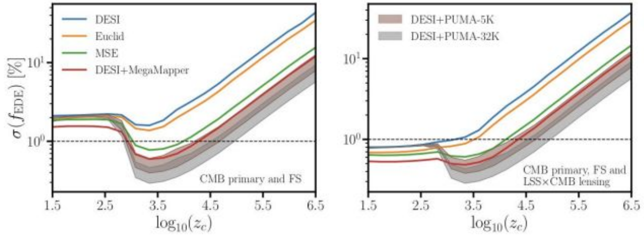
Euclid
MSE
MegaMapper
PUMA-32K
z

$\Omega_{\mathrm{DE}}(z)$
z

1σ uncertainty
PSD
+ PUMA-32K
+ PUMA-32K + τ prior
LSD + PUMA-32K
$+M_\nu$, N_{eff}, Ω_k
$+M_\nu$, N_{eff}
$+M_\nu$
Base ΛCDM
$10^3 h$
$10^3 \ln(A_s)$
$10^3 n_s$
$10^4 \omega_c$
$10^5 \omega_b$
$10^3 \tau$

+ 3PE
+ 2PE
Base ΛCDM + 1PE
$\frac{M_\nu}{1\,\mathrm{meV}}$
$10^3 N_{\mathrm{eff}}$
$10^5 \Omega_k$

$\sigma(f_{\mathrm{EDE}})$ [%]
DESI
Euclid
MSE
DESI+MegaMapper
CMB primary and FS
DESI+PUMA-5K
DESI+PUMA-32K
CMB primary, FS and LSS×CMB lensing
$\log_{10}(z_c)$

Scientific possibilities

Guaranteed Science:

- Expansion history in pre-acceleration era (dark energy)
- Features in the primordial power spectrum (inflation)
- Primordial non-Gaussianity (inflation)
- Geometric curvature constraints
- General parameter improvements

Likely Science:

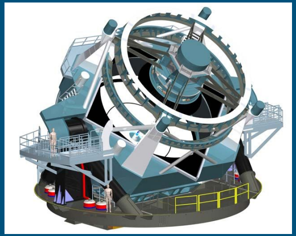
- Redshift-space distortion with external calibration:
  - Cross-correlation
  - Damped Ly-α systems
- Weak-lensing of the 21-cm field
- Tidal-reconstruction of the 21-cm field

Speculative Science:

- FRB to calibrate kinetic SZ
- Direct expansion history measurements
- Non-linear transformations of the field

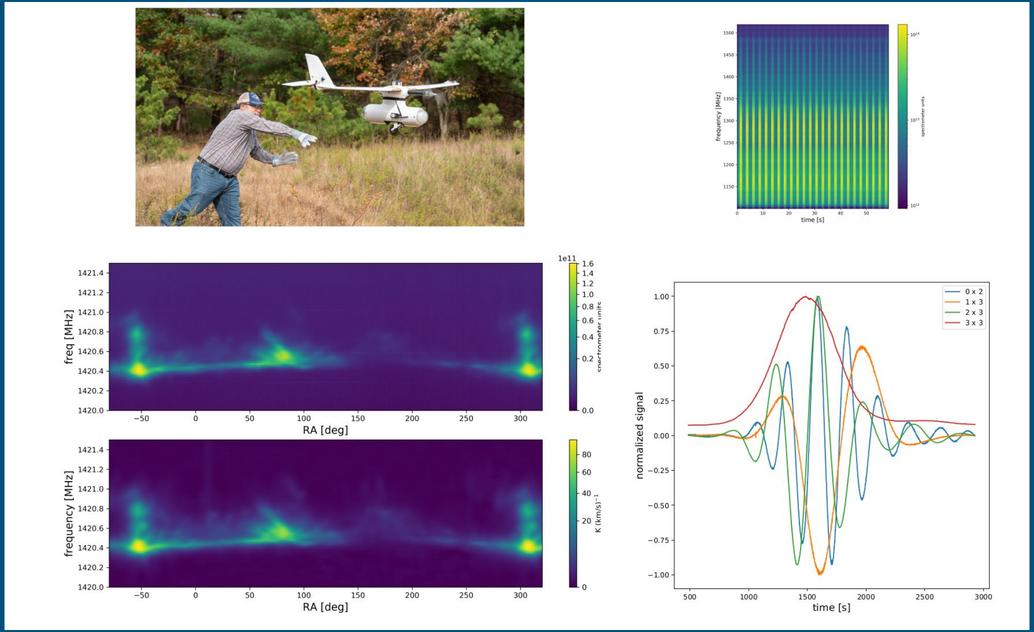
Opens up cross-correlation science with CMB lensing reconstruction

21-cm cosmology: why DOE HEP involvement?

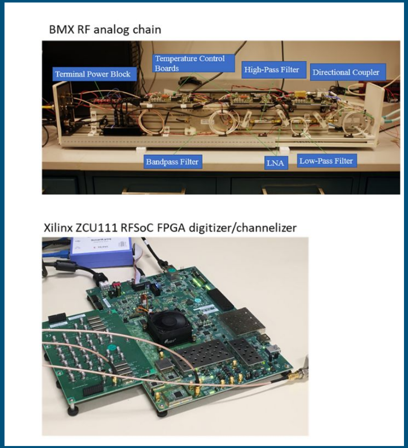


(HERA experiment)

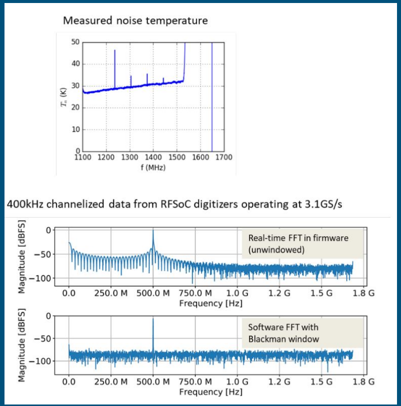
	Example: LSST	Stage 2 21-cm experiment	Core DOE competencies
Science	Will characterize dark energy, constrain inflation, measure neutrino mass.	Will characterize dark energy at higher redshift, improve all basic cosmological parameters, inflationary physics, baryon-dark matter coupling, test modified gravity paradigms	DOE Cosmic Frontier does P5 science. Focus on fundamental physics. Small signals and hard systematics require large collaborations. Particle physics developed appropriate collaborative culture. Traditional radio astronomy community is focused on PI-led astronomy projects.
Dedicated long-term Research & Development	First astronomical project of this scale. Dedicated read-outs, optical design, dedicated data-pipe from Chile, photon-level system simulation	Current designs rely on off-shelf amplifiers, digitizers and GPUs for correlations. Next gen will require dedicated low-power on-chip solutions from sustained R&D.	DOE is capable of focused long-term development in anticipation of future projects. Direct transfer of know-how from accelerator experiments: RFI technology, massive data throughputs.
Large-scale hardware replication	21 rafts, 189 CCDS total	30,000 receiving elements, 2 billion pair correlator. Elements need to be cheap and accurately replicated.	Requires professional project management not available in university settings. Semi-industrial production capabilities and QA tracking crucial.
Data rates	20 TB/night, 60 PB survey, 15PB catalog	~100 PB/day raw, ~1 PB/day real-time reduced	Beyond ATLAS/CMS instantaneous bandwidth. Require highly sophisticated triggering for Fast Radio Burst Environment. Data reduction will require HPC environment.
Instrument characterization and calibration	Cosmology side of the project reliant of weak-lensing and precise photometry, both require 10^{-4} level system understanding	Signal to foreground radiation at 10^{-4} level. Due to raw data volumes forcing real-time reduction, cannot post-calibrate.	Need sub-percent level system understanding to achieve science goals. Full system simulations and characterization well beyond what is normally done is radio astronomy. Need focused infrastructure staff doing “less glamorous” science.



frequency [MHz]
time [s]
spectrometer units
1e11
freq [MHz]
RA [deg]
spectrometer units
frequency [MHz]
RA [deg]
K (km/s)$^{-1}$
0 x 2
1 x 3
2 x 3
3 x 3
normalized signal
time [s]

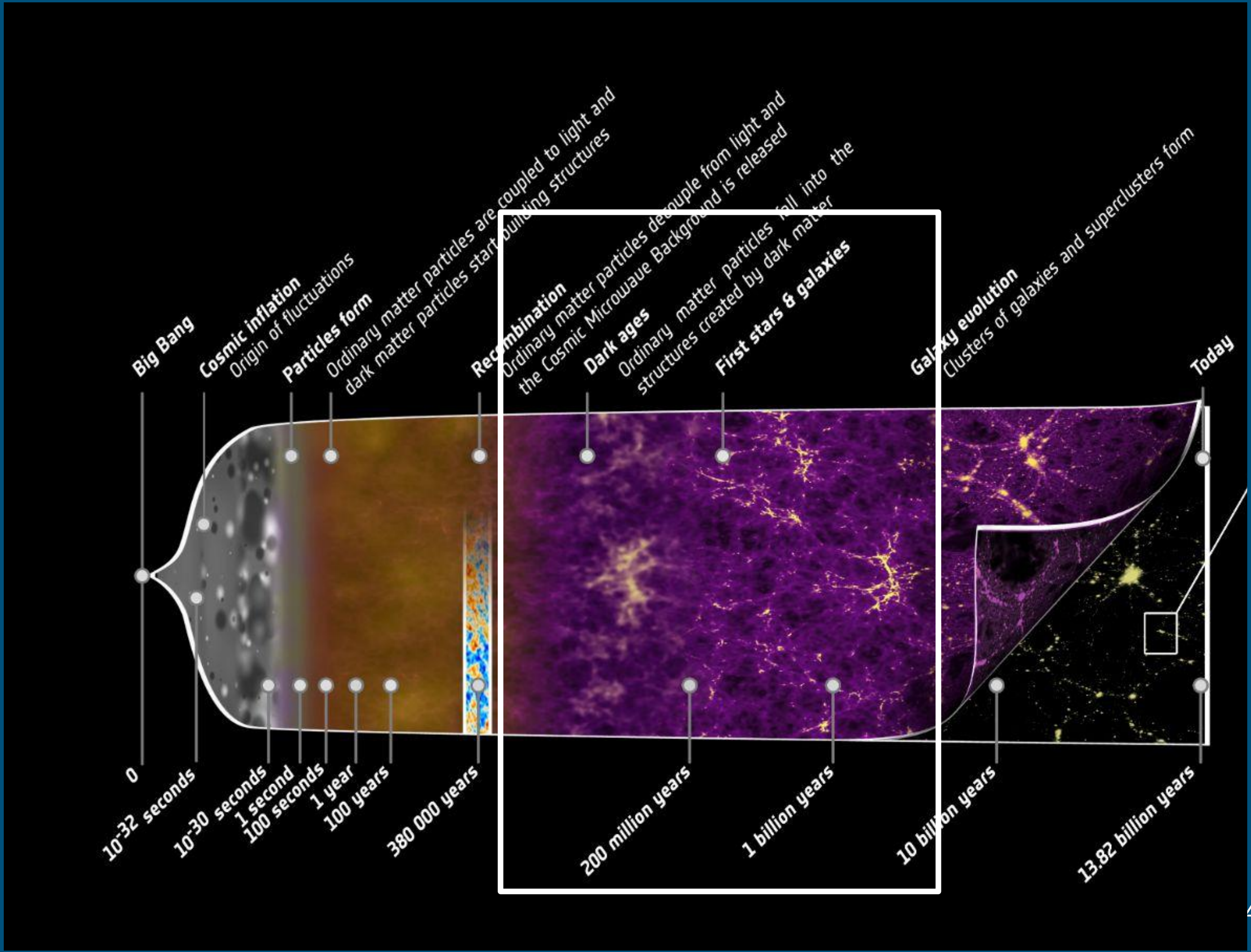


BMX RF analog chain
Terminal Power Block
Temperature Control Boards
High-Pass Filter
Directional Coupler
Bandpass Filter
LNA
Low-Pass Filter
Xilinx ZCU111 RFSoC FPGA digitizer/channelizer



Measured noise temperature
T_r (K)
f (MHz)
400kHz channelized data from RFSoC digitizers operating at 3.1GS/s
Magnitude [dBFS]
Real-time FFT in firmware (unwindowed)
Frequency [Hz]
Magnitude [dBFS]
Software FFT with Blackman window
Frequency [Hz]

Slide with context in current/future gal surveys (in terms of constraints?) - ‘justify’ out to redshift 6+



Why do galaxy surveys?

- Use the Higgs boson as a tool for discovery
- Pursue the physics associated with Neutrino Mass
- Identify new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the Universe: new particles, interactions, physical principles

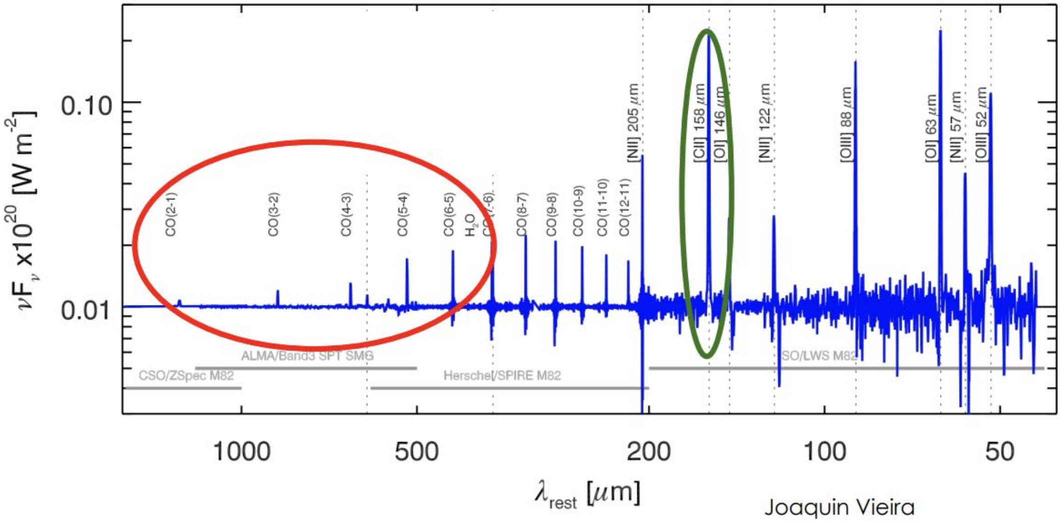
Portion of SDSS galaxy map

Another intensity mapping candidate: Far-IR lines

- About half of the optical light in the Universe has been absorbed by dust and re-radiated in the far-IR.
- On top of the thermal emission, atomic and molecular lines are also excited and can be used to trace LSS in 3D.

- **CO** J→J-1 rotational ladder
- **[CII]** extremely bright; observed in galaxies through reionization (z~8)

At high redshift, these lines can be observed from the ground.

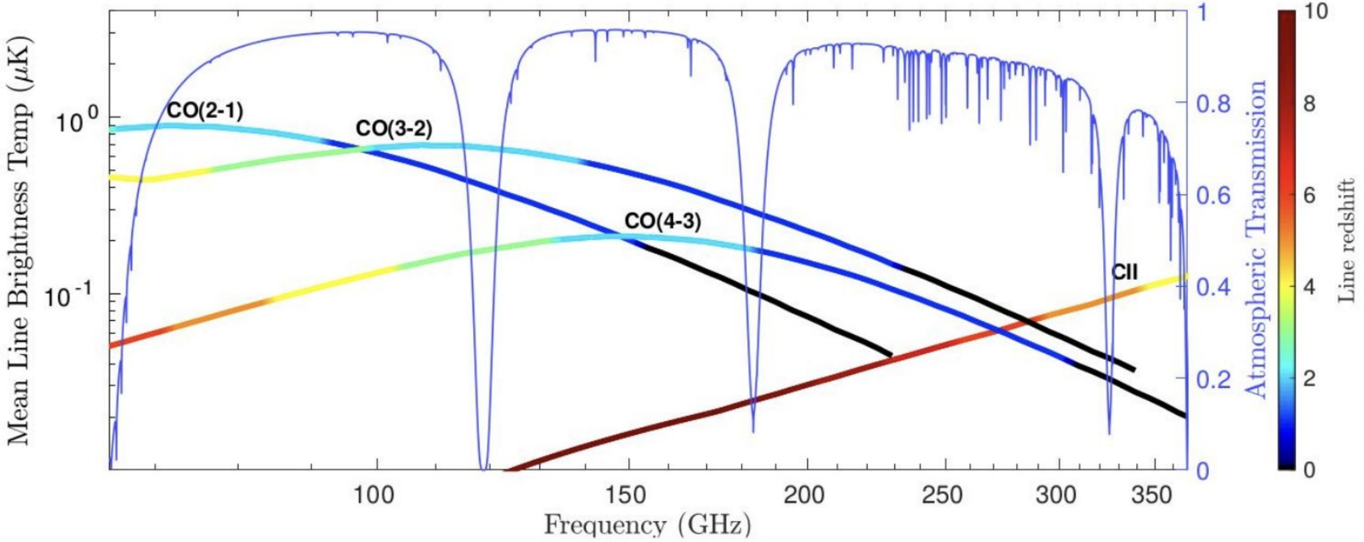


Joaquin Vieira

Brookhaven National Laboratory

Redshift coverage

Karkare+ 2022
2203.07258



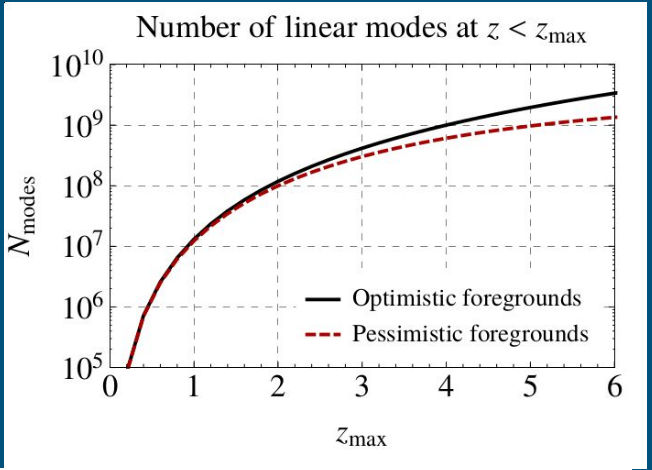
Instruments covering standard ground-based CMB frequencies (80-300 GHz), could detect [CII] and CO over the entire range of $0 < z < 10$!

Just need to add spectroscopy to existing CMB telescopes.

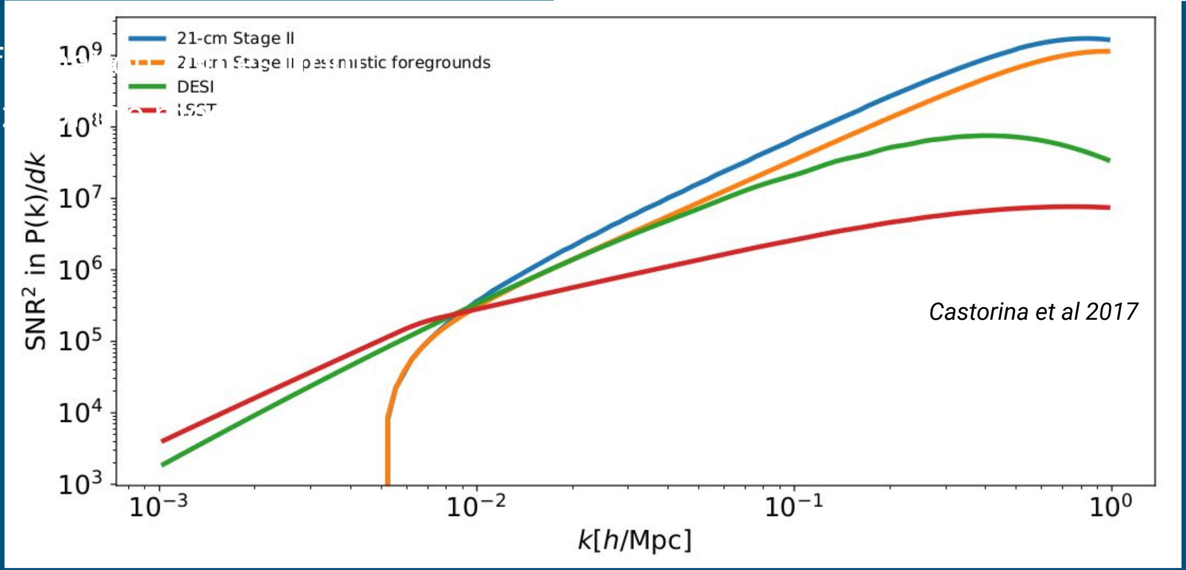
Brookhaven

How do we improve our statistics?

Higher redshift (further in the past)
- Lots of **volume** (this is just expansion)
- More **linear** (gravity hasn't complicated things)



Put SNR where its most useful
- Most cosmological inf
  scales that are ~the si



Castorina et al 2017

Science Targets:

Snowmass #4: Understand Cosmic Acceleration (dark energy + inflation)

- Expansion history
- Inflation: Inflationary theories can be described in terms of a few parameters
  - **Spectroscopic surveys** measure $\mathbf{f_{NL}}$
  - **CMB-S4** measures **r**
  - In combination, explores the range of single-field + multi-field Inflation
- Inflation: features/defects/models
  -