CPAD

DEVELOPMENT OF ON-CHIP SPECTROMETER MICROWAVE KINETIC INDUCTANCE DETECTOR ARRAYS AS A TECHNOLOGY FOR MM-WAVE LINE INTENSITY MAPPING

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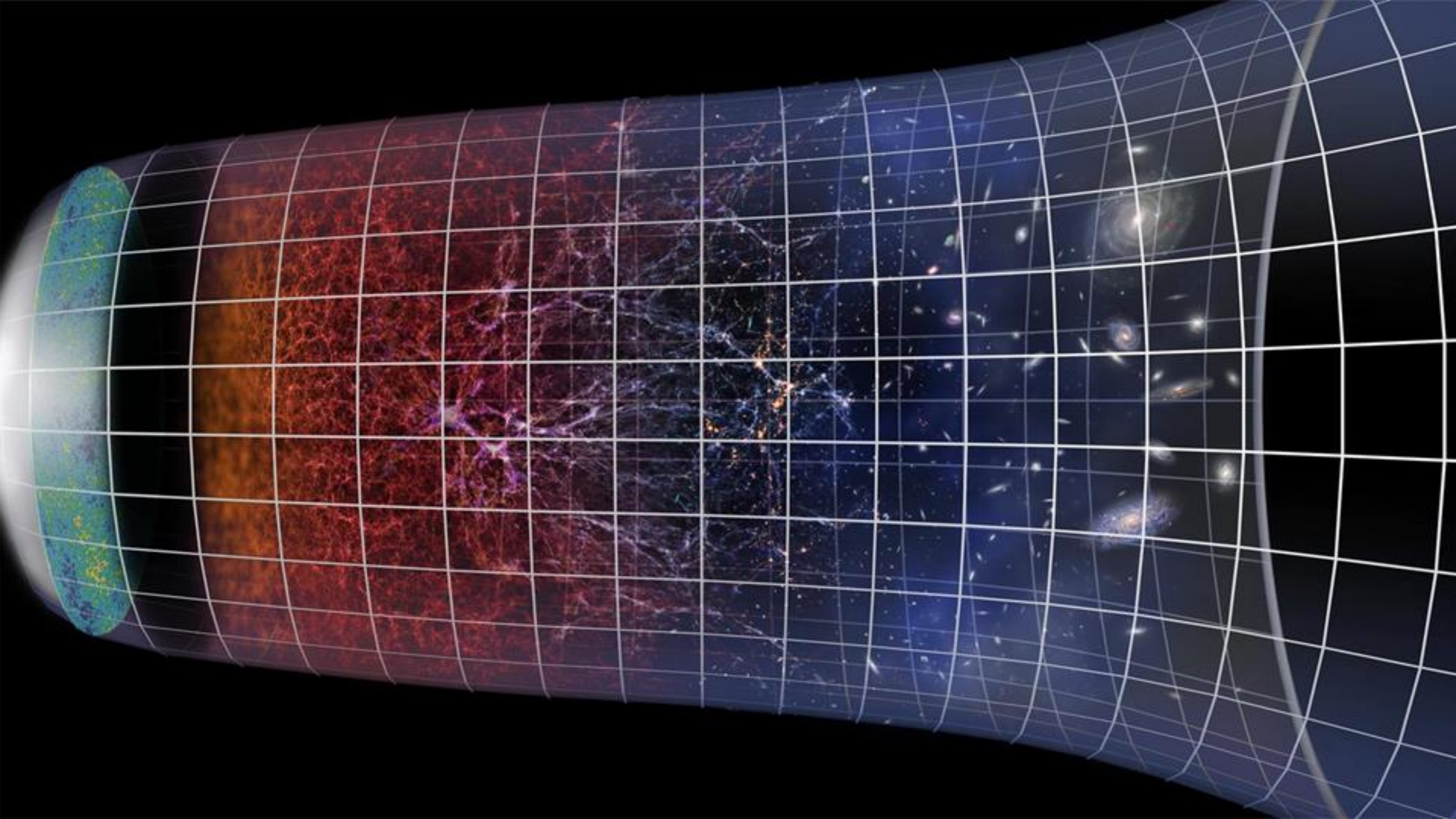
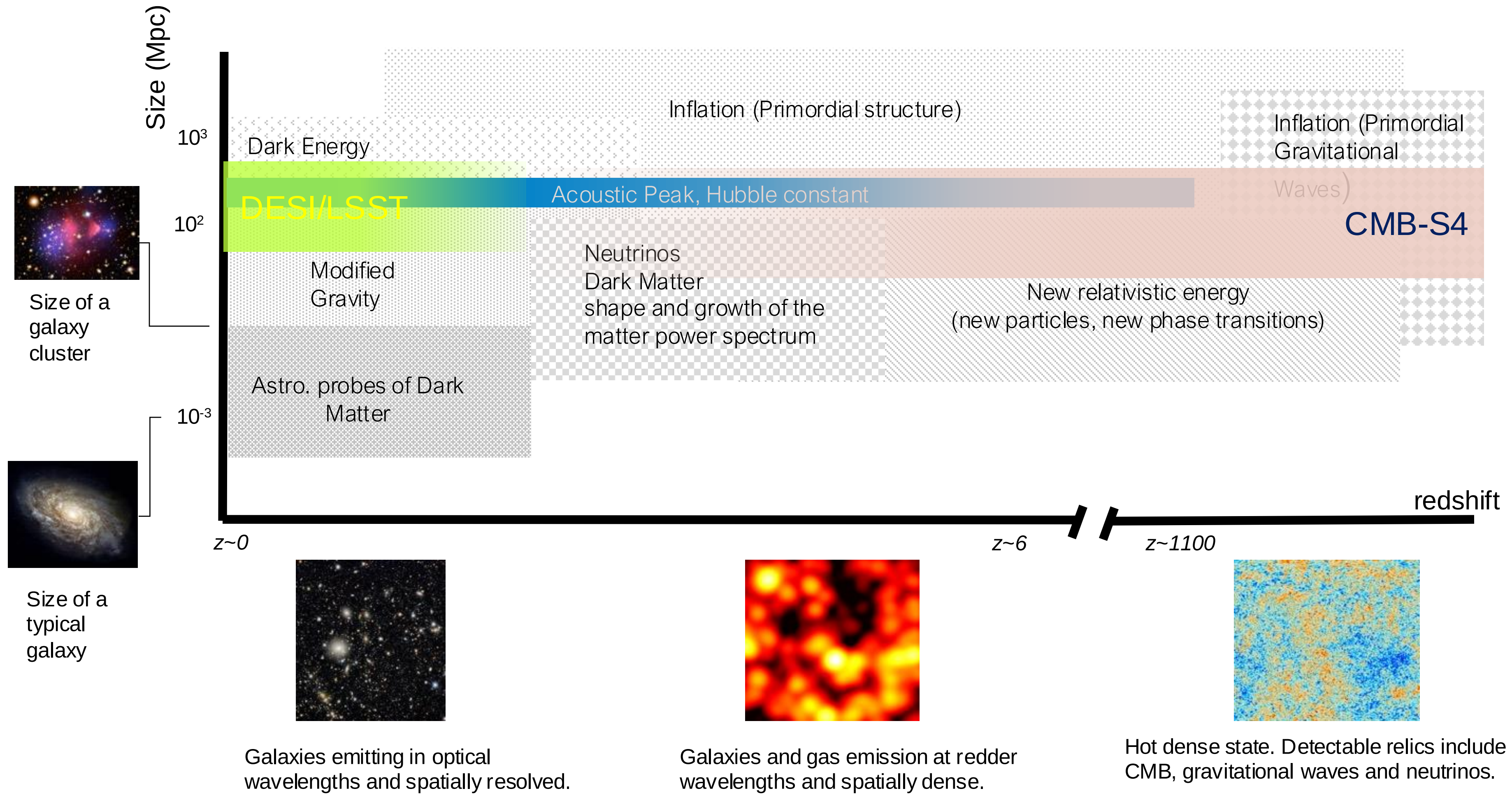
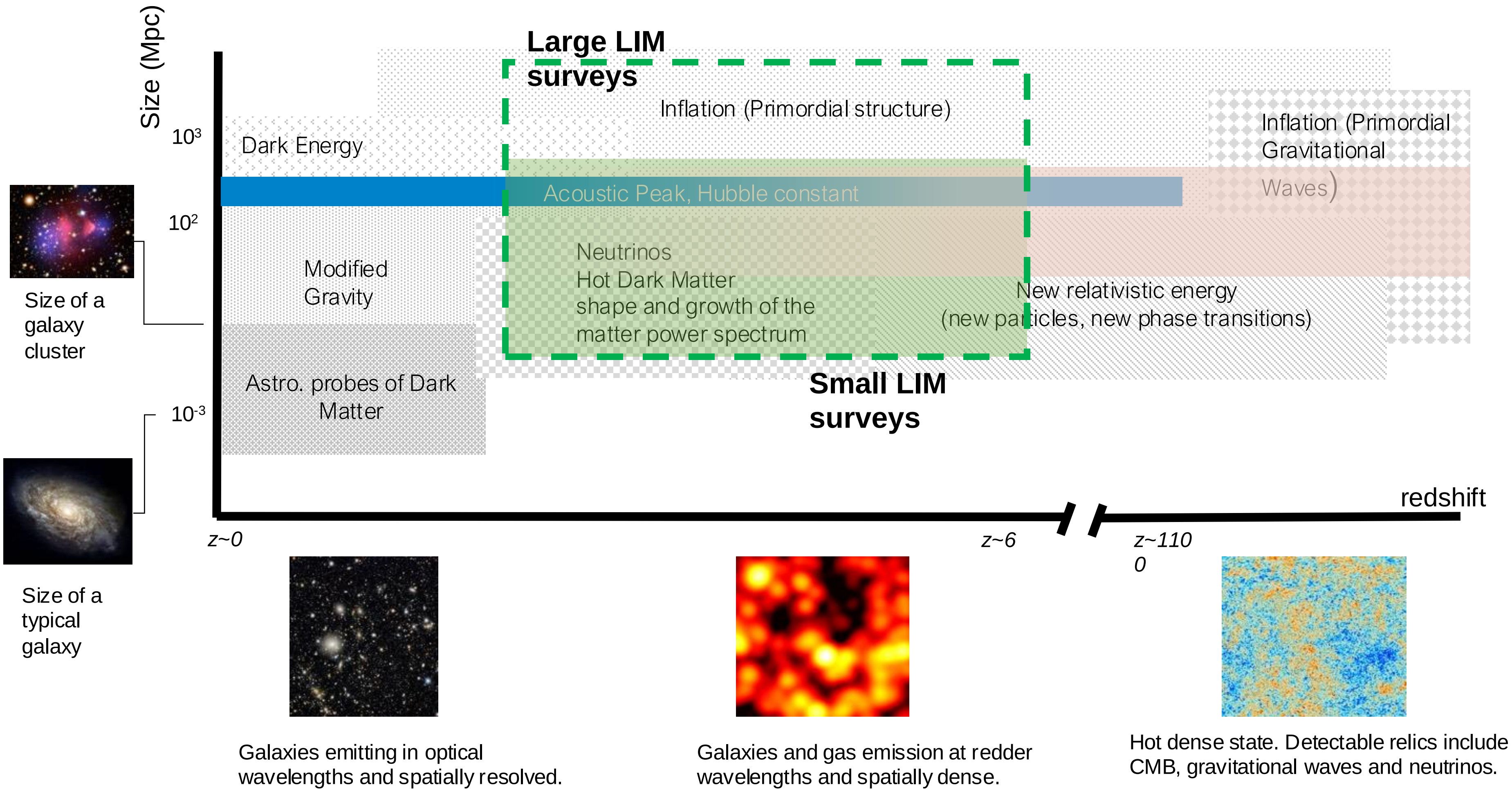
Nov 20, 2024





Size (Mpc)
10³
10²
10⁻³
Inflation (Primordial structure)
Dark Energy
Inflation (Primordial
Gravitational
Waves)
DESI/LSST
Acoustic Peak, Hubble constant
CMB-S4
Neutrinos
Dark Matter
shape and growth of the
matter power spectrum
Modified
Gravity
New relativistic energy
(new particles, new phase transitions)
Astro. probes of Dark
Matter
Size of a
galaxy
cluster
Size of a
typical
galaxy
redshift
z~0
z~6
z~1100
Galaxies emitting in optical
wavelengths and spatially resolved.
Galaxies and gas emission at redder
wavelengths and spatially dense.
Hot dense state. Detectable relics include
CMB, gravitational waves and neutrinos.



Large LIM surveys
Small LIM surveys
Size (Mpc)
10^3
10^2
10^-3
Dark Energy
Inflation (Primordial structure)
Inflation (Primordial Gravitational Waves)
Acoustic Peak, Hubble constant
Modified Gravity
Neutrinos
Hot Dark Matter
shape and growth of the matter power spectrum
New relativistic energy
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Astro. probes of Dark Matter
Size of a galaxy cluster
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z~0
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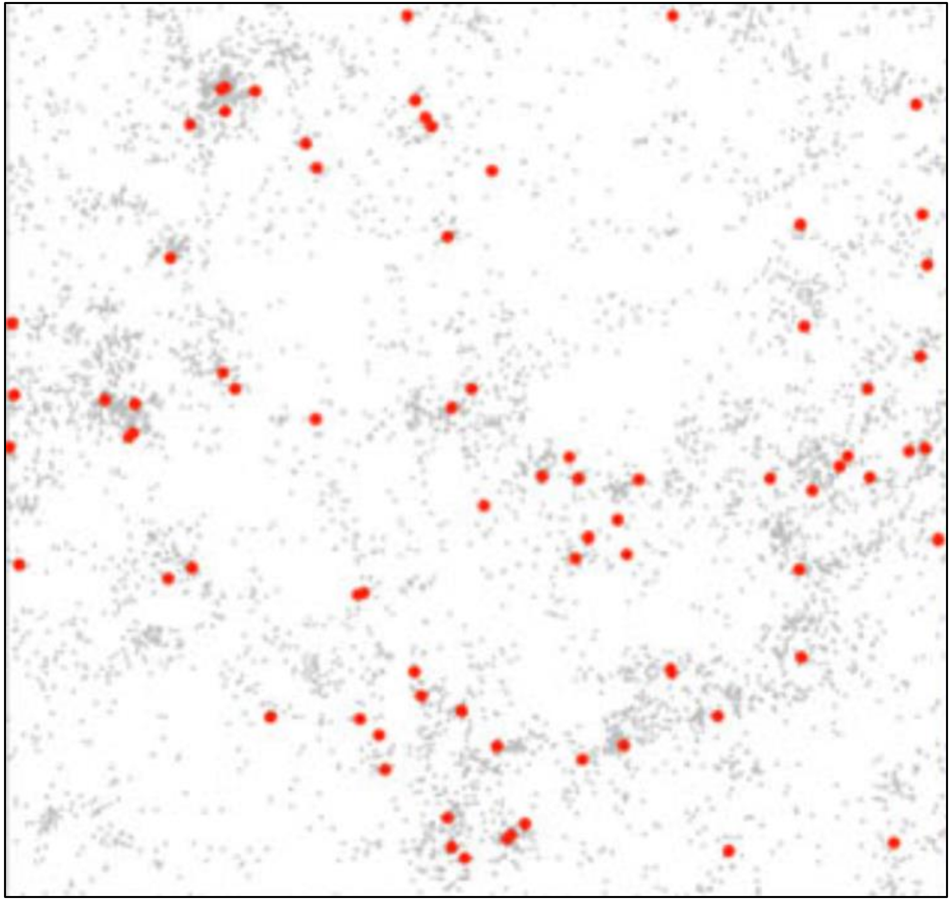
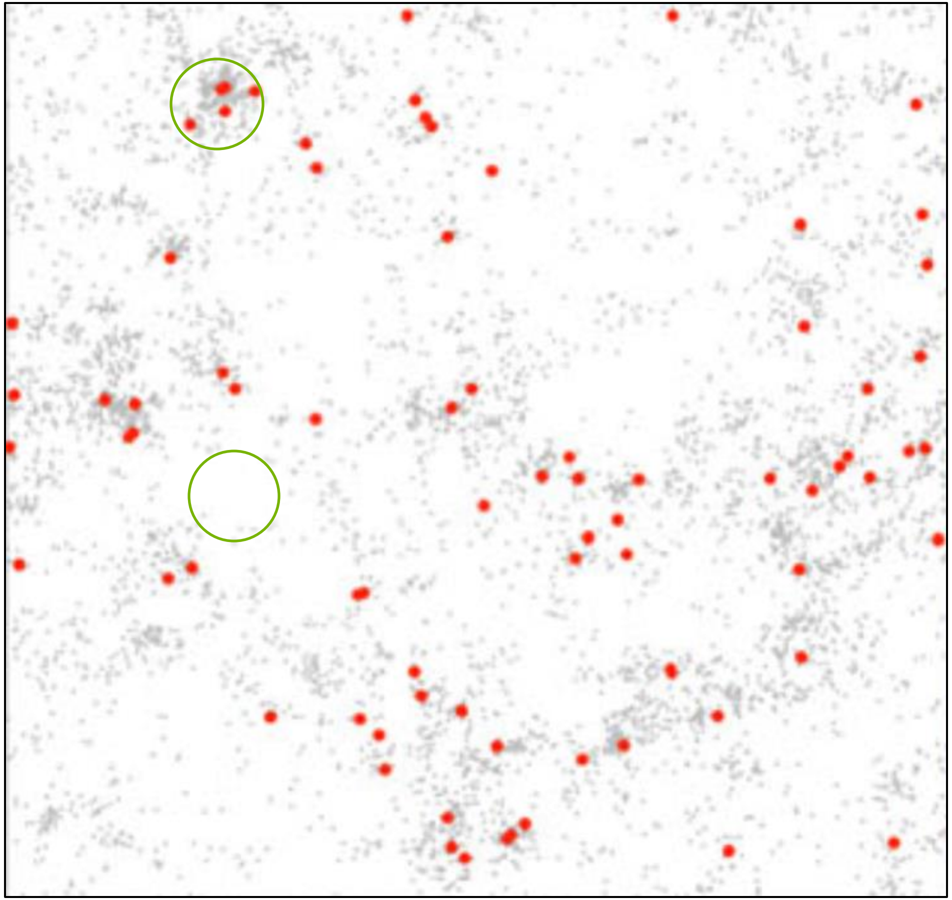
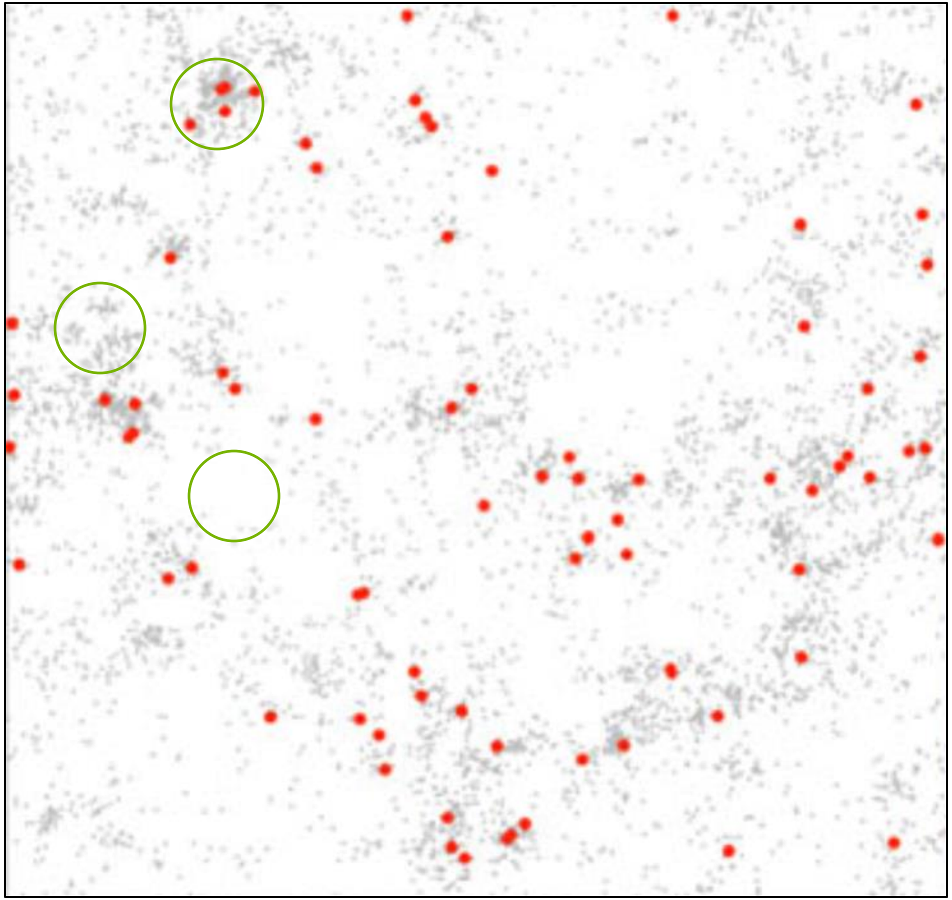
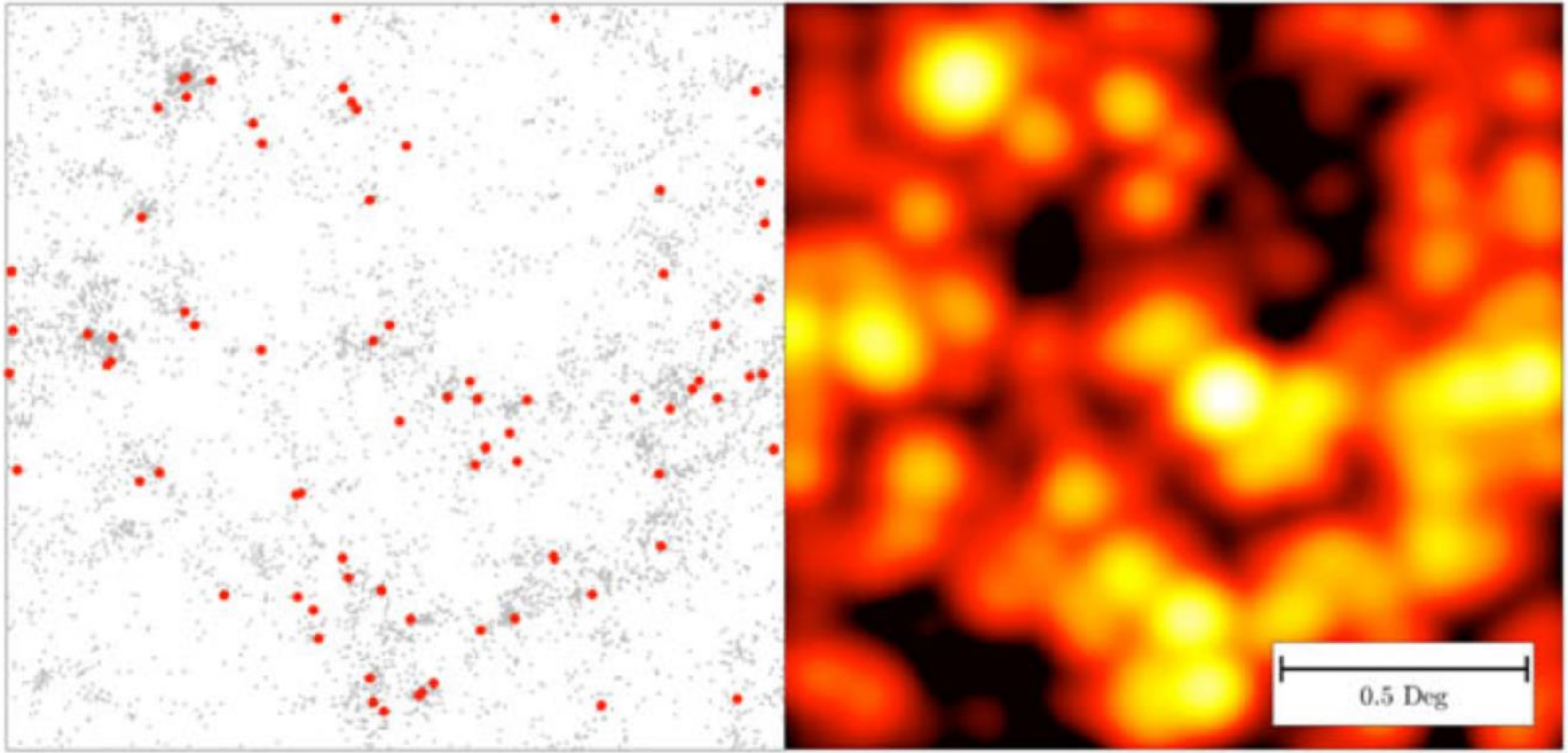
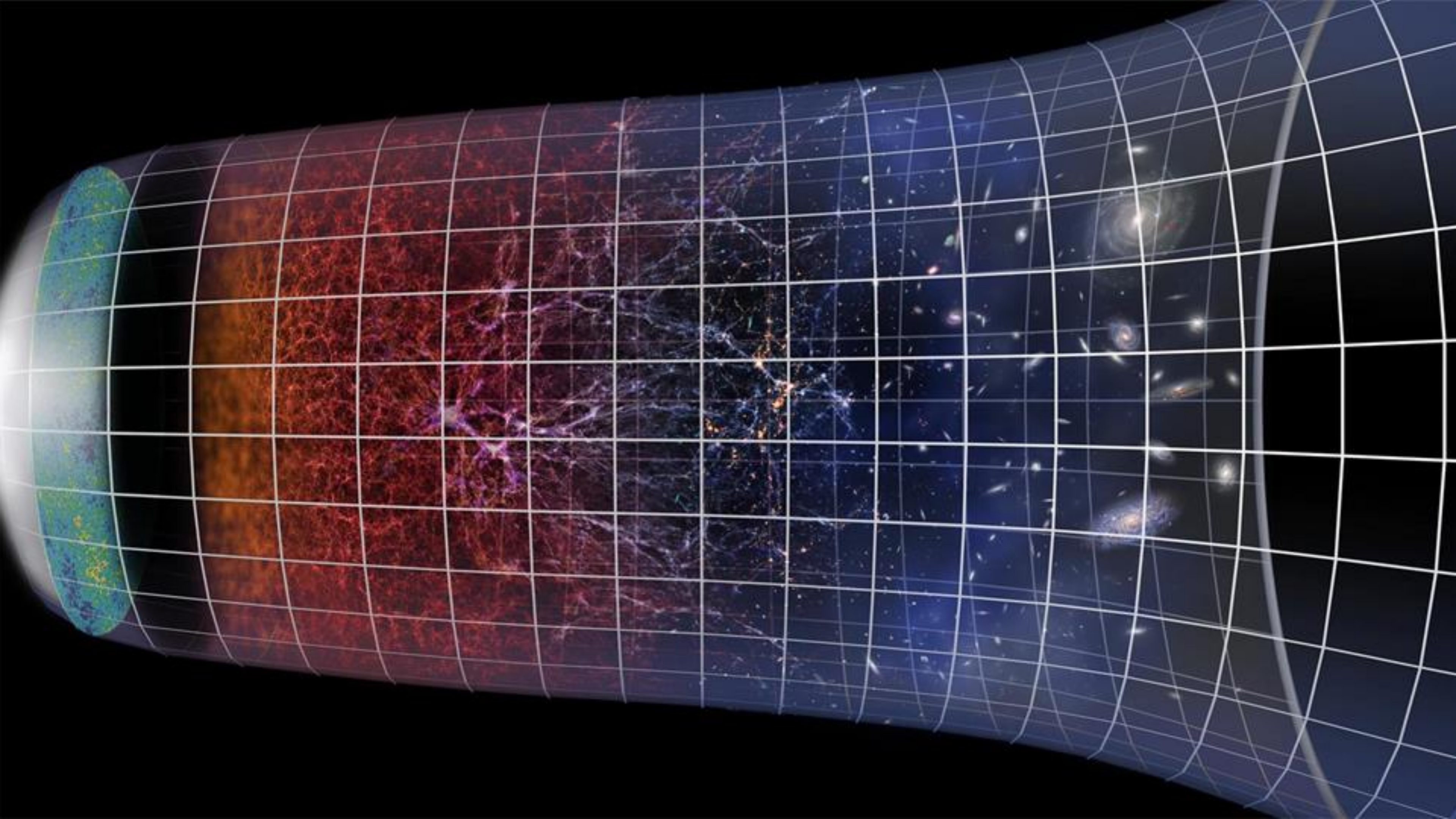




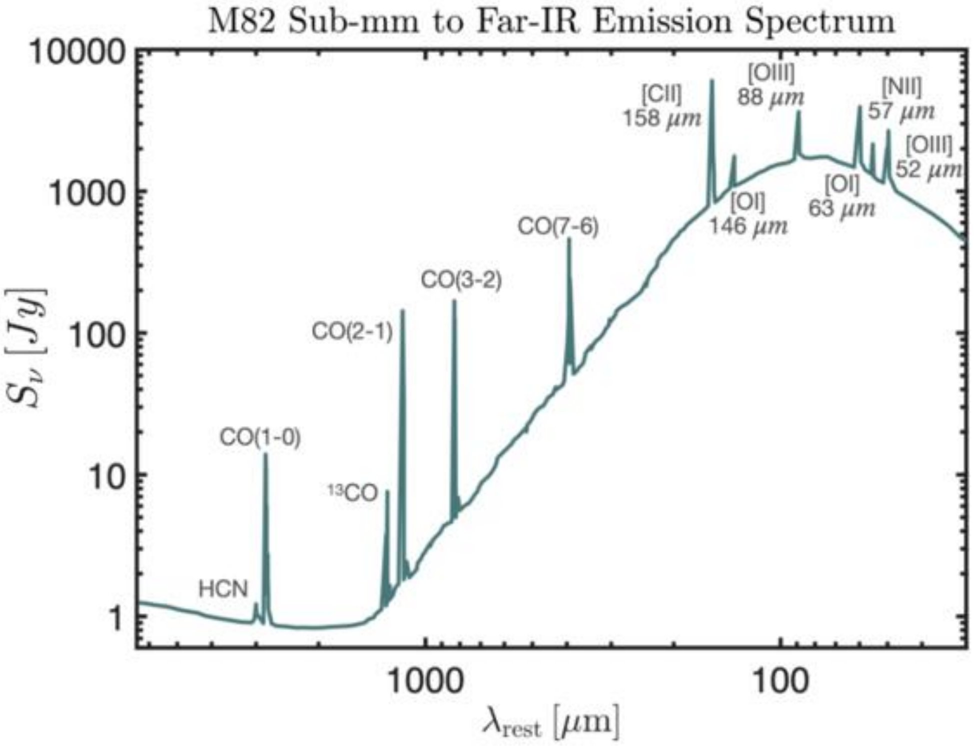



0.5 Deg



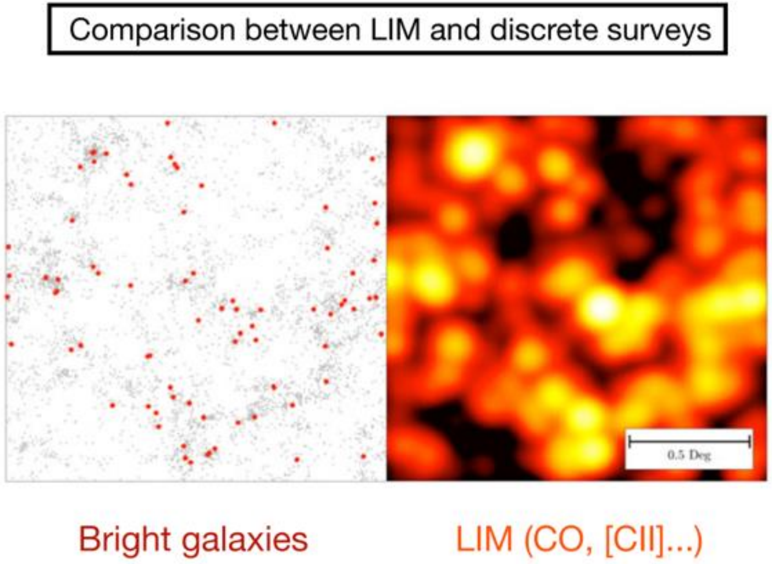
EXPLOIT TWO ADDITIONAL PHENOMENA

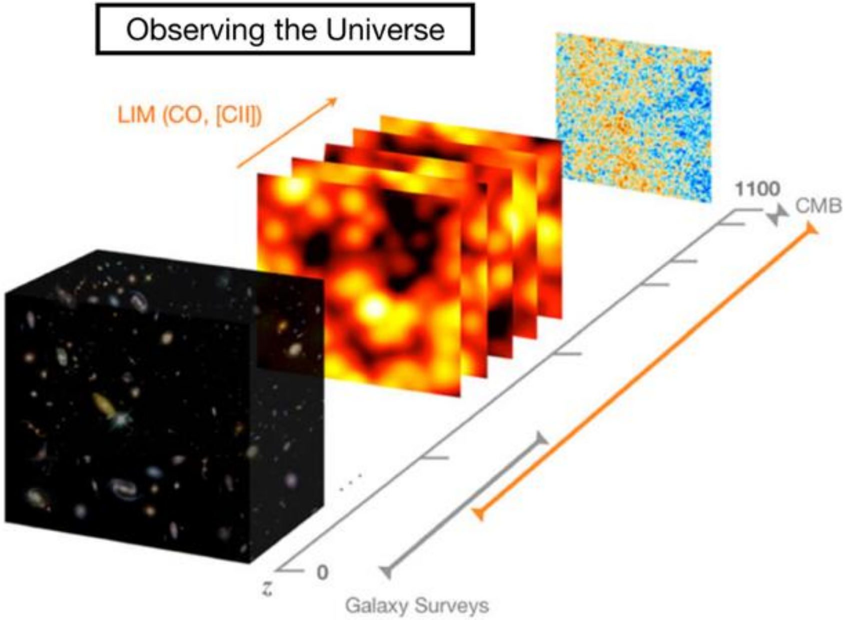
- Galactic line emission
  - Narrowband emission dominated by molecular line emission
- Cosmological redshift
  - shifts restframe wavelength into different observed wavelengths



LIM: LINE INTENSITY MAPPING

Survey large volume of the universe. 3D distribution of matter.





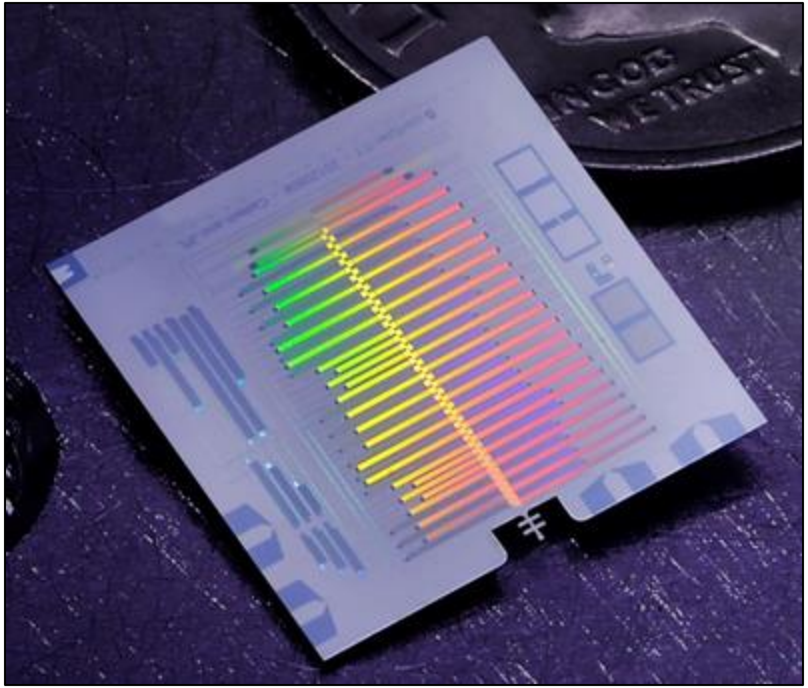
Silva+, Experimental Astronomy (2021) 51:1593–1622

REQUIREMENTS

LIM proposed using IR, 21 cm, and mm-wave

- At mm, measuring CO and CII emission
- Requirements
  - modest angular resolution (~0.5 deg)
  - Modest spectral resolution (R~200-300)
  - Large throughput (FOV ~deg^2)
- At mm-wave can build off CMB instrumentation
  - Telescopes already designed for modest angular resolution with well controlled systematics and high throughput
  - Focal planes already fill large FOV, just broadband

FOUNDATIONS



uchicago news

Erik Shirokoff, astronomer who built instruments to map the universe, 1979-2023

Remembered as patient and generous teacher and mentor

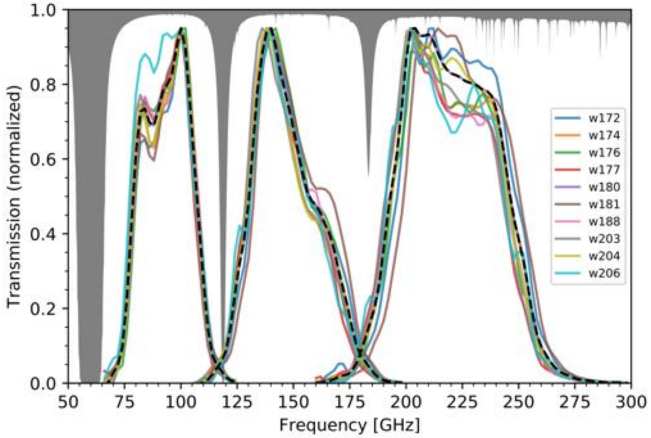
Assoc. Prof. Erik Shirokoff, a University of Chicago astronomer who built instruments to understand the earliest ages of the universe, died Jan. 26. He was 43.

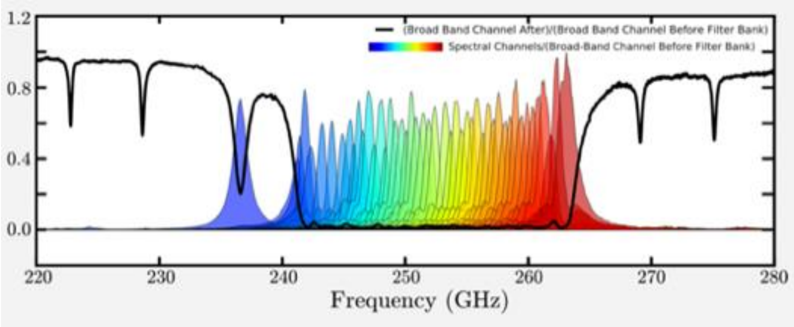
By Louise Lerner
Feb 3, 2023

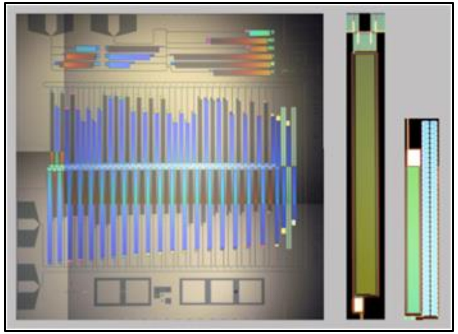
ON-CHIP SPECTROMETERS

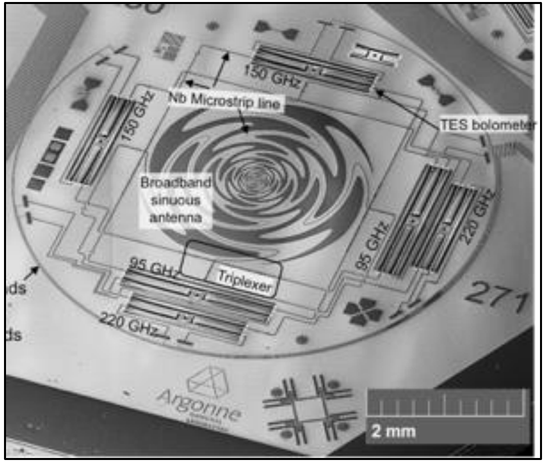
Building off broadband CMB detector arrays

- CMB “photometers” use antennas+microstrip
  - In-line filters define optical bands (~40%)
- Implement narrowband filters to realize on-chip spectrometers
  - Scalable to arrays
  - Large increase in detector density



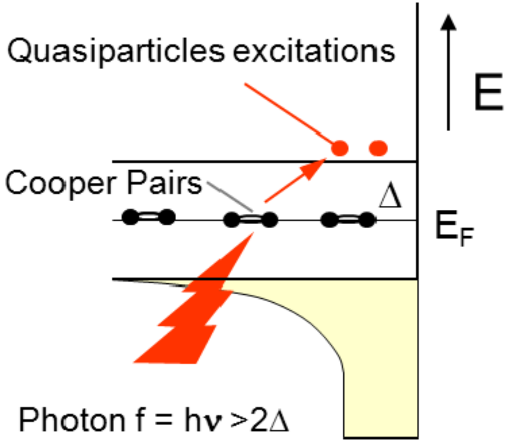


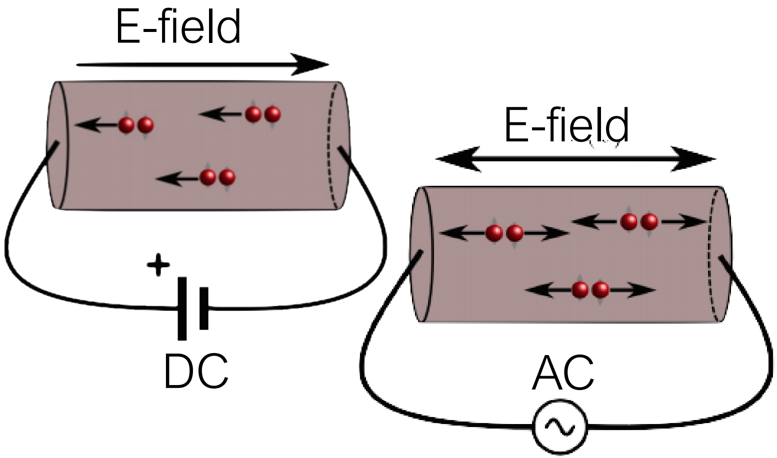




KINETIC INDUCTANCE

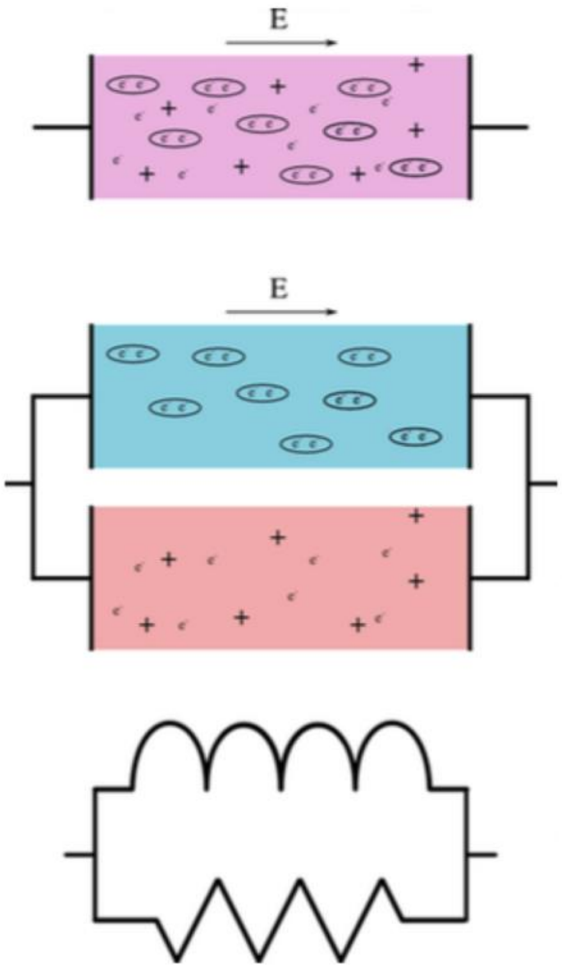
- Pairing of electrons into Cooper pairs
  - Energy gap between ground state and next excited state
- Quasiparticles are Cooper pair “excitations”
  - Fermions vs bosons
  - “Broken” Cooper pairs
- Cooper pairs have mass and momentum
  - Do not scatter. Charge flow (current) has no dissipation (real(Z) = 0)
  - Inertial response to changes in E-field. Charge flow lags field (imag(Z) ≠ 0)





SURFACE IMPEDANCE

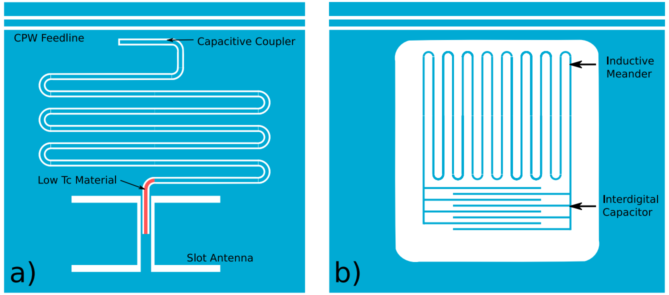
- Imagine superconductor as a fluid with two particles (Cooper pairs and quasiparticles)
- Complex conductivity depends on contributions from both
  — Cooper pairs:
    - No dissipation. Kinetic inductance.
  — Quasiparticles:
    - Dissipate
    - Small kinetic inductance
- Total complex conductivity depends on the population of pairs vs qps
  — Breaking pairs lead to a change in the complex impedance



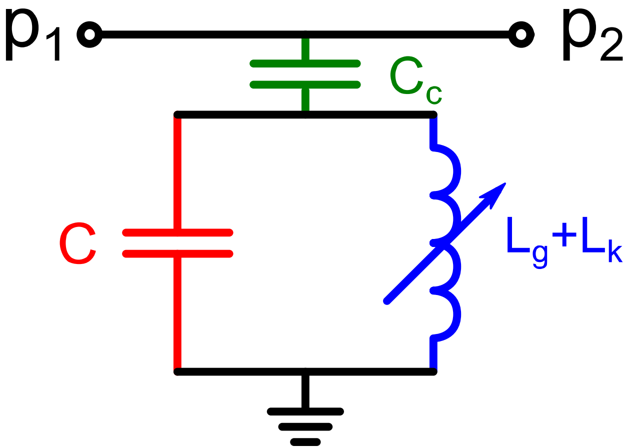
KINETIC INDUCTANCE DETECTORS

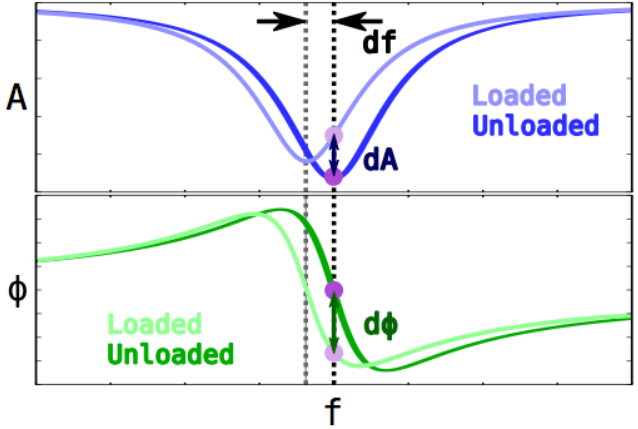
Measure Lk, Rs shift using LC resonator

- Resonator complex transfer function → phase + amplitude, frequency + Q



Distributed   Lumped element



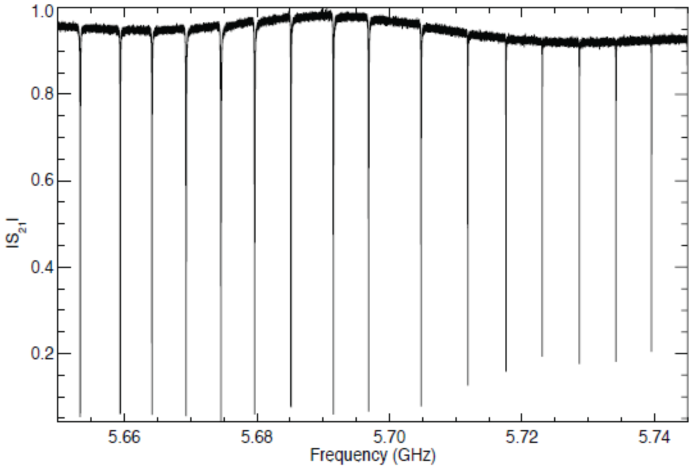


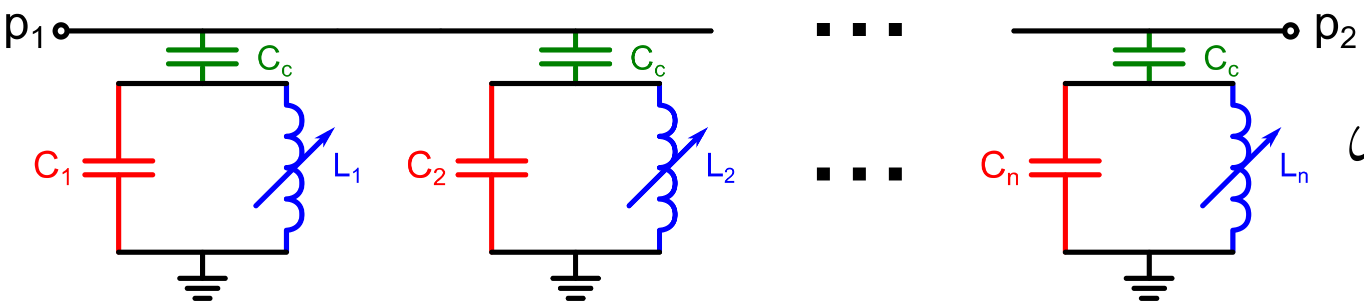
$$w_0 = \frac{1}{\sqrt{LC}}$$

$$Q_i = \frac{w_0 L}{R}$$

NATURALLY MULTIPLEXED

- LC resonator has specific F0
- Multiple resonators on a single line (just design w/ different f0s)
  - Readout w/ RF electronics
- Should be able to achieve few 10^3 / octave





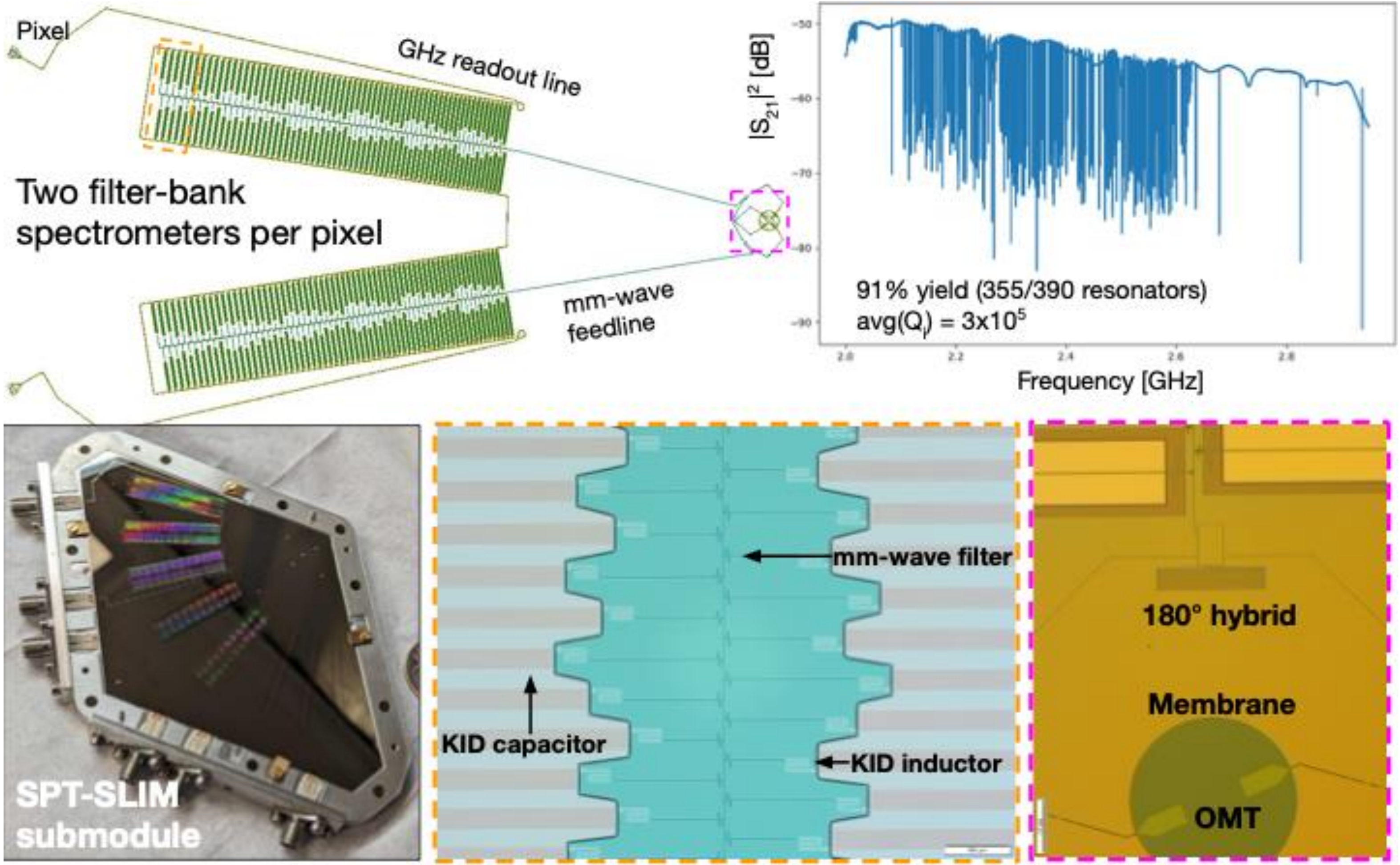
$$\omega_n = \frac{1}{\sqrt{L_n C_n}}$$

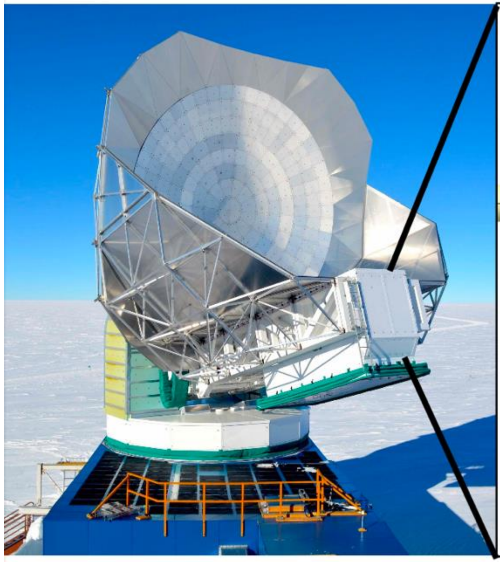
SCALING UP THE TECHNOLOGY

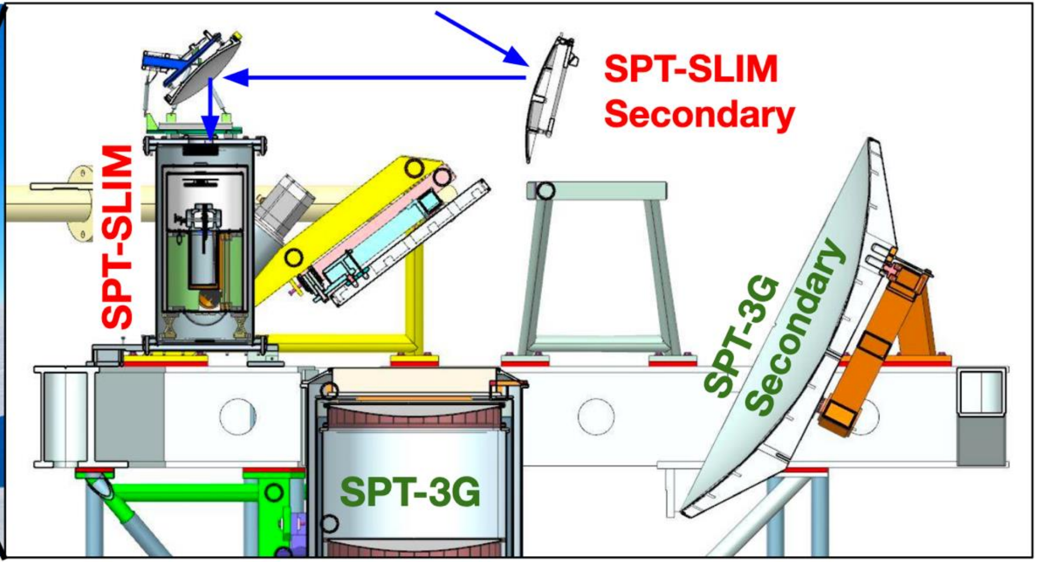
Spec-hrs	Example	Time-scale	$\sigma(f_{\rm NL})$	$\sigma(M_\nu)$ (meV)	$\sigma(N_{\rm eff})$	$\sigma(w_0) \times 10^2$	$\sigma(w_{\rm a}) \times 10^2$	FoM
10^5	TIME, CCAT-p, SPT-SLIM	2022	5.1 (5.1)	61 (65)	0.1 (0.11)	13 (14)	51 (52)	0.0015
10^6	TIME-EXT	2025	4.7 (5)	43 (47)	0.082 (0.087)	5.3 (6.3)	21 (26)	(0.09-0.1)
10^7	SPT-like 1 tube	2028	3.1 (4.2)	23 (28)	0.043 (0.051)	2 (2.2)	8.5 (9.7)	(1.7-3.1)
10^8	SPT-like 7 tubes	2031	1.2 (3)	9.7 (13)	0.02 (0.023)	0.93 (1)	3.8 (4.3)	(9.5-28)
10^9	CMB-S4-like 85 tubes	2037	0.48 (2.4)	4.1 (6.8)	0.013 (0.016)	0.61 (0.73)	2.1 (2.8)	(21-108)
Planck			5.1	83	0.187	41	100	—

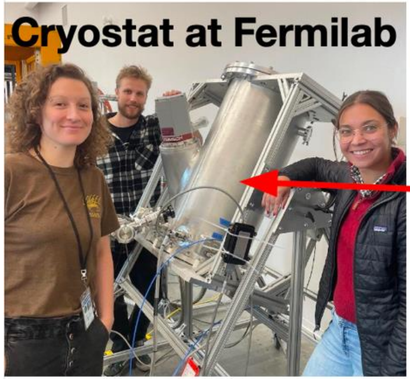
Karkare+, arXiv:2203.07258

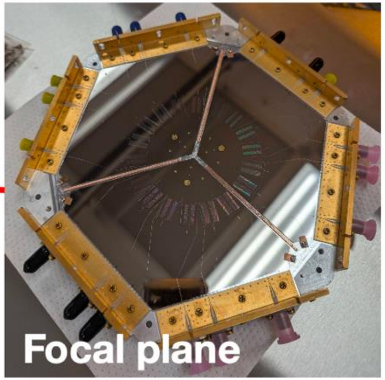
SPT-SLIM:
THE SOUTH POLE TELESCOPE SUMMERTIME LINE INTENSITY MAPPER

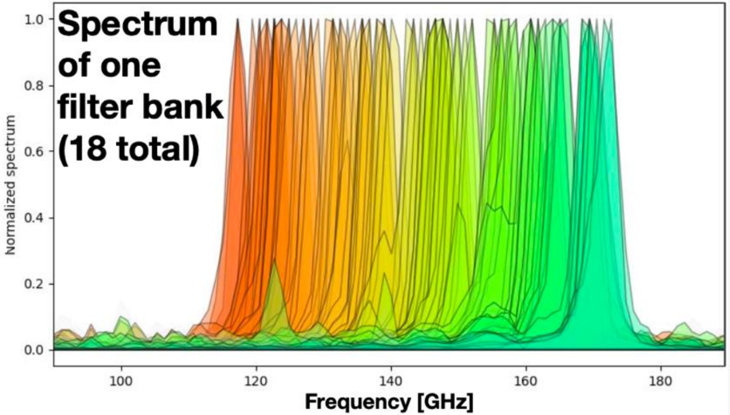

Pixel
GHz readout line
Two filter-bank spectrometers per pixel
mm-wave feedline
$|S_{21}|^2$ [dB]
Frequency [GHz]
91% yield (355/390 resonators)
avg(Q_i) = 3x10^5
SPT-SLIM submodule
mm-wave filter
KID capacitor
KID inductor
180° hybrid
Membrane
OMT




SPT-SLIM
Secondary
SPT-SLIM
SPT-3G
Secondary
SPT-3G


Cryostat at Fermilab


Focal plane


Spectrum
of one
filter bank
(18 total)
Normalized spectrum
Frequency [GHz]
0.0
0.2
0.4
0.6
0.8
1.0
100
120
140
160
180


DNF
DNF
DNF
DNF

NEXT STEPS

Spec-hrs	Example	Time-scale	$\sigma(f_{\rm NL})$	$\sigma(M_\nu)$ (meV)	$\sigma(N_{\rm eff})$	$\sigma(w_0) \times 10^2$	$\sigma(w_{\rm a}) \times 10^2$	FoM
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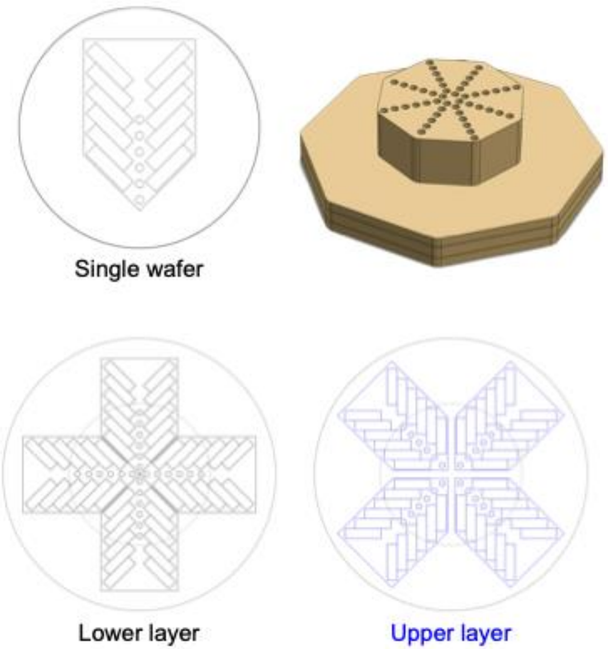
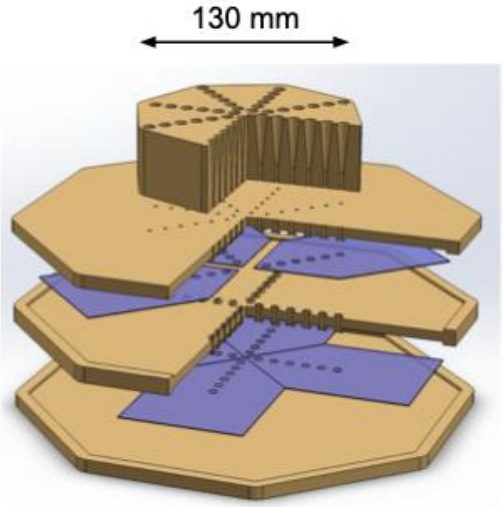
Karkare+, arXiv:2203.07258

COLIMATE

COsmology Line Intensity Mapping with Advanced Technology Experiment

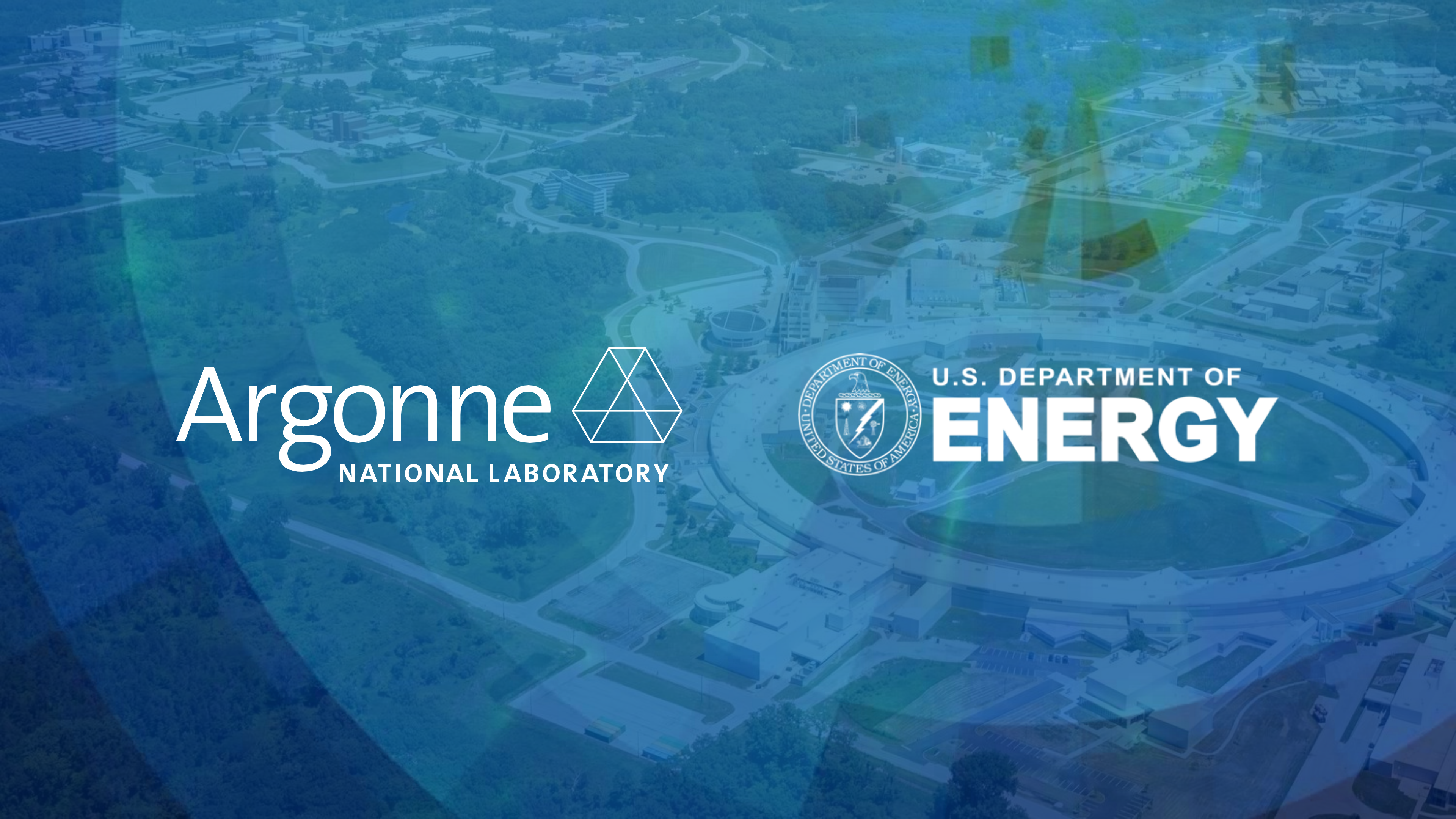
- Advance technical readiness of scaled arrays
  - Focal plane for 130 mm optics tubes
  - Target survey observations
- Multi-tiered packaging increases detector count
- Additional improvements of microstrip materials





RECAP

- LIM is a fast, low spatial/spectral survey technique for cosmology
- Mm-wave requires developing and scaling up on-chip spectrometers
  - Builds off CMB heritage and instrumentation
- SPT-SLIM targets deployment this season
  - On-sky demo of multipixel spec array (scaling up from single pixel)
- Next steps is further R&D to drive technology forward
  - Build off SLIM technology for straightforward scaling up & fielding of even larger arrays
  - Opportunity for new approaches to improve optical and packing efficiency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ENERGY