Intensity Mapping Cosmology

Snowmass Colloquium

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With help from Kirit Karkare, University of Chicago

24 June 2022

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U.S. DEPARTMENT OF ENERGY

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Intensity mapping in a nutshell

- Intensity mapping is a general concept
- It is a new way to look at the galaxy surveys:
  - don’t resolve individual galaxies, but look at the aggregate signal from many galaxies
  - you can optimize your instrument to have signal-to-noise where you need it
- Potentially a very cost-effective way of doing future surveys
- Typically used in context of 21cm (100-1400MHz) and molecular line mapping (10-600GHz), but can in principle be applied at any frequency

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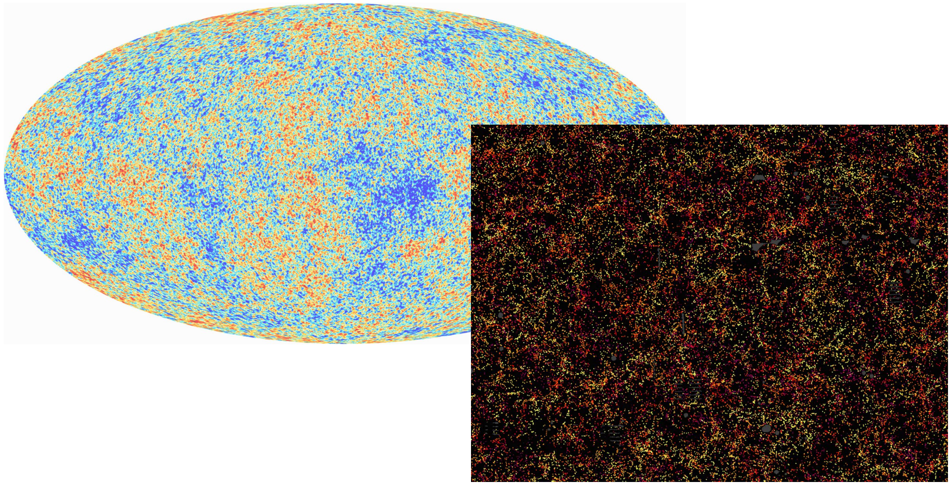
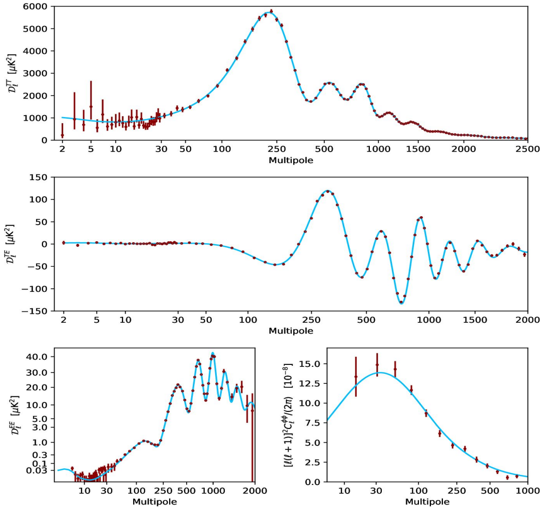
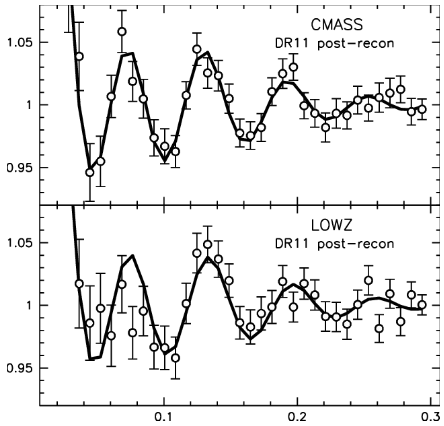
Fluctuations tell us everything!



Planck Power spectra



SDSS BAO spectra



- Majority of cosmological information comes from mapping the universe and measuring statistics on the fields of density fluctuations

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Linear and non-linear scales

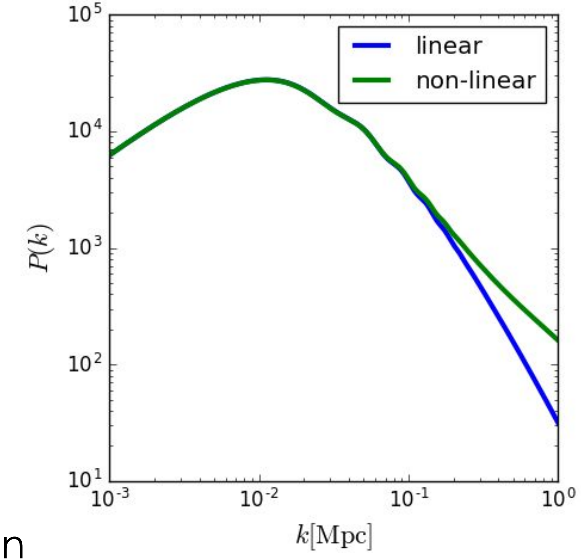
- Structure in the universe forms from the small initial seed fluctuations
- In linearized gravity fourier modes grow independently

$$\delta(k,t) = \frac{g(t)}{g(t_0)}\delta(k,t_0)$$

- Galaxy further trace dark matter linearly on large scales (only assuming locality)

$$\delta_g(k,t) = b\delta(k,t)$$

- Small scales:
  - harder to model
  - mode coupling tends to erase primordial information
  - really small virialized scales forget about their cosmological origin (but they still know new physics)



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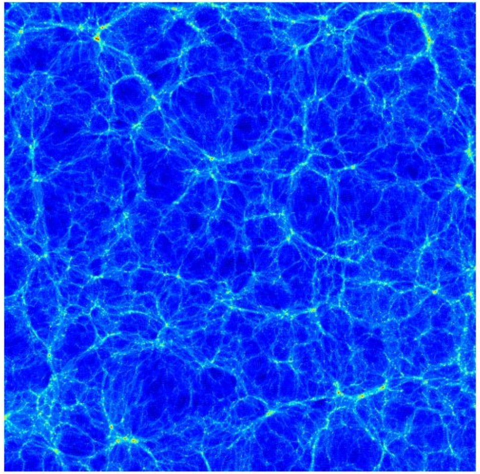
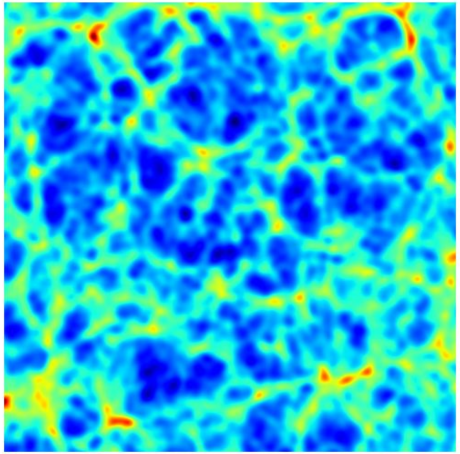
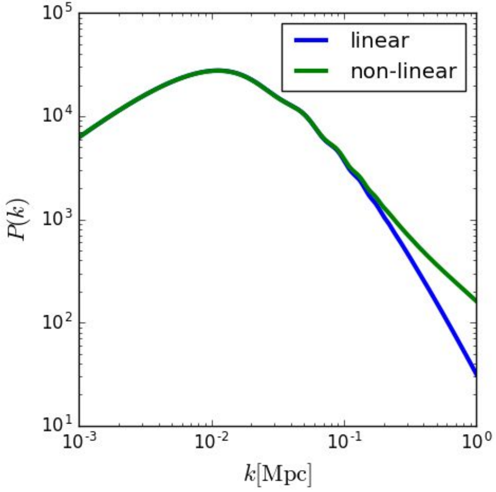
Intensity mapping

- In traditional galaxy surveys, you get the same SNR on all scales, but majority of information still comes from large scales
- Why don't we just give up the smalls scale information?
- For scales much bigger than individual galaxies, the overall signal will still trace the underlying number density of galaxies
- Put SNR where you really need it -- linear large scale modes





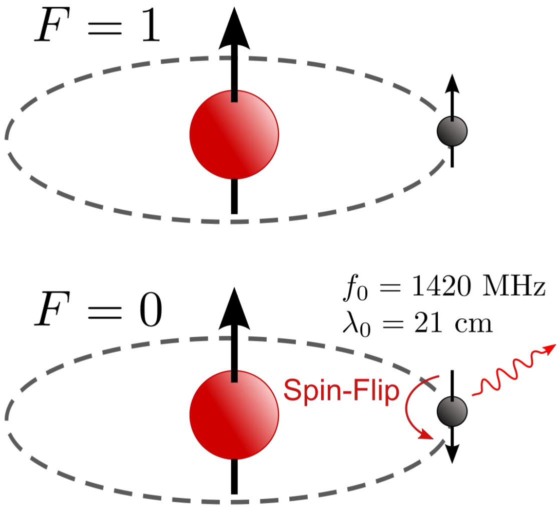


When is intensity mapping used

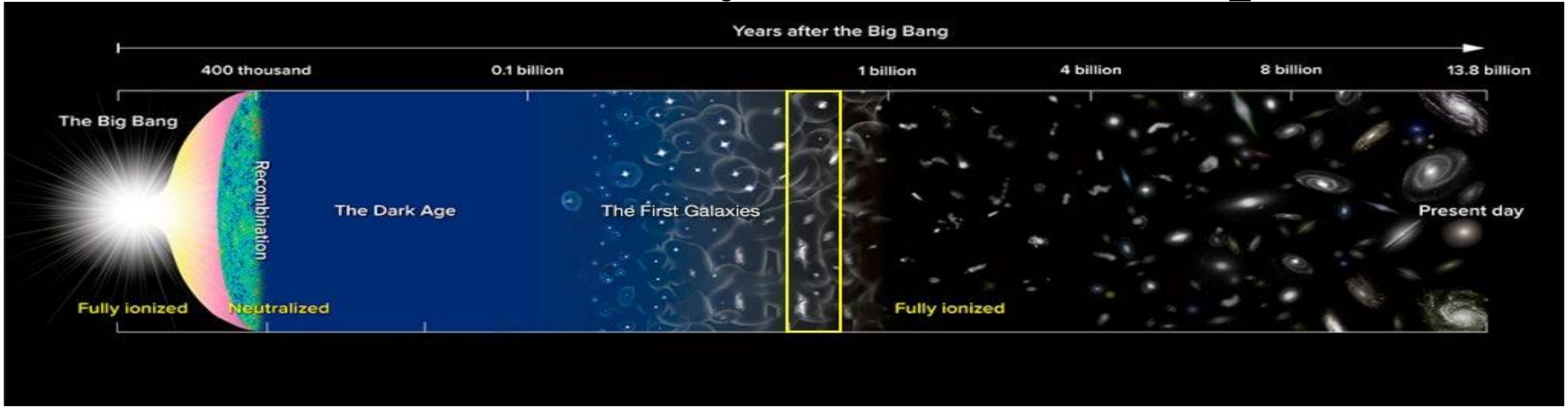
- It is used mostly to beat the natural resolution limit of the telescope:
  - 21cm
  - molecular lines
- It can be used to beat the noise limitation of the telescope:
  - Marginal 2-sigma peaks in the noise could be real or not
  - Instead of worrying, one can cross-correlate intensity with an external tracer and pull out signal below the noise of individual pixels
  - (in other words, 2-sigma peaks happen more often in the regions of high density)

21cm emission

- Hyperfine transition in neutral hydrogen at ν=1420MHz, λ=21.1cm;
- This is the **only** transition around -- if you see a line at 710MHz, it is a z=1 galaxy;
- (not true in other bands)
- Universe is mostly hydrogen (75%), but at low redshift we are sensitive to **pockets of neutral hydrogen in galaxies**;
- 21cm surveys are galaxy surveys in radio



21cm shines differently at different epochs



Dark Ages
$20 \lesssim z \lesssim 150$

- Pristine primordial density field
- We see 21cm in emission / absorption against CMB light from the global density field
- Subject of LuSEE-Night pathfinder experiment

Epoch of Reionization
$6 \lesssim z \lesssim 20$

- First stars and galaxies are reionizing universe
- Large bubbles of ionized gas among neutral medium
- Signal driven by astrophysics
- Non-DOE science

Low redshift
$z \lesssim 6$

- Universe is reionized
- pockets of neutral hydrogen in galaxies
- Very similar science to standard galaxy surveys
- We don’t aim to go after individual galaxies

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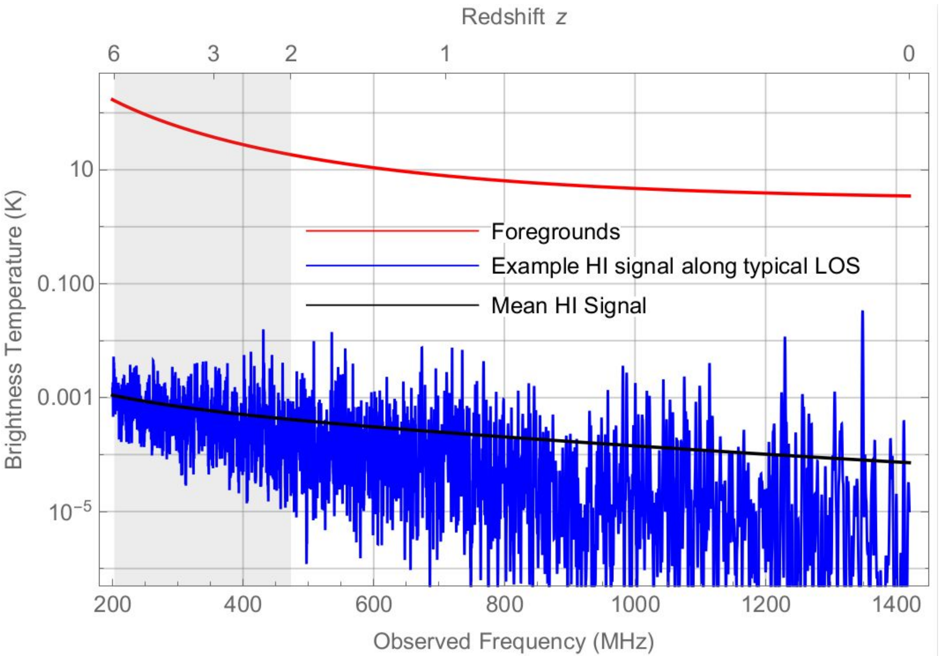
But 21cm is not the only radio signal…



- Signal is subdominant, but the only non-smooth component.
- Of course, instrument can have non-smooth, time-varying response too!

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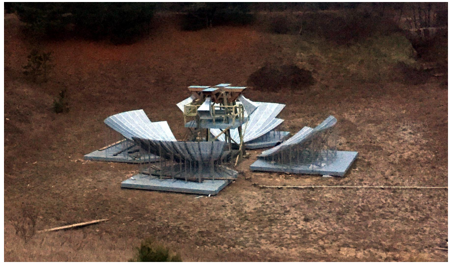
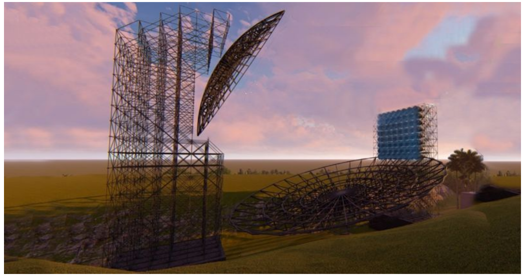
Operating and Proposed Dedicated Experiments



BMX pathfinder

CHIME

PUMA



BINGO

HIRAX

CHORD

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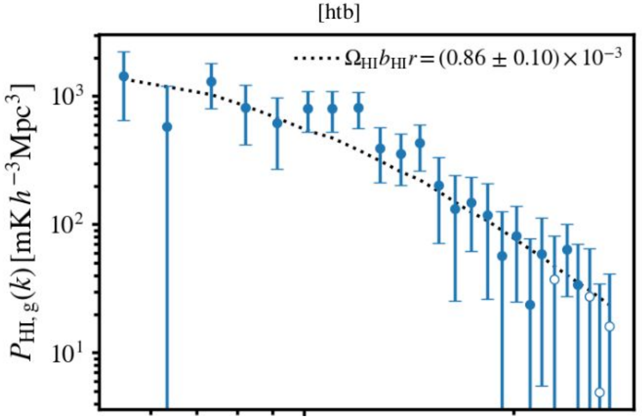
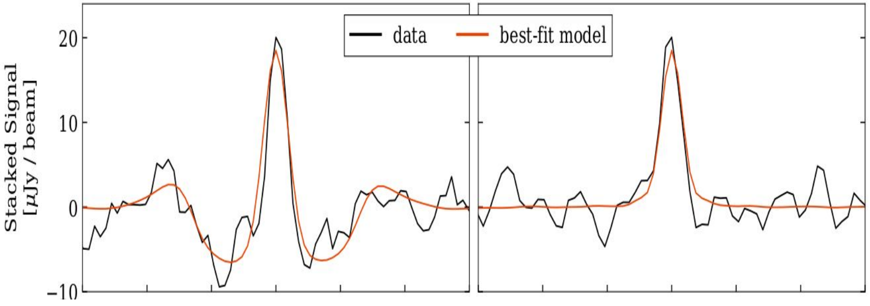
Current experimental status

- Experiments are getting many-sigma detections in cross-correlations
- Not yet cosmologically competitive
- Calibration remains the main issue:
    - Instrument chromaticity makes foreground leak into the signal region



7 sigma: MeerKAT x WiggleZ



11 sigma: CHIME x BOSS QSO

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R&D for 21cm intensity mapping

- The issues are entirely technical and can be overcome with sufficient R&D
- Bridging the credibility gap by contributing analysis to near-term existing experiments
- Long-term, 21cm is a good match to DOE institutional strengths

DSA-2000, a non-IM focused “radio camera” that could also do IM

PUMA: dedicated next-get concept

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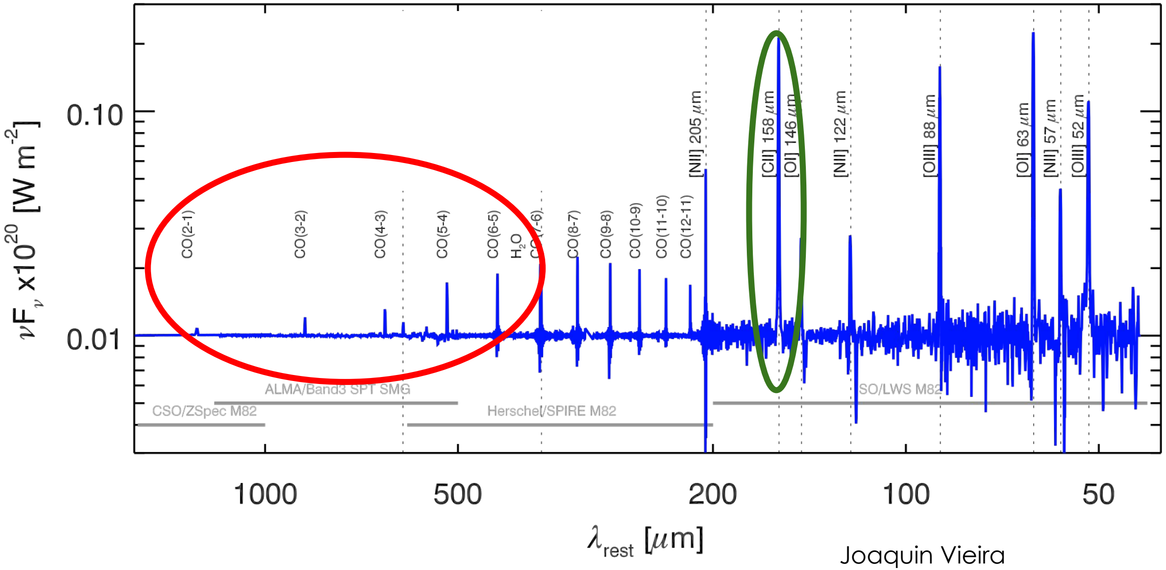
Another intensity mapping candidate: Far-IR lines

- 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

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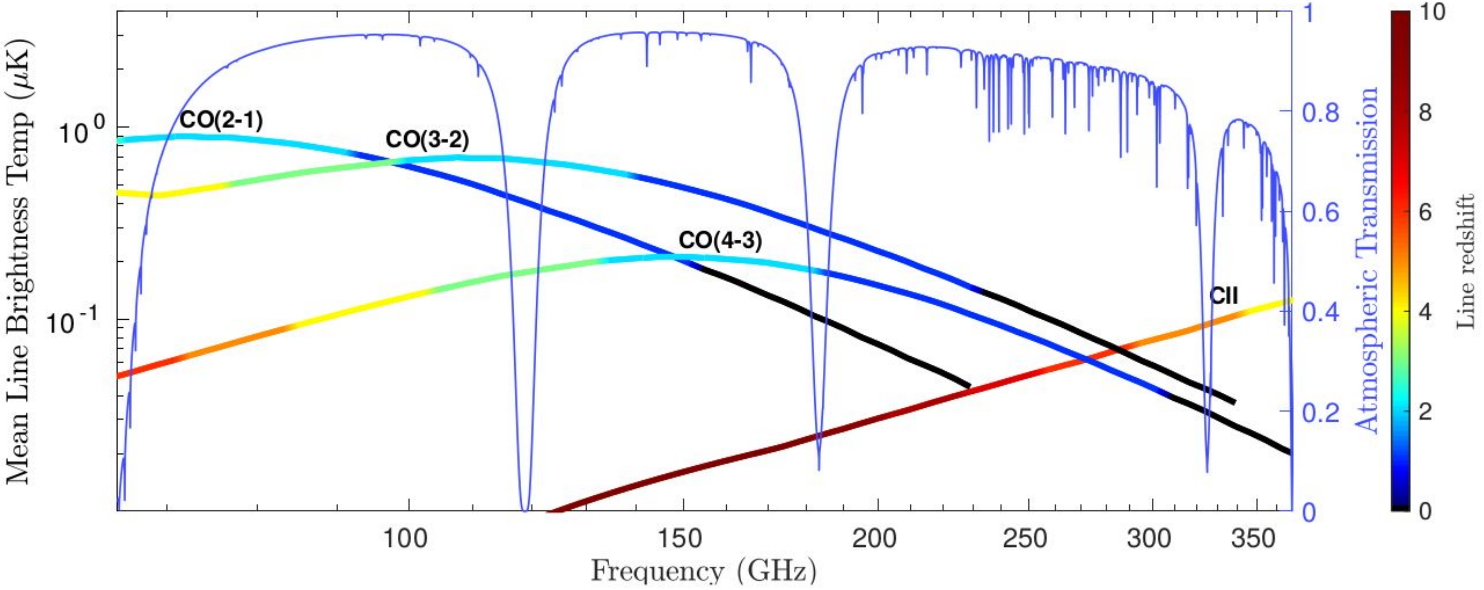
Redshift coverage

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.

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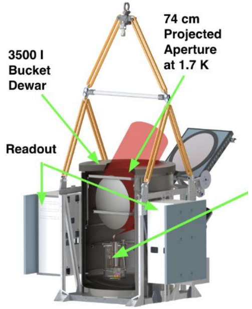
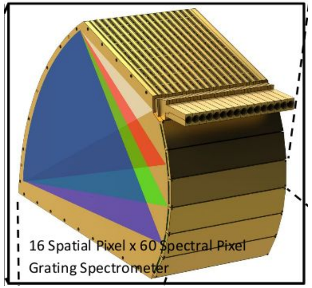
Current mm-wave LIM status

- Preliminary detections of CO at small scales, and [CII] in cross-correlation.
- Many pathfinder experiments are now operating or will deploy in the next few years, targeting lines across a wide range of redshifts, using a wide variety of spectrometer technologies.
- Expect solid detections soon, refining models and cosmological projections.

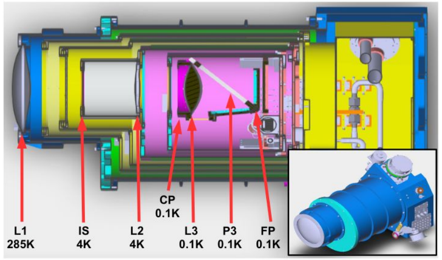


EXCLAIM

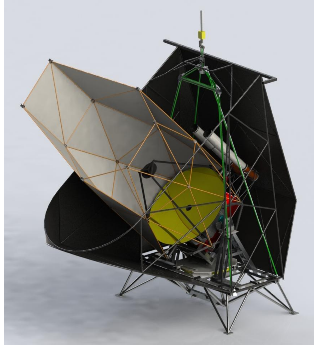
COMAP



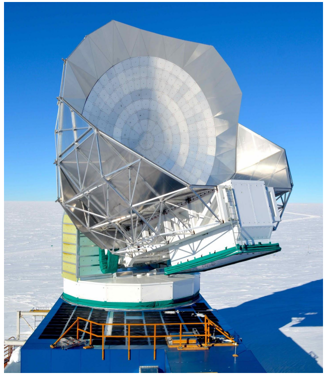
TIME



CONCERTO



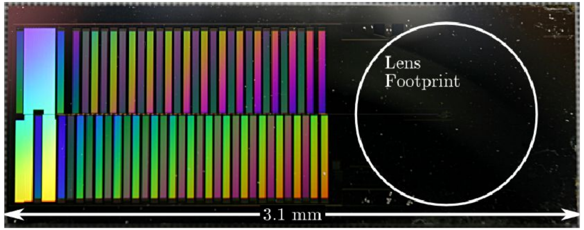
TIM



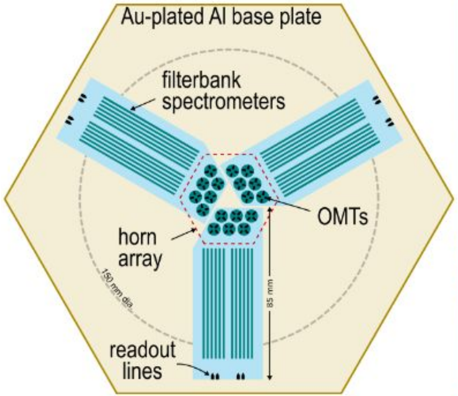
SPT-SLIM

R&D for mm-wave LIM

- Current instruments are sensitivity-starved. We need to develop high-density mm-wave spectrometers that can be deployed at scale
  - **On-chip spectroscopy** extremely promising, using techniques developed for CMB detectors
- Primary analysis challenge is line separation
  - Many techniques exist in the literature but haven't been validated on real data
- Complementary to 21cm
  - Continuum foregrounds more favorable, but need to deal with interlopers
  - Different calibration challenges
  - Can reuse existing CMB facilities



SuperSpec (6 spectrometers) → SPT-SLIM (38 spectrometers)



For more details see mm-LIM white paper, 2203.07258

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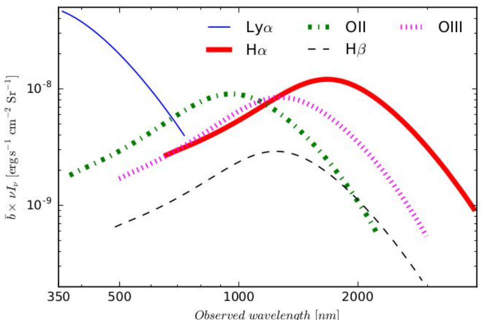
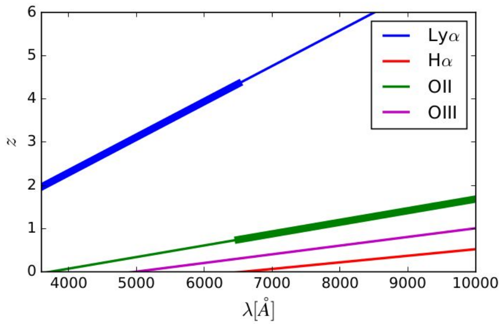
Intensity mapping in optical

- The most natural candidates are Lyman-alpha (2 ->1) and Ha (3->2) lines
- Instruments are either photometric or fiber fed spectrographs: not naturally suited
- From the ground there are additional atmospheric background fluctuations and optical artifacts





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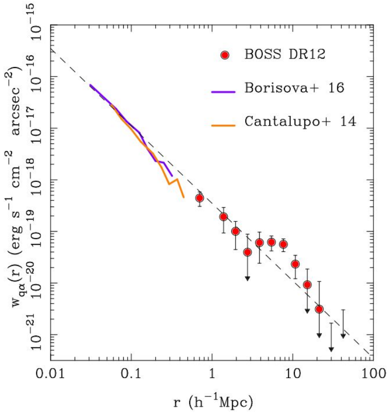
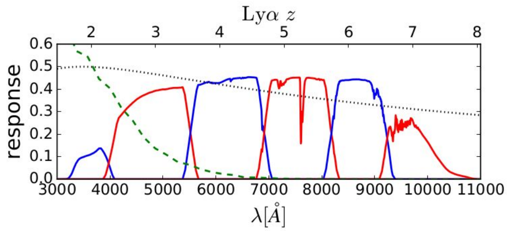
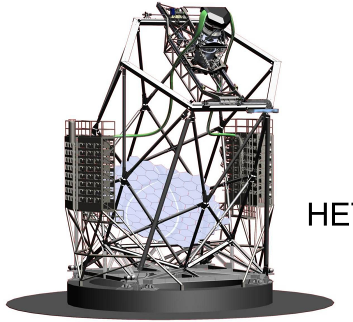
Intensity mapping in optical

- Spectroscopic: subctract best-fit galaxy models from galaxy spectra (Croft et al)
  - with e.g. DESI
- Photometric: Live with fat bands and rely on cross-correlation (after removing galaxies)
  - with e.g. LSST
- SphereX: spectra per pixel via LVF
- HETDEX: integral field spectroscopy

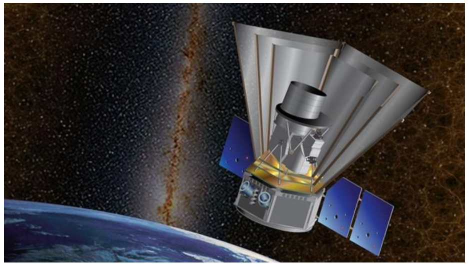


Croft et al 2018





HETDEX



SphereX: linear variable filter

What can future experiments do?

- In the CF4 group we have identified two distincit possibilities for future surveys:
  - **large volume, high N_{lin}**
  - large number density, high nP
- Majority of results from the Ferraro et al whitepaper.

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass2021 Cosmic Frontier White Paper:
Cosmology and Fundamental Physics from the
three-dimensional Large Scale Structure

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for the Snowmass 2021 Cosmic Frontier 4 Topical Group

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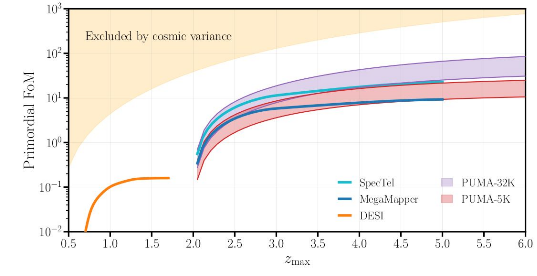
[2]Berkeley Center for Cosmological Physics, Department of Physics, University of California, Berkeley, CA 94720, USA
[3]Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

March 16, 2022

Current and proposed experiments



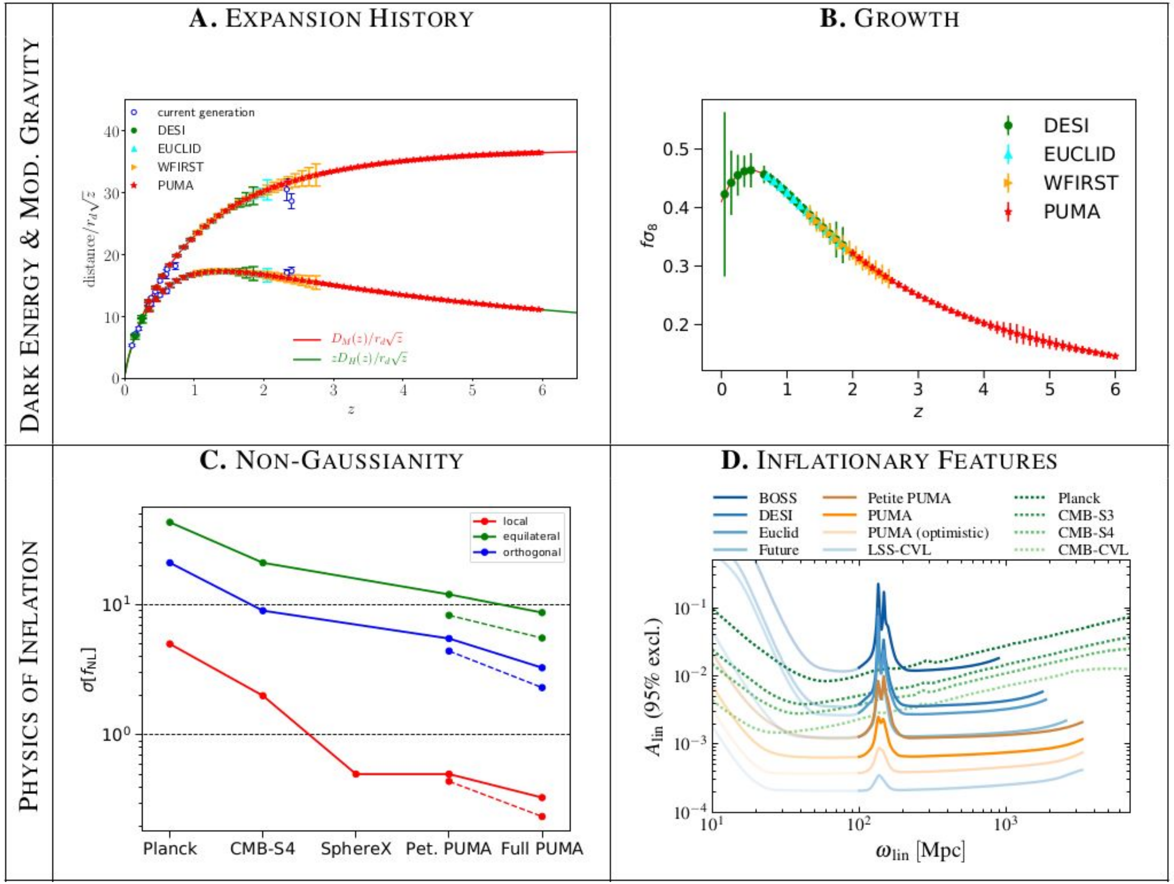
in the pipeline

	Experi-ment type	Concept	Redshift Range	Primordial FoM	Time-scale	Technical Maturity	
DESI	spectro	5000 robotic fiber fed spectrograph on 4m Mayall telescope	$0.7 < z < 2.0$	0.16	now	operating	
Rubin LSST	photo	*ugrizy* wide FoV imaging on a 6.5m effective diameter dedicated telescope	$0 < z < 3$	-	2025-2035	on schedule	Targeting survey for next generation spectroscopic instruments
SPHEREx	narrow-band	Variable Linear Filter imaging on 0.25m aperture from space	$0 < z < 4$	-	2024	on schedule	Focus on primordial non-Gaussianity
MSE+†	spectro	up to 16,000 robotic fiber fed spectrograph on 11.25 m telescope	$1.6 < z < 4$ (ELG+LBG samples)	< 6.1	2029-	high	
MegaMapper	spectro	20,000 robotic fiber fed spectrograph on 6m Magellan clone	$2 < z < 5$	9.4	2029-	high	Builds upon existing hardware and know-how
SpecTel†	spectro	20,000-60,000 robotic fiber fed spectrograph on a dedicated 10m+ class telescope	$1 < z < 6$	< 23	2035-	medium	Potentially very versatile next generation survey instruments
PUMA	21 cm	5000-32000 dish array focused on intensity 21 cm intensity mapping	$0.3 < z < 6$	85 / 26 (32K / 5K optimistic)	2035-	to be demon-strated	Very high effective number density, but $k_{\parallel}$ modes lost to foregrounds
mm-wave LIM concept	mi-crowave LIM	500-30000 on-chip spectrometers on existing 5-10m telescopes, 80-300 GHz with R∼300-1000	$0 < z < 10$	up to 170	2035 -	to be demon-strated	CMB heritage, can deploy on existing telescopes, signal uncertain, $k_{\parallel}$ modes lost to foregrounds & resolution

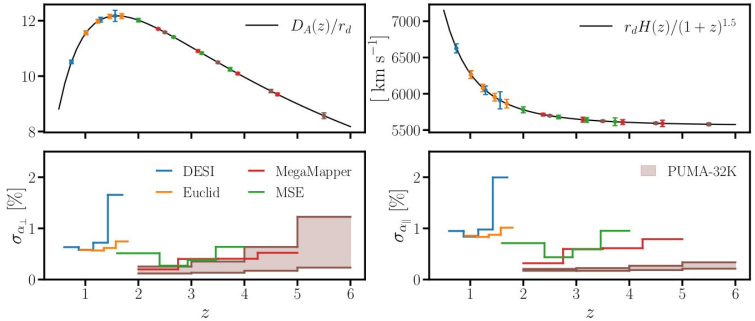
proposed spectroscopic

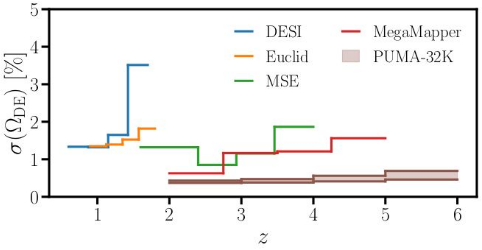
proposed Intensity Mapping

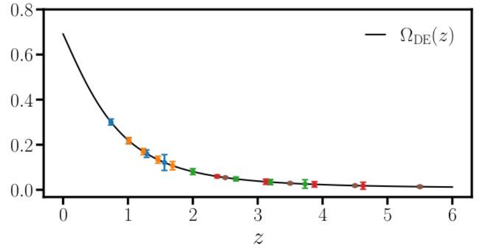
Intensity mapping science

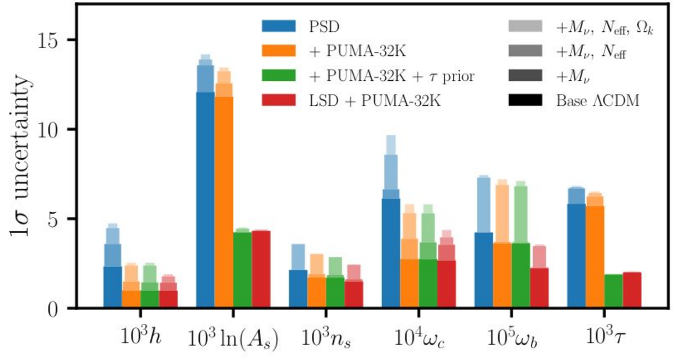


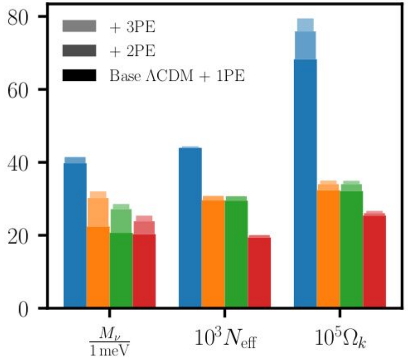
Intensity Mapping Experiments can go far!

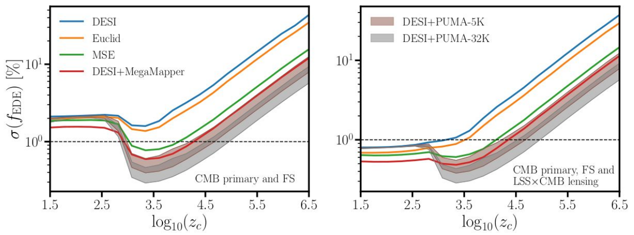












Take home message

Intensity mapping is a new to think about survey Cosmology.
Can enable amazing science for little money.

Radio:

- 100-1440 MHz
- Synergistic with a big EoR community
- Rides commoditization of RF equipment
- Hydrogen is everywhere
- Pathfinder towards future lunar Dark Ages (e.g. Decadal Discovery Area)
- Calibration remains a main issue in presence of foregrounds
- Would benefit from injection of R&D, particularly in analyzing current-gen data

Sub-mm:

- 10-600 GHz
- Can rely on upgrades of existing telescopes
- Foregrounds and calibration considerably easier
- Interlopers, need for cryo are drawbacks
- Would benefit from injection of R&D, particularly in development of sub-mm spectrometer

Optical:

- 3600-10000 Ang
- No effective way of measuring spectra and images at the same time
- Will likely remain a niche area for a while
- Could potentially offer new science from DESI/LSST at the cost of a few postdocs