Title: Spectral Line Intensity Mapping of Cosmic Structures

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Abstract: <p>Line Intensity Mapping has emerged as a powerful tool to probe the large-scale structure across redshift, with the potential to shed light on dark energy at low redshift and the cosmic dawn and reionization process at high redshift. Multiple spectral lines, including the redshifted 21cm, CO, [CII], H-alpha, and Lyman-alpha emissions, are promising tracers in the intensity mapping regime, with several experiments on-going or in the planning. I will discuss results from current pilot programs, prospects for the upcoming TIME experiment, and the outlook of future space missions such as SPHEREx. I will illustrate how the use of cross-correlation between multiple line intensity maps will enable unique and insightful measurements, revealing for example the tomography of reionization and the physics of multiple phases of the interstellar medium across redshift.</p>

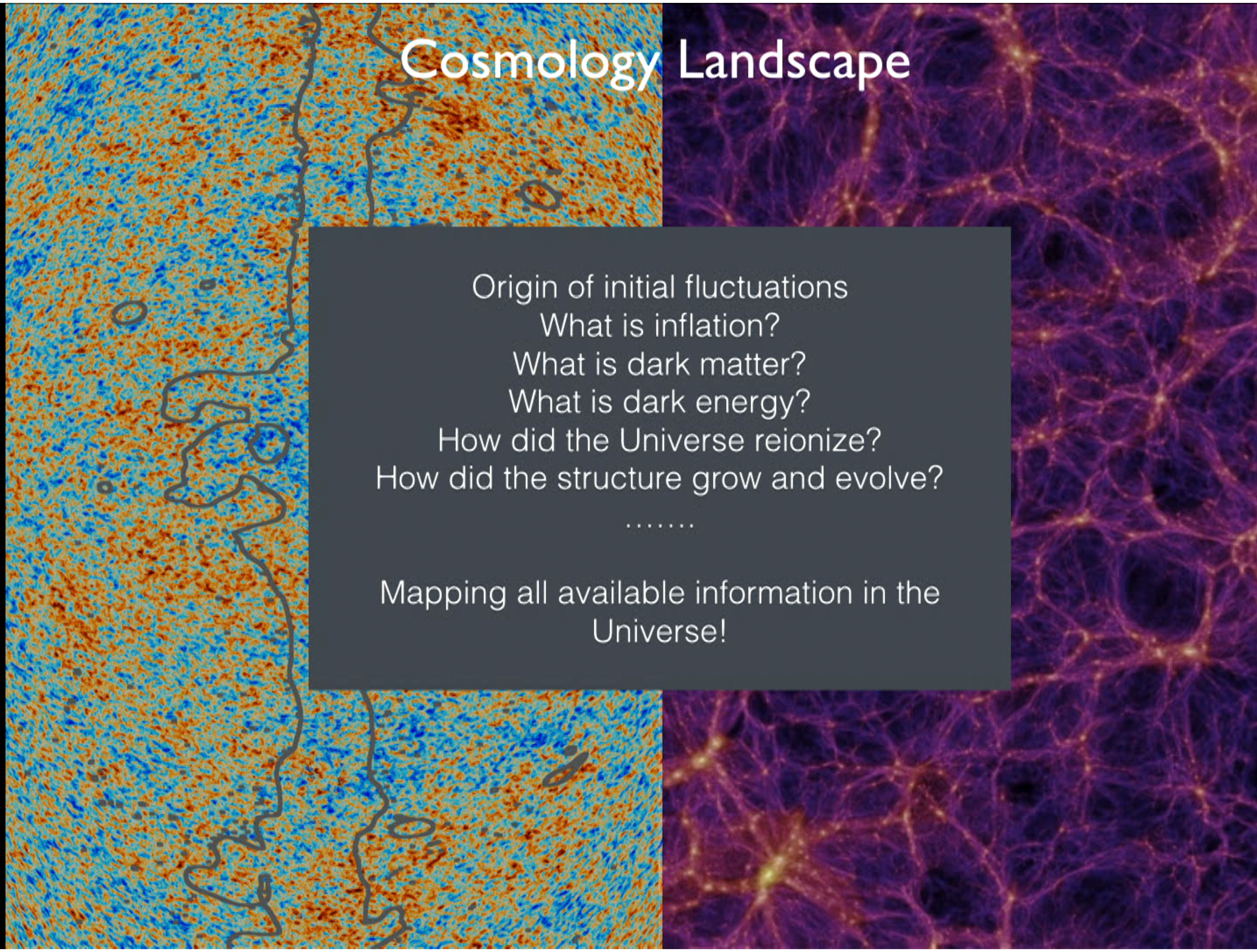
Intensity Mapping of Cosmic Structures

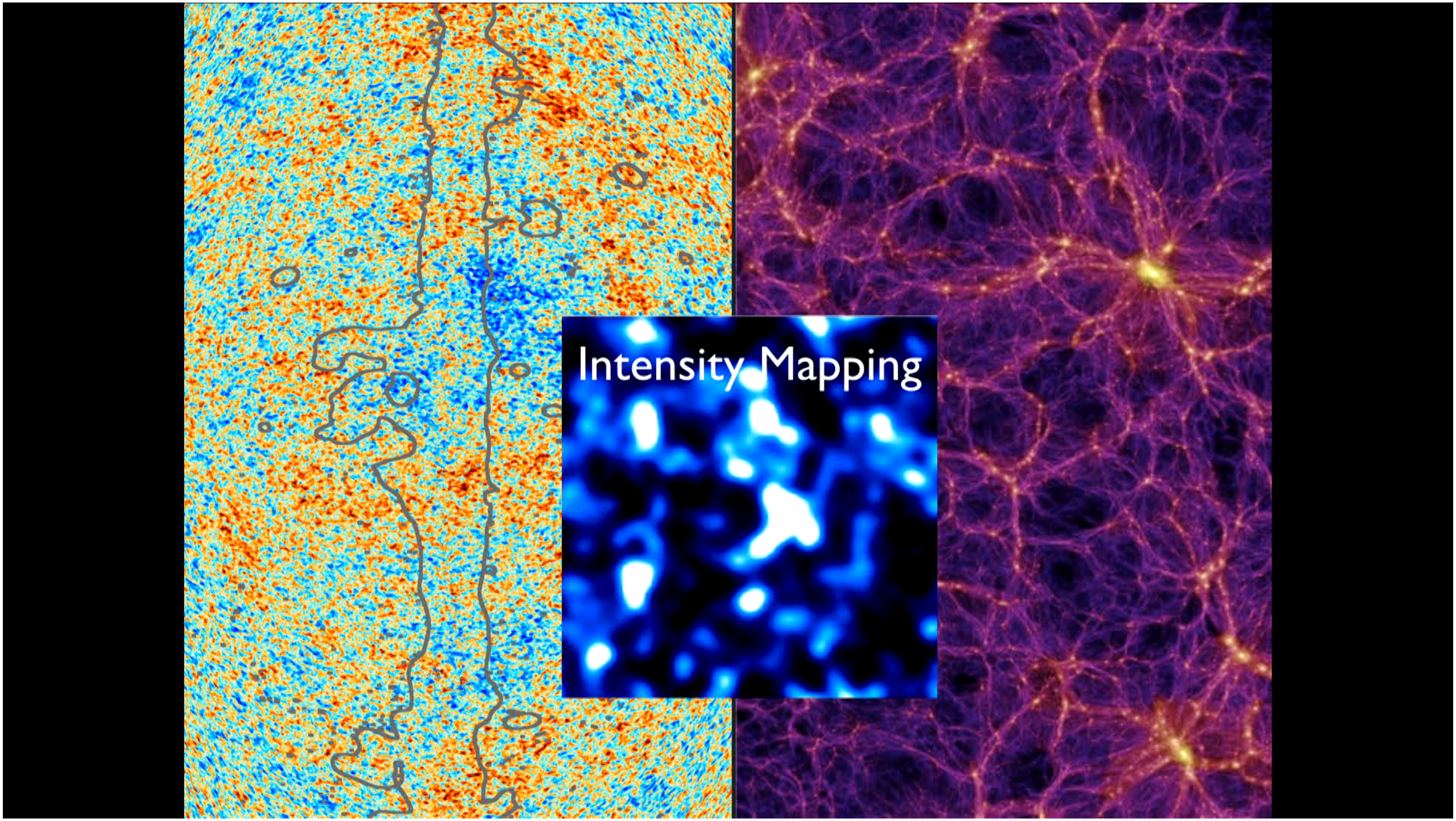
Tzu-Ching Chang
Jet Propulsion Laboratory, California Institute of Technology

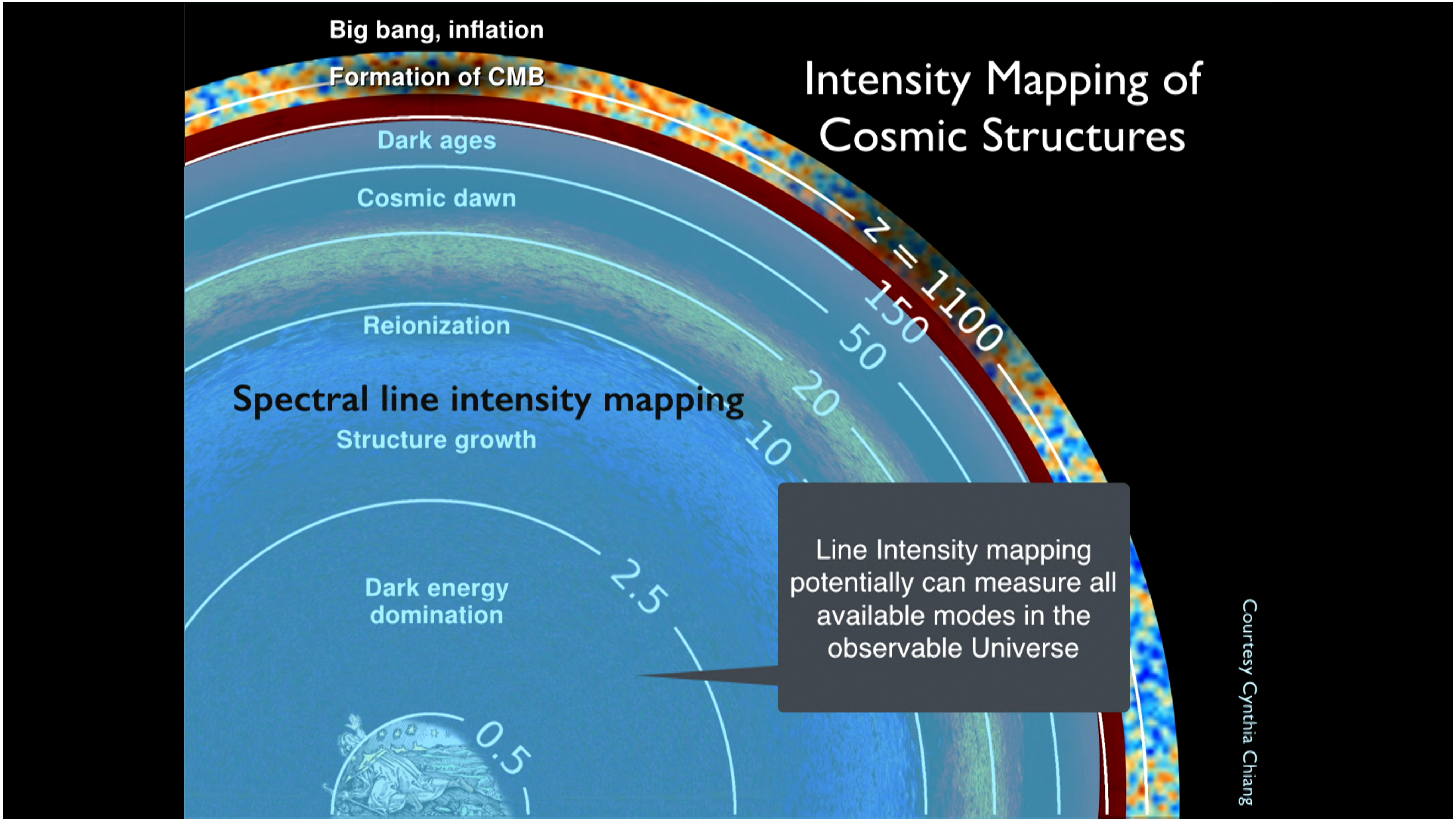
TIME Collaboration

Jamie Bock, Matt Bradford, Abigail Crites, Yun-Ting Cheng, Steve Halley-Dunsheath, Jonathan Hunacek, Roger O'Brient, Jason Sun, Bade Uzgil (Caltech/JPL)
Patrick Koch, Chao-Te Li (ASIAA), Mike Zemcov (RIT), Dan Marrone (Arizona)
Asantha Cooray (UCI)

SPHEREx Science Team

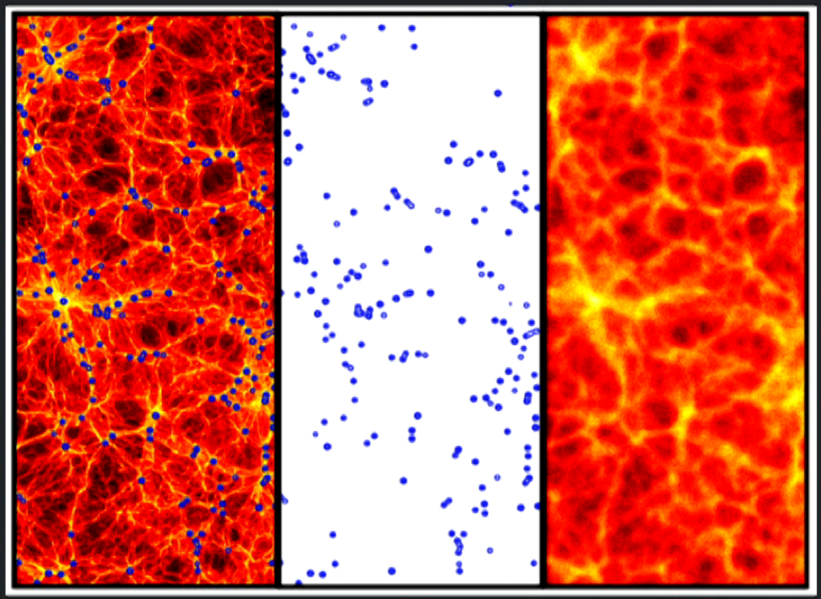

Cosmology Landscape
Origin of initial fluctuations
What is inflation?
What is dark matter?
What is dark energy?
How did the Universe reionize?
How did the structure grow and evolve?
....
Mapping all available information in the Universe!


Intensity Mapping



Big bang, inflation
Formation of CMB
Dark ages
Cosmic dawn
Reionization
Spectral line intensity mapping
Structure growth
Dark energy domination
z = 1100
150
50
20
10
2.5
0.5
Intensity Mapping of Cosmic Structures
Line Intensity mapping potentially can measure all available modes in the observable Universe
Courtesy Cynthia Chiang

Line Intensity Mapping (IM)



courtesy Phil Korngut

•"Intensity Mapping" (Chang+ 2008, Wyithe & Loeb 2008):

- •Measure the collective emission from a large region, more massive and luminous, without spatially resolving down to galaxy scales.

• Use spectral lines as tracers of structure, retain high frequency resolution thus redshift information

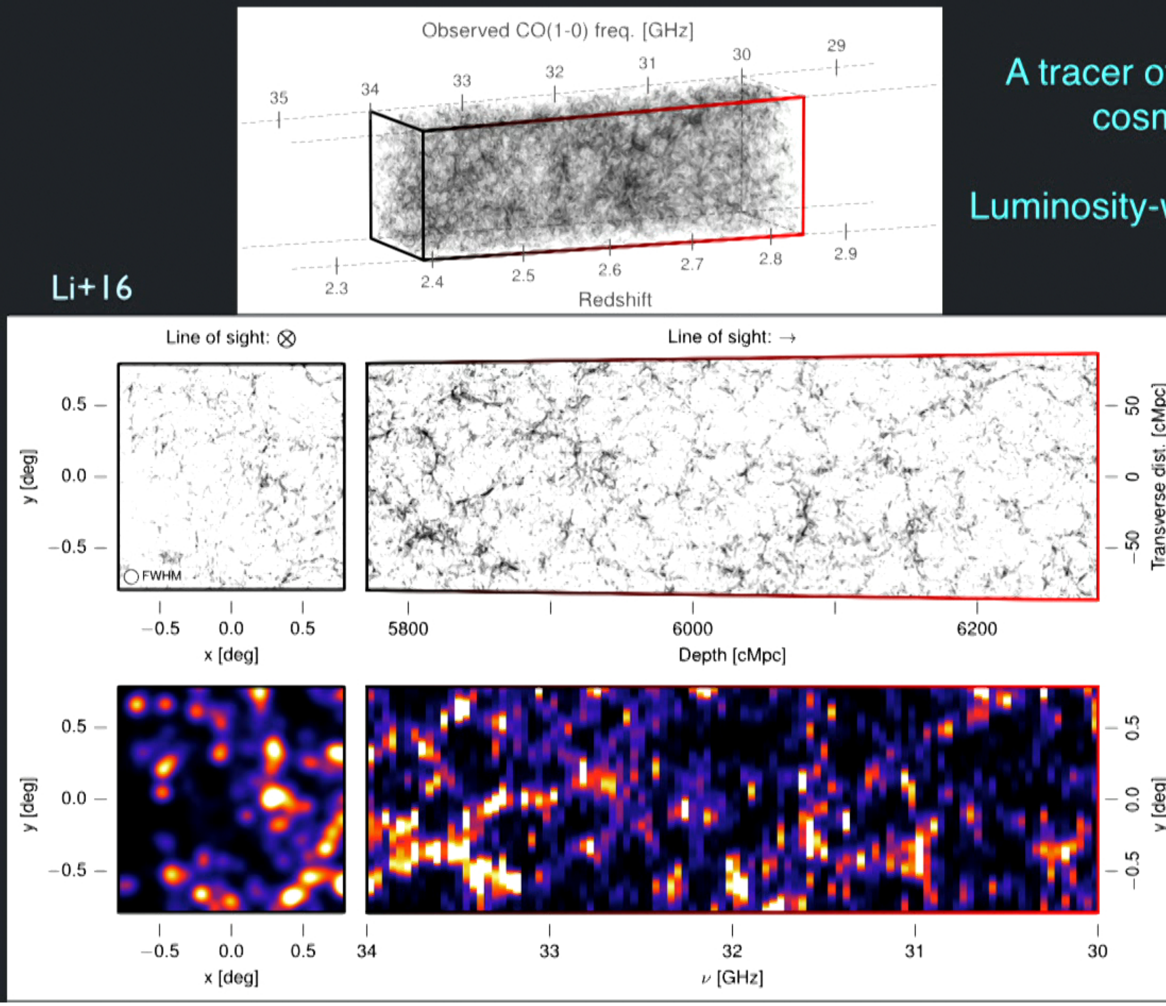
• Measure brightness temperature fluctuations on the sky: just like CMB temperature field, but in 3D

• Low-angular resolution redshift surveys: economical, large survey volumes

• Confusion-limited. Foreground-limited.

Intensity Mapping Sciences

Li+16



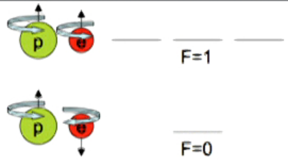
A tracer of the 3D large-scale cosmic structures:

Luminosity-weighted density field

Astrophysics: L(M)
Cosmology: $P_L(k, z)$

Brightness temperature fluctuations $dT(\theta, \nu)$

The 21cm Line



$$\Delta E = \frac{4}{3}\alpha^4 g_p \frac{m_e}{m_p} m_e c^2 = 5.9\mu\text{eV} = h(1420\text{MHz})$$

$$\lambda = 21\,\text{cm}$$

Courtesy C. Hirata

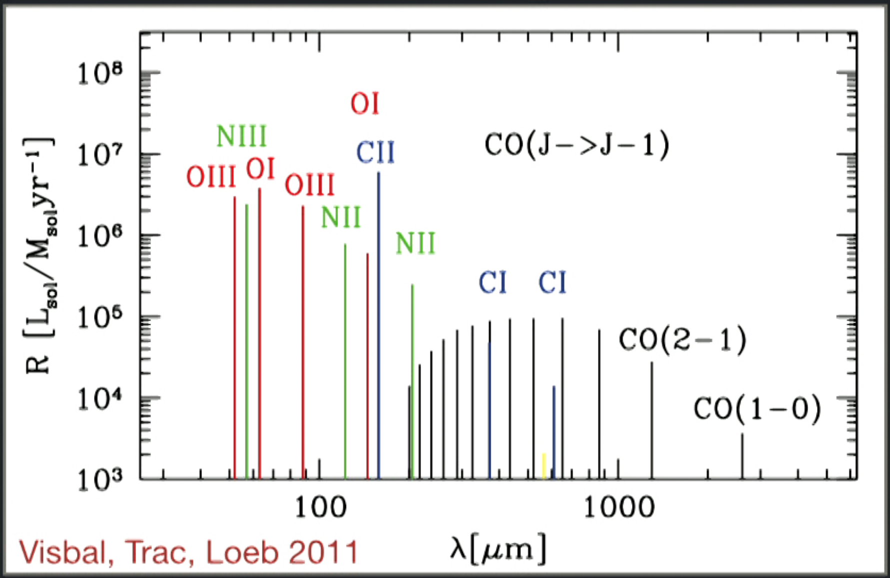
$$\frac{n_{F=1}}{n_{F=0}} = 3e^{-\Delta E/kT_s}$$

- Neutral hydrogen: most abundant baryonic element in the Universe.
- 21cm radiation: ground state spin-lip hyperfine transition of neutral hydrogen
- Optically thin along most line of sight
- Can be observable up to z~150, in emission or absorption against the CMB background:
  - $T_{spin} < T_{cmb}$: absorption (~15 < z < ~150)
  - $T_{spin} > T_{cmb}$: emission (z < 10)
- Expressed in terms of brightness temperature:

$$\Delta T = \frac{3 n_{\rm HI} \lambda^3 T_*}{32\pi H \tau_{1\to 0}(1+z)}\left(1 - \frac{T_{cmb}}{T_s}\right)$$

$$= 180\,(1+\delta)\left(\frac{\Omega_{HI}}{10^{-3}}\right)\left(\frac{h}{0.73}\right)\left(\frac{\Omega_m + (1+z)^{-3}\Omega_\Lambda}{0.35}\right)^{-0.5}\left(\frac{1+z}{1.9}\right)^{0.5}\mu\text{K}$$

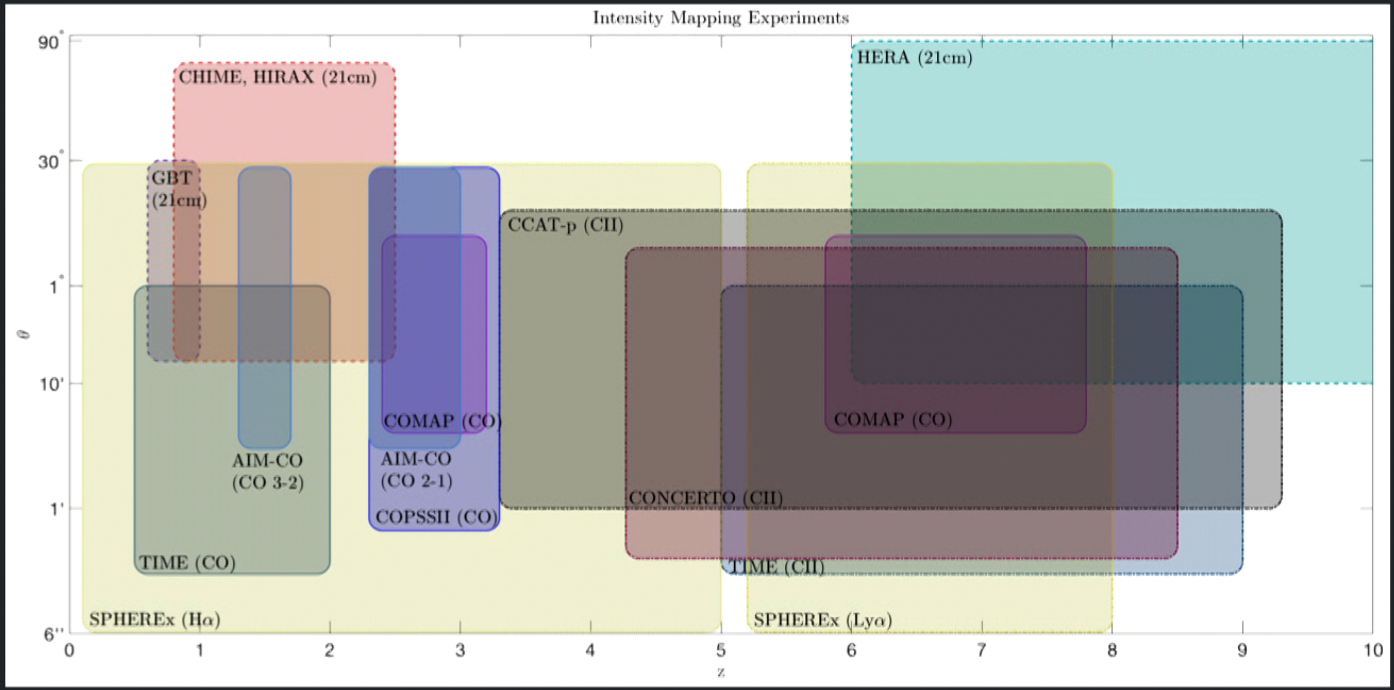
And all other spectral lines



- CO IM - CO rotational lines (CO(1-0) at 115 GHz rest frame): Righi+ 08, Visbal & Loeb 2010, Carilli 2011, Gong+11, Lidz+11, Pullen+13, Breysse+14, Breysse+15, Li+ 15, Mashian+ 15, Keating+15, +16)
- [CII] IM - singly ionized carbon (158 μm rest frame): Gong+12, Silva+14, Yue+ 15, Serra+16, Cheng+16
- Lyman-alpha IM - Lya emission(1216 A rest frame): Silva+12, Pullen+13, Croft+16, +18
- H-alpha IM - Ha emission (6562 A rest frame): Gong+ 16; Silva+ 17
- HeII IM - HeII (1640 A): Visbal, Haimann, Byran 2015

(21cm, CO, [CII], Lya, Ha) Intensity Mapping Experiments

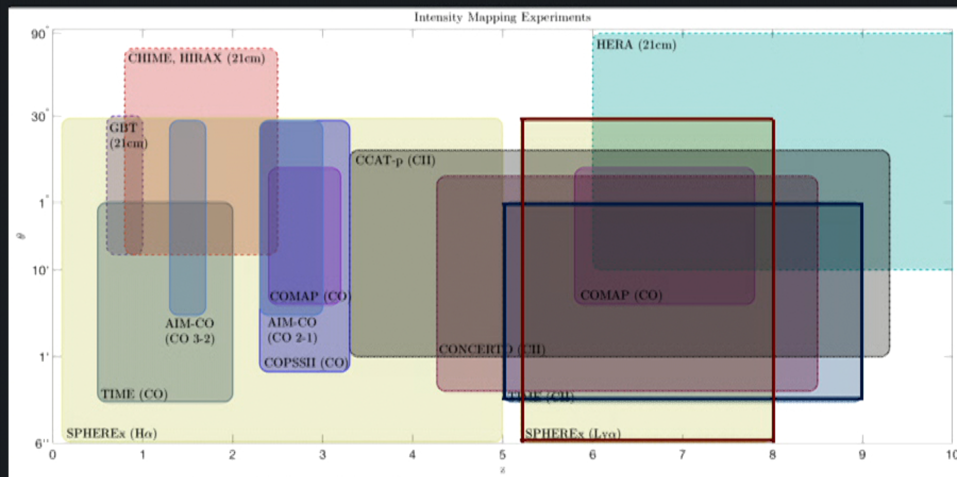
θ



z

Intensity Mapping status report (Kovetz+ 2018)

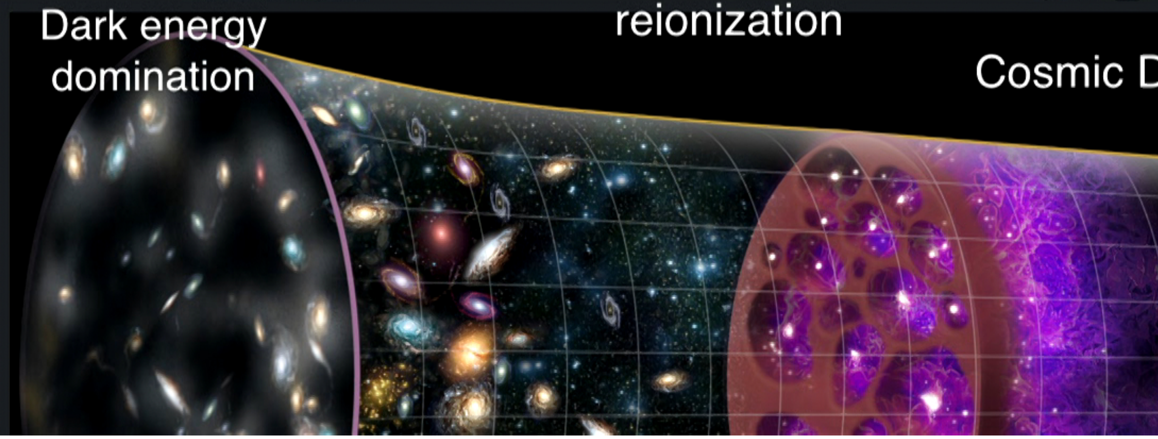
IM: a representative view of the Universe



Peak of Star formation

Cosmic reionization

z

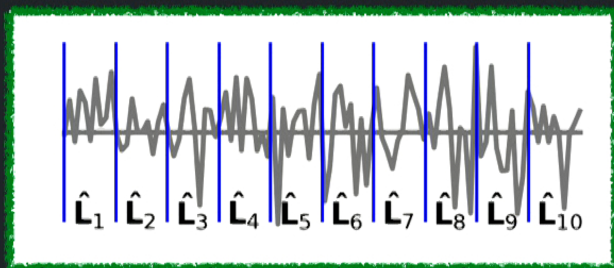


Why Intensity Mapping?

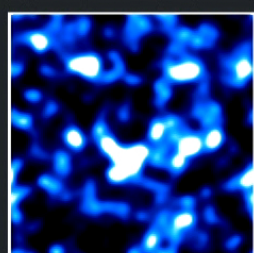
- In the context of a fast expanding field of large-scale structure surveys, is IM really a better strategy?
- "IM measures the integral of faint sources" - is this the correct picture?

IM vs. Spectro. Galaxy Surveys

w/ Yun-Ting Cheng (Caltech), Roland de Putter, O. Doré



- Goal: map out the 3D large-scale structure by measuring the voxel luminosity *L* of a tracer in a 3D volume.
- Density field, δ, is traced by observable *O(L)*.



- Spectro. galaxy survey: *O(L)* a step function.
  - *O(L)=1*, if $L > L_{th}$,
  - *O(L)=0*, otherwise. A digitized 3D map.
- IM: include all photons. *O(L)=L*. A continuous 3D map.

IM vs. Spectro. Galaxy Surveys
A Toy Model

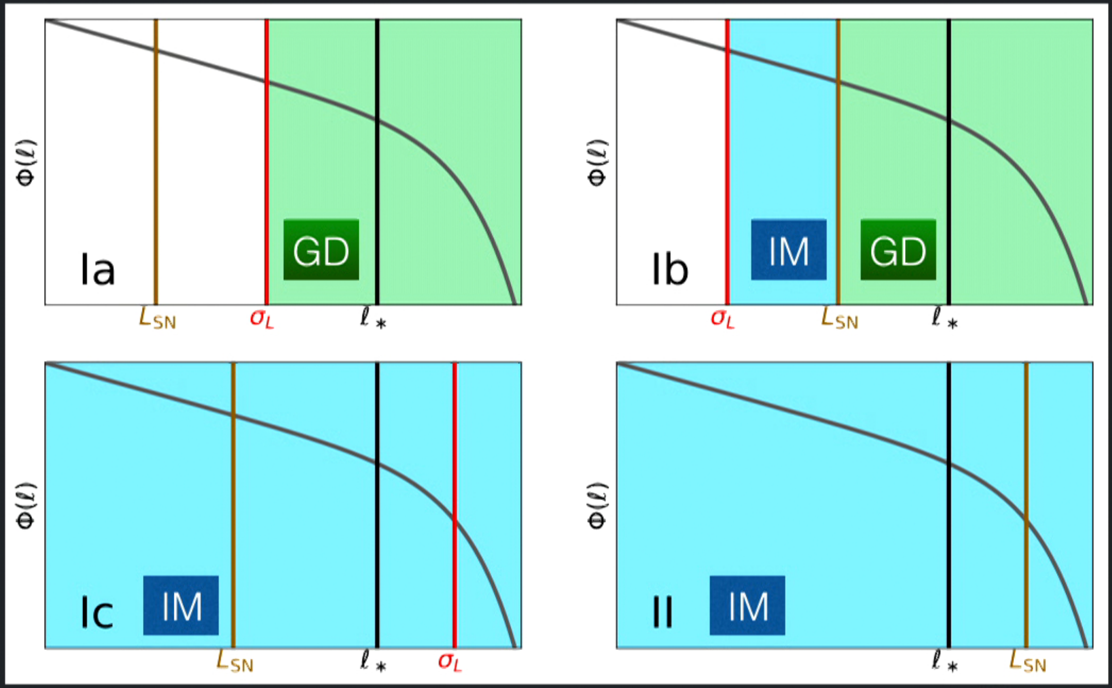
- Question: Given a tracer luminosity function $\Phi(l, \delta)$, what is the optimal observable, $O_{opt}(L)$?

- Tool: Use *P(D)* — the voxel luminosity PDF in density field δ, $P(L, \delta)$, to derive $O_{opt}(L)$.

- Parameters:
  - *Signal*: tracer luminosity function, $\Phi(l, \delta)$, *assume a Schechter func* → ℓ_*
  - *Noise:* assume Gaussian thermal noise → $\sigma(L)$
  - *Confusion noise: shot noise from fainter sources* → L_{SN}

- Optimal Observable:
  - $\mathcal{O}^{\rm opt}(L) = \partial_\delta \ln \mathrm{P(L}, \delta)$
  - *Calculate information context for IM and GD*

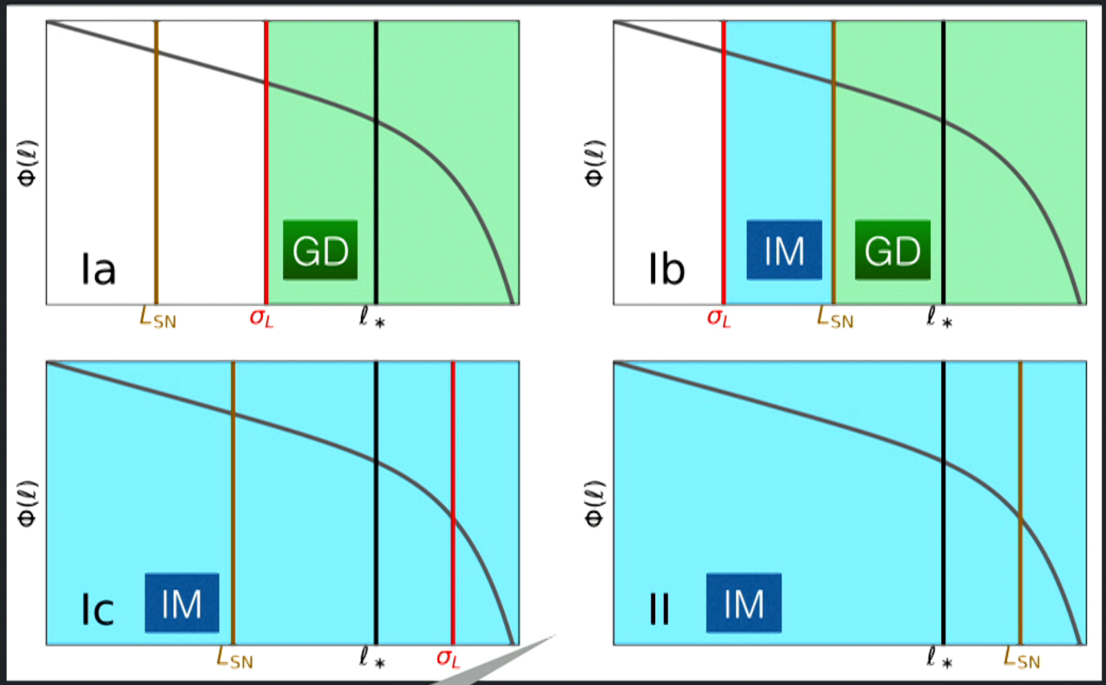
Intensity Mapping (IM) vs. Galaxy Detection (GD)



Cheng et al., 2018

ℓ_* – characteristic source luminosity
σ_L – instrument noise
L_{SN} – confusion scale

IM vs. Spectro. Galaxy Surveys



Cheng et al., 2018

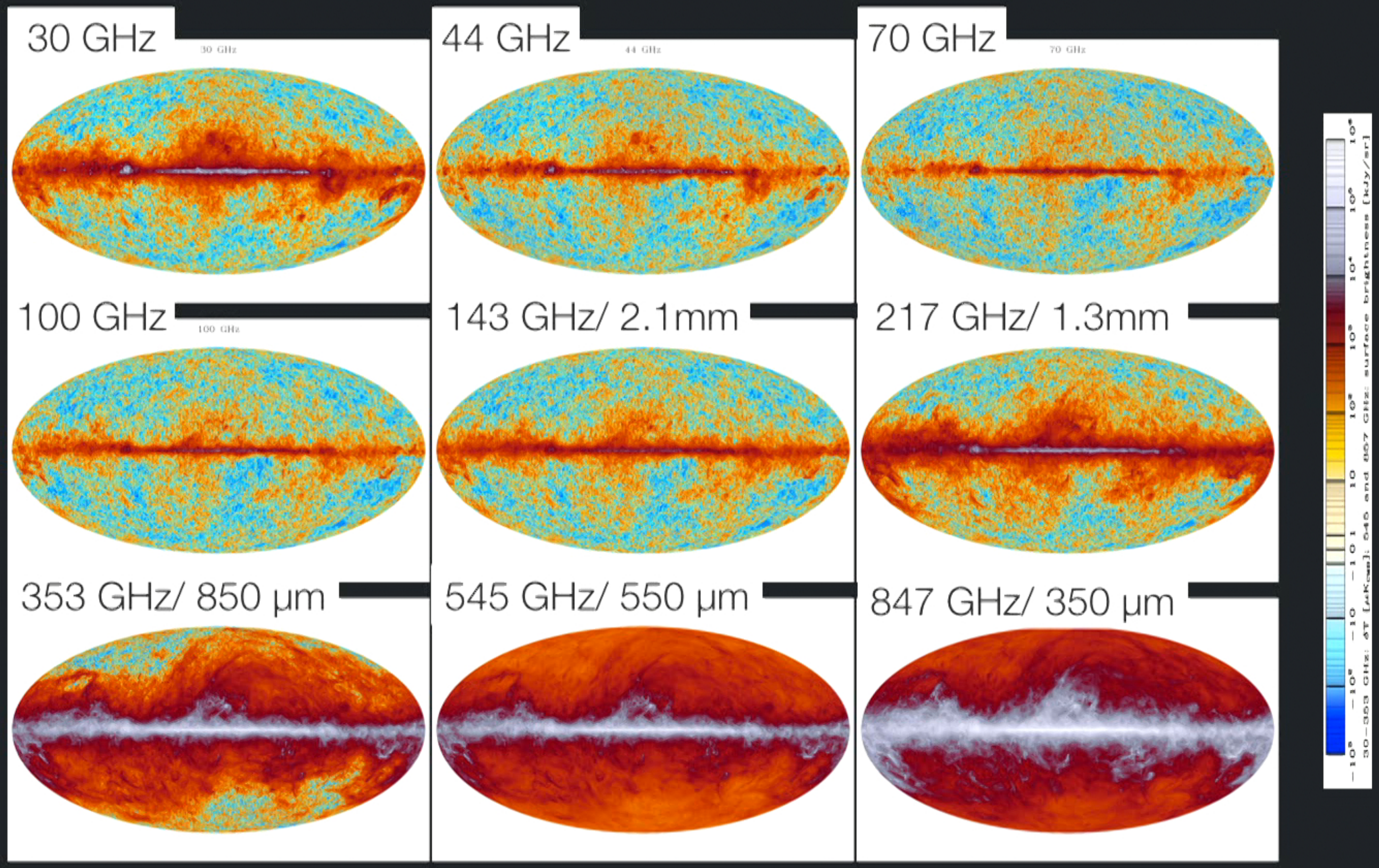
21cm
Intensity Mapping

ℓ_* – characteristic source luminosity
σ_L – instrument noise
L_{SN} – confusion scale

Large-scale Structure (LSS): Cross-correlation

[CII] Intensity Maps at z~2-3 with Planck and BOSS

Planck nine frequency maps



Planck Collaboration

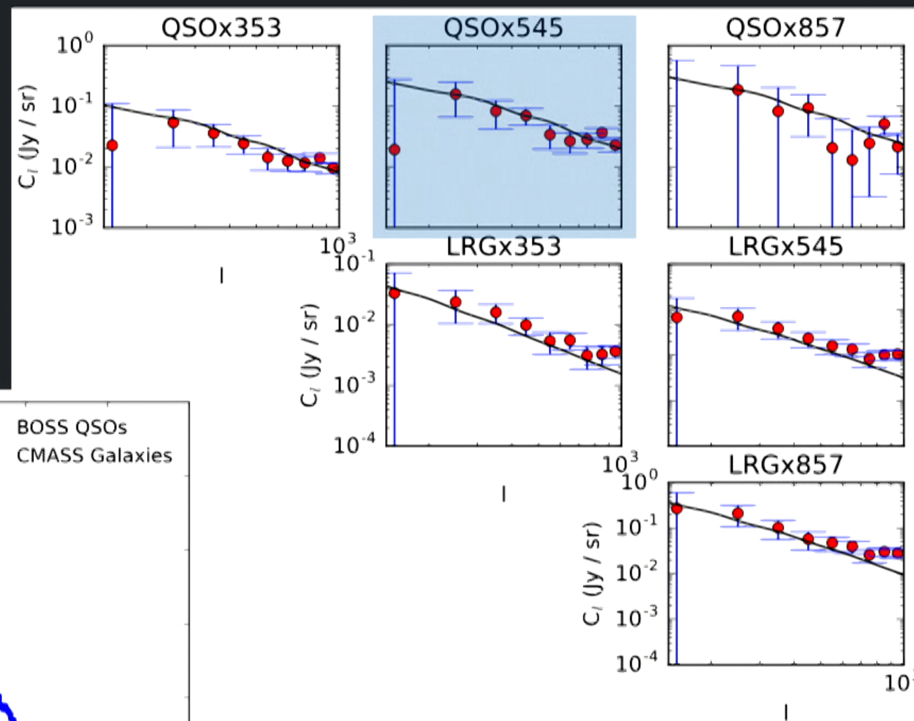
Planck x BOSS/CMASS

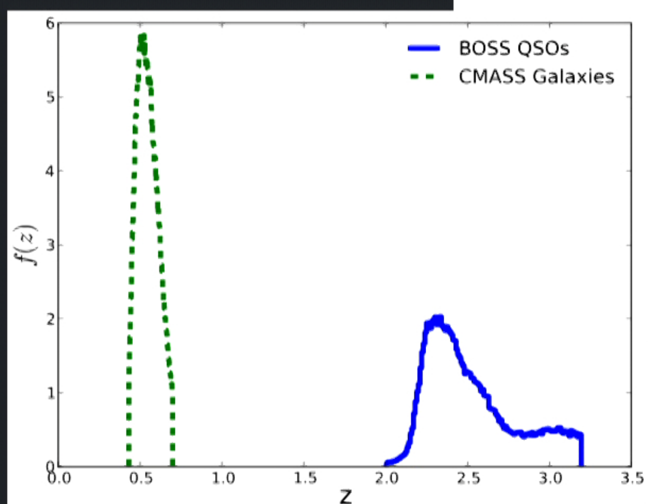
w/ Anthony Pullen, Olivier Doré, Shirley Ho, Paolo Serra

- [CII]: rest frame158 um =1.9 THz, brightest line in SFR galaxies
- Use Planck x BOSS to extract redshifted [CII] in Planck (projected along dz) associated with LSS traced by quasars
- [CII] tracers
  - Planck: 545 GHz → z(CII)~2-3
- LSS tracers
  - BOSS: CORE sample at z=2-3
  - CMASS: LRGs at z~0.5; null-test.
- Foregrounds
  - Galactic dust: 43% masked using Planck mask
  - CMB: subtracted using Planck 100 and143 GHz bands
  - CIB, tSZ, and [CII] jointly modeled in the cross-correlation with 353 and 857 GHz bands

Planck x BOSS/CMASS

- Blue curve: best-fit model of CIB T_{dust}, z-dep., A(tSZ), A(CII)
- $100 < l < 1000$, $0.02 < k_{perp} < 0.2$ [h/Mpc]

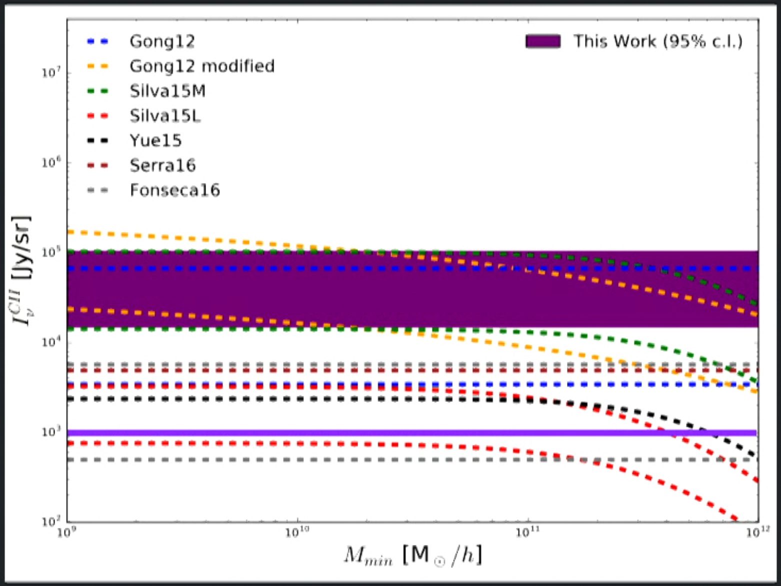




Pullen+ 2018, arXiv:1707.06172

Cosmic [CII] abundance

I_{CII} measurements

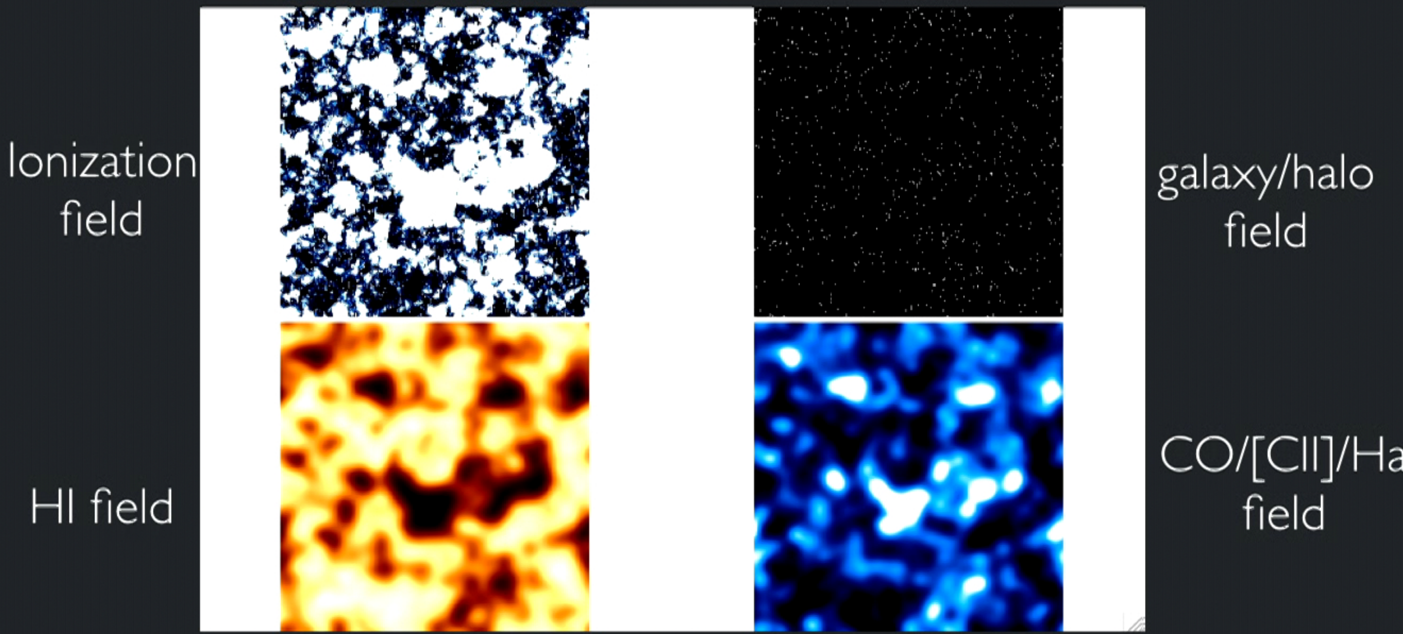


Carilli+ 16, ASPECS-pilot @242GHz, 0.55 uK

Pullen+ 2018, arXiv:1707.06172

- Planck x BOSS: Pullen+18 weak constraint on $I_{[CII]} \sim 5.5^{+4.8}_{-4.2}$ (95%) x 10^4 Jy/sr at z=2-3, or T ~ 30 uK at 242 GHz
- ASPECS-Pilot: at z~6, Carilli+ 16 can be a lower limit (only detected point sources) but amount of CO contamination is unclear.

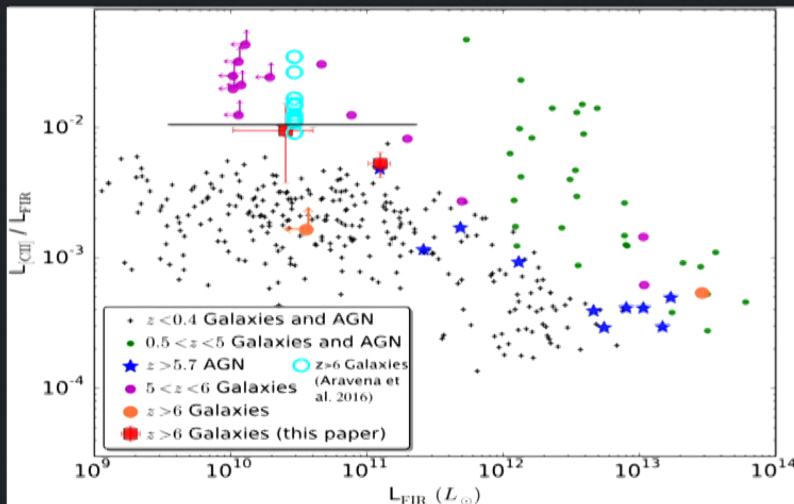
[CII] Intensity Mapping



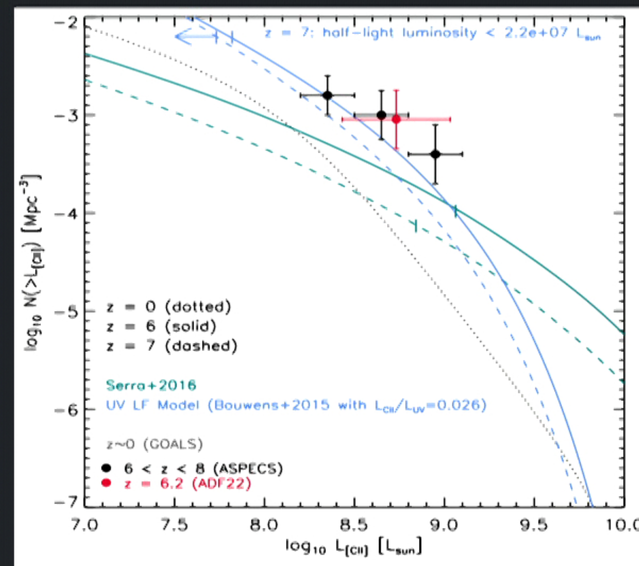
Lidz et al. 2011

- [CII] trace star formation activities on large-scales at EoR, anti-correlate with 21cm emissions on ionized bubble scales and can be used to derive bubble evolution and reionization history (Lidz et al. 2009; Chang et al. 2015).
- Continuum foregrounds are much less of an issue. Need to worry about line interlopers.

[CII] at high-z



Willott et al. 2015

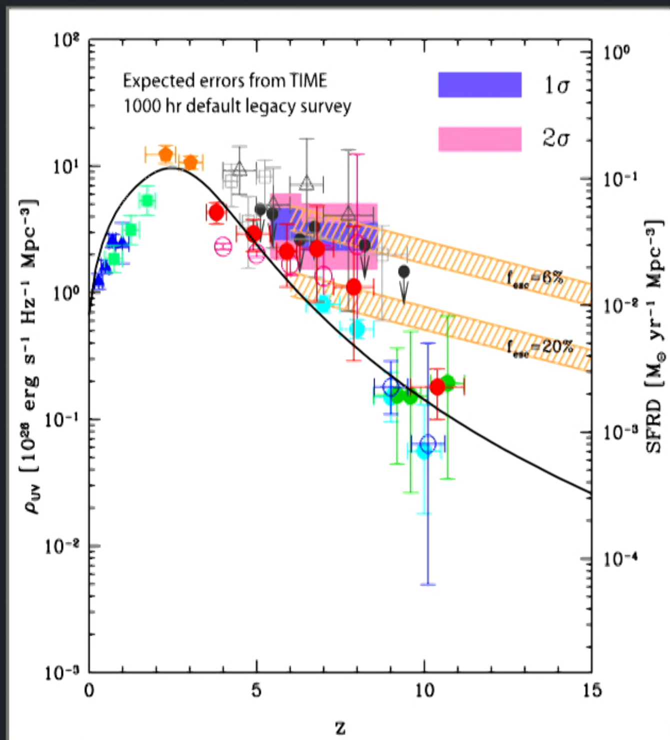


TIME collaboration

- [CII] is the major coolant in ISM, a tracer of Star formation activities.
- $L_{[CII]}/L_{FIR}$ appears to be > 0.01 at high-z from recent ALMA observations (Aravena et al. 2016, Capak et al. 2015)
- ALMA starts to constrain $10^{8.5\text{-}9}$ L_{sun} systems (Aravena et al. 2016, Hayatsu+17)

TIME: [CII] Intensity Mapper

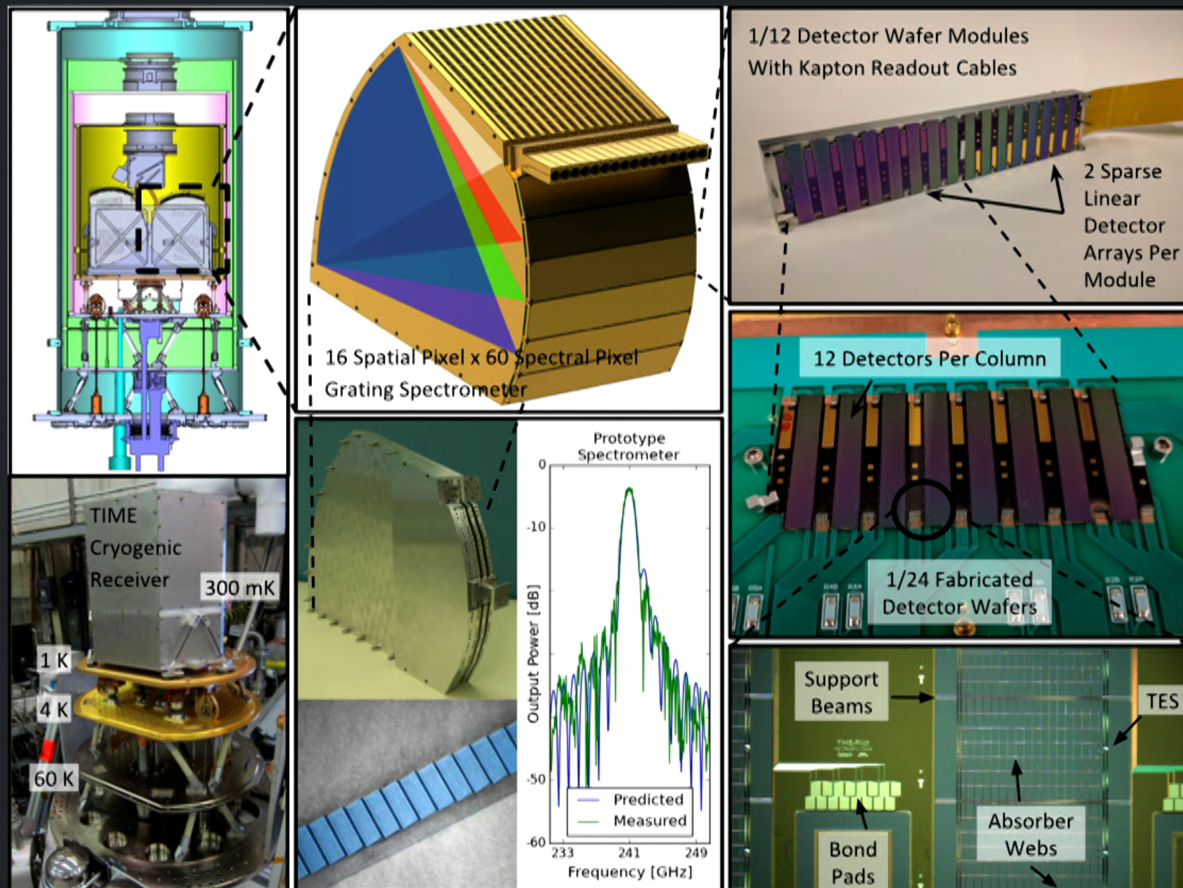
Tomographic Ionized-C Mapping Experiment



TIME collaboration

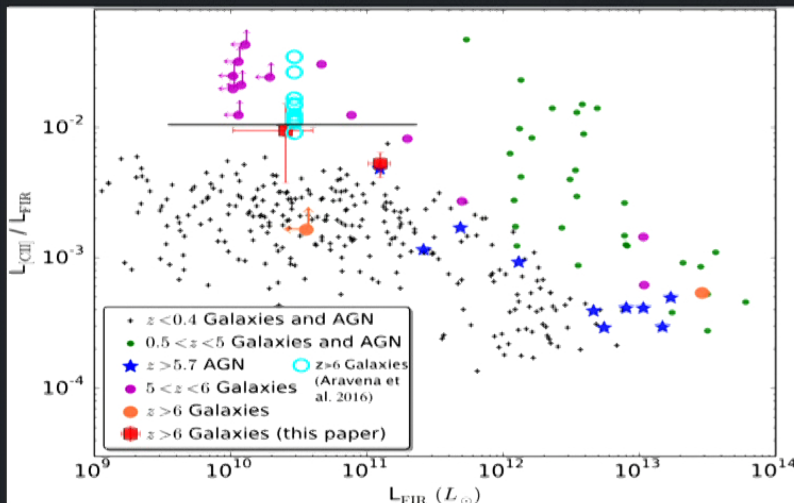
- A [CII] Intensity Mapper for EoR at 6<z<9
  - 1840 TES bolometer array
  - 195-295 GHz, 32-channel spectrometer
  - to be installed on APA 12-m at Kitt Peak
  - engineering run February 2019.
  - 1000 hours of observation, starting winter 2019

TIME Instrument

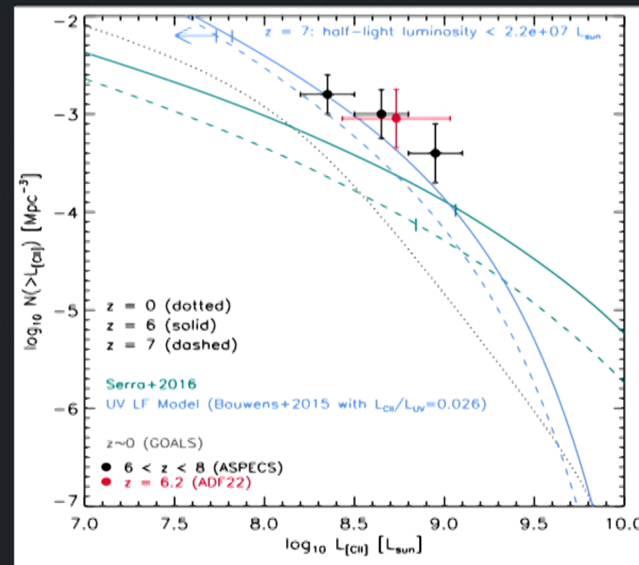


TIME collaboration

[CII] at high-z



Willott et al. 2015



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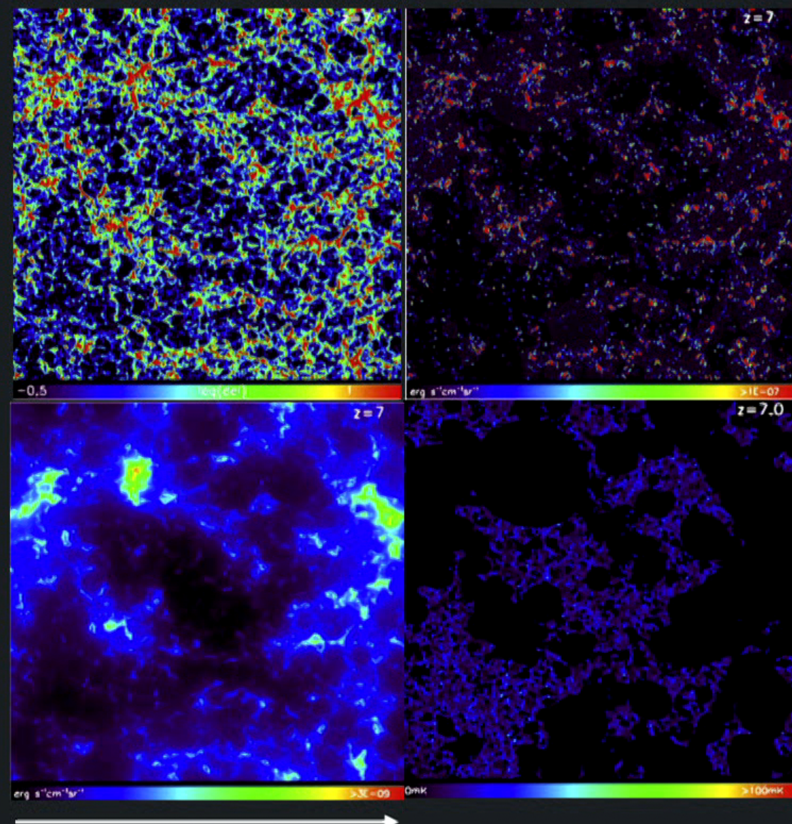
21cm, Ha, Lya Intensity Mapping: a powerful EoR probe

Density fluctuation
z~7

Ionizing sources
(traced by galactic Lya)



Ionized IGM
(traced by
scattering Lya)

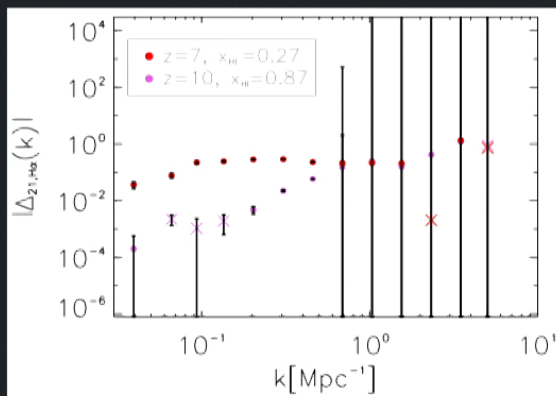
Neutral IGM
(traced by 21cm)

200 Mpc

Heneka et al., 2017

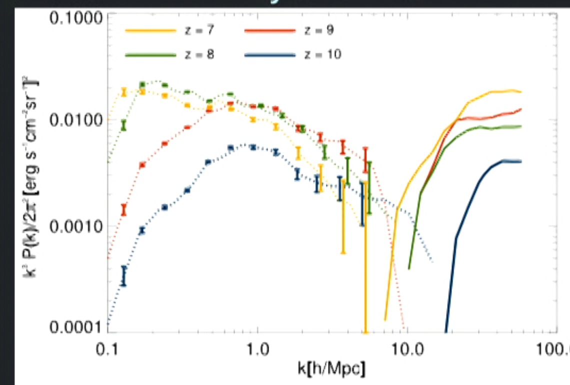
21cm, Ha, Lya cross-correlations

Ha x 21cm



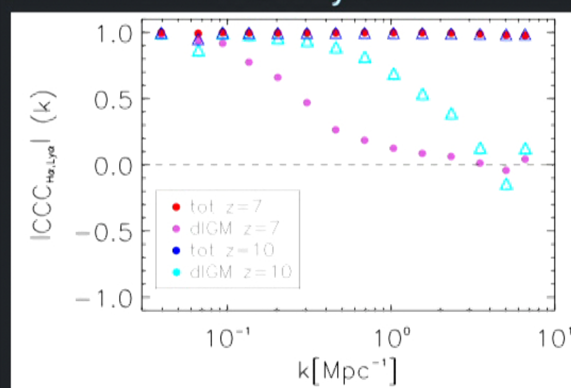
Heneka+ in prep

Lya x 21cm

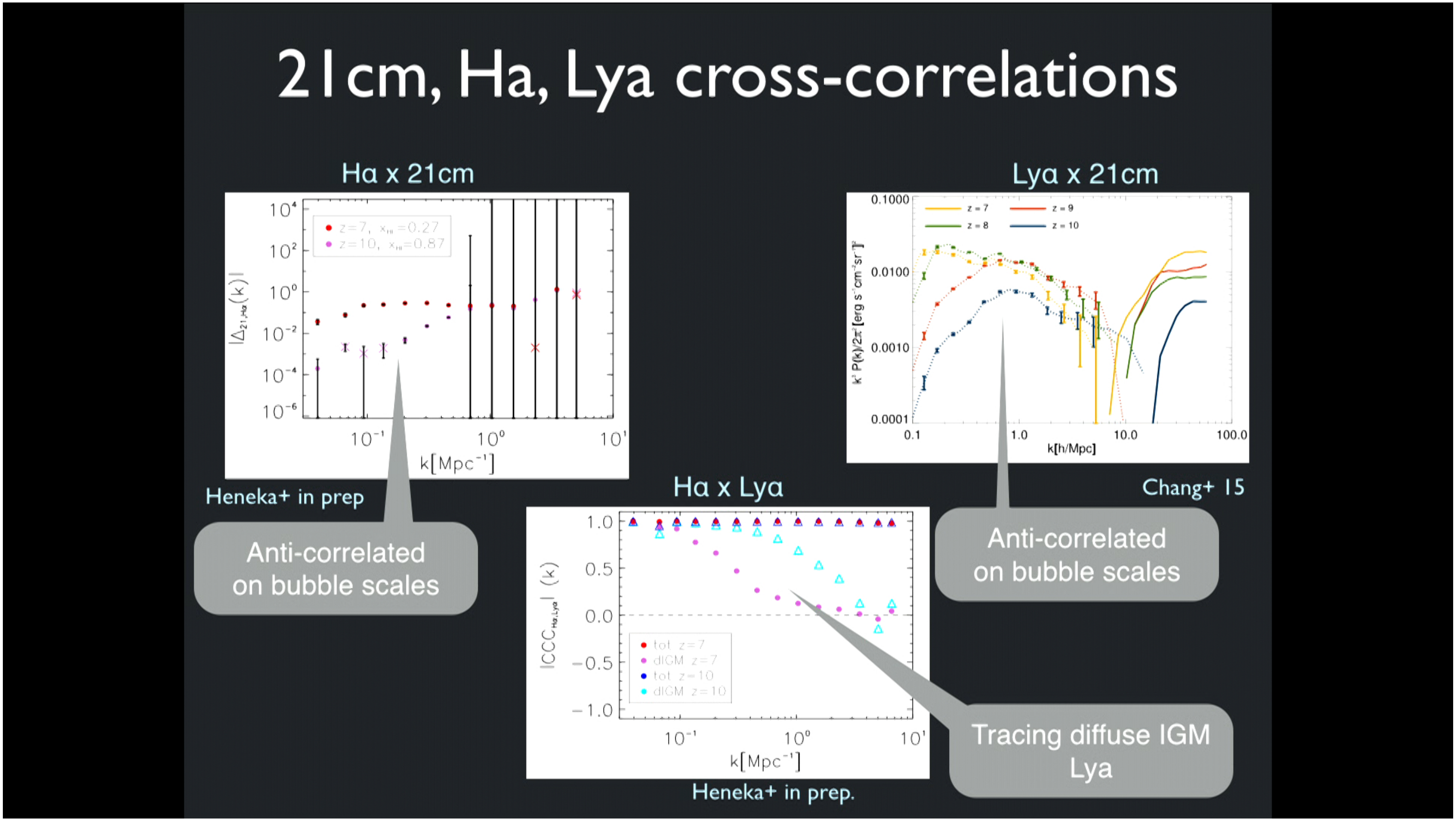


Chang+ 15

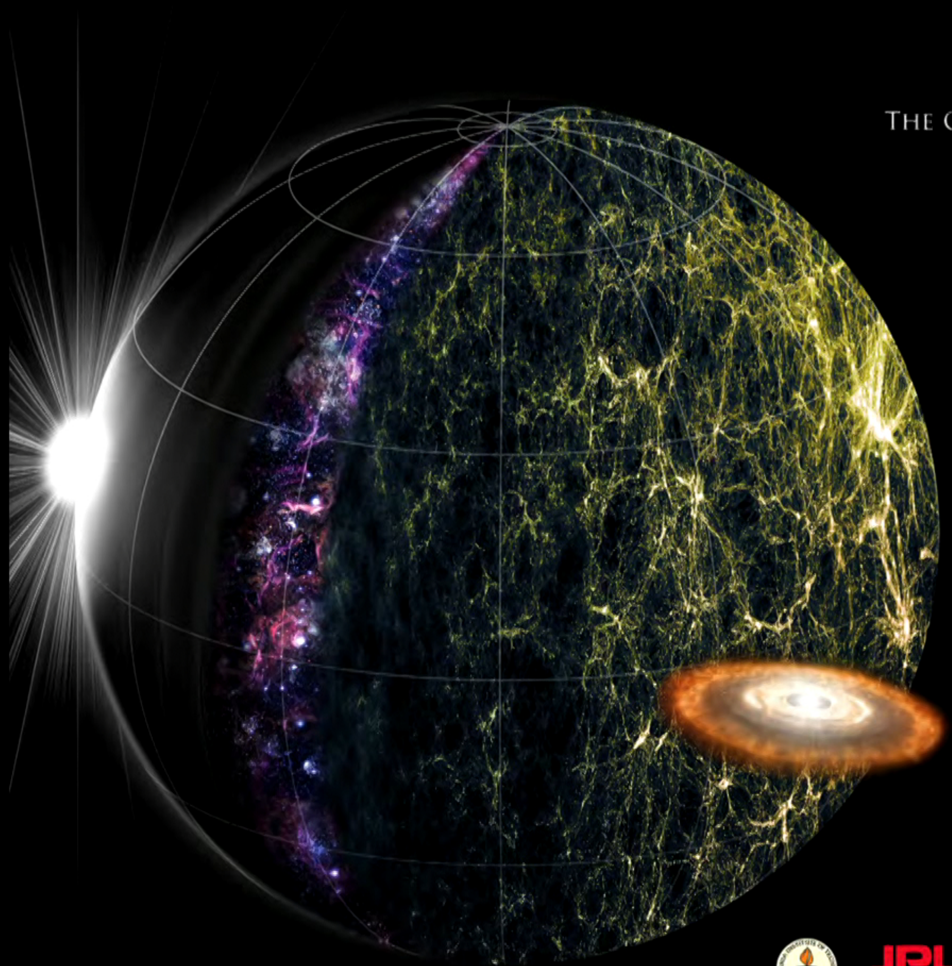
Ha x Lya



Heneka+ 17


21cm, Ha, Lya cross-correlations
Ha x 21cm
Heneka+ in prep
Anti-correlated on bubble scales
Ha x Lya
Heneka+ in prep.
Lya x 21cm
Chang+ 15
Anti-correlated on bubble scales
Tracing diffuse IGM Lya
k[Mpc⁻¹]
k[h/Mpc]

SPHEREx



An All-Sky Spectral Survey

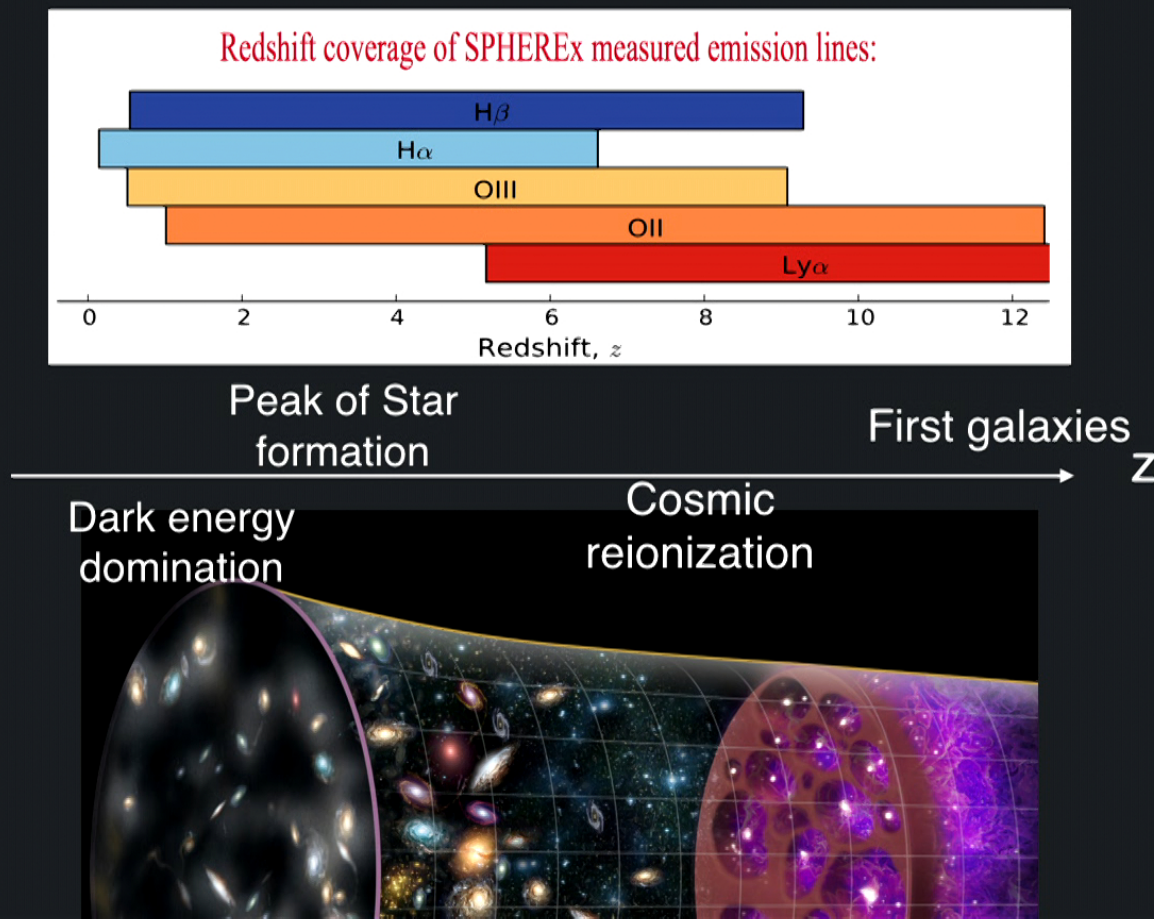
DESIGNED TO EXPLORE:

THE ORIGIN OF THE UNIVERSE
THE ORIGIN AND HISTORY OF GALAXIES
THE ORIGIN OF WATER IN PLANETARY SYSTEMS

PI: J. Bock
PS: O. Doré

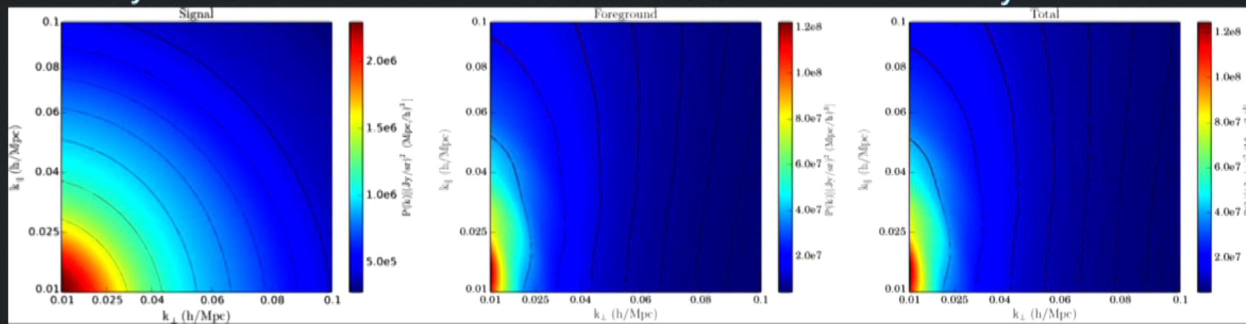
http://spherex.caltech.edu

SPHEREx deep fields in NEP and SEP: Line Intensity Mapping in ~200 deg²



Line signal de-confusion

Lyα at z~7 | Hα at z~0.5 | Lyα + Hα



Gong+ 14

- High-z Lyα and low-z Hα lines can be confused in SPHEREx in the IM regime.
- We are planning to use a combination of well-demonstrated techniques:
  - Masking bright, low-z sources: employed in CMB, CIB, EBL and studied for IM (e.g., Sun+16, Silva+17).
  - Use the anisotropic power spectrum shape of Lyα and Hα (from observing to comoving coordinates) to distinguish the lines (Visbal & Loeb 2010; Gong+14; Lidz & Taylor 2016; Cheng+ 2016).
  - Cross-correlations of different lines at same redshift (e.g., Visbal & Loeb 2010; Gong+12, +17).
  - Cross-correlations with galaxy tracers (e.g., Chang+10, Masui+13, Pullen+13, +17).

Summary

- Line Intensity Mapping offers an exciting and unique probe of a significant fraction of the Universe
- 21cm Intensity Mapping proof of concept demonstrated at z~0.8 (Chang et al. 2010).
    - 21cm IM at z~0.08 cross-power spectrum probes astrophysics (Anderson et al. 2017).
    - Opens up 21-cm 3D large-scale structure studies (GBT-HIM multi-beam array; HIRAX, CHIME, Tian-Lai in progress; and possibly SKA1-mid.)
- [CII] Intensity Mapping offers a complementary probe of the Epoch of Reionization
    - TIME will probe the [CII] source clustering at $6 < z < 9$. First light expected 2019.
- CO Intensity Mapping: a ~2-sigma detection at z=2-3 (Keating et al. 2016).
    - TIME will probe CO and infer molecular gas density at $0.5 < z < 2$.
- Lyman-alpha IM: a 3-sigma cross-correlation detection at z~2-3.5 (Croft et al. 2016, 2018).
    - SPHEREx may potentially probe Lya IM at z~6-8. HETDEX at z=2-3.
- EoR 21-cm detection may come from several groups with different approaches soon (LOFAR, PAPER, MWA). HERA/SKA1-LOW will bring next generation transformational sciences.