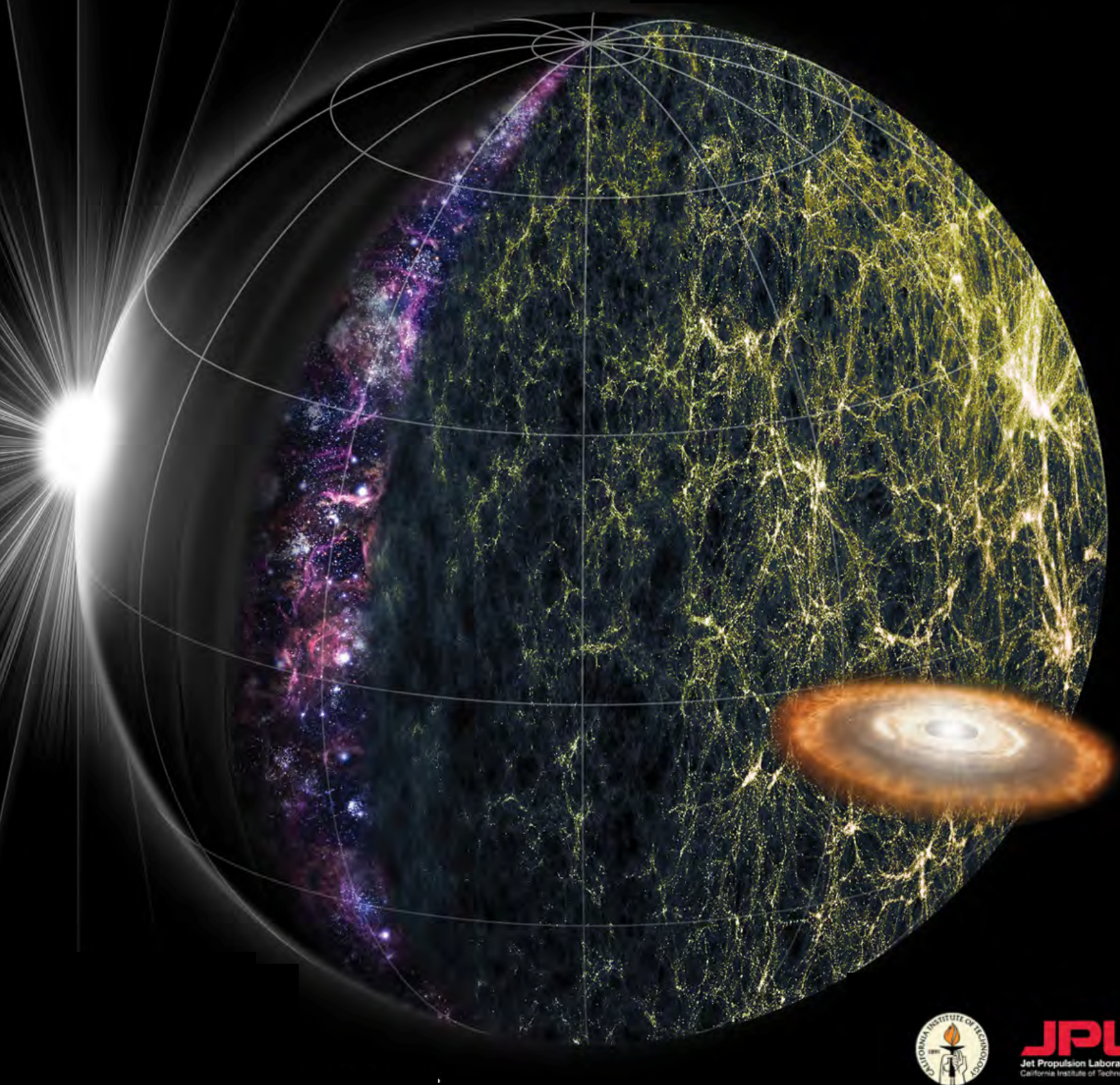
Every Photon Counts:
Intensity Mapping of the Universe with SPHEREx



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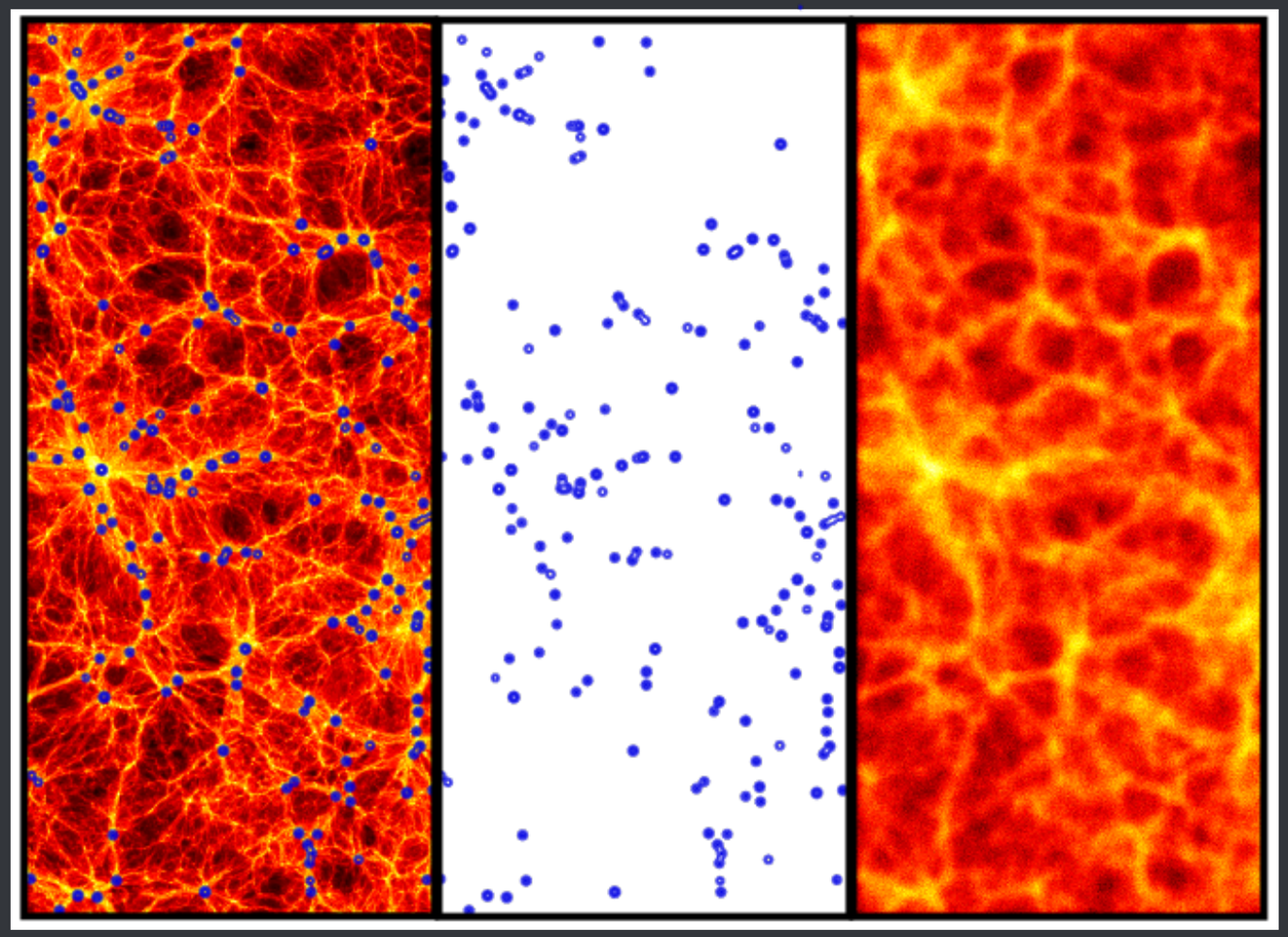
SPHEREx Science Team

Line Intensity Mapping (LIM)



courtesy of Phil Korngut (Caltech)

- "Intensity Mapping" (Chang+ 2008, Wyithe & Loeb 2008, Visbal & Loeb 2010):
  - Measure the collective spectral line emission from a large region containing multiple sources, without spatially resolving down to galaxy scales.
- Use spectral lines as tracers of structure, retain frequency resolution thus redshift information.

Cosmology

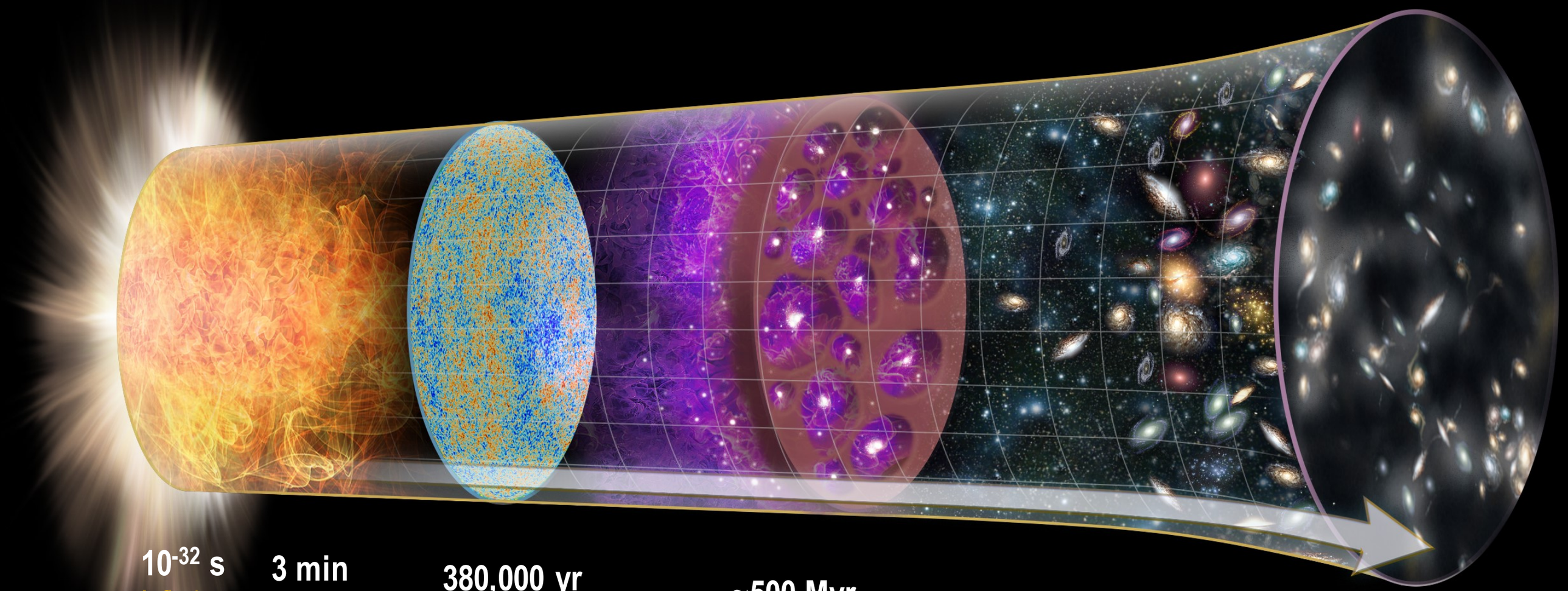
Landscape

Intensity Mapping

CMB

Galaxy Survey

The Observable Universe



10^{-32} s
Inflation

3 min
Light Elements

380,000 yr
Cosmic Microwave Background

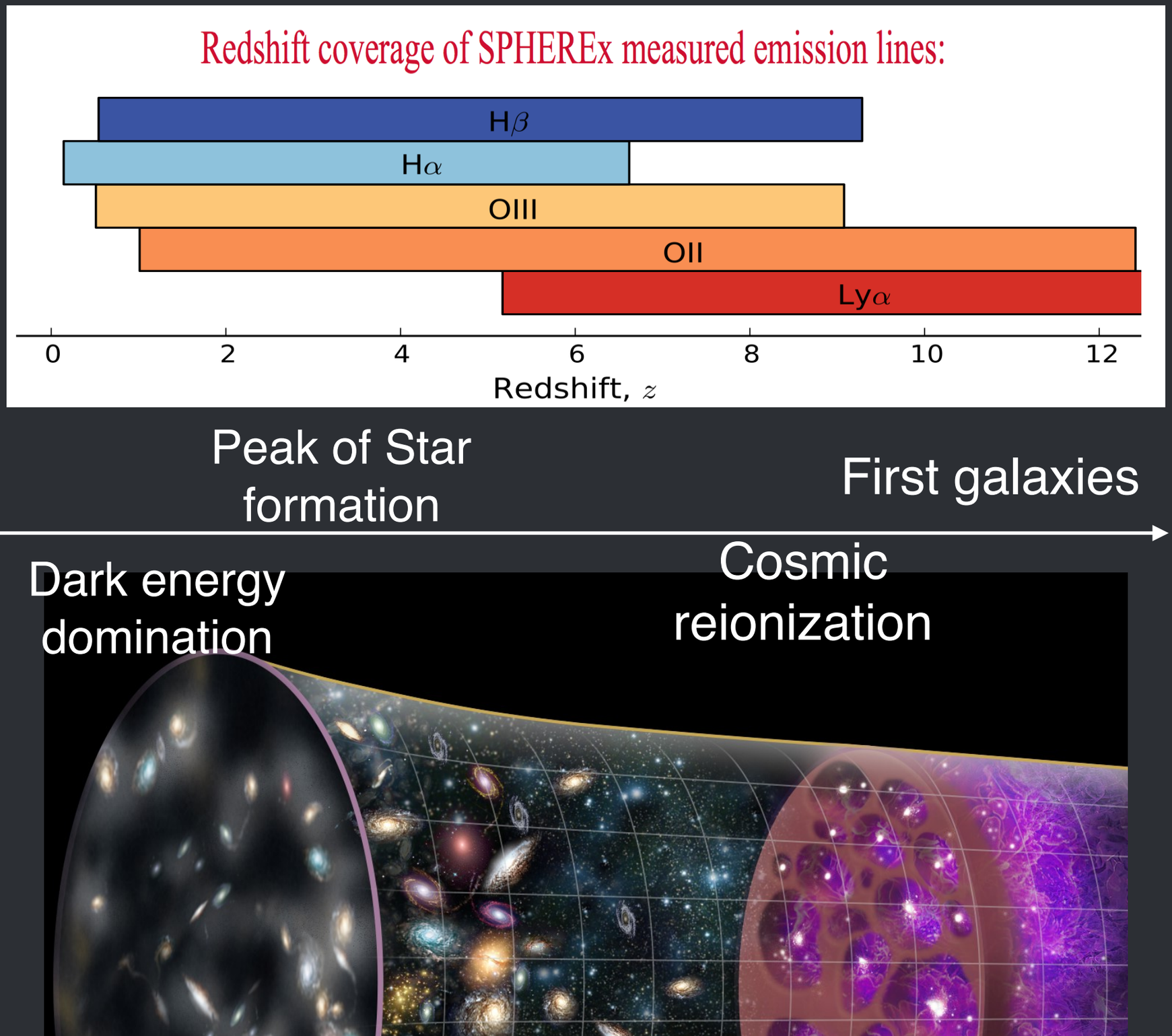
~500 Myr
First Galaxies
Epoch of Reionization

~5 Gyr
Peak Star Formation

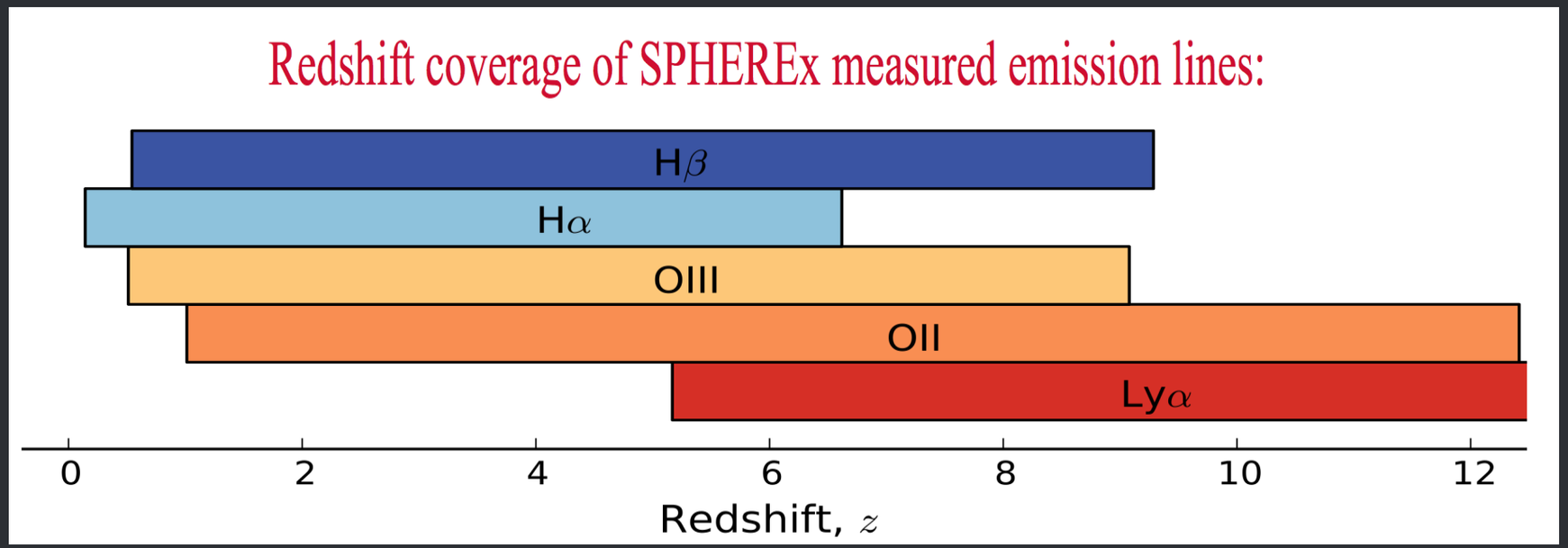
13.8 Gyr
Present-day Universe

Time

SPHEREx:
Multi-line intensity maps of the Universe



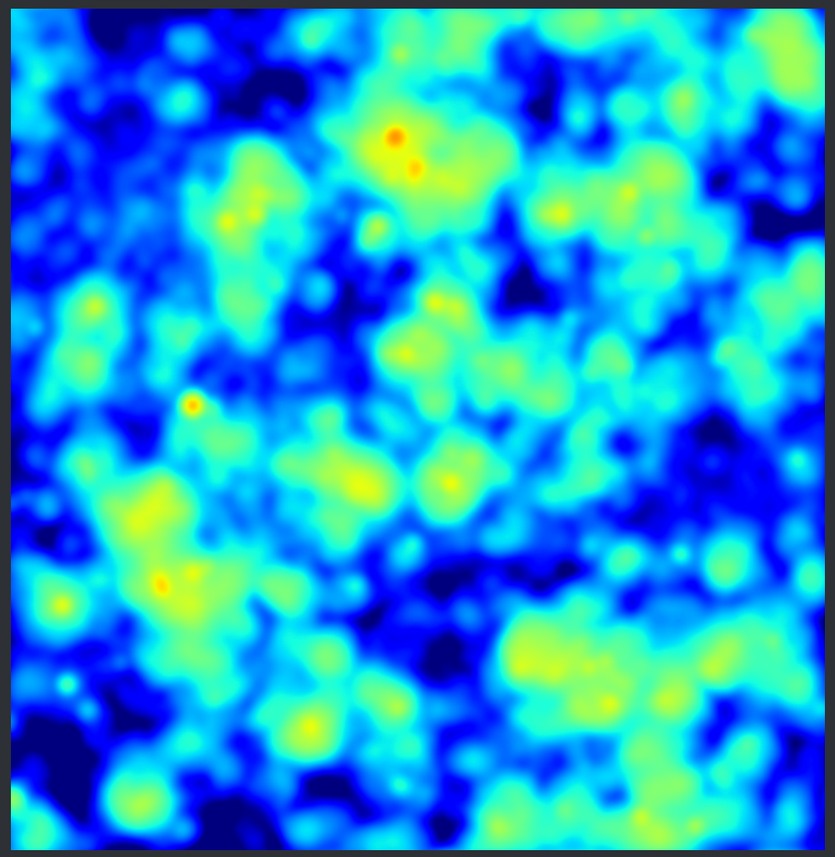
SPHEREx:
Multi-line intensity maps of the Universe



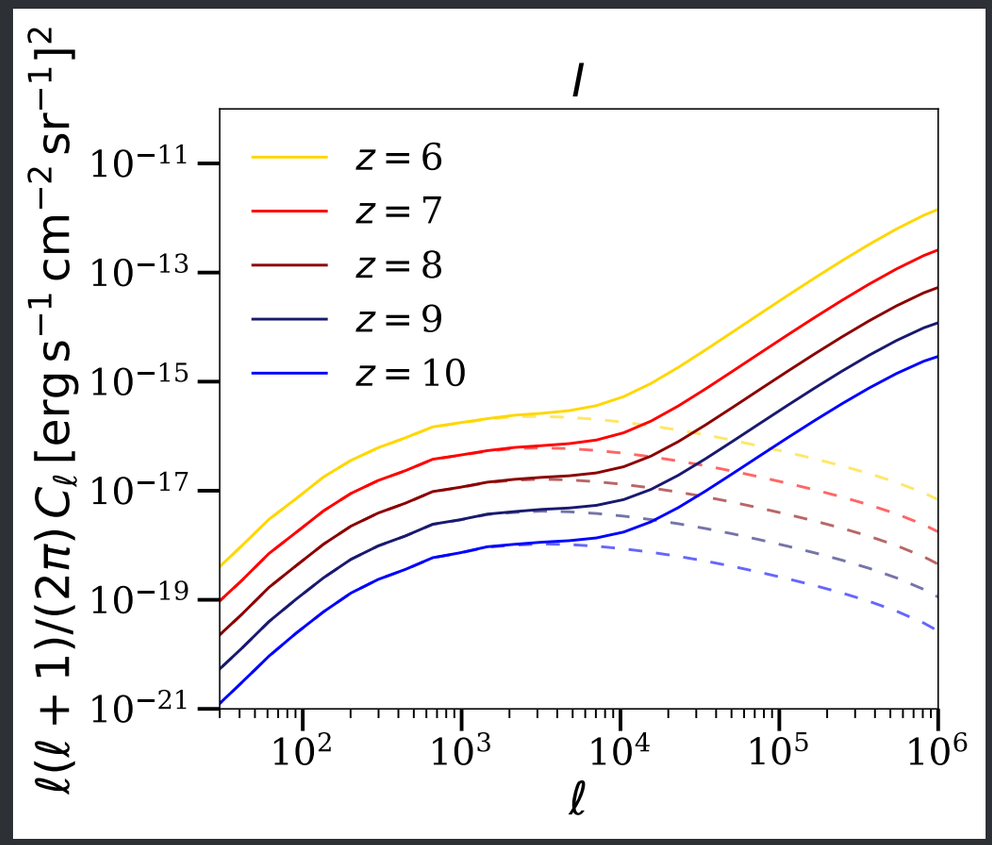
- SPHEREx will produce 96 spectral images and map 3D intensity fluctuations of multiple line tracers across redshift.
- SPHEREx has access to multiple lines at $0 < z < \sim 7$.
- Multi-line cosmology and EoR! But line deconfusion a potential issue.
- Focusing on EoR and Cosmology science cases on high-z with ~200 deg^2 deep fields for now.

Lya Intensity Mapping with SPHEREx

Lyα fluctuations at z=6.6



Sadoun+ 19

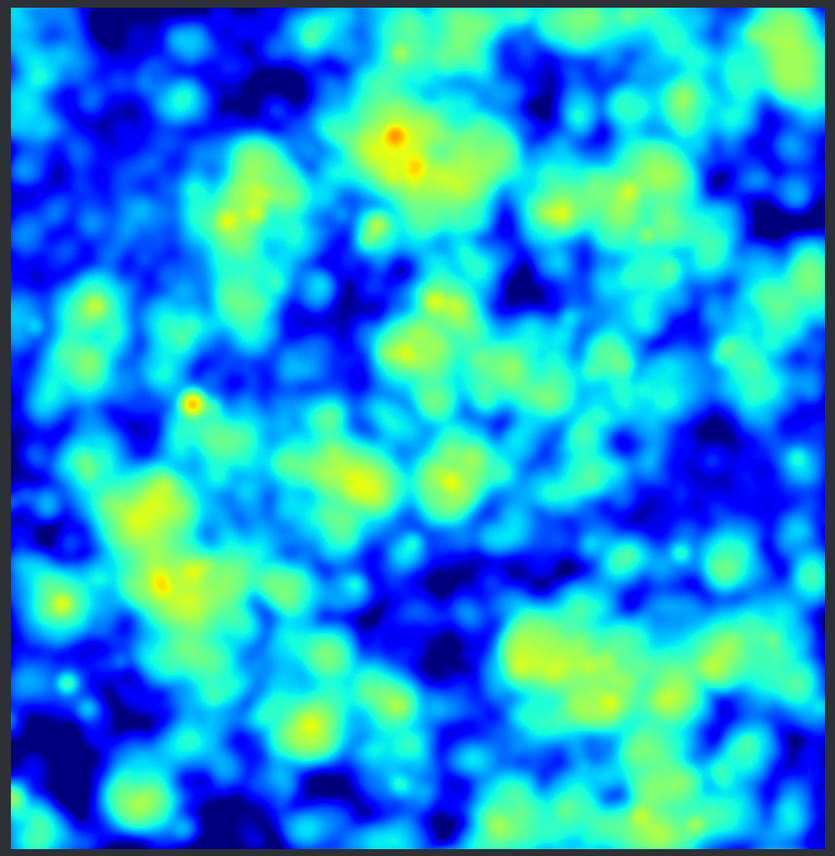


Mas-Ribas & Chang 2020; also Pullen+14, Silva+14

- Extracting Lya fluctuation signals may be feasible but challenging; signal could be boosted if IGM contribution is substantial.
- (Hα, [OIII], [OII]) signatures during EoR could be interesting.

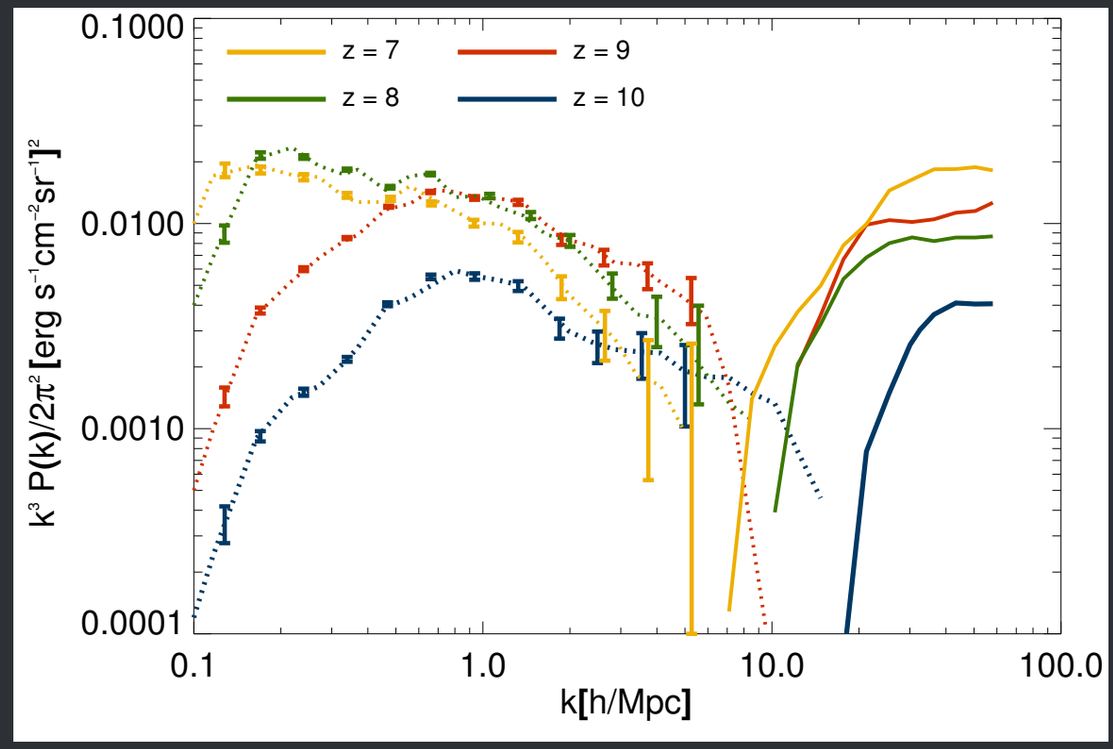
Lya Intensity Mapping with SPHEREx

Lyα fluctuations at z=6.6



50 Mpc

Lyα x 21cm, z=7



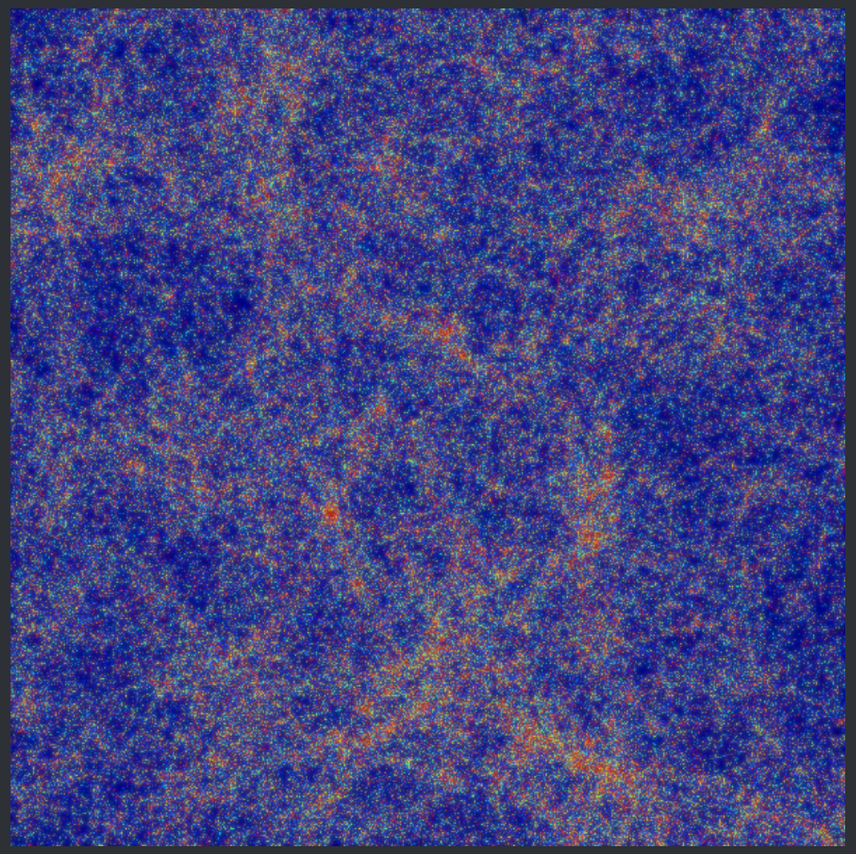
Silva+ 14, Chang+ 15

- Building simulation tool, LIMFAST, based on 21cmFAST semi-analytical approach to allow fast and coherent modeling of Lya, [OIII], [OII], Ha and 21cm signals with varying reionization scenarios.

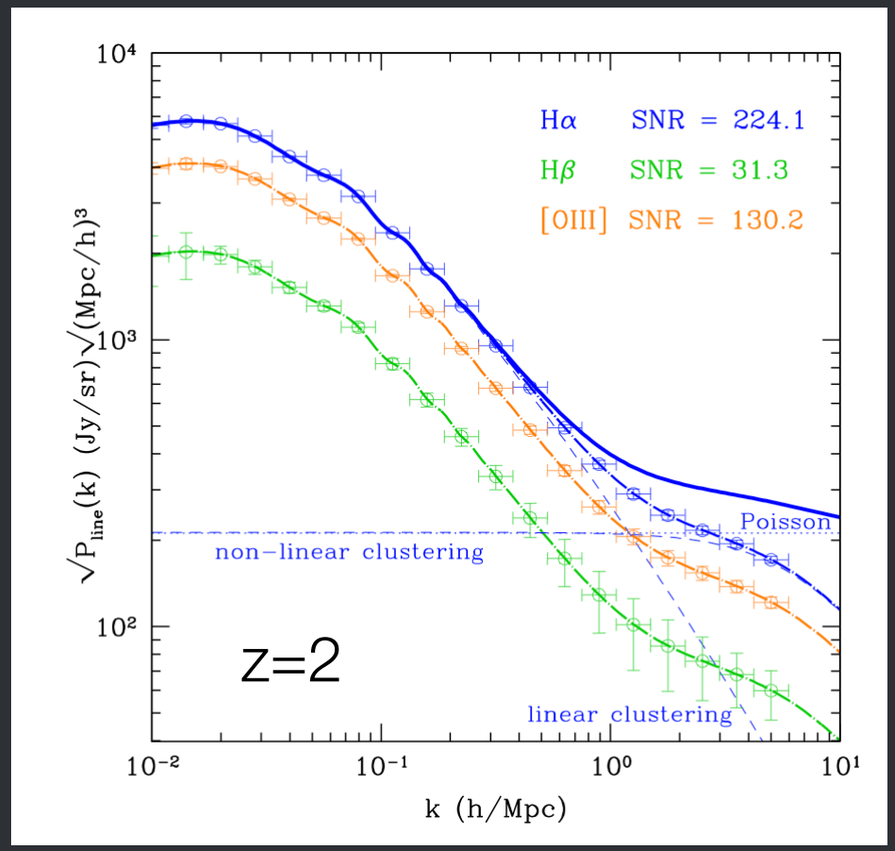
- Incorporating realistic galaxy models to generate multiple line emissions and Lya radiative transfer analytical prescription (Mas-Ribas, Sun, Chang, Furlanetto)

Hα, [OIII], [OII], Hβ Intensity Mapping with SPHEREx

Hα fluctuations at z~2



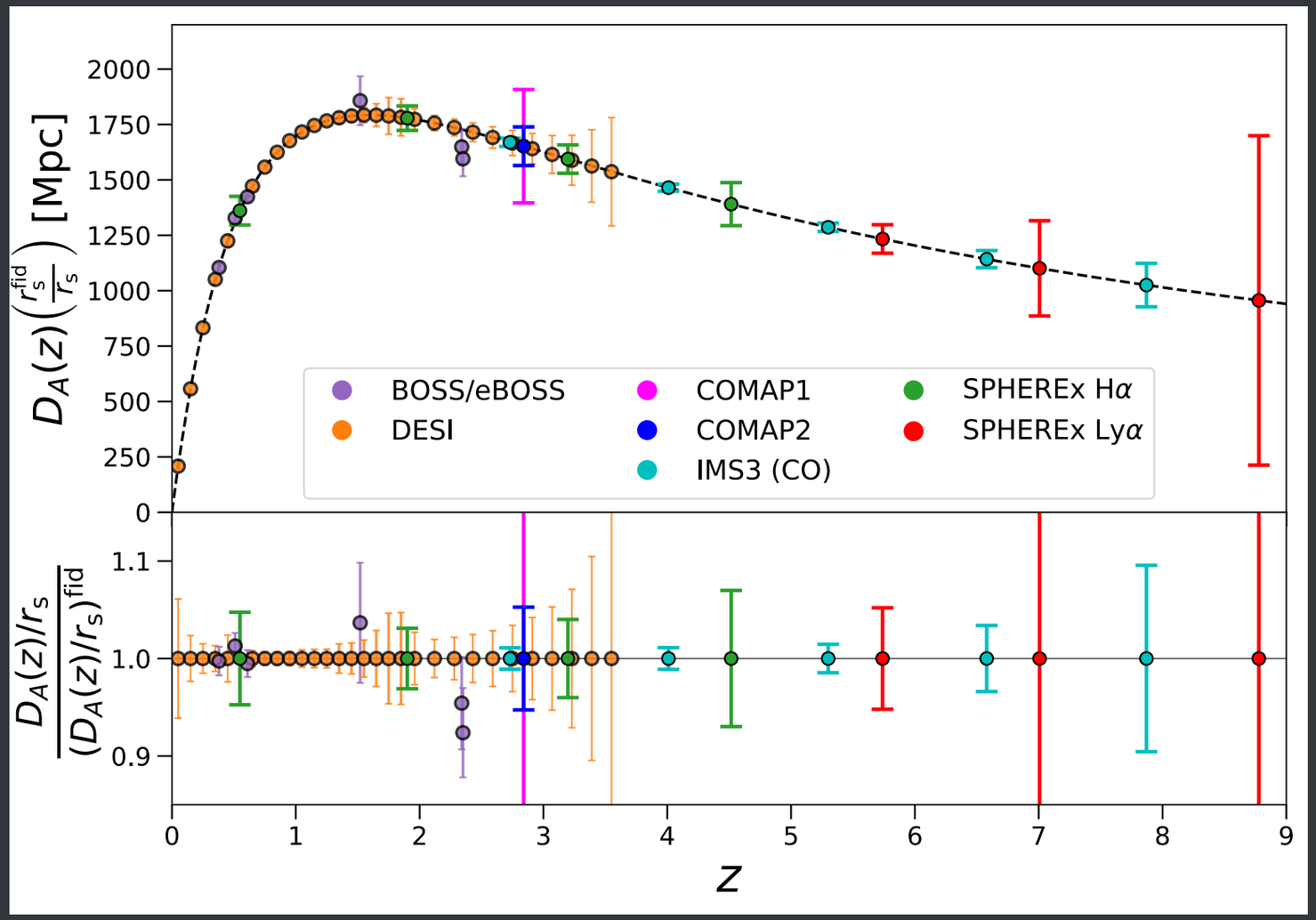
Power Spectra of Emission Lines



Doré+ 14, Gong+ 17

- SPHEREx will measure statistically the fluctuations of multiple spectral lines associated with cosmic structures across redshift.
- SPHEREx will measure at high SNR the 3D clustering of multiple line tracers and the luminosity-weighted biases at 1 < z < ~5.

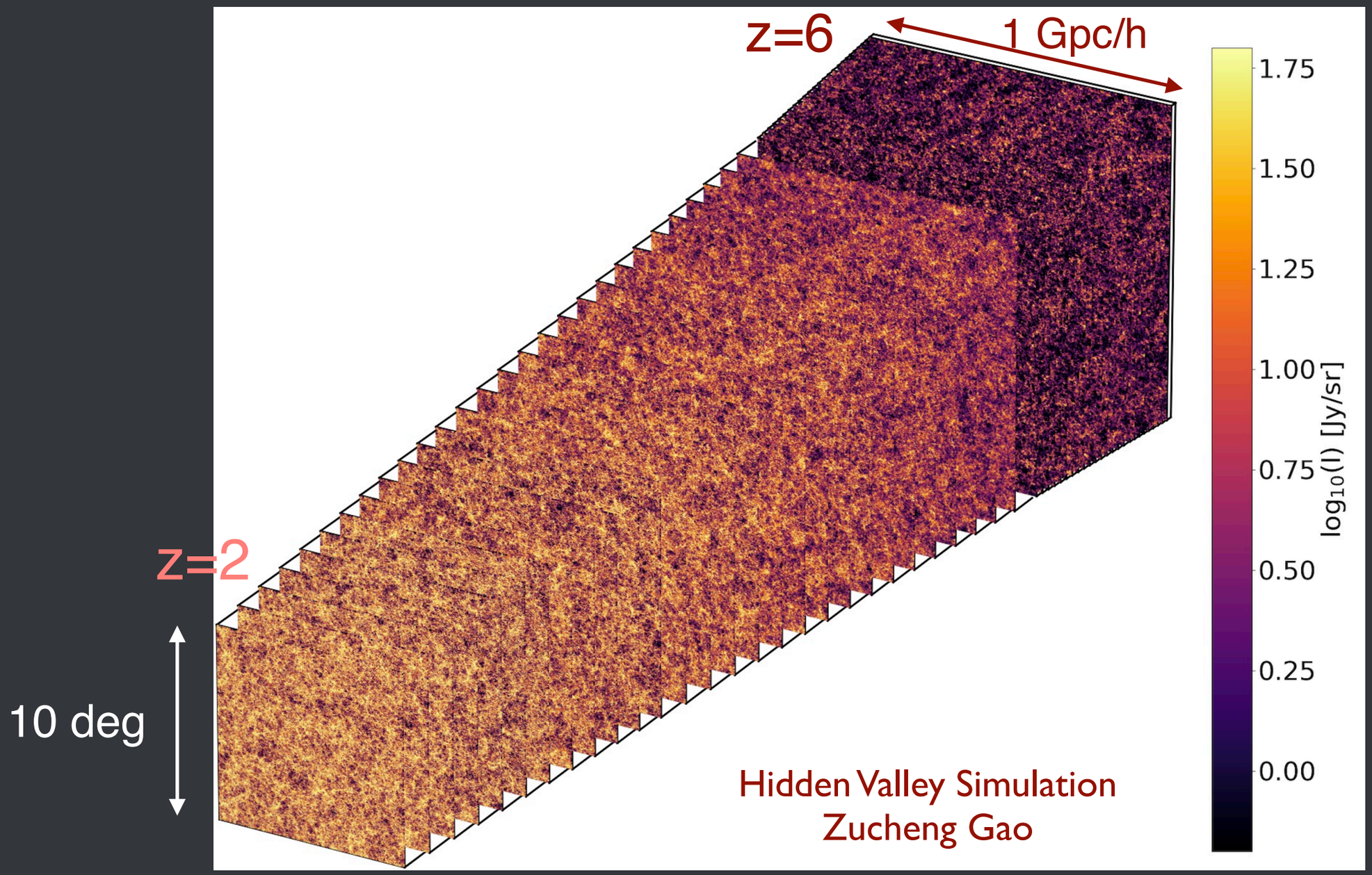
SPHEREx BAO intensity mapping



Bernal, Breysse et al. 2019

- SPHEREx can be a (high-z) BAO cosmology machine!
- Measure $D_A(z)$ and $H(z)$ using galaxies and low-z and LIM at high-z.
- Make use of multi-line / multi-tracer feature to enhance cosmological constraints and mitigate line confusion issue (e.g., Beane & Lidz 2019, Gong+ 2020)

SPHEREx Hα intensity mapping lightcone



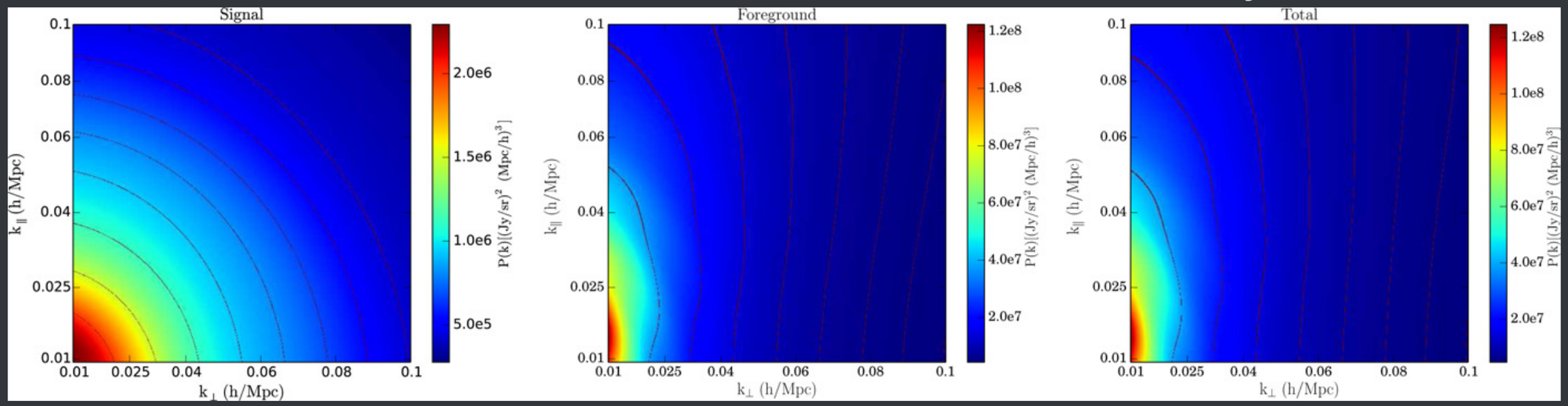
- Building a SPHEREx lightcone based on the Hidden Valley N-body simulation
- Incorporating full galaxy SED per halo, ie multiple lines and stellar continuum.
- Quantifying impact of cumulative stellar continuum (CIB) to the line investigations.

Instrumental Systematics

- Important systematics include those common to EBL investigation (dark current, thermal stability, stray-light from earth, extended PSF inside and outside FOV, detector persistent).
- Specific to LIM is to minimize spatial-spectral mode coupling, which can result from
    - Detector readout scheme
    - Survey scanning strategy through image persistence
- Currently minimizing the impacts through careful instrument design, mitigation strategy in analysis and accurate modeling.

Astrophysical systematics: Line signal de-confusion

Lyα at z~7 | Hα at z~0.5 | Lyα + Hα

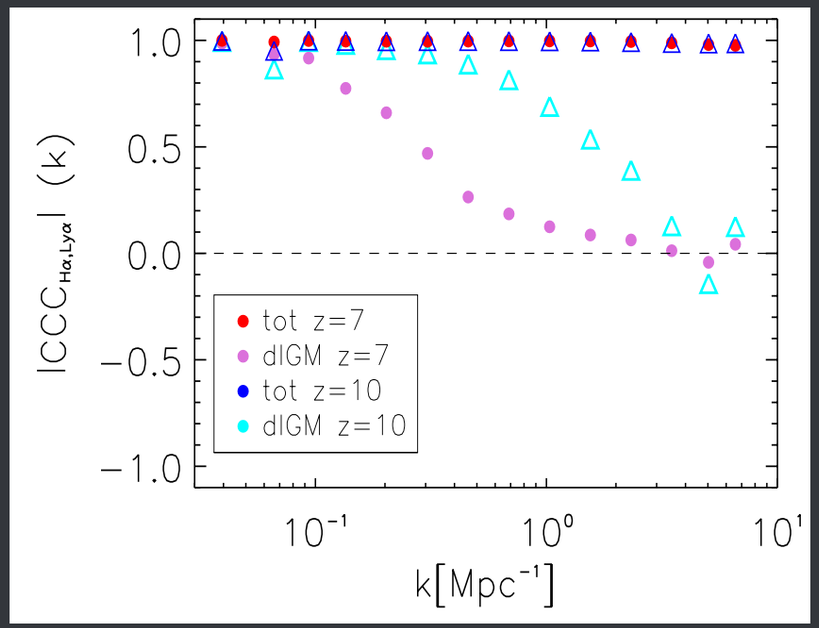


Visbal & Leob 2010, Gong+ 14, Cheng+ 16, Lidz & Taylor 16

- 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).
  - Map-Space reconstruction technique (e.g., Moriwaki+2020, Cheng, Chang, Bock 2020)
  - 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).

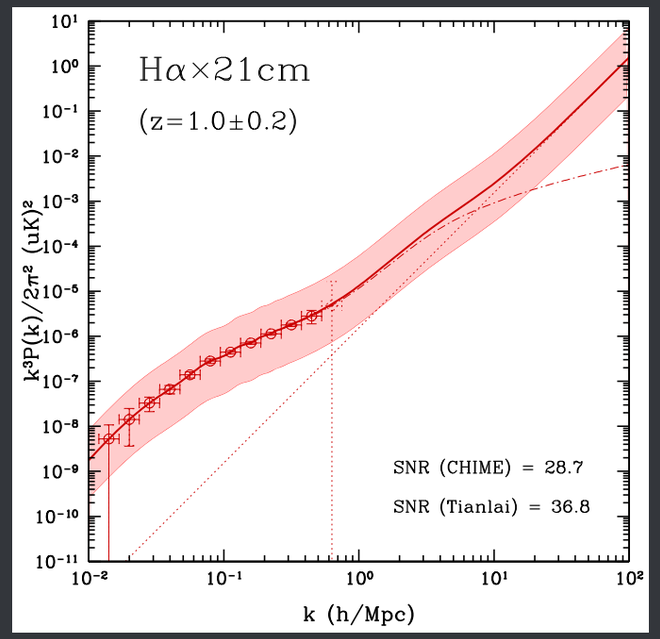
Multi-line / dataset cross-correlations

Hα x Lyα, z=6



Heneka+ 17

Hα x 21cm, z=1



Gong+ 17

- At z=5.2-6.6, SPHEREx measures both Lyα and Hα lines. Cross-correlation can probe the scales of Lyα photon scattering in the IGM during EoR.
- Cross-correlations with 21cm at z=0.8-2.5 from CHIME/HIRAX, and at z=6-8 from SKA1-LOW, respectively probing large-scale structures and ionizing bubble evolution during EoR.
- Cross-correlation with e.g. WFIRST HLS Hα galaxies at z=0.5-1.8, and Euclid deep field Hα and [OII] galaxies for signal validation and foreground mitigation. Probing faint-end luminosity functions below WFIRST detection limits.
- Cross-correlation with CMB lensing (see Emmanuel Schaan's talk)

Outlook

- SPHEREx LIM offers a rich and unique dataset, complementary to EBL and Cosmology galaxy survey sciences.
- SPHEREx LIM offers an exciting 3D probe of a significant fraction of the Universe.
  - Hα, [OIII], [OII] IM: tracing cosmic structure (incl. BAO) at $1 < z < 5$.
  - Lyα, [OIII], Hα IM: tracing ionization progress during EoR at z~5.5-8.
- Work in progress:
  - Building two simulation tools for Cosmology and EoR sciences for mock observations and science interpretation, and to quantify astrophysical systematic effects.
  - Refining Cosmology and EoR science cases with IM including multi-tracer approach and estimate of systematic effects
- Multiple cross-correlation signals with external data sets, such as galaxies in spectroscopic or imaging data, CMB (lensing), and LIM surveys remain to be explored.