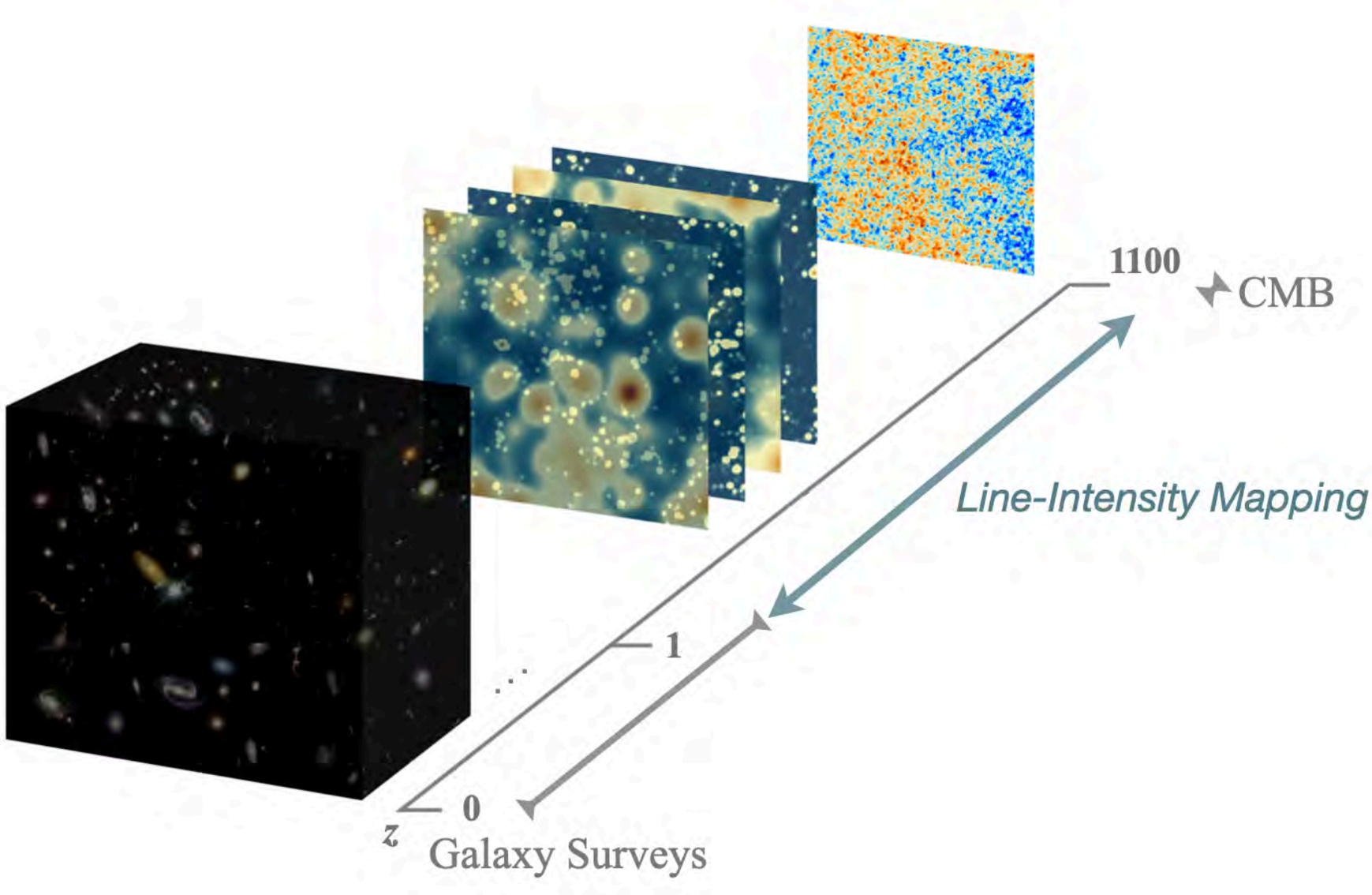
Line*-Intensity Mapping: Review and Outlook

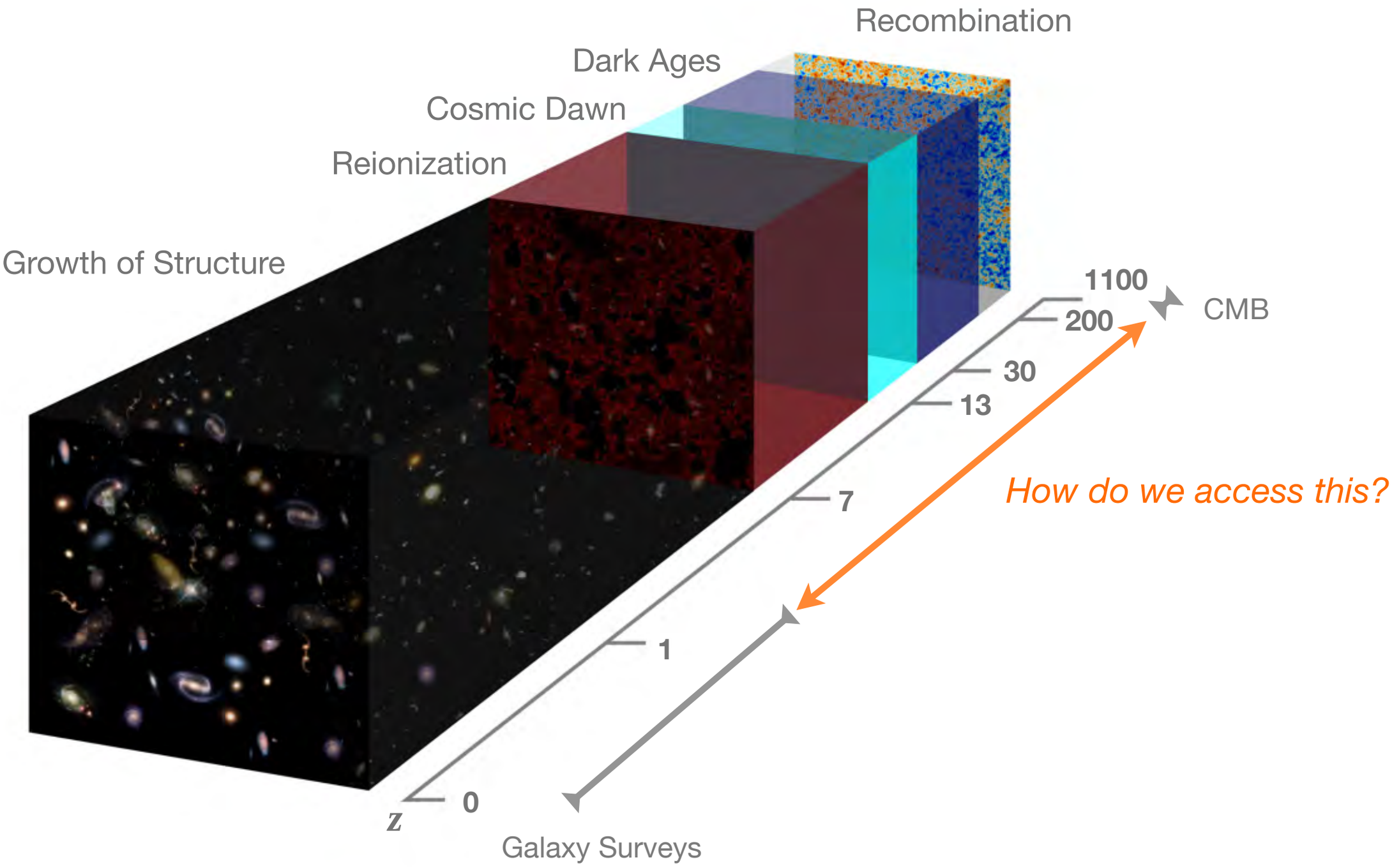
*with a focus on star-formation lines

Ely Kovetz, Ben-Gurion University



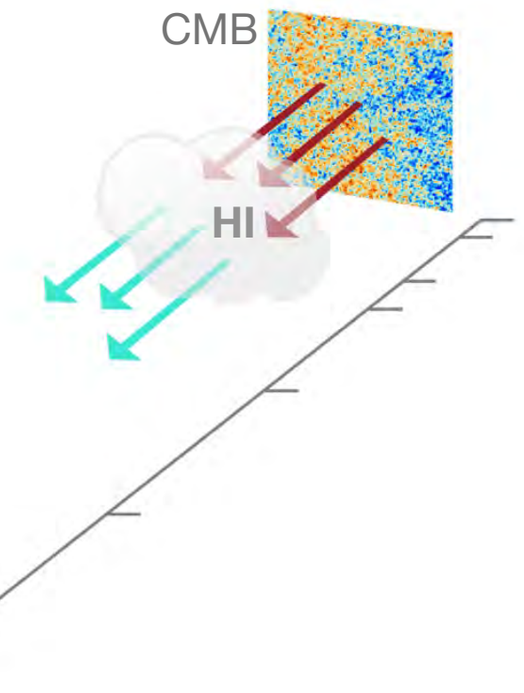
21cm Cosmology Workshop, Hangzhou, July 2024

Line-Intensity Mapping: Introduction



Line-Intensity Mapping: Introduction

Earliest LIM signal: CMB interaction with HI



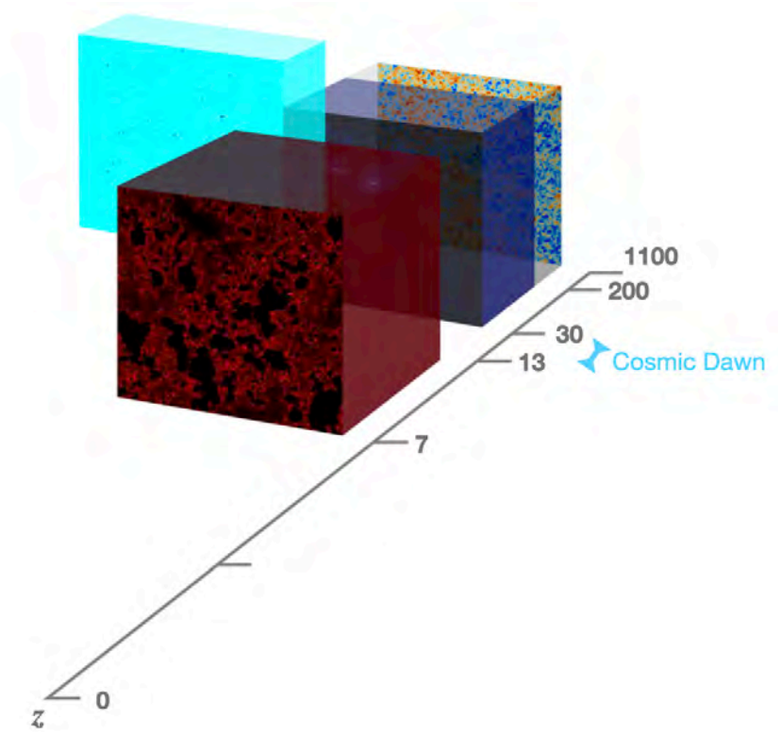
Line-Intensity Mapping: Introduction

Earliest LIM signal: CMB interaction with HI

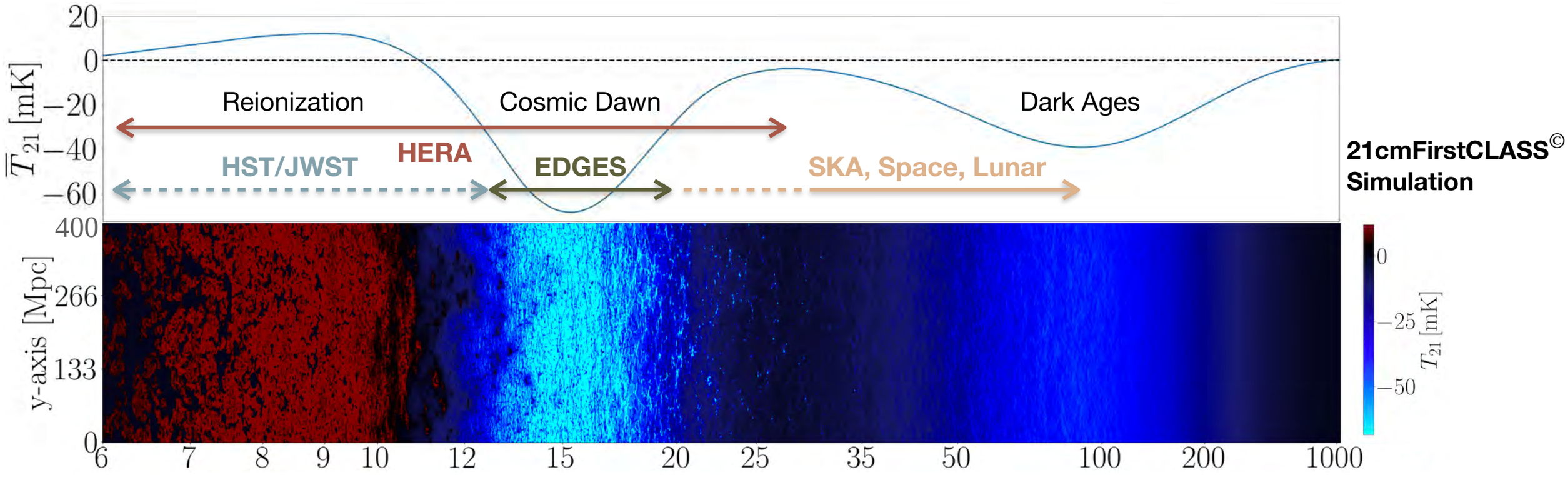
Dark Ages: adiabatic gas cooling; no stars

Cosmic dawn: turns on via Lyα from first stars

Reionization: emission against the CMB



The 21cm brightness temperature contrast:



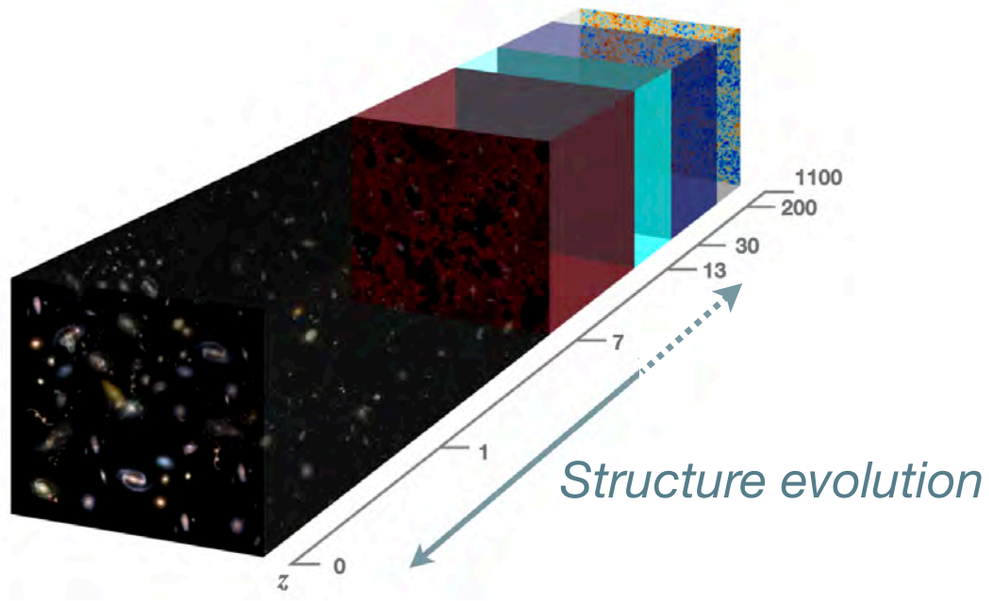
21cmFirstCLASS© Simulation

Flitter and Kovetz, PRD 2024

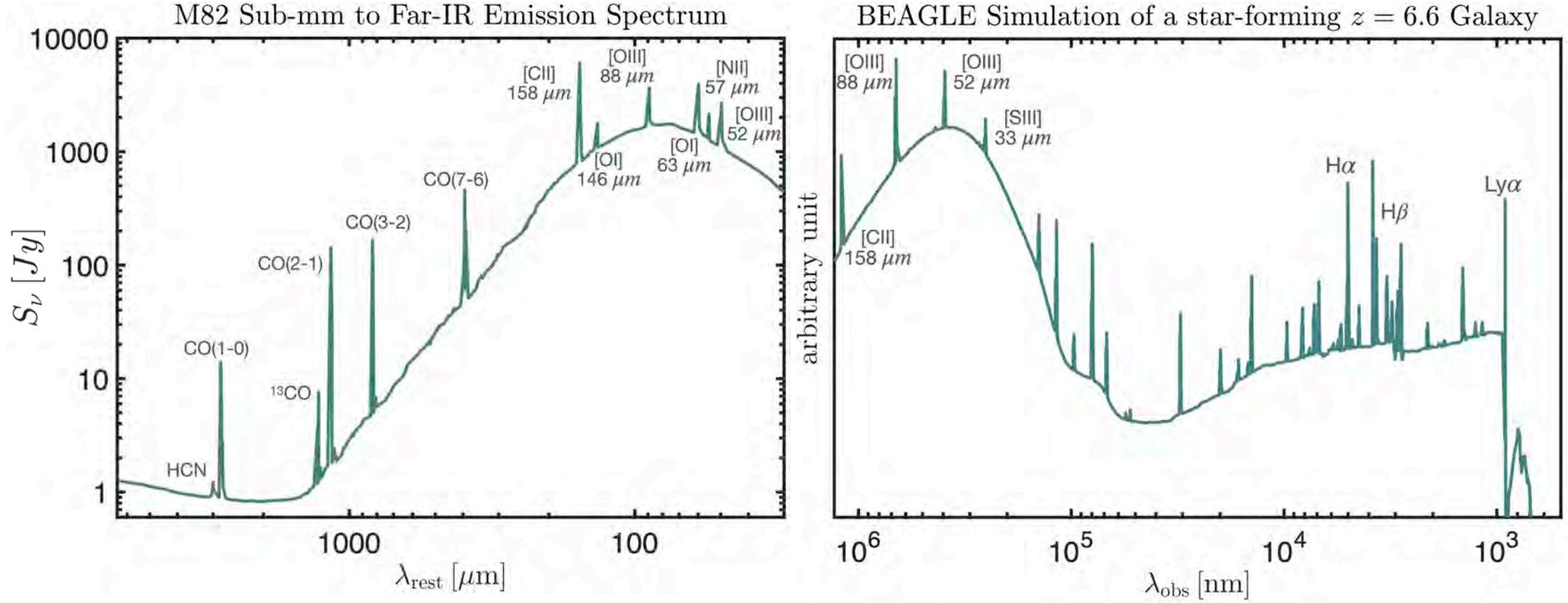
Line-Intensity Mapping: Introduction

Growth of Structure:

In galaxies: host of atomic and molecular transitions



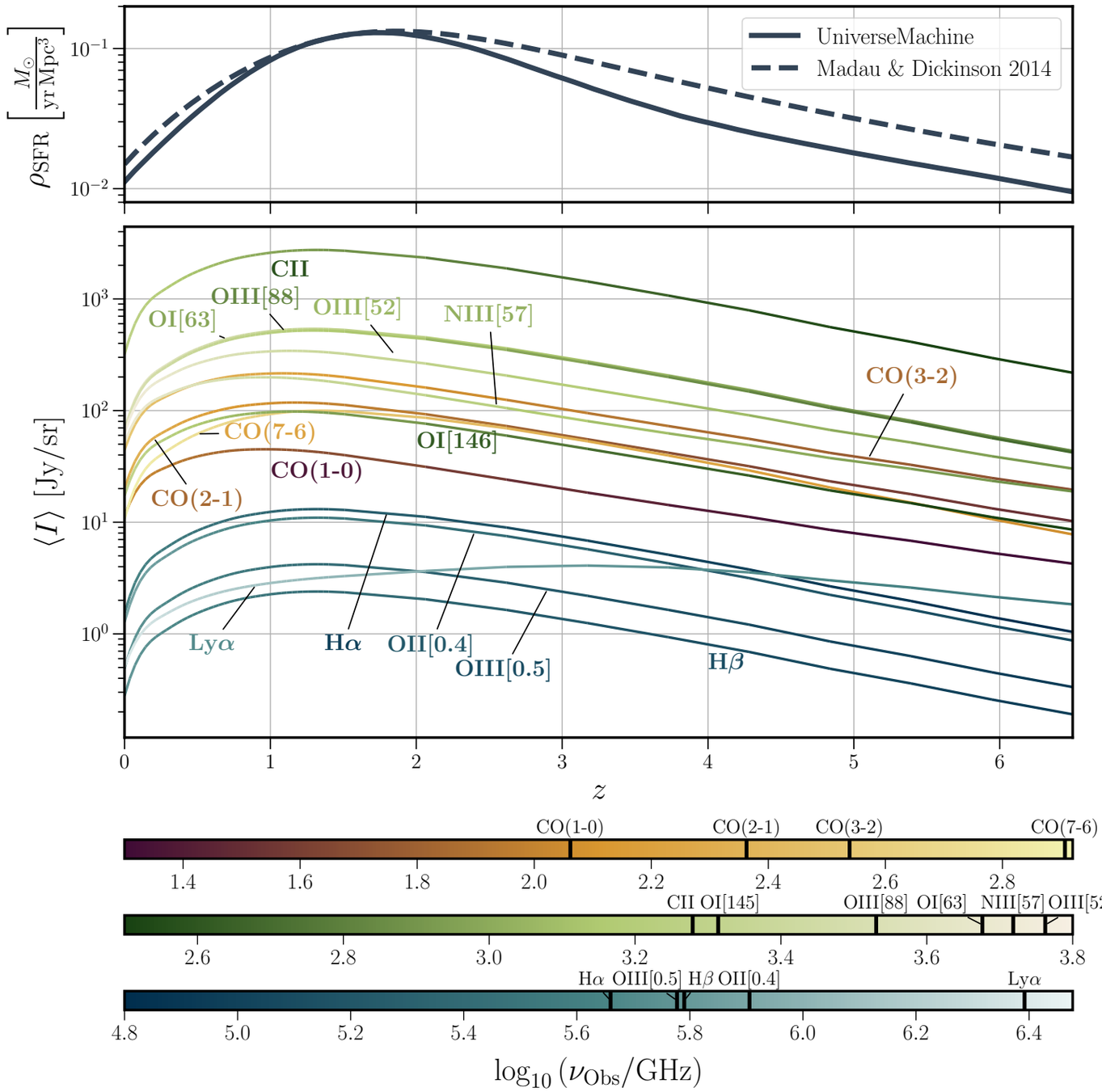
Spectrum of a typical galaxy:

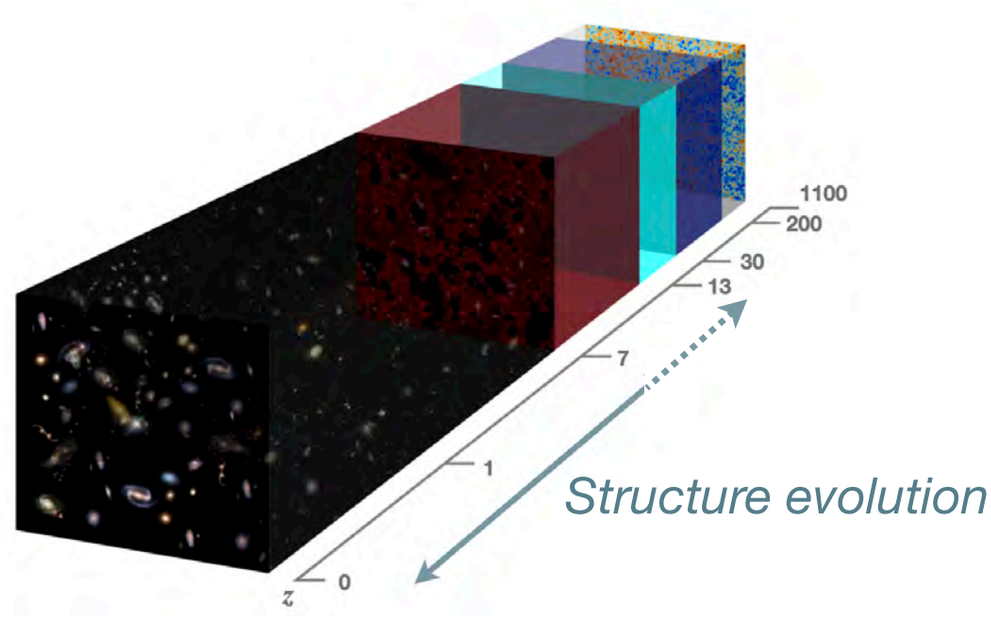


Bernal and Kovetz, The Astronomy and Astrophysics Review 2023

Line-Intensity Mapping: Introduction

Growth of Structure: Star-formation lines

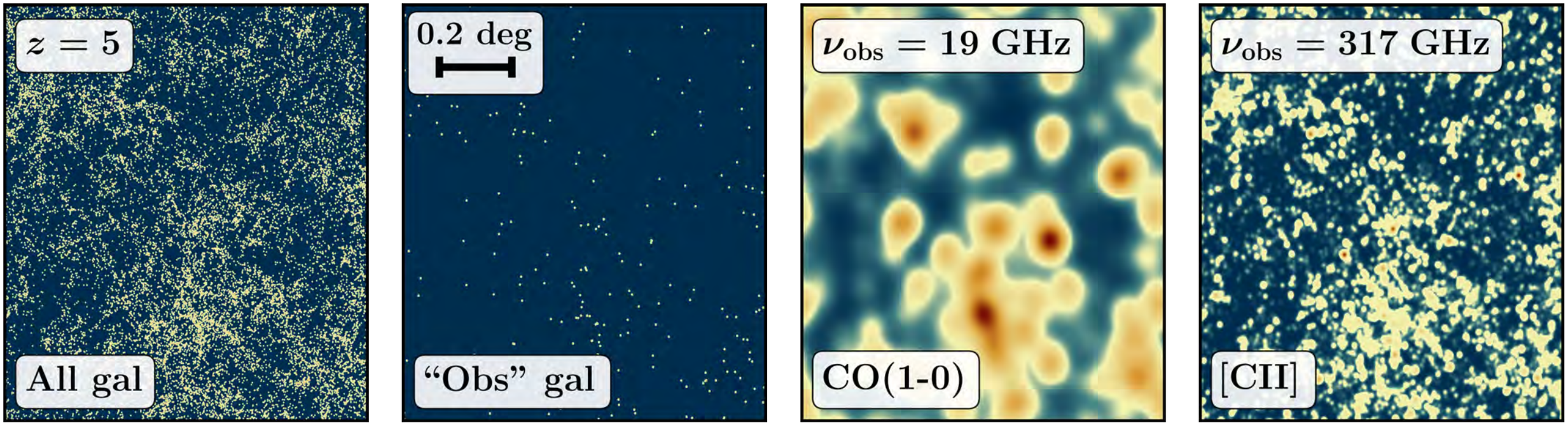




Bernal and Kovetz, The Astronomy and Astrophysics Review 2023

Line-Intensity Mapping: Introduction

Mapping galactic line-emission:



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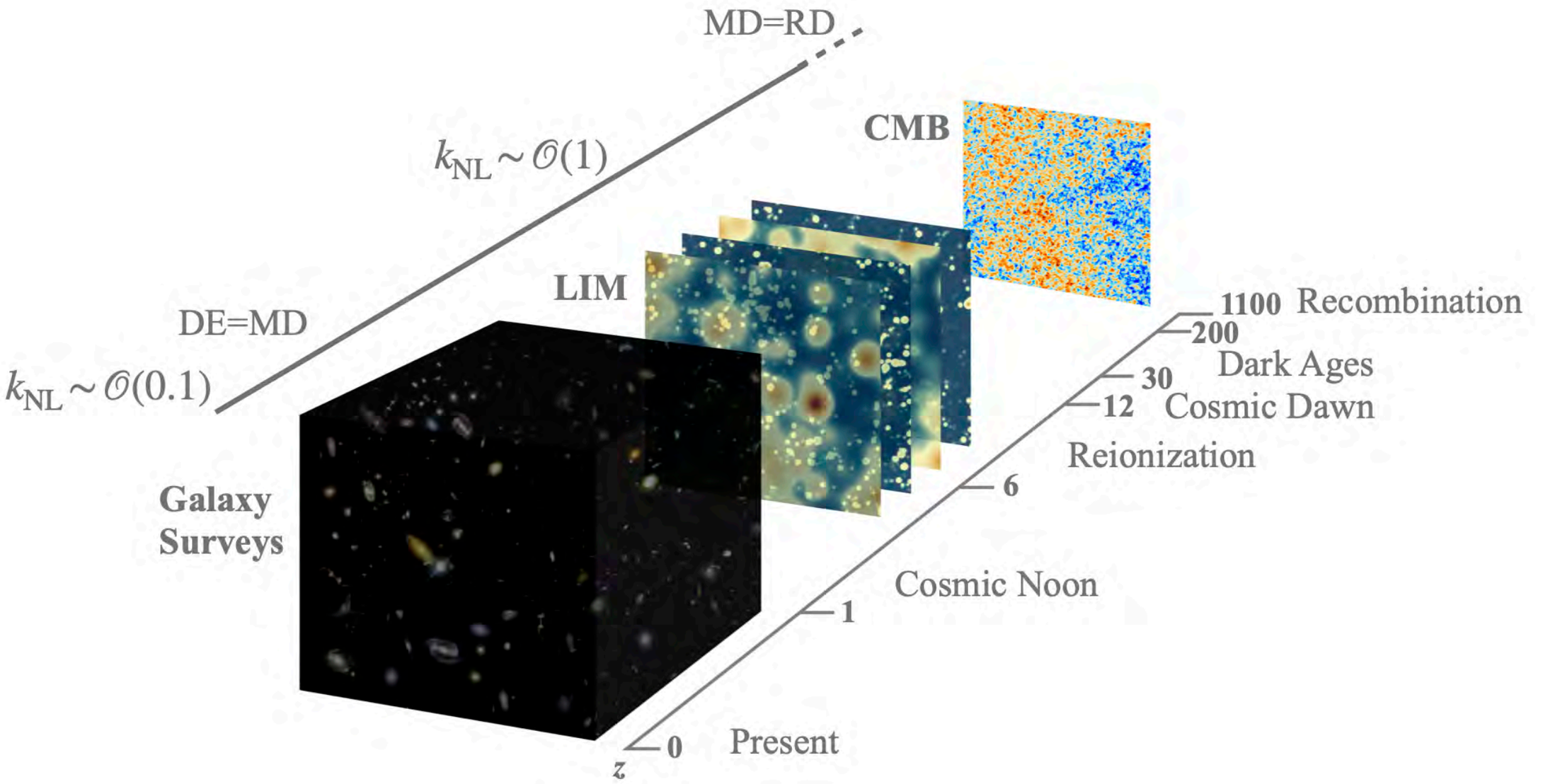
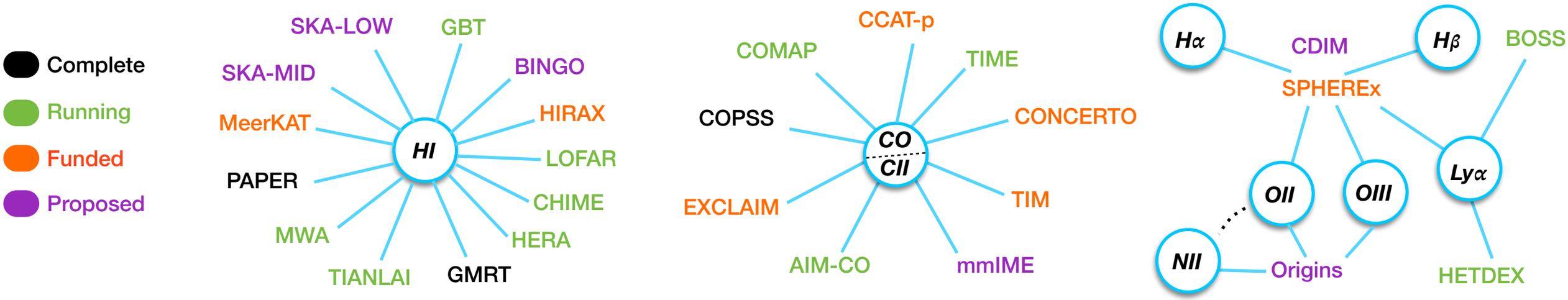


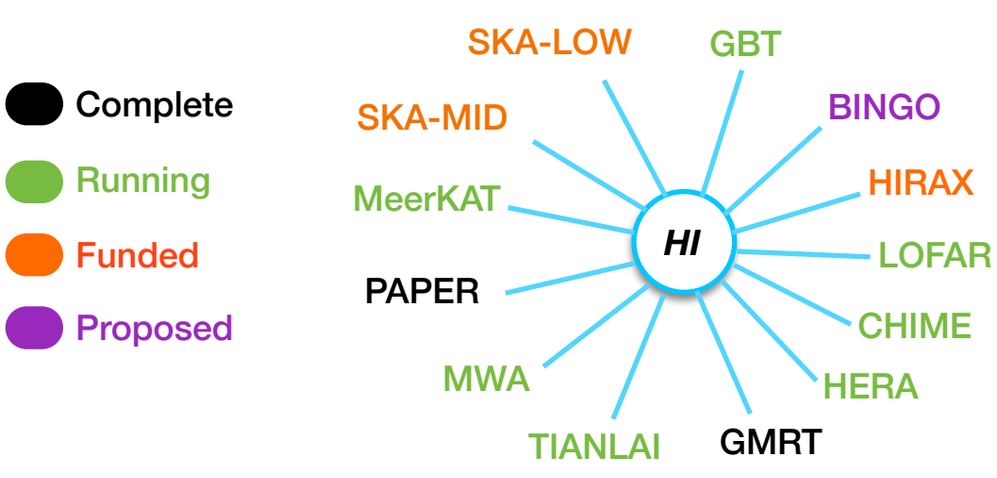
Bernal and Kovetz, The Astronomy and Astrophysics Review 2023

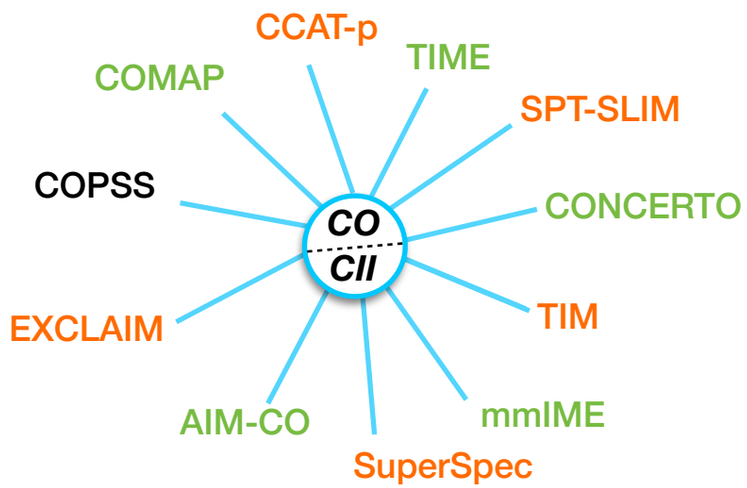
Line-Intensity Mapping: Experimental Landscape

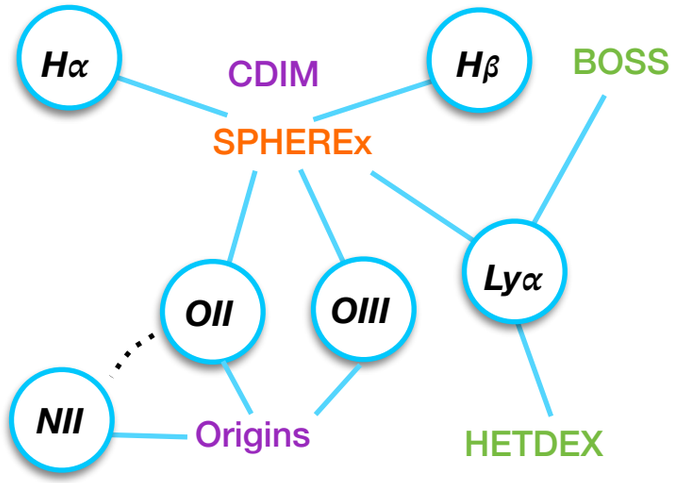


Astro2020: Kovetz et al. [arXiv:1903.04496]

Line-Intensity Mapping: Experimental Landscape







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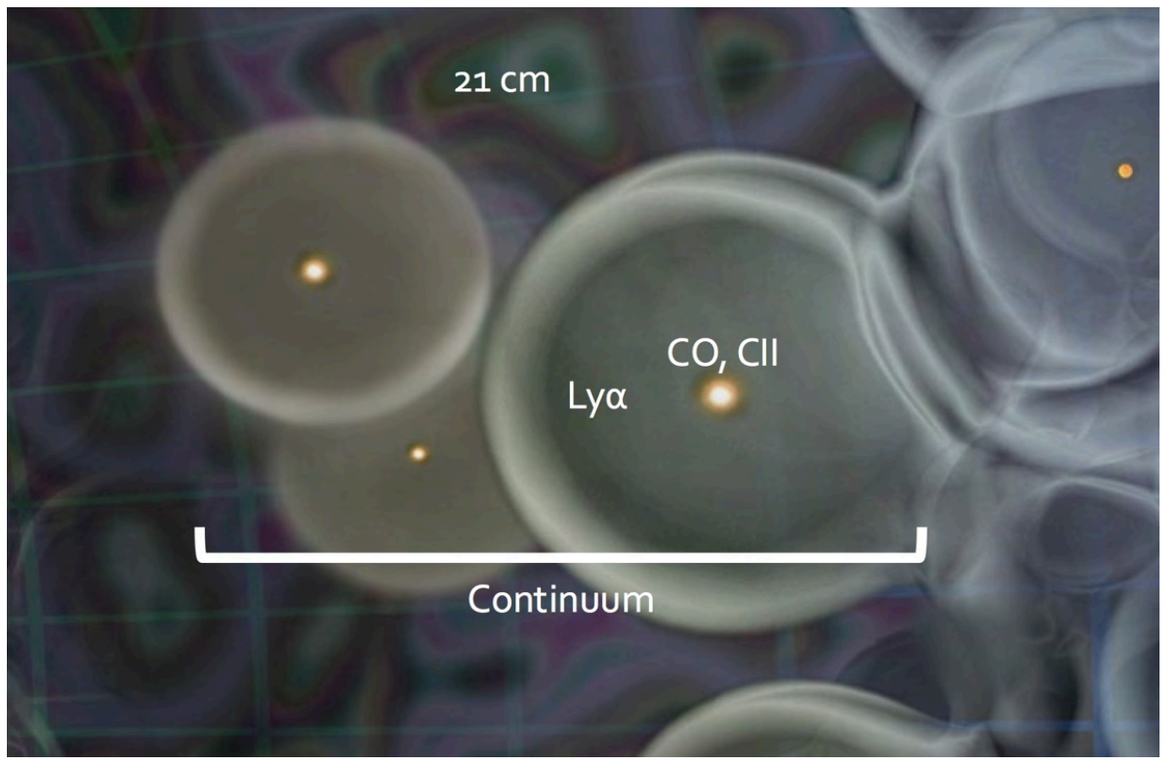
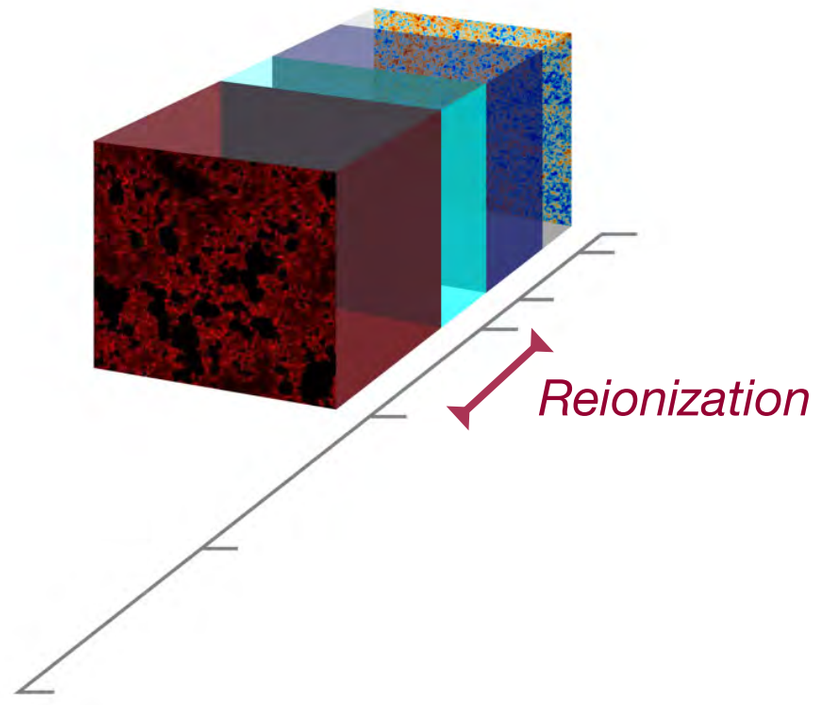


Kovetz et al., LIM Status Report [arXiv:1709.09066]



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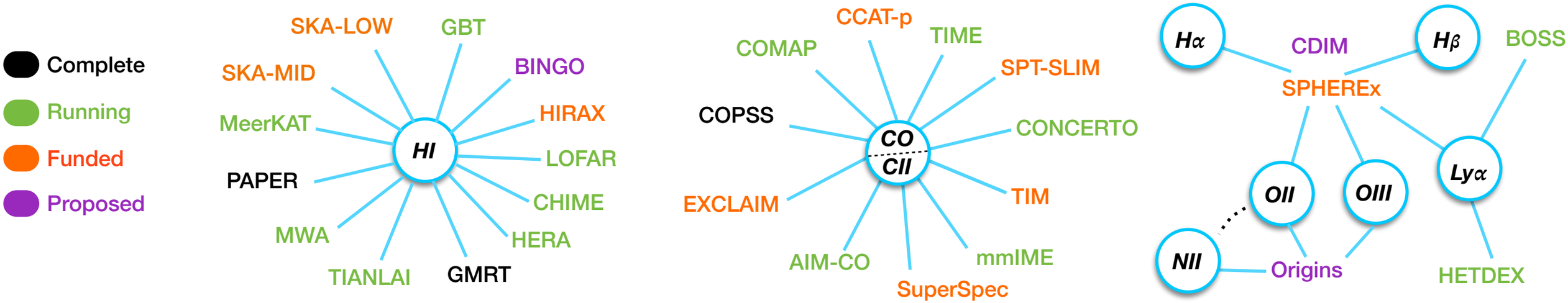
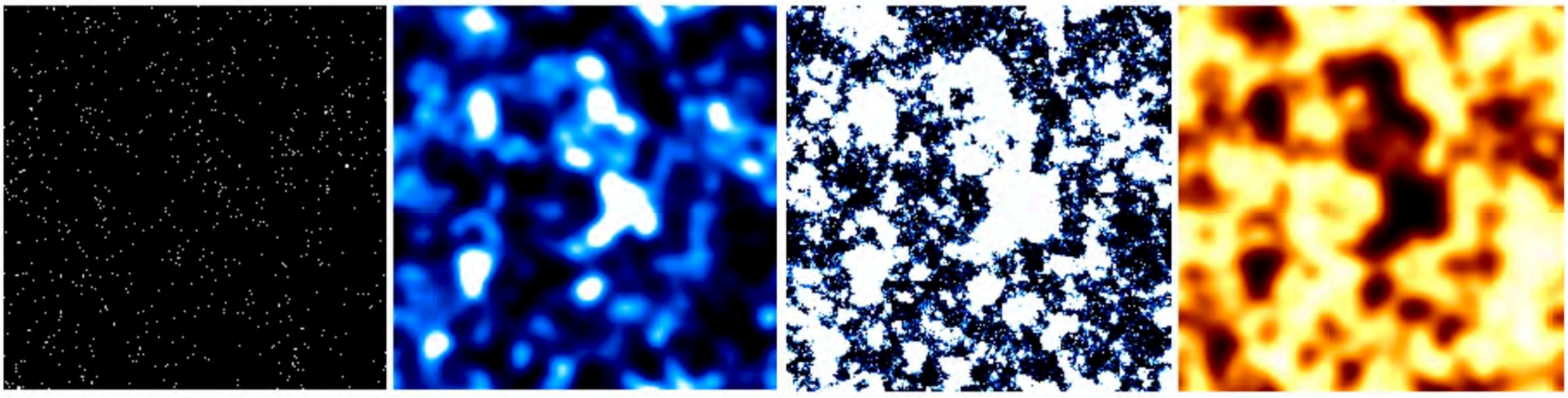


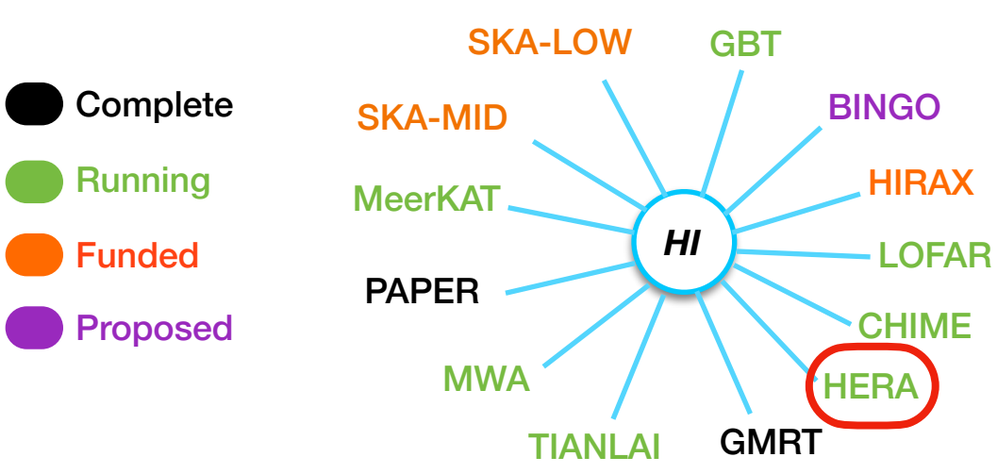
Astro2020: Kovetz et al. [arXiv:1903.04496]

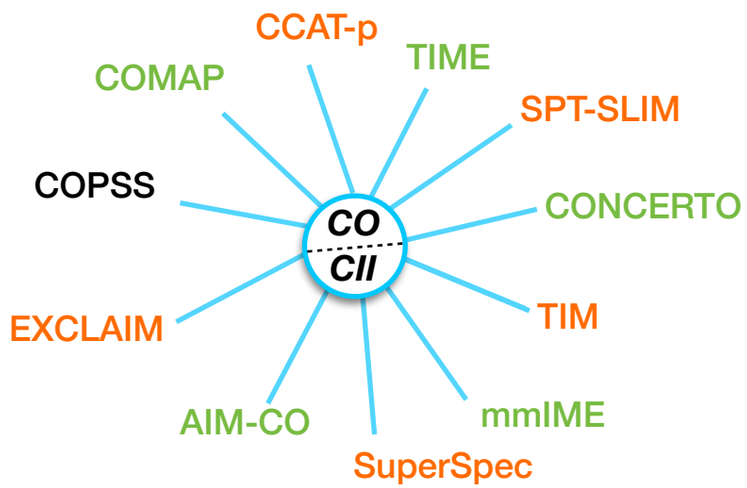
EoR Galaxies | CO(2-1) LIM | Ionization field | Redshifted 21cm

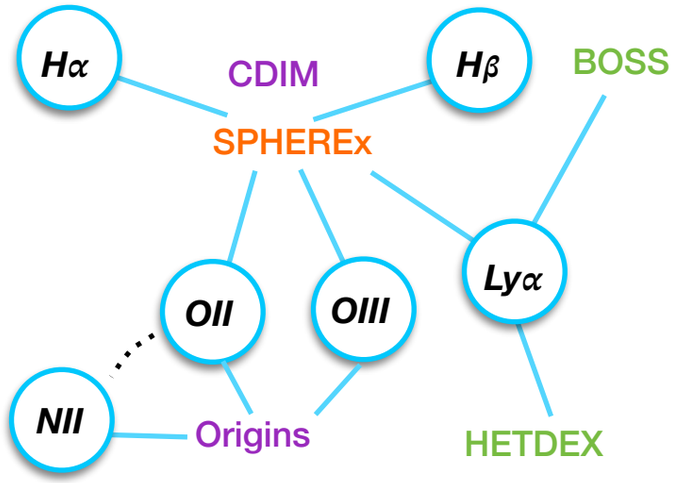


(Courtesy of A. Lidz)

Line-Intensity Mapping: Experimental Landscape







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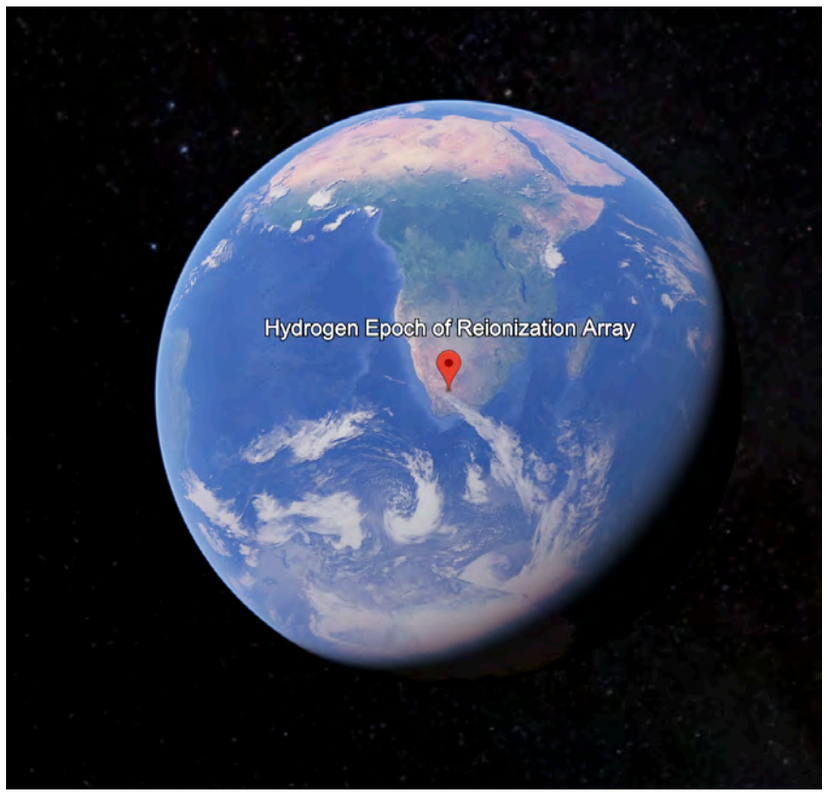

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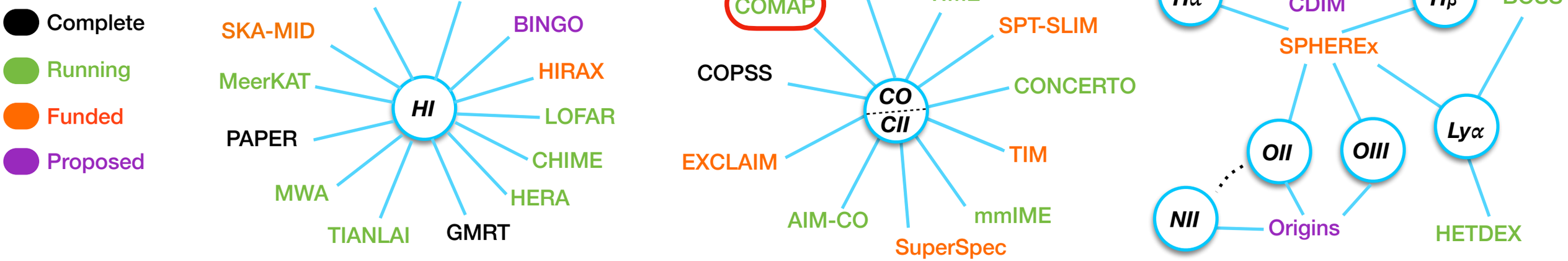

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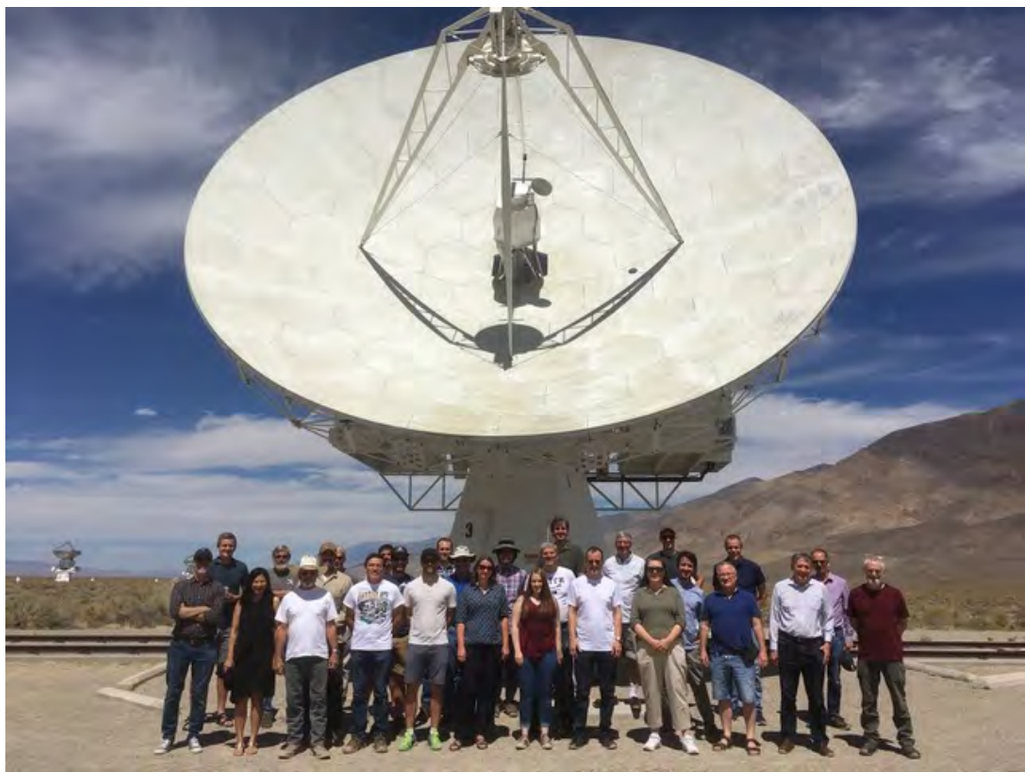

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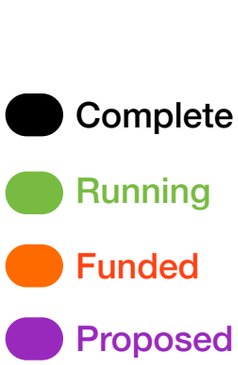

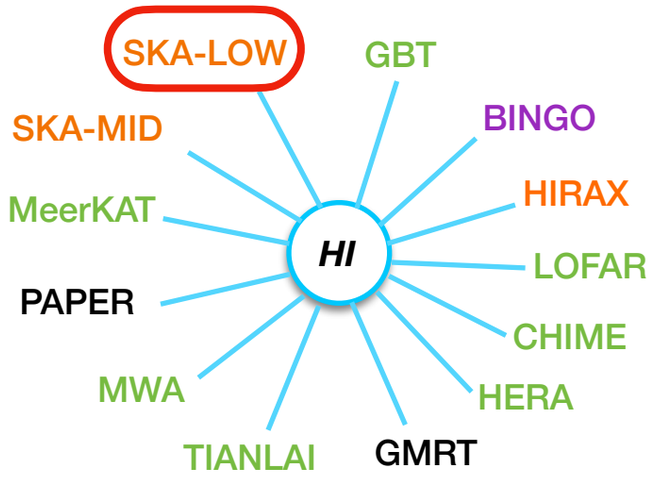

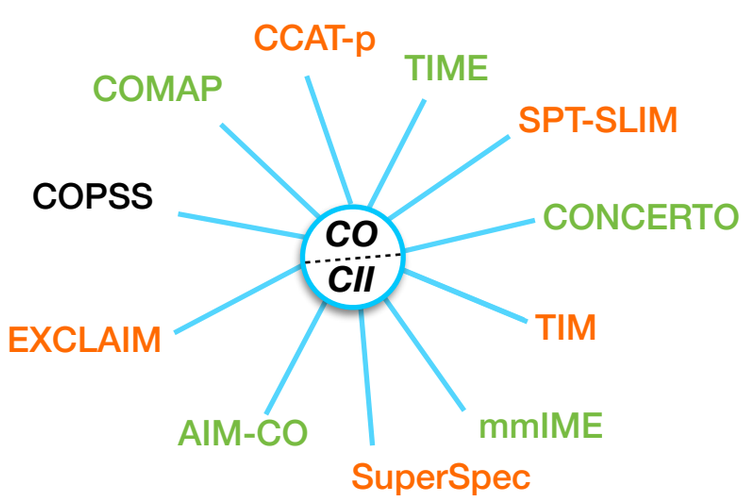

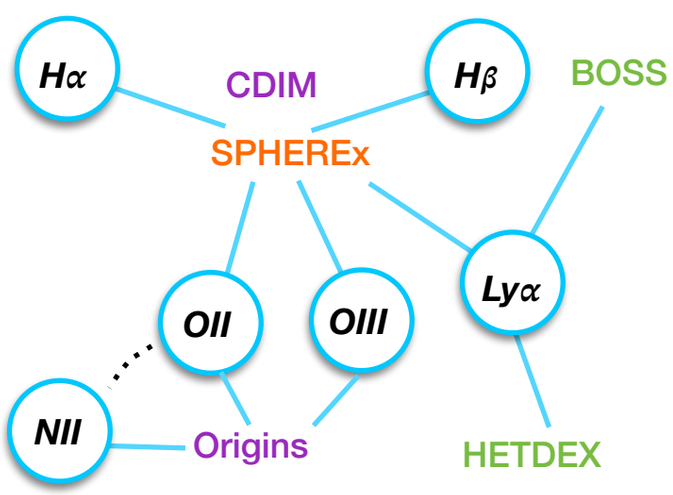

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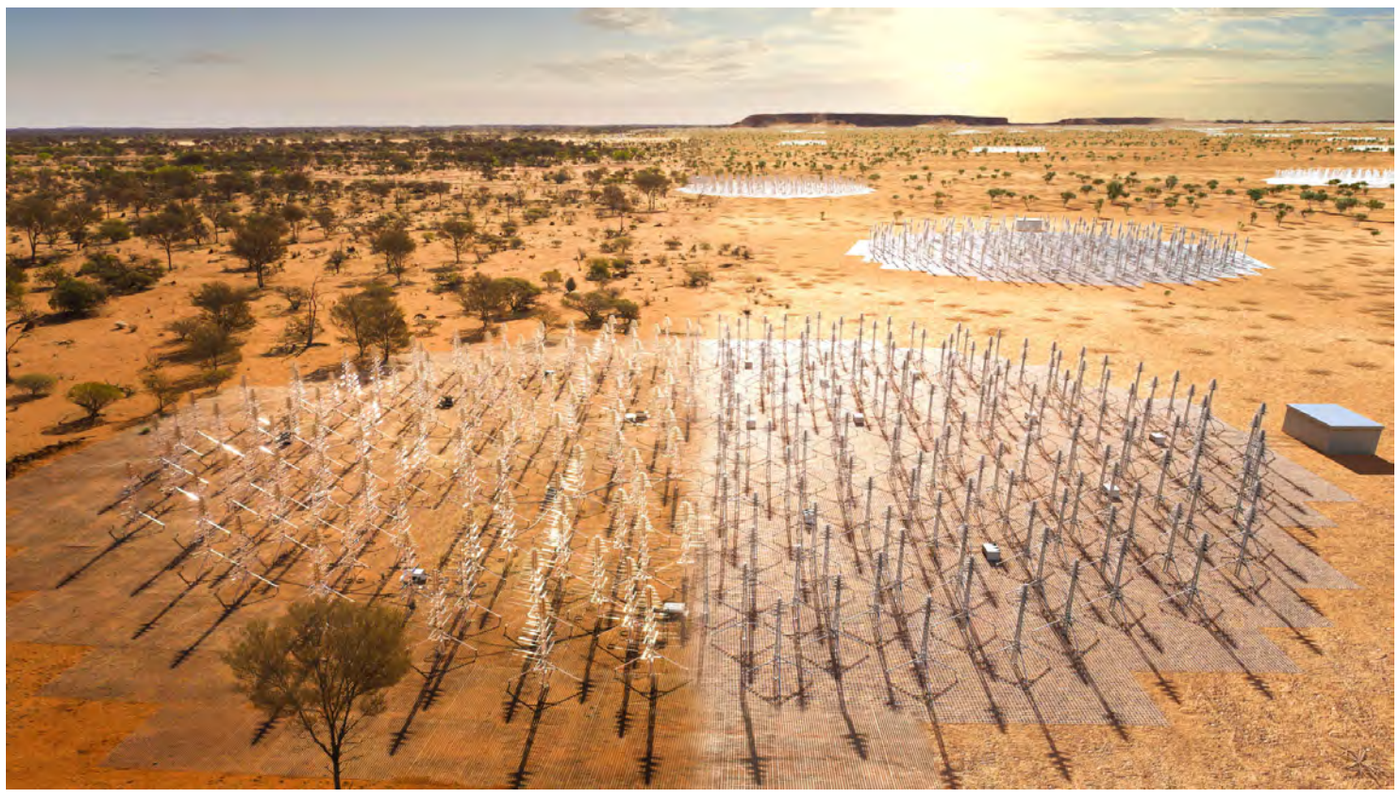

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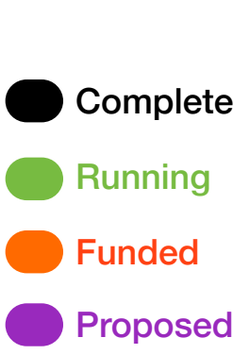

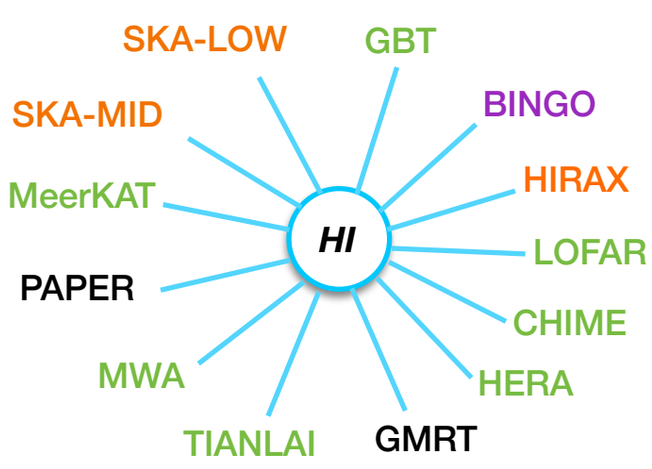

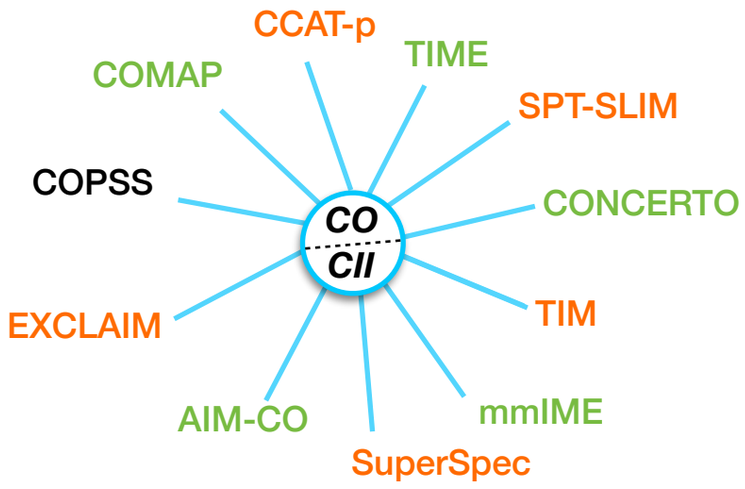

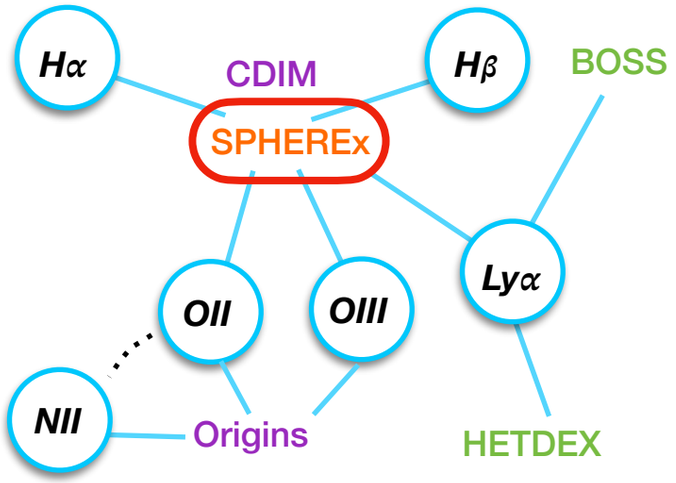

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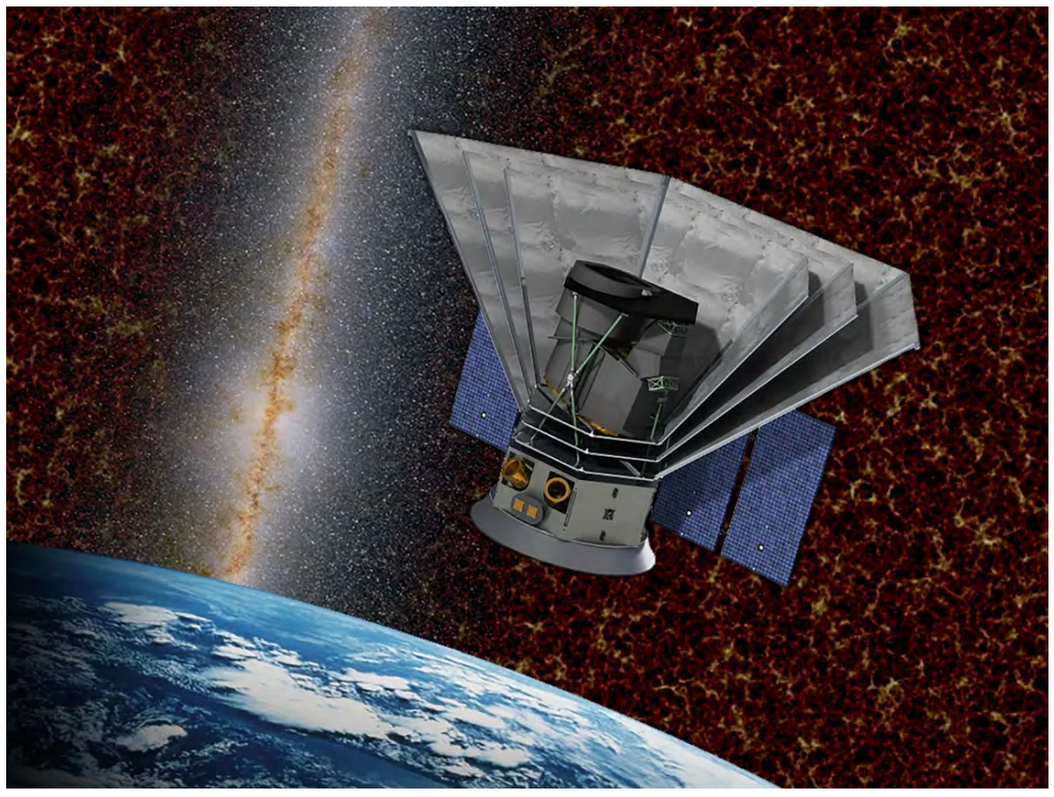
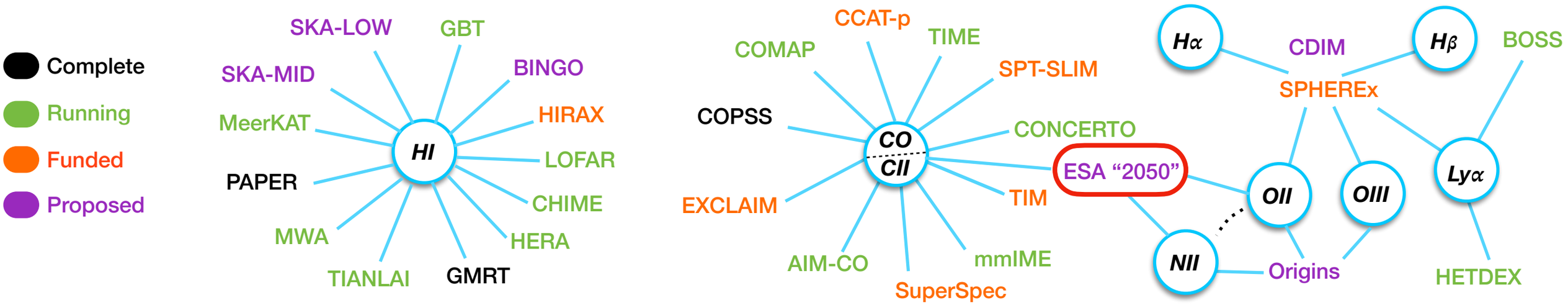


Line-Intensity Mapping: Experimental Landscape



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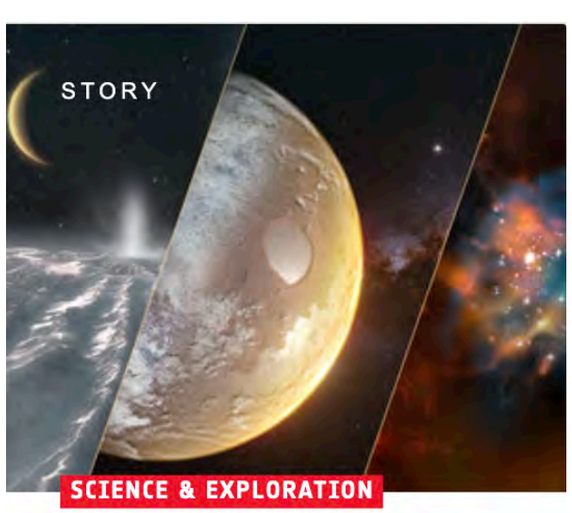
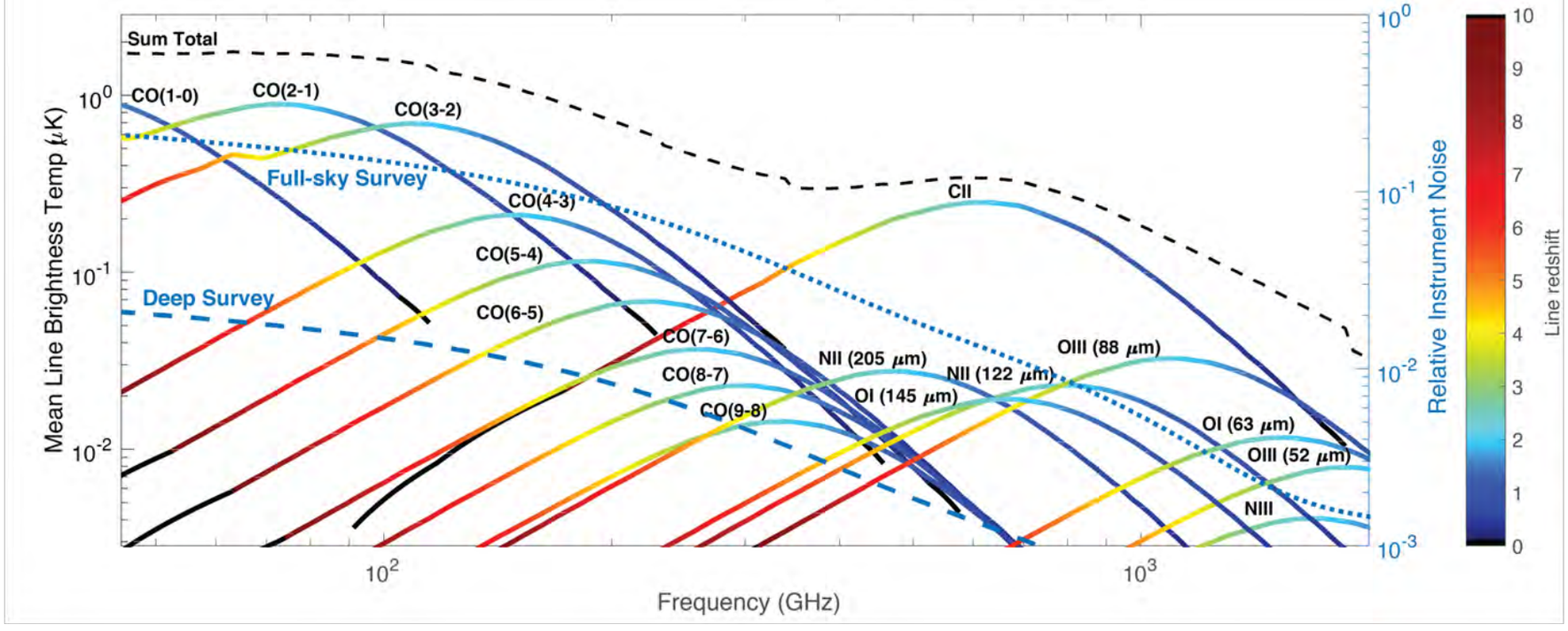
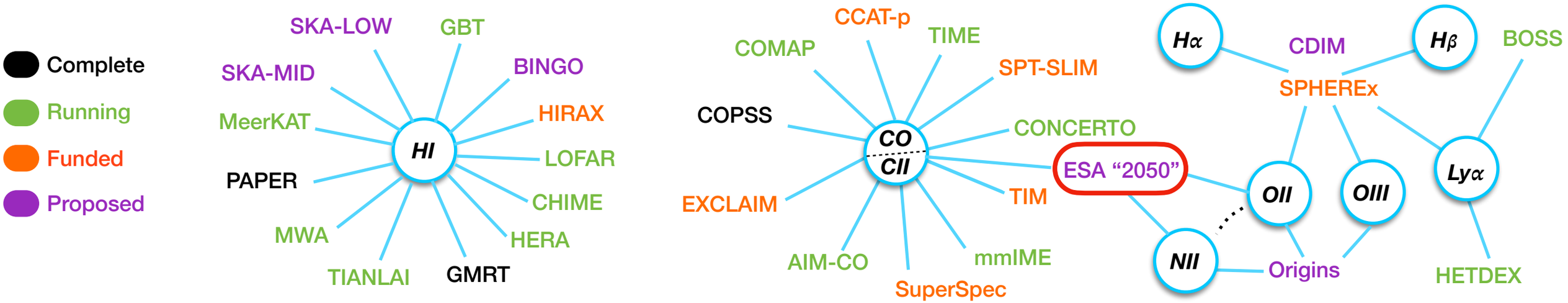




(Courtesy of K. Keating)

ESA2050 proposal: Silva, Kovetz et al. [arXiv:1908.07533]

Takeaway: Line-Intensity Mapping is Coming!



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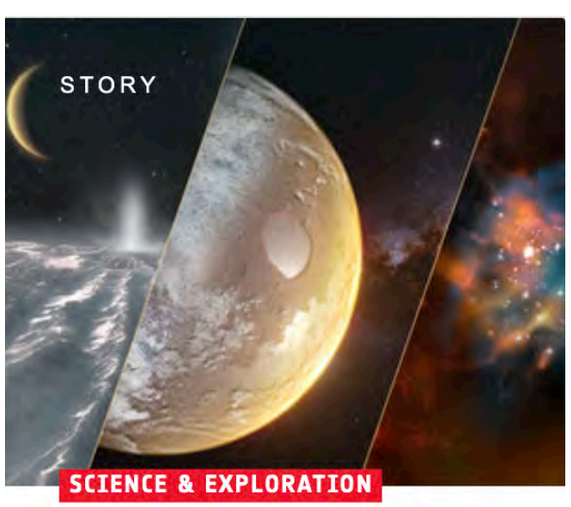

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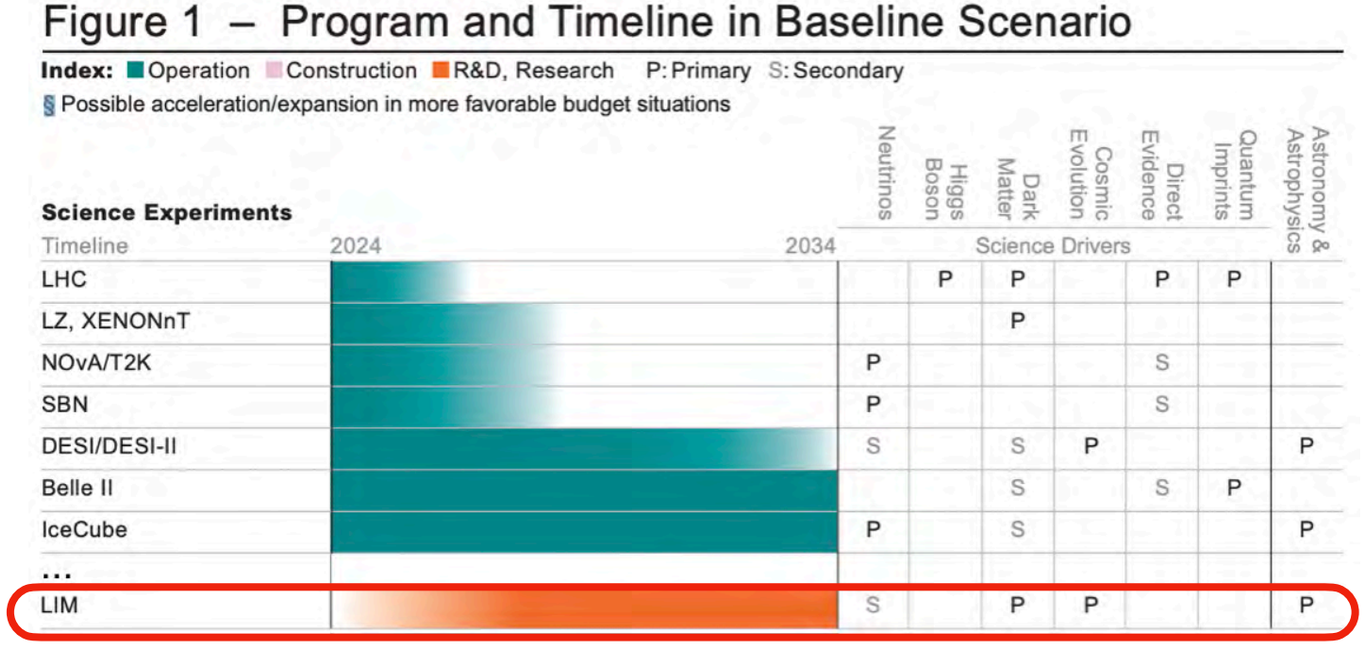


Particle Physics Project Prioritization Panel (P5) Recommendation

Snowmass White Paper: Karkare et al. [arXiv:2203.07258]

Line-Intensity Mapping: Modeling Approaches

Two main approaches:

1) Physical:

Numerical simulations and semi-analytical models of galaxy formation and evolution.

- Model ISM physics: collisional excitations, radiative processes (spontaneous, stimulated)...
- Add diffuse IGM component as needed.

$\longrightarrow$ Requires numerous assumptions and many free parameters

2) Phenomenological:

Use a series of empirical scaling relations to map halo mass to line luminosity.

- Relate halo mass to star-formation rate (SFR): $M_h \longrightarrow \mathrm{SFR}(M_h)$
- Connect SFR to FIR luminosity and then to line luminosity: $\mathrm{SFR}(M_h) \longrightarrow L_{\mathrm{FIR}} \longrightarrow L_{\mathrm{[CII]/CO/...}}$
- Allow for scatter at each step.

$\longrightarrow$ Based on very limited datasets from particular redshifts

Main challenge: how to interpret a measurement?

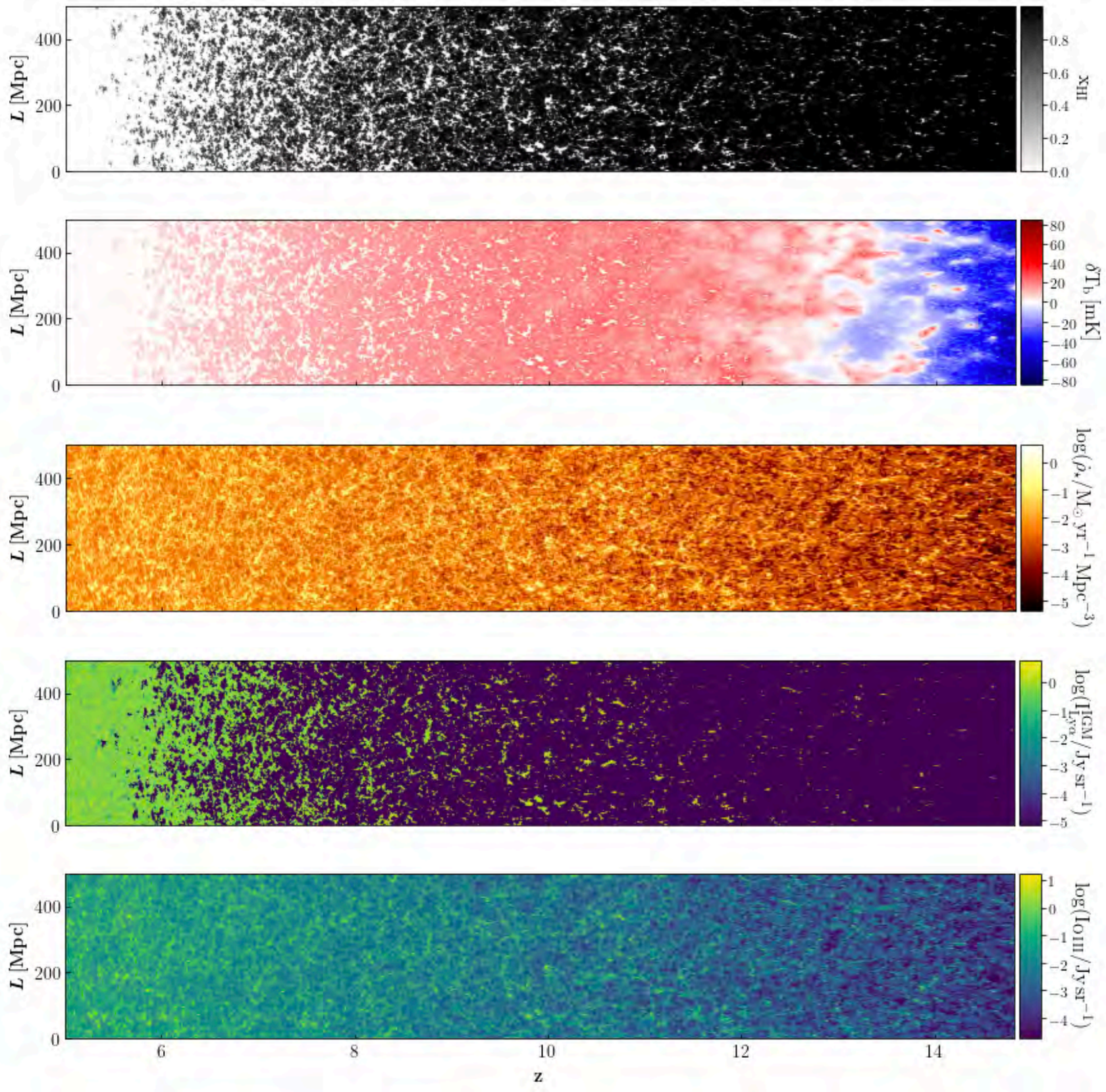
Line-Intensity Mapping: Simulations

Reionization:

21cmFAST

↓

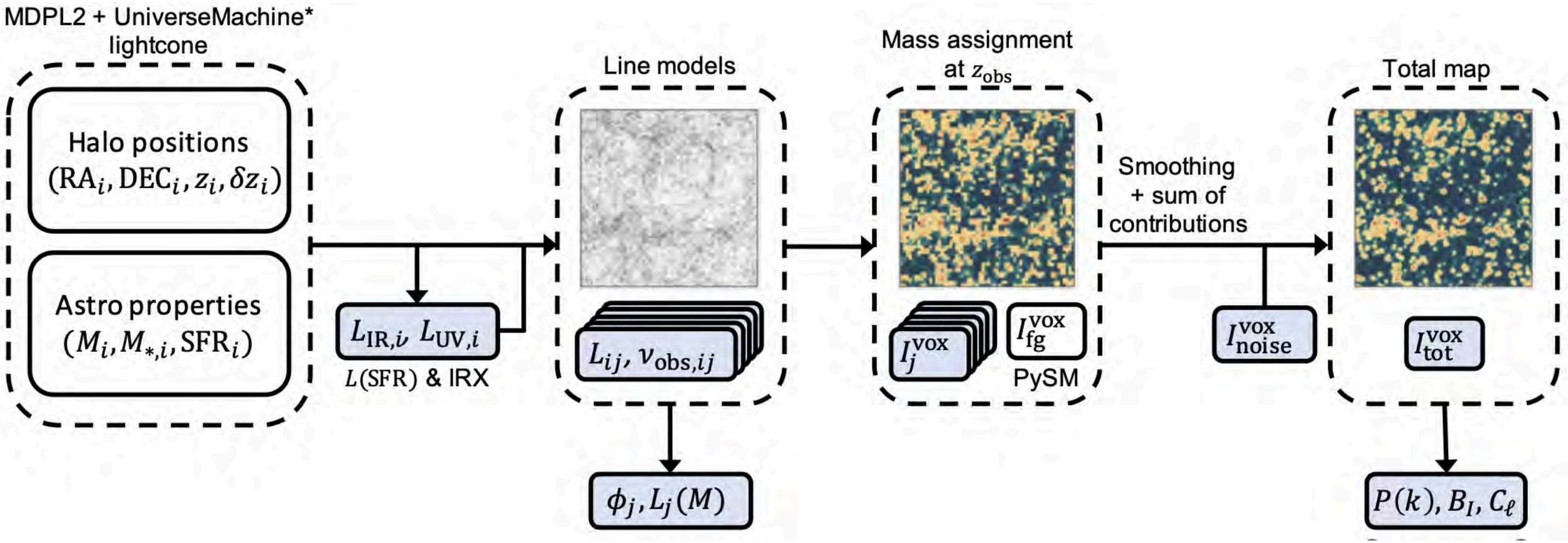
LIMFAST package
Mas-Ribas et al.,
arXiv:2206.14185

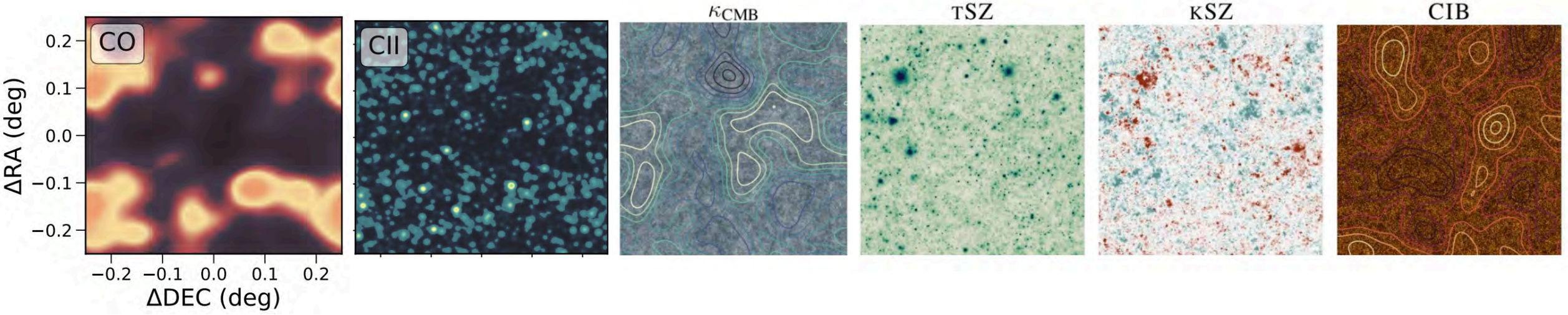


Line-Intensity Mapping: Simulations

Multi-tracer light cones:

Skyline, Sato-Polito et al., arXiv: arXiv:2212.08056





Line-Intensity Mapping: What Can it Probe?

Astrophysics:

- Reionization: bubble sizes, ionized fraction, duration
- Star formation rate (history, peak rise/fall, Pop III stars)
- Metallicity history
- AGN feedback
- Molecular gas density
- IGM density, evolution, clustering
- Faint end of luminosity function
- …
- …

Cosmology:

- Inflation (running, non-gaussianity, oscillations, CIP, etc.)
- Dark matter (clustering, decaying, annihilating, interacting)
- Expansion rate history (BAO, VAO)
- Dark energy (c.c. or dynamical? w_0/w_a, etc.)
- Neutrinos (sum of masses, hierarchy, decay)
- Optical depth to Reionization (SFR, degeneracies, etc.)
- Modified gravity
- …
- …

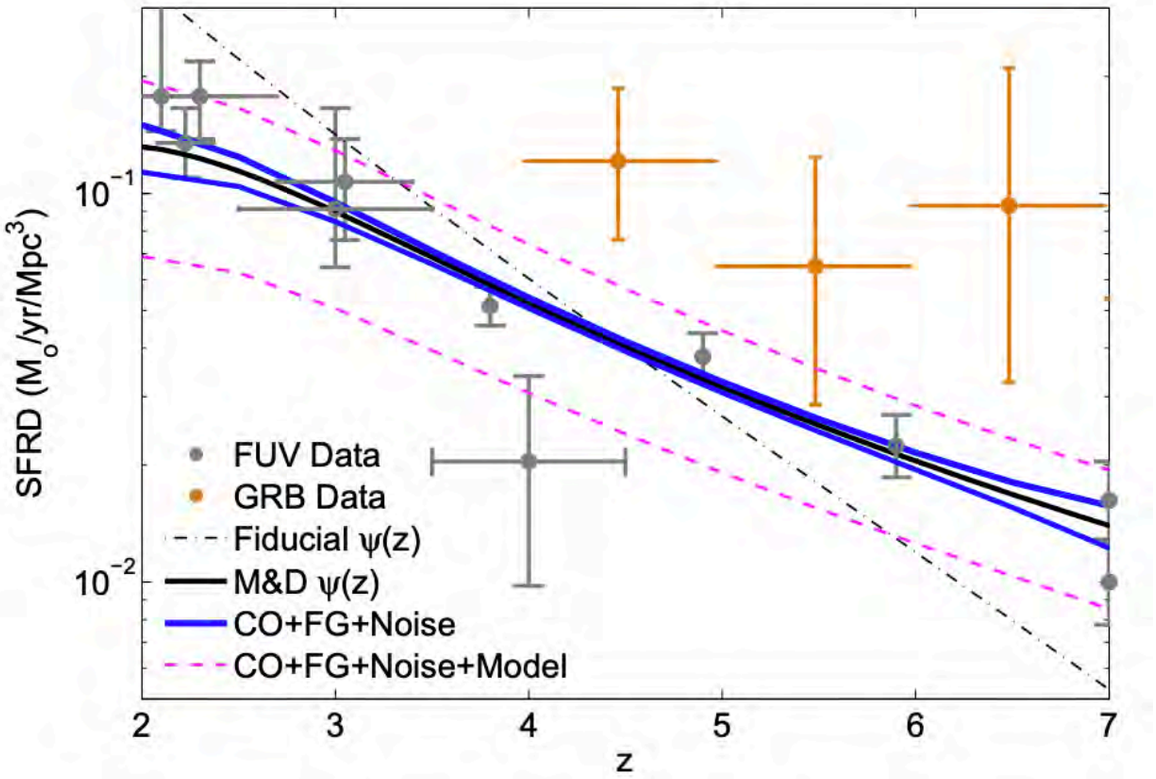
One’s signal is another’s foreground

Reviews: Kovetz et al., LIM 2017 Status Report arXiv:1709.09066; Bernal and Kovetz, The Astronomy and Astrophysics Review 2023

WPs: *Astro2020*: Kovetz et al., 1903.04496; *ESA2050*: Silva, Kovetz et al., 1908.07533; *Snowmass2021*: Karkare et al., 2203.07258

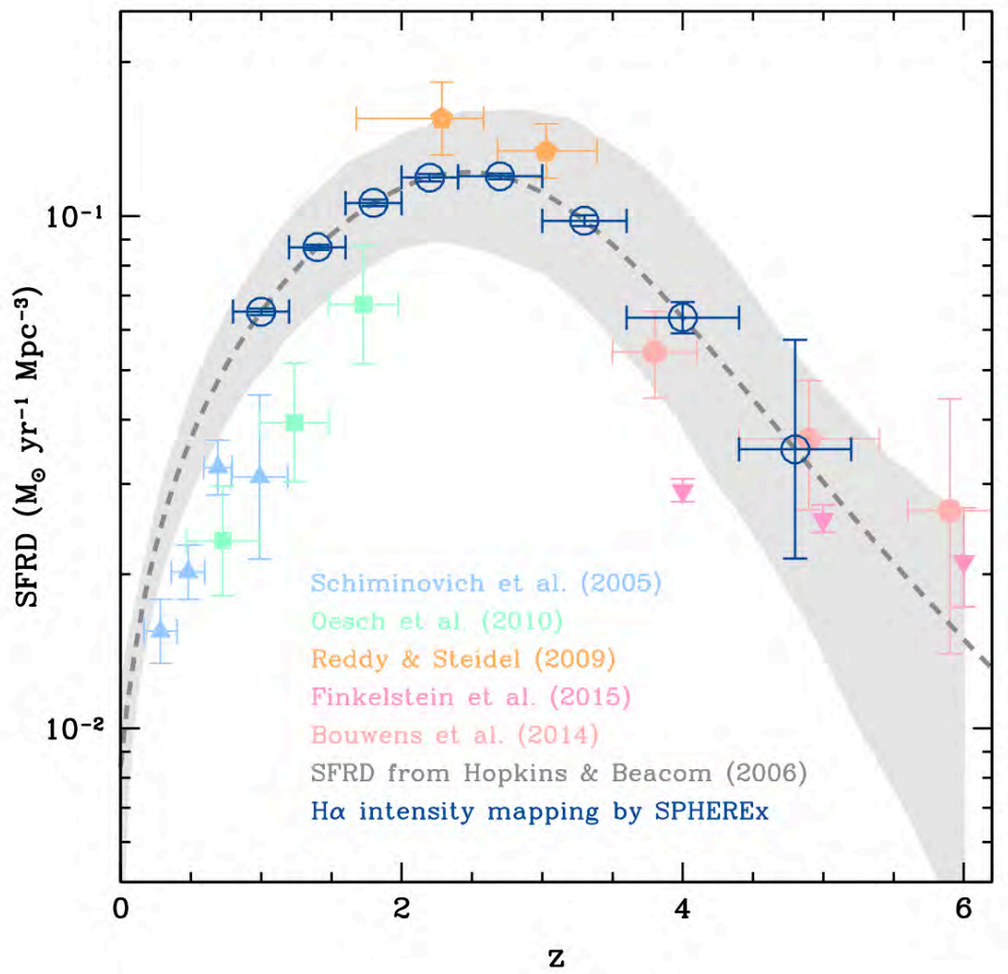
LIM Astrophysics: Star-Formation Rate Density

How optimistic can we be?



Breysse, Kovetz et al., MNRASL, 457, L127 (2016)

"Ideal world: 1% uncertainty at z~3"

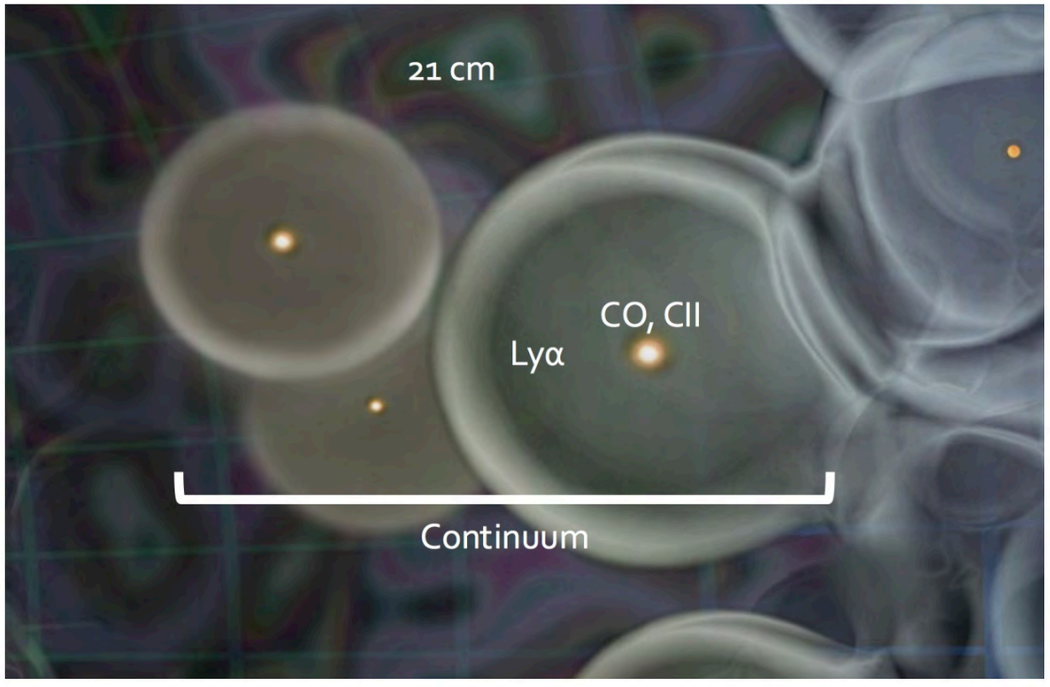


Gong et al., ApJ, 835, 273 (2017)

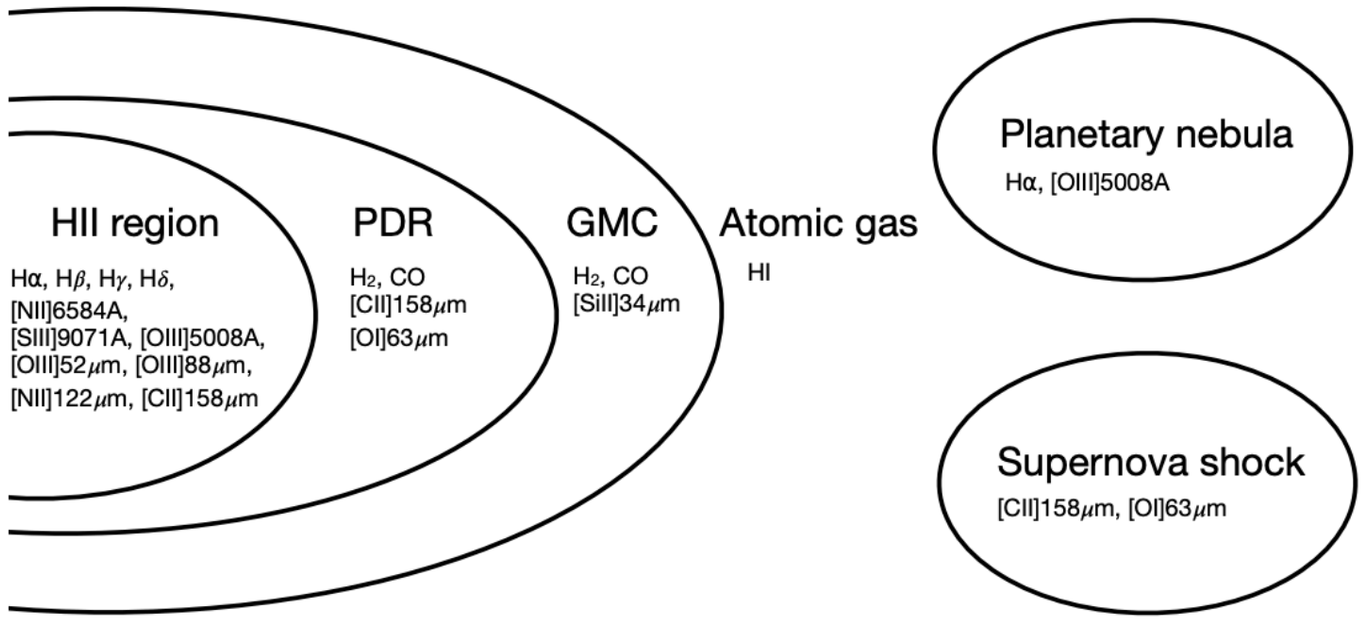
"Accuracy 7% at z~4"

LIM Astrophysics: Gastrophysics Galore

Examples: probe reionization, ISM, IGM, IMF, molecular gas, metallicity, etc.



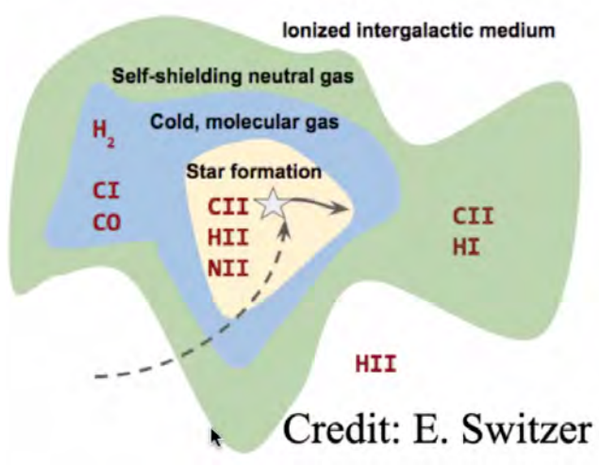
Kovetz et al., LIM: Status Report, arXiv:1709.09066



Schaan and White, JCAP (2021)

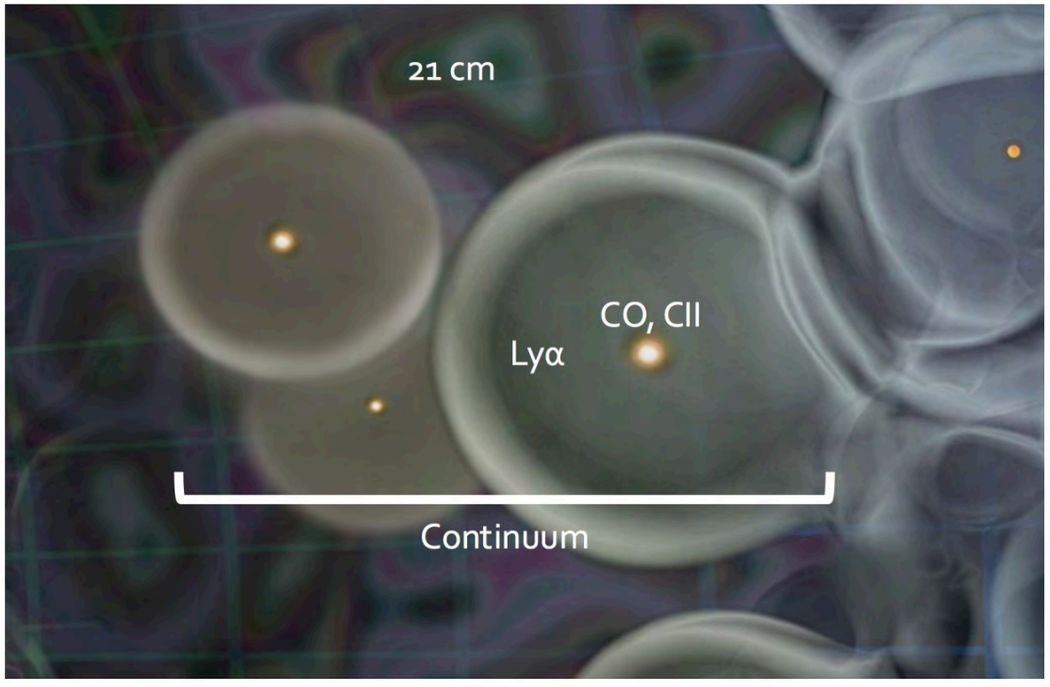
Lots of creative ideas being explored:

- r(HI x [CII])=-1 for validation of HI detection, bubble morphology
- Anti-symmetric HI x CO cross-correlation for reionization evolution
- CO isotopologues for molecular gas density
- [CII]/TIR deficit or line ratios, e.g. NII/Hα, for metallicity history
- Pop III stars SFRD/IMF with He II x CO, Lyα, Hα…
- Cosmic dawn SFR/metallicity with OIII (OII)
- …

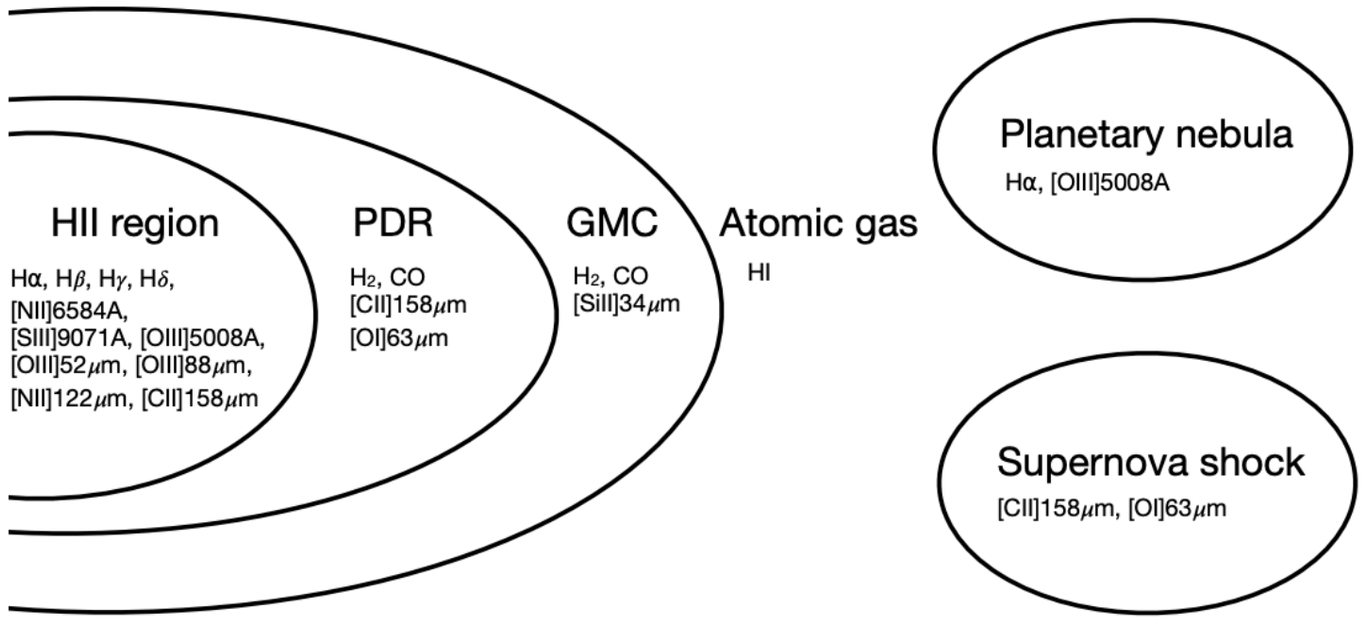


Takeaway: LIM is a Unique Probe of Astrophysics

Examples: probe reionization, ISM, IGM, IMF, molecular gas, metallicity, etc.



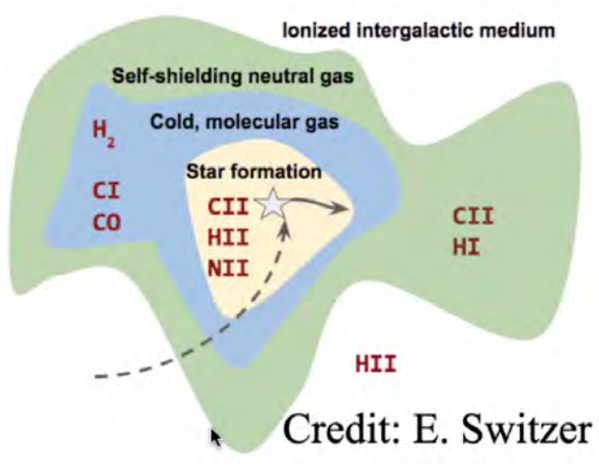
Kovetz et al., LIM: Status Report, arXiv:1709.09066



Schaan and White, JCAP (2021)

Lots of creative ideas being explored:

- r(HI x [CII])=-1 for validation of HI detection, bubble morphology
- Anti-symmetric HI x CO cross-correlation for reionization evolution
- CO isotopologues for molecular gas density
- [CII]/TIR deficit or line ratios, e.g. NII/Hα, for metallicity history
- Pop III stars SFRD/IMF with He II x CO, Lyα, Hα…
- Cosmic dawn SFR/metallicity with OIII (OII)
- …



Line-Intensity Mapping: What Can it Probe?

Astrophysics:

- Reionization: bubble sizes, ionized fraction, duration
- Star formation rate (history, peak rise/fall, Pop III stars)
- Metallicity history
- AGN feedback
- Molecular gas density
- IGM density, evolution, clustering
- Faint end of luminosity function
- …
- …

Cosmology:

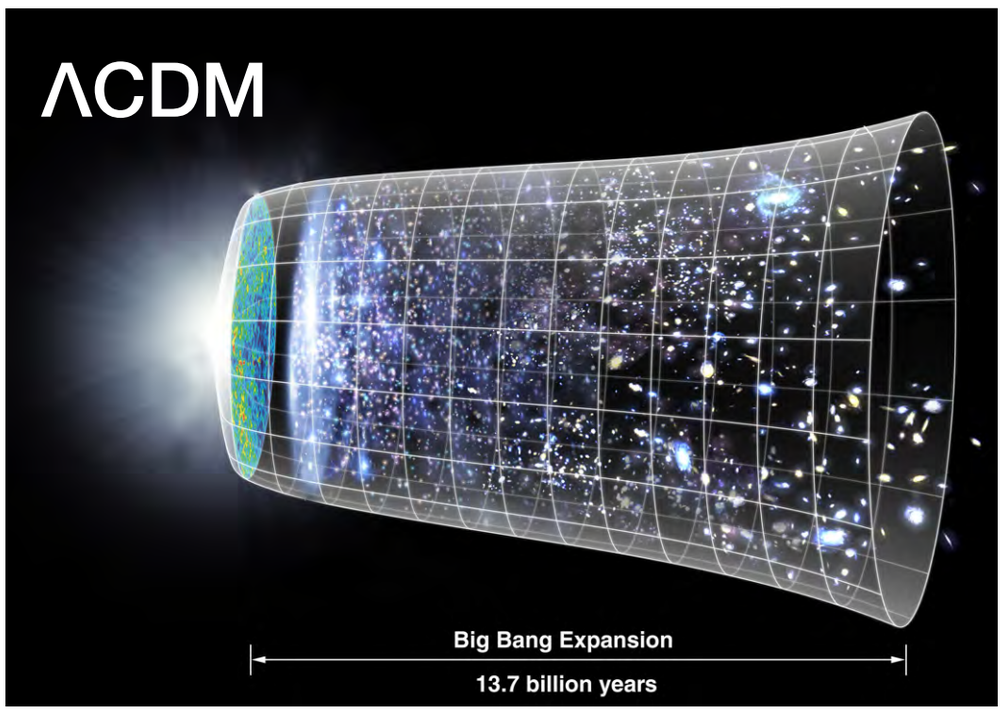
- Inflation (running, non-gaussianity, oscillations, CIP, etc.)
- Dark matter (clustering, decaying, annihilating, interacting)
- Expansion rate history (BAO, VAO)
- Dark energy (c.c. or dynamical? w_0/w_a, etc.)
- Neutrinos (sum of masses, hierarchy, decay)
- Optical depth to Reionization (SFR, degeneracies, etc.)
- Modified gravity
- …
- …

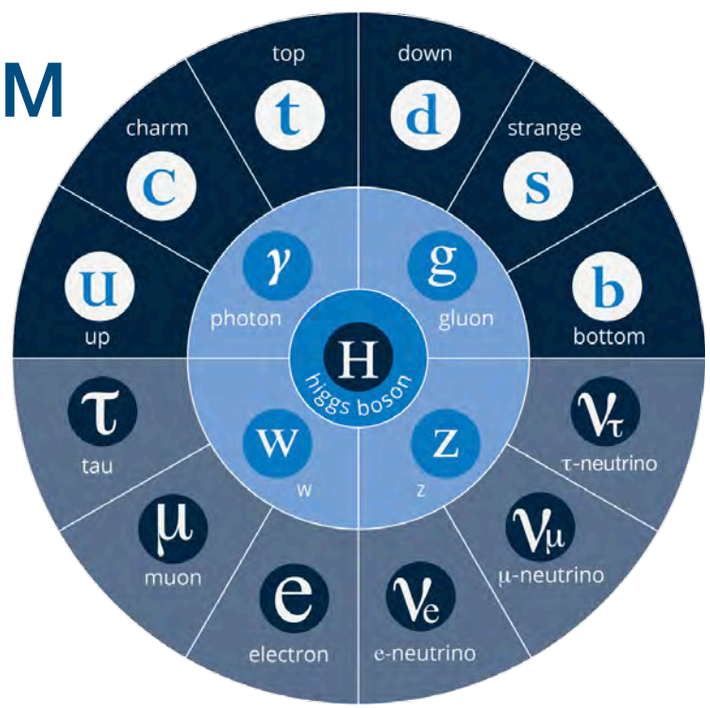
One’s signal is another’s foreground

Reviews: Kovetz et al., LIM 2017 Status Report arXiv:1709.09066; Bernal and Kovetz, The Astronomy and Astrophysics Review 2023

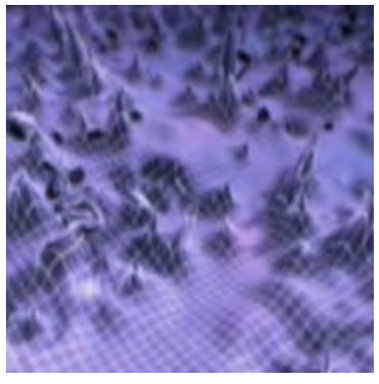
WPs: *Astro2020*: Kovetz et al., 1903.04496; *ESA2050*: Silva, Kovetz et al., 1908.07533; *Snowmass2021*: Karkare et al., 2203.07258

LIM Probes the *Standard* Questions in Cosmology



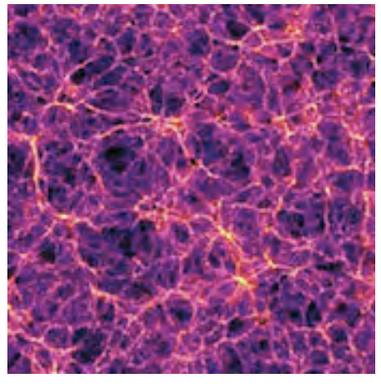


Core questions in cosmology?



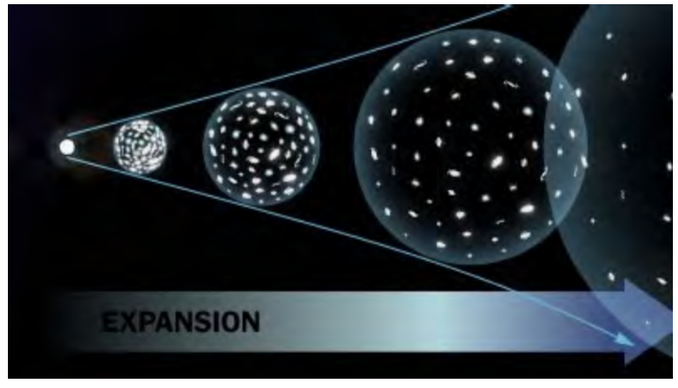
Inflation

$\phi : m_\phi, V(\phi)$



Dark Matter

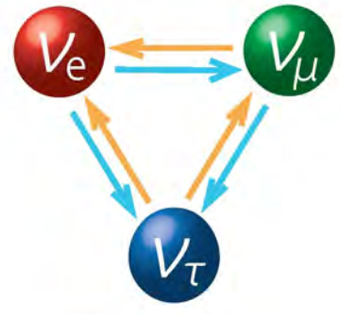
$\chi : m_\chi, \mathscr{L}(\chi)$



Dark Energy

$\Lambda ?\ w(a) = w_0 + (1-a)w_a ?$

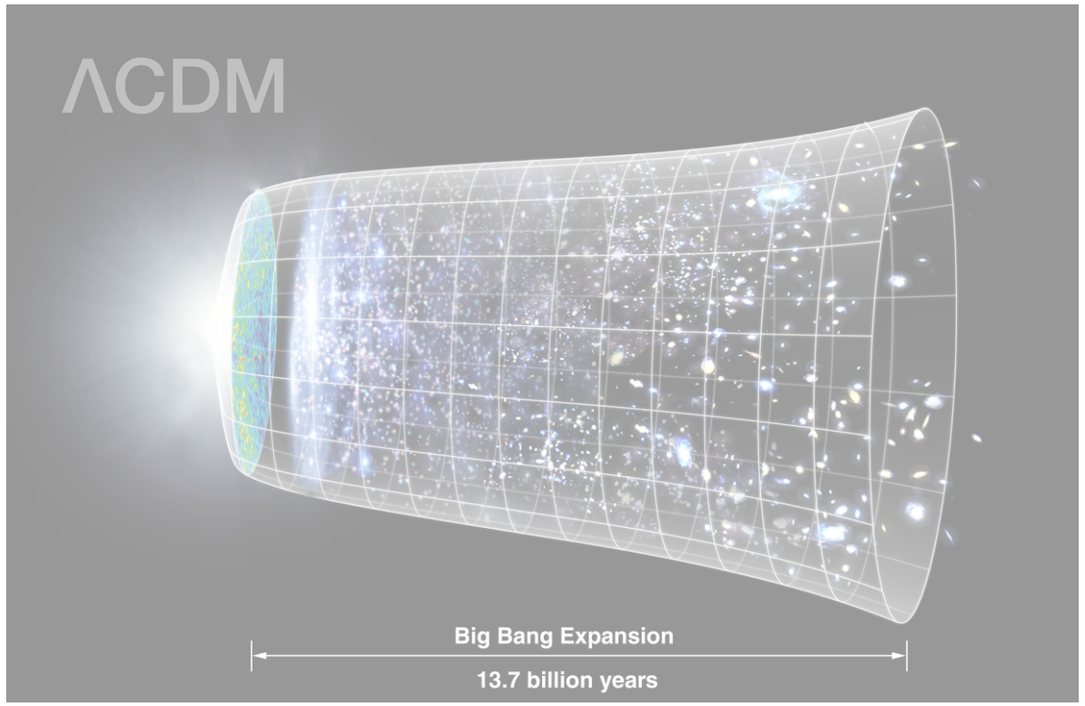
Can *cosmology* weigh in?

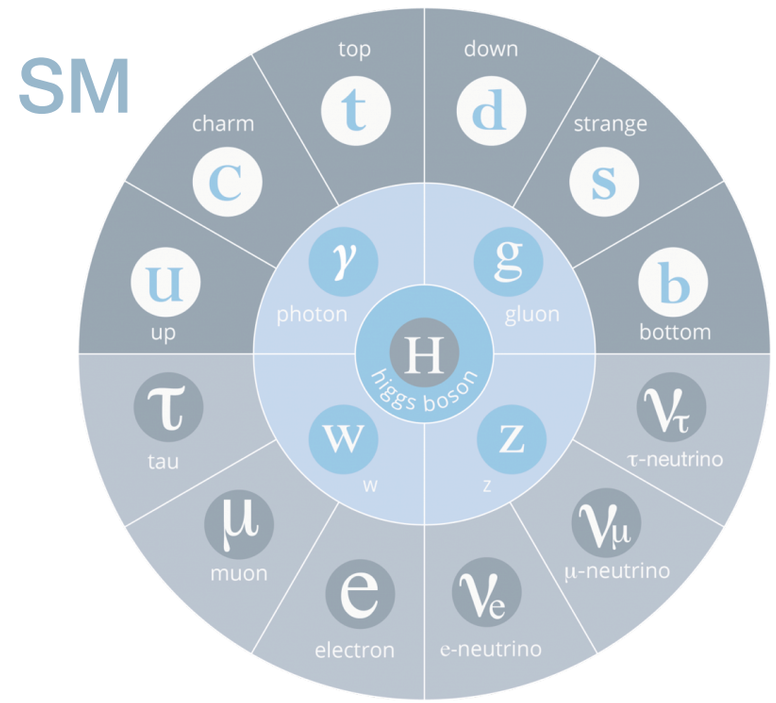


Neutrino masses

$\sum_{e,\mu,\tau} m_\nu \gtrsim 60\,\mathrm{meV}?\ 100\,\mathrm{meV}?$

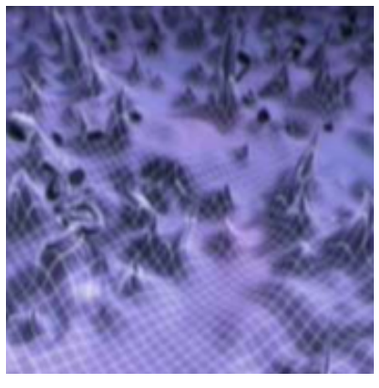
Takeaway: LIM can *uniquely* probe all of these!





Core questions in cosmology?

Can *cosmology* weigh in?



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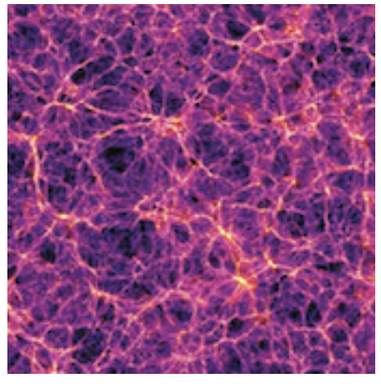

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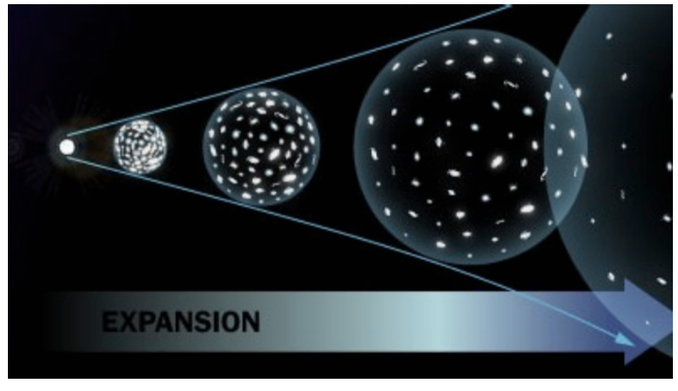

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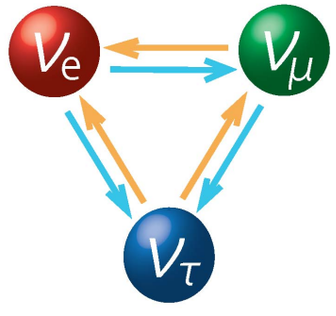

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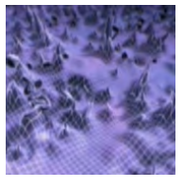
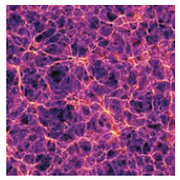



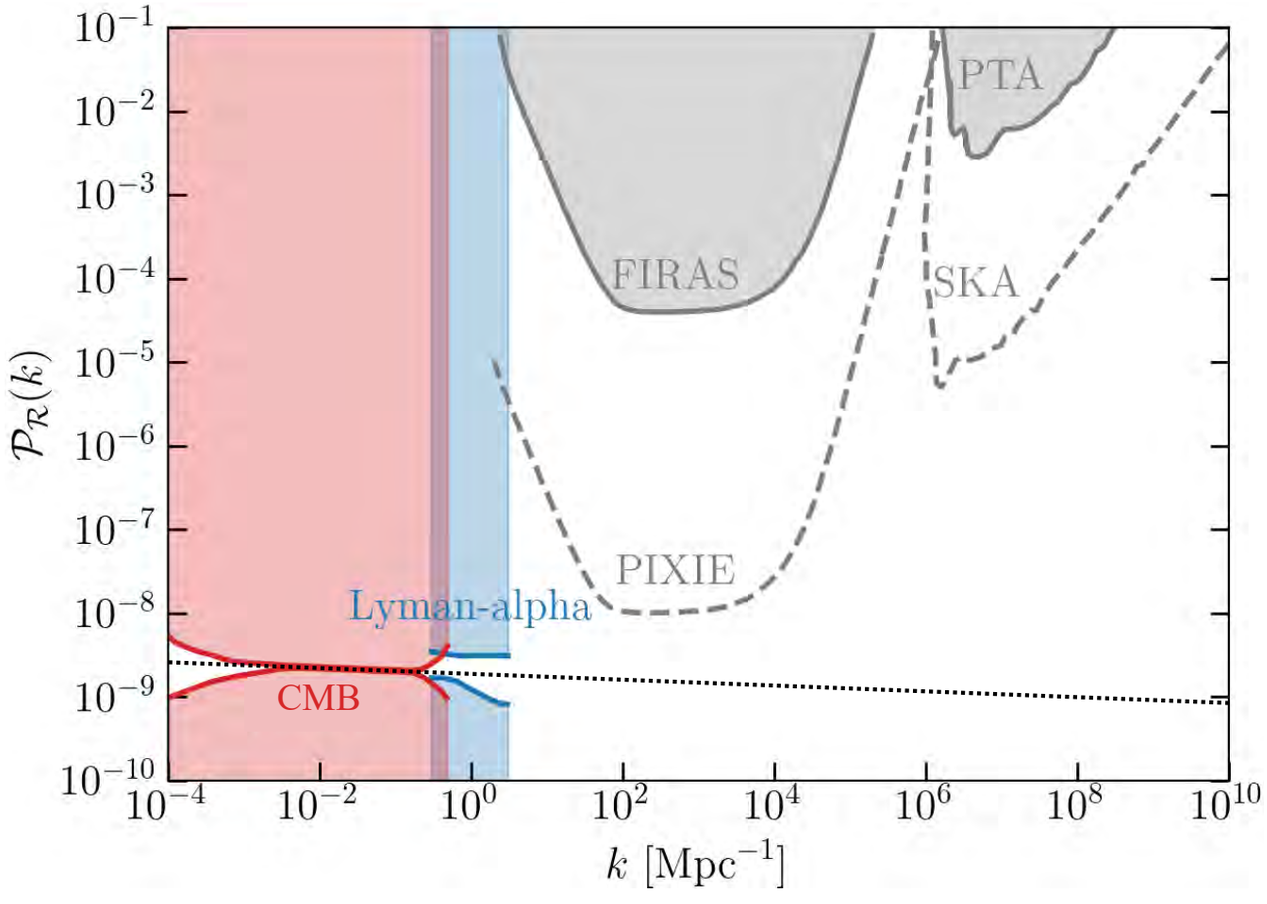
LIM Cosmology: Small-Scale Fluctuations

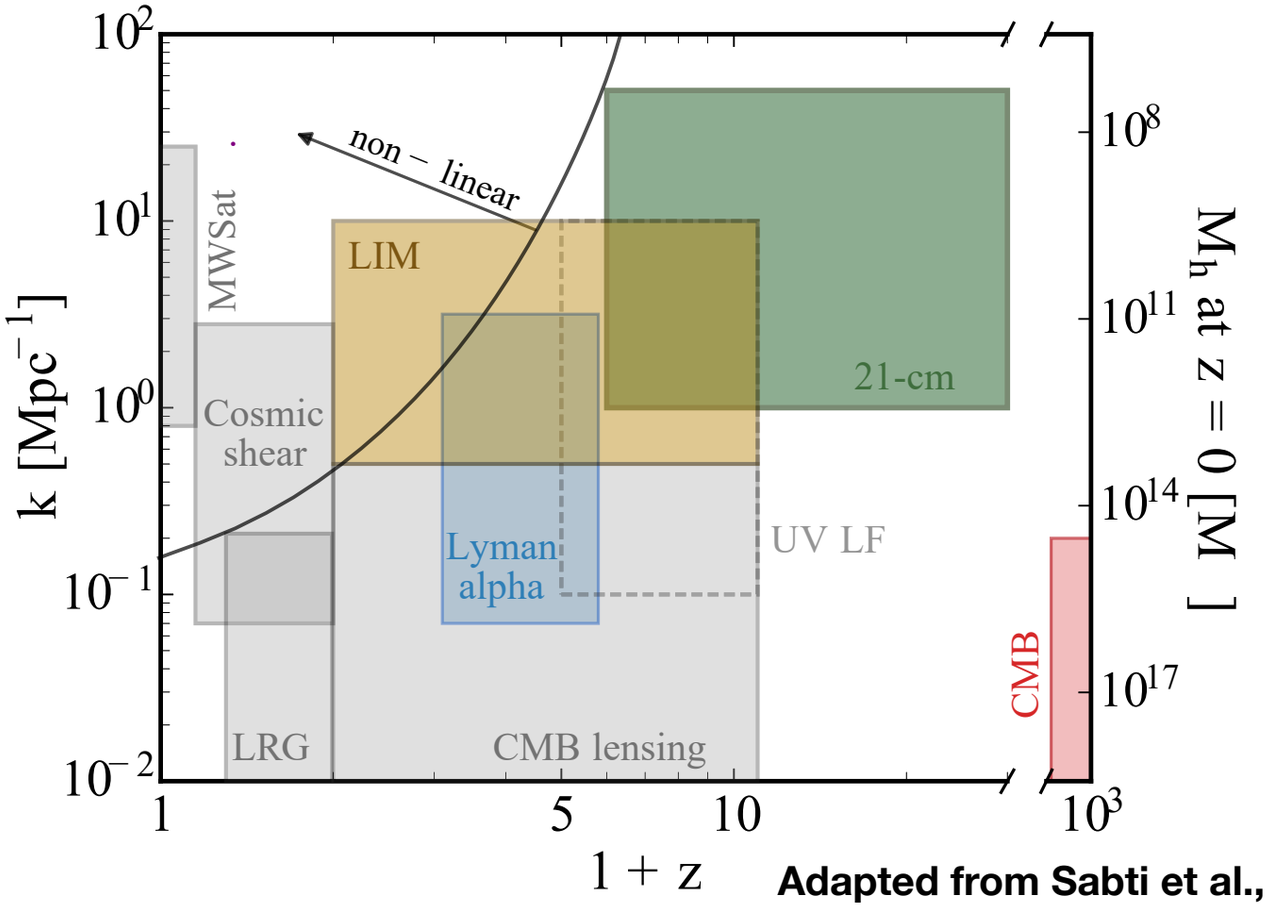
Inflation predicts scale-invariance over >20 orders of magnitude. We've probed only ~4.

(i) CMB: limited by Silk damping. (ii) LSS: theoretical control limited to linear scales.

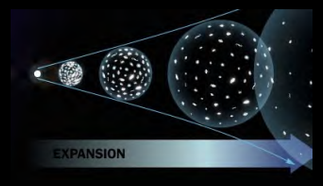
LIM can access far smaller scales via galaxies residing in the smallest dark matter halos:

- 21-cm: Sensitive to the first (and smallest) galaxies in the Universe
- Star-formation LIM: Sensitive to the integrated signal from the faintest galaxies





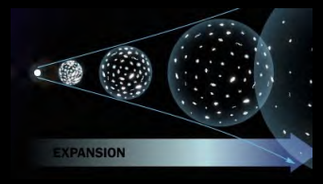
Adapted from Sabti et al., ApJL 2022



LIM Cosmology: Cosmic Expansion History

Credit: NASA/WMAP Science Team

Structure: stars, ISM, galaxies, IGM, clusters



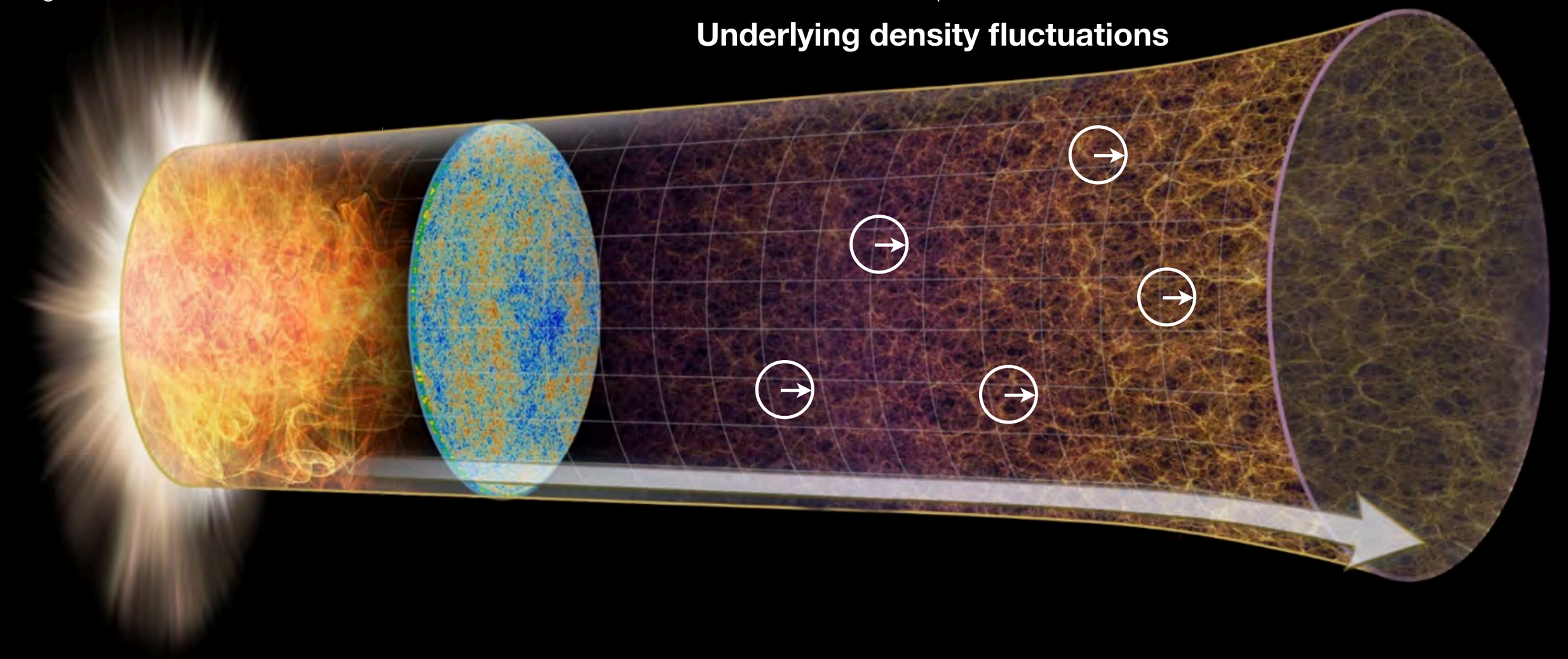
LIM Cosmology: Cosmic Expansion History

Structure: stars, ISM, galaxies, IGM, clusters

↓

Underlying density fluctuations

Image Credit: SPHEREx collaboration

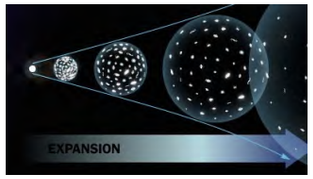


Prescription: ***"A User's Guide to Extracting Cosmological Information from Line-Intensity Maps"***

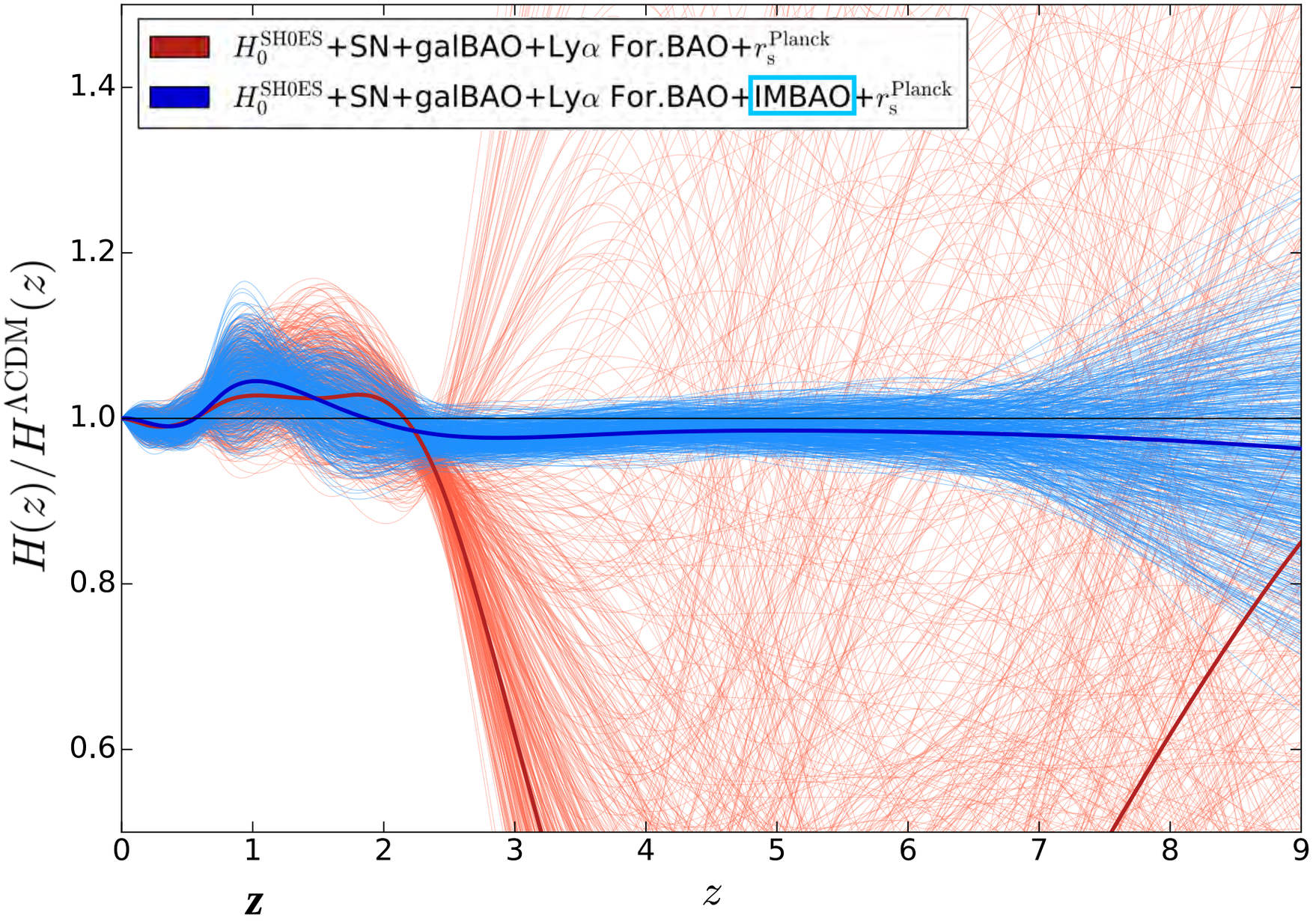
Bernal, Breysse, Gil-Marin and Kovetz, PRD 2019

Forecasts: ***"Cosmic Expansion History with Line-Intensity Mapping"***

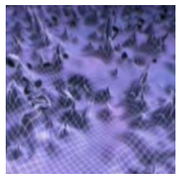
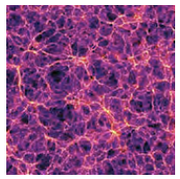
Bernal, Breysse, and Kovetz, PRL 2019



LIM Cosmology: Cosmic Expansion History

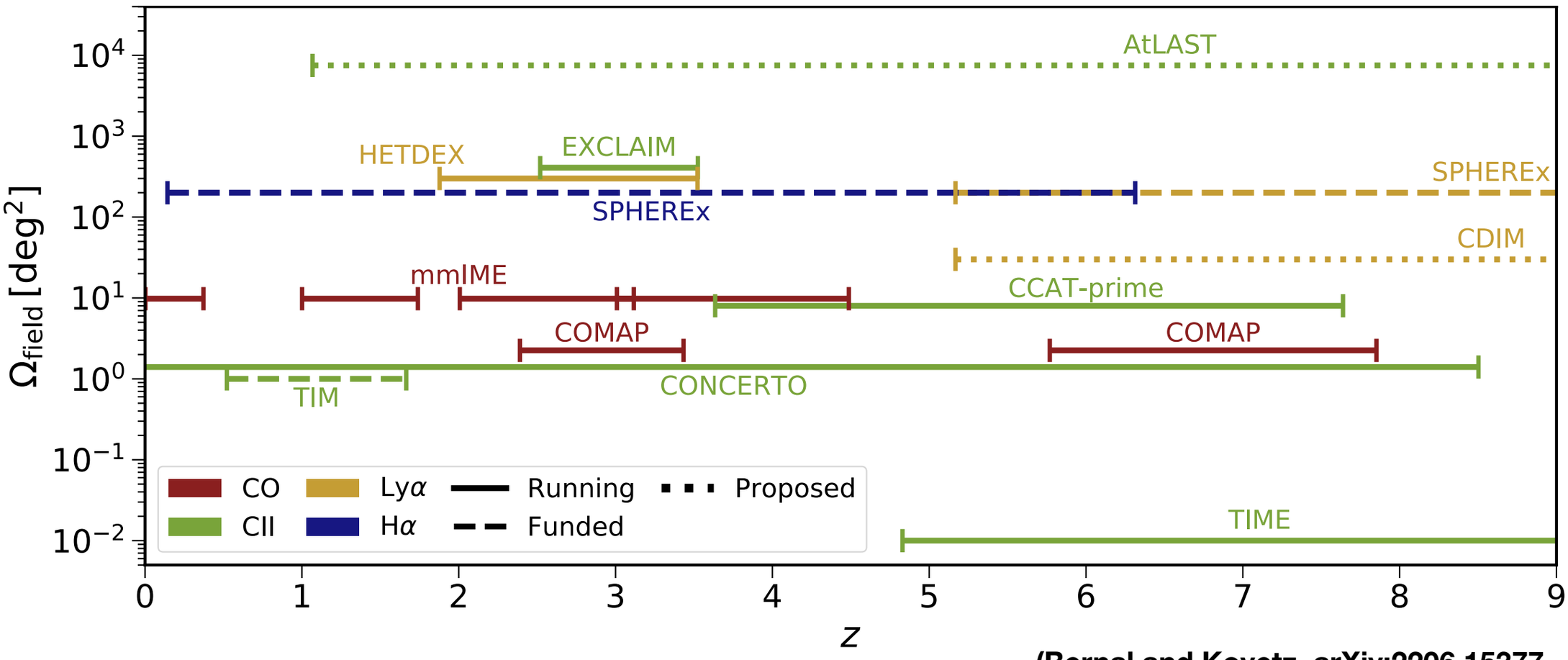


Bernal, Breysse and Kovetz, PRL 2019

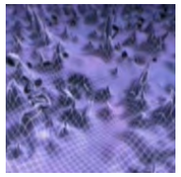
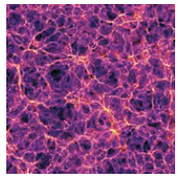
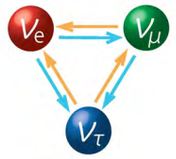



LIM Cosmology: Large-Scale Fluctuations

Disclaimer: This will take time…

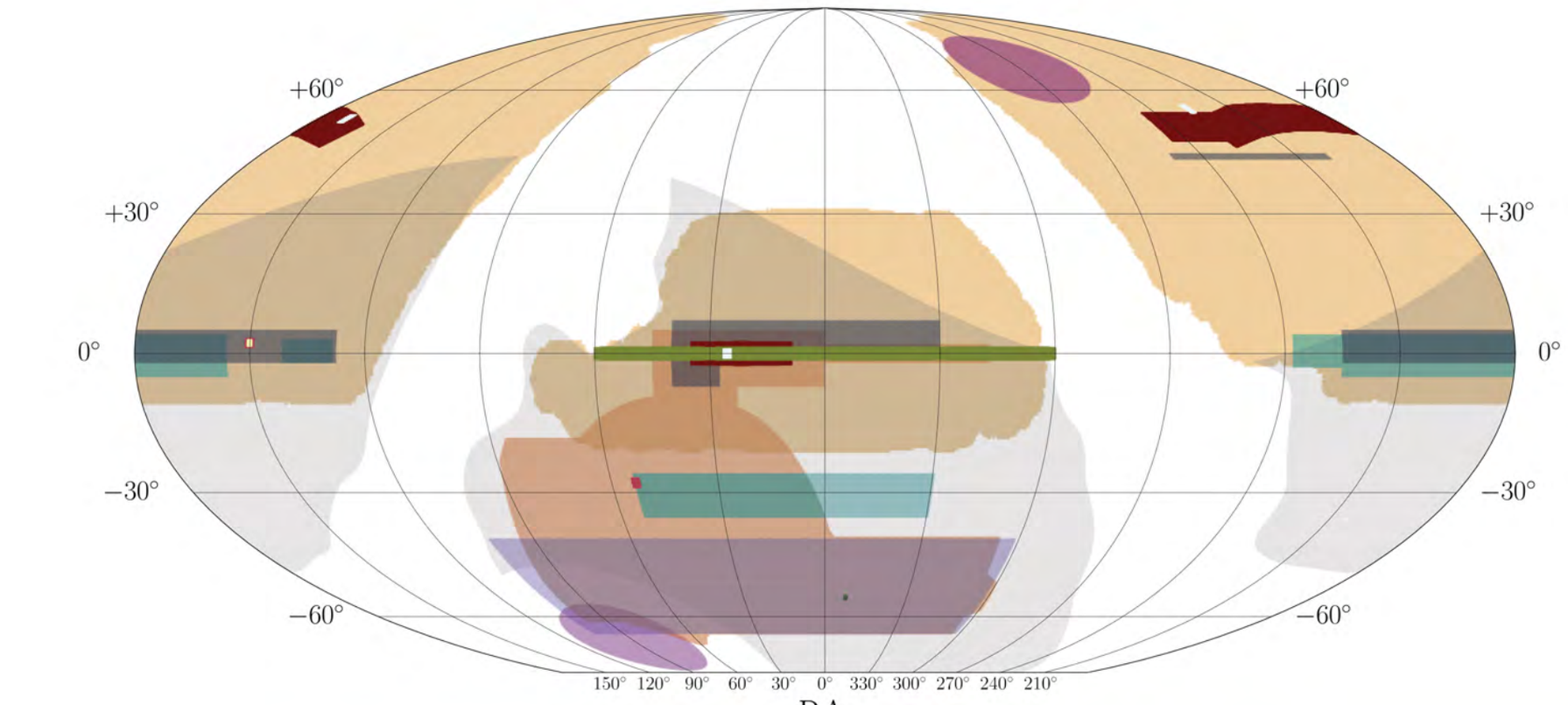


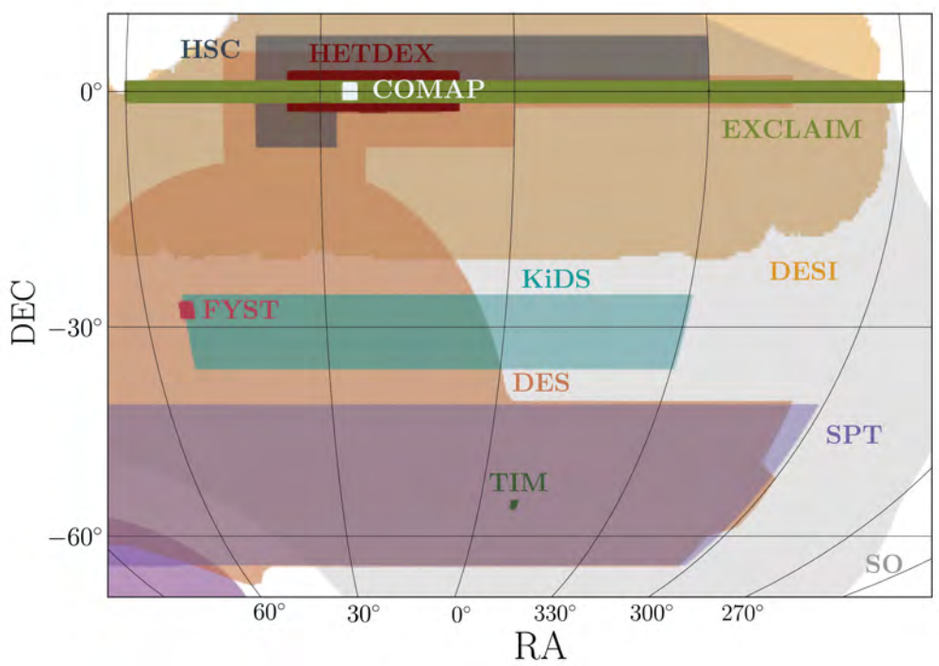
(Bernal and Kovetz, arXiv:2206.15377, Astronomy and Astrophysics Review)

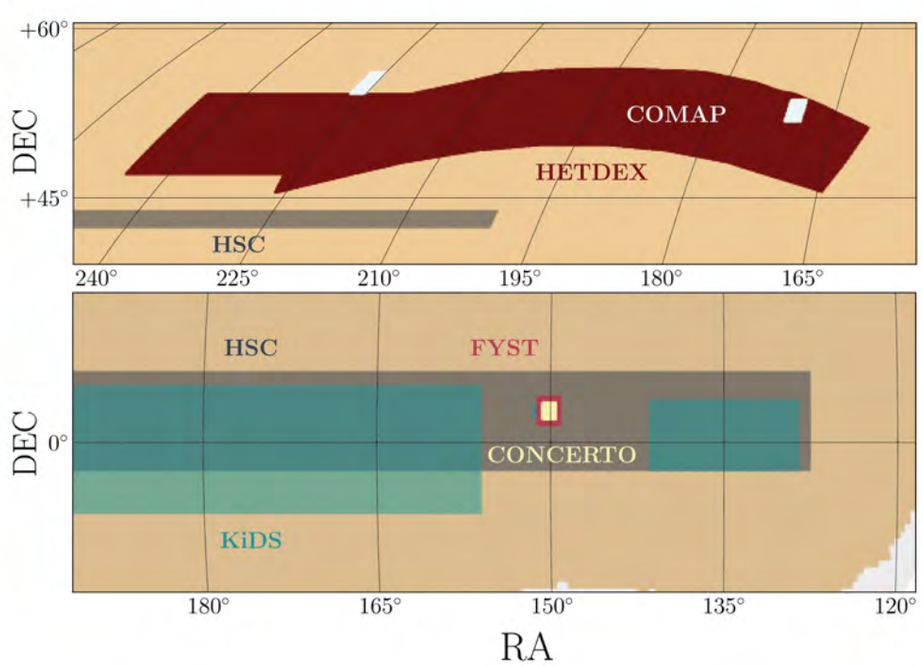




LIM Cosmology: Cross Correlations!

(Bernal and Kovetz, arXiv:2206.15377, The Astronomy and Astrophysics Review)

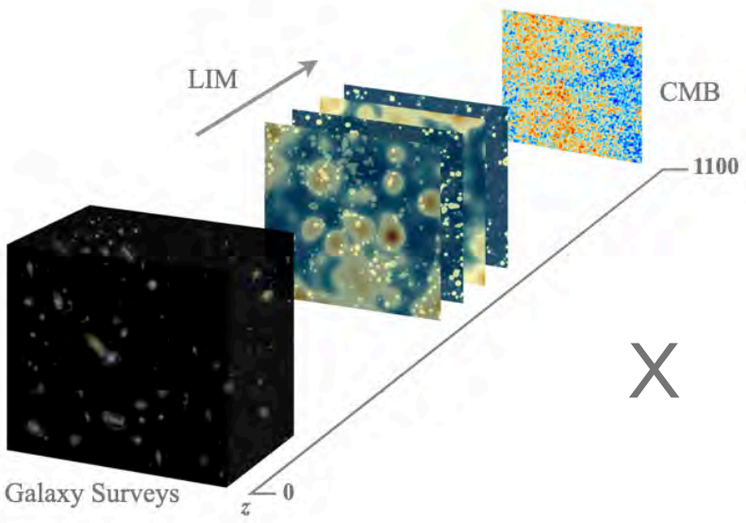




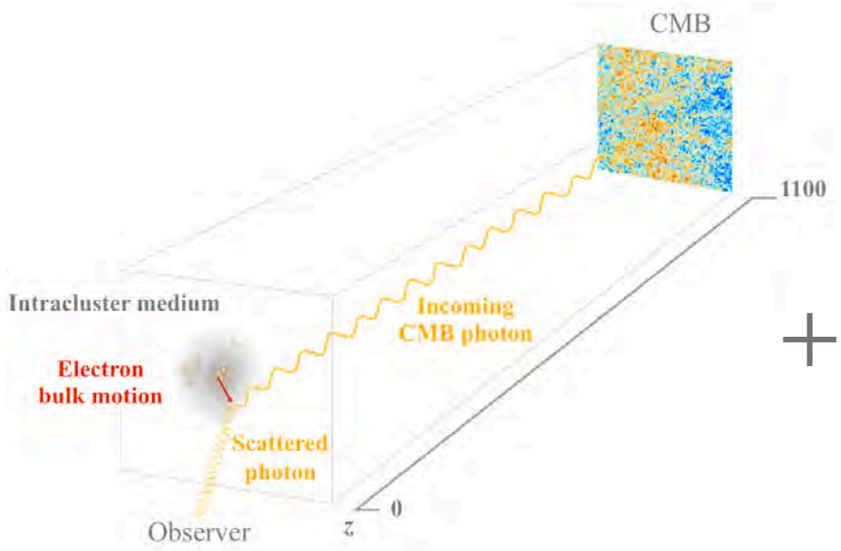


LIM Cosmology: Sum of Neutrino Masses

To appear: reconstructing 3D velocity field from CII LIM x (kSZ + moving-lens)



X



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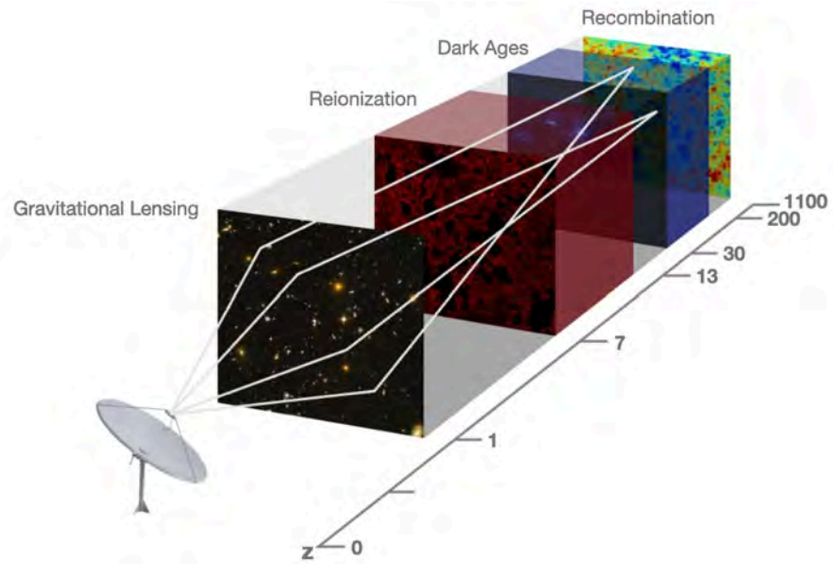
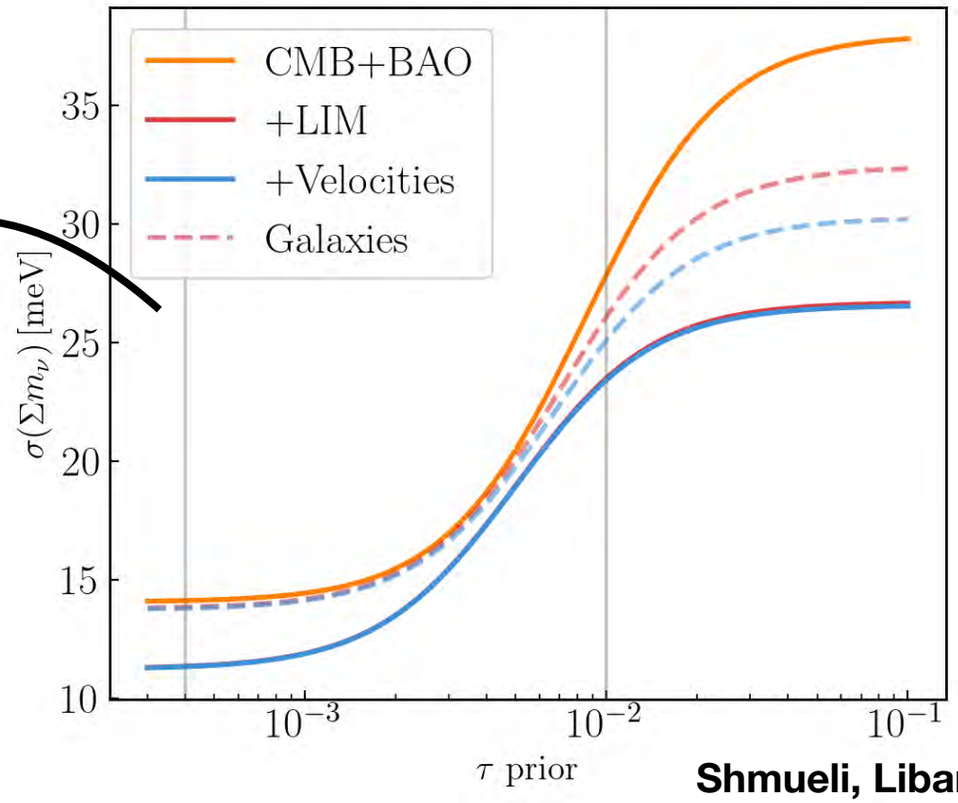


Prior on τ from 21cm!

Shmueli, Sarkar and Kovetz, PRD 2023



Shmueli, Libanore and Kovetz, to appear

Line*-Intensity Mapping: Review and Outlook

*with a focus on star-formation lines