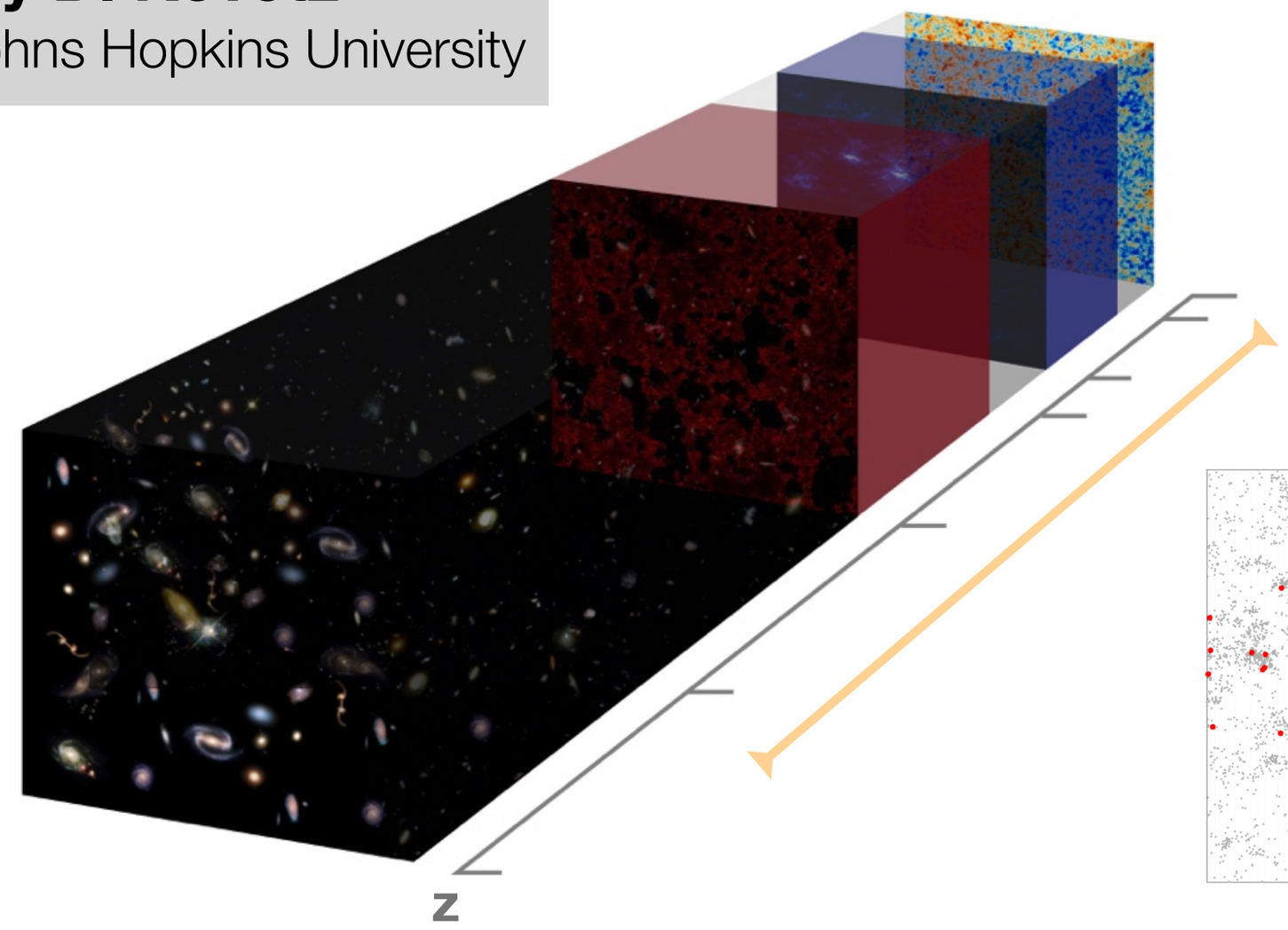
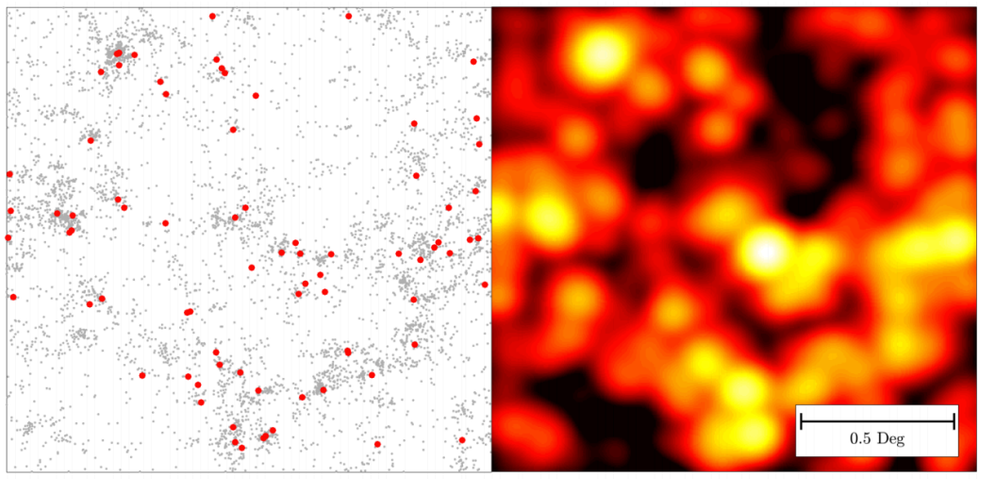
Line-Intensity Mapping
(Bird's-Eye) Theory Review

Ely D. Kovetz
Johns Hopkins University

Aspen workshop
Feb. 5th, 2018

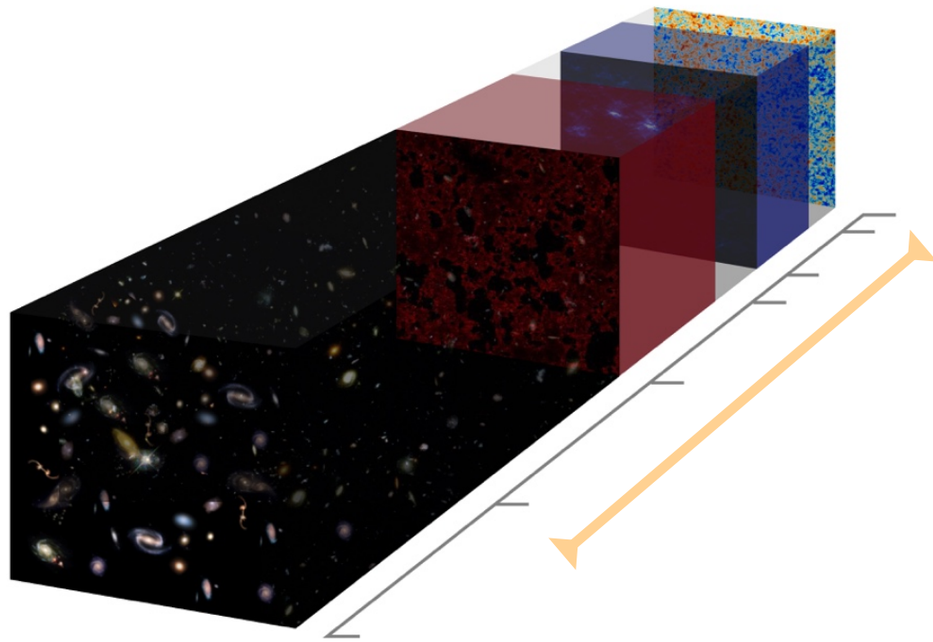




Based on:
Kovetz, Viero, Lidz, Newburgh, Rahman, Switzer et al., **"Line-Intensity Mapping: a 2017 Status Report"**, Physics Reports, in process.

Outline

Ely D. Kovetz
Aspen, Feb. 2018



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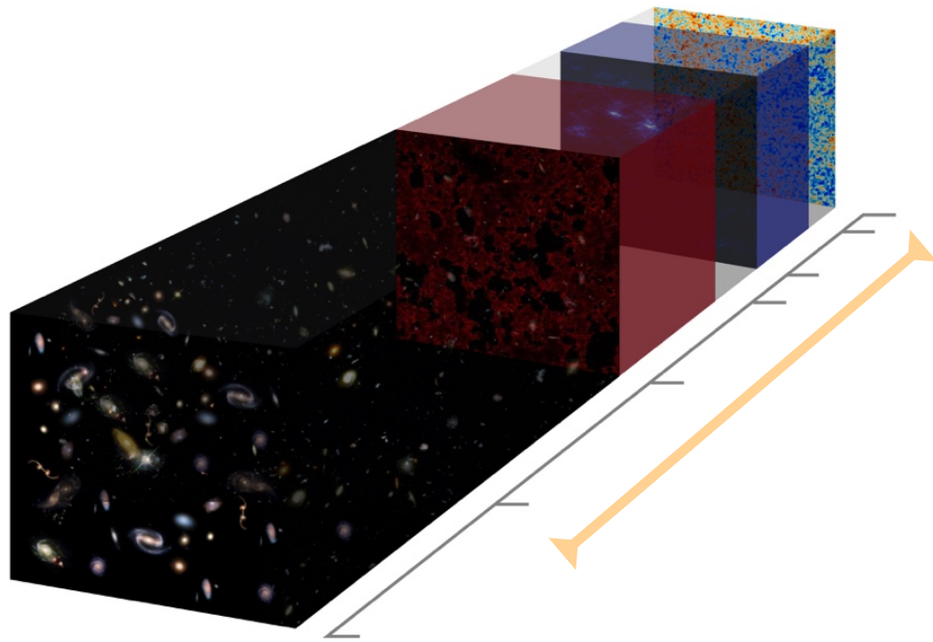
- Introduction to Line-Intensity Mapping



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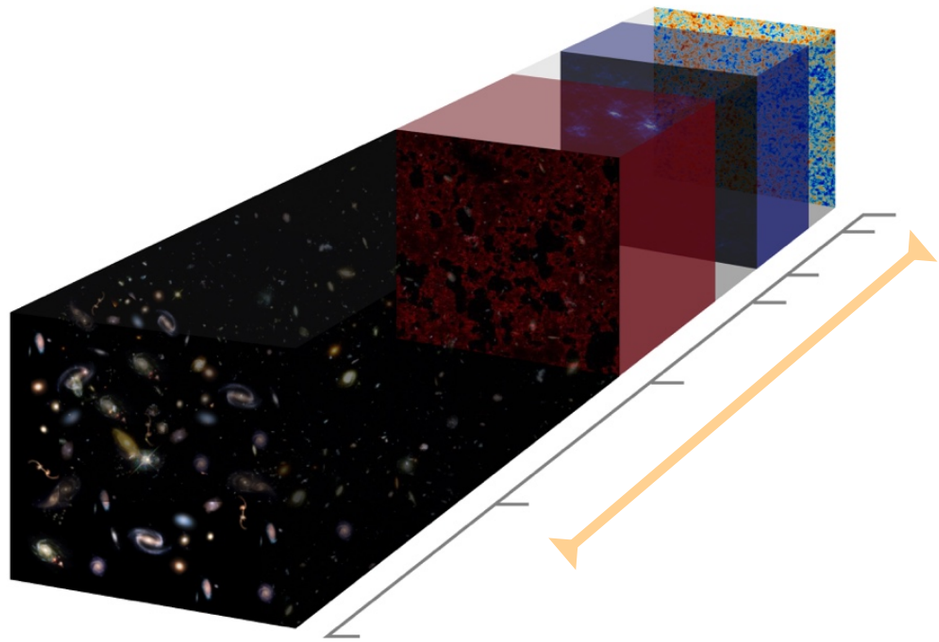
- Introduction to Line-Intensity Mapping
- Science Goals of Line-Intensity Mapping



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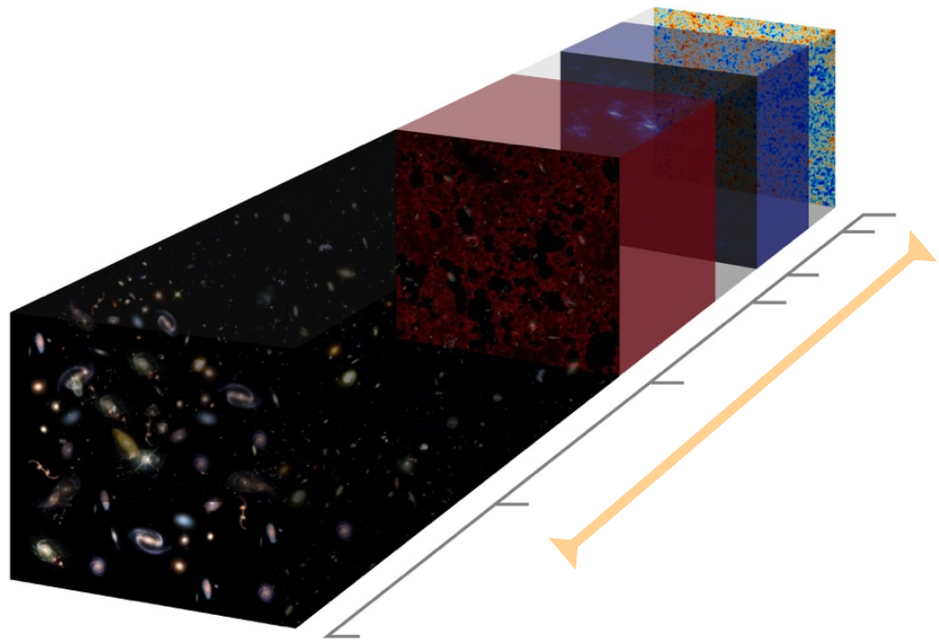


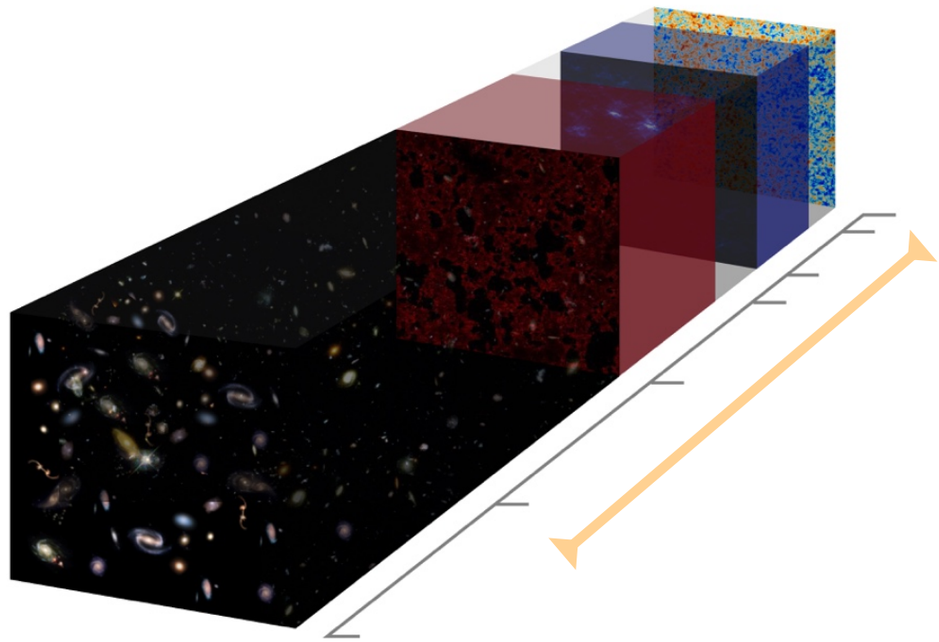
- Science Goals of Line-Intensity Mapping

- Theoretical Backbone (Modeling+Techniques)

Outline

Ely D. Kovetz
Aspen, Feb. 2018

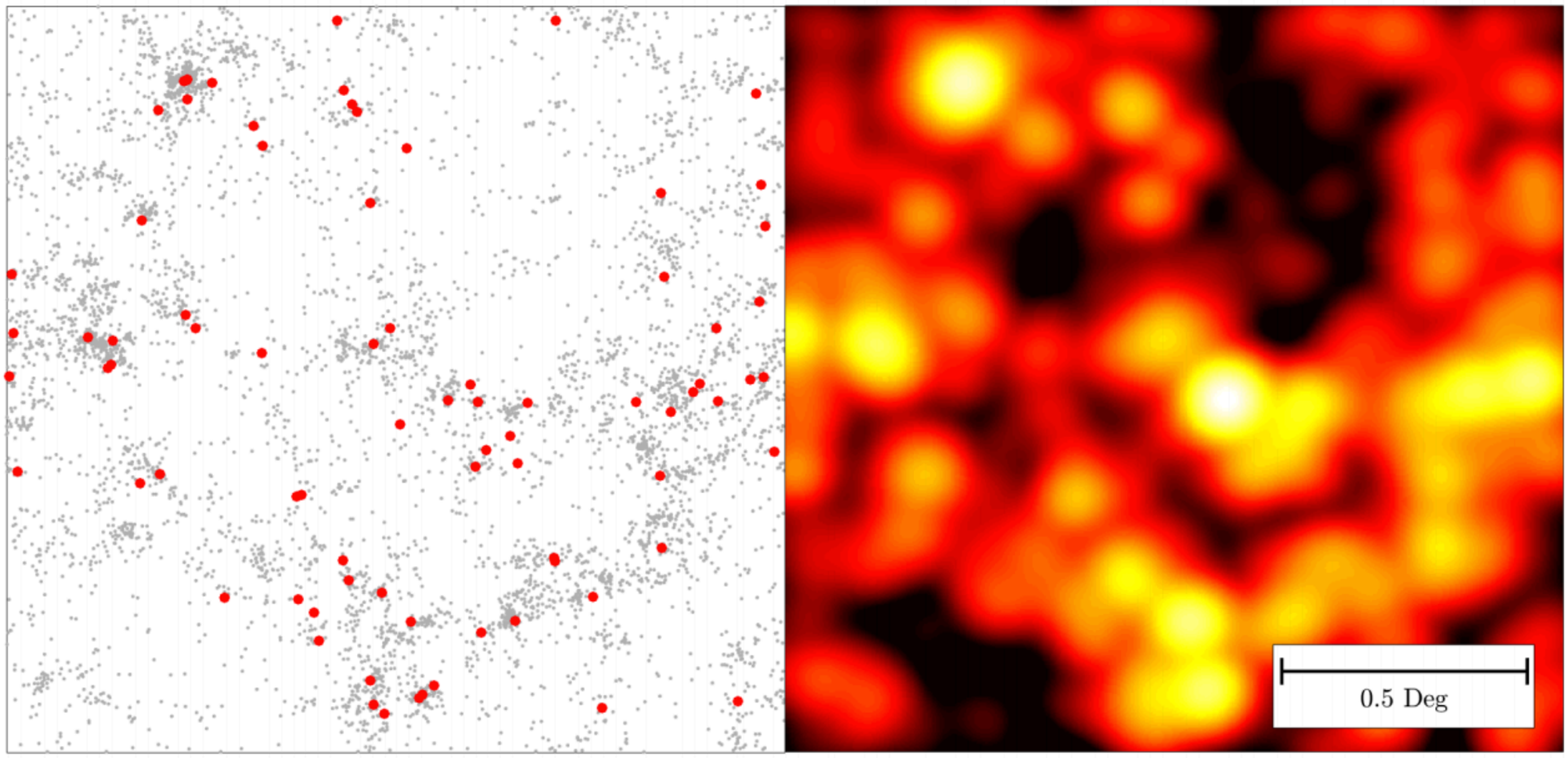
- Introduction to Line-Intensity Mapping
- Science Goals of Line-Intensity Mapping
- Theoretical Backbone (Modeling+Techniques)
- Conclusions and Outlook



Introduction to Line-Intensity Mapping

Introduction to Line-Intensity Mapping

Intensity mapping: 3D mapping of the specific intensity due to line emission.



LIMFAST© Simulation

(Courtesy of P. Breysse)

- Left: in ~4500 hours, VLA can detect ~1% of the total number of CO-emitting galaxies.
- Right: in ~1500 hours, COMAP will map CO intensity fluctuations throughout the field.

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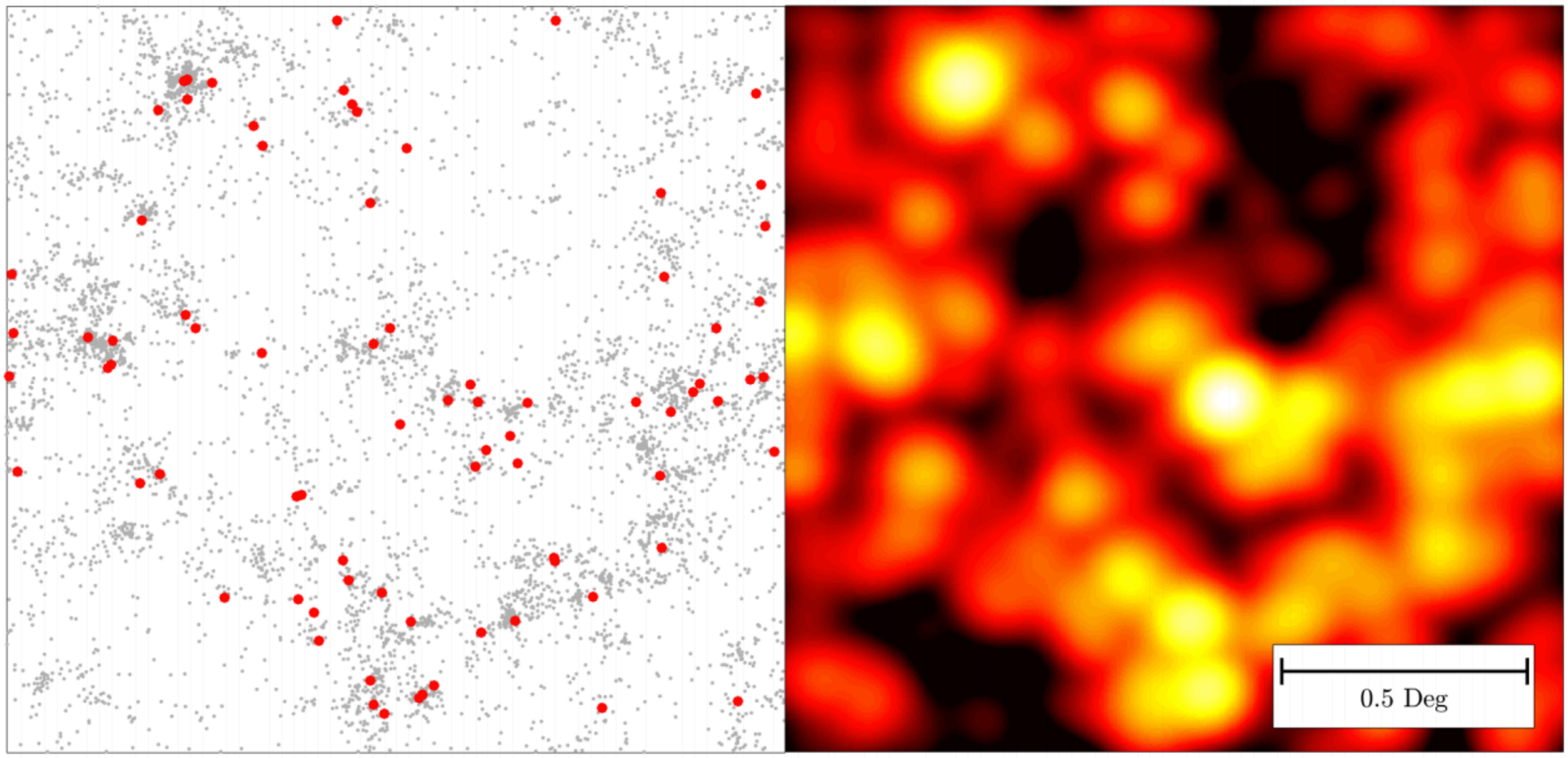
Galaxy surveys give detailed properties of brightest galaxies



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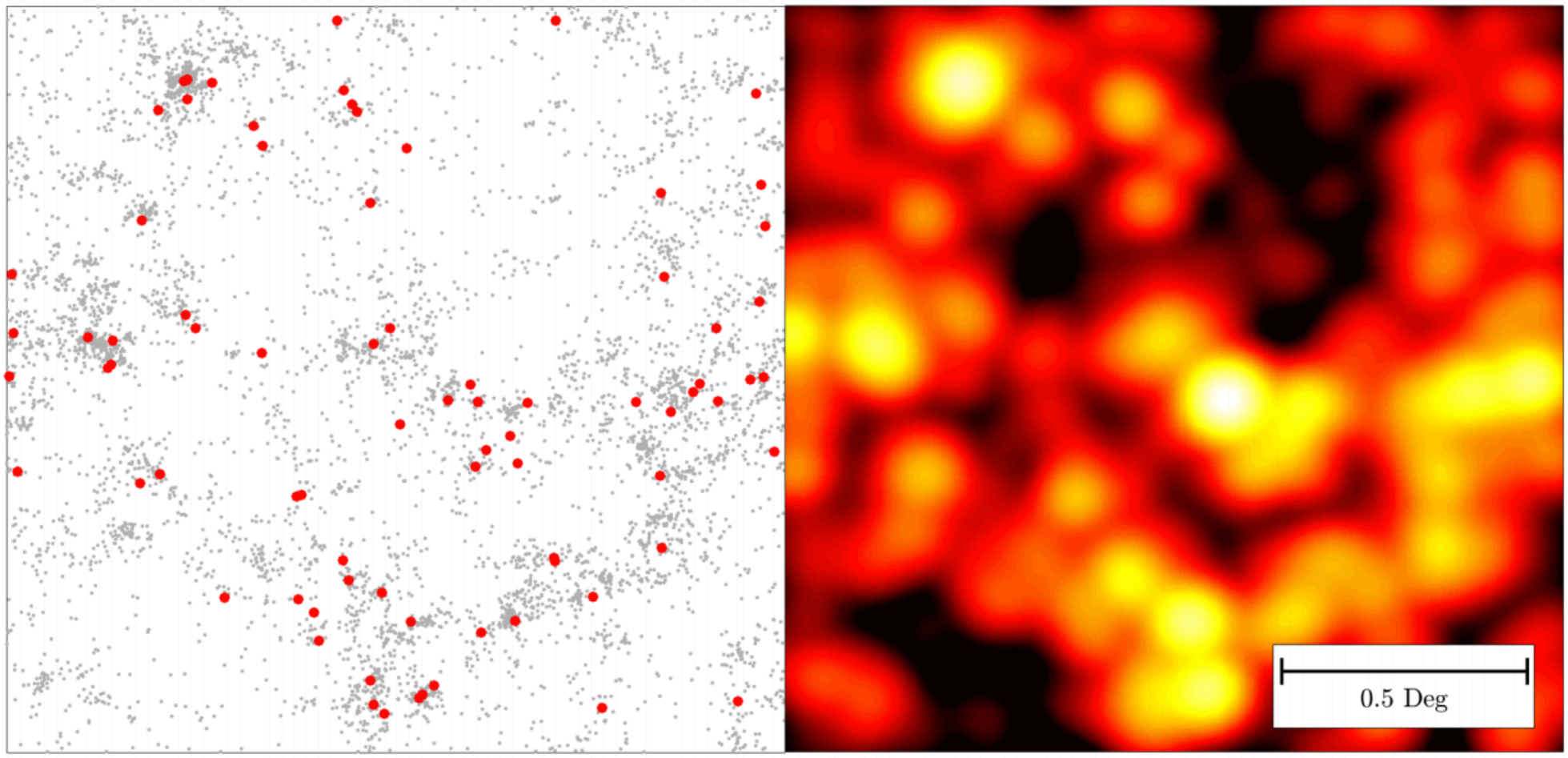
Intensity maps give statistical properties of all galaxies



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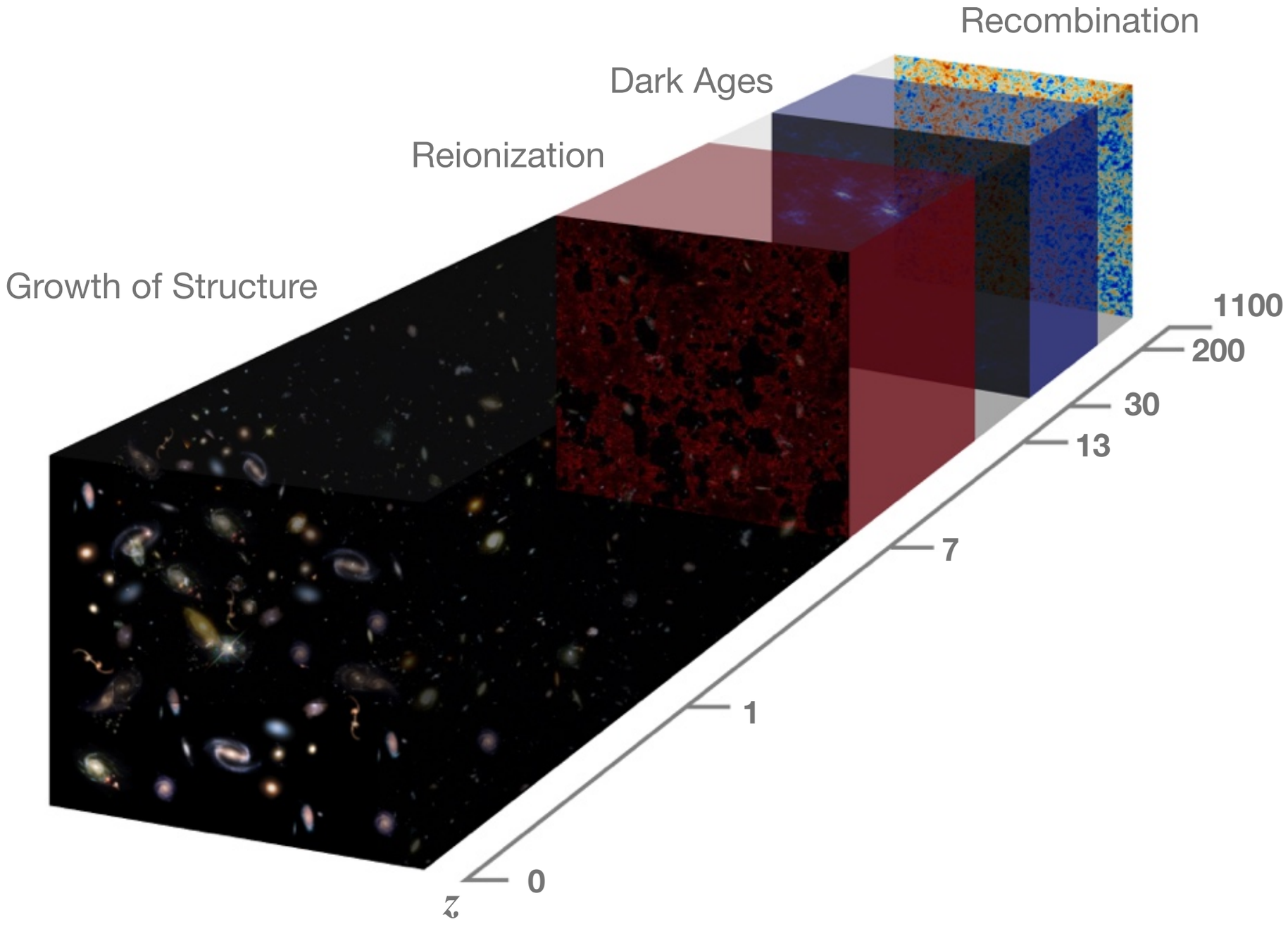
Introduction to Line-Intensity Mapping

The promise of line-intensity mapping:



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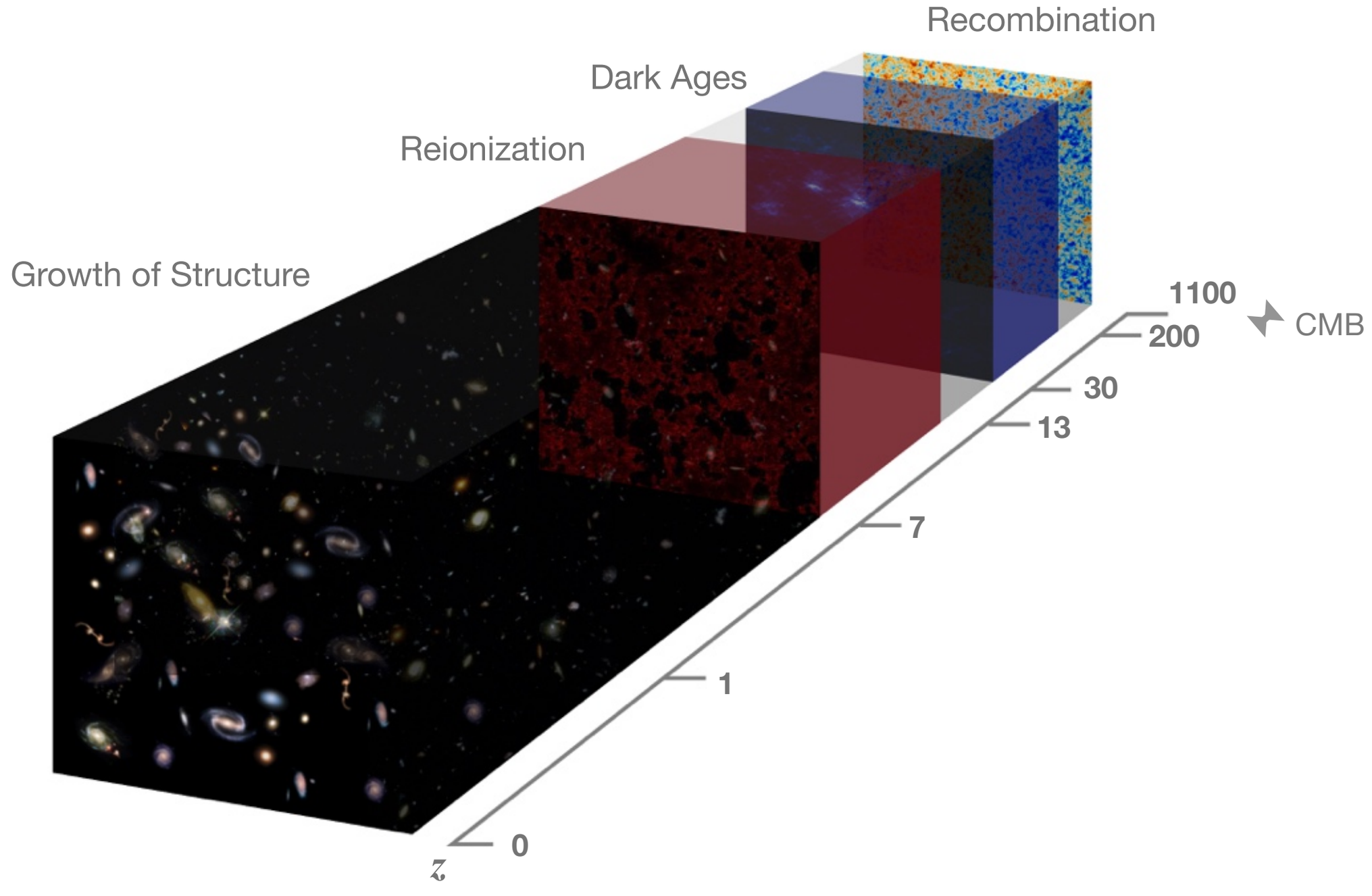

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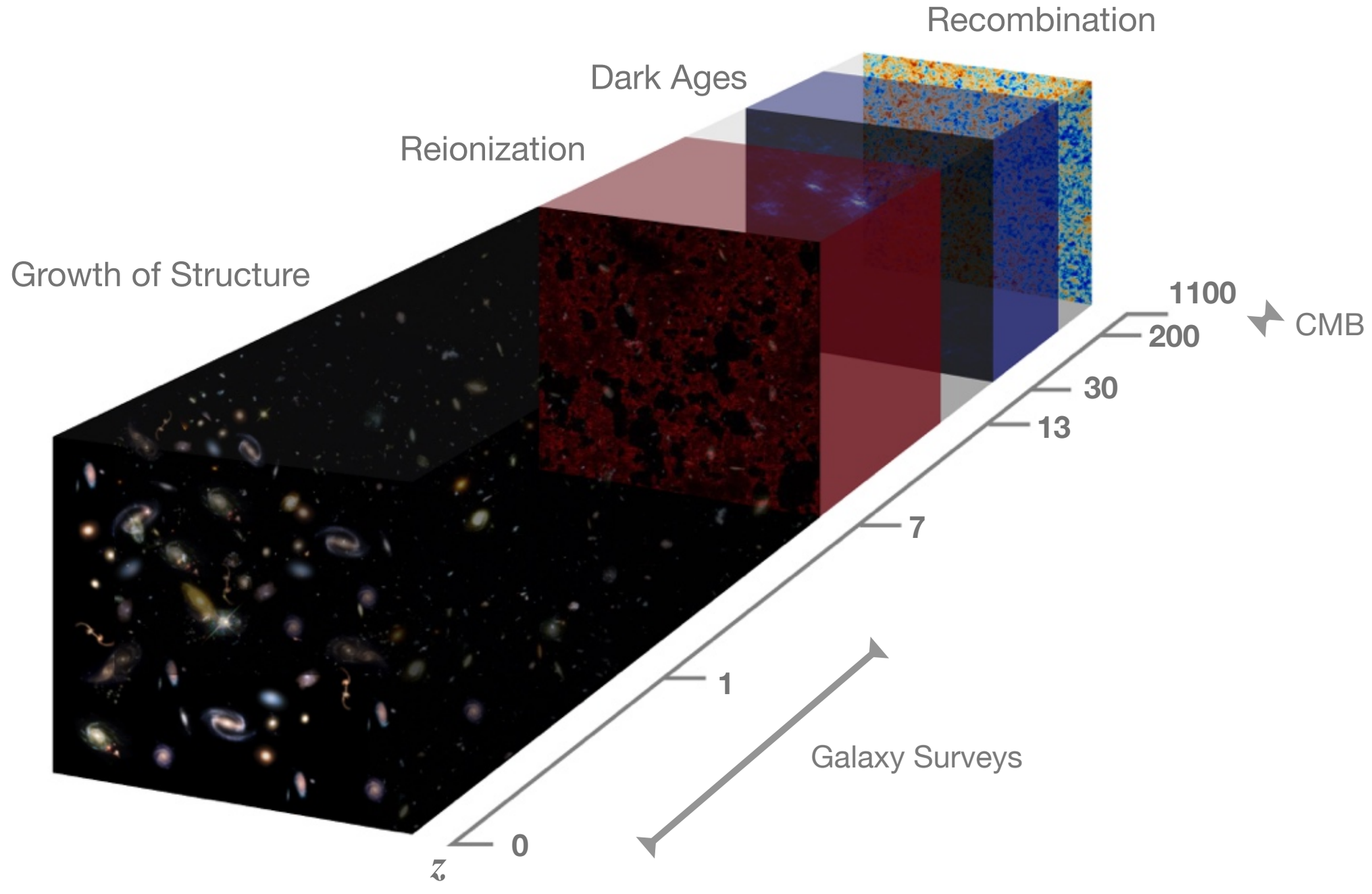

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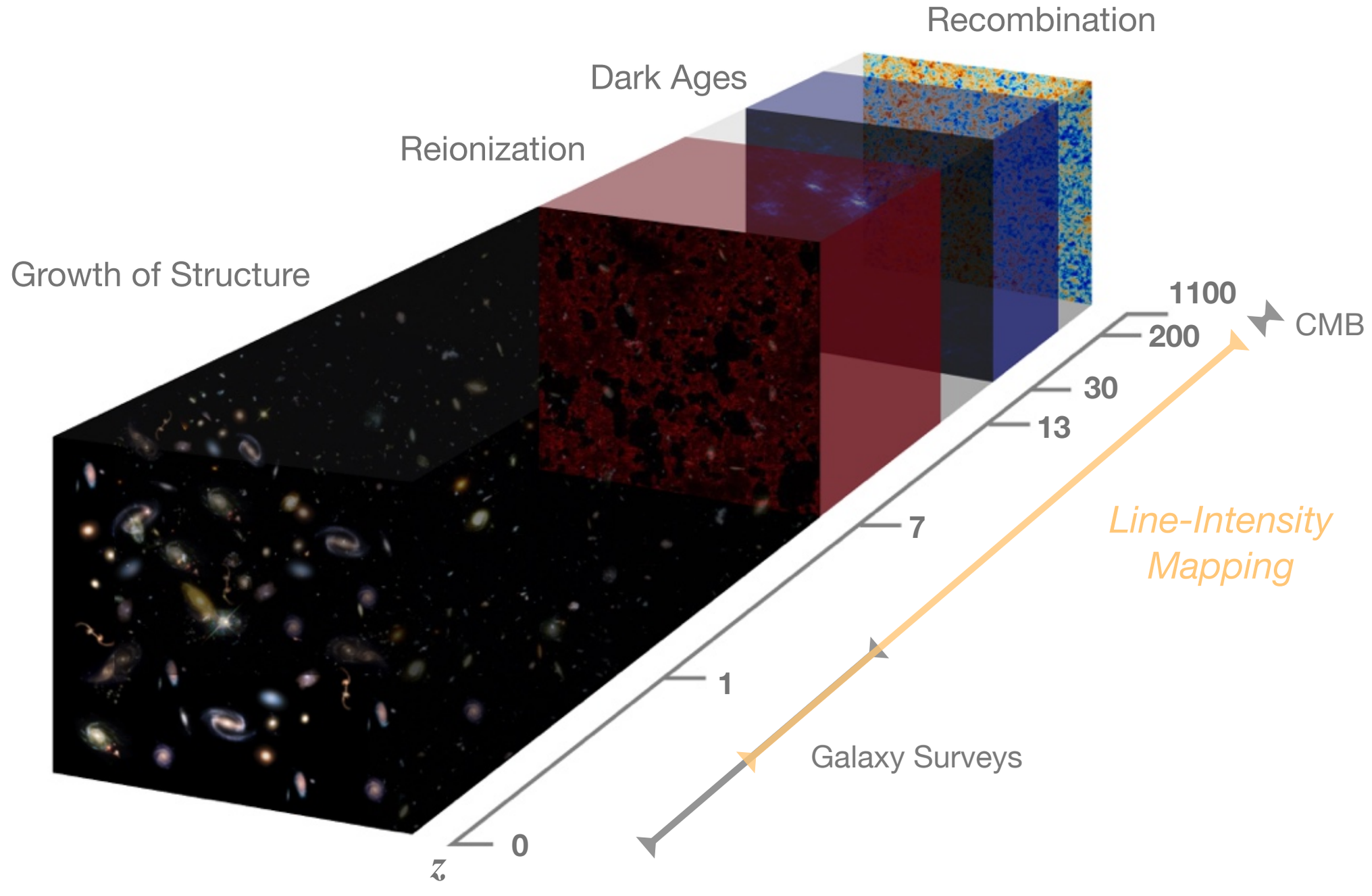

Introduction to Line-Intensity Mapping

Different epochs can be probed with multiple lines at different frequencies.

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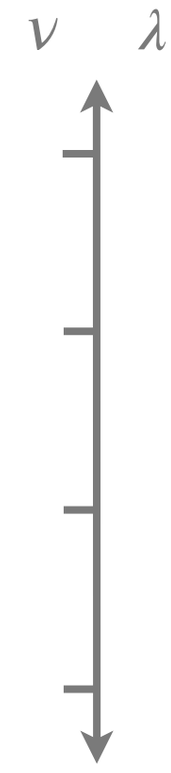

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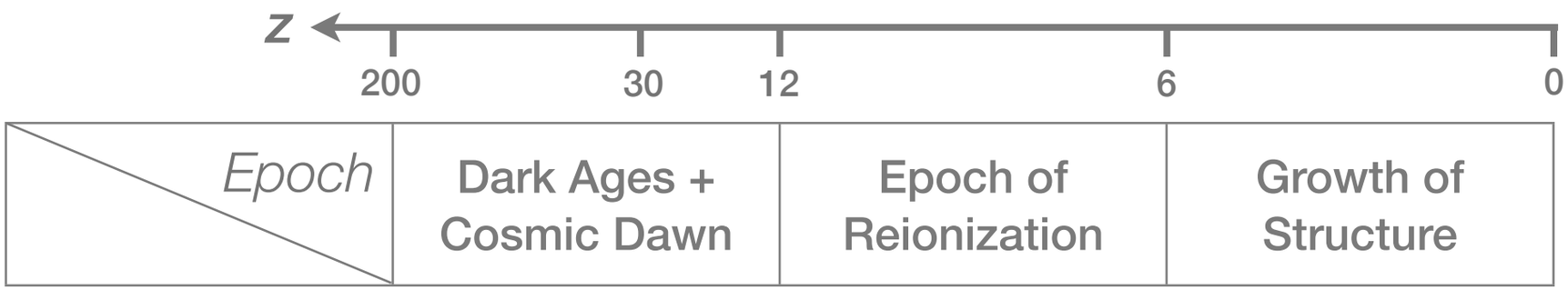

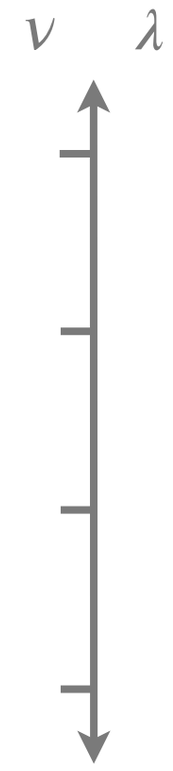

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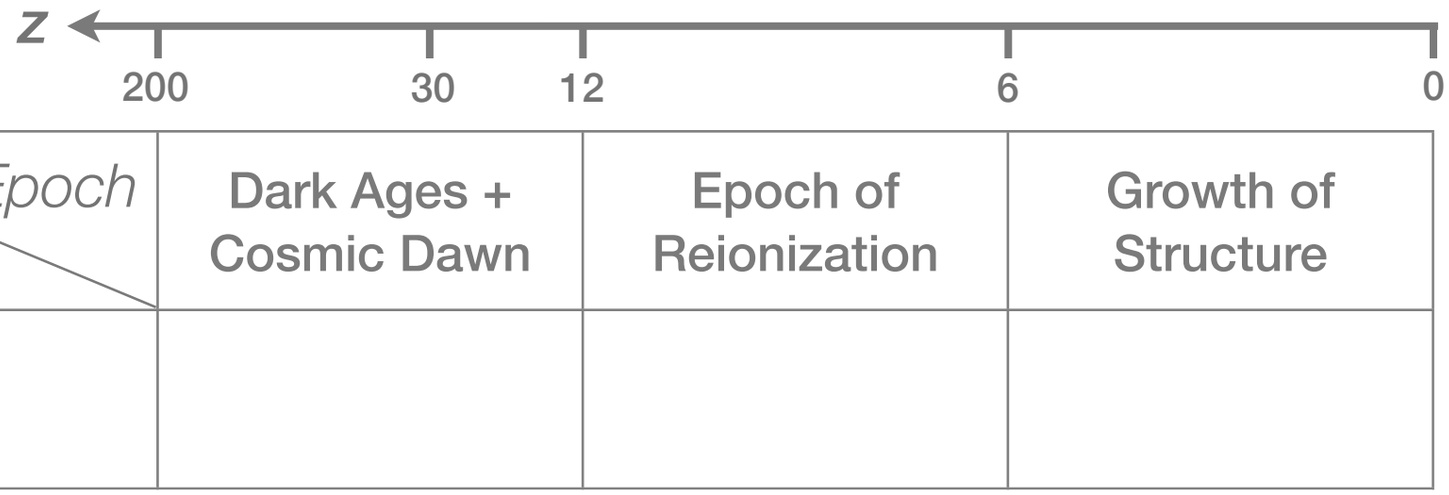
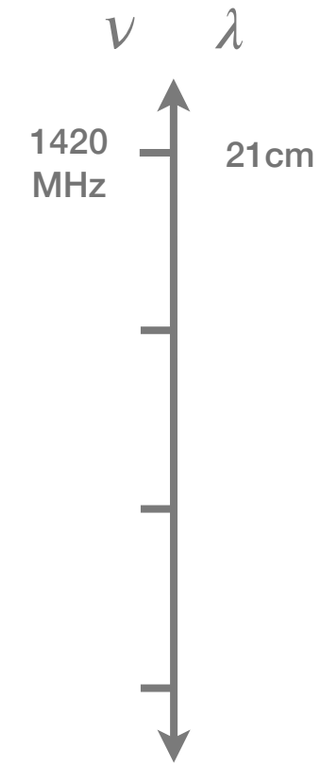


Probe \ Epoch	Dark Ages + Cosmic Dawn	Epoch of Reionization	Growth of Structure
HI			



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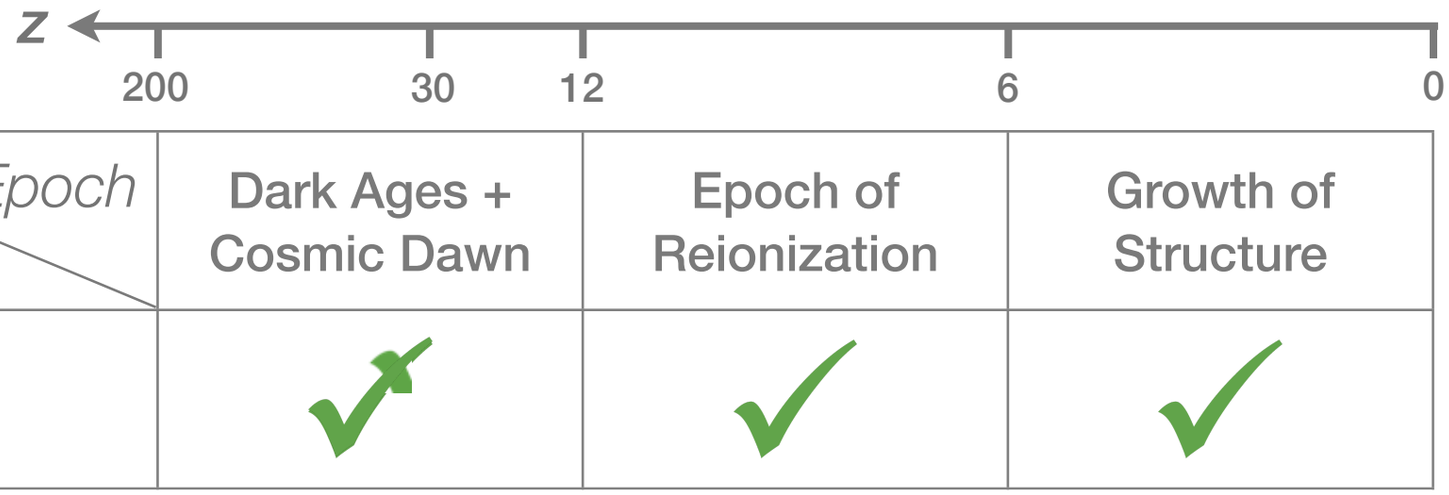

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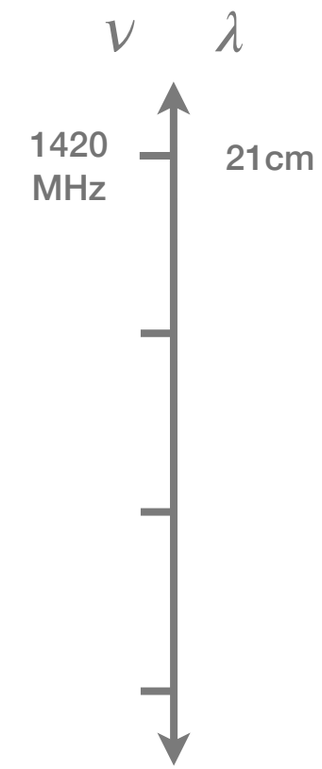

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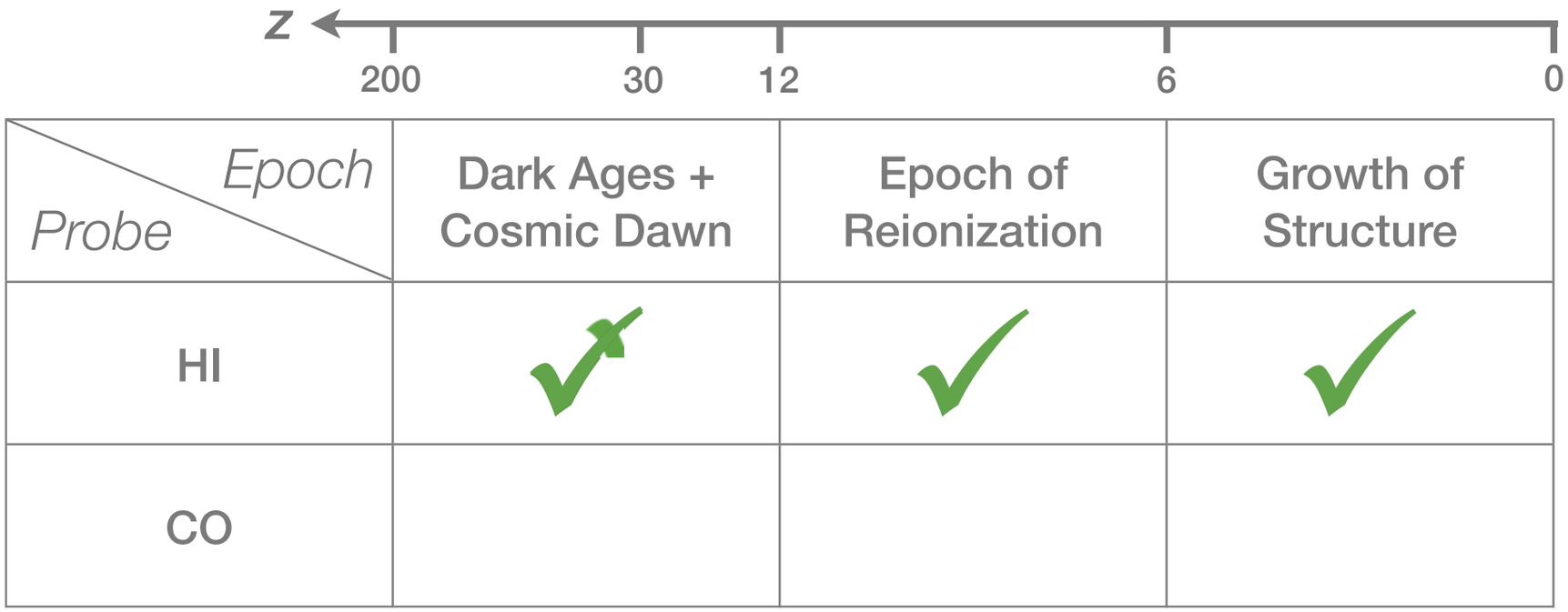
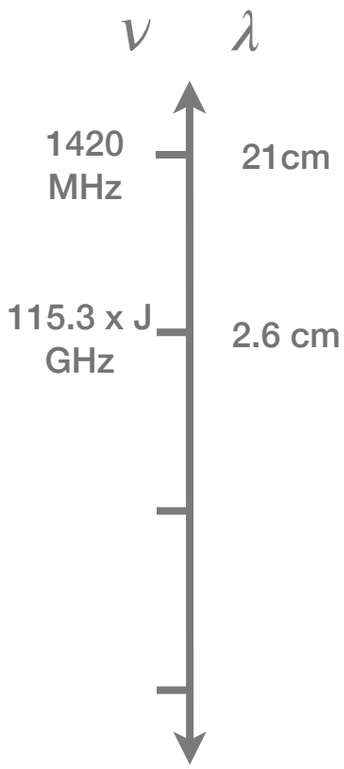


Probe \ Epoch	Dark Ages + Cosmic Dawn	Epoch of Reionization	Growth of Structure
HI	✓	✓	✓
CO			



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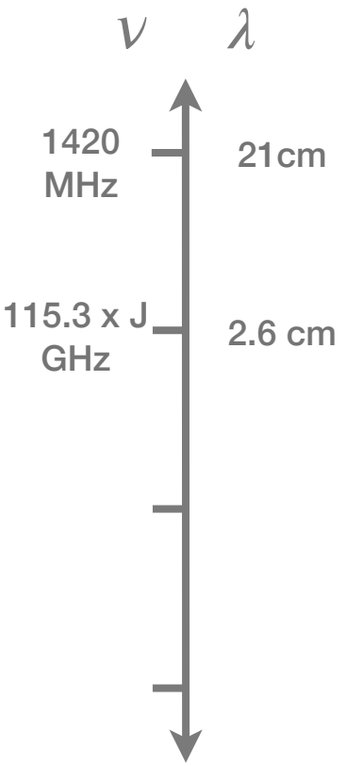

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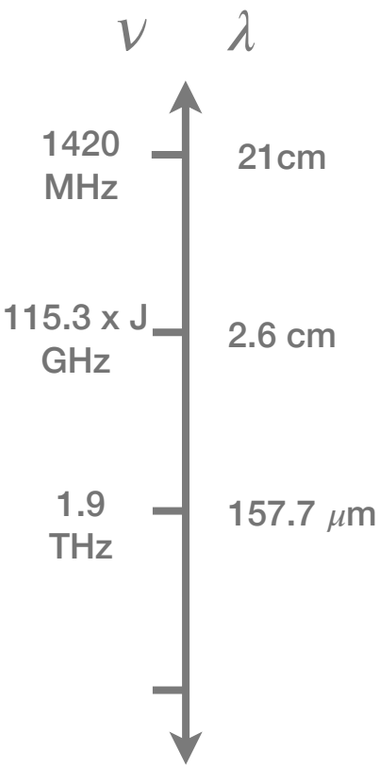
[CII]			



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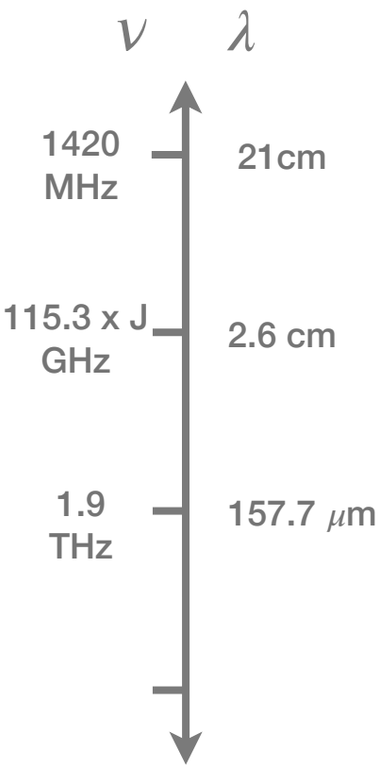

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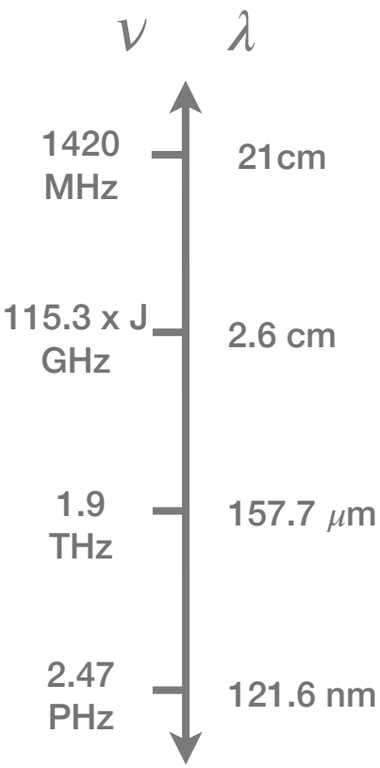
Lyα			



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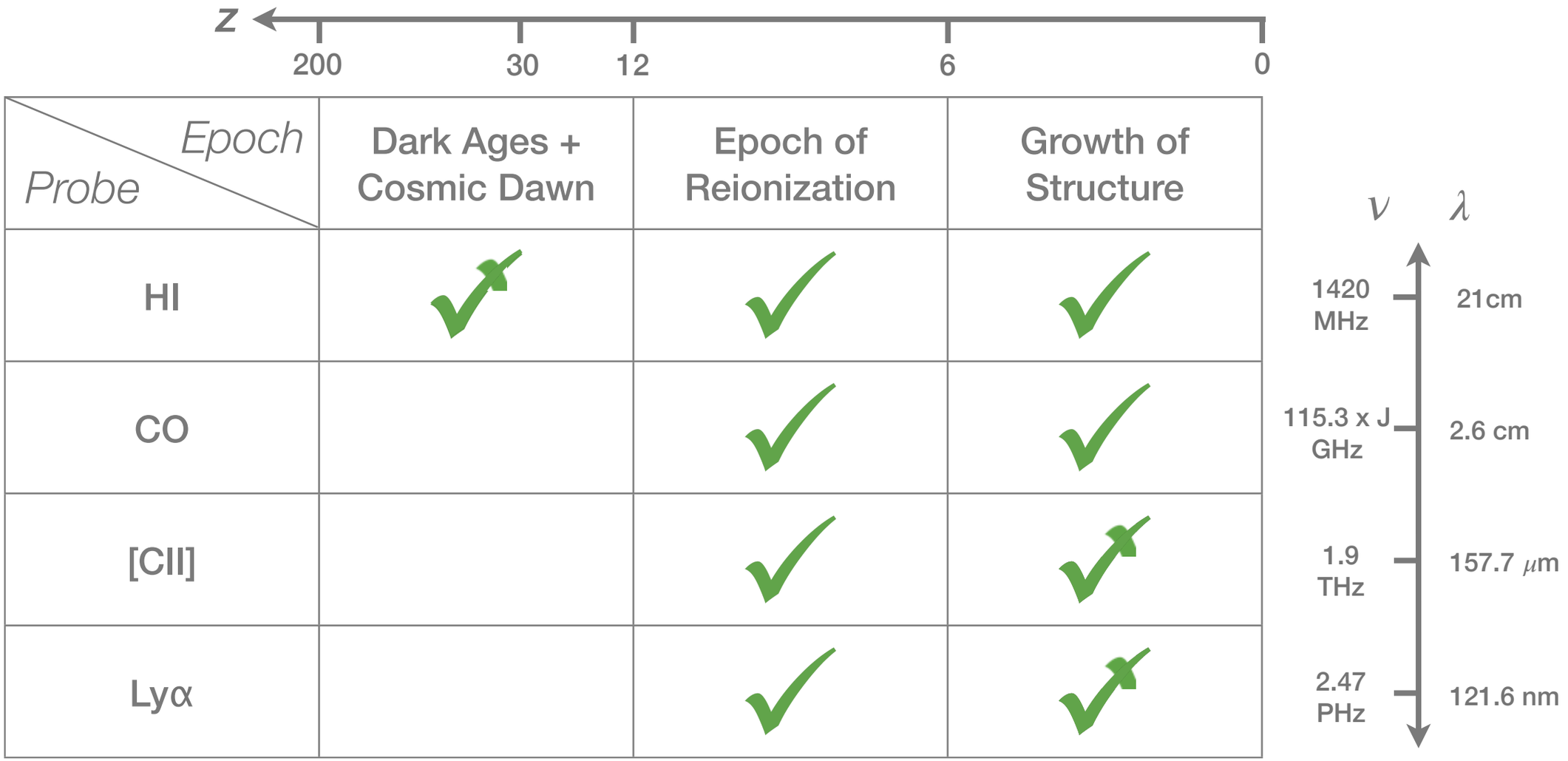

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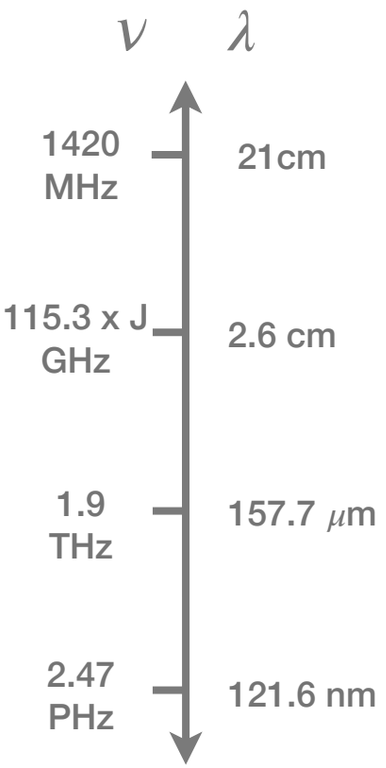
Lyα		✓	✓
Hα ⋮			



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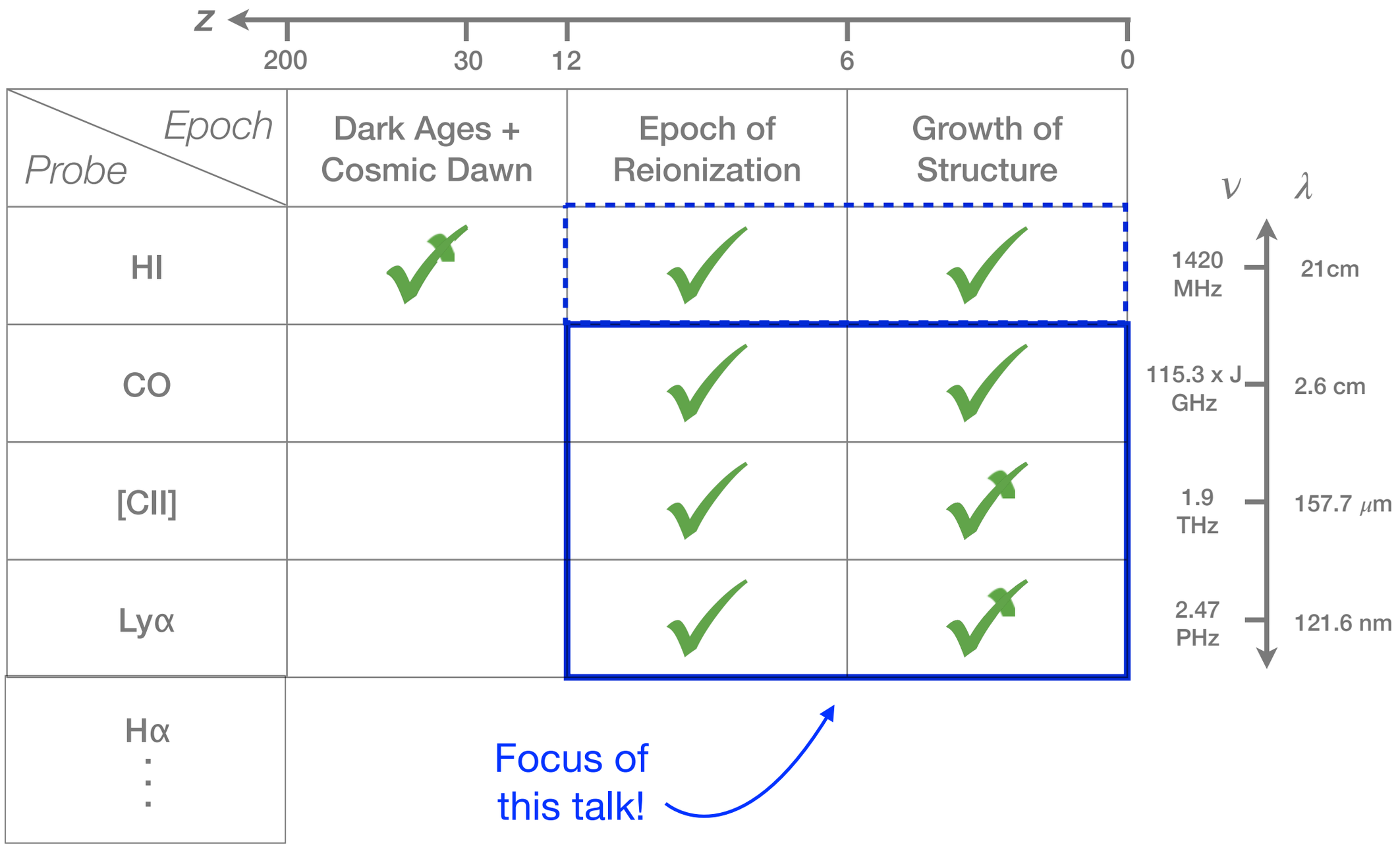

Introduction to Line-Intensity Mapping

The experimental landscape:

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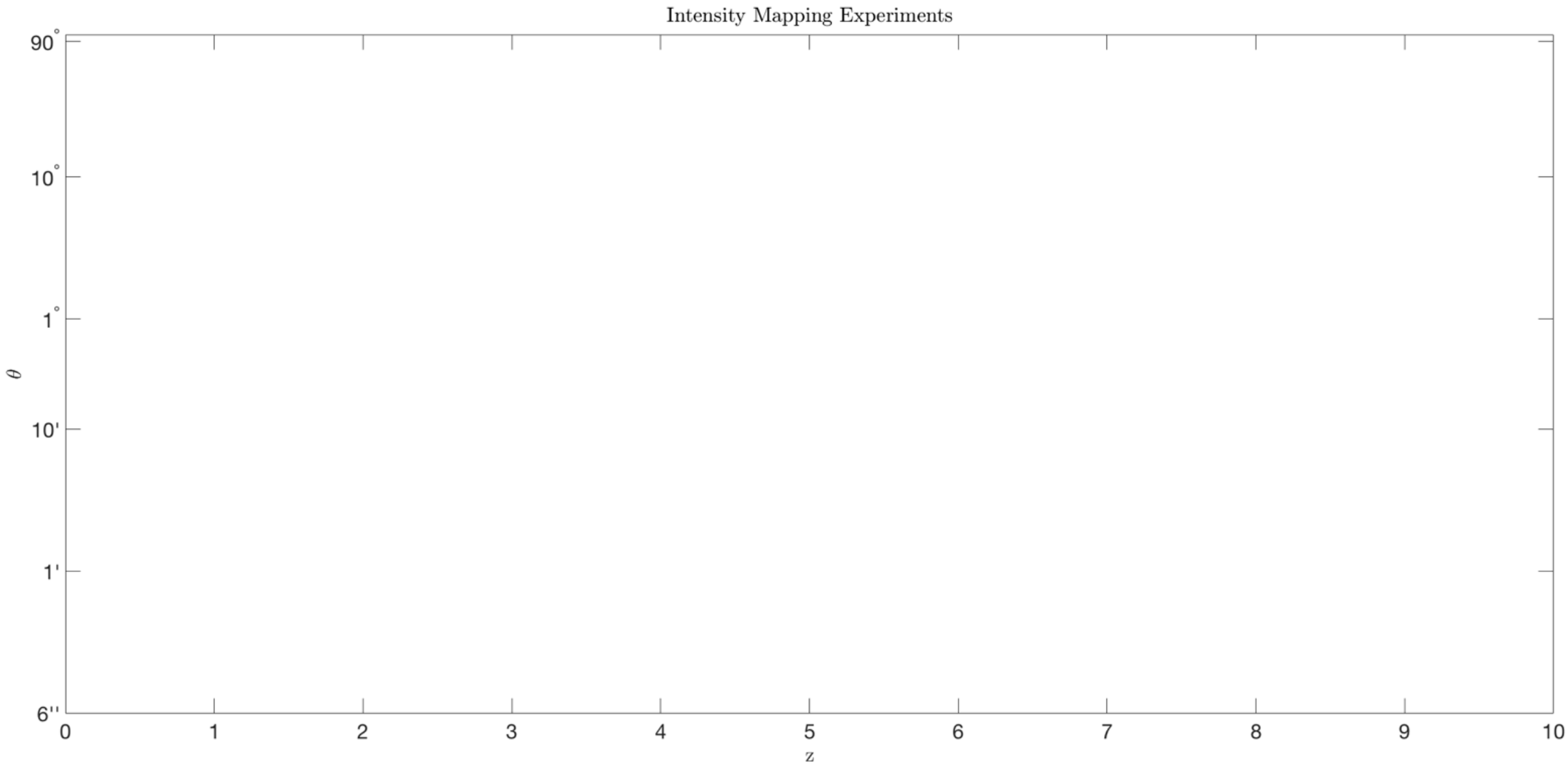

- horizontal: redshift range of each experiment
- vertical: range between maximum resolution and total sky coverage.

Introduction to Line-Intensity Mapping

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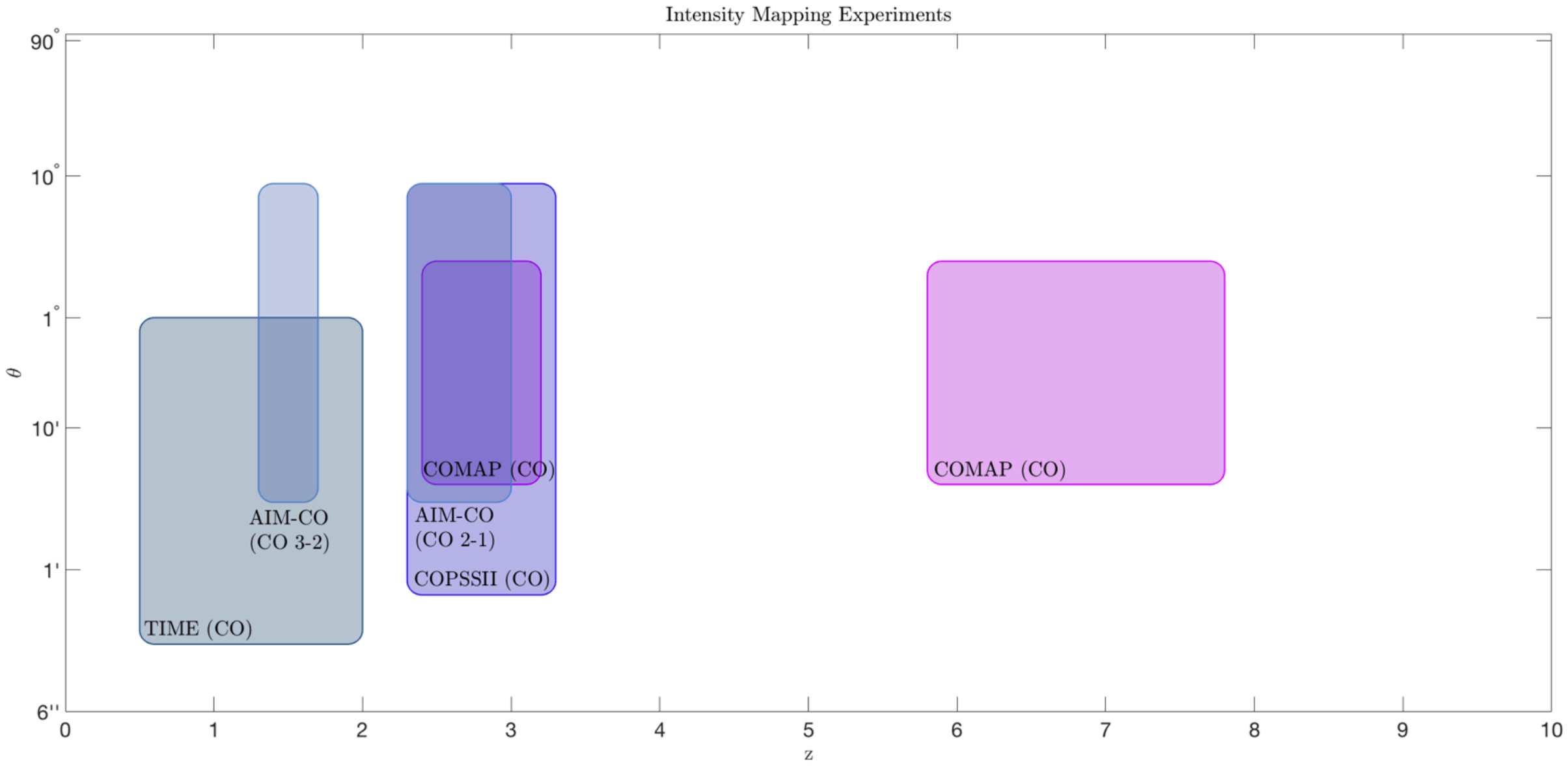

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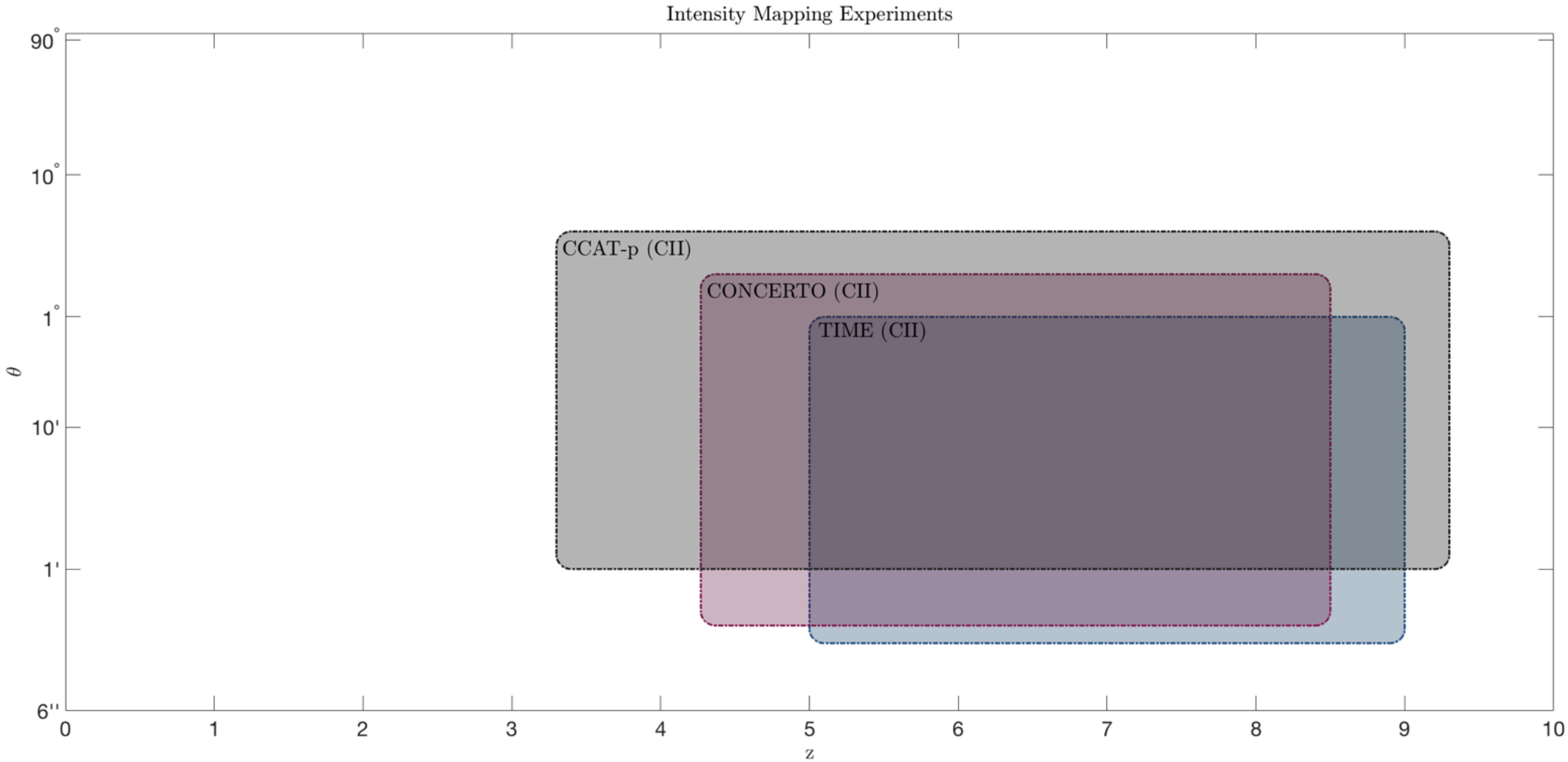

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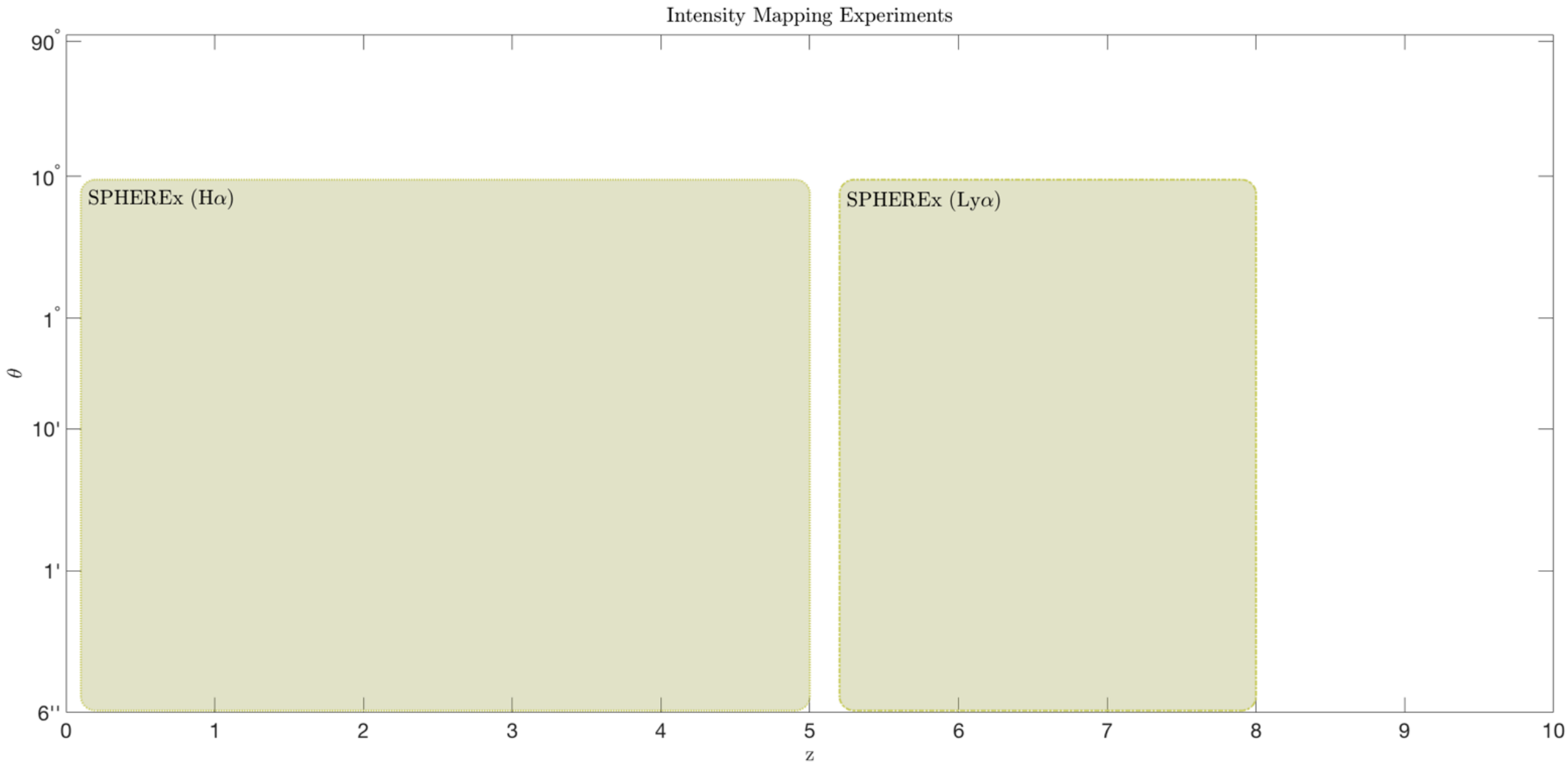

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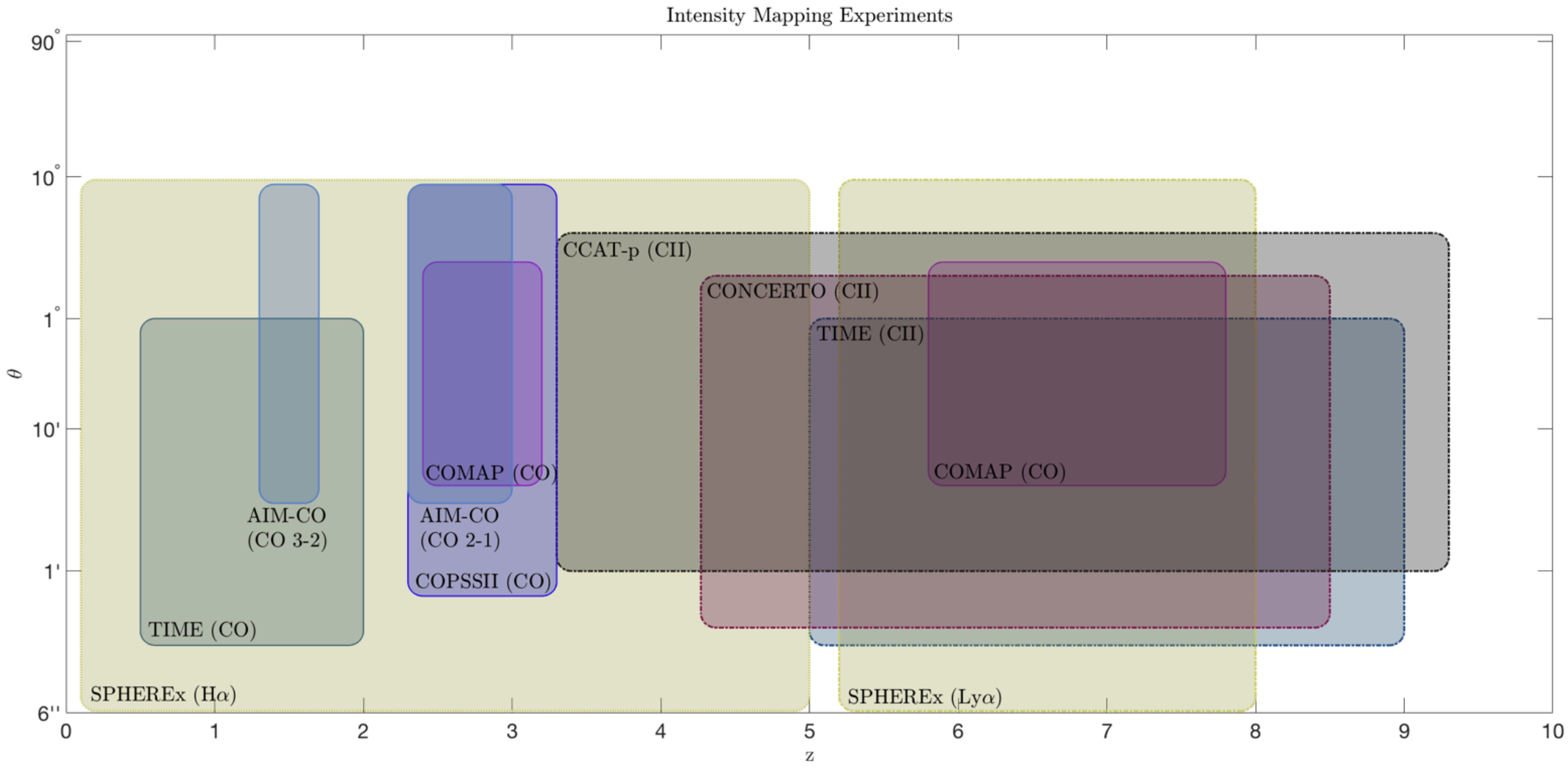

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Introduction to Line-Intensity Mapping

Basic formalism: power spectrum of line-intensity fluctuations

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$$P_{\rm line}(k,z) =$$

Introduction to Line-Intensity Mapping

Basic formalism: power spectrum of line-intensity fluctuations

$$P_{\rm line}(k,z) = \qquad\qquad P_m(k,z)$$

Emitters trace the underlying dark matter density field

Introduction to Line-Intensity Mapping

Basic formalism: power spectrum of line-intensity fluctuations

$$P_{\rm line}(k,z) = b^2(z) P_m(k,z)$$

Galaxies are
biased tracers
of dark matter

Introduction to Line-Intensity Mapping

Basic formalism: power spectrum of line-intensity fluctuations

$$P_{\rm line}(k,z) = \langle I_{\rm line}(z)\rangle^2 b^2(z) P_m(k,z)$$

Convert from galaxy spectrum to line spectrum

Introduction to Line-Intensity Mapping

Basic formalism: power spectrum of line-intensity fluctuations

$$P_{\rm line}(k,z) = \langle I_{\rm line}(z)\rangle^2 b^2(z) P_m(k,z) + P_{\rm shot}(z)$$

We measure emission from discrete sources

Introduction to Line-Intensity Mapping

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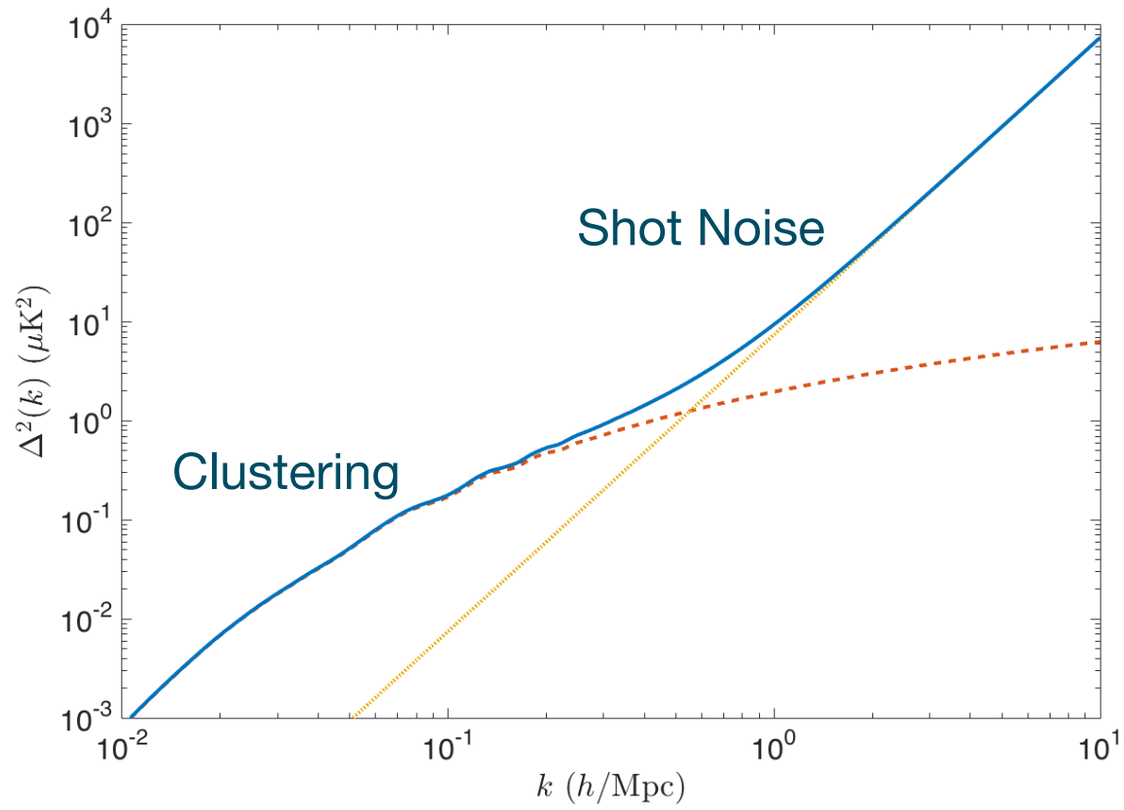

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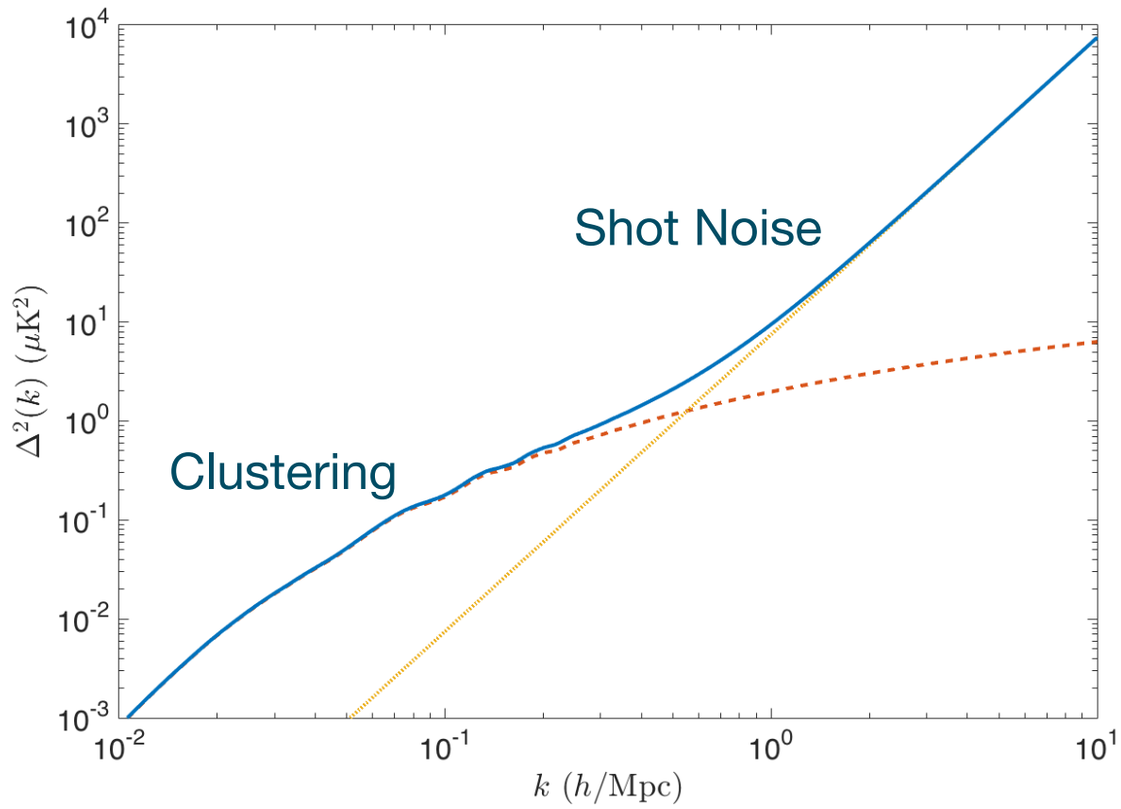
Luminosity function

$$\langle I_{\rm line}(z)\rangle \propto \int L \frac{dn(z)}{dL} dL$$



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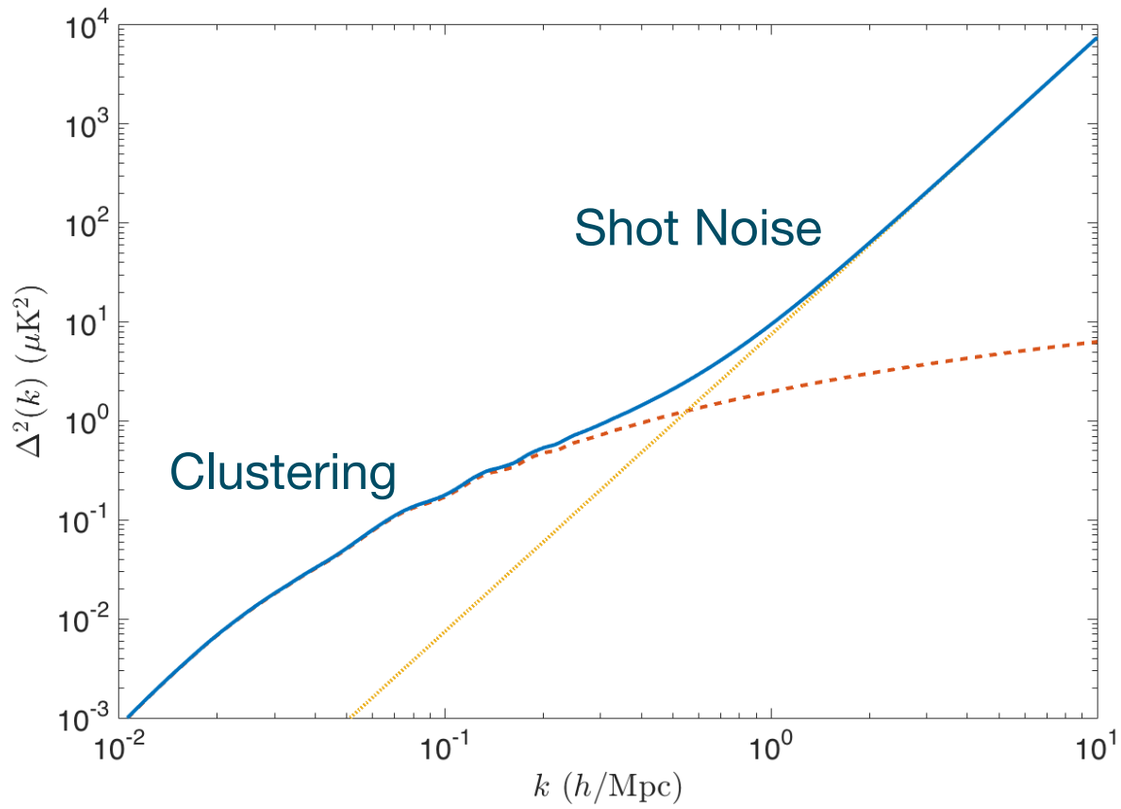

Introduction to Line-Intensity Mapping

Which lines to target? Important to consider intensity *and* bias!

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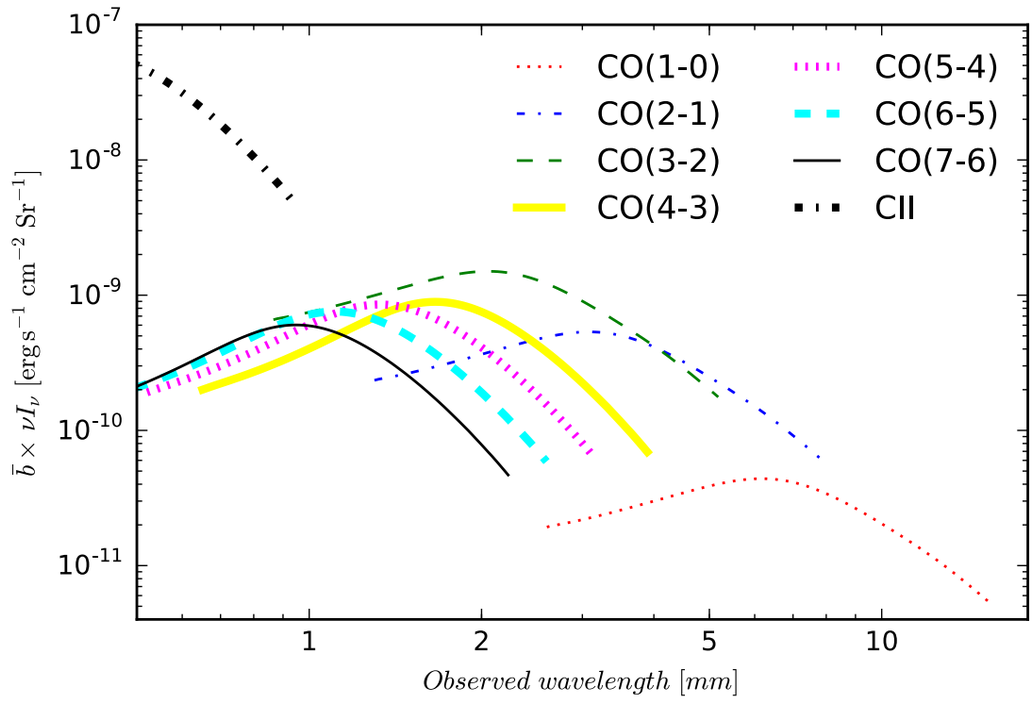

(Courtesy of J. Fonseca)

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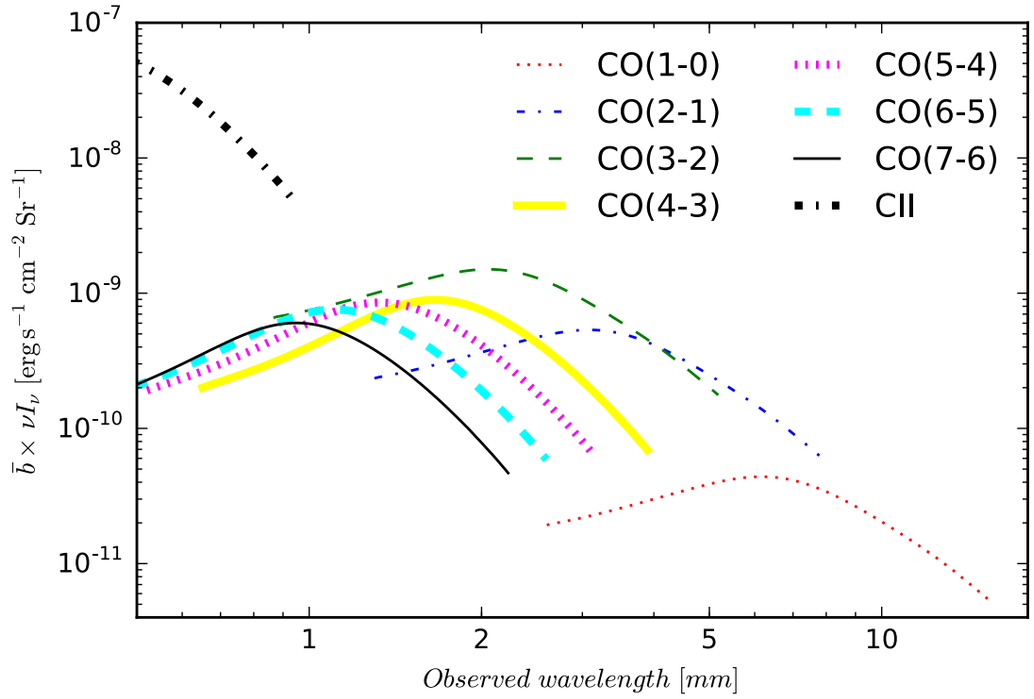

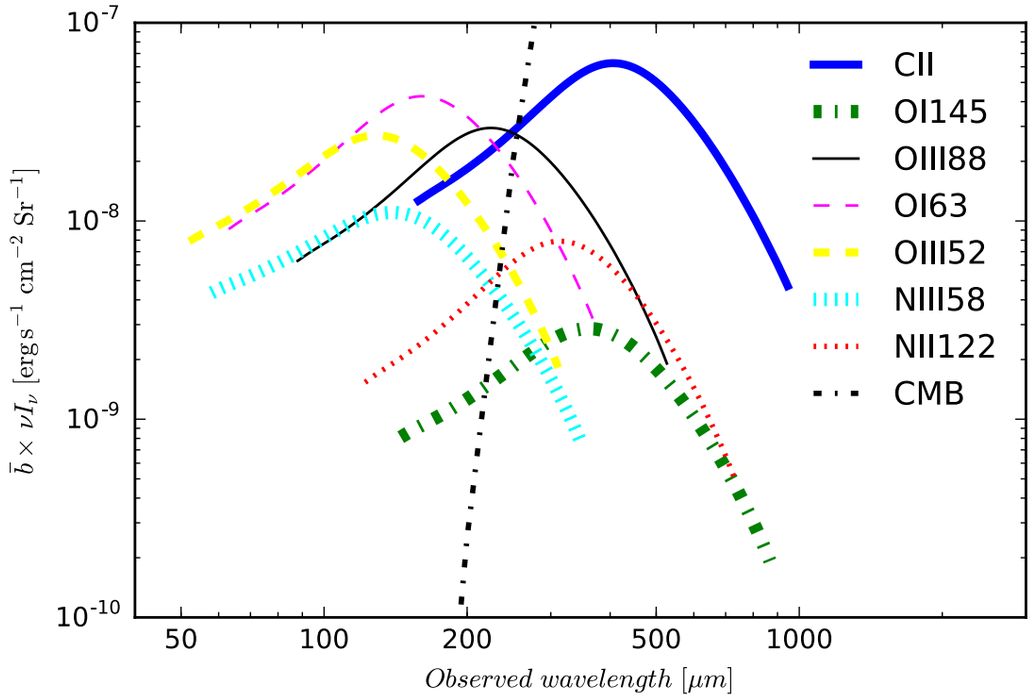

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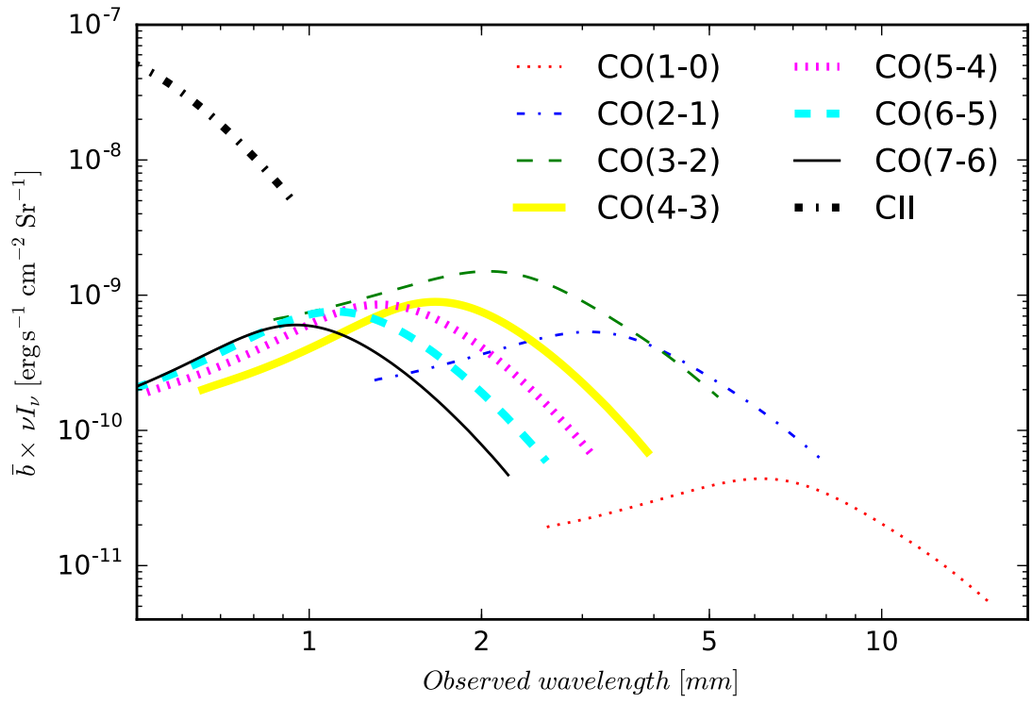
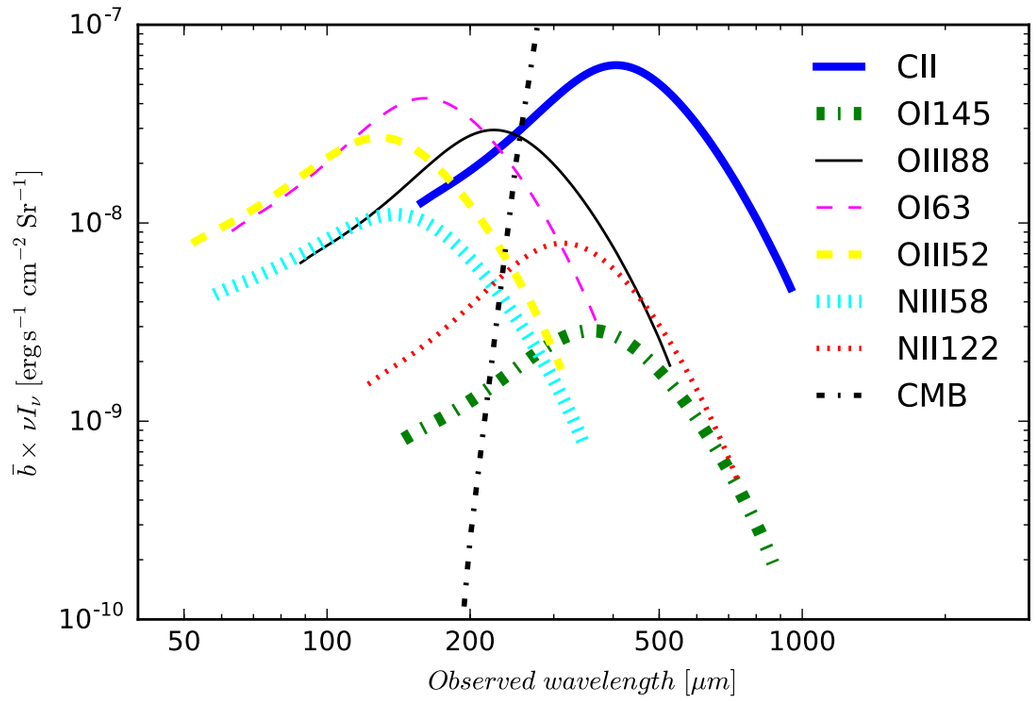
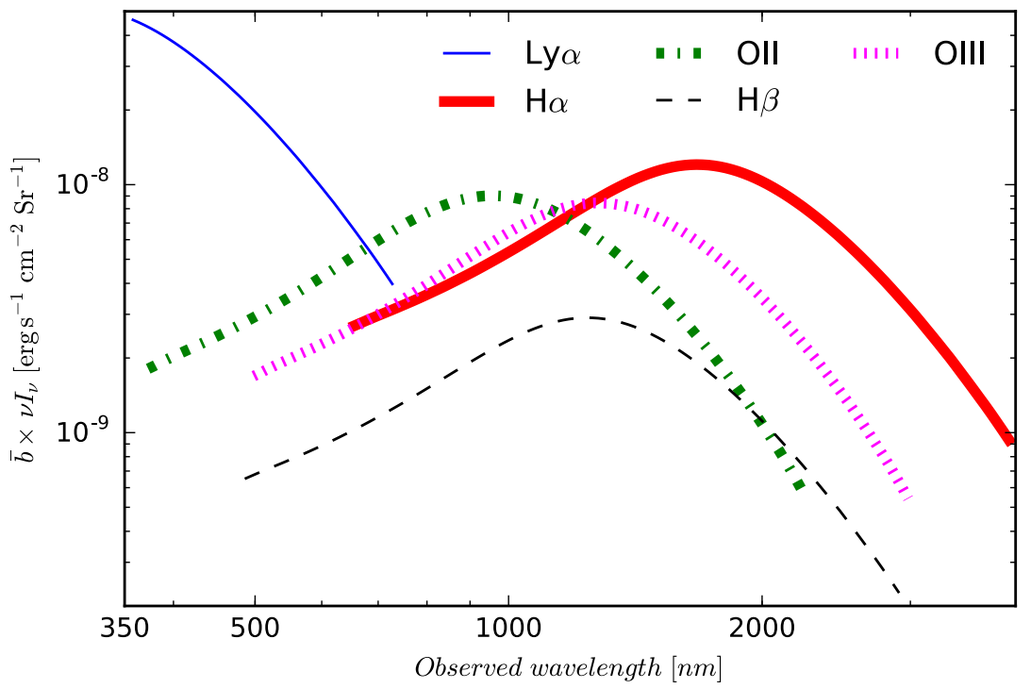




(Courtesy of J. Fonseca)



Introduction to Line-Intensity Mapping

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The reach of future surveys:

Introduction to Line-Intensity Mapping

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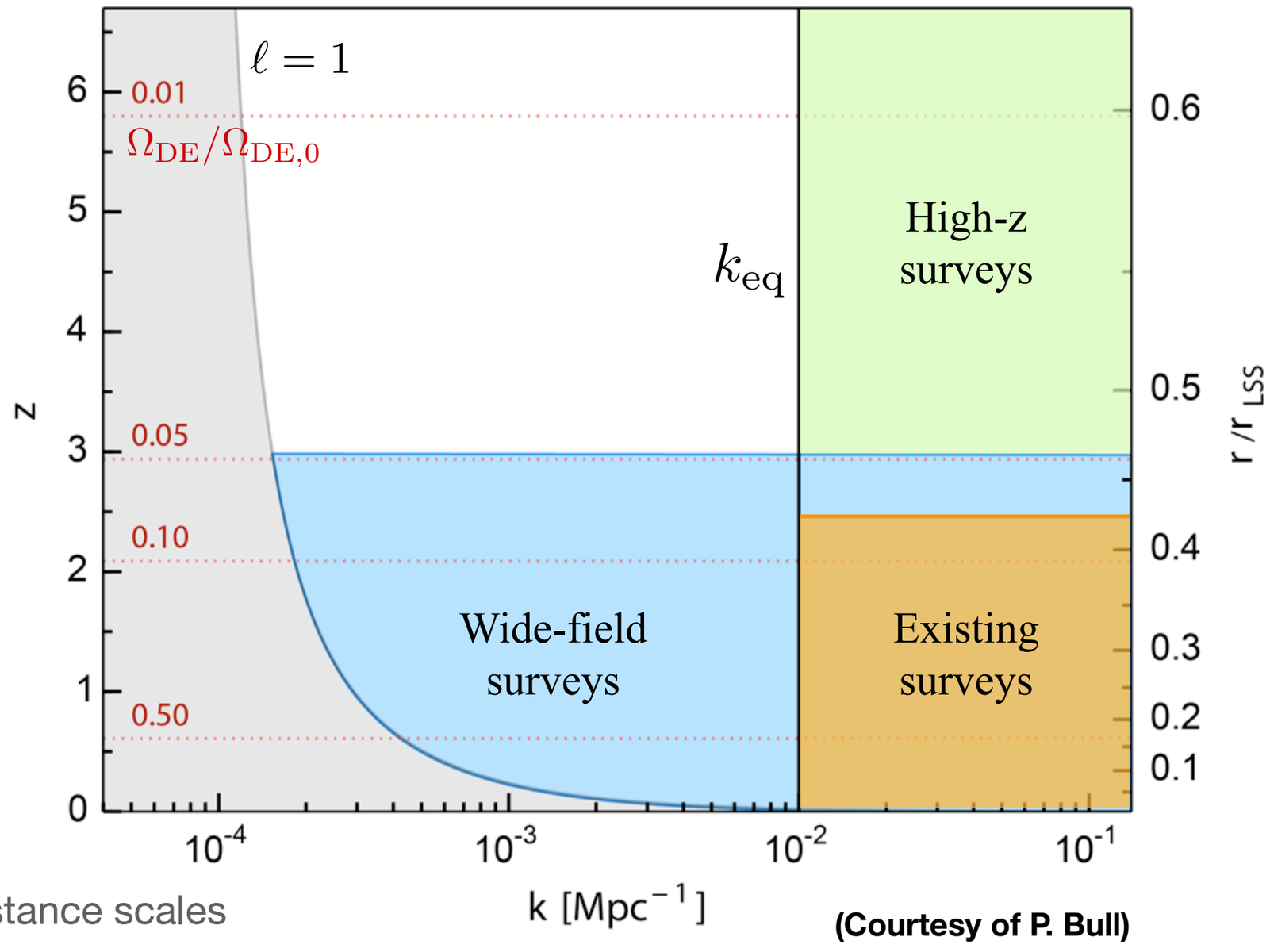


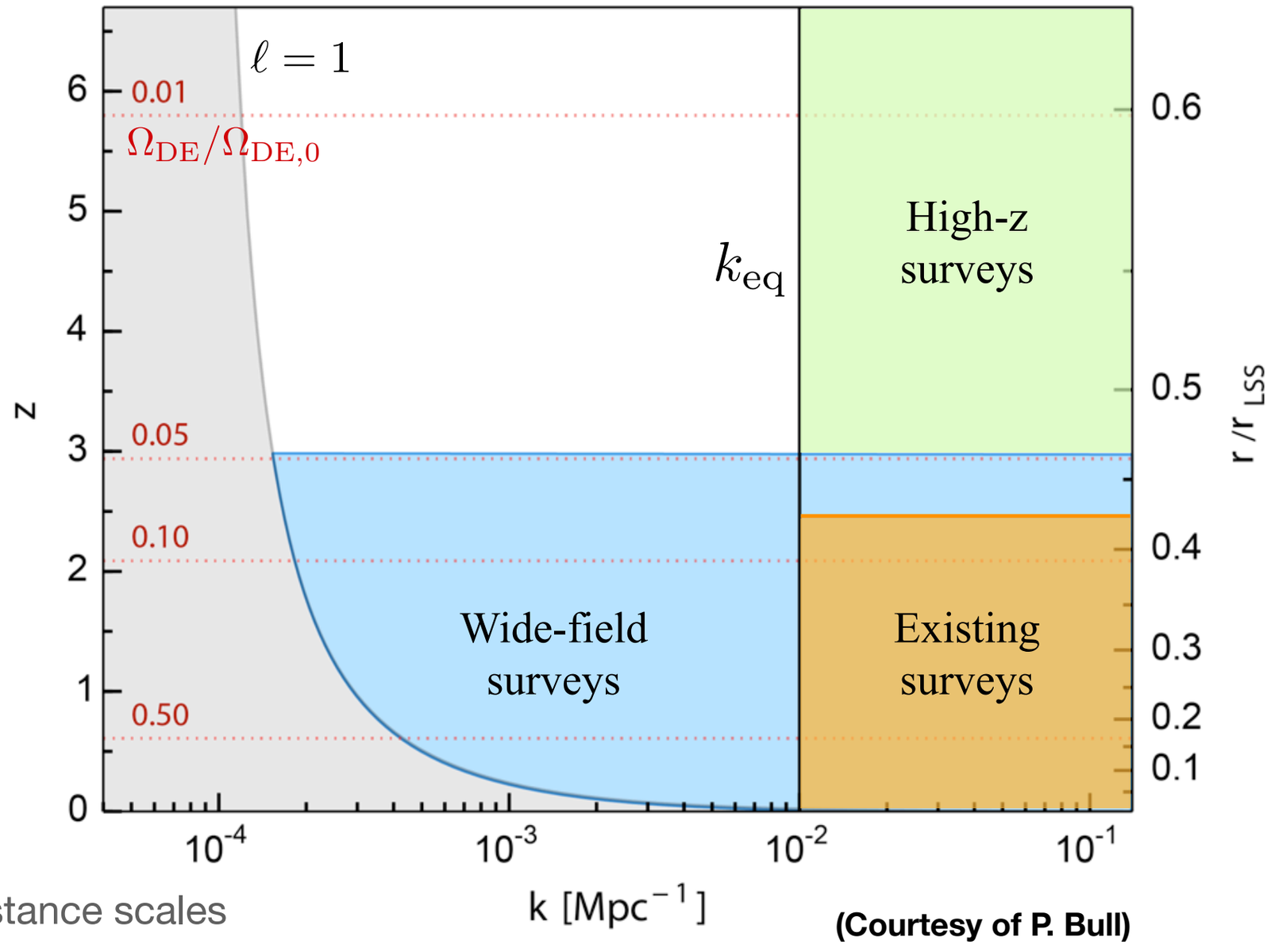
(Courtesy of P. Bull)

- horizontal: distance scales
- vertical: redshift / distance to LSS.

Introduction to Line-Intensity Mapping

The reach of future surveys:

LIM is highly competitive with galaxy surveys on *large scales* and at *high redshift*!



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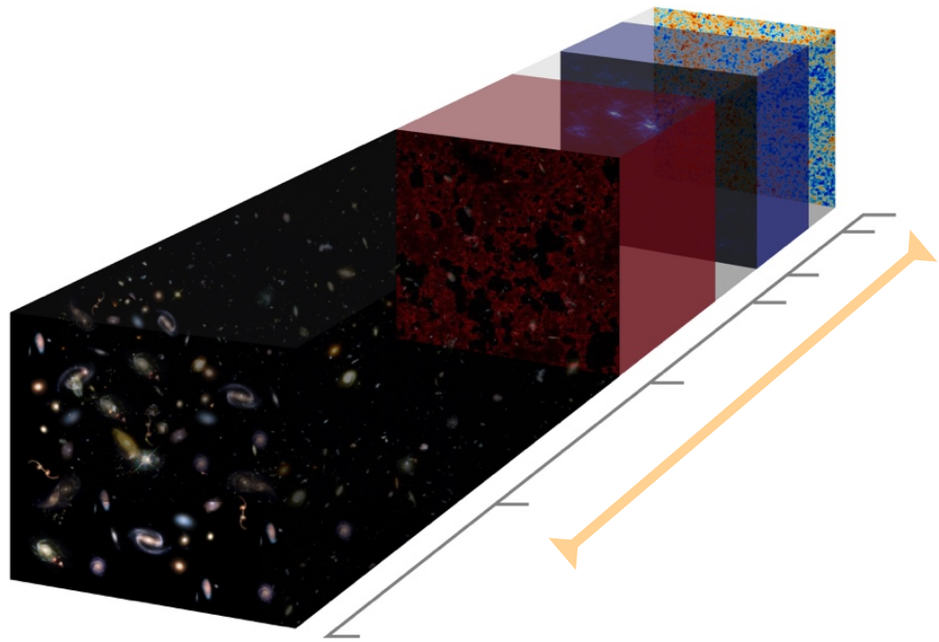
Outline

Ely D. Kovetz
Aspen, Feb. 2018

- Introduction to Line-Intensity Mapping



Outline

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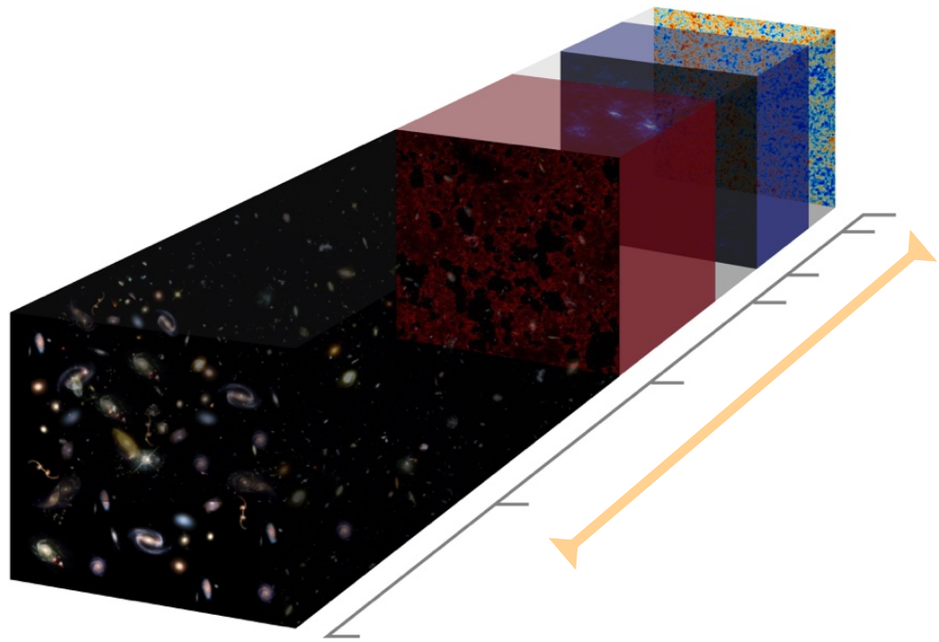
- Introduction to Line-Intensity Mapping
- Science Goals of Line-Intensity Mapping



Science Goals of Line-Intensity Mapping

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Tests of ΛCDM Cosmology (and beyond):

Science Goals of Line-Intensity Mapping

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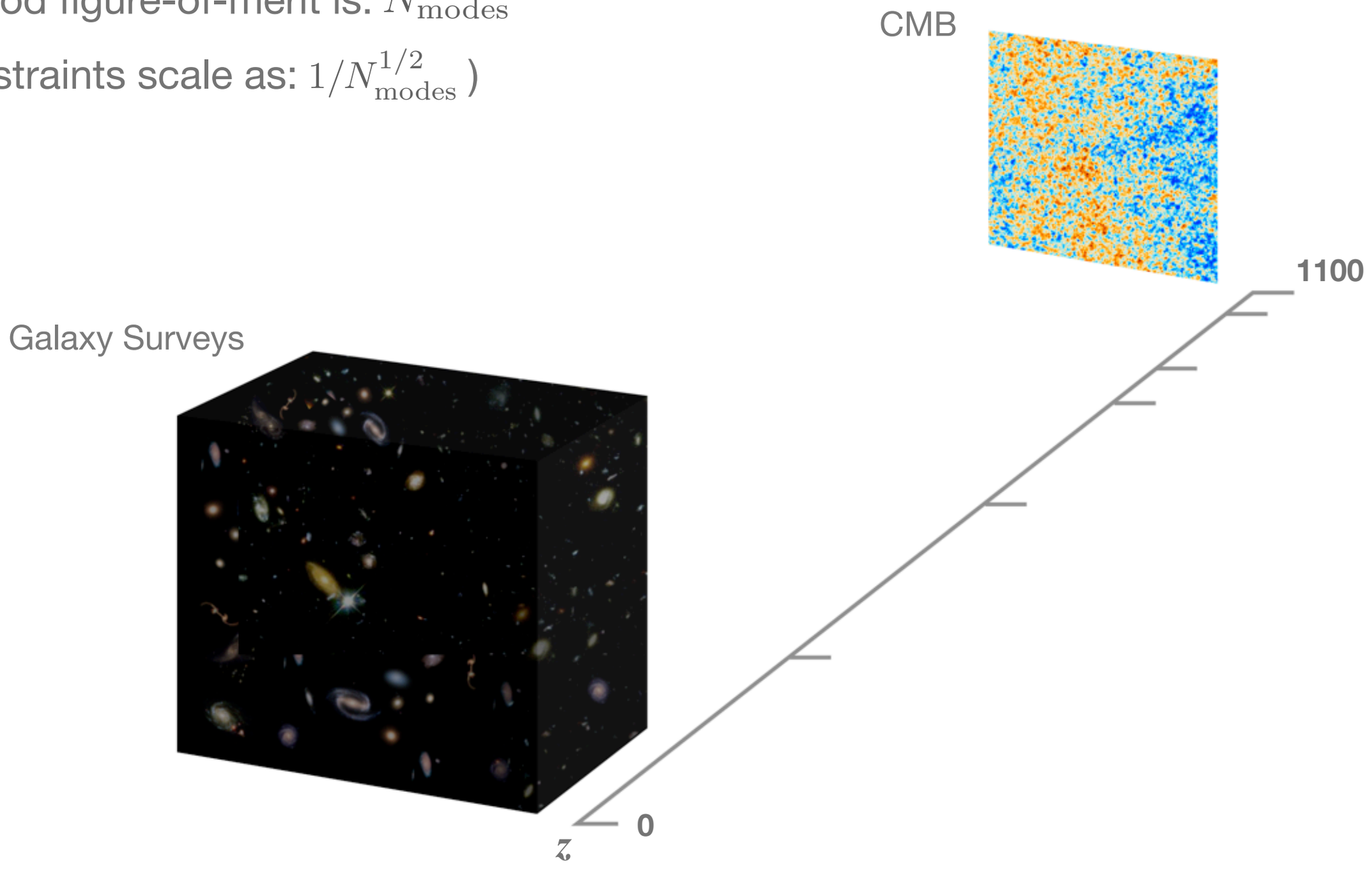

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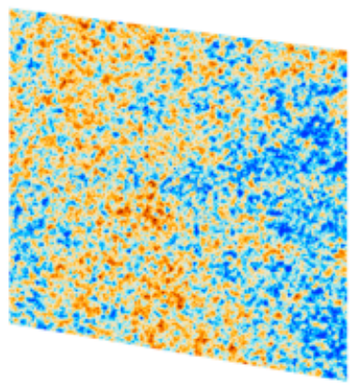
CMB

$N_{\rm modes}^{\rm CMB} \sim \ell_{\rm max}^2 \sim 10^7$



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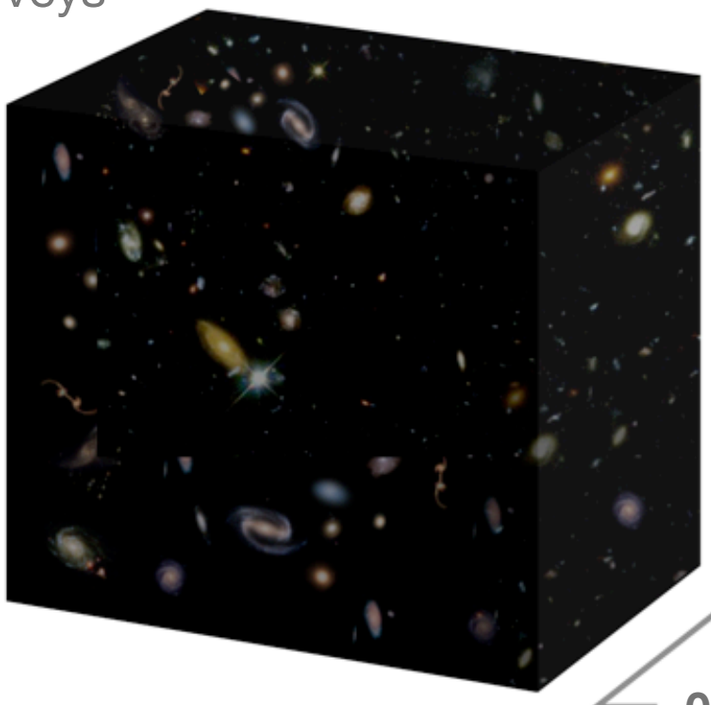
Galaxy Surveys



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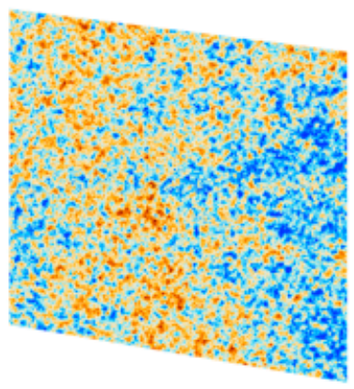

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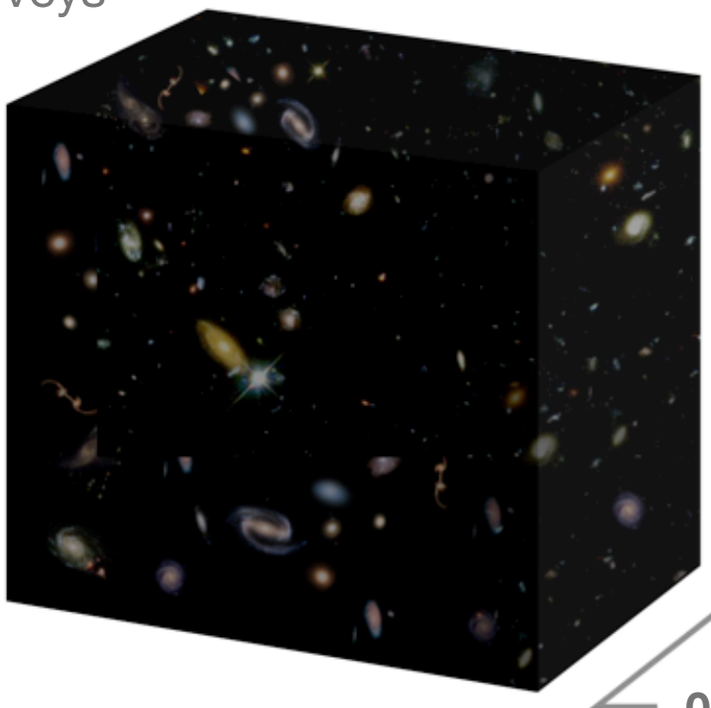

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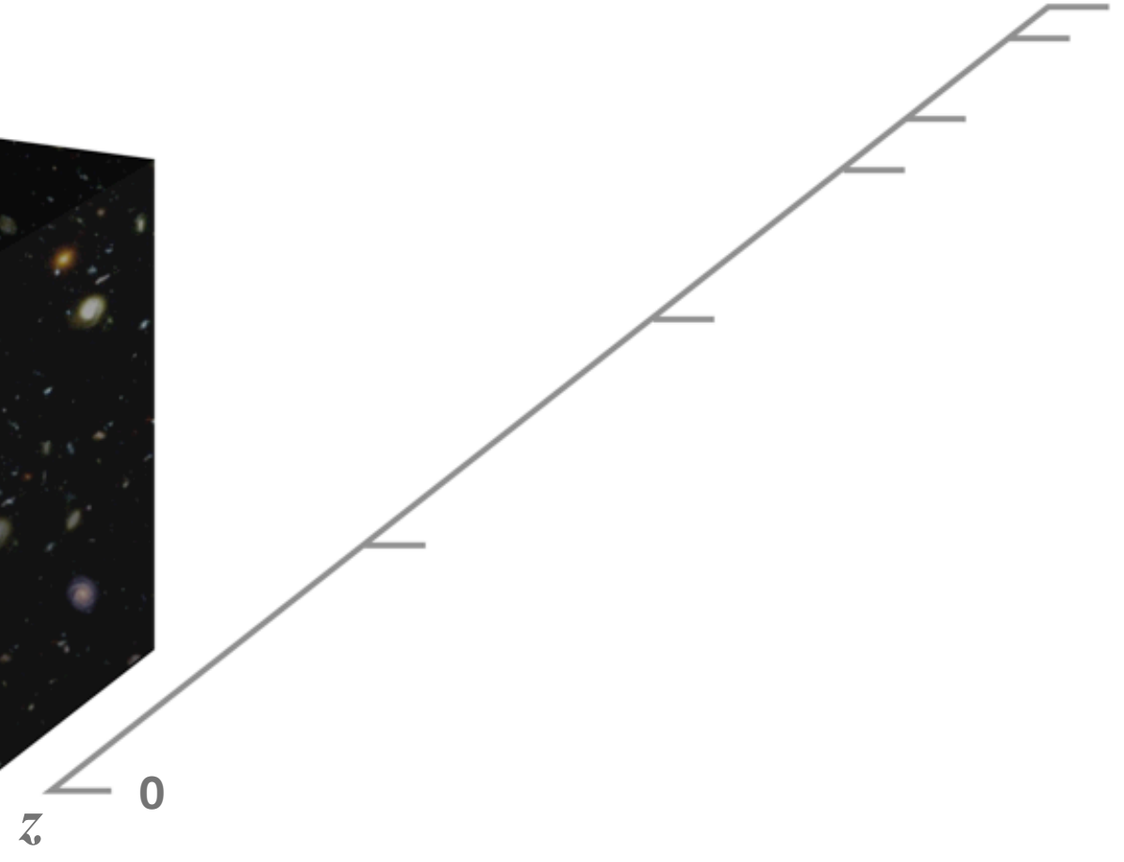
$\longrightarrow N_{\rm sources} > 10^8$ (Euclid, LSST?)



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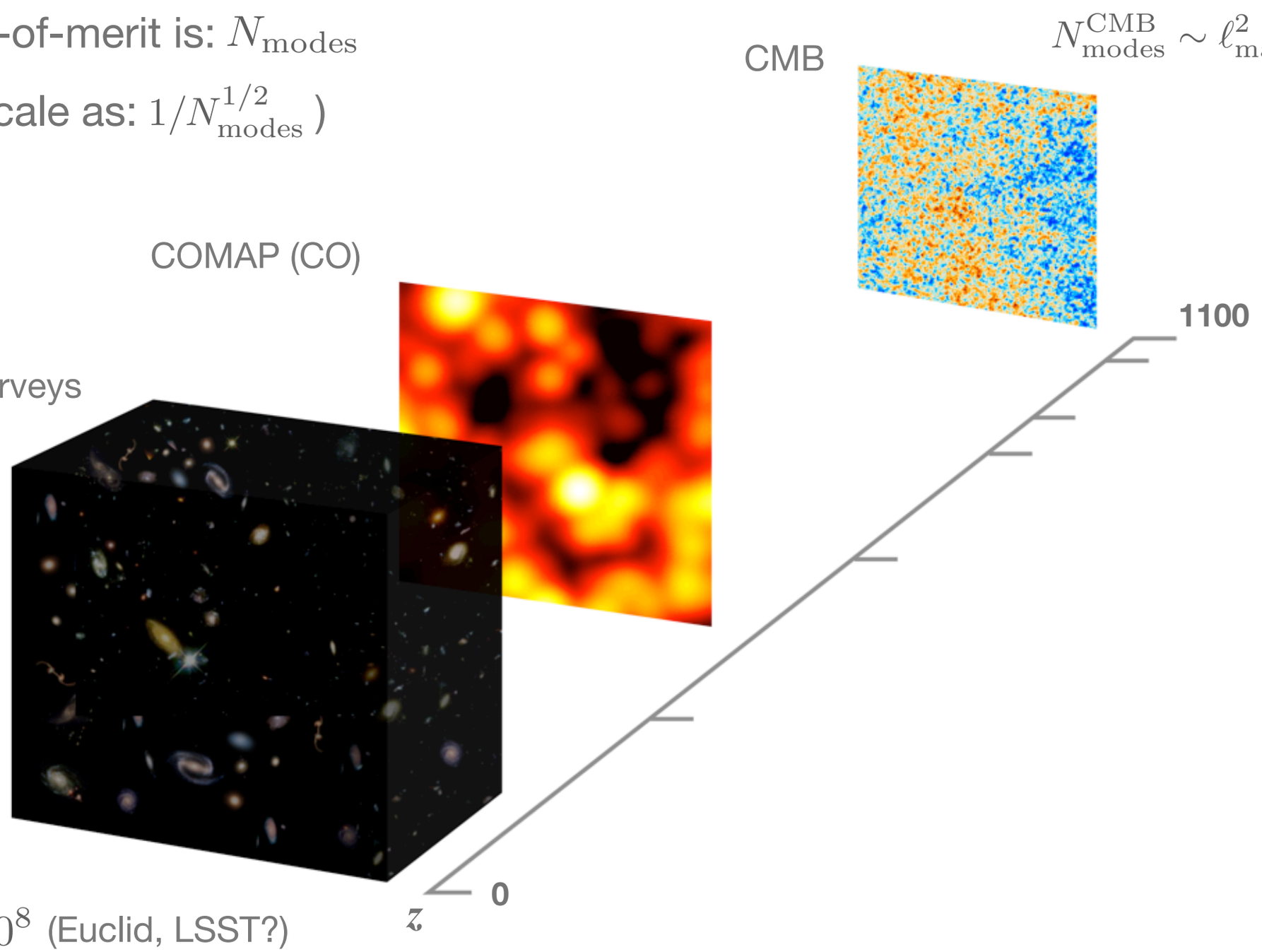

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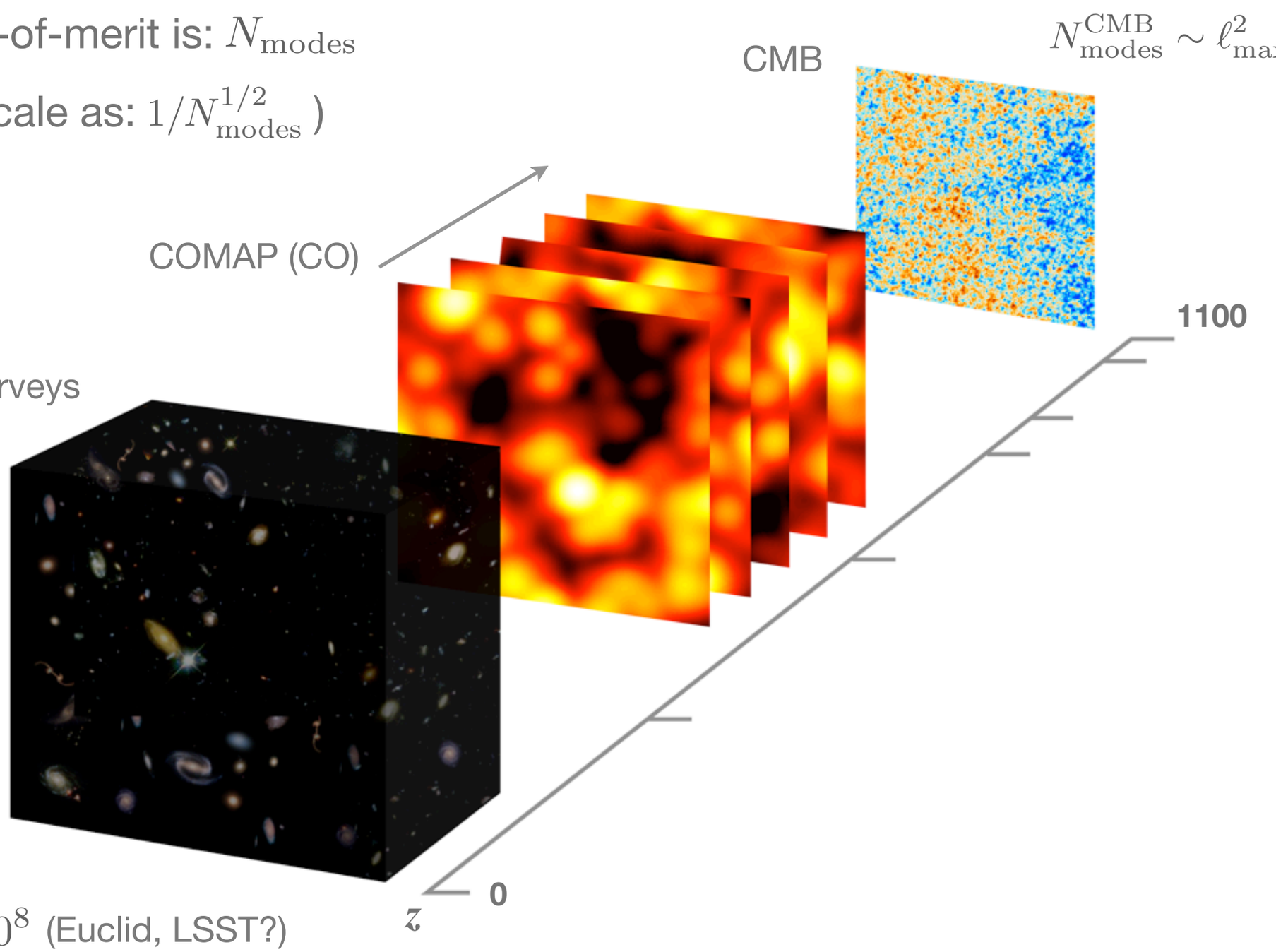

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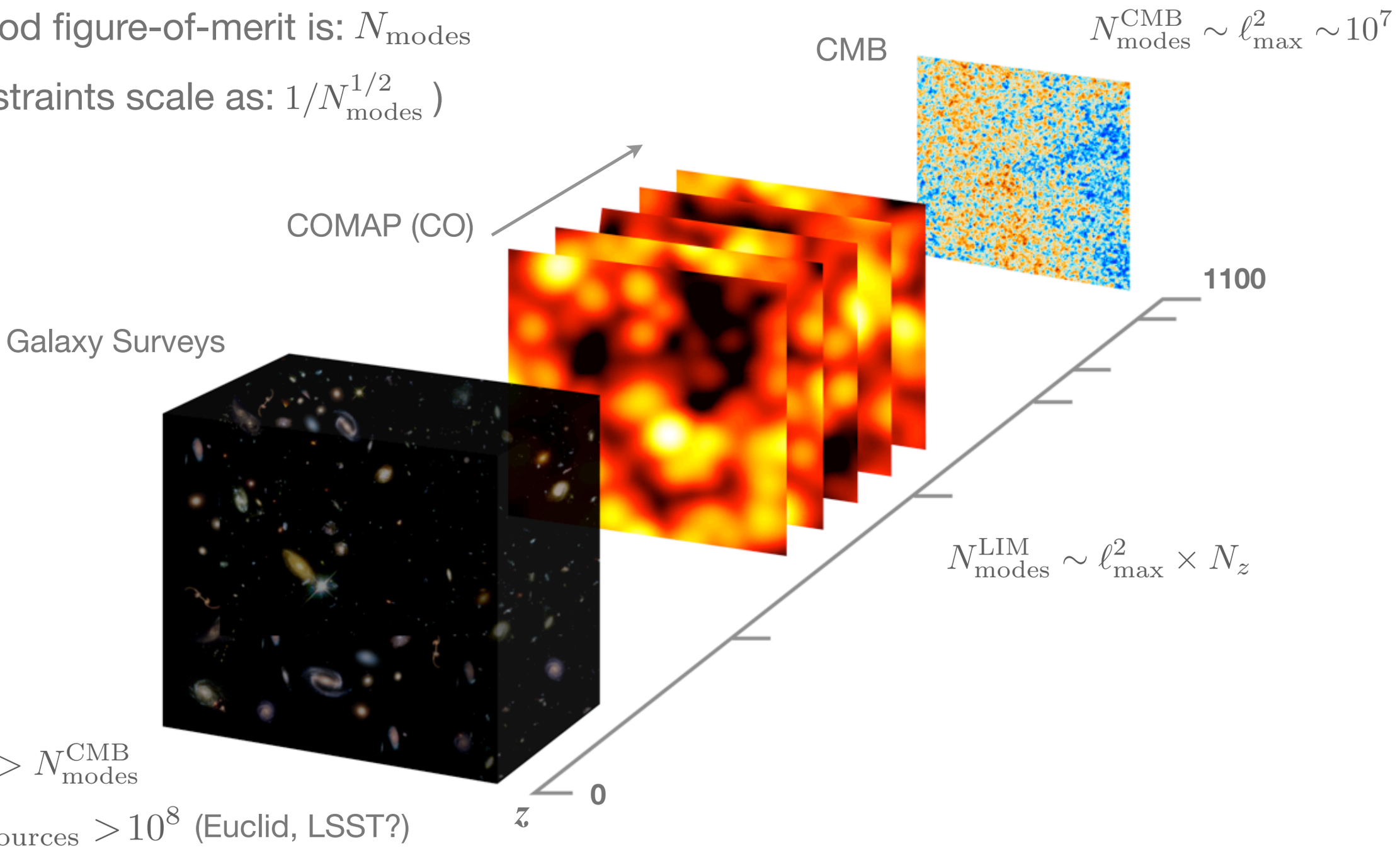

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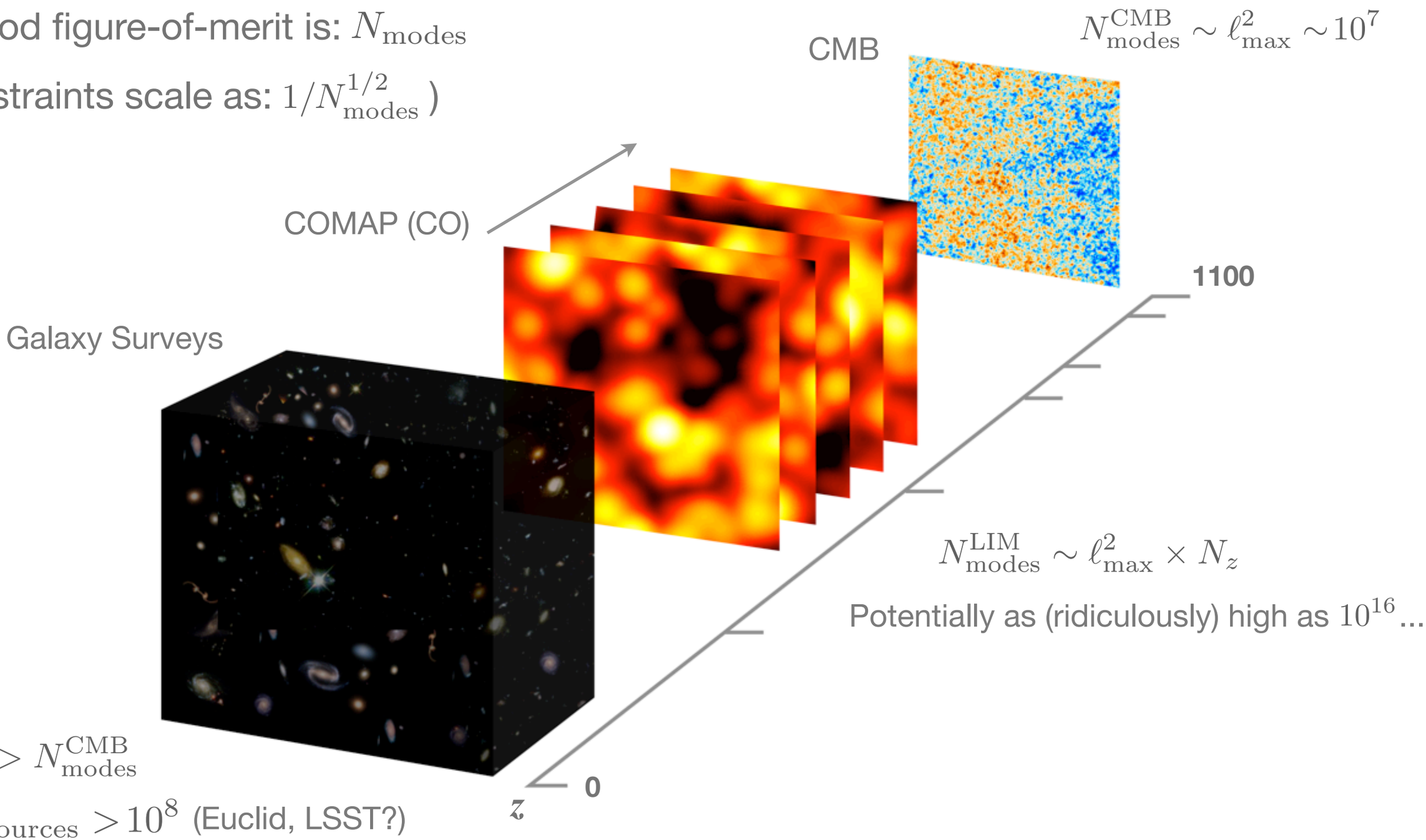

$N_{\rm modes}^{\rm LIM} \sim \ell_{\rm max}^2 \times N_z$

Potentially as (ridiculously) high as 10^{16}...

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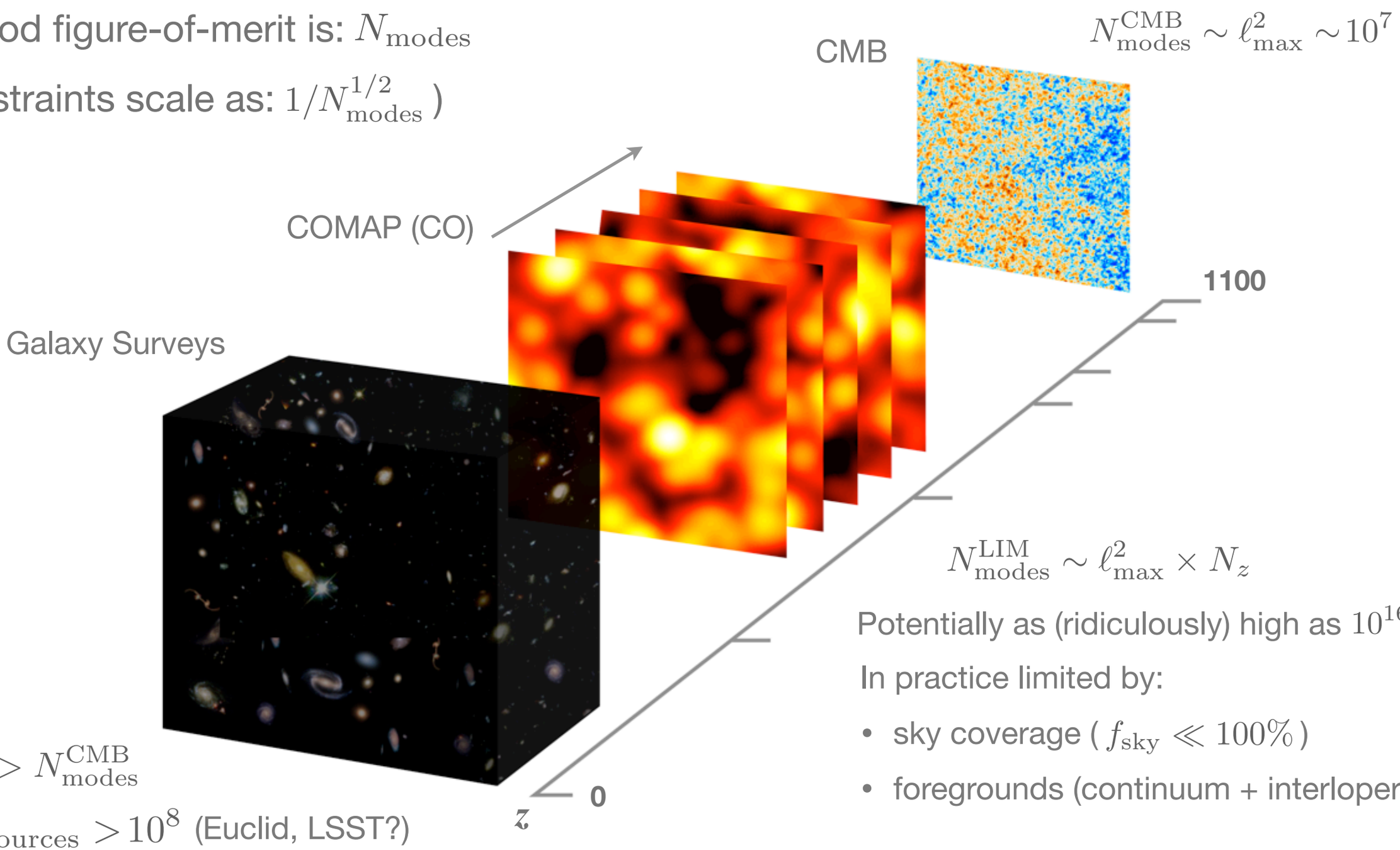

Potentially as (ridiculously) high as 10^{16}...

In practice limited by:

- sky coverage ($f_{\rm sky} \ll 100\%$)
- foregrounds (continuum + interlopers)

$N_{\rm modes}^{\rm Gal} > N_{\rm modes}^{\rm CMB}$

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Science Goals of Line-Intensity Mapping

Tests of ΛCDM Cosmology (and beyond):

- Baryon acoustic oscillations (up to high redshift)
- Optical depth to reionization (improve CMB estimate)
- Neutrino masses (in synergy with galaxies, CMB)
- Inflation (primordial non-gaussianity, power spectrum oscillations)
- Dark energy (constrain equation of state)
- Dark matter (decaying, annihilating, interacting)
- Modified Gravity (Chameleon, Hordenski)

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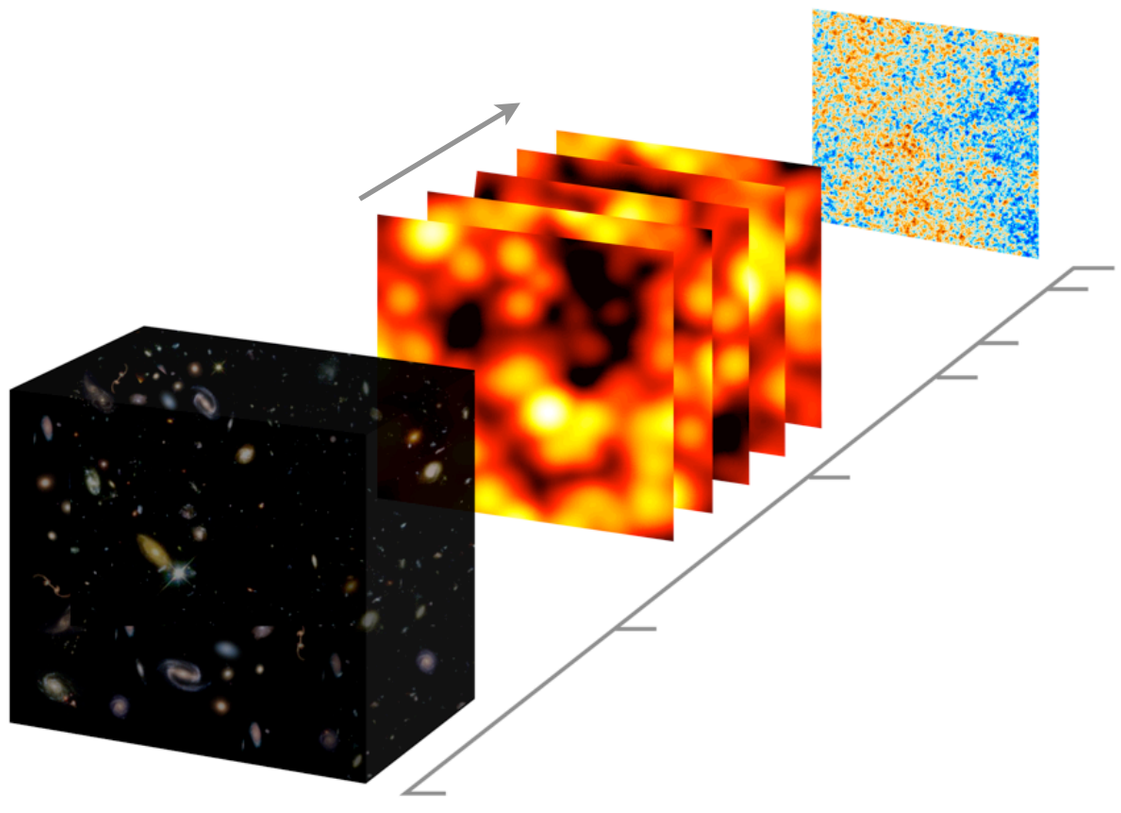
For references and more details:

see LIM: 2017 Status Report!



Science Goals of Line-Intensity Mapping

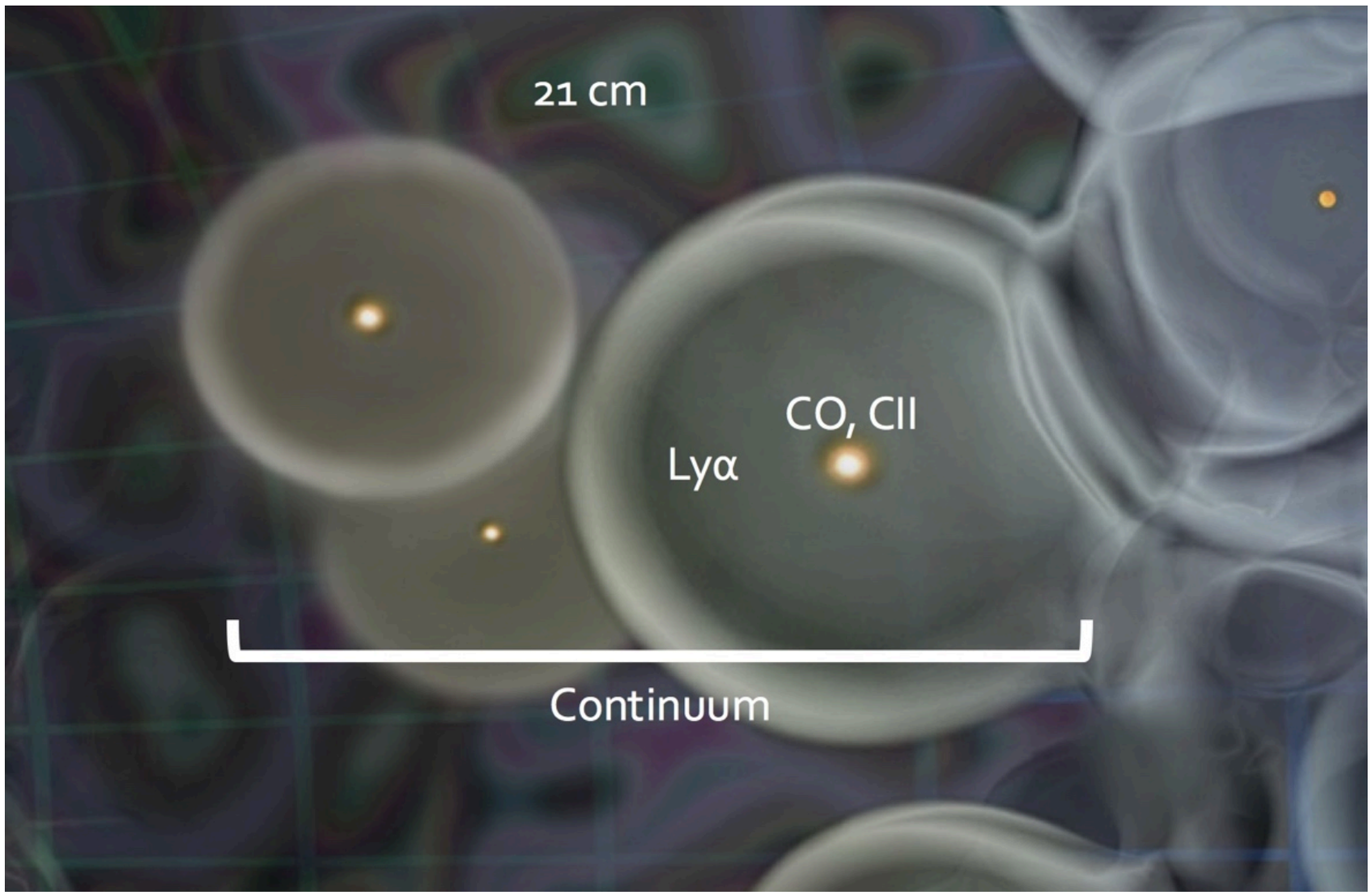
Physics of reionization:

Science Goals of Line-Intensity Mapping

Physics of reionization: synergy of lines will give the complete picture

Science Goals of Line-Intensity Mapping

Physics of reionization: synergy of lines will give the complete picture



(Courtesy of P. Breysse, Background: Sci. Am.,)

- HI (21cm): maps the neutral IGM, outside of the ionized bubbles.
- CO/[CII]: trace the star-forming galaxies that source the ionizing photons.
- Lyman-α: probes the galaxies along with the halos around them.

Science Goals of Line-Intensity Mapping

Physics of reionization: synergy of lines will give the complete picture

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Example: on large scales, the CO and 21-cm fields are anti-correlated:

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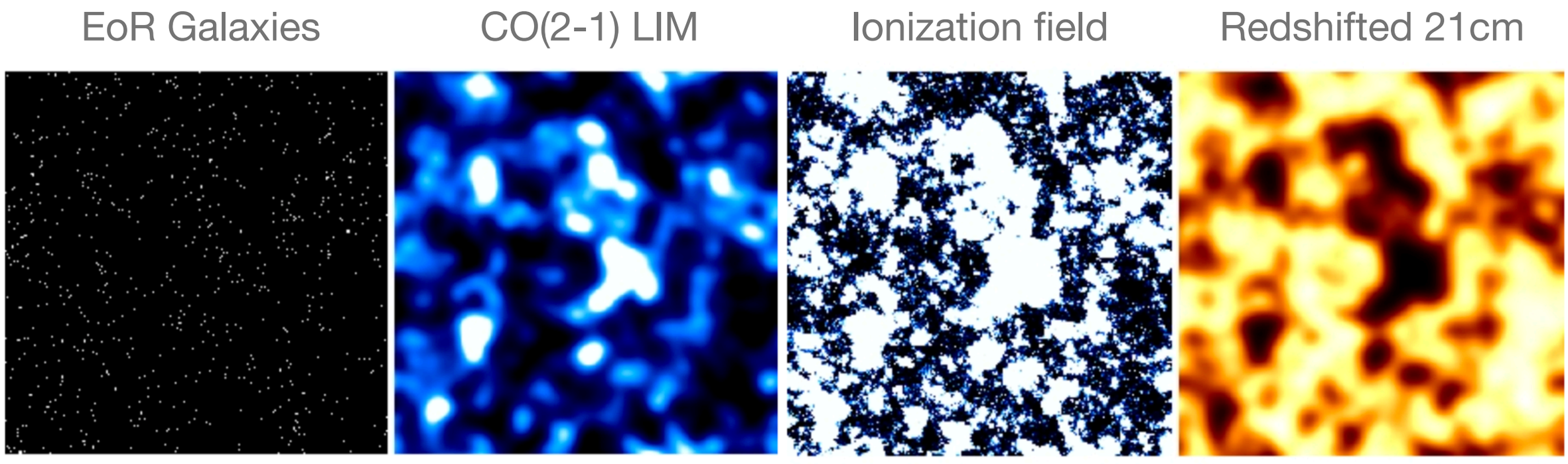


(Courtesy of A. Lidz)

- Each simulation slice is 130 co-moving Mpc/h on a side (roughly a sky degree), and 0.25 Mpc/h thick.
- CO(2-1) and 21-cm maps smoothed to 6’ spatial resolution and 0.035 GHz spectral resolution.

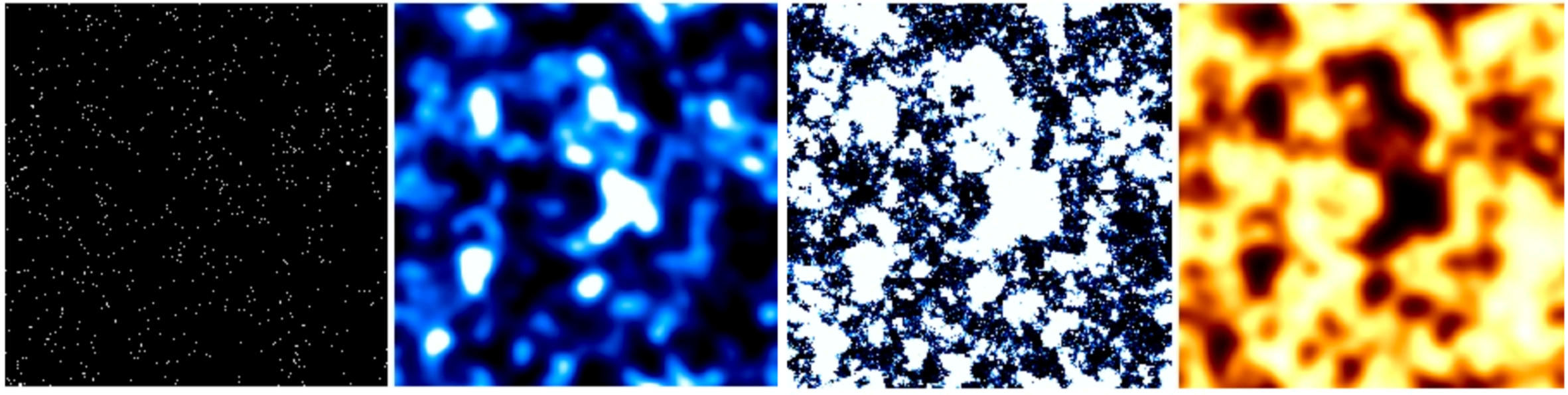
Science Goals of Line-Intensity Mapping

Physics of reionization: synergy of lines will give the complete picture

Example: on large scales, the CO and 21-cm fields are anti-correlated:

- Can be used to confirm a possible 21-cm detection.

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



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Physics of reionization: synergy of lines will give the complete picture

Example: on large scales, the CO and 21-cm fields are anti-correlated:

- Can be used to confirm a possible 21-cm detection.
- Can improve our understanding of cosmic reionization.

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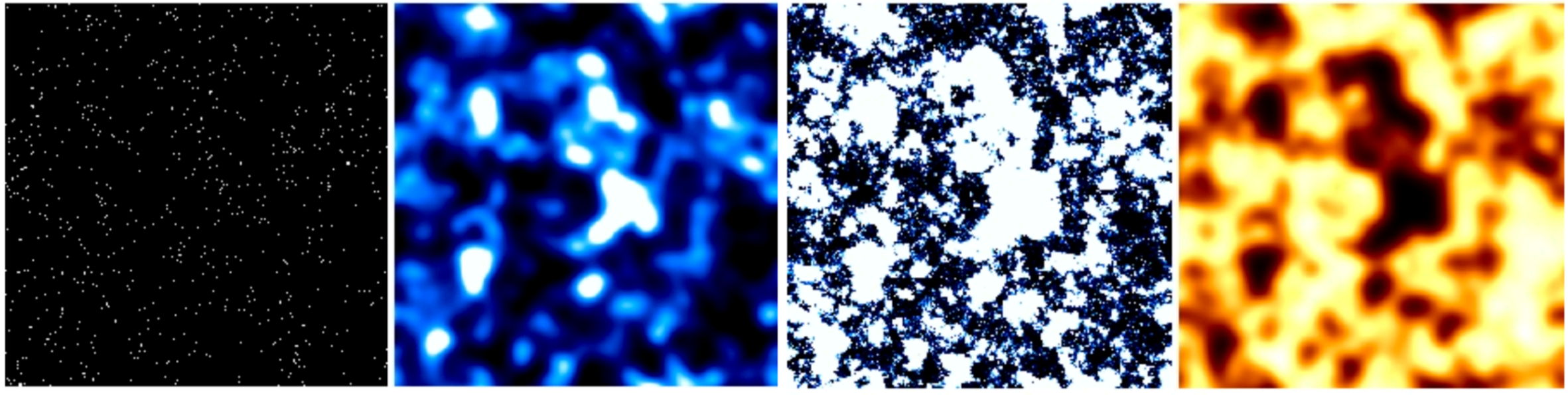

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Cosmology vs. Astrophysics:

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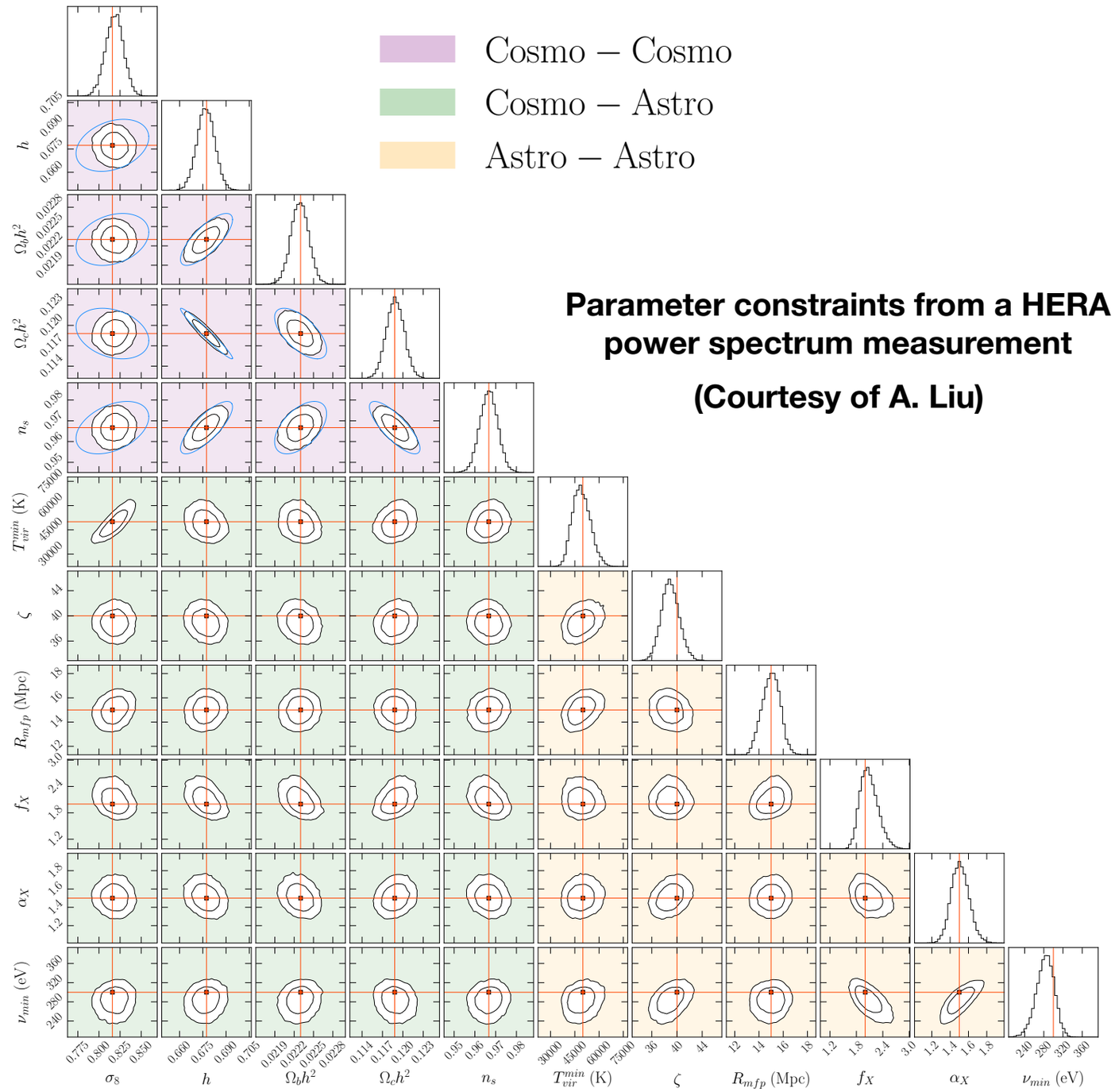

Parameter constraints from a HERA power spectrum measurement

(Courtesy of A. Liu)

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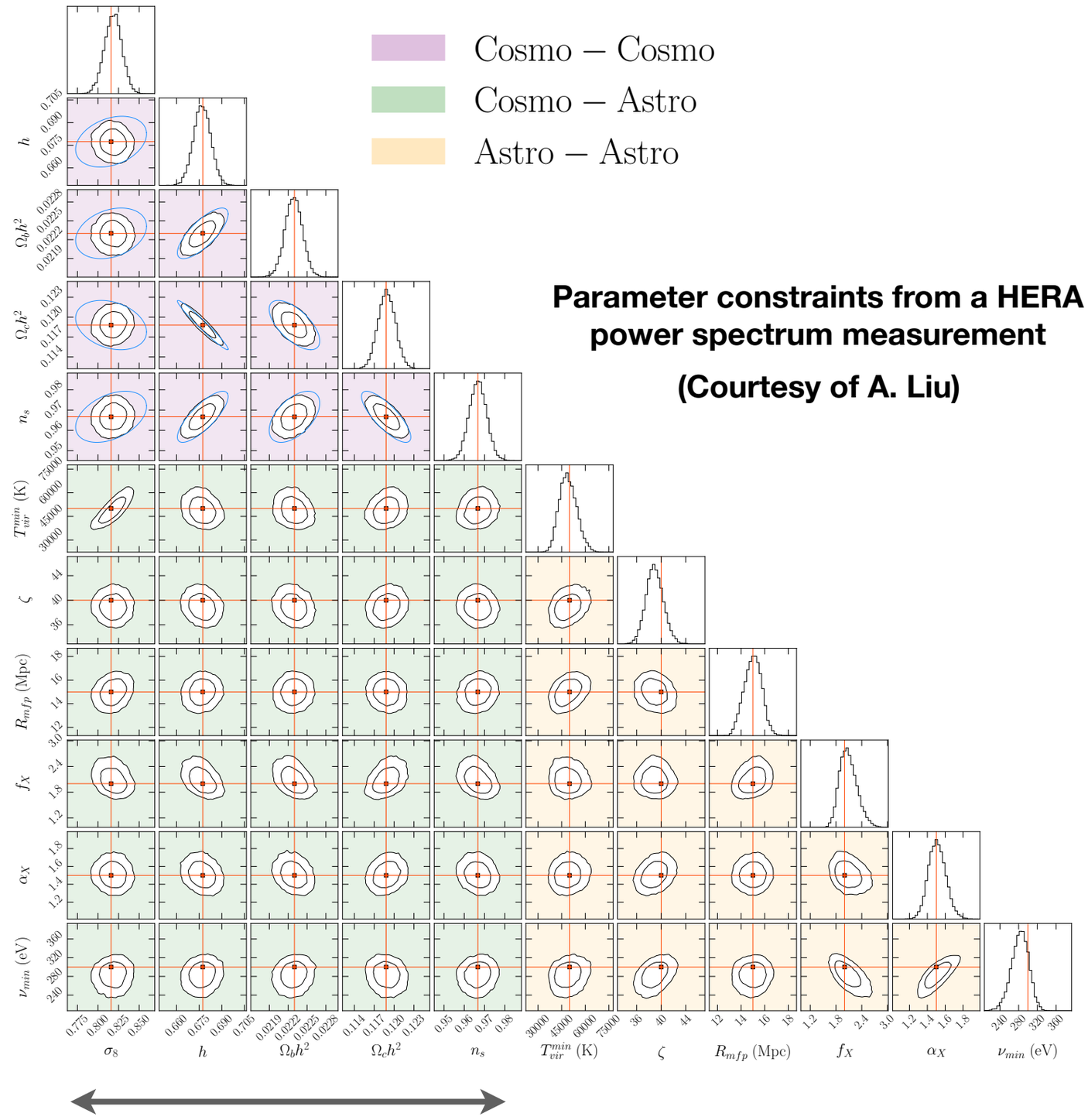

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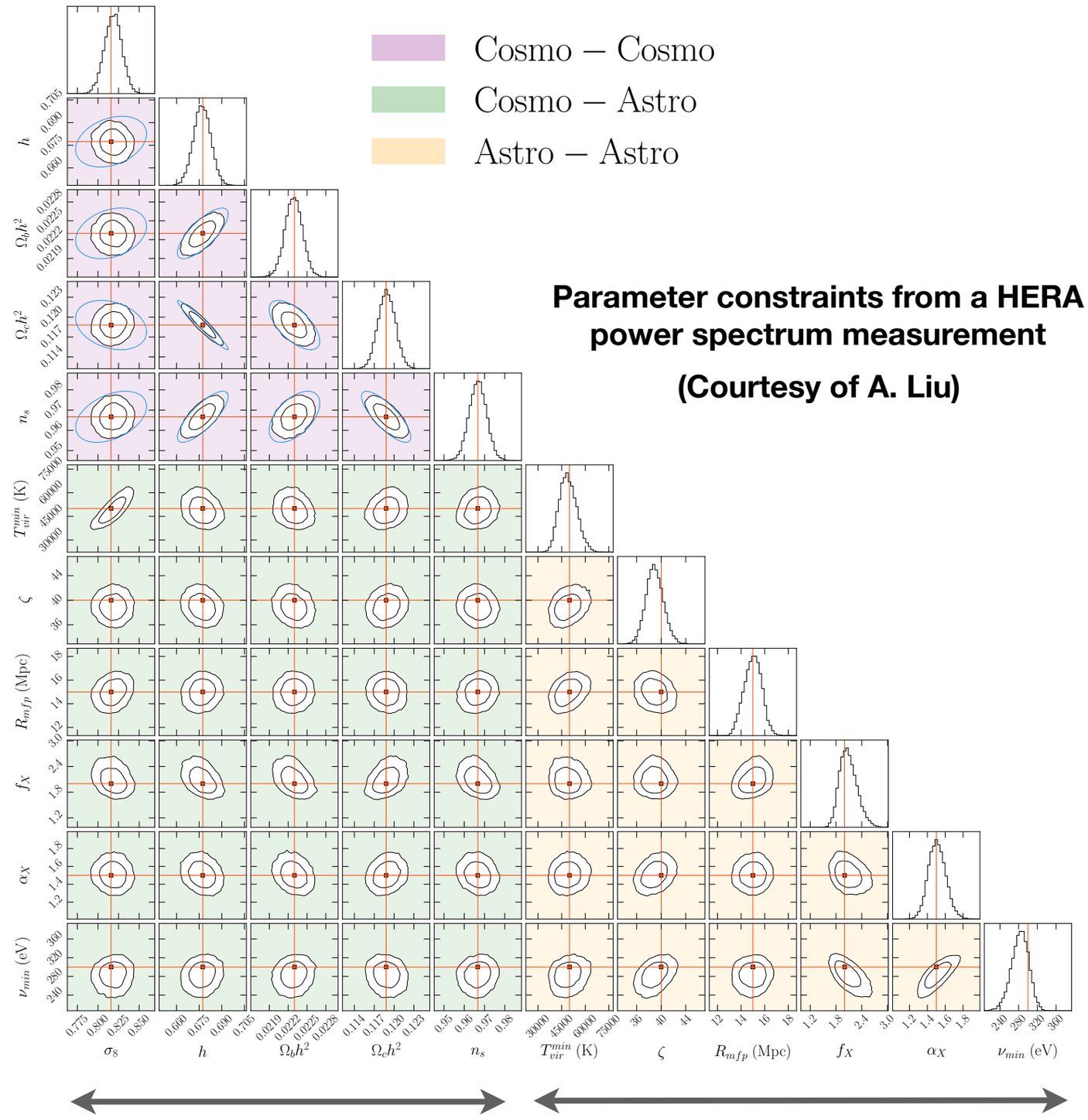

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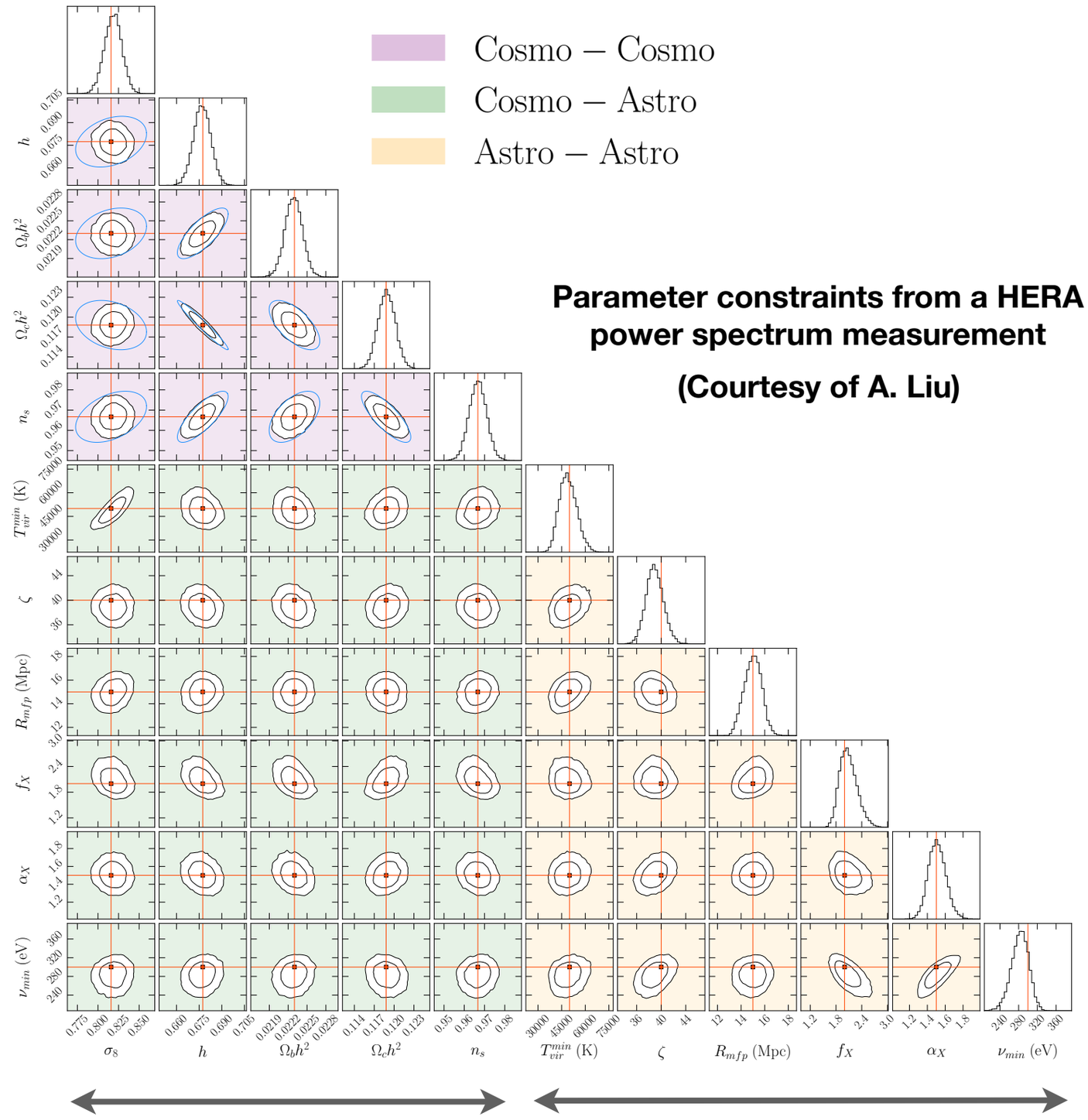
Cosmology vs. Astrophysics:

One’s *nuisance* is another’s *signal*



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Astrophysics? Example: SFR history at high-redshift

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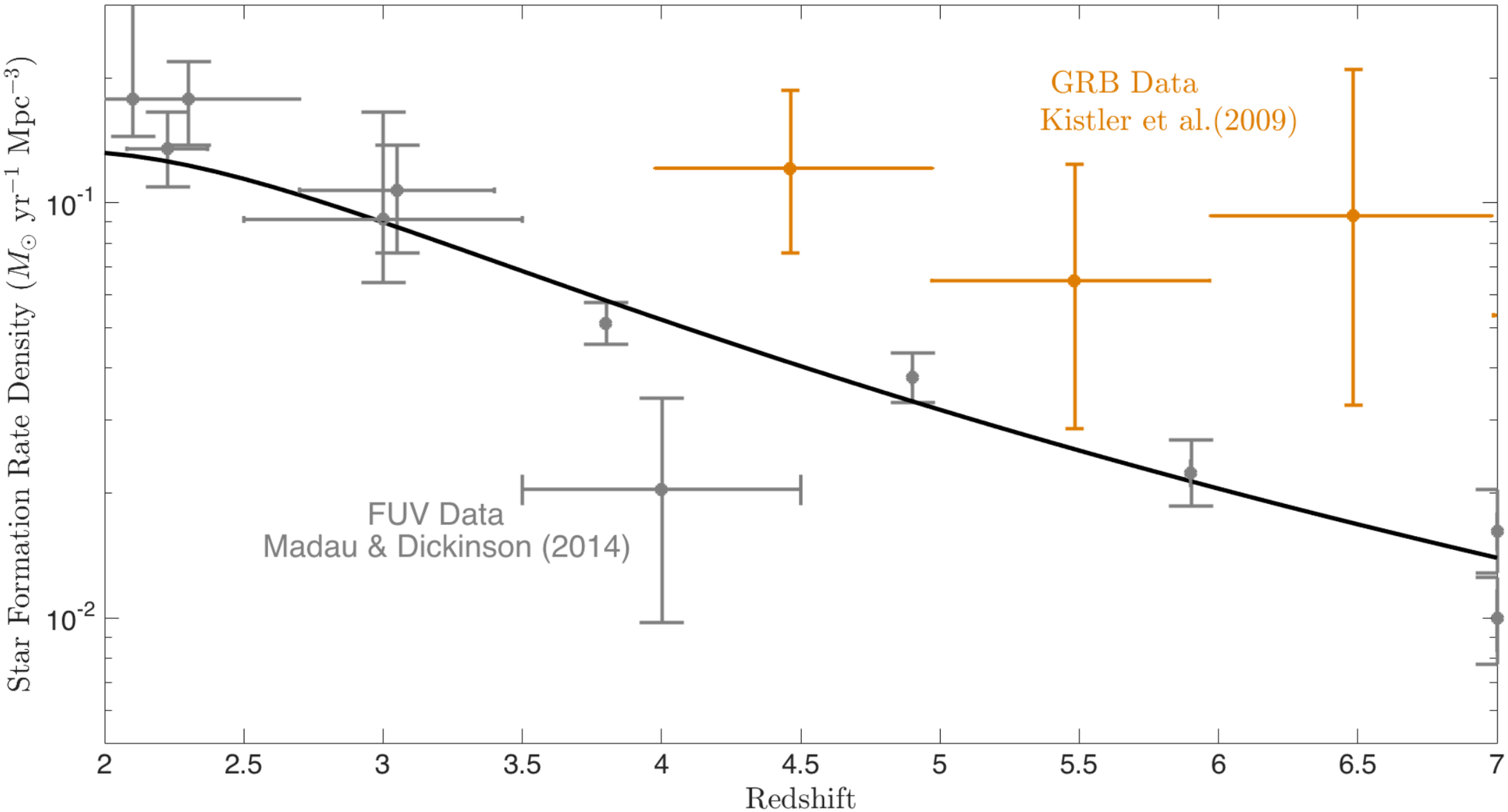

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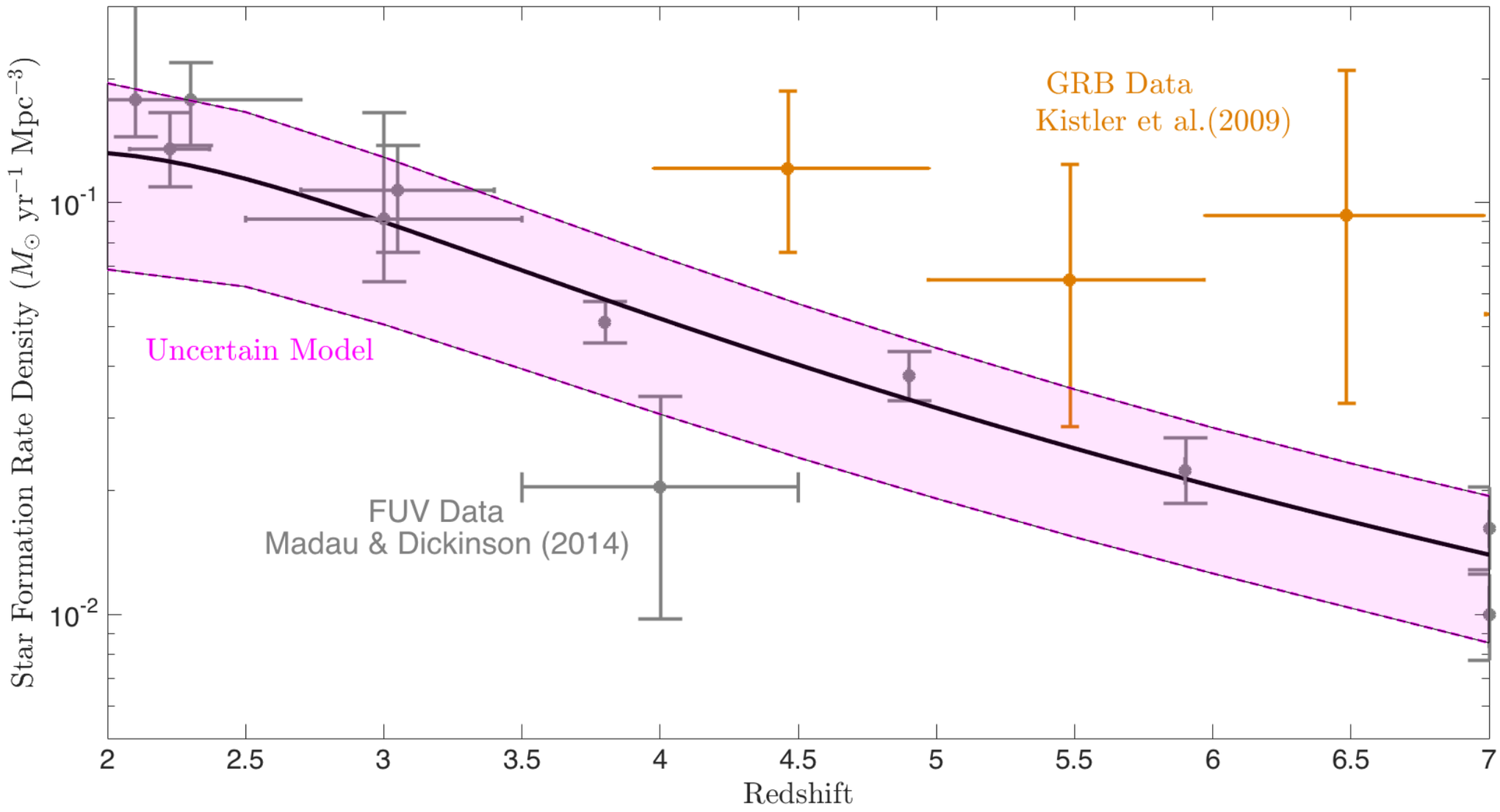

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Science Goals of Line-Intensity Mapping

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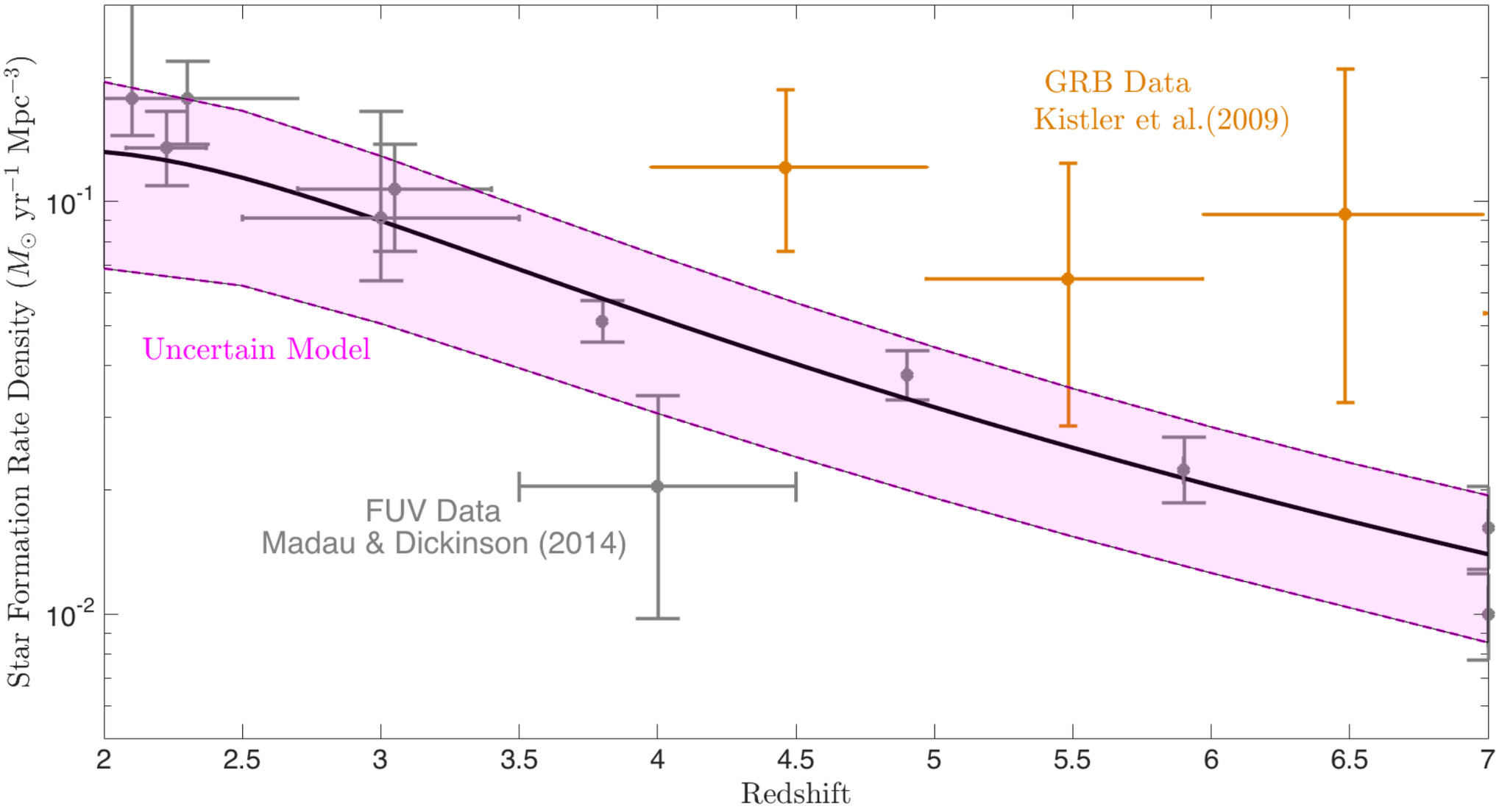

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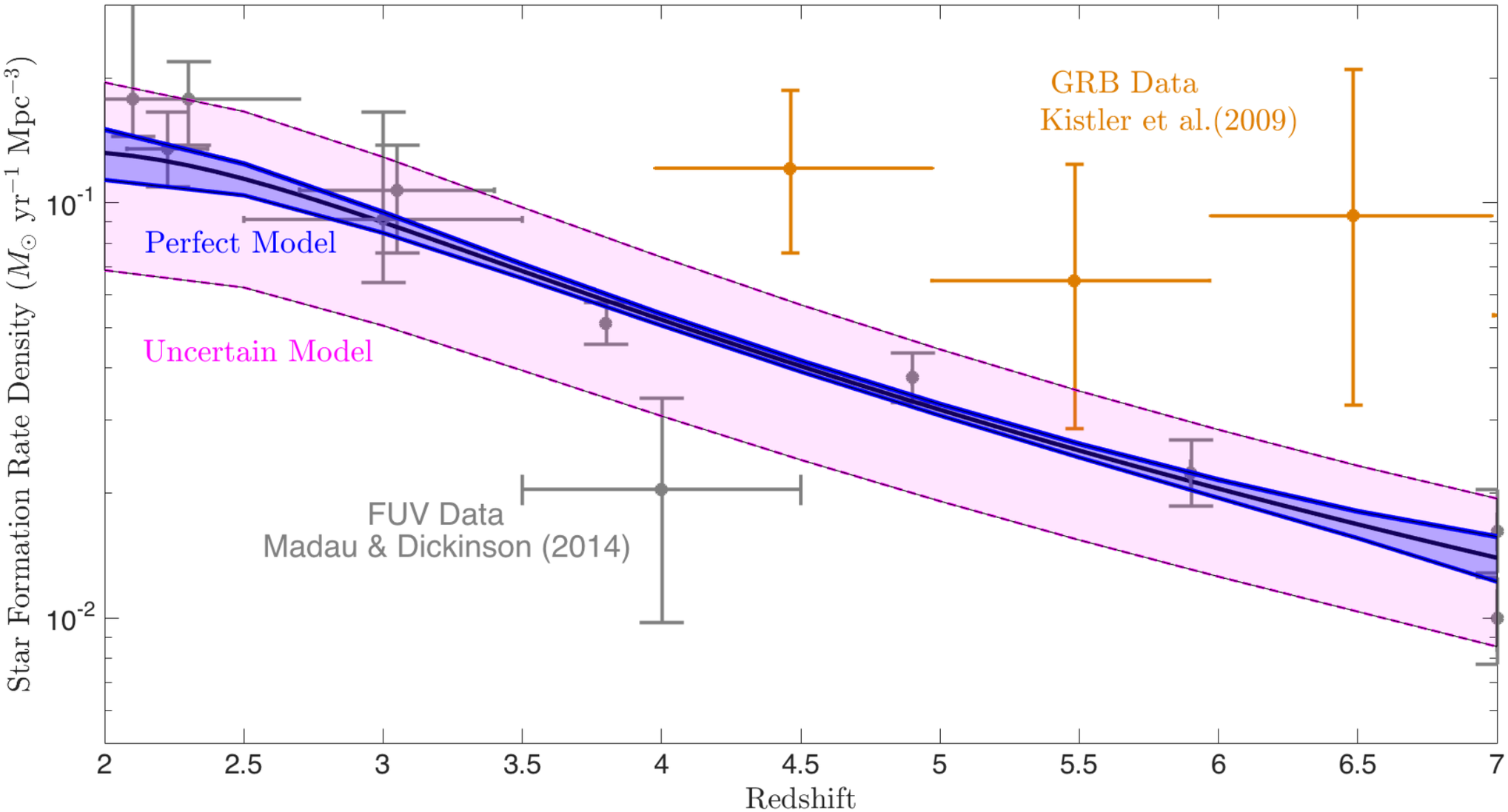

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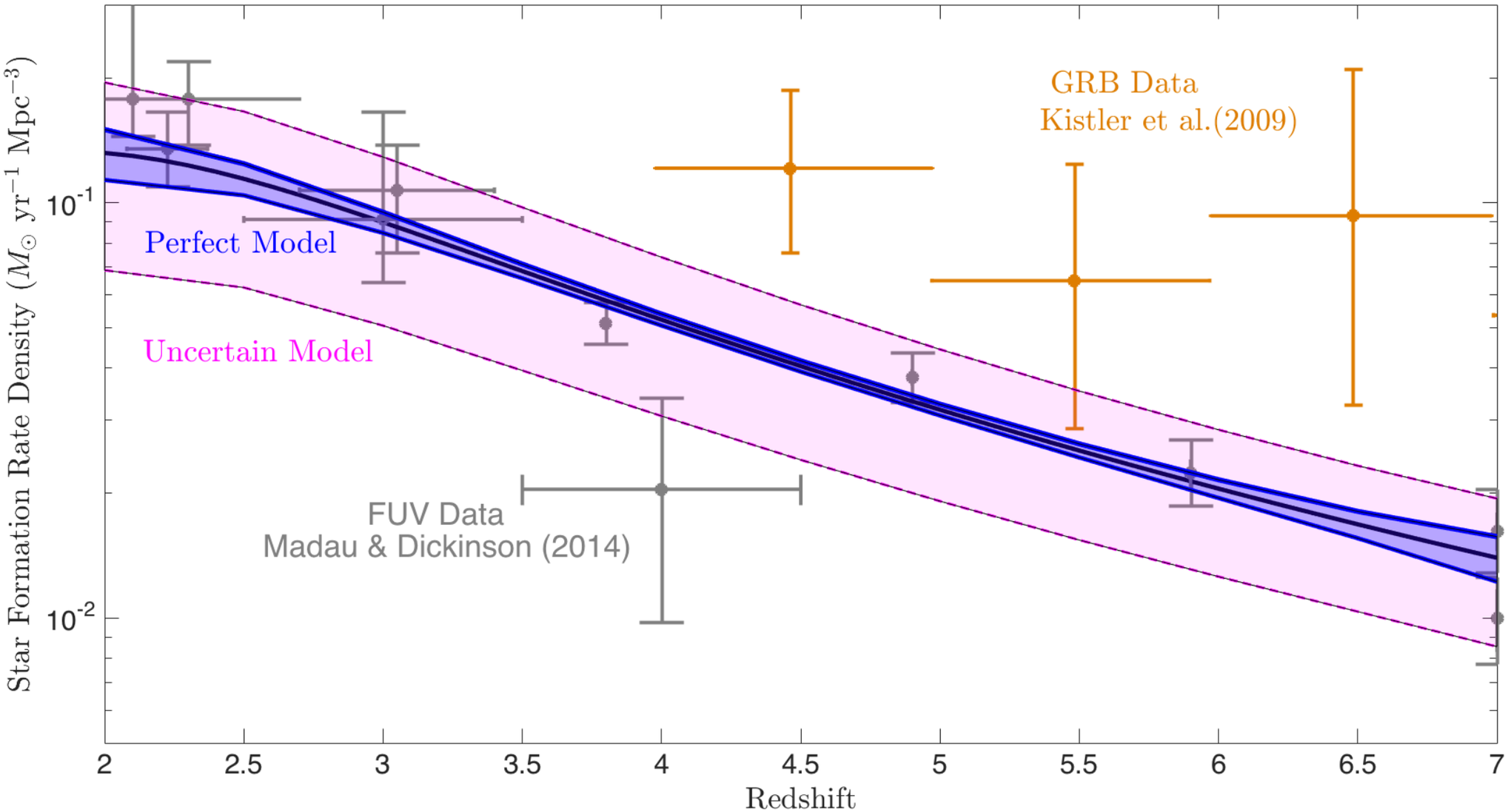

(Courtesy of P. Breysse & E. Kovetz)

- <u>Lots of other astrophysics:</u> Pop III stars with He II; Molecular gas density with CO isotopologues; IGM density, evolution and clustering with Lyα, etc., etc.

Science Goals of Line-Intensity Mapping

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Cross-correlations with non-LIM datasets:

Science Goals of Line-Intensity Mapping

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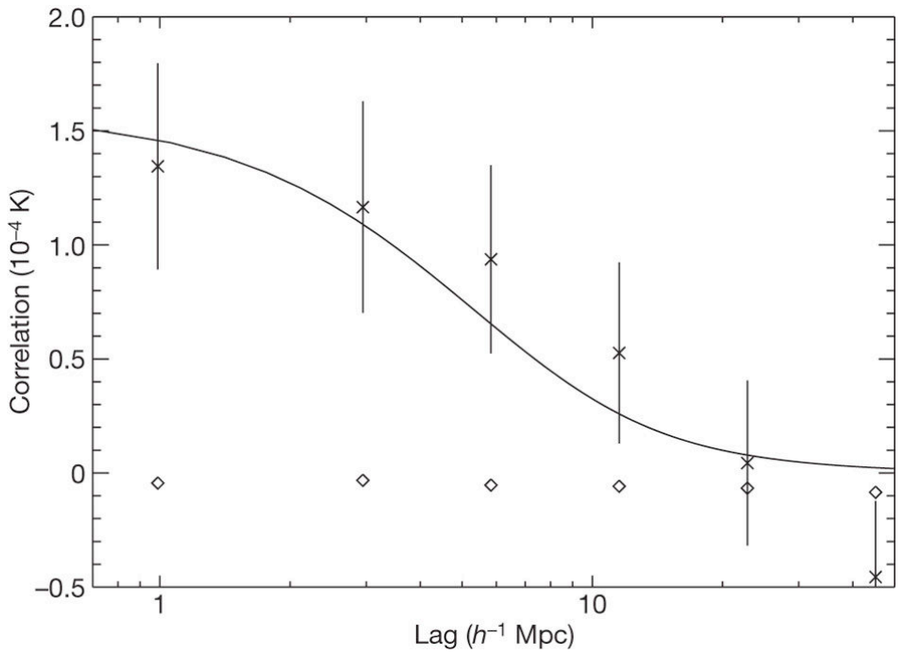

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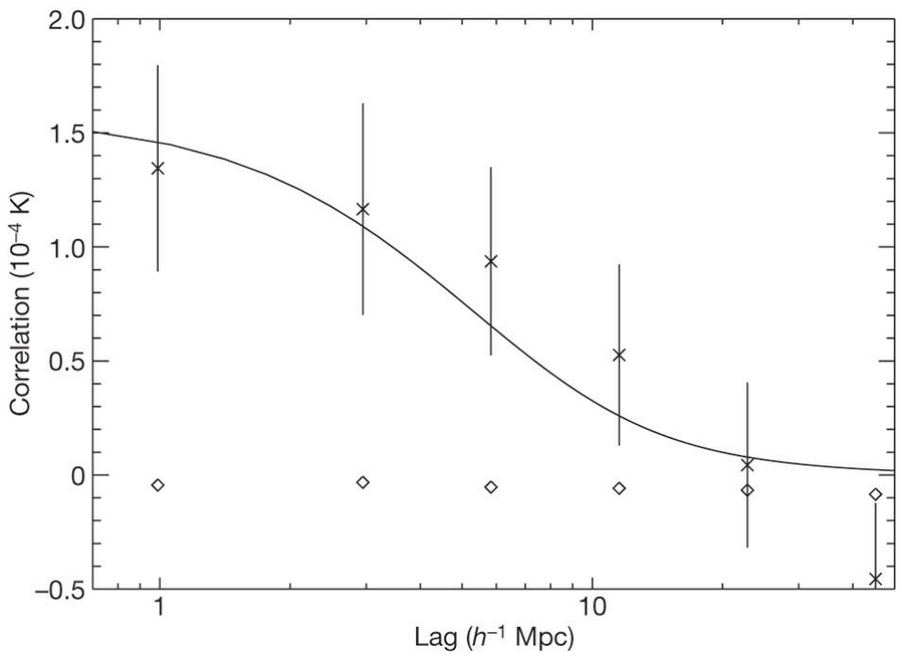
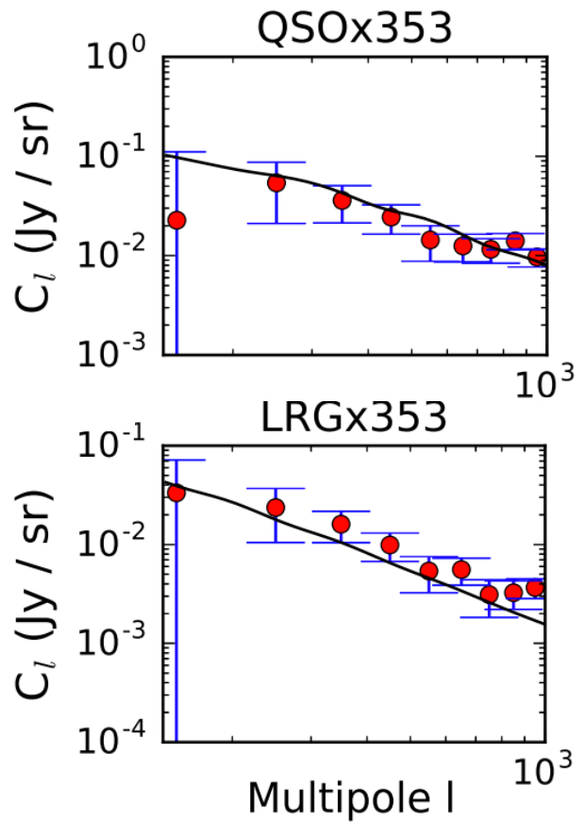


(Courtesy of T.-C. Chang)

CII: QSOs/LRGs x Planck CMB



(from Pullen et. al, 2017)

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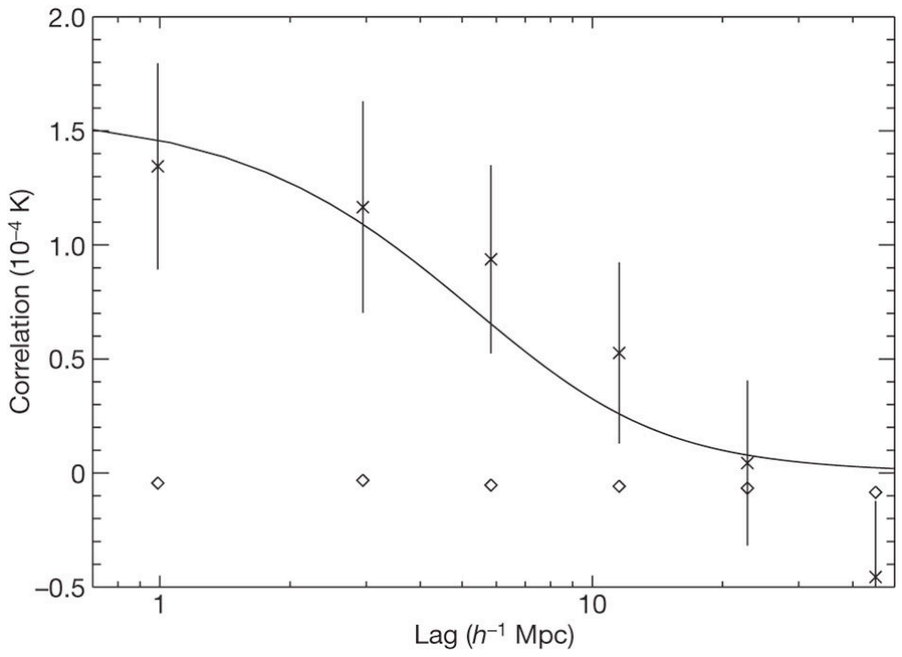

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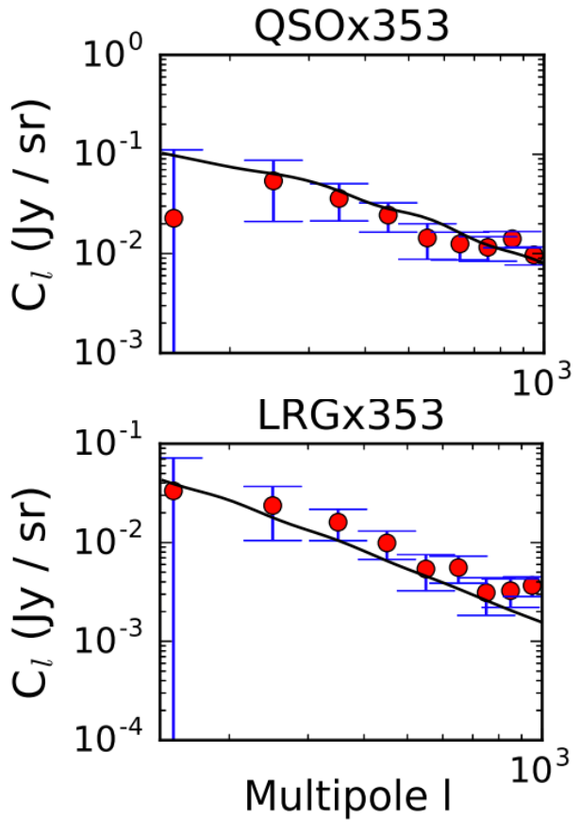
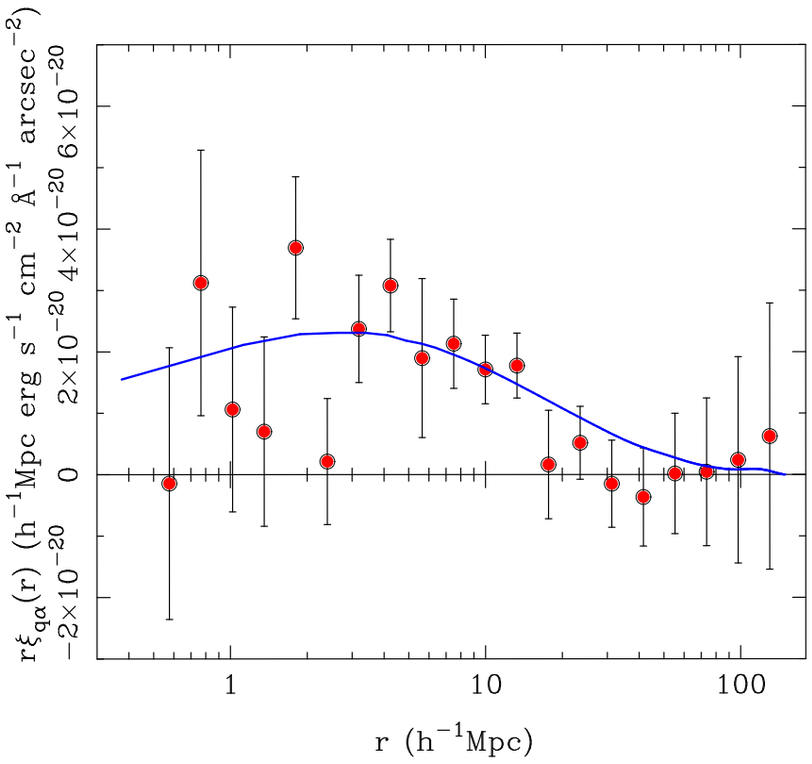


(from Pullen et. al, 2017)

Lyα: BOSS spectra - LRGs x SDSS Quasars



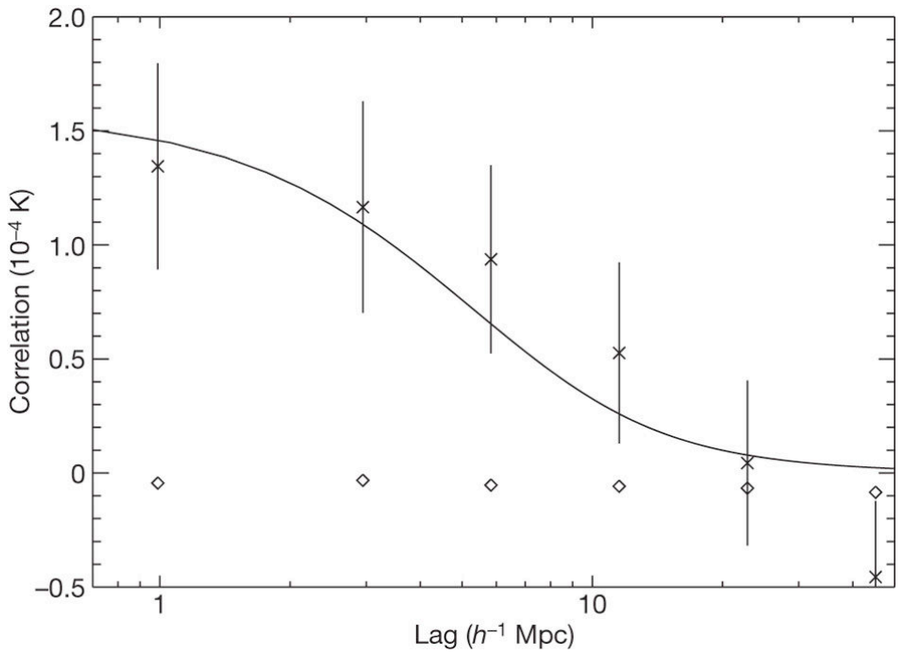
(Courtesy of R. Croft)

Science Goals of Line-Intensity Mapping

Cross-correlations with non-LIM datasets:

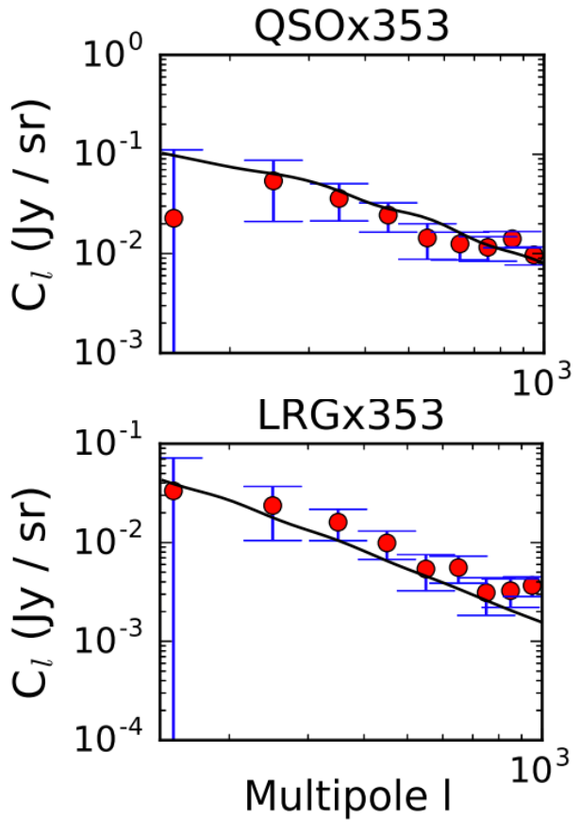
- Enabled some of the current detections:

HI: GBT x DEEP2 galaxies



(Courtesy of T.-C. Chang)

CII: QSOs/LRGs x Planck CMB



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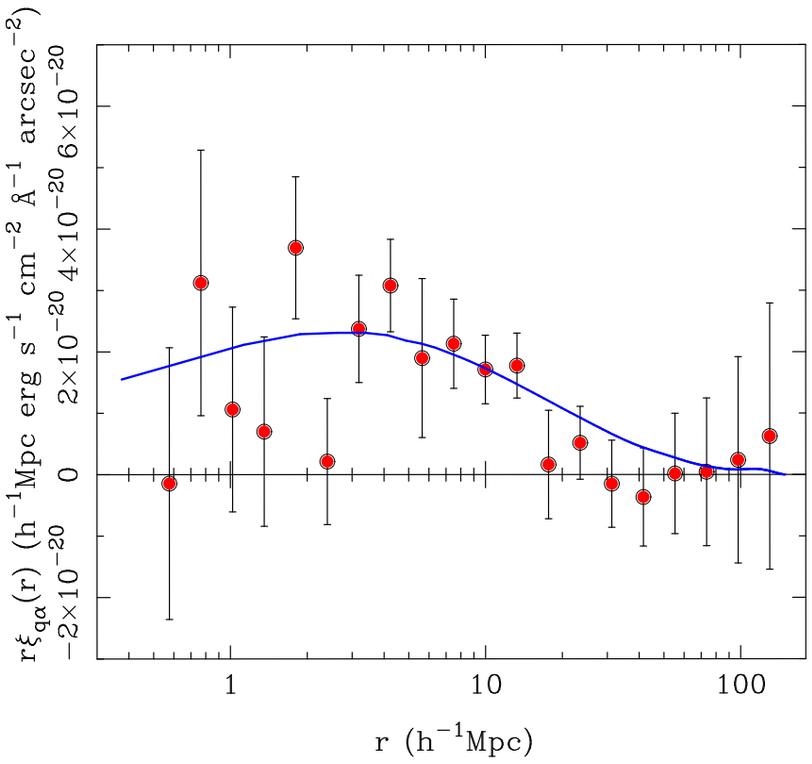

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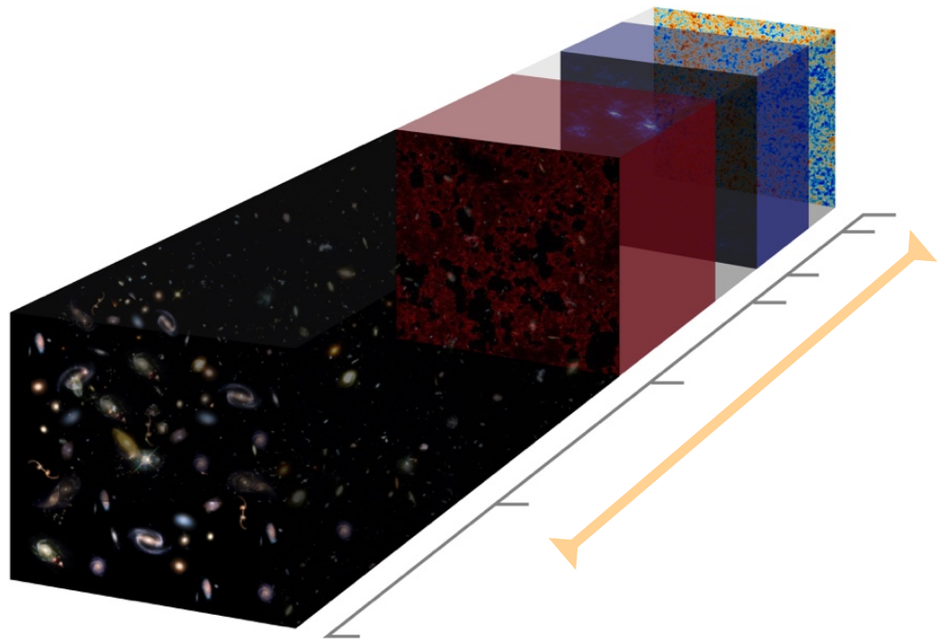
- Lots of additional opportunities:

  CMB Lensing x HI (@ higher order): measure biases; IM x Galaxies: improve BAO, photometry...

Outline

Ely D. Kovetz
Aspen, Feb. 2018

- Introduction to Line-Intensity Mapping
- Science Goals of Line-Intensity Mapping



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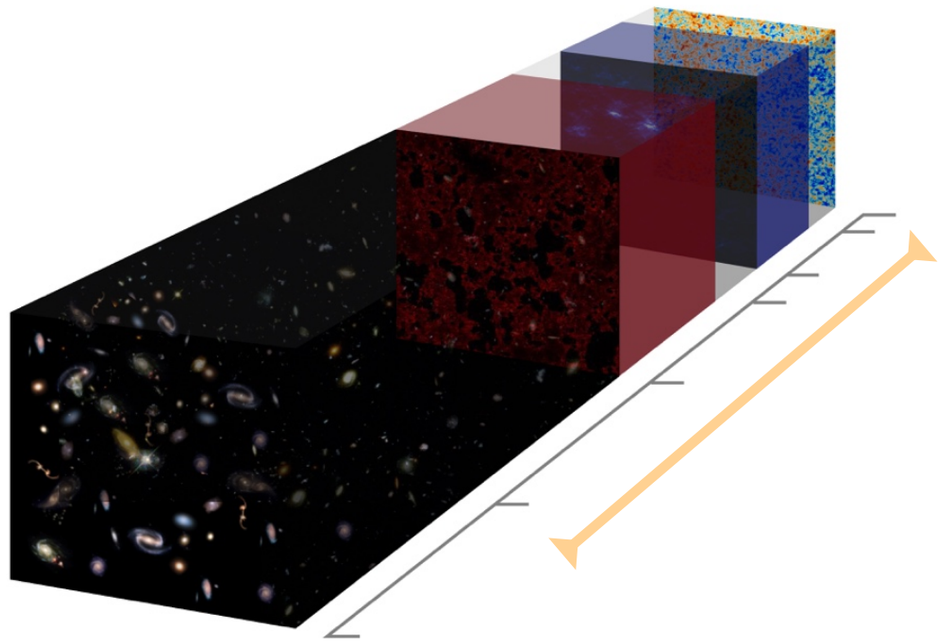
- Introduction to Line-Intensity Mapping

- Science Goals of Line-Intensity Mapping

- Theoretical Backbone (Modeling+Techniques)



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

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Main challenge: how to interpret a measurement?

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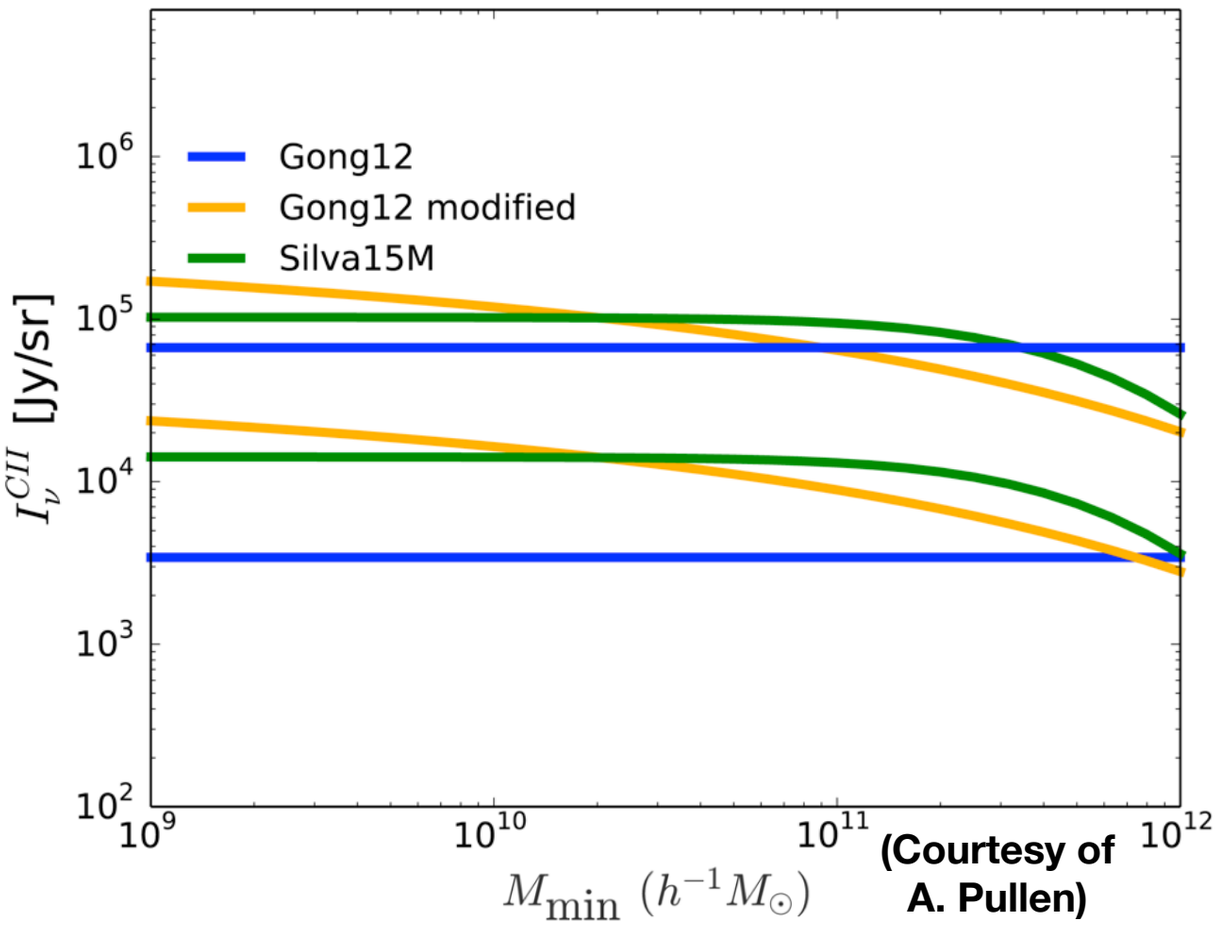

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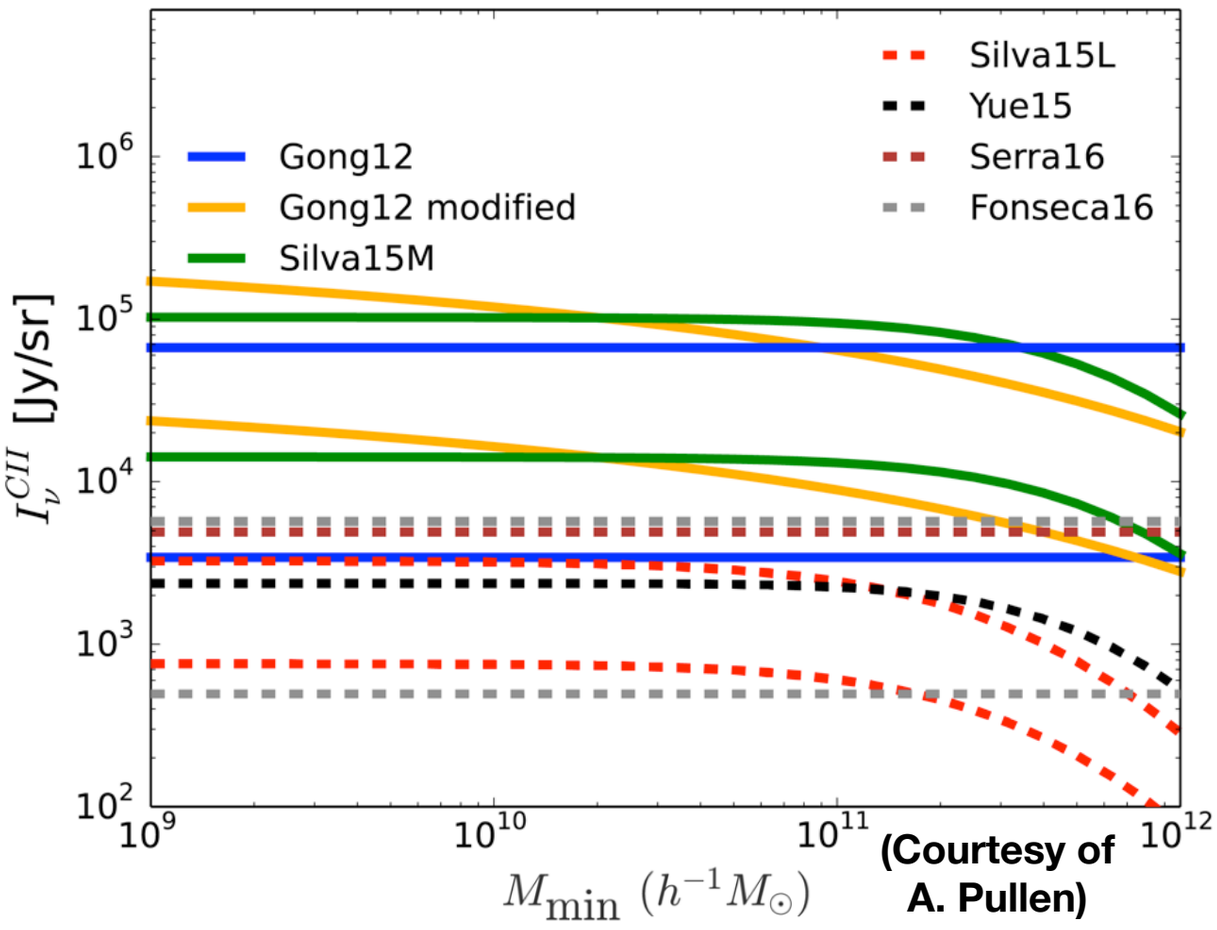

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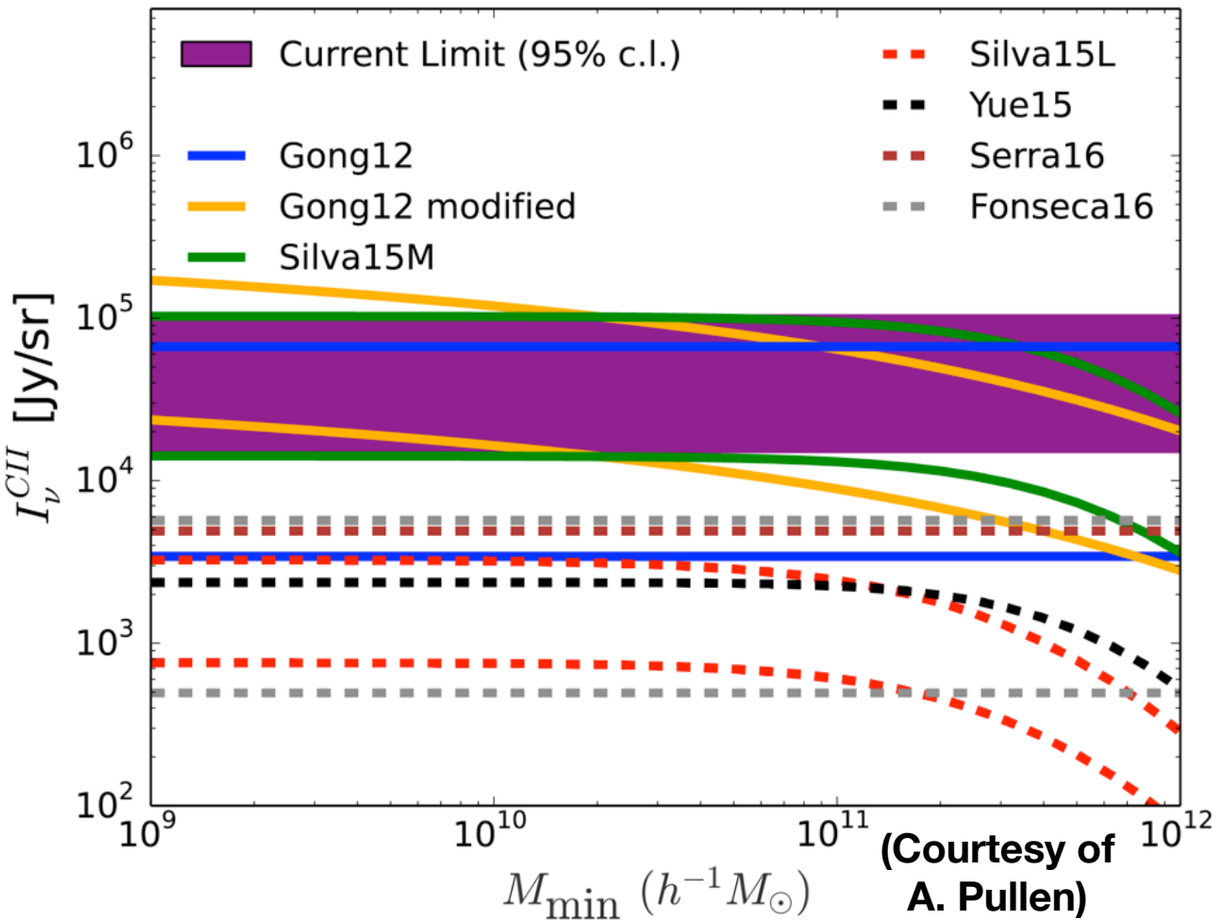

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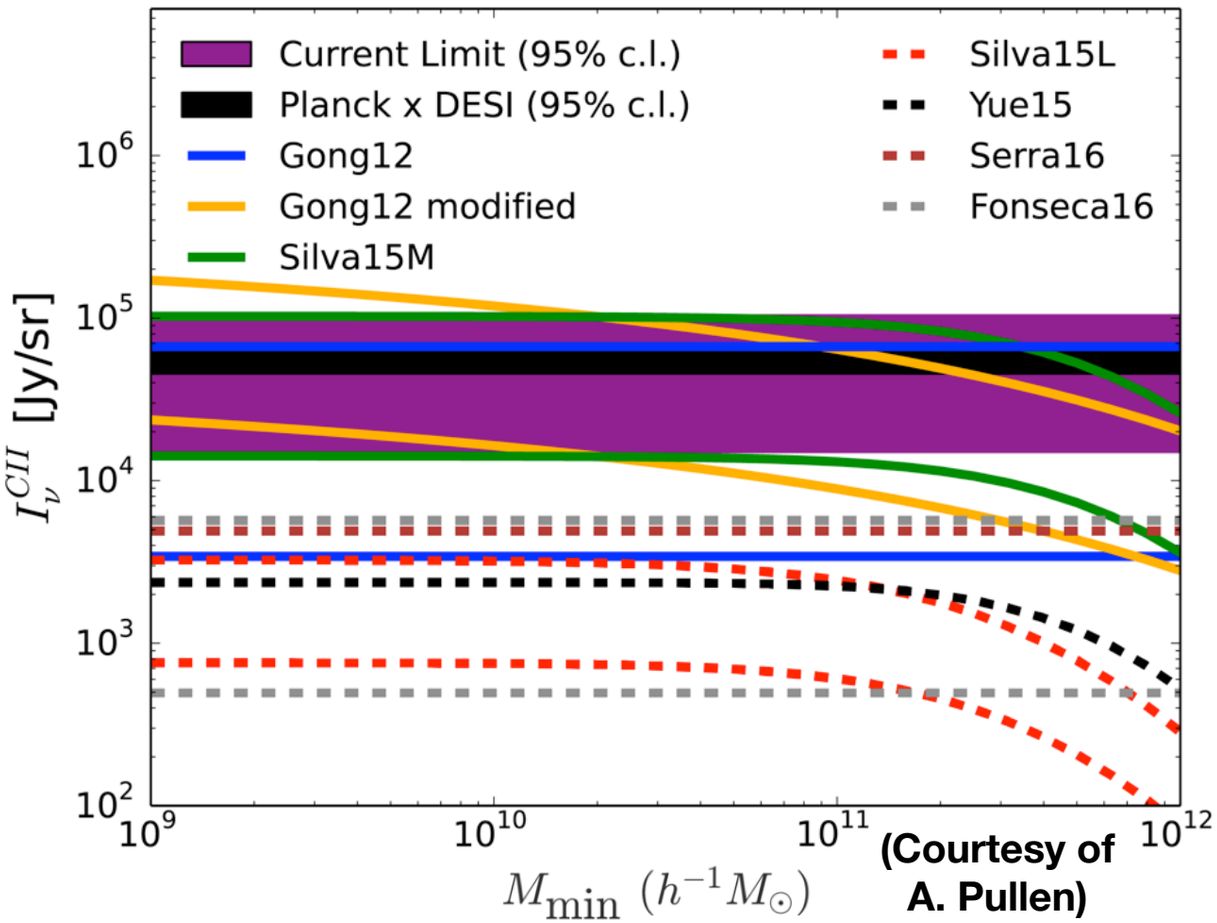

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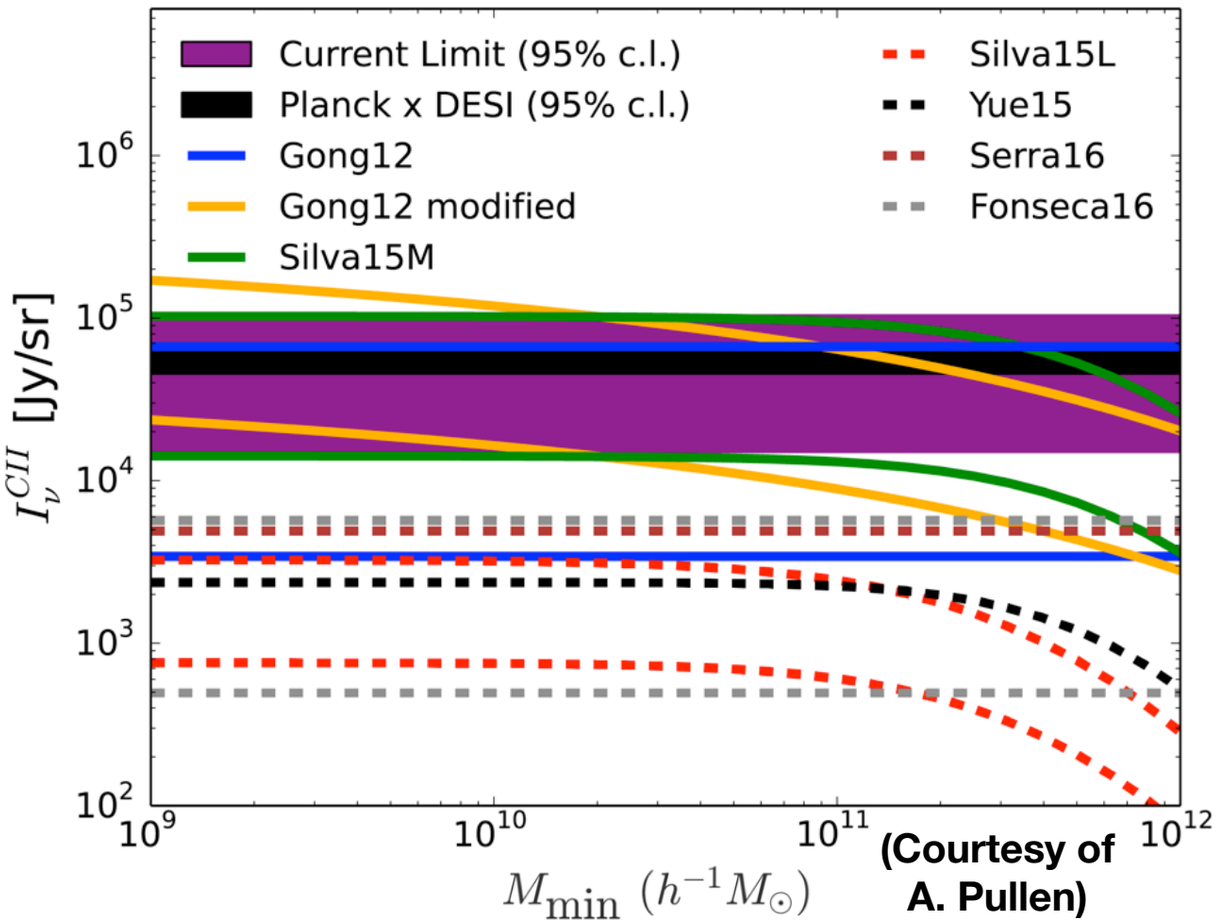

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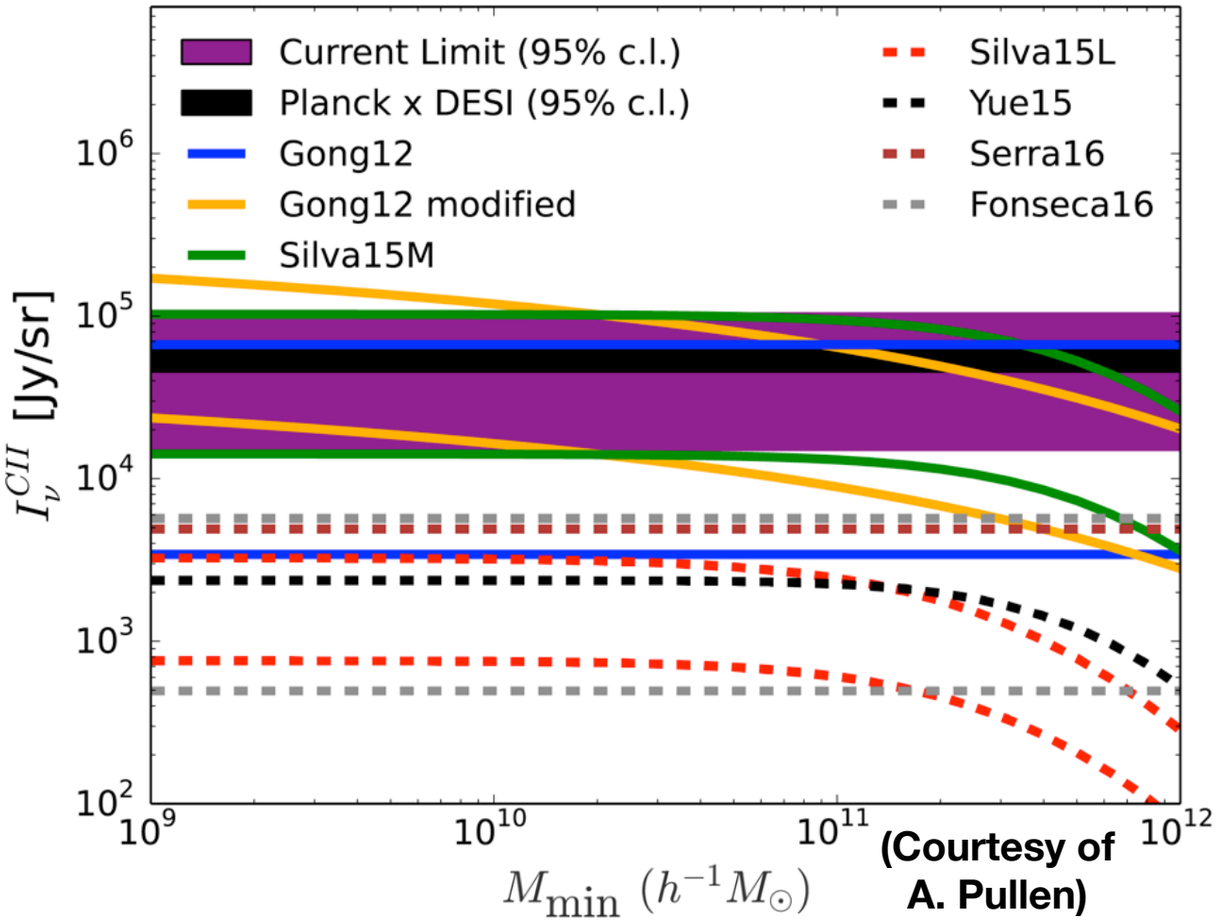

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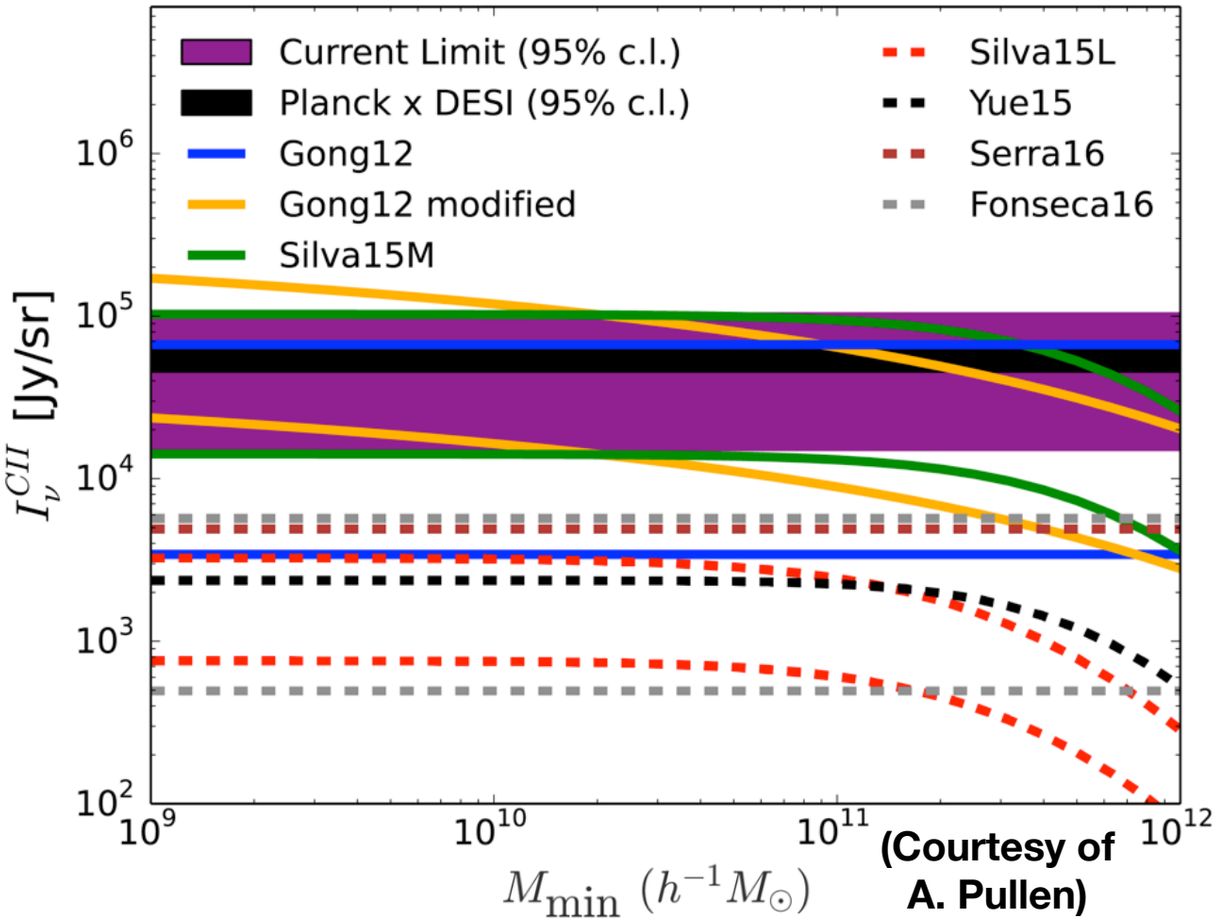

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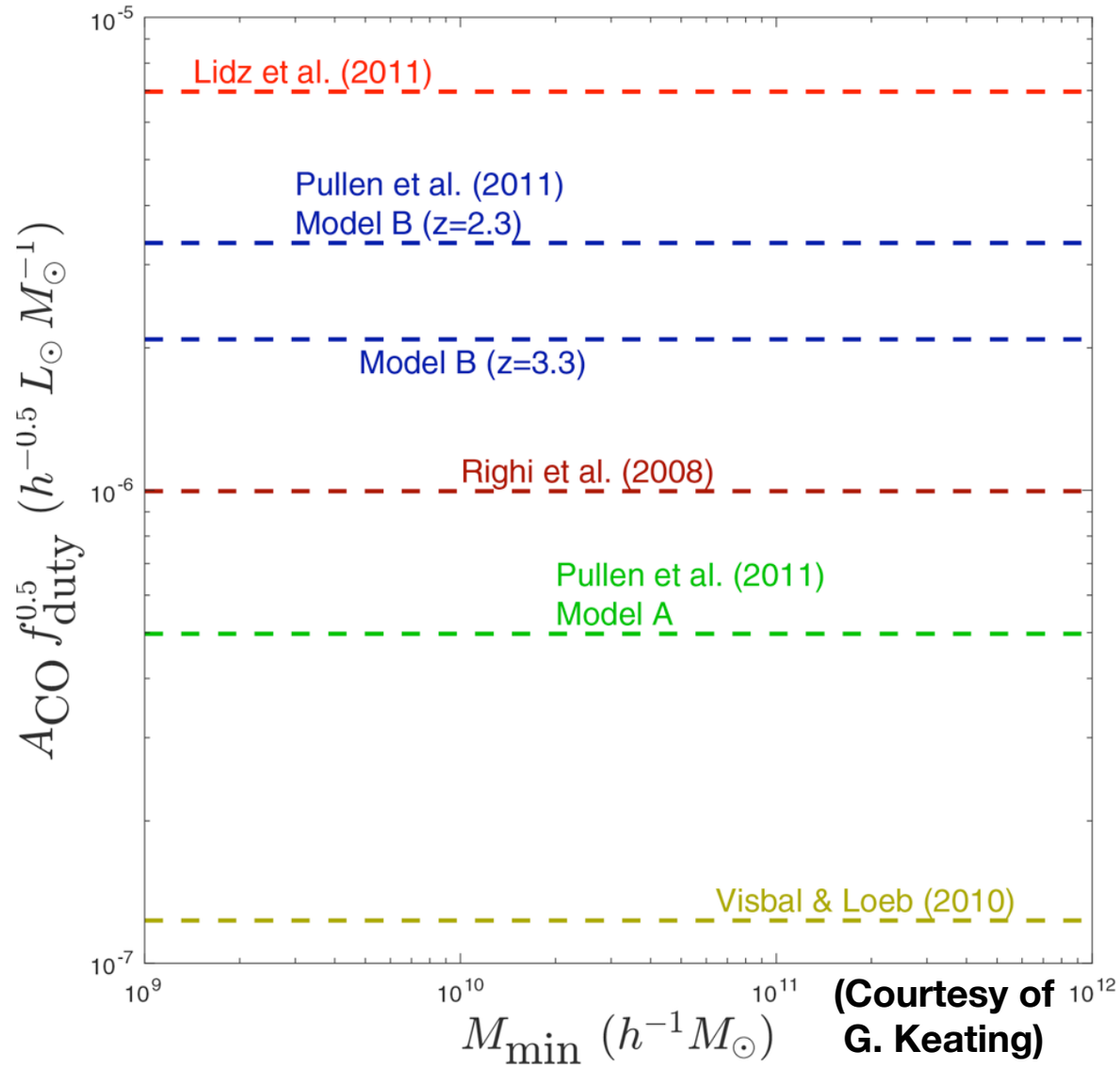

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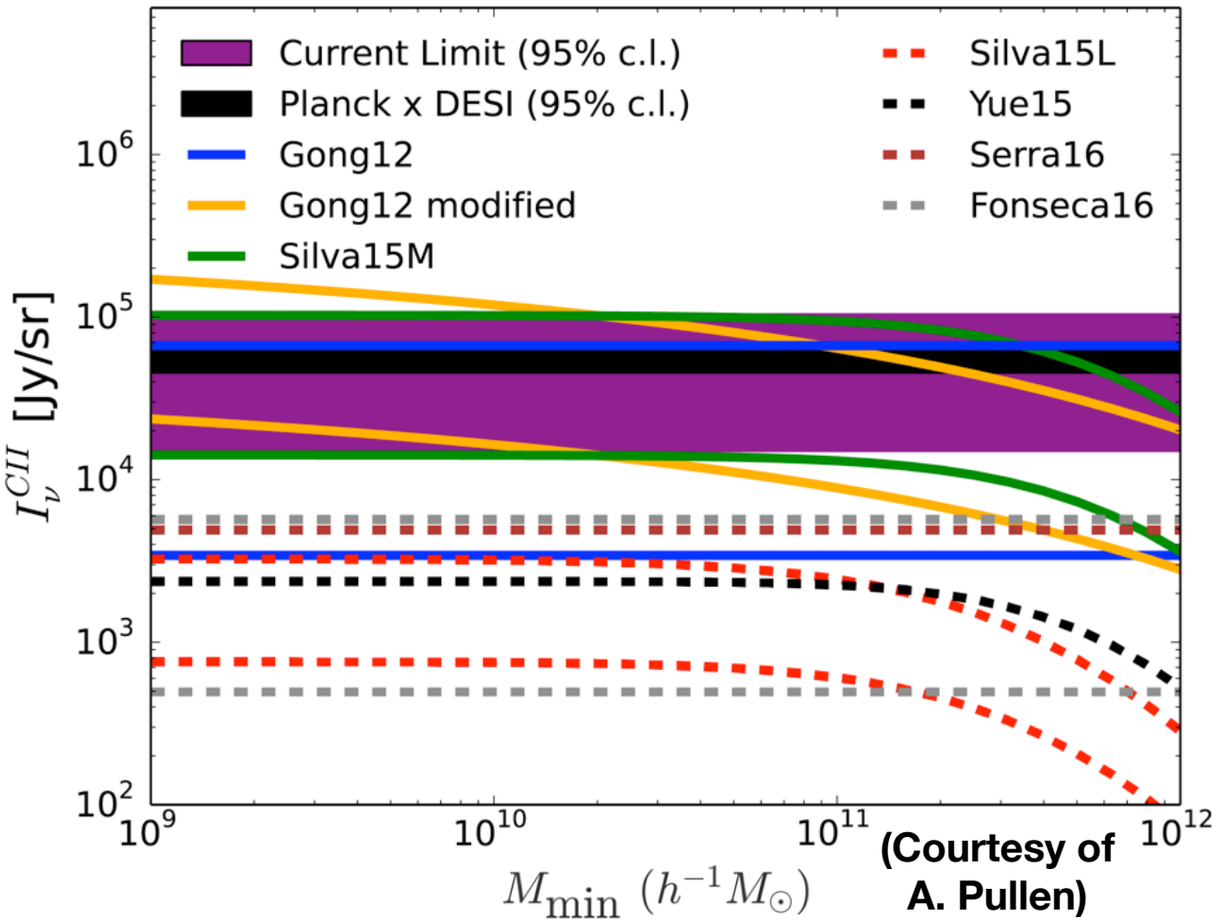

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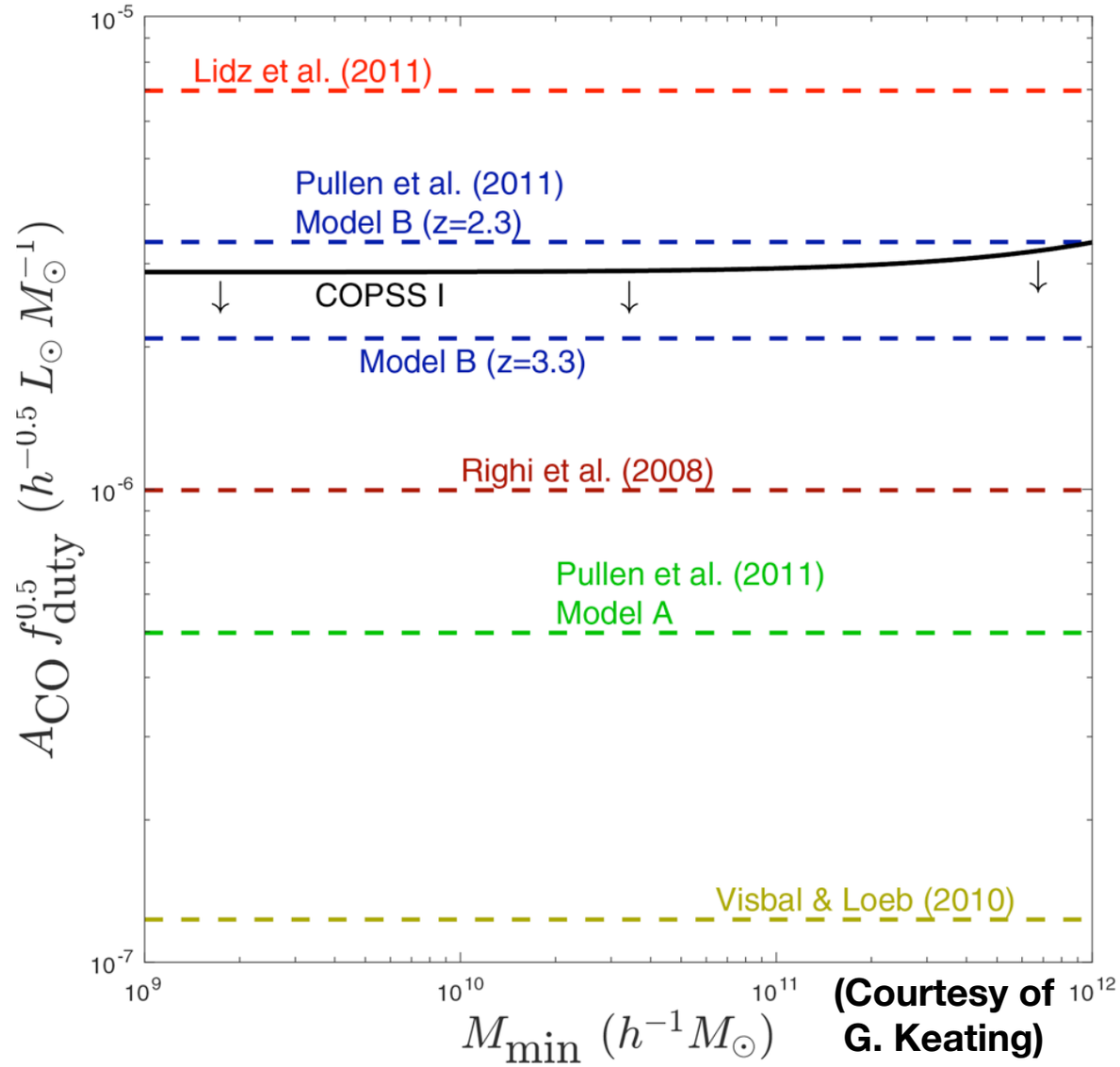

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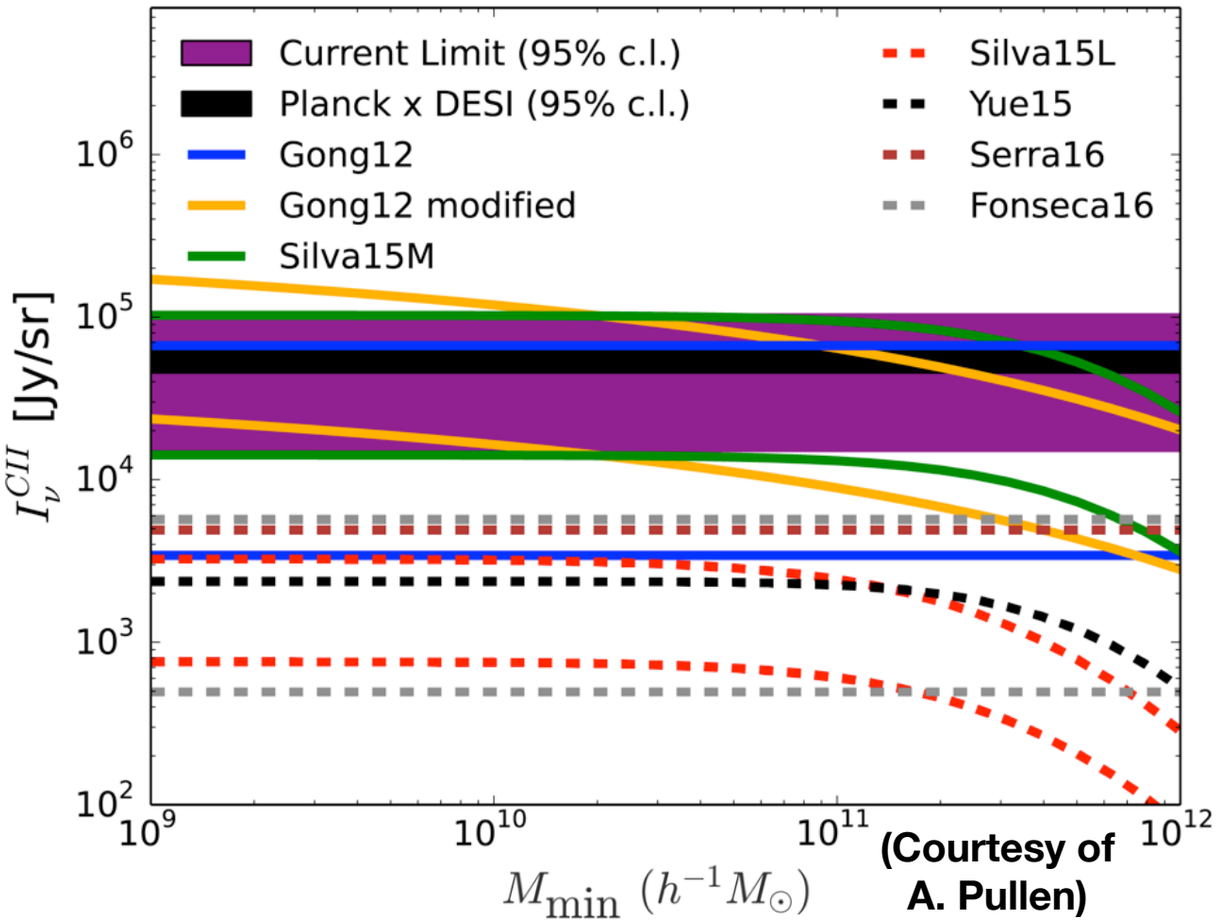

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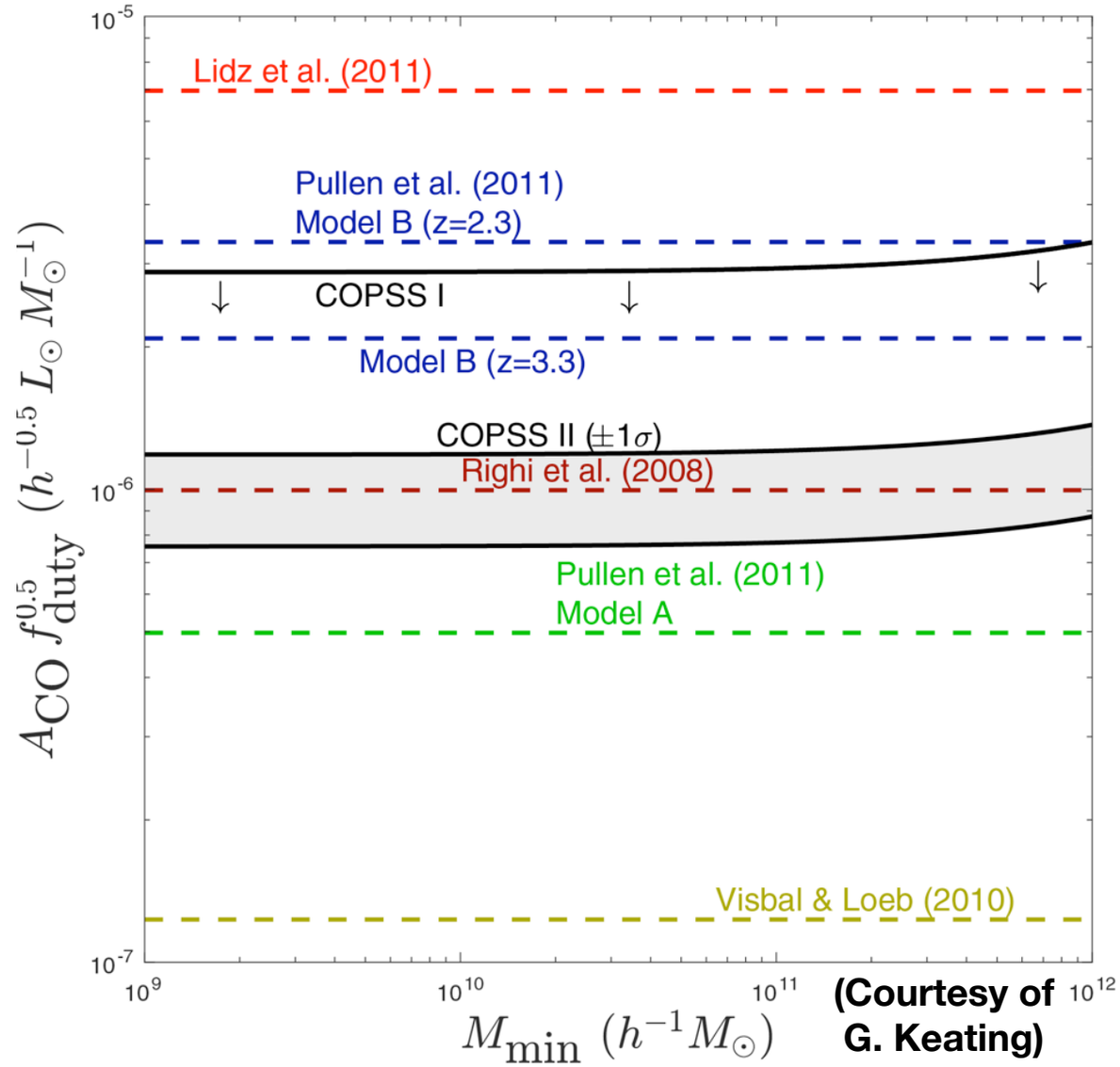

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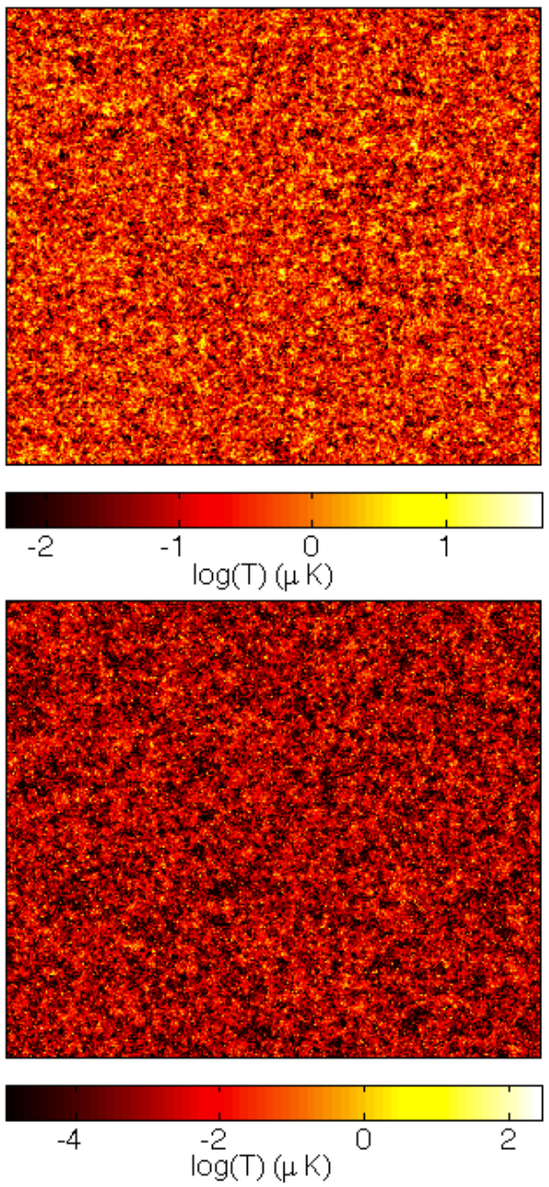

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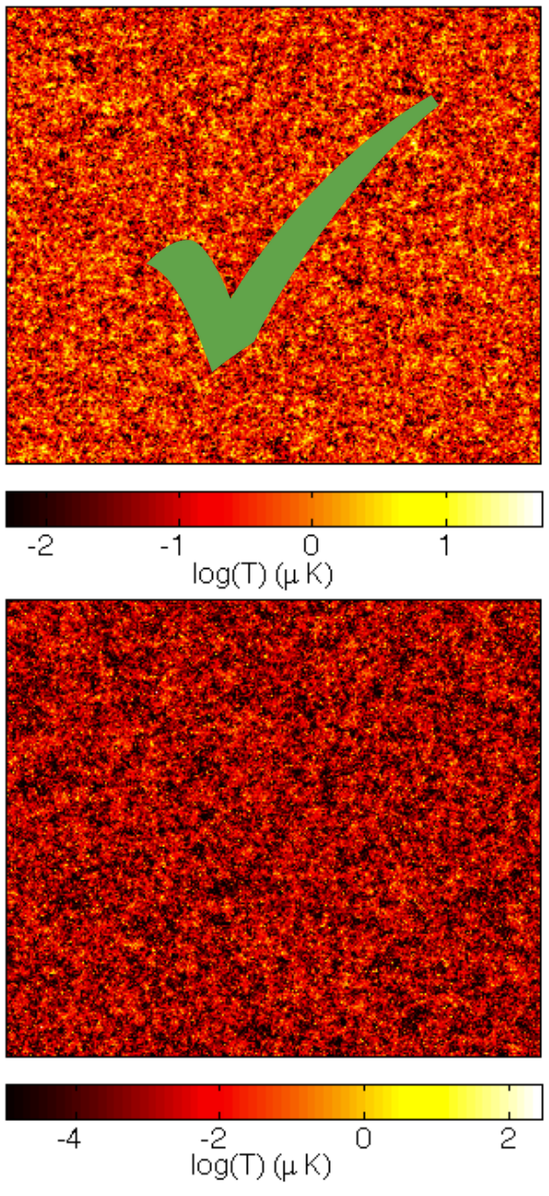

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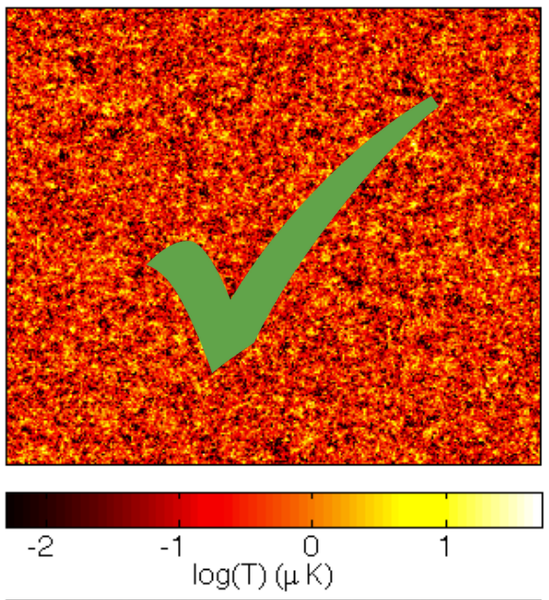
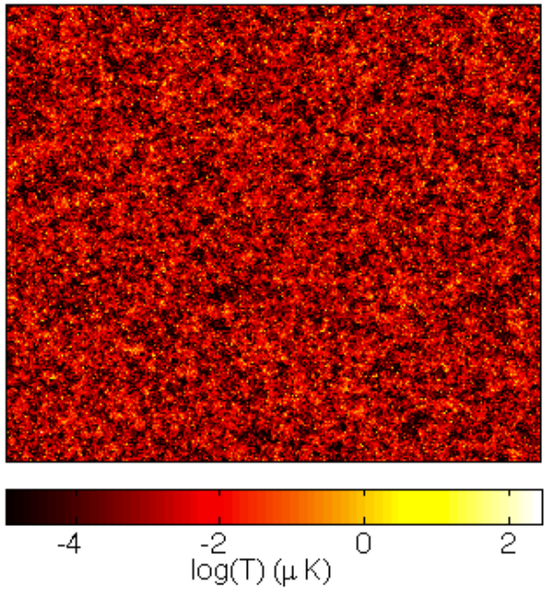
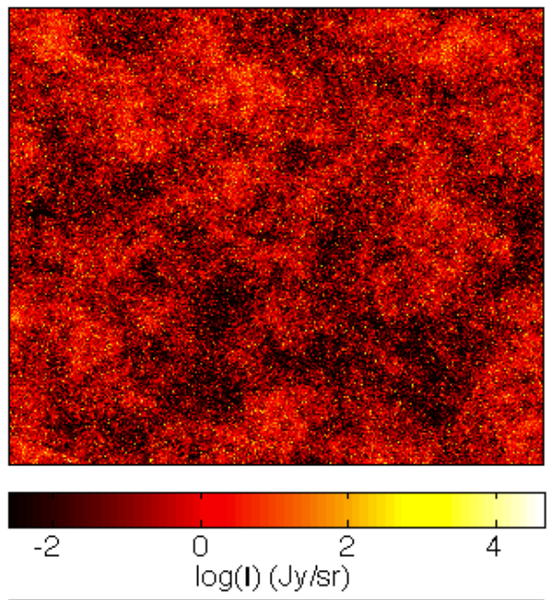
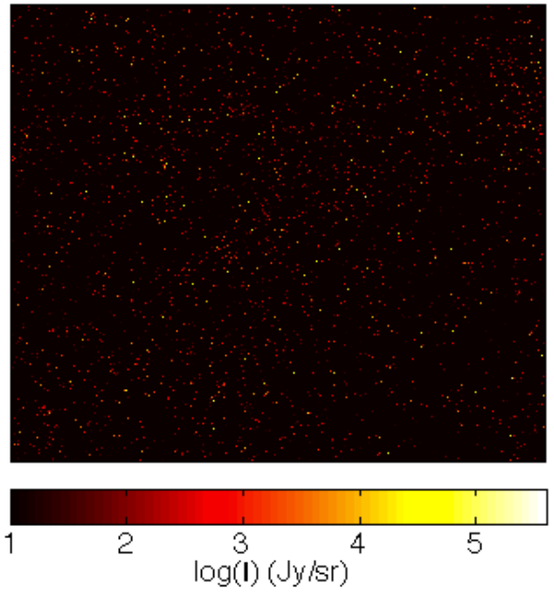




Lyα (Hα,CII,CIII)





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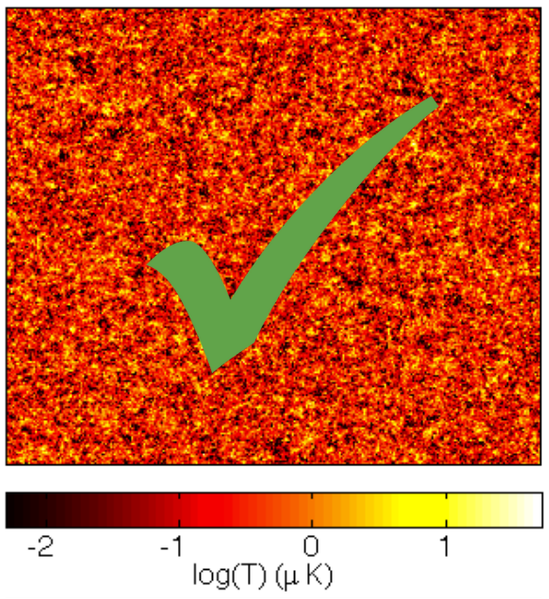

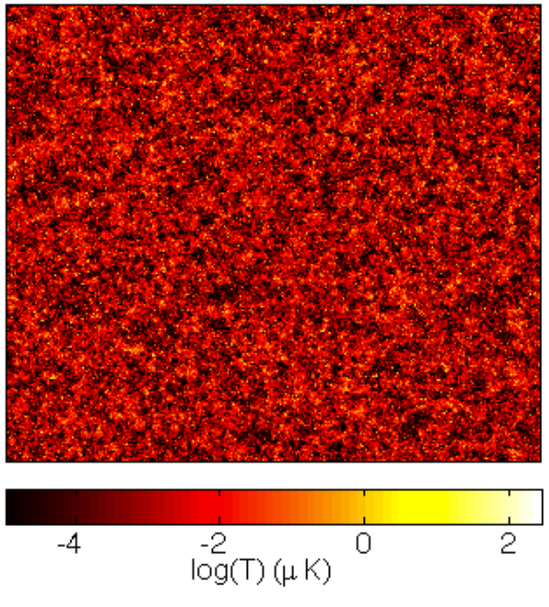

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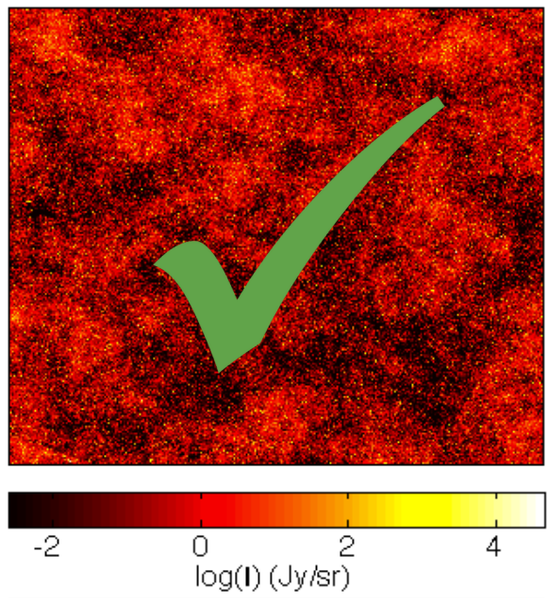

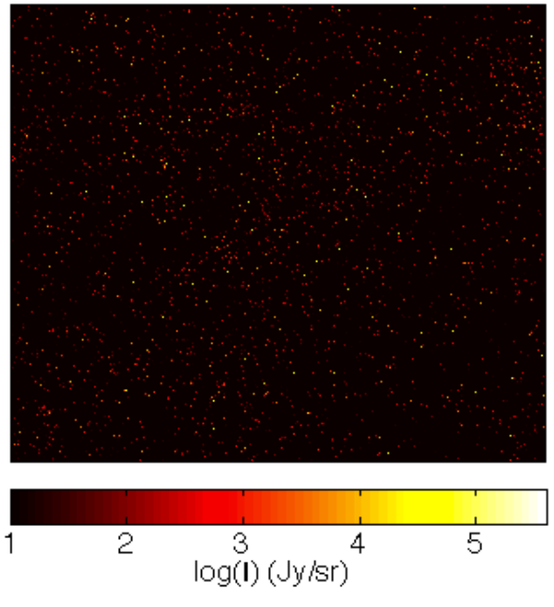

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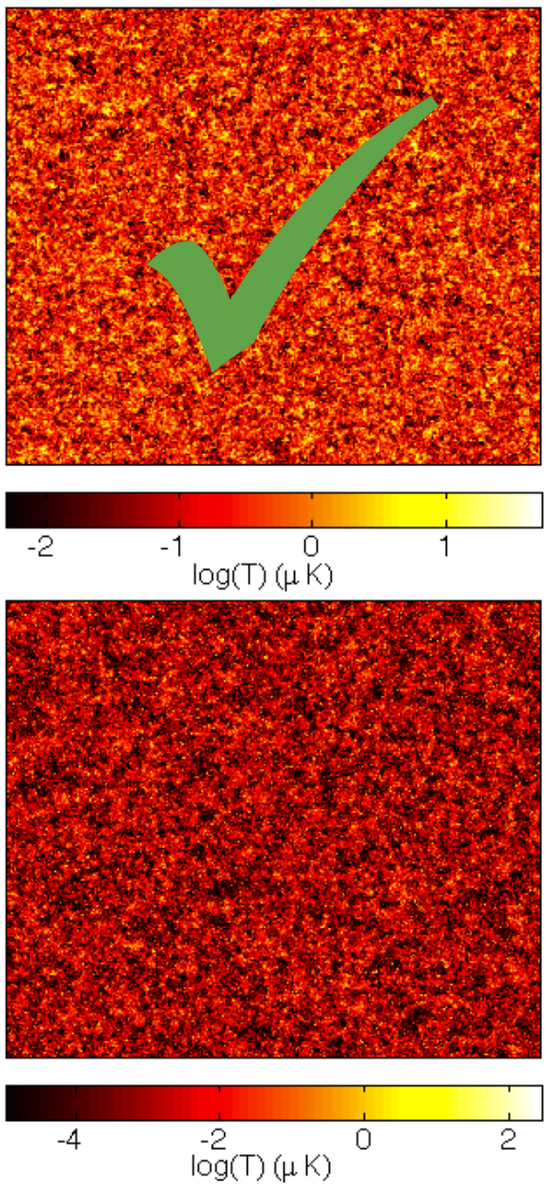

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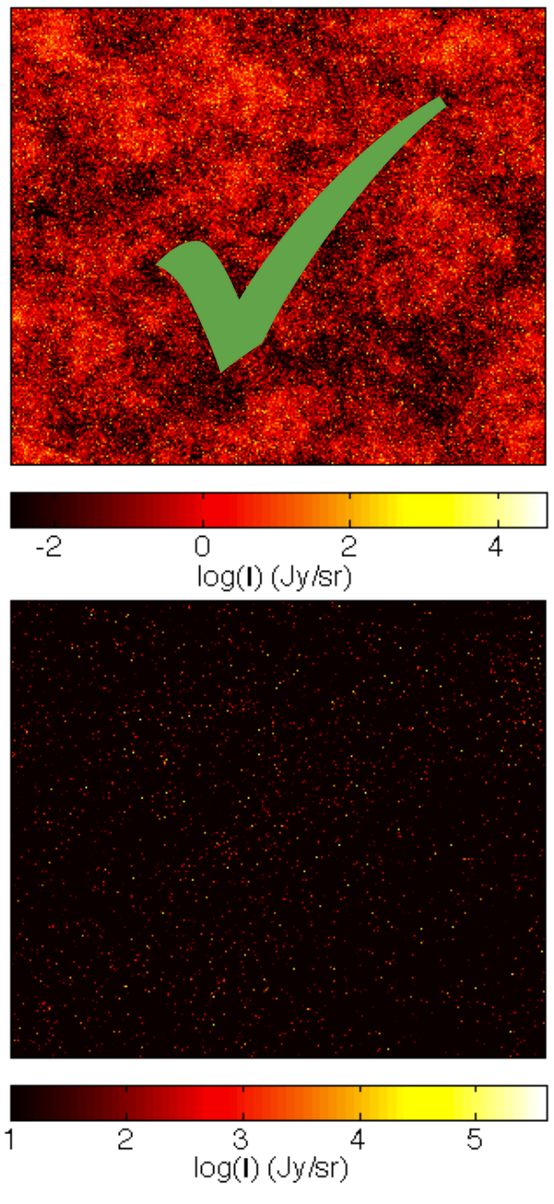

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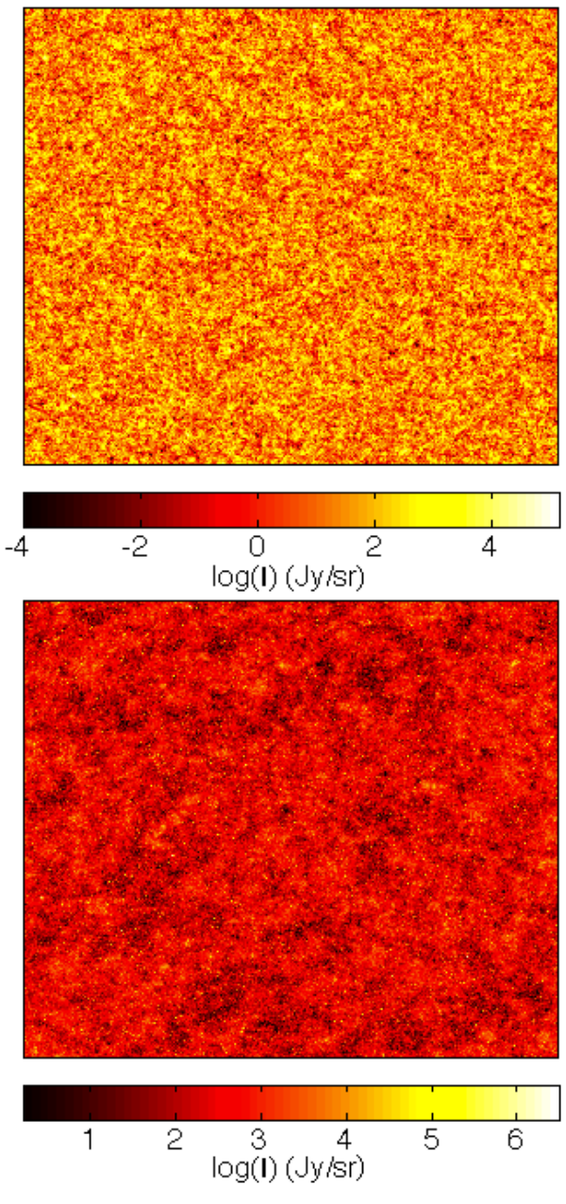

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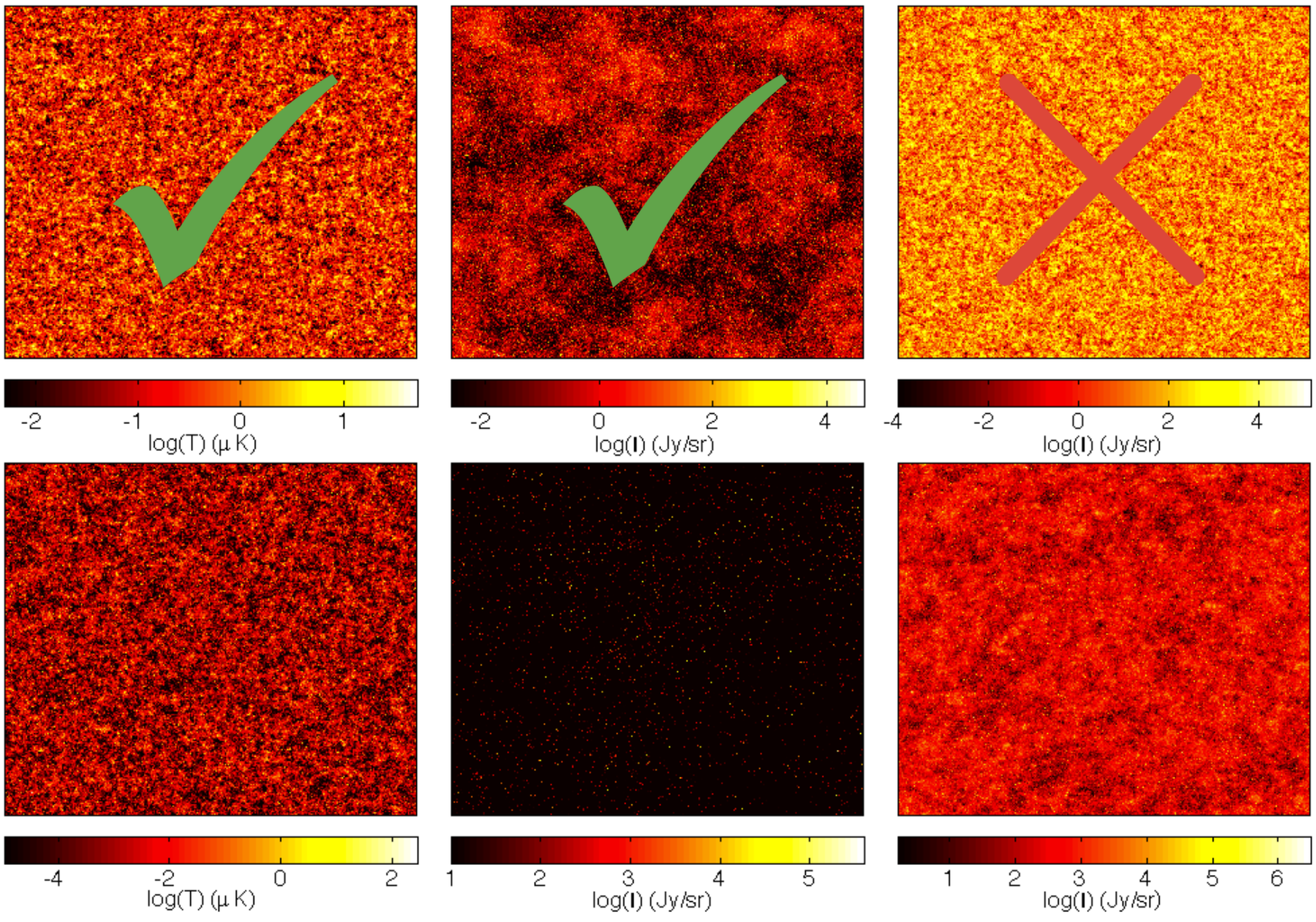

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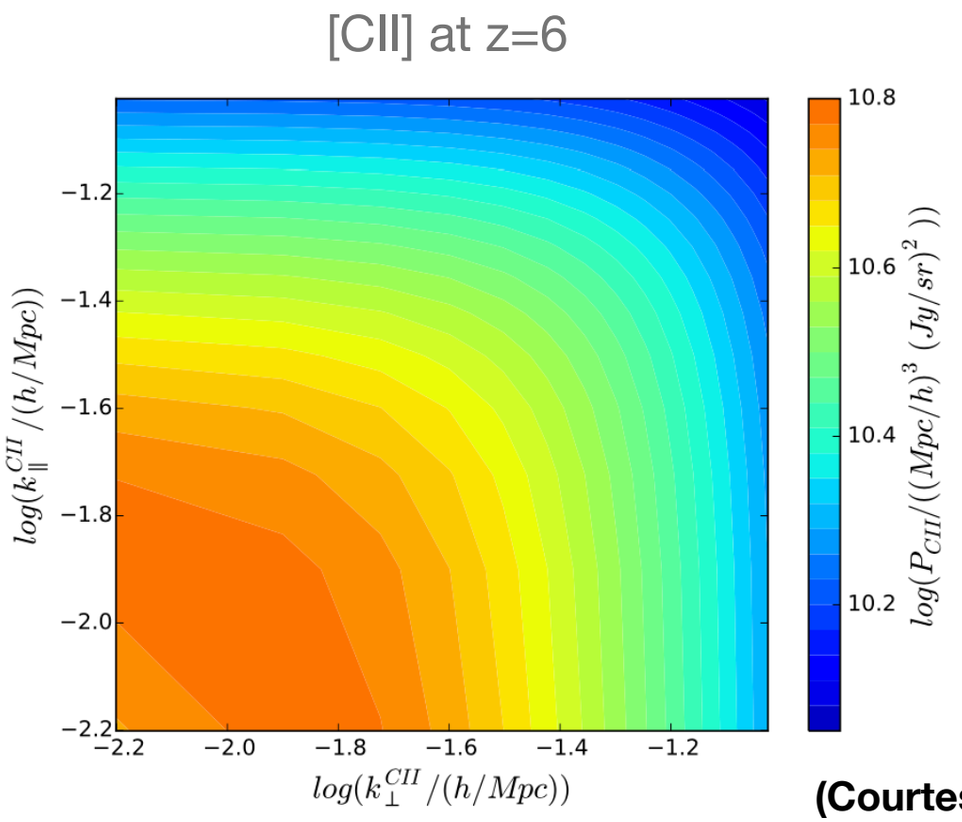

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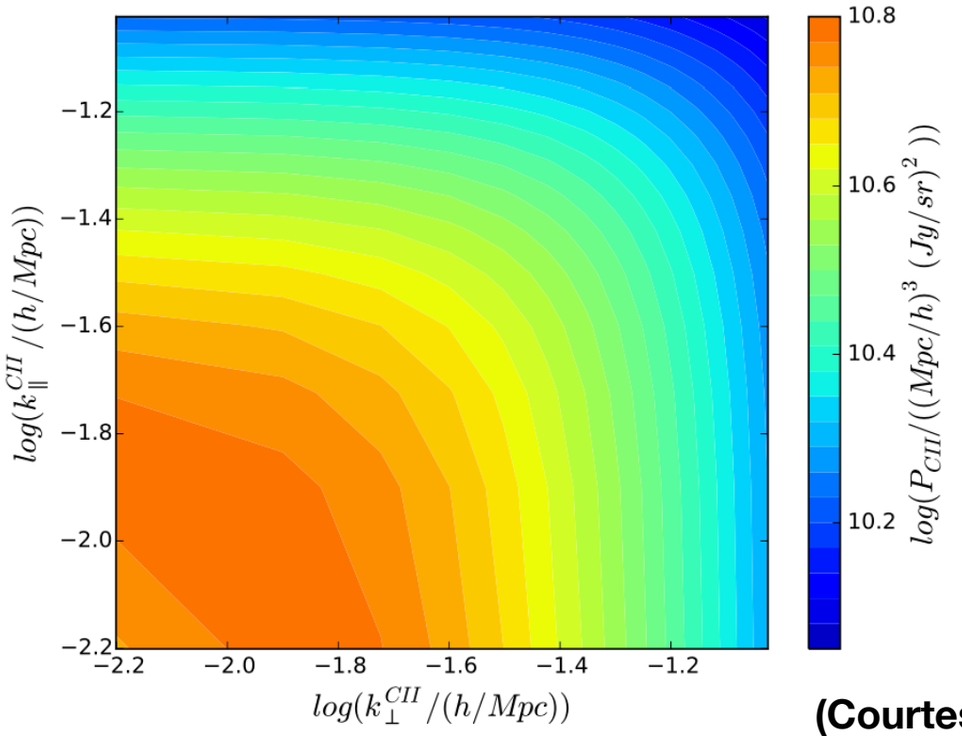
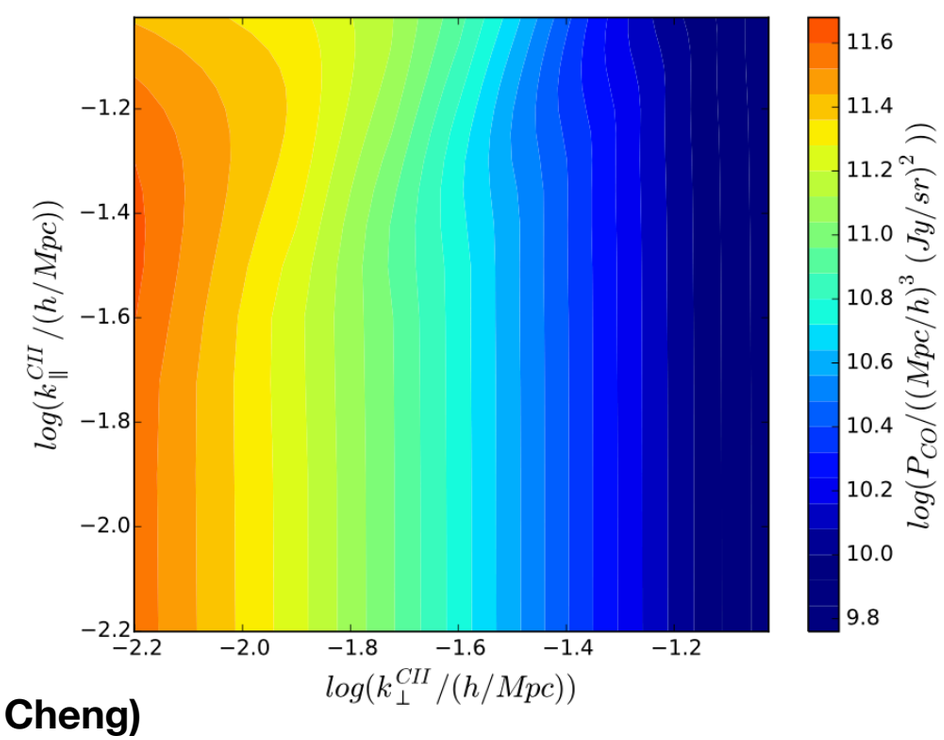
[CII] at z=6



CO(3-2) from z=0.27, projected onto [CII] comoving frame



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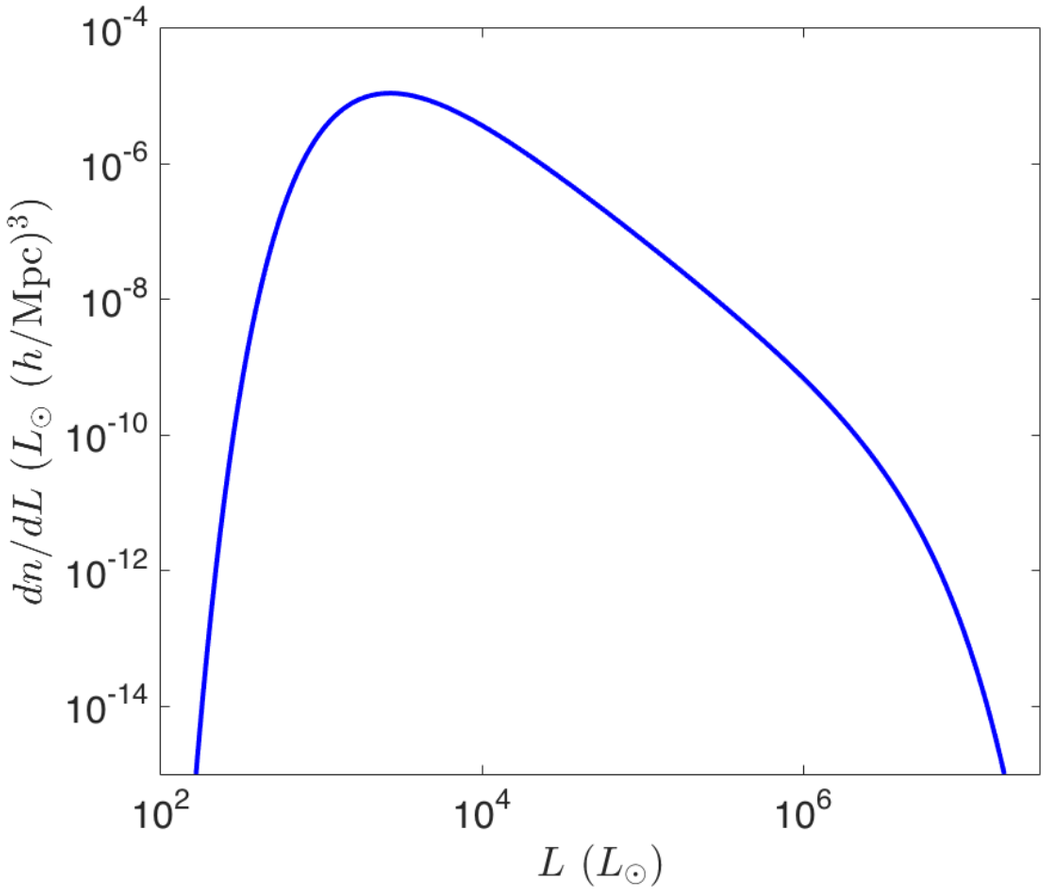

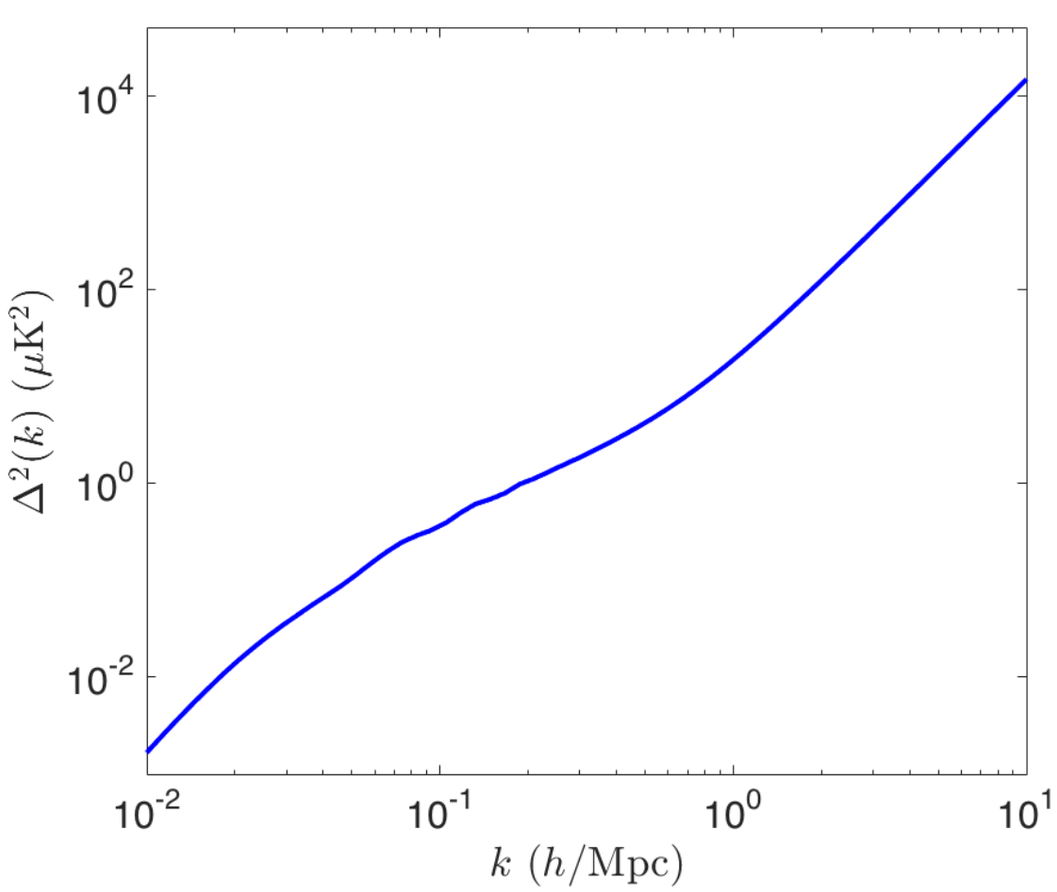

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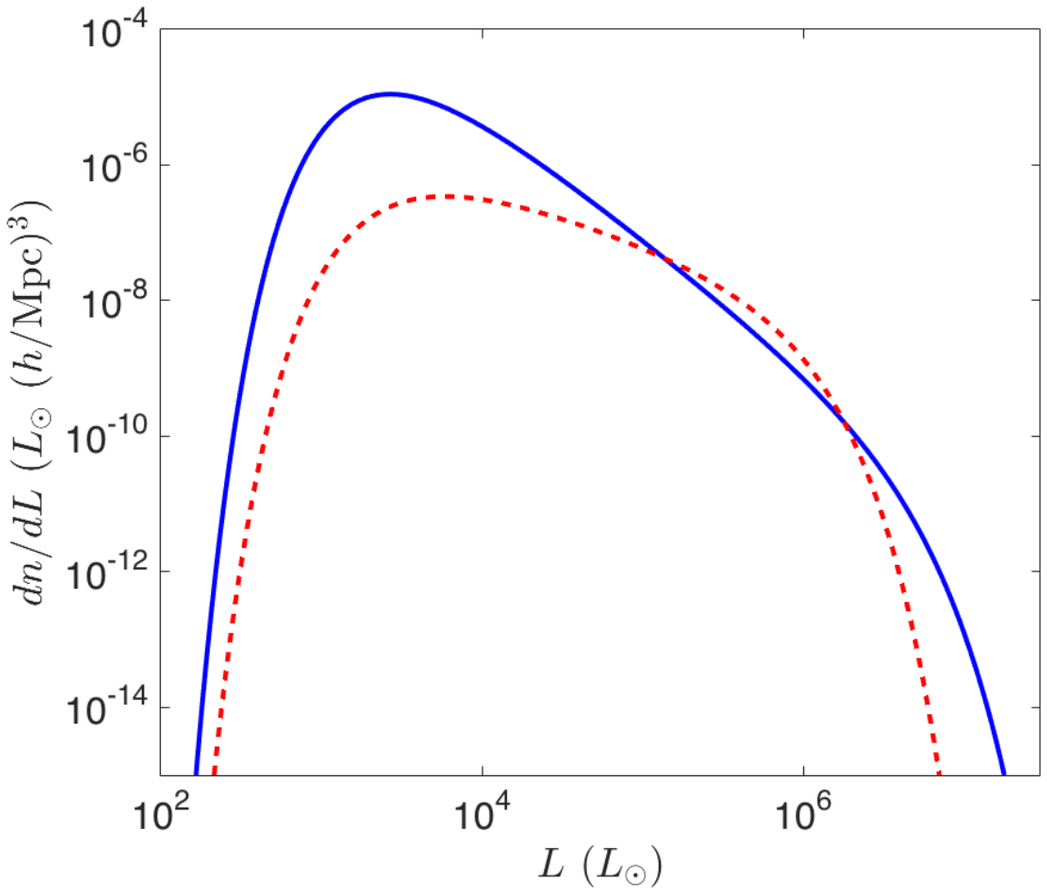
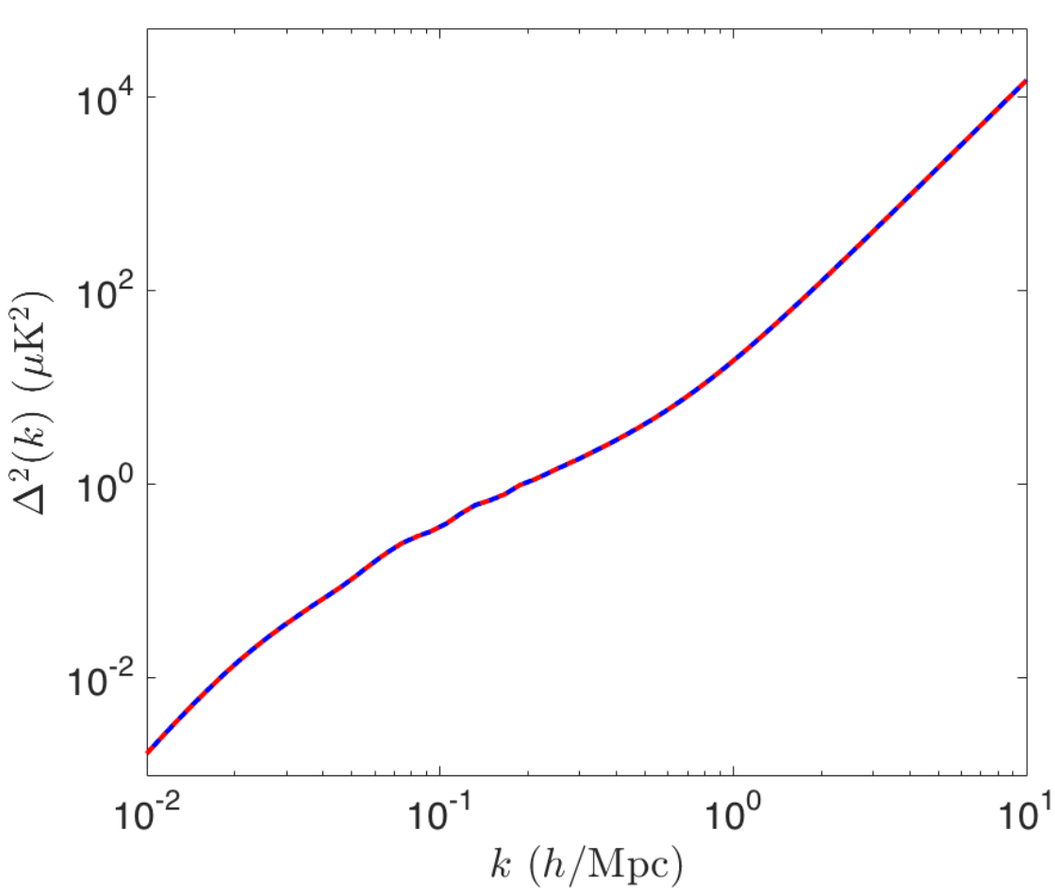
The power spectrum contains all of the information in a map if and only if the map is Gaussian

An alternative to the power spectrum is the one-point PDF:





(Courtesy of P. Breysse)

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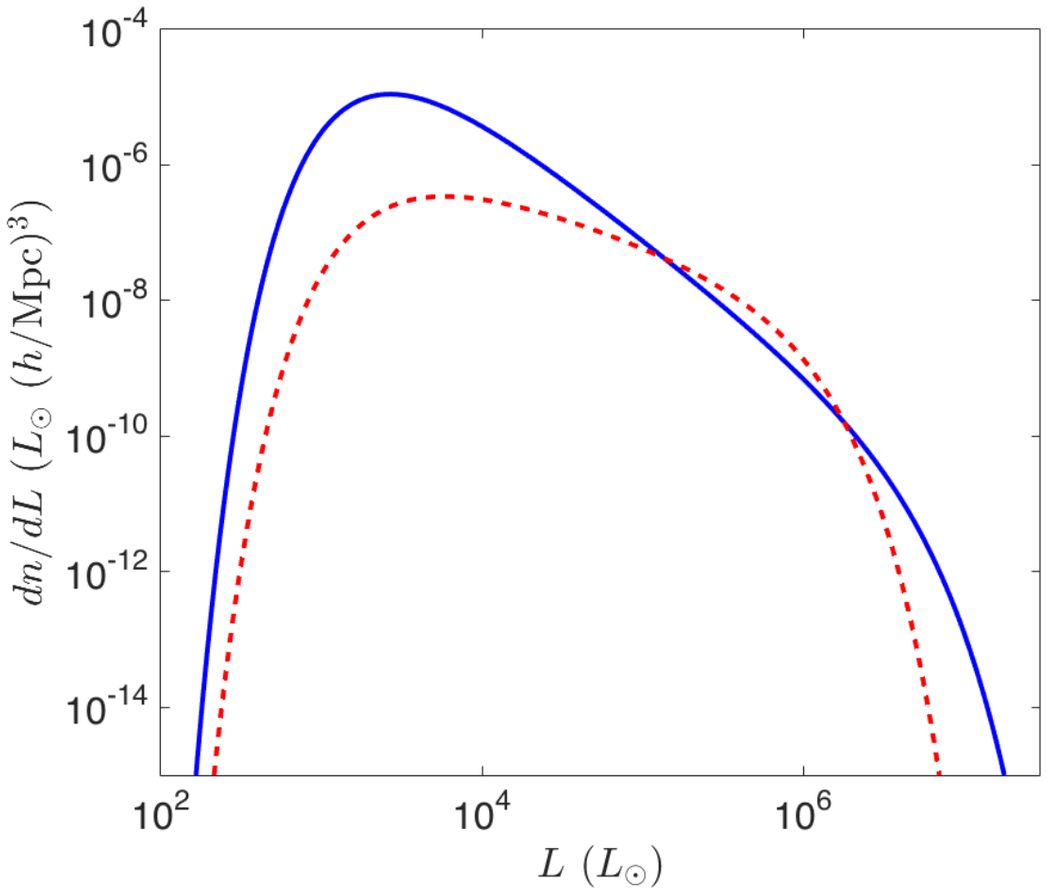

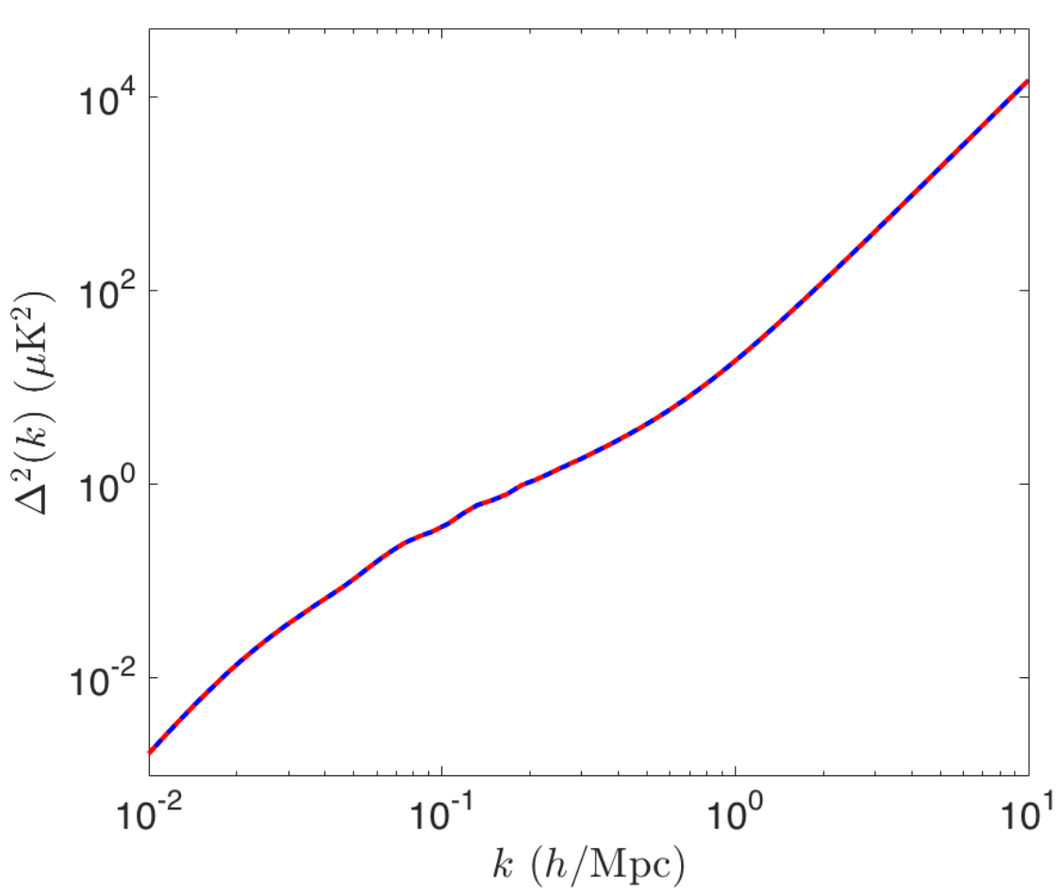

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Power spectrum gives full clustering behavior, integrals over luminosity function.

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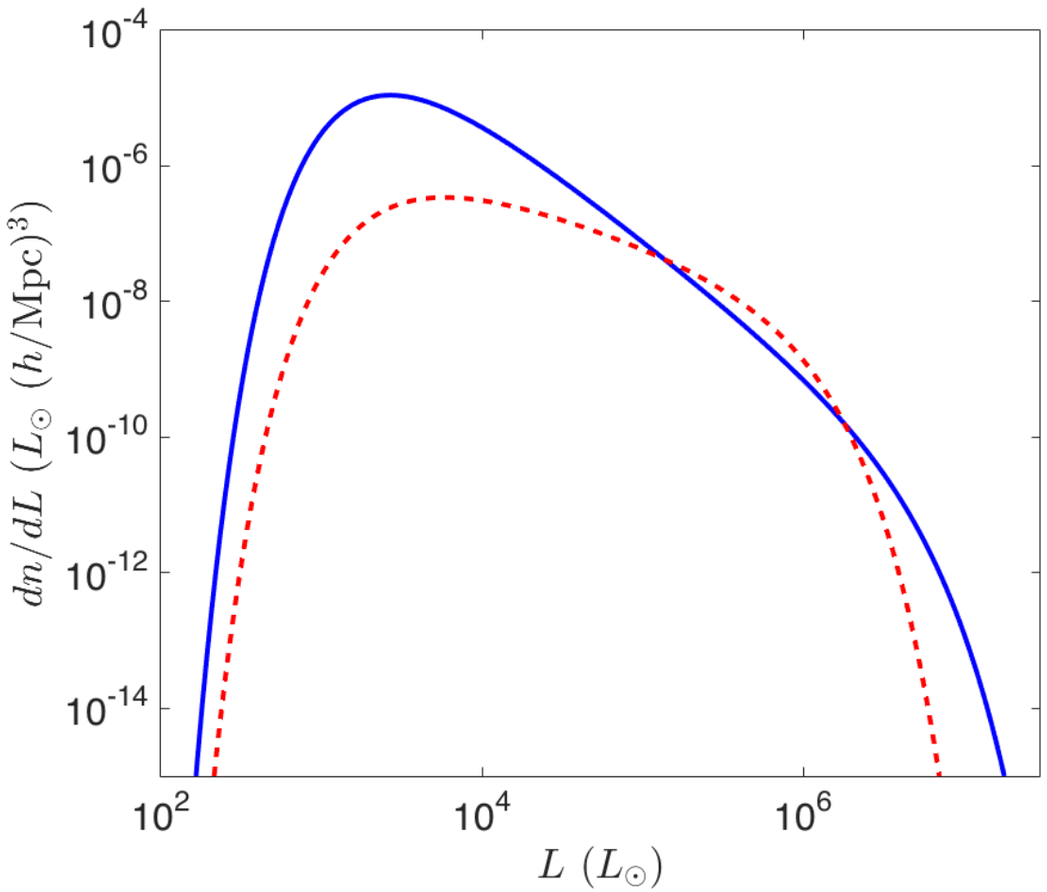

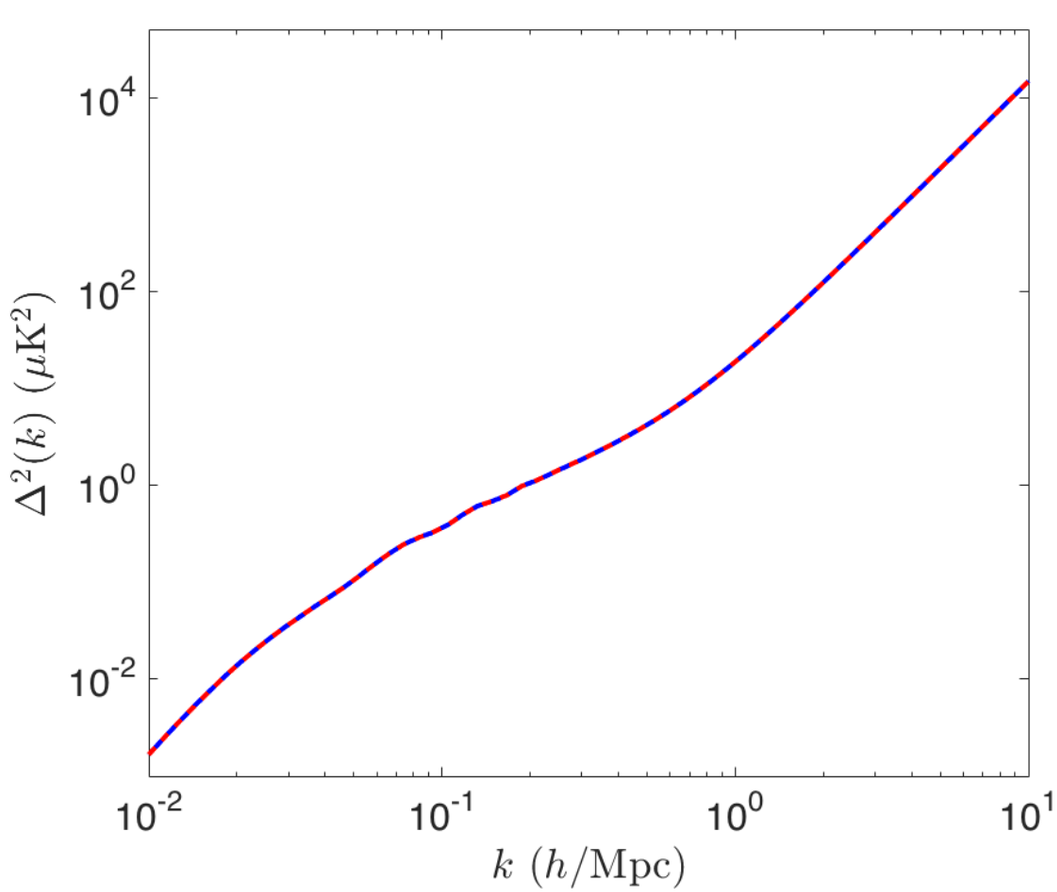

(Courtesy of P. Breysse)

Power spectrum gives full clustering behavior, integrals over luminosity function.
Voxel Intensity Distribution gives full luminosity function, integrals over clustering.

LIM Techniques: Developing Mocks

Dedicated LIM simulations:

- Simulate large volumes.
- Run halo finder (PeakPatches).
- Assign line flux to each halo.
- Add scatter.
- Bin by angular position and frequency.
- Repeat for any desired line.
- Repeat for different cosmologies.
- Extract covariances.

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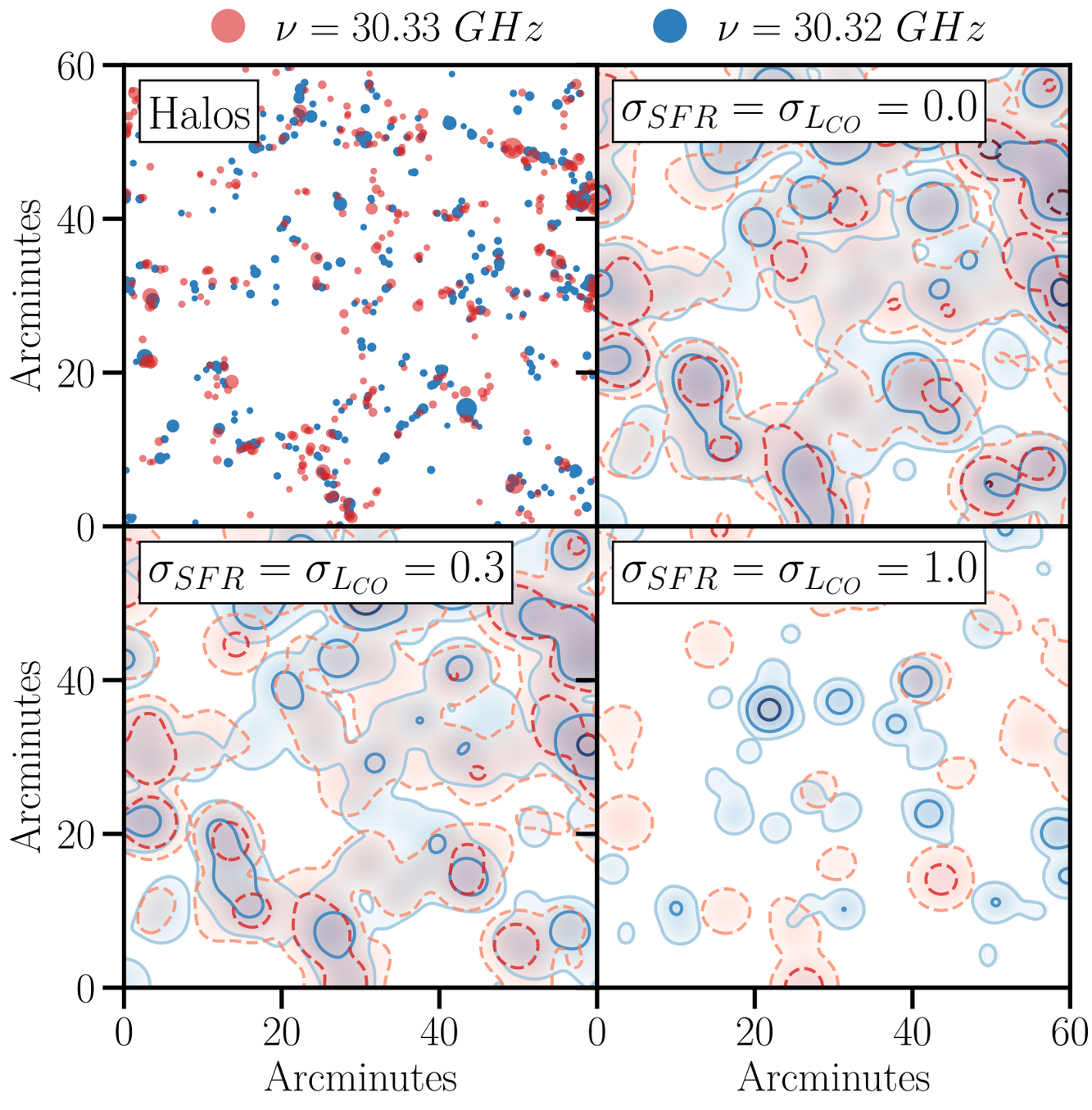
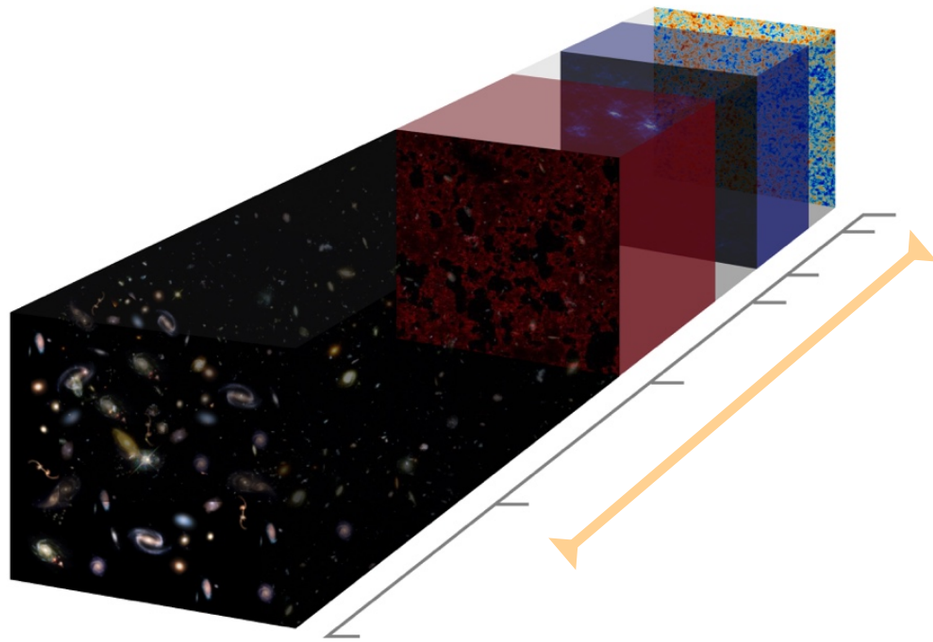


(Courtesy of G. Stein)

Outline

Ely D. Kovetz
Aspen, Feb. 2018

- Introduction to Line-Intensity Mapping
- Science Goals of Line-Intensity Mapping
- Theoretical Backbone (Modeling+Techniques)



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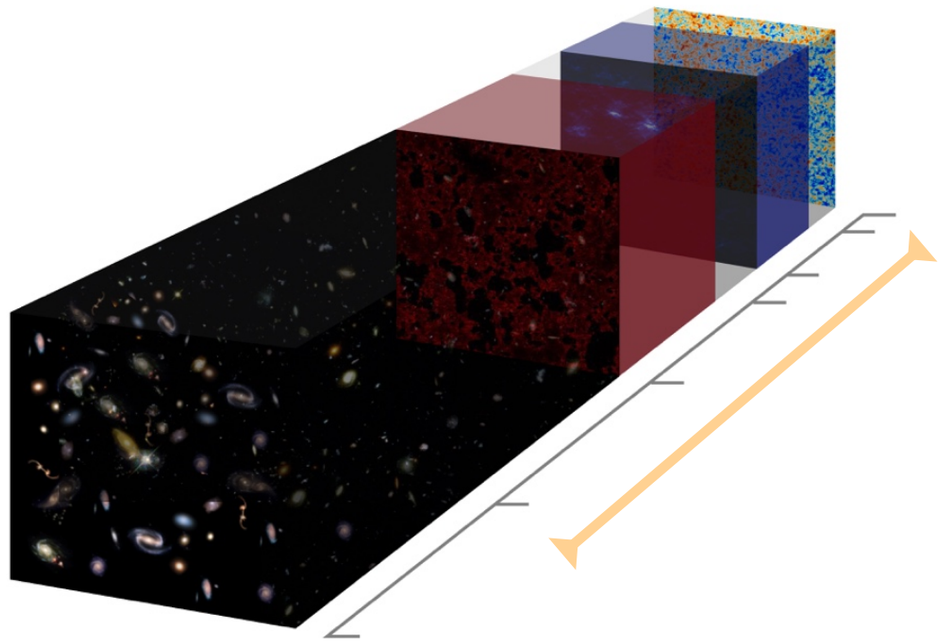

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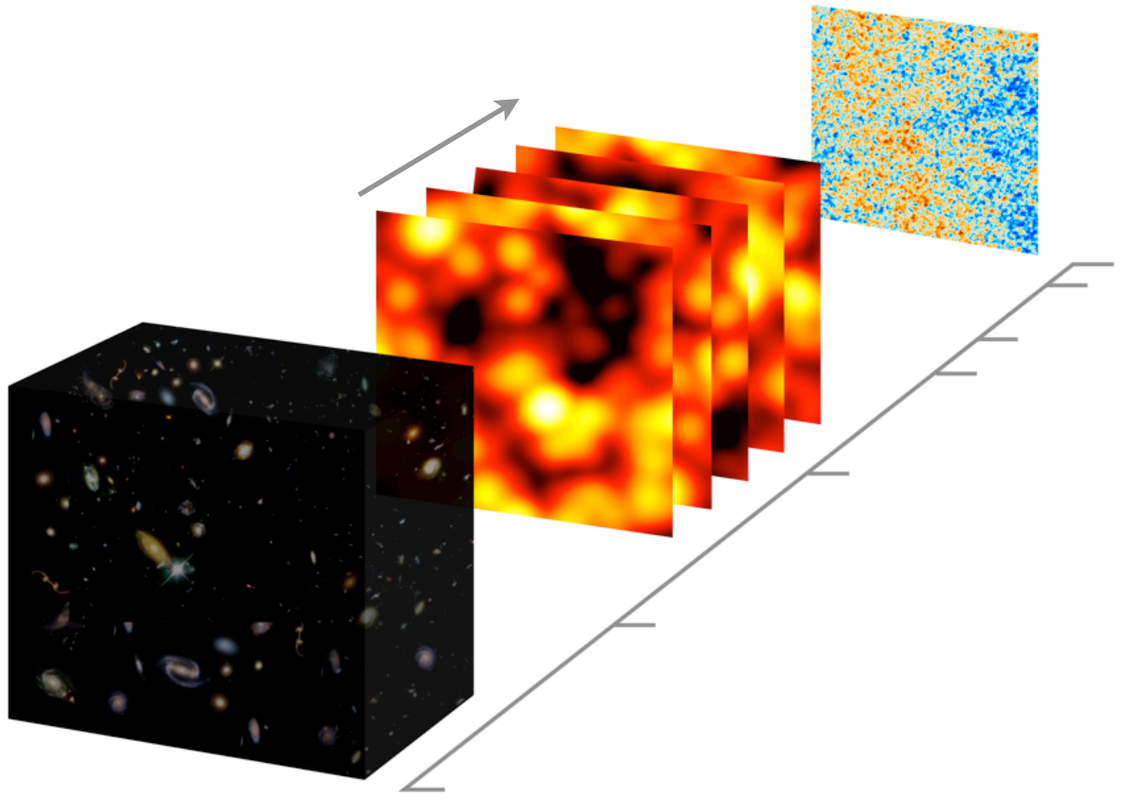
Conclusions and Outlook



Conclusions and Outlook

Opportunities:

- Cosmology: Inflation, dark matter, dark energy, modified gravity...
- Epoch of reionization: bubble sizes, ionized fraction, duration,....
- Astrophysics: star-formation, galaxy assembly, metallicity history,....
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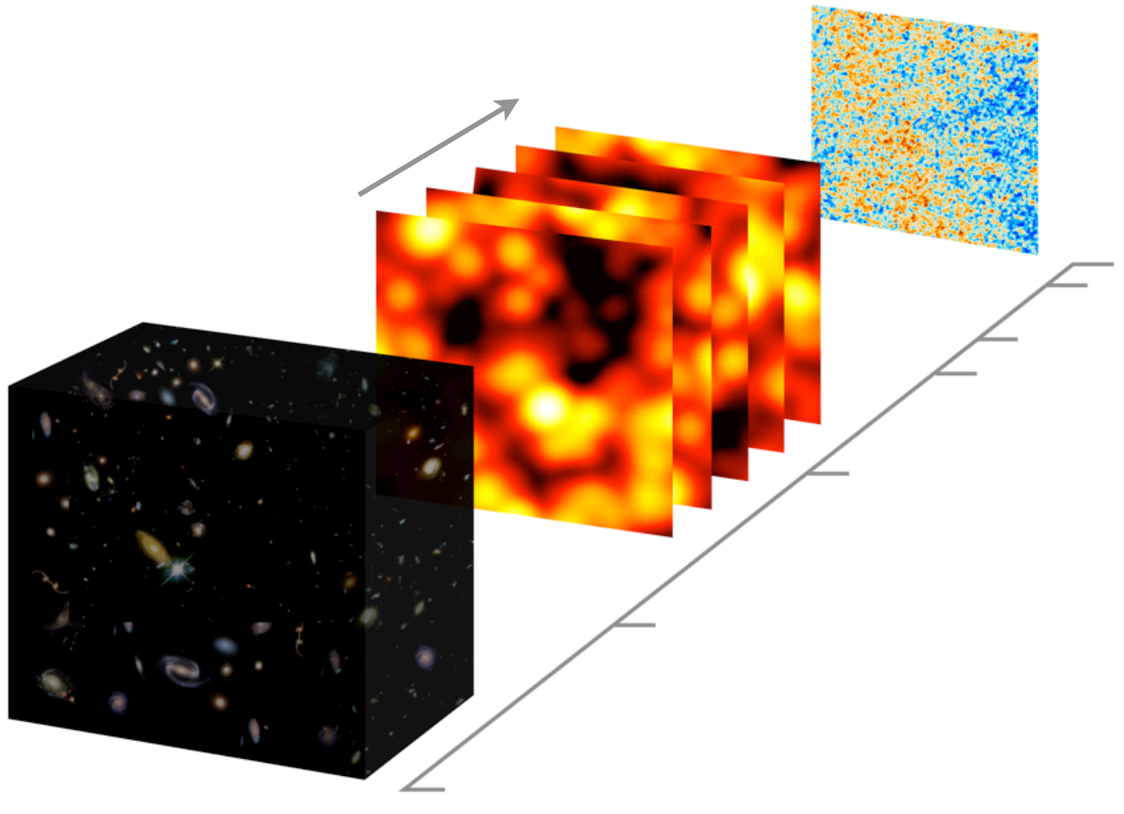

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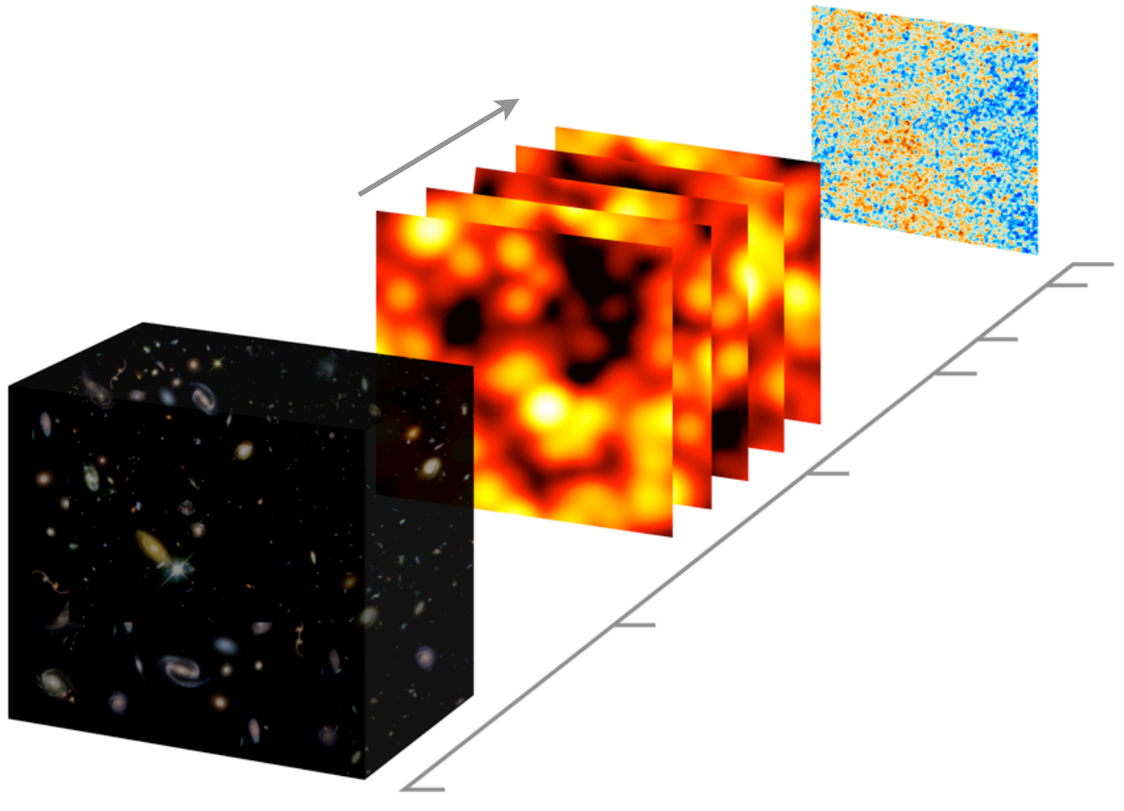
Challenges + suggested discussion points:

- Foregrounds?!
- Modeling: how to interpret a measurement?
- Optimal observables
- Simulations



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Lots of excitement re: line-intensity mapping! (yet, # of theory papers still <= # experimental papers)

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KIPAC, Stanford 2016

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Line-Intensity Mapping: 2017 Status Report

Physics Reports (2018), in process.

Endorsed by:

James Aguirre[1], Matthieu Bethermin[2], James Bock[3], Geoffrey C. Bower[4], Charles M. Bradford[3], Patrick C. Breysse[5], Philip Bull[6], Tzu-Ching Chang[6], Yun-Ting Cheng[3], Dongwoo Chung[10], Sarah Church[10], Kieran Cleary[3], Asantha Cooray[11], Rupert A. C. Croft[12], Clive Dickinson[13], Joshua S. Dillon[14], Olivier Doré[3,6], Michael W. Eastwood[3], Andrea Ferrara[15], Pedro G. Ferreira[16], Anastasia Fialkov[17], José Fonseca[18], Steven R. Furlanetto[19], Brandon Hensley[6], Daniel Jacobs[20], Marc Kamionkowski[21], Garrett K. Keating[22], Ely D. Kovetz[21], Elisabeth Krause[10], Guilaine Lagache[23], Daniel Lenz[3,6], Adam Lidz[1], Adrian Liu[24,25], Abraham Loeb[17,26], Tobias Marriage[21], Daniel P. Marrone[27], Kiyoshi Masui[28], Norman Murray[5], Laura Newburgh[29], Gergo Popping[30], Alkistis Pourtsidou[31], Anthony R. Pullen[32], Mubdi Rahman[21], J. Richard Bond[5], Dominik A. Riechers[33], Brant Robertson[34], Shun Saito[35], Mario G. Santos[18], Marta B. Silva[36], Rachel S. Somerville[37,38], Gordon J. Stacey[33], George Stein[5], Guochao Sun[3], Eric Switzer[39], Joaquin D. Vieira[40], Matteo Viel[41], Marco P. Viero[10], Francisco Villaescusa-Navarro[38], Eli Visbal[38], Amanda Weltman[42]

Conclusions and Outlook

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