High-Redshift Astrophysics Using Every Photon

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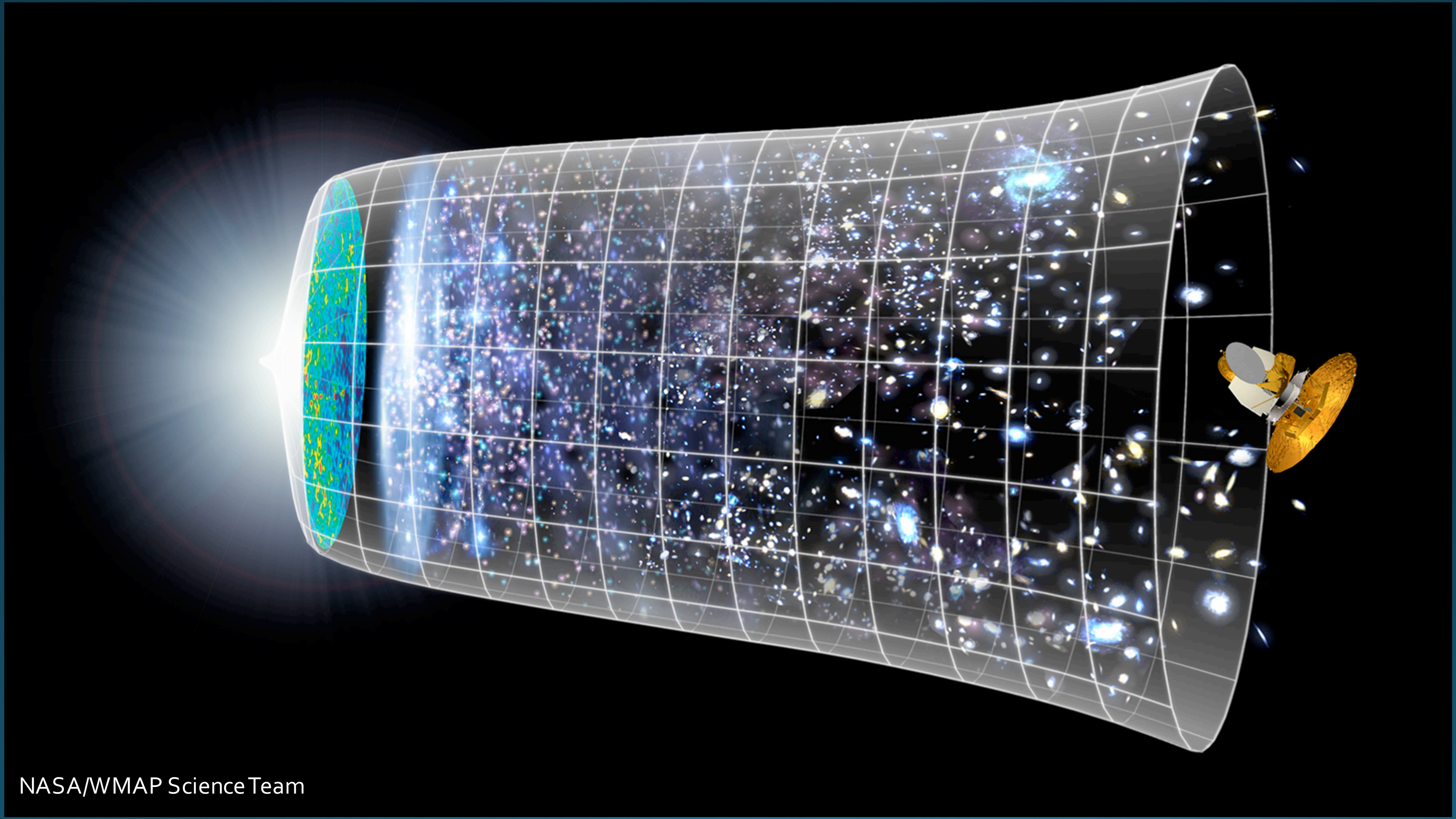
With Ely D. Kovetz, Mubdi Rahman, and Marc Kamionkowski

UC Berkeley, 10 January 2017

Introduction



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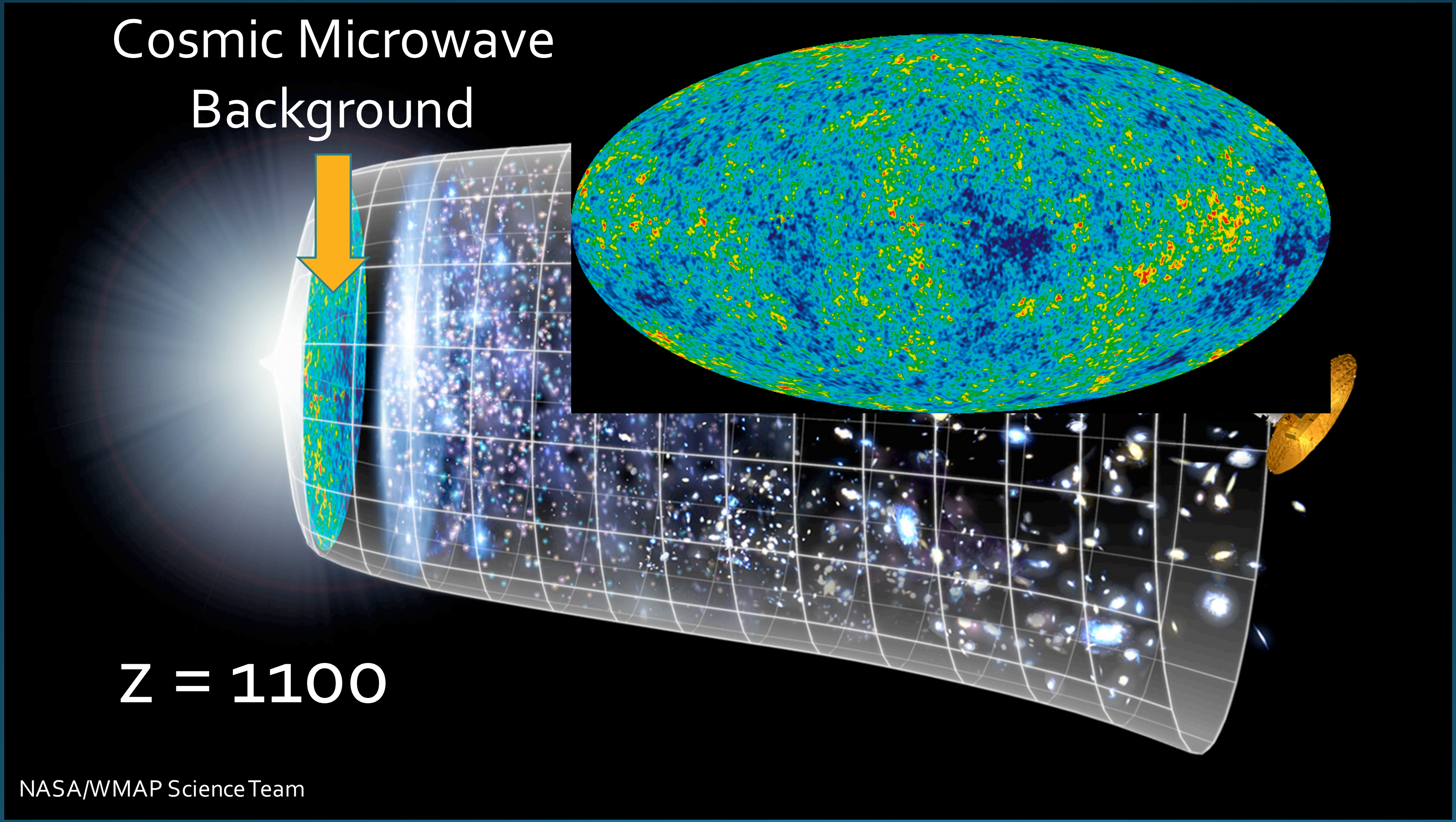

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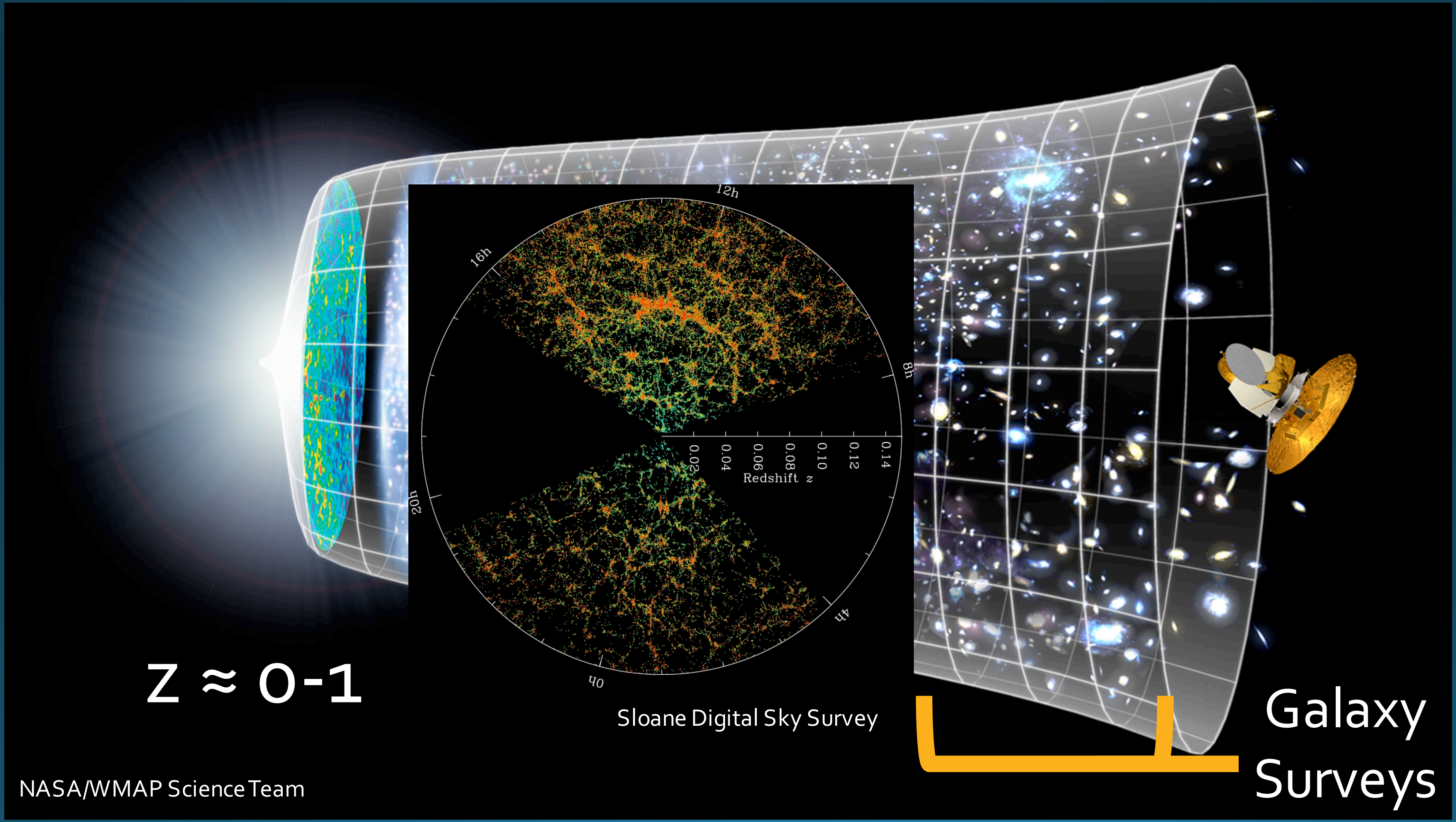

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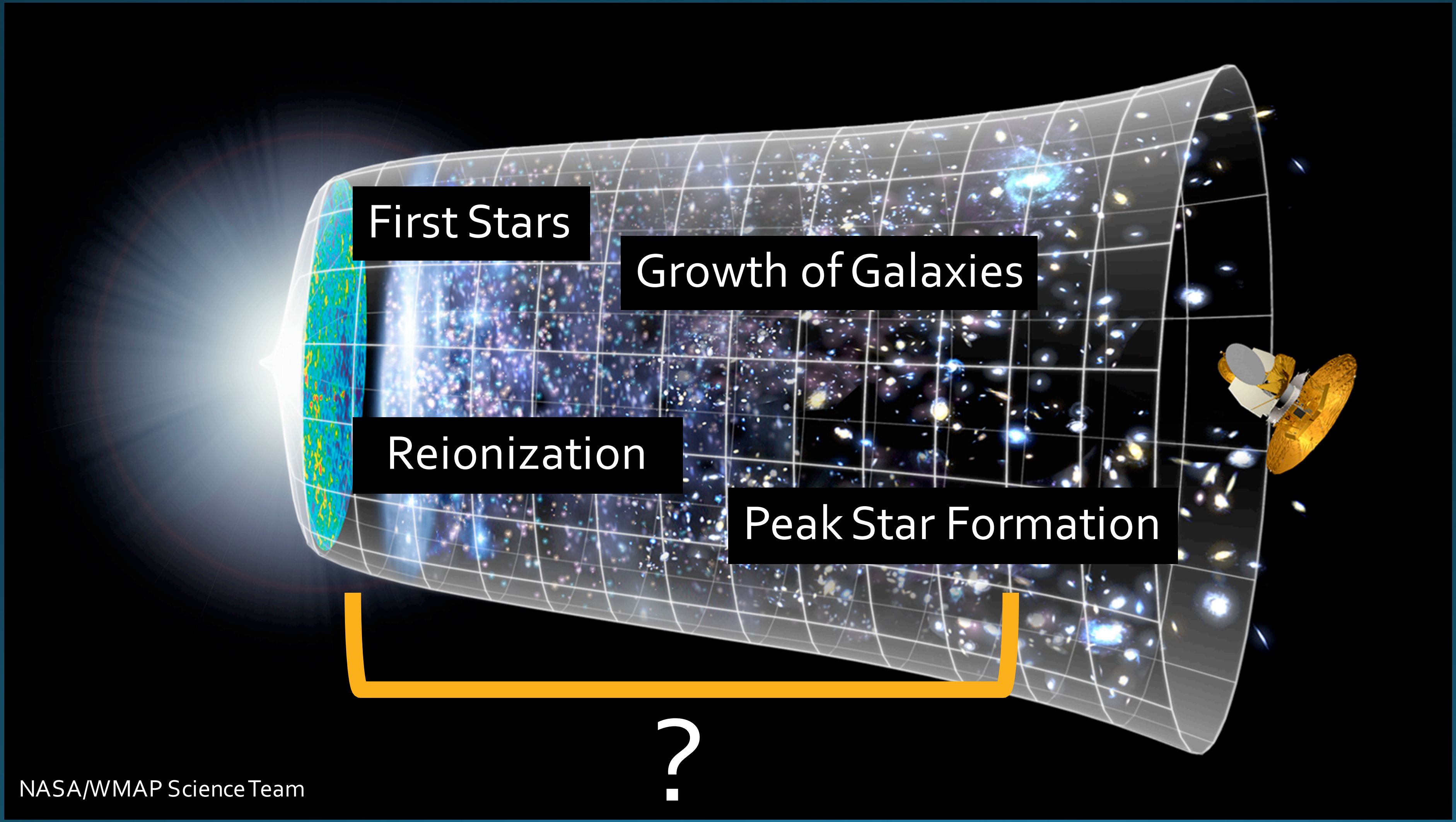


Use all of the photons

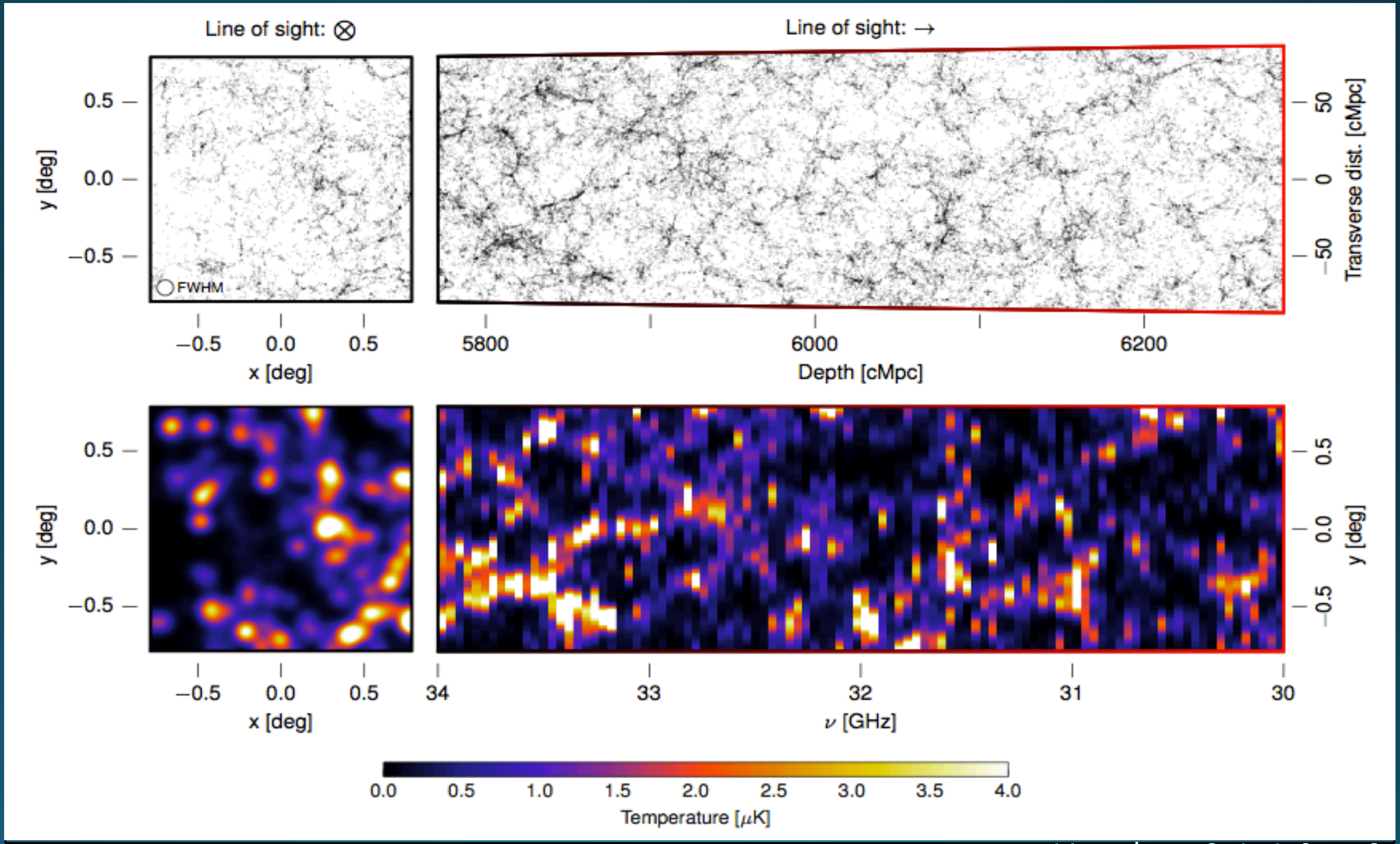
Intensity Mapping

Pick a spectral line

Map large-scale intensity fluctuations

$\nu_{obs} \leftrightarrow z$

Line intensity traces galaxy structure

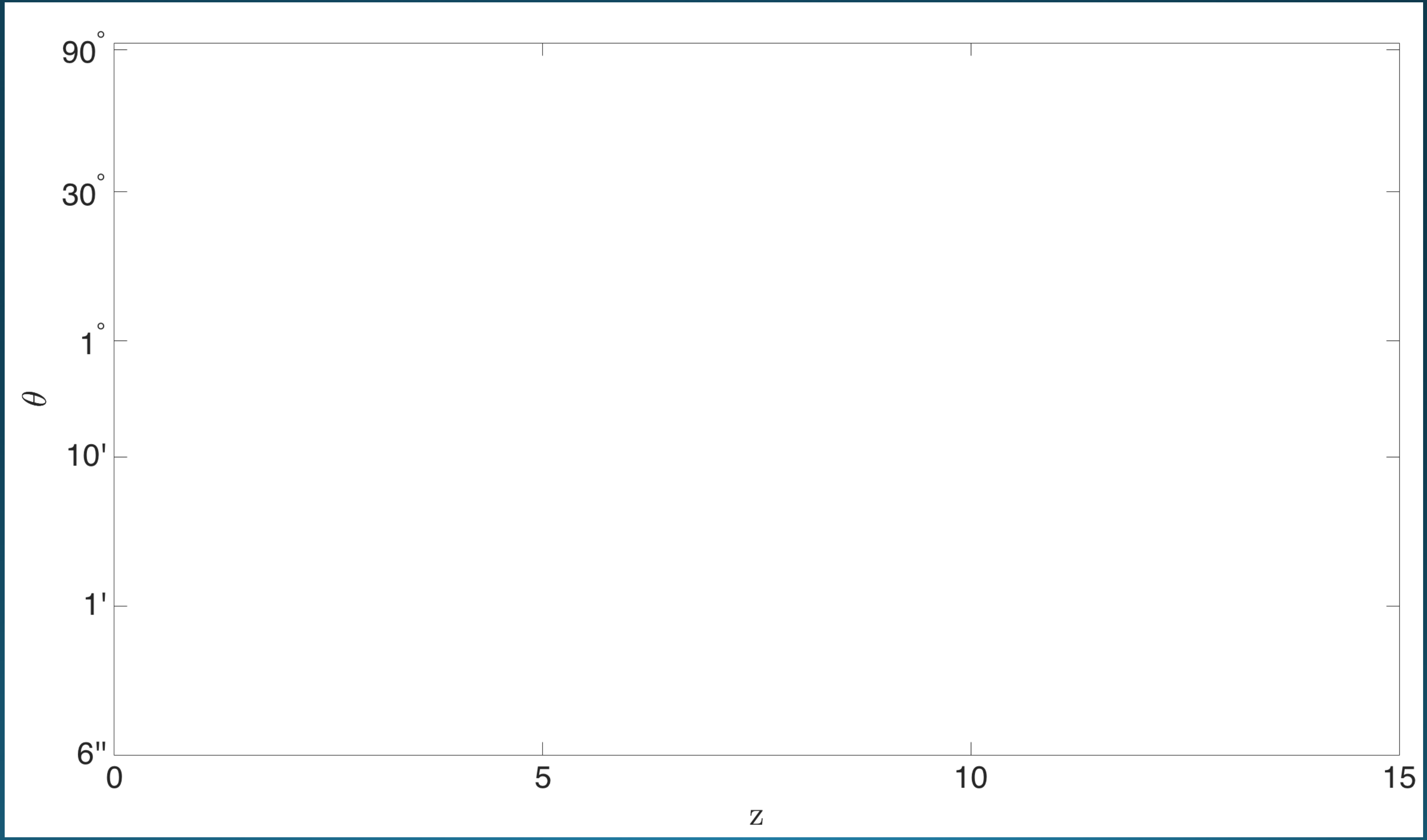


Li et al. 2016, ApJ, 817,169

Galaxy surveys give detailed properties of brightest galaxies

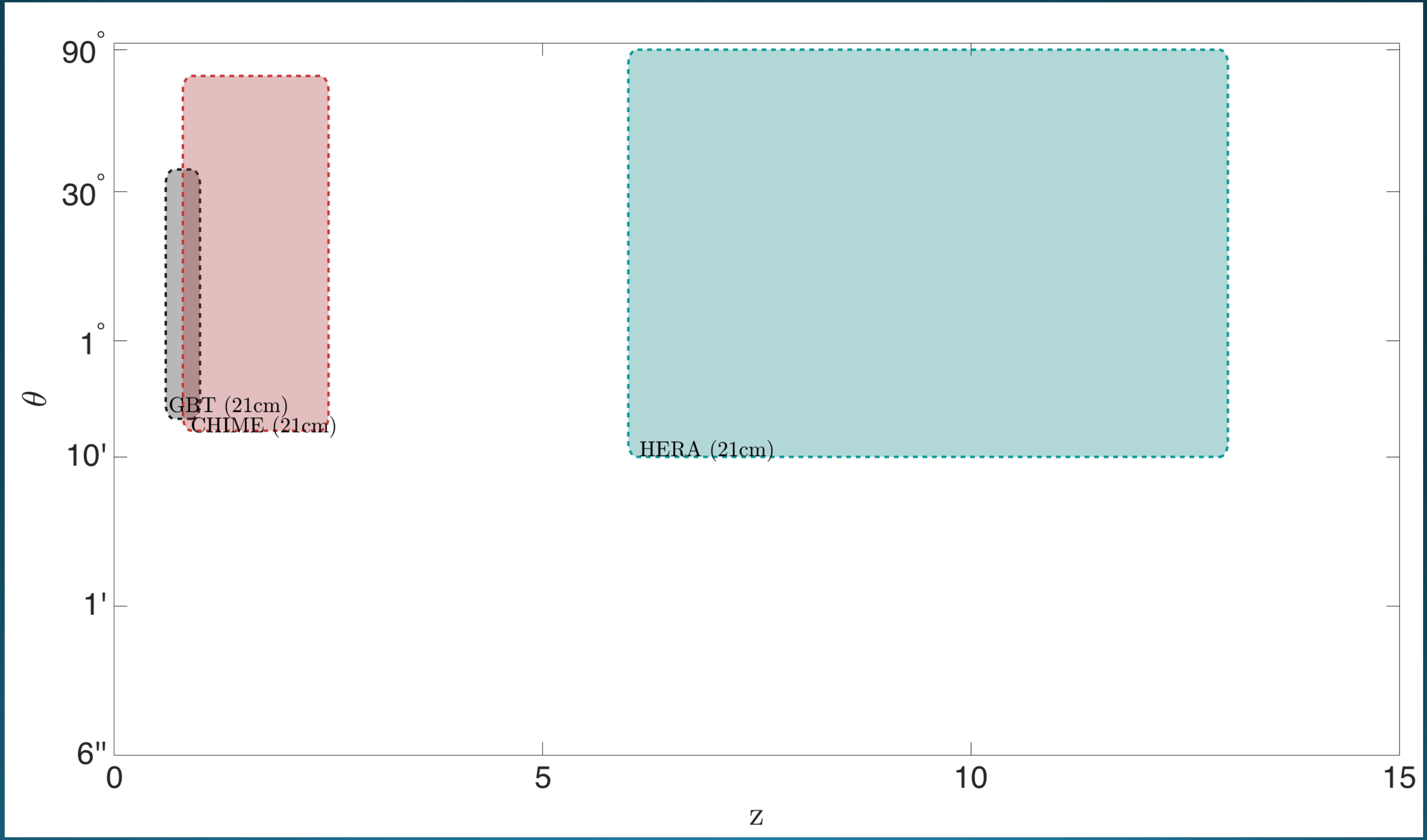
Intensity maps give statistical properties of all galaxies

Lines and Experiments



Lines and Experiments

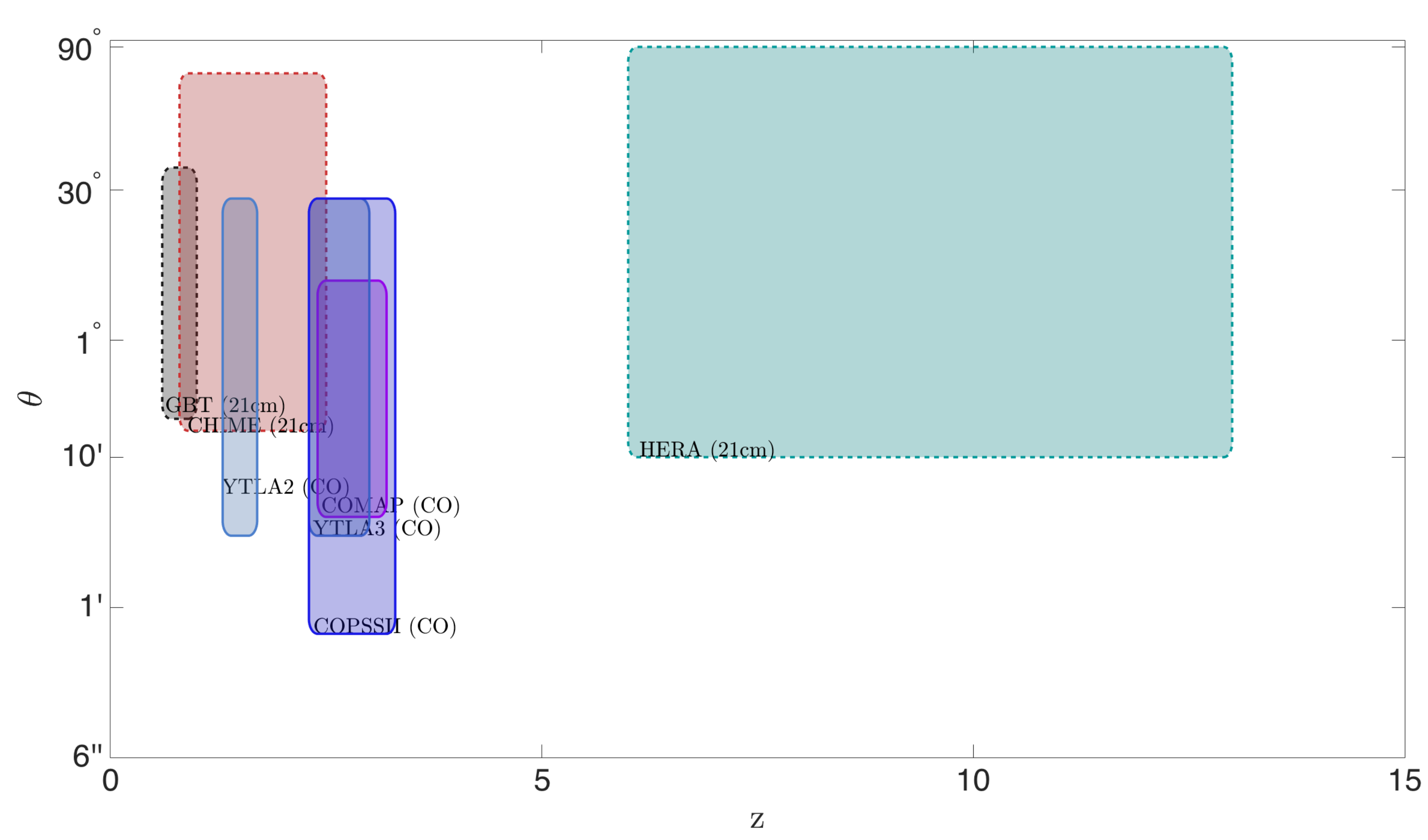
21 cm



Lines and Experiments

21 cm

CO

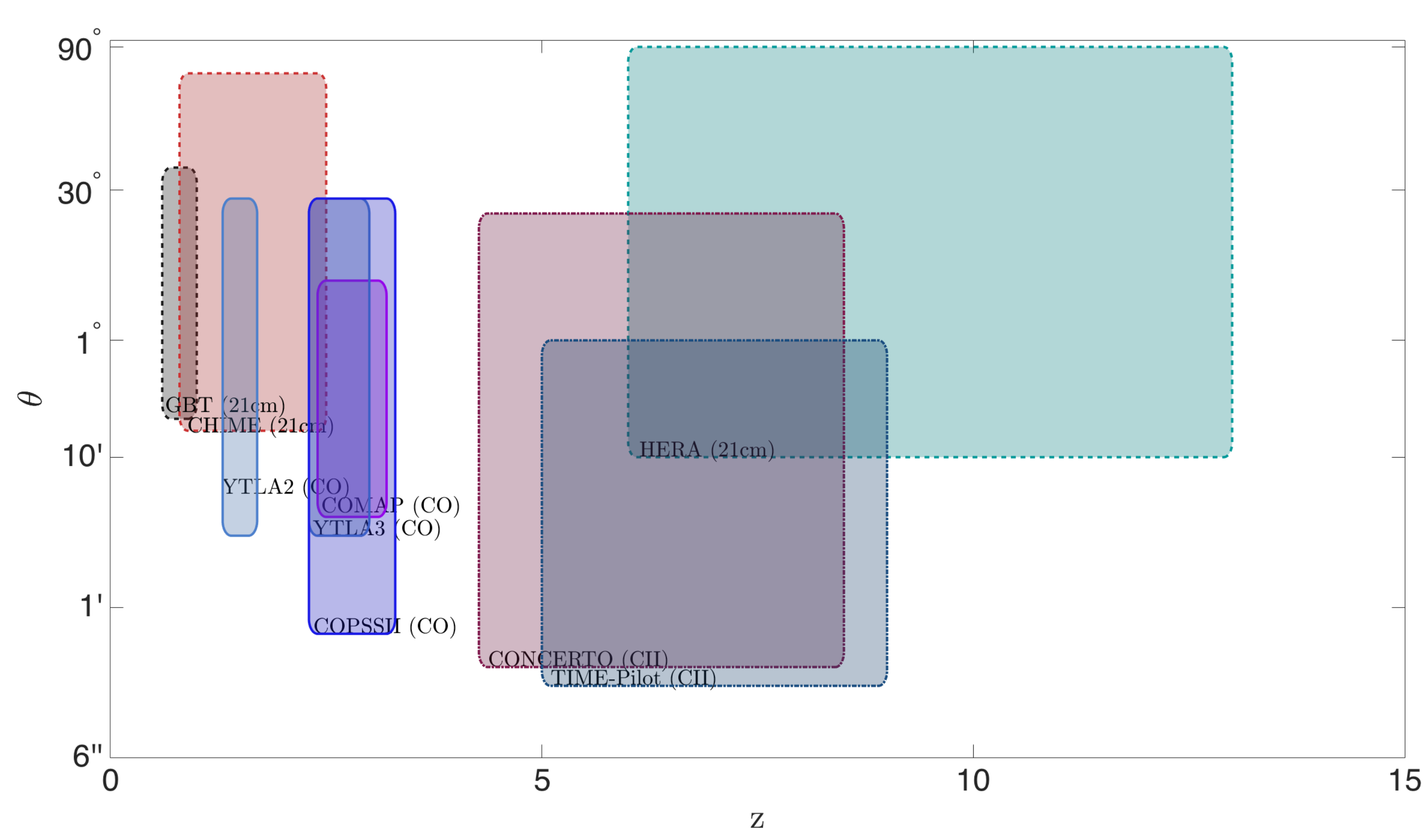


Lines and Experiments

21 cm

CO

CII



Lines and Experiments

21 cm

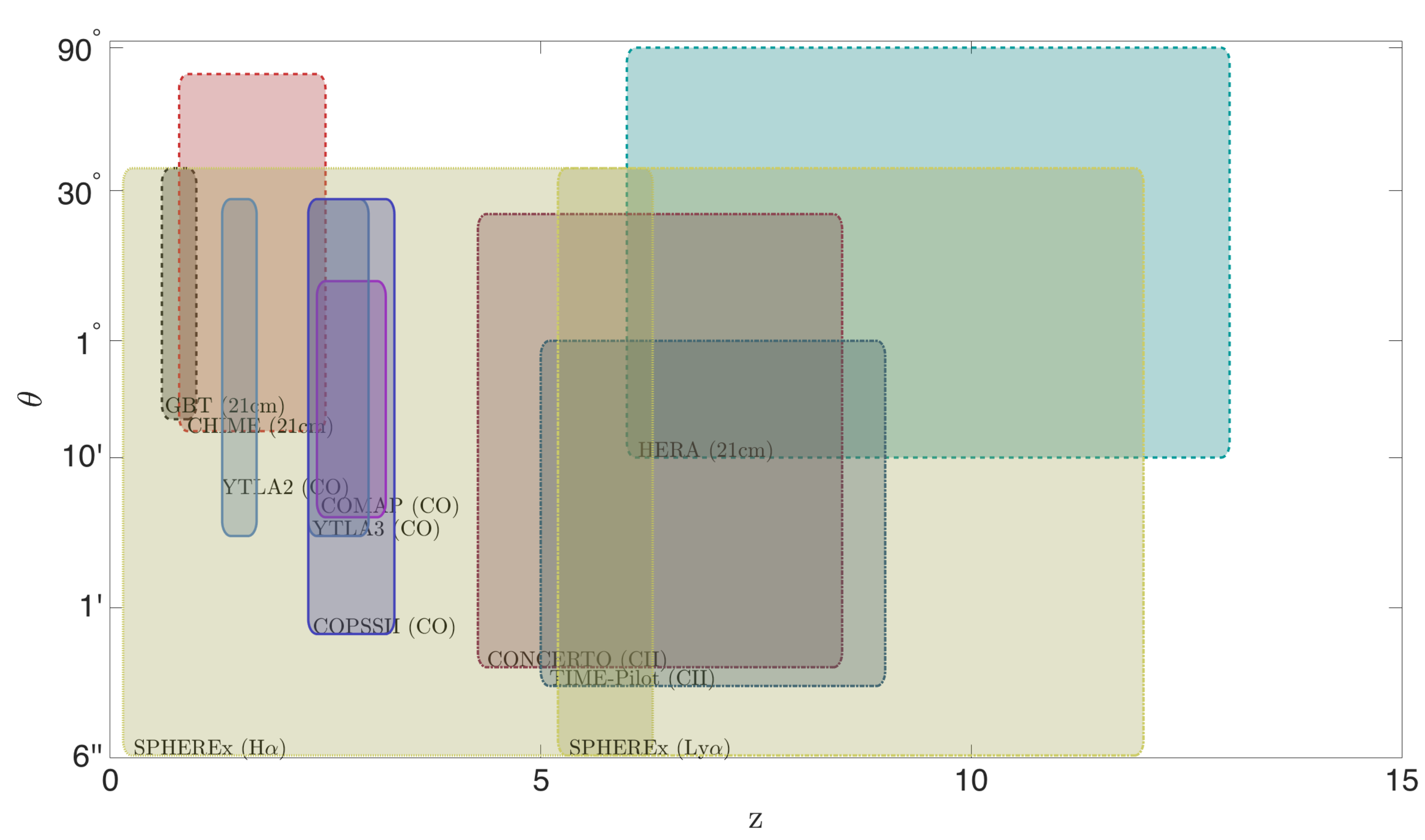
CO

CII

Lyα

Hα

Etc.



Outline

- Formalism
  - Power spectrum
  - One-point statistics
- Example: CO Intensity Mapping
  - Luminosity functions
  - Star formation history
- Multiple Lines
  - Foreground contamination
  - Cross-correlations

Formalism

Breysse, P. C., Kovetz, E. D., & Kamionkowski, M. 2014, MNRAS, 443, 3506
Breysse, P. C., Kovetz, E. D., & Kamionkowski, M. 2016, MNRAS Lett., 457, L127
Breysse, P.C., Kovetz, E. D., Behroozi, P. S., Dai, L., Kamionkowski, M., 2016, arXiv:1609.01728

Power Spectrum

$$P(k, z) =$$

Power Spectrum

$$P(k,z) = \underbrace{P_m(k,z)}$$

Galaxies trace underlying dark matter distribution

Power Spectrum

$$P(k,z) = b^2(z)\, P_m(k,z)$$

Galaxies are a biased tracer

Power Spectrum

$$P(k,z) = \langle T \rangle^2(z)\, b^2(z)\, P_m(k,z)$$

Convert galaxy spectrum
to intensity spectrum

Power Spectrum

$$P(k,z) = \langle T \rangle^2(z) b^2(z)\, P_m(k,z) + P_{\text{shot}}(z)$$

Poisson noise due to discrete emission

Power Spectrum

$$P(k,z) = \langle T \rangle^2(z) b^2(z)\, P_m(k,z) + P_{\text{shot}}(z)$$

$$\langle T \rangle(z) \propto \int L \frac{dn(z)}{dL} dL$$

Line luminosity function

$$P_{\text{shot}}(z) \propto \int L^2 \frac{dn(z)}{dL} dL$$

Power Spectrum

$$P(k,z) = \langle T \rangle^2(z) b^2(z)\, P_m(k,z) + P_{\mathrm{shot}}(z)$$

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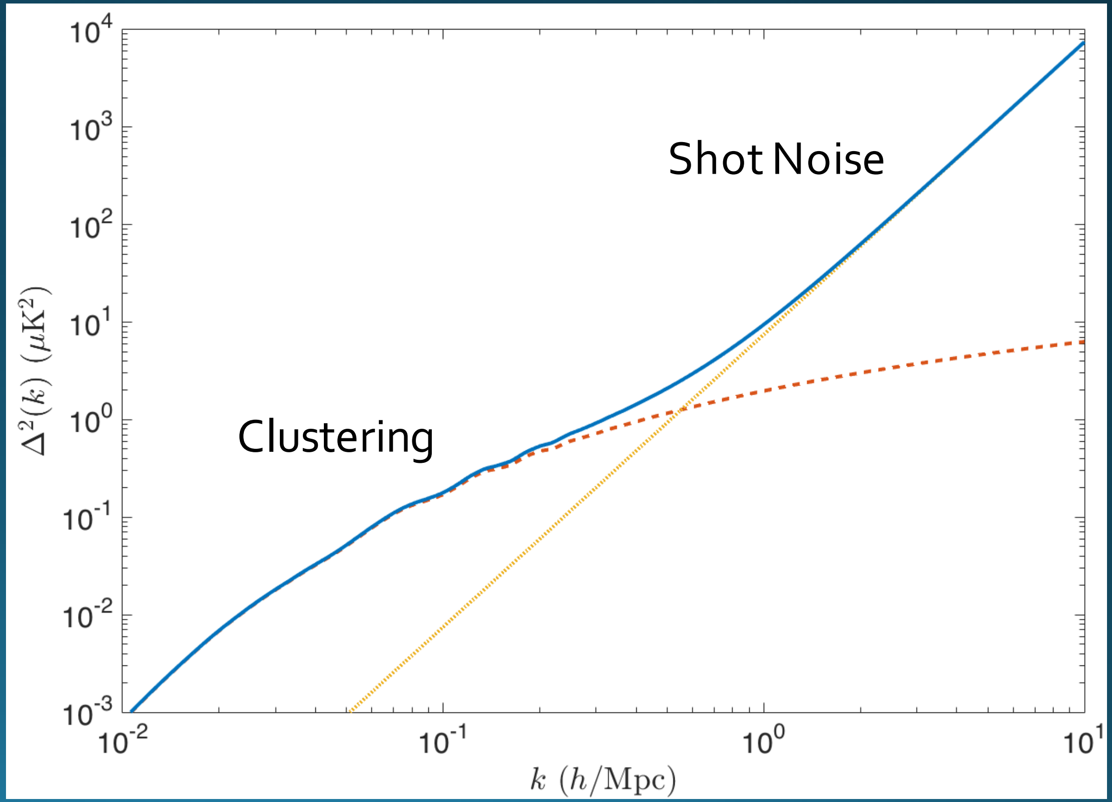
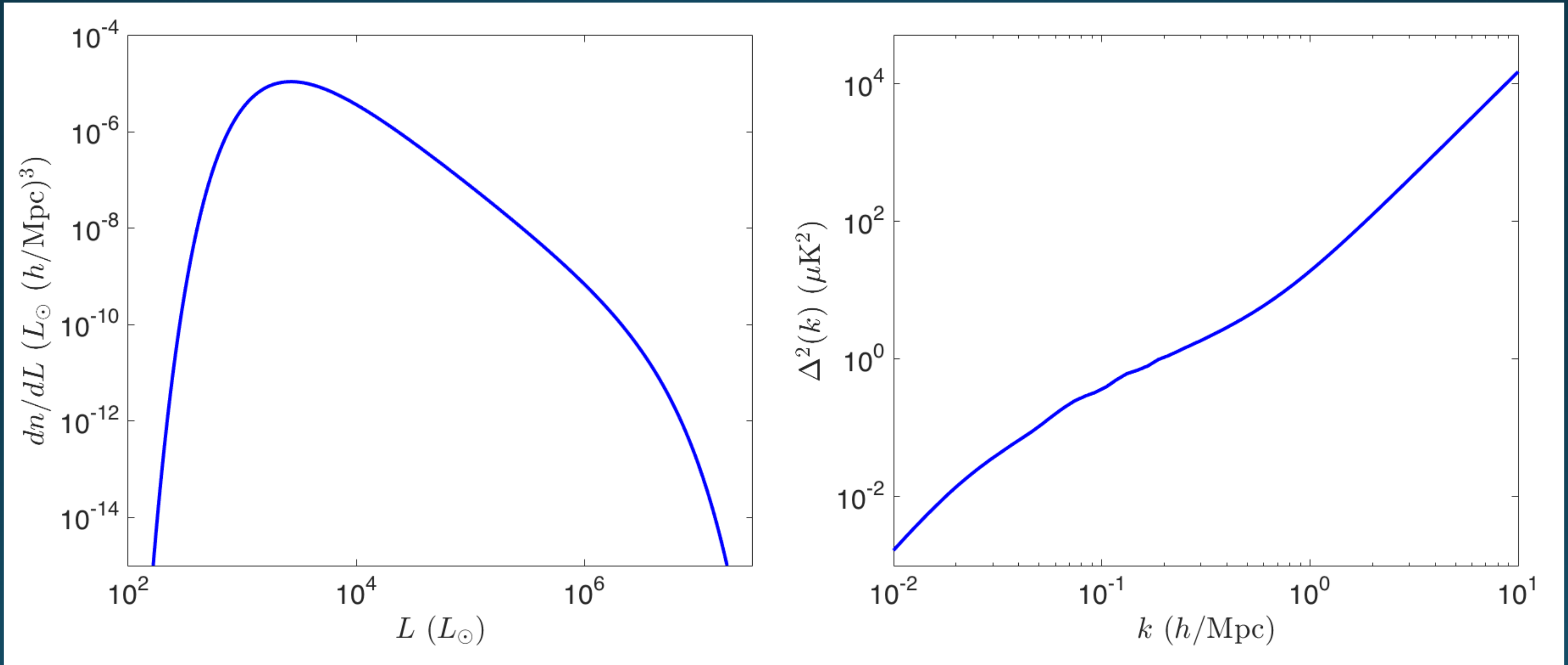
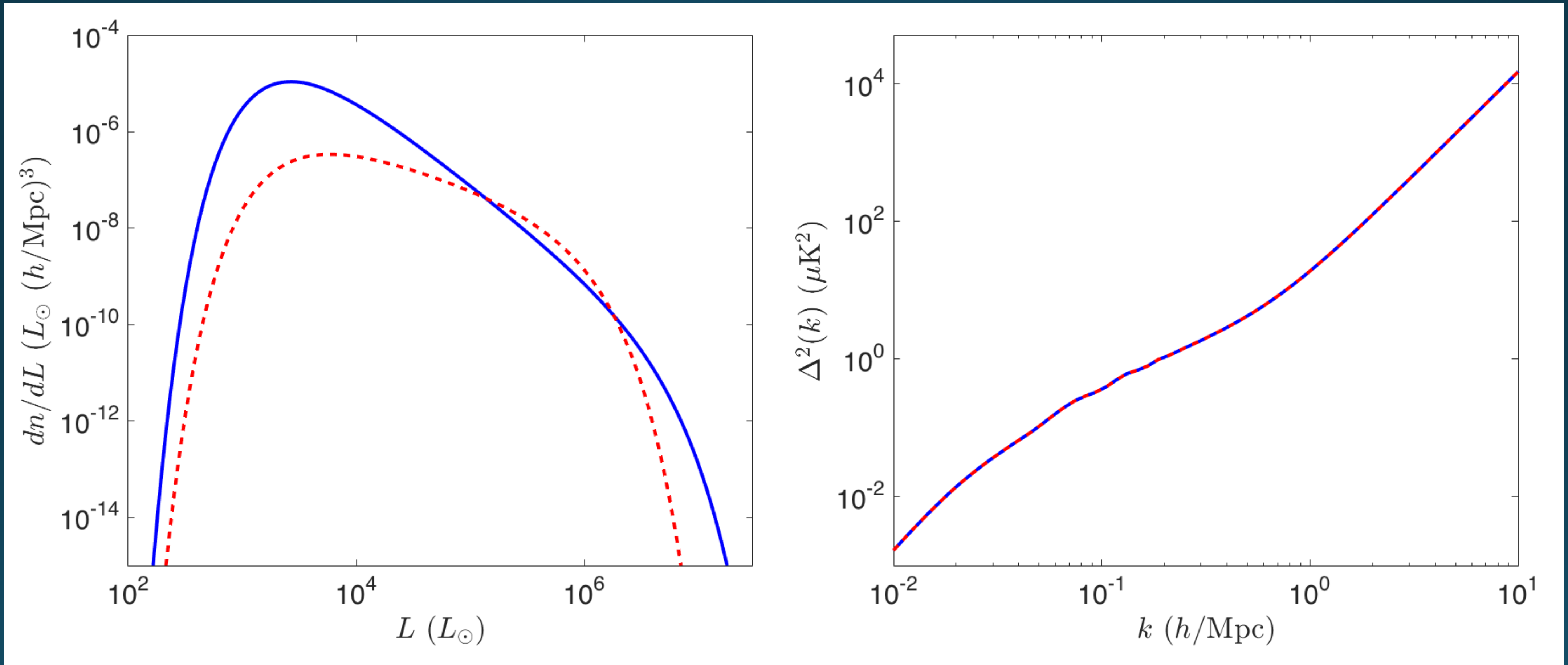


Problem:
The power spectrum contains all of the information in a map if and only if the map is Gaussian

Power Spectrum Limitations



Power Spectrum Limitations



Solution: One-Point Statistics

$P(D)$ Analysis

$\mathcal{P}(T)$

Probability of observing T
in a given voxel

Breysse, P.C., Kovetz, E. D., Behroozi, P. S., Dai, L., Kamionkowski, M., 2016, arXiv:1609.01728

$P(D)$ Analysis

$$\mathcal{P}(T) = \sum_{N=0}^{\infty} \mathcal{P}_N(T)$$

Probability of observing T in a voxel containing exactly N sources

Breysse, P.C., Kovetz, E. D., Behroozi, P. S., Dai, L., Kamionkowski, M.,2016, arXiv:1609.01728

$P(D)$ Analysis

$$\mathcal{P}(T) = \sum_{N=0}^{\infty} \mathcal{P}_N(T)\mathcal{P}(N)$$

Probability of a voxel to contain exactly N sources

Breysse, P.C., Kovetz, E. D., Behroozi, P. S., Dai, L., Kamionkowski, M., 2016, arXiv:1609.01728

$P(D)$ Analysis

$$\mathcal{P}(T) = \sum_{N=0}^{\infty} \mathcal{P}_N(T)\mathcal{P}(N)$$

$$\mathcal{P}_N(T) \Leftarrow \frac{dn}{dL}$$

Computed from luminosity function

Breysse, P.C., Kovetz, E. D., Behroozi, P. S., Dai, L., Kamionkowski, M., 2016, arXiv:1609.01728

$P(D)$ Analysis

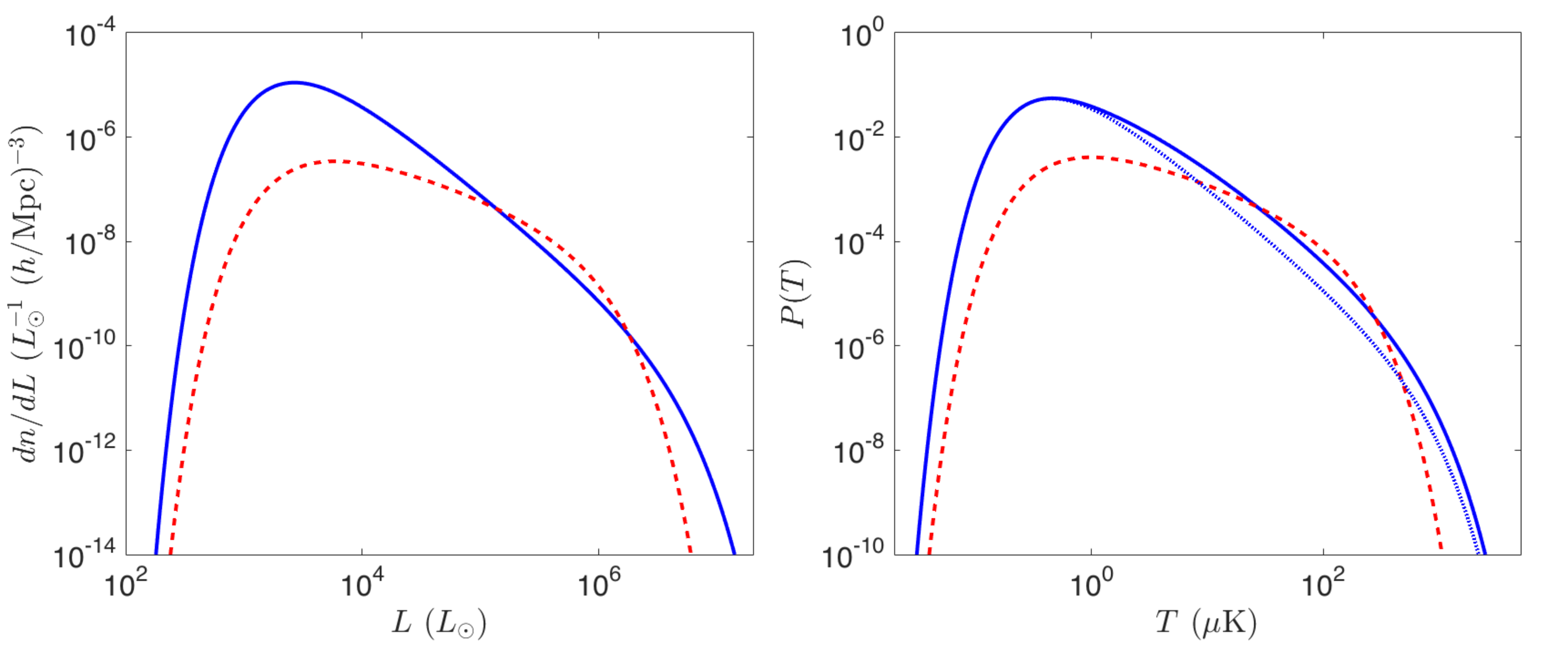
$$\mathcal{P}(T) = \sum_{N=0}^{\infty} \mathcal{P}_N(T)\mathcal{P}(N)$$

$$\mathcal{P}_N(T) \Leftarrow \frac{dn}{dL}$$ Computed from luminosity function

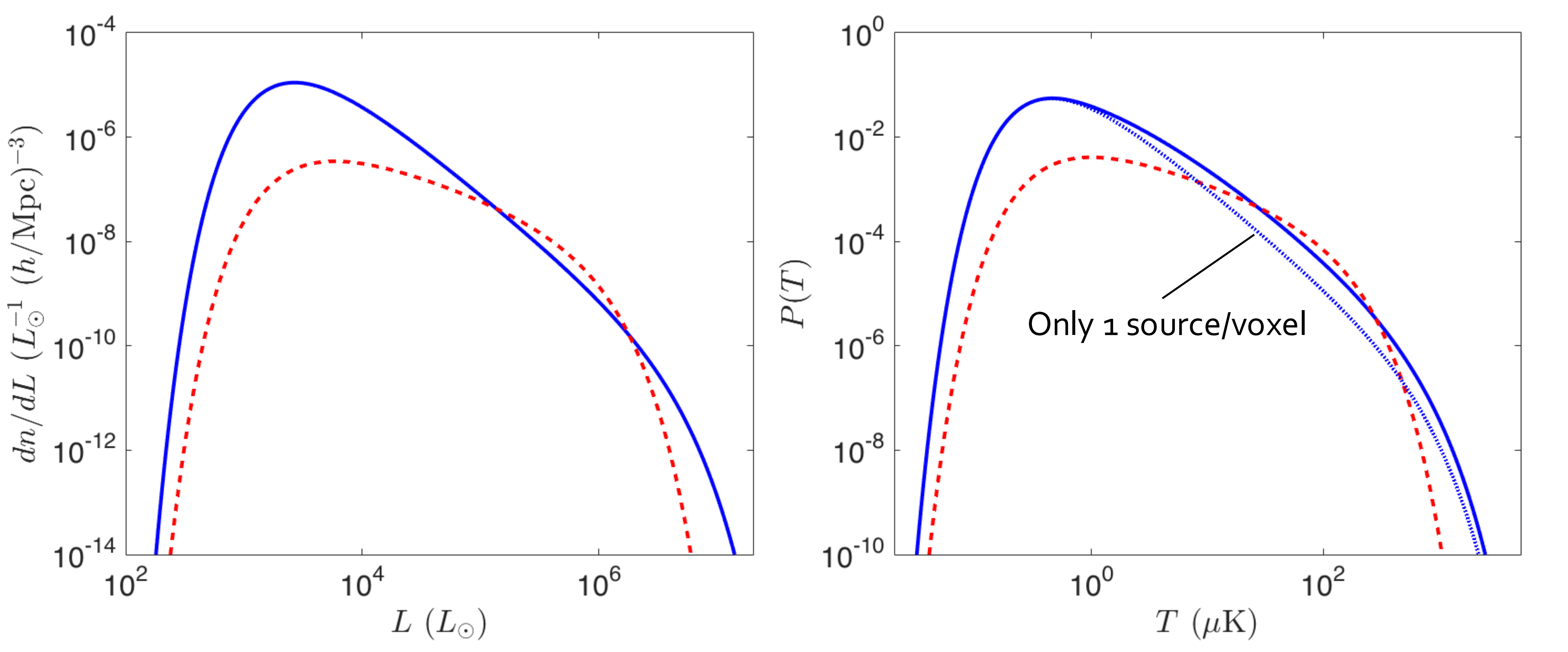
$$\mathcal{P}(N) \Leftarrow \int P_m(k)dk$$ Related to integrals of power spectrum

Breysse, P.C., Kovetz, E. D., Behroozi, P. S., Dai, L., Kamionkowski, M., 2016, arXiv:1609.01728

Voxel Intensity Distribution



Voxel Intensity Distribution



Power spectrum gives detailed clustering, integrals over luminosity function

VID gives detailed luminosity function, integrals over clustering

Example: CO Intensity Mapping

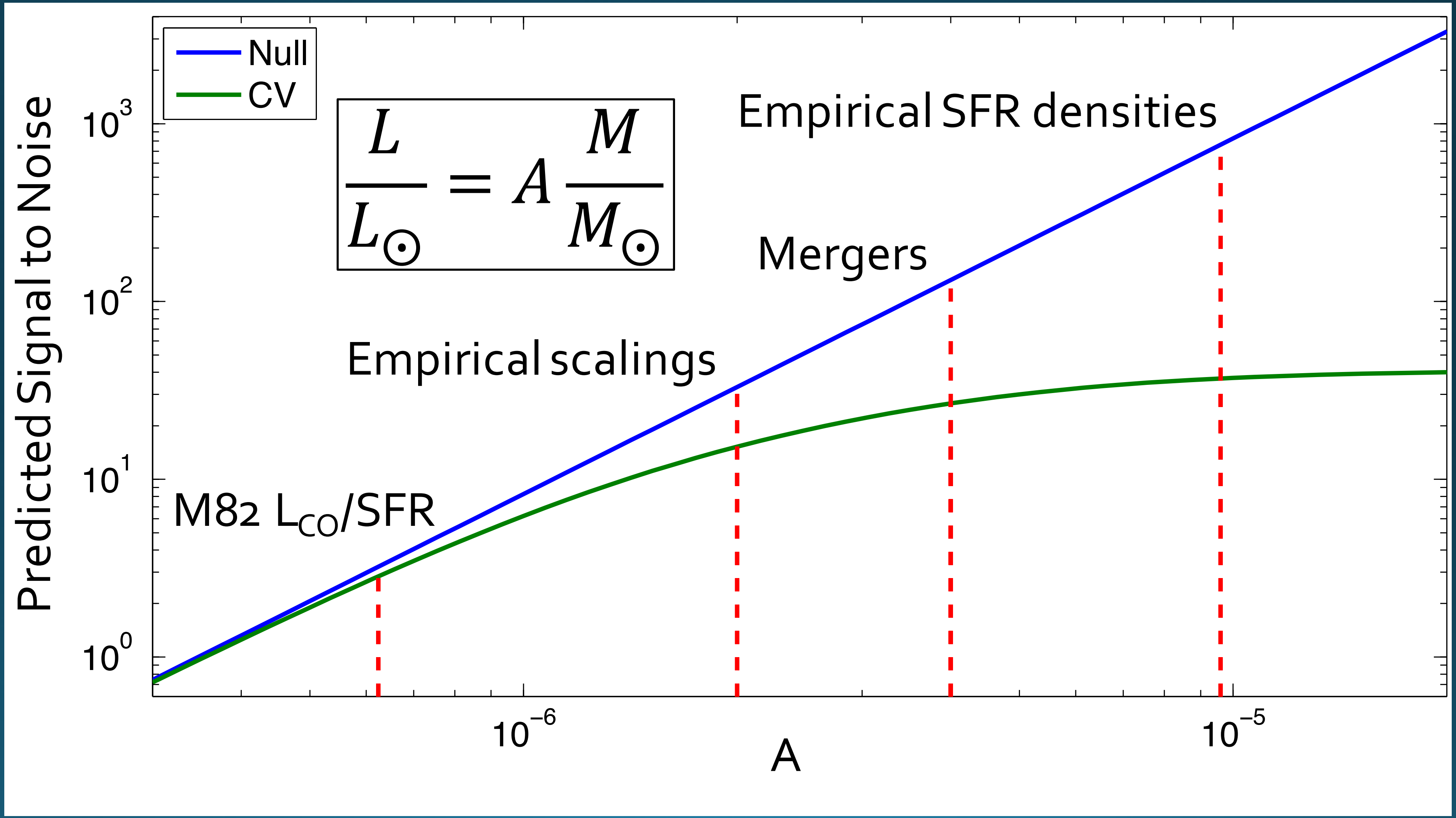
CO Intensity Mapping

- 115 GHz CO(1-0) rotational transition
- Popular tracer of molecular gas and star formation
- Properties at high redshift are very uncertain
- Current experiments targeting atmospheric window at ~30 GHz (z~3)

CO Intensity Mapping

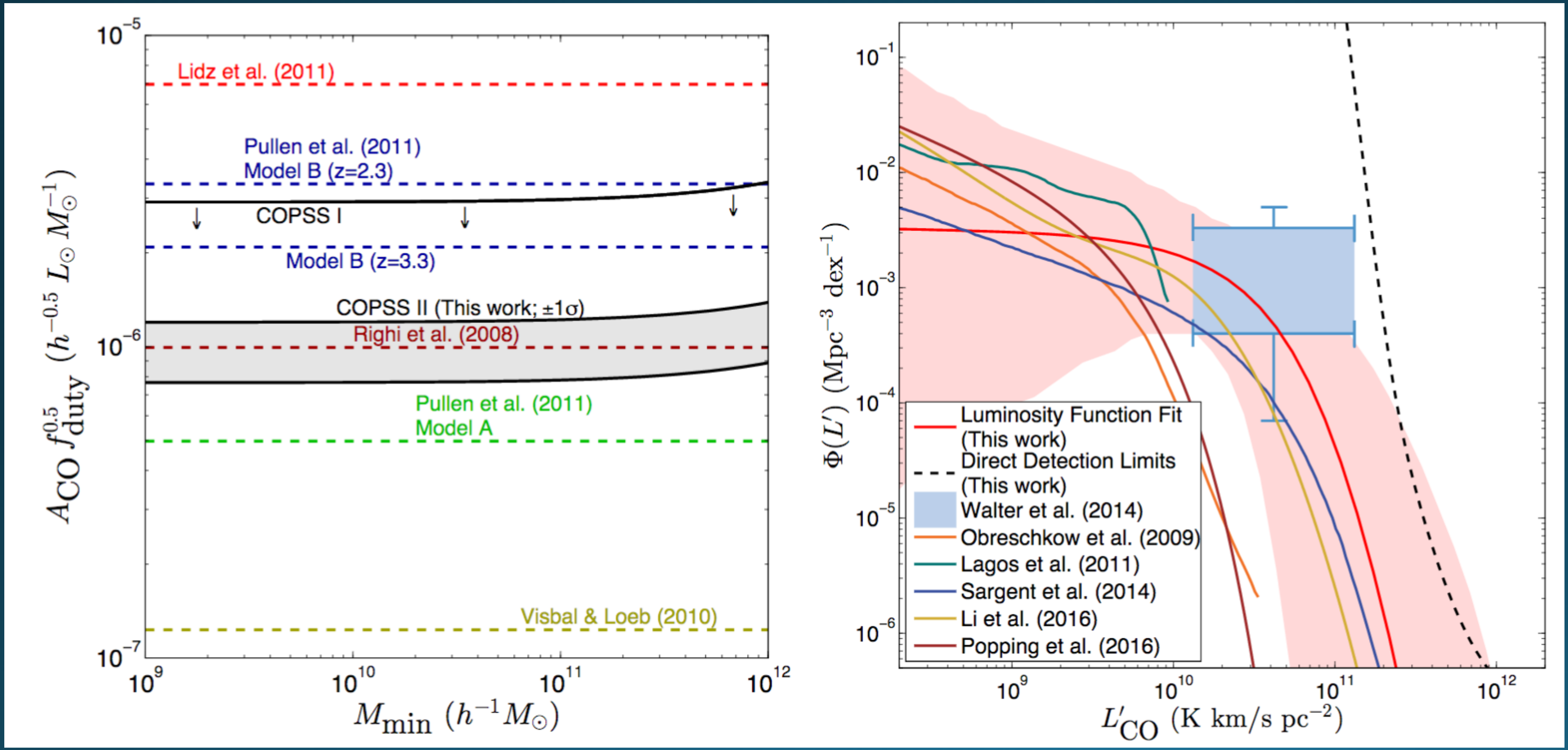
2014

(THEORY)



Breysse, P. C., Kovetz, E. D., & Kamionkowski, M. 2014, MNRAS, 443, 3506

CO Intensity Mapping



2016

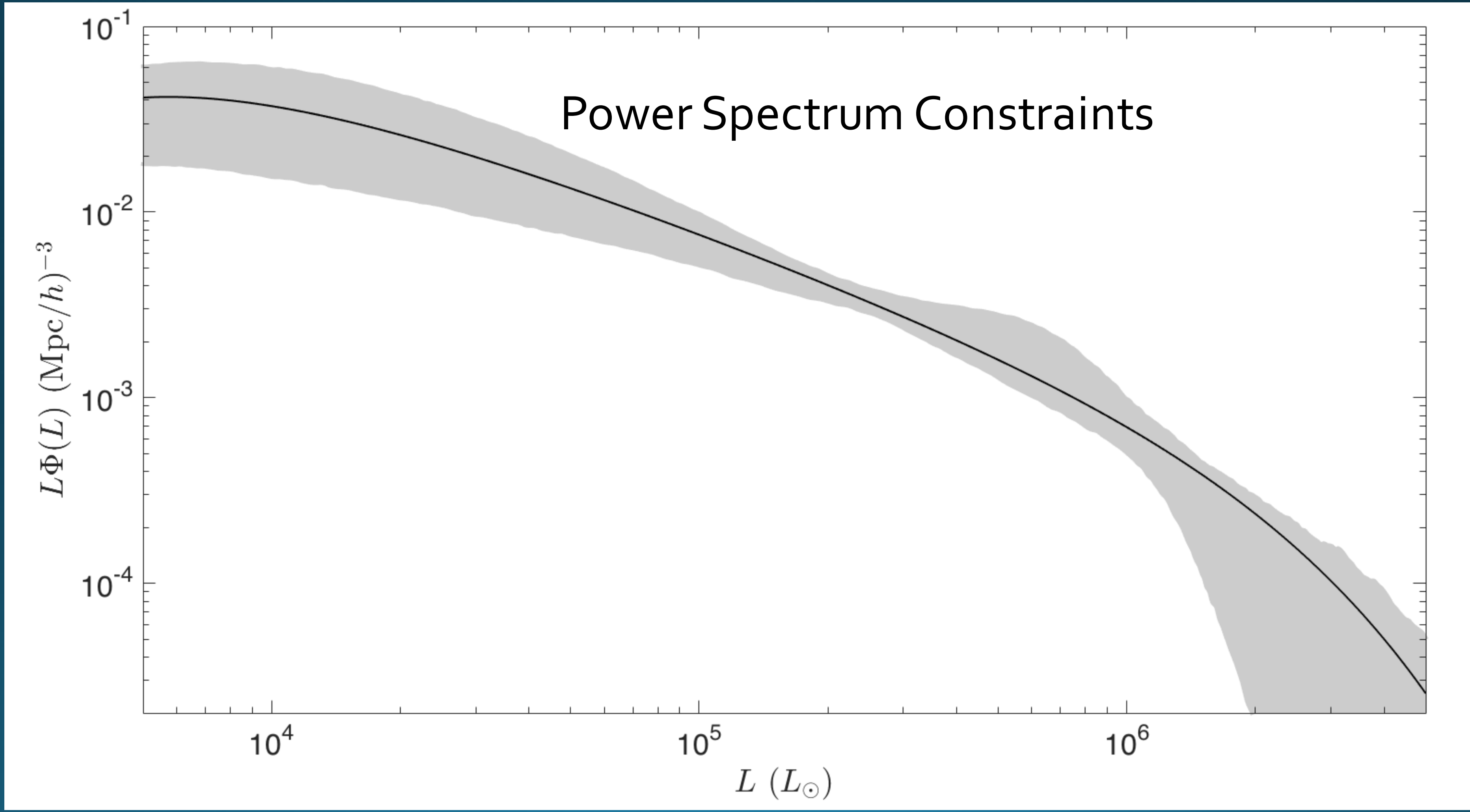
(COPSS)

Keating, G. K. et al., 2016, arXiv:1605.03971

CO Intensity Mapping

~2020

(COMAP)



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CO Intensity Mapping

~2020

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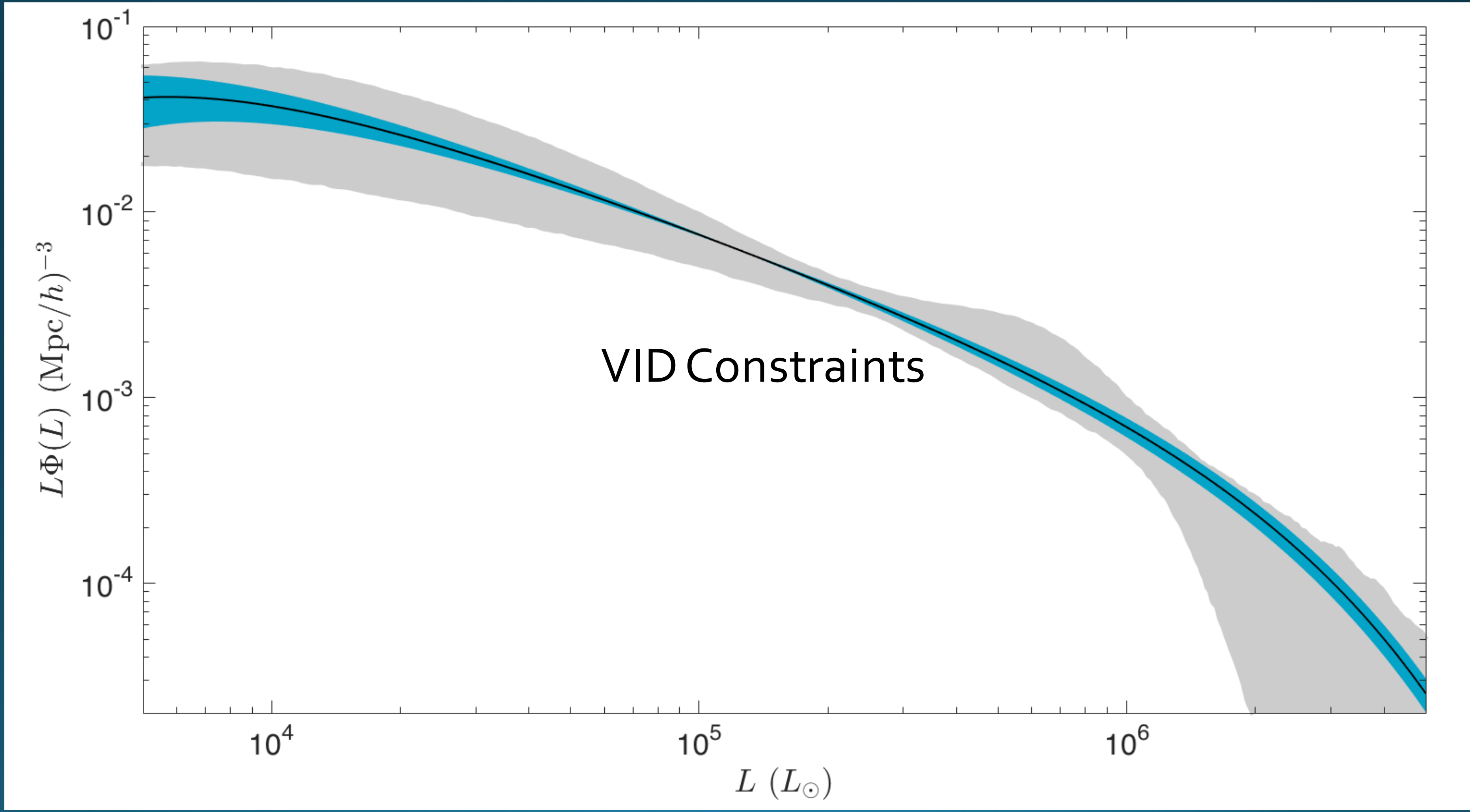

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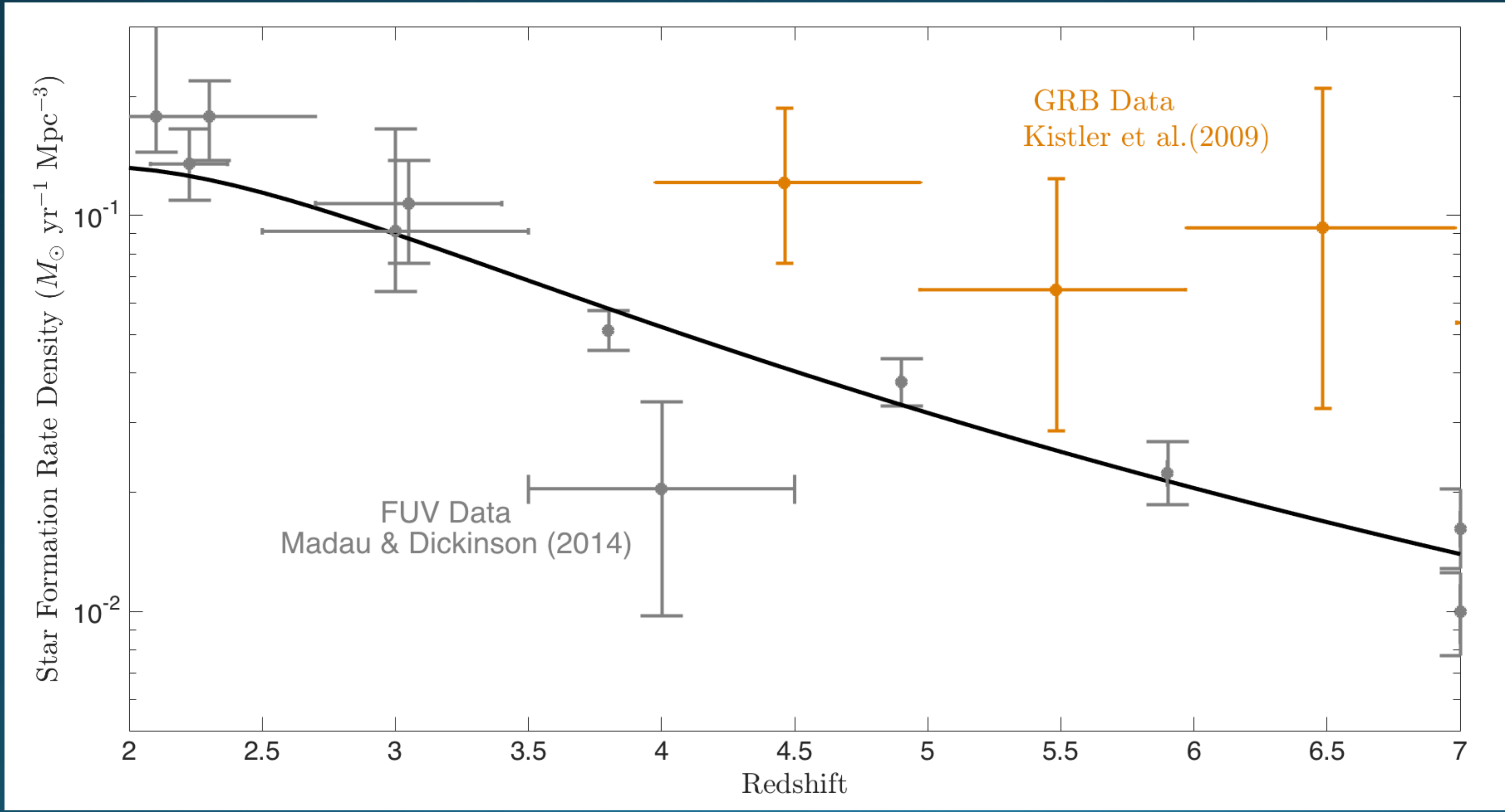
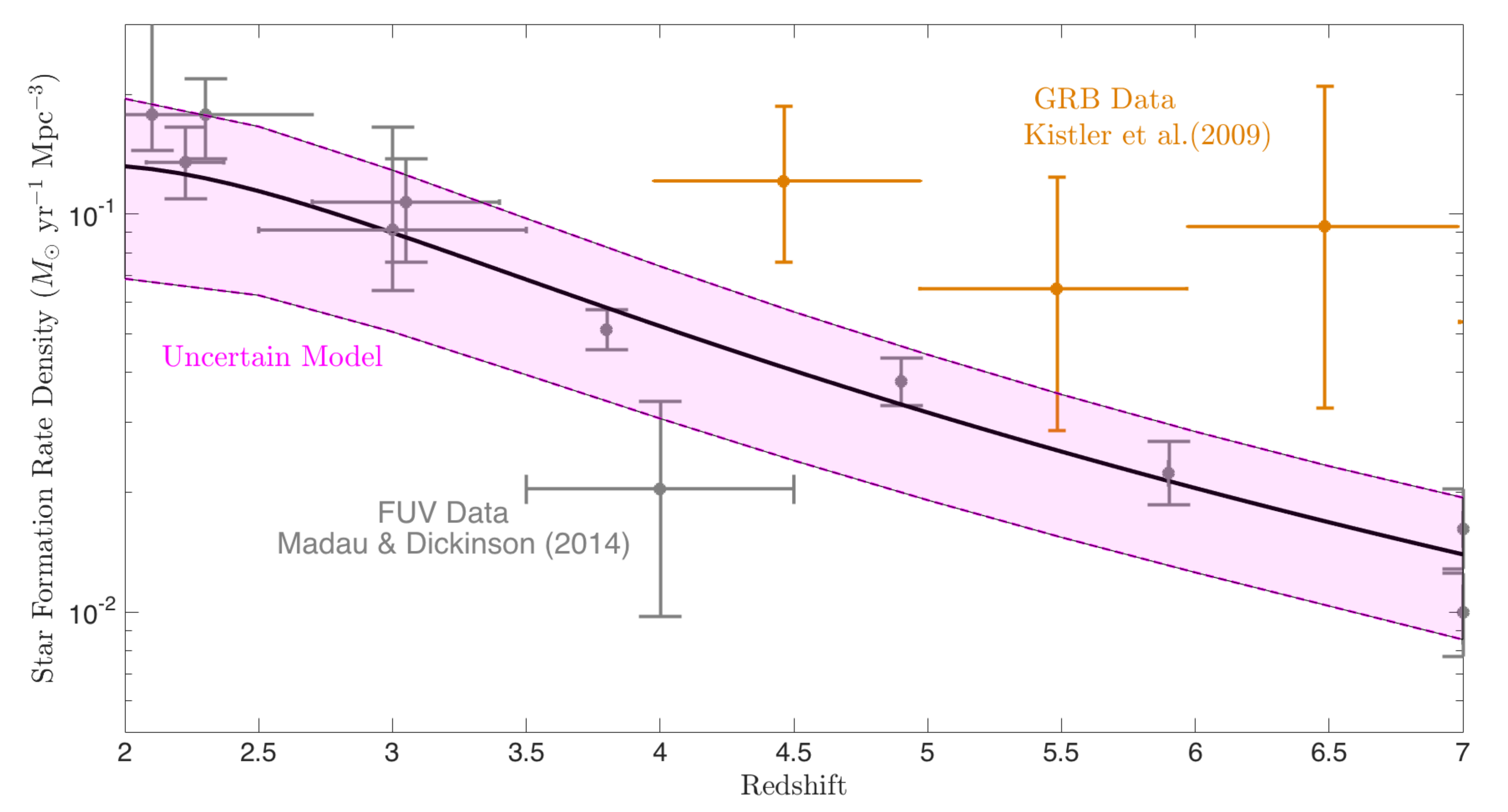
Cosmic Star Formation History

Star Formation History



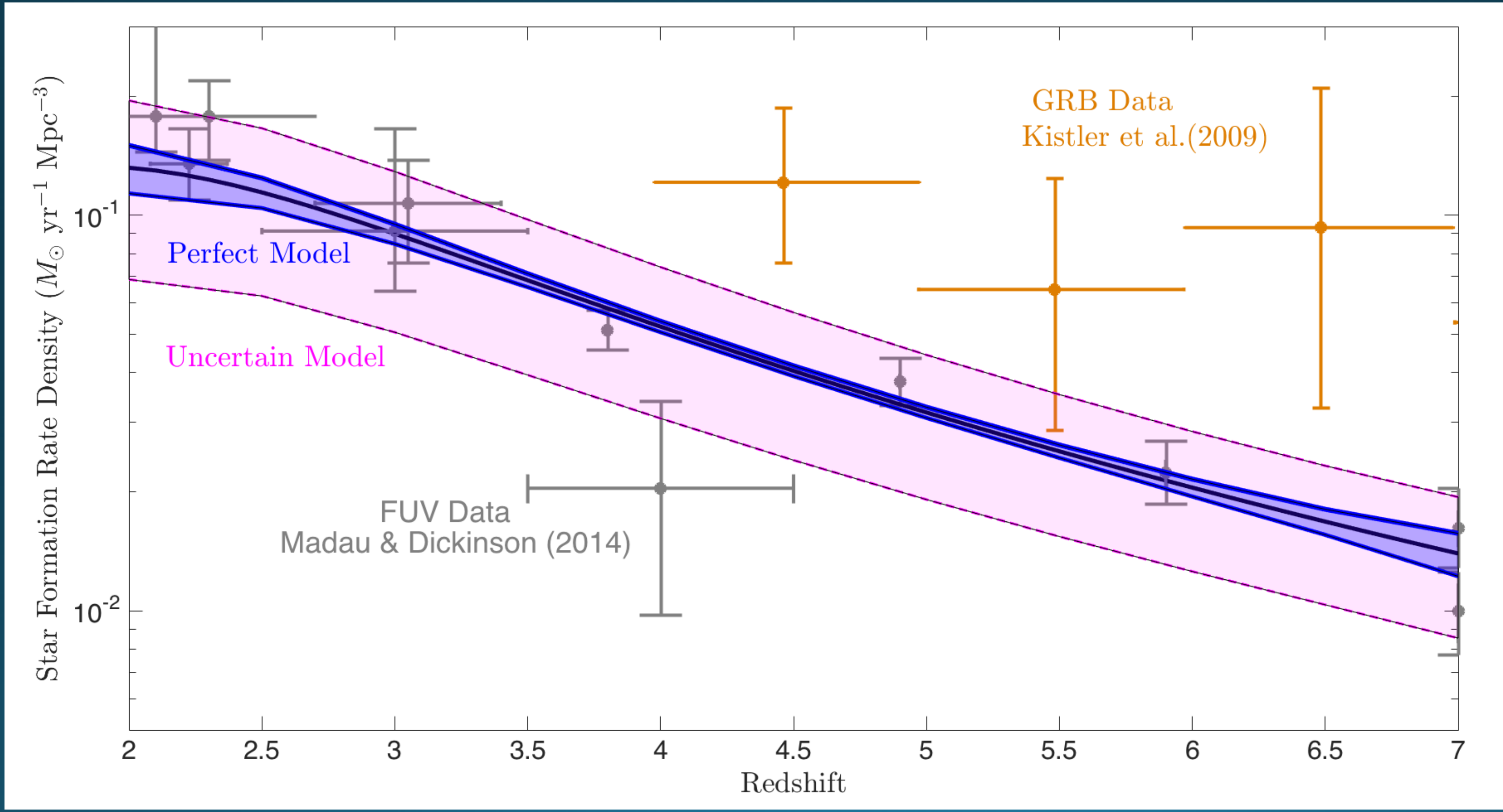
Kistler et al. 2009, ApJ 705, L104; Madau & Dickinson 2014, ARA&A, 52, 415

Star Formation History



Breysse et al., 2016, MNRAS 457, L127; Kistler et al. 2009, ApJ 705, L104; Madau & Dickinson 2014, ARA&A, 52, 415

Star Formation History



Breysse et al., 2016, MNRAS 457, L127; Kistler et al. 2009, ApJ 705, L104; Madau & Dickinson 2014, ARA&A, 52, 415

Future

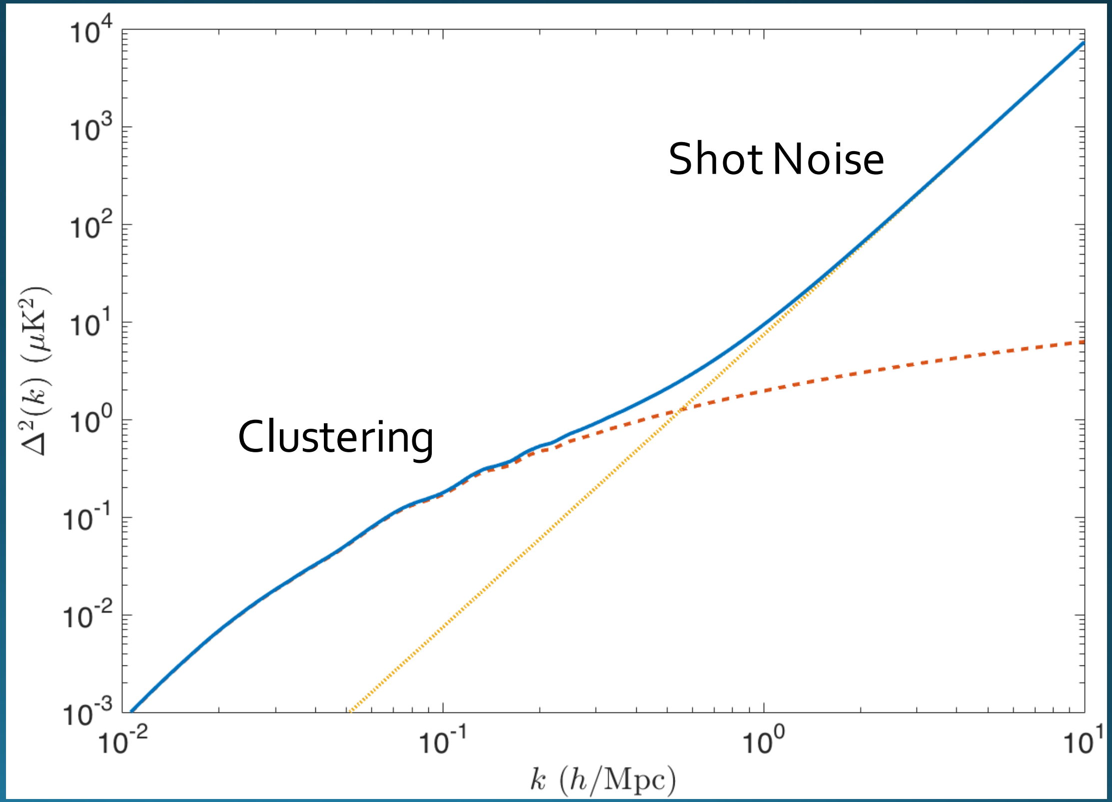
- Reionization
- Cosmological parameter constraints- BAO, etc.
- Redshift space distortions- measure bias?
- Bulk gas motions within galaxies- rotational vs. thermal support

Power Spectrum

$$P(k,z) = \langle T \rangle^2(z) b^2(z)\, P_m(k,z) + P_{\text{shot}}(z)$$

$$\langle T^2(z) \rangle \propto \int L \frac{dn(z)}{dL} dL$$

$$P_{\text{shot}}(z) \propto \int L^2 \frac{dn(z)}{dL} dL$$



Future

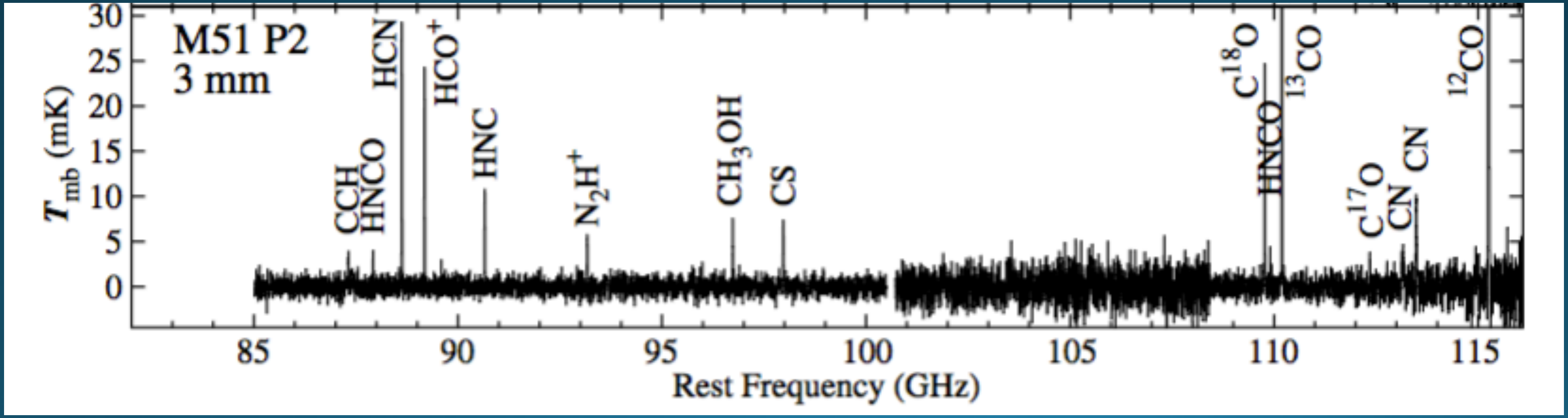
- Forecasts for other lines
- Cosmological parameter constraints- BAO, etc.
- Redshift space distortions- measure bias?
- Bulk gas motions within galaxies- rotational vs. thermal support

Using Multiple Lines

Breysse, P. C., Kovetz, E. D., & Kamionkowski, M. 2015, MNRAS, 452, 3408
Breysse, P. C., Rahman M., 2016, arXiv:1606.07820

Using Multiple Lines

- Any intensity map will contain emission from other lines besides target line
- Each frequency bin contains emission from many lines at many redshifts

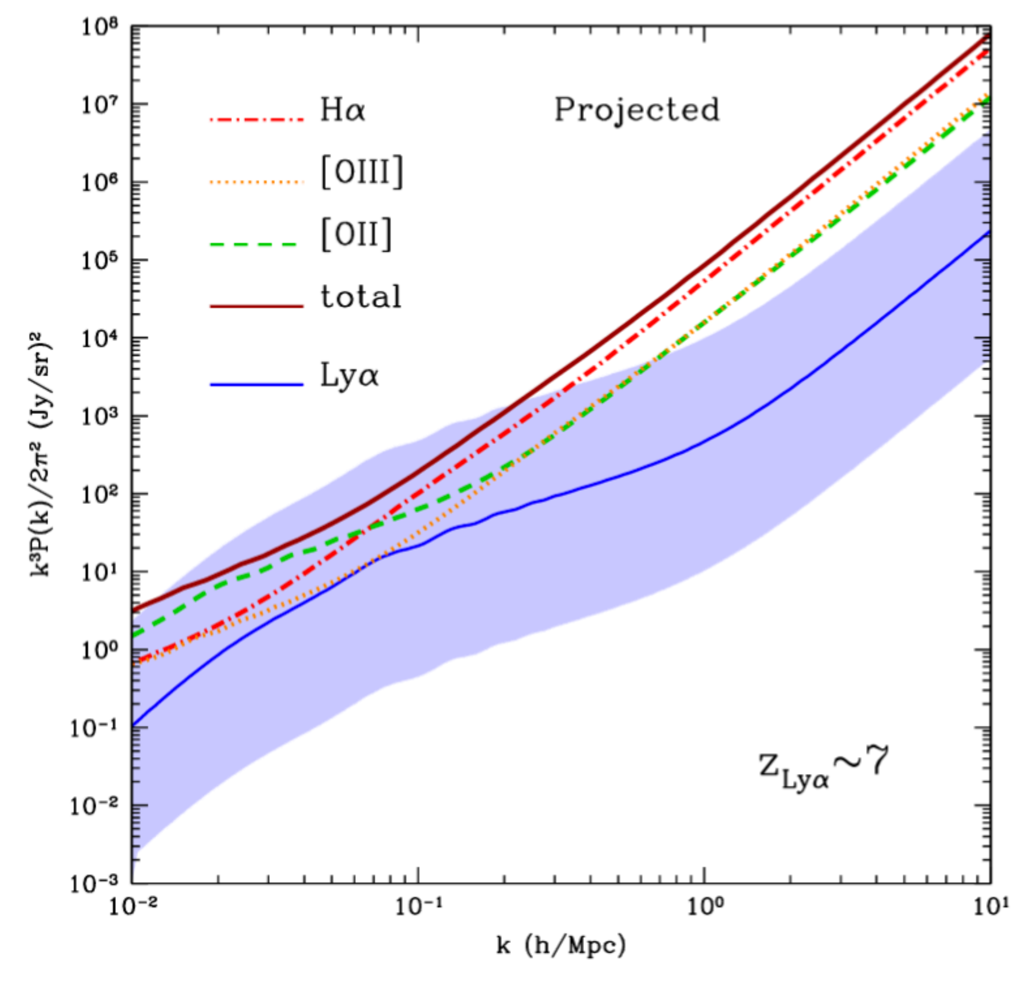


Juan R. Pardo *et al.* 2007 *ApJ* **661** 250

Foreground Contamination

- Bright lines redshifted into the same frequency band can wash out signal from desired line

- Examples:
  - CII contaminated by higher-J CO lines
  - Lyα contaminated by OII, OIII, Hα



Gong, Y., Silva, M., Cooray, A.,\& Santos, M.~G. 2014, ApJ, 785, 72

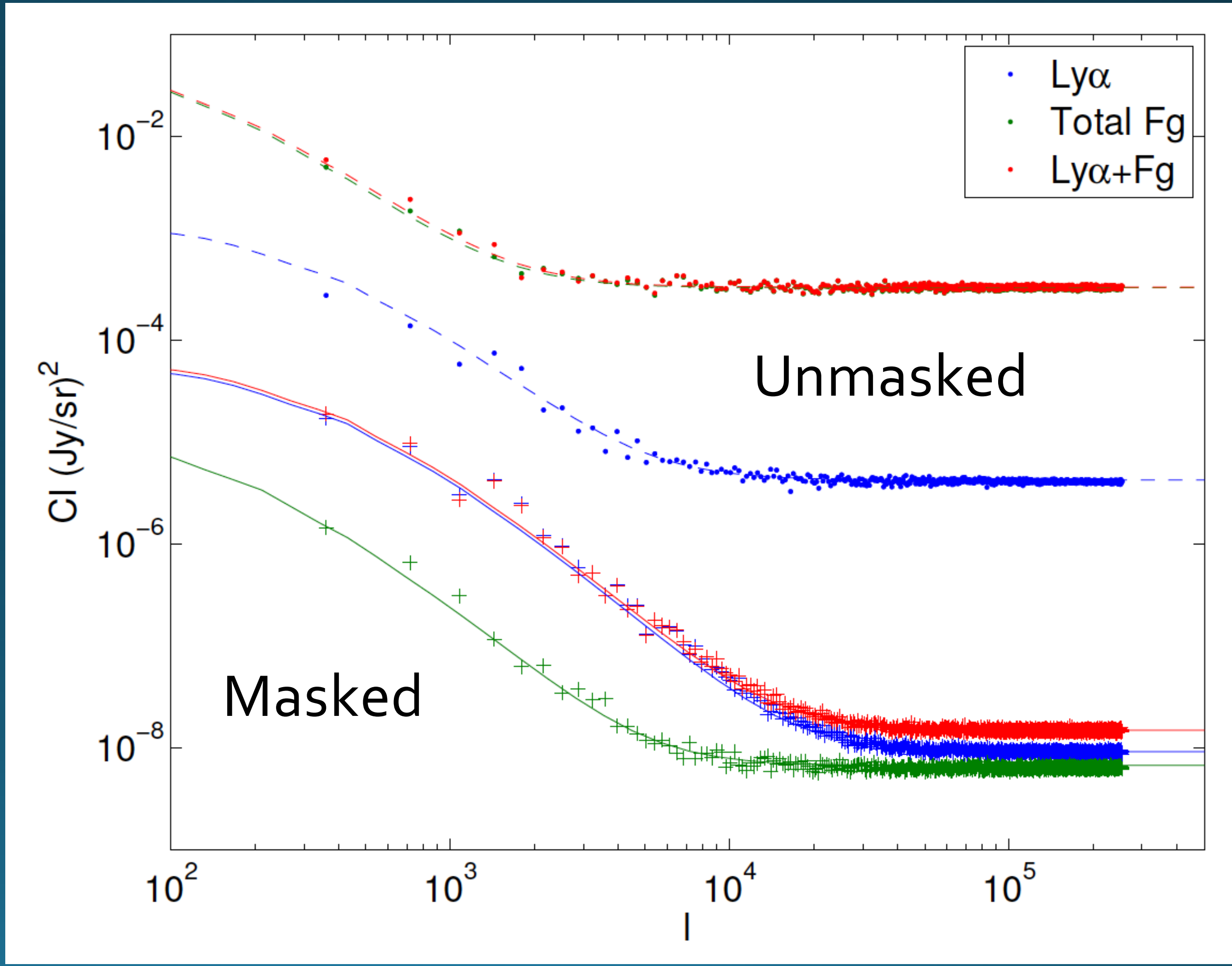
Cleaning Foregrounds

Blind Masking

- Foreground tends to dominate most in brightest voxels
- Mask out brightest parts of map to get at signal

Targeted Masking

- Use external data set to mask only bright foreground voxels



Breysse, P. C., Kovetz, E. D., & Kamionkowski, M. 2015, MNRAS, 452, 3408

Cleaning Foregrounds

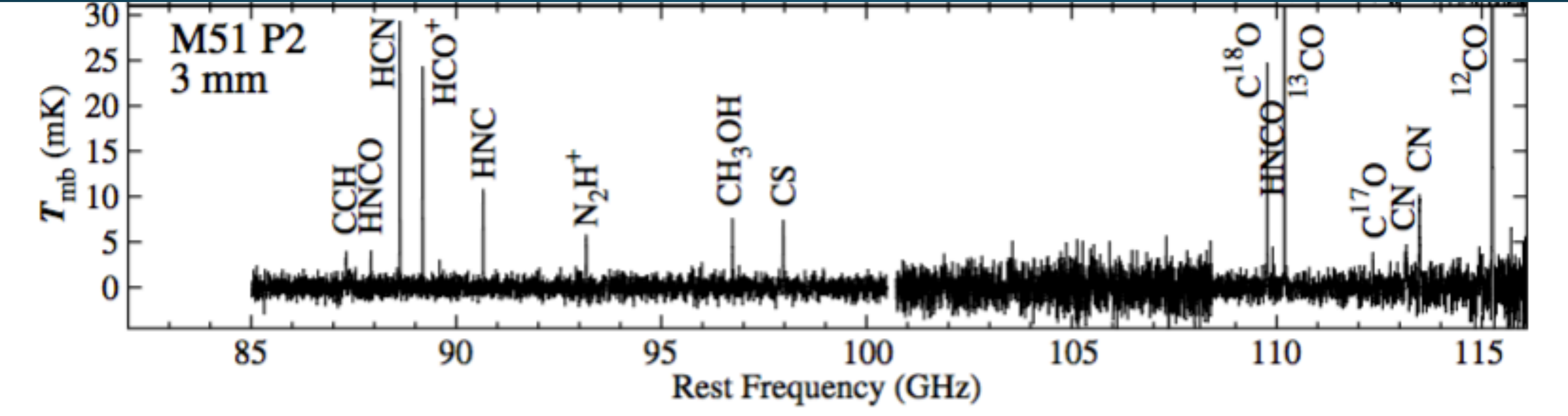
Power spectrum anisotropies

- Foreground spectrum will have different behavior with $(k_\parallel, k_\perp)$ (see e.g. arXiv:1604.05737)

- Cross-correlations
  - Correlate map with an external data set at the same redshift
  - Can be another intensity map or a galaxy survey

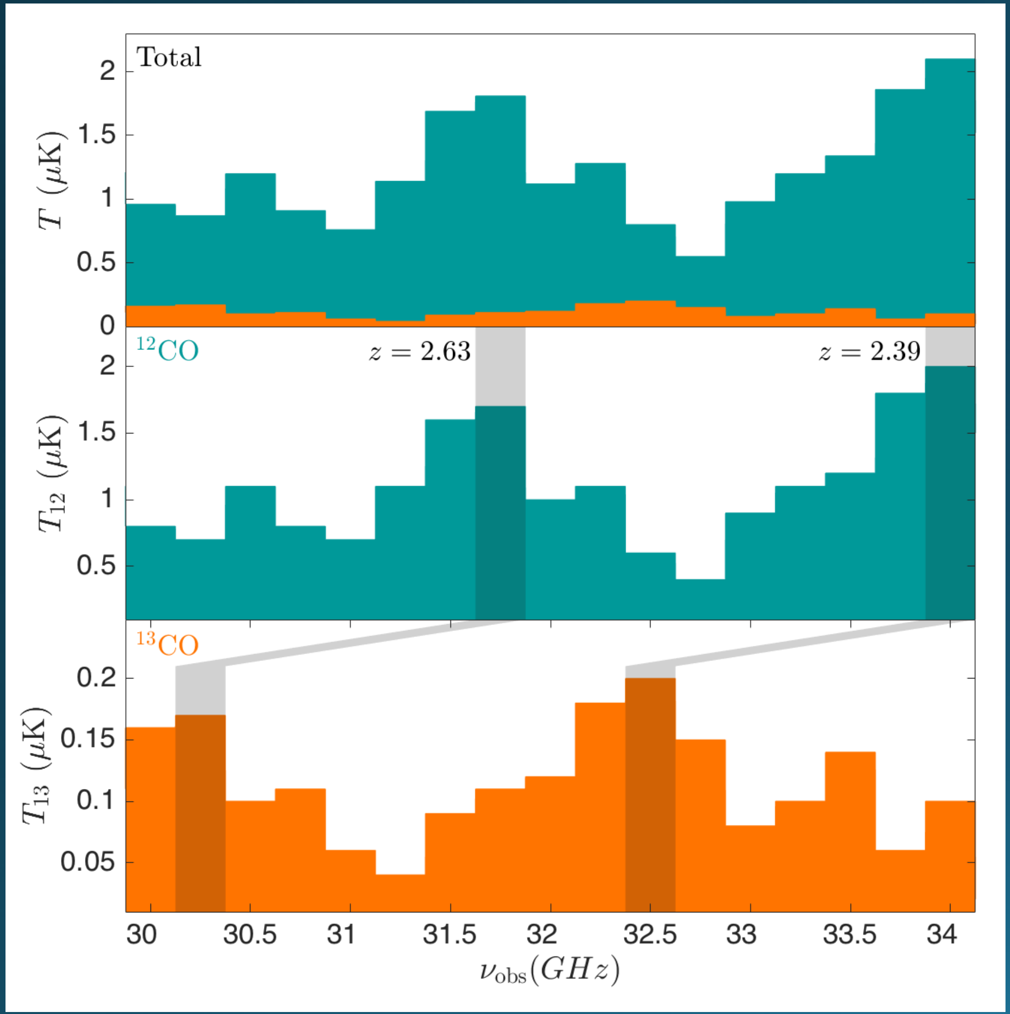
Cross-Correlations

Can also use cross correlations to get at information contained in fainter lines



Juan R. Pardo *et al.* 2007 *ApJ* **661** 250

Example: ^{13}CO



- Any ^{12}CO survey will also contain emission from ^{13}CO
- ^{13}CO is much fainter than ^{12}CO, so ^{12}CO dominates any given pixel
- Frequency bins separated by ~1.4 GHz contain ^{12}CO and ^{13}CO at the same redshift

Breysse, P. C., Rahman M., 2016, arXiv:1606.07820

Cross-Spectrum

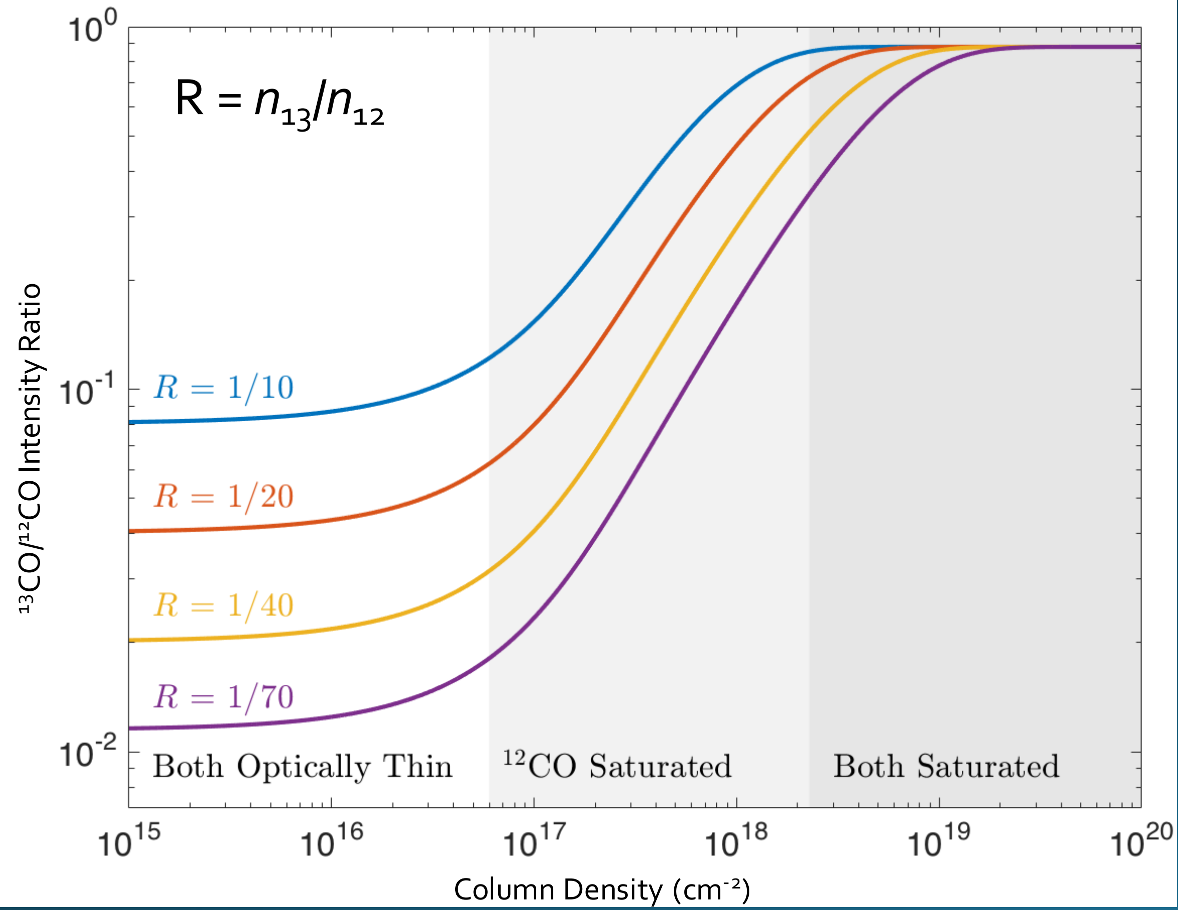
- Assume both lines come from the same population of galaxies
- Luminosity L_2 of line 2 is a function of the luminosity of line 1

$$P_{1,2}(k) = \langle T_1 \rangle \langle T_2 \rangle \, b_1 b_2 P_m(k) + P_{1,2,shot}$$

$$P_{1,2,shot} \propto \int L_1 L_2(L_1) \frac{dn}{dL_1} dL_1$$

Breysse, P. C., Rahman M., 2016, arXiv:1606.07820

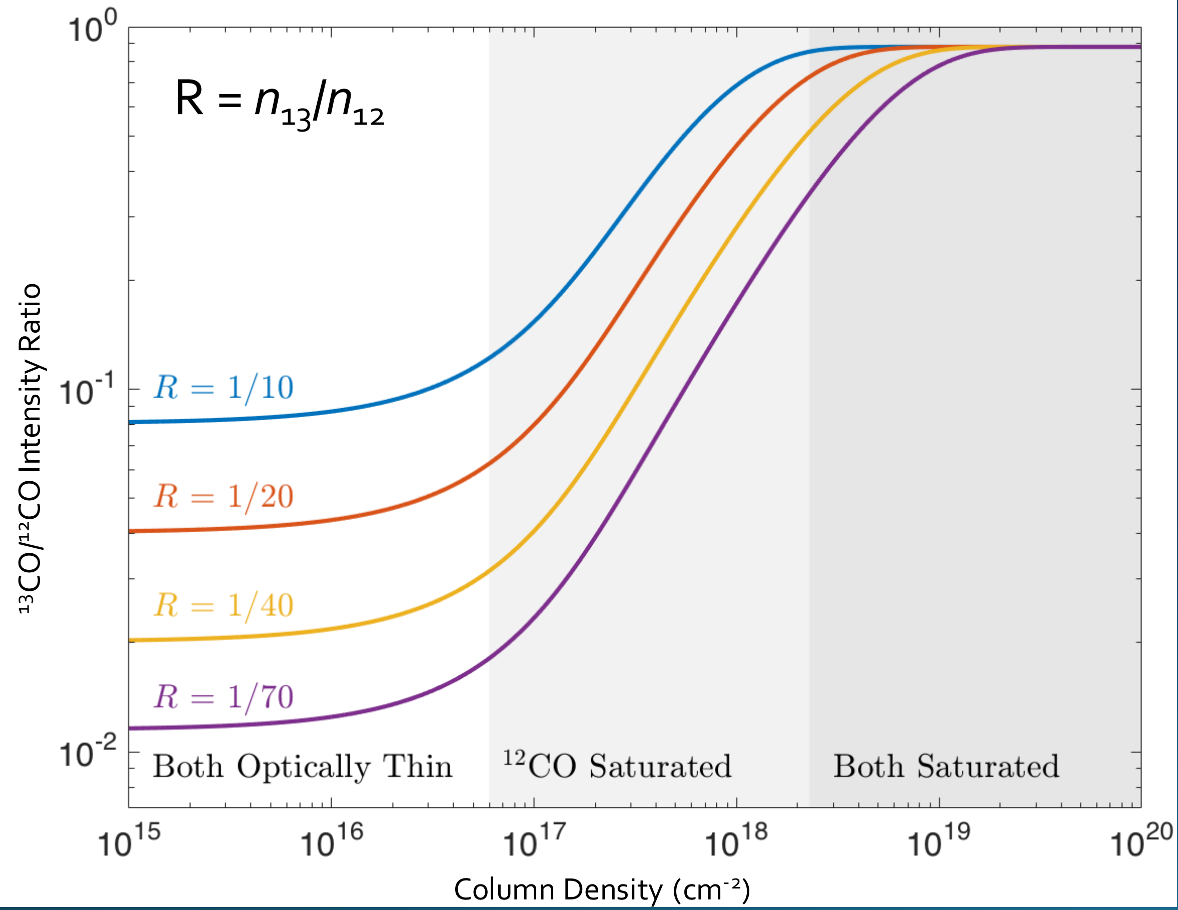
Molecular Gas Properties

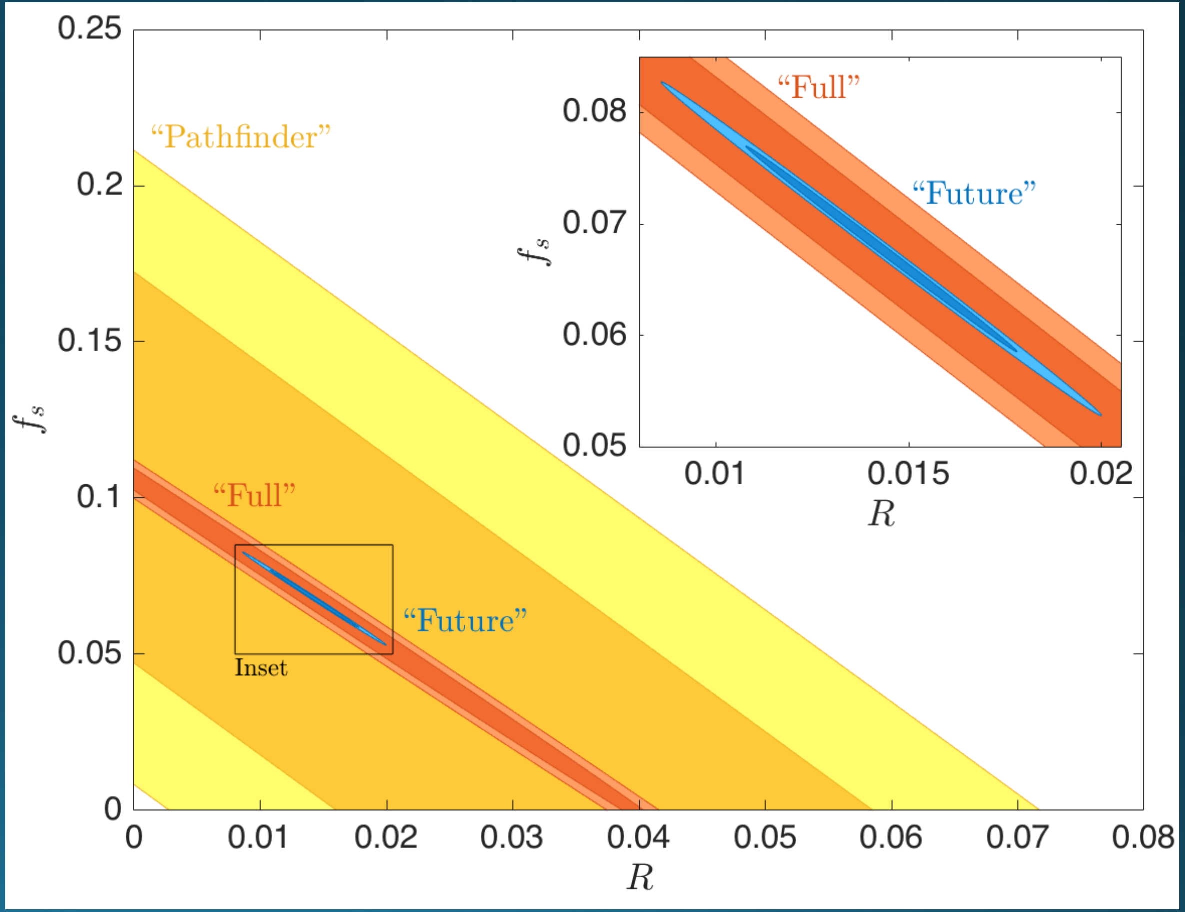


- ^{12}CO saturates very quickly
- ^{13}CO traces deeper into molecular clouds
- Intensity ratio depends on abundance ratio, optical depth

Breysse, P. C., Rahman M., 2016, arXiv:1606.07820

Molecular Gas Properties





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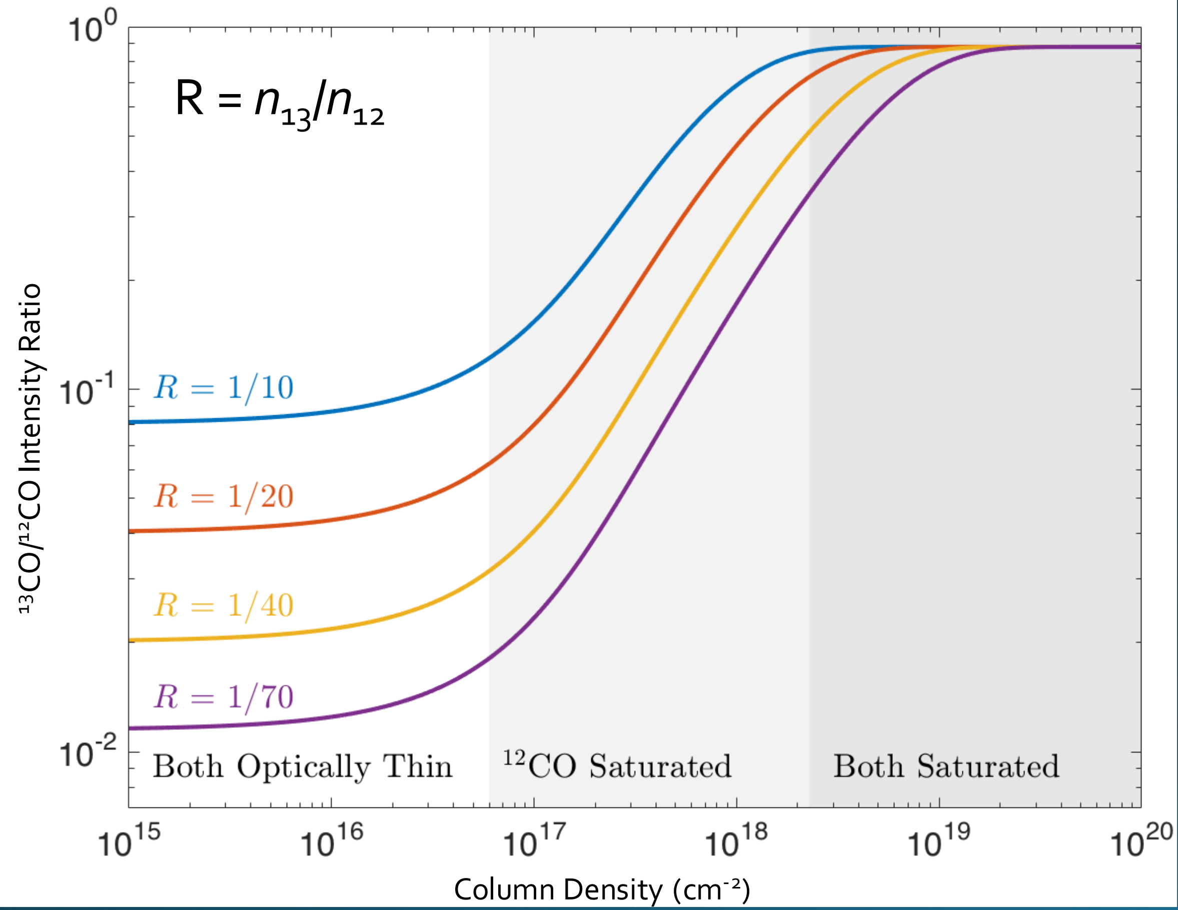

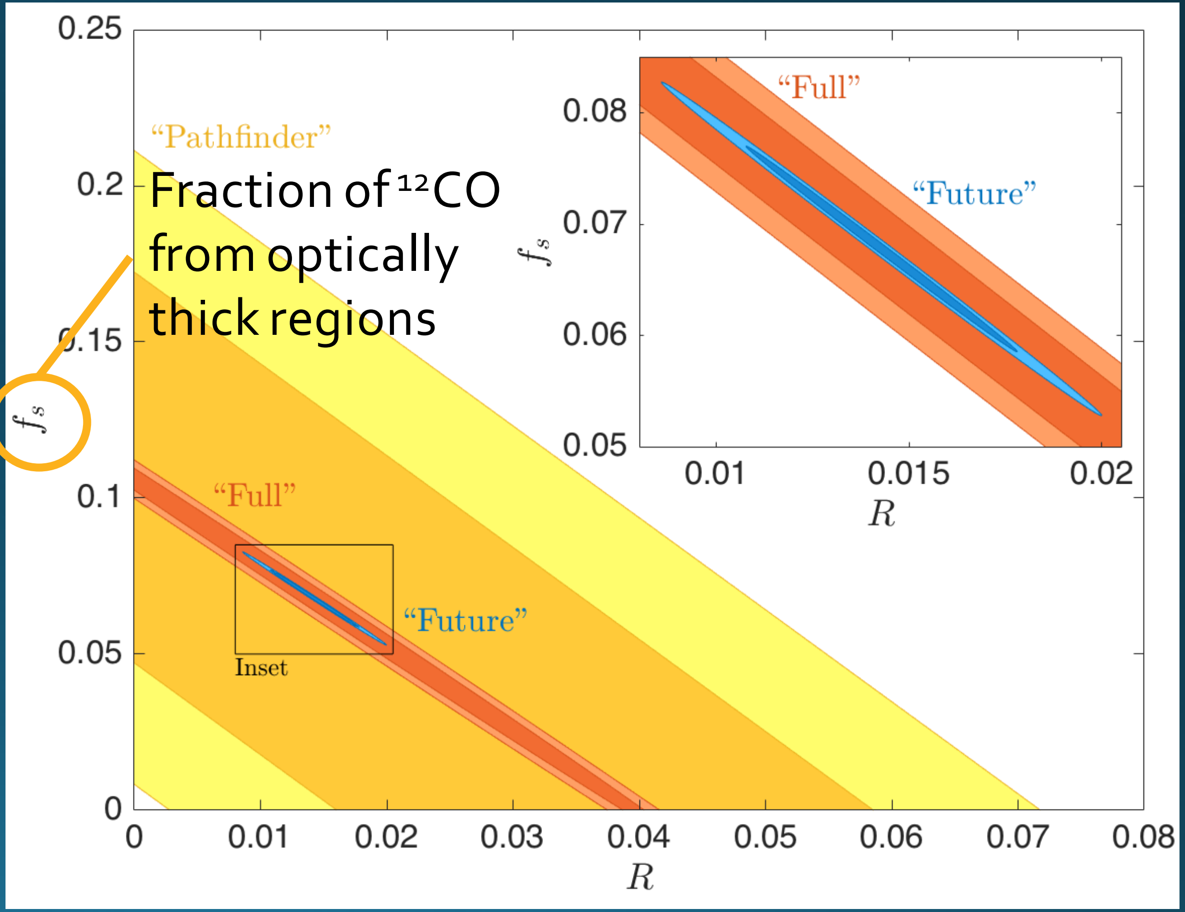

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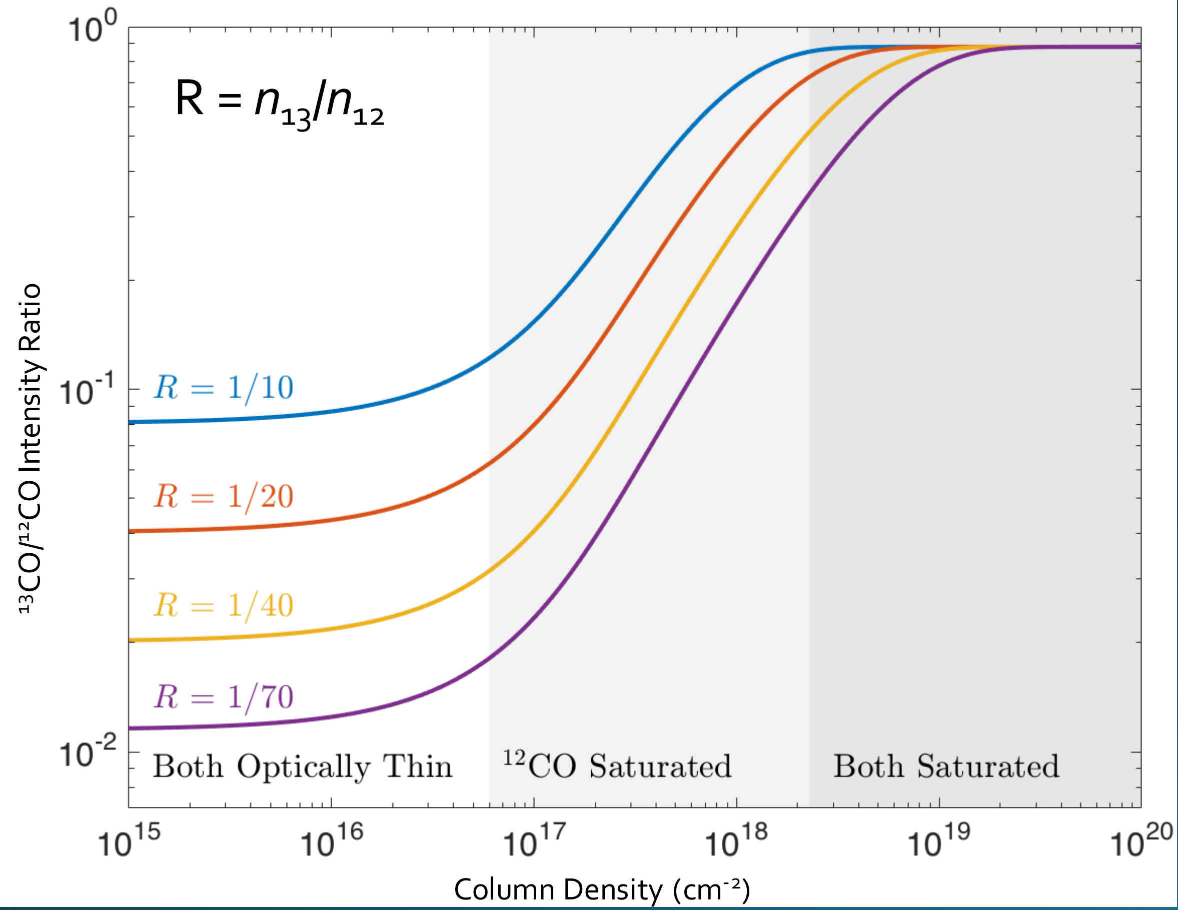
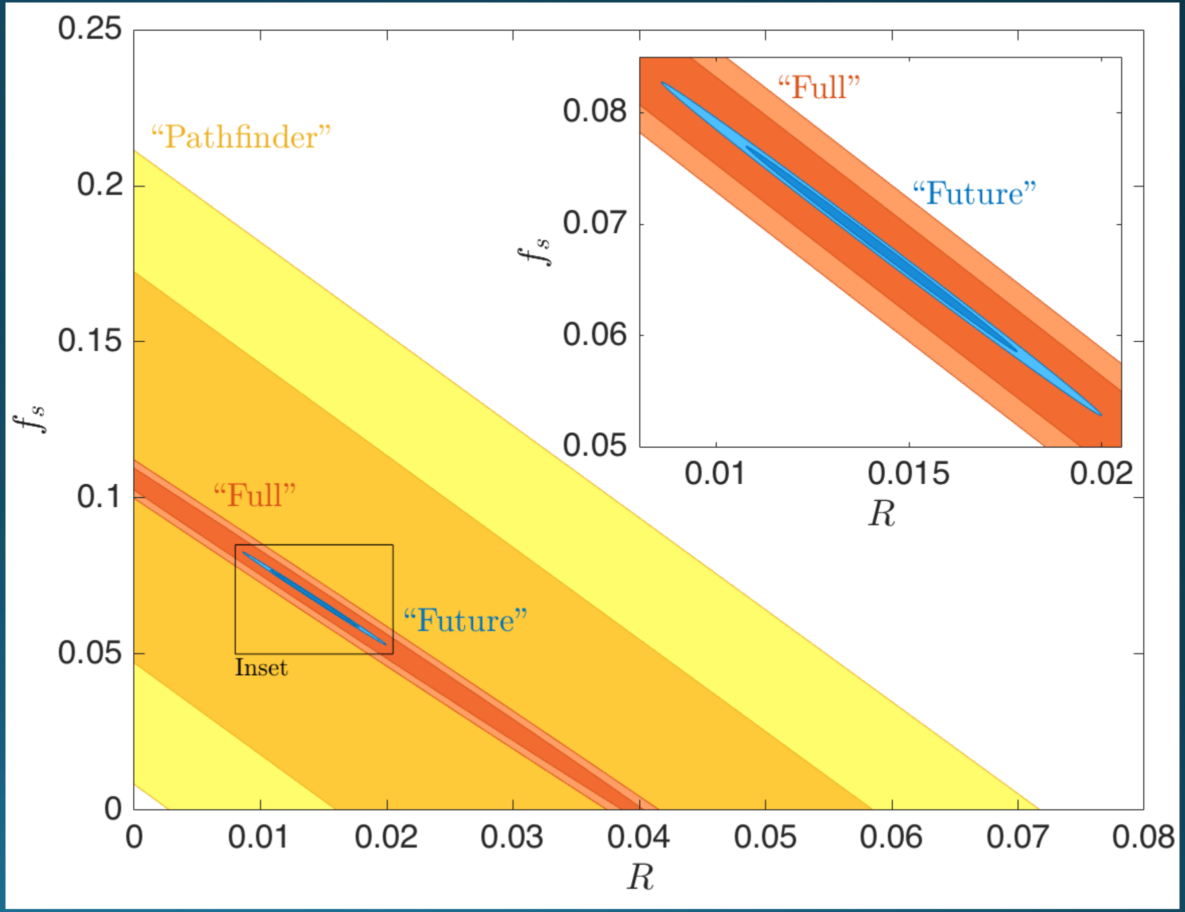
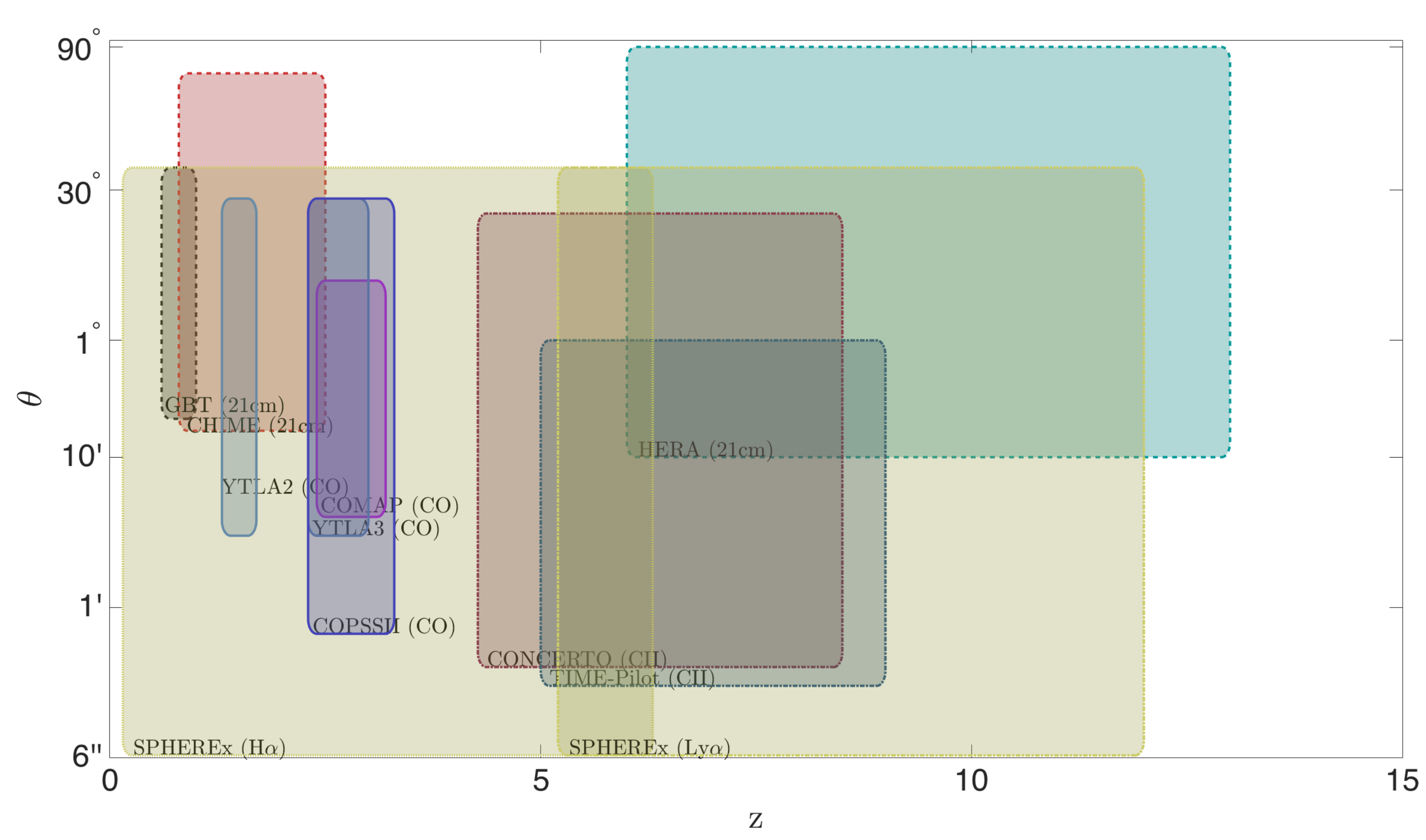




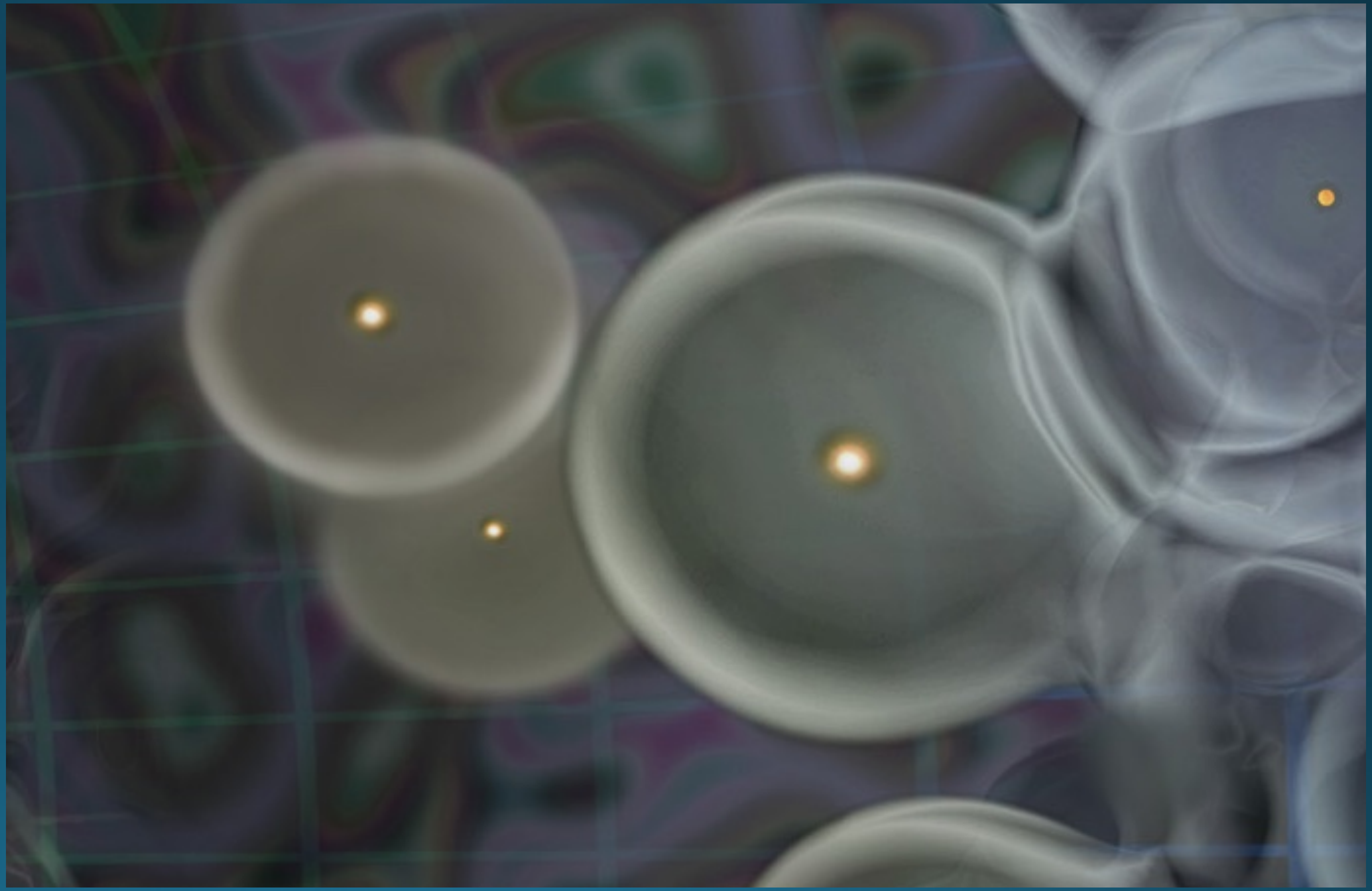
Breysse, P. C., Rahman M., 2016, arXiv:1606.07820

Multiple Lines



Use all of the photons

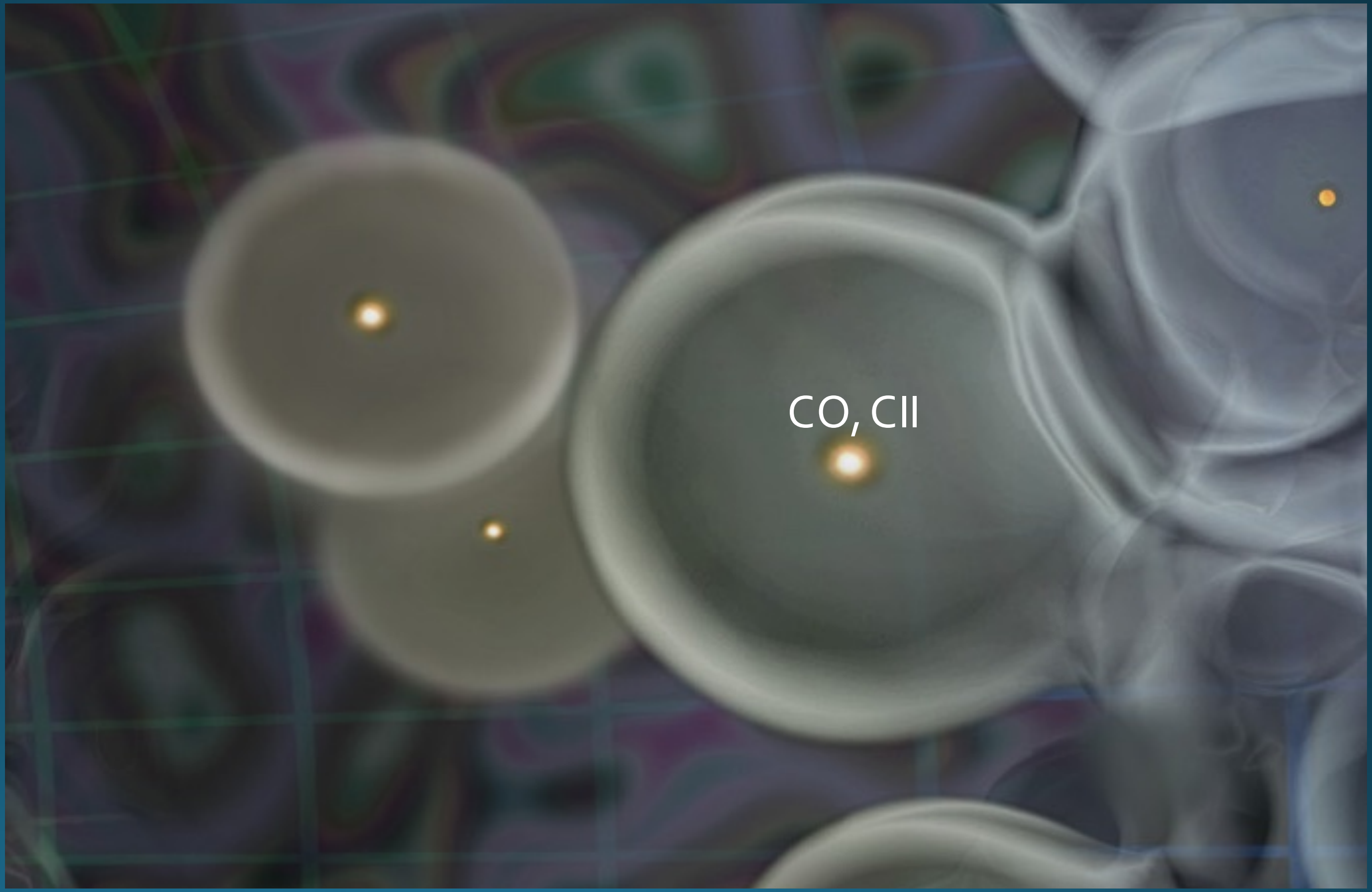
The Future



Original image credit: Loeb, 2006, Scientific American

The Future

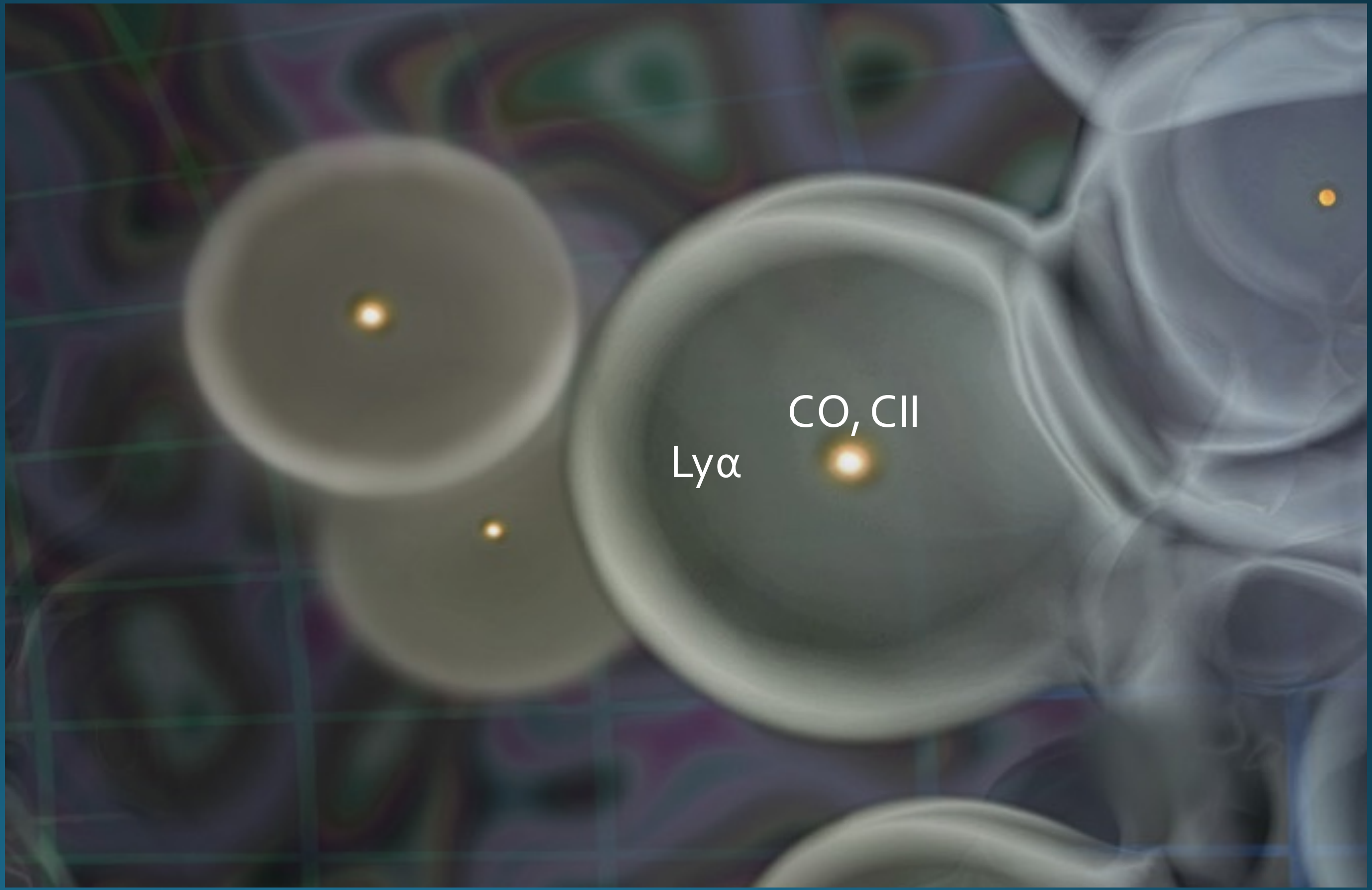
- CO, CII from within galaxies



Original image credit: Loeb, 2006, Scientific American

The Future

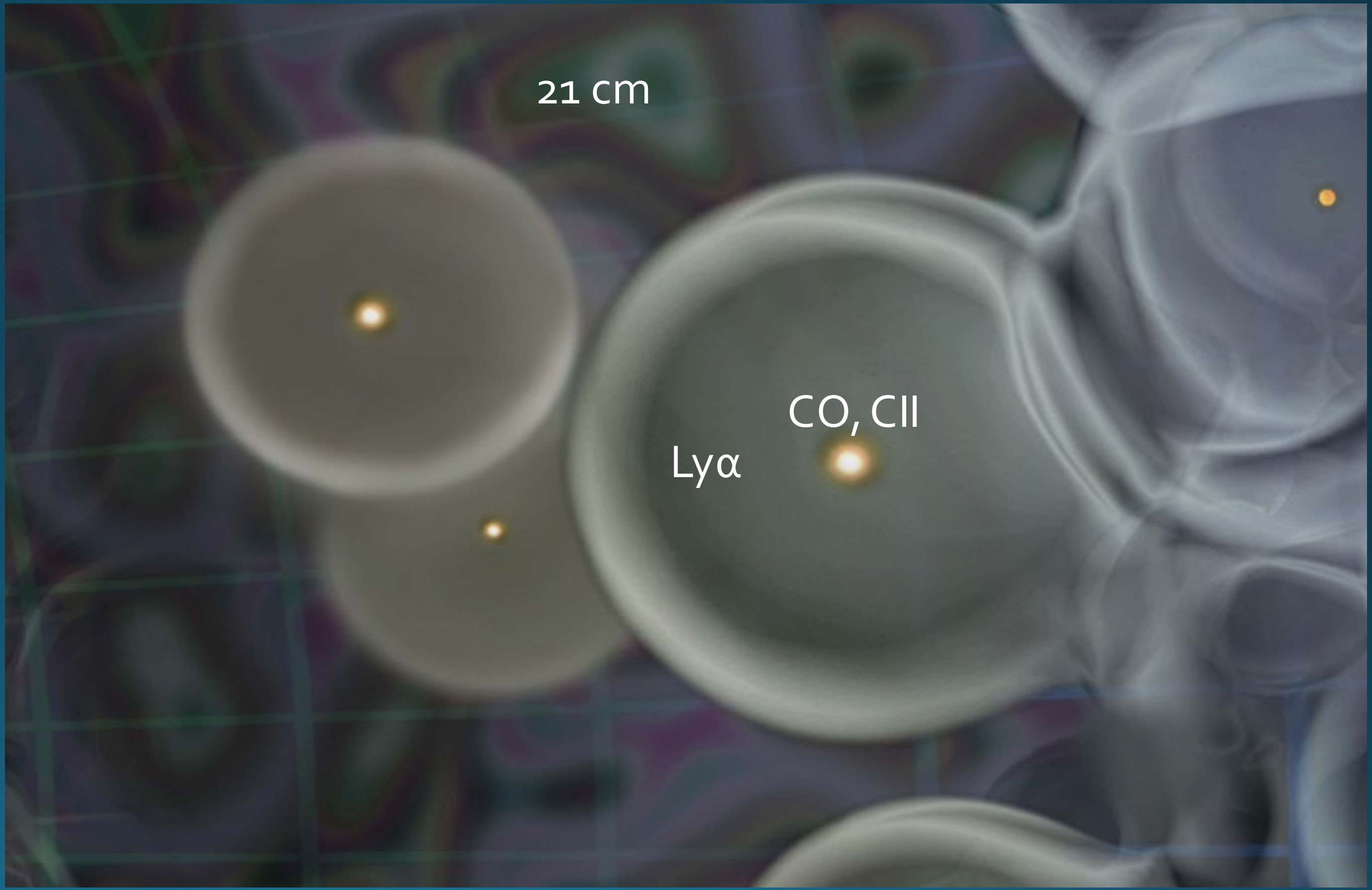
- CO, CII from within galaxies
- Lyα from around galaxies



Original image credit: Loeb, 2006, Scientific American

The Future

- CO, CII from within galaxies
- Lyα from around galaxies
- 21 cm from neutral IGM



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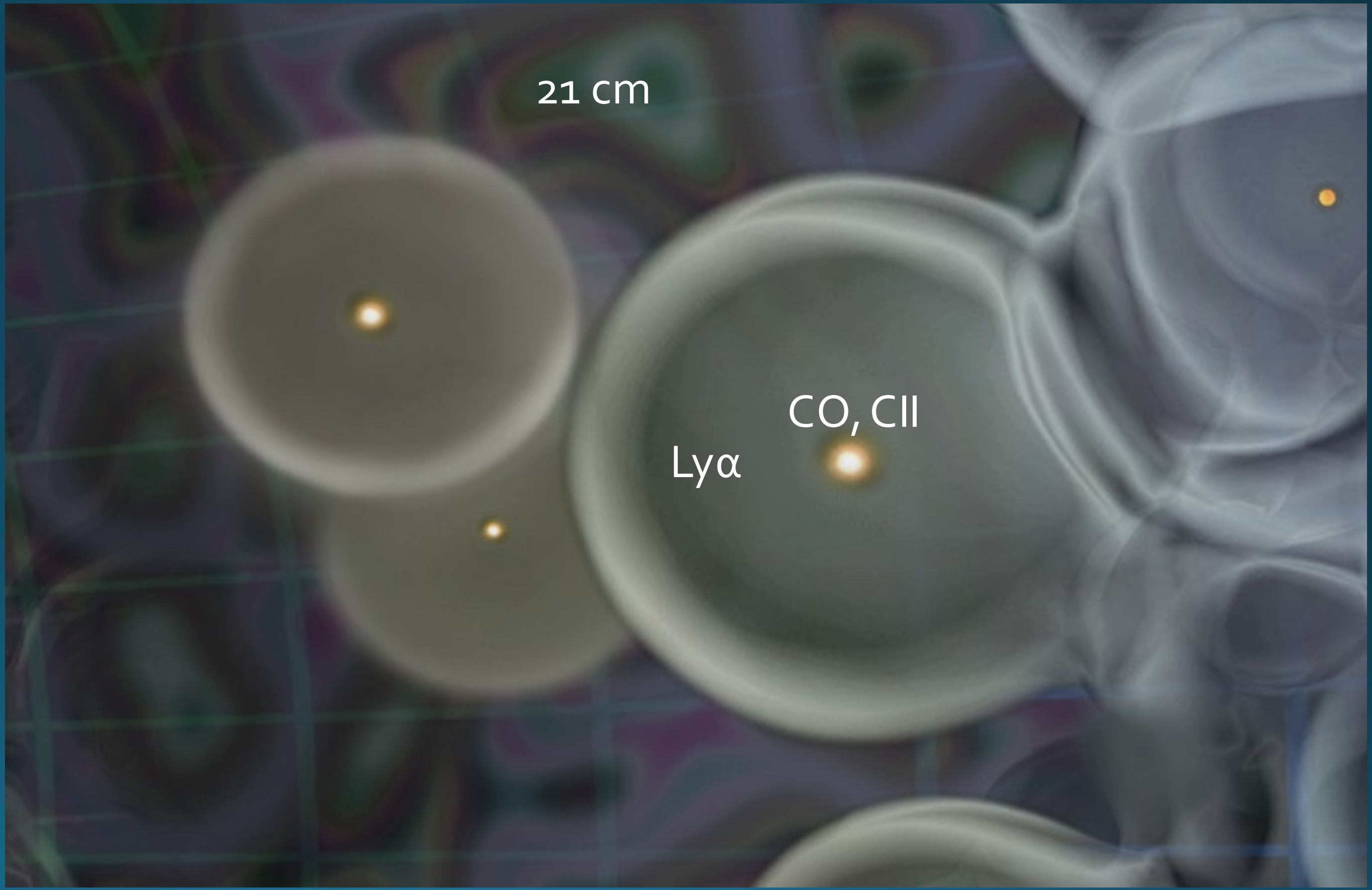
The Future

- CO, CII from within galaxies
- Lyα from around galaxies
- 21 cm from neutral IGM
- Fainter lines in cross-correlation



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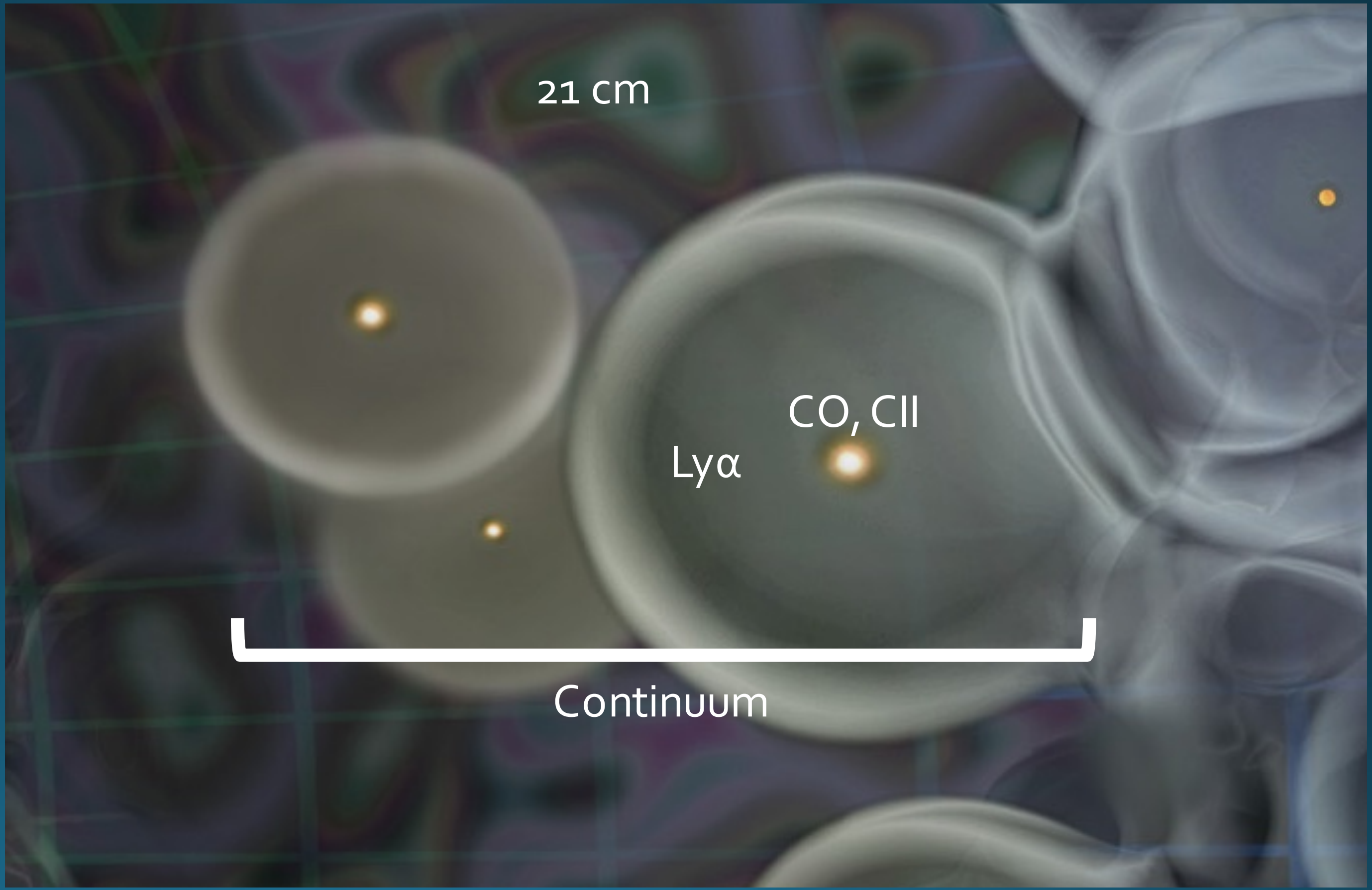
The Future

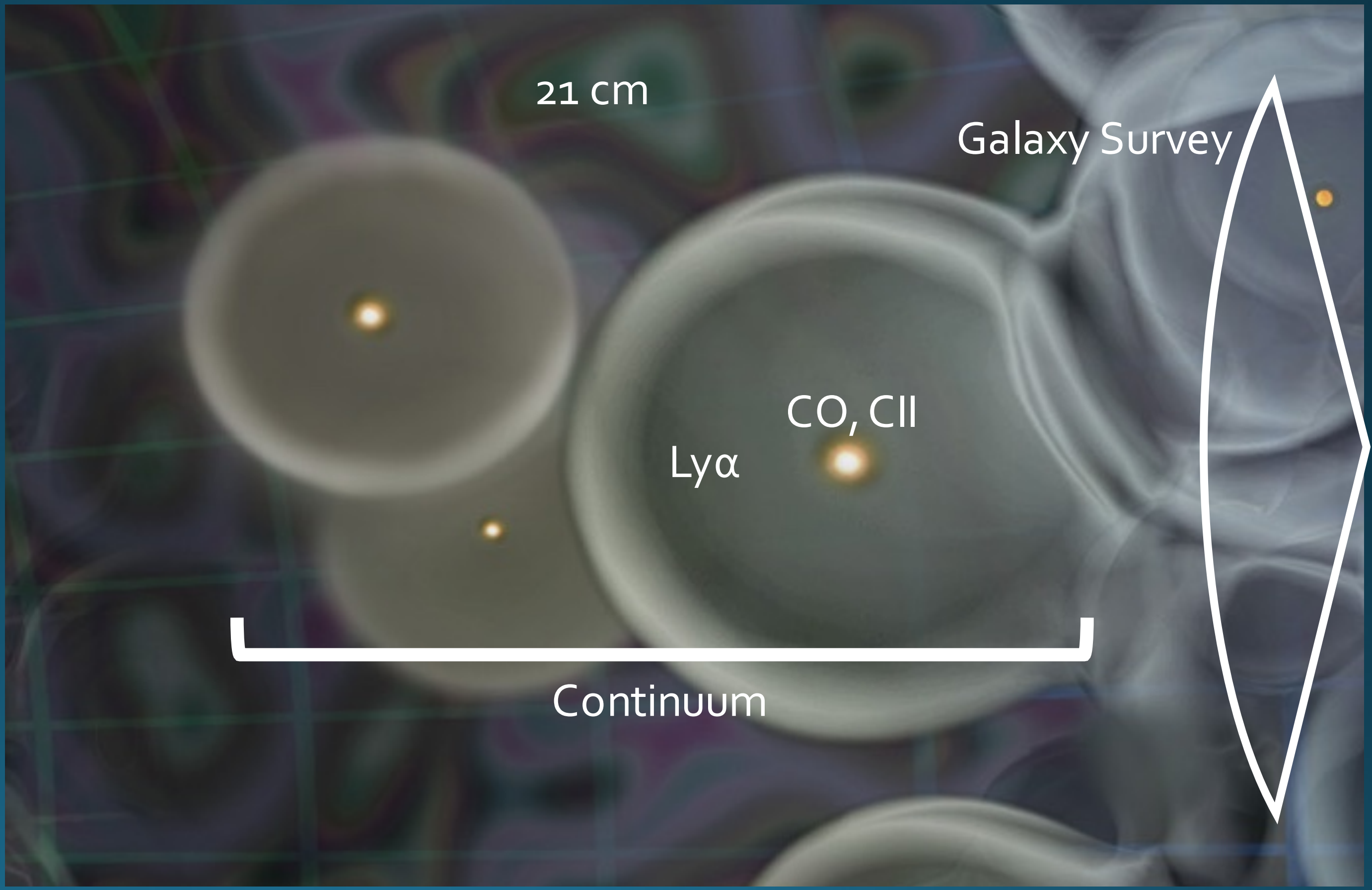
- CO, CII from within galaxies
- Lyα from around galaxies
- 21 cm from neutral IGM
- Fainter lines in cross-correlation
- Continuum from CIB



Original image credit: Loeb, 2006, Scientific American

The Future

- CO, CII from within galaxies
- Lyα from around galaxies
- 21 cm from neutral IGM
- Fainter lines in cross-correlation
- Continuum from CIB
- Bright sources from galaxy surveys, deep fields



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The Future

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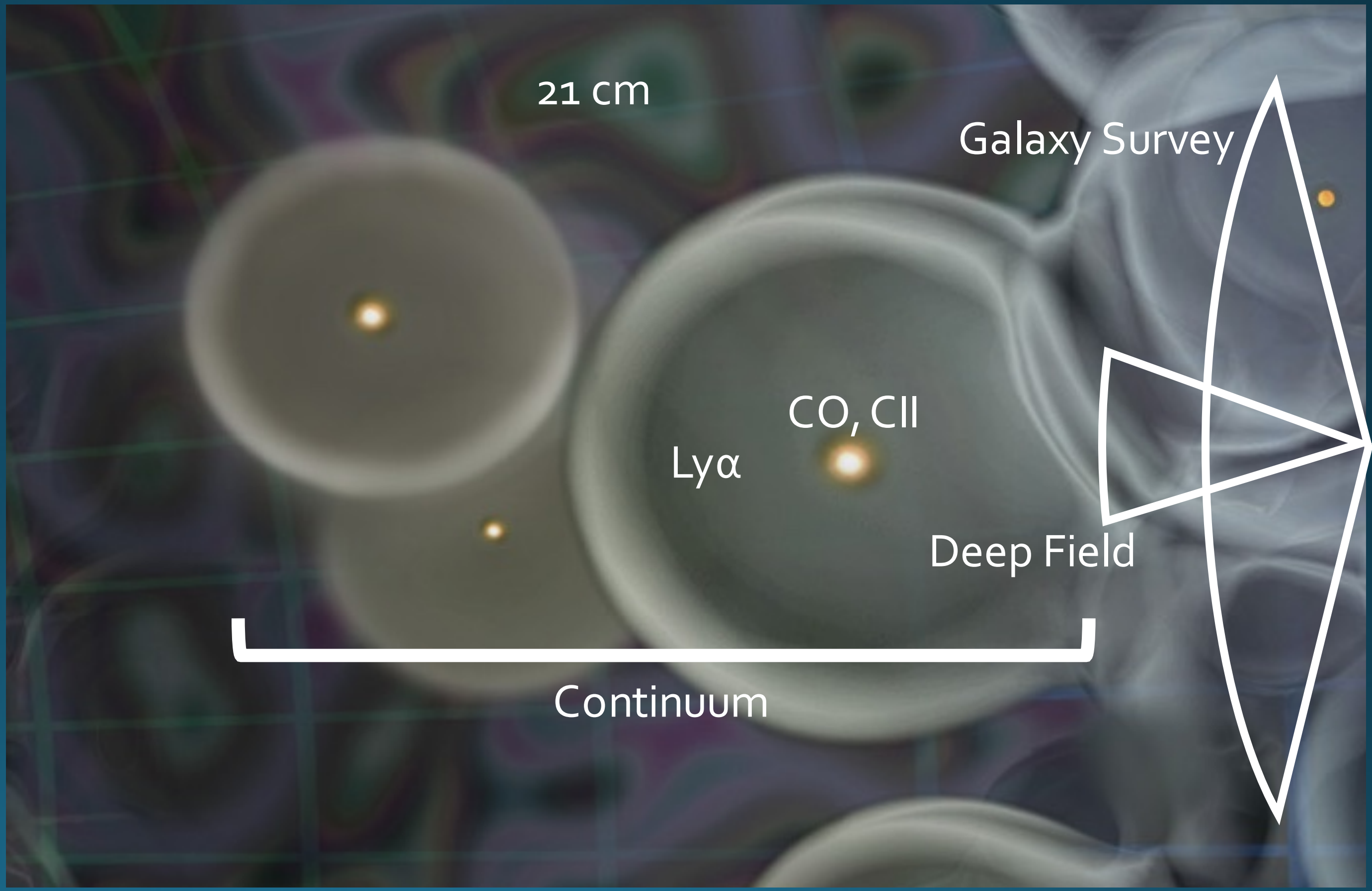

Original image credit: Loeb, 2006, Scientific American

Summary

- Intensity mapping is a powerful complement to galaxy surveys at high redshifts
- Power spectrum analysis is useful, but adding new one-point statistics formalism dramatically improves luminosity function constraints
- Cross-correlations can let you access even very faint lines, study sub-galactic physics in detail
- In the future- Combining future intensity maps with each other and with galaxy surveys to squeeze the most physics out of every photon

arXiv: 1405.0489 1503.05202 1507.06304 1606.07820 1609.01728