Title: High-redshift astrophysics using every photon

Speakers: Patrick Breysse

Series: Cosmology & Gravitation

Date: September 24, 2019 - 11:00 AM

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Abstract: Large galaxy surveys have dramatically improved our understanding of astrophysics and cosmology in the high-redshift universe, but they are fundamentally limited by the need to integrate long enough to detect each individual source. Line intensity mapping has recently arisen as a powerful alternative to these surveys, offering access to fainter sources and larger volumes than conventional techniques. There has been a surge of experimental interest in this technique, with surveys planned or in progress across the electromagnetic spectrum. In this talk, I will describe the wide variety of science which we will obtain from these experiments in the next few years and illustrate the methods by which we can go from maps of confused line emission to useful astrophysics. I will show how intensity maps can give new insights into topics ranging from star formation to the high-redshift ISM to the Hubble constant tension. I will further discuss the utility of combining intensity maps with conventional surveys, both for systematics control and for studying processes like AGN feedback. I will close with a discussion of how modern machine learning methods can be used to further extend what we can learn from these surveys.

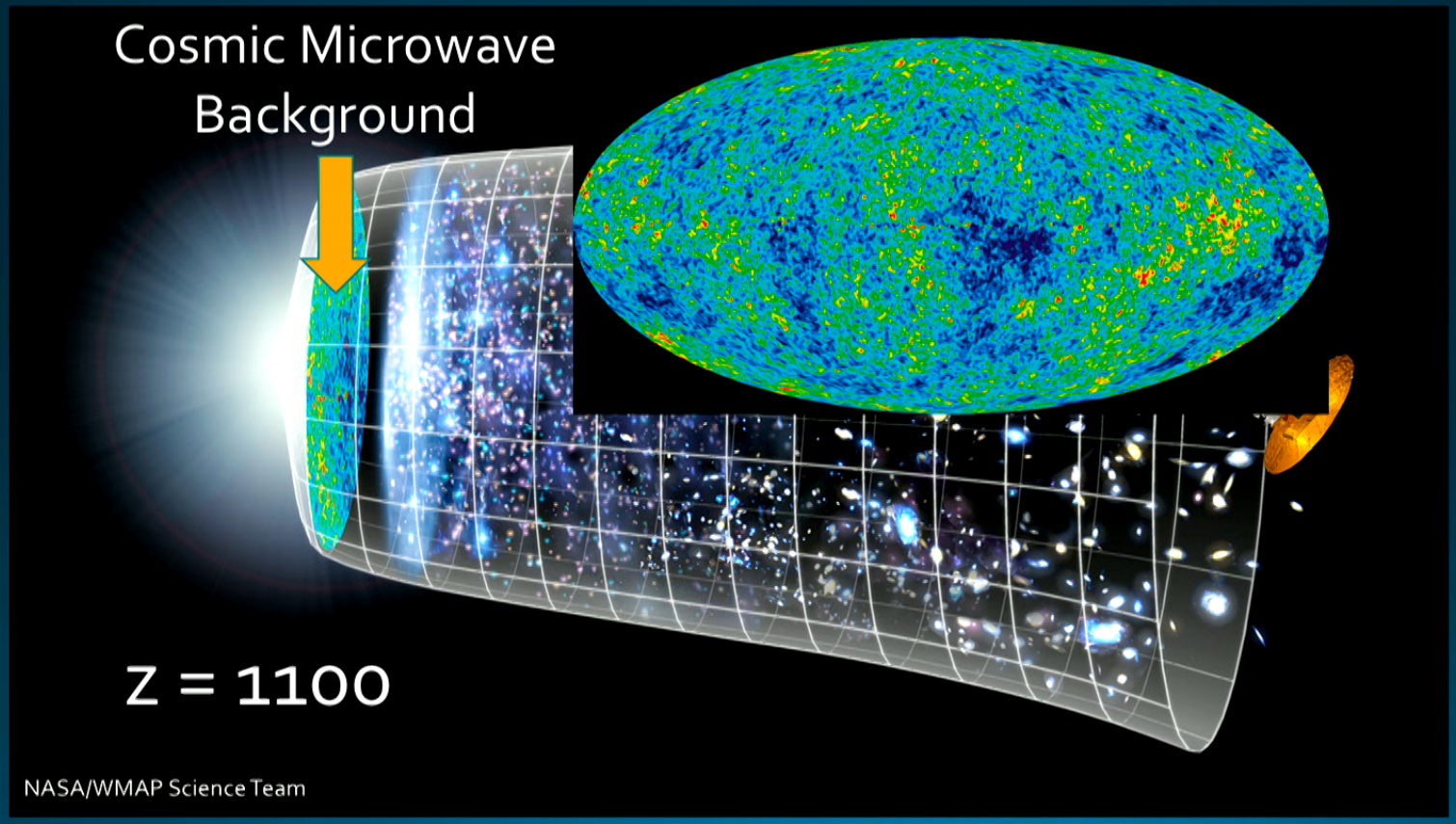
High-Redshift Astrophysics Using Every Photon

Science with line intensity mapping

Patrick C. Breysse
CITA

Peimeter Cosmology Seminar, 25 September 2019

Introduction



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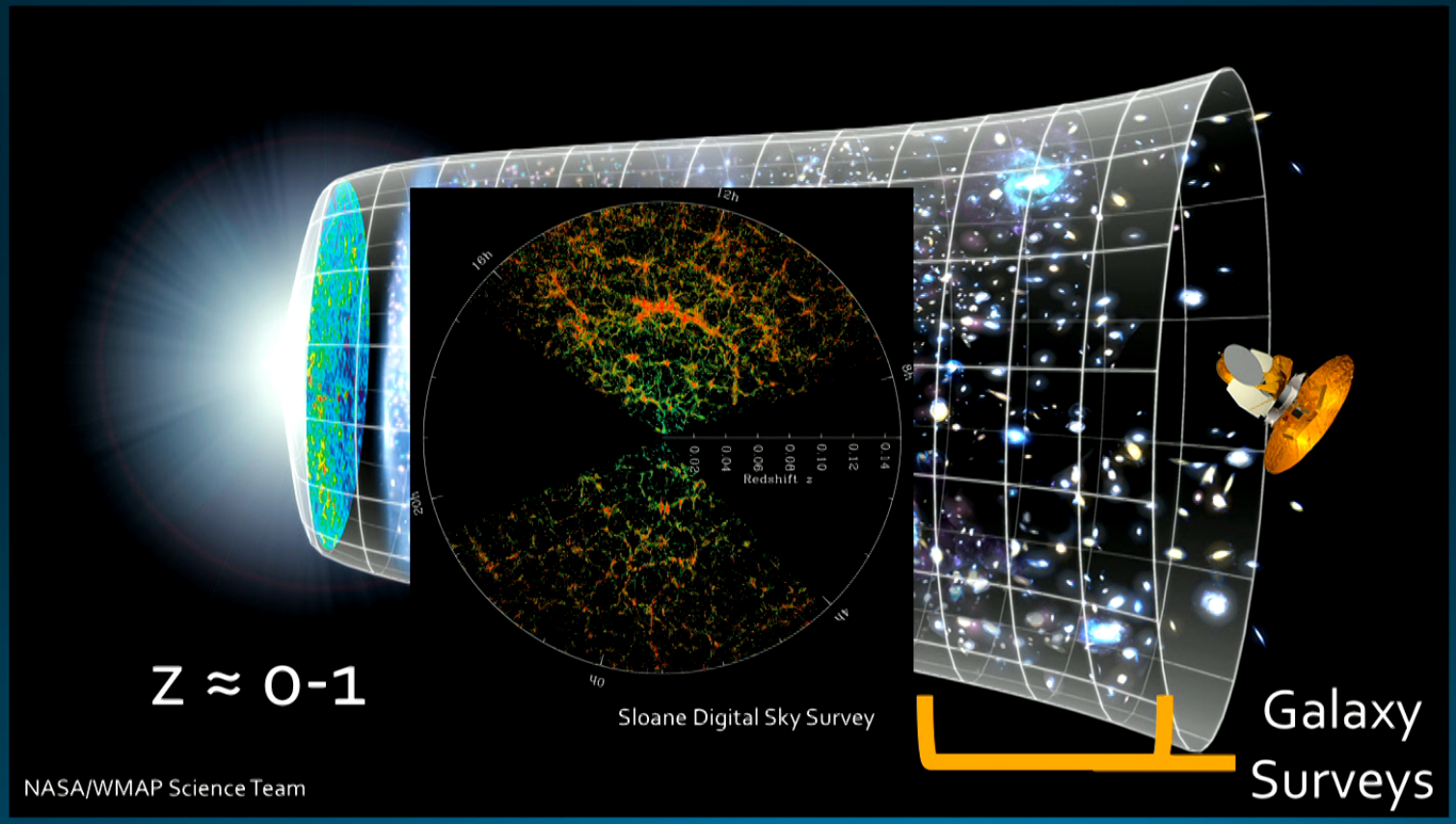

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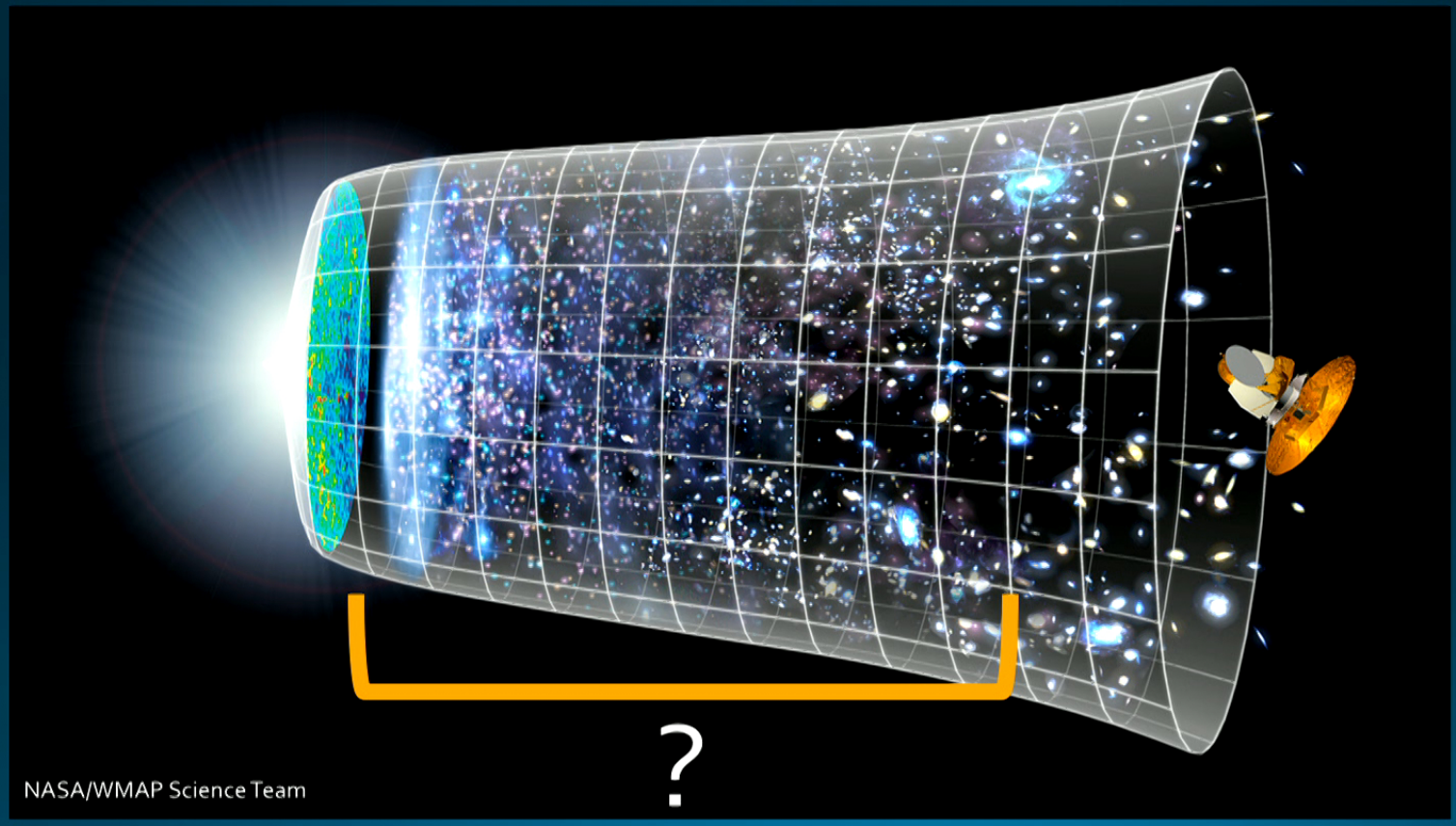

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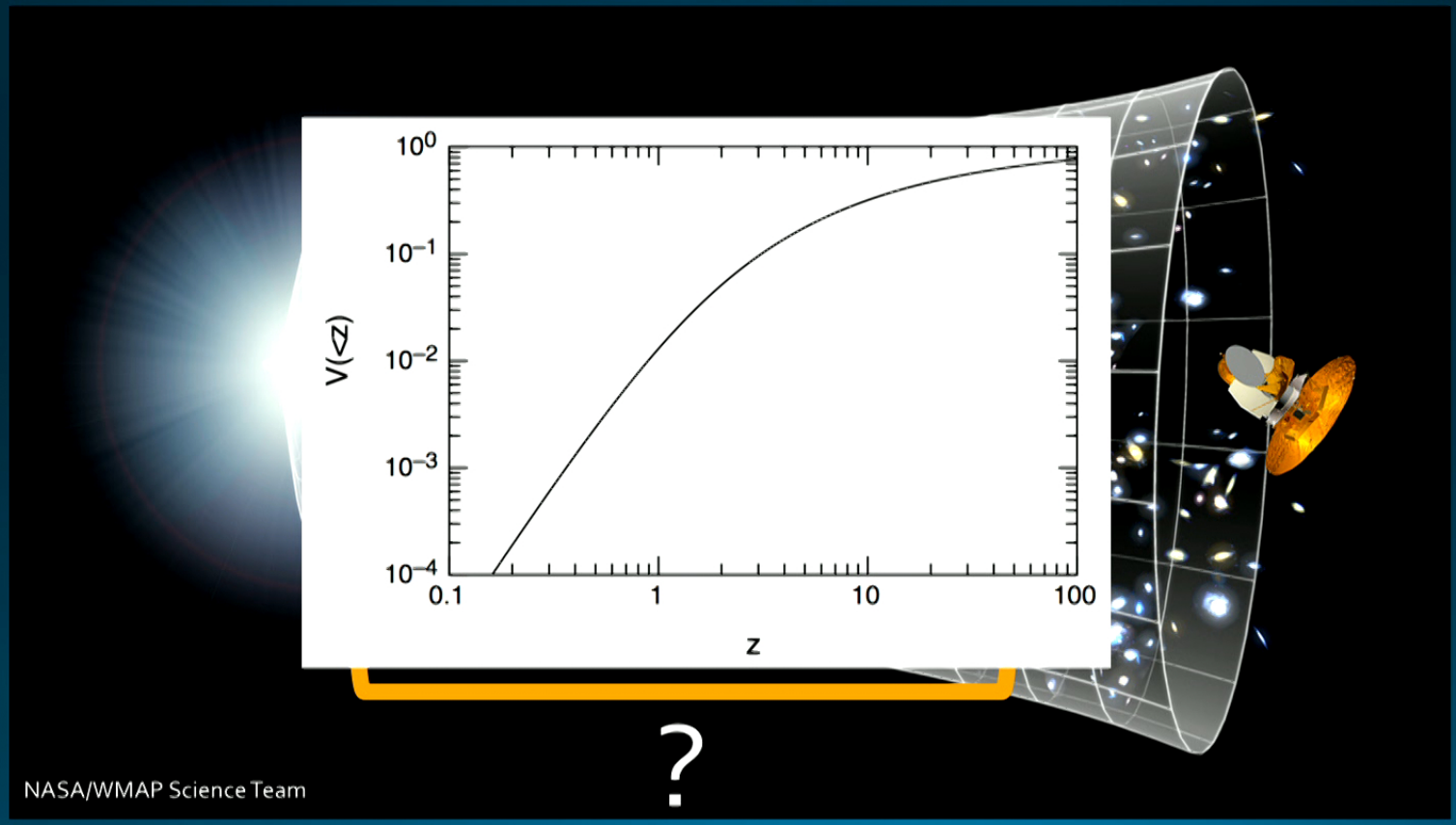

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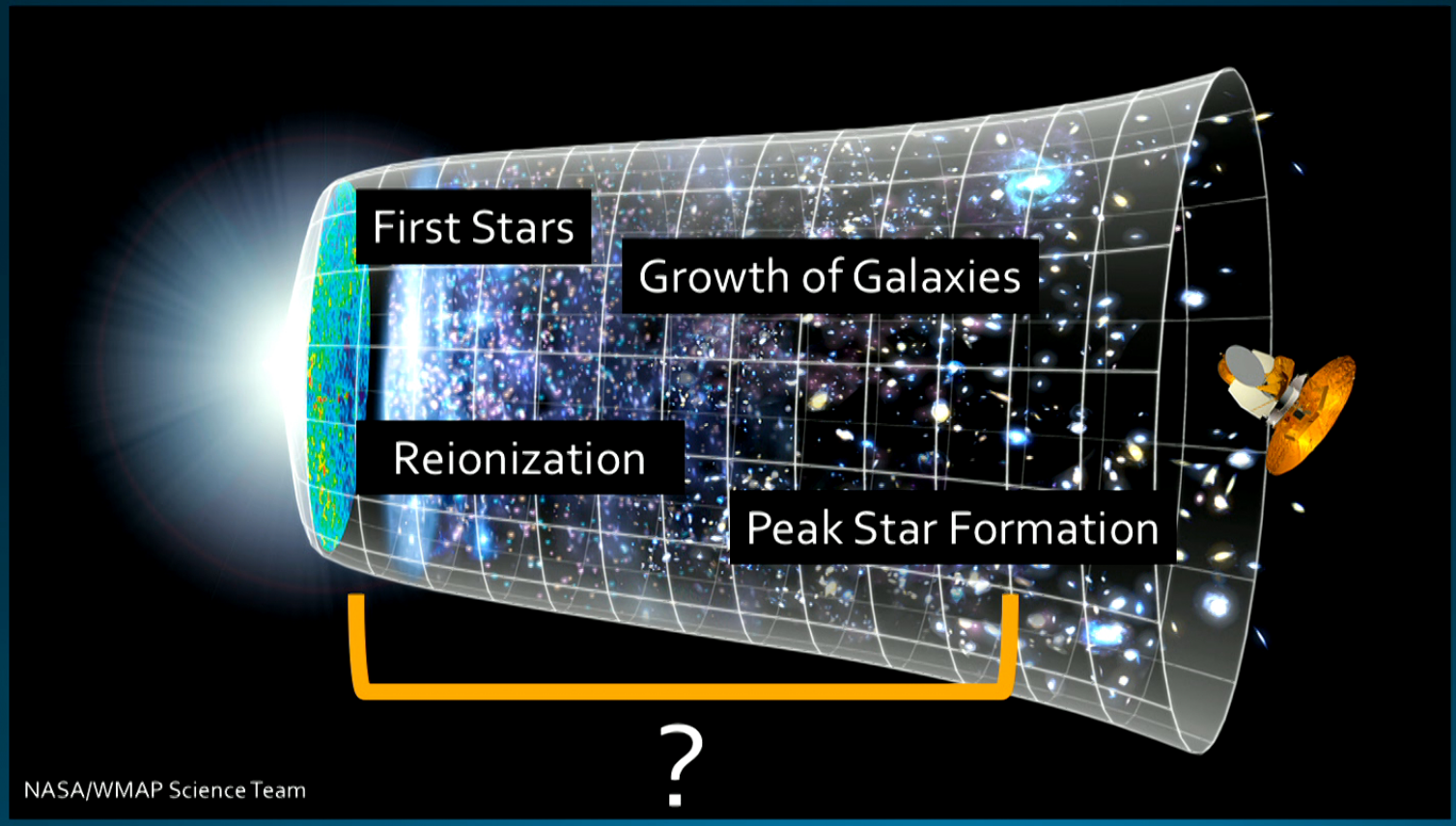
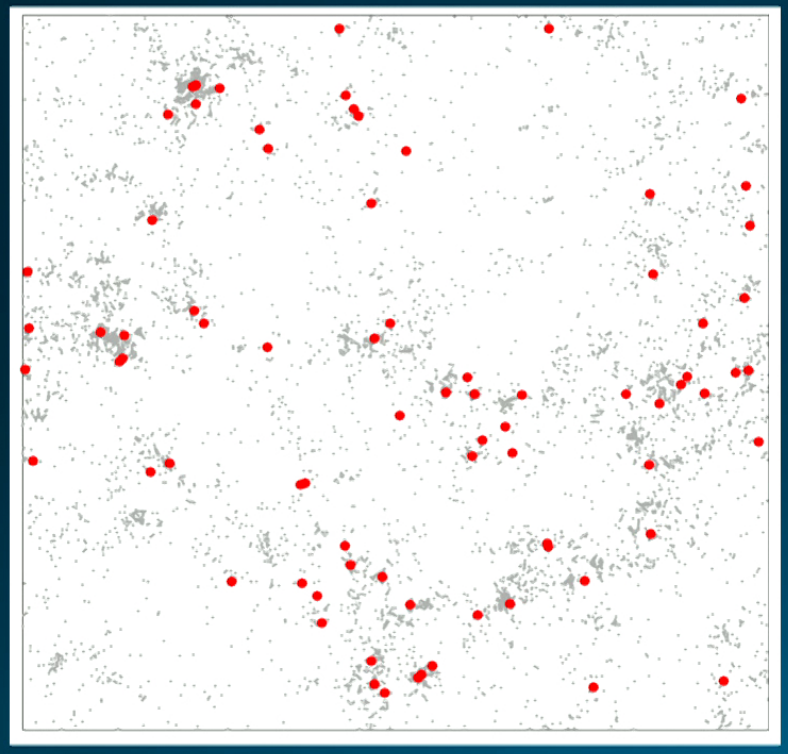


Use all of the photons

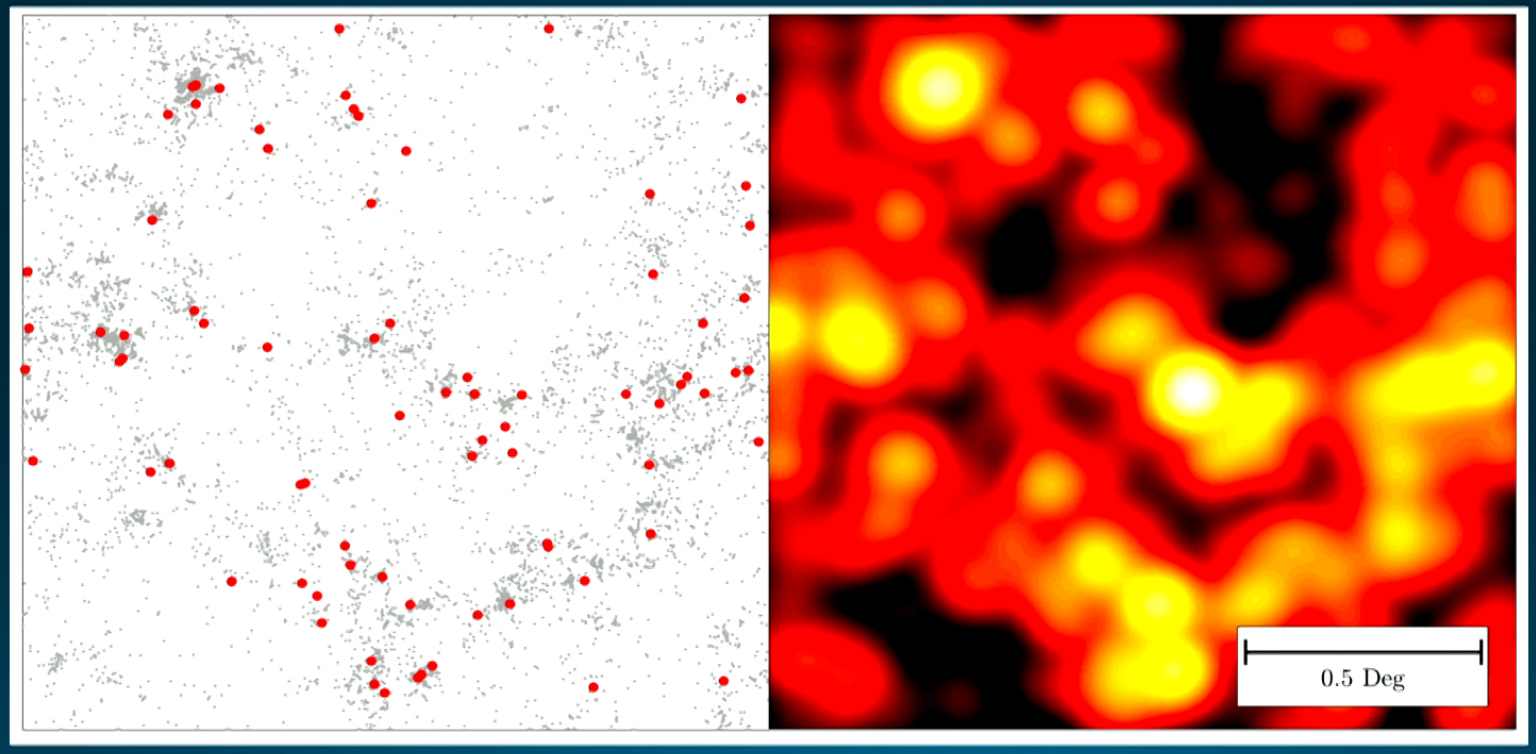
Line Intensity Mapping



Faint Galaxies Bright Galaxies

- Consider a blind spectroscopic survey of line emitters
- Example- CO(1-0) at z~3 over 2.5 deg^2 with VLA
- With ~4500 hours, can detect red points (<1% of all sources)

Line Intensity Mapping



Faint Galaxies Bright Galaxies Line Emission

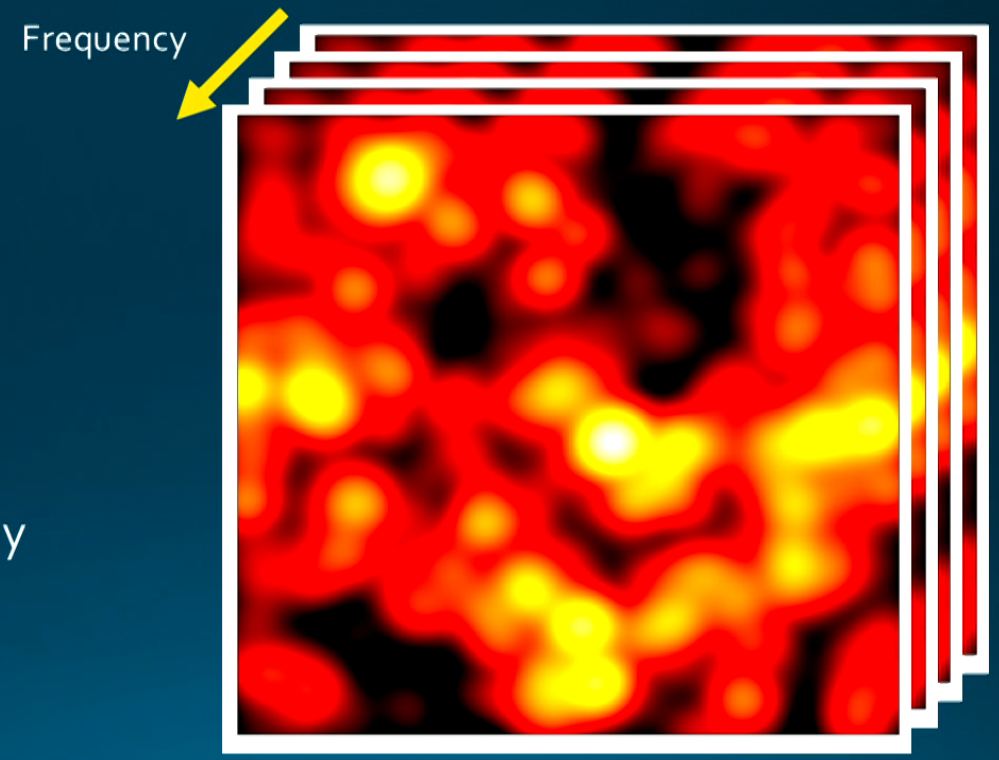
Line Intensity Mapping

Observing Frequency

↕

Redshift

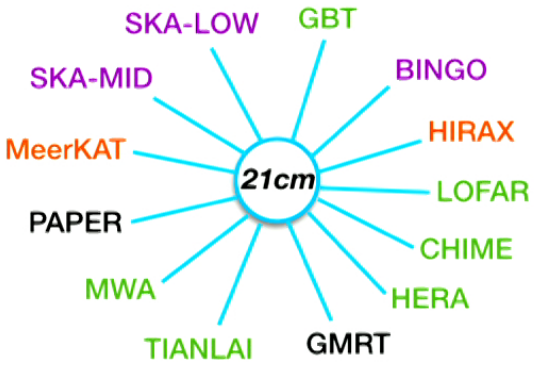
Can make 3D measurements by observing at many, closely-spaced frequencies

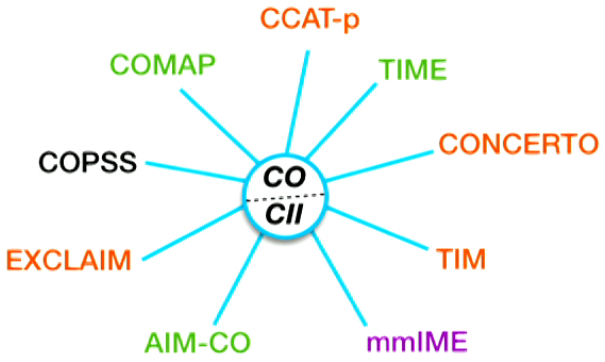


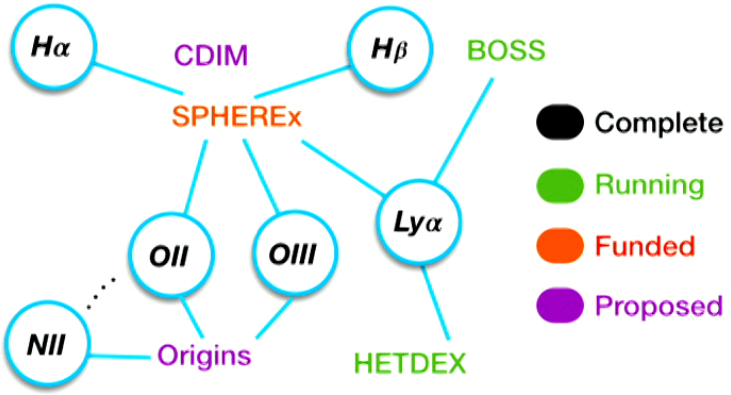
Galaxy surveys give detailed properties of brightest galaxies

Intensity maps give statistical properties of all galaxies

Lines and Experiments







HI spin-flip transition

Traces neutral gas

Directly map process of reionization as neutral IGM disappears

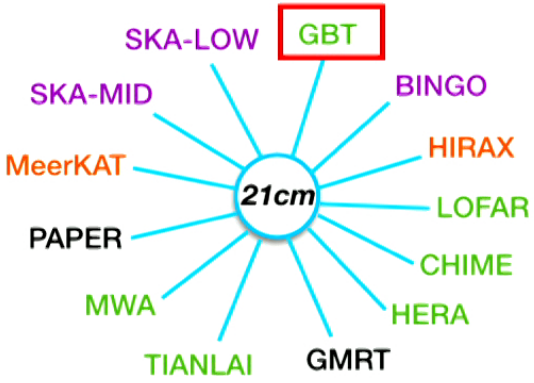
CO rotational transitions trace molecular clouds

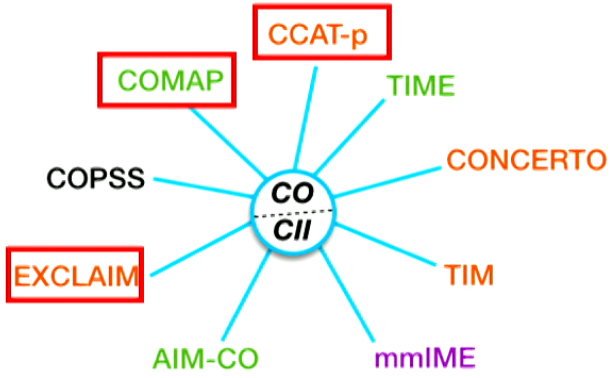
CII fine structure is an important cooling line, traces PDRs

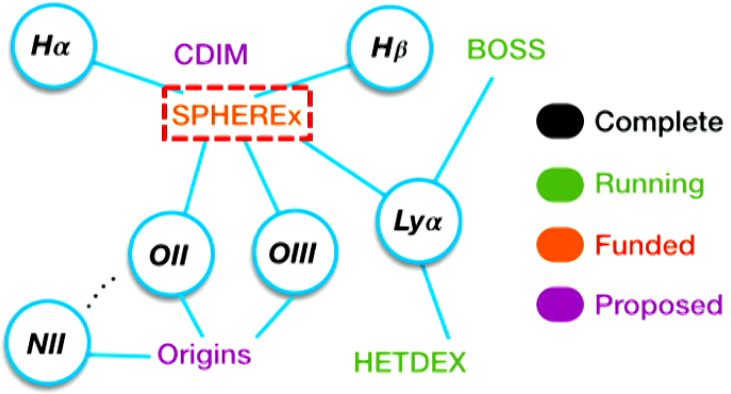
Both trace star forming galaxies

Many other ISM, IGM properties

Lines and Experiments







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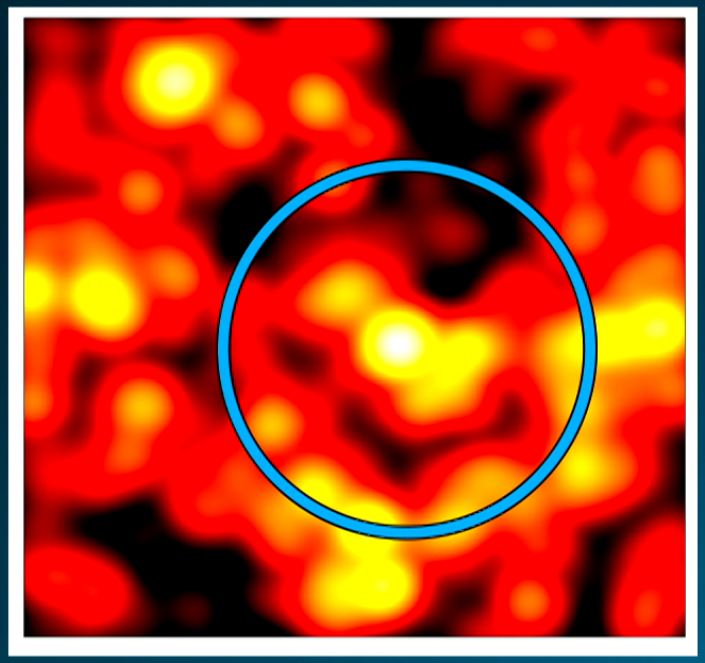
$I(\nu, \hat{n})$

Cosmology
Galaxy physics
Reionization
Inflation
Etc.

LIM Science

Galaxy Clustering



Cosmology

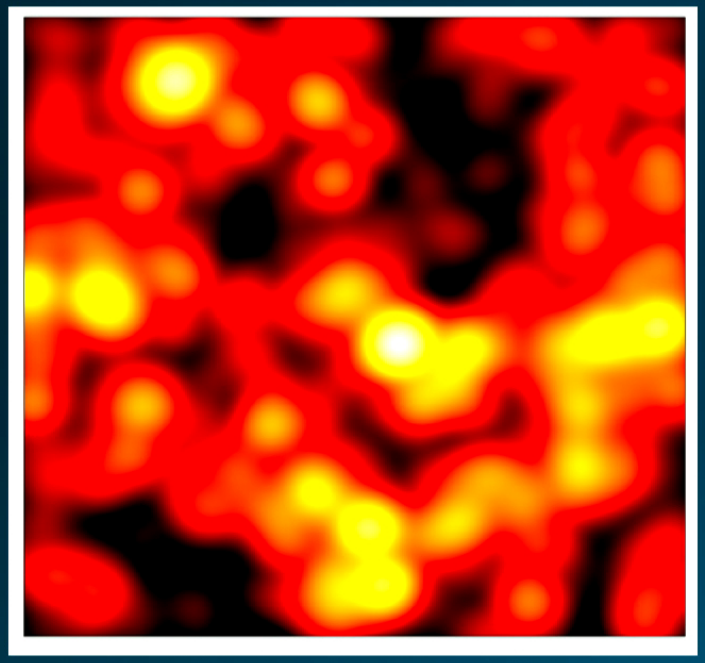
Large-scale Structure
BAO
Hubble tension
Inflation
Etc.

How do we connect confused line emission to interesting physics

$I(\nu, \hat{n})$

Cosmology
Galaxy physics
Reionization
Inflation
Etc.

Intensity Maps are…



Confused

Non-Gaussian

Contaminated

Power Spectrum

It is a truth universally acknowledged that a cosmologist in possession of a new observable must compute its power spectrum

- Jane Austen (paraphrased)

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

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

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

Line luminosity function

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

Power Spectrum

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

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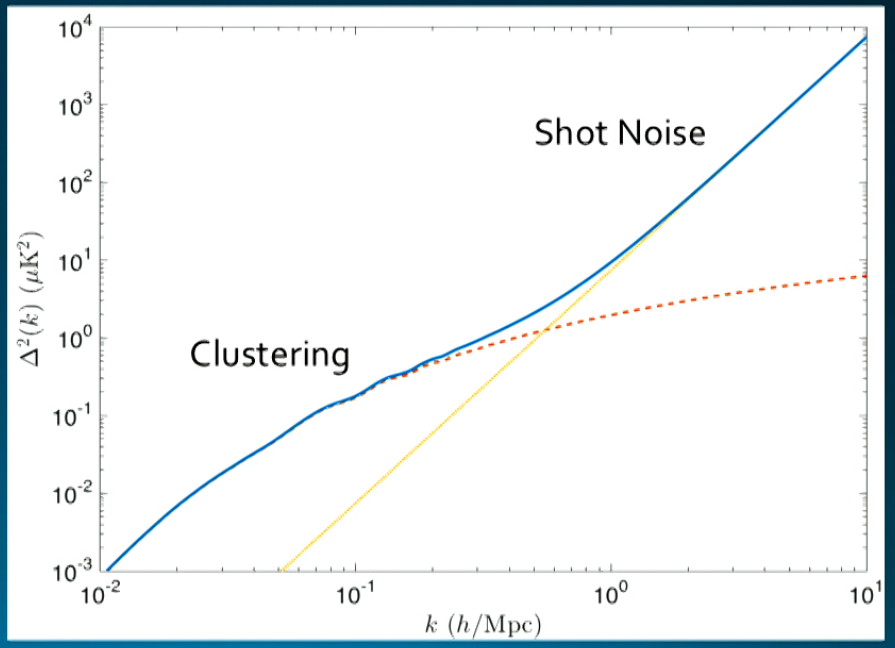

Power Spectrum

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

ISM physics

Star formation

Galaxy formation

Large-scale Structure

Cosmic evolution (BAO)

Inflation/non-Gaussianity

Galaxy-Halo Connection

etc....

Power Spectrum

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

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

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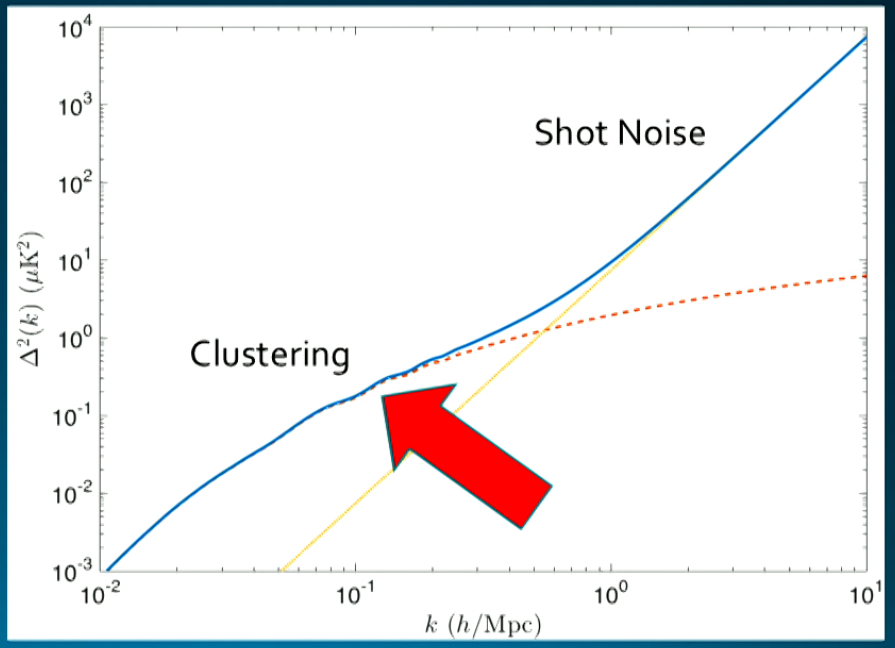


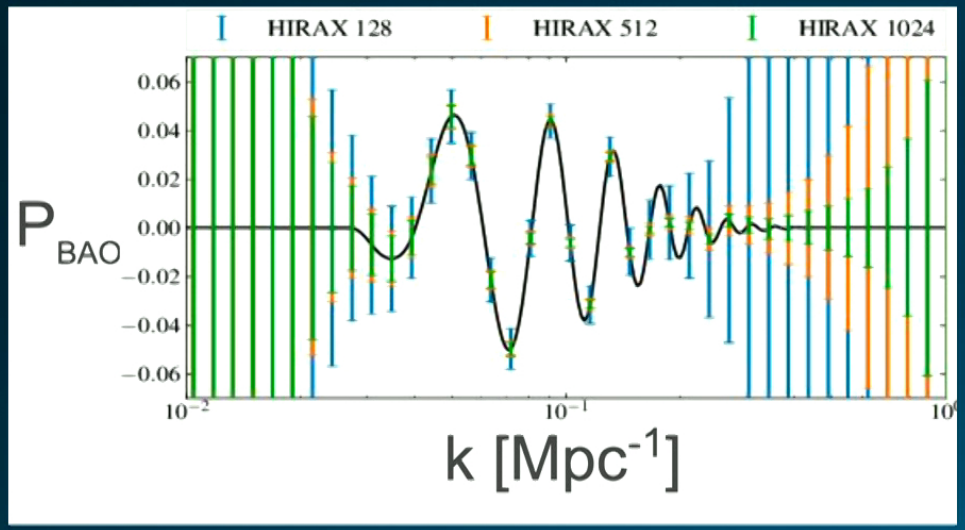
Power Spectrum- Cosmic Evolution

Map 21 cm over large scales- measure the BAO standard ruler

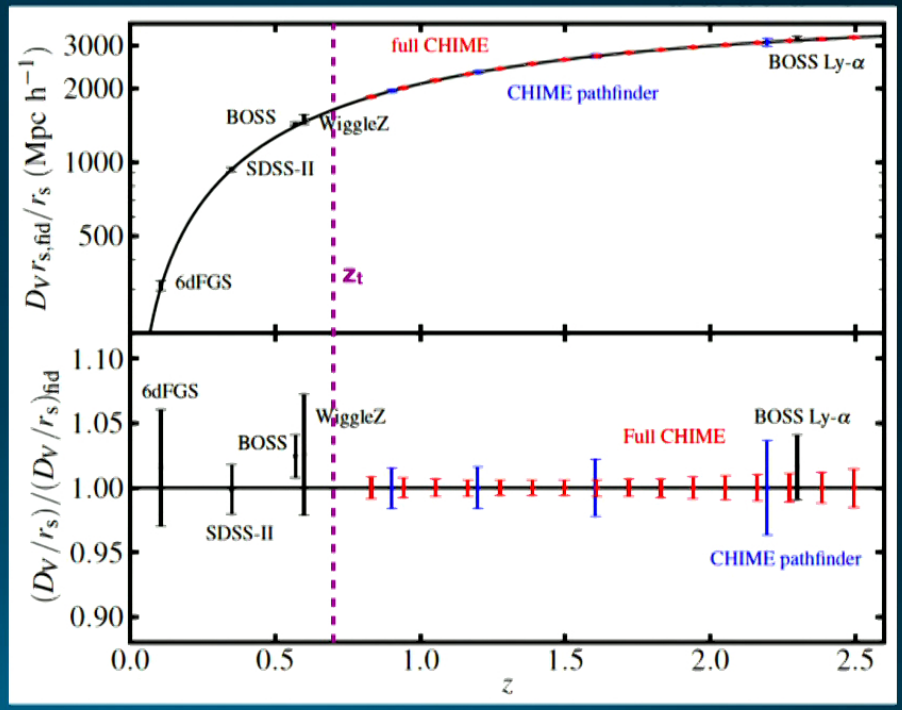
CHIME (Canada)

HIRAX (South Africa)

Power Spectrum- Cosmic Evolution



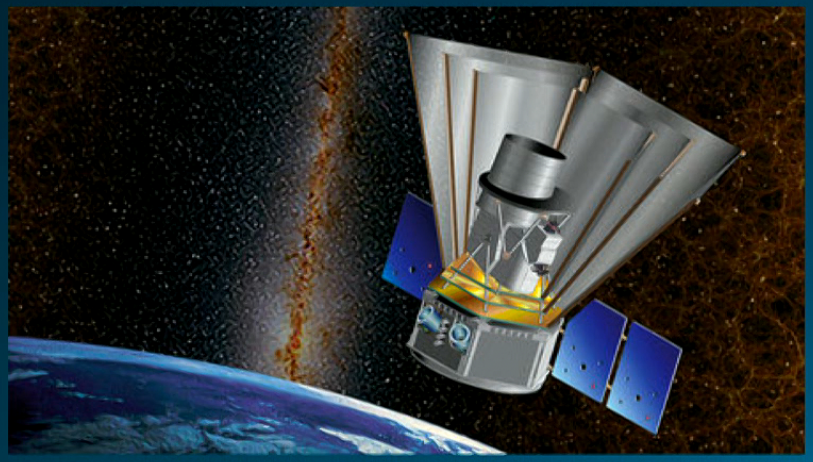
Credit Devin Crichton, HIRAX

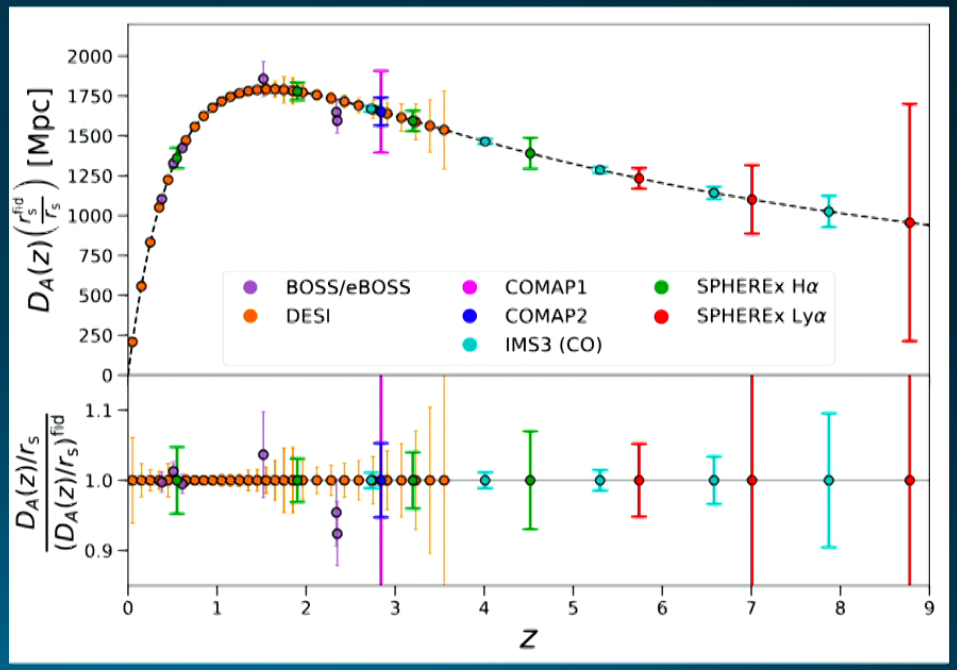


Bandura+ 2014

Power Spectrum- Cosmic Evolution

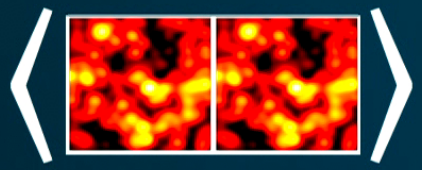
SPHEREx- All-sky survey,
sensitive to Hα, Lyα, others





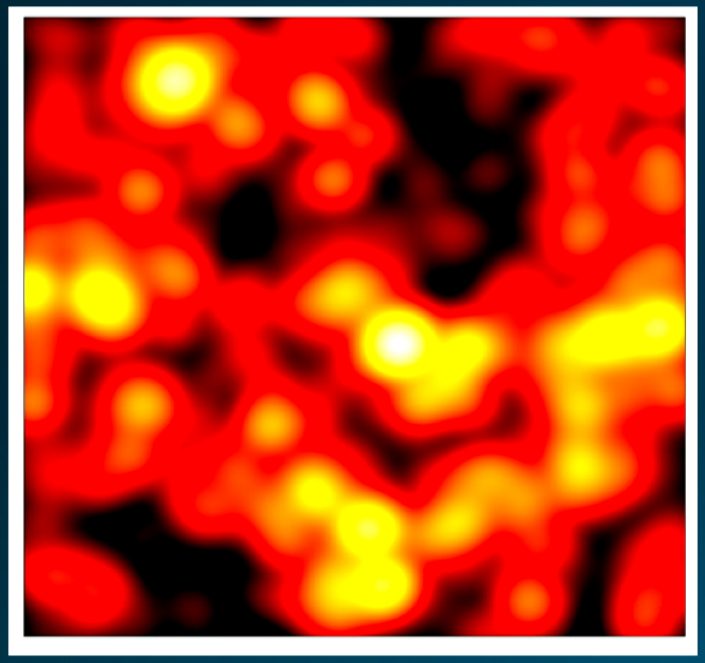
Bernal, PB+ 2019

Power Spectrum



Mean, variance of luminosity function
Galaxy bias
Large Scale Structure

Intensity Maps are…

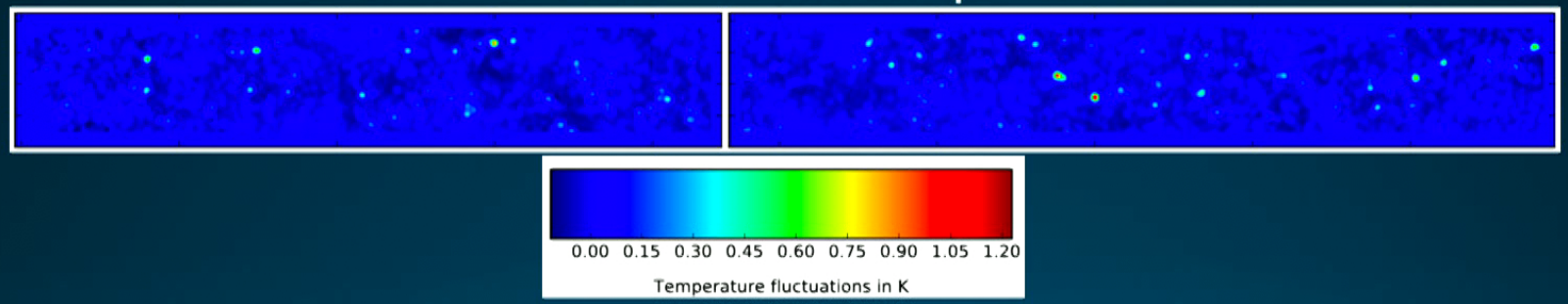


Confused
Contaminated
Non-Gaussian

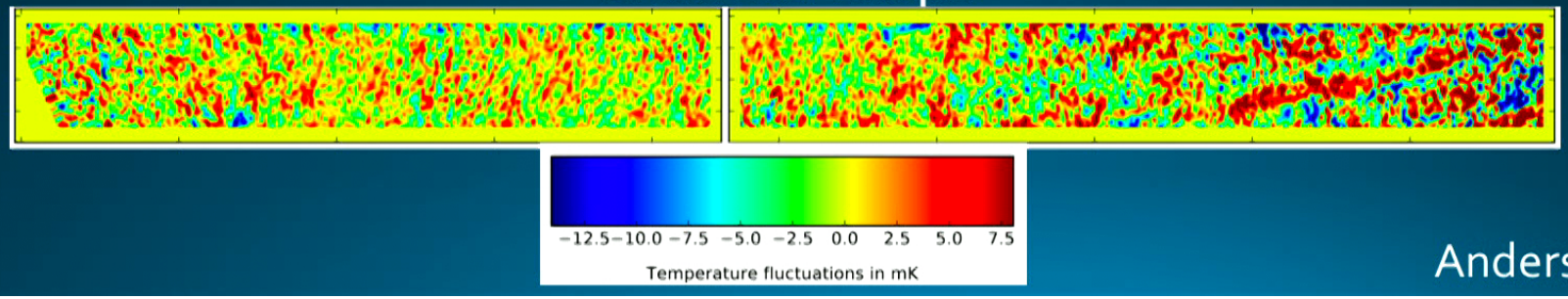
Foregrounds

21 cm data- foregrounds 3-5 orders of magnitude above signal

Raw 21 cm maps

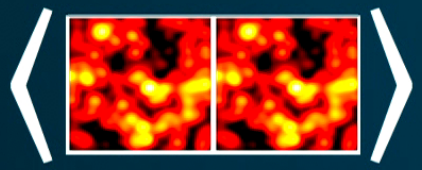


Cleaned Maps



Anderson+ 2018

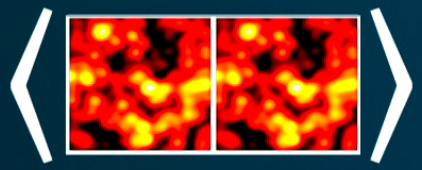
Power Spectrum



Mean, variance of luminosity function
Galaxy bias
Large Scale Structure

Foreground-Unbiased?

Power Spectrum



Mean, variance of luminosity function
Galaxy bias
Large Scale Structure

Cross-Spectrum

Cross-Spectrum

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

Cross-Spectrum, Line x Galaxy

$$P(k,z) = \langle T \rangle b \; b_g \; r_\times \; P_m + P_{\text{shot}}$$

Bias of galaxy sample

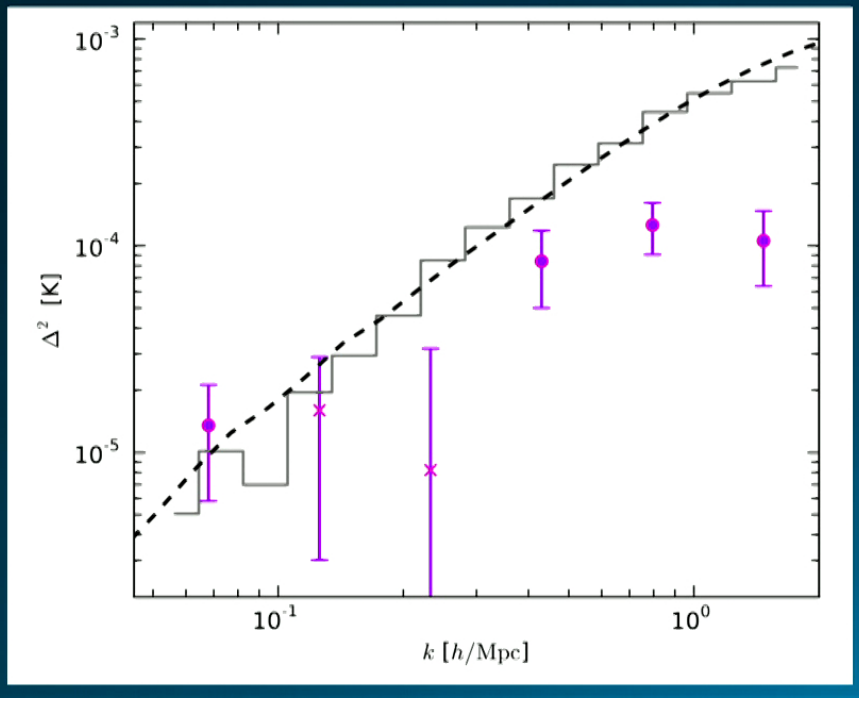
Cross-Spectrum, Line x Galaxy

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

Less than 1, line/galaxies don't trace dark matter the same way

Cross-Spectrum, Line x Galaxy

$$P(k,z) = \langle T \rangle b\, b_g\, r_\times\, P_m + P_{\rm shot}$$



5σ detection of cross-power

Low amplitude on small scales, maybe HI avoiding dense regions

(Chang+2010, Masui+2017, Anderson+ 2018)

Cross-Spectrum Detections

- GBT x WiggleZ, 7σ HI detection at z~0.8 (Chang+ 2010, Masui+ 2013)
- Parkes x 2dF, 5σ HI detection at z~0.05 (Anderson+ 2018)
- Planck x BOSS, 4σ CII detection at z~3 (Pullen+ 2018, Yang+ 2019)
- BOSS x Quasars, 5σ Lyα detection at z~2.5 (Croft+ 2016,2018)

Auto-Spectrum Detections

- GBT upper limit at z~0.8 (Switzer+ 2013)
- COPSS, 3σ detection of CO shot noise at z~3 (Keating+ 2015,2016)

Cross-Spectrum, Line x Galaxy

$$P(k,z) = \langle T \rangle b\, b_g\, r_\times\, P_m + \underbrace{\langle L \rangle_g}$$

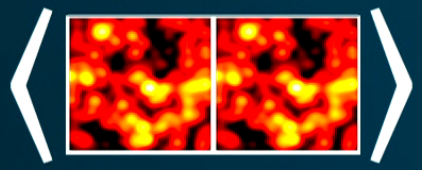
Can project out different galaxy populations

HI mass vs. galaxy color (Wolz+2017)

CO mass in AGN- quasar feedback (Breysse+Alexandroff 2019)

Cross-shot noise gives mean line luminosities of cross-correlation galaxies

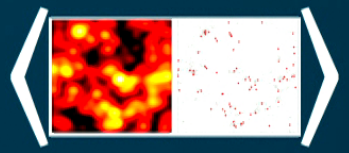
Power Spectrum



Mean, variance of luminosity function
Galaxy bias
Large Scale Structure

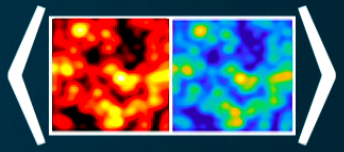
Cross-Spectrum

Line x Galaxy



Line properties of galaxy population

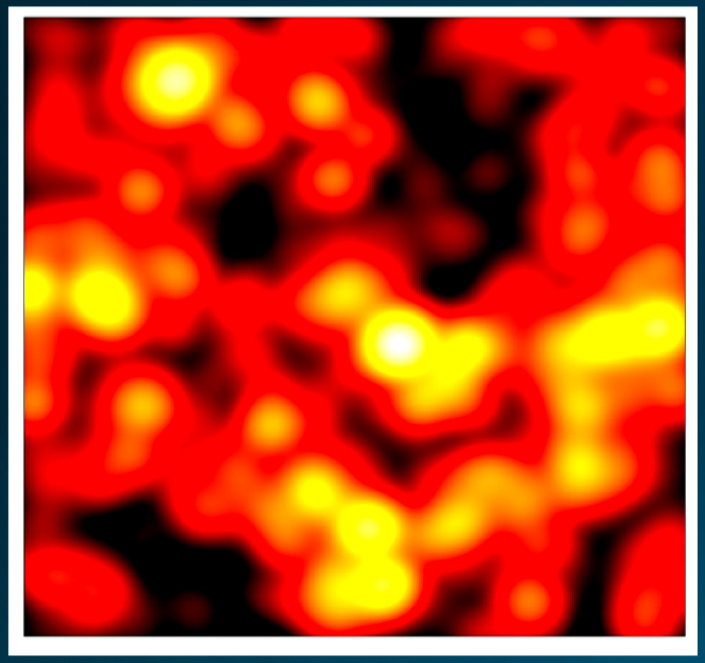
Line x Line



How lines vary with respect to each other

Foreground Safe

Intensity Maps are…



Confused

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Non-Gaussian

Power Spectrum

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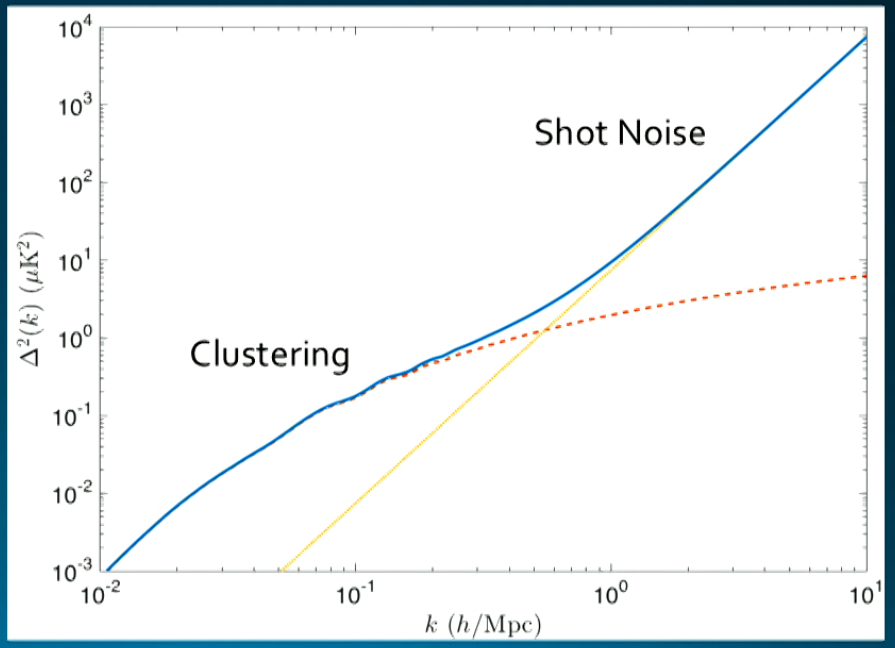
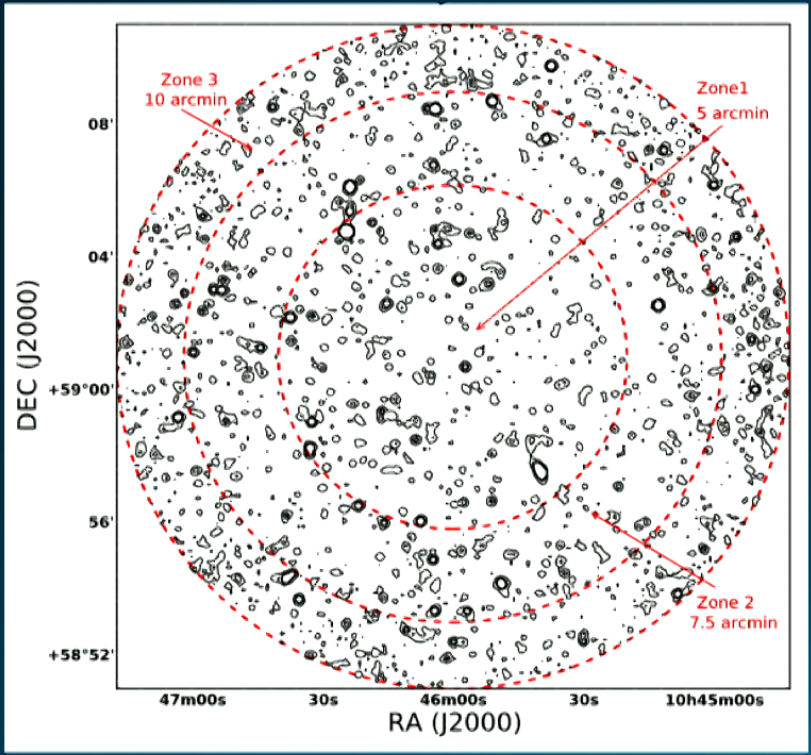
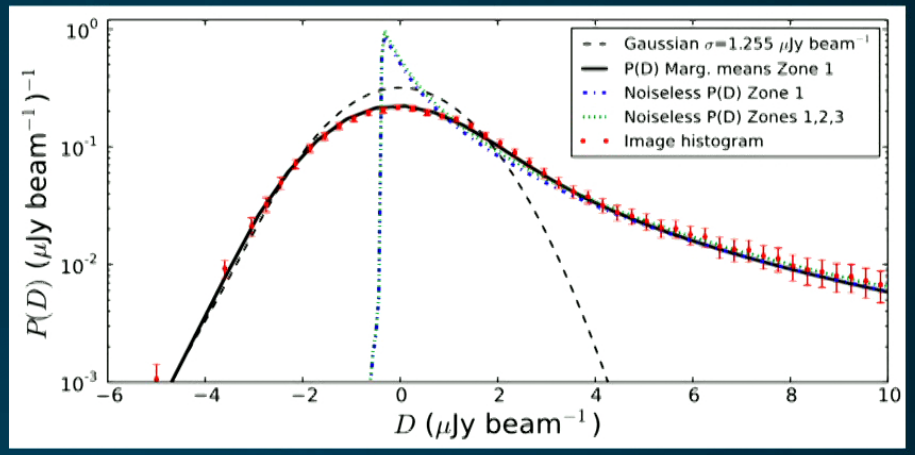


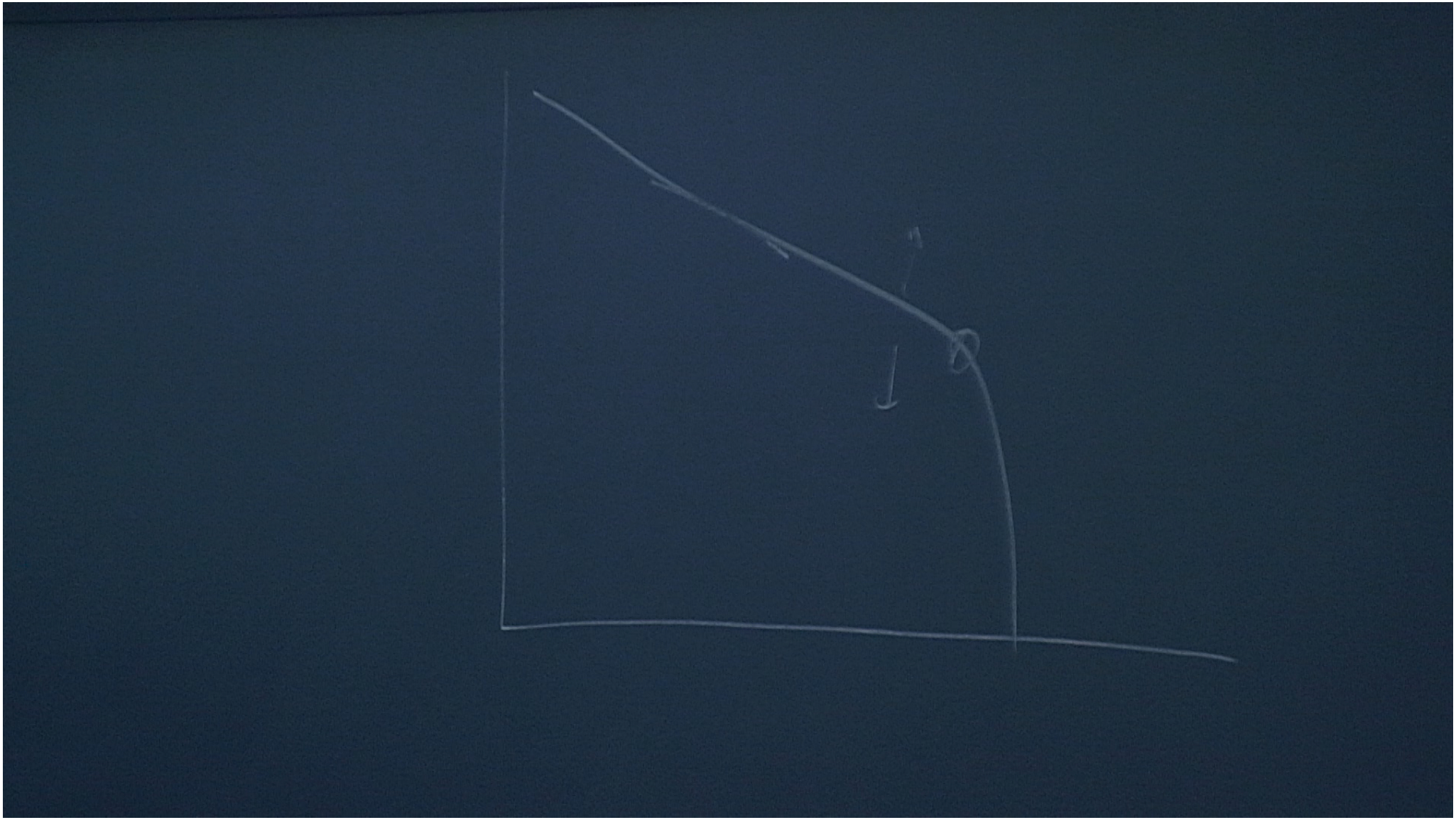
P(D) Analysis





- Short for "Probability of Deflection"
- Method for calculating the PDF of finding a beam with a given intensity value

Vernstrom et al., 2014, MNRAS, 440, 2791

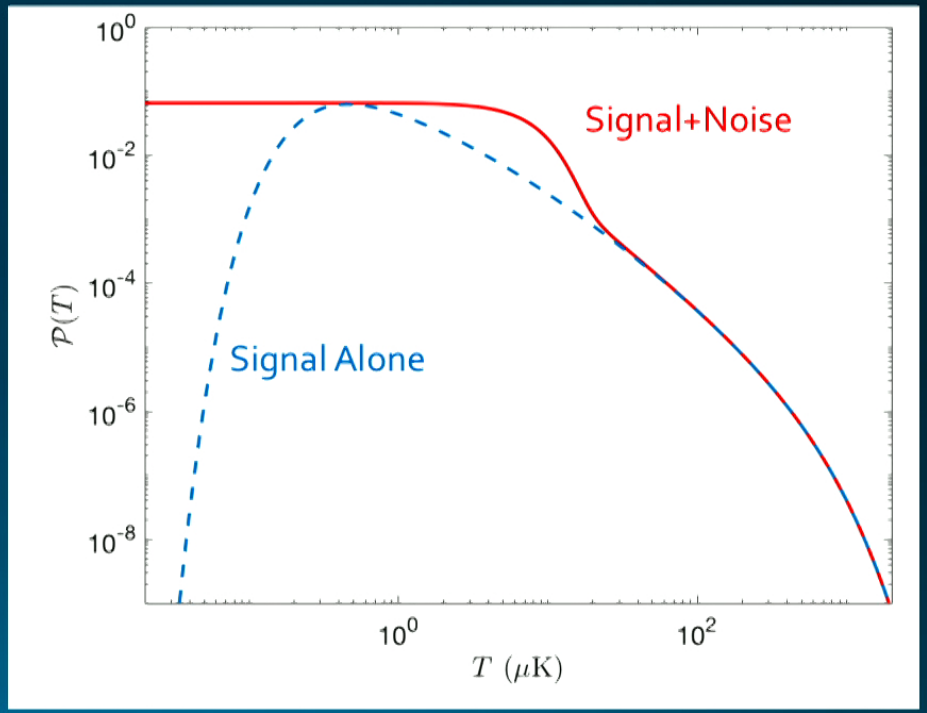


Voxel Intensity Distribution

$\mathcal{P}(T)$ - Probability of observing a voxel with a given intensity

P(D) analysis- map between $\mathcal{P}(T)$ and dn/dL,

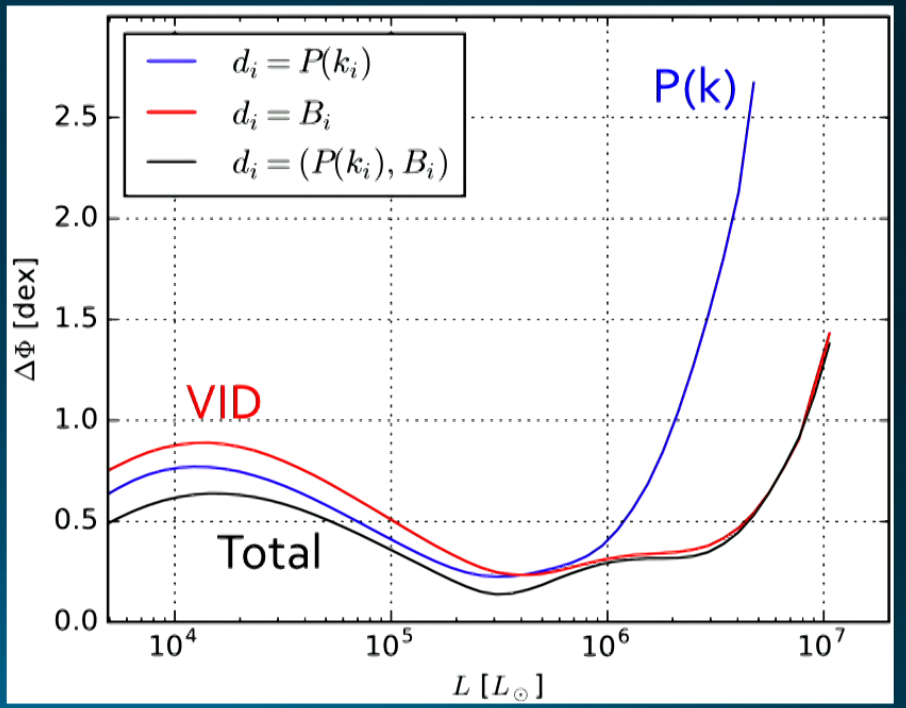
Allows probing full luminosity function (PB++2016,2017)



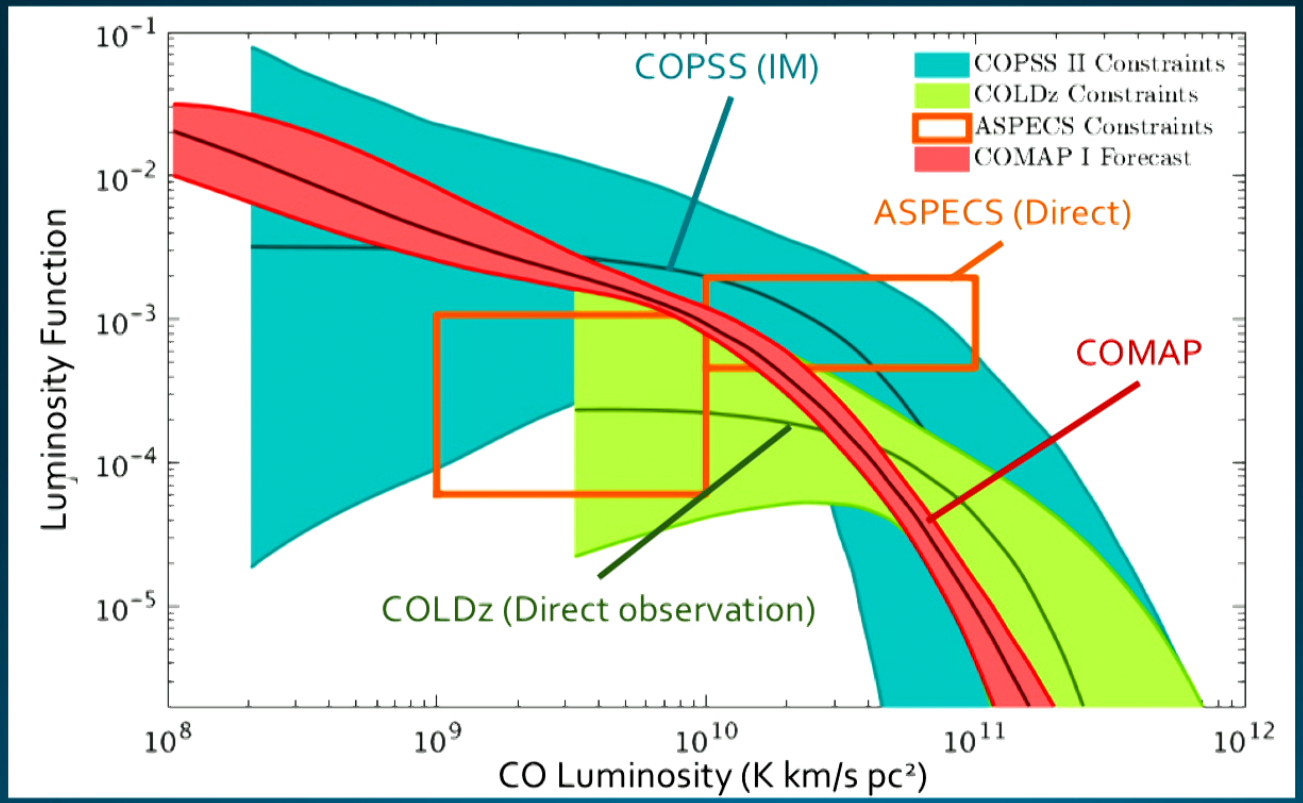
Voxel Intensity Distribution

Simulations confirm- VID gives independent information from P(k)

(Ihle++ 2018 inc. PB)

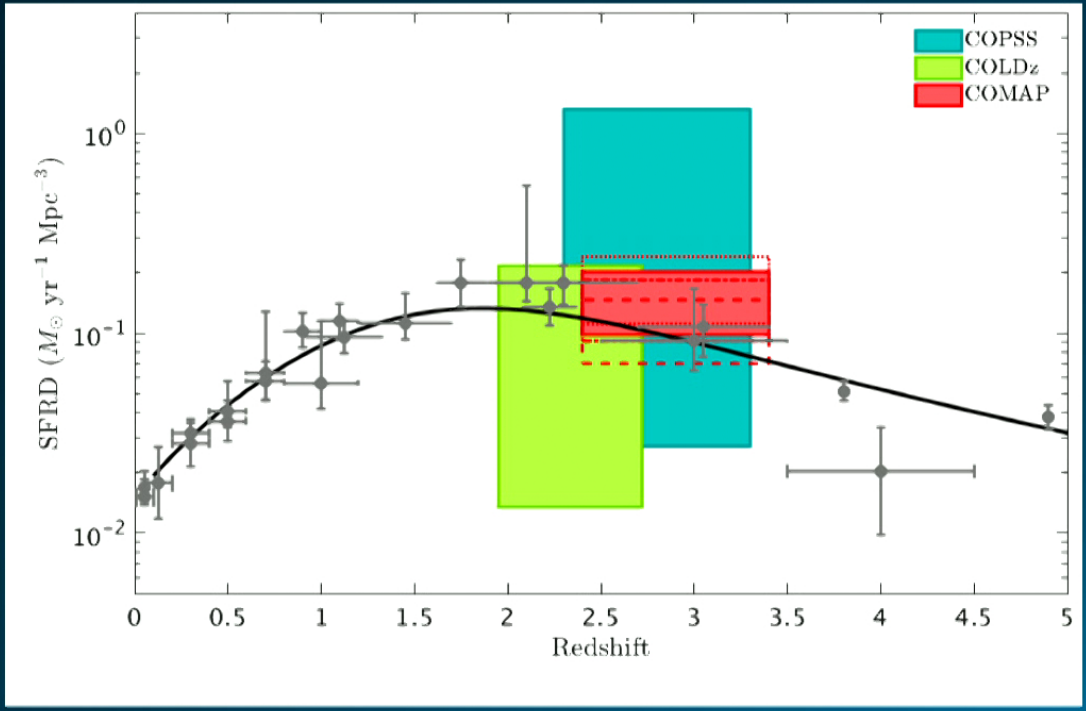


CO Luminosity Function



Ihle+2018 (inc. PCB), Keating+ 2016, Riechers+2018, Decarli+2016

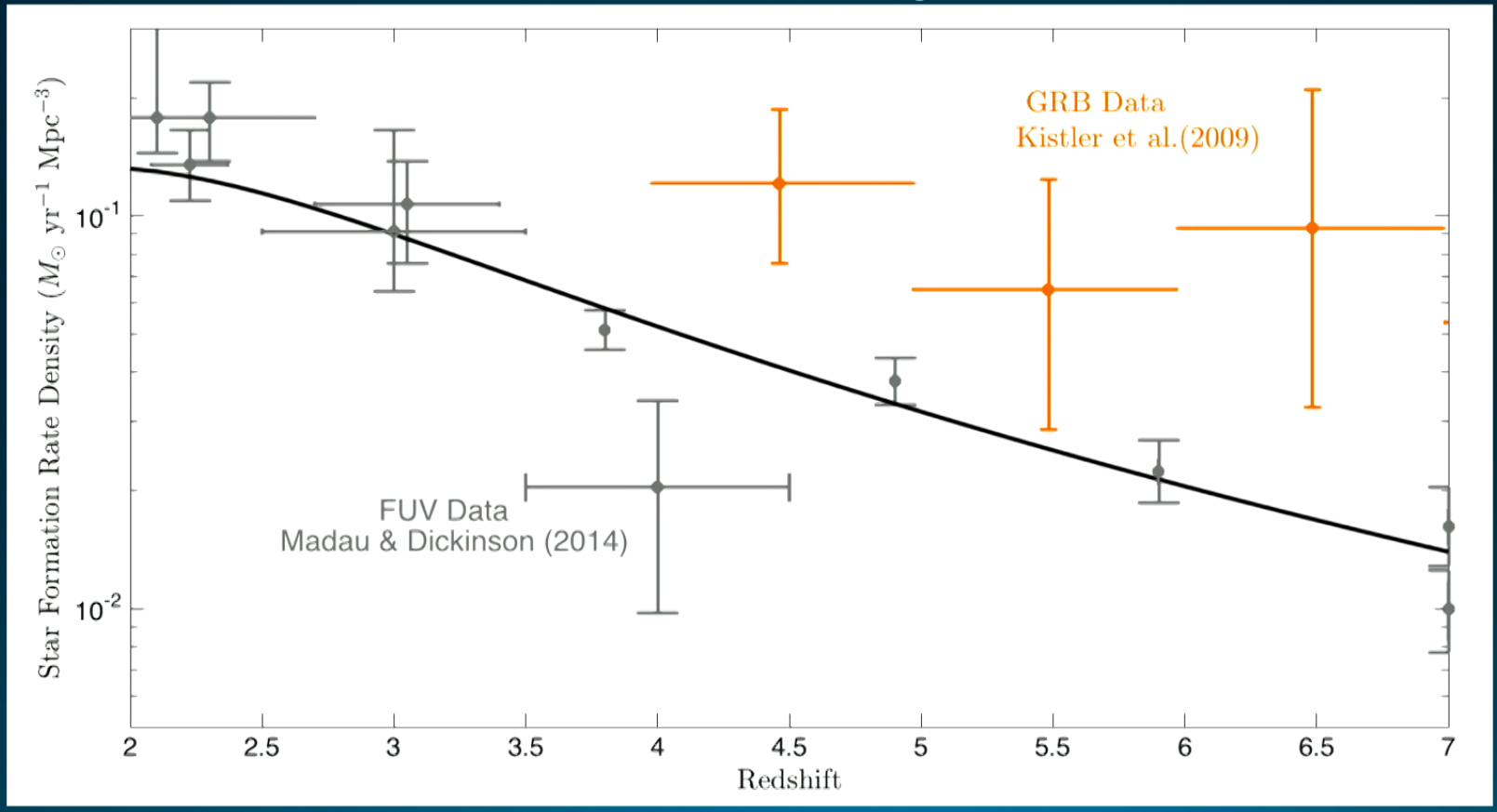
Cosmic Star Formation History



CO Luminosity <-> SFR, but often nonlinearly, so $\langle T_{CO} \rangle$ doesn't map onto SFRD

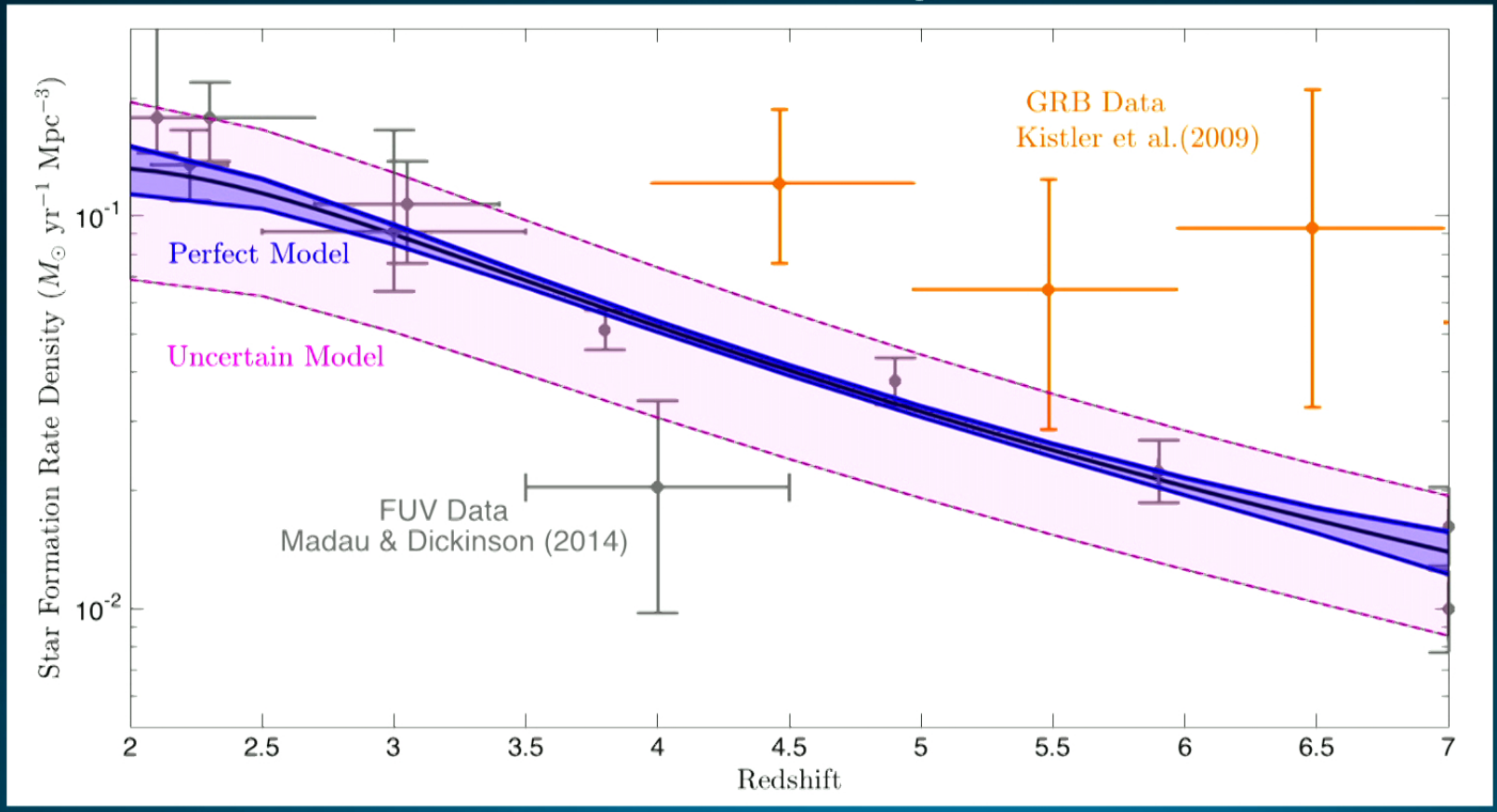
VID enables counting CO emitters, measuring SFRD

Star Formation History



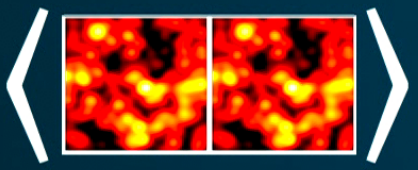
Breysse et al., 2016, MNRAS 457, L127; Kistler et al. 2009, ApJ 705, L104; Madau & Dickinson 2014, ARA&A, 52, 415

Star Formation History



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

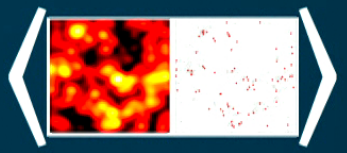
Power Spectrum



Mean, variance of luminosity function
Galaxy bias
Large Scale Structure

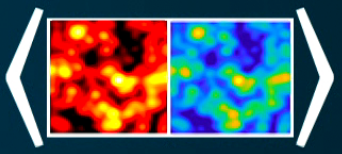
Cross-Spectrum

Line x Galaxy



Line luminosity of galaxy population

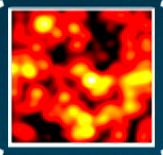
Line x Line



How lines vary with respect to each other

Foreground Safe

Voxel Intensity Distribution

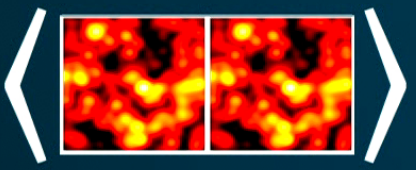
$P\left(\right.$  $\left.\right)$

Full, non-Gaussian luminosity function

What if I'm greedy?

Can we combine the benefits of VID and cross-spectrum?

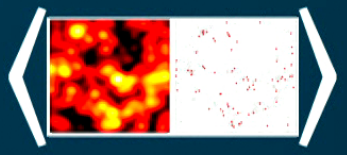
Power Spectrum



Mean, variance of luminosity function
Galaxy bias
Large Scale Structure

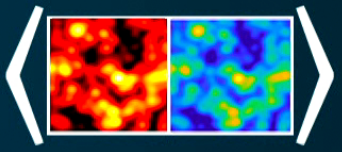
Cross-Spectrum

Line x Galaxy



Line luminosity of galaxy population

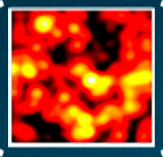
Line x Line



How lines vary with respect to each other

Foreground Safe

Voxel Intensity Distribution

P ()

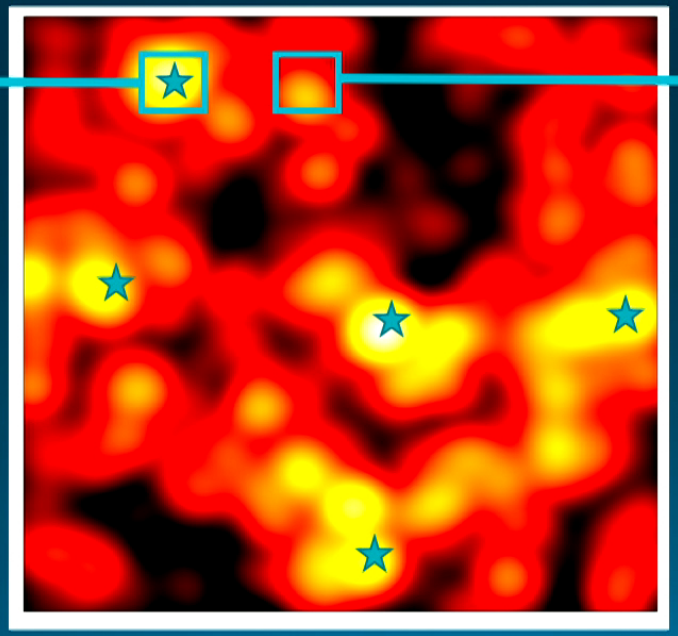
Full, non-Gaussian luminosity function

Foreground-Unbiased One-Point Statistic

Conditional VID

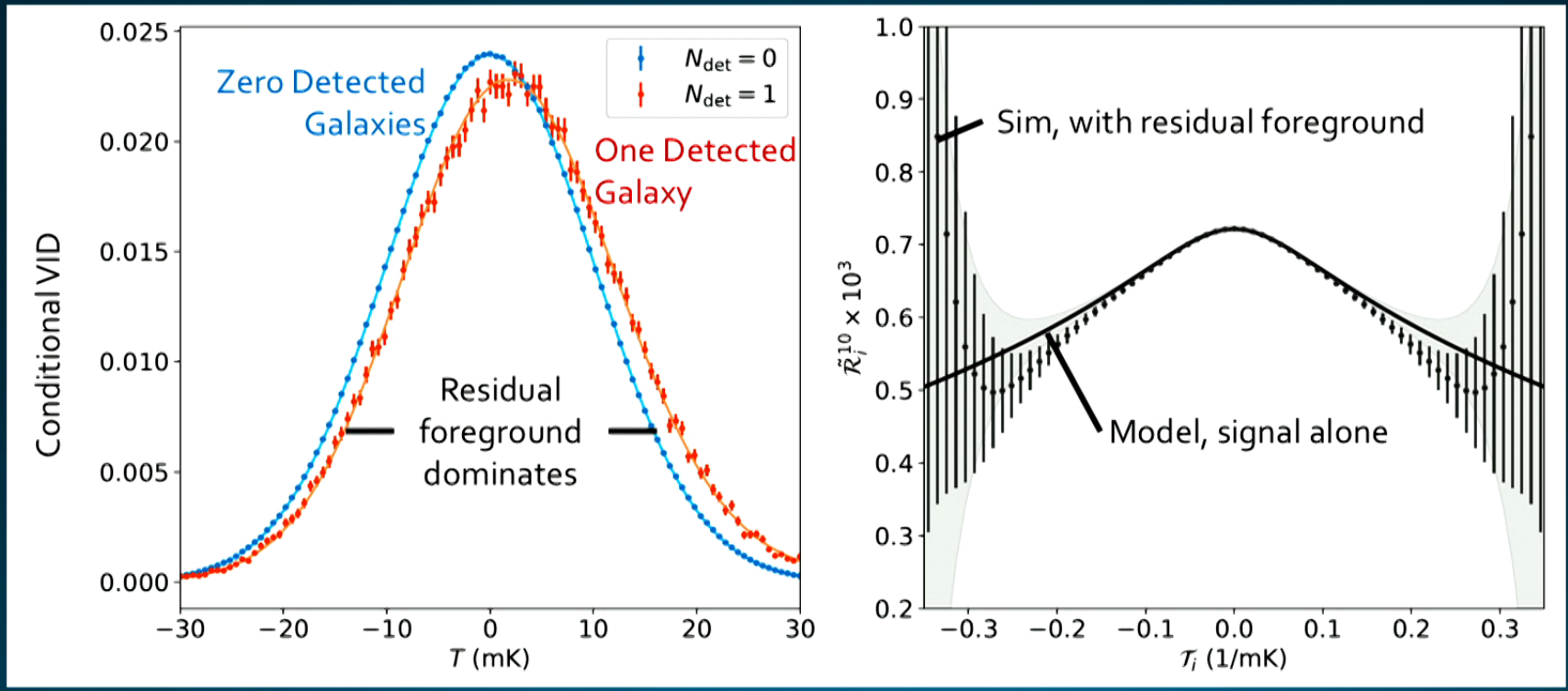
$P(T|N_{\mathrm{det}})$

$P(T|1)$



$P(T|0)$

Conditional VID

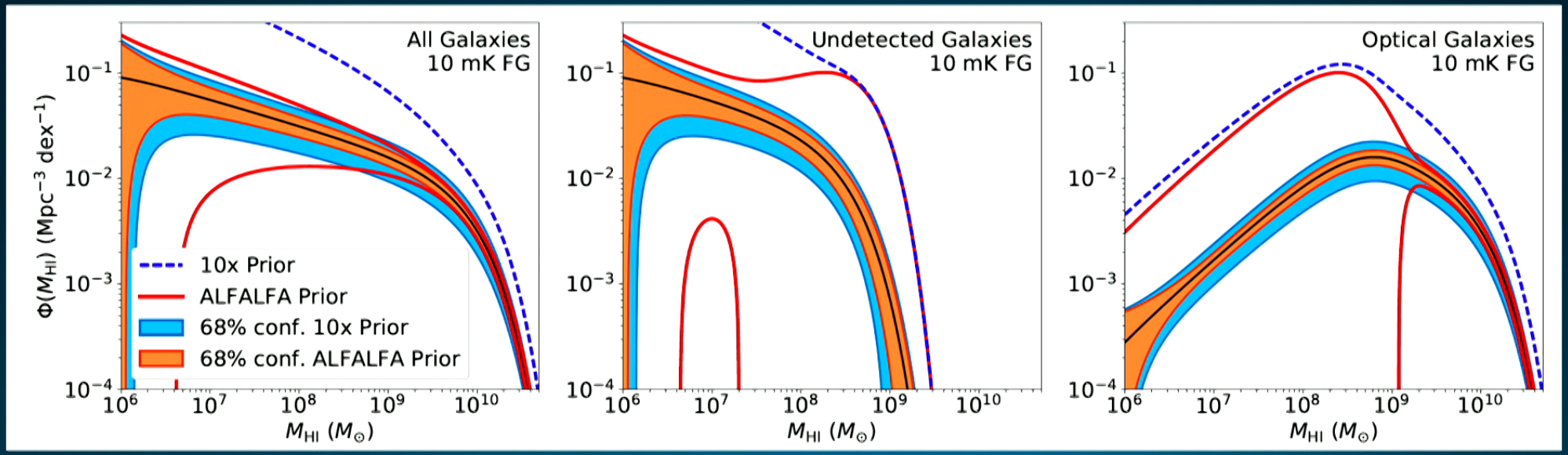


PB+2019

Conditional VID- Parkes 21cm

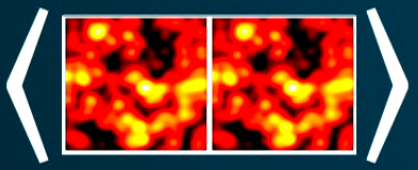
5σ detection of 21cm cross 2DF optical galaxies (Anderson++2017)

Fisher forecast for conditional VID:



PB+2019

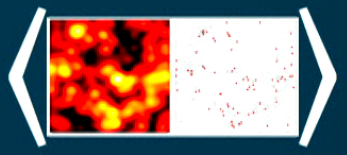
Power Spectrum



Mean, variance of luminosity function
Galaxy bias
Large Scale Structure

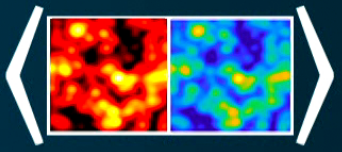
Cross-Spectrum

Line x Galaxy



Line luminosity of galaxy population

Line x Line

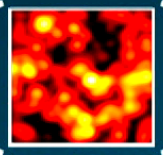


How lines vary with respect to each other

Foreground Safe

Voxel Intensity Distribution

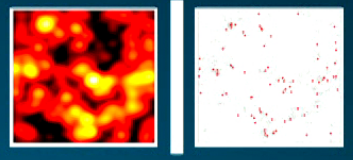
$$P\left(\;\right)$$



Full, non-Gaussian luminosity function

Conditional VID

$$P\left(\;\middle|\;\right)$$



Line Luminosity Function of subset populations