A Galaxy Property Census with Line Intensity Mapping

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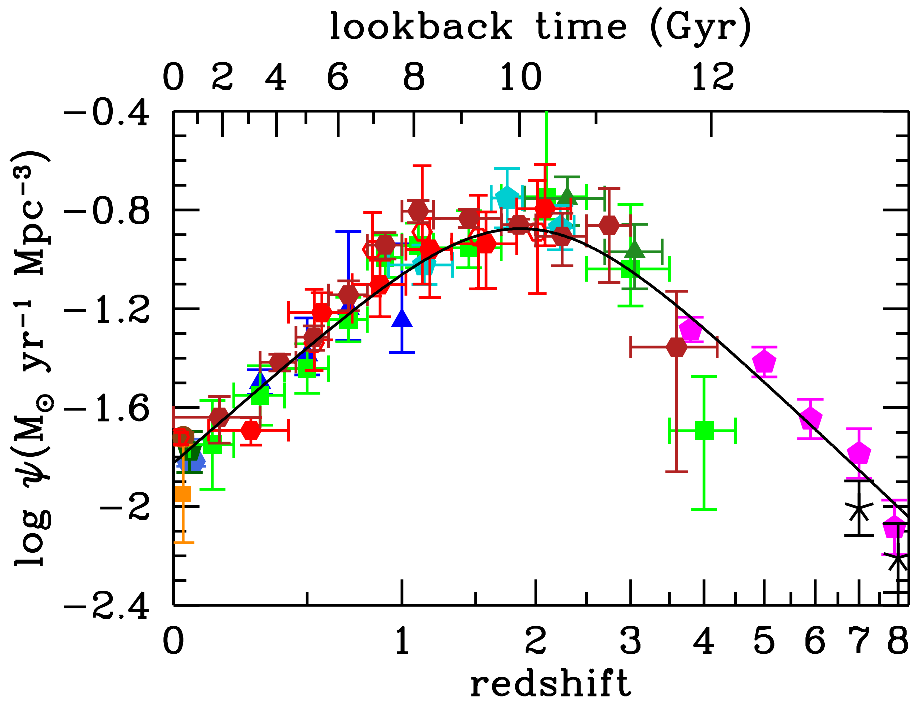
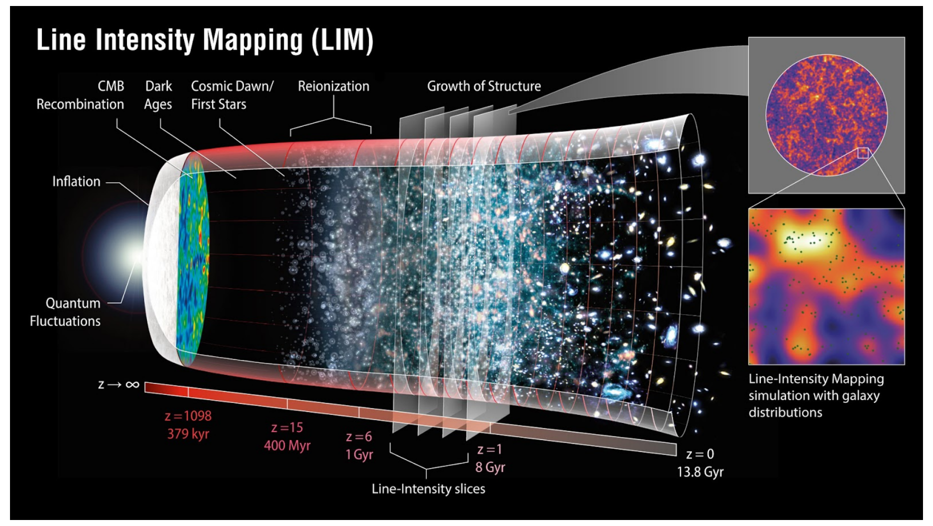
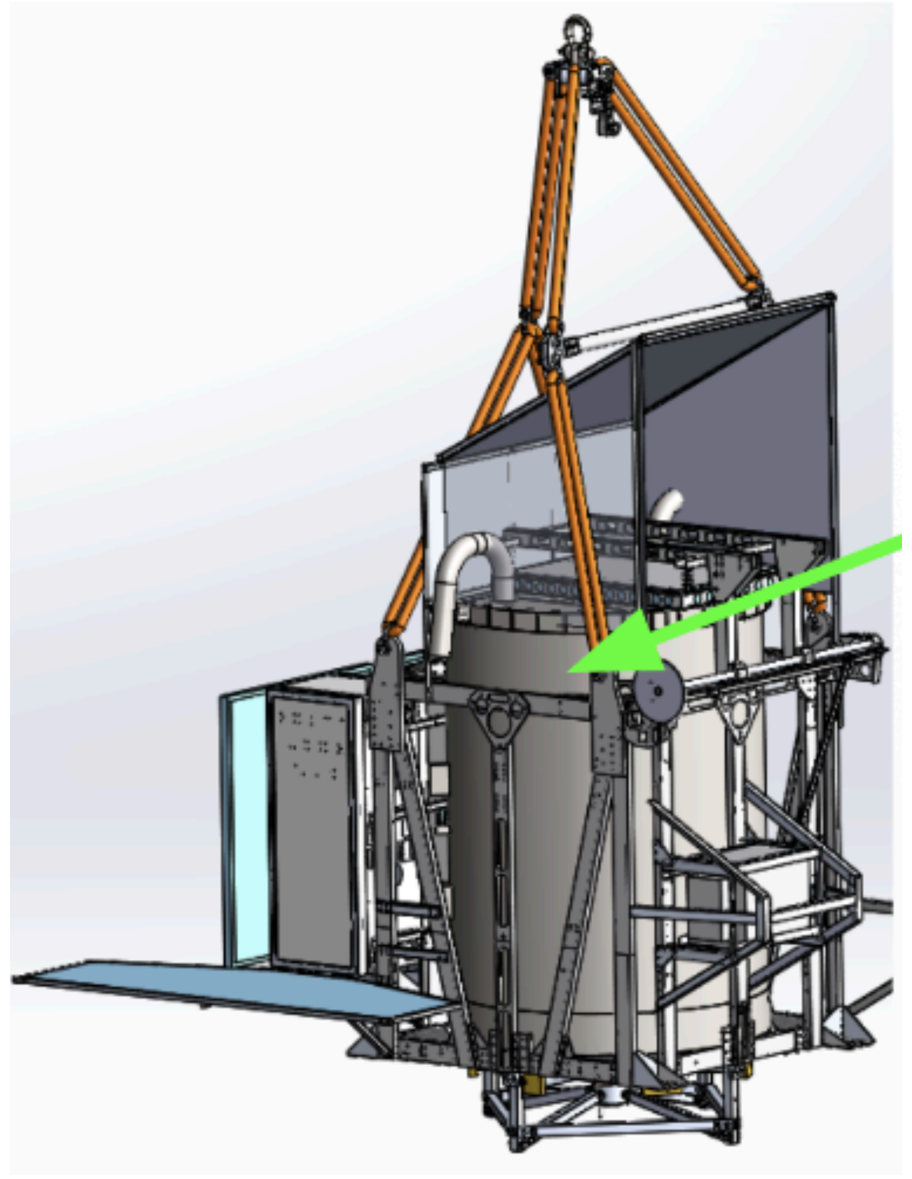
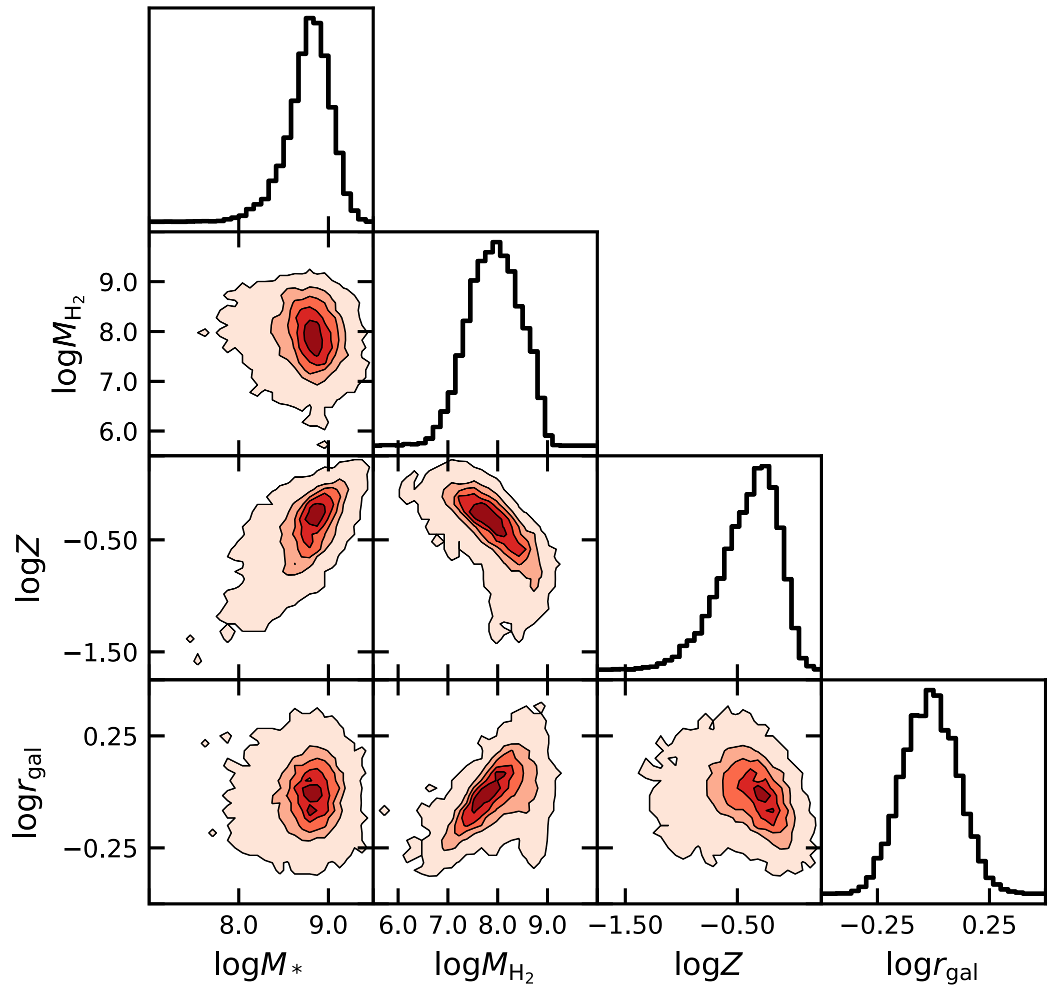
Outline

- Galaxy Evolution Review
- Line Intensity Mapping Measurements
- EXCLAIM Survey
- Upcoming LIM science applications

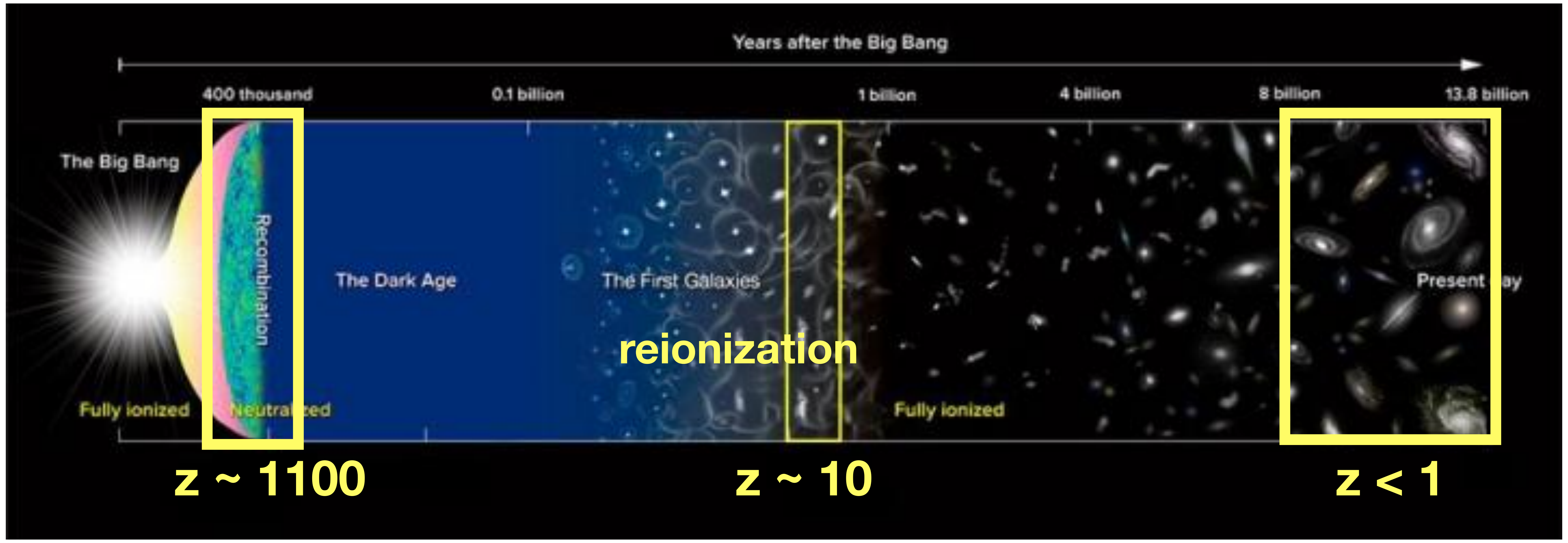








Cosmic Dawn

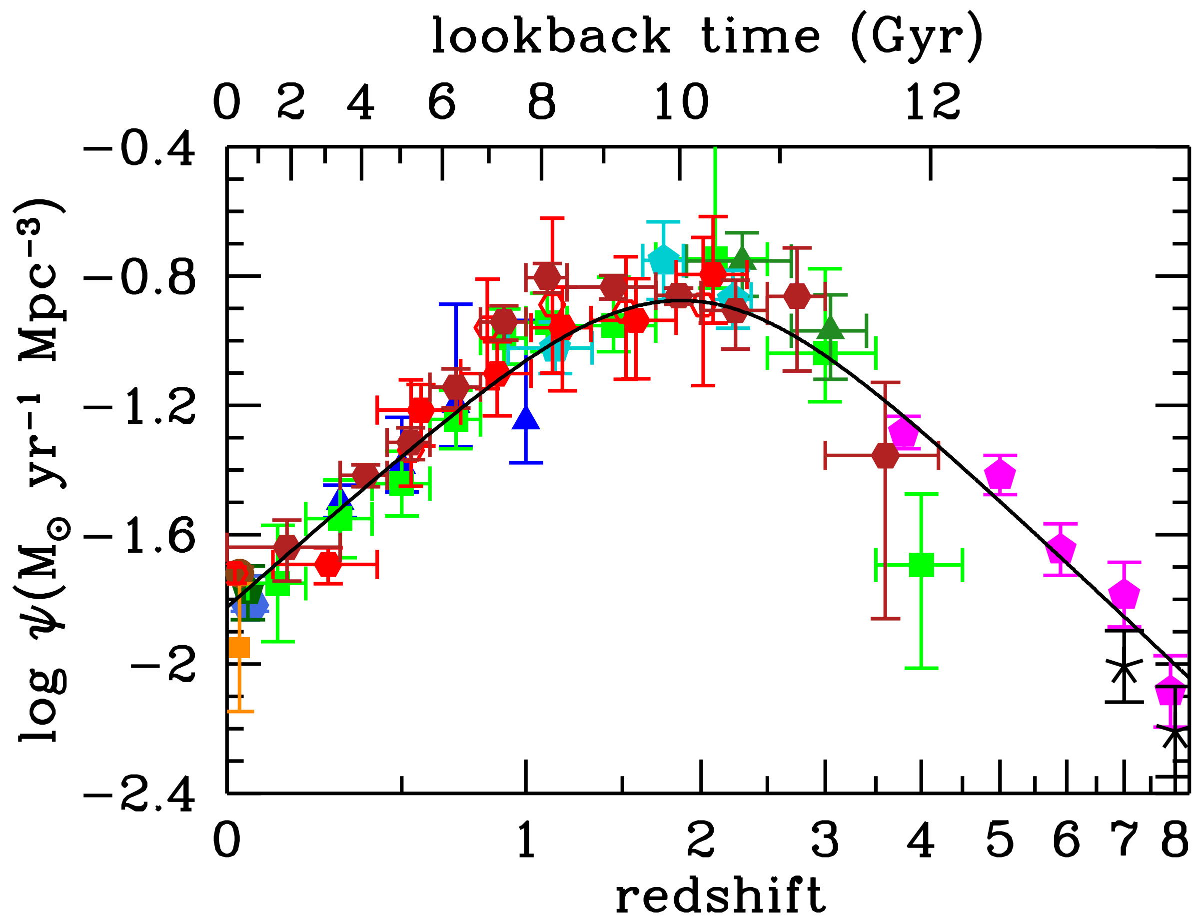


Credit: NAOJ

- Dark Ages: universe consists mostly of low-density HI/He formed after recombination.
- ***Cosmic Dawn: First stars form ~ 400 Myrs after Big Bang***
- UV photons from stars reionize the intergalactic medium made of HI/He
- Future generations of star form in nebulae within galaxies, generate heavier elements that help seed the chemical makeup of the universe.

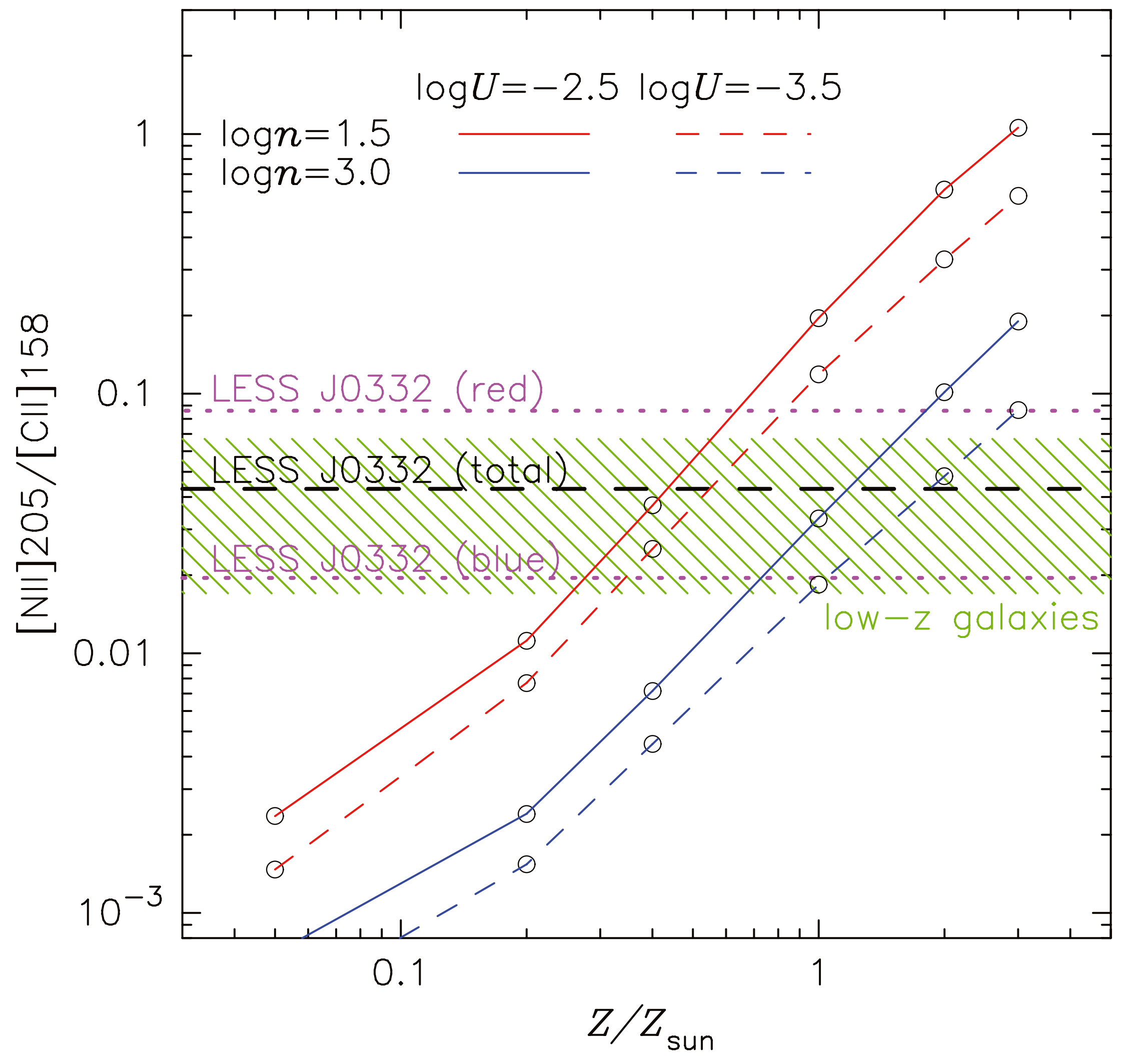
Galaxy evolution is traced by galaxy properties

Star Formation Rate Density



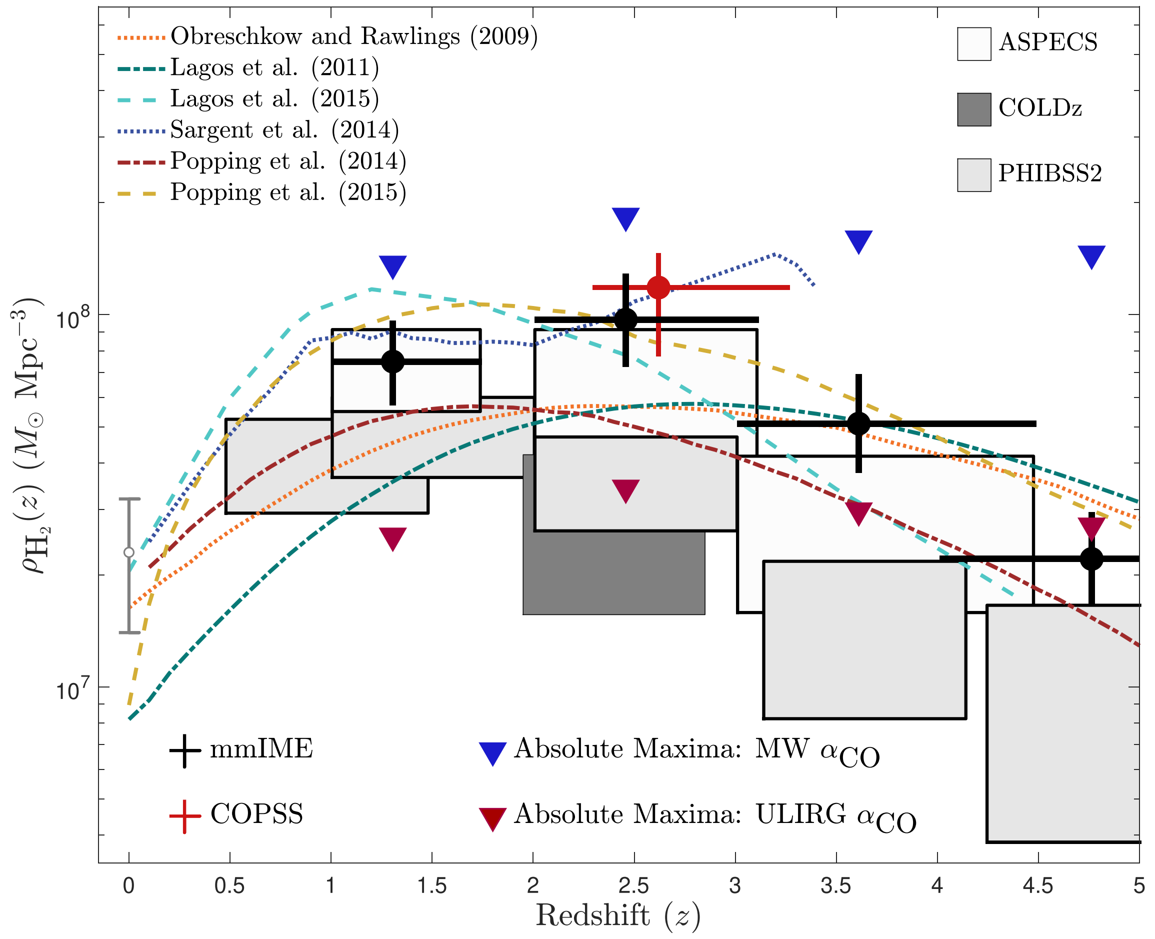
Credit: Madau & Dickerson (2014)

Metallicity



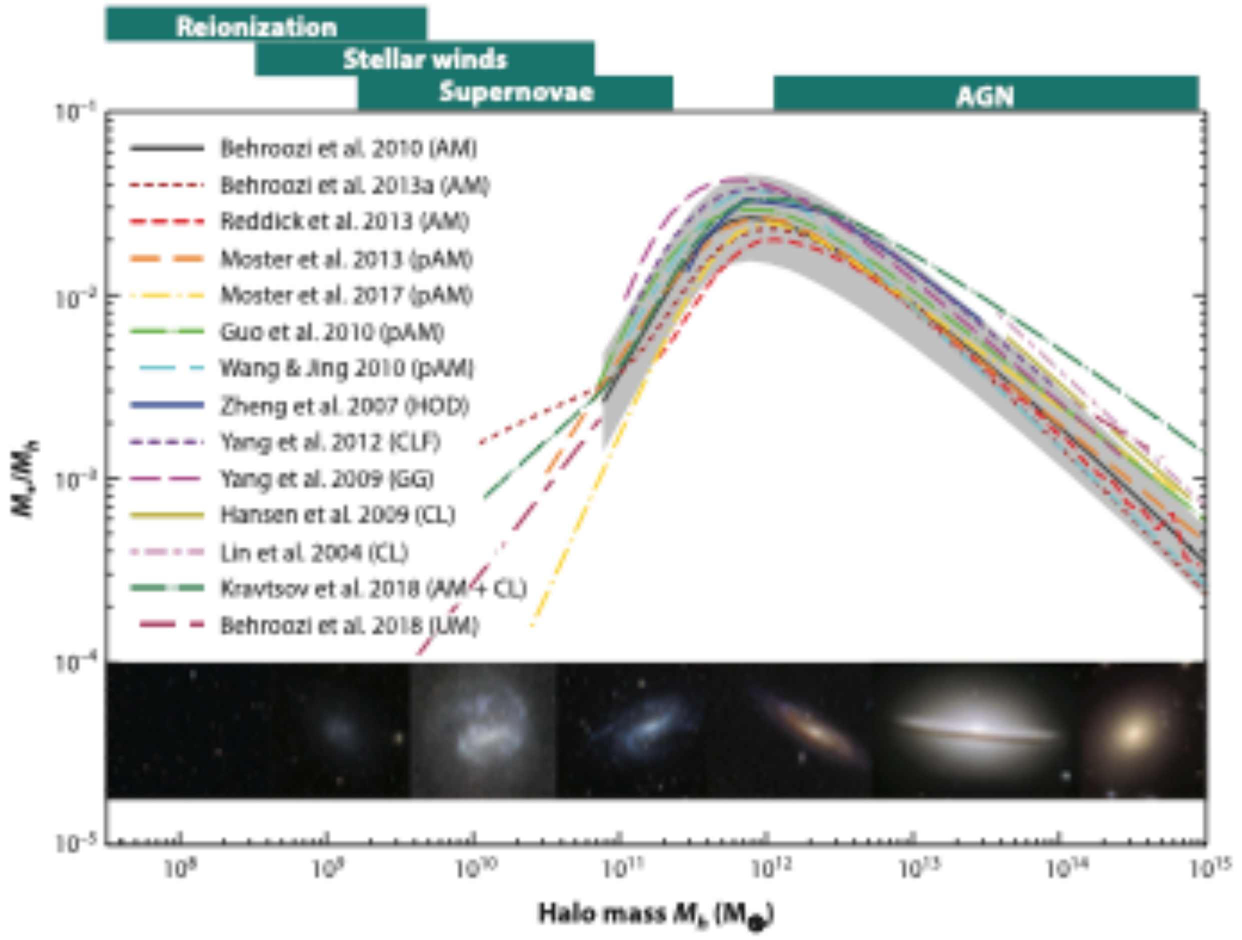
Credit: Nagao et al. (2012)

Molecular Hydrogen Density



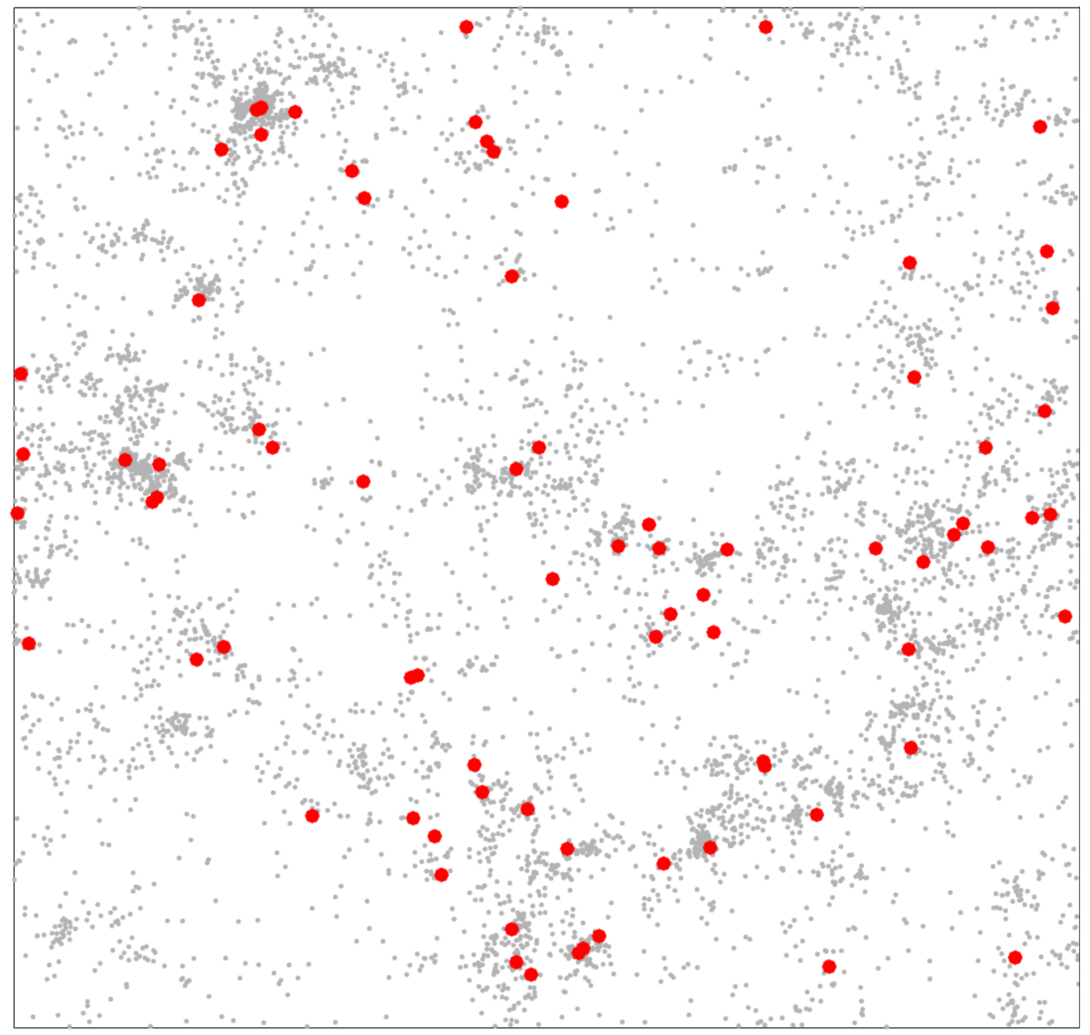
Keating, Marrone+ (2020)

Stellar Mass Ratio



Credit:Wechsler & Tinker (2018)

Missing Galaxies

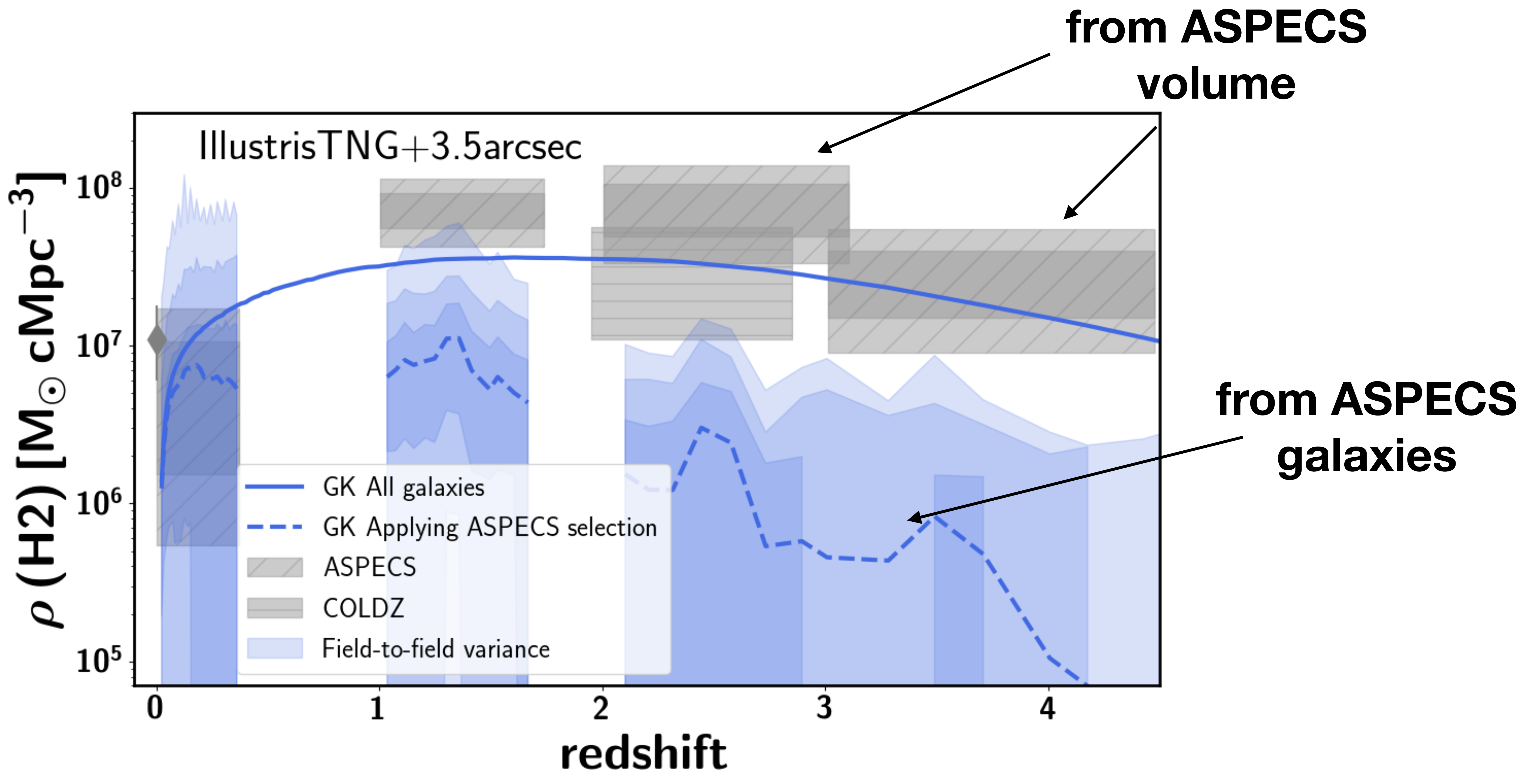


Brightest Galaxies
Very Large Array

Can we *statistically* probe all the galaxies?

Image Credit: Patrick Breysse

Most H_2 outside galaxies

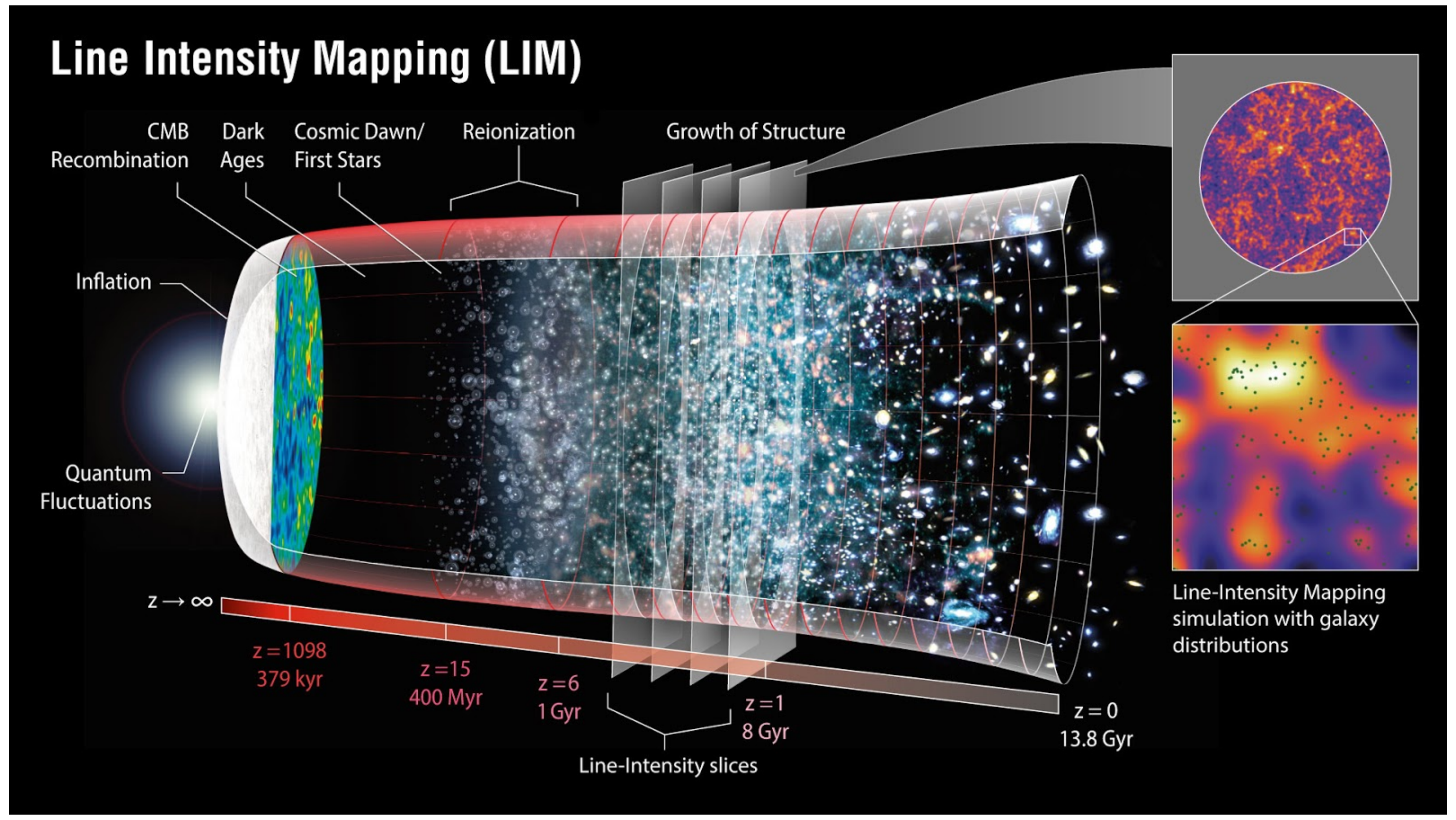


Galaxy surveys will not capture most of the molecular hydrogen, particularly at high redshifts.

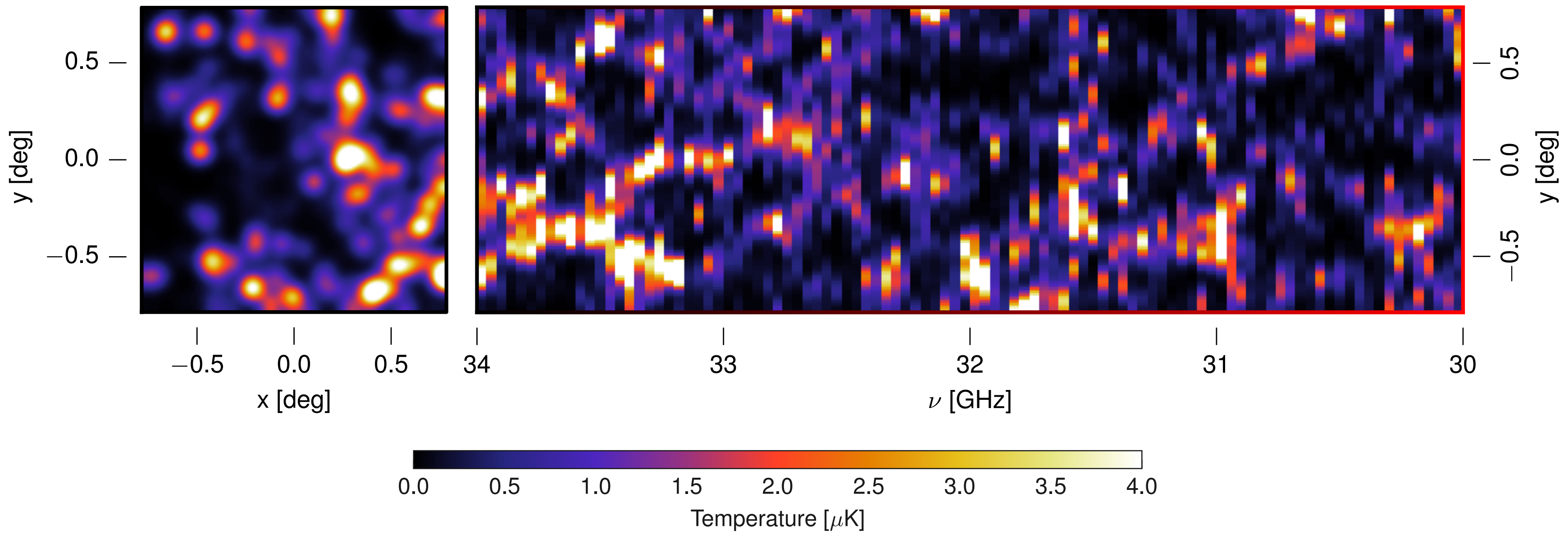
Credit: Popping et al. (2019)

LIM Measurements

Line Intensity Mapping



Credit: NASA

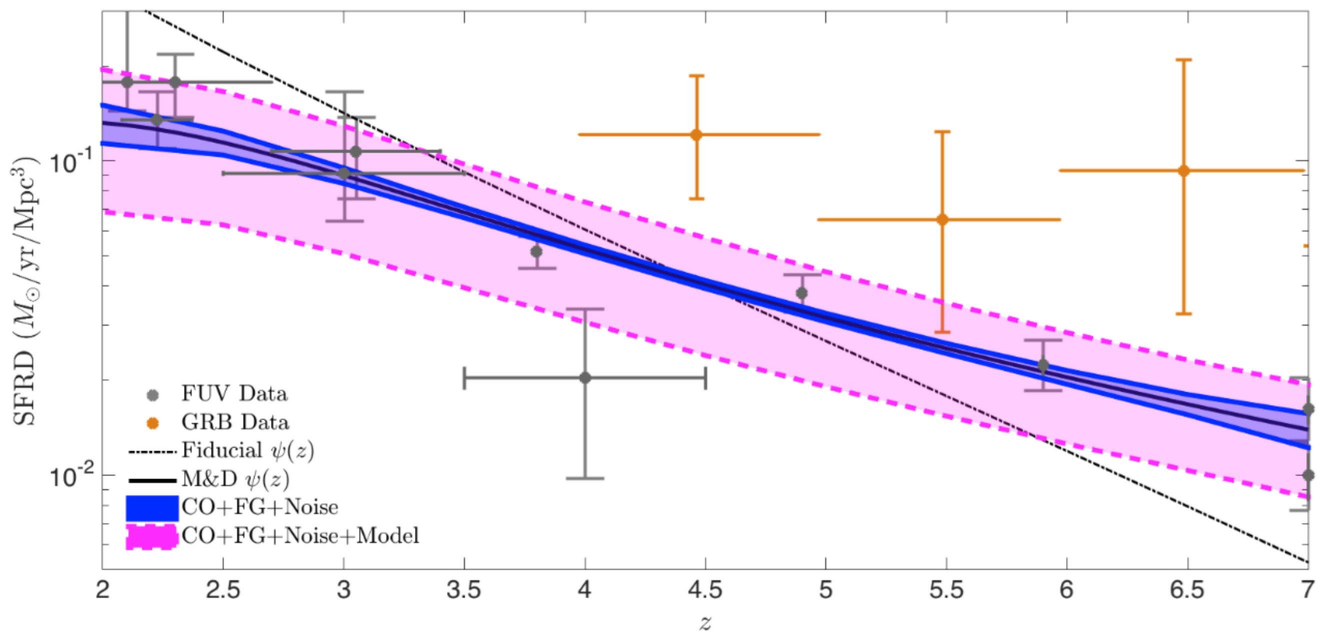


Credit: Li et al. 2015

- Measures **aggregate intensity** in large 2D pixels in multiple frequency bins
- Large aperture accepts low angular resolution for high sampling
- Not correlated across frequency bands — separable from continuum
- Maps large areas — reduces cosmic variance

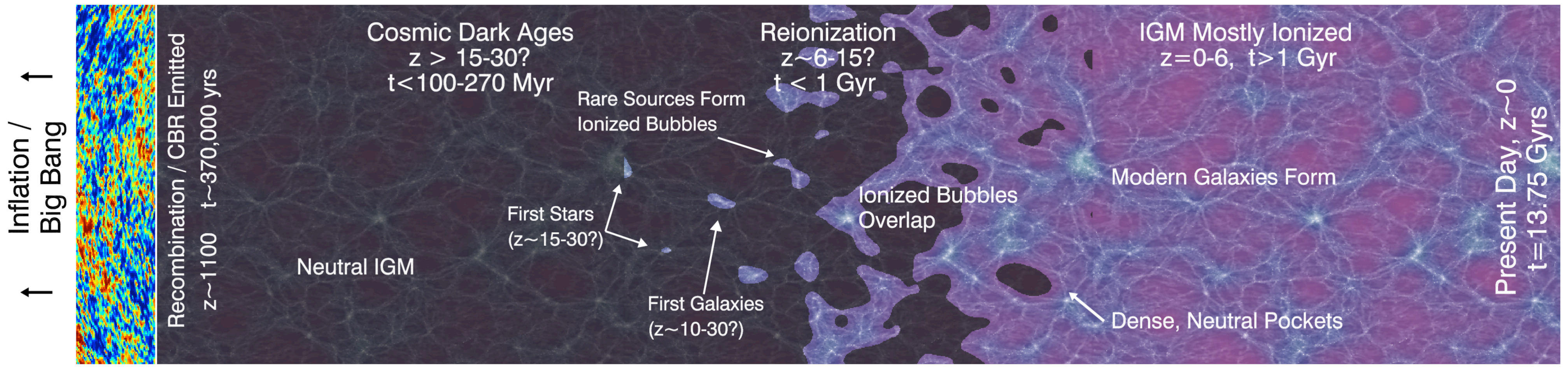
Why Intensity Mapping?

Star Formation



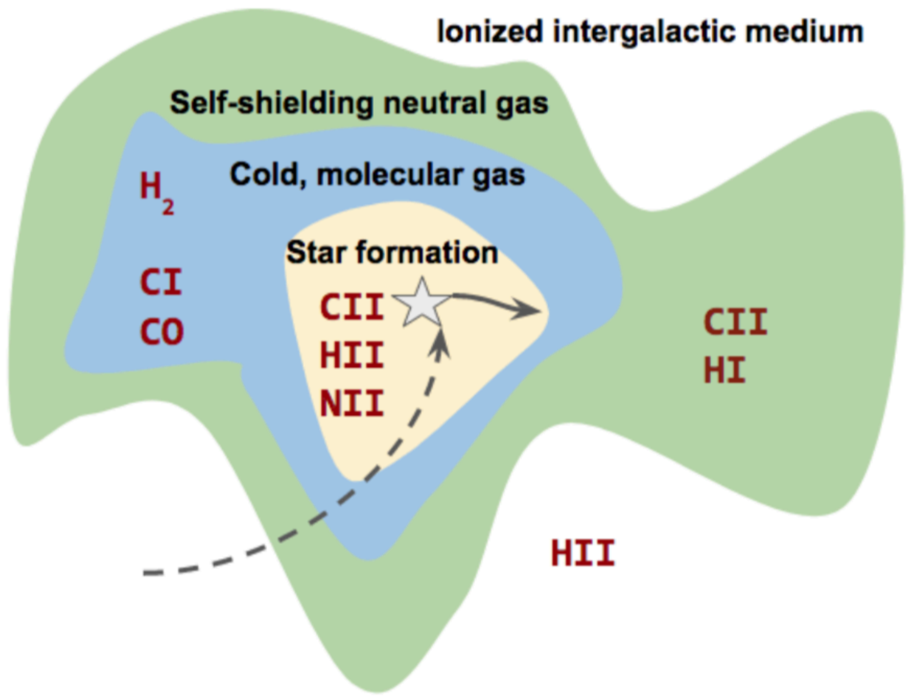
Credit: Patrick Breysse

Reionization

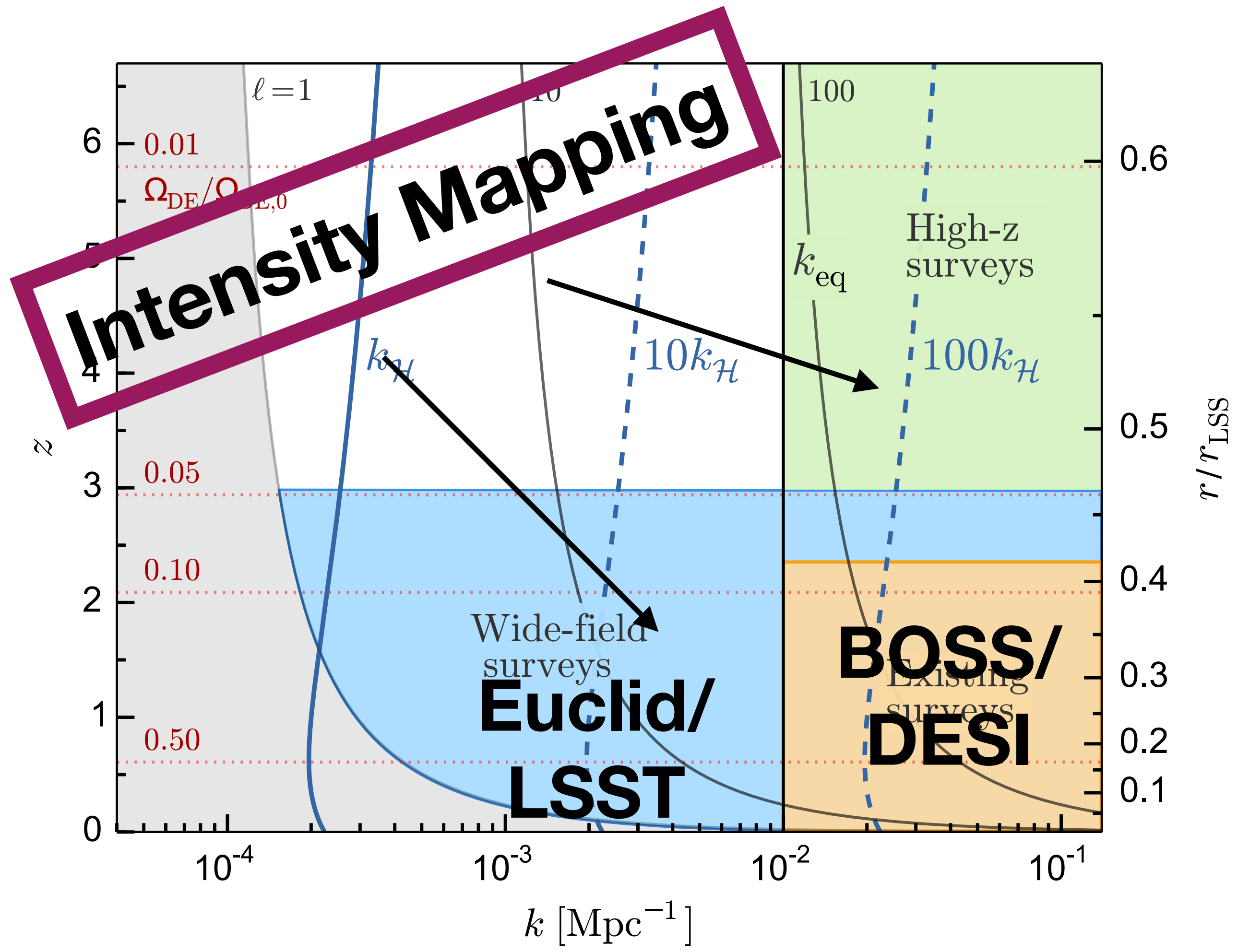


Credit: Brant Robertson

Interstellar Medium



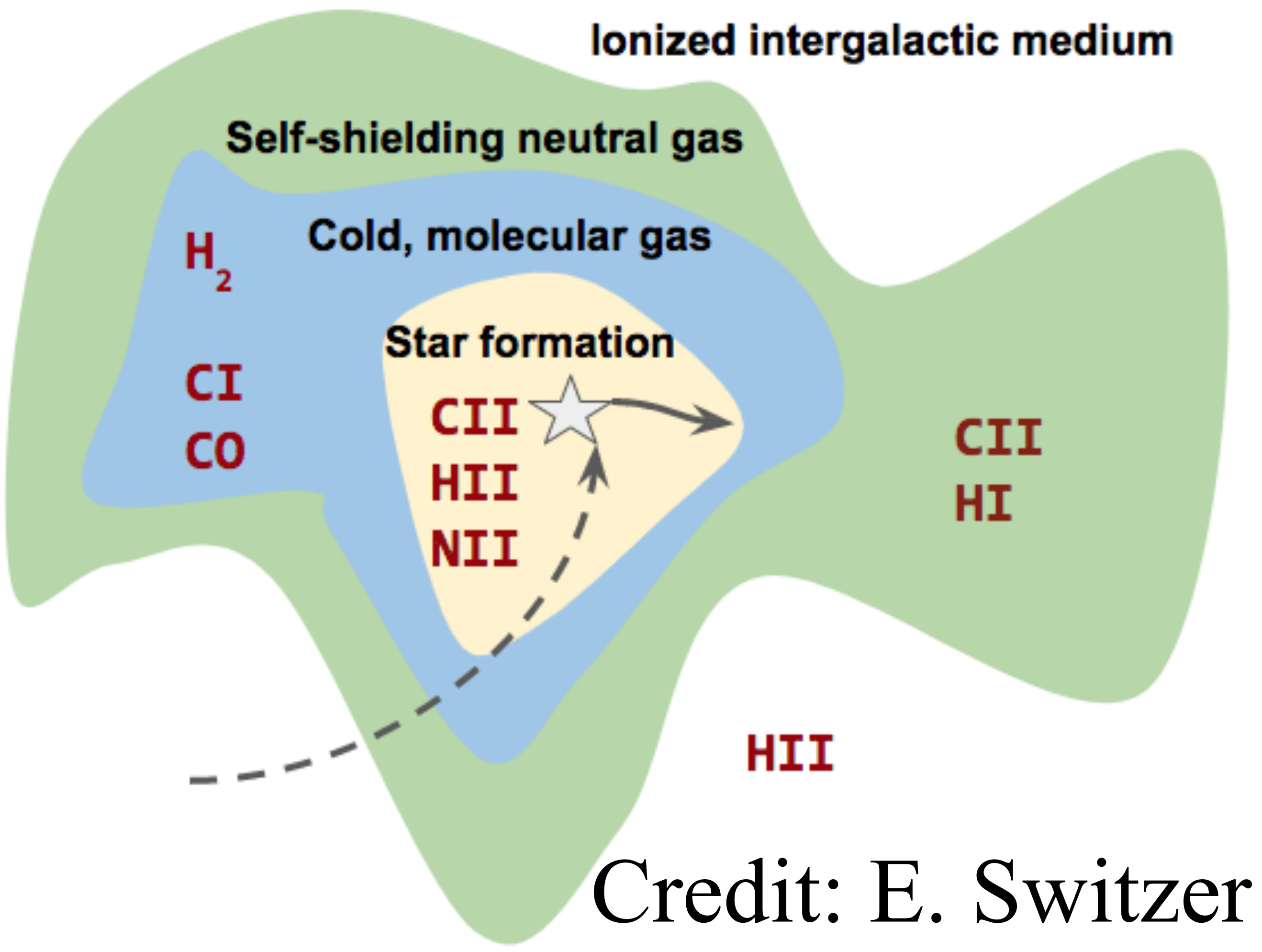
GR/Inflation



Credit: Phil Bull

Multi-line IM opens ISM window

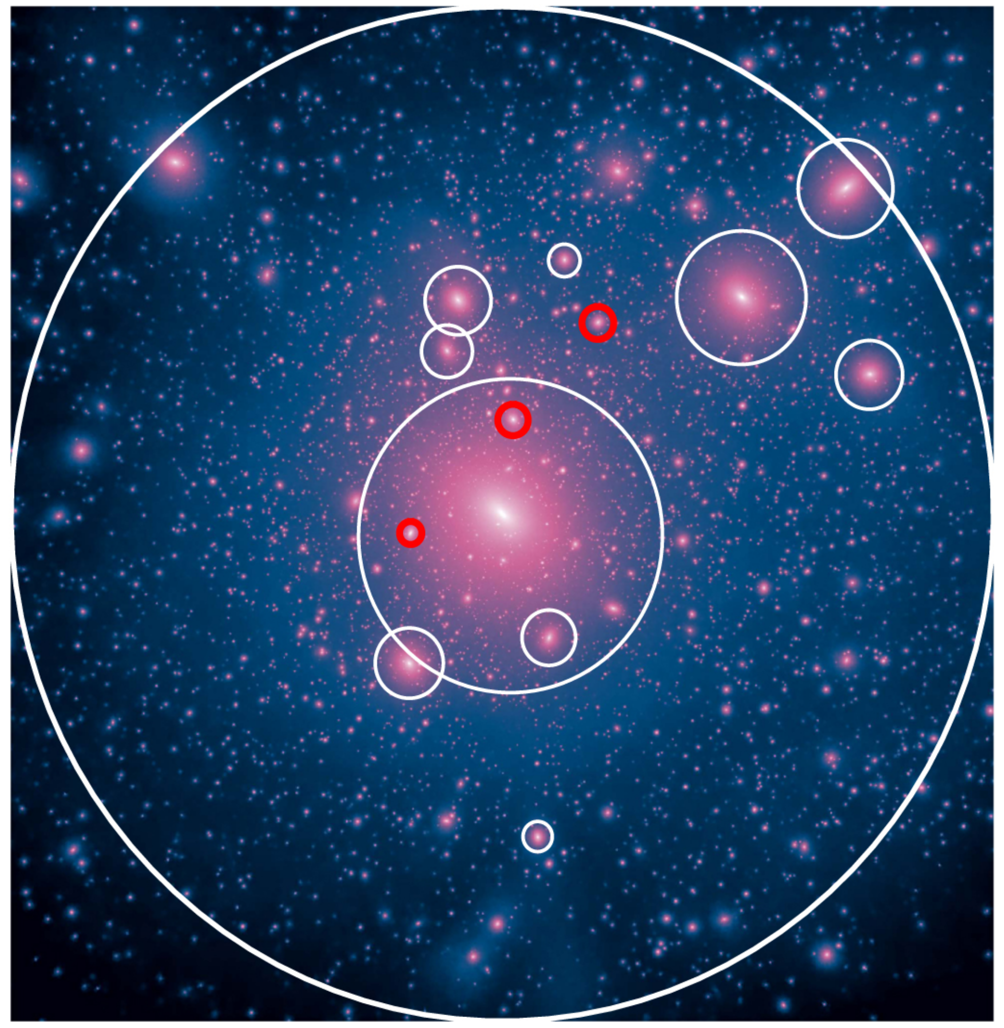
- Molecular regions: CO, [CI], [CII]
- CO is a ladder of lines with rotation transitions $J \rightarrow J$-1
- HII regions: Hα, [NII], [OIII] & more
- Lines sourced by different regions trace different galaxy properties
- e.g. low-J CO traces H_2; [CII] and high-J CO traces SFR; [NII]/[CII] ratio traces metallicity



Credit: E. Switzer

Halo Luminosities are Mass-dependent (mostly)

- Halo luminosities are just sums over all constituent galaxy luminosities
- Galaxy luminosities should be a function of galaxy properties
- Assumption: Halo mass and redshift determine distribution of galaxy properties
- **Result: Halo luminosities should be functions of halo mass and redshift**
- Distribution of halo masses given by ***halo mass function n(M)***
- $n(M)dM$ = number density of halos within mass range $[M, M+dM]$



Credit: Caterpillar Simulation of Milky Way (Kaley Bauer, MIT)

Line intensities sourced by halos

$$I_\nu^{\text{line}} = \frac{1}{4\pi\nu_0}\frac{c}{H(z)}\mathcal{L}(z)$$

$$\mathcal{L}(z) = \int dM\, n(M,z) L(M,z)$$

line rest frequency

Hubble expansion rate

luminosity density

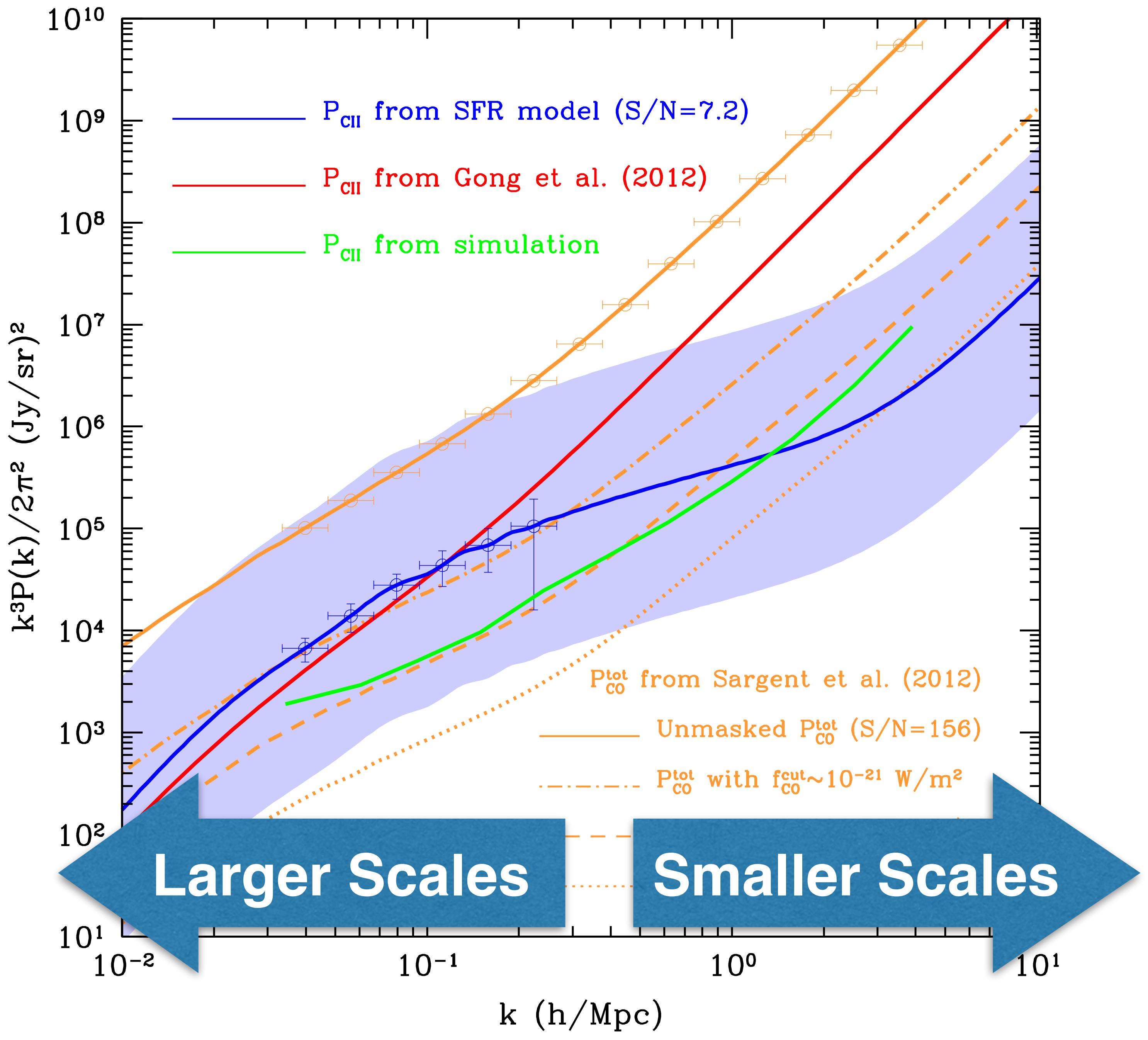
halo mass function

halo luminosity-mass relation

- An intensity measurement can measure $\mathcal{L}$ at redshift z and potentially $L(M)$.
- **Requires priors on cosmology and halo-mass function**
- $L(M, z)$ is sourced by the luminosities of individual galaxies of the host halo.

Power spectra probes Line Intensity

- Variance of Fourier modes in intensity map.
- Separates signal from large scale foregrounds
- Sourced by $P_m(k)$ from large-scale structure
- Probes (bI); $U \sim \langle L^2 \rangle$ in constant term tough to probe
- b = clustering bias; (mostly) set by $n(M)$



Credit: Crites et al. 2014

$$P_I(k) = \boxed{(bI)^2} P_m(k) + \boxed{\frac{U}{n_{\mathrm{halo}}} + \frac{I^2}{n_{\mathrm{gal}}}}$$

How can LIM probe galaxies?

1. Easy if that property is proportional to L; lets you measure the property directly
2. Not easy if the property is not proportional to L; must measure $L(M)$→ property(M)→ property density

$$L_{CO(1-0)} \propto M_{H_2} \Rightarrow \mathcal{L}_{CO(1-0)} \propto \rho[\mathrm{H}_2]$$

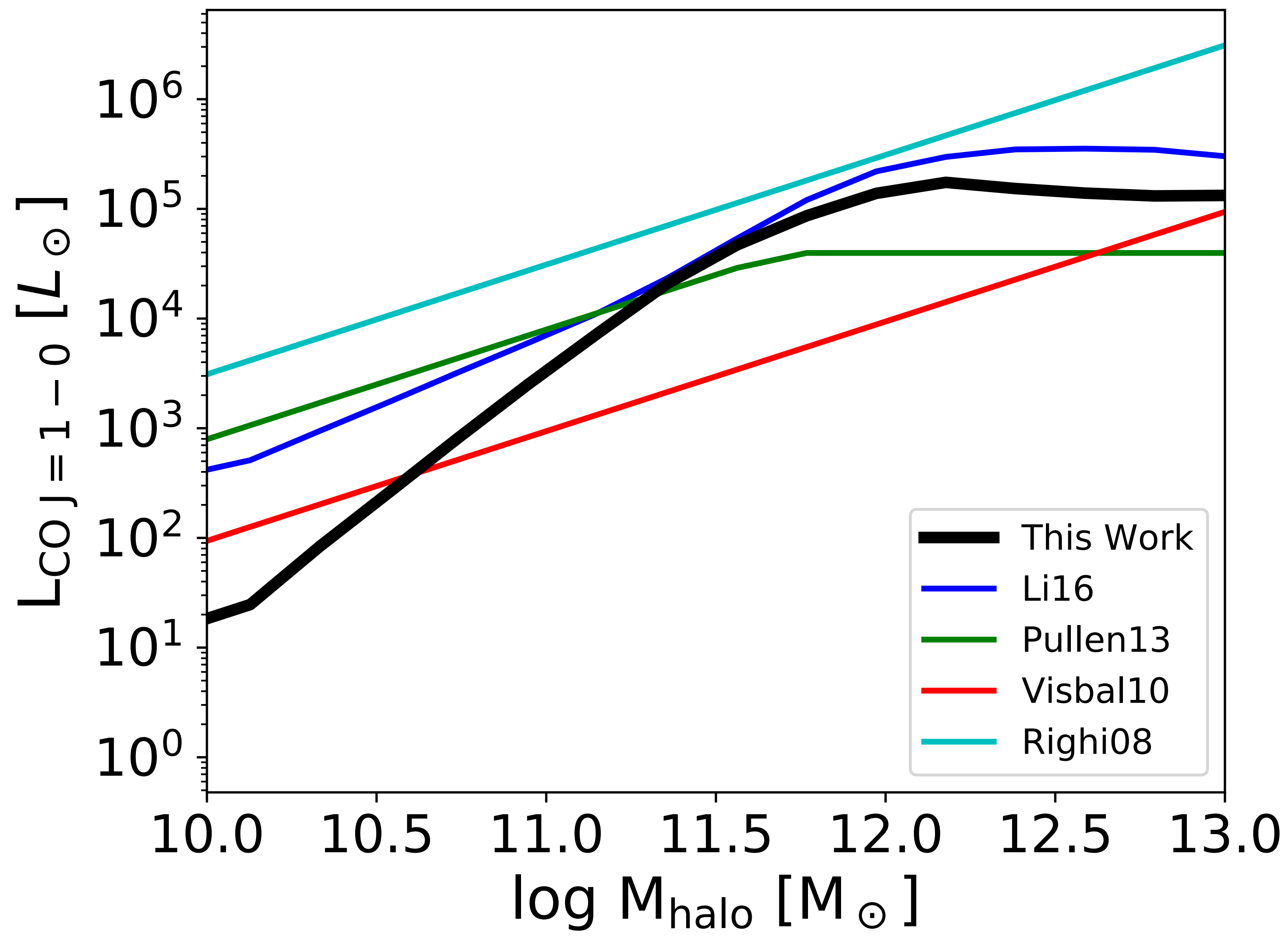
$$L_{CO(5-4)} \propto SFR \Rightarrow \mathcal{L}_{CO(5-4)} \propto \rho[SFR]$$

$$L_{[CII]} \propto SFR^{1.7}$$

$$\Rightarrow \mathcal{L}_{[CII]} \propto \int dM\, n(M) SFR^{1.7}(M) \neq \rho[SFR]$$

Large Spread for LIM models

- Models for lines vary greatly
- Tend to agree where models are calibrated ($10^{11\text{-}12}$ M_{sun})
- Tend to disagree where they are not (high redshifts/low masses)
- True for both empirical, *ad hoc* models, semi-analytic models (SAMs), and simulations



Yang, Somerville, AP+ (2021)

LIM can constrain *L*(*M*) models

$$\mathcal{L}(z) = \int dM\, n(M,z) L(M,z)$$

$$L_{[CII]}(M,z) = \left(\frac{M}{M_1}\right)^{\beta} e^{-N_1/M} \left(\frac{(1+z)^{2.7}}{1+[(1+z)/2.9]^{5.6}}\right)^{\alpha}$$

[CII] model (Padmanabhan 2019)

- We can write $\mathcal{L}$ in terms of *L(M)* parameters
- Use your favorite MC sampler to measure the parameters
- ***Will need reasonable priors on parameters to make them not fully degenerate***

Parameters → L(M)?

$$\langle L(M)\rangle = \int d^N p\, L(M|\mathbf{p}) f(\mathbf{p})$$

parameter distribution

parameter vector

L(*M*) is drawn from a parameter posterior distribution

$$\sigma^2[L(M)] = \langle L^2(M)\rangle - \langle L(M)\rangle^2$$

Example: $\mathbf{p} = \{\alpha, \beta, M_1, N_1\}$ for [CII] model

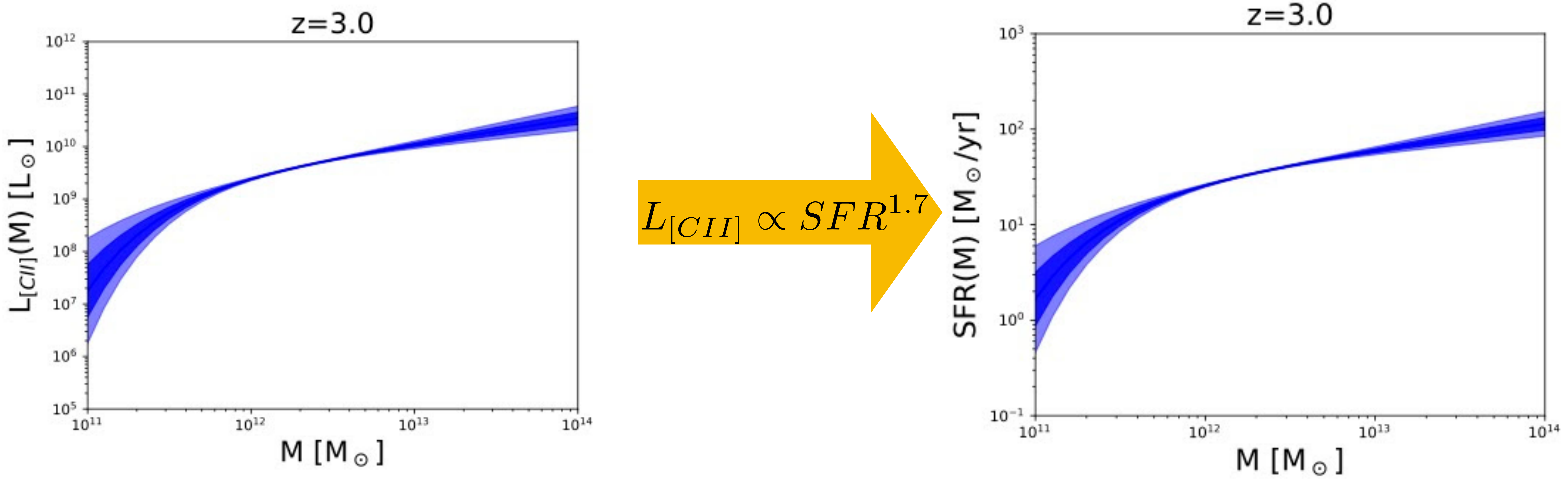
Assumptions: (1) Expand *L*(*M*) to first-order in (**p**-<**p**>); (2) Make *f*(**p**) a multivariate Gaussian

$$\langle L(M)\rangle = L(M|\langle\mathbf{p}\rangle)$$

$$\sigma^2[L(M)] = \nabla_{\mathbf{p}} L|_{\langle\mathbf{p}\rangle} \cdot \mathbf{C} \cdot \nabla_{\mathbf{p}} L|_{\langle\mathbf{p}\rangle}$$

parameter covariance matrix

Example: L(M) & SFR(M) limits



EXCLAIM Survey

EXCLAIM Collaboration

NASA Goddard
Eric Switzer (PI)
Tom Essinger-Hileman (DPI, Instrument lead)
Giuseppe Cataldo (Mission SE)
Emily Barrentine (Spectrometer lead)

Chris Anderson (Map analysis, JHU coop)
Alyssa Barlis (SECP, optical test design)
Berhanu Bulcha (Resonator design)
Paul Cursey (Machinist)
Negar Ehsan (Antenna design)
Jason Glenn (Receiver, MKIDs)
James Hays-Wehle
Larry Hess (Fabrication)
Amir Jahromi (ADR)
Mark Kimball (ADR)
Mona Mirzaei (Fabrication)
Alan Kogut (Gondola)
Luke Lowe (Flight Electronics)
Jacob Nellis (ADR)
Omid Noroozian (MKID design and test)
Tatsat Parekh (Mechanical)
Samelys Rodriguez (Wirebonding)
Thomas Stevenson (Spectrometer)
Ed Wollack (Spectrometer)
Aaron Yung (Science team)

Funded partners

NYU/CCA: Simulation and interpretation
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Rachel Somerville
Shengqi Yang
Patrick Breysse

UMD:
Alberto Bolatto (Galactic field, interpretation)
Carolyn Volpert (grad, spectrometer test, survey)

ASU: (Readout)
Phil Mauskopf (Readout Lead)
Adrian Sinclair
Ryan Stephenson
Cody Roberson

UWisc: (MKID modelling, forecasting)
Trevor Oxholm, Gage Siebert
Peter Timbie

CITA: Simulation and interpretation
Ue-Li Pen

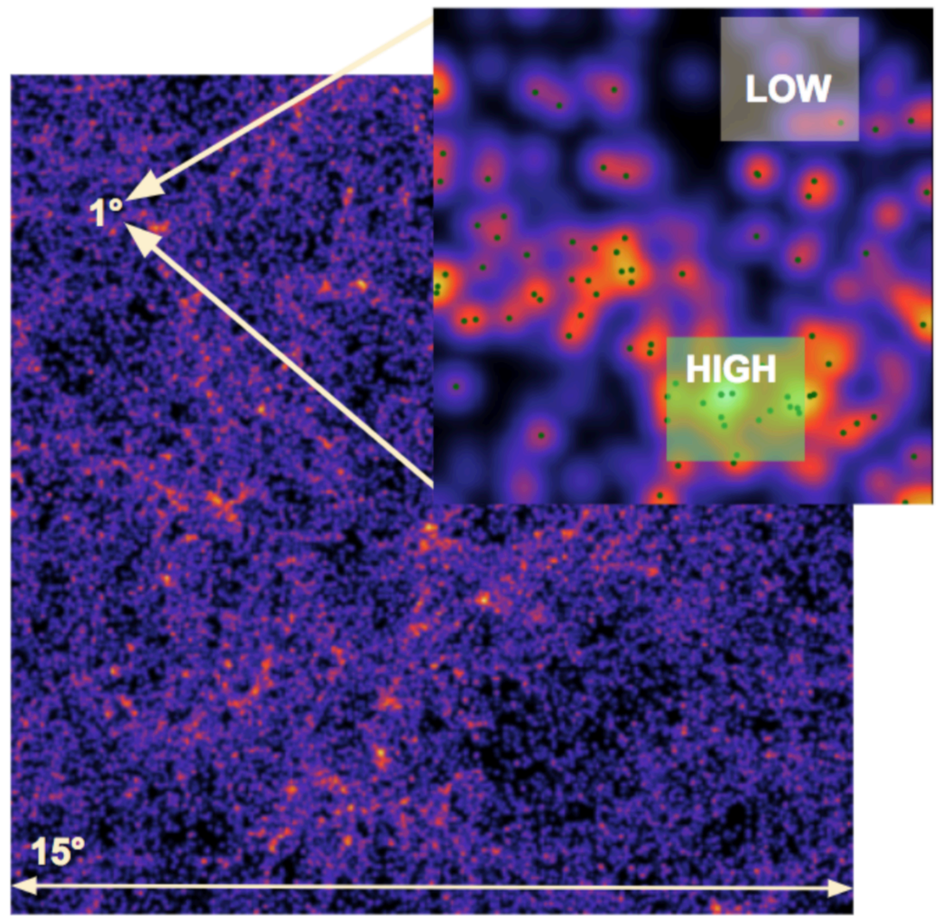
U Chicago: (Silicon lens AR) Jeffrey McMahon
Cardiff: (Filters) Peter Ade, Carole Tucker
NIST: Jake Connors
UToledo: Eli Visbal

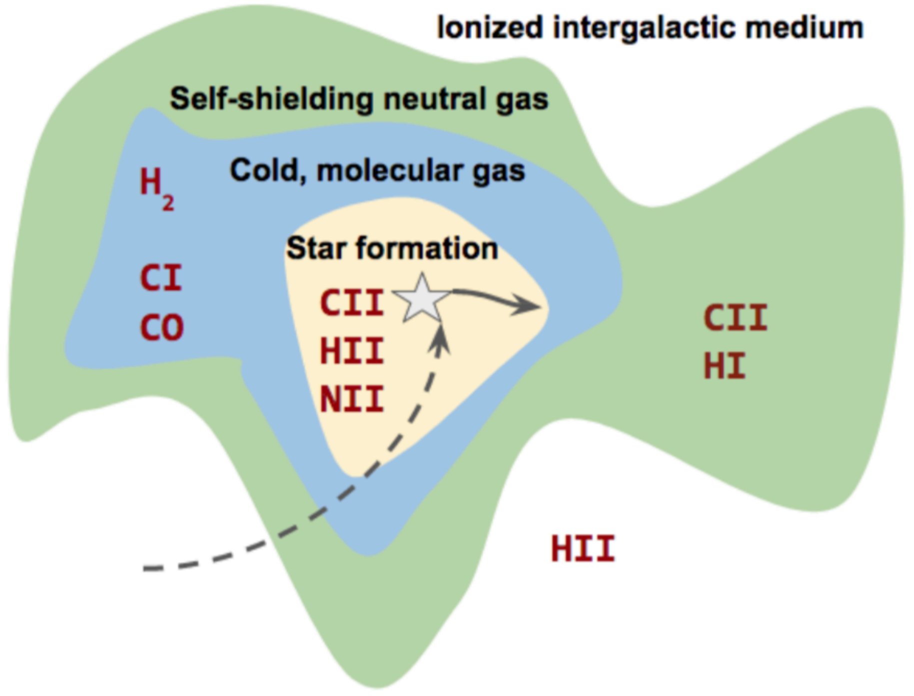
EXCLAIM - CO & CII Mapper

The EXperiment for Cryogenic Large-Aperture Intensity Mapping

EXCLAIM will address the following outstanding questions:

- What factors led to the dramatic decline in star formation from $z \sim 2$ to the present?
- What is the typical abundance and excitation of the molecular gas which forms stars?
- What is the abundance of H_2 in the Milky Way?
- Is intensity mapping a viable option to probe high redshifts?

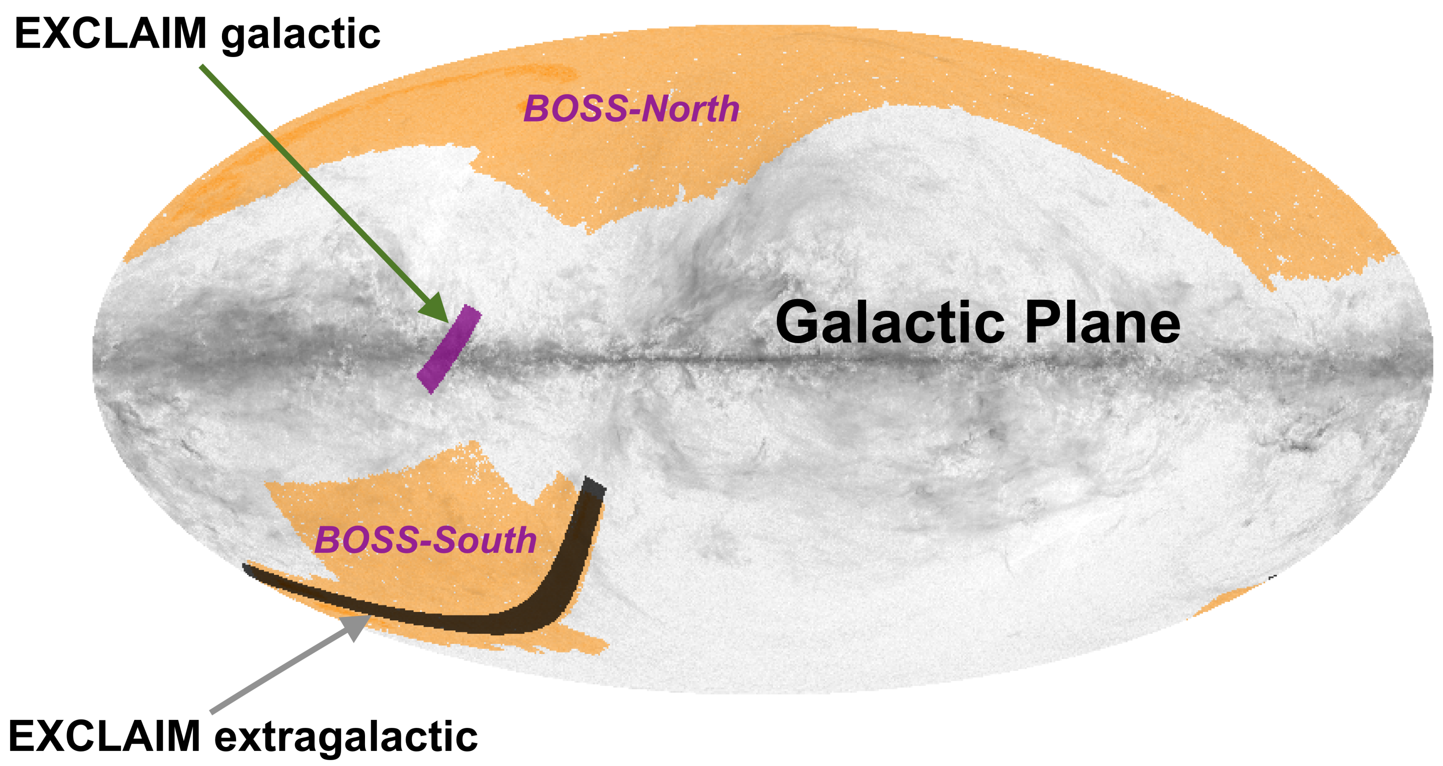




PI: Eric Switzer (NASA Goddard)

Method: Cross-correlations

- **Cross-correlation with BOSS for primary science**
- Large area: Cross-correlation can/should go **wide**; in contrast, auto-power aims for SNR~1 per mode.
- Access **linear and nonlinear scales** ($k \sim 0.03 - 1\ h\ Mpc^{-1}$).

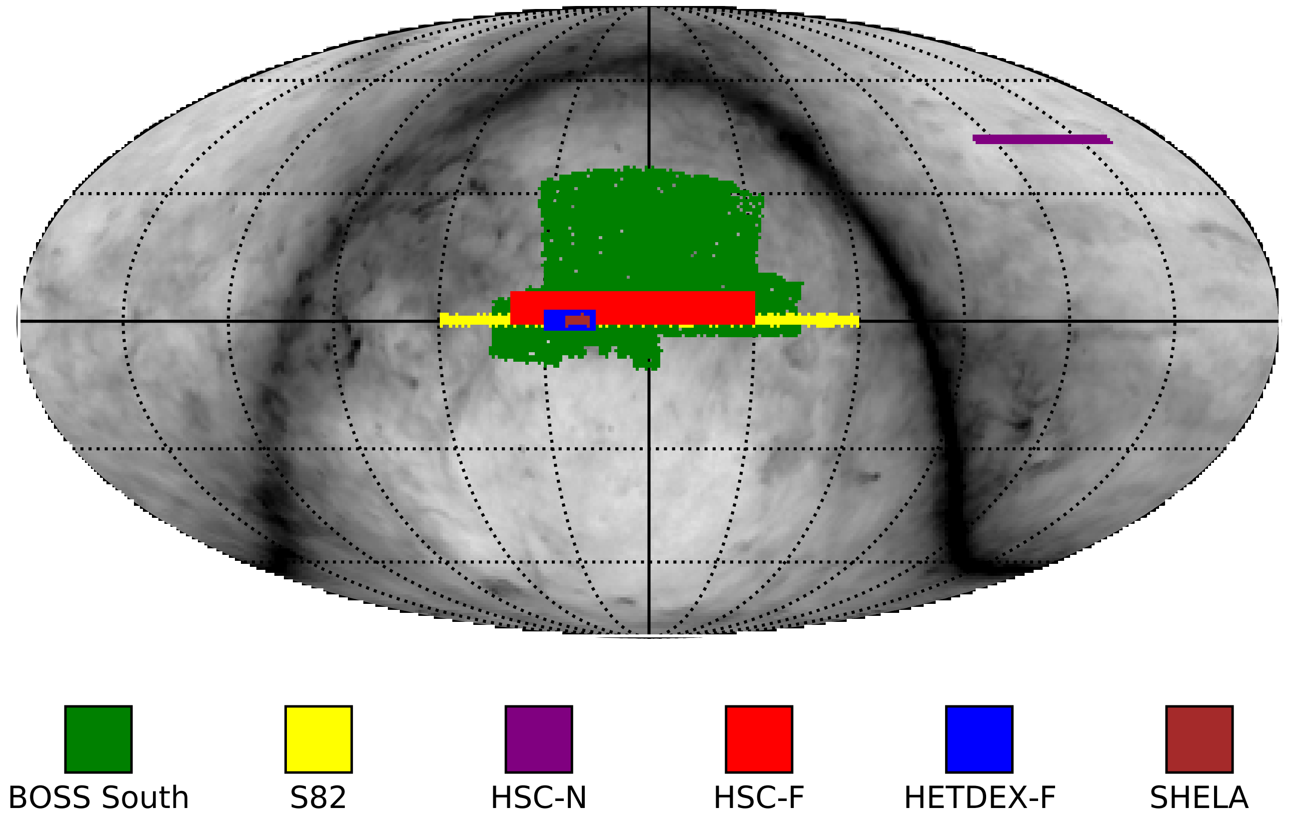


Extragalactic field: 8 PM - 4 AM, 320 deg^2 using 10° Az scan

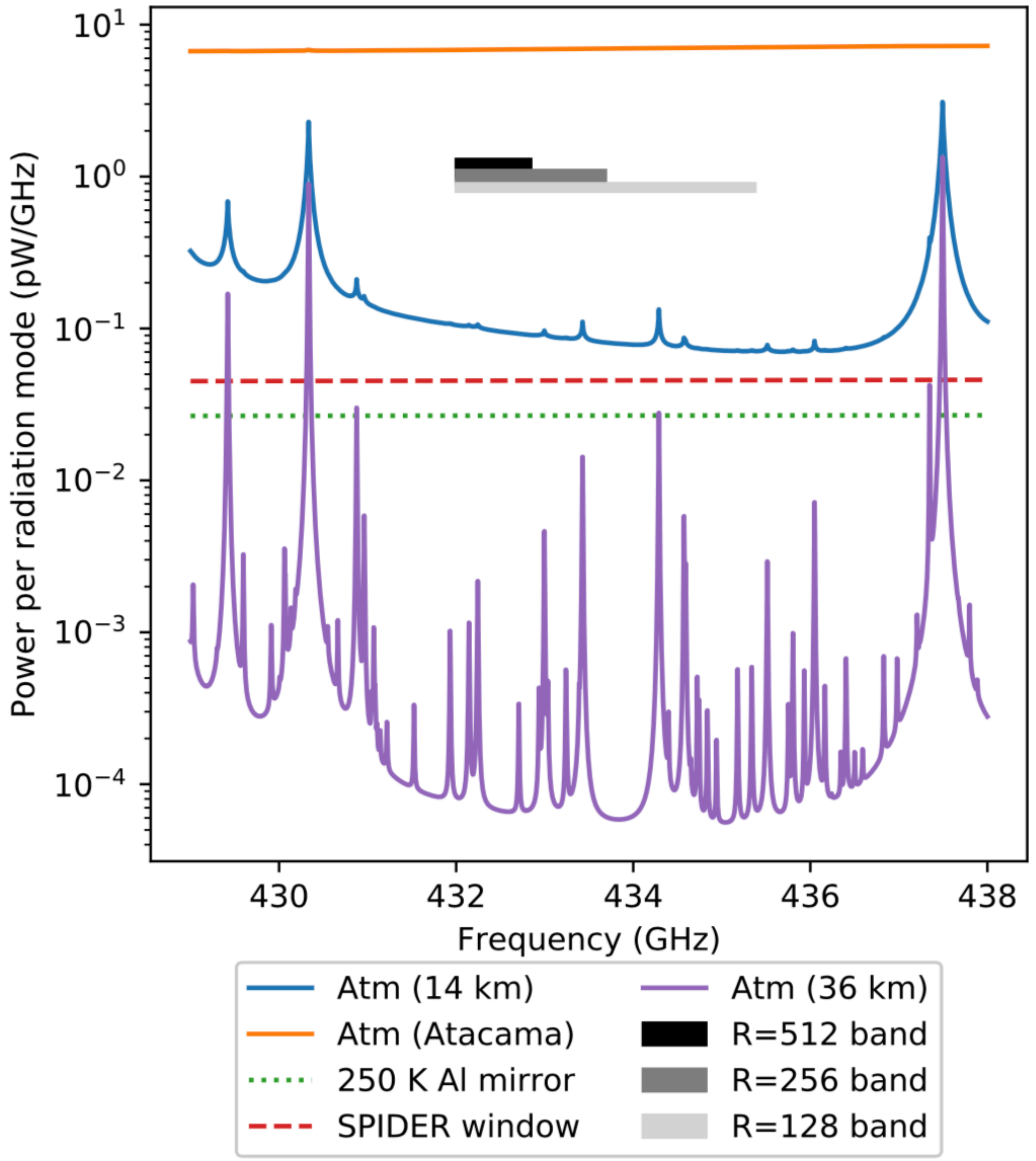
Galactic field: 4 AM - 6 AM, 90 deg^2 using 10° Az scan

- **Conventional flight** from Fort Sumner, NM: well-matched to **BOSS-South region & Stripe 82**, simple logistics, high recovery rate, more flights
- Engineering flight (Oct 2022): one spectrometer, sky dips to verify atmospheric line model; preliminary galactic and extragalactic science.
- Science flight (Oct 2023): 6 spectrometers
- Versatile platform for testing FIR spectrometer technology in space-like environment.

Potential galaxy surveys to be cross-correlated with EXCLAIM

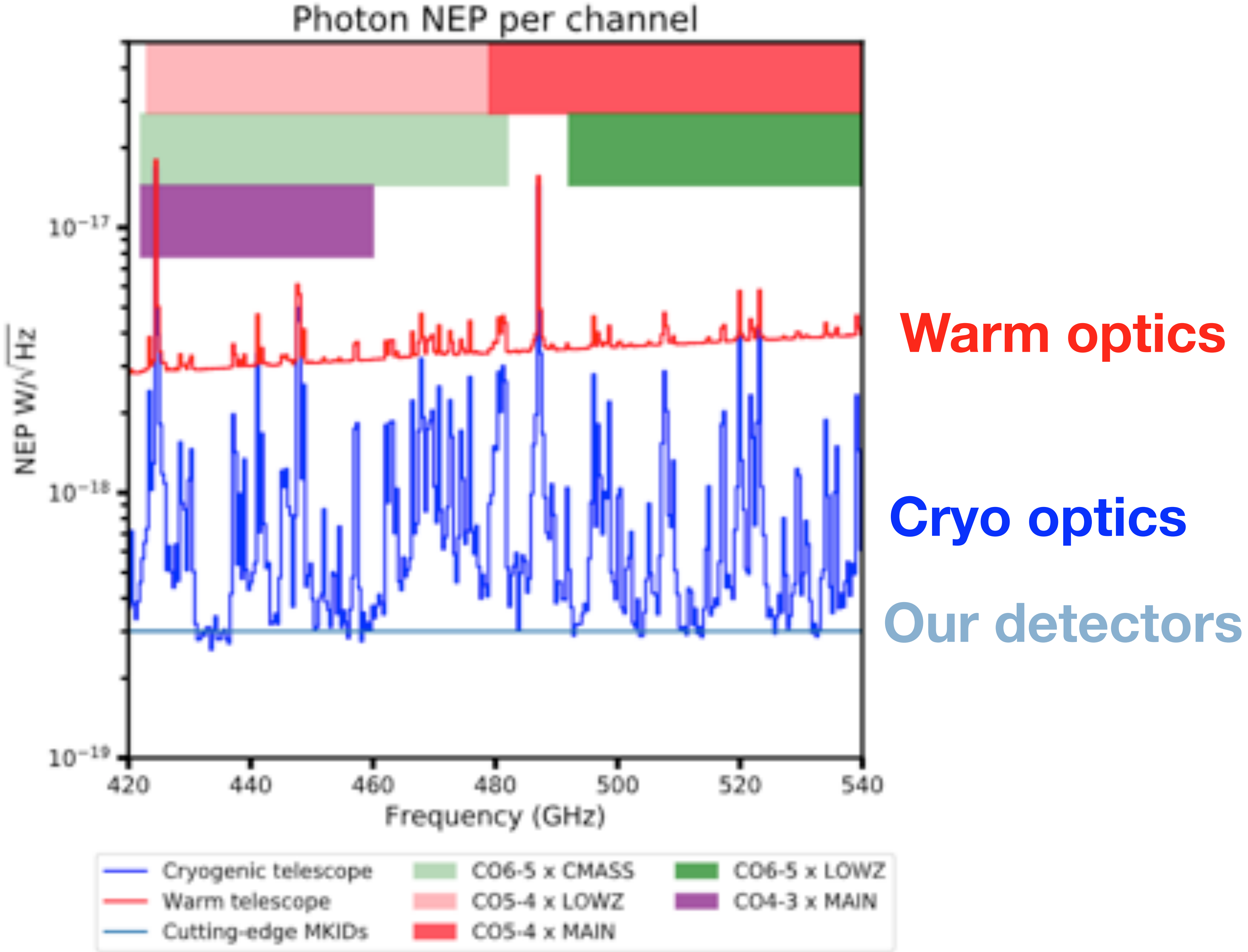


High-Altitude Atmosphere



Δν(bright lines) ~ 5 GHz

Δν(spectrometer) ~ 1 GHz



EXCLAIM observes through windows in the upper atmosphere at 36km (purple) that can only be exploited using all-cryogenic optics and narrow-band measurements. Averaged over R = 512 bands, an all-cryogenic telescope in this window is ~100x faster than a 300K telescope, turning 33 days of integration into 8 hours. Test detectors in space-like conditions.

EXCLAIM Science Goals

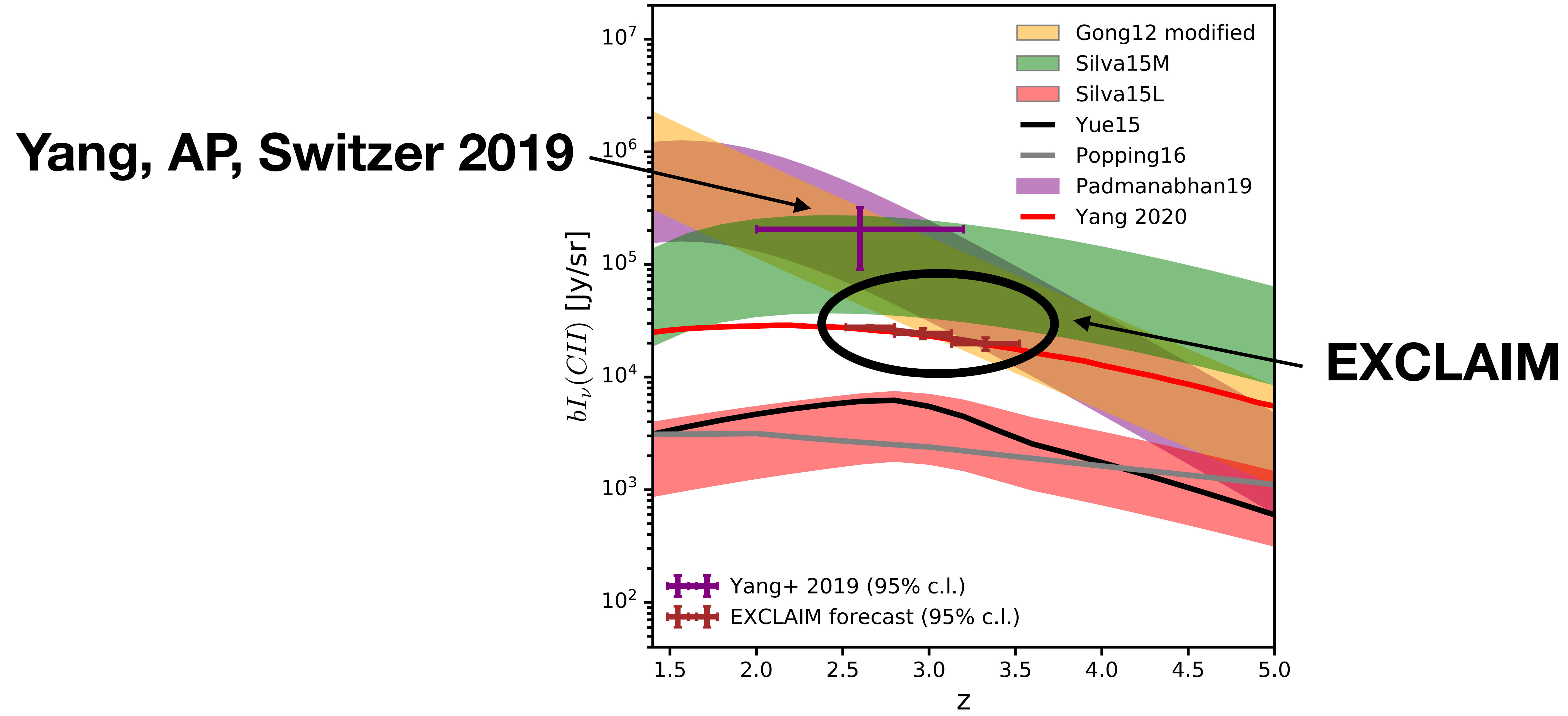
Map both CII and CO, including coverage of adjacent CO ladder emission at common z. **R=512, ν=421-540 GHz, ~400 deg², BOSS Cross-correlation.**

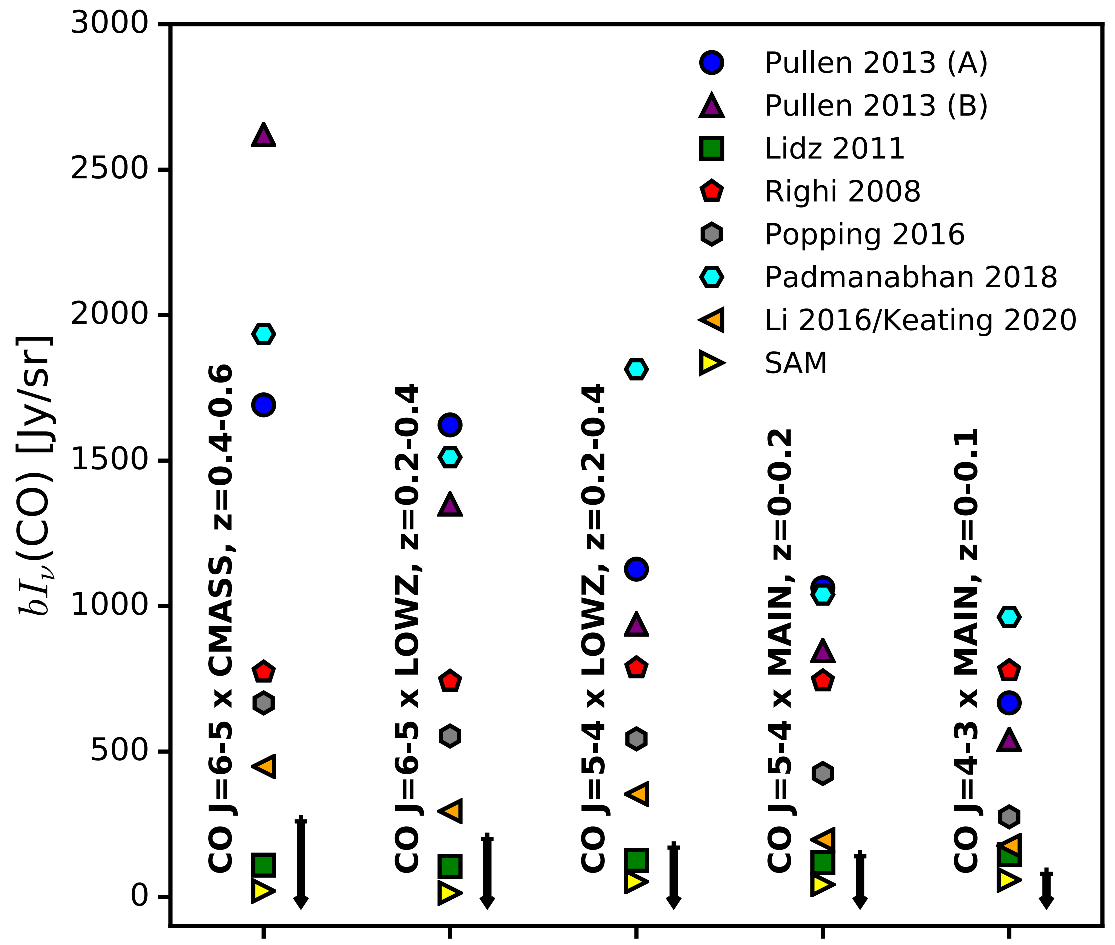
CII: BOSS QSO correlation for 2.5 < z < 3.5. Definitive test of CII brightness in **Yang, AP, Switzer 2019.**

CO:

- MAIN 0 < z < 0.2 for J=5-4, J=4-3
- LOWZ 0.2 < z < 0.4 for J=6-5, J=5-4
- CMASS 0.4 < z < 0.7 for J=7-6, J=6-5
- eBOSS for z > 0.7 and higher J
- Decarli et al 2016 find 3-10x decline in H_2 from z=2 to 0.
  IM is sensitive to integral emission and bias.

Both [CII] and CO lines will measure SFRD
-> Forecasts coming soon!



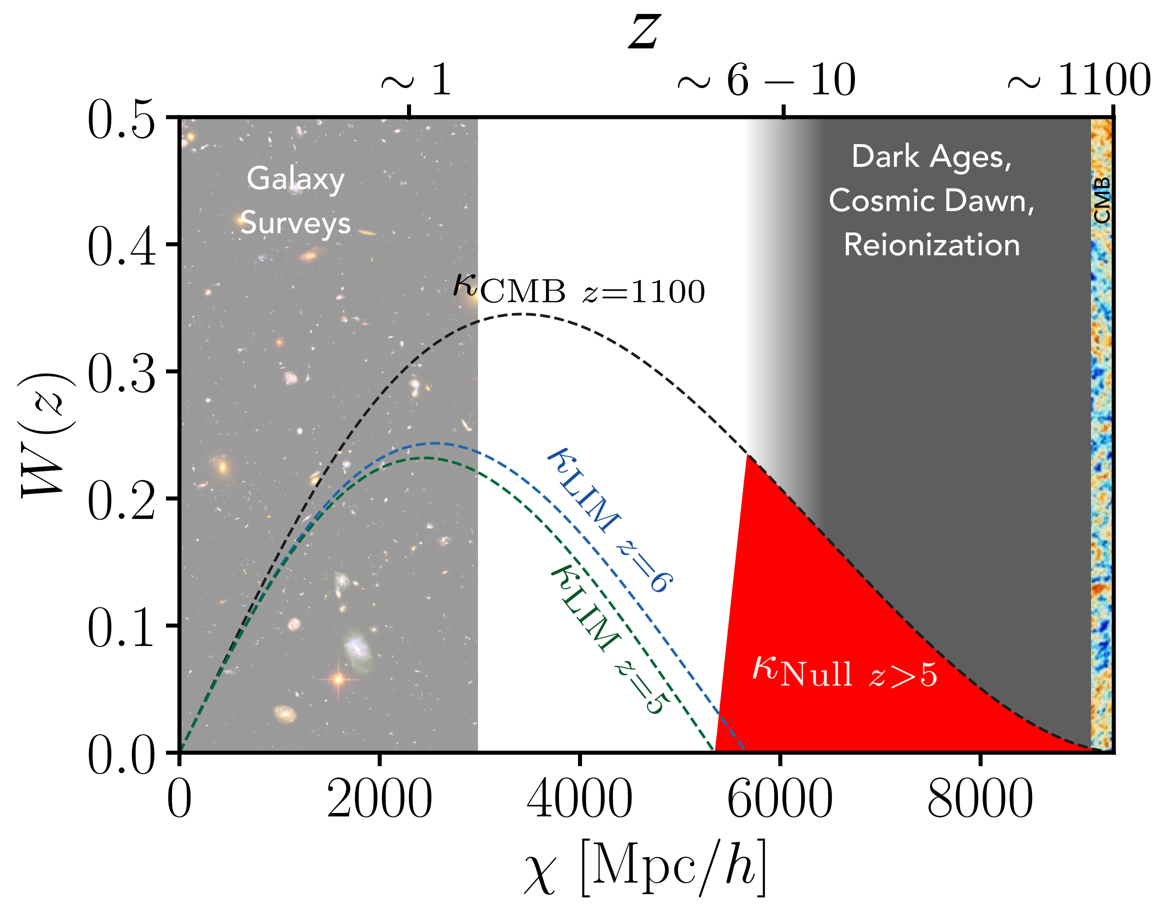


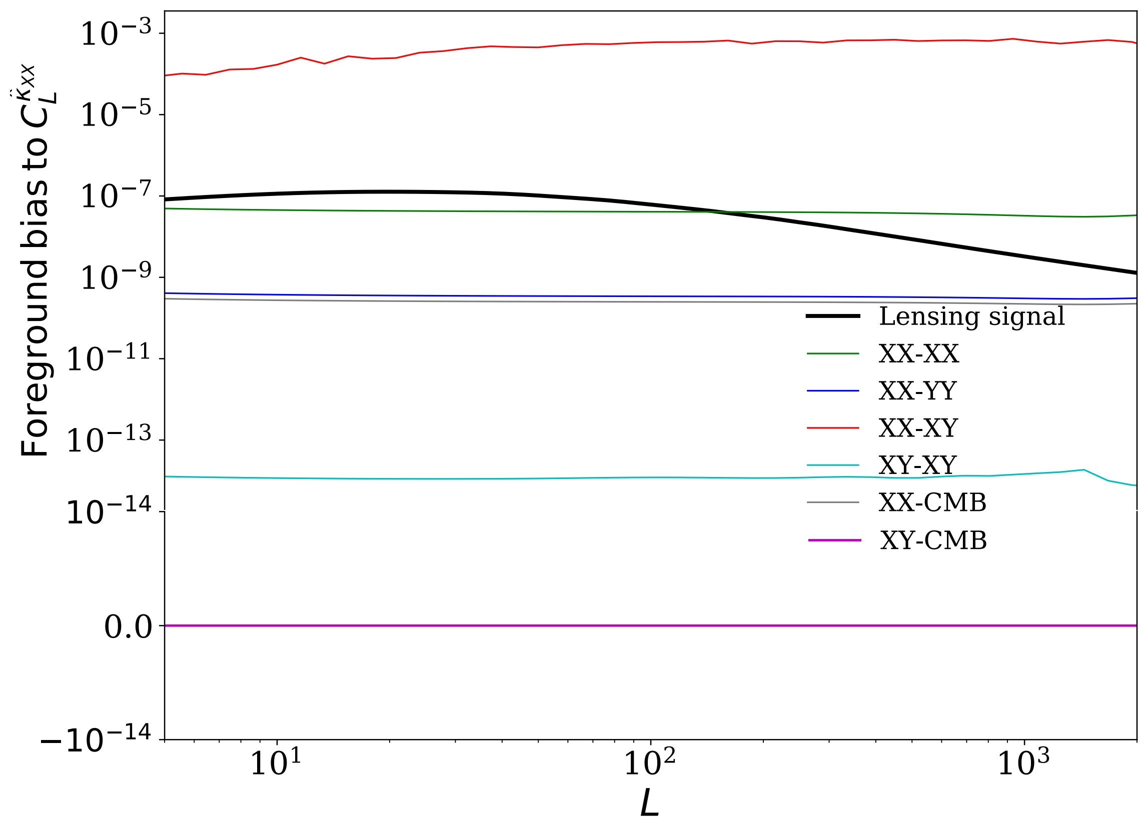
A. Pullen (Science Lead)

Upcoming LIM
Science Applications

LIM Lensing Cross-correlations

- LIM lensing cancel the low-redshift part in CMB lensing, probing structure at very high redshifts
- Line interlopers could bias this signal
- “LIM-pair” estimators are biased by bispectrum (κgg) and trispectrum (gggg) terms
- Cross-correlating the LIM-pair estimator with CMB lensing can drastically reduce this bias





Credit: Maniyar, Schaan, AP (2021)

Limitations when measuring *L*(*M*)

- Clustering bias depends a little on $L(M)$; makes even linear L-SFR relations difficult to probe

$$b = \frac{\int dM\, n(M) b_h(M) L(M)}{\int dM\, n(M) L(M)}$$

- L_{gal} is typically nonlinear and multi-dimensional in galaxy properties; e.g. $L_{[CII]}$(SFR,Z)

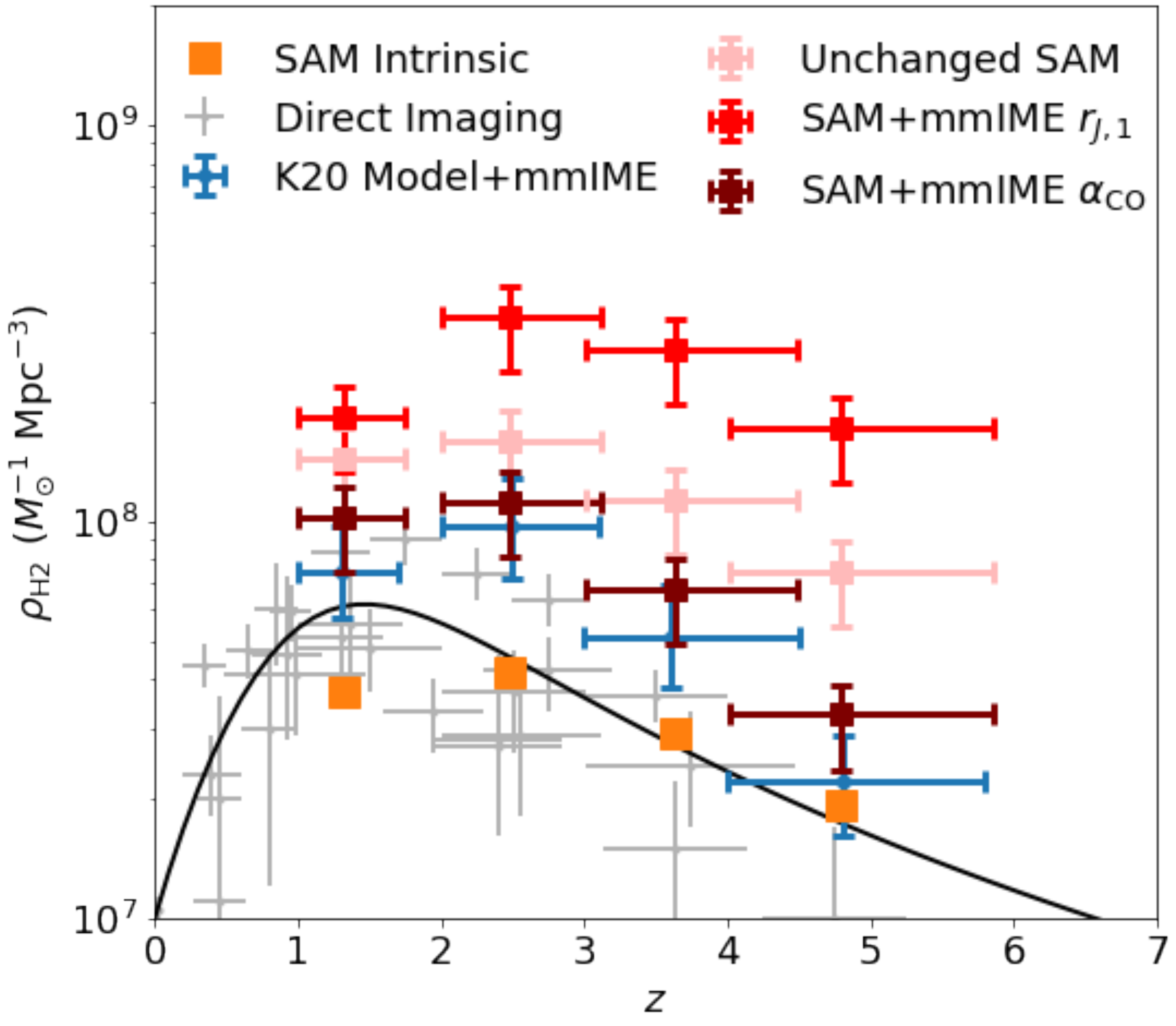
- Line luminosity ratio relations to galaxy properties, e.g. Z=f([CII]/[NII]), require a lot of questionable assumptions to use

$$\frac{\mathcal{L}_{[CII]}}{\mathcal{L}_{[NII]}} = \frac{\int dM\, n(M) L_{[CII]}(M)}{\int dM\, n(M) L_{[NII]}(M)}$$

$$\neq \frac{L_{[CII]}}{L_{[NII]}}$$

Interpreting LIM is challenging!

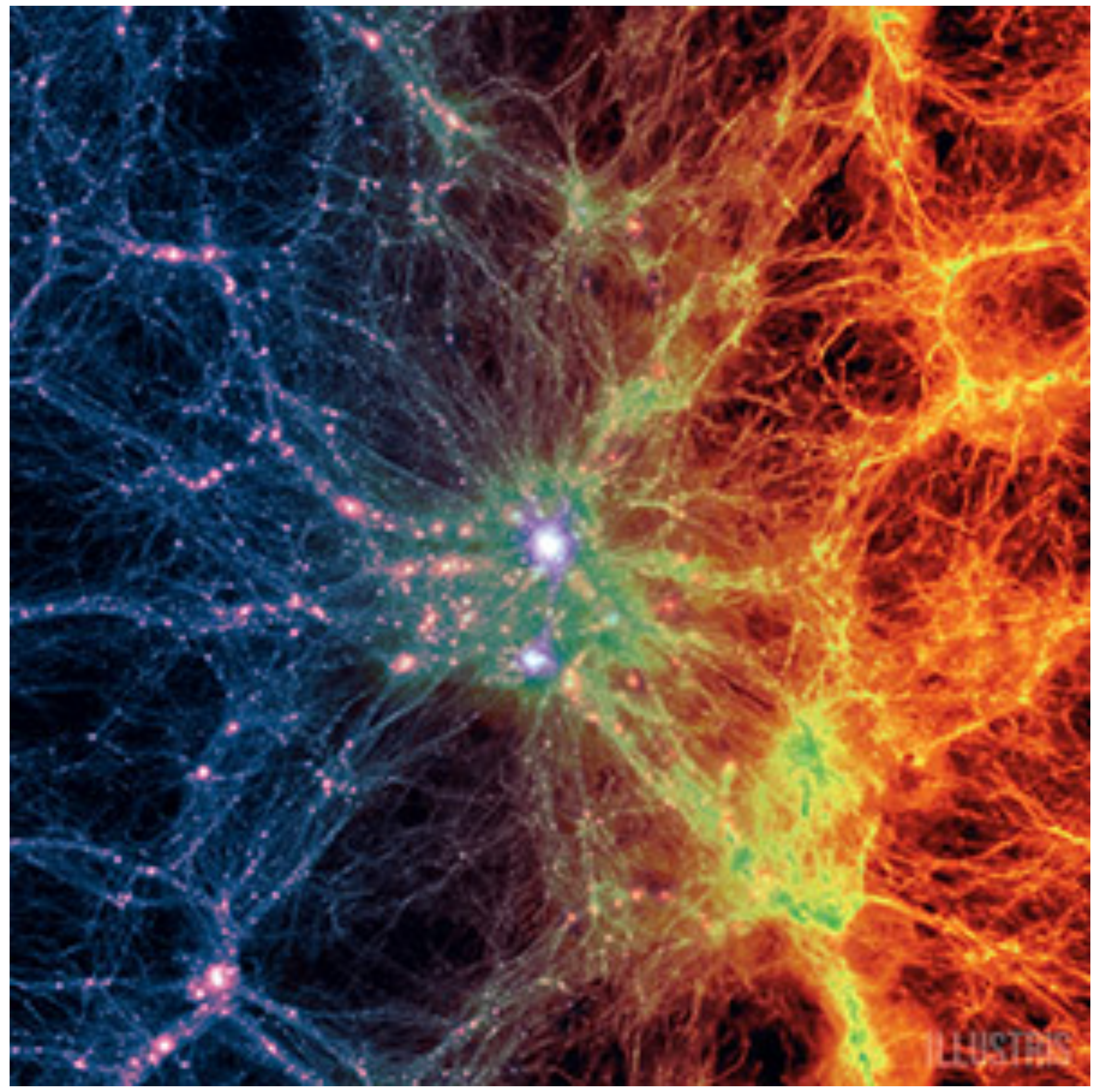
- Hopes for measuring H_2 rely on a constant $\alpha_{CO} = M_{H2}/L_{CO}$
- Different scaling assumptions can lead to very different results
- The Santa Cruz SAM predicts non-uniform α_{CO} which greatly affects a ρ_{H2} measurement
- Methods that sample $L(M,z)$ and its physical sources directly may be necessary



Breysse, Yang, Somerville+ (2021)

Semi-Analytic Modeling

- We use SAMs to paint star formation and galaxy evolution models onto DM halos in N-body sims
- Much more accurate than “scaling relations” from low-z observations, yet a fraction of the runtime of hydro sims
- Calibrated to hydro sims and observations
- Built to include nonlinear effects, i.e. stellar feedback, ionization, gas heating



Credit: Illustris

“Santa Cruz” semi-analytic model: Rachel Somerville & collaborators

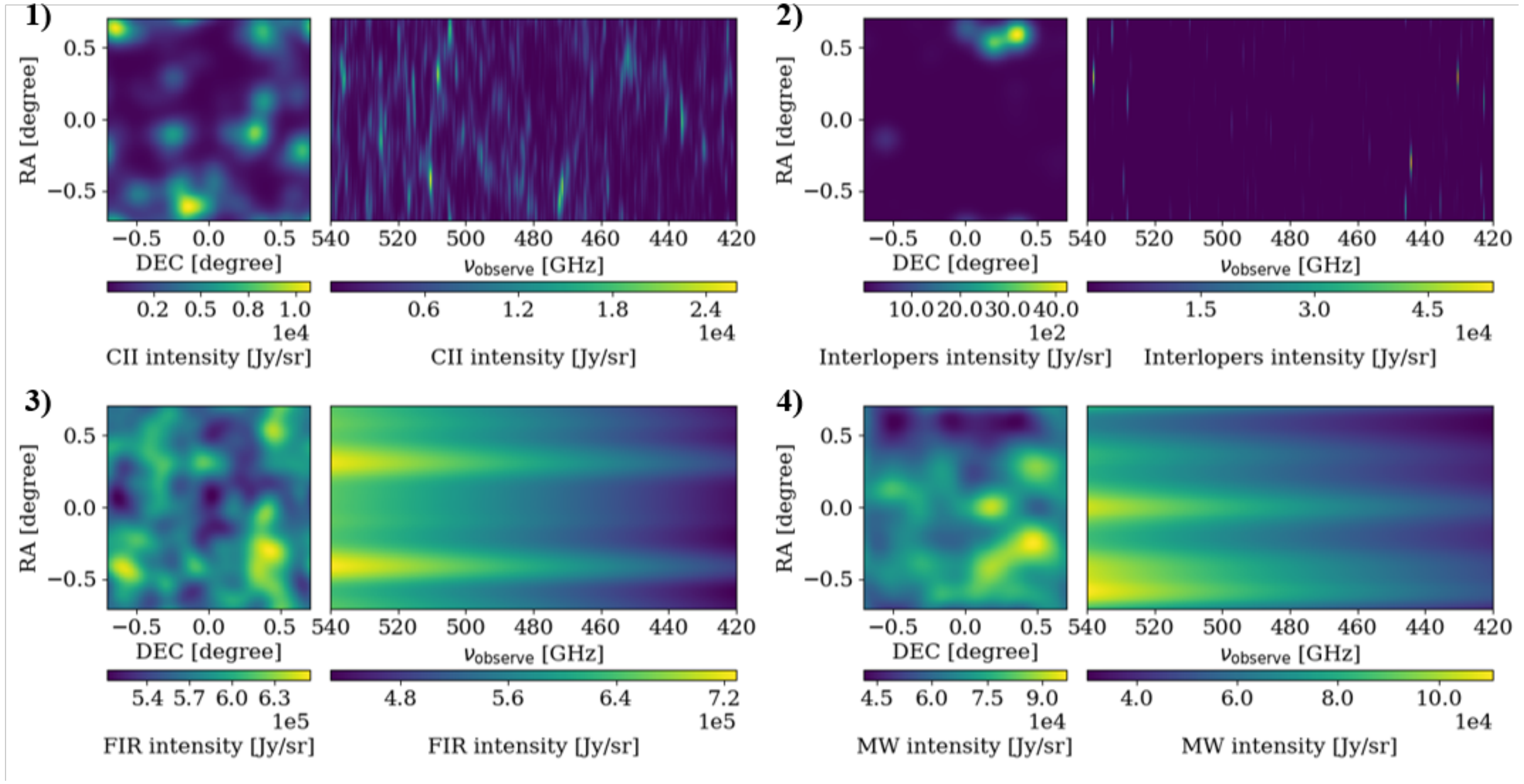
LIM Mocks

[CII]
z = 3

Interlopers
(CO, CI)

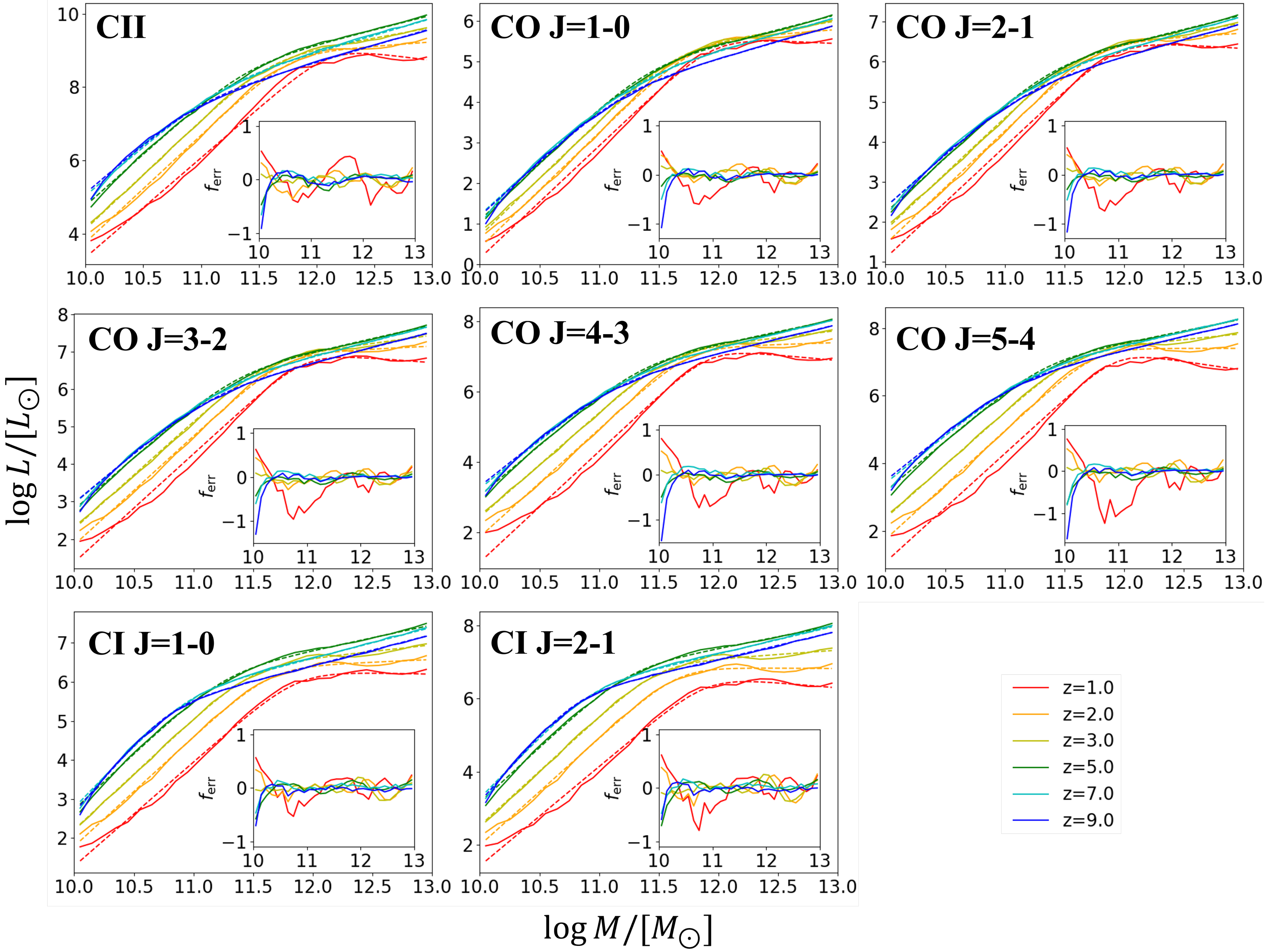
CIB

Milky Way



Yang, Somerville, AP+ (2021)

L(*M*) empirical models



SAM results vs. fitting functions

Yang, Popping, Somerville, AP+ (2021)

Conditional Galaxy Property Distribution

$$L_i(M, z) = \int d^N g \, \Phi(\mathbf{g}|M, z) L_i(\mathbf{g}, z)$$

Conditional Galaxy Property Distribution

Line Luminosity Relation

i = emission line

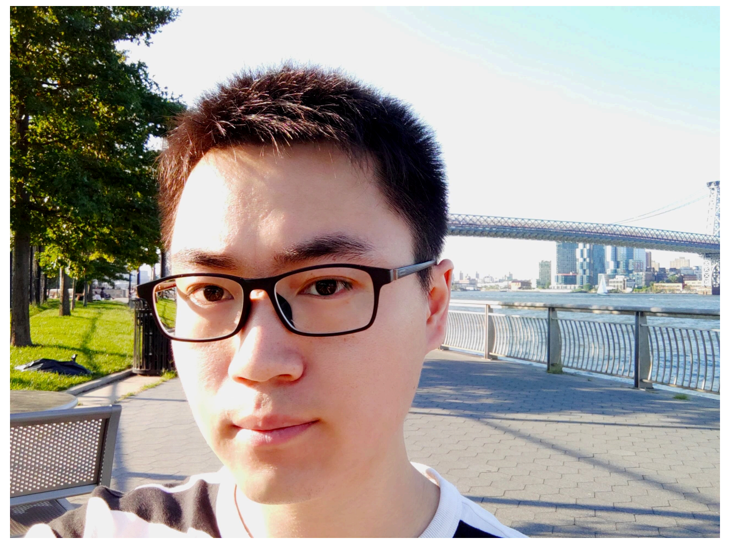
- CGPD (Φ) encodes all information on the current state of galaxies (given M and z)
- $\mathbf{g} = \{M_{H2}, \text{SFR}, M_*, R_d, Z\}$ ($N = 5$ major galaxy properties)
- LLR's z-dependence only due to the gas-heating CMB
- Assumes galaxy luminosities are universal (not explicitly halo-dependent)

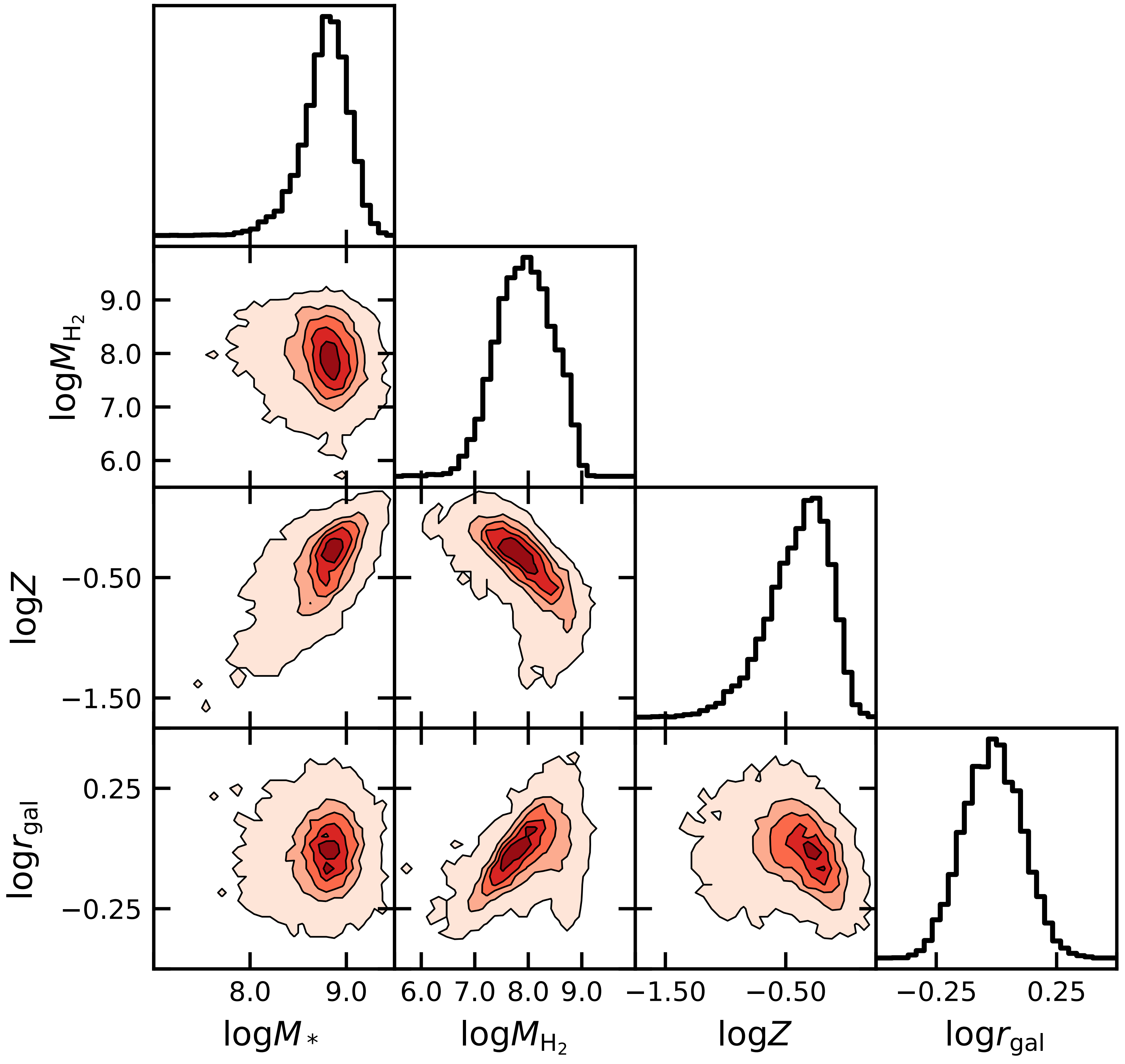
Can we measure CGPD?

$$L_i(M,z) = \int d^N g\, \Phi(\mathbf{g}|M,z) L_i(\mathbf{g},z)$$

- Separates LLR, which is line-independent, from Φ, which sources all lines
- If LLR is known, we can use multiple lines to estimate Φ
- Is Φ parametrizable, e.g. a multi-variate Gaussian distribution or a mixture model?
- How do we find the LLR?

Conditional Galaxy Property Distribution (SC-SAM)





700 centrals

5900 satellites

$10^{10.9} < (M/M_{sun}) < 10^{11.1}$

Zhang, AP+ 2022 (in prep.)

Future plans

- Build parametric mixture model of the CGPD
- Model galaxy line luminosity relation (LLR)
- Discover the principle parameters (or linear combinations) that dominate the CGPD and the LLR
- Compare SAM and hydro-simulation results (Illustris TNG)

Summary

- Galaxy evolution science is currently reliant on empirical models from the highest-mass galaxies
- Line intensity mapping has the potential to produce a full property census of all the galaxies in the cosmic volume
- Upcoming LIM surveys can shed new light on the stellar and metallicity evolution of galaxies
- New techniques partnered with simulations will be required for LIM science to reach its full potential

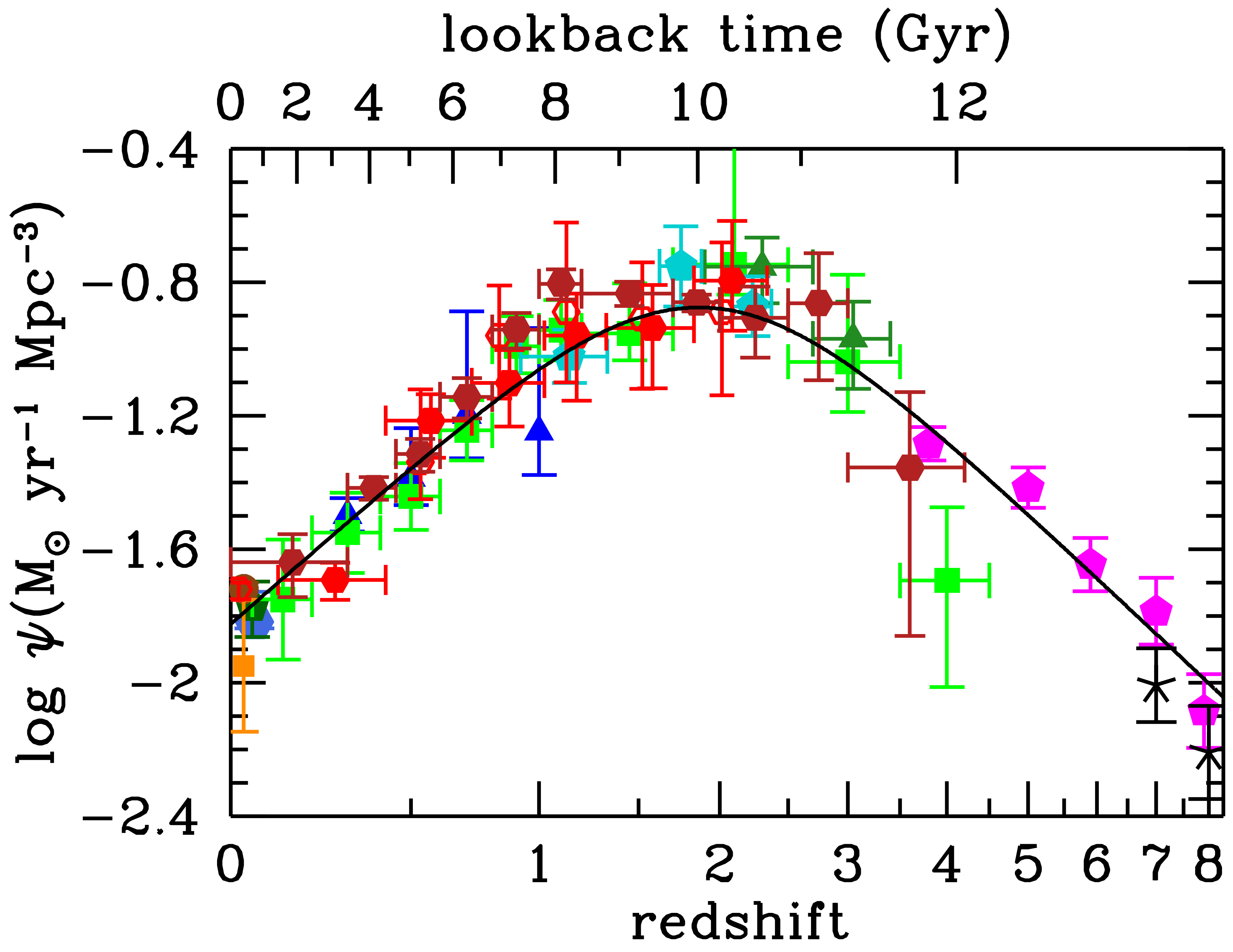
Extra Slides

Star Formation Downturn at low redshifts

Star Formation Rate Density (SFRD)

$$\text{SFRD} = \frac{\text{Mass in New Stars Produced}}{\text{(Time) x (Volume)}}$$

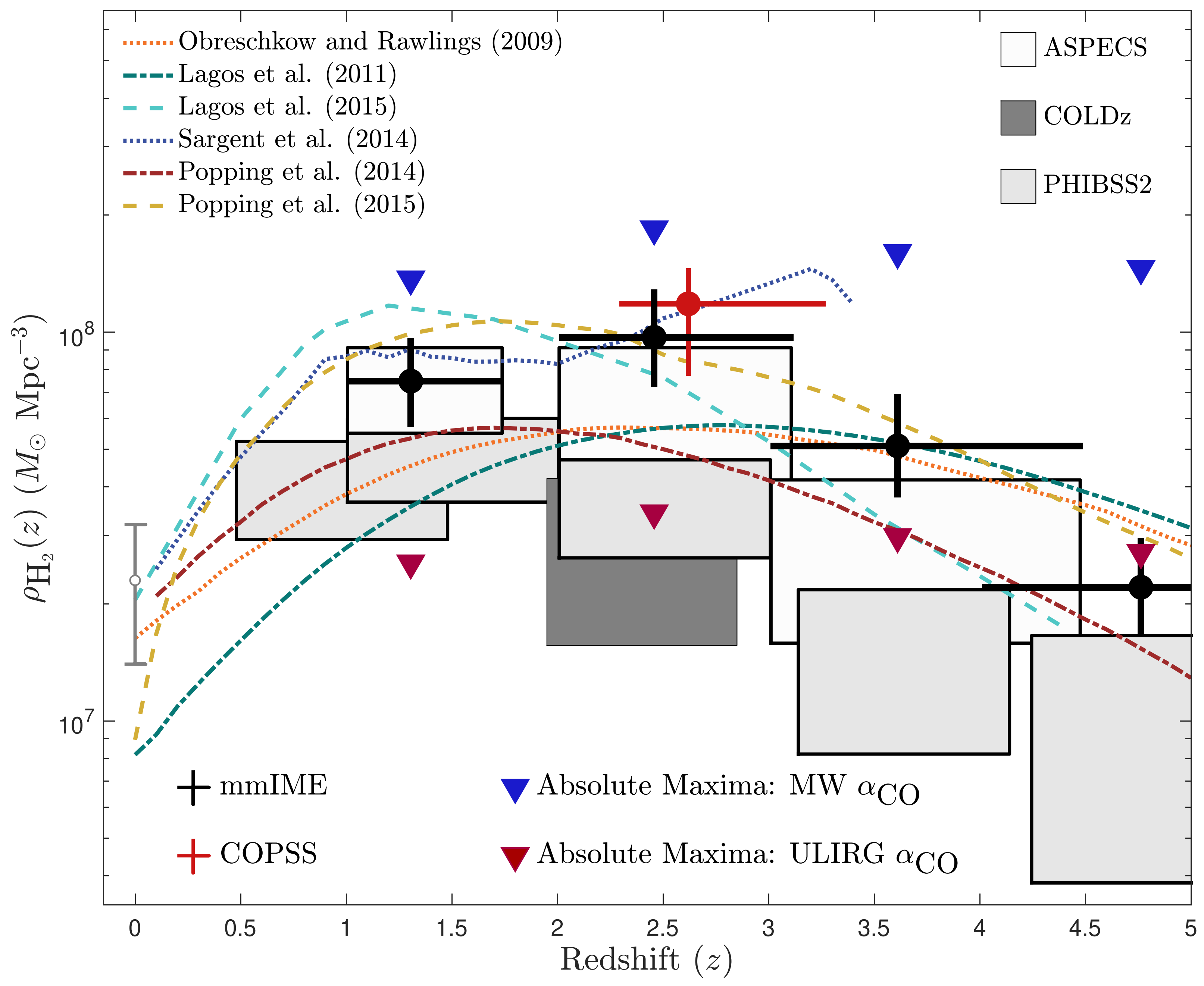
- SFRD reduced 20x since z = 2
- DM structure increases 100x over same period!
- Only 5% of baryons condense into stars
- Mapping the gas emission would probe the ISM and stellar evolution



Credit: Madau & Dickerson (2014)

H_2 Cosmic Density

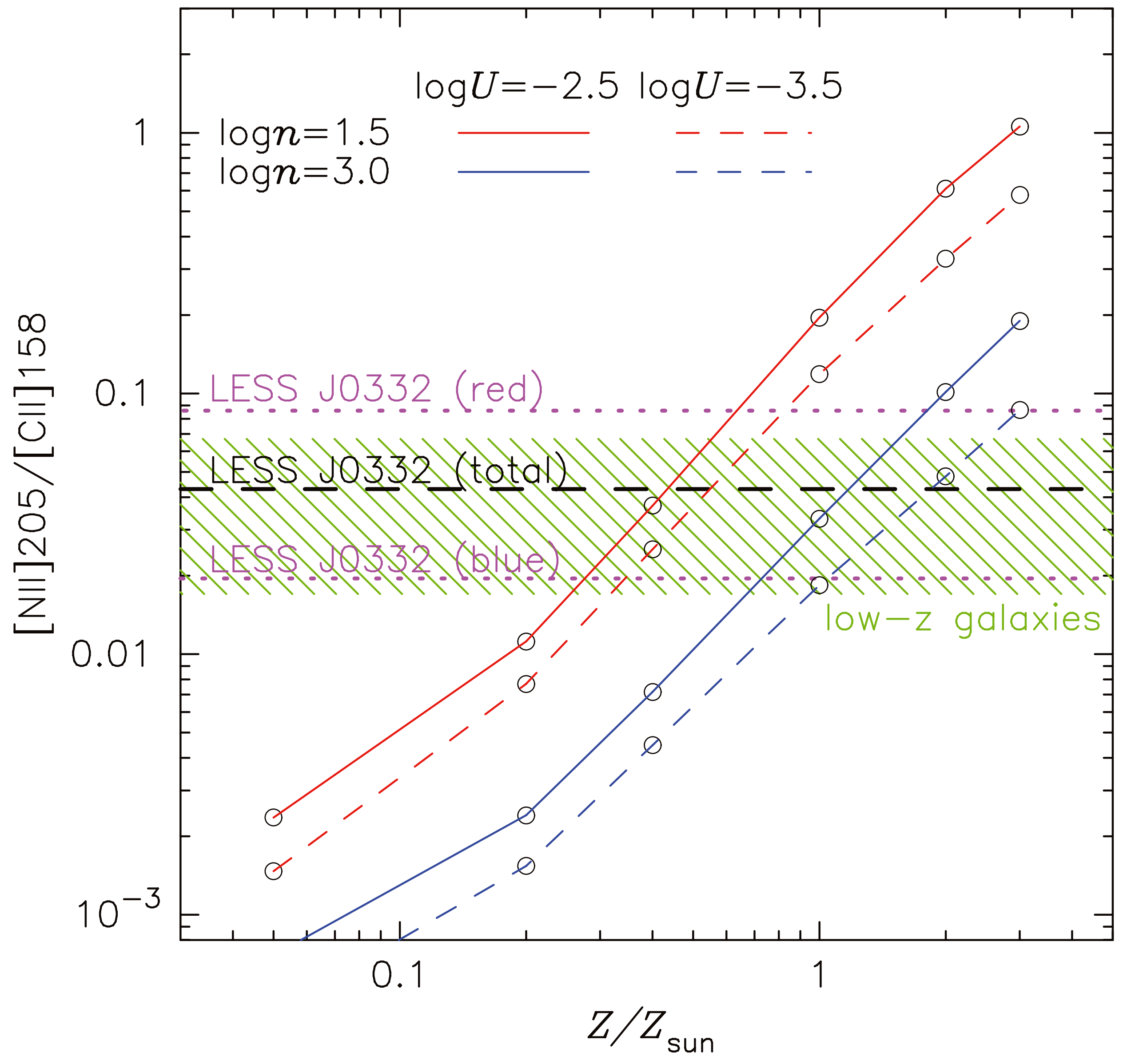
- H_2 is a potent precursor of star formation
- Does not have a permanent dipole, so its emission is weak, unlike HI
- The CO(1-0) line is highly correlated with H_2, so CO(1-0) is often used to trace H_2



Keating, Marrone+ (2020)

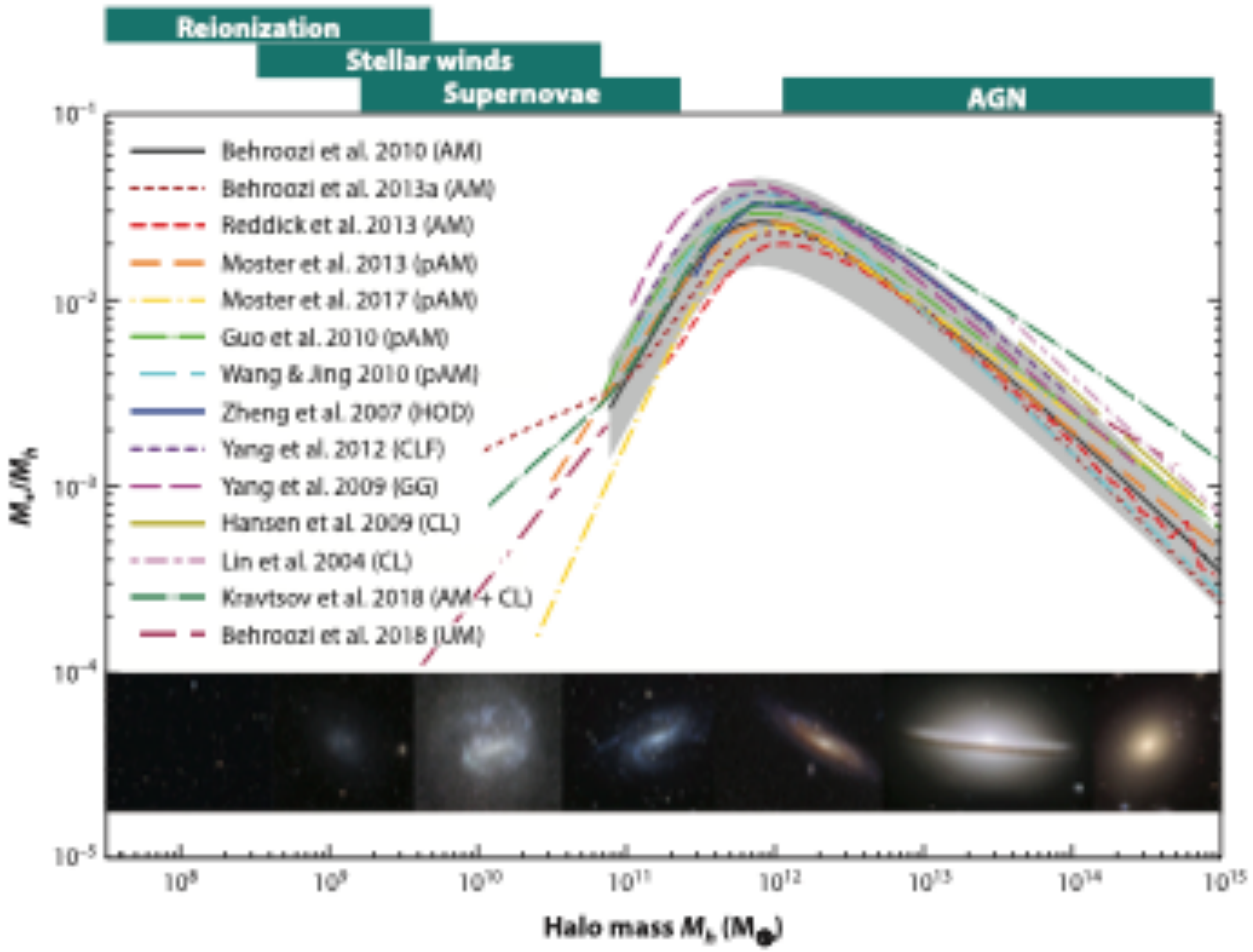
Metallicity

- Metallicity = fraction of mass that isn't hydrogen or helium
- Traces chemical evolution of stars
- Can be traced by line emission
- [NII]:[CII] line ratio is a common candidate



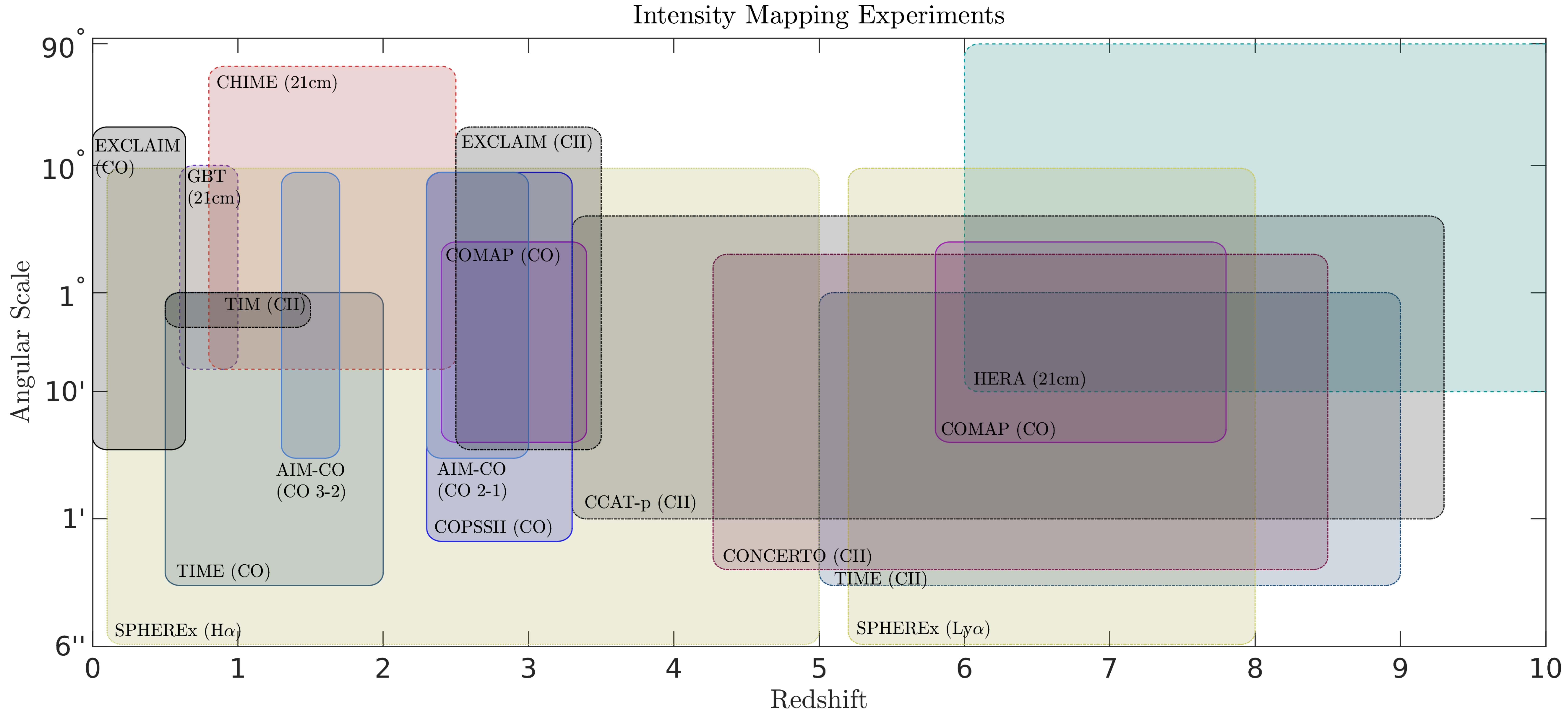
Credit: Nagao et al. (2012)

Stellar Mass



Credit:Wechsler & Tinker (2018)

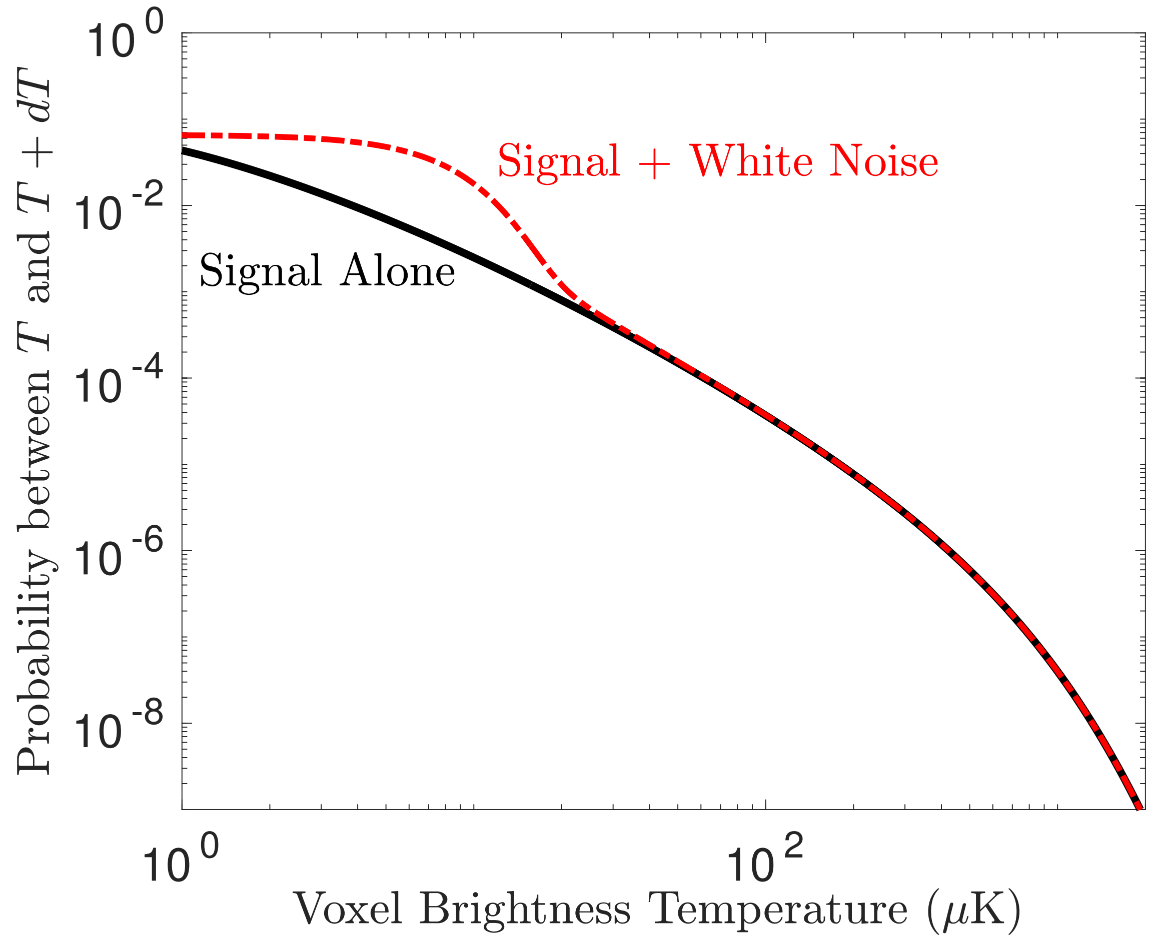
Planned LIM Surveys



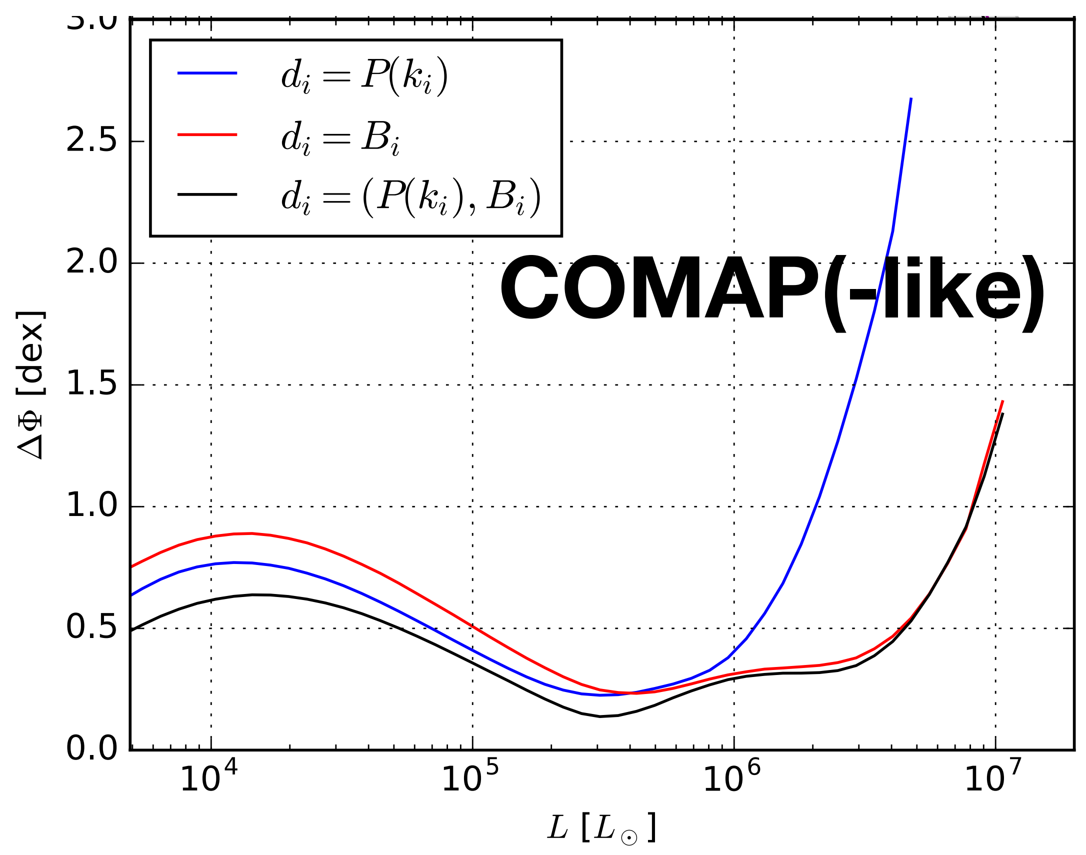
Credit: Patrick Breysse

Voxel Intensity Distribution

- Histogram of intensities per *voxel*
- Sensitive to full luminosity function
- Probe gas properties and distribution of emitters
- VID & P(k) break astro-cosmology degeneracy

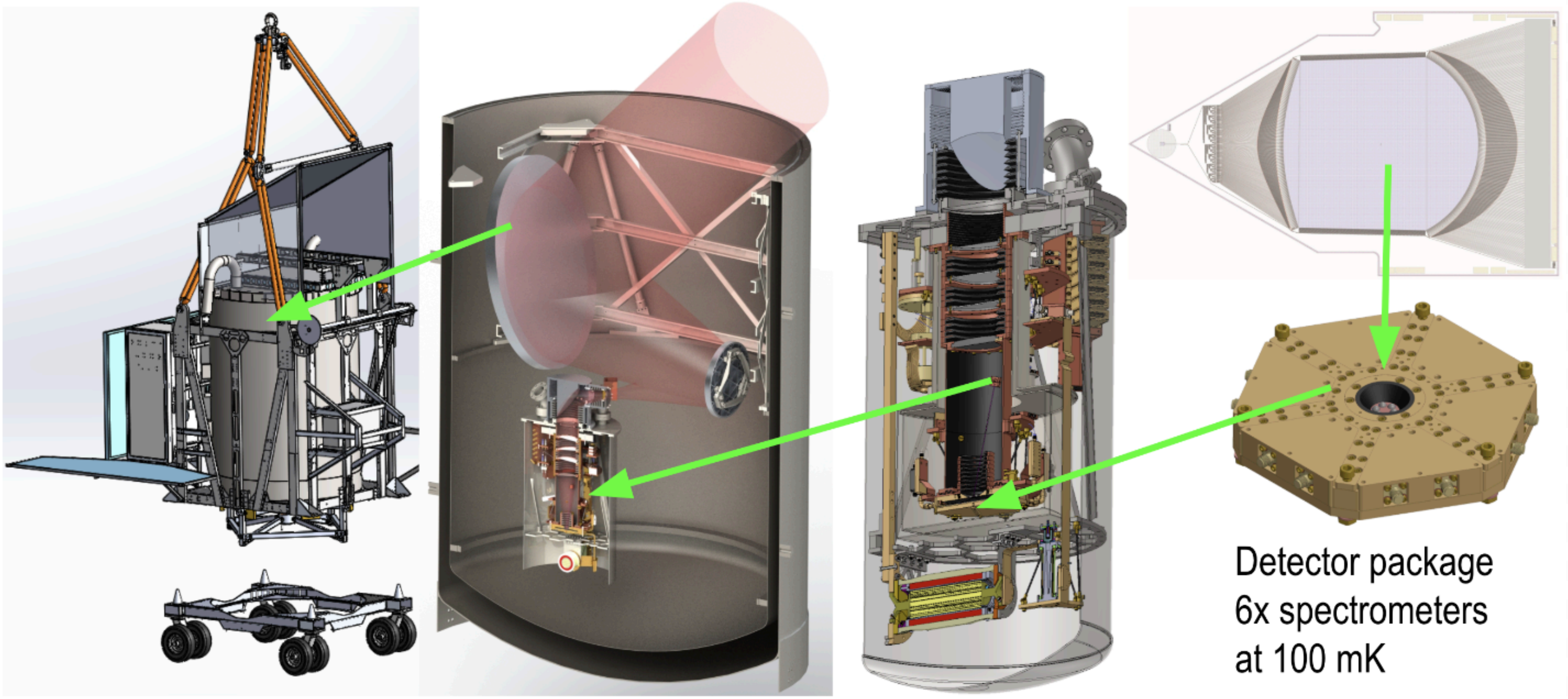


Credit: Patrick Breysse

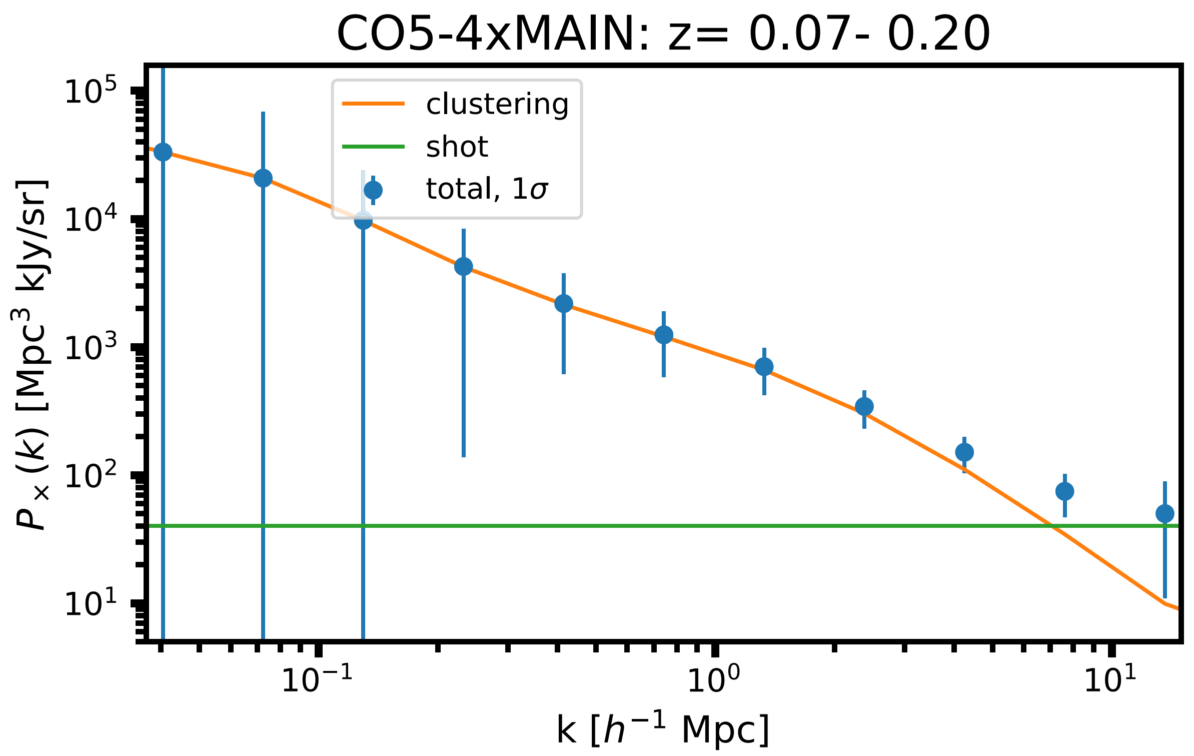


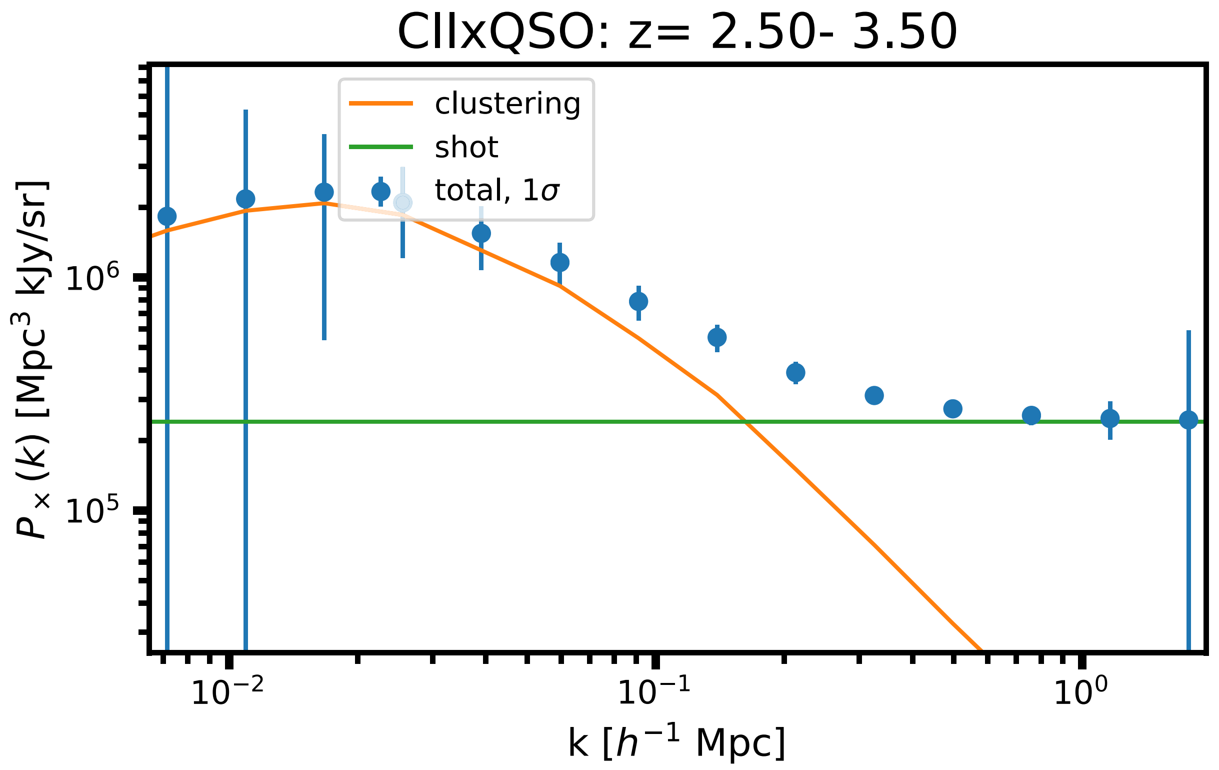
Credit: Ihle+ (2019)

EXCLAIM Instrument



EXCLAIM Statistics



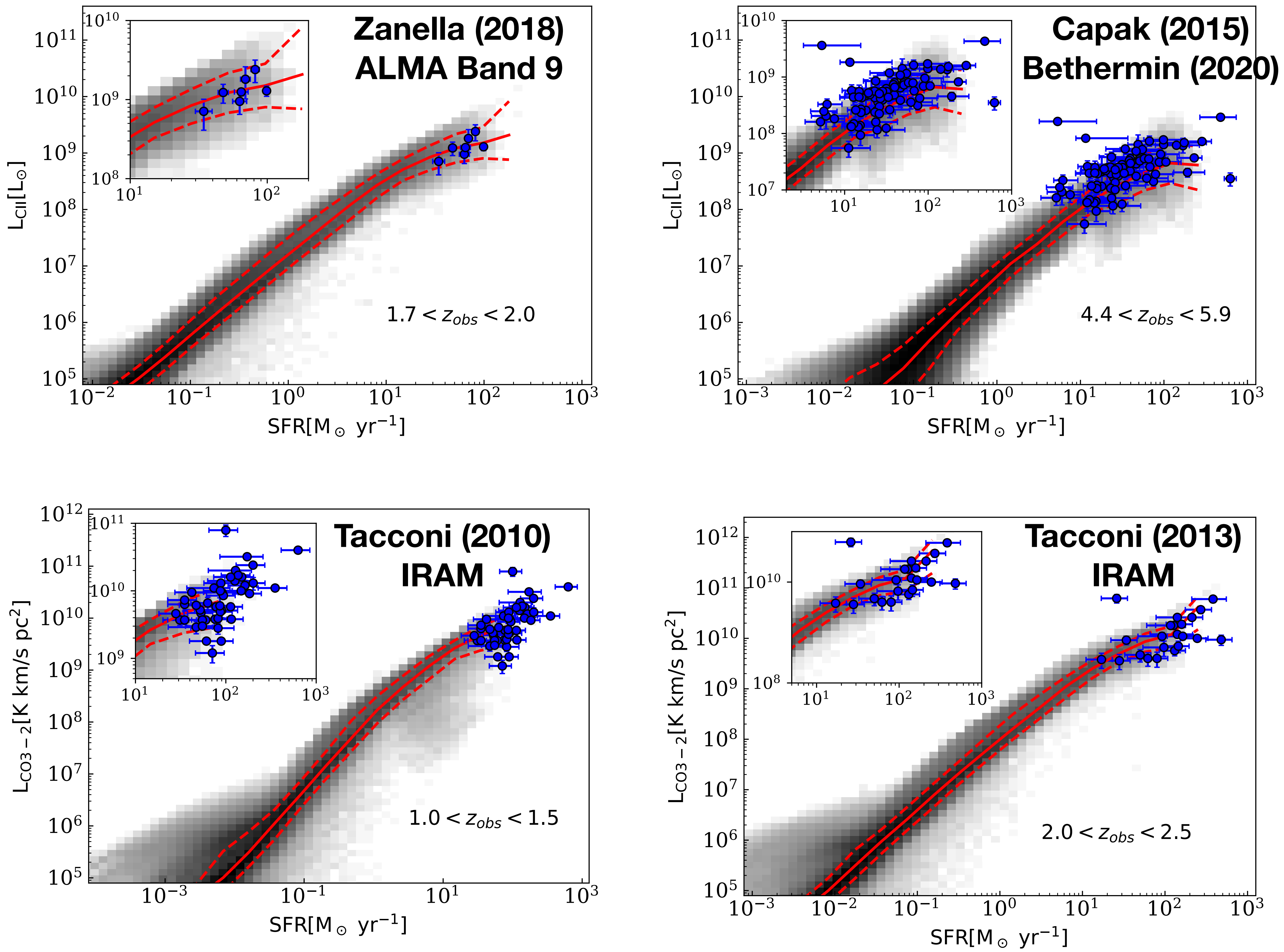


- Models based on Pullen 2012 CO model and our Planck [CII] measurement

SAM+Despotic predicts correct line emissions

[CII]

CO(3-2)



Yang, Somerville, AP+ (2021)

calibrated only on SFR and broadband emission