Revealing CII Emission with LSS Cross-correlations

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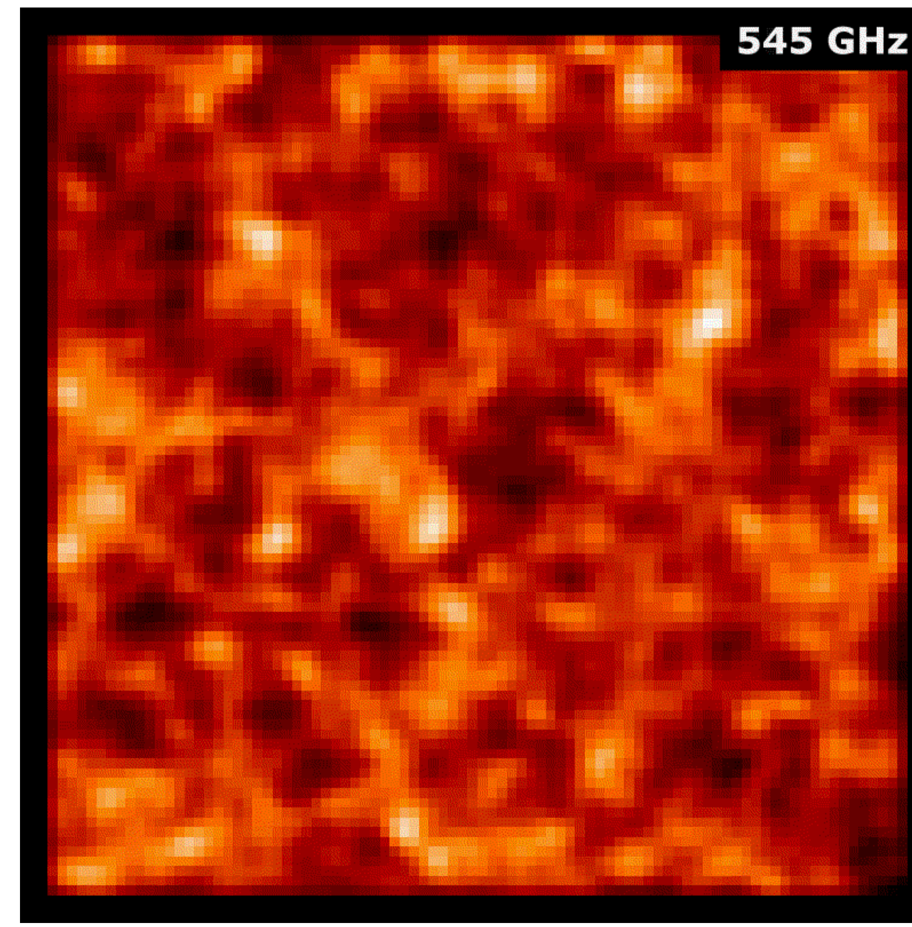


Image Credit: Planck Collaboration

Pre-print
arXiv:1707.06172

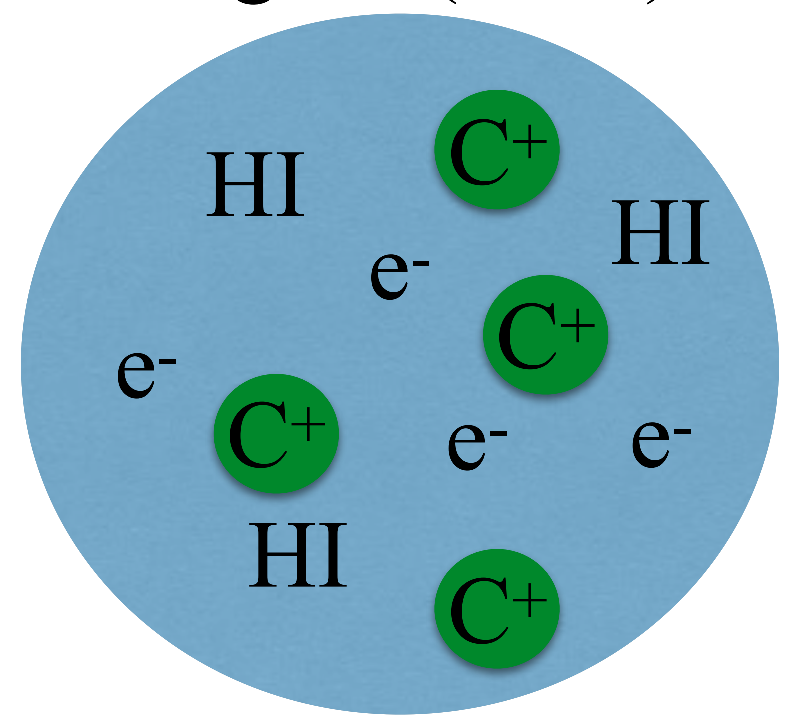
Outline

- CII Basics
- Why intensity mapping?
- Method for estimating CII intensity
- Cross-power spectra
- CII intensity - what did we learn?
- Forecasts for future surveys
- Next Steps

The CII Line

- CII - fine structure line of ionized carbon
- Emission due to CII ion spin transitions due to collisional excitations in PDRs
- Traces star-forming galaxies
- Typically **brightest line** in SF galaxies (0.1-1% of total FIR)

Photo-Dissociation Region (PDR)

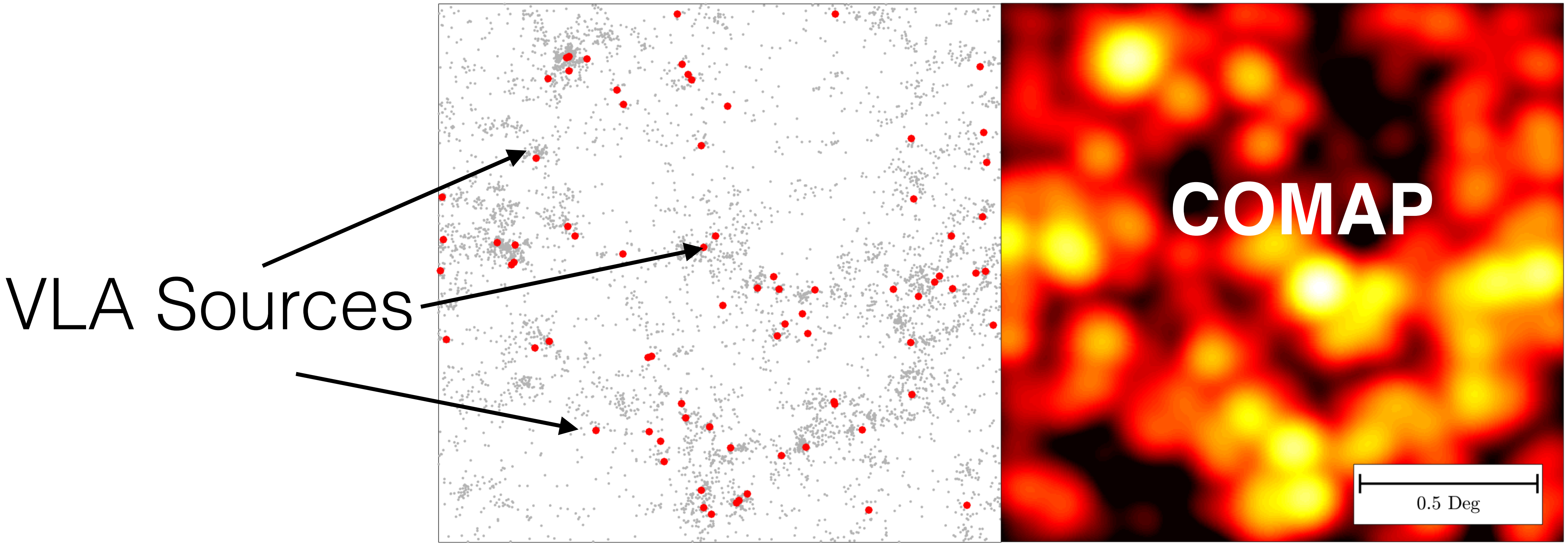


$\boxed{\lambda_{CII} = 157 \mu m}$

Gong et al. 2012, Silva et al. 2015, Yue et al. 2015

Missing Galaxies

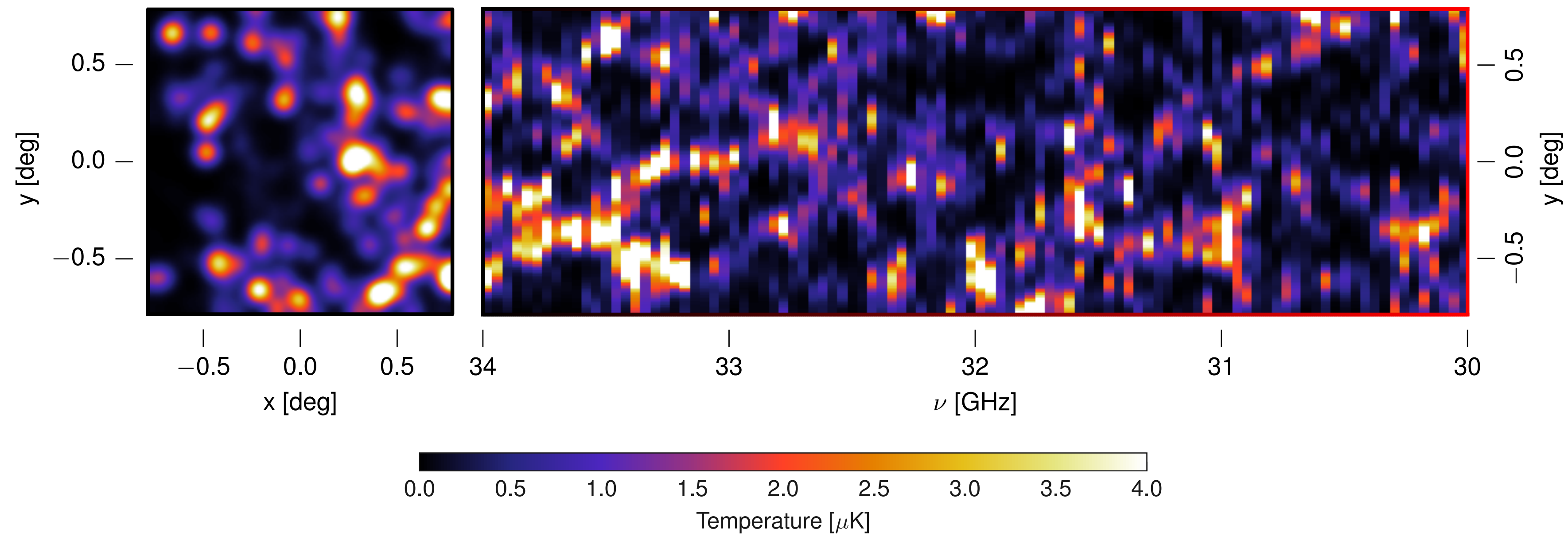
(CO Emitters)



Credit: Patrick Breysse

How do we probe the numerous faint galaxies?

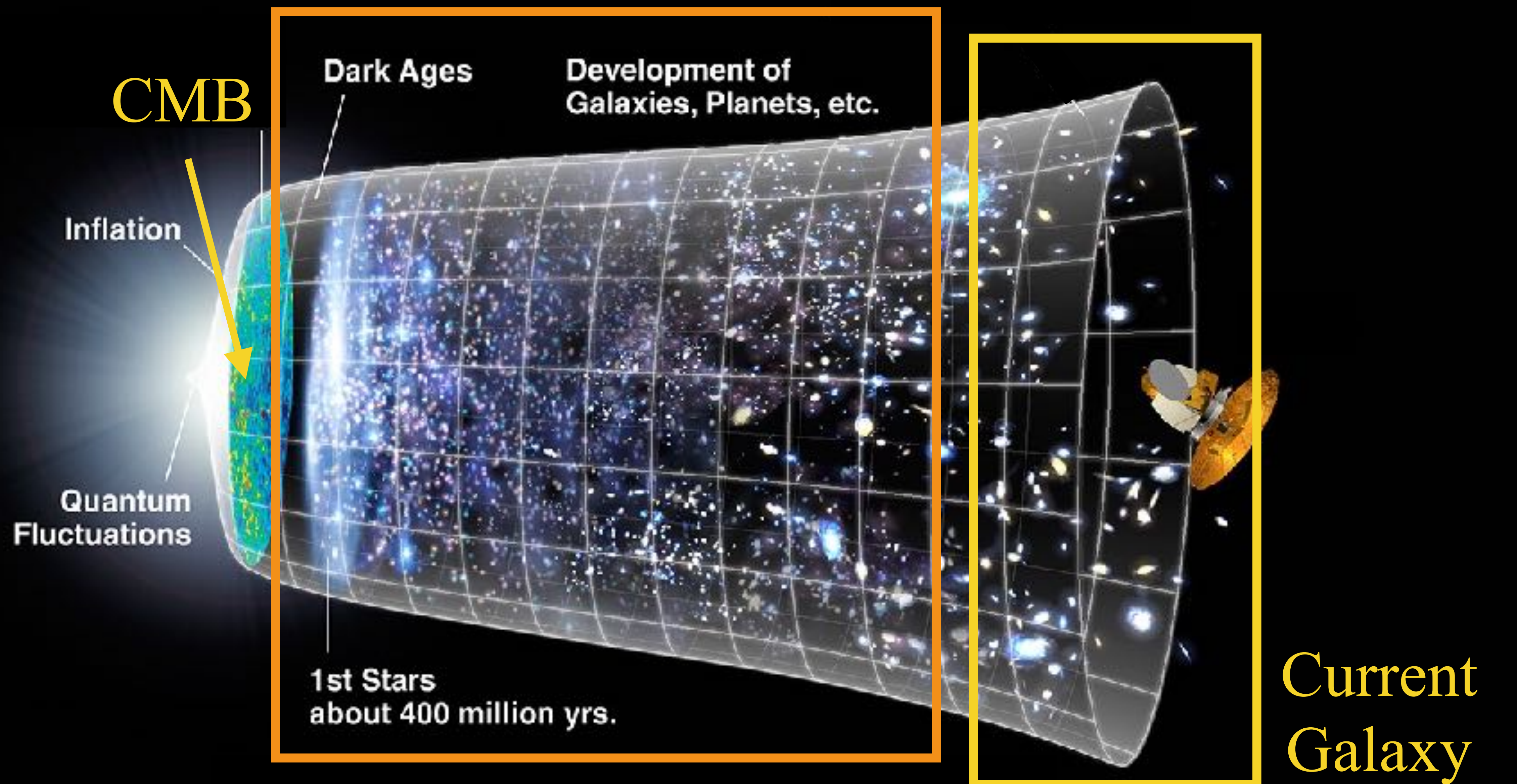
Intensity Mapping



- Measures aggregate intensity in large pixels (like a CMB probe)
- Accepts low angular resolution for high sampling
- Better redshift precision than continuum surveys
- High redshifts (z > 6) & fast scans allow large volumes to access many modes for LSS

Image Credit: Li et al. 2015

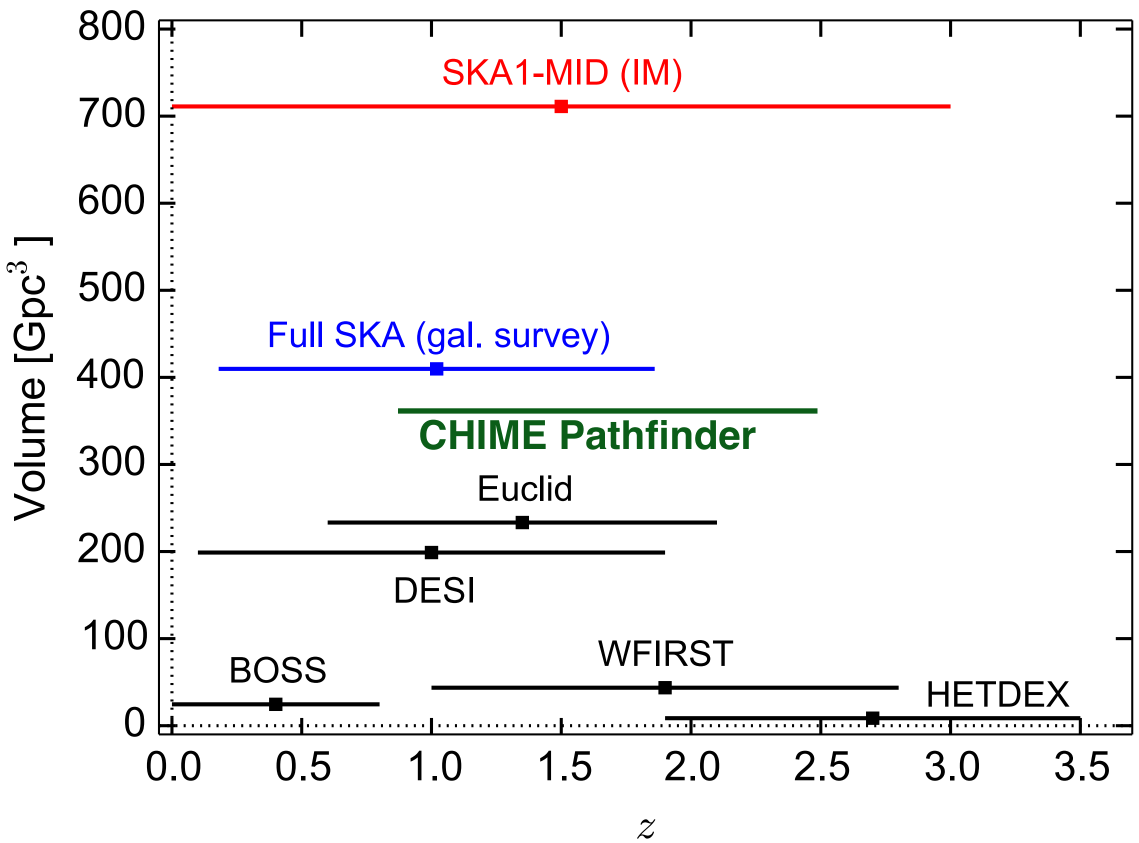
Missing Cosmic History



Lack of observational probes
(Intensity Mapping Potential)

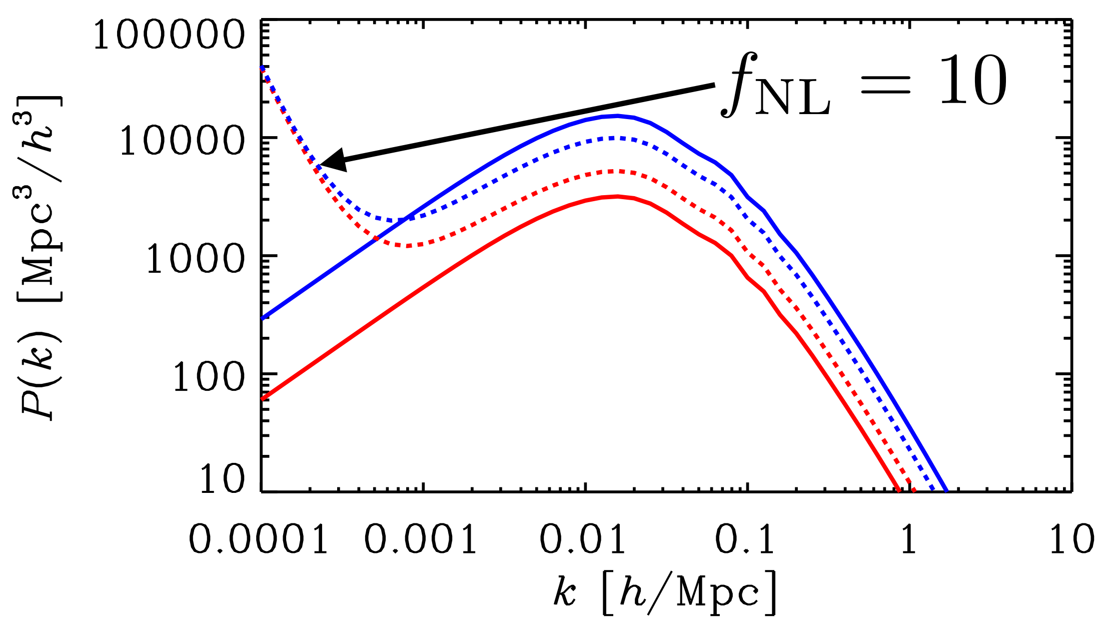
Credit: NASA/WMAP

IM probes the largest volumes



Credit: Santos et al. 2015 (SKA)

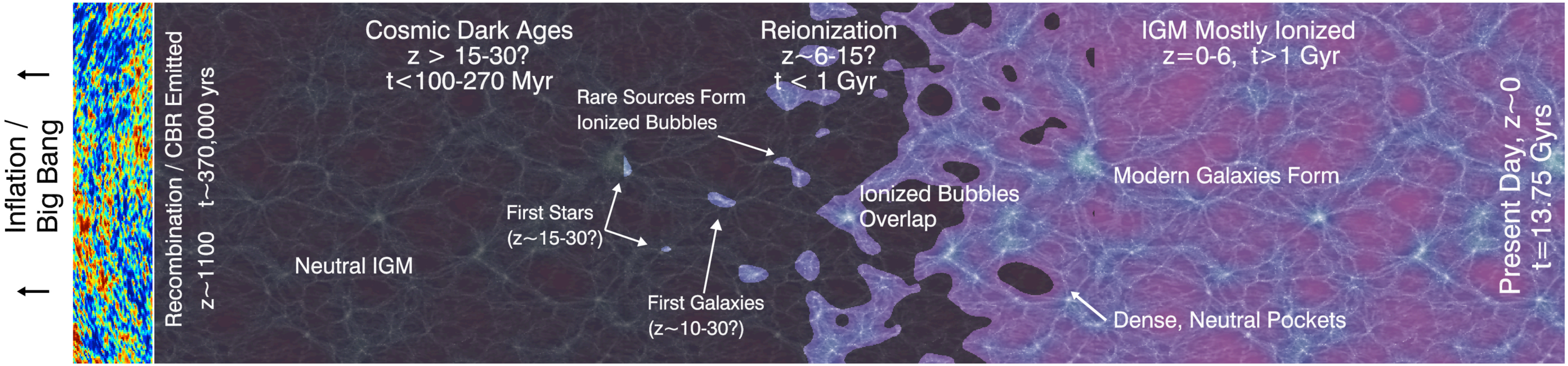
Non-Gaussian Inflation



Credit: Camera et al. 2013 (SKA)

- Probes the largest scales with many modes
- Ideal for non-gaussianity, GR tests, modified gravity

Reionization



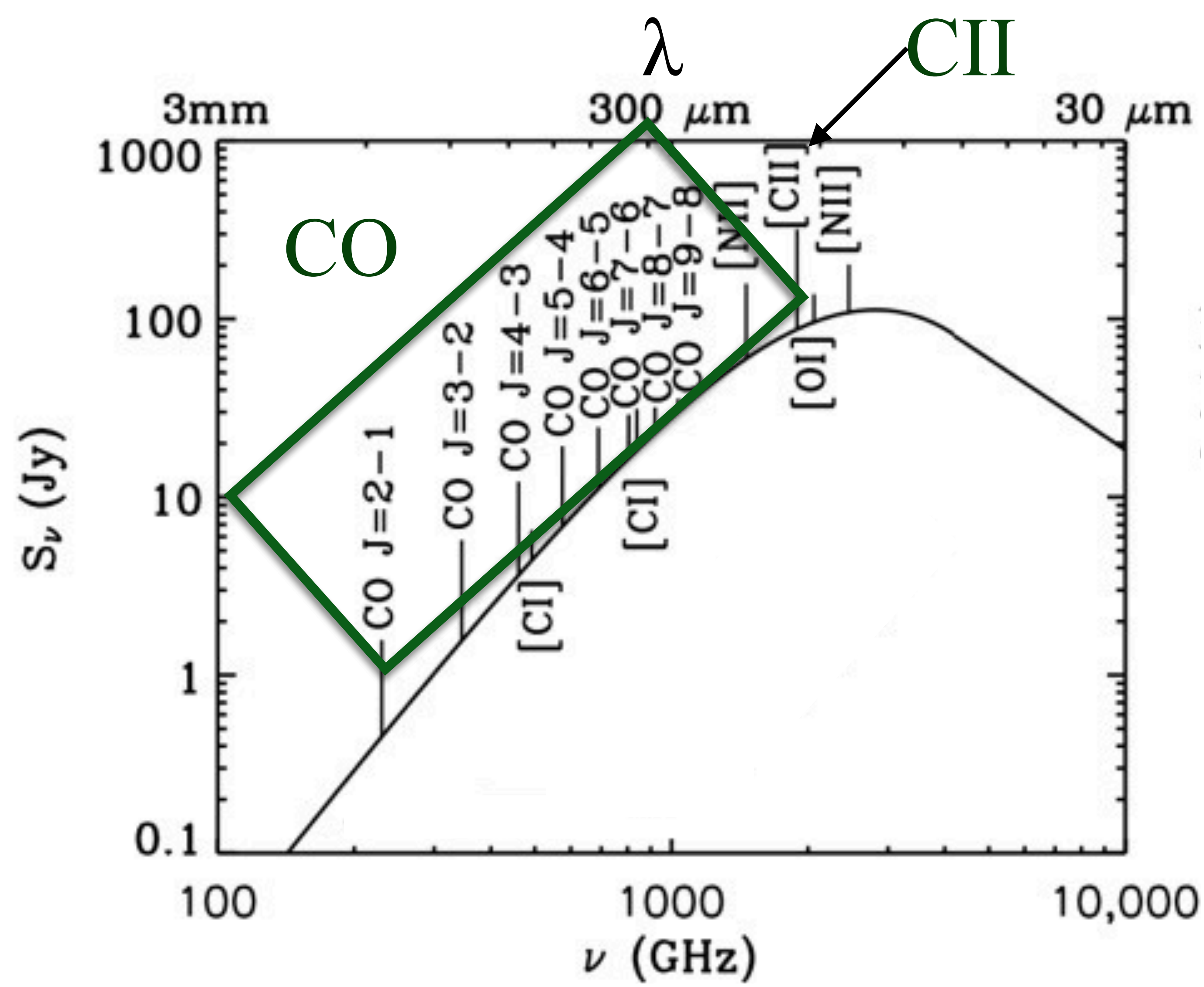
Credit: Robertson et al. 2010

- 21-cm emission ideal for probing IGM at high redshifts
- Direct τ measurement: break CMB degeneracies (A_s, Σm_ν)
- 21 cm x galactic lines enhance reionization probes

Barkana & Loeb 2001, Gunn & Peterson 1965, Liu et al. 2016

Galactic emission lines

- CO, CII, Lyα, Hα, etc.
- Better foregrounds than 21 cm emission - F/I=10^2
- Single-dish - no foreground wedge
- Line confusion is an issue
- Use cross-correlations to reduce foreground biases



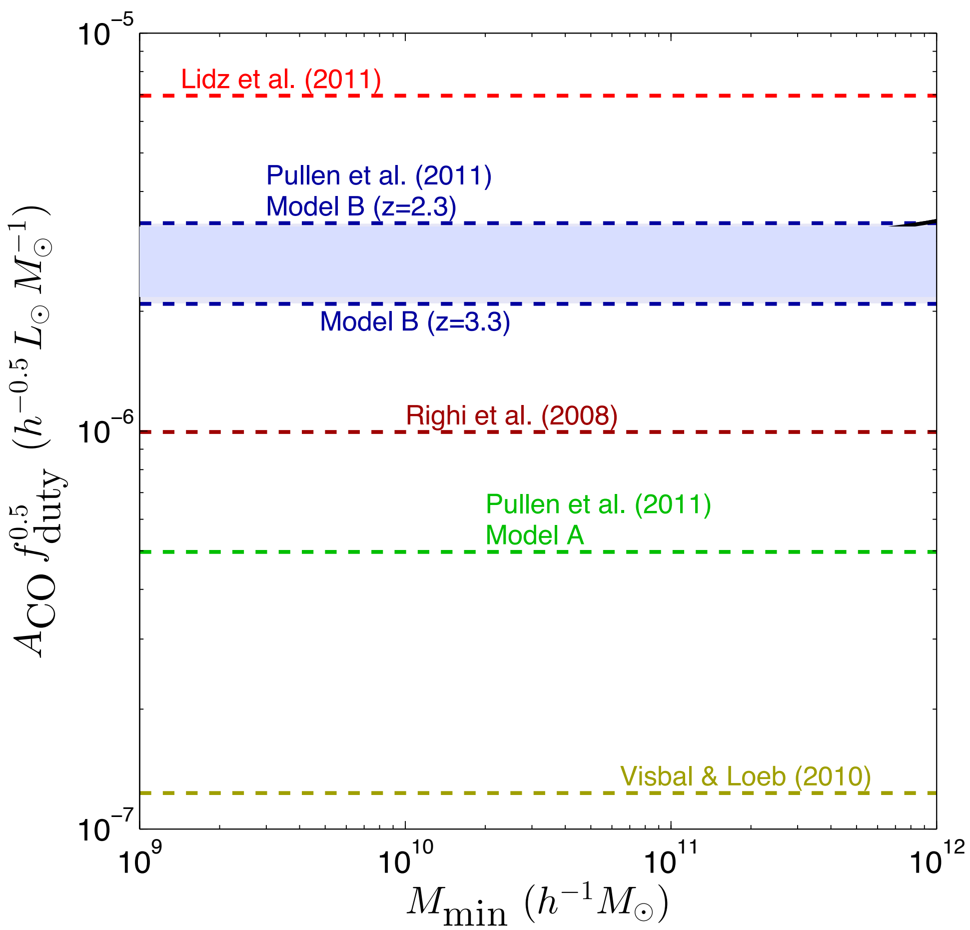
Credit: Iname et al. 2008

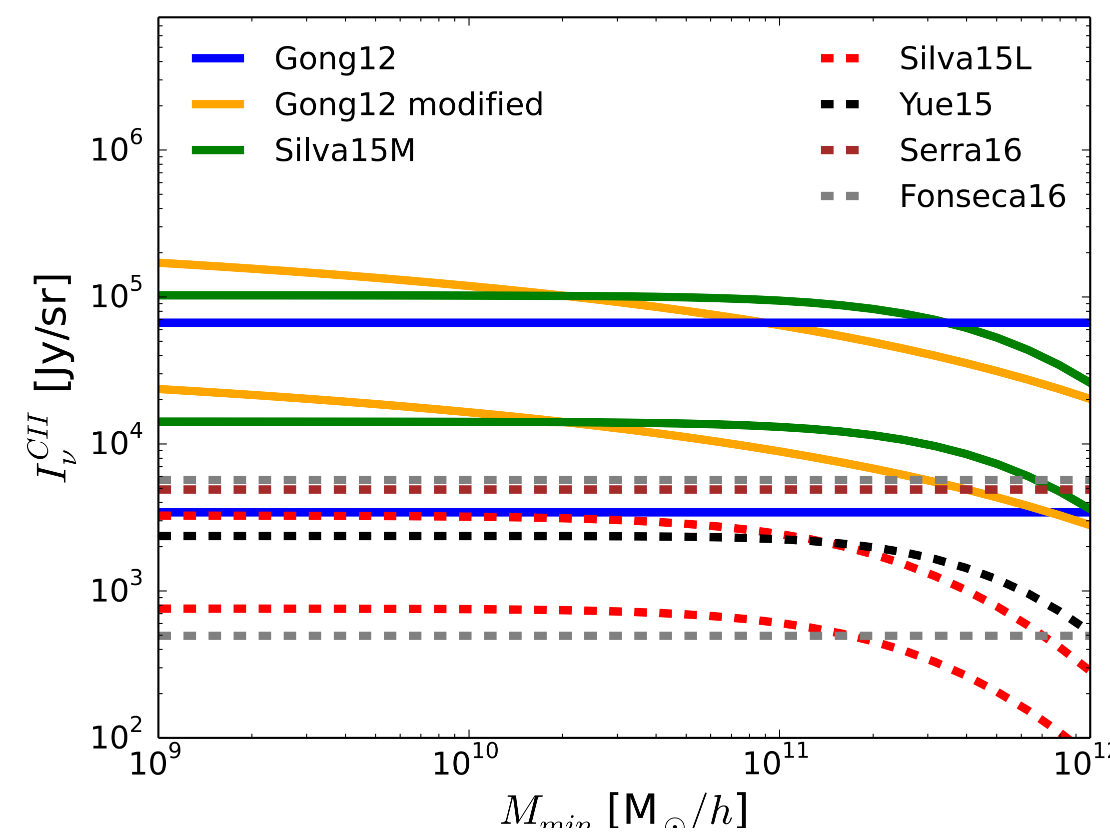
Righi et al. 2008, Gong et al. 2011, Lidz et al. 2011, **Pullen** et al. 2013, Breysee et al. 2014

What are the intensities?

We don't know

Models vary over 2 orders of magnitude!





Credit: Keating et al. 2015

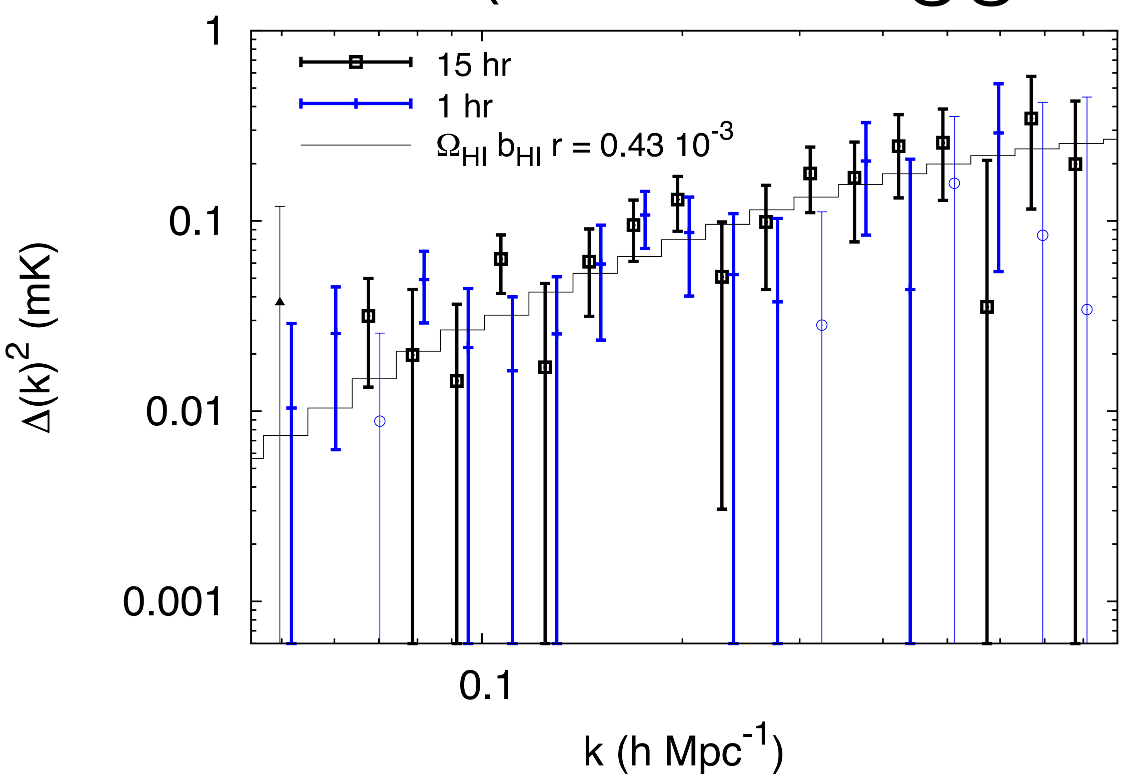
$$\boxed{A_{\rm line} = \frac{L_{\rm line}}{M_{\rm halo}}}$$

Measure line intensities at moderate redshifts ($z < 3$)

- Cross-correlate moderate redshift IM with galaxy surveys
- Constrain star formation rate from more abundant, low-mass halos
- Predict spectral foregrounds for high-redshift surveys
- Plan for future large-volume and/or high-redshift surveys

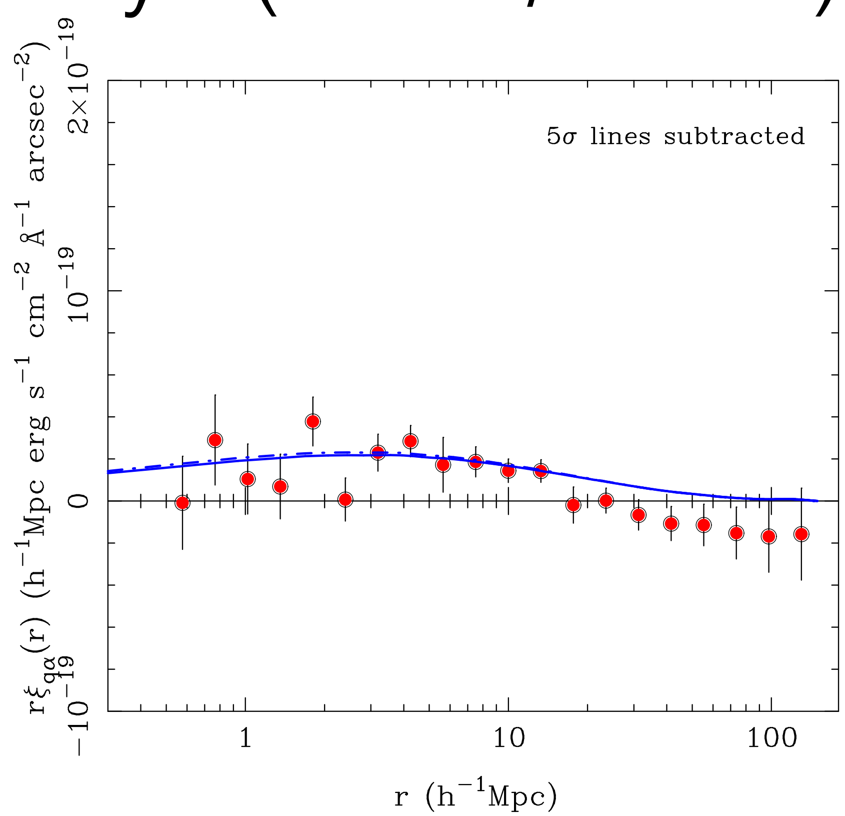
CC measurements

21 cm (GBT x WiggleZ)



Credit: Masui et al. 2013

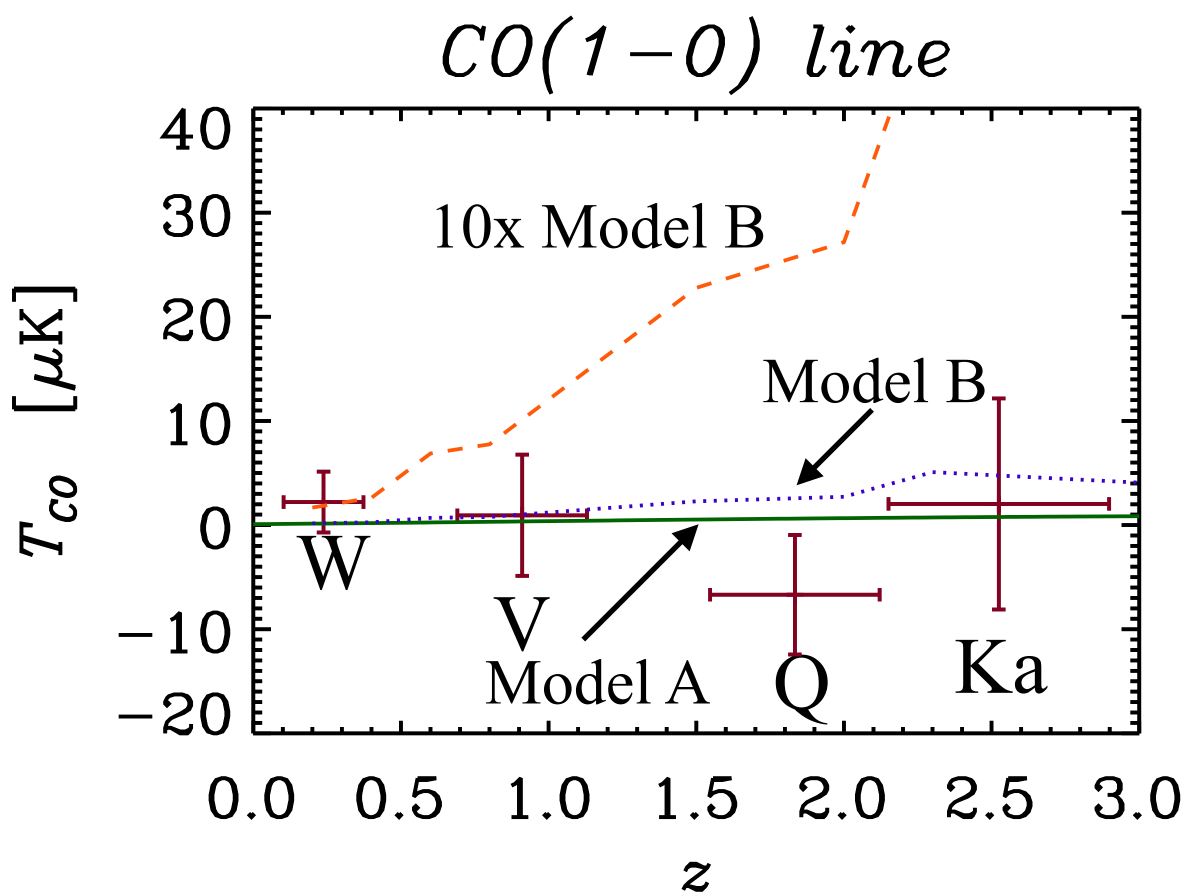
Lyα (SDSS/BOSS)



Credit: Croft et al. 2016

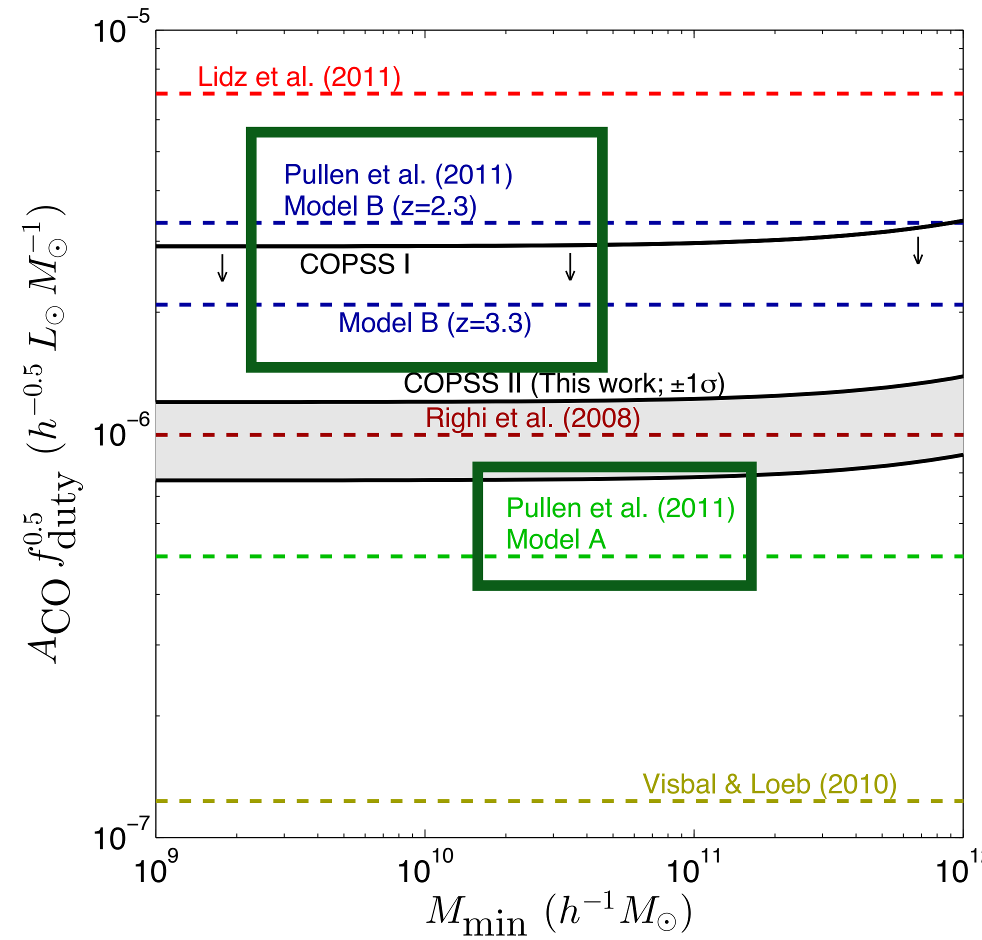
CO Measurements

WMAP x SDSS QSOs



Credit: **AP**, Chang, Doré & Lidz 2013

COPSS survey



Credit: Keating et al. 2016

CII Intensity

$$I_\nu^{\mathrm{CII}} = \frac{A_{\mathrm{CII}}}{4\pi\nu_{\mathrm{CII}}}\frac{c}{H(z)}\rho_{\mathrm{halo}}(M_{\mathrm{min}}, z)$$

Minimum Halo Mass

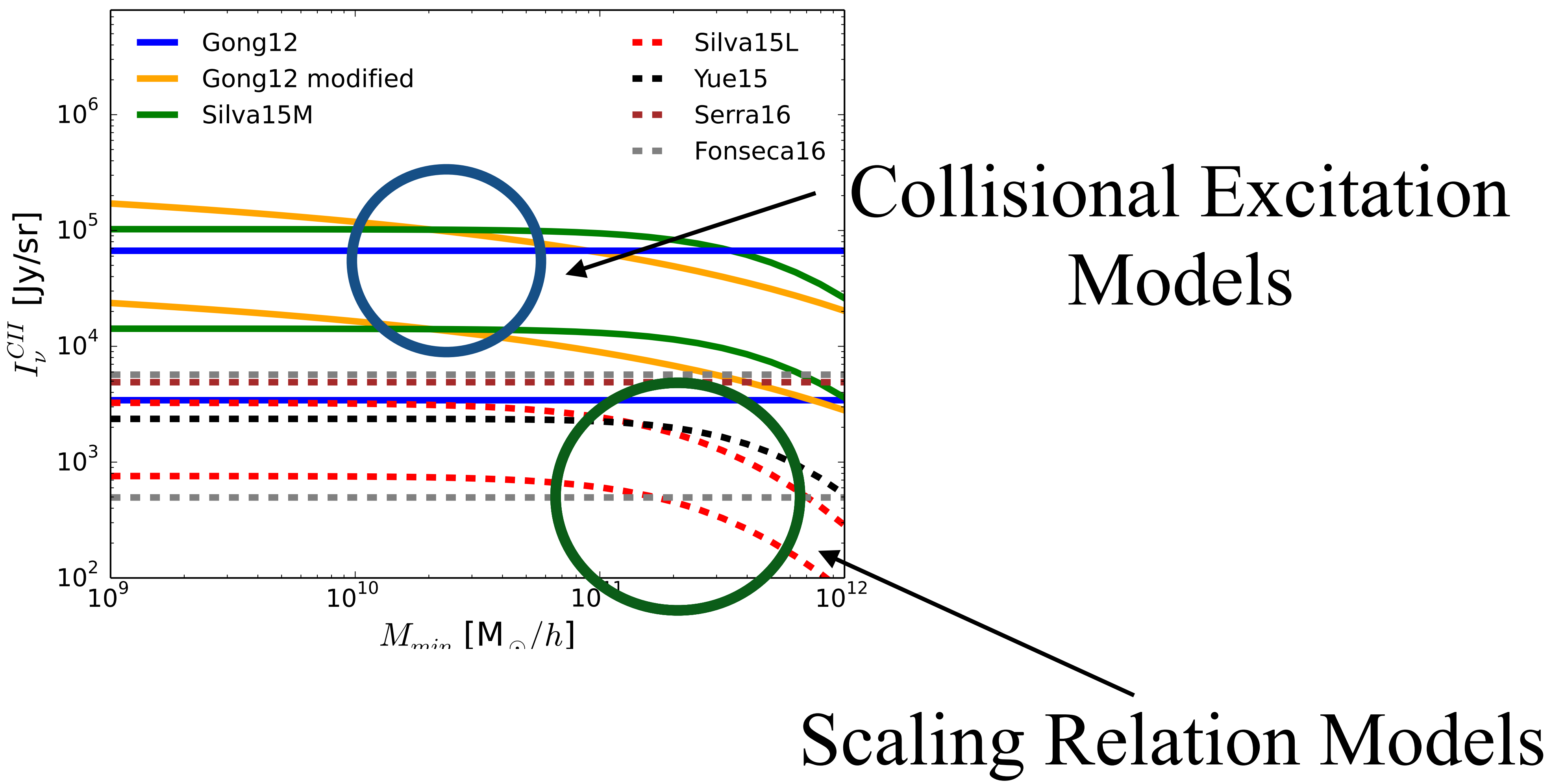
Halo Mass Density

$$A_{\mathrm{CII}} = \frac{L_{\mathrm{CII}}}{M_{\mathrm{halo}}}$$

Luminosity-Halo Mass Ratio

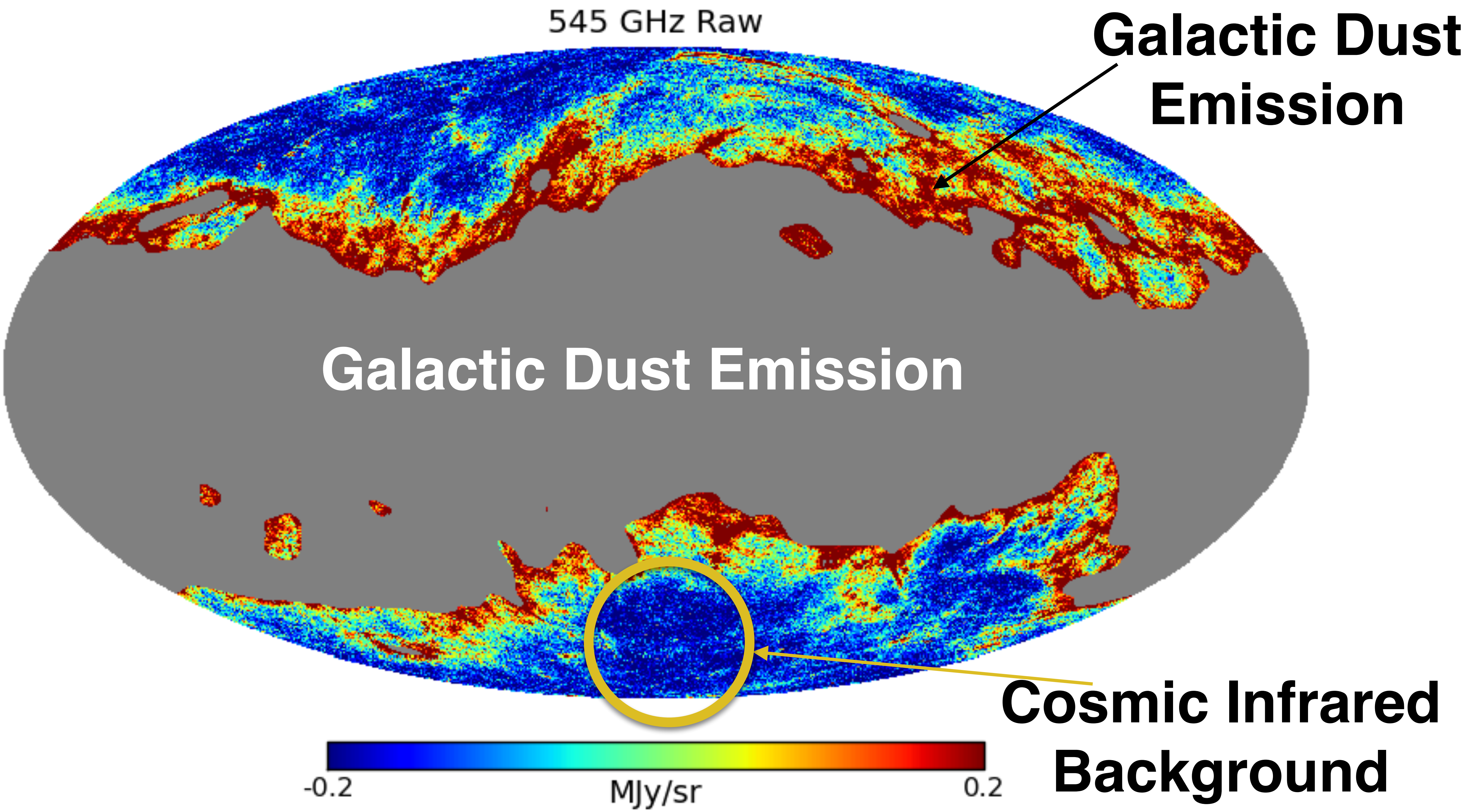
***A_{CII}* sets the CII intensity**

Collisional excitation models predict higher intensities than LF models



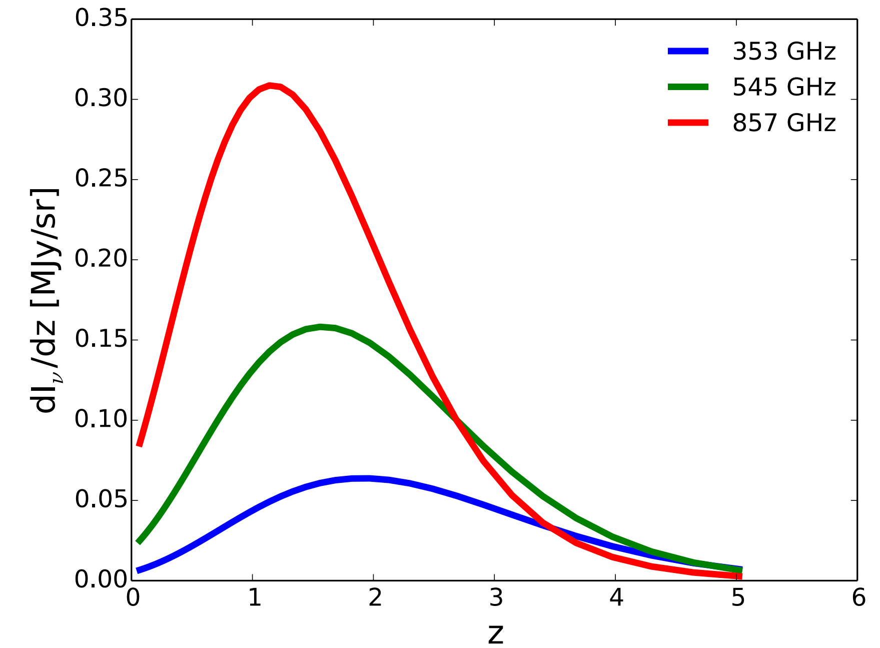
AP, Serra, Chang, Doré, Ho (2017)

Dust and CIB Dominate Signal



Cosmic Infrared Background

- Emitted by dusty (young) stars
- Tracer of large-scale structure
- Must be removed to reveal CII signal



Credit: **AP,** Chang, Doré, Ho, Serra (2017)

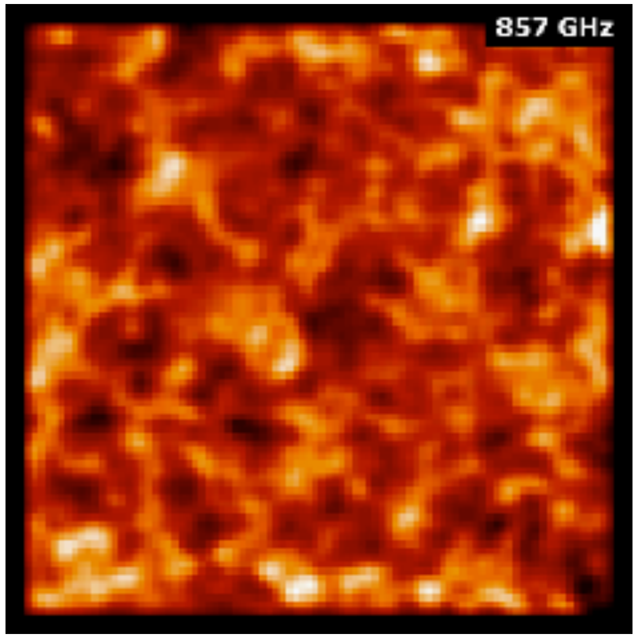


Image Credit: Planck Collaboration

CII-Tracer Cross-Power

$$P_{\mathrm{CII-Tr}}(k,z) = r_{CII-Tr} b_{\mathrm{CII}} b_{\mathrm{Tr}} I_\nu^{\mathrm{CII}} P_m(k,z)$$

galaxies,
quasars,
etc.

cross-correlation
coefficient

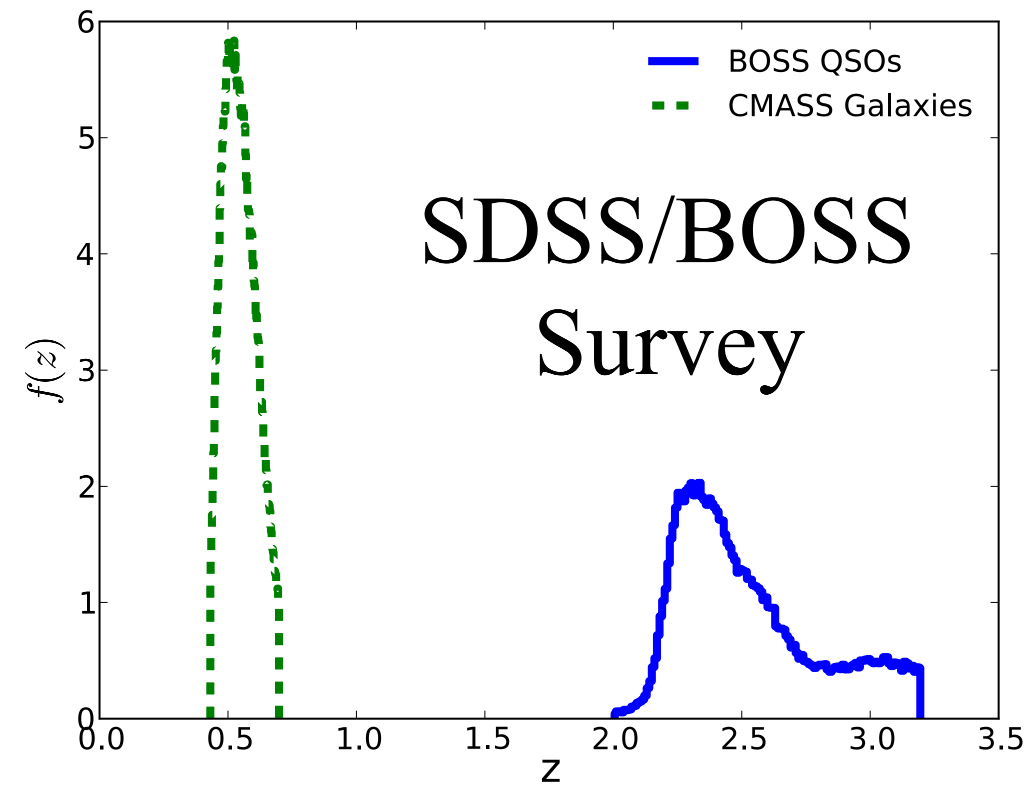
- No noise bias ✓
- Foregrounds cancel ✓
- Additional cross-correlation coefficient ✗

We measure CII emission using cross-correlations

- Probe CII at z = 2.5 in Planck 545 GHz map.
- CII cross-correlates with BOSS quasars (z = 2-3.2).
- Cross-correlation avoids dust contamination in signal.
- CIB model highly uncertain → Fit jointly for CIB & CII emission.
- Use 353, 857 GHz Planck bands and cross-correlations with SDSS-CMASS galaxies to break CIB/CII degeneracies.

How we estimate cross-correlations

- $C_\ell^{TQ} and C_\ell^{TG}$ is measured in 9 l-bins
- Mode-coupling is included in pseudo-C_l estimate and covariances
- Use Planck maps over 33% of sky to constrain CIB and CII
- Use BOSS Core Quasar Sample and CMASS LRGs to constrain CIB and CII

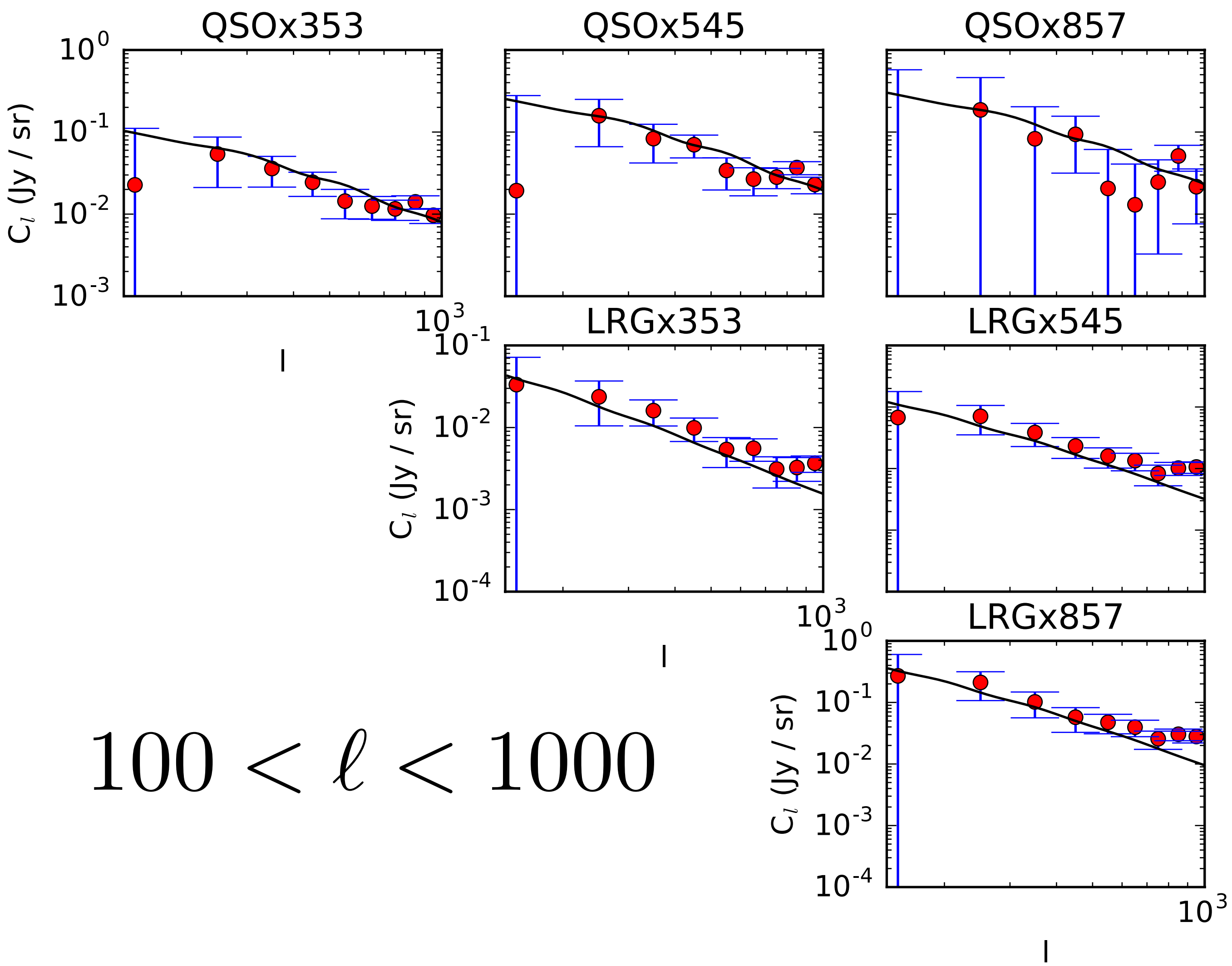


Credit: **AP,** Serra, Chang, Doré, Ho (2017)

Planck - 353, 545, 857 GHz

Cross-Correlations fit CIB/CII model

- Measurement fits well to a CIB halo model both with and without CII emission
- Consistent with measurement using 20% Galactic Plane mask
- Jackknives are well within statistical errors
- Excess on small scales for LRGs do not affect result



$$100 < \ell < 1000$$

Credit: **AP,** Serra, Chang, Doré, Ho (2017)

MCMC for CIB/CII model

$$C_\ell^{T_i-LSS} = \boxed{C_\ell^{CIB_i-LSS}} + \boxed{C_\ell^{CII_{545}-Q}\delta_{i,545}\delta_{LSS,Q}}$$

CIB-LSS cross-correlation

CII-Quasar cross-correlation

Normalized using mean CIB measurements

3 CIB parameters

L_0 = CIB luminosity

T_d = dust temperature

$(1+z)^\delta$ = redshift evolution

A_{CII} = CII:CIB ratio

SZ template included in 353 GHz band

Hint of CII emission

- We fit the CIB parameters and the CII amplitude
- CIB constraints consistent with previous measurements from Planck auto-correlation analysis
- Implies CIB & QSOs/LRGs are perfectly correlated
- CII intensity disfavors null hypothesis at 95% confidence

$$\boxed{\chi^2/N_{\mathrm{dof}} = 1.2}$$

$$T_d = 27.4 \pm 0.8\mathrm{K}$$

$$\delta = 2.3 \pm 0.1$$

$$\boxed{\mathrm{I}_{[\mathrm{CII}]} = 5.7^{+4.8}_{-4.2} \cdot 10^4 \ \mathrm{Jy/sr} \quad (95\% \ \mathrm{c.l.})}$$

AP, Serra, Chang, Doré, Ho (2017)

What about other lines?

- Broad-band Planck maps should contain other lines that correlate with QSOs and LRGs
- QSOs - OI, OIII; LRGs - NII
- We compute C_ℓ contributions from these lines using our CII measurement and measured line ratios
- We find a biases for CIB and CII < 3%.

C_ℓ	Interlopers	$\Delta C_\ell / C_\ell [\%]$
353-QSO	^{12}CO(10-9), ^{12}CO(11-10), ^{12}CO(12-11)	0.55
545-QSO	OI	0.28
857-QSO	OIII	1.1
$\boxed{\text{353-CMASS}}$	$\boxed{^{12}\text{CO(5-4)}, ^{13}\text{CO(5-4)}, \text{HCN(6-5)}}$	$\boxed{2.3}$
545-CMASS	^{12}CO(7-6), ^{12}CO(8-7), CI, ^{13}CO(7-6), ^{13}CO(8-7)	1.2
857-CMASS	^{12}CO(11-10), ^{12}CO(12-11), NII	0.44
$\boxed{\text{C II-QSO}}$	$\boxed{\text{all interlopers}}$	$\boxed{2.5}$

Credit: **AP,** Serra, Chang, Doré, Ho (2017)

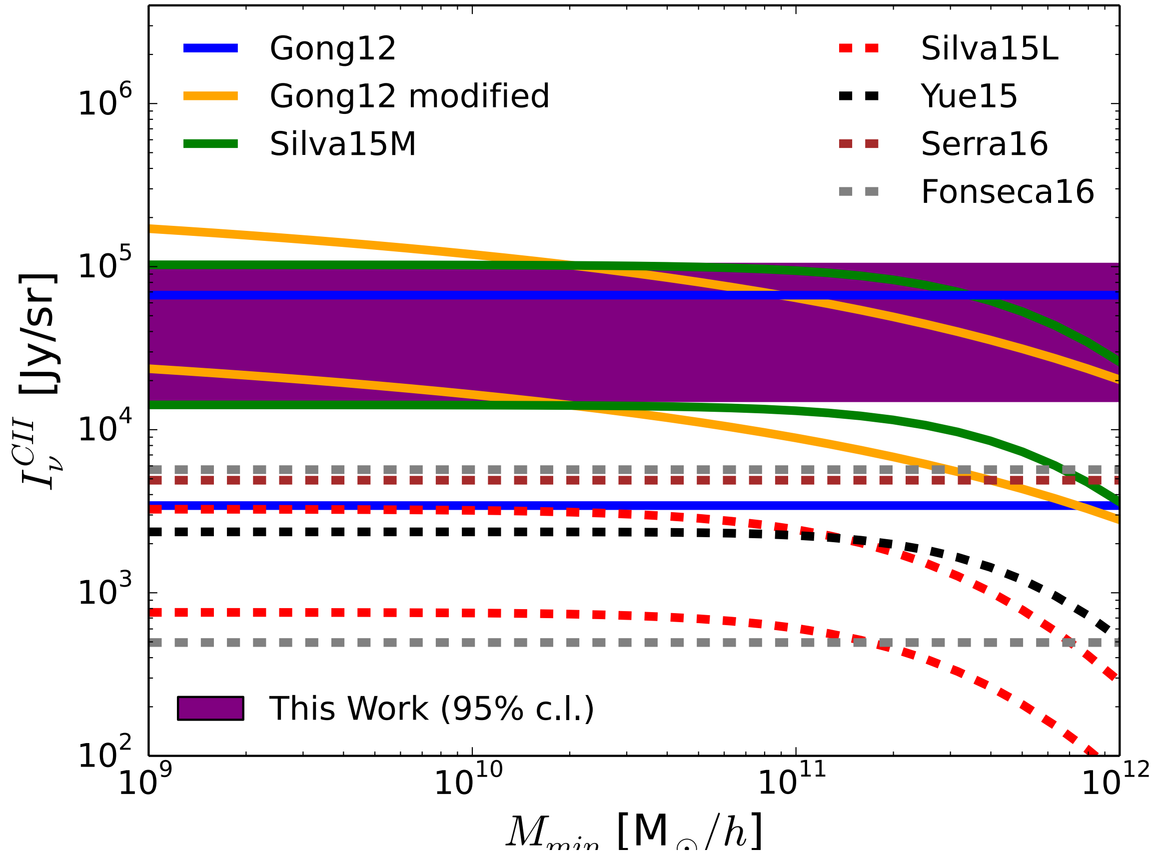
Visbal & Loeb 2011

Did We Overfit?

- We need to make sure our CII excess we see is not due to overfitting the data by including more parameters
- Bayesian evidence ratio compares the fits from the CII and no-CII models
- Accounts for the no-CII model having 1 less parameter
- The ratio is less than 3, meaning no measurable preference between the models
- More precise measurements can confirm or reject CII hypothesis

CII Model Constraints

- Assuming CII excess is real
- Given as a function of the minimum halo mass for CII emission
- Favors collisional excitation models
- Disfavors LF models, but not ruled out



Credit: **AP,** Serra, Chang, Doré, Ho (2017)

Next Steps

Removing CII Foregrounds

Includes all foregrounds

$$\sigma^2(C_\ell^{TQ}) \simeq \frac{(C_\ell^{TQ})^2 + D_\ell^{TT} D_\ell^{QQ}}{(2\ell+1) f_{\rm sky}}$$

Cleaned CII map

$$\mathbf{x}_{\rm clean} = \mathbf{x}_{545} - \beta_{353}\mathbf{x}_{353} - \beta_{857}\mathbf{x}_{857}$$

- Foregrounds uncorrelated with quasars still appear in errors, including thermal dust emission
- We can improving analysis by constructing a template for all foregrounds from a linear combination of Planck bands
- Goal: remove all foregrounds that correlated across bands
- Team: Eric Switzer, Shengqi Yang (NYU grad student)

Prospects with DESI

- Replacing BOSS with DESI LRGs & quasars could increase the CII precision 5x!
- PIXIE intensity maps x DESI LRGs & quasars should decrease CII uncertainty 10x.
- If confirmed, extrapolated reionization signal could be seen by TIME-Pilot (SNR ~ 7)

Mayall 4m telescope
will be used for DESI
(Credit: NOAO, AURA, NSF)

Kogut et al. 2011, Hill et al. 2016, Levi et al. 2013, Crites et al. 2014

21 cm CCs to probe cosmology

- 21 cm x gal CCs could constrain growth rate while avoiding foreground bias
- IM CCs could make high-z growth rate, NG measurements
- Forecasts for half-sky Hα survey with CDIM-detector competitive at low-redshifts
- Next step: high-z forecasts, NG constraints

SKA1 x Stage IV galaxy survey

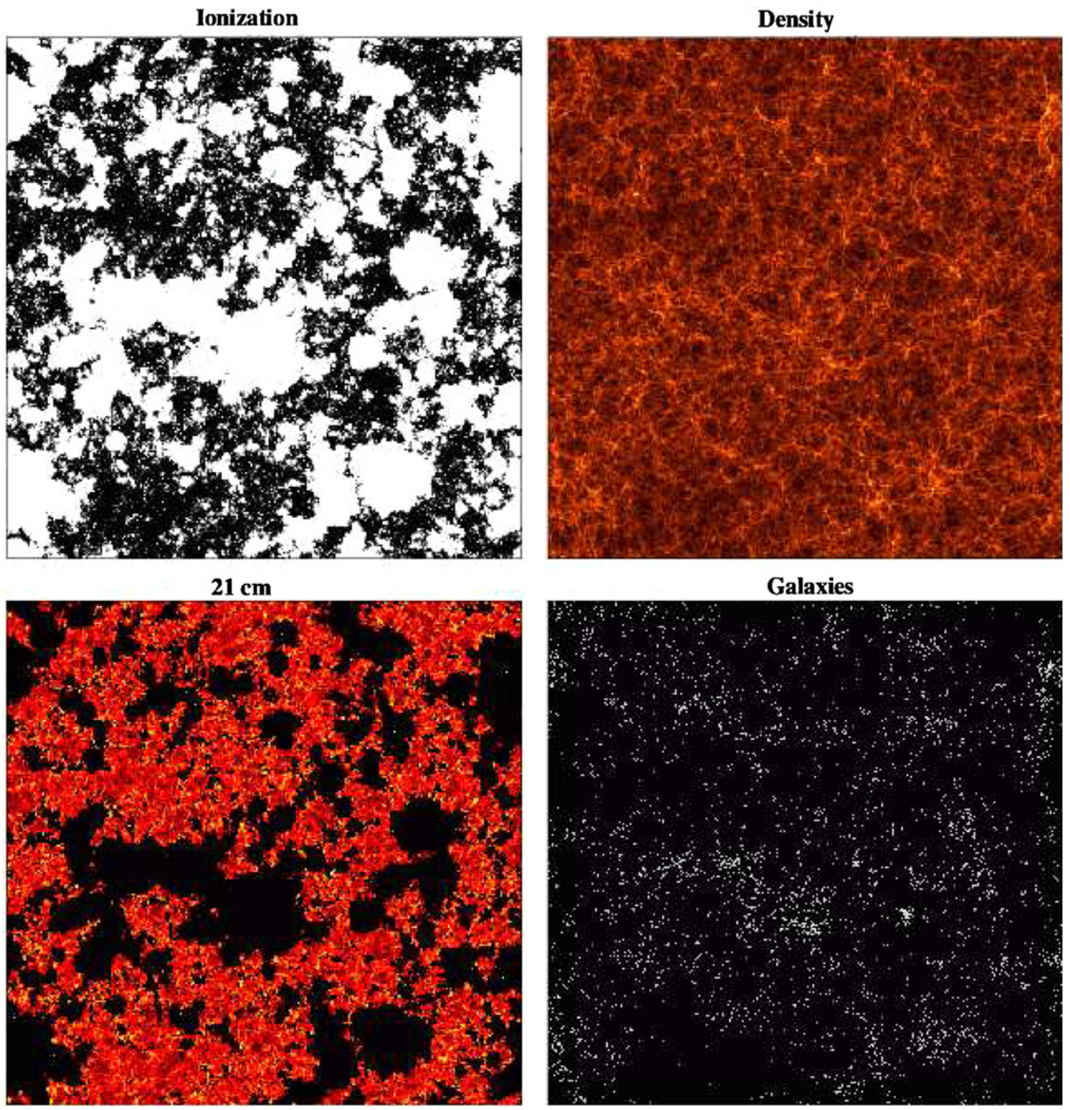
z	$\delta(f\sigma_8)/(f\sigma_8)$	$\delta D_A/D_A$	$\delta H/H$
UHF band			
0.6	–	–	–
0.7	0.04	0.03	0.02
0.8	0.05	0.03	0.02
0.9	0.05	0.03	0.03
1.0	0.06	0.04	0.03
1.1	0.07	0.04	0.03
1.2	0.08	0.05	0.03
1.3	0.10	0.06	0.03
1.4	0.11	0.06	0.04

Credit: Pourtsidou et al. 2016

CDIM - Cosmic Dawn Intensity Mapper - Cooray et al. 2016

Multi-line IM simulations

- More surveys → more sims
- Problem: Lack of IM simulations over large volumes with realistic small-scale physics
- Seeking to construct large-volume sims to be used by IM surveys for astrophysics and cosmology studies
- Team: Rachel Sommerville, Marcelo Alvarez, Eli Visbal



Credit: Lidz et al. 2009

Summary

- We search for CII emission in high-frequency Planck maps using LSS cross-correlations, jointly fitting for CIB
- We find a hint of a CII signal at $z = 2.5$ using cross-correlations of Planck maps with LSS
- Measurement favors collisional excitation models, but better data needed
- Cross-correlations with DESI LRGs & QSOs have a great chance at confirming this CII signal.
- Next: Foreground Removal, HI CCs, IM Simulations