Understanding Cosmological Evolution of Galaxies with Intensity Mapping

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BCCP/Cosmology Seminar, Berkeley
November 5th, 2019

Today's contents

1. **Background**
   - What is intensity mapping (IM)? And why?
   - A few more quick facts about IM
2. **[CII]/CO intensity mapping with TIME**
   - Probing the epoch of reionization
   - Challenges & opportunities from foregrounds
3. **A simple model for multi-line IM**
   - Dissecting global ISM properties
4. **Summary**

What is intensity mapping (IM)?

- Broad definition: a *statistical* measurement of spatial fluctuations in the intensity of certain emission *without resolving individual emitters*

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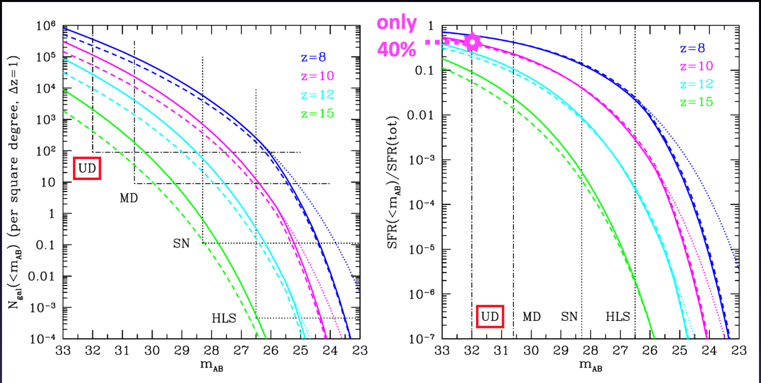
- More specifically,
  - Continuum intensity mapping: e.g., CMB
  - **Line intensity mapping (LIM):**
    - Extension into 3D space
    - First pioneered in H I 21cm
    - Other lines: Ly α, [C II], CO, etc.

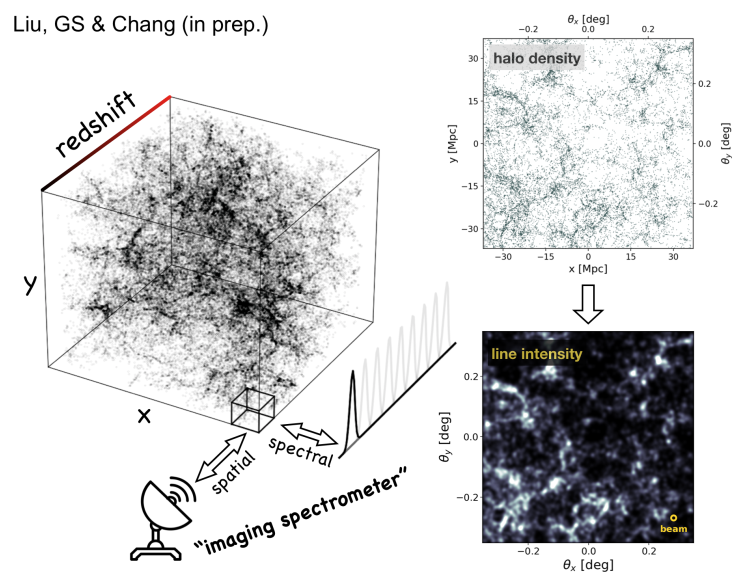
LIM: motivations & methodology



Furlanetto, Mirocha, Mebane & GS (2017)

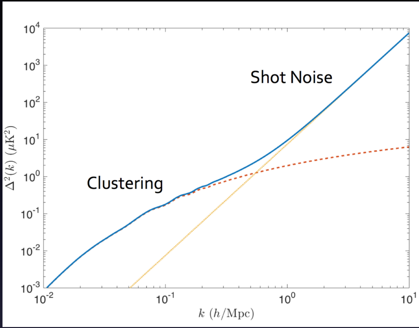
- Powerful telescopes (e.g., JWST, ALMA) do see very far
- Yet a significant fraction of SF/light might be missed!

LIM: motivations & methodology



LIM: a statistical measurement

- **Power spectrum**
  - Fourier transform of two-point correlation function (2PCF)
  - Non-gaussianity: 2nd moment (i.e., variance) not enough!



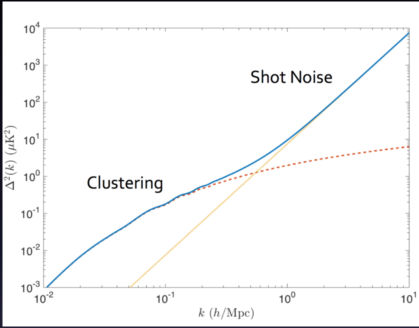
Kovetz et al. (2017)

$$P_{\mathrm{clustering}}(k) \propto \left(\int \frac{L \mathrm{d}N}{\mathrm{d}L} \mathrm{d}L \right)^2 P_{\delta\delta}(k)$$

$$P_{\mathrm{shot\ noise}} \propto \int \frac{L^2 \mathrm{d}N}{\mathrm{d}L} \mathrm{d}L$$

LIM: a statistical measurement

- **Power spectrum**
  - Fourier transform of two-point correlation function (2PCF)
  - Non-gaussianity: 2nd moment (i.e., variance) not enough!
- **One-point statistics**
  - Intensity maps: *non-gaussian*, especially on small scales
  - VID, CIC, etc.: constrain large deviations (e.g., LF bright end)
- **Higher-order statistics**
  - Bi-spectrum (F. T. of 3PCF)



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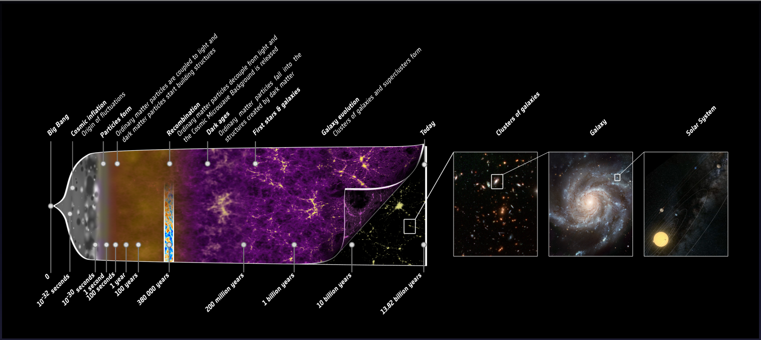
LIM: scientific objectives (big pictures)



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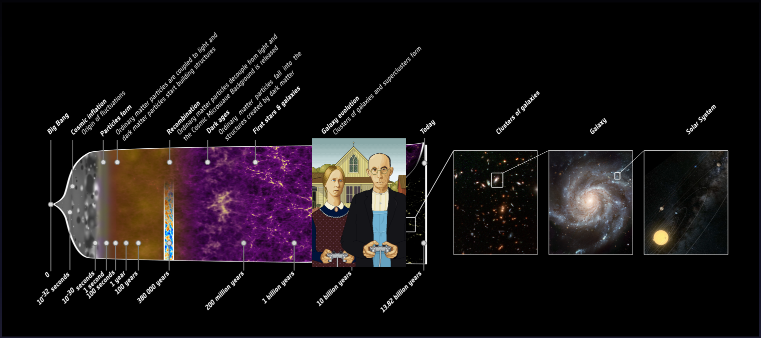

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  - Halo-galaxy connection, SF and gas fueling, ISM conditions, etc.

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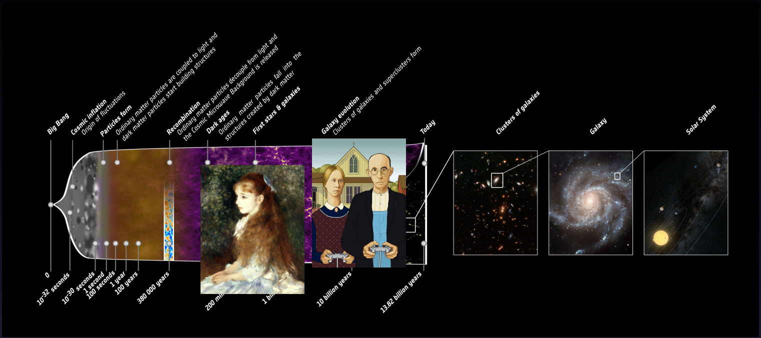

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  - Topology, progression, ionizing sources (galaxies, quasars), etc.

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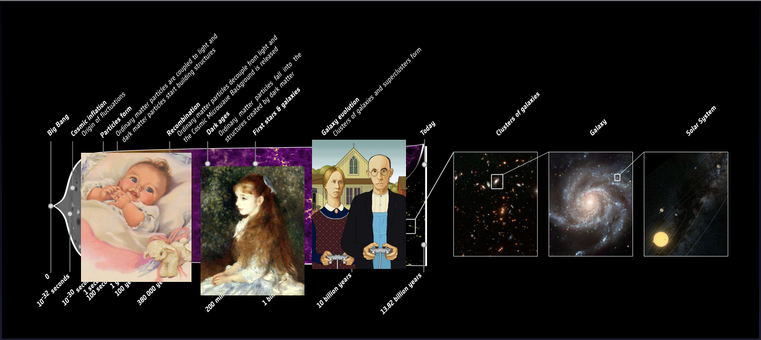

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- **The Reionization Era and Cosmic Dawn**
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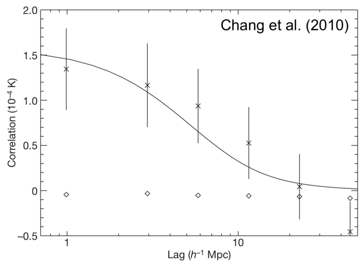
- **Cosmology**
  - LSS imprints $\Longrightarrow$ dark energy, primordial non-gaussianity, etc.

LIM: observational frontiers

First detections(?):

- H I with GBT (Chang+2010, Switzer+2013, Masui+2013)



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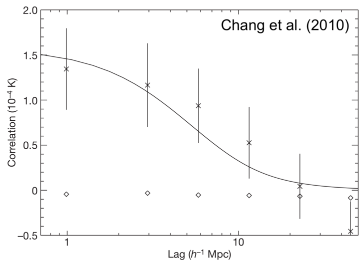

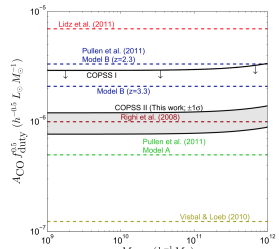

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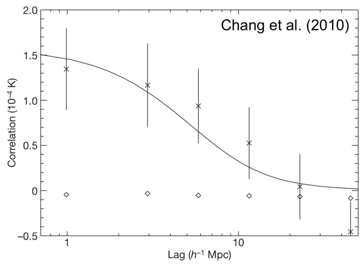

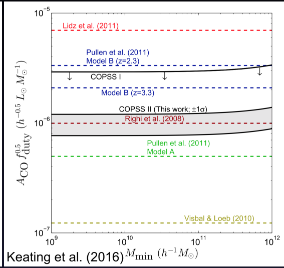

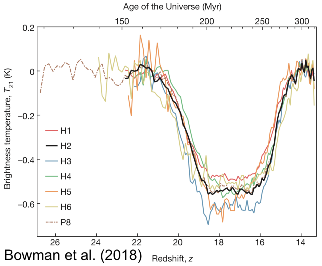

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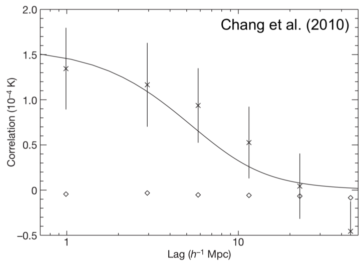
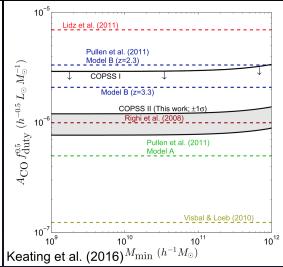
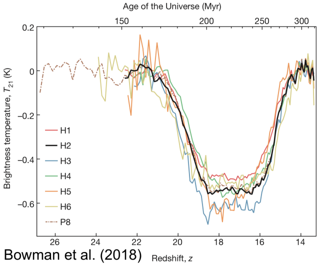
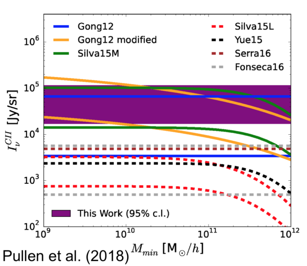
- [C II] via CIB x galaxies/QSOs (Pullen+2018)









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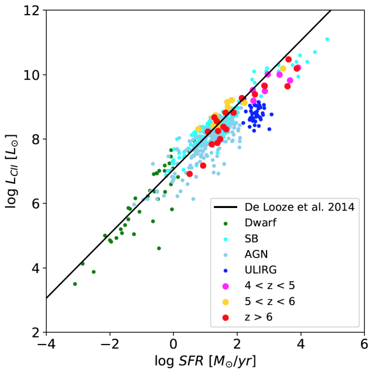
EoR intensity mapping with [C II]

- 158 μm [C II] line: major coolant of neutral ISM — brightest FIR line (up to 1% of $L_{\rm FIR}$), and a good tracer for *star formation* and *metal production*



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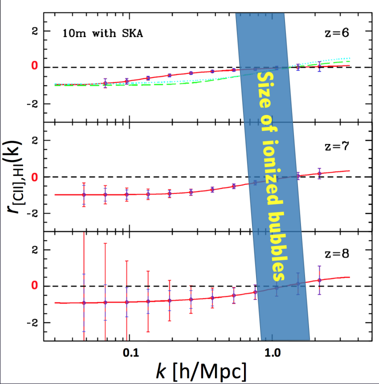

Gong et al. (2012)

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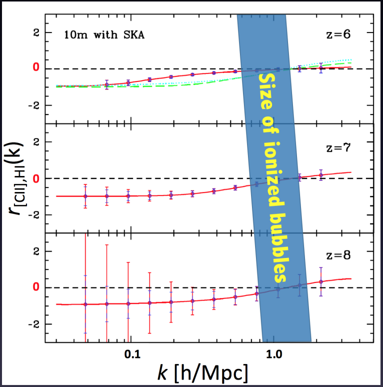
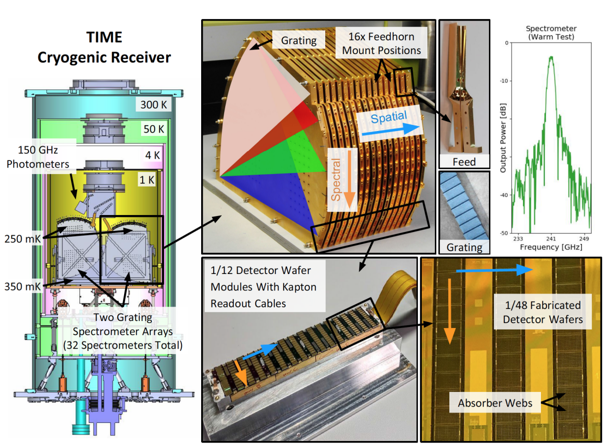
- Complementary to H I surveys — [C II]–H I cross-correlation constrains *bubble size* and EoR geometry
- EoR [C II] signal redshifted into transparent atmospheric window — crucial for ground-based observations



Gong et al. (2012)

Tomographic Ionized-Carbon Mapping Experiment

TIME Overview



- A high-throughput imaging spectrometer array: grating spectrometers + TES on a 12 m antenna @ Kitt Peak

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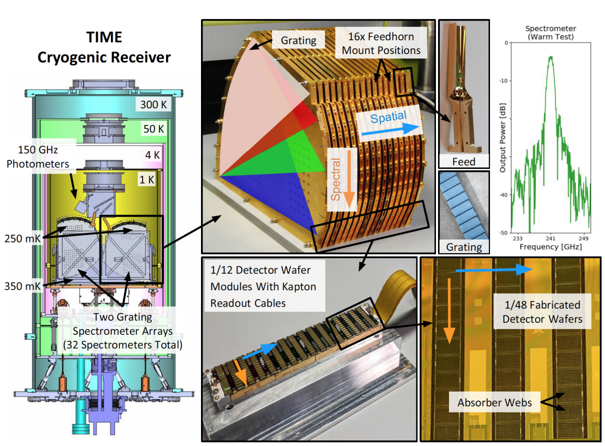
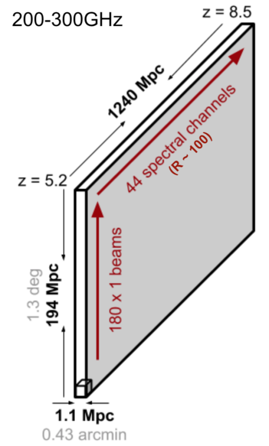
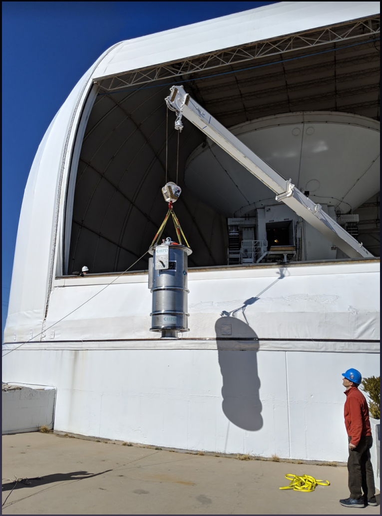


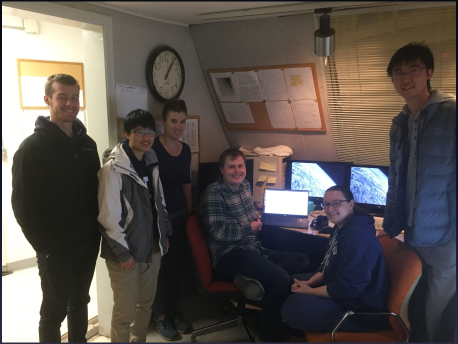


- A high-throughput imaging spectrometer array: grating spectrometers + TES on a 12 m antenna @ Kitt Peak
- Spectral coverage: 200 GHz to 300 GHz
- Targets: SF at EoR ([C II]), and H_2 near cosmic noon (CO)

TIME: first engineering run!

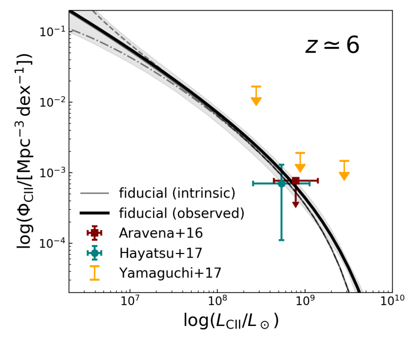


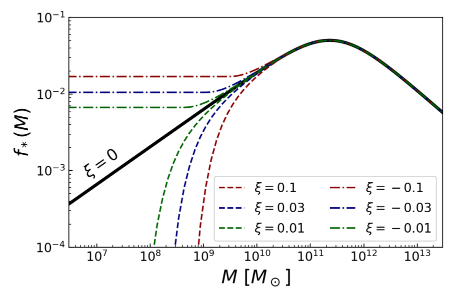
New home for cryostat



Moment of first light

Modeling: linking [C II] to SF





Sun et al. (in prep.)

$$\log\left(\frac{L_{\rm C\,II}}{L_\odot}\right) = a \log\left(\frac{L_{\rm UV}}{{\rm erg\,s^{-1}\,Hz^{-1}}}\right) + b\ ,\ \text{plus scatter}$$

$$(\Omega_b/\Omega_m) f_\star(M,\xi)\dot{M} = \dot{M}_\star = \mathcal{K}_{\rm UV} L_{\rm UV}$$

$$\Phi_{\rm C\,II} = \frac{{\rm d}n}{{\rm d}\log M}\frac{{\rm d}\log M}{a\,{\rm d}\log L_{\rm UV}} \Longrightarrow \Phi^{\rm obs}_{\rm C\,II} = \Phi_{\rm C\,II} * P_{\rm s}$$

Modeling: high-z SFH & EoR

Halo abundance matching (HAM)

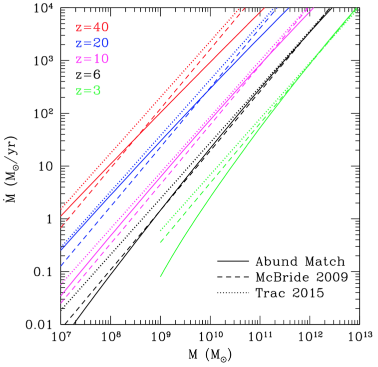
- HMFs at z & $z + \mathrm{d}z$: halo growth, $\dot{M}$
- UVLF & HMF at z: SF efficiency, $f_\star$

SF–halo connection

$$\dot{\rho}_\star(z) \propto \int_{M_\mathrm{min}}^{M_\mathrm{max}} \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M} f_\star(M, \xi) \dot{M}(M)$$

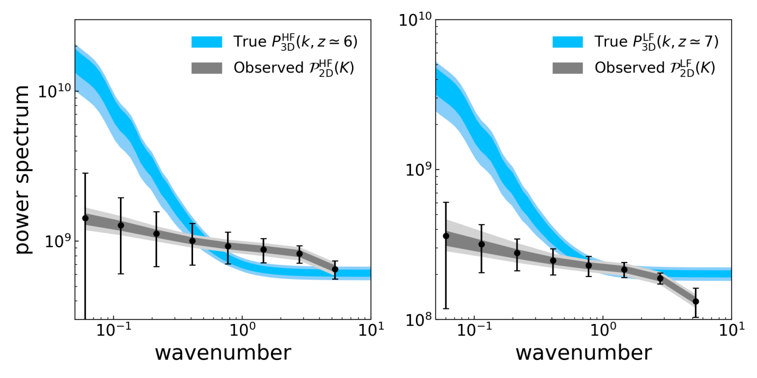
EoR: ionization vs. recombination

- source term: $\propto A_\mathrm{He} f_\mathrm{esc} f_\gamma \dot{\rho}_\star(z)$
- sink term: $\frac{C(z)\alpha_\mathrm{B}(T_\mathrm{e})}{H(z)}(1+z)^2 \bar{n}_\mathrm{H}^0 Q_\mathrm{H\,II}$



Furlanetto et al. (2017)

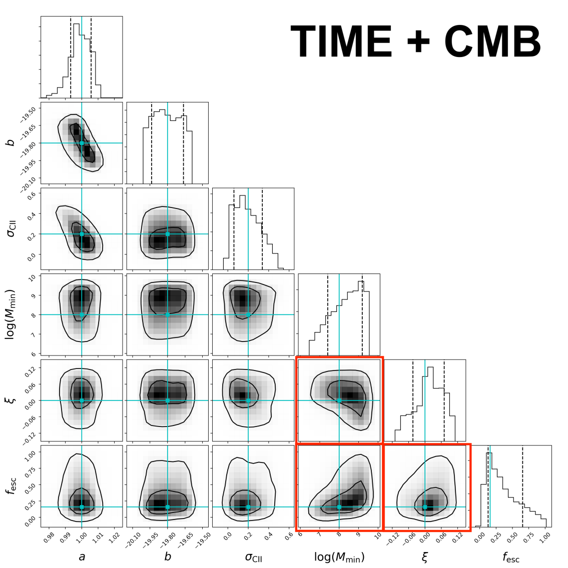
Mock observations: detectability



Sun et al. (in prep.)

- TIME is expected to measure $\mathcal{P}_{2D}$ at S/N∼15 (mode counting)
- Must solve the inverse problem to reconstruct P_{3D} from $\mathcal{P}_{2D}$!

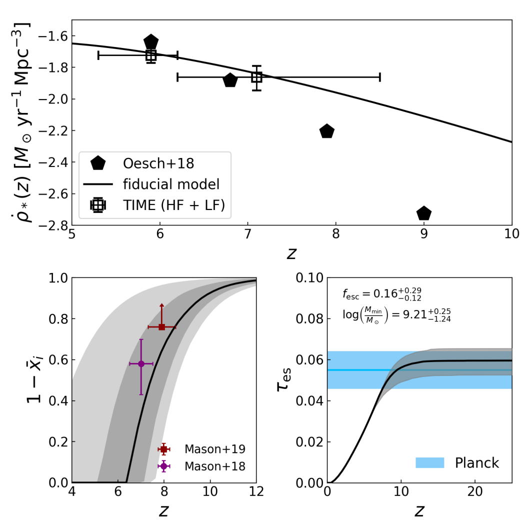
Mock observations: constraints



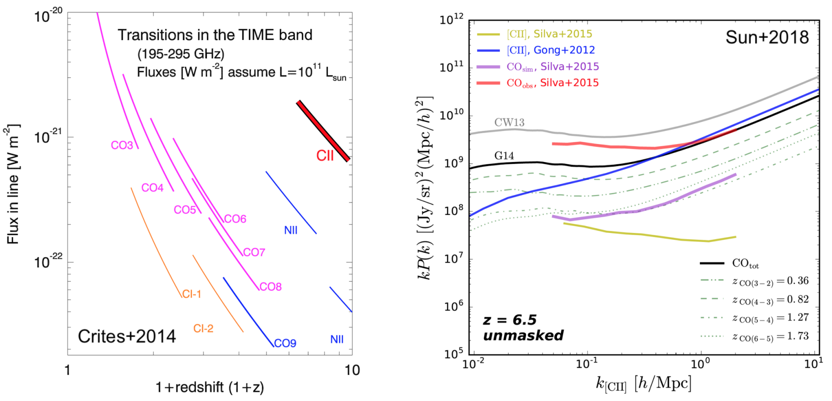
- Recap
  - a, b, σ: [C II]-SFR
  - $M_{\rm min}, \xi$: SFH
  - $f_{\rm esc}$: EoR
- Parameters jointly constrained by *observed* power spectra and $\tau_{\rm CMB}$
- $M_{\rm min} \nearrow$: $\xi \searrow$ or $f_{\rm esc} \nearrow$
- $\xi \nearrow$: $f_{\rm esc} \nearrow$

Mock observations: EoR implications

- SFH constraints w/o faint-end extrapolation
- Caveat: [C II] $\rightarrow$ SFR?
- Comparison with inferred IGM neutrality at $6 < z < 8$
- Consistency with τ_{CMB} guanranteed



Challenges: foreground is a foe



Observed data sets are "*interloped*" by low-z CO lines

- Lower redshifts $\Longrightarrow$ generally brighter
- Projection effect in k space $\Longrightarrow$ FG power enhanced

Masking: a cleaning strategy

- Directly measuring CO foreground strength is hard
  - Galaxy surveys $\rightarrow$ only brightest CO sources
  - CO IM $\rightarrow$ not yet constraining

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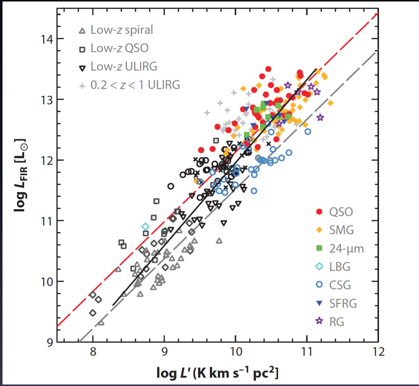
Masking: a cleaning strategy

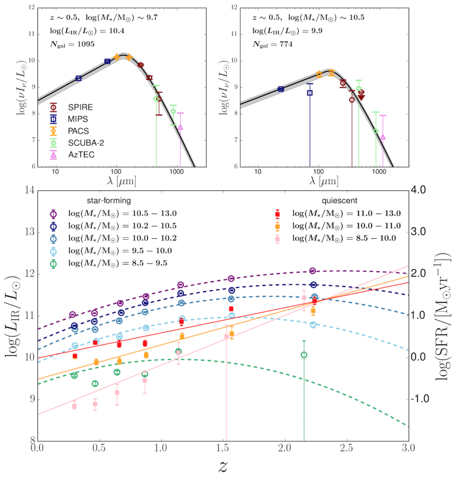
- Directly measuring CO foreground strength is hard
  - Galaxy surveys $\rightarrow$ only brightest CO sources
  - CO IM $\rightarrow$ not yet constraining
- Interloper-cleaning methods: e.g., cross-correlation, k-space anisotropy
- Alternatively, *proxies* for CO w/ 3D info can be used for (guiding) masking
  - Well-established correlation between $L_{\rm CO}$ and $L_{\rm IR}^{8-1000}$
  - Need *mean* AND *scatter*!



Carilli & Walter (2013)

Modeling IR luminosity as a CO proxy

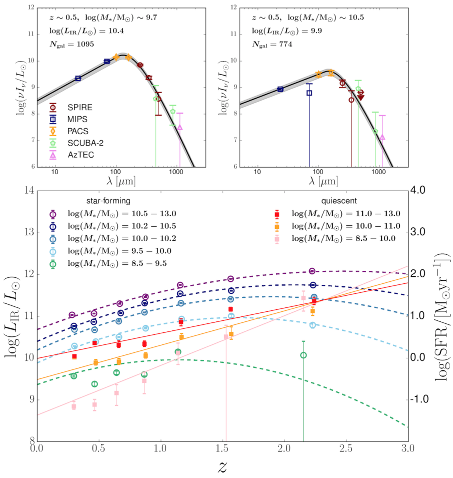
- To model the *mean* IR (and CO) luminosity
  - Simultaneously stacking multi-band, FIR data on NIR selected sources (COSMOS)
  - SED fitting (modified BB)



Sun et al. (2018)

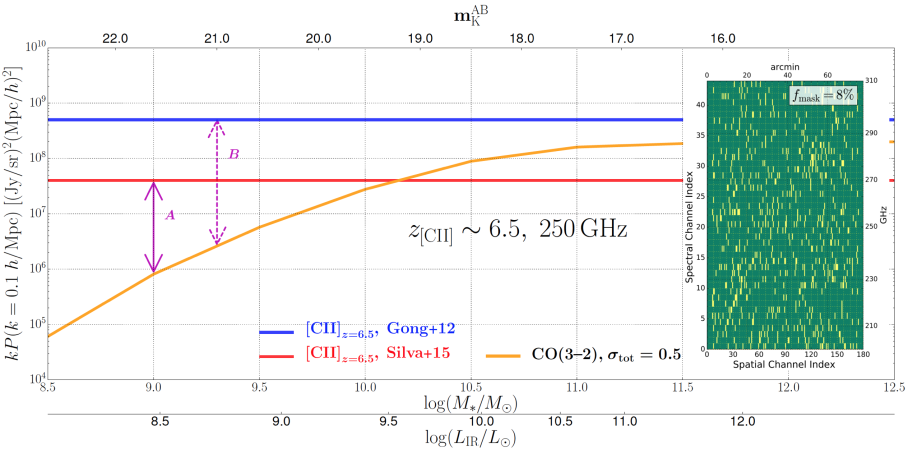
Modeling IR luminosity as a CO proxy

- To model the *mean* IR (and CO) luminosity
  - Simultaneously stacking multi-band, FIR data on NIR selected sources (COSMOS)
  - SED fitting (modified BB)
- To find the *scatter*
  - Compare real maps against scatter-injected, mock maps
  - Result (~ 0.3 dex) tested with end-to-end simulations



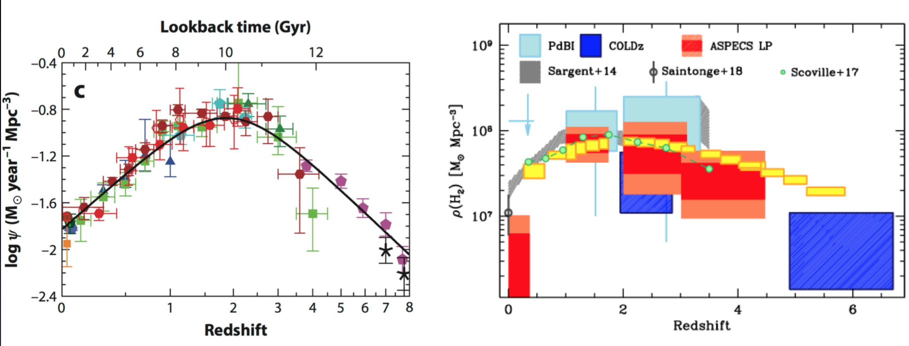
Sun et al. (2018)

Masking guided by CO proxy



- Removing $z \lesssim 1$ galaxies with $M_\star \gtrsim 10^9\ M_\odot$ ($m_K^{AB} \lesssim 22$)
- Over-masking if needed in presence of scatter
- Desirable [C II]/CO ratio with $< 10\%$ voxels masked

Opportunities: foreground is a friend



Walter et al. (2019)

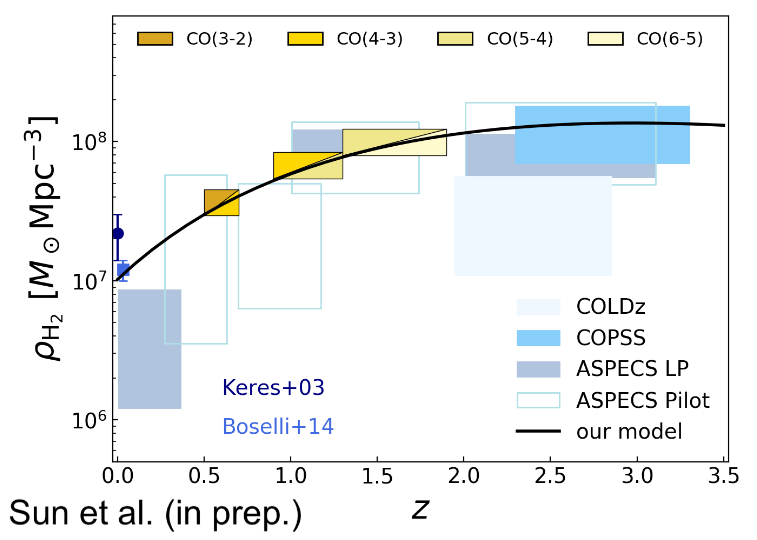
- Intriguing connection between SFRD and ρ_{H_2}
- CO: good *tracer of cold H_2 gas* (hard to observe)
- TIME will measure CO lines near "*cosmic noon*"

H_2 census with CO cross-correlation

$$\log\left[\frac{L'_{\mathrm{CO}(J\to J-1)}}{\mathrm{K\,km\,s^{-1}\,pc^2}}\right] = \alpha^{-1}\left[\log\left(\frac{L_{\mathrm{IR}}}{L_\odot}\right) - \beta\right] + \log r_J$$

- We cross-correlate TIME bands corresponding to a pair of adjacent CO lines emitted from the same redshift.
- Pick up only spatially-correlated signals, less subject to foregrounds
- Caution: continuum also correlated

H_2 census with CO cross-correlation



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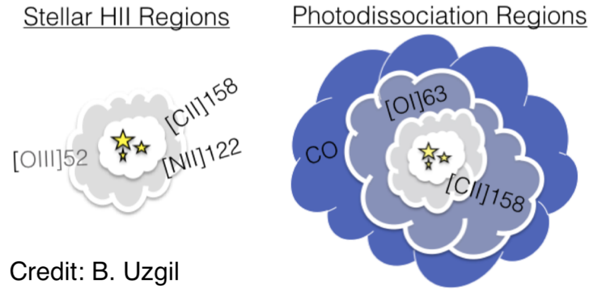
Multi-line IM: multi-phase ISM



- Lines $\rightarrow$ probes of different ISM phases

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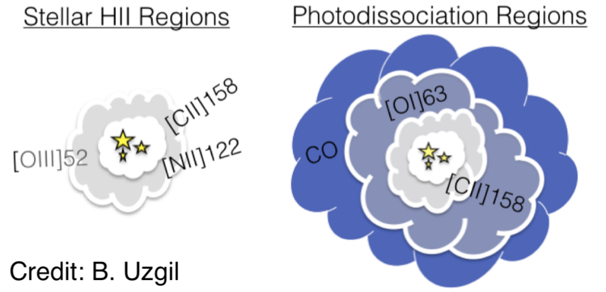
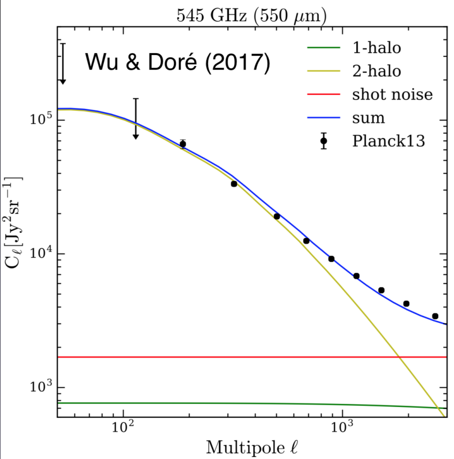


- Lines → probes of different ISM phases
- Rich physics to be learned:
  - Cosmic evolution of mean ISM physical conditions
  - Interplay among energetic sources, gas and dust
- Modeling: scaling relations (e.g., Serra+2016) v.s. sophisticated simulations (e.g., Popping+2019)
- **A model bridging this gap is desired!**

Baseline model: CIB

- Line signals closely associated with star formation
- Starlight heavily obscured by dust, reprocessed into IR
- IR sources unresolved, SF information encoded in CIB
- Apply halo model formalism to fit observed CIB anisotropy



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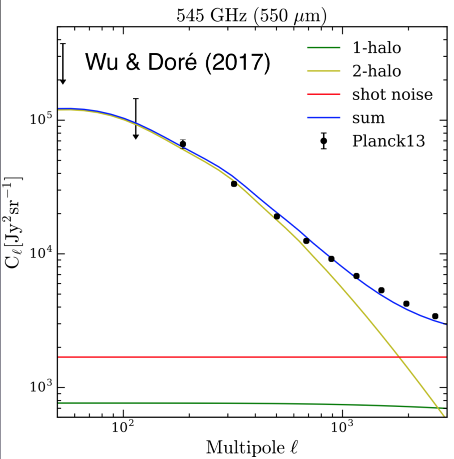
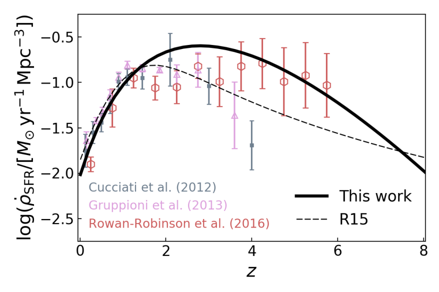
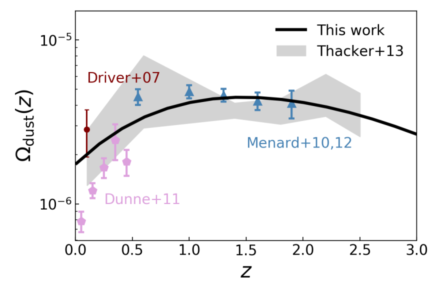
- Apply halo model formalism to fit observed CIB anisotropy



$$\mathbf{L}_{\mathrm{IR},(\mathbf{1}+\mathbf{z})\nu}\left(\mathbf{M},\mathbf{z}\right)=\mathbf{L}_{\mathrm{IR},\mathbf{0}}\mathbf{\Phi}\left(\mathbf{z}\right)\mathbf{\Sigma}\left(\mathbf{M}\right)\mathbf{\Theta}\left[\left(\mathbf{1}+\mathbf{z}\right)\nu\right]$$

Physical properties of DM halos



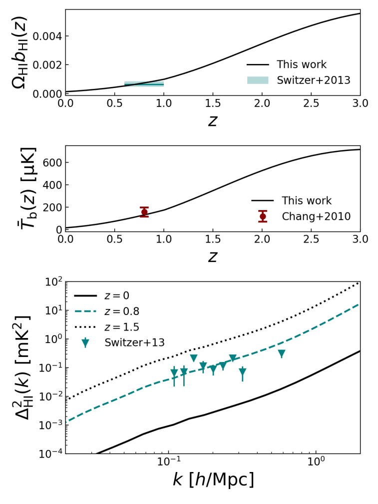


Sun et al. (2019)

- **Star formation rate**: $L_{\rm IR}$-SFR correlation
- $\rm M_{Dust}$ (not in CIB model): dust/gas ratio + dust emissivity
- $\rm M_{Hydrogen}$: matched with galaxy evolution models
- **Metallicity**: scaling as dust/gas ratio

Lines from different ISM phases

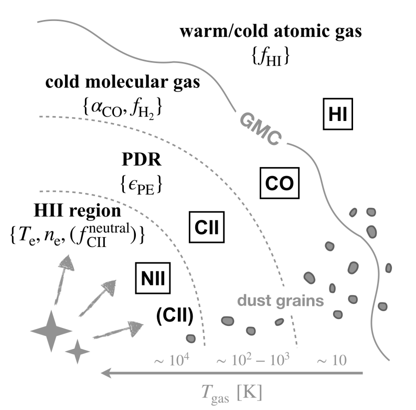
- **HI 21 cm**
  - HI mass



Sun et al. (2019)

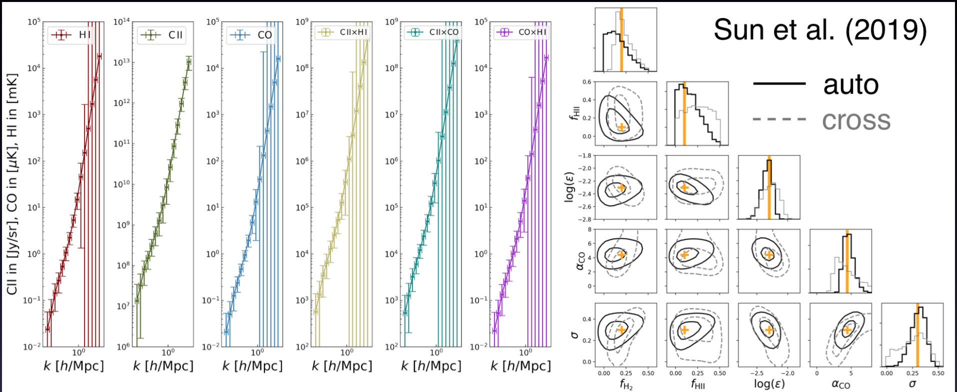
Lines from different ISM phases

- **HI 21 cm**
  - HI mass
- **[CII] 158 micron**
  - Photoelectric heating efficiency in photo-dissociation regions (PDRs)
  - H_2 fraction (indirectly)
- **CO(1-0) 115 GHz**
  - Conversion factor α_{CO} (n_{H_2}, T_{exc}) from luminosity to H_2 mass
- **[NII] 122 and 205 micron**
  - Density and temperature of HII region



Sun et al. (2019)

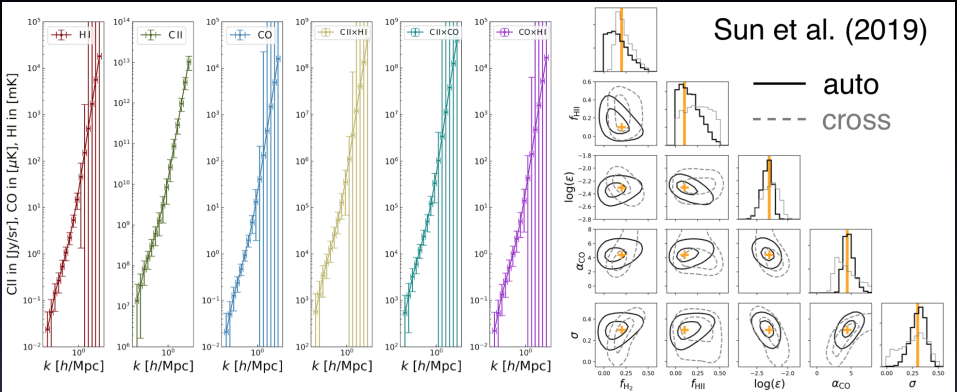
Dissecting ISM with multiple tracers



With HI 21 cm, [CII] and CO(1-0) lines...

- Constrain $\{f_{\mathrm{H_2}}, f_{\mathrm{HII}}, \epsilon_{\mathrm{PE}}, \alpha_{\mathrm{CO}}, \sigma\}$ with auto/cross PS
- Coherently study mean properties of multiple ISM phases

Dissecting ISM with multiple tracers



With HI 21 cm, [CII] and CO(1-0) lines...

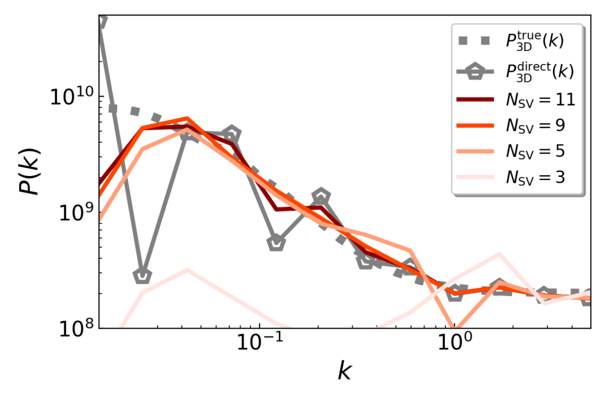
- Constrain $\{f_{\rm H_2}, f_{\rm HII}, \epsilon_{\rm PE}, \alpha_{\rm CO}, \sigma\}$ with auto/cross PS
- Coherently study mean properties of multiple ISM phases

Mapping "distributions" to "coarse-grained averages"!

Summary

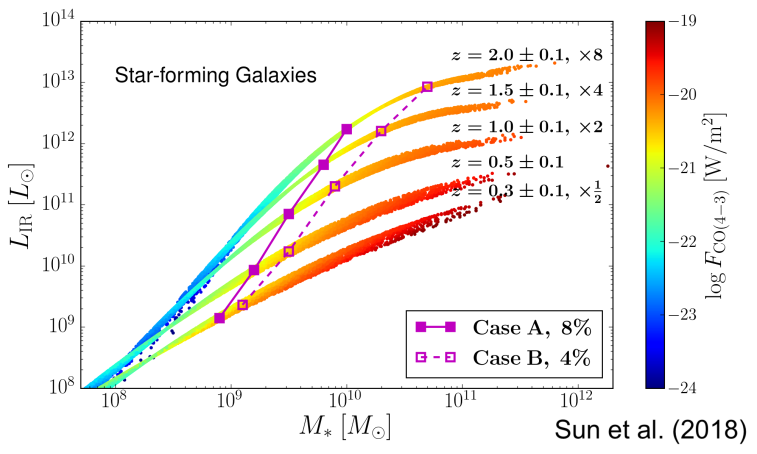
- Intensity mapping is a promising tool to study cosmological evolution of galaxies.
- TIME will shed light onto the EoR by constraining total star formation with [C II] power spectrum.
- CO foreground makes extracting EoR [C II] signal hard — needs cleaning techniques like masking, while providing a useful way to trace molecular gas growth.
- Multi-line intensity mapping can be utilized to study cosmic evolution of mean ISM conditions, though the interpretation can be challenging!

Survey inversion (non-parametric)



- $\mathcal{P}_{2D}\left(\vec{K}_i\right) \propto \int dk k^2 P_{3D}(k) W_{ii}\left(k, \vec{K}_i\right)$ *need de-convolution!*
- Stabilize inversion by truncated singular-value decomposition (tSVD) method (keep only statistically important modes).

Masking guided by CO proxy



- Trade-off between masking depth and survey volume
- Evolving stellar mass cut $\Longrightarrow$ constant CO flux