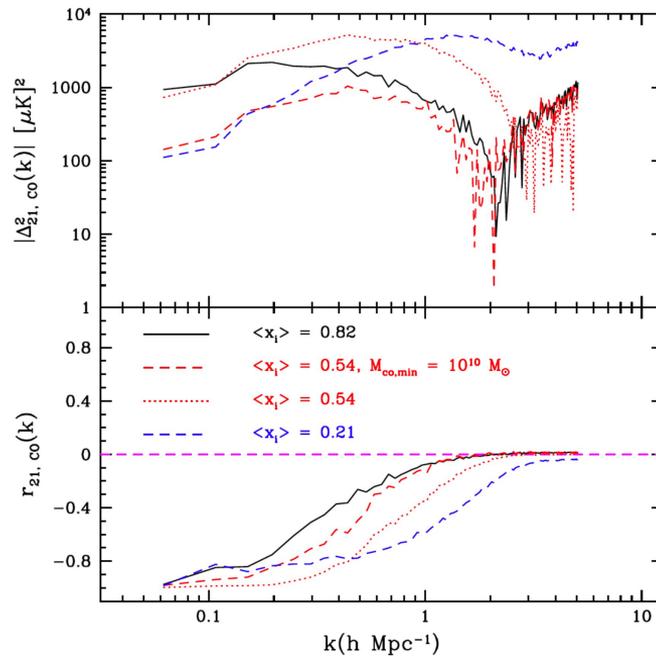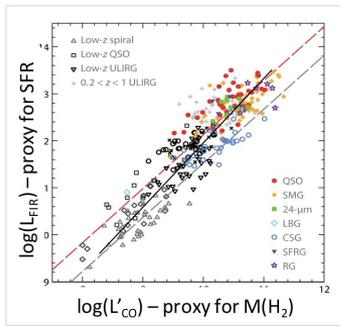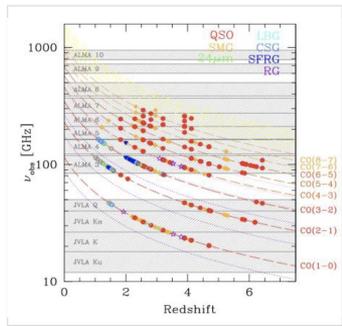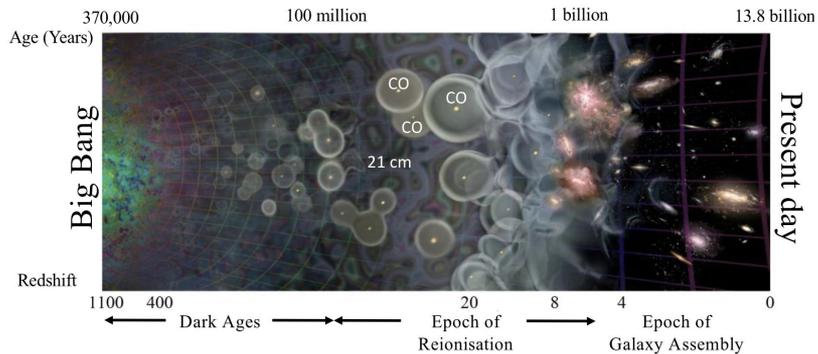# COMAP × LOFAR

Forecasting the Cross-Correlation between CO(2–1) and 21-cm Lines during Reionization

Jianrong Tan

Postdoc Researcher @ SMU

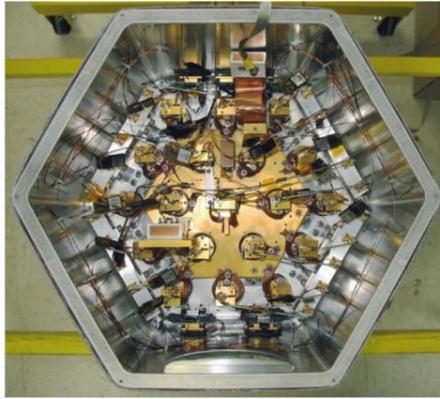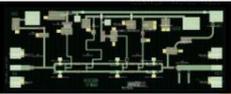# Why CO x 21-cm?

Credit: Kieran Cleary

Credit: Lidz et al. 2011

C O M A P Pathfinder

Pathfinder frequency coverage: 26-34 GHz

Sensitive to: CO(1-0) @ z = 2.4 – 3.4
CO(2-1) @ z = 6 - 8

Primary goal: Detect CO power spectrum at z ~ 3

C O M A P Timeline

2024-2028
COMAP-*wide*
Construction Begins

2019
Pathfinder Observing
Begins

2022-2025
Operations
& Survey Science

2026-2027
ngVLA Antenna
Available

2015-2019
Pathfinder
Construction &
Commissioning

Pathfinder survey

Season 1

Season 2

Season 3

2015   2019   2024   2026

C O M A P Timeline

COMAP S1 + S2 results out!

Credit: Chung et al. 2024

C O M A P Timeline

2019
Pathfinder Observing
Begins

2024-2028
COMAP-*wide*
Construction Begins

2022-2025
Operations
& Survey Science

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Construction &
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Pathfinder survey

Season 1

Season 2

Season 3

2015   2019   2024   2026

COMAP
Pathfinder

CO(3-2)

CO(2-1)

CO(1-0)

COMAP-*EoR*

Redshift

Frequency (GHz)

Credit: Breysse et al. 2022

Credit: Breysse et al. 2022

COMAP LOFAR Mode Overlap

LOFAR Ultra-Deep Observation (LUDO)

LOFAR Ultra-Deep Observation (LUDO)

- The field: Euclid Deep Field North (EDFN)
- 3,200 hours (400 x 8 hour observations) at 0.3" resolution
- Dithering pattern of 5 pointings to provide more even sensitivity across central 3.7 deg2
- Field of view will be larger for lower resolution imaging (but impacted by confusion noise)

LOFAR Ultra-Deep Observation (LUDO)

- The field: E
- 3,200 hours
- Dithering pa ... y across central 3.7 deg2
- Field of vie ... npacted by confusion noise)

Credit: Delaney Dunne

Forecasting Tools:

- **oLIMpus** An effective model for line intensity mapping auto- and cross- power spectra in cosmic dawn and reionization

  https://github.com/slibanore/oLIMpus Libanore, Muñoz and Kovetz, *oLIMpus: An Effective Model for Line Intensity Mapping Auto- and Cross- Power Spectra in Cosmic Dawn and Reionization*, arXiv:2507.15922

- **LIMstat** A end-to-end pipeline for the simulation and analysis of line intensity maps

  https://github.com/McGill-Cosmic-Dawn-Group/LIMstat

Sarah Libanore

Hannah Fronenberg

Zeus21
with Population II and III stars

correlations.py
- Effective Model for Cosmic Dawn 21cm
- Analytical 21cm Power Spectrum

reionization.py
- Bubble model and reionization (*)

COSMOLOGY
zeus21/cosmology.py
- Interfaced with CLASS
- Linear evolution of density perturbations
- EPS formalism for local Halo Mass Function

$$P_m(k, z), \frac{dn}{dM_h}(\delta_R)$$

STAR FORMATION RATE
zeus21/sfrd.py
- Computed from SFR-halo mass relation
- Default based on UV luminosity function
- Easy to customize

$$\dot{\rho}_*(\delta_R) = \int dM_h \frac{dn}{dM_h}(\delta_R)\dot{M}(M_h)$$

LIMpus
Effective LIM Spectra at Reionization

- ⬭ inherited from Zeus21
- ⬭ theory building blocks
- ⬭ outputs

SECOND ORDER LOGNORMAL APPROXIMATION

$$\exp\left[\gamma_R \delta_R(x) + \gamma_R^{NL}\delta_R^2(x)\right]$$

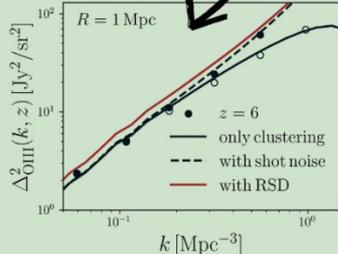## LINE LUMINOSITY
LIM_modeling.py ; LIM_luminosities.py
- Default models for OIII, OII, Ha, Hb, CII, CO
- Stochasticity
- Easy to customize

$$\rho_L(\delta_R) = \int dM_h \frac{dn}{dM_h}(\delta_R)L(\dot{M}_*)p(L(\dot{M}_*)|M_h)$$

AUTO- & CROSS-POWER SPECTRA
correlations_LIM.py
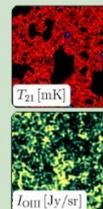
- LIM Power Spectra for Star Forming Lines
- Cross Power Spectrum with 21cm (*)
- Include shot noise
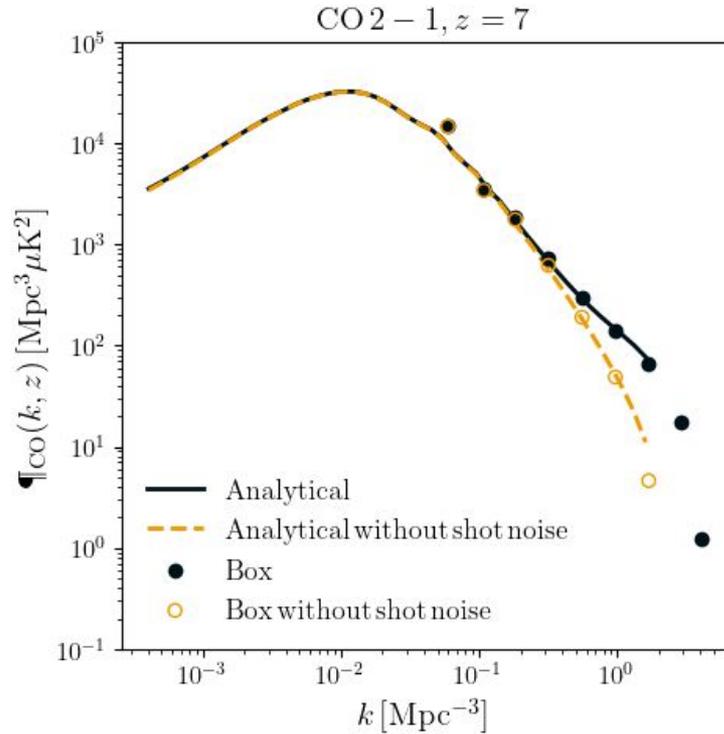- Include linear redshift space distortions

COEVAL BOXES & LIGHTCONES
zeus21/maps.py ; maps_LIM.py

- Star forming lines and 21cm (*)
- Option 1: Gaussian field from analytical Pk
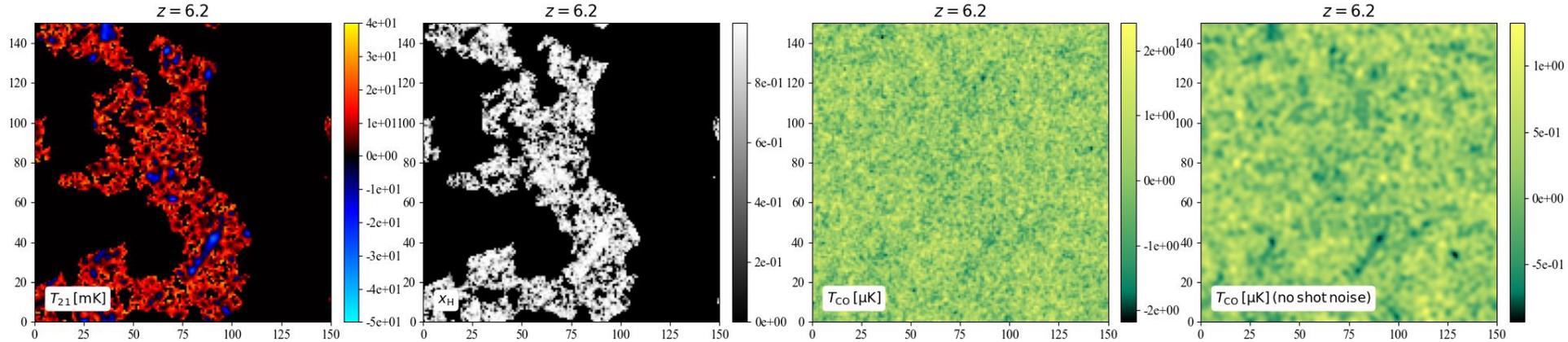- Option 2: Cell-by-Cell computation

Credit: Libanore et al. 2025

TACOS @ SHSU

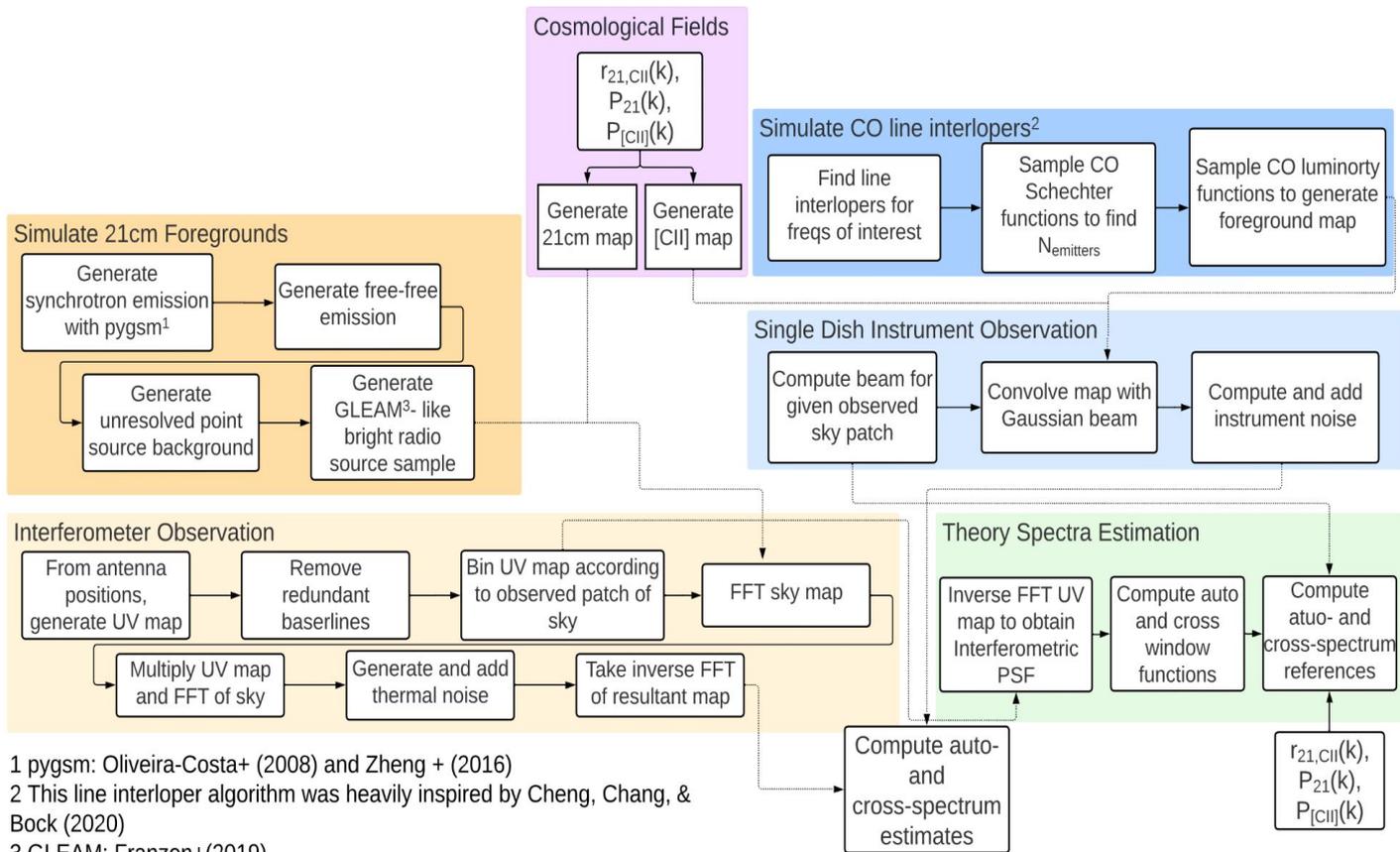# oLIMpus

CO 2 − 1, z = 7

In ~10 seconds

oLIMpus

In ~ 10 Minutes

LIMstat

1 pygsm: Oliveira-Costa+ (2008) and Zheng + (2016)
2 This line interloper algorithm was heavily inspired by Cheng, Chang, & Bock (2020)
3 GLEAM: Franzen+(2019)

Credit: Fronenberg et al. 2024

TACOS @ SHSU

Simulation

CO(2-1) ✗ 21-cm

Simulation

CO(2-1)

$\times$

21-cm

Preliminary Results

S/N ~ 0.2

FoV ~ 12 deg2
σ_rms ~ 600 uk

z = 7, Li16/Keating20 model

Preliminary Results

S/N ~ 4

t_obs ~ 1000 hr

Preliminary Results

S/N ~ 0.3

$\alpha_* = 0.50 \pm 0.88$
$\alpha_* = 0.50 \pm 0.87$

$\beta_* = -0.50 \pm 0.90$
$\beta_* = -0.50 \pm 0.90$

$\varepsilon_* = 0.10 \pm 0.71$
$\varepsilon_* = 0.10 \pm 0.39$

$f_{esc} = 0.10 \pm 0.75$
$f_{esc} = 0.10 \pm 0.45$

$\alpha_{esc} = 0.00 \pm 1.20$
$\alpha_{esc} = 0.00 \pm 1.20$

$L_{40} = 3.00 \pm 2.00$
$L_{40} = 3.00 \pm 2.00$

$E_0 = 500.00 \pm 1200.00$
$E_0 = 500.00 \pm 1200.00$

$\alpha_X = -1.00 \pm 3.20$
$\alpha_X = -1.00 \pm 3.20$

21cm auto only

21cm auto + CO(2-1) auto + Cross

TACOS @ SHSU

Thank you!

Backup Slides

Our final CO model, from Yang et al. (2021a), provides fitting functions optimized for intensity mapping based on semianalytic models (SAMs) from Yang et al. (2021b). Unlike most of the above models, which rely heavily on empirical scalings, it attempts to self-consistently model the underlying physics that gives rise to CO emission. The SAMs are calibrated to a wide variety of galaxy observations, including lower-redshift CO lines. By providing fitting funct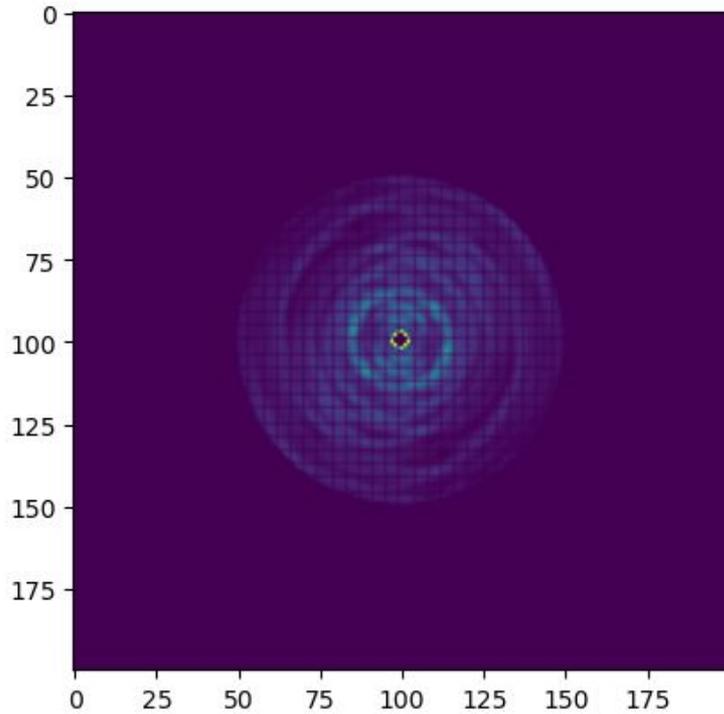ions, this model enables easy application of the SAM results to intensity mapping forecasts like our work here. Mass-luminosity functions here take the form

$$\frac{L}{L_\odot} = 2N \frac{M}{M_\odot} \left[\left(\frac{M}{M_1} \right)^{-\alpha} + \left(\frac{M}{M_1} \right)^{\beta} \right]^{-1} . \qquad (35)$$

The double-power-law shape of Eq. (35) is common to many data-driven treatments of star formation tracers (see, e.g. Moster et al. 2010; Padmanabhan 2018). Values of N, M_1, α, and β are provided for both CO lines, as well as separate fitting functions for σ_{sc} and f_{duty}. We assume $M_{min} = 10^{10} \; M_\odot$, which here is set by the resolution limits of the semianalytic simulations.

Backup Slides

Backup Slides

$$\dot{M}_* = f_* f_b \dot{M}_h, \tag{10}$$

where $f_b = \Omega_b/\Omega_m$ is the baryon fraction (which we take to be mass independent) and the mass accretion rate $\dot{M}_h$ is found from the extended Press-Schechter formalism fitted in Neistein & van den Bosch (2006) (we also include an exponential model, where $M_h(z) \propto e^{\alpha z}$ with $\alpha = 0.5$ Schneider et al. 2021 as an alternative). In both cases we assume a functional form for the efficiency

$$f_*(M_h) = \frac{2\,\epsilon_*}{(M_h/M_{\mathrm{pivot}})^{-\alpha_*} + (M_h/M_{\mathrm{pivot}})^{-\beta_*}} f_{\mathrm{duty}}, \tag{11}$$

where

$$f_{\mathrm{duty}} = \exp(-M_{\mathrm{turn}}/M_h) \tag{12}$$