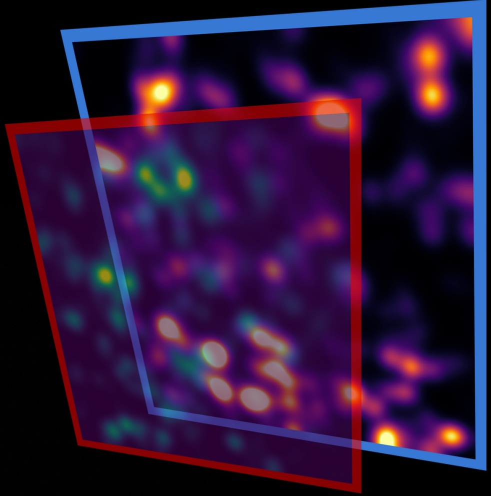
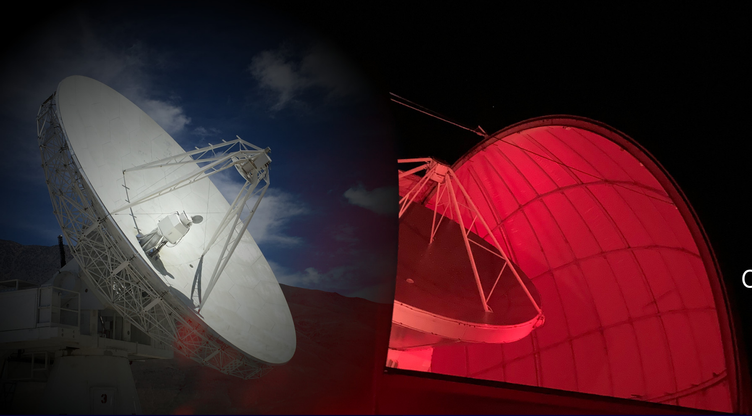
([C II]) single-dish line-intensity mapping

—observational and theoretical outlook at the epoch of reionisation





Dongwoo Chung

CITA/Dunlap Institute, University of Toronto

2023/02/07

the name of the game: map large cosmic volumes

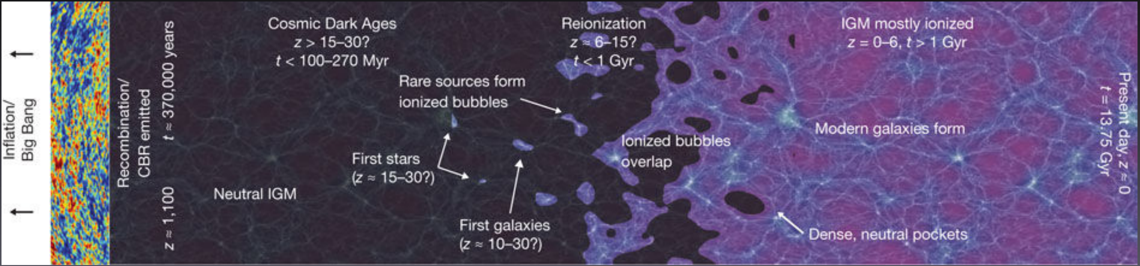


Figure: Robertson+10 (arXiv:1011.0727)

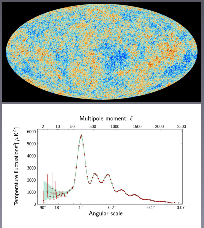


Figure: Planck (IPAC website gallery)

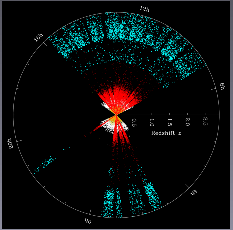
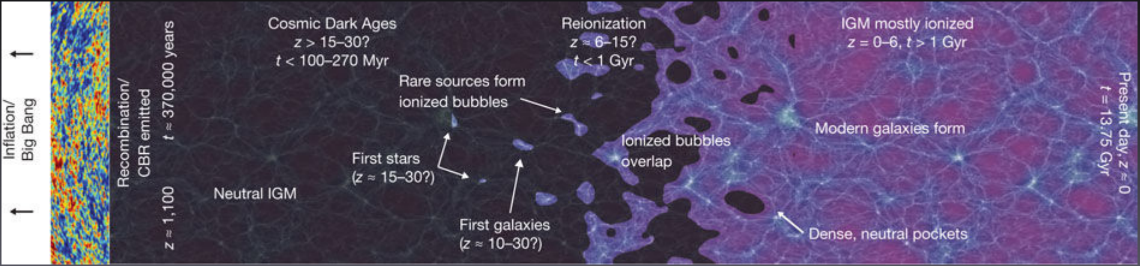


Figure: Blanton via SDSS blog

the name of the game: map large cosmic volumes *at high redshift*



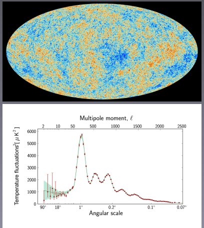


Figure: Planck (IPAC website gallery)

?

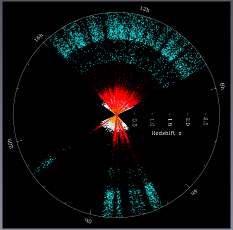
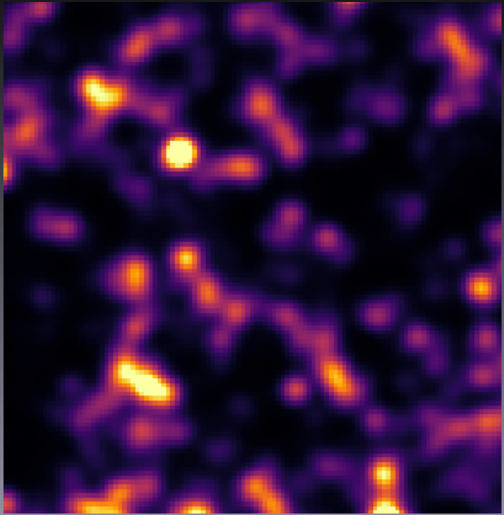


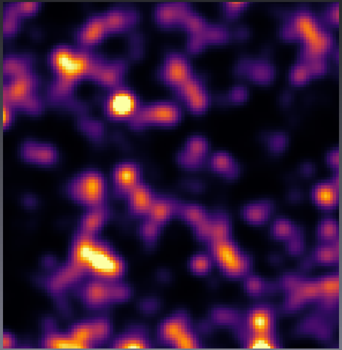
Figure: Blanton via SDSS blog

line-intensity mapping: spatial-spectral fields, not individual sources



$I(\mathbf{x})$ [or $T(\mathbf{x})$], not $\mathbf{x}_i$

line-intensity mapping: spatial-spectral fields, not individual sources



$I(\mathbf{x})$

$\Longrightarrow$

summary statistics

- $P(k)$ (and anisotropic moments)
- voxel intensity distribution
- cross-correlations with other observables

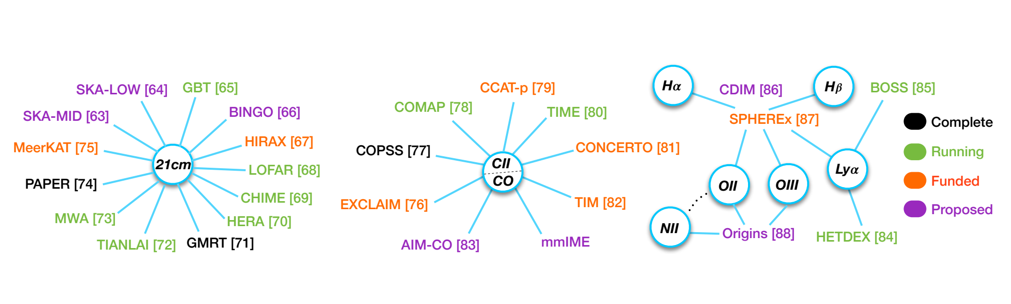
incorporate clustering of faint sources

$\Longrightarrow$

astrophysics/cosmology

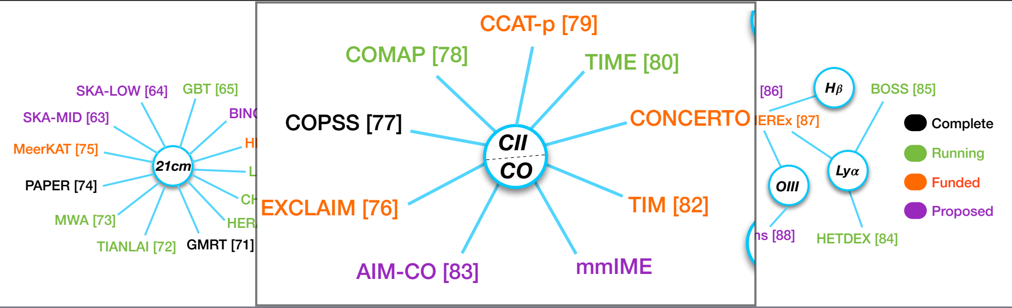
- luminosity functions
- cosmic densities of star-formation rate, molecular gas, ...
- **the nature of the high-z cosmic web** and the processes that flow through and illuminate it

the current LIM experimental landscape



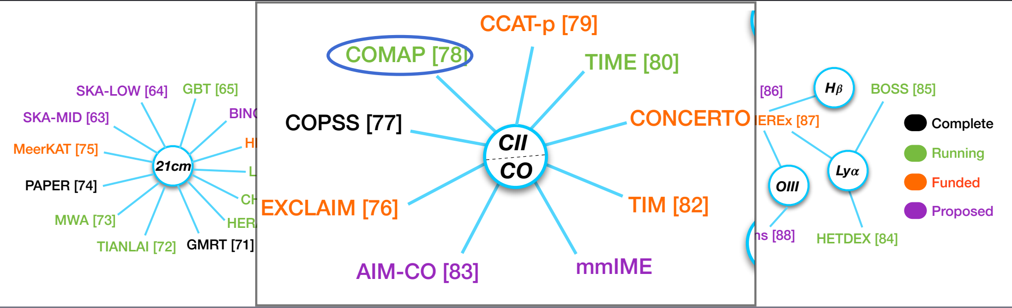
Kovetz+19 [1903.04496]

the current LIM experimental landscape



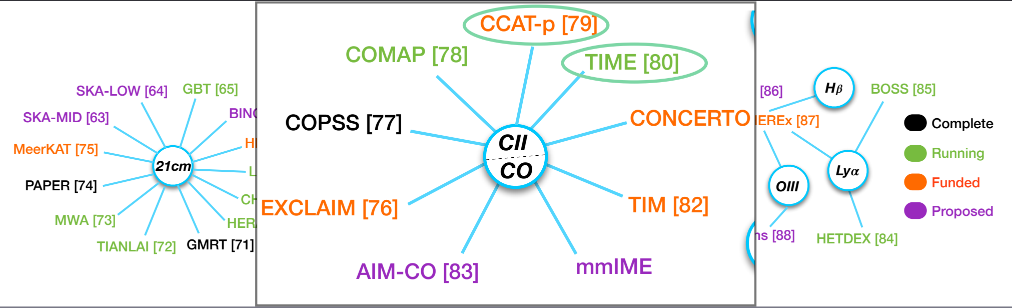
Kovetz+19 [1903.04496]

the current LIM experimental landscape



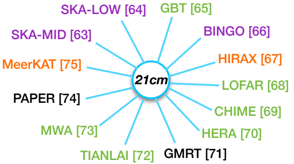
Kovetz+19 [1903.04496]

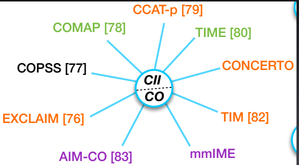
the current LIM experimental landscape

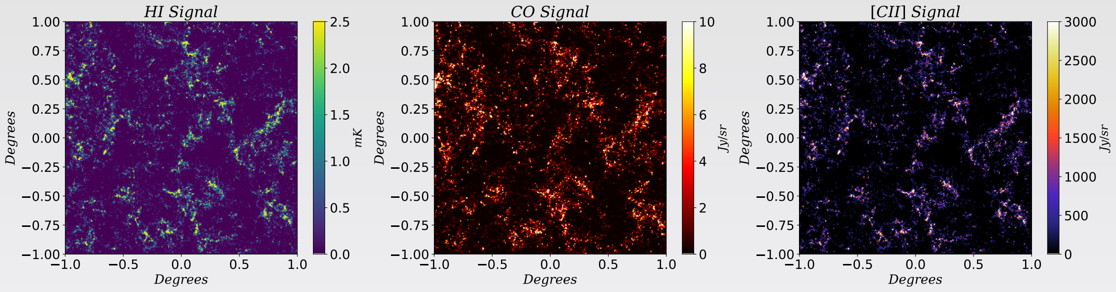


Kovetz+19 [1903.04496]

LIM will probe the same cosmic web with different lines

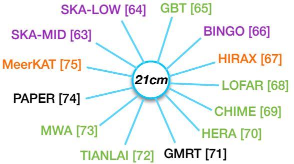


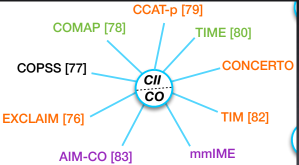


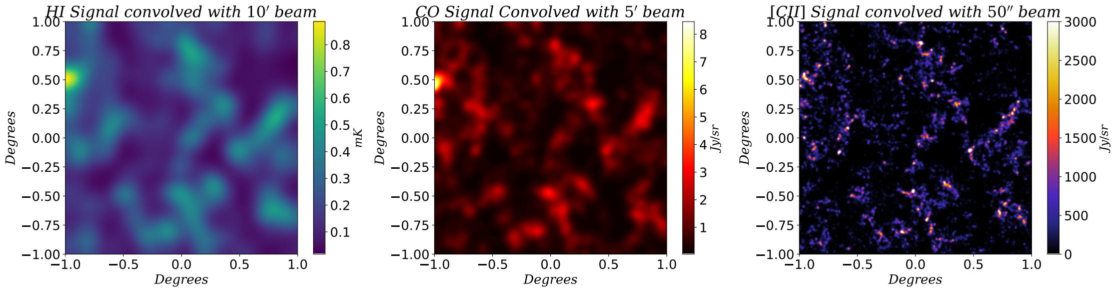


Simulations: courtesy Patrick Horlaville

LIM will probe the same cosmic web with different lines







Simulations: courtesy Patrick Horlaville

the future will see cosmological LIM experiments!

Cosmology with mm-wave line intensity mapping

Spec-hrs	Example	Time-scale	$\sigma(f_{\mathrm{NL}})$	$\sigma(M_\nu)$ (meV)	$\sigma(N_{\mathrm{eff}})$	$\sigma(w_0) \times 10^2$	$\sigma(w_{\mathrm{a}}) \times 10^2$	FoM
10^5	TIME, CCAT-p, SPT-SLIM	2022	5.1 (5.1)	61 (65)	0.1 (0.11)	13 (14)	51 (52)	0.0015
10^6	TIME-EXT	2025	4.7 (5)	43 (47)	0.082 (0.087)	5.3 (6.3)	21 (26)	(0.09-0.1)
10^7	SPT-like 1 tube	2028	3.1 (4.2)	23 (28)	0.043 (0.051)	2 (2.2)	8.5 (9.7)	(1.7-3.1)
10^8	SPT-like 7 tubes	2031	1.2 (3)	9.7 (13)	0.02 (0.023)	0.93 (1)	3.8 (4.3)	(9.5-28)
10^9	CMB-S4-like 85 tubes	2037	0.48 (2.4)	4.1 (6.8)	0.013 (0.016)	0.61 (0.73)	2.1 (2.8)	(21-108)
Planck			5.1	83	0.187	41	100	—

Table: from Karkare+22 whitepaper [arXiv:2203.07258]

the future will see cosmological LIM experiments!

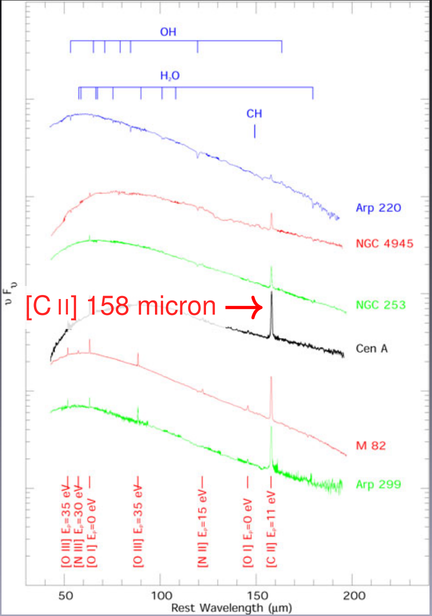
Cosmology with mm-wave line intensity mapping

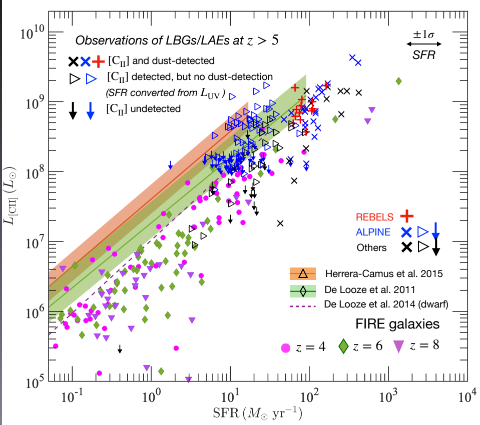
Spec-hrs	Example	Time-scale	$\sigma(f_{\rm NL})$	$\sigma(M_\nu)$ (meV)	$\sigma(N_{\rm eff})$	$\sigma(w_0)\times 10^2$	$\sigma(w_a)\times 10^2$	FoM
10^5	TIME, CCAT-p, SPT-SLIM	2022	5.1 (5.1)	61 [illegible]	[illegible]	[illegible]	[illegible]	0.0015
10^6	TIME-EXT	2025	4.7 (5)	43 (47)	0.082 (0.087)	5.3 (6.3)	21 (26)	(0.09-0.1)
10^7	SPT-like 1 tube	2028	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10^8	SPT-like 7 tubes	2031	1.2 (3)	9.7 (13)	0.02 (0.023)	0.93 (1)	3.8 (4.3)	(9.5-28)
10^9	CMB-S4-like 85 tubes	2037	0.48 (2.4)	4.1 (6.8)	[illegible]	[illegible]	2.1 (2.8)	(21-108)
Planck			5.1	83	0.187	41	100	—

pathfinders targeting initial detections
↓
intermediate stages characterising line-intensity clustering
↓
cosmological LIM

Table: from Karkare+22 whitepaper [arXiv:2203.07258]

the target for mm-wave LIM: [C II], a bright FIR cooling line

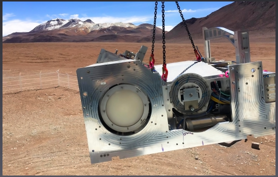




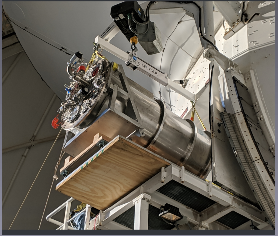
Figures: (Left) Fischer00 (arXiv:astro-ph/0009395), (Right) Liang+23 (incl DTC, arXiv:2301.04149)

first steps to cosmological LIM: pathfinders eyeing an initial detection

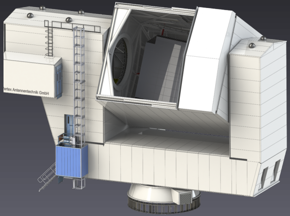
CONCERTO (2021–)

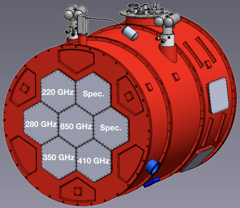


TIME (2023–)



EoR-Spec on FYST (2024?–)





see also: SPT-SLIM, balloon-based experiments at higher frequencies (EXCLAIM, TIM)

the Tomographic Ionised-carbon Mapping Experiment

Cornell University

Abby Crites [PI]
Sophia Pereira
Sukhman Singh
Ibrahim Shehzad

Caltech JPL

Jamie Bock
Matt Bradford
Tzu-Ching Chang
Yun-Ting Cheng
Clifford Frez
Jonathon Hunacek
Paolo Madonia
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Asantha Cooray

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Lisa Nasu-Yu

supported in part by:

NSF [AST 1910598]

Keck Institute for Space Studies

- conservative(-ish) instrumentation to ease development and analysis
- initial survey targeting 1.3 deg $\times$ 0.43 arcmin (180 $\times$ 1 beams) over 1000 hours
- engineering runs at ARO in winter 2019–20 and 2021–22
- expect full science operations to begin 2023

the Tomographic Ionised-carbon Mapping Experiment

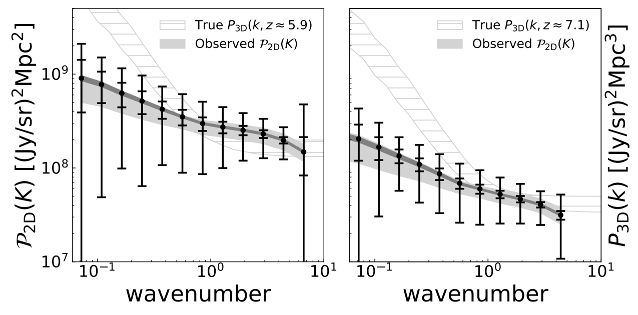
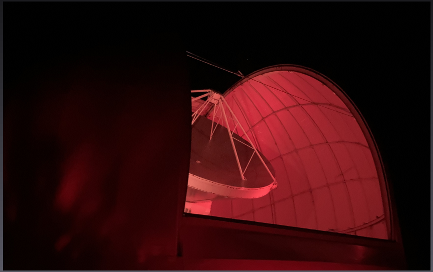


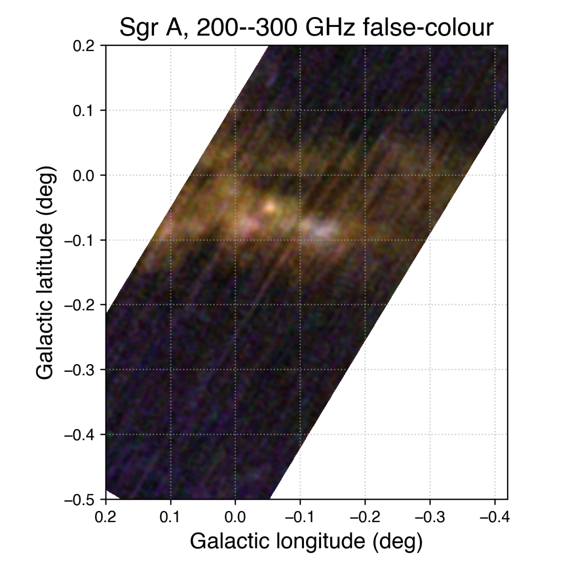
Figure: Sun+21 (arXiv:2012.09160)

- conservative(-ish) instrumentation to ease development and analysis
- initial survey targeting 1.3 deg $\times$ 0.43 arcmin (180 $\times$ 1 beams) over 1000 hours
- engineering runs at ARO in winter 2019–20 and 2021–22
- expect full science operations to begin 2023

from 2022 engineering run w/ partially integrated instrument

we show working spectral imaging using Galactic CO emission





from 2022 engineering run w/ partially integrated instrument

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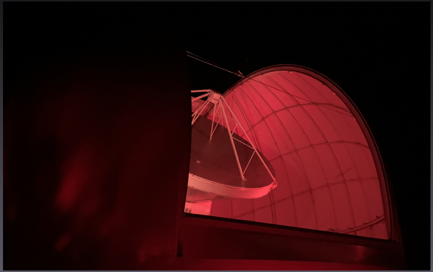
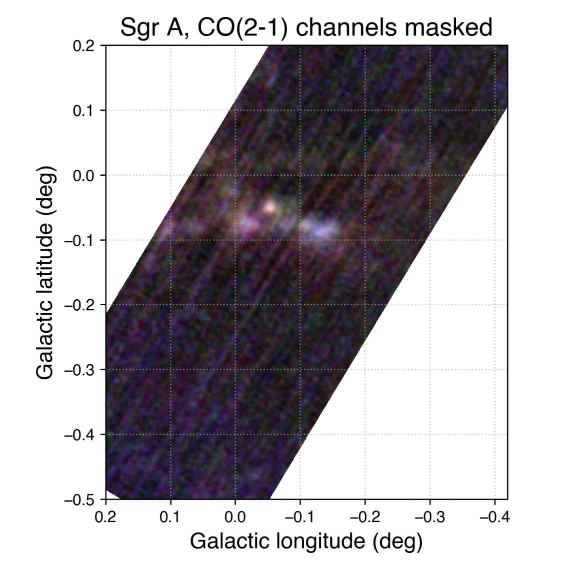




the Epoch of Reionisation Spectrometer (EoR-Spec) on FYST

part of the CCAT-prime facility

- the CCAT-prime observatory
  - a partnership between American and German institutions
  - Cornell, CATC (led by Waterloo), Köln, Bonn, MPIA, University of Chile, ...
- the Fred Young Submillimetre Telescope (FYST like 'feast')
  - site on Cerro Chajnantor at 5600 m elevation (40 m below summit/TAO, 540 m above ALMA/APEX)
  - extremely stable, low-emissivity, large-FoV system optimised for fast mapping speed across broad frequency range
- [C II] LIM at EoR is one of the key science programmes of CCATp

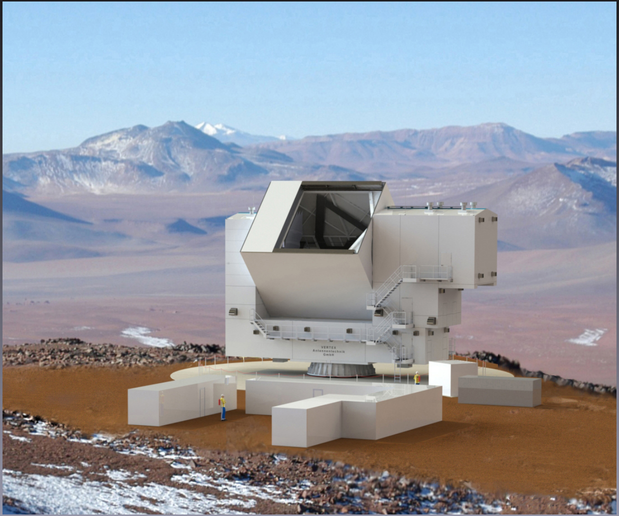


Figure: courtesy Vertex/CCATp

the Deep Spectroscopic Survey on FYST
will bring OoM improvements in sensitivity over current surveys (incl. TIME)

- 4000-hour programme in total
- two 4 deg^2 fields (E-COSMOS, E-CDFS)
- less conservative instrumentation allows for large detector counts over wider observing band
- *high site and low emissivity aid the first steps down the path to wide-field/cosmological LIM*

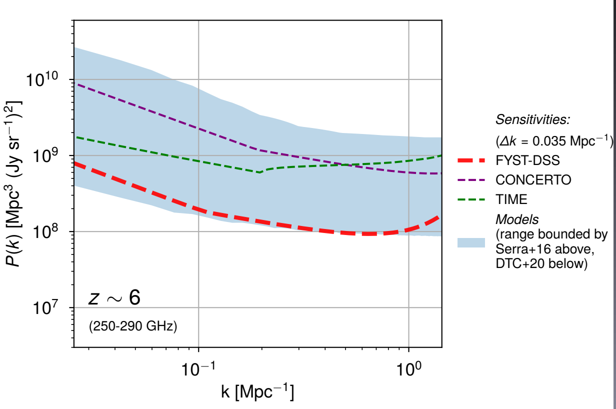
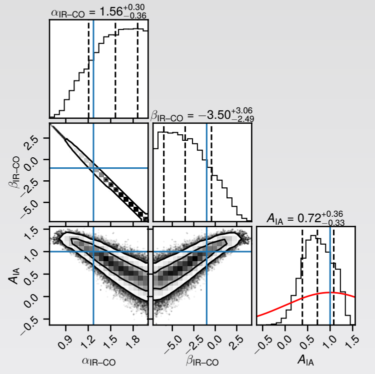
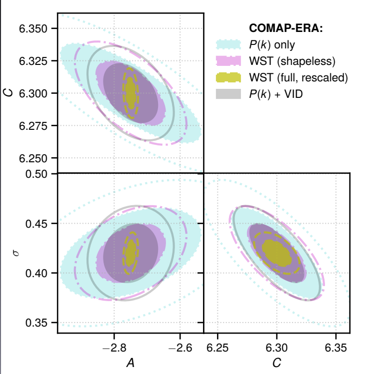


Figure: adapted from CCATp Collaboration+21 (arXiv:2107.10364)

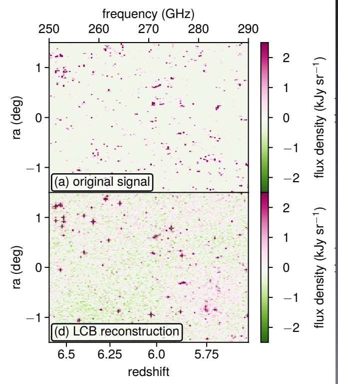
my work tries to anticipate and implement LIM analyses



arXiv:2203.12581: cross-correlating LIM and WL data to measure correlated nuisances (incl. IA)

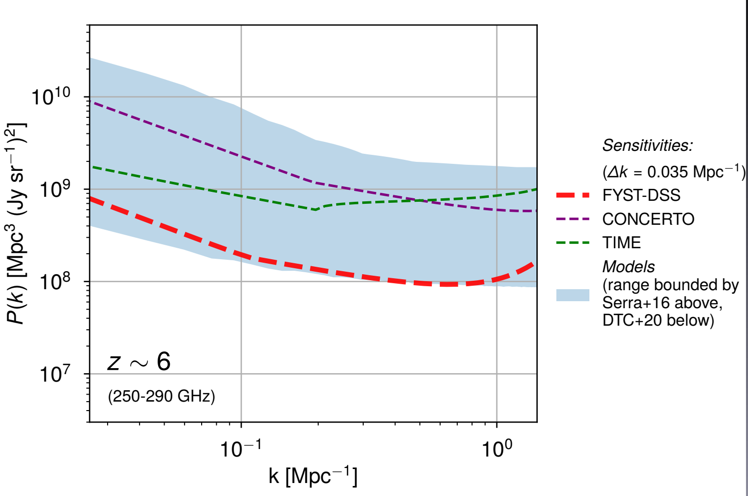


arXiv:2207.06383: exploration of wavelet scattering transform applications to LIM



arXiv:2209.07500: using covariance-based filtering to improve linear-scale LIM reconstruction

... which demands a framework for anticipating the signal



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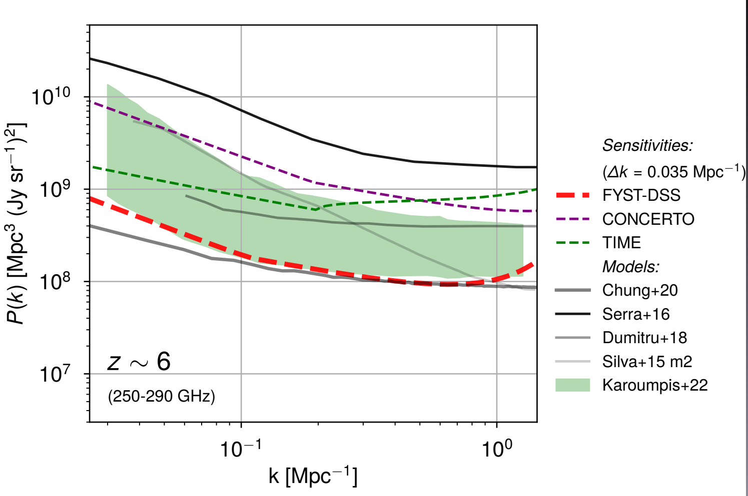

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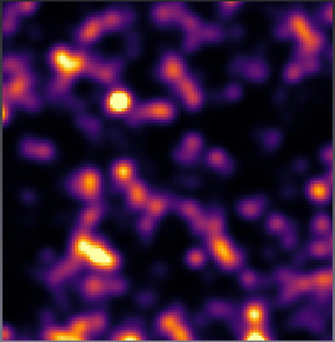
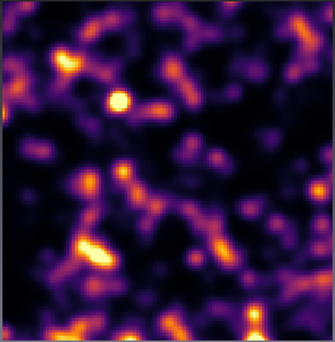
the galaxy–halo connection drives LIM design and analysis



$I(\mathbf{x})$

$$\underbrace{\delta_I}_{\text{line-intensity fluctuations}} = \overbrace{\langle Ib \rangle}^{\substack{\textit{bias} \\ \text{(scaled by line intensity)}}} \underbrace{\delta_m}_{\text{matter fluctuations}}$$

the galaxy–halo connection drives LIM design and analysis



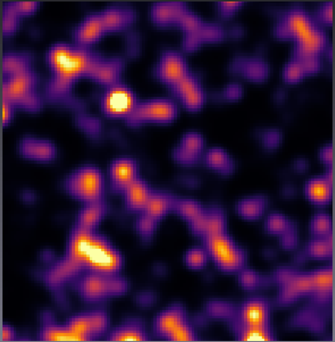
$I(\mathbf{x})$

bias
(scaled by line intensity)

$$\underbrace{\delta_I}_{\text{line-intensity fluctuations}} = \overbrace{\langle Ib\rangle}^{\text{bias}}\ \underbrace{\delta_m}_{\text{matter fluctuations}}$$

$$\overbrace{P_{\text{line}}(k)}^{\text{line-intensity power spectrum}} = \underbrace{\langle Ib\rangle^2\,\overbrace{P_m(k)}^{\text{matter power spectrum}}}_{\text{clustering}} + \underbrace{P_{\text{shot}}}_{\text{shot noise}}$$

the galaxy–halo connection drives LIM design and analysis



$I(\mathbf{x})$

$$\underbrace{\delta_I}_{\text{line-intensity fluctuations}} = \overbrace{\langle Ib\rangle}^{\substack{\textit{bias}\\ \text{(scaled by line intensity)}}} \underbrace{\delta_m}_{\text{matter fluctuations}}$$

$$\langle Ib\rangle \propto \int dM_h\, \overbrace{\frac{dn}{dM_h}}^{\text{halo mass function}}\, \underbrace{L(M_h)}_{\text{the galaxy–halo connection}}\, \overbrace{b(M_h)}^{\text{halo bias}}$$

[C II]–SFR: empirically observed, tenuous physical connection

Photo: Lichen Liang (CITA)

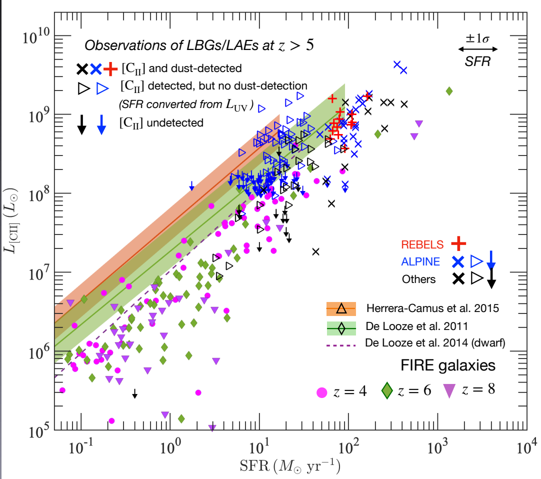


Figure: Liang+23 (incl DTC, arXiv:2301.04149)

[C II]–SFR: empirically observed, tenuous physical connection

Photo: Lichen Liang (CITA)

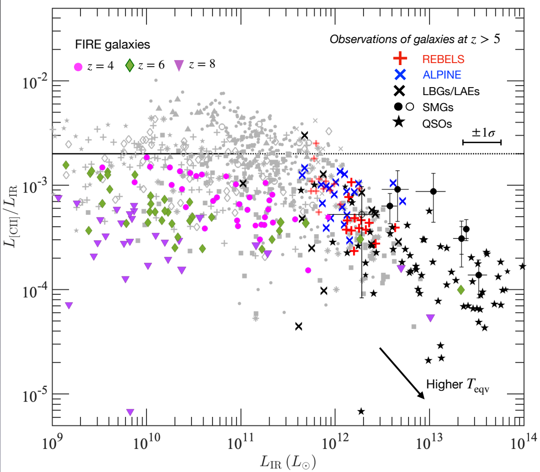


Figure: Liang+23 (incl DTC, arXiv:2301.04149)

[C II]–gas mass: physically motivated; known modulating factors

Photo: Lichen Liang (CITA)

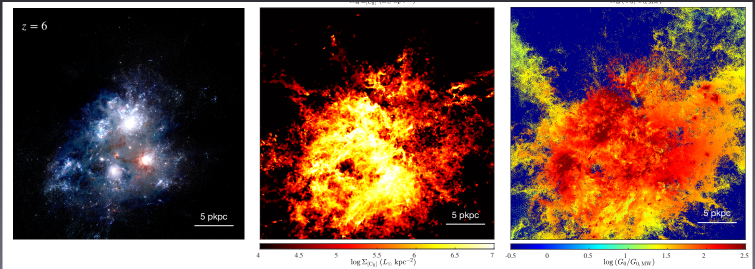


Figure: Liang+23 (incl DTC, arXiv:2301.04149)

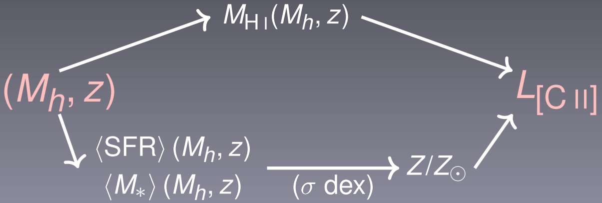
[C II]–gas mass: physically motivated; known modulating factors

Photo: Patrick Horlaville (McGill), Lichen Liang (CITA)

- physical insight grounded on FIRE simulations and observational data:

$$L_{[\mathrm{C\,II}]} \propto f_{[\mathrm{C\,II}]} M_{\mathrm{gas}} Z_{\mathrm{gas}} \sim M_{\mathrm{H\,I}} Z_{\mathrm{gas}}$$

- corresponding halo model:



[C II]–gas mass: physically motivated; known modulating factors

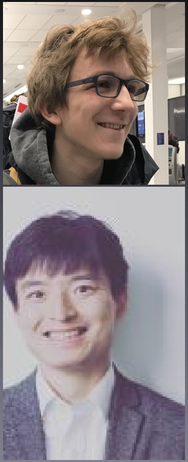


Photo: Patrick Horlaville (McGill), Lichen Liang (CITA)

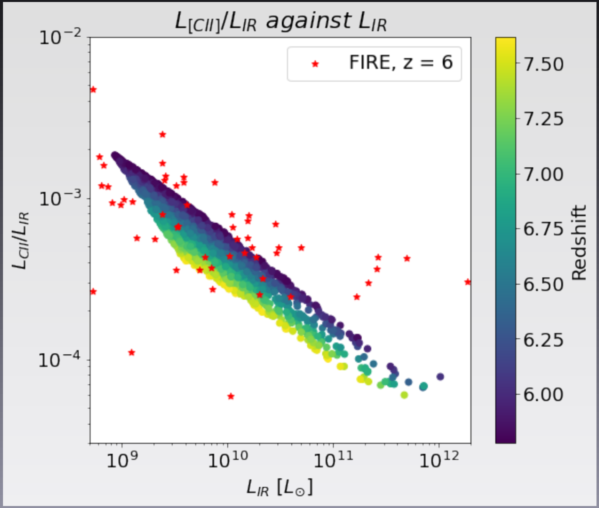


Figure: Horlaville+23 in prep (preliminary!)

[C II]–gas mass: physically motivated; known modulating factors

Photo: Patrick Horlaville (McGill), Lichen Liang (CITA)

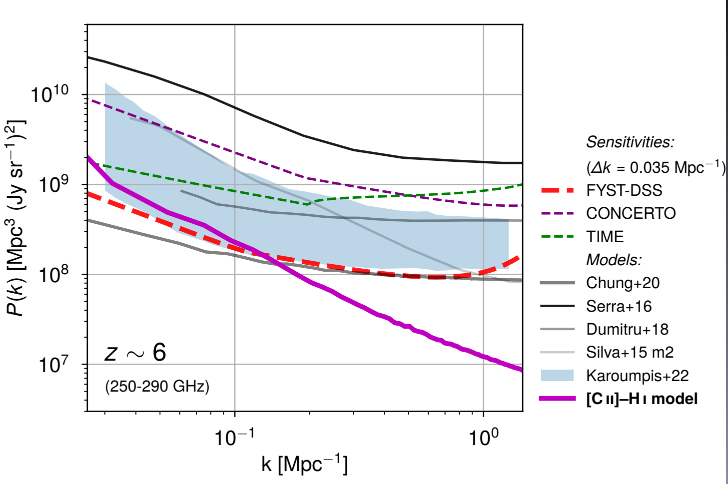


Figure: (preliminary!)

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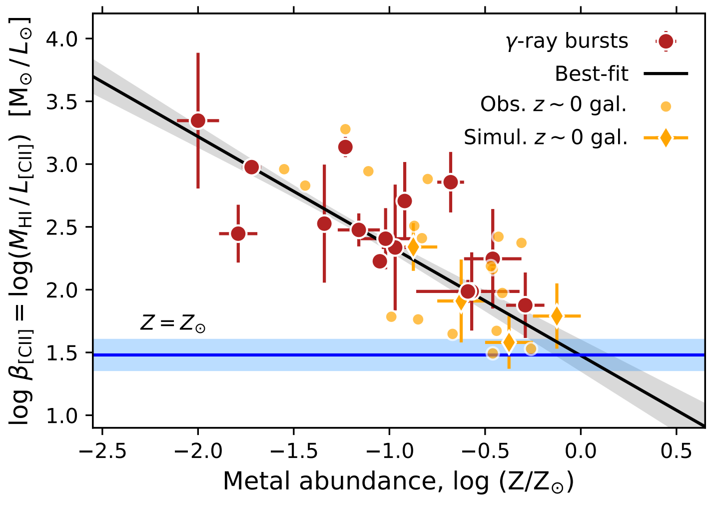

Figure: Heintz+21 (arXiv:2108.13442)

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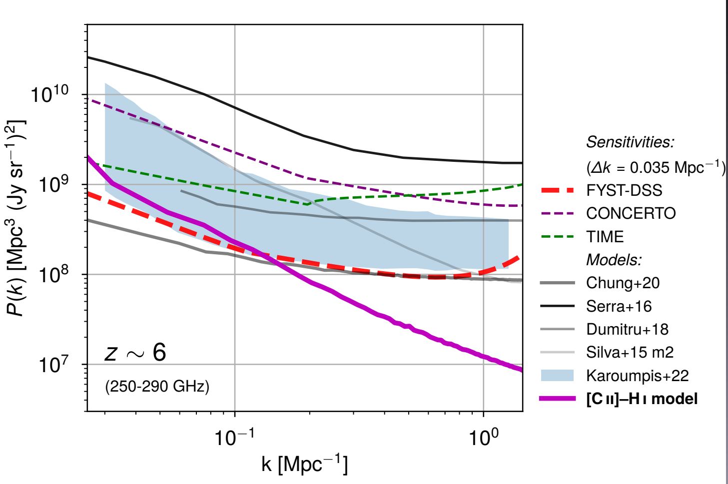

Figure: (preliminary!)

in summary

- line-intensity mapping will observe the multiscale cosmic web, surveying large-scale structure lit up by small-scale baryonic physics
- experimental progress in mm-wave LIM is picking up
  - TIME commissioning data cause for optimism for 2023 science start date
  - FYST construction proceeding, EoR-Spec survey and instrument development continuing
- getting the galaxy–halo connection right (as much as possible) is key to the theoretical outlook of [C II] LIM and requires interaction across astrophysicists working at all scales
  - pairing small-scale simulations with observational data and physical insights can inform halo models for even approximate cosmological simulations
  - cross-correlation between LIM and other LSS/Cosmic Web probes could be vital for producing interpretable scientific output

the galaxy–halo connection

is only truly fully probed through multiple tracers

$$\overbrace{\delta_{T,1}}^{\text{line-intensity fluctuations}} = \langle Tb\rangle_1 \underbrace{\delta_m}_{\text{matter fluctuations}} \qquad \overbrace{\delta_{T,2}}^{\text{different line-intensity fluctuations}} = \langle Tb\rangle_2 \underbrace{\delta_m}_{\text{same matter fluctuations}} \qquad \overbrace{\delta_{n,\text{gal}}}^{\text{galaxy density fluctuations}} = b_\text{gal} \underbrace{\delta_m}_{\text{still the same matter fluctuations}}$$

$$P_{1\times 2}(k) \simeq \underbrace{\langle Tb\rangle_1 \langle Tb\rangle_2 \overbrace{P_m(k)}^{\text{matter power spectrum}} + P_{\text{shot},1\times 2}}_{\text{signals can de- or anti-correlate depending on physics at different scales and epochs}}$$

$$P_{1\times\text{gal}}(k) \simeq \langle Tb\rangle_1\, b_\text{gal} P_m(k) + \underbrace{P_{\text{shot},1\times\text{gal}}}_{\text{line–galaxy shot noise relates to average line luminosity per galaxy}}$$

linear covariance-based filtering

can use cross-correlations to look right through interloper emission

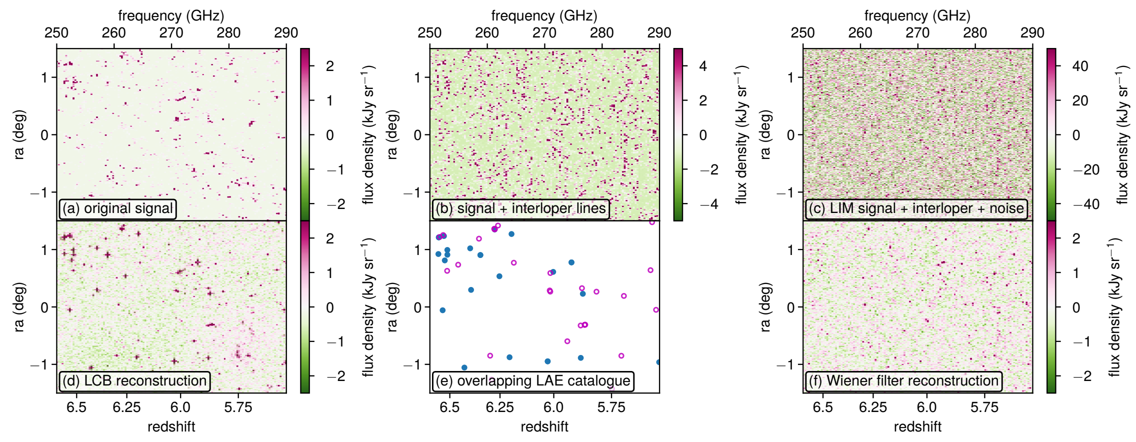

Figure: DTC23 (arXiv:2209.07500)

the future of cm/mm-wave LIM

reasons for optimism?

- generalising CMB expertise and heritage towards spectroscopy
  - the work of developing ways to build and read out large focal planes has been done
  - continuum foregrounds have been mapped to death at these wavelengths
  - direct involvement and overlap between LIM and CMB
    - Oslo CMB+CO group on COMAP and (post-)Planck
    - CCAT-prime cooperation with Simons Observatory
- one arm of many reaching towards EoR
  - cross-correlations or joint analyses with 21 cm, JWST, ALMA, Roman, etc all possible