Synergizing sub-mm and 21 cm surveys

— new empirical insights —

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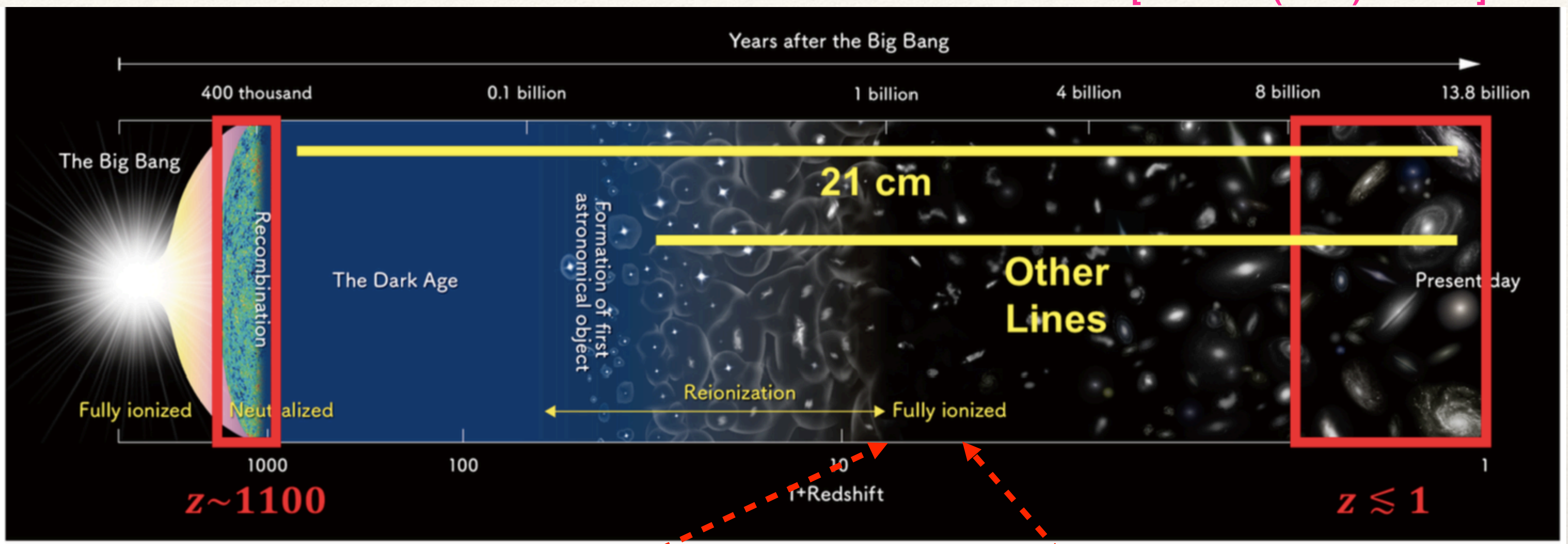
Based on :
Hamsa Padmanabhan, *Synergizing 21 cm and sub-millimetre surveys during reionization: new empirical insights, under review,* https://arxiv.org/abs/2212.08077

UNIVERSITÉ DE GENÈVE

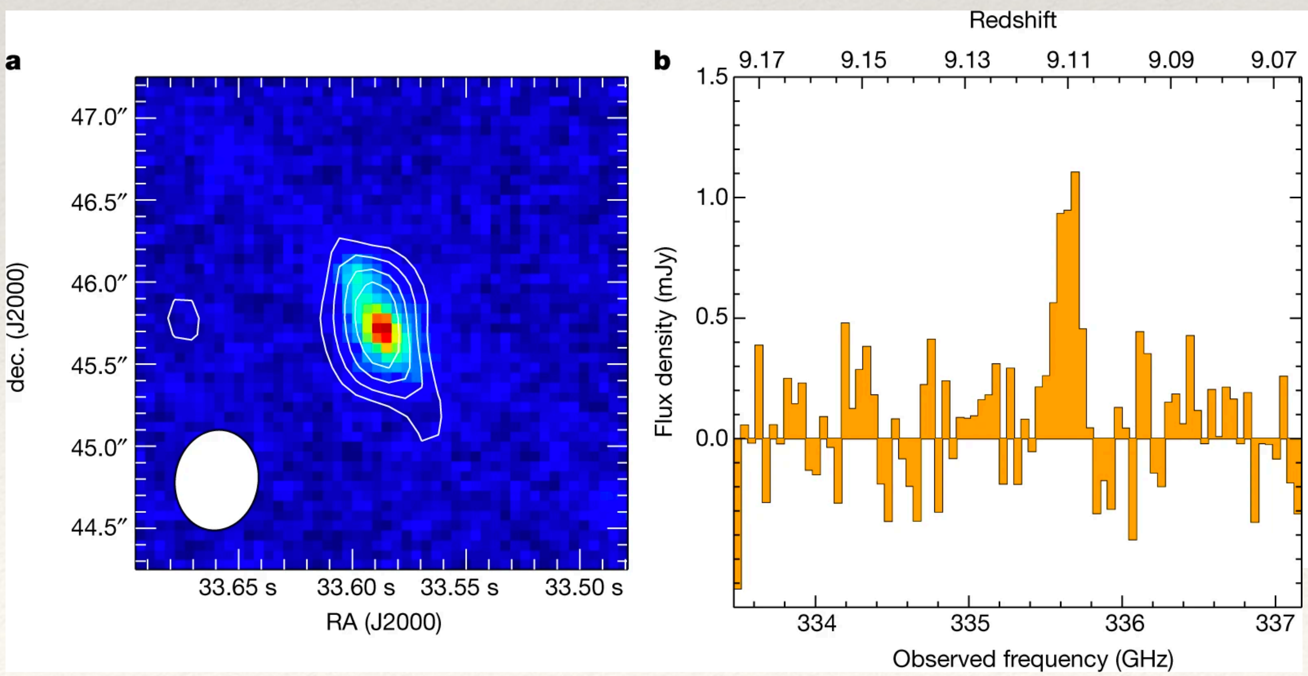
Swiss National Science Foundation

The sub-millimetre regime

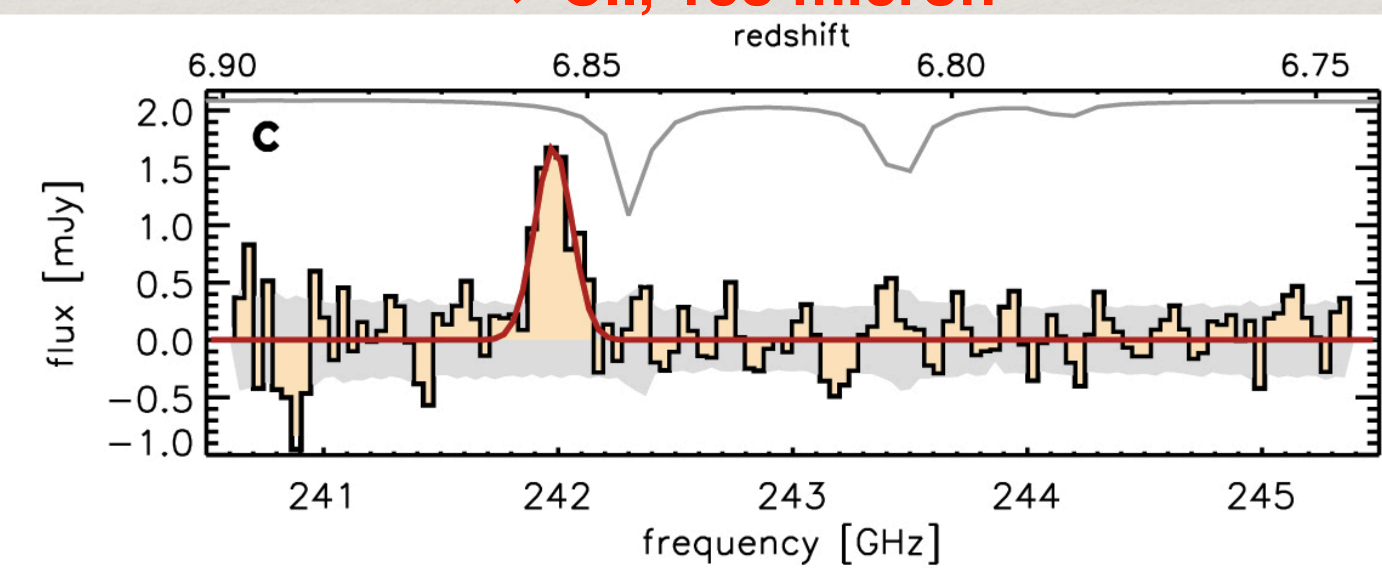
[Kovetz+ (2017) / NAOJ]



[OIII] 88 micron



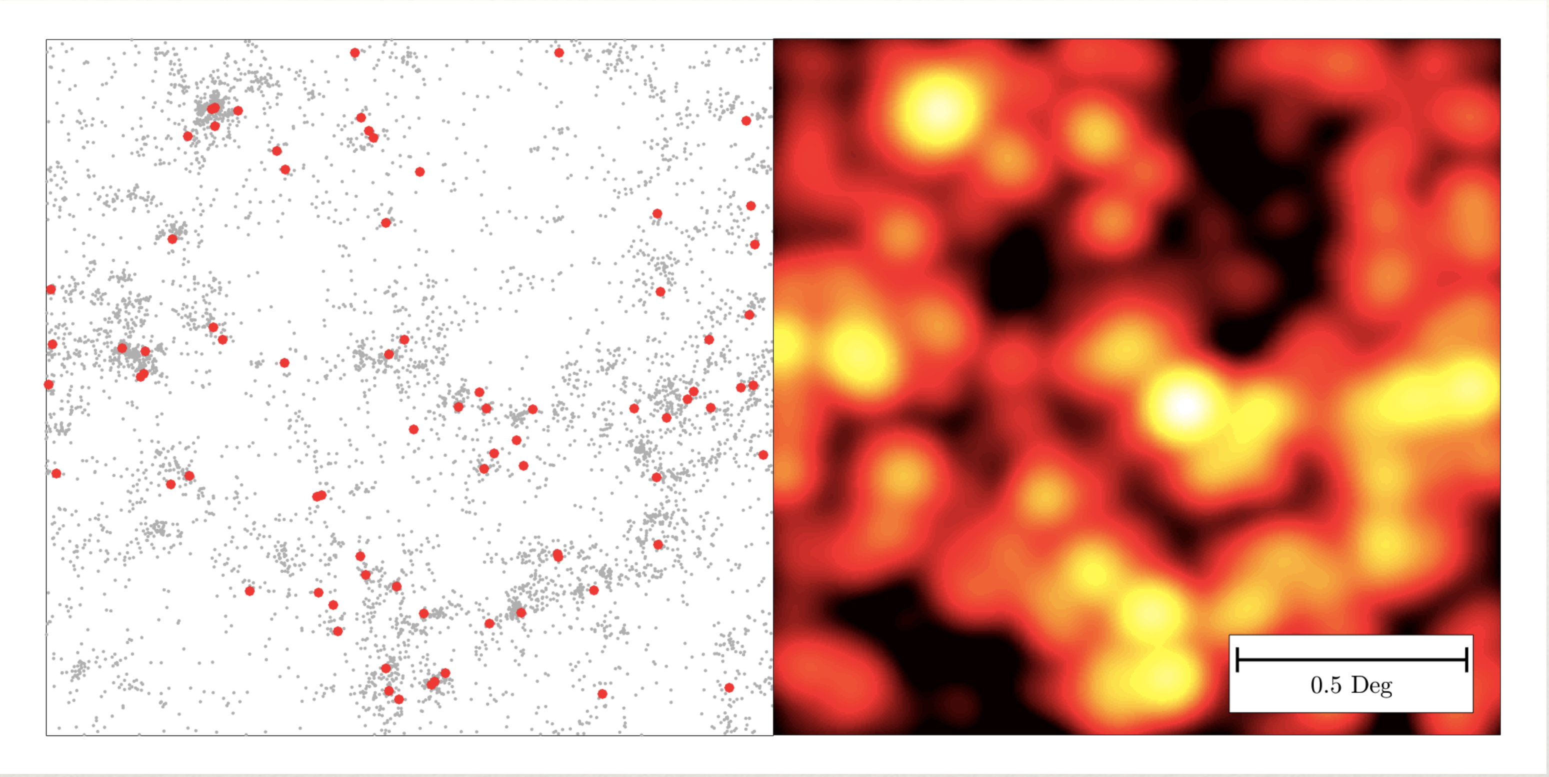
CII, 158 micron

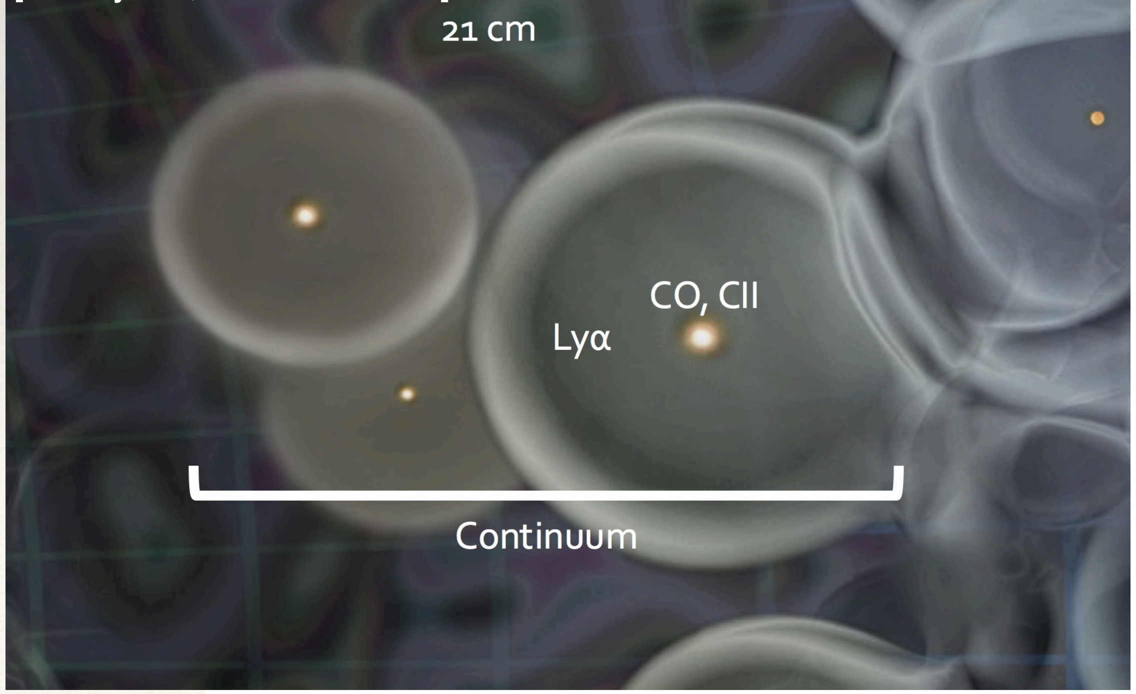


[Smit+ (2018), Pentericci+ (2017), Hashimoto+ (2018, 2019), Laporte+ (2017, 2019), Harikane+ (2020)]

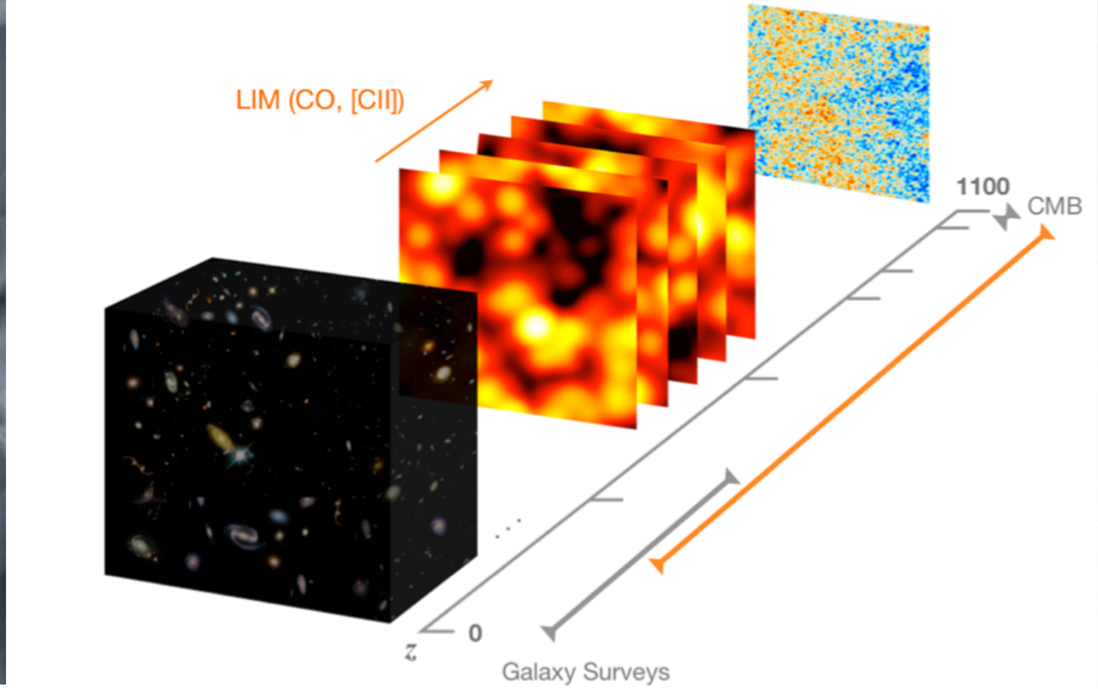
Intensity mapping (IM)

[Early studies: Hogan and Rees 1979, Sunyaev and Zeldovich 1972,1974, Bebington 1986]



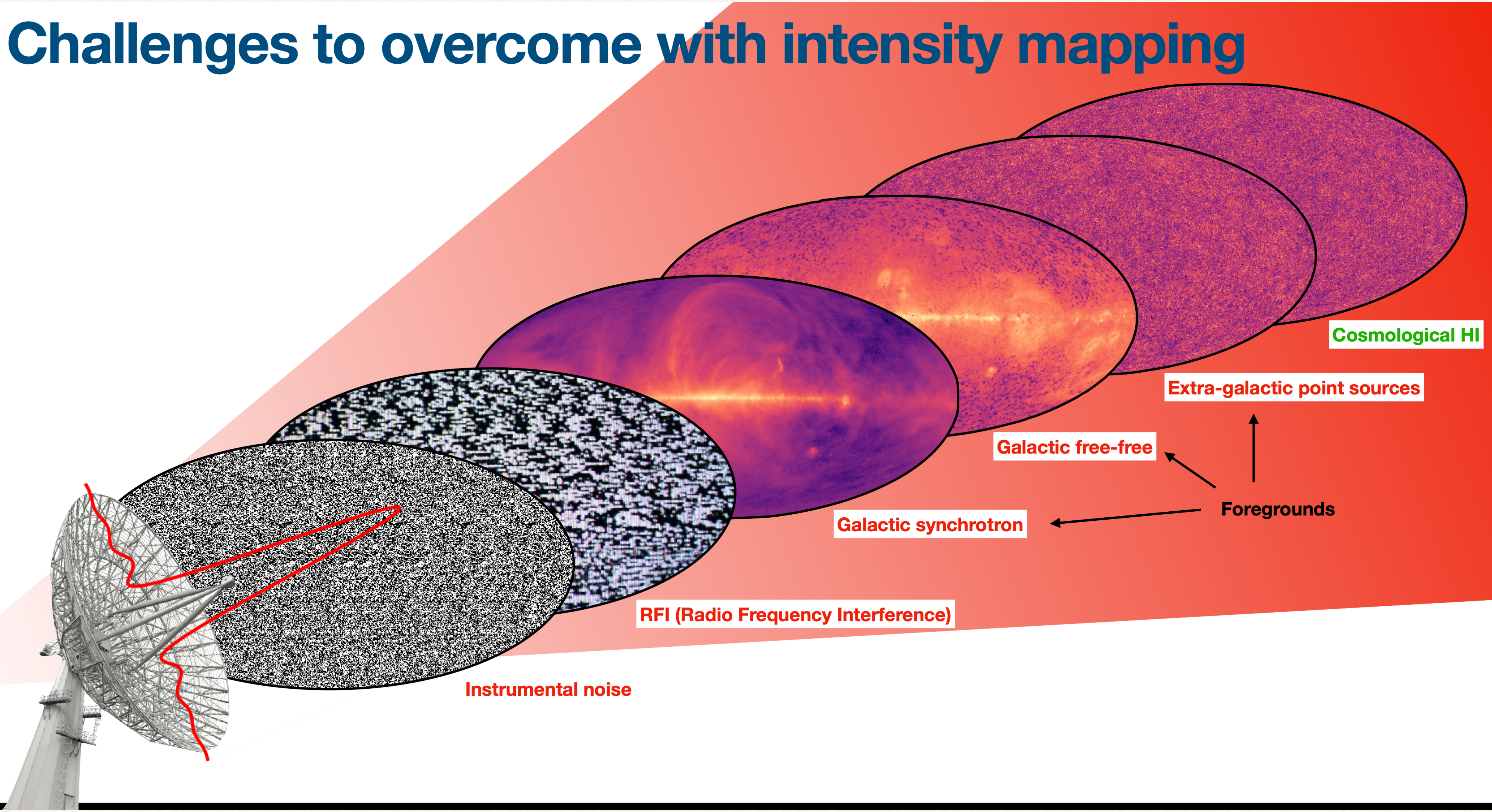


[P.Breysse, credit Sc. Am.]



[Silva+ 2019, ESA Voyage 2050]

21 cm IM is not easy …



Slide credit: Steve Cunnington

Synergies in IM

Cross-correlations mitigate systematics

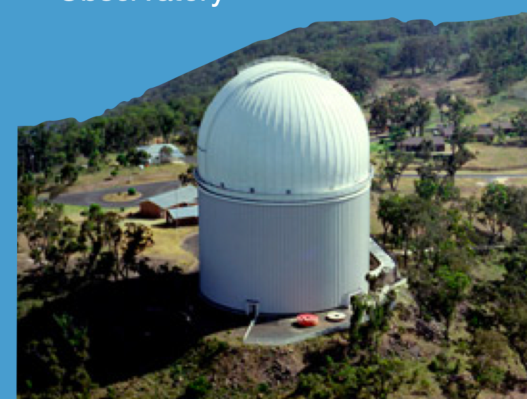
Radio

MeerKAT radio telescope

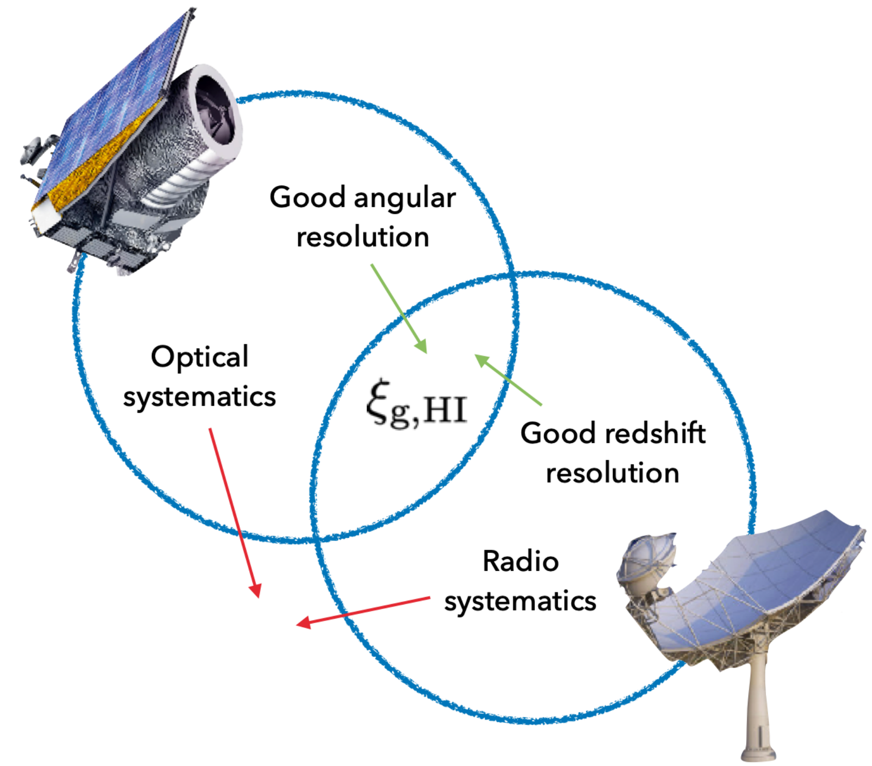
$$\mathbf{X}_{\rm rad} = \mathbf{S}_{\rm rad} + \mathbf{N}_{\rm rad}$$

Optical

Anglo-Austrailian Observatory



$$\mathbf{X}_{\rm opt} = \mathbf{S}_{\rm opt} + \mathbf{N}_{\rm opt}$$



Auto Correlation:

uncorrelated

$$\langle \mathbf{X}_{\rm rad}\mathbf{X}_{\rm rad}\rangle = \langle \mathbf{S}_{\rm rad}\mathbf{S}_{\rm rad}\rangle + 2\,\cancel{\langle \mathbf{S}_{\rm rad}\mathbf{N}_{\rm rad}\rangle} + \langle \mathbf{N}_{\rm rad}\mathbf{N}_{\rm rad}\rangle$$

$$\langle \mathbf{X}_{\rm rad}\mathbf{X}_{\rm rad}\rangle = \langle \mathbf{S}_{\rm rad}\mathbf{S}_{\rm rad}\rangle + \langle \mathbf{N}_{\rm rad}\mathbf{N}_{\rm rad}\rangle$$

signal you want *noise/residuals/systematics you don't want*

Cross Correlation:

$$\langle \mathbf{X}_{\rm opt}\mathbf{X}_{\rm rad}\rangle = \langle \mathbf{S}_{\rm opt}\mathbf{S}_{\rm rad}\rangle + \cancel{\langle \mathbf{S}_{\rm opt}\mathbf{N}_{\rm rad}\rangle} + \cancel{\langle \mathbf{S}_{\rm rad}\mathbf{N}_{\rm opt}\rangle} + \cancel{\langle \mathbf{N}_{\rm opt}\mathbf{N}_{\rm rad}\rangle}$$

21cm intensity mapping will provide benefits in future cross-correlations

Slide credit: Steve Cunnington

Cross-correlation with photometric galaxy survey < few sq. deg.: information lost in the areas of cross-power spectrum most affected by foregrounds **[Lidz+ (2009)]**

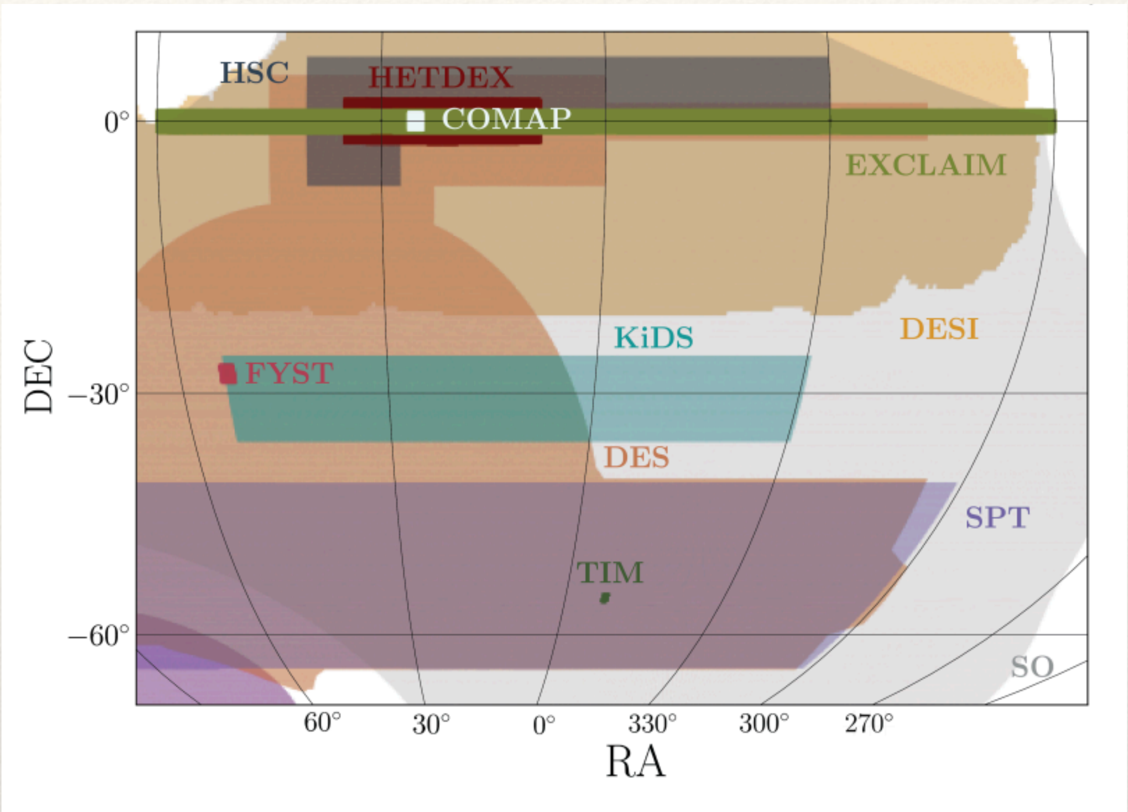
Largely mitigated by using IM with e.g., [CII], covering ~ few ten square degrees or more

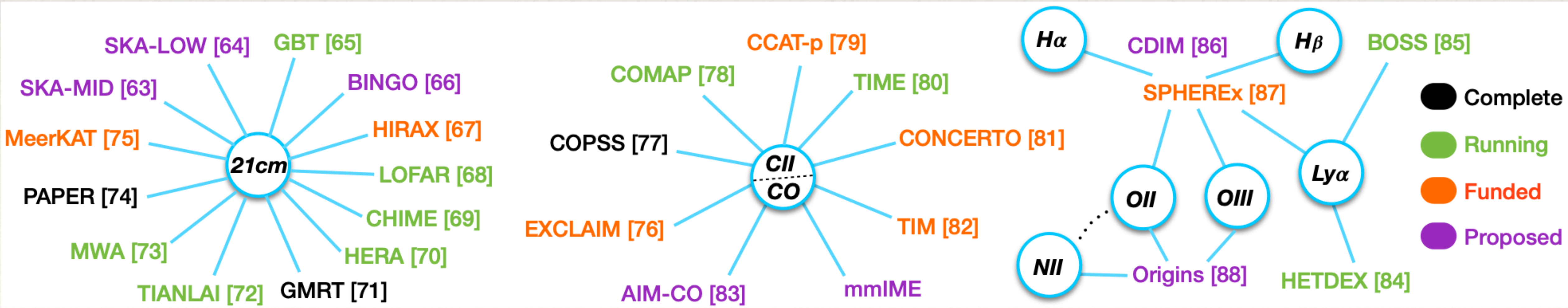
[Beane & Lidz (2018), Beane et al. (2019)]

Intensity mapping in the sub-mm

[reviews: Kovetz+ (2019), Karkare+ (2022), Bernal & Kovetz (2022)]

- Novel window into reionization, sensitive to evolution of star-formation rate and molecular gas density
- [CII] brightest line, ~ 1% of total IR luminosity, non-affected by dust and photodissociation (caveat: CO transitions at lower redshift a possible contaminant, but can be mitigated, especially by cross-correlation)
- [OIII]: hard radiation > 35 eV; HII regions
- ALMA observations: [CII] 'deficit' at high-z; if confirmed by IM, indicates hard ISM field and/or larger HII regions
- Sky noise much smaller at 10-100 GHz
- Point source foregrounds at ~ 30 GHz effectively removed





Intensity mapping in the sub-mm

Experiment for Cryogenic Large Aperture Intensity Mapping (EXCLAIM)

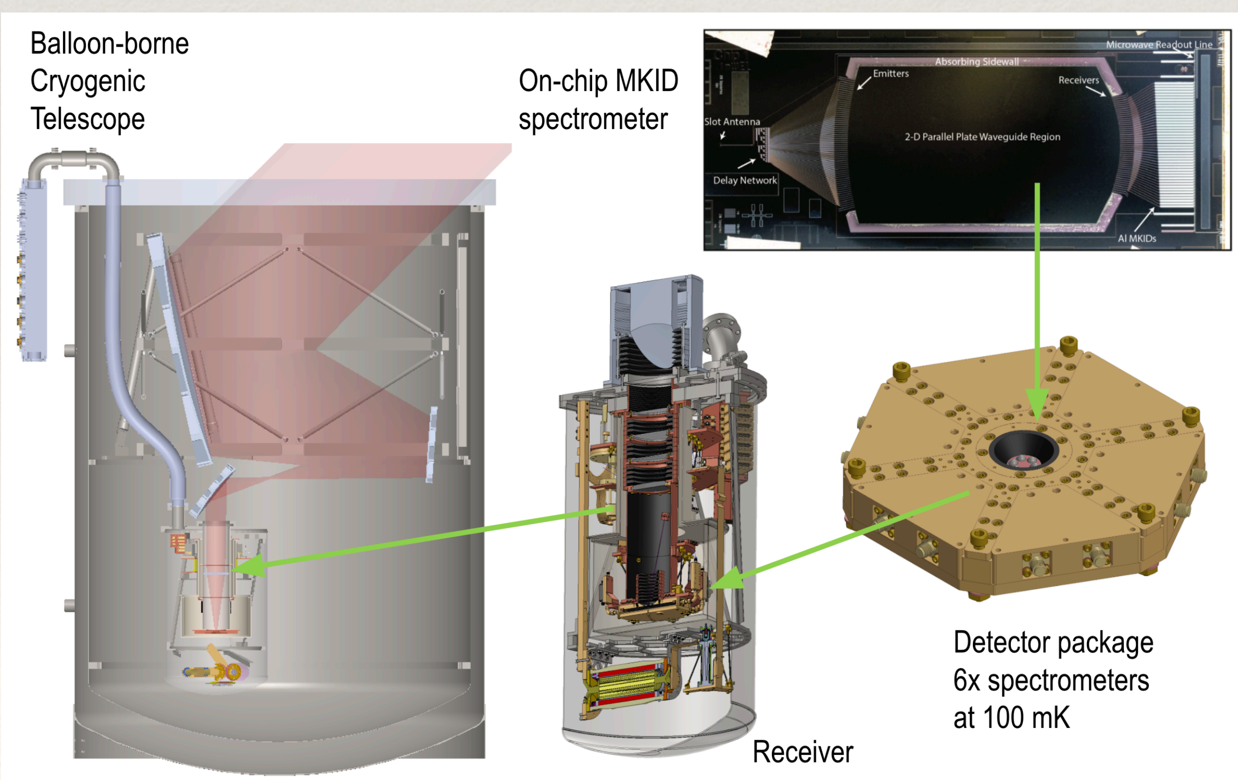
(2023 -)

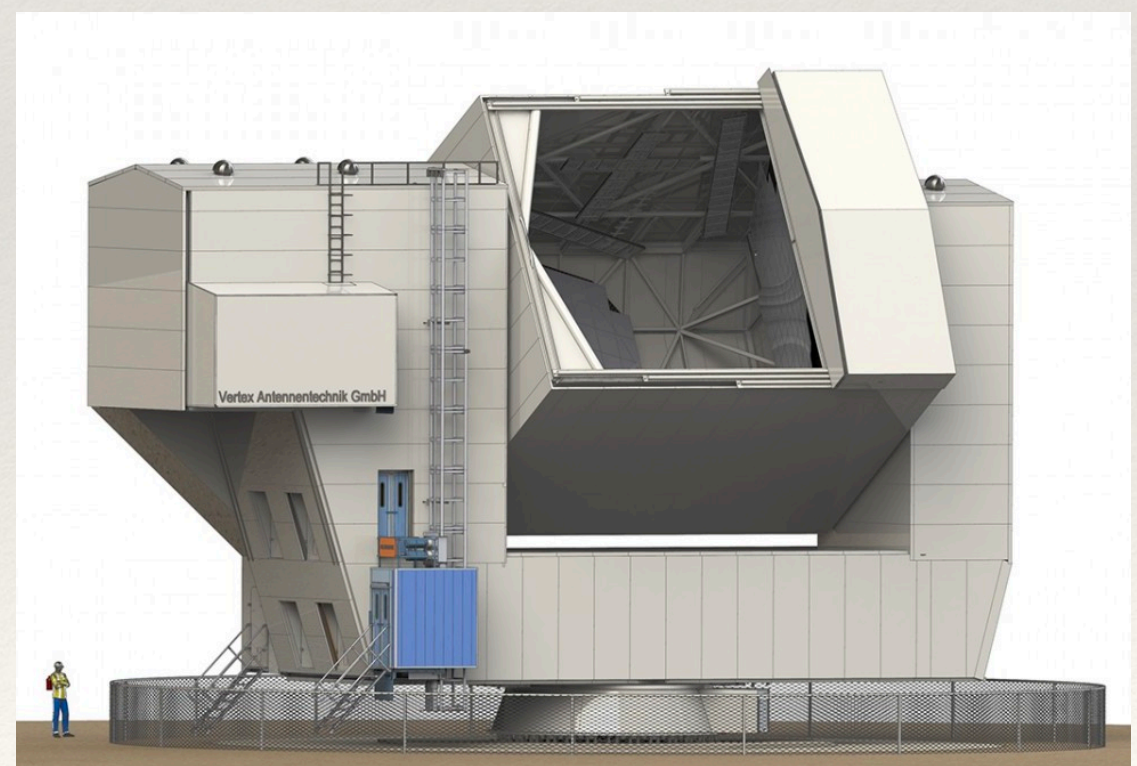
[Cataldo+ (2020), SPIE, arXiv:2101.11734; Ade+ (2020), JLTP, arXiv:1912.07118]

EoR-Spec on Fred Young Submillimetre Telescope (FYST)

(2024 -)

[Aravena+ (2021), arXiv:2107.10364; Duell+ (2020), SPIE, arXiv: 2012.10411]





Improved versions of current architecture

EXCLAIM

$$D_{\rm dish} = 0.74 \text{ m}$$
$$\Delta\nu = 1000 \text{ MHz}$$
$$N_{\rm spec,eff} = 6$$
$$S_{\rm A} = 400 \text{ sq.deg.}$$
$$\sigma_{\rm N} = 600000 \text{ Jys}^{1/2}/\text{sr}$$
$$B_\nu = 40 \text{ GHz}$$
$$t_{\rm obs} = 8\text{h}$$
$$\text{Bandwidth} = 420 - 540 \text{ GHz}$$

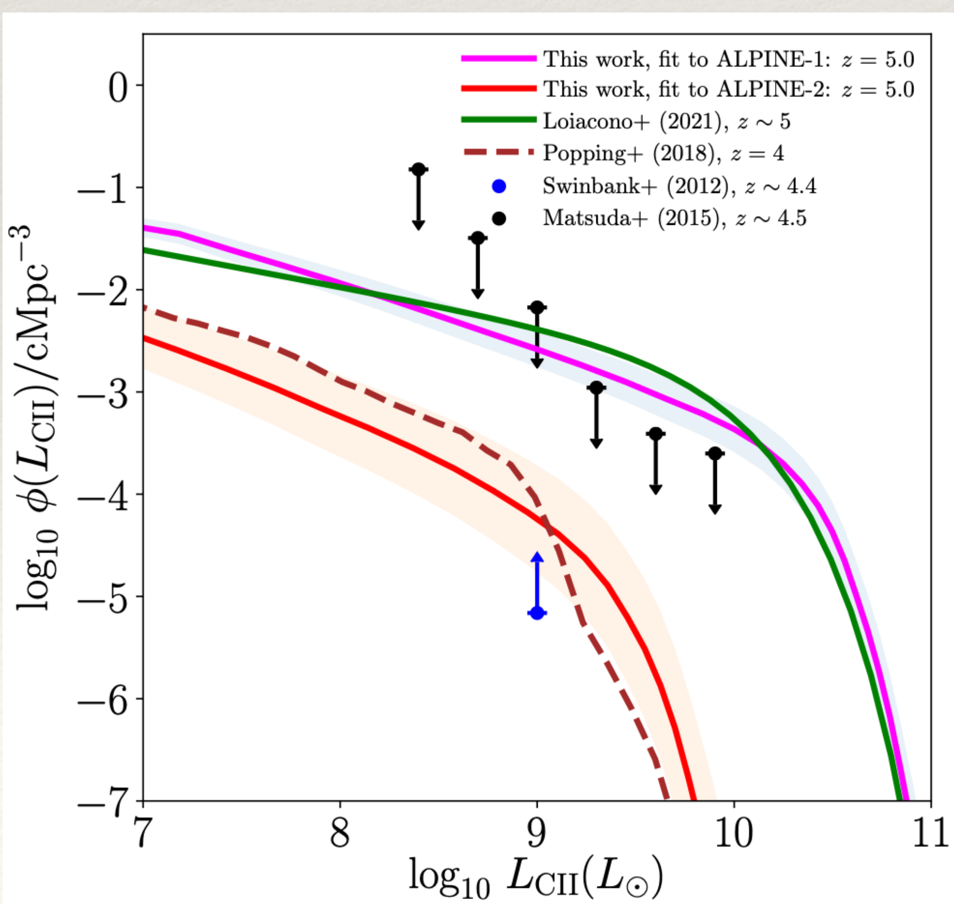
FYST

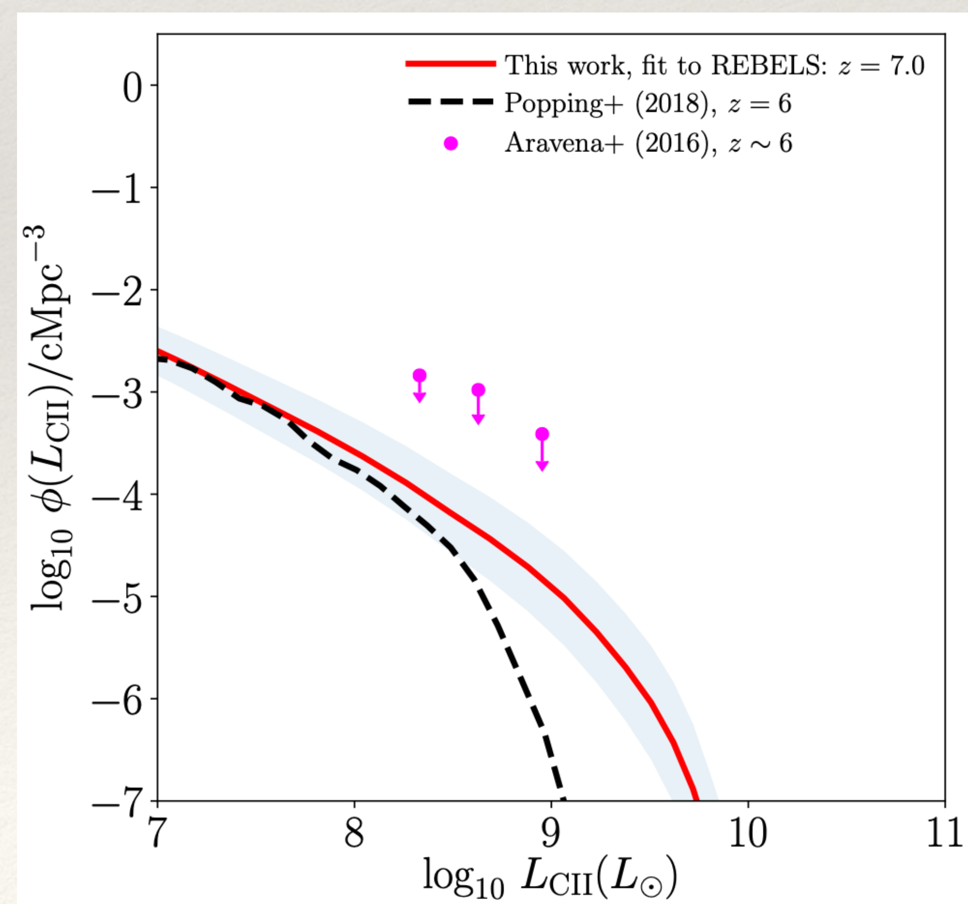
$$D_{\rm dish} = 6 \text{ m}$$
$$\Delta\nu = 2500 \text{ MHz}$$
$$N_{\rm spec,eff} = 20$$
$$S_{\rm A} = 8 \text{ sq.deg.}$$
$$\sigma_{\rm N} = 500000 \text{ Jys}^{1/2}/\text{sr}$$
$$B_\nu = 40 \text{ GHz}$$
$$t_{\rm obs} = 4000\text{h}$$
$$\text{Bandwidth} = 212 - 428 \text{ GHz}$$

[e.g., HP (2019), HP+ (2022), Chung+ (2020), Breysse+ (2021)]

The ALPINE and REBELS surveys: constraints on high-z [CII] LF

- ALPINE: [CII] emission in galaxies at z ~ 4.5 - 6 in Chandra Deep Field South and COSMOS fields [Le Fevre et al. (2020), Faisst et al. (2020), Bethermin et al. (2020)]
- Targeted and serendipitous sources, 'clustered' subsample connected to known overdensities in the COSMOS field [Loiacono+ (2021), Oesch+ (2022)]
- REBELS: 42 sources, spectroscopic redshifts z ~ 6.4 - 7.7 [Oesch+ (2022)]
- [CII] luminosity to host halo mass found by abundance matching to dark matter mass function [HP (2023), submitted, arXiv:2212.08077, HP (MNRAS 2019)]





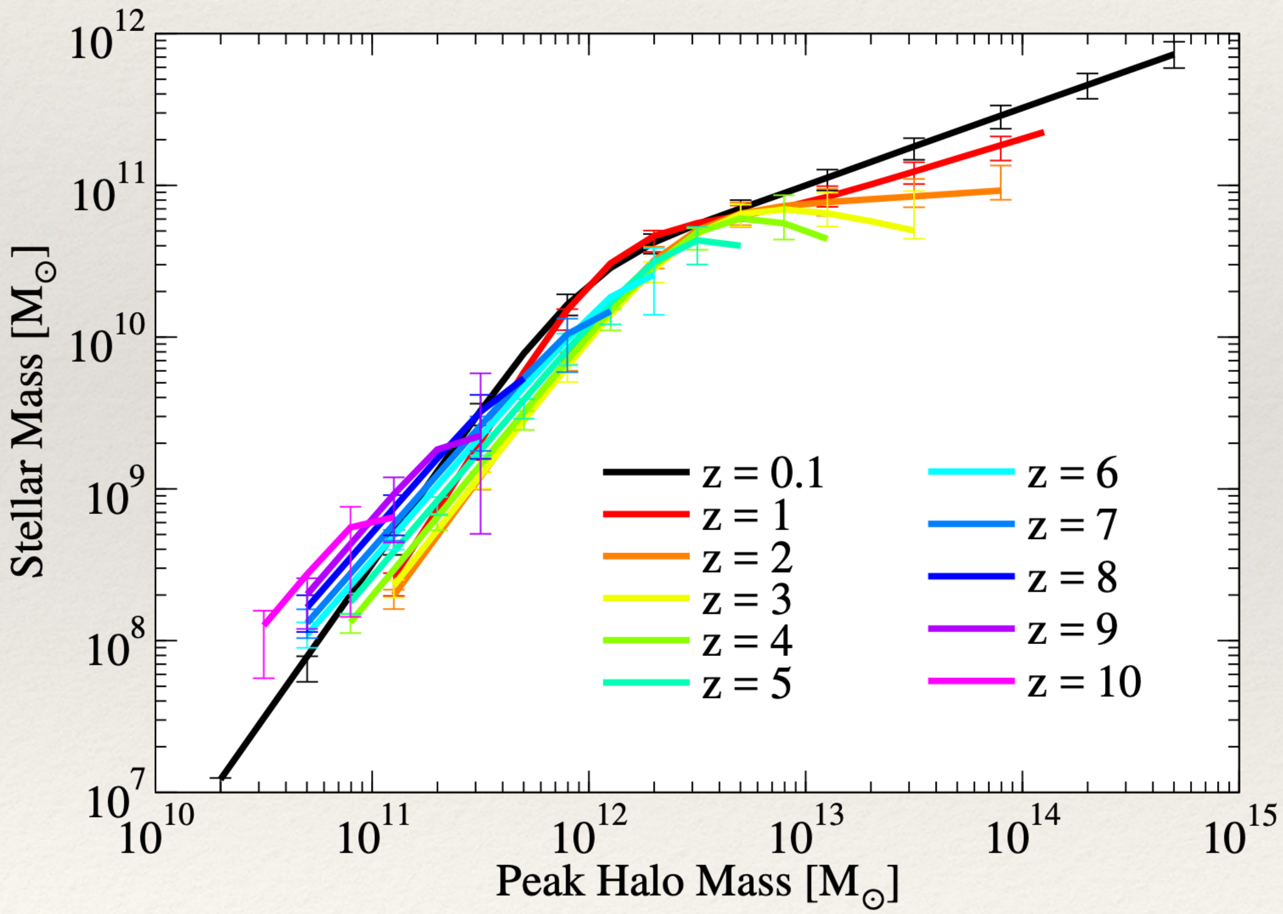
[OIII] power spectra

[Early work: Visbal & Loeb (2010), Gong+ (2016), Visbal+ (2011) …]

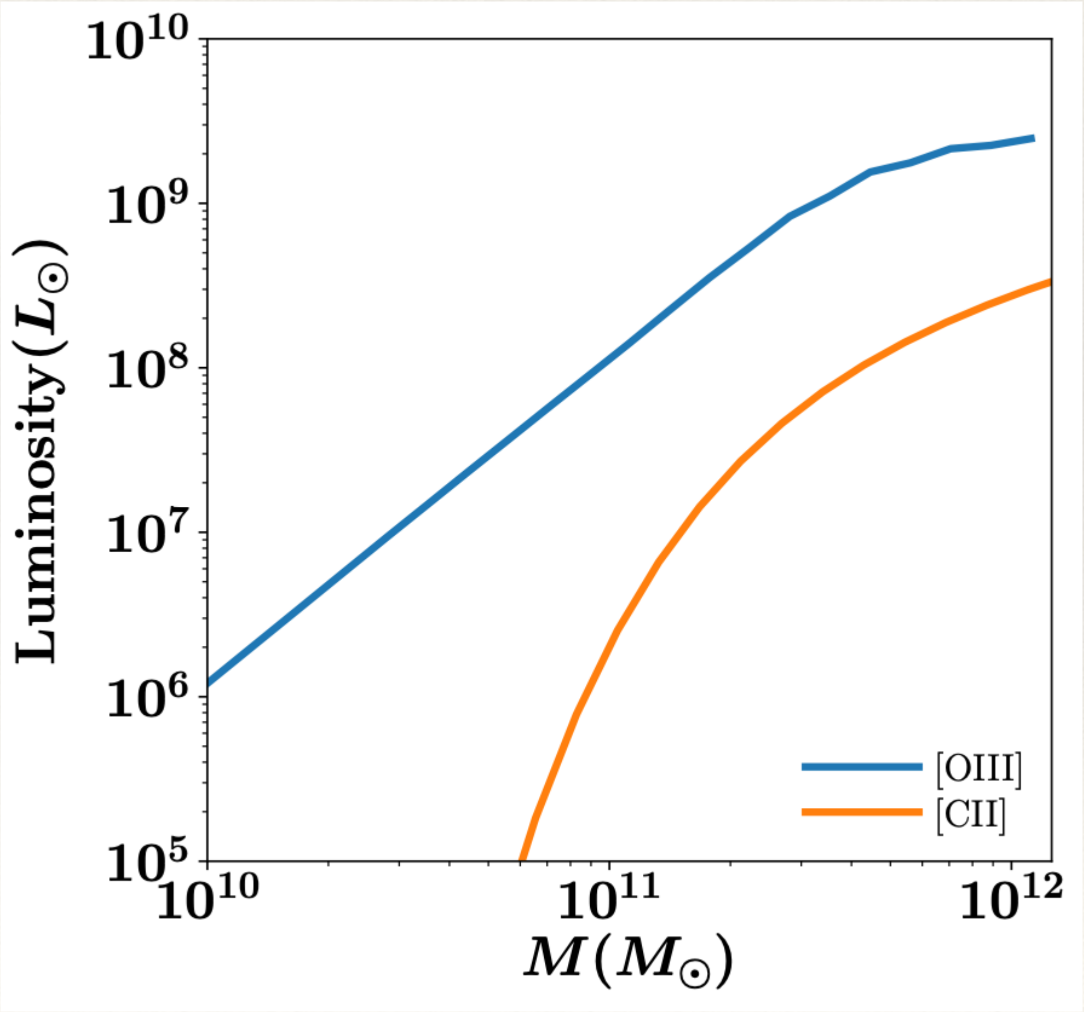
$$\log\left(\frac{L_{\rm OIII}}{L_\odot}\right) = 0.97 \times \log\frac{\rm SFR}{[M_\odot {\rm yr}^{-1}]} + 7.4$$

[Harikane+ (2020)]

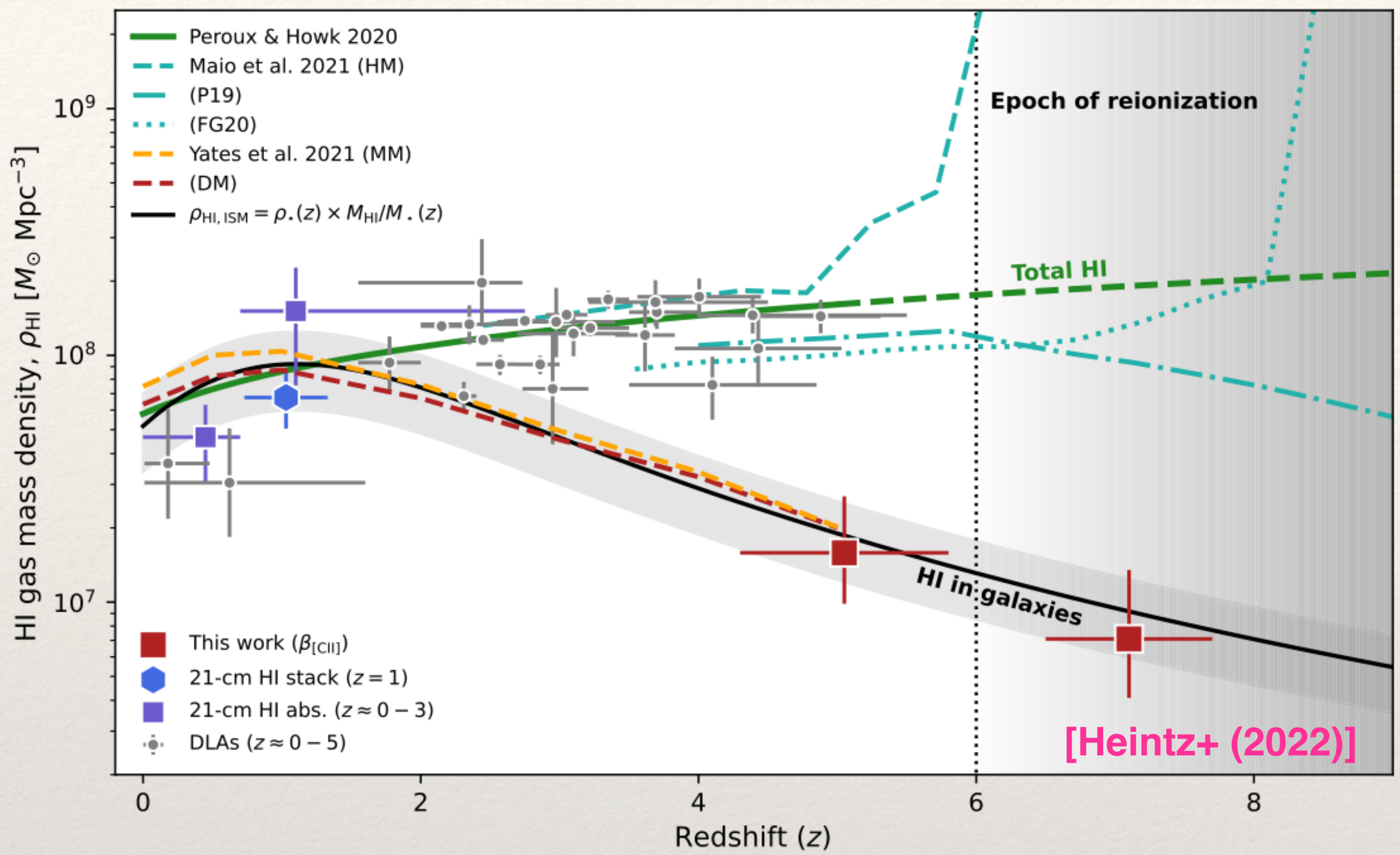
[Behroozi+ (2018)]

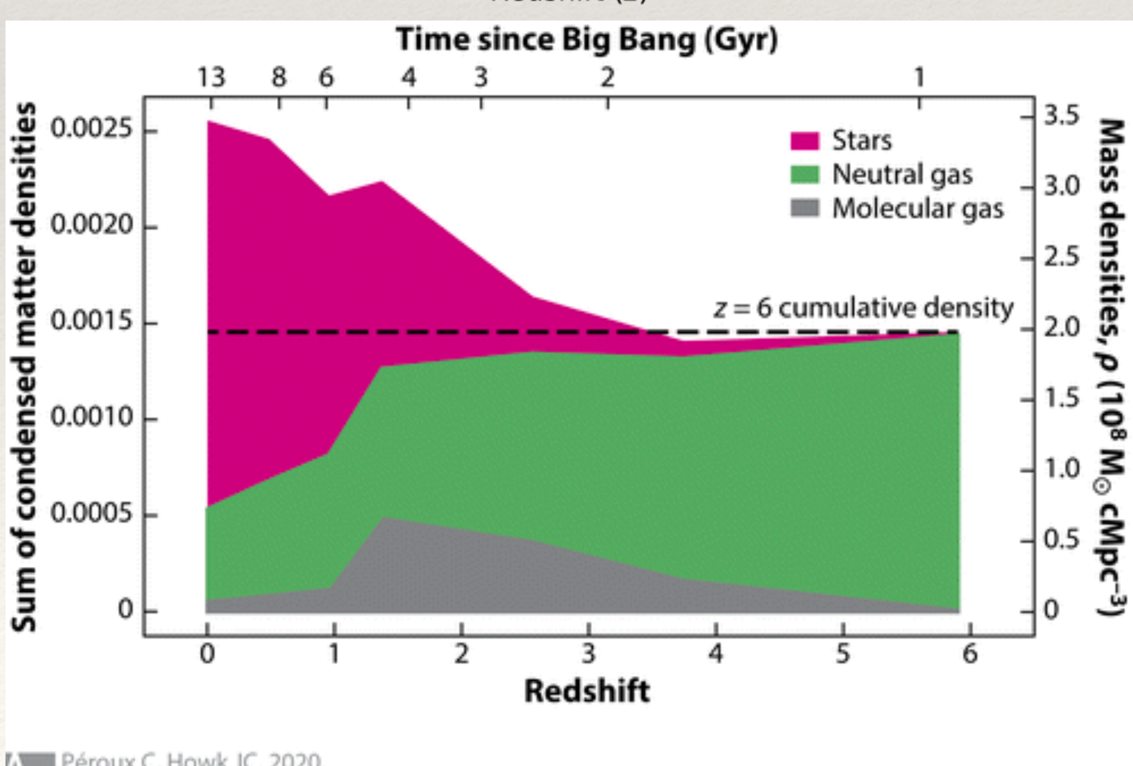


[HP+, MNRAS (2022)]



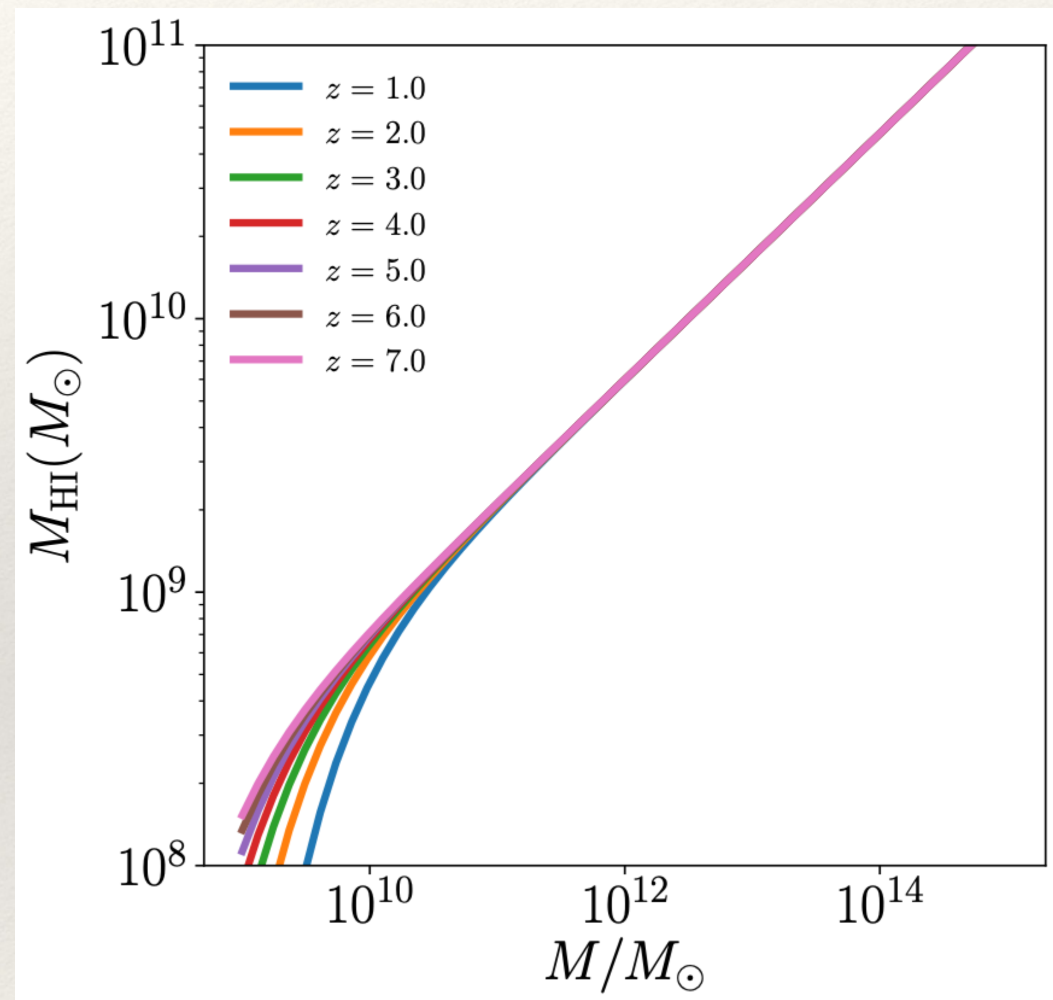
New empirical insights on HI at z ~ 5-7





[Peroux & Howk (2020)]

Consistent with the HI halo model in its present form!*

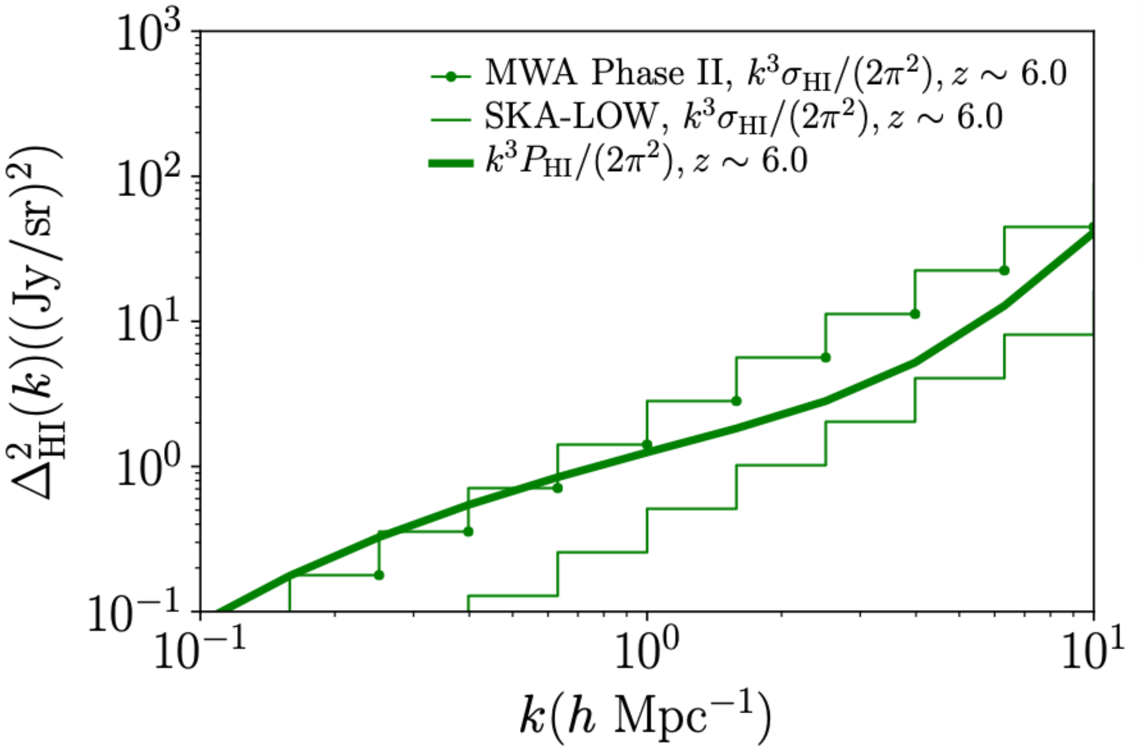


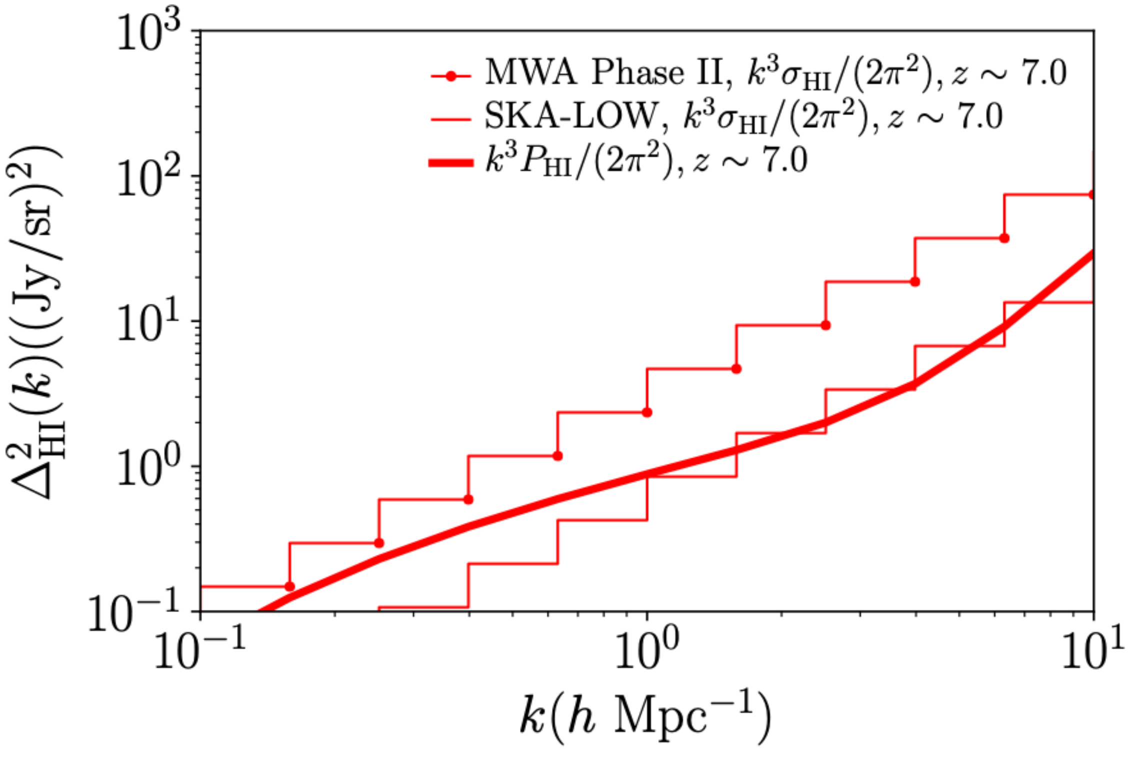
[HP, Refregier, Amara, MNRAS (2017)]

Note: total power only, scale dependence unconstrained

Auto-correlation forecasts

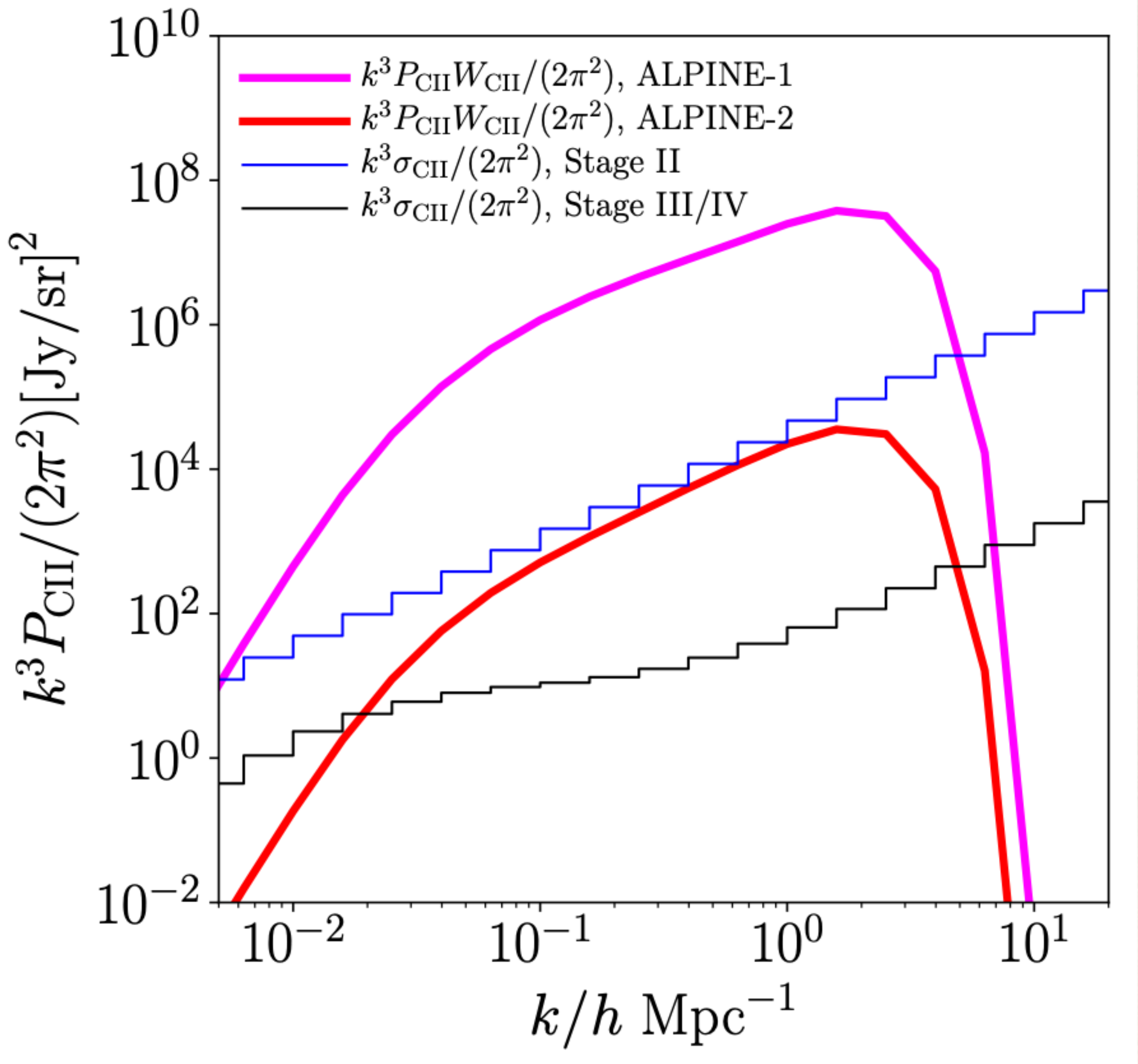
MWA/SKA, z ~ 6-7





Configuration	$d_{\rm max}$	$N_{\rm a}$	$n_{\rm pol}$	$T_{\rm inst}$[K]	$A_{\rm eff}$ (m^2)	$t_{\rm obs}$[h]	$S_{\rm A}$[deg.sq]
MWA	1000 m	256	2	28	14.5	2000	1000
SKA-LOW	40000 m	512	2	28	964	2000	1000

FYST++, z ~ 6

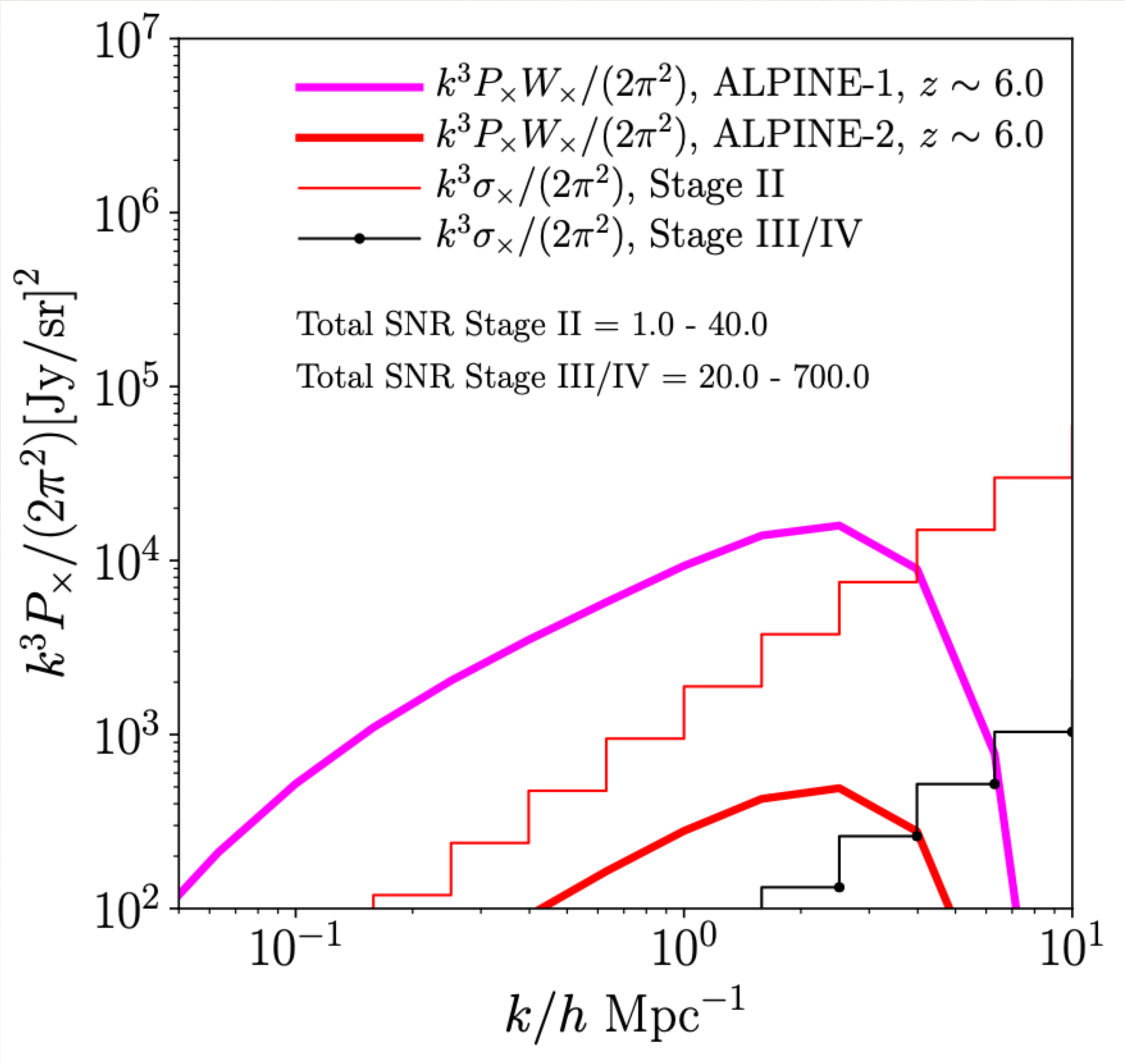


Cross-correlation forecasts*

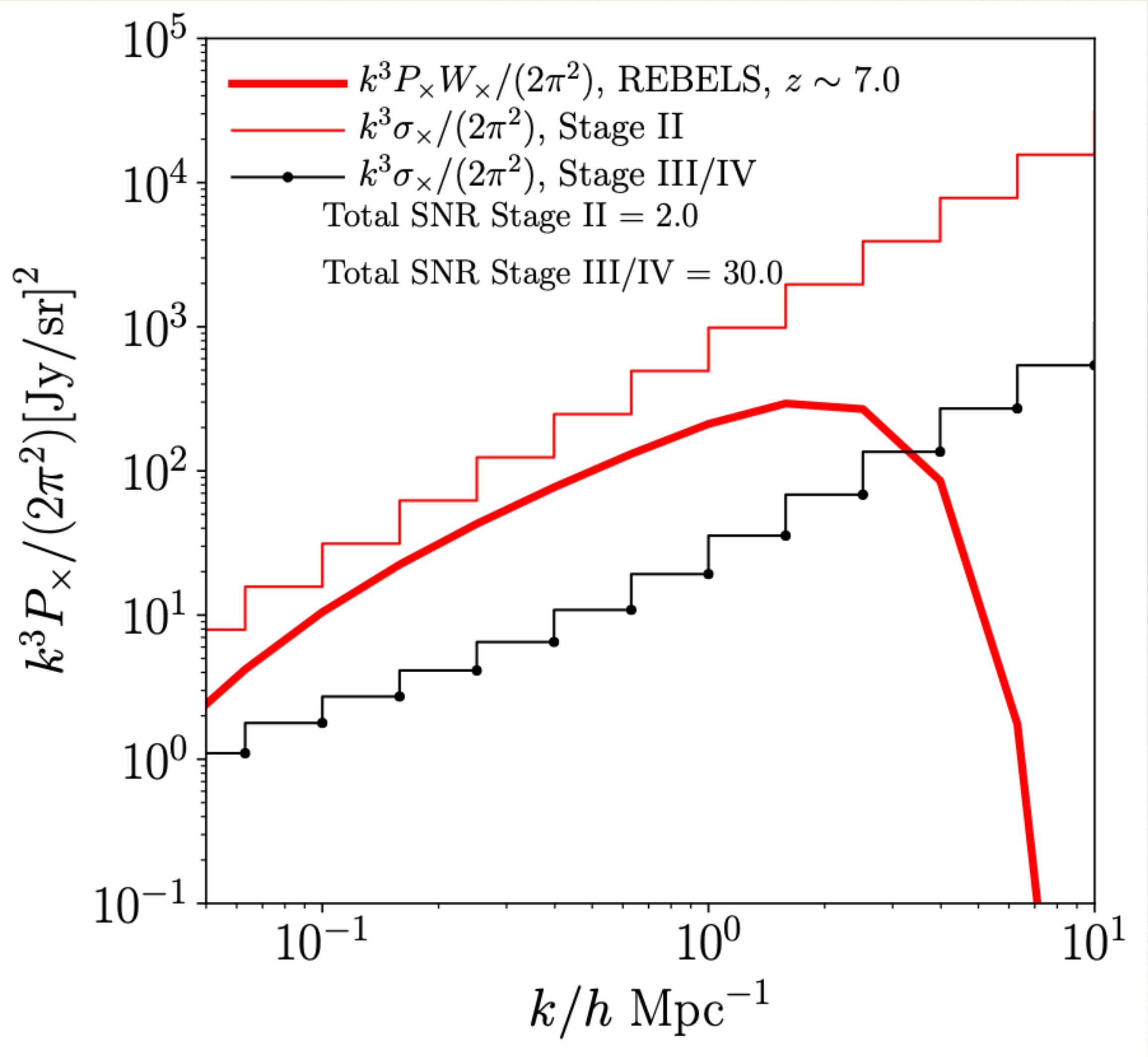
*Assumes complete overlap

(FYST++) x MWA/SKA

z ~ 5.5-6.5, [CII] 158 x HI (MWA)



z ~ 6.4-7.7, [CII] 158 x HI (SKA)

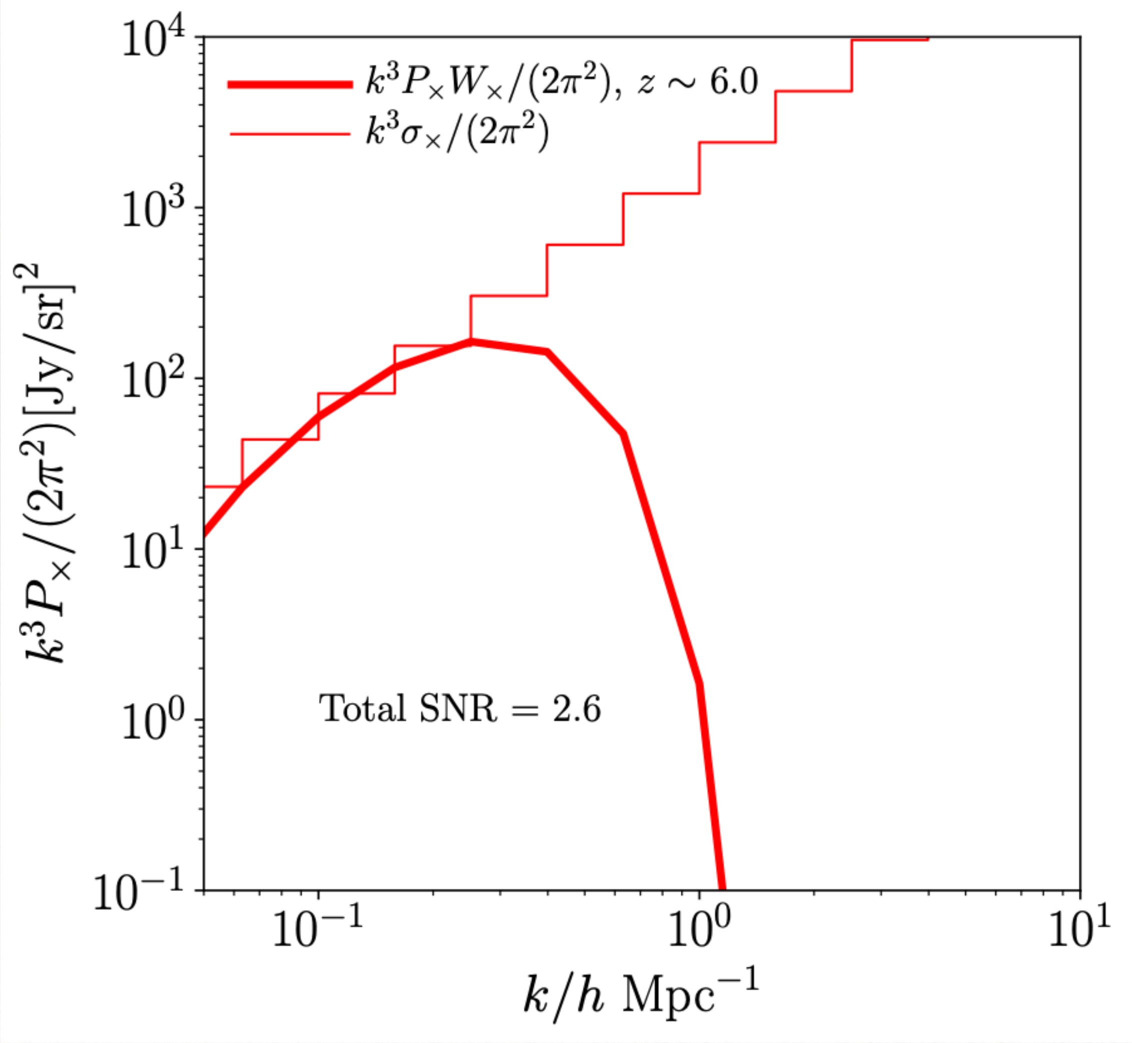


Cross-correlation forecasts*

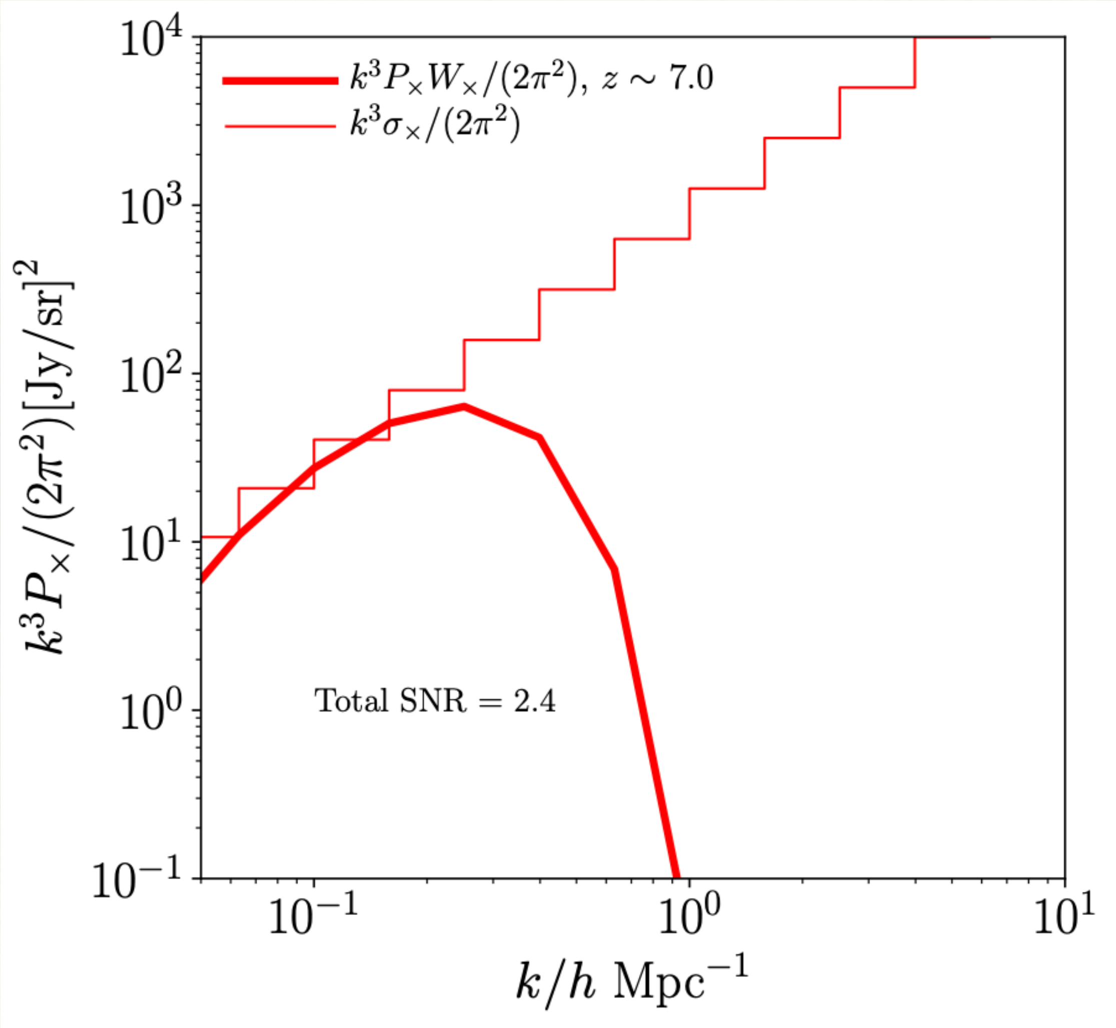
*Assumes complete overlap

(EXCLAIM++) x MWA/SKA

z ~ 5.5-6.5, [OIII] 88 x HI (MWA)



z ~ 6.4-7.7, [OIII] 88 x HI (SKA)



Summary

- LIM: promising to survey large volumes over a wide range of redshifts, several species of interest
- Observing in the sub-mm band: several advantages, complementary to 21 cm
- Cross correlations reduce systematics and foregrounds for 21 cm, remove line interloper contaminants for sub-mm
- Latest data from ALMA (ALPINE/REBELS) allow for a characterization of the [CII]-halo mass relation at z ~ 5, 6, and 7 (extending previous analyses); bracketing allowed range in [CII] luminosities
- Recent results suggest near-constancy of the total HI evolution over z ~ 0-7 — consistent with halo model expectations extrapolated from z ~ 0-5
- Cross-correlation improves the detection significance by factors of a few to ***a few ten*** beyond that from the individual sub-mm and 21 cm forecasts
- Improved versions of current architecture (EXCLAIM, FYST) reach secure to ***several 10 sigma detections*** in cross-correlation with MWA and SKA-LOW at *z* ~ 5-7
- Future: constraints on scale dependence, synergies with COMAP, JWST…

Thank you!

Low enough opacity to observe with the ground

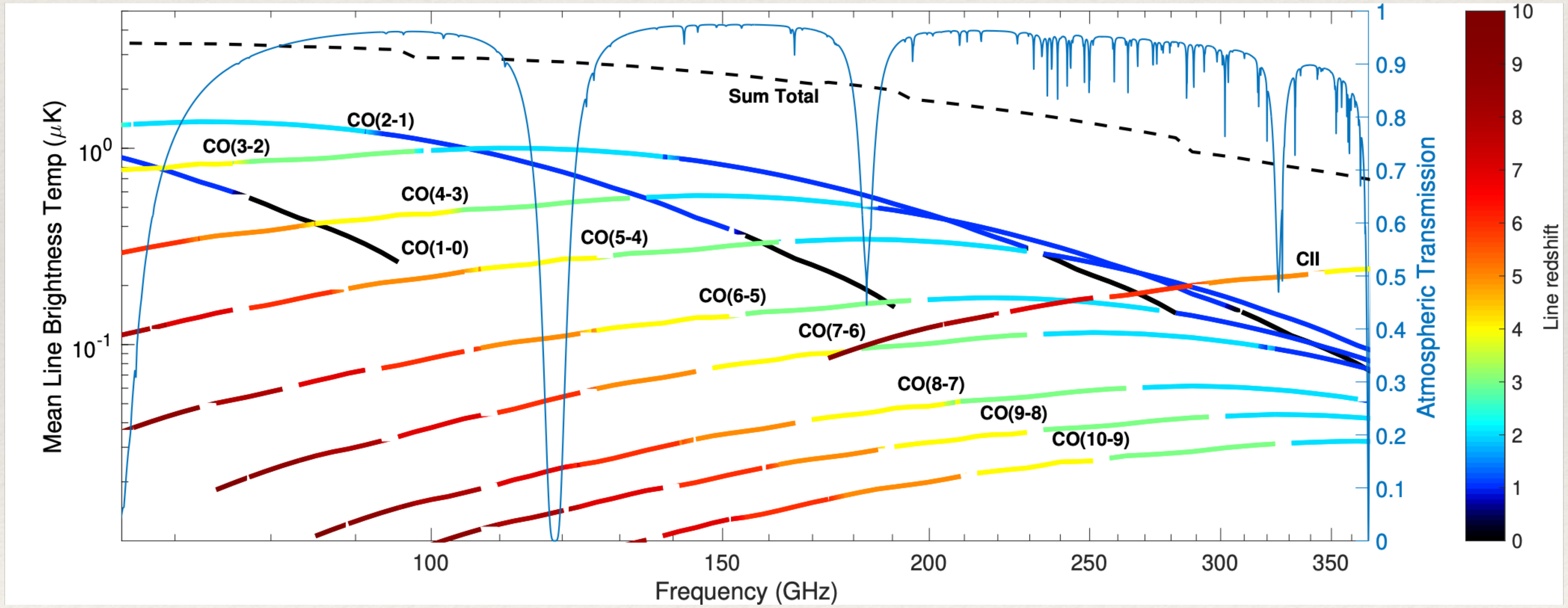
Sky noise is much much smaller at 10-100 GHz

Continuum foregrounds lie in between the synchrotron and the dust continuum

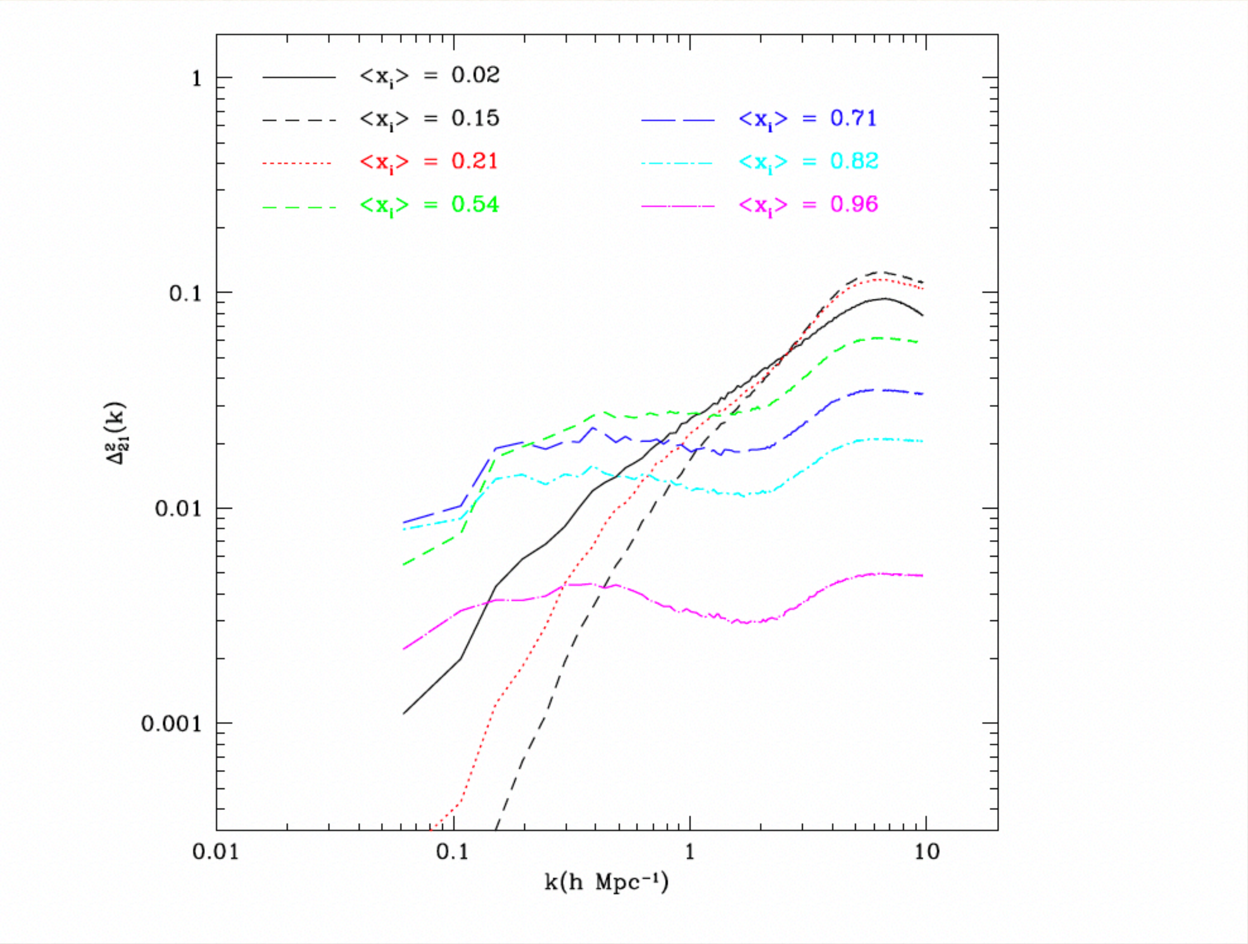
Point sources foregrounds at ~ 30 GHz **[Sharp+ (2010)]**

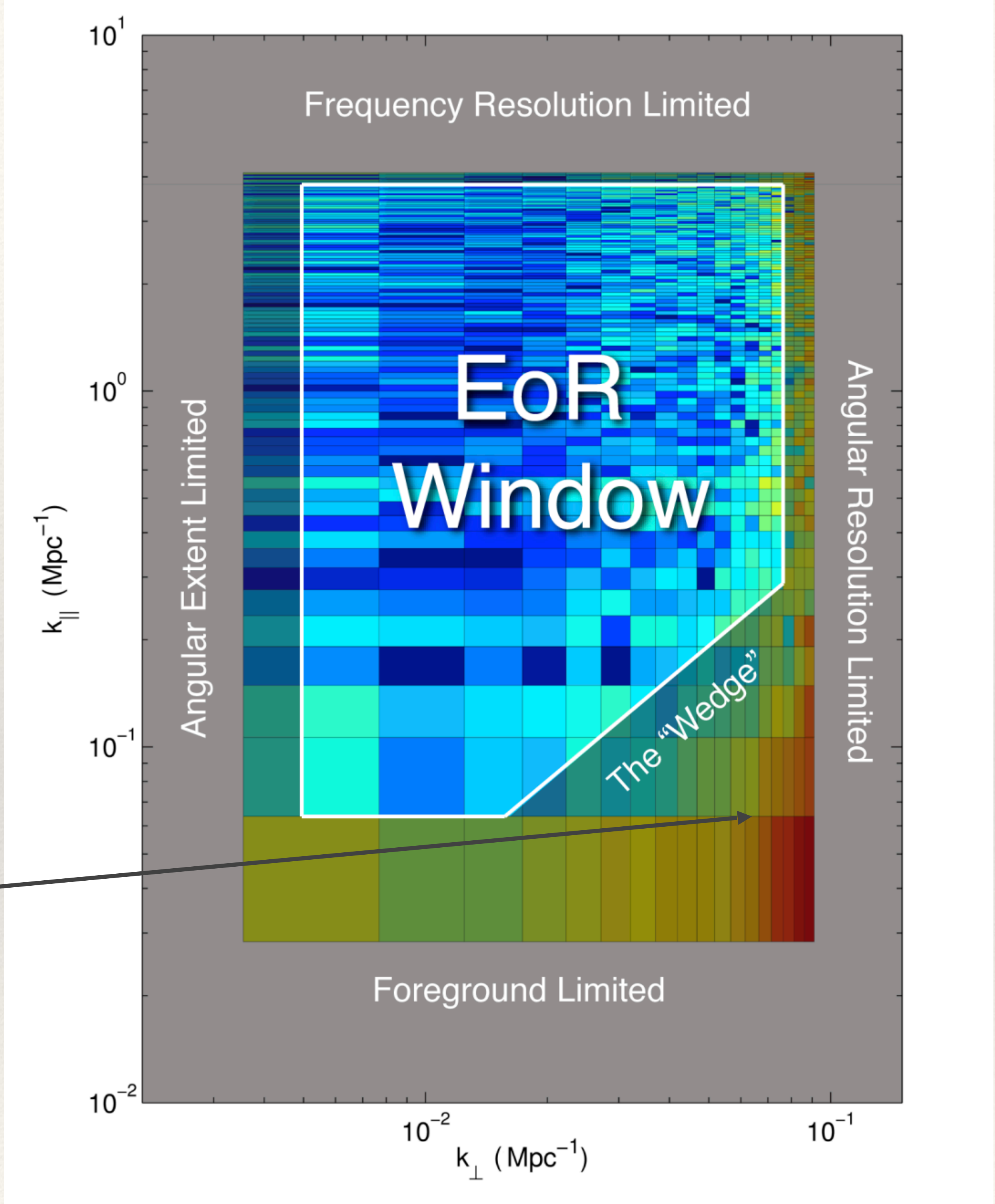
can be effectively removed **[Keating+ (2016)]**

Large fields of view and good spectral resolution available



[Dizgah, Keating, Karkare, Crites, Choudhury, ApJ (2022), arXiv:2110.00014]





Small-area galaxy surveys mostly measure modes
lost from 21 cm data
to foreground cleaning/avoidance.