Line-intensity mapping

and the physics of Cosmic Reionization

Hamsa Padmanabhan

Scientific collaborator and PI, SNSF Ambizione Grant
Université de Genève

with Alexandre Refregier, Adam Amara, Girish Kulkarni, Patrick Breysse, Adam Lidz, Eric. R. Switzer, and the COMAP collaboration

UNIVERSITÉ DE GENÈVE

Swiss National Science Foundation

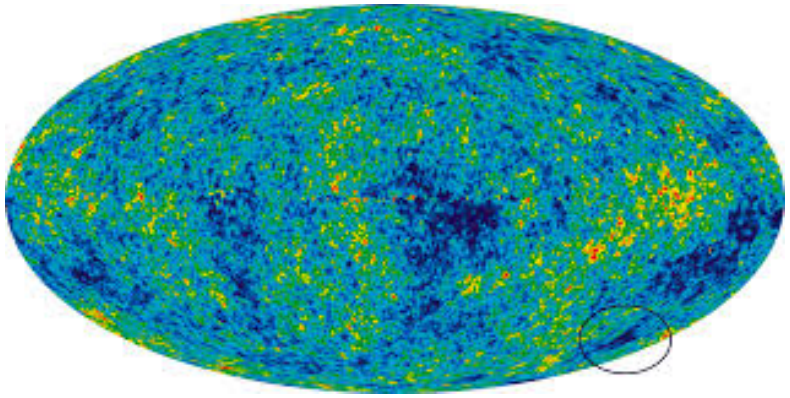
The Epoch of Reionization (EoR)

— *the final observational frontier* —

The Epoch of Reionization (EoR)

— the final observational frontier —

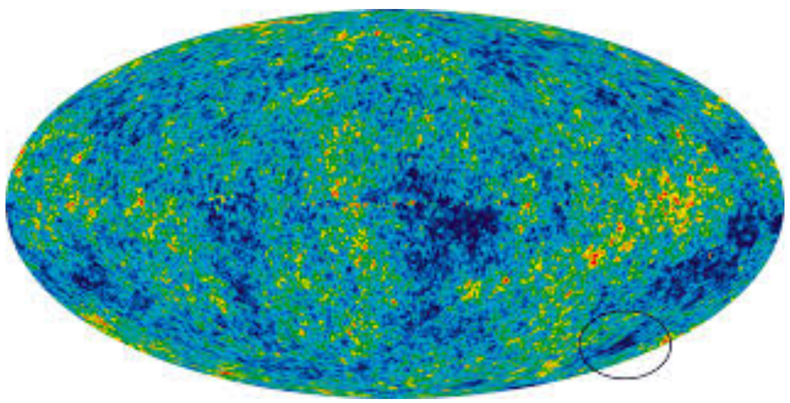
Hydrogen in the Universe was neutral at z ~ 1100 (to better than 1 part in 10^4)

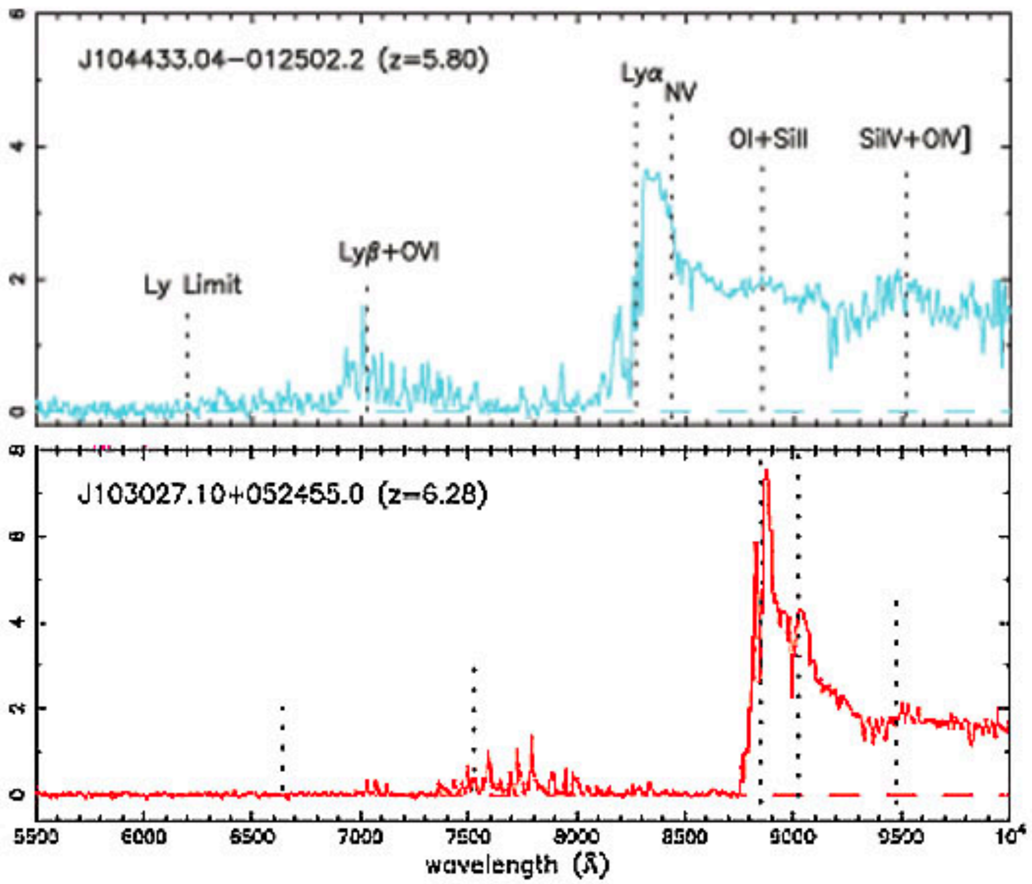


The Epoch of Reionization (EoR)

— the final observational frontier —

Hydrogen in the Universe was neutral at z ~ 1100 (to better than 1 part in 10^4)





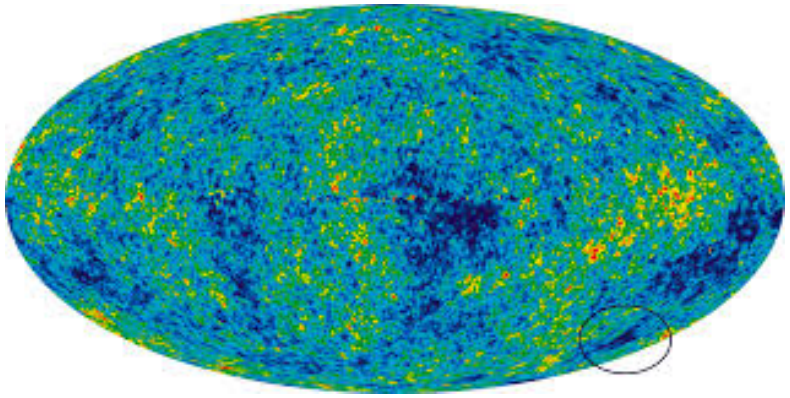
SDSS

The quasar absorption spectra show us that hydrogen is highly ionised at z ~ 6 (to better than 1 part in 10^5!)

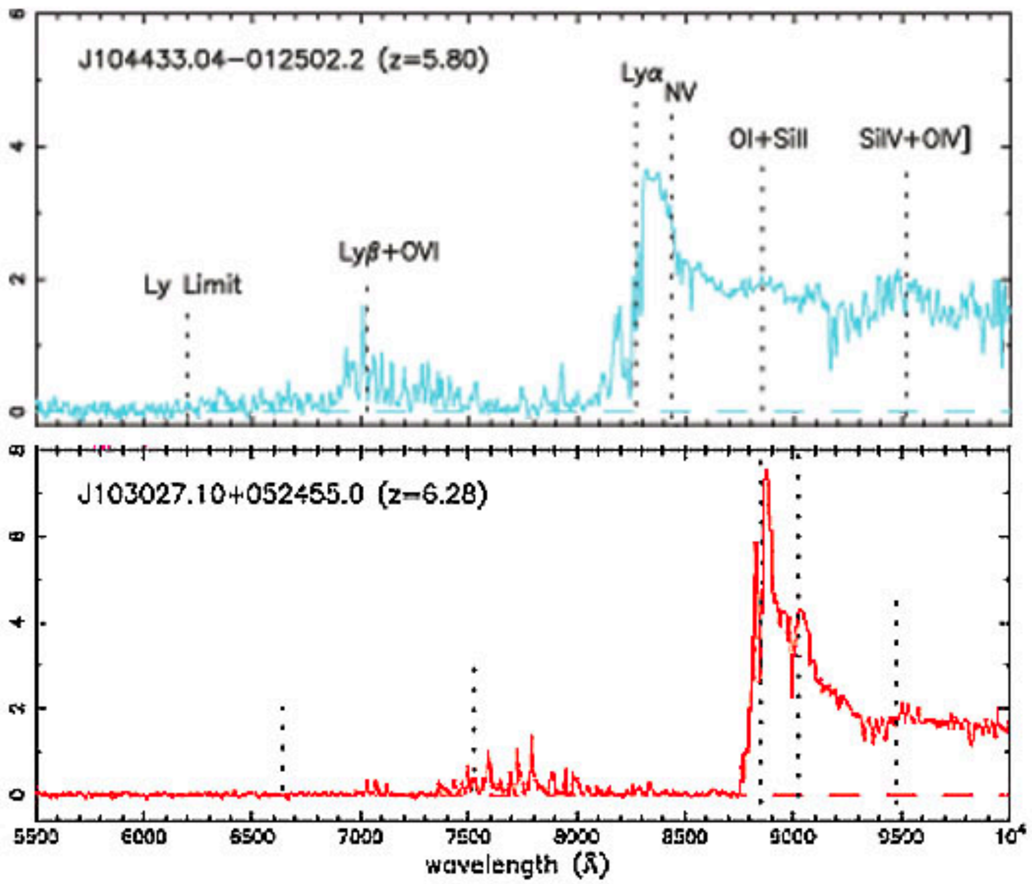
The Epoch of Reionization (EoR)

— the final observational frontier —

Hydrogen in the Universe was neutral at z ~ 1100 (to better than 1 part in 10^4)



How did this come about?



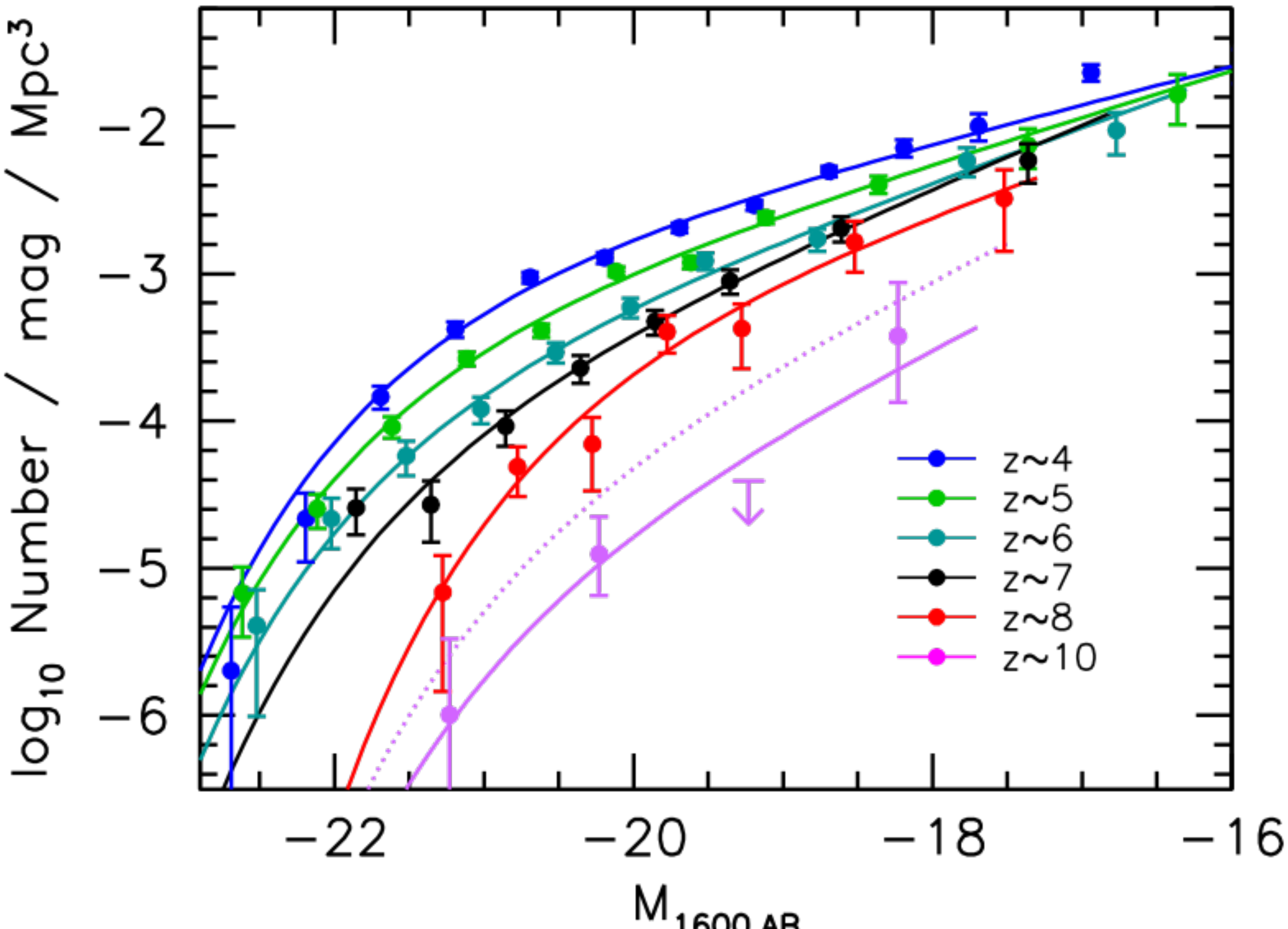
SDSS

The quasar absorption spectra show us that hydrogen is highly ionised at z ~ 6 (to better than 1 part in 10^5!)

Slide credit: Andrei Mesinger

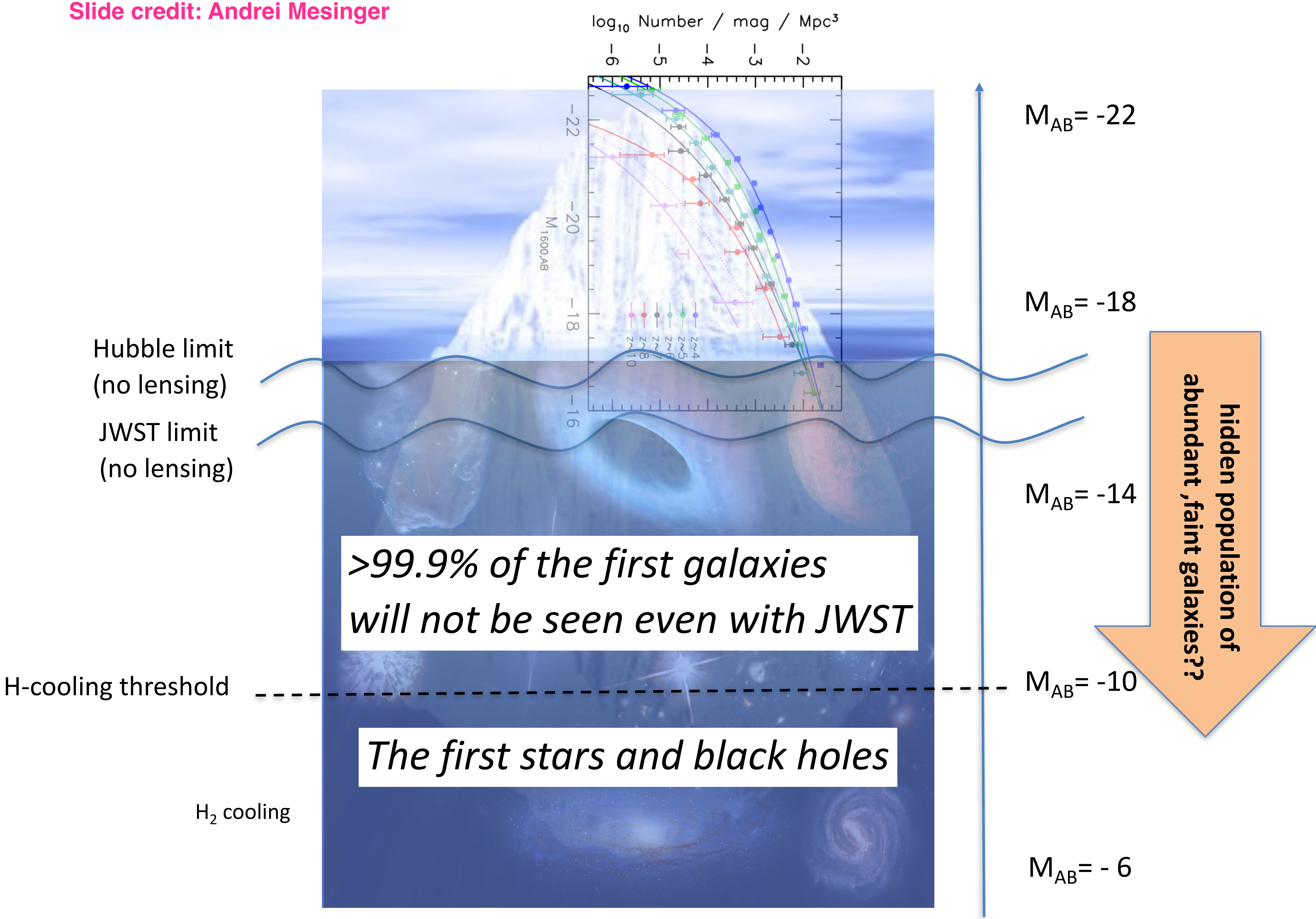
Galaxies during the first billion years

Telescopes like Hubble and ALMA have enabled detailed studies of *the brightest galaxies*



[Bouwens+ (2015)]

Slide credit: Andrei Mesinger

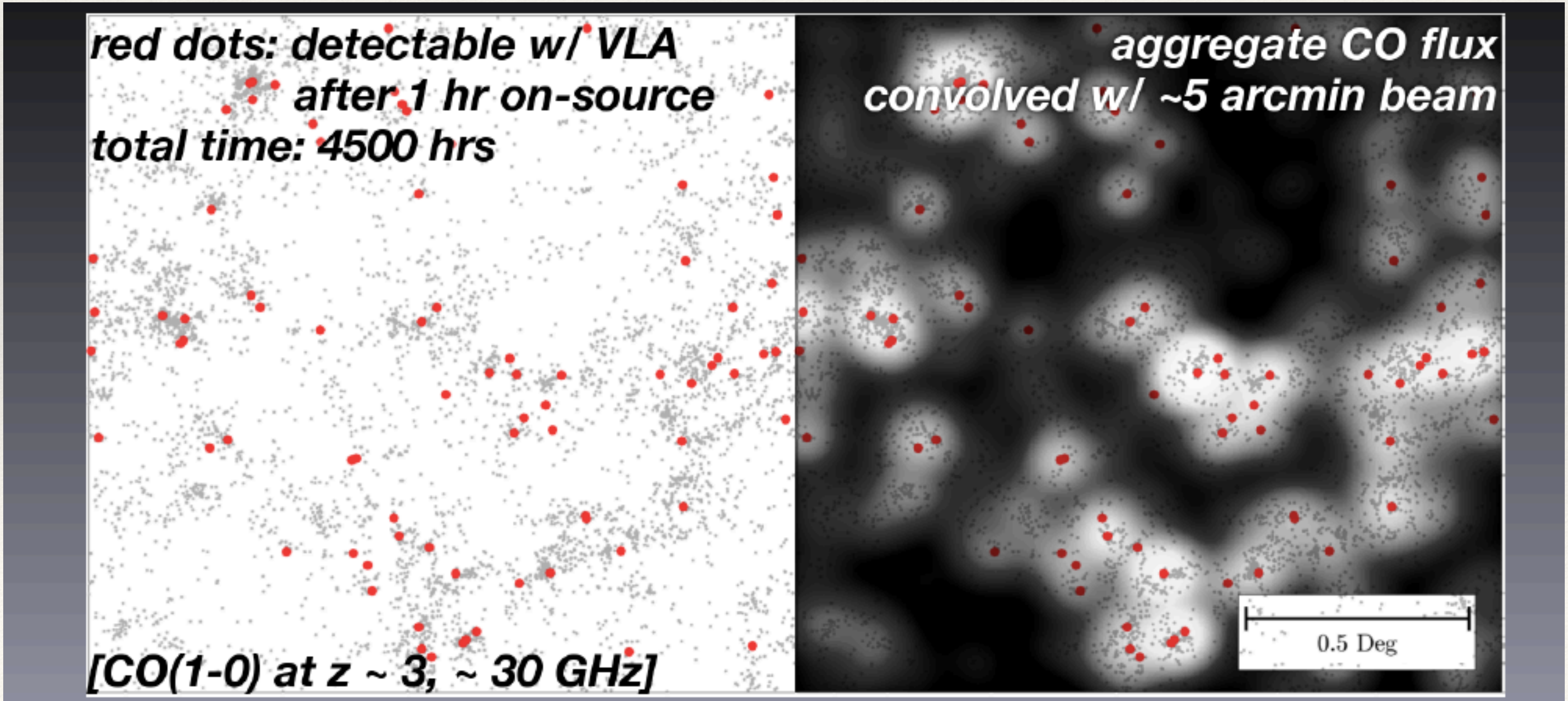


(Line) Intensity mapping (IM)

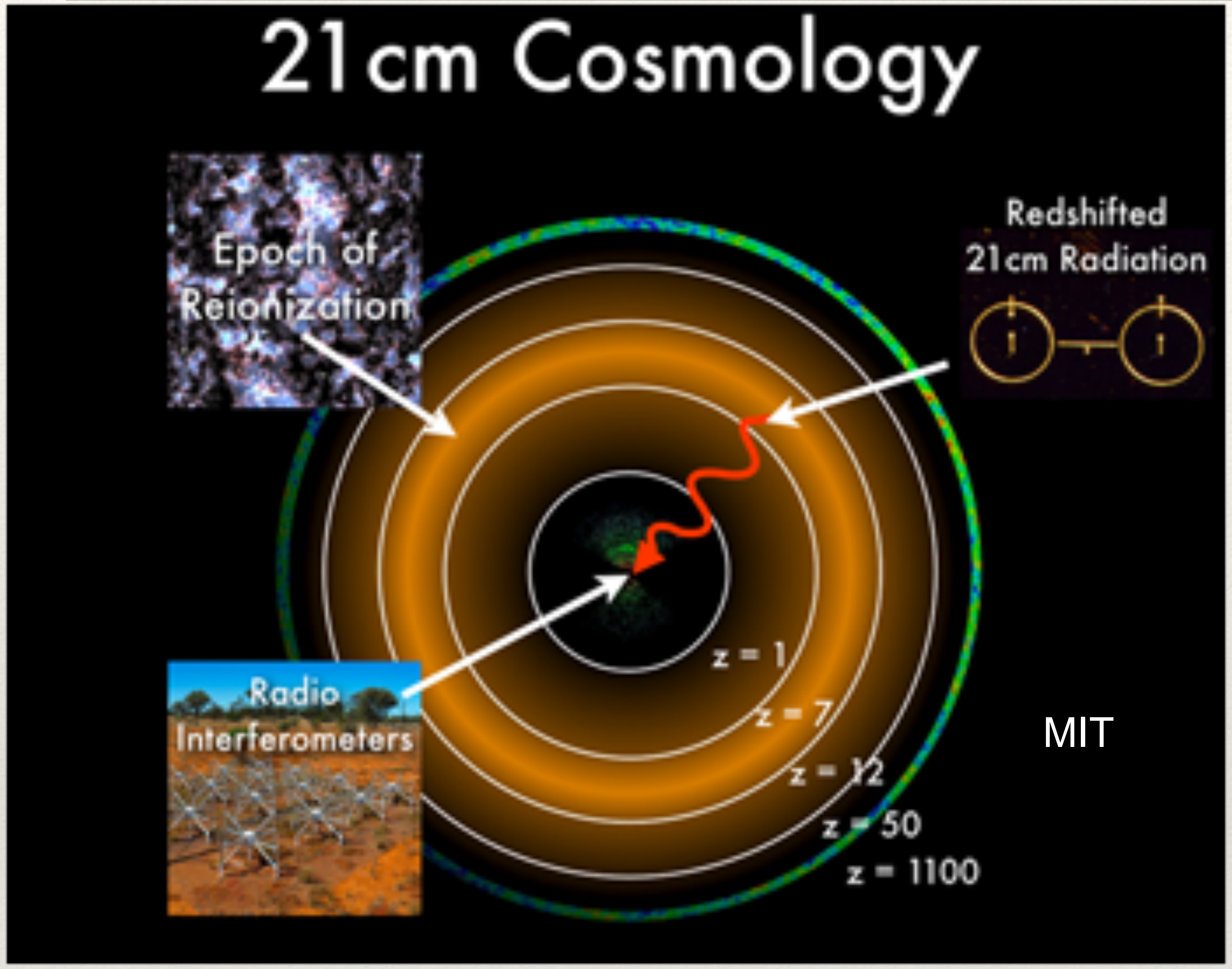
[Early studies: Hogan and Rees 1979, Sunyaev and Zeldovich 1972,1974, Bebington+ 1986]

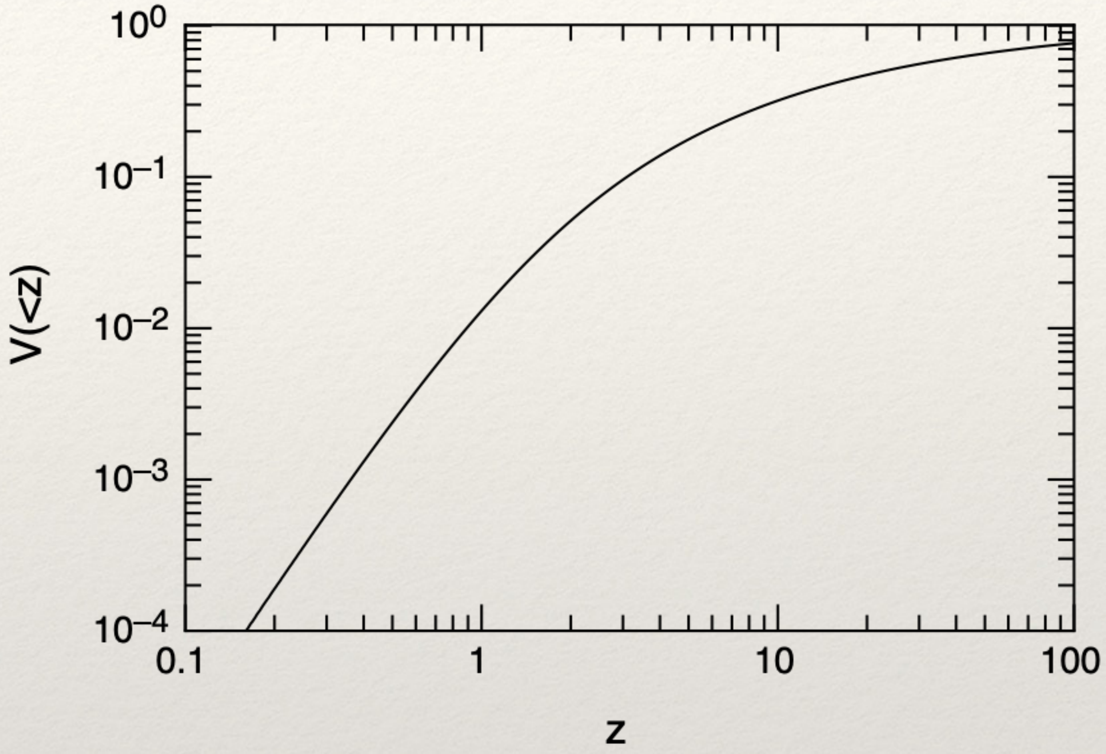
- Measure all structure; sensitive to the integrated emission of all the sources; including foregrounds
- Foregrounds are spectrally smooth, different from the signal
- Different environments, different lines

Credit: Dongwoo Chung



Cosmology with IM

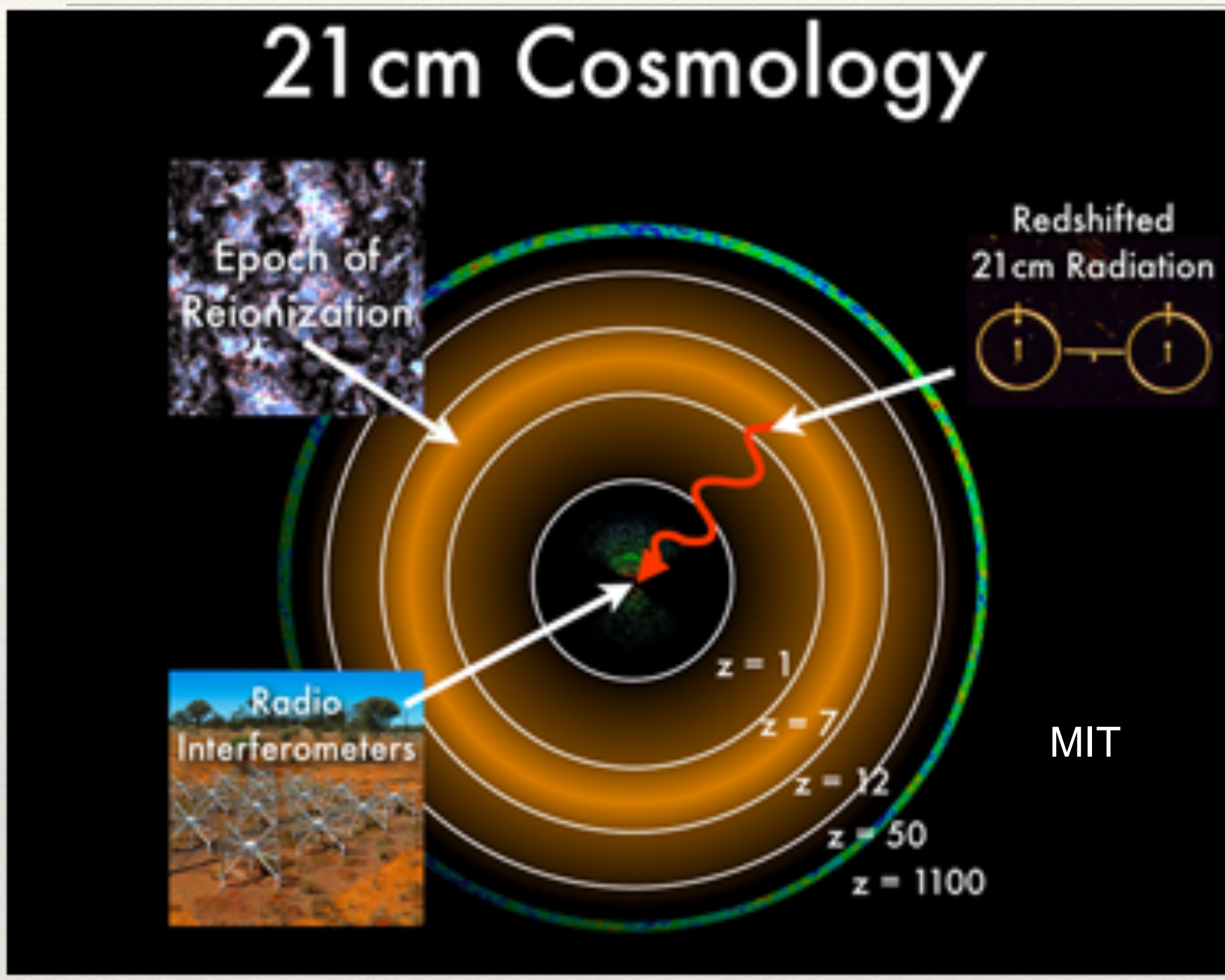


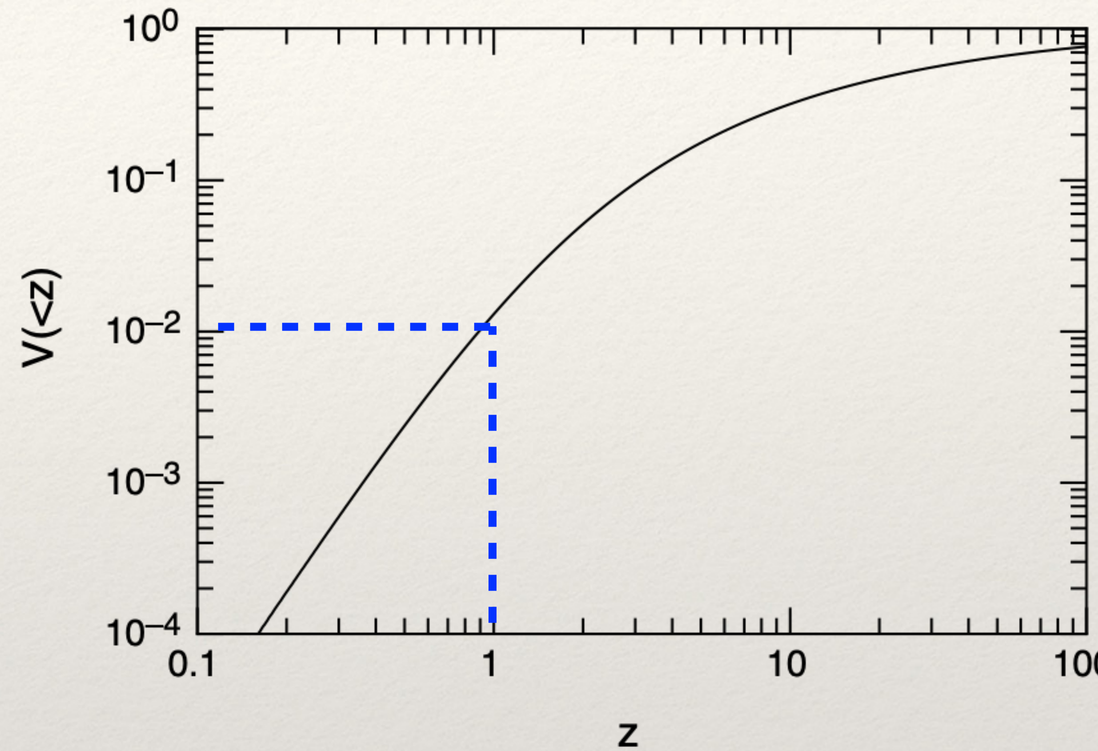


[Loeb & Wyithe (2008)]

Several thousand more modes, much smaller scales than galaxy surveys/CMB

Cosmology with IM

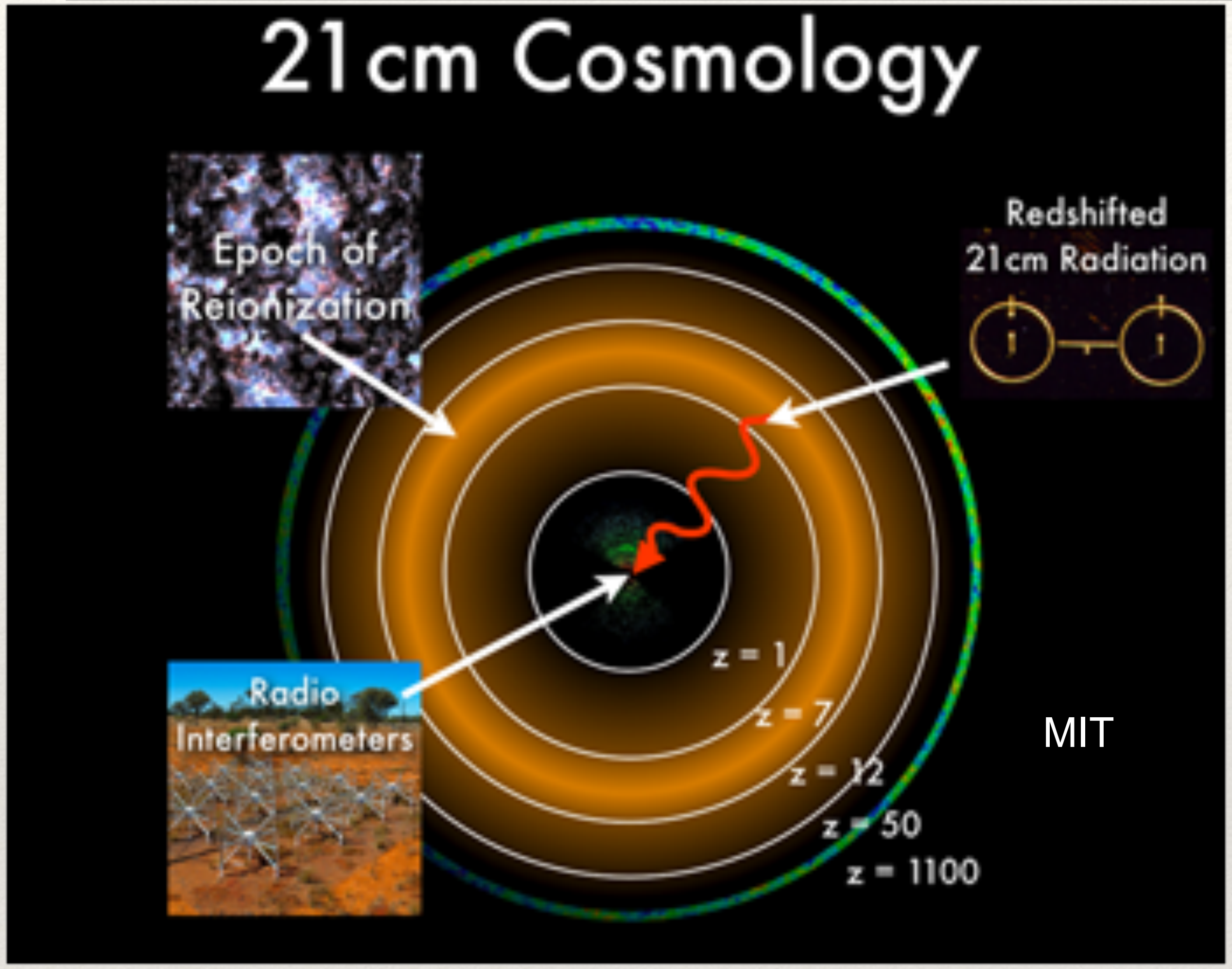




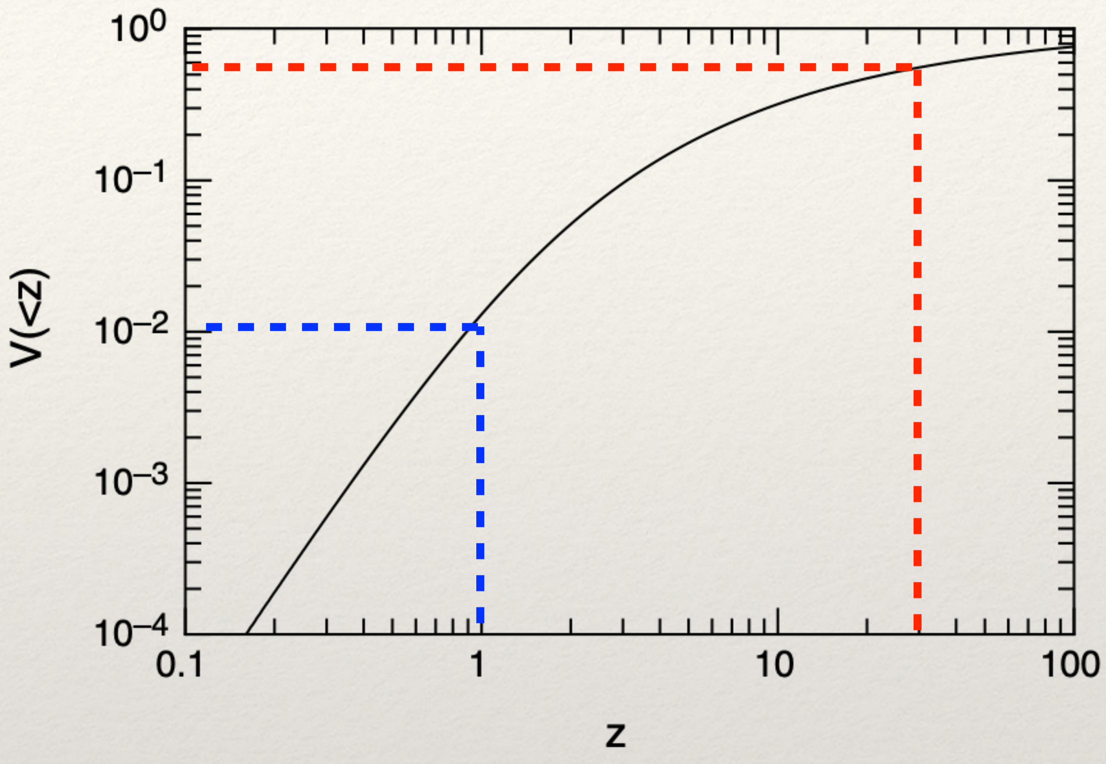
[Loeb & Wyithe (2008)]

Several thousand more modes, much smaller scales than galaxy surveys/CMB

Cosmology with IM



Several thousand more modes, much smaller scales than galaxy surveys/CMB



[Loeb & Wyithe (2008)]

$$N_{21\mathrm{cm}} \sim 8 \times 10^{11} \left(\frac{k_{\mathrm{max}}}{3\ \mathrm{Mpc}^{-1}}\right)^3 \left(\frac{\Delta\nu}{\nu}\right) \left(\frac{1+z}{100}\right)^{-1/2}$$

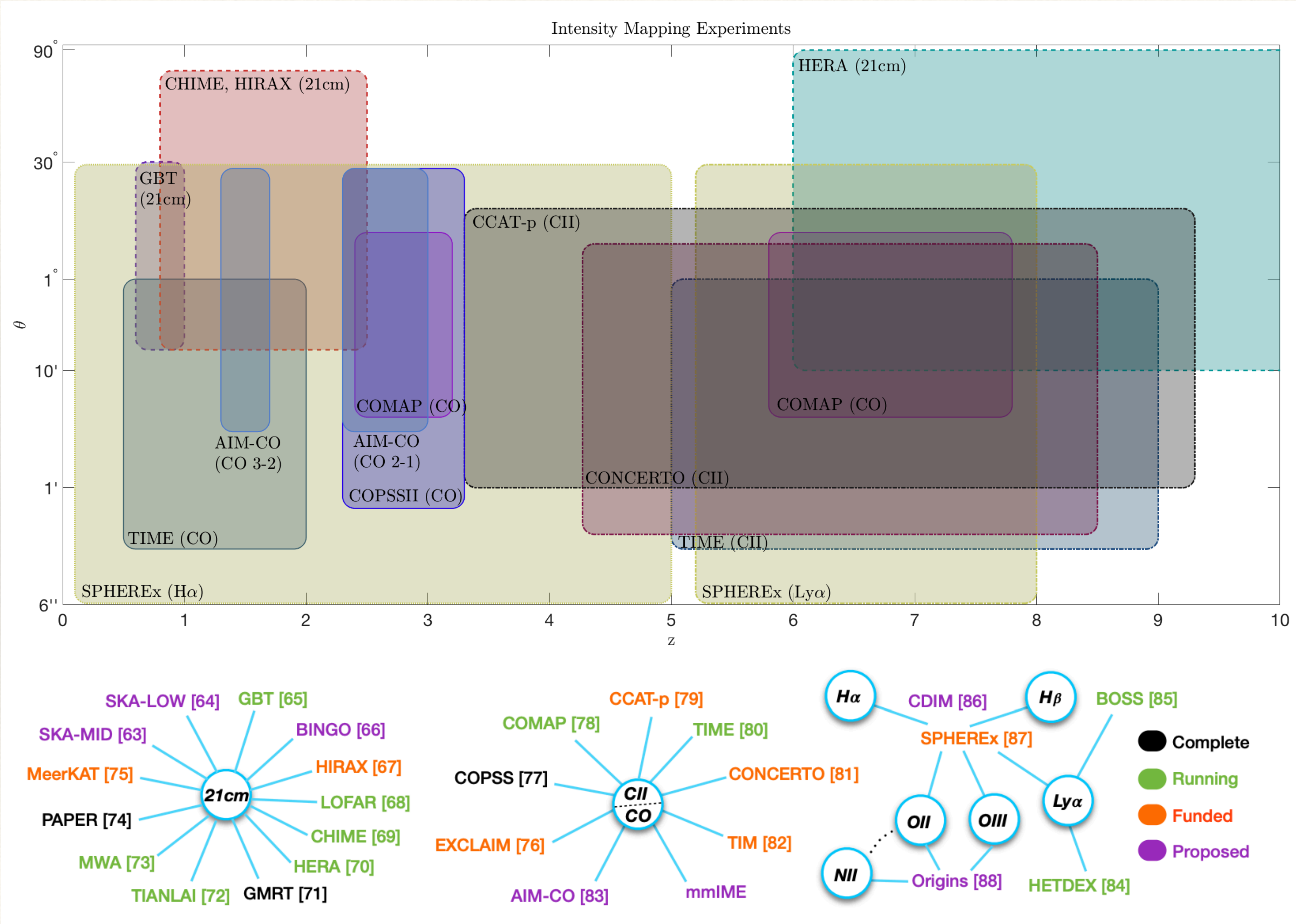
$$\mathrm{Dark\ \ Ages} : k_{\mathrm{max}} \sim 1000\mathrm{Mpc}^{-1}$$

$$N_{\mathrm{CMB}} \sim 10^7$$

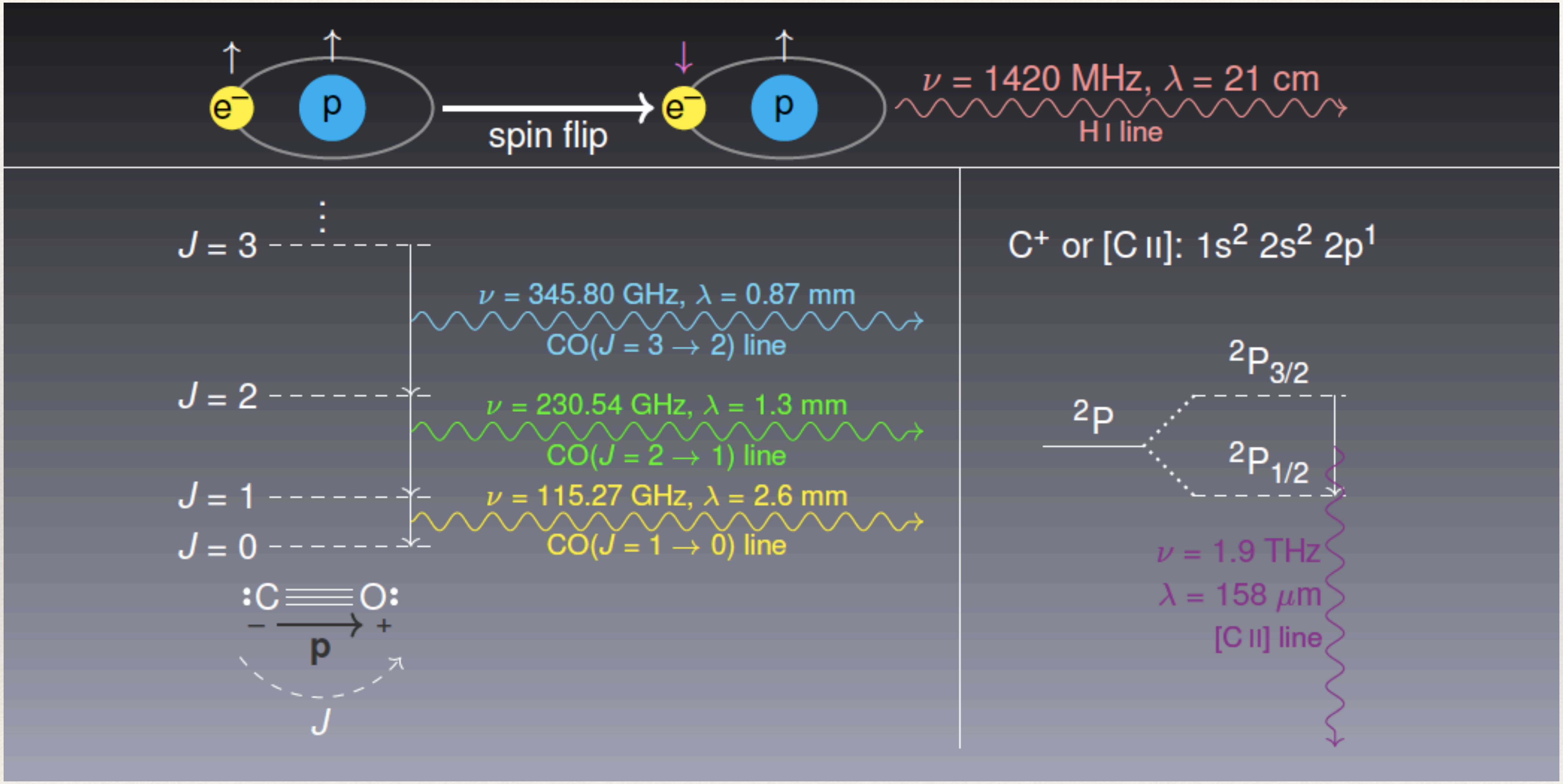
[Furlanetto (2019)]

A plethora of experiments …

[reviews: Kovetz+ (2017, 2019), Bernal and Kovetz (2022)]

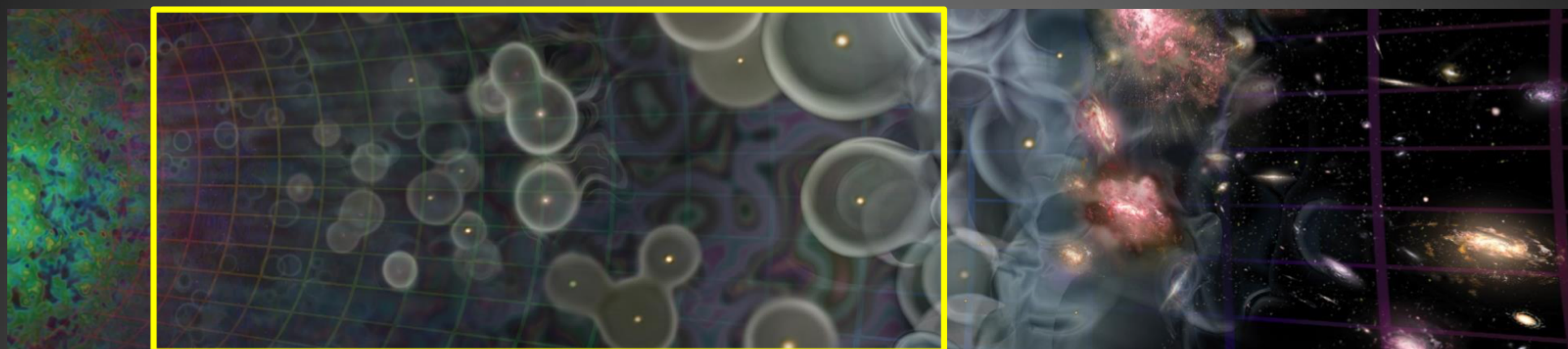


Atomic and molecular lines

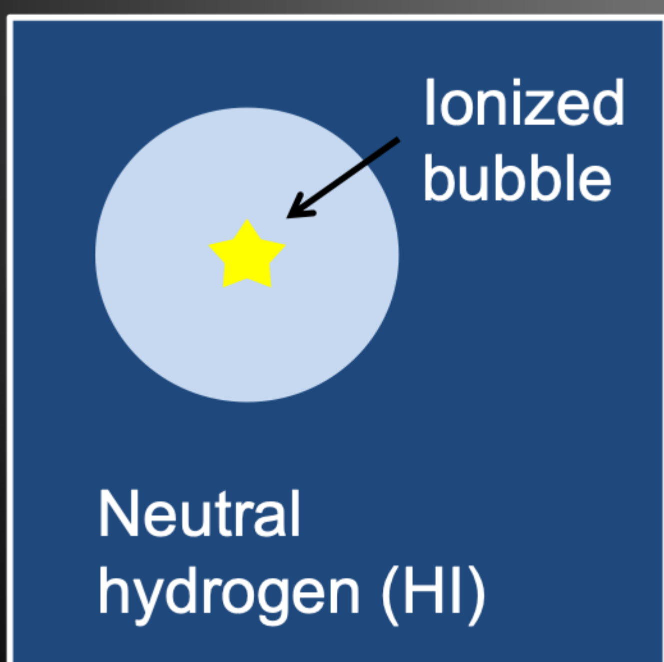


Credit: Dongwoo Chung

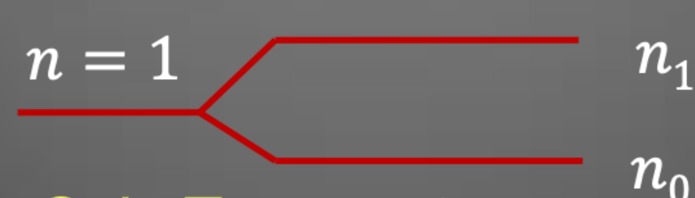
Signature of the Neutral Gas
21-cm Signal



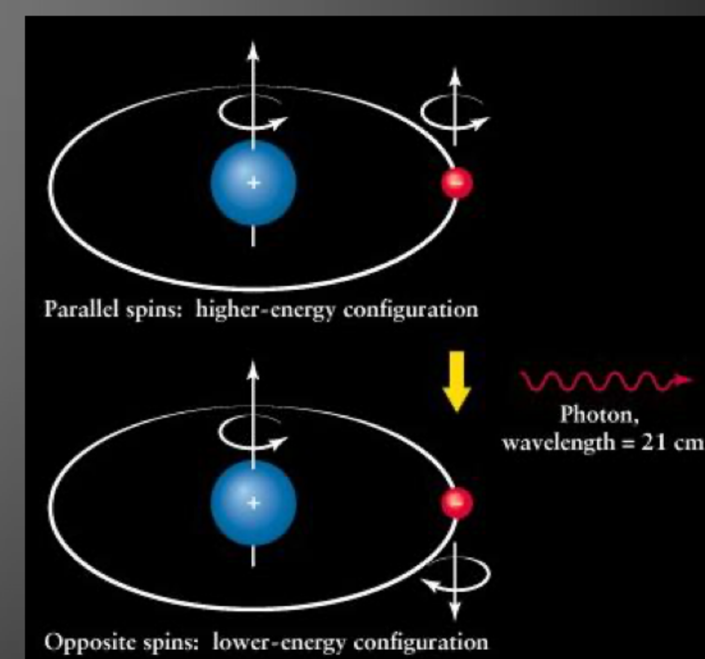
- Useful: 21-cm line (spin-flip transition)
- Can be observed today in Radio



λ = 21 cm
ν = 1420 MHz



Spin Temperature
$n_1/n_0 \equiv 3\exp(-T_*/T_S)$,
$T_* = 0.068$ K



Slide credit: Anastasia Fialkov

The 21 cm IM signal

- Radiative transfer:

$$T_b(\nu) = T_S(1 - e^{-\tau_\nu}) + T_\gamma e^{-\tau_\nu}$$

- Spin temperature:

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp(-E_{10}/kT_S)$$

- Optical depth:

$$\tau_0 = \frac{3\lambda_{10}^3 A_{10}}{32\pi} \left(\frac{0.068\ \mathrm{K}}{T_S}\right) (1+\delta) \left(\frac{x_{HI} n_H}{H(z)}\right);\ A_{10} = 2.85 \times 10^{-15} s^{-1}$$

- Observable:

$$\delta T_b(\nu) = \frac{T_S - T_\gamma(z)}{(1+z)}(1 - e^{-\tau_0})$$

$$\approx \quad 16 x_{HI}(1+\delta) \left[\left(\frac{1+z}{10}\right)\left(\frac{0.3}{\Omega_m h^2}\right)\right]^{0.5} \left[1 - \frac{T_\gamma(z)}{T_S}\right] \left(\frac{\Omega_b h^2}{0.02}\right) \mathrm{mK}$$

The 21 cm IM signal

Statistical fluctuations

in the intensity mapping signal:

$$\delta_{21}(\mathbf{x}) \equiv [\delta T_b(\mathbf{x}) - \delta \overline{T_b}]/\delta \overline{T_b}$$

$$\left\langle \tilde{\delta}_{21}(\mathbf{k}_1)\tilde{\delta}_{21}(\mathbf{k}_2) \right\rangle \equiv (2\pi)^3 \delta_D(\mathbf{k}_1 - \mathbf{k}_2) P_{21}(\mathbf{k}_1)$$

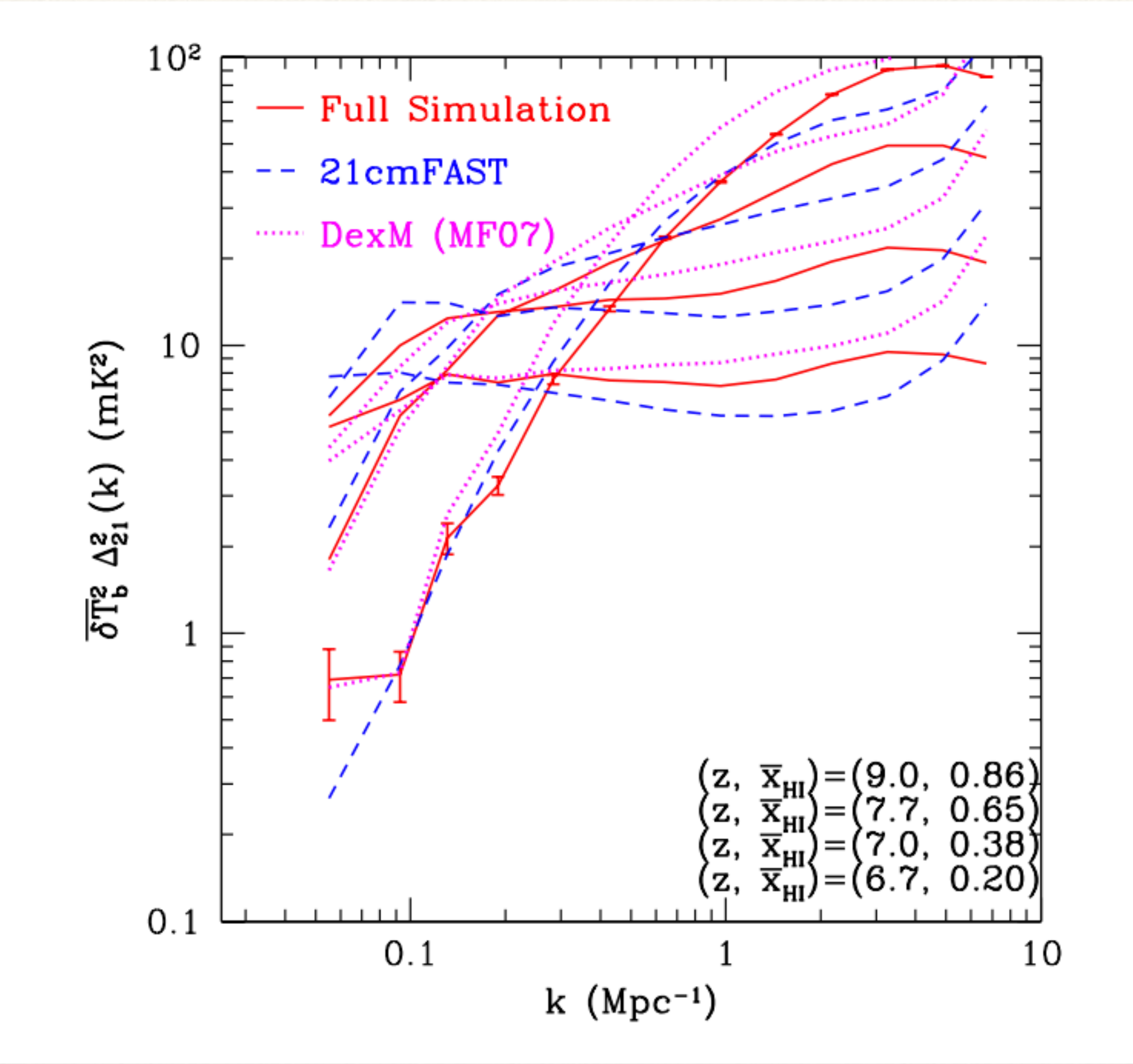
P_{21} will be a function of both k and z

$$\delta_{21} = b_m \delta_m + \ldots$$

In the limit of the linewidth of sources

<< frequency resolution,

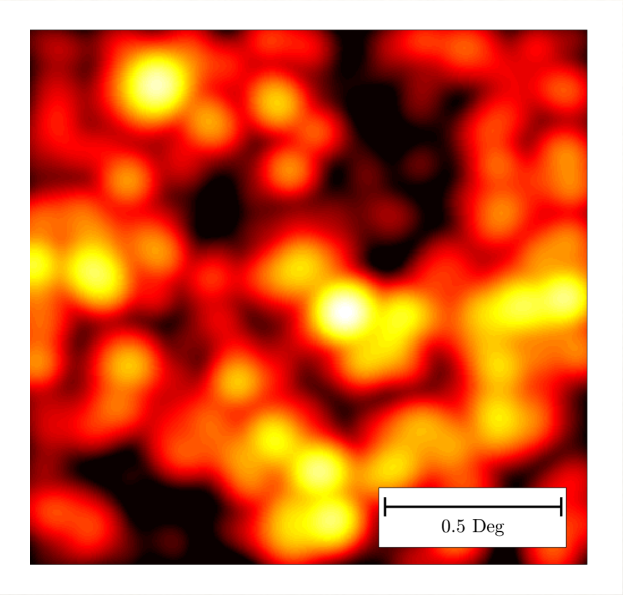
we can write P_{21} in terms of $P_{\rm cdm}$

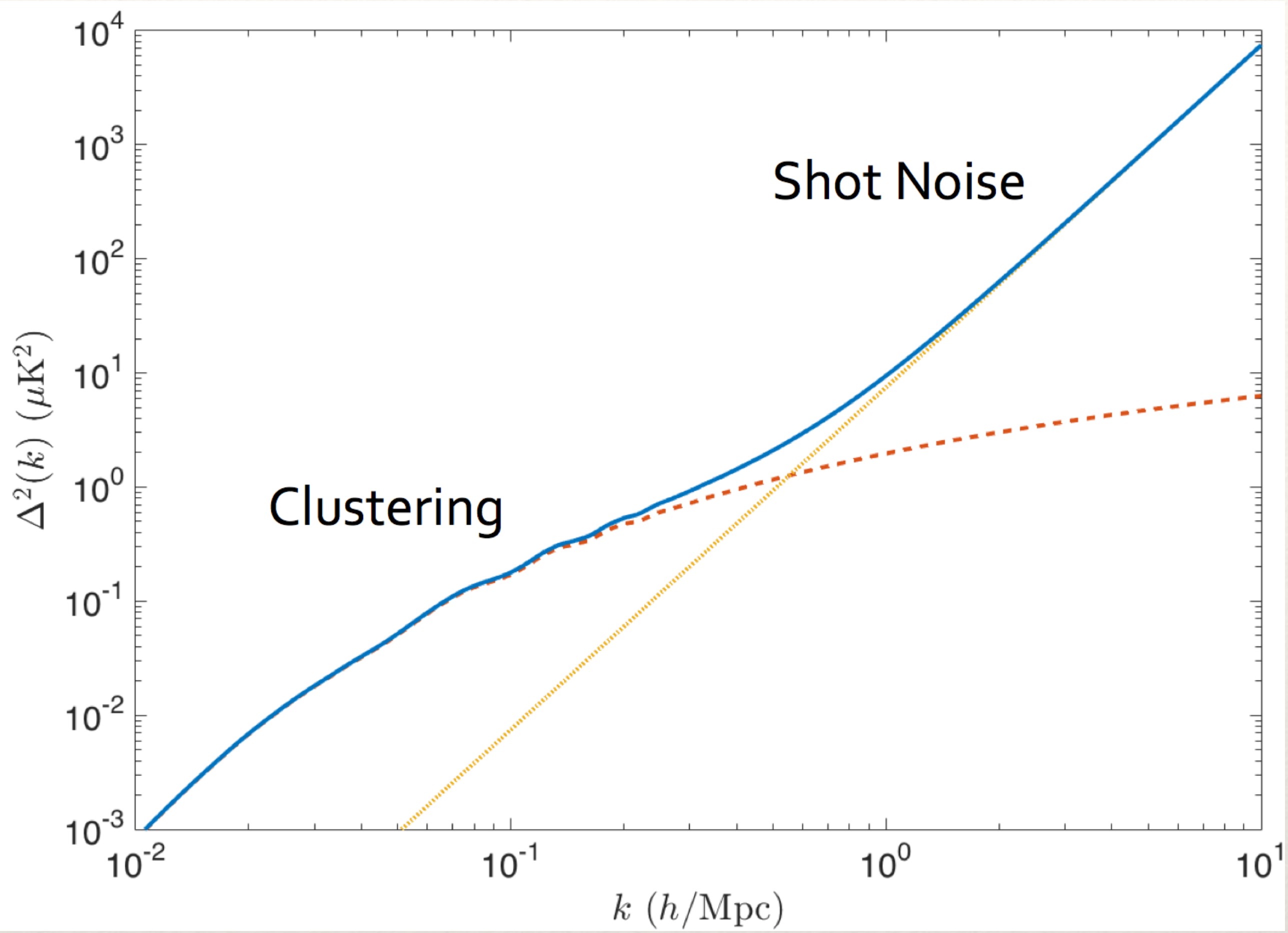


21cmFAST; Mesinger, Furlanetto & Cen (2011)

Fluctuations: as a function of fixed transverse scale, or fixed redshift

The ‘astrophysical systematic’





$$P_{\mathrm{line}}(k,z) = \langle I(z)\rangle^2 b^2(z) P_{\mathrm{cdm}}(k,z) + P_{\mathrm{shot}}(z)$$

ASTROPHYSICS **COSMOLOGY**

There is an interplay of astrophysics and cosmology

The tracer-halo connection

$$P_{\rm line}(k,z) = \langle I(z)\rangle^2 b^2(z) P_{\rm cdm}(k,z) + P_{\rm shot}(z)$$

Bias times line intensity

Matter fluctuations

Halo bias

$$b(z) \propto \int dM_h \frac{dn}{dM_h}(z) L_{\rm tr}(M_h, z) b_h(M_h)$$

Tracer-halo relation

$$I(z) \propto \int dM_h \frac{dn}{dM_h}(z) L_{\rm tr}(M_h, z)$$

Halo mass function

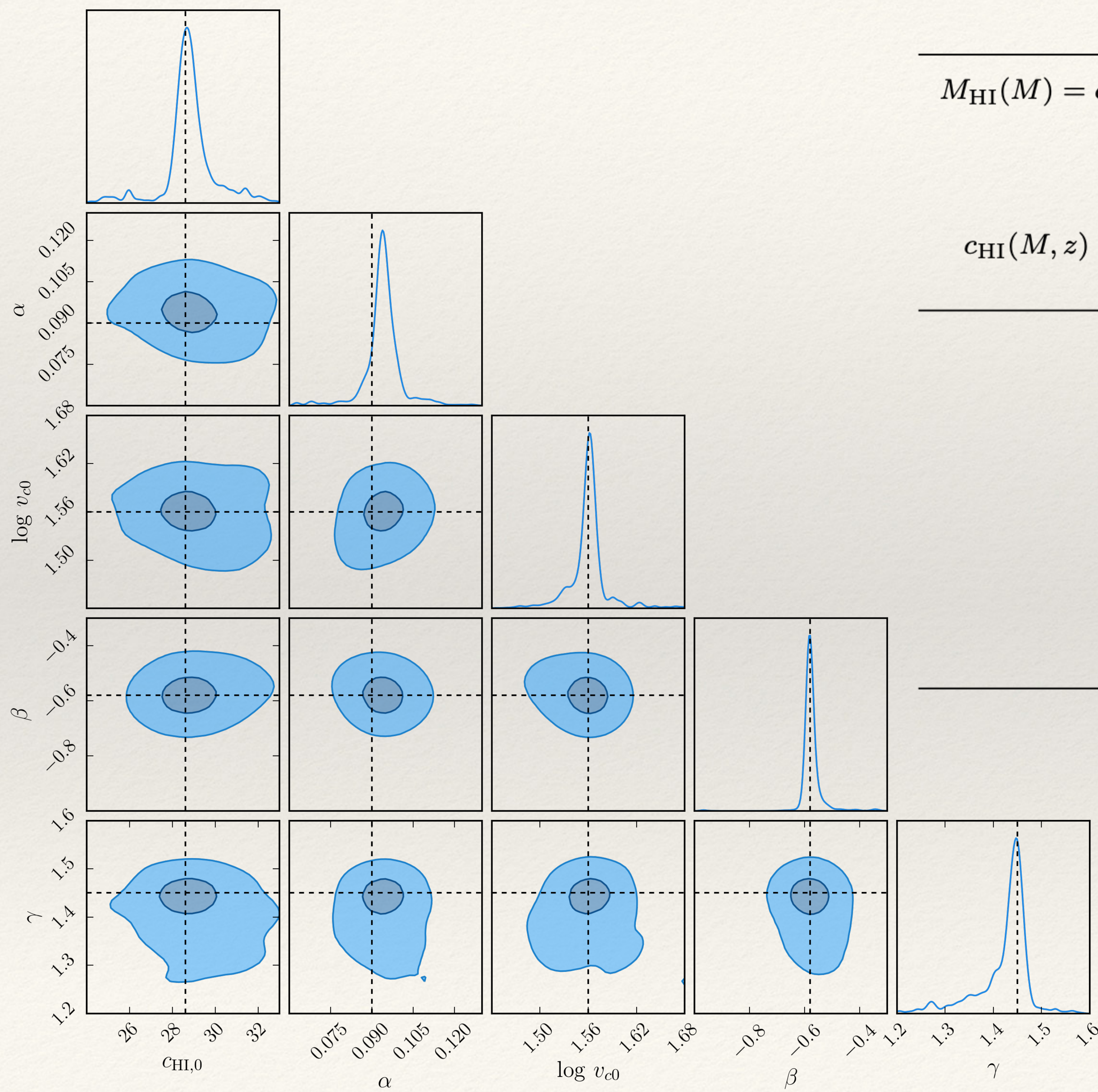
$$P_{\rm 1h} \propto \int dM_h \frac{dn}{dM_h} L_{\rm tr}(M_h, z)^2 \,|\, u_{\rm tr}(k\,|\,M)\,|^2$$

Shot noise

Small scales; tracer profile in halo

A halo model for HI

[HP+, MNRAS (2017a, b), HP & Kulkarni (2017)]



$$M_{\rm HI}(M) = \alpha f_{H,c} M \left(M/10^{11} h^{-1} M_{\odot}\right)^{\beta} \exp\left[-\left(v_{c0}/v_c(M)\right)^3\right]$$

$$\rho_{\rm HI}(r) = \rho_0 \exp(-r/r_s);$$

$$c_{\rm HI}(M, z) \equiv R_v/r_s = c_{\rm HI,0} \left(M/10^{11} M_{\odot}\right)^{-0.109} 4/(1+z)^{\gamma}$$

$$c_{\rm HI,0} = 28.65 \pm 1.76$$

$$\alpha = 0.09 \pm 0.01$$

$$\log v_{c,0} = 1.56 \pm 0.04$$

$$\beta = -0.58 \pm 0.06$$

$$\gamma = 1.45 \pm 0.04$$

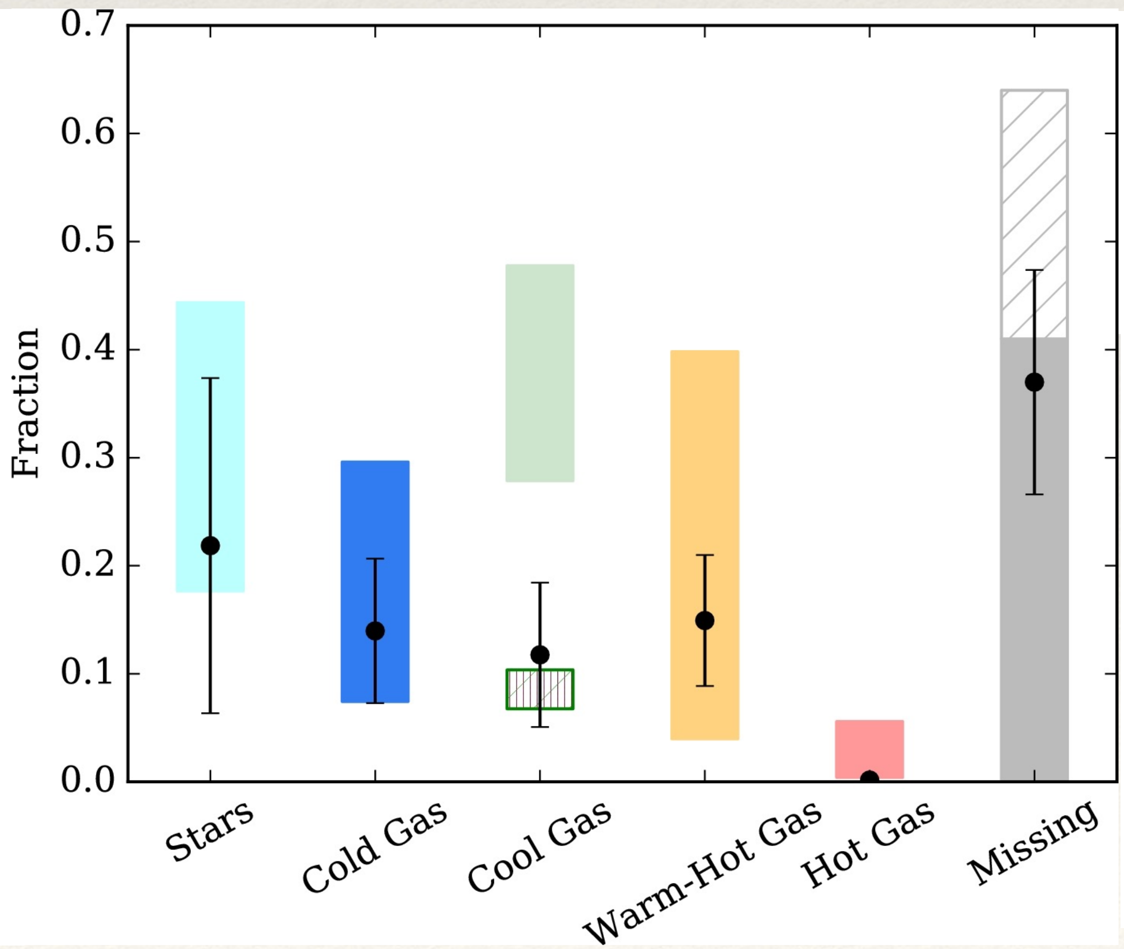
CONSTRAINTS FROM CURRENT HI GALAXY, DLA, IM DATA

Insights

$$\alpha f_{\mathrm{H,c}} M \left(\frac{M}{10^{11} h^{-1} M_\odot}\right)^{\beta} \exp\left[-\left(\frac{v_{c,0}}{v_c(M,z)}\right)^{3}\right]$$

HI Fraction relative to cosmic

$\alpha = 0.09$



ON THE (NON)EVOLUTION OF H I DISKS OVER COSMIC TIME

J. Xavier Prochaska[1] and Arthur M. Wolfe[2]

Draft version October 30, 2018

Accretion of fresh HI = Consumption for star formation

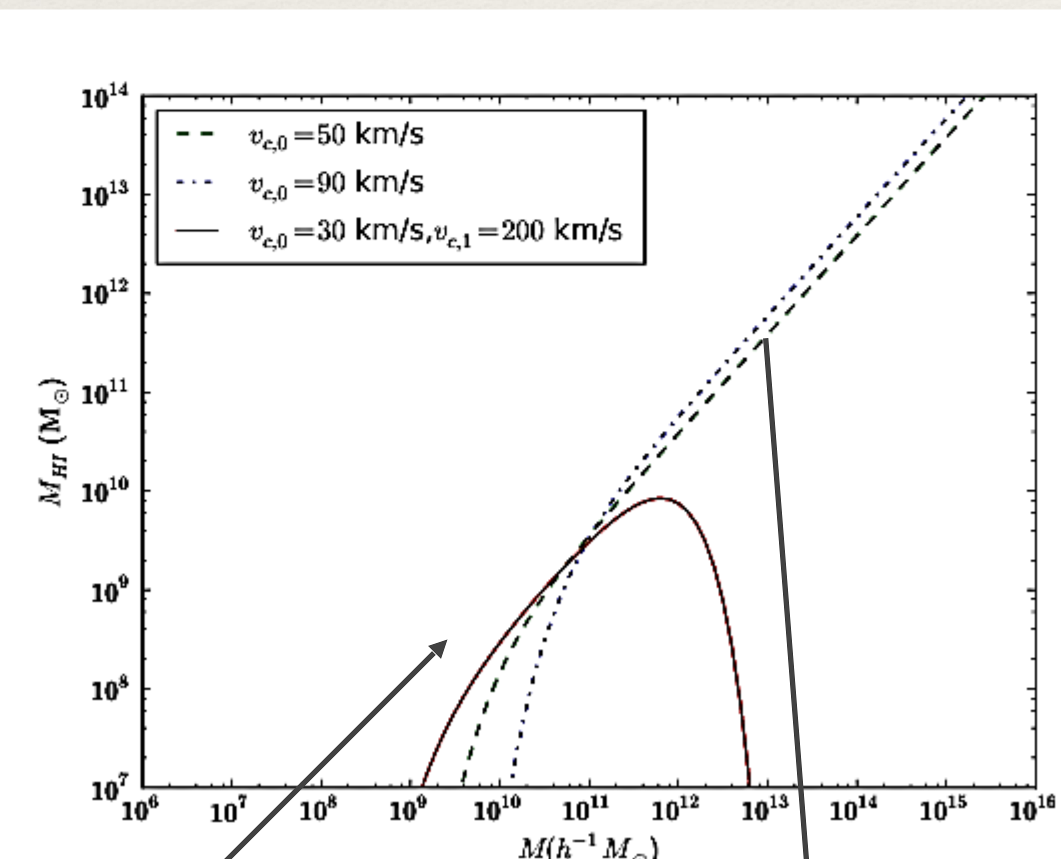
[Dutton+ (2016), Werk+ (2014), Stern+ (2016), Prochaska & Wolfe (2008)]

Insights

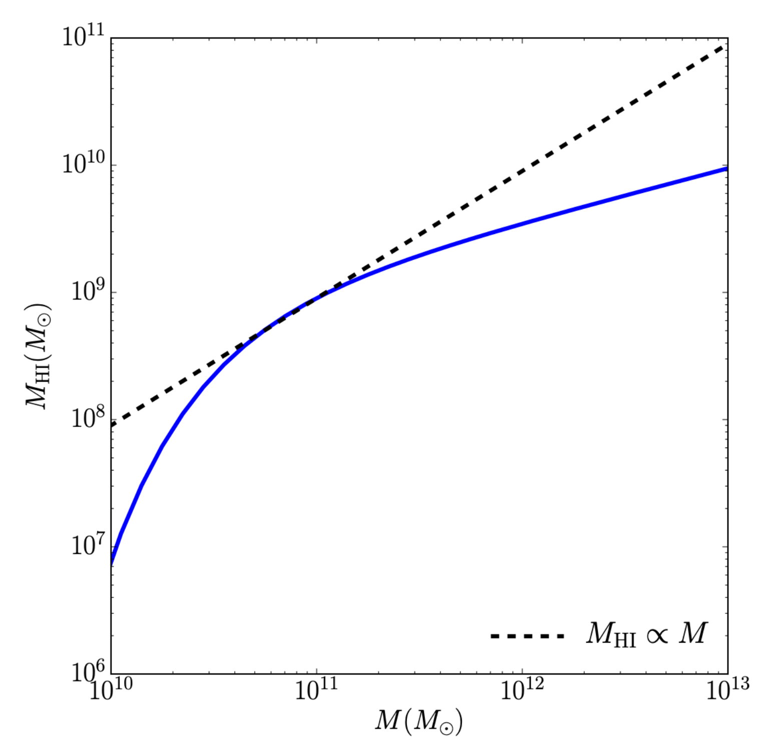
$$\alpha f_{\mathrm{H,c}} M \left(\frac{M}{10^{11} h^{-1} M_\odot}\right)^{\beta} \exp\left[-\left(\frac{v_{c,0}}{v_c(M,z)}\right)^3\right]$$

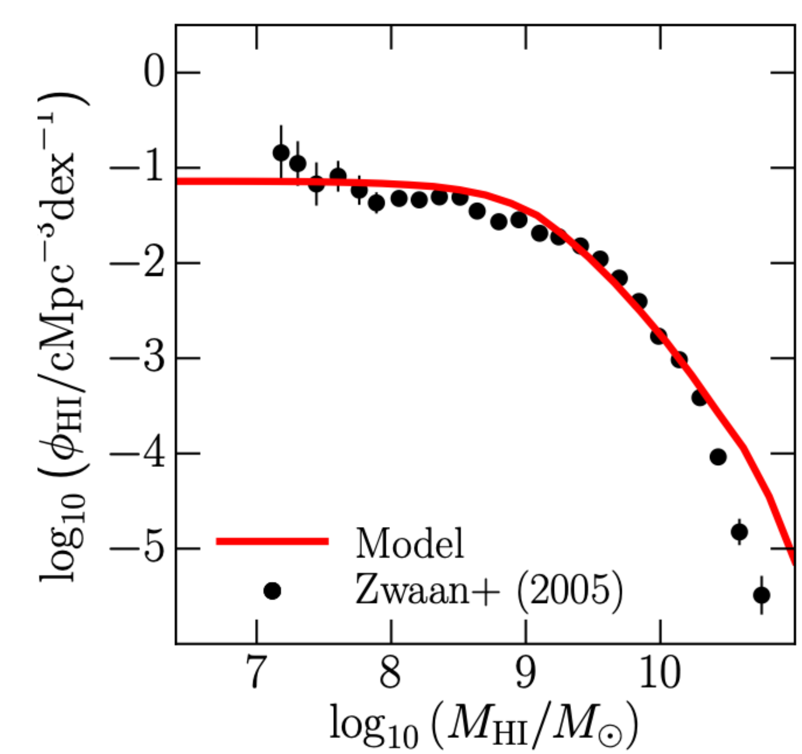
Slope

[Barnes & Haehnelt 2014; Bagla+ (2010), HP+ (2016)]



$\beta = -0.58$





21-cm based **DLA based**

Non-unit slope **of HIHM: quenching, feedback** [Birnboim+ 2007; Finlator+ (2013)]

Insights

$$\alpha f_{\mathrm{H,c}} M \left(\frac{M}{10^{11} h^{-1} M_\odot} \right)^{\beta} \exp\left[- \left(\frac{v_{c,0}}{v_c(M,z)} \right)^3 \right]$$

Lower cutoff

$$v_{\mathrm{c},0} = 36.3\ \mathrm{km/s}$$

Photoionization increases cooling timescales

Constraints on UV background

Mon. Not. R. Astron. Soc. **278,** L49–L54 (1996)

Photoionization and the formation of dwarf galaxies

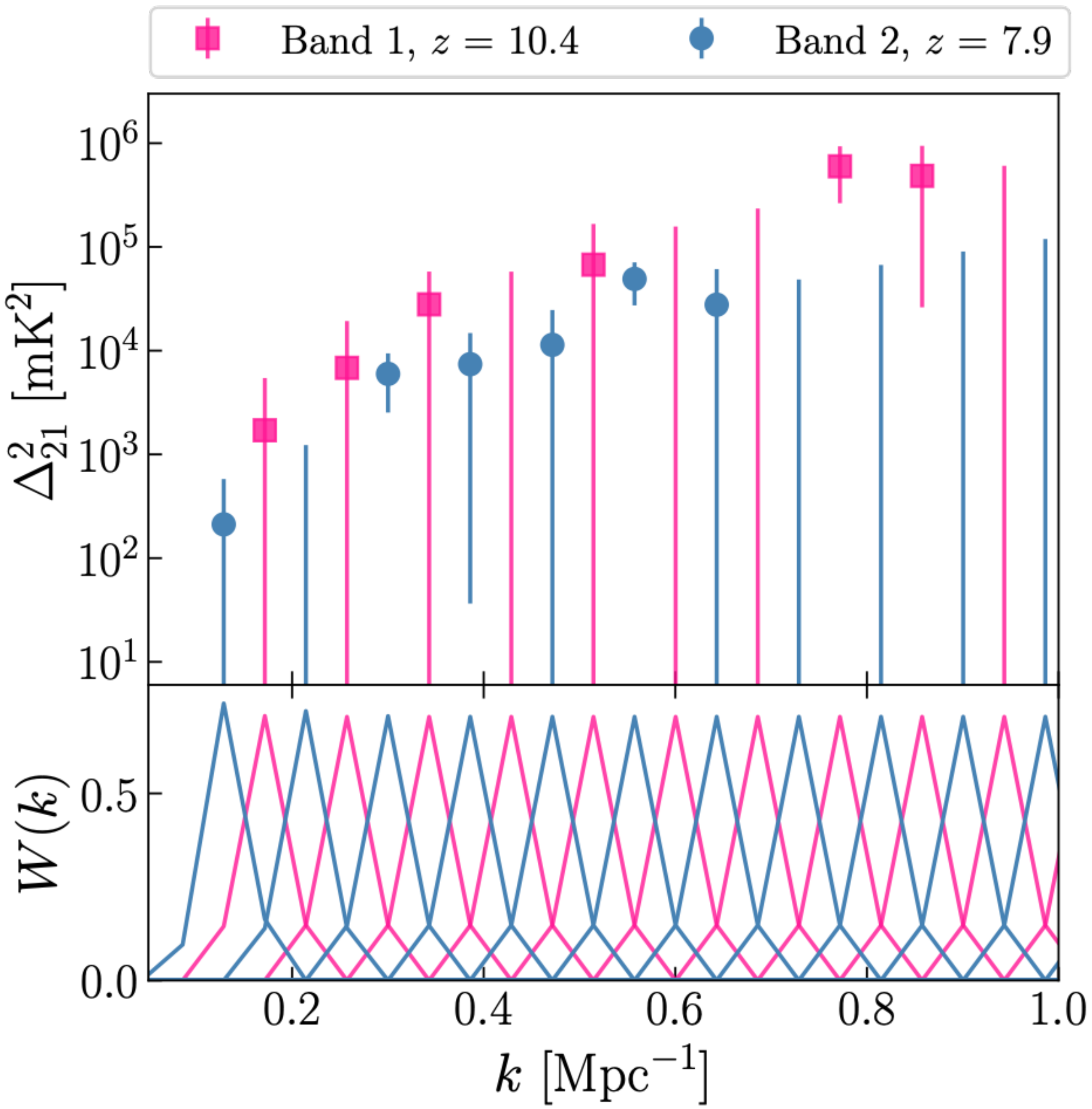
Thomas Quinn,[1] Neal Katz[1] and George Efstathiou[2]
[1] *Department of Astronomy, University of Washington, Seattle, WA 98195, USA*
[2] *Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH*

… suppression: circular speeds ~ 37 km/s!

[Rees (1986), Efstathiou (1992), Babul & Rees (1992),Quinn+ (1996), …]

21 cm IM observations

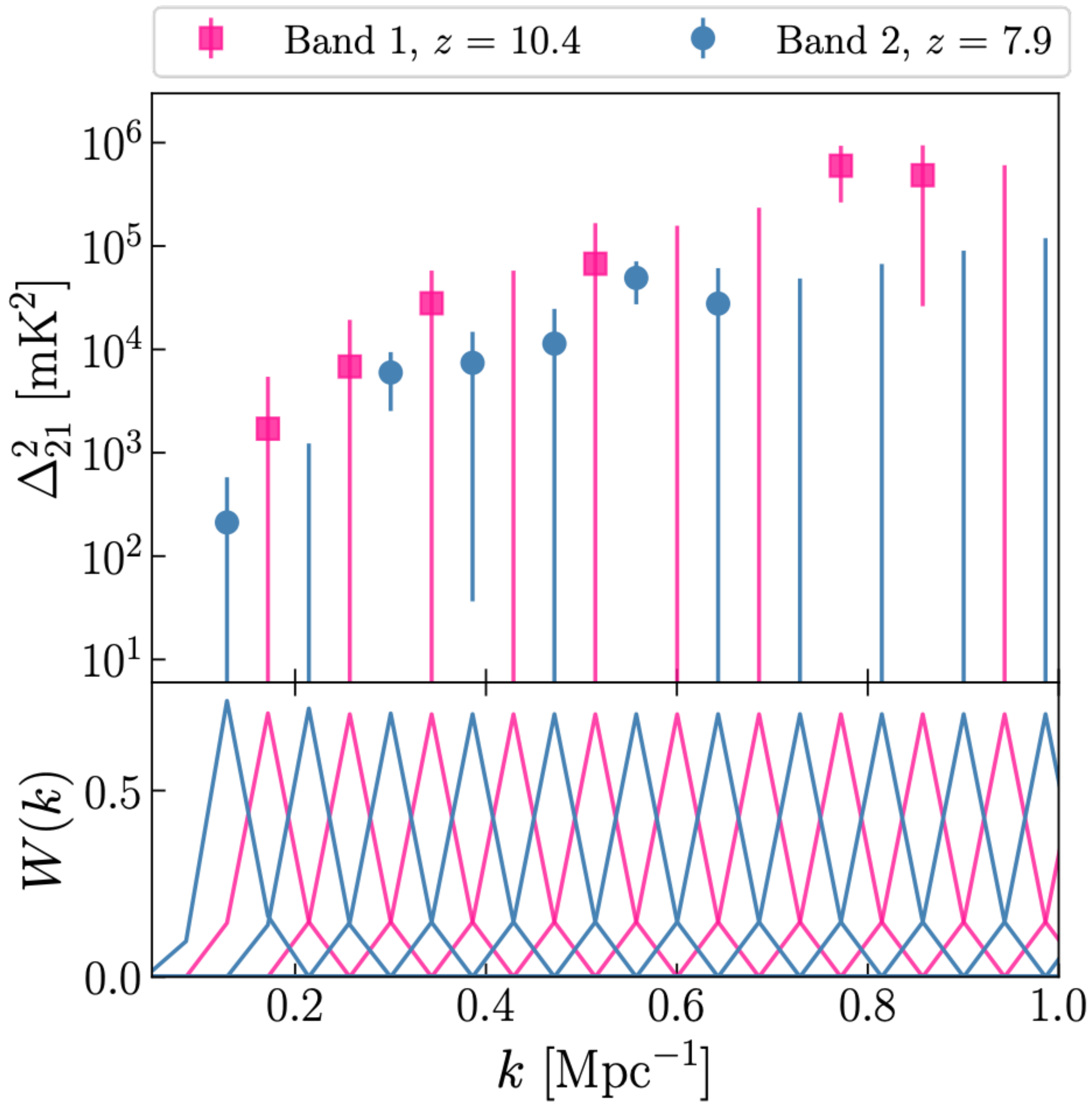
Slide credit: Jordan Mirocha



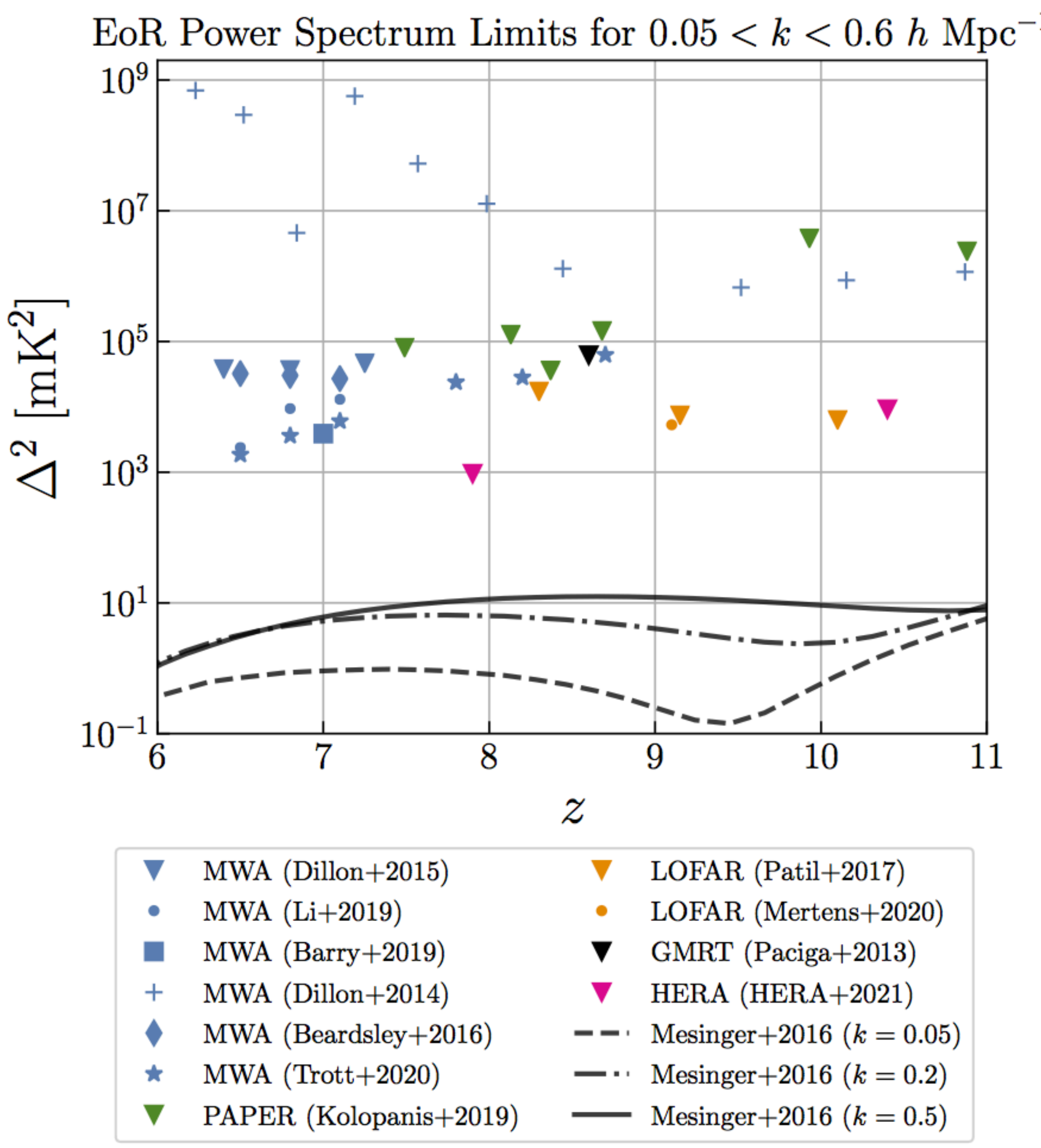
HERA Collaboration (2022a)

21 cm IM observations

Slide credit: Jordan Mirocha

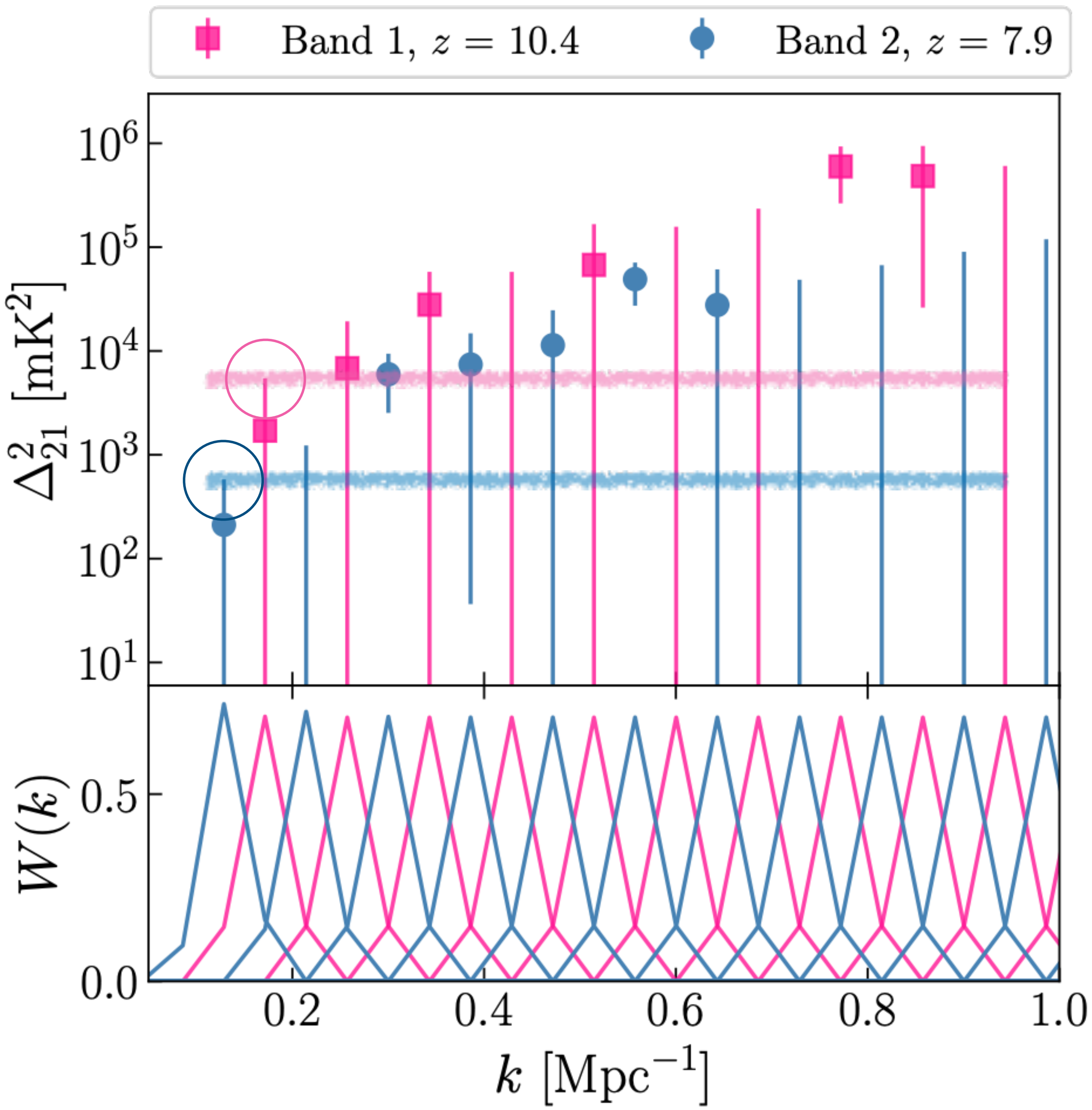


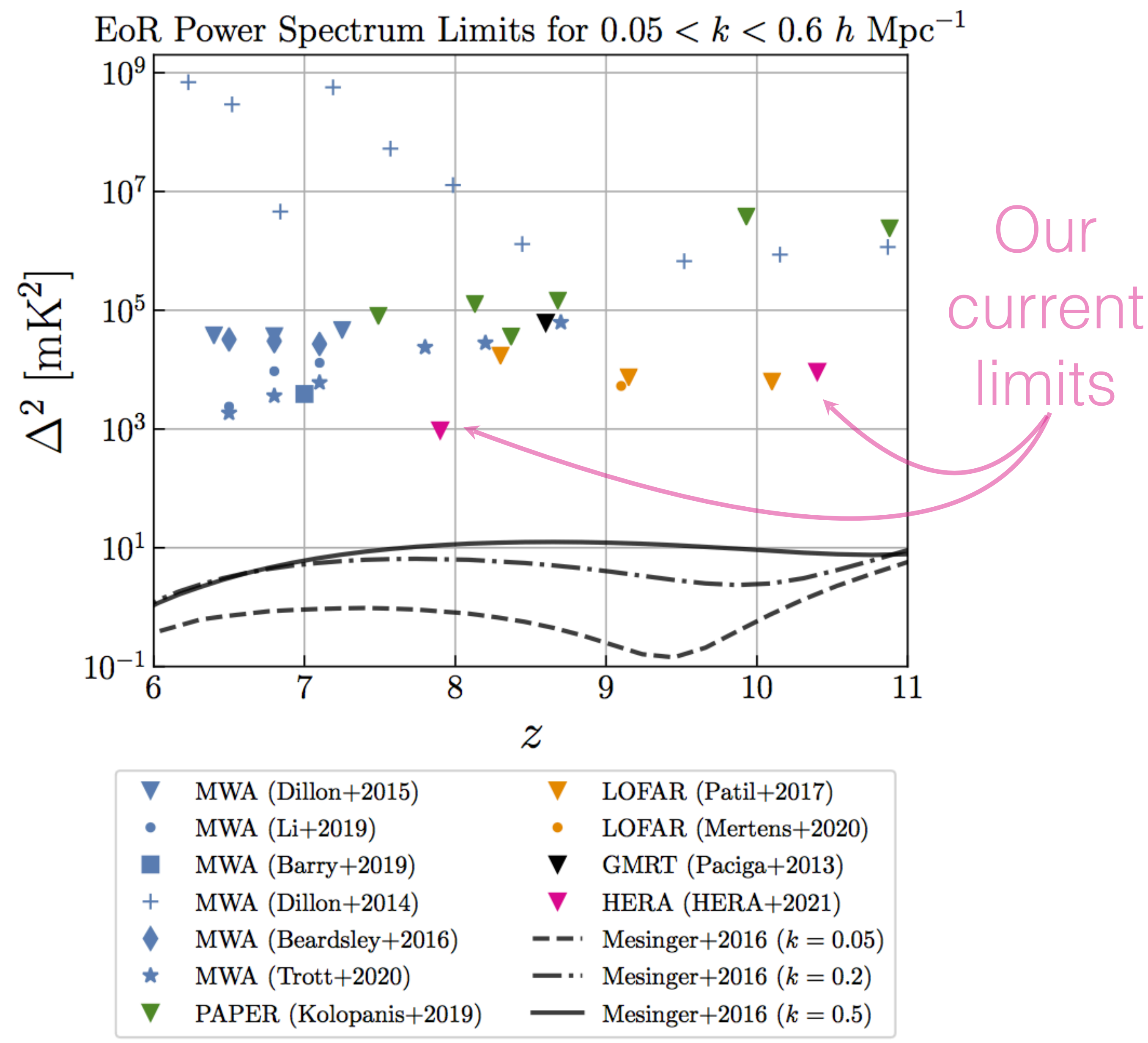
HERA Collaboration (2022a)



21 cm IM observations

Slide credit: Jordan Mirocha



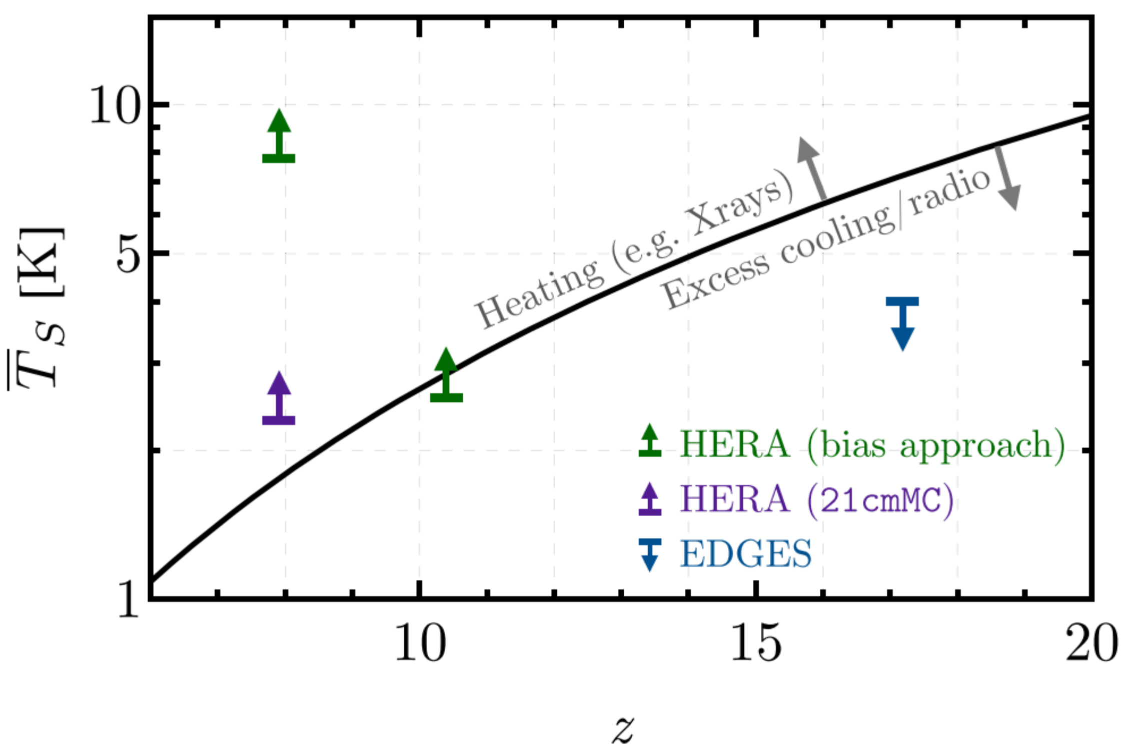


HERA Collaboration (2022a)

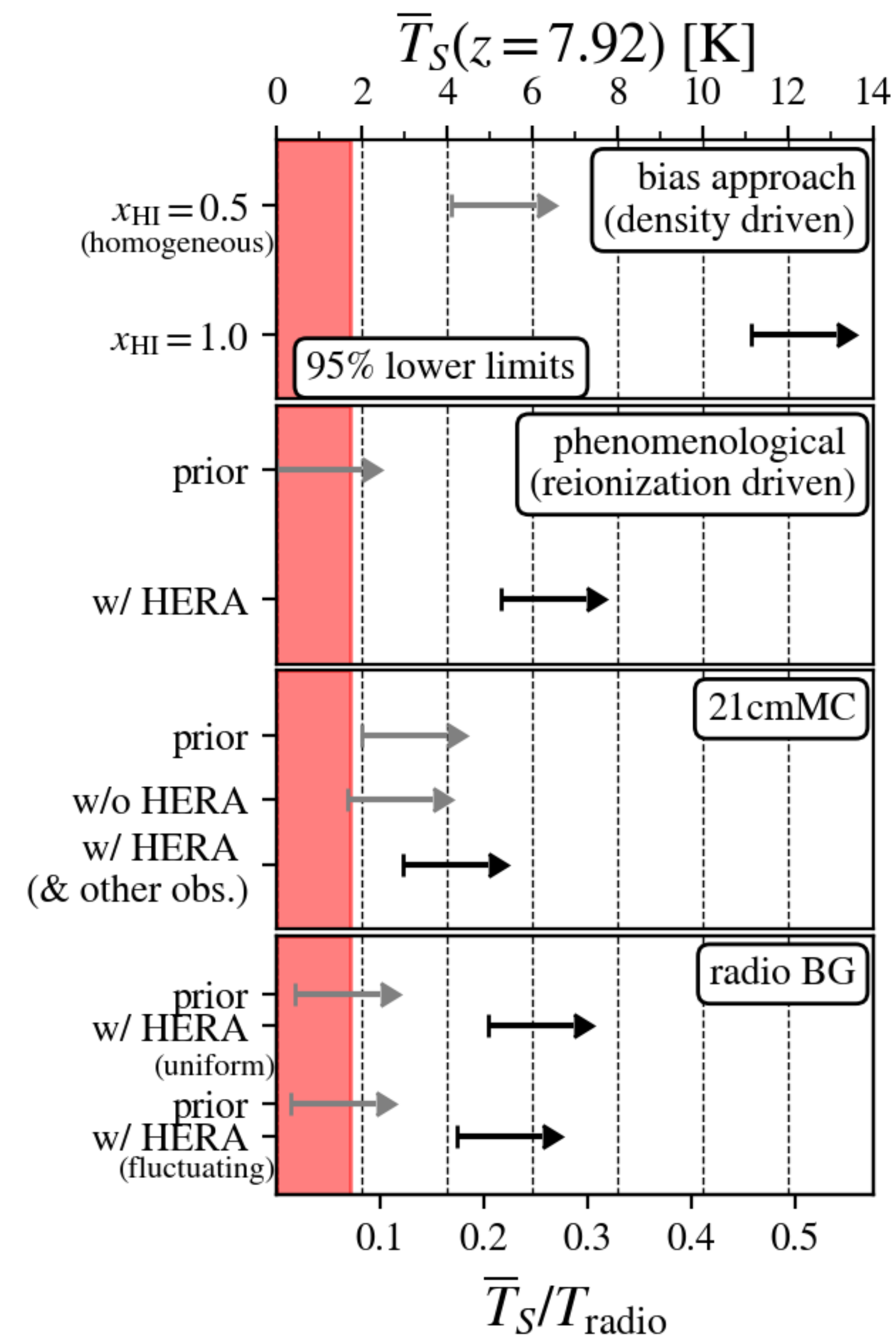
HERA constraints on physics

Slide credit: Jordan Mirocha

- Constraints on IGM temperature
- Simplest model predicts the highest temperature
- **Remaining models consistent with 95% lower limit on z~8 temperature of ~3-5 Kelvin, clearly above the adiabatic cooling limit (1.8 K at z=8).**

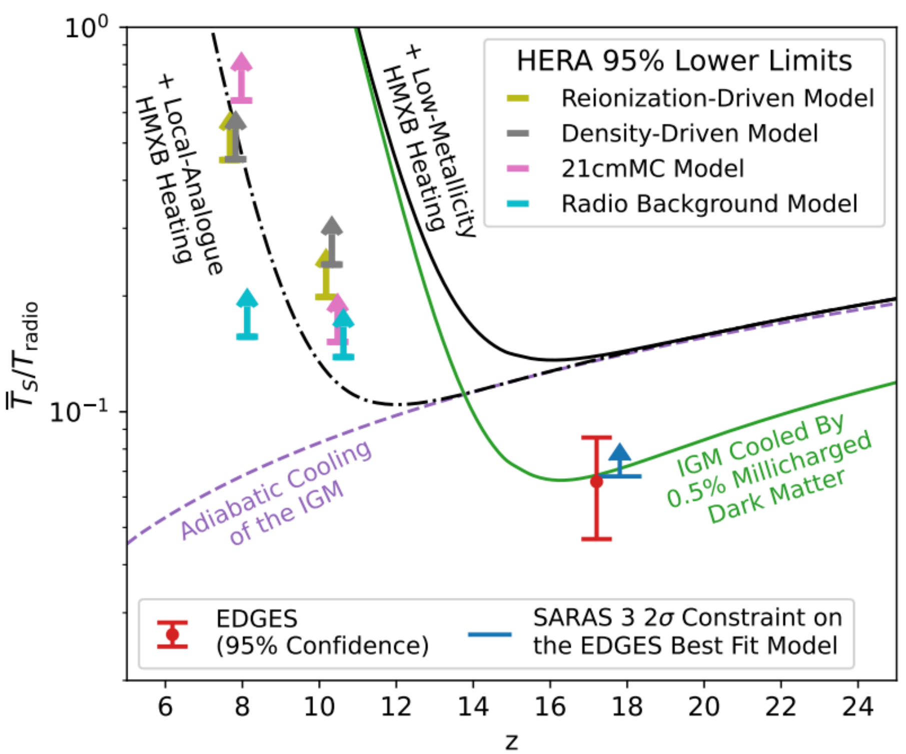


HERA Collaboration et al. (2022b)
(2108.07282)

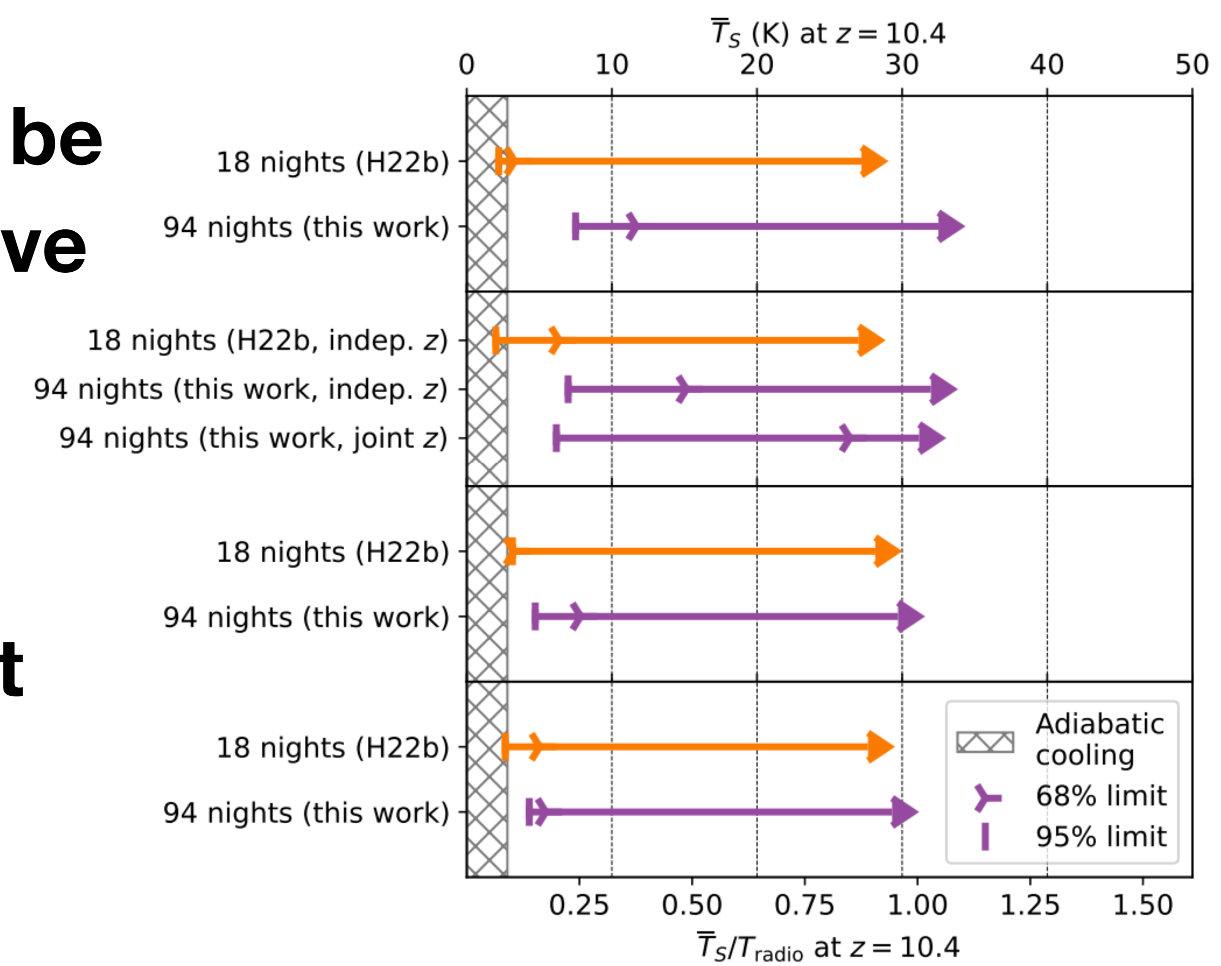


Improved HERA constraints

- 94 nights (compared to 18 nights) of observing
- Improvements by factors of 2.1 and 2.6 on the previous HERA limits at z ~ 7.9, 10.4

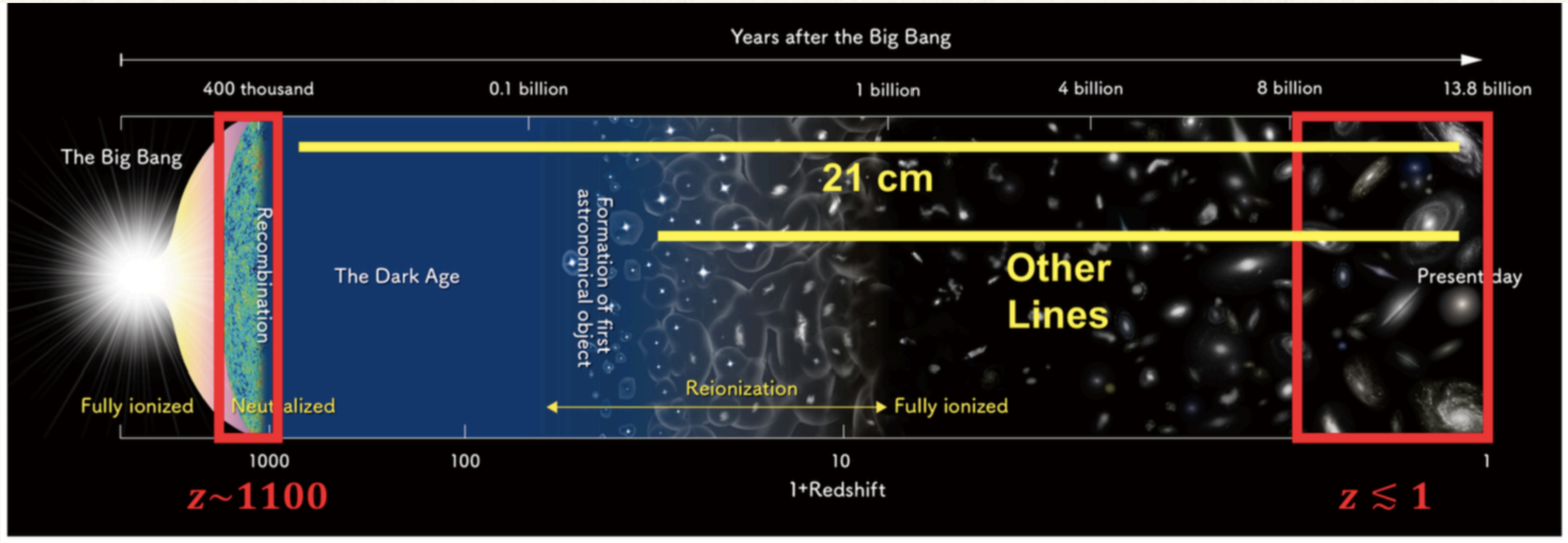


IGM has to be heated above adiabatic cooling by z ~ 10.4 at the latest

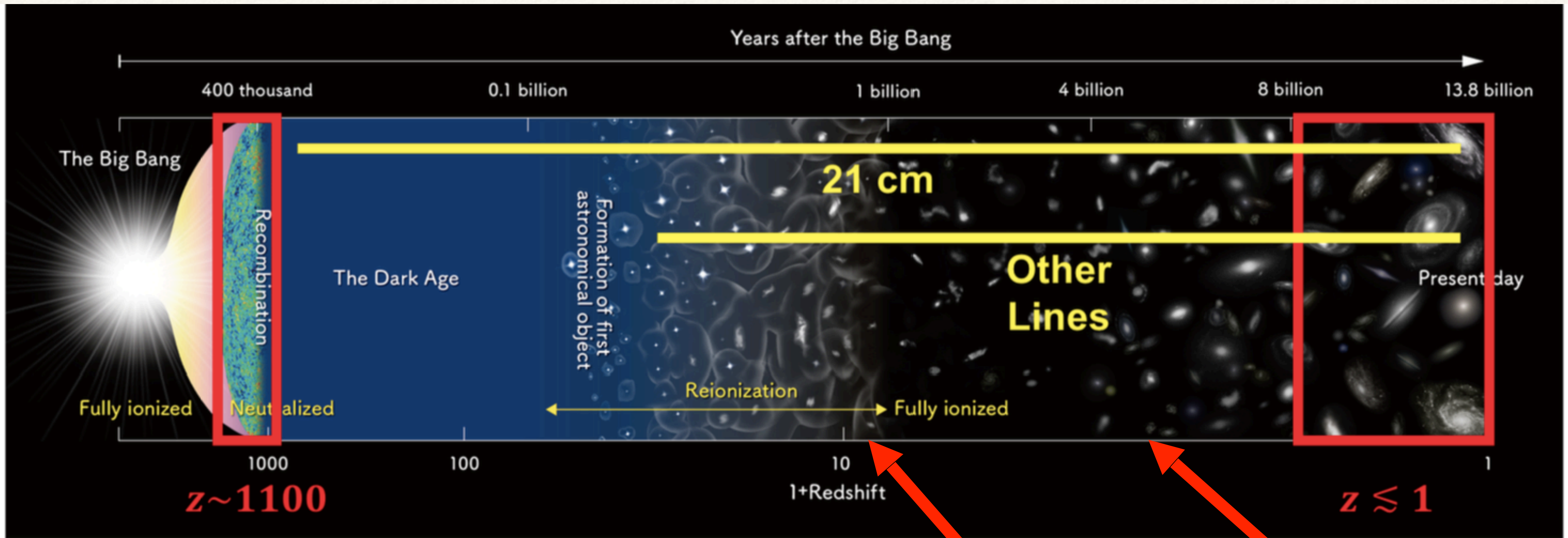


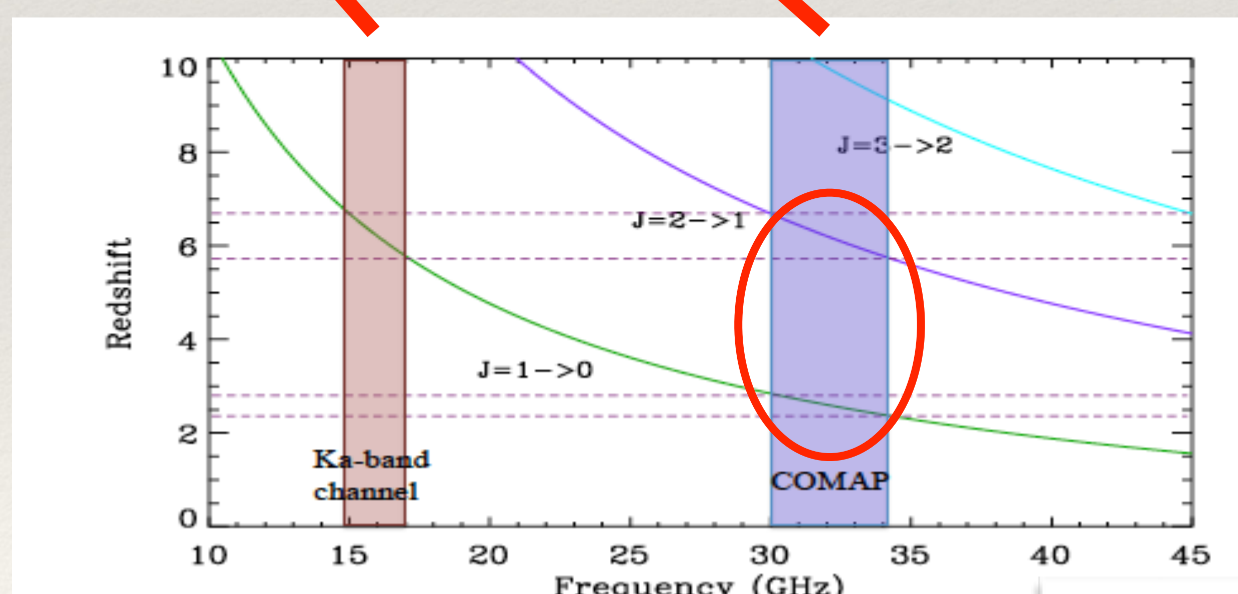
HERA Collaboration et al. (2023)
(2210.04912)

What about other tracers?



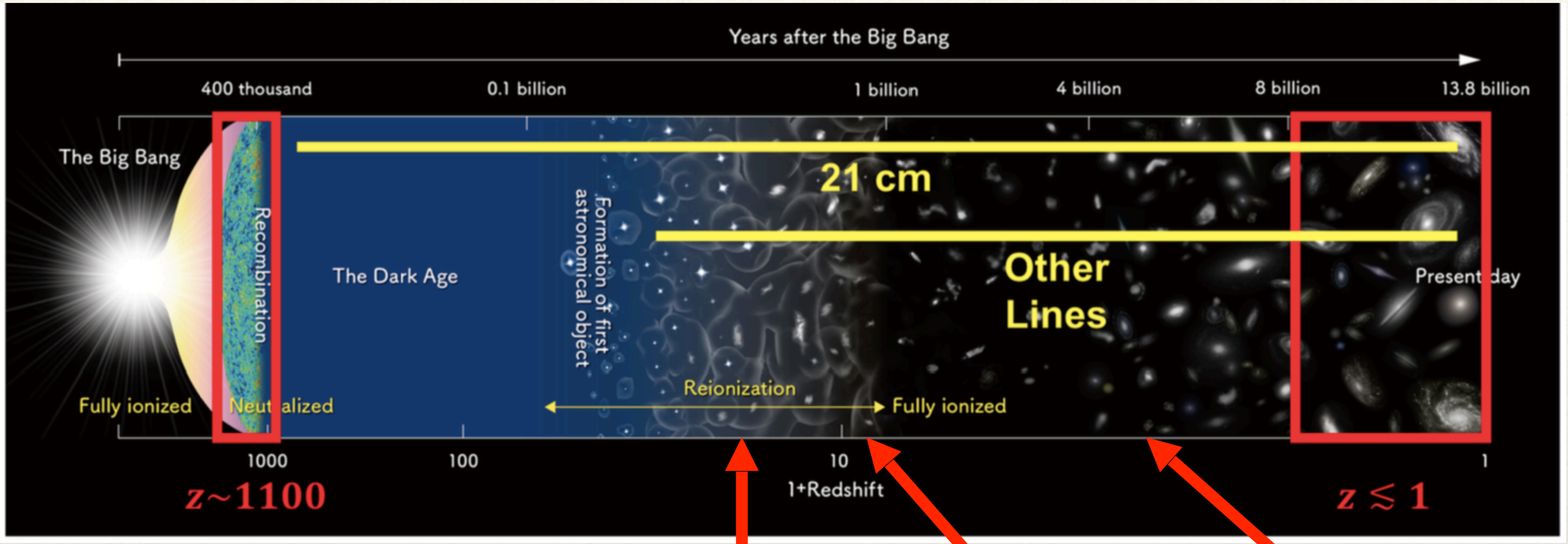
What about other tracers?

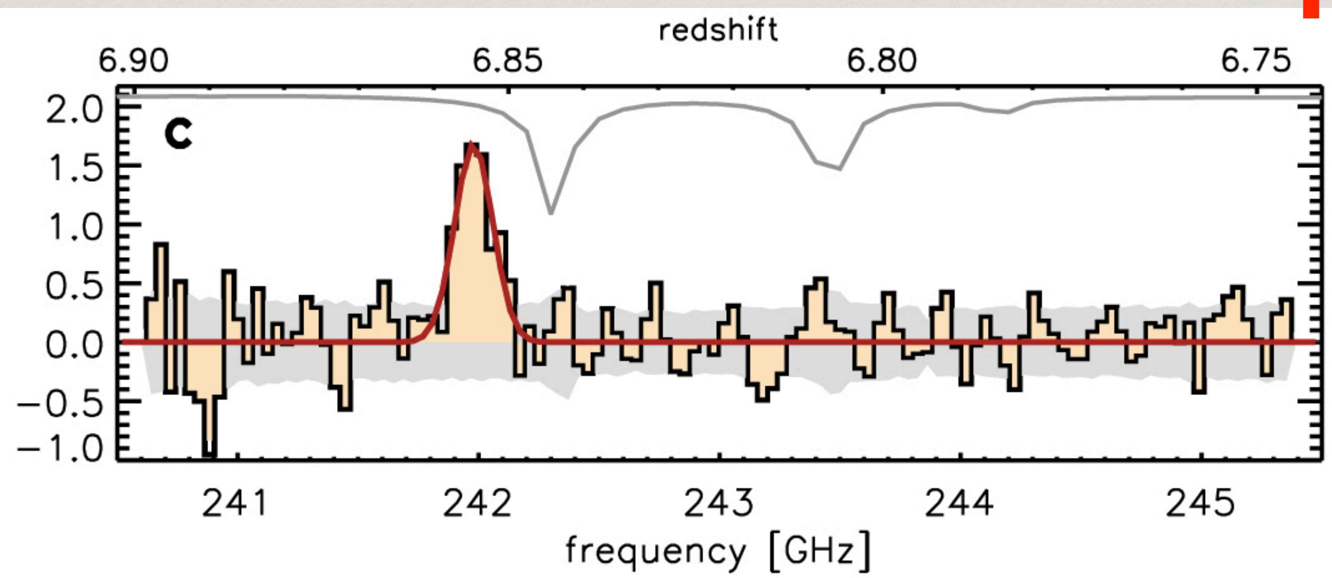


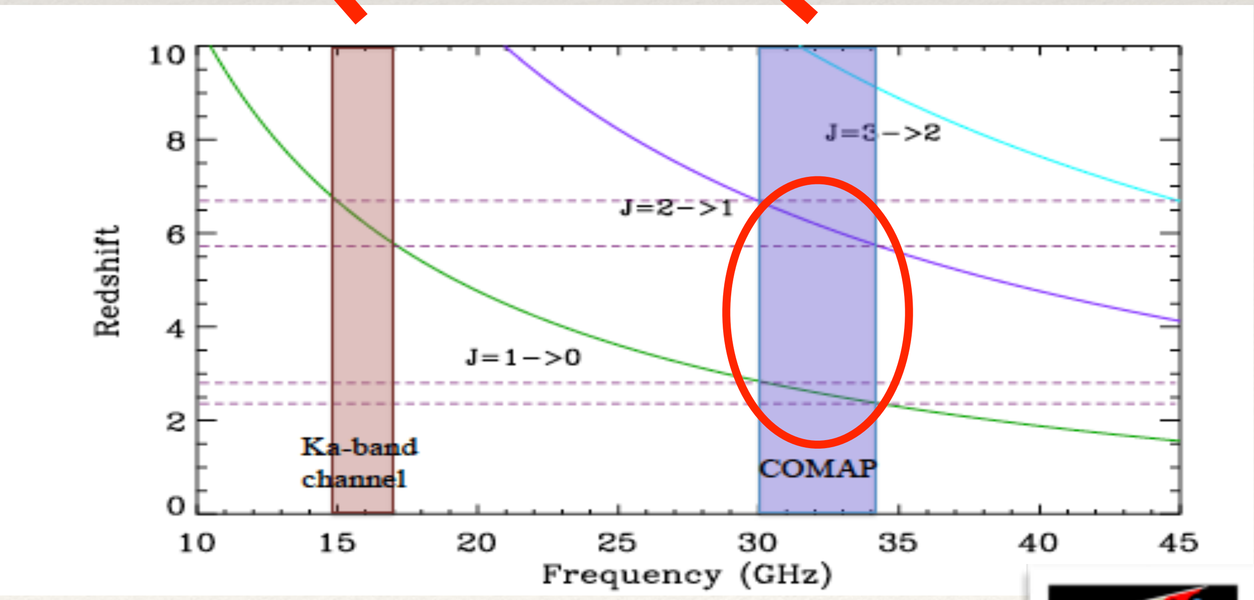


CO transitions

What about other tracers?







CII, 158 micron

[Smit+ (*Nature*, 2018), Pentericci+ (2017)]

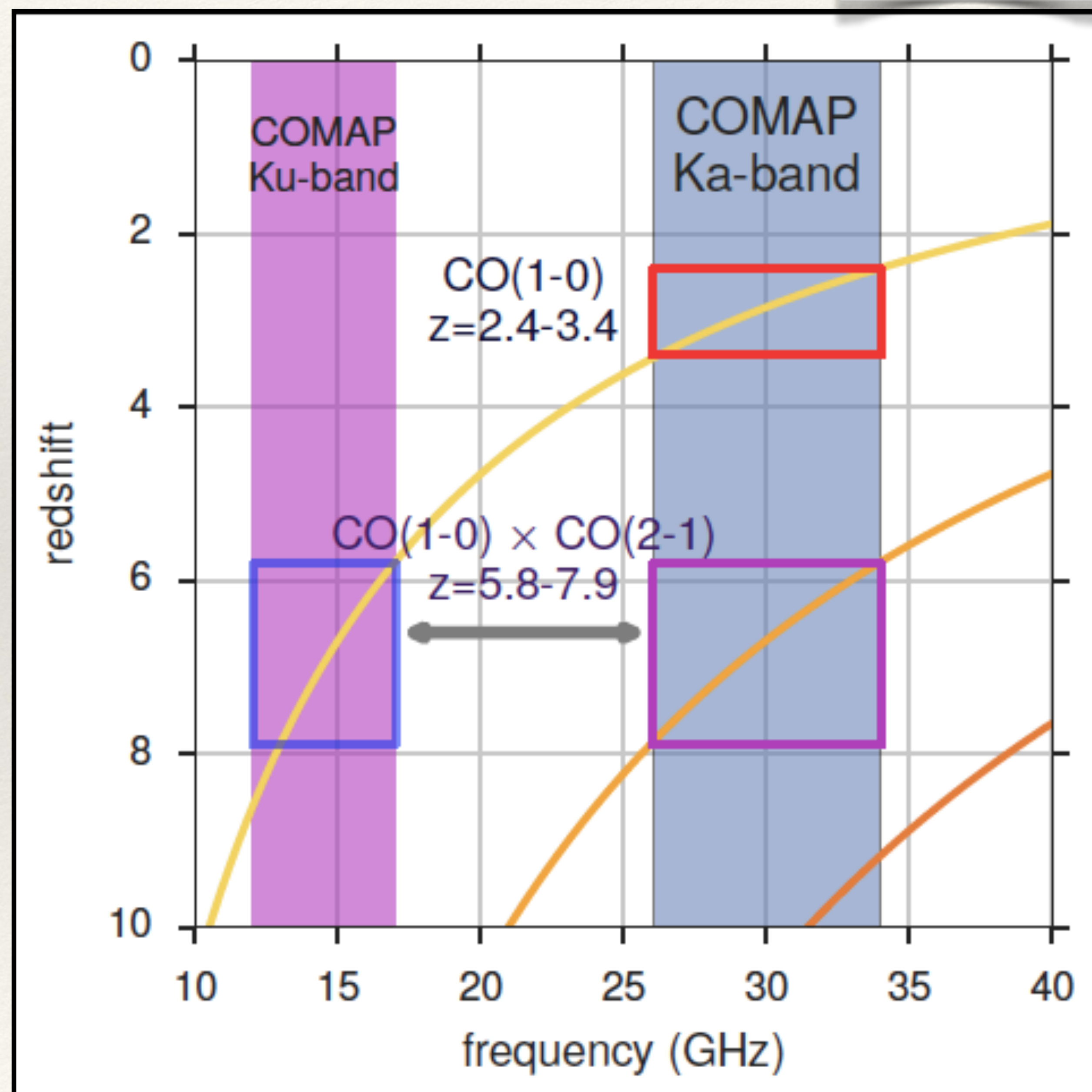
CO transitions

The microwave regime

— The CO Mapping Array Project —

- CO is a major tracer of star formation/ molecular hydrogen, bright even at high redshifts
- 'Ladder' of lines
- Pathfinder: a proof-of-concept, single dish focal plane array, 26-34 GHz
- Three fields, ~ 4 $\deg^2$ per field

CO transitions

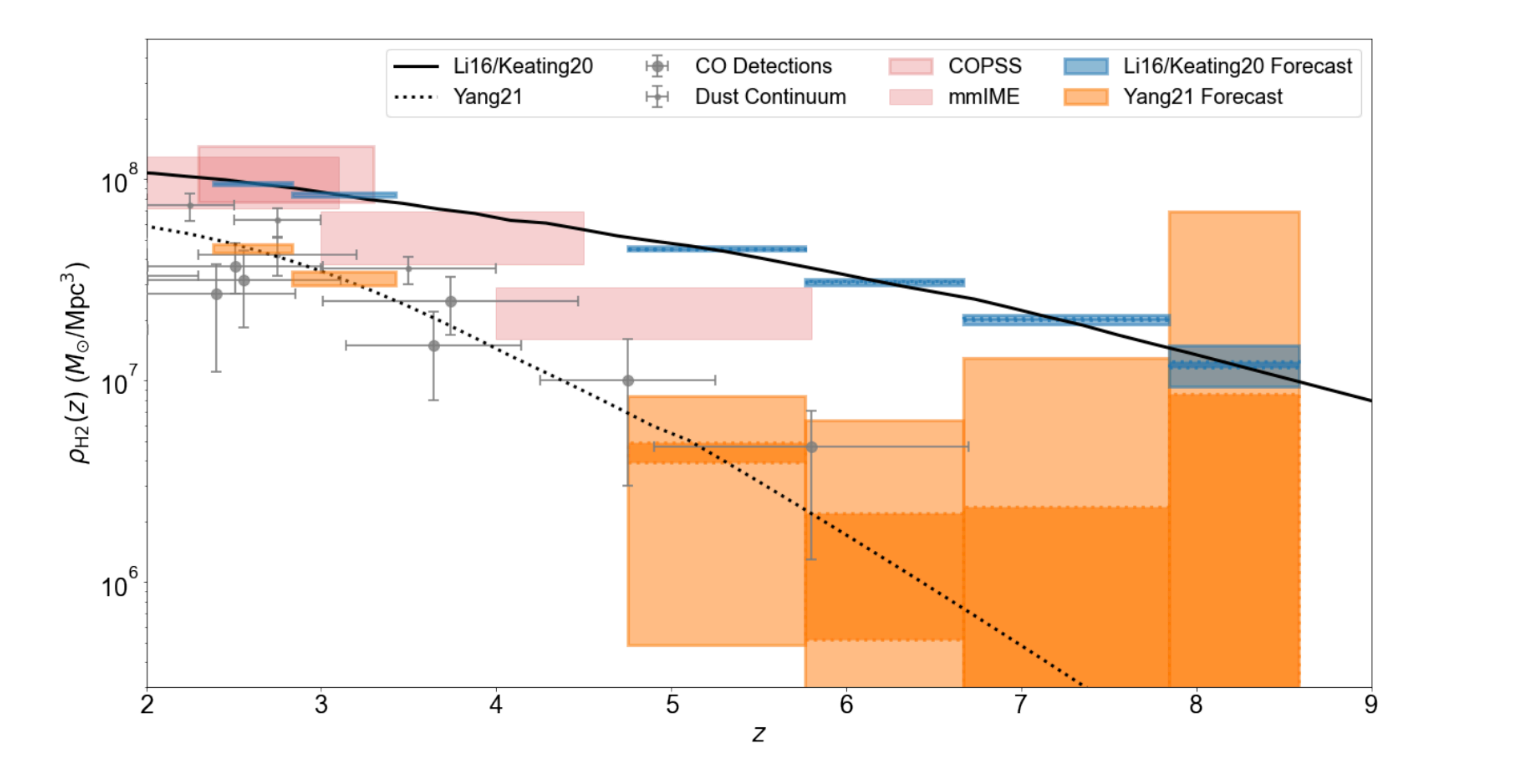


Credit: Dongwoo Chung

CO at reionization

COMAP-*EoR*: Planned second frequency band (13–17 GHz) CO(1-0) line at z = 5.8 – 7.9 ; cross-correlation picks up the EoR signal

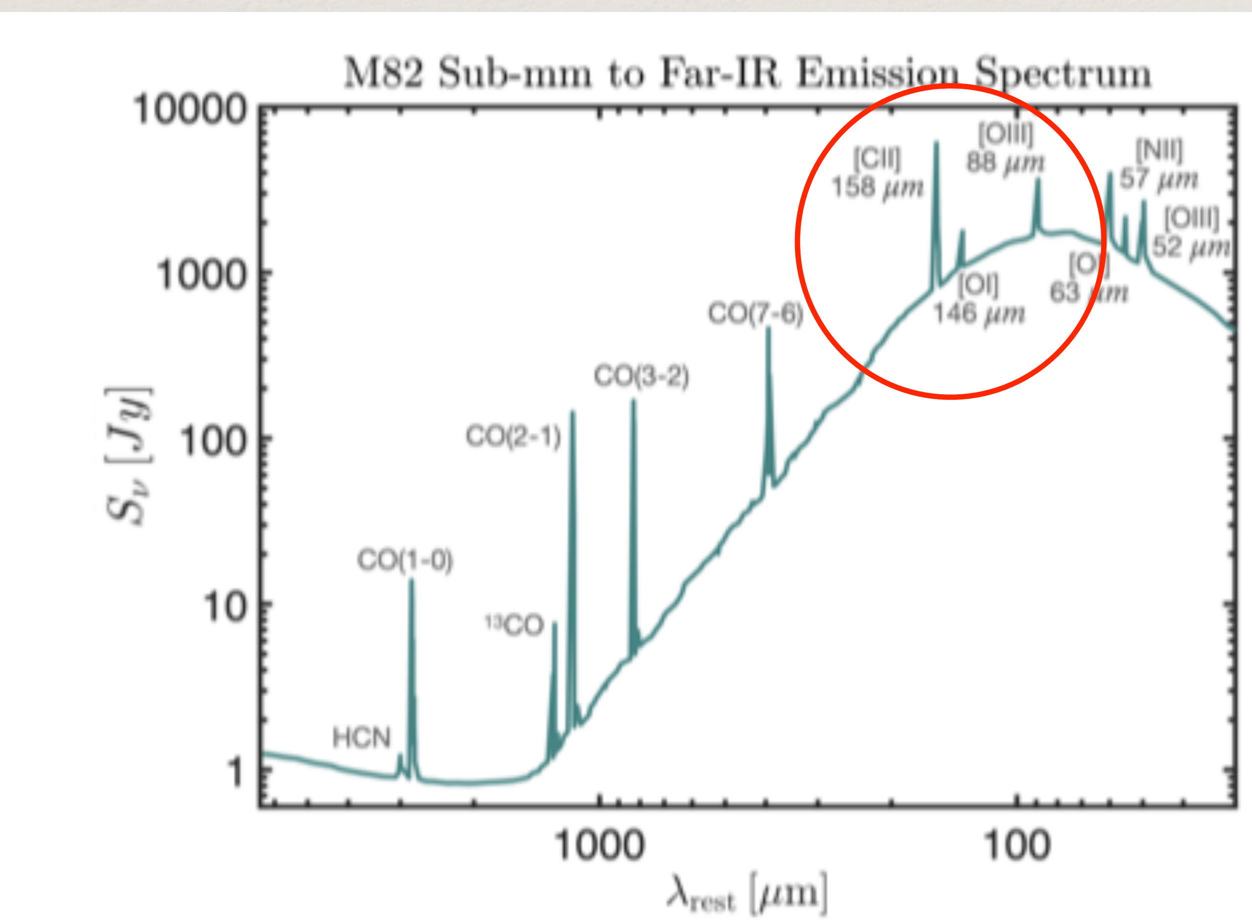
Forecasted constraints on molecular hydrogen; population of faint galaxies

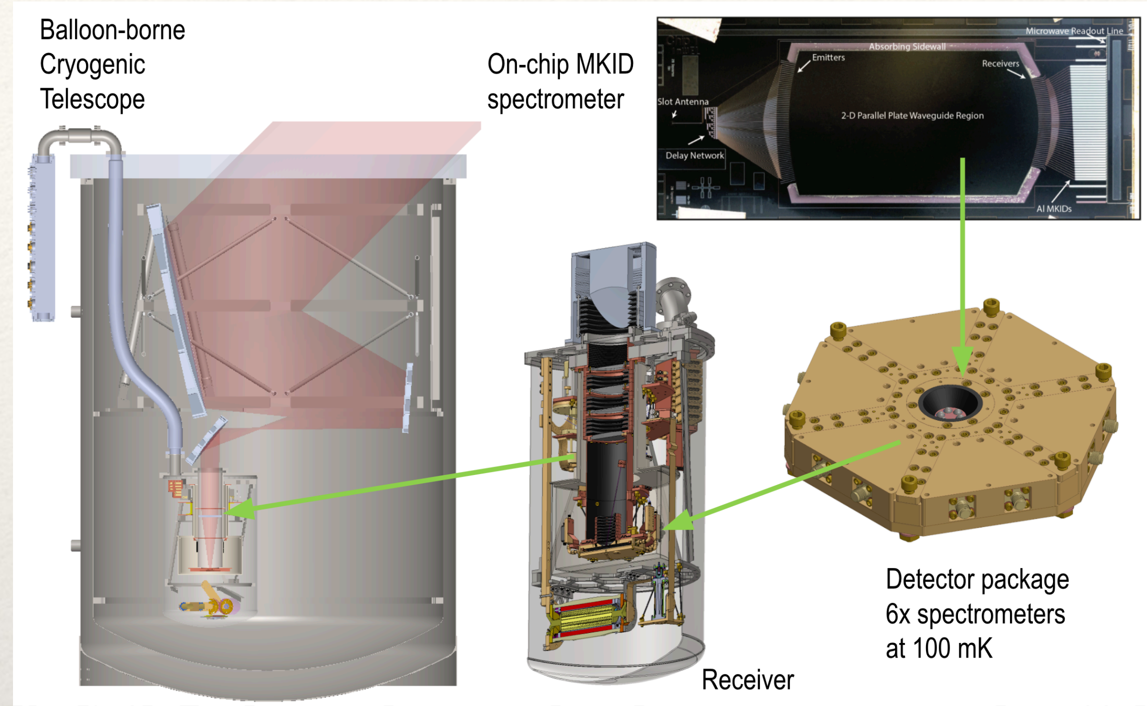


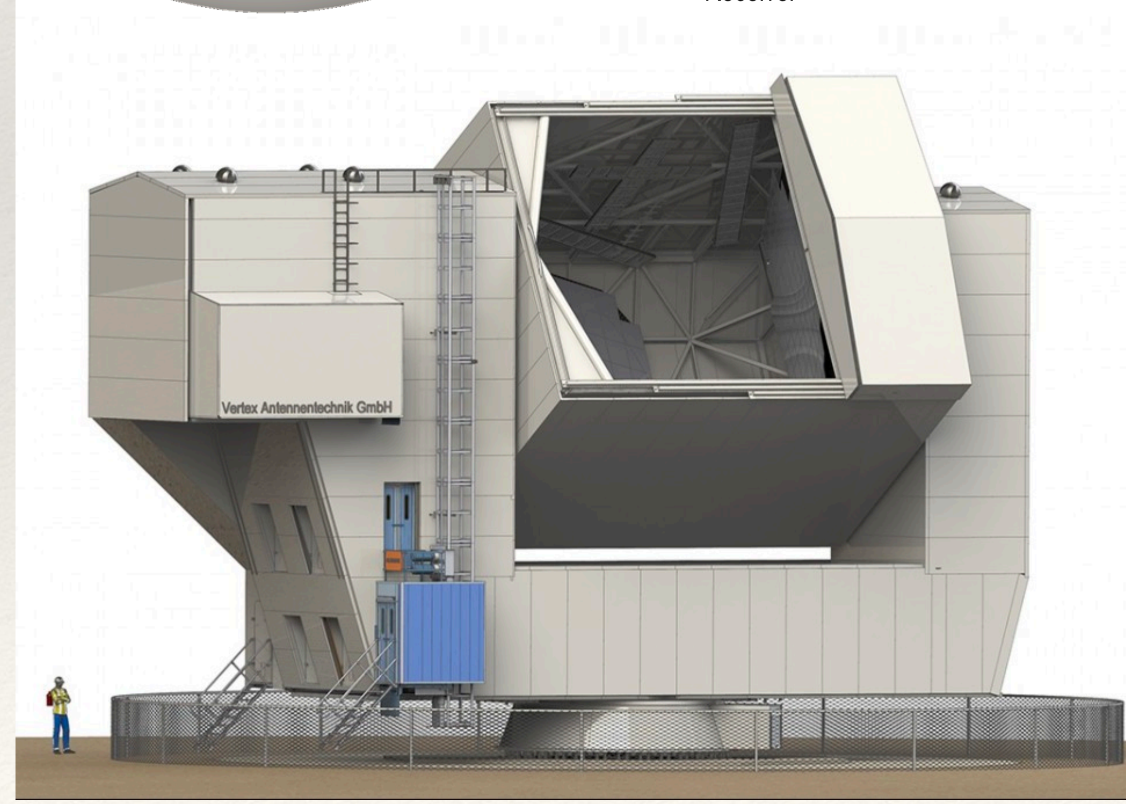
[Breysse+ (2021)]

The submillimetre regime: [CII] and [OIII]

- [OIII] 88 μm and [CII] 158 μm
- Good tracers of star forming regions
- Brightest infrared lines
- Sky noise/point sources much smaller
- **Fred Young Submillimetre Telescope (FYST)** : 212 - 428 GHz
- **EXperiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM)** : 420 - 540 GHz





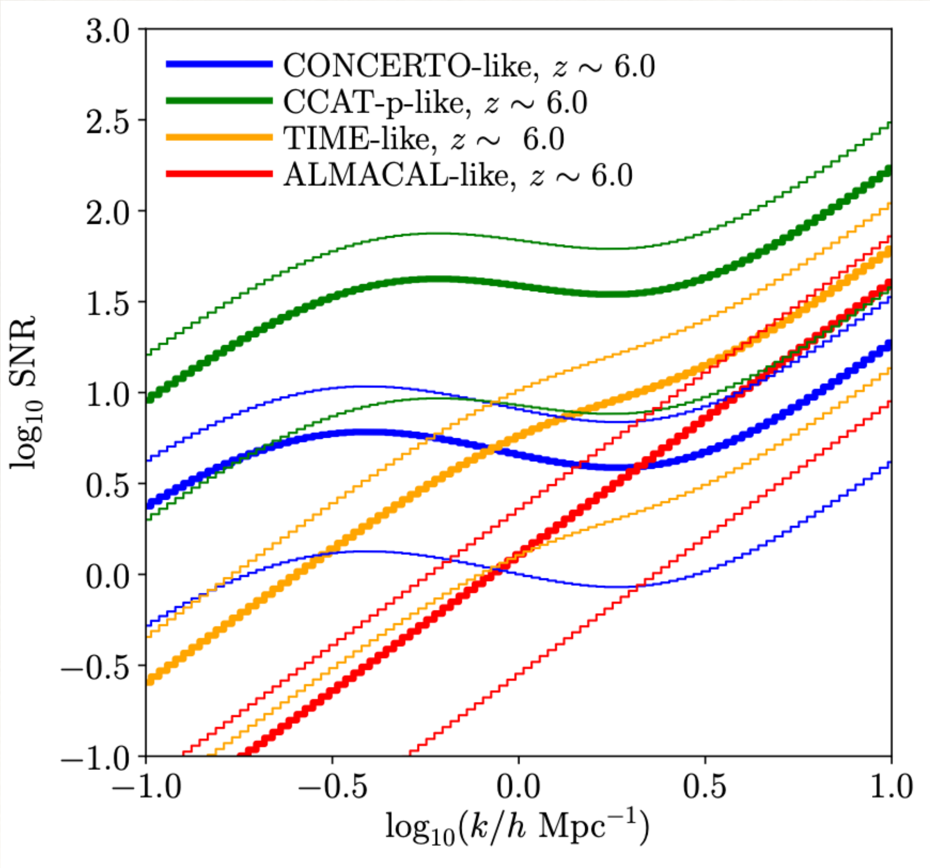


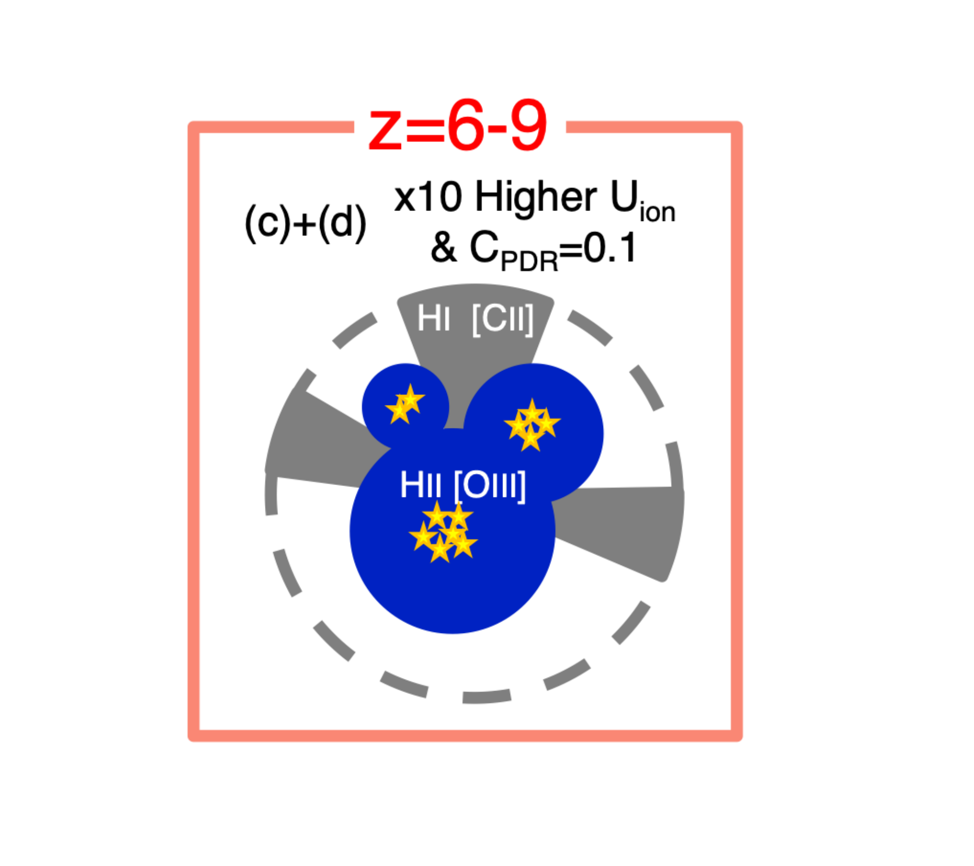
[CII] at reionization

$$L_{\rm CII}(M,z) = \left(\frac{M}{M_1}\right)^{\beta} \exp(-N_1/M) \left(\frac{(1+z)^{2.7}}{1+[(1+z)/2.9)]^{5.6}}\right)^{\alpha}$$

Observations indicate [CII] ‘deficit’ at high-z; if confirmed by IM, indicates hard ISM field and/or larger HII regions (but may also result from underestimation of [CII] in targeted observations)

[HP (MNRAS 2019), arXiv:1811.01968]





[Harikane+ (2020), Vallini+ (2021), Laporte+ (2019), Pallotini+ (2017, 2019), Carniani + (2020)…]

Cross-correlations with 21 cm

Cross-correlations mitigate systematics

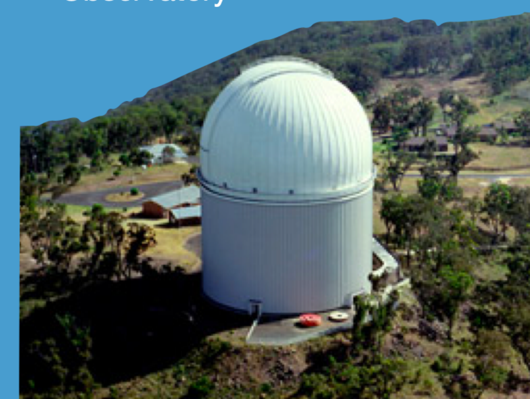
Radio

MeerKAT radio telescope

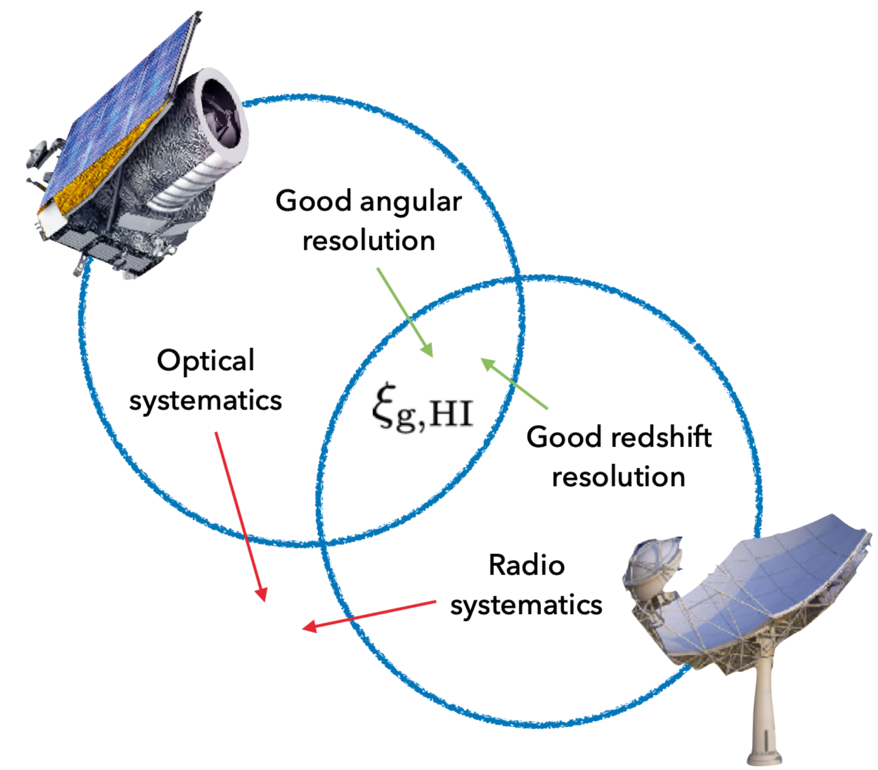
$$\mathbf{X}_{\rm rad} = \mathbf{S}_{\rm rad} + \mathbf{N}_{\rm rad}$$

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:

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

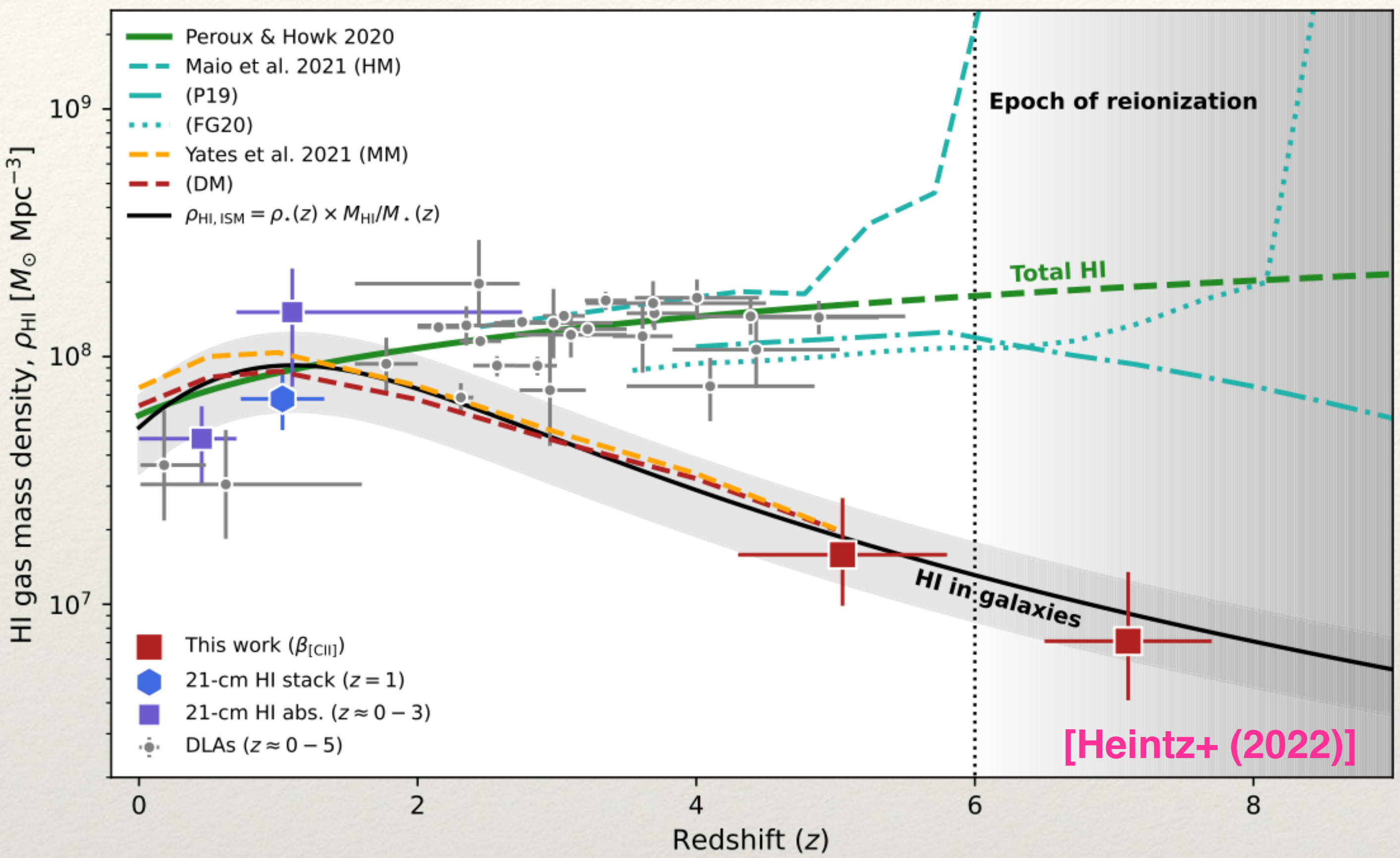
21cm intensity mapping will provide benefits in future cross-correlations

Slide credit: Steve Cunnington

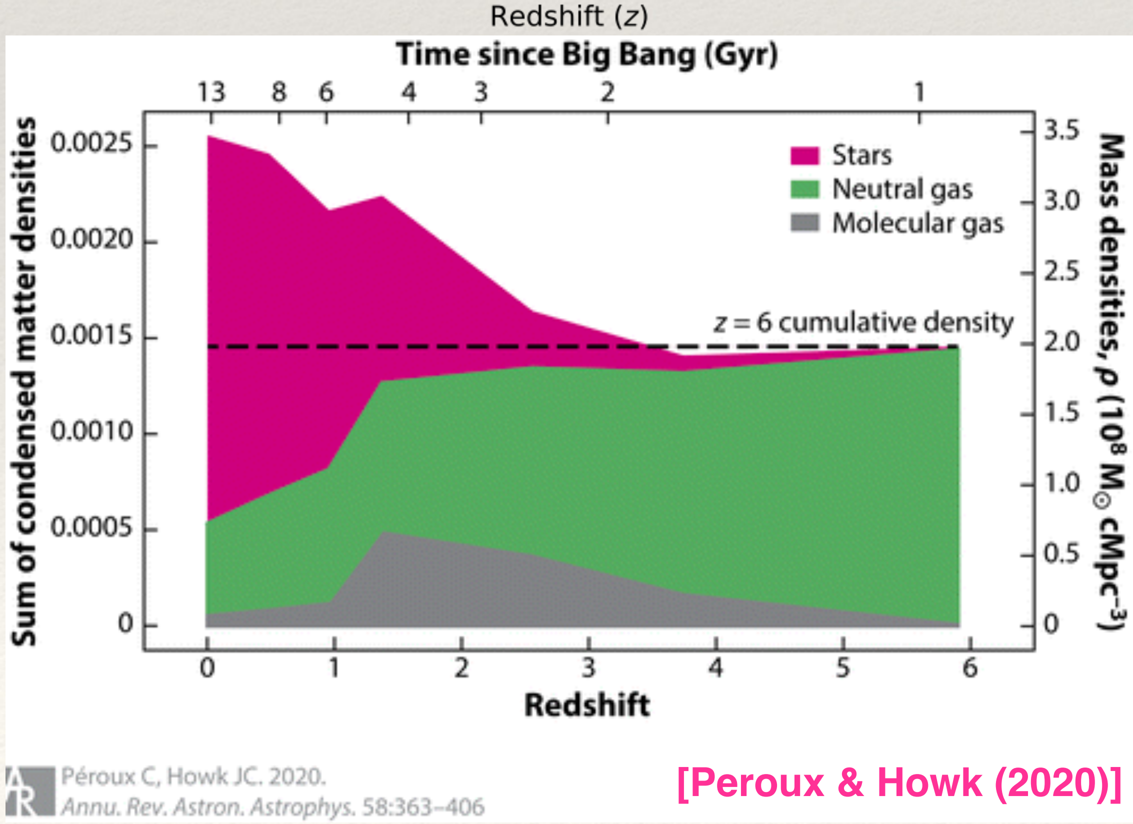
Cross-correlation with galaxy survey < few sq. deg.: information loss in areas most affected by foregrounds
Mitigated by using IM with e.g. [CO], covering ~ few ten square degrees or more

[Lidz+ (2009), Beane & Lidz (2018), Beane et al. (2019), Sato-Polito+ (2020), Zhou+ (2020)]

New empirical insights on HI at z ~ 5-7

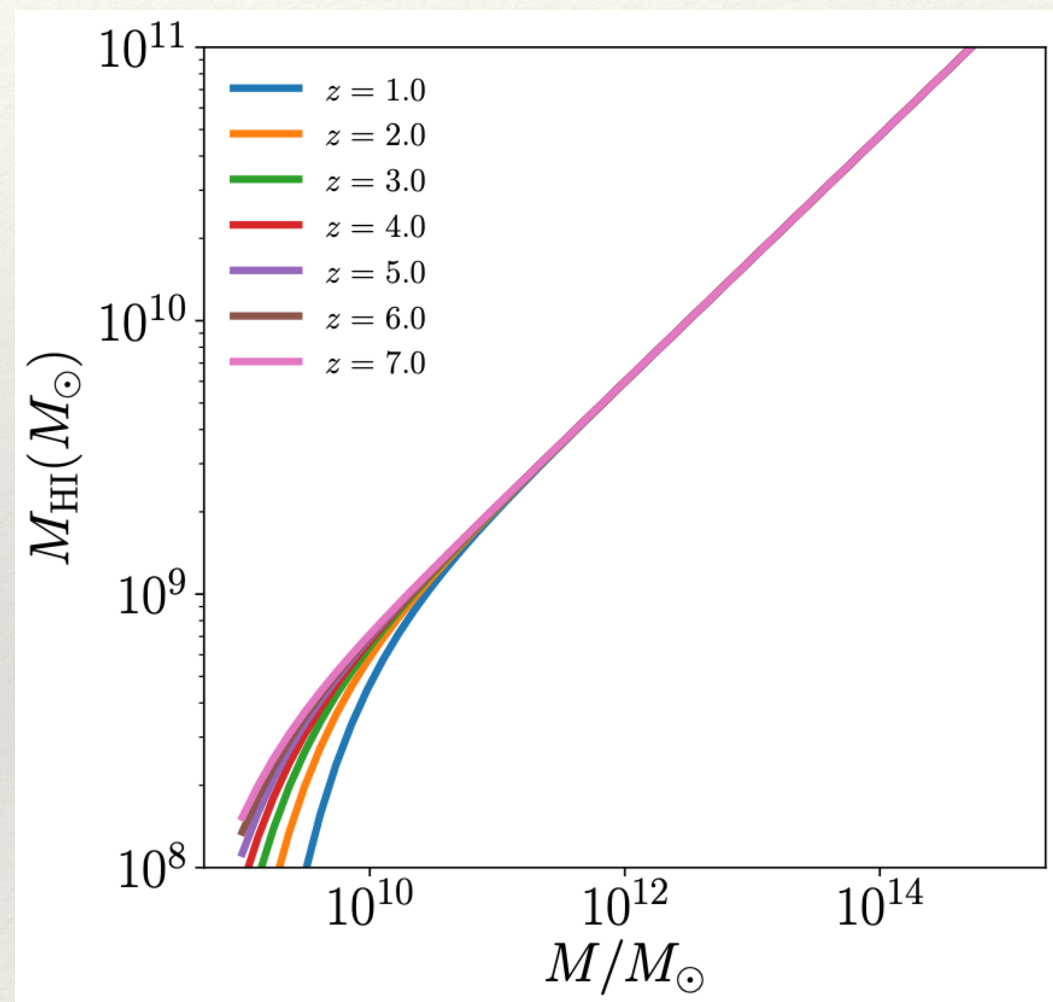


[Heintz+ (2022)]



[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*

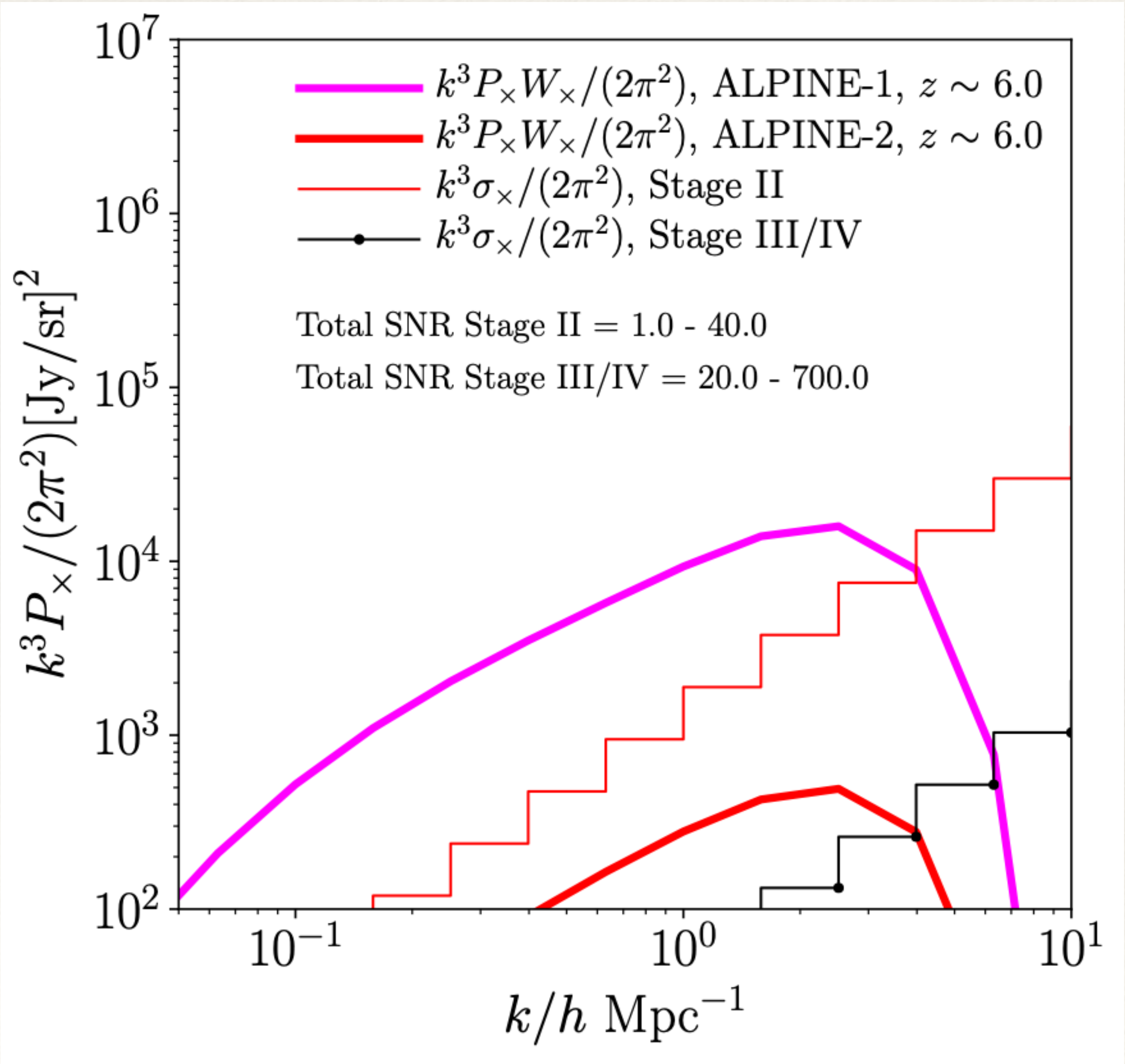
Cross-correlations of sub-mm & 21 cm

- near Reionization -

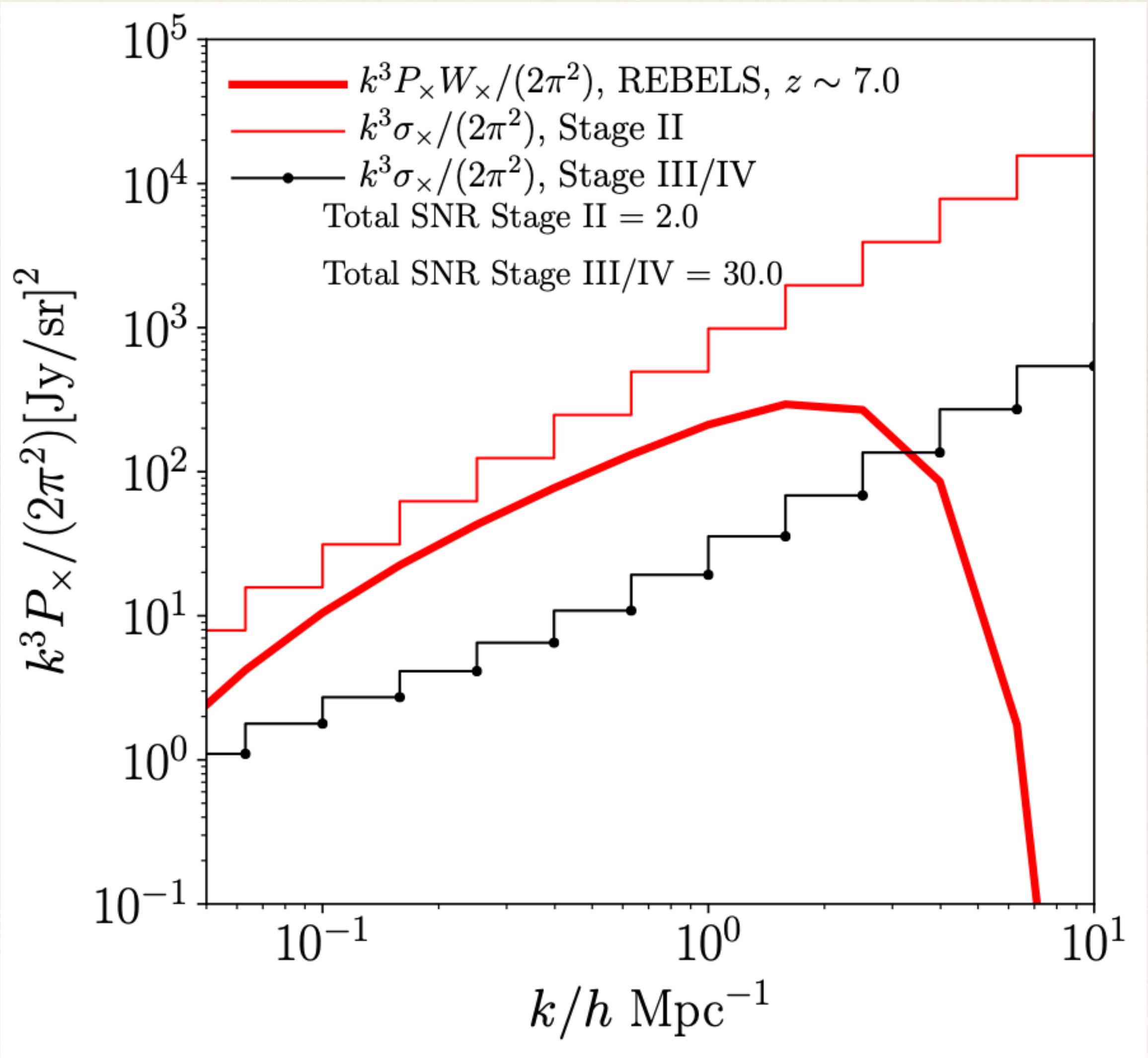
**Assumes complete overlap*

(FYST++) x MWA/SKA

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



z ~ 7, [CII] 158 x HI (MWA)



[HP (MNRAS, 2018), HP (MNRAS 2019), HP+ (MNRAS 2022), HP (MNRAS 2023, arXiv:2212.08077)]

To summarize …

Summary

Summary

- Line Intensity Mapping (IM): large volumes over a wide range of redshifts, species
- Epoch of Reionization: second major phase transition of cosmological hydrogen; within reach of direct observations; effectively probed by 21 cm line of hydrogen
- *Astrophysical systematic* in IM can be efficiently handled via a *data driven halo model,* predicts mean hydrogen abundance out to z ~ 7 **[HP+ (2015, 2016, 2017a, b), HP & Kulkarni (2017), HP (2023)]**
- Latest 21 cm power spectrum upper limits from HERA show that the hydrogen in the IGM must have been heated during reionization, by e.g., X-rays **[HERA Collaboration (2021, 2022)]**
- Sub-mm IM (CO/CII/OIII): several advantages, cross-correlations help mitigate foreground challenge in 21 cm **[e.g., Lidz+ (2011), Sato-Polito+ (2020), Visbal+ (2015)]**
- COMAP: upper limits on CO power at z ~ 3; COMAP-EoR and COMAP-ERA will constrain faint galaxies and molecular hydrogen at the EoR **[Breysse+ (2022)]**
- Future: Proposed experiments (SPHEREX, CDIM) to perform IM with other lines, H α and Lyman-α, out to the EoR; Population III stars from He II IM **[Mas-Ribas+ (2017), Heneka & Cooray (2021), Parsons+ (2021), Visbal+ (2015)]**

Summary

- Line Intensity Mapping (IM): large volumes over a wide range of redshifts, species
- Epoch of Reionization: second major phase transition of cosmological hydrogen; within reach of direct observations; effectively probed by 21 cm line of hydrogen
- *Astrophysical systematic* in IM can be efficiently handled via a *data driven halo model,* predicts mean hydrogen abundance out to z ~ 7 **[HP+ (2015, 2016, 2017a, b), HP & Kulkarni (2017), HP (2023)]**
- Latest 21 cm power spectrum upper limits from HERA show that the hydrogen in the IGM must have been heated during reionization, by e.g., X-rays **[HERA Collaboration (2021, 2022)]**
- Sub-mm IM (CO/CII/OIII): several advantages, cross-correlations help mitigate foreground challenge in 21 cm **[e.g., Lidz+ (2011), Sato-Polito+ (2020), Visbal+ (2015)]**
- COMAP: upper limits on CO power at z ~ 3; COMAP-EoR and COMAP-ERA will constrain faint galaxies and molecular hydrogen at the EoR **[Breysse+ (2022)]**
- Future: Proposed experiments (SPHEREX, CDIM) to perform IM with other lines, H α and Lyman-α, out to the EoR; Population III stars from He II IM **[Mas-Ribas+ (2017), Heneka & Cooray (2021), Parsons+ (2021), Visbal+ (2015)]**

Thank you!

Redshift space: dark matter

[White (2000), Seljak (2000), Cooray and Sheth (2002) …]

$$P_{2\mathrm{h}}(k) = P_{\mathrm{lin}}(k)[\frac{1}{\bar{\rho}_{\mathrm{m}}}\int dMn(M)Mb_{\mathrm{h}}(M)\,|\,\underbrace{u_{\mathrm{h}}(k\,|\,M)}_{\text{Halo profile FT}}\,|\,]^2$$

$$P_{1\mathrm{h}}(k) = \frac{1}{\bar{\rho}_{\mathrm{m}}^2}\int dMn(M)M^2\,|\,u_{\mathrm{h}}(k\,|\,M)\,|^2$$

In redshift space

$$\delta_{\mathrm{redshift}} = \delta_{\mathrm{real}}\left(1 + f\mu^2\right)e^{-(k\sigma\mu)^2/2}$$

$$\overline{P}^s_{2h}(k) = \left(1 + \frac{2}{3}f + \frac{1}{5}f^2\right)P_{\mathrm{lin}}(k) \times \left[\left|\int \frac{1}{\bar{\rho}_{\mathrm{m}}}\int dMn(M)Mb_{\mathrm{h}}(M)\mathscr{R}_1(k\sigma)\,|\,u_{\mathrm{h}}(k;M)\,|\right]^2$$

$$\overline{P}^s_{1h}(k) = \frac{1}{(\bar{\rho}_m)^2}\int dMn(M)M^2\mathscr{R}_2(k\sigma)\,|\,u_{\mathrm{h}}(k;M)\,|^2$$

$$\mathscr{R}_1(y = k\sigma) = \sqrt{\frac{\pi}{2}}\frac{\mathrm{erf}(y/\sqrt{2})}{y}$$

$$\mathscr{R}_2(y = k\sigma) = \frac{\sqrt{\pi}}{8}\frac{\mathrm{erf}(y)}{y^5}\left[3f^2 + 4fy^2 + 4y^4\right] - \frac{e^{-y^2}}{4y^4}\left[f^2(3 + 2y^2) + 4fy^2\right]$$

Redshift space: number weighted biased tracers (galaxies)

[Seljak (2000)]

$$P_{\rm g}^{2h}(k) = P_{\rm lin}(k)\left[\frac{1}{\overline{n}_g}\int dMMn(M)\left\langle N\right\rangle b_{\rm h}(M)u_g[k,M]\right]^2$$

Mean number density of galaxies

$$P_{\rm g}^{1h}(k) = \frac{1}{\overline{n}_{\rm g}^2}\int dMn(M)\left\langle N(N-1)\right\rangle |u_g(k,M)|^2 + {\rm SN},$$

$$\delta^g_{\rm redshift} = \left(\delta^g_{\rm real} + \delta_{\rm h} f\mu^2\right), \delta_g \to \delta_g e^{-(k\sigma\mu)^2/2}$$

$$\overline{P}^s_g(k) = \left(F_{\rm g}^2 + \frac{2}{3}F_{\rm m}F_{\rm g} + \frac{1}{5}F_{\rm m}^2\right)P_{\rm lin}(k) + \frac{1}{\overline{n}_g^2}\int dMn(M)\left\langle N(N-1)\right\rangle \mathscr{R}_2(k\sigma)|u_g(k,M)|^2$$

$$F_{\rm m} = \frac{f}{\overline{\rho}_{\rm m}}\int dMMn(M)b_{\rm h}(M)\mathscr{R}_1(k\sigma)u_{\rm h}(k,M),$$

Mean number of galaxies within a halo

$$F_{\rm g} = \frac{1}{\overline{n}_g}\int dMMn(M)\left\langle N\right\rangle b_{\rm h}(M)\mathscr{R}_1(k\sigma)u_{\rm g}(k,M)$$

Redshift space: mass weighted biased tracers (HI)

[HP (2021), HP+ (2023)]

Subtlety:
Shot noise with and without FoG term:

$$P_{\rm SN} = \frac{1}{\bar{\rho}_{\rm HI}^2} \int dM n(M) M_{\rm HI}^2$$

$$P_{\rm SN}^{\rm fog}(k) = \frac{1}{\bar{\rho}_{\rm HI}^2} \int dM n(M) M_{\rm HI}^2 \mathcal{R}_3(k\sigma)$$

$$\mathcal{R}_3(y) = \frac{\sqrt{\pi}}{2} \frac{\mathrm{erf}(y)}{y} .$$