Title: Mapping the baryonic universe: from reionization to present-day galaxies

Speakers: Hamsa Padmanabhan

Series: Cosmology & Gravitation

Date: May 21, 2019 - 11:00 AM

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Abstract: The history of the baryonic (normal) matter in the universe is an excellent probe of the formation of cosmic structures and the evolution of galaxies. Over the last decade, considerable effort has gone into investigating the physics of baryonic material, particularly after the epoch of Cosmic Dawn: signalling the birth of the earliest stars and
galaxies --- widely considered the â€˜final frontierâ€™ of observational cosmology today. The technique of (line) â€˜intensity mappingâ€™ (IM) has emerged as a powerful tool to explore this phase of the universe by measuring the integrated emission from sources over a broad range of frequencies. I will overview my current research on the mapping of atomic hydrogen over 12 billion years of cosmic time, based on a data-driven framework developed for interpreting current and future IM observations. I will then describe extensions of this approach which provide a comprehensive picture of molecular gas evolution, and interpret results from ongoing observations. This opens up the exciting potential of constraining fundamental physics from Cosmic Dawn.

Mapping the baryonic universe

- from reionization to present-day galaxies -

Hamsa Padmanabhan
CITA Fellow
Canadian Institute for Theoretical Astrophysics, Toronto

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Outline

- Introduction and motivation
- A halo model for HI: formalism and observations
- A halo model for HI: forecasting for surveys
- CO intensity mapping
- Constraining CII evolution
- Prospects for reionization
- Summary and outlook

Based on …

HP, Choudhury, Refregier, arXiv:1505.00008 (MNRAS 2016)

HP, Refregier, arXiv:1607.01021 (MNRAS 2016)

HP, Refregier, Amara, arXiv:1611.06235 (MNRAS 2017a)

HP, Kulkarni, arXiv:1608.00007 (MNRAS 2017b)

HP, Refregier, Amara, arXiv:1804.10627 (MNRAS 2019)

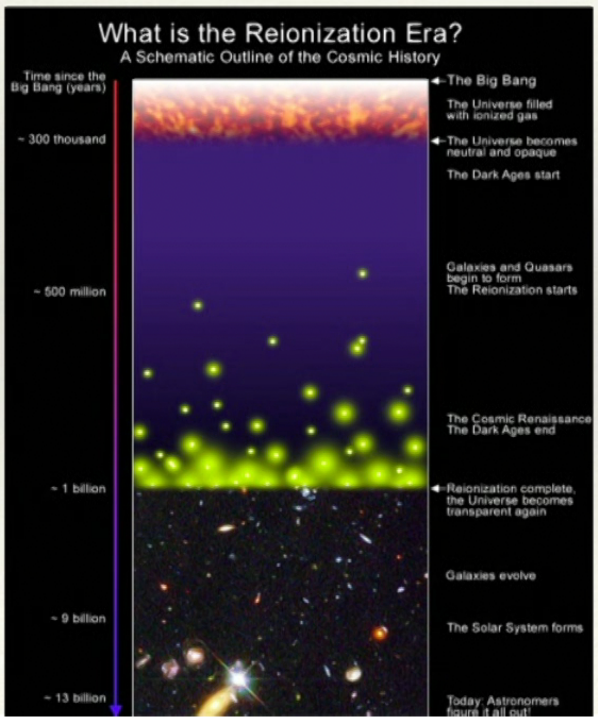
HP, arXiv:1706.01471, MNRAS (2018)

HP, arXiv:1811.01968 (MNRAS under review)

A brief history of the baryonic universe

Two major phase transitions!

- Recombination (~ 300,000 y)
- Reionization (~ 1 billion y)



Djorgovski/Caltech

Gas decoupled from radiation

Cosmic "Dark ages"

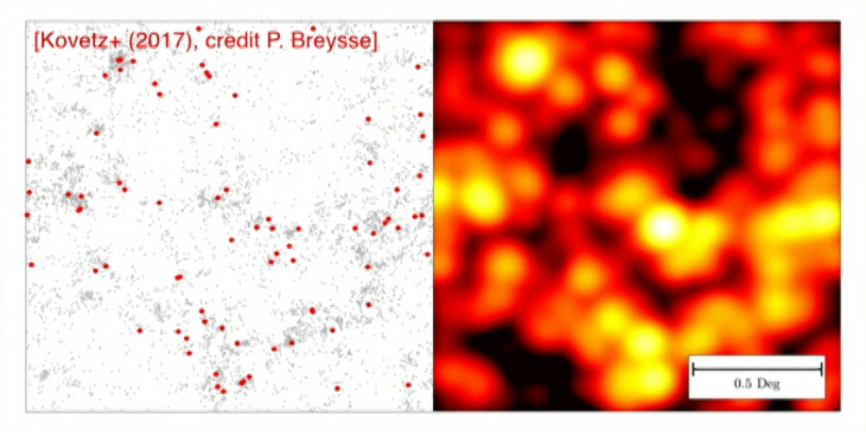
First light; cosmic Dawn

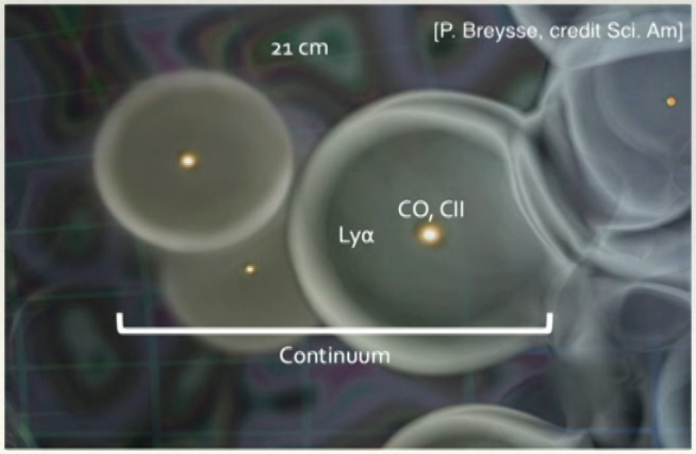
Today, a HIGHLY (re)ionized universe

Mapping the baryonic universe

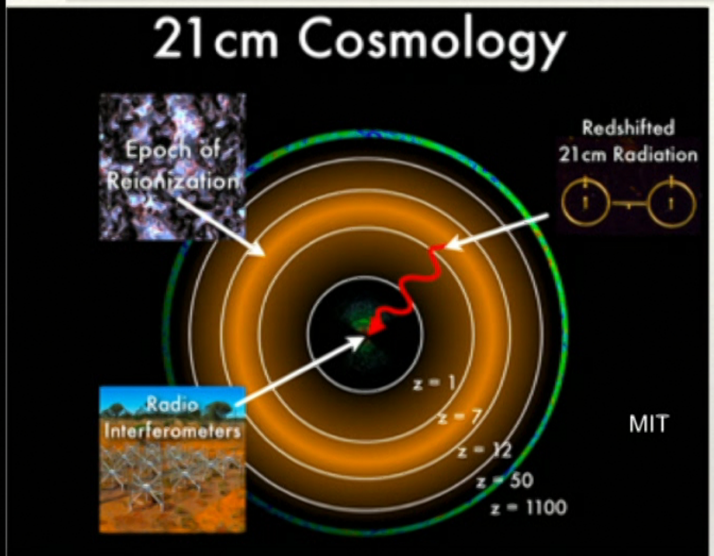
- LOFAR (Netherlands)
- BINGO, CHIME, TianLai, HIRAX…
- SKA (South Africa/Australia)
- ALMA, COMAP, COPSS, …
- CCAT-p, TIME, CONCERTO …

Intensity mapping

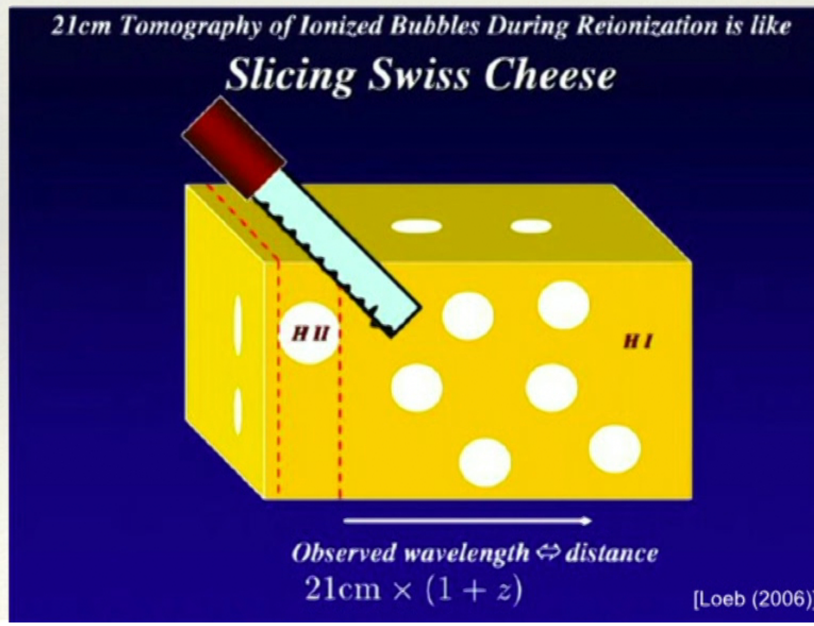




21 cm cosmology



Tomography: each frequency is a different epoch



N ~ 3 × 10^{16} modes, much smaller scales than CMB

[Loeb & Zaldariagga (2004)]

Impact of astrophysics

$$P_{\rm HI} \equiv [\delta T_{\rm HI}(k,z)]^2 = \bar{T}(z)^2 [b_{\rm HI}(k,z)]^2 \frac{k^3 P_{\rm cdm}(k,z)}{2\pi^2}$$

$$\bar{T}(z) = 44\ \mu{\rm K} \left(\frac{\Omega_{\rm HI}(z) h}{2.45 \times 10^{-4}}\right) \frac{(1+z)^2}{E(z)}$$

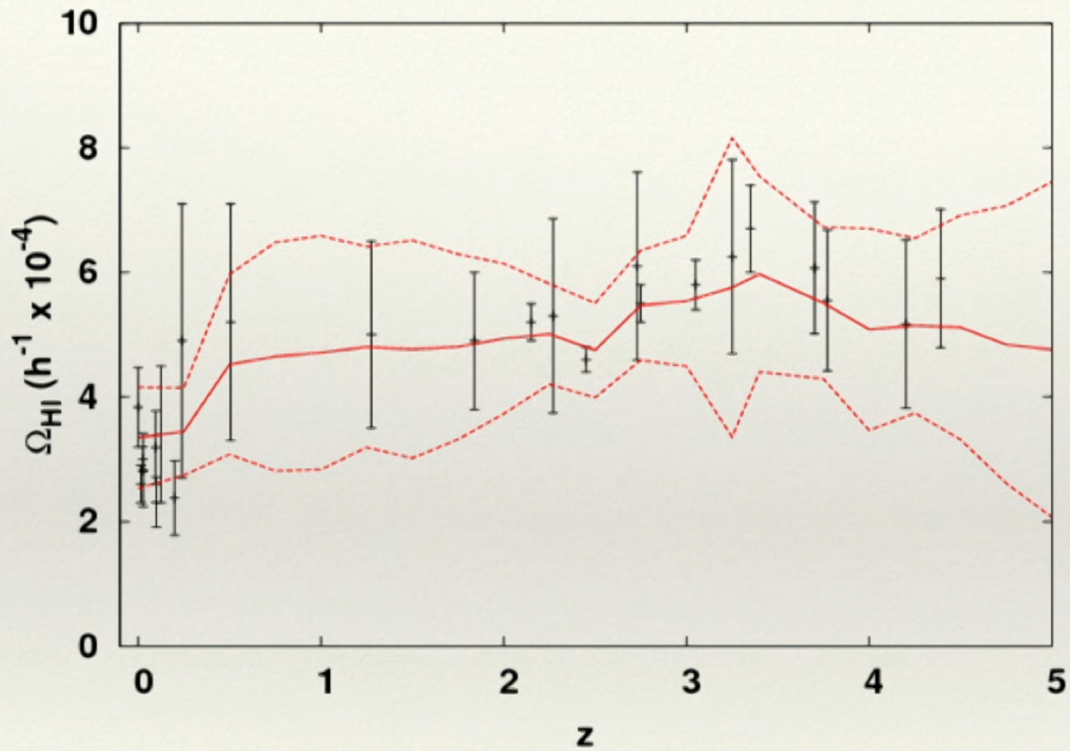
ASTROPHYSICS **COSMOLOGY**

Interplay of astrophysics and cosmology

The ‘astrophysical systematic’

The 'astrophysical systematic'

The 'astrophysical systematic'



60% - 100% uncertainty in HI power spectrum

[HP, Choudhury, Refregier, MNRAS (2015)]

How can we quantify this in predictions?

Efficiently model the astrophysics

A halo model for neutral hydrogen

Combine IM observations with individual objects

$M_{\mathrm{HI}}(M, z)$

Average HI mass associated with a halo of mass M at redshift z

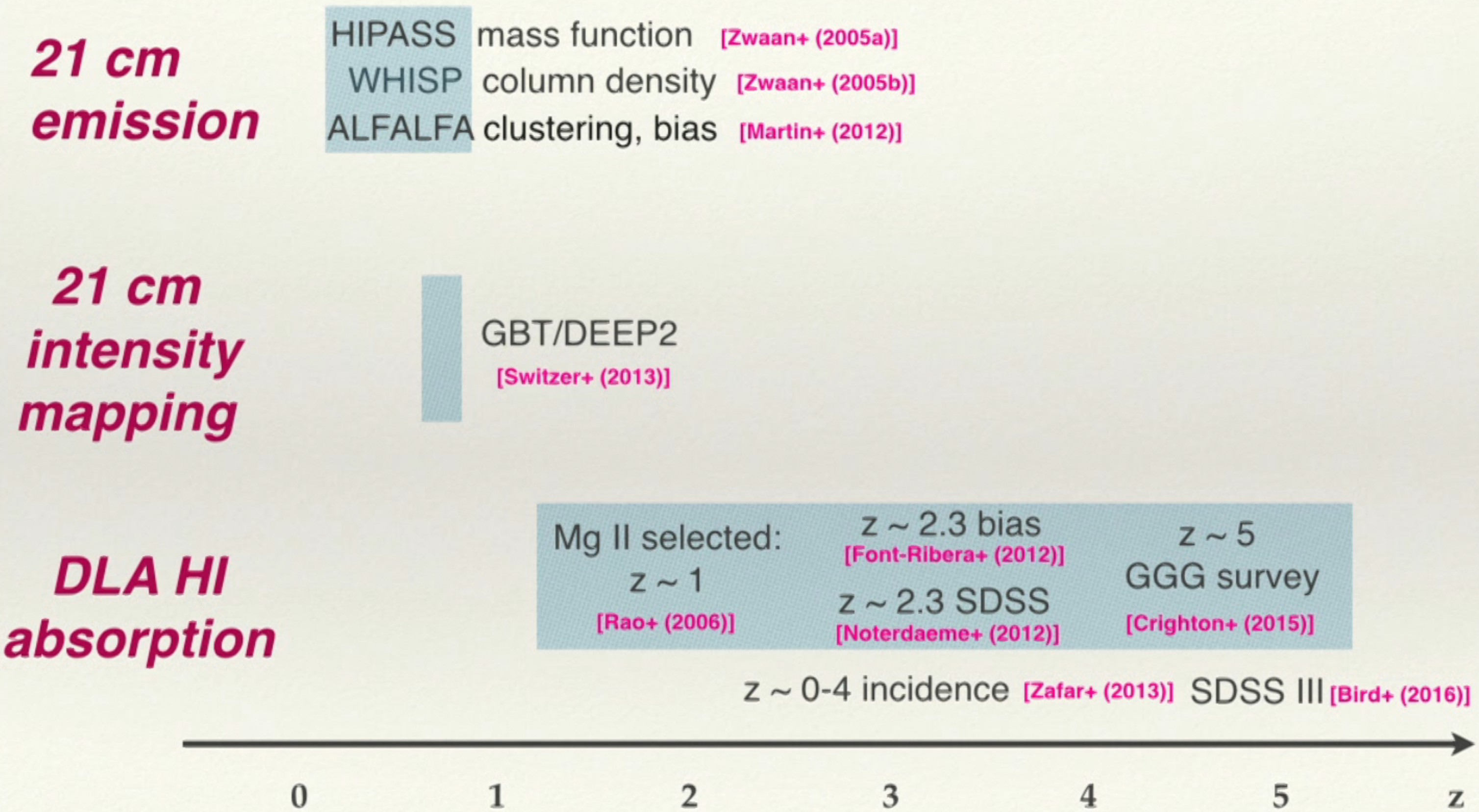
$\rho_{\mathrm{HI}}(r, M, z)$

Radial HI distribution within a halo of mass M at redshift z

Allows us to derive HI observables

[HP, Choudhury, Refregier, MNRAS (2016)]

Available HI data



$M_{\mathrm{HI}}(M, z)$

HI HALO MODEL

$\rho_{\mathrm{HI}}(r, M, z)$

[Barnes & Haehnelt (2010, 2014), Villaescusa-Navarro + (2015), ...]

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

HI Fraction relative to cosmic **Slope** **Lower cutoff**

HI HALO MODEL

$$\rho_{\rm HI}(r,M,z)$$

[Barnes & Haehnelt (2010, 2014),
Villaescusa-Navarro + (2015), ...]

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

HI Fraction relative to cosmic **Slope** **Lower cutoff**

HI HALO MODEL

$$\rho_0 \exp(-r/r_s); \; r_s = R_v(M)/c_{\rm HI}(M,z)$$

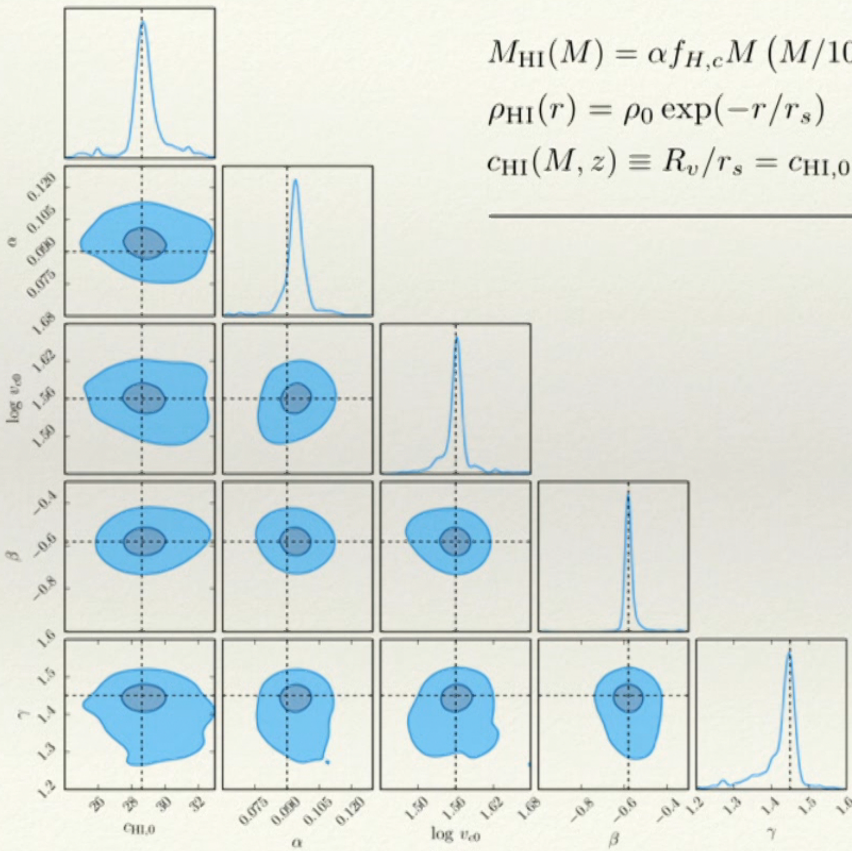
$$\rho_{\rm HI}(r, M, z) \quad c_{\rm HI}(M,z) = c_{\rm HI,0} \left(\frac{M}{10^{11} M_\odot} \right)^{-0.109} \frac{4}{(1+z)^{\gamma}}$$

concentration parameter **Evolution with redshift**

[e.g. Wang+ (2014),
Bigiel & Blitz (2012)...]

Constraints

[HP, Refregier, Amara, MNRAS (2017), arXiv:1611.06235]



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

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

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

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

$$\alpha = 0.09 \pm 0.01$$

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

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

$$\gamma = 1.45 \pm 0.04$$

DATA : HI GALAXY, DLA, IM

A halo model for neutral hydrogen

Combine IM observations with individual objects

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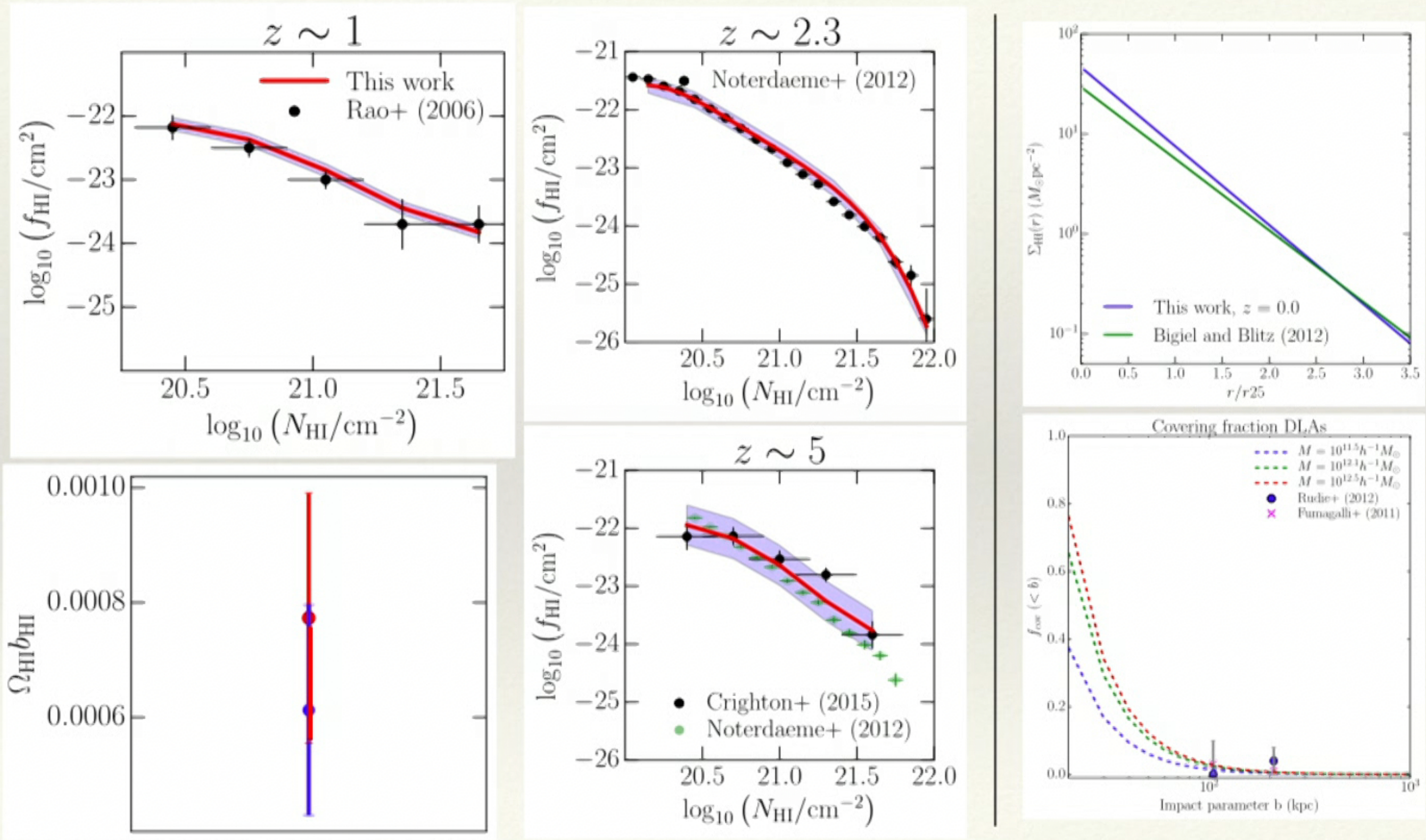
Allows us to derive HI observables

[HP, Choudhury, Refregier, MNRAS (2016)]

One shoe fits all!



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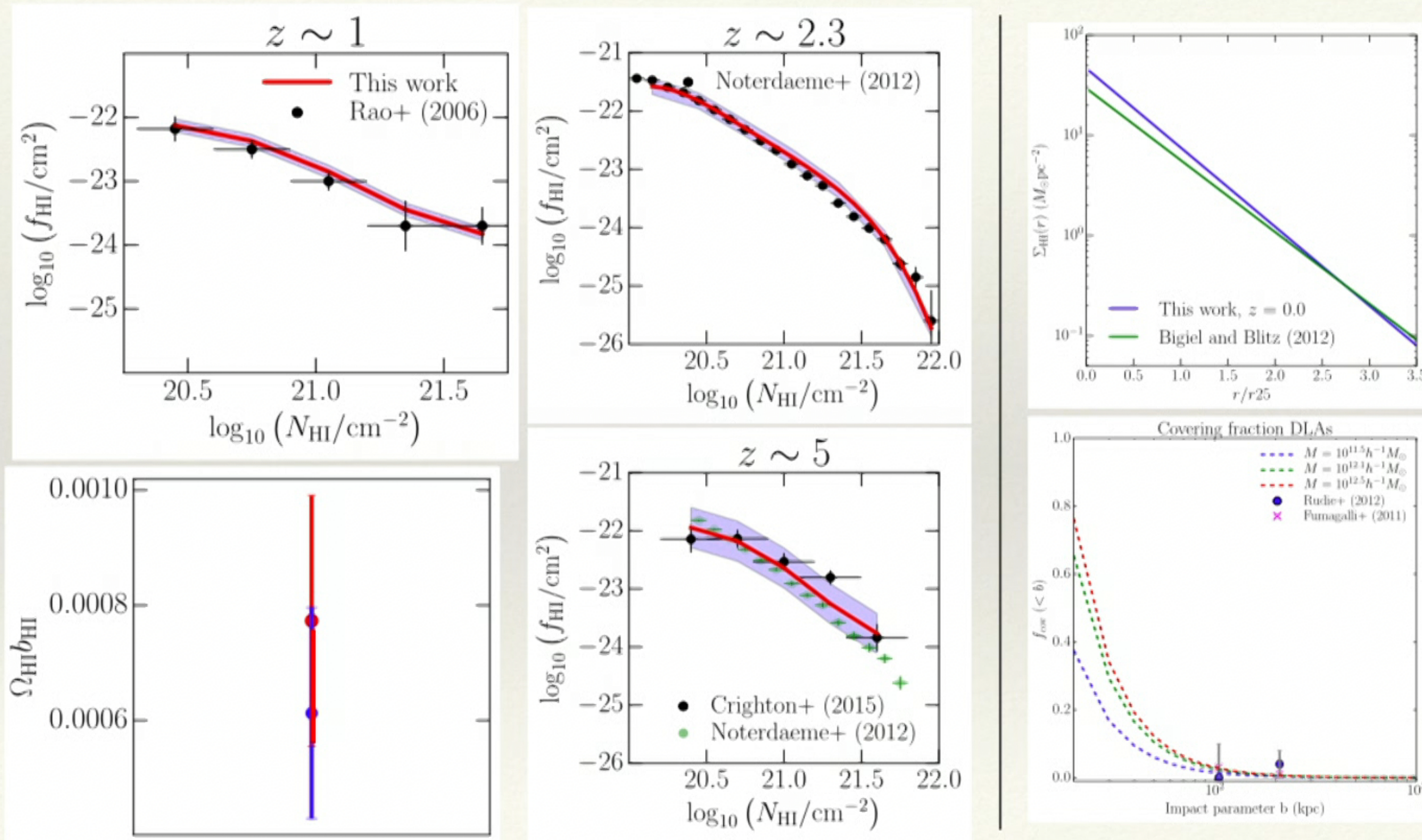

Formalism

Column density distribution, incidence and clustering of DLAs

$$\sigma_{\rm DLA}(M) = \pi s_*^2; \;\; N_{\rm HI}(s_*) = 10^{20.3} {\rm cm}^{-2}$$

$$dN/dX = (c/H_0) \int_0^\infty n(M,z) \sigma_{\rm DLA}(M,z) dM$$

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Column density distribution, incidence and clustering of DLAs

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$$f(N_{\rm HI},z) = (c/H_0)\int_0^\infty n(M,z)\left|\frac{d\sigma}{dN_{\rm HI}}(M,z)\right|\ dM$$

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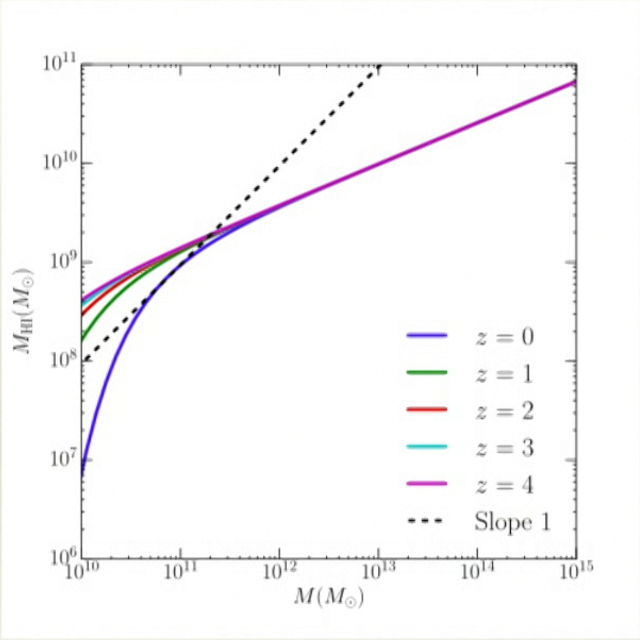
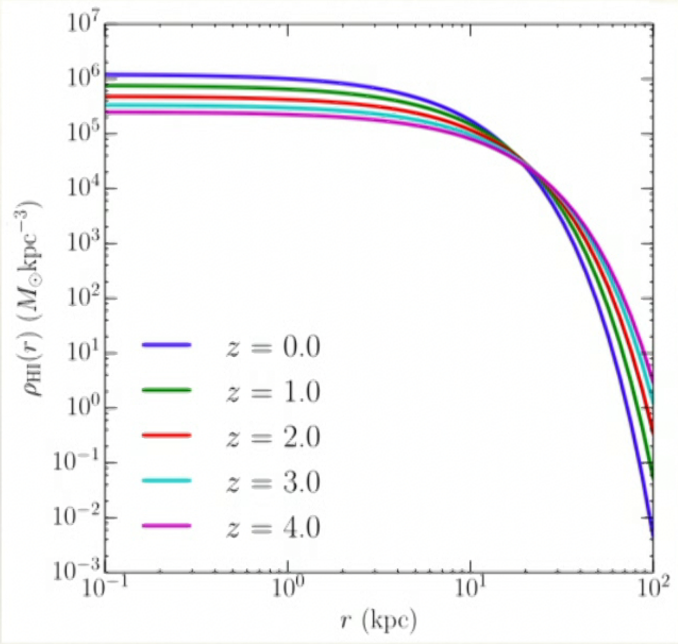
$$f(N_{\rm HI}, z) = (c/H_0) \int_0^\infty n(M,z) \left| \frac{d\sigma}{dN_{\rm HI}}(M,z) \right| \, dM$$

$$b_{\rm DLA}(z) = \frac{\int_0^\infty dM n(M,z) b(M,z) \sigma_{\rm DLA}(M,z)}{\int_0^\infty dM n(M,z) \sigma_{\rm DLA}(M,z)}$$

Best fit halo model





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

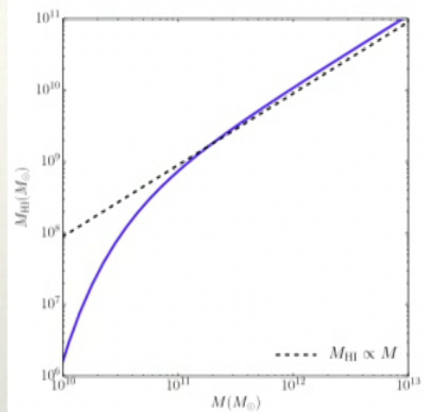
Non-unity slope!

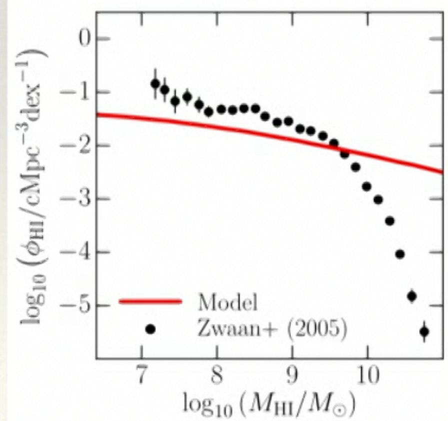
Exponential profile

What do we learn?

Insights from the modelling

- HIHM relations adopted in the literature **[Barnes & Haehnelt 2014; Bagla+ (2010)]**
- Combining the relations **[HP, Choudhury, Refregier, MNRAS (2016)]** does not fit HI mass function well





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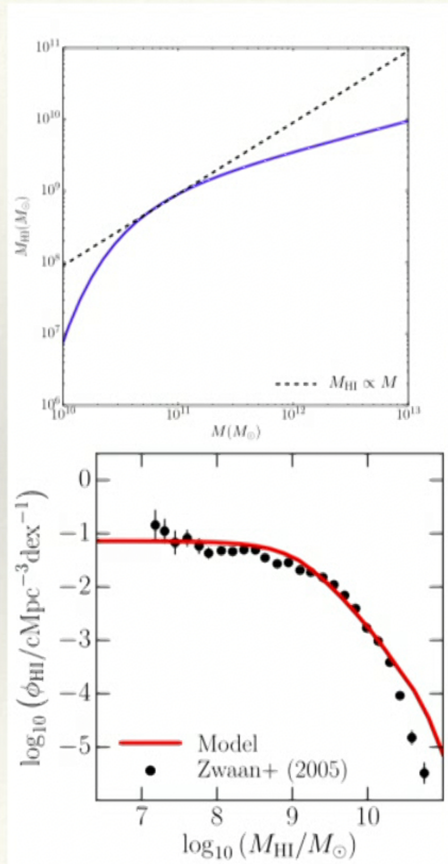

Insights from the modelling

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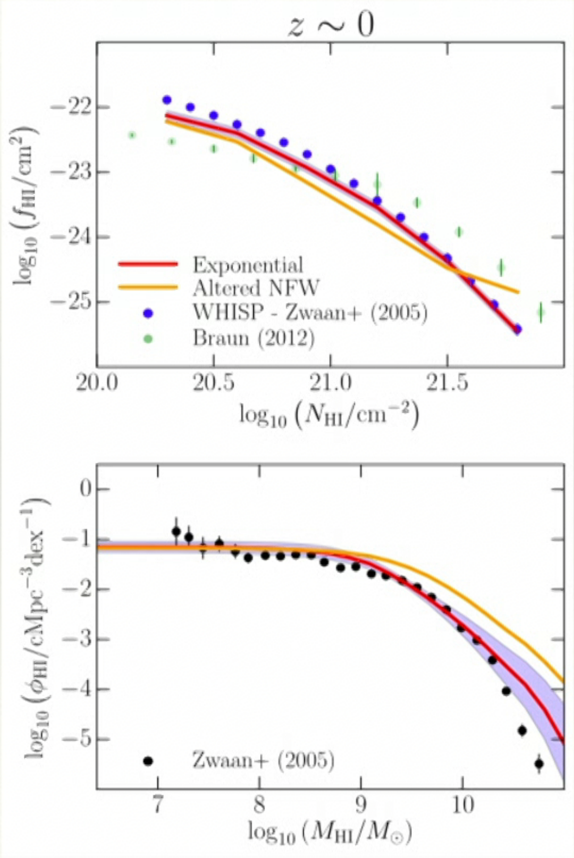
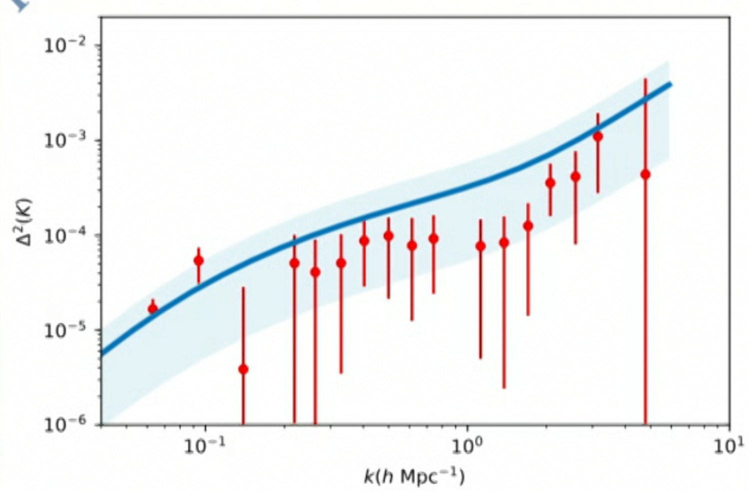
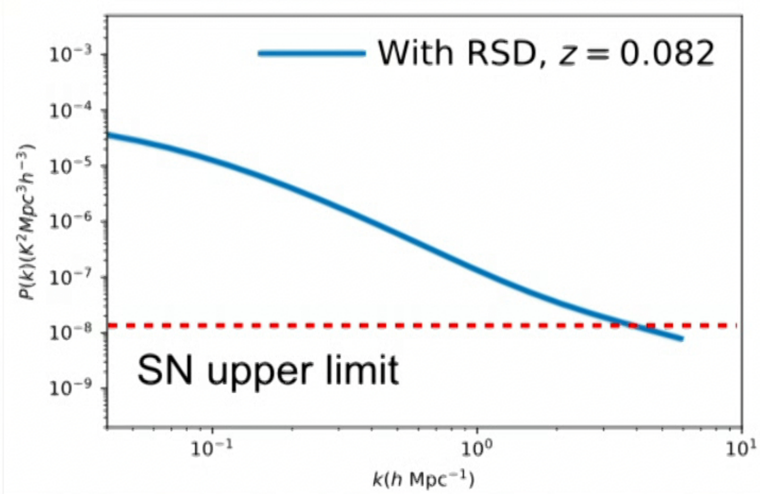
- Combining the relations **[HP, Choudhury, Refregier, MNRAS (2016)]** does not fit HI mass function well
- Fitting the mass function requires a ***non-unit slope*** of HIHM **[HP & Refregier, MNRAS (2017)]**
- An ***exponential profile*** reduces previously observed tension between the HIHM and the column density **[HP, Refregier, Amara, MNRAS (2017)]**



PRELIMINARY

HI IM observations





Parkes x 2dF

Anderson+ (2017)

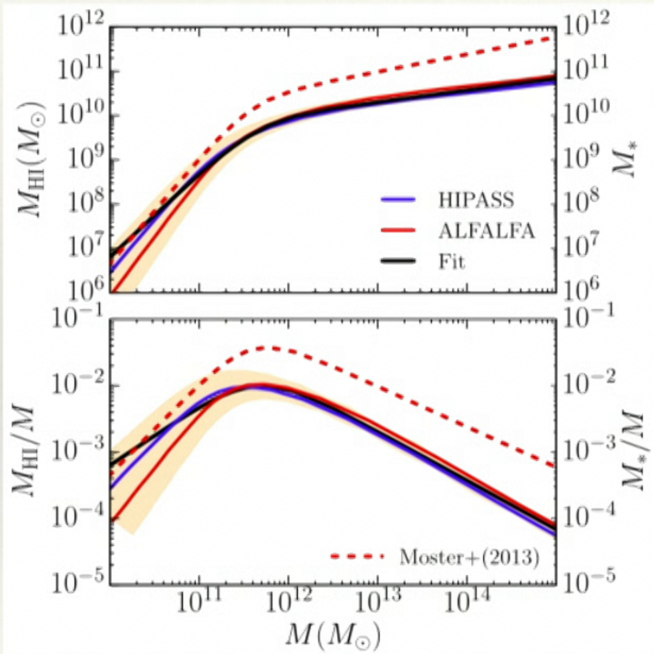
Parkes auto

with GBT/Parkes collaboration

RSD effects on tracers **[Seljak (2001), White (2001)]**

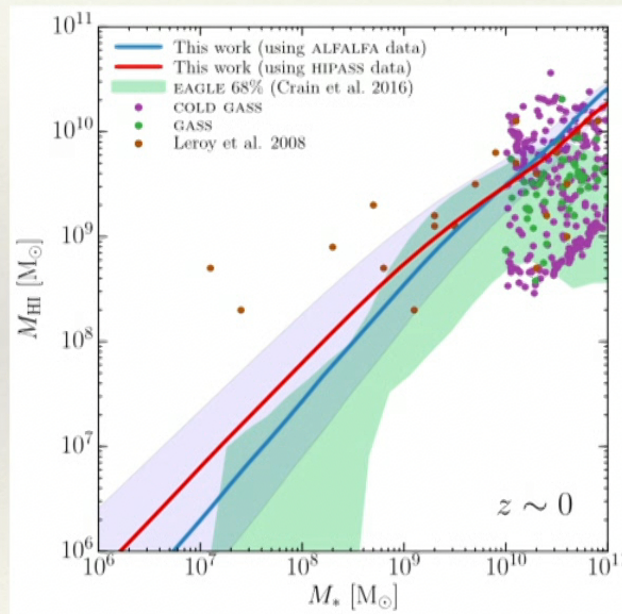
Reverse engineering …

[HP & Kulkarni, MNRAS (2017)]



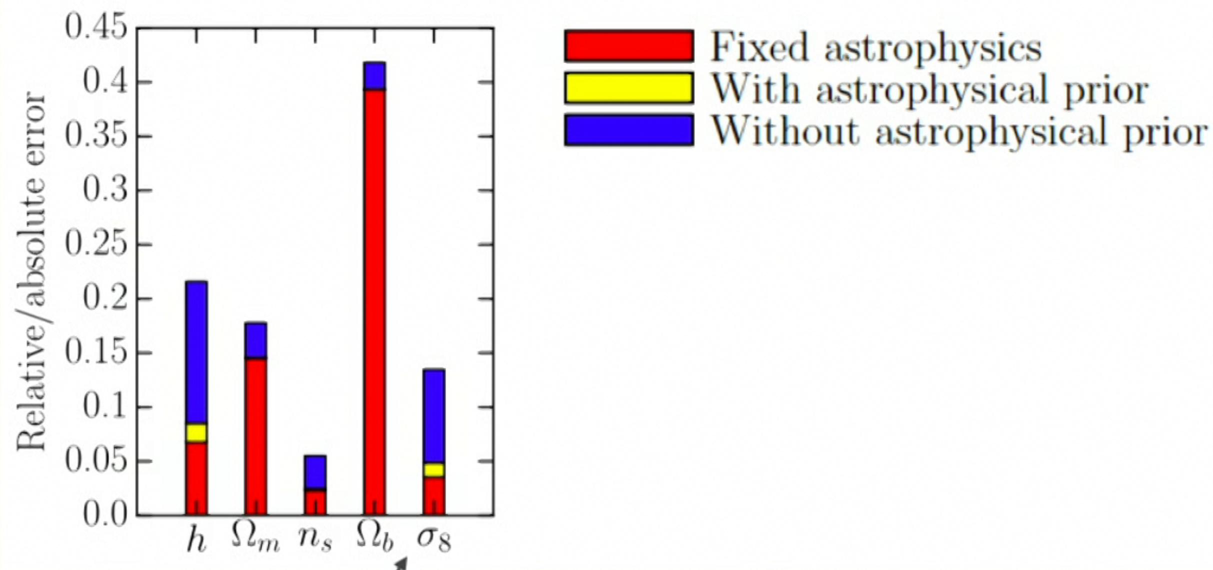
HI abundance matching
(quantify scatter ~ 60%)

Good match to HI-stellar relations



From astrophysics to cosmology

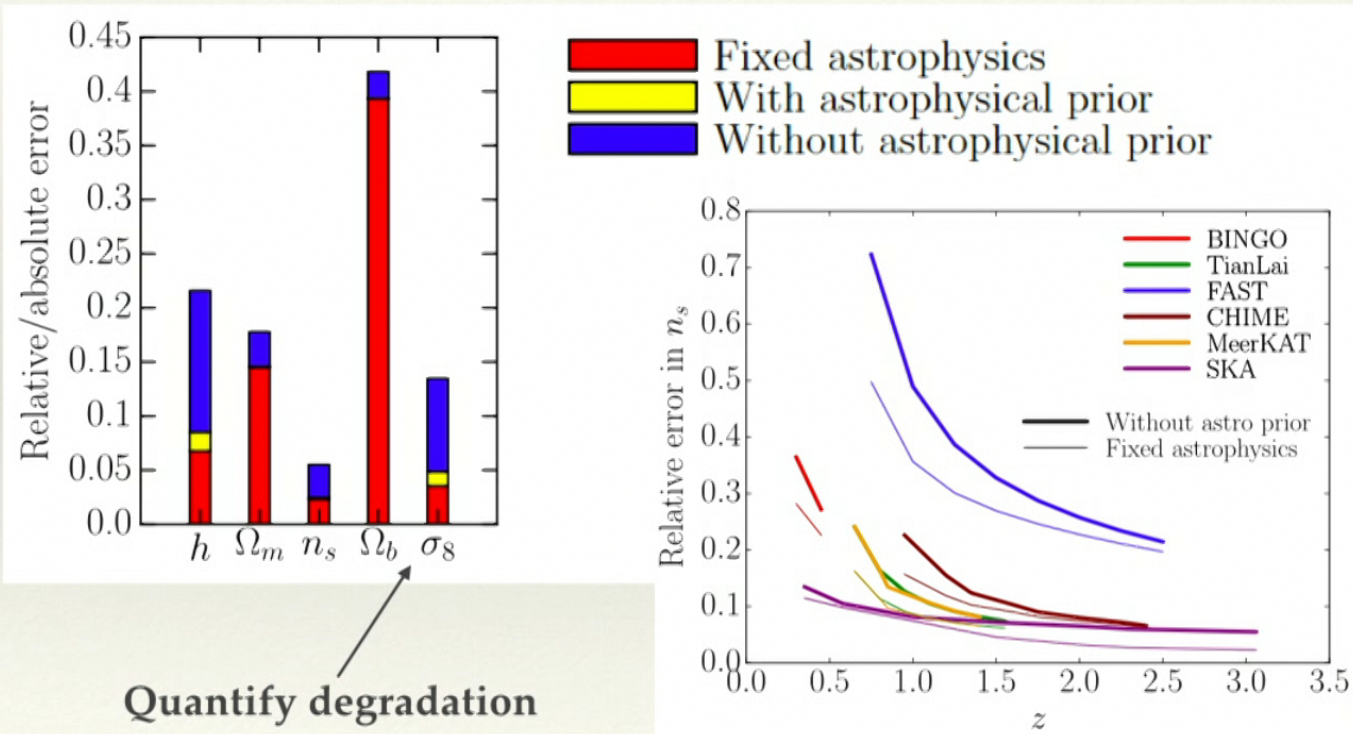
[HP, Refregier, Amara, MNRAS (2019), arXiv:1804.10627]



Quantify degradation from astrophysics ...

From astrophysics to cosmology

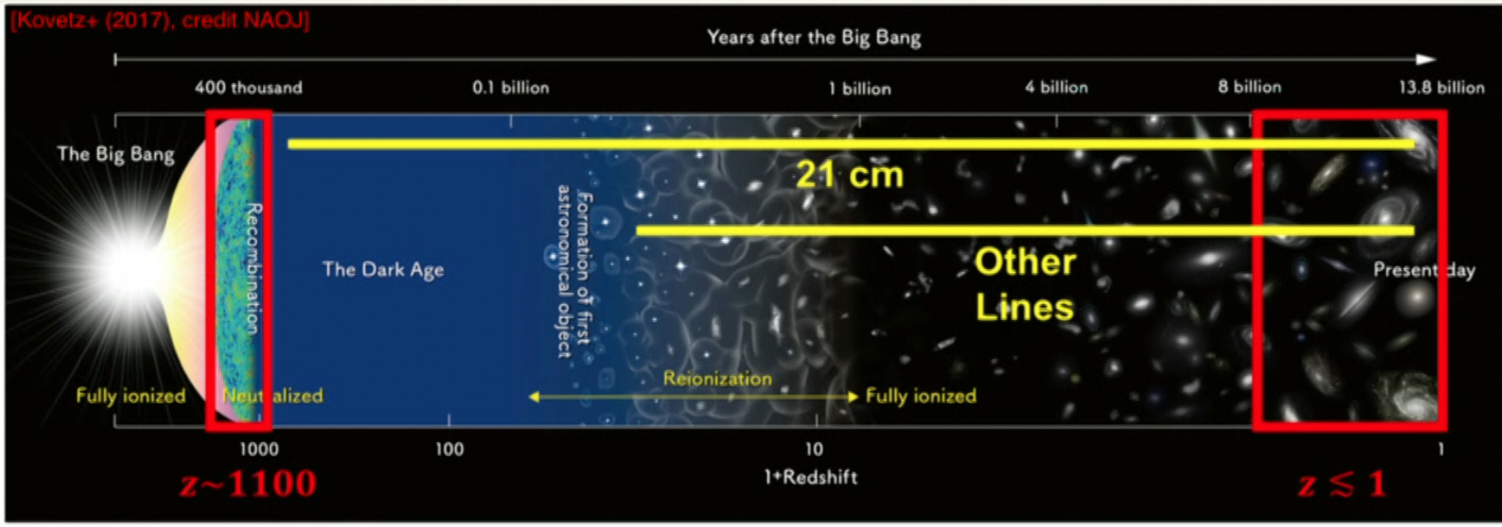
[HP, Refregier, Amara, MNRAS (2019), arXiv:1804.10627]



Quantify degradation from astrophysics …

… alleviated by tomography

Intensity mapping with the CO line(s)

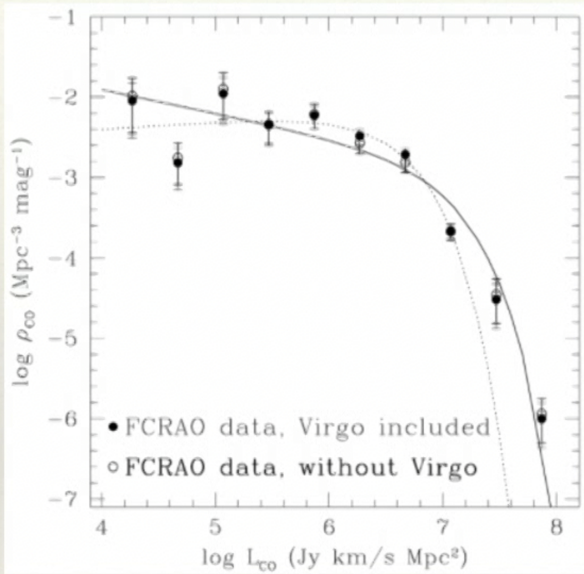


Keating+ (2015, 2016), CARMA: first auto-constraints

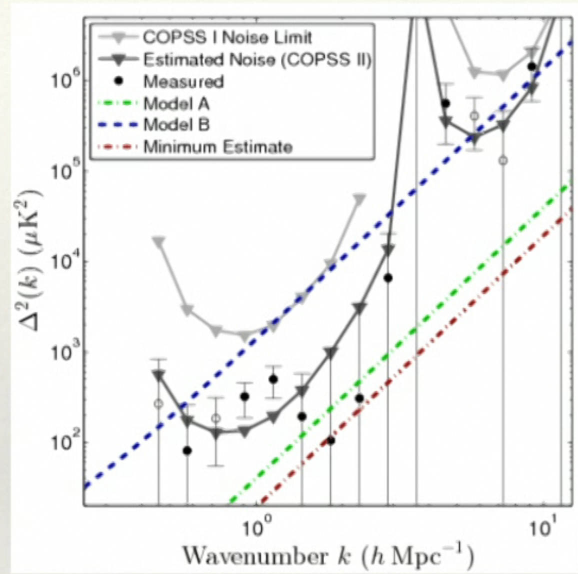
COMAP collaboration

CO constraints : z ~ 0-3

[HP (2018), MNRAS, arXiv:1706.01471]



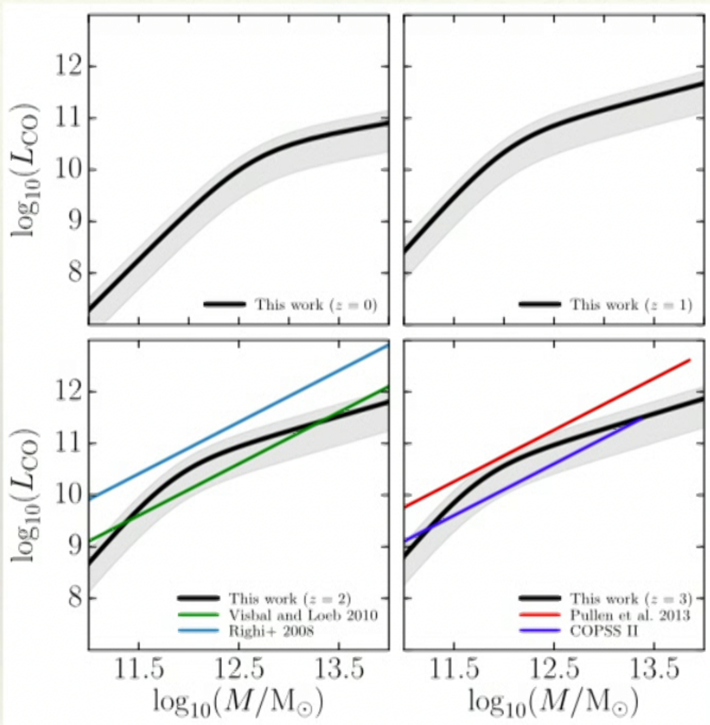
[z ~ 0; Keres+ (2003)]



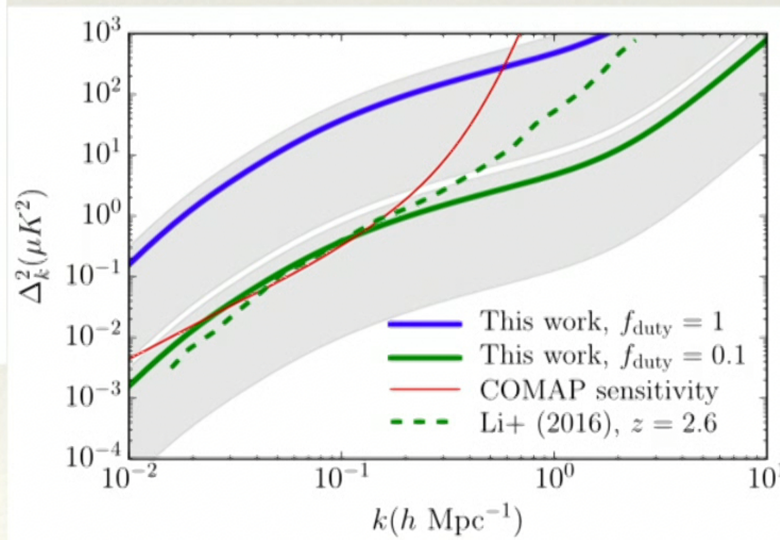
[z ~ 3; Keating+ (2016)]

A halo model for carbon monoxide

[HP (MNRAS, 2018), arXiv:1706.01471]



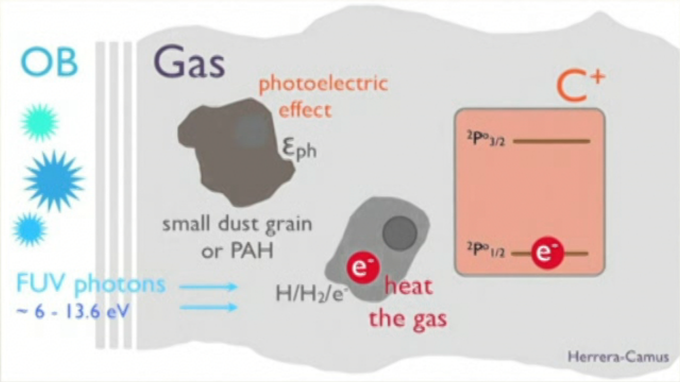
$$L_{\rm CO}(M, z) = \frac{2N(z)M}{(M/M_1(z))^{-b(z)} + (M/M_1(z))^{y(z)}}$$

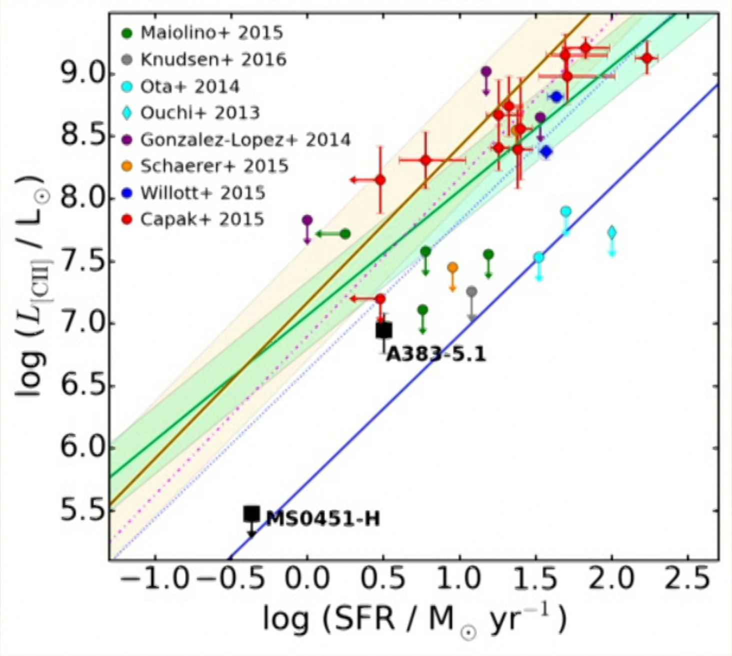


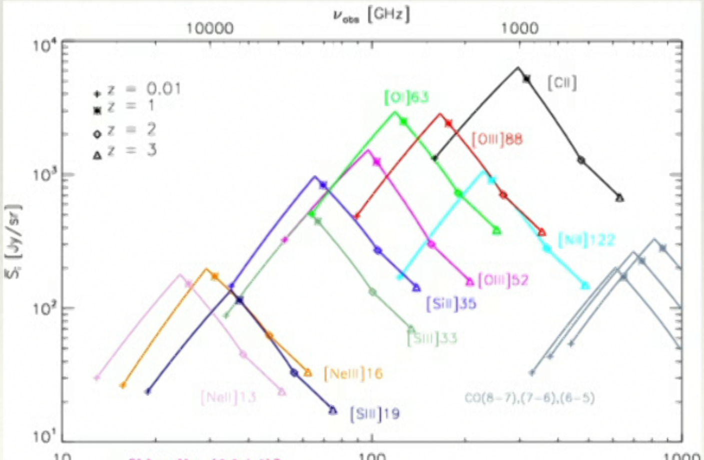
More CO at z ~ 3?

IM with redshifted [CII]

[Aravena + (2016),Herrera-Camus+ (2014), Bradac+ (2016)]





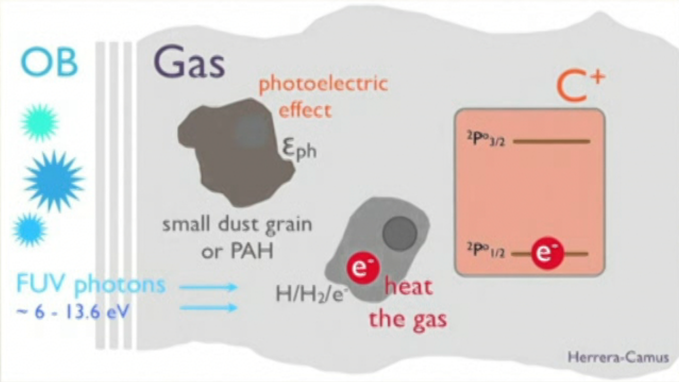


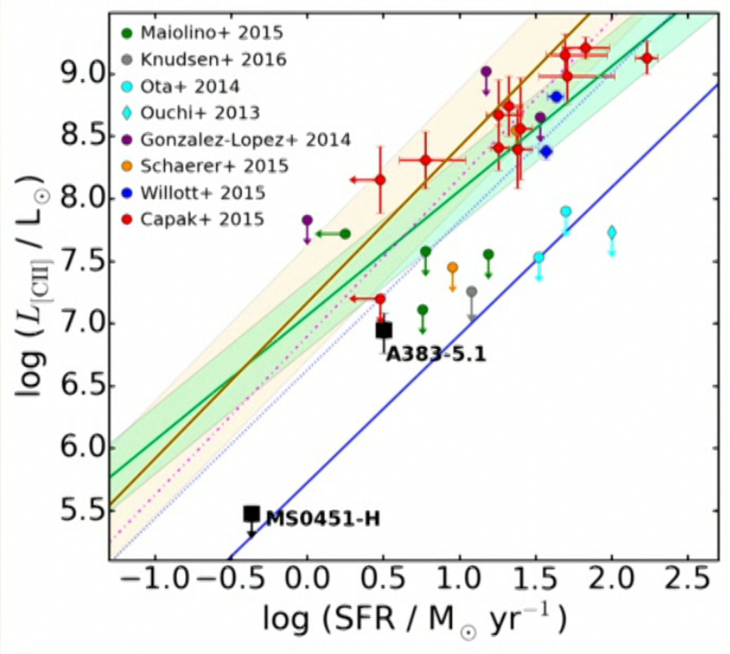
[Uzgil+ (2014)]

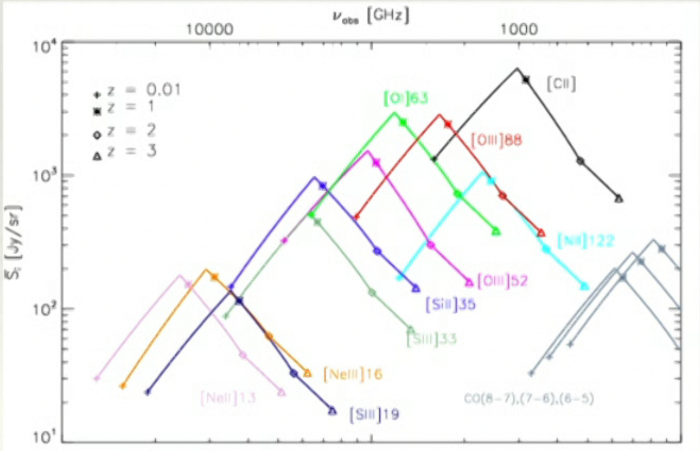
[Knudsen+ (2016)]

IM with redshifted [CII]

[Aravena + (2016),Herrera-Camus+ (2014), Bradac+ (2016)]





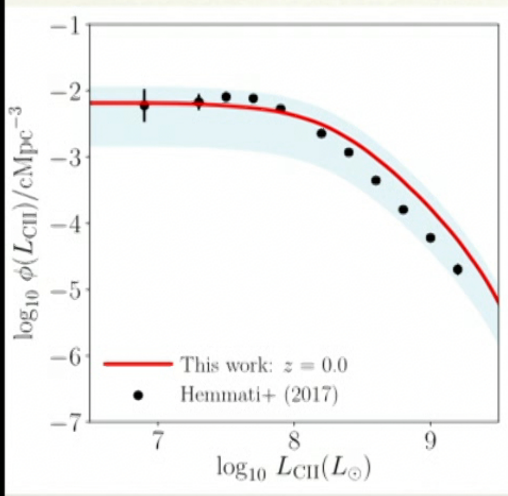


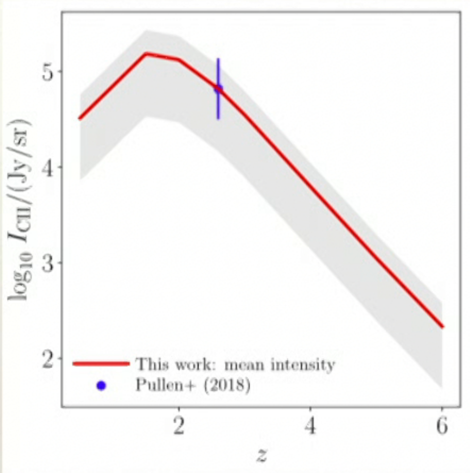
[Uzgil+ (2014)]

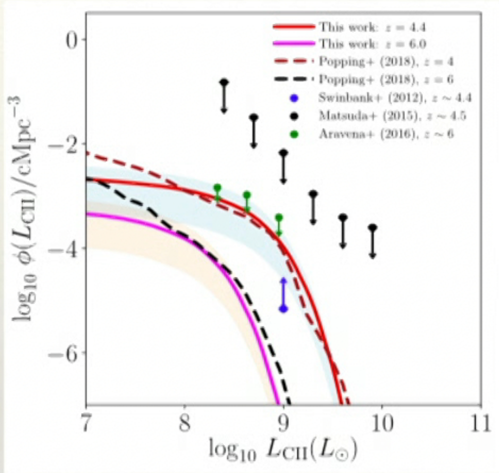
[Knudsen+ (2016)]

CII IM + CII galaxy LF

[HP (2018), arXiv:1811.01968]







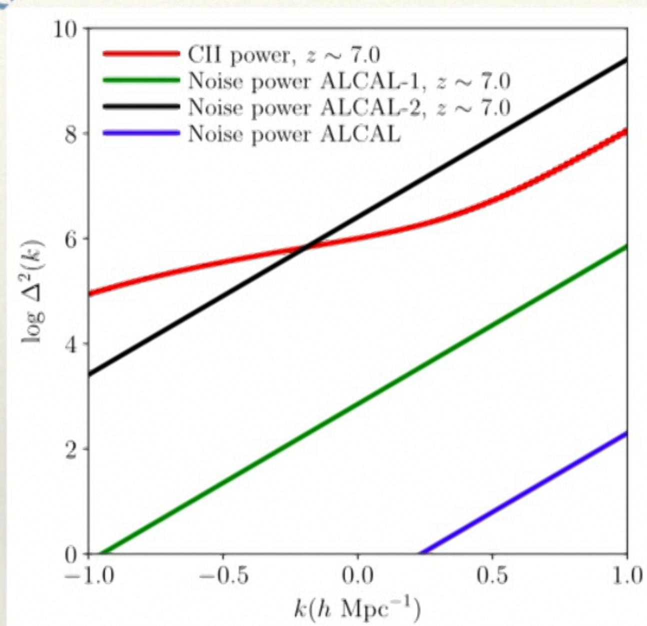
$$L_{\rm CII}(M,z) = F(z)[(M/M_1)^{\beta}\exp(-N_1/M)]$$

$$F(z) = ((1+z)^{2.7}/(1+[(1+z)/2.9]^{5.6}))^{\alpha}$$

SFR evolution

PRELIMINARY

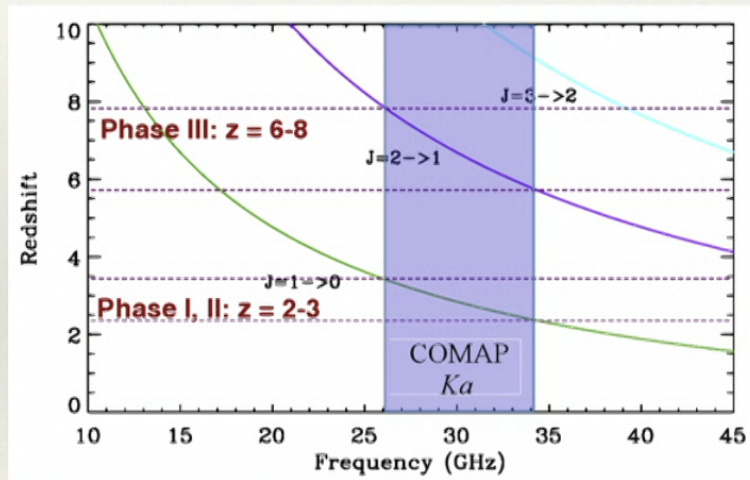
Reionization



ALMA UDF (with ESO)

ALMA CII pencil beam surveys

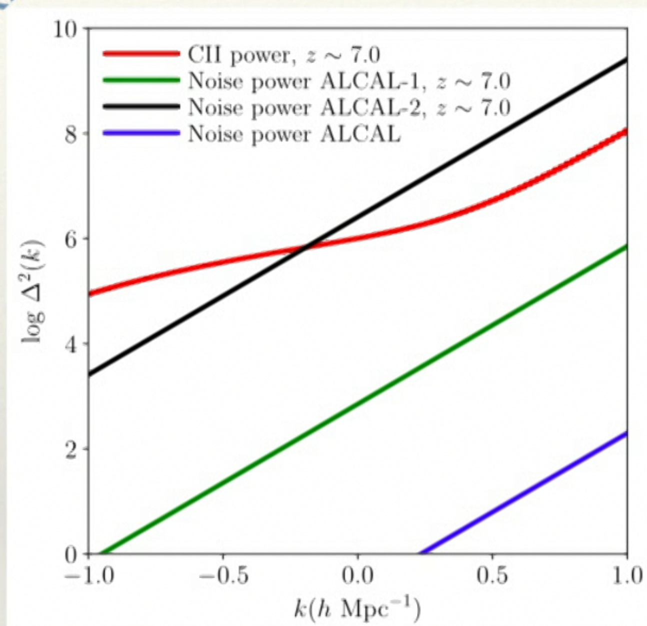
26 - 34 GHz; CO 1-0 line @ z ~ 2-3 *and* CO 2-1 @ z ~ 6-8 (EoR!)



COMAP Phases II/III

Reionization

PRELIMINARY



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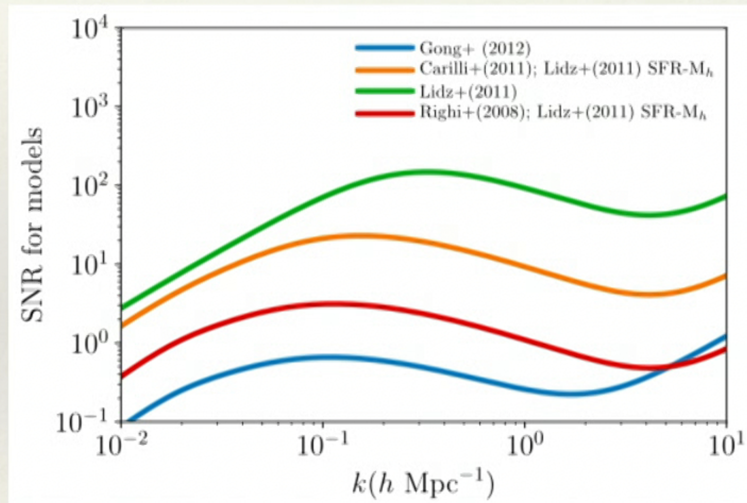

COMAP Phases II/III

EoR HI

Fundamental Physics with the SKA, chapter on *Cosmic Dawn and Reionization (2018), HP & Jonathan Prichard (co-lead)*

Summary and future …

Summary and future …

- A data-driven, halo model formalism to interpret future observations of HI (CHIME/SKA/MeerKAT …)
- Forecasting to investigate the 'astrophysical systematic' expected in surveys; Primordial non-Gaussianity / axions (**with S. Camera / D. Marsh**)
- Extensions to other tracers — molecular and ionised carbon (CO, CII …)
- Probes of the epoch of reionization (SKA/COMAP/ALMA/CCAT-p, …) the 'final frontier' of observational cosmology (**with COMAP/ALMA-ESO collaborations**)
- Extensions to halo model invoking environmental effects, comparison to high-z observations, DLAs (**with GBT/Parkes collaboration**)
- Cross-correlations of gas tracers with large galaxy surveys (e.g., Euclid, LSST, DES, DESI … **with A. Refregier and A. Amara**)

Summary and future …

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Thank you!