Mapping the baryonic Universe

— a new window into the cosmos —

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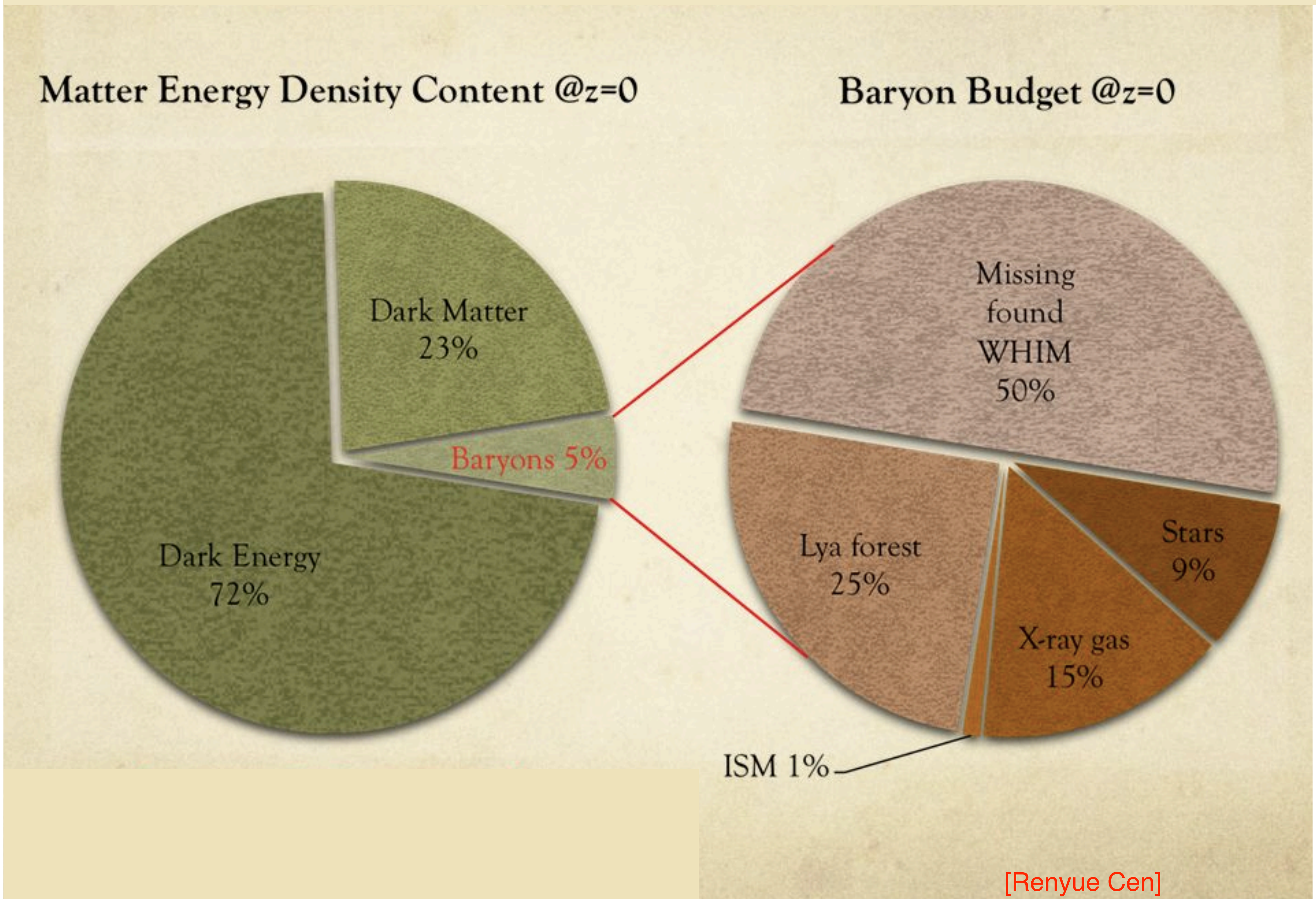
UNIVERSITÉ DE GENÈVE

Swiss National Science Foundation

Introducing the baryonic universe



[Renyue Cen]

Mapping the baryonic universe

- GMRT (Pune, India)
- LOFAR (the Netherlands)
- CHIME (Canada)
- PAPER, MeerKAT (South Africa)
- BINGO, TianLai, HIRAX…
- COMAP, COPSS, …
- ALMA, FYST, TIME, CONCERTO…
- SKA (South Africa/Australia)

The Square Kilometre Array (SKA)

An international venture, IGO

Radio telescope (operational ~ 2029)

1 square kilometre collecting area

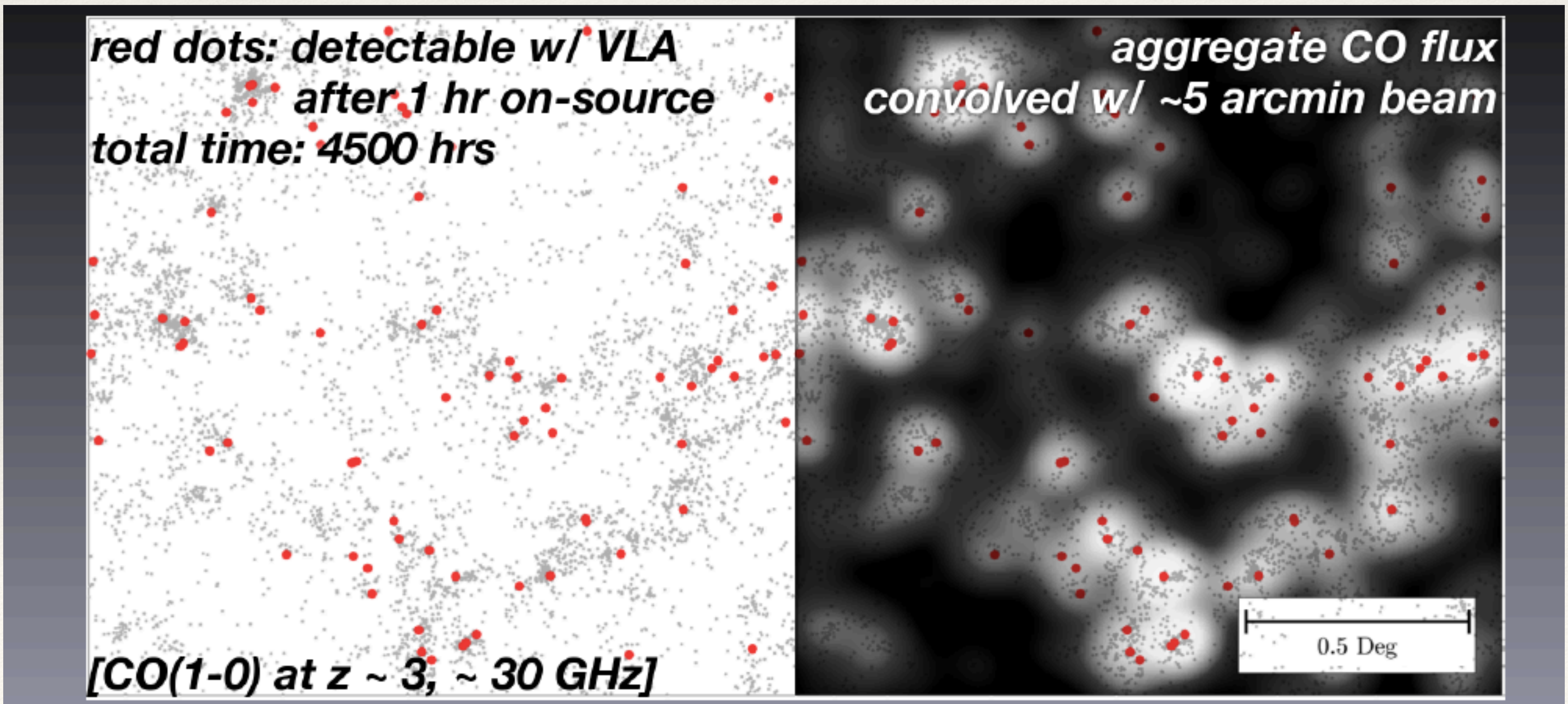
~ 200 dishes; 350 MHz - 14 GHz

Intensity mapping (IM)

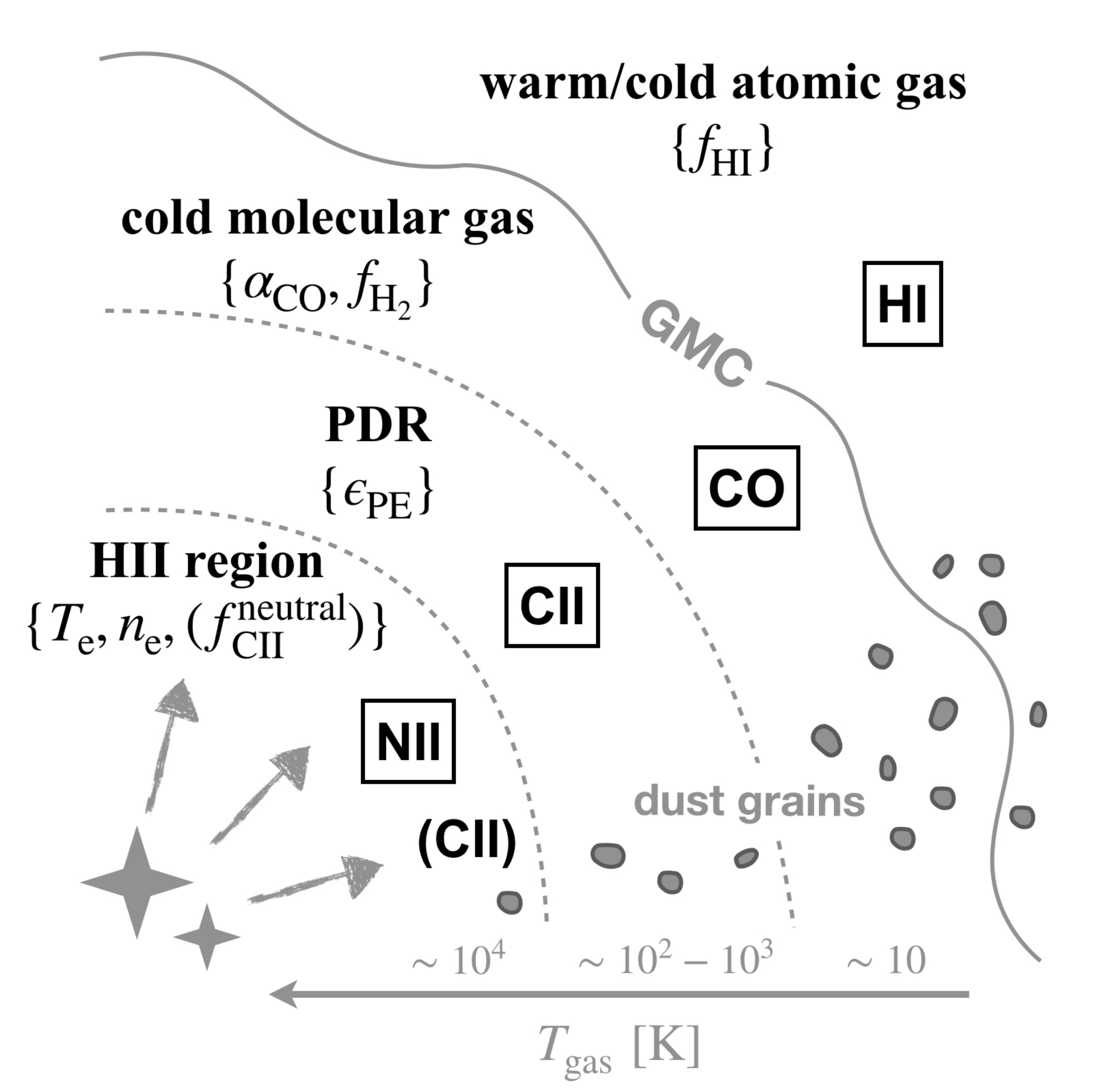
[Early studies: Hogan and Rees 1979, Sunyaev and Zeldovich 1972,1974, Bebington+ 1986]

- 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

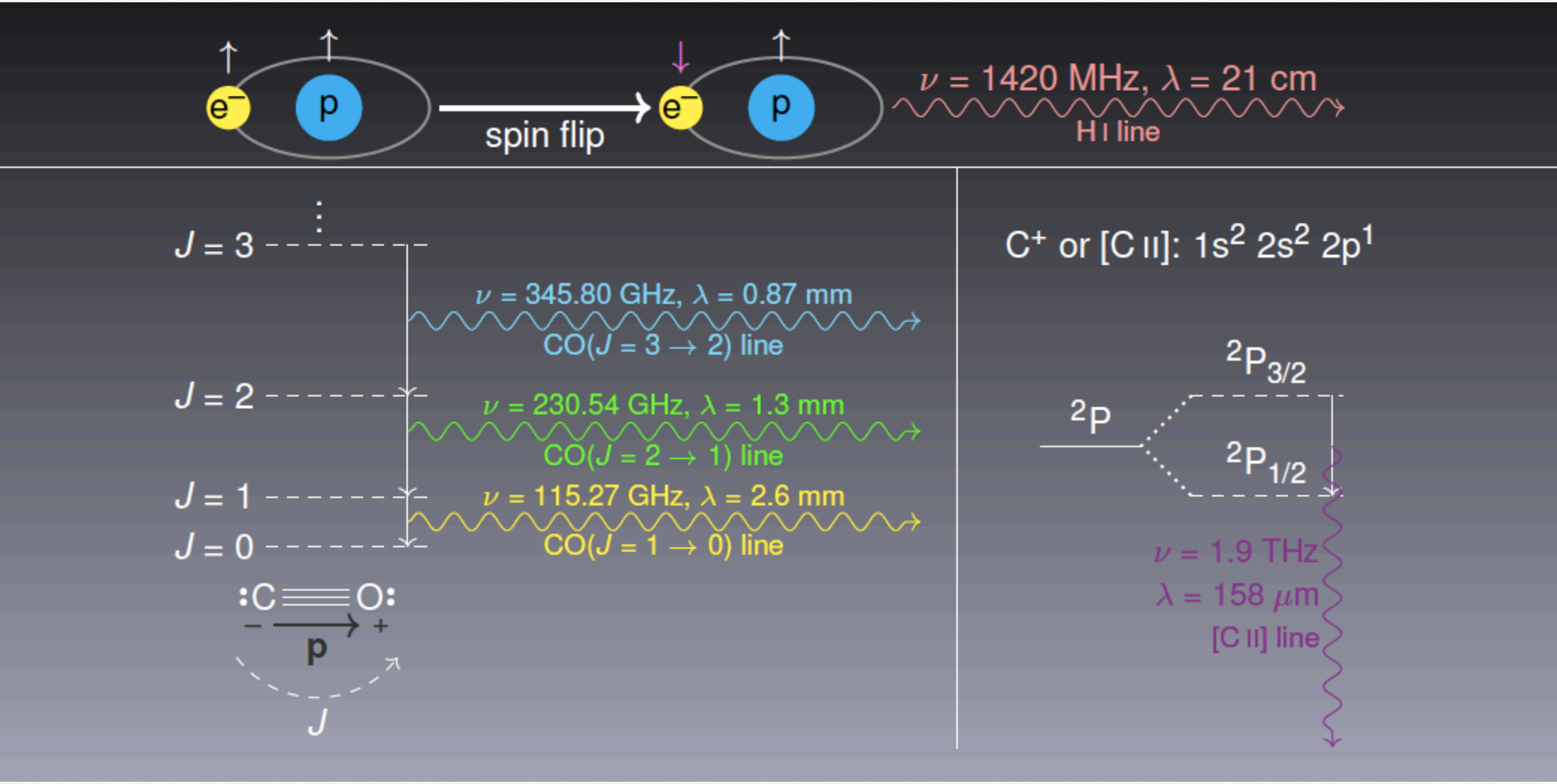


Lines and environments



[Sun+ (2020), ApJ, arXiv:1907.02999]

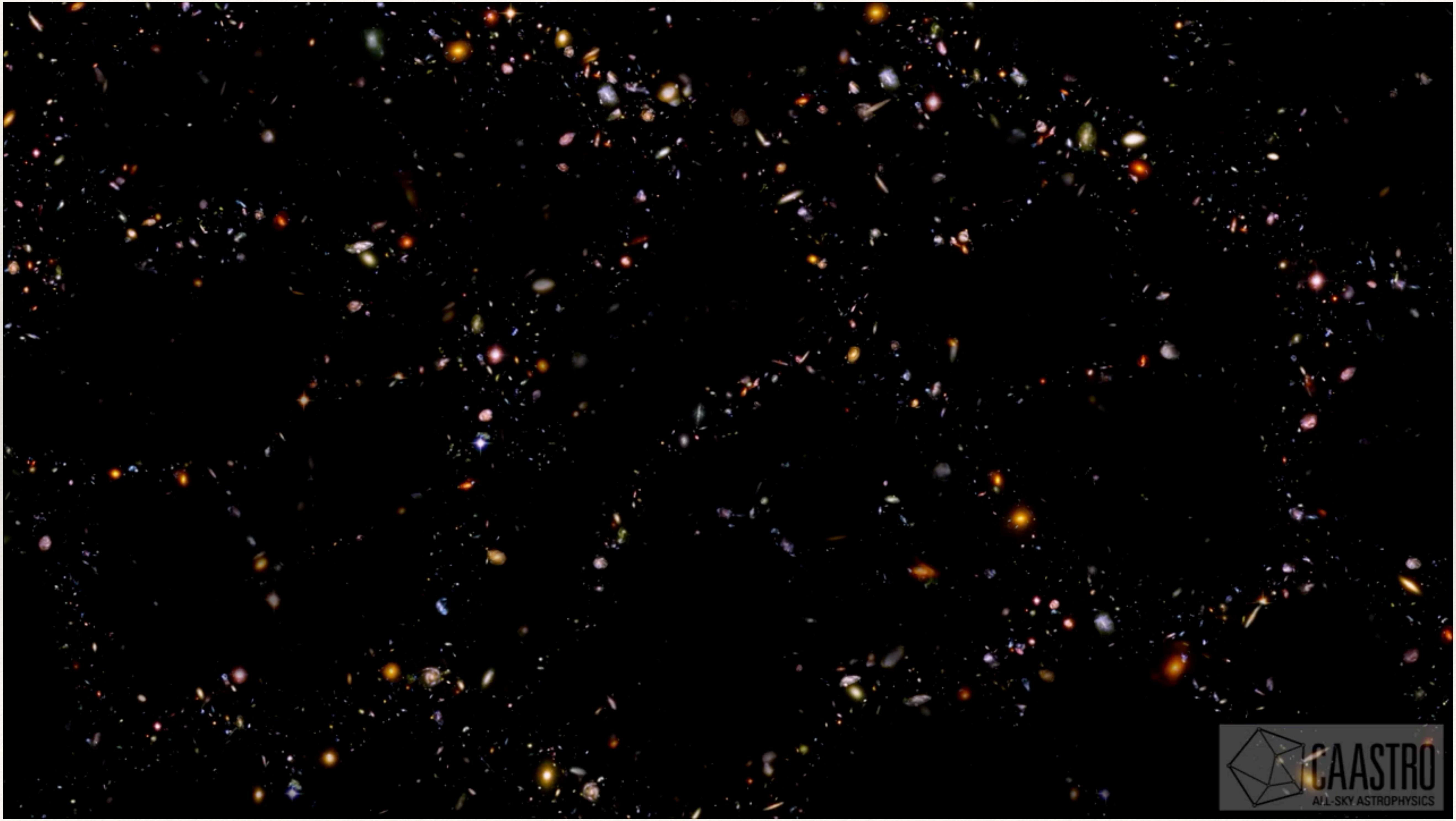
Atomic and molecular lines



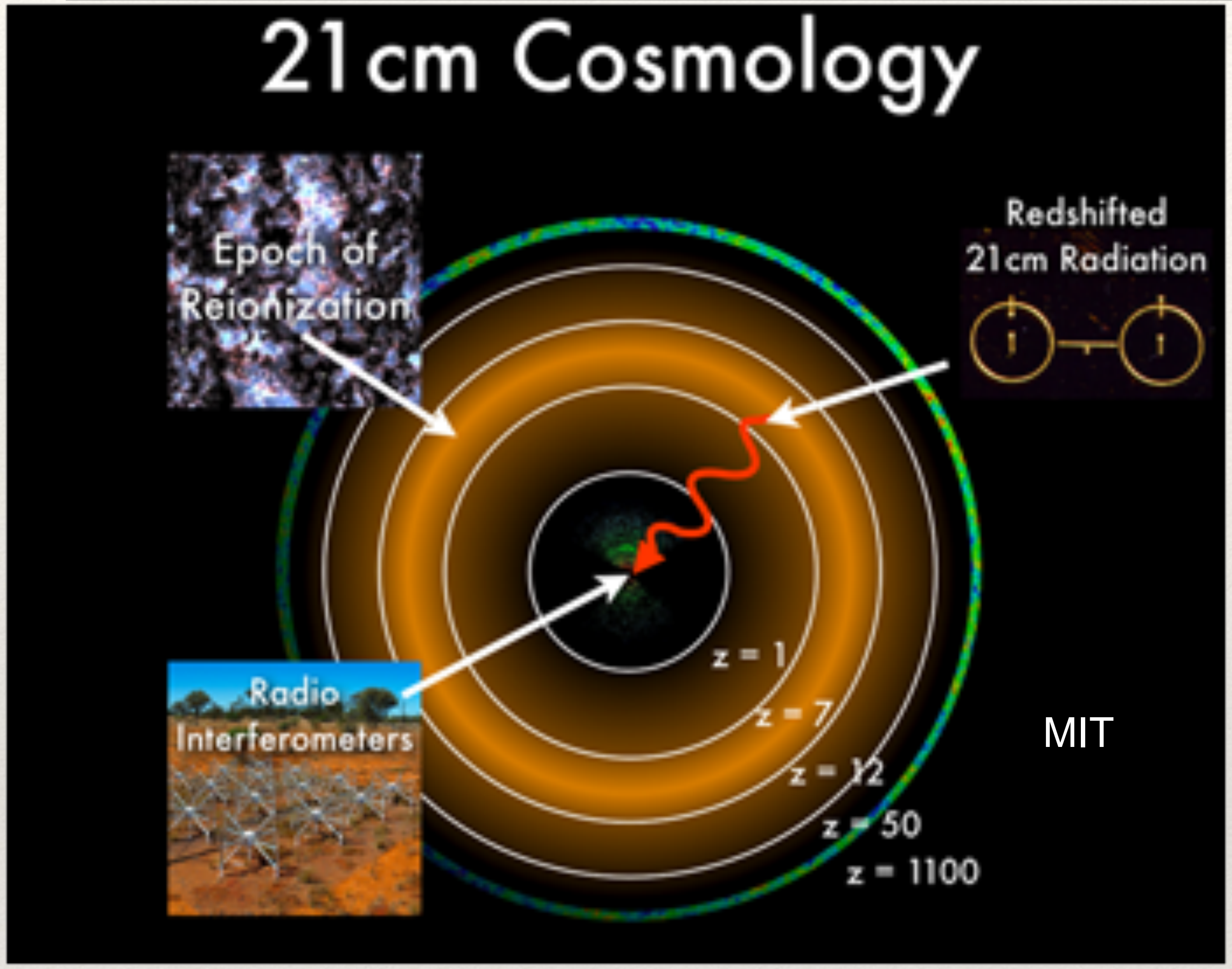
Credit: Dongwoo Chung

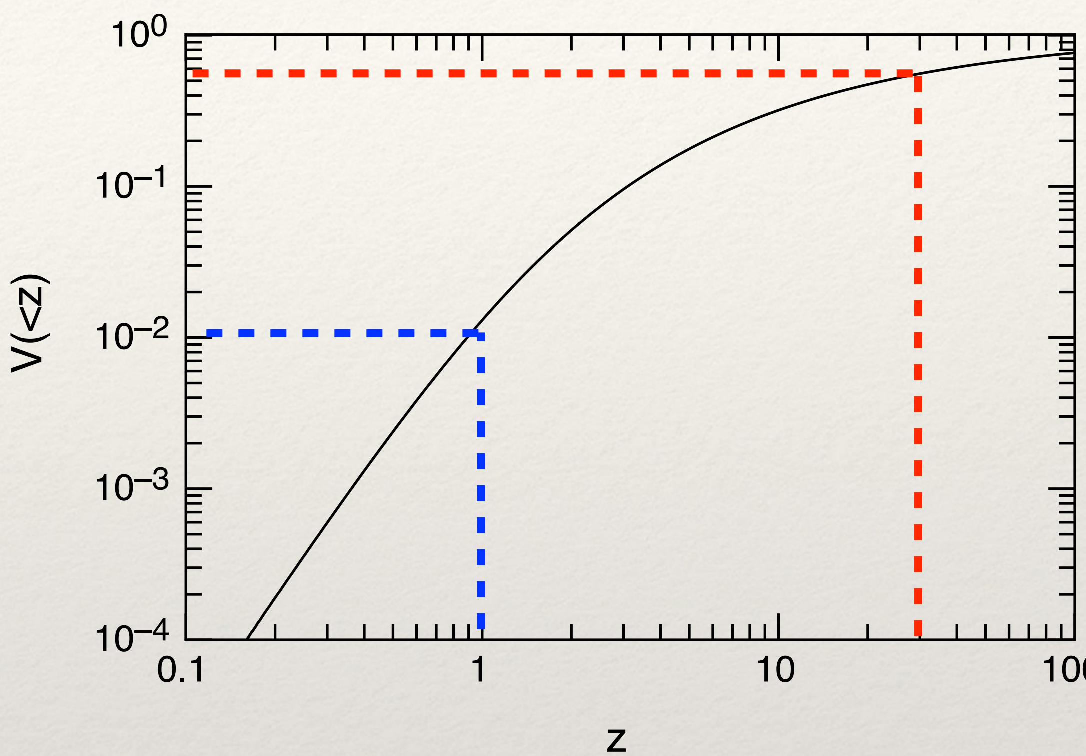
21 cm intensity mapping

Chang+ (2010), Masui+ (2013), Switzer+ (2013), Anderson+ (2018), Wolz+ (2021), CHIME collaboration (2022), Cunnington+ (2022), Paul+(2023) …



Cosmology with IM





[Loeb & Wyithe (2008)]

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

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

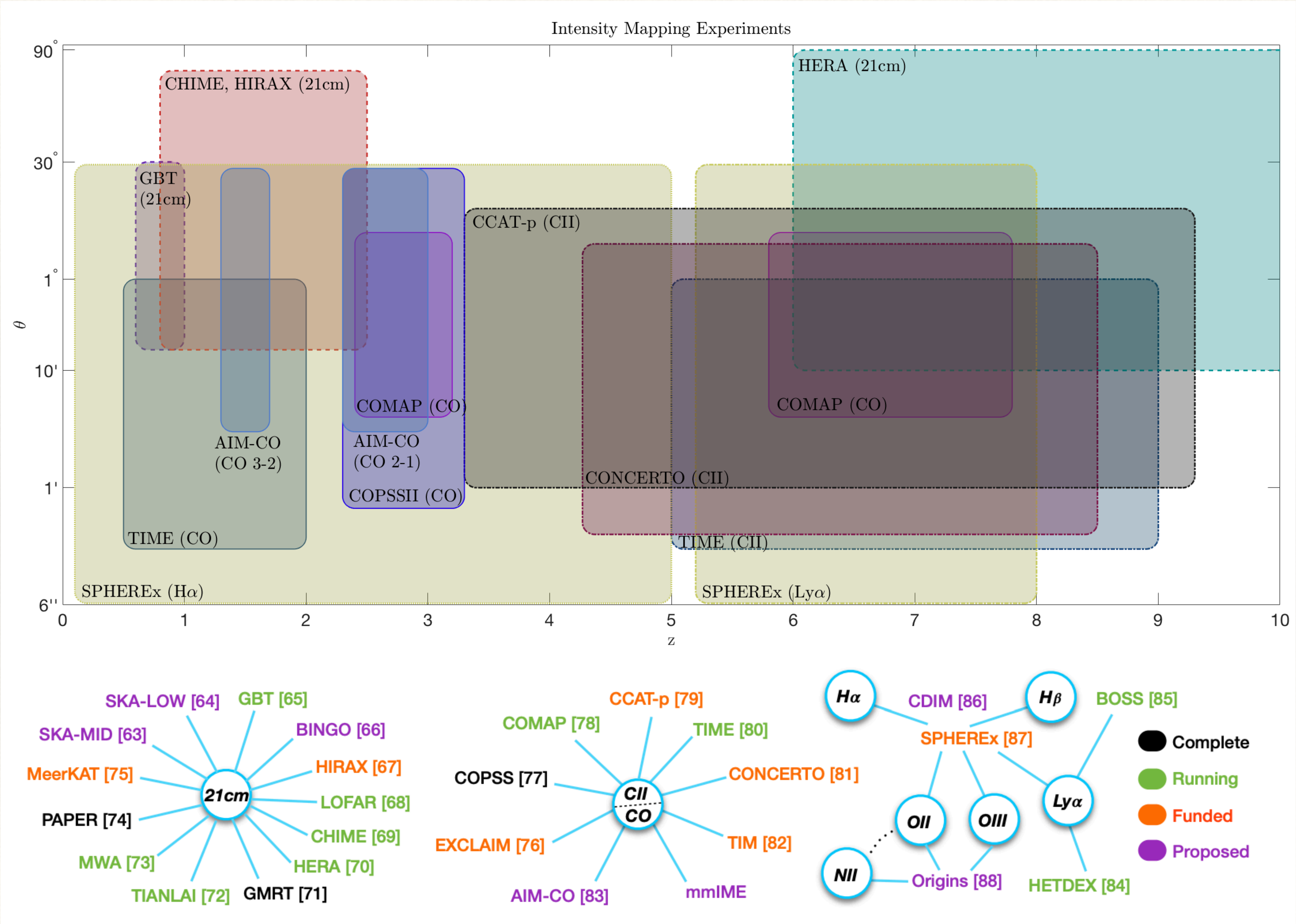
$$\mathrm{Dark\ \ Ages}: k_{\mathrm{max}} \sim 1000 \mathrm{Mpc}^{-1}$$

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

[Furlanetto (2019)]

A plethora of experiments …

[Kovetz+ (2017, 2019)]

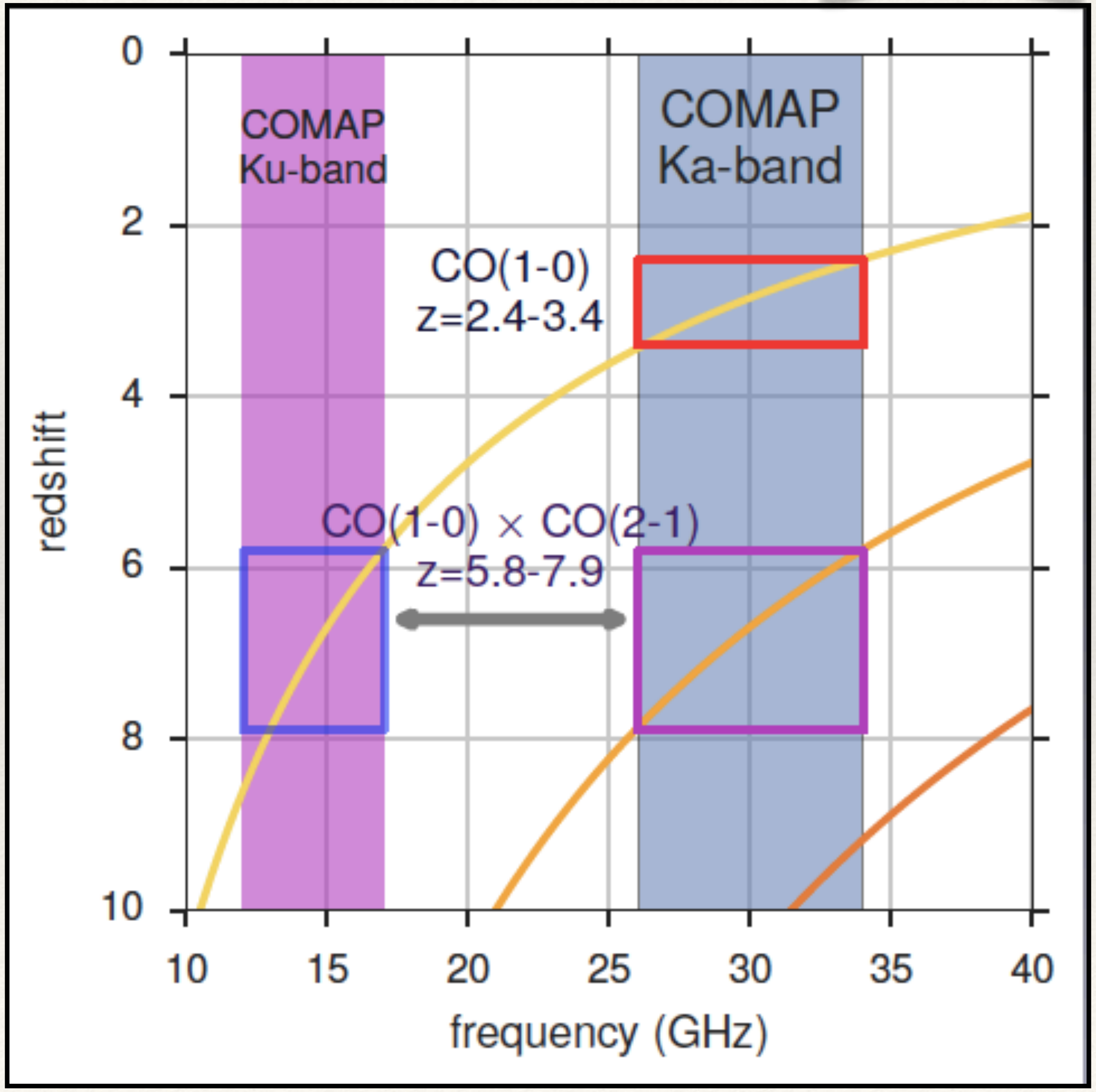


The microwave regime

— The CO Mapping Array Project —

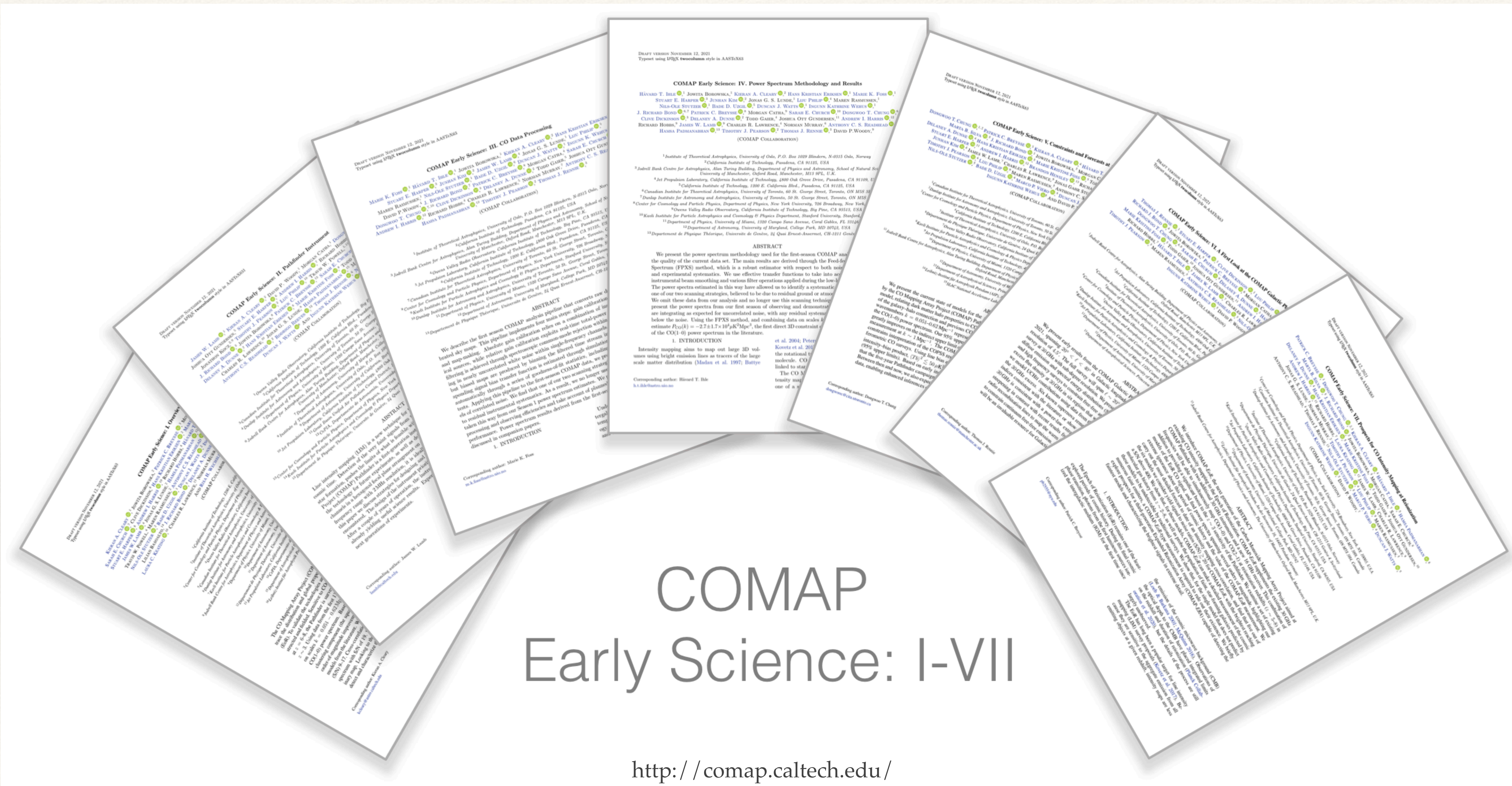
- CO is a major tracer of star formation, bright even at high redshifts
- ‘Ladder’ of lines
- Pathfinder: a proof-of-concept, single dish focal plane array, 26-34 GHz
- Three fields, ~ 4 deg^2 per field

CO transitions



COMAP Early Science

Seven Early Science papers on arXiv, covering first 13 months of observing

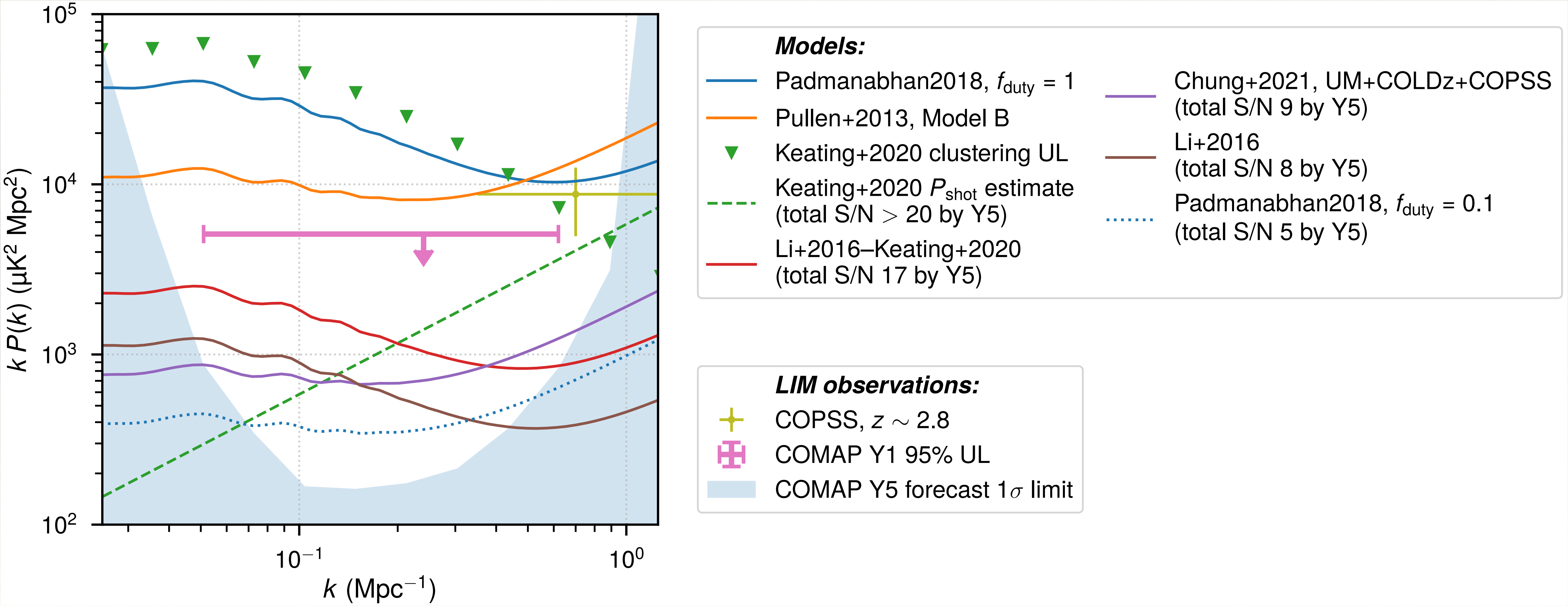


[Cleary+ (2021), Lamb+ (2021), Foss+ (2021), Ihle+ (2021), Chung+ (2021), Rennie+ (2021), Breysse+ (2021), To appear in ApJ; arXiv:2111.5927-5933]

COMAP Early Science

The first direct 3D measurement of the CO power spectrum on large scales
[Cleary+ (2021)]

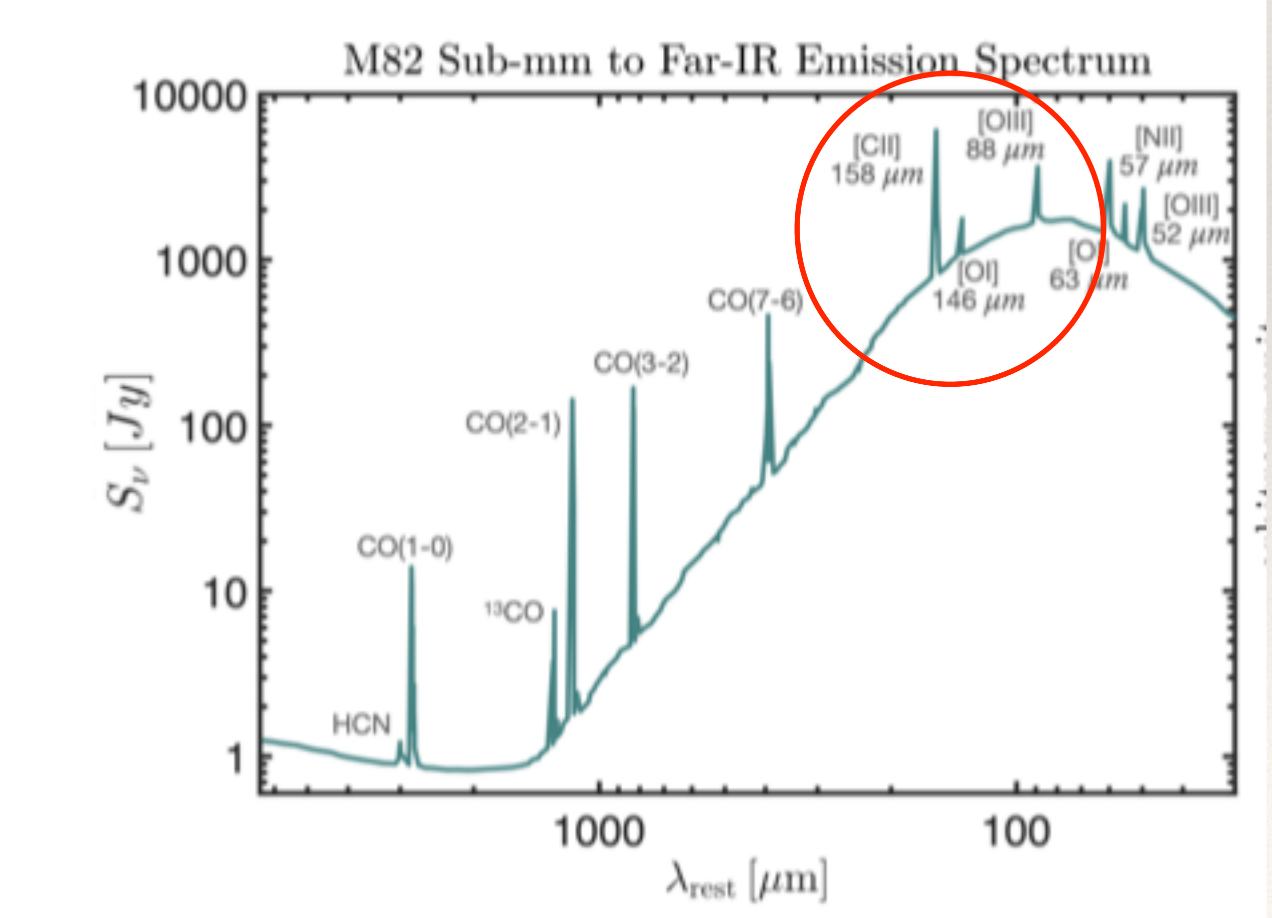
Nearly an order of magnitude improvement compared to the previous best measurement

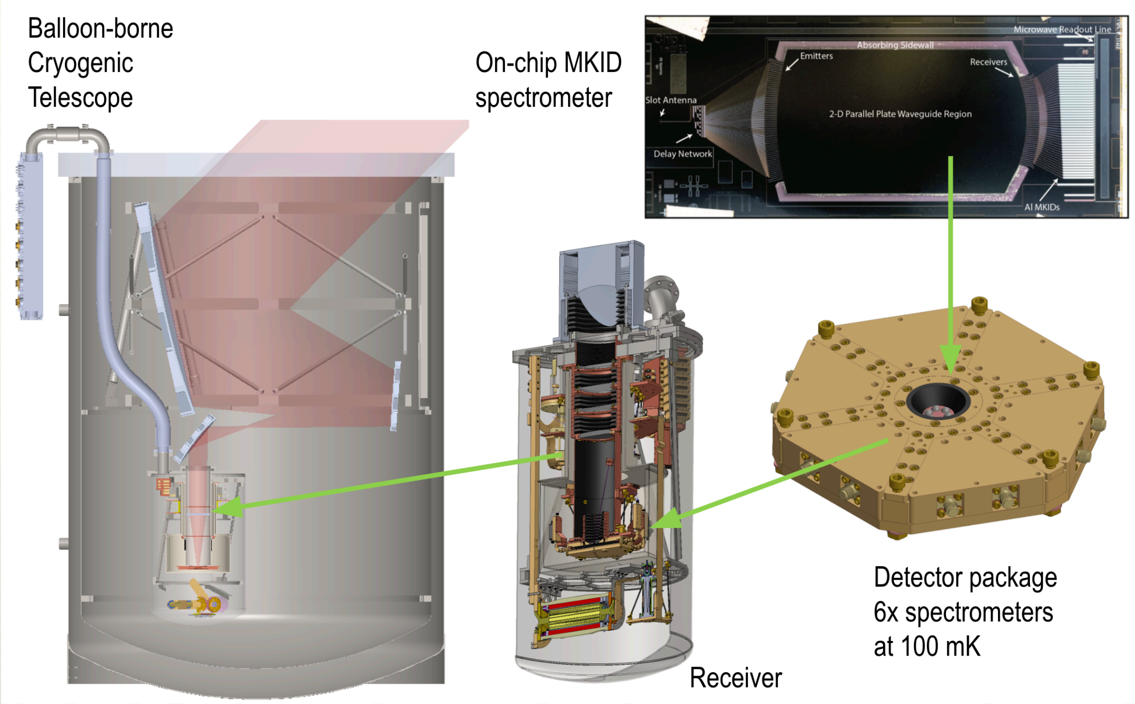


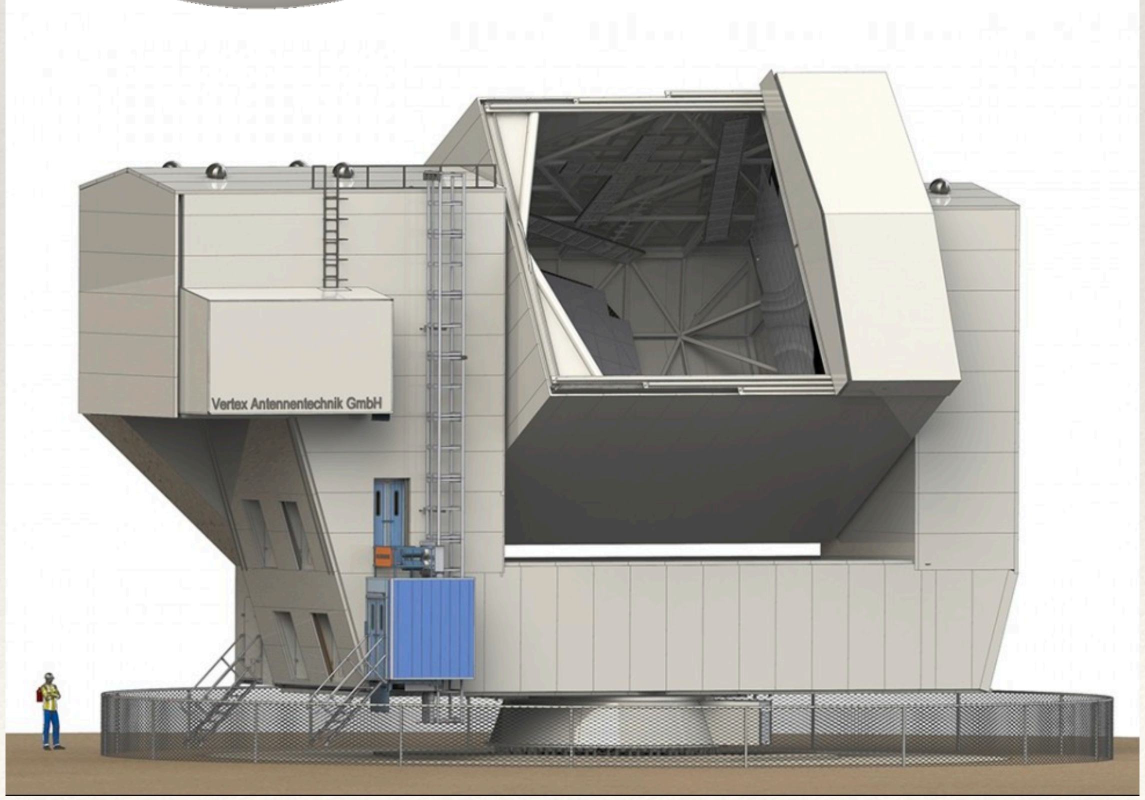
[Chung+ (2021), Ihle+ (2021)]

Intensity mapping at GHz frequencies

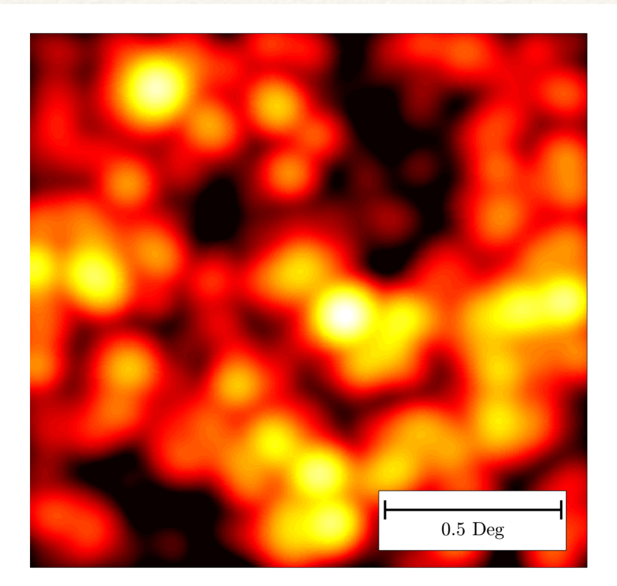
- [OIII] 88 μm and [CII] 158 μm
- Good tracers of star forming regions
- Brightest infrared lines
- **Fred Young Submillimetre Telescope (FYST)** : 212 - 428 GHz
- **EXperiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM)** : 420 - 540 GHz

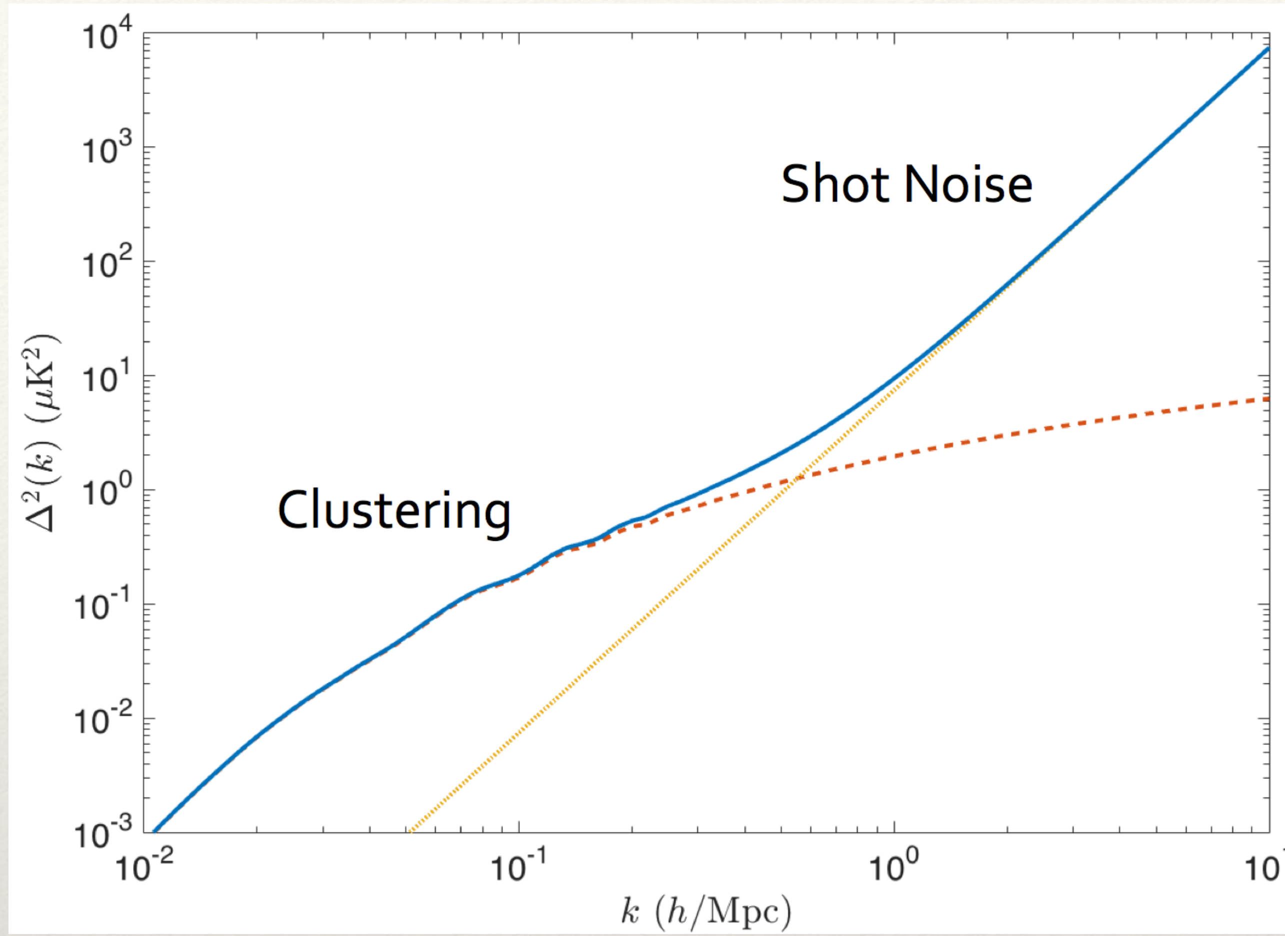






The power spectrum



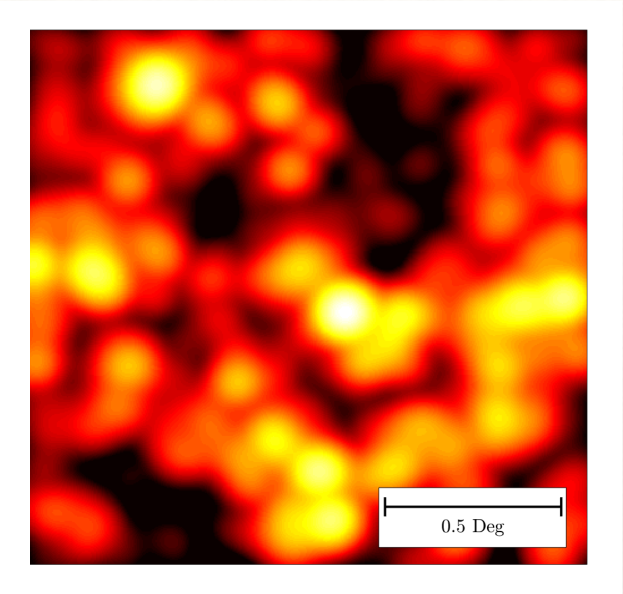


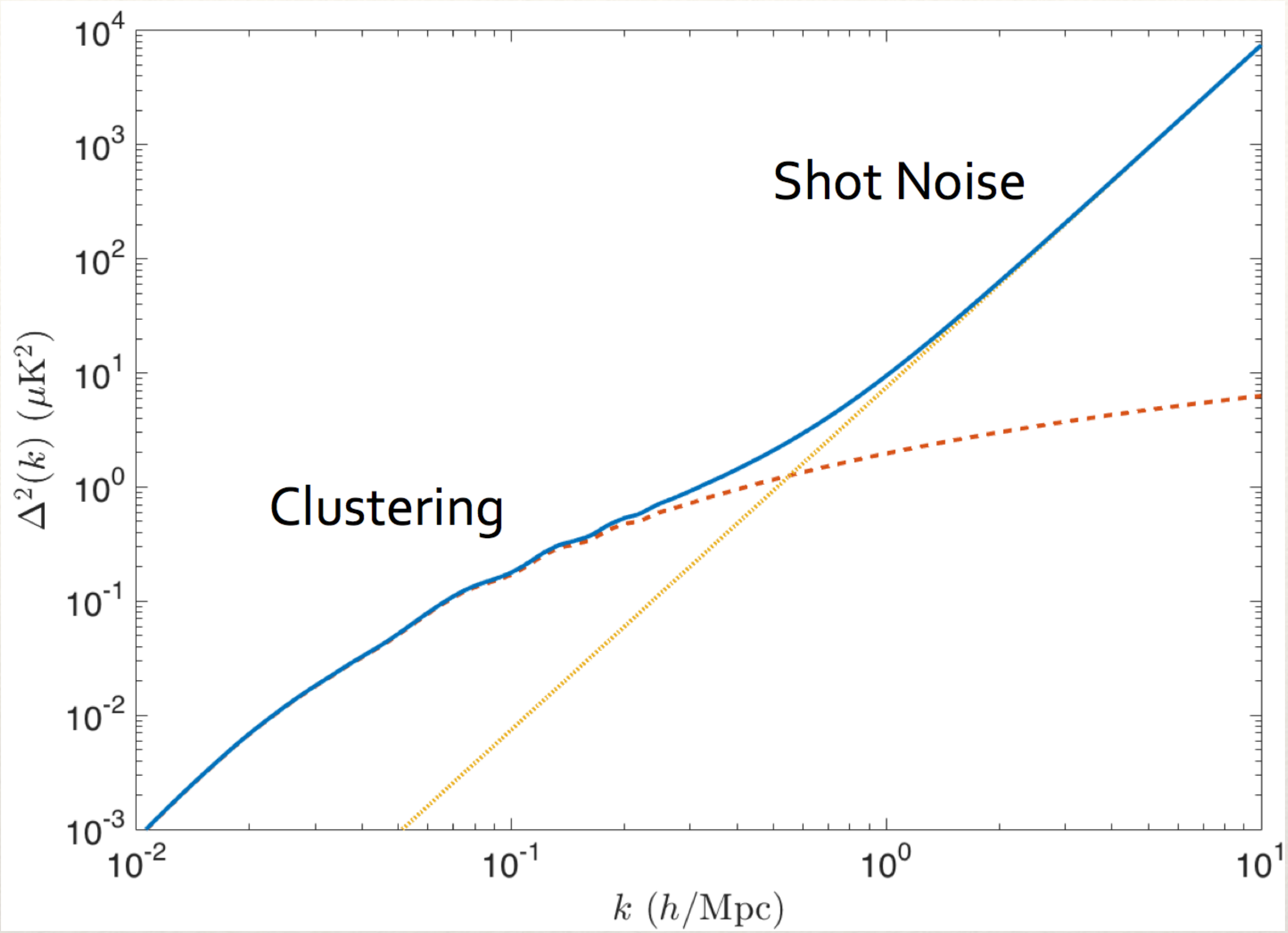
$$P_{\rm line}(k,z) = \langle I(z)\rangle^2 b^2(z) P_{\rm cdm}(k,z) + P_{\rm shot}(z)$$

Abundance **Bias** **Shot noise**

Clustering

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

How can we quantify this in predictions?

Model the astrophysics efficiently …

… using a halo model for baryonic gas

***Hamsa Padmanabhan**, Alexandre Refregier, Adam Amara,*
MNRAS 469 (2), 2323 (2017) [arXiv:1611.06235]

***Hamsa Padmanabhan**, Alexandre Refregier, MNRAS 464(4), 4008 (2017) [arXiv:1607.01021]*

The tracer-halo connection

$$P_{\rm line}(k,z) = \underbrace{\langle I(z)\rangle^2 b^2(z)}_{\text{Bias times line intensity}} \underbrace{P_{\rm cdm}(k,z)}_{\text{Matter fluctuations}} + P_{\rm shot}(z)$$

Bias times line intensity

Matter fluctuations

Halo bias

$$b(z) \propto \int dM_h \frac{dn}{dM_h}(z)\; \underbrace{L_{\rm tr}(M_h, z)}_{\text{Tracer-halo relation}}\; \overbrace{b_h(M_h)}^{\text{Halo bias}}$$

Tracer-halo relation

$$I(z) \propto \int dM_h \underbrace{\frac{dn}{dM_h}(z)}_{\text{Halo mass function}}\; L_{\rm tr}(M_h, z)$$

Halo mass function

$$P_{\rm 1h} \propto \underbrace{\int dM_h \frac{dn}{dM_h} L_{\rm tr}(M_h, z)^2}_{\text{Shot noise}}\; \underbrace{|u_{\rm tr}(k|M)|^2}_{\text{Small scales; tracer profile in halo}}$$

Small scales; tracer profile in halo

Shot noise

A halo model for neutral hydrogen

Combine IM observations with individual objects

$$M_{\rm HI}\,(M_h, z)$$

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

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

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

21 cm emission

HIPASS mass function [Zwaan+ (2005a)]

WHISP column density [Zwaan+ (2005b)]

ALFALFA clustering, bias [Martin+ (2012)]

21 cm intensity mapping

GBT/DEEP2 [Switzer+ (2013)]

DLA HI absorption

Mg II selected: z ~ 1 [Rao+ (2006)]

z ~ 2.3 bias [Font-Ribera+ (2012)]

z ~ 2.3 SDSS [Noterdaeme+ (2012)]

z ~ 5 GGG survey [Crighton+ (2015)]

z ~ 0-4 incidence [Zafar+ (2013)]

SDSS III [Bird+ (2016)]

0 1 2 3 4 5 z

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

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

HI Fraction relative to cosmic

Slope

Lower cutoff

HI HALO MODEL

$$\rho_0 \exp(-r/r_{\rm s,HI}); \;\; r_{s,\rm HI} = R_v(M_h)/c_{\rm HI}(M_h, z)$$

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

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

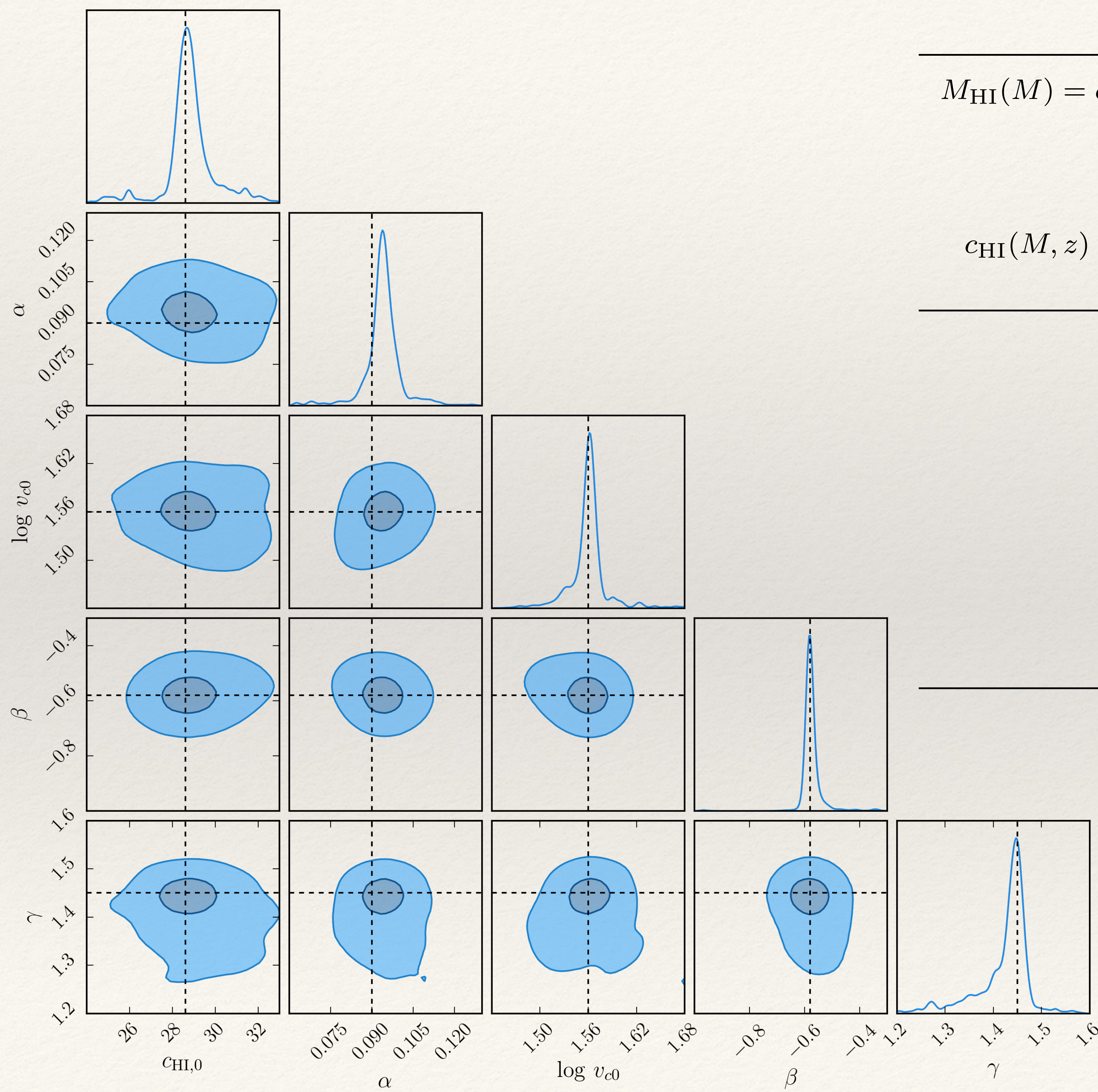
Concentration parameter

Evolution with redshift

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

Constraints

[HP+, MNRAS (2017), HP & Refregier (2017), HP & Kulkarni (2017)]



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

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

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

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

$$\alpha = 0.09 \pm 0.01$$

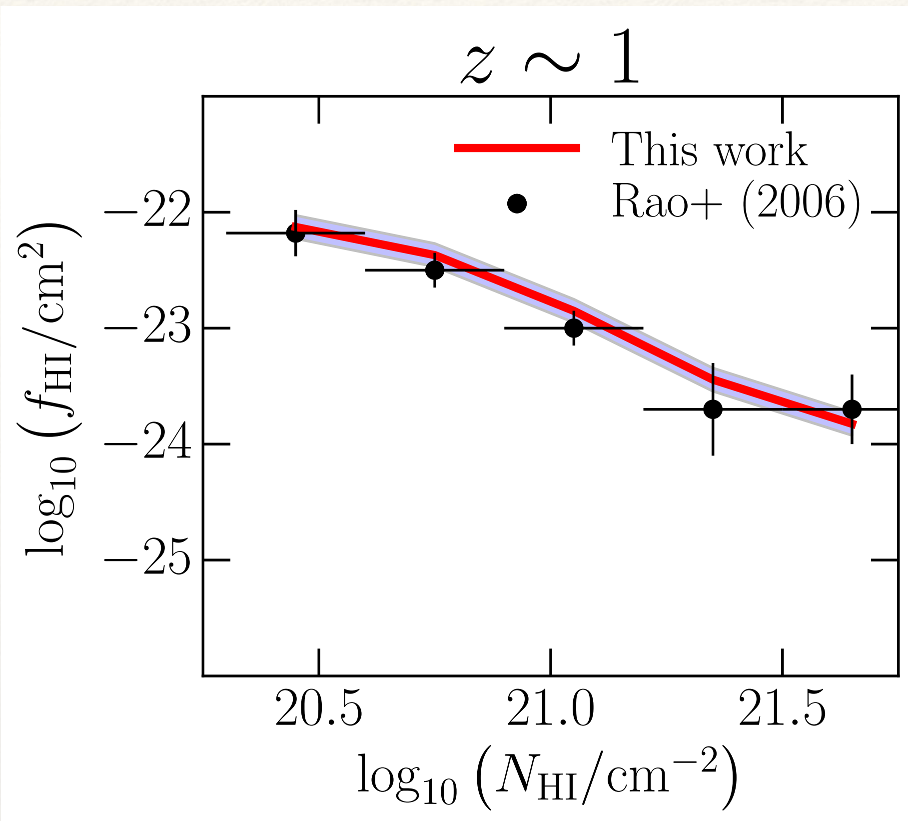
$$\log v_{c,0} = 1.56 \pm 0.04$$

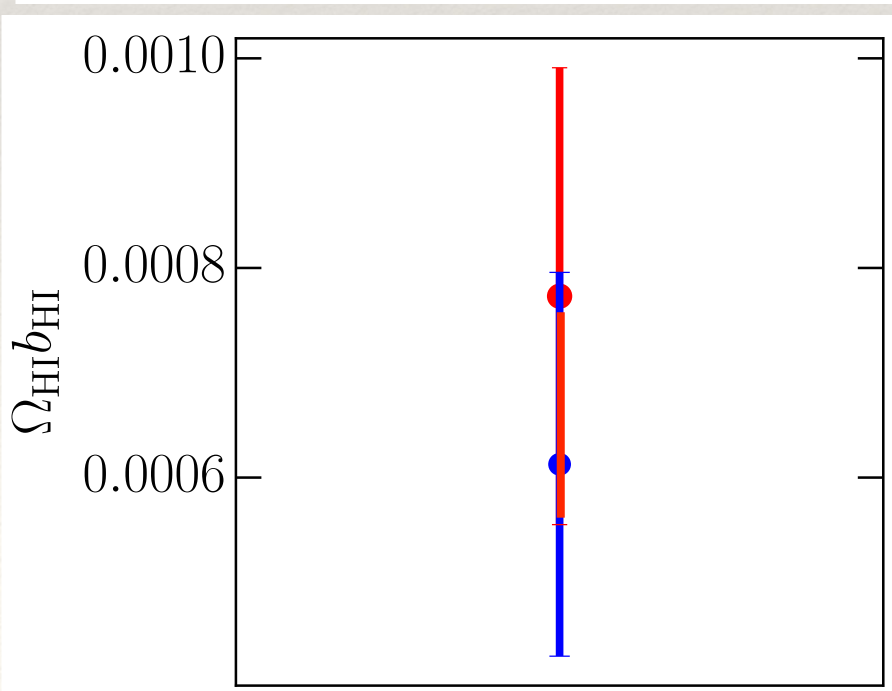
$$\beta = -0.58 \pm 0.06$$

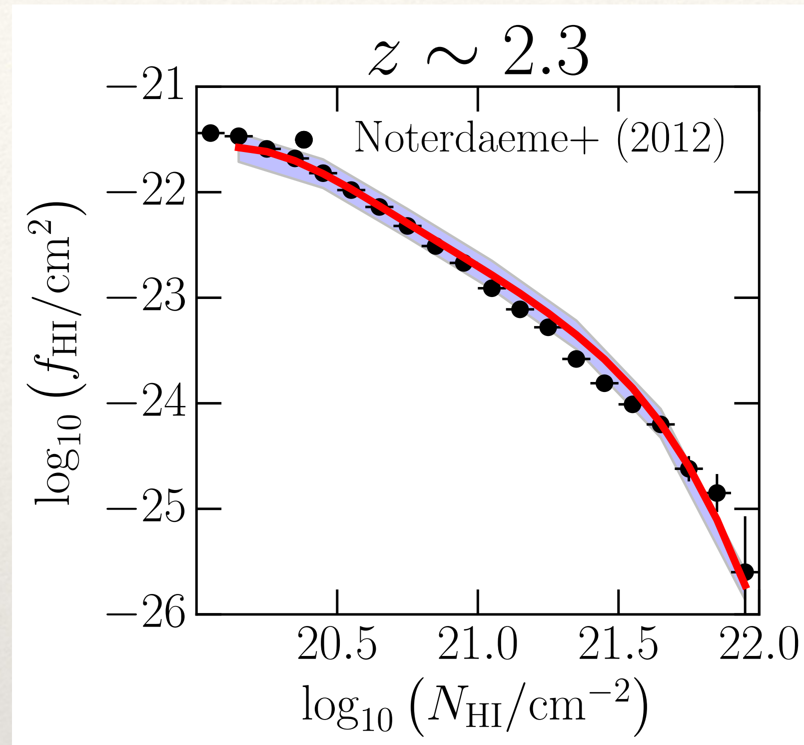
$$\gamma = 1.45 \pm 0.04$$

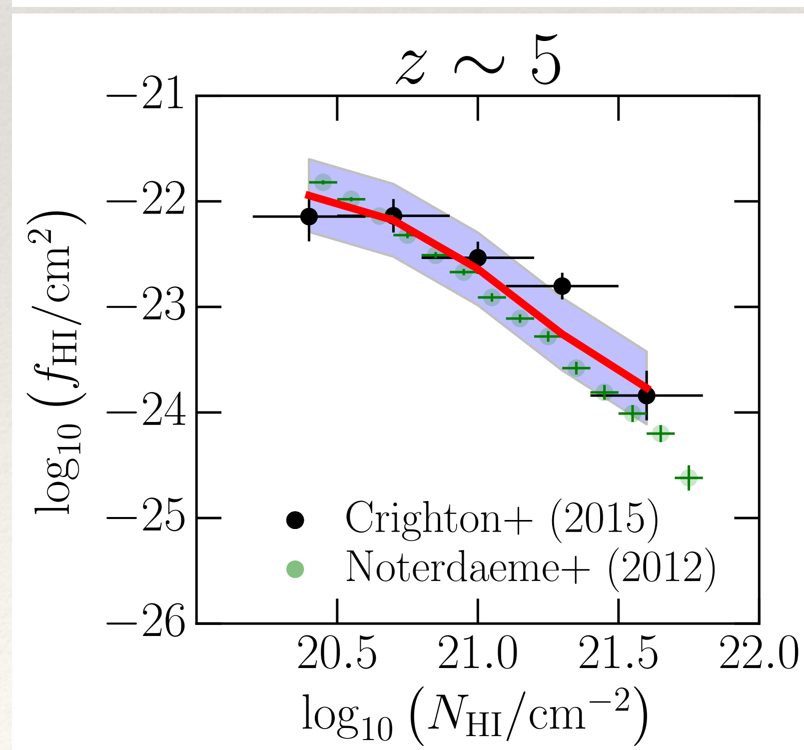
CONSTRAINTS FROM CURRENT HI GALAXY, DLA, IM DATA

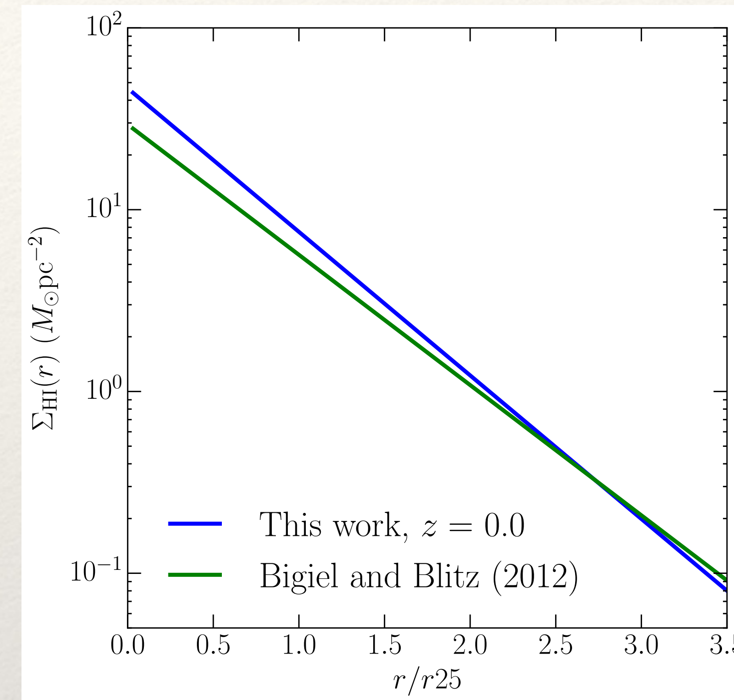
One shoe fits all!

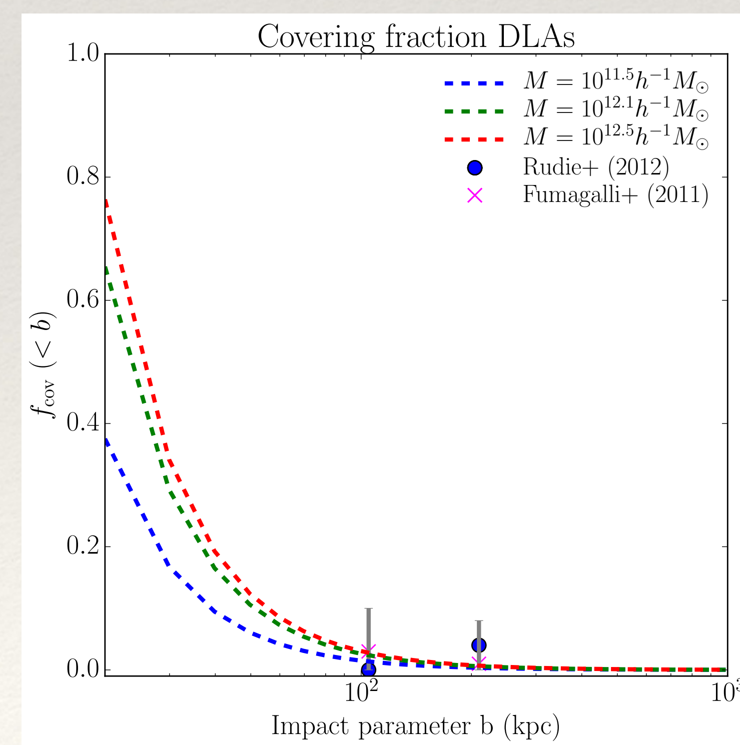




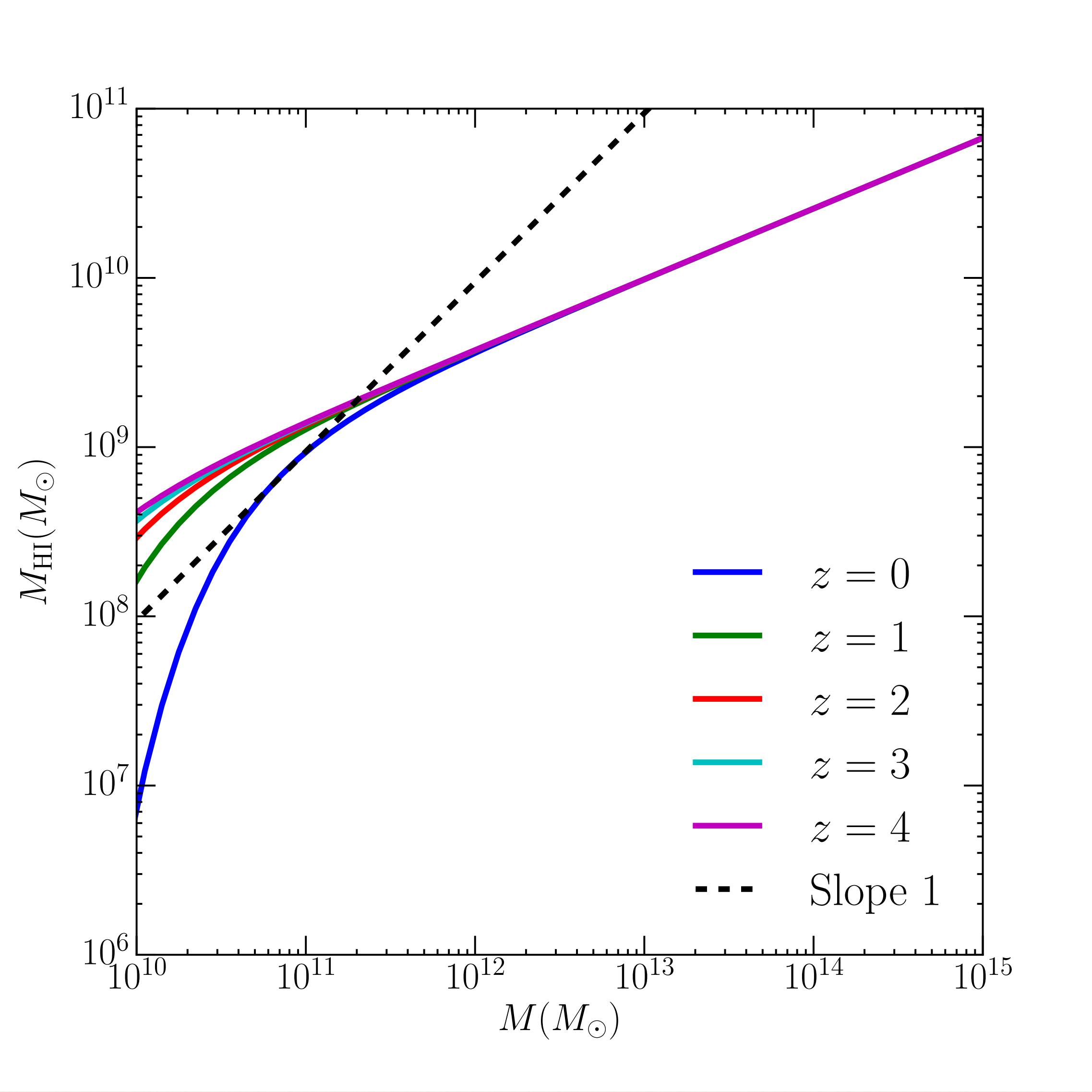


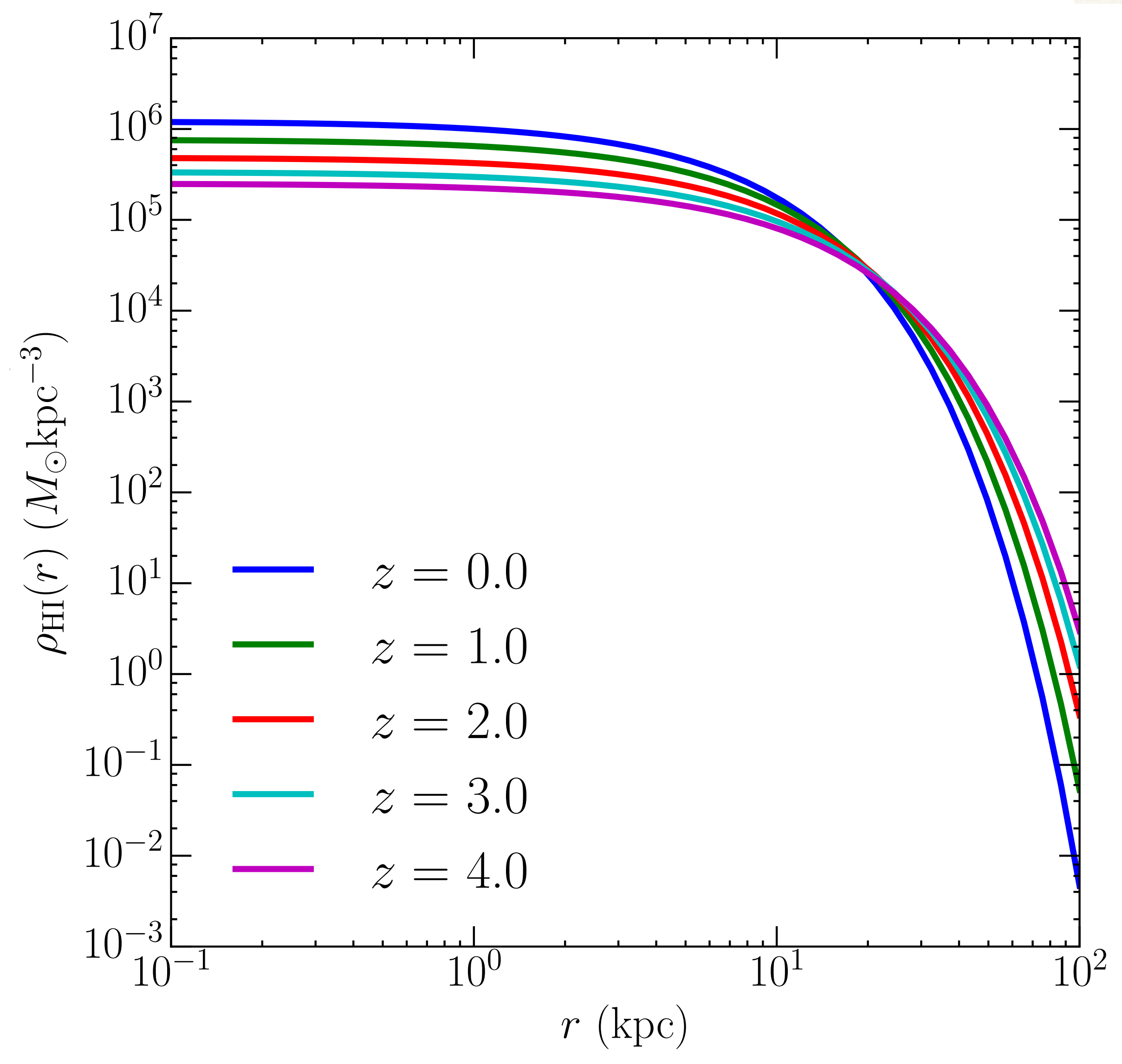






Best fit halo model





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

Non-unity slope!

Exponential profile

Insights

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

HI Fraction relative to cosmic

Slope

Lower cutoff

Insights

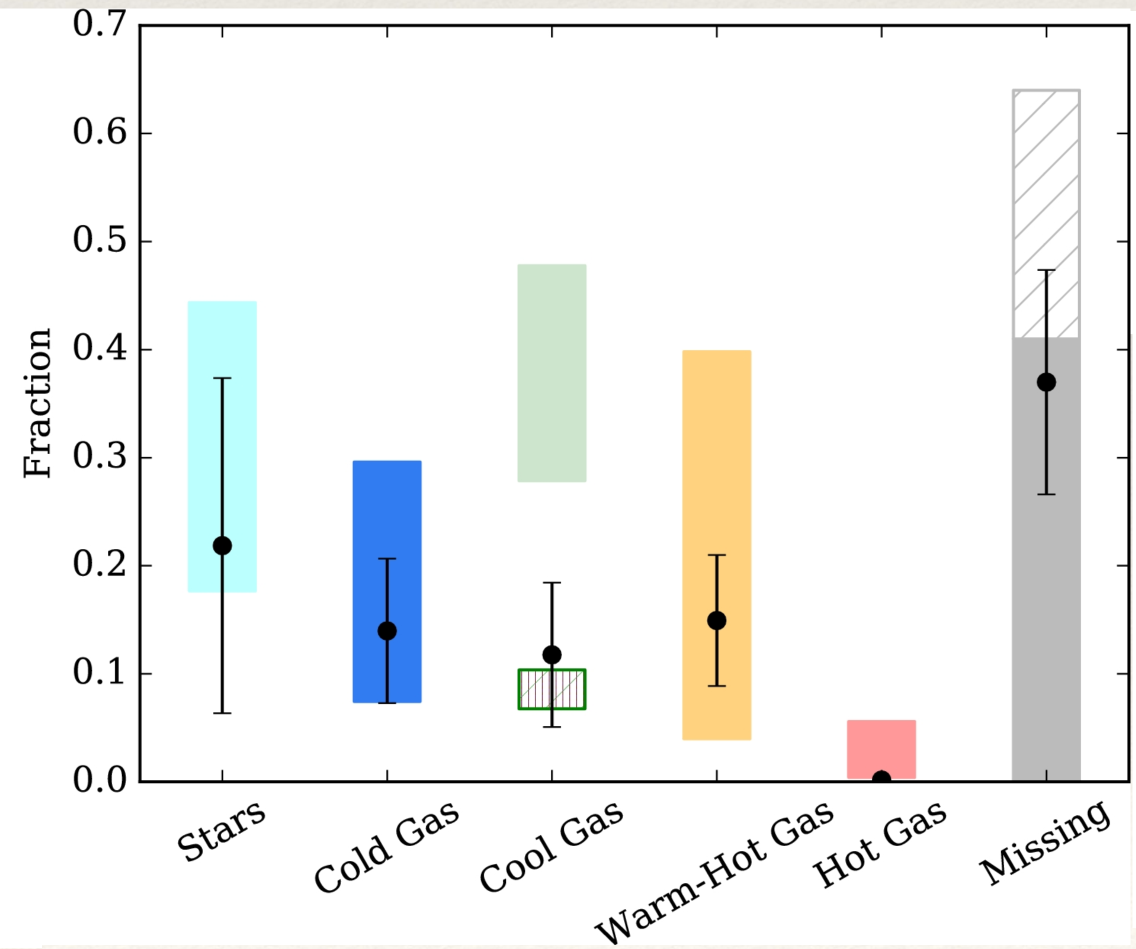
$$M_{\rm HI}(M_h, z) = \alpha f_{\rm H,c} M_h \left(\frac{M_h}{10^{11} h^{-1} M_\odot} \right)^{\beta} \exp\left[-\left(\frac{v_{c,0}}{v_c(M_h, z)} \right)^3 \right]$$

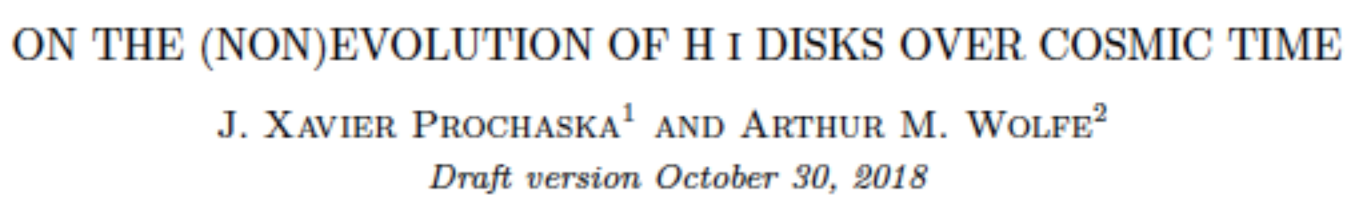
HI Fraction relative to cosmic

Slope

Lower cutoff

$\alpha = 0.09$




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

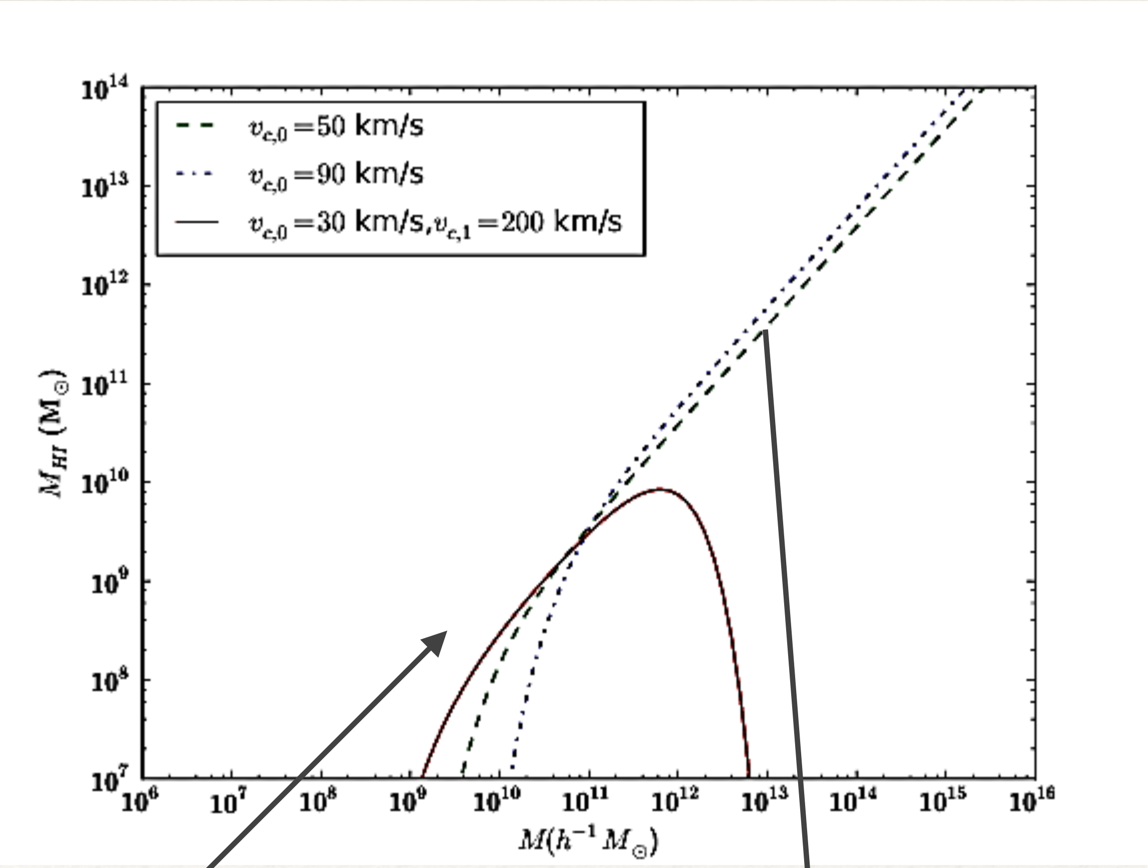
[Dutton+ (2016), Werk+ (2014), Stern+ (2016), Prochaska & Wolfe (2008)]

Insights

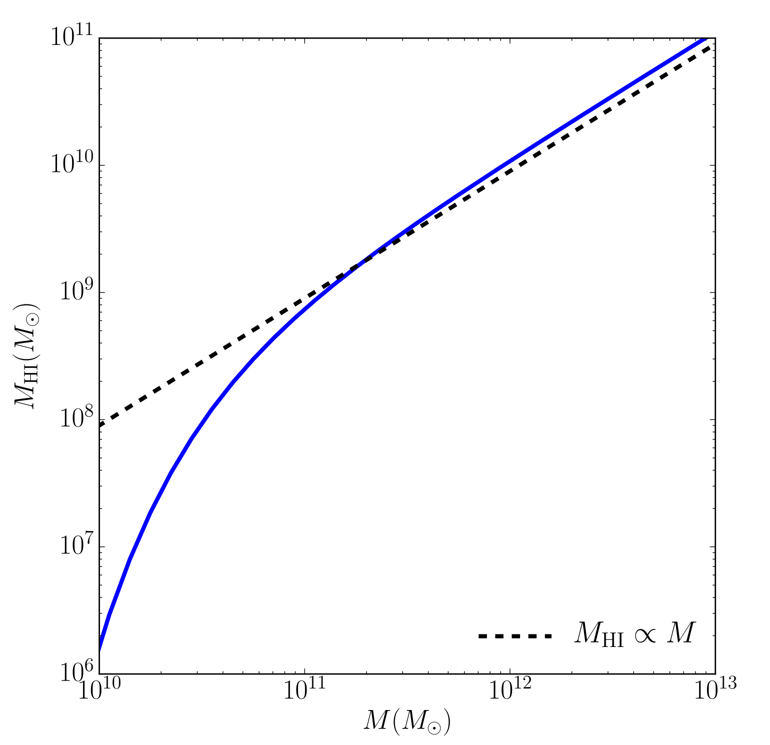
$$M_{\rm HI}(M_h, z) = \alpha f_{\rm H,c} M_h \left(\frac{M_h}{10^{11} h^{-1} M_\odot} \right)^{\beta} \exp\left[-\left(\frac{v_{c,0}}{v_c(M_h, z)} \right)^3 \right]$$

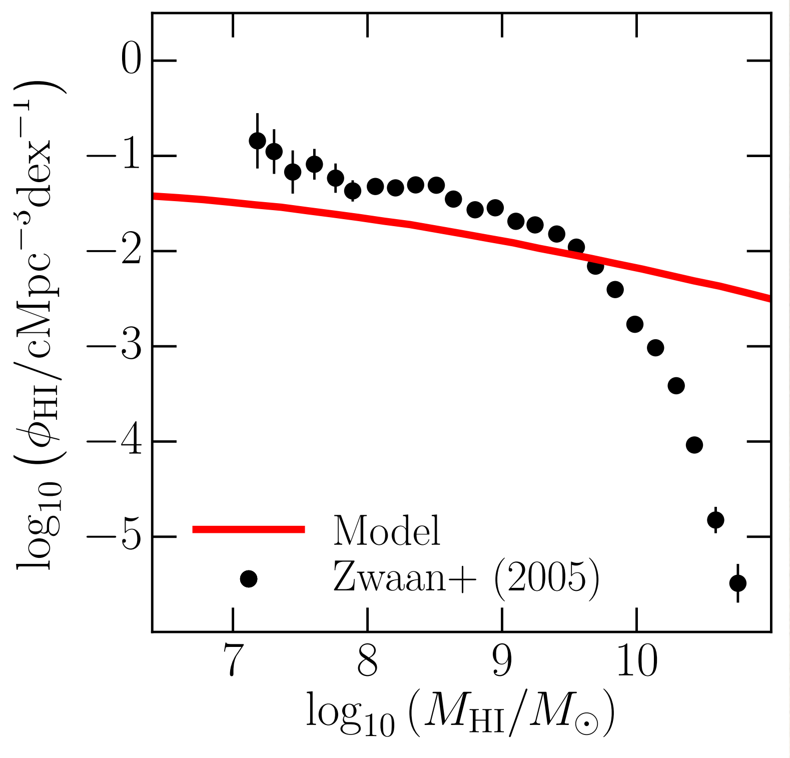
Slope

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



$\beta = 0$





21-cm based

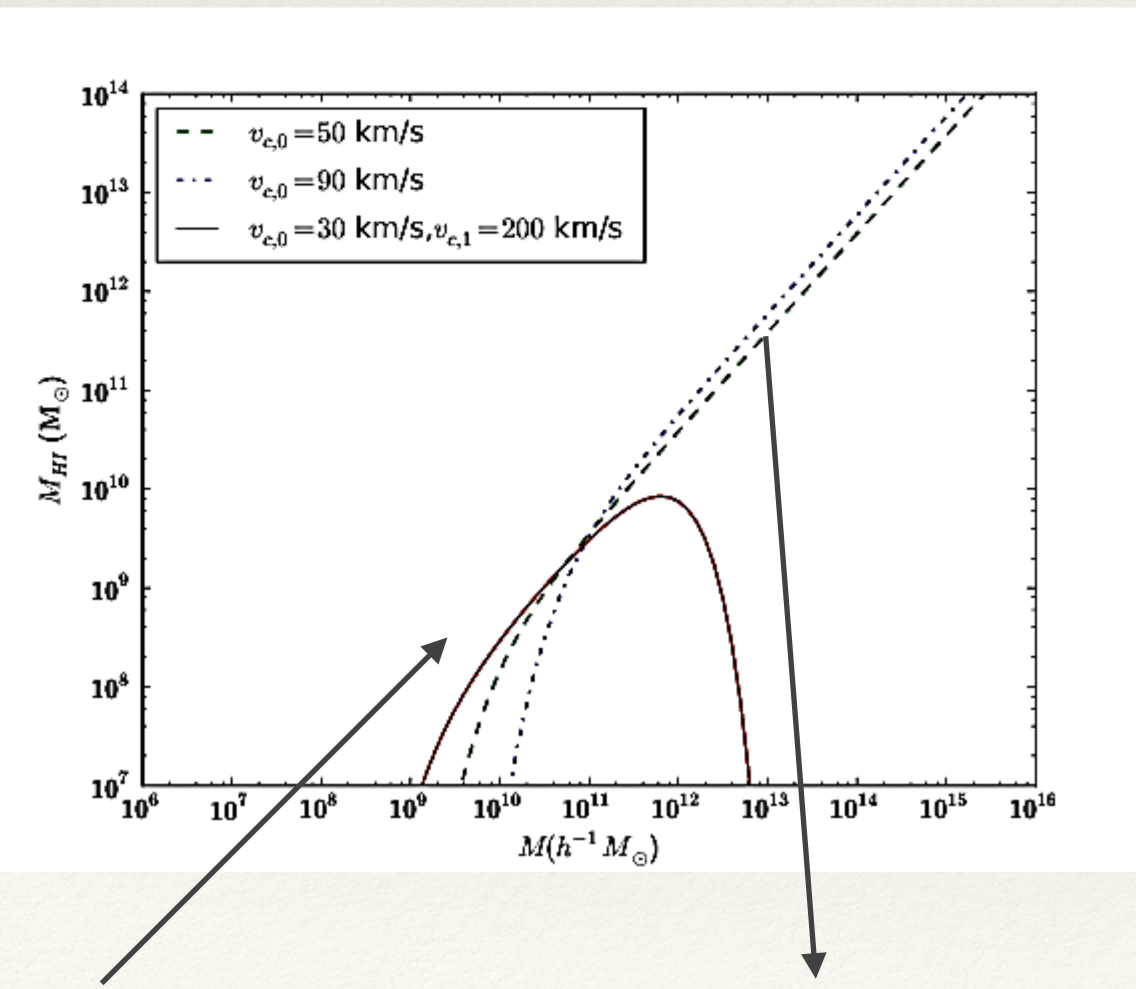
DLA based

Insights

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

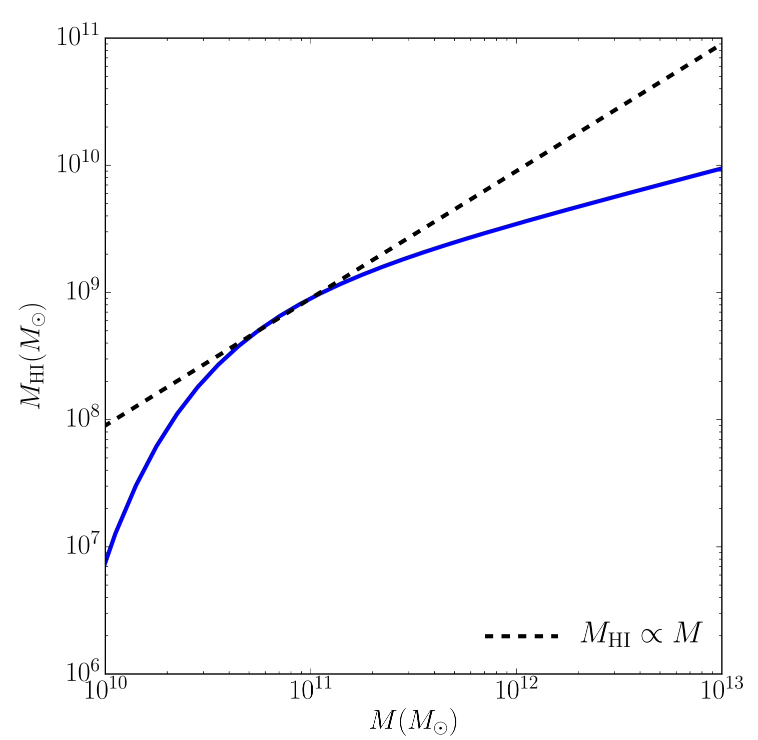
Slope

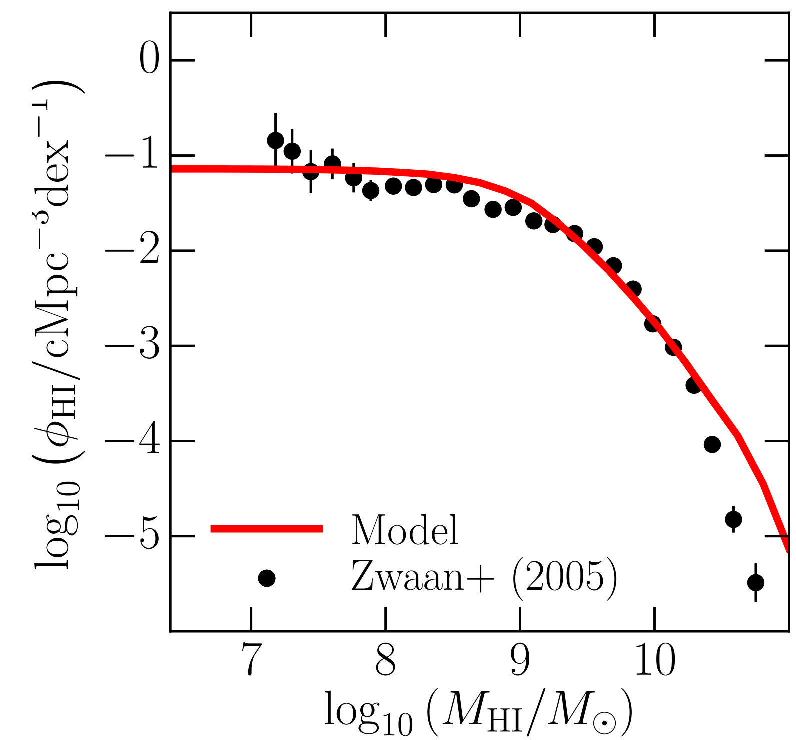
[Barnes & Haehnelt 2014; Bagla+ (2010), HP+ (2016)]



21-cm based **DLA based**

$\beta = -0.58$





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

Insights

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

Lower cutoff

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

Photoionization increases cooling timescales

Constraints on UV background

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

Photoionization and the formation of dwarf galaxies

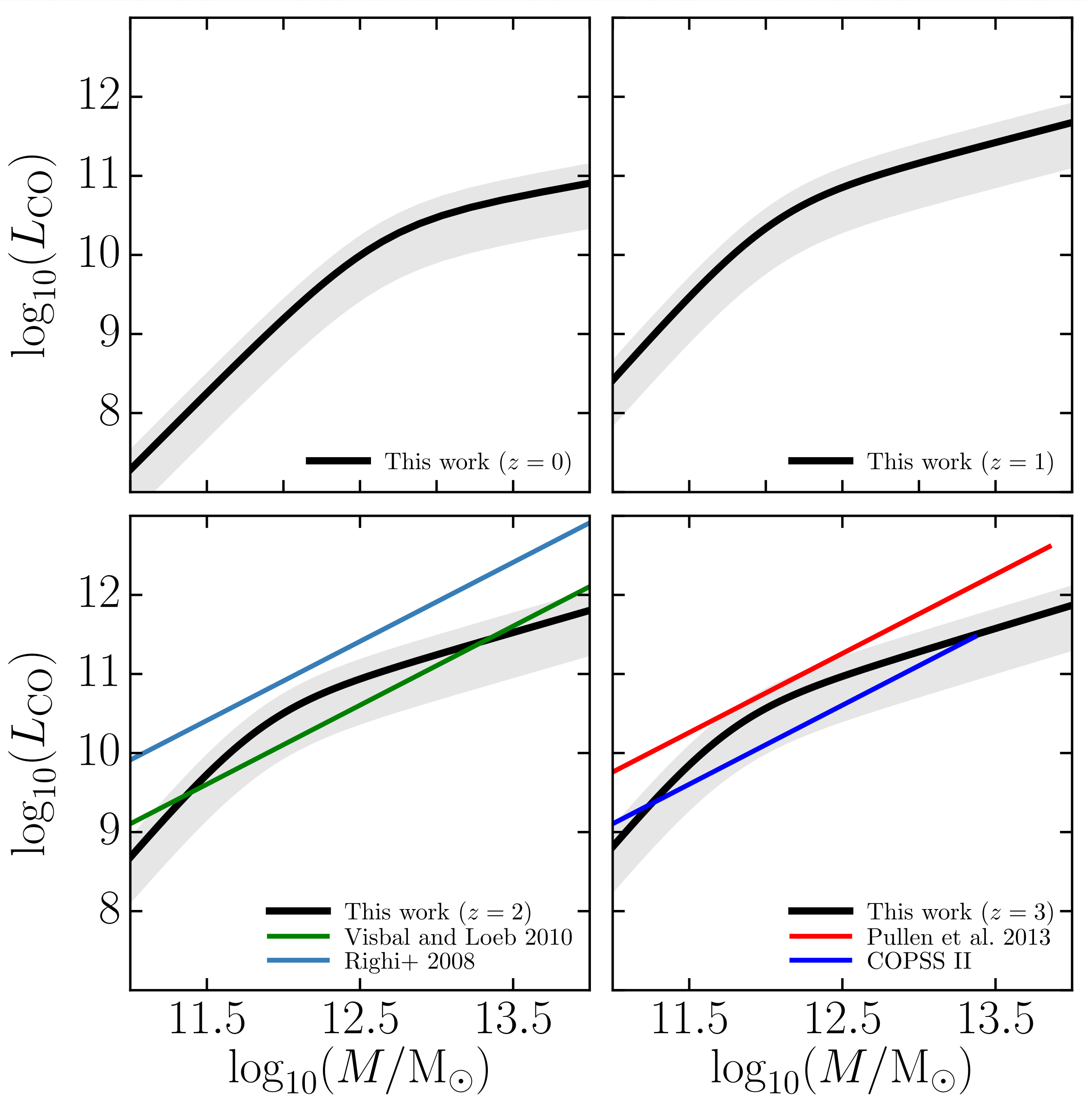
Thomas Quinn,[1] Neal Katz[1] and George Efstathiou[2]
[1] *Department of Astronomy, University of Washington, Seattle, WA 98195, USA*
[2] *Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH*

… suppression: circular speeds ~ 37 km/s!

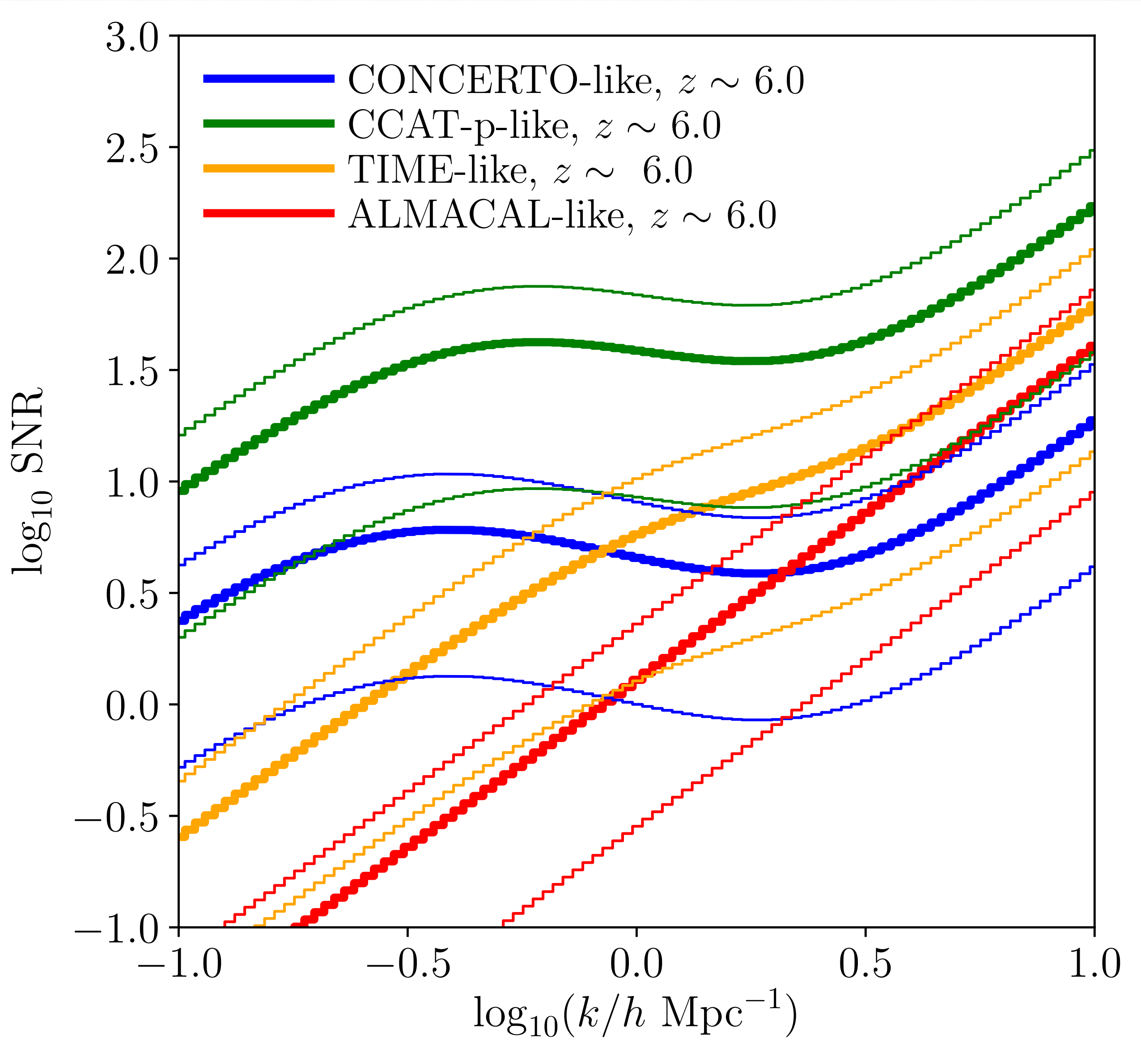
[Rees (1986), Efstathiou (1992), Babul & Rees (1992),Quinn+ (1996), …]

Describing IM with other lines

[HP (MNRAS, 2018)]



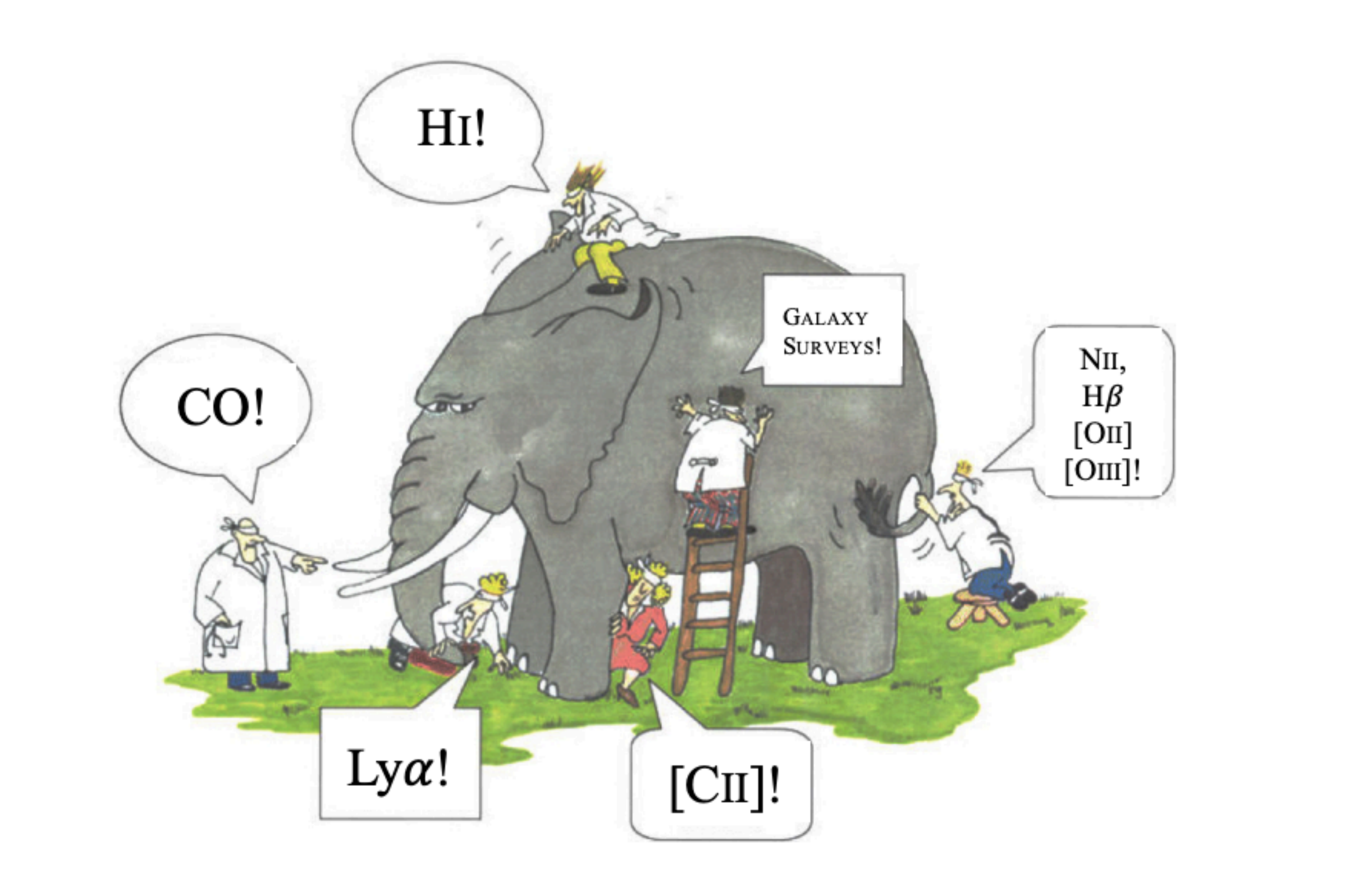
$$L_{CO}(M_h, z) = \frac{2N(z)M_h}{[(M_h/M_1(z))^{-b(z)} + (M_h/M_1(z))^{y(z)}]}$$



Intensity mapping with [CII] and [OIII]

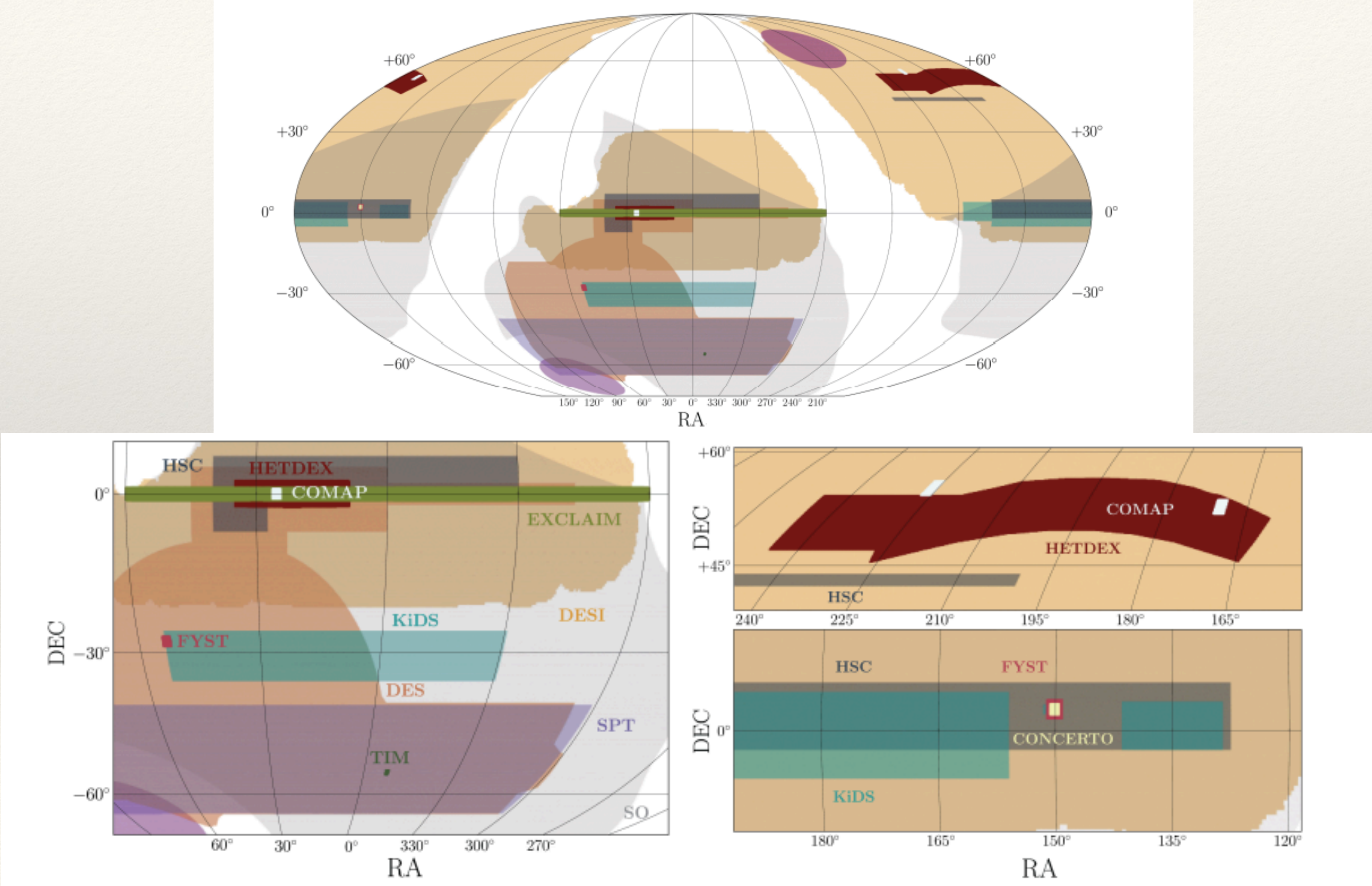
[HP (MNRAS, 2019), HP+ (MNRAS, 2022)]

Bringing it all together …

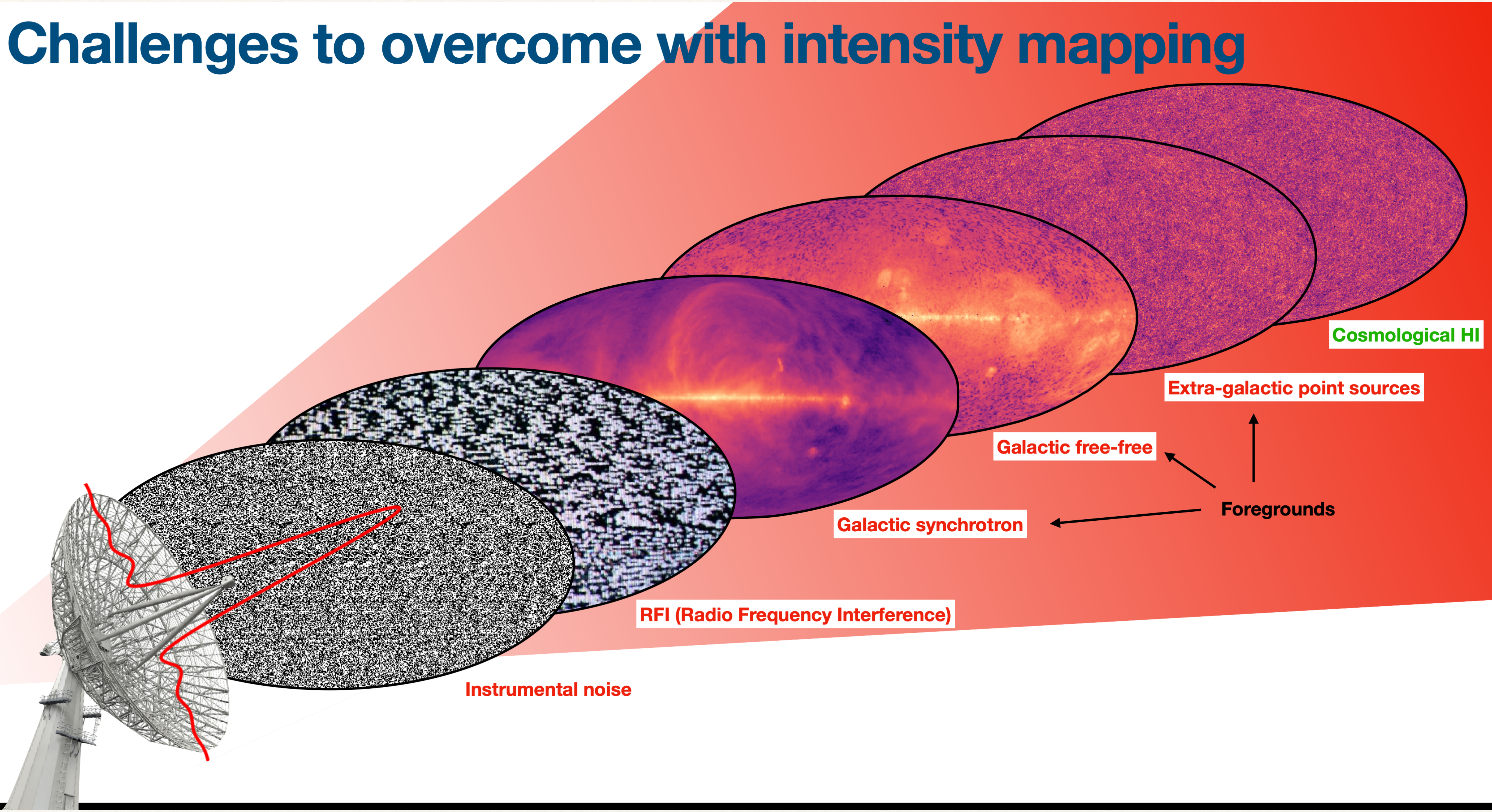


Synergies with galaxy surveys

[Bernal & Kovetz (2023), ARAA review]



21 cm IM is not easy …



Slide credit: Steve Cunnington

Cross-correlations with 21 cm

Cross-correlations mitigate systematics

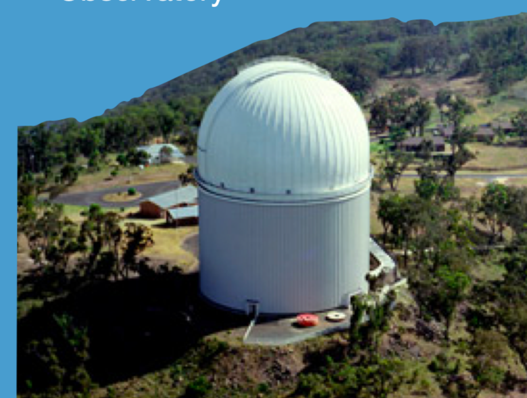
Radio

MeerKAT radio telescope

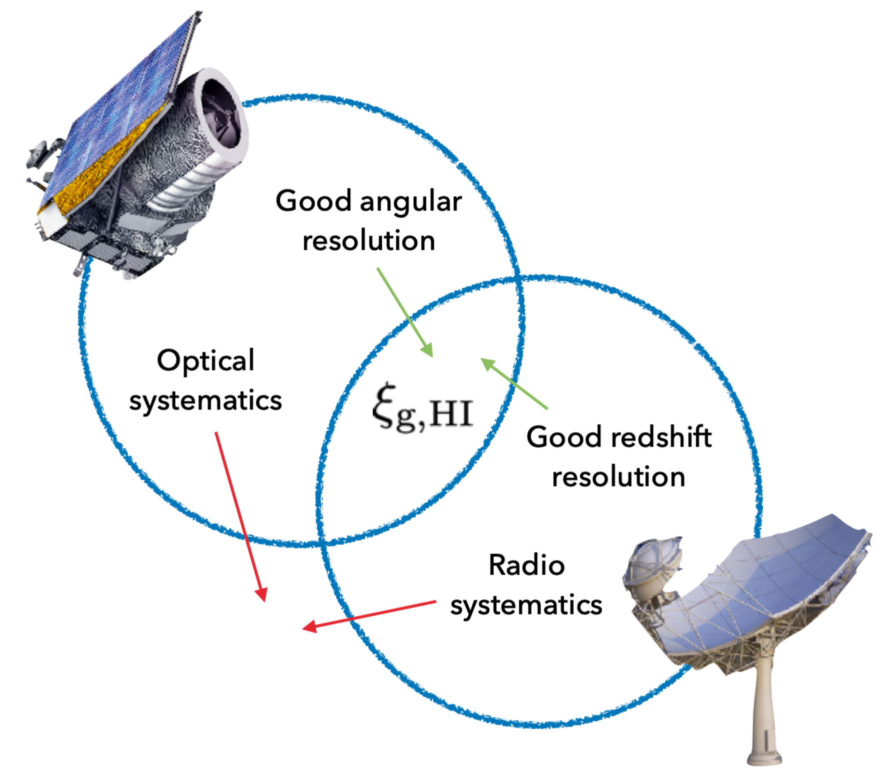
$$\mathbf{X}_{\rm rad} = \mathbf{S}_{\rm rad} + \mathbf{N}_{\rm rad}$$

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. [CII], covering ~ few ten square degrees or more

[Lidz+ (2009), Beane & Lidz (2018), Beane et al. (2019)]

Cross correlation of a 21 cm and galaxy survey

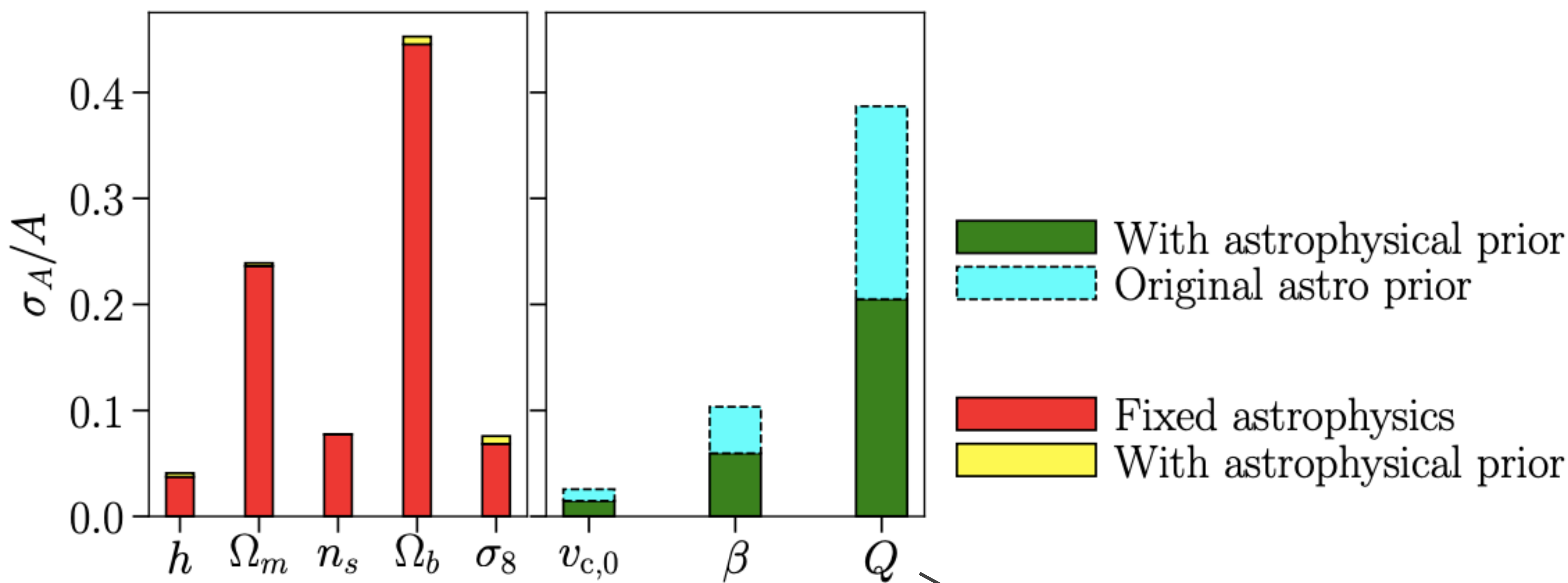
[HP, Refregier, Amara, MNRAS (2020)]

CHIME ~ 25000 deg^2; DESI ~ 14000 deg^2

Galaxy parameter Q, influences bias

Constraints comparable to SKA I MID auto

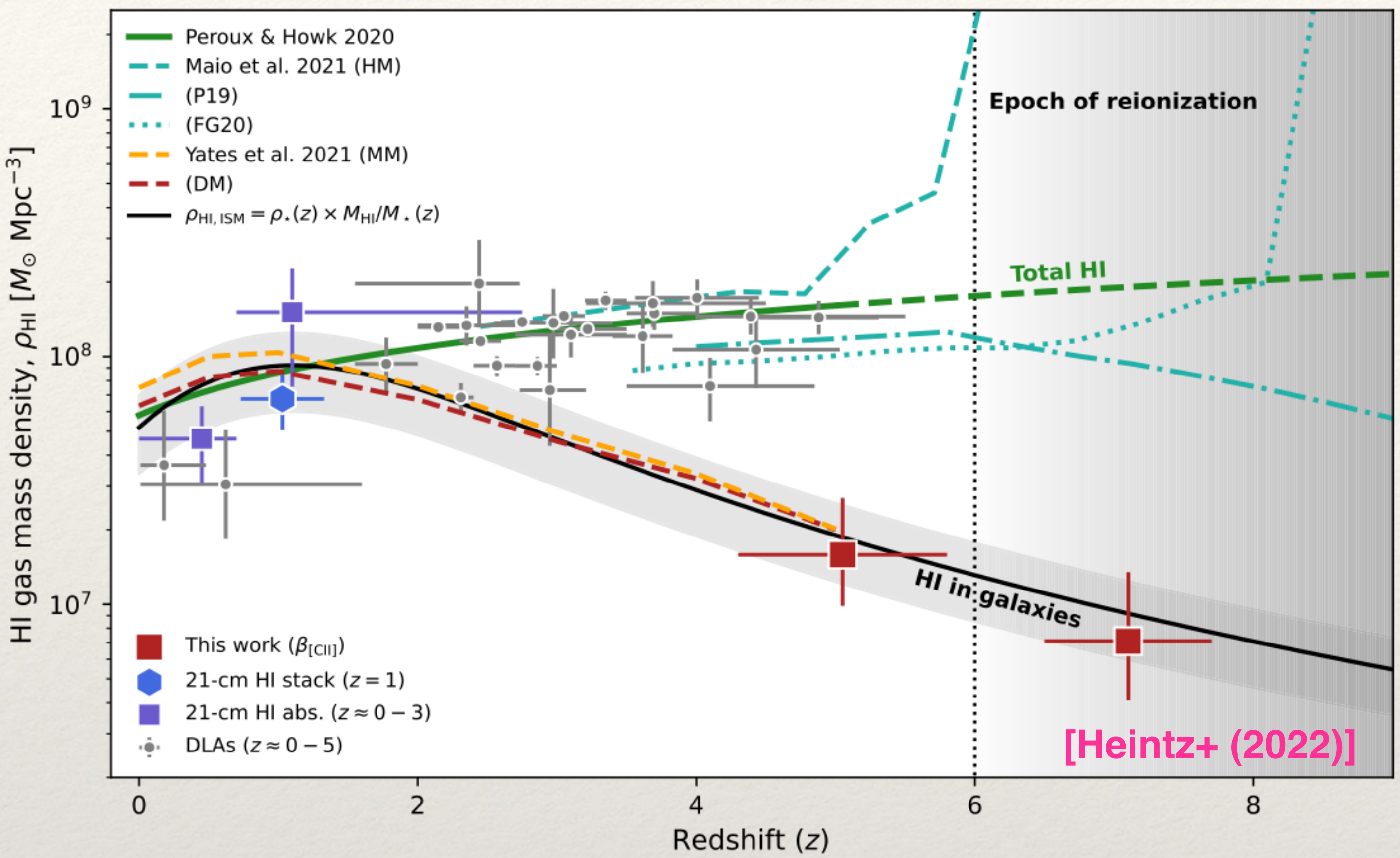
Astrophysical constraints improve by factors of 2-3 from the present priors



HI astrophysics

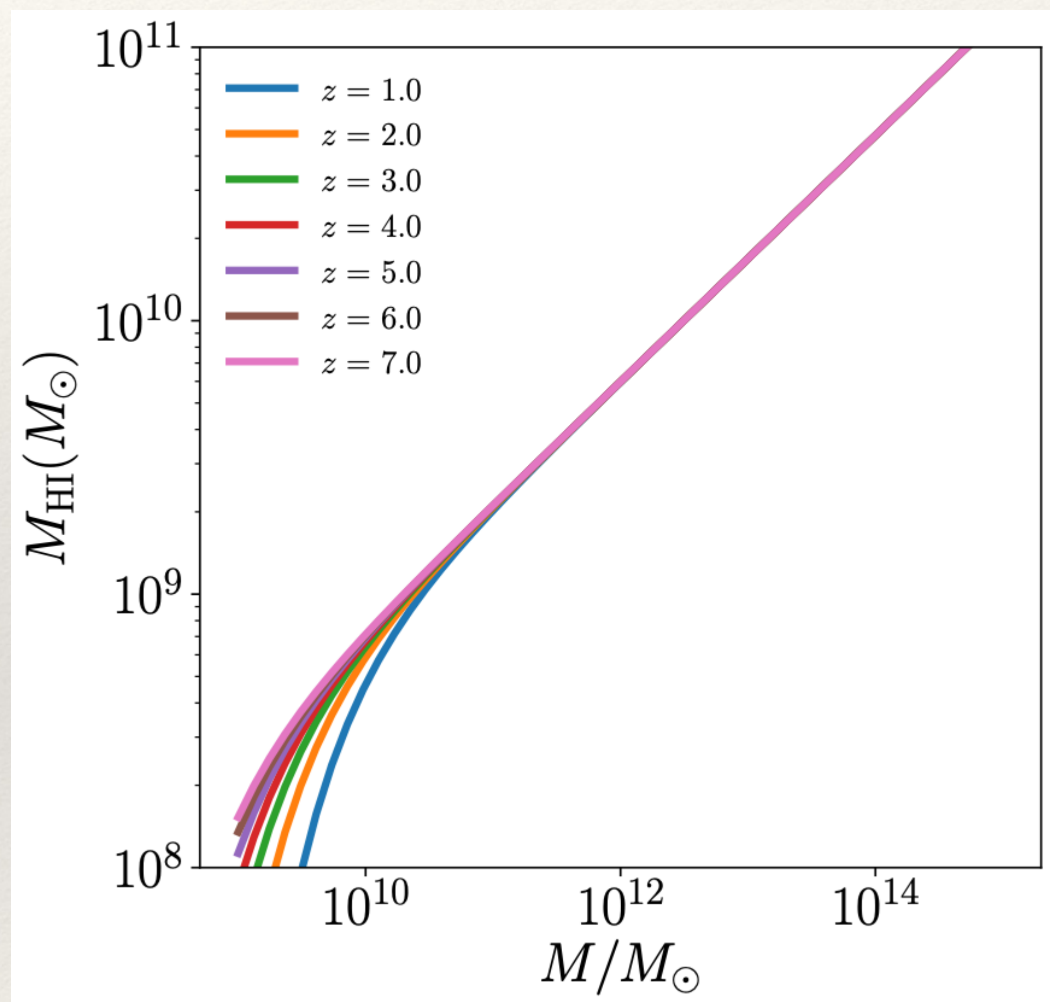
Galaxy astrophysics

New empirical insights on HI at z ~ 5-7

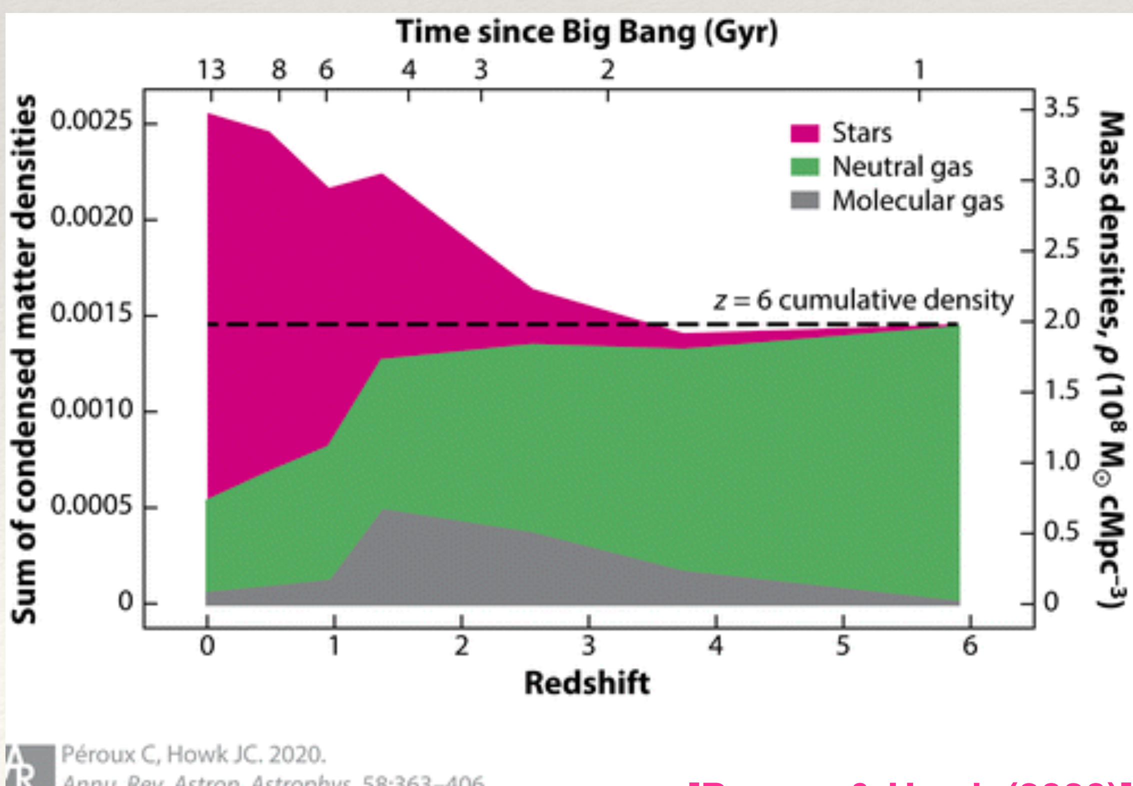


[Heintz+ (2022)]

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



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



[Peroux & Howk (2020)]

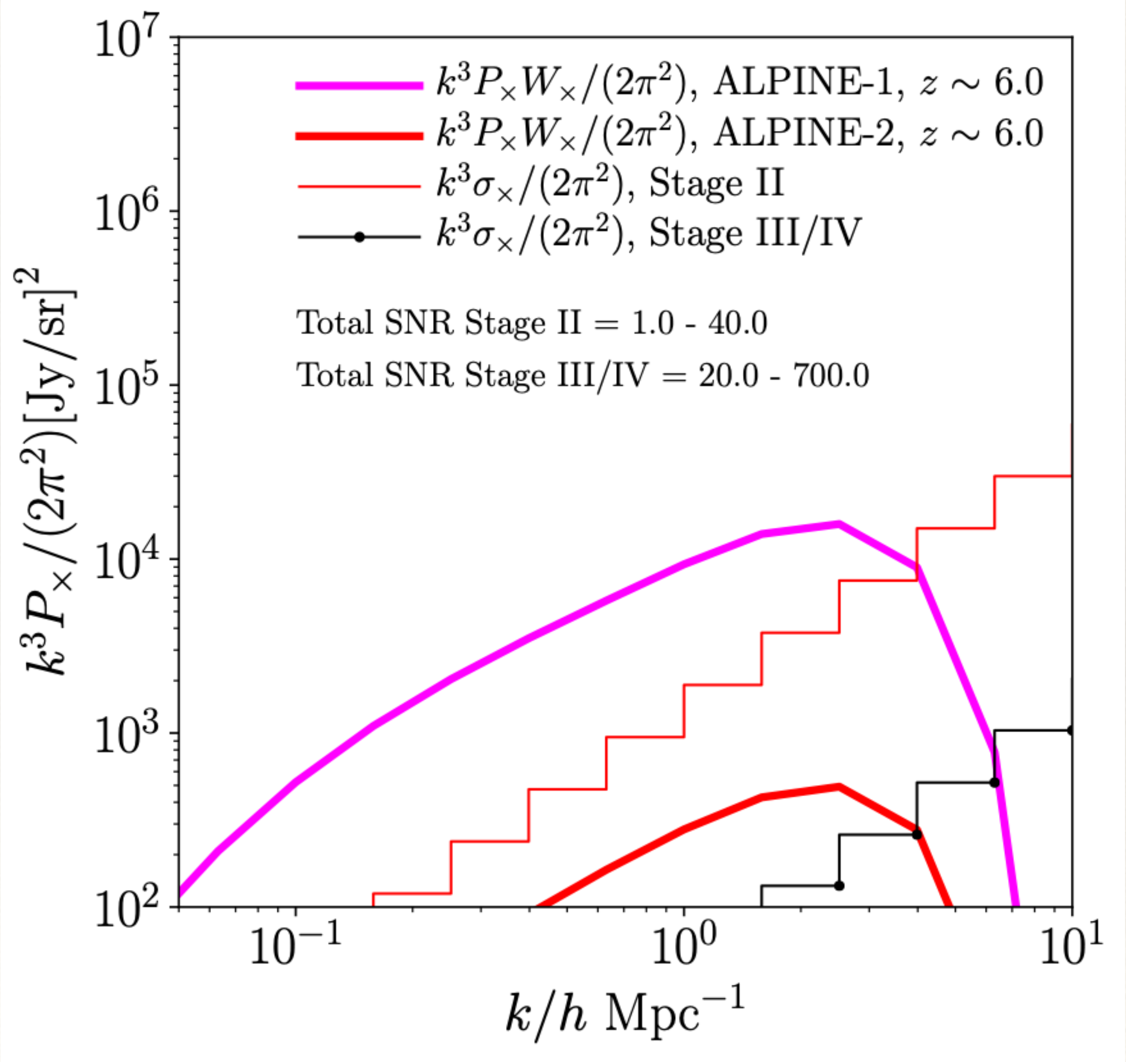
Note: total power only, scale dependence unconstrained

Cross-correlation of 21 cm and sub-mm surveys

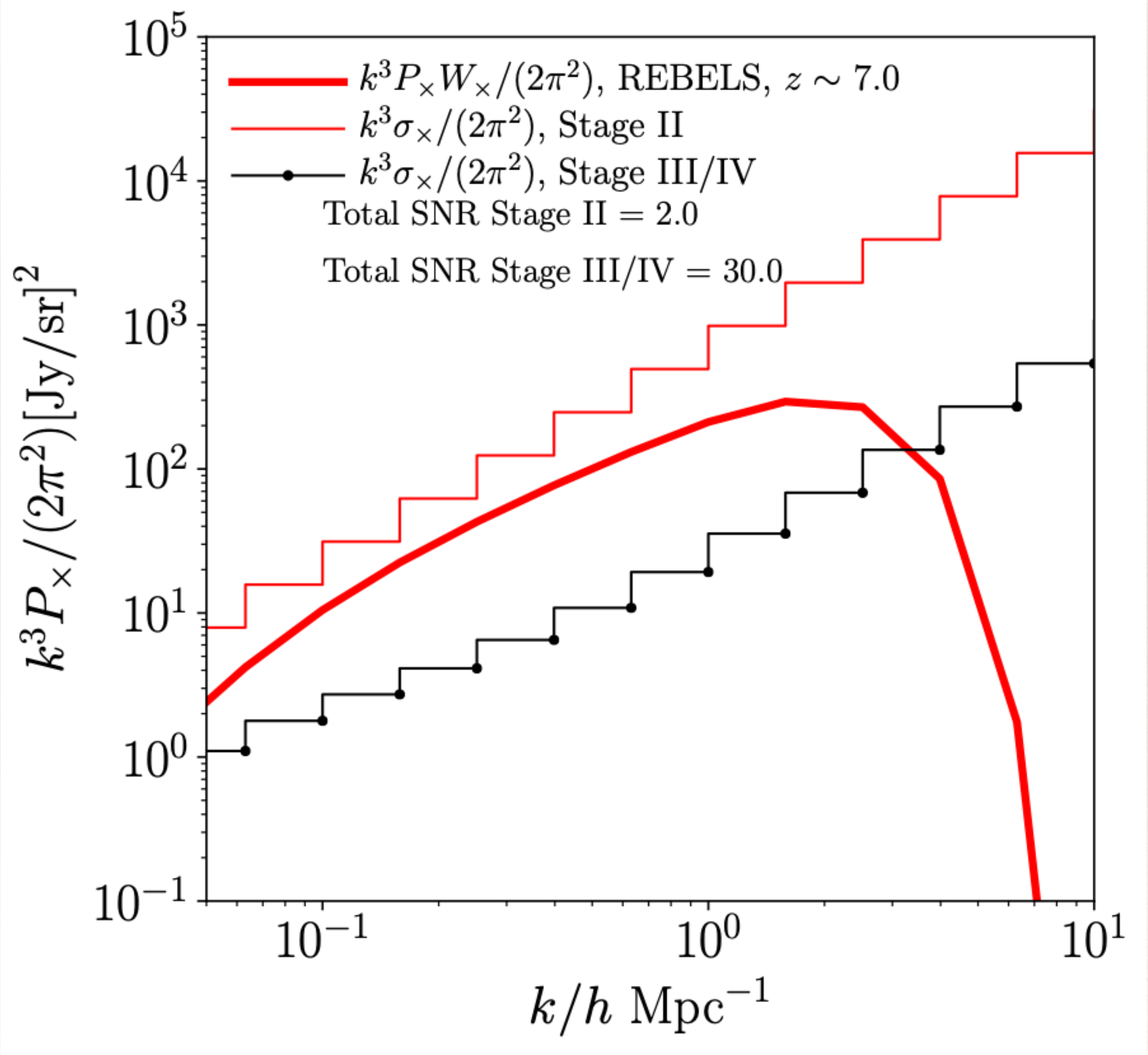
**Assumes complete overlap*

(FYST++) x MWA/SKA

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



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

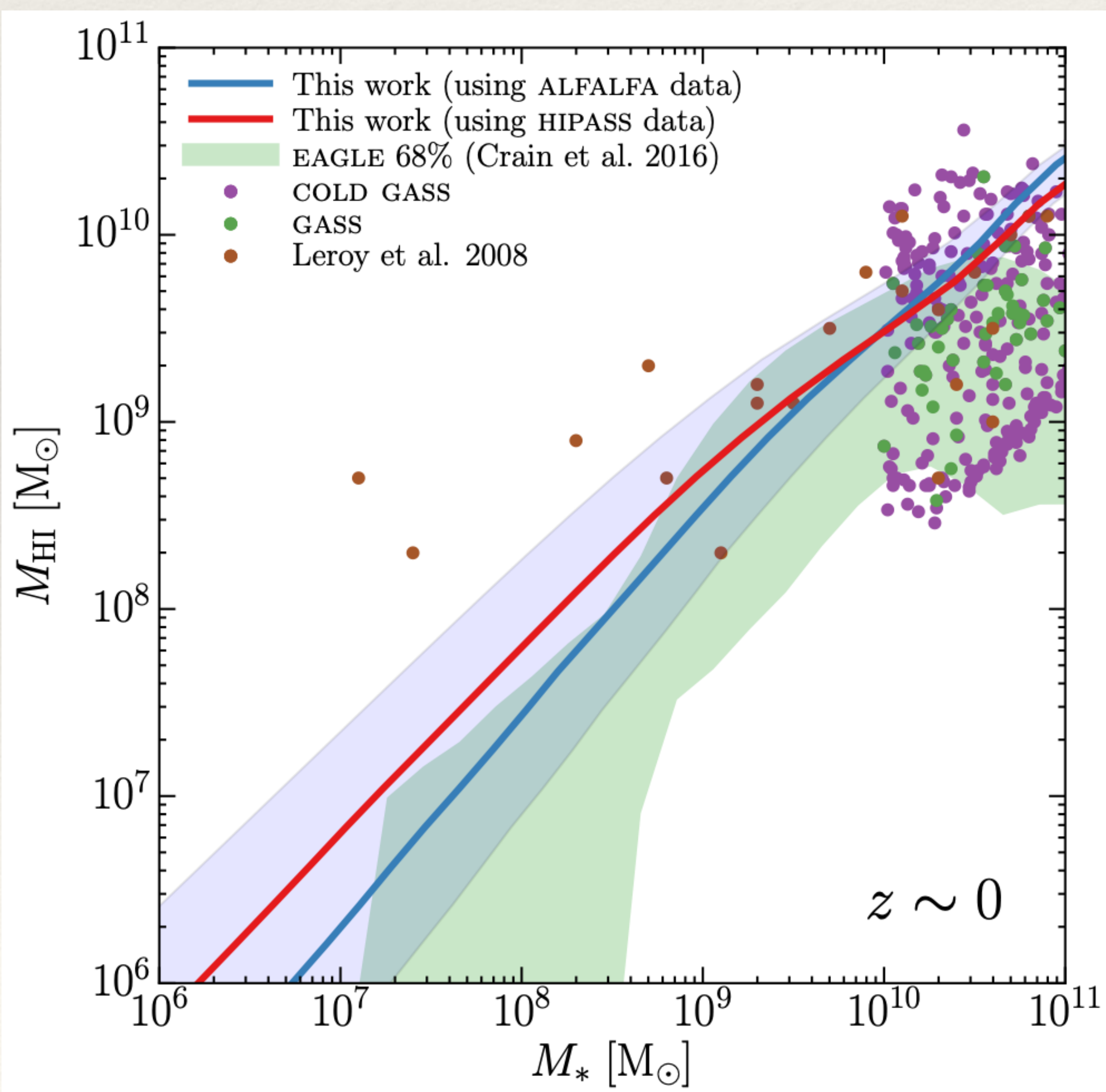


[HP (MNRAS, 2018), HP (MNRAS 2019), HP+ (MNRAS 2022), HP (2023, arXiv:2212.08077)]

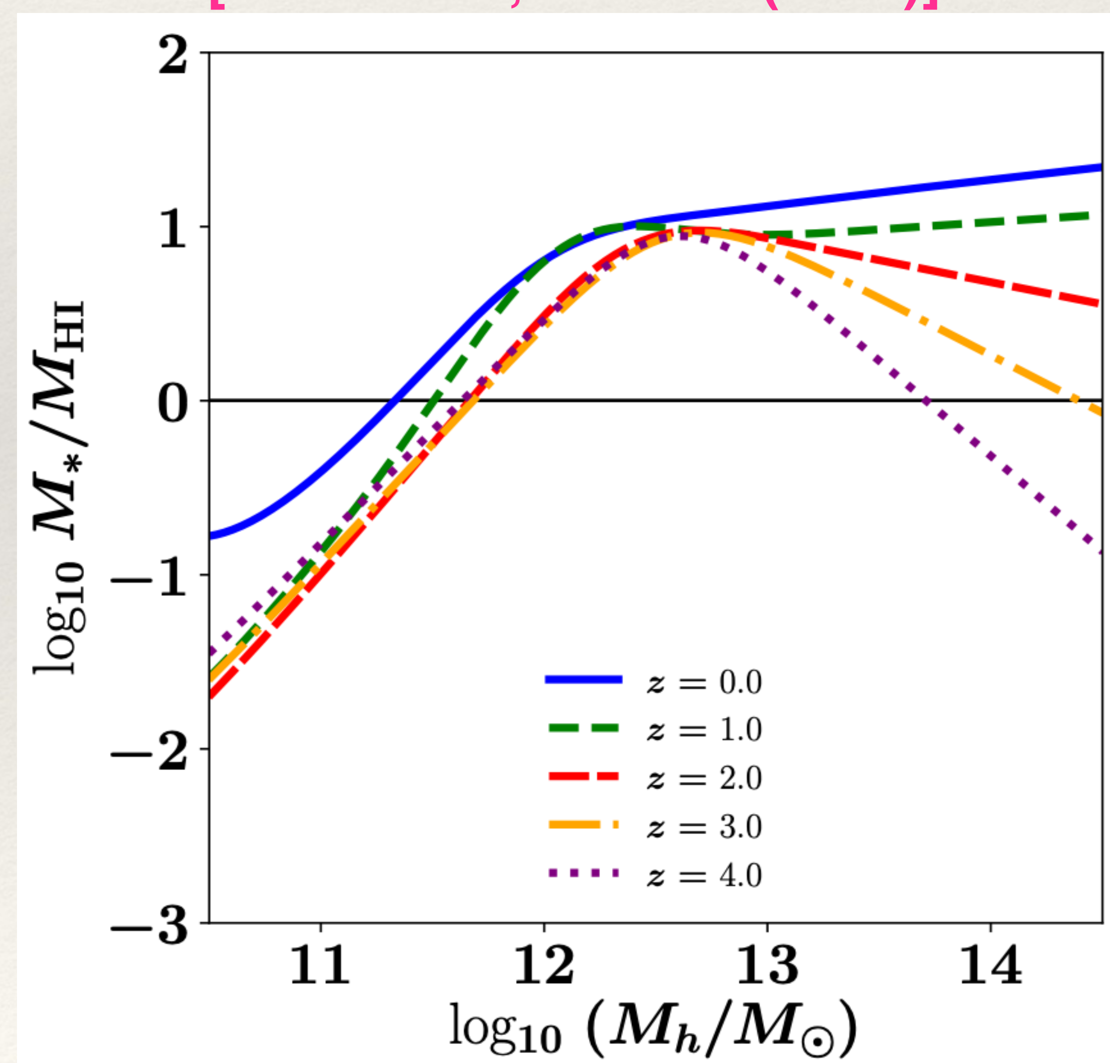
The gas-stars relation

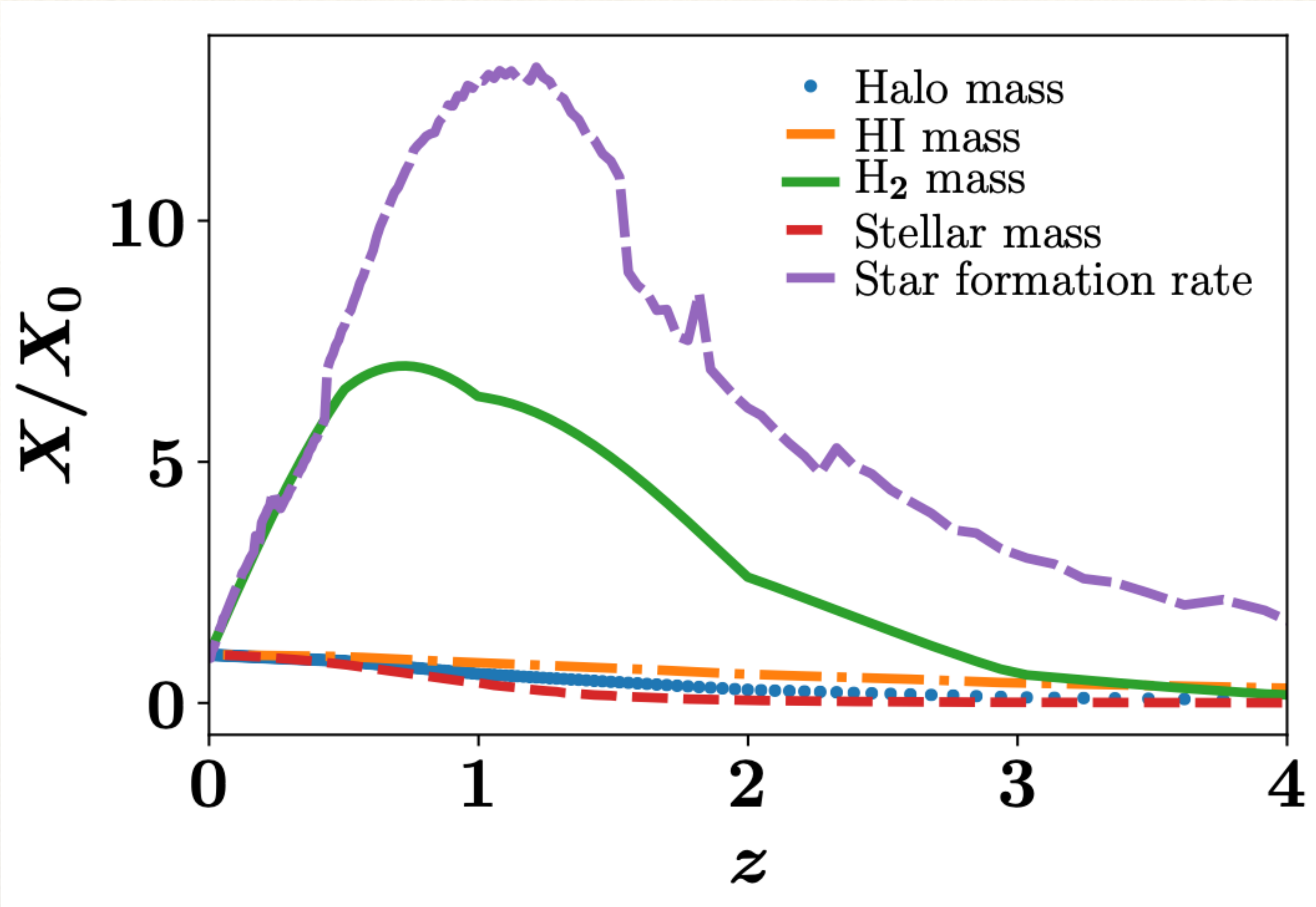
Combine HI constraints with empirical evolution of stellar-halo relations

[HP & Kulkarni, MNRAS (2017)]



[HP & Loeb, MNRAS (2020)]





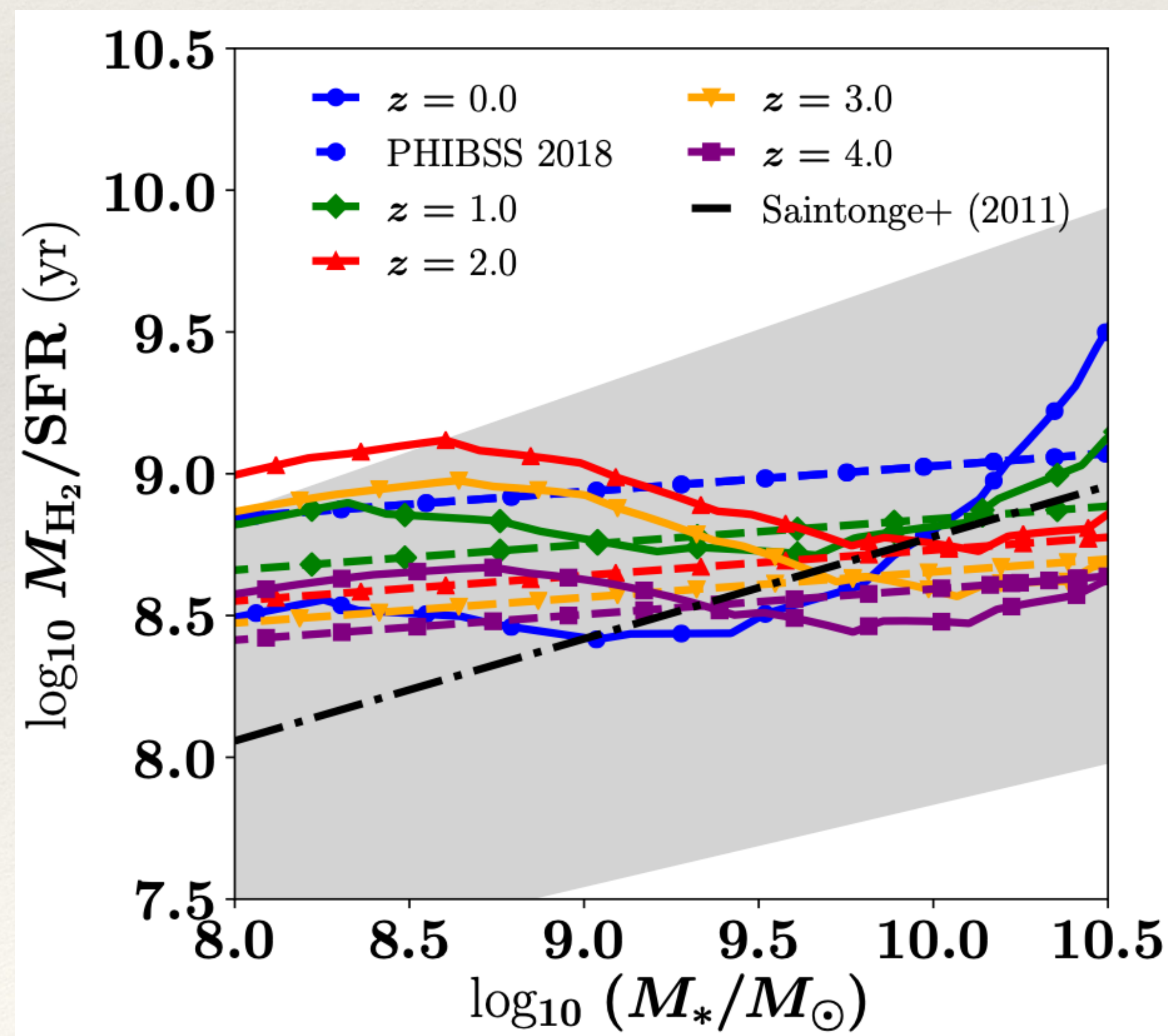
Molecular (not atomic) gas the chief tracer of star formation (but see recent work)

[Choudhury+ (2021, 2022)]

[HP & Loeb, MNRAS (2020)]

Depletion timescale evolves with z; characteristic value 1 Gyr (but some high-L outliers)

[Harrrington+ (2018), Berman+ (2022)]



From astrophysics to cosmology …

Cosmology and astrophysics from the 21 cm power spectrum

Angular power spectrum

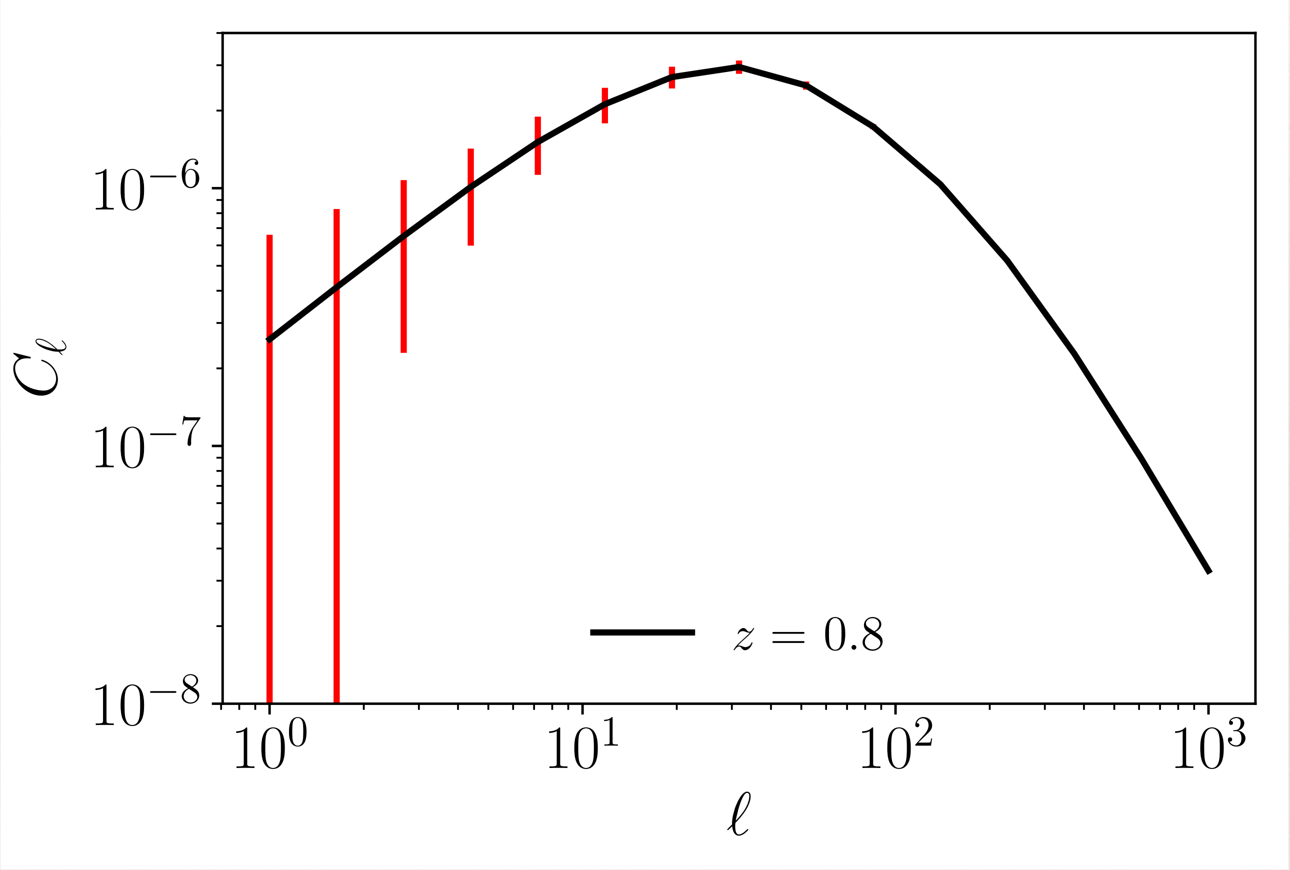
Cosmology

$$h, \Omega_m, n_s, \Omega_b, \sigma_8$$

+

Astrophysics

$$c_{\mathrm{HI}}, \alpha, v_{\mathrm{c},0}, \beta, \gamma$$

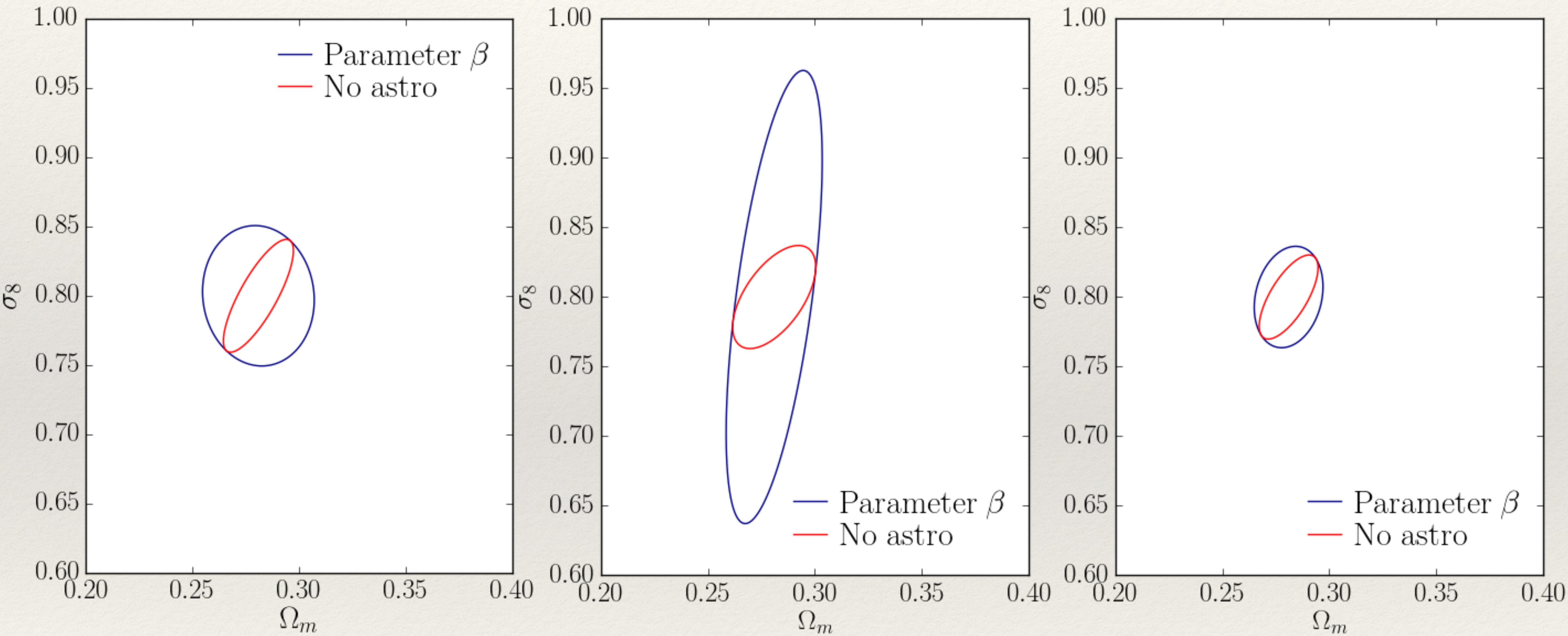


Priors from current astrophysics using the halo model!

Cosmological constraints: *precision*

[HP+ (MNRAS, 2019), arXiv:1804.10627]

Quantify degradation from astrophysics … **alleviated by tomography**



z = 0.1 z = 0.35 Combined

Experiments like CHIME/SKA going up to z ~ 2.5 achieve ~ full alleviation

Going beyond ΛCDM with intensity mapping …

*Stefano Camera and **Hamsa Padmanabhan**, Beyond ΛCDM with HI intensity mapping: robustness of cosmological constraints in the presence of astrophysics,*
MNRAS 496, 4115 (2020)
[arXiv:1910.00022]

*Bauer et al. (incl. **Hamsa Padmanabhan)**, Intensity mapping as a probe of axion dark matter,*
MNRAS 500, 3162 (2021)
[arXiv: 2003.09655]

Cosmological constraints: *accuracy*

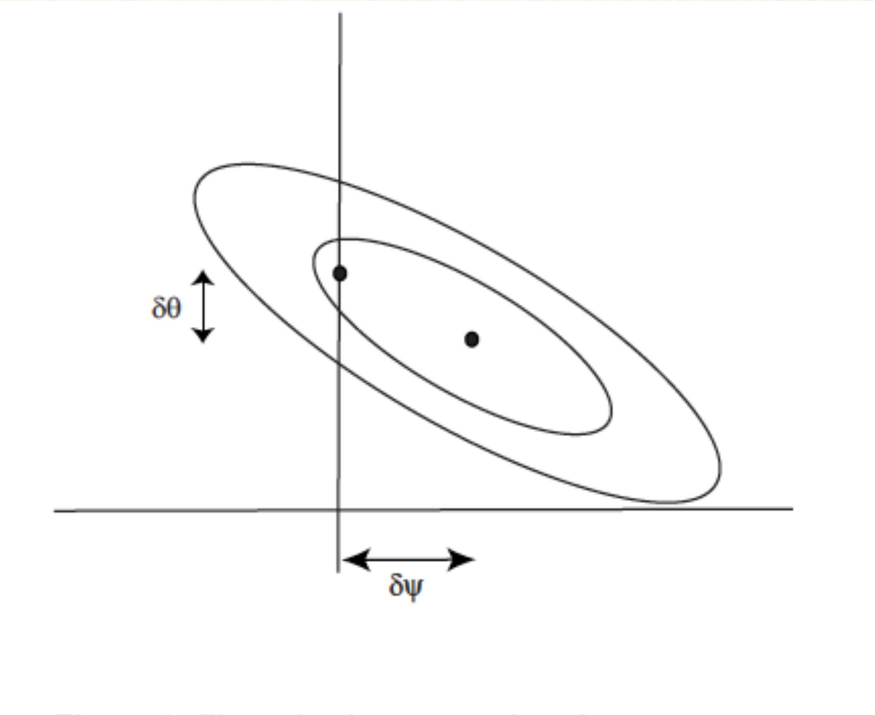
[Camera+ (2011,2014), Camera & HP (MNRAS, 2020)]

How do incorrect HI astrophysics assumptions impact cosmological constraints?

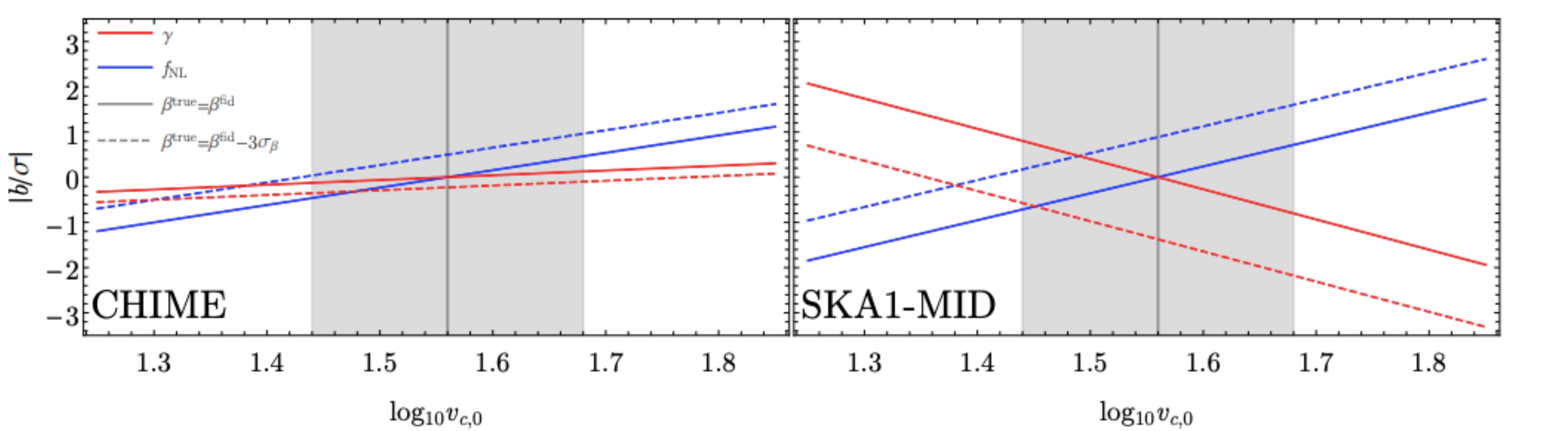
Nested likelihoods framework

Most parameters within a few σ

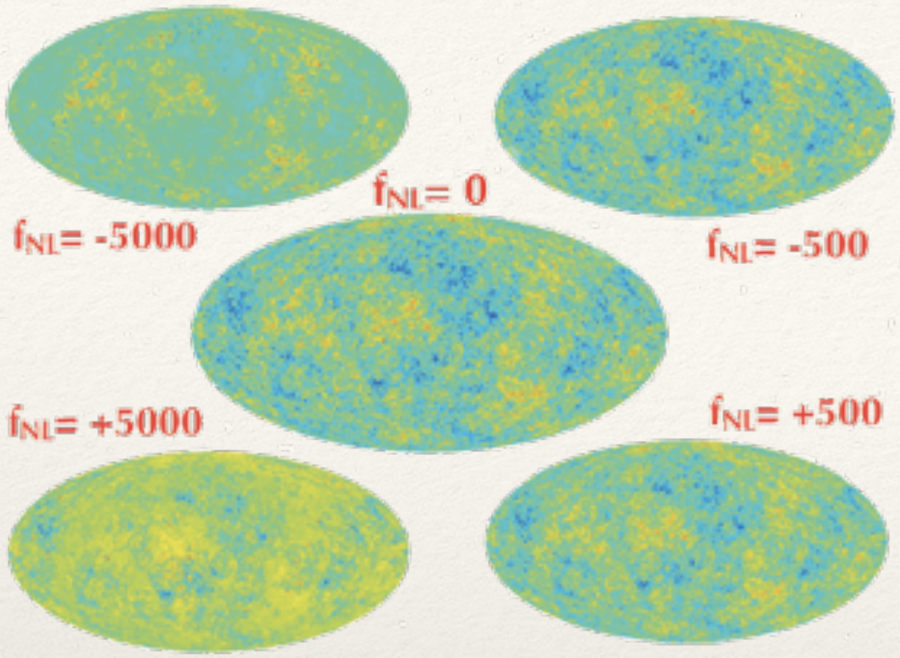
[Heavens+ (2007)]



Present uncertainty in astrophysics



Is it ΛCDM or …



[U Michigan]

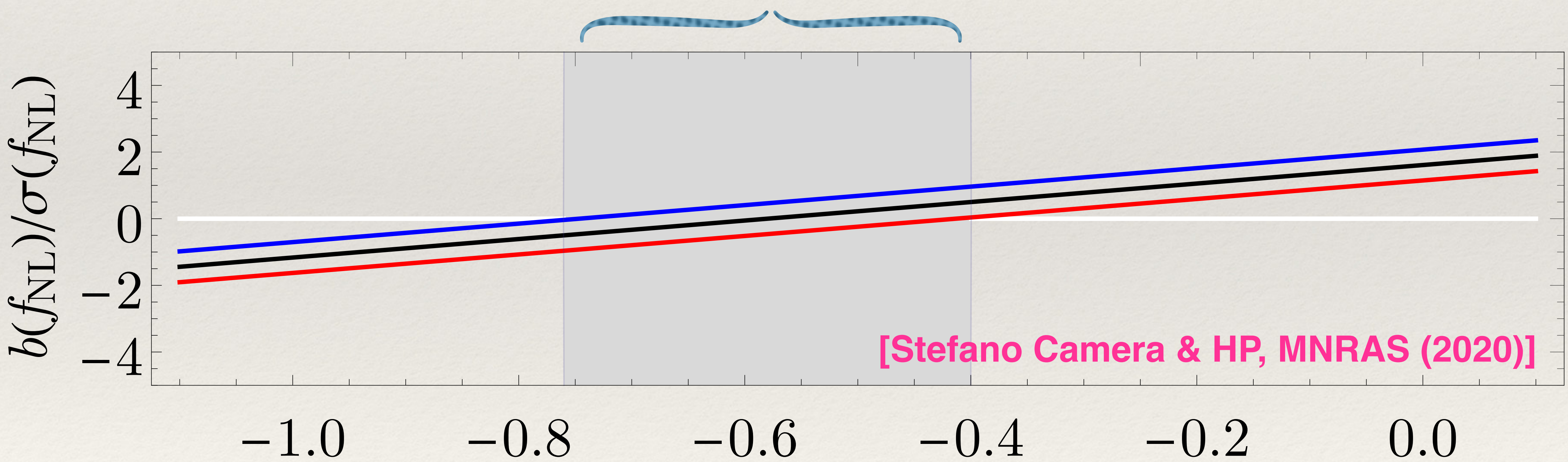
[Planck 2013]

$$f_{\rm NL} = 0.8 \pm 5$$

[Dalal (2008), Verde & Matarese (2011)]

$$\Delta b_h(M_h, z, k) \propto [b_h(M_h, z) - 1]\; f_{\rm NL}$$

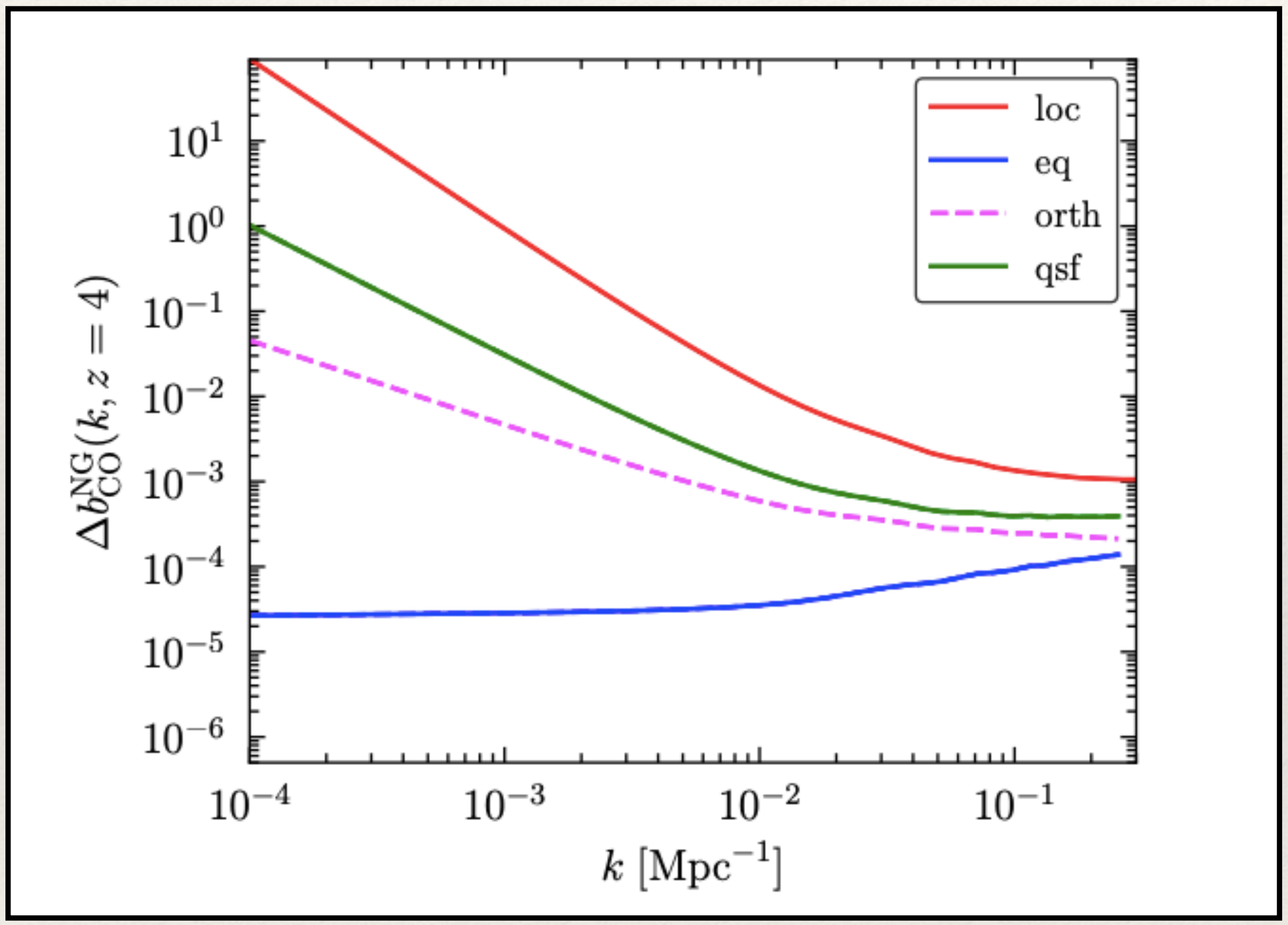
Present uncertainty in astrophysics

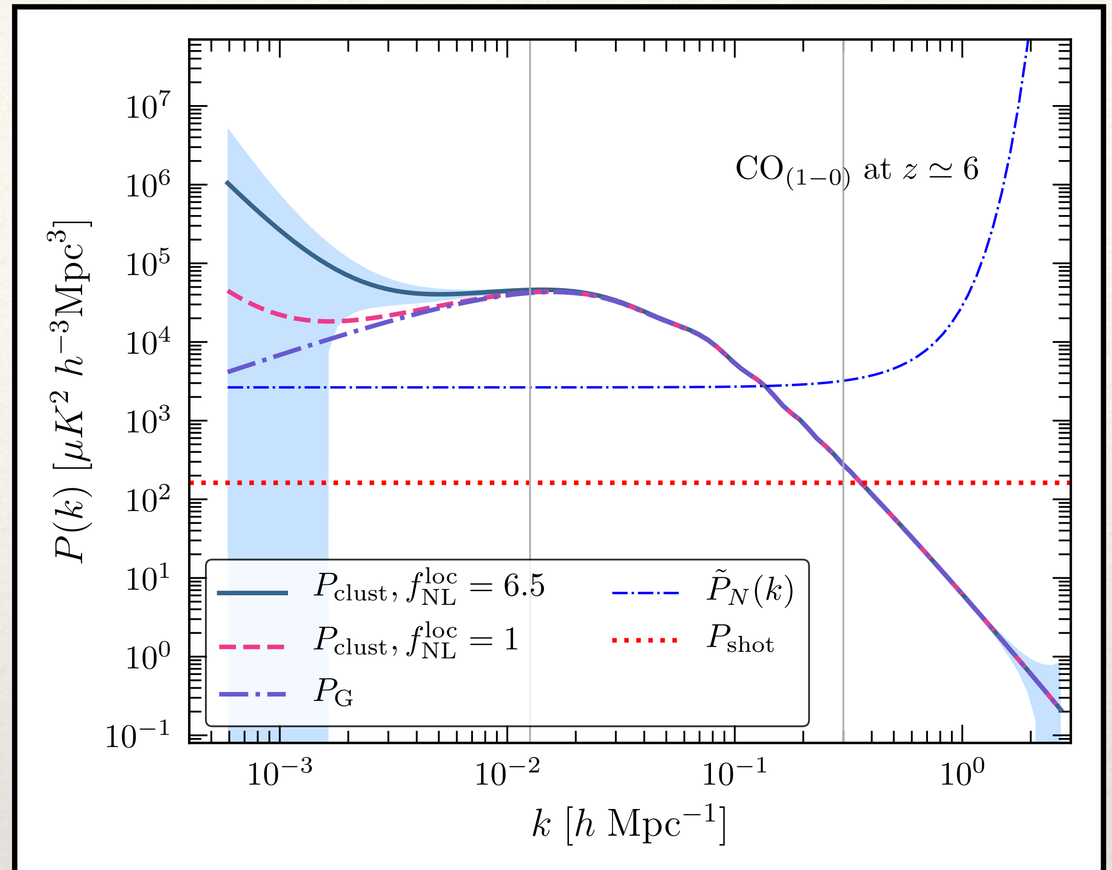


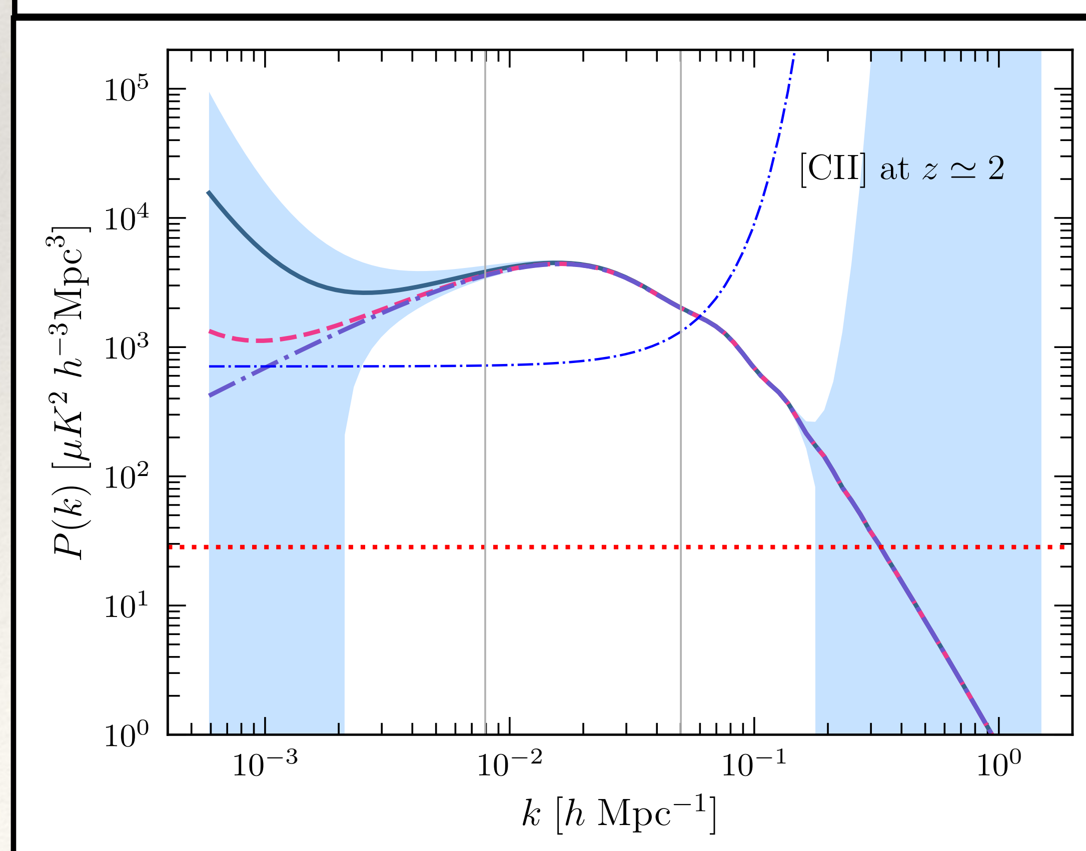
Primordial non-Gaussianity is negligibly affected by astrophysical uncertainties in HI IM surveys

Primordial non-Gaussianity with CO/[CII]

[Dizgah+ (2018), Liu & Breysse (2020), …]



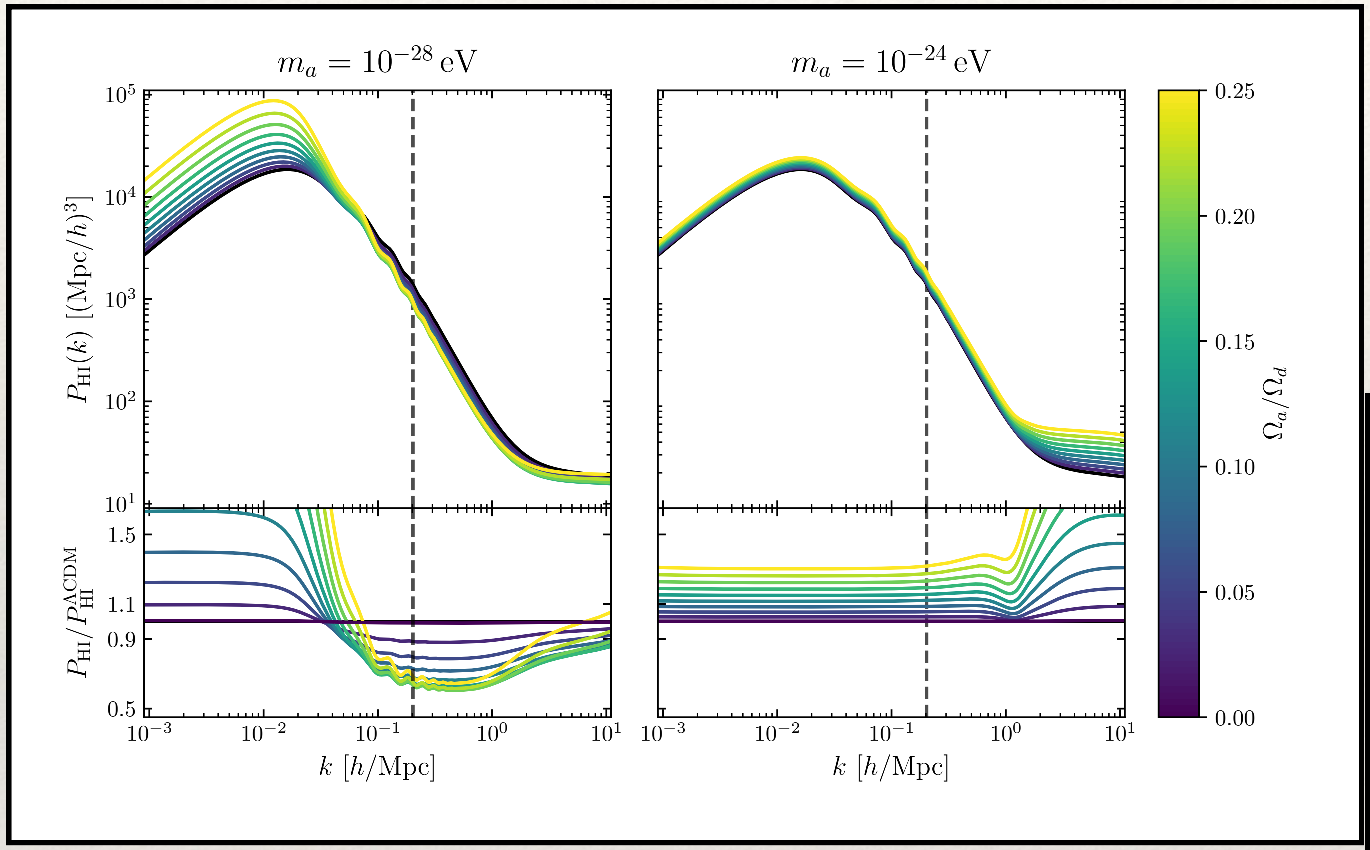




line	$\sigma(f_{\rm NL}^{\rm loc})$	$\sigma(f_{\rm NL}^{\rm eq})$	$\sigma(f_{\rm NL}^{\rm orth})$	$\sigma(f_{\rm NL}^{\rm qsf})$	$\sigma(\nu)$
CO	1.00	125	44.9	62.1	14.8
[CII]	1.00	89.8	39.6	45.9	11.7

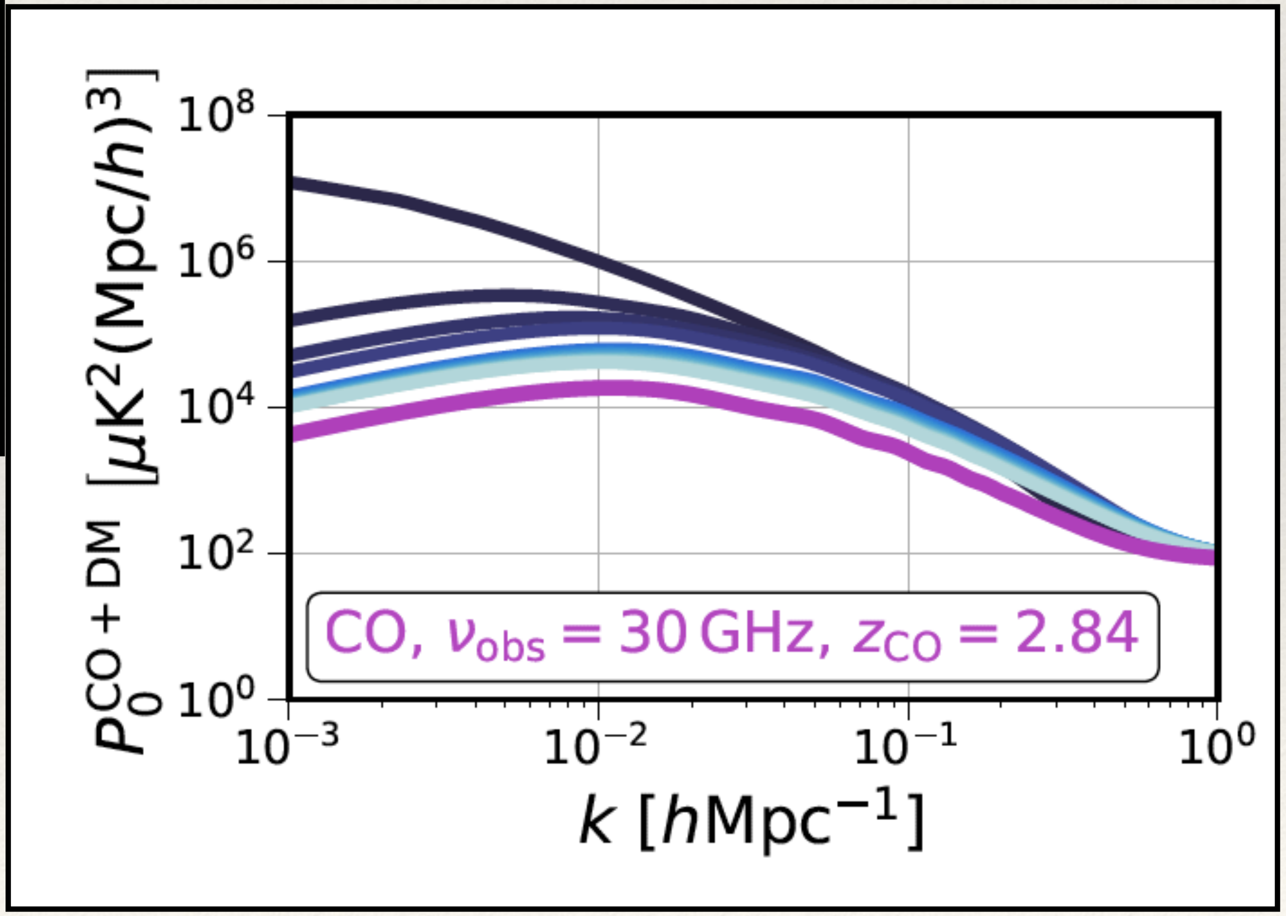
Nature of dark matter

Fuzzy DM with axion mass < 10^{-22} eV constrained at few percent level from 21 cm



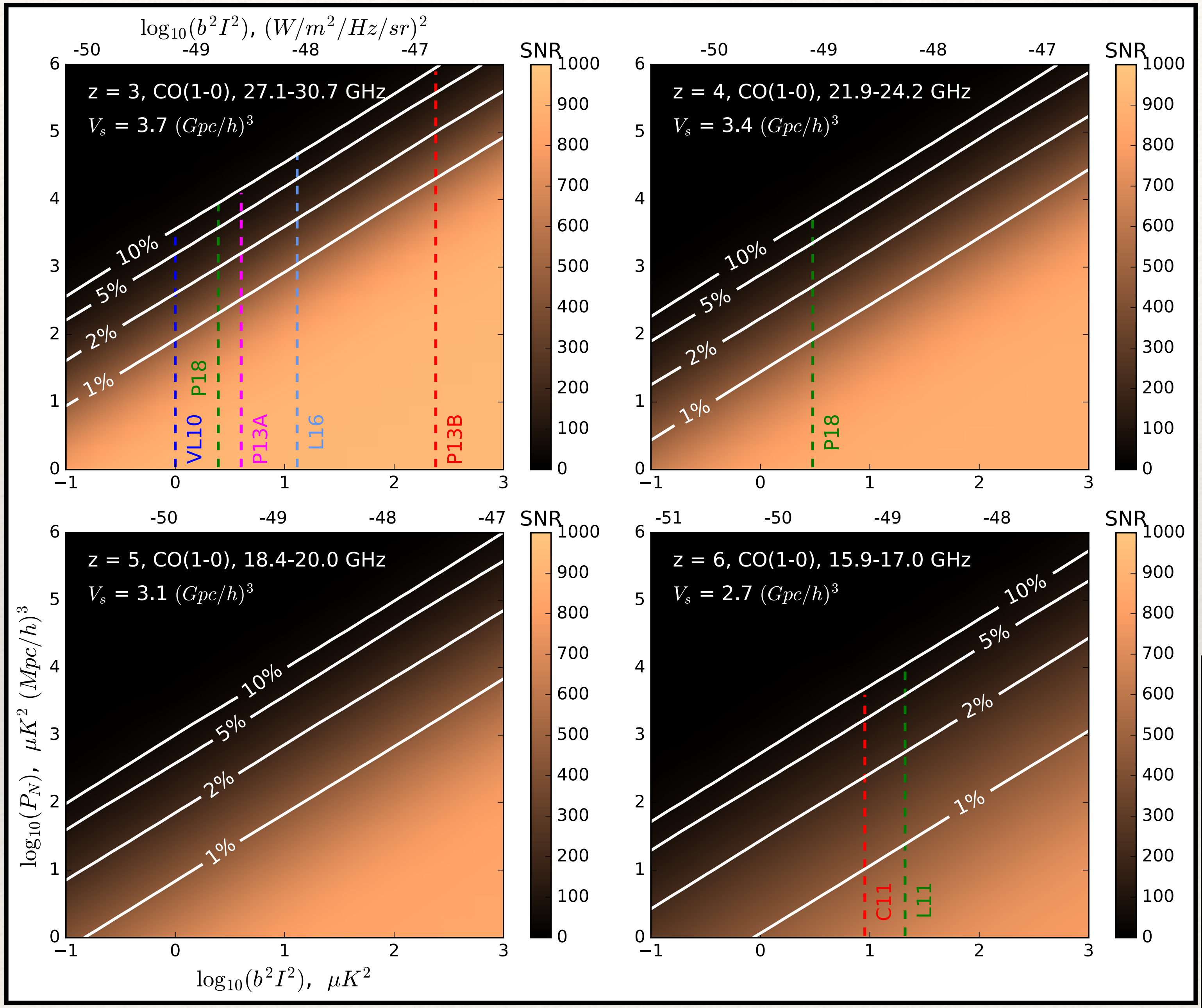
[Bauer, … HP, … MNRAS (2021)]

Dark matter decay signature on CO power spectrum



[Bernal+ (2020)]

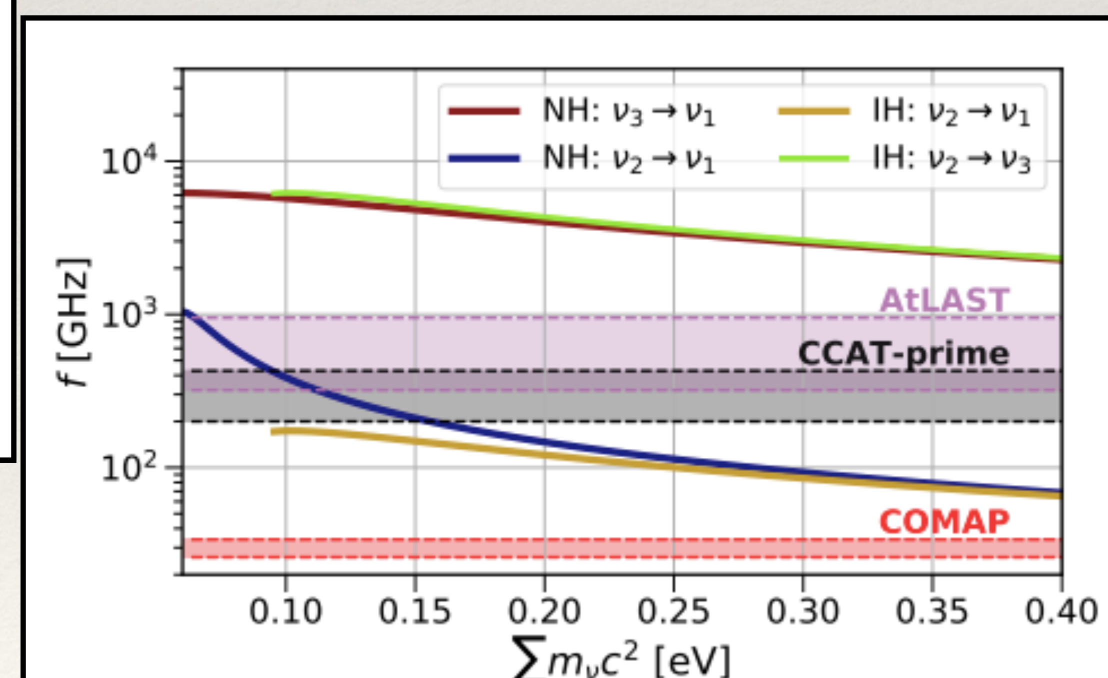
BAOs and neutrino properties



[Karkare+ (2018)]

BAO scales detectable with CO IM

Neutrino decay signature in different models show up in GHz to THz frequencies



Bernal+ (PRL, 2021)

Fundamental physics from the Cosmic Dawn …

ULB-TH/20-03

Variations in fundamental constants at the cosmic dawn

Laura Lopez-Honorez,[1,*] Olga Mena,[2,†] Sergio Palomares-Ruiz,[2,‡] Pablo Villanueva-Domingo,[2,§] and Samuel J. Witte[2,¶]

Gravitational wave backgrounds from coalescing black hole binaries at cosmic dawn: an upper bound

Kohei Inayoshi,[1] Kazumi Kashiyama,[2,3] Eli Visbal,[4] and Zoltán Haiman[5]

Fuzzy Dark Matter at Cosmic Dawn: New 21-cm Constraints

Olof Nebrin,[a] Raghunath Ghara,[a] Garrelt Mellema[a]

Implications of the possible 21-cm line excess at cosmic dawn on dynamics of interacting dark energy

Chunlong Li[a,b,c], Xin Ren[a,b,c], Martiros Khurshudyan[a,b,c,d,e], Yi-Fu Cai[a,b,c,*]

and several more …

arXiv.org > astro-ph > arXiv:1810.02680

Astrophysics > Cosmology and Nongalactic Astrophysics

Fundamental Physics with the Square Kilometer Array

Review article, Weltman+ *(2020)*, PASA, chapter on *Cosmic Dawn and Reionization [chapter leads: HP, Jonathan Pritchard]*

To summarize …

- Intensity mapping bridges a large gap between deep and wide spectroscopic surveys of galaxies
- *Astrophysical systematics* in intensity mapping can be efficiently handled via a *data driven halo model* **[HP+ (2015, 2016, 2017a, b), HP & Kulkarni (2017)]**
- … to explore the impact of astrophysics on the *precision* **[HP+ (2019b)]** *and accuracy* of cosmological forecasts, … **[Camera & HP (2020), Bauer+ (2021)]**
- … *cross correlations* with large galaxy surveys (e.g. DES, DESI, Euclid, LSST …) **[HP, Refregier, Amara (2020)]** and extensions to the *sub-mm regime* **[HP (2018, 2019, 2023), HP+ (2022)]**
- … *and physics beyond LCDM* … **[Karkare+ (2018), Bernal+ (2020), Dizgah+ (2018), Breysse & Liu (2020) …]**
- … aiming towards the best possible constraints on Fundamental Physics from the Cosmic Dawn … **[Fundamental Physics with the SKA (PASA, 2020)]**

Thank you!