The 21cm IM signal at z<6:

modelling, dependence on cosmology, synergies with other probes

Isabella Paola Carucci

University College London at the moment
CEA, Paris Saclay in a month

CCA Workshop, New York, Feb 21 2019

The 21cm IM signal at z<6:

- modelling
- dependence on cosmology
- synergies with other probes

Distribution of HI in the post-reionization universe

$b_{HI} \simeq 0.8$ at $z \sim 0$

- the clustering of **HI selected galaxies at z ~ 0** from the ALFALFA survey (Martin+ 2012, Guo+ 2017)

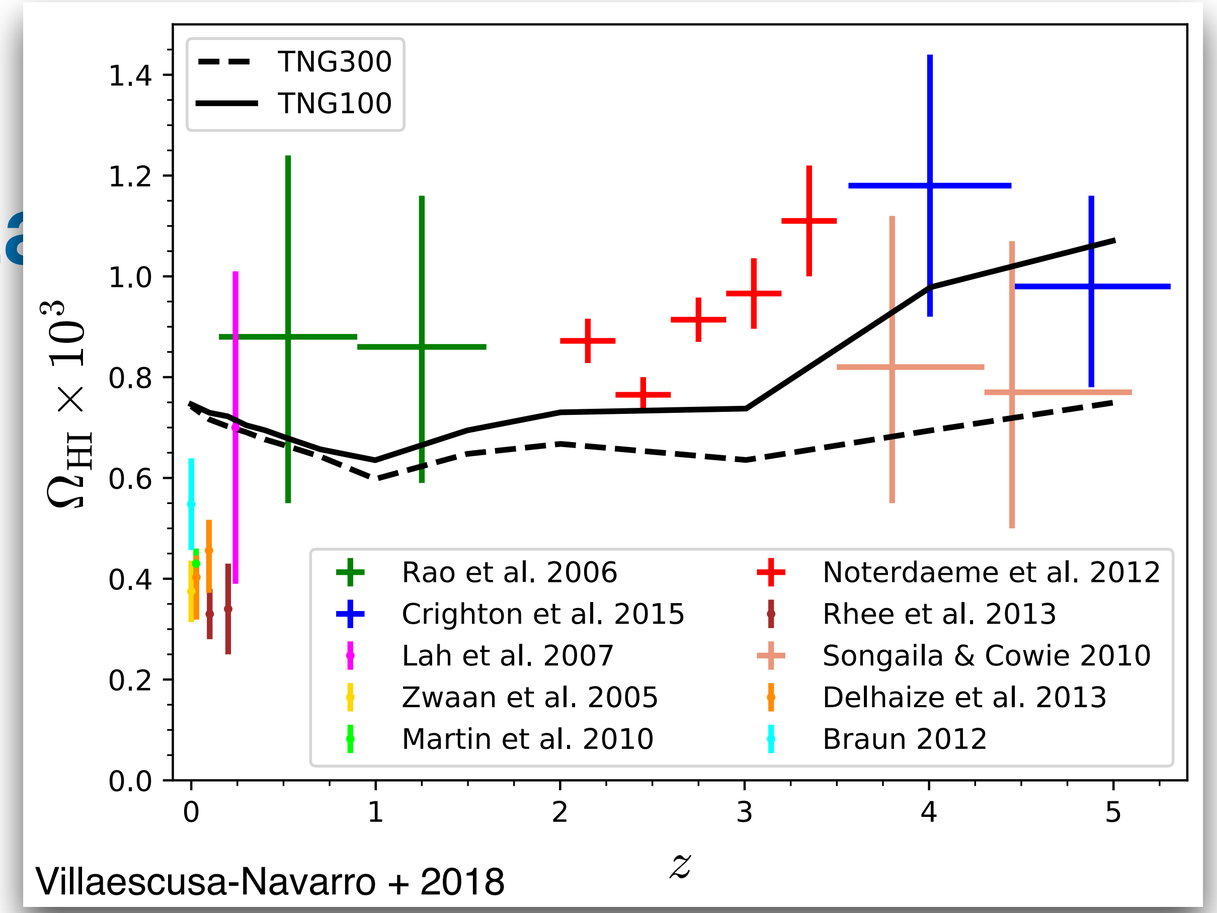
$b_{DLAs} = 1.99 \pm 0.11$ at $z \sim 2.3$

- the bias of the Damped Lyman-α systems **(DLAs) at z ~ 2.3** by BOSS collaboration (Perez-Rafols+ 2017)

$\Omega_{HI} \times b_{HI} = 0.62 \times 10^{-3}$ at $z \sim 0.8$

- HI cosmic abundance times its linear bias, from **21cm IM observations at z ≃ 0.8** performed with the GBT by (Switzer+ 2013)

Distribution of HI in the post-reioniza



$\Omega_{HI} \times b_{HI} = 0.62 \times 10^{-3}$
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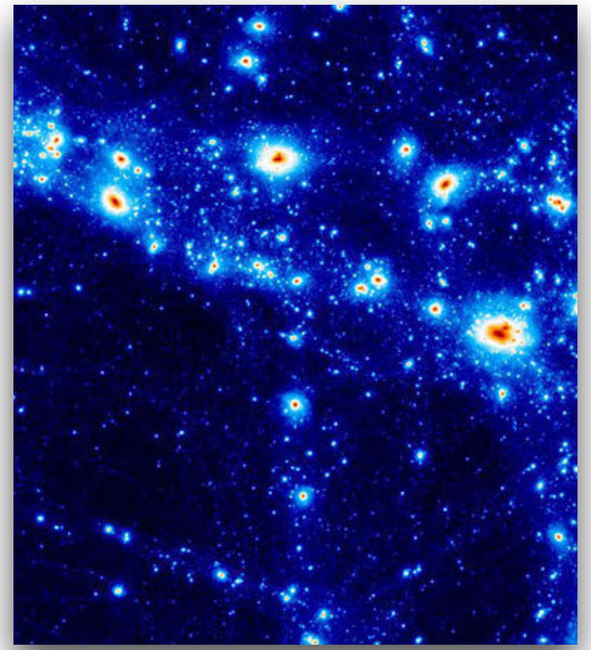
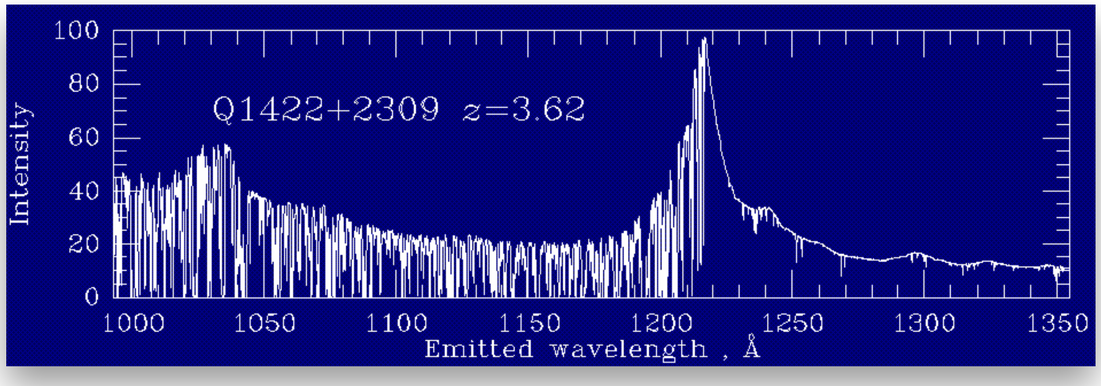
Distribution of HI
in the post-reionization universe



Distribution of HI
in the post-reionization universe

Filaments

mostly ionised H



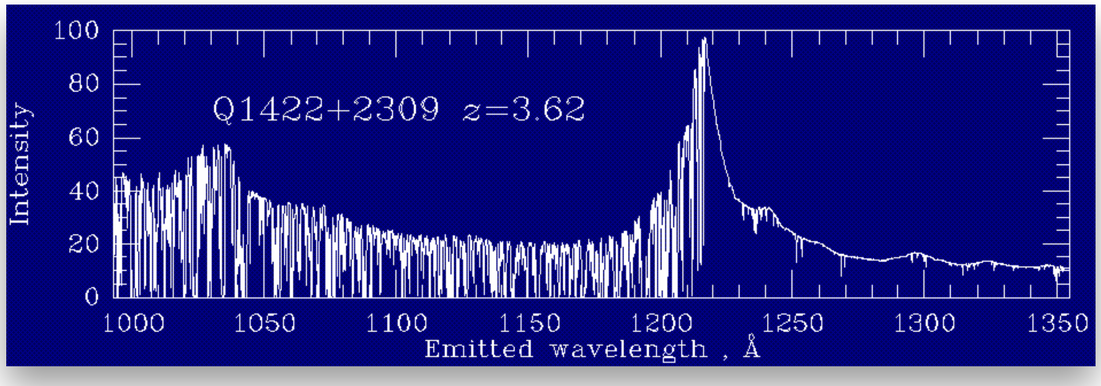
Distribution of HI
in the post-reionization universe

Halos (DLAs, i.e. galaxies)

Dense, self-shielding —> HI

Filaments

mostly ionised H



Distribution of HI
in the post-reionization universe

Strategy 1:
HI resides in DM halos

Distribution of HI
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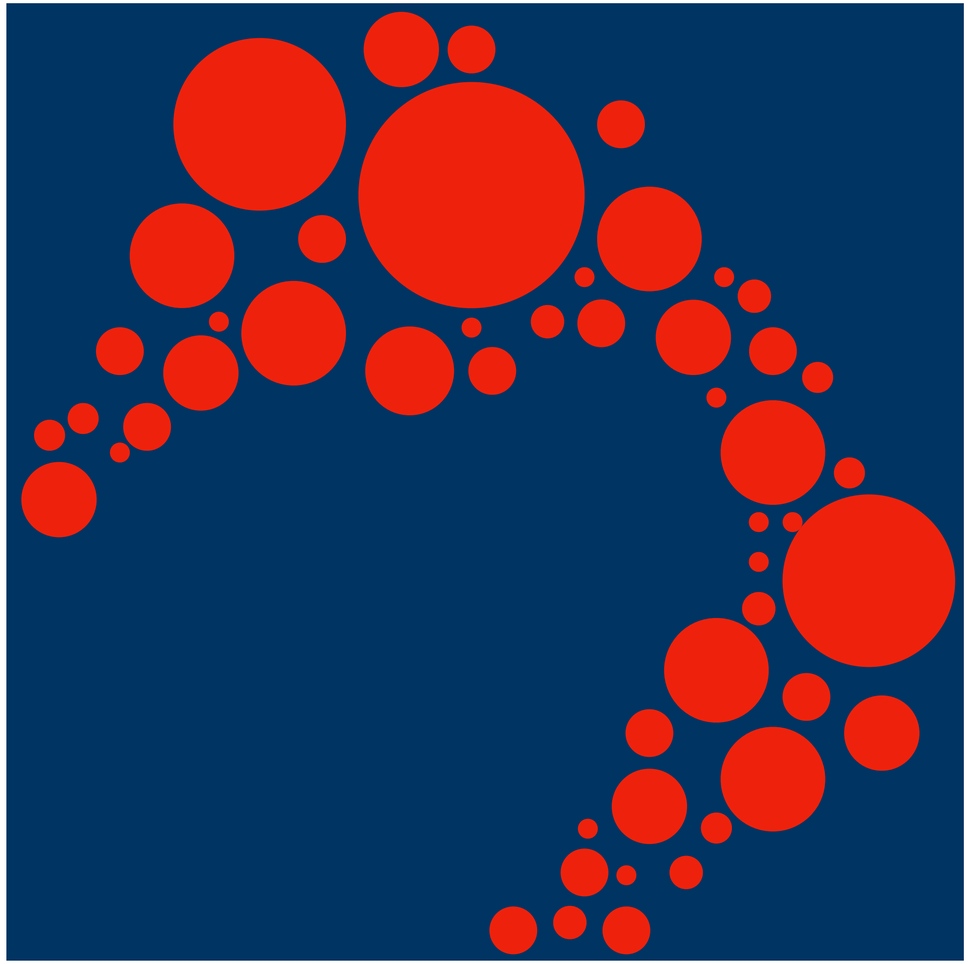

Distribution of HI
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Strategy 1:
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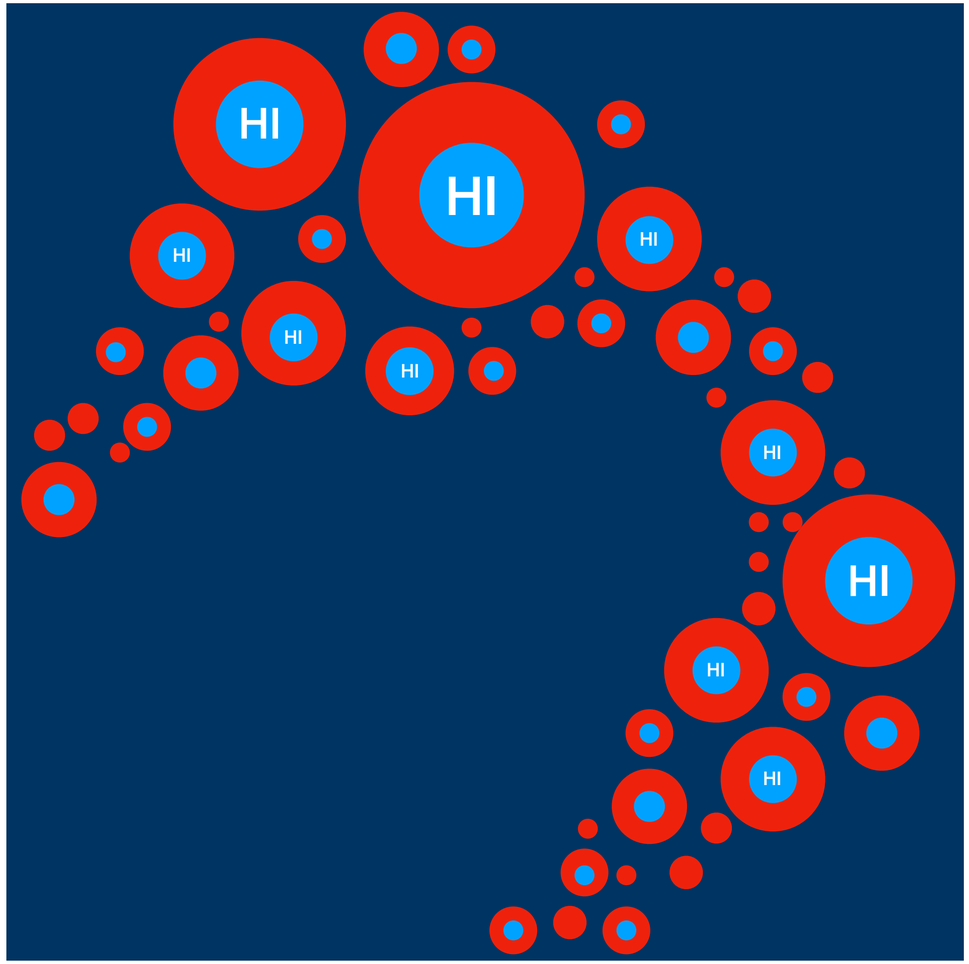

$M_{HI} = M_{HI}(M_{halo})$

if $M_{halo} > M_{min}$

Distribution of HI in the post-reionization universe

Strategy 1:
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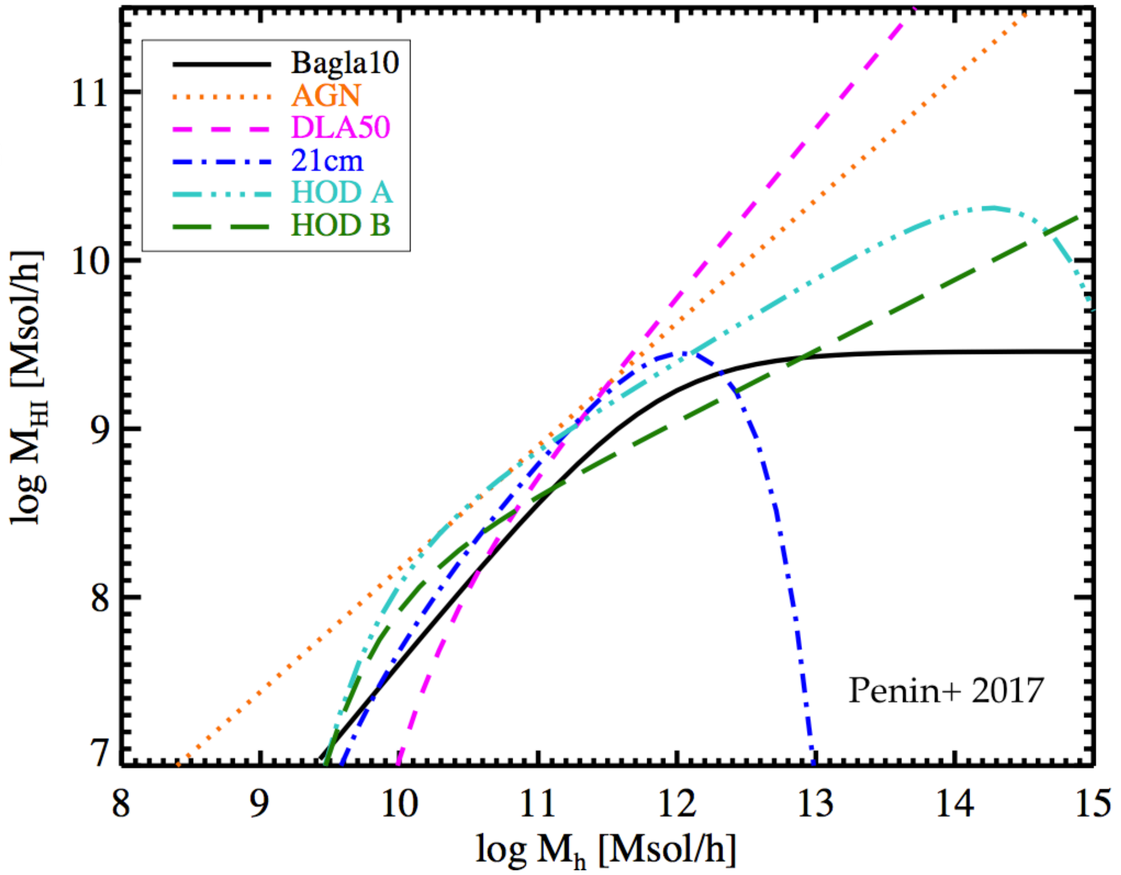


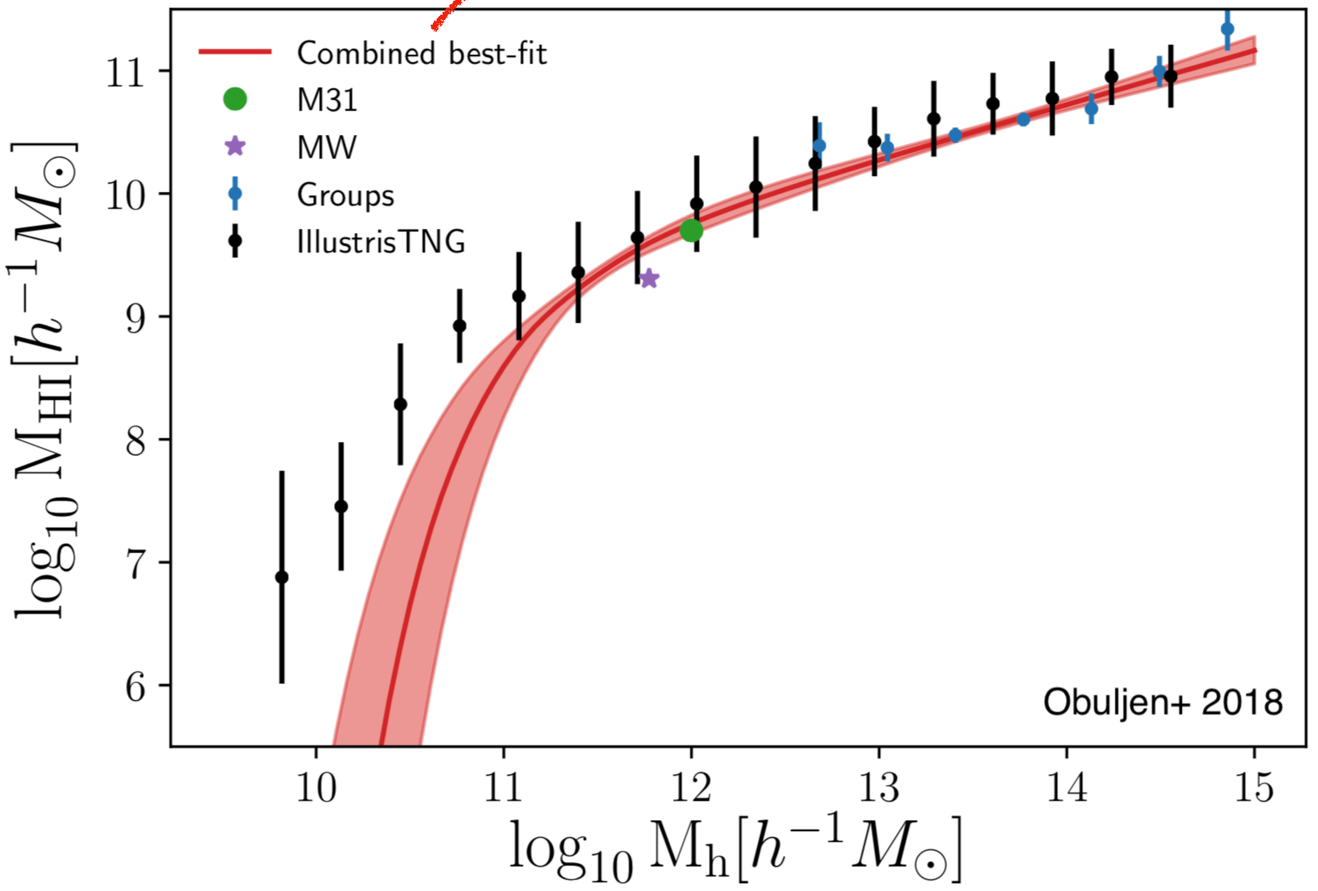
$M_{HI} = M_{HI}(M_{halo})$
if $M_{halo} > M_{min}$

z = 1

Distribution of HI in the post-reionization universe

Strategy 1:
HI resides ir

ALFALFA galaxies with SDSS groups



$M_{HI} = M_{HI}(M_{halo})$
if $M_{halo} > M_{min}$

z = 0

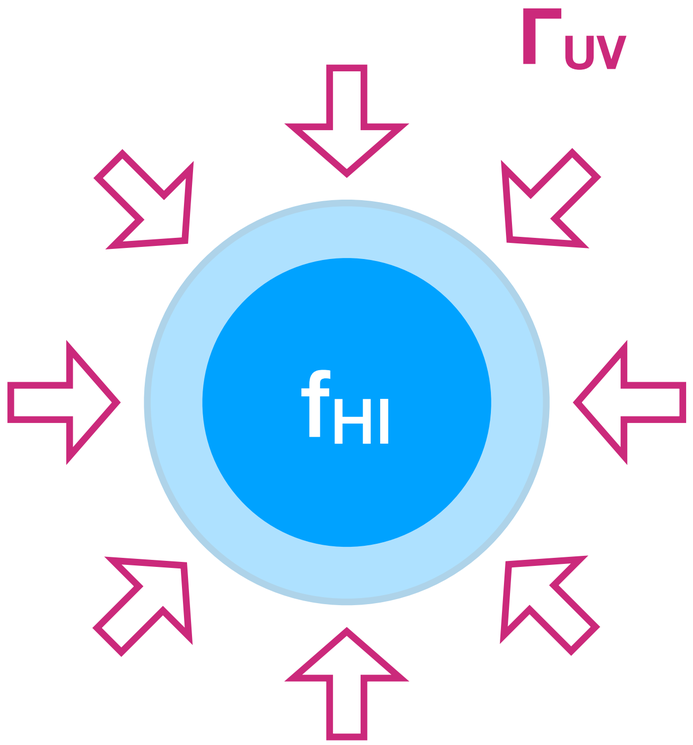
Distribution of HI
in the post-reionization universe

Strategy 2:
Hydro sims

Distribution of HI in the post-reionization universe

Strategy 2:
Hydro sims

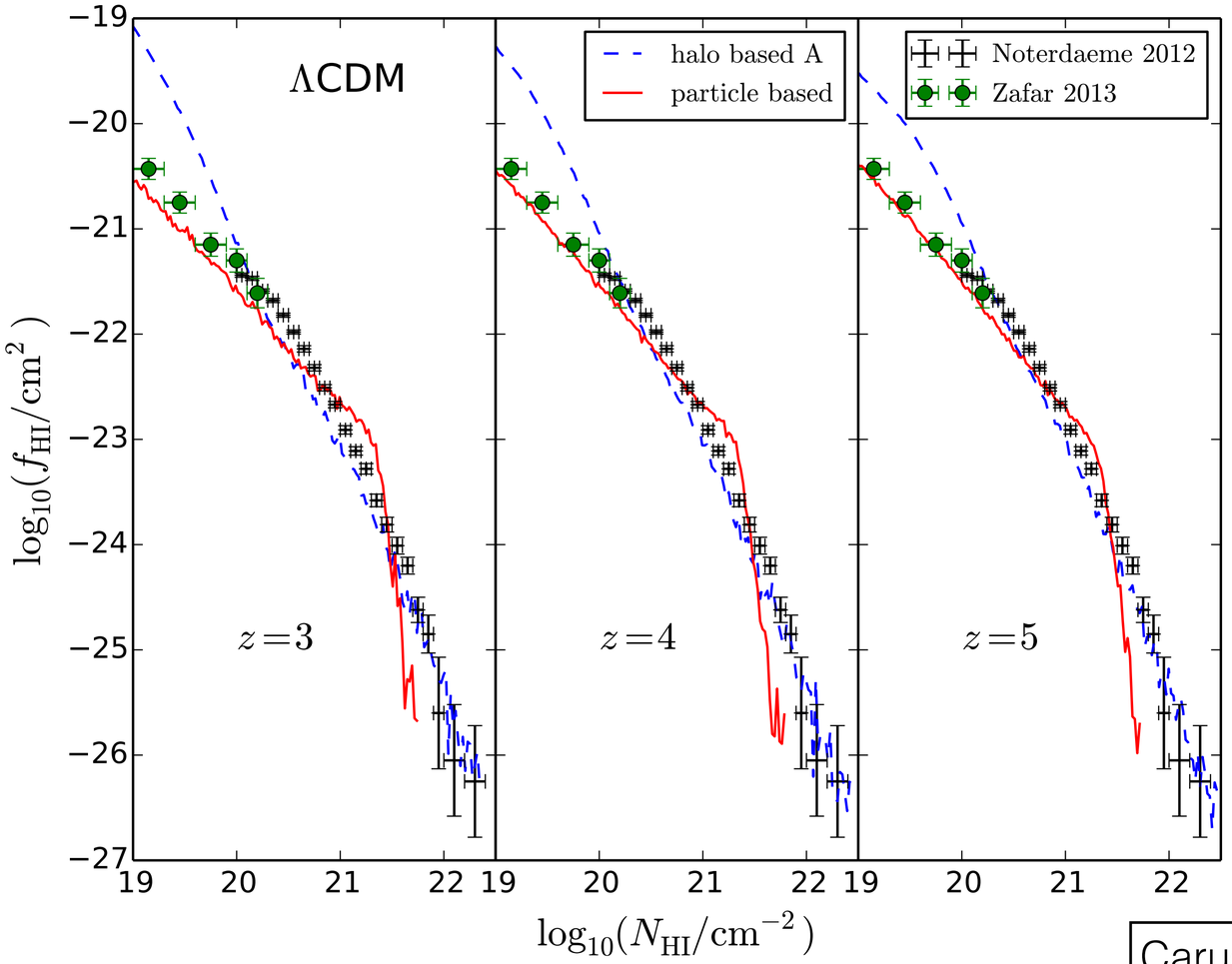
- assuming photo-ionization equilibrium, setting the HI/H fraction in order to reproduce the Lyman-α mean transmission flux
- mimicking HI self-shielding for high enough density regions
- letting H_2 forming for even denser regions



Davé+ 2013, Rahmati+ 2015, …

Distribution of HI in the post-reionization universe

How can we test these methods?



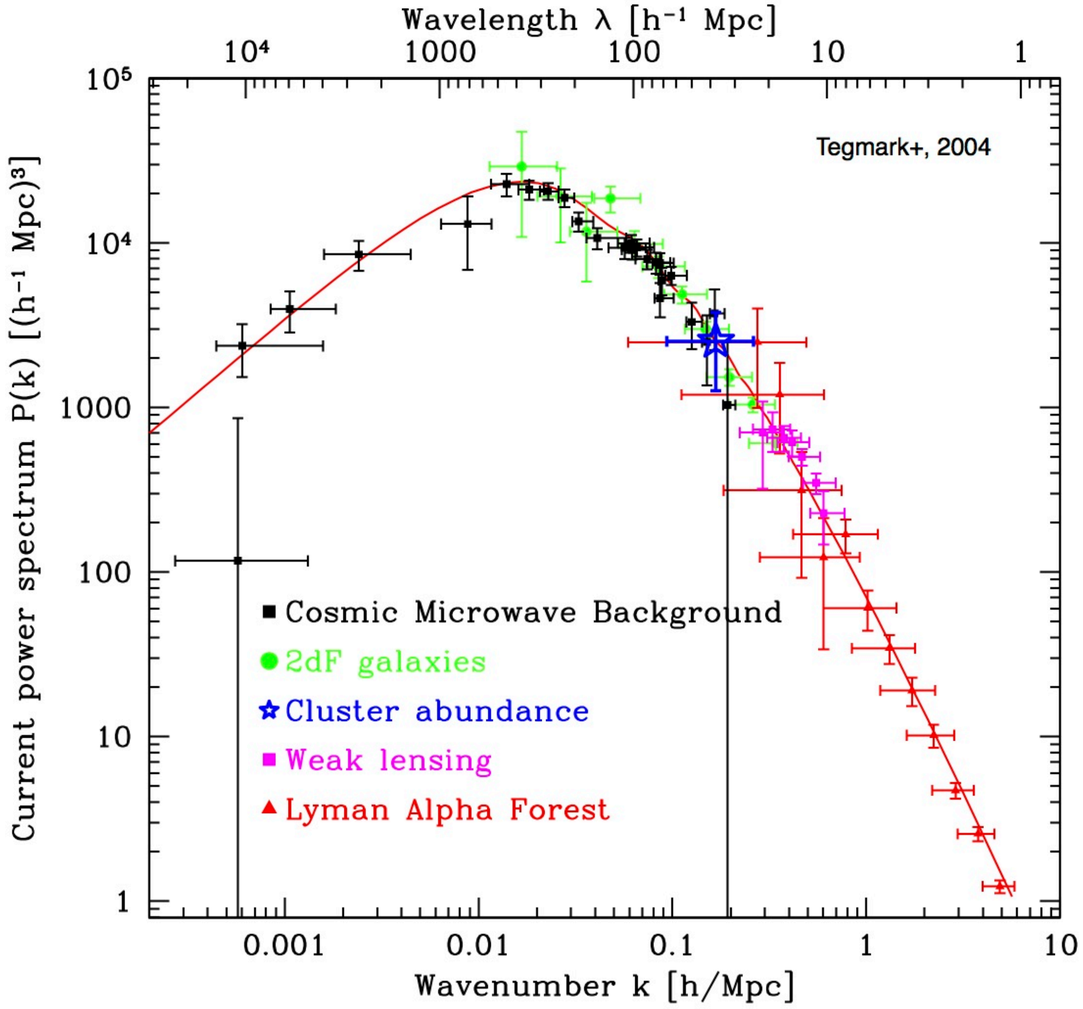
HI column density distribution function

Carucci + 2015

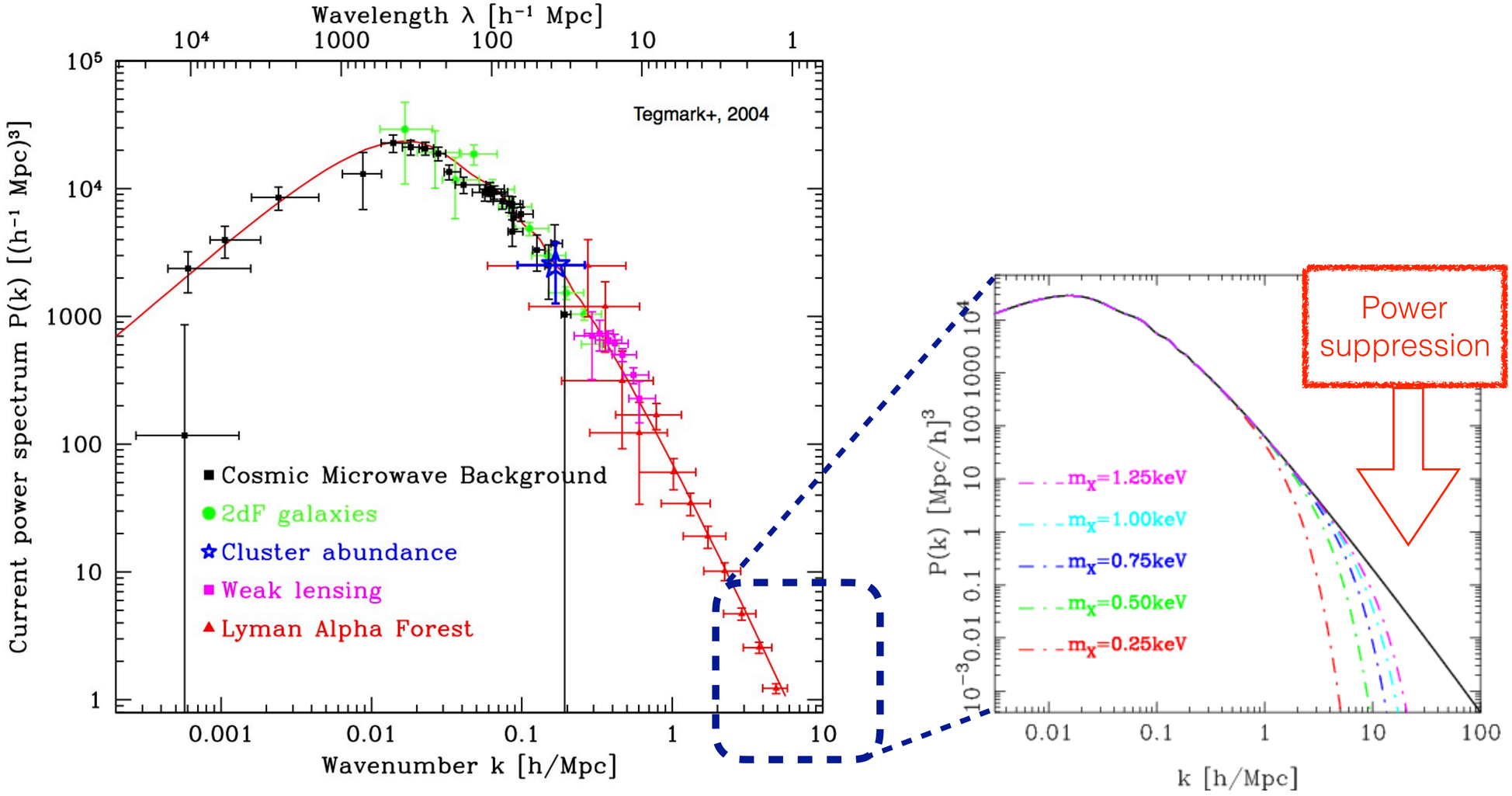
The 21cm IM signal at z<6:

- modelling
- dependence on cosmology
- synergies with other probes

Dark matter


Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
Tegmark+, 2004
Current power spectrum P(k) [(h⁻¹ Mpc)³]
10⁵
10⁴
1000
100
10
1
Cosmic Microwave Background
2dF galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]

Dark matter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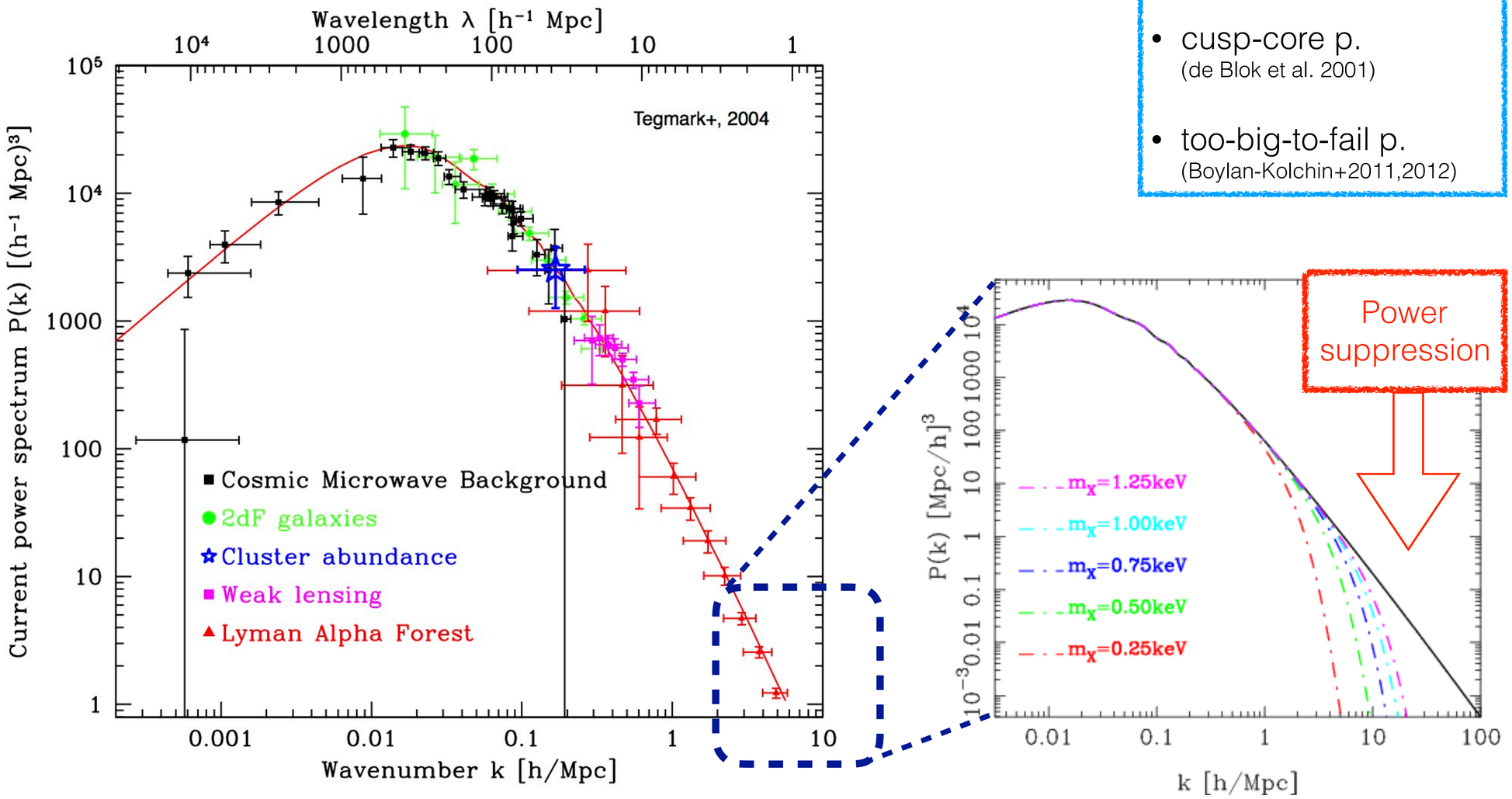
Wavenumber k [h/Mpc]
P(k) [Mpc/h]³
m_x=1.25keV
m_x=1.00keV
m_x=0.75keV
m_x=0.50keV
m_x=0.25keV
k [h/Mpc]
Power suppression

Dark matter

< Mpc problems

- missing satellite p.
  (Moore+1999; Klypin+1999)
- cusp-core p.
  (de Blok et al. 2001)
- too-big-to-fail p.
  (Boylan-Kolchin+2011,2012)



Dark matter

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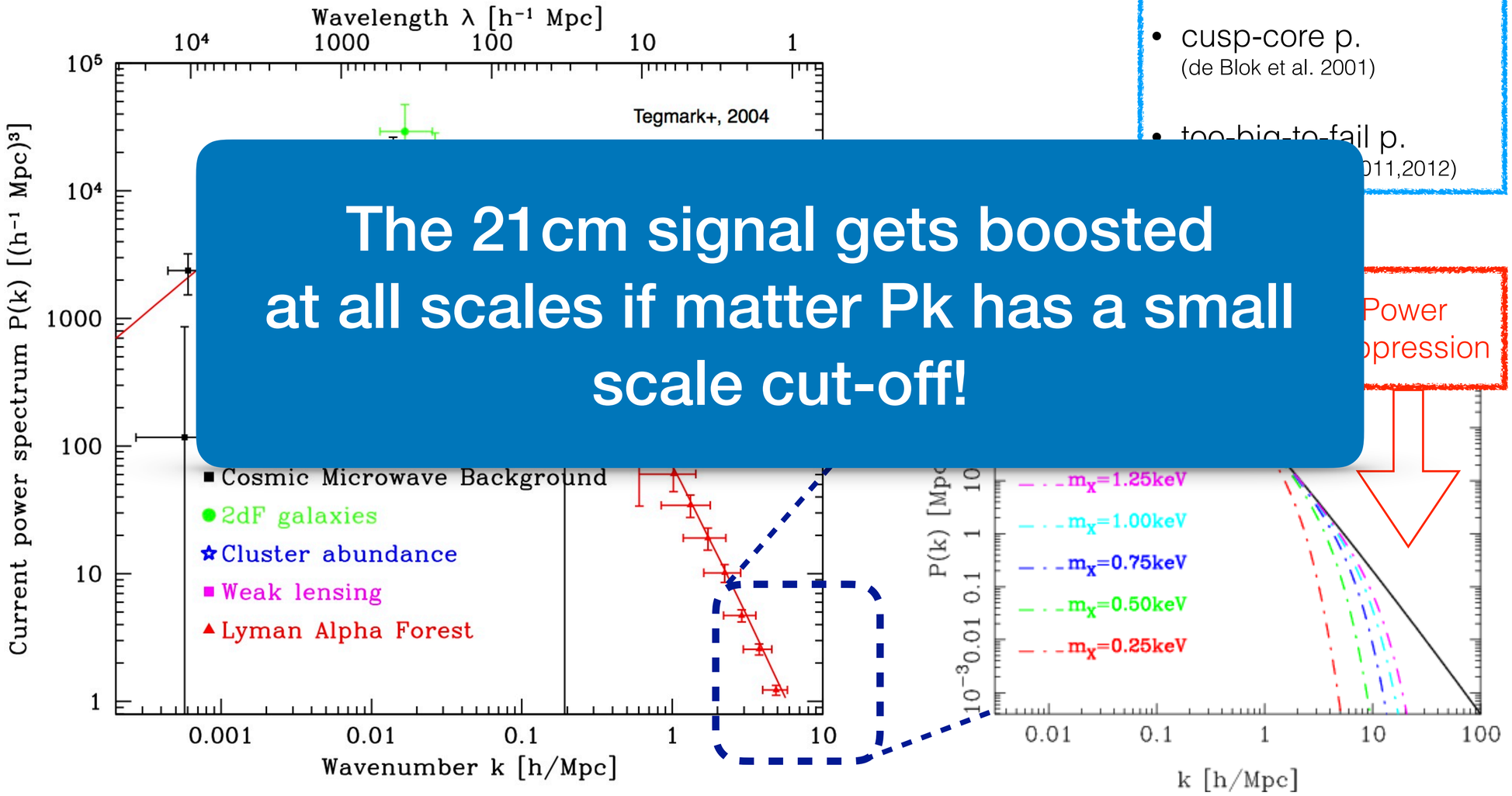
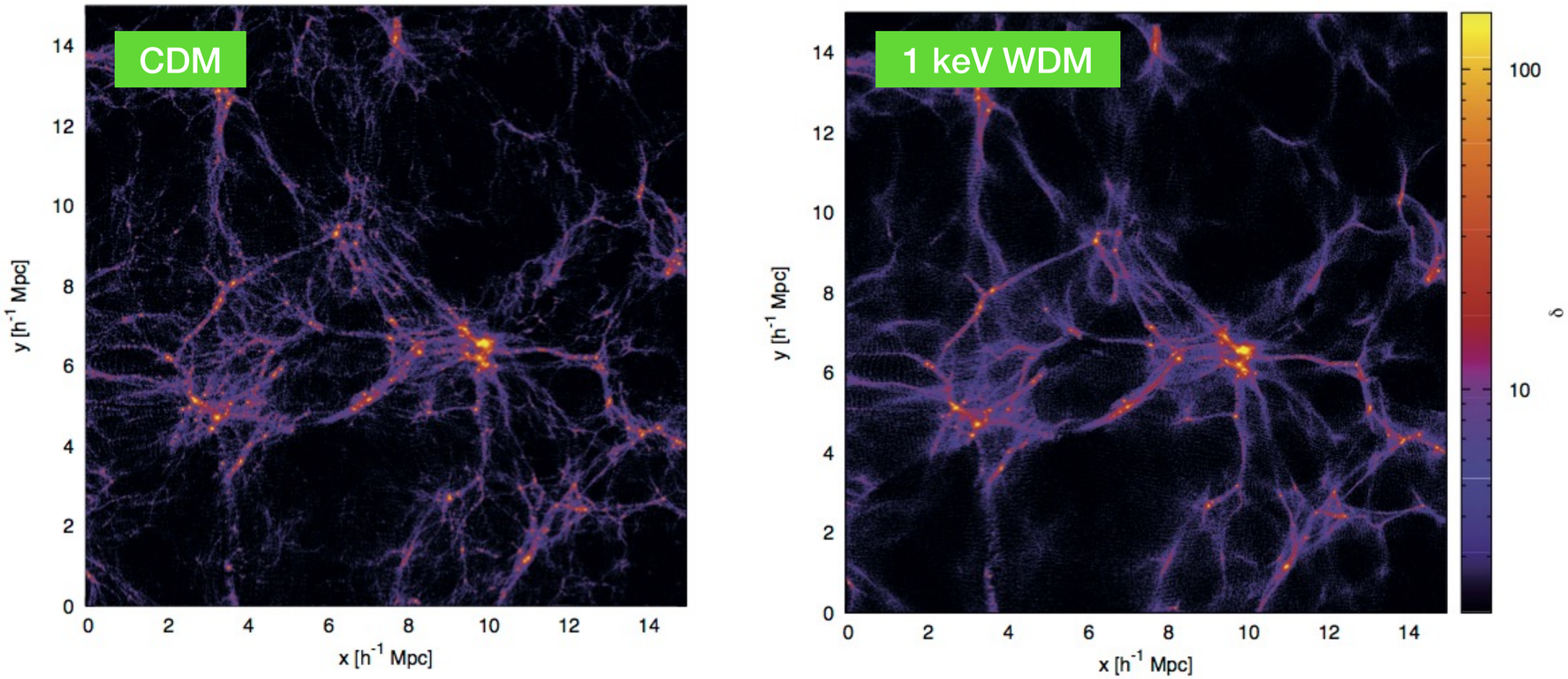
  011,2012)

Power
pression

The 21cm signal gets boosted at all scales if matter Pk has a small scale cut-off!



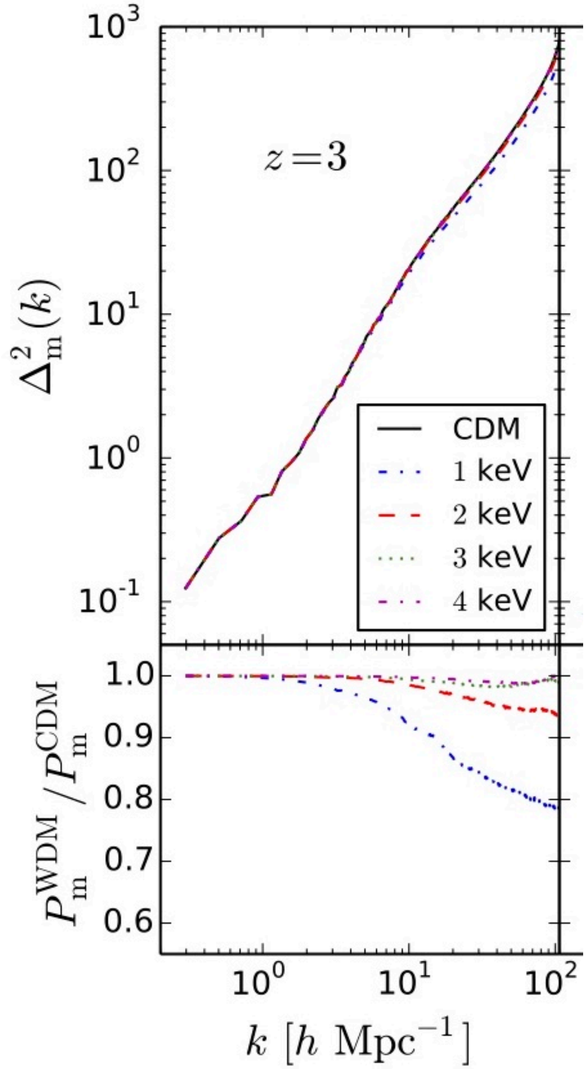
Dark matter models (hydro) simulations

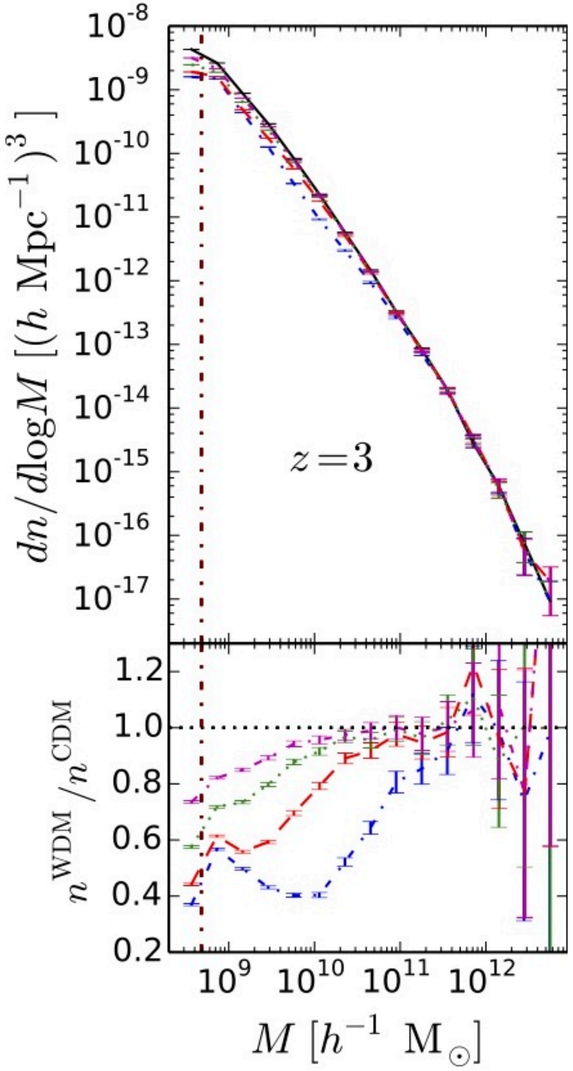


Carucci + 2015

Dark matter models (hydro) simulations

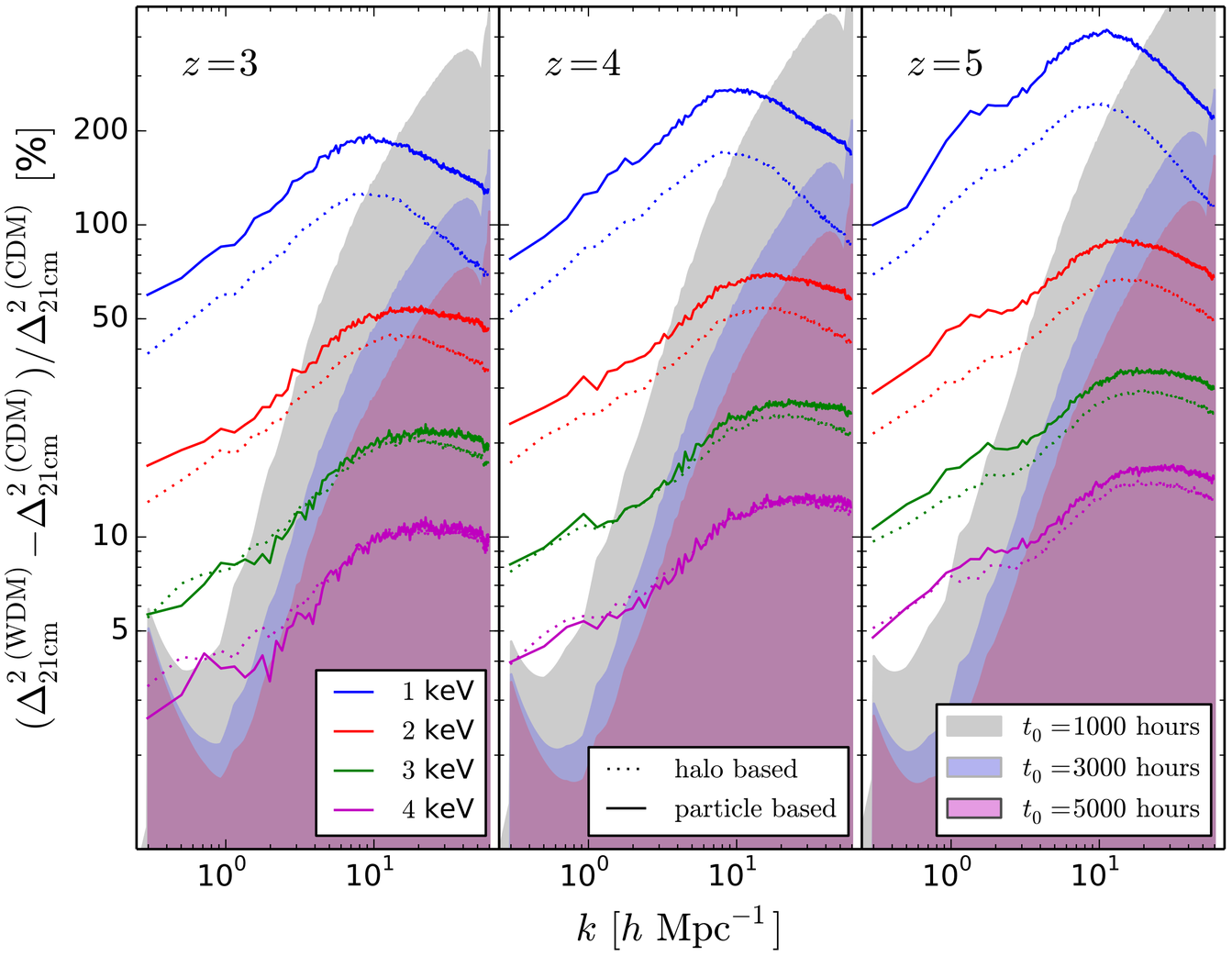
Total matter Pk





Halo mass function

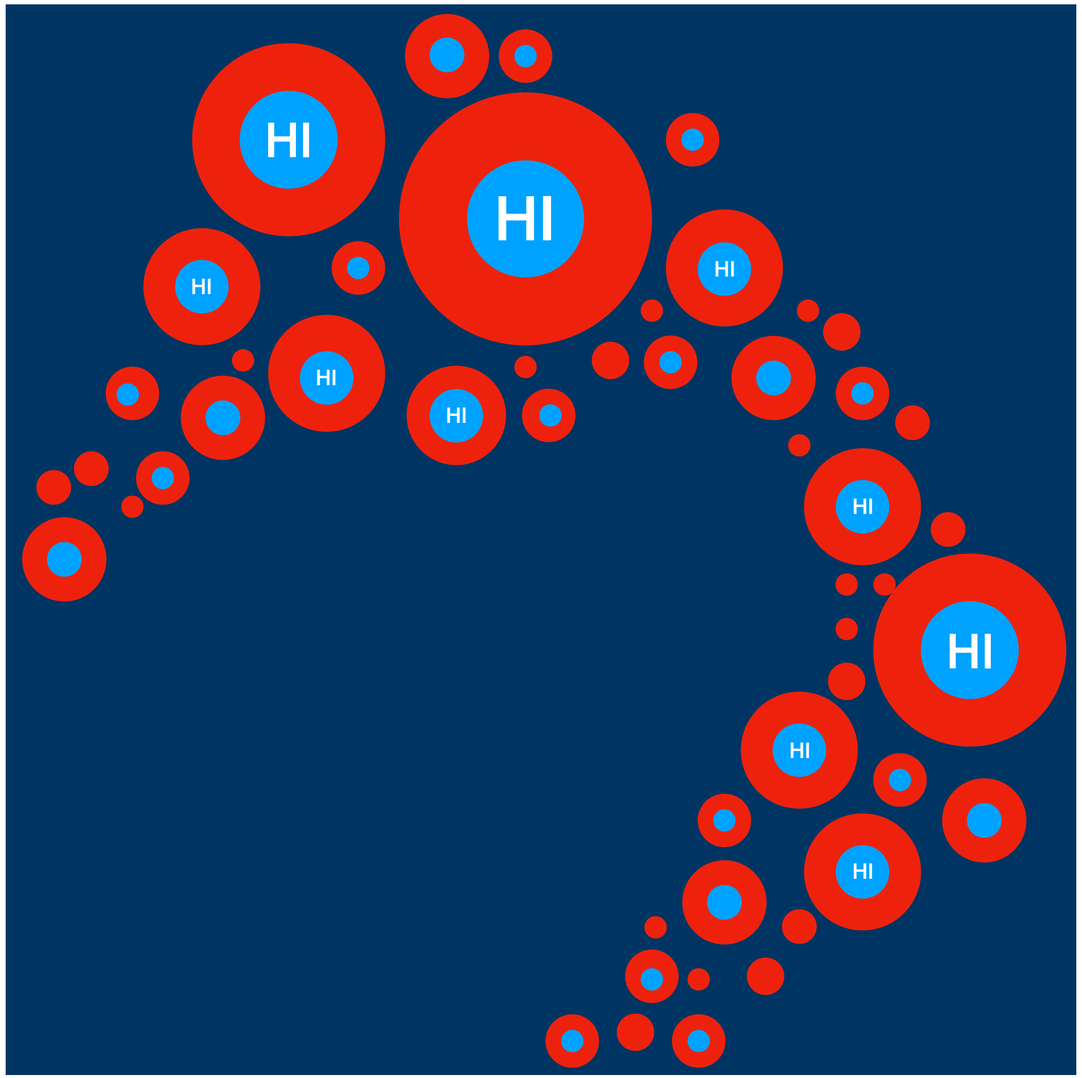
Dark matter models: 21cm IM signal



SKA can rule out a 4kev mass, with 5000 hour observation, at z >3, with 3σ

Carucci + 2015

Dark matter models: 21cm IM signal



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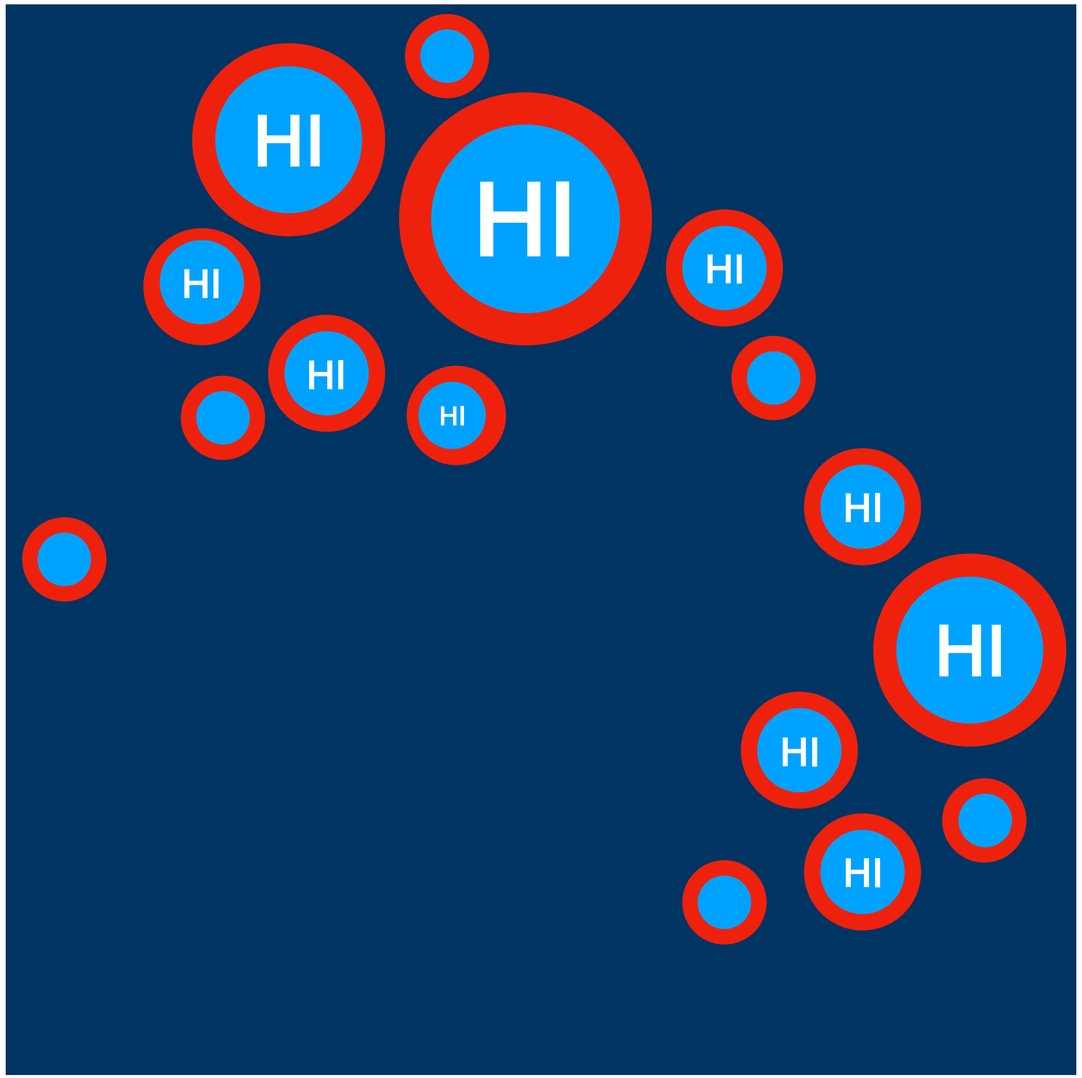

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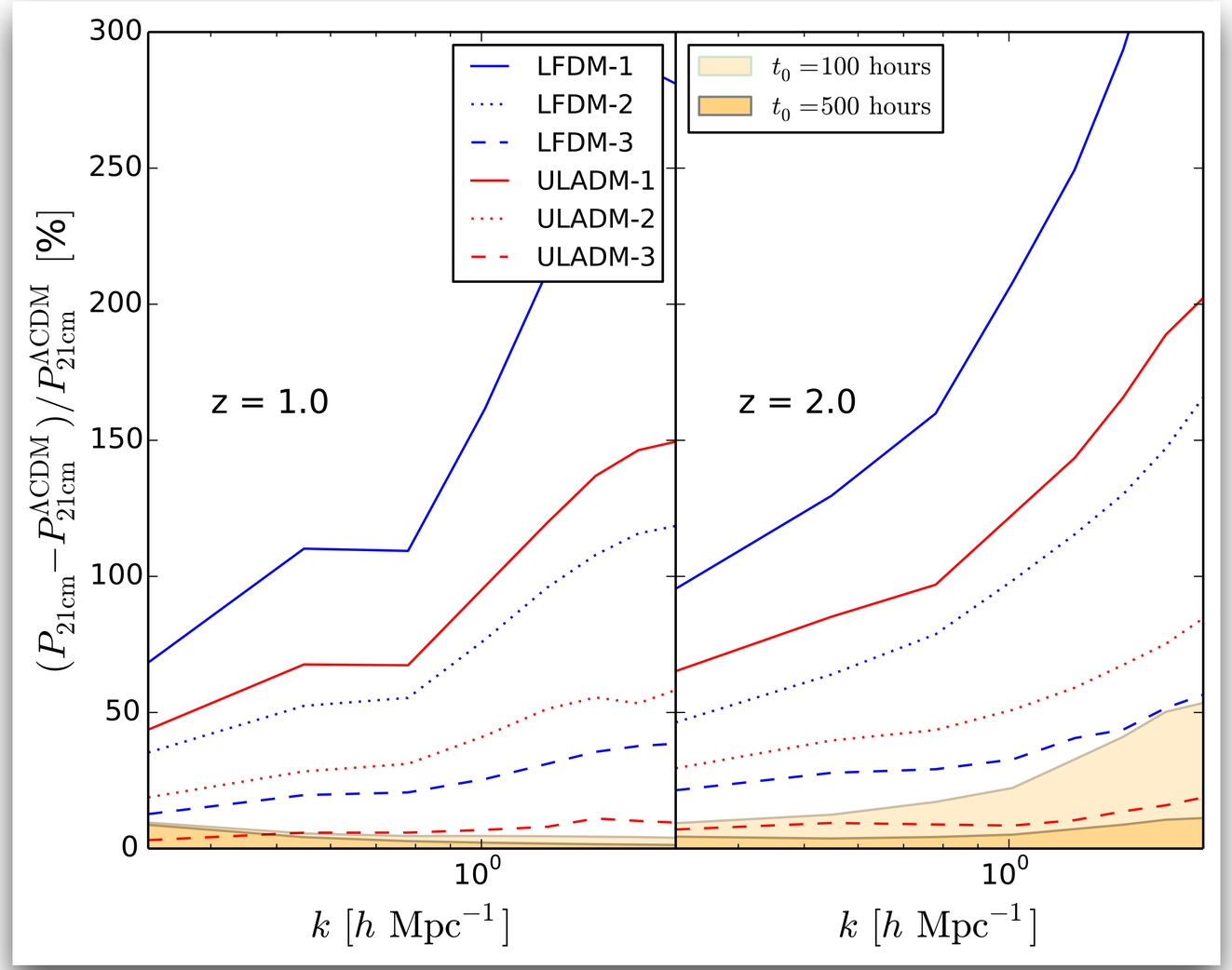


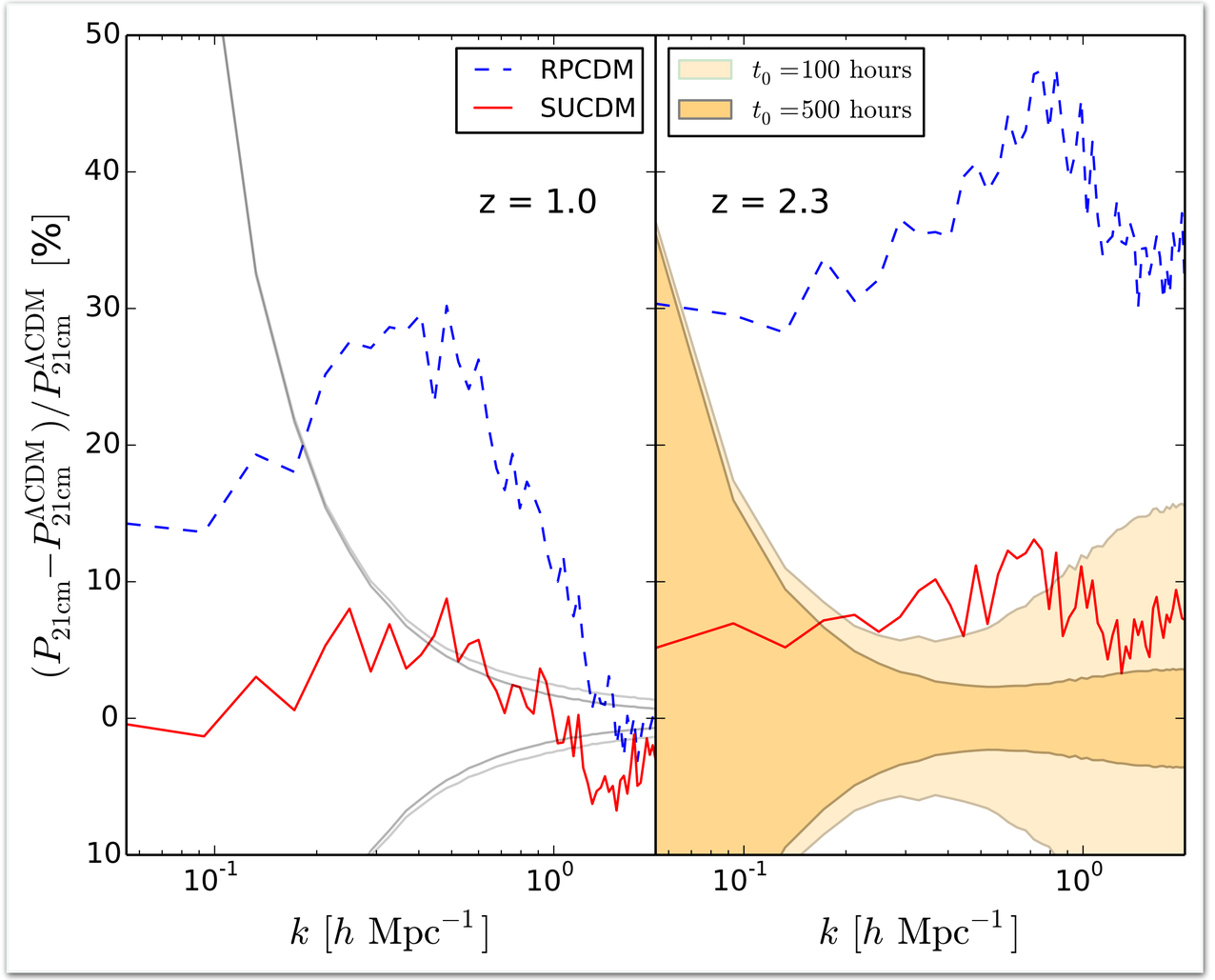
- ultra-light axions (*fuzzy* or *scalar* DM)
- late-forming DM

IPC, Corasaniti & Viel 2017

What about dark energy?

Model	Ω_m	σ_8	w_0	w_a
ΛCDM-W5	0.26	0.80	−1	0
RPCDM-W5	0.23	0.66	−0.87	0.08
SUCDM-W5	0.25	0.73	-0.94	0.19

statistically indistinguishable from ΛCDM (using CMB and SN1A data)



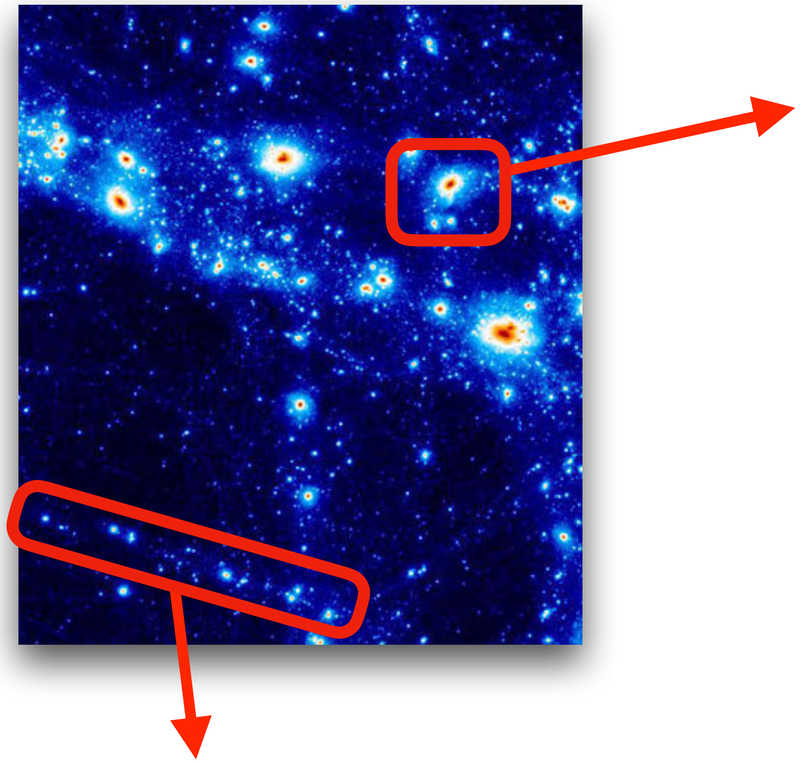
IPC, Corasaniti & Viel 2017

The 21cm IM signal at z<6:

- modelling
- dependence on cosmology
- synergies with other probes:

  CMB-lensing, photo-z galaxies,…

Cross correlating with the Lyman-α forest flux



21cm radiation in IM

- same epoch (high z probes!)
- different systematics
- different foregrounds
- future promising observations

(Ly-α flux already well measured at z >2)

Lyman-α forest flux

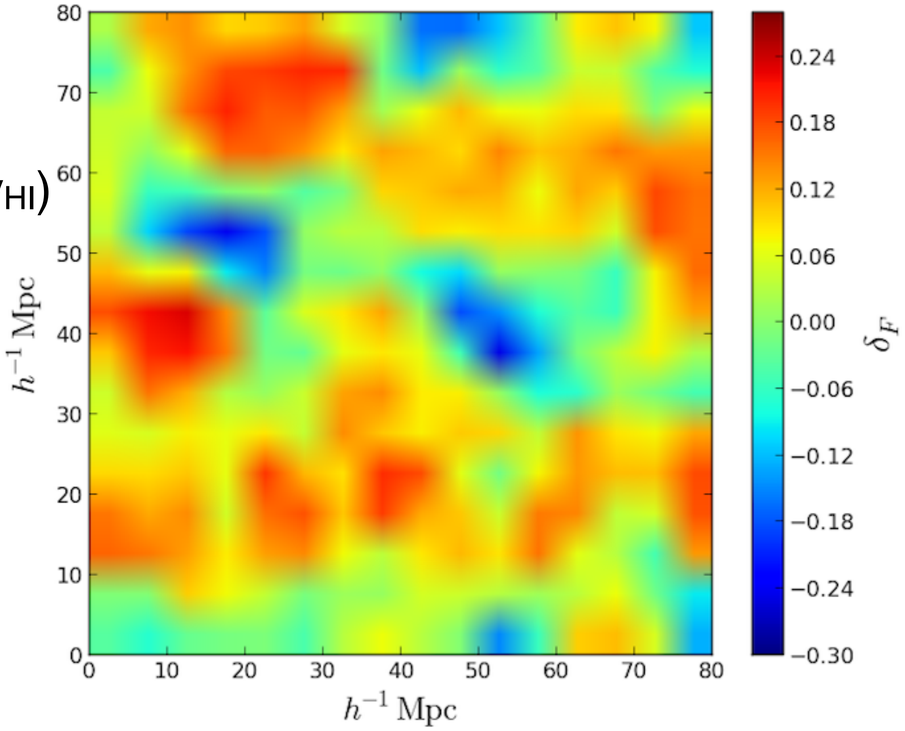
Cross correlating with the Lyman-α forest flux

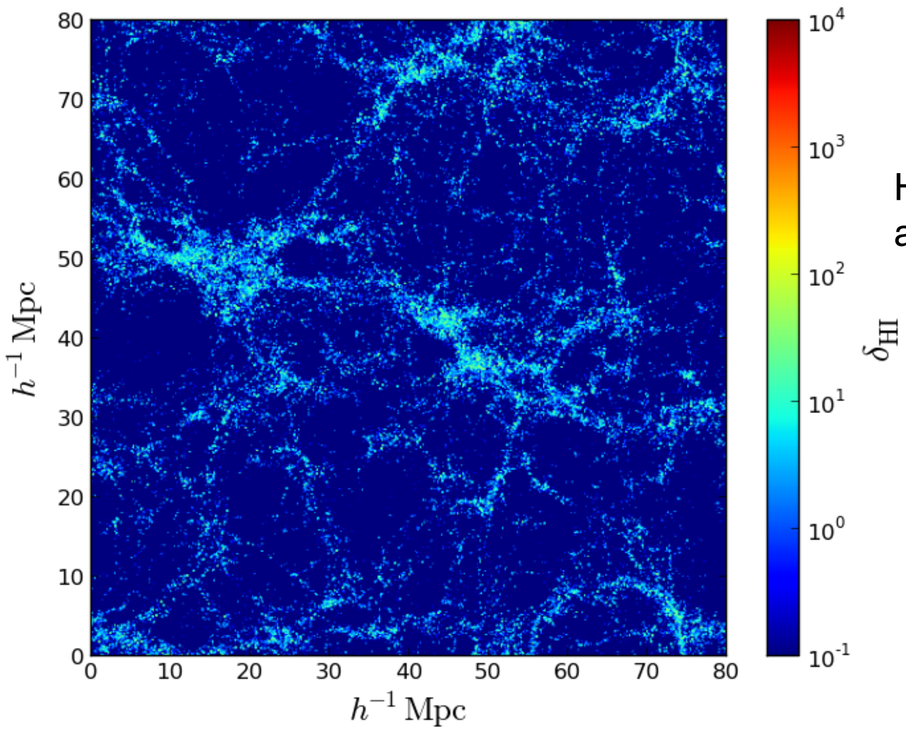
Carucci, Villaescusa-Navarro & Viel 2017

$F = e^{-\tau}$

$\tau = \tau(\rho_g, f_{HI}, T_{HI}, v_{HI})$

SPH interpolation





Halo based HI assignment

Simulations from the Sherwood suite (Bolton+ 2017): State-of-the-art sims for the low density Universe: converging properties for intergalactic medium

Cross correlating with the Lyman-α forest flux

Carucci, Villaescusa-Navarro & Viel 2017

$F = e^{-\tau}$

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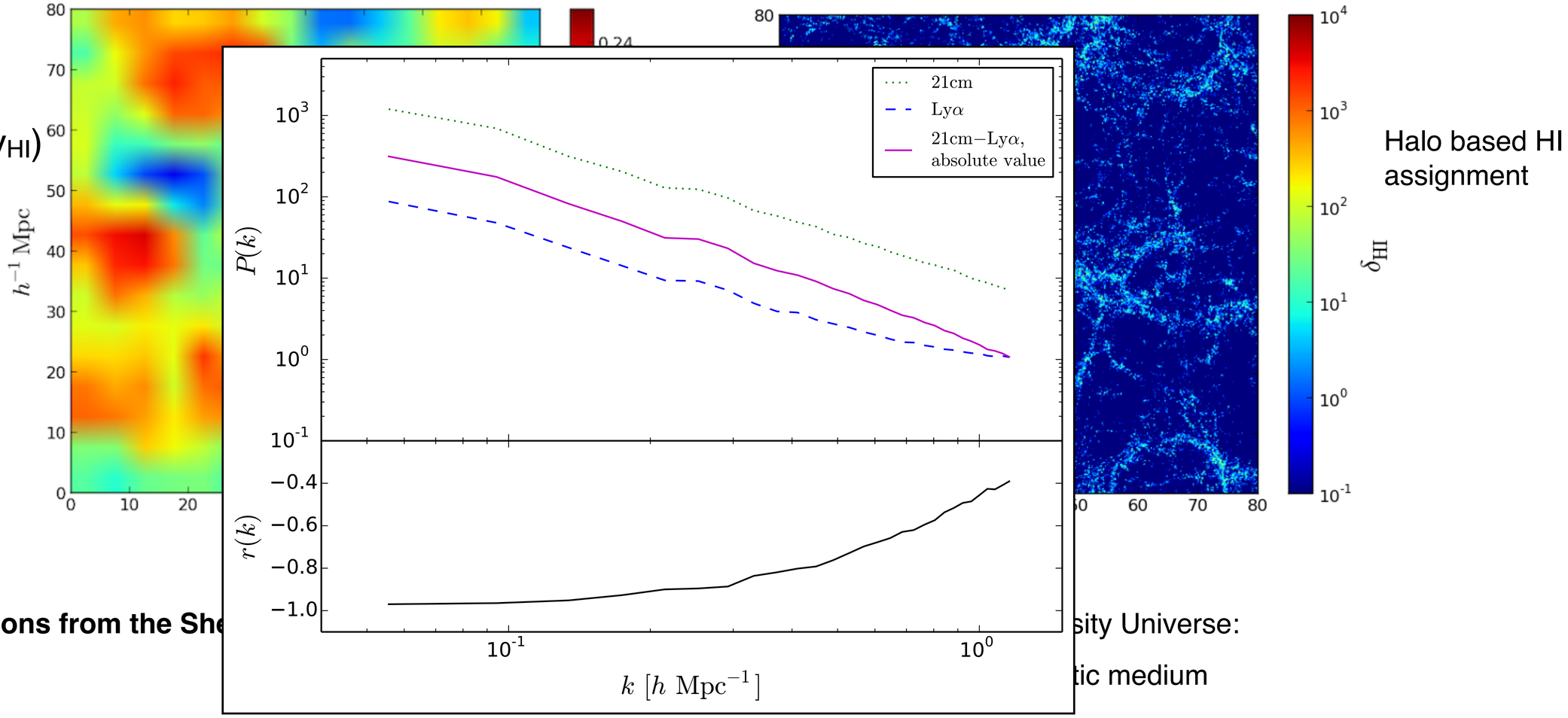

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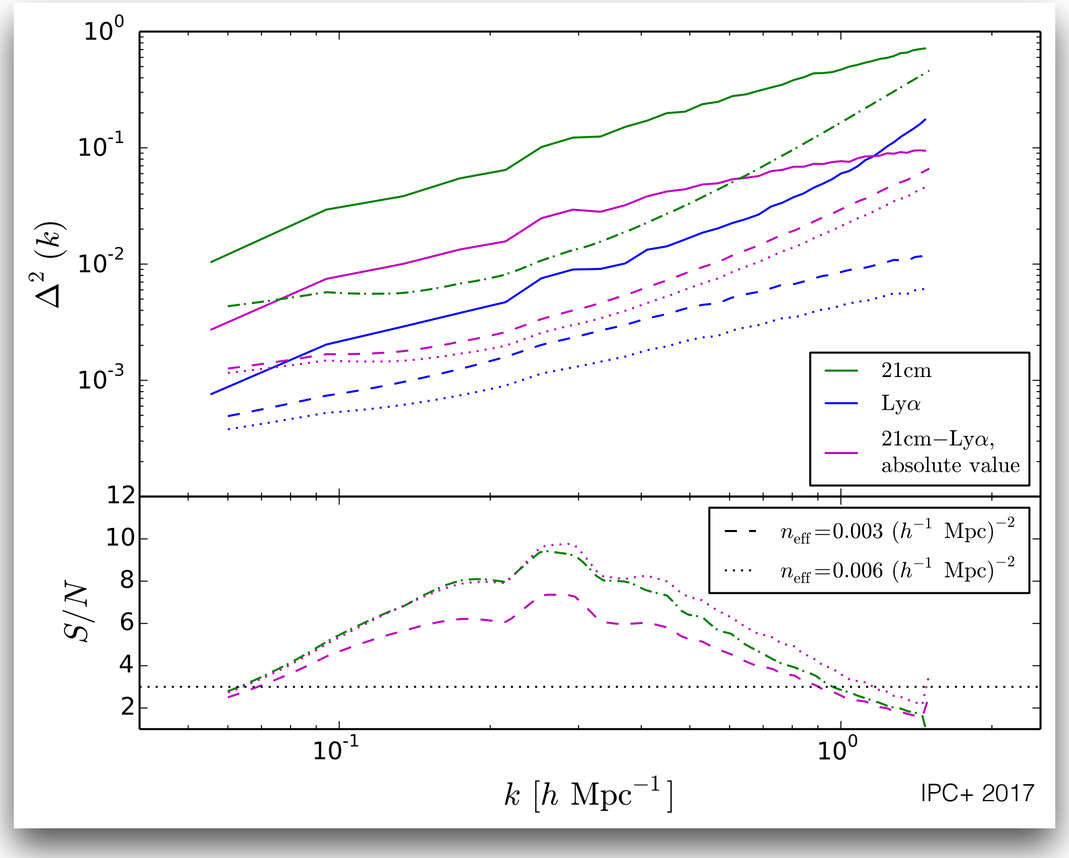
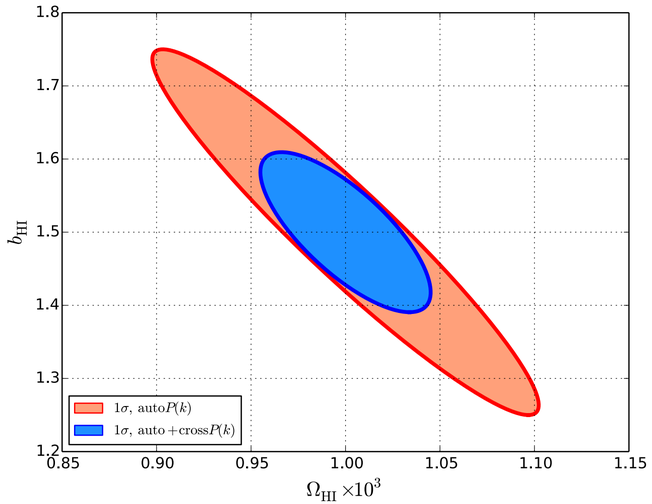
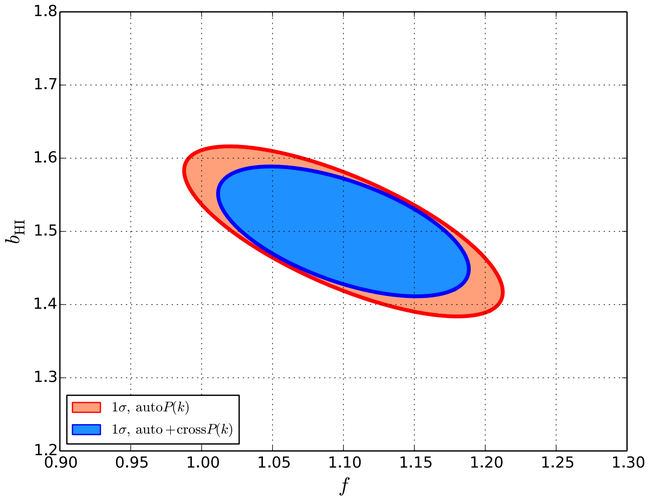
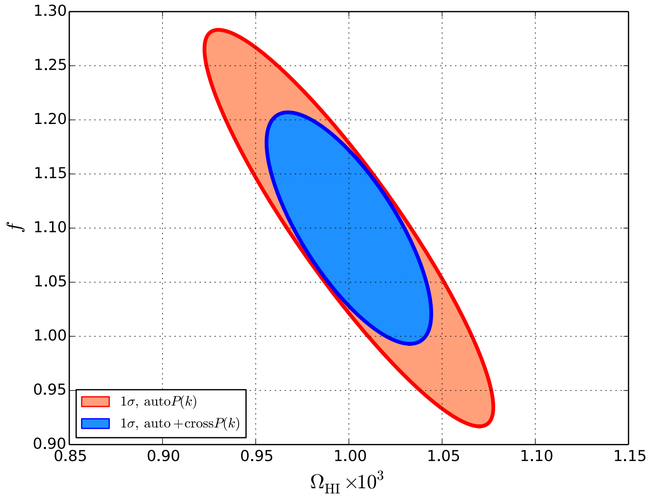
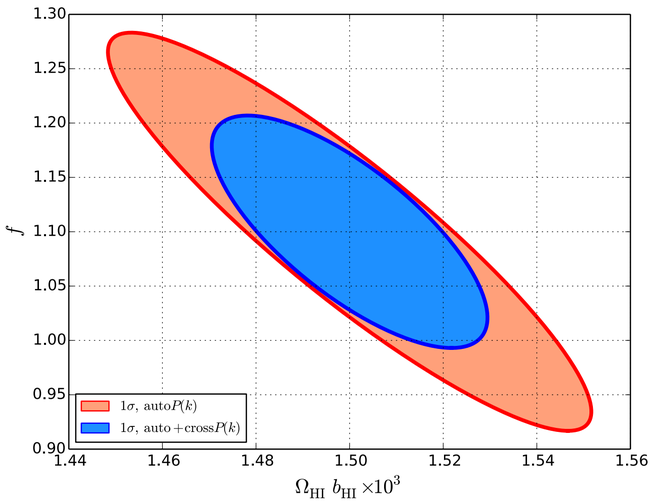




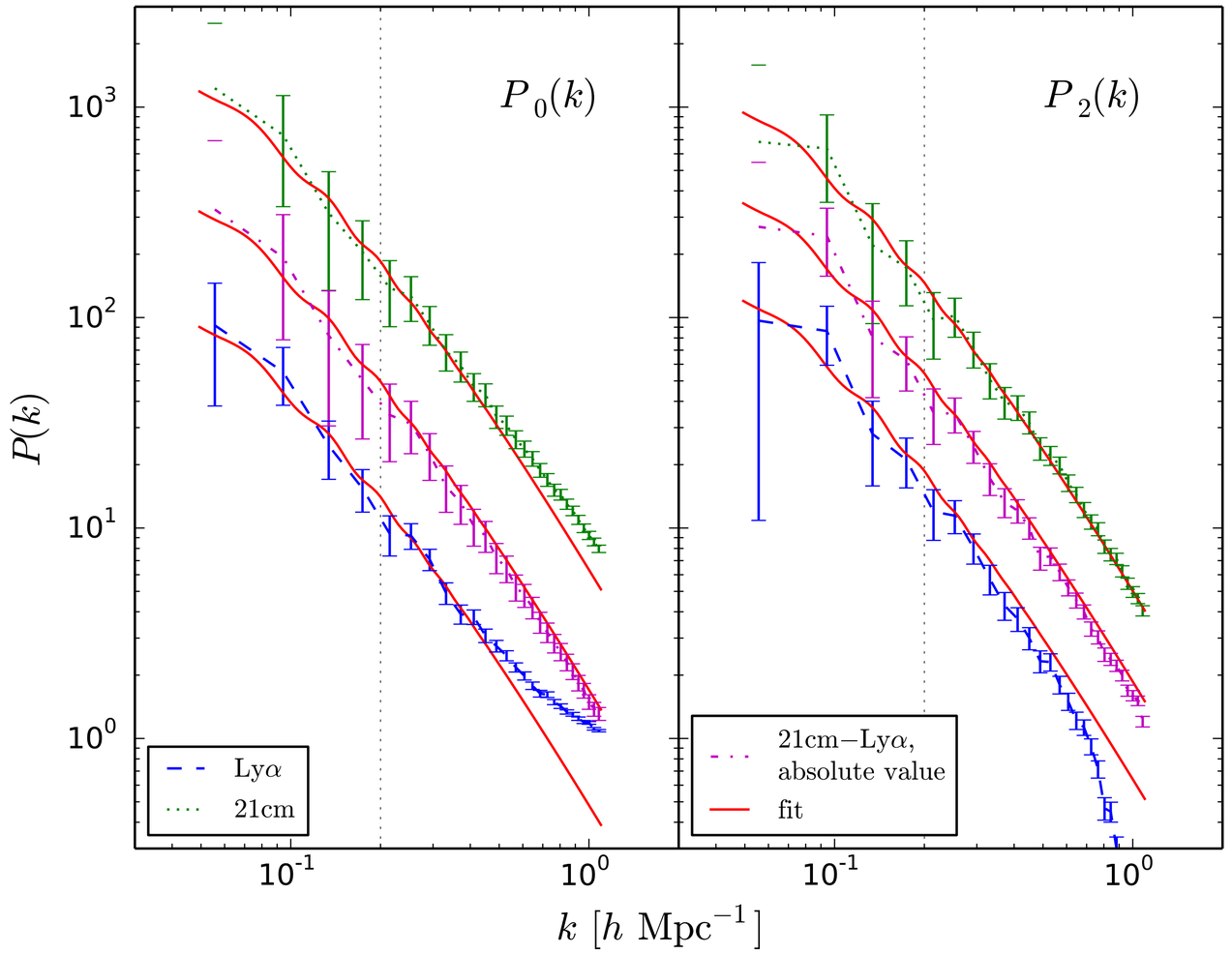






$$P_{21\rm cm}(k,\mu) = A^2\Omega_{\rm HI}^2 b_{\rm HI}^2\left(1+\beta_{\rm HI}\mu^2\right)^2 P_{\rm m}(k) \qquad \beta_{\rm HI}\times b_{\rm HI} = f$$

Cross correlating with the Lyman-α forest flux



IPC+ 2017

The 21cm IM signal at z<6:

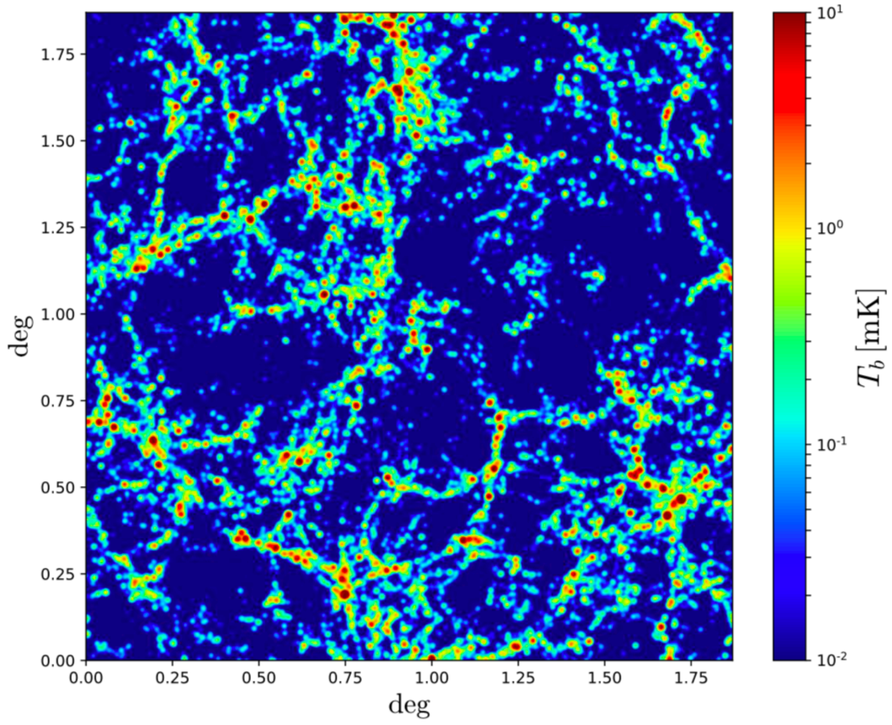
- will be a unique test for the **nature of dark matter** and generally for theories that modify the **growth of structures**

- High complementarity with the other LSS probes

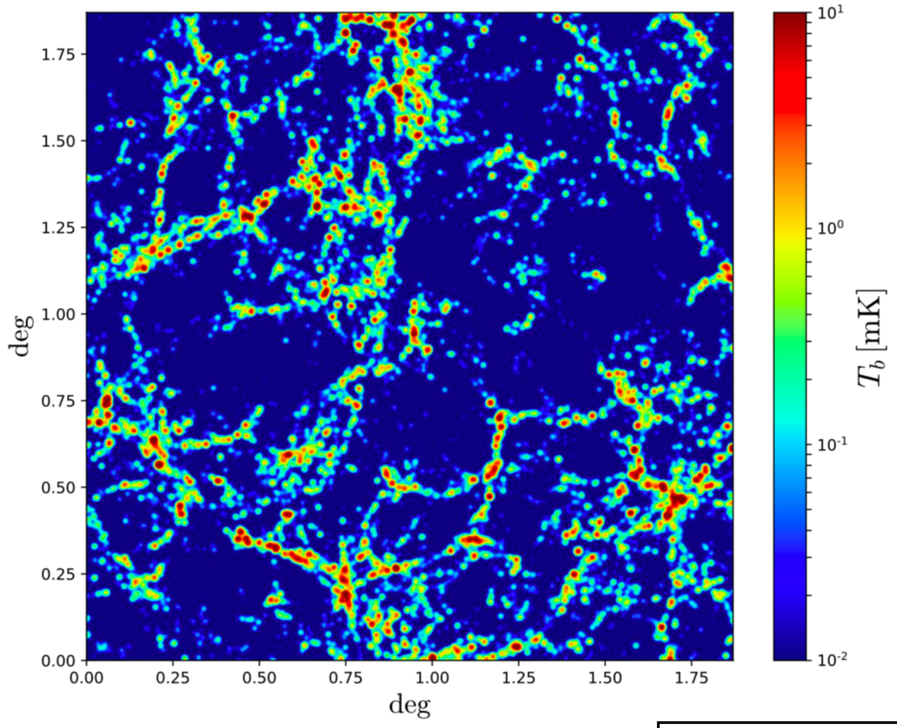
Thanks!

Distribution of HI
in the post-reionization universe

cheap Nbody



IllustrisTNG

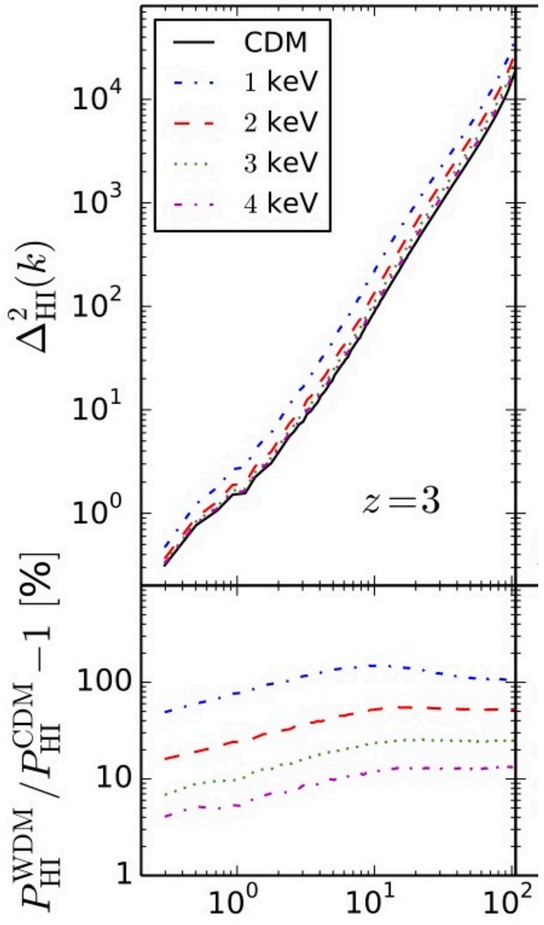


Villaescusa-Navarro + 2018

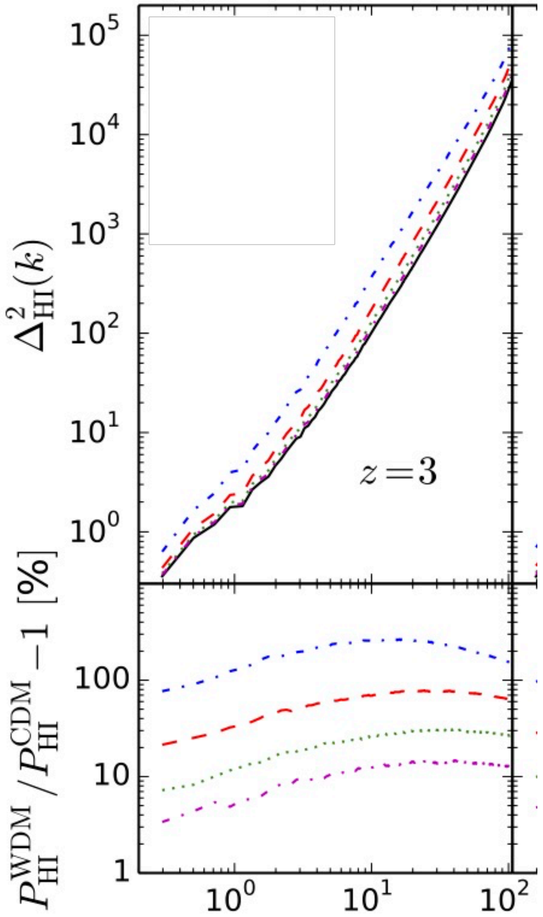
Dark matter models hydro simulations

HI power spectrum

Halo method



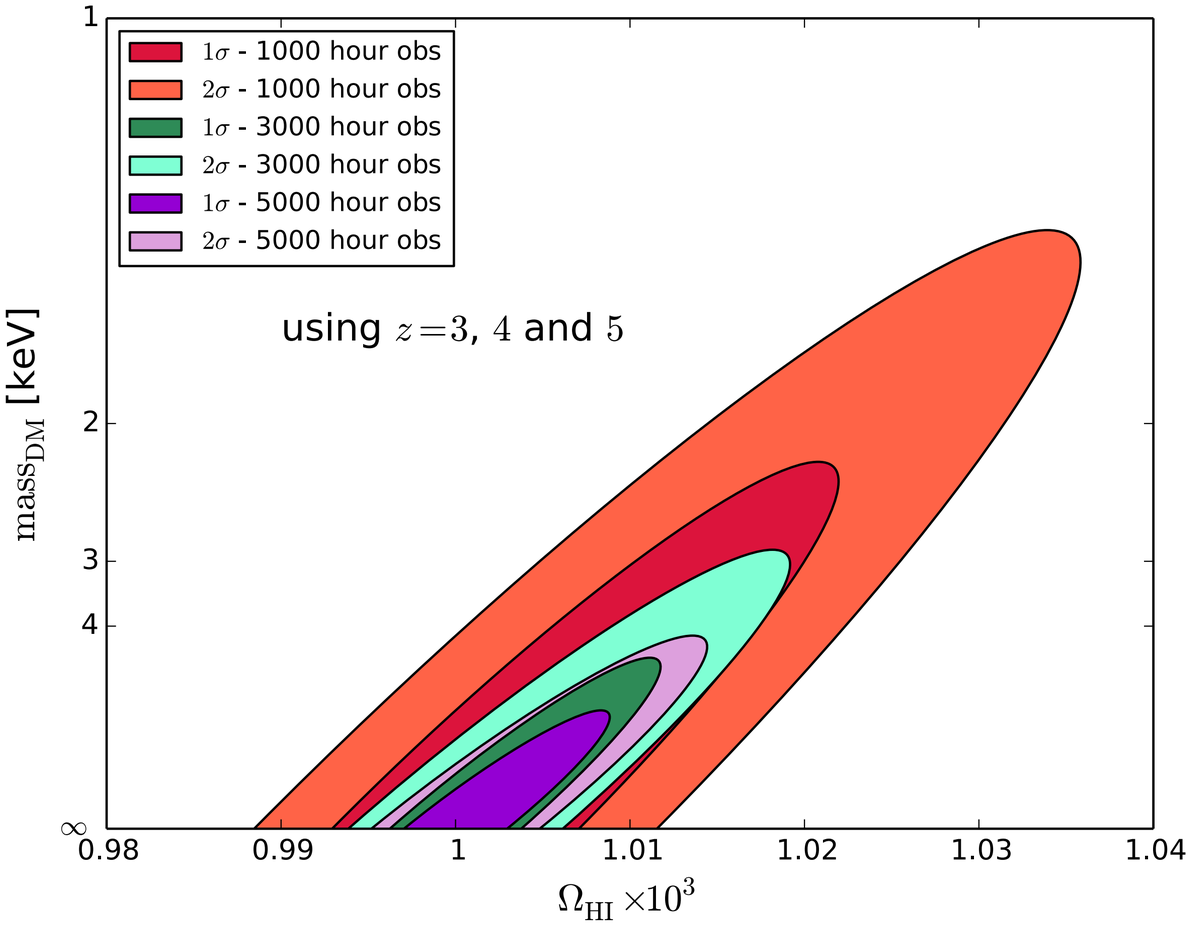
Hydro method

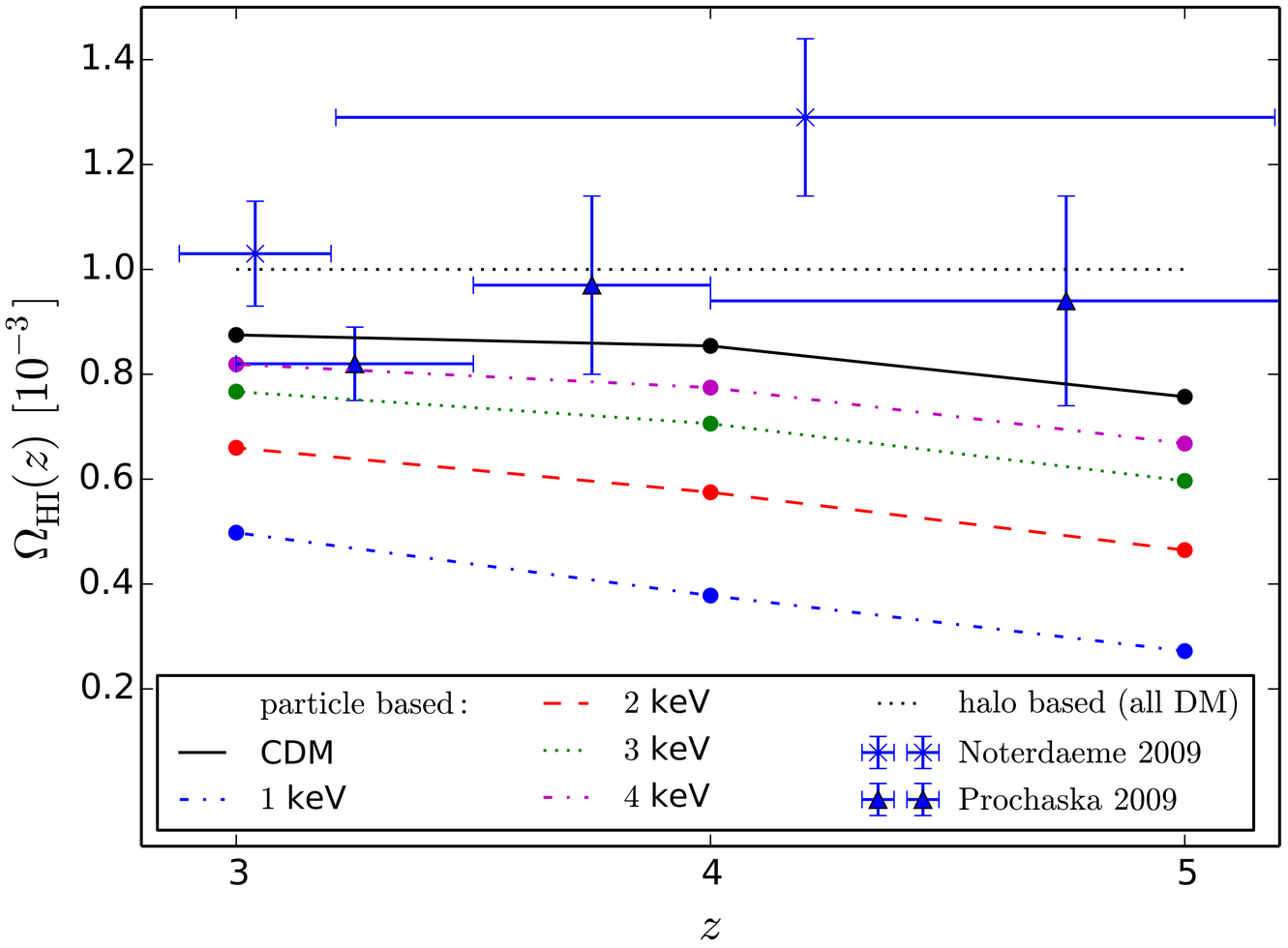


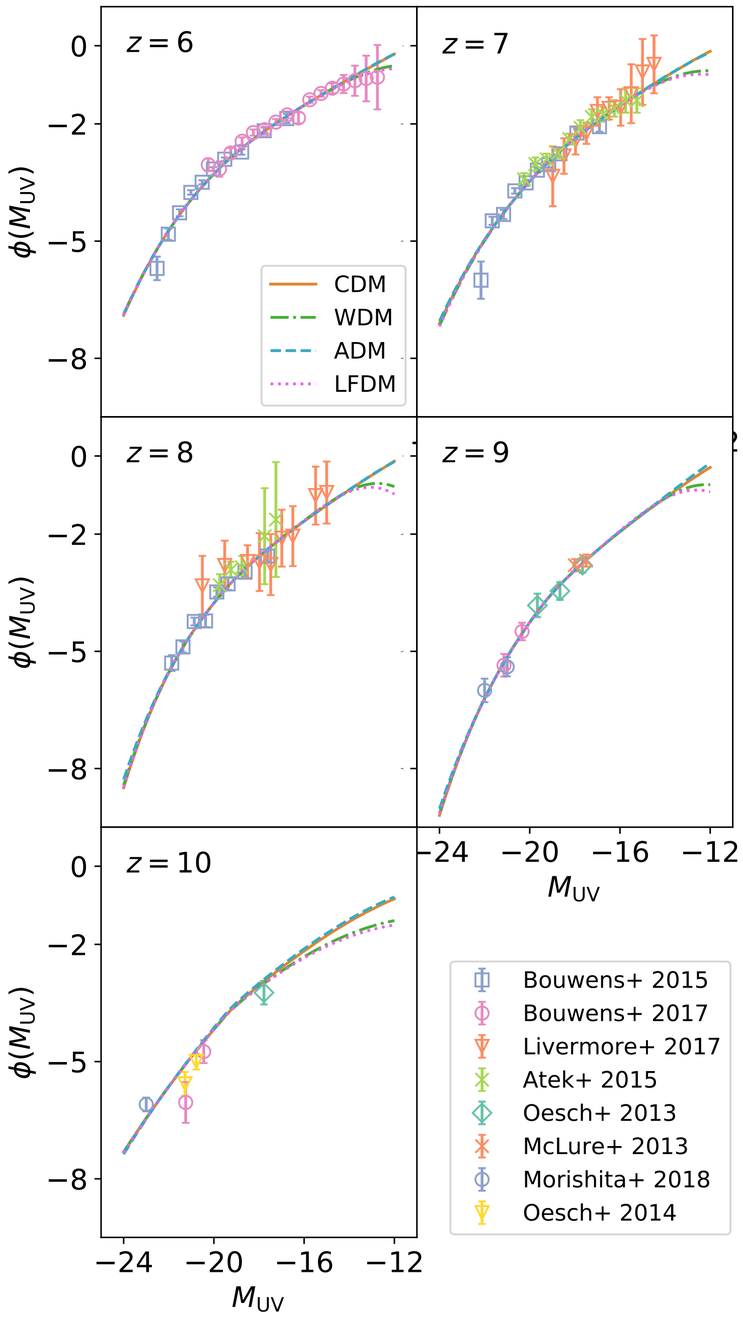
the Ω_{HI} - m_{WDM} degeneracy

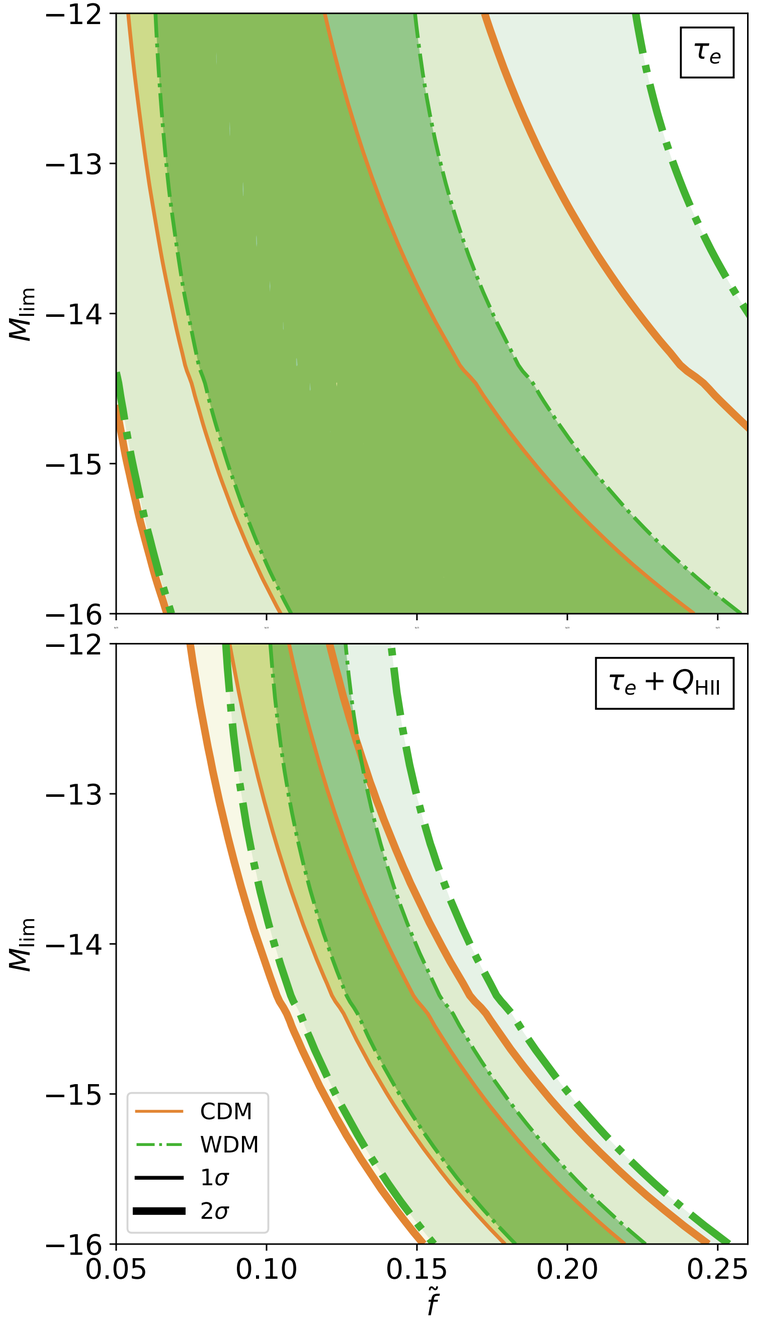
reference model

- $\Omega_{HI} = 10^{-3}$
- $m_{DM} = \infty$ (CDM)

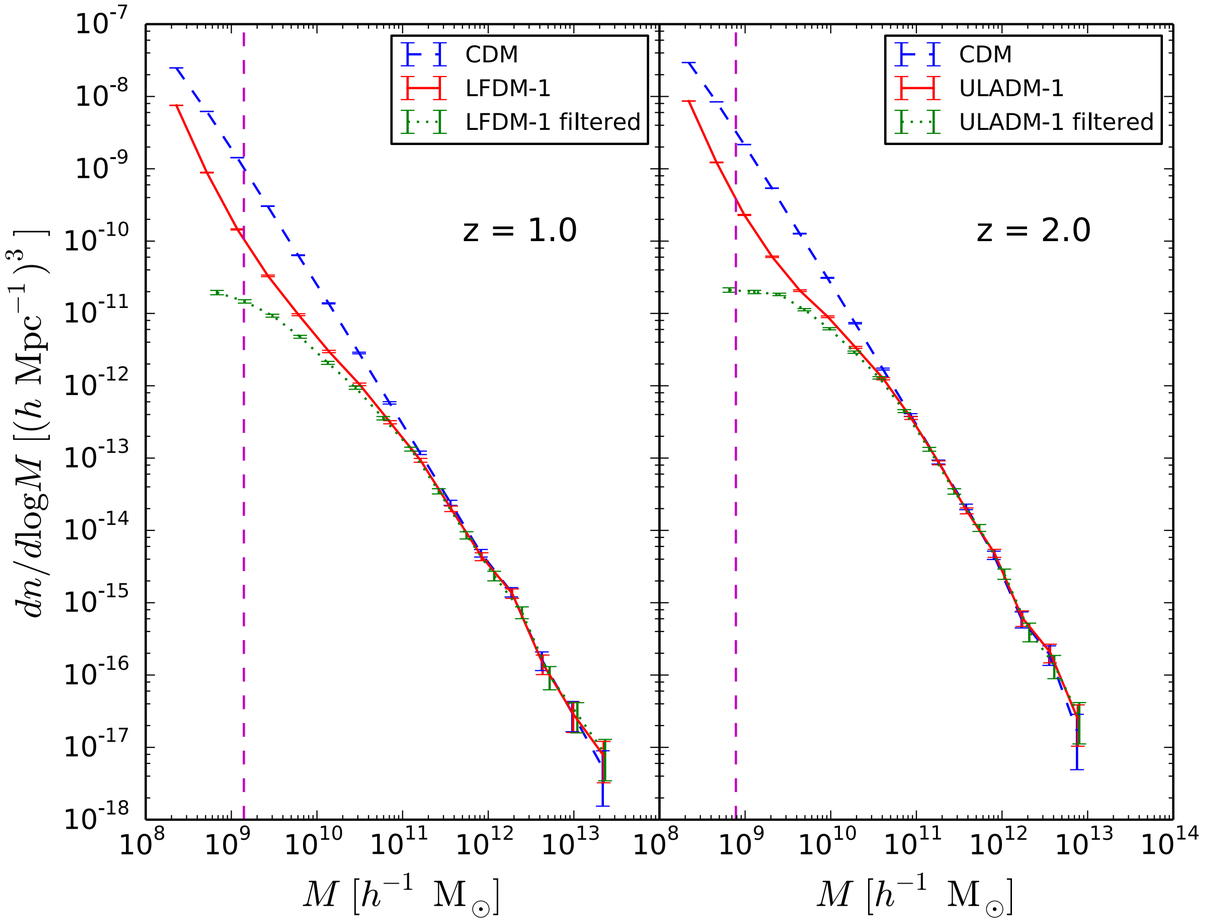



1.4
1.2
1.0
0.8
0.6
0.4
0.2
$\Omega_{\rm HI}(z)$ $[10^{-3}]$
3
4
5
z
particle based:
CDM
1 keV
2 keV
3 keV
4 keV
halo based (all DM)
Noterdaeme 2009
Prochaska 2009

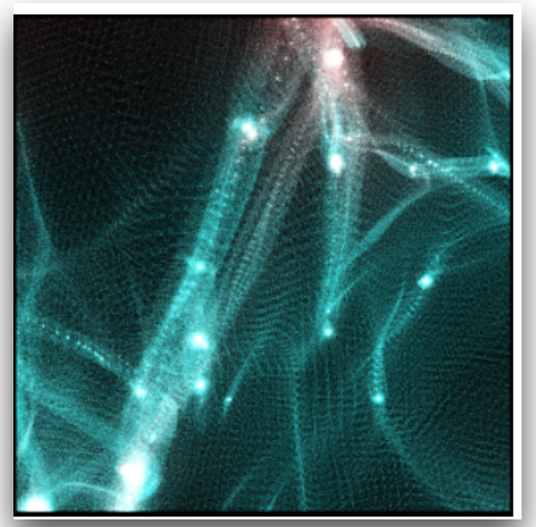

$z = 6$
$z = 7$
$z = 8$
$z = 9$
$z = 10$
$\phi(M_{\rm UV})$
$M_{\rm UV}$
CDM
WDM
ADM
LFDM
Bouwens+ 2015
Bouwens+ 2017
Livermore+ 2017
Atek+ 2015
Oesch+ 2013
McLure+ 2013
Morishita+ 2018
Oesch+ 2014


τ_e
$\tau_e + Q_{\rm HII}$
$M_{\rm lim}$
$\tilde{f}$
CDM
WDM
1σ
2σ

spurious fragmentation



IPC, Corasaniti & Viel 2017



Agarwal 2015

$$0 < \frac{2\,K}{|E|} < 1.5$$

redshift space anisotropy analysis

well-constrained
(Blomqvist+ 2015)

$$P_{21\mathrm{cm}}(k,\mu) = A^2\Omega_{\mathrm{HI}}^2 b_{\mathrm{HI}}^2 \left(1+\beta_{\mathrm{HI}}\mu^2\right)^2 P_{\mathrm{m}}(k),$$

$$P_{\mathrm{Ly}\alpha}(k,\mu) = b_F^2 \left(1+\beta_F\mu^2\right)^2 P_{\mathrm{m}}(k),$$

$$P_{\mathrm{X}}(k,\mu) = A\Omega_{\mathrm{HI}} b_{\mathrm{HI}} \left(1+\beta_{\mathrm{HI}}\mu^2\right) b_F \left(1+\beta_F\mu^2\right) P_{\mathrm{m}}(k)$$

$$b_{\mathrm{HI}}(z) = \frac{\int_0^\infty b(M,z)n(M,z)M_{\mathrm{HI}}(M,z)dM}{\int_0^\infty n(M,z)M_{\mathrm{HI}}(M,z)dM}$$

$$\beta_{\mathrm{HI}} \times b_{\mathrm{HI}} = f$$