Unveiling the astrophysics of reionization in the post-reionization era

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Tsinghua University, Department of Astronomy

Image credit: David Kirby

LBNL Seminar

January 25, 2022

Brief Bio

- Born in Costa Rica.

- Undergraduate degree (in Physics) from “Universidad de Costa Rica”.

- Master and Ph.D. (in Physics) from The Ohio State University, USA.
  Advisor: Christopher Michael Hirata.

- Shui Mu fellow at Department of Astronomy, Tsinghua University, China.
  Supervisor: Yi Mao

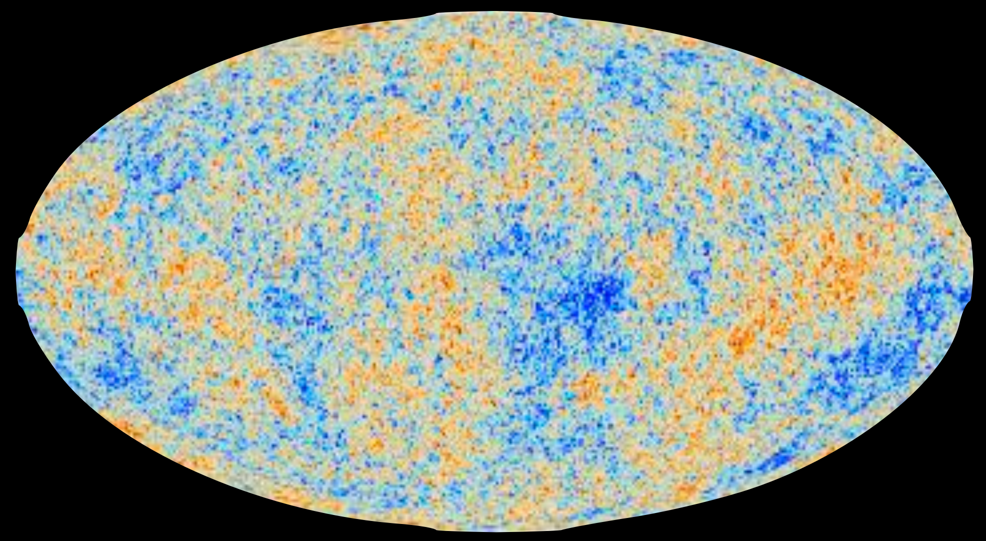
Some extra info:

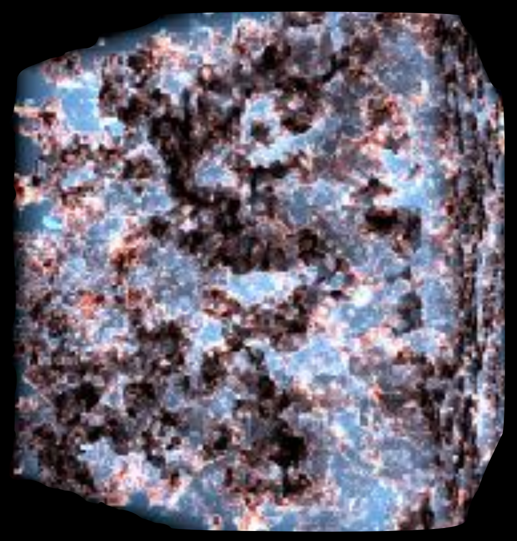
- **Awards/Grants:** NSFC Research Fund for International Young Scientist (200000 rmb), Tsinghua Shui Mu scholarship, Tsinghua Office of International Affairs grant for exceptional journal club.

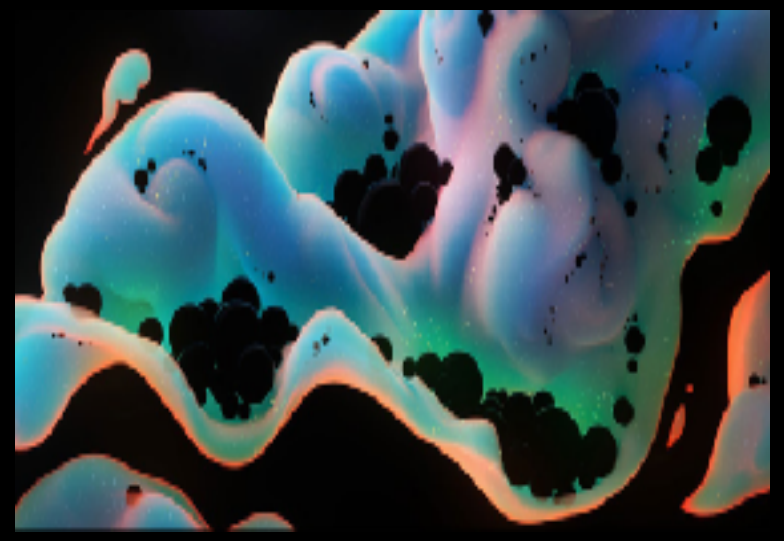
- **Teaching:** Co-supervised 5 students (4 graduate, 1 undergraduate) and supervised 1 undergraduate student.

My research interests

CMB | **21 cm** | **Lya forest** | **Dark matter**







z ~ 1060 | z ~ [35, 5] | z ~ [4, 2] | z ~ [EoR, 0]

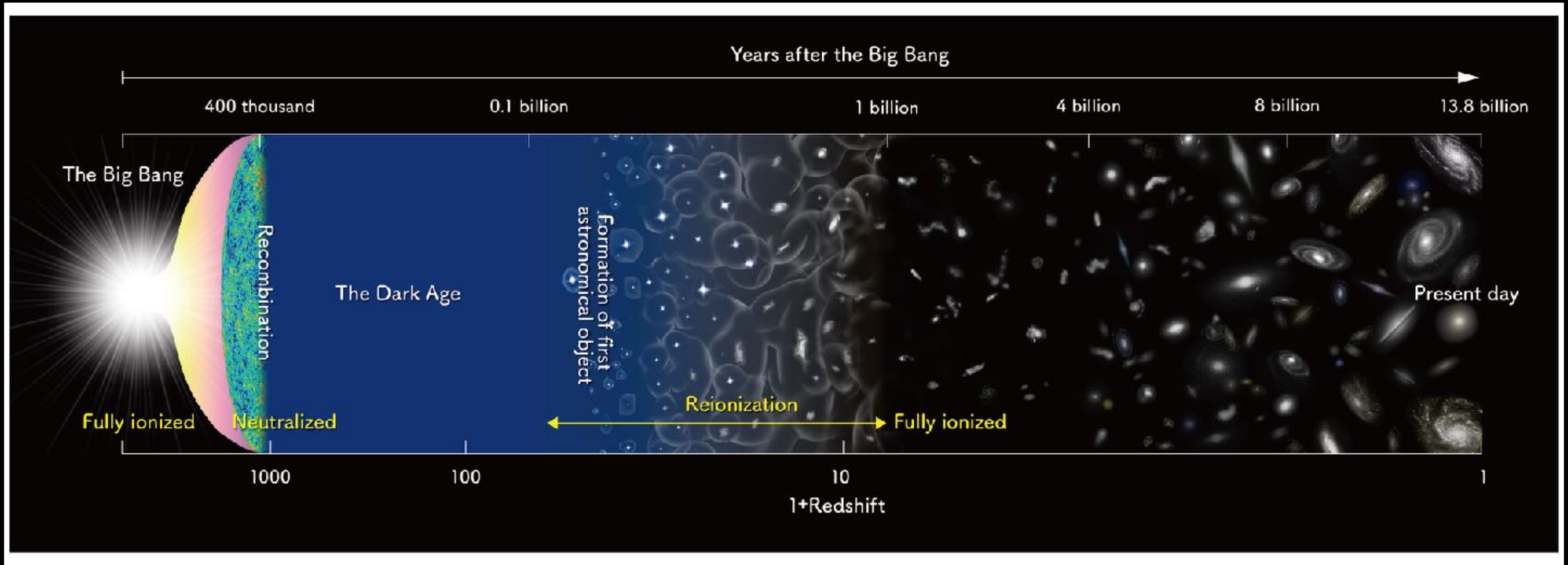
Some examples:

- **CMB:** circular polarization — PMC & C. M. Hirata (2018).
- **21 cm + Lya forest:** PMC, C. M. Hirata, P. Martini, and K. Honscheid (2019), PMC & Y. Mao (2020), and PMC & Y. Mao (2021).
- **Dark matter:** primordial black holes — PMC, X. Fang, G. Vasquez, M. Silva, and C. M. Hirata (2019)

Why is reionization interesting?

Neutral IGM → Ionized IGM

Image credit: NAOJ



Reionization occurs in a **patchy** way: **dense regions ionize first**

Glossary: IGM = intergalactic medium

Why is reionization interesting?

Neutral IGM → Ionized IGM

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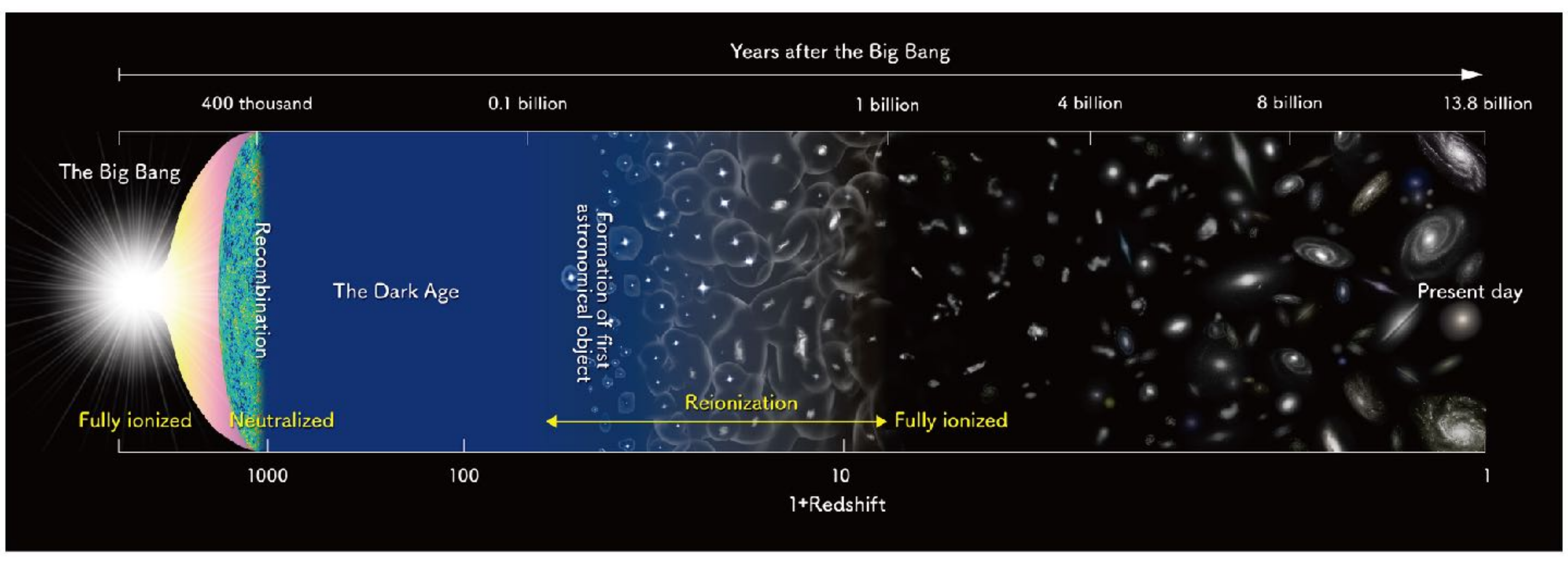
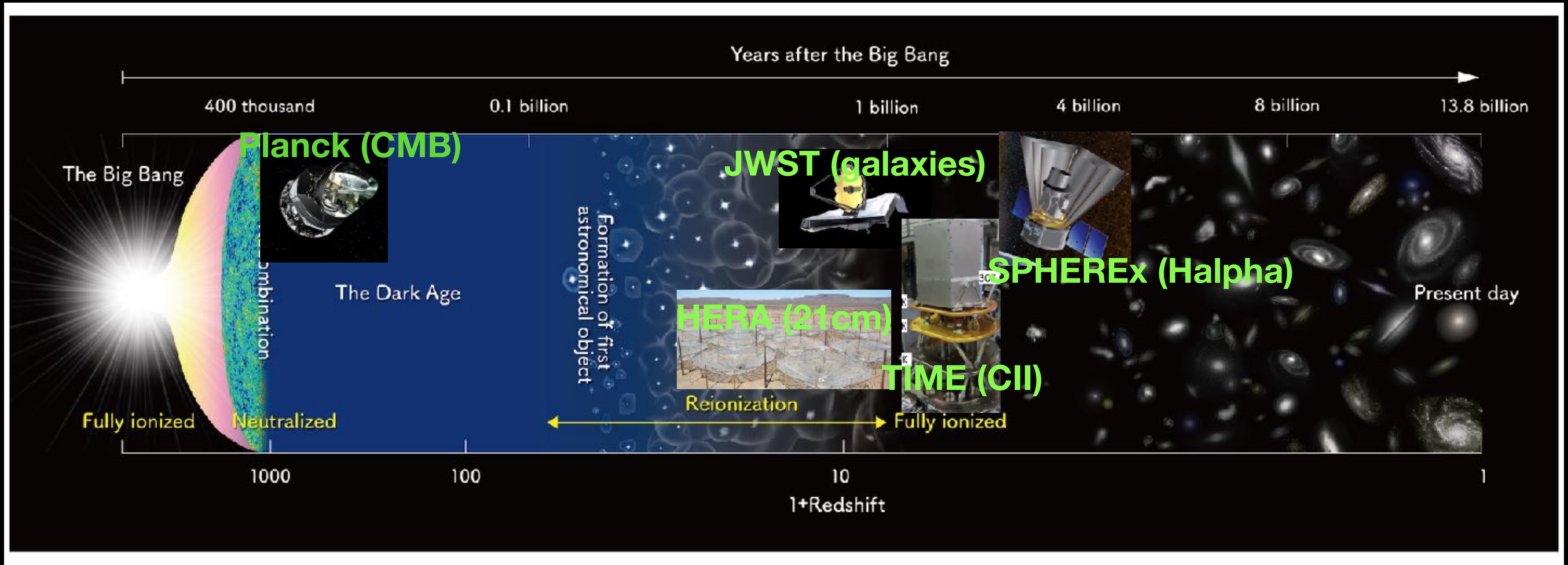


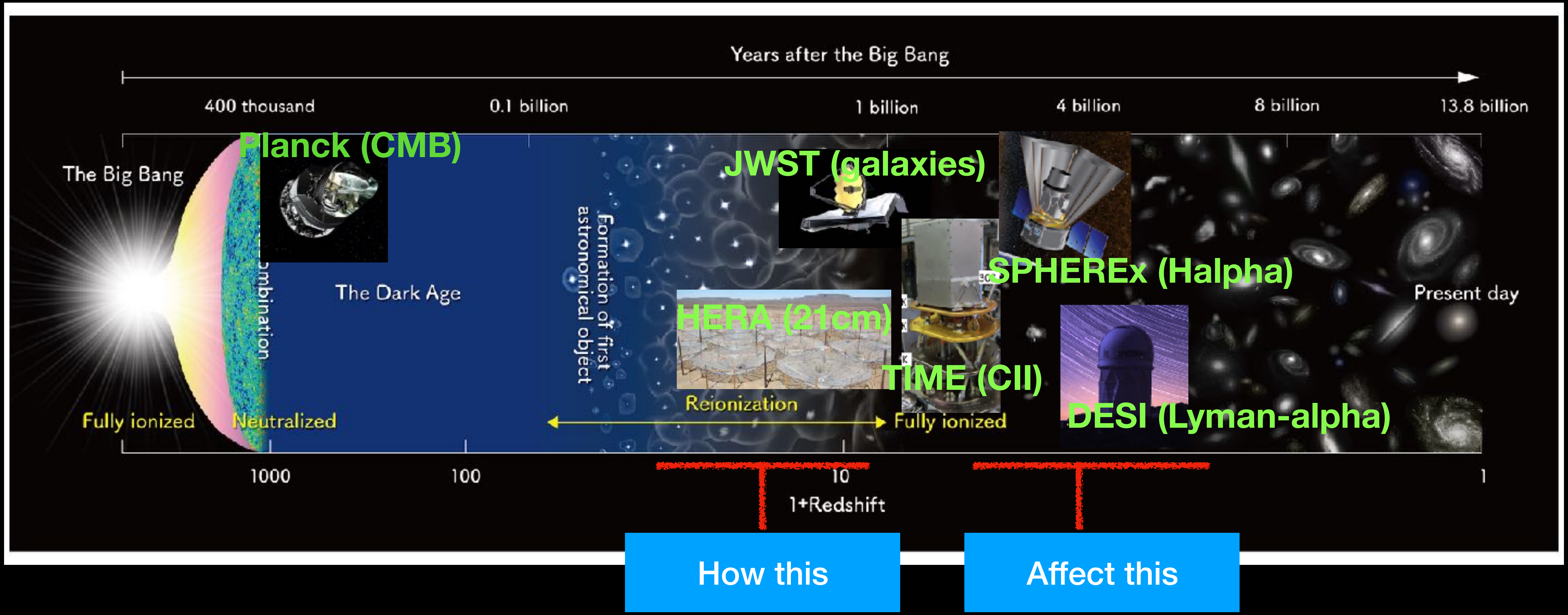
Decadal Survey: **Summary of Capabilities Needed for the Discovery Area**

Needed capabilities include next-generation 21 cm interferometers targeting both the reionization epoch and lower redshifts, along with planning toward very high redshift mapping. Progress will require both higher sensitivity and a better understanding of instrumental systematics and astrophysical couplings.

Cosmic Reionization and how to probe it



Cosmic Reionization like adolescence leaves a mark in the adult Universe



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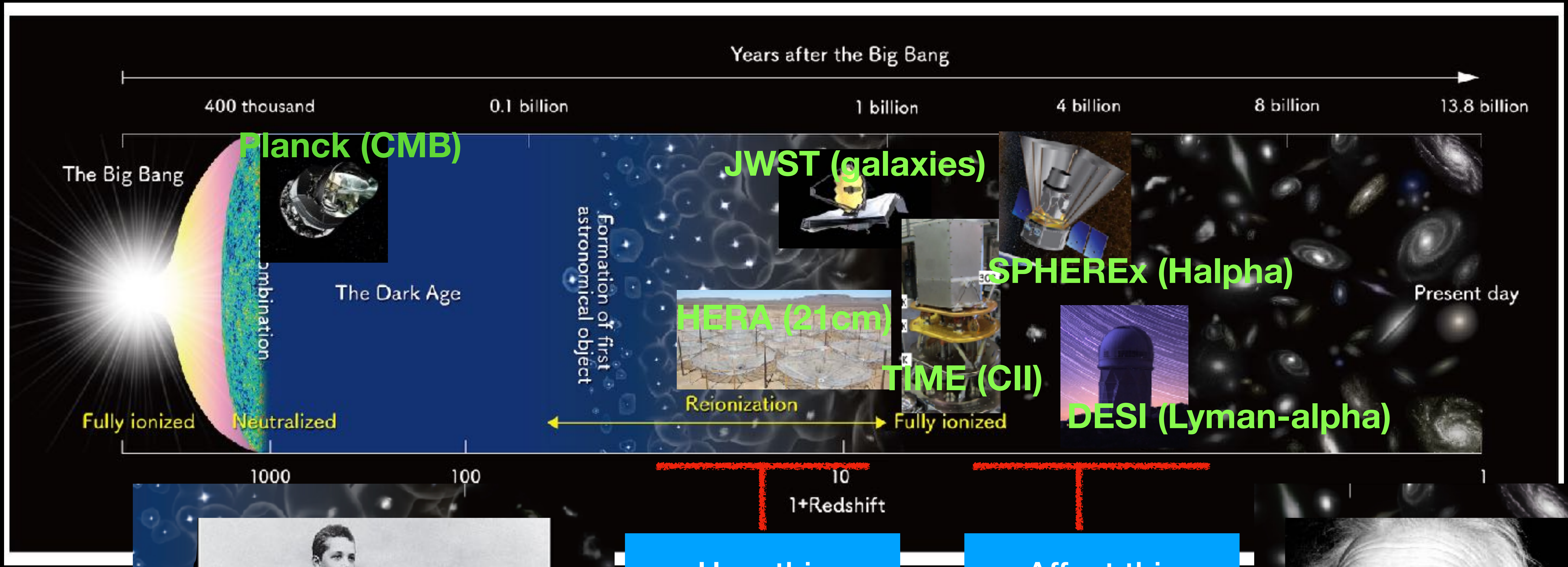
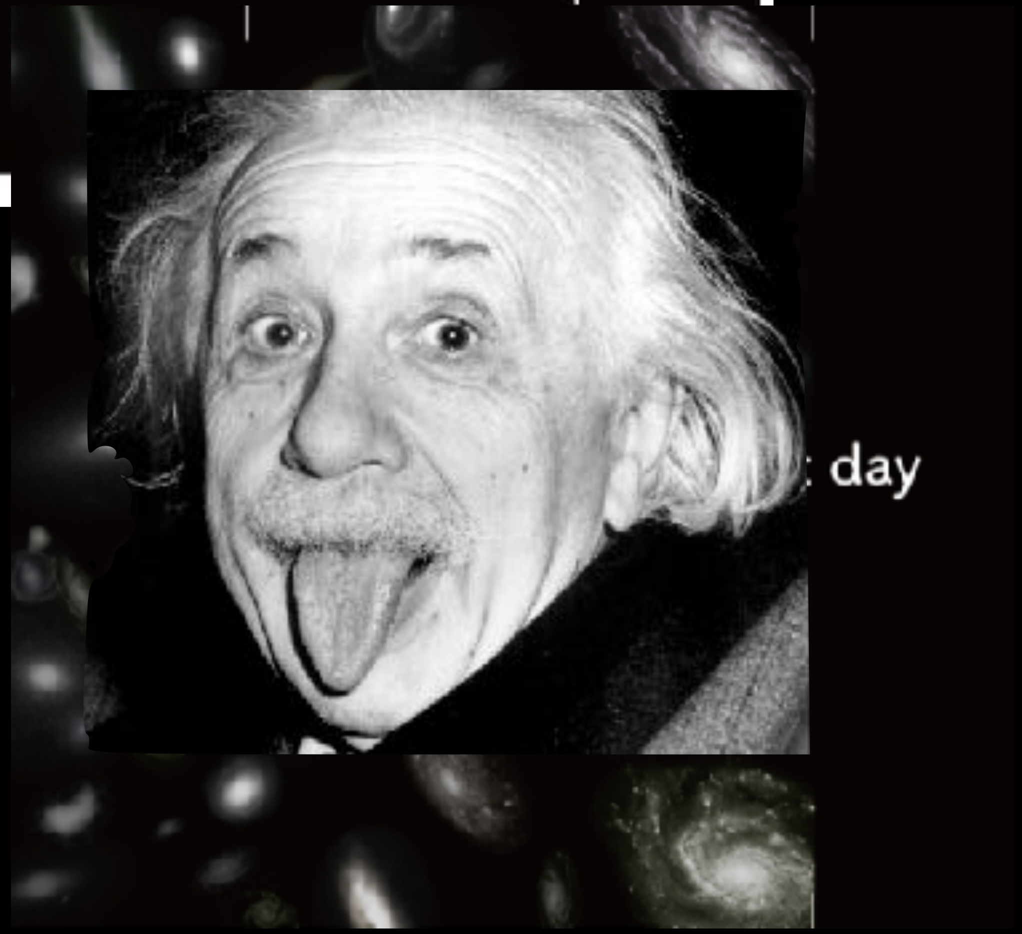


How this

Affect this



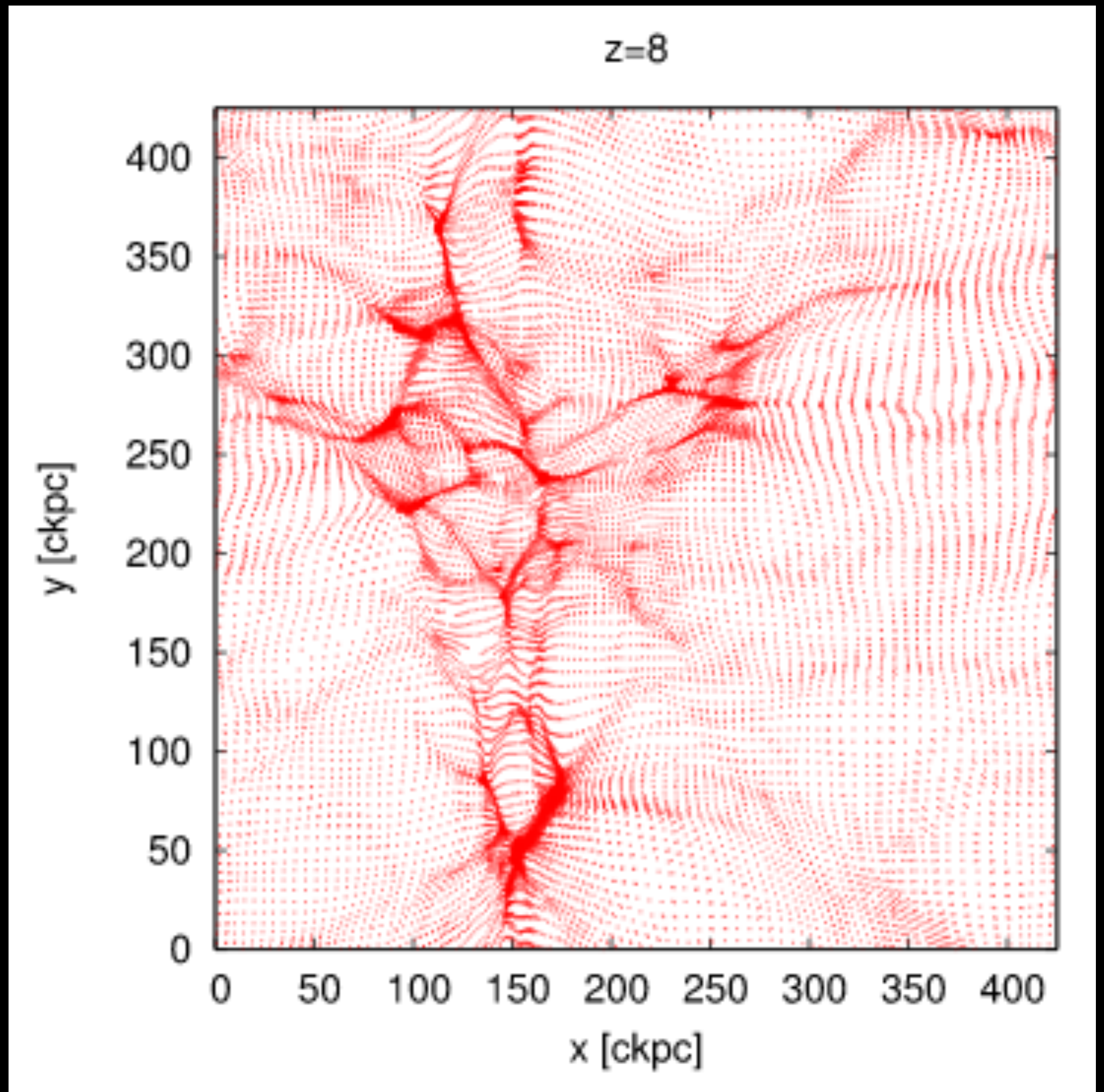
Impact of reionization in the post-reionization IGM
Why does it matter?

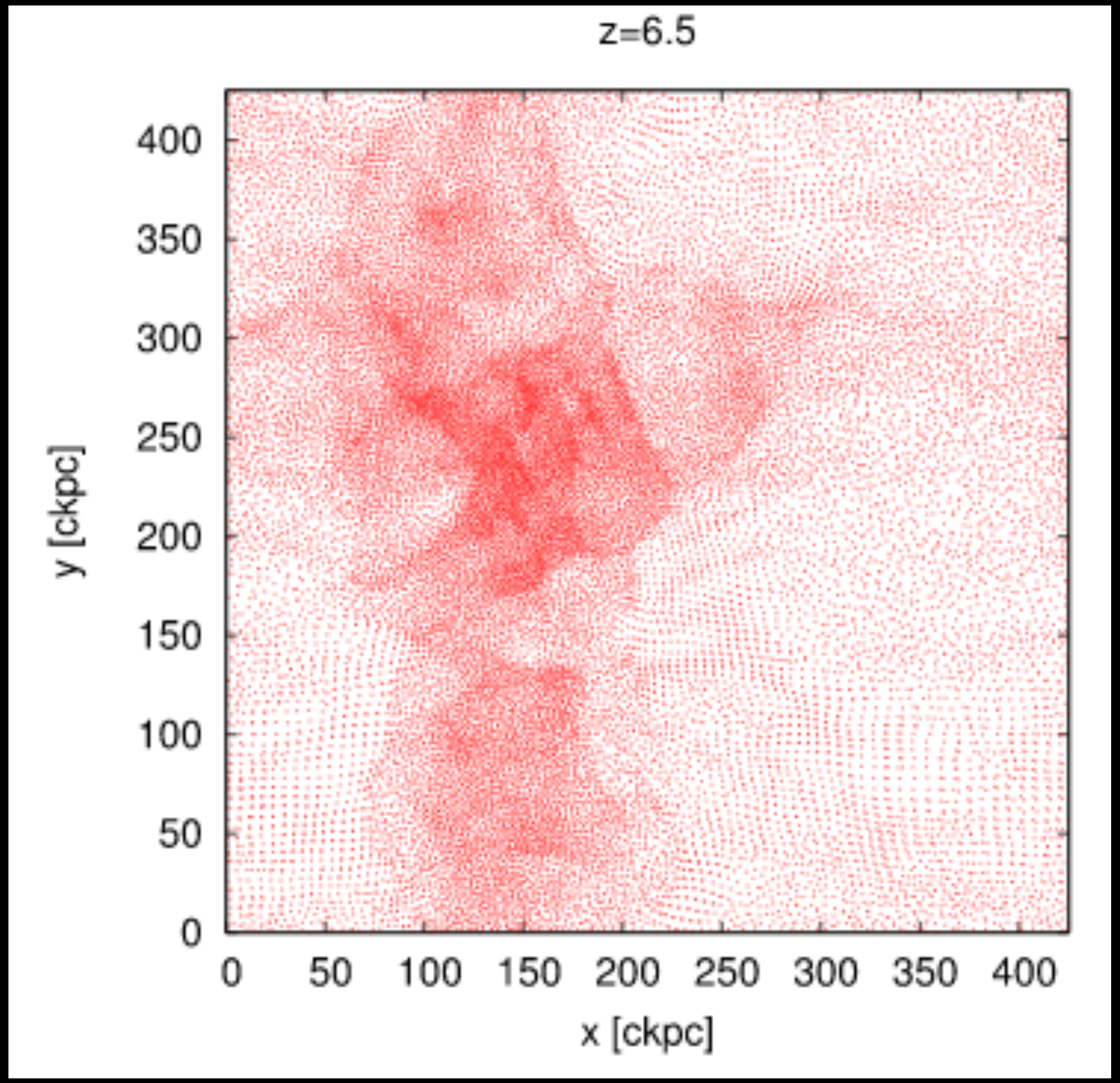
Table 7: *Best-fit value and 68% confidence levels of the cosmological parameters of the model fitted to the flux power spectrum measured with the SDSS or XQ-100 Lyα data [18] in combination with other data sets. Column (1): results of PY15 with BOSS alone corresponding to PYB13. Column (2): results with eBOSS (this work). Column (3): results for the combined fit of eBOSS (this work) and Planck 2018 [77]. Column (4): results for the combined fit of eBOSS (this work), XQ-100 and Planck 2018. For columns (1-2), we used a Gaussian constraint,* $H_0 = 67.3 \pm 1.0$.

Parameter	Lyα BOSS + $H_0^{\rm Gaussian}$ (PY15) (1)	Lyα eBOSS + $H_0^{\rm Gaussian}$ (This work) (2)	Lyα eBOSS + Planck (TT+lowE) (3)	Lyα eBOSS + XQ-100 + Planck (TT+lowE) (4)
T_0 (z=3) (10^3K)	8.9 ± 3.9	10.3 ± 1.7	11.3 ± 1.6	13.7 ± 1.5
γ	0.9 ± 0.2	0.8 ± 0.1	0.7 ± 0.1	0.9 ± 0.1
σ_8	0.855 ± 0.025	0.820 ± 0.021	0.817 ± 0.007	0.804 ± 0.008
n_s	0.937 ± 0.009	0.955 ± 0.005	0.954 ± 0.004	0.961 ± 0.004
Ω_m	0.288 ± 0.012	0.269 ± 0.009	0.330 ± 0.009	0.309 ± 0.011
H_0 (km s^{-1} Mpc^{-1})	67.1 ± 1.0	67.1 ± 1.0	66.2 ± 0.6	67.6 ± 0.8

Chabanier et al. (2019)

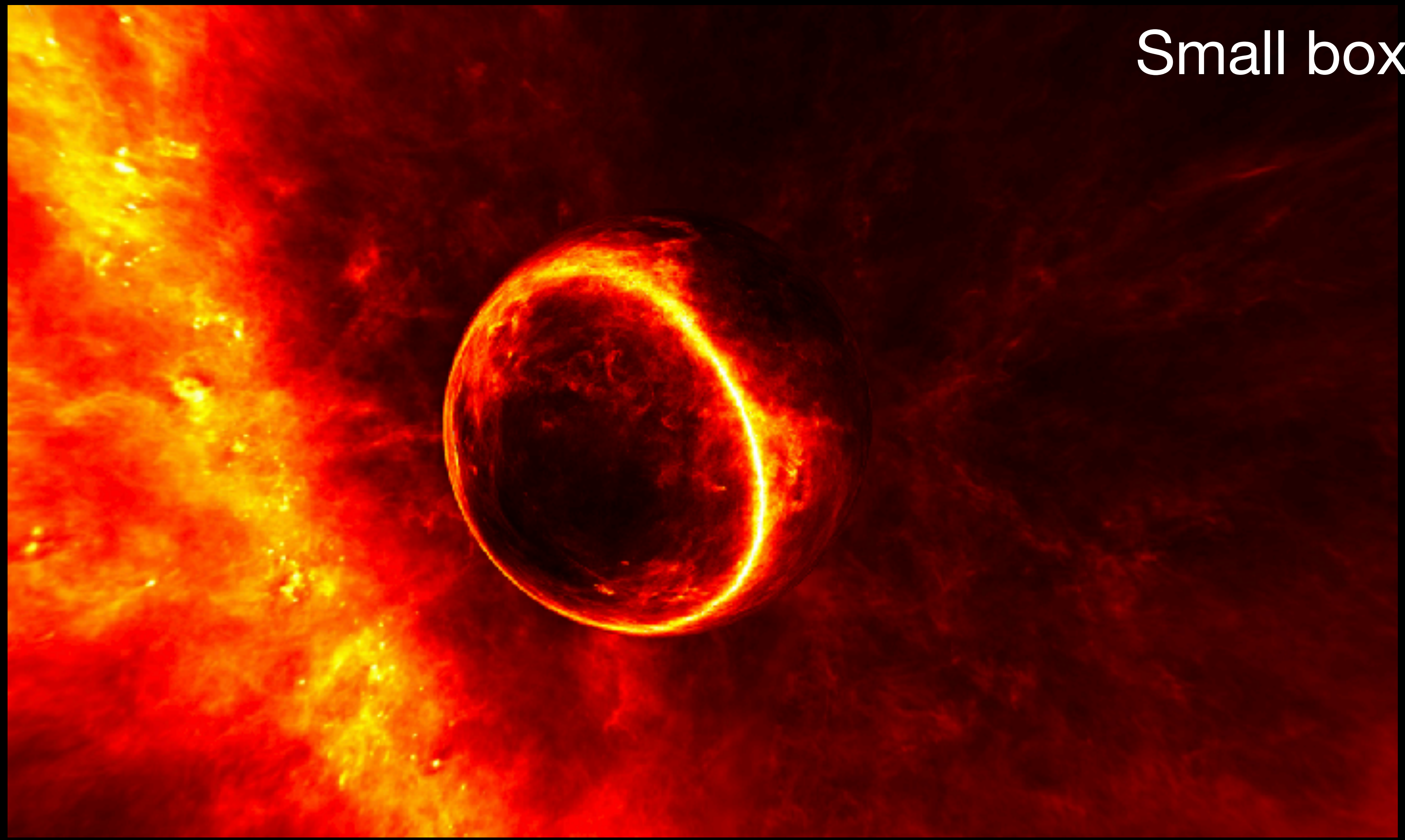
Impact of reionization in the post-reionization IGM
I) Role of small-scale structure

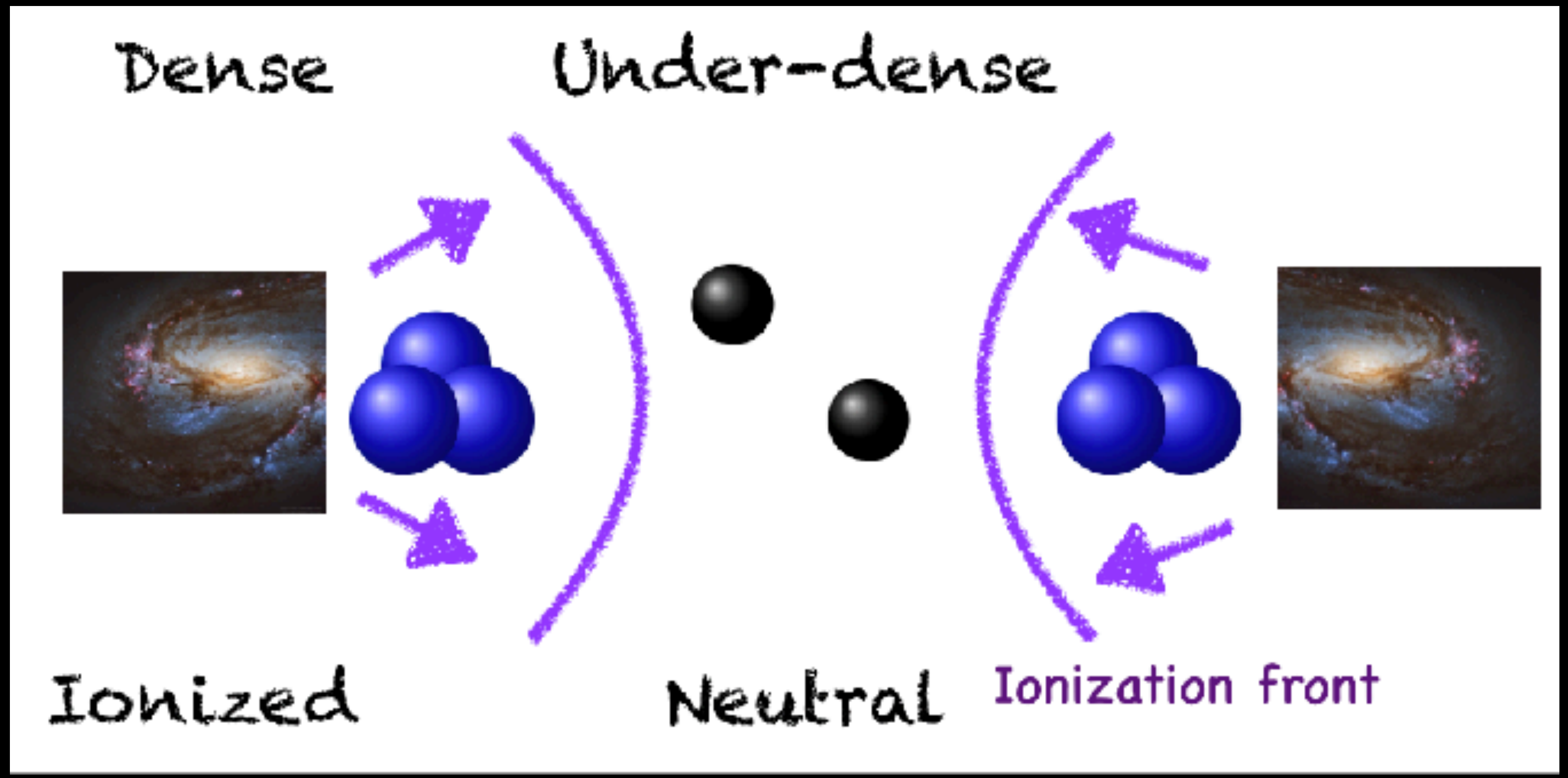




Red = Gas particles

Small box hence instantaneous reionization





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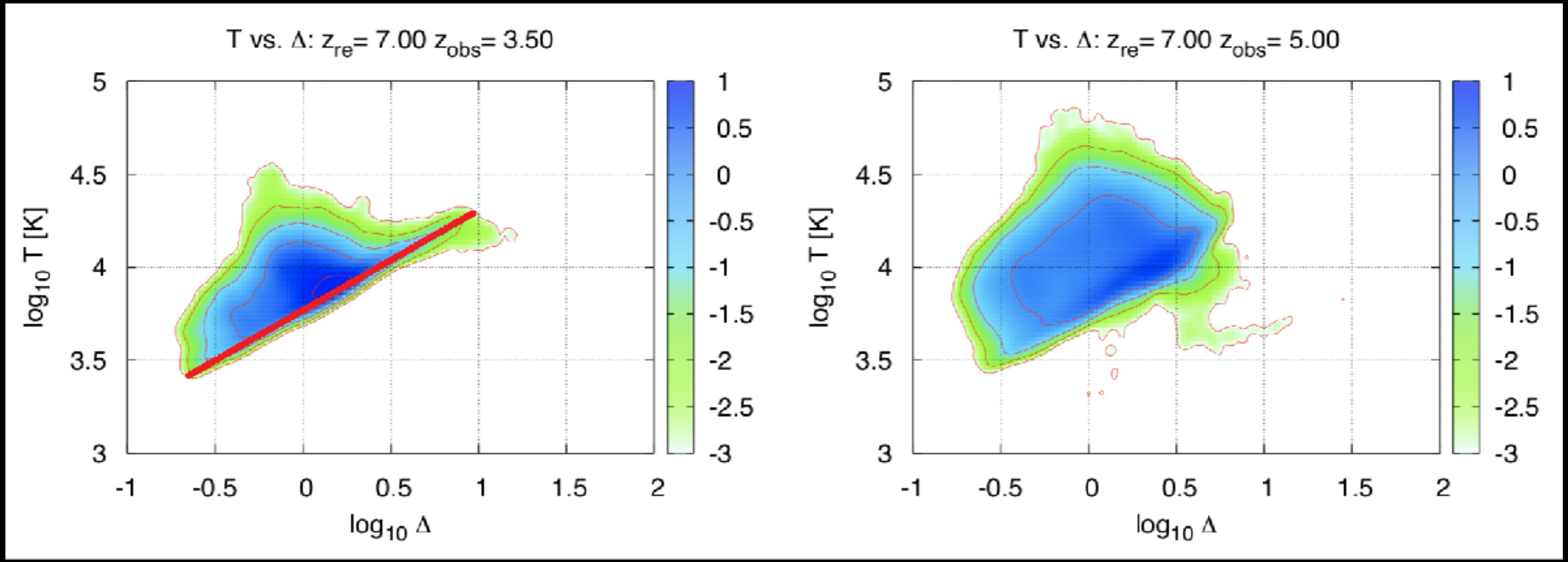
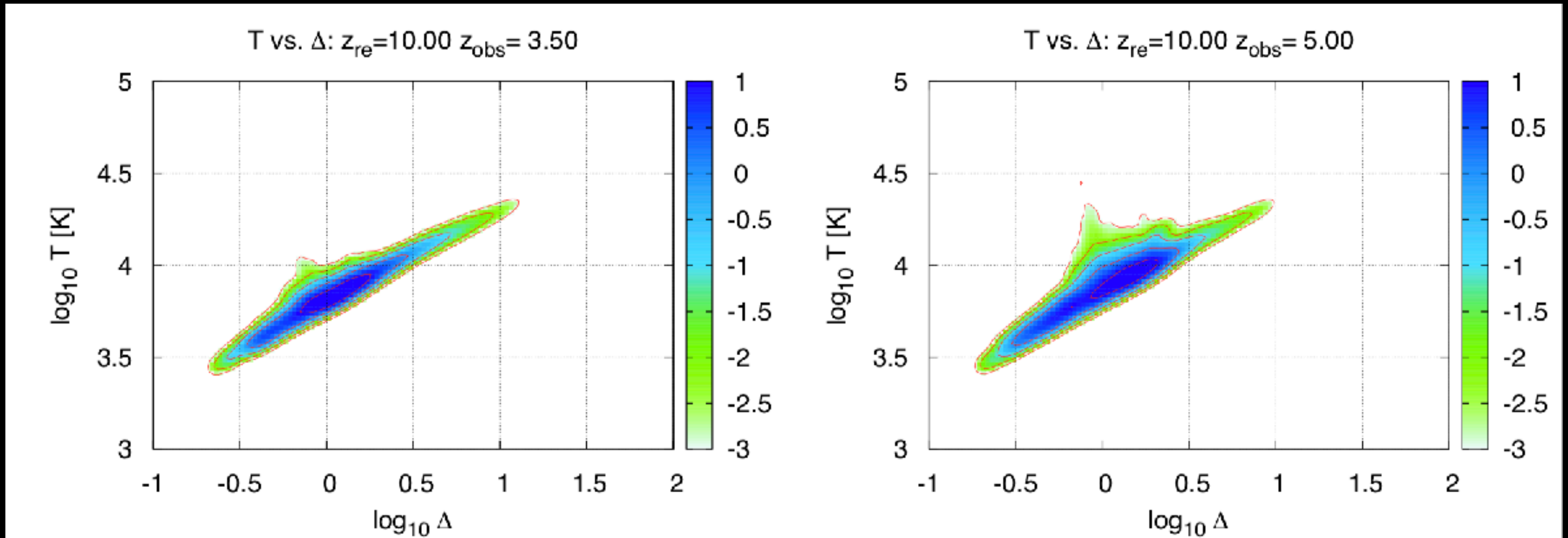


Later reionization

Lower-z observation

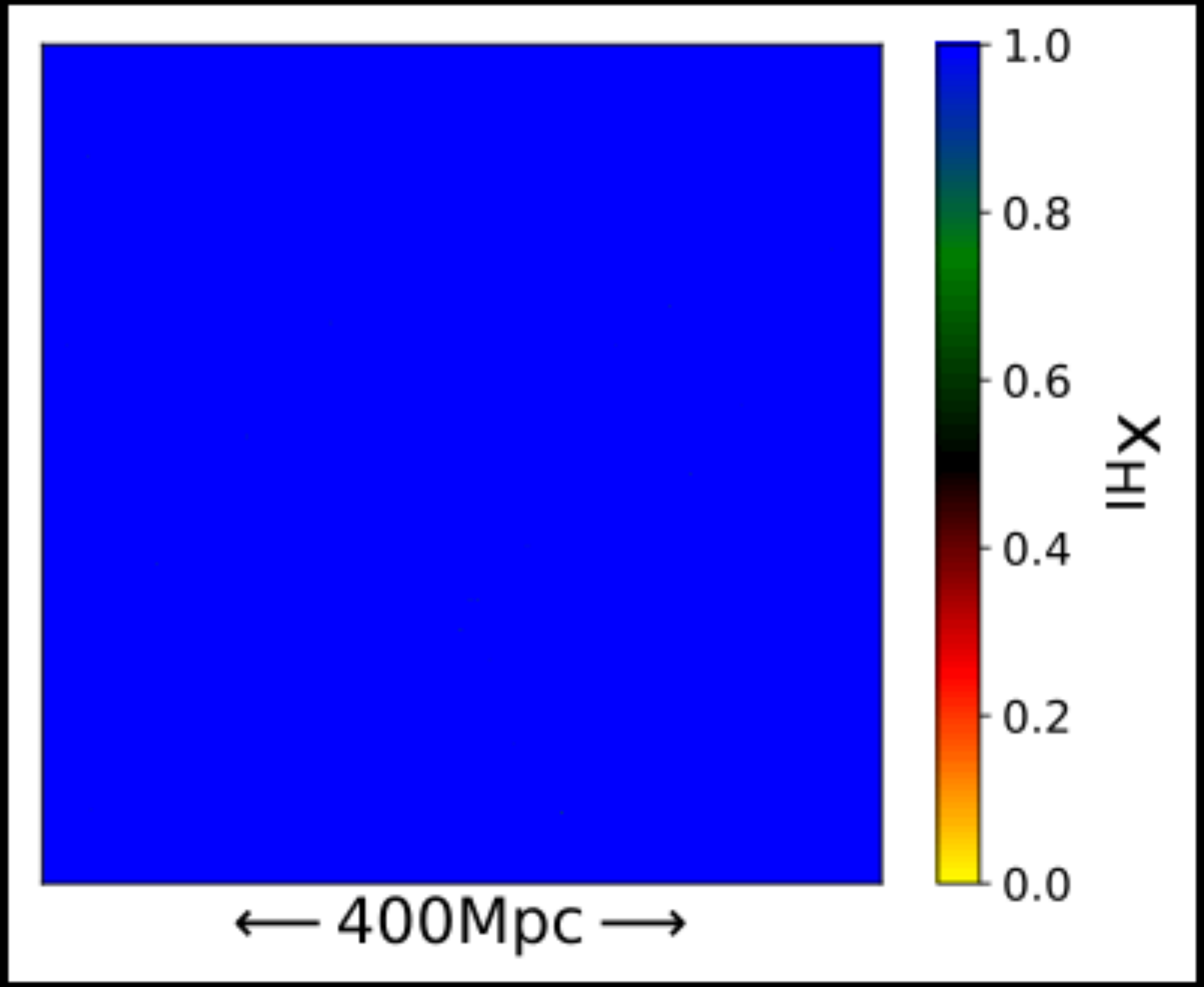
Higher-z observation

Hirata (2018)



Earlier reionization

Impact of reionization in the post-reionization era
II) Patchy nature



Starting redshift: z = 35
Blue: completely neutral

Ending: z = 6
Yellow: totally ionized

21cmFAST simulation

Impact of reionization in the post-reionization era
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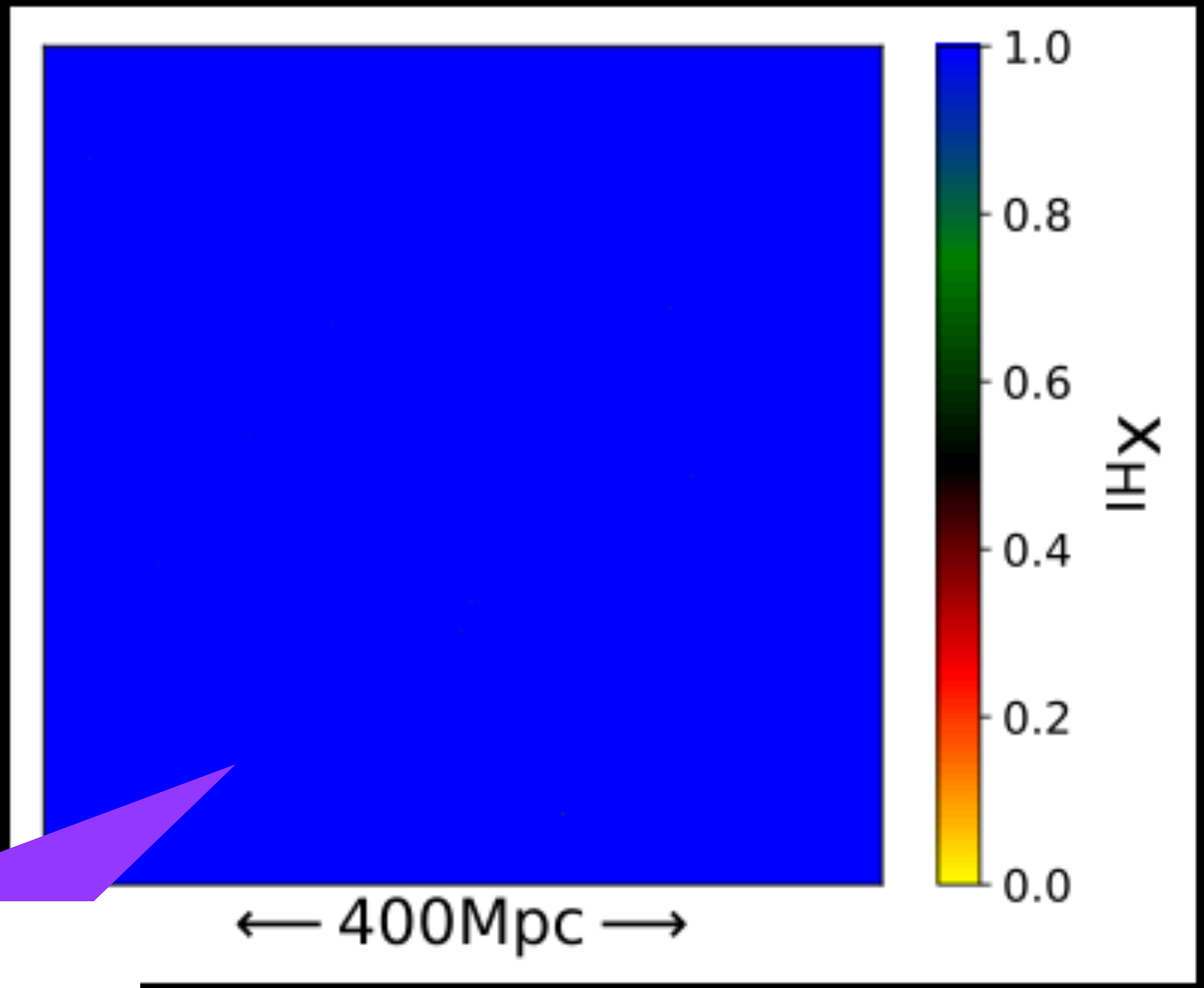

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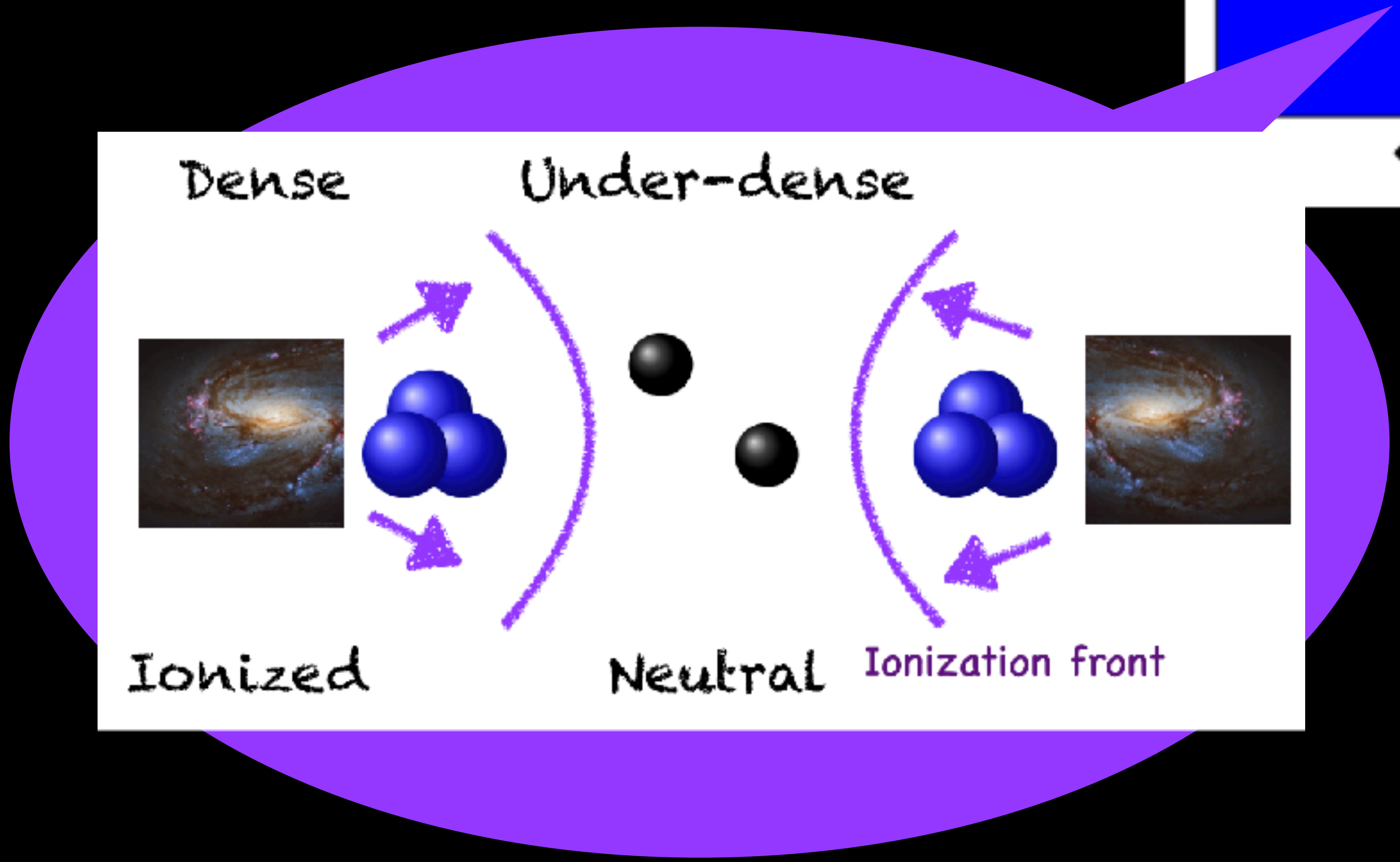
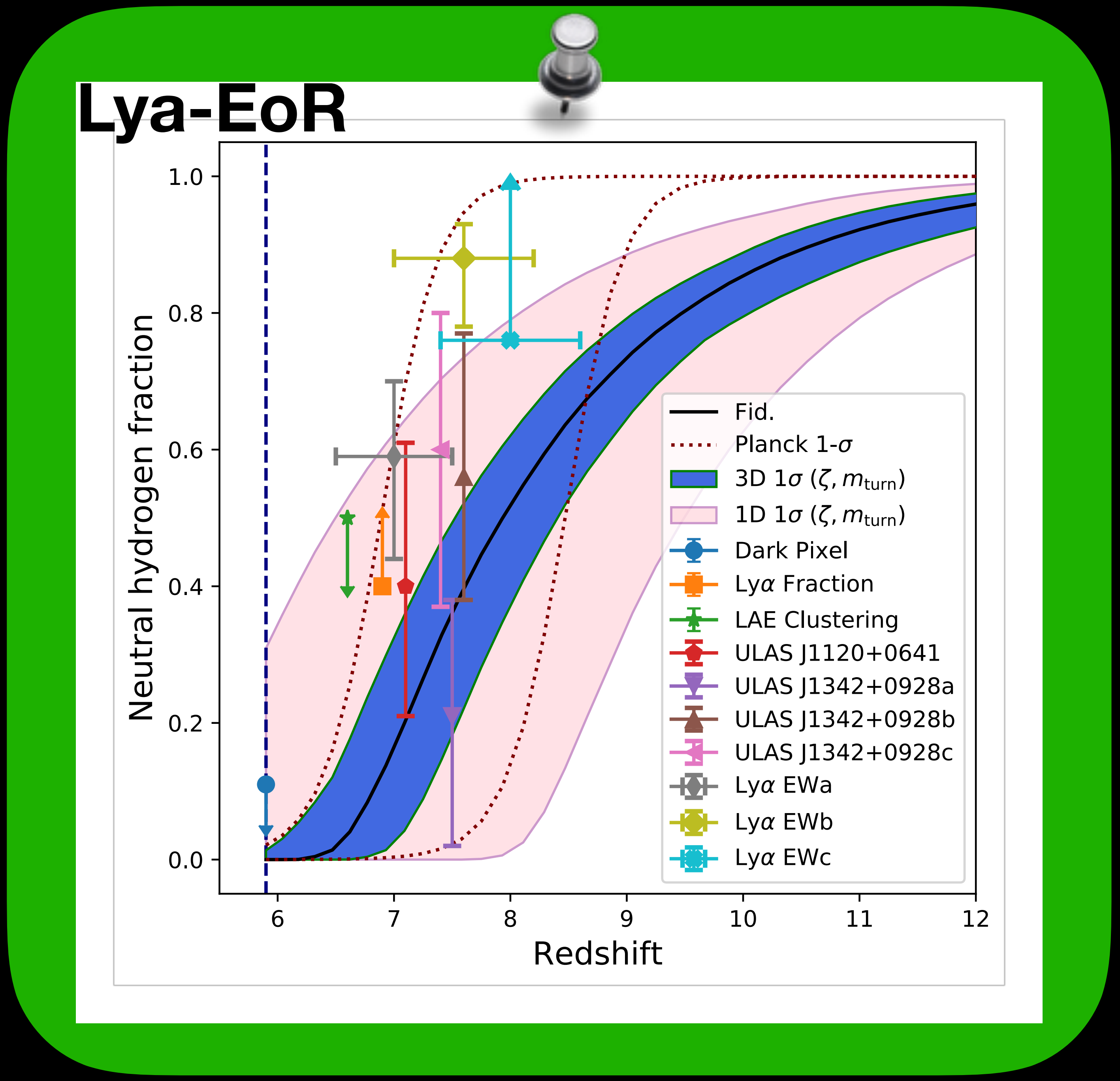
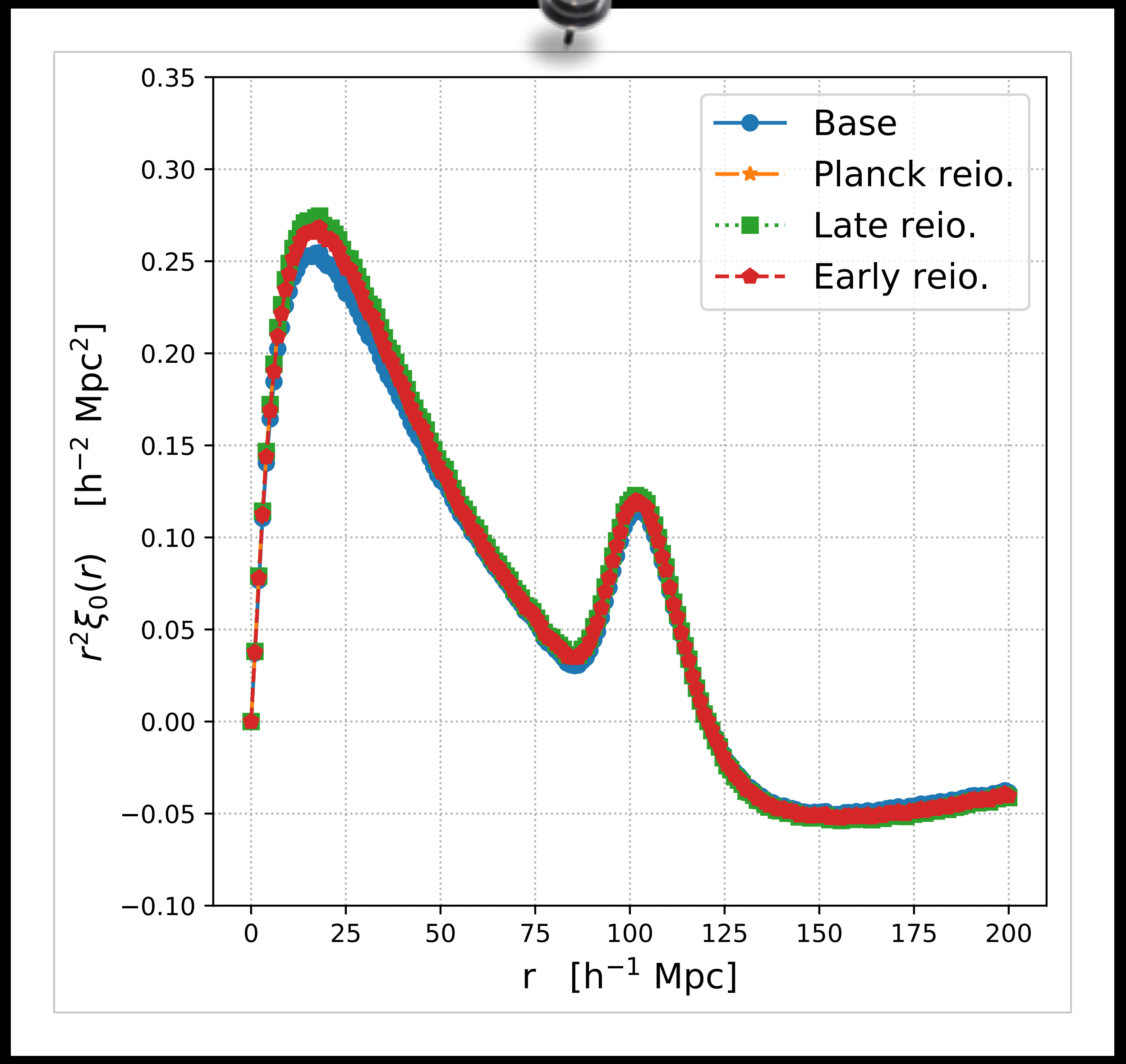
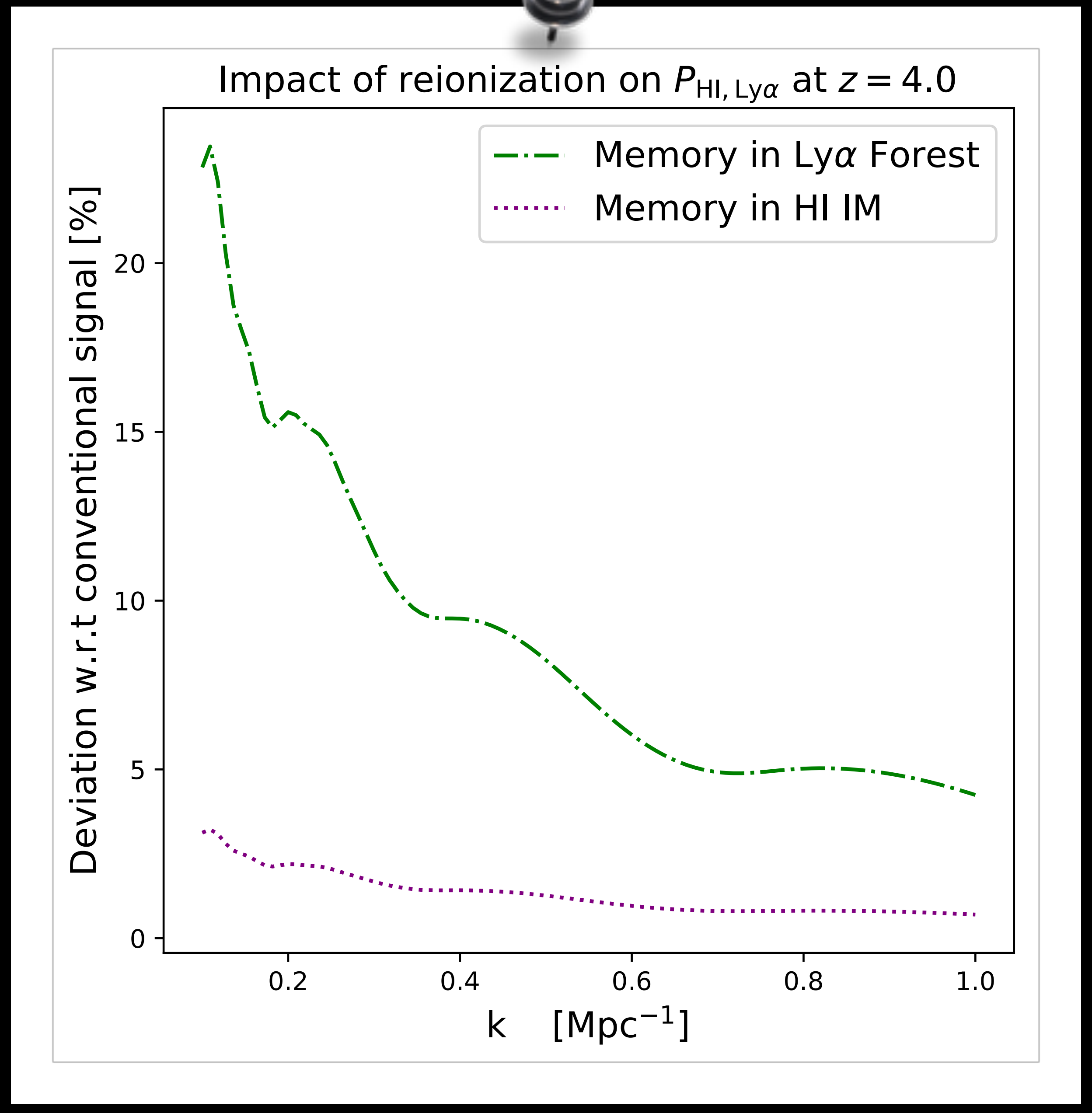
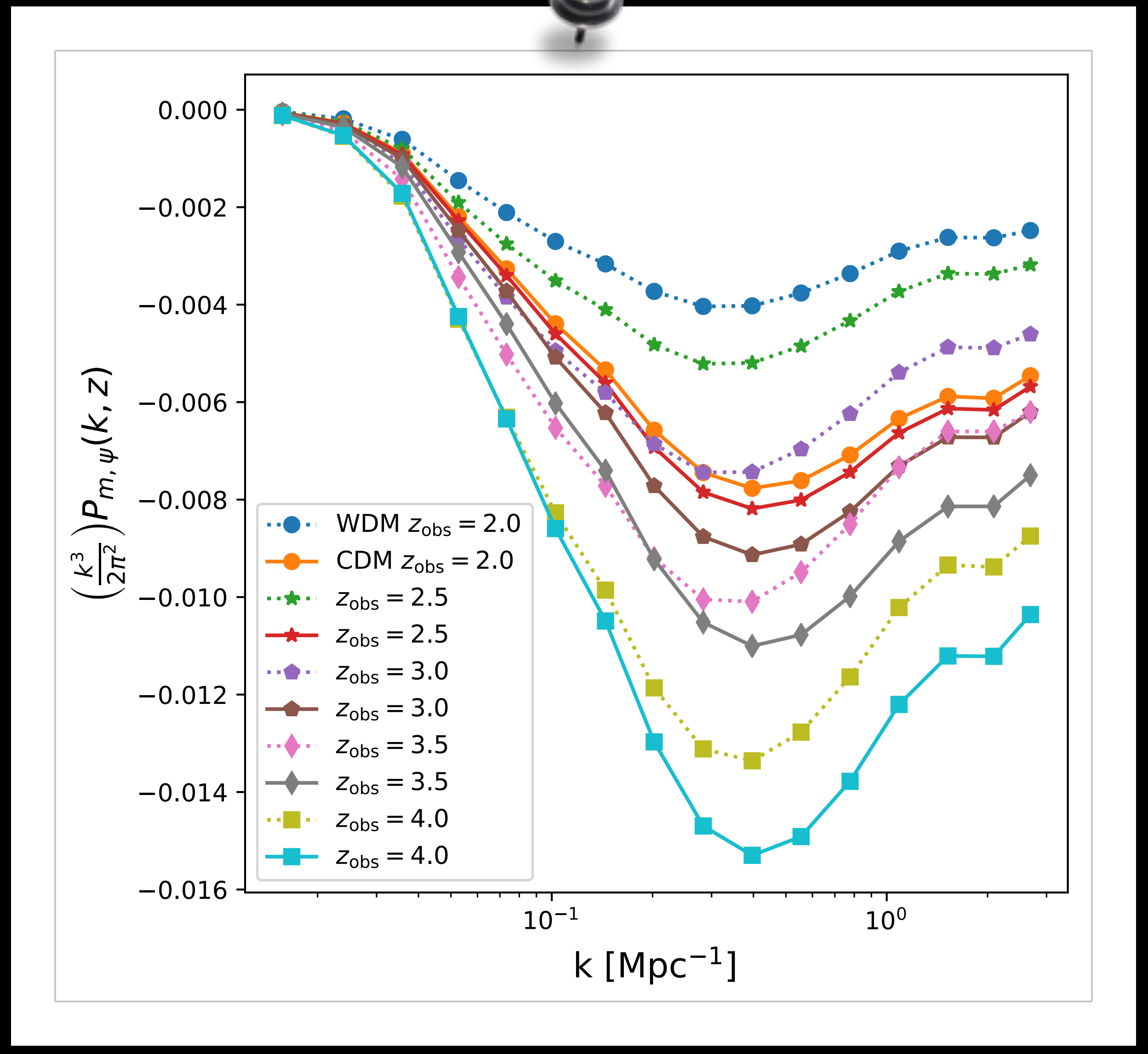


21cmFAST simulation


Lya-EoR
Neutral hydrogen fraction
Redshift
Fid.
Planck 1-σ
3D 1σ (ζ, m_turn)
1D 1σ (ζ, m_turn)
Dark Pixel
Lyα Fraction
LAE Clustering
ULAS J1120+0641
ULAS J1342+0928a
ULAS J1342+0928b
ULAS J1342+0928c
Lyα EWa
Lyα EWb
Lyα EWc


Base
Planck reio.
Late reio.
Early reio.
$r^2\xi_0(r)$ [h^{-2} Mpc^2]
r [h^{-1} Mpc]


Impact of reionization on $P_{\mathrm{HI,Ly}\alpha}$ at $z = 4.0$
Memory in Lyα Forest
Memory in HI IM
Deviation w.r.t conventional signal [%]
k [Mpc^{-1}]


WDM $z_{\mathrm{obs}} = 2.0$
CDM $z_{\mathrm{obs}} = 2.0$
$z_{\mathrm{obs}} = 2.5$
$z_{\mathrm{obs}} = 2.5$
$z_{\mathrm{obs}} = 3.0$
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$z_{\mathrm{obs}} = 4.0$
$z_{\mathrm{obs}} = 4.0$
$\left(\frac{k^3}{2\pi^2}\right)P_{m,\psi}(k,z)$
k [Mpc^{-1}]

Quick interlude: Lyman-alpha forest (Lya)

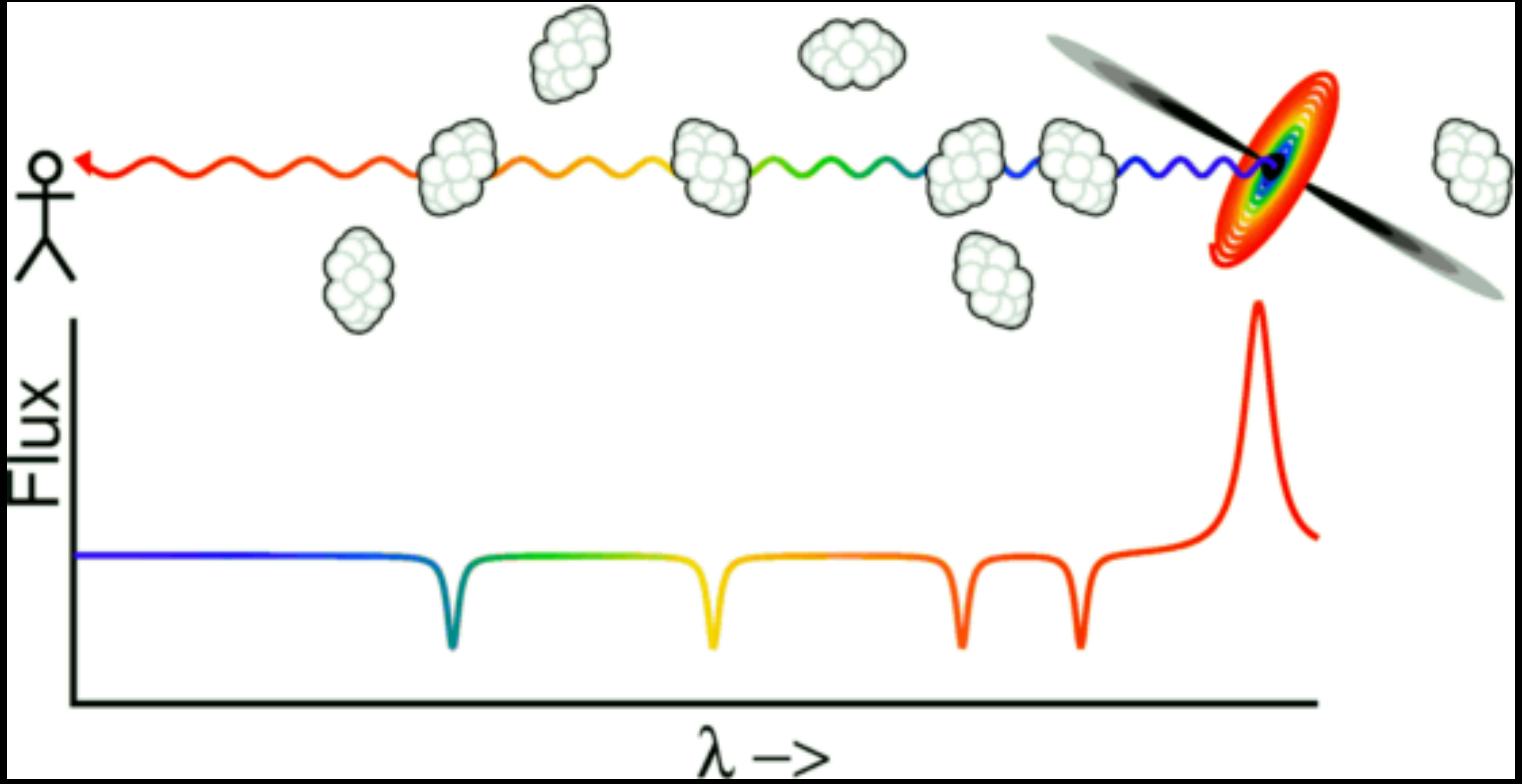

Image credit: Edward Wright

Each absorption feature inform us about location of neutral hydrogen cloud

$$z_{\rm obs} = 121.6 \text{ nm } (1 + z_{\rm cloud})$$

Lya forest traces neutral hydrogen thus **biased tracer of matter content**

$$\delta_{\rm F} \propto \delta_m$$

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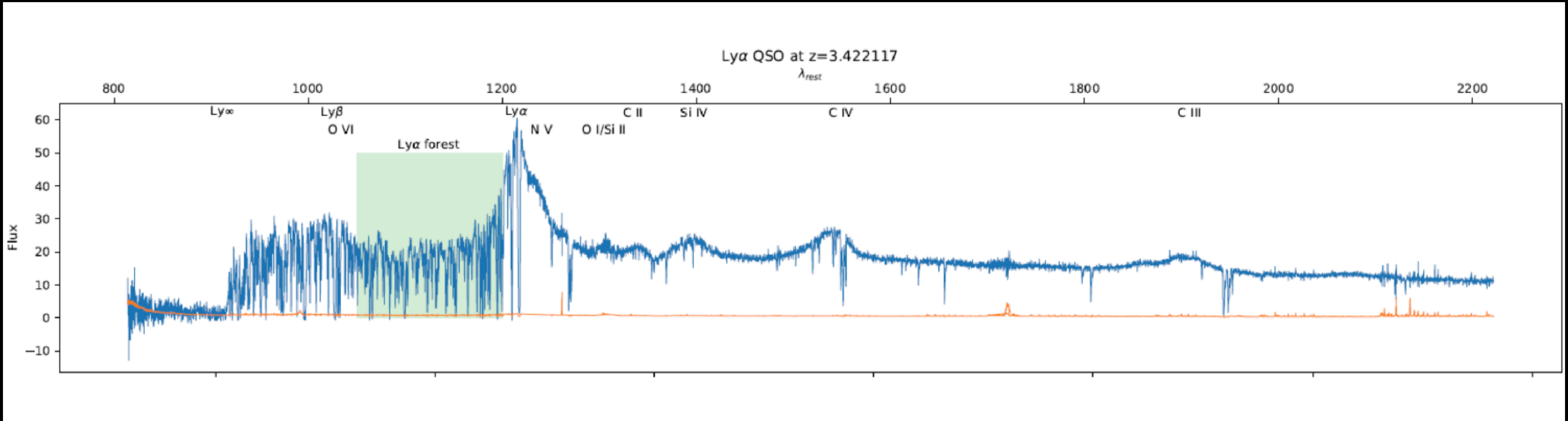


Image credit: Corentin Raveux (& DESI!)

Each absorption feature inform us about location of neutral hydrogen “cloud”

$$z_{\text{obs}} = 121.6 \text{ nm } (1 + z_{\text{cloud}})$$

Lya forest traces neutral hydrogen thus **biased tracer of matter content**

$$\delta_{\text{F}} \propto \delta_m$$

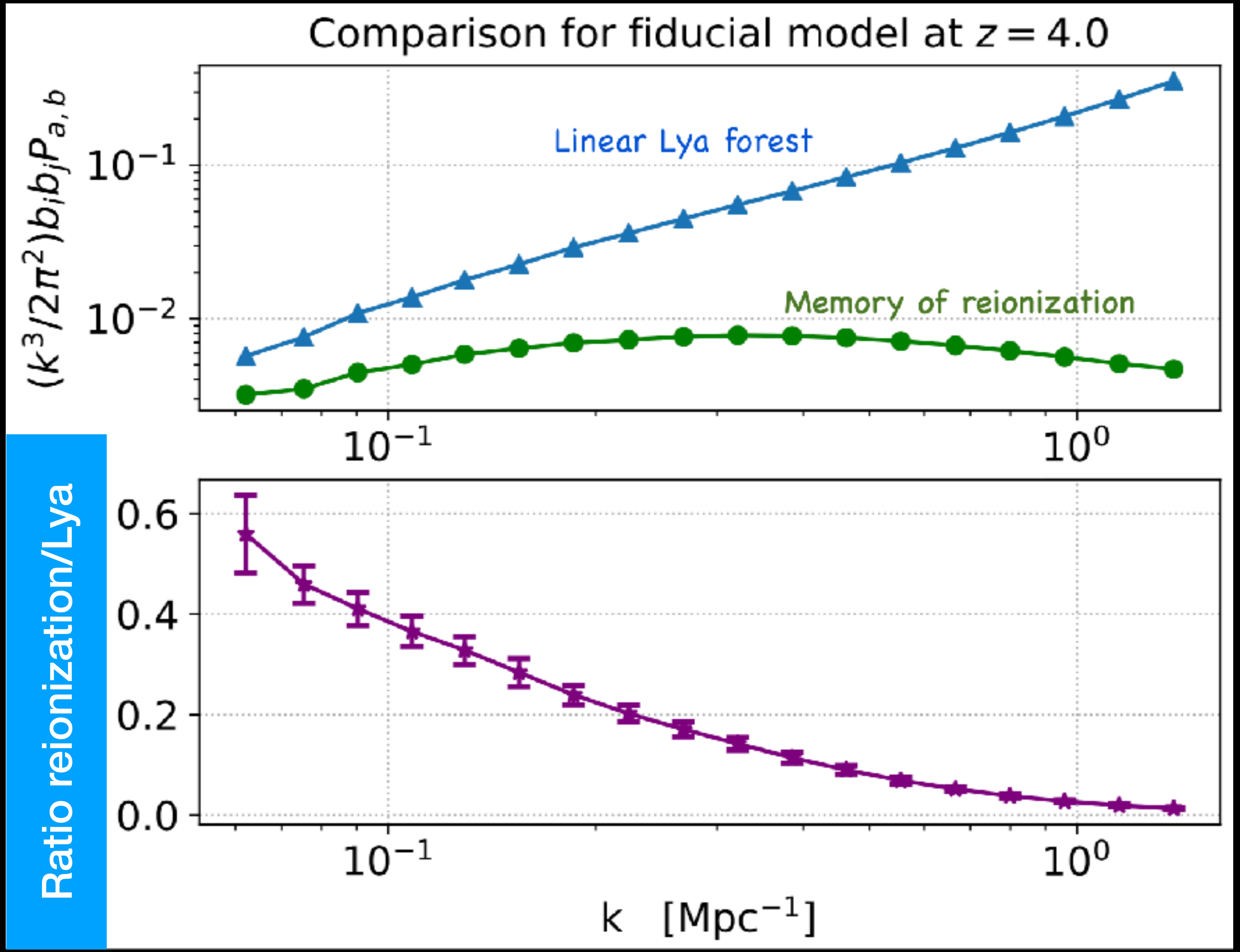
Reionization in Lya forest: a powerful systematic

PMC et al. (2019): small-scale + patchiness = impact on IGM, and thus impact on Lya forest.

Effect of reionization is:

- Hard to remove and it cannot be ignored!
- Stronger at high redshift of observation and at large scales.
- Stronger if reionization occurs later.

$$P_F = \underbrace{b_F^2(1+\beta\mu^2)^2 P_m}_{\text{Cosmology}} + \underbrace{2b_F b_\Gamma(1+\beta\mu^2)P_{m,\psi}}_{\text{Reionization}}$$



C. Hirata (OSU)

P. Martini (OSU)

K. Honscheid (OSU)

Reionization in Lya forest: a window into reionization

PMC et al. (2019): small-scale + patchiness = impact on IGM, and thus impact on Lya forest.

Effect of reionization is:

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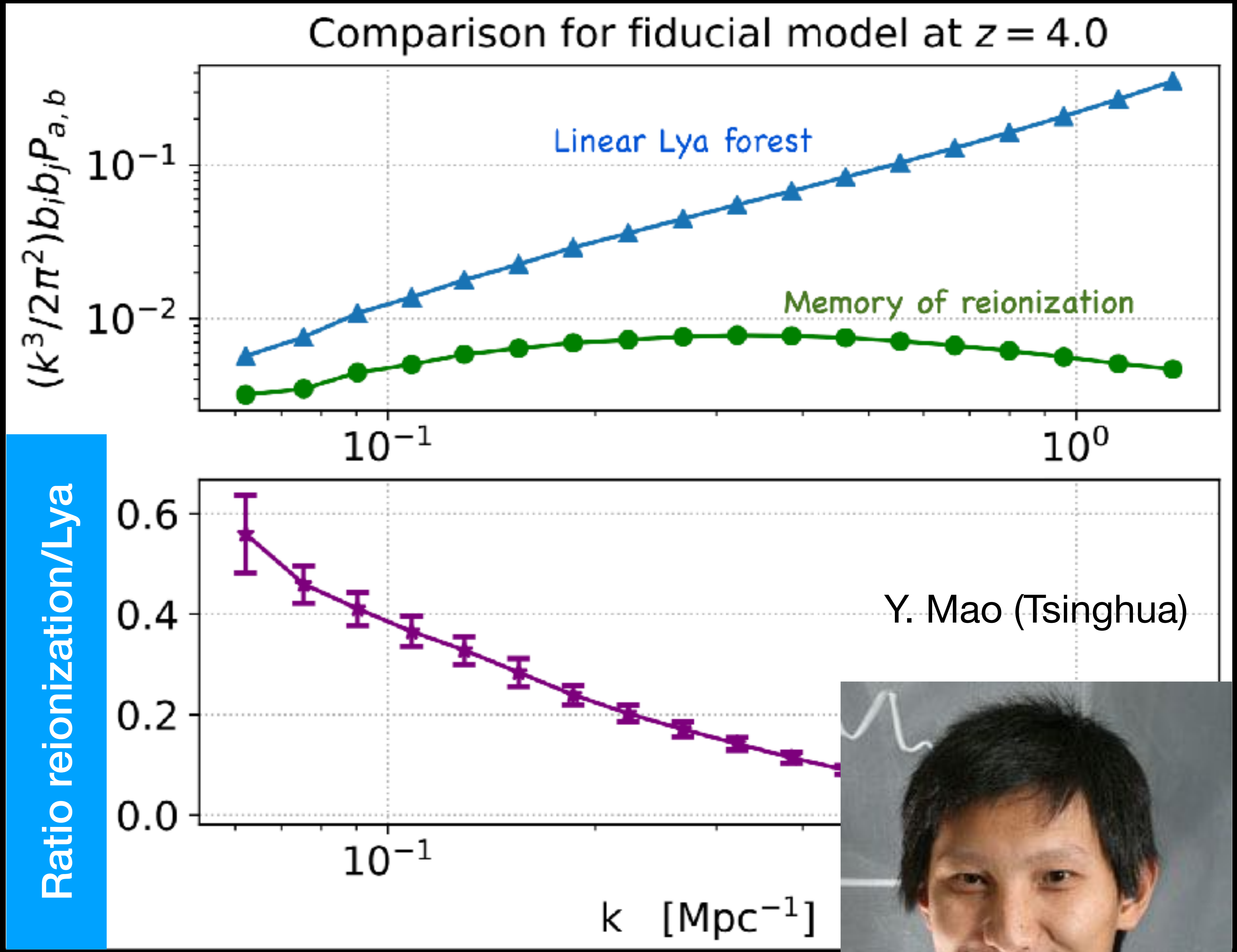
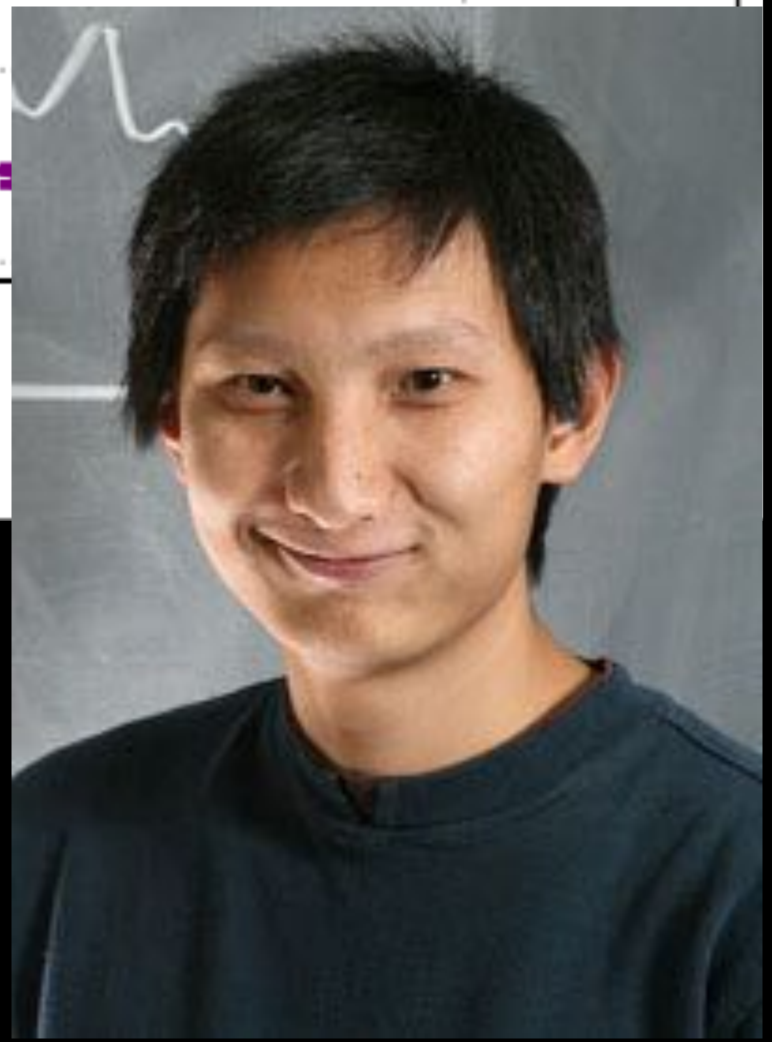
$$P_F = \underbrace{b_F^2(1+\beta\mu^2)^2 P_m}_{\text{Cosmology}} + \underbrace{2b_F b_\Gamma (1+\beta\mu^2) P_{m,\psi}}_{\text{Reionization}}$$

But it can be modeled, so instead make it a new science goal!

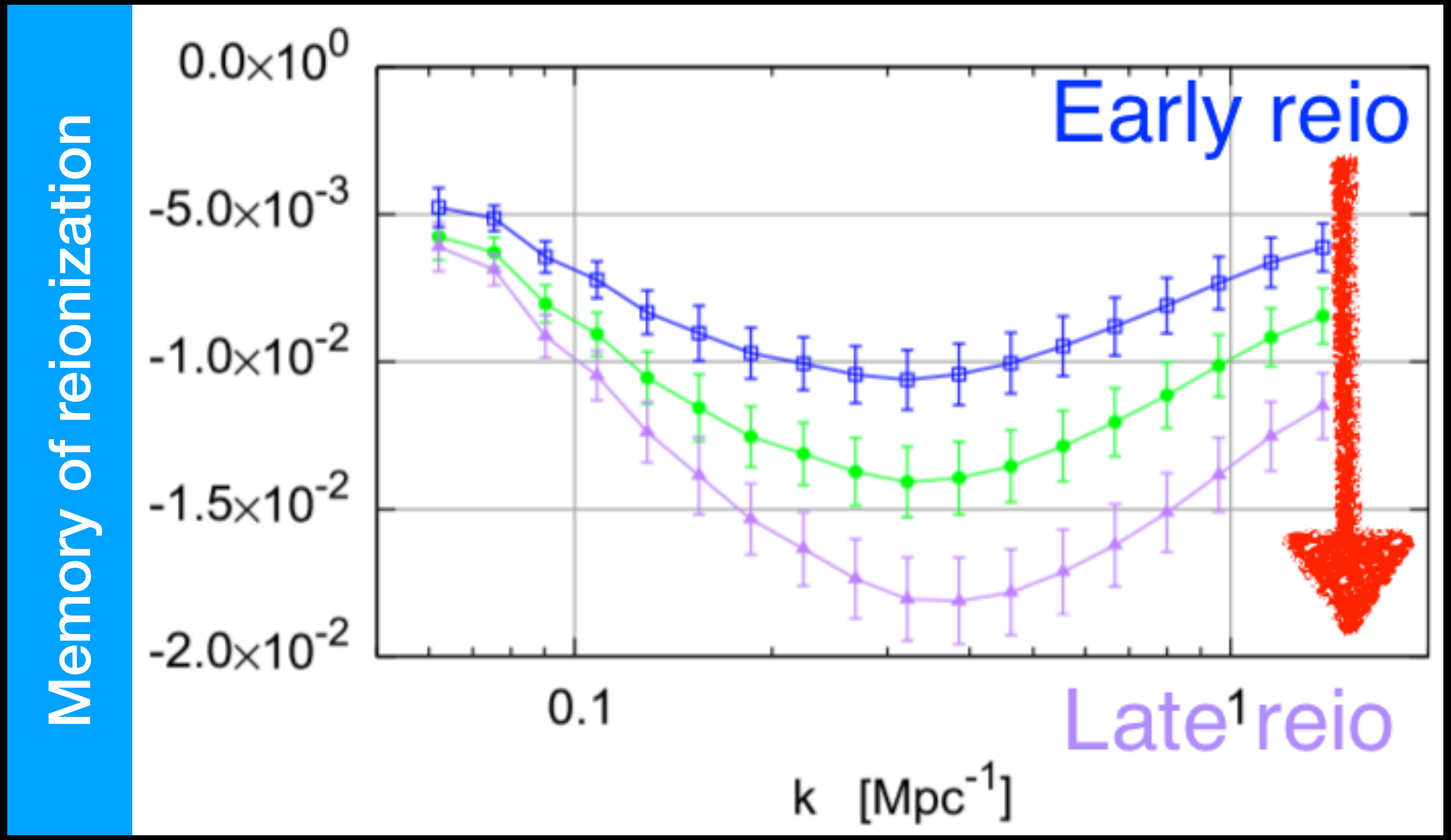
- How does it depend on reionization model?
- What is the dependence with X-ray preheating?
- # density of QSO decreases with redshift, is a measurement feasible?

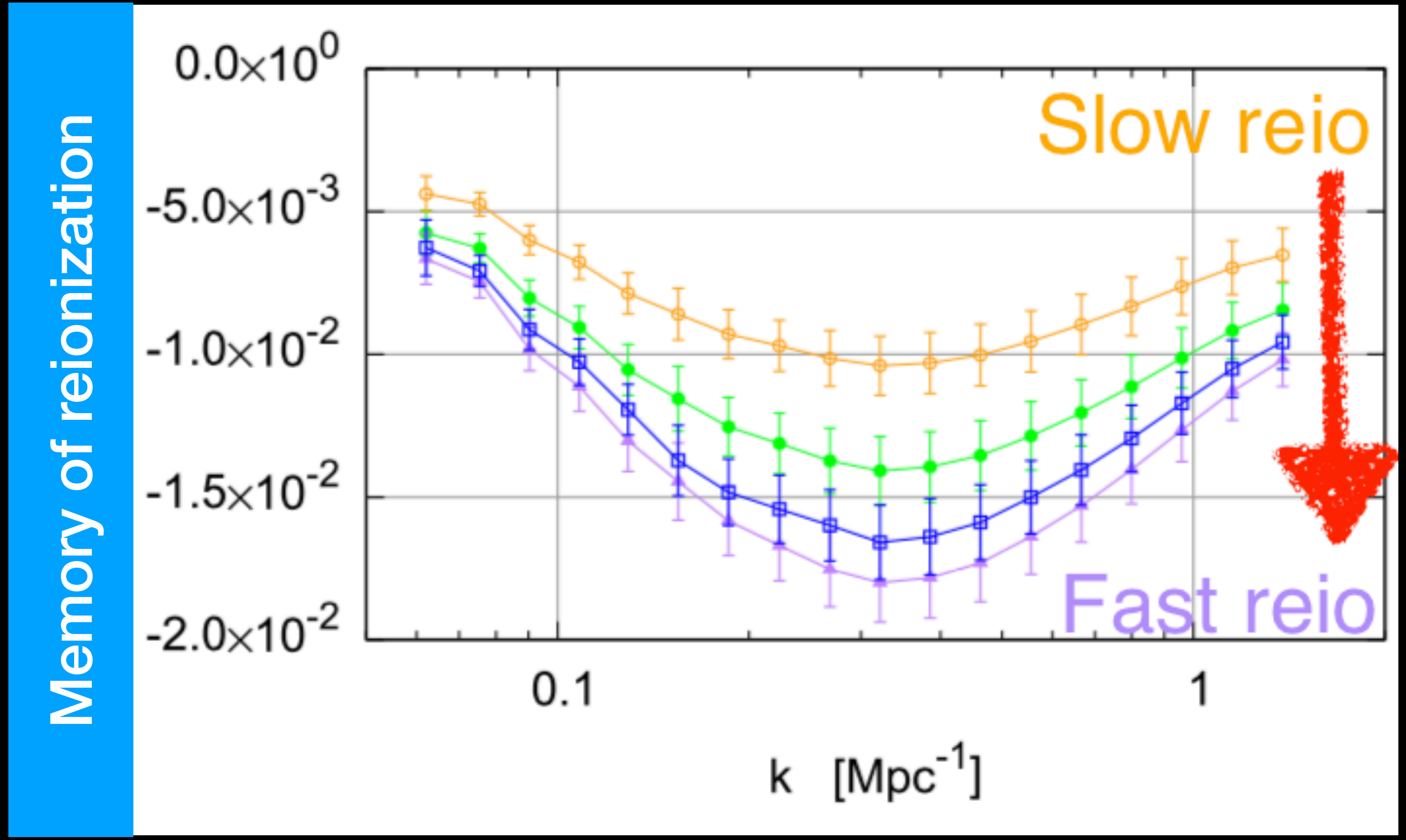


Y. Mao (Tsinghua)

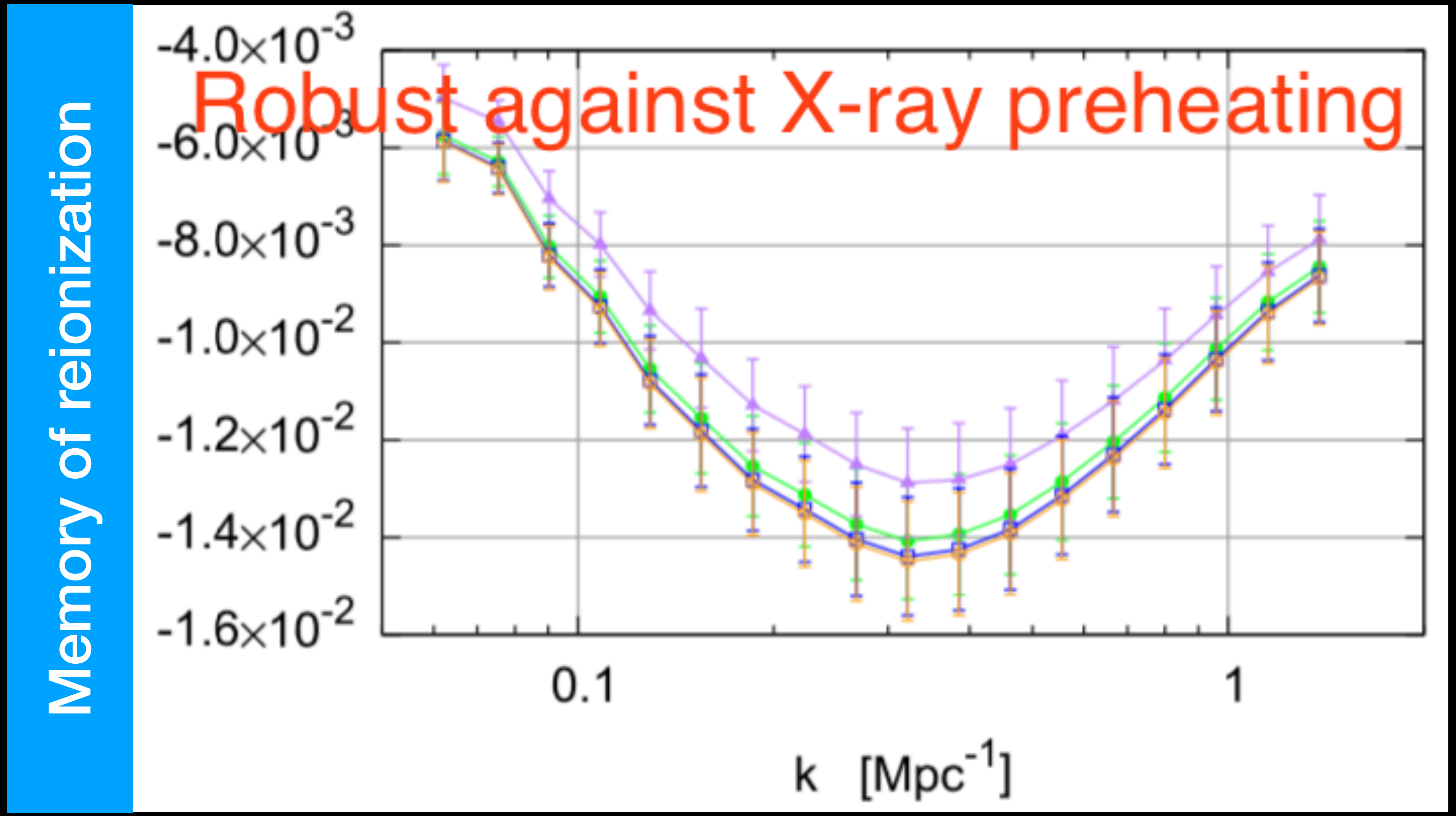


Dependence with reionization history and X-ray preheating





PMC & Mao (2020)

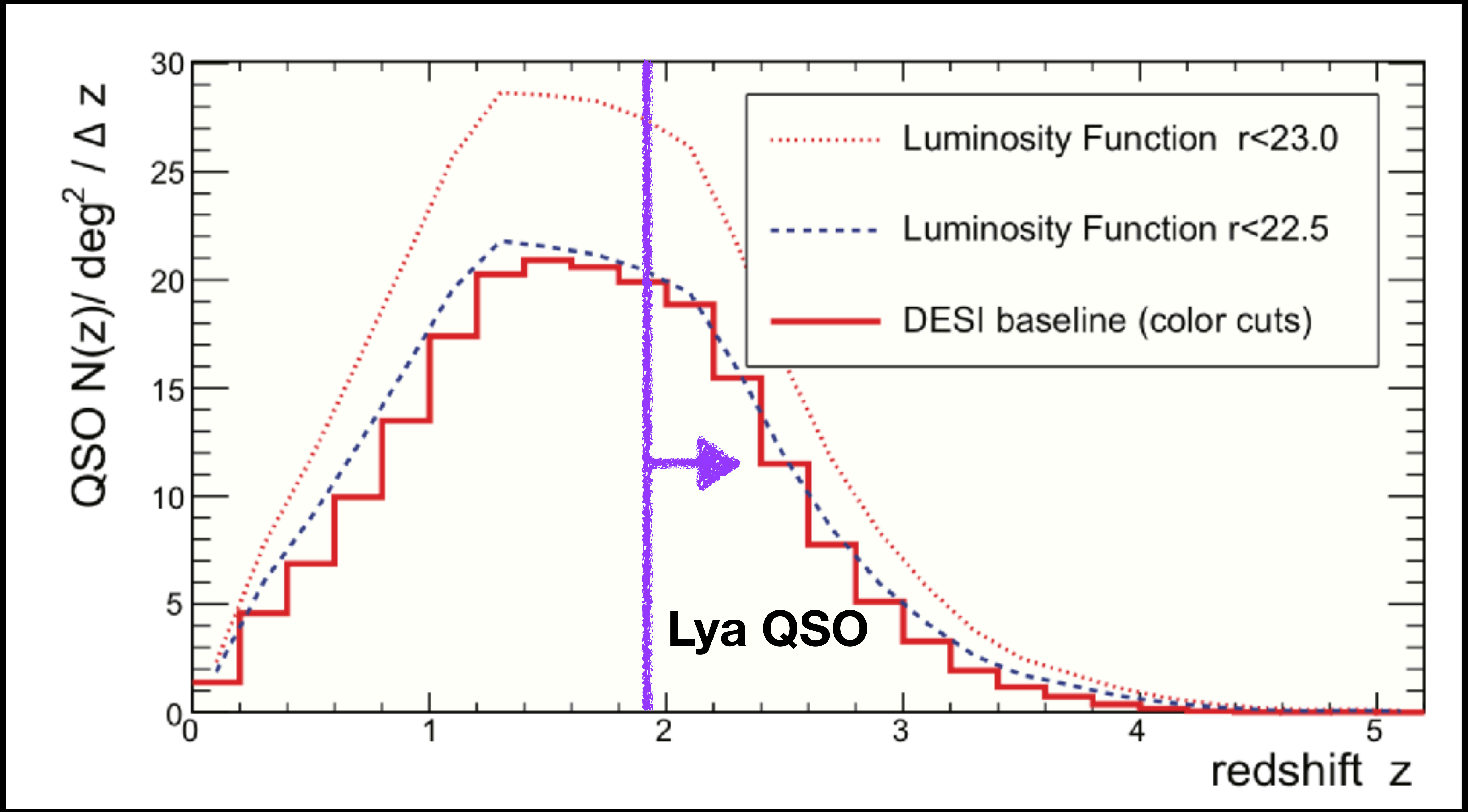


What about feasibility?

Feasibility

- Memory of reionization is stronger at high redshift.
- Number of QSO decreases with higher redshift.
- Need to be able to simultaneously constrain cosmology and EoR astrophysics.

Glossary:
EoR = epoch of reionization

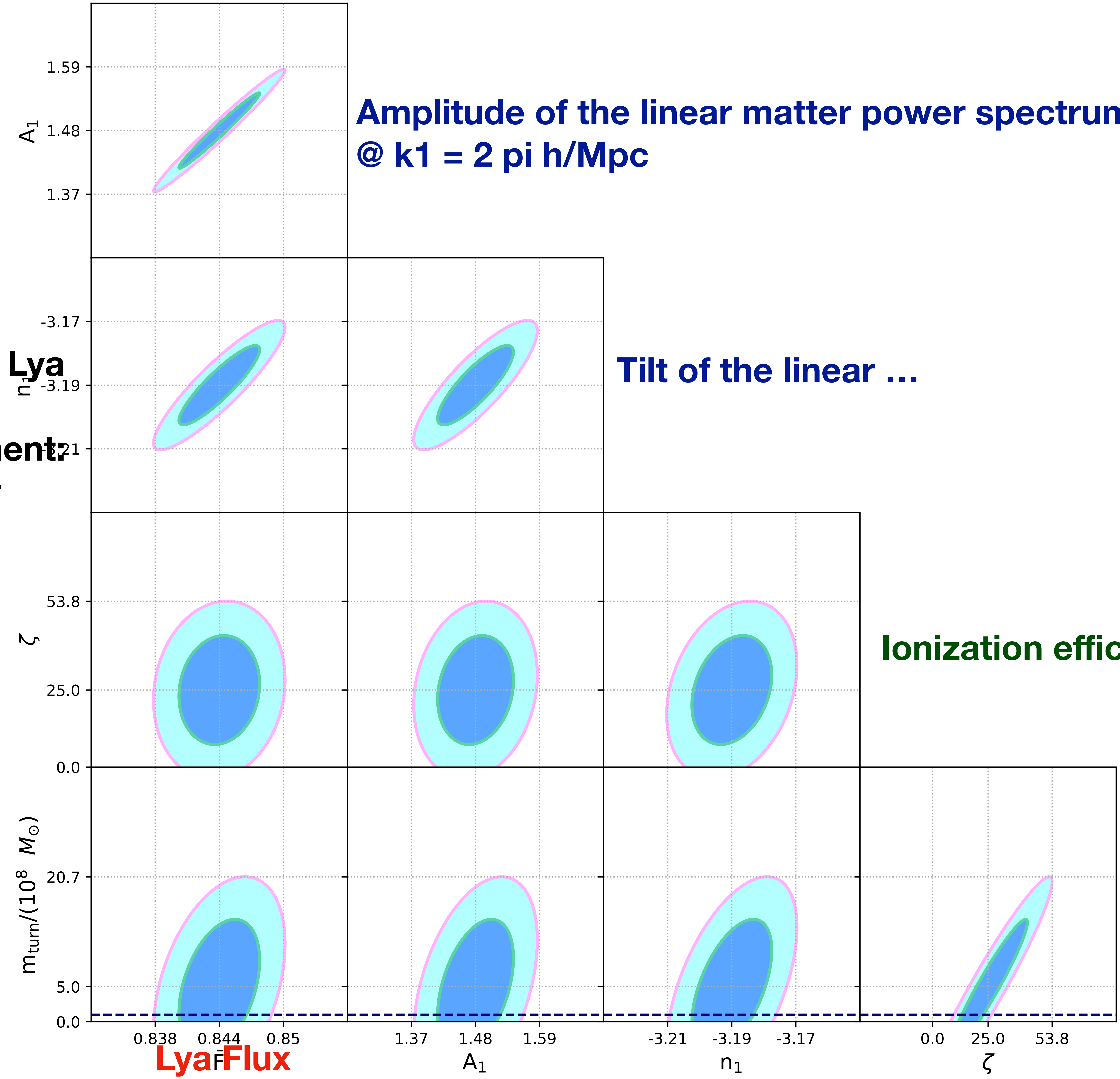


DESI has already measured a bunch of QSO spectra > 250k Lya QSO!!!

Lya astrophysics

DESI specs:
- **2 < z < 4**
- **Targeted line: Lya**

DESI measurement:
- **3D Lya power spectrum**



Amplitude of the linear matter power spectrum @ k1 = 2 pi h/Mpc

Tilt of the linear …

Ionization efficiency

Mass cut-off

PMC & Mao (2021)

Cosmology

Reio astrophysics

Lya astrophysics

DESI specs:
- 2 < z < 4
- Targeted line: Lya

DESI measurement:
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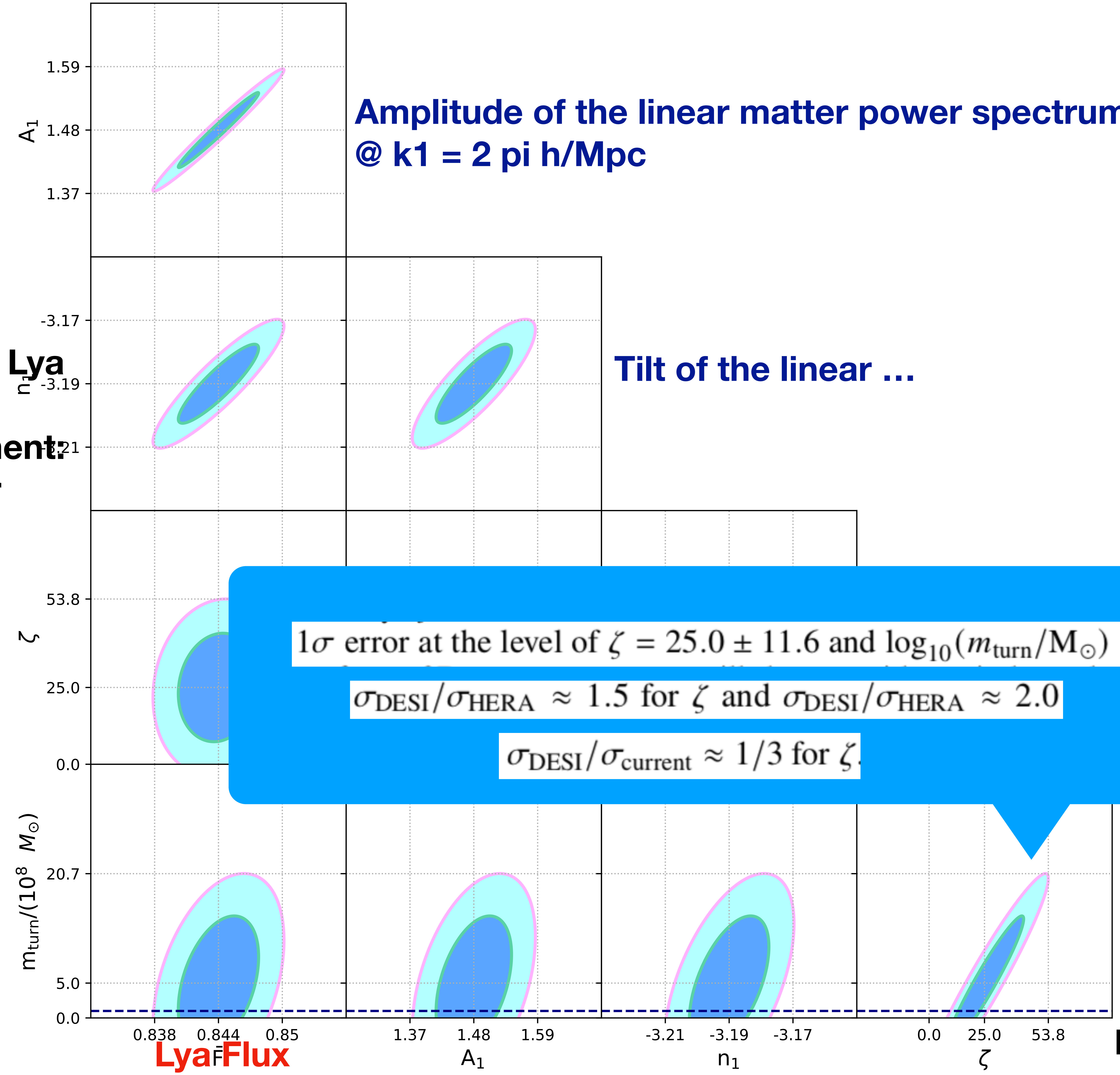


LyaFlux

Amplitude of the linear matter power spectrum @ k1 = 2 pi h/Mpc

Tilt of the linear …

1σ error at the level of $\zeta = 25.0 \pm 11.6$ and $\log_{10}(m_{\rm turn}/{\rm M}_\odot) = 8.7^{+0.36}_{-0.70}$

$\sigma_{\rm DESI}/\sigma_{\rm HERA} \approx 1.5$ for ζ and $\sigma_{\rm DESI}/\sigma_{\rm HERA} \approx 2.0$

$\sigma_{\rm DESI}/\sigma_{\rm current} \approx 1/3$ for ζ.

Mass cut-off

PMC & Mao (2021)

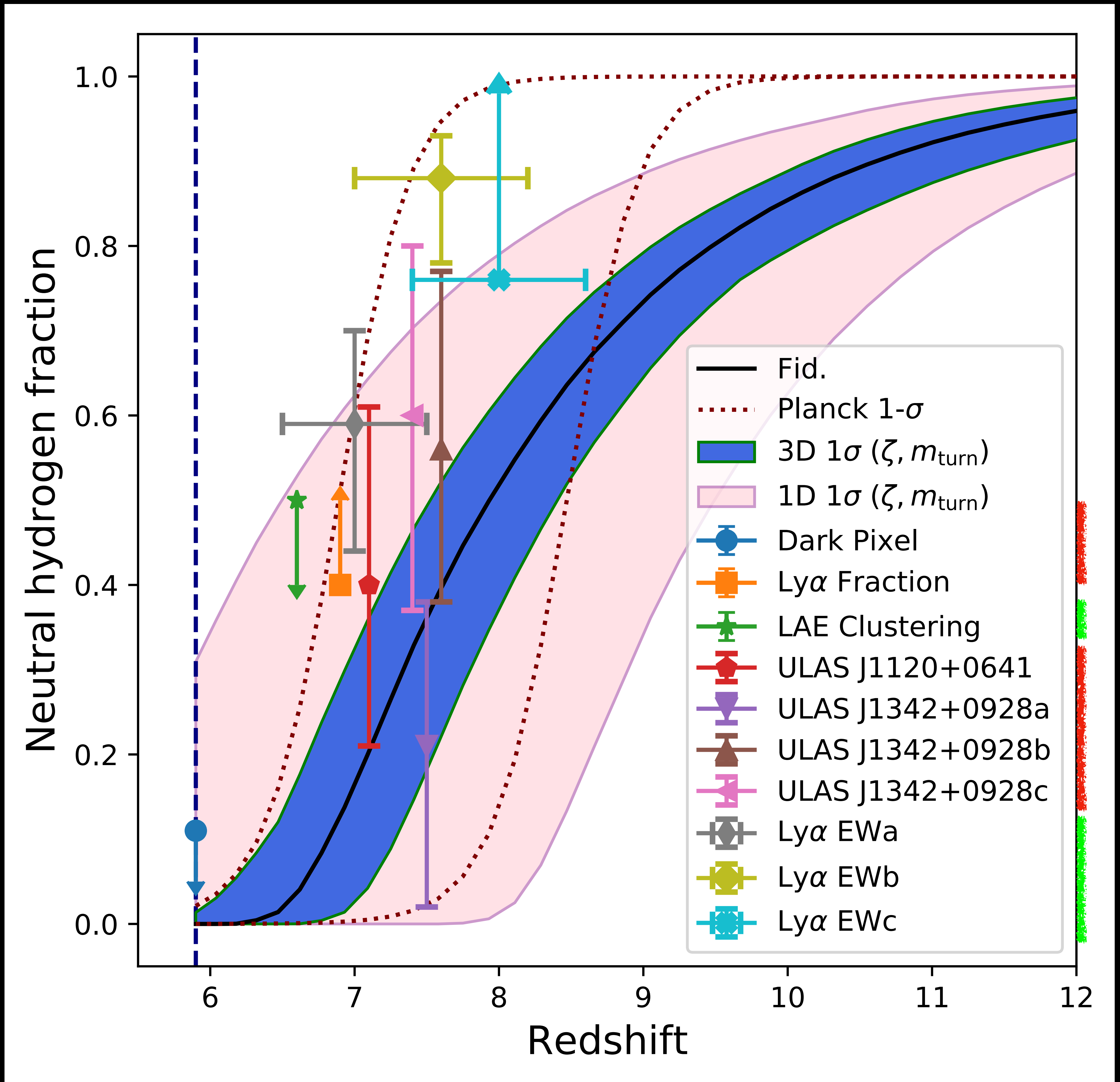
Cosmology

Reio astrophysics

Relevant HERA specs:
- EoR redshifts
- Targeted line: 21cm

HERA measurement:
- 21 cm power spectrum

DESI will be able to constrain the timeline of reionization!



High-z quasars

High-z galaxies

High-z quasars

High-z galaxies

PMC & Mao (2021)

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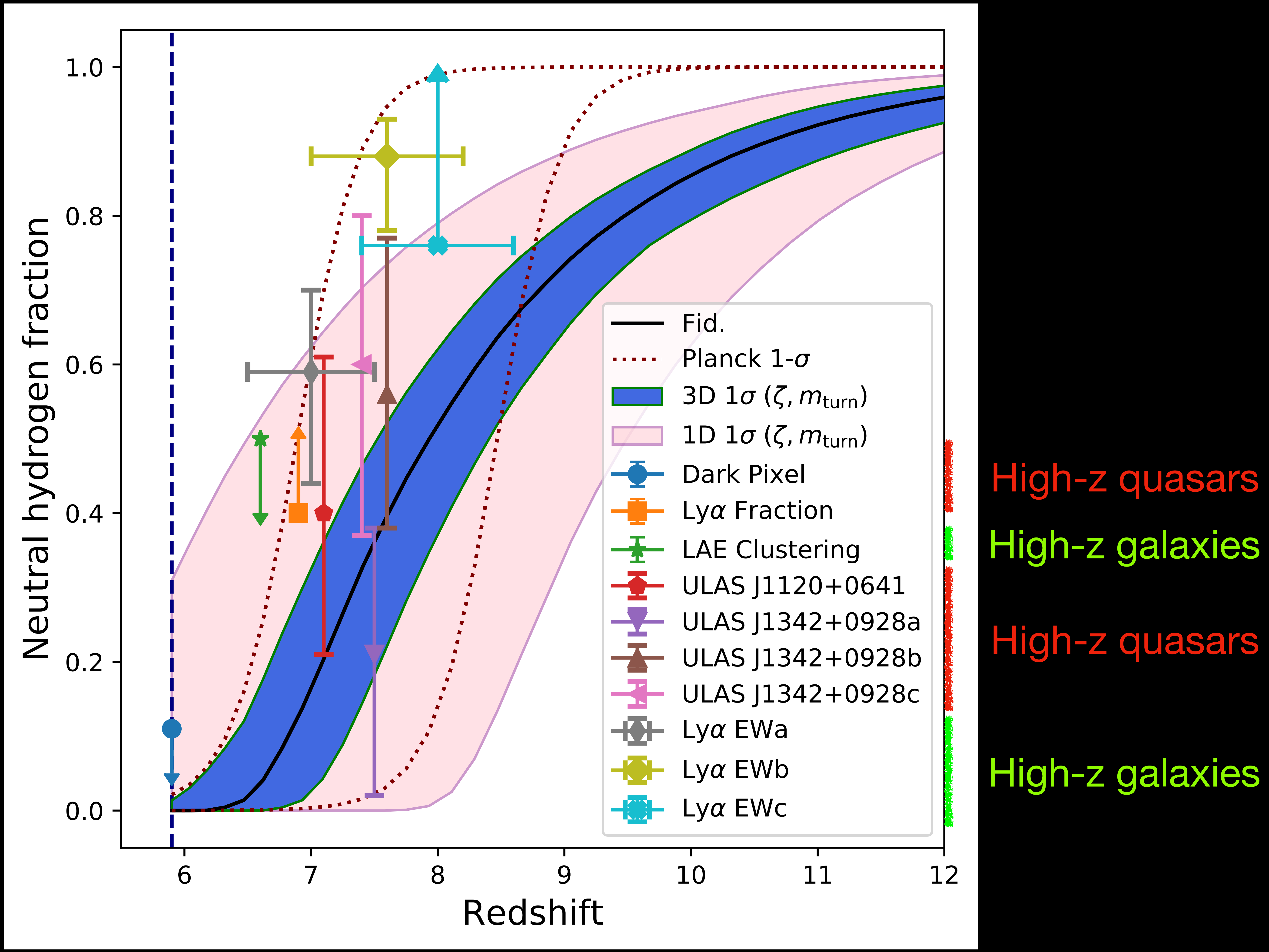


PMC & Mao (2021)

No such thing as a free meal, what is the price?

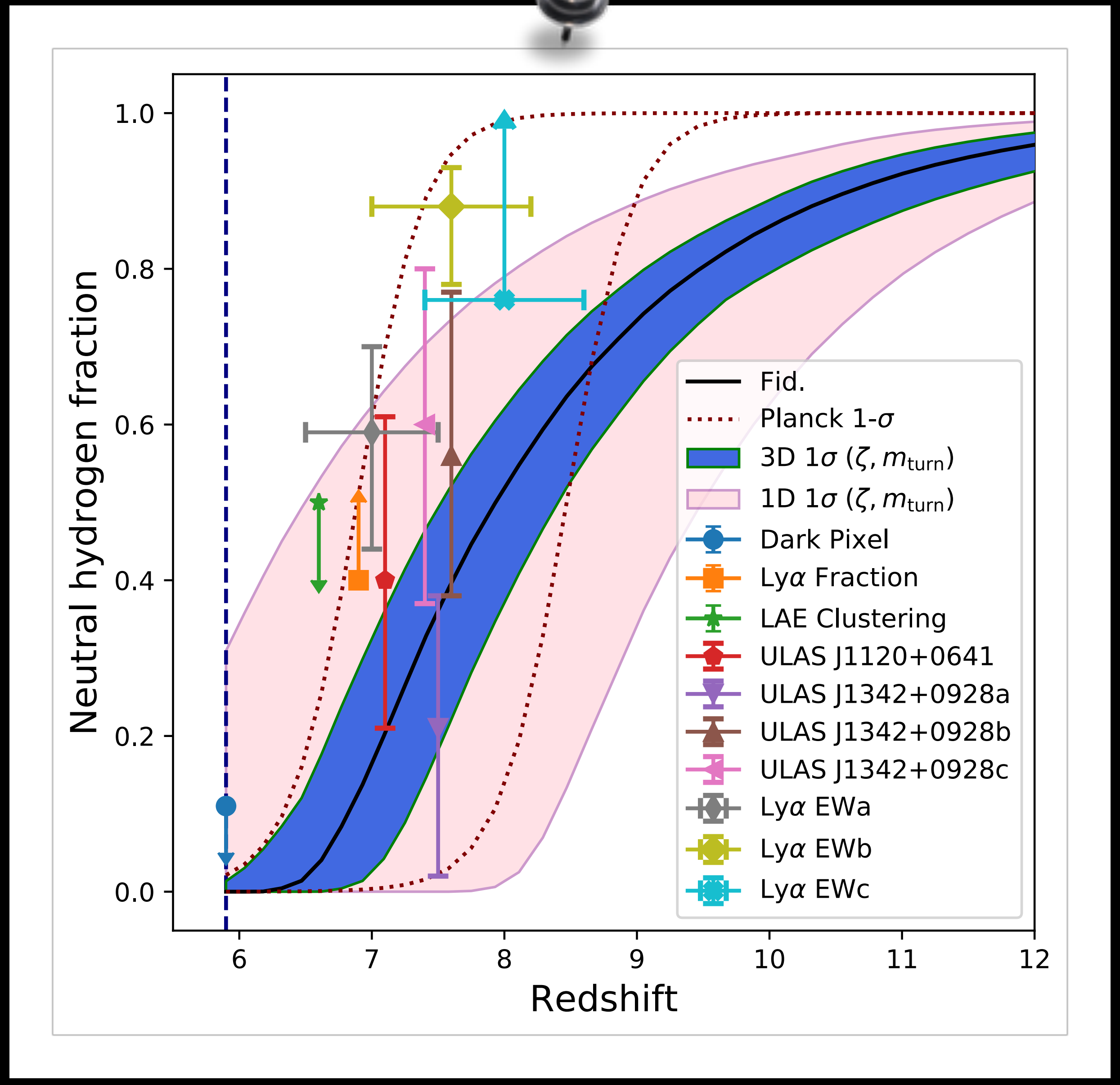
“The price”
Spoiler: I will talk about BAO soon I promise!

Realistically, there is a **significant** price. But first consider we neglect the memory of reionization, and thus:

- Biased cosmological parameters.
- Underestimation of error bars.

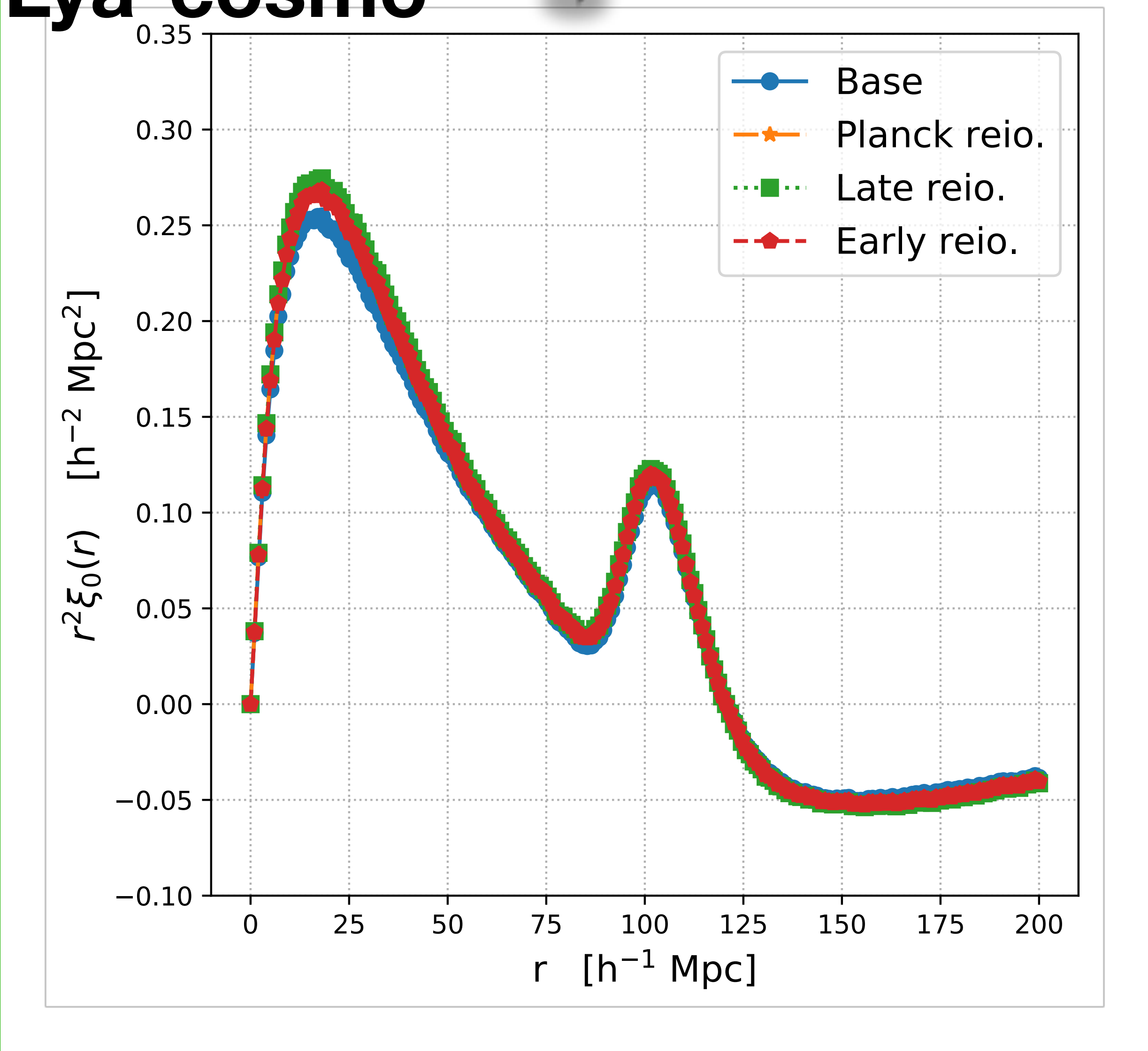
If we account for the memory of reionization then:

- *Lower* performance when extracting cosmological information (estimate ~ 2 increase on errors for P3D).
- Transformed **broadband systematic** into a **window of the EoR!**

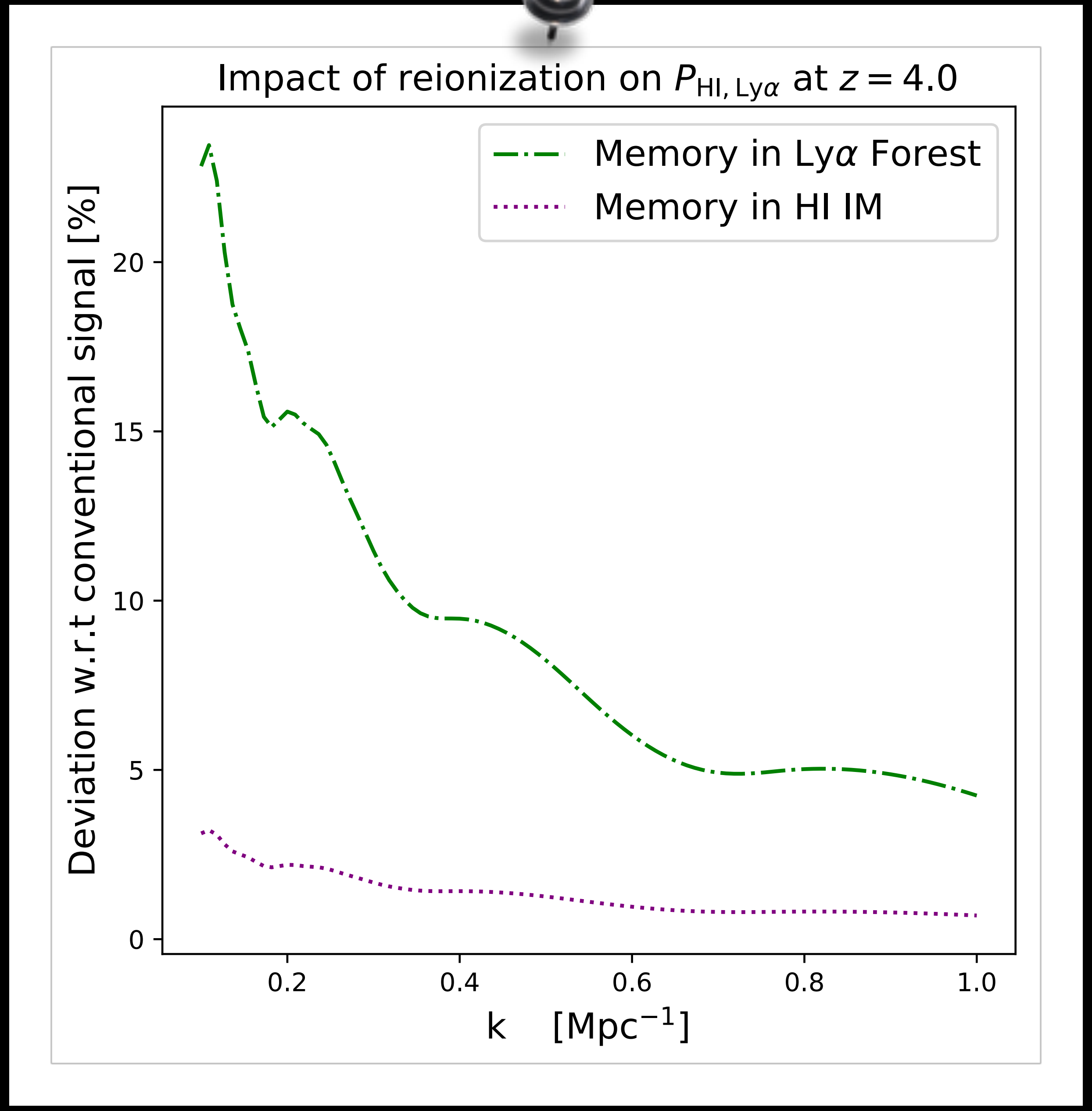


Neutral hydrogen fraction
Redshift
Fid.
Planck 1-σ
3D 1σ (ζ, m_{turn})
1D 1σ (ζ, m_{turn})
Dark Pixel
Lyα Fraction
LAE Clustering
ULAS J1120+0641
ULAS J1342+0928a
ULAS J1342+0928b
ULAS J1342+0928c
Lyα EWa
Lyα EWb
Lyα EWc

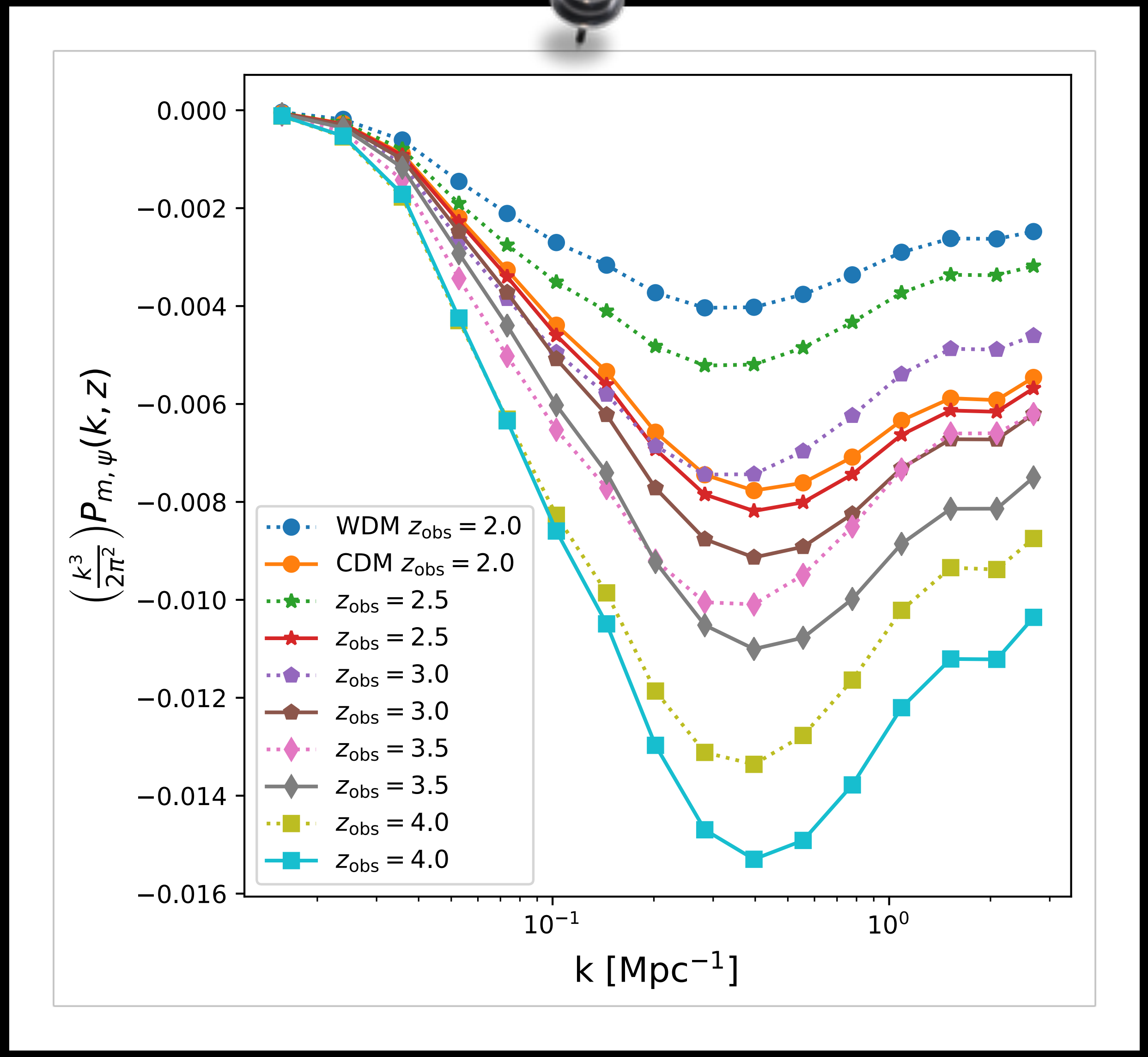
Lya-cosmo



$r^2\xi_0(r)$ [h^{-2} Mpc^2]
r [h^{-1} Mpc]
Base
Planck reio.
Late reio.
Early reio.



Impact of reionization on $P_{\mathrm{HI,Ly}\alpha}$ at $z = 4.0$
Deviation w.r.t conventional signal [%]
k [Mpc^{-1}]
Memory in Lyα Forest
Memory in HI IM



$\left(\frac{k^3}{2\pi^2}\right)P_{m,\psi}(k,z)$
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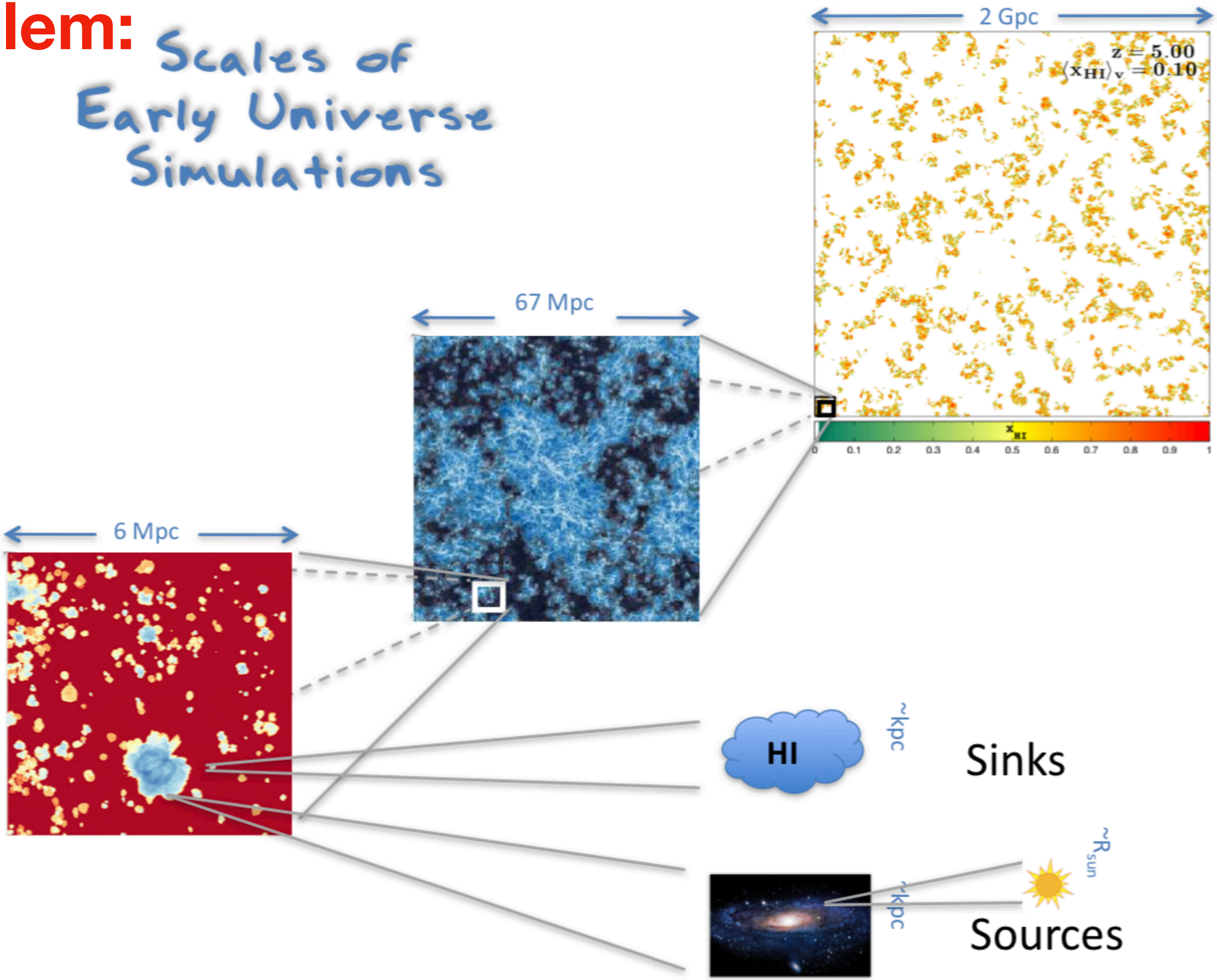
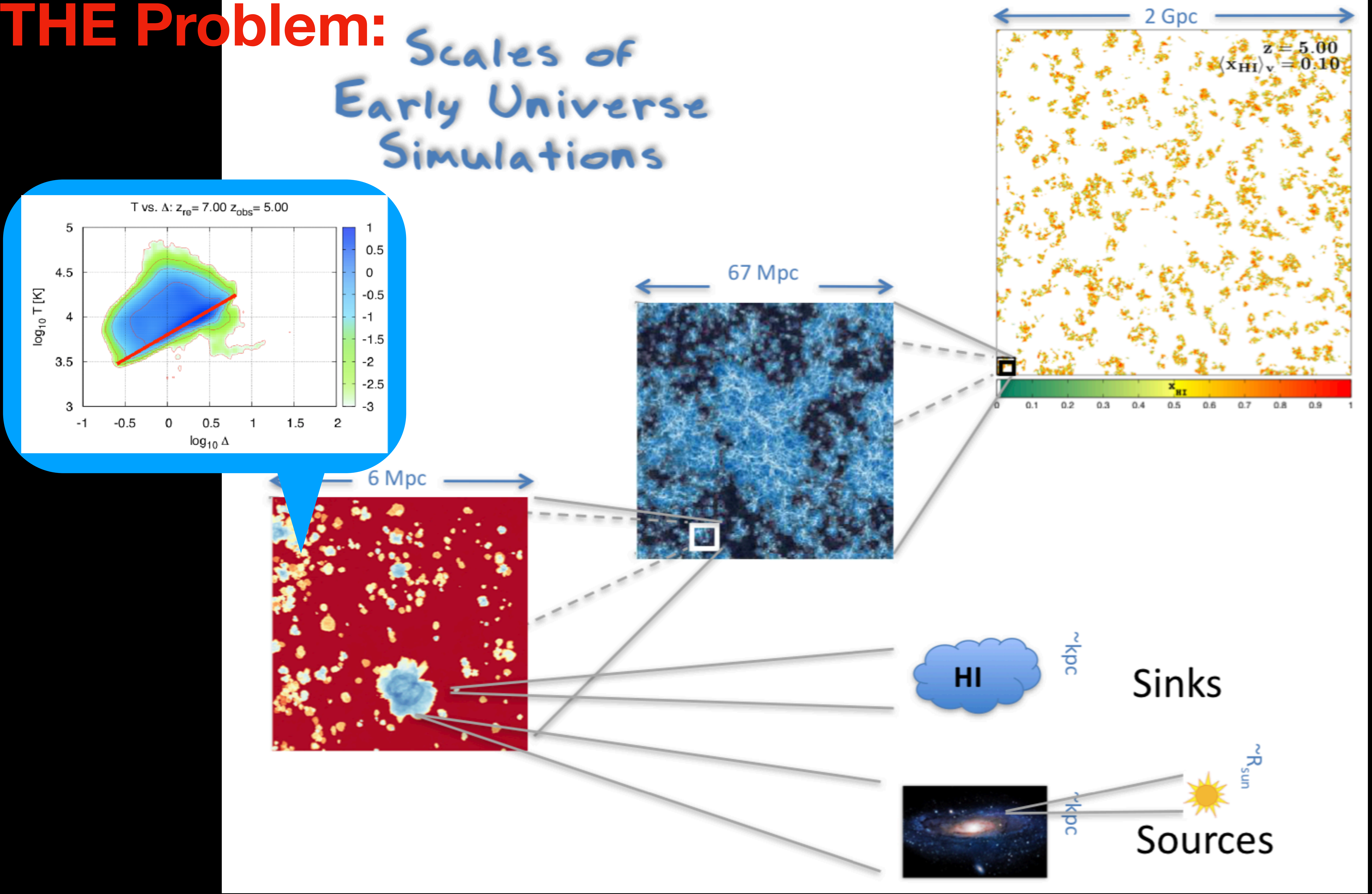
THE Problem: Scales of Early Universe Simulations



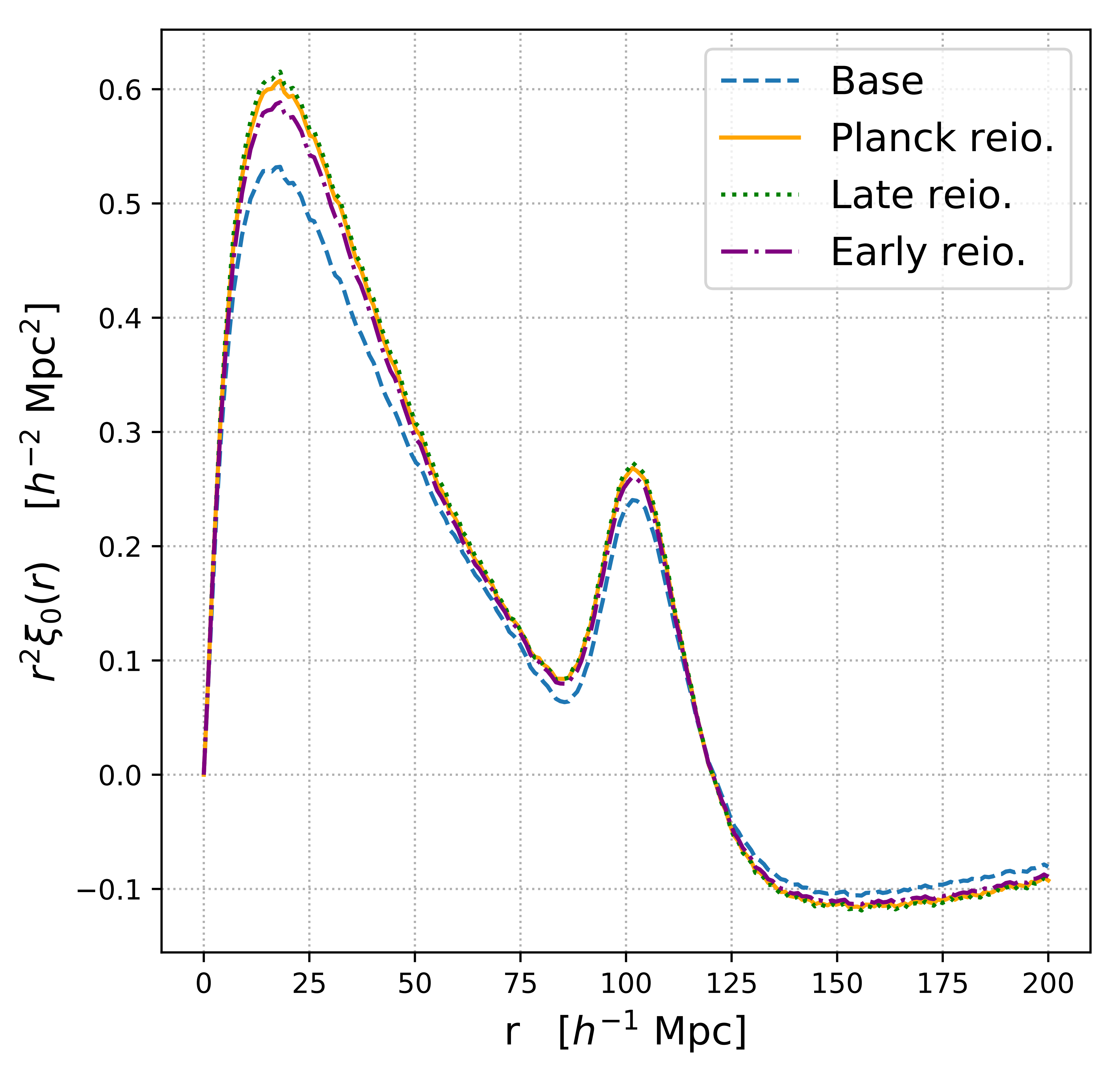
Mesinger (2018)

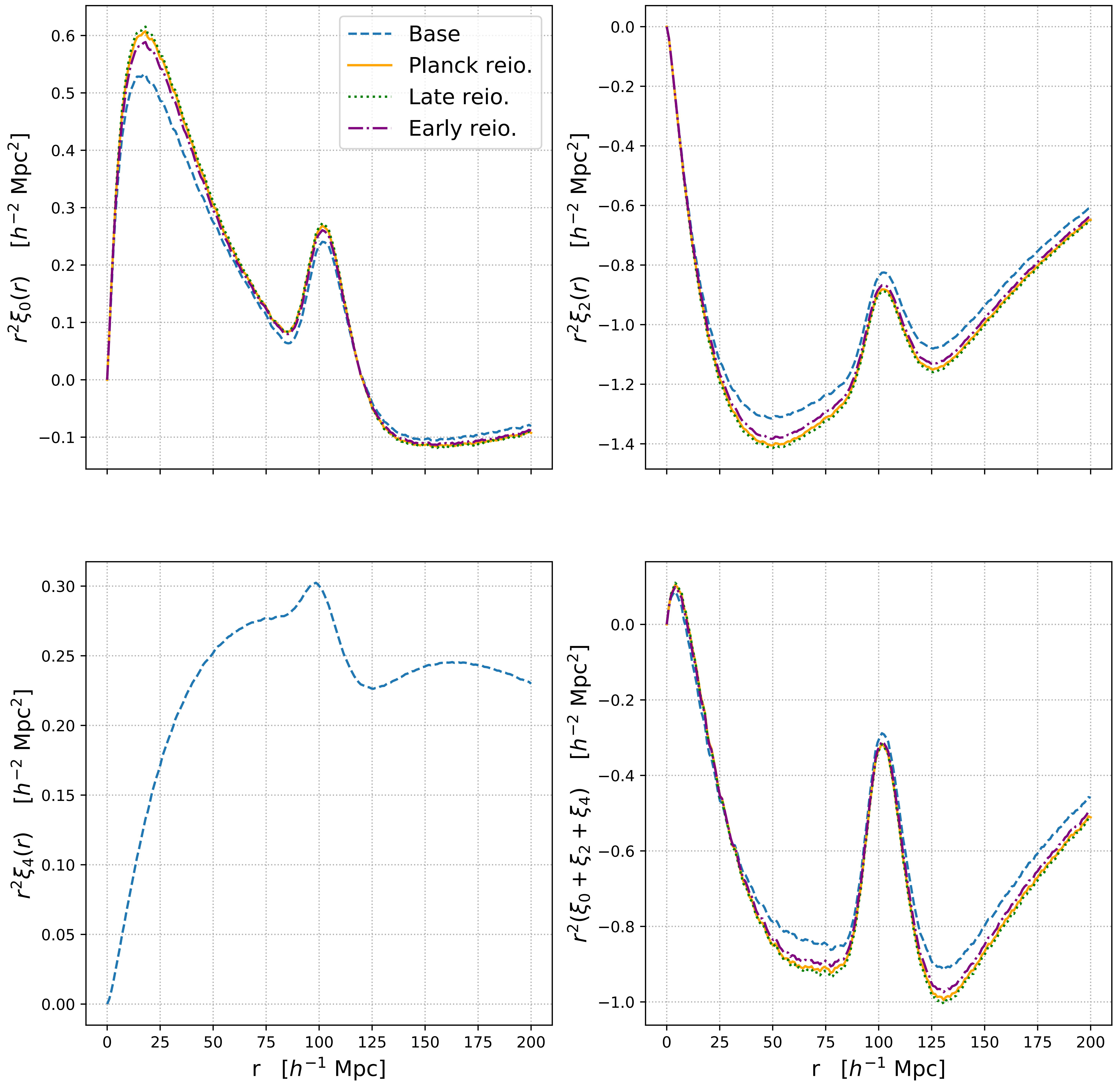
THE Problem: Scales of Early Universe Simulations



Mitigation

- Good news: BAO won't be affected, since this is a broadband effect.
- But if we ignore memory of reionization cosmological parameters **will be biased.**
- However, high-res hydro sims are **too slow** for typical MCMC strategies.
- Need a separation strategy!





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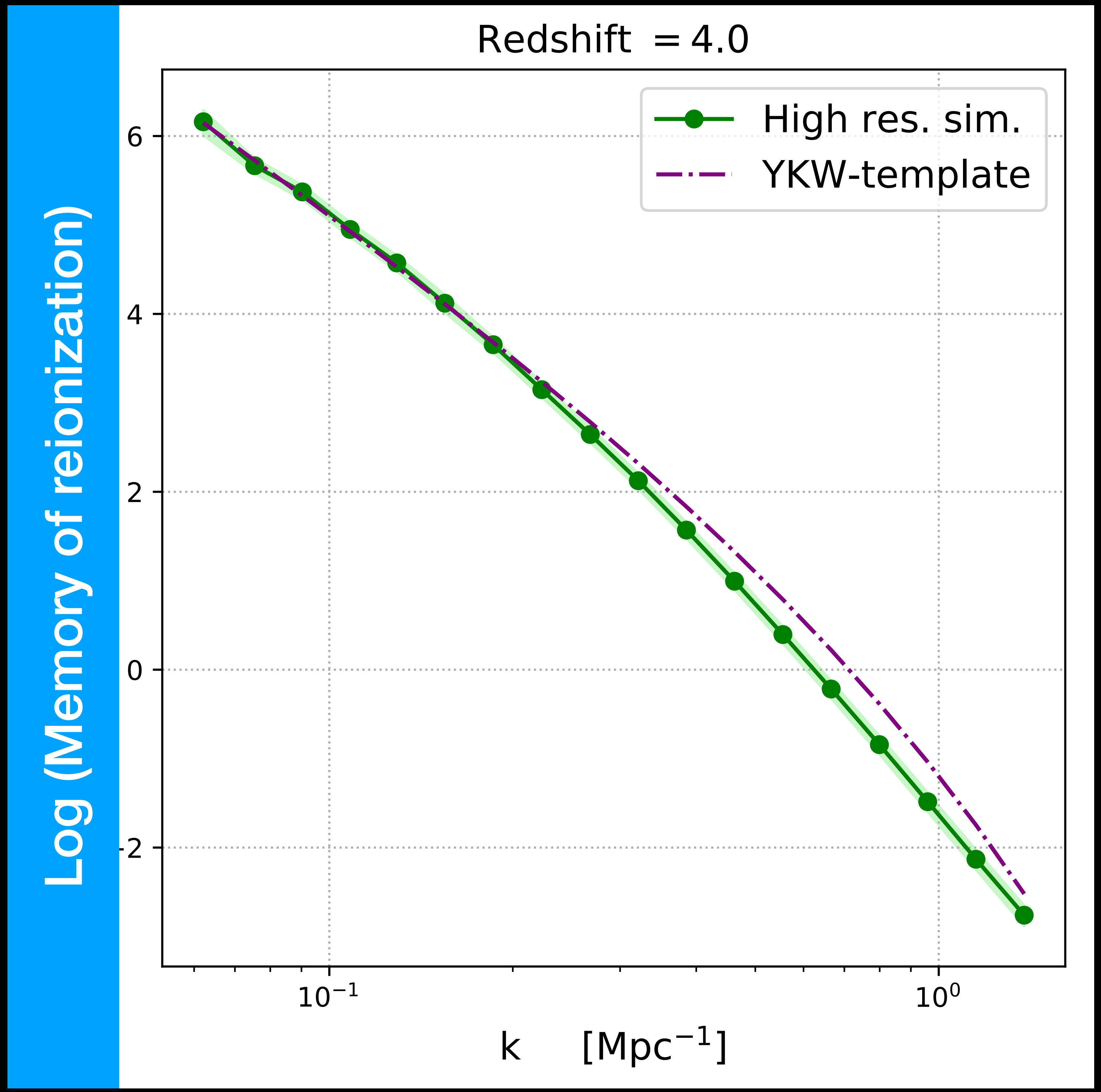
$r^2\xi_2(r)$ $[h^{-2}$ Mpc$^2]$
$r^2\xi_4(r)$ $[h^{-2}$ Mpc$^2]$
$r^2(\xi_0+\xi_2+\xi_4)$ $[h^{-2}$ Mpc$^2]$
r $[h^{-1}$ Mpc$]$
r $[h^{-1}$ Mpc$]$

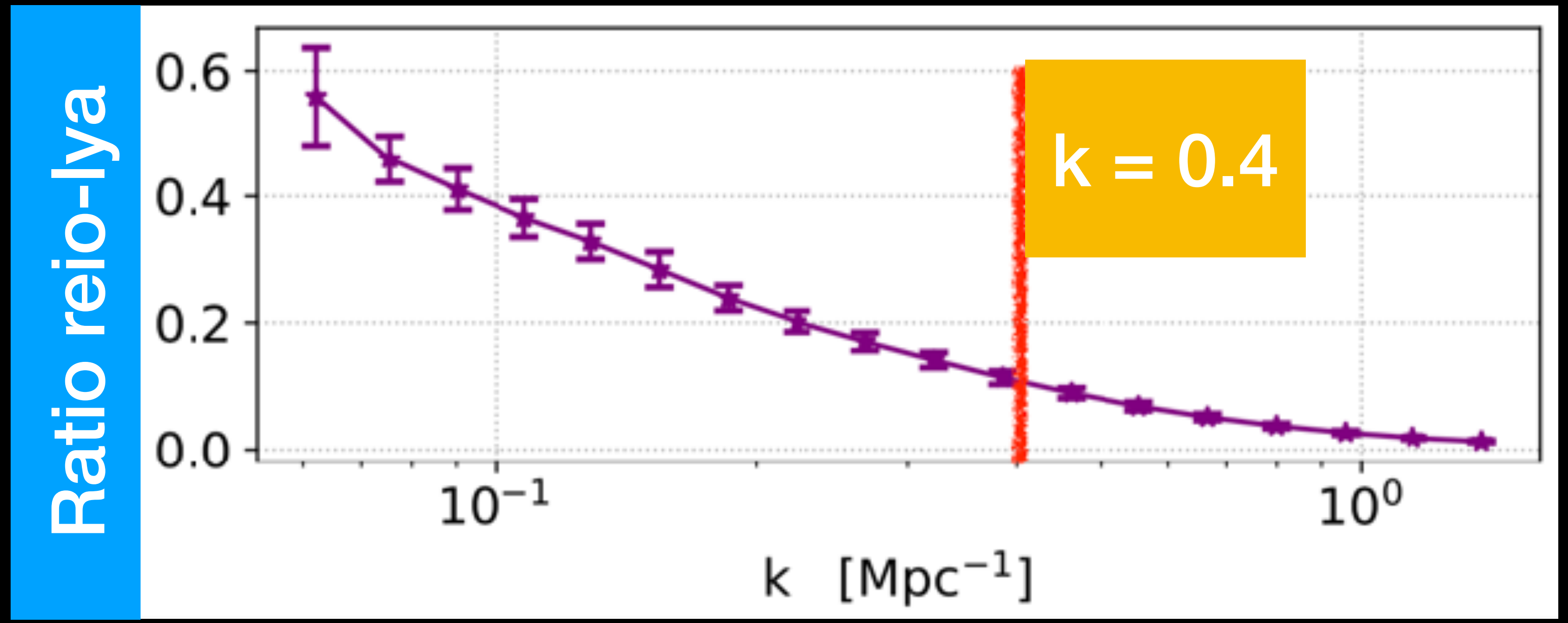
A Yukawa-inspired shape

$$\text{Memory of reionization} = -\frac{Ae^{-\alpha\left(\frac{k}{k_0}\right)}}{\left(\frac{k}{k_0}\right)^{\beta}}$$

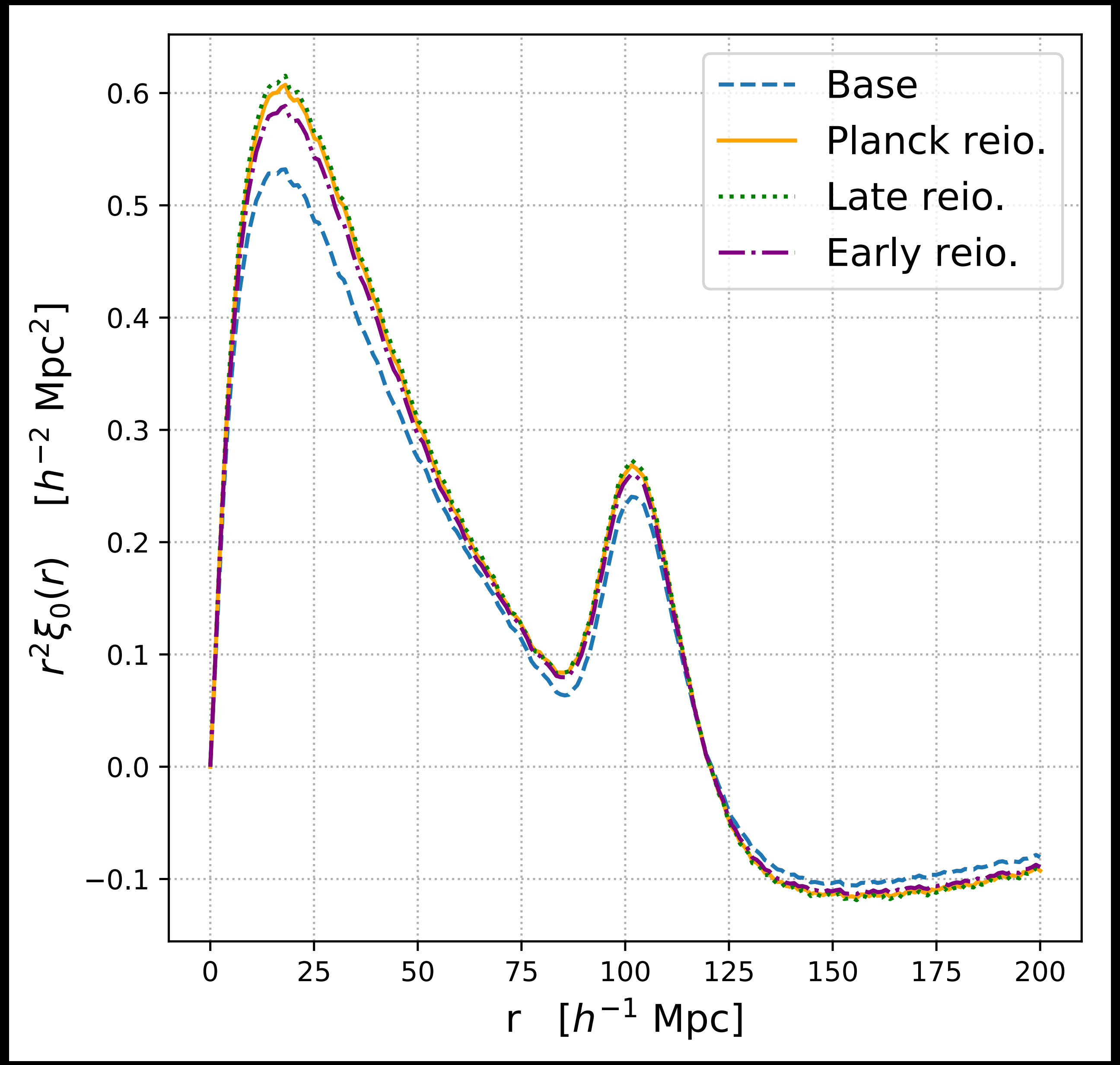


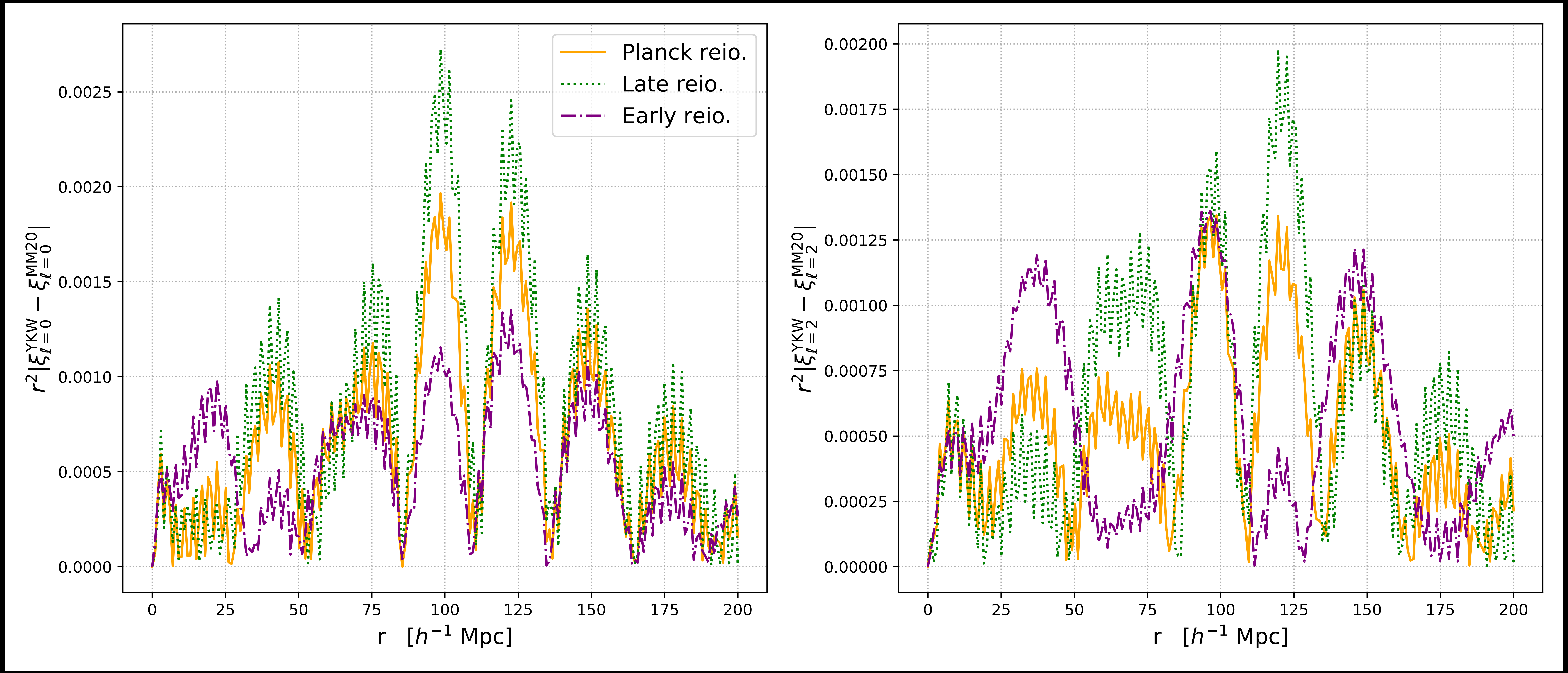
- A: overall normalization factor.
- 1/alpha: effective range, i.e. *"screen effect".*
- Beta: corrects the small-k behavior (in QED is related to the photon propagator).

But, remember that:



A Yukawa-inspired shape





But what happens when we do not know the reionization history**?

A Yukawa-inspired shape: a better test

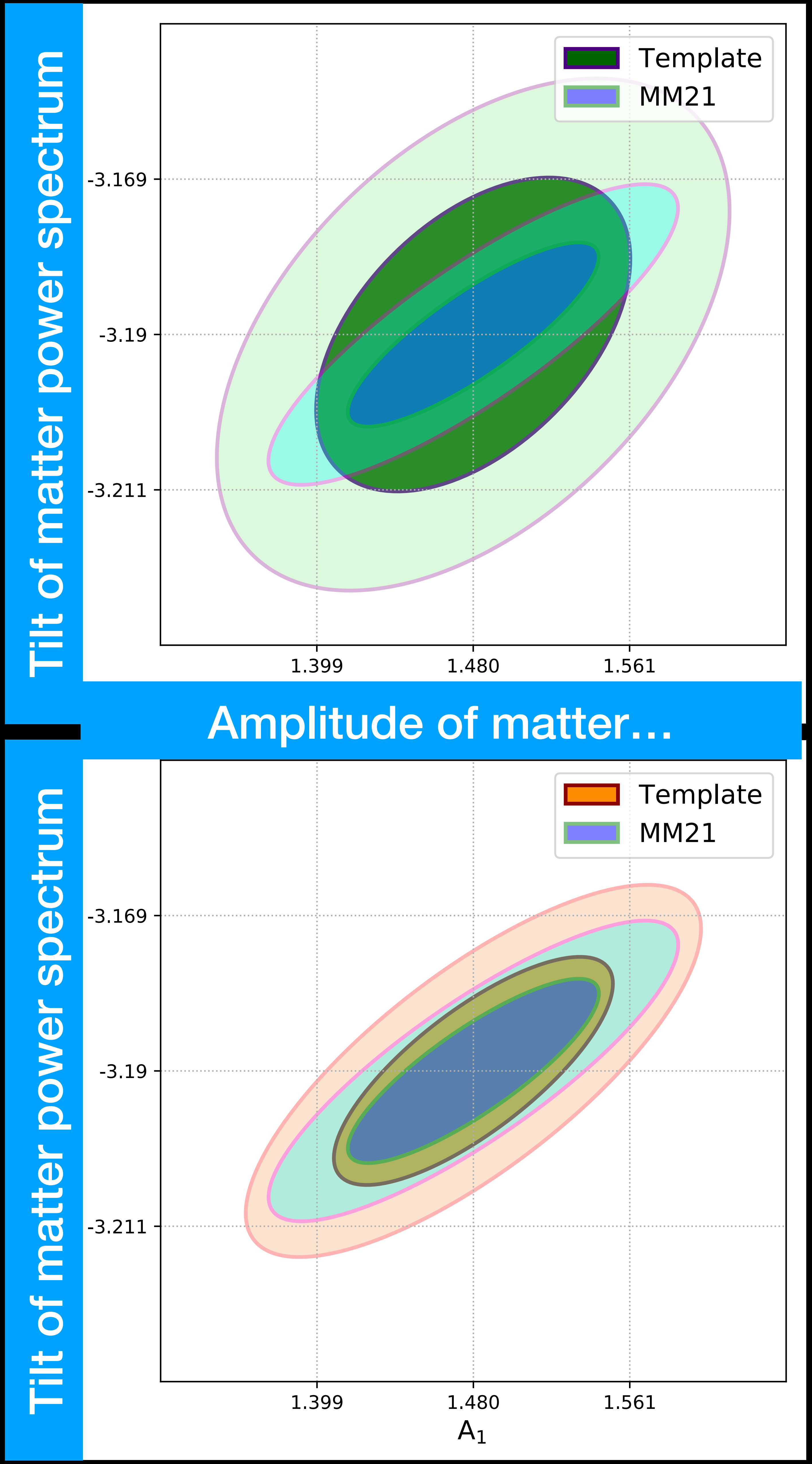
$$\text{Memory of reionization} = -\frac{A e^{-\alpha\left(\frac{k}{k_0}\right)}}{\left(\frac{k}{k_0}\right)^{\beta}}$$

Lya forest

Lya forest + Planck priors

But template still ignores cosmology dependence

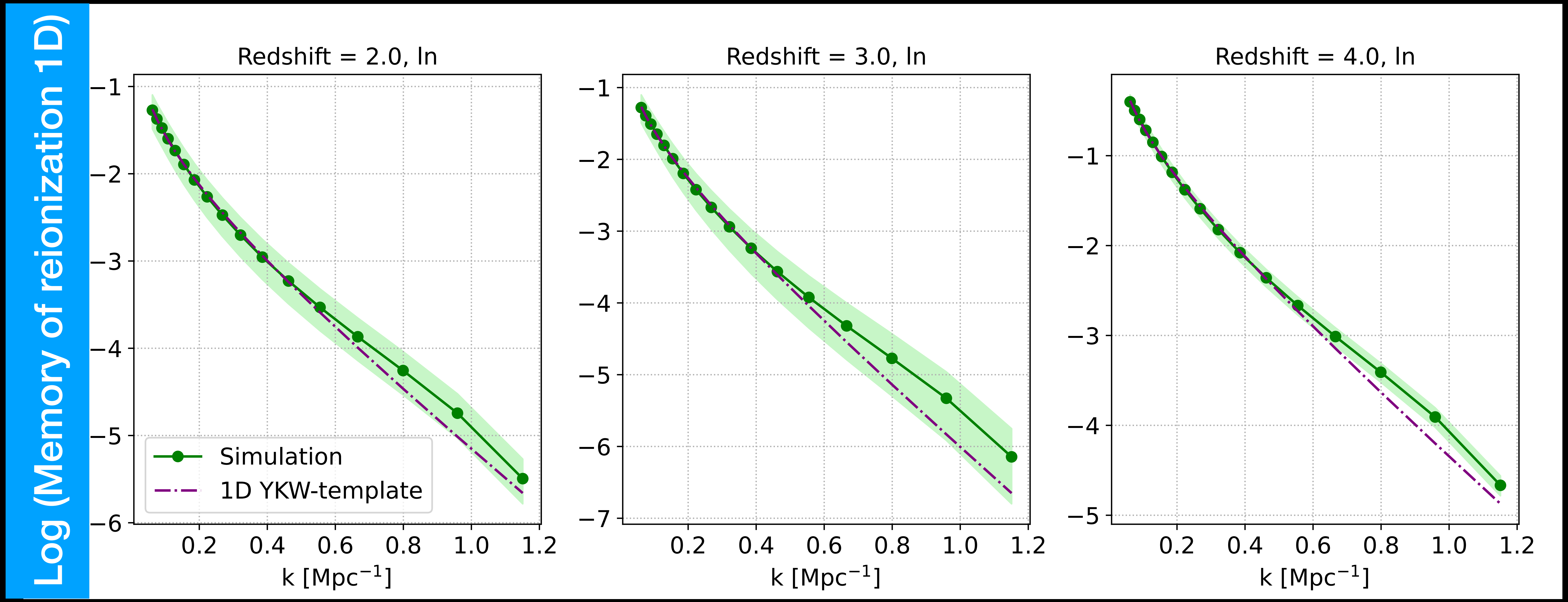
Y. Liu (UCL, undergraduate student)



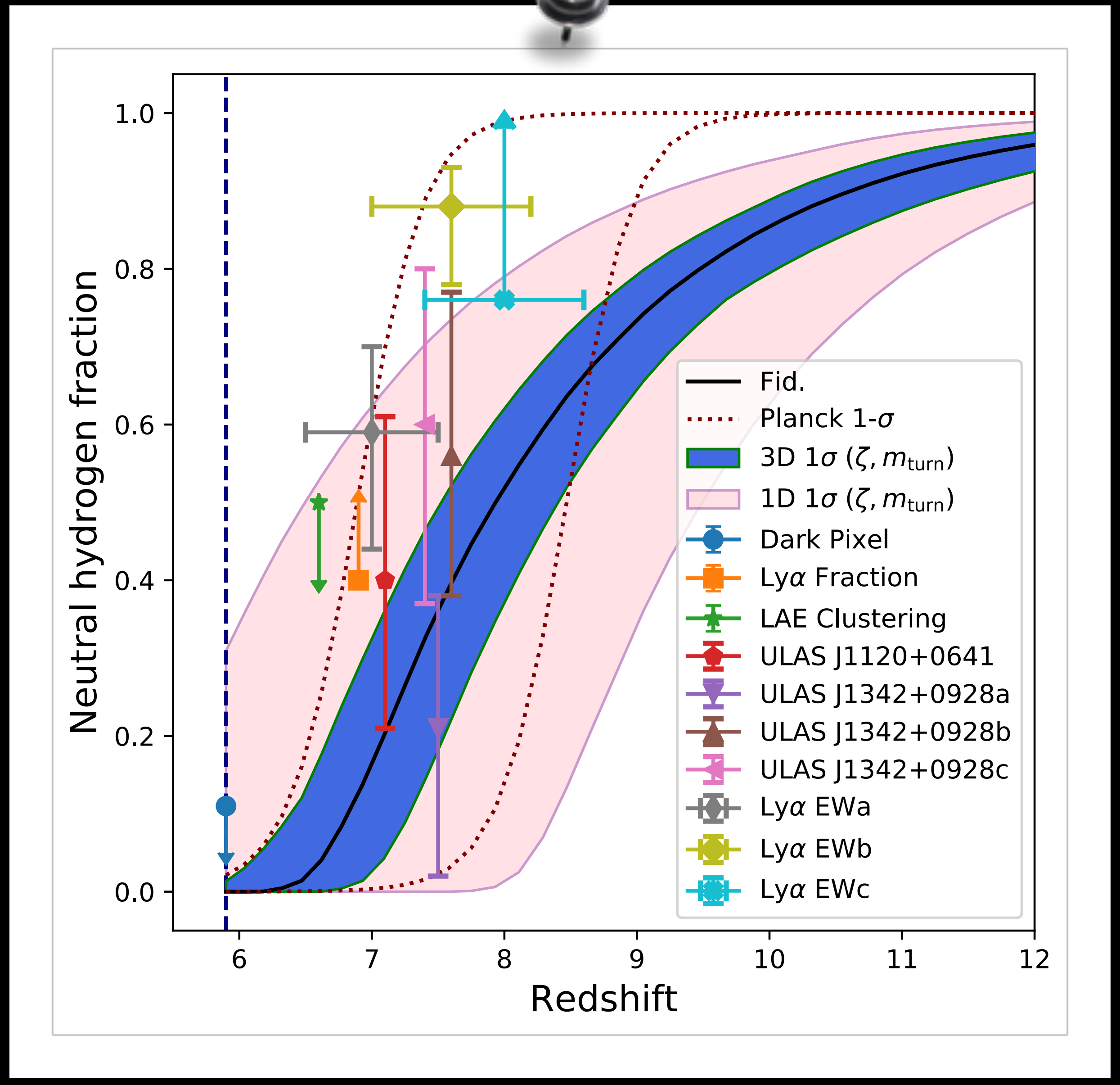
PMC, Liu & Mao (in prep.)

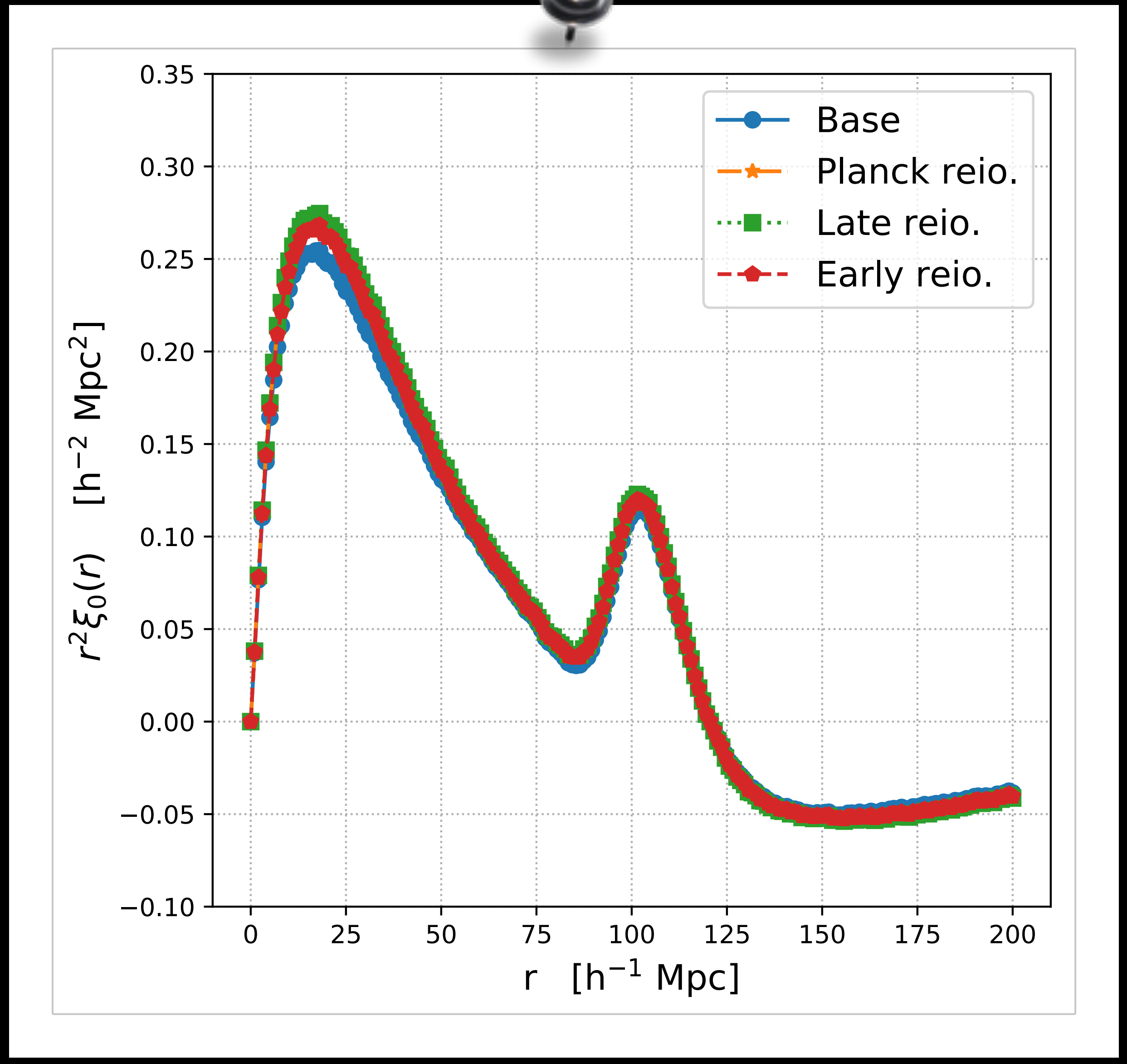
A Yukawa-inspired shape for 1D

Memory of reionization 1D $= -\dfrac{Ae^{-\alpha\left(\frac{k}{k_0}\right)}}{\left(\frac{k}{k_0}\right)^{\beta}}$

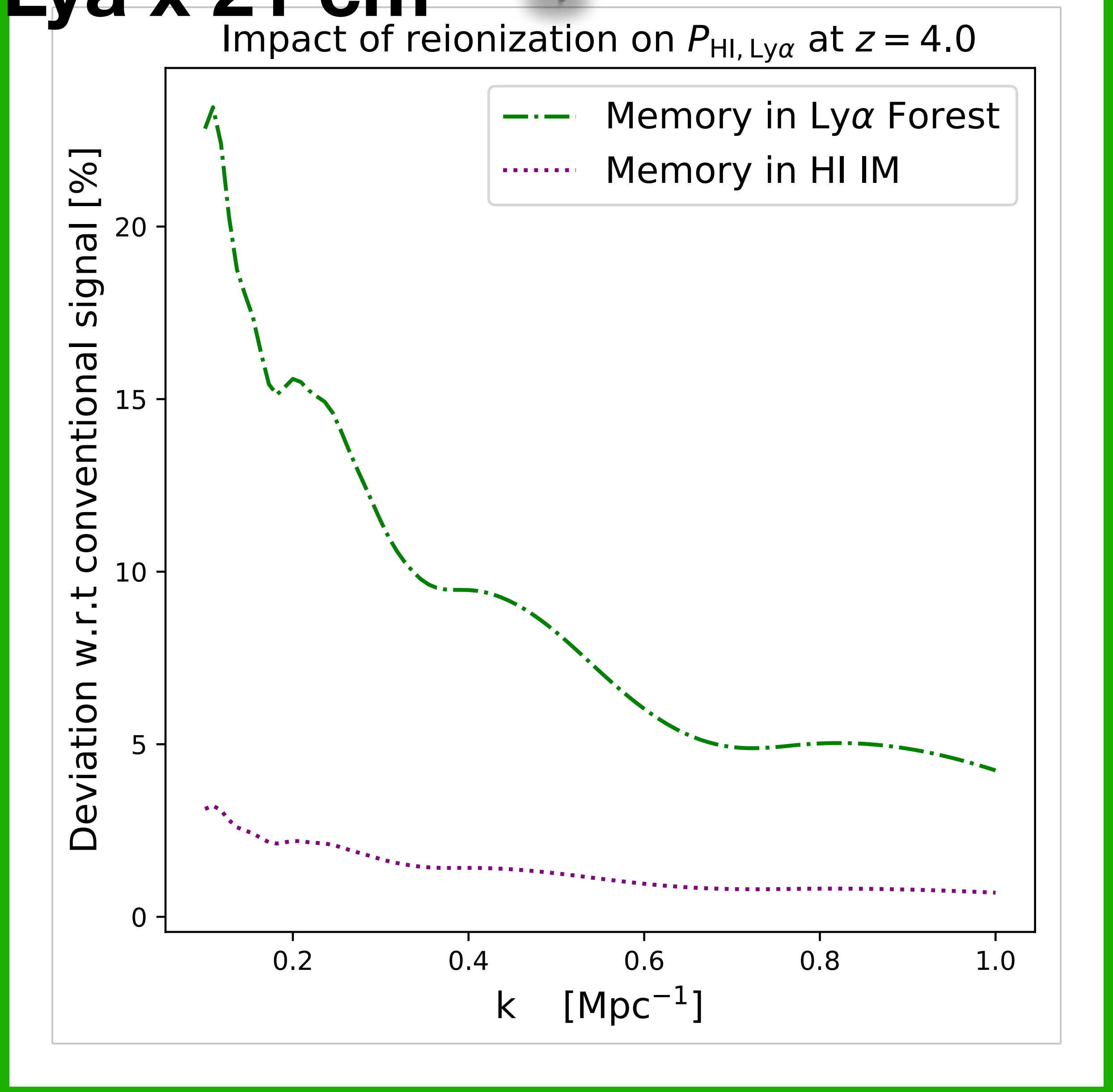


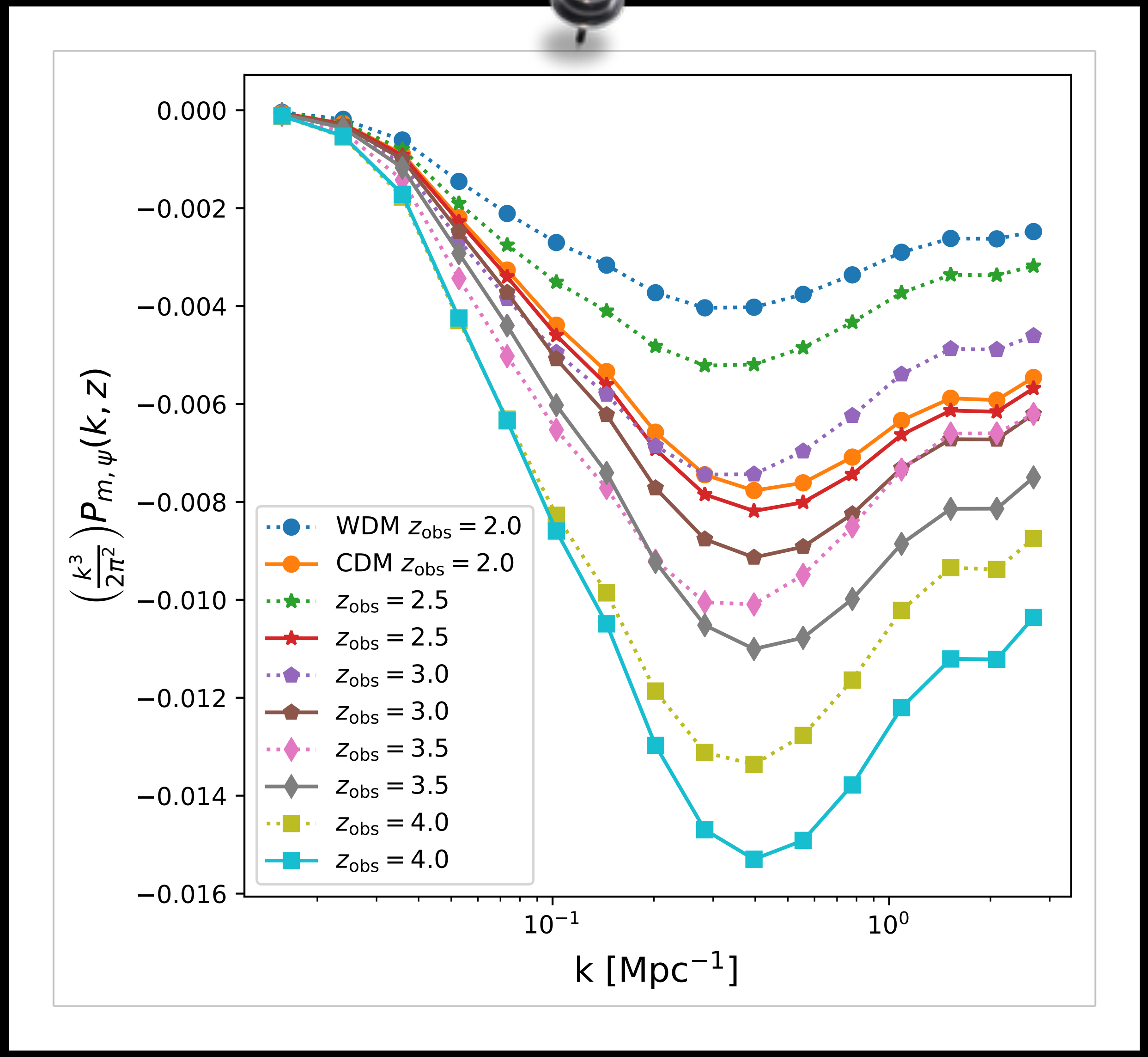
PMC, Liu & Mao (in prep.)


Neutral hydrogen fraction
Redshift
Fid.
Planck 1-σ
3D 1σ (ζ, m_turn)
1D 1σ (ζ, m_turn)
Dark Pixel
Lyα Fraction
LAE Clustering
ULAS J1120+0641
ULAS J1342+0928a
ULAS J1342+0928b
ULAS J1342+0928c
Lyα EWa
Lyα EWb
Lyα EWc


Base
Planck reio.
Late reio.
Early reio.
$r^2\xi_0(r)$ [h^{-2} Mpc^2]
r [h^{-1} Mpc]

Lya x 21 cm


Impact of reionization on $P_{\mathrm{HI,Ly}\alpha}$ at $z = 4.0$
Memory in Lyα Forest
Memory in HI IM
Deviation w.r.t conventional signal [%]
k [Mpc^{-1}]


WDM $z_{\mathrm{obs}} = 2.0$
CDM $z_{\mathrm{obs}} = 2.0$
$z_{\mathrm{obs}} = 2.5$
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$z_{\mathrm{obs}} = 3.0$
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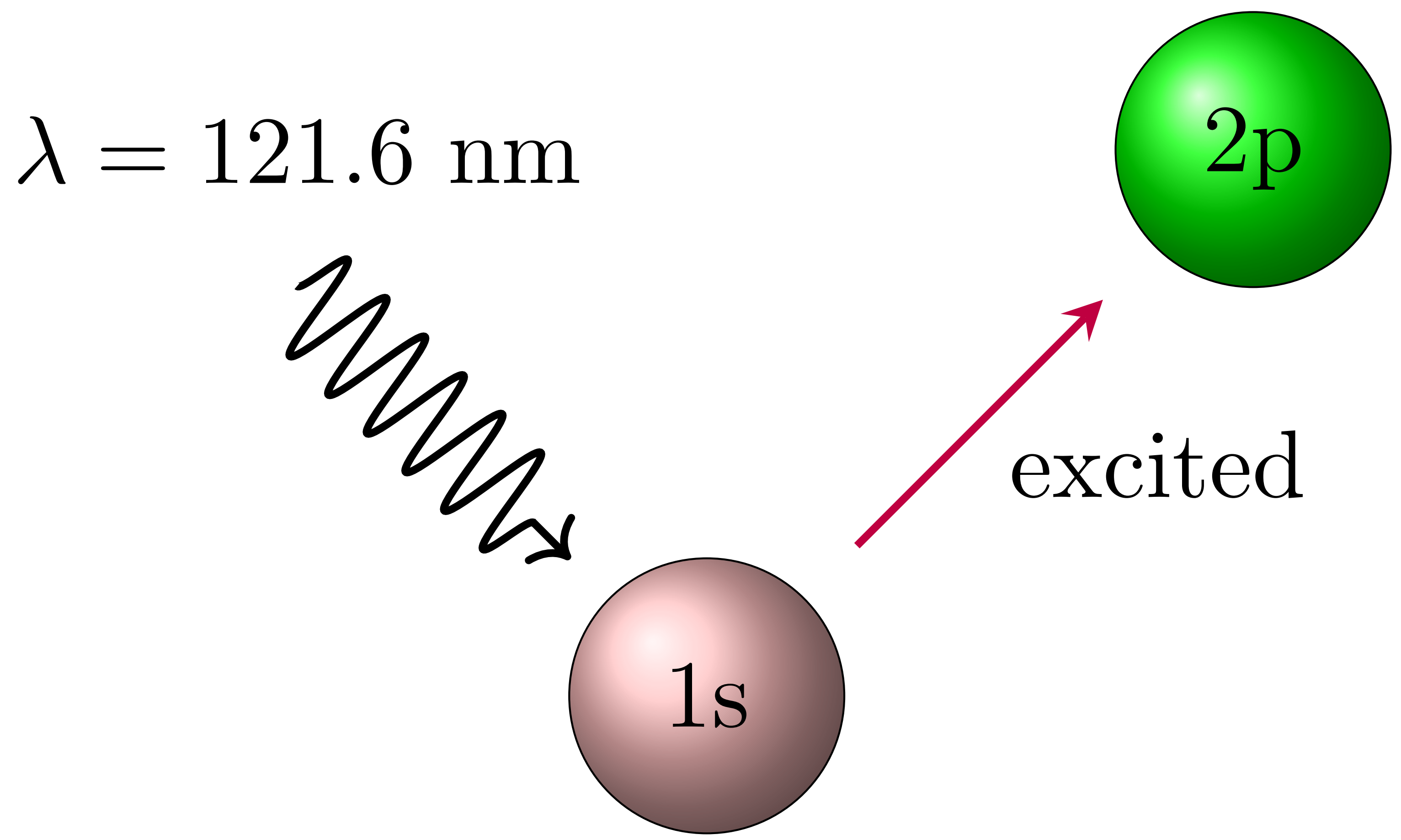
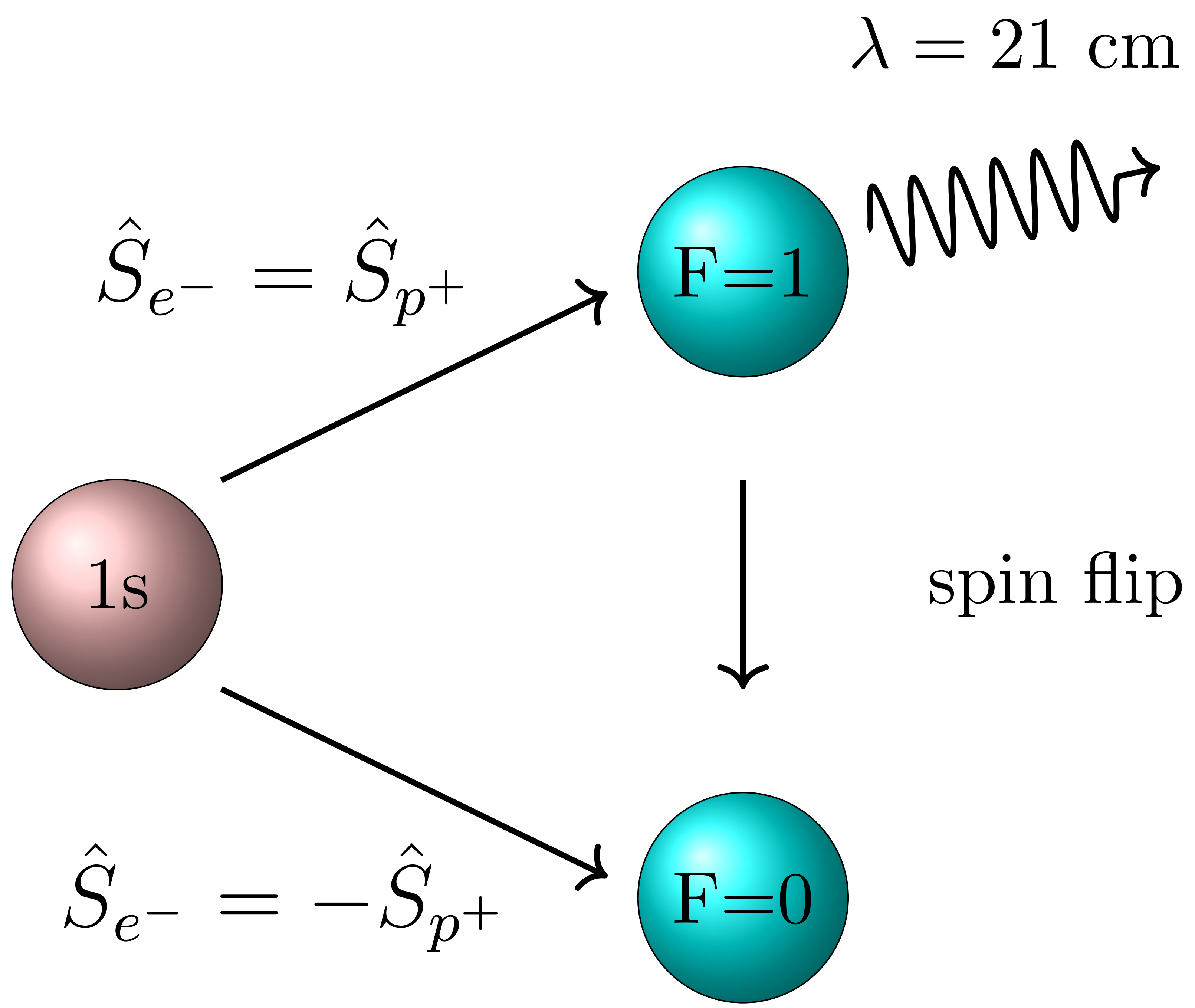
$\left(\frac{k^3}{2\pi^2}\right)P_{m,\psi}(k,z)$
k [Mpc^{-1}]

Lyman-alpha

21 cm





- Lifetime: ~ 10 nano seconds.
- Ultraviolet (at emission).

- Lifetime: ~ 100 Tera seconds (roughly **3 million years**).
- Microwave (at emission).

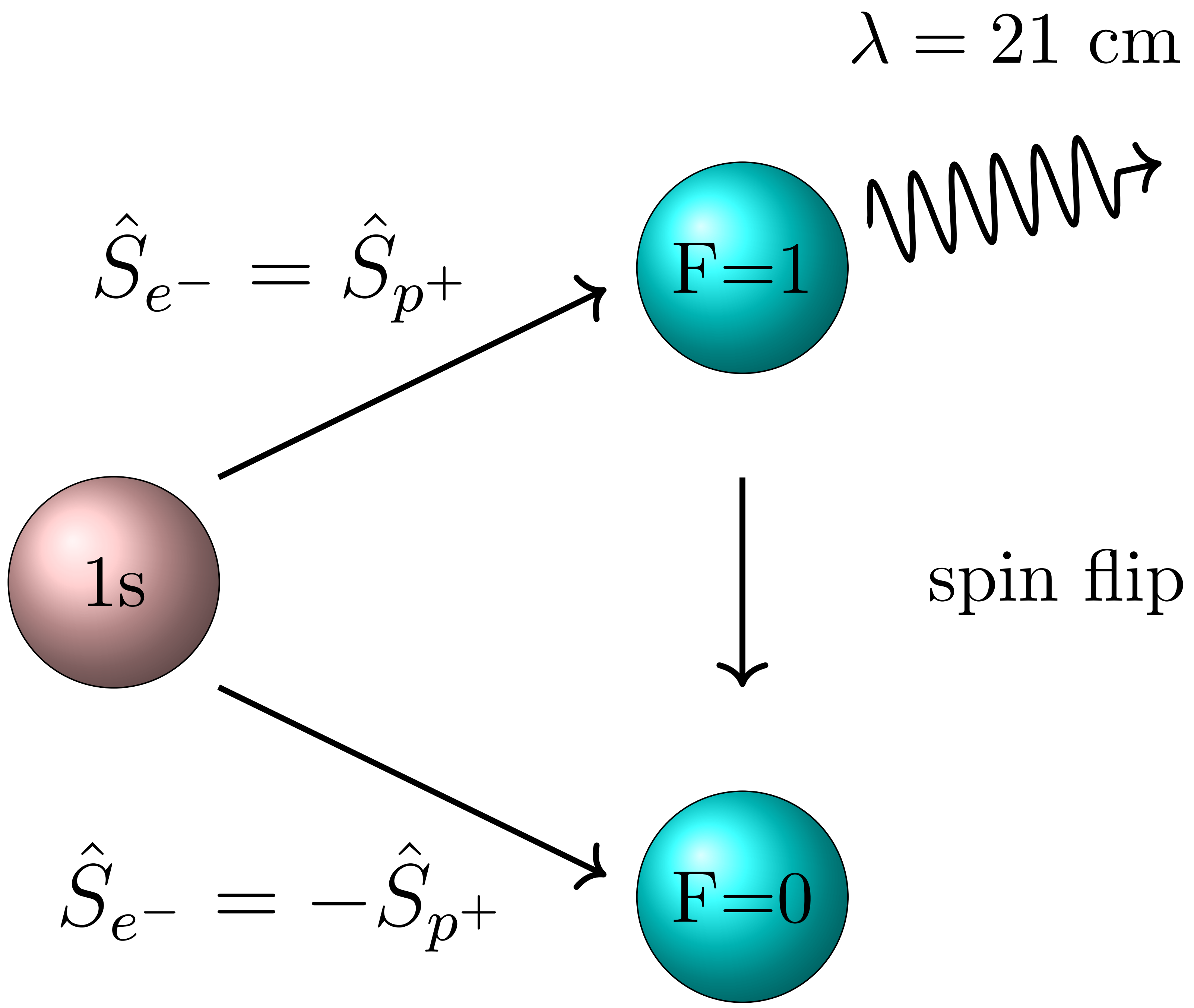
21 cm cosmology

* Capable of 3D maps of the Universe (think 3D CMB!)

* Forbidden transition, but:

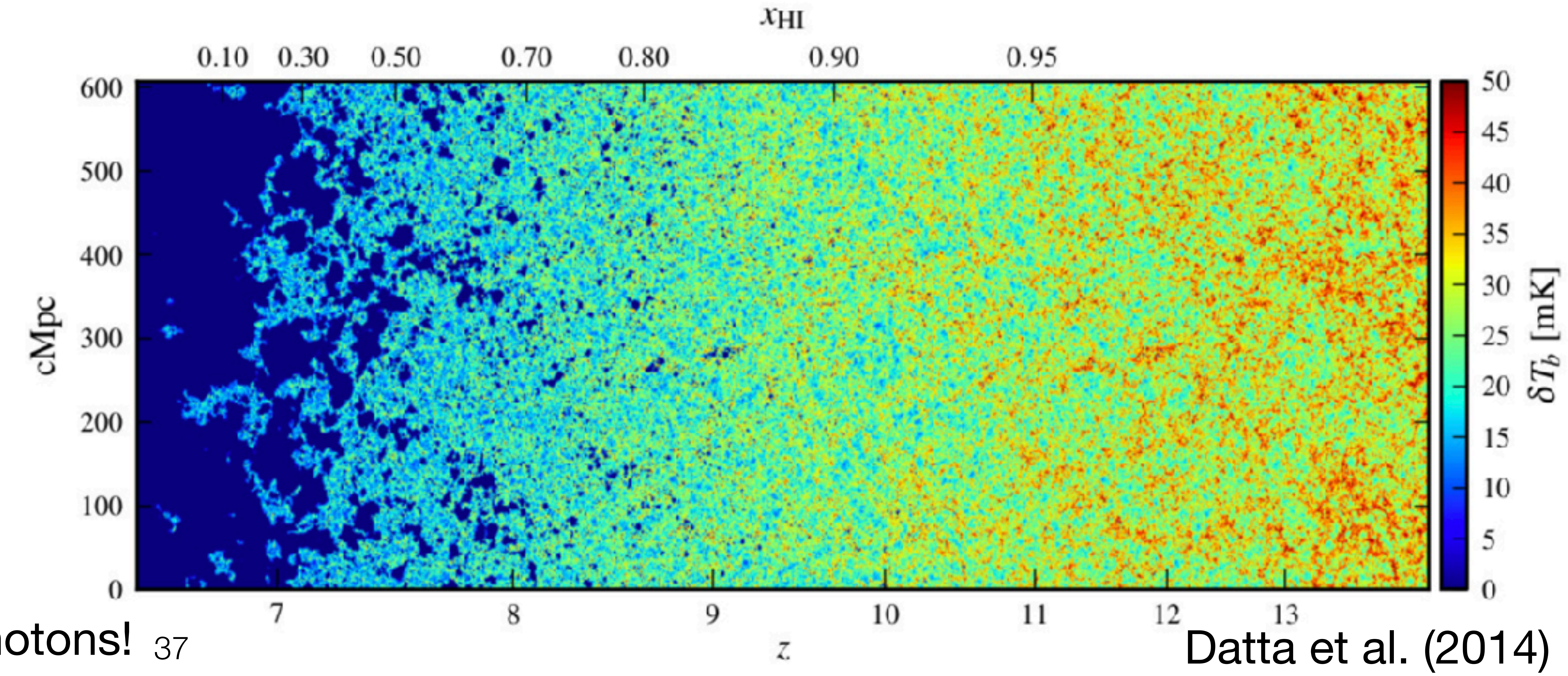
  ✓ **Gargantuan** amounts of hydrogen!

  ✓ **Colossal time** scales



At 1 + z = 20, we have:

$$
\begin{aligned}
n_H &\sim 10^3 \text{ m}^{-3} \\
V_c &\sim 10^{80} \text{ m}^3 \\
\Rightarrow N_H^{\text{tot}} &\sim 10^{83} \text{ H atoms} \\
t_{\text{age}} &\sim 10^{15} \text{ s} = 0.19 \text{ Gyr}
\end{aligned}
$$



Datta et al. (2014)

So **0.2 billion years > 3 million years** thus many 21 cm photons!

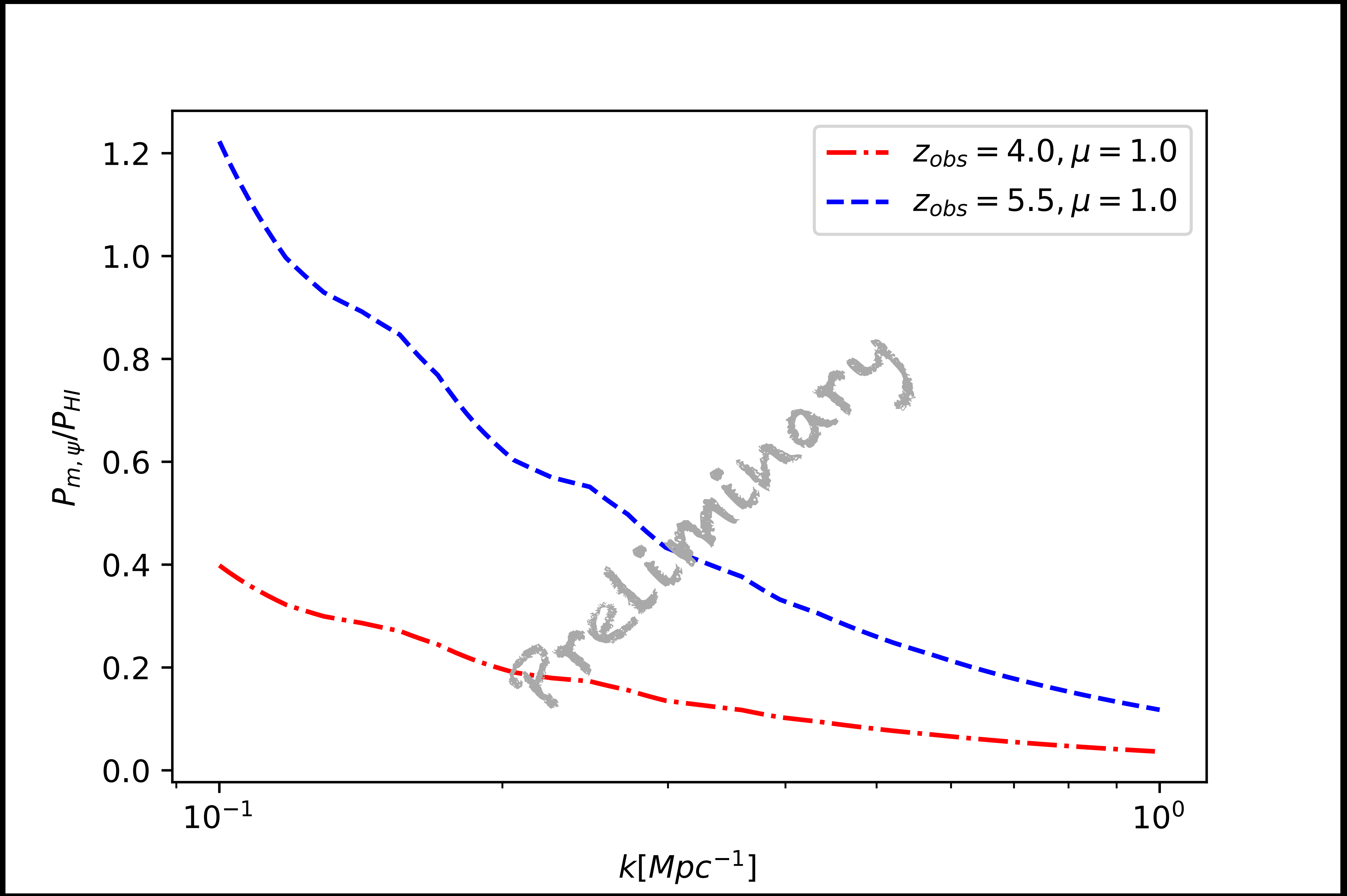
A new hope: Memory in 21 cm LIM (post-reionization)

H. L.

C. M.

C. M. H.

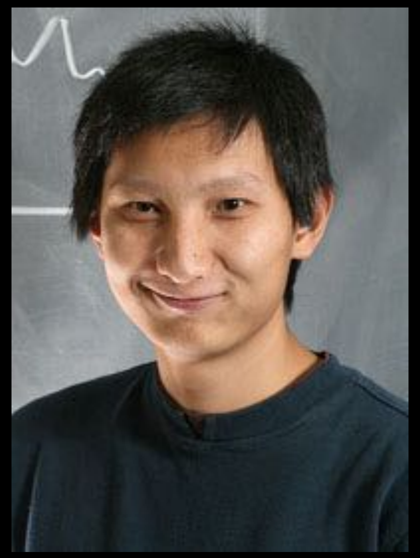
- Reionization **affects denser regions too** -> Memory of reionization in 21 cm.
- For galaxies with shallow potential wells inhomogeneous reionization modulates the amount of baryons that can sit on a given halo.
- Instead of thermal evolution of the IGM, the key question here is how 21 cm intensity changes for a patch of sky that reionizes at z1 vs one that did at z2.



An easier measurement: Memory in Lya forest X 21 cm LIM

H. L.

C. M.



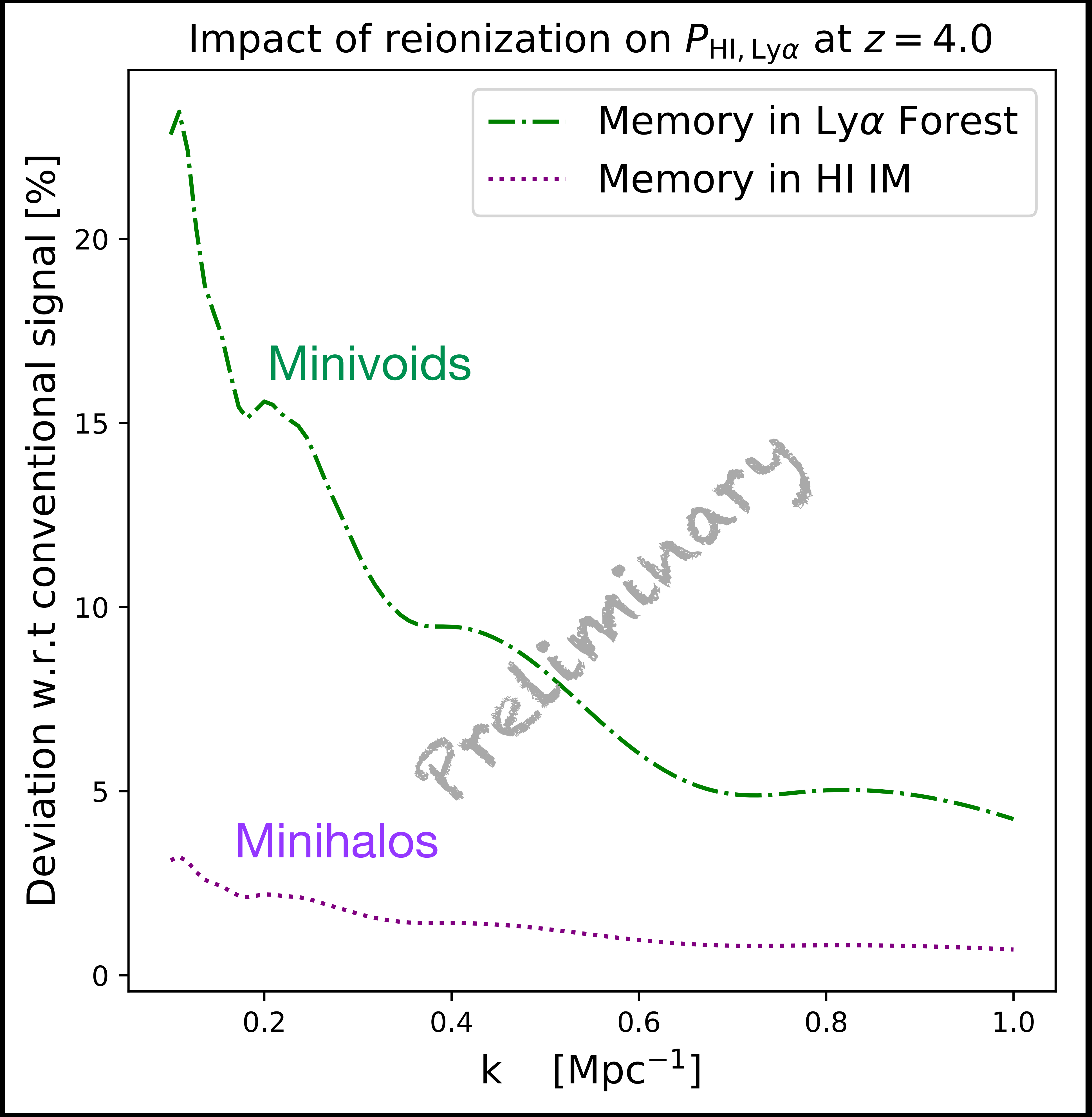
Y. M.

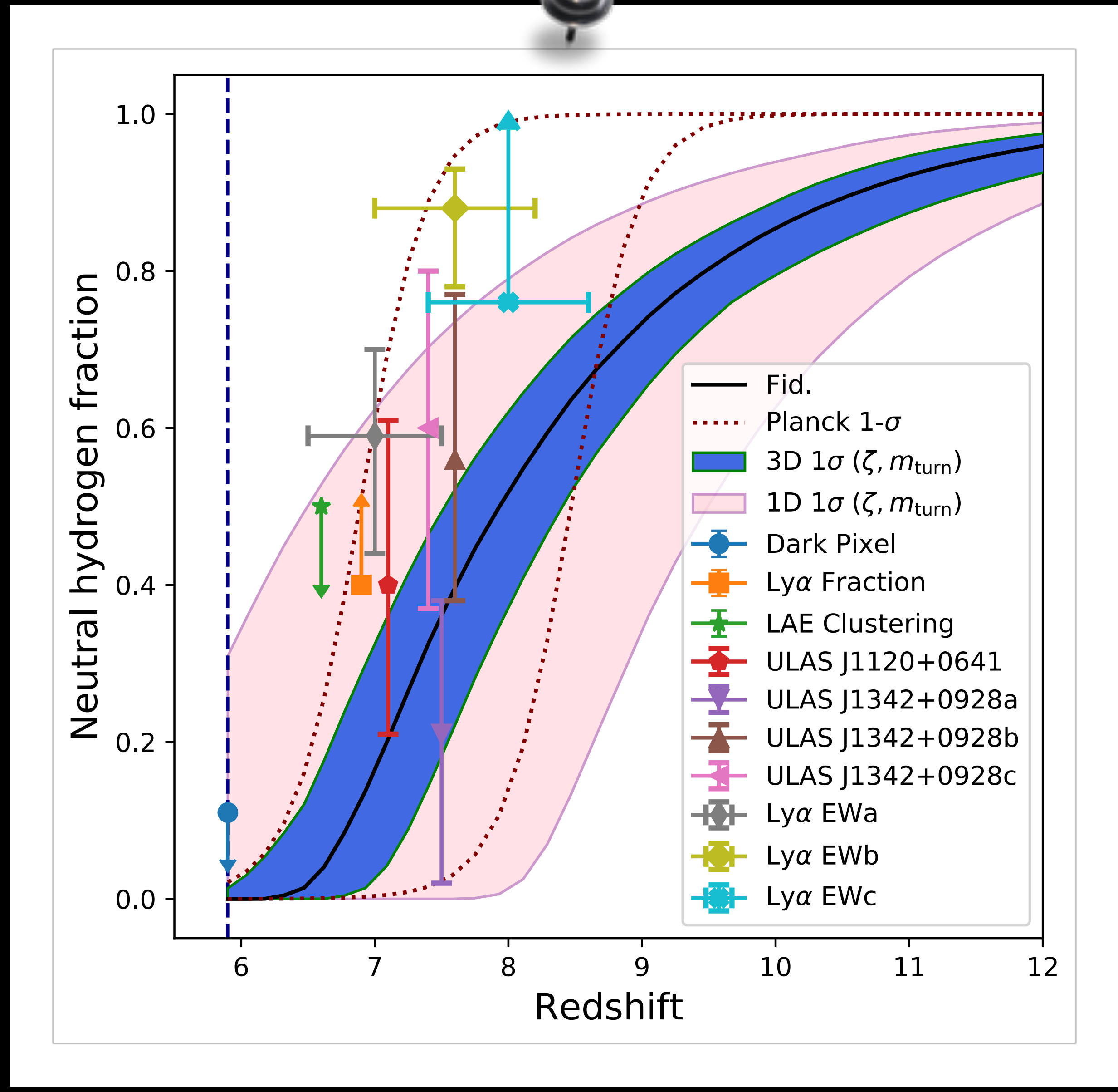
C. M. H.

- 21 cm unlocks cross-correlation with Lya forest (Reionization effect on dense vs underdense regions).
- 21 cm LIM hard due to foregrounds.
- Lya forest hard due to sparse sampling of QSO at high-z.

Systematics are uncorrelated!

- Memory of reionization in 21 cm also unlocks other emission lines, looking at CO and [CII] lines next!
- Further along: HD, H-alpha, Lya emission.





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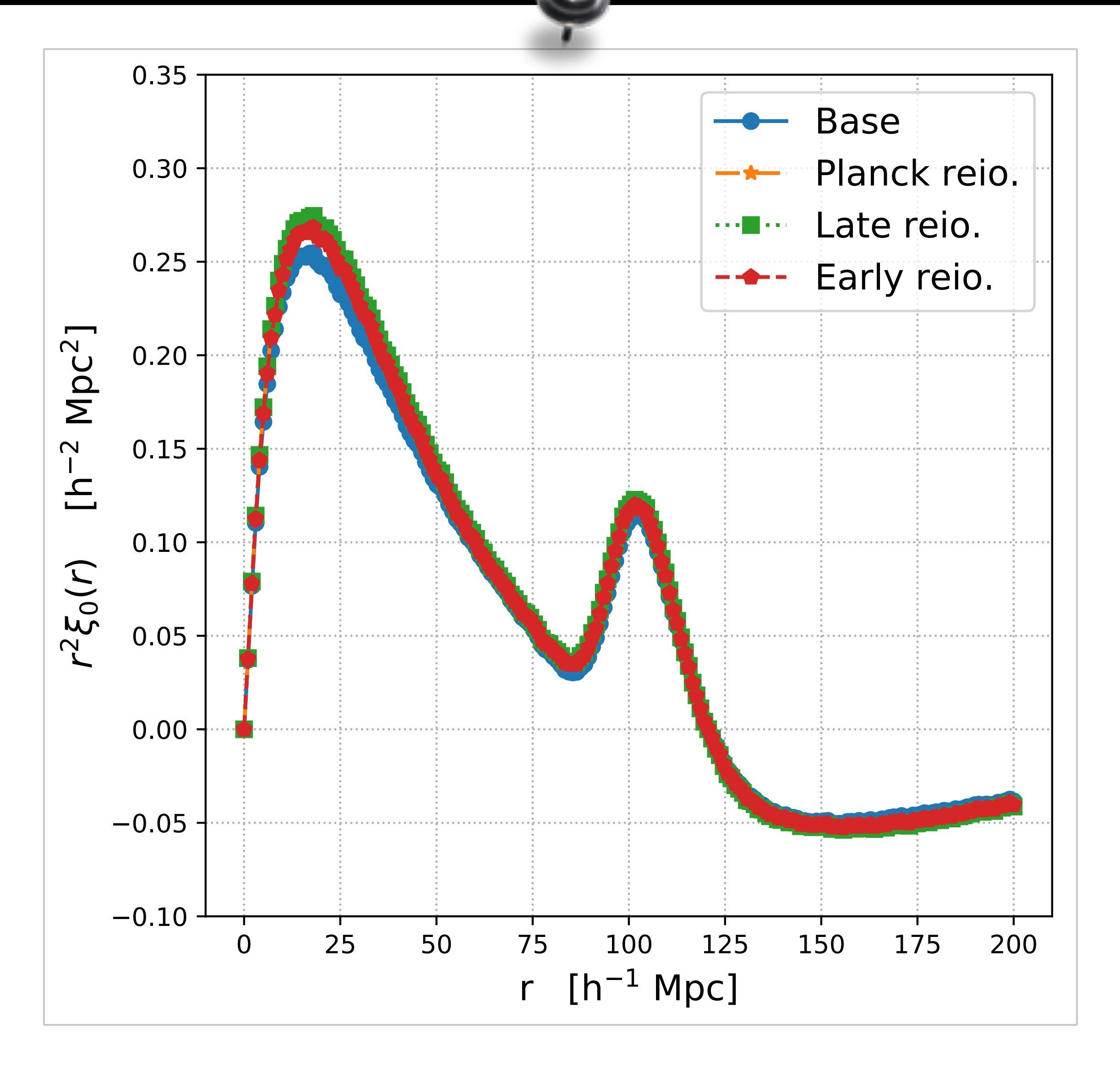

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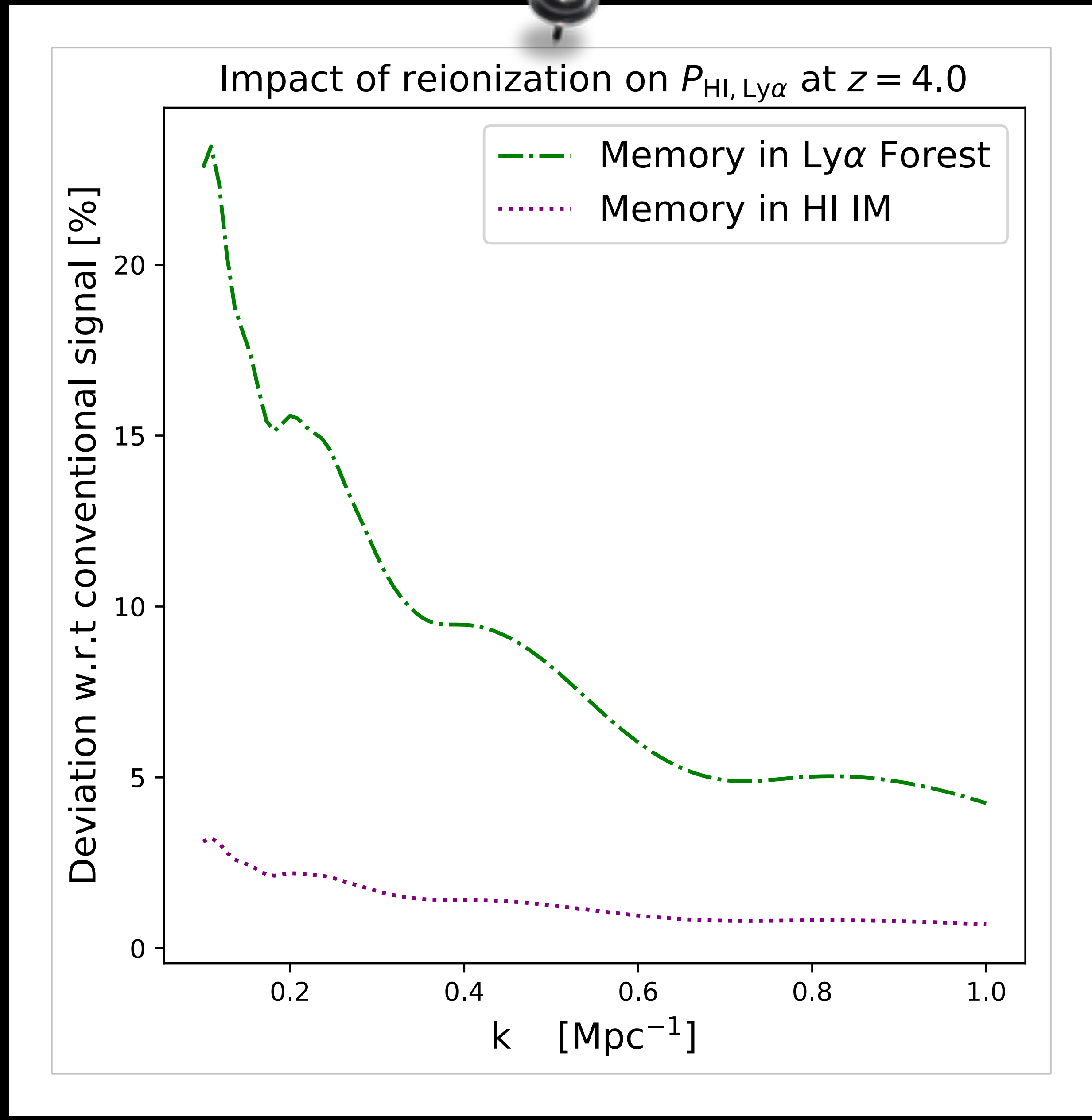
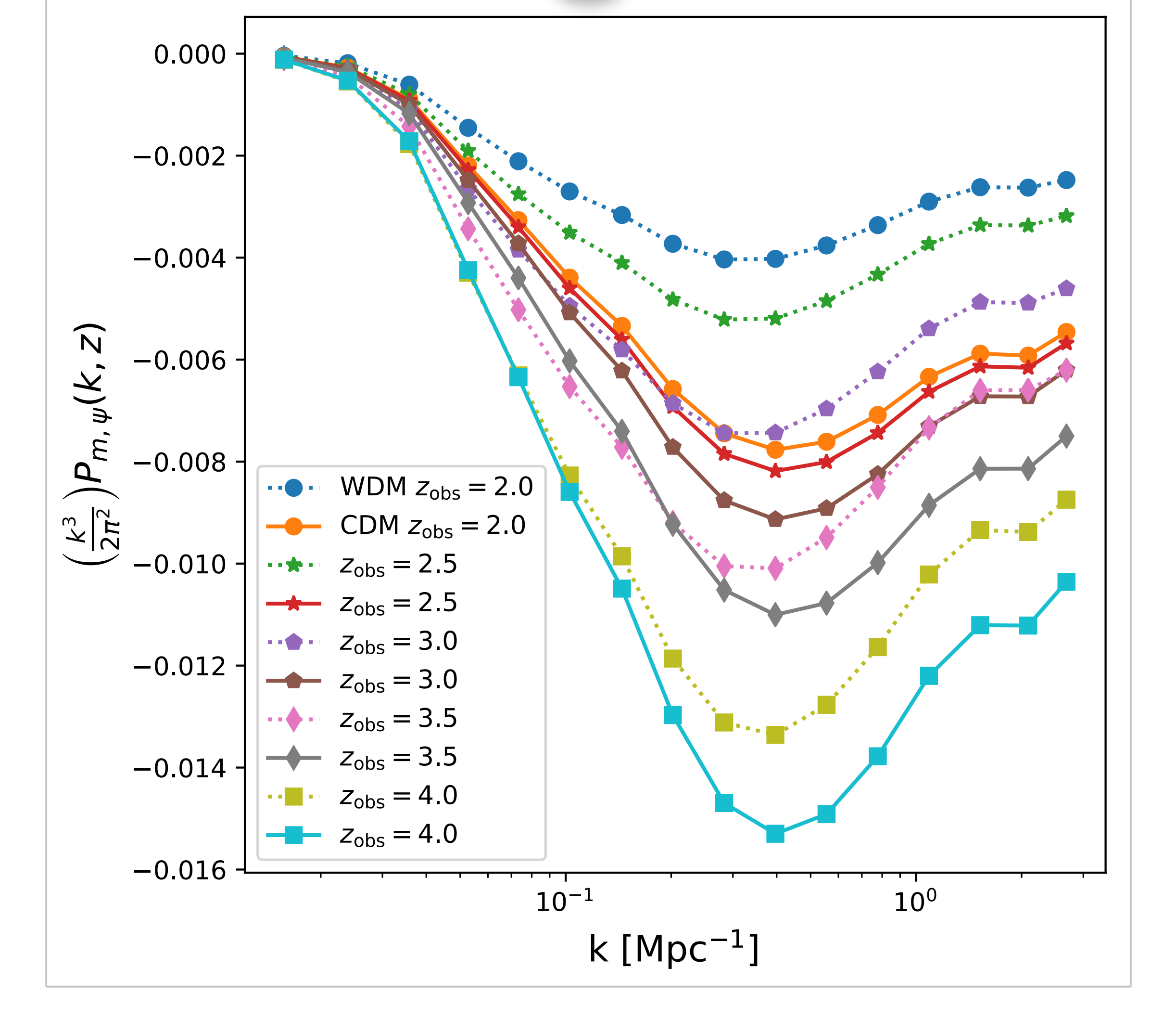


Impact of reionization on $P_{\mathrm{HI,Ly}\alpha}$ at $z = 4.0$
Memory in Lyα Forest
Memory in HI IM
Deviation w.r.t conventional signal [%]
k [Mpc^{-1}]

Dark matter



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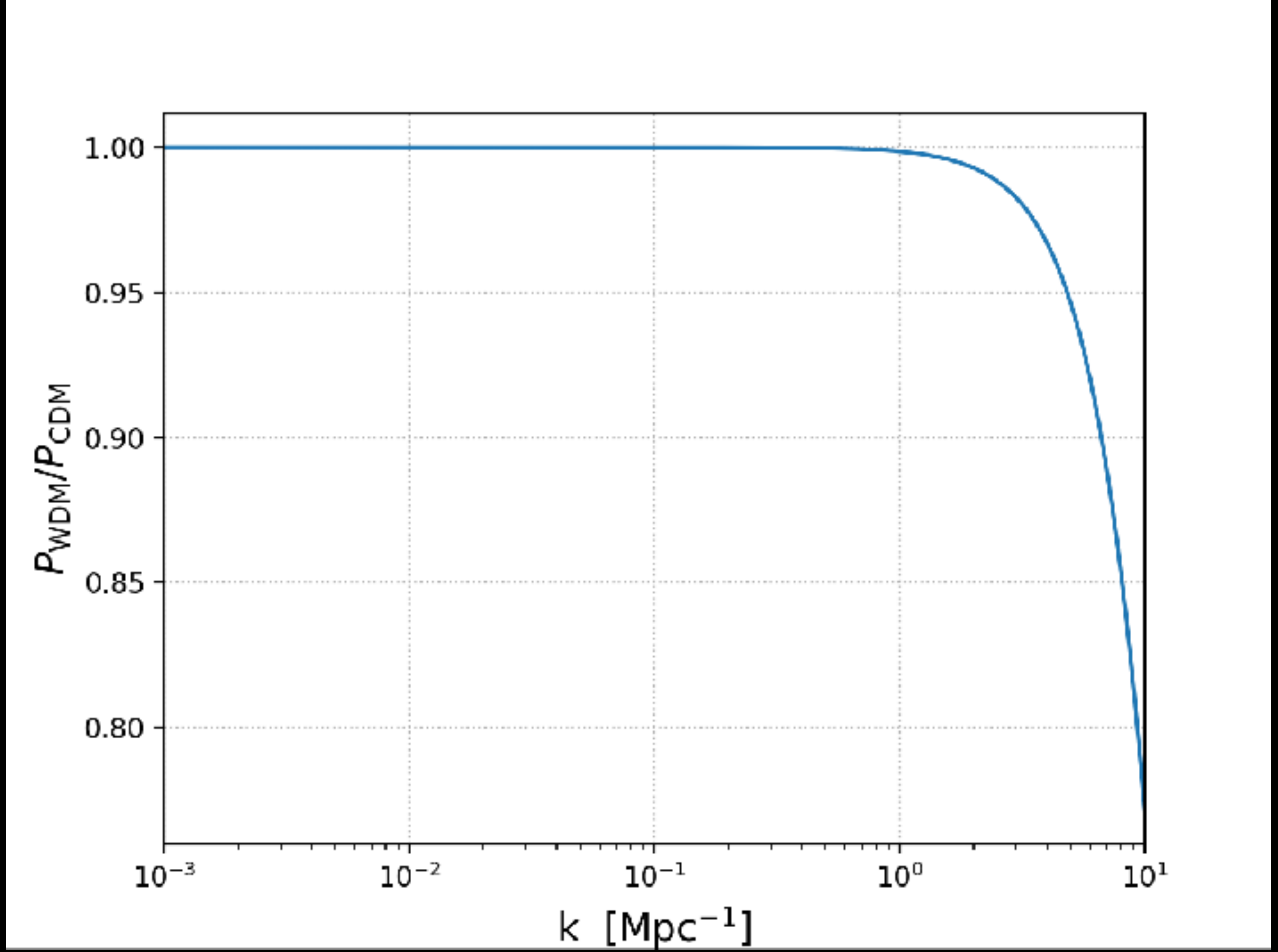
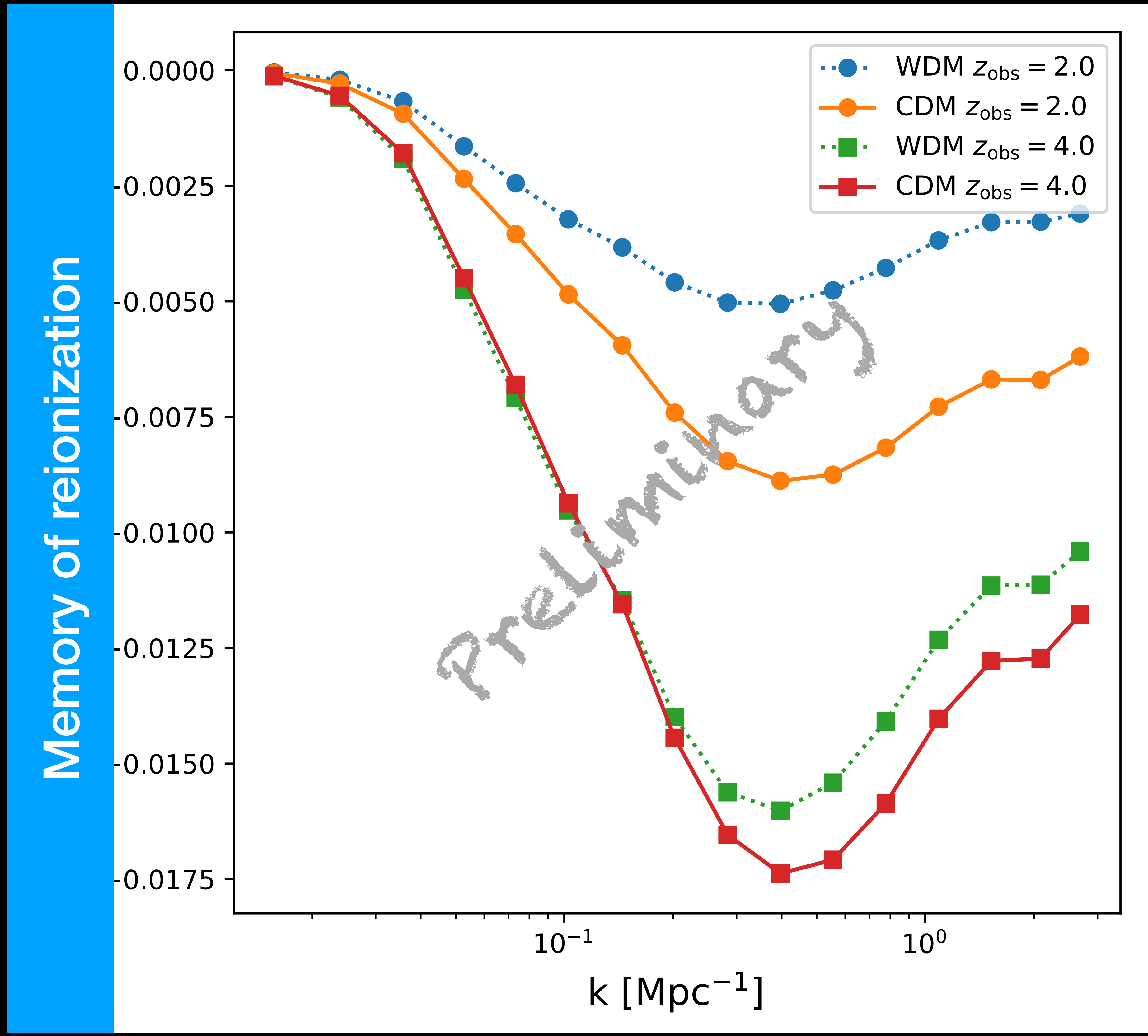
$\left(\frac{k^3}{2\pi^2}\right) P_{m,\psi}(k, z)$
k [Mpc^{-1}]

Memory of reionization and dark matter nature





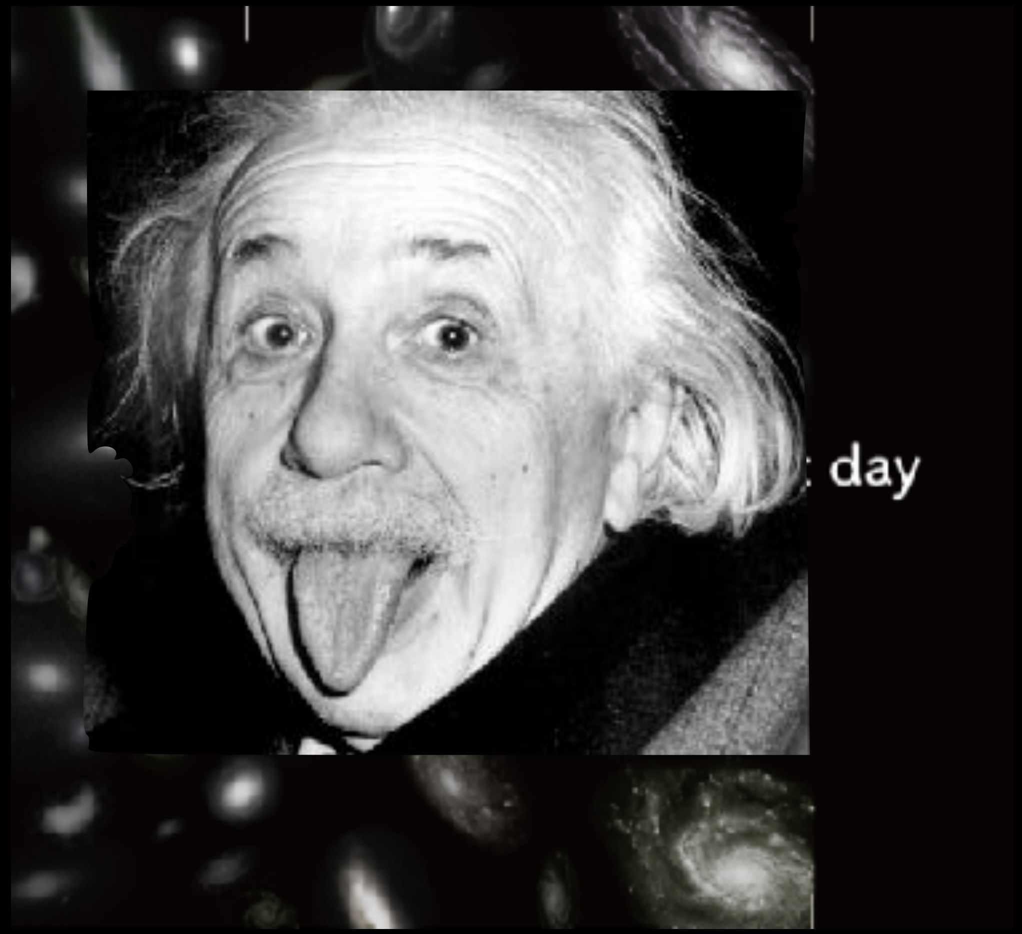
Sensitivity to small scales makes the memory of reionization a **competitive probe of the nature of dark matter**.

Y. Zhang (Fudan, undergraduate student)

Conclusion

The astrophysics of cosmic reionization remain a mystery. Luckily, we can unveil this mystery through the imprint reionization leaves in the IGM:

- In particular, DESI will be able to use the Lya forest to measure the timeline of reionization.
- Neglecting the memory of reionization will lead to underestimation of errors and biased cosmological parameters.
- 21 cm LIM in the post-reionization era will also teach us about the astrophysics of reionization and it will unlock novel cross-correlations and other emission lines.
- Exquisite sensitivity to small scales makes the memory of reionization in the IGM a novel competent probe of dark matter candidates.



Thank you for your attention!

pmontero@tsinghua.edu.cn