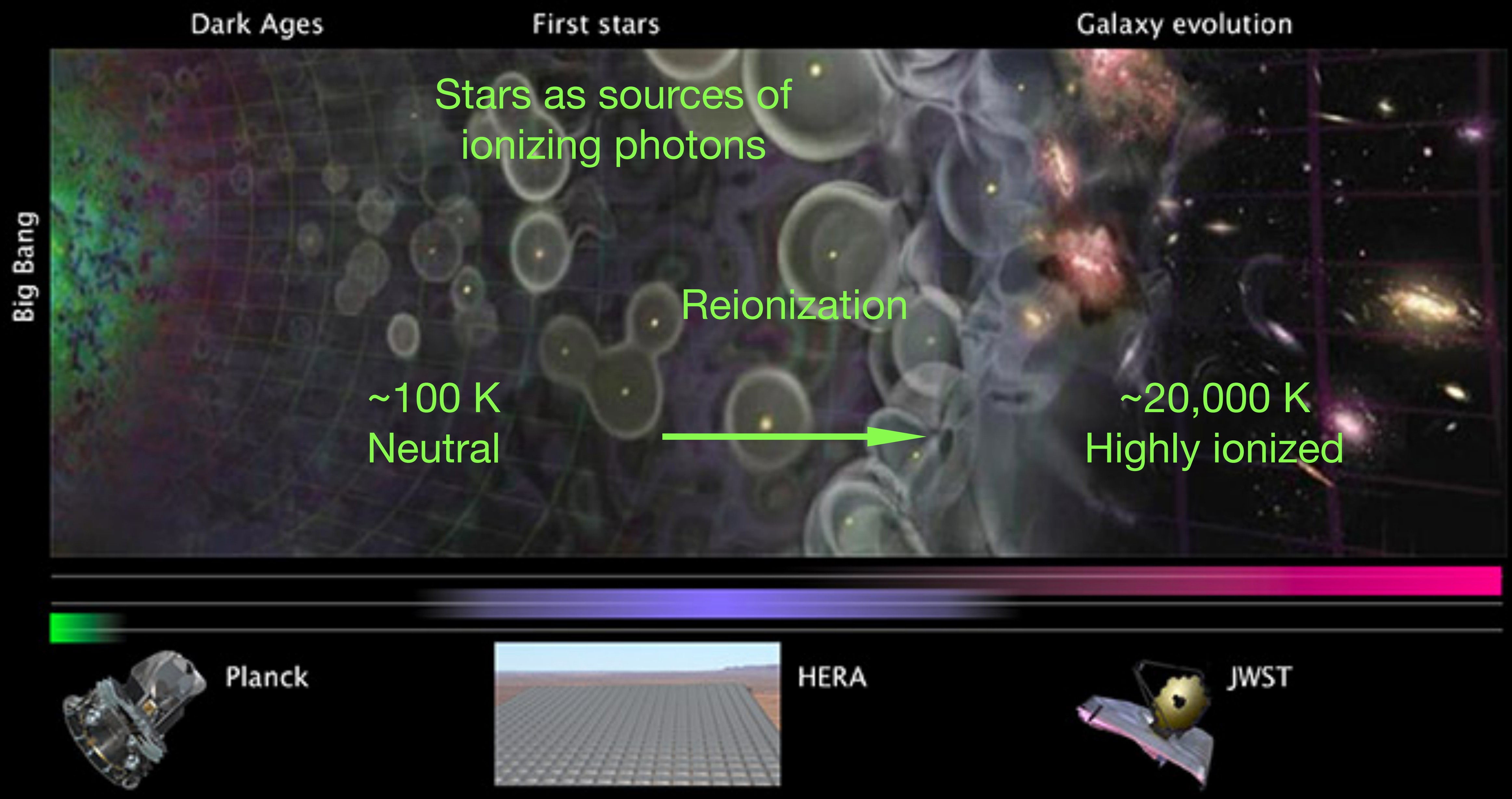
Potential new insights about reionization from the cosmic microwave background(?) and the Lyman alpha forest

Xiaohan Wu (Harvard CfA)

Hydrogen reionization

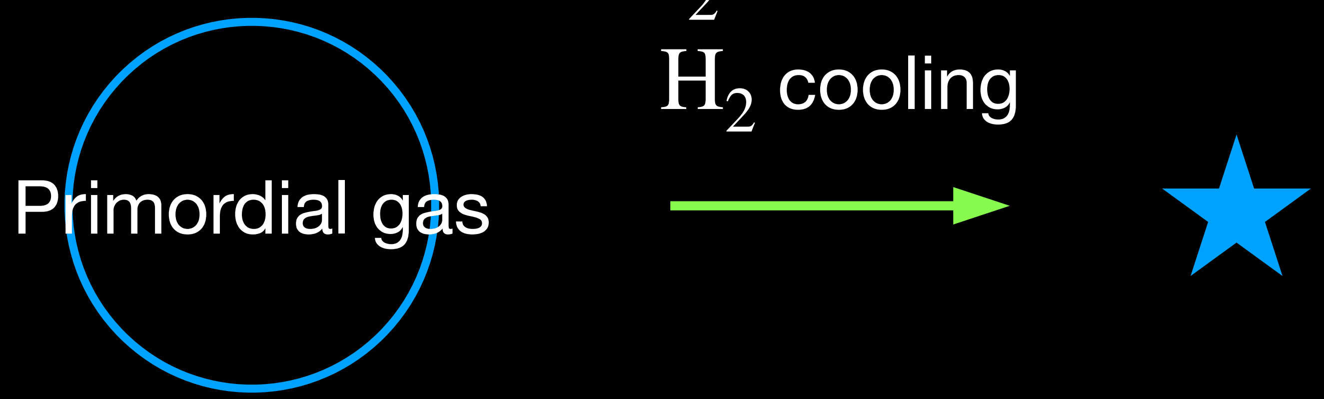


The first generation of stars (Pop-III)

$10^5 - 10^6\ M_\odot$ halos
at z=20–30
$T_{\rm vir} \sim$ a few $100 - 1000$ K

Massive
metal free star
~100 $M_\odot$

H_2 formation
H_2 cooling



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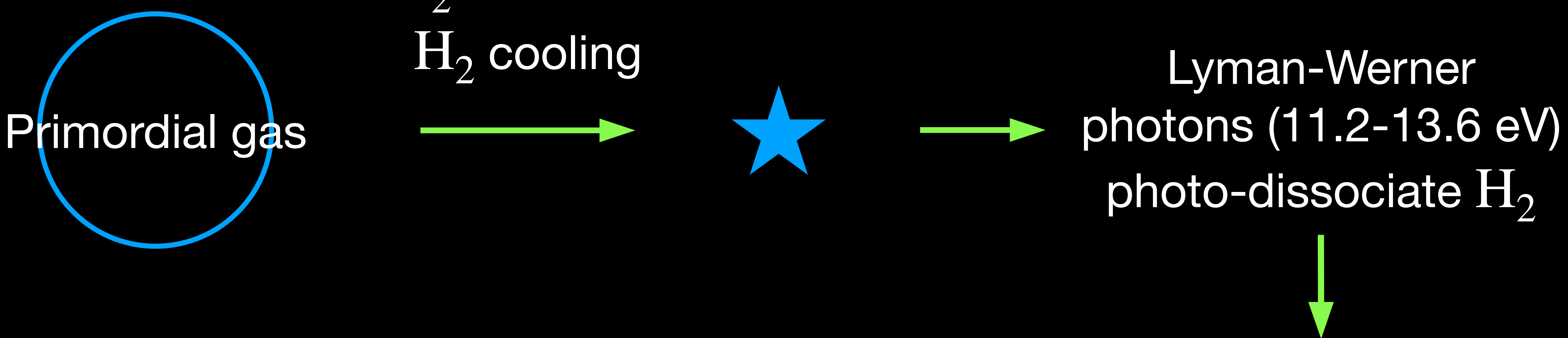

Pop-III star formation self-regulates; star formation rate density $\lesssim 10^{-5} - 10^{-4}\ M_\odot/{\rm yr}/{\rm Mpc}^3$

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Primordial gas → H_2 formation, H_2 cooling → ★ → Lyman-Werner photons (11.2-13.6 eV) photo-dissociate H_2

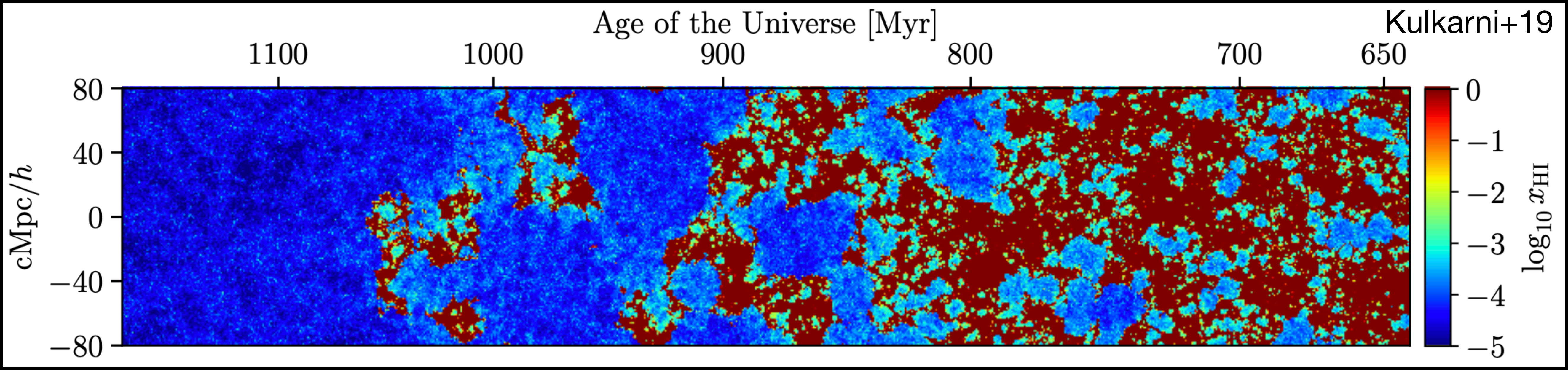
↓

Pop-III star formation self-regulates; star formation rate density $\lesssim 10^{-5} - 10^{-4}\ M_\odot/{\rm yr}/{\rm Mpc}^3$

← Pop-III stars can only ionize ~1–10% of the universe at z>15

The second generation of stars (Pop-II)

- Enriched by Pop-III; atomic cooling
- Most simulations of reionization only involve Pop-II
- Drives the bulk of reionization at z<12
- Patchy morphology illustrated by sims



Narrative arc

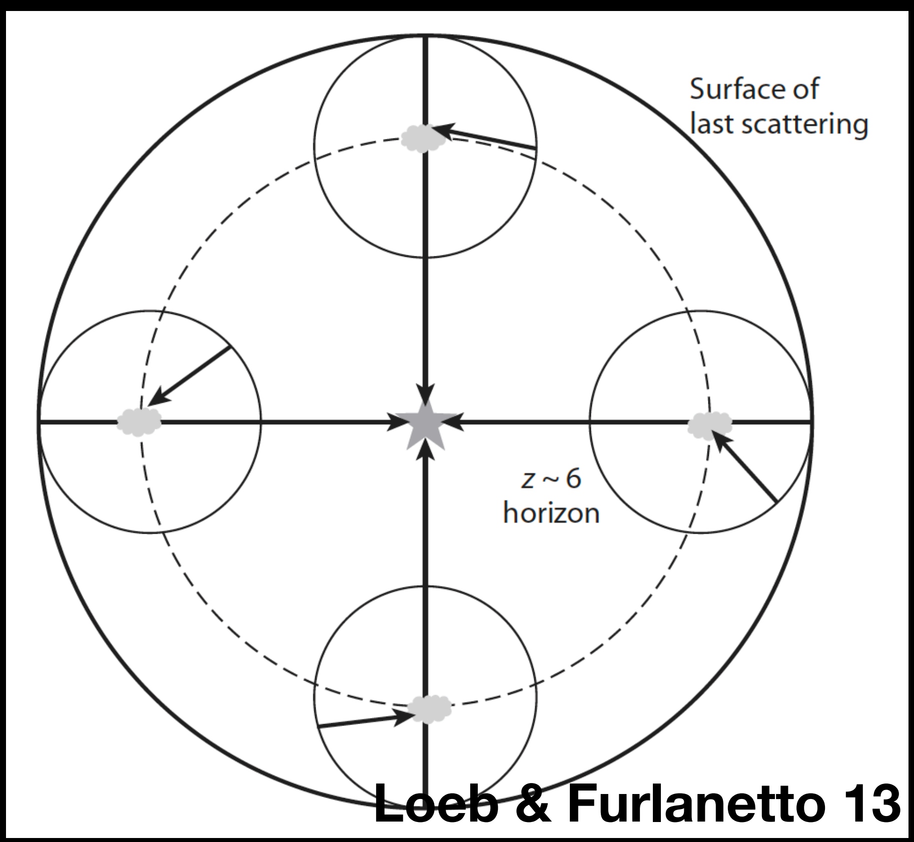
- Constraining Pop-III reionization at z>15 using the cosmic microwave background:
  - To what extent can state-of-the-art Pop-III models ionize the z>15 universe?
  - Will future CMB surveys help constrain Pop-III models? (No)
- Constraining Pop-II reionization at z<12 using the post-reionization Lyman-alpha forest:
  - Do temperature fluctuations from patchy reionization leave detectable imprints on the forest? (Yes, on large scales)
  - Do temperature fluctuations bias current measurements of IGM temperature and constraints on WDM/FDM? (Unlikely)

Constraining Pop-III reionization at $z>15$ using the CMB

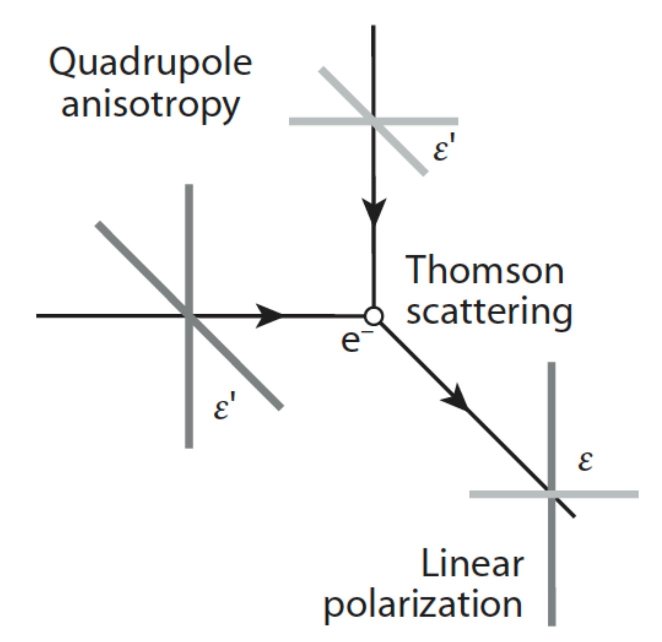
Wu+21, arxiv: 2105.08737

Imprints of reionization on the large-scale CMB E-mode polarization

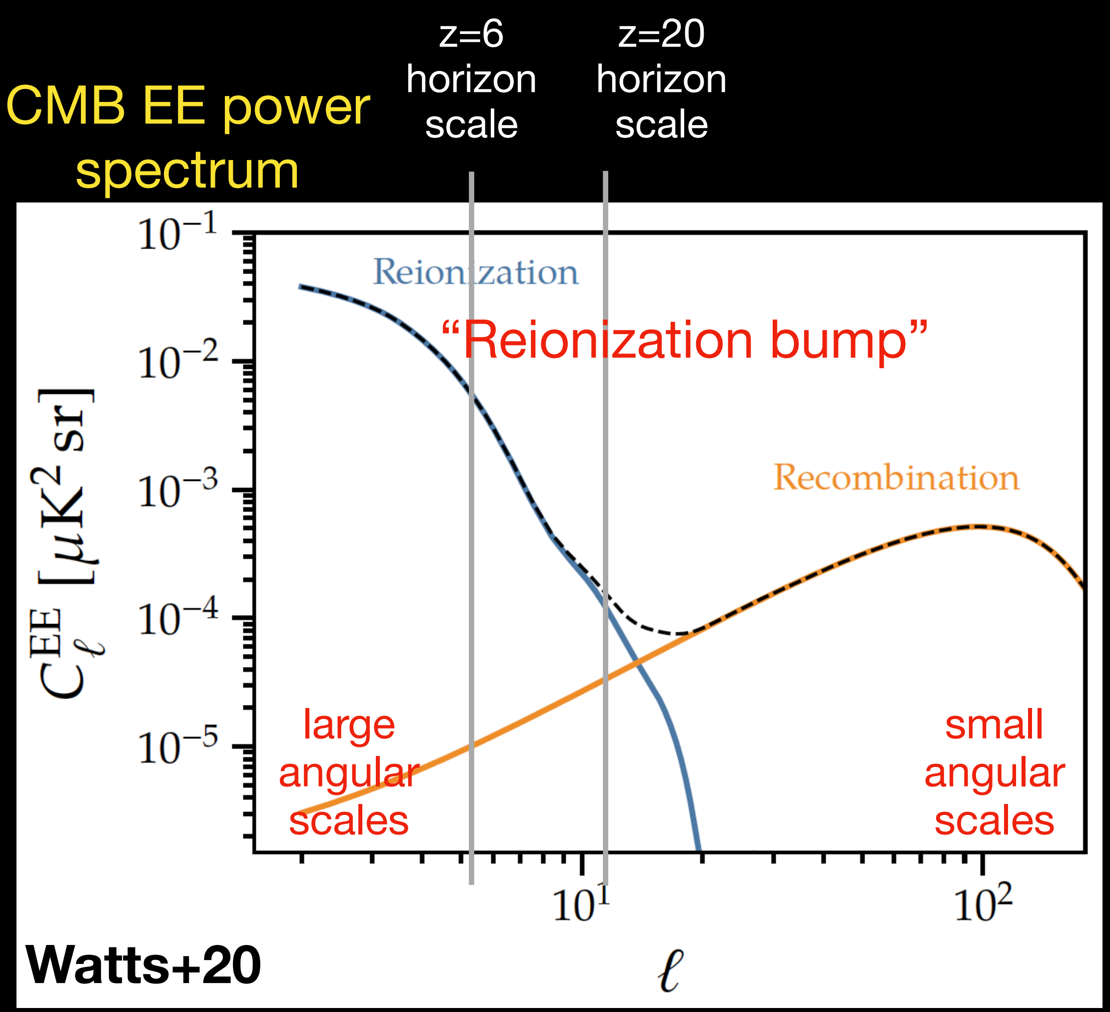
After reionization occurs…



A free electron can scatter photons that originated within the causal horizon at that time



Quadrupole anisotropy in the radiation background



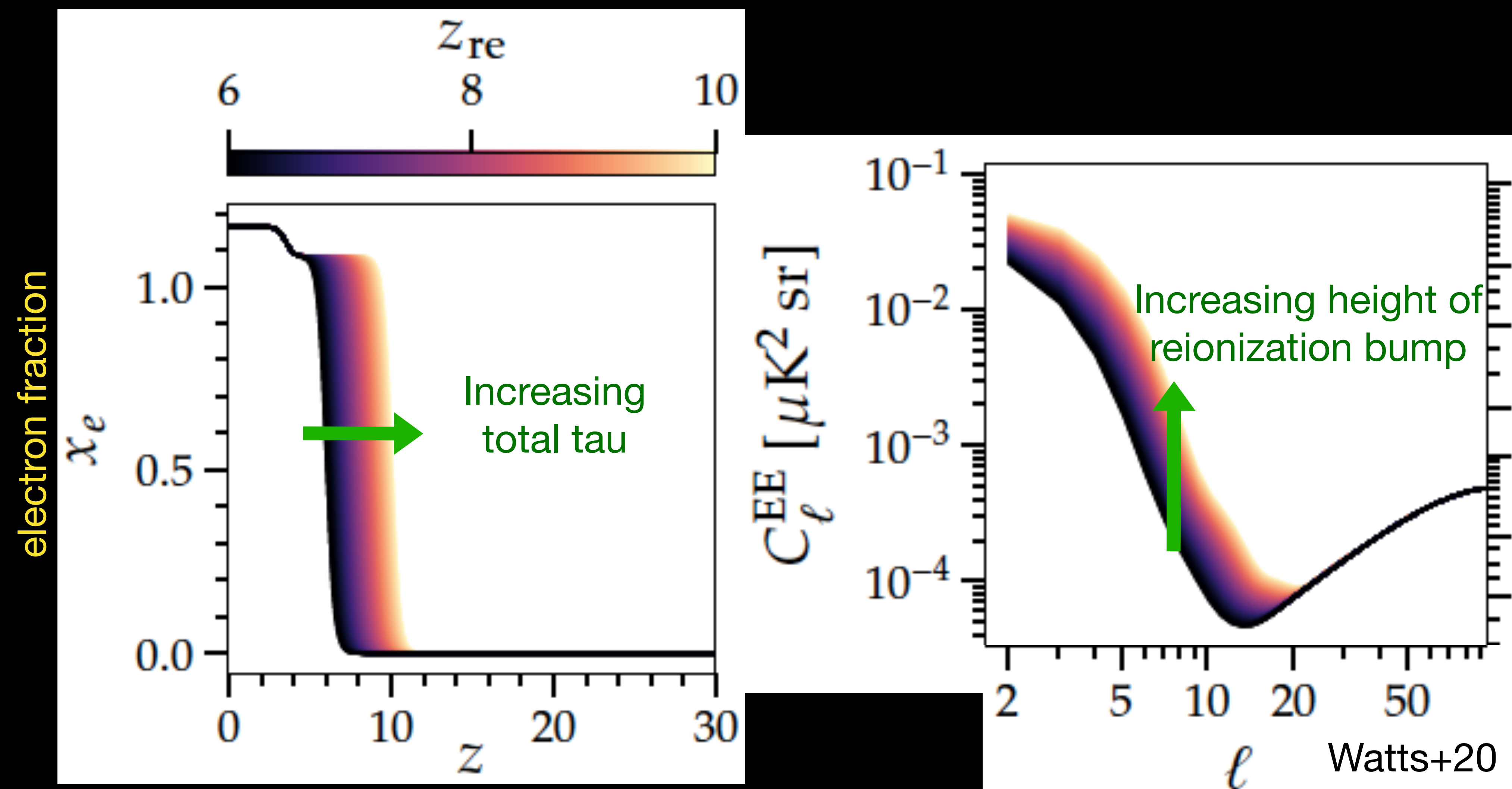
Large-scale anisotropy in the CMB E-mode polarization;

Angular scale π/ℓ = horizon scale at time of scattering / distance

Constraints on reionization from the low-ell CMB

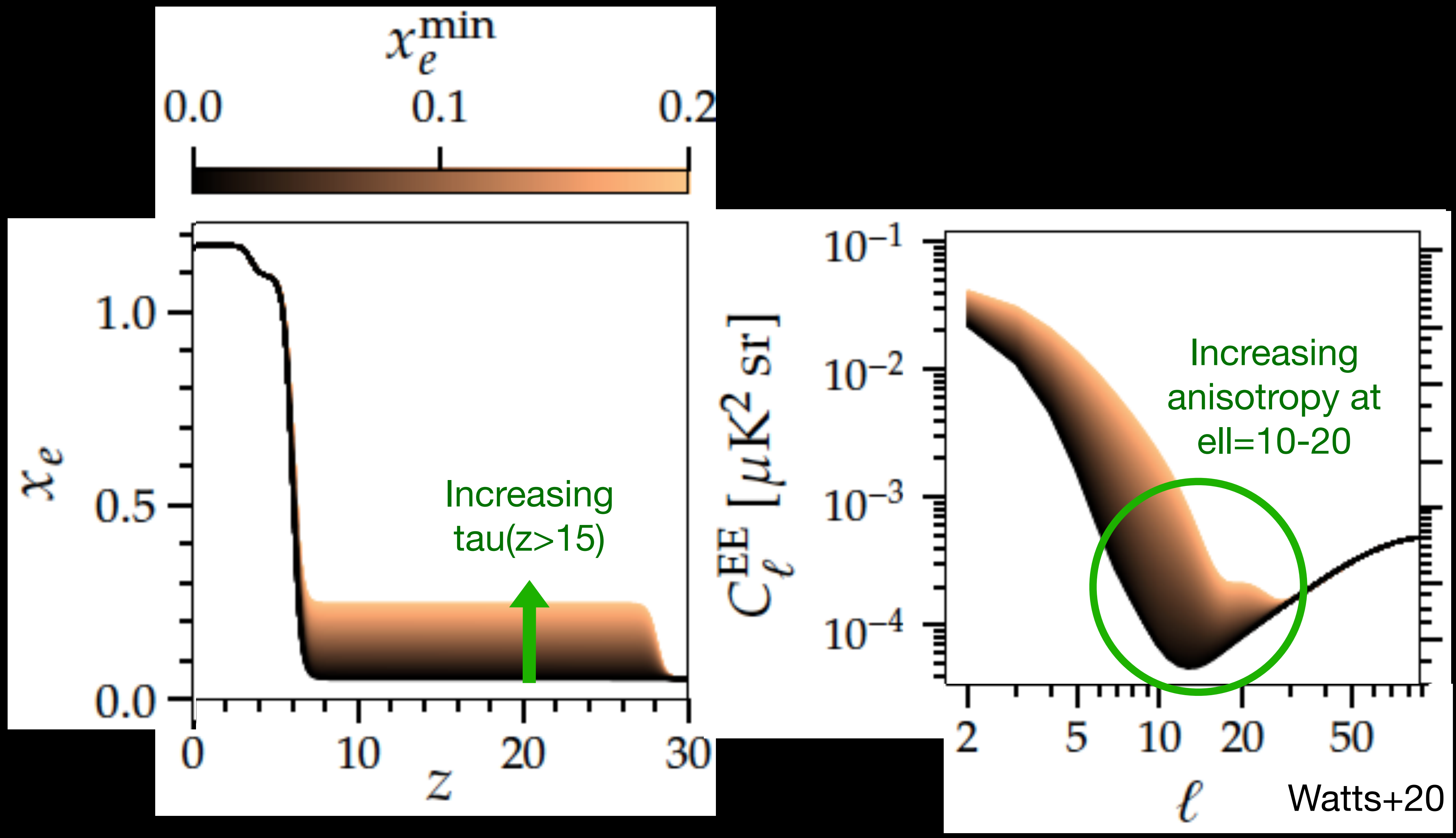
- Height and shape of the reionization bump contains information about the global reionization history, integrated into the optical depth tau
- Total tau through reionization is mostly sensitive to midpoint of reionization
- Planck has put stringent limits on total tau (0.054±0.007), but is there more information on reionization we can obtain from low-ell EE power spectrum?

$$\tau(z, z_{\rm max}) = \int_{z_{\rm max}}^{z} n_{\rm e}(z')\ \sigma_T\ (c{\rm d}t/{\rm d}z')\ {\rm d}z'$$



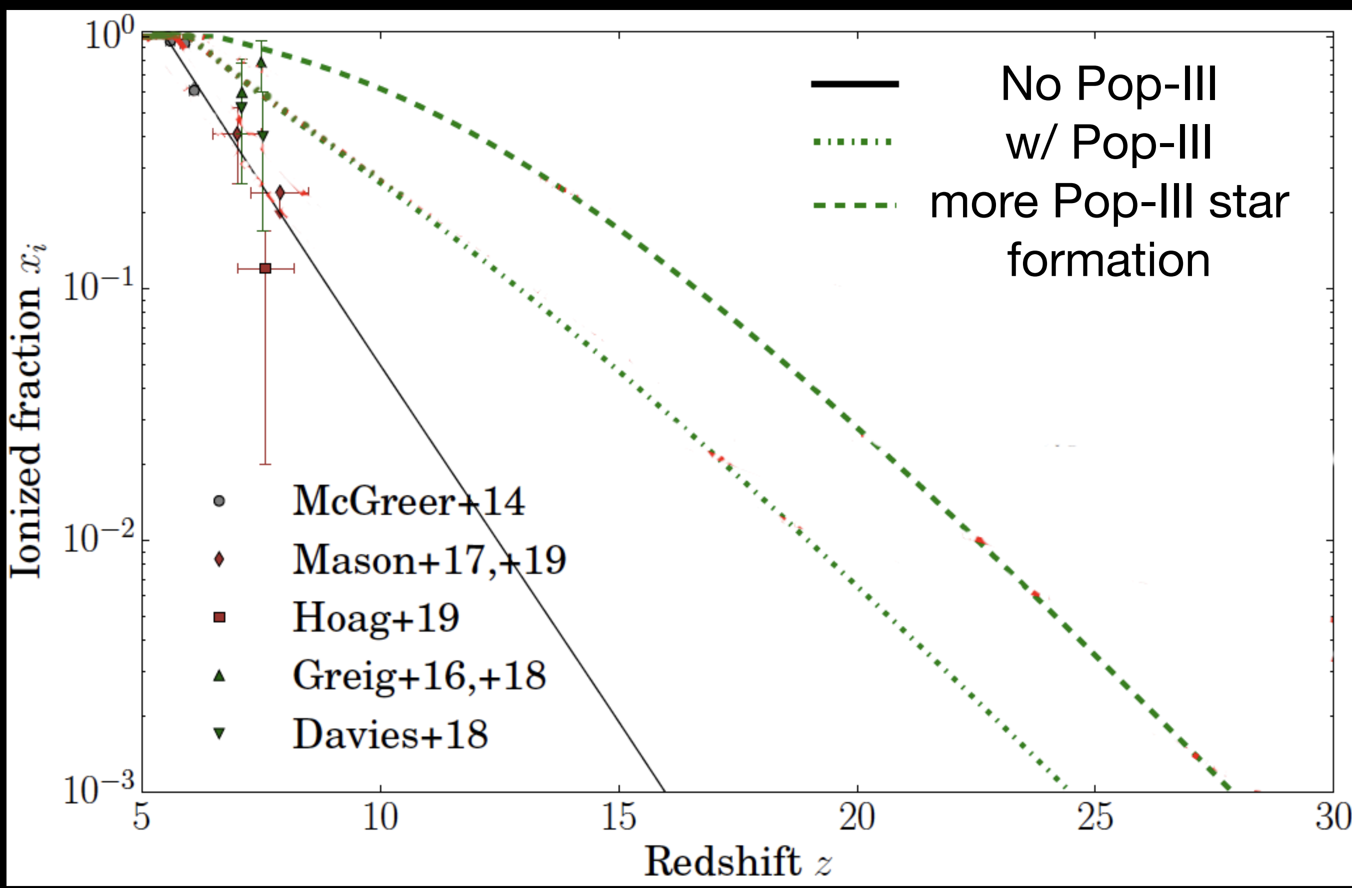
Imprints of Pop-III reionization on CMB

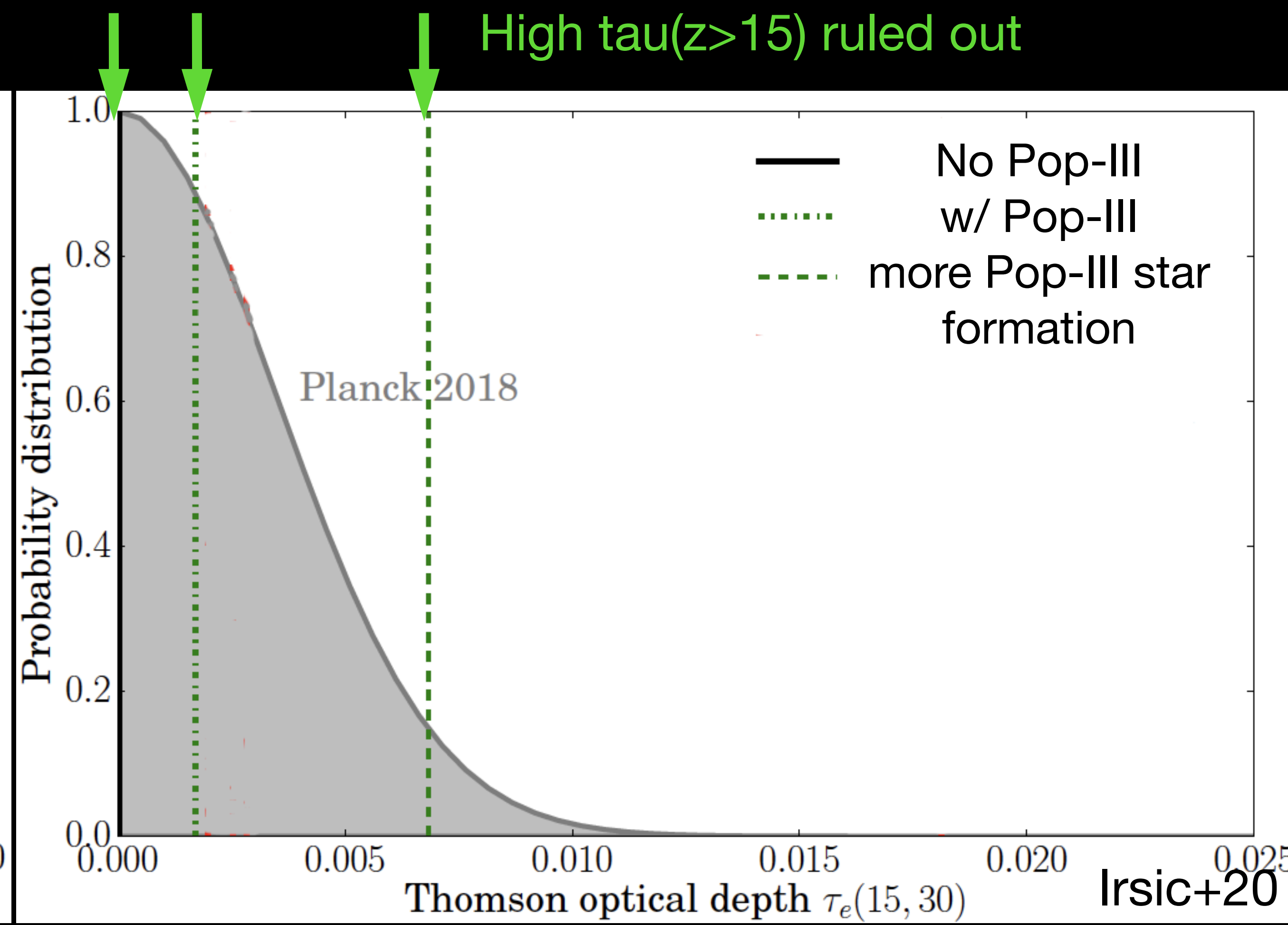
- Universe ionized at 1–10% level at z>15 → more anisotropy in E-mode polarization at ell=10–20 (ionization at higher z → anisotropy at smaller angular scales), non-zero $\tau(z > 15)$



Constraining Pop-III models using the low-ell CMB

- Planck 2-sigma upper limit $\tau(z > 15) < 0.006$ can rule out some Pop-III models (number not correct anymore)
- Future CMB surveys can measure EE power at ell=10–20 with higher signal-to-noise and better constrain $\tau(z > 15) \rightarrow$ rule out more Pop-III models?
- Pop-III modeling is highly uncertain; a lot of models exist





Irsic+20

Constraining Pop-III models using the low-ell CMB

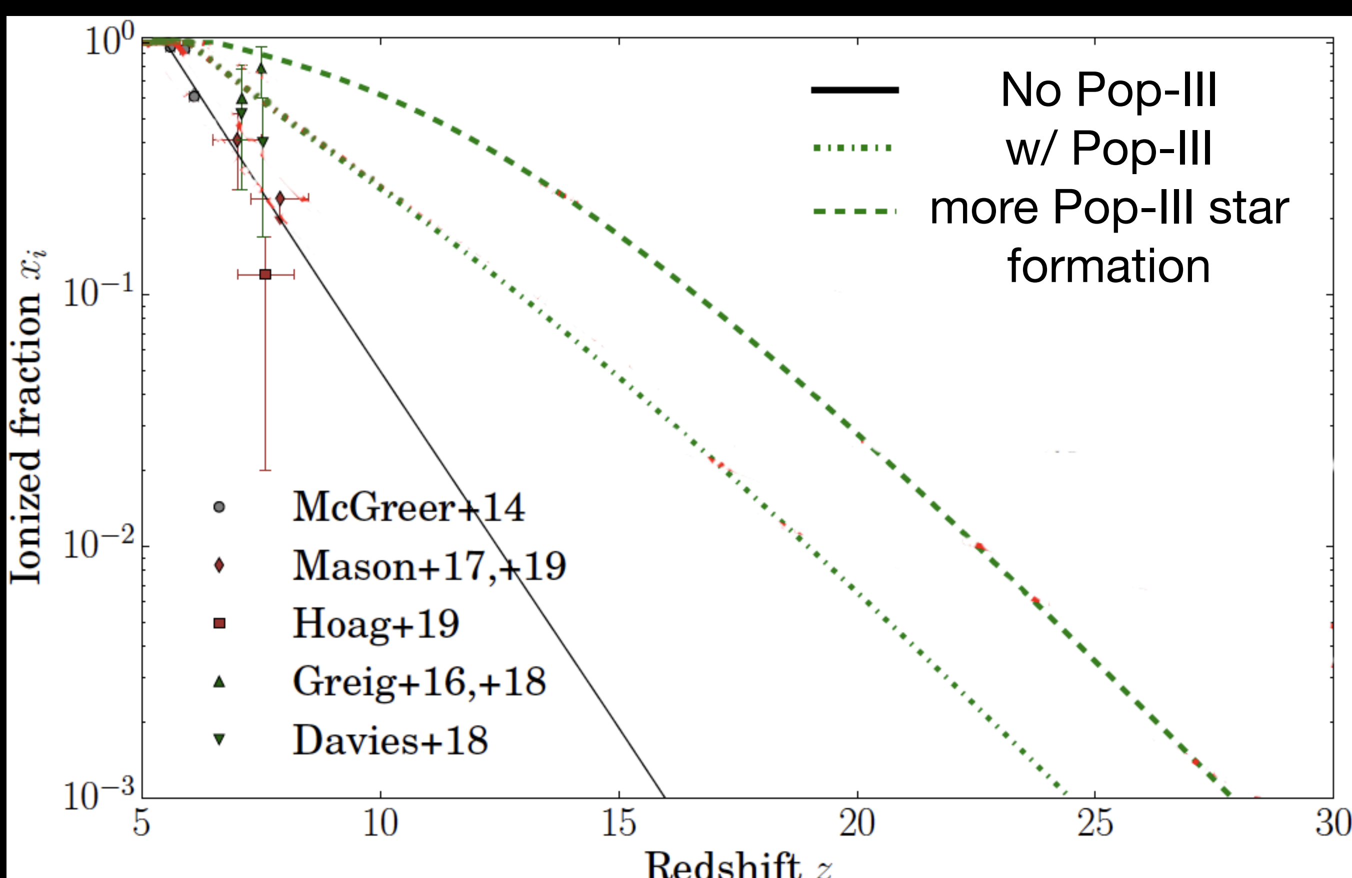
- For a large set of Pop-III parametrizations, how much can state-of-the-art Pop-III models ionize the z>15 universe?

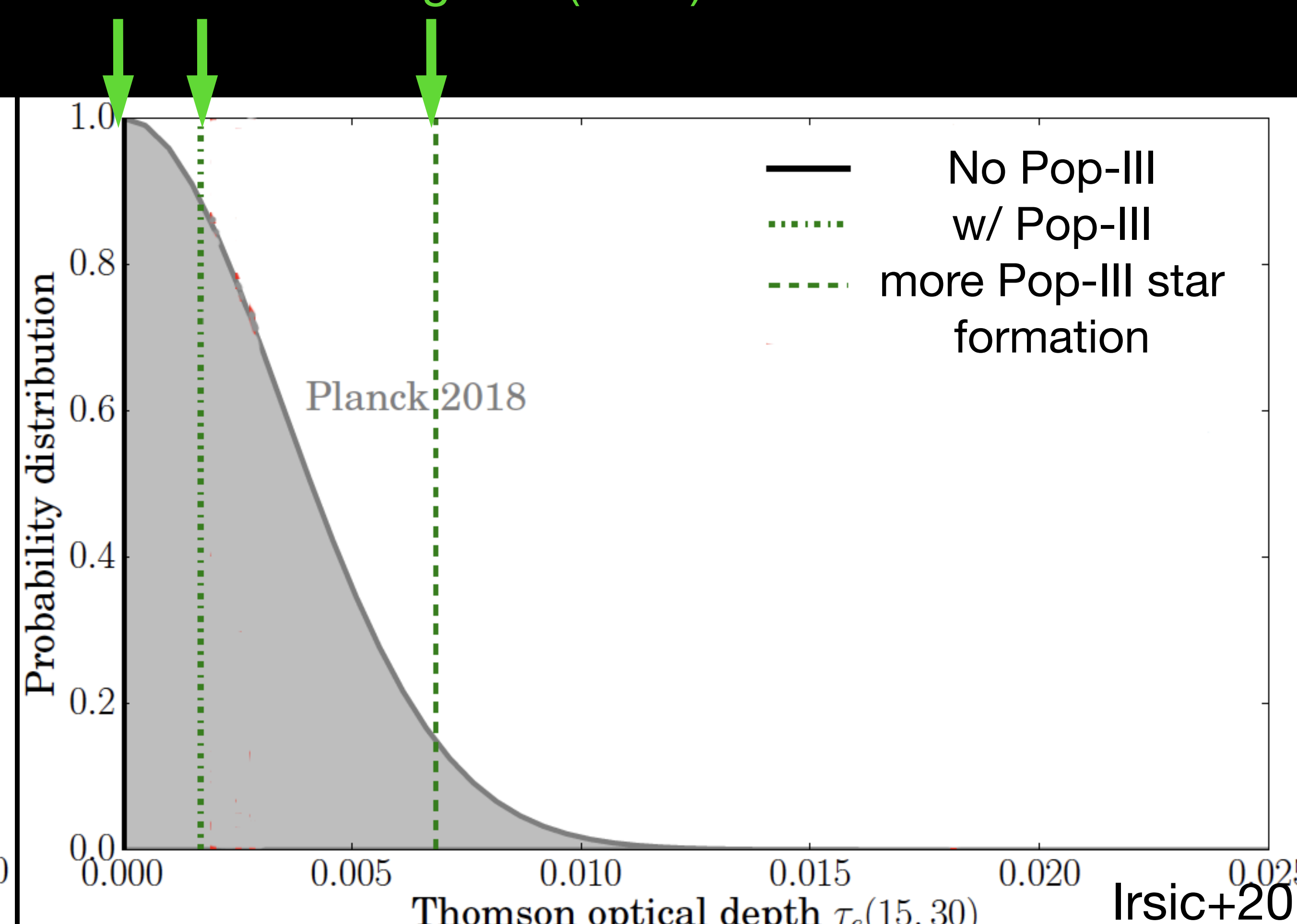
(Large ionization fractions not allowed because of low total tau by Planck)

- Will future CMB measurements of the EE power at ell=10–20 help constrain Pop-III models?

(Actually no)

High tau(z>15) ruled out





Irsic+20

Reionization with Pop-III

- Calculating the reionization history with the simplest Pop-III model:

Pop-III star formation in $10^5 - 10^6\ M_\odot$ halos at z=20–30 with a star formation efficiency

Free parameter:
Star formation efficiency
6 values from 0.0001 to 0.03

Lyman-Werner photons form a background and photo-dissociate H2 → increased minimum halo mass ($M_{\rm min}$) for Pop-III star formation (e.g. Machacek+01)

Free parameter:
Strength of LW feedback
e.g. fiducial and strong LW

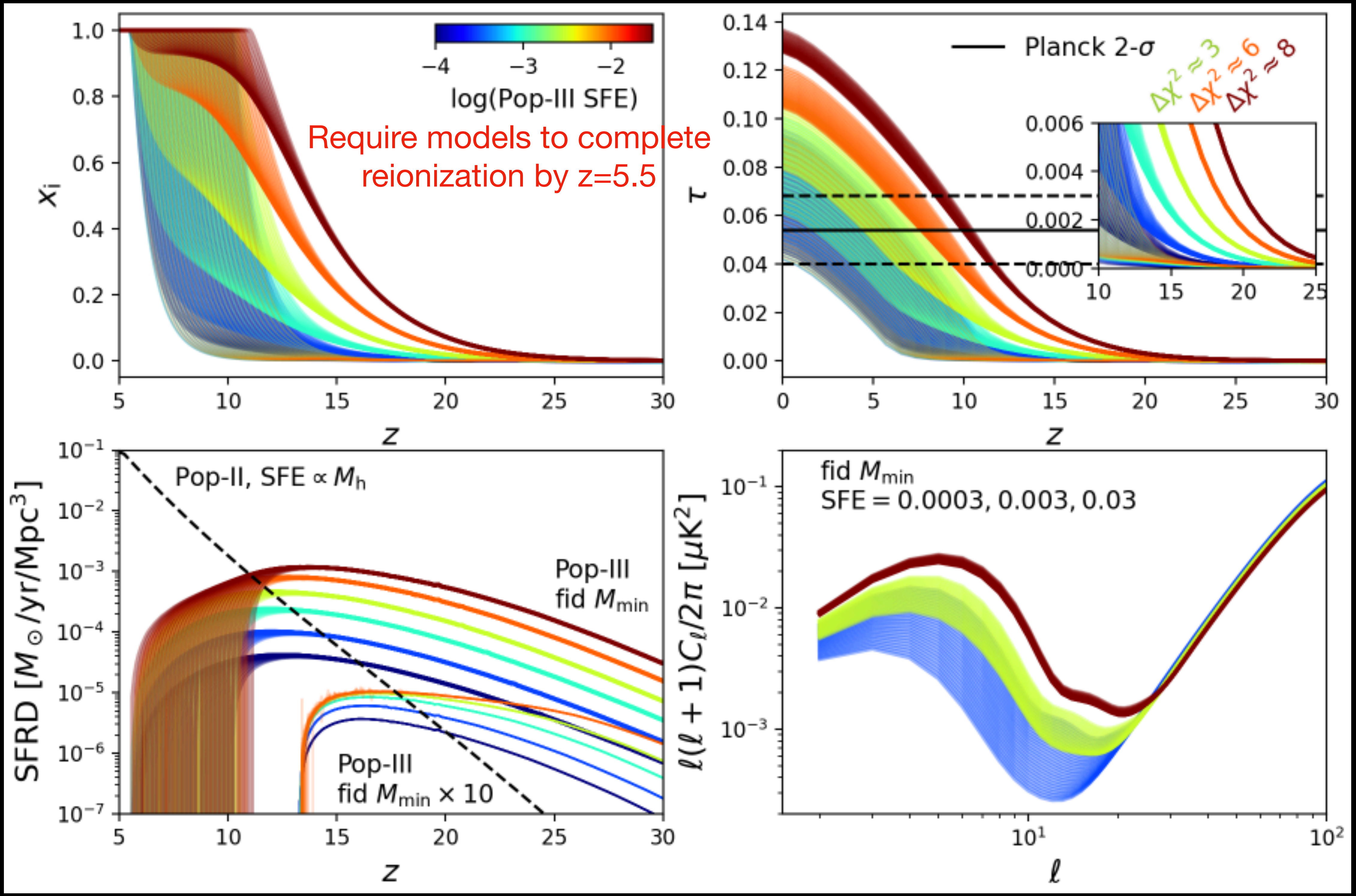
How many ionizing photons emitted by Pop-III stars
(+ state-of-the-art Pop-II model)

↓

Reionization history

The resulting huge range of Pop-III models

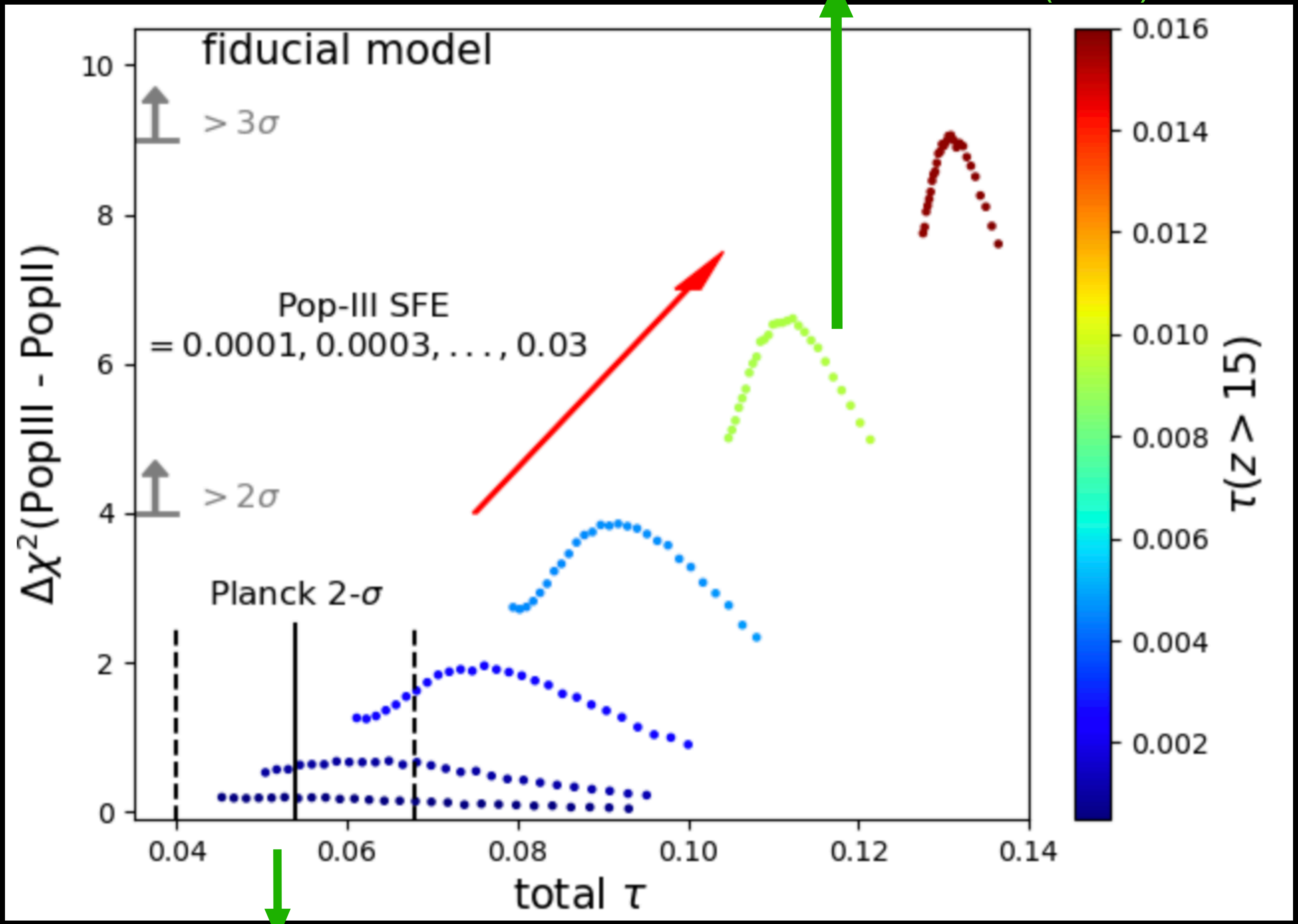
- Compare each Pop-III model to a Pop-II-only model with the same total tau
- $\Delta\chi^2$ of the EE power spectra at ell=2–100 in the cosmic variance limit



Summary of results

- The requirement to satisfy low total tau and endpoint of reionization already *ruled out most of the Pop-III parameter space* (high z structure formation + LW feedback -> hard to get very extended reionization)

Pop-III models get distinguishable from Pop-II-only when tau(z>15) > 0.008



$\Delta\chi^2$ of the EE power in the cosmic variance limit

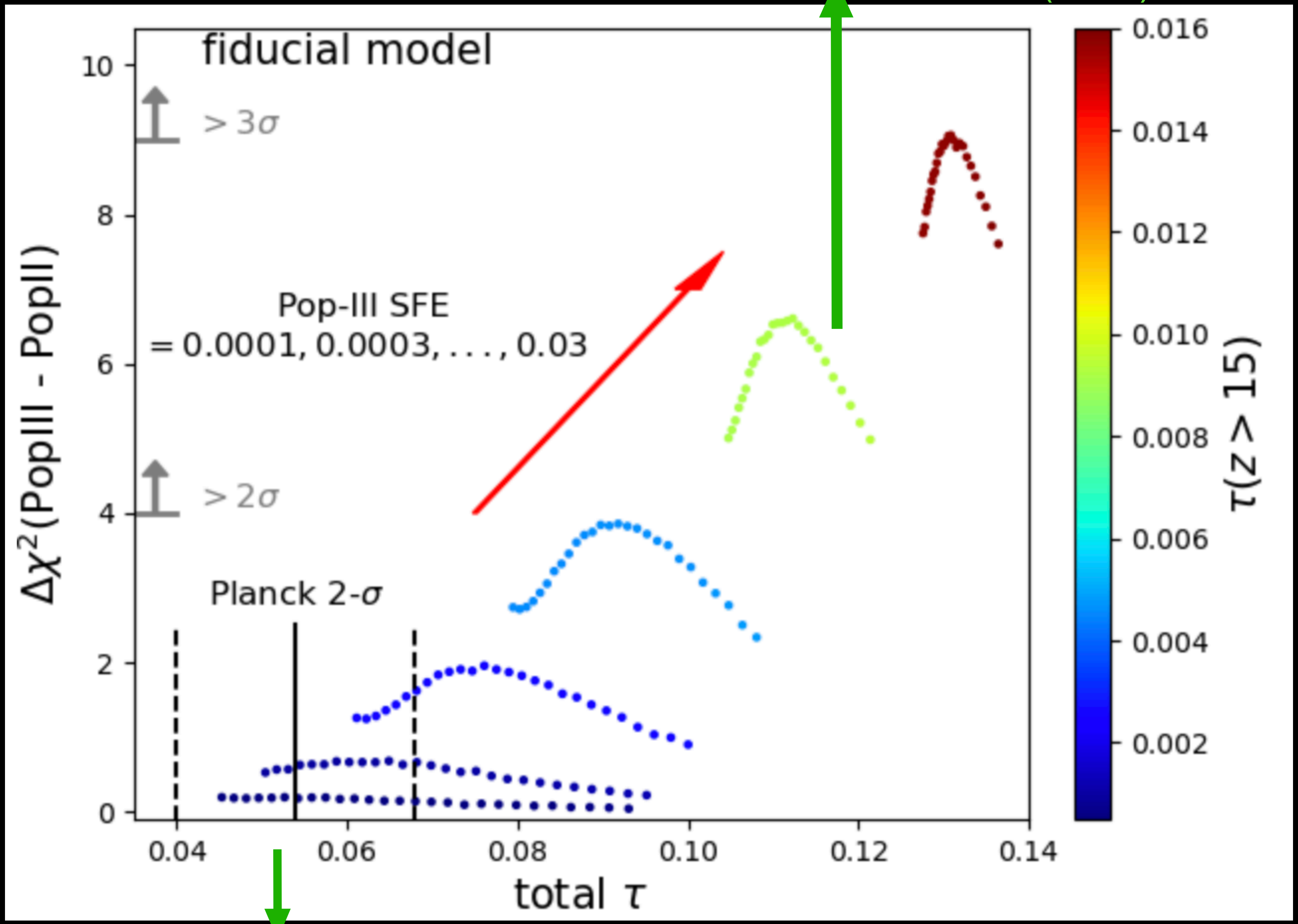
The low total tau does not allow high tau(z>15)

Summary of results

- The requirement to satisfy low total tau and endpoint of reionization already *ruled out most of the Pop-III parameter space* (high z structure formation + LW feedback -> hard to get very extended reionization)
- Future surveys looking at low-ell CMB unlikely to help constrain Pop-III models

Pop-III models get distinguishable from Pop-II-only when tau(z>15) > 0.008

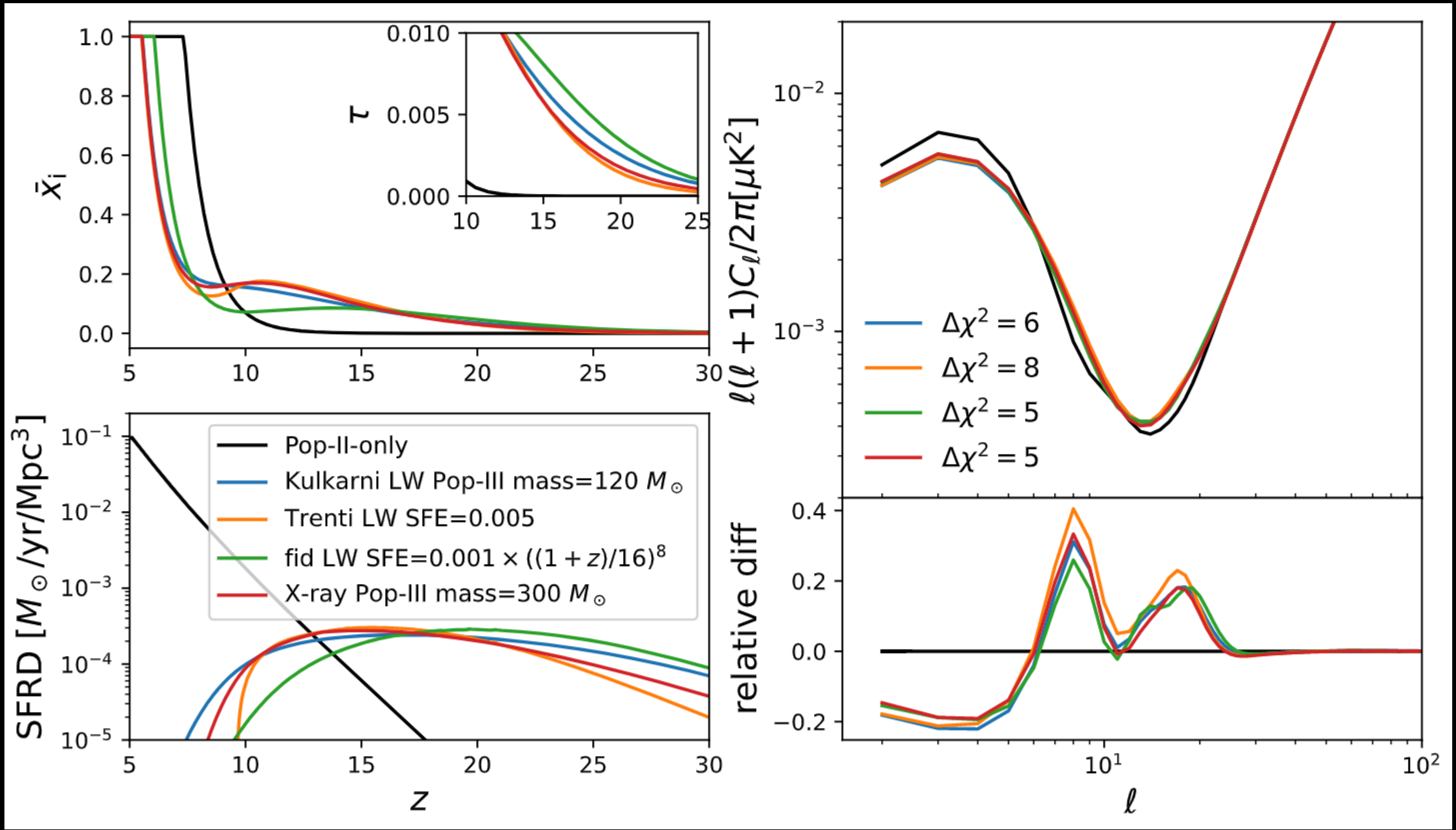
$\Delta\chi^2$ of the EE power in the cosmic variance limit



The low total tau does not allow high tau(z>15)

More exotic(?) Pop-III models may be detectable using the low-ell CMB

- Models that can quench Pop-III efficiently at low z and/or boost Pop-III at high z -> more plateaued high-z reionization or “double reionization”
- Other forms of LW feedback, X-ray feedback, etc.



(Ad:) non-parametric Lagrangian biasing model

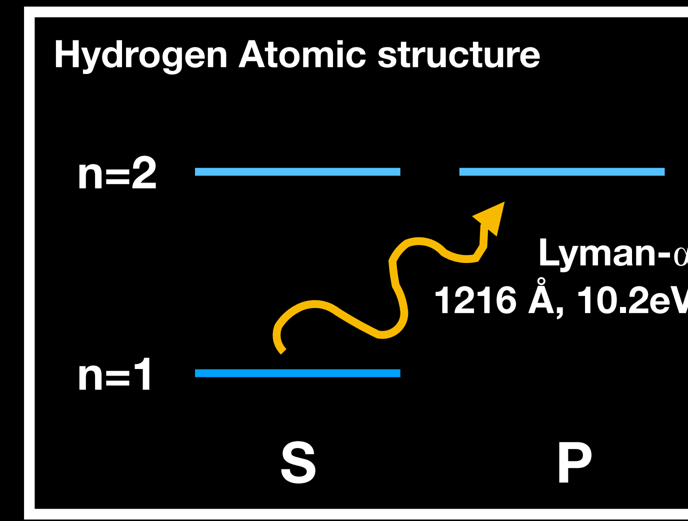
- Traditional bias expansion doesn’t seem to describe the clustering of z=20-30 minihalos well
- We (with Daniel Eisenstein, Julian Munoz) developed a non-parametric Lagrangian biasing model and tested it against z=0.5 halos in N-body sims

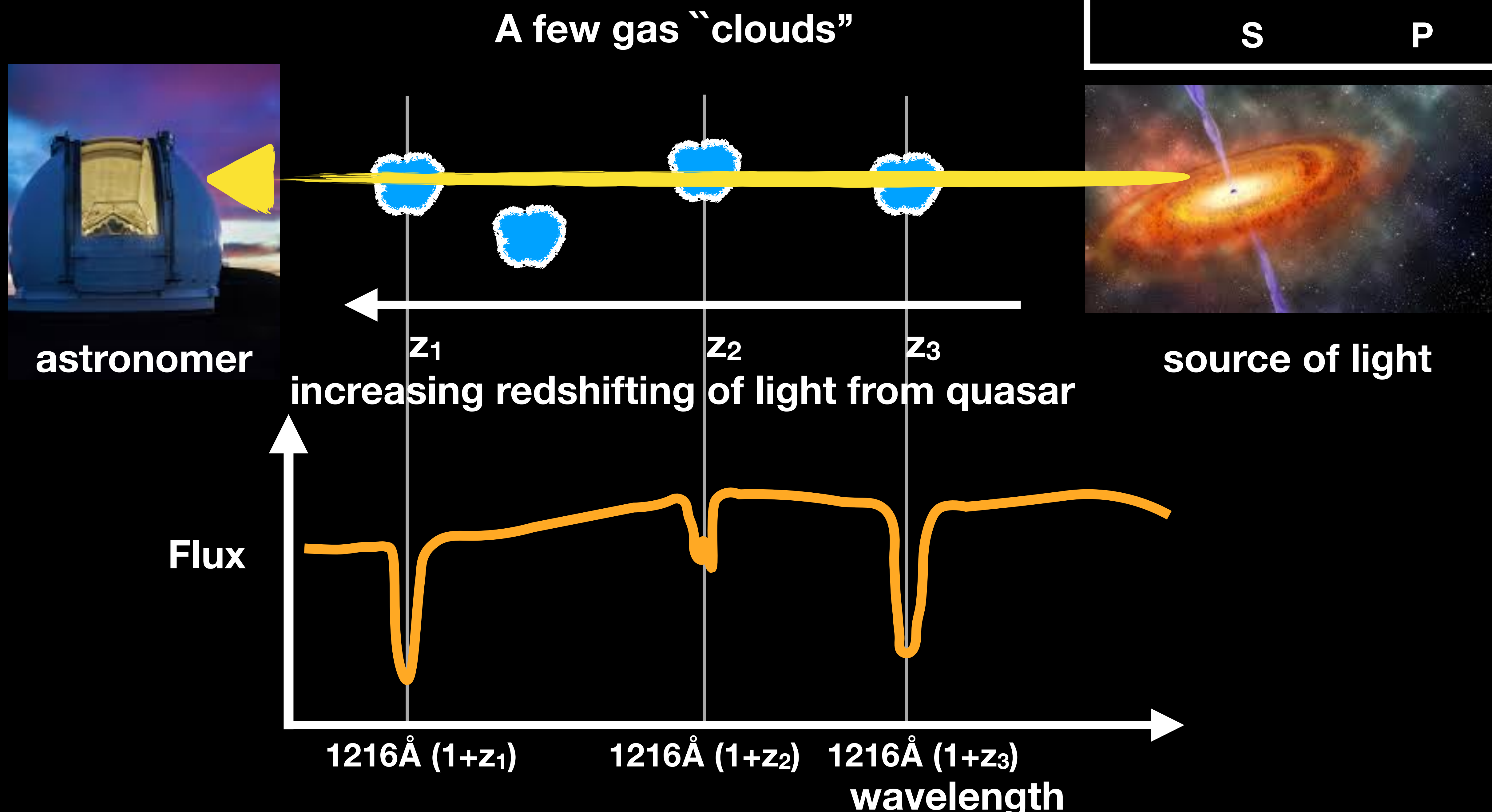
Constraining Pop-II reionization at z<12 using the post-reionization Lyman-alpha forest

Wu+19, arxiv:1907.04860

Lyman-alpha forest

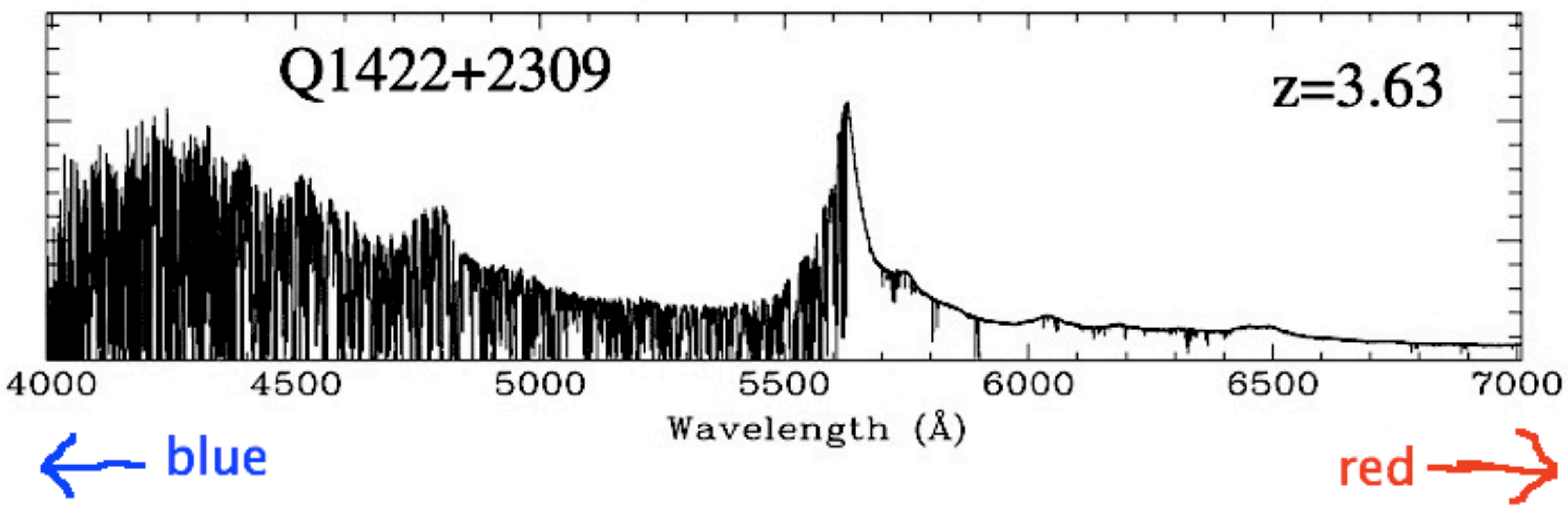
- 1216Å Lyman-alpha absorption of neutral H atoms along line of sight





Lyman-alpha forest

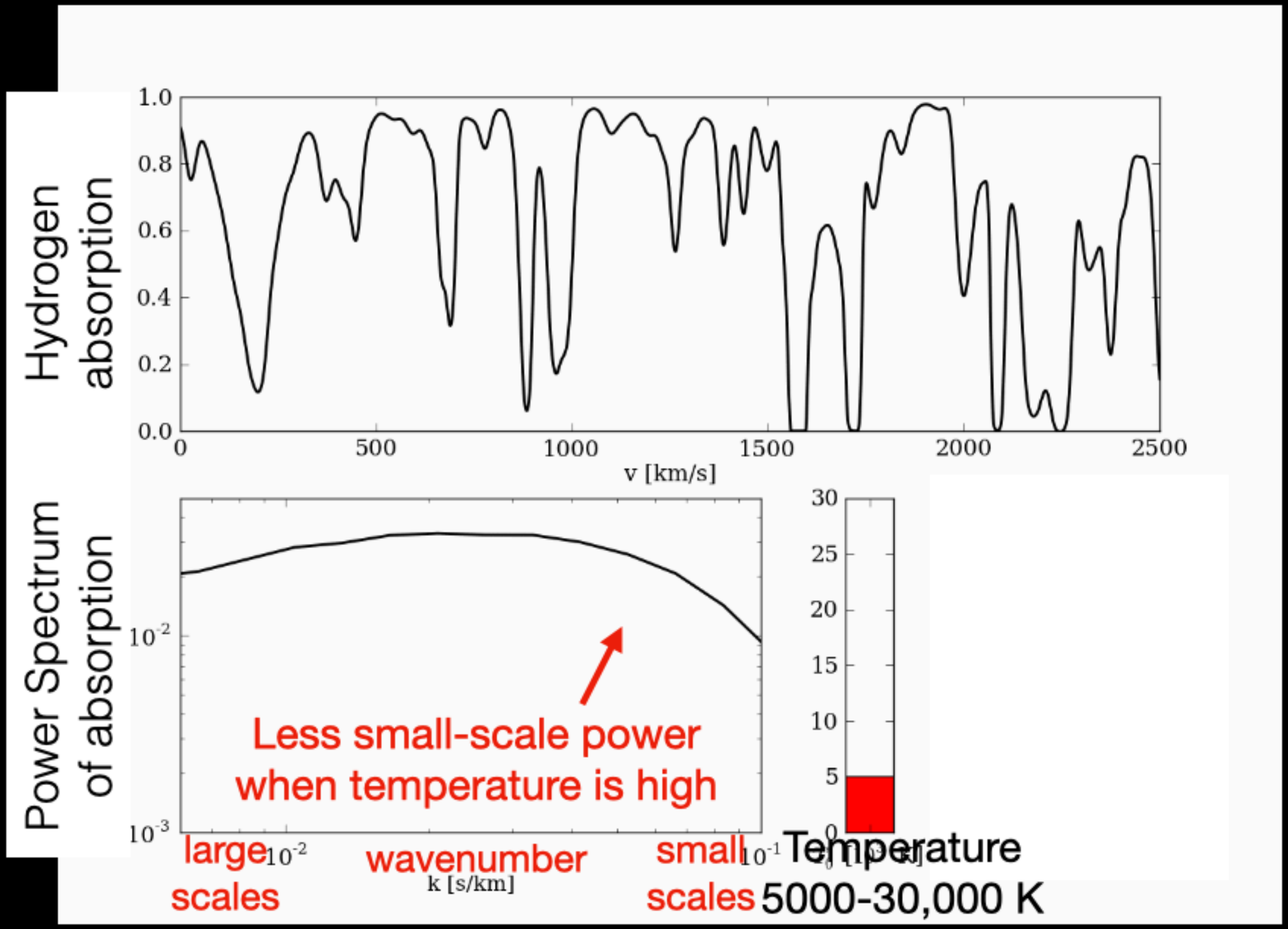
- 1216Å Lyman-alpha absorption of neutral H atoms along line of sight
- A continuously fluctuating intergalactic medium with ~0.1–10 x mean density, neutral H fraction ~$10^{-5} - 10^{-4}$
- Very easy to saturate → the universe is highly ionized at z<6; lower limit on endpoint of reionization



We call this forest of absorption lines the Lyman-alpha forest

Connecting the forest with reionization via the gas temperature

- Effects of the gas temperature: width of the absorption lines and amount of neutral hydrogen $\propto T^{-0.7}$ → small-scale shape of the flux power spectrum



Movie curtesy of Alberto Rorai

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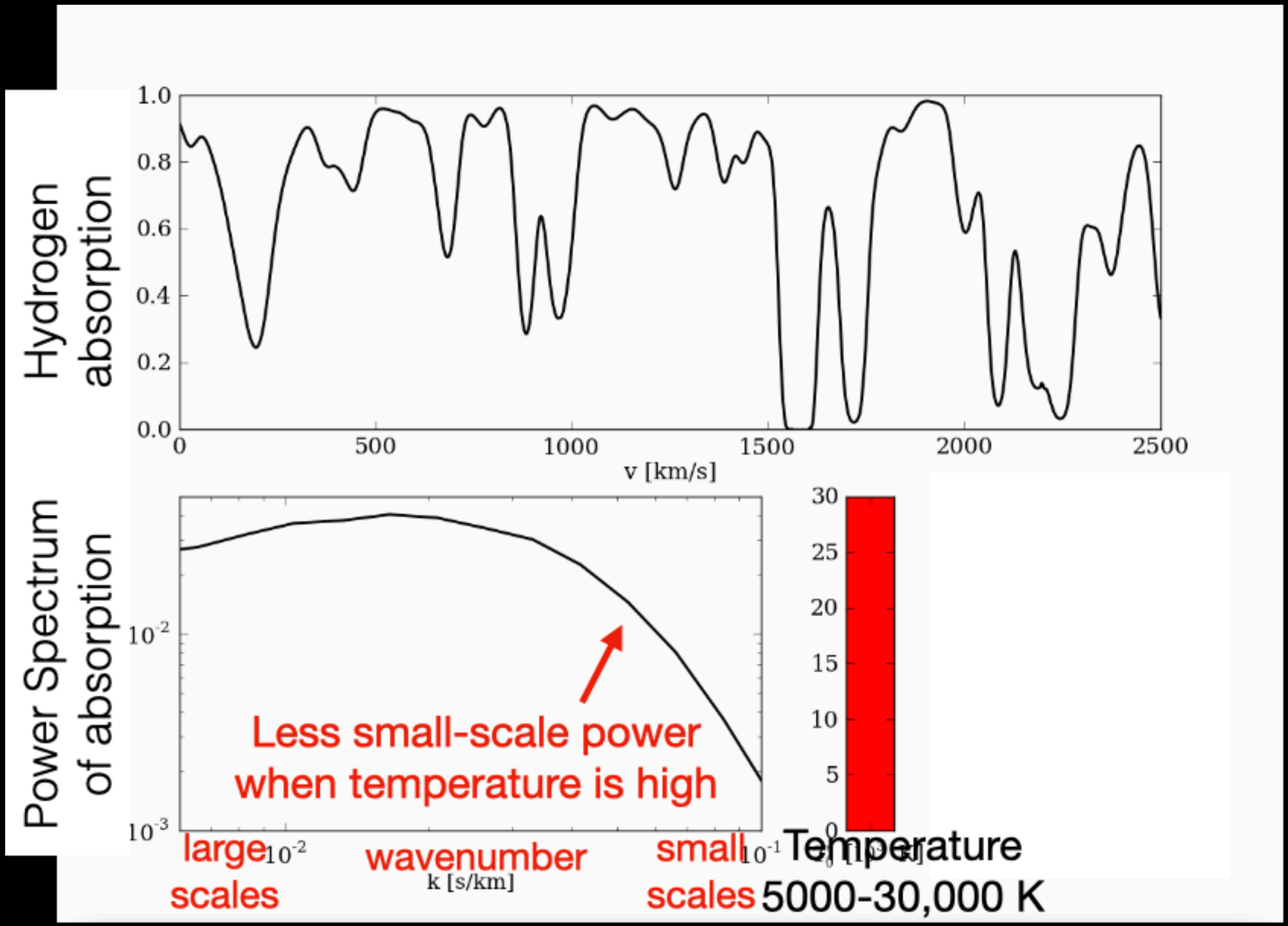

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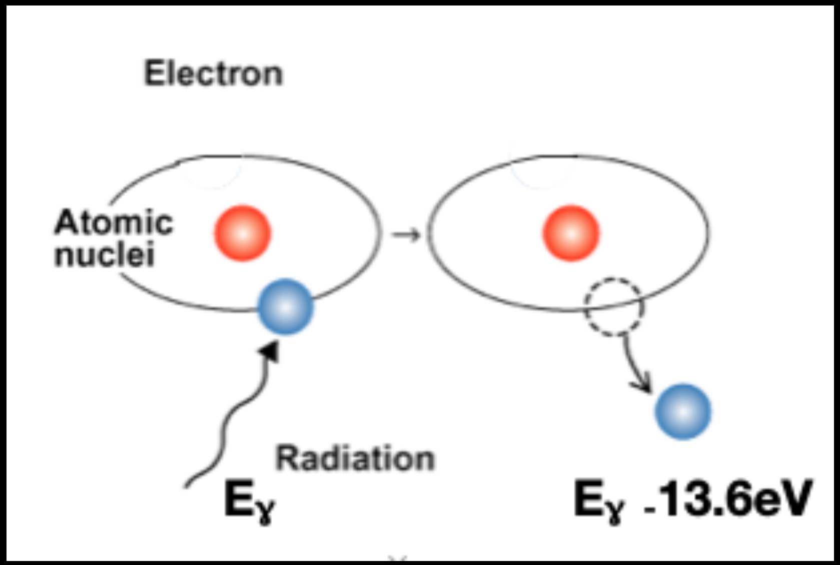
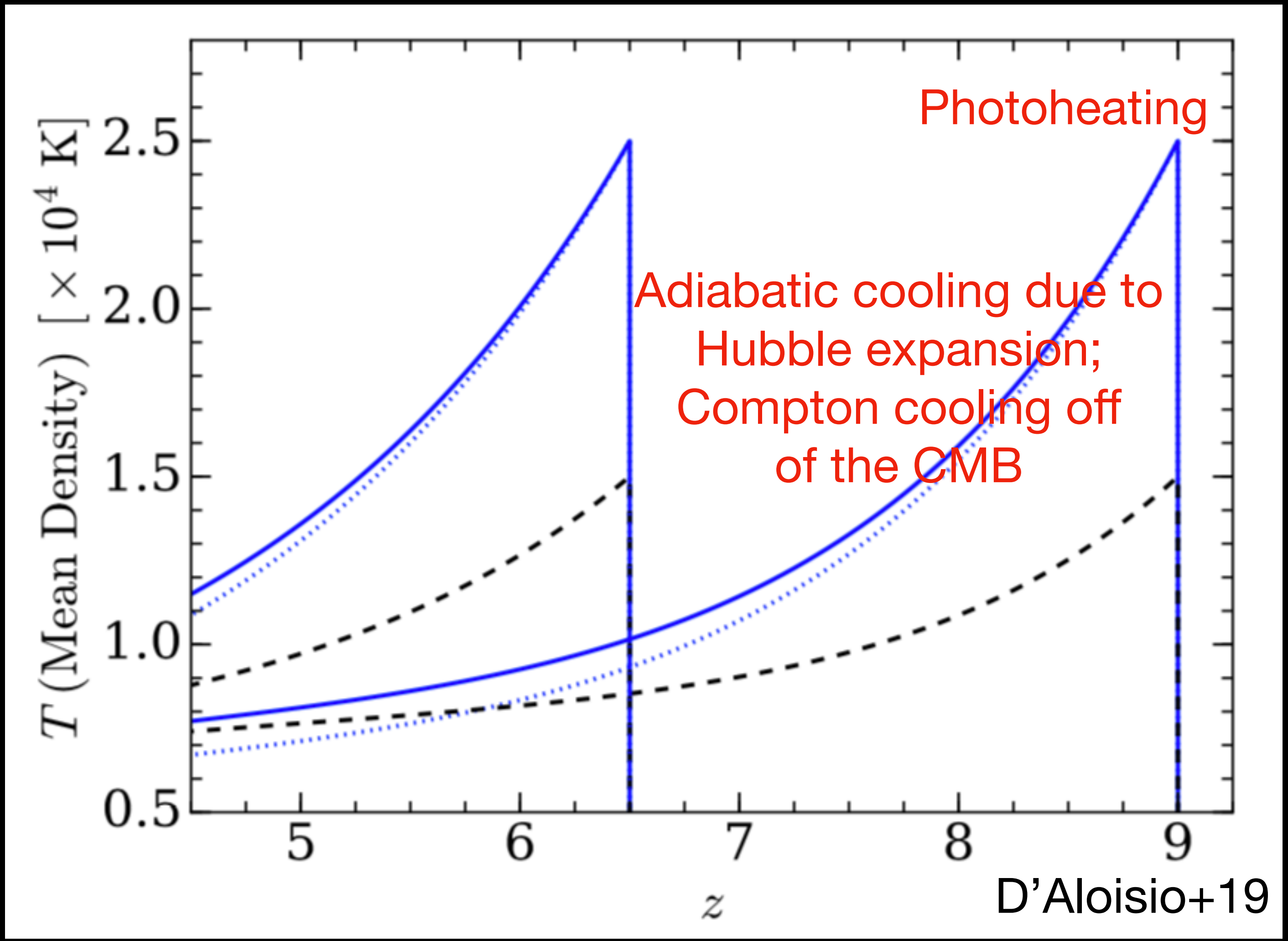
Connecting the forest with reionization via the gas temperature

- Effects of the gas temperature: width of the absorption lines and amount of neutral hydrogen $\propto T^{-0.7} \rightarrow$ small-scale shape of the flux power spectrum
- Temperature set by photoionization heating during reionization and cooling afterwards





Flux power spectrum as a probe of IGM thermal state

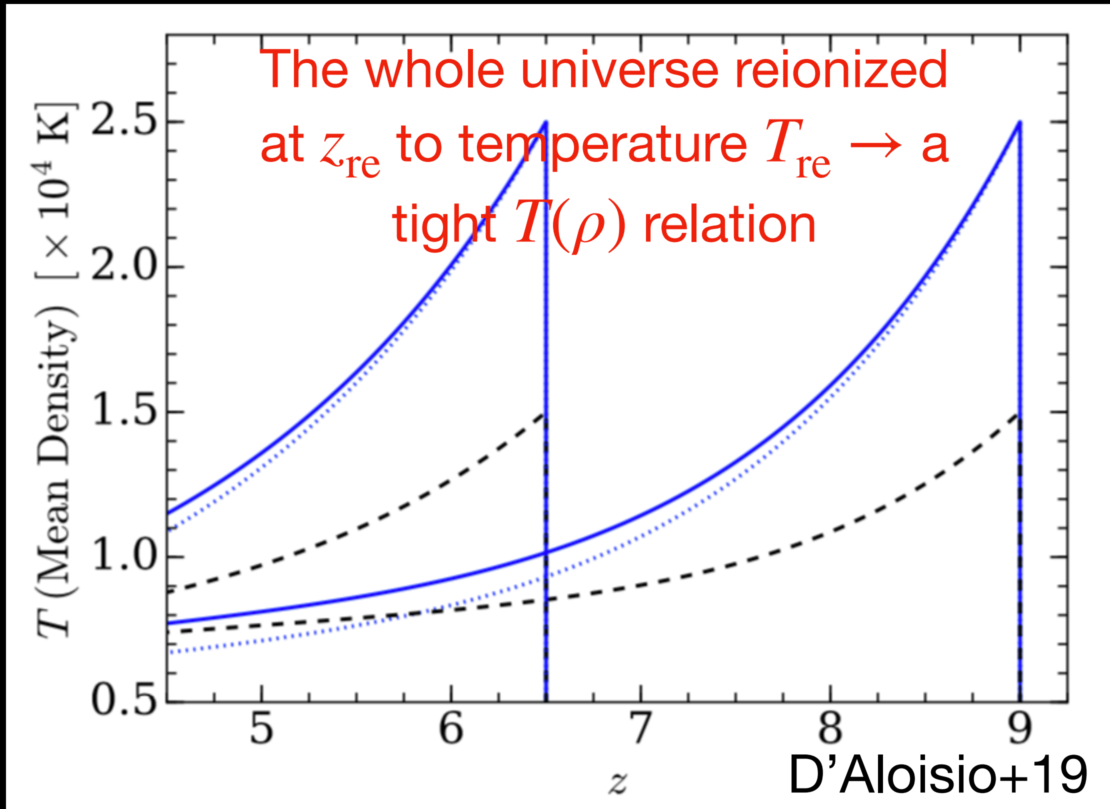
- Effects of the gas temperature: width of the absorption lines and amount of neutral hydrogen $\propto T^{-0.7}$ → small-scale shape of the flux power spectrum
- Temperature set by photoionization heating during reionization and cooling afterwards
- Flux power spectrum of the forest as a tool for constraining IGM temperature and probing reionization models (e.g. Boera+19)

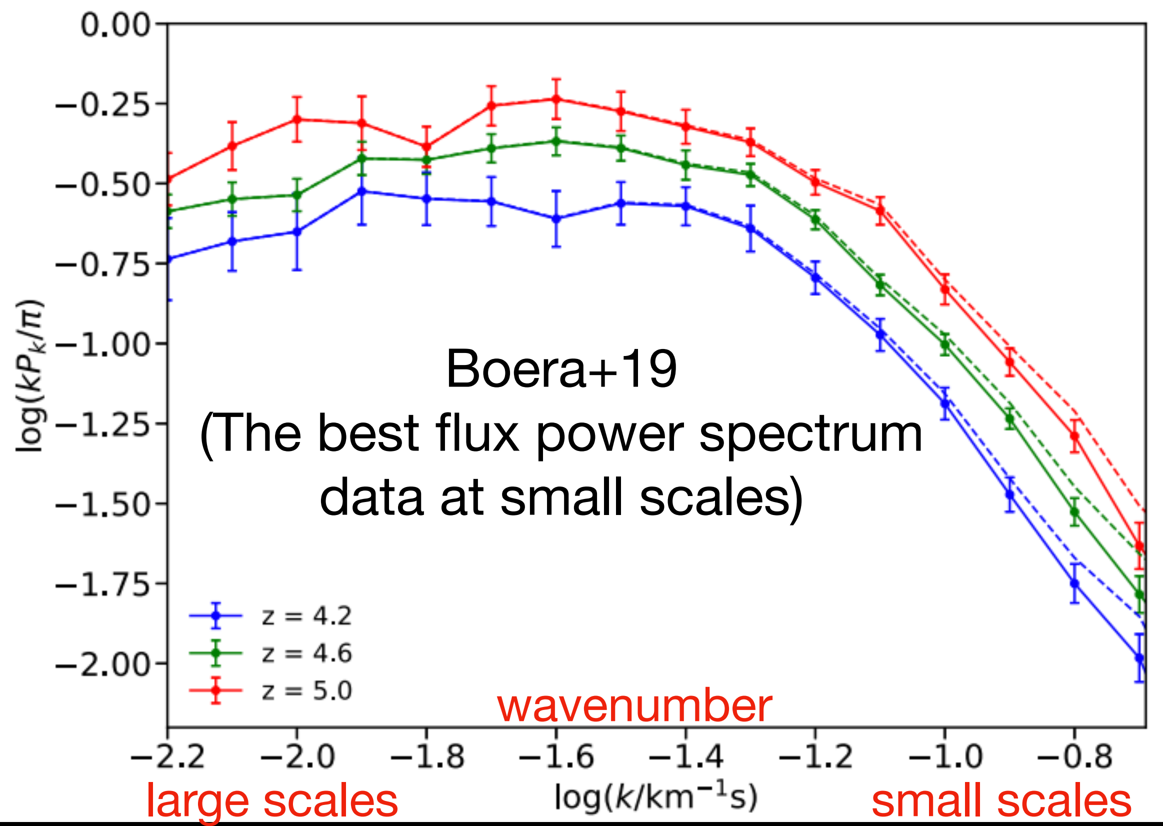
constrain

A model of reionization (with CDM / WDM / FDM)
→ IGM thermal history

Small-scale shape of flux power spectrum

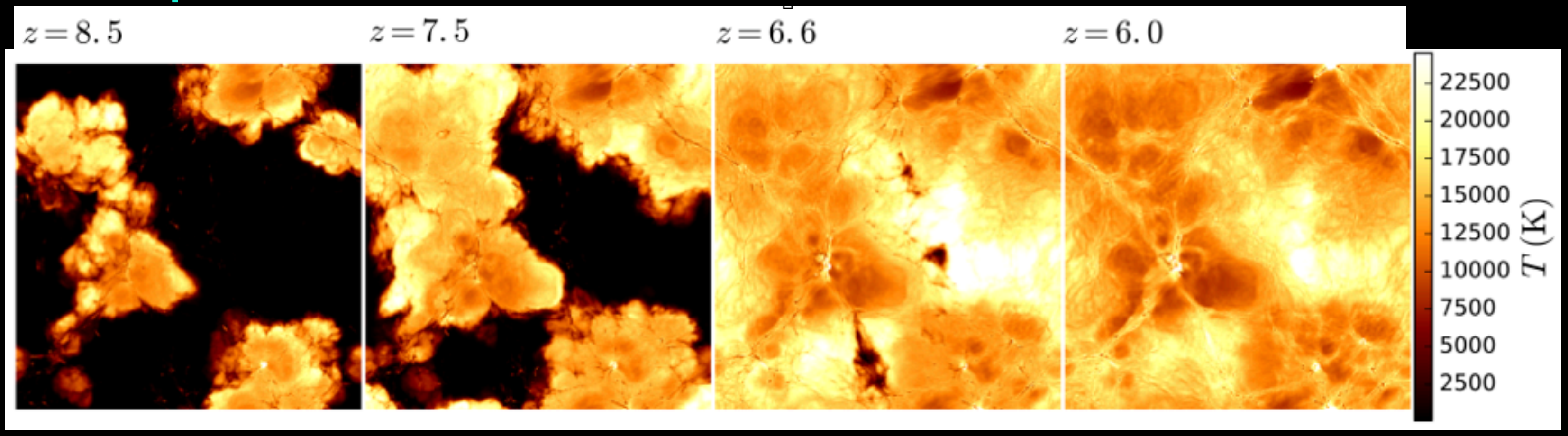
predict



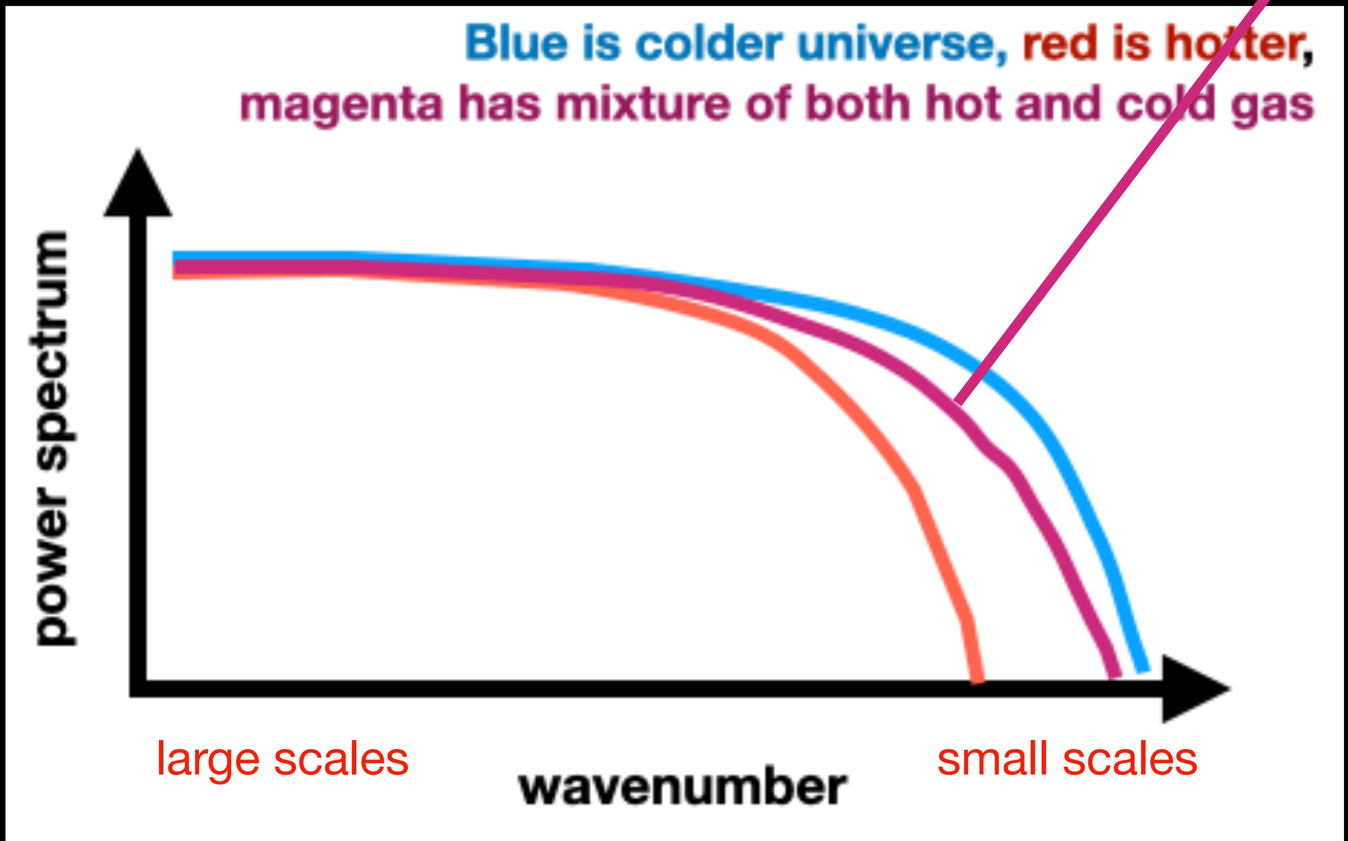


Complication from patchy reionization

- Patchy reionization: different regions of the universe reionized at different times → order unity temperature fluctuations after reionization; not a single $T(\rho)$ relation anymore
- How does patchy reionization affect the small-scale shape of flux power spectrum?



Temperature fluctuations may bias IGM temperature measurements that assume tight $T(\rho)$ relations; May also bias WDM/FDM constraints using the small-scale forest power spectrum



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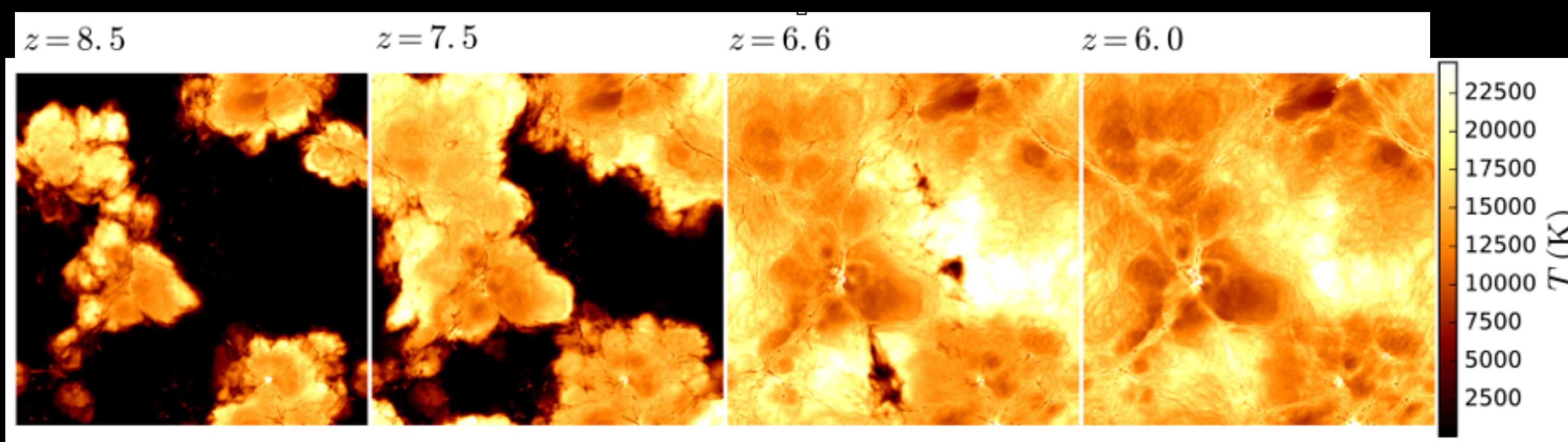
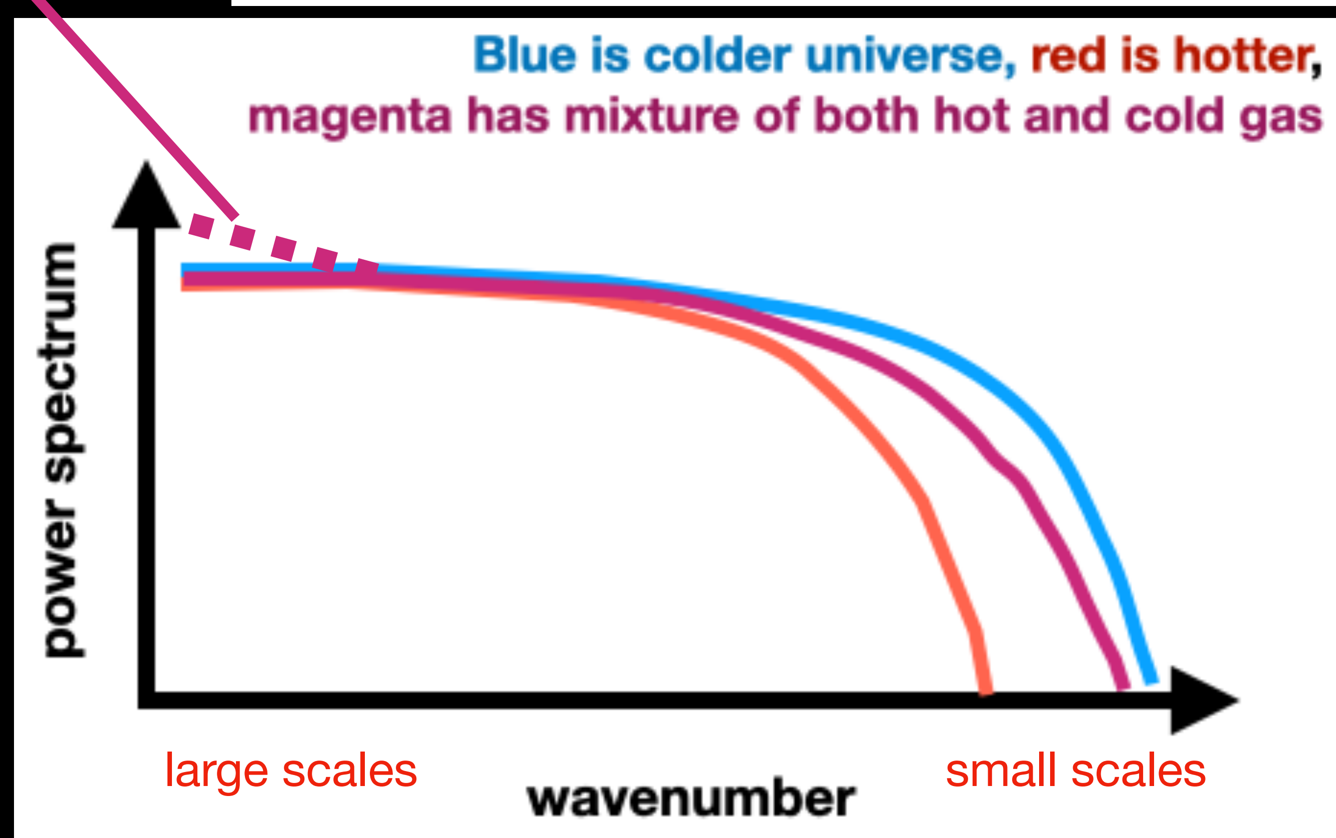
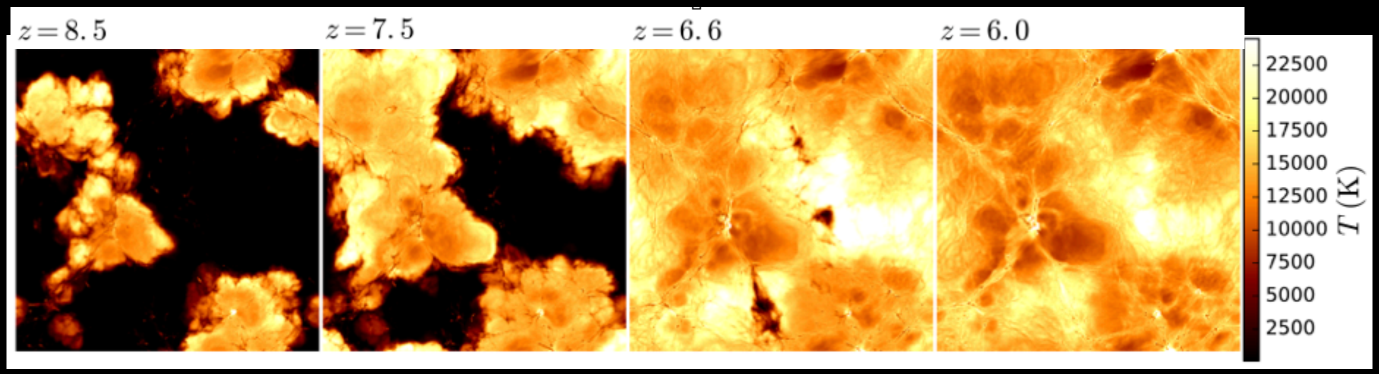


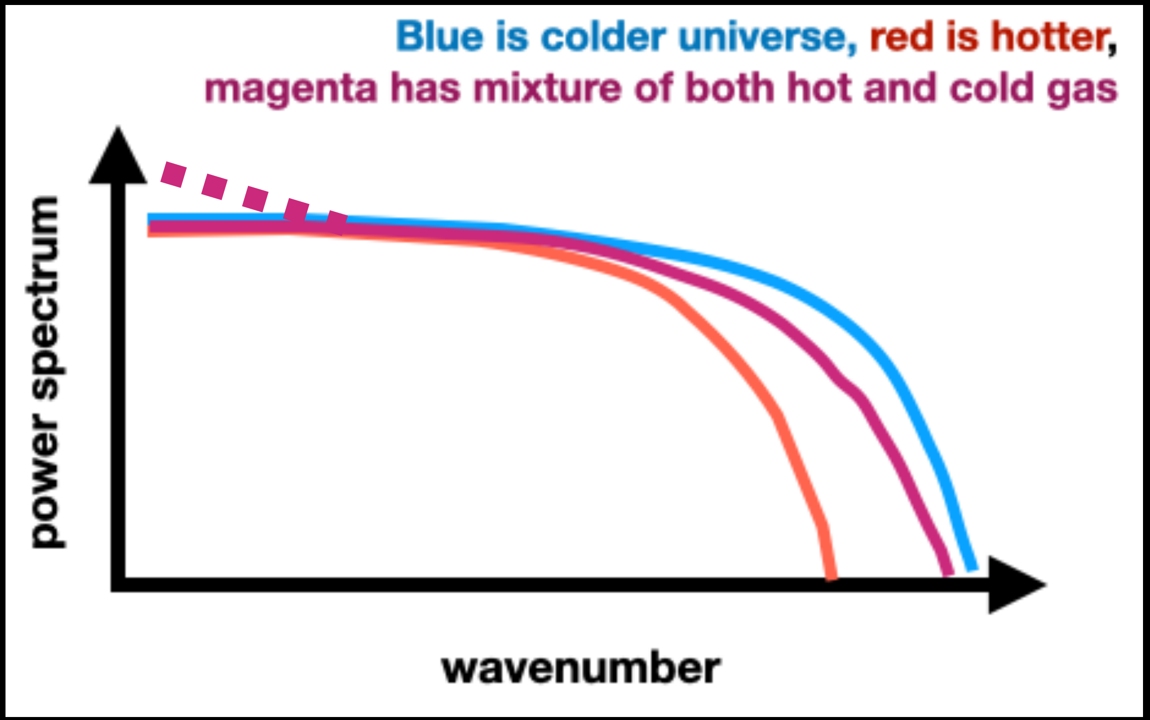
Coherent temperature fluctuations on scales of the ionized bubbles (~10 comoving Mpc) → large-scale excess power?



Putting everything together

How do the order unity temperature fluctuations due to patchy reionization affect the shape of the Lyman-alpha forest flux power spectrum, on both large and small scales? (Small-scale effects negligible)

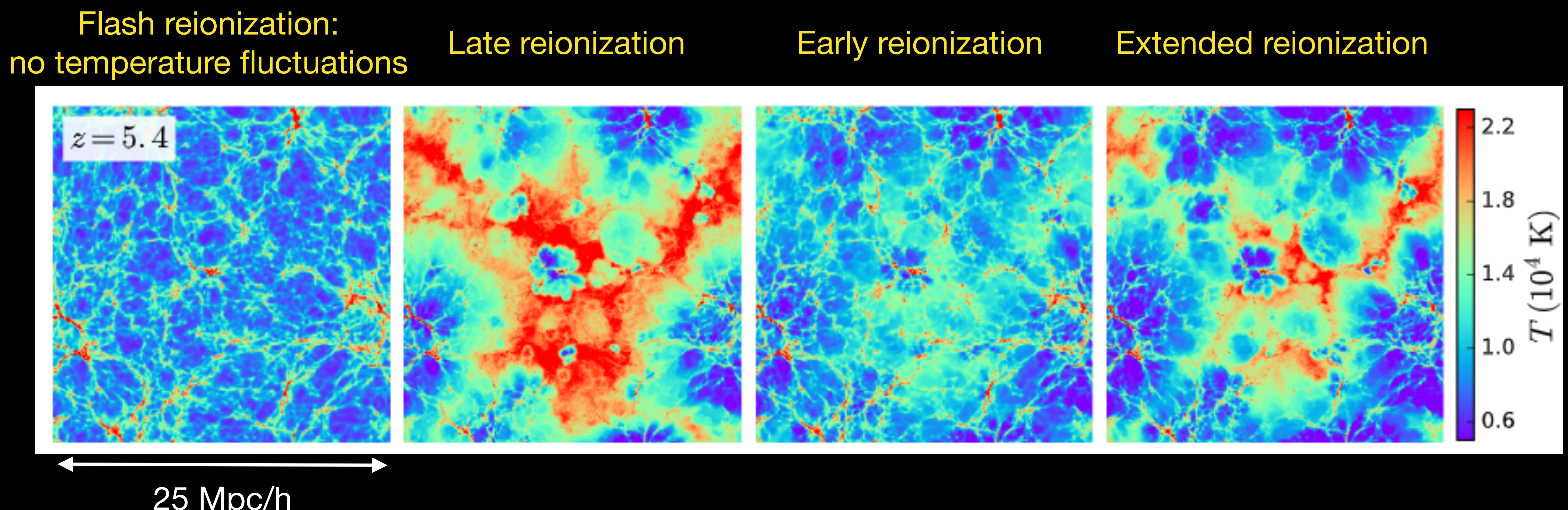




Can the shape of the flux power spectrum give us information about the patchiness of reionization? (Yes, on large scales)

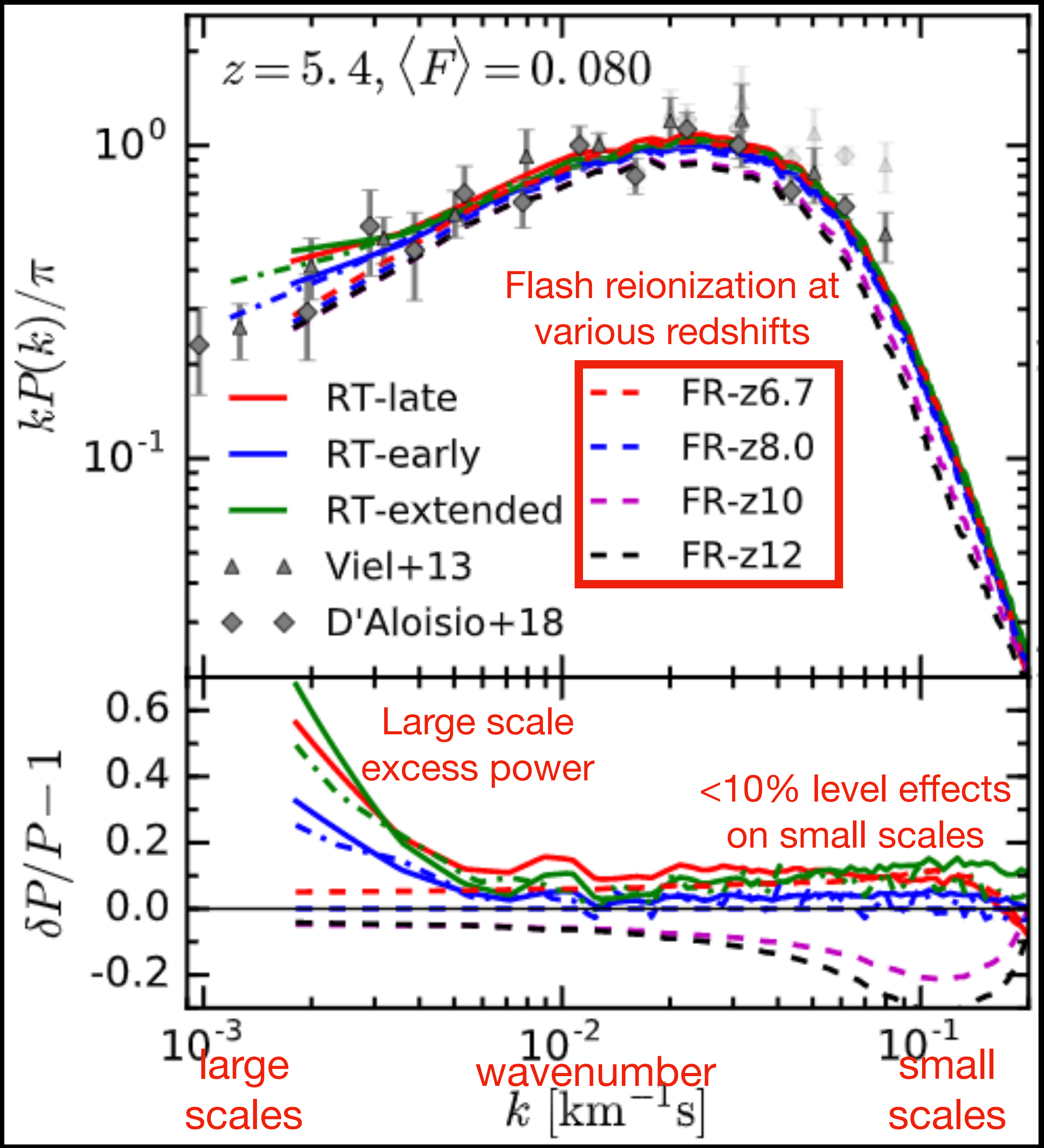
Imprints of temperature fluctuations on the forest flux power spectrum

- Radiation-hydrodynamic simulations of reionization with the Illustrius galaxy formation model — all gas physics modeled self-consistently (propagation of I-fronts, galaxy formation feedback…); the first study to directly fit simulated flux power spectrum to data (Wu+19, arxiv:1907.04860)
- Detailed examinations of simulations: Wu+19 arxiv:1903.06167
- Accuracy of radiative transfer methods: Wu+21 arxiv:2009.07278



Summary of results

- 20-60% excess large-scale power due to large-scale coherent temperature fluctuations
- Temperature fluctuations affect small scale power at <10% level because of a large cancellation between thermal broadening of the absorption lines and smoothing of the gas due to thermal relaxation



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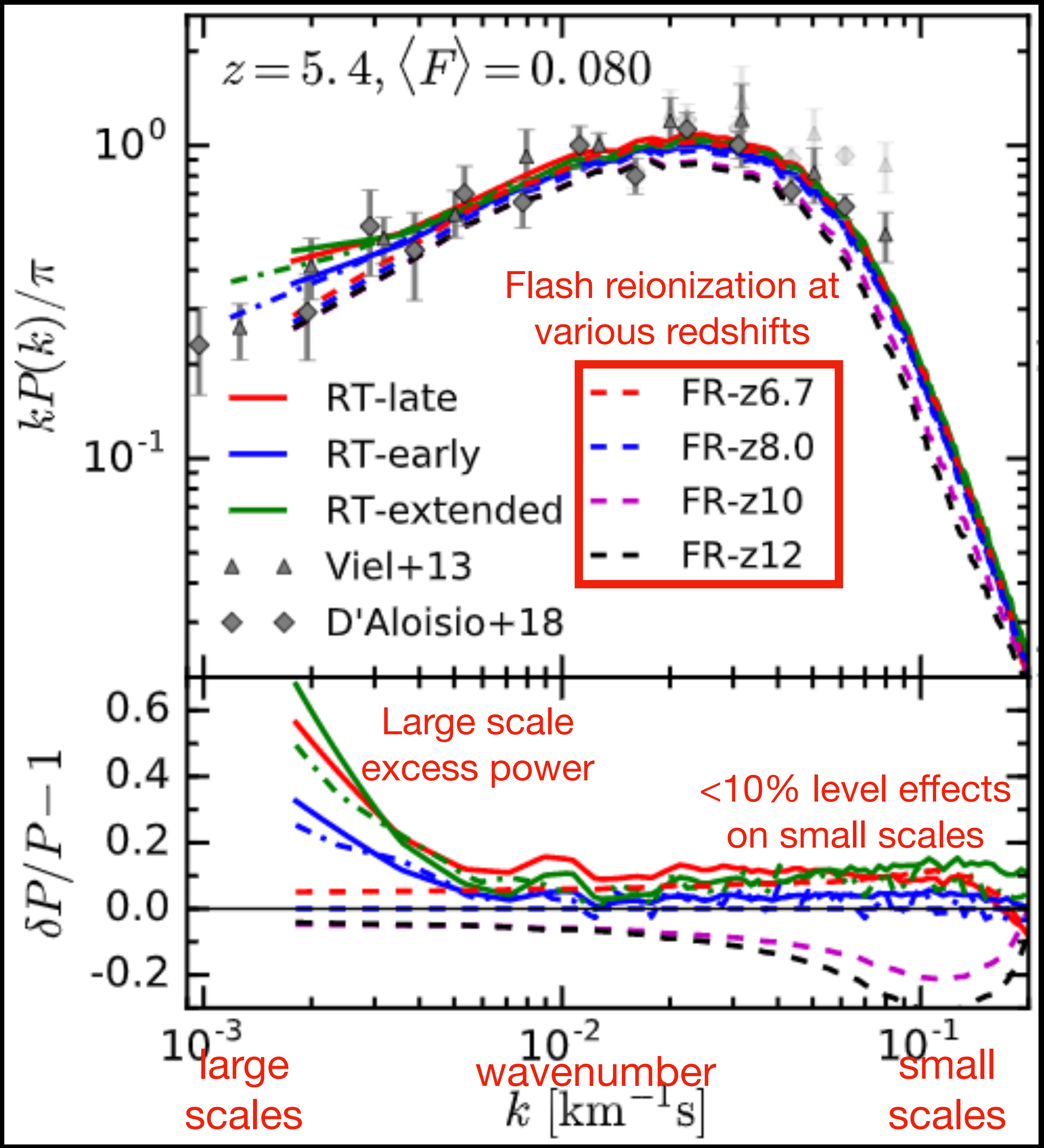

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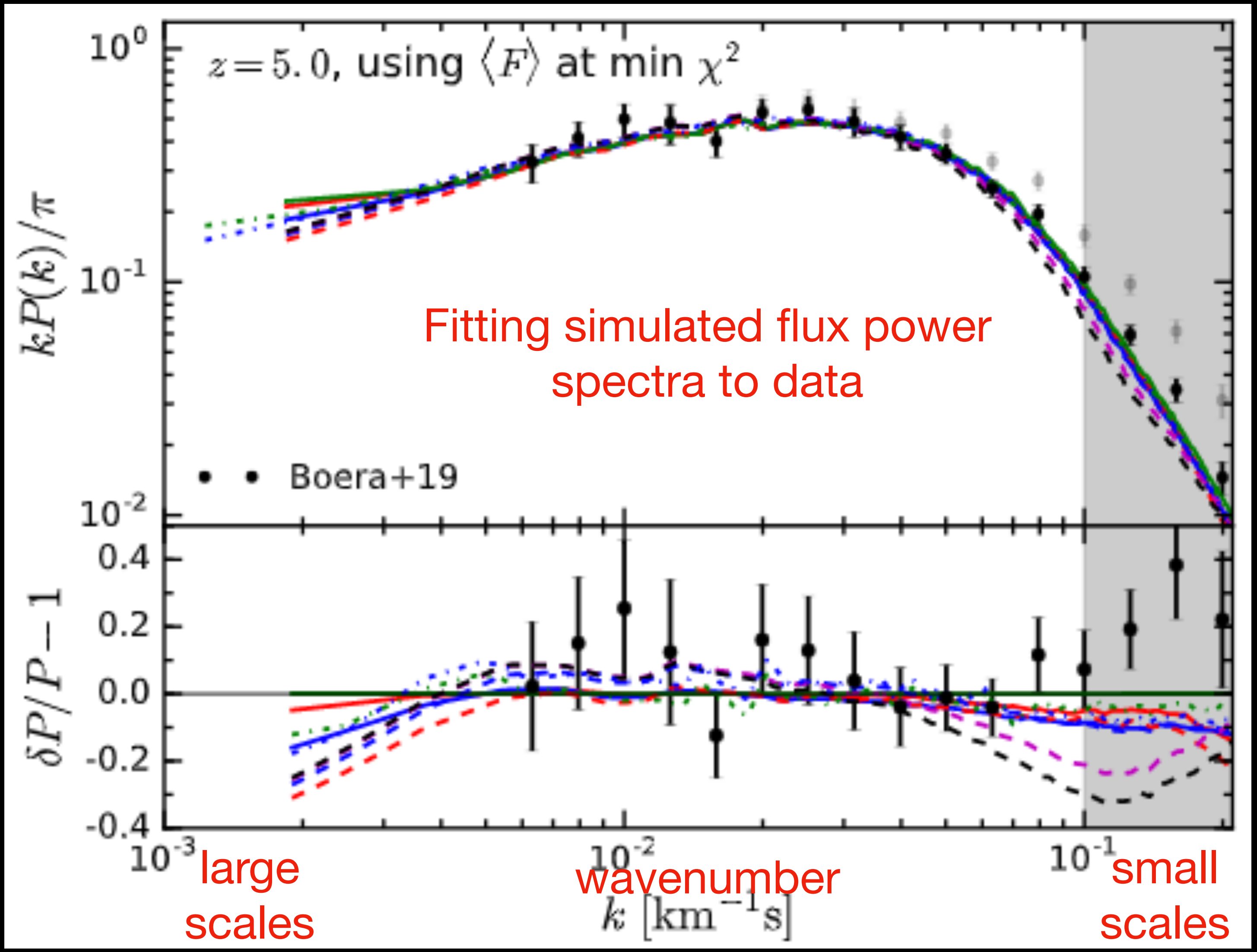
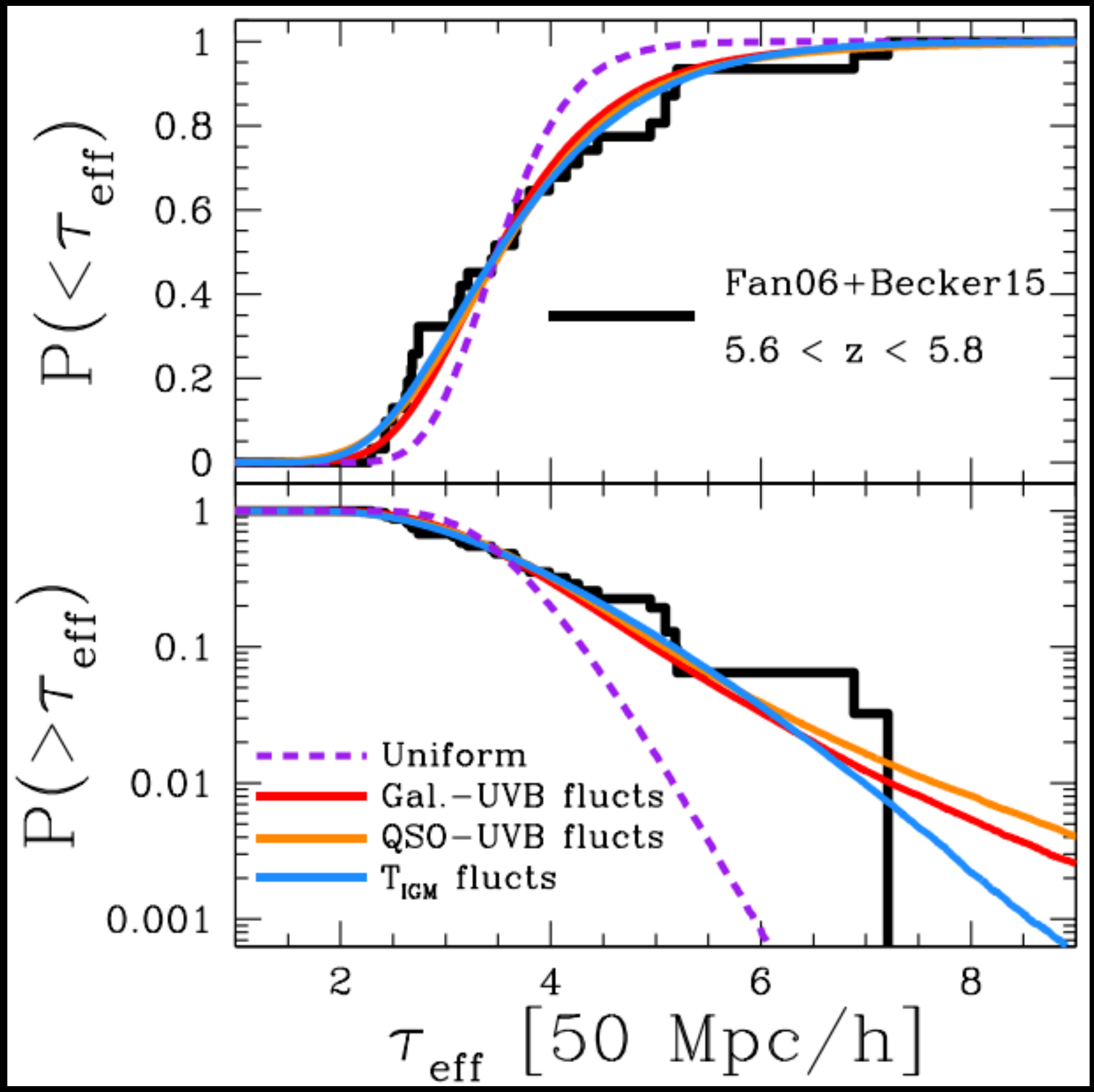
- Temperature fluctuations affect small scale power at <10% level because of a large cancellation between thermal broadening of the absorption lines and smoothing of the gas due to thermal relaxation → temperature fluctuations unlikely to bias temperature measurements or WDM/FDM constraints for now
- Small-scale power mostly determined by midpoint of reionization; we can rule out $z_{\rm re} > 8$ at 2.5-sigma level using the small-scale power



We ignored ionizing background fluctuations

- Large spatial fluctuations in the (post-reionization) Lyman-alpha forest opacity suggest large-scale fluctuations in the ionizing background after reionization
- $n_{\rm HI} \propto T^{-0.7}\Delta^2/\Gamma$
- It has been a campaign for sims to reproduce the observed large spatial scatter in the forest opacity
- Implications for sources of reionization, gas relaxation, abundance of photon sinks…

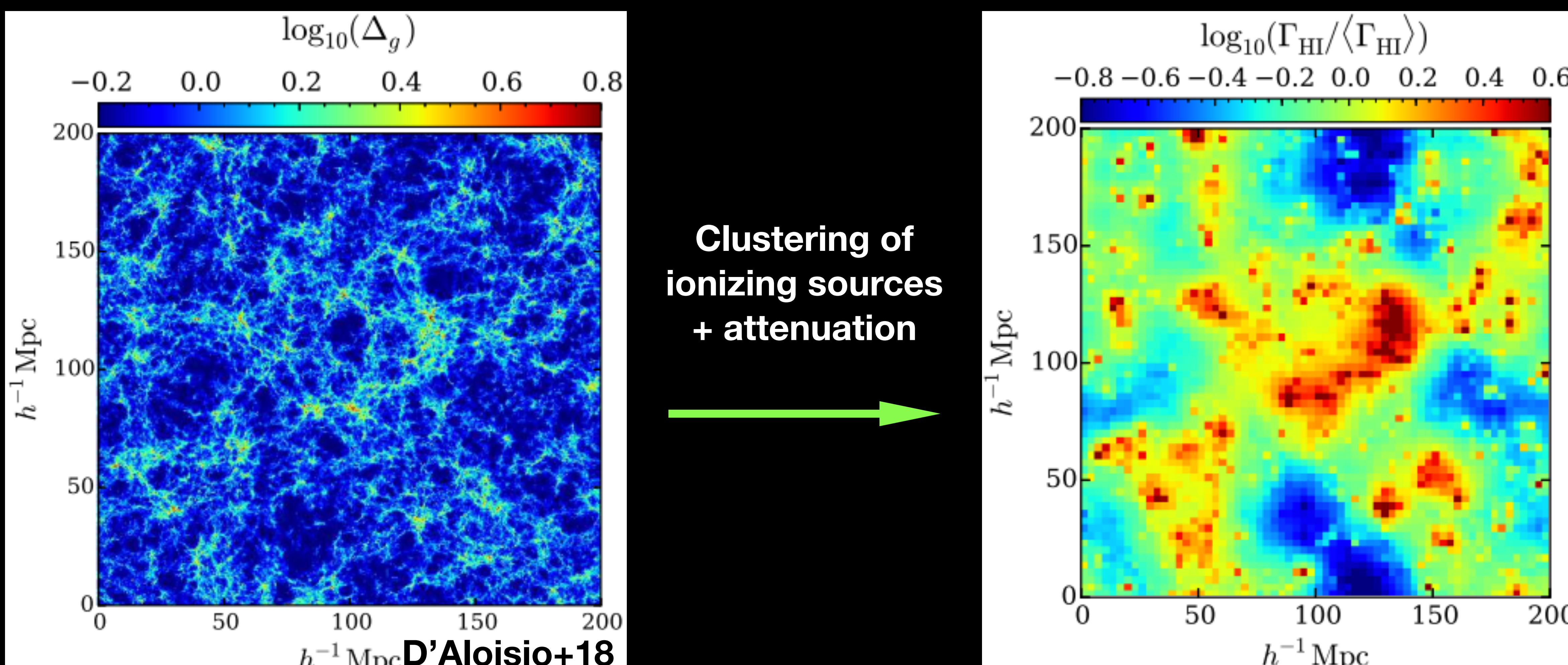


Becker+18

What is the impact of using the approximate radiative transfer method on reproducing the post-reionization ionizing background fluctuations

We ignored ionizing background fluctuations

- $n_{\rm HI} \propto T^{-0.7}\Delta^2/\Gamma$ — ionizing background fluctuations can also lead to fluctuations in forest transmission
- We have ignored UV background fluctuations in the previous project, but observational evidence support the existence of large scale (~50 comoving Mpc/h) ionizing background fluctuations
- Simulations of reionization aim to reproduce ionizing background fluctuations, but we show such sims have huge caveats



Radiative transfer simulations are likely biased at reproducing ionizing background fluctuations

- The 6D RT equation

Direction of radiation field — **Absorption coefficient (photon sink)** — **Emissivity (source term)**

$$\frac{1}{c}\frac{\partial I}{\partial t} + \vec{n}\cdot\nabla I = -\kappa I + j$$

- Ray-tracing expensive; reduce the dimensionality of the RT equation by integrating out the angular dependence of intensity

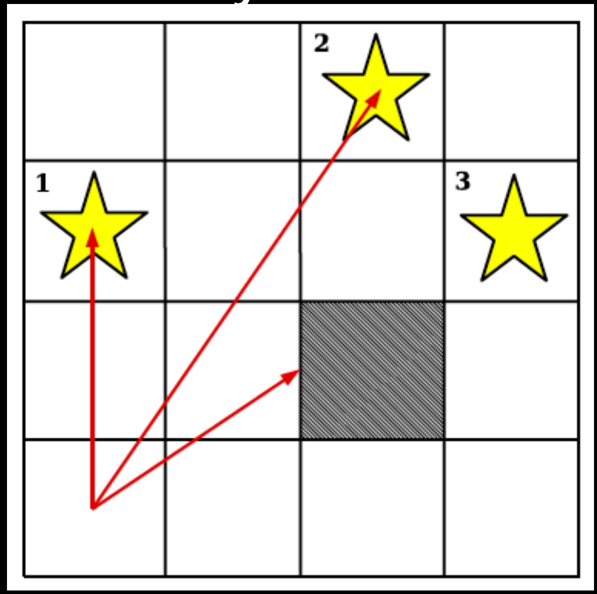
Photon density — **Photon flux** — **Radiation pressure tensor**

$$E = \frac{1}{4\pi}\int I \, \mathrm{d}\Omega; \quad \vec{F} = \frac{1}{4\pi}\int \hat{\mathbf{n}} I \, \mathrm{d}\Omega; \quad \boldsymbol{P} = \frac{1}{4\pi}\int \hat{\mathbf{n}} \otimes \hat{\mathbf{n}} \, I \mathrm{d}\Omega,$$

- Moment-based RT equations:

$$\frac{1}{c}\frac{\partial E}{\partial t} + \frac{1}{a}\nabla\cdot\boldsymbol{F} = -\kappa E + j$$

$$\frac{1}{c}\frac{\partial \boldsymbol{F}}{\partial t} + \frac{1}{a}\nabla\cdot\boldsymbol{P} = -\kappa\boldsymbol{F},$$



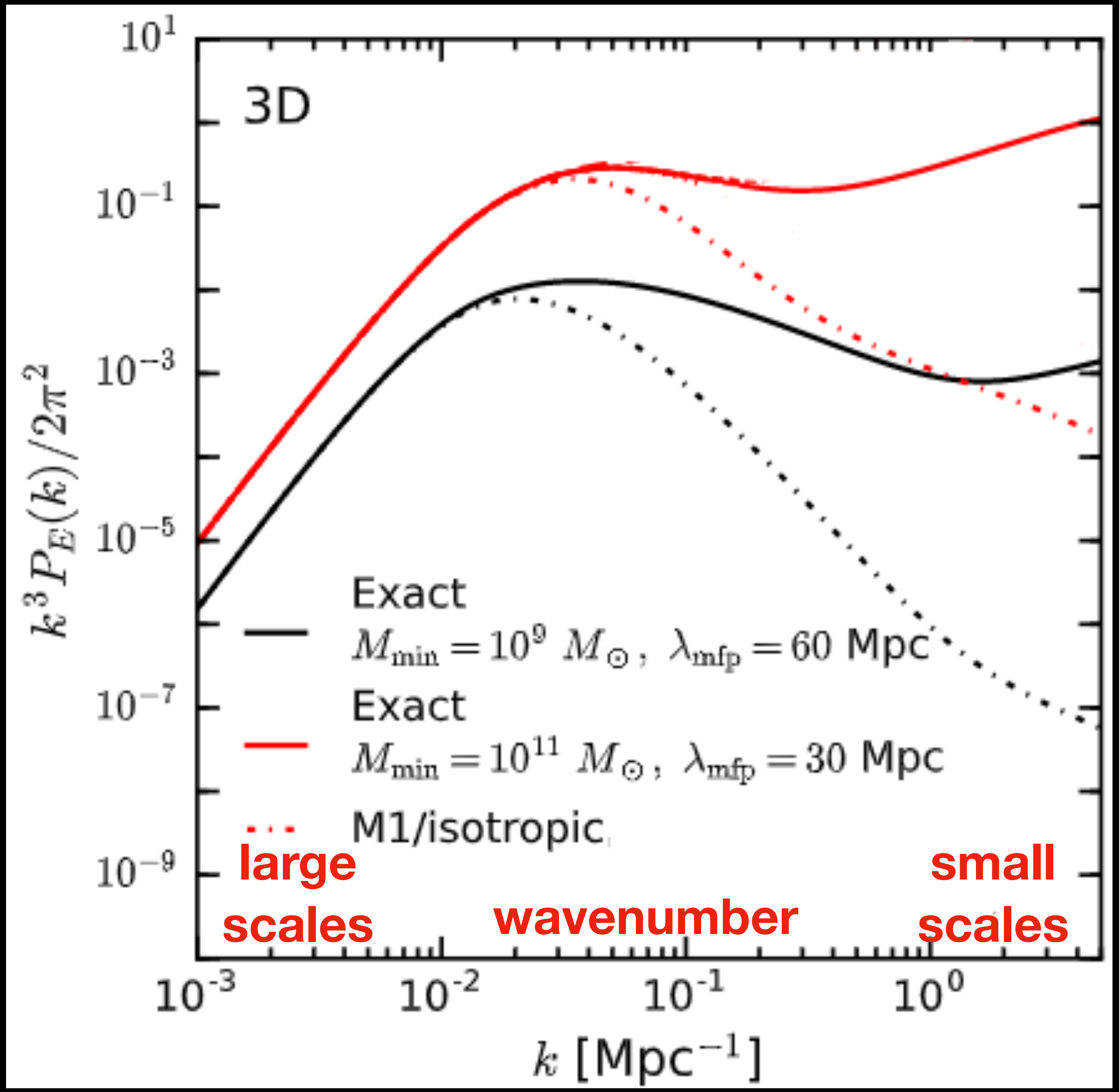
Finlator+09

- 2 equations, 3 unknowns, introduce the Eddington tensor $E h_{mn} = P_{mn}$ and make an ansatz for h_mn to close the moment equations
- e.g. M1 closure $$h_{mn} = \frac{1-\chi}{2}\delta^K_{mn} + \frac{3\chi - 1}{2}\hat{\mathrm{n}}_m\hat{\mathrm{n}}_n; \quad \hat{\mathrm{n}}_m = \frac{F_m}{|\boldsymbol{F}|}$$ $$\chi = \frac{3+4g^2}{5+2\sqrt{4-3g^2}}; \quad g = \frac{|\boldsymbol{F}|}{E}$$

Radiative transfer simulations are likely biased at reproducing ionizing background fluctuations

- Simulations of reionization use approximate methods for performing radiative transfer -> properties of the radiation field changed
- Solve linear order ionizing background fluctuations…
- For instance, the widely-used M1 algorithm of radiative transfer drastically underestimates ionizing background fluctuations on scales below the photon mean free path

3D power spectrum of ionizing background fluctuations from perturbation theory calculations



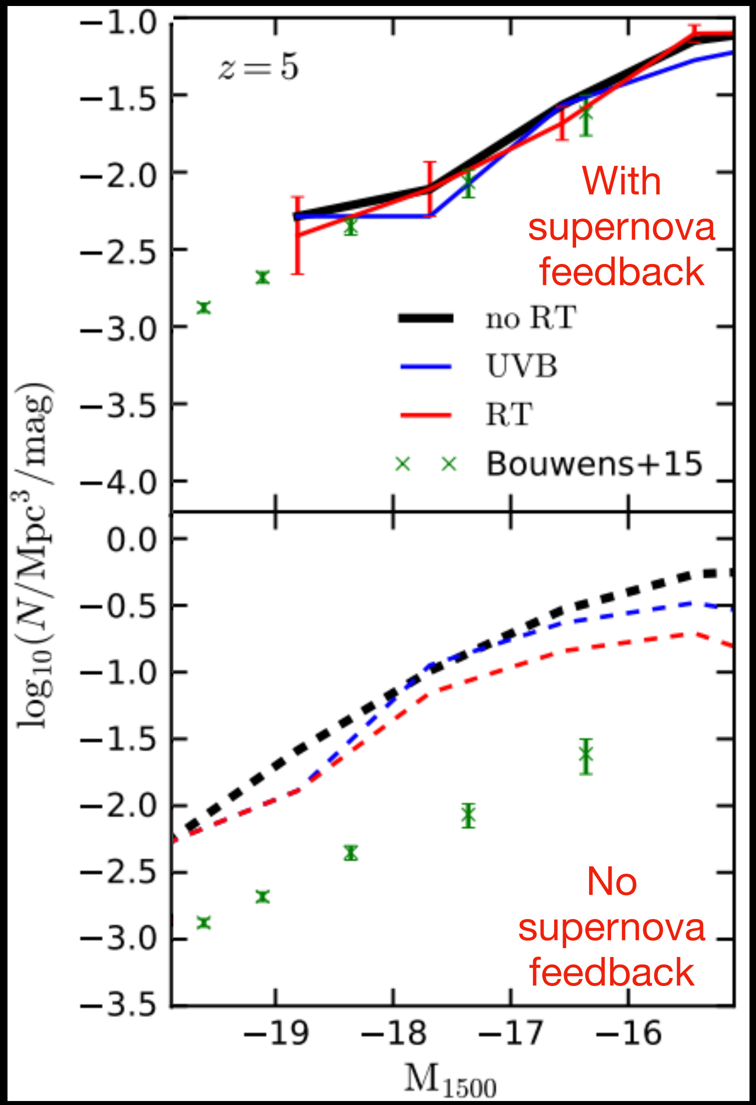
Wu+21, arxiv:2009.07278

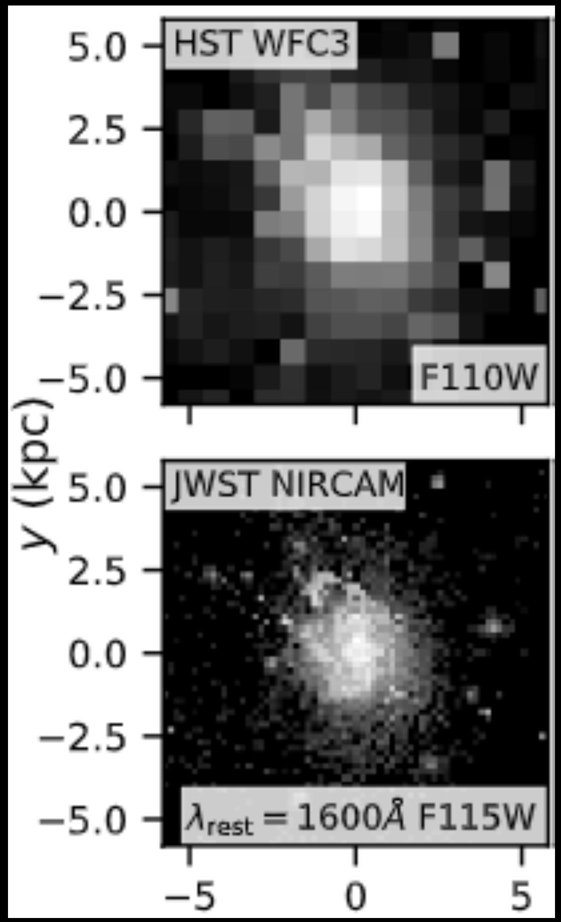
Other things I've worked on — reach out to me if you are interested in hearing more!

UV luminosity function as a probe of reionization:

Unlikely to be plausible because supernova feedback dominates over photoheating feedback due to reionization

Wu+19, arxiv:1903.06167





Photometric properties of z=6 galaxies in Simba simulations

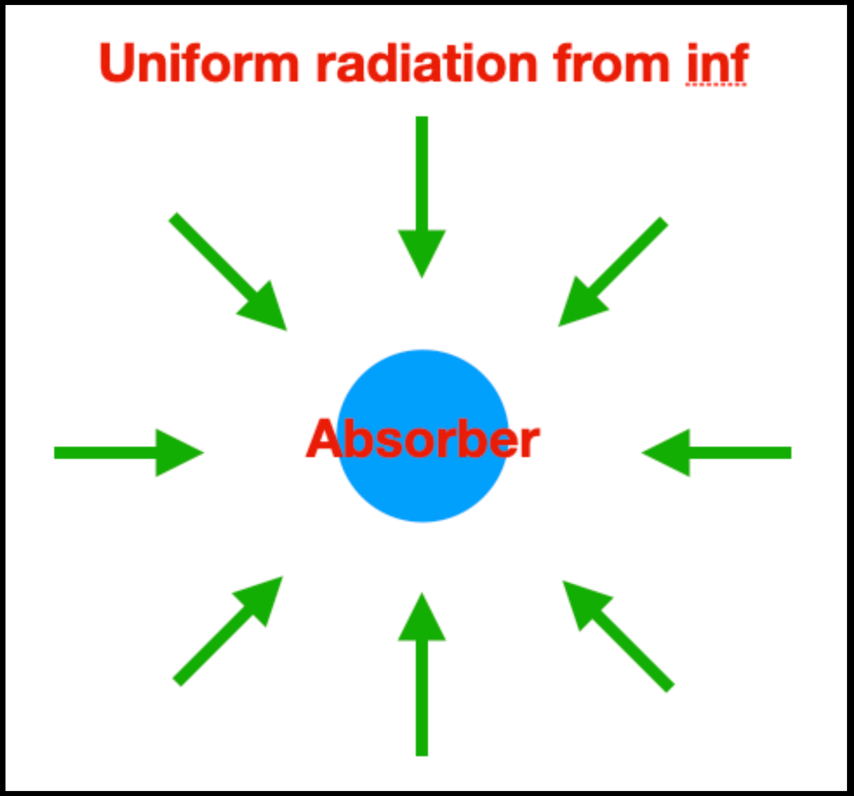
Testing how galaxy formation models work at high redshift

Wu+20, arxiv:1911.06330

Accuracy of radiative transfer methods on simulating reionization

Moment-based methods likely biased at matching Lyman-alpha forest observations

Wu+21, arxiv:2009.07278

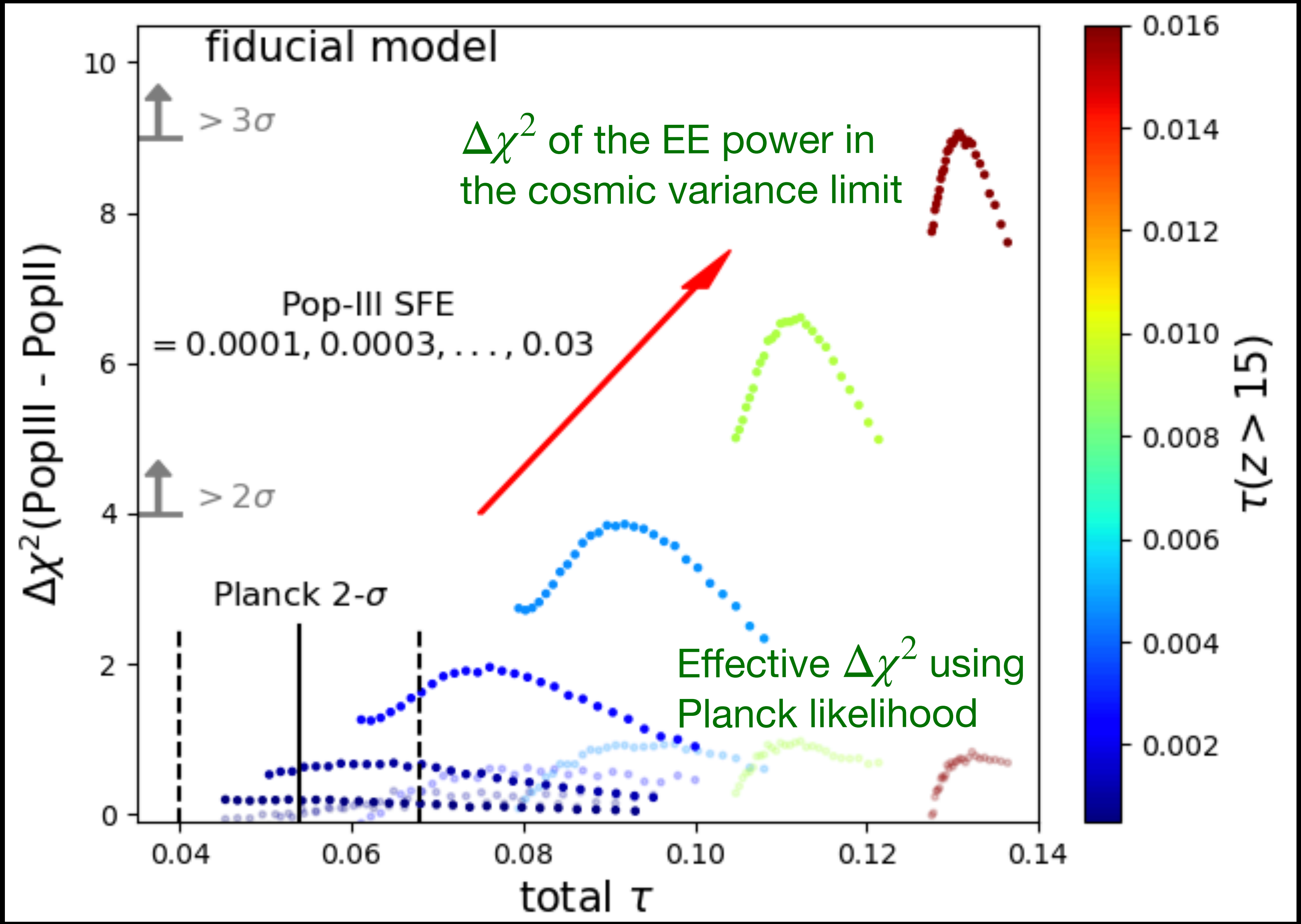


Conclusions

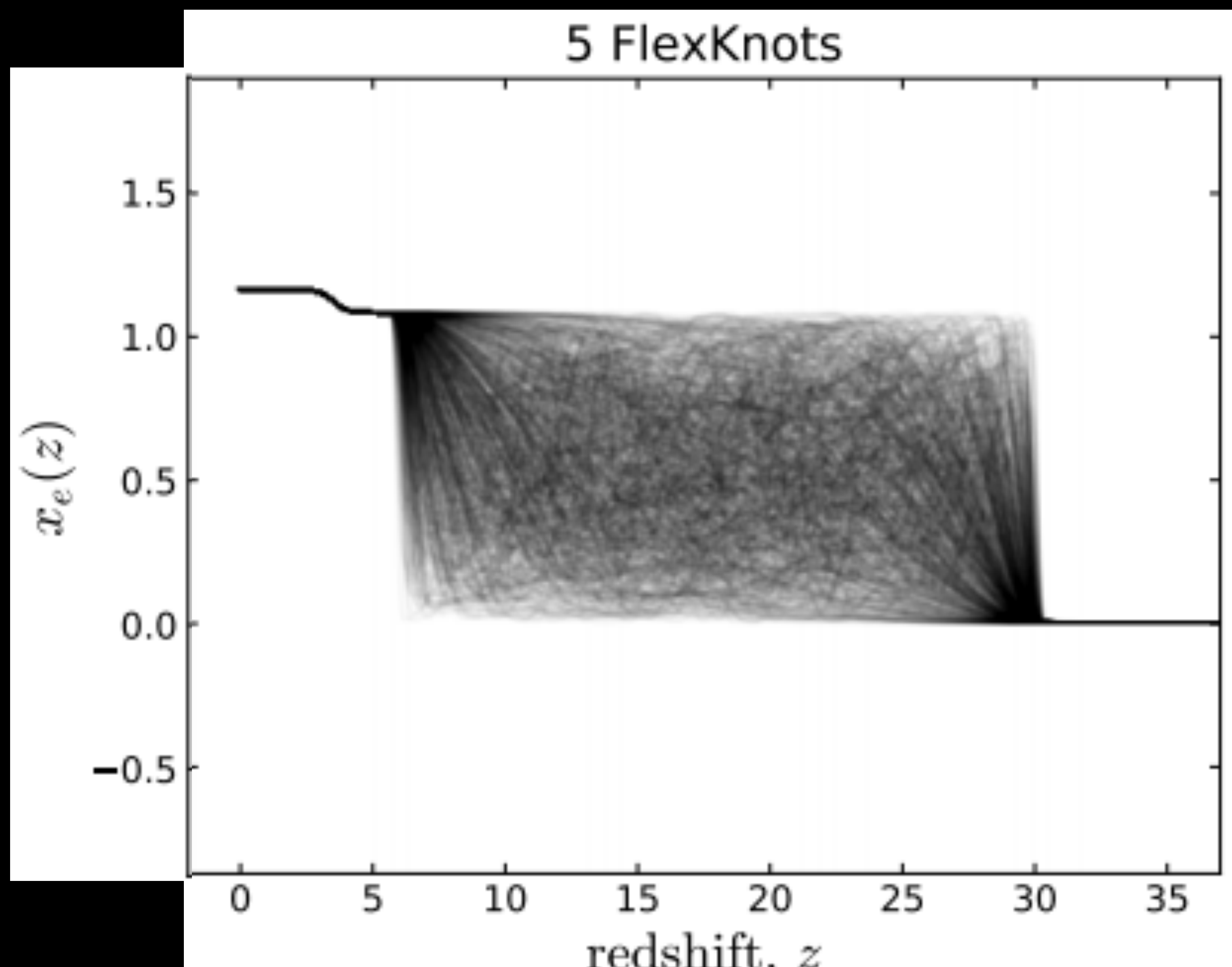
- Constraining Pop-III with the low-ell CMB: contribution of the Pop-III stars to reionization at z>15 is unlikely to be constrained by large-scale CMB E-mode polarization (Wu et al. arxiv: 2105.08737)
- Effects of temperature fluctuations from patchy reionization on the Lyman-alpha forest flux power spectrum: the most evident imprints are on the large scales; negligible impacts on small scales
- Temperature fluctuations are unlikely to affect IGM temperature measurements and WDM/FDM constraints; the small and intermediate-scale power can be used to constrain of the midpoint of reionization (Wu+19, arxiv:1907.04860)
- Accuracy of radiative transfer methods: radiative transfer simulations of reionization are likely biased at reproducing the large-scale fluctuations in the Lyman-alpha forest transmission due to approximate radiative transfer methods (Wu+21, arxiv:2009.07278)

Backup slides

The Planck tau(z>15)?



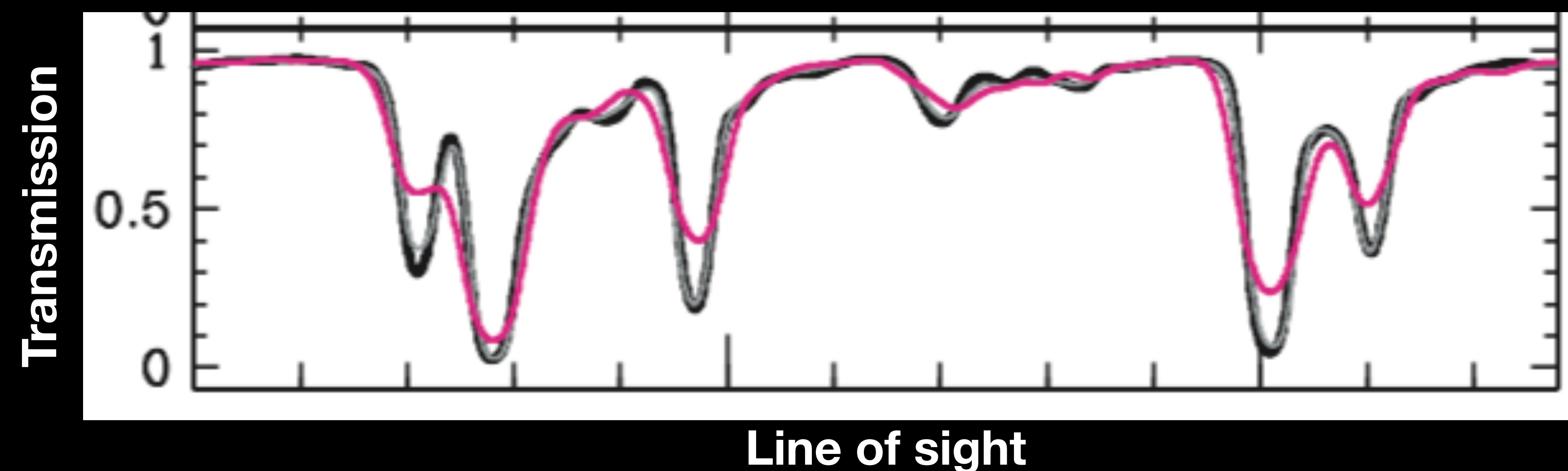
FlexKnot reionization histories



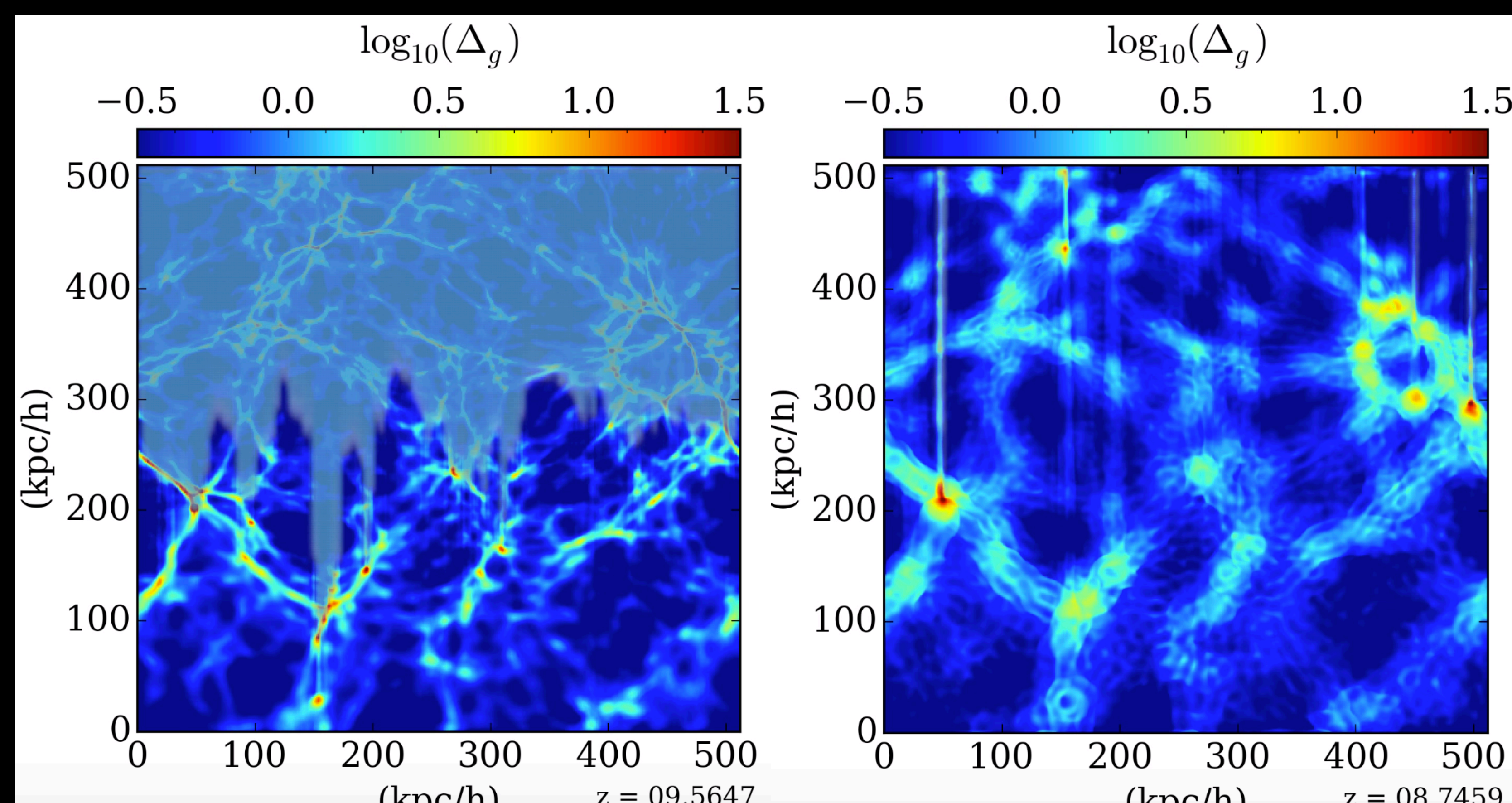
Millea & Bouchet 2018

Thermal broadening vs pressure smoothing

- Thermal broadening

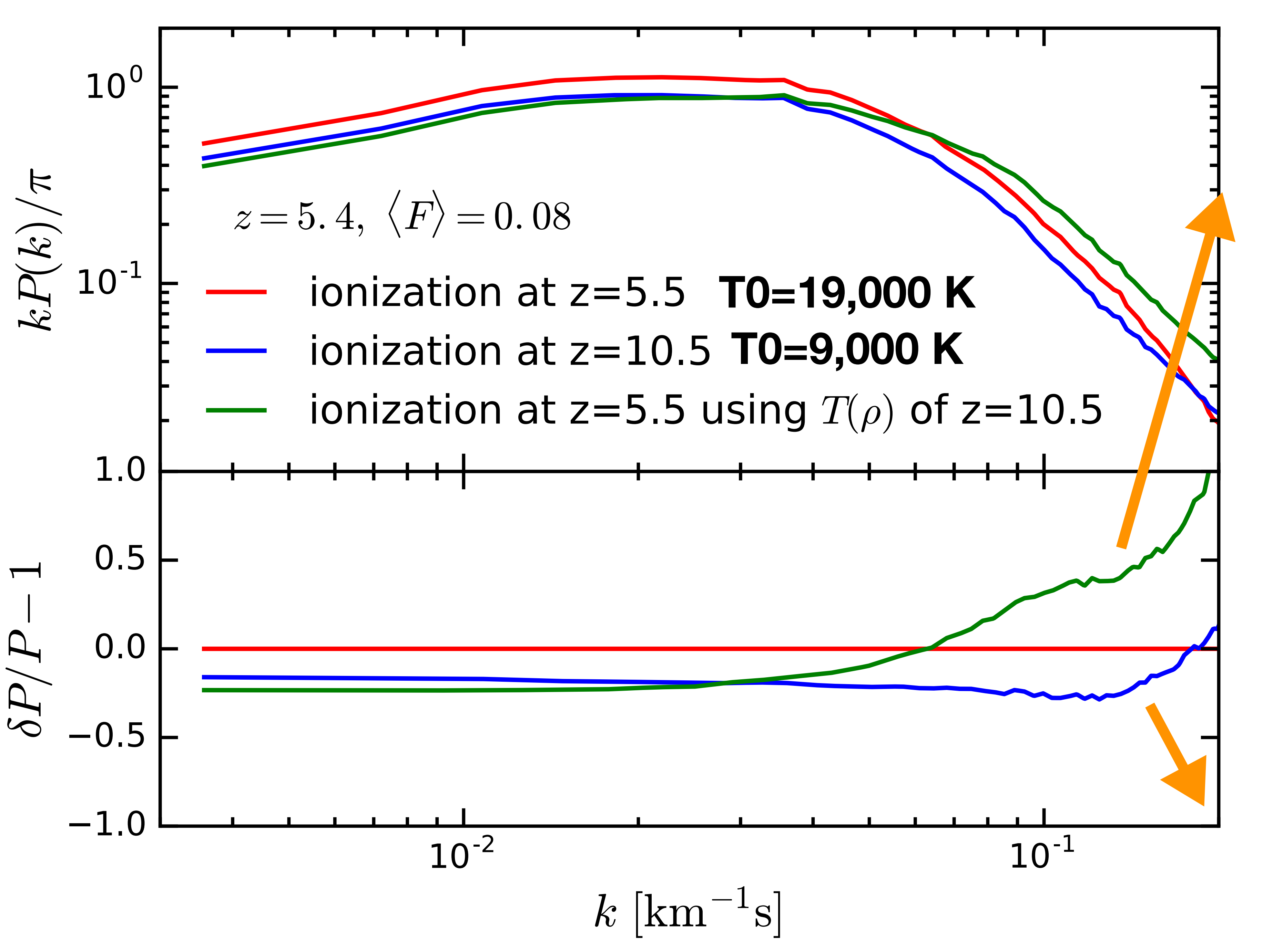


- Pressure smoothing due to gas relaxation



Thermal broadening vs pressure smoothing

- A cancellation between pressure smoothing and thermal broadening



Pressure smoothing suppresses small-scale power by ~50%

Cancelling thermal broadening effects

<30% differences

UV luminosity function as a probe of reionization?

Wu+19, arxiv:1903.06167

- Gas photoheated to ~10^4 K during reionization -> gas reservoir of low mass halos expelled, accretion onto low mass halos suppressed -> a suppression of the faint end slope of the UV luminosity function?
- Supernova feedback dominates the regulation of star formation; photoheating feedback subdominant -> unlikely to observe a suppressed faint end slope due to reionization