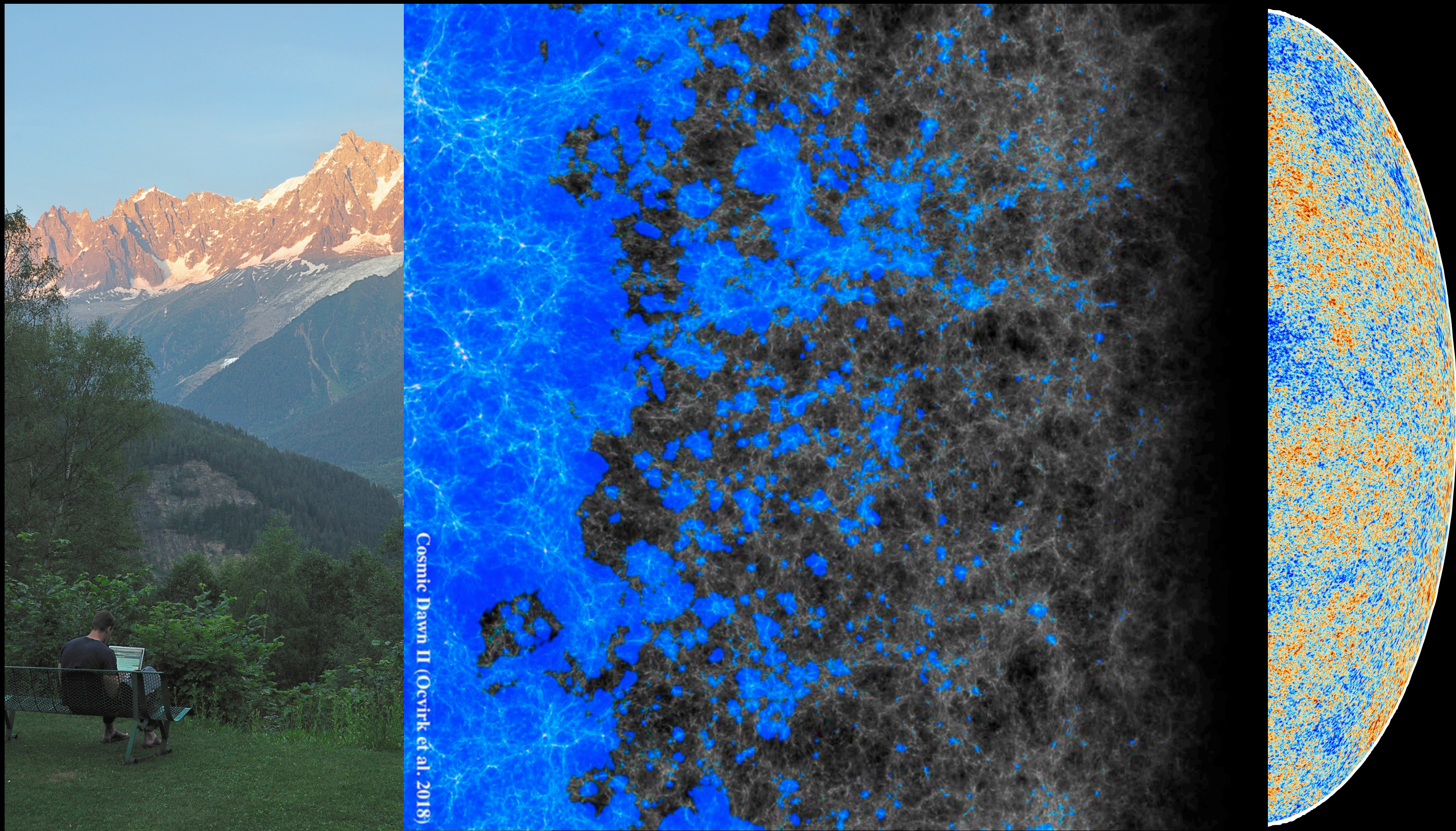
IAS
Institut d'Astrophysique Spatiale
Orsay

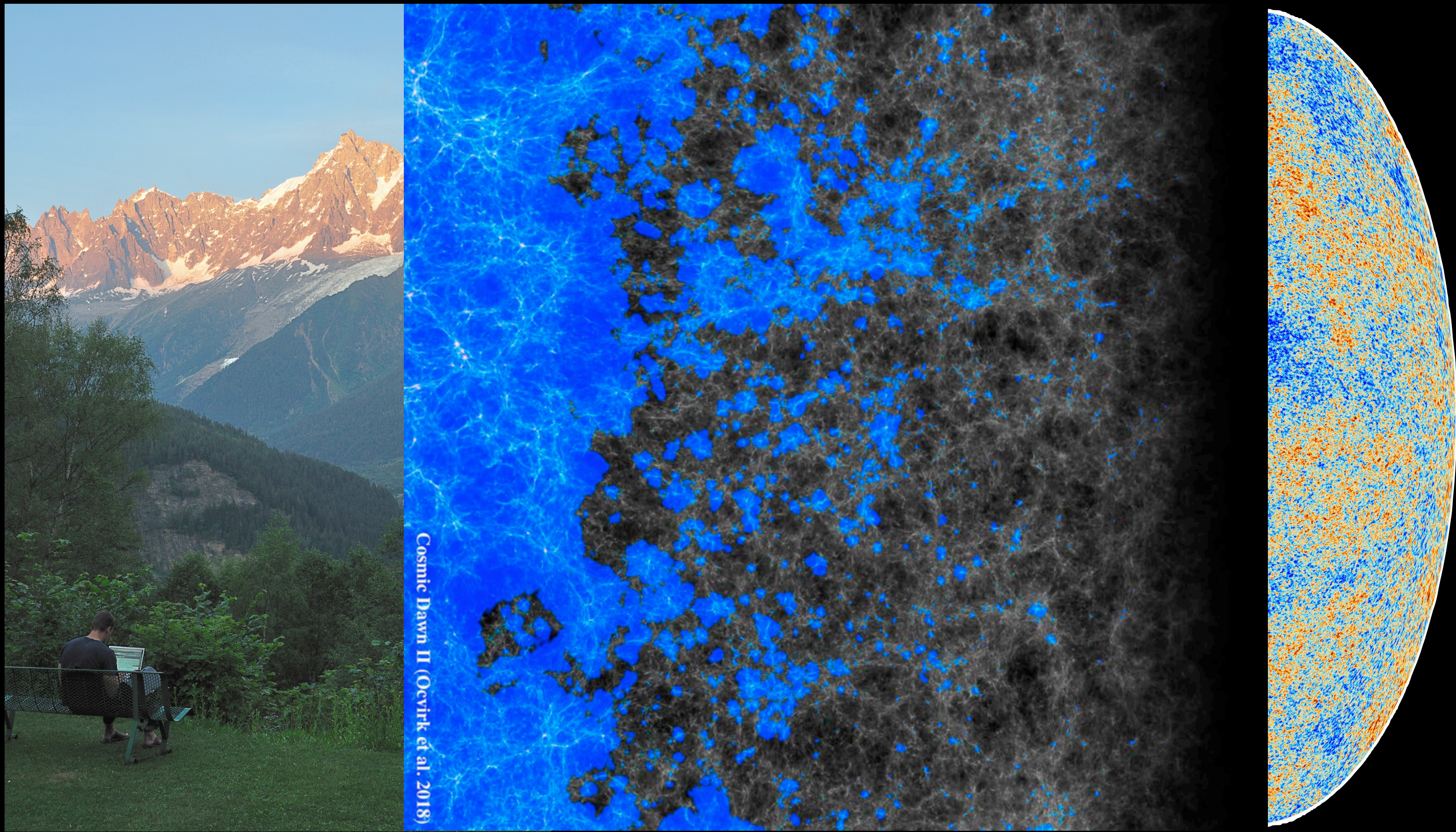
ÉCOLE DE PHYSIQUE DES HOUCHES

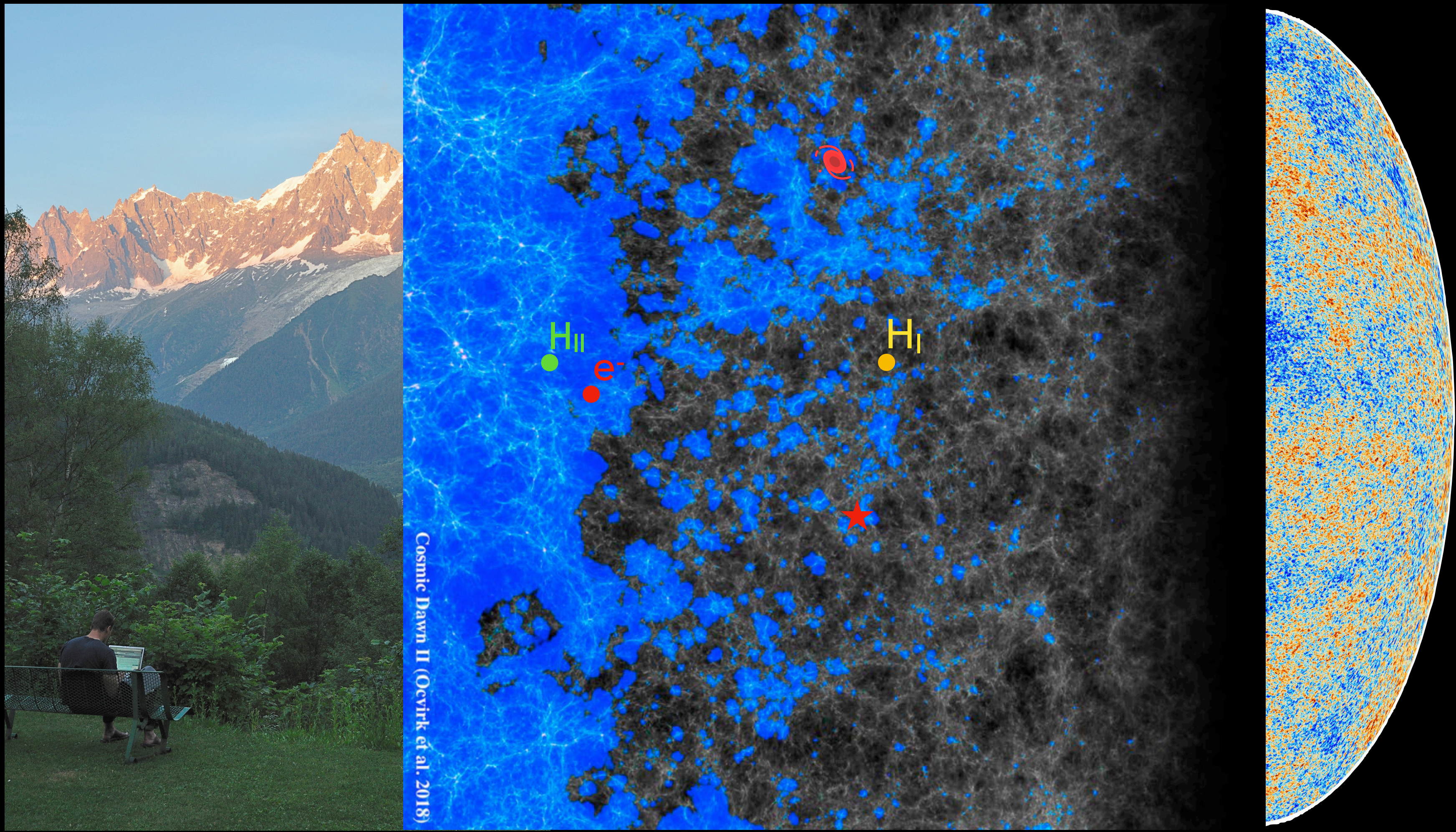
Reionisation: (some)Observations

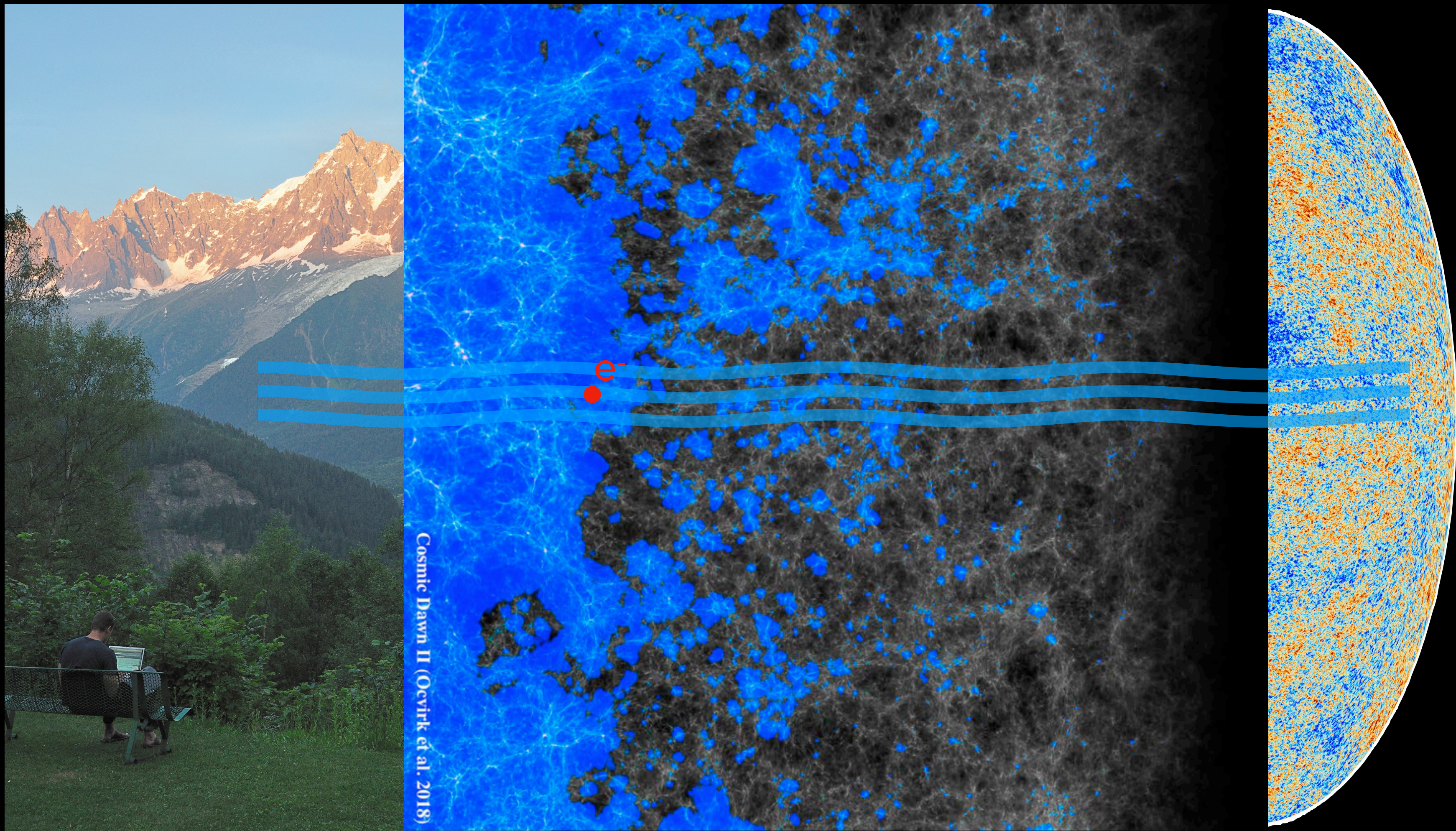
Marian Douspis
IAS, Orsay


Cosmic Dawn II (Ocvirk et al. 2018)

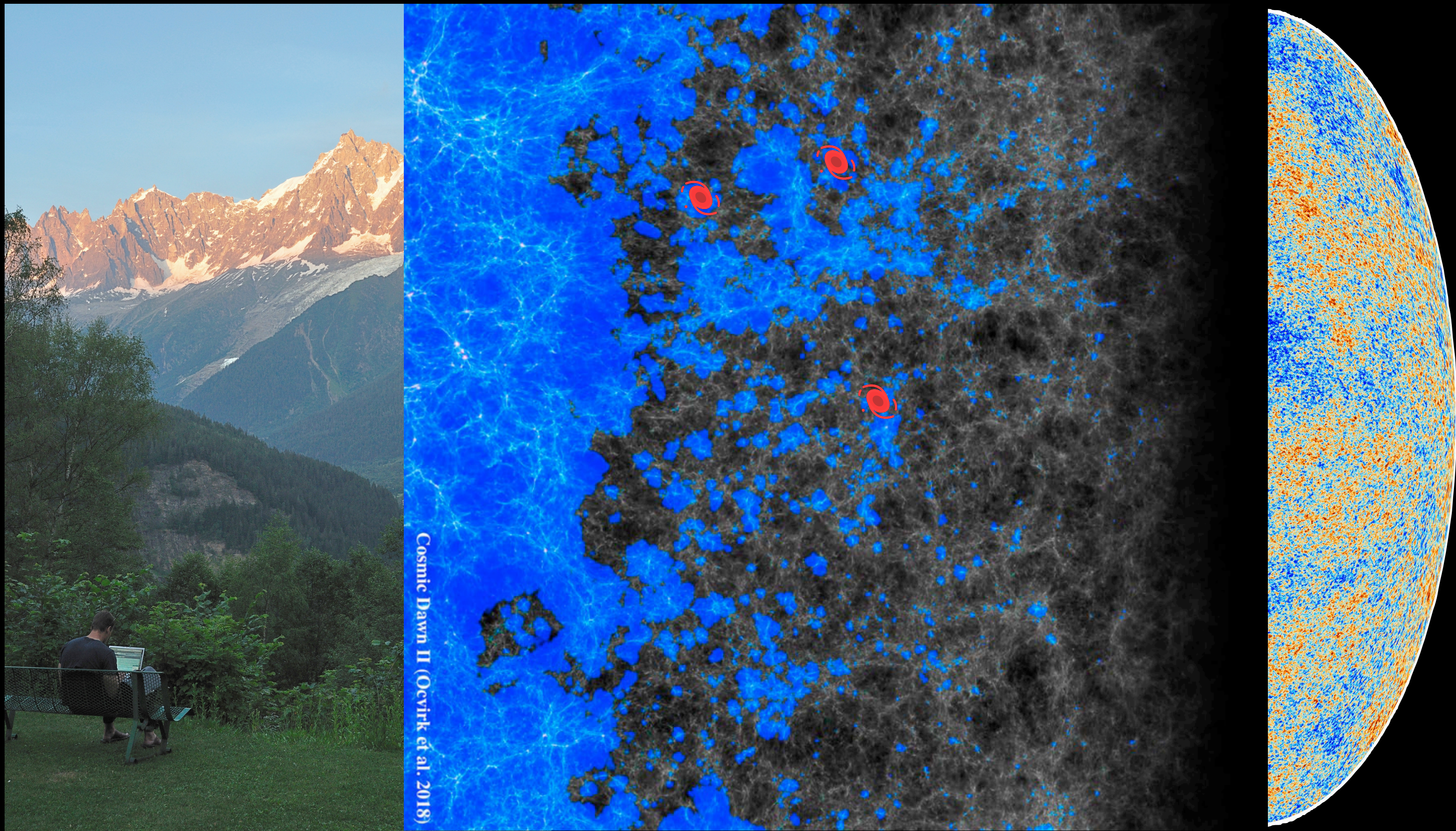
When ? how long ? what sources ?



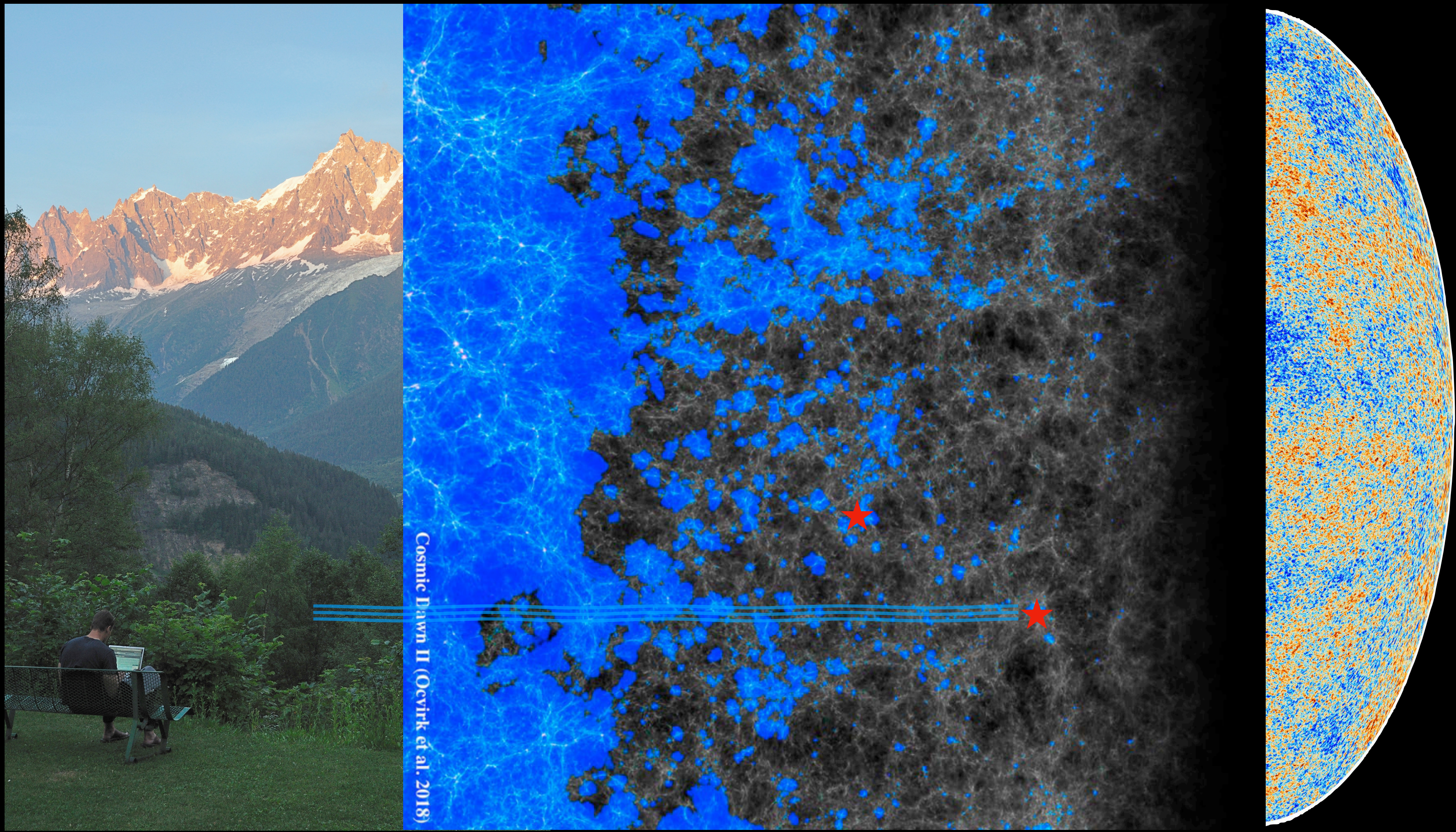

Cosmic Dawn II (Ocvirk et al. 2018)
H_{II}
e^-
H_I



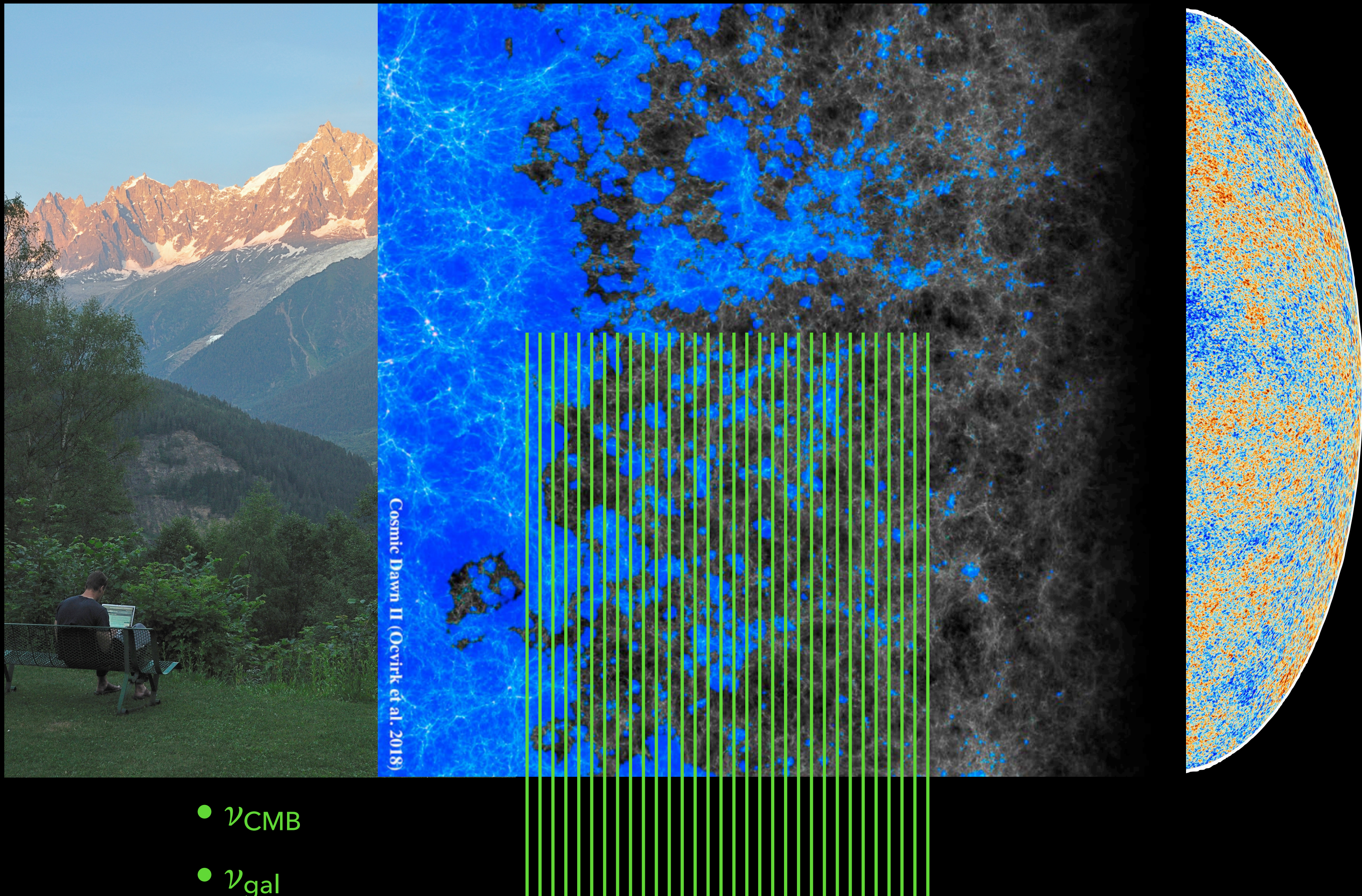
- e^-, ν_{CMB}



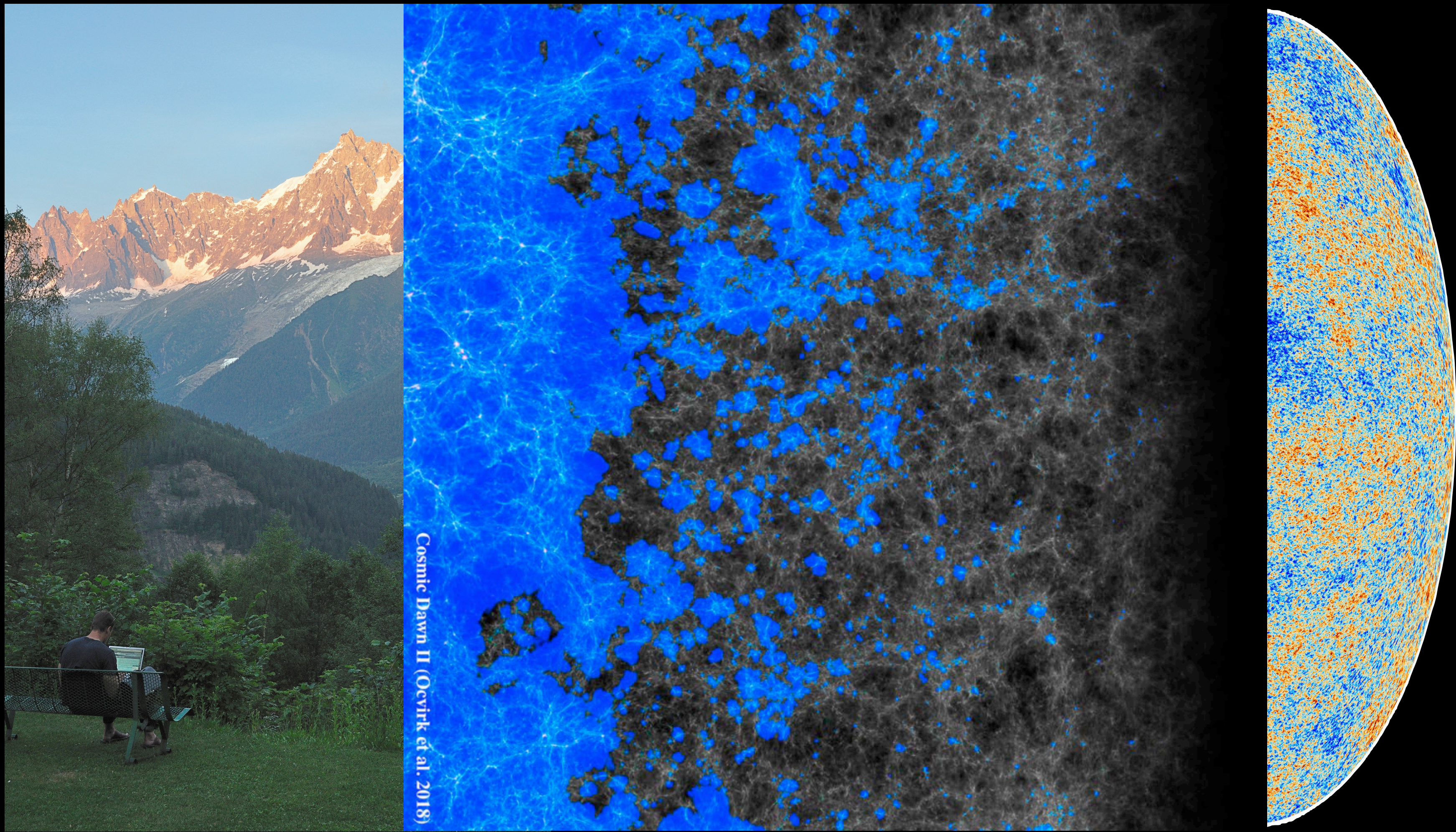
- e$^-$, ν_{CMB}
- ν_{gal}



- e^-, ν_{CMB}
- ν_{gal}
- HI



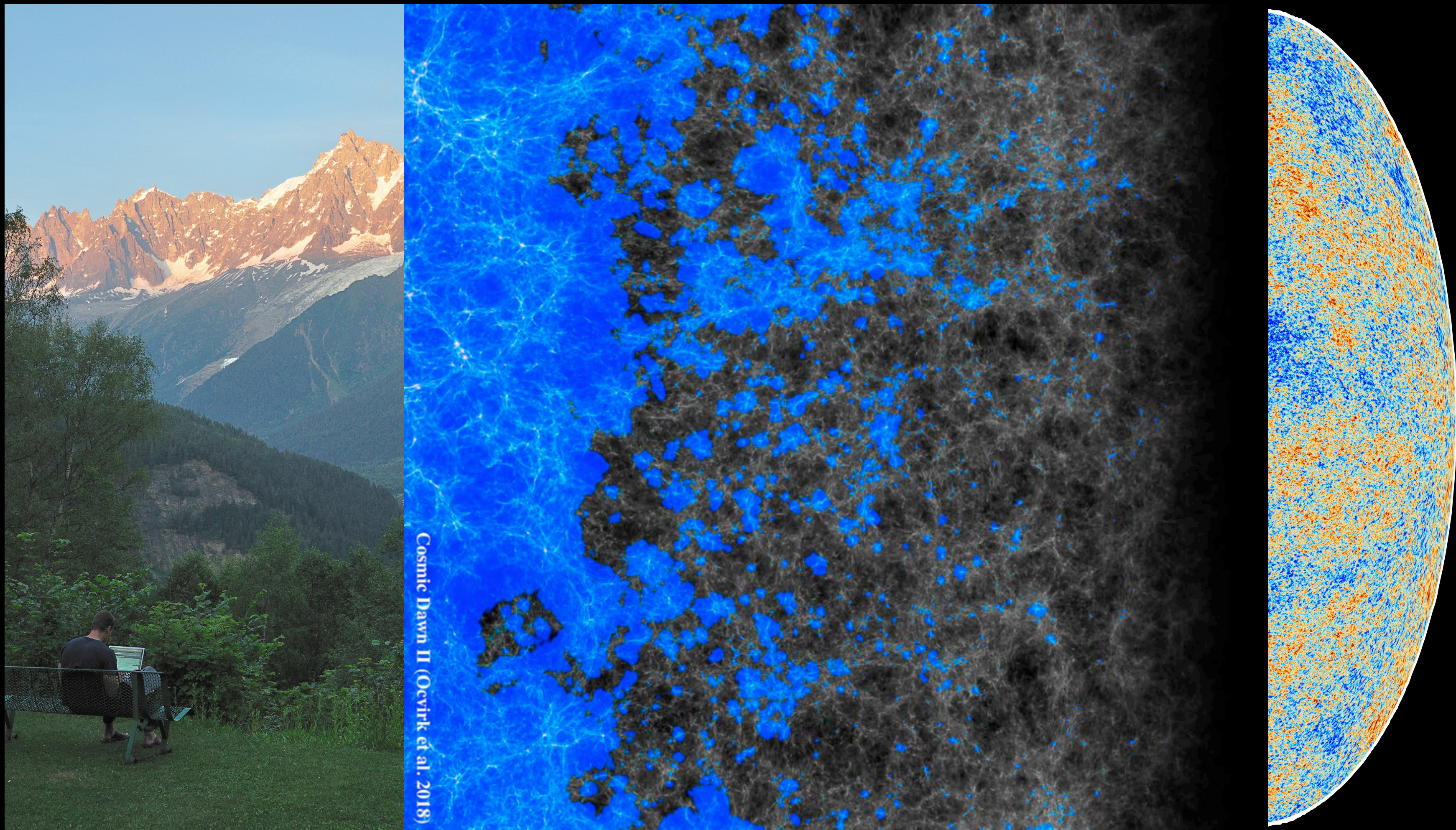
- ν_{CMB}
- ν_{gal}
- HI
- HI/HII



- ν_{CMB}
- ν_{gal}
- HI
- HI/HII

$\Longrightarrow$

- τ
- $x_e(z)$
- $x_e(z, \mathbf{n})$



- ν_{CMB}
- ν_{gal}
- HI
- HI/HII

- τ
- $x_e(z)$
- $x_e(z, \mathbf{n})$

- time
- time+ duration
- morphology

Outline

- Probing reionisation with CMB data (milimeter observations) — e^-, ν_{CMB}
- Probing reionisation with high redshift galaxy luminosity function (infra-red observations) — ν_{gal}
- Probing reionisation with quasars observations — HI
- Probing reionisation with 21cm observations — HI/HII

Principles
Limitations of the observations
Some results

Basic Equations

$$\tau_e(z) = \int_0^z \frac{c(1+z')^2}{H(z')} Q_{H_{II}}(z')\sigma_T \langle n_H \rangle_0 (1 + \eta(z') \frac{Y_p}{\frac{m_{He^4}}{m_{H_I}} X_p}) dz'$$

$$x_e(z) = Q_{H_{II}}(z)(1 + \eta(z) \frac{Y_p}{\frac{m_{He^4}}{m_{H_I}} X_p}) = \frac{n_e}{n_H}$$

$$Q_{H_{II}} = \frac{n_{H_{II}}}{n_H}$$

$$x_{H_I} = \frac{n_{H_I}}{n_H}$$

$$\langle n_H \rangle_0 = X_p \Omega_b \rho_c / m_H$$

$$z_{reio} = z(x_e = 0.5)$$

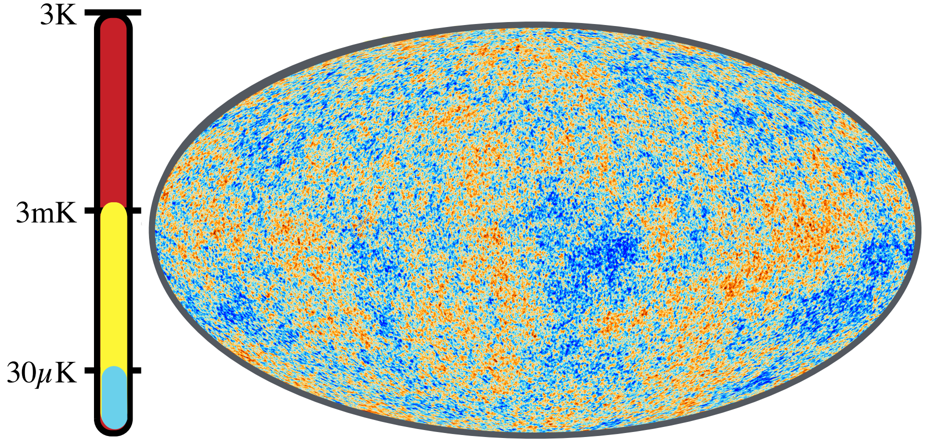
$$\begin{aligned} \eta(z) &= 1 \;\; \text{First He reionisation } z \gtrsim 4 \\ &= 2 \;\; \text{Second He reionisation } z \lesssim 4 \\ &\equiv 1.5 + 0.5 * tanh((z_{He} - z)/\Delta_{z_{He}}) \end{aligned}$$

$$\begin{aligned} Y_p &= 0.2448 \\ X_p &\sim 1 - Y_p \sim 0.7552 \\ \frac{m_{He^4}}{m_{H_I}} &= \frac{4.002602}{1.008} \sim 3.9708 \end{aligned}$$

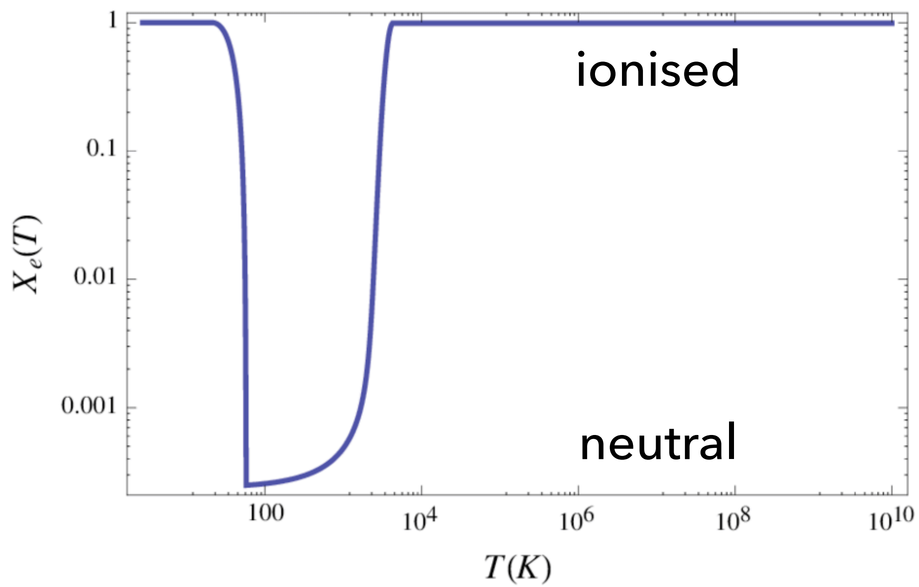
Signatures of Reionisation in CMB obs

- CMB in a nutshell
- Damping of Angular Power Spectrum (APS)
- Large scale bump in polarisation APS
- Small scales anisotropies in intensity APS: kSZ

CMB in a nutshell



- Light emitted at the recombination, when Universe become transparent
- p+e⁻ → H



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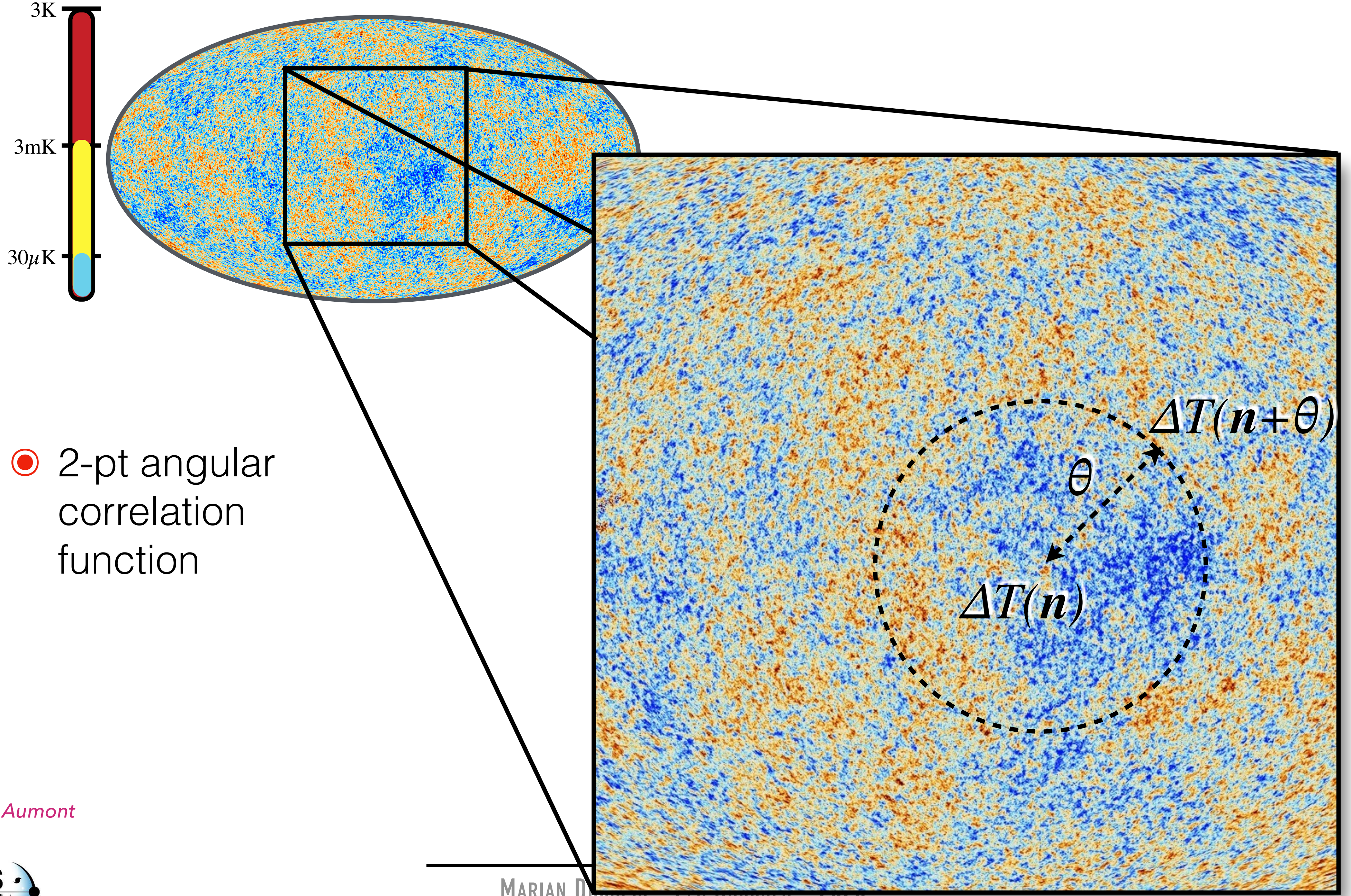
CMB IN A NUTSHELL



- 2-pt angular correlation function

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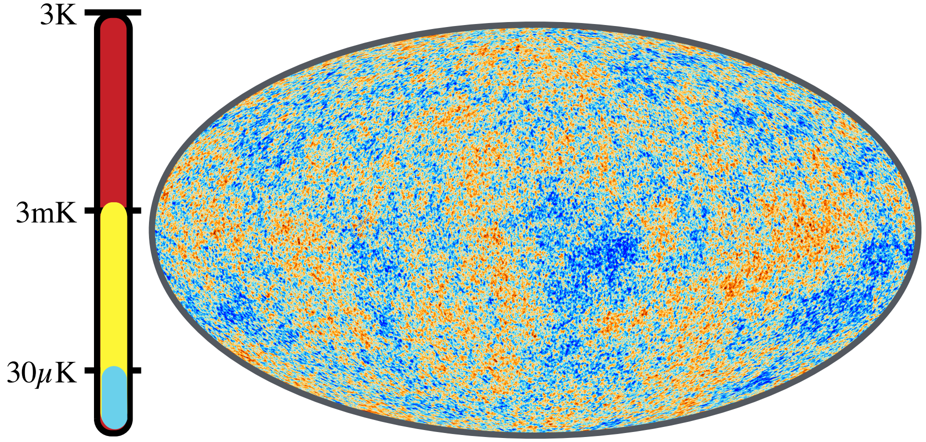
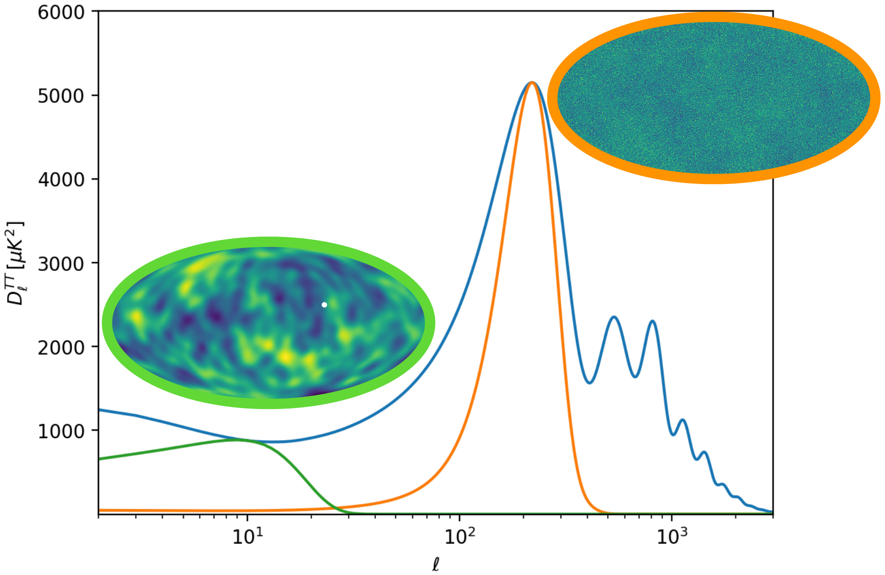


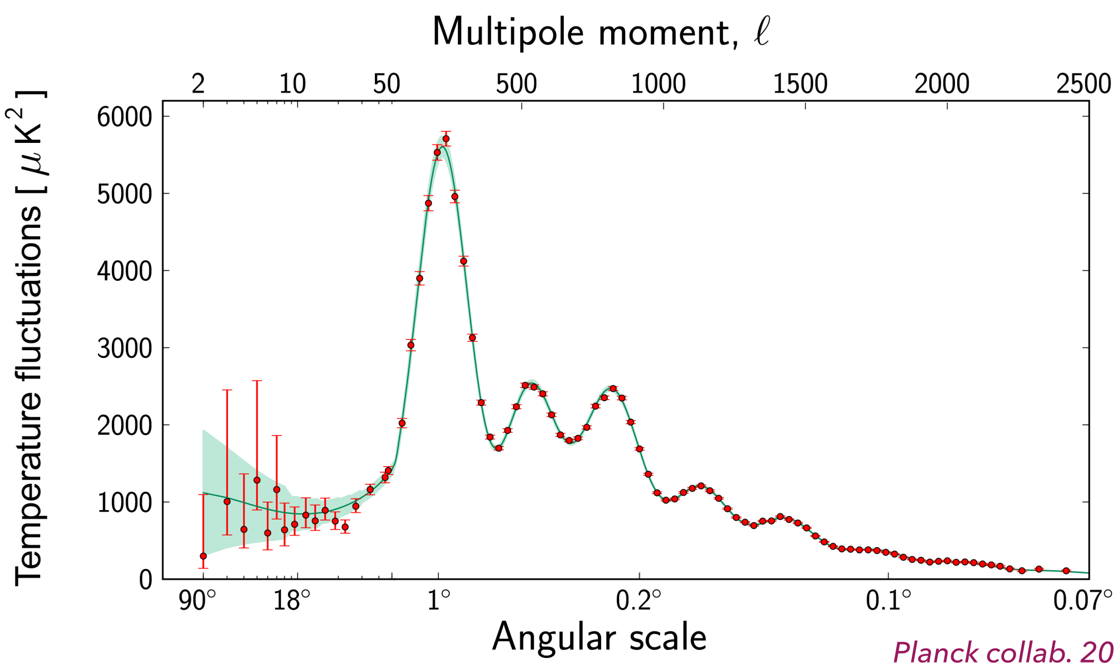
Spherical Harmonics

$$a_{l,m} = \int_{\theta,\phi} \Delta T(\theta,\phi) Y_{l,m}(\theta,\phi)$$

Angular power spectrum

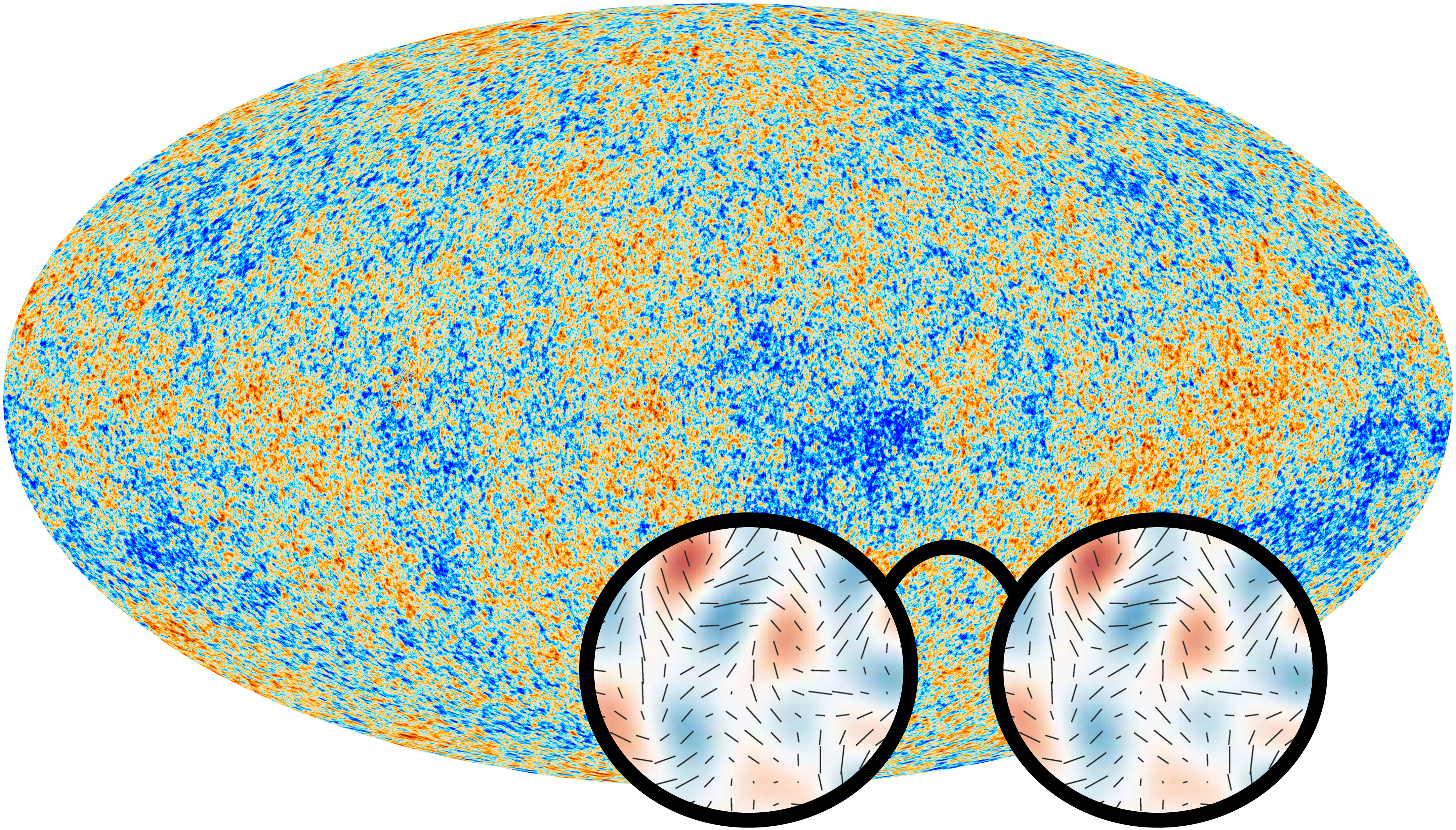
$$C_l = \sum_{m=-l}^{m=l} \frac{|a_{l,m}|^2}{2\ell+1}$$





Planck collab. 2014

CMB IN A NUTSHELL



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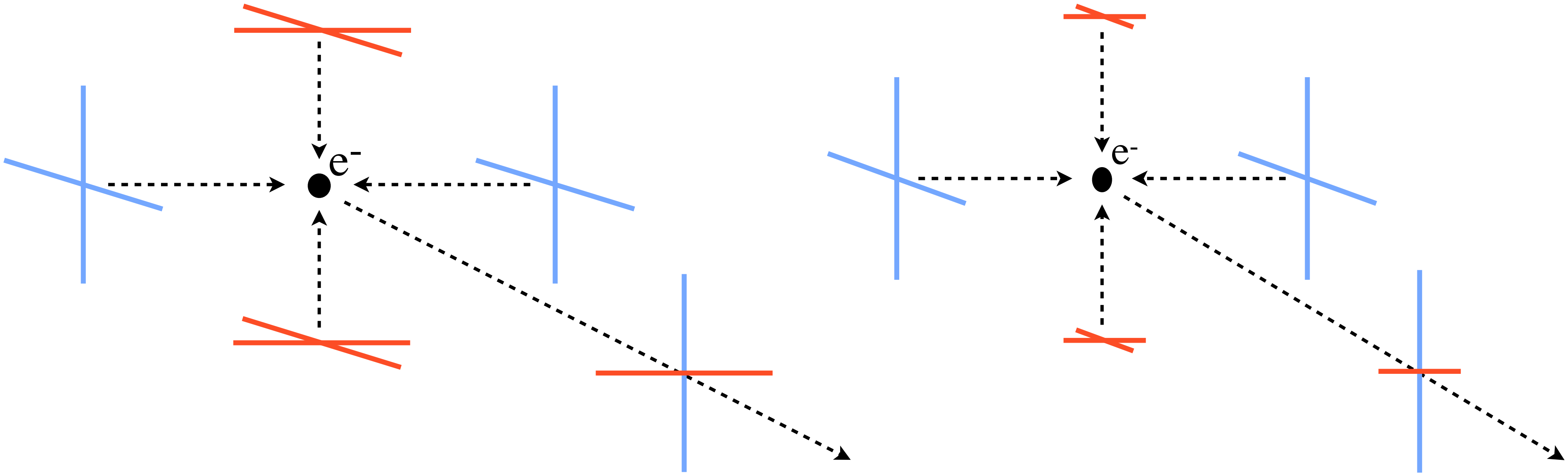
CMB is polarized

CMB IN A NUTSHELL

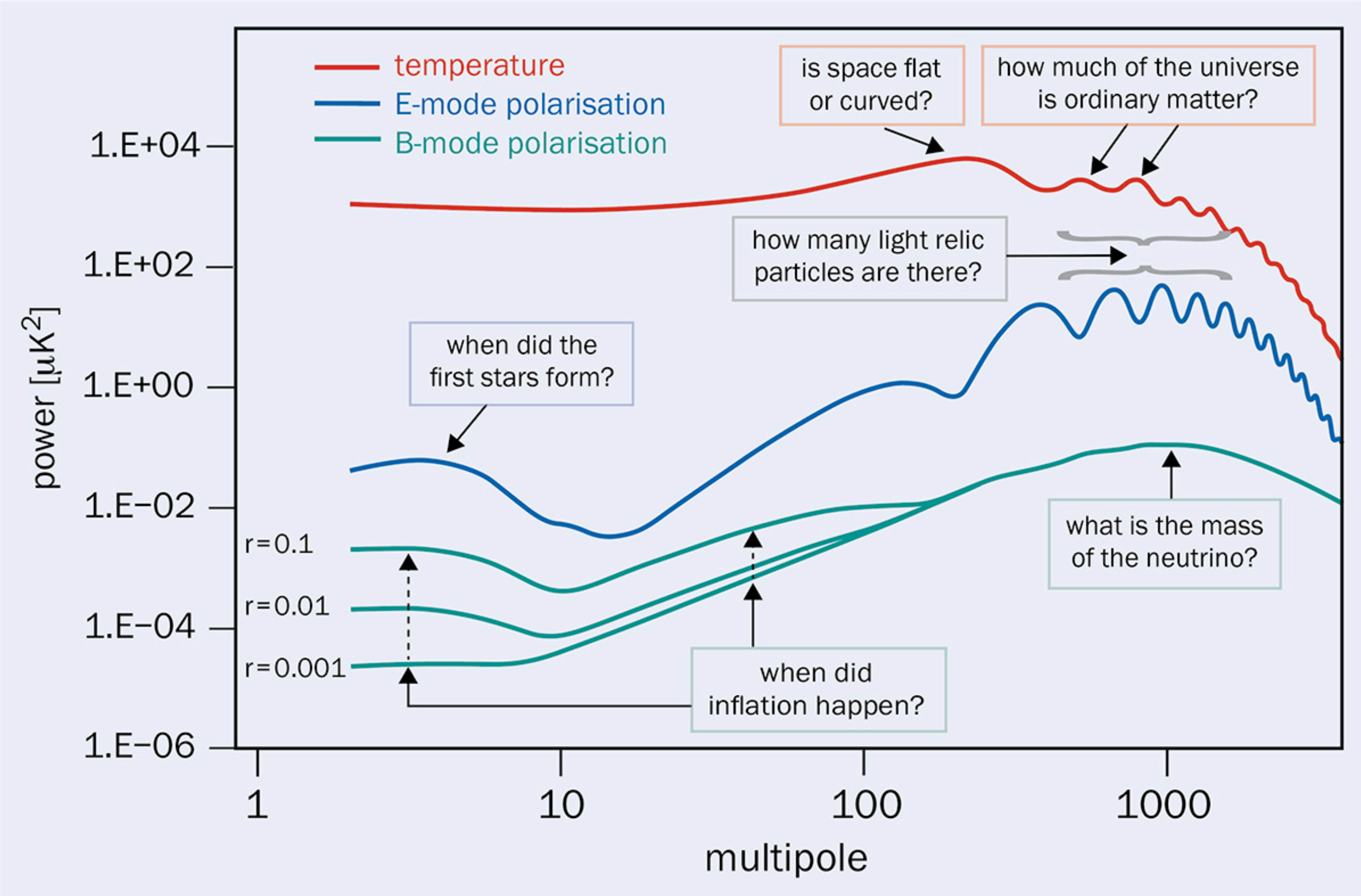
- CMB is a polarised light
- Polarisation created by quadrupolar anisotropies @ decoupling



- Obs in Intensity and polarisation : TT, EE, TE, BB

More and better during the Advanced CMB lecture

CMB in a nutshell



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CMB I : DAMPING

- Probability of photon scattering between initial time t_i and present t_0 is given by $1\text{-}e^{-\tau(t_0)}$ with **τ** the optical depth

$$\tau \equiv \int_{t_i}^{t_0} \sigma_T n_e(t) dt$$

scattered out   scattered in

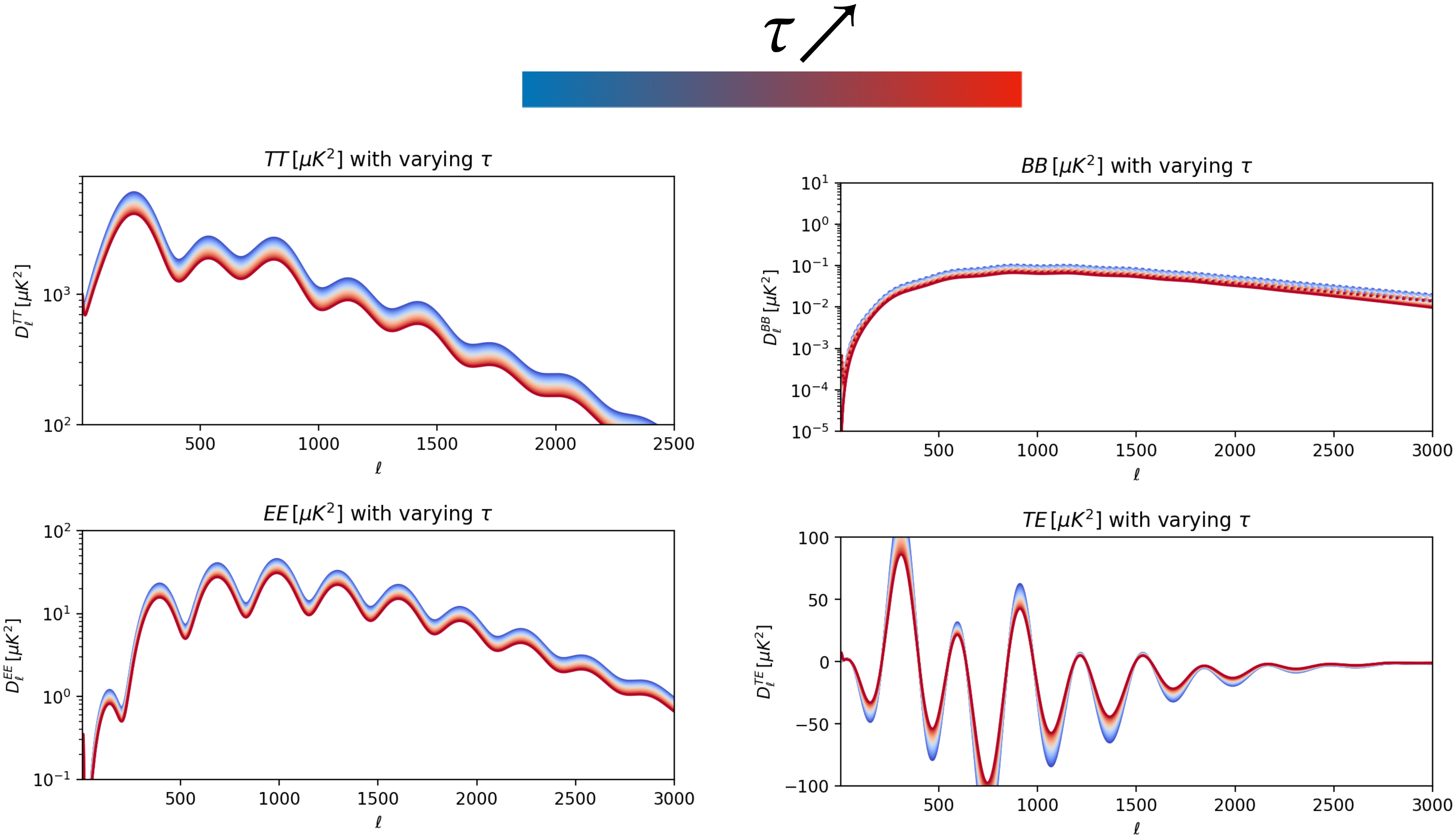
$$\begin{aligned} \bar{T} + \Delta T \quad &\rightarrow \quad (\bar{T} + \Delta T) - (\bar{T} + \Delta T)\left(1 - e^{-\tau}\right) + \bar{T}\left(1 - e^{-\tau}\right) \\ &\rightarrow \quad \bar{T} + \Delta T e^{-\tau} \end{aligned}$$

$$C_l \rightarrow C_l e^{-2\tau}$$

- but at large scales damping does not occur

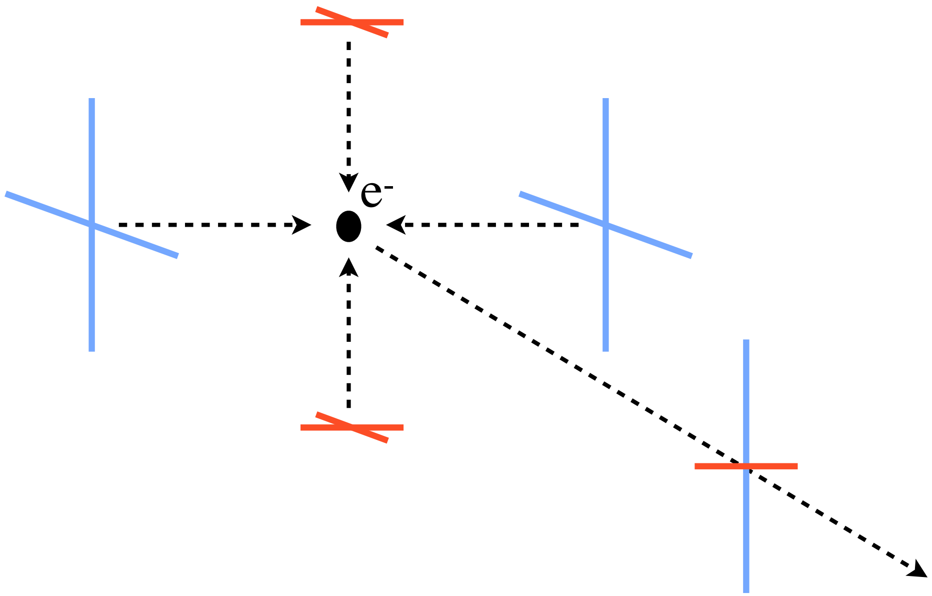
- need anyway a xe(z) to compute the τ(z) thus Cls

CMB I : DAMPING

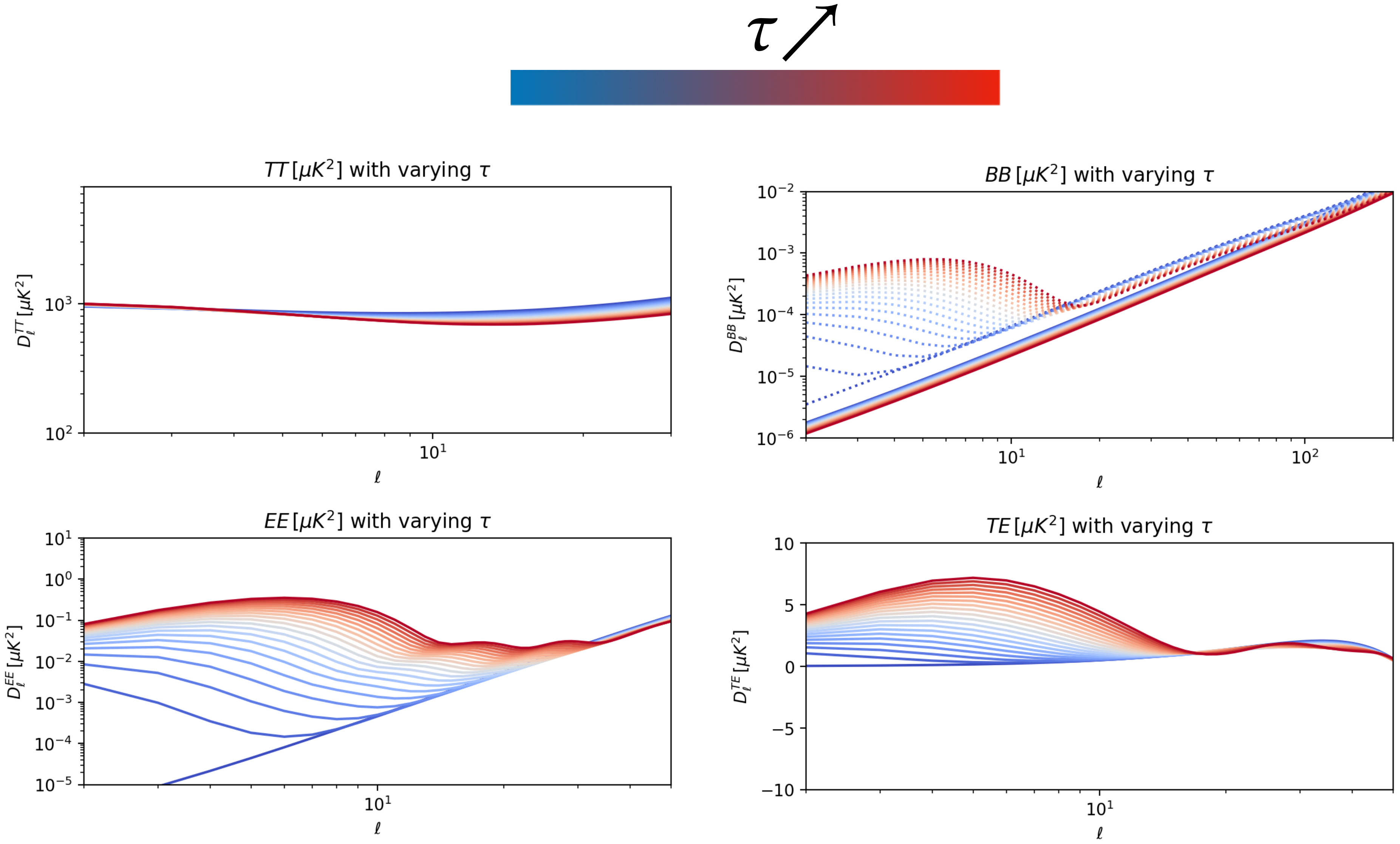


CMB II: EE LOW L BUMP

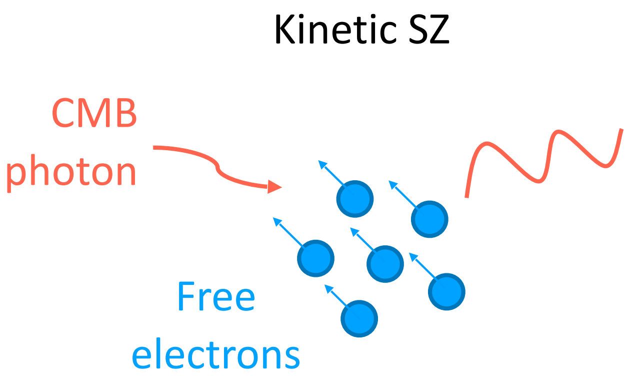
- Reionisation creates CMB polarisation anisotropies
- Free electrons exposed to large scale CMB quadrupole
- Peaks at ~horizon at EoR
- signal $\propto \tau$, bump in EE spectrum $\propto \tau^2$



CMB II: EE low l bump



- The bulk velocity of free electrons relative to the CMB introduces a Doppler shift to the scattered photons



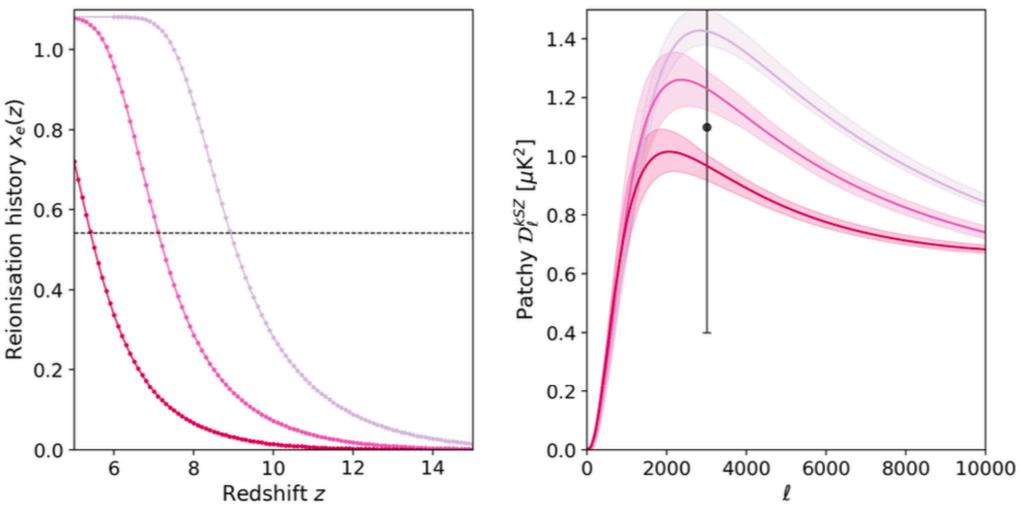
Bulk motion in reionised gas in late universe
→ homogeneous kSZ

Bulk motion in reionised bubbles in reionisation era
→ patchy kSZ

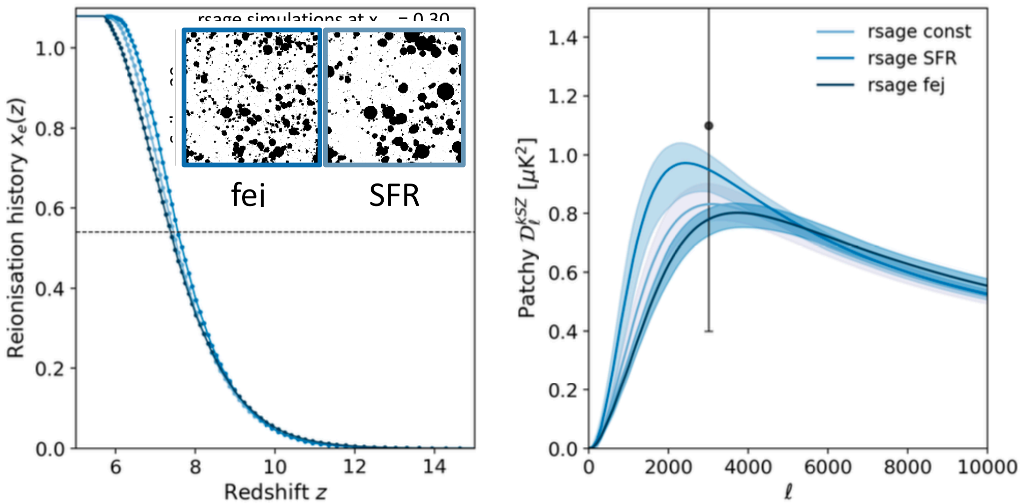
$$\frac{\Delta T_{kSZ}}{T_{CMB}}(\hat{\mathbf{n}}) = \sigma_T \int \frac{e^{-\tau(z,\hat{\mathbf{n}})}}{(1+z)H(z)} n_e(z,\hat{\mathbf{n}})\ \hat{\mathbf{n}}\,.\,\mathbf{v}\ dz$$

$$n_H(z,\hat{\mathbf{n}})x_e(z,\hat{\mathbf{n}}) \ = \langle n_H(z)\rangle\langle x_e(z)\rangle(1+\delta_b(z,\hat{\mathbf{n}})+\delta_x(z,\hat{\mathbf{n}})+\delta_b\delta_x(z,\hat{\mathbf{n}}))$$

CMB III: KINETIC SZ EFFECT



- Different histories of EoR
  - time and duration

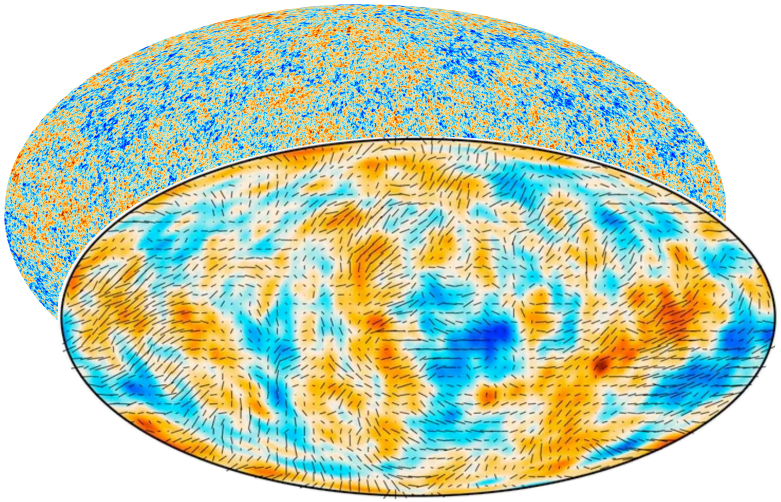


- Different sources of reionisation
  - morphology

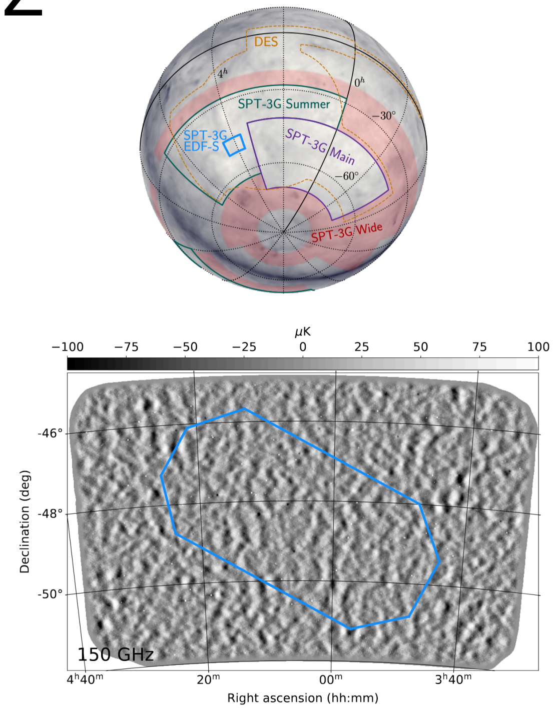
Gorce et al 2020

CMB: Can we measure all this ?

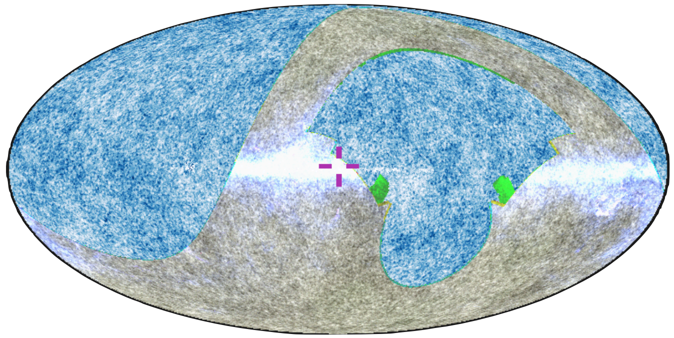
- Need for:
  - large ell coverage TT+EE for Damping
  - Large scales for EE bump
  - Small scales for kSZ



Planck

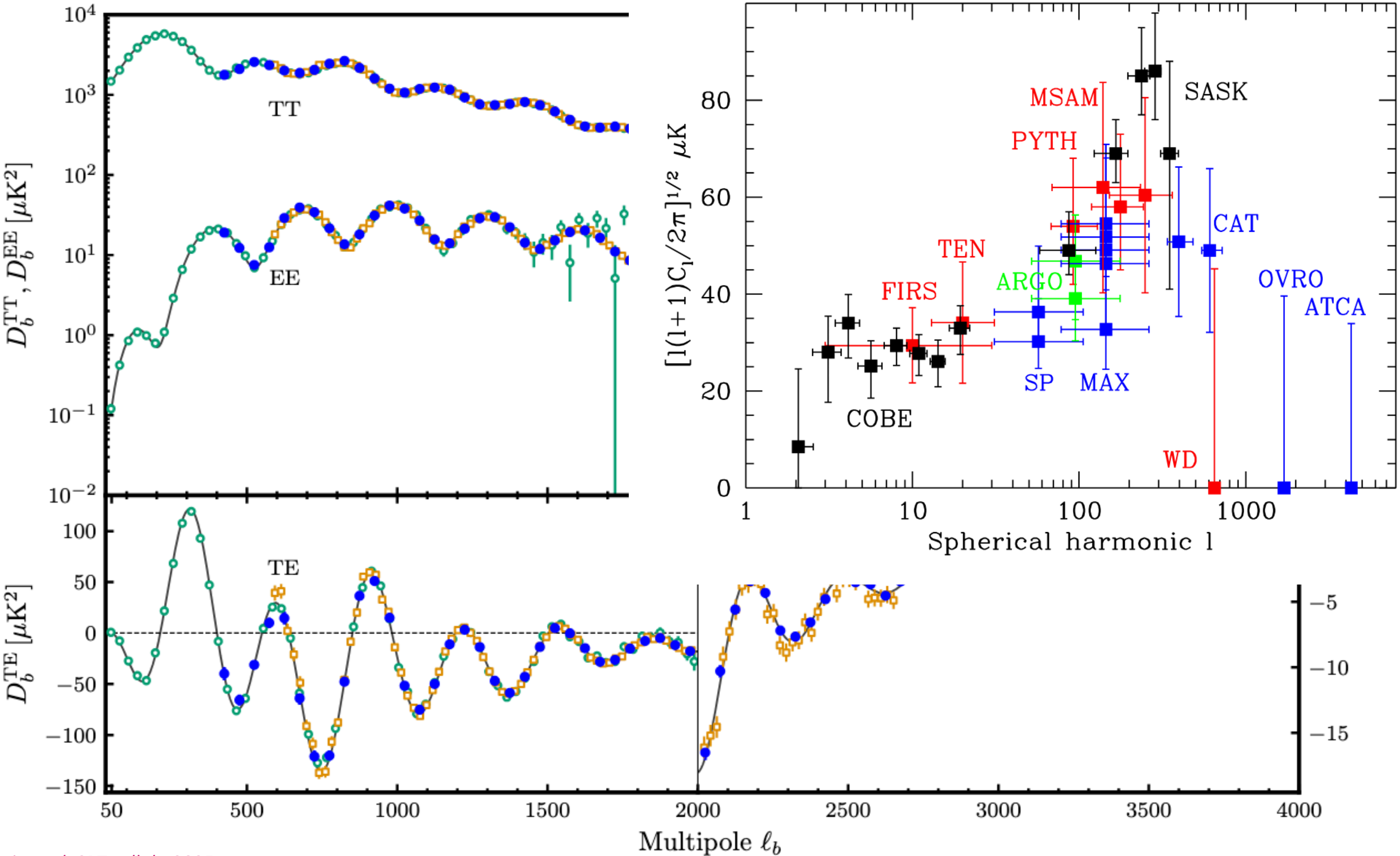


SPT



ACT

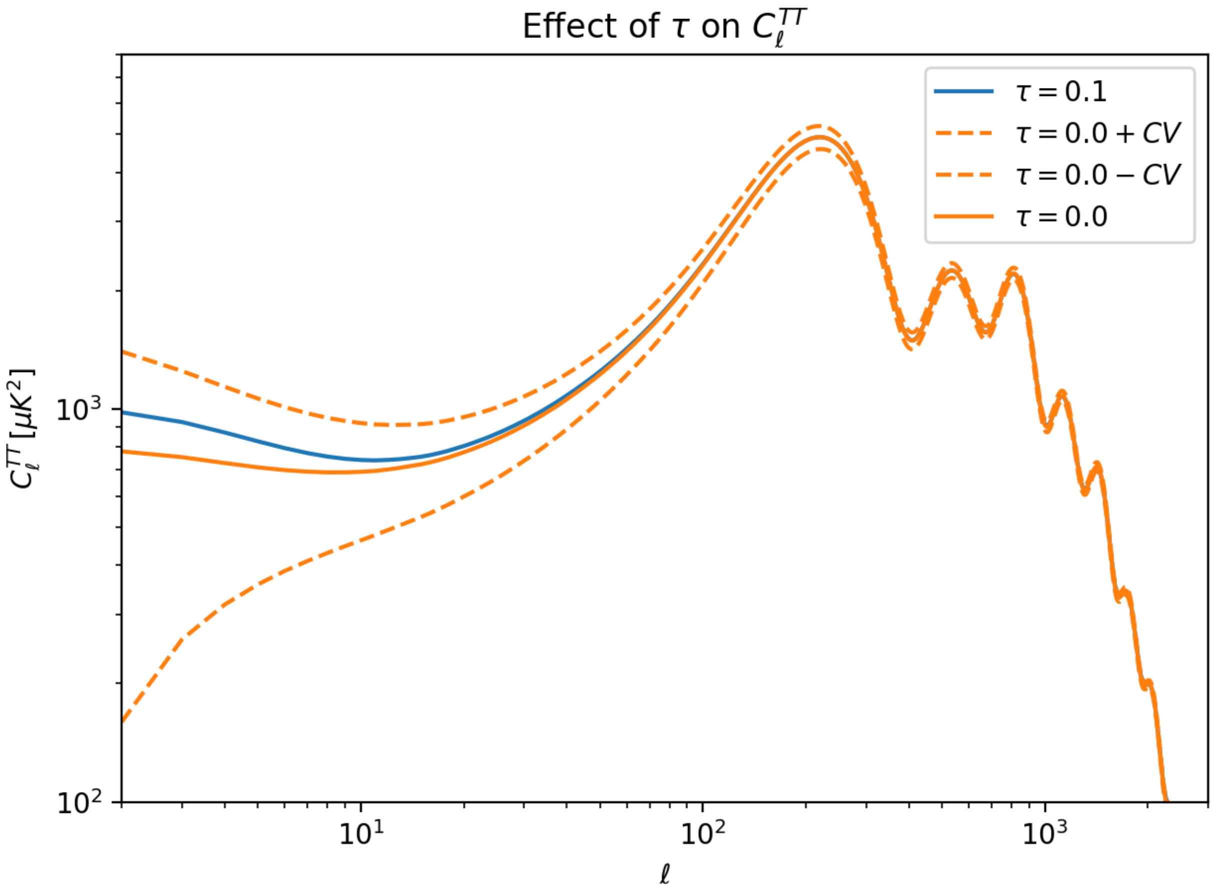
CMB: Can we measure all this ?



Camphuis et al. SPT collab. 2025

CMB: Can we measure all this ?

- Limitation : degeneracy and Cosmic variance



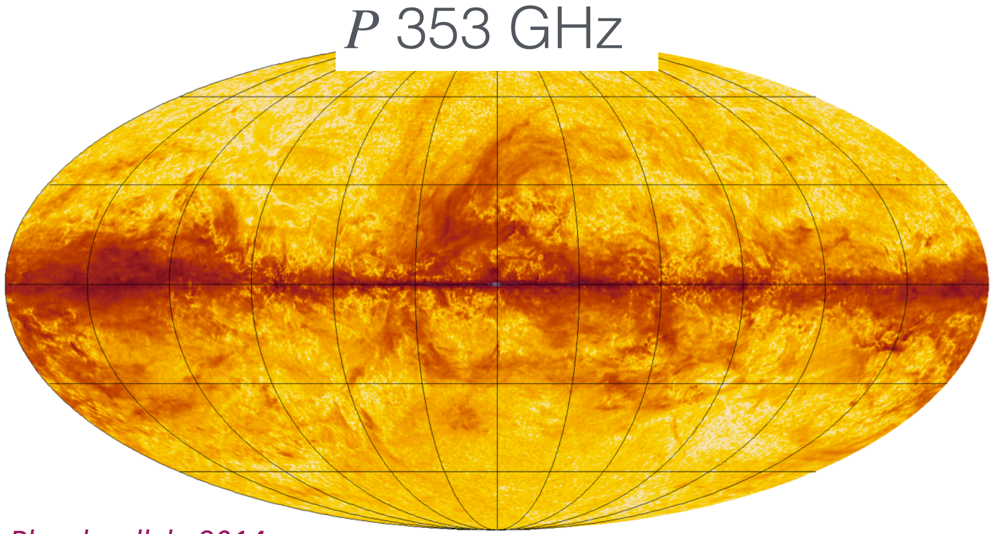
$$C_l = \sum_{m=-l}^{m=l} \frac{|a_{l,m}|^2}{2\ell+1}$$

$$C_\ell \;\alpha\; A_s e^{-2\tau}$$

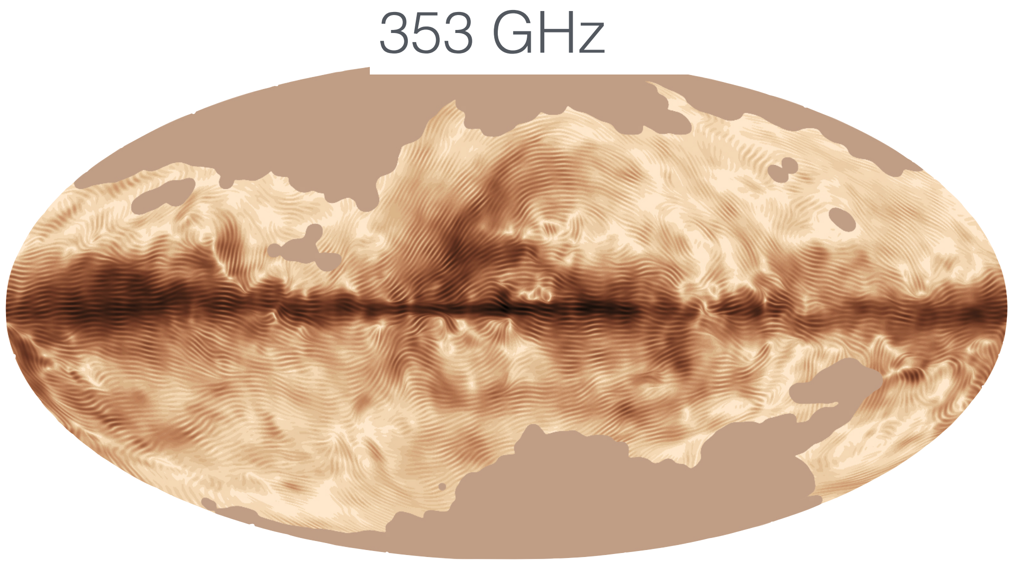
$$CV : \frac{\Delta C_\ell}{C_\ell} = \frac{1}{f_{sky}}\sqrt{\frac{2}{2\ell+1}}$$

CMB: Can we measure all this ?

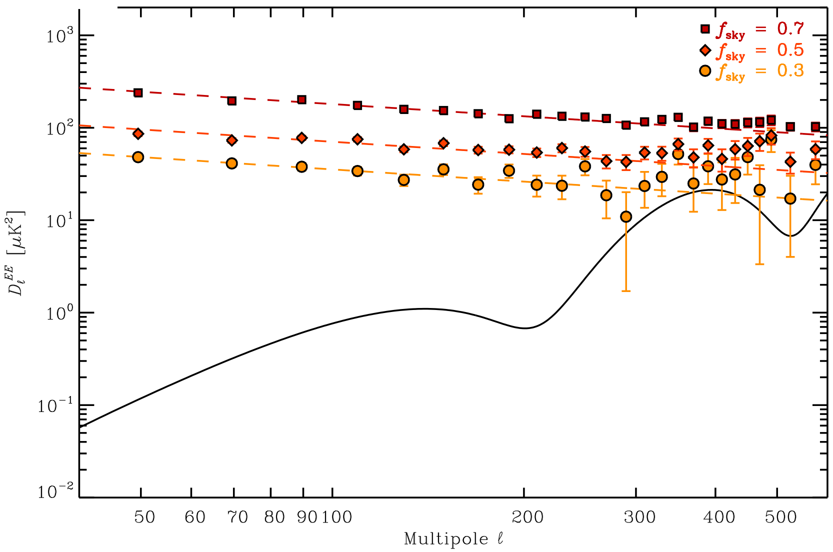
- Foregrounds EE



Planck collab. 2014



Planck collab. 2014

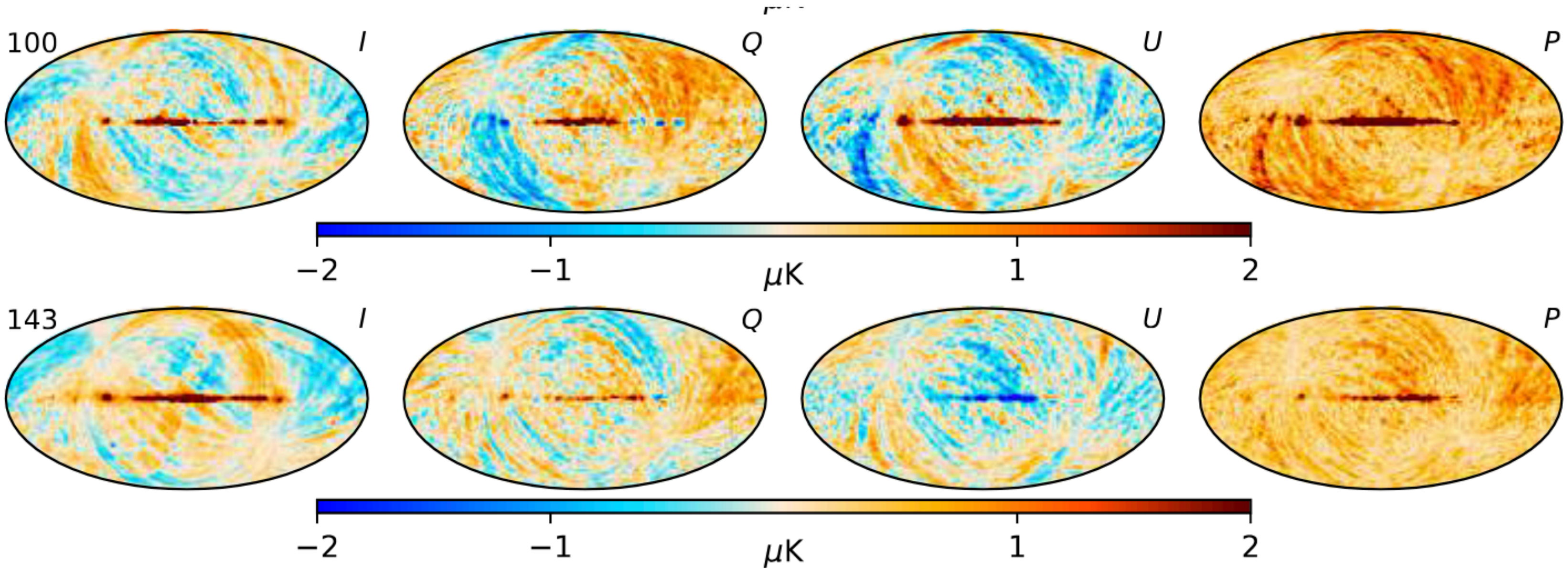


- dominate @ low ell

➡ model fgds, clean and marginalise over residuals

CMB: Can we measure all this ?

- Systematics EE



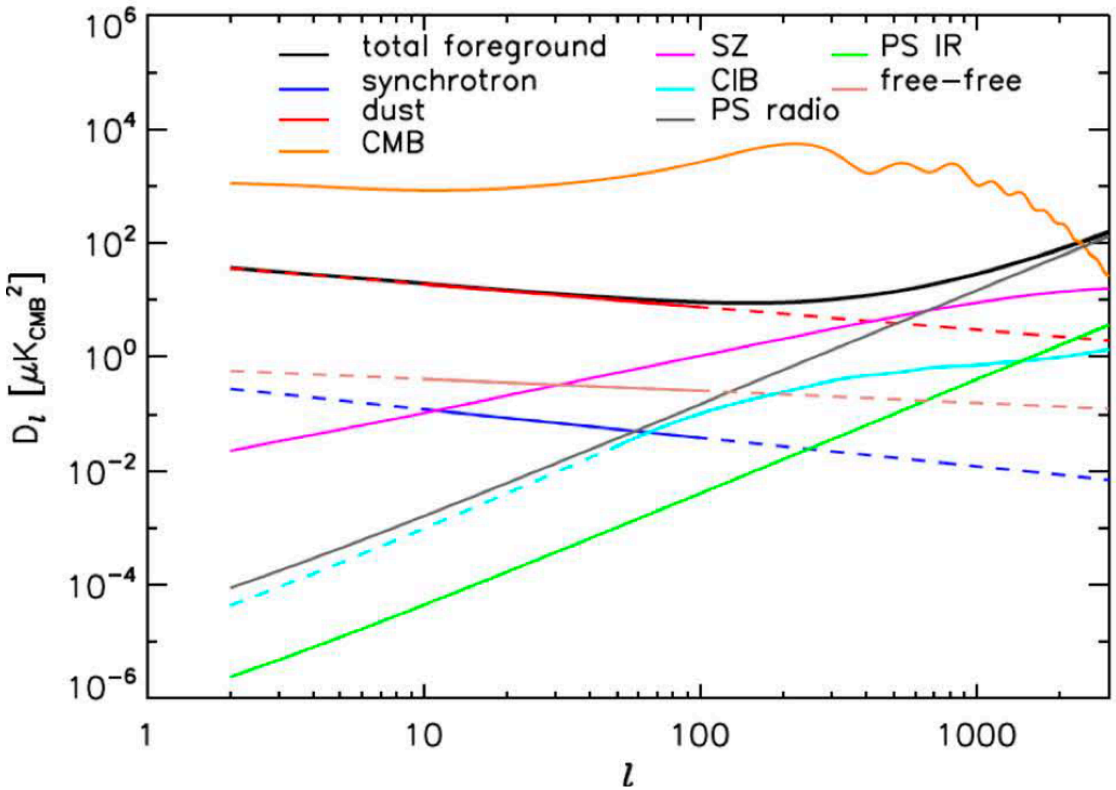
Planck collab. 2018

- Large scale structures in the maps @ low ell

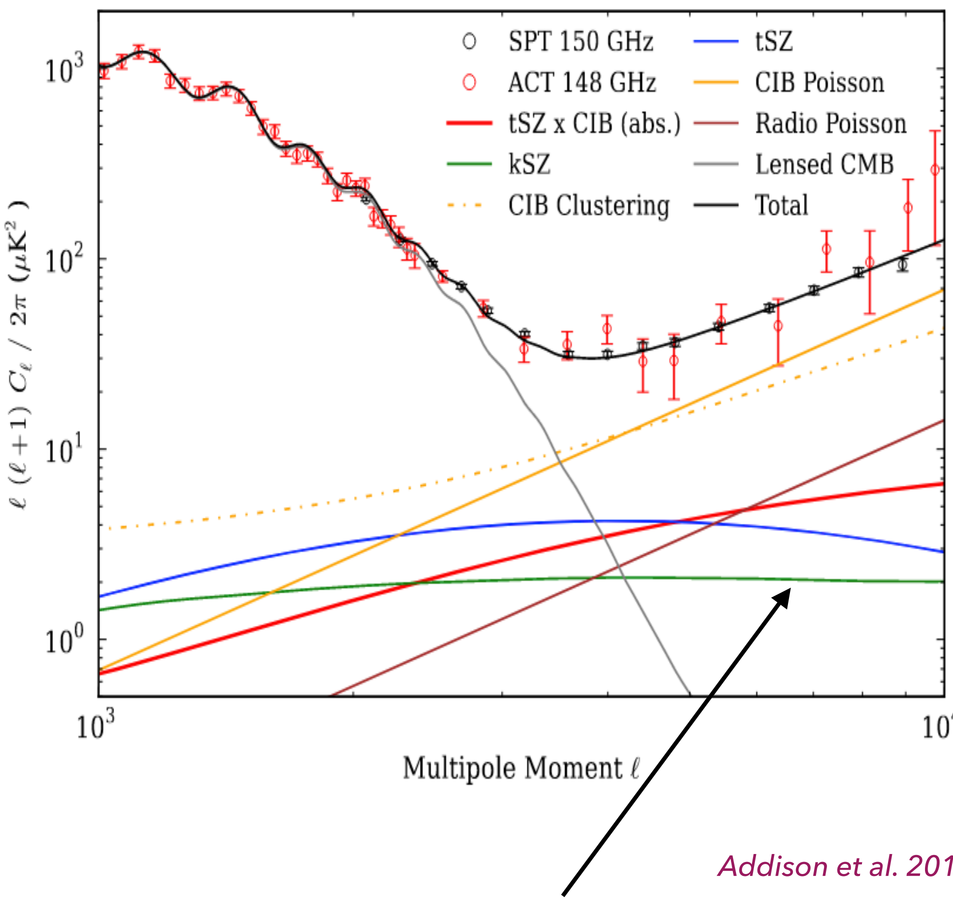
➡ model systematics, clean and marginalise over residuals

CMB: Can we measure all this ?

- kSZ is one of many foregrounds

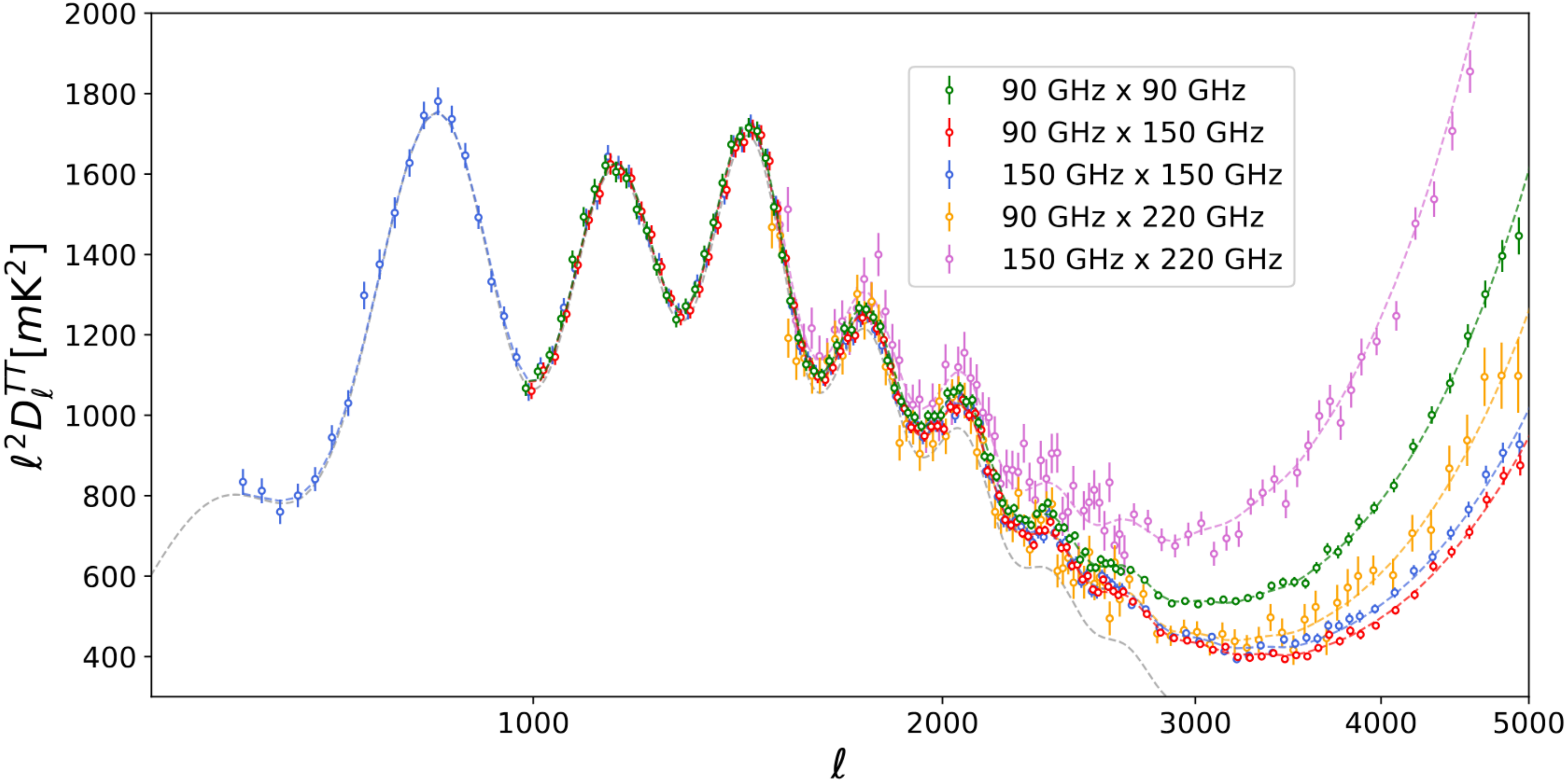


Planck collab. 2015



Addison et al. 2012

➡ Mitigation of kSZ thanks to many frequencies



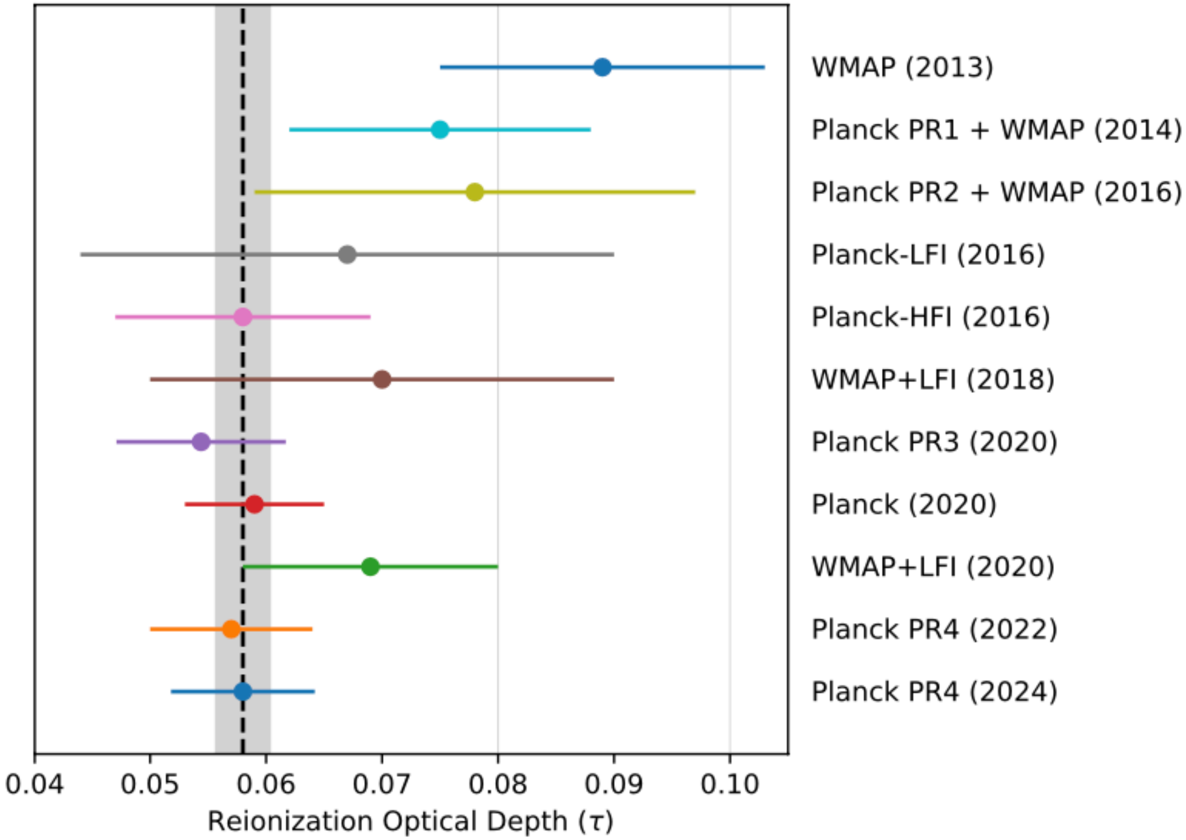
ACT collab. 2025

CMB : Constraints on EoR

- Reionisation in one number (TT+EE)

from WMAP TE with residual dust

first use of HFI EE bump



CMB : Constraints on EoR

- Can we learn more than τ ?
  - usual approach 1 or 2 params z_{re}, Δ_z

$$x_e(z) \propto \frac{1}{2}\left[1+\tanh\left(\frac{1}{\Delta z_{re}}\frac{(1+z_{re})^\gamma-(1+z)^\gamma}{\gamma(1+z_{re})^{\gamma-1}}\right)\right],$$

$$\tau_e \equiv \int_0^{1100} \sigma_T x_e(z) dz$$

  - more realistic

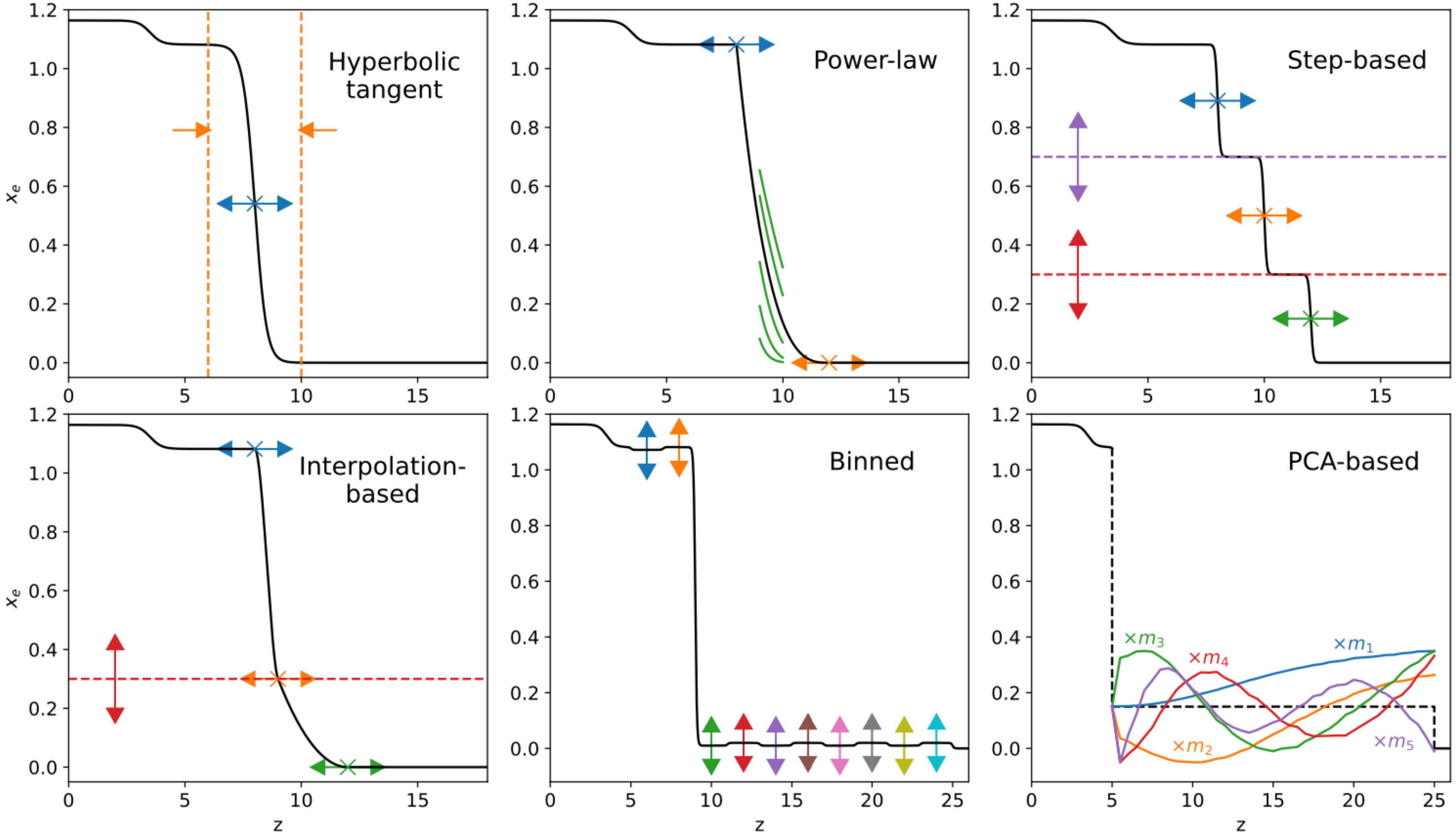
$$x_e(z) = \begin{cases} (1+f_{He}) & \text{for } z \le z_{end}, \\ (1+f_{He})\left(\frac{z_{beg}-z}{z_{beg}-z_{end}}\right)^\alpha & \text{for } z > z_{end}. \end{cases}$$

Douspis et al. 2015
Planck collab 2016

  - parametric forms

CMB : Constraints on EoR

Models

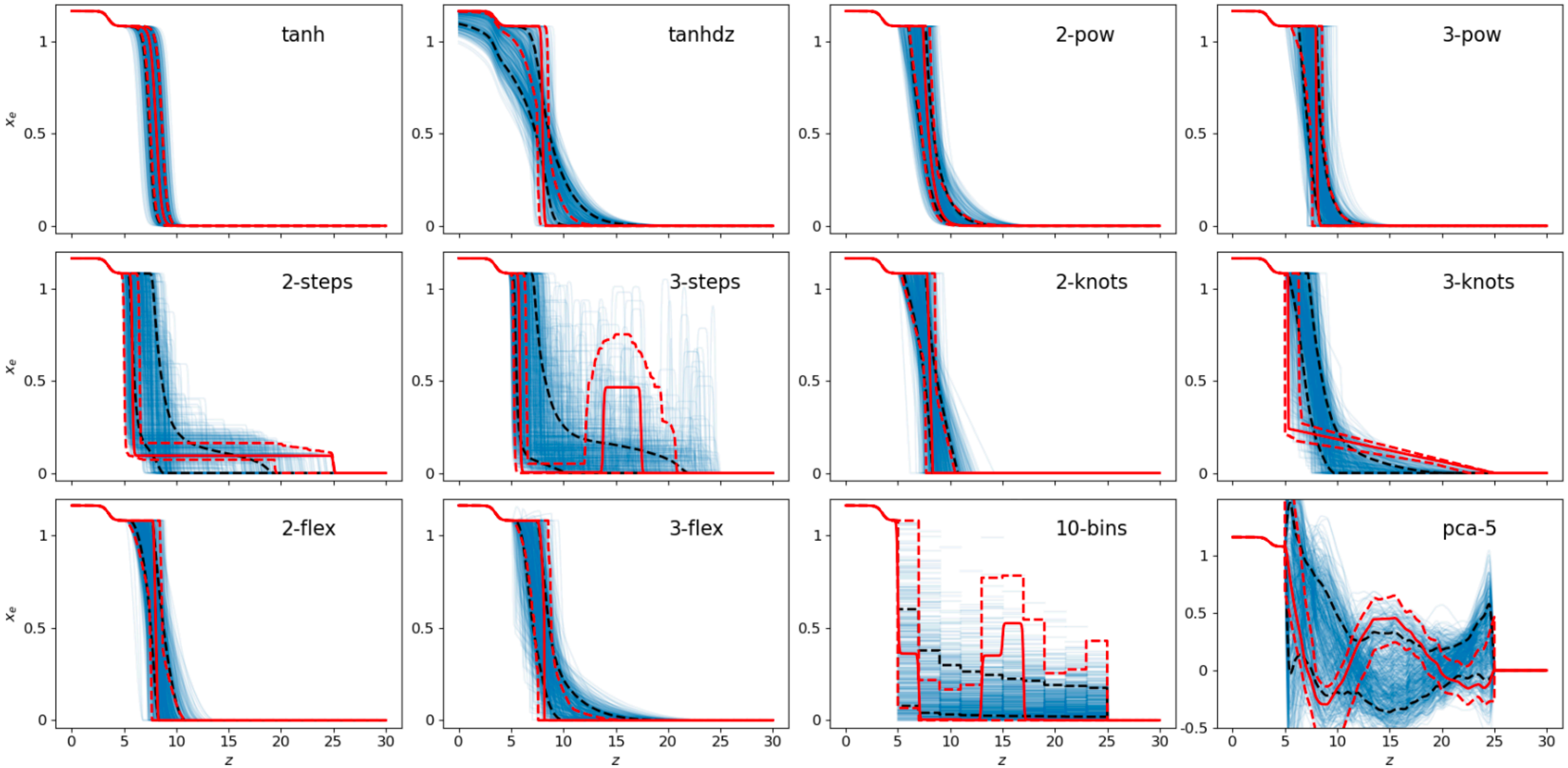


Ilic et al 2025

CMB : Constraints on EoR

ÉCOLE DE PHYSIQUE DES HOUCHES

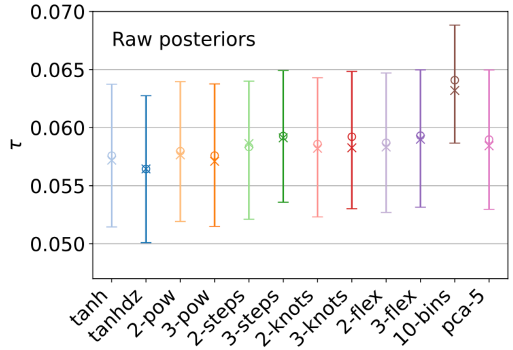
- Results

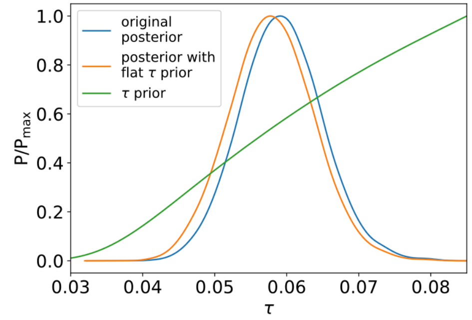


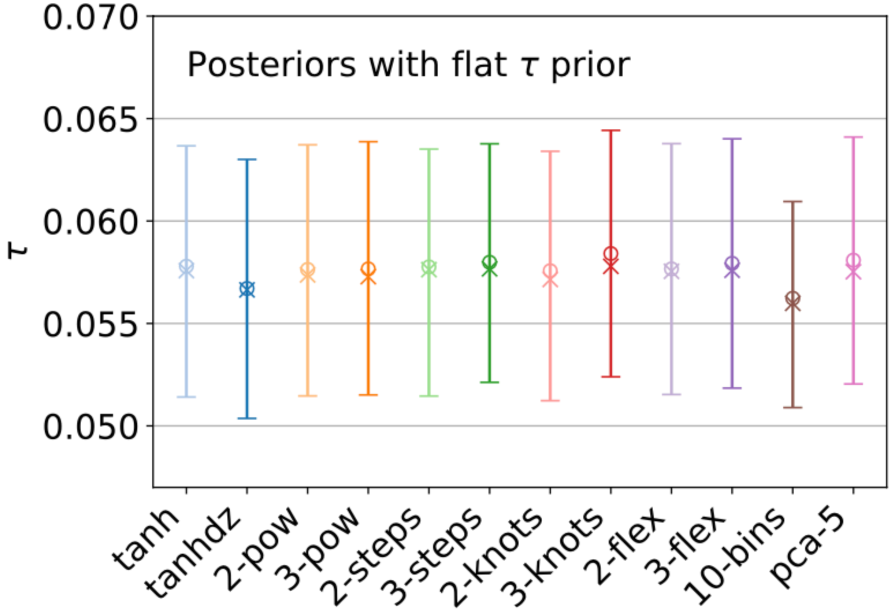
Ilic et al 2025

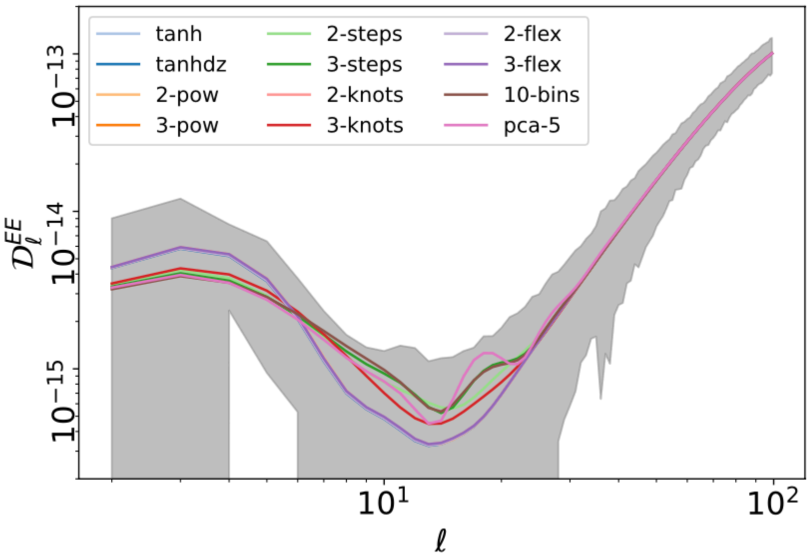
CMB : Constraints on EoR

- τ constraints are super stable





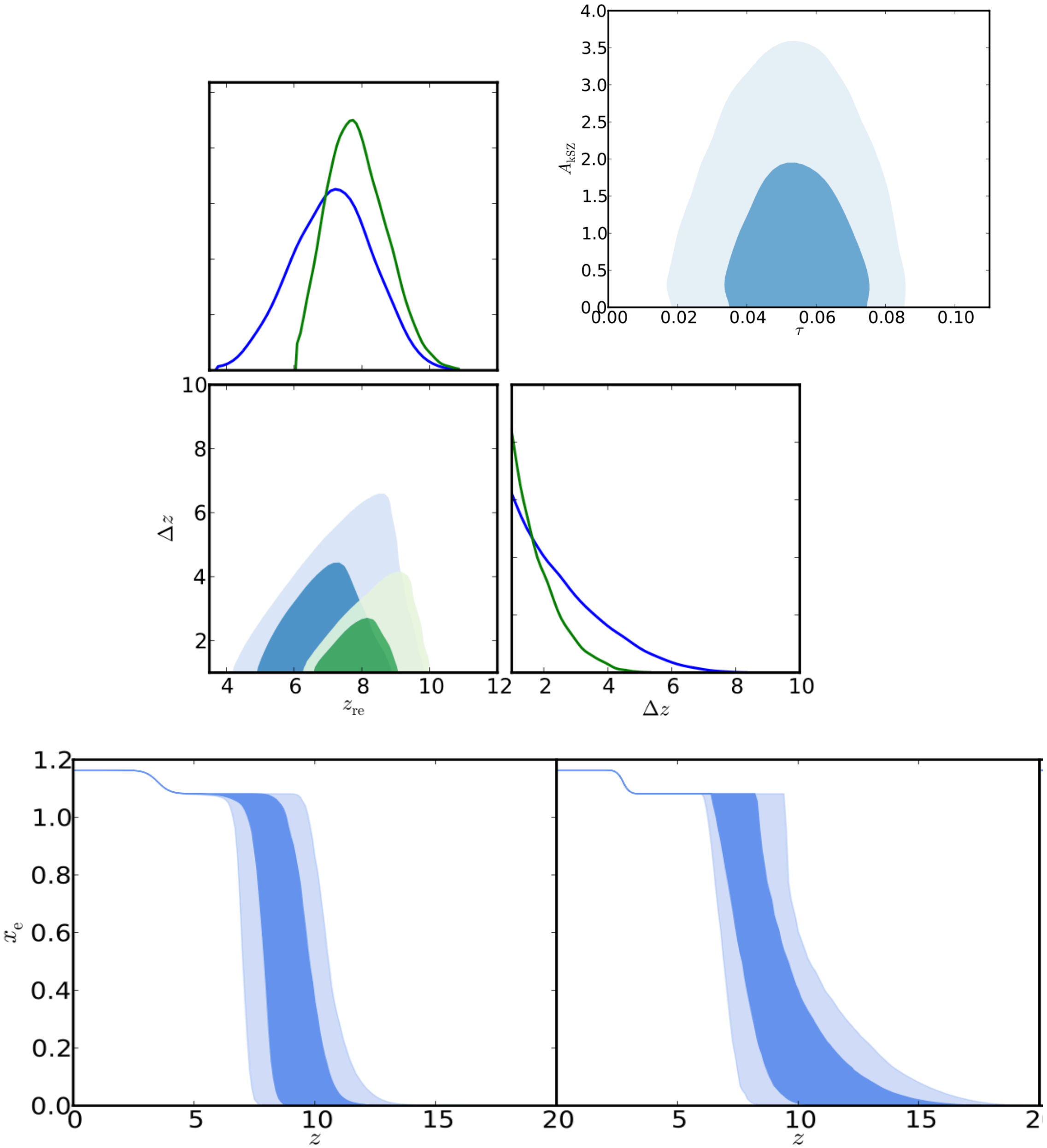




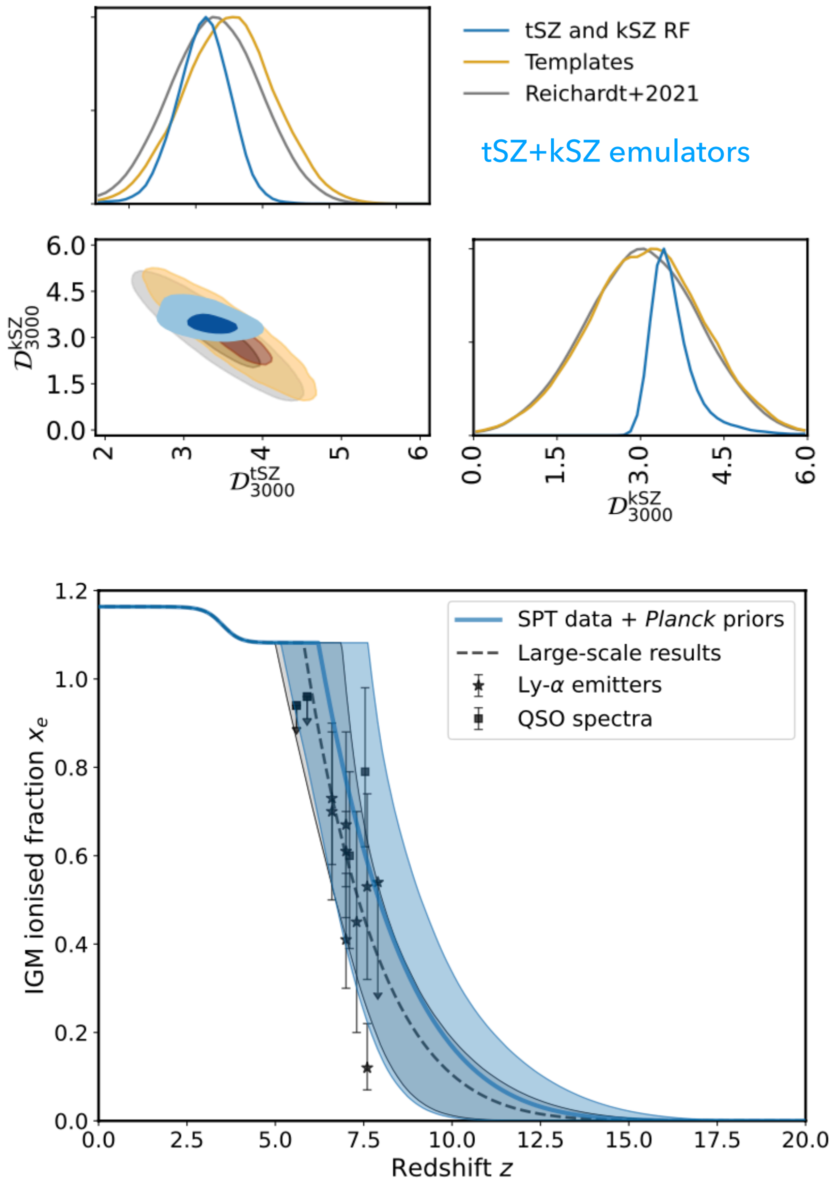
- Need CV limited to gain factor 2 on error bars

Ilic et al 2025

CMB : Constraints on EoR (TT+EE+kSZ)



Planck 2016



Gorce et al. 2022

CMB : CONCLUSIONS

- Data
  - TT Damping : best data Planck ✅
  - EE Damping : Planck+ACT+SPT ✅
  - EE Bump : Space needed to go to CV → LiteBIRD
  - kSZ : SPT+ACT → SO, ~~S4~~, …
  - Foregrounds/syste: masking, cleaning : ok but continues
- Modelling
  - bibliotheque of $x_e(z)$ ready for new data
- Results
  - τ constraints stable over years and models: low τ
  - if CV on EE and better kSZ, maybe learn on shape of x_e

CMB : PROSPECTS

- higher orders
  - bi-spectrum, trispectrum of kSZ
- reconstruction of patchyness
  - $n_H(z,\hat{\mathbf{n}})x_e(z,\hat{\mathbf{n}}) = \langle n_H(z)\rangle\langle x_e(z)\rangle(1+\delta_b(z,\hat{\mathbf{n}})+\delta_x(z,\hat{\mathbf{n}})+\delta_b\delta_x(z,\hat{\mathbf{n}}))$
  - $C_\ell^{\tau\tau}$
  - informs on the morphology
- Internal cross-correlations
  - $C_\ell^{\tau kSZ}$
  - 3pt combinaisons: τ-kSZ-kSZ , τ-τ-kSZ

➡ complement but come with own limitations

Outline

- Probing reionisation with CMB data (milimeter observations)
- Probing reionisation with high redshift galaxy luminosity function (infra-red observations)
- Probing reionisation with quasars observations
- Probing reionisation with 21cm observations

- ν_{CMB}
- τ
- ν_{gal}
- HI
- HI/HII

Principles
Limitations of the observations
Some results

GALAXY LUMINOSITY FUNCTION

- How can we relate the history of reionisation and the galaxy luminosity function?
- Let's focus on the ionizing photons

$$\dot{Q}_{\rm H_{II}} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H} \rangle} - \frac{Q_{\rm H_{II}}}{t_{\rm rec}},$$

Source ionisation

Sink recombination

$\dot{n}_{ion}$: production rate of ionizing photons
$\langle n_H \rangle$: mean hydrogen number density

Q_{HII} : ionized hydrogen fraction
t_{rec} : averaged gas recombination time

GALAXY LUMINOSITY FUNCTION

$$\dot{Q}_{\mathrm{H_{II}}} = \frac{\dot{n}_{\mathrm{ion}}}{\langle n_{\mathrm{H}} \rangle} - \frac{Q_{\mathrm{H_{II}}}}{t_{\mathrm{rec}}},$$

- Mean Hydrogen number today

$$\langle n_H \rangle_0 = X_p \Omega_b \rho_c / m_H$$

- Recombination time

$$t_{\mathrm{rec}} = \frac{1}{C_{\mathrm{H_{II}}} \alpha_{\mathrm{B}}(T)(1 + Y_{\mathrm{p}}/4X_{\mathrm{p}})\langle n_{\mathrm{H}} \rangle (1+z)^3},$$

C_{HII}: clumping factor

- Production rate of ionising photons

$$\dot{n}_{\mathrm{ion}} = \int_{-\infty}^{M_{\mathrm{trunc}}} f_{\mathrm{esc}}(M_{\mathrm{UV}}) \xi_{\mathrm{ion}}(M_{\mathrm{UV}}) \Phi(M_{\mathrm{UV}}) L(M_{\mathrm{UV}}) dM_{\mathrm{UV}}$$
$$\equiv \langle f_{\mathrm{esc}} \xi_{\mathrm{ion}} \rangle \, \rho_{\mathrm{UV}}, \quad (28)$$

f_{esc}: escape fraction
ξ_{ion}: ionising photon

$$\rho_{\mathrm{UV}}(z) = \int_{-\infty}^{M_{\mathrm{trunc}}} \Phi(M_{\mathrm{UV}}) L(M_{\mathrm{UV}}) dM_{\mathrm{UV}},$$

GALAXY LUMINOSITY FUNCTION

$$\rho_{\rm UV}(z) = \int_{-\infty}^{M_{\rm trunc}} \Phi(M_{\rm UV}) L(M_{\rm UV}) dM_{\rm UV},$$

- Galaxy luminosity function Φ at z
  - Press&Schechter form: $\Phi(M) = 0.4 \ln 10 \phi_\star [10^{0.4(M_\star - M)}]^{1+\alpha} \exp[-10^{0.4(M_\star - M)}]$
  - M_{trunc} ? until which magnitude you can extrapolate

- Summary
  - if you have galaxies, you can measure Φ, you have ρ_{UV}, you have n_{ion}, you can resolve: $\dot{Q}_{\rm H_{II}} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H} \rangle} - \frac{Q_{\rm H_{II}}}{t_{\rm rec}}$, so have τ and $x_e(z)$

GLF : In practice

- need to measure the number of galaxies per redshift and magnitude per volume
  - harder at high redshift/low luminosity
  - good z, good L, many galaxies

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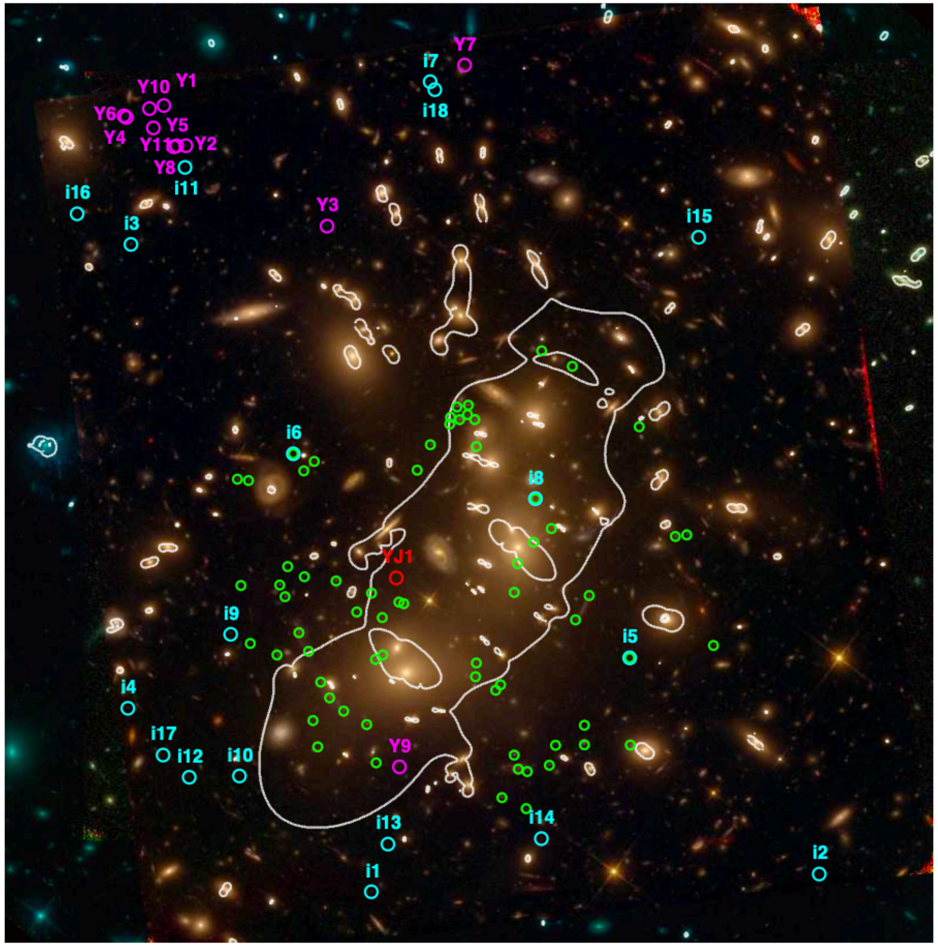
Use a telescope… a gravitational telescope

Lensing allows you to see further and fainter galaxies

skip many details of how to measure z and L



GLF : In practice

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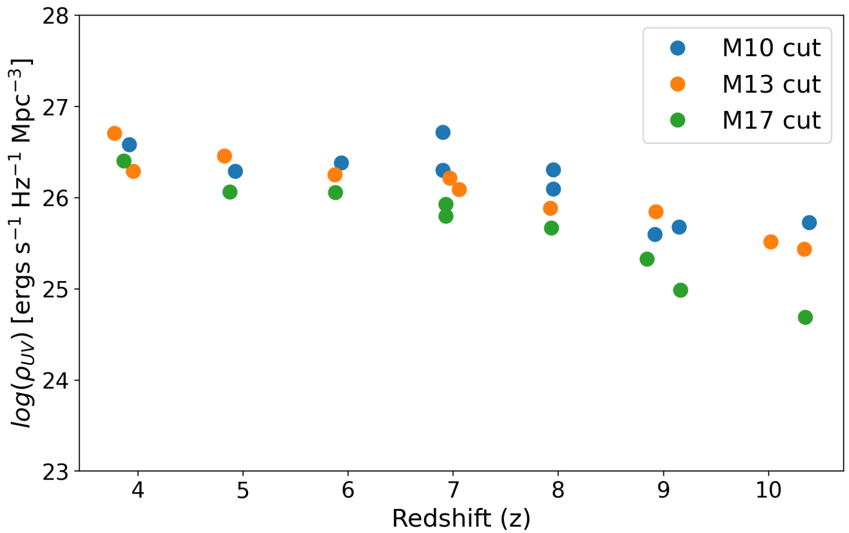
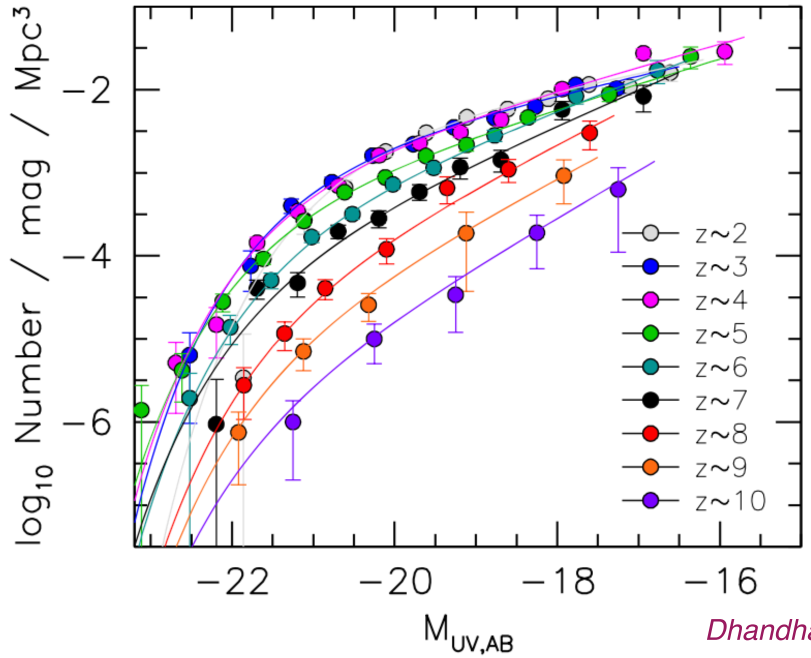


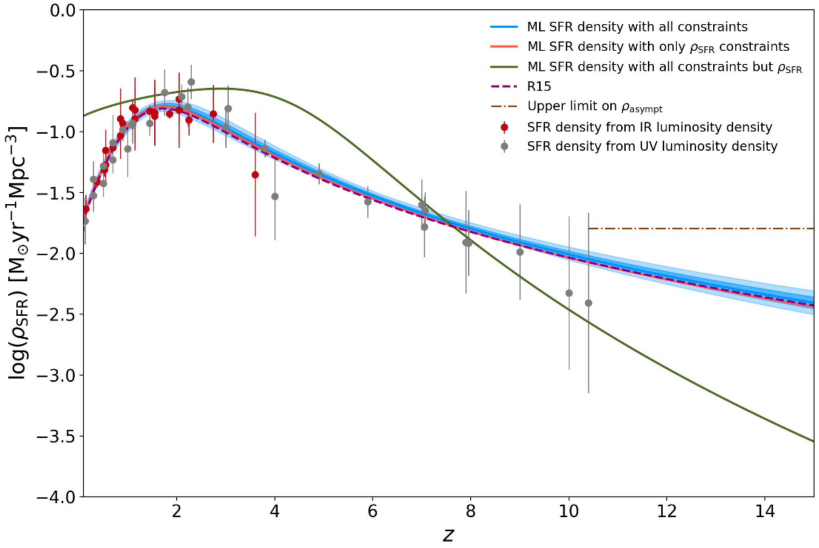


Dhandha et al. 2025

GLF : In practice

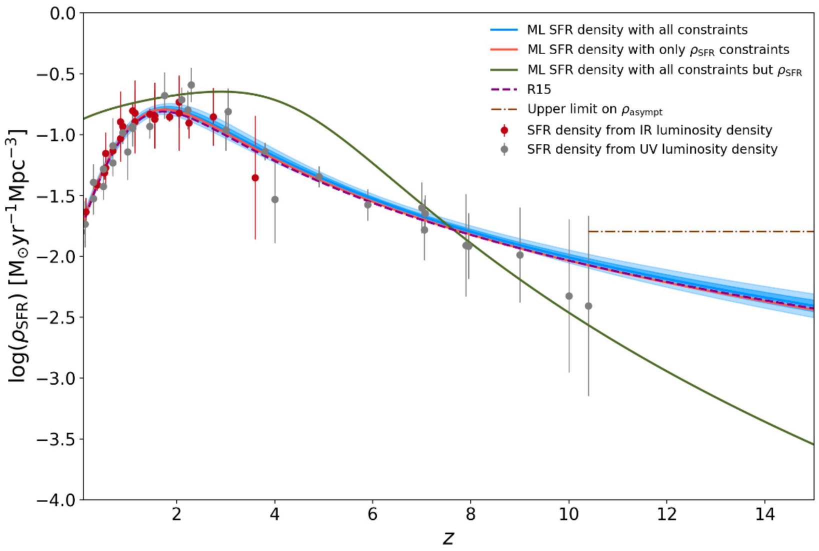
- need to measure the number of galaxies per redshift and magnitude per volume
  - harder at high redshift/low luminosity
  - good z, good L, many galaxies
- fit Φ and integrate to find $\rho_{\rm UV}$
  - need to decide $M_{\rm trunc}$
- fit $\rho_{\rm UV}$ and integrate to find Q
  - need $f_{\rm esc}$, $\xi_{\rm ion}$, $C_{\rm HII}$ and extrapolate $\rho_{\rm UV}$ to z~30
  - Resolve Q(z) get τ

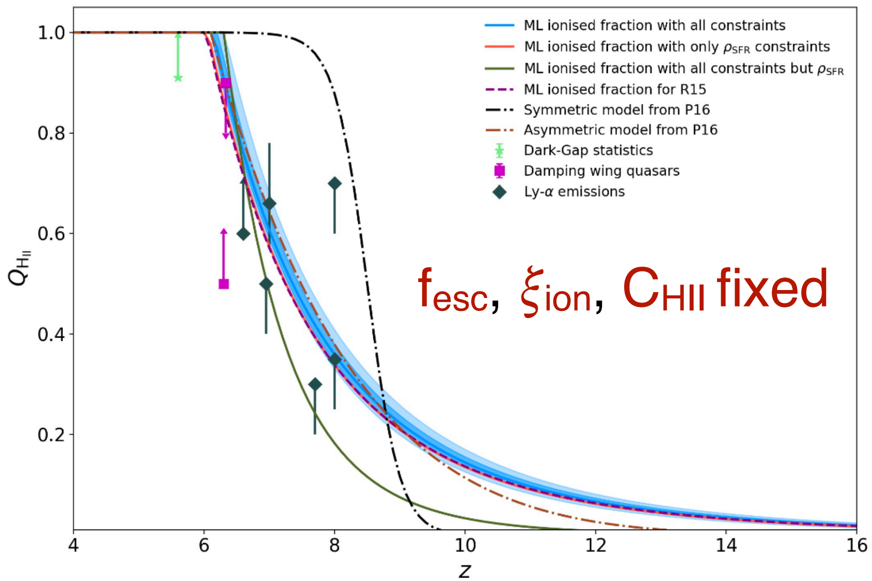
GLF : Results



Gorce et al. 2018

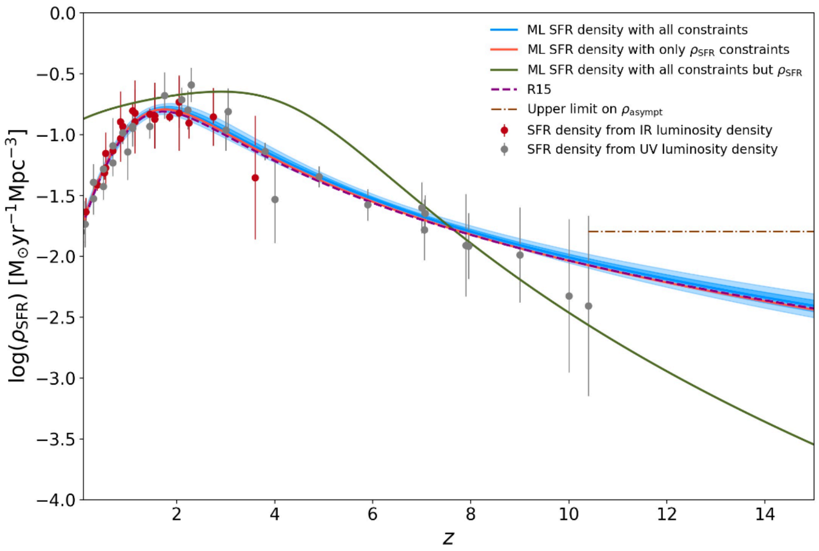
GLF : Results

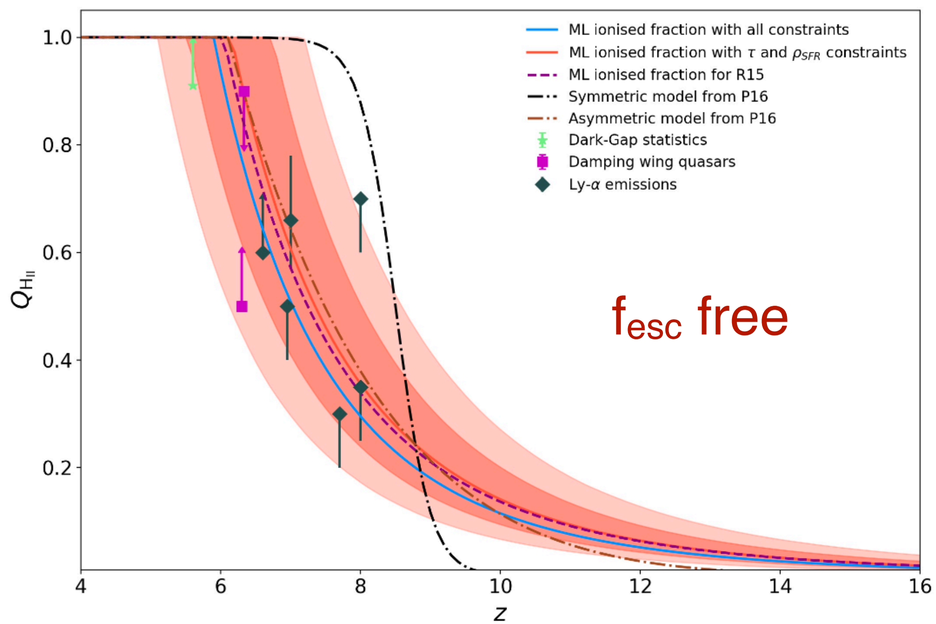


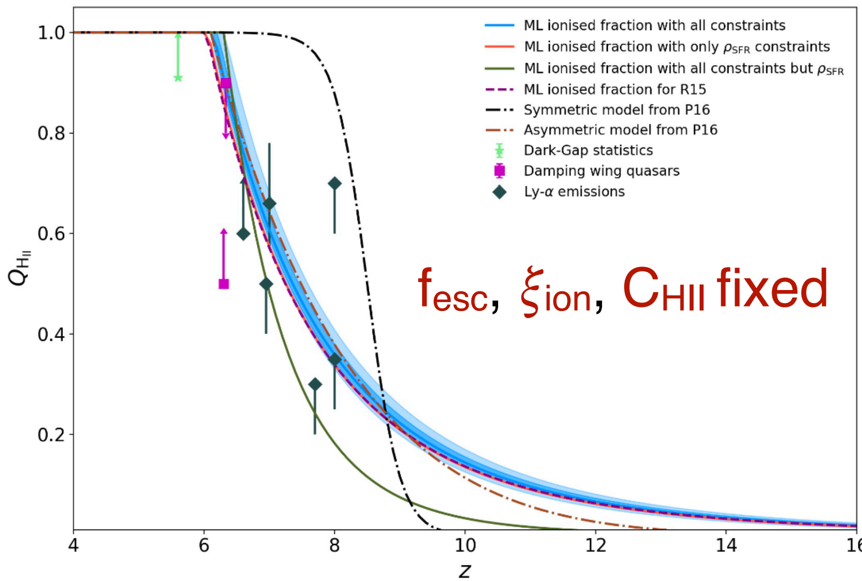


Gorce et al. 2018

GLF : Results

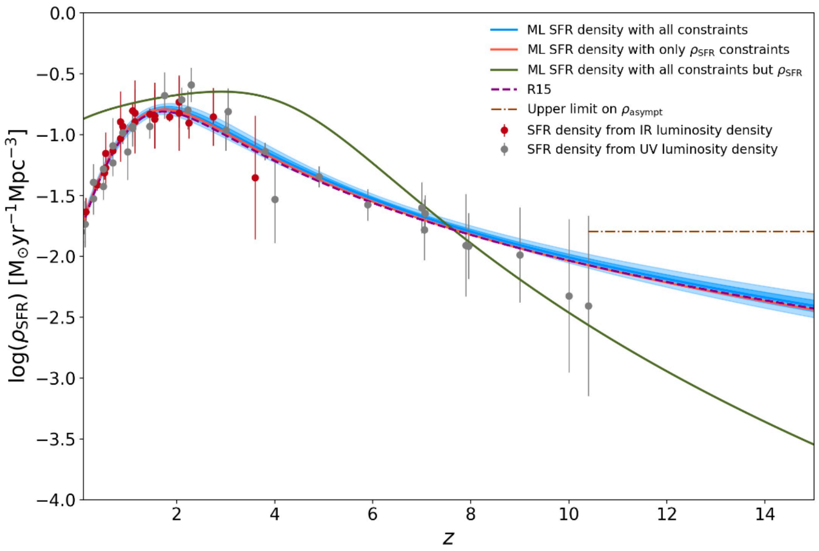


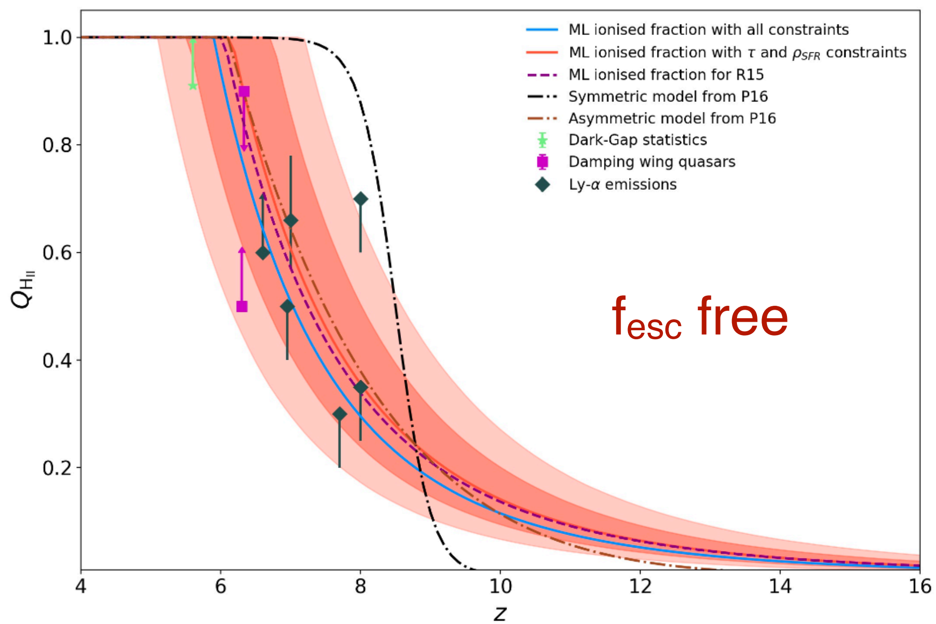


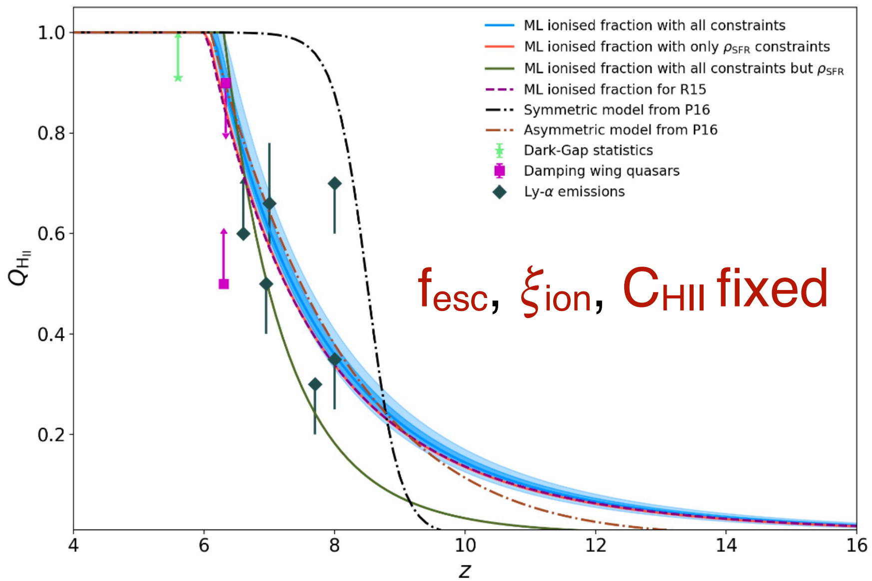


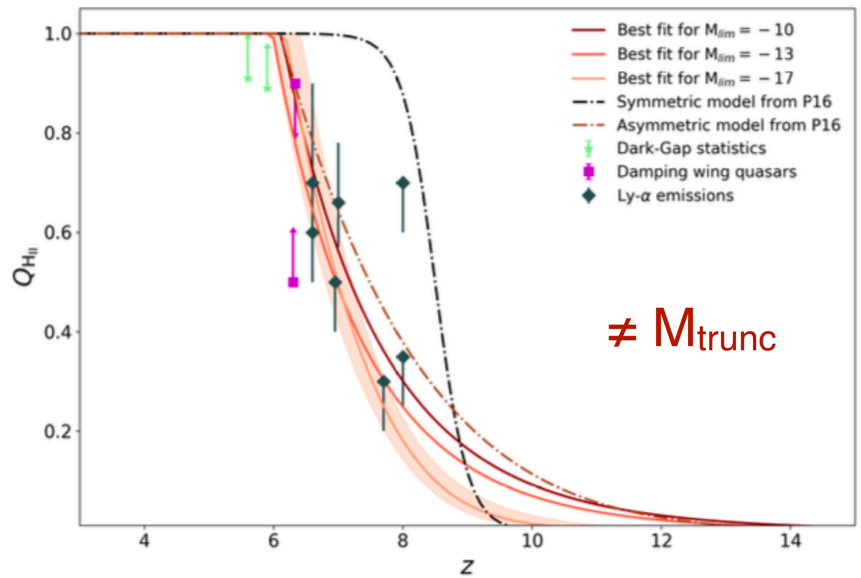
Gorce et al. 2018

GLF : Results



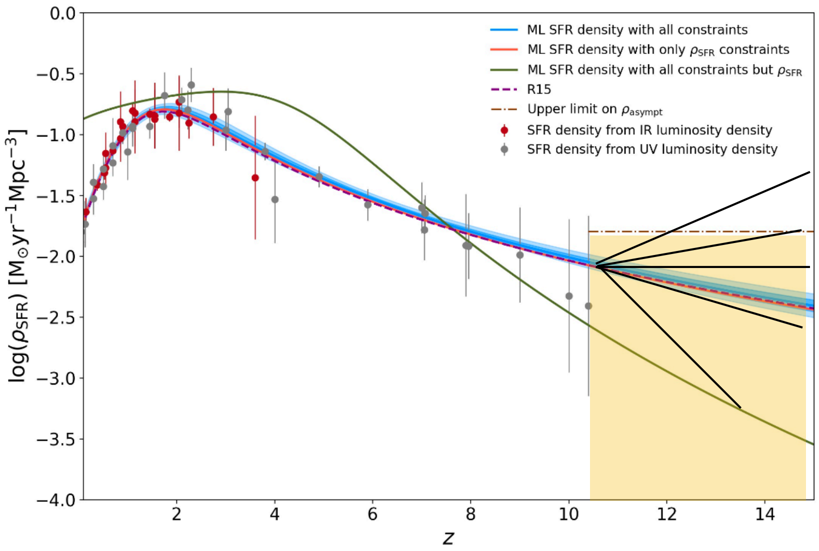






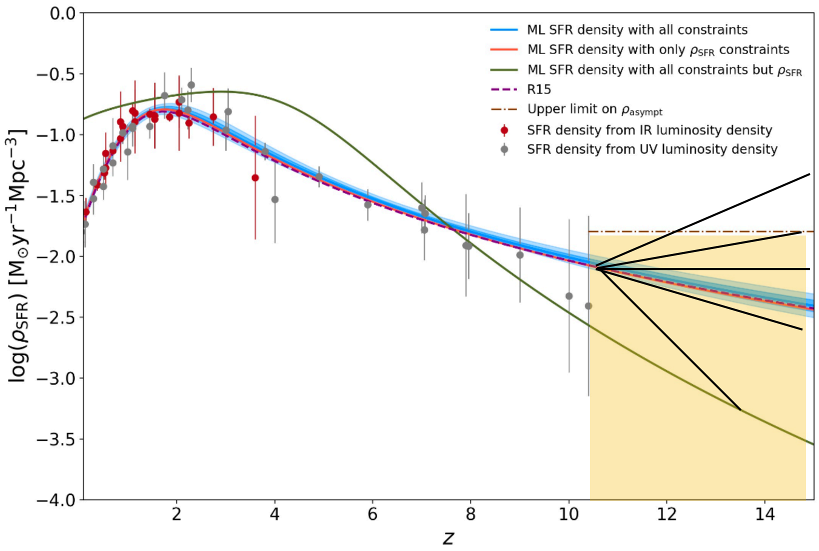
Gorce et al. 2018

GLF : Results



Gorce et al. 2018

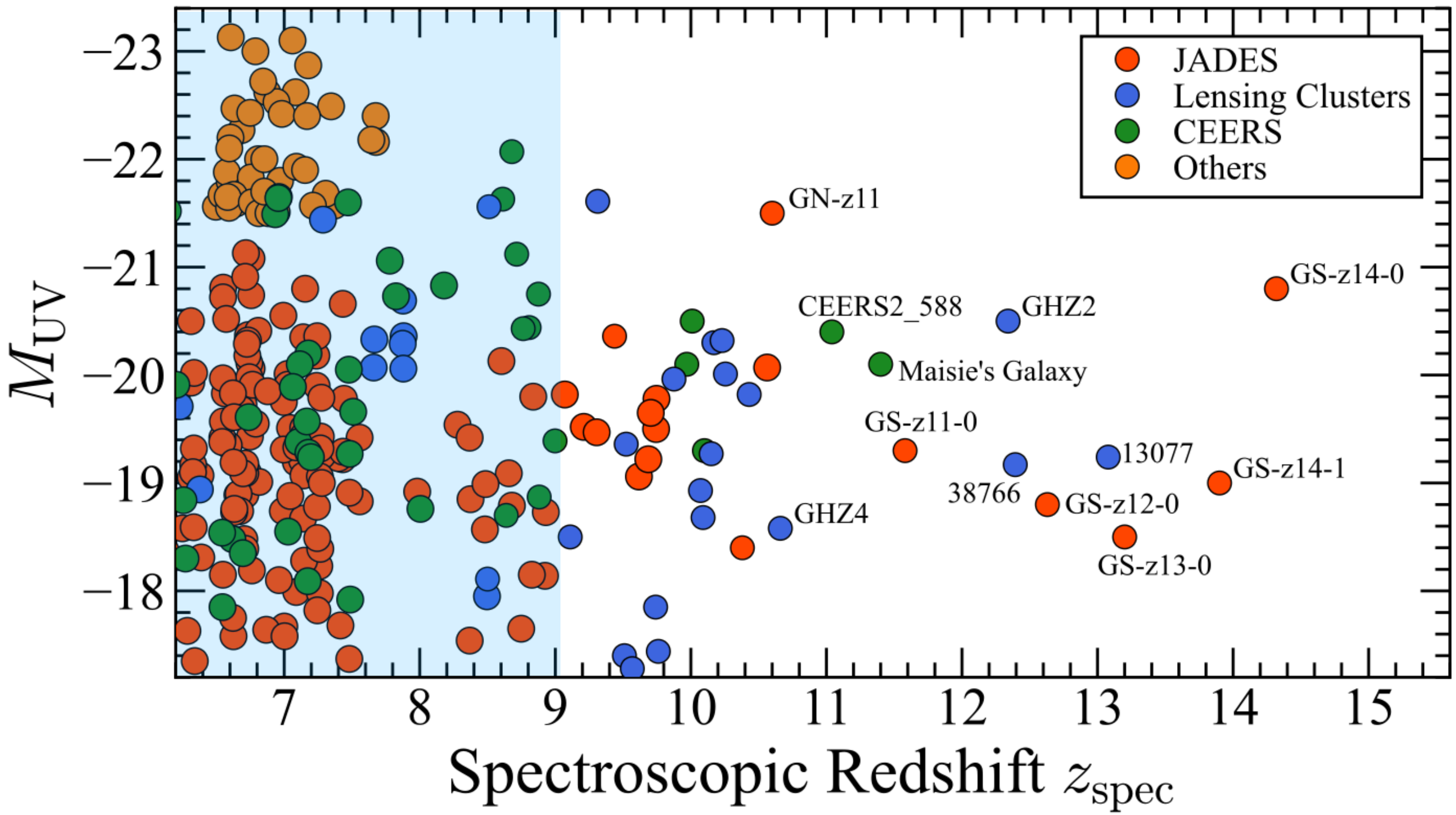
GLF : Results



Gorce et al. 2018

- Reconstructed EoR depends on f_{esc}, ξ_{ion}, C_{HII} fixed, free or redshift dependent
- Reconstructed EoR depends on M_{trunc}, so the number of unseen faint galaxies
- High redshift ionising flux unknown. Combining all constraints : soft upper limit
- Need for high-z low-L galaxies

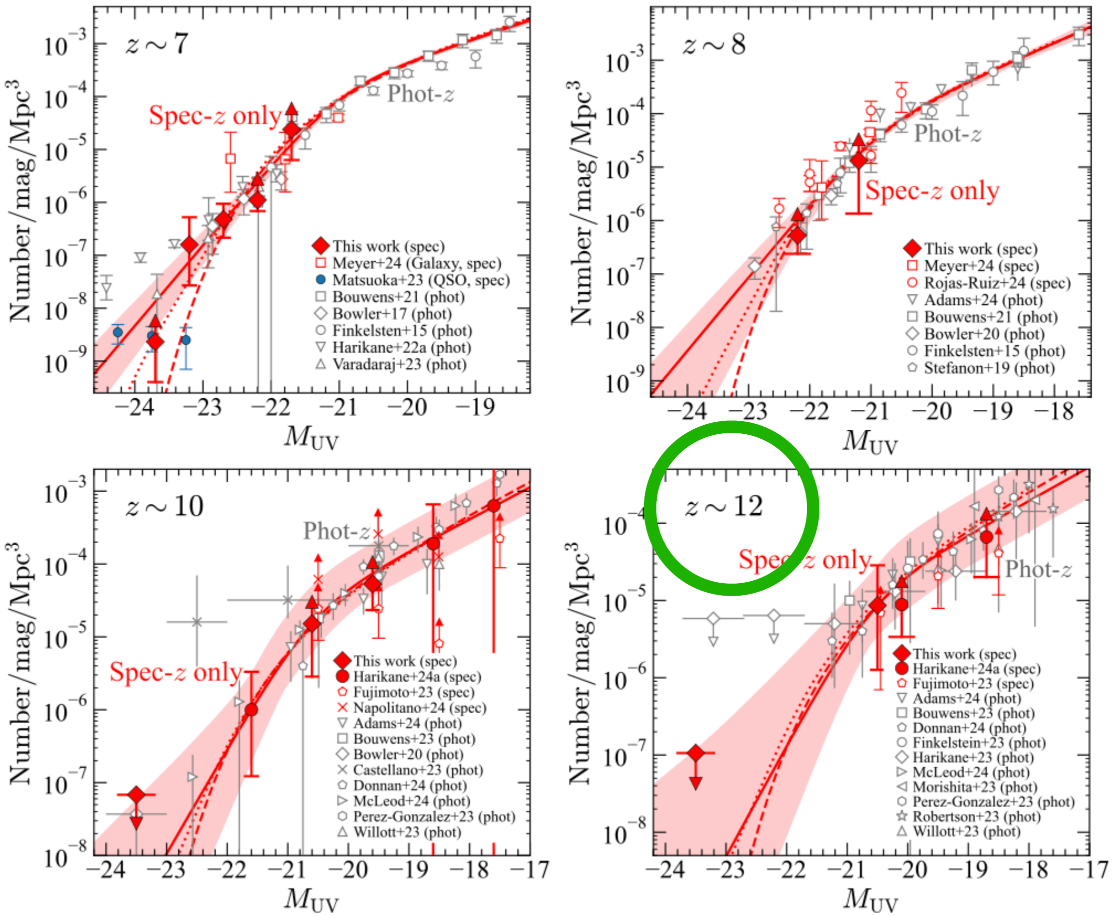
GLF : Results JWST

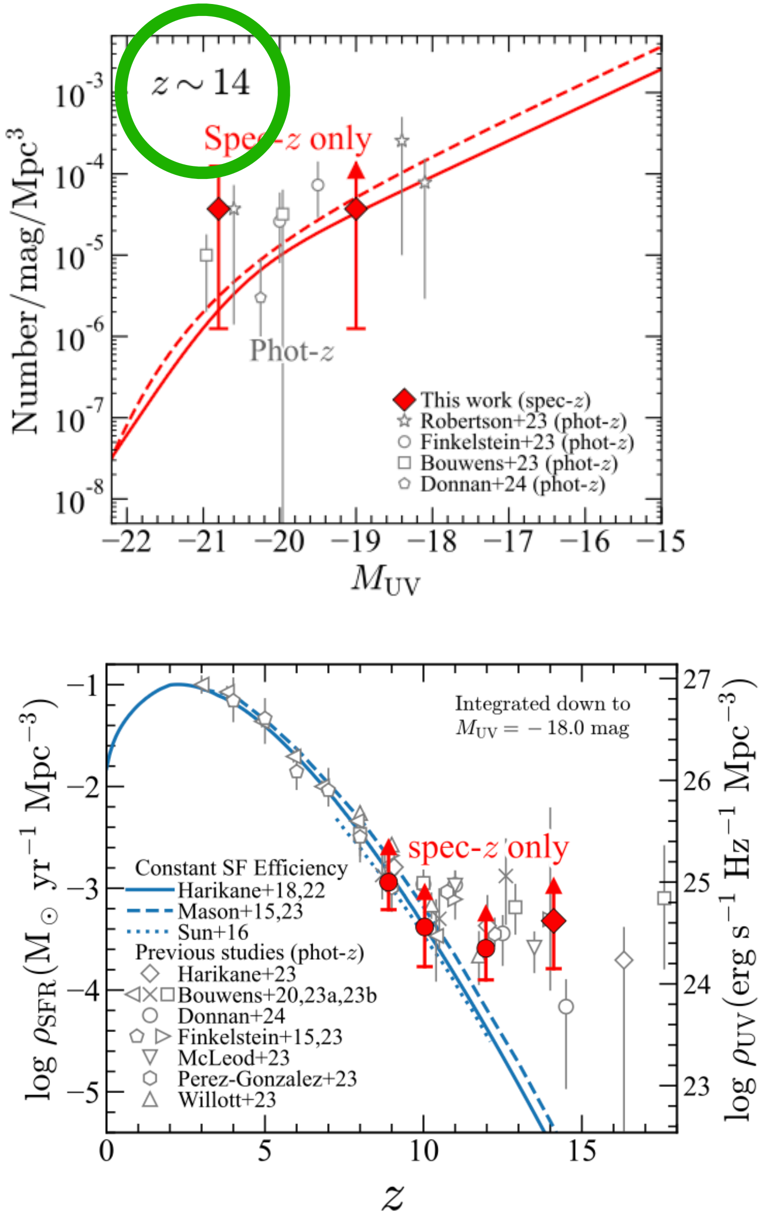


Harikane et al.. 2025

GLF : Results JWST

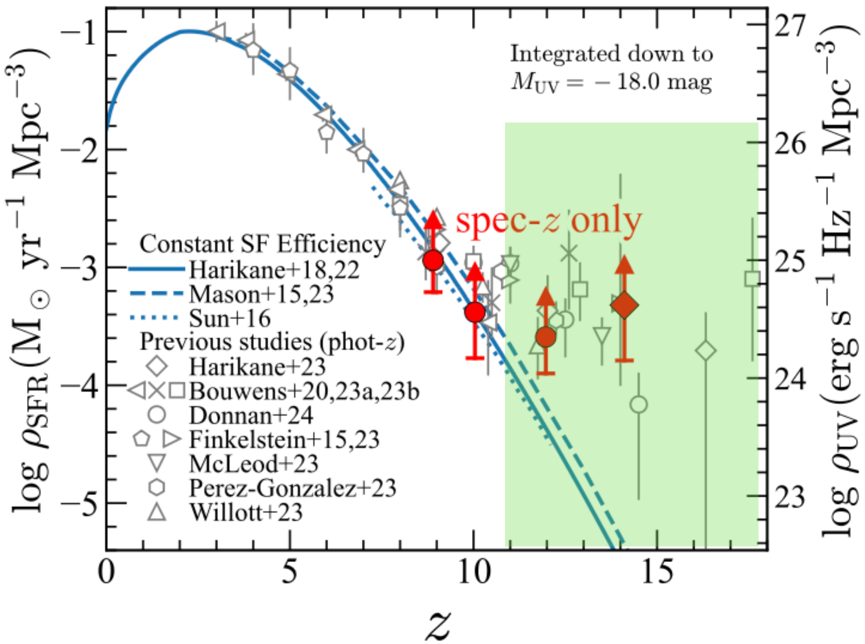
- Once volume estimated



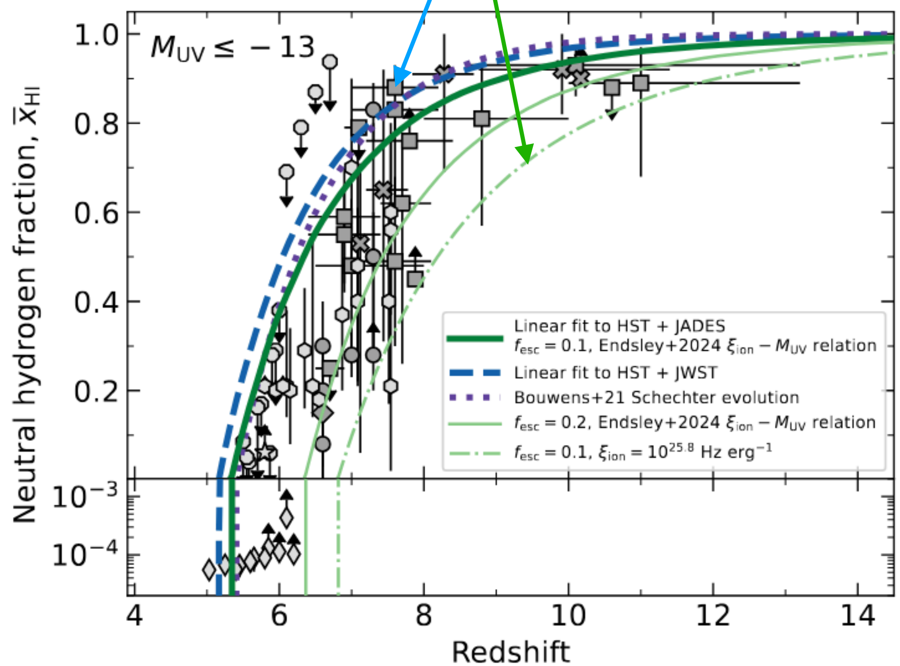


Harikane et al.. 2025

GLF : Results JWST



Varying f_{esc}, ξ_{ion}



Harikane et al.. 2025

- Hint for too many bright galaxies
  - mergers, low stats
  - high ρ_{UV} → high τ → but freedom in models
  - still not in tension when marginalised over unknowns

GLF : CONCLUSION

- GLF : potential probe of reionisation
- Need for spectroscopy
  - interlopers at low z in photo-z samples
- Mergers and AGNs may increase luminosity
  - revision of models : higher star formation efficienty
- stochasticity of star formation
  - large datasets
- high ρ_{UV} at high z thus high τ
  - may be compensated by low f_{esc} etc….

Outline

- Probing reionisation with CMB data (milimeter observations)
- Probing reionisation with high redshift galaxy luminosity function (infra-red observations)
- Probing reionisation with quasars observations
- Probing reionisation with 21cm observations

- $\nu_{\rm CMB}$
- τ
- $\nu_{\rm gal}$
- $x_e(z)$
- HI
- HI/HII

Principles
Limitations of the observations
Some results

Outline

- Probing reionisation with CMB data (milimeter observations)
- Probing reionisation with high redshift galaxy luminosity function (infra-red observations)
- Probing reionisation with quasars observations
    - end of reionisation
    - Damping Wings
    - Equivalent Width

- ν_{CMB}
- ν_{gal}
- HI
- HI/HII

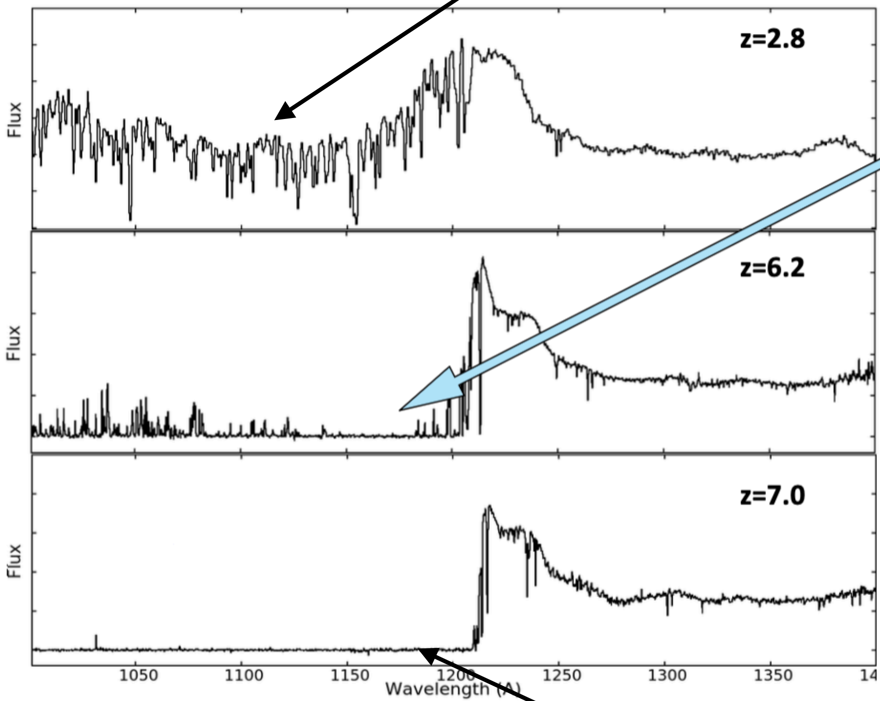
- τ
- $x_e(z)$

Principles
Limitations of the observations
Some results

Quasars : End of Reionisation

- Gunn-Peterson effect : Lyman-α absorption by neutral medium of distant quasar emission

no absortion: no neutral medium, fully reionised



absortion as soon as $x_{HI}>0.001$

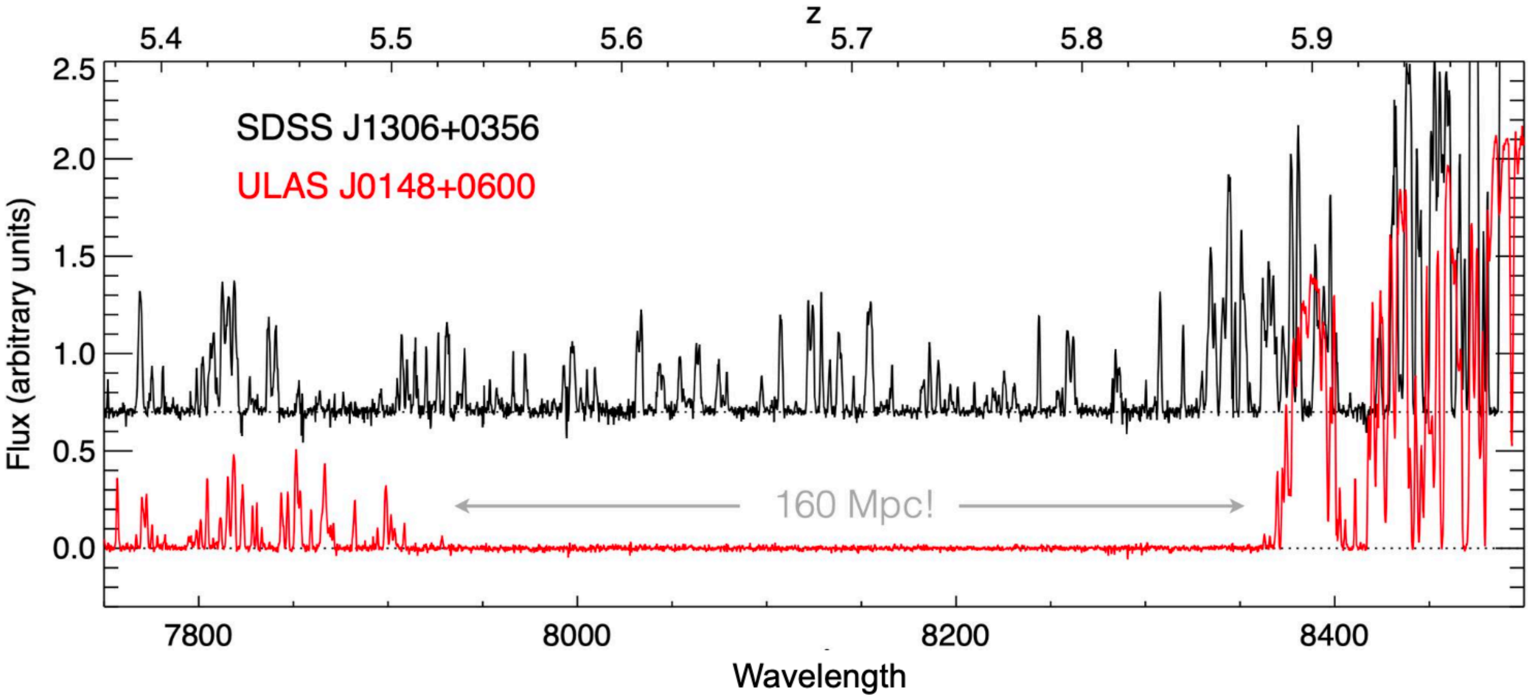
©Bosman

full Gunn-Peterson trough: fully neutral

- end of reionisation $2.8 < z_{end} < 7.0$

QUASARS : END OF REIONISATION

- Different lines of sight

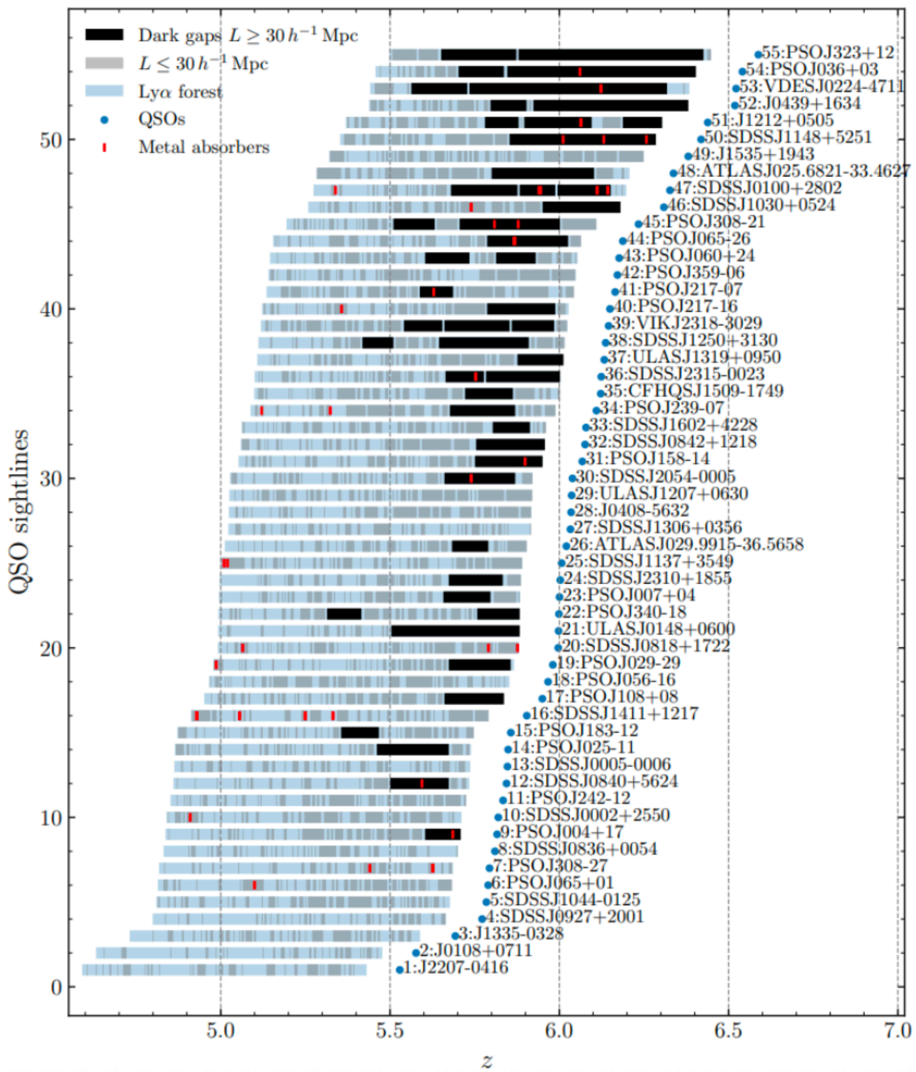


Becker et al 2015

$$x_e(z,\hat{\mathbf{n}}) = \langle x_e(z)\rangle(1+\delta_{x_e}) = \langle x_e(z)\rangle(1+\delta_b(z,\hat{\mathbf{n}})+\delta_x(z,\hat{\mathbf{n}})+\delta_b\delta_x(z,\hat{\mathbf{n}}))$$

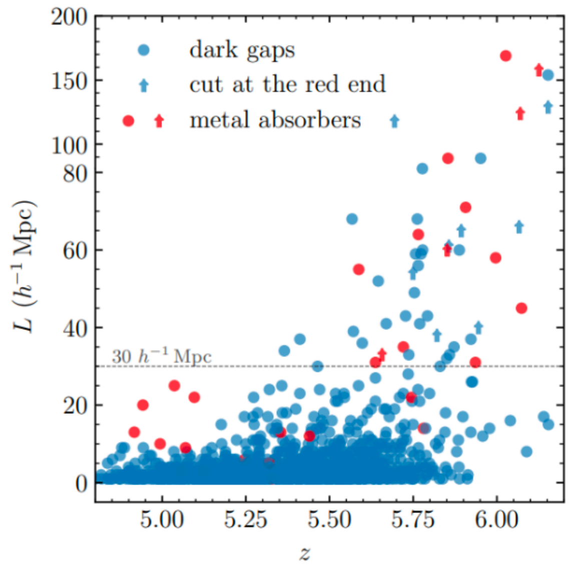
- too large dispersion (not explained by δ_b)
  - needs to be inhomogeneous end of reionisation

Quasars : End of Reionisation



Strong redshift evolution of the fraction of IGM located inside a dark gap of length >30 cMpc

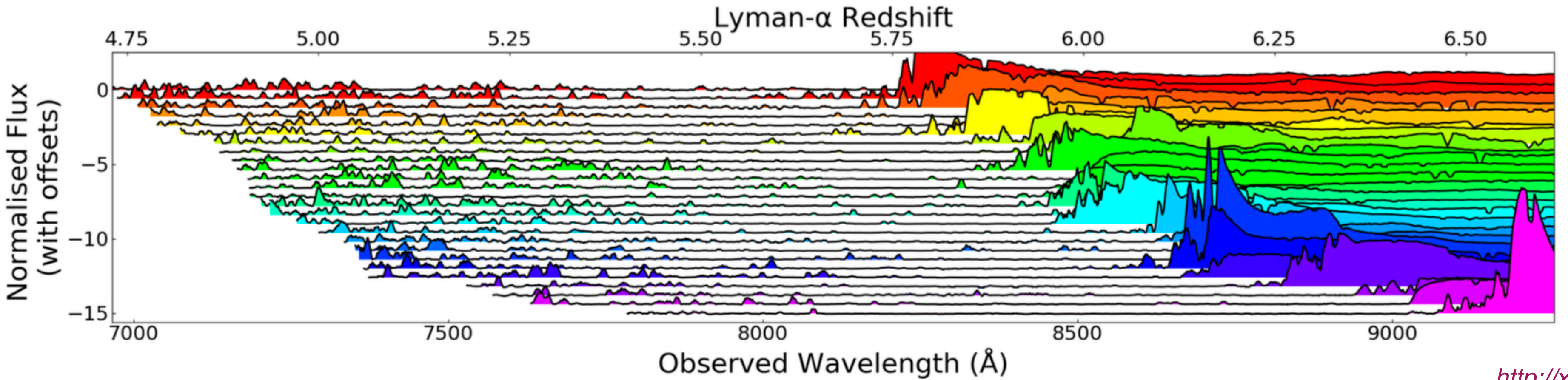
0% at z=5 to >80% at z=6



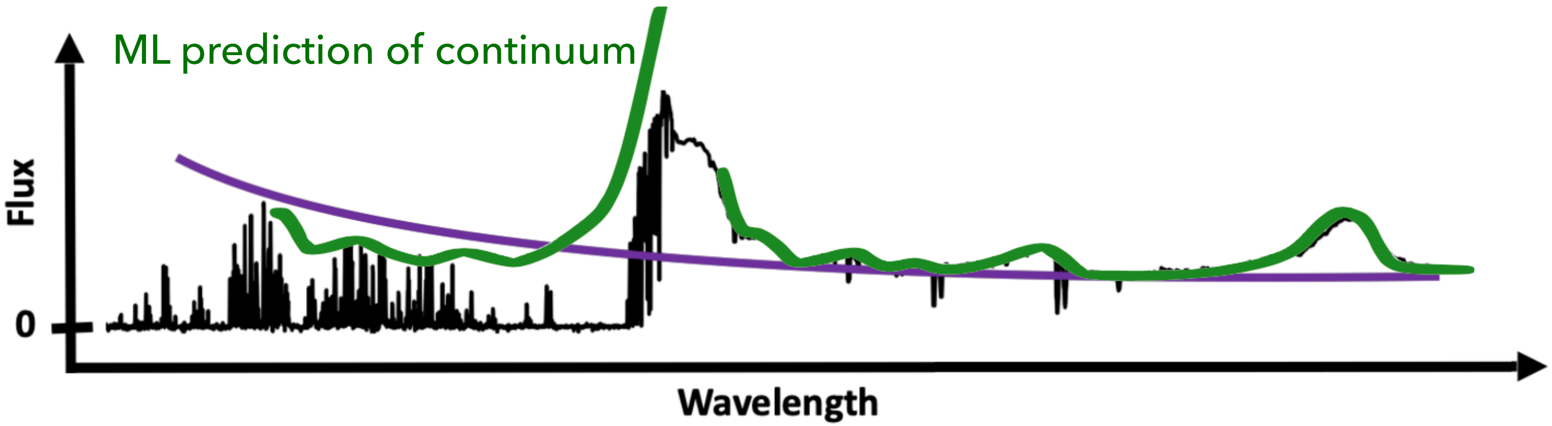
Zhu, SB+XQR-30 2021

Quasars : End of Reionisation

- statistical analysis (67 quasars)



http://xqr30.inaf.it/



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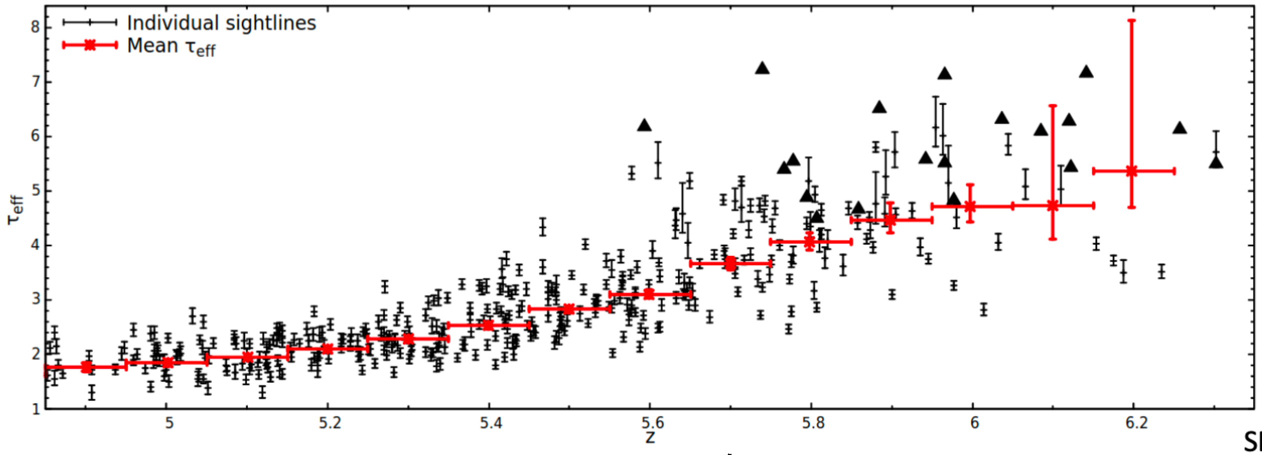
$$\tau_{\rm eff} = -\ln \langle F_{\rm obs} / {\rm F}_{\rm cont} \rangle_{\Delta z = 0.1}$$

QUASARS : END OF REIONISATION

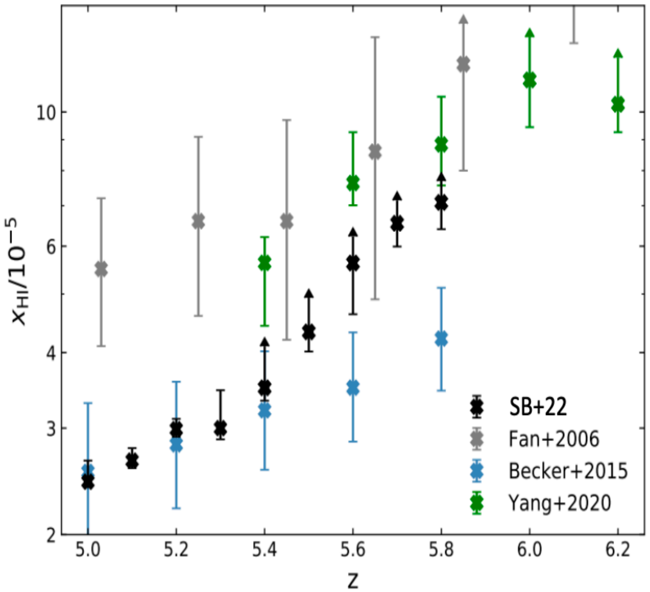


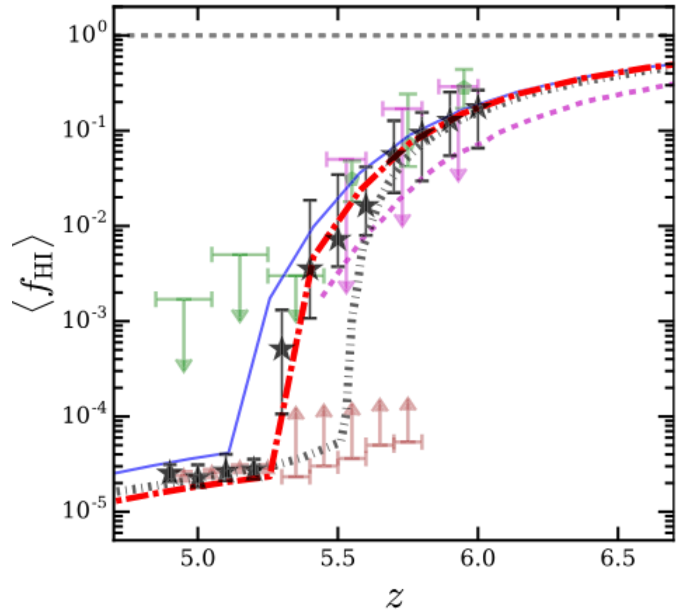
Neutral

Reionised

SB+22

simulations





Bosman et al. 2022

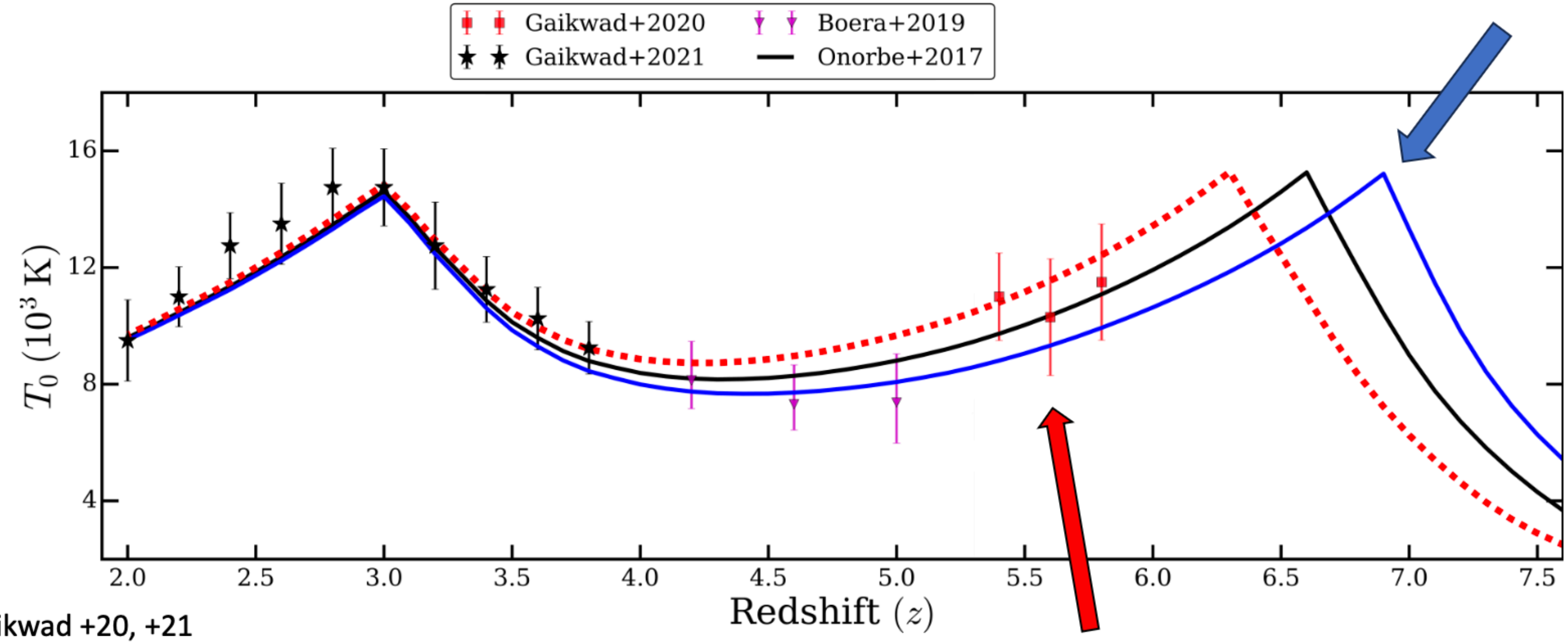
Gaikwad et al. 2023

QUASARS : END OF REIONISATION: TEMPERATURE

ÉCOLE DE PHYSIQUE DES HOUCHES

Temperature of the high-z IGM

Bulk of IGM heating above z~7.5: would cool down too much!



Gaikwad +20, +21

IGM heated to >10000K by z=5.7,
&
Has not significantly cooled yet

Quasars : End of Reionisation: Conclusion

- Excess scatter in effective optical depths at z>5.3
- Existence of long coherent absorption at z>5.3
- IGM has been heated fairly recently at z=5.7

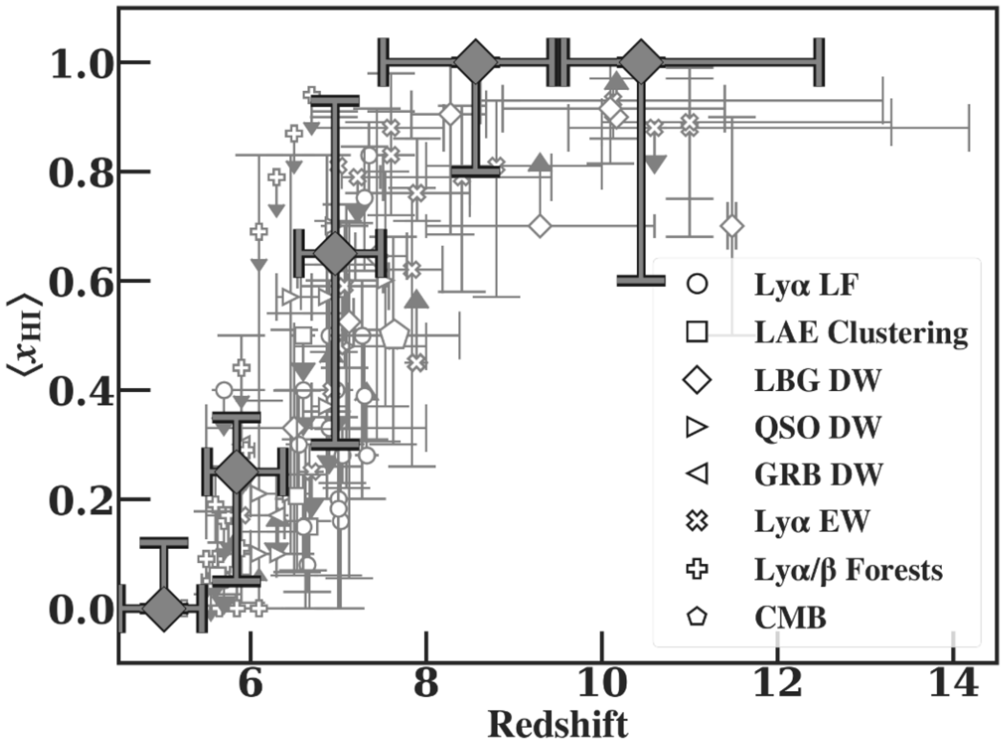
➡

- UV light does not percolate the Universe until z=5.3 (+- 0.1)
- Only possible if reionisation is
  - very late: midpoint of reionisation at z~7 is most likely
  - patchy

OTHER REIONISATION PROBES

Same idea of interaction photons-HI

- the damping wing absorption from neutral IGM in quasar (et al.)
- Ly-α equivalent width
- the distribution of dark gaps in quasar spectra *Greig et al.*
- the size and evolution of the proximity zone around quasars
- the number density and clustering of Ly-α emitters



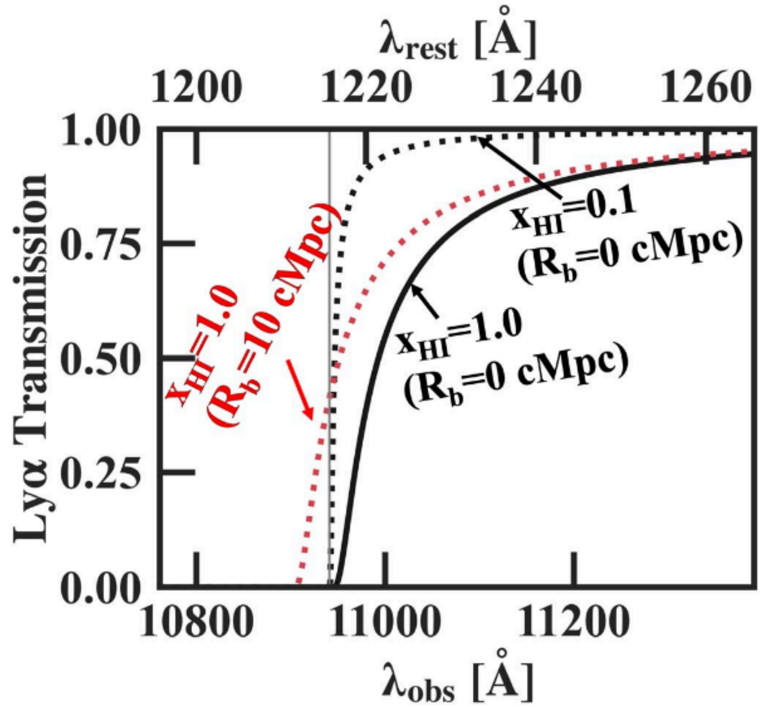
Umeda et al. 2025

Others: Damping wings

- If enough HI, the absorption profile is dominated by the natural line broadening described by the Lorentzian component of the Voigt profile (Meiksin 2009) → damping wing.

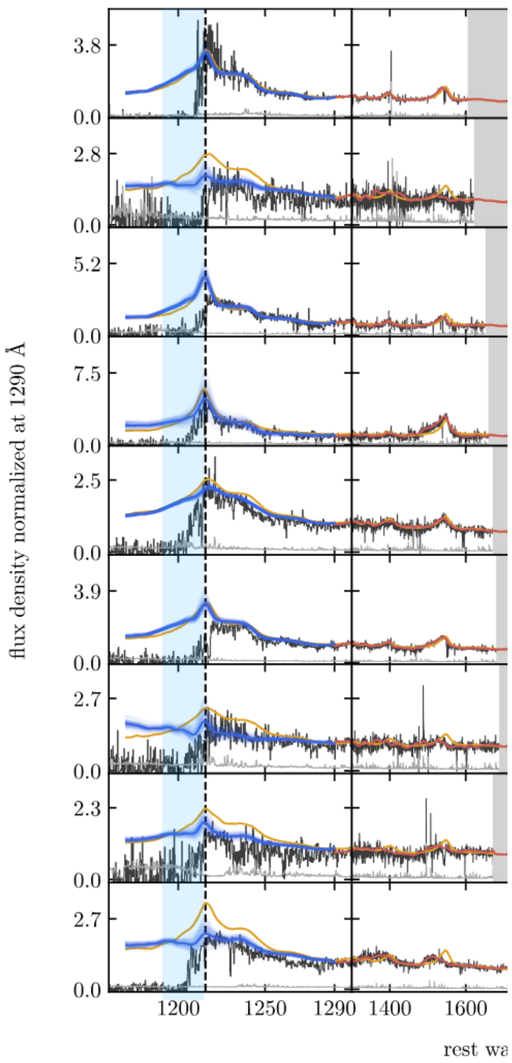
- Strength of the damping wing is proportional to the optical depth of the diffuse IGM and hence the volume-averaged neutral fraction

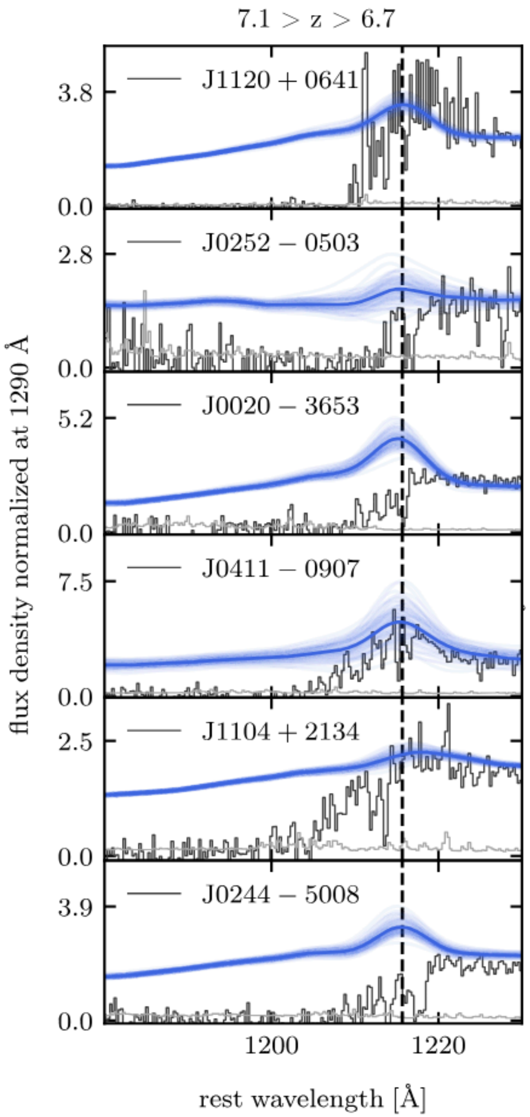
➡ Constraints on the reionization history from individual bright objects

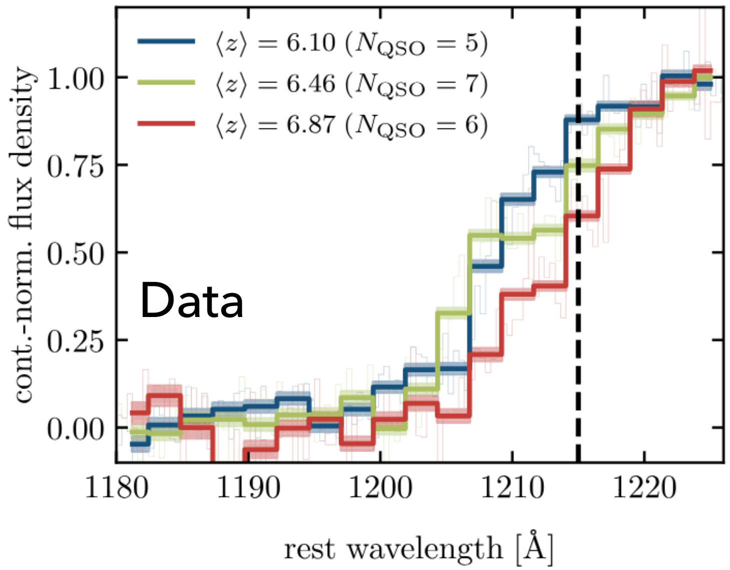


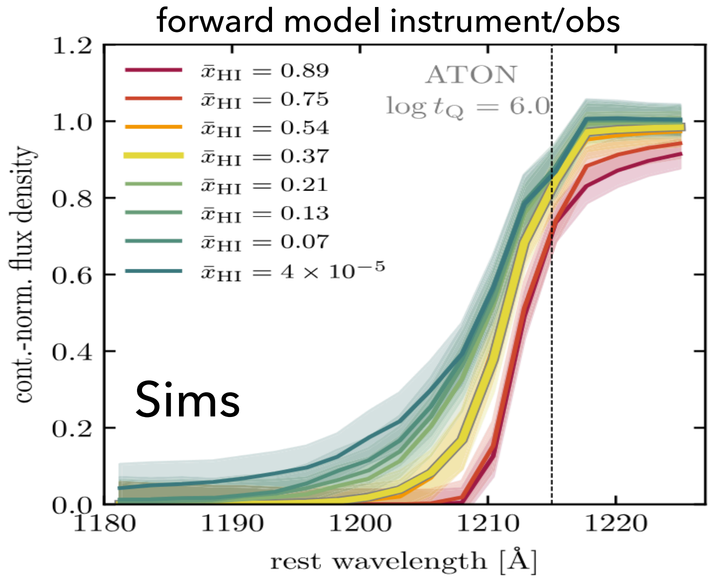
Umeda et al. 2025

OTHERS: DAMPING WINGS



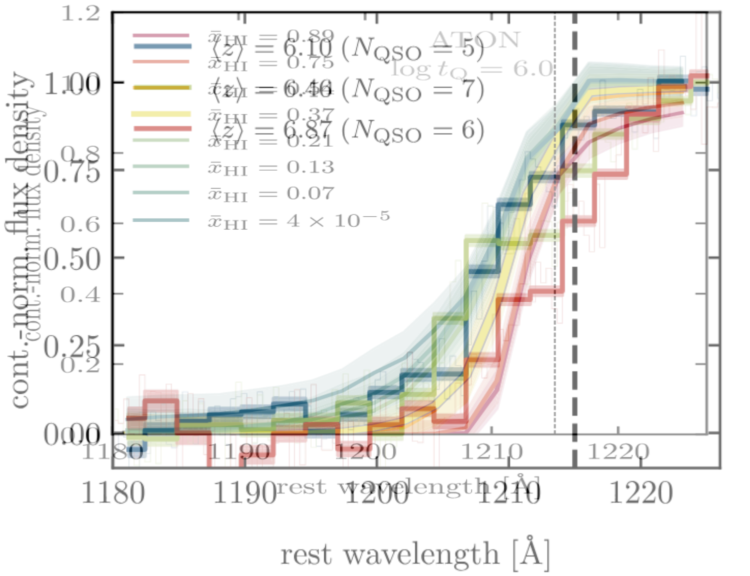


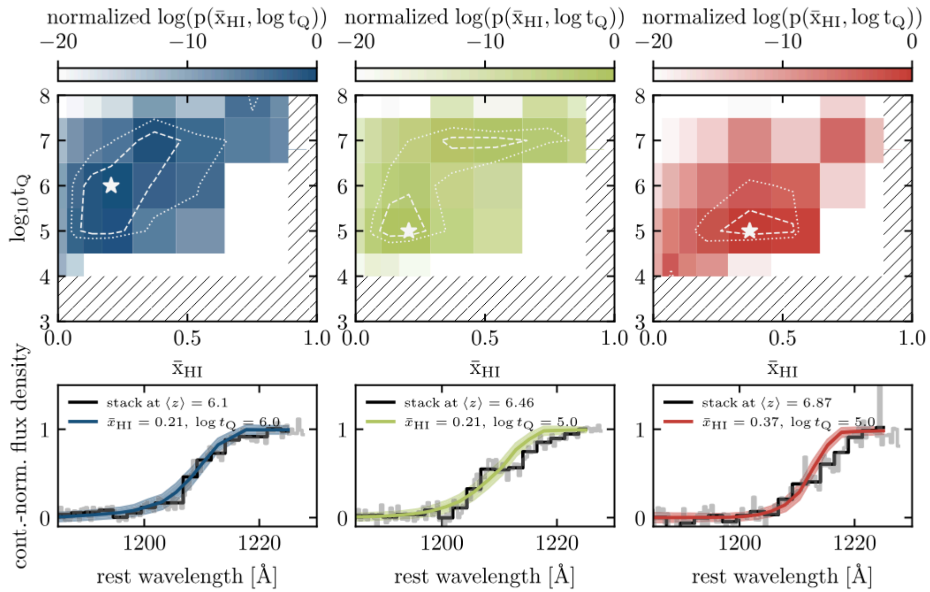


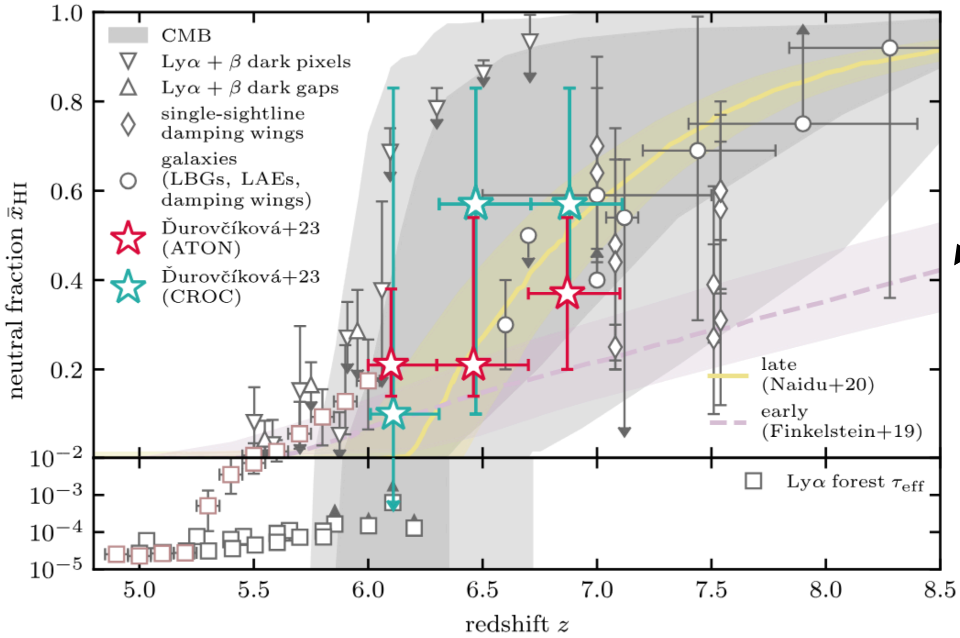


Ďurovčíková et al 2024

Others: Damping wings



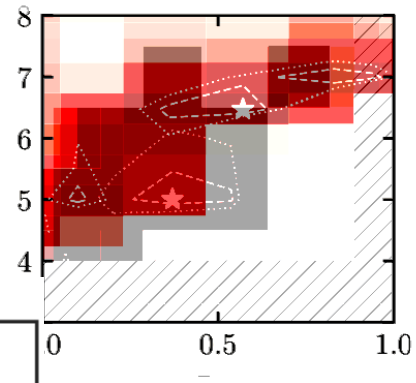


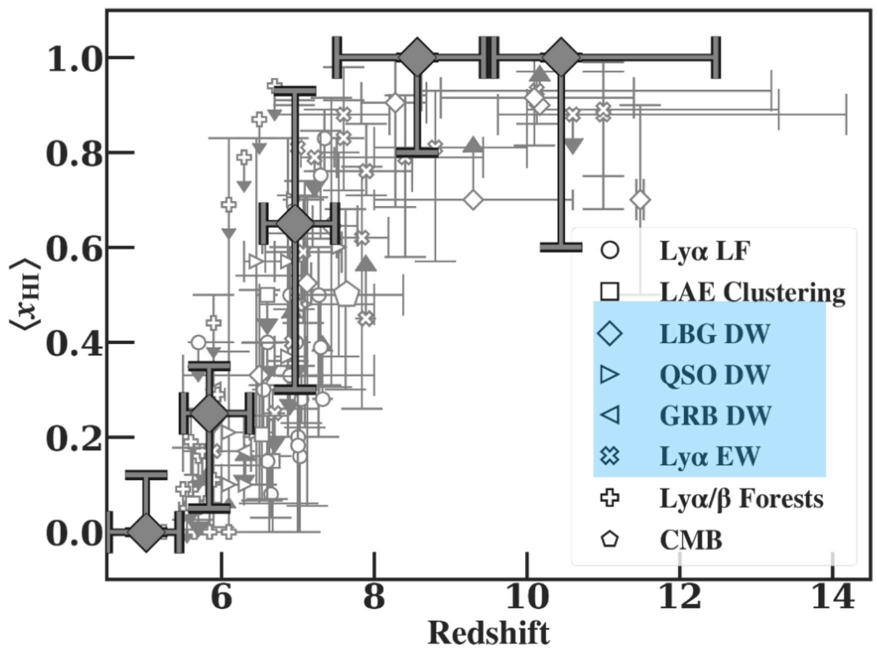


Ďurovčíková et al 2024

Others: Damping wings

- Limitations
  - proximity zone effect ↔ average quasar lifetime ↔ DW
  - need continuum reconstruction
  - simulation dependent
  - high LOS variation
- Results:
  - late reionisation





Ďurovčíková et al 2024

Others: Ly-α Equivalent Width

- Ly-α Equivalent Width (EW) is defined by a Ly-α flux relative to a UV continuum flux
  - it reflects the intensity of the Ly-α emission
  - it is sensitive to x_{HI} as the flux is damped by the amount of HI

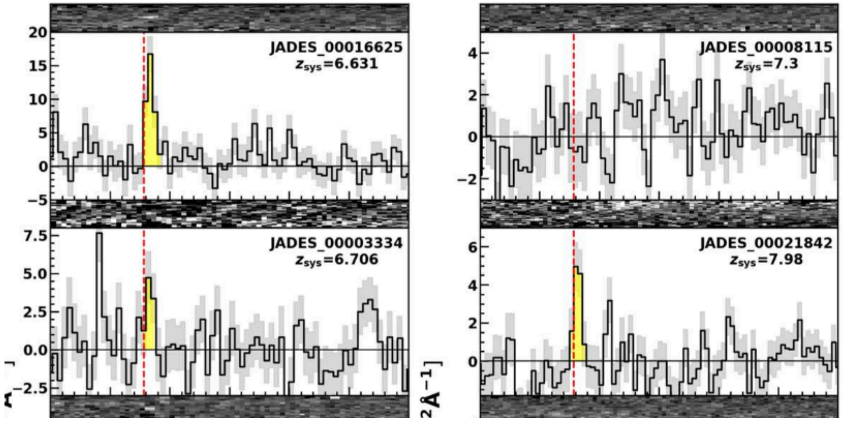
$$F_{\mathrm{Ly}\alpha} = \int_{\lambda_{min}}^{\lambda_{max}} d\lambda A e^{-\left(\frac{\lambda - \lambda_{\mathrm{cen}}}{\sigma}\right)^2} \times e^{-\tau(\lambda)},$$

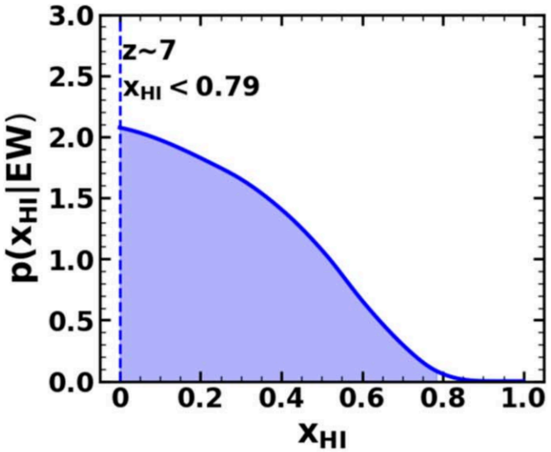
$$\mathrm{EW}_{0,\mathrm{Ly}\alpha} = \frac{F_{\mathrm{Ly}\alpha}}{f_c(1 + z_{\mathrm{sys}})},$$

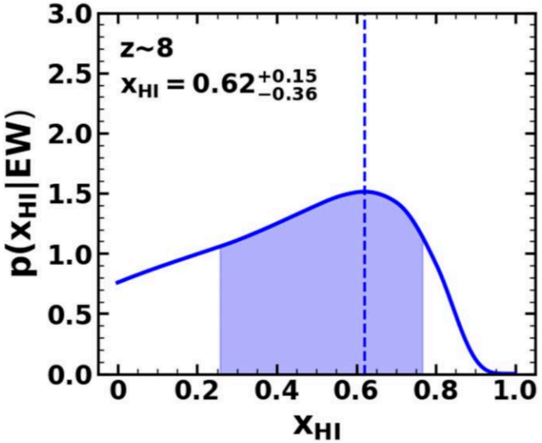
$$p(\mathrm{EW}_i | x_{\mathrm{H\,I}}) = \int_0^\infty d\mathrm{EW}\, \frac{e^{-\frac{(\mathrm{EW}-\mathrm{EW}_i)^2}{2\sigma_i^2}}}{\sqrt{2\pi}\,\sigma_i} p(\mathrm{EW}|x_{\mathrm{H\,I}}),$$

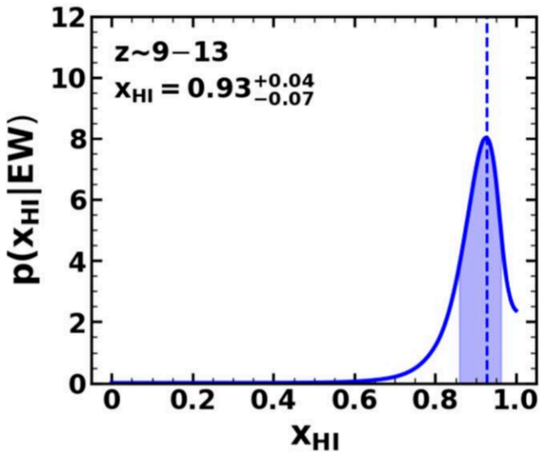
Nakane et al 2024

Others: Ly-α Equivalent Width



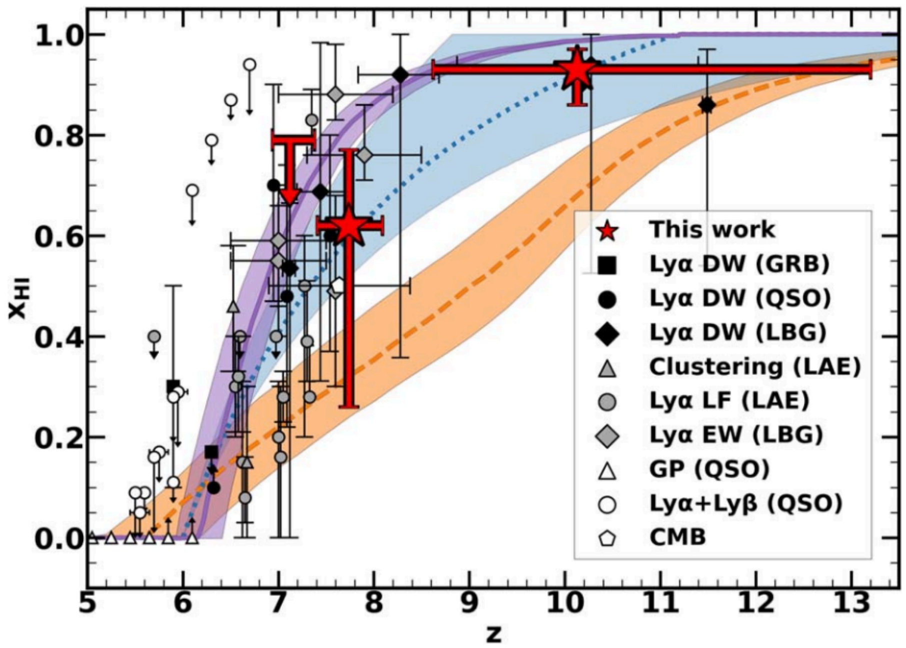




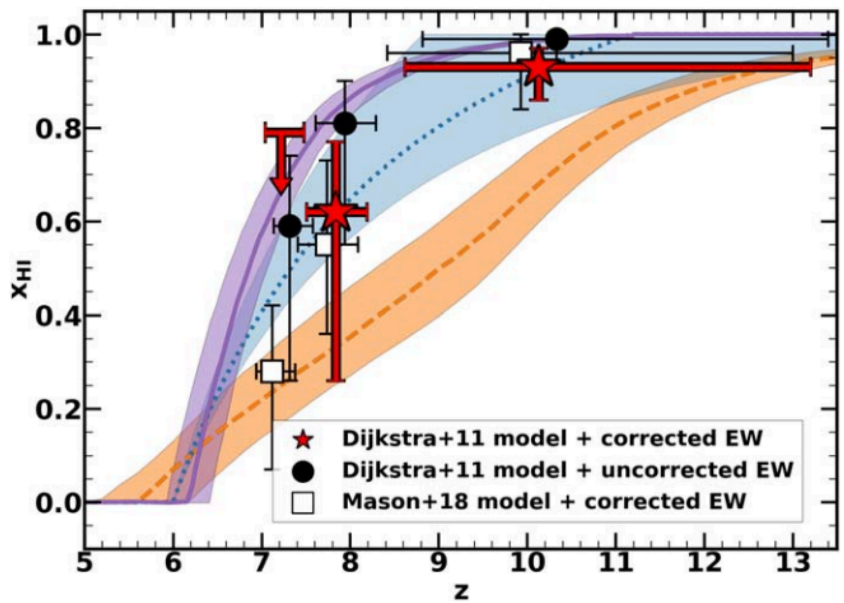


Others: Ly-α Equivalent Width

- Consistent with other probes



- Favors late reionisation



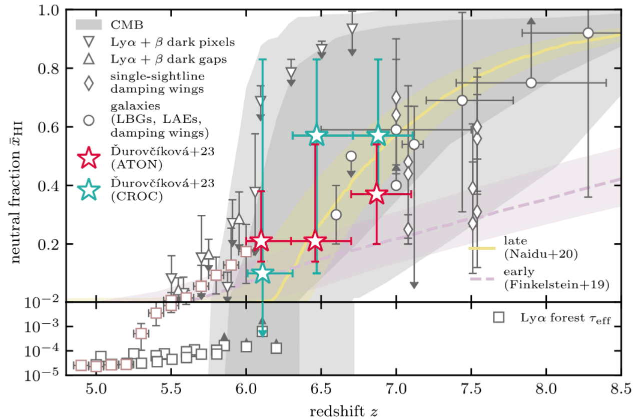
Nakane et al. 2024

Conclusions: What can we learn ?

- CMB gives you τ, more or less time, and duration (morphology)
- Gal. Lum. Functions gives you history $x_e(z)$
- Quasars give you information on the end of reionisation and intermediate redshifts
- 21cm should give you tomography and morphology $x_e(z,\mathbf{n})$

➡ a chance to have many probes !

CONCLUSIONS: WHAT DO WE KNOW ?



- CMB: $\tau = 0.056 \pm 0.0045$
  - late and fast end (z~7.7)
- GLF
  - late and fast, need to adjust high z gal. from JWST
- End of reionisation
  - later than z=6 (z~5.3), patchy
- DW and EW
  - late reionisation

➡ *each probe is (more or less) limited by systematics but they all converge towards late reionisation*

➡ *approch should be global - combination of probes*

Conclusions: what do we don't know ?

- **Exact shape of $x_e(z)$**
  - Improvement of CMB factor 2 on EE may (or not) help make difference between all shapes
    - LiteBIRD* 2030+ for large scales
  - GLF to fainter and higher-z galaxies
    - years of JWST, and using lenses, for higher stats, but limited by environment (f_{esc}, …)
  - More quasars and better sims
    - JWST spectra
  - 21cm data ! SKA

* 1/20years

Conclusions: what do we don't know ?

- **Morphology**
  - if kSZ(reio) is measured
    - SO, ~~CMB-S4**~~, adv-SO, …
    - trick to remove late time kSZ by cross-correl
    - Cl(τ)
  - 21cm !! SKA
    - big challenge on systematics, calibration…
    - big challenge with foregrounds
    - statistical analyses (3pt,…) will come first
- **Sources**
  - full picture is needed to undestand the contribution of galaxies, quasars at each z

➡ *Still some work to do !!*

** cancelled on the 10/07/25 by DOE/NSF