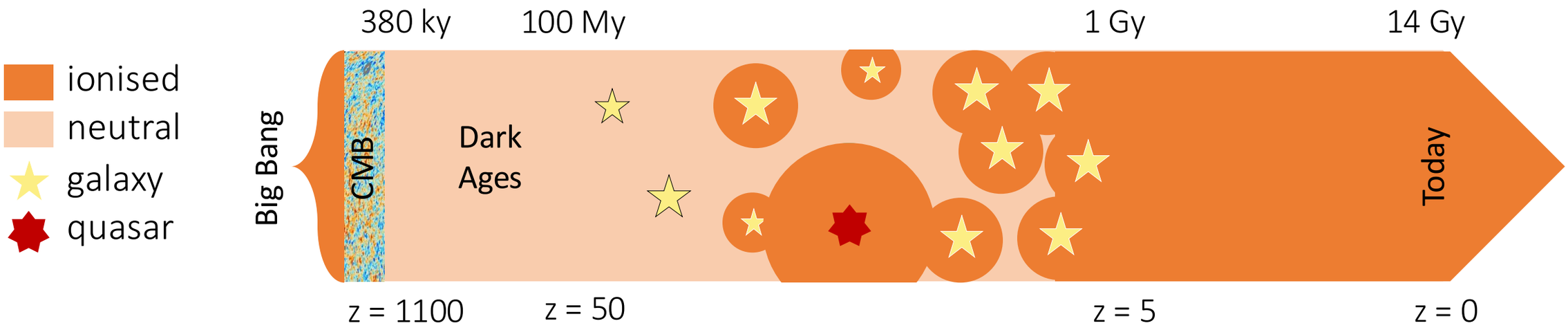
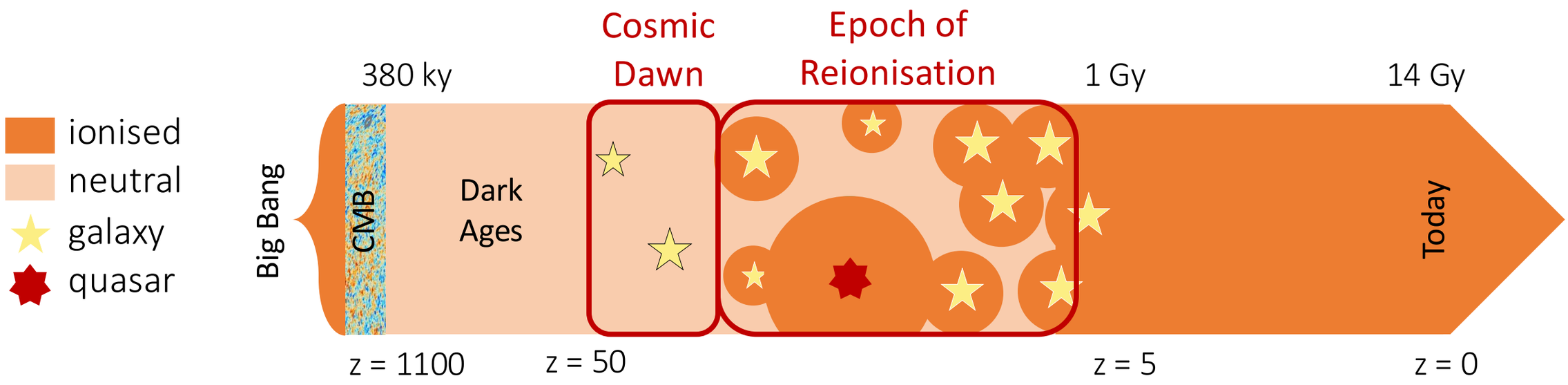
A consistent, physical, and analytic model for CMB observables of reionisation

Adélie Gorce

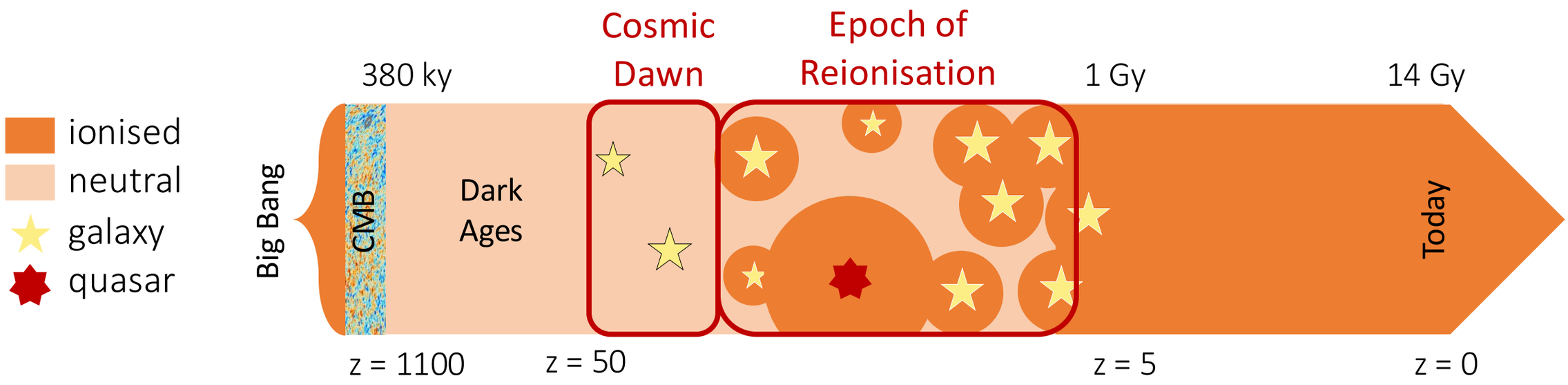
Reionisation & Cosmic Dawn



Reionisation & Cosmic Dawn



Reionisation & Cosmic Dawn

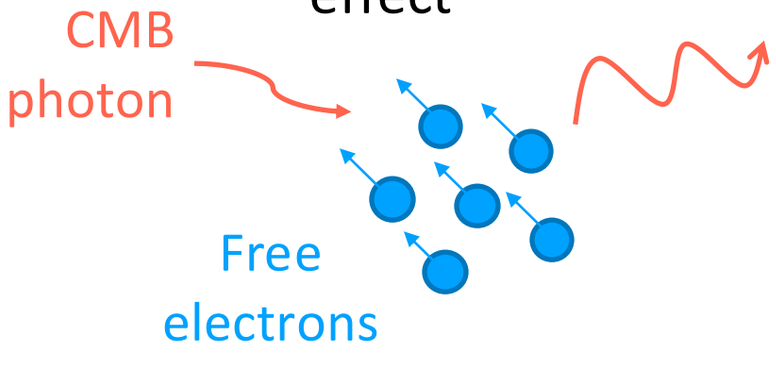


Large scales

Small scales

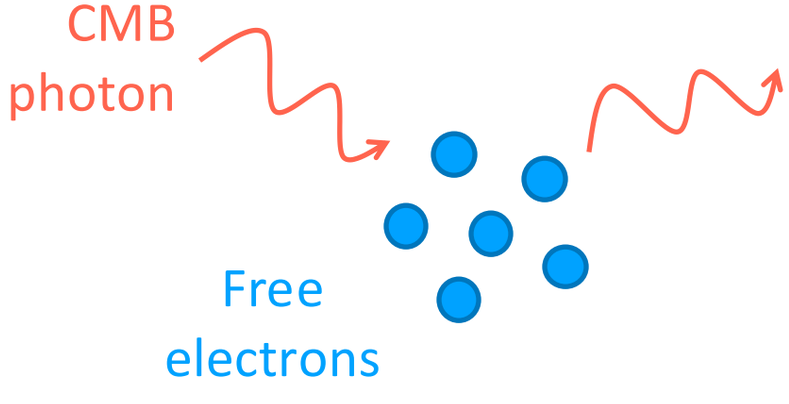
CMB Photons vs. Electrons

Kinetic Sunyaev-Zel'dovich effect



- Doppler shift
  → T anisotropies ↗

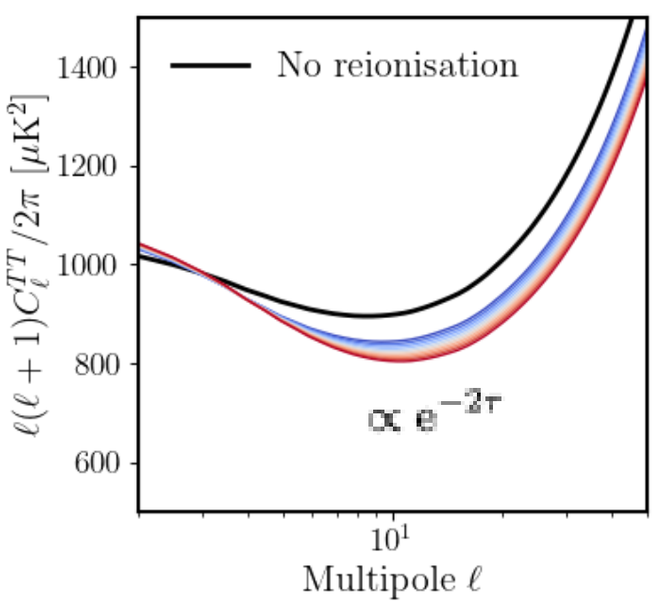
Thomson scattering



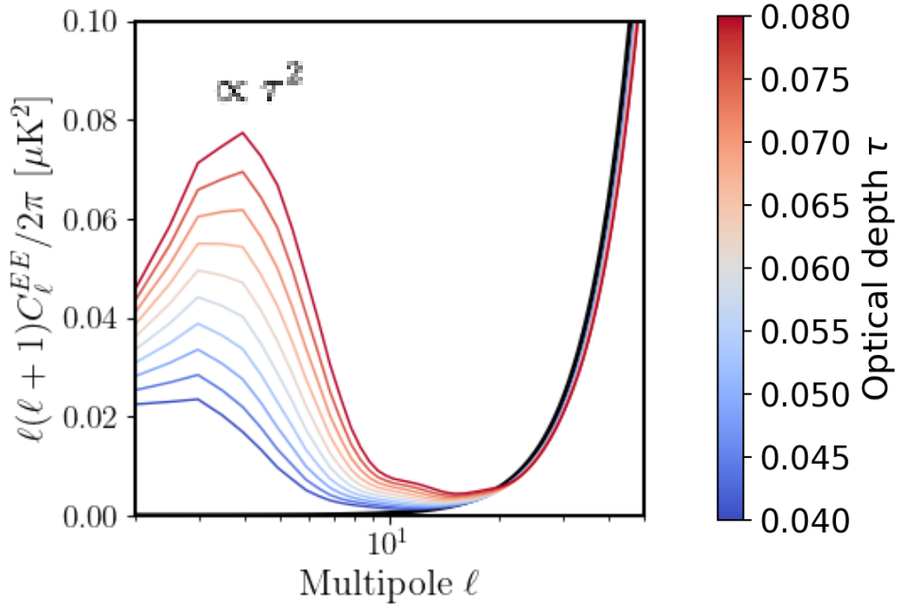
- Photon scattered away from the line of sight
  → T anisotropies ↘
- Scattered light is polarised
  → E, B anistropies ↗

CMB SCATTERING: HOMOGENEOUS REIONISATION

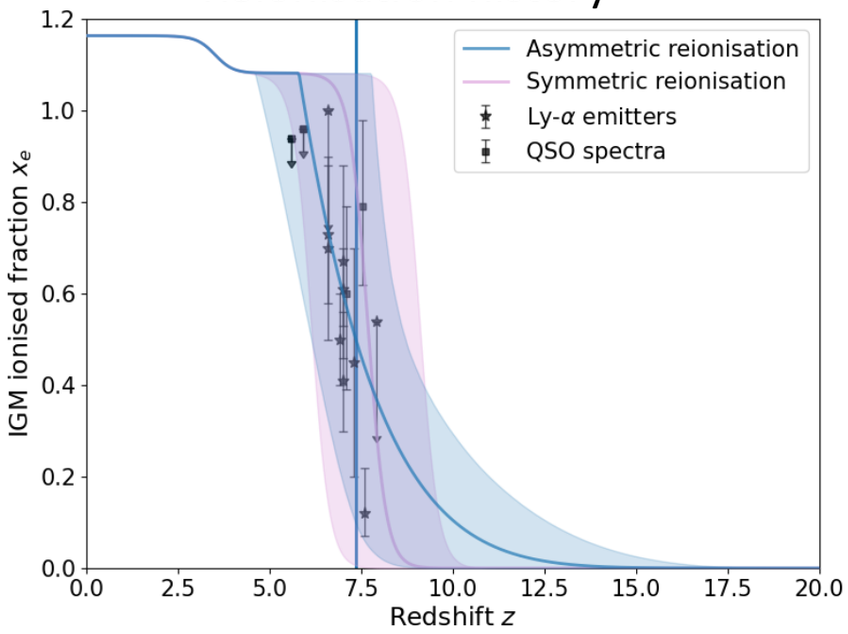
TEMPERATURE



POLARISATION



Reionisation history



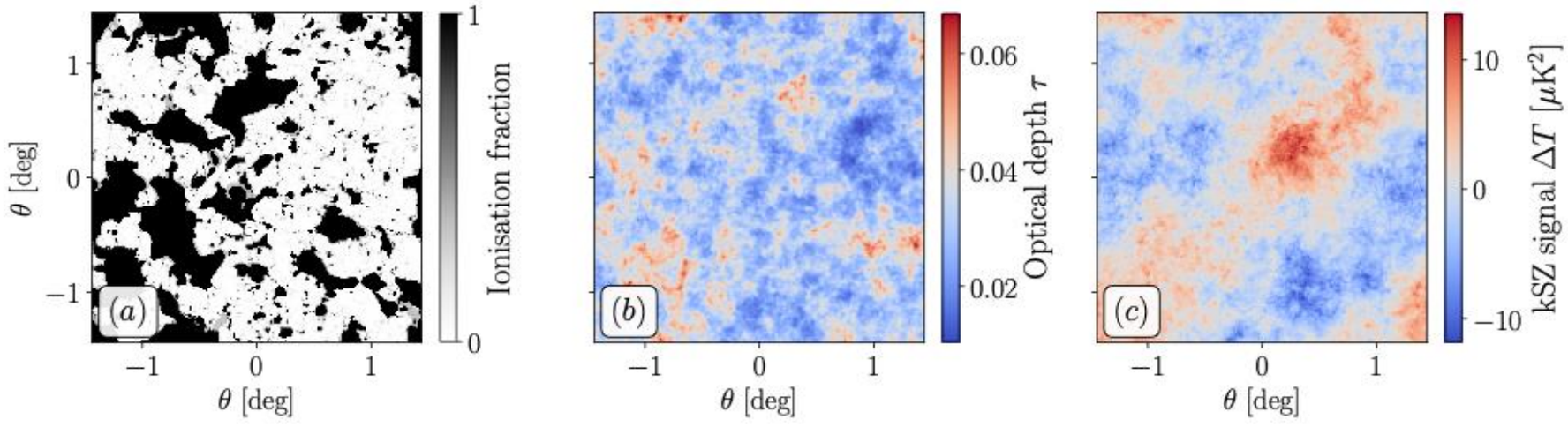
$$\tau(z) = c\,\langle n_{\rm H}\rangle\,\sigma_{\rm T} f_{\rm e} \int_0^z x_e(z')/H(z')\,(1+z')^2\ {\rm d}z'$$

τ = 0.054 ± 0.007
(Planck+2018)

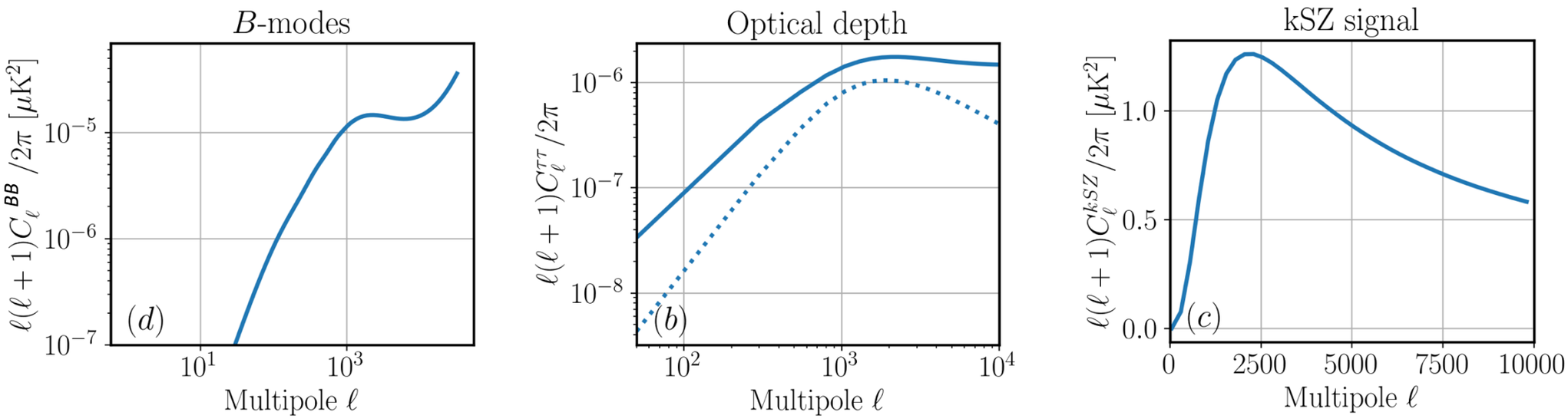
See, e.g., Gorce+2022, Qin+2020, Stéphane's talk

CMB SCATTERING: PATCHY REIONISATION

Reionisation is a *patchy* process which imprints the CMB.



POLARISATION TEMPERATURE

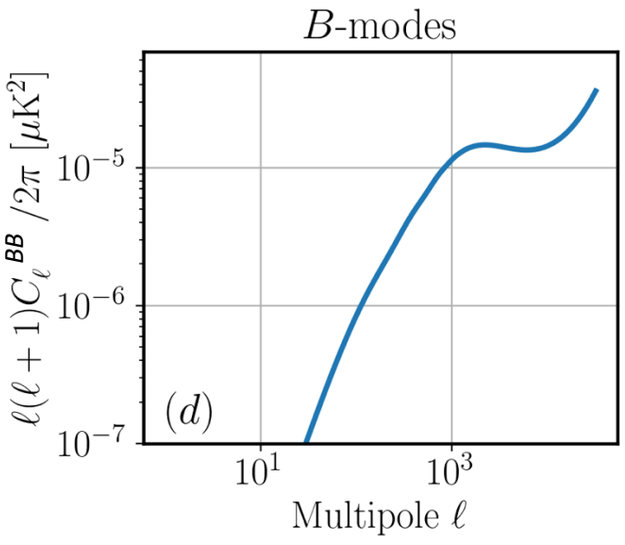


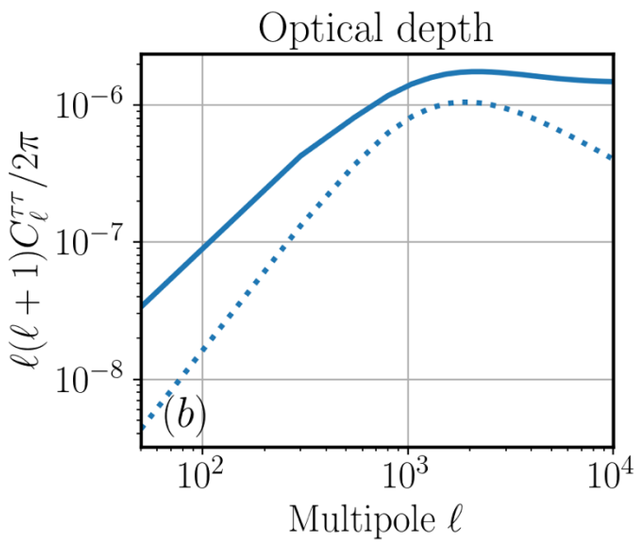
+ y-distortions… (Iliev+2024)

see, e.g., Aghanim+1996, Dvorkin & Smith 2009, Roy+2018, 2020, Gorce+2020

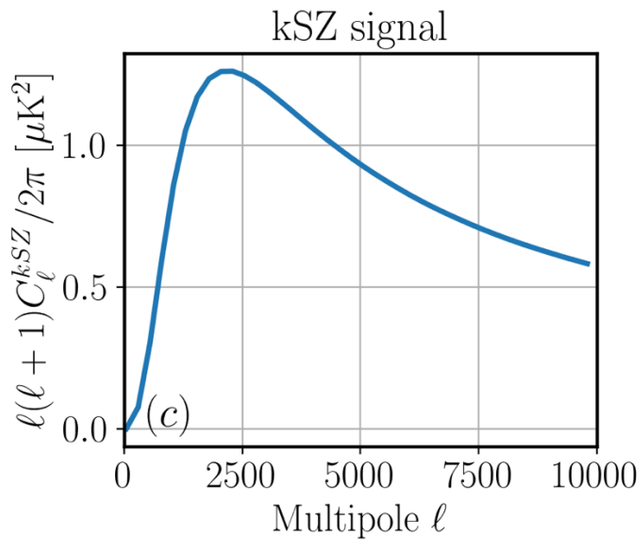
CMB vs. Reionisation: Modelling

Thomson scattering





kSZ effect



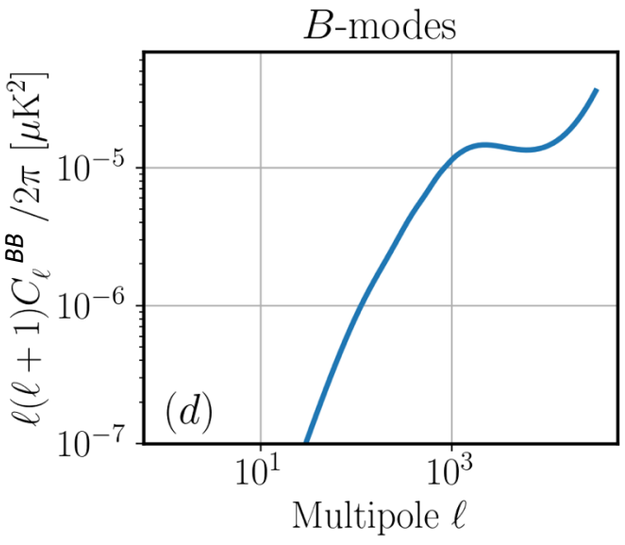
$$\tau(\hat{\mathbf{n}}, z) = \sigma_T \int_0^z \mathrm{d}\eta' \, n_e(\hat{\mathbf{n}}, \eta')$$

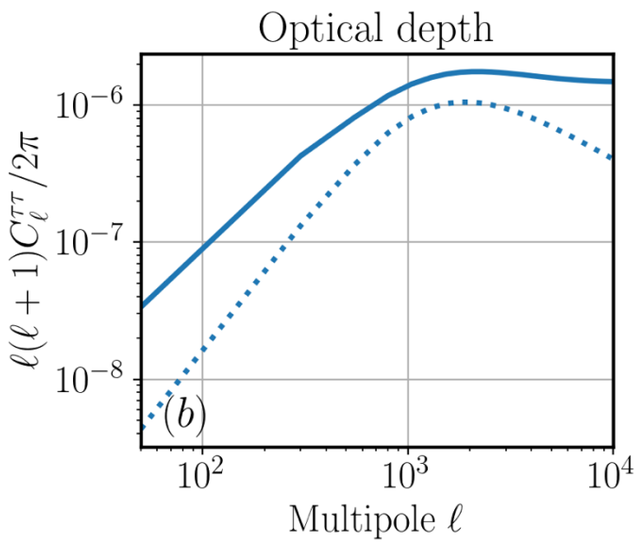
$$\delta T_{\mathrm{kSZ}}(\hat{\mathbf{n}}, z) = \frac{\sigma_T}{c} \int_0^z \mathrm{d}\eta \, \frac{e^{-\tau(\hat{\mathbf{n}}, z)}}{(1+z)} n_e(\hat{\mathbf{n}}, z) \mathbf{v} \cdot \hat{\mathbf{n}}$$

Reionisation

CMB vs. Reionisation: Modelling

Thomson scattering





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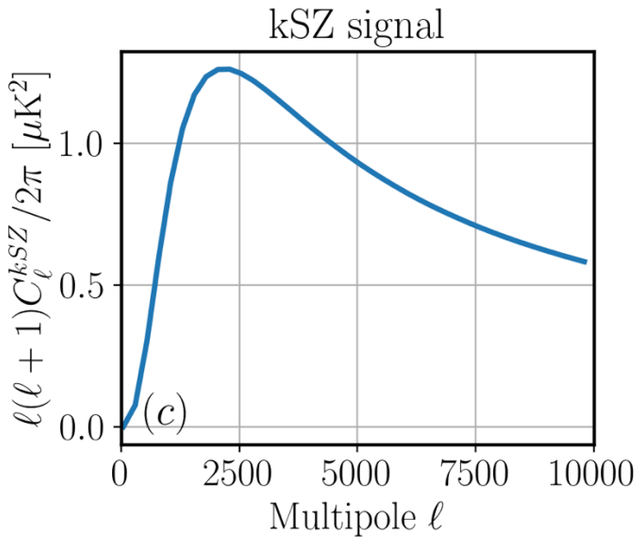


$$\tau(\hat{\mathbf{n}}, z) = \sigma_T \int_0^z \mathrm{d}\eta' \, n_e(\hat{\mathbf{n}}, \eta') \qquad \delta T_{\mathrm{kSZ}}(\hat{\mathbf{n}}, z) = \frac{\sigma_T}{c} \int_0^z \mathrm{d}\eta \, \frac{\mathrm{e}^{-\tau(\hat{\mathbf{n}}, z)}}{(1+z)} n_e(\hat{\mathbf{n}}, z) \boldsymbol{v} \cdot \hat{\mathbf{n}}$$

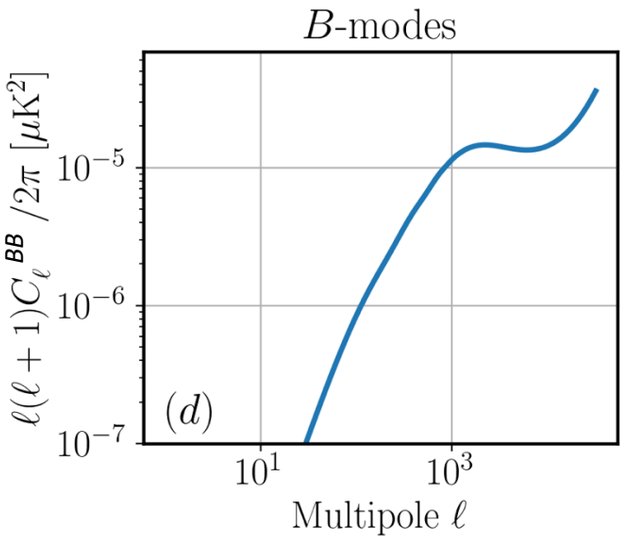
$$C_\ell^{TT} \propto \int \frac{\mathrm{d}\eta'}{\eta'^2} P_{ee}(k = \ell/\eta', z') (1+z')^2 \bar{x}_e(z')^2$$

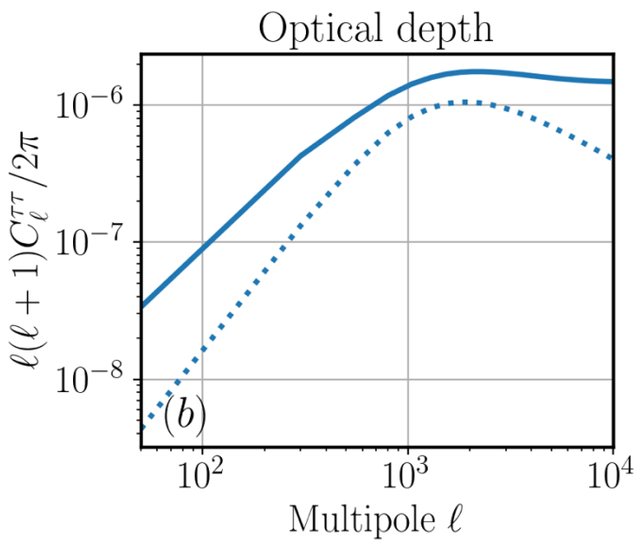
$$C_\ell^{BB(\mathrm{scal})} \propto \int \frac{\mathrm{d}\eta'}{\eta'^2} P_{ee}(k = \ell/\eta', z') \bar{x}_e(z')^2 (1+z')^2$$

$$C_\ell^{\mathrm{kSZ}} \propto \int \frac{\bar{n}_e(z)^2}{(1+z)^2} \Delta_{B,\ell}^2(\ell/\eta, z) \, \mathrm{e}^{-2\tau(z)} \, \eta(z) \, \frac{\mathrm{d}\eta}{\mathrm{d}z} \, \mathrm{d}z$$

CMB vs. Reionisation: Modelling

Thomson scattering





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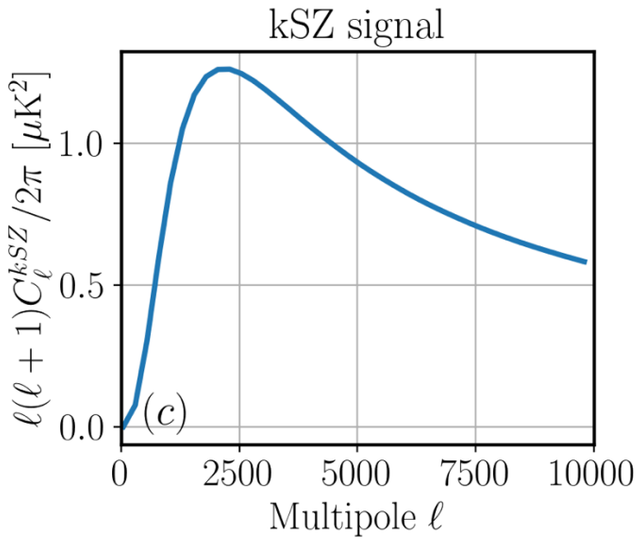

$$\tau(\hat{\mathbf{n}}, z) = \sigma_T \int_0^z \mathrm{d}\eta' \, n_e(\hat{\mathbf{n}}, \eta')$$

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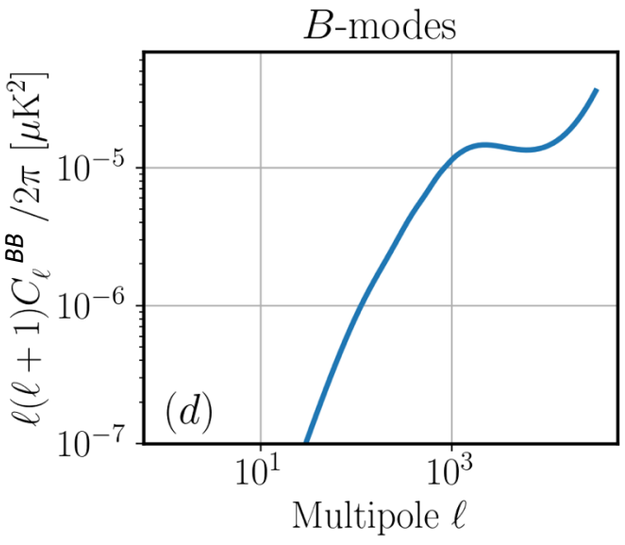
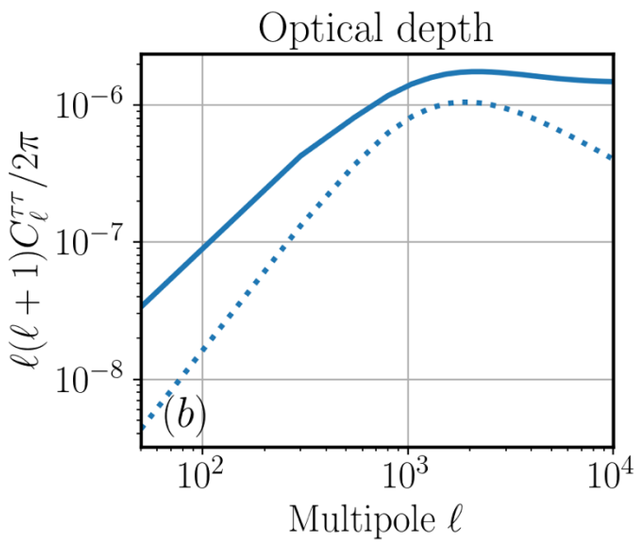
$$C_\ell^{\mathrm{kSZ}} \propto \int \frac{\bar{n}_e(z)^2}{(1+z)^2} \Delta^2_{B,\ell}(\ell/\eta, z) \, \mathrm{e}^{-2\tau(z)} \, \eta(z) \, \frac{\mathrm{d}\eta}{\mathrm{d}z} \, \mathrm{d}z$$

Global reionisation history

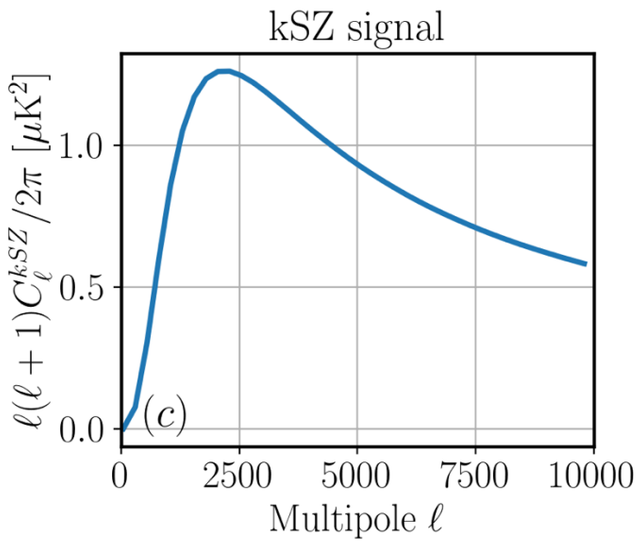
CMB vs. Reionisation: Modelling

Thomson scattering





kSZ effect



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Distribution of electrons: (patchy) reionisation

Global reionisation history

$$C_\ell^{TT} \propto \int \frac{\mathrm{d}\eta'}{\eta'^2} P_{ee}(k = \ell/\eta', z') (1+z')^2 \bar{x}_e(z')^2$$

$$C_\ell^{BB(\mathrm{scal})} \propto \int \frac{\mathrm{d}\eta'}{\eta'^2} P_{ee}(k = \ell/\eta', z') \bar{x}_e(z')^2 (1+z')^2$$

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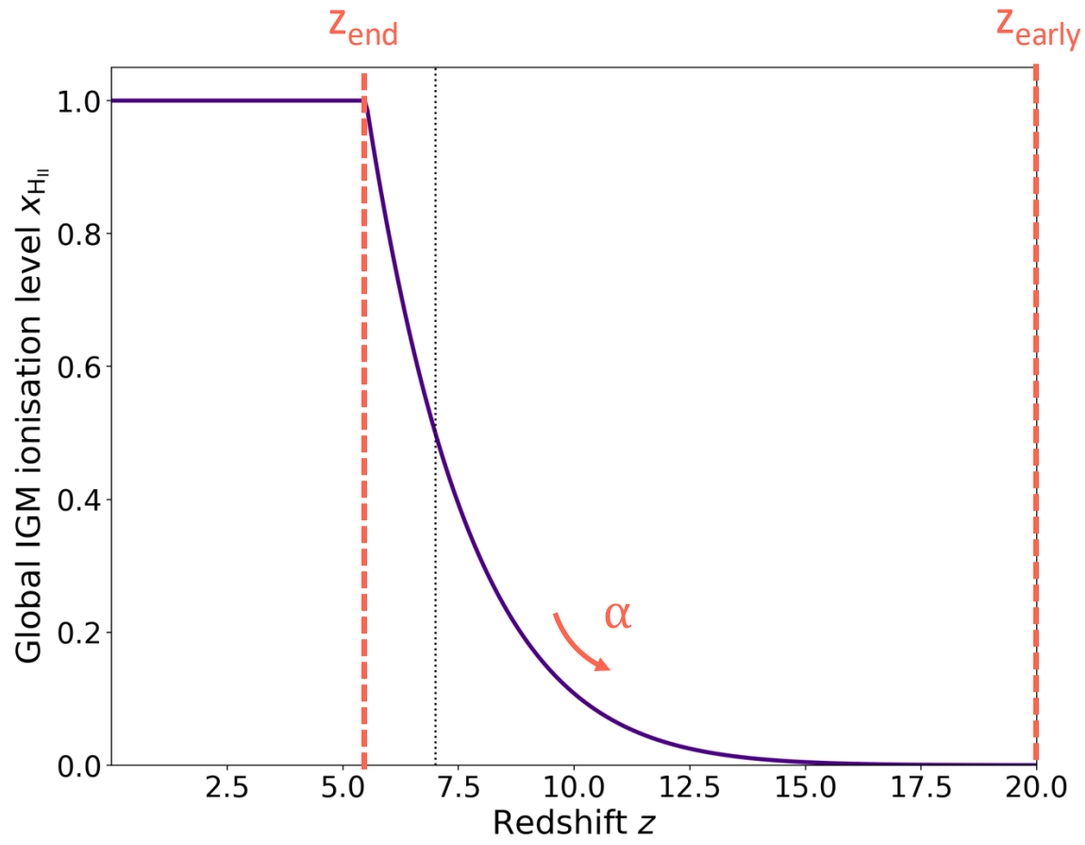
$$\Delta^2_{B,e}(k, z) = \frac{1}{3} \frac{k^3}{2\pi^2} v^2_{\mathrm{rms}}(z) P_{ee}(k, z)$$

Modelling reionisation history

Need a model to describe the cosmological time-evolution of sky-averaged ionised fraction

$$x_e(z) = \begin{cases} f_e & \text{for } z < z_{end} \\ f_e \left(\frac{z_{early} - z}{z_{early} - z_{end}} \right)^{\alpha} & \text{for } z > z_{end} \end{cases}$$

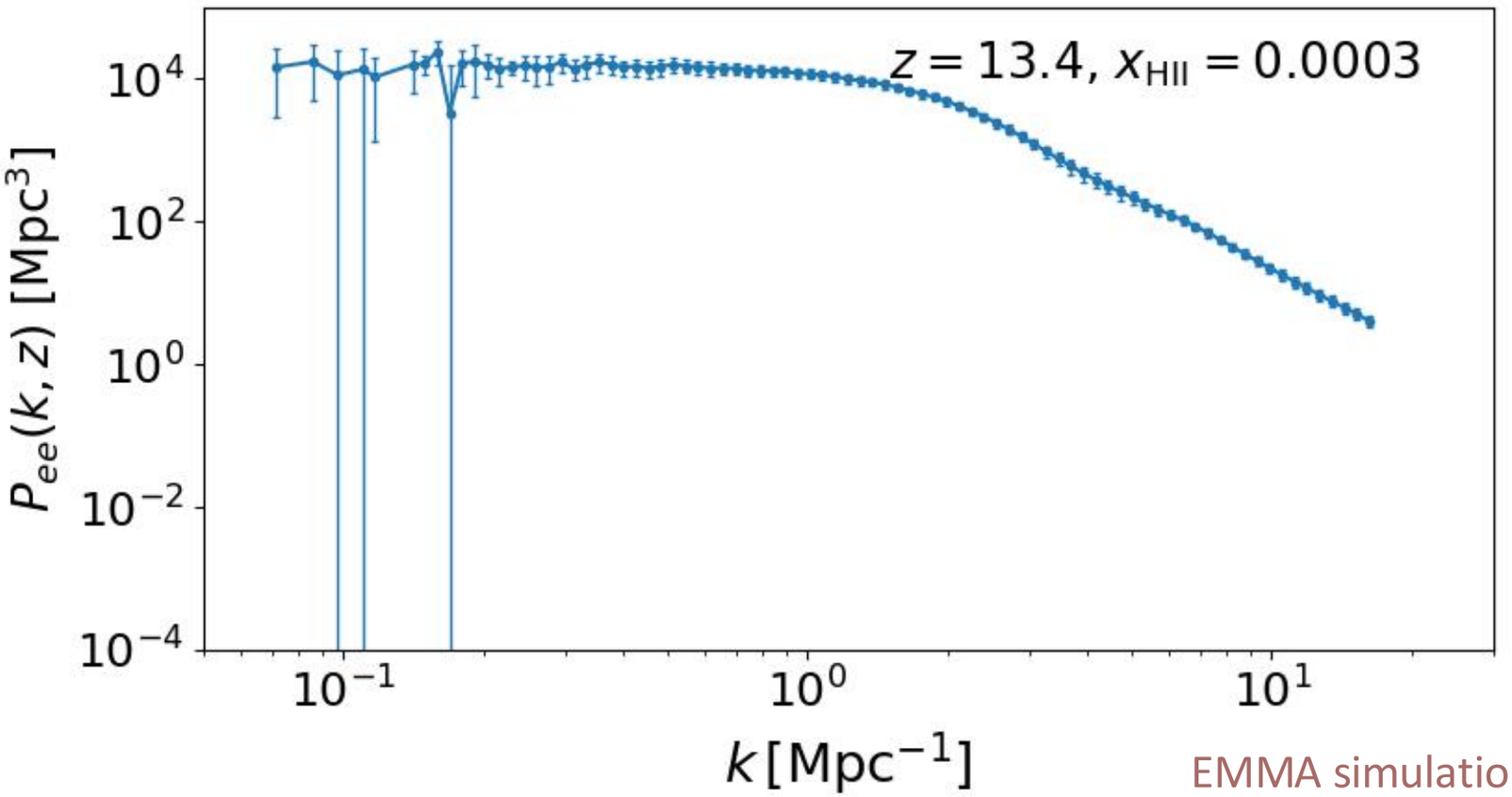


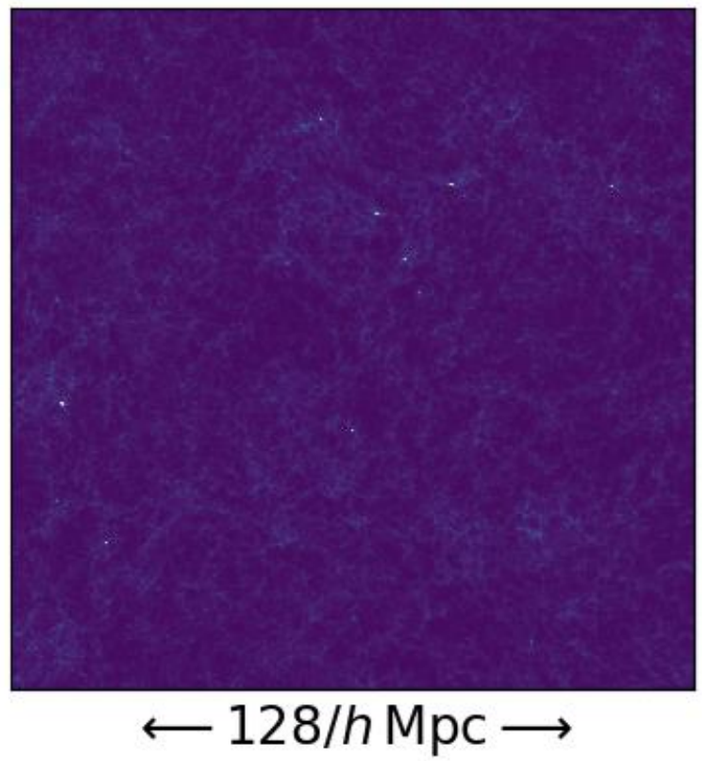
see, e.g., Douspis+2015, Planck XLVII 2016

Modelling cosmic electron density

Need a model to describe the cosmological time- and scale-evolution of electron density

Power spectrum of electron density fluctuations throughout EoR





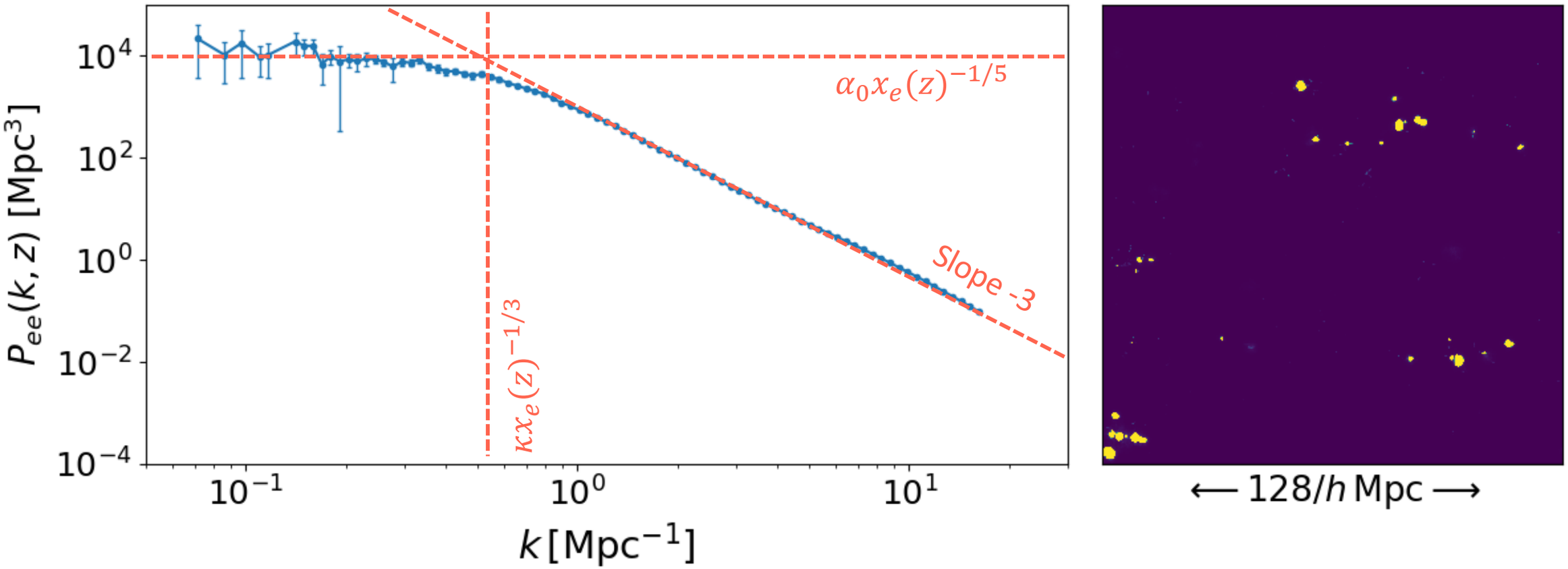
EMMA simulation (see Aubert+2015, Chardin+2019)

MODELLING COSMIC ELECTRON DENSITY

Need a model to describe the cosmological time- and scale-evolution of electron density

Early times: power-law $P_{ee}(k,z) = \frac{\alpha_0\, x_e(z)^{-1/5}}{1 + [k/\kappa]^3 x_e(z)}$

$z = 10.1,\ x_{\rm HII} = 0.0117$



- α_0 : constant amplitude on large scales ⟷ variance of the field
- κ: drop-off frequency ⟷ minimal size of ionised regions

Gorce+2020

MODELLING COSMIC ELECTRON DENSITY

Need a model to describe the cosmological time- and scale-evolution of electron density

Depends on cosmology and four reionisation parameters (z_{re}, $z_{end,}$, α_0, κ)

$$P_{ee}(k,z) = \underbrace{\left[f_H - x_e(z)\right]\frac{\left(1+z_0\right)^{-1/5}}{1+[k/\kappa]^3 x_e(z)}}_{\text{High-redshift (power-law) Gorce+2020}} + \underbrace{x_e(z)\, b_{\delta e}(k,z)^2 P_{\delta\delta}(k,z)}_{\text{Low-redshift (biased matter PS) Shaw+2012}}$$

ONGOING

But… model parameters have no clear link with astrophysics

- Recalibrate parameterisation on LoReLi simulations: 10 000 simulations of reionisation varying astrophysics, e.g., minimum halo mass to form stars, X-ray luminosity, ionising escape fraction… (Meriot+2023, 2024)
- Include a dependence on source properties

See next talk

Modelling cosmic electron density

The power spectrum of free electrons can be used to derive the reionisation observables

Depends on cosmology and four reionisation parameters (z_{re}, $z_{end,}$, α_0, κ)

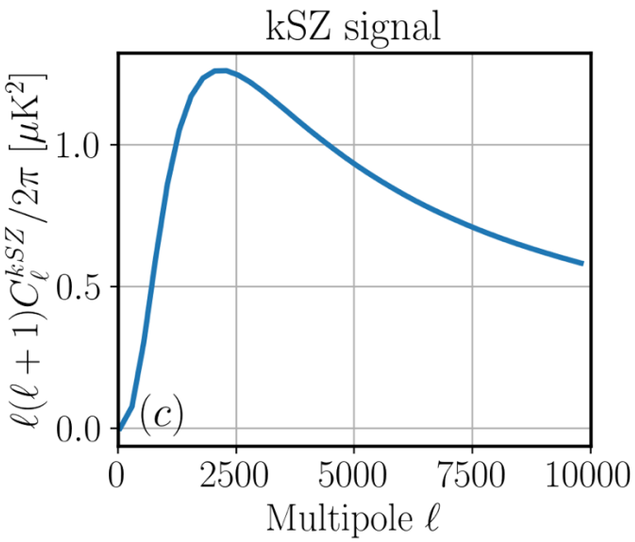
$$P_{ee}(k,z) = \left[\bar{f}_H - x_e(z)\right]\left[\frac{\xi_0\, x_e(z)^{-1/5}}{1+[k/\kappa]^3 x_e(z)} + x_e(z)\right] b_{\delta e}(k,z)^2 P_{\delta\delta}(k,z)$$

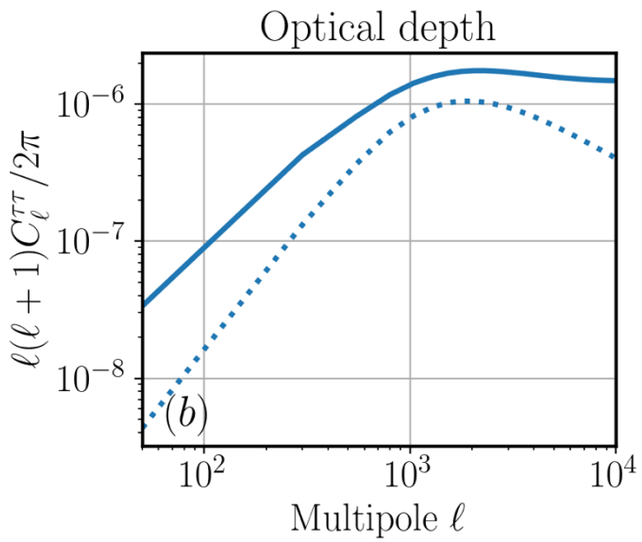
Patchy kSZ spectrum

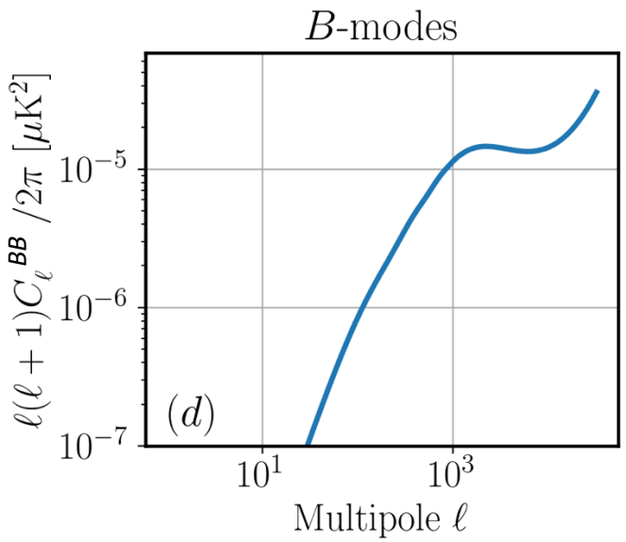
τ spectrum

EoR-induced BB

Gorce+2022





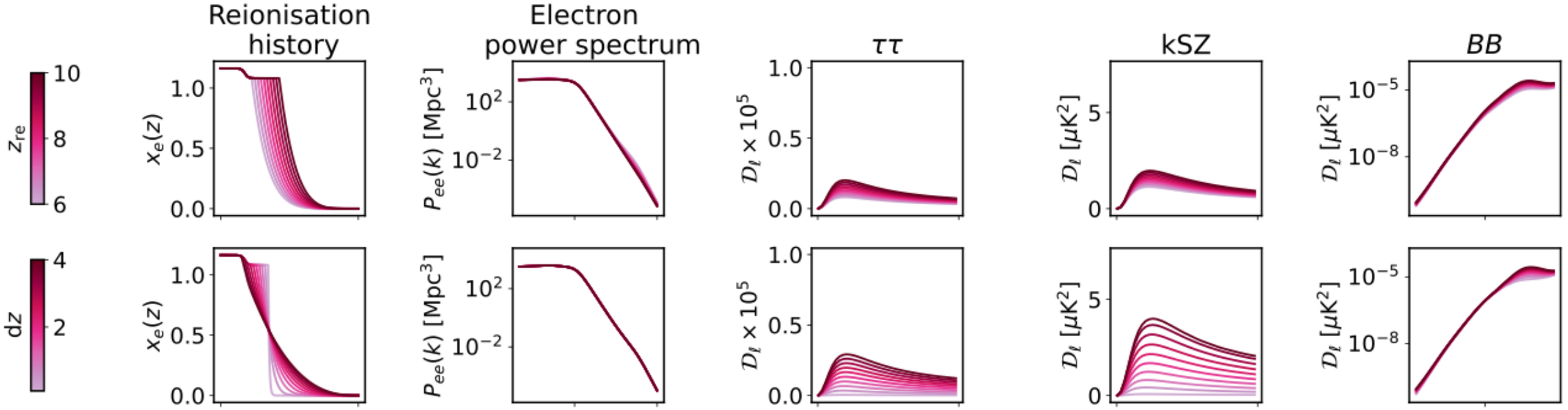


- Can also be used to derive the 21cm power spectrum (Georgiev, Gorce, & Mellema 2024)
  - Allows joint and cross-analyses between datasets… (Béguin, Liu, & Gorce 2022)

Reionisation information

There is information about reionisation in these imprints…

1. About global reionisation history

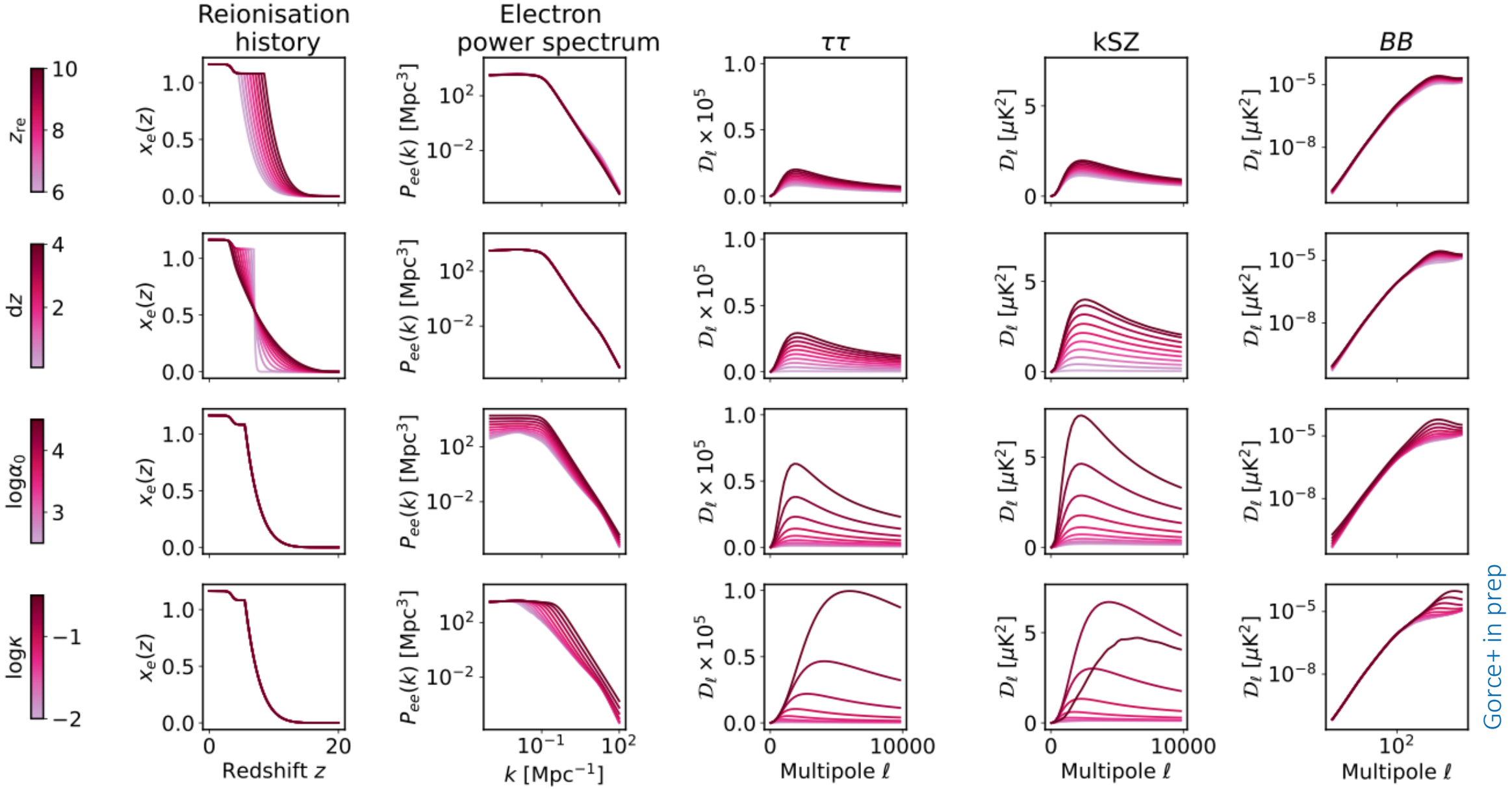


Gorce+2020, see, e.g., McQuinn+2005; Iliev+2007; Battaglia+2013; Park+2013…

Reionisation information

There is information about reionisation in these imprints…

1. About global reionisation history
2. About reionisation morphology (and effectively galaxy properties)



Gorce+ in prep

Reionisation information

There is information about reionisation in these imprints…

1. About global reionisation history
2. About reionisation morphology (and effectively galaxy properties)

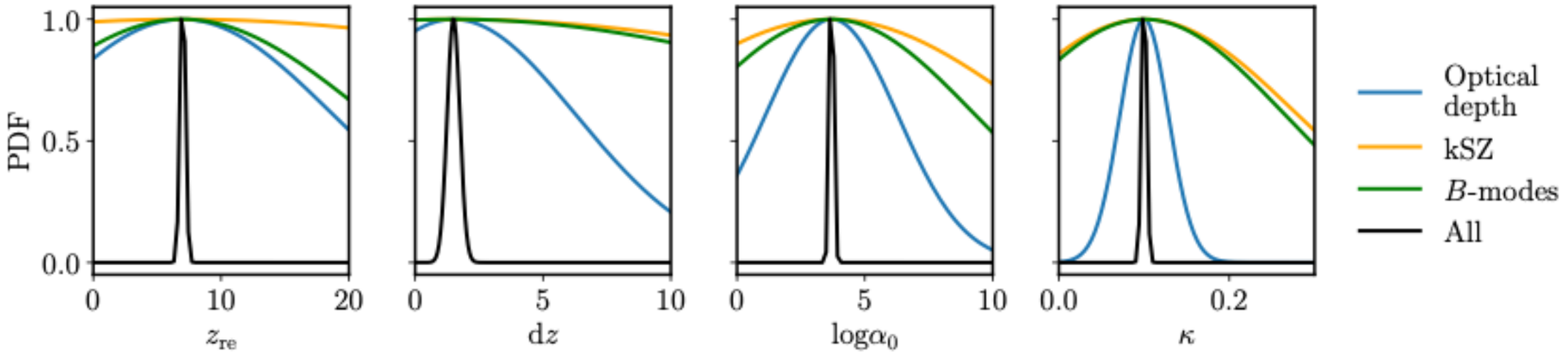
What is the constraining power of each observable?

Assume 10% errors on each observable and compute Cramer-Rao errors…

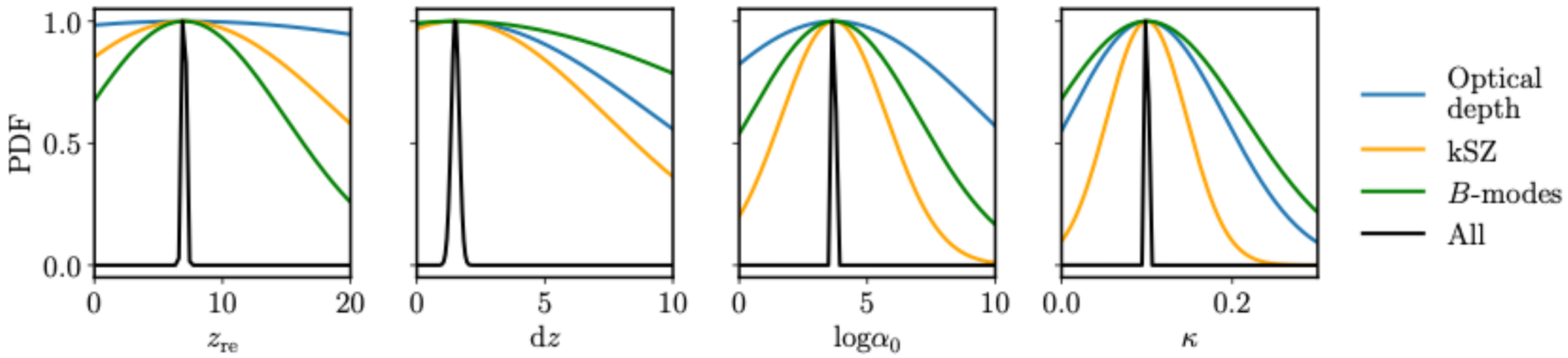
Reionisation information: Forecast

There is information about reionisation in these imprints…

Assume SNR=10 for each observable and compute minimal errors…



Assume cosmic variance limited and 1’ resolution telescope and compute minimal errors…

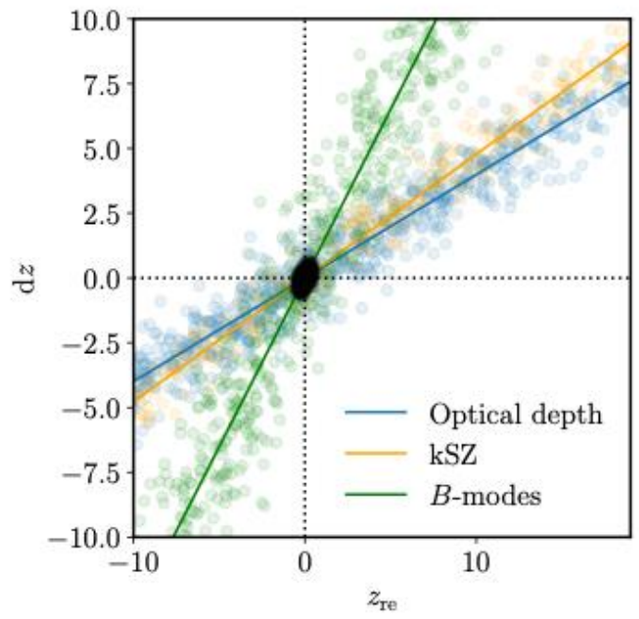


Gorce+ in prep

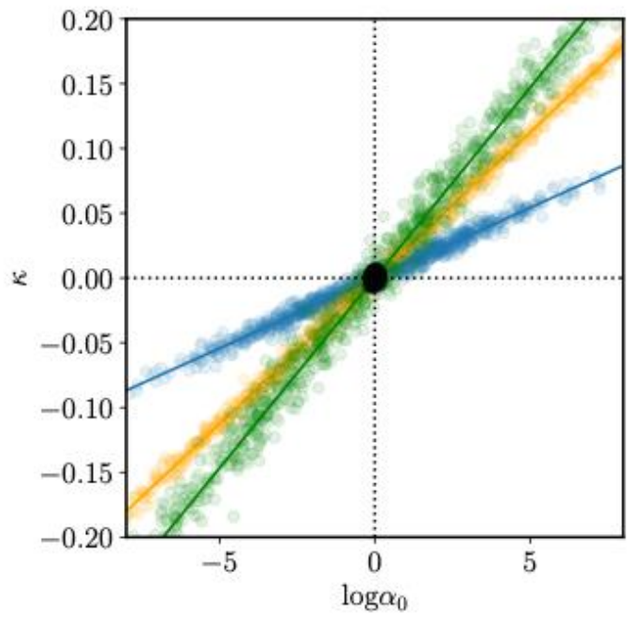
Reionisation information: Forecast

There is information about reionisation in these imprints…

Global history



Morphology

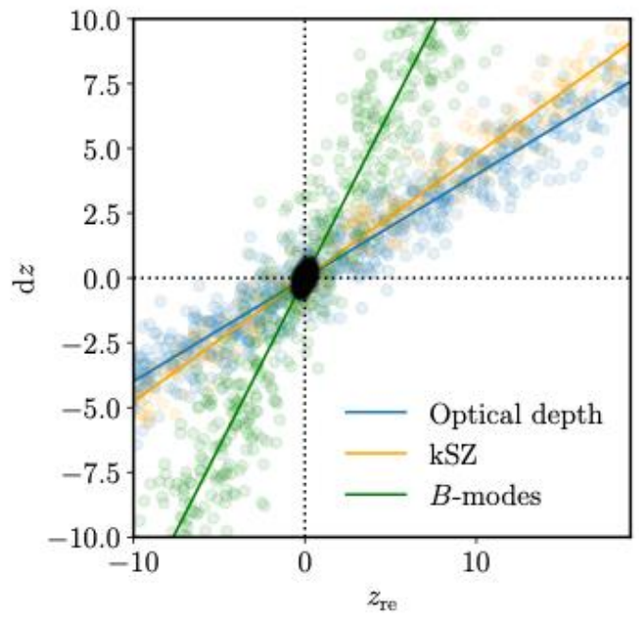


Combining observables breaks degeneracies and gives tighter constraints

Reionisation information: Forecast

There is information about reionisation in these imprints…

Global history



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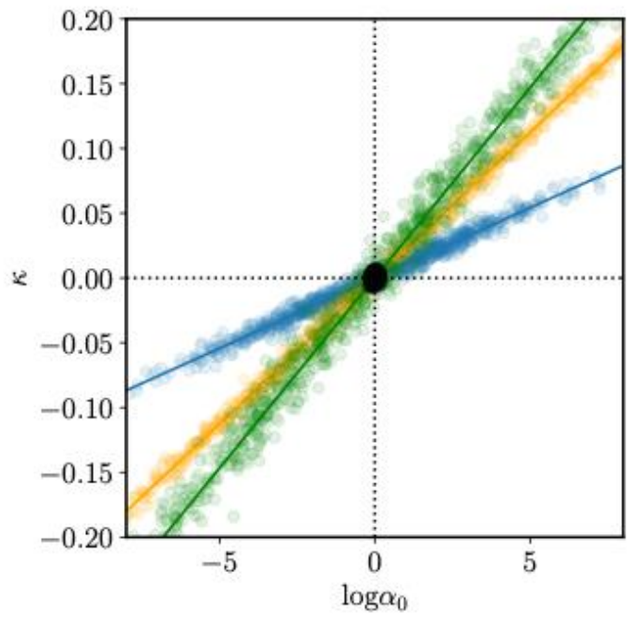
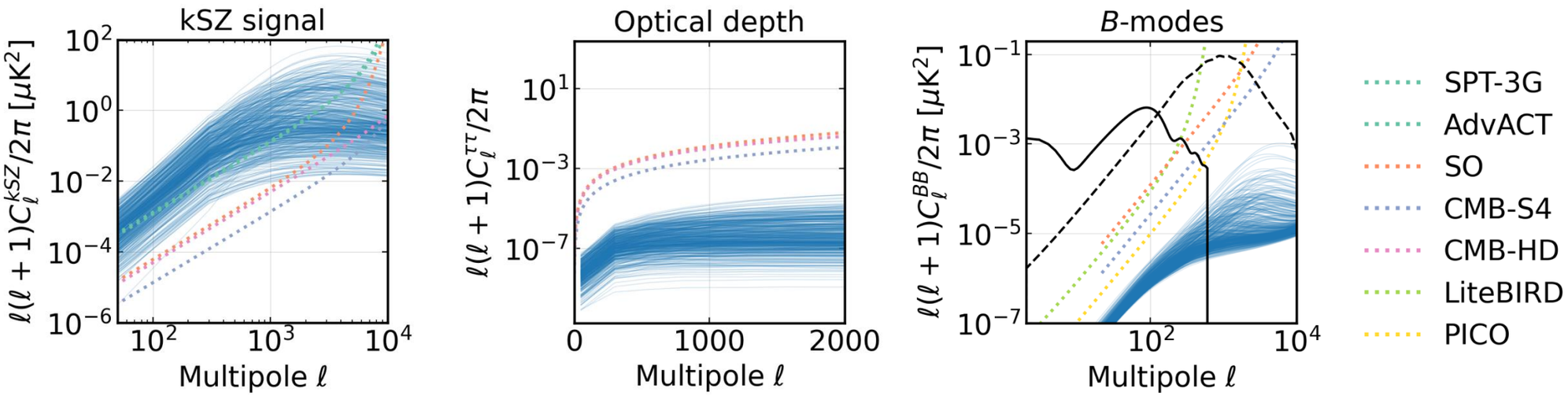


Combining observables breaks degeneracies and gives tighter constraints



For these models, kSZ only detectable observable in the near future….

Gorce+ in prep

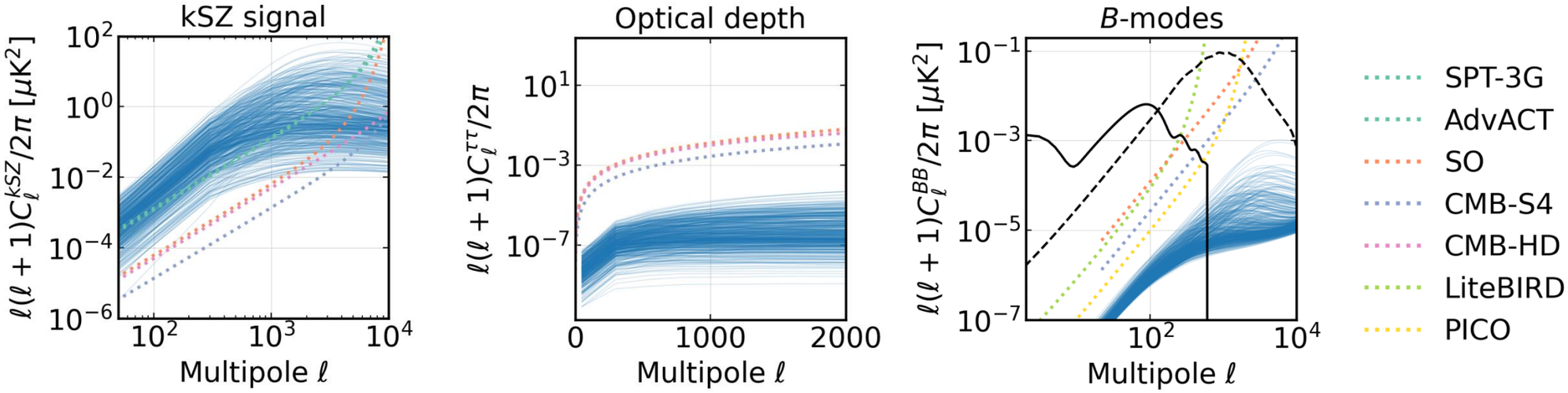
CONCLUSIONS

- Simple, physically-motivated analytical model to derive EoR observables in CMB data

  → Code will be made publicly available

- Illustrates the potential of CMB to constrain history and morphology of reionisation.
- Signal might be too weak

  → Can also derive the 21cm x CMB spectra from the model! *(ongoing…)*



Thank you!

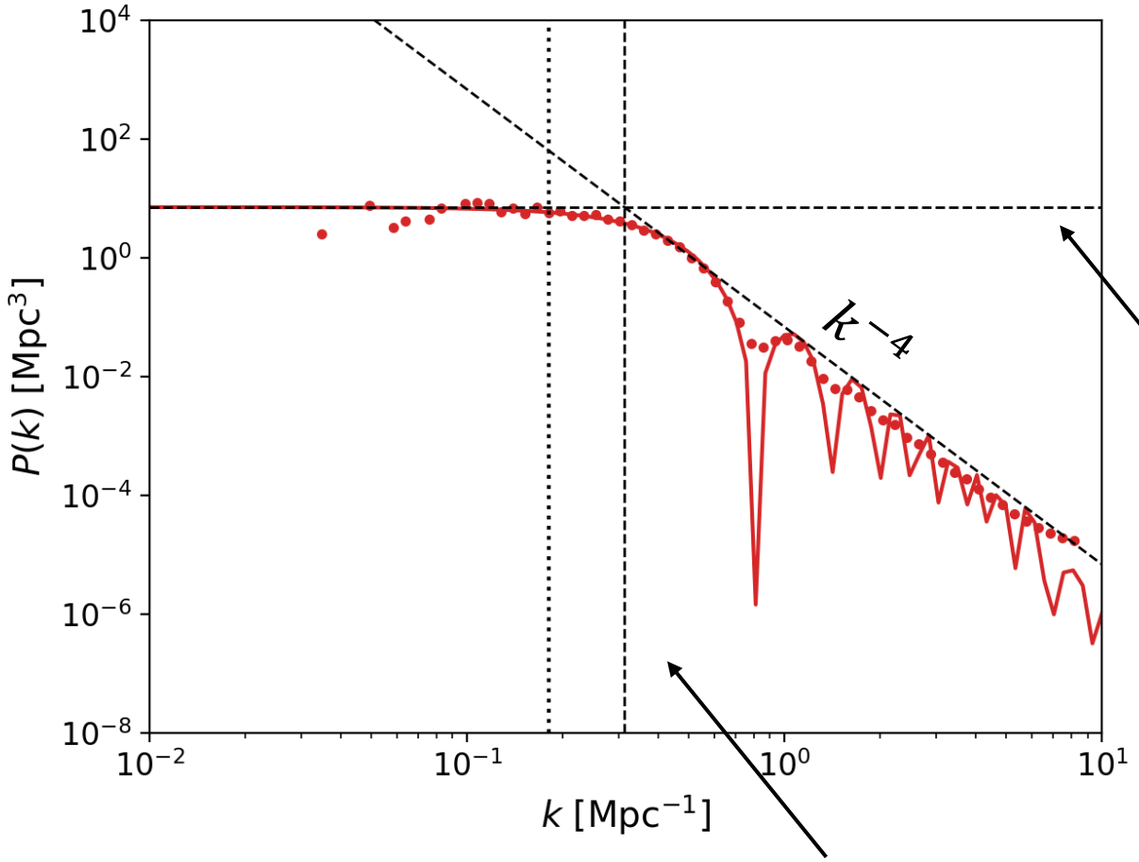
Gorce+ in prep

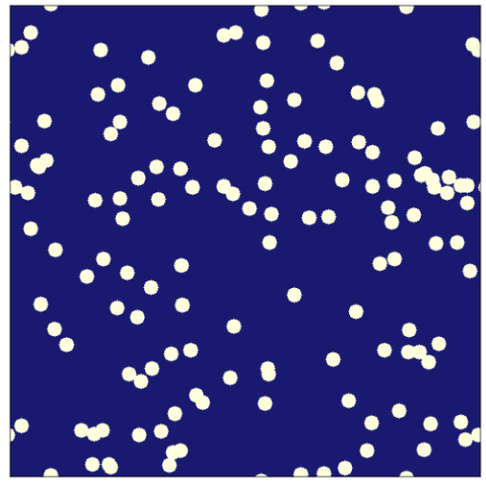
BACKUP SLIDES

The power spectrum of free electrons P_{ee}

Toy model: n ionised bubbles of radius R filling f % of a box

$$P_{ee}(\boldsymbol{k}) = \frac{4}{3}\pi R^3 \, \frac{1}{f} W^2(kR)$$





$$\frac{4\pi R^3}{3f} \leftrightarrow \alpha_0 x_e(z)^{-1/5}$$

$$\frac{1}{R} \leftrightarrow \kappa x_e(z)^{-1/3}$$

(Bharadwaj & Pandey 2005)

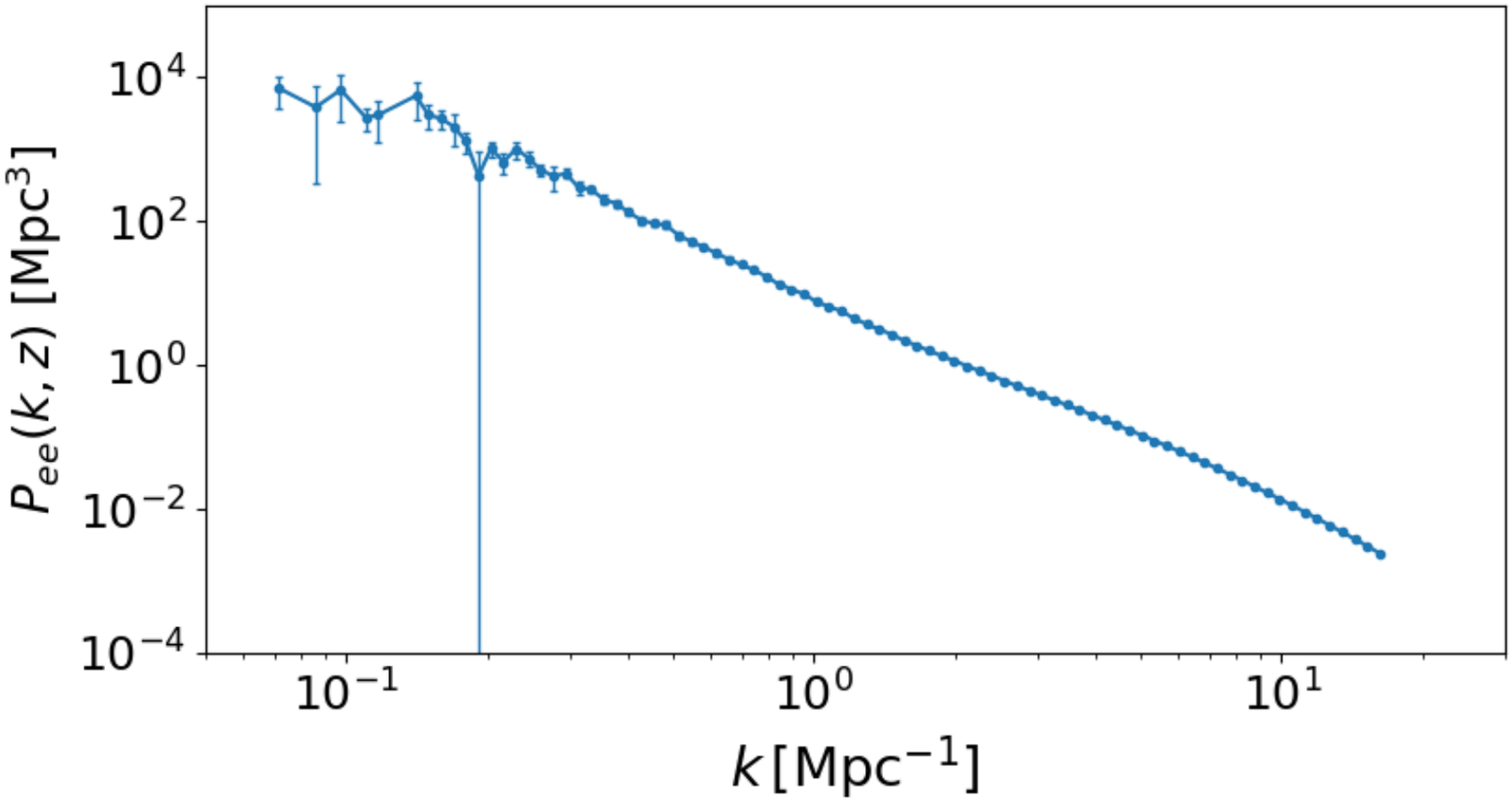
The power spectrum of free electrons P_{ee}

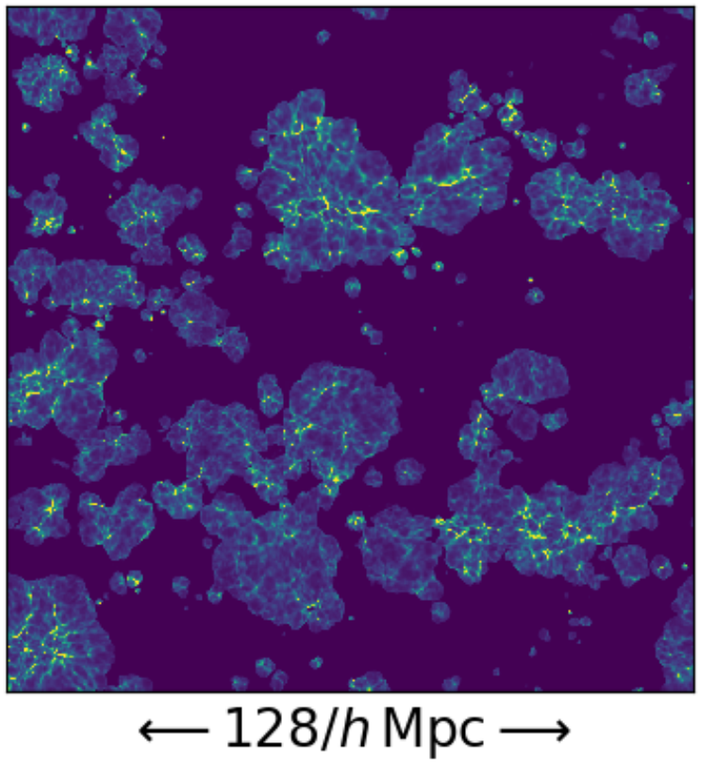
Late times: biased matter power spectrum

$$P_{ee}(k,z) = b_{\delta e}(k,z)^2 P_{\delta\delta}(k,z) \quad \text{for} \quad b_{\delta e}(k,z)^2 = \frac{1}{2}\, e^{-k/k_f} + \frac{1}{1+(gk/k_f)^{7/2}}$$

(Shaw+2012)

$$z = 7.2,\ x_{\rm HII} = 0.4707$$





$$\mathcal{F}_{ij} = \frac{\partial \mathbf{o}^T}{\partial \theta_i} \mathbf{\Pi}^{-1} \frac{\partial \mathbf{o}}{\partial \theta_j}$$

Normalised derivatives: