Retrieving EoR constraints from small-scale CMB data with an improved kSZ model

Marian Douspis

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"Improved constraints on reionisation from CMB observations: A parameterisation of the kSZ effect", *Gorce, Ilic, Douspis, Aubert, Langer, A&A 2020, arXiv:2004.06616*

"Retrieving cosmological information from small-scale CMB foregrounds I. The thermal Sunyaev Zel'dovich effect", *Douspis, Salvati, Gorce, Aghanim, A&A 2022, arXiv:2109.03272*

"Retrieving cosmological information from small-scale CMB foregrounds II. The kinetic Sunyaev Zel'dovich effect", *Gorce, Douspis, Salvati, A&A 2022, arXiv:2202.08698*

*: lot of inputs from

IAS Institut d'Astrophysique Spatiale Orsay

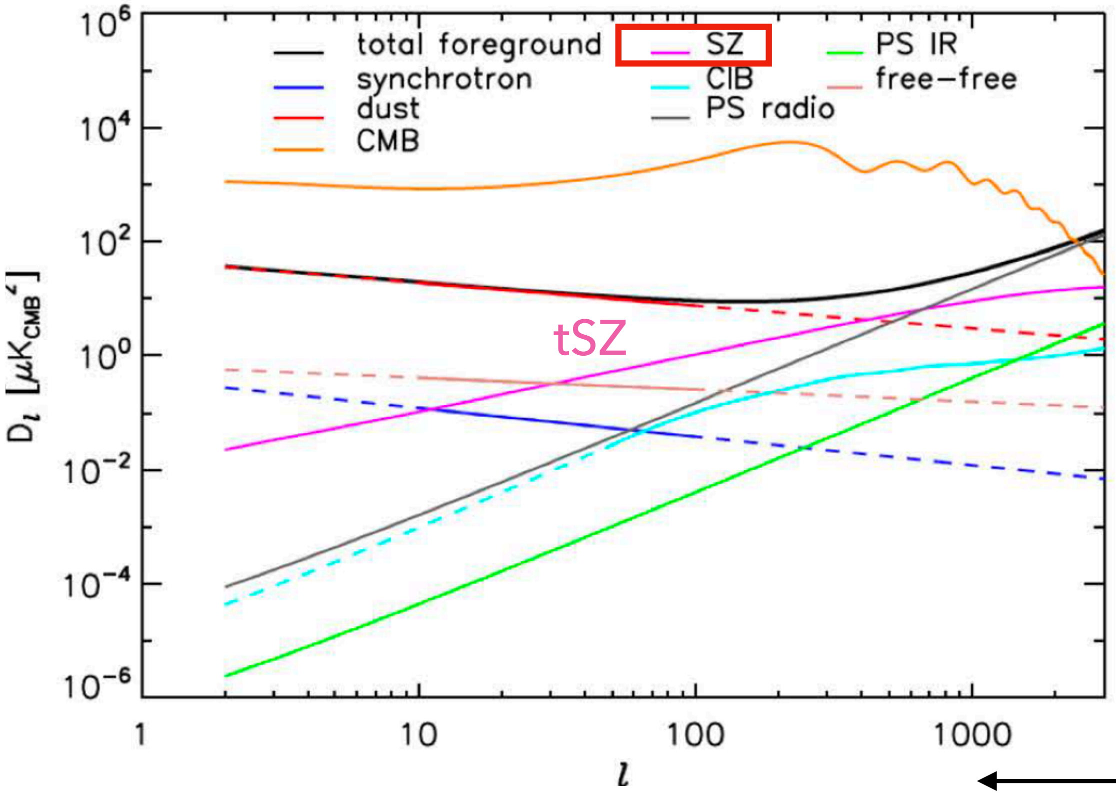
Better Accuracy and robusTness for Mass Assessment of Neutrinos

anr agence nationale de la recherche

SECONDARIES IN FREQUENCY MAPS

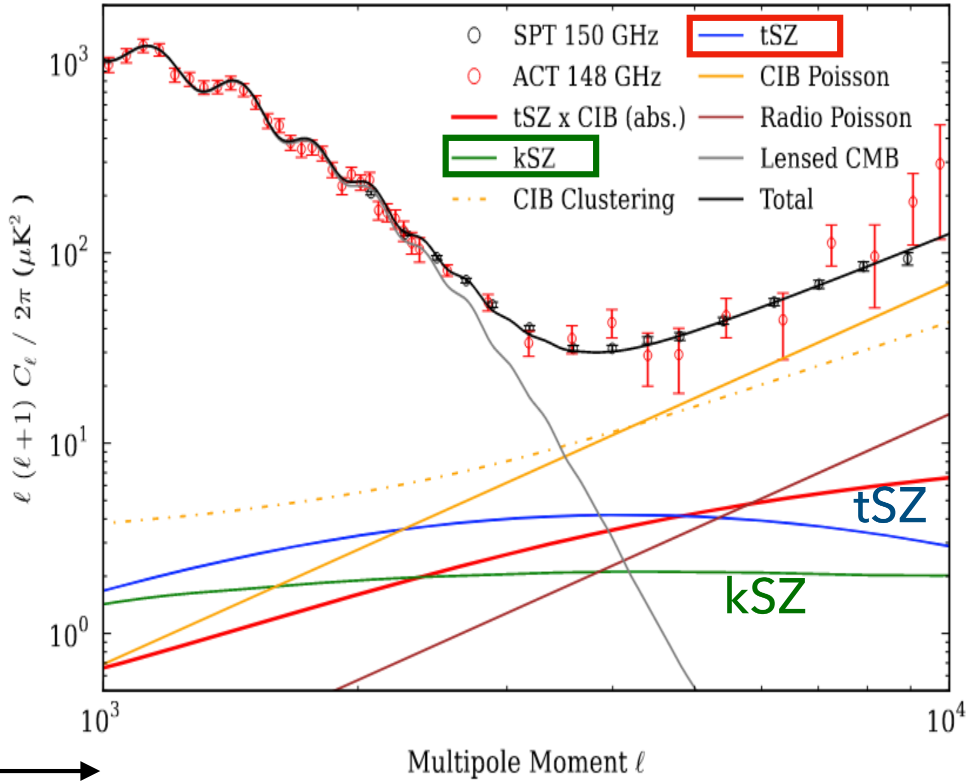
- tSZ/kSZ is hidden among many other signals
- tSZ/kSZ not negligible at small scales as Primordial CMB damped

Planck/Large scales



Planck coll. 2013

SPT/small scales



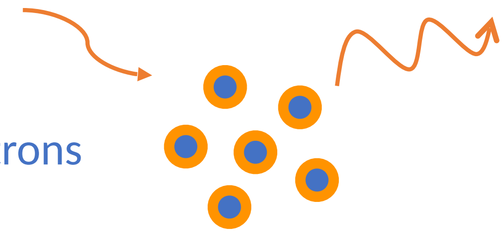
Addison et al. 2012

The Sunyaev Zel'dovich effects

Thermal SZ

CMB photon

Free electrons

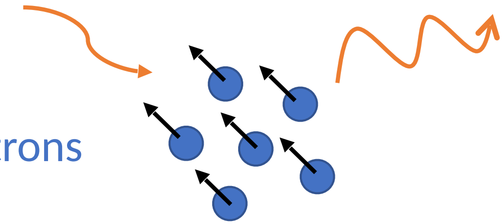


$$y = \int \frac{k_B \boldsymbol{T_e}}{m_e c^2} \boldsymbol{n_e} \sigma_T dl$$

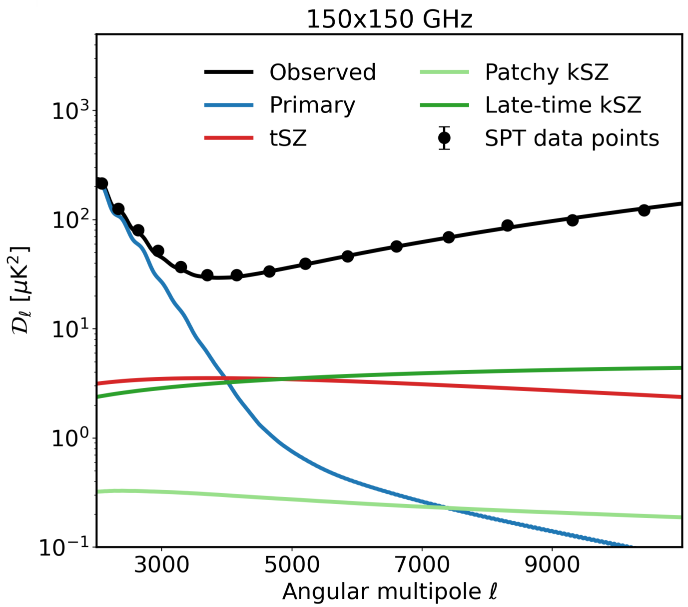
Kinetic SZ

CMB photon

Free electrons

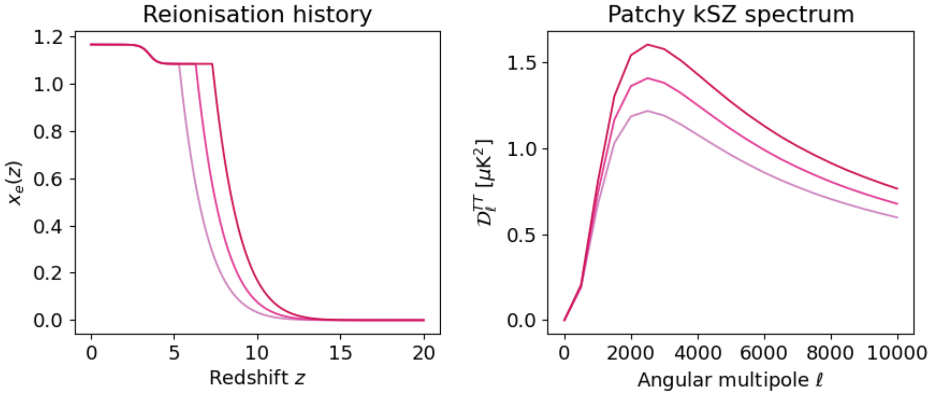


$$\hat{\boldsymbol{n}} \cdot \boldsymbol{v}(\eta, \hat{\boldsymbol{n}}) \; (1 + \delta(\eta, \hat{\boldsymbol{n}}) + \delta_x(\eta, \hat{\boldsymbol{n}}) + \delta(\eta, \hat{\boldsymbol{n}})\delta_x(\eta, \hat{\boldsymbol{n}}))$$



The kinetic Sunyaev Zel'dovich effect

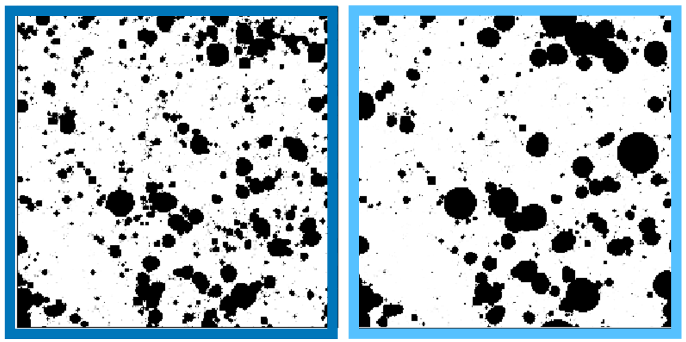
- Information on reionisation history



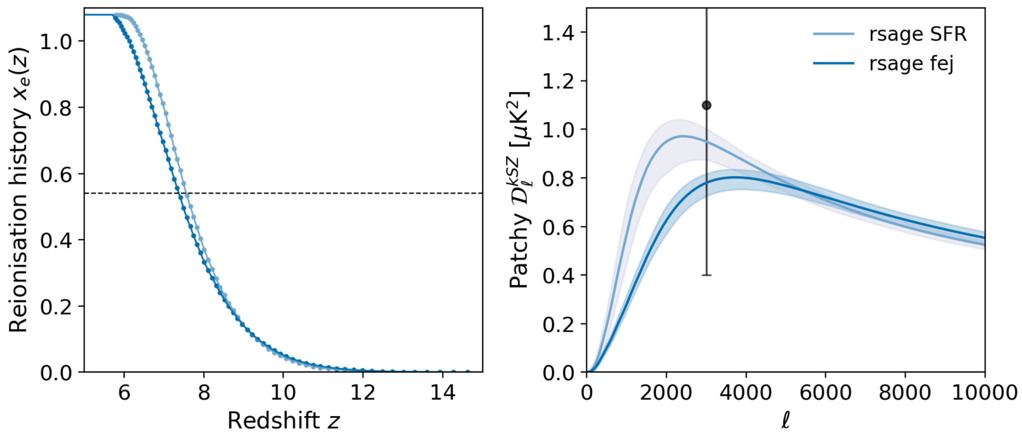
- Information on reionisation morphology

rsage simulations at x_{HII} = 0.30

Seiler+2019



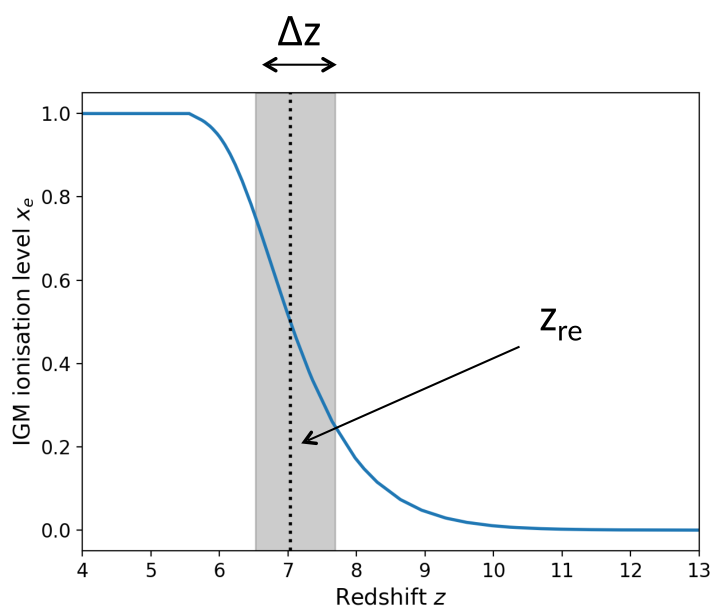
fej SFR



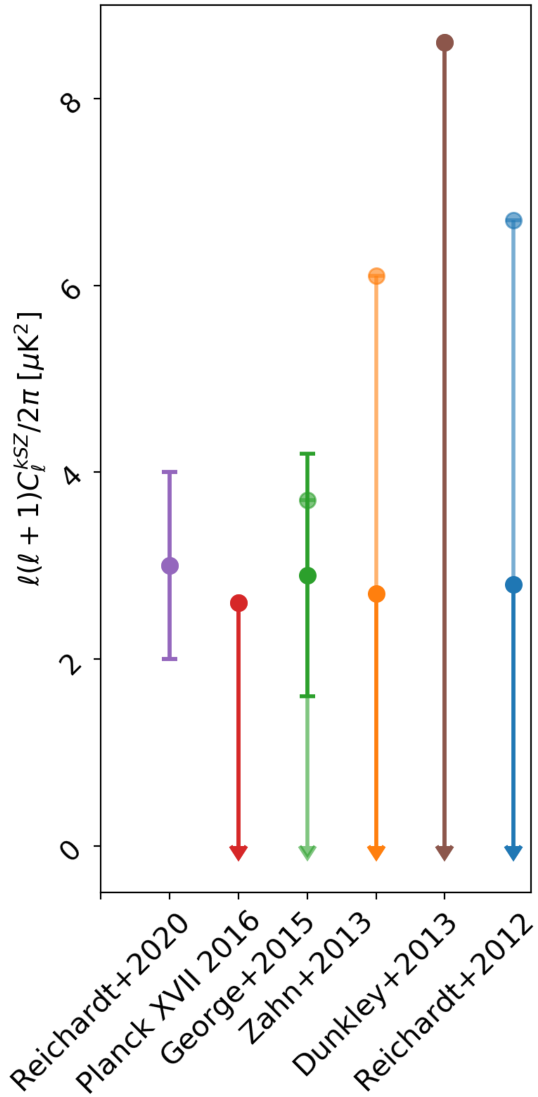
Gorce+2020, see also McQuinn+2005; Iliev+2007; Battaglia+2013; Mesinger+2012, Park+2013, Chen+2022…

Current constraints

- CMB experiments constrain kSZ amplitude and propagate to reionisation:
  - $D^{\text{late-time}}(l=3000) \propto \tau^{0.44}$ *(Shaw+2012)*
  - $D^{\text{patchy}}(l=3000) \propto z_{re}$ and $\Delta z^{0.51}$ *(Battaglia+2013)*
- Most recent constraints: SPT+Planck
  - $D^{p}_{3000} = 1.1\ {+1.0}/{-0.7}\ \mu K2$
  - $\Delta z = 1.1\ {+1.6}/{-0.7}$



Total kSZ amplitude (μK2)

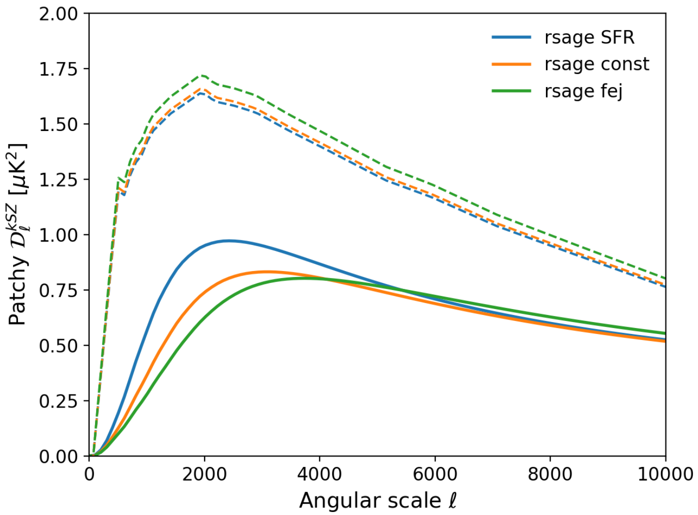


Current constraints

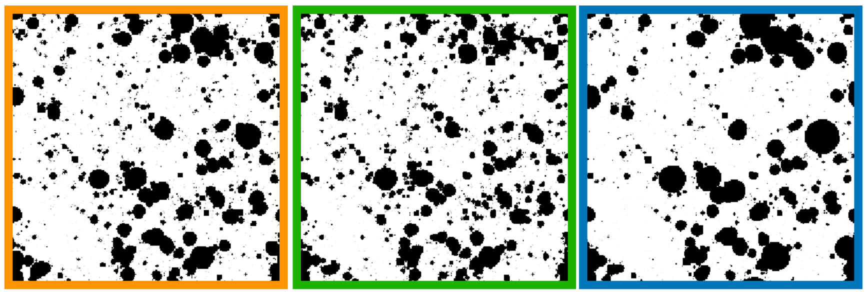
Issues in the way EoR is currently modelled in CMB data analysis:

- Use of templates although amplitude and shape depend on reionisation *(e.g. McQuinn+2006, Iliev+2007, Mesinger+2012)*
- Scaling relations between kSZ amplitude and EoR parameters are largely dependent on the simulations used *(Park+2013)*
- Different xe(z) used for large- and small-scale modelling

⟶ Inconsistent hypotheses: Motivation to develop a semi-analytic derivation of the kSZ power based on cosmology and EoR parameters



rsage simulations at x_{HII} = 0.30



(Seiler+2019)

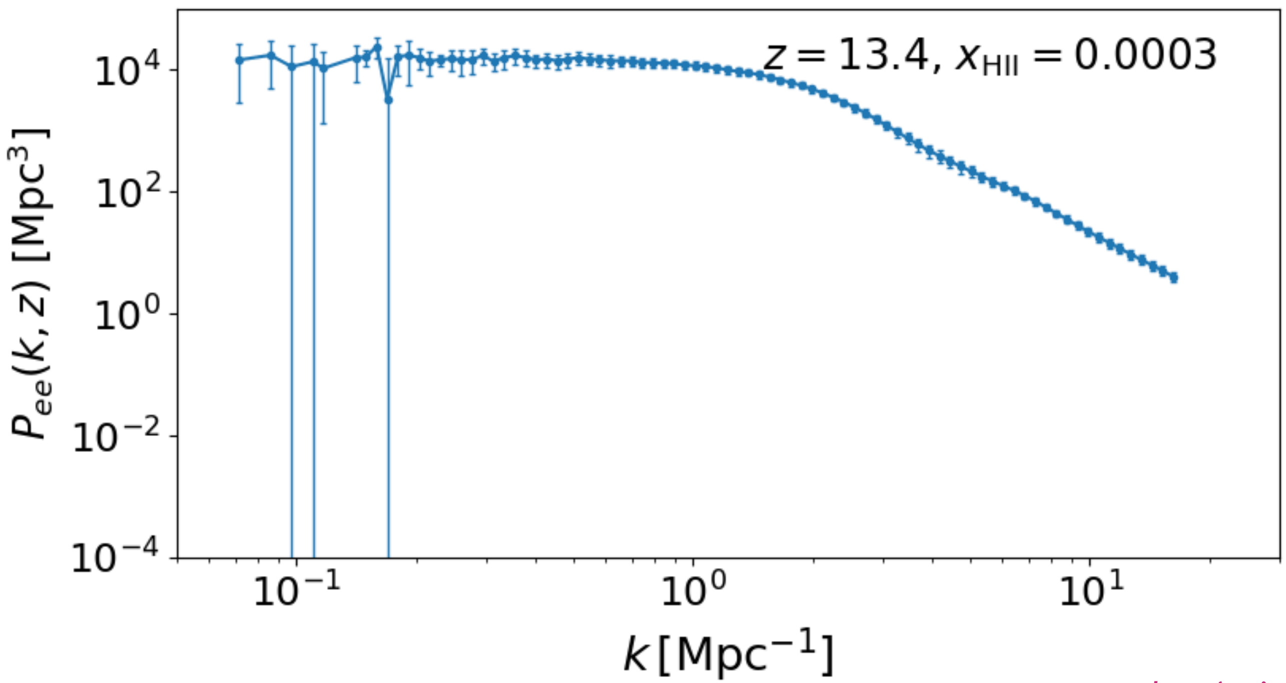
Deriving the kSZ power spectrum

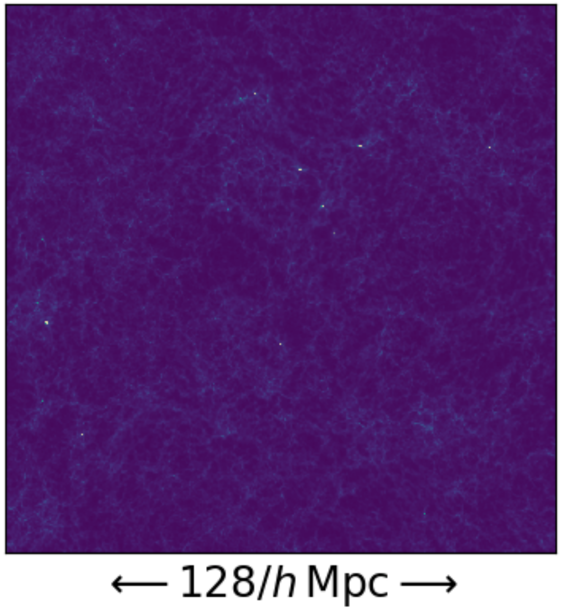
Shape

Amplitude

$$C_\ell = \frac{8\pi^2}{(2\ell+1)^3}\frac{\sigma_T^2}{c^2}\int \frac{\bar{n}_e(z)^2}{(1+z)^2}\Delta^2_{B,e}(\ell/\eta, z)\, e^{-2\tau(z)}\,\eta\,\frac{d\eta}{dz}\,dz$$

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

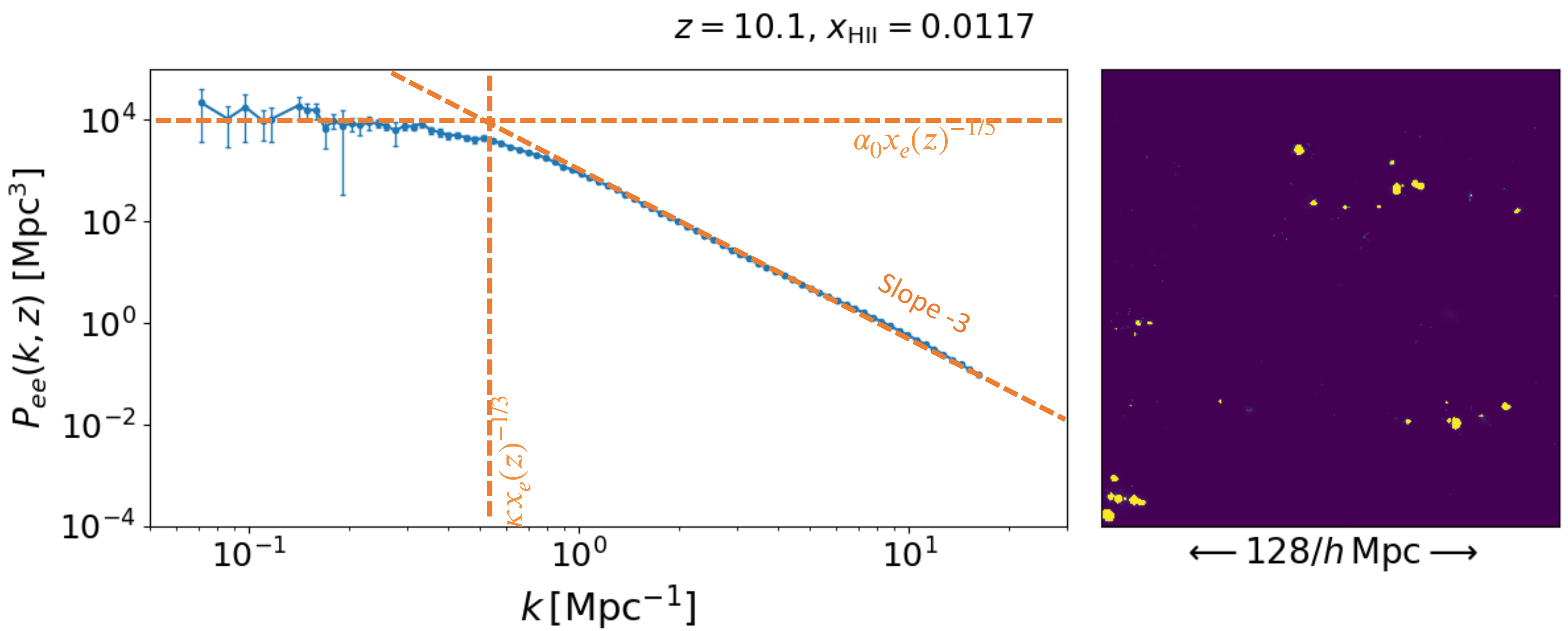




D. Aubert's simulation (see Aubert+2015, Chardin+2019)

THE POWER SPECTRUM OF FREE ELECTRONS $P_{EE}(K,Z)$

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



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

Gorce+, A&A 2020

A SIMPLE PARAMETERISATION

Fitting formula to the spectra of simulations

$$P_{ee}(k,z) = [f_{\rm H} - x_e(z)] \times \frac{\alpha_0 \; x_e(z)^{-1/5}}{1 + [k/\kappa]^3 x_e(z)} + x_e(z) \times b_{\delta e}(k,z)^2 P_{\delta\delta}(k,z)$$

High redshift
(Power-law)
Gorce et al. 2020

Low redshift
(Biased matter PS)
Shaw et al. 2012

Posteriors on the two parameters α_0 and κ
Known reionisation history

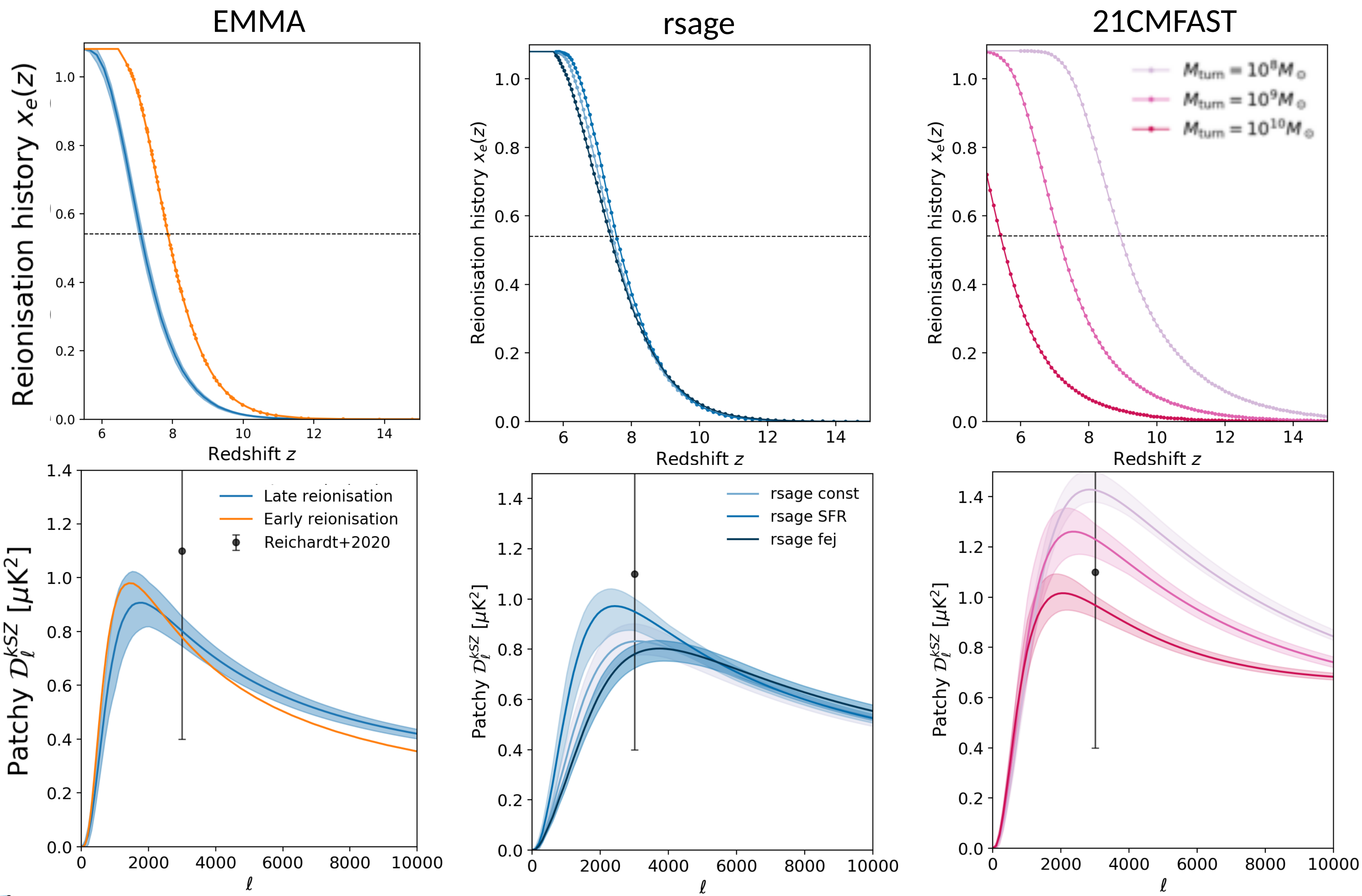
Compute the angular patchy kSZ power spectrum

Applied to three types of simulations:

- rsage: Three different models of the escape fraction *(Seiler+2019)*
- 21CMFAST: Semi-numerical simulations of reionisation *(Mesinger+2007, 2011, Park+2018)*
- EMMA: r-hydro simulations with ≠ star formation *(Aubert+2015, Chardin+2019)*

→ Robust to different physics

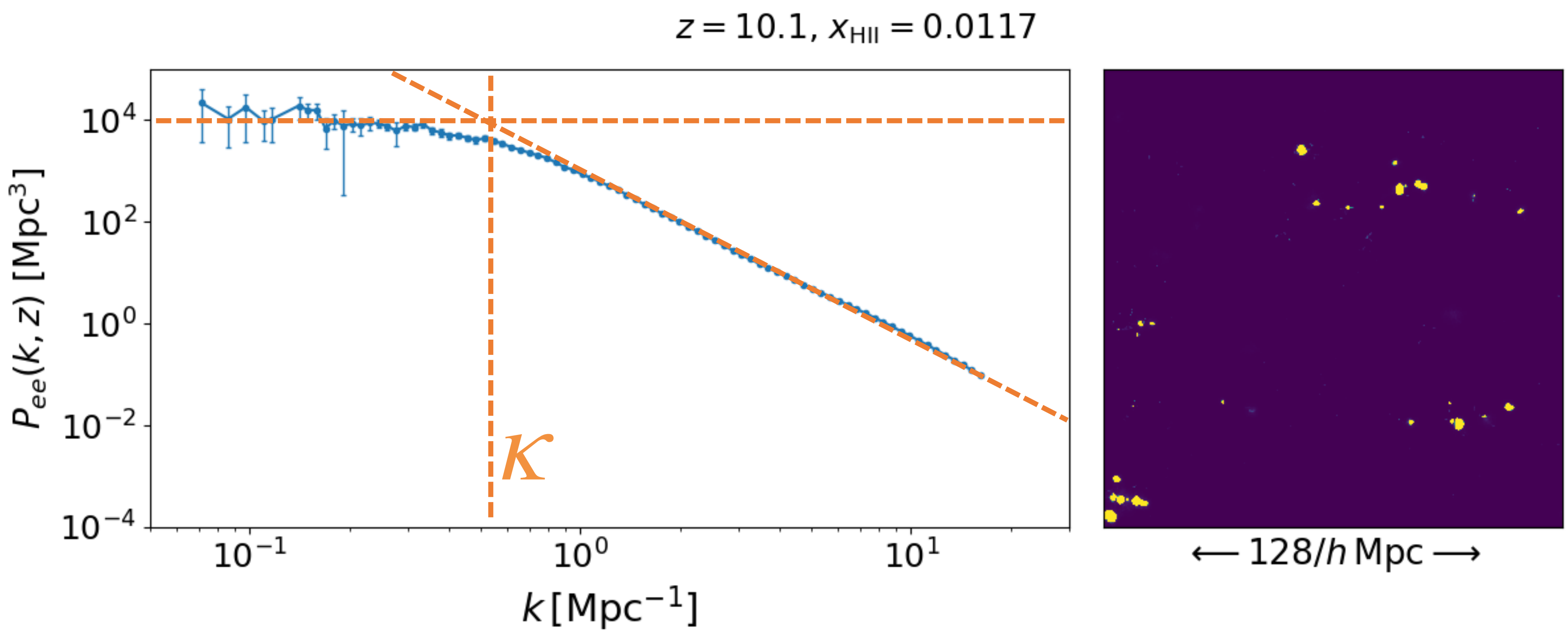
Patchy kSZ for various simulations



Gorce+, A&A 2020

PHYSICAL INTERPRETATION: K VS. ℓ_{MAX} & BUBBLE SIZE

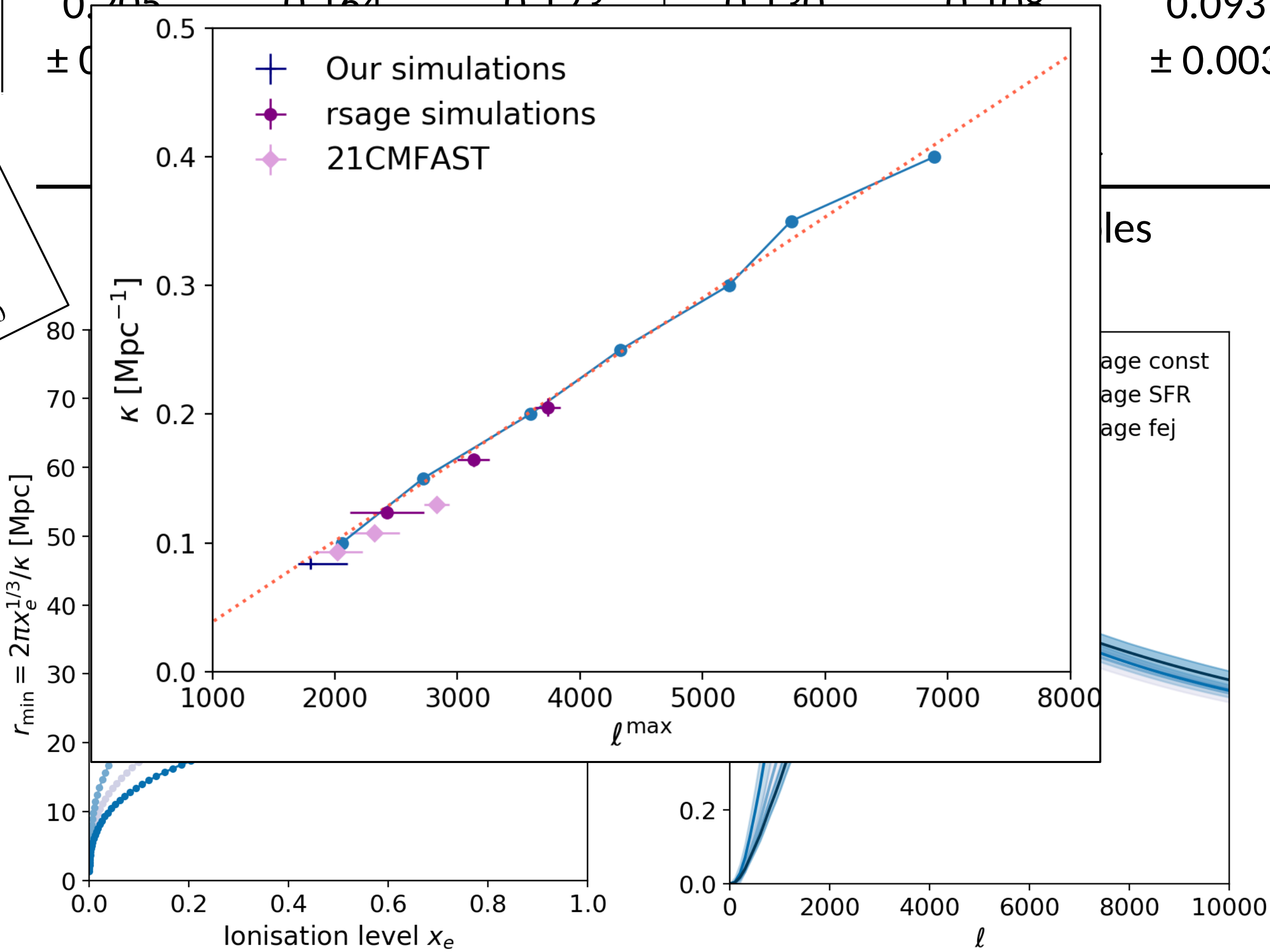
Early times: power-law $$P_{ee}(k,z) = \frac{\alpha_0 \; x_e(z)^{-1/5}}{1 + [k/\kappa]^3 x_e(z)}$$



Physical interpretation: κ vs. ℓ^{max} & bubble size

	rsage			21CMFAST		
	fej	const	SFR	M8	M9	M10
(Mpc^{-1})	0.205	0.164	0.123	0.120	0.108	0.093
	± [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	± 0.003

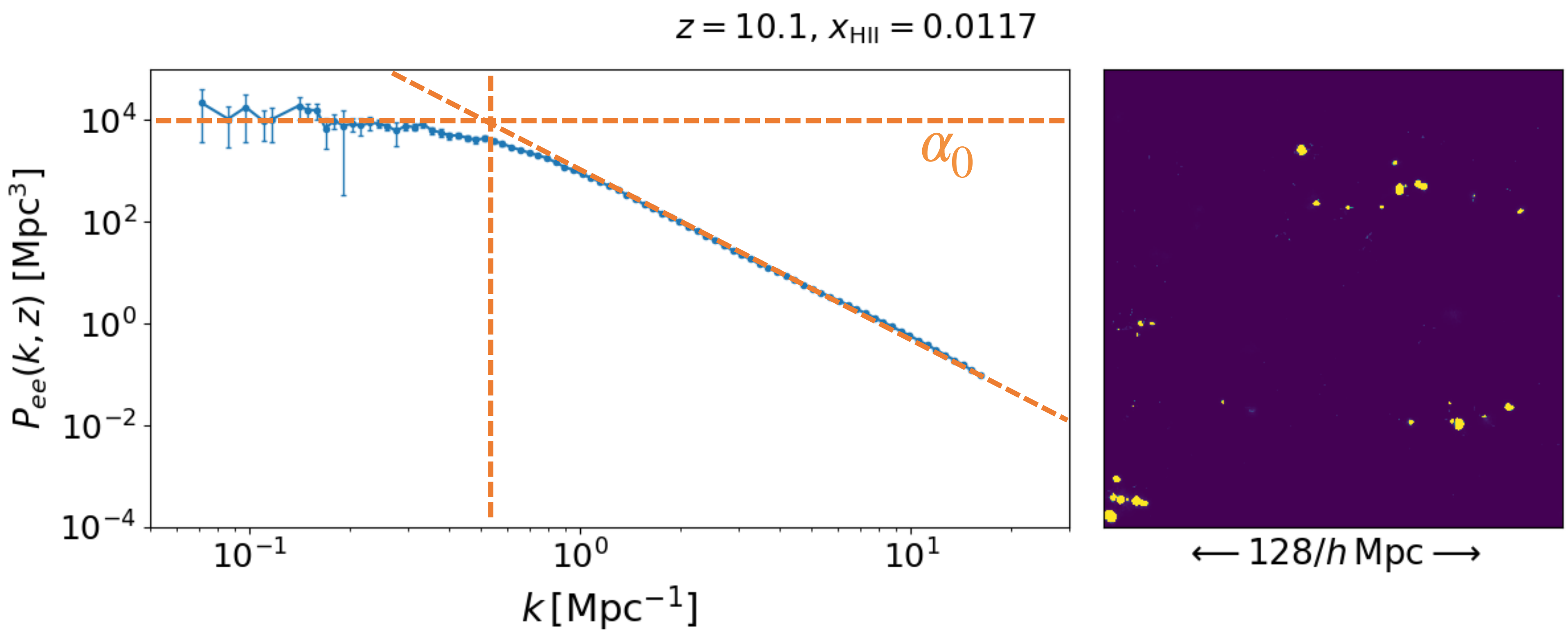
Independent of reionisation history and α_0



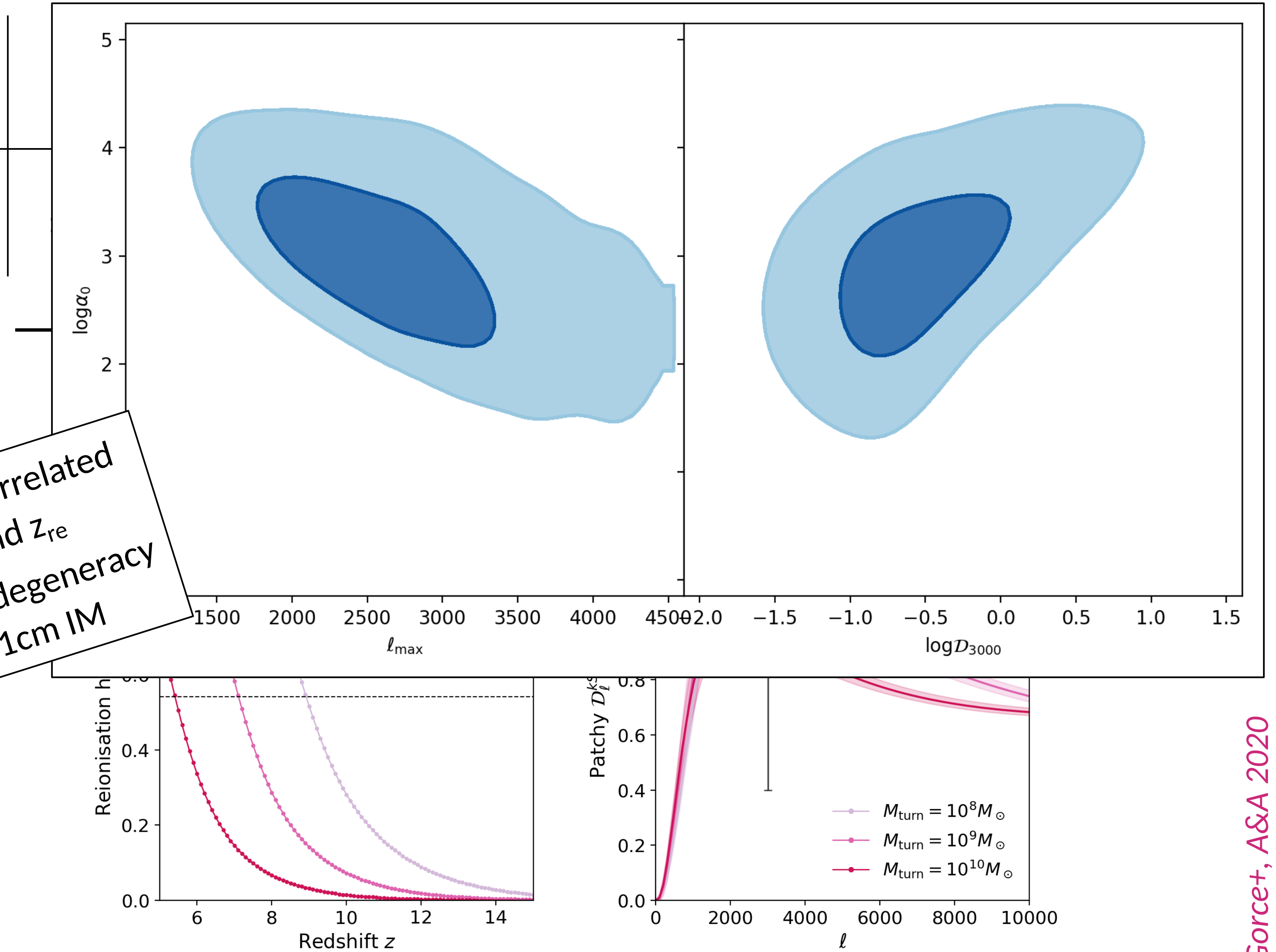
Gorce+, A&A 2020

PHYSICAL INTERPRETATION: A_0 VS. AMPLITUDE

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



log
(Mpc³)



α_0 strongly correlated to Δz and z_{re}

→ Break degeneracy with 21cm IM

Gorce+, A&A 2020

Current high-L analyses

- There is information about reionisation in the kSZ spectrum…

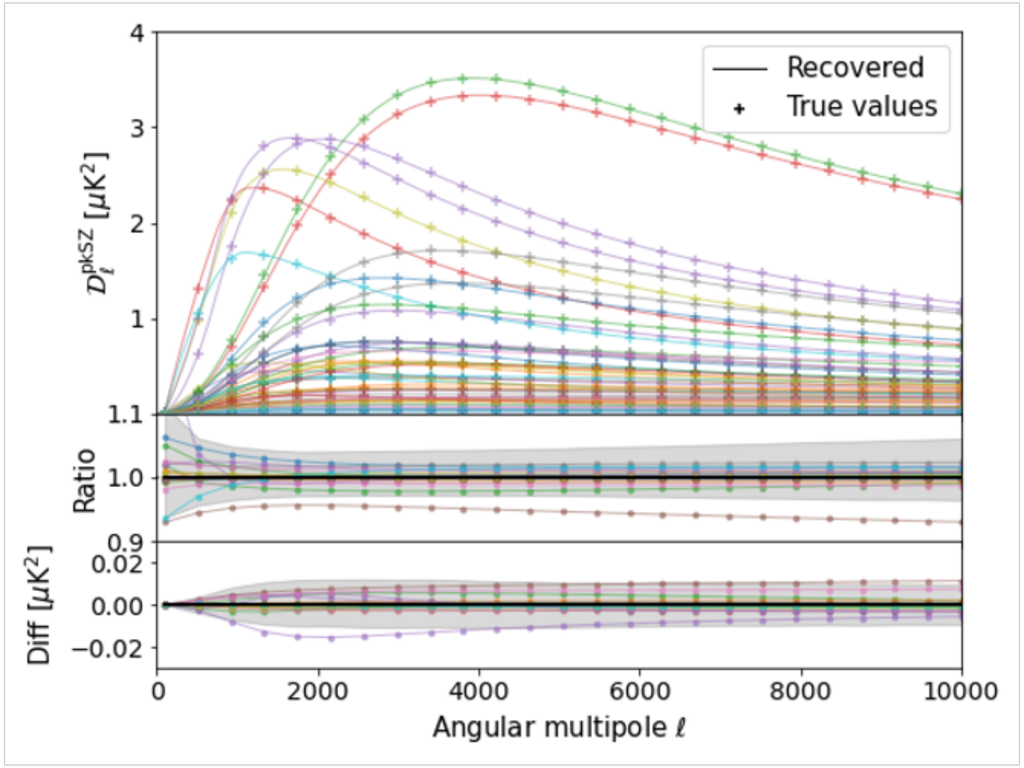
  … but it is not used in current analyses, resulting in imprecise constraints

- Proposed solution:
  - Replace templates by analytic derivations of the SZ spectra to retrieve the cosmological information enclosed in the foregrounds
  - For the tSZ spectrum → *Douspis, Salvati, Gorce & Aghanim 2022*
    → *CMBFrance#2*
  - For the kSZ spectrum → *Gorce, Douspis & Salvati 2022*

- But the computation is expensive (one min per l…)

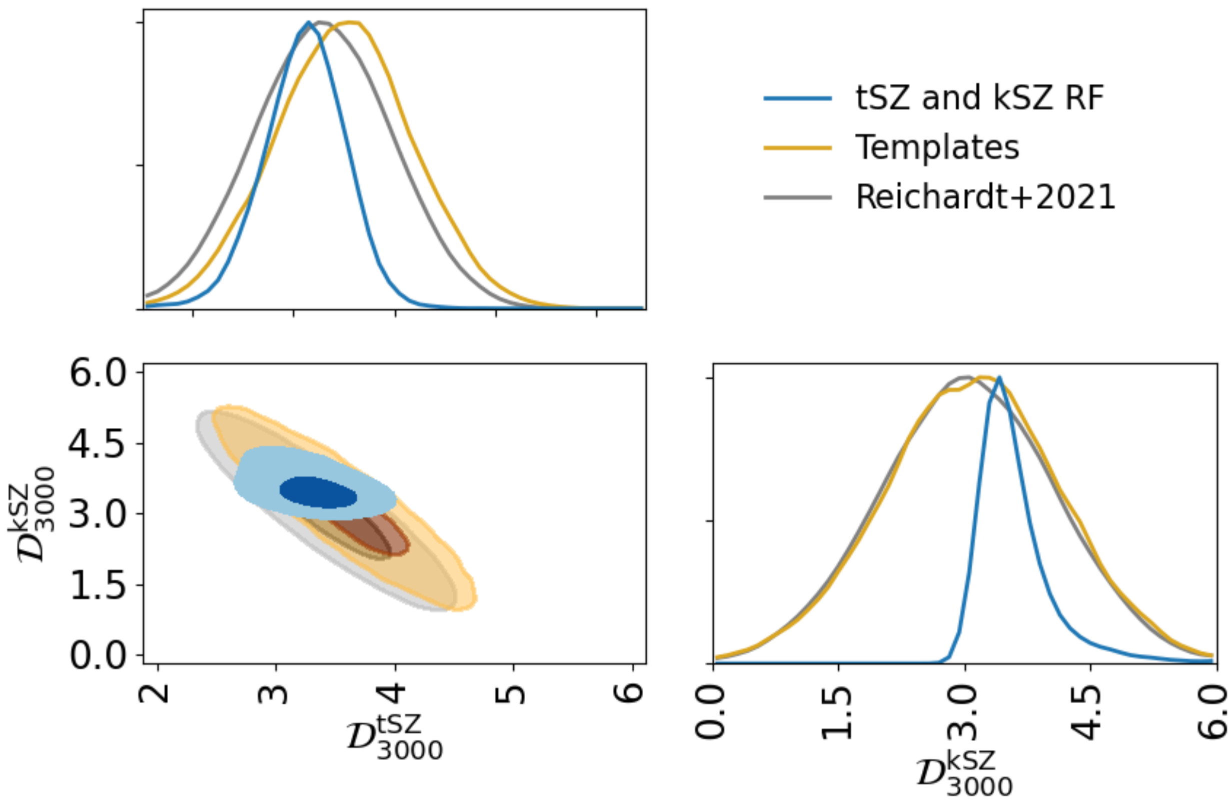
EMULATING KSZ POWER SPECTRUM

- Training Random forest with random values of 9 params on 25 l-values of the Cls (l=100 to l=10500) [scikit-learn]
  - 5 cosmo + 2 Reio + 2 kSZ
- Training 50000 models (test on 20%)
- RF Score of 99%
- Reconstruction error < 5%
  - (<1% late time)
- Absolute error < 0.02 µK2



RESULTS ON SPT DATA: FIXED COSMOLOGY

- Results on tkSZ amplitudes:
  - Clean and consistent measurement of the tSZ and kSZ amplitudes
  - Breaks the degeneracy



DkSZ = 3.5 ± 0.6 μK2

(1σ)

→ 3σ to 6σ meas.

Gorce, Douspis, Salvati 2022

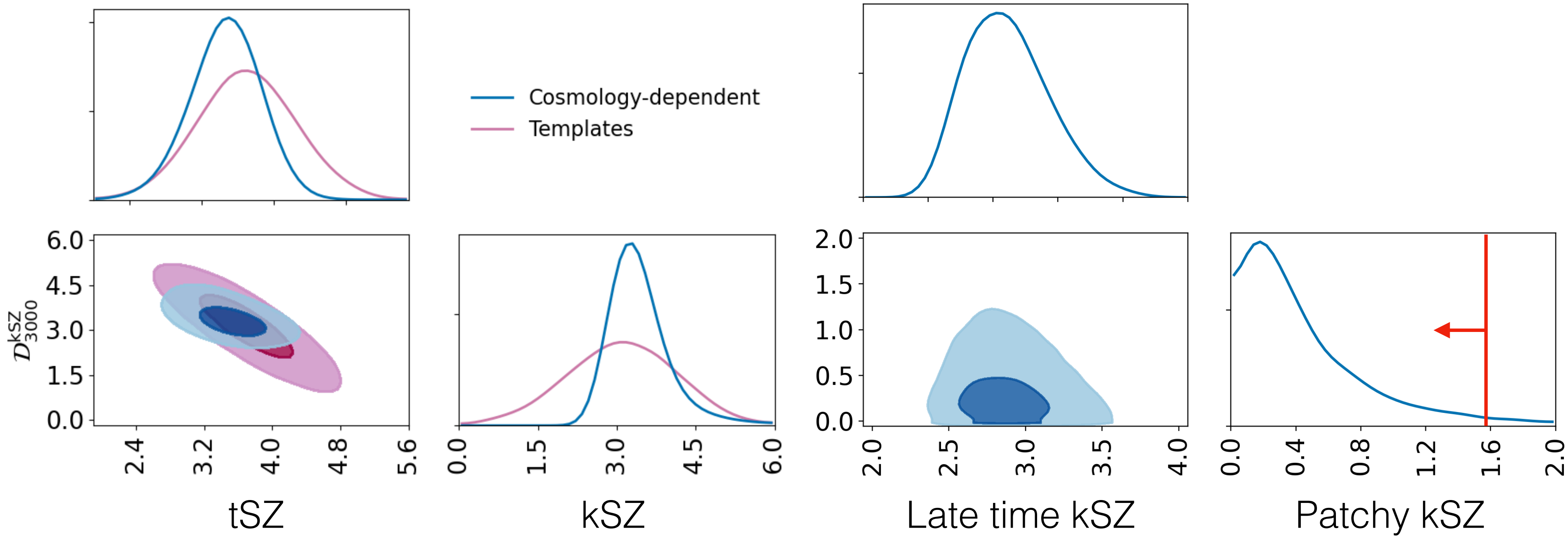
Results on SPT data: Fixed cosmology

- Results on tkSZ amplitudes:
  - Clean and consistent measurement of the tSZ and kSZ amplitudes
  - Breaks the degeneracy

- **But constraints on EoR depend on cosmology**

Results on SPT data: Free cosmology

- Planck 2018 priors on $\Omega_b h^2$, $\Omega_c h^2$, θ_{MC}, ns
- Flat priors on other parameters (A_s, reion)

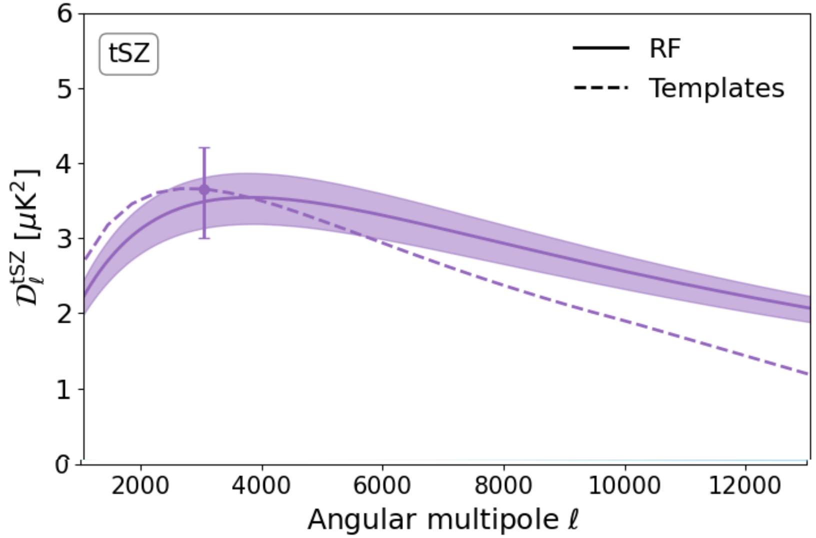


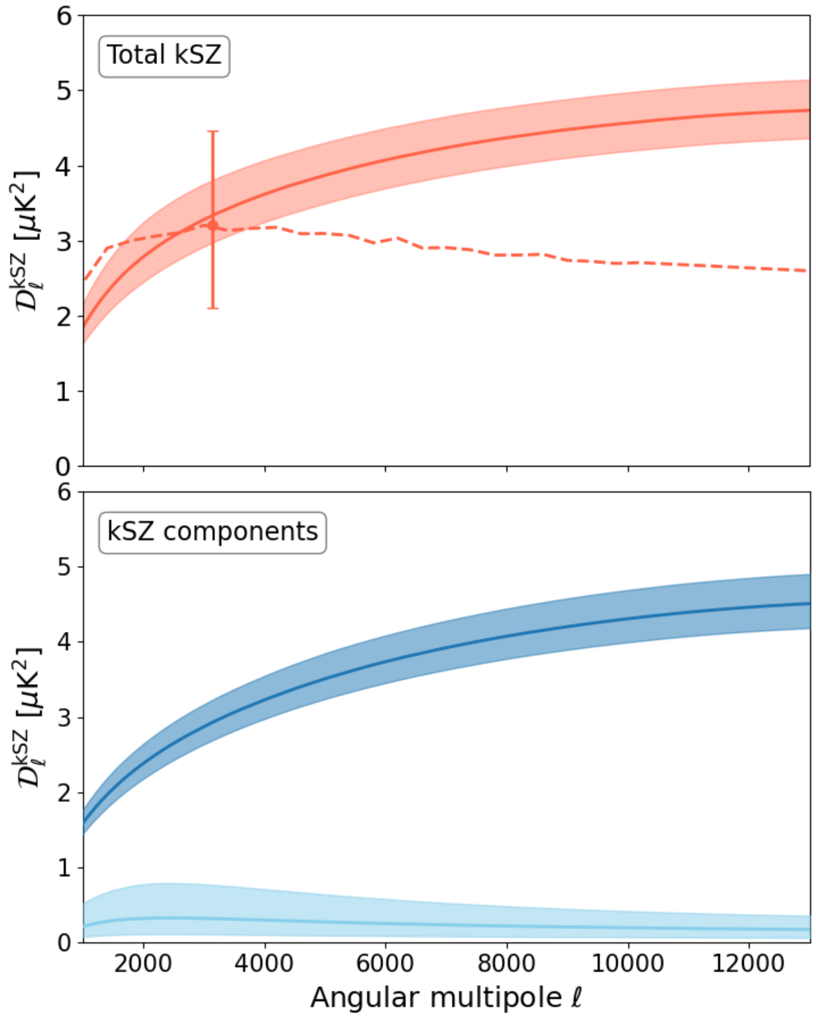
9 and 5σ measurements
of tSZ and kSZ resp.
(≠ tSZ alone results)

Separate components:
Late-time contributes to 85%
D_{pkSZ} < 1.6 μK2 (95%)

Gorce, Douspis, Salvati 2022

Results on SPT data: Free cosmology



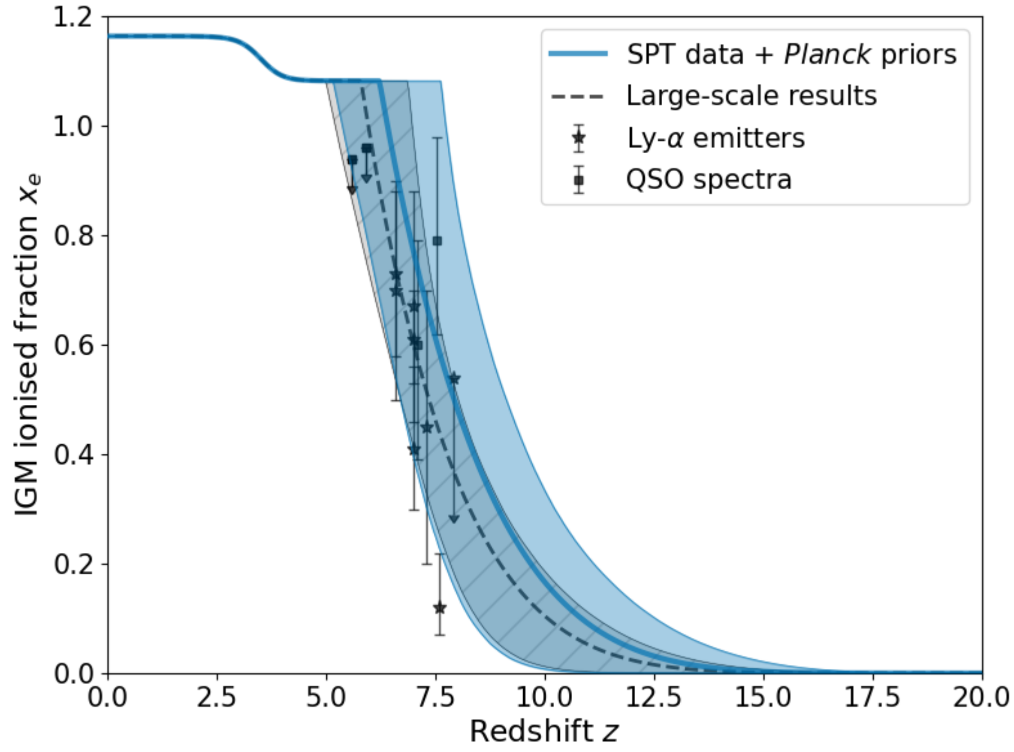


Can see the shape of the spectra!!

Gorce, Douspis, Salvati 2022

Results on SPT data: Free cosmology

- Results on EoR



SPT data favour a different cosmology than Planck, including earlier reionisation:

$\tau = 0.062 \pm 0.012$ (1σ)

zre = 7.9 ± 1.1 (1σ)

Gorce, Douspis, Salvati 2022

Conclusions

- There is potential in the small-scale CMB, even at the 2-point level
  - Already with SPT (and ACT), leveraging the cosmological information in foregrounds leads to
    - cleaner measurements

      $D_{kSZ} = 3.4 \pm 0.5$ μK2, 1σ

      $D_{pkSZ} < 1.59$ μK2 (95% C.L.)

    - Self-consistent constraints on reionisation:

      $z_{re} = 7.9 \pm 1.1$ (1σ)

      $\tau = 0.062 \pm 0.012$

  - … but mostly with CMB-S4
- Next:
  - Improve modelling of other foregrounds
  - Consistent analysis with large-scale data (SPT-Planck tension?)
  - Joint constraints of kSZ with other data sets
- tSZ & kSZ computations are public and available: https://szdb.osups.universite-paris-saclay.fr

French ANR funding project “**BATMAN**” on

CMB constraints on neutrinos with acurrate reionisation history and gas physics

$\Longrightarrow$ 3 postdoc positions opened now !!

http://batman-anr.ias.universite-paris-saclay.fr

https://inspirehep.net/jobs/2170877 -> IAS

https://inspirehep.net/jobs/2170876 -> IRAP

https://inspirehep.net/jobs/2170871 -> IJCLab