IAS
Institut d'Astrophysique Spatiale
Orsay

Better Accuracy and robusTness for Mass Assessment of Neutrinos

Small scale CMB cosmological information

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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*

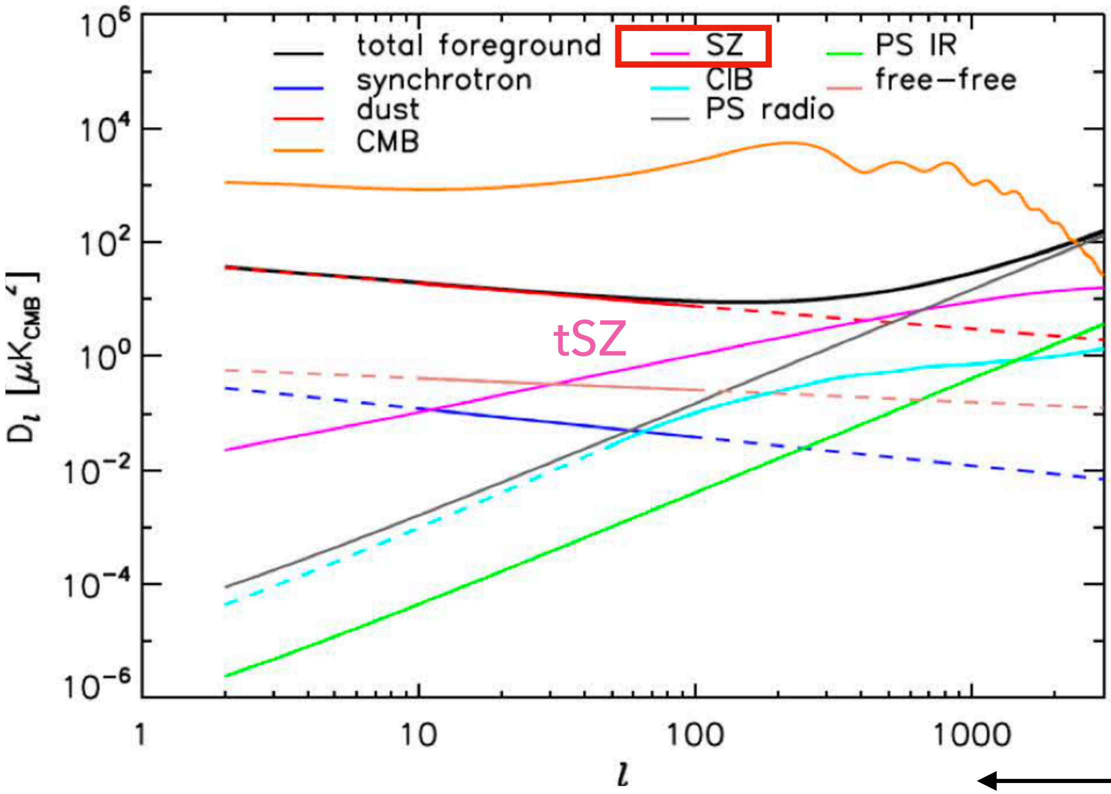
"Retrieving cosmological information from small-scale CMB foregrounds II. The kinetic Sunyaev Zel'dovich effect", *Gorce, Douspis, Salvati, A&A 2022, arXiv:2202.08698*

anr agence nationale de la recherche

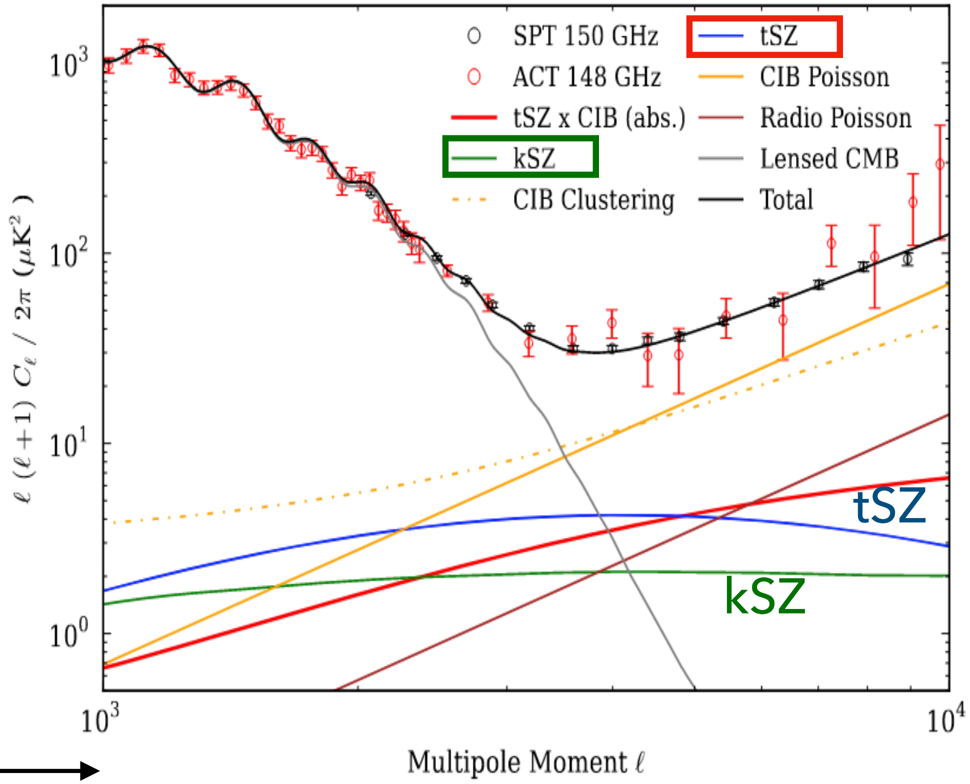
SECONDARIES IN FREQUENCY MAPS

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

Planck/Large scales



SPT/small scales



Planck coll. 2013

Addison et al. 2012

RATIONALE

- Can we exploit the full cosmological information of extragalactic components (tSZ, kSZ, CIB, …) in CMB analyses ?
- Yes by using coherent modelling and coherent analysis !

Douspis et al 2006

SPT analysis

Reionisation

$$C_\ell^{obs} = C_\ell^{CMB}(\Theta, xe = tanh) + A^{tSZ} C_\ell^{temp-t} + A^{kSZ} C_\ell^{temp-k} + ...$$

Cosmology

RATIONALE

- Can we exploit the full cosmological information of extragalactic components (tSZ, kSZ, CIB, …) in CMB analyses ?
- Yes by using coherent modelling and coherent analysis !

Douspis et al 2006

Replace in SPT analysis

Reionisation

$$\cancel{C_\ell^{obs} = C_\ell^{CMB}(\Theta, xe = tanh) + A^{tSZ} C_\ell^{temp-t} + A^{kSZ} C_\ell^{temp-k} + \ldots.}$$

Cosmology

By

$$C_\ell^{obs} = C_\ell^{CMB}(\Theta, xe = asym) + C_\ell^{tSZ}(\Theta) + C_\ell^{kSZ}(\Theta, xe = asym) + \ldots.$$

Taburet et al. 2009

Halo model

Gorce et al. 2020

Semi-analytical model

tSZ power spectrum from Halo Model

$$Cls[\Theta] \equiv \iiint dMdz \; dV \; \chi(obs) \; S(obs-M) \; \frac{dN}{dMdz} \; p(M,z)$$

Cosmology

Selection function

Given by experiment and observing strategy
From simulations or analytical formulae [Planck 2013,15…]

See also talk of Stefano Gallo

Scaling Relation

Needed to relate the observable (flux, size) to the mass and redshift. Given by comparison HM with simulations or WL measurements [Planck 2013., Nagai et al., …]

$$E^{-\beta}(z)\left[\frac{D_A^2(z)\,Y_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = Y^*\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{(1\text{-}b)\;M_{500}}{6\cdot 10^{14} M_\odot}\right]^{\alpha}$$

See also talk of Gaspard Aymerich on scaling and Theo Lebeau and Miren Muñoz Echeverría on bias

Mass function

Number of halos in bins of mass and redshift. From numerical simulations, known 10% scatter between teams [Tinker et al., Watson et al. , Despali et al.]

$$\frac{dN(M_{500},z)}{dM_{500}} = f(\sigma)\frac{\rho_m(z=0)}{M_{500}}\frac{d\ln\sigma^{-1}}{dM_{500}}$$

$$f(\sigma) = A\left[1+\left(\frac{\sigma}{b}\right)^{-a}\right]\exp\left(-\frac{c}{\sigma^2}\right)$$

$$\sigma \; needs \int P(k)$$

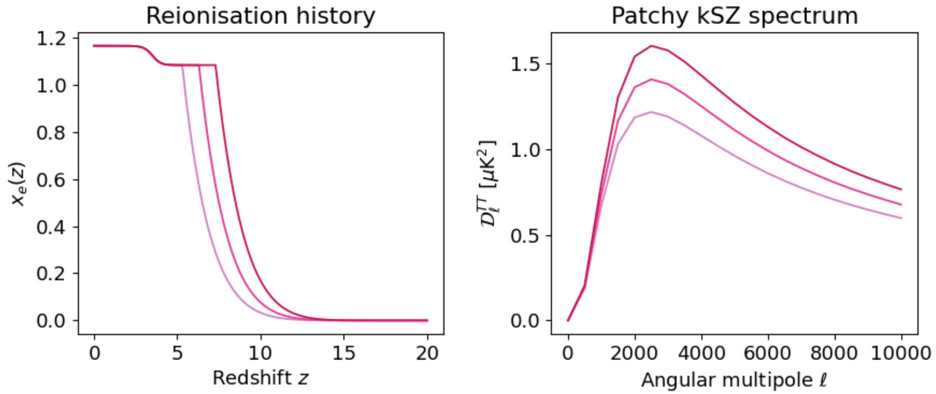
Profile

Describes the spatial distribution of the hot gas. Assume Universal pressure profile, the GNFW [Nagai et al., Arnaud et al. , Planck 2014]

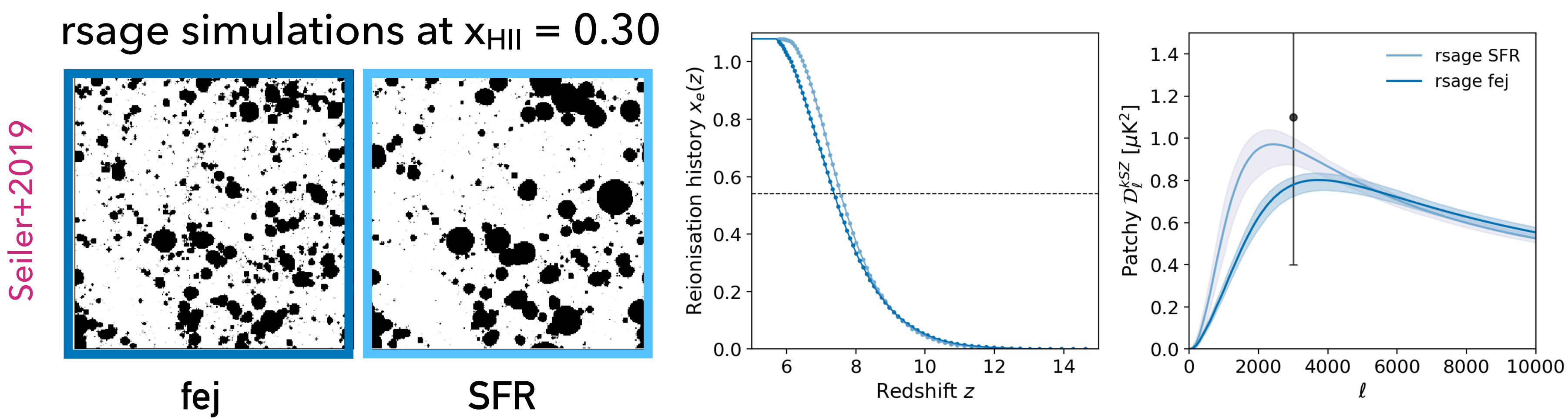
See also talk of Corentin Hanser

The kinetic Sunyaev Zel'dovich effect

- Information on reionisation history



- Information on reionisation morphology

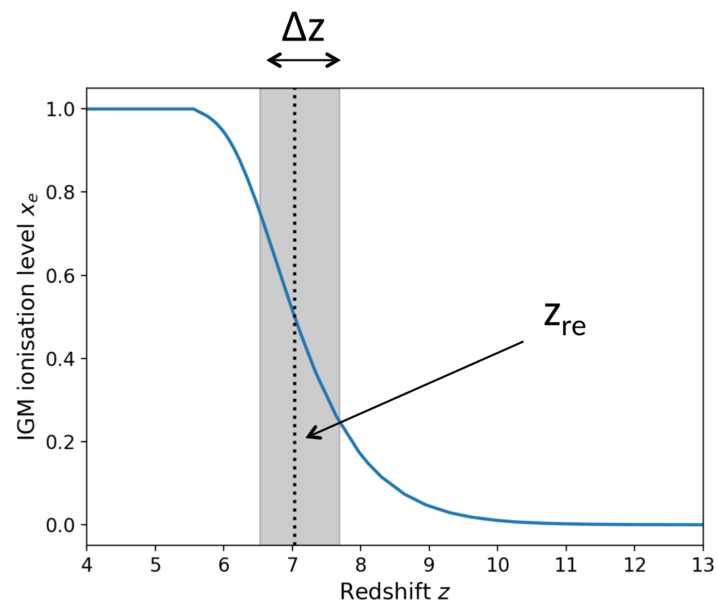


Gorce+2020, see also McQuinn+2005; Iliev+2007; Battaglia+2013; Mesinger+2012, Park+2013, Chen+2022…

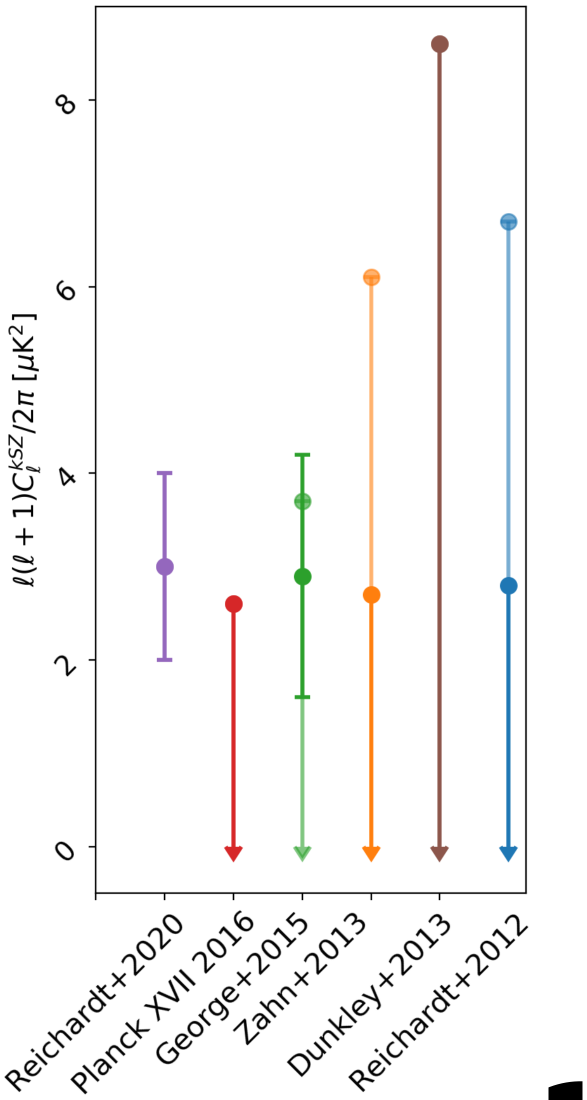
Current constraints

- 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
  - $D^{p}_{3000} = 1.1\ {+1.0/{-0.7}}\ \mu K2$
  - $\Delta z = 1.1\ {+1.6/{-0.7}}$

See also talk of Srinivasan Raghunathan for prospects



Total kSZ amplitude (μK2)

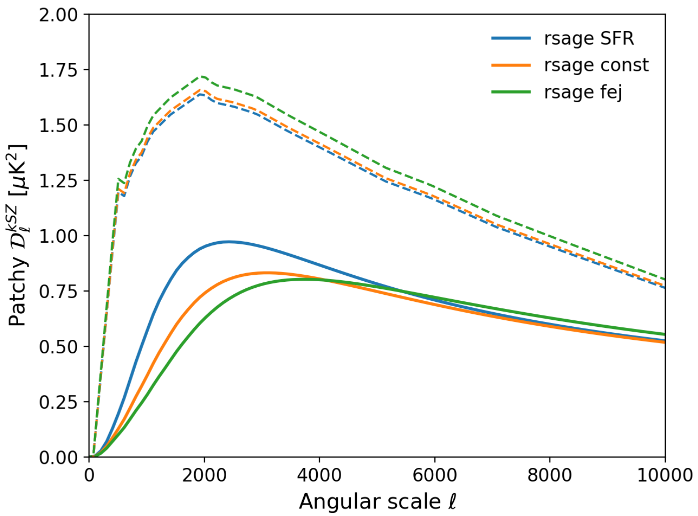


Current constraints

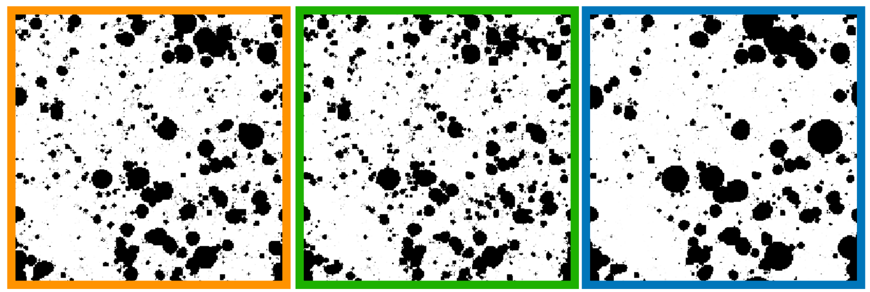
Issues in the way EoR is currently modelled in CMB data analysis:

- 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)

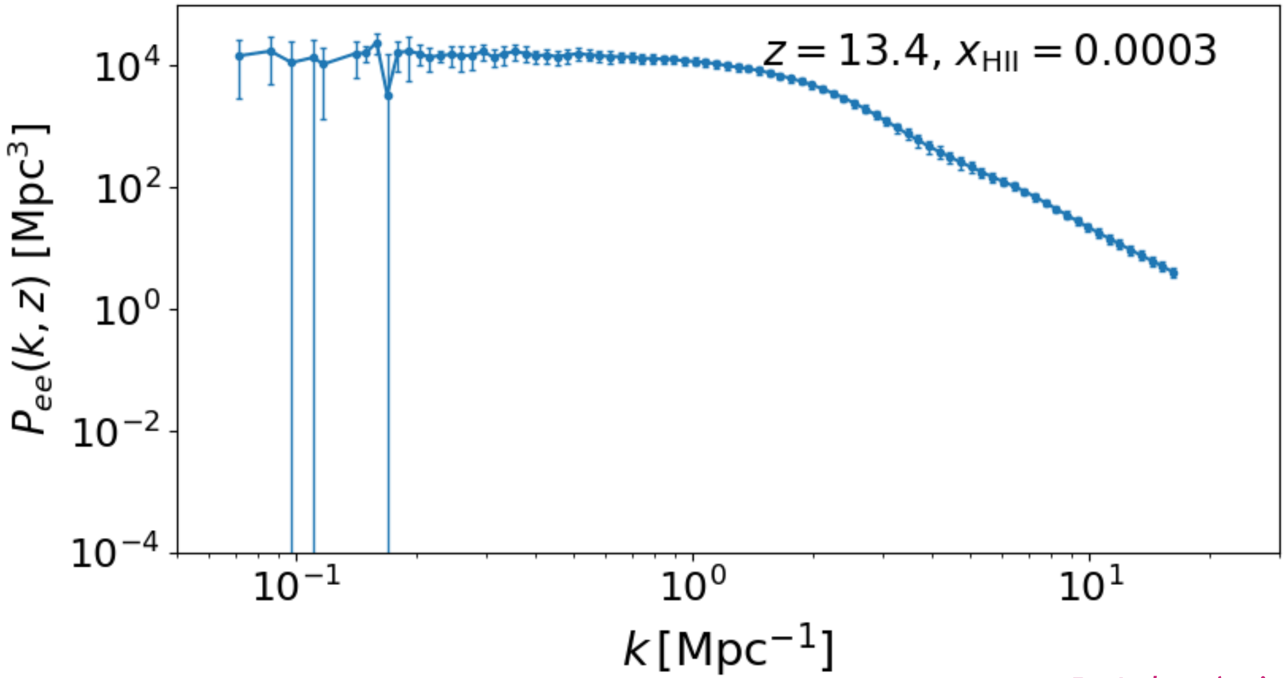
Deriving the kSZ power spectrum

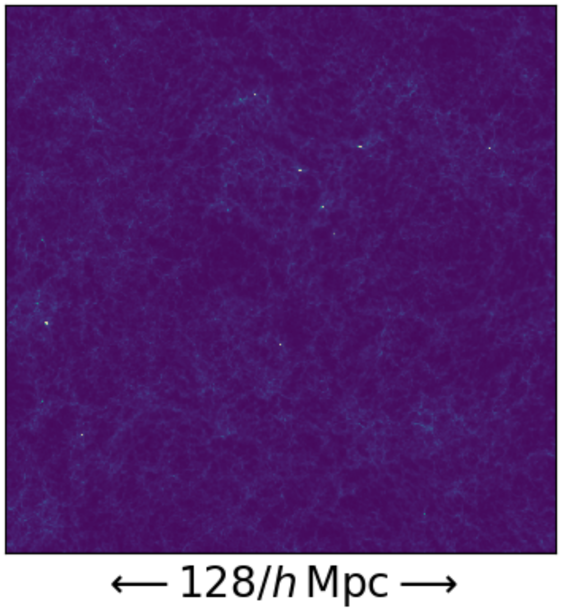
Shape

Amplitude

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

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

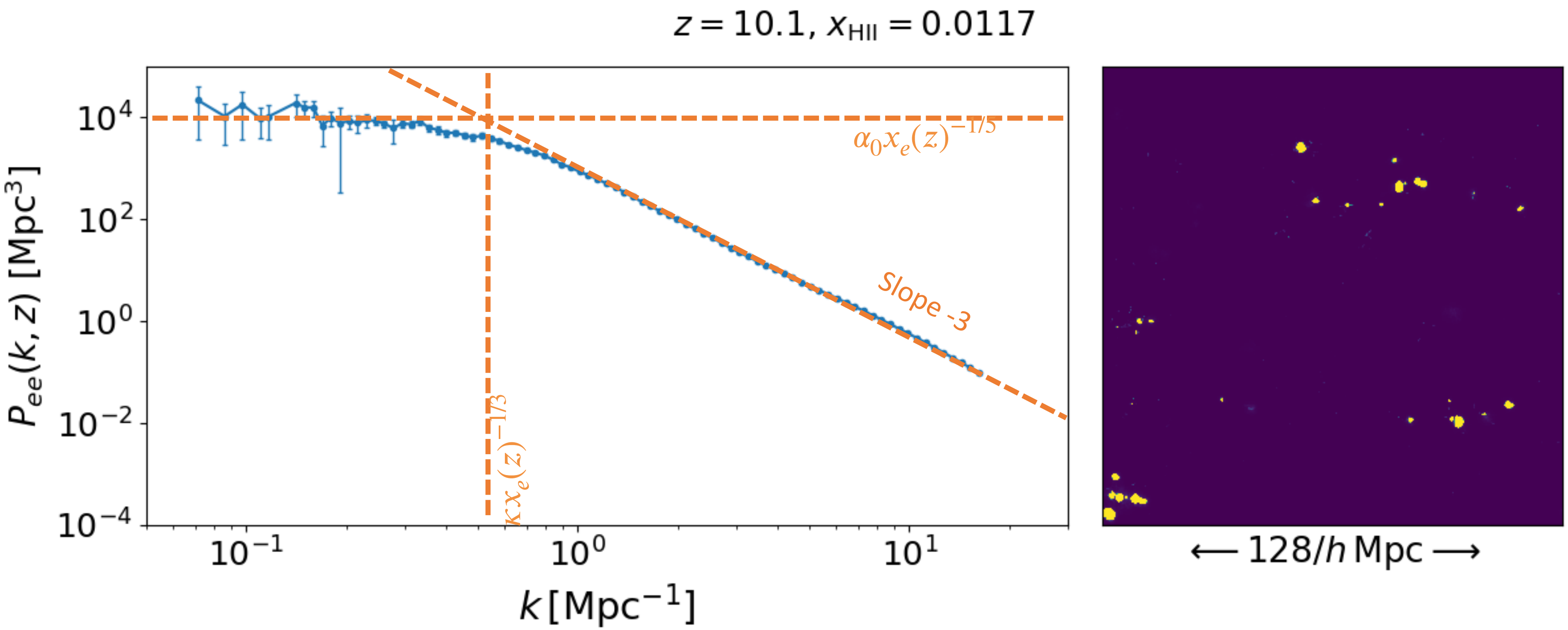




D. Aubert's simulation (see Aubert+2015, Chardin+2019)

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

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



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

Gorce+, A&A 2020

A SIMPLE PARAMETERISATION

Fitting formula to the spectra of simulations

$$P_{ee}(k,z) = \underbrace{[f_{\rm H} - x_e(z)] \times \frac{\alpha_0\ x_e(z)^{-1/5}}{1+[k/\kappa]^3 x_e(z)}}_{\text{High redshift (Power-law)}} + \underbrace{x_e(z) \times b_{\delta e}(k,z)^2 P_{\delta\delta}(k,z)}_{\text{Low redshift (Biased matter PS)}}$$

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 x_e

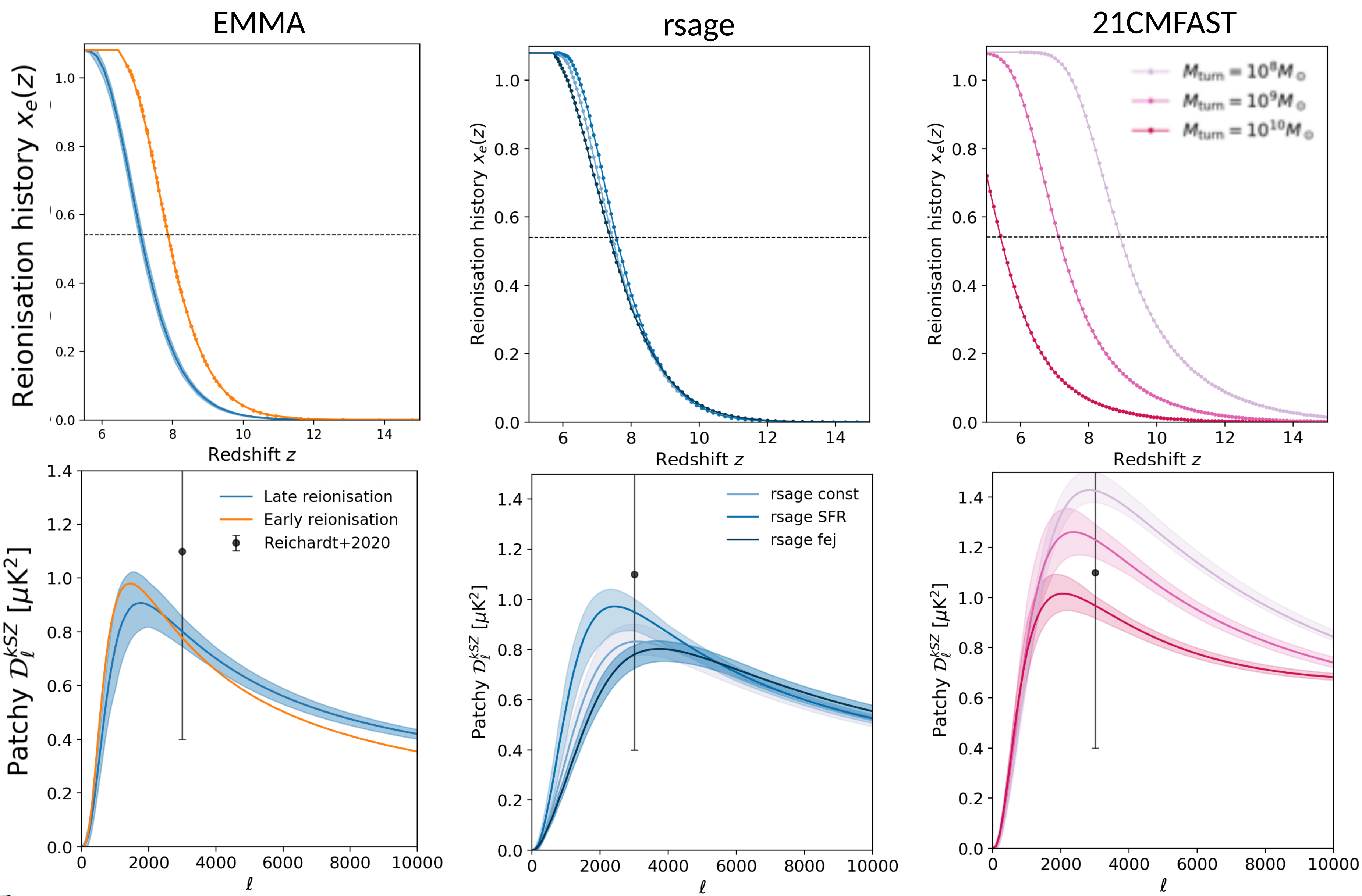
Compute the angular patchy kSZ power spectrum

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**

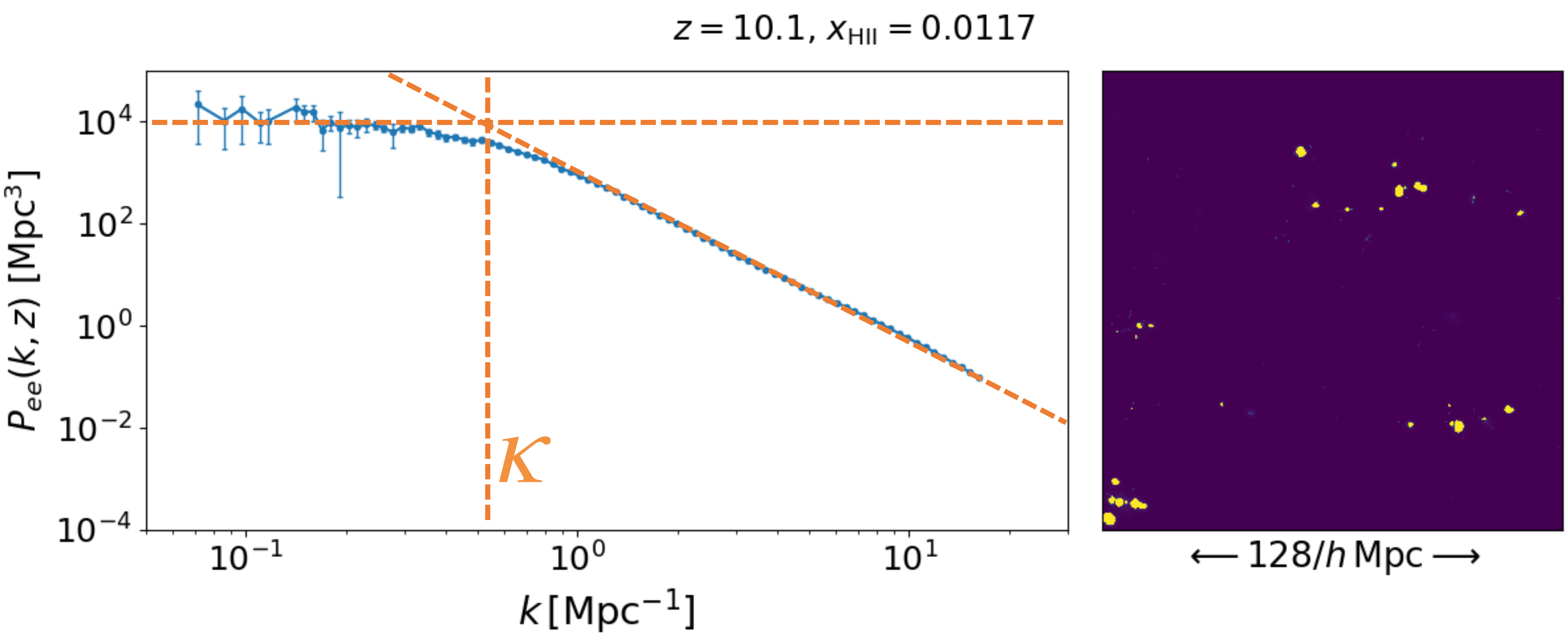
Patchy kSZ for various simulations



Gorce+, A&A 2020

Physical interpretation: k vs. ℓ_{max} & bubble size

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

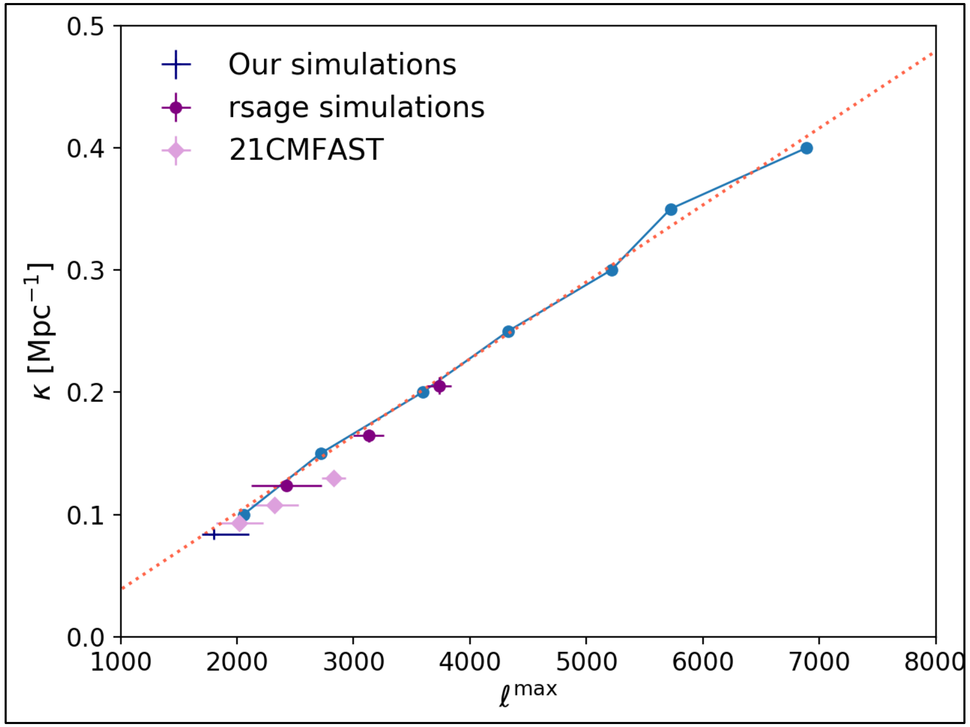


Physical interpretation: κ vs. ℓ_{max} & bubble size

	rsage			21CMFAST		
	fej	const	SFR	M8	M9	M10
(Mpc^{-1})	0.205 ± 0.007	0.164 ± 0.005	0.123 ± 0.004	0.130 ± 0.003	0.108 ± 0.004	0.093 ± 0.003

Smaller κ → Larger bubbles

Smaller κ → Larger bubbles



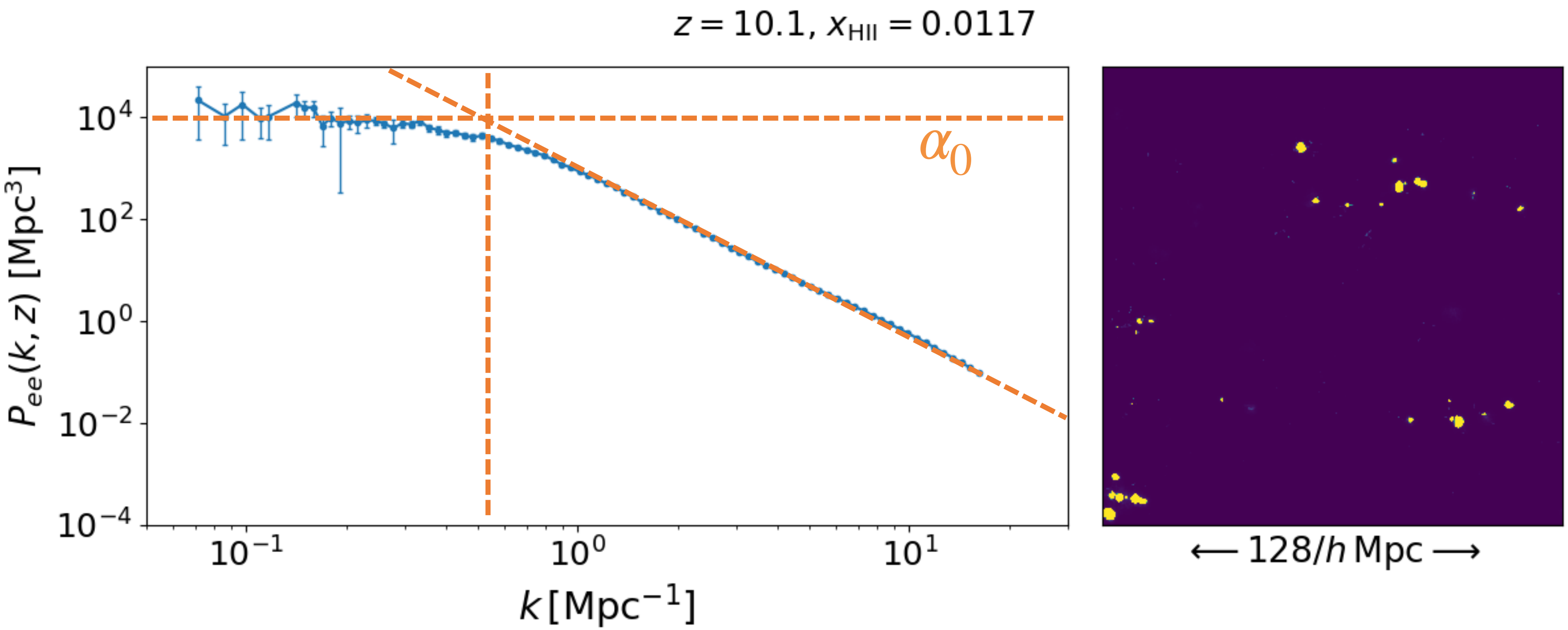
Independent of reionisation history and α_0

Gorce+, A&A 2020

Physical interpretation: A_0 vs. amplitude

Early times: power-law

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



Physical interpretation: A_0 vs. amplitude

	rsage			21CMFAST		
	fej	const	SFR	M8	M9	M10
log (Mpc³)	2.87 ± 0.04	3.12 ± 0.04	3.47 ± 0.04	3.30 ± 0.03	3.58 ± 0.04	3.79 ± 0.04

Larger α_0 → Larger bubbles

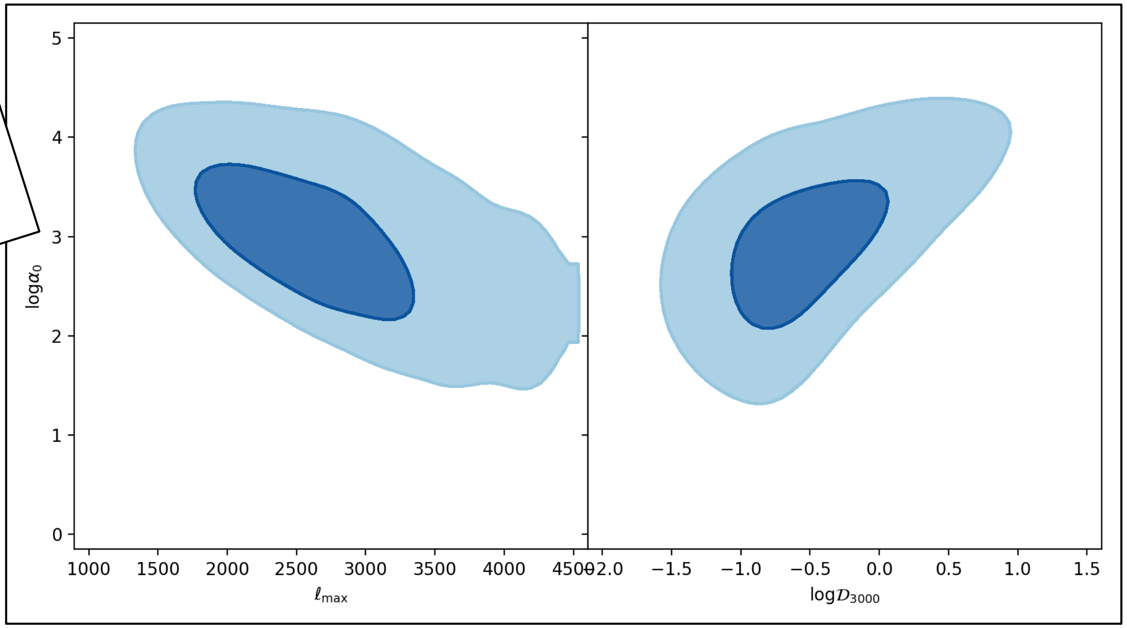
Higher power

Larger α_0 → Larger bubbles

Lower power

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*
  - For the kSZ spectrum → *Gorce, Douspis & Salvati 2022*

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

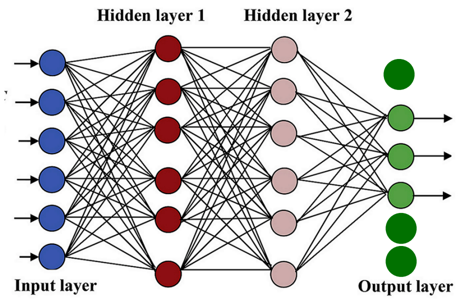
Building an SZ emulator

- tSZ and kSZ too long to compute in MCMC
- Training Random forest with random values of 5+3/4 params (15000 models) on 15 l-values of the Cls (l=10 to l=11000) [scikit-learn]
- RF Score > 96%

Emulator

σ_8	Amplitude of fluctuations
Ω_m	Matter density
Ω_b	Baryon density
n_s	Spectral index
H_0	Hubble constant
$1-b$	Mass bias parameter
α	SR Mass exponent
$logY^*$	SR amplitude

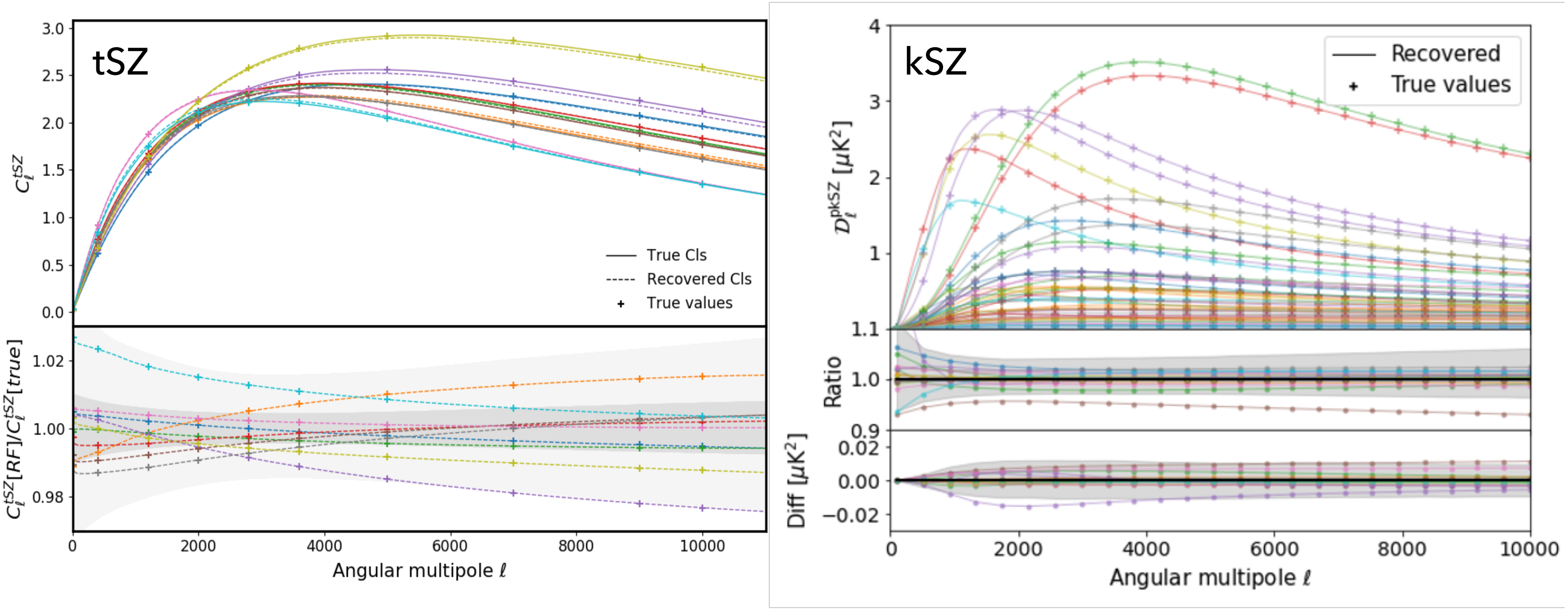
RF training



C_{10}
C_{100}
C_{800}
...
C_{1100}

Interpolation → Cls at all ells

Emulating tSZ and kSZ



± 2% while observation errors are ~20%

Asbolute 0.02 μK²

More than 100 times faster to compute

*Paper I: **Douspis** et al. 2022*

*Paper II: **Gorce** et al. 2022*

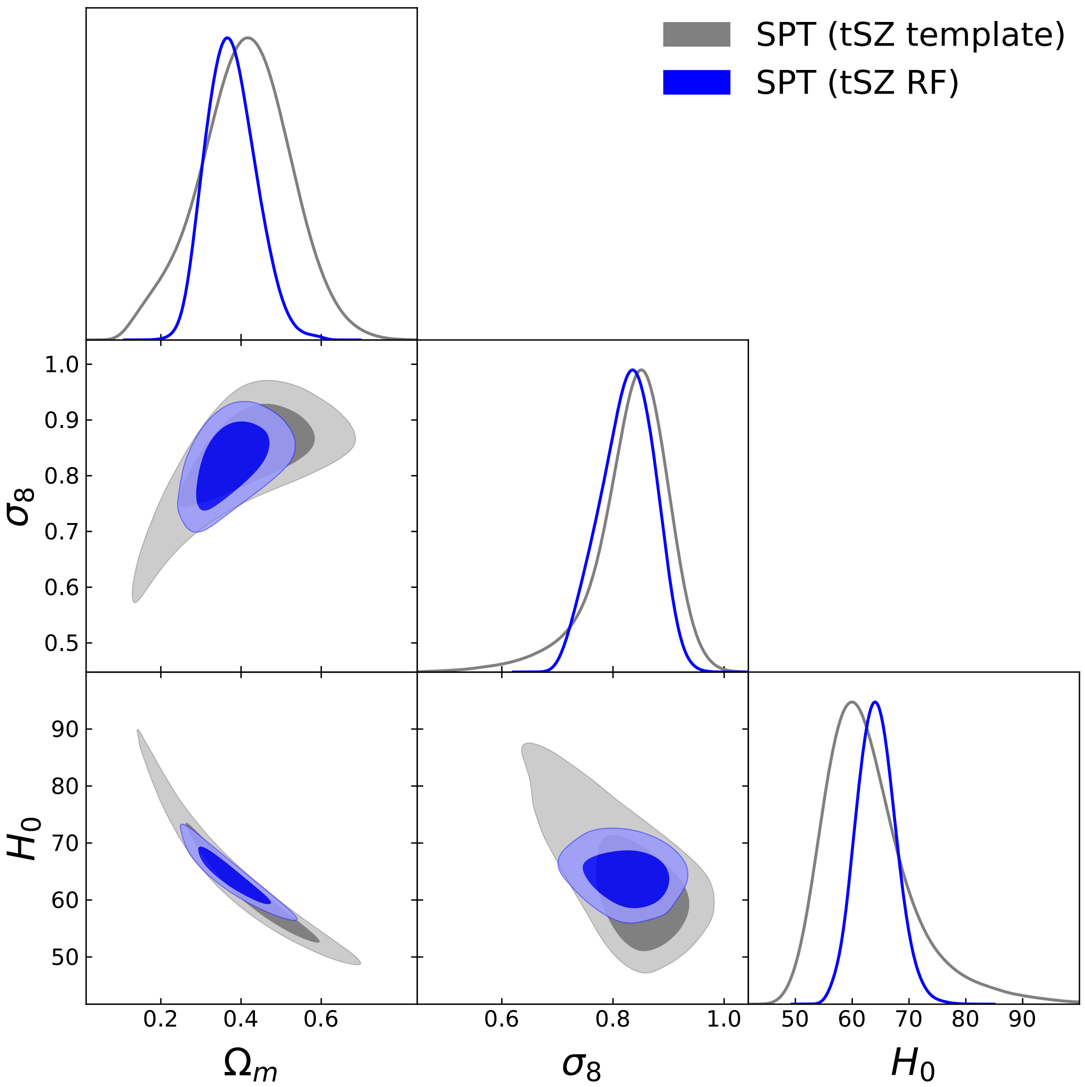
See also talk of Boris Bolliet

RESULTS ON SPT DATA: COSMOLOGY

- Effect of cosmological information of tSZ

Ω_M
Ω_b
H_0
n_s
σ_8
A_{tSZ}
$Y*$
α
$(1-b)$

+ 6 foreg
+ 4 instrum
prior on $\Omega_b h^2$
prior on n_s
prior on α
prior on $Y*$



Compatibility of results

Better χ^2 with free cosmological parameters:

Fixed Cosmo Template	Free Cosmo Template	Free Cosmo RF(Θ)
236	216	215
dof	~dof-3	~dof-3

Stronger constraints on $(\Omega_M,\ \sigma_8)$

Douspis et al. 2022

Results on SPT data: cosmology

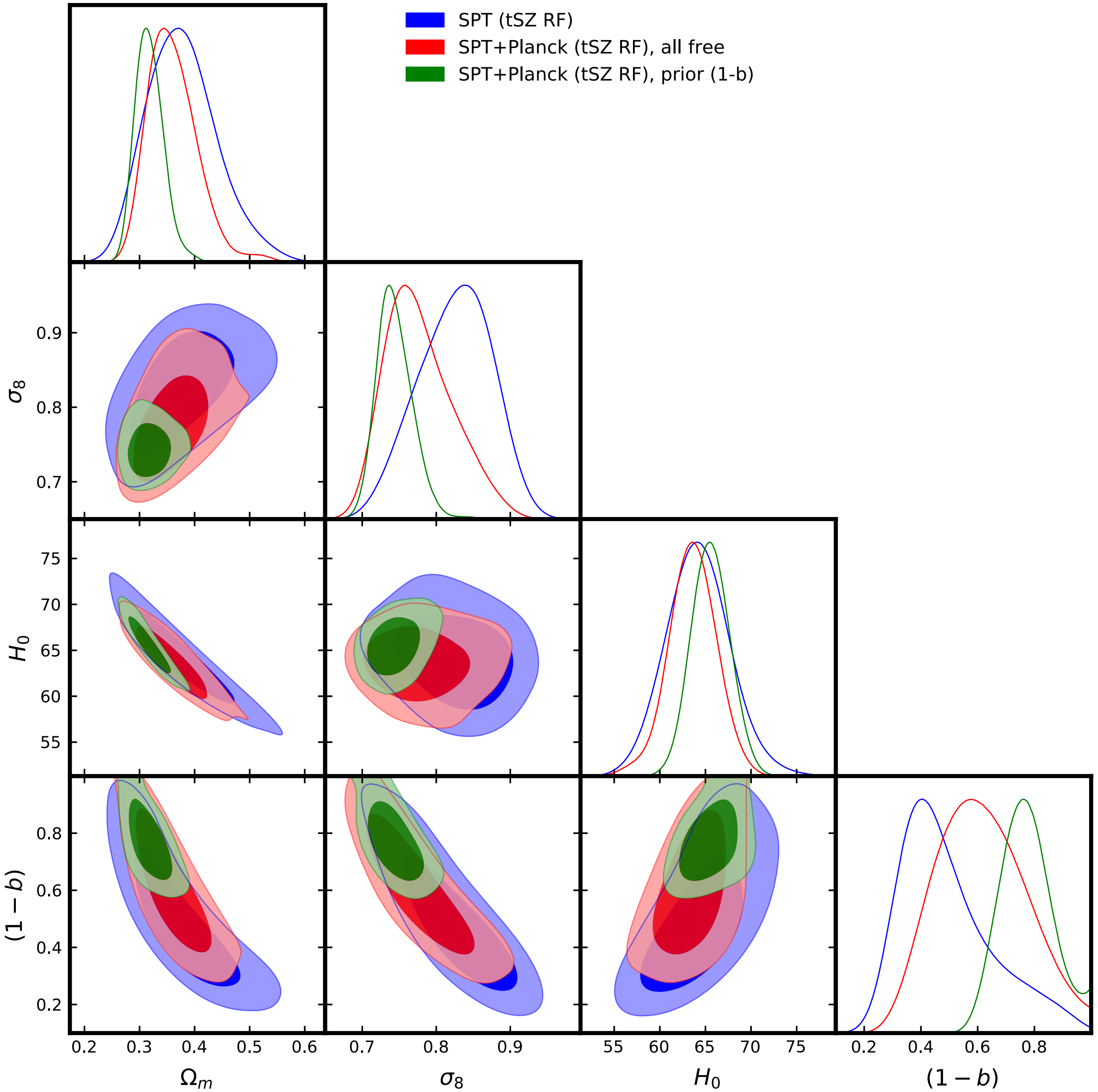
- Adding more information

Ω_M
Ω_b
H_0
n_s
σ_8

$Y*$
α
$(1-b)$

+ 6 foreg
+ 4 instrum

prior on $\Omega_b h^2$
prior on n_s
prior on α
prior on $Y*$



Adding Planck tSZ spectrum shifts parameters to more usual values of $(\Omega_M,\ \sigma_8)$
But do not improve drastically the error bars

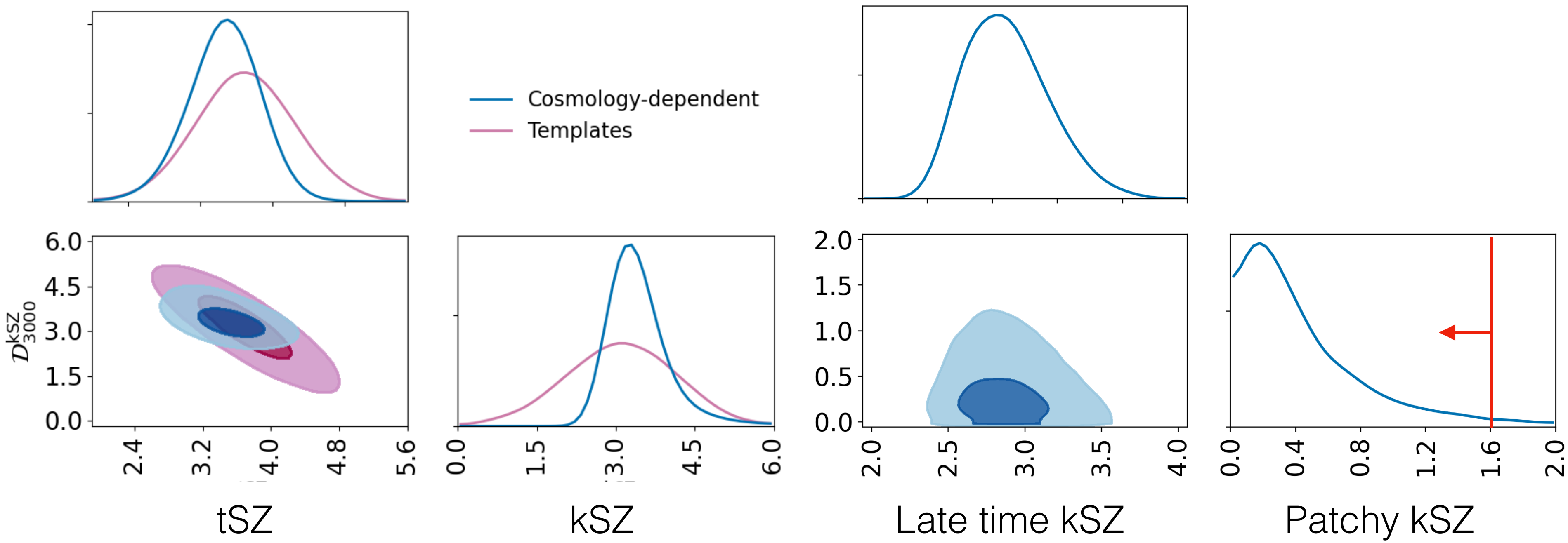
Adding Planck tSZ spectrum and prior on the mass bias reduces by factor 2 error bars

CCCP: Hoekstra et al. b=0.21±0.09

*PR4 ymap: **Tanimura** et al. 2021*
***Douspis** et al. 2022*

RESULTS ON SPT DATA: REIONISATION

- Planck 2018 priors on $\Omega_b h^2$, $\Omega_c h^2$, θ_{MC}, ns
- Flat priors on other parameters (A_s, reion)
  - Clean and consistent measurement of the tSZ and kSZ amplitudes
  - Breaks the degeneracy

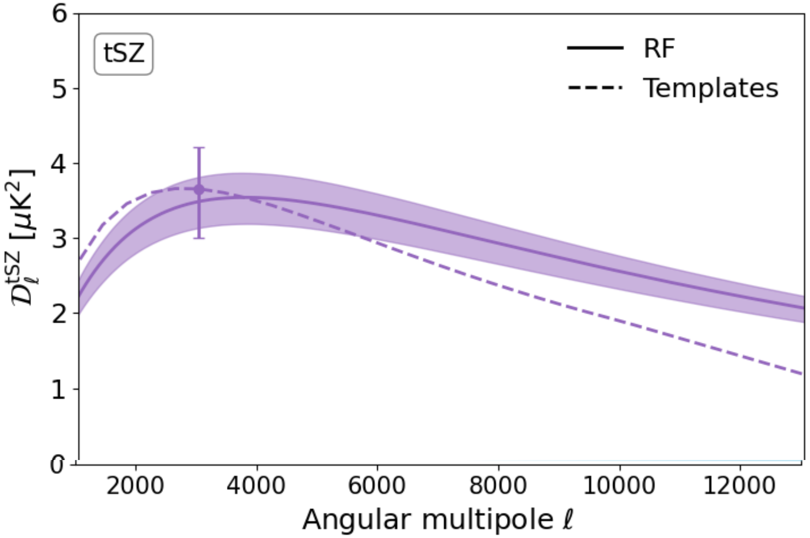


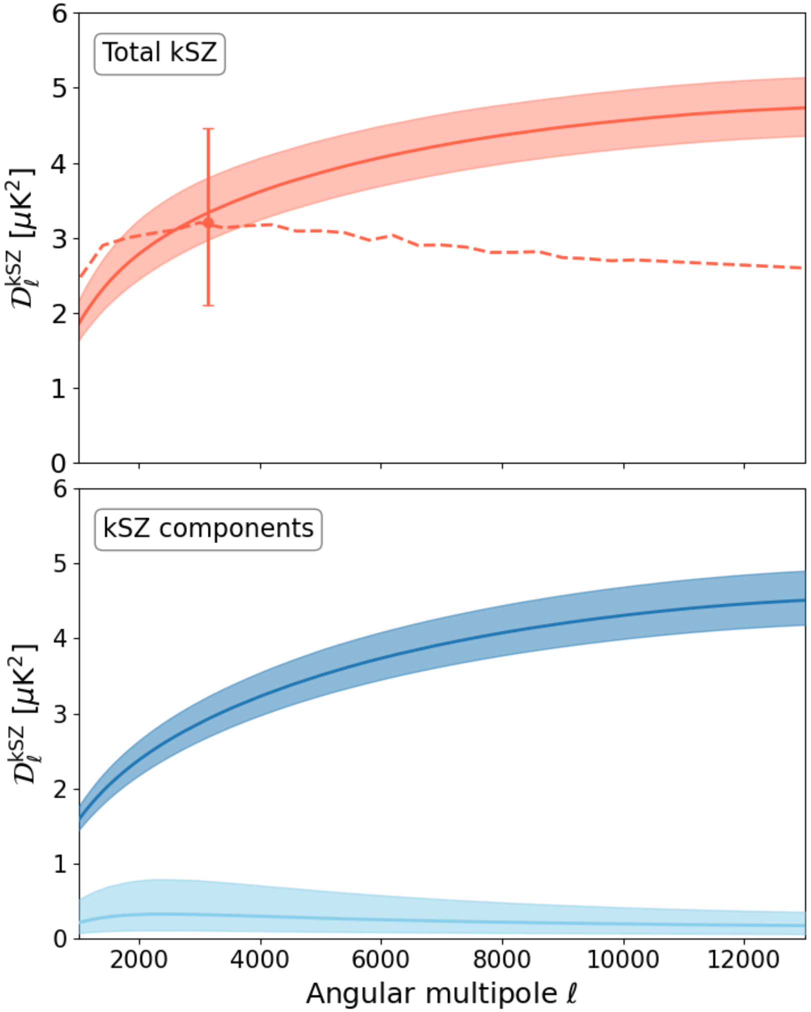
9 and 5σ measurements of tSZ and kSZ resp.

Separate components:
Late-time contributes to 85%
$D_{pkSZ} < 1.6\ \mu K2$ (95%)

Gorce, Douspis, Salvati 2022

Results on SPT data: Free cosmology



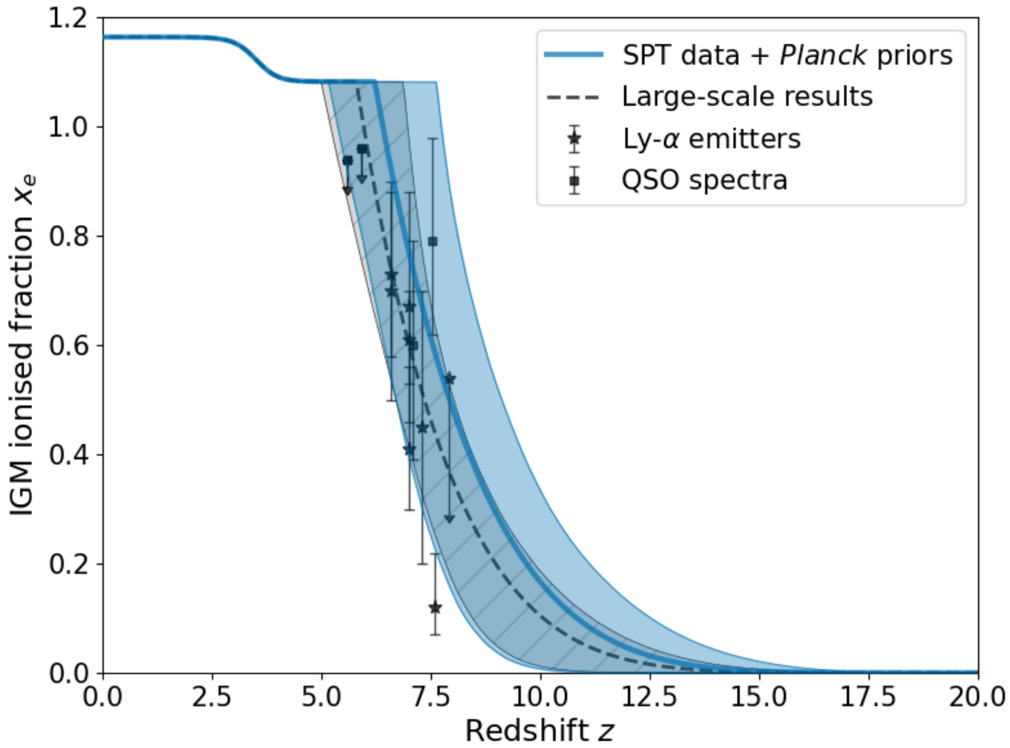


Can see the shape of the spectra!!

Gorce, Douspis, Salvati 2022

Results on SPT data: Free cosmology

- Results on epoch of reionisation: x_e



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

$\tau = 0.062 \pm 0.012$ (1σ)

$z_{re} = 7.9 \pm 1.1$ (1σ)

Gorce, Douspis, Salvati 2022

Conclusions

- First attempt to bring full information of high ell components (focusing on tSZ and kSZ)
- Already with SPT (and ACT), leveraging the cosmological information in foregrounds leads to
  - Stronger constraints on cosm. param.
  - Cleaner measurements
  - Self-consistent constraints on reionisation
- … but mostly with upcoming releases:
  - ACT/SPT/SO/CMB-S4

PROSPECTIVES

- Moving for a full all-ell cosmological analysis with coherent foregrounds extracting all cosmological information from all CMB data (PLANCK+ACT+SPT: BATMAN project)
  - Generalised Halo model / emulator to CIB, CIBxSZ cross correlation, …, for Cobaya module
  - Add coherently Cluster counts and baryon fraction

    See also talk of Raphael Wicker
  - Joint constraints of kSZ with other data sets
- Emulator 100 times faster, allows to make many tests: tSZ and kSZ, available with other products:

  https://szdb.osups.universite-paris-saclay.fr

Thank you

Better Accuracy and robusTness for Mass Assessment of Neutrinos