Coherent analysis of CMB primary and secondary anisotropies

Marian Douspis

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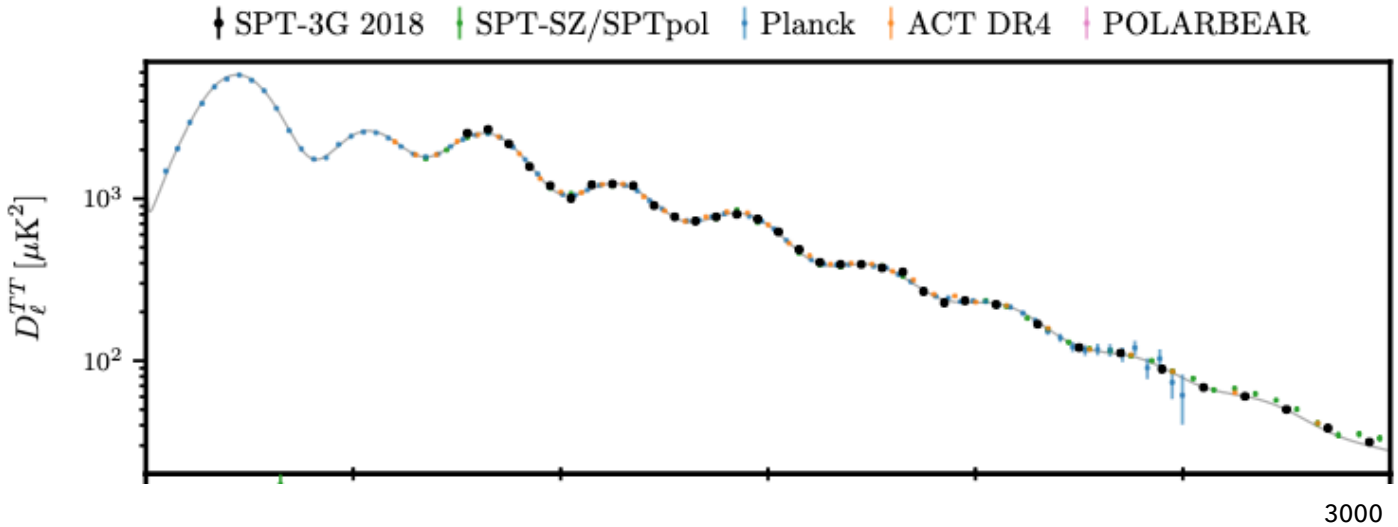
"Improved constraints on reionisation from CMB observations: A parameterisation of the kSZ effect", *Gorce, Ilic, Douspis, Aubert, Langer, A&A 2020, arXiv:2004.06616*

"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*

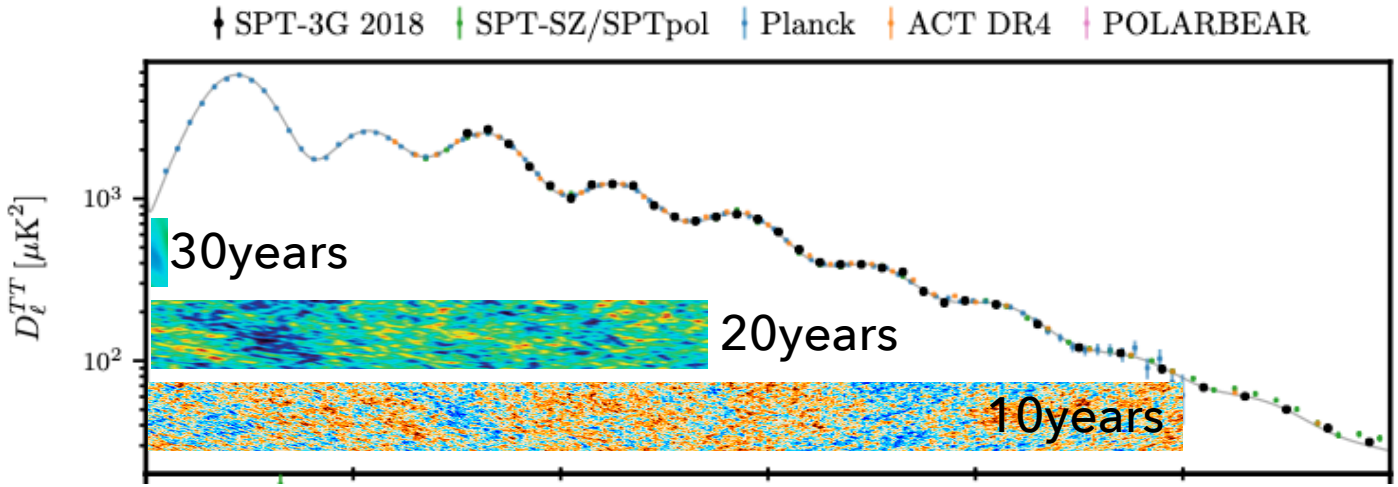
"Retrieving cosmological information from small-scale CMB foregrounds II. The kinetic Sunyaev Zel'dovich effect", *Gorce, Douspis, Salvati, A&A 2022, arXiv:2202.08698*

CMB TEMPERATURE SPECTRUM



Balkenhol et al. 2023

CMB TEMPERATURE SPECTRUM



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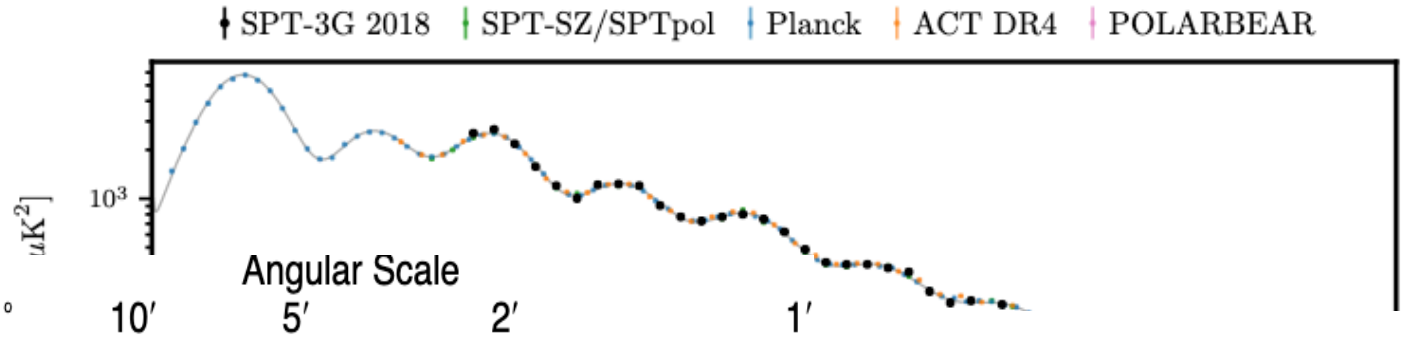
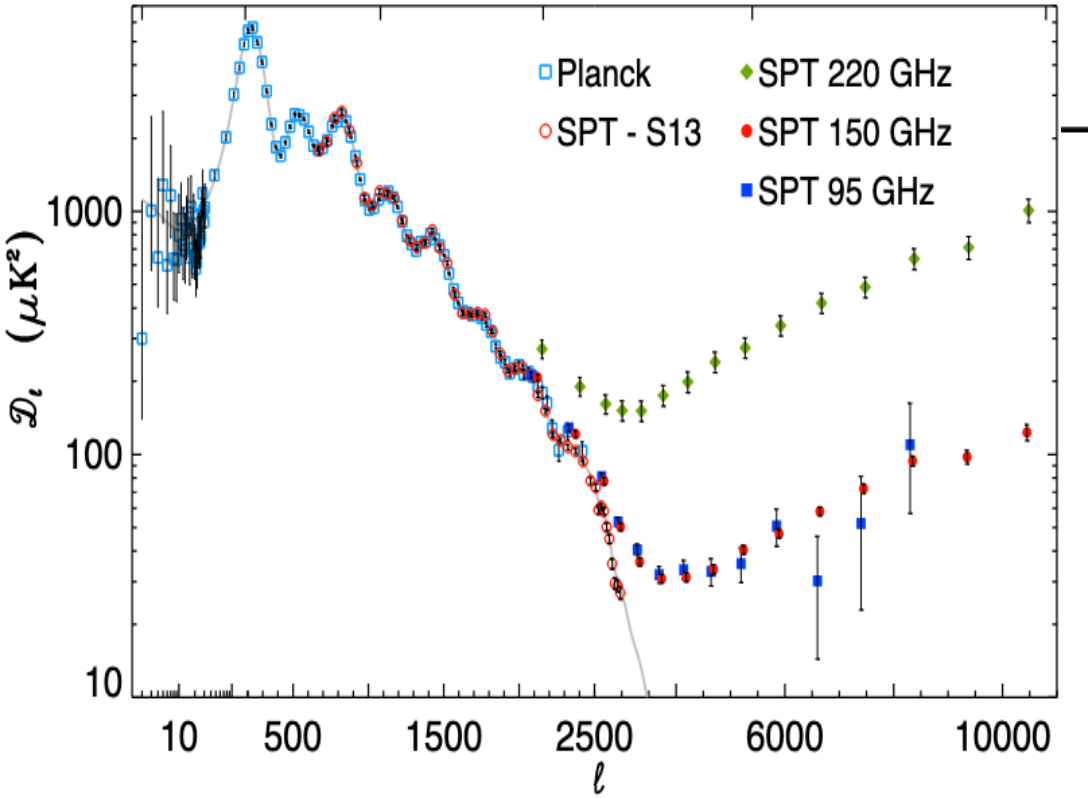
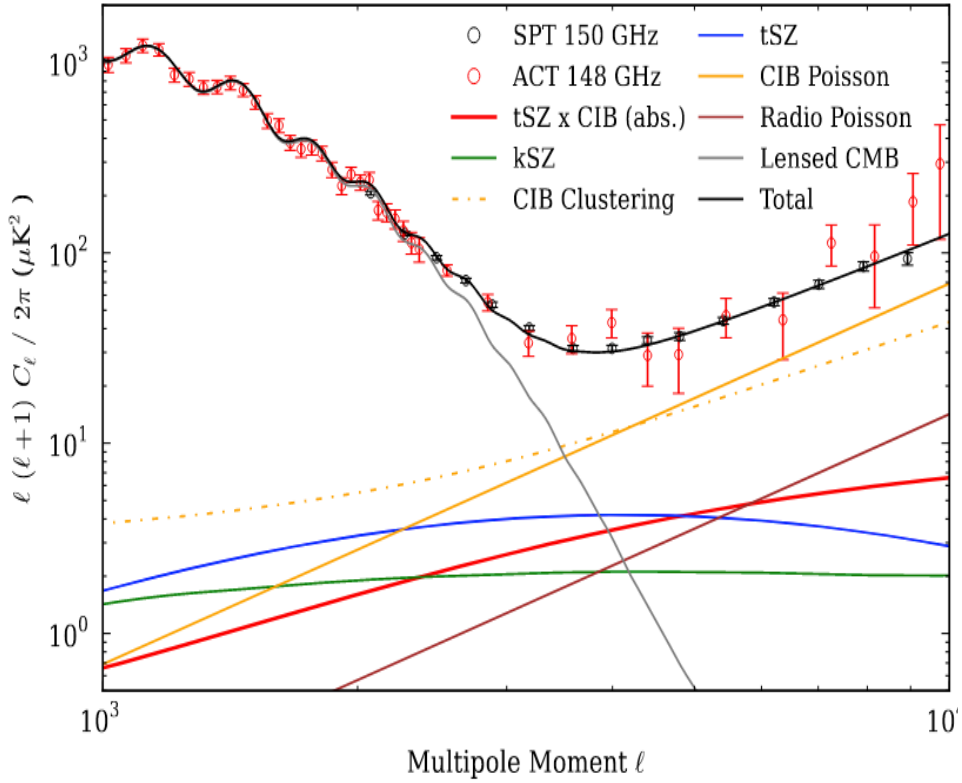


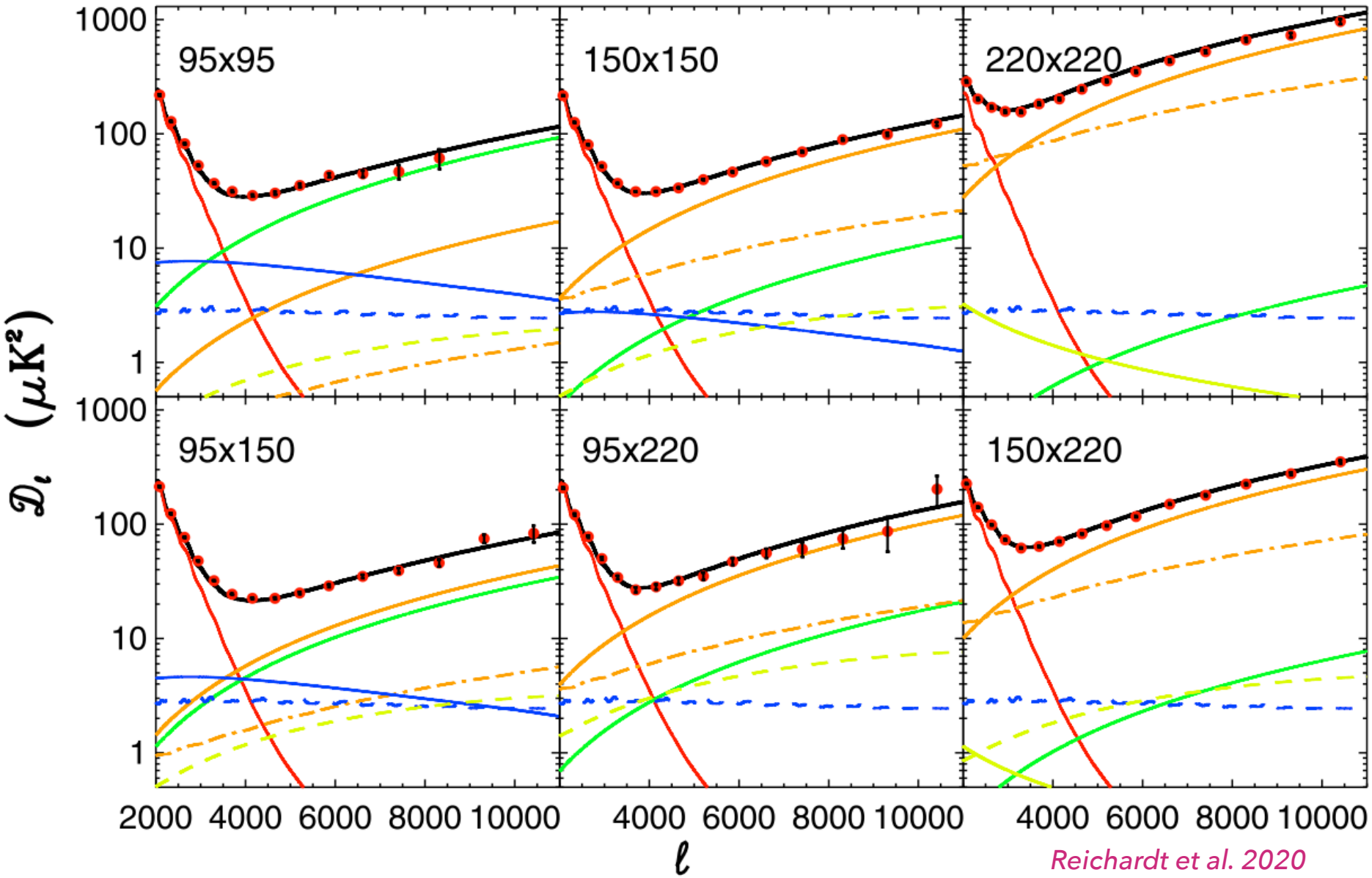


George et al. 2014



Addison et al. 2012

CMB TEMPERATURE SPECTRUM



Reichardt et al. 2020

Total — tSZ — DSFG Poisson — Radio Poisson — abs(tSZ-CIB)

CMB — kSZ — DSFG Clustering — Gal. Cirrus

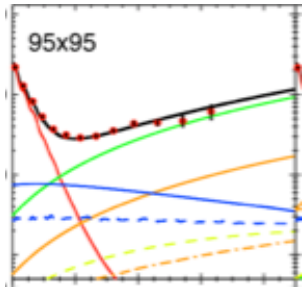
Secondary anisotropies

- Thermal Sunyaev Zeld'ovich effect : tSZ
- Kinetic Sunyaev Zeld'ovich effect : kSZ
- Cosmic Infrared Background : CIB
- tSZ x CIB
- Infrared point sources
- Radio point sources

CURRENT HIGH ELL ANALYSES

$$C_\ell^{obs} = C_\ell^{CMB}(\Theta) + C_\ell^{tSZ} + C_\ell^{kSZ} + \dots$$

For all 6 cross spectra simultaneously



SPT/Planck/ACT analysis uses templates for tSZ and kSZ

$$C_\ell^{tSZ} = A^{tSZ} \times C_\ell^{template}$$

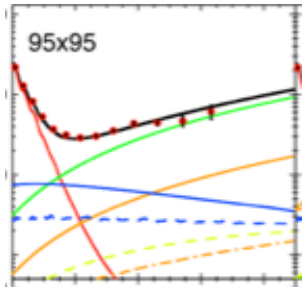
$$C_\ell^{kSZ} = A^{kSZ} \times C_\ell^{template}$$

Then marginalize over A^{tSZ} and A^{kSZ} to retrieve Θ

CURRENT HIGH ELL ANALYSES LIMITATIONS

$$C_\ell^{obs} = C_\ell^{CMB} + C_\ell^{tSZ} + C_\ell^{kSZ} + \ldots$$

For all 6 cross spectra simultaneously



SPT/Planck/ACT analysis uses templates for tSZ and kSZ

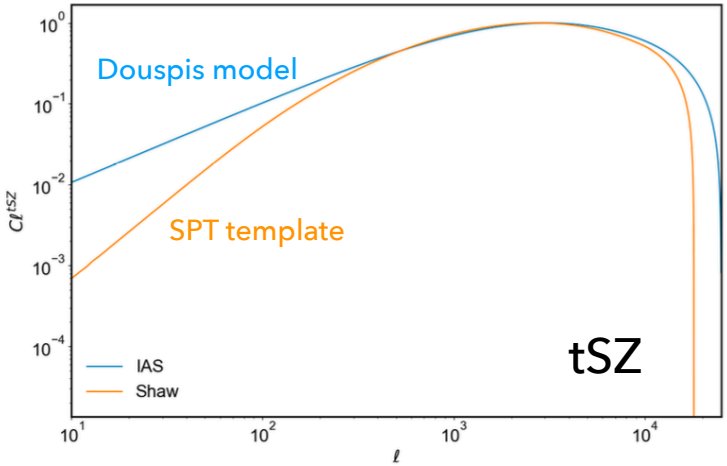
$$C_\ell^{tSZ} = A^{tSZ} \times C_\ell^{template}$$

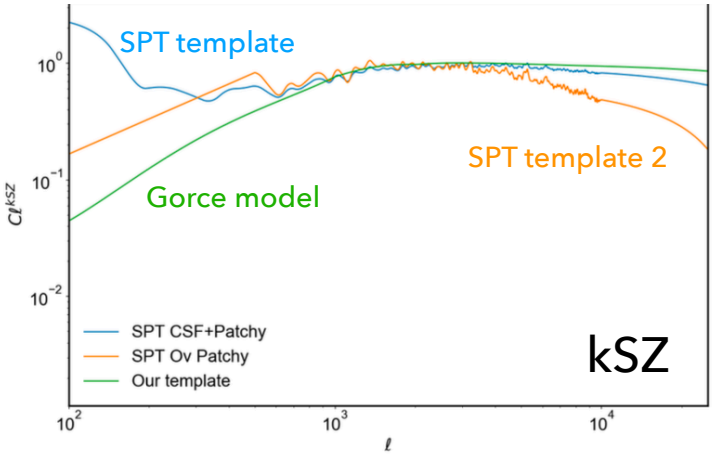
Sims with cosmo1

$$C_\ell^{kSZ} = A^{kSZ} \times C_\ell^{template}$$

Sims with cosmo2

- Not coherent analysis
- Depends on assumed template





Secondary anisotropies

- Thermal Sunyaev Zeld'ovich effect : tSZ Θ

  *Hu & Seljak, **Taburet et al.**, **Planck 2013** , Bolliet et al., **Salvati et al.***

- Kinetic Sunyaev Zeld'ovich effect : kSZ Θ, reio

  *Sunyaev & Zel'dovich, Mc Quin et al., Mesinger et al., Zahn et al., **Planck 2016**, **Gorce et al. 2020***

- Cosmic Infrared Background : CIB Θ, galprop

  Puget et al., Lagache et al., Knox et al., Maniya et al.

- tSZ x CIB Θ, galprop

  *Addison et al. , **Hurier et al.***

- Infrared point sources

- Radio point sources

Secondary anisotropies

- Thermal Sunyaev Zeld'ovich effect : tSZ Θ

Known spectral signature Spatial: Halo model, simulations Scaling relation, P profile

- Kinetic Sunyaev Zeld'ovich effect : kSZ Θ, reio

Known spectral signature Spatial: semi-analytical, simulations Reion history

- Cosmic Infrared Background : CIB Θ, galprop

Approximated spectral signature Spatial: halo model, simulations Gal emissivity

- tSZ x CIB Θ, galprop

Approximated spectral signature Spatial: halo model+, approximation, simulations

- Infrared point sources

Mask dependent

- Radio point sources

Mask dependent

Secondary anisotropies

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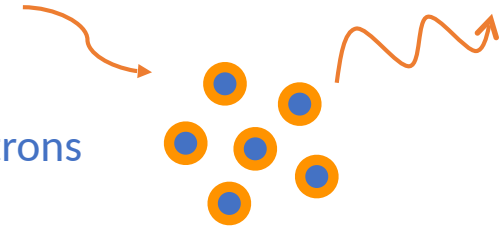
- Radio point sources

Mask dependent

The Sunyaev Zel'dovich effects

Thermal SZ

CMB photon

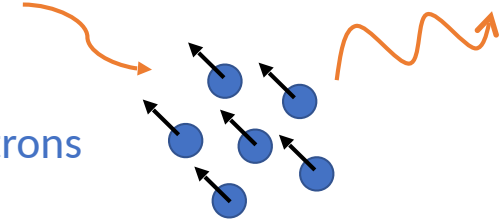


Free electrons

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

Kinetic SZ

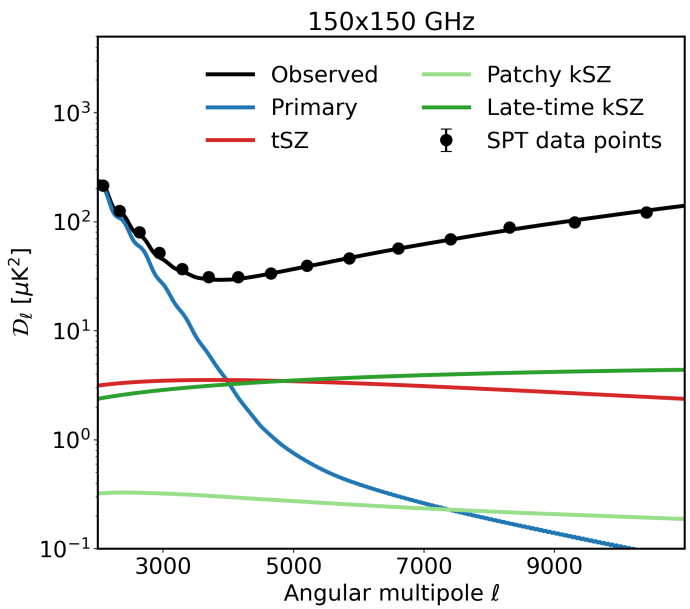
CMB photon



Free electrons

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

Gas Pressure



Reionisation epoch

+

Late gas distribution

tSZ power spectrum from Halo Model

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

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., ...]*

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

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]*

Cosmology Θ

SZ power spectrum as geometrical and growth probe

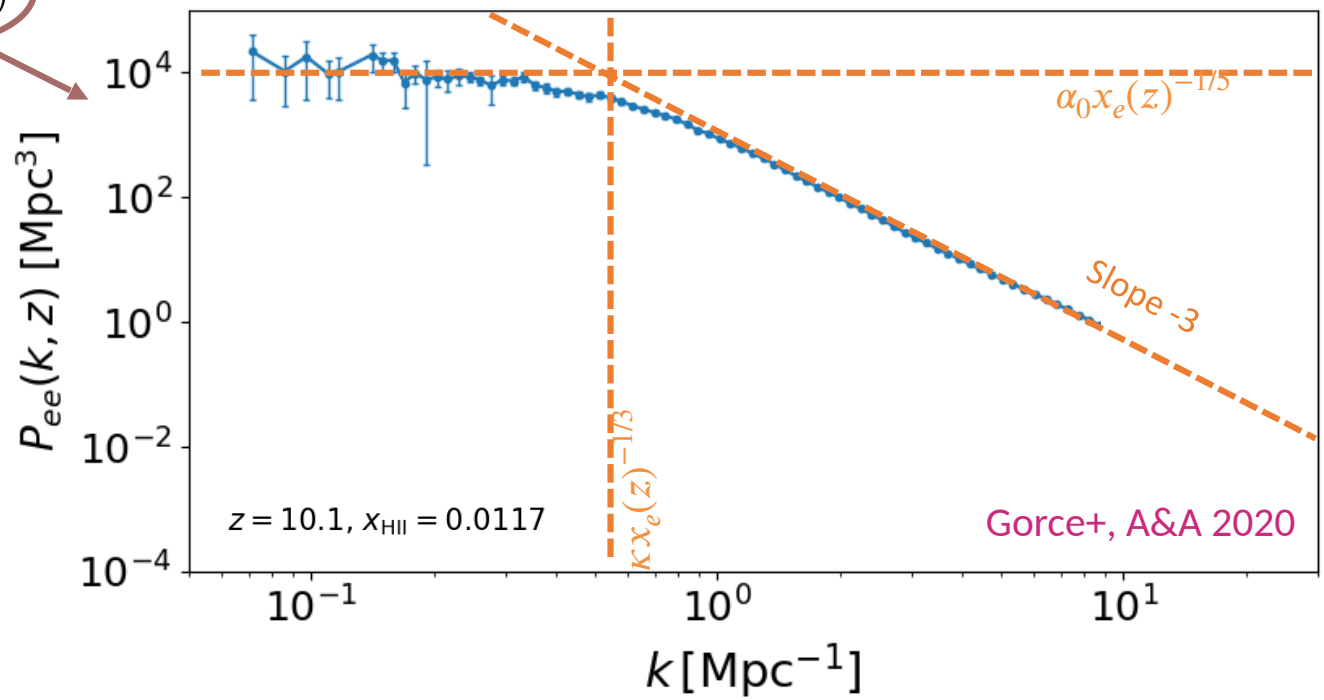
Deriving the kSZ power spectrum

Shape

Amplitude

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

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



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

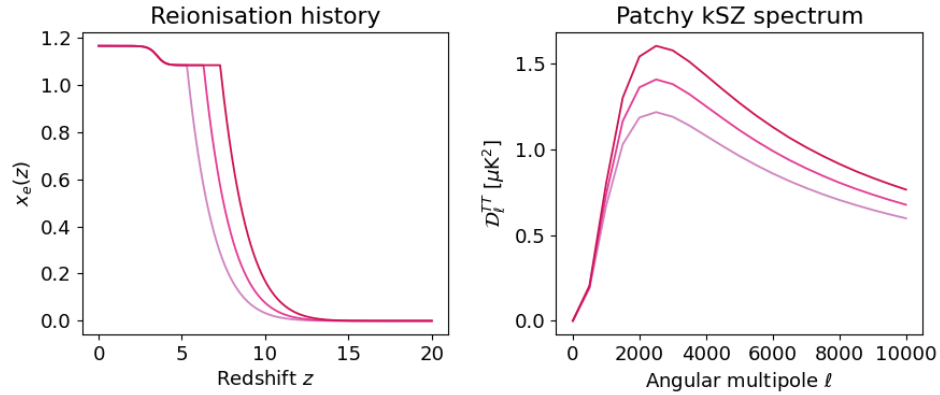
High redshift
(Power-law)
Gorce et al. 2020

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

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

THE kSZ POWER SPECTRUM INFORMATION

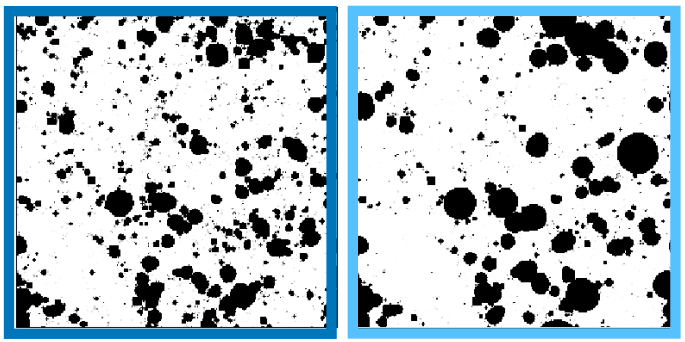
- Information on reionisation history



- Information on reionisation morphology

rsage simulations at x_{HII} = 0.30

Seiler+2019



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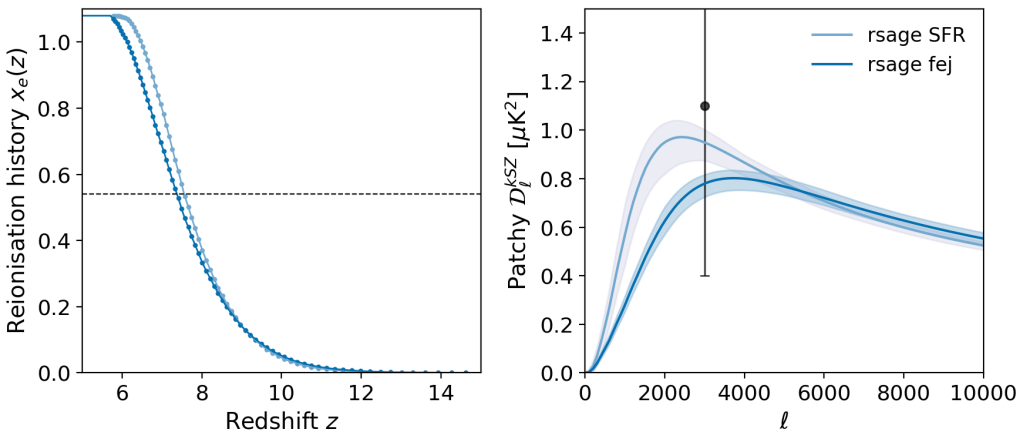


Gorce+2020, see also McQuinn+2005; Iliev+2007; Battaglia+2013; Mesinger+2012, Park+2013, Chen+2022…

NEW HIGH-L ANALYSES

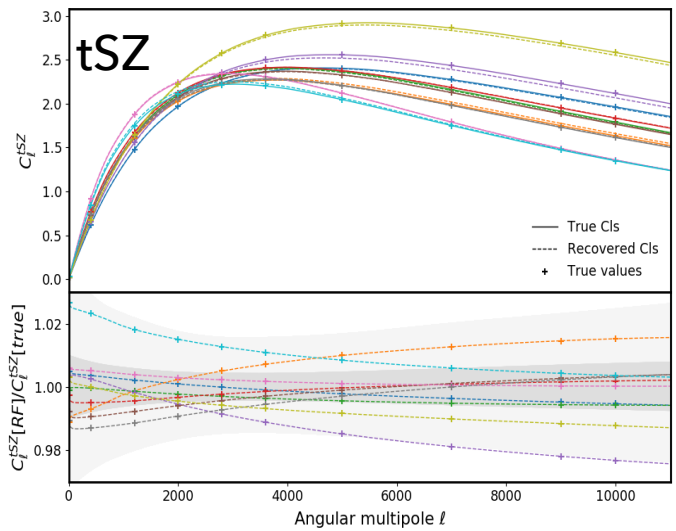
- There is information about cosmology and reionisation in the tSZ and kSZ spectra…

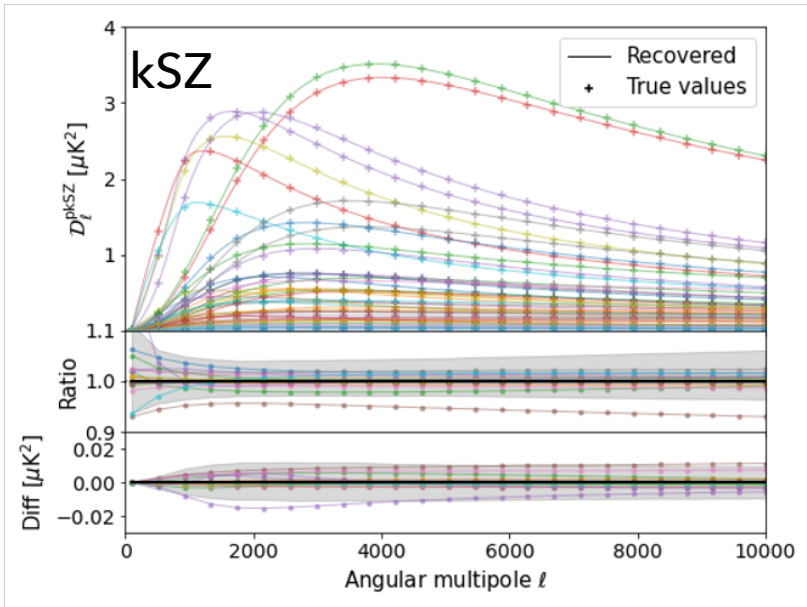
  … but it is not used in current analyses, resulting in imprecise constraints

- Proposed solution:
  - Replace templates by analytic derivations of the SZ spectra to retrieve the cosmological information enclosed in the foregrounds *(Douspis, Aghanim, Langer 2006)*
  - 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…)

EMULATING TKSZ POWER SPECTRA

- Training Random forest with random values of ~10 params on 25 l-values of the Cls (l=100 to l=10500) [scikit-learn]
  - 5 cosmo + 2 Reio + 2 kSZ + 3 tSZ
- Training 50000 models (test on 20%)
- RF Score of 99%





- Reconstruction error < 5%
  - (<1% late time) —> error < 0.02 μK² vs Obs err. ~ 0.4 μK²

100 to 1000 times faster

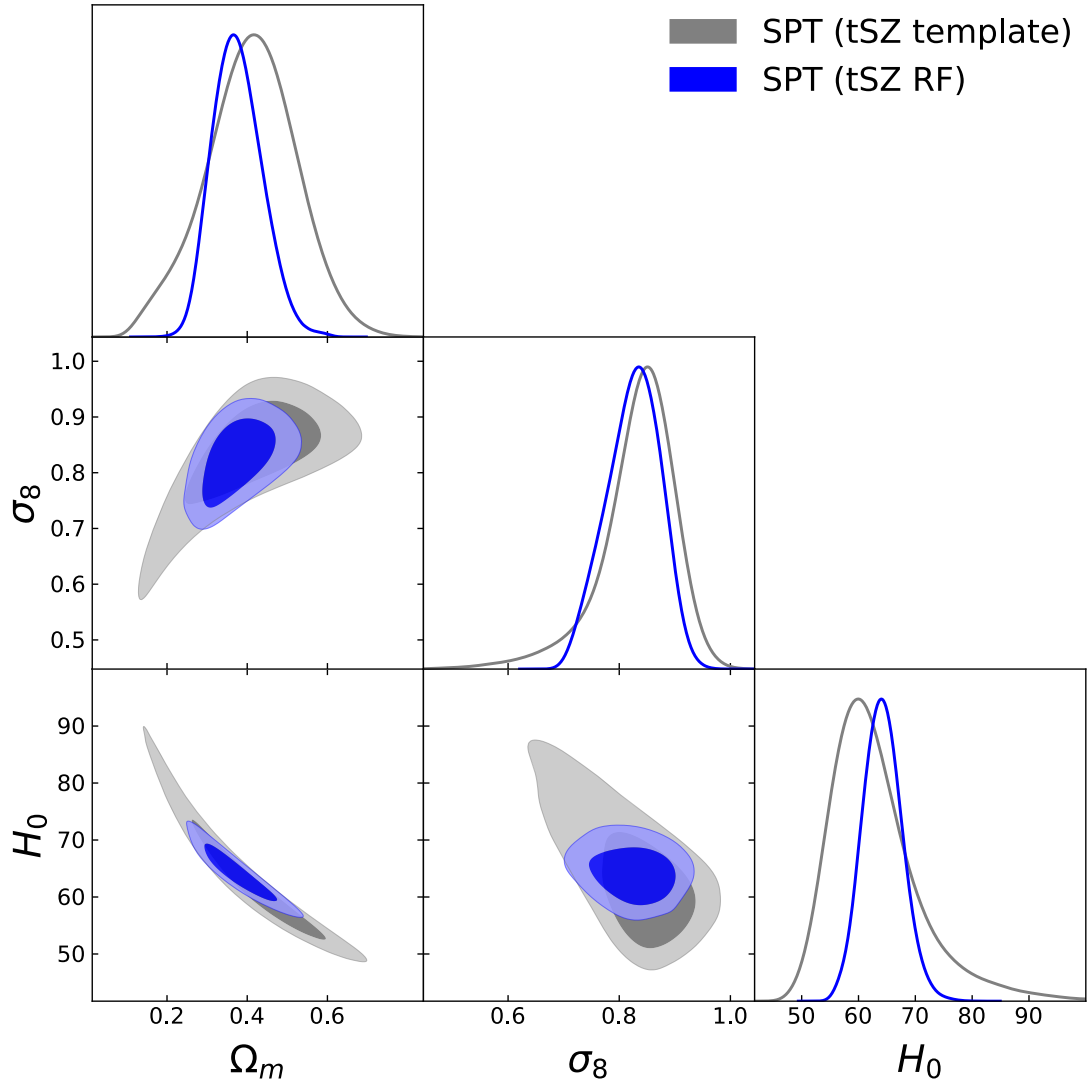
New Analysis of SPT: cosmological parameters

- 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 $Y*$



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

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

Douspis et al. 2022

New Analysis of SPT and SPT+Planck

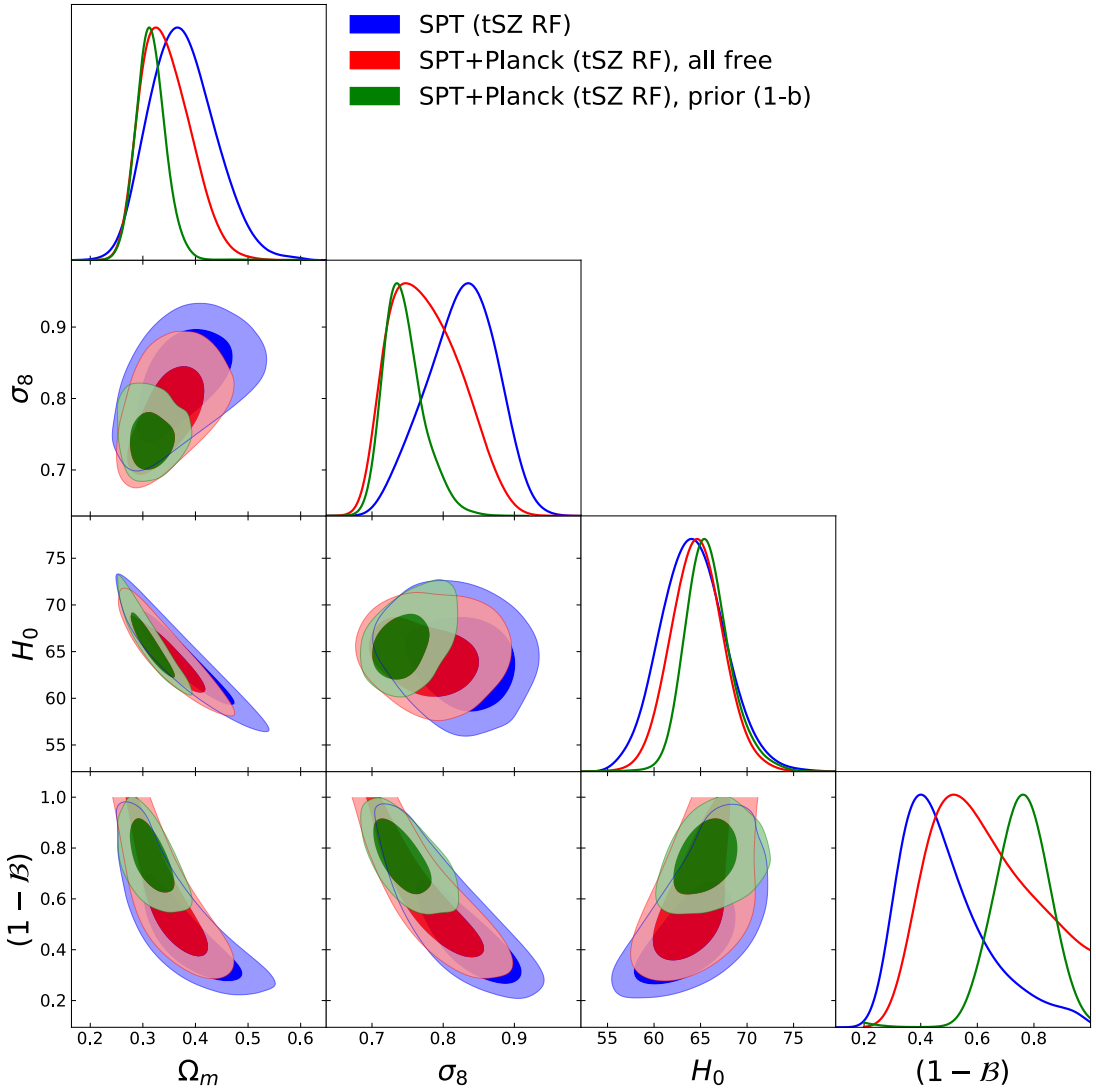
- Adding more information

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

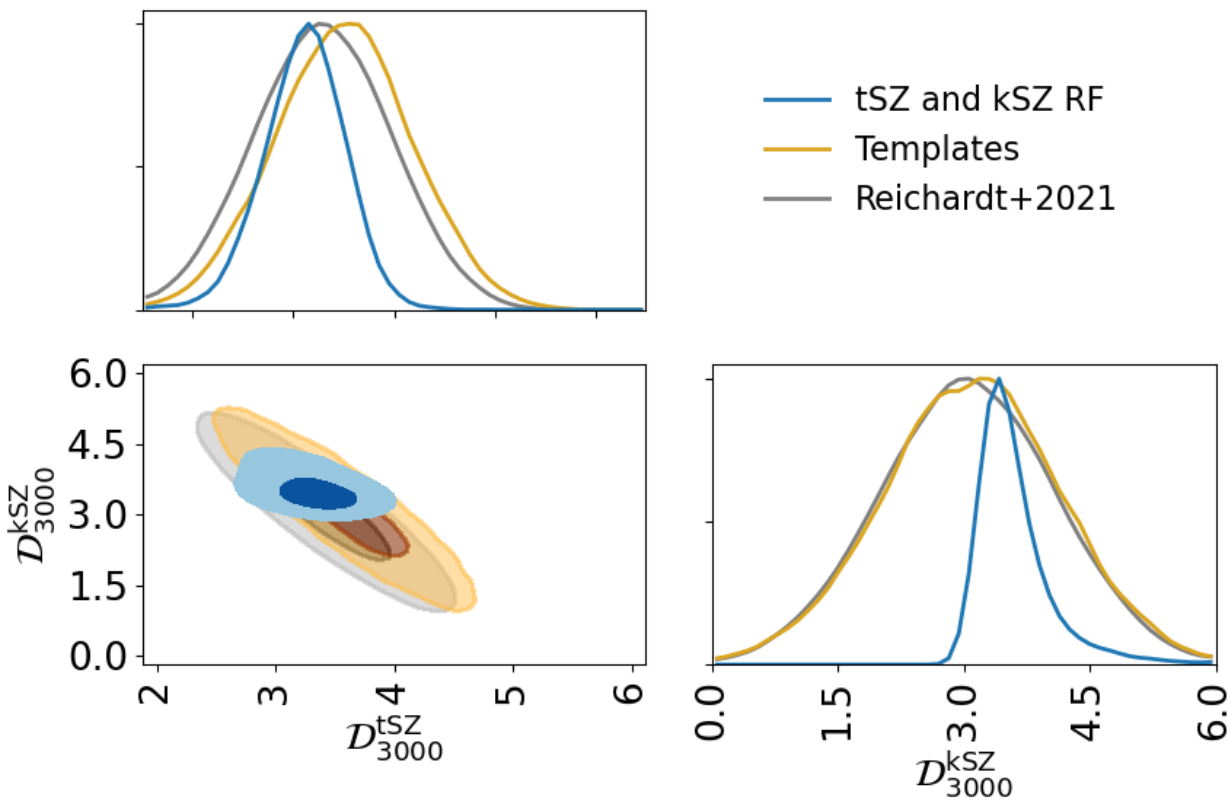
Adding Planck tSZ spectrum and prior on the mass bias reduces by factor 2 error bars

CCCP: Hoekstra et al.

***Douspis** et al. 2022*

New Analysis of SPT: fixed cosmo

- 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

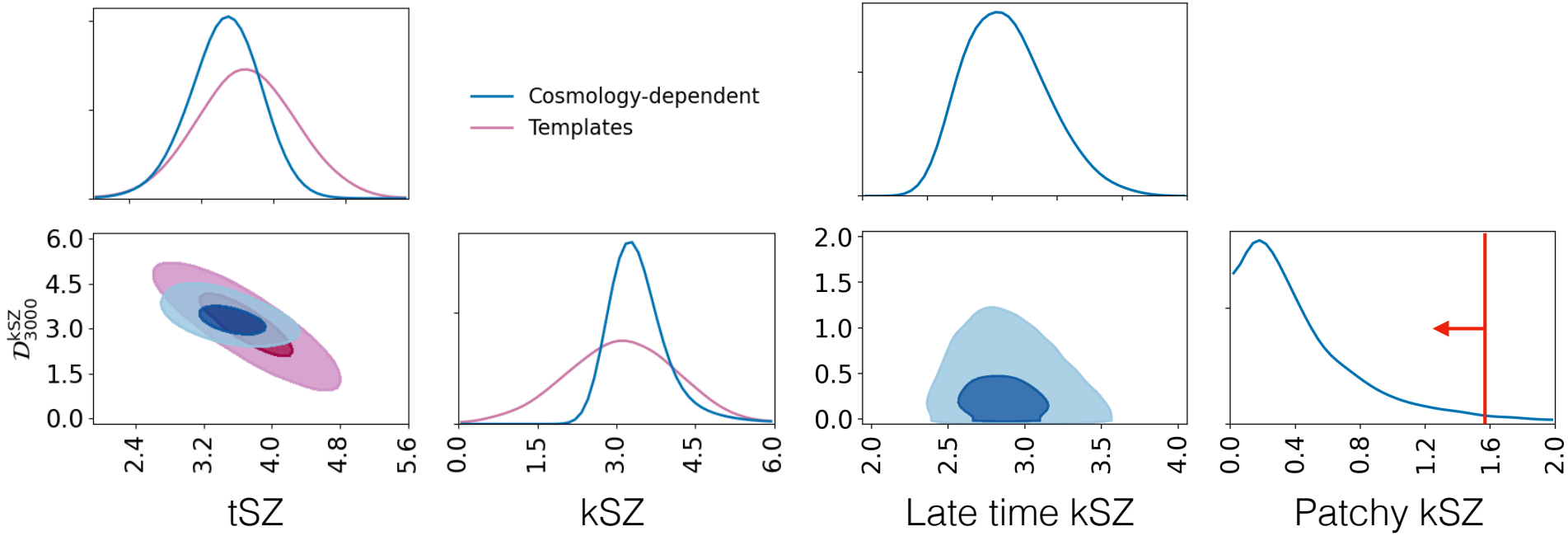
Results on SPT data: Fixed cosmology

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

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

New Analysis of SPT: 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)



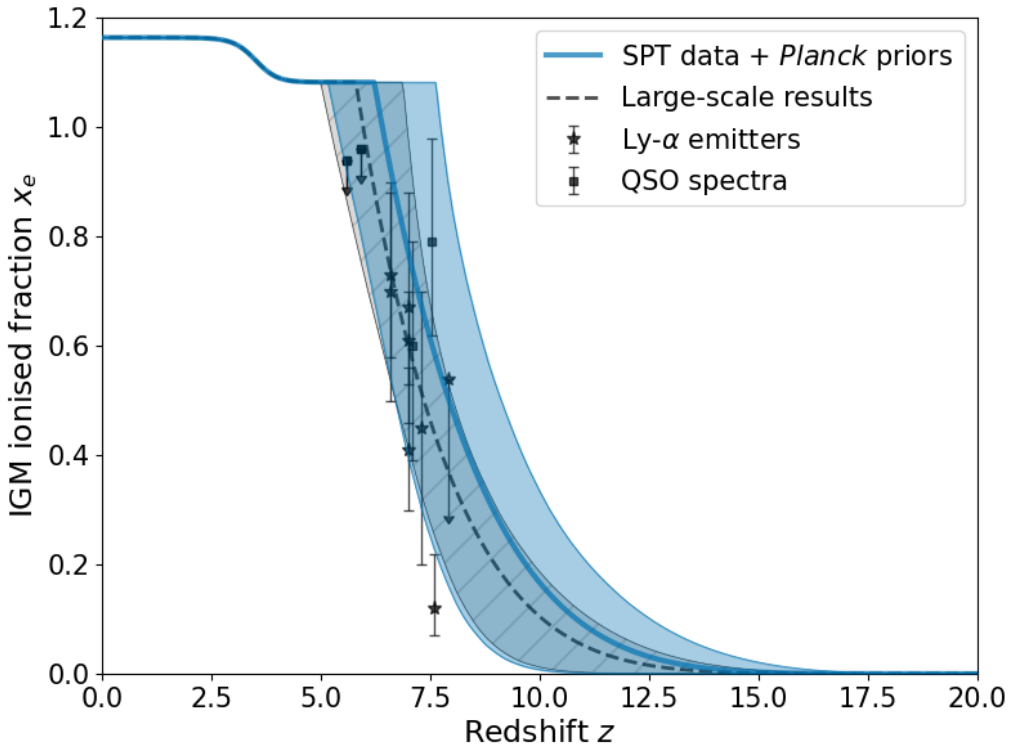
9 and 5σ measurements of tSZ and kSZ resp.

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

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)

$z_{re} = 7.9 \pm 1.1$ (1σ)

Gorce, Douspis, Salvati 2022

Conclusions

- There is potential in the small-scale CMB, even at the 2-point level
  - Already with SPT, leveraging the cosmological information in secondaries leads to :
    - Improved cosmological parameter constraints
    - cleaner measurements
    - Self-consistent constraints on reionisation:

$D_{kSZ} = 3.4 \pm 0.5\ \mu K2,\ 1\sigma$ $\quad$ $z_{re} = 7.9 \pm 1.1\ (1\sigma)$

$D_{pkSZ} < 1.59\ \mu K2\ (95\%\ C.L.)$ $\quad$ $\tau = 0.062 \pm 0.012$

Perspectives

- Improve modelling of other foregrounds, and emulators
- Consistent analysis with small/large-scale data:
  - Using Planck, SPT high-ell/3G, ACT
  - Improve Reionisation information to tackle neutrino mass (BATMAN ANR)
- Joint constraints of CMB with other reionisation probes
- Waiting for SO and S4…
- tSZ & kSZ emulators are public and available:

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