Small-scale CMB anisotropies for Cosmology and Reionization

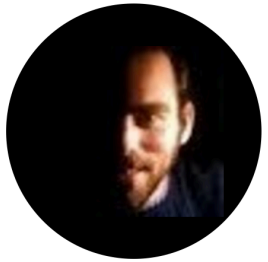
Marian Douspis

Adélie Gorce, Laura Salvati, Mathieu Tristram

and the BATMAN collaboration







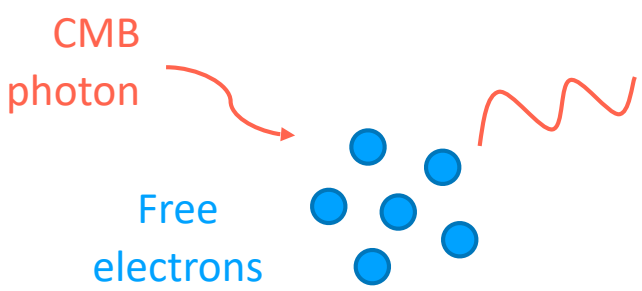
CAMPUS FRANCE PHC STAR

cnrs université PARIS-SACLAY

anr agence nationale de la recherche

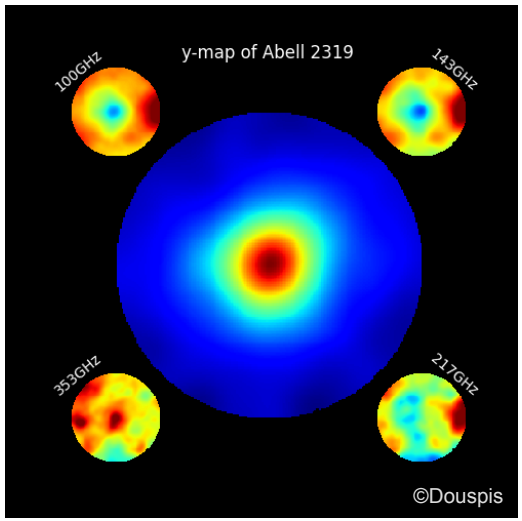
THE SUNYAEV ZEL'DOVICH EFFECTS

Thermal SZ



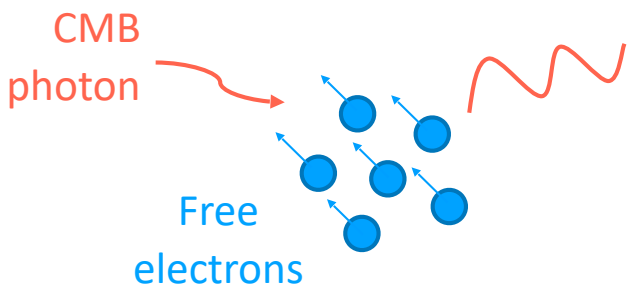
$$y = \int \frac{k_B T_e}{m_e c^2} n_e \sigma_T dl$$

Hot and dense gas : late universe



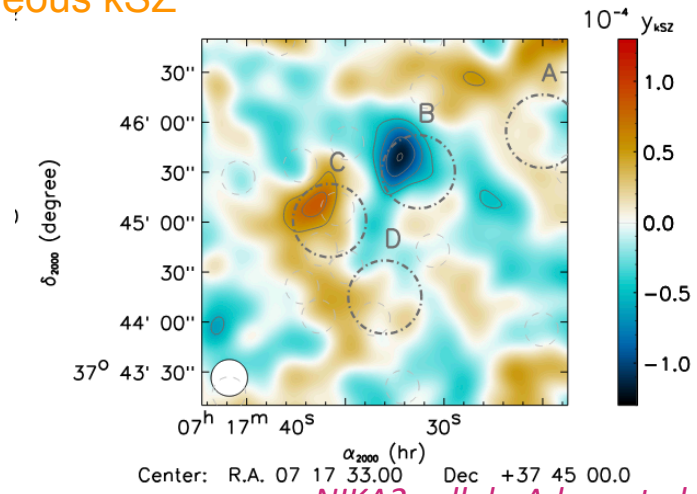
Planck collab.

Kinetic SZ



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

Bulk motion in reionised gas in late universe
→ homogeneous kSZ

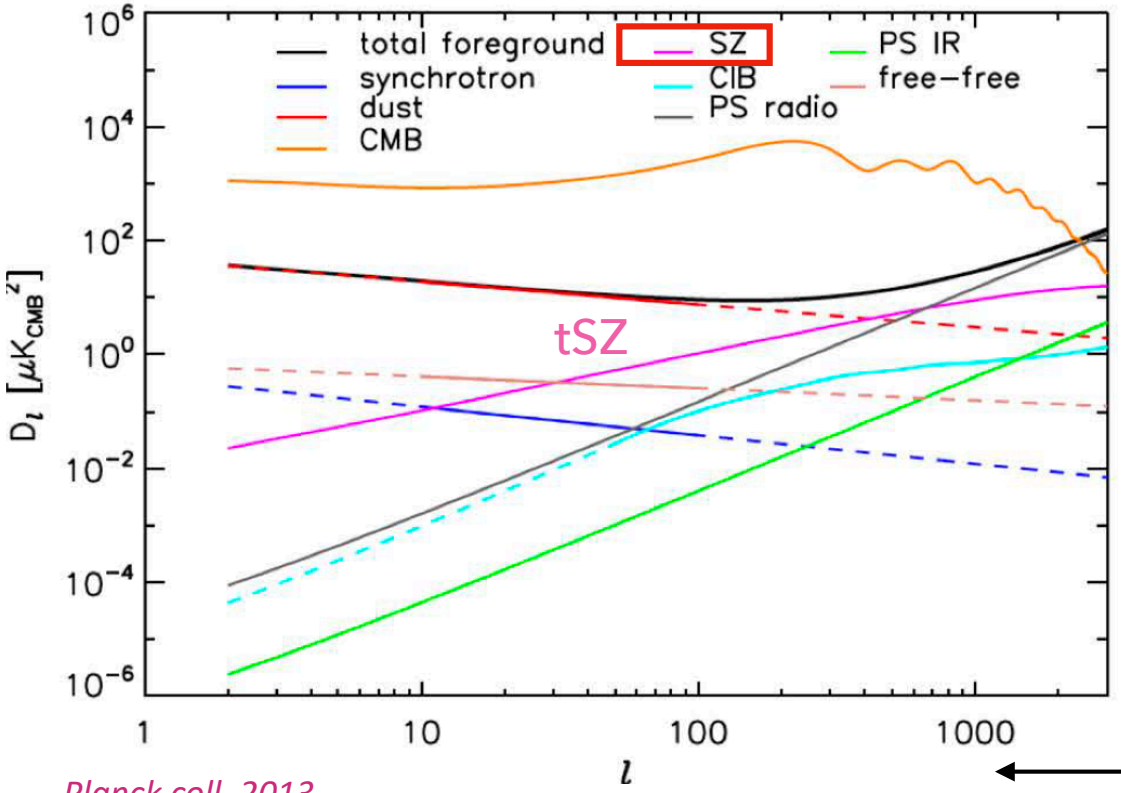


NIKA2 collab. Adam et al.

Bulk motion in reionised bubbles in reionisation era
→ patchy kSZ

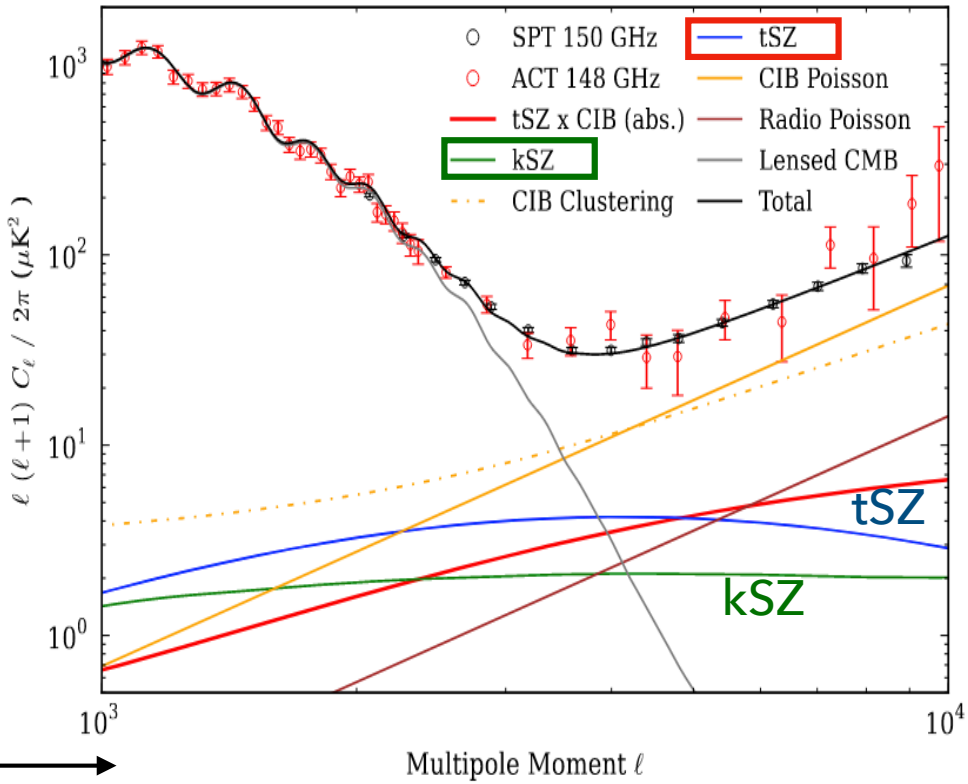
SECONDARIES IN CMB ANALYSES

Planck/Large scales



Planck coll. 2013

SPT/small scales



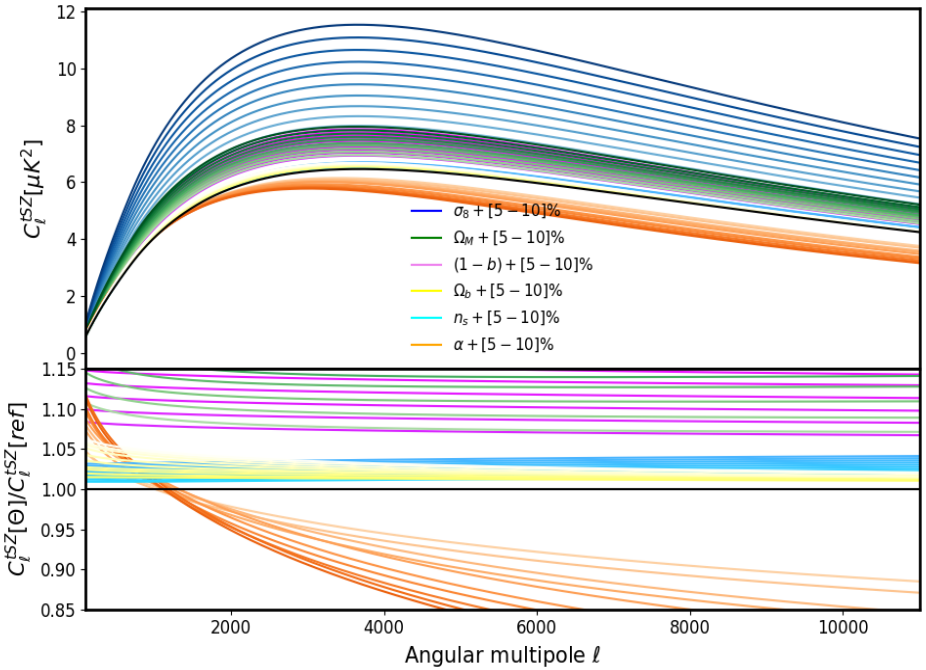
Addison et al. 2012

- tSZ/kSZ is hidden among many other signals
- tSZ/kSZ not negligible at small scales as Primordial CMB damped
  - ➡ transform contaminents in cosmology probes

THE SUNYAEV ZEL'DOVICH EFFECTS

tSZ

1. Probes cosmology (mostly Ω_m and σ_8)



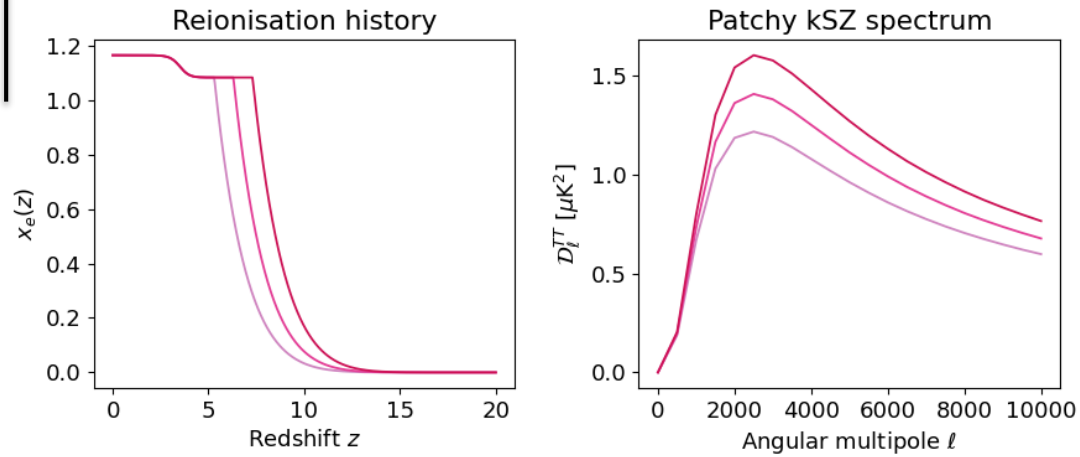
2. Probes astrophysics of clusters/groups

scaling relation, pressure profile,
hydrostatic mass bias

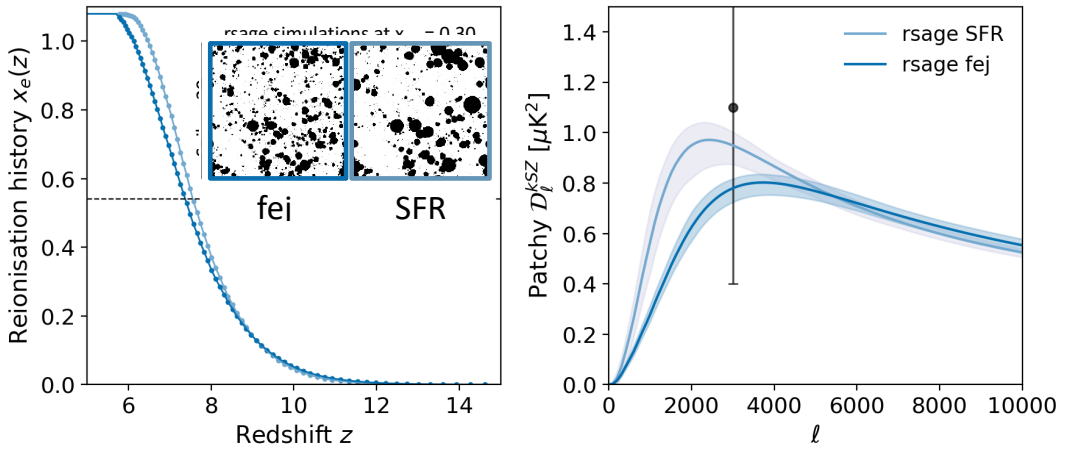
Komatsu & Seljak, Taburet et al 2009, Bolliet et al., Salvati et al. , Planck collab., Douspis et al

kSZ (patchy)

1. Probes global reionisation history



2. Probes reionisation morphology (and effectively galaxy properties)



Gorce+2020, see, e.g., McQuinn+2005; Iliev+2007; Battaglia+2013; Park+2013; Paul+2021, Chen+2023...

IMPROVING THE CMB ANALYSES

- Let's exploit the full cosmological information of extragalactic components (tSZ, kSZ, …) in CMB analyses in coherent modelling and coherent analyses !

Douspis et al 2006

Replace in SPT analysis *Reichardt et al 2021*

Reionisation

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

Cosmology

By

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

Halo model

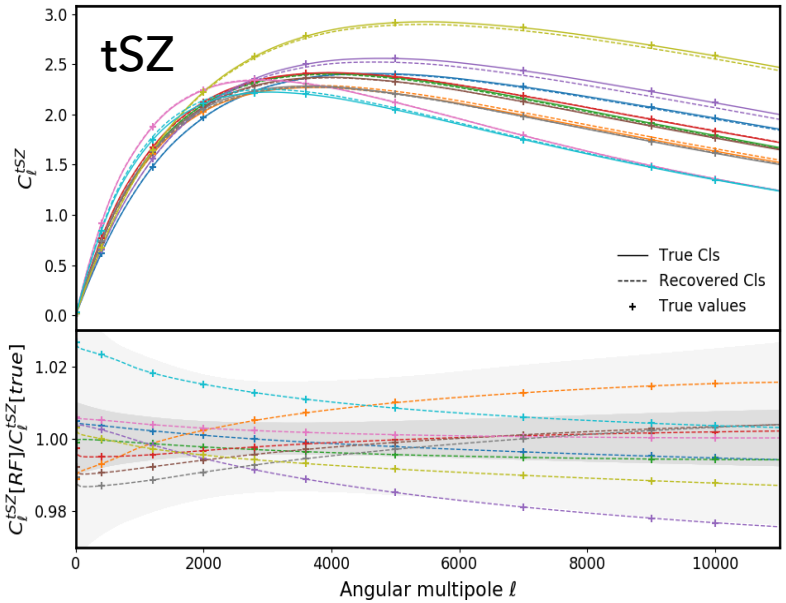
Semi-analytical model

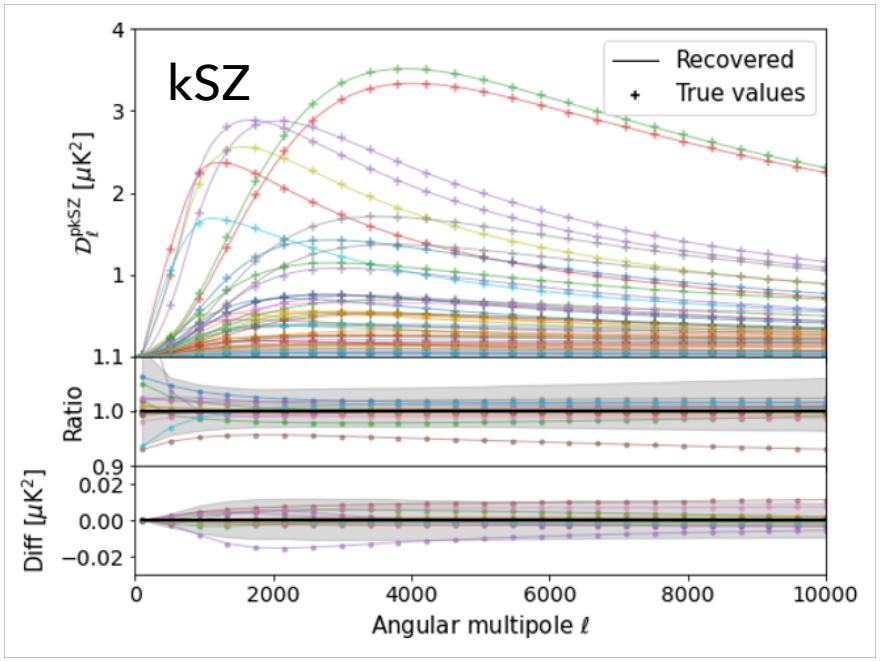
Taburet et al. 2009, Douspis, Salvati, Gorce, Aghanim 2022

Gorce et al 2020, Gorce, Douspis, Salvati 202.

EMULATING TKSZ POWER SPECTRA

- Training Random forest on 5 cosmo + 2 Reio + 2 kSZ + 3 tSZ
- Training 50000 models (test on 20%)





- Reconstruction error < ~1% (0.02 μK² vs Obs err. ~ 0.4 μK²)

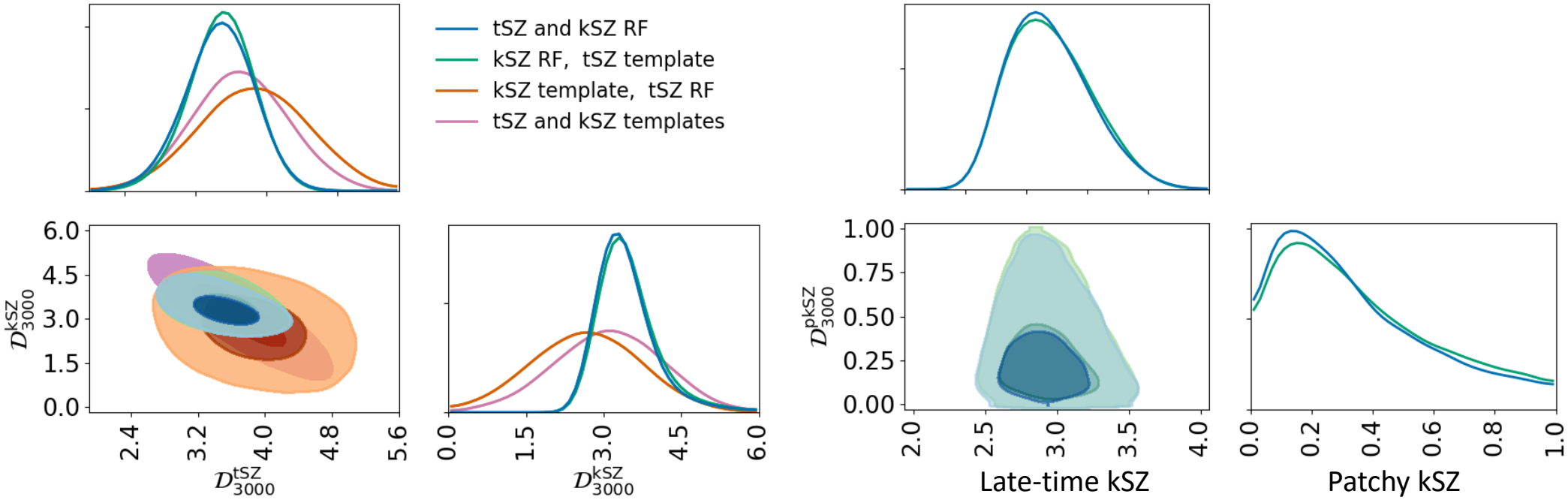
100 to 1000 times faster

➡ moving to NN cosmopower like (Spurio Mancini+2021) for better accuracy

➡ used in LiteBIRD SZ analysis *Remazeilles, Douspis, LiteBIRD collab+2024*

RESULTS ON SPT DATA + PLANCK PRIORS

- When cosmology is "free": **amplitudes** of tkSZ
  - Planck 2018 priors on $\Omega_b h^2$, $\Omega_c h^2$, θ_{MC}, n_s
  - Flat priors on other parameters (As and reion: zre, zend, κ, α0)

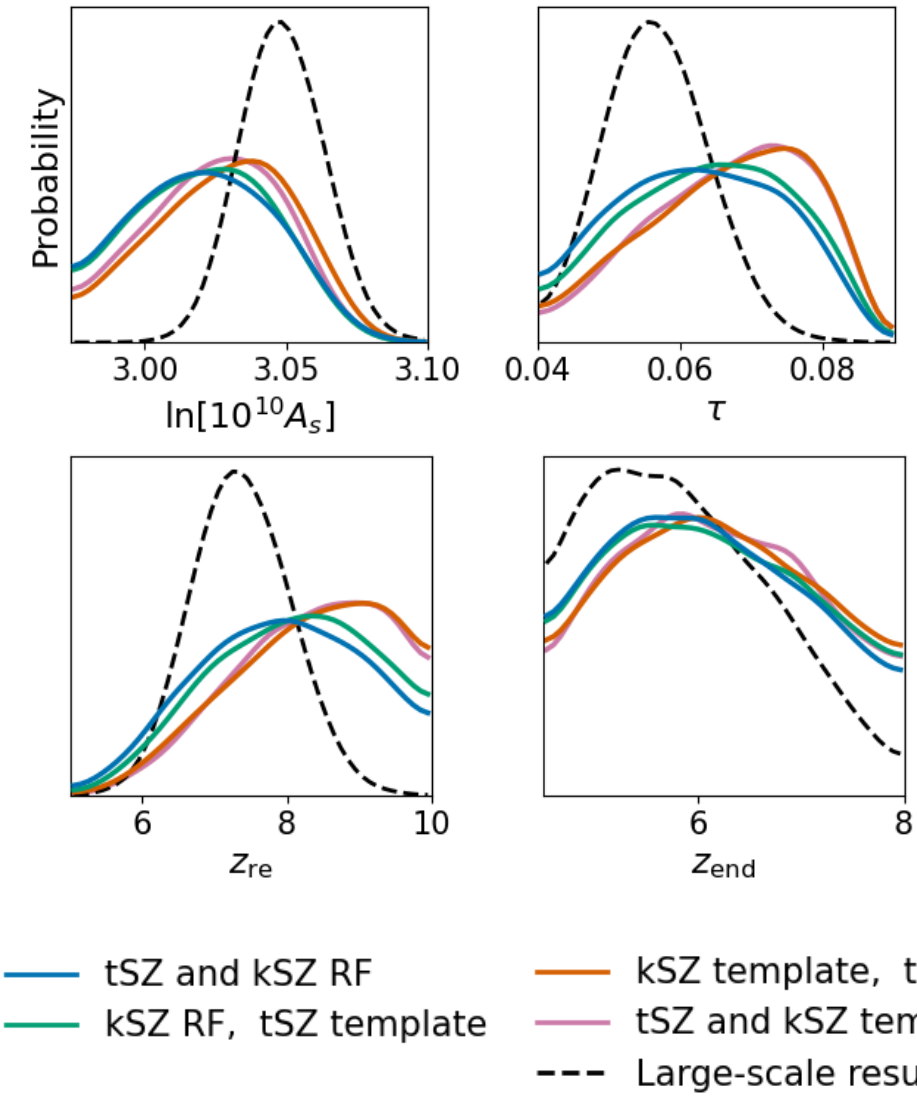


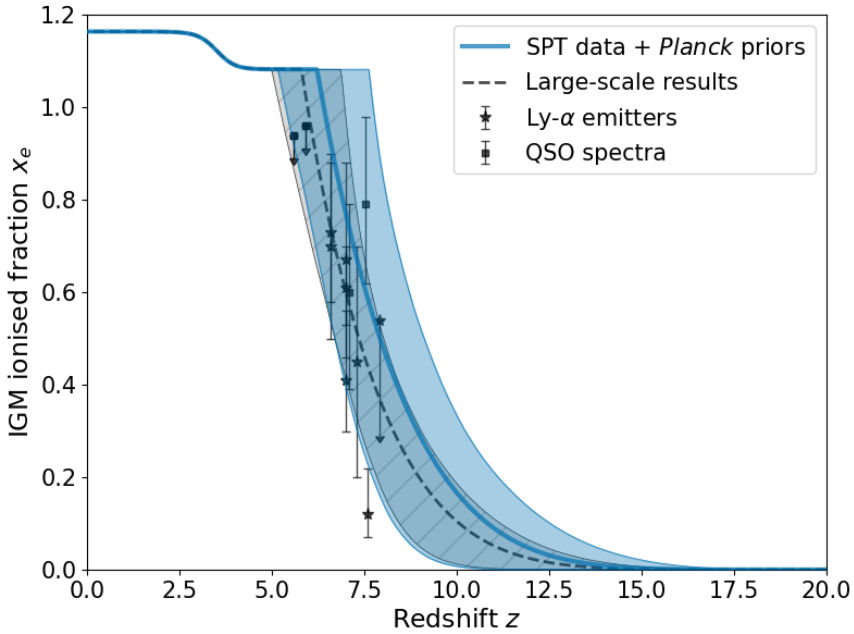
9 and 5σ measurements of tSZ and kSZ resp.
(≠ tSZ alone results)

Gorce, Douspis, Salvati 2022

Results on SPT data + Planck priors

- When cosmology is "free": **cosmology** and **EoR**





SPT data include models of earlier reionisation than Planck:

$\tau = 0.062 \pm 0.012$ (1σ)

$z_{re} = 7.9 \pm 1.1$ (1σ)

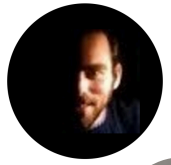
See also Jain+2023, Nikolic+2023

Gorce, Douspis, Salvati 2022

CONSISTENT ANALYSIS ACROSS SCALES

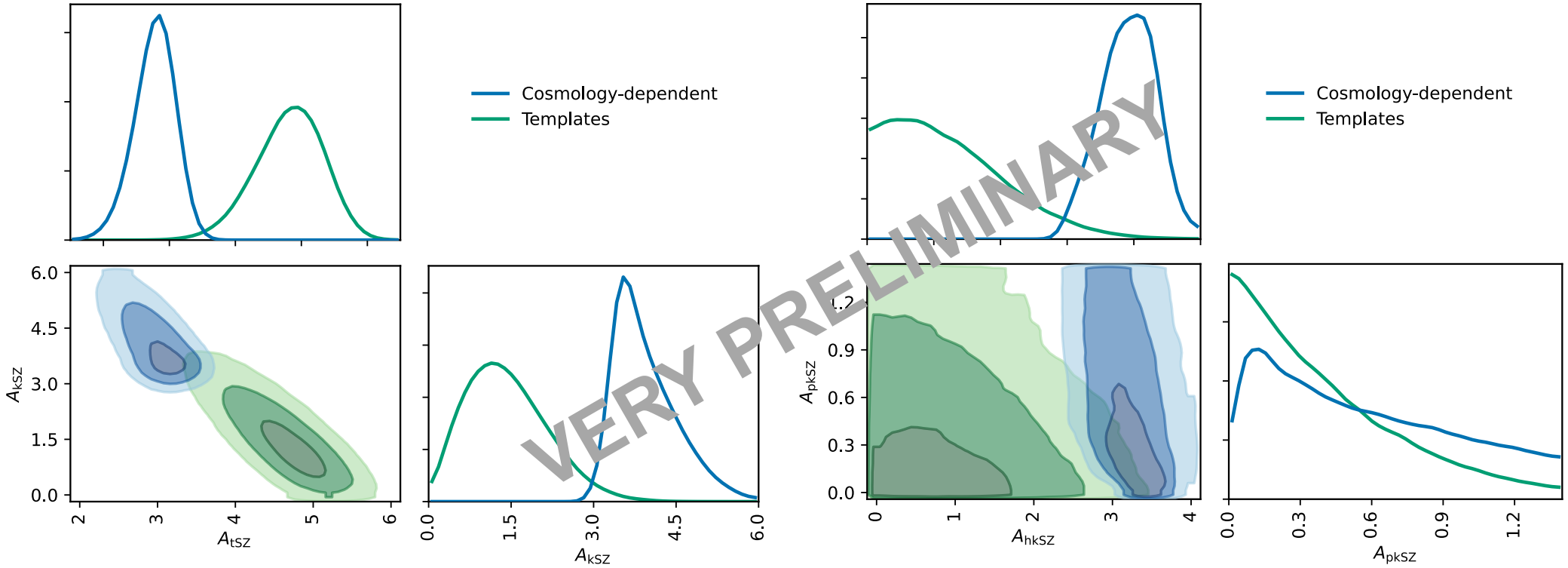
Common foregrounds model and likelihood for Planck+SPT+ACT

- based on Planck PR4 likelihood *(Tristram+24)*
- extended to ACT, SPT *(Choi+20, Recihardt+20)* ,
- using emulators of tSZ and kSZ *(Douspis+22, Gorce+22)*
- with asymetric EoR *(Douspis+ 15)*





ONGOING



CONCLUSIONS

- What?
  - Use an analytical model of tkSZ PS to include it in cosmological parameter inference
  - Combine cosmological information across scales
- How?
  - Parameterisation of the electron power spectrum calibrated on hydrodynamical simulations
  - Emulators of the tkSZ angular PS (soon updated)

    (available at https://**szdb.osups**.universite-paris-saclay.fr)
- Results:
  - First self-consistent constraints on reionisation:

    $z_{re} = 7.9 \pm 1.1 \longleftrightarrow \tau = 0.062 \pm 0.012$
- Ongoing:
  - Improved reionisation kSZ model and tSZ pressure profiles
  - Consistent/coherent analysis of Planck+SPT+ACT
  - Joint analysis with other reionisation observables
  - Application to neutrino mass constraints

Better Accuracy and
robusTness for
Mass Assessment of
Neutrinos

DERIVING POWER SPECTRA

Douspis, Salvati, Gorce, Aghanim 2022

tSZ

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

Mass function

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

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

Scaling relation

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

Gas pressure profile

Arnaud et al, Planck, PACT, …

kSZ

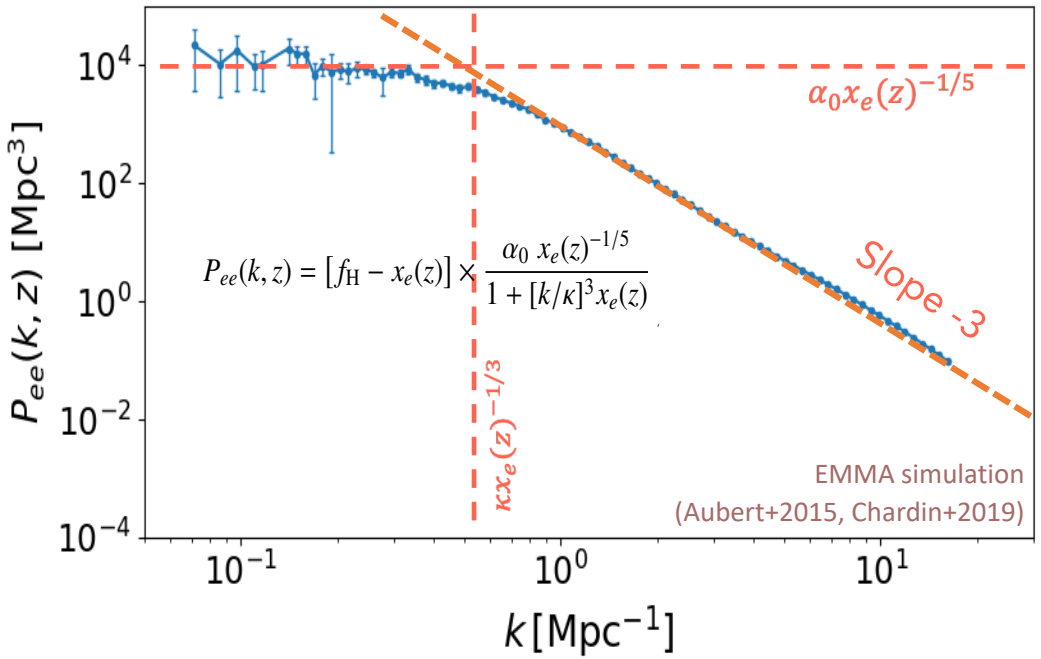
Gorce, Ilic, Douspis, Langer 2020

Amplitude

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

Shape

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



➡ Improvement on scaling and profile with new cluster/ group samples, eg CHEXMATE



Miren Muñoz-Echeverría

➡ Recalibrate on LoReLi simulations: 10 000 simulations of reionisation varying astrophysics Meriot & Semelin 2023

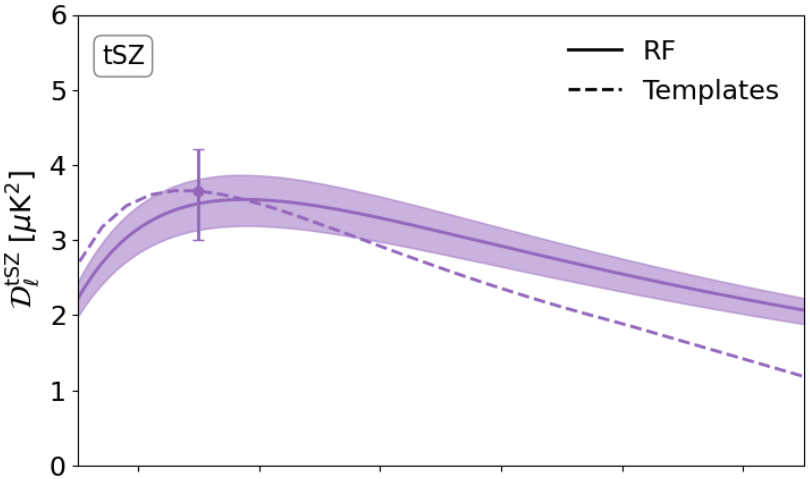
➡ Include a physical dependence, e.g., with symbolic regression



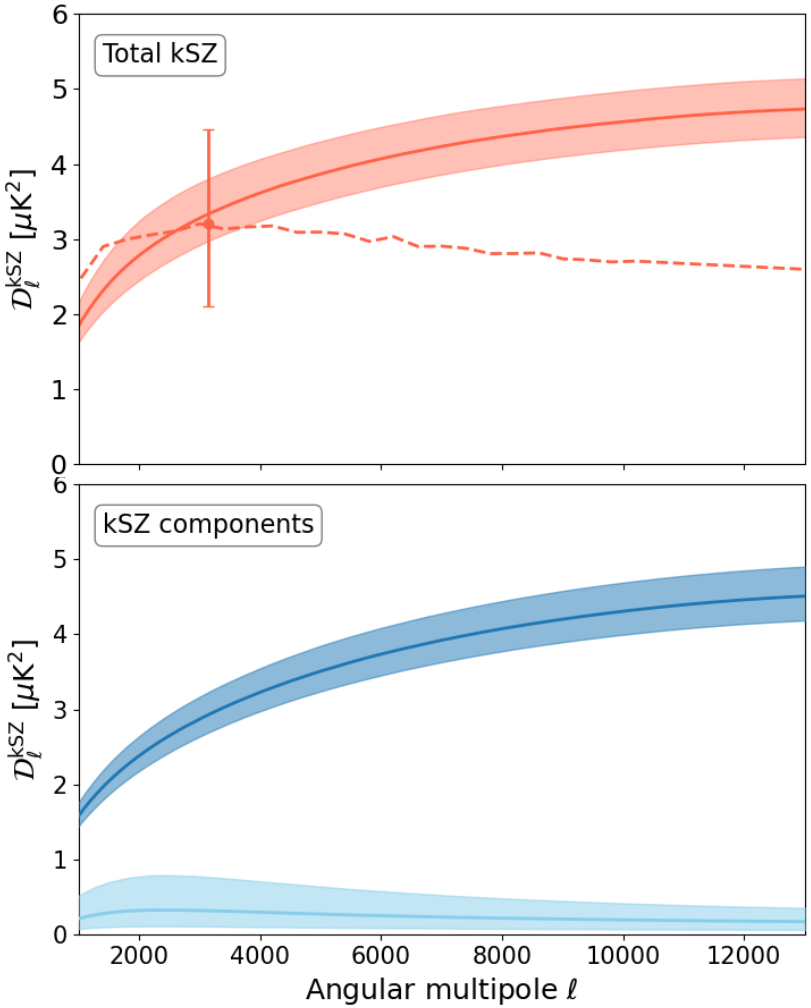
Lisa Mc Bride

Results on SPT data: Free cosmology

- When cosmology is "free": **shapes** of tkSZ
  - Planck 2018 priors on $\Omega_b h^2$, $\Omega_c h^2$, θ_{MC}, n_s
  - Flat priors on other parameters (As and reion: zre, zend, κ, α0)



Can see the shape of the spectra!!



Gorce, Douspis, Salvati 2022