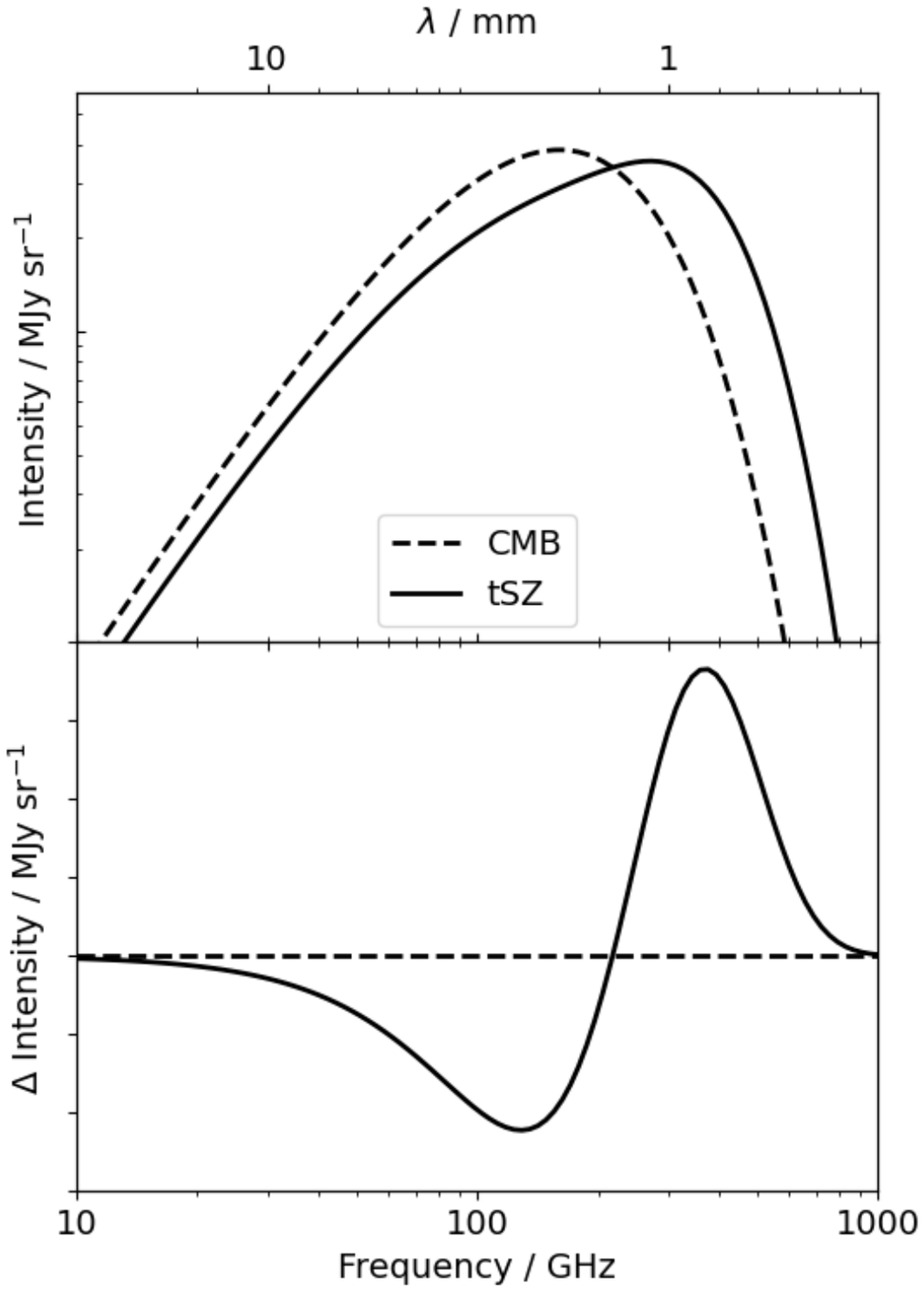
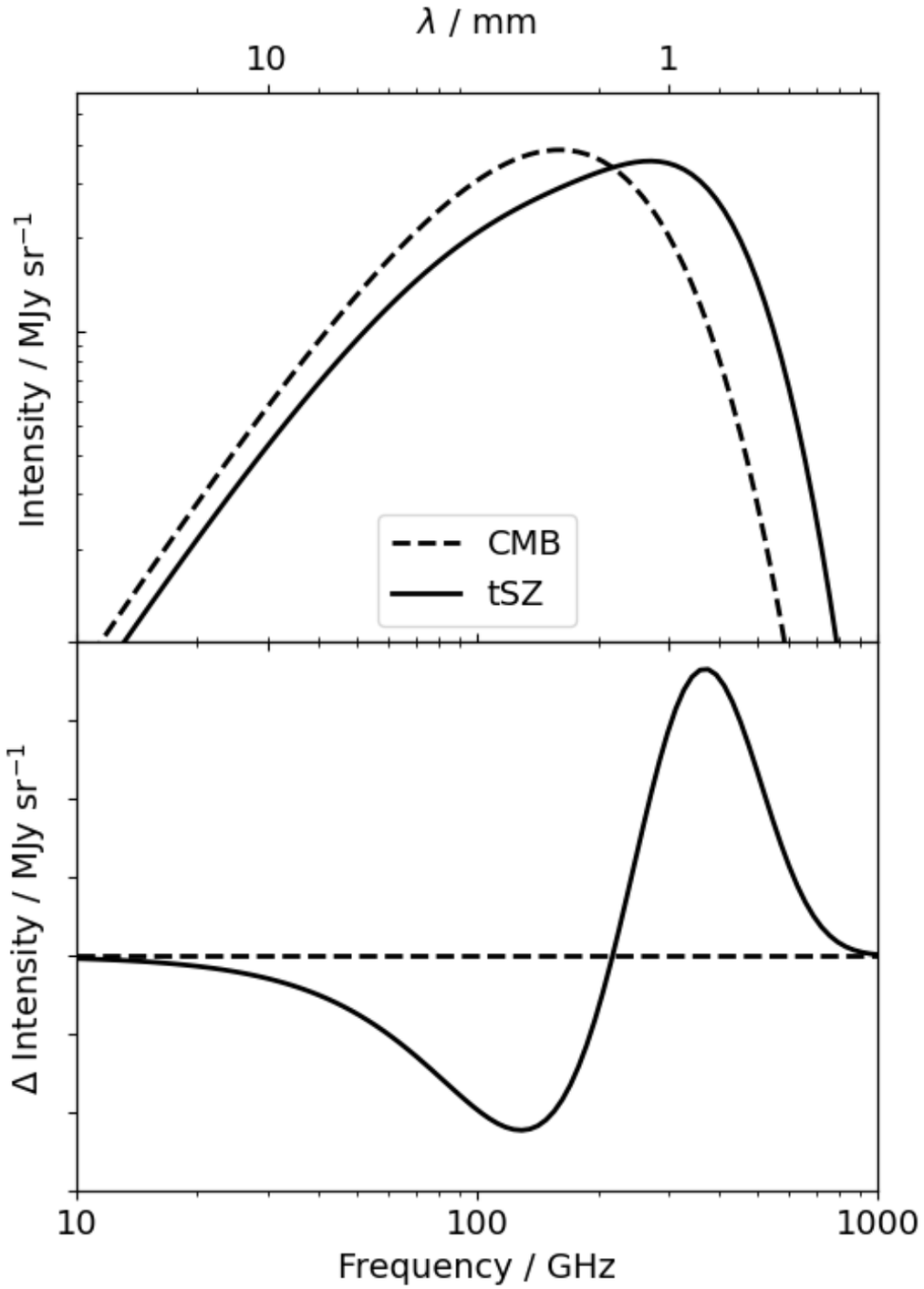
Temperature measurements with the relativistic Sunyaev-Zel'dovich effect

Planck y-map, from "*Planck* 2015 results XXII. A map of the thermal Sunyaev-Zeldovich effect".

Relativistic SZ spectrum

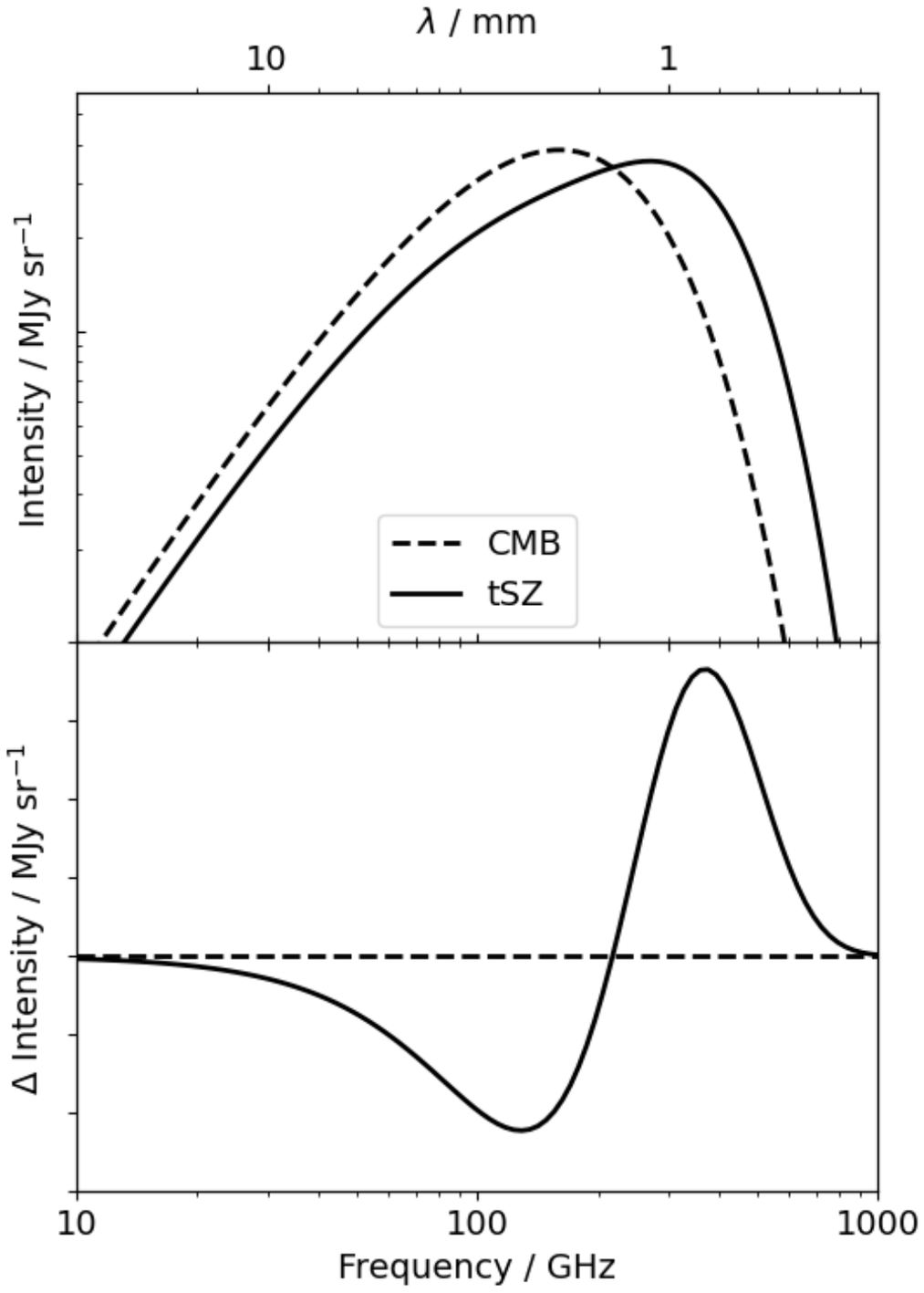


Relativistic SZ spectrum



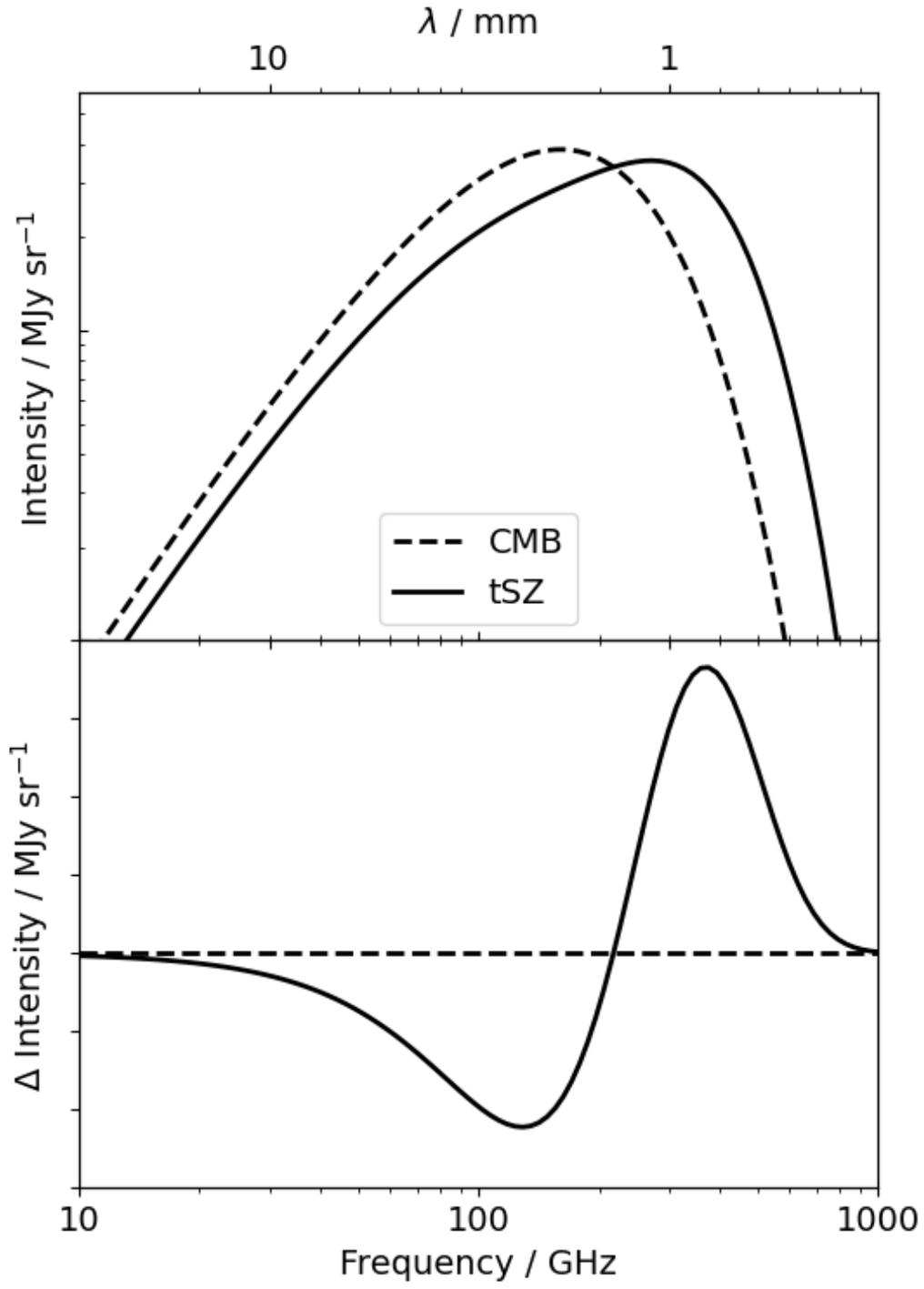
- Classical thermal SZ spectrum is actually the non-relativistic limit (Kompaneets equation)

Relativistic SZ spectrum



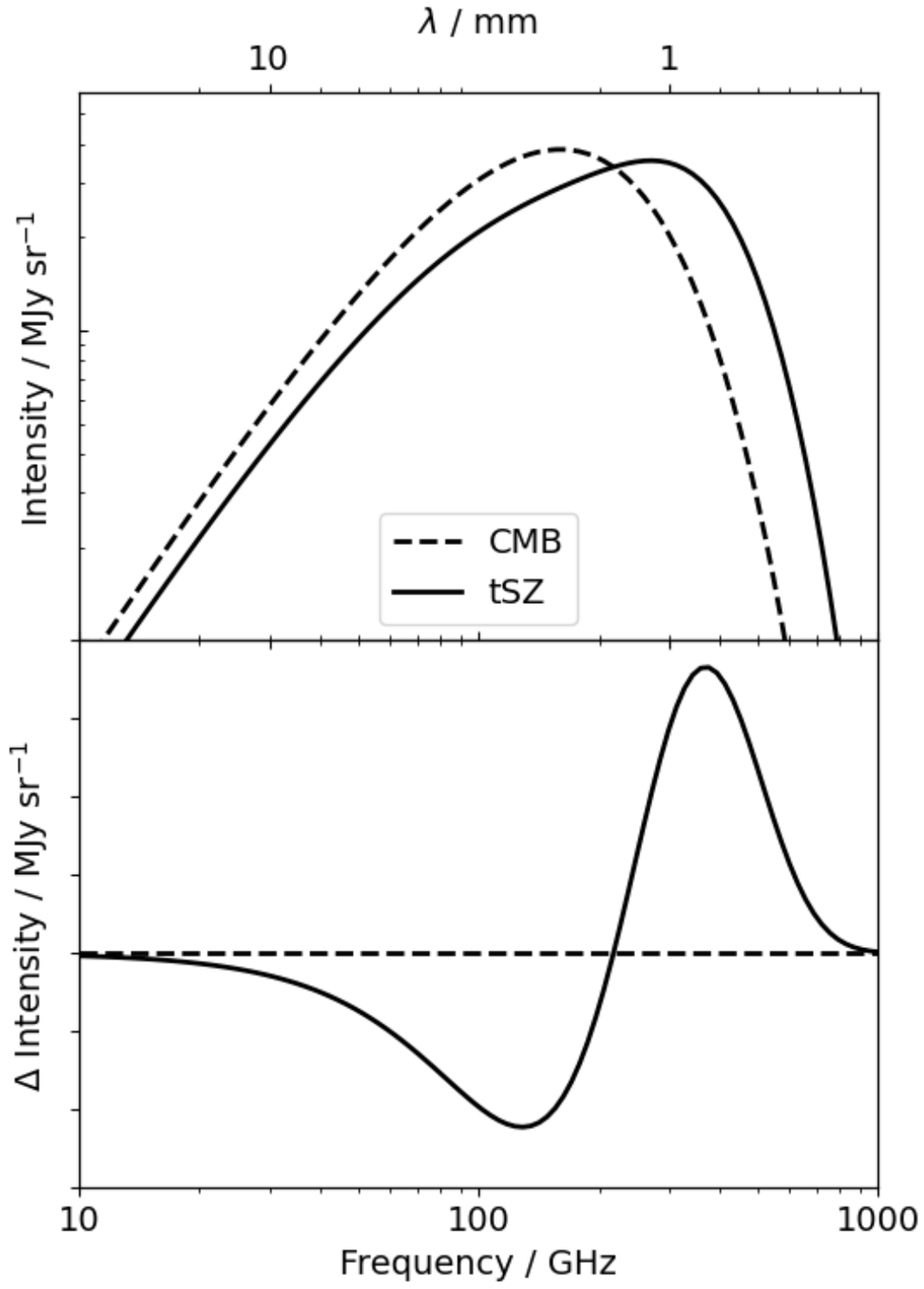
- Classical thermal SZ spectrum is actually the non-relativistic limit (Kompaneets equation)
- But ICM of massive clusters is at temperatures $\sim$ 5 - 10 keV $\Rightarrow$ typical electron speeds $\sim 0.2c$

Relativistic SZ spectrum



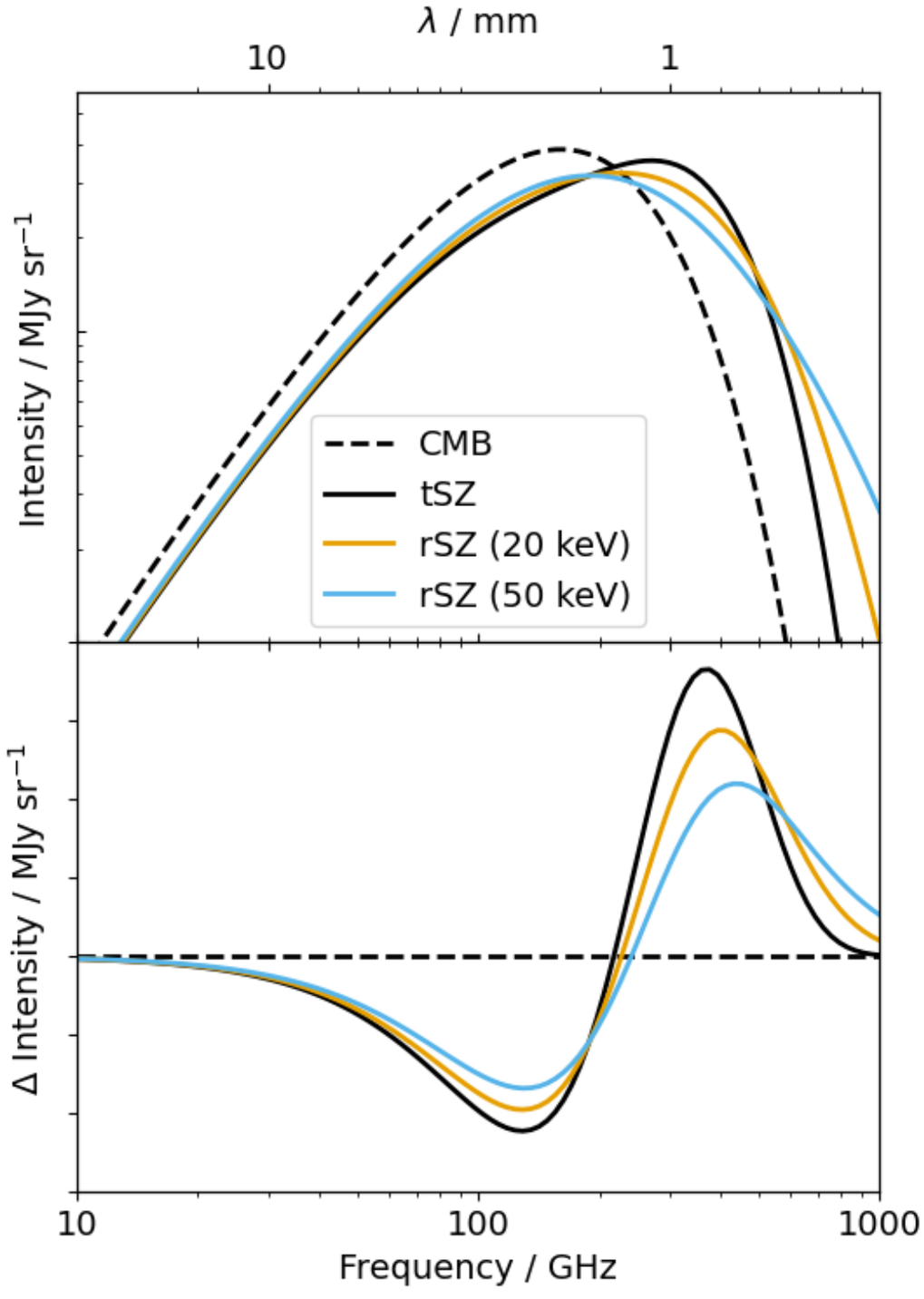
- Classical thermal SZ spectrum is actually the non-relativistic limit (Kompaneets equation)
- But ICM of massive clusters is at temperatures $\sim$ 5 - 10 keV $\Rightarrow$ typical electron speeds $\sim 0.2c$
- Relativistic beaming means more photons are up-scattered than down-scattered

Relativistic SZ spectrum



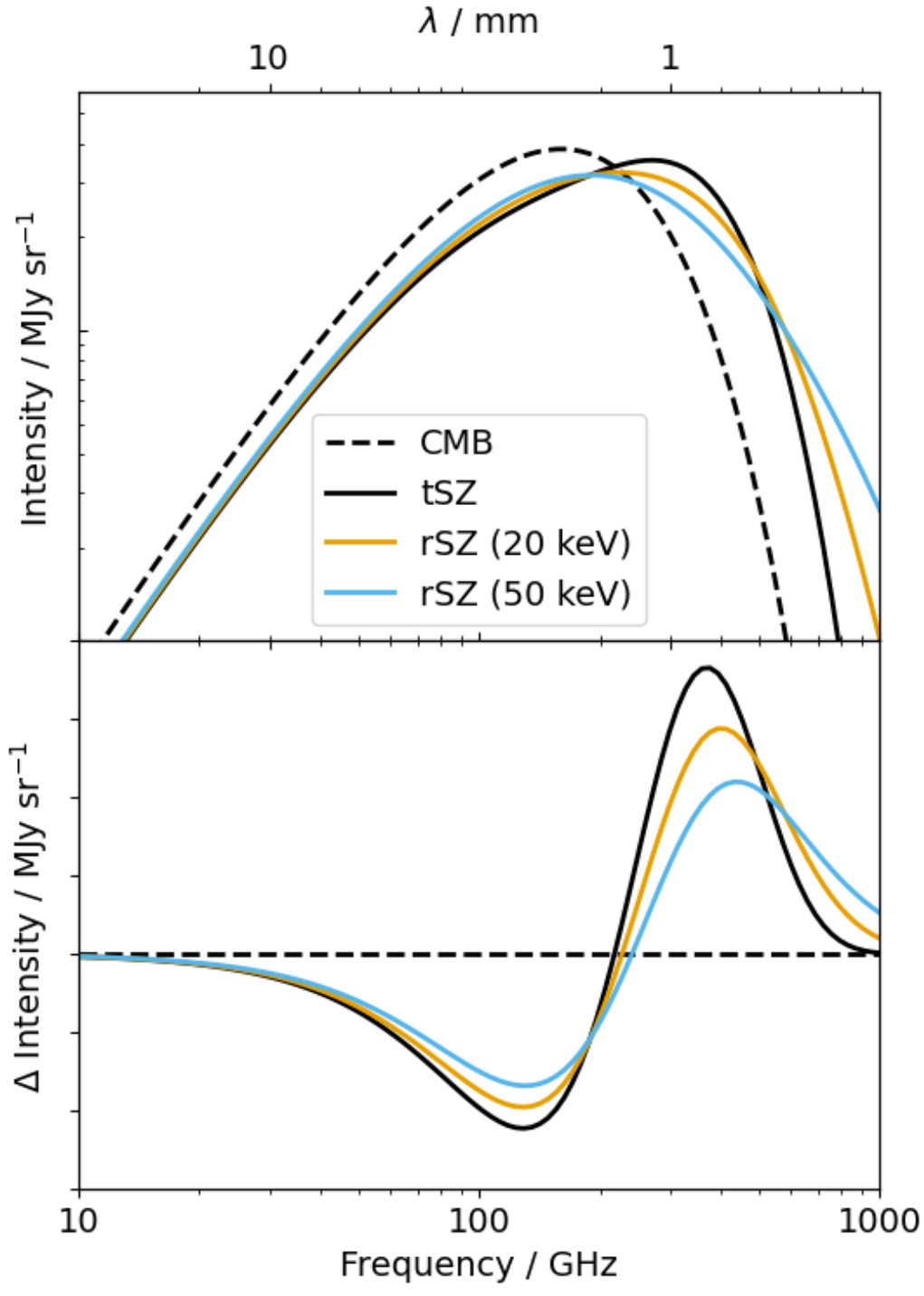
- Classical thermal SZ spectrum is actually the non-relativistic limit (Kompaneets equation)
- But ICM of massive clusters is at temperatures $\sim$ 5 - 10 keV $\Rightarrow$ typical electron speeds $\sim 0.2c$
- Relativistic beaming means more photons are up-scattered than down-scattered
- Spectrum becomes a function of electron temperature

Relativistic SZ spectrum



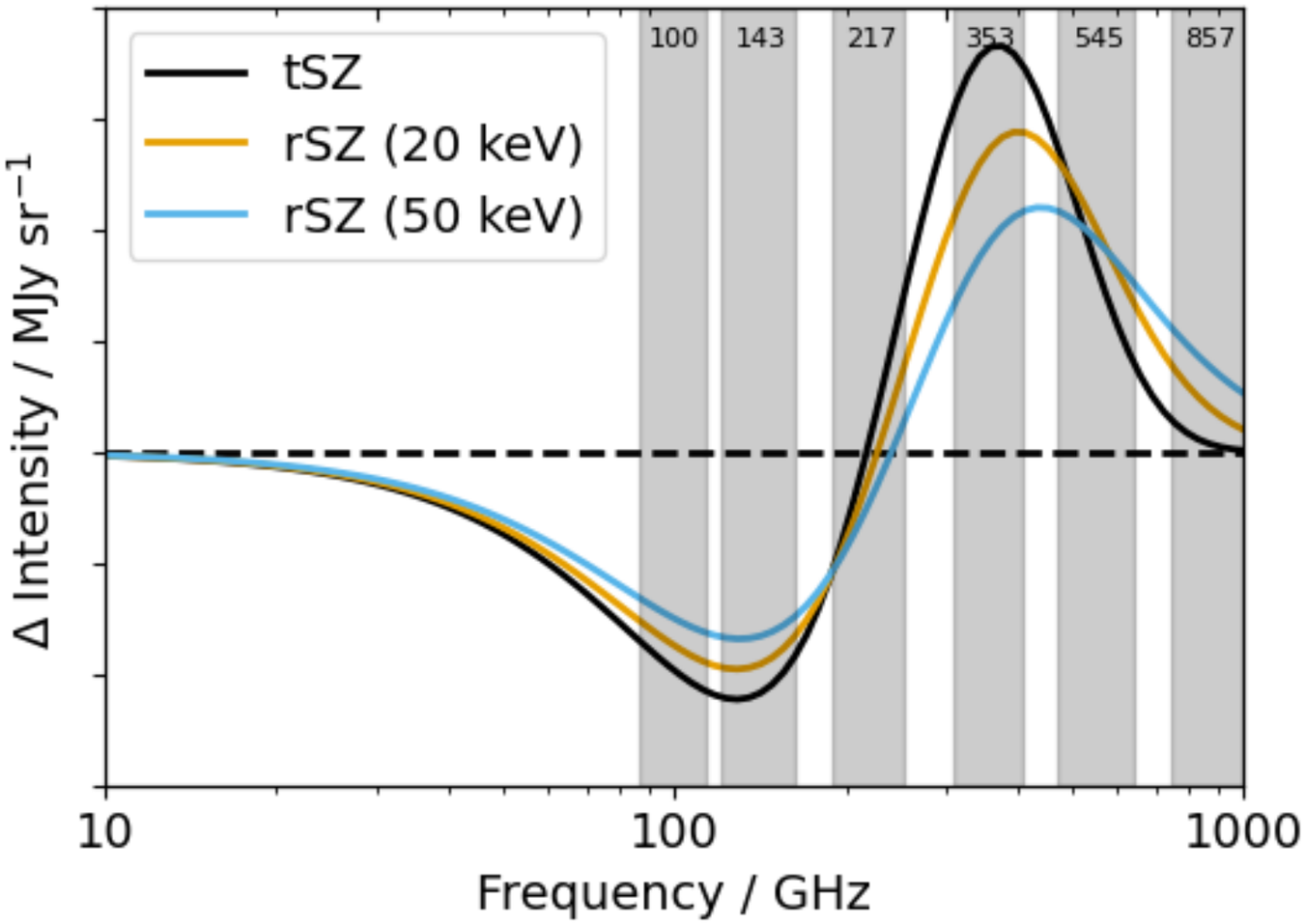
- Classical thermal SZ spectrum is actually the non-relativistic limit (Kompaneets equation)
- But ICM of massive clusters is at temperatures $\sim$ 5 - 10 keV $\Rightarrow$ typical electron speeds $\sim 0.2c$
- Relativistic beaming means more photons are up-scattered than down-scattered
- Spectrum becomes a function of electron temperature

Relativistic SZ spectrum

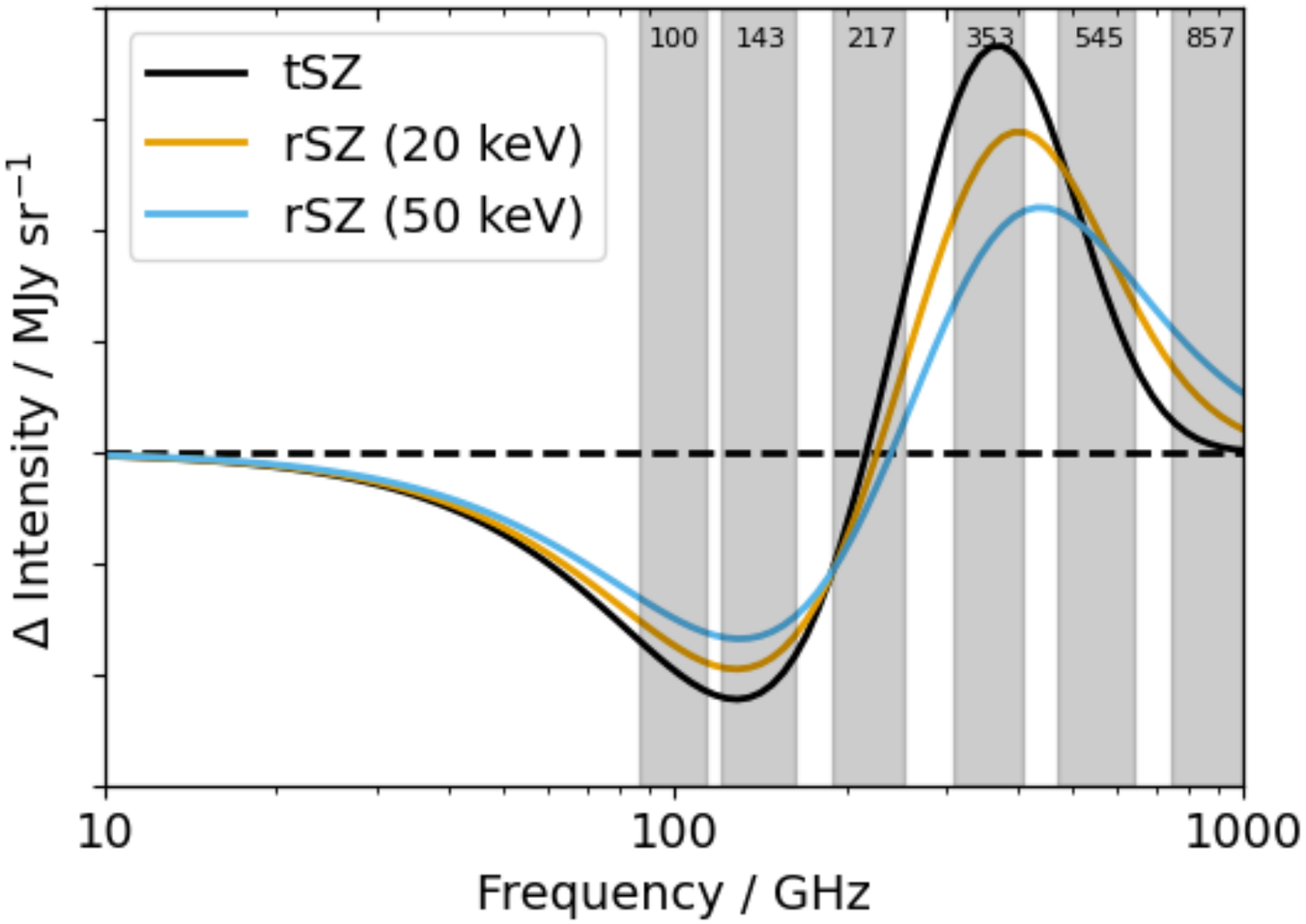


- Classical thermal SZ spectrum is actually the non-relativistic limit (Kompaneets equation)
- But ICM of massive clusters is at temperatures ~ 5 - 10 keV ⇒ typical electron speeds $\sim 0.2c$
- Relativistic beaming means more photons are up-scattered than down-scattered
- Spectrum becomes a function of electron temperature
- Computation is now tractable (Chluba et al 2012, 2013: SZpack)

Relativistic SZ spectrum

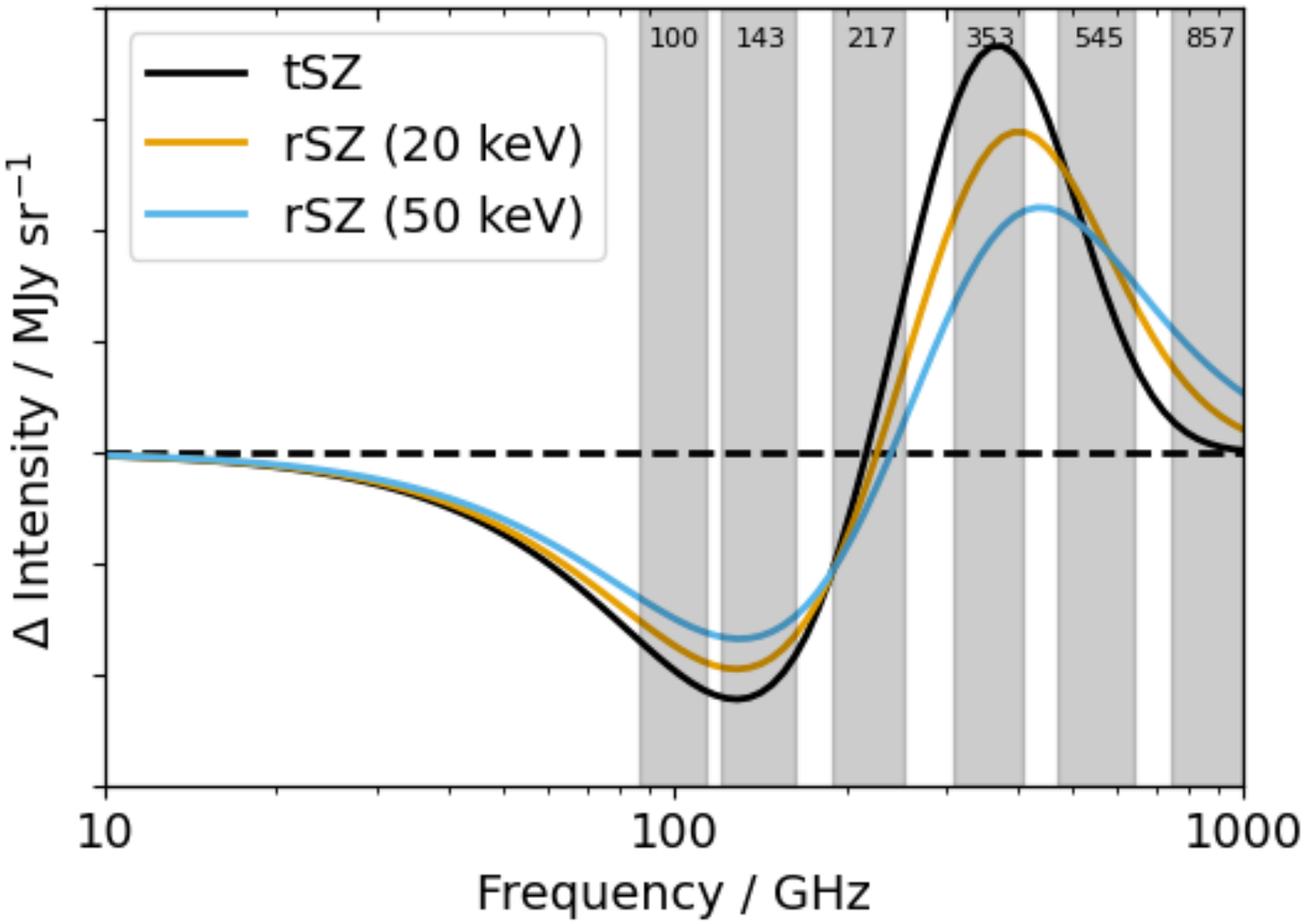


Relativistic SZ spectrum



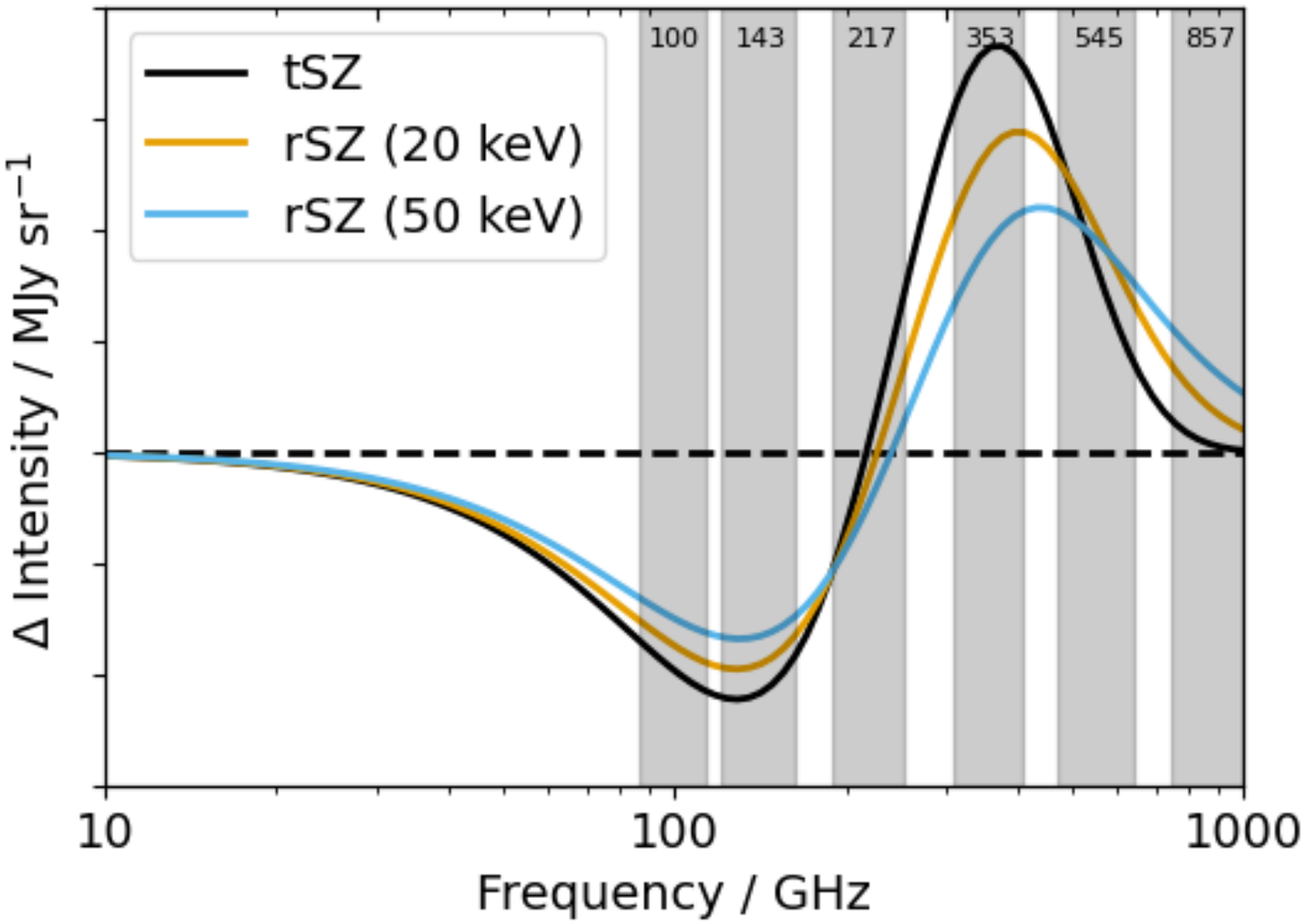
- At frequencies below ≈ 500 GHz, effect is to *decrease* the signal

Relativistic SZ spectrum



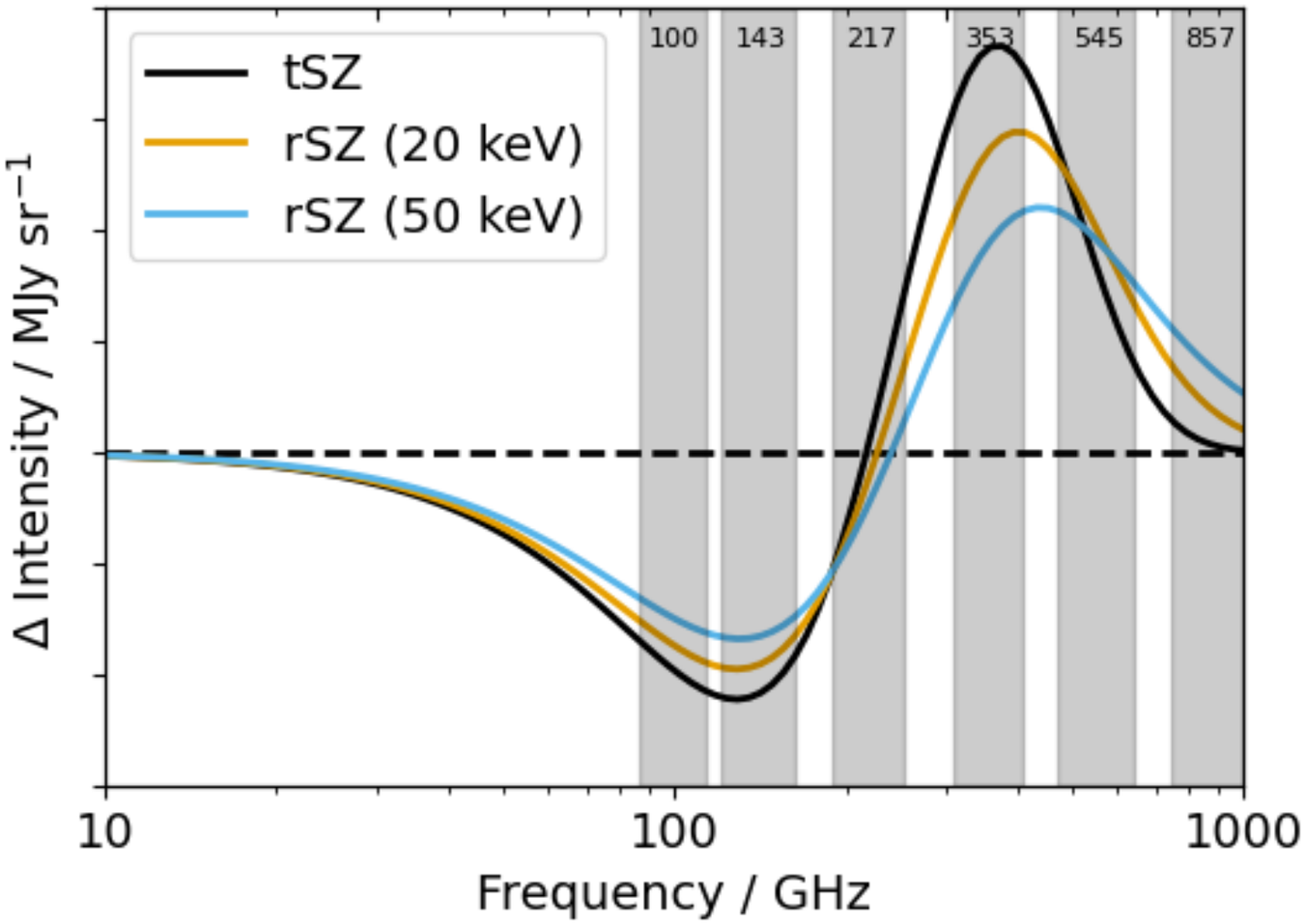
- At frequencies below ≈ 500 GHz, effect is to *decrease* the signal
- At higher frequencies, signal increases

Relativistic SZ spectrum



- At frequencies below ≈ 500 GHz, effect is to *decrease* the signal
- At higher frequencies, signal increases
- Null shifts position

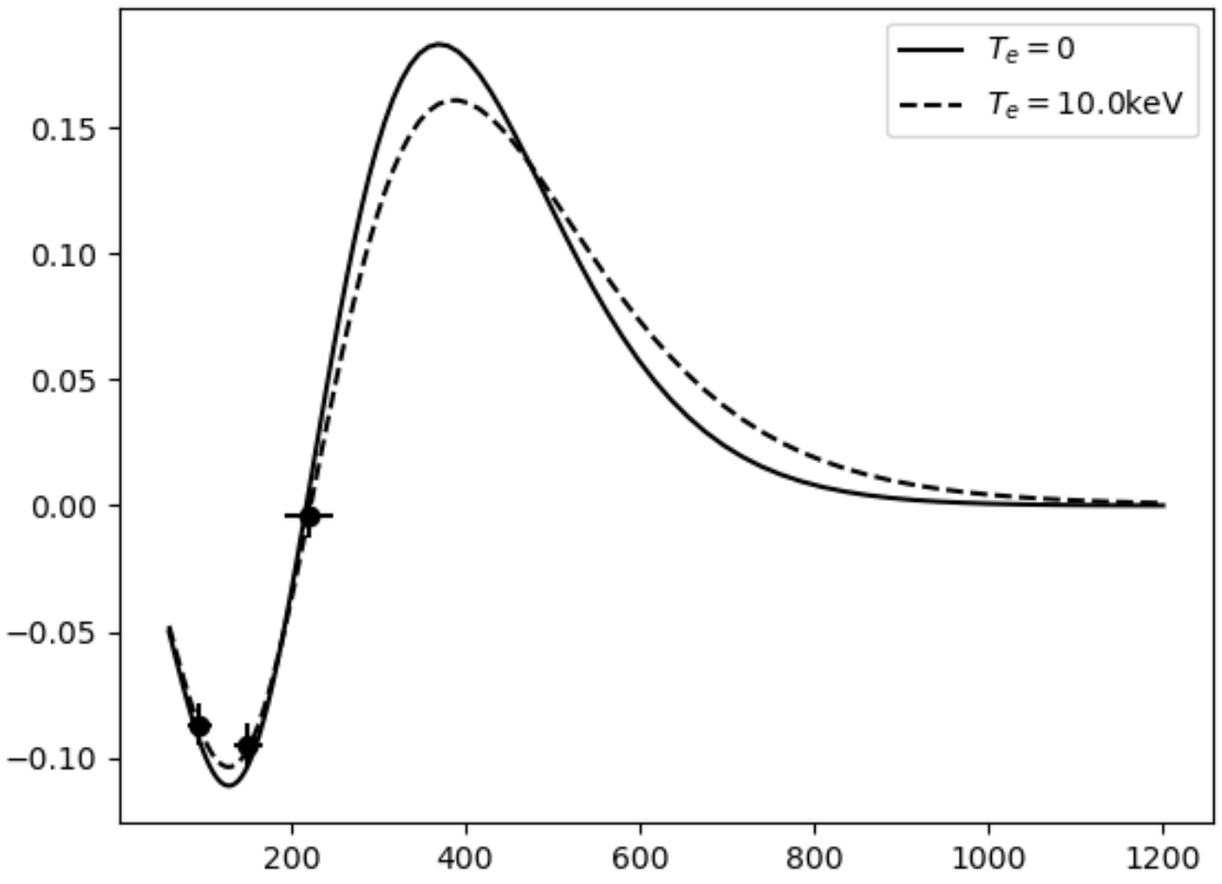
Relativistic SZ spectrum



- At frequencies below ≈ 500 GHz, effect is to *decrease* the signal
- At higher frequencies, signal increases
- Null shifts position
- With multi-band observations, opportunity to measure temperature in a new way

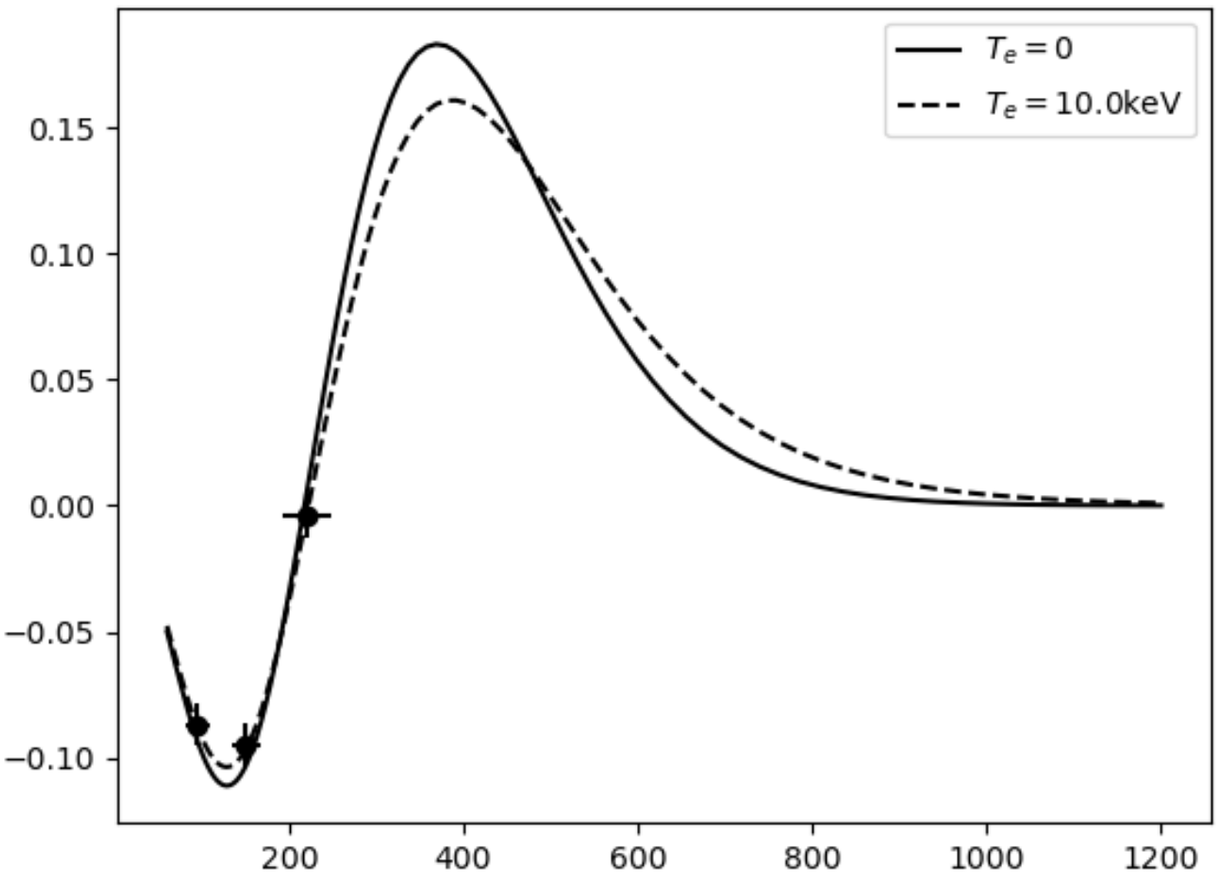
Quick demonstration

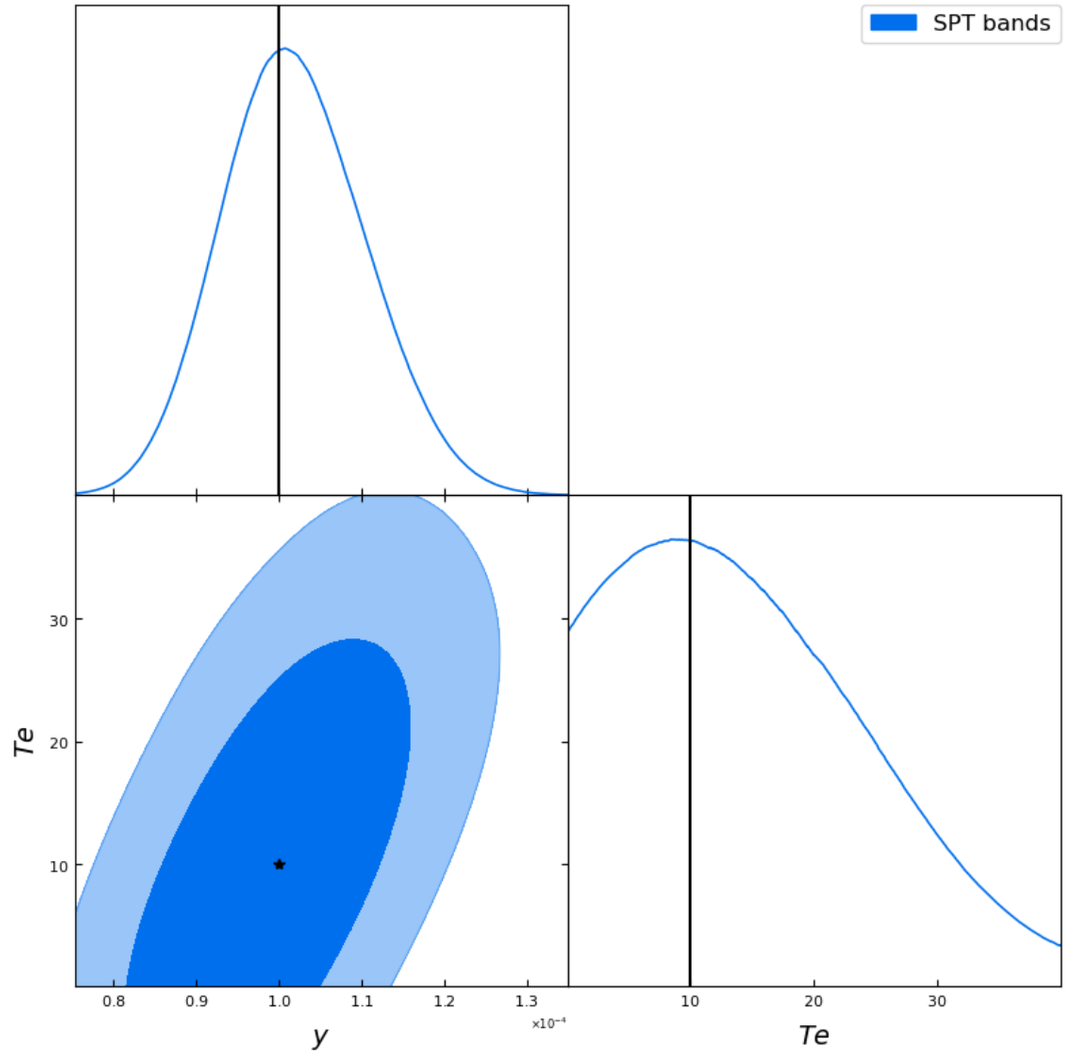
- Rough approximation to SPT bands



Quick demonstration

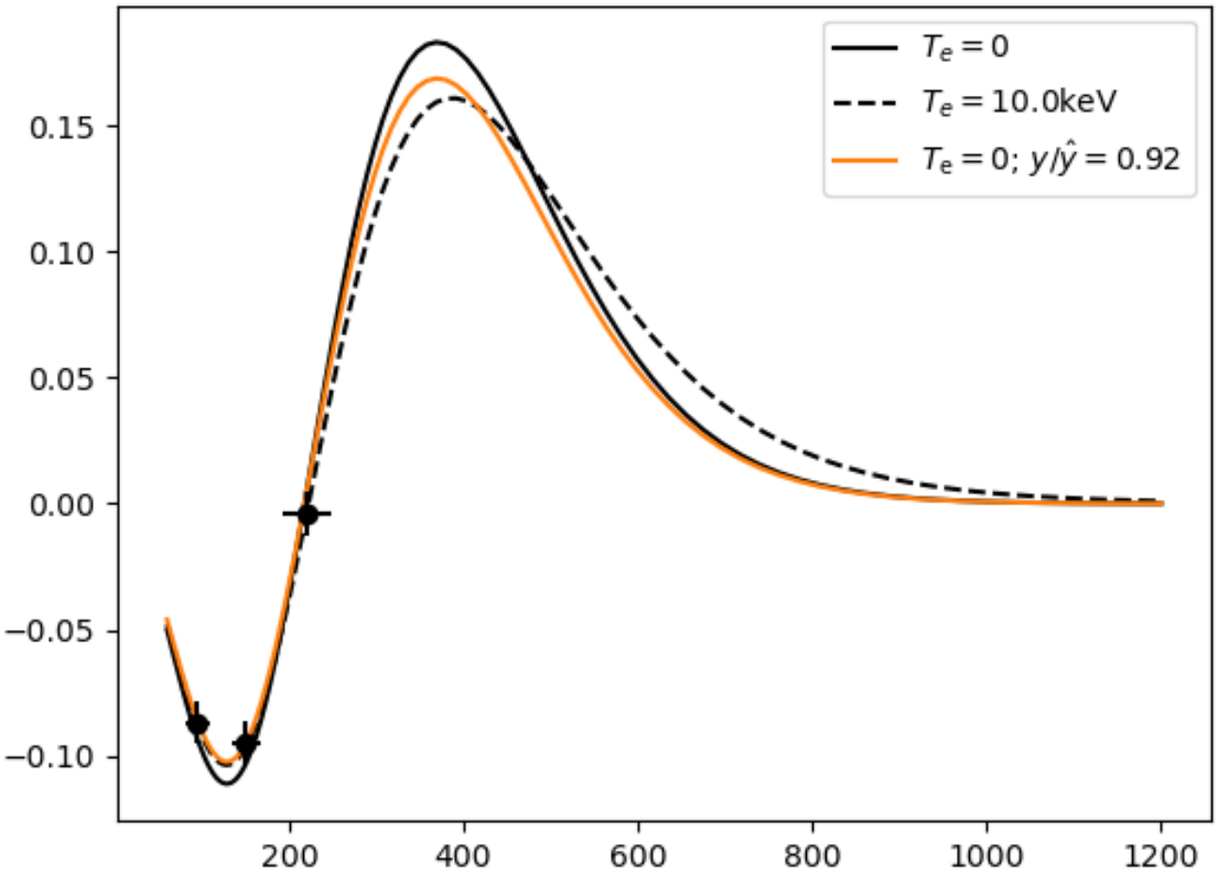
- Rough approximation to SPT bands

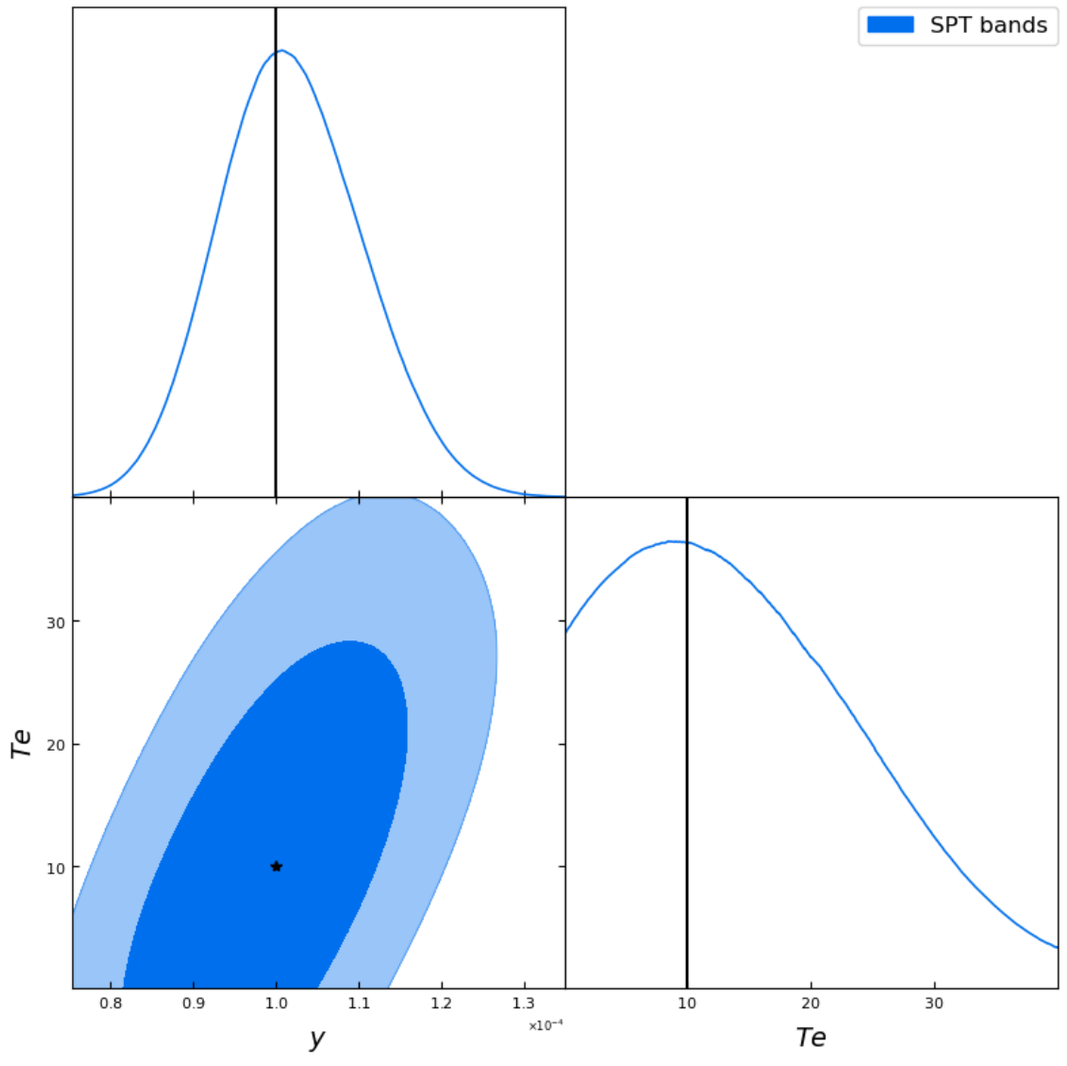




Quick demonstration

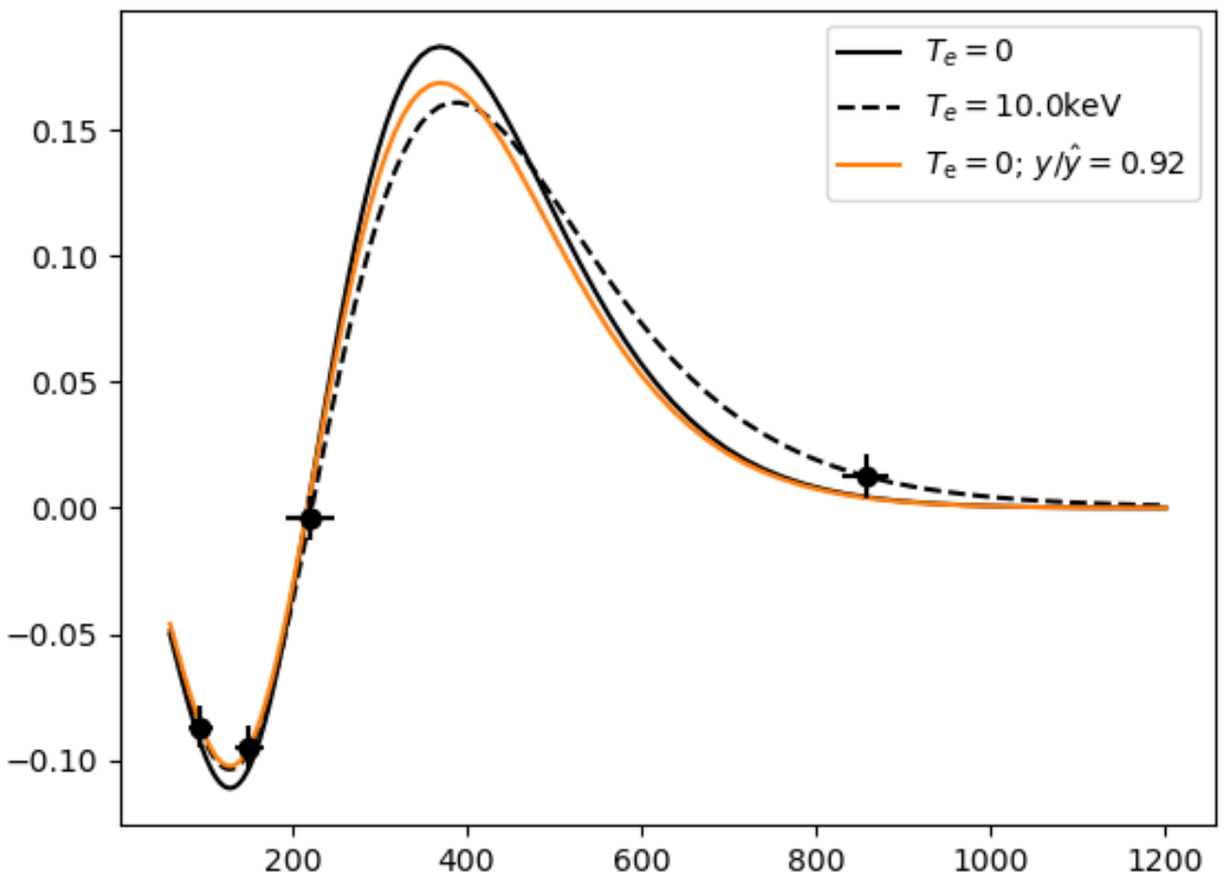
- Rough approximation to SPT bands





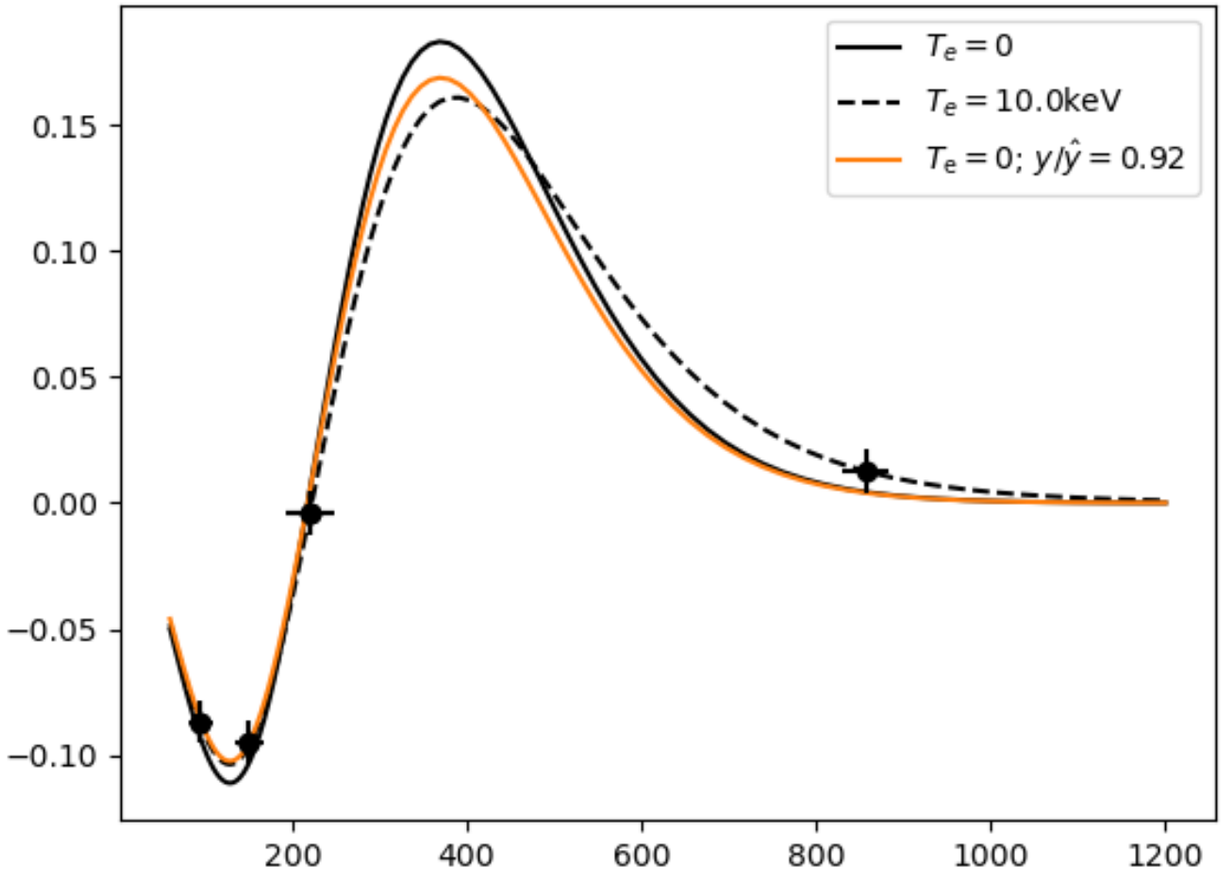
Quick demonstration

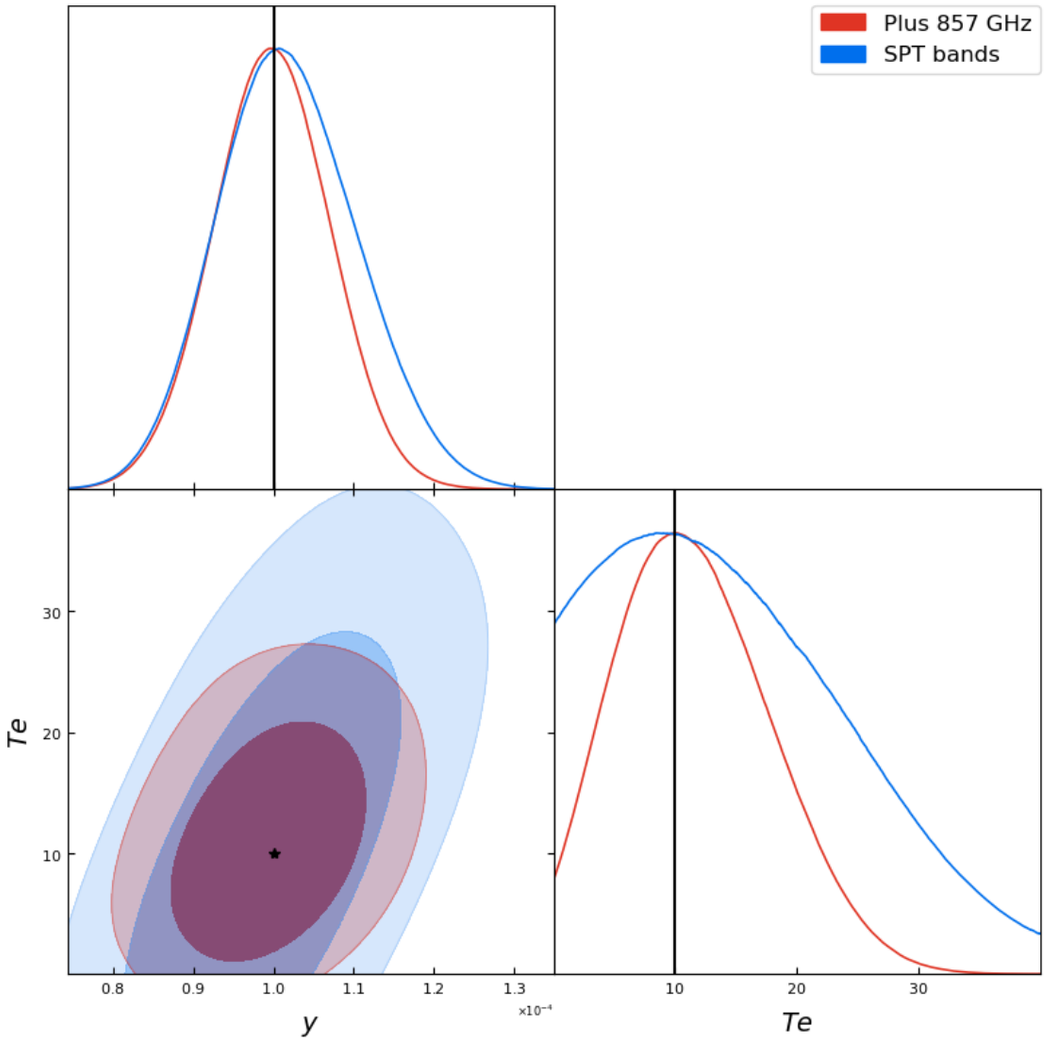
- Rough approximation to SPT bands
- Add an 857 GHz band



Quick demonstration

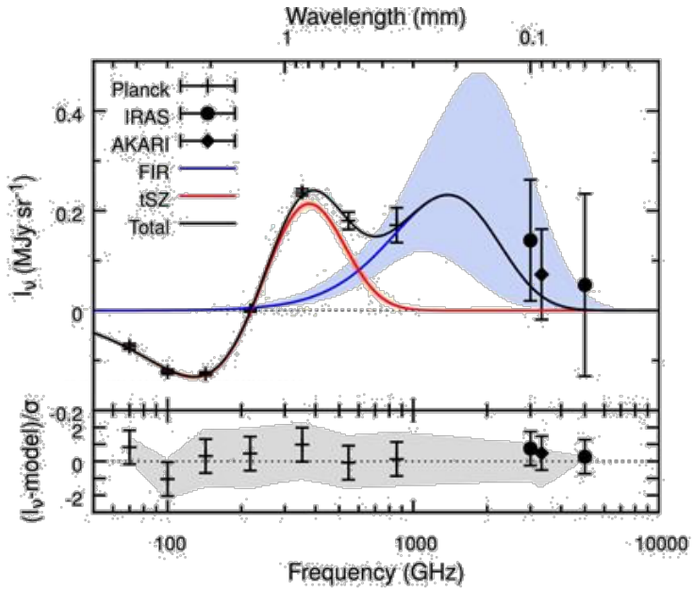
- Rough approximation to SPT bands
- Add an 857 GHz band

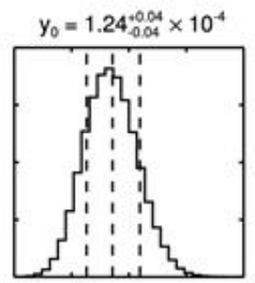


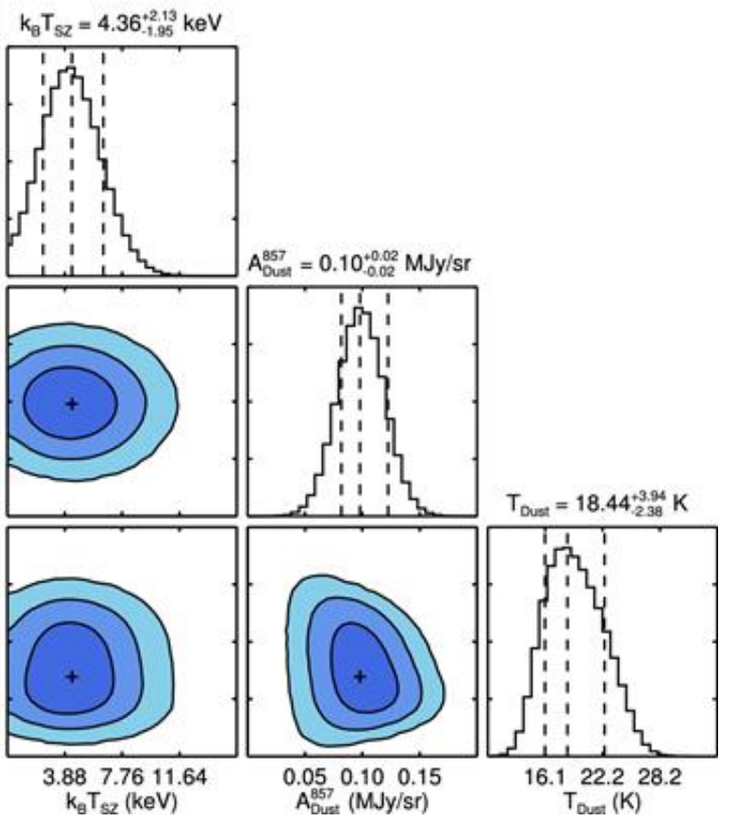


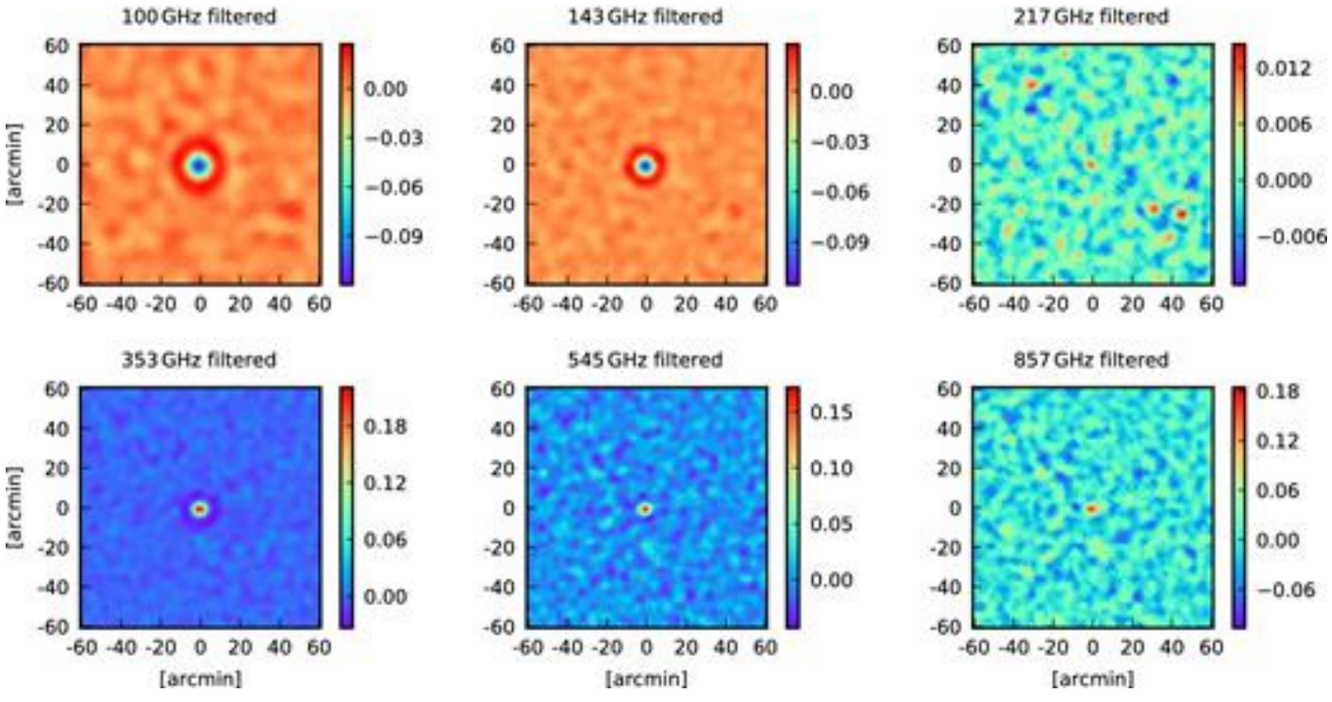
Stacking results

- Erler et al 2018: 772 *Planck* clusters + IRAS + *Akari*
- 2σ detection of rSZ temperature
- Spatially correlated dust component



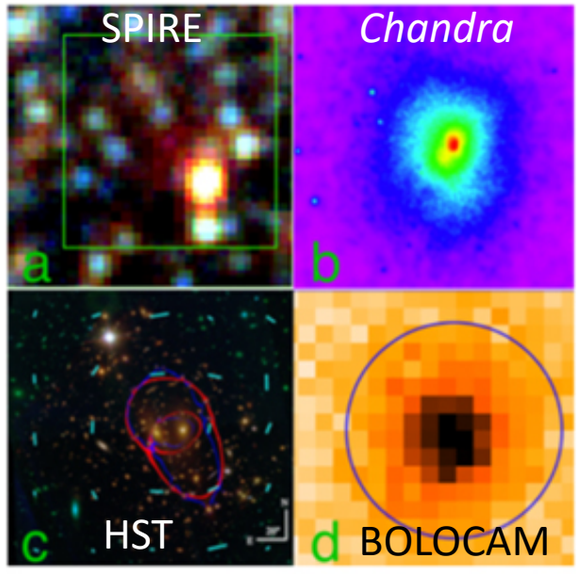


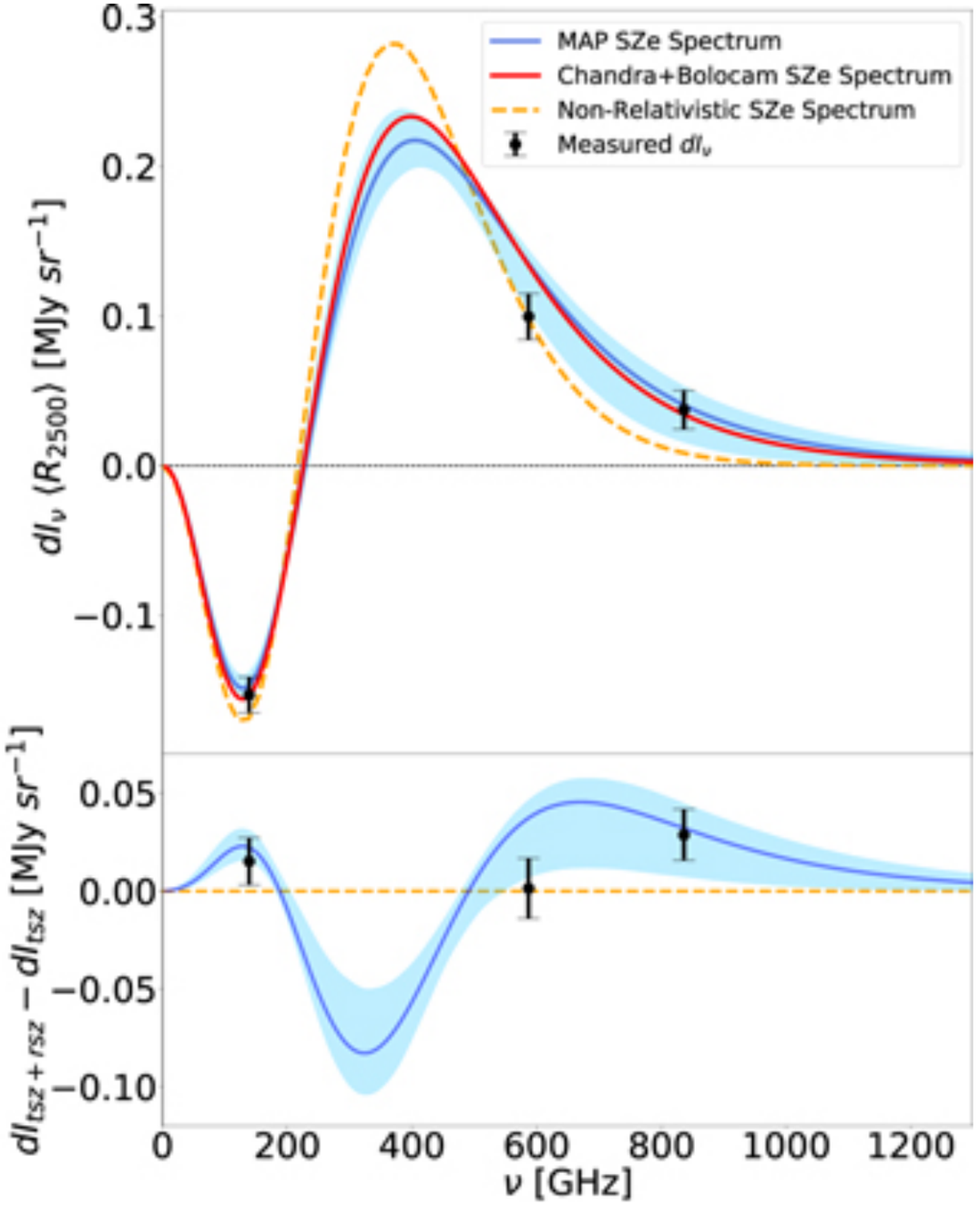




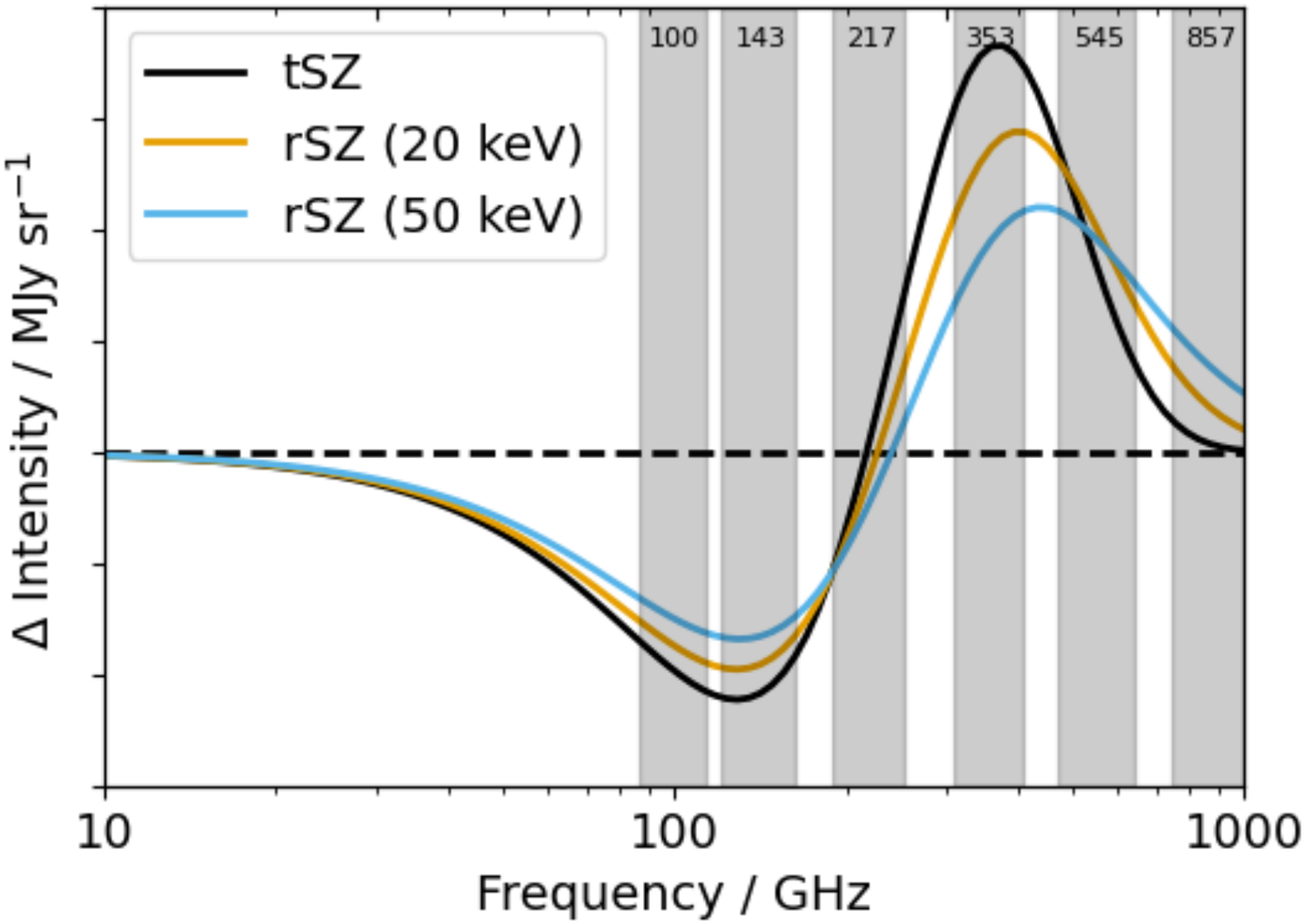
Individual clusters

- Butler et al 2022: RX J1347.5-1145
- Massive, relaxed cluster but shock near the core from past minor merger
- Careful consideration of CIB, cirrus foregrounds
- Core temperature measurement of 22.4^{33}_{10} keV, consistent with X-ray pressure-weighted prediction
- Future high-sensitivity, angular resolution instruments (AtLAST, CSST) will do better



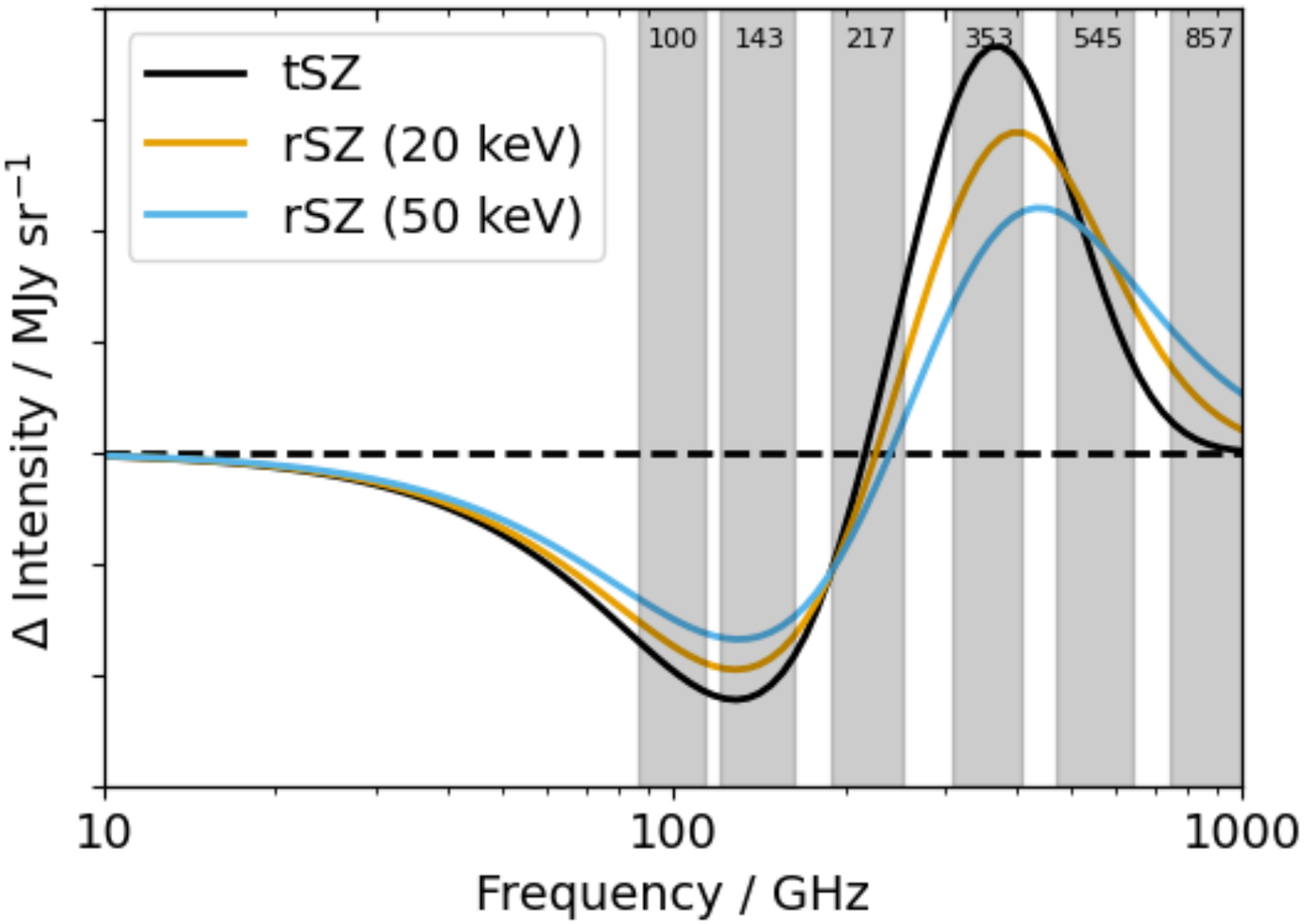


Relativistic SZ spectrum



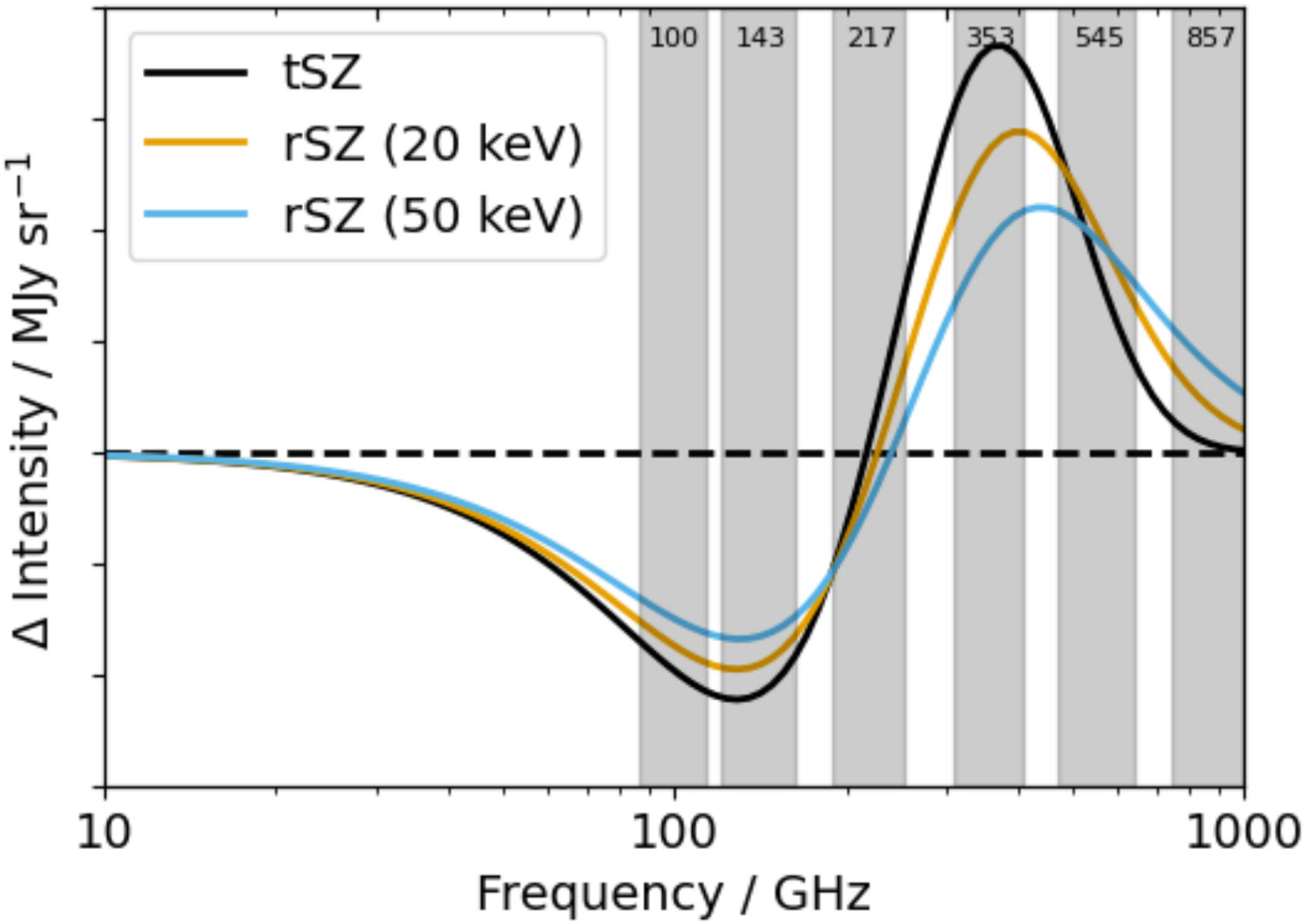
Relativistic SZ spectrum

- *Planck* bands span the frequency range



Relativistic SZ spectrum

- *Planck* bands span the frequency range
- Is there enough signal to noise to constrain temperature in individual clusters with *Planck*?



Individual *Planck* clusters

Individual *Planck* clusters

- rSZ predicted to cause ≈10% bias in *Planck* Y_{500} measurements for massive clusters

Individual *Planck* clusters

- rSZ predicted to cause ≈10% bias in *Planck* Y_{500} measurements for massive clusters
- Simulations to check: realistic physical model for cluster thermodynamic properties, relativistic SZ effect predicted using SZpack

Individual *Planck* clusters

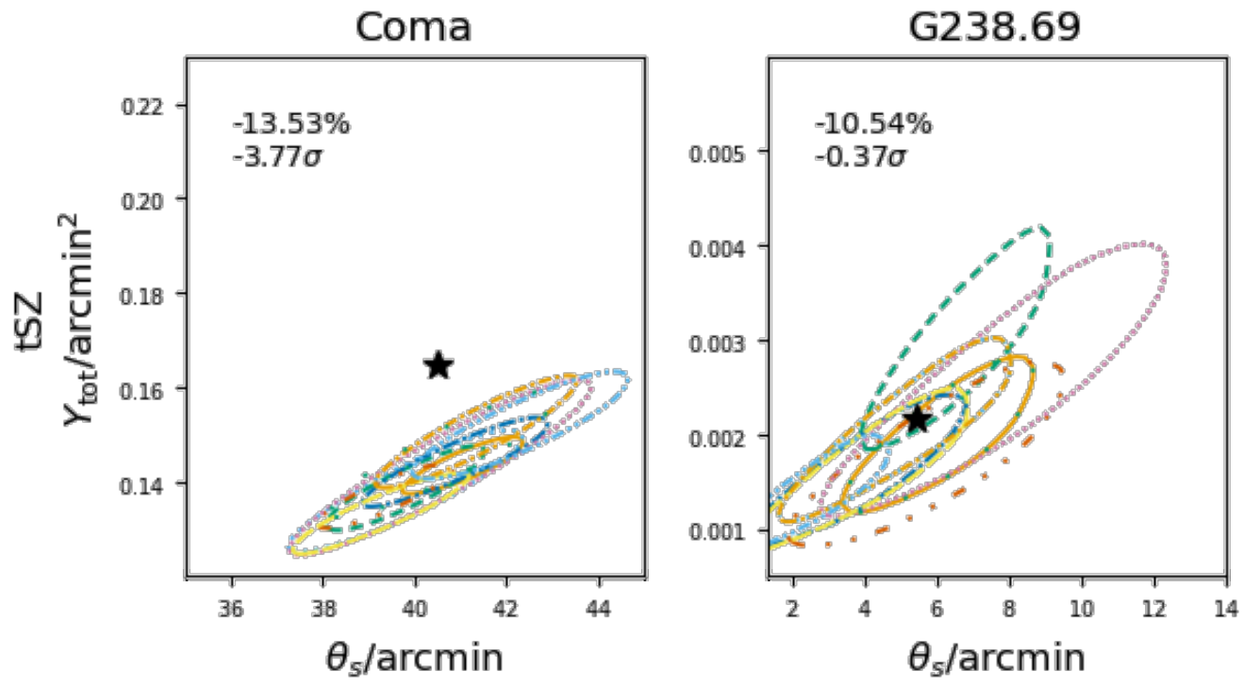
- rSZ predicted to cause ≈10% bias in *Planck* Y_{500} measurements for massive clusters
- Simulations to check: realistic physical model for cluster thermodynamic properties, relativistic SZ effect predicted using SZpack
- Injected into real *Planck* data

Individual *Planck* clusters

- rSZ predicted to cause ≈10% bias in *Planck* Y_{500} measurements for massive clusters
- Simulations to check: realistic physical model for cluster thermodynamic properties, relativistic SZ effect predicted using SZpack
- Injected into real *Planck* data
- Analyzed using PowellSnakes software

Individual *Planck* clusters

- rSZ predicted to cause ≈10% bias in *Planck* Y_{500} measurements for massive clusters
- Simulations to check: realistic physical model for cluster thermodynamic properties, relativistic SZ effect predicted using SZpack
- Injected into real *Planck* data
- Analyzed using PowellSnakes software



From Perrott et al, in prep.

Individual *Planck* clusters

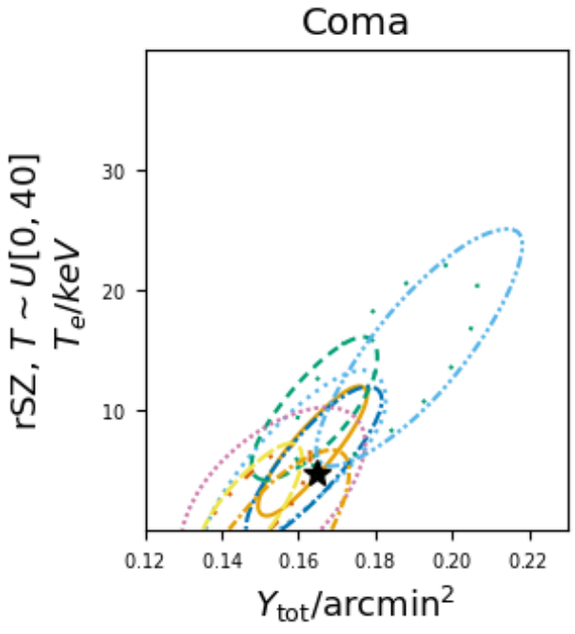
- Can an average SZ temperature be constrained?

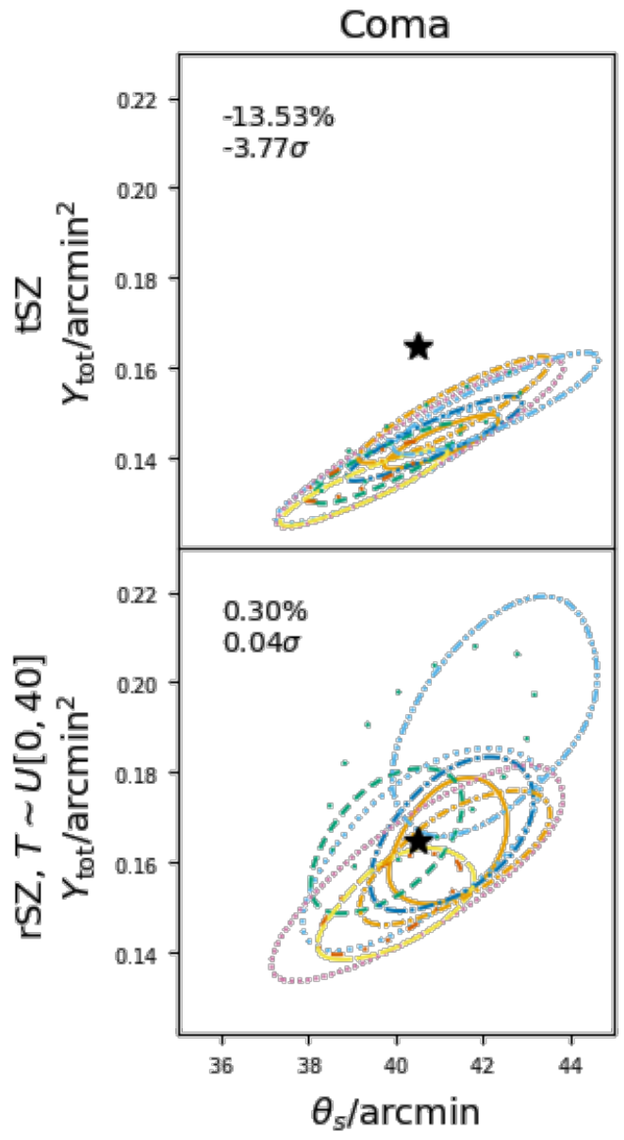
Individual *Planck* clusters

- Can an average SZ temperature be constrained?
- In high-SNR cases – yes, but with very low significance

Individual *Planck* clusters

- Can an average SZ temperature be constrained?
- In high-SNR cases – yes, but with very low significance

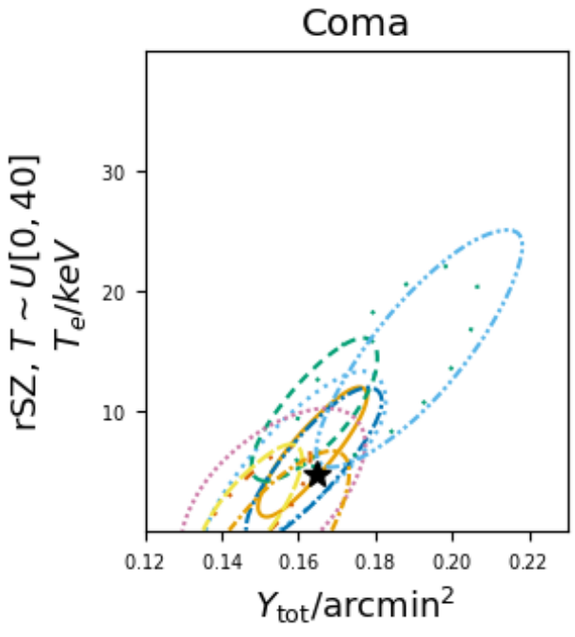


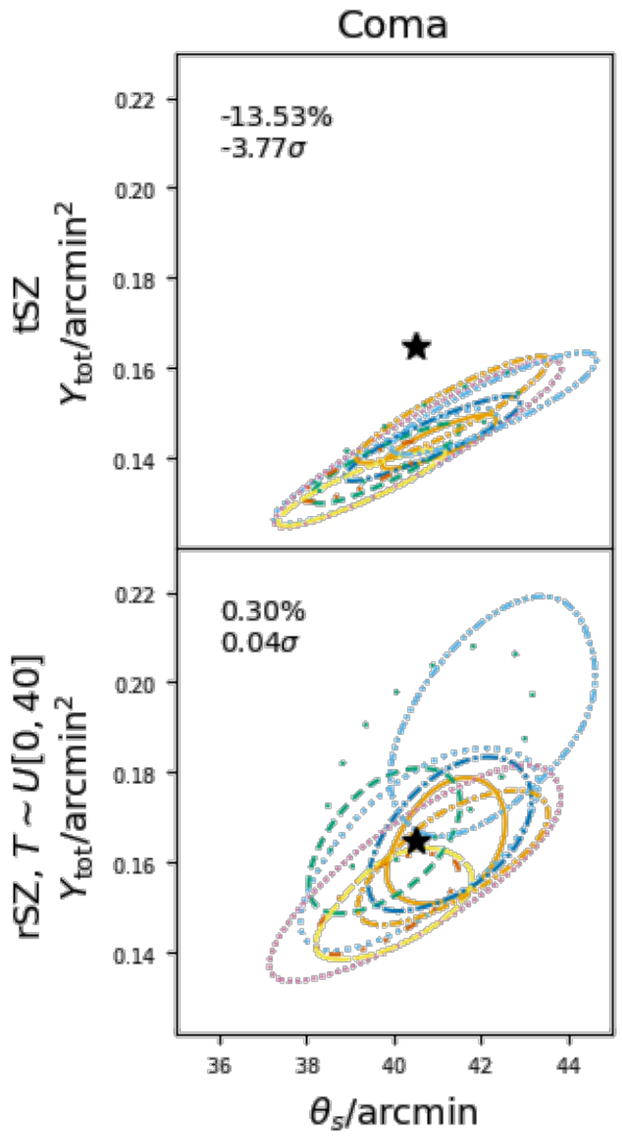


From Perrott et al, in prep.

Individual *Planck* clusters

- Can an average SZ temperature be constrained?
- In high-SNR cases – yes, but with very low significance
- In lower-SNR cases – no, and the Y constraints become biased upward

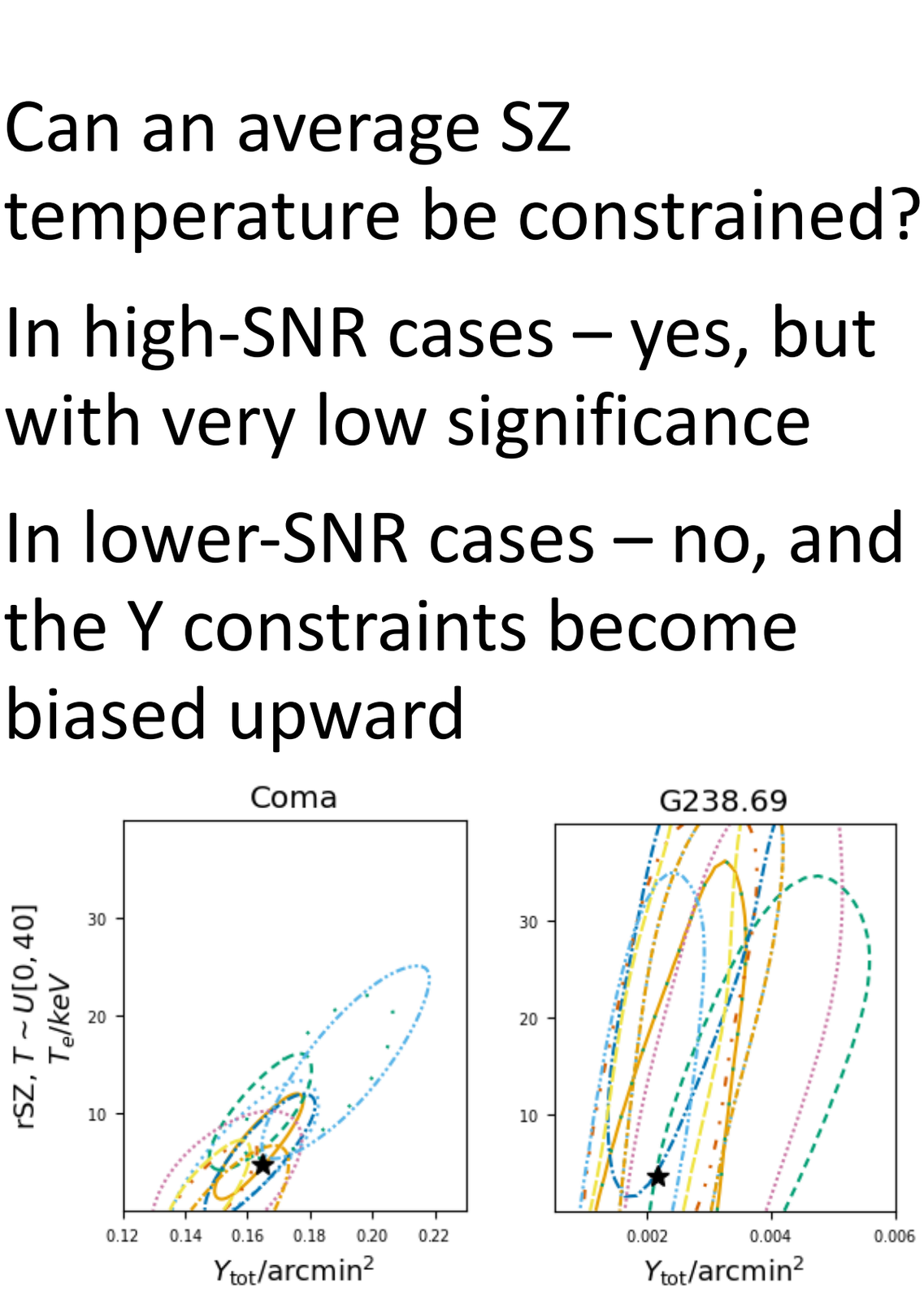


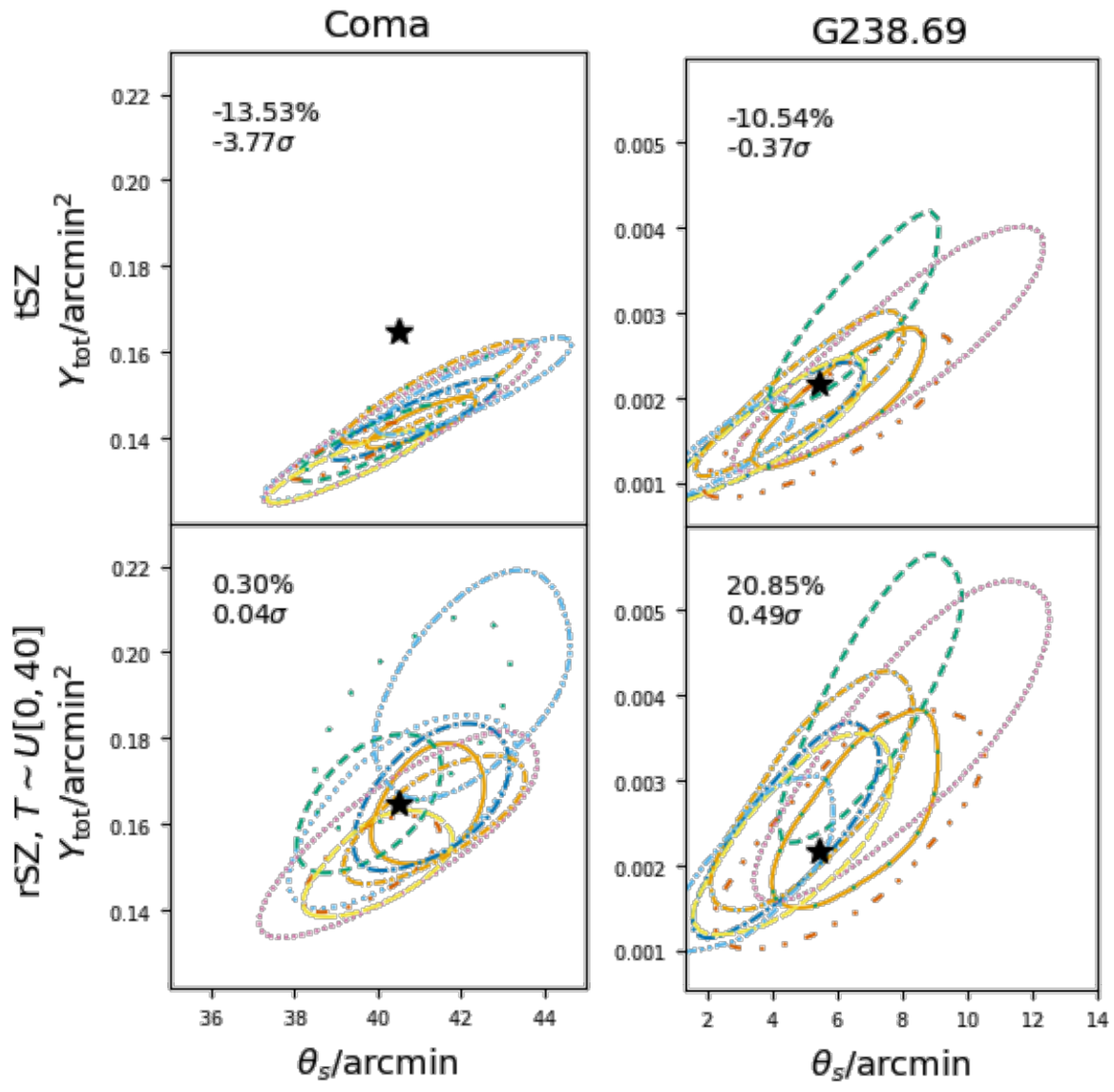


From Perrott et al, in prep.

Individual *Planck* clusters

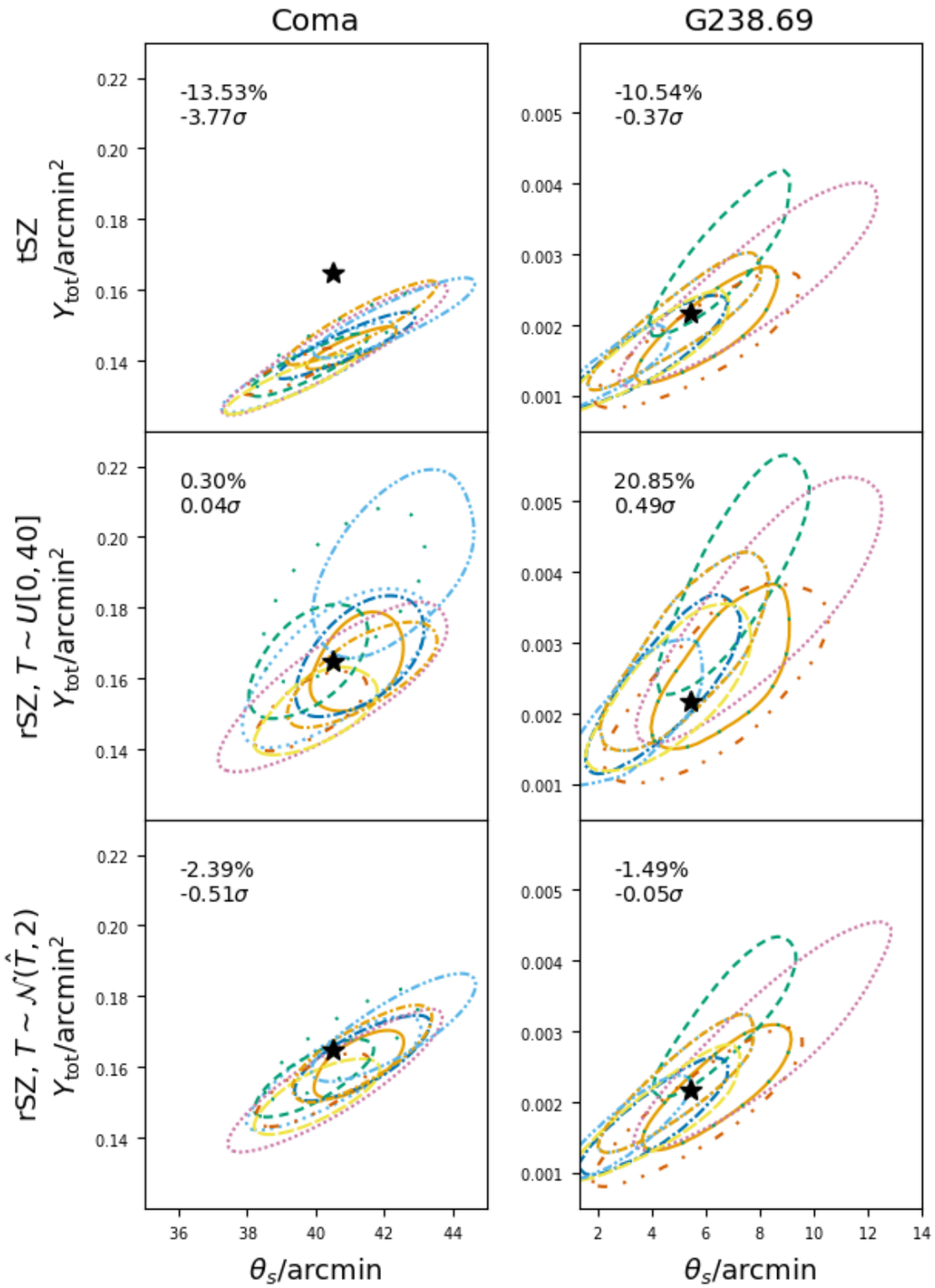
- Can an average SZ temperature be constrained?
- In high-SNR cases – yes, but with very low significance
- In lower-SNR cases – no, and the Y constraints become biased upward





From Perrott et al, in prep.

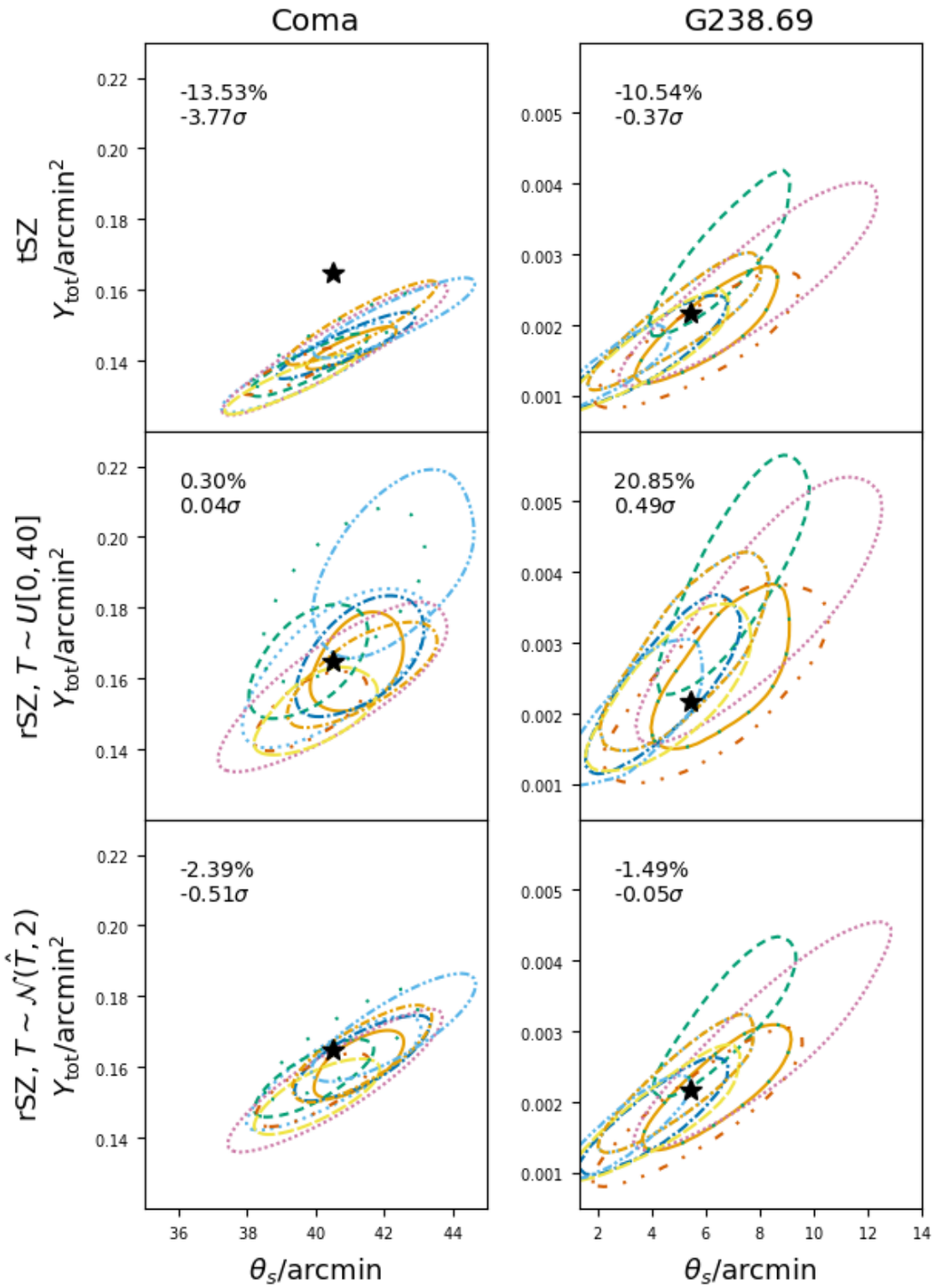
Individual *Planck* clusters



Perrott et al, in prep.

Individual *Planck* clusters

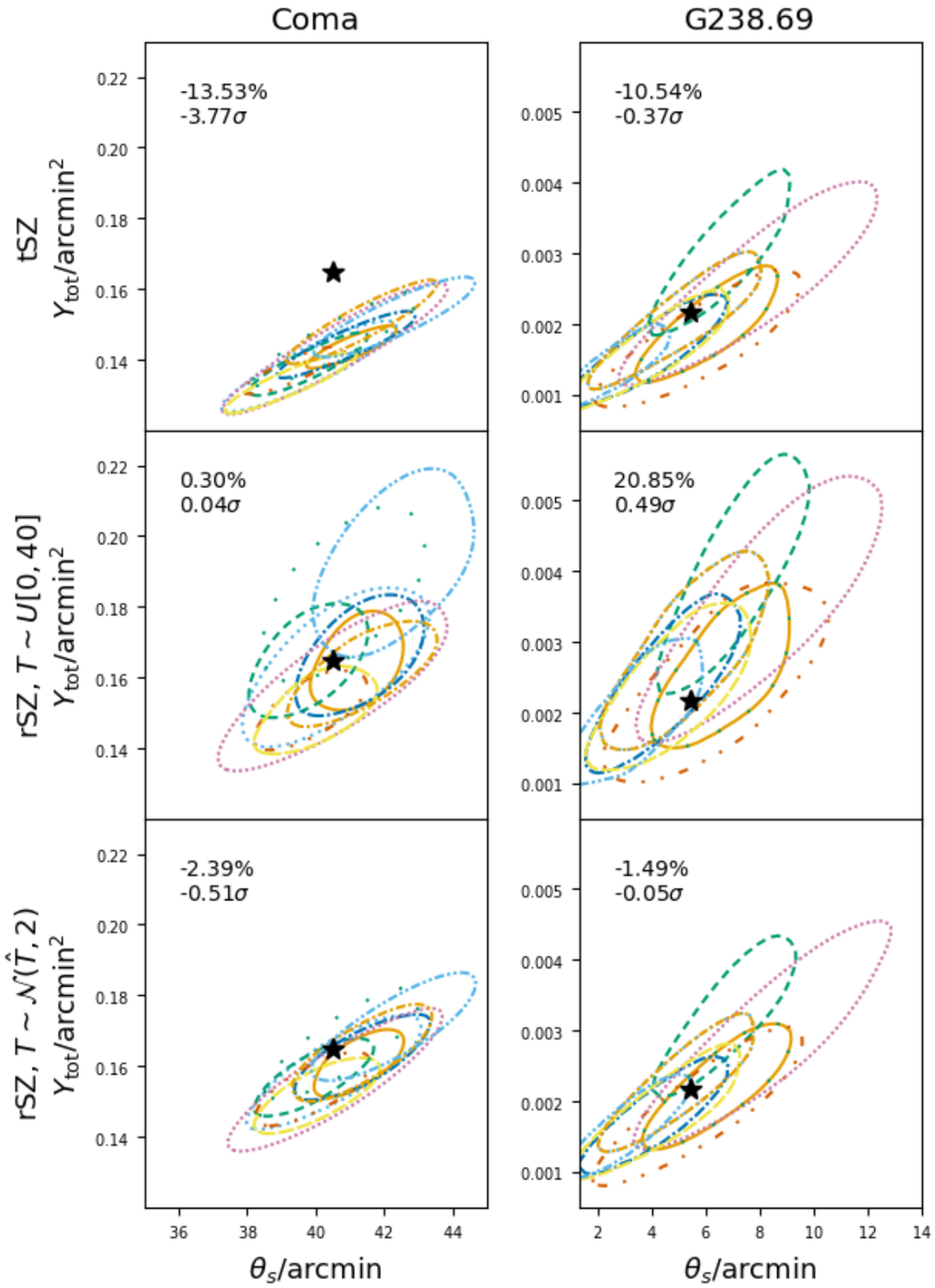
- With an appropriate temperature constraint, Y values are recovered correctly



Perrott et al, in prep.

Individual *Planck* clusters

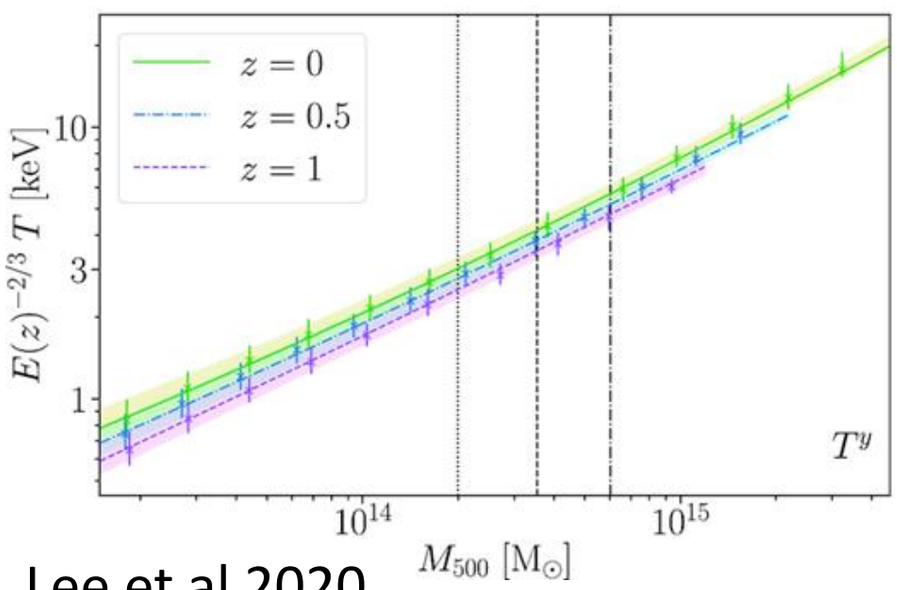
- With an appropriate temperature constraint, Y values are recovered correctly
- X-ray, scaling relation from numerical simulations (Lee et al 2020) seem to work equally well



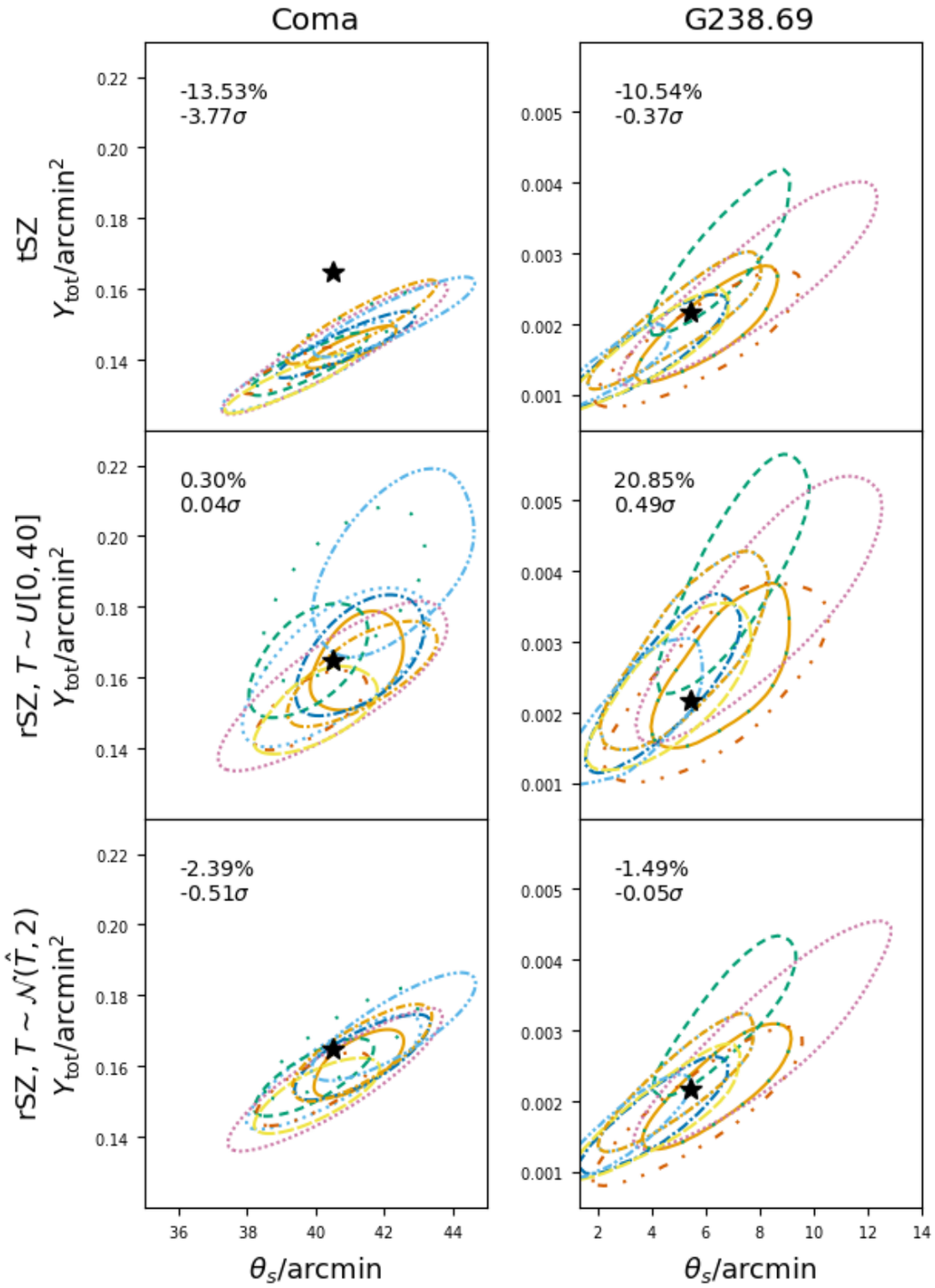
Perrott et al, in prep.

Individual *Planck* clusters

- With an appropriate temperature constraint, Y values are recovered correctly
- X-ray, scaling relation from numerical simulations (Lee et al 2020) seem to work equally well



Lee et al 2020

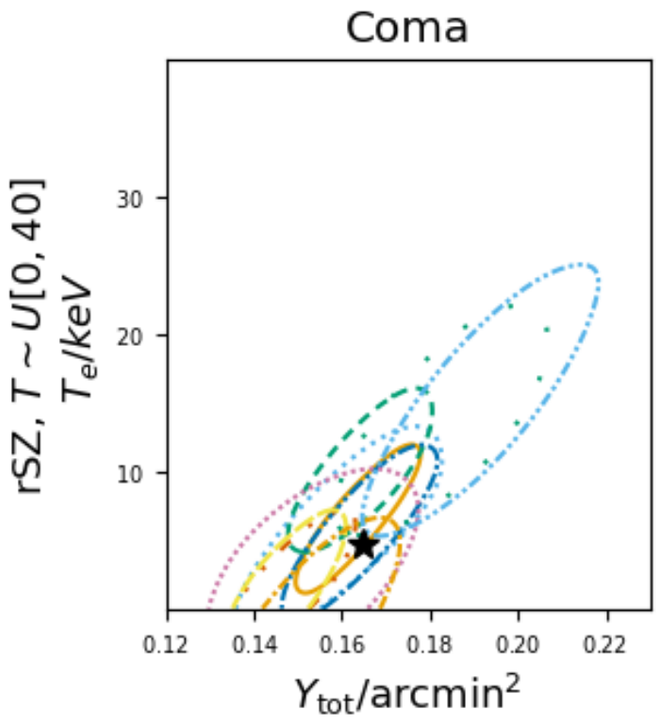


Perrott et al, in prep.

Conclusions from *Planck*

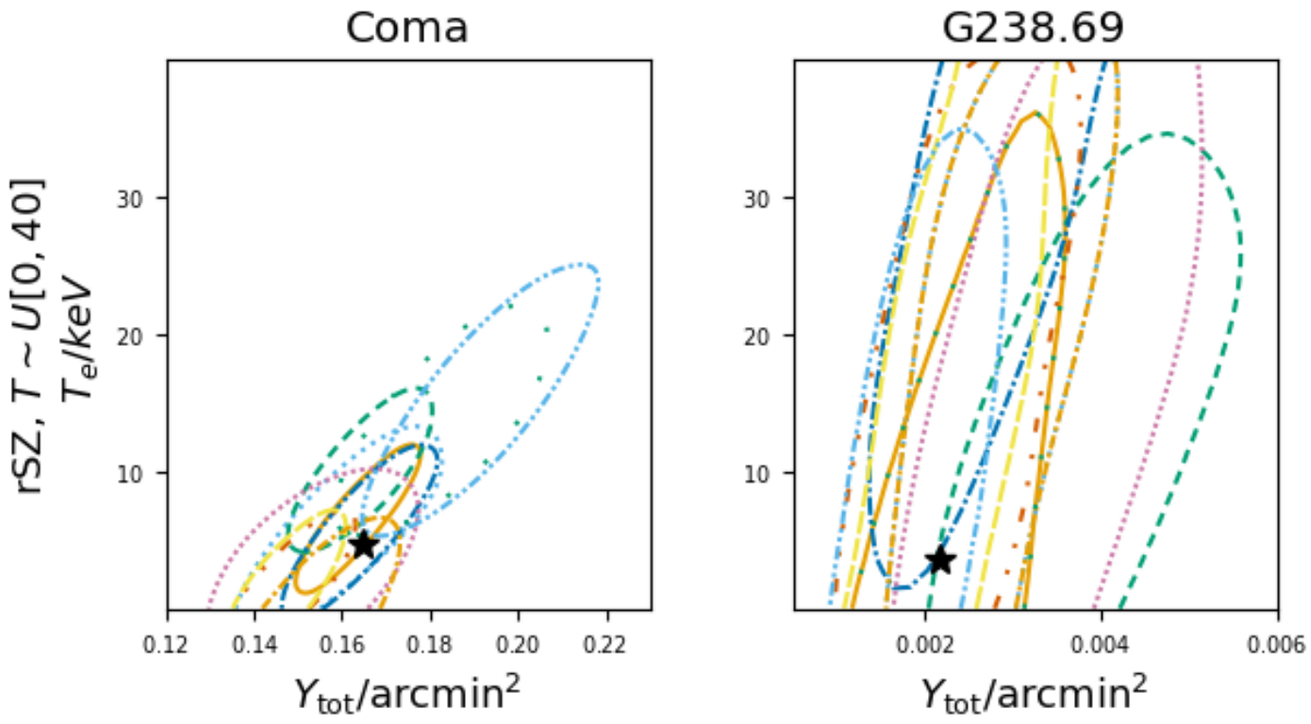
Conclusions from *Planck*

- rSZ can be used to constrain (weakly) temperature in the most massive clusters

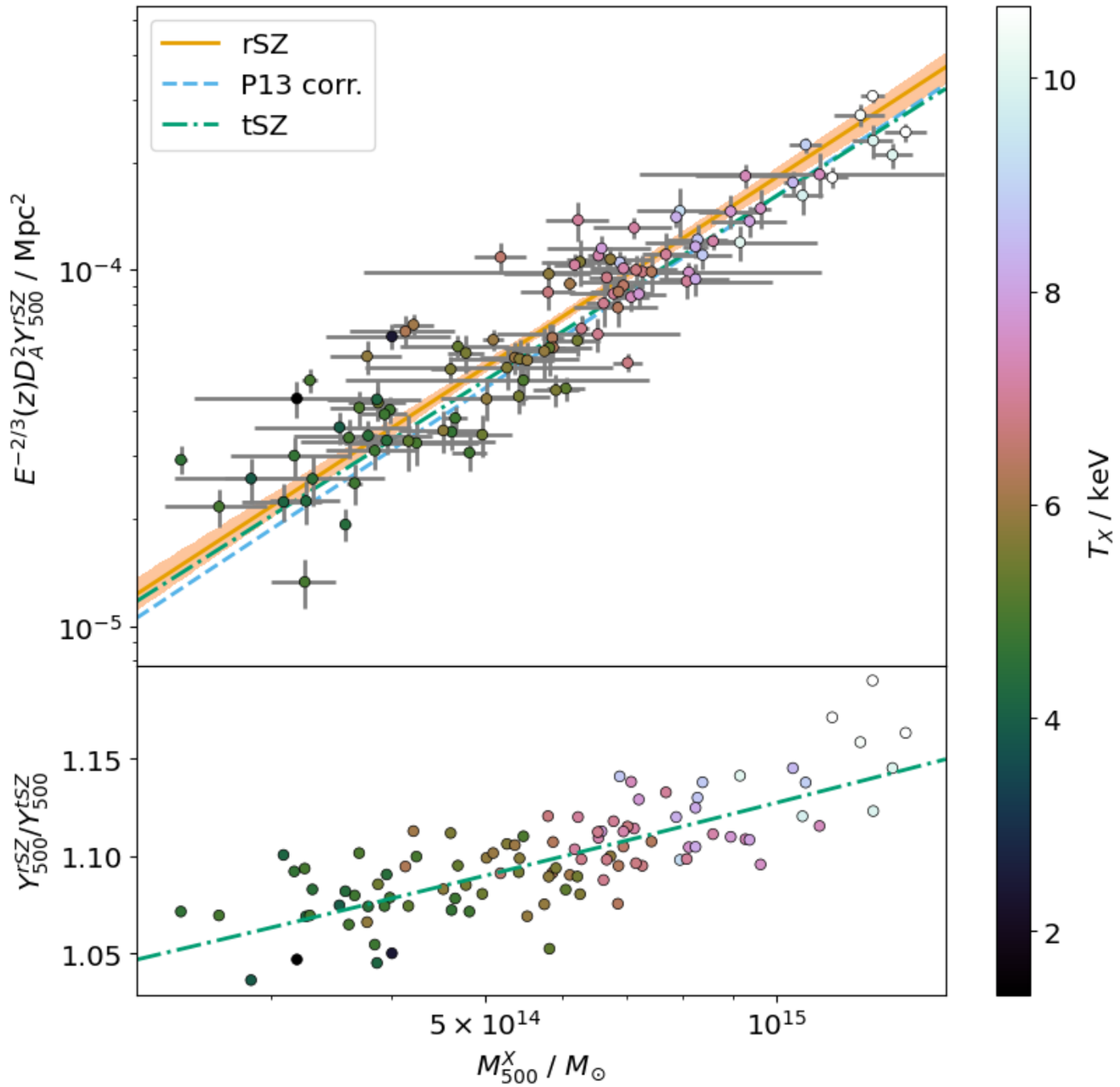


Conclusions from *Planck*

- rSZ can be used to constrain (weakly) temperature in the most massive clusters
- In the bulk of the *Planck* cluster population, it causes a bias which an external temperature estimate is required to remove.



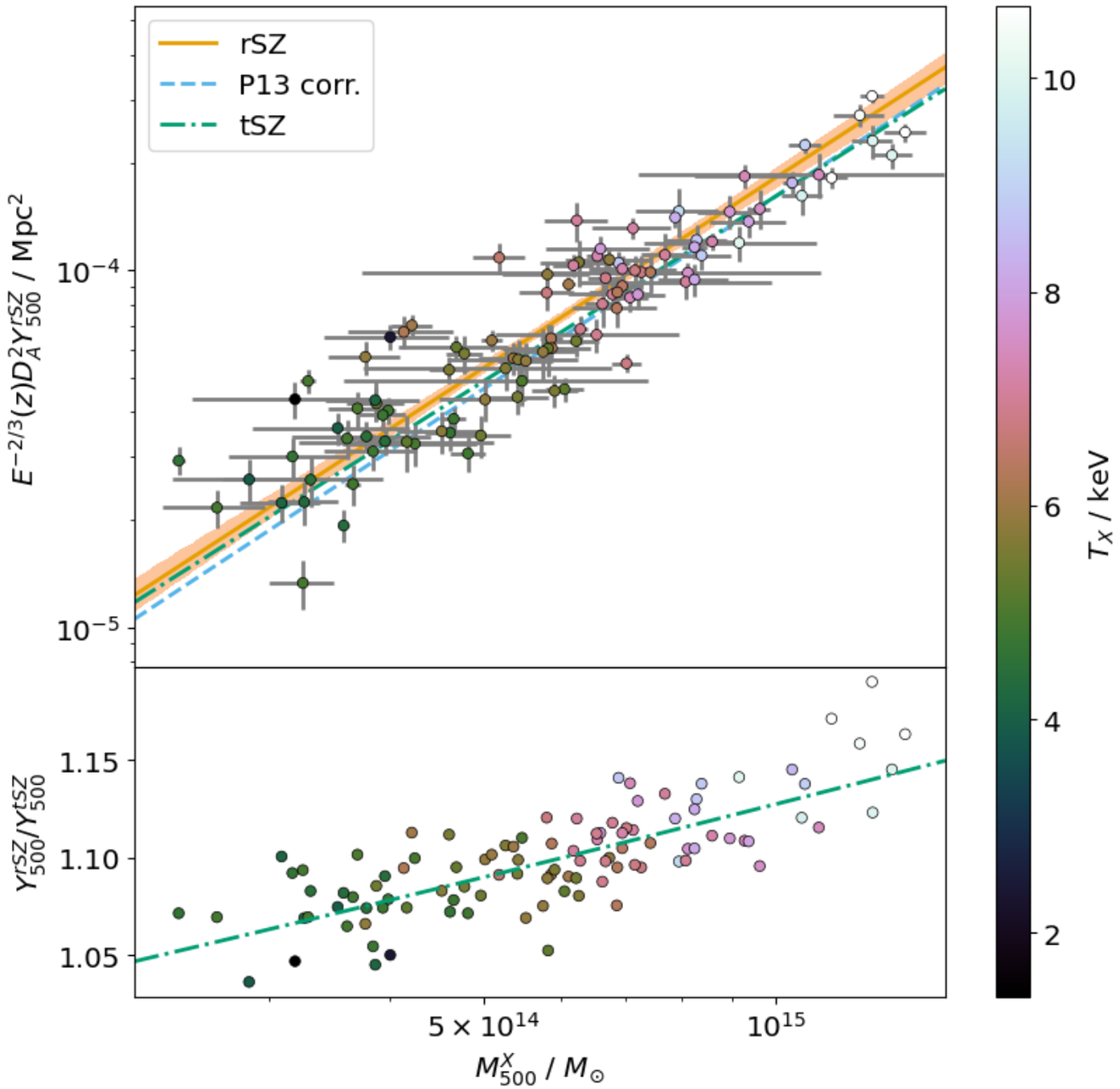
Scaling relations



Perrott et al, in prep.
Preliminary!

Scaling relations

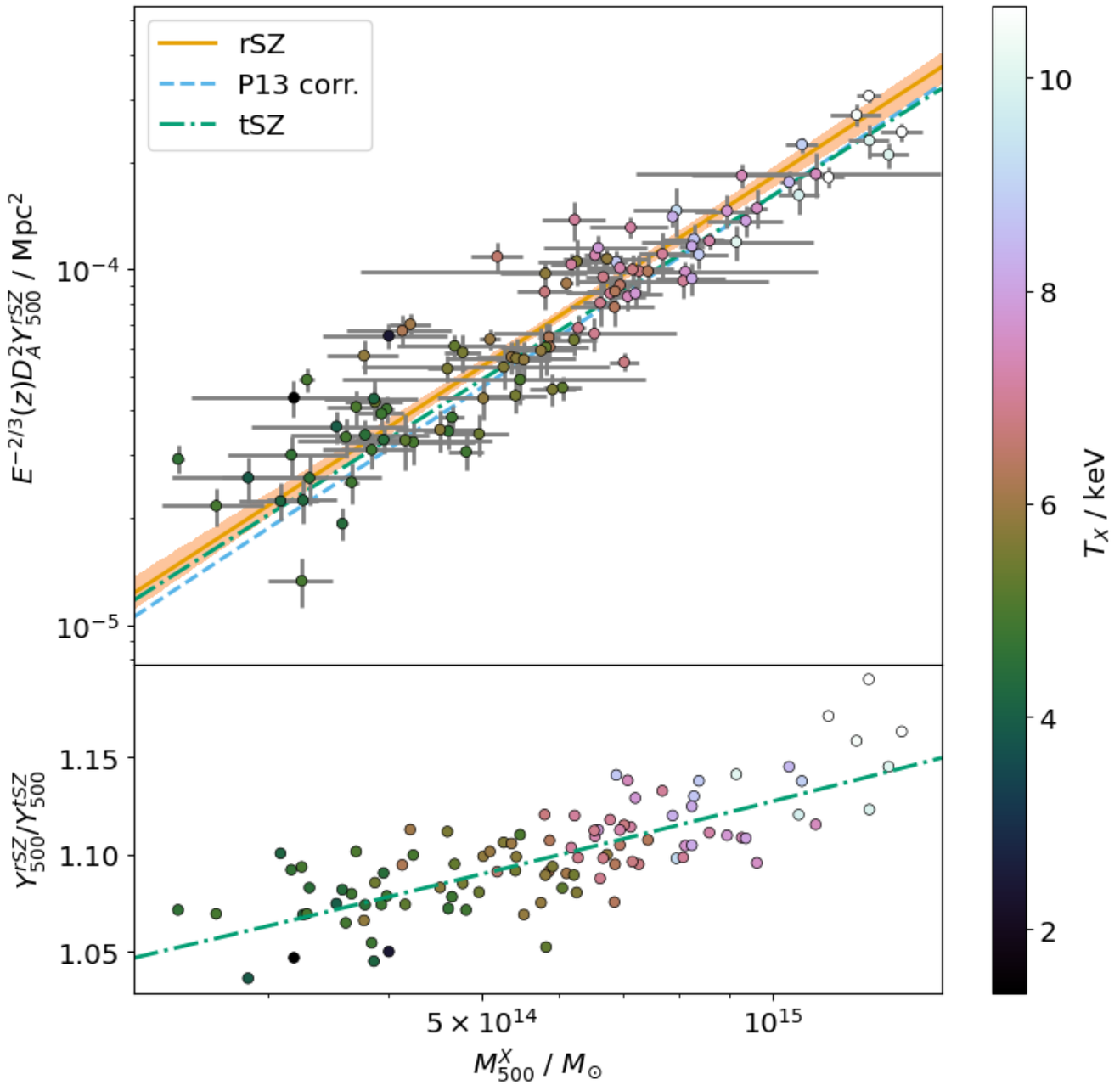
- Recalibration of M_{500}-Y_{500} scaling relation using X-ray hydrostatic masses, temperatures from XMM-*Newton* (Lovisari et al 2020)



Perrott et al, in prep.
Preliminary!

Scaling relations

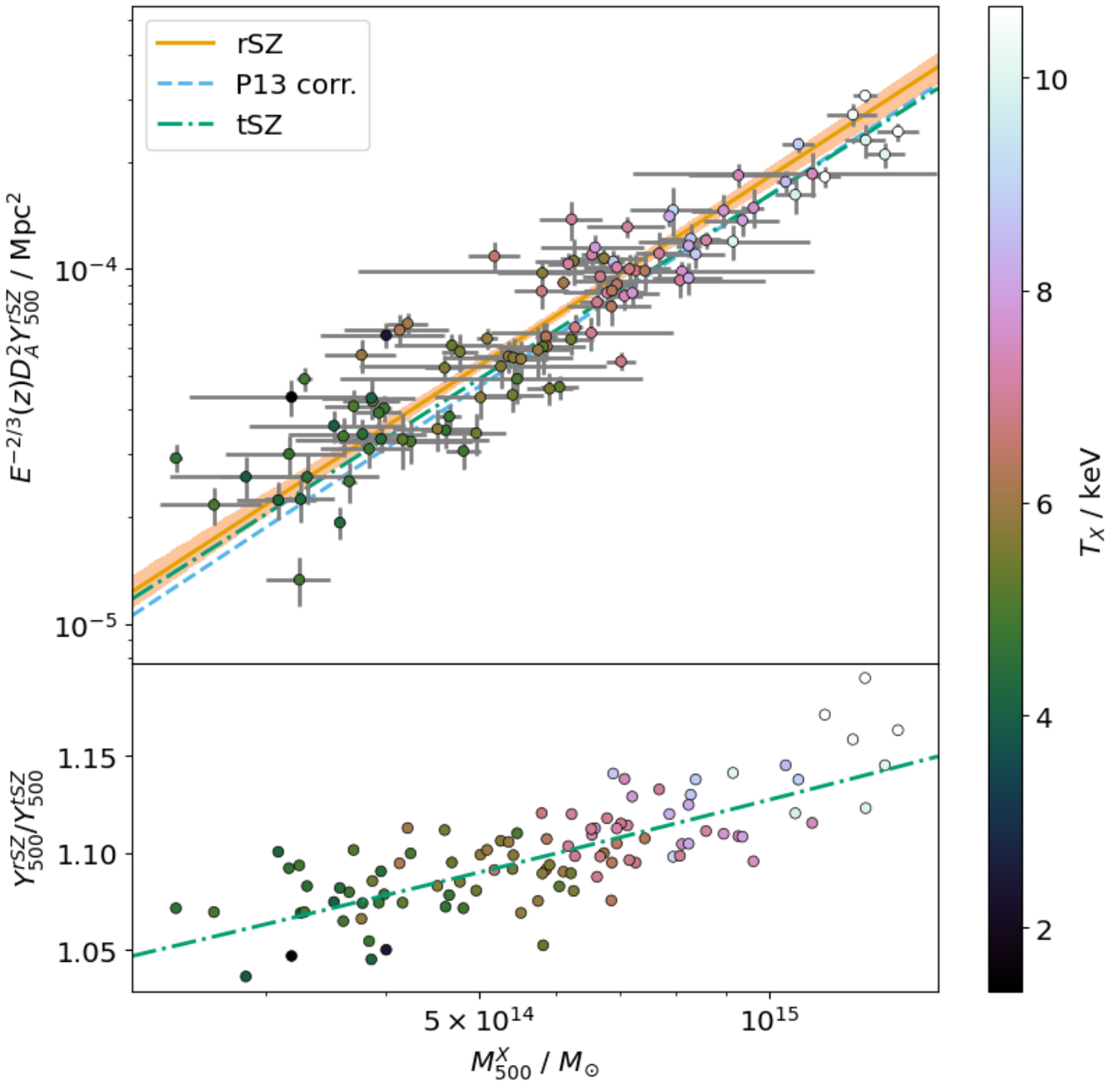
- Recalibration of M_{500}-Y_{500} scaling relation using X-ray hydrostatic masses, temperatures from XMM-*Newton* (Lovisari et al 2020)
- Updated *Planck* data (NPIPE release), fitting pressure profile shape, implementing rSZ spectrum



Perrott et al, in prep.
Preliminary!

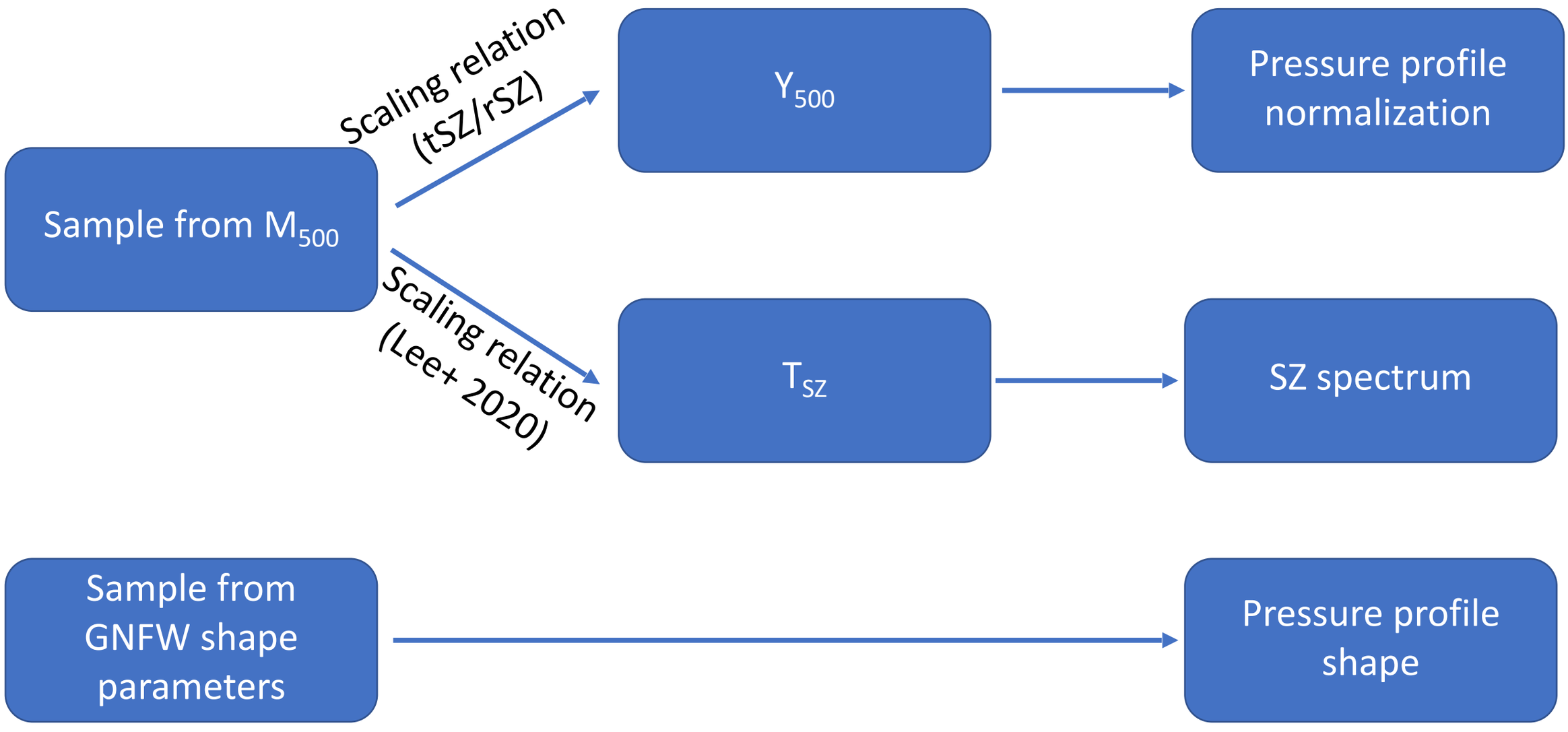
Scaling relations

- Recalibration of M_{500}-Y_{500} scaling relation using X-ray hydrostatic masses, temperatures from XMM-*Newton* (Lovisari et al 2020)
- Updated *Planck* data (NPIPE release), fitting pressure profile shape, implementing rSZ spectrum
- Mass-dependent 5-15% bias in scaling relation found

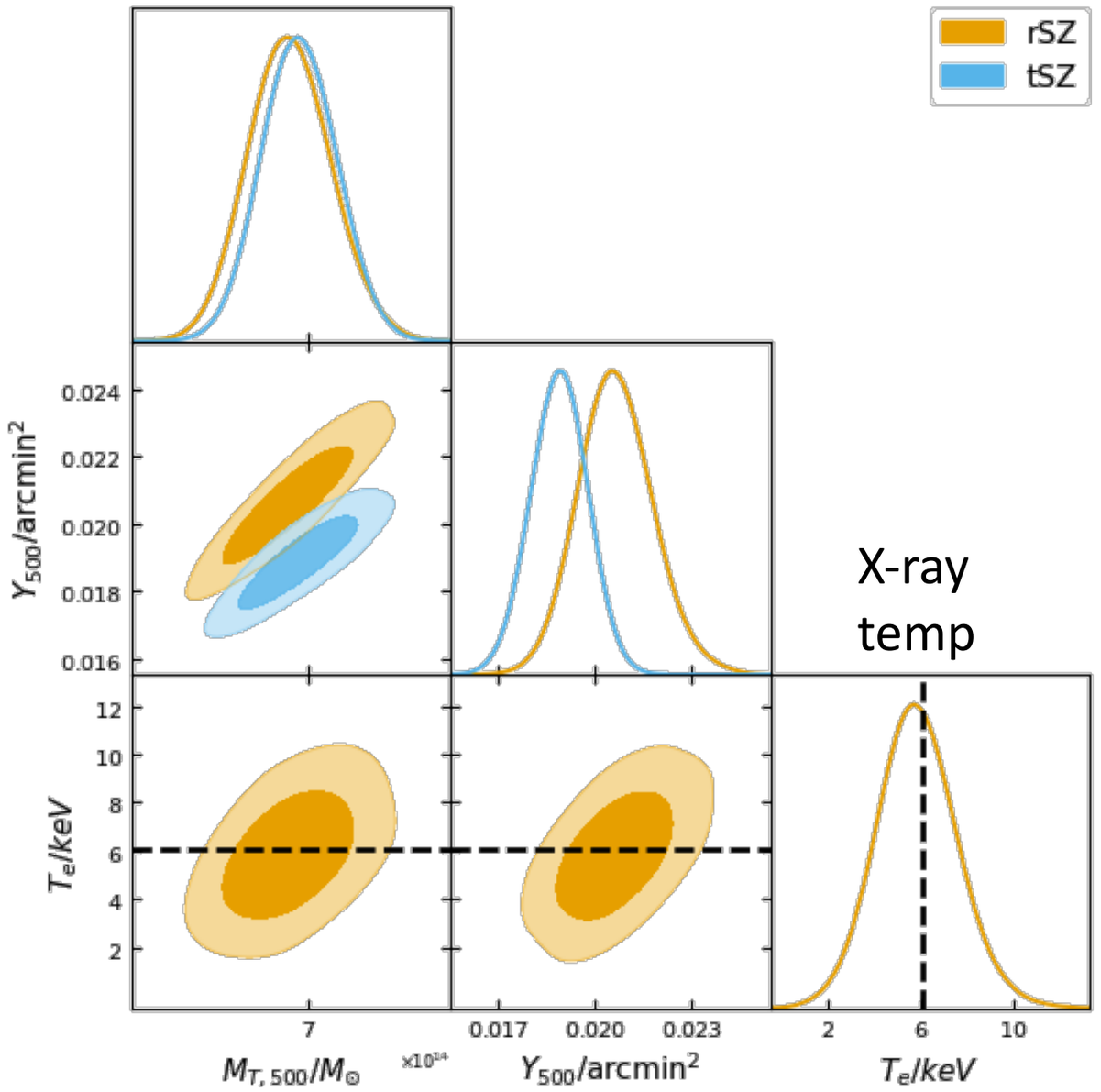


Perrott et al, in prep.
Preliminary!

Implementation



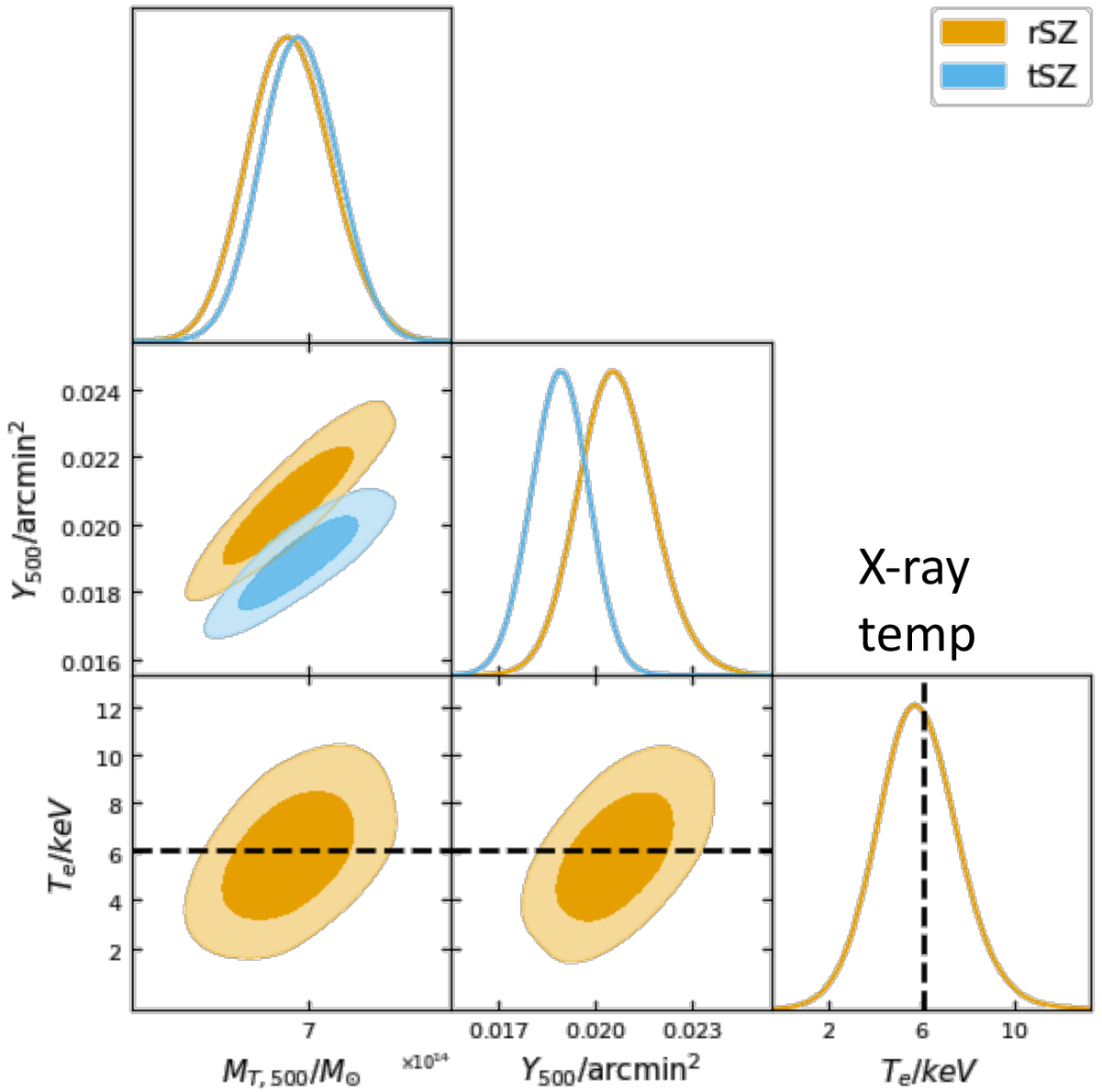
Results



Updated *Planck* constraints for Abell 3266.
Perrott et al, in prep. Preliminary!

Results

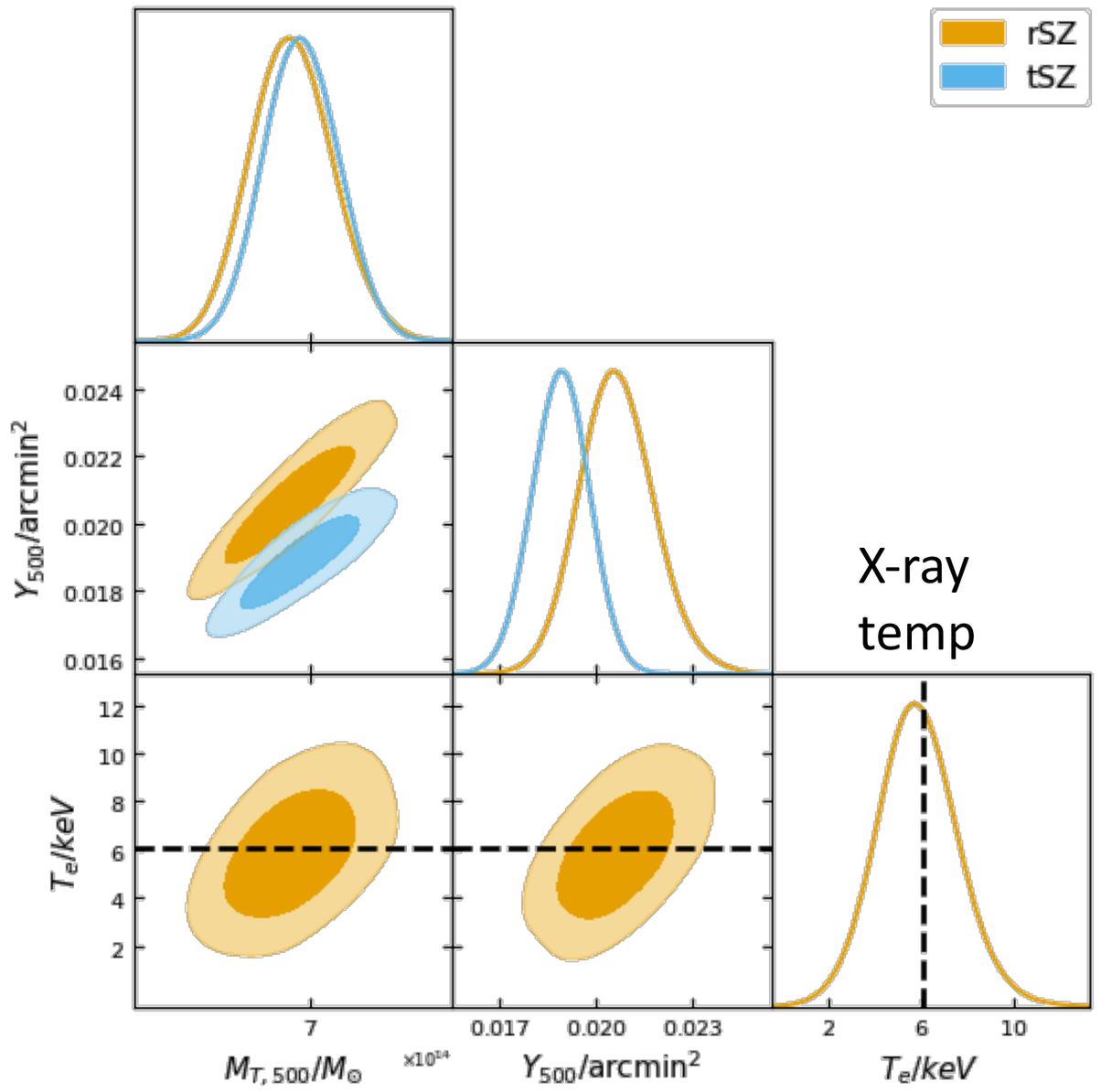
- No difference to *Planck* masses! Model applies biased scaling relation to biased Y



Updated *Planck* constraints for Abell 3266. Perrott et al, in prep. Preliminary!

Results

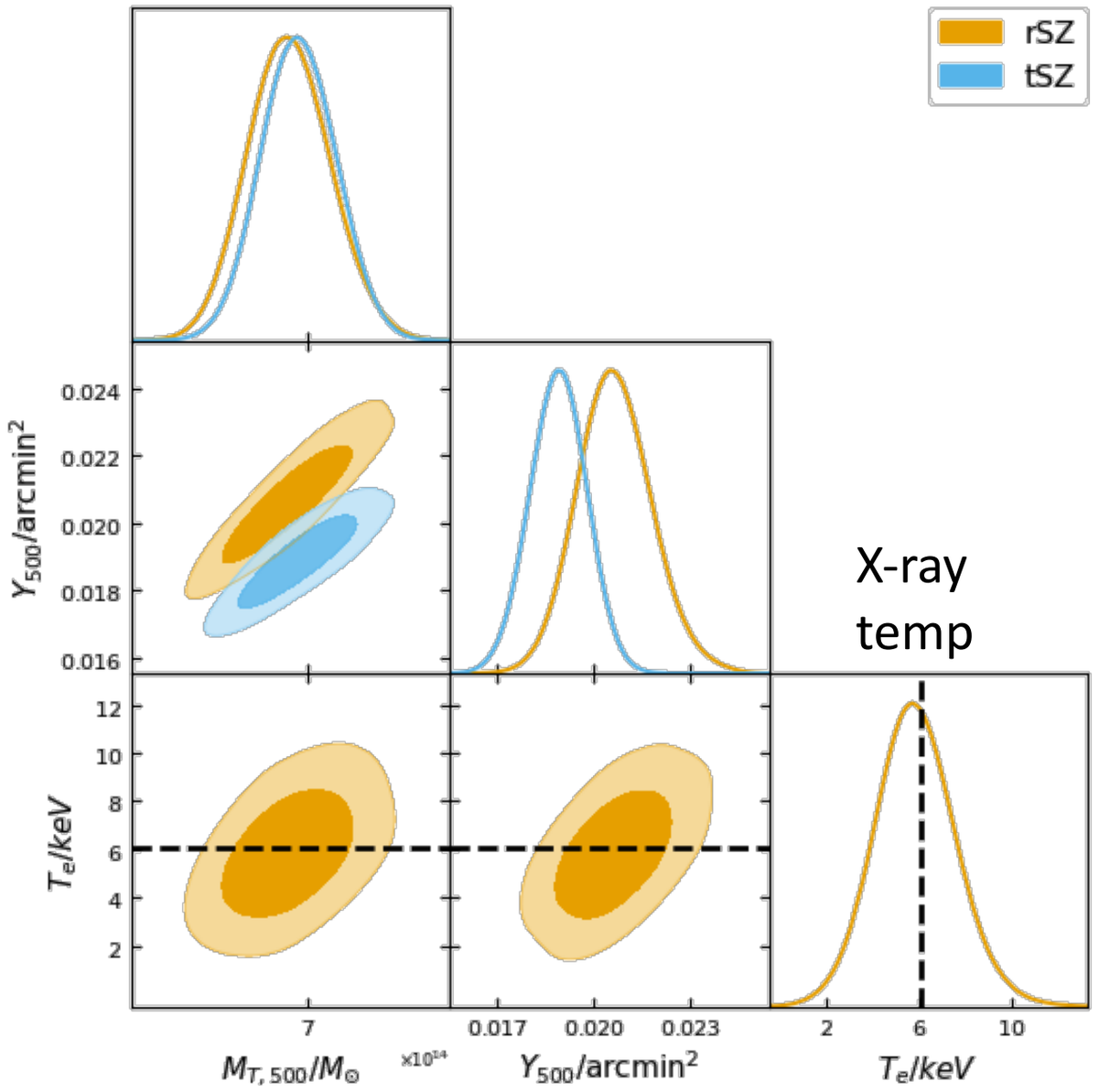
- No difference to *Planck* masses! Model applies biased scaling relation to biased Y
- Unbiased Y values recovered: important for cross-instrument validation/combination (eg Butler+ 2022 used *Planck* to constrain large scales)



Updated *Planck* constraints for Abell 3266. Perrott et al, in prep. Preliminary!

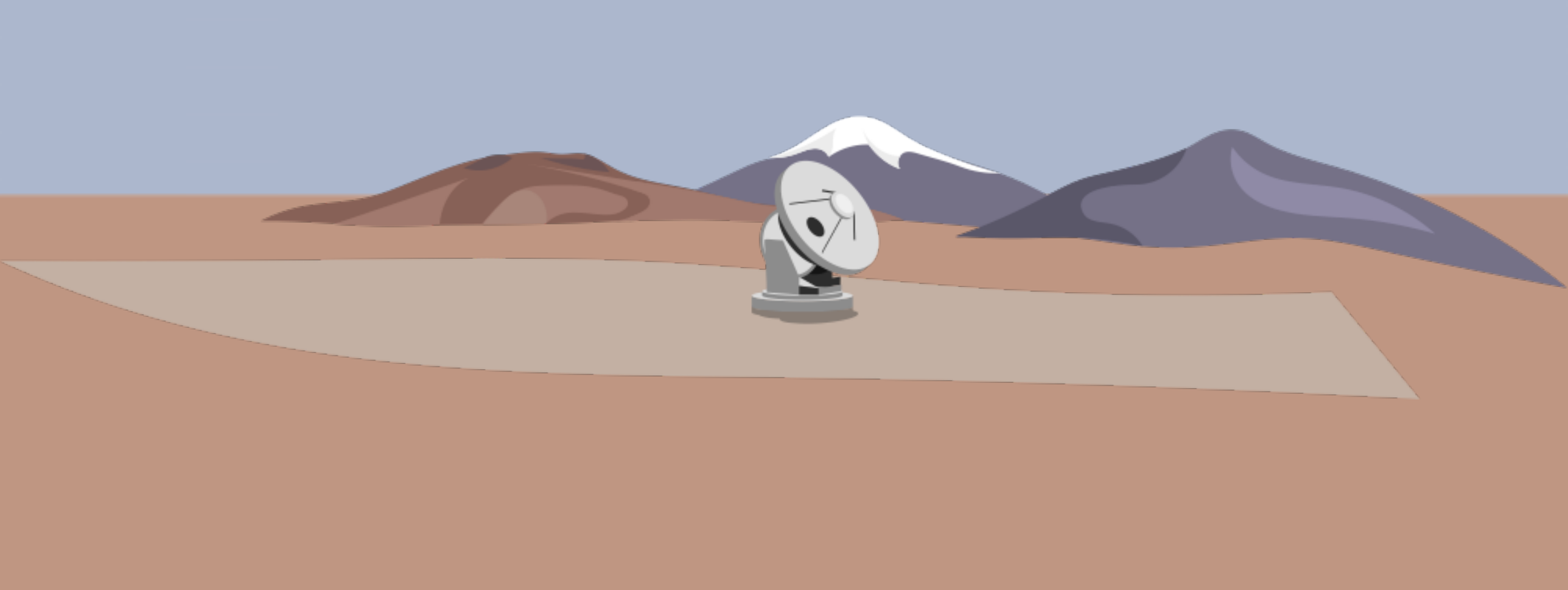
Results

- No difference to *Planck* masses! Model applies biased scaling relation to biased Y
- Unbiased Y values recovered: important for cross-instrument validation/combination (eg Butler+ 2022 used *Planck* to constrain large scales)
- Unbiased M_{500}-Y_{500} scaling relation should be applied to SZ measurements with other instruments (eg Hilton+ 2021 use the rSZ spectrum to analyze ACT clusters but apply the *Planck* tSZ M_{500}-Y_{500} scaling relation)



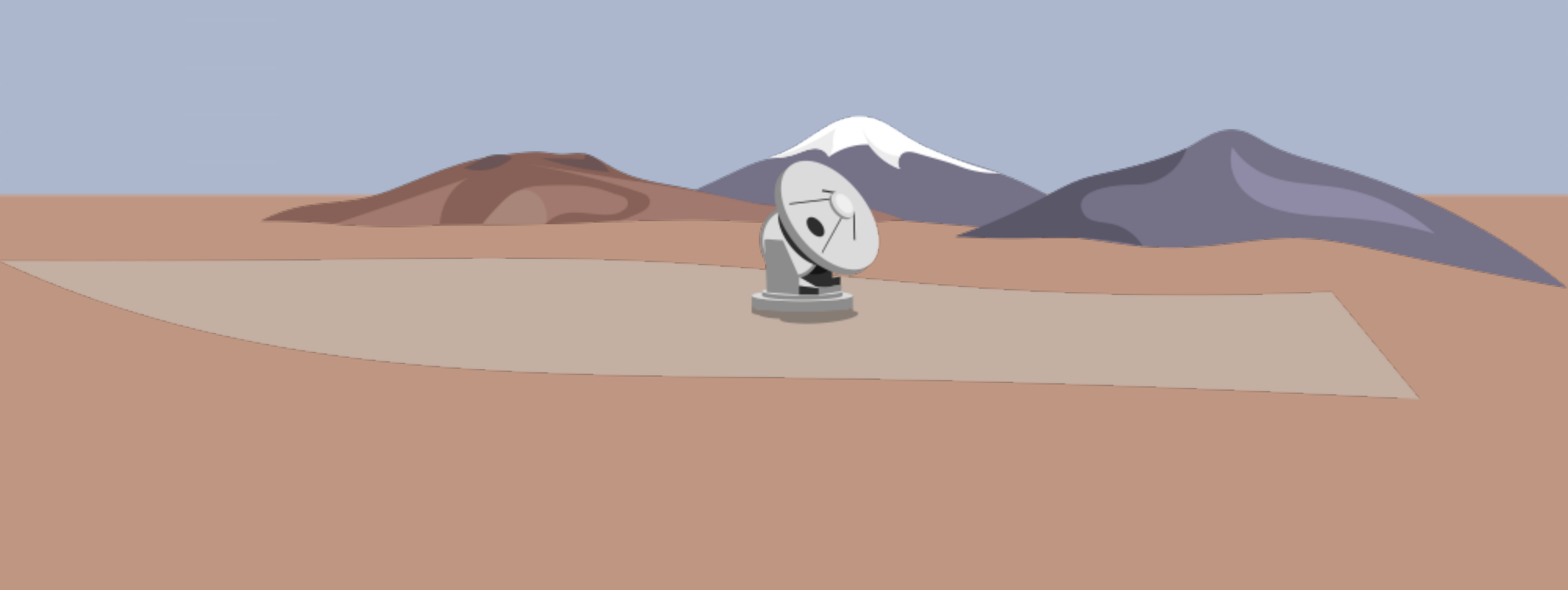
Updated *Planck* constraints for Abell 3266. Perrott et al, in prep. Preliminary!

AtLAST



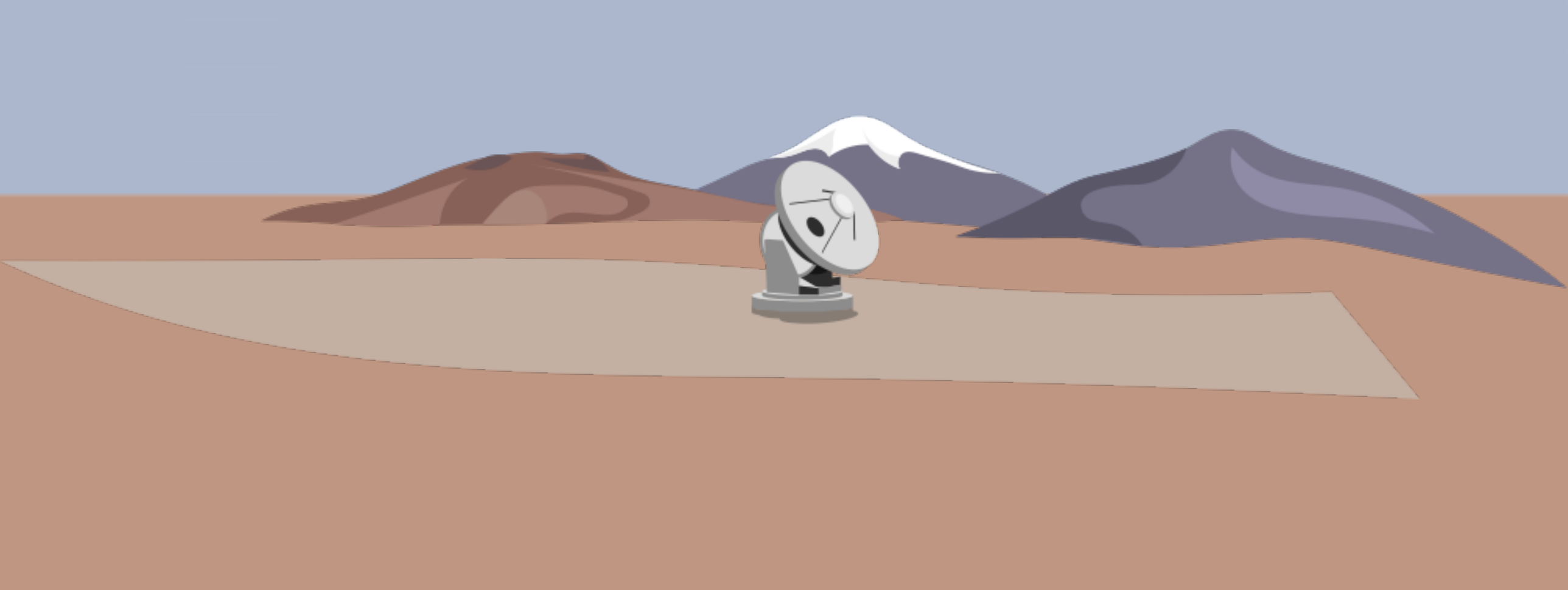
AtLAST

- Proposed 50m single dish telescope → high angular resolution



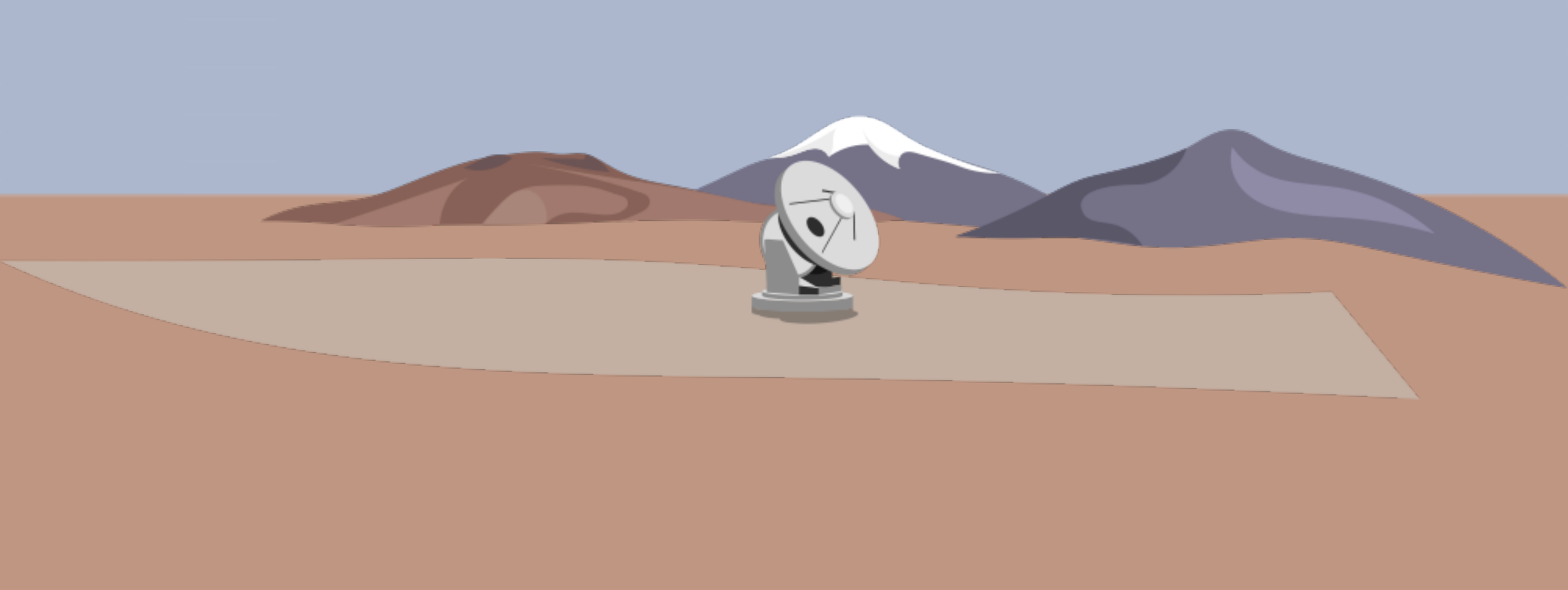
AtLAST

- Proposed 50m single dish telescope → high angular resolution
- To be situated in the Atacama desert → access to high frequencies

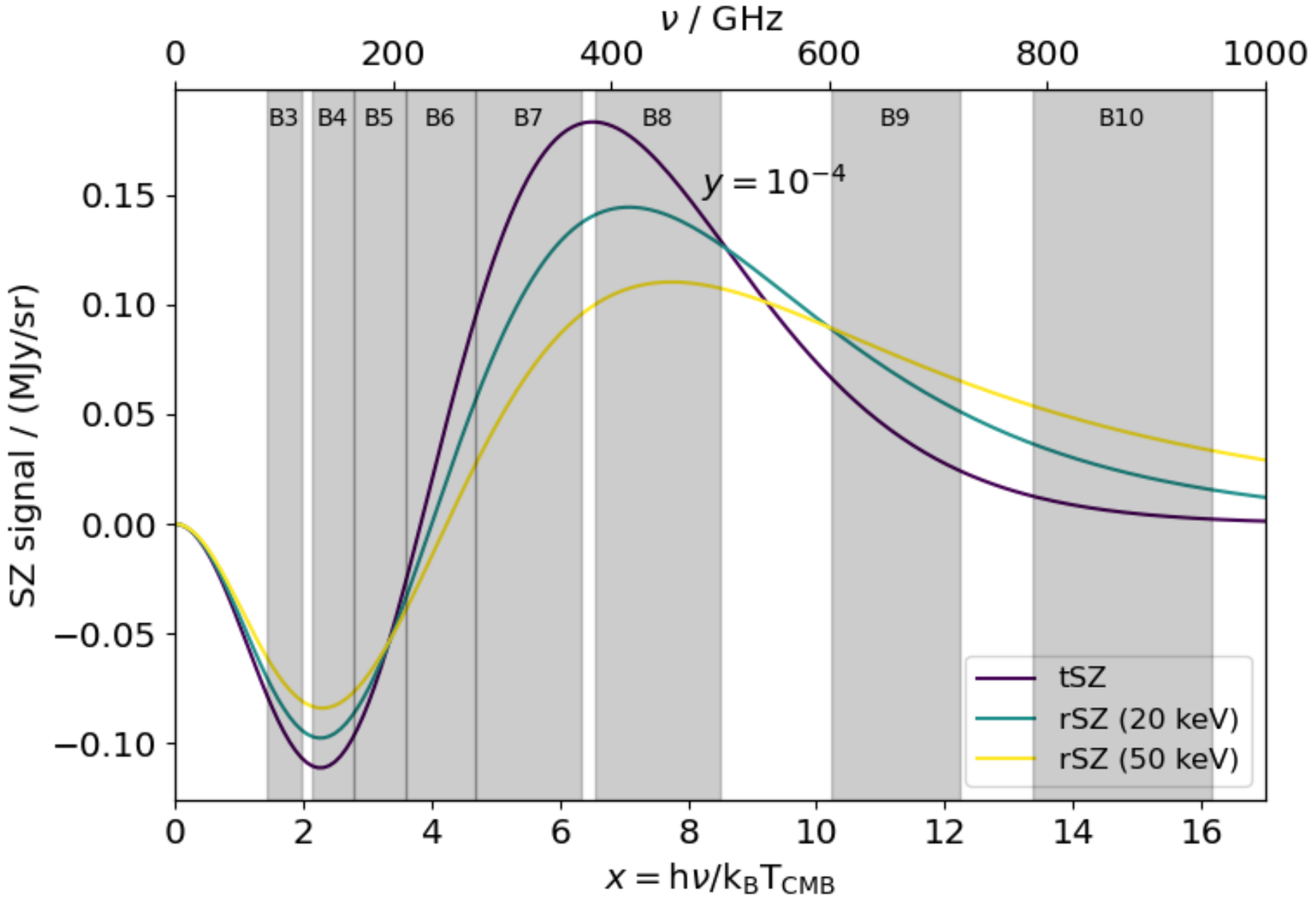


AtLAST

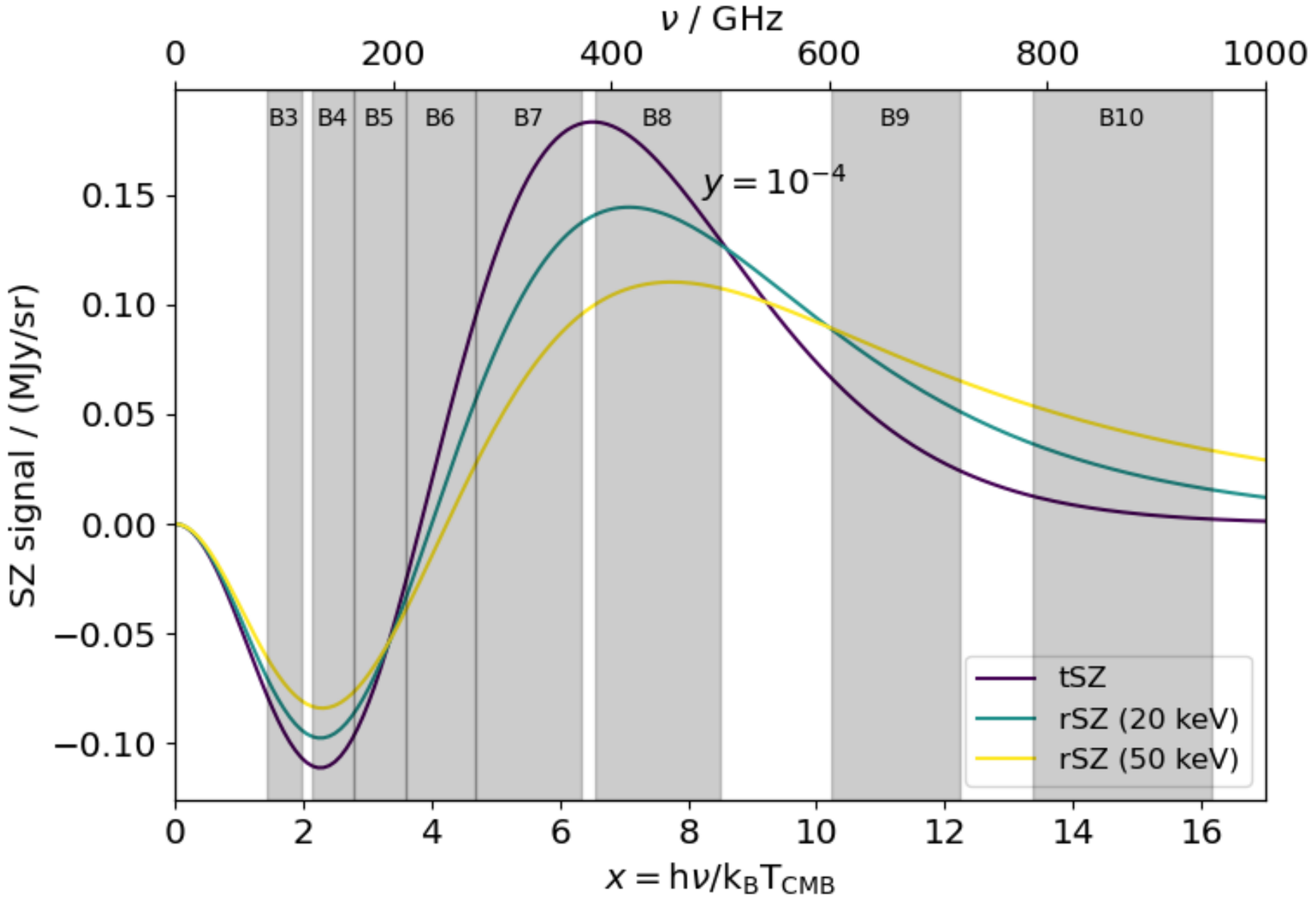
- Proposed 50m single dish telescope → high angular resolution
- To be situated in the Atacama desert → access to high frequencies
- Will observe from ≈ 80 - 1000 GHz



Proposed frequency bands

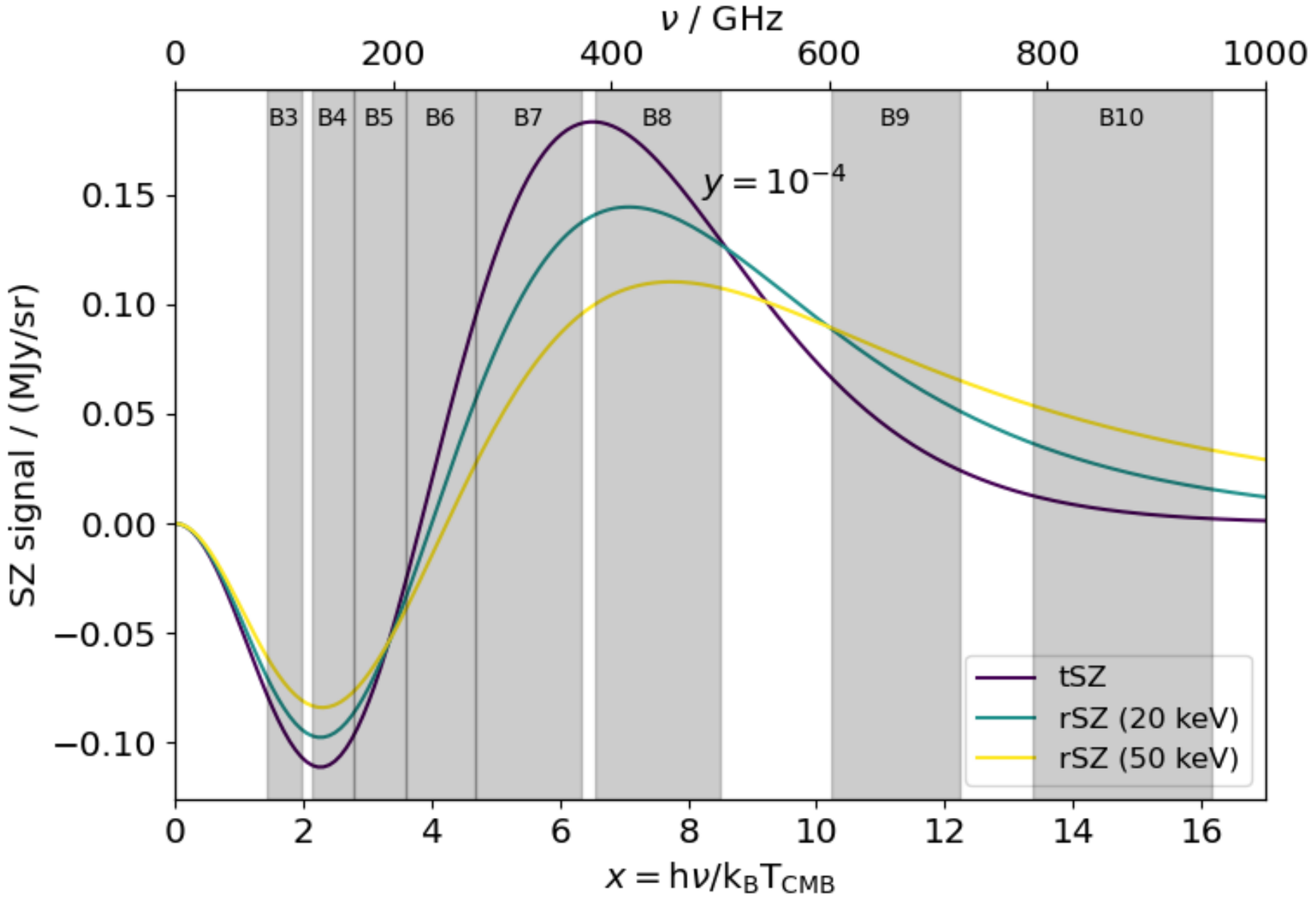


Proposed frequency bands



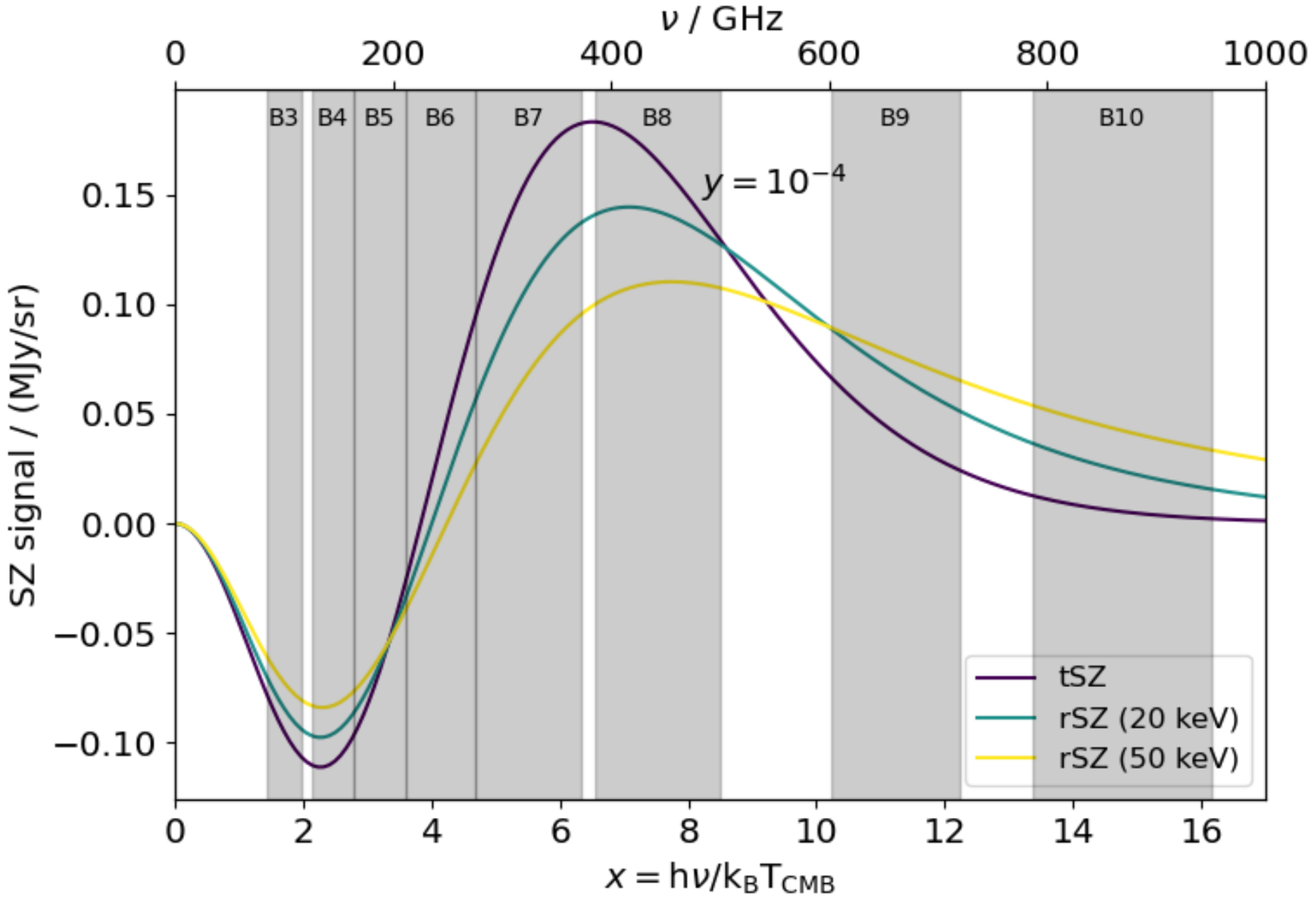
- Similar frequency coverage to *Planck*

Proposed frequency bands



- Similar frequency coverage to *Planck*
- More, narrower bands? May be better for constraining the rSZ spectrum

Proposed frequency bands

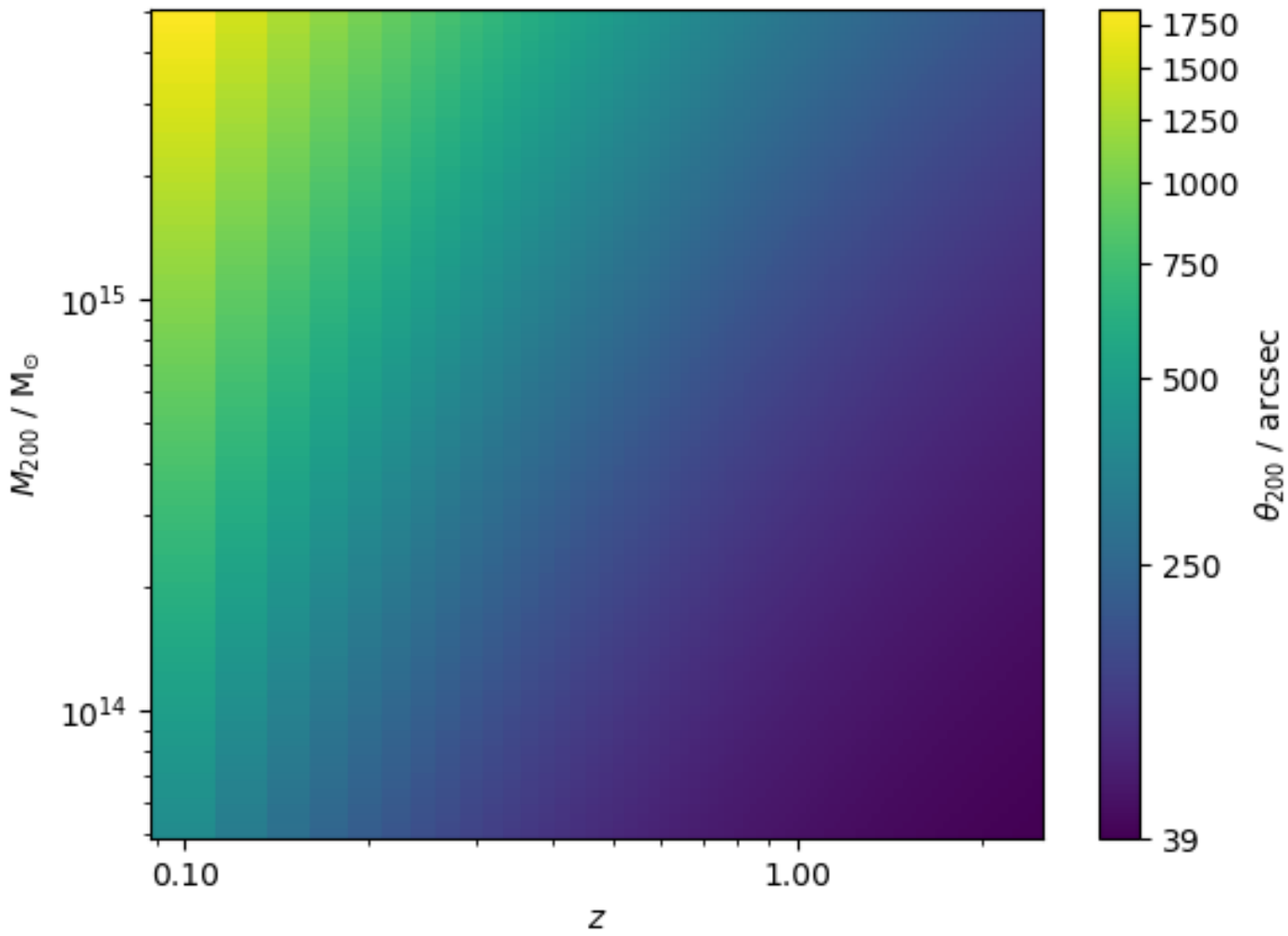


- Similar frequency coverage to *Planck*
- More, narrower bands? May be better for constraining the rSZ spectrum

Angular resolution

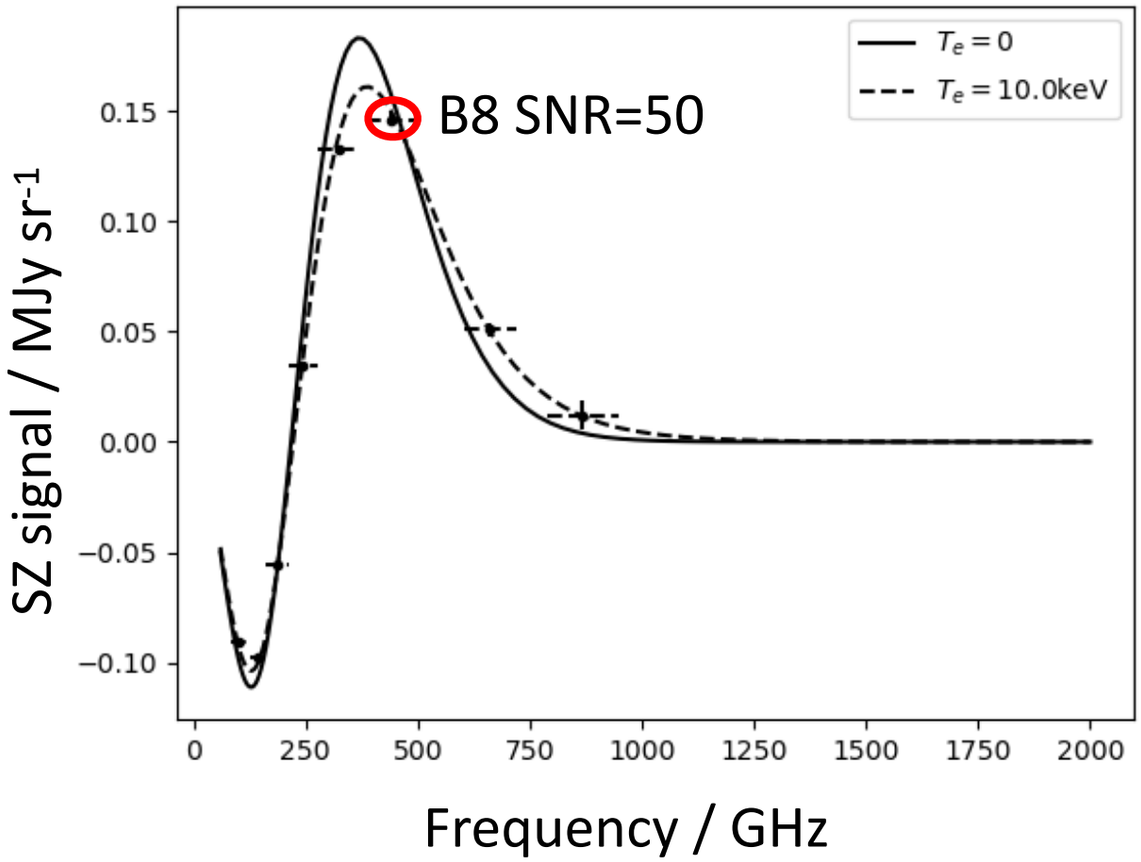
Band	Central frequency (GHz)	Angular resolution (arcsec)
3	100	14.84
4	144	10.31
5	187	7.94
6	243	6.11
7	324	4.58
8	442	3.35
9	661	2.25
10	868	1.71

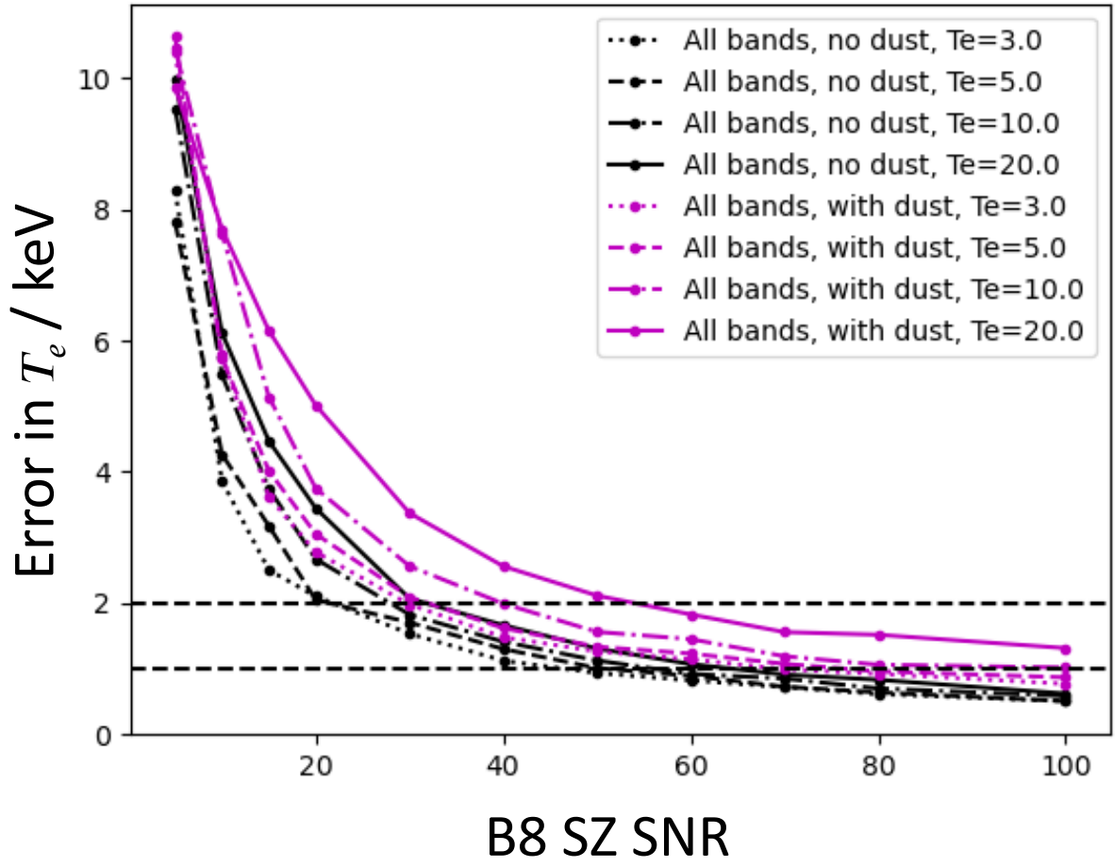
- Angular resolution should allow resolved temperature profile measurements



Sensitivity – Preliminary!

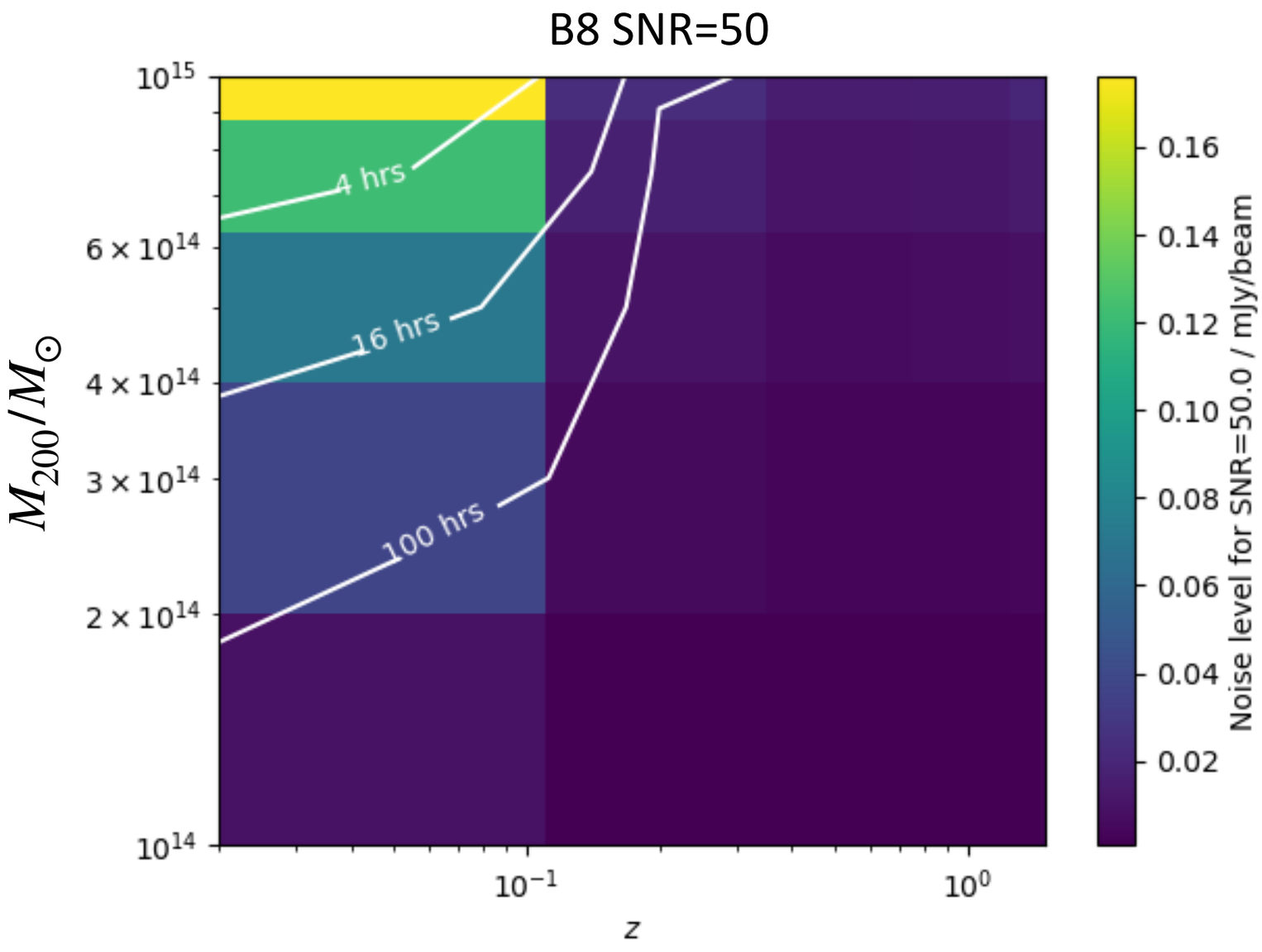
- What kind of sensitivity do you need to constrain rSZ temperature?
- Assume same observing time for all bands; test temperature constraints as a function of SNR in reference band





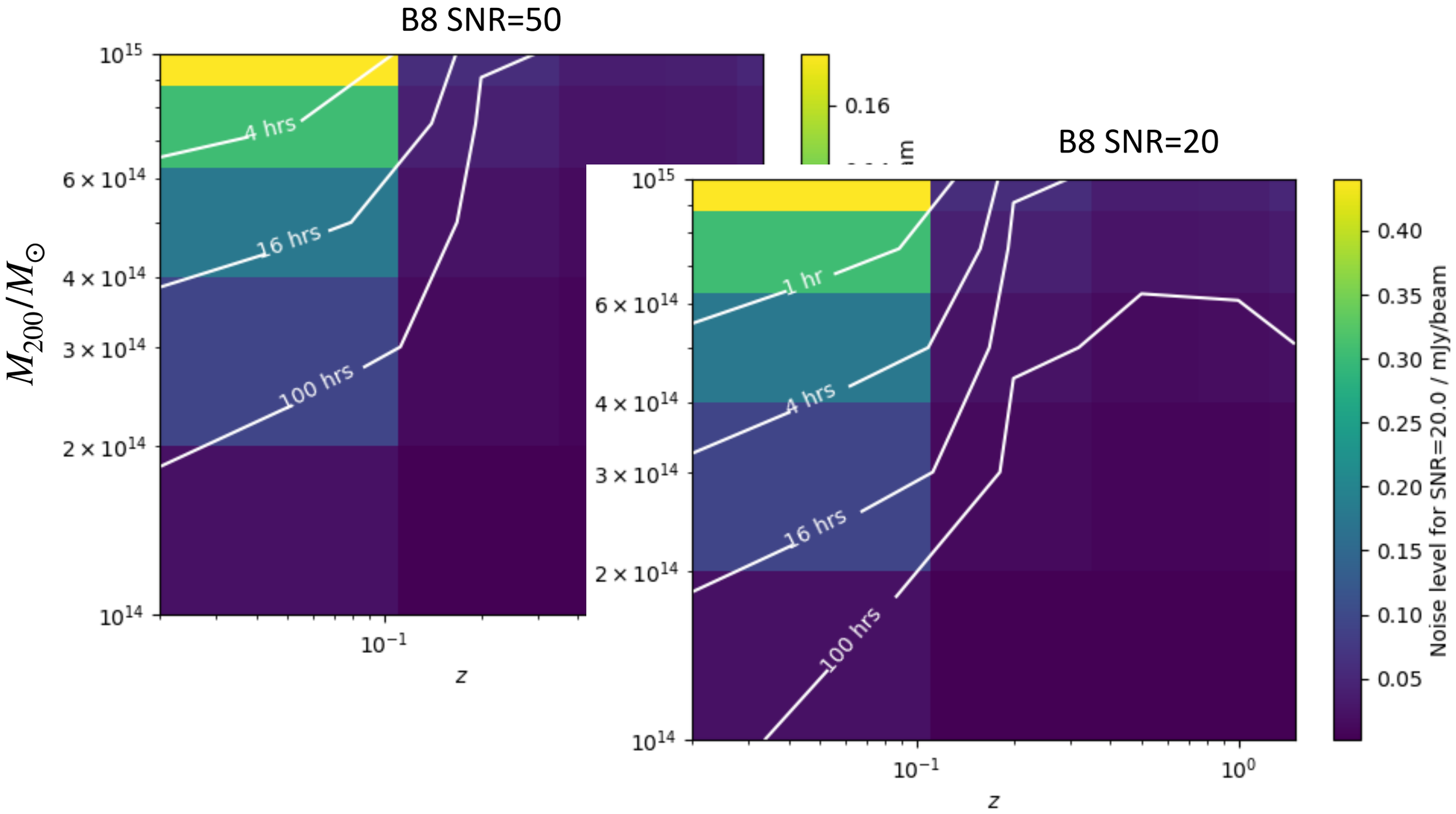
Global temperature - Preliminary!

- Testing SNR on simulations… Average temperature within θ_{200}



Global temperature - Preliminary!

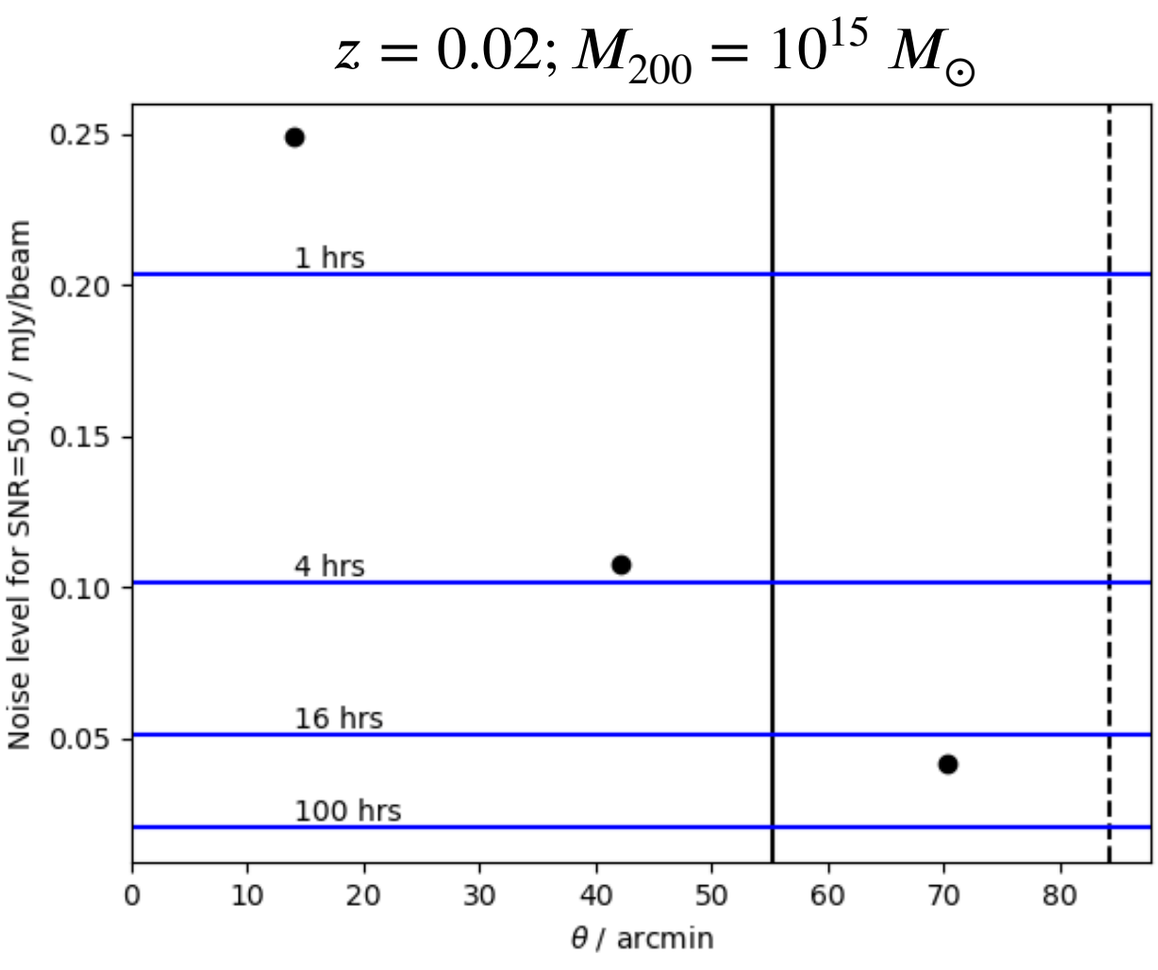
- Testing SNR on simulations… Average temperature within θ_{200}

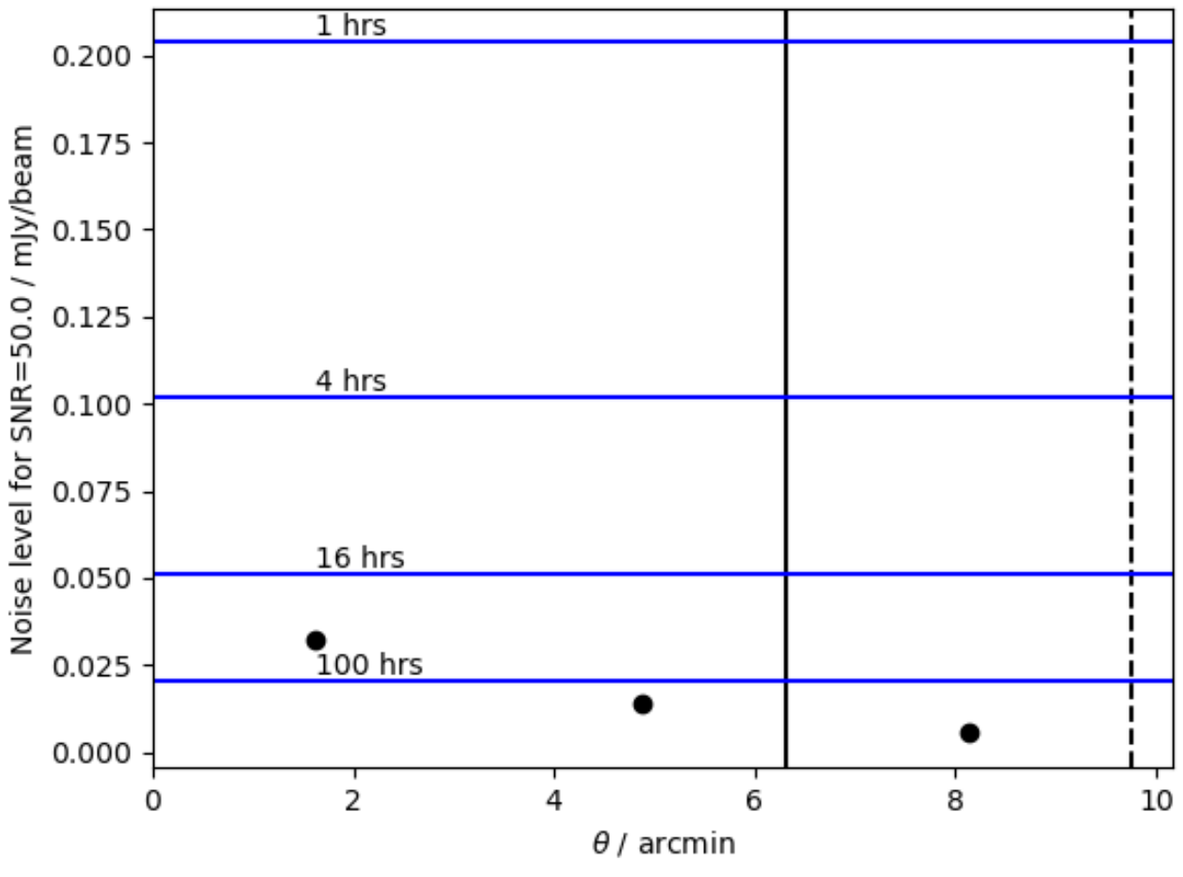


Resolved profiles – Preliminary!

- Testing SNR on simulations… dividing into θ bins

B8 SNR=50

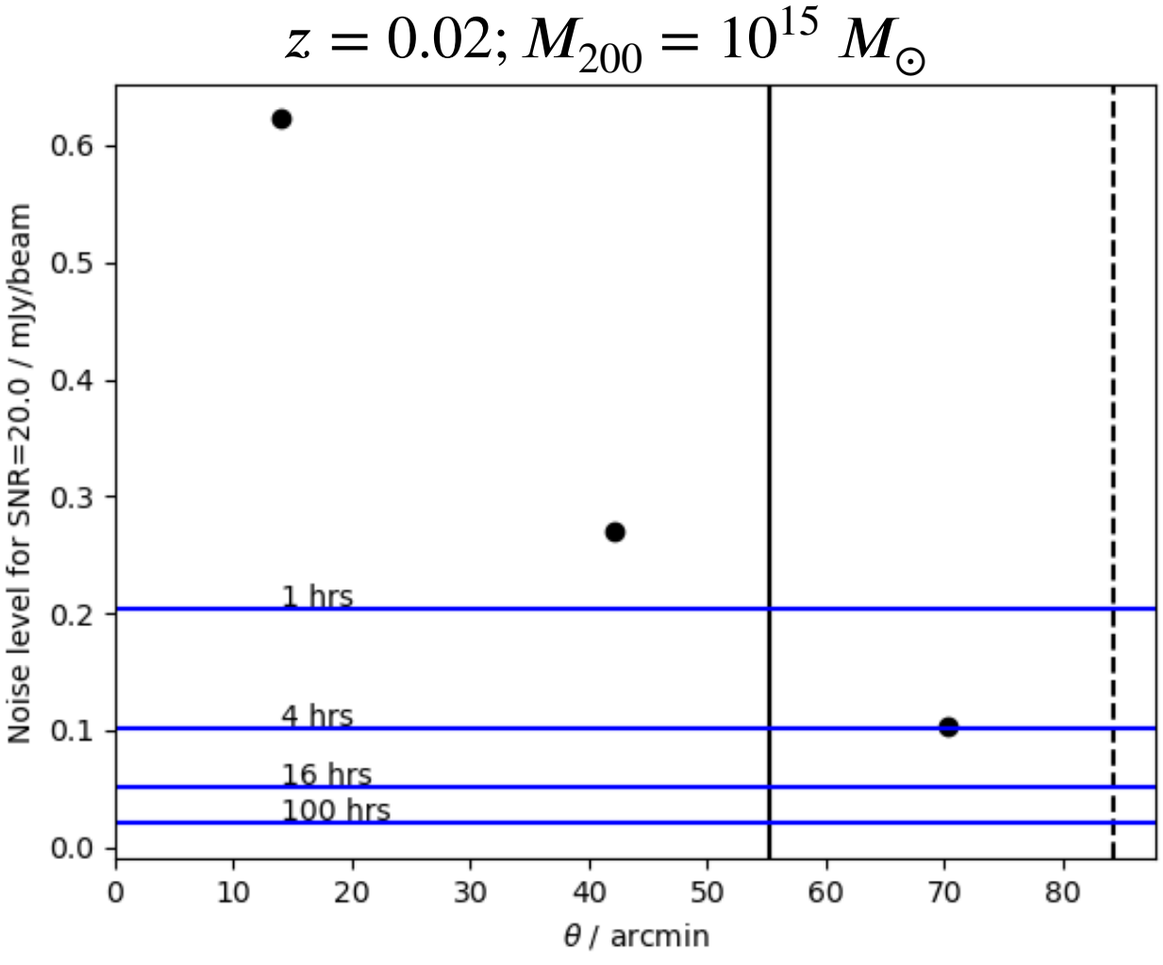


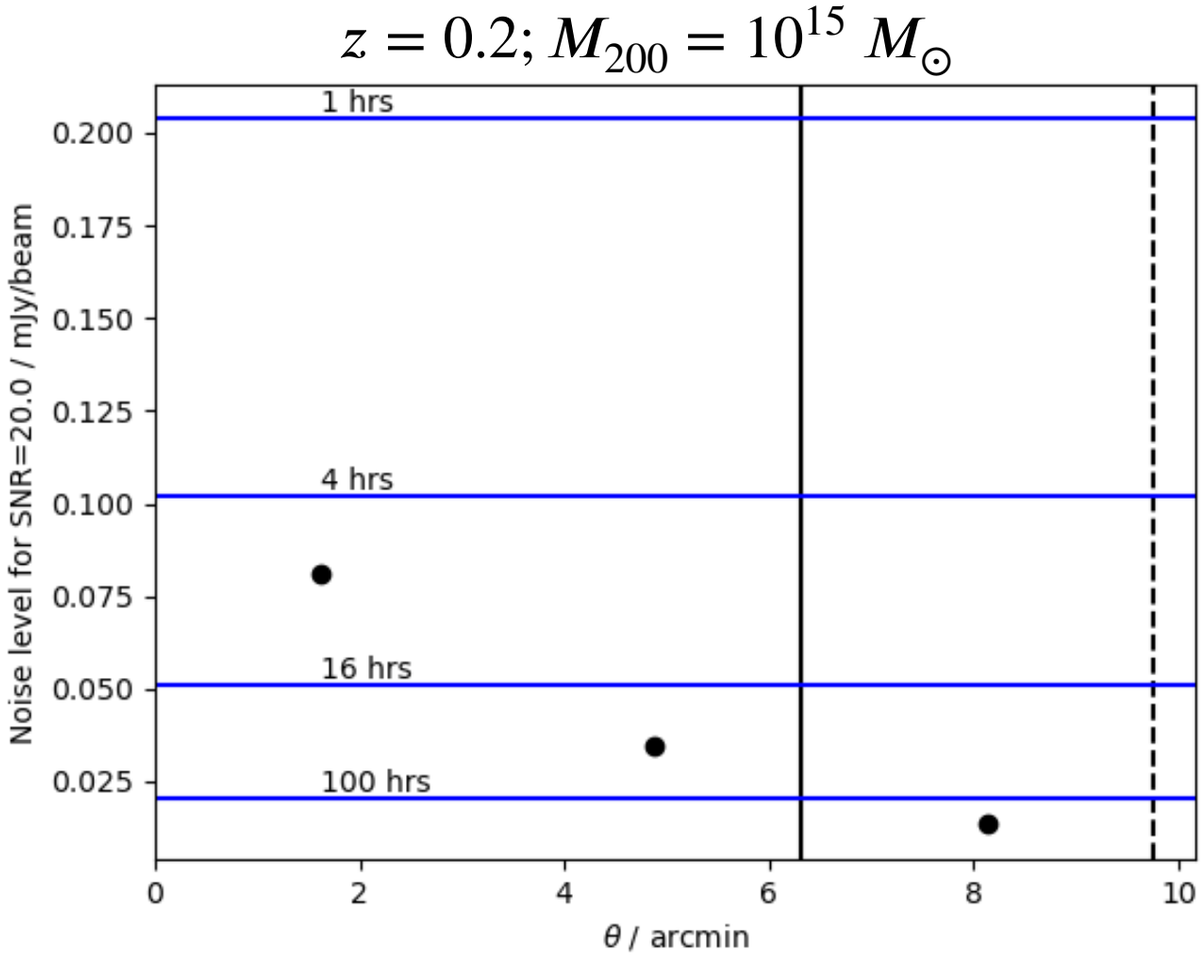


Resolved profiles – Preliminary!

- Testing SNR on simulations… dividing into θ bins

B8 SNR=20





More to do…

More to do...

- Better constraints if more observing time is focussed on higher frequencies?

More to do...

- Better constraints if more observing time is focussed on higher frequencies?
- Forward (parametric/non-parametric) model fitting?

More to do...

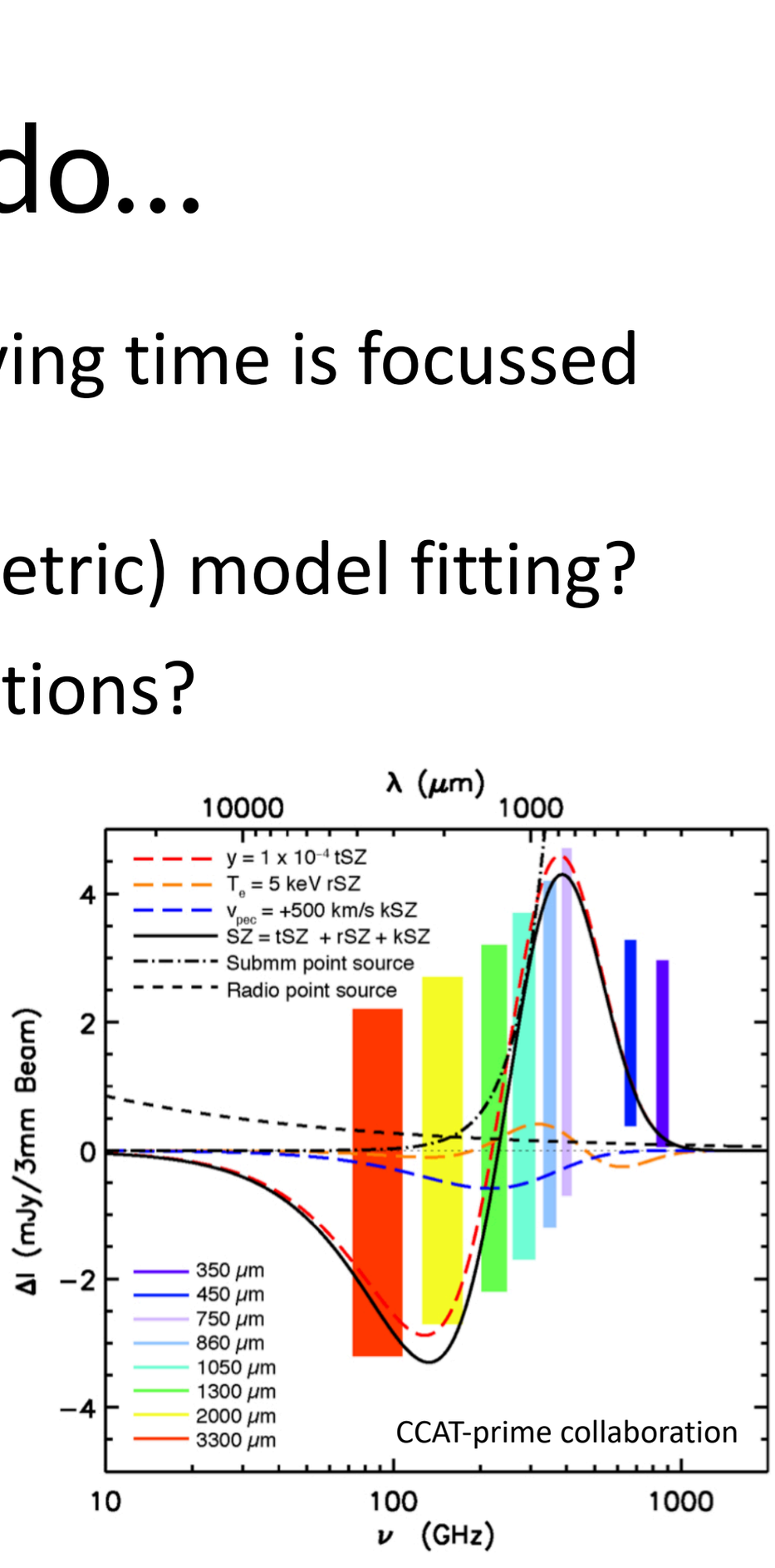
- Better constraints if more observing time is focussed on higher frequencies?
- Forward (parametric/non-parametric) model fitting?
- Better (numerical) cluster simulations?

More to do...

- Better constraints if more observing time is focussed on higher frequencies?
- Forward (parametric/non-parametric) model fitting?
- Better (numerical) cluster simulations?
- Accurate incorporation of foregrounds/backgrounds?

More to do...

- Better constraints if more observing time is focussed on higher frequencies?
- Forward (parametric/non-parametric) model fitting?
- Better (numerical) cluster simulations?
- Accurate incorporation of foregrounds/backgrounds?
- Intermediate option: CCAT-prime?



Conclusions

- With the precision and sensitivity of current and forthcoming instruments, the non-relativistic SZ spectrum is no longer an adequate approximation
- The relativistic M_{500}-Y_{500} scaling relation differs by up to 15% at the high-mass end and should be used to calibrate SZ masses from instruments other than *Planck*
- Relativistic SZ temperature measurements are an exciting future prospect!

The “Cheshire Cat” galaxy group.
Credit: X-ray - NASA / CXC / J. Irwin et al.; Optical - NASA/STScI.
https://apod.nasa.gov/apod/ap220511.html