A **halo model** approach to describe clustering and emission of the **two** main star-forming **galaxy populations** for Cosmic Infrared Background studies

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Based on https://arxiv.org/pdf/2406.19069

Università degli Studi di Ferrara

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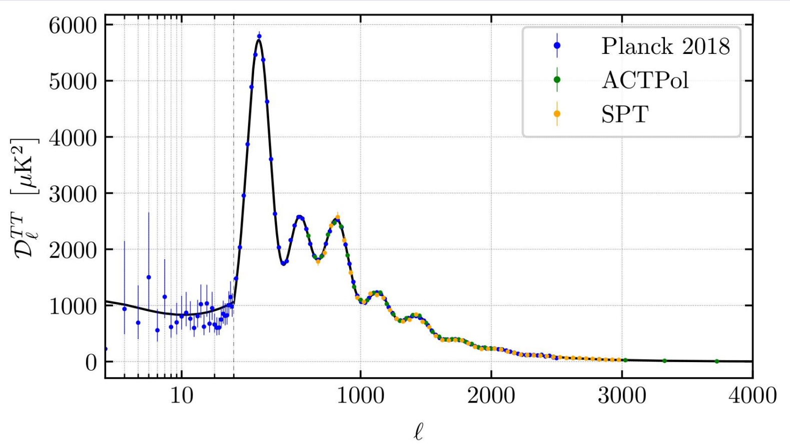
Kavli Institute for Cosmological Physics at The University of Chicago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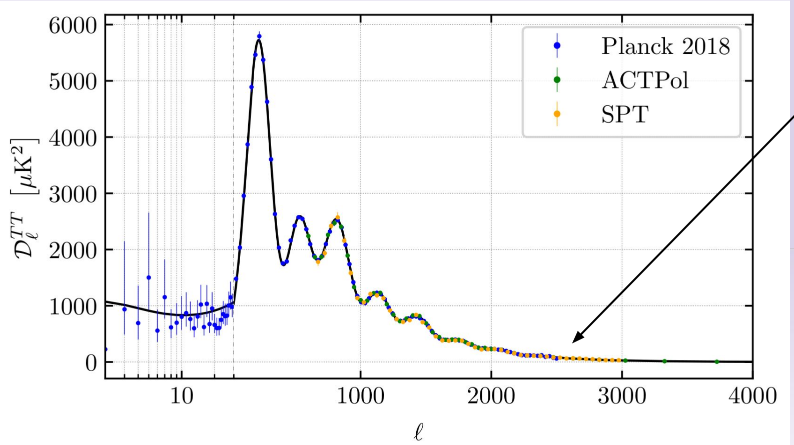
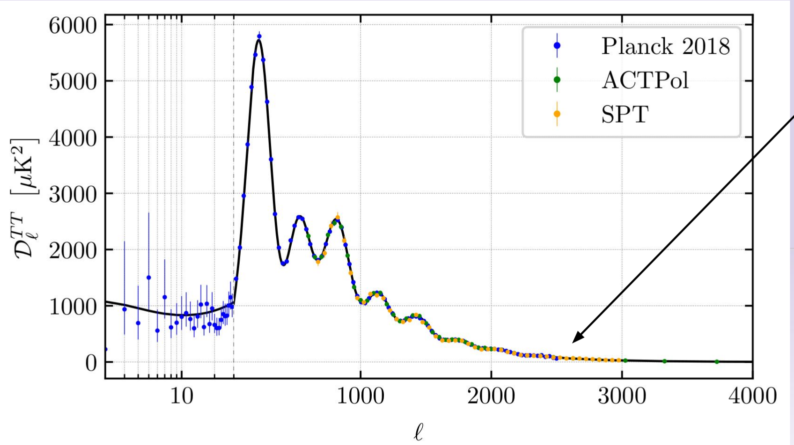


High ℓ analysis

- ↓ cosmic variance
- ↑ foregrounds contamination



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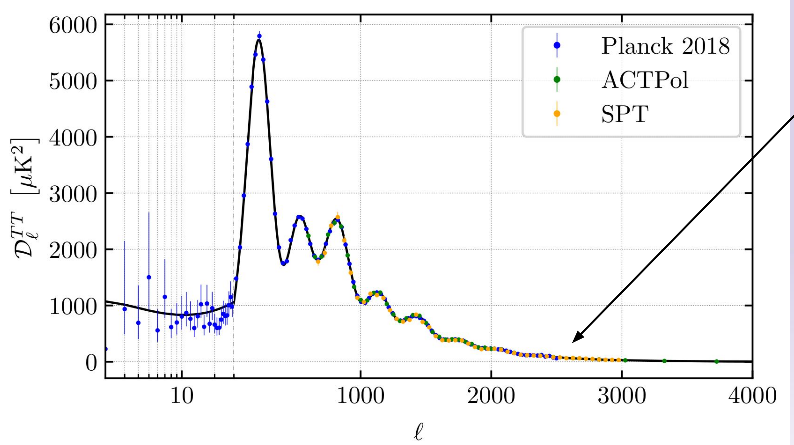
? Why should we study extragalactic foregrounds



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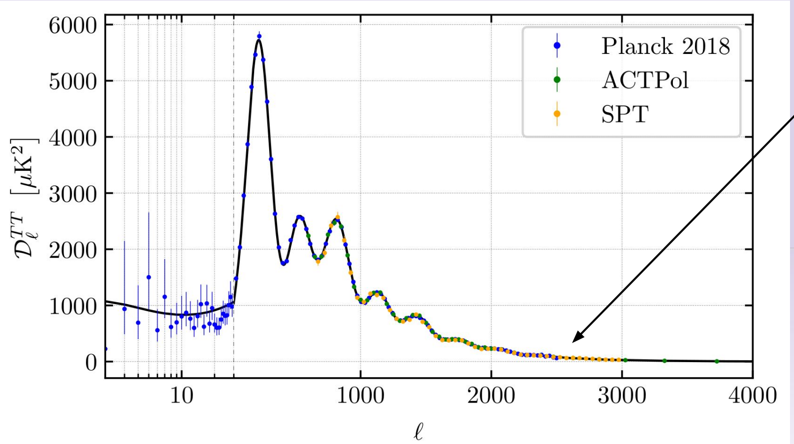
Contaminants of the primary CMB signal



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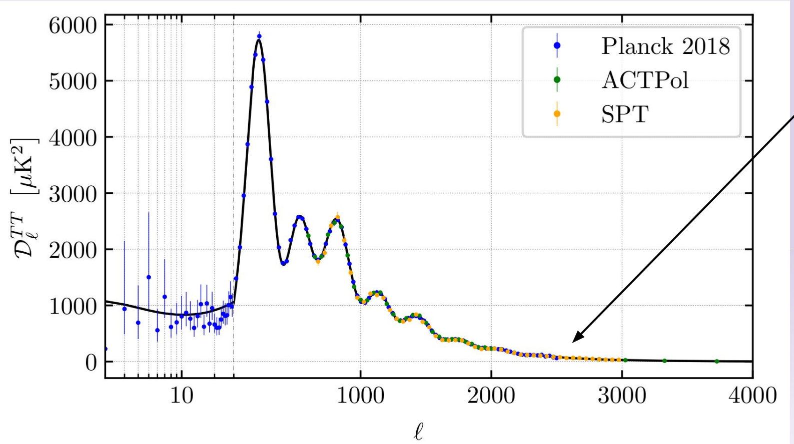
Tracers of the matter density field

clustering studies and insights on formation and evolution of the LSS of the Universe



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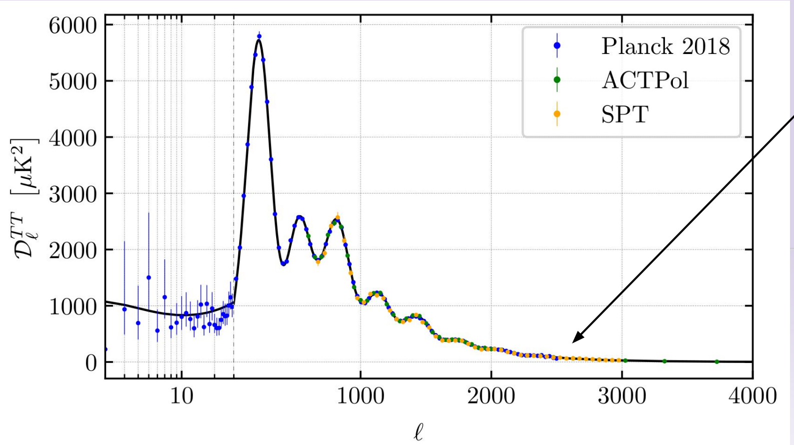

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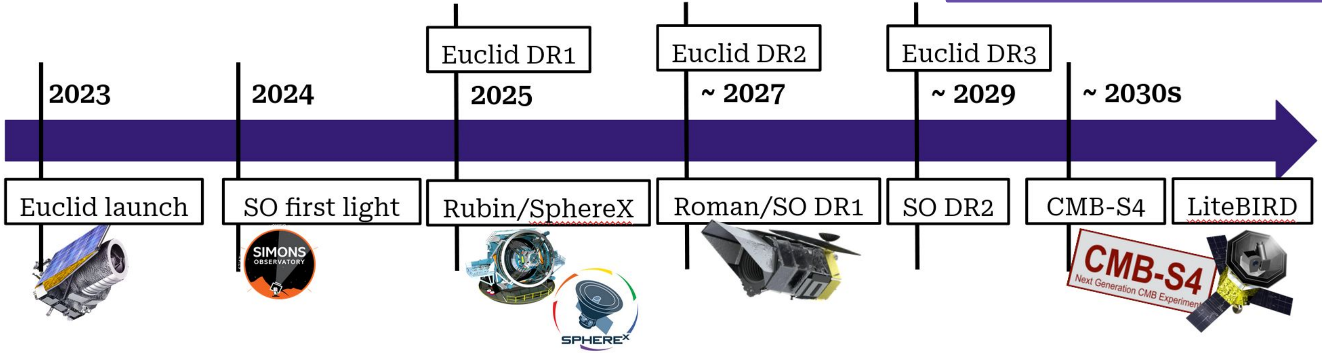

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Model fit to data

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Model fit to data

- Halo Model
- CIB Model
- Datasets
- Model fit to data
- Results
- Conclusion

Halo Model : tool to predict non-linear matter and galaxy power spectra

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1. Halo mass function
   Tinker et al. (2008)
2. Halo bias
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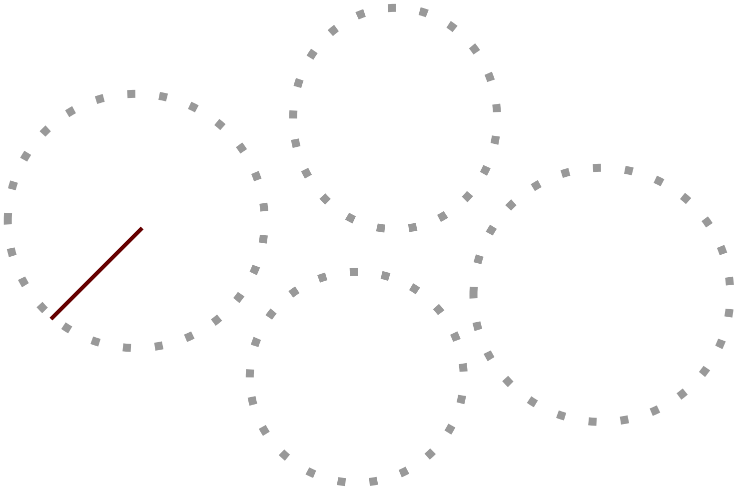

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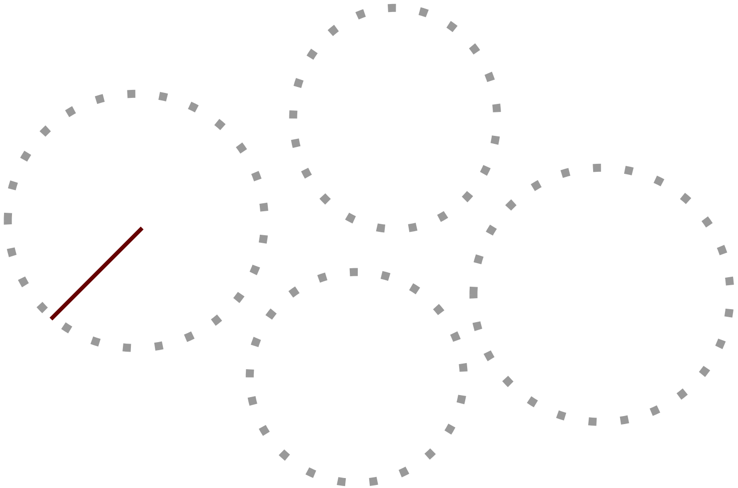

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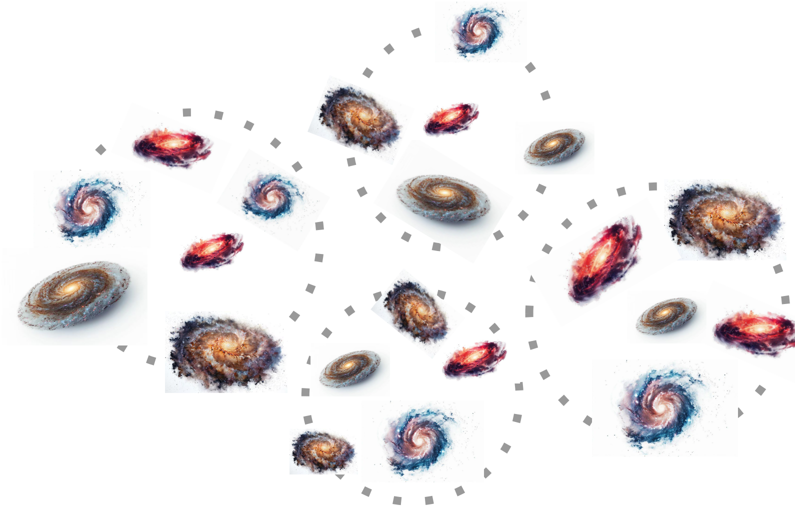

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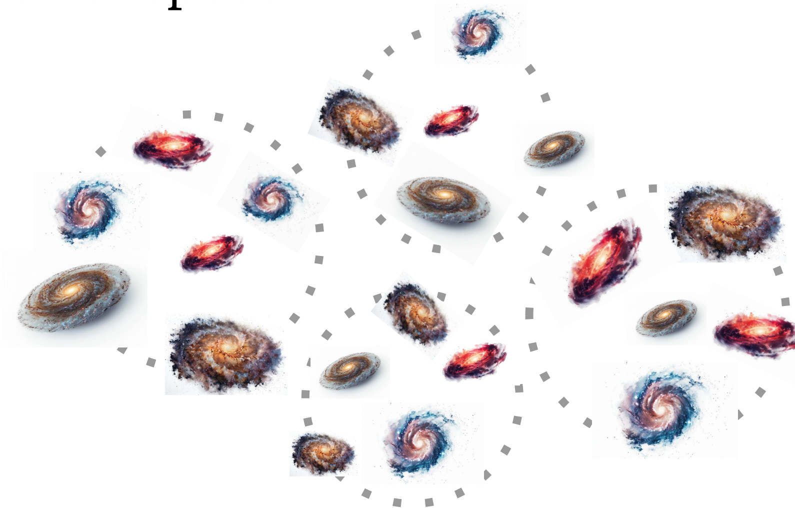
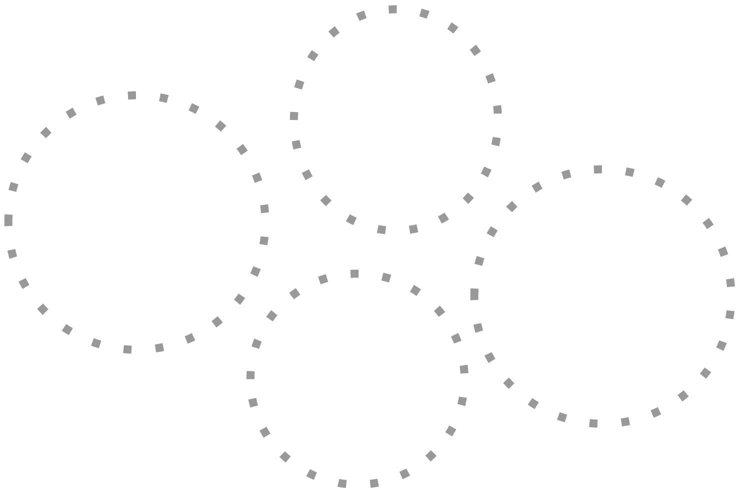


Halo Occupation distribution

Tinker & Wetzel (2010)



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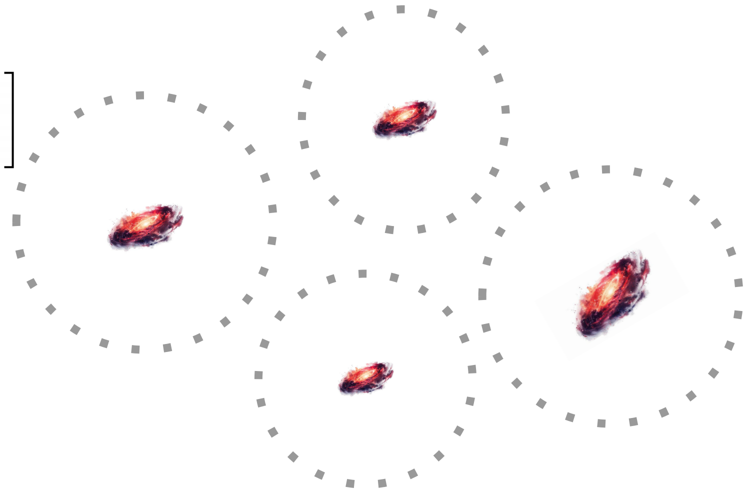
Central galaxies

$$N_{\rm cent} = \frac{1}{2}\left[1 + {\rm erf}\left(\frac{\log M - \log M_{\rm min}}{\sigma_{\log M}}\right)\right]$$



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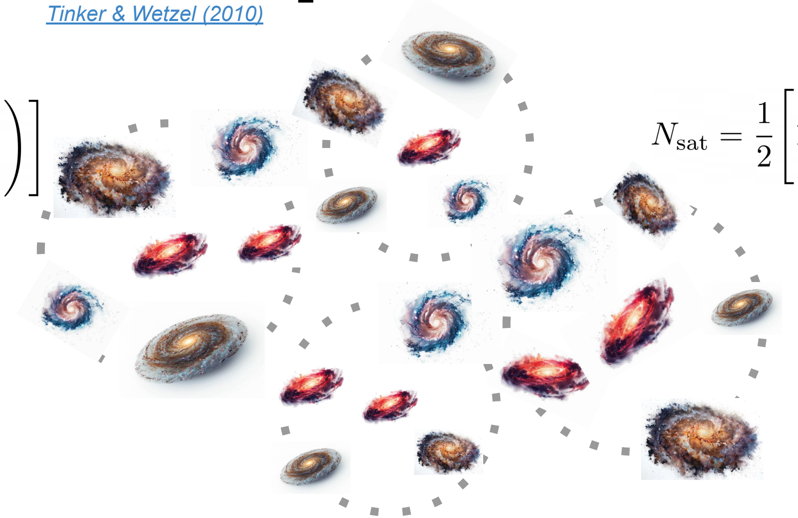

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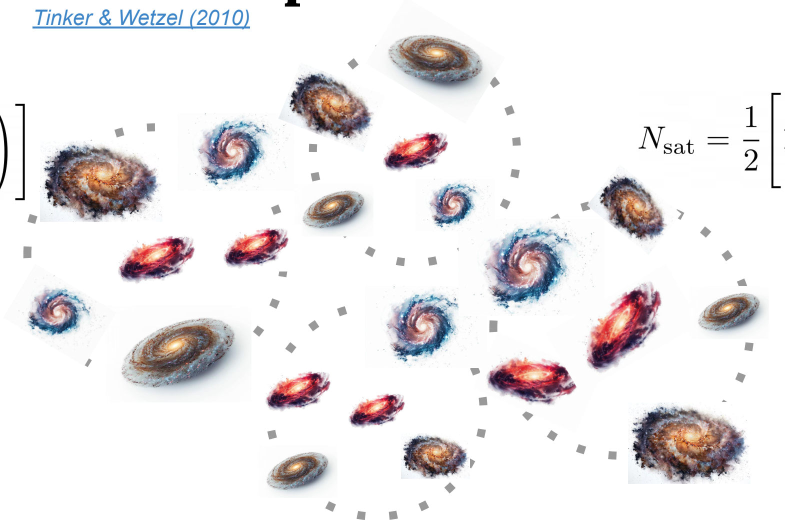

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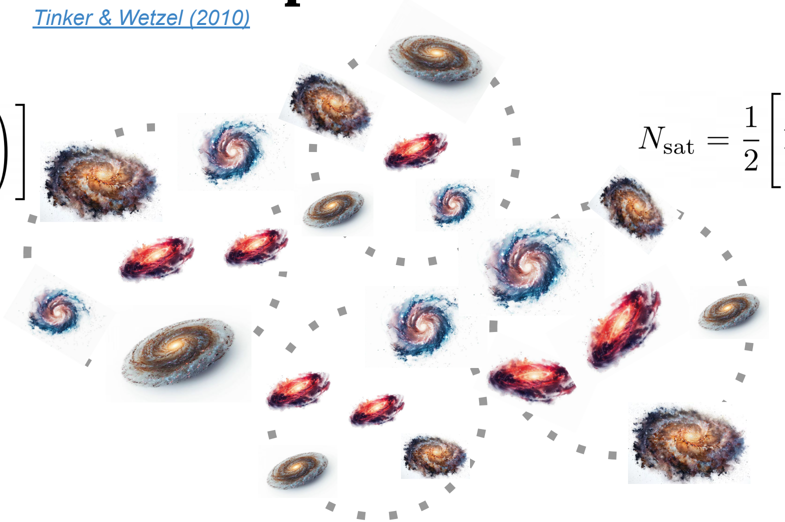

Two galaxy populations

- Early-type (ET) galaxies
- Late-type (LT) galaxies

Halo Occupation distribution

[Tinker & Wetzel (2010)](#)

Central galaxies

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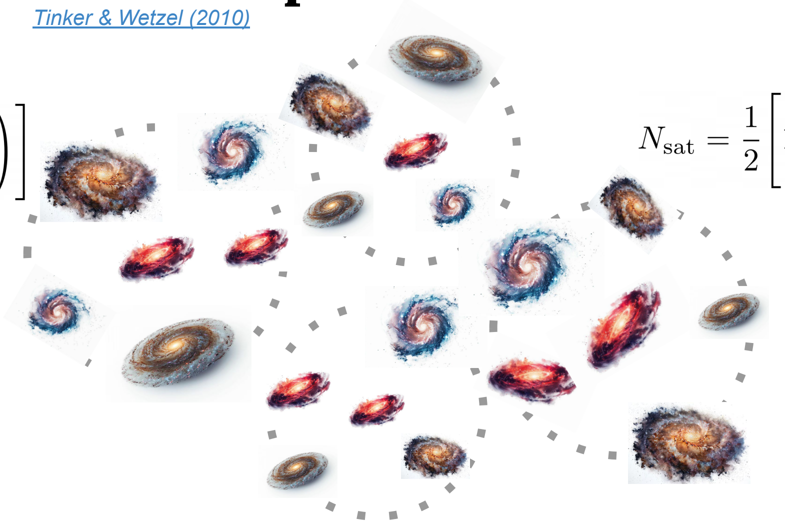
$$M^{ET}_{min} \quad M^{LT}_{min}$$



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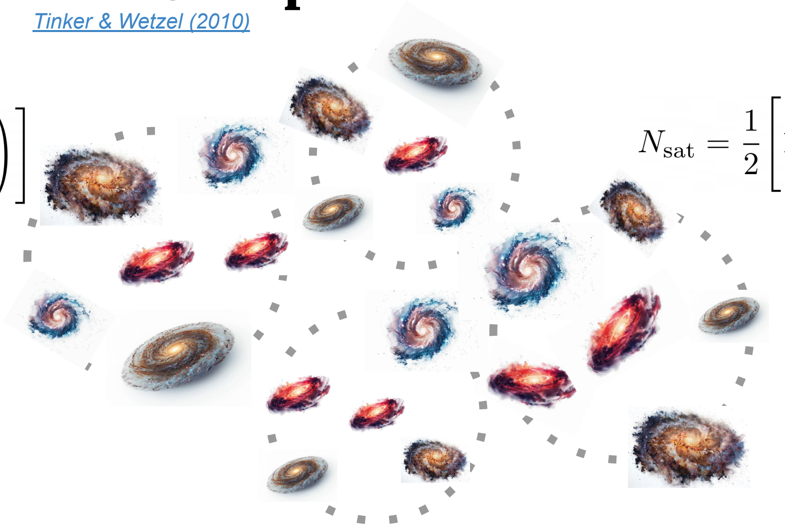

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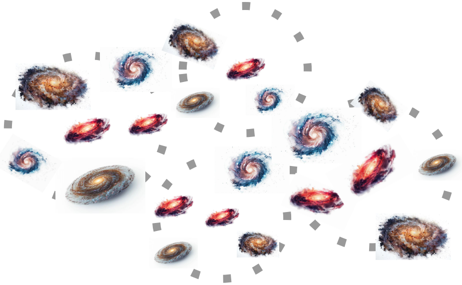
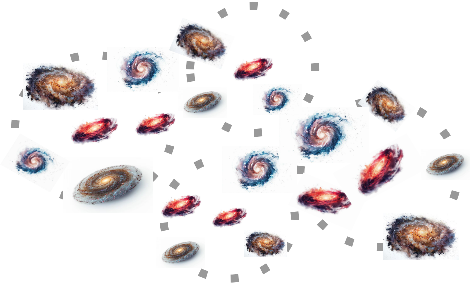
$$P_{gal}(k) = P_{gal}^{ET}(k) + P_{gal}^{LT}(k) + P_{gal}^{ET\times LT}(k)$$



HM: how dark matter is distributed

HOD: how galaxies are distributed



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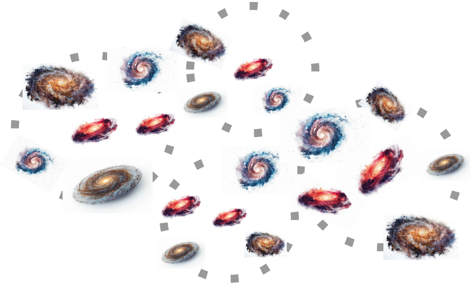
Emissivity function (luminosity function)

$$j_\nu(z)$$

ET

LT



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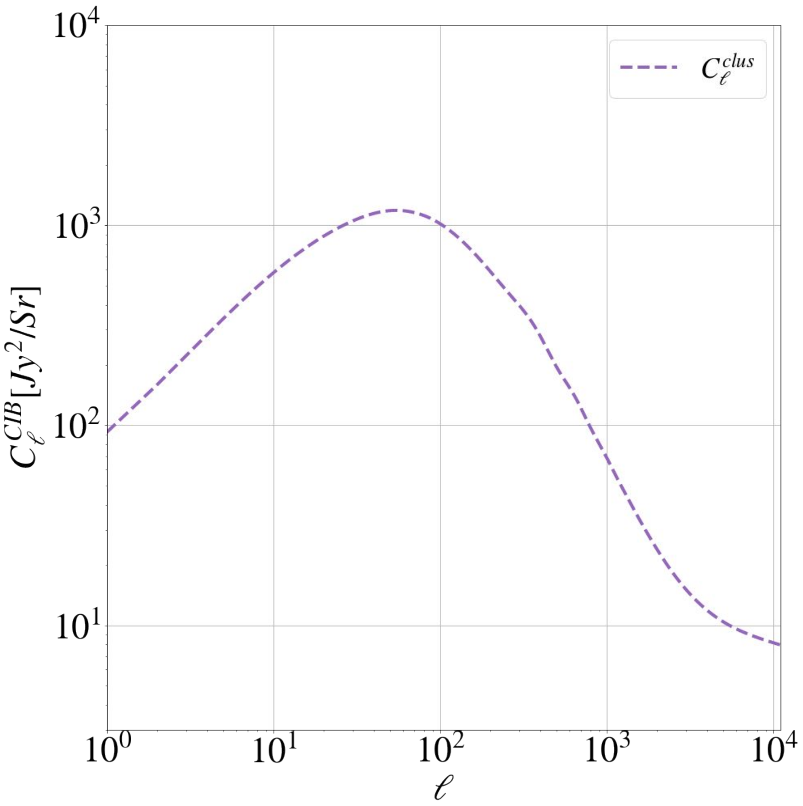
$$C^{CIB}_{\ell,\nu\times\nu'} = C^{\mathrm{clust}}_{\ell,\nu\times\nu'} + C^{SN}_{\ell,\nu\times\nu'}$$



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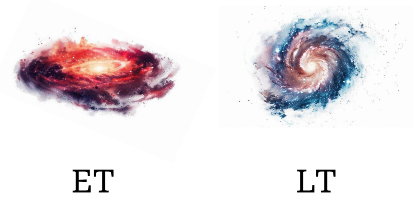
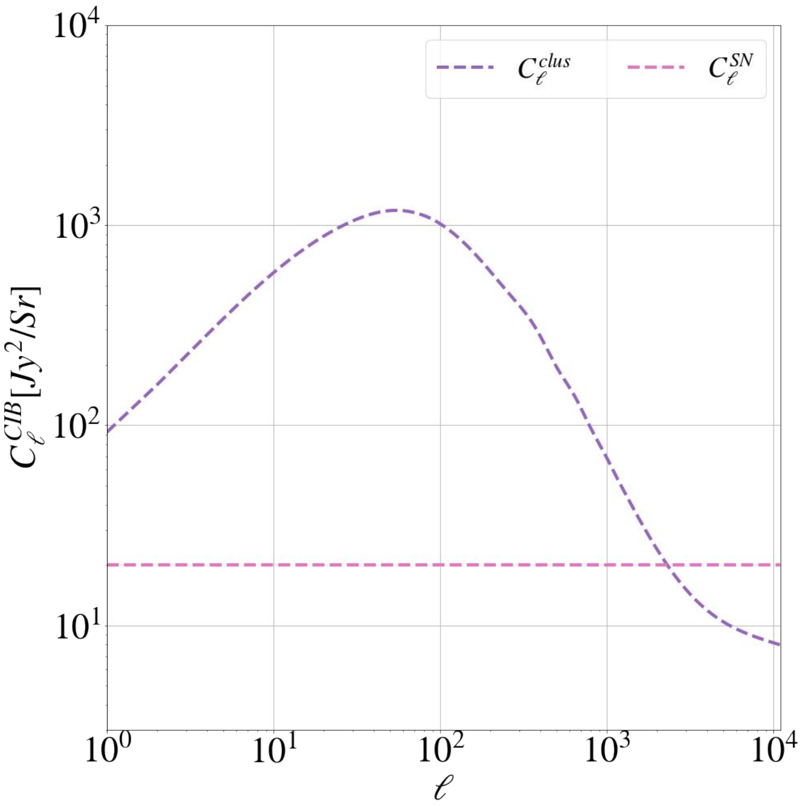


$$C_{\ell,\nu\times\nu'}^{CIB} = C_{\ell,\nu\times\nu'}^{\text{clust}} + C_{\ell,\nu\times\nu'}^{SN}$$

Clustering term

- Clustering parameters
- Emissivity functions

$$C_{\ell,\nu\times\nu'}^{\text{clust}} = \int \frac{dz}{\chi^2}\frac{dz}{d\chi} j_\nu(z) j_{\nu'}(z) P_{\text{gal}}$$



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Shot noise term

Flat contribution dependent of experimental features

$$C^{SN}_{\ell,\nu} = \int_0^{S_\nu^{\text{lim}}} S_\nu^2 \frac{d^2N(S_\nu)}{dS_\nu d\Omega} dS_\nu$$

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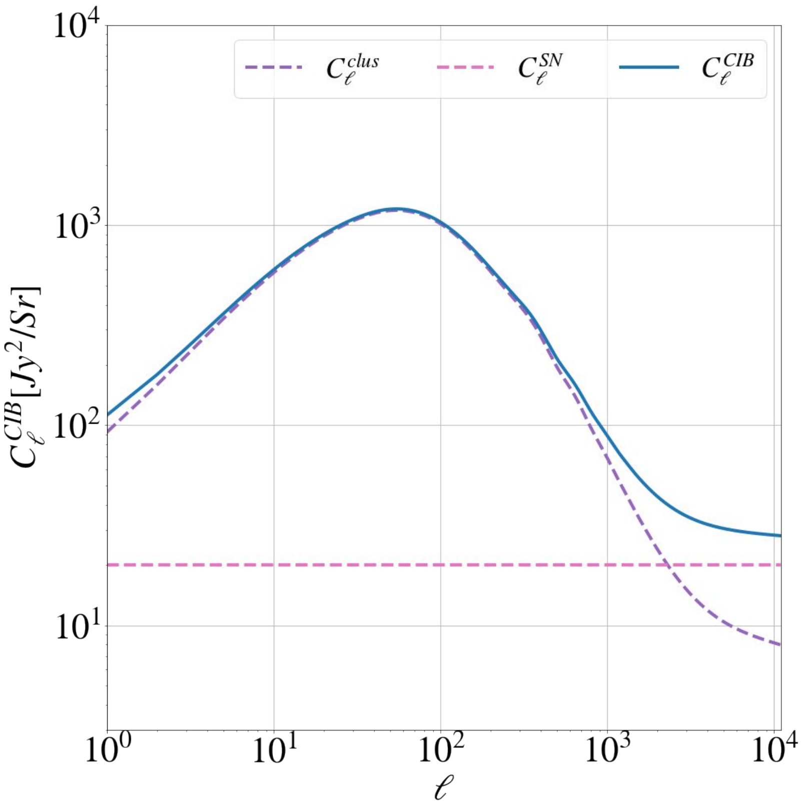

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P14	2240	217, 353, 545, 857	150-2500	Logarithmic	1.119, 1.097, 1.068, 0.995
L19	2240	353, 545, 857	75-2500	Linear	1.097, 1.068, 0.995
V19	90	600, 857, 1200	600-11000	Linear and logarithmic	0.9988, 0.9929, 0.9957

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ET + LT

ET *clustering*

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ET + LT *shot noise*

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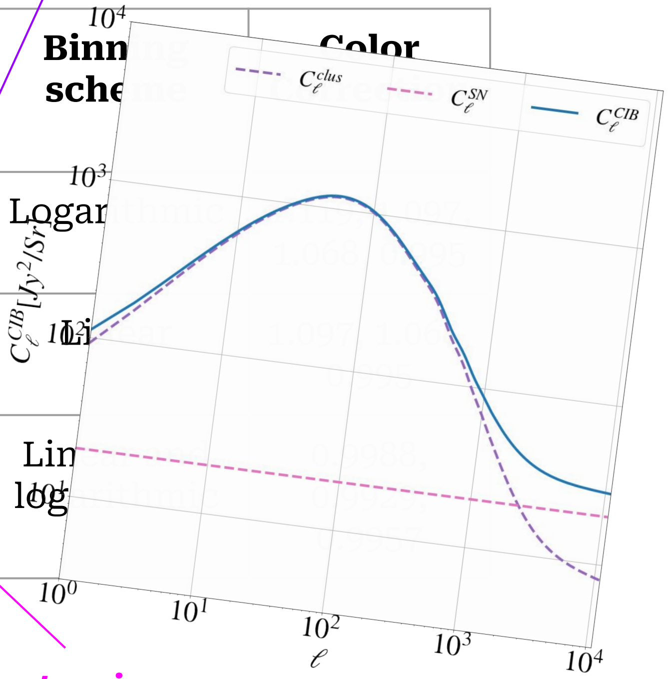

ET + LT

shot noise

How to compare model predictions and observed data

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$$C_{\ell,\nu_1\times\nu_2}^{CIB,\mathrm{data}} = \mathcal{A}_{\nu_1 x \nu_2} \times cc_{\nu_1} \times cc_{\nu_2} \times C_{\ell,\nu_1\times\nu_2}^{CIB,\mathrm{model}}$$

calibration uncertainties

color corrections

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MCMC analysis:

- emcee sampler
- Gaussian likelihood

$$\log \mathcal{L}(C_\ell^{\mathrm{data}}|C_\ell^{\mathrm{obs}}) \propto -\frac{1}{2}\sum_\ell \frac{\left(C_\ell^{\mathrm{data}} - C_\ell^{\mathrm{obs}}\right)^2}{\sigma_\ell^2}$$

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How to deal with the shot noise term

$$C_{\ell,\nu\times\nu\prime}^{SN} = \mathcal{C}_{\nu\times\nu\prime}\sqrt{SN_\nu \times SN_{\nu\prime}}$$

How to compare model predictions and observed data

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$$C_{\ell,\nu\times\nu'}^{SN} = \mathcal{C}_{\nu\times\nu'}\sqrt{SN_\nu \times SN_{\nu'}}$$

Two scenarios:

- Maximal correlation between the shot noise contributions

$$\mathcal{C}_{\nu\times\nu'} = 1$$

- Free parameters in the MCMC analysis [-1 ,1]

How to compare model predictions and observed data

$$C_{\ell,\nu_1 \times \nu_2}^{CIB,\text{data}} = \mathcal{A}_{\nu_1 x \nu_2} \times cc_{\nu_1} \times cc_{\nu_2} \times C_{\ell,\nu_1 \times \nu_2}^{CIB,\text{model}}$$

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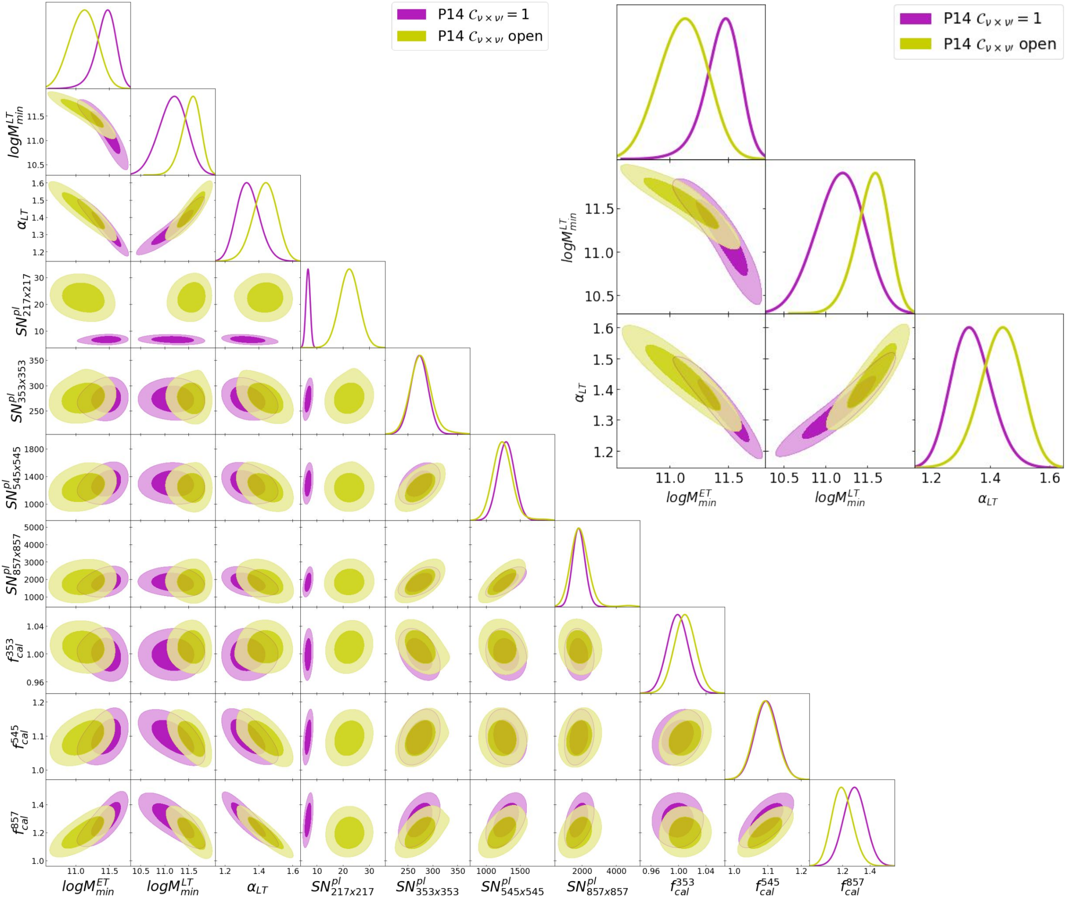
Free parameters of the fit

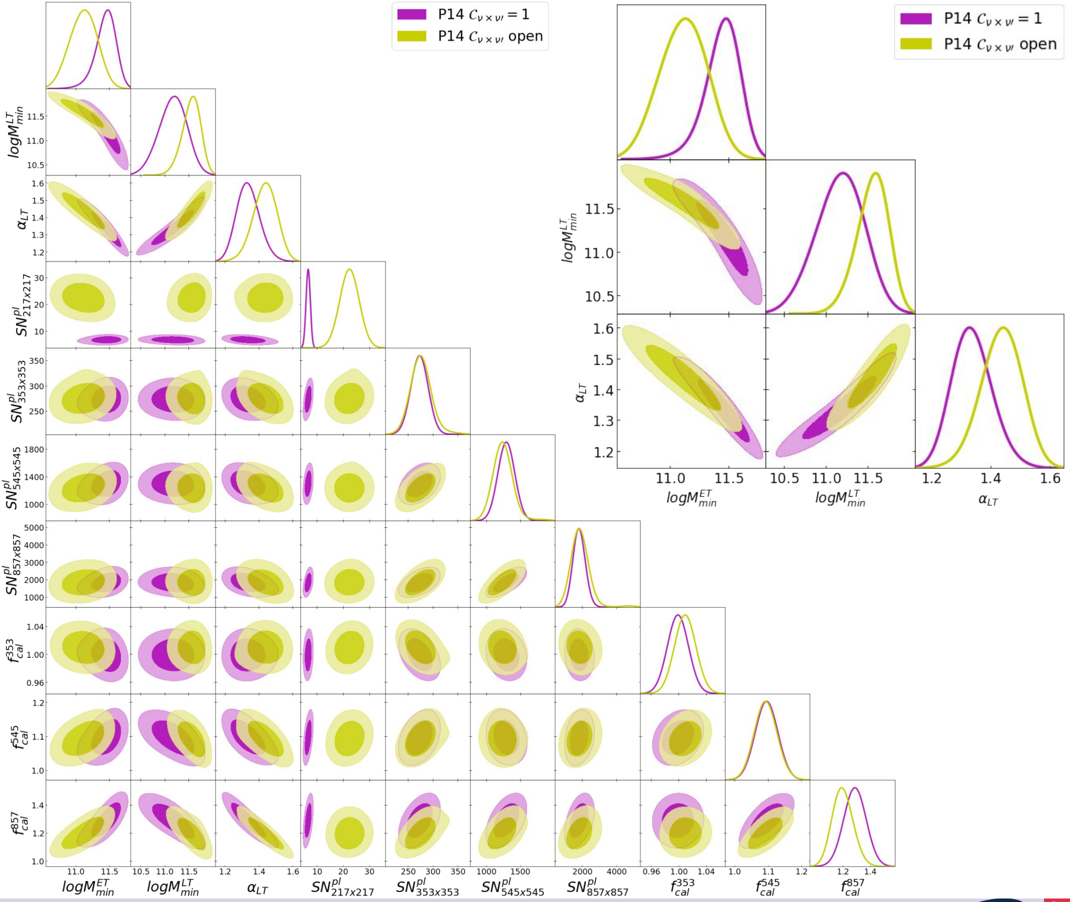
$M_{min}^{ET}, \alpha_{ET}$

$M_{min}^{LT}, \alpha_{LT}$

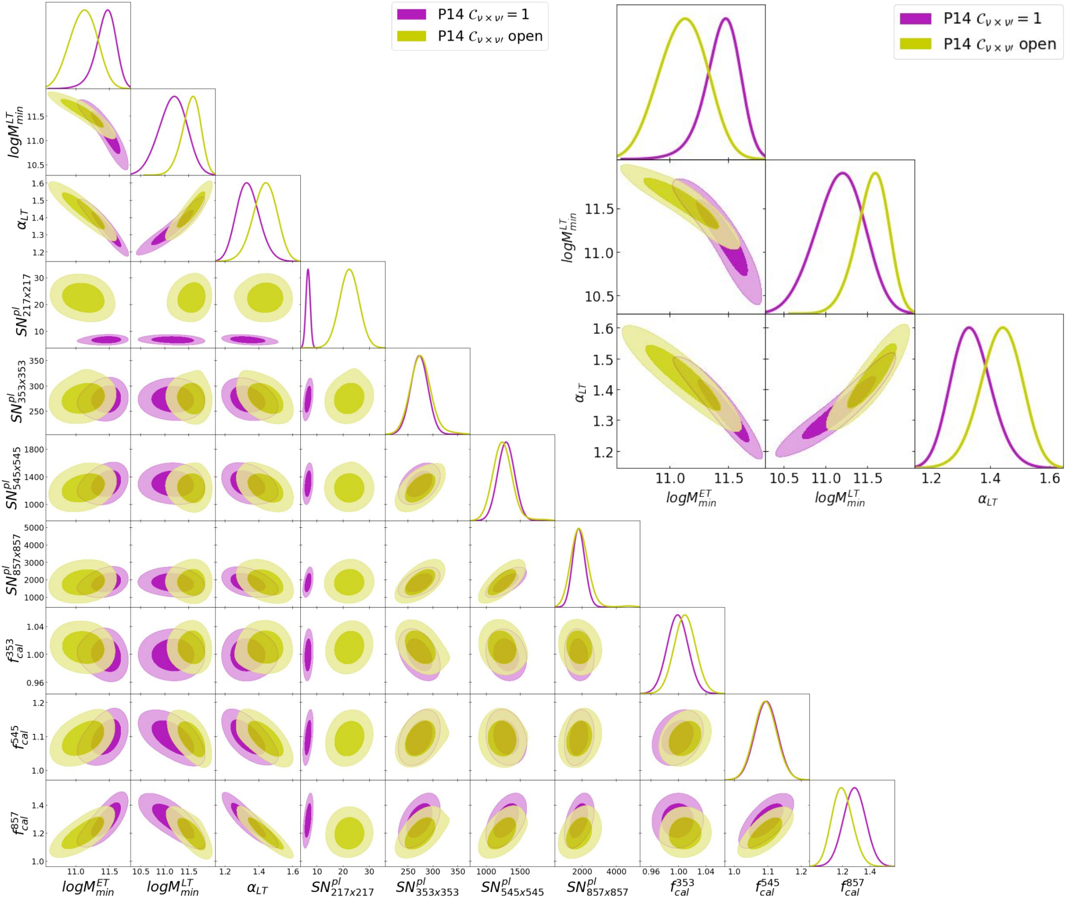
SN_ν, f_{cal}^{ν}

$(\mathcal{C}_{\nu \times \nu'})$

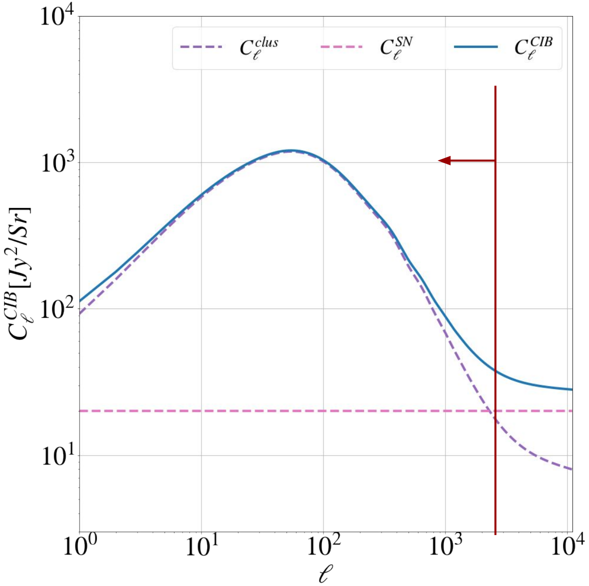

P14 $C_{\nu\times\nu'} = 1$
P14 $C_{\nu\times\nu'}$ open
$logM^{ET}_{min}$
$logM^{LT}_{min}$
α_{LT}
$SN^{pl}_{217x217}$
$SN^{pl}_{353x353}$
$SN^{pl}_{545x545}$
$SN^{pl}_{857x857}$
f^{353}_{cal}
f^{545}_{cal}
f^{857}_{cal}

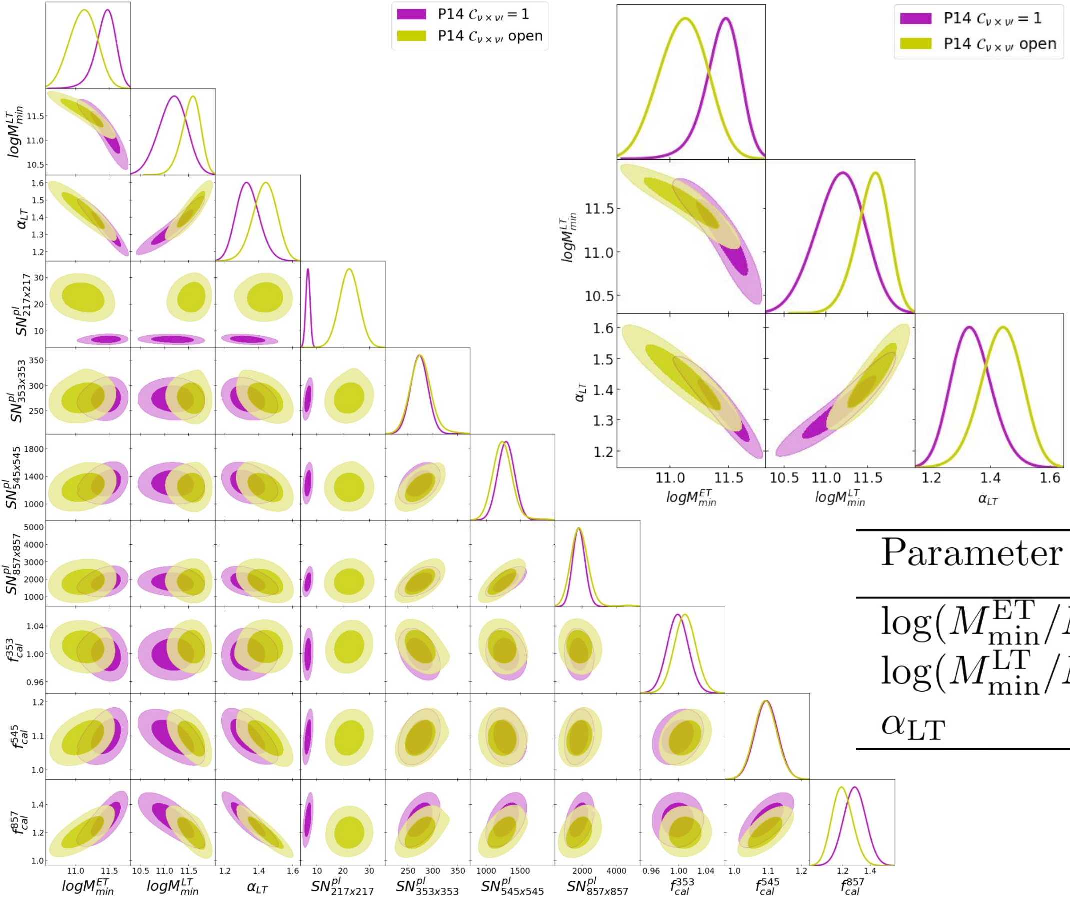


- α_{ET} unconstrained



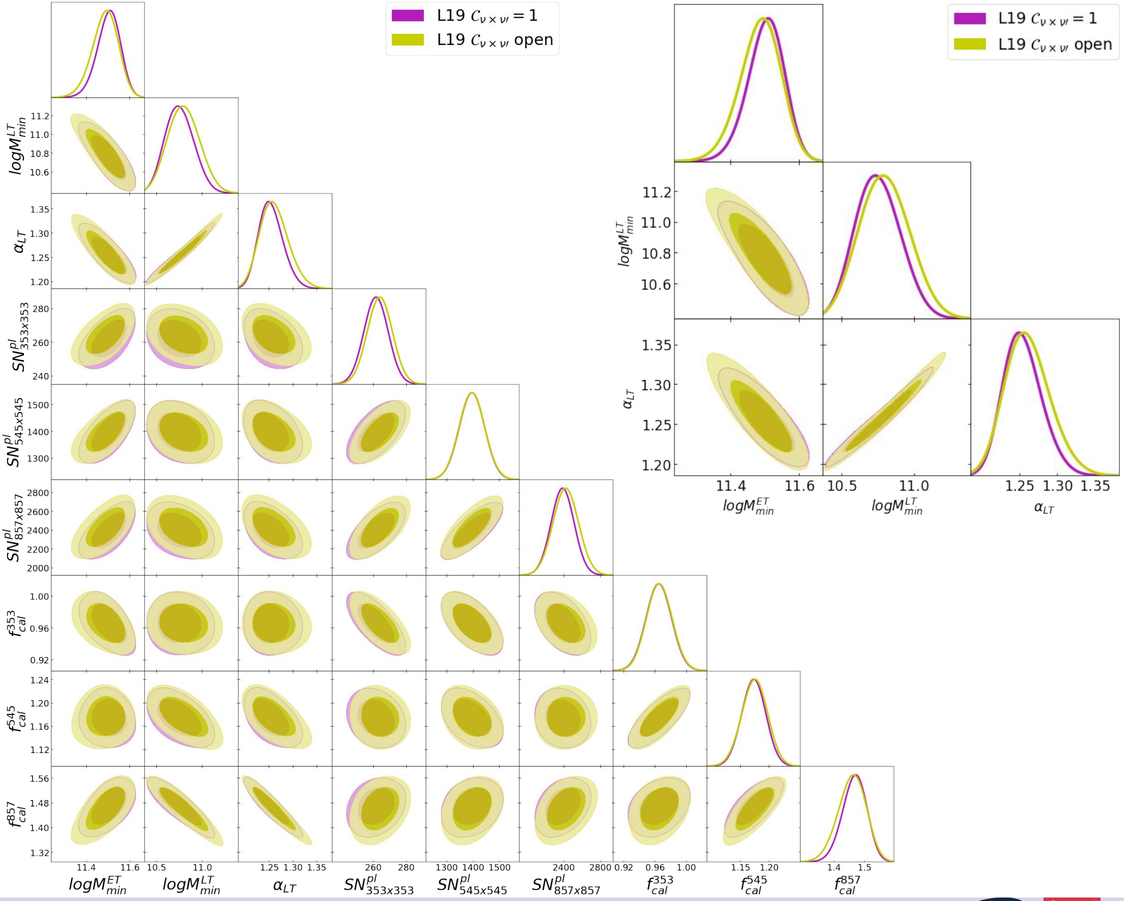
- $\alpha_{\rm ET}$ unconstrained
- Good agreement between the two scenarios

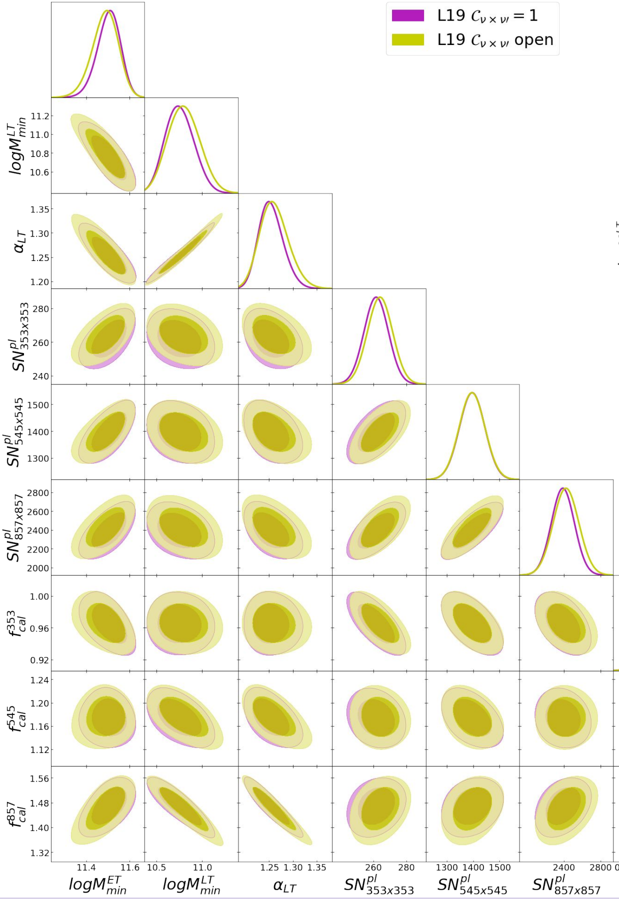


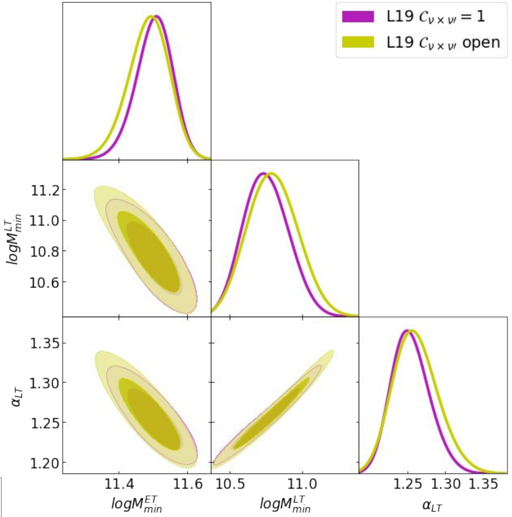


- α_{ET} unconstrained
- Good agreement between the two scenarios
- No clear distinction between the two galaxy populations' clustering parameters

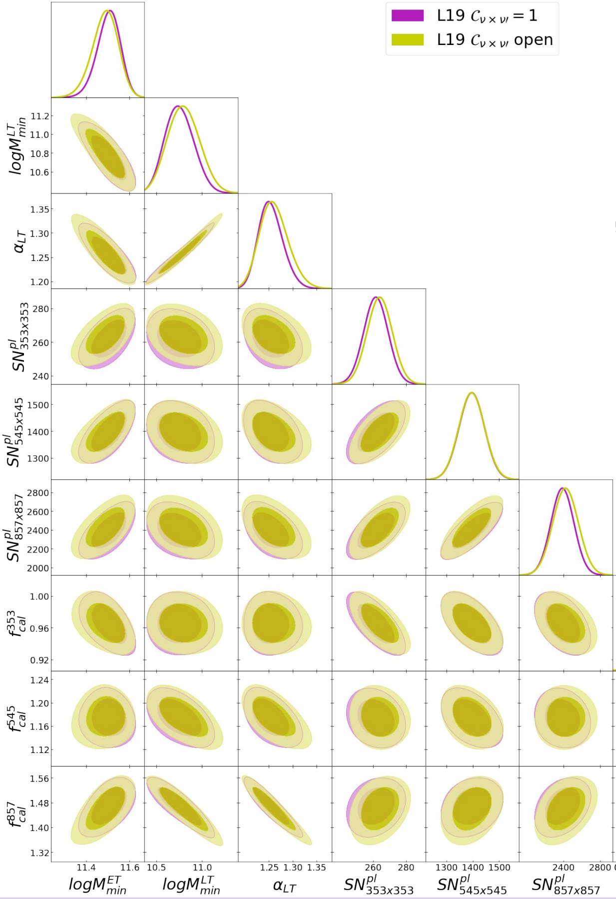
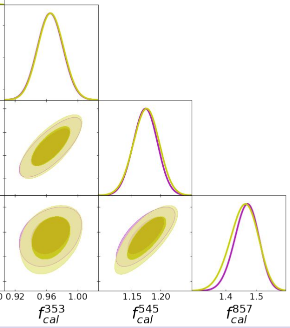
Parameter	$\mathcal{C}_{\nu_1\times\nu_2}=1$	$\mathcal{C}_{\nu_1\times\nu_2}$ open
$\log(M^{\mathrm{ET}}_{\mathrm{min}}/M_\odot h^{-1})$	$11.45^{+0.16}_{-0.13}$	11.12 ± 0.19
$\log(M^{\mathrm{LT}}_{\mathrm{min}}/M_\odot h^{-1})$	$11.18^{+0.31}_{-0.27}$	$11.56^{+0.21}_{-0.17}$
α_{LT}	$1.337^{+0.063}_{-0.072}$	$1.436^{+0.075}_{-0.067}$

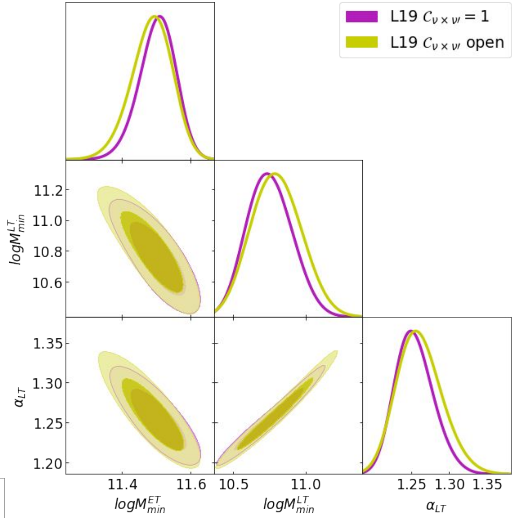

L19 $C_{\nu\times\nu'}=1$
L19 $C_{\nu\times\nu'}$ open
$logM^{ET}_{min}$
$logM^{LT}_{min}$
α_{LT}
$SN^{pl}_{353x353}$
$SN^{pl}_{545x545}$
$SN^{pl}_{857x857}$
f^{353}_{cal}
f^{545}_{cal}
f^{857}_{cal}
L19 $C_{\nu\times\nu'}=1$
L19 $C_{\nu\times\nu'}$ open
$logM^{ET}_{min}$
$logM^{LT}_{min}$
α_{LT}





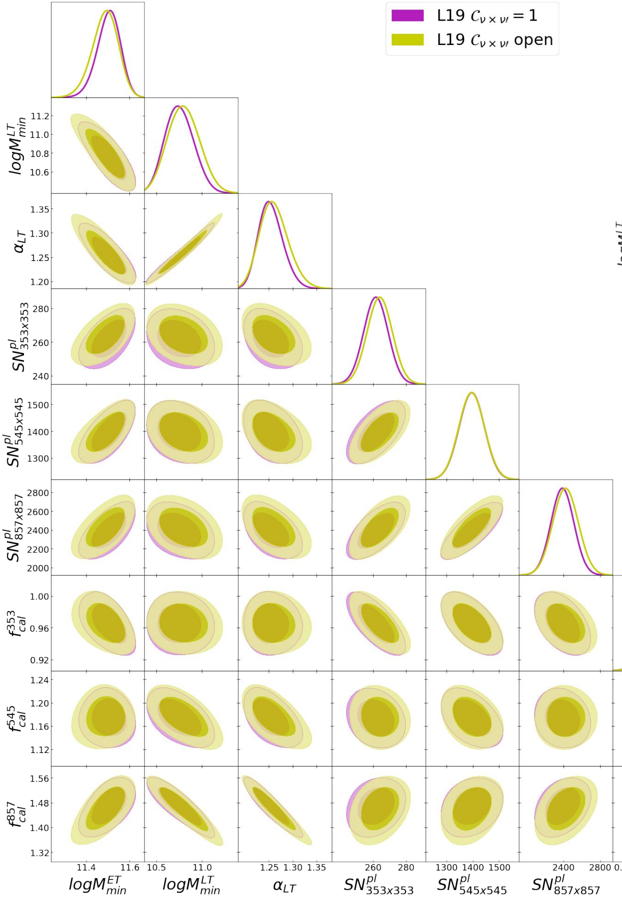
- α_{ET} unconstrained
- Good agreement between the two scenarios
- No clear distinction between the two galaxy populations' clustering parameters
- Too high χ^2, only qualitative conclusions

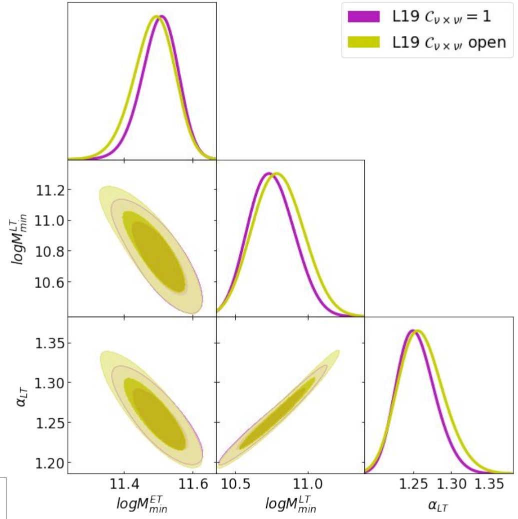





- α_{ET} unconstrained
- Good agreement between the two scenarios
- No clear distinction between the two galaxy populations' clustering parameters
- Too high χ^2, only qualitative conclusions

WHY?

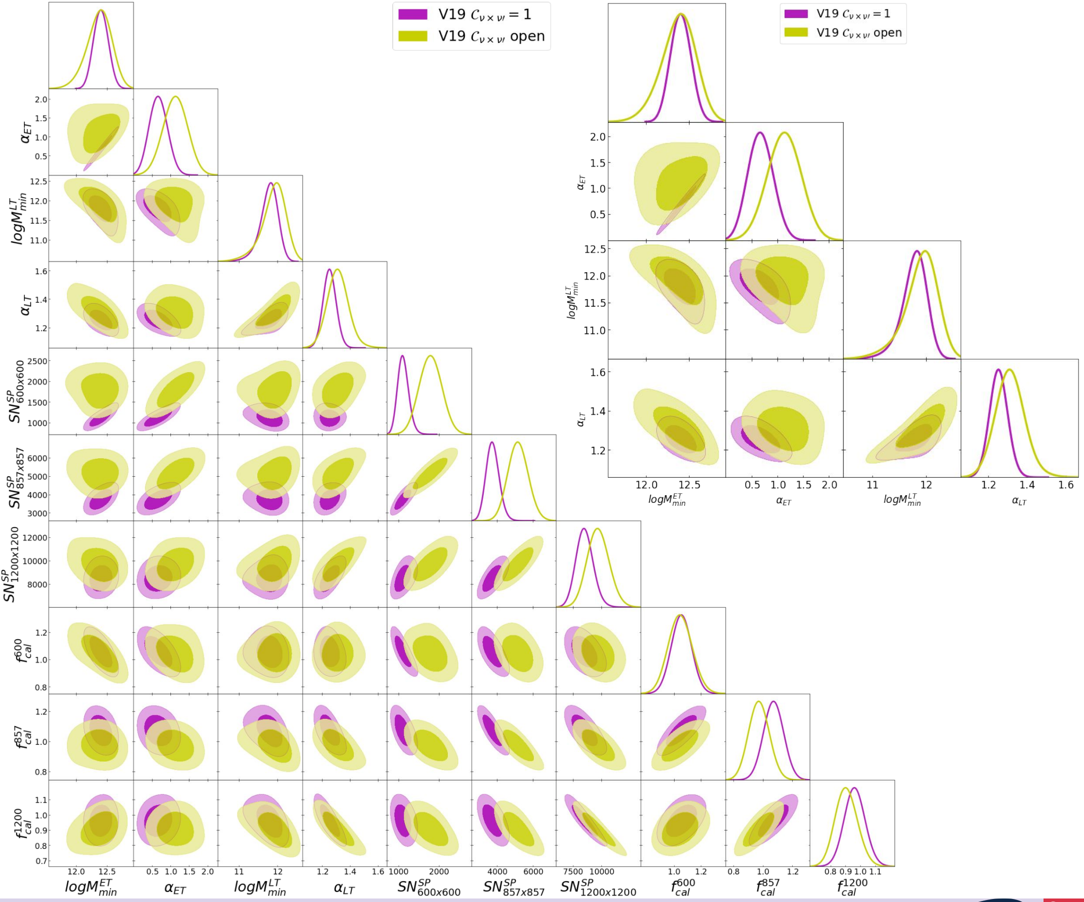


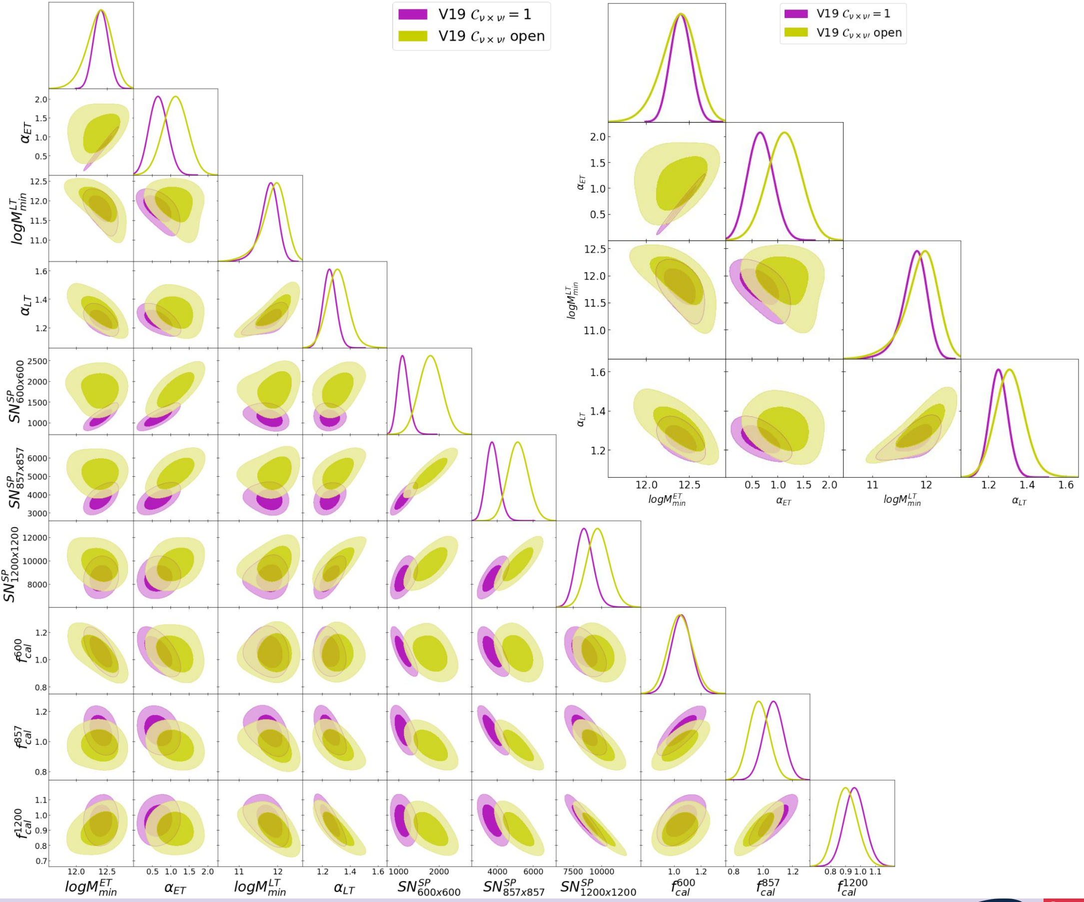


- α_{ET} unconstrained
- Good agreement between the two scenarios
- No clear distinction between the two galaxy populations' clustering parameters
- Too high χ^2, only qualitative conclusions

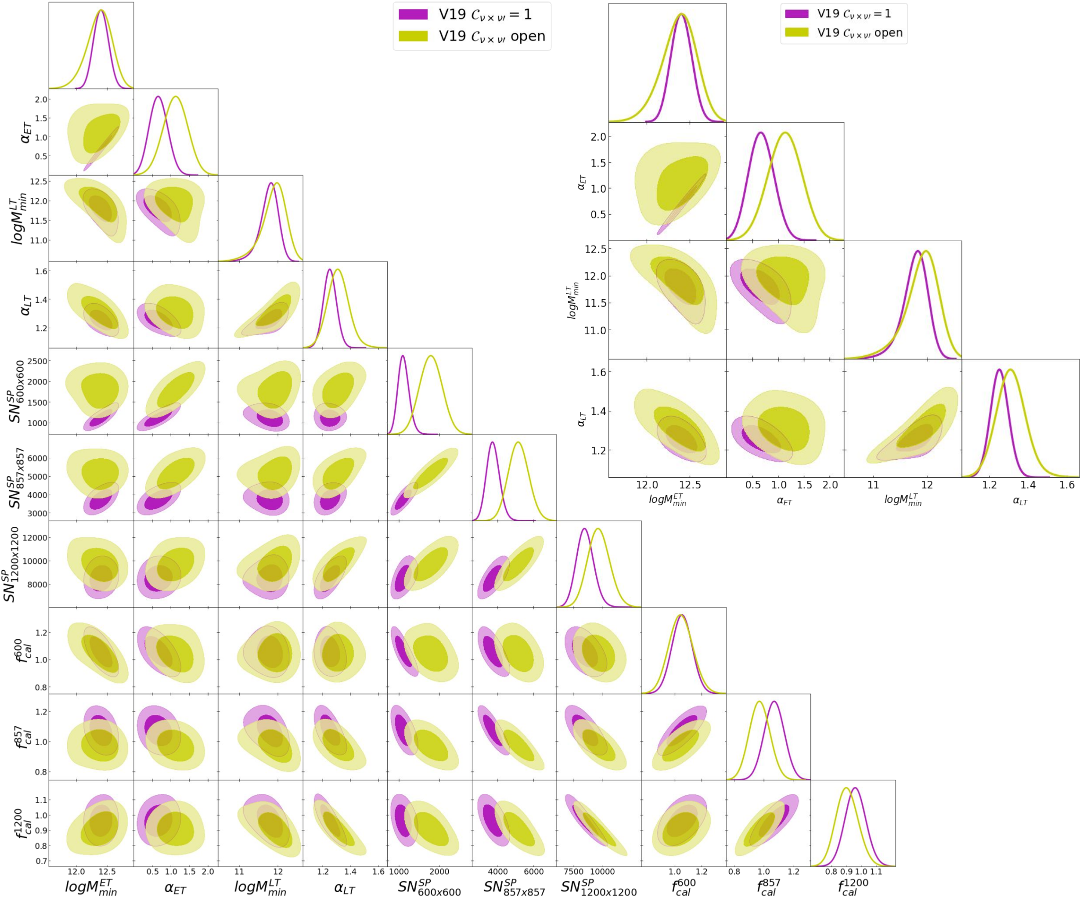
WHY?

Hint of possible dust contamination…

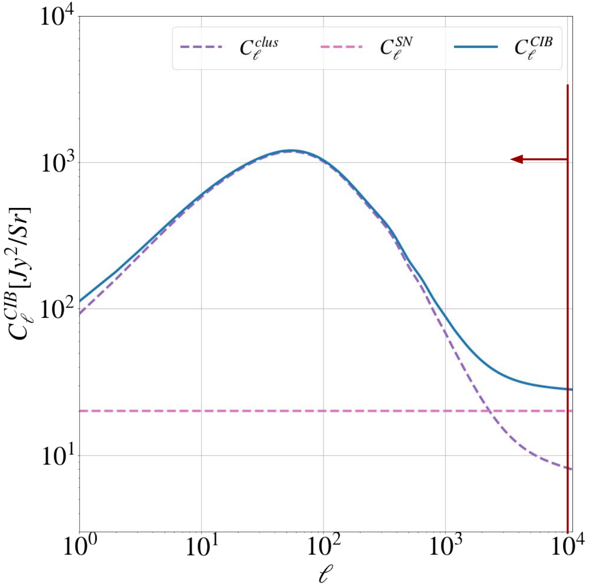

V19 $C_{\nu\times\nu'} = 1$
V19 $C_{\nu\times\nu'}$ open
$logM_{min}^{ET}$
α_{ET}
$logM_{min}^{LT}$
α_{LT}
$SN_{600x600}^{SP}$
$SN_{857x857}^{SP}$
$SN_{1200x1200}^{SP}$
f_{cal}^{600}
f_{cal}^{857}
f_{cal}^{1200}

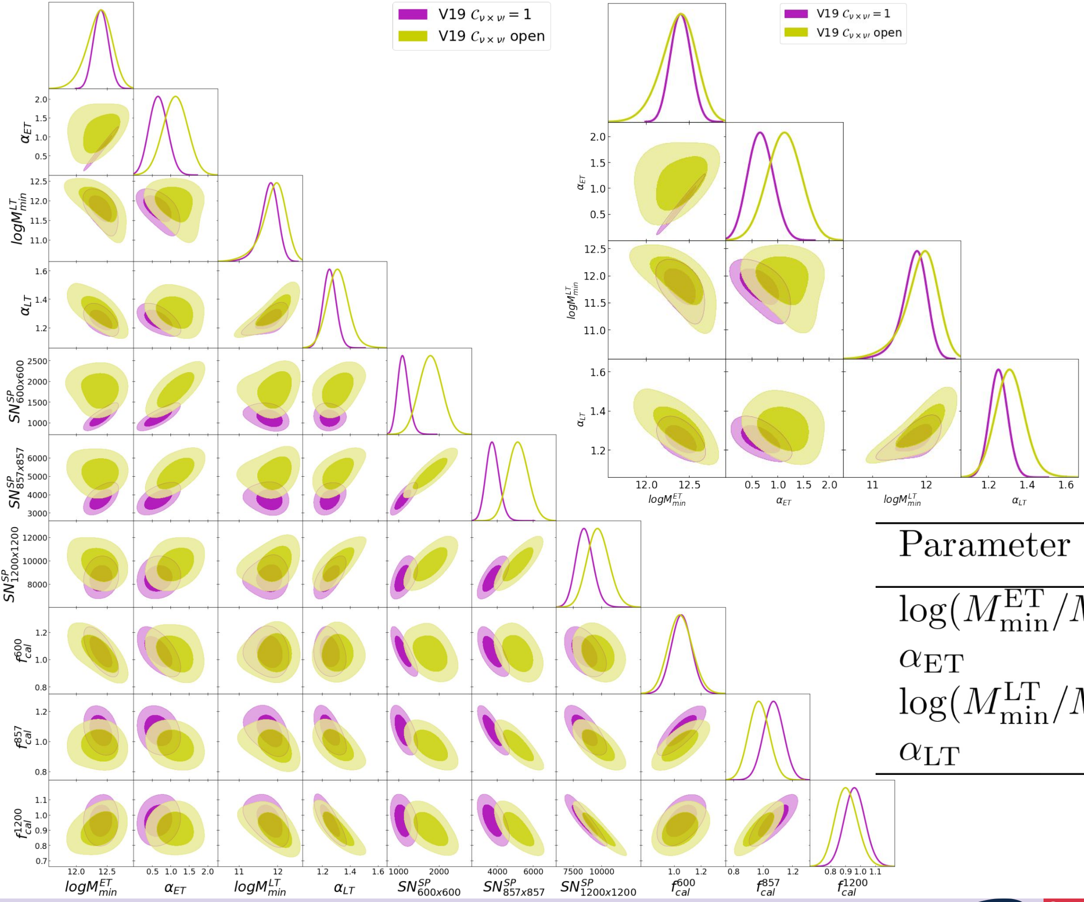


- α_{ET} constrained



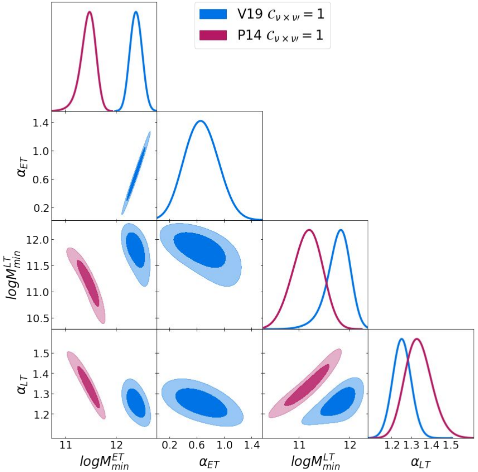
- α_{ET} constrained
- More marked difference between the two scenarios

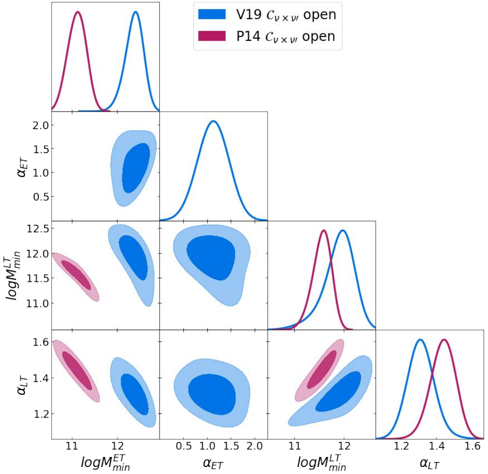




- $\alpha_{\rm ET}$ constrained
- More marked difference between the two scenarios
- Distinction between the two galaxy populations' clustering parameters

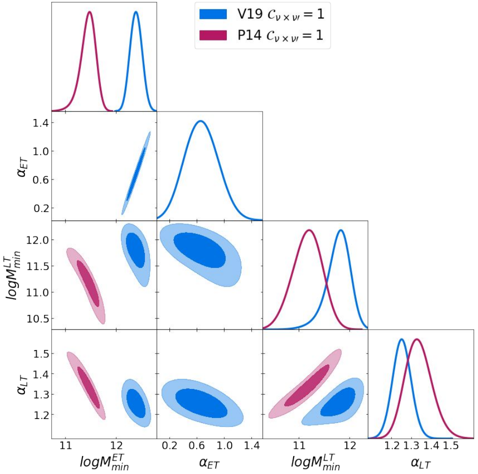
Parameter	$\mathcal{C}_{\nu_1\times\nu_2}=1$	$\mathcal{C}_{\nu_1\times\nu_2}$ open
$\log(M_{\rm min}^{\rm ET}/M_\odot h^{-1})$	12.40 ± 0.11	$12.38^{+0.22}_{-0.18}$
$\alpha_{\rm ET}$	0.67 ± 0.23	1.12 ± 0.31
$\log(M_{\rm min}^{\rm LT}/M_\odot h^{-1})$	$11.79^{+0.25}_{-0.19}$	$11.91^{+0.34}_{-0.25}$
$\alpha_{\rm LT}$	1.253 ± 0.044	1.311 ± 0.071

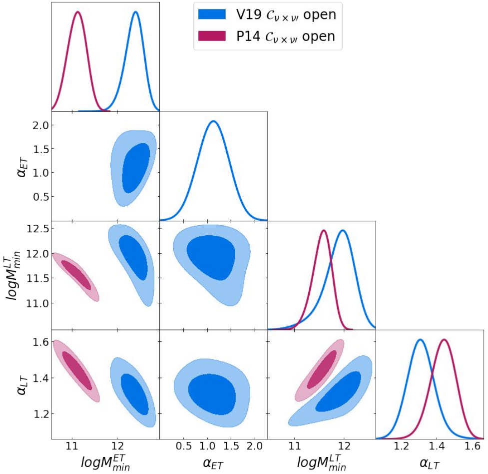




Planck and SPIRE comparison

5σ tension between the best fit values of the minimum mass for ET galaxies.

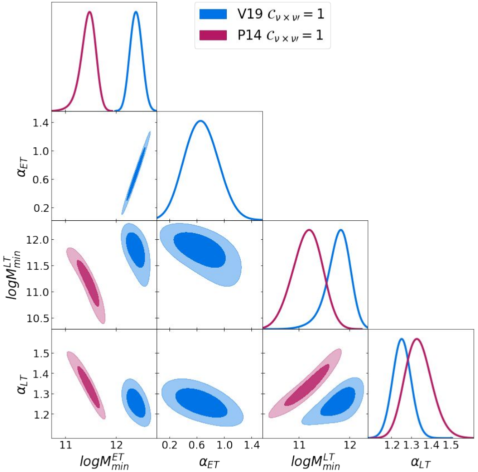


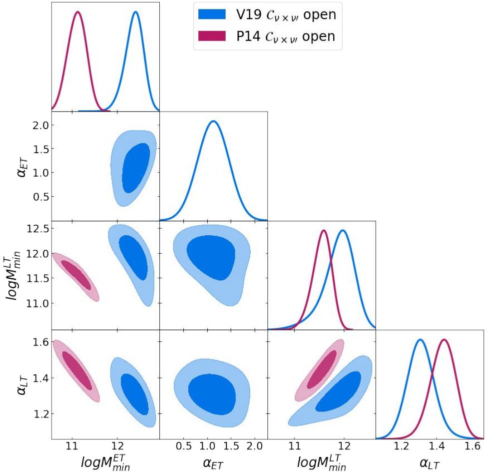


Planck and SPIRE comparison

5σ tension between the best fit values of the minimum mass for ET galaxies.

All the attempts to alleviate the tension among the two datasets have failed.



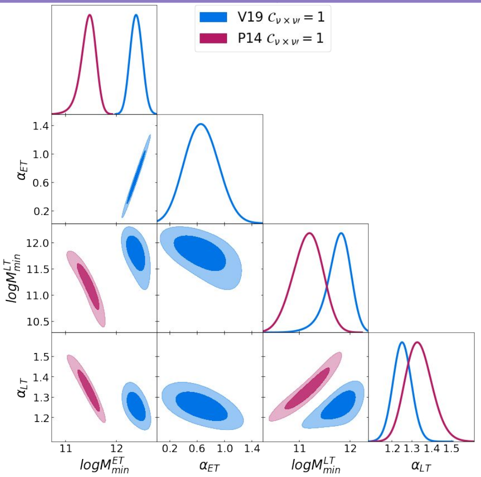


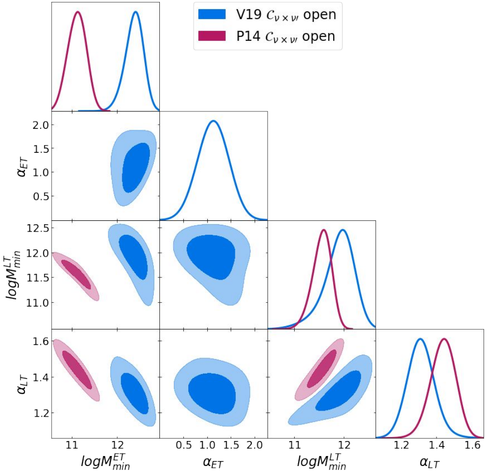
Planck and SPIRE comparison

5σ tension between the best fit values of the minimum mass for ET galaxies.

All the attempts to alleviate the tension among the two datasets have failed.

? Where does this tension come from





Planck and SPIRE comparison

5σ tension between the best fit values of the minimum mass for ET galaxies.

All the attempts to alleviate the tension among the two datasets have failed.

? Where does this tension come from

- data
- model
- both

Thank you

$$P^{1h}_{uv}(k) = \int_0^\infty \hat{W}_u(m,k)\hat{W}_v(m,k)\frac{dn}{dm}dm;$$

$$P^{2h}_{uv} = P^{lin}_{mm}(k)\prod_{n=u,v}\left[\int_o^\infty \hat{W}_n(m,k)b(m)\frac{dn}{dm}dm\right].$$

- $$\frac{dn}{d\ln m} = -\frac{1}{2}f(\sigma,z)\frac{\bar{\rho}}{m}\frac{d\ln\sigma^2}{d\ln m},$$
  $$f(\sigma,z) = A(z)\left[\left(\frac{\sigma}{b(z)}\right)^{-a(z)} + 1\right]e^{-c(z)/\sigma^2}$$
- $$\delta_h(m,z_1|M,V,z_0) = b(m,z_1)\delta,$$
  $$b(m,z_1) = 1 - A\frac{\nu^a}{\nu^a+\delta_c^a} + B\nu^b + C\nu^c,$$
- $$\rho(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

$$P^{1h}_{\rm ET}(k) = \frac{1}{\left(\bar{n}^{\rm ET}_{\rm gal}\right)^2}\int_0^\infty dm\frac{dn}{dm}[2N^{\rm ET}_{\rm cent}N^{\rm ET}_{\rm sat}u(m,k)+ \left(N^{\rm ET}_{\rm sat}\right)^2 u(k,m)^2],$$

$$P^{1h}_{\rm LT}(k) = \frac{1}{\left(\bar{n}^{\rm LT}_{\rm gal}\right)^2}\int_0^\infty dm\frac{dn}{dm}[2N^{\rm LT}_{\rm cent}N^{\rm LT}_{\rm sat}u(m,k)+ \left(N^{\rm LT}_{\rm sat}\right)^2 u(k,m)^2],$$

$$P^{2h}_{\rm ET}(k) = P^{lin}_{mm}(k)\left[\int_0^\infty dm\frac{dn}{dm}b(m)\frac{N^{\rm ET}_{\rm gal}}{\bar{n}^{\rm ET}_{\rm gal}}u(k,m)\right]^2,$$

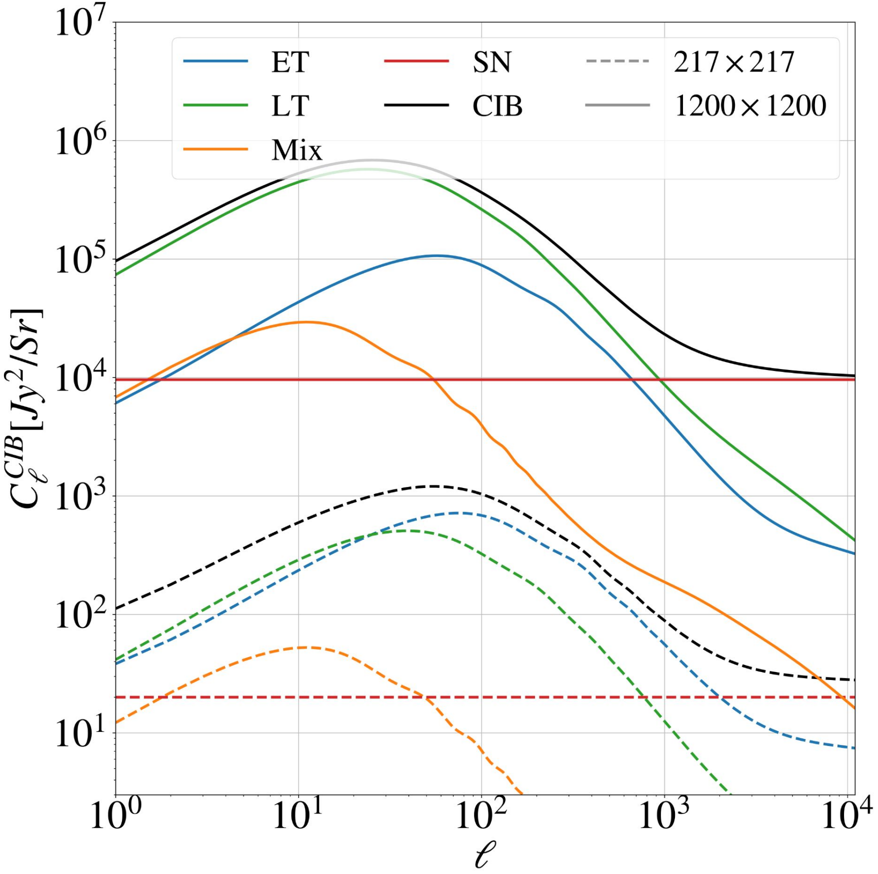
$$P^{2h}_{\rm LT}(k) = P^{lin}_{mm}(k)\left[\int_0^\infty dm\frac{dn}{dm}b(m)\frac{N^{\rm LT}_{\rm gal}}{\bar{n}^{\rm LT}_{\rm gal}}u(k,m)\right]^2.$$

$$P^{1h}_{\rm mix}(k) = \frac{1}{\bar{n}^{\rm ET}_{\rm gal}\bar{n}^{\rm LT}_{\rm gal}}\int_0^\infty dm\frac{dn}{dm}[(N^{\rm ET}_{\rm cent}N^{\rm LT}_{\rm sat} + N^{\rm ET}_{\rm sat}N^{\rm LT}_{\rm cent})u+ N^{\rm ET}_{\rm sat}N^{\rm LT}_{\rm sat}u^2],$$

$$P^{2h}_{\rm mix}(k) = P^{lin}_{mm}\left[\int_0^\infty dm\frac{dn}{dm}b(m)\frac{N^{\rm ET}_{\rm gal}}{\bar{n}^{\rm ET}_{\rm gal}}u\right]\times \left[\int_0^\infty dm\frac{dn}{dm}b(m)\frac{N^{\rm LT}_{\rm gal}}{\bar{n}^{\rm LT}_{\rm gal}}u\right].$$

Non-linear galaxy power spectrum in a halo model framework

	X12	P11	C13
$\log(M_{\rm min}^{\rm ET}/M_{\odot}h^{-1})$	12.09 ± 0.06	11.95 ± 2.10–12.21 ± 0.51	12.00 ± 0.04
$\alpha_{\rm ET}$	1.81 ± 0.04	1.02 ± 0.87–1.30 ± 1.16	1.55 ± 0.05
$\log(M_{\rm min}^{\rm LT}/M_{\odot}h^{-1})$	$\equiv 10.85$	-	10.85 ± 0.06
$\alpha_{\rm LT}$	$\equiv 1$	-	$\equiv 1$


ET
LT
Mix
SN
CIB
217×217
1200×1200
$C_\ell^{CIB}[Jy^2/Sr]$
ℓ
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7

The luminosity function for ET galaxies is a convolution of the halo formation rate (obtained as the time derivative of the hmf) and the galaxy luminosity distribution (log-normal distribution).

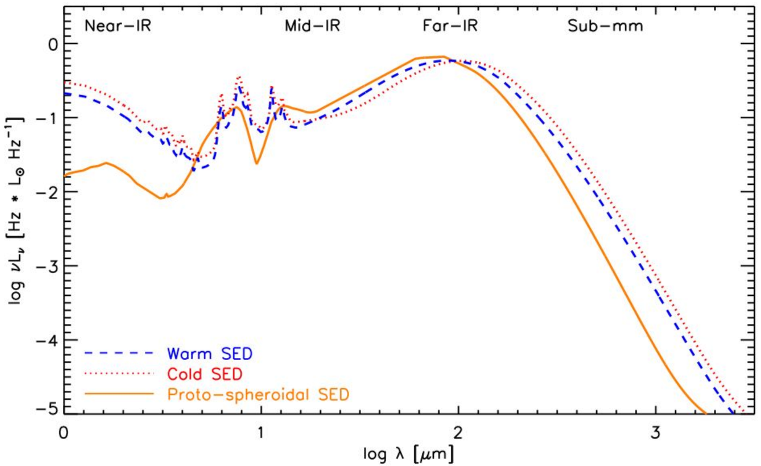
$$\boxed{\frac{\mathrm{d}n}{\mathrm{d}t_{\rm vir}} = \mathrm{d}n\frac{\mathrm{d}\ln(\nu f(\nu))}{\mathrm{d}t_{\rm vir}}.}$$

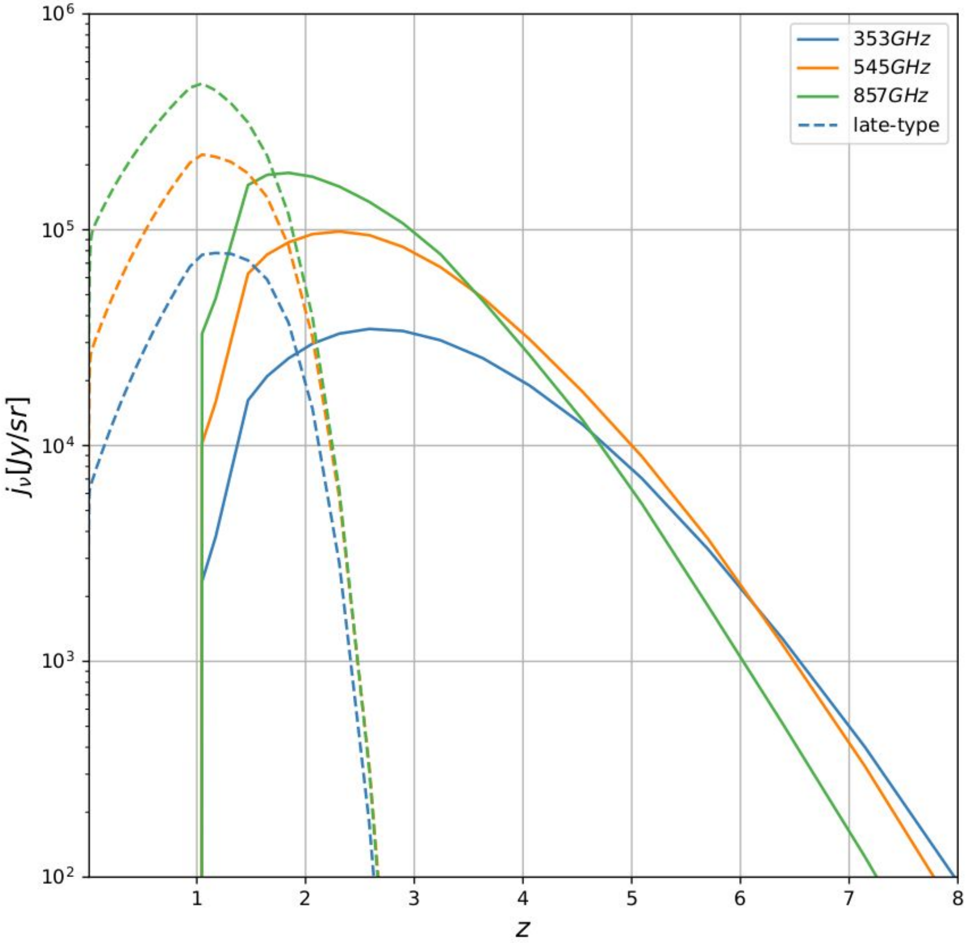
$$\boxed{P(\log L|\log \bar{L})\mathrm{d}\log L = \frac{\exp\{-\log^2(L/\bar{L})/2\sigma^2\}}{\sqrt{2\pi\sigma^2}}\mathrm{d}\log L,}$$

$$\Phi(\log L, z) = \int_{M_{\rm vir}^{\rm min}}^{M_{\rm vir}^{\rm max}} \mathrm{d}M_{\rm vir} \int_{z_{\rm vir}^{\rm min}}^{z_{\rm vir}^{\rm max}} \mathrm{d}z_{\rm vir} \left|\frac{\mathrm{d}t_{\rm vir}}{\mathrm{d}z_{\rm vir}}\right| \frac{\mathrm{d}n}{\mathrm{d}t_{\rm vir}} P(\log L, z).$$

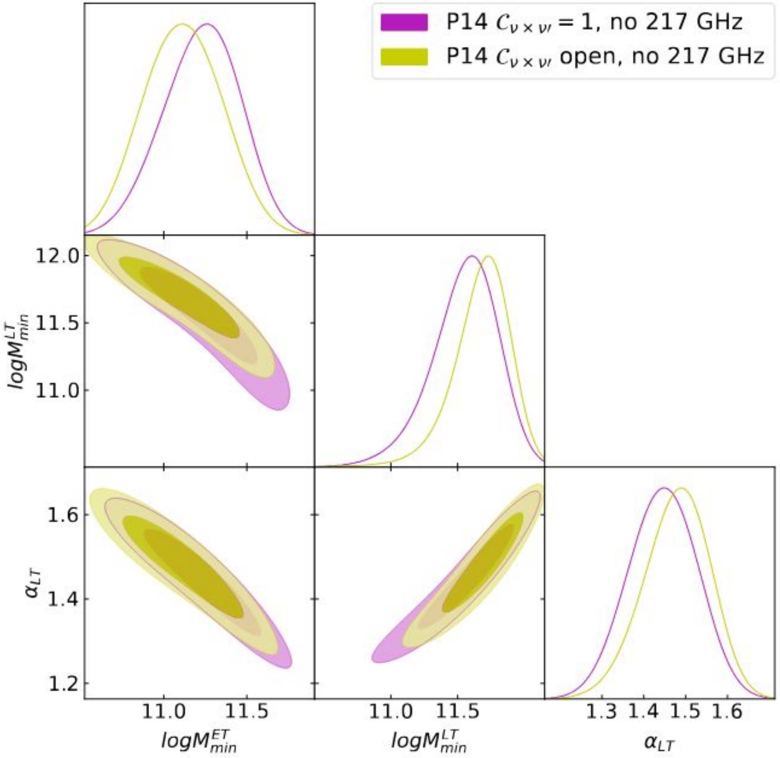
Required an empirical parameterization for the luminosity function of LT galaxies.

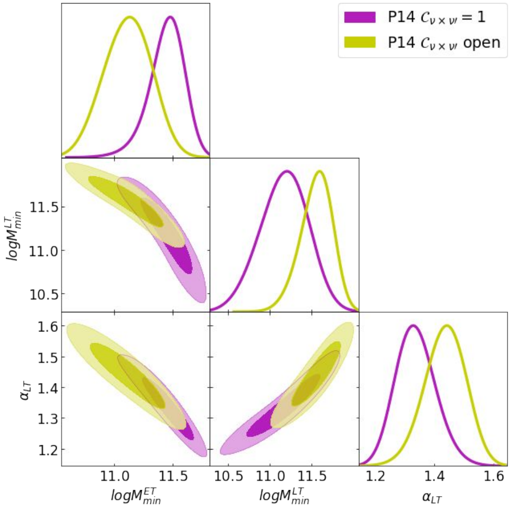
NB: from bolometric to freq-dependent LF we used a data-driven approach using SEDs (different SEDs for the two different galaxy populations)





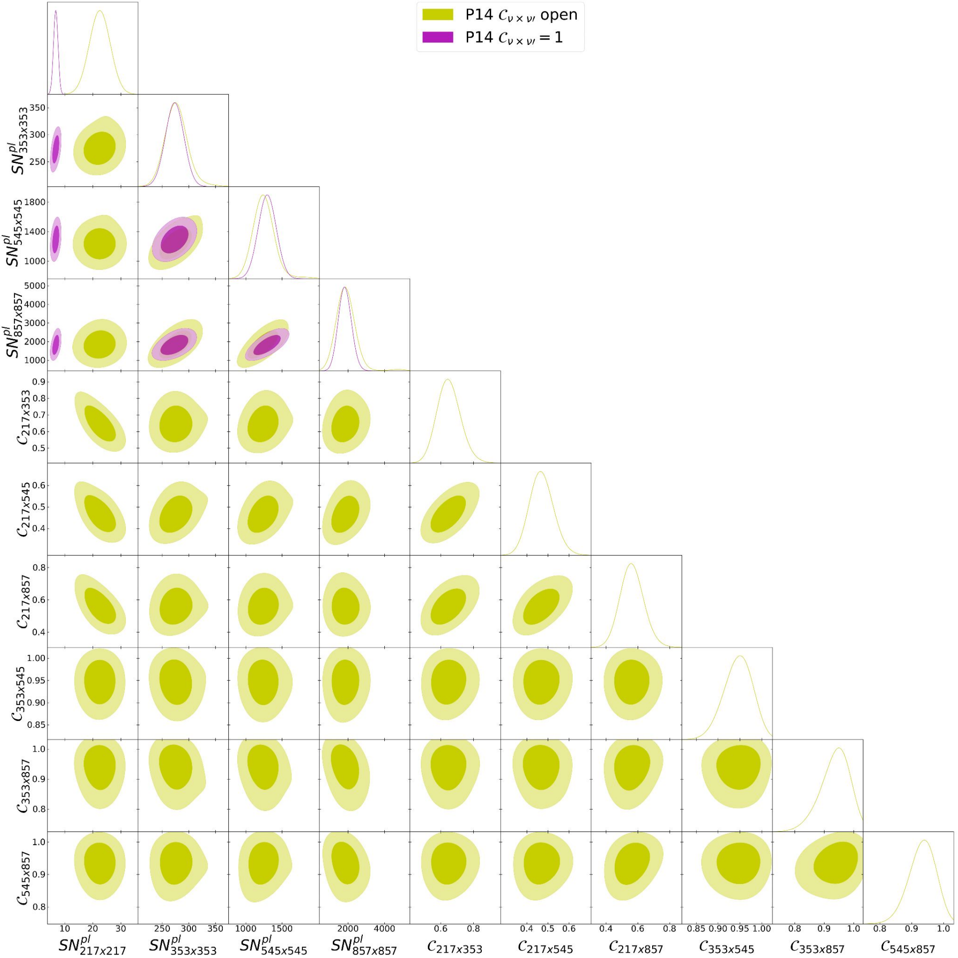
NB: broader contribution over redshifts from ET galaxies.
The fact that we don't expect any contribution from ET galaxies at very low redshifts is encoded in the emissivity functions (cut-off)





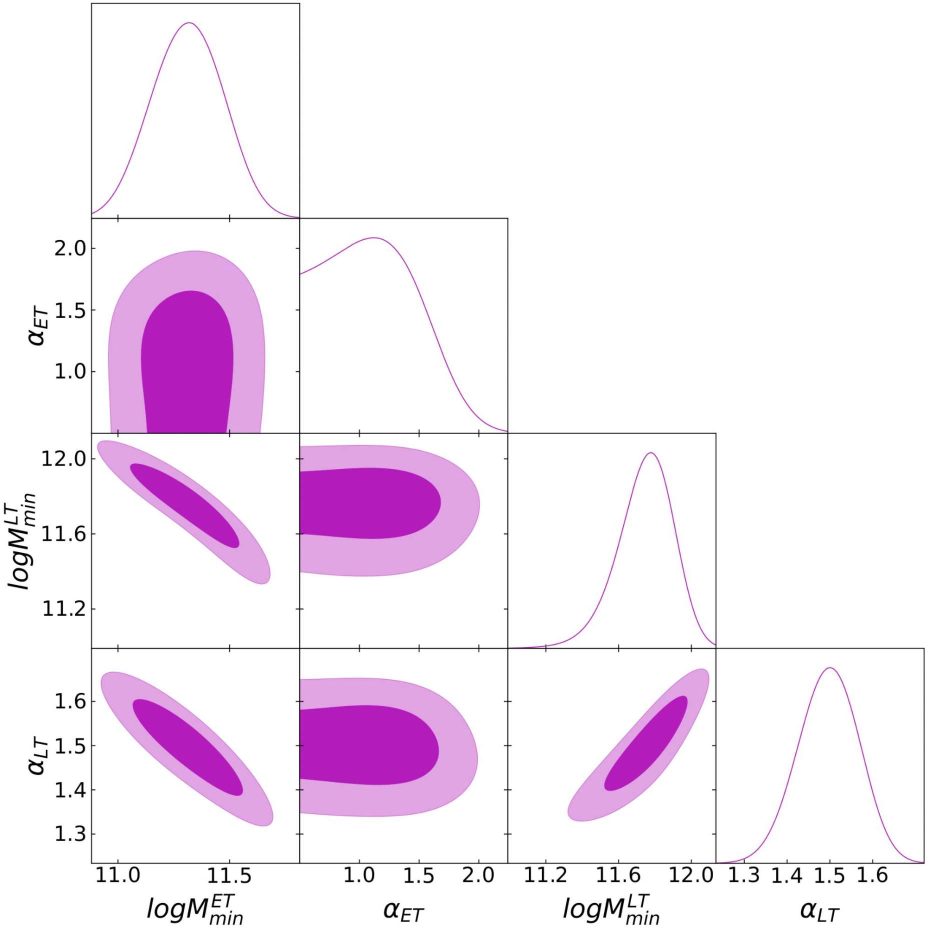
Smaller shift in the 2D posterior distributions. To understand this we need to look at the full parameter space explored by the fit. We find a tension in the two scenarios for the value of the shot noise level of the 217 GHz frequency channel. Specifically, we obtain a value for the shot noise level which is higher in the case with free correlations than in the case with fixed correlations. We also see that the correlation coefficients involving the 217 GHz frequency channel are significantly lower than unity. We explain this behavior by noting the degeneracy between the shot noise level and the correlation coefficients at 217 GHz, which P14 data are not able to break. Specifically, they are anti-correlated, meaning that a shift of the shot noise level toward a lower value, closer to the one obtained in the first scenario, leads to higher values of the corr coeff.

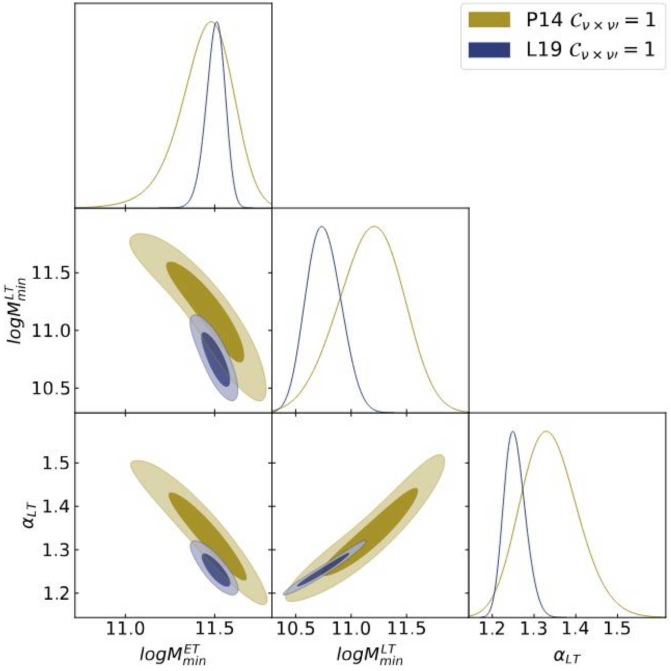
The exclusion of the 217GHz frequency channel makes the results of the fits more stable among the two scenarios.

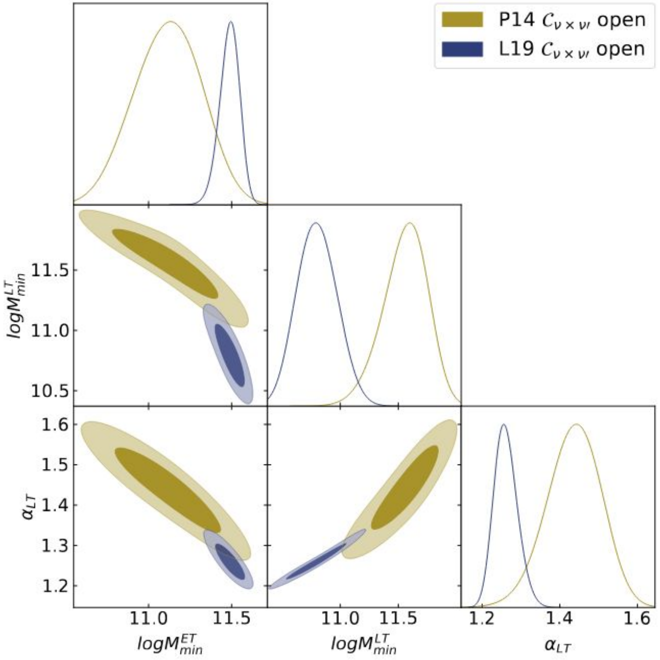


Parameter	Prior	Results $C_{\nu_1\times\nu_2}=1$	Results $C_{\nu_1\times\nu_2}$ open
$\log(M_{\rm min}^{\rm ET}/M_\odot h^{-1})$	[10.7,12.8]	$11.45^{+0.16}_{-0.13}$	11.12 ± 0.19
$\log(M_{\rm min}^{\rm LT}/M_\odot h^{-1})$	[10.5,12.8]	$11.18^{+0.31}_{-0.27}$	$11.56^{+0.21}_{-0.17}$
$\alpha_{\rm LT}$	[0.2,3.5]	$1.337^{+0.063}_{-0.072}$	$1.436^{+0.075}_{-0.067}$
$\rm SN_{217}$	[0,50]	6.72 ± 0.76	22 ± 4
$\rm SN_{353}$	[50,500]	273 ± 16	276 ± 20
$\rm SN_{545}$	[400,4000]	1296 ± 120	1247 ± 100
$\rm SN_{857}$	[200,8000]	1827 ± 300	1899^{+400}_{-600}
$f^{353}_{\rm cal}$	1 ± 0.0156	0.999 ± 0.014	1.010 ± 0.015
$f^{545}_{\rm cal}$	1 ± 0.122	1.096 ± 0.032	1.094 ± 0.032
$f^{857}_{\rm cal}$	1 ± 0.128	1.289 ± 0.076	1.200 ± 0.072
$C_{217\times353}$	[-1, 1]	-	$0.648^{+0.068}_{-0.075}$
$C_{217\times545}$	[-1, 1]	-	0.469 ± 0.054
$C_{217\times857}$	[-1, 1]	-	0.562 ± 0.070
$C_{353\times545}$	[-1, 1]	-	$0.946^{+0.035}_{-0.031}$
$C_{353\times857}$	[-1, 1]	-	$0.937^{+0.056}_{-0.042}$
$C_{545\times857}$	[-1, 1]	-	$0.934^{+0.046}_{-0.039}$

Backup slides: α_{ET} unconstrained







The overlap between the two data sets is good (the largest shift is noted in the 1D posterior distribution of the minimum masses for the LT galaxies in the second figure,).

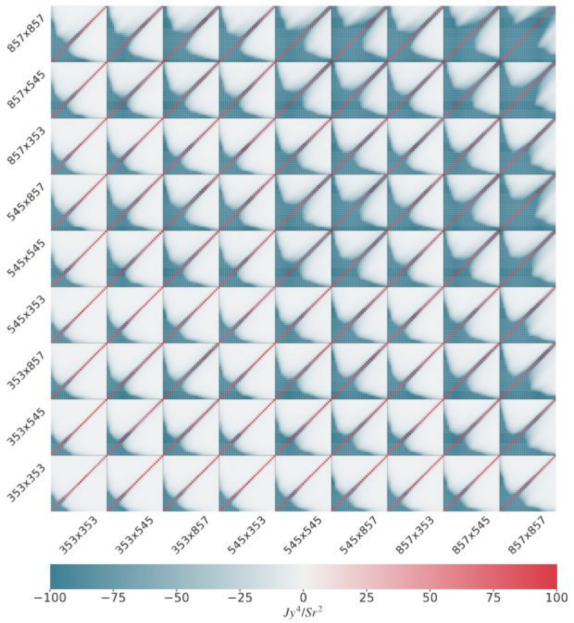


Fig. B.3. Covariance matrix of the L19 CIB measurements.

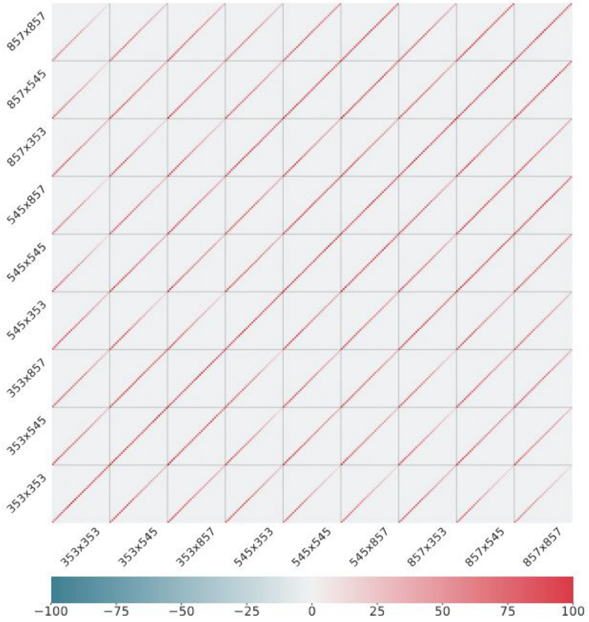
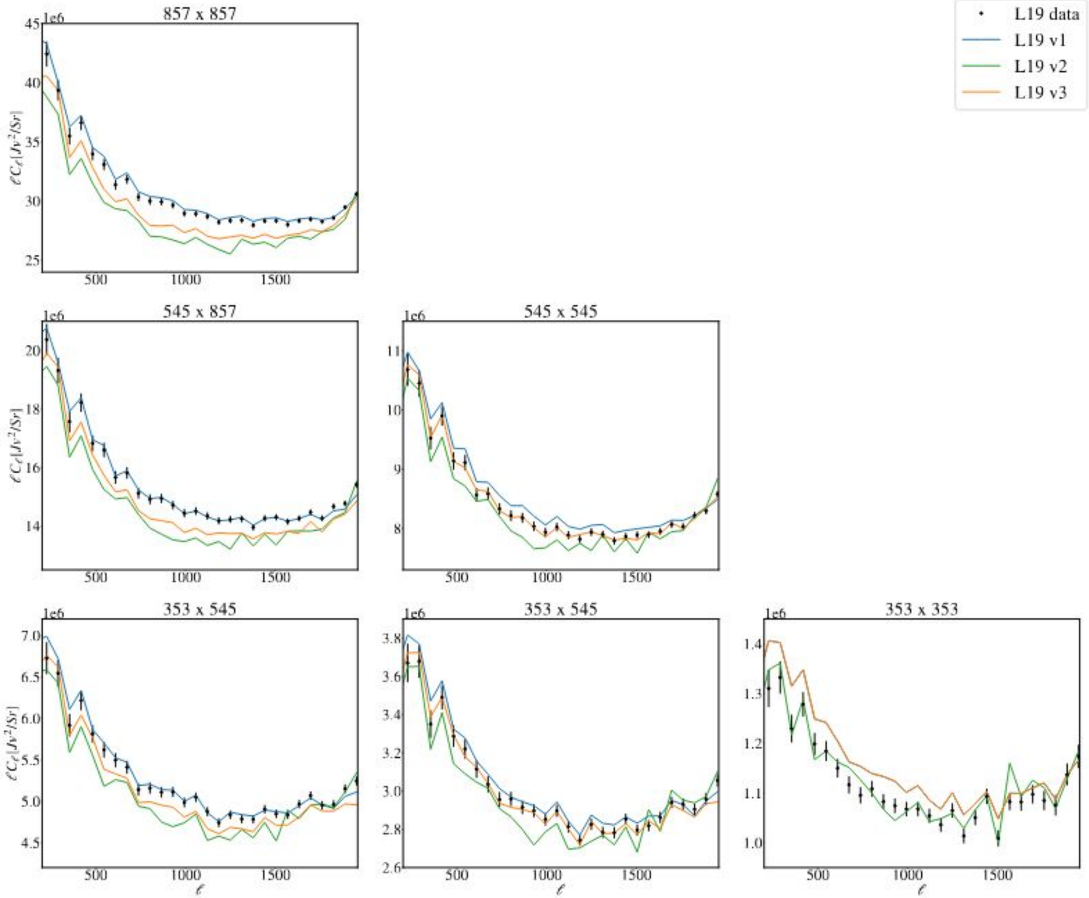


Fig. B.4. Correlation matrix of the L19 CIB measurements.

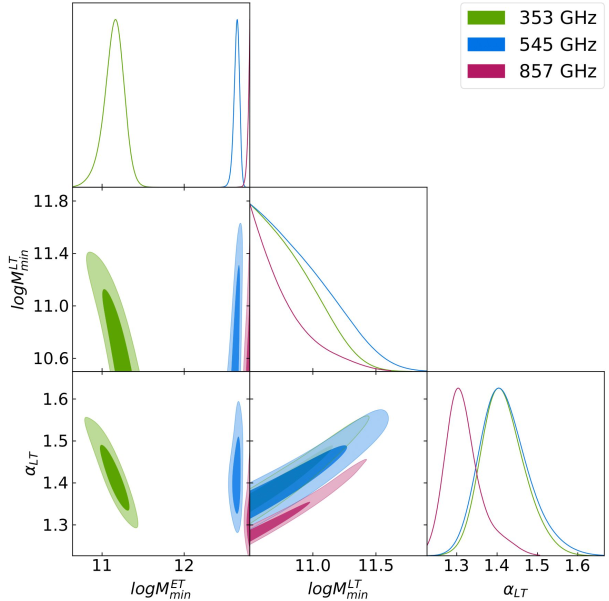
As initial step, we implement L19's pipeline to compute the CIB power spectra and extend it to build a Gaussian covariance matrix. We do this to explore the impact of possible bin-to-bin correlations in the fit and in the chi2. From these, we note that there is no significant correlation among different multipoles, but there is very significant correlation between the same bin at different frequencies. However, re-running the analysis including this new matrix showed no impact on the chi2 of the fit.



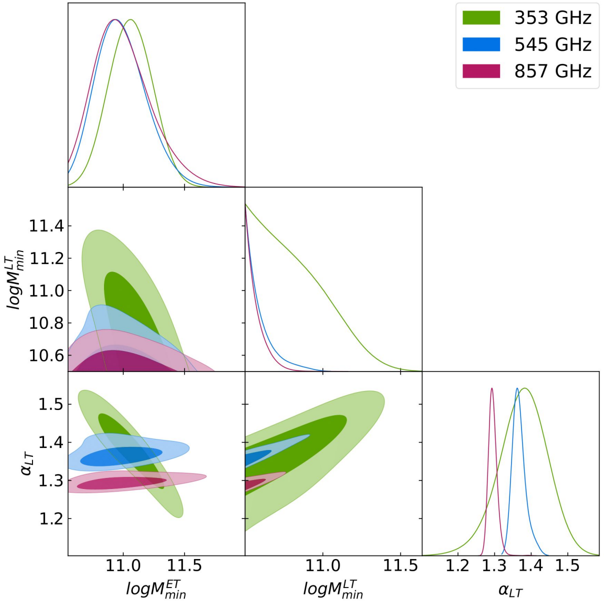
Three different datasets obtained after a re-analysis of the maps.

- The first version of the data set was obtained applying the same neutral hydrogen column density (N_{HI}) threshold of 2.5 x 10^{20} cm^{-2} across all three frequency channels (blue curve).
- The second data set applied a lower N_{HI} threshold of 1.5 x 10^{20} cm^{-2} across all channels to explore the impact of dust and in particular of dust residuals in the analysis (green curve).
- The third data set has been obtained following the prescription of L19 and imposing a different threshold for each frequency channel. Specifically we set N_{HI} = 2.5 x 10^{20} cm^{-2} , 2.0 x 10^{20} cm^{-2} and 1.8 x 10^{20} cm^{-2} for 353, 545 and 857 GHz respectively (orange curve).

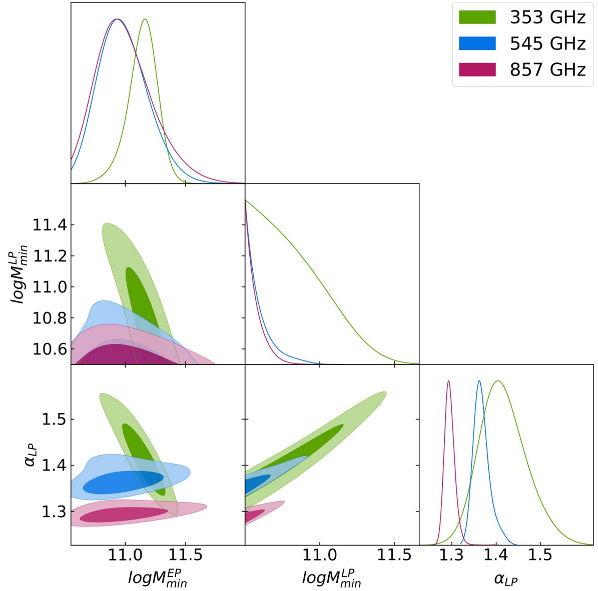
Backup slides: L19 analysis and possible dust contamination



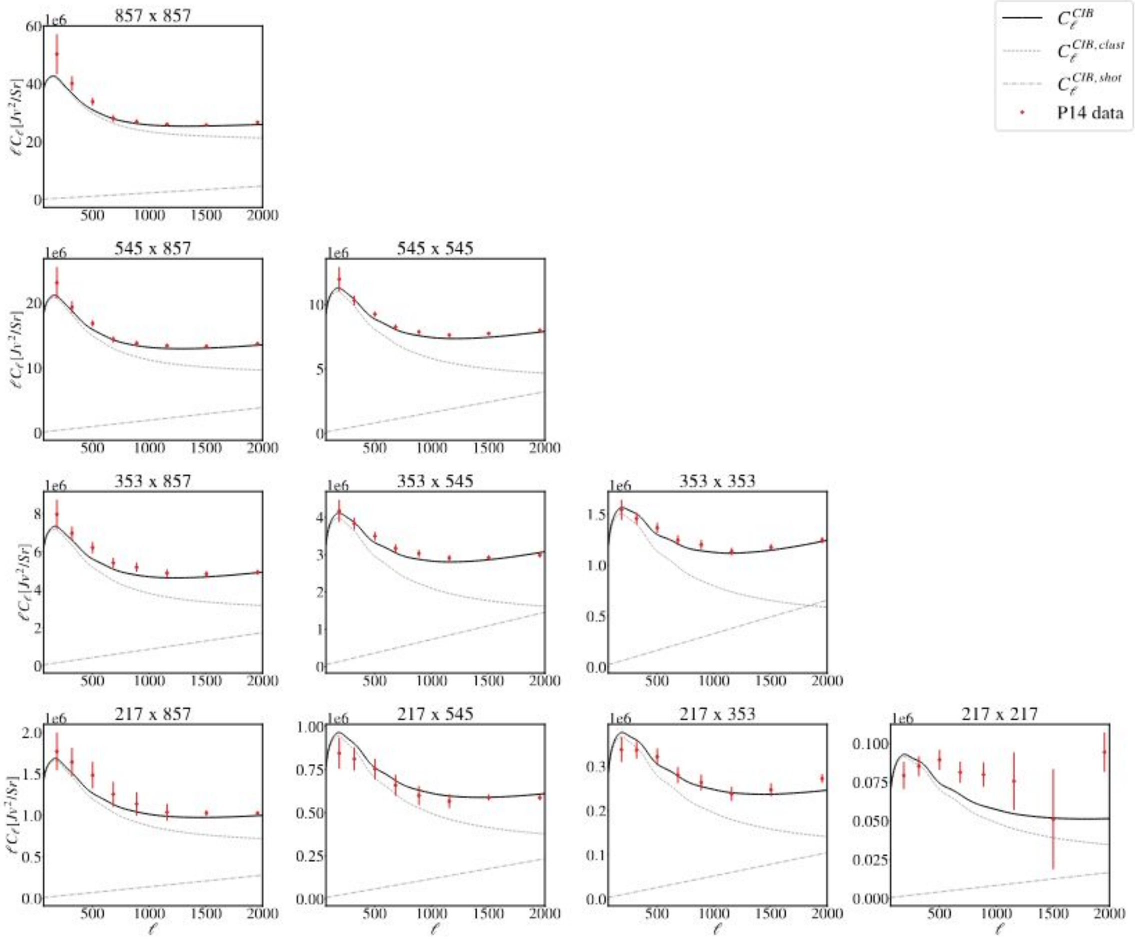
the two higher frequency channels result in much higher best-fit values for the Mmin of ET galaxies. Recalling that this clustering parameter acts as a re-scaling of the power spectrum, the high values could possibly be hinting at an excess of power coming from dust residuals.



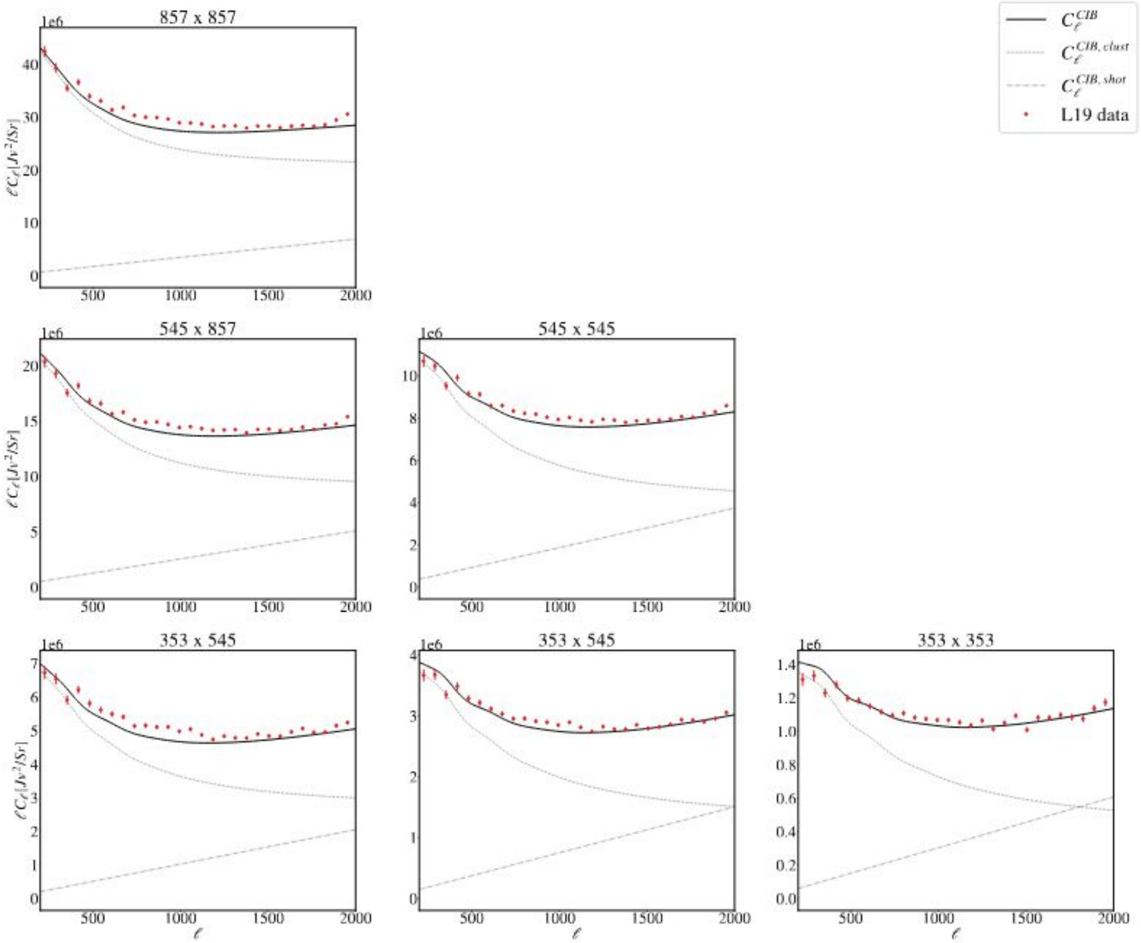
more aggressive mask, so smaller contamination. The behavior of the posterior distributions of the clustering parameters changes significantly. There is no tension between the minimum masses of ET galaxies, supporting the hypothesis of a ***dust residual***.



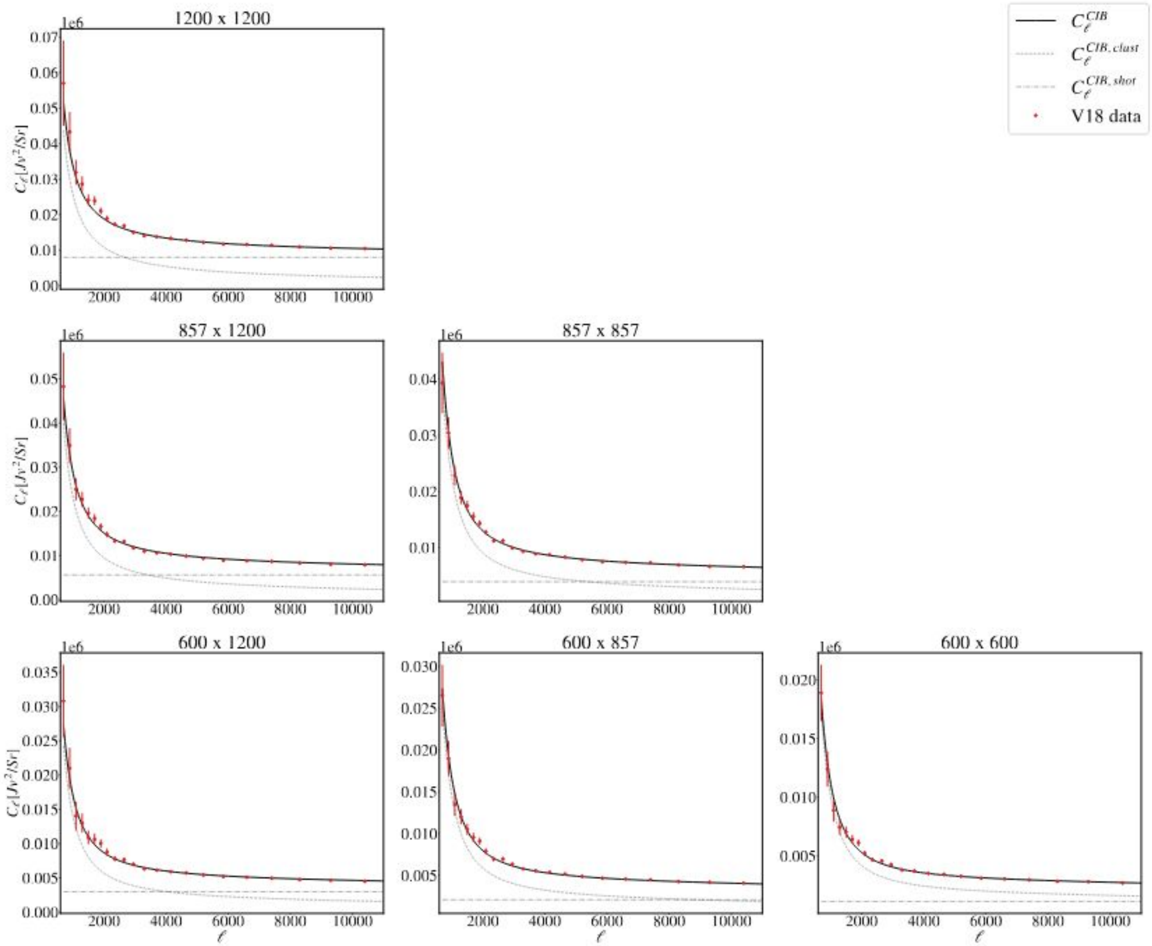
different thresholds for the three frequency channels, showed no significant differences from the second data set, except for the 353 GHz frequency channel which provided more constraining power due to more data retained.


857 x 857
545 x 857
545 x 545
353 x 857
353 x 545
353 x 353
217 x 857
217 x 545
217 x 353
217 x 217
1e6
$\ell C_\ell [Jy^2/Sr]$
ℓ
C_ℓ^{CIB}
$C_\ell^{CIB,clust}$
$C_\ell^{CIB,shot}$
P14 data

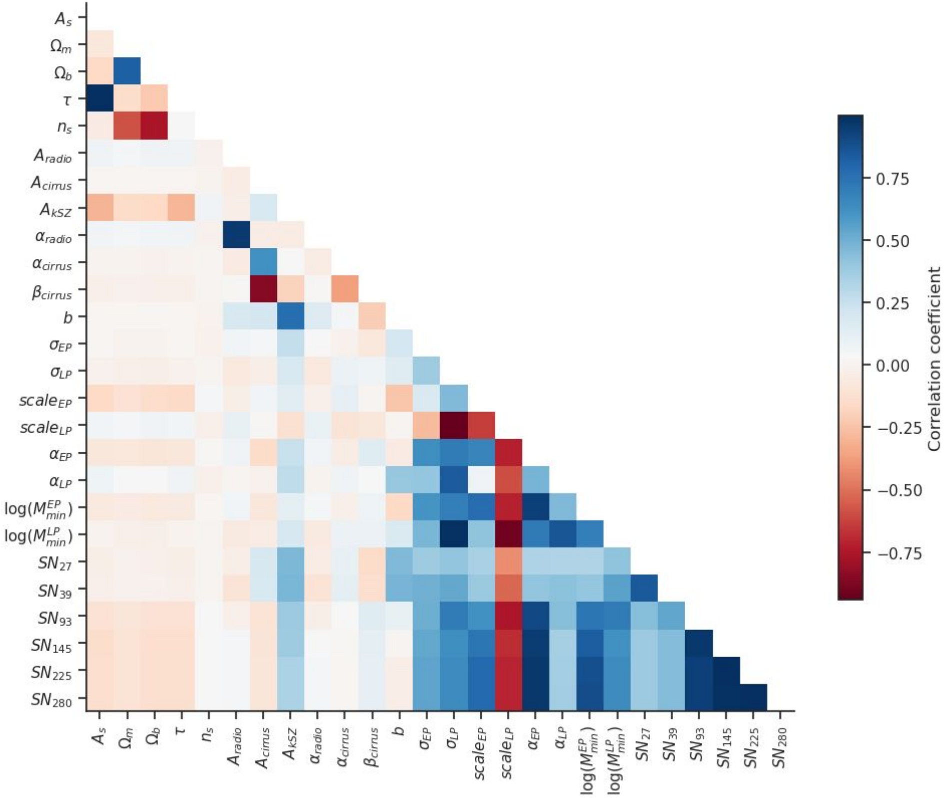
Backup slides: L19 model-data

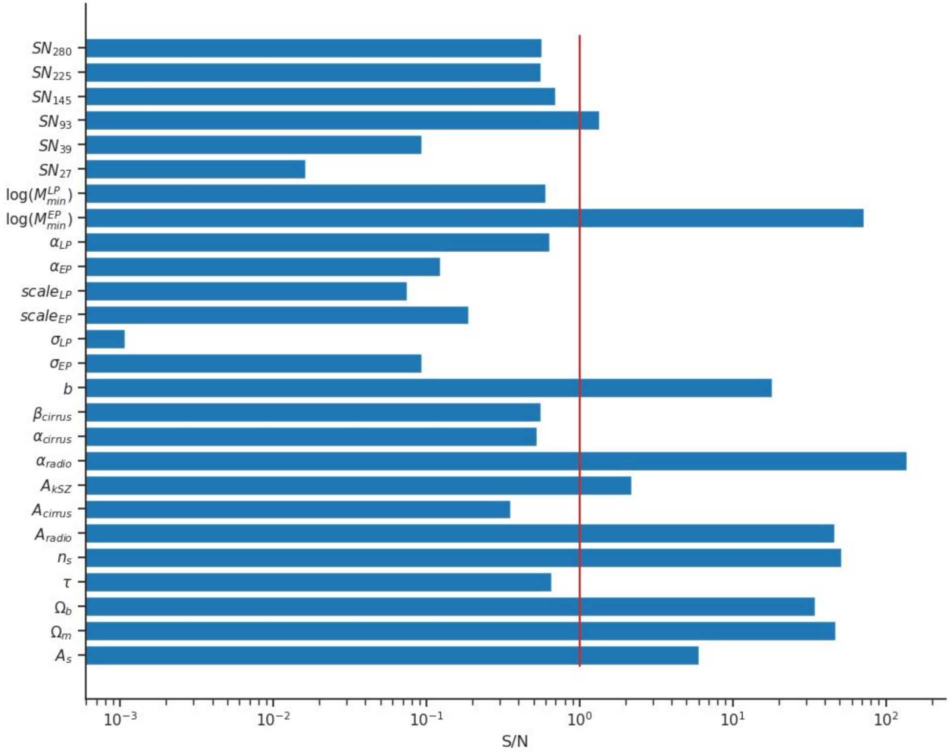


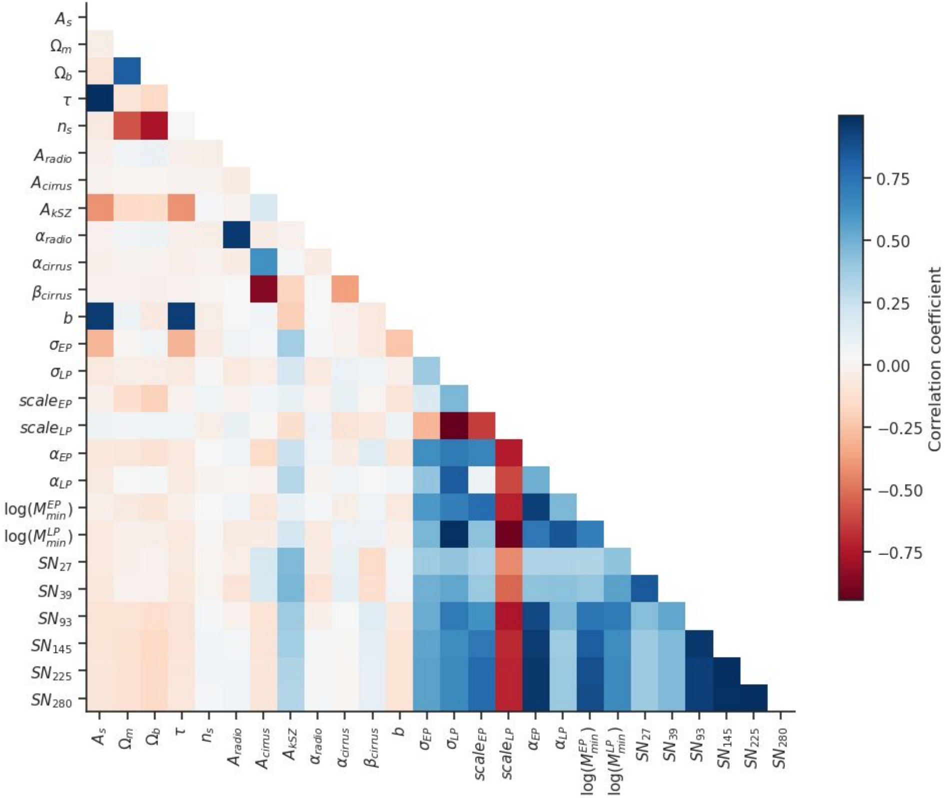
Backup slides: V19 model-data



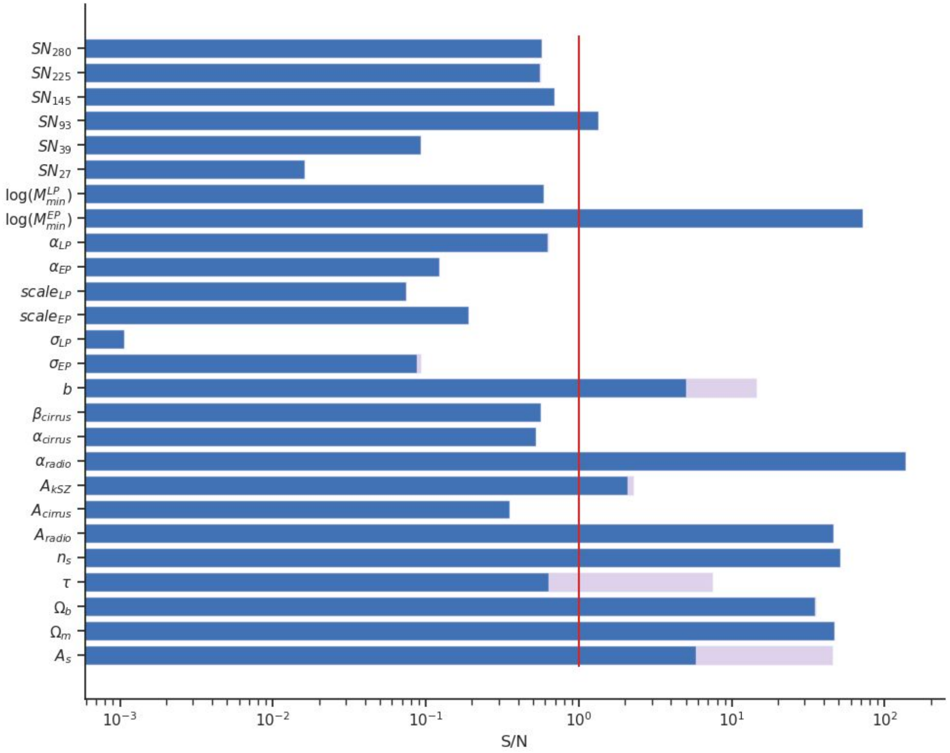
Backup slides: full model, fisher corr, fisher SNR - Planck/ACT like analysis





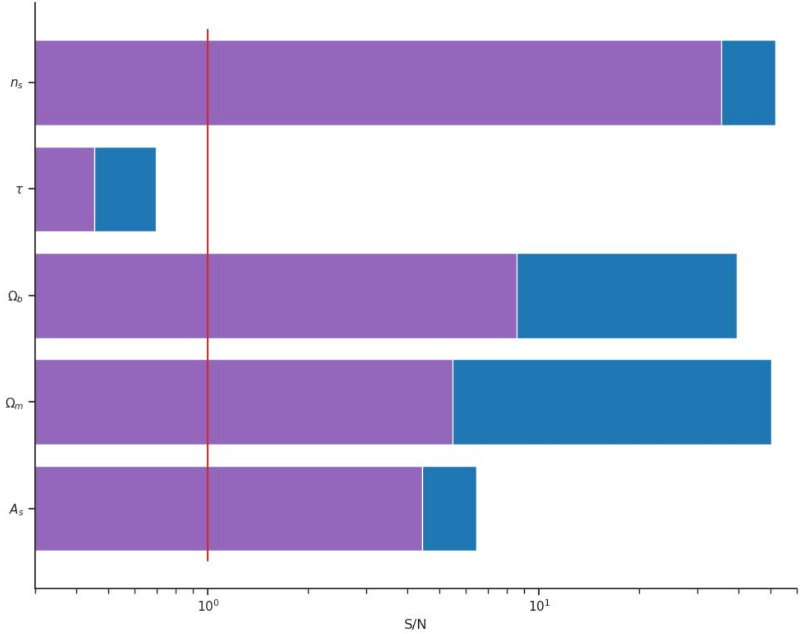


A_s
Ω_m
Ω_b
τ
n_s
A_{radio}
A_{cirrus}
A_{kSZ}
α_{radio}
α_{cirrus}
β_{cirrus}
b
σ_{EP}
σ_{LP}
$scale_{EP}$
$scale_{LP}$
α_{EP}
α_{LP}
$\log(M^{EP}_{min})$
$\log(M^{LP}_{min})$
SN_{27}
SN_{39}
SN_{93}
SN_{145}
SN_{225}
SN_{280}
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
Correlation coefficient



SN_{280}
SN_{225}
SN_{145}
SN_{93}
SN_{39}
SN_{27}
$\log(M^{LP}_{min})$
$\log(M^{EP}_{min})$
α_{LP}
α_{EP}
$scale_{LP}$
$scale_{EP}$
σ_{LP}
σ_{EP}
b
β_{cirrus}
α_{cirrus}
α_{radio}
A_{kSZ}
A_{cirrus}
A_{radio}
n_s
τ
Ω_b
Ω_m
A_s
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
S/N

Focus on cosmological parameters only



Purple: fixed cosmology entering the FG modeling

Blue: varying cosmology in the FG modeling

! *Higher Fisher Signal-to-Noise Ratio*

? *What's next*

- Go through MCMC analysis of different setups
- Find the best configuration to constrain the kSZ amplitude
- Further investigation on the tSZxCIB cross-correlation