Tomographic Measurement of the Cosmic Gas Pressure

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also: ***David Alonso*** *(Oxford),* ***Maciej Bilicki*** *(Polish Academy of Sciences),* ***John Peacock*** *(Edinburgh)*

motivation

analysis

results

conclusions

motivation

analysis

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Gas Pressure? huh?

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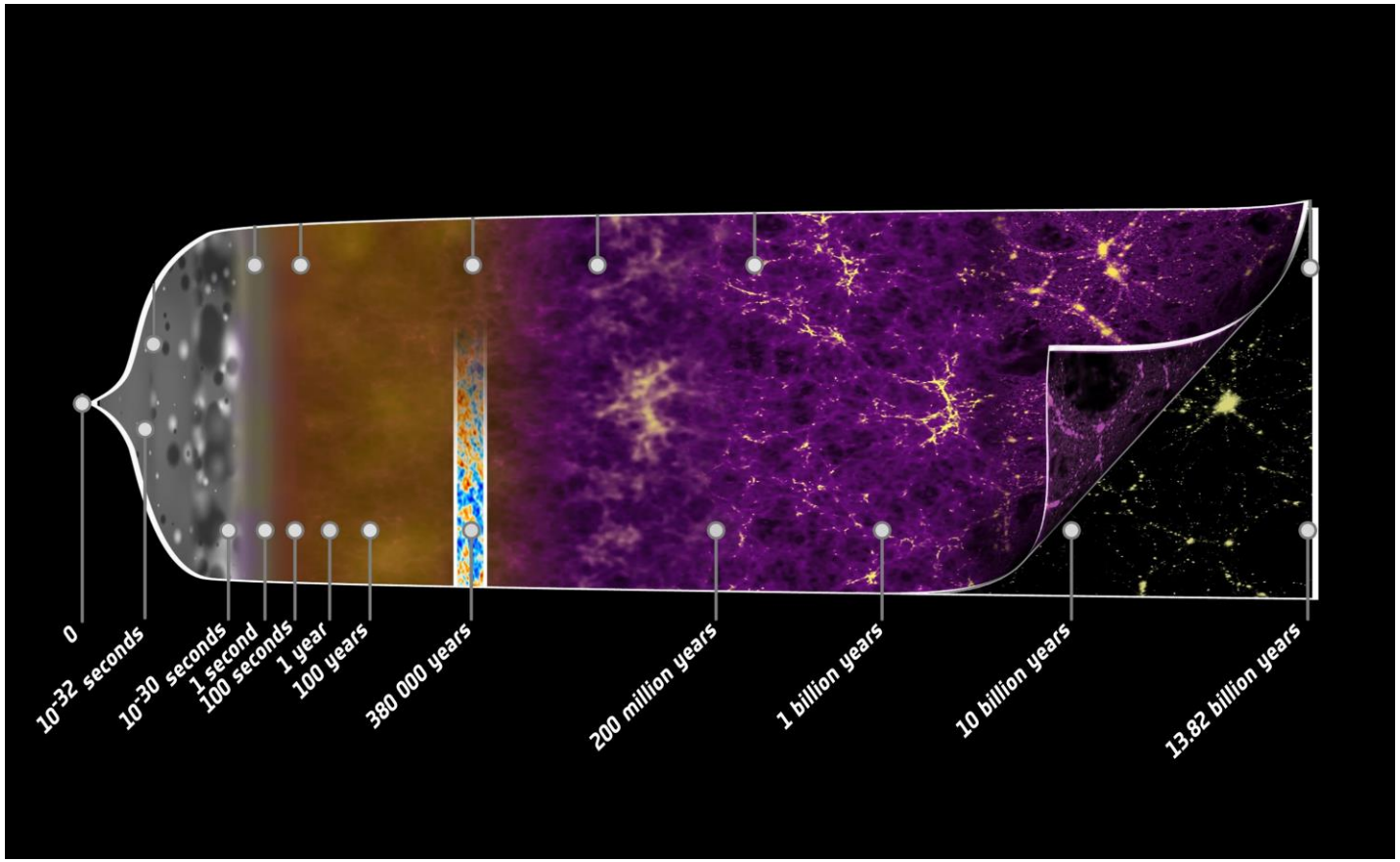
- ✔ high-precision cosmology
- ✔ probe fundamental physics



Gas Pressure? huh?

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Observations
- Instrumental uncertainties
- Noise
- Selection effects

Observables
- Astrophysical systematics

Cosmological Observables
- Theoretical uncertainties

Cosmological Parameters
- BINGO

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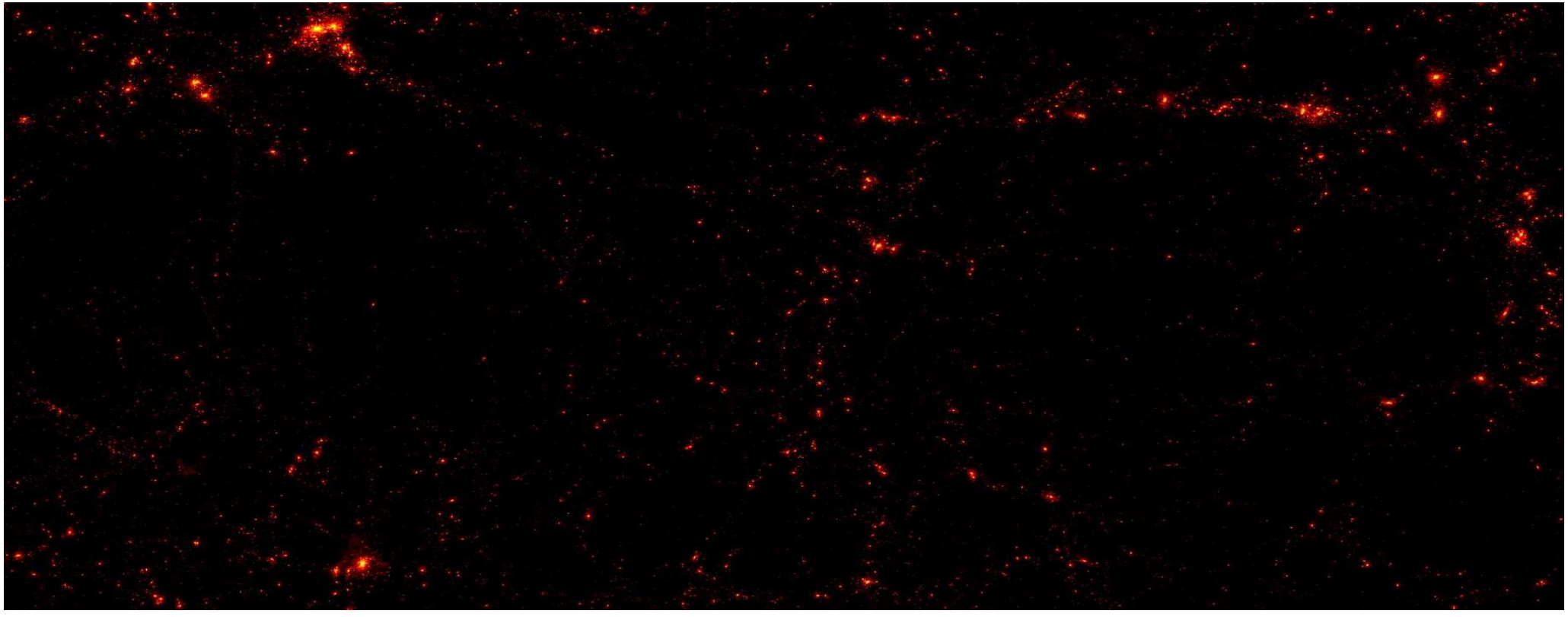
✗ we don't know the **small-scale hydrodynamics**

What we don't understand very well



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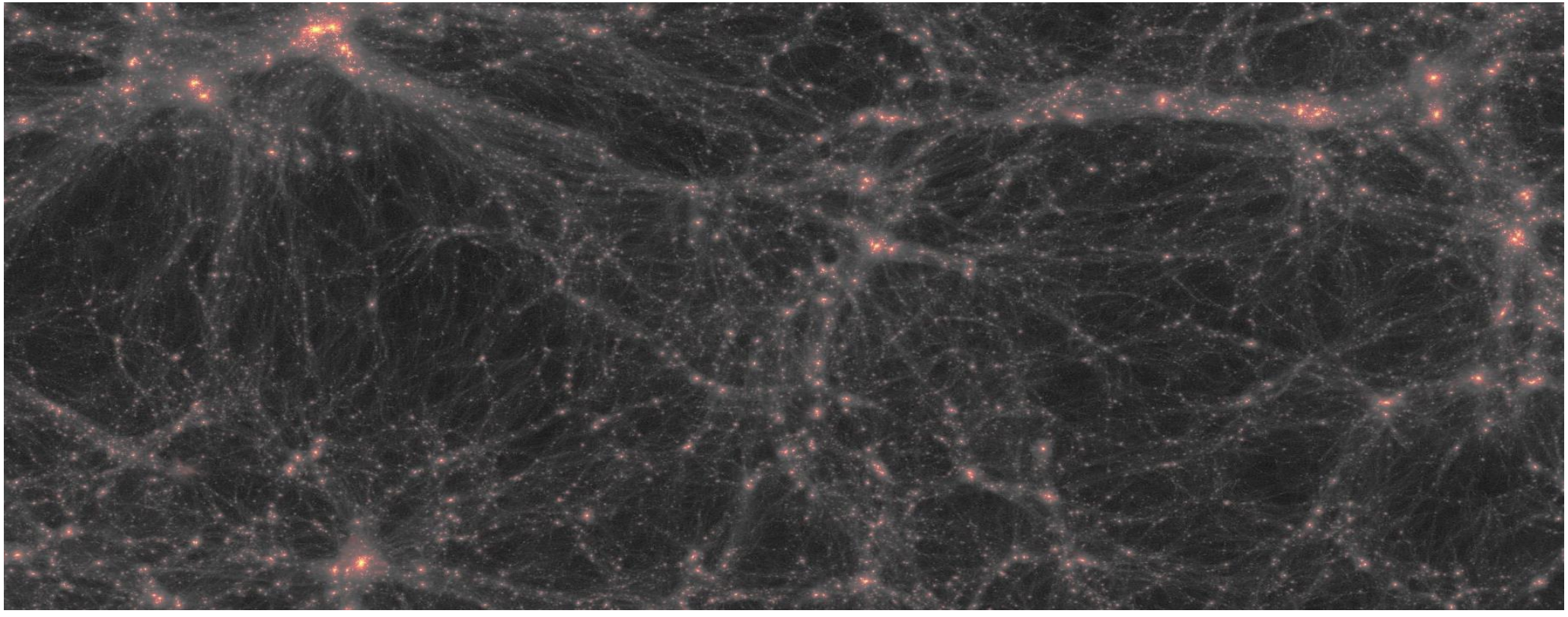
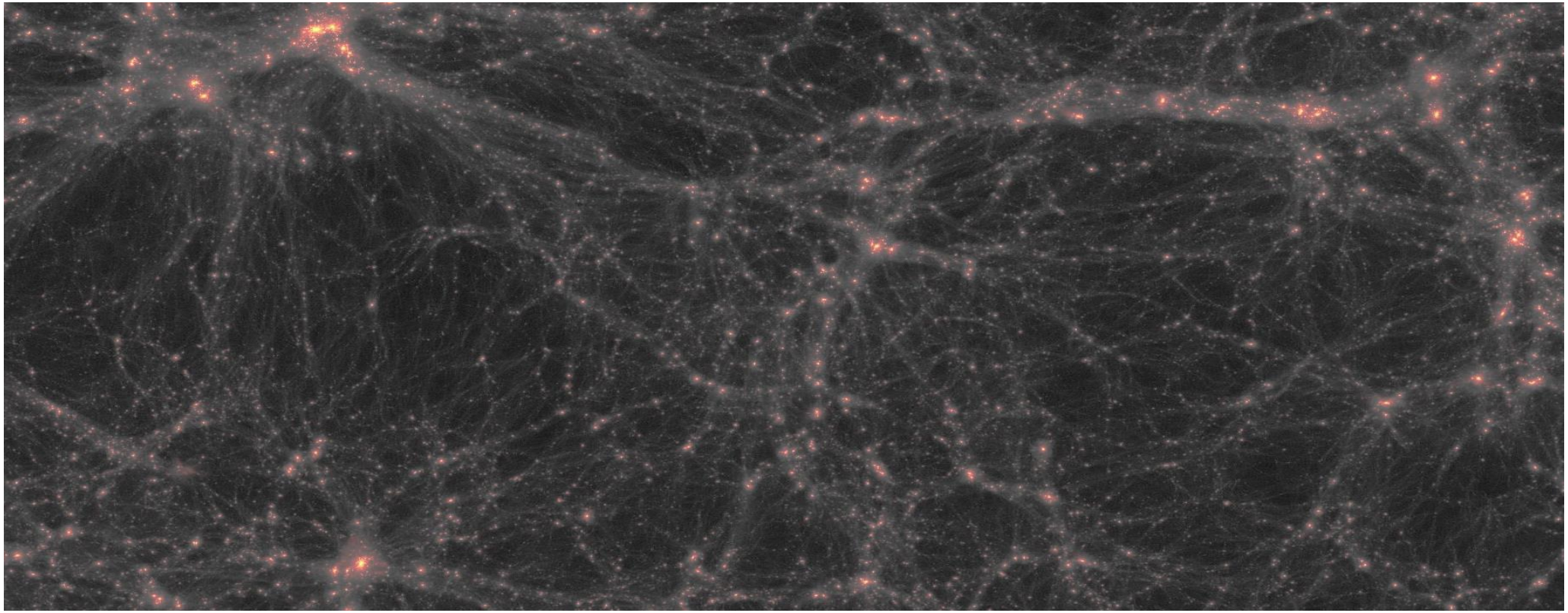


What we don't understand very well

Clustering of galaxies	Galaxy-DM connection
Cluster number counts	Mass-Observable relation
Cosmic shear	Baryonic feedback / Intrinsic alignments
CMB	Small-scale astrophysical foregrounds



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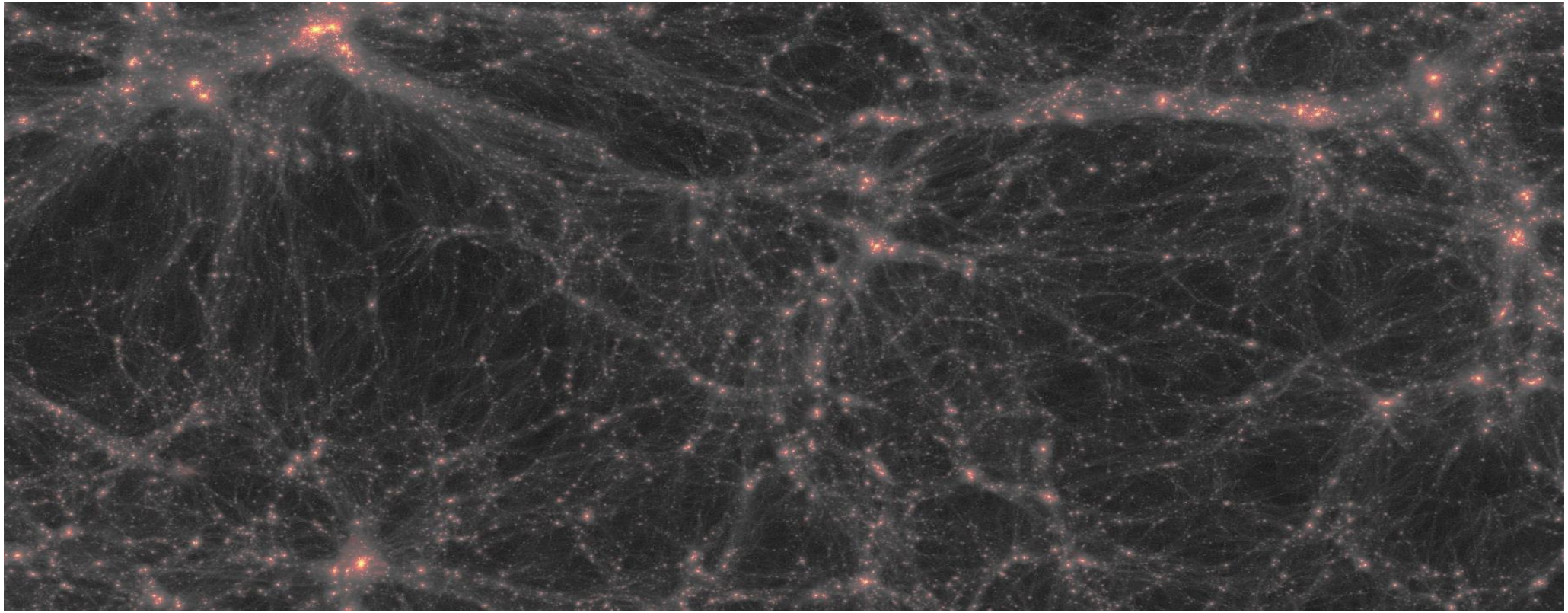
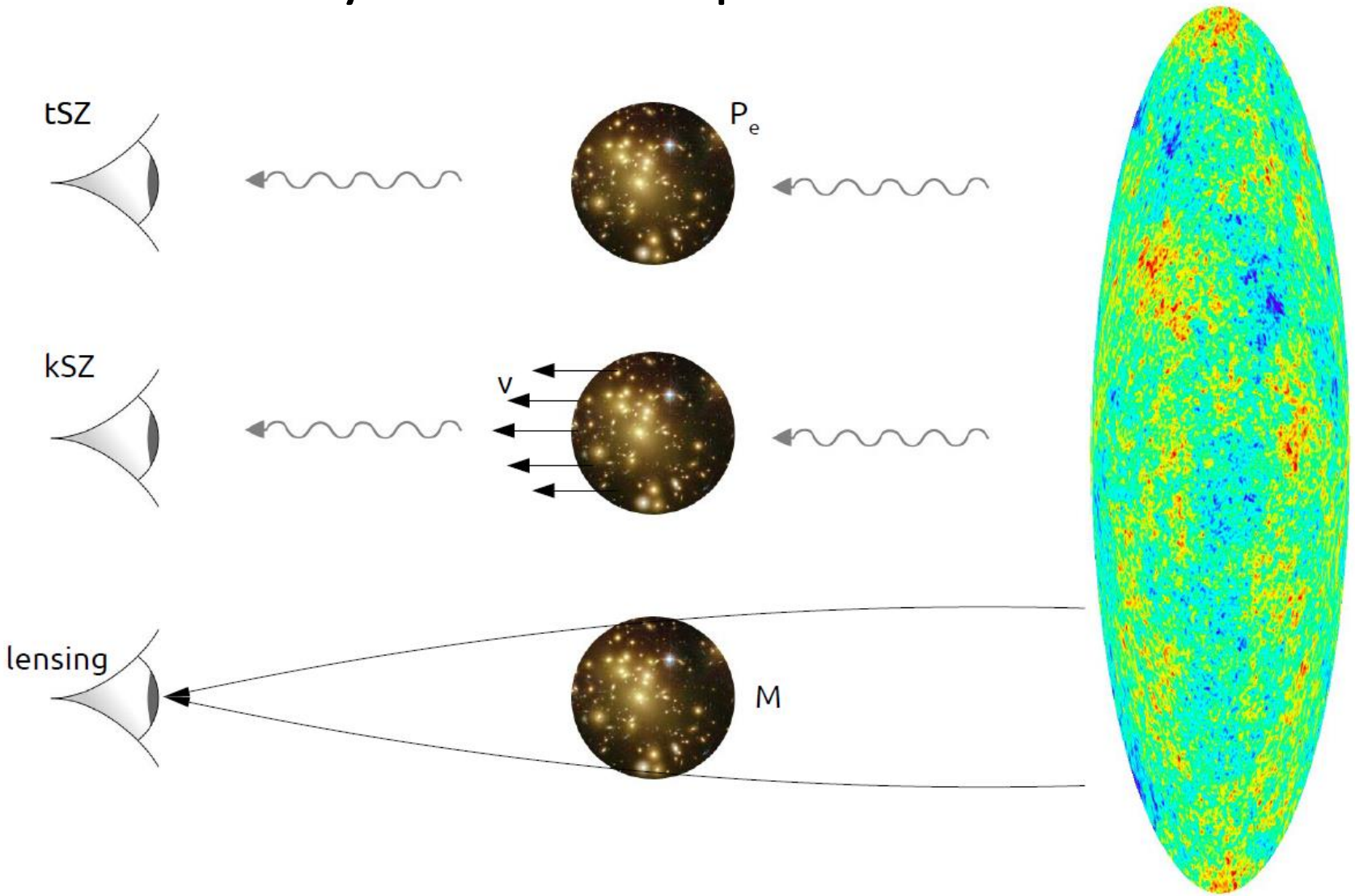


Secondary anisotropies of the CMB



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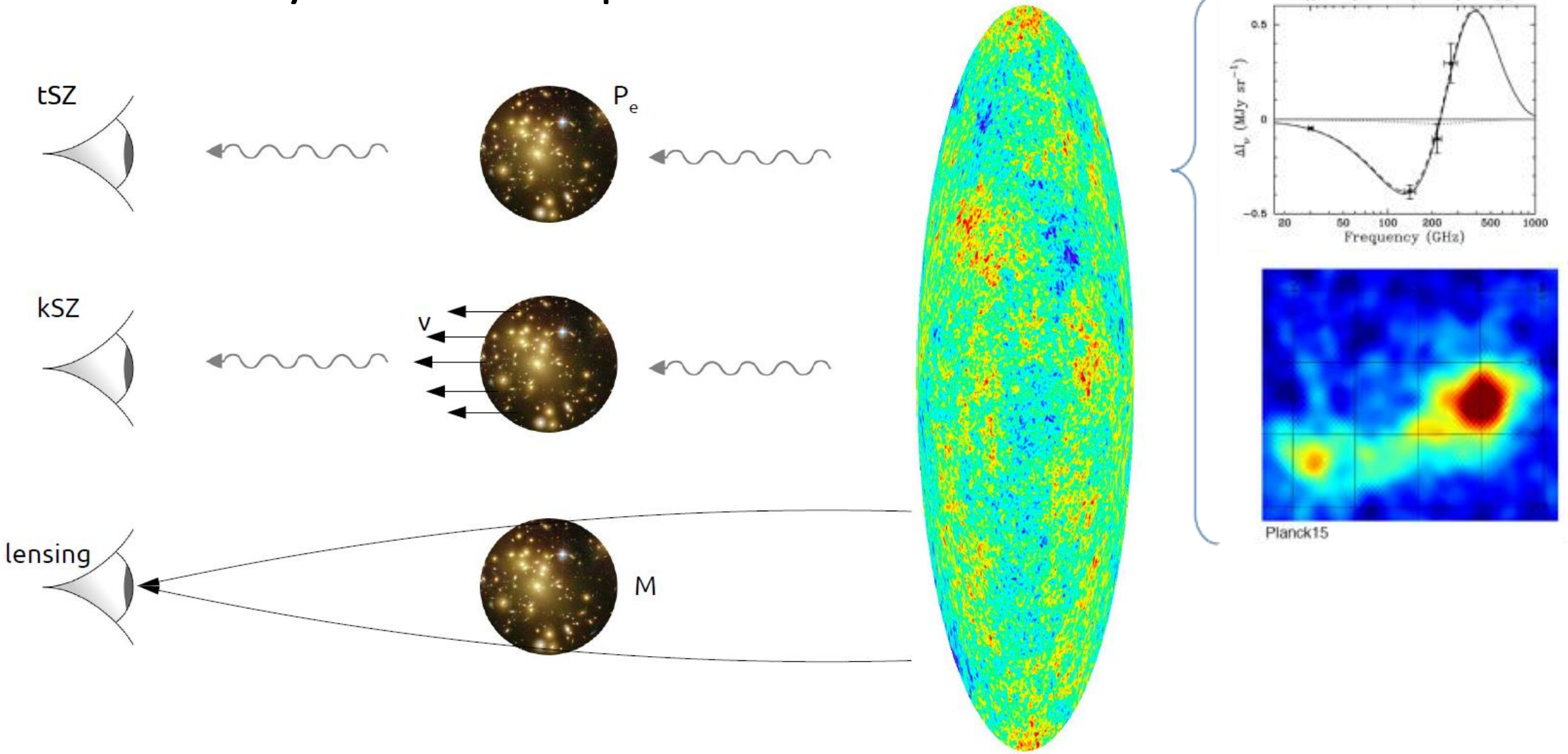

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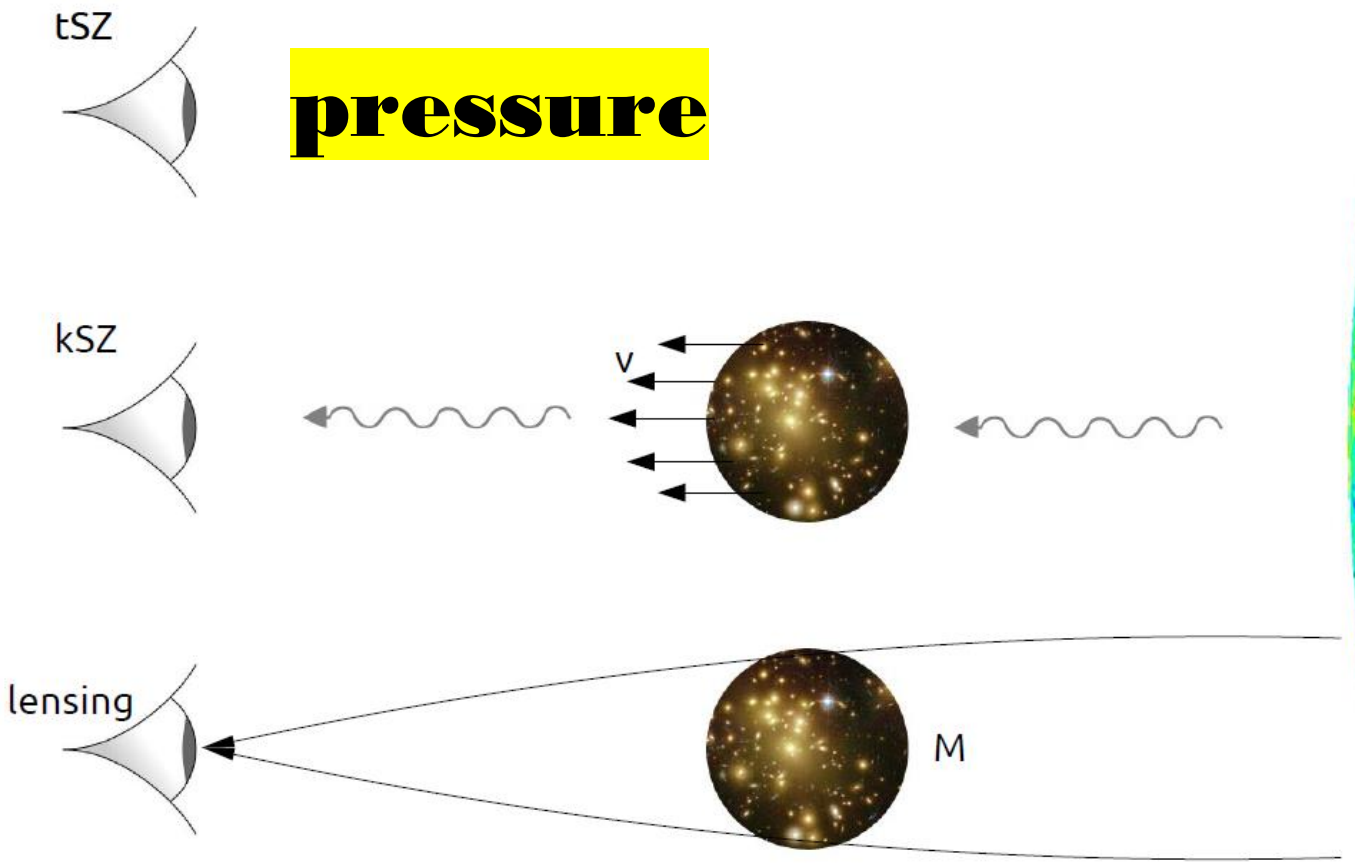
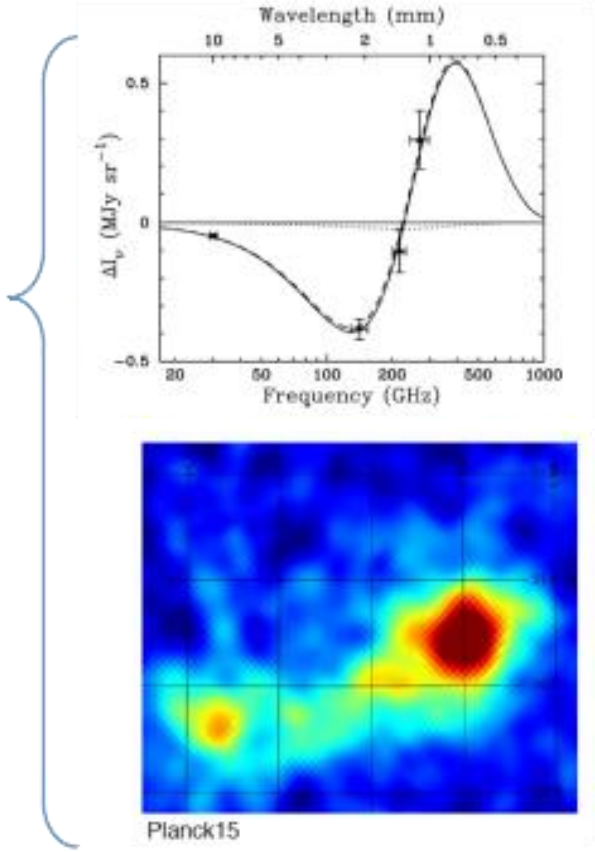
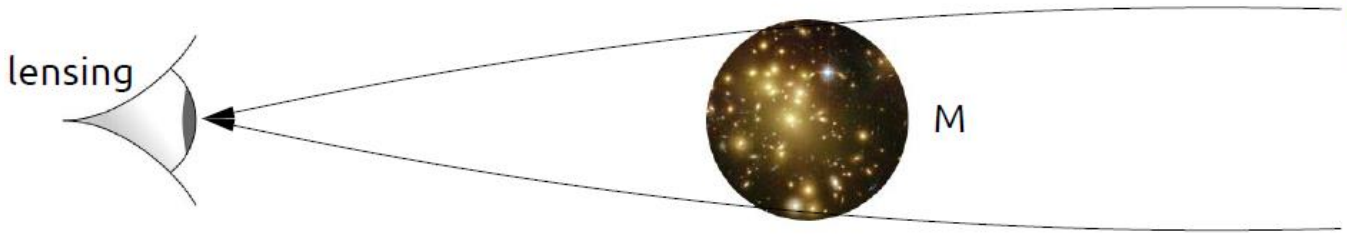


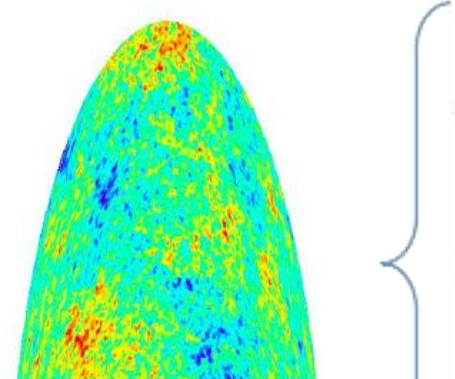


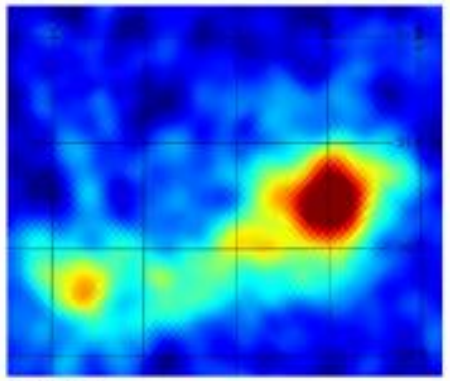
Secondary anisotropies of the CMB

pressure

gas density







Secondary anisotropies of the CMB

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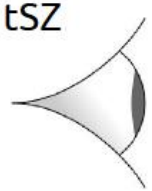
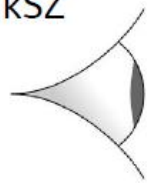


pressure

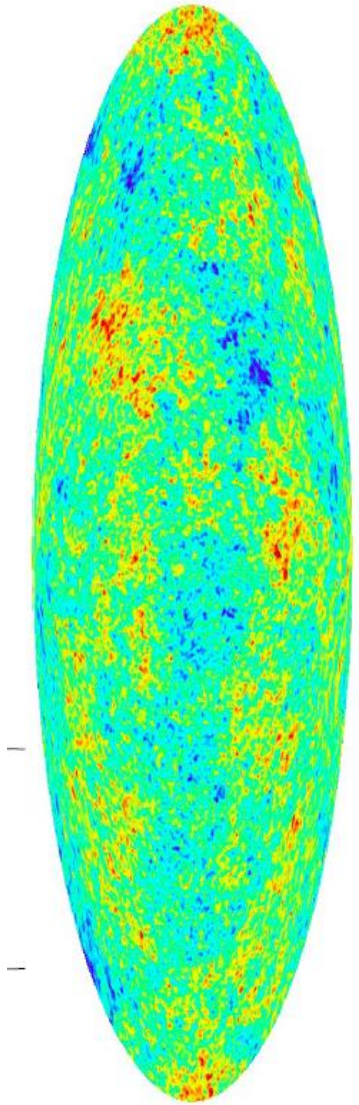
kSZ

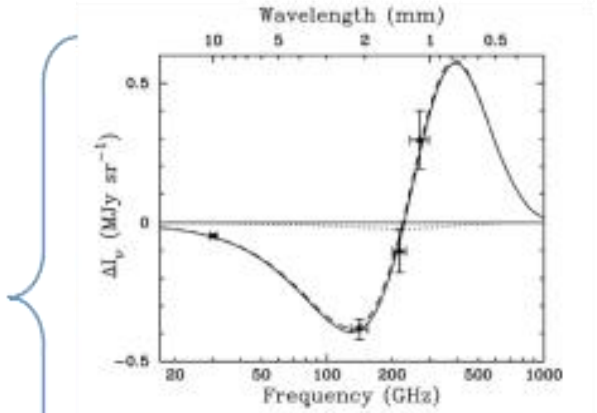


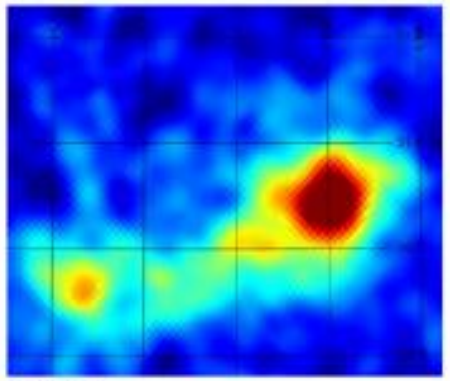
gas density

lensing

matter density







Planck15

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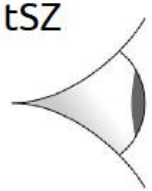
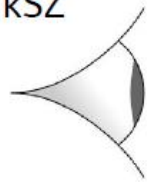


$$\left.\frac{\Delta T}{T}\right|_{tSZ}(\nu,\hat{\mathbf{n}}) = f_{tSZ}(\nu)\frac{\sigma_T}{m_e c^2}\int P_e(l_z,\hat{\mathbf{n}})\,dl_z$$
$$\equiv f_{tSZ}(\nu)\,y(\hat{\mathbf{n}})$$

kSZ



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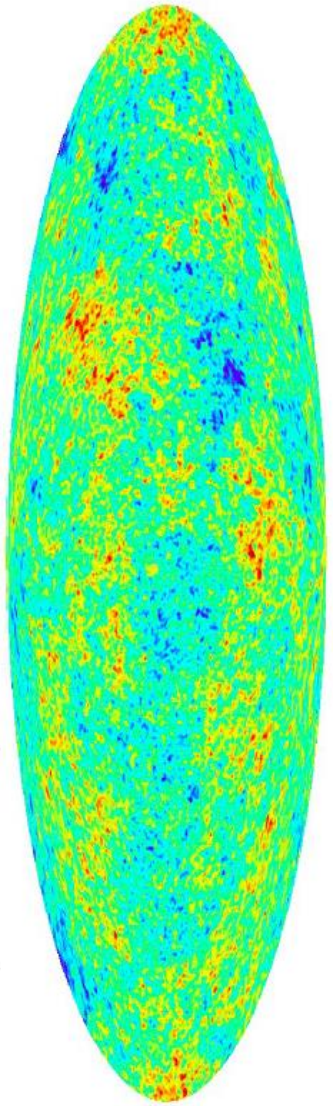
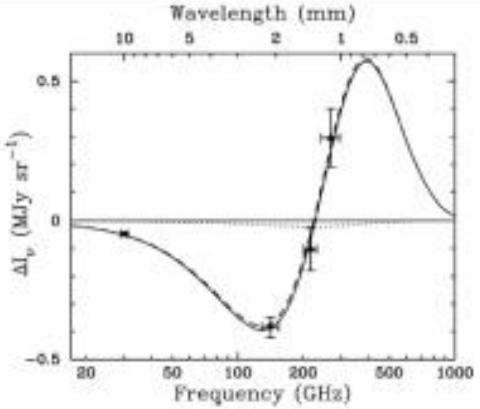
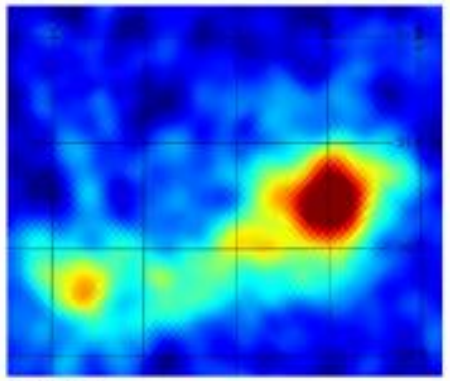
$$\equiv -\beta_r\,\tau(\hat{\mathbf{n}}),$$

lensing

$$\kappa(\boldsymbol{x}) = \Sigma(\boldsymbol{x})/\Sigma_{crit}$$
$$\Sigma(\boldsymbol{x}) \equiv \int_{-\infty}^{\infty} dl\,\rho(l,\boldsymbol{x}),\quad \Sigma_{crit} \equiv \frac{c^2 d_S}{4\pi G\,d_L\,d_{LS}}$$







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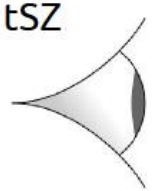

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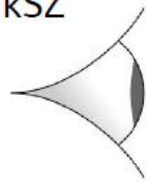

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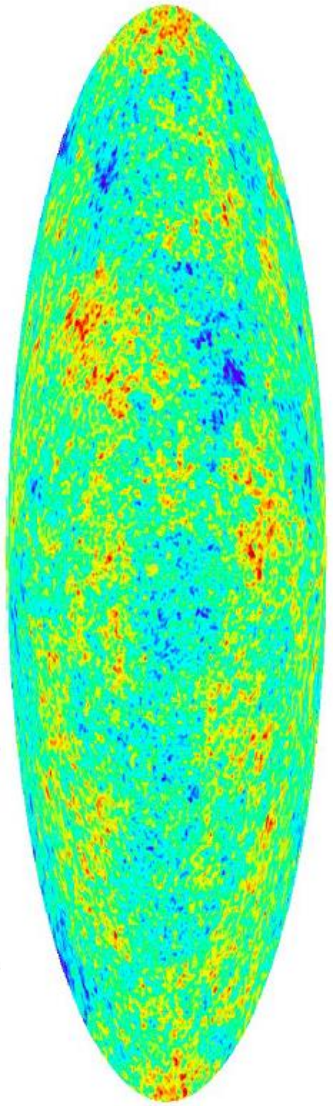

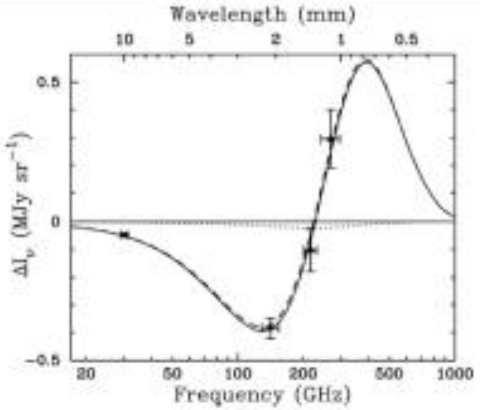

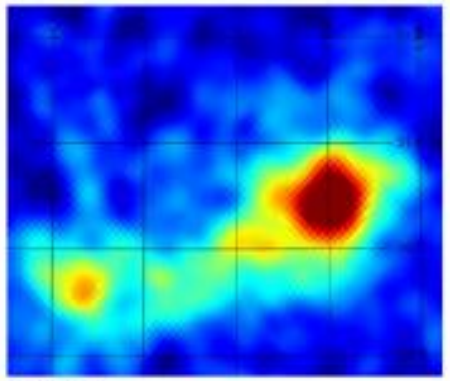

Planck15

thermal Sunyaev Zel'dovich (tSZ)

$$y(\hat{\boldsymbol{\theta}}) = \frac{\sigma_T}{m_e c^2} \int \frac{d\chi}{1+z} P_e(\chi \hat{\boldsymbol{\theta}})$$

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Measure gas pressure → Link to mass → Measure mass of many clusters → Cosmological mass function → Infer cosmology

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- ✔ Good mass proxy

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$$E^{-\beta}(z)\left[\frac{D_A^2(z)\bar{Y}_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = Y_*\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{(1-b)M_{500}}{6\times10^{14}\,\mathrm{M}_\odot}\right]^{\alpha}$$

Planck Coll et al. 1502.01596

✗ Calibrate *y-M* relation
✗ *hydrostatic mass bias*

What have we done?

$$y(\hat{\boldsymbol{\theta}}) = \frac{\sigma_T}{m_e c^2} \int \frac{d\chi}{1+z} P_e(\chi \hat{\boldsymbol{\theta}})$$

✔ Cross-correlations of **galaxy clustering** with **tSZ** from Planck

What have we done?

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$$\delta_g(\hat{\boldsymbol{\theta}}) = \int \delta z \, \varphi_g(z) \, \Delta_g(\chi(z), \hat{\boldsymbol{\theta}})$$

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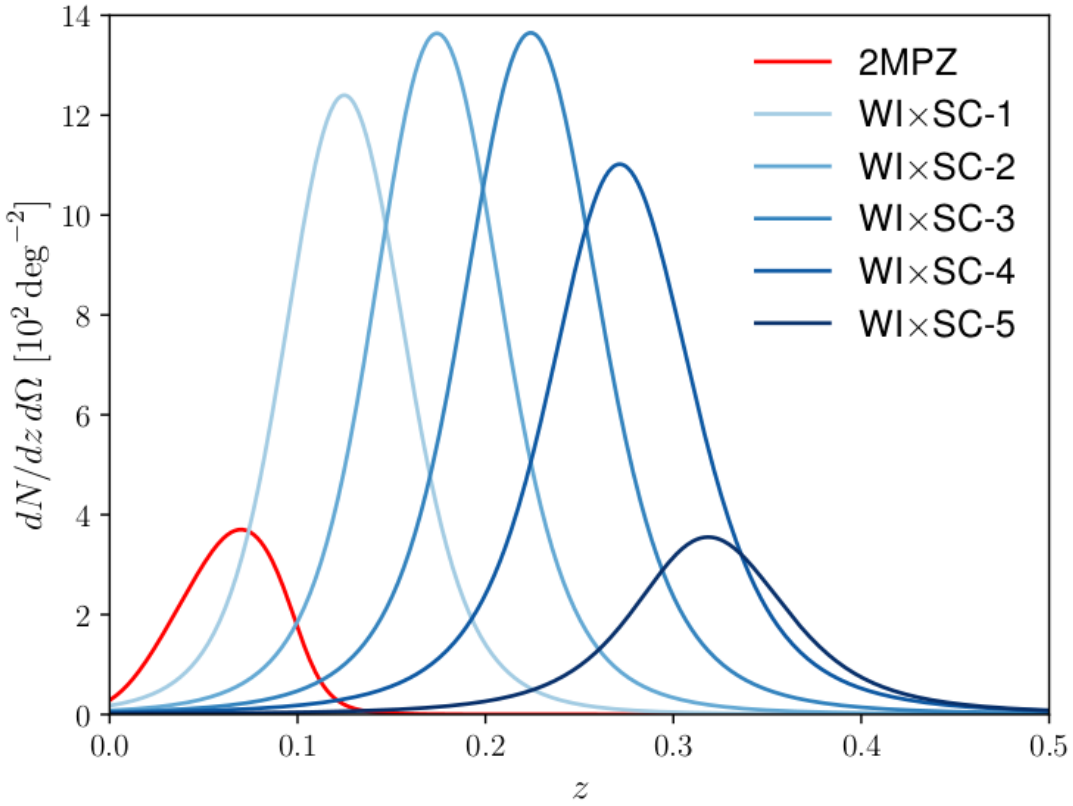
- ✔ Cross-correlations of **galaxy clustering** with **tSZ** from Planck
- ✔ 20 million galaxies – split them in **redshift bins** to measure **evolution**



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Number Distribution

Halo Occupation Distribution

Berlind & Weinberg 2002, Zheng et al. 2005, van den Bosch et al. 2013

Density Profile

NFW Profile

Navarro, Frenk, White 1996

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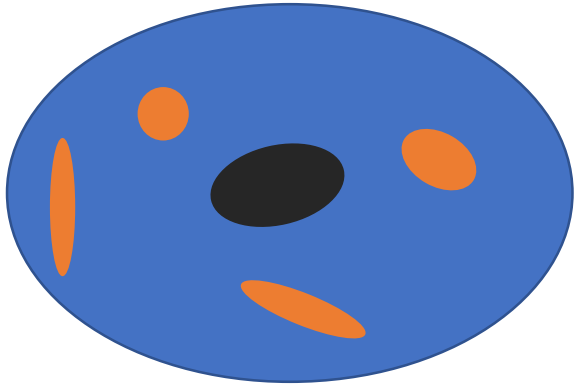

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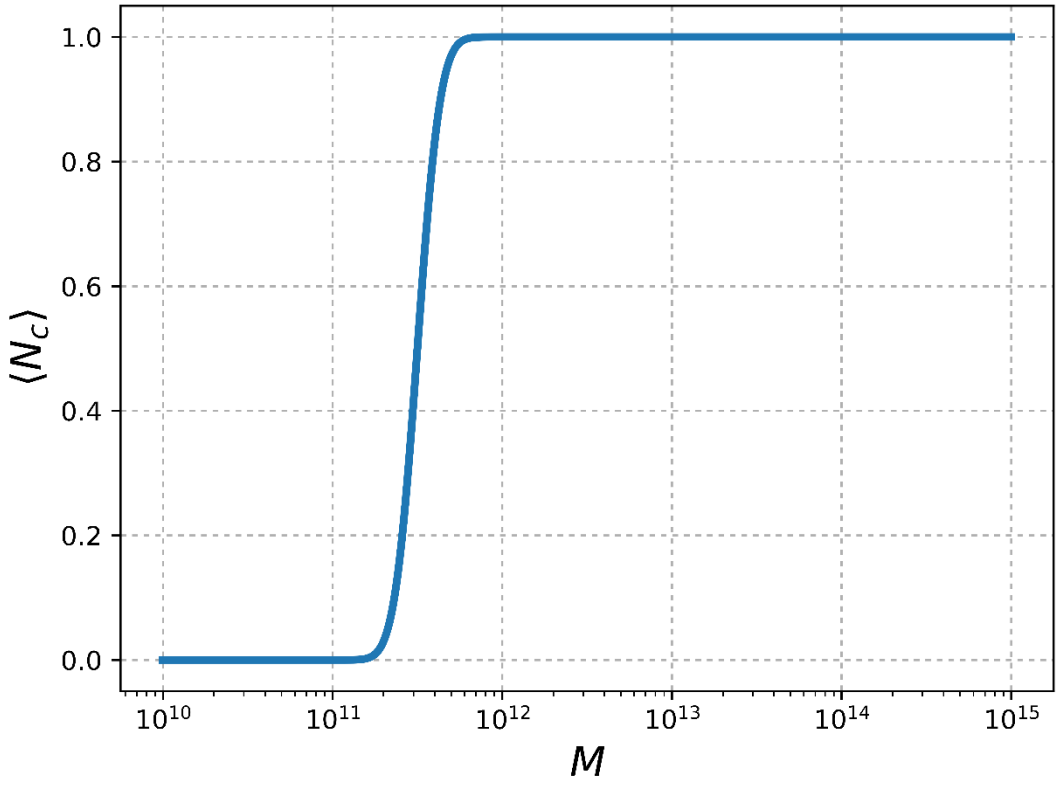

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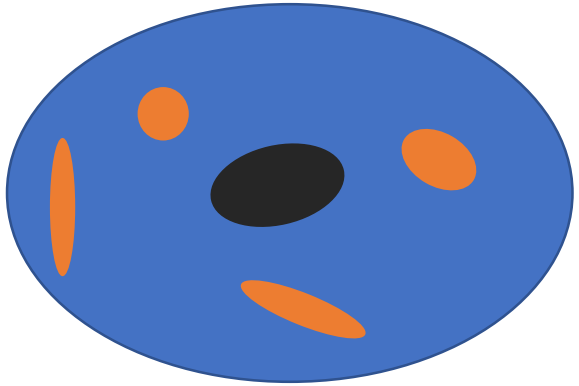

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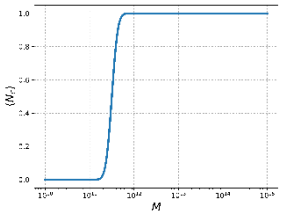

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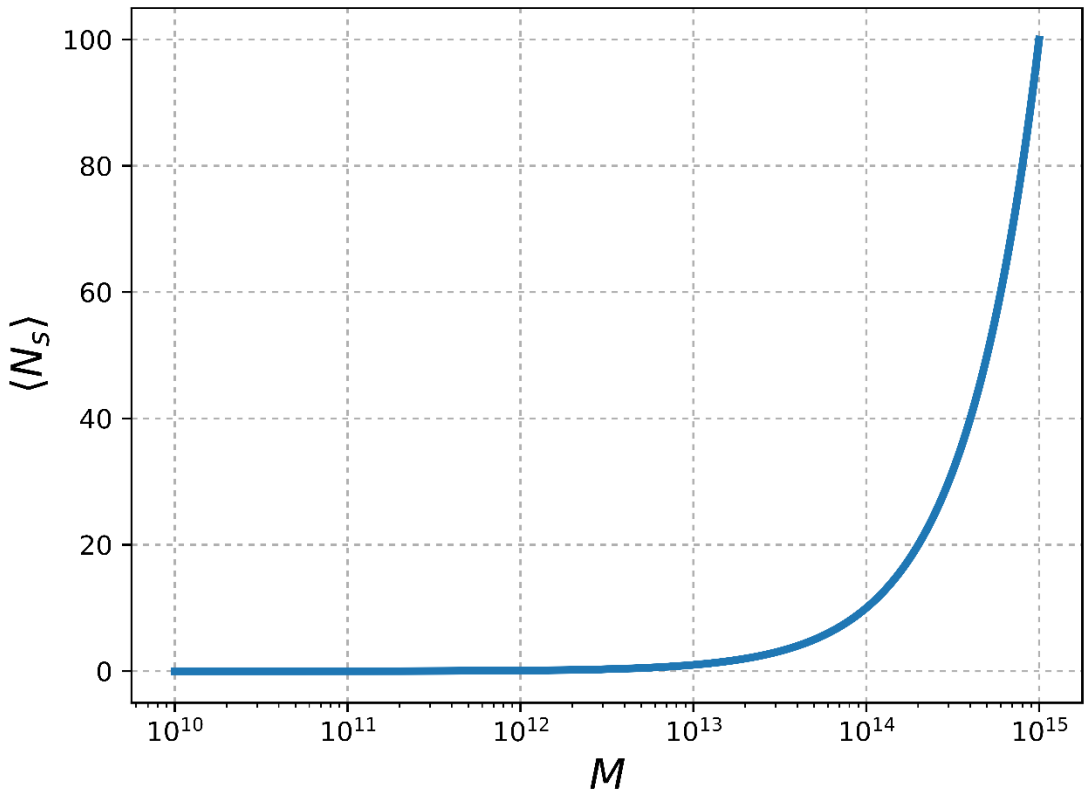

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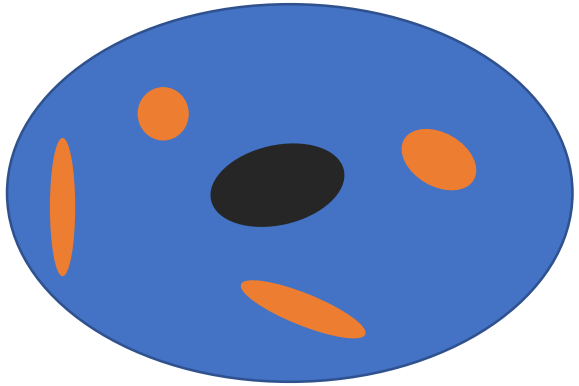

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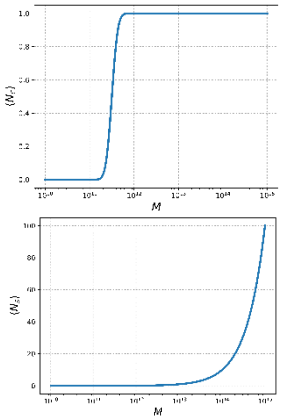

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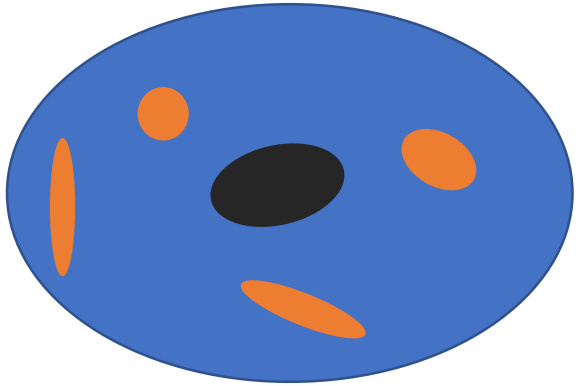

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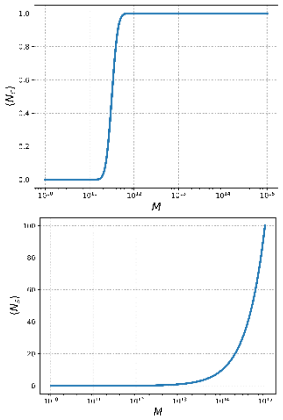

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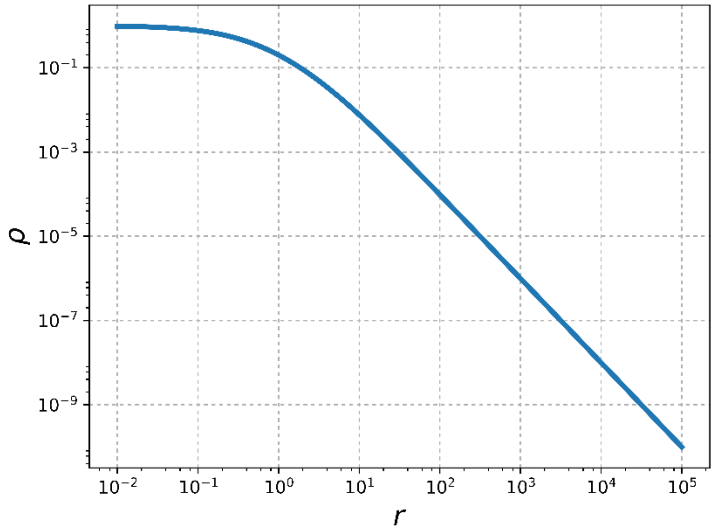
Navarro, Frenk, White 1996

$$\rho_r = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$



tSZ

$$y(\hat{\boldsymbol{\theta}}) = \frac{\sigma_T}{m_e c^2} \int \frac{d\chi}{1+z} P_e(\chi \hat{\boldsymbol{\theta}})$$

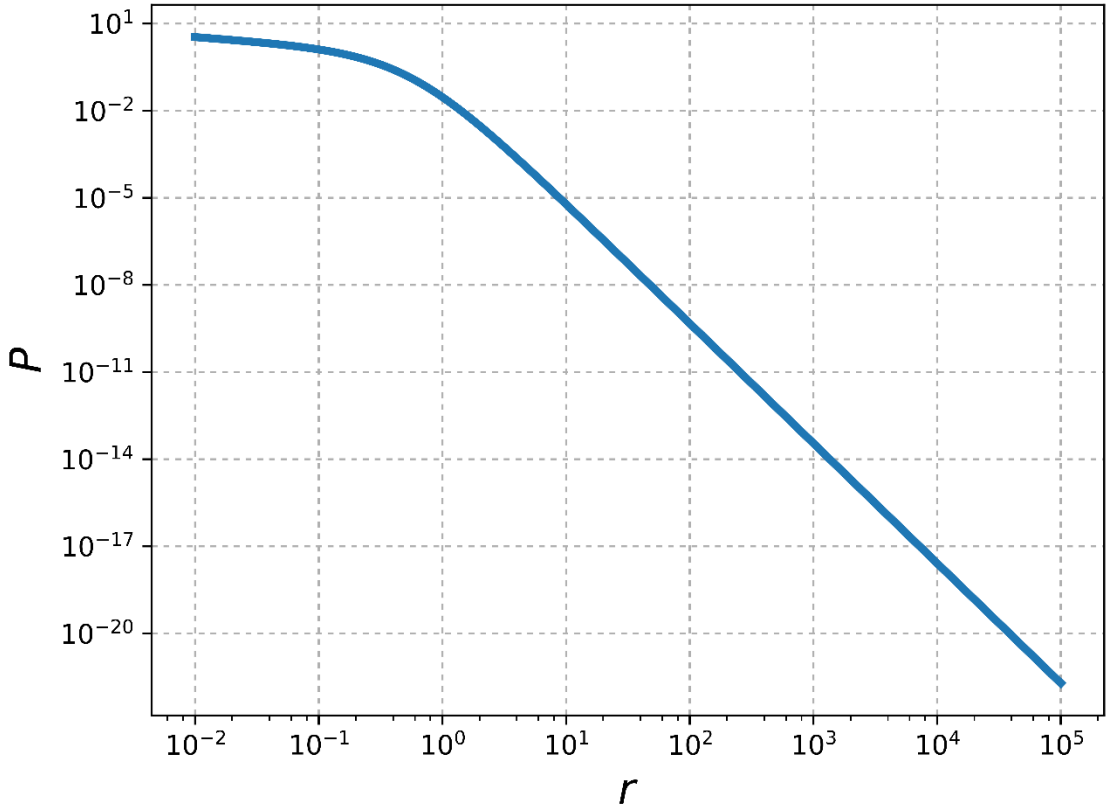
Pressure Profile

generalised NFW Profile

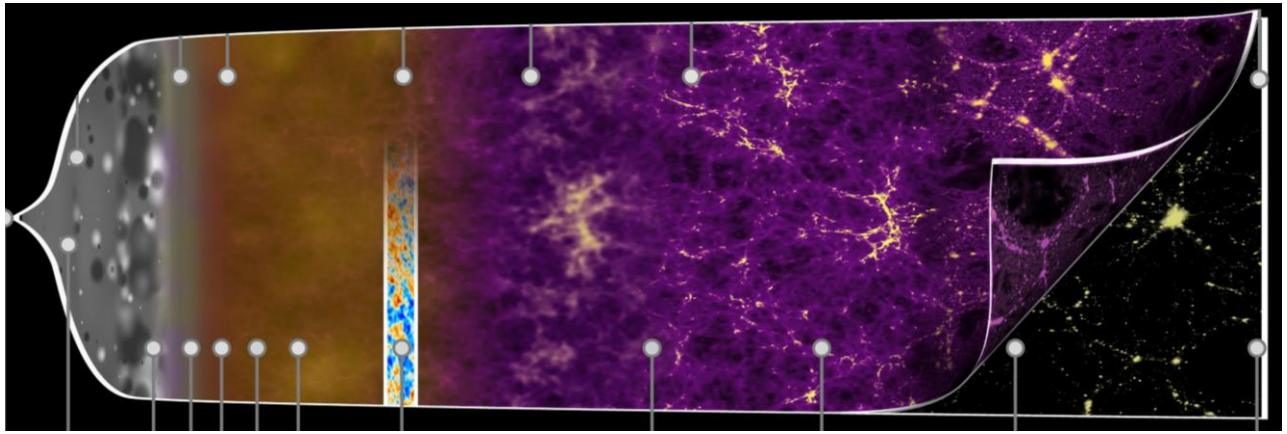
Arnaud et al. 2010, Planck Collaboration et al. 2016

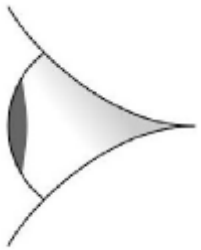
$$P_e(r) = P_* \, p(r/r_{500c})$$

$$\begin{cases} P_* = 6.41 \, (1.65 \text{ eV cm}^{-3}) \, h_{70}^{8/3} \left(\dfrac{h_{70}(1-b_H) M_{500c}}{3 \times 10^{14} \text{ M}_\odot} \right)^{0.79} \\ p(x) = (c_P x)^{-\gamma} (1 + (c_P x)^{\alpha})^{(\gamma-\beta)/\alpha} \end{cases}$$



3D → 2D





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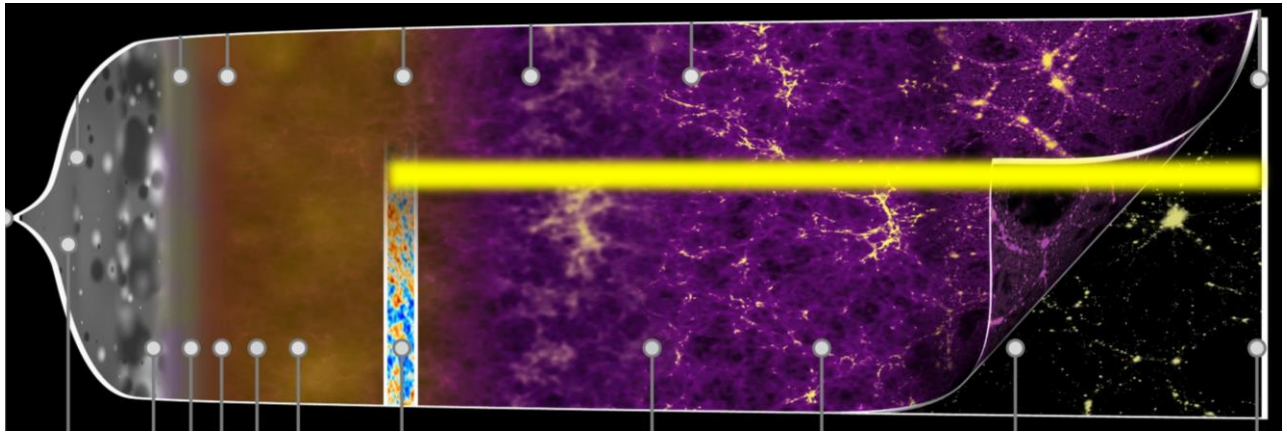

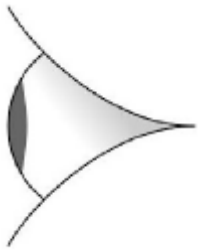

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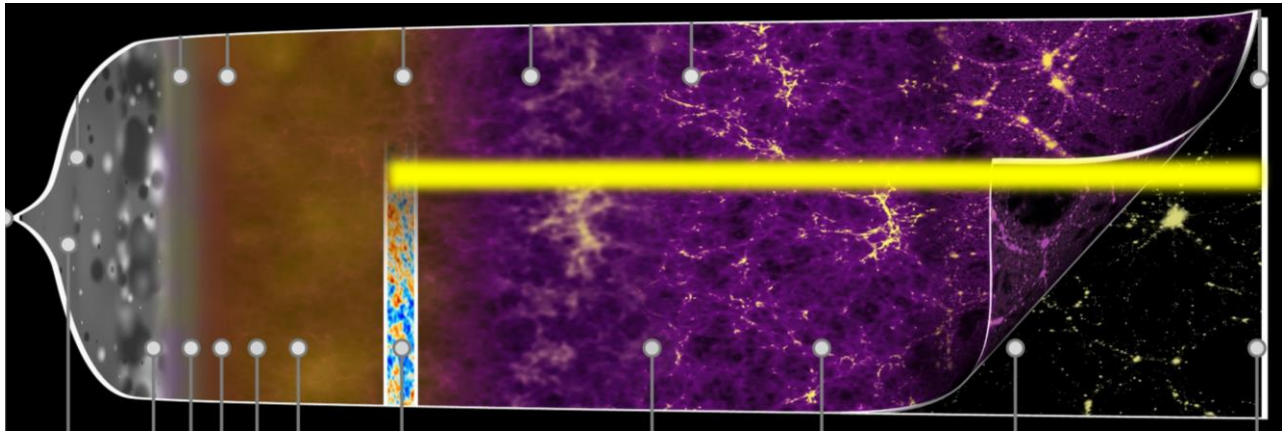
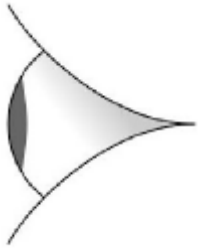
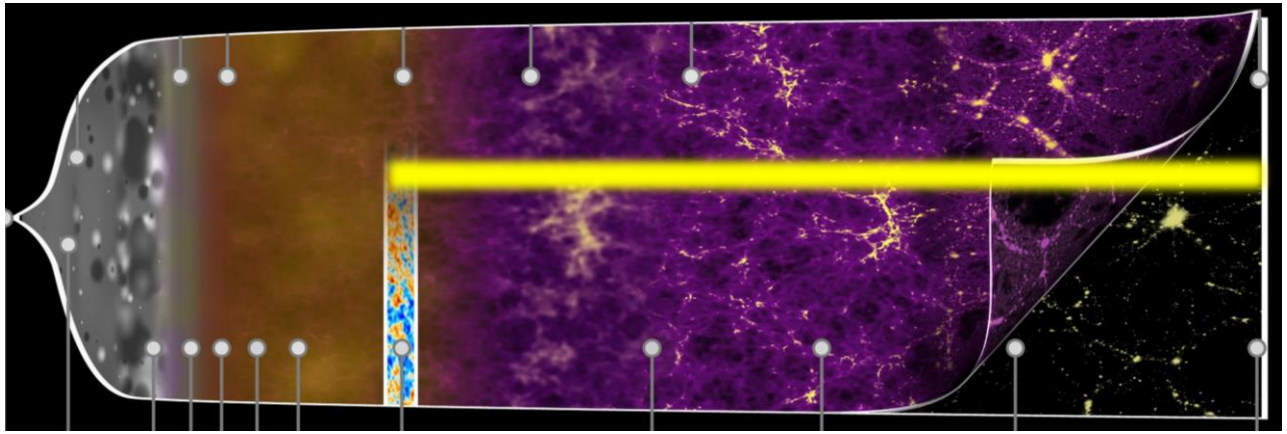
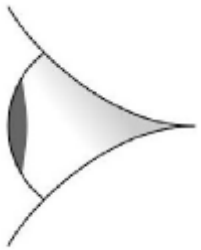




$$u(\hat{\boldsymbol{\theta}}) = \int d\chi \, W_u \, U(\chi\hat{\boldsymbol{\theta}})$$

3D → 2D





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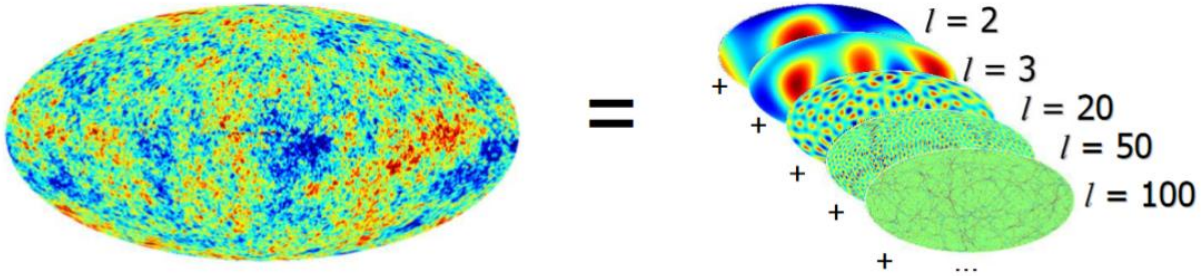

$$C_l^{uv} = \int d\chi \frac{W_u \, W_v}{\chi^2} \, \mathrm{P}_{UV}(k, z)$$

The Halo Model

$$C_l^{uv} = \int d\chi \frac{W_u\, W_v}{\chi^2}\, \mathrm{P}_{UV}(k, z)$$

The Halo Model

$$P_{UV}(k) = P_{UV}^{1h}(k) + P_{UV}^{2h}(k)$$

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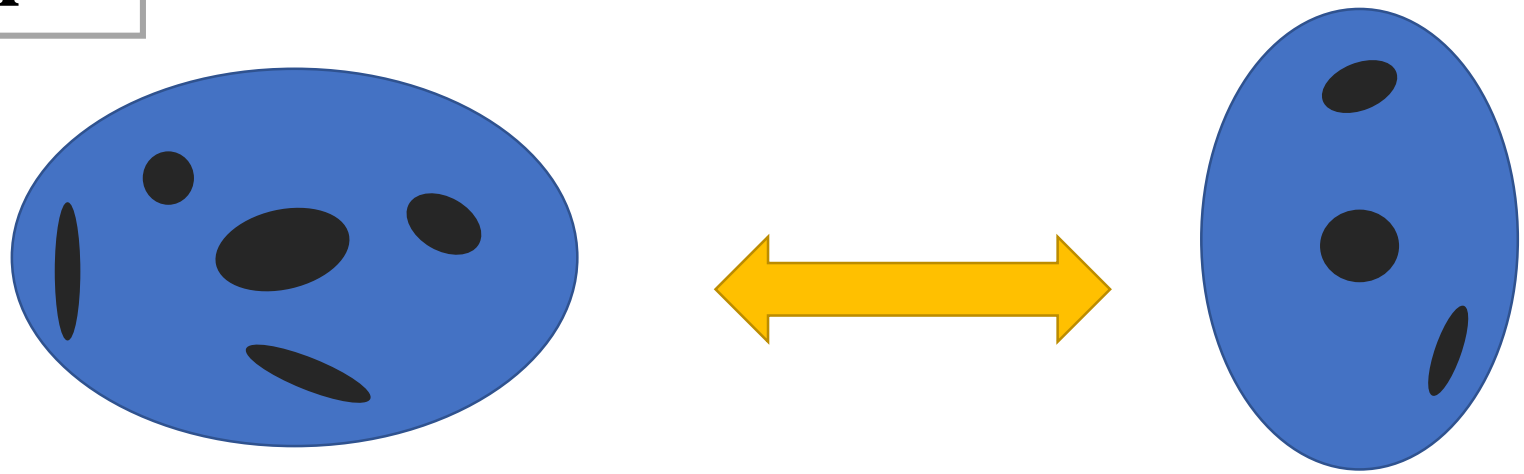
The Halo Model

$\mathbf{P}^{2h}$



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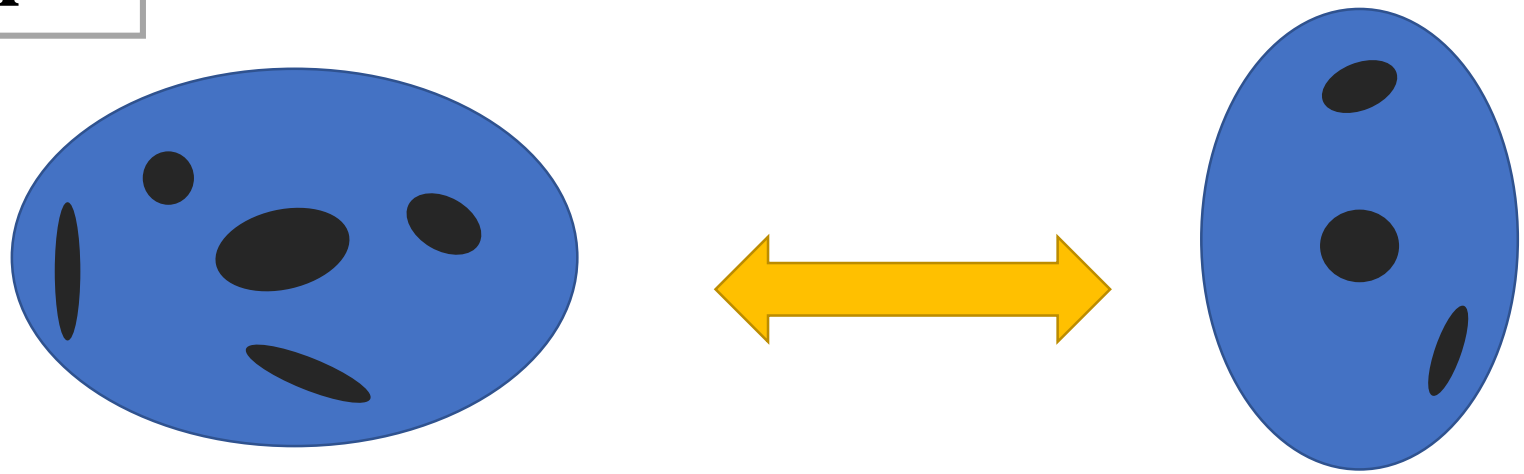
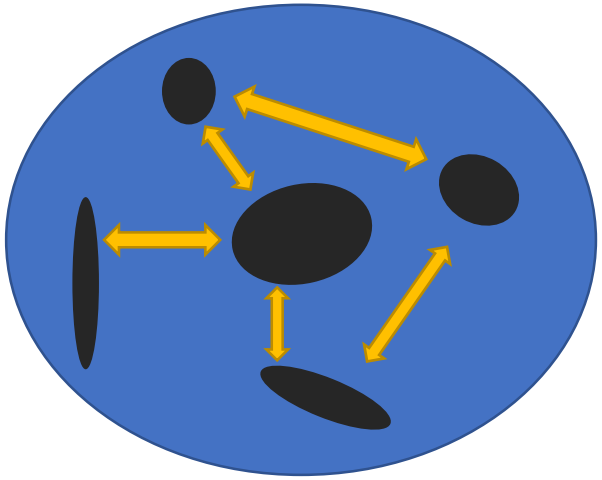


$\mathbf{P}^{1h}$



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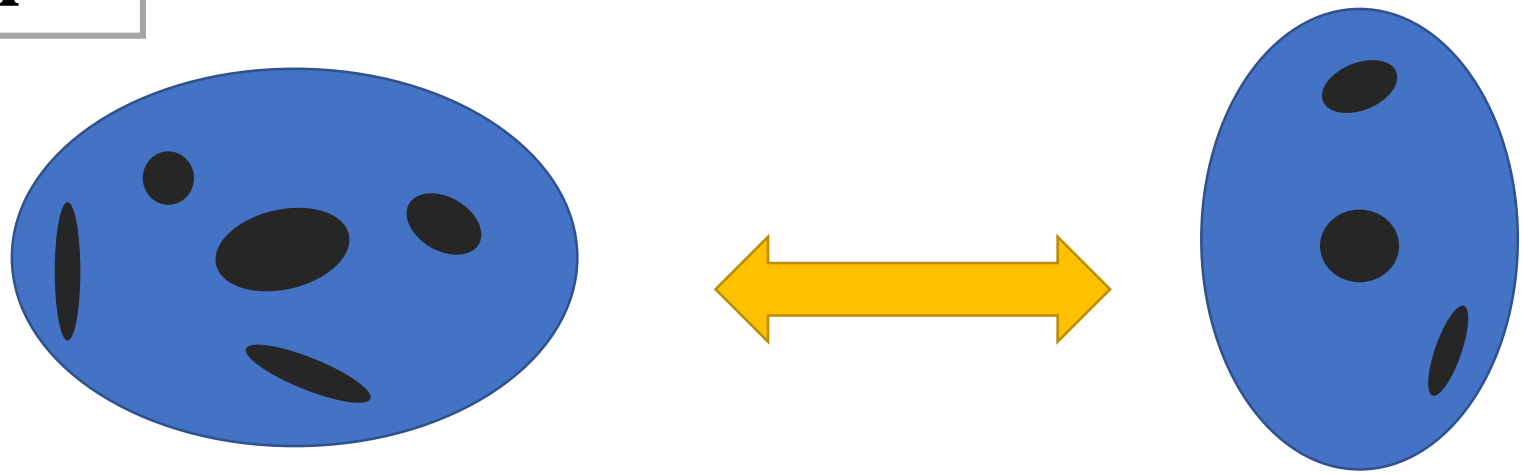

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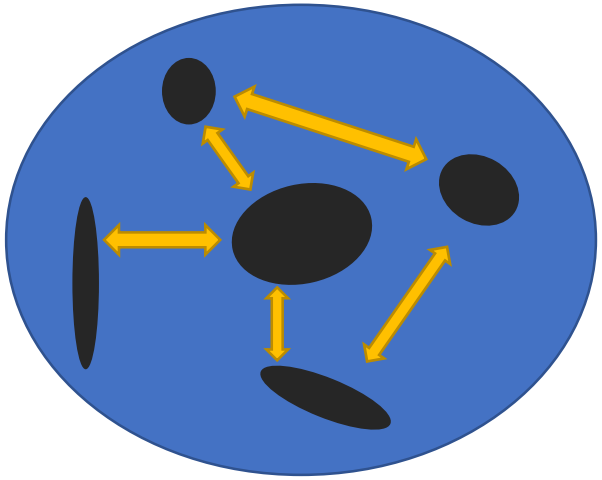

$$P_{UV}^{1h}(k) = \int dM \frac{dn}{dM} \langle U(k|M)\, V(k|M) \rangle$$

$$P_{UV}^{2h}(k) = \langle b_U \rangle \langle b_V \rangle P_L(k)$$

$$\langle b_U \rangle = \int dM \frac{dn}{dM}\, b_h(M)\, \langle U(k|M) \rangle$$

$$P_{UV}(k) = P_{UV}^{1h}(k) + P_{UV}^{2h}(k)$$

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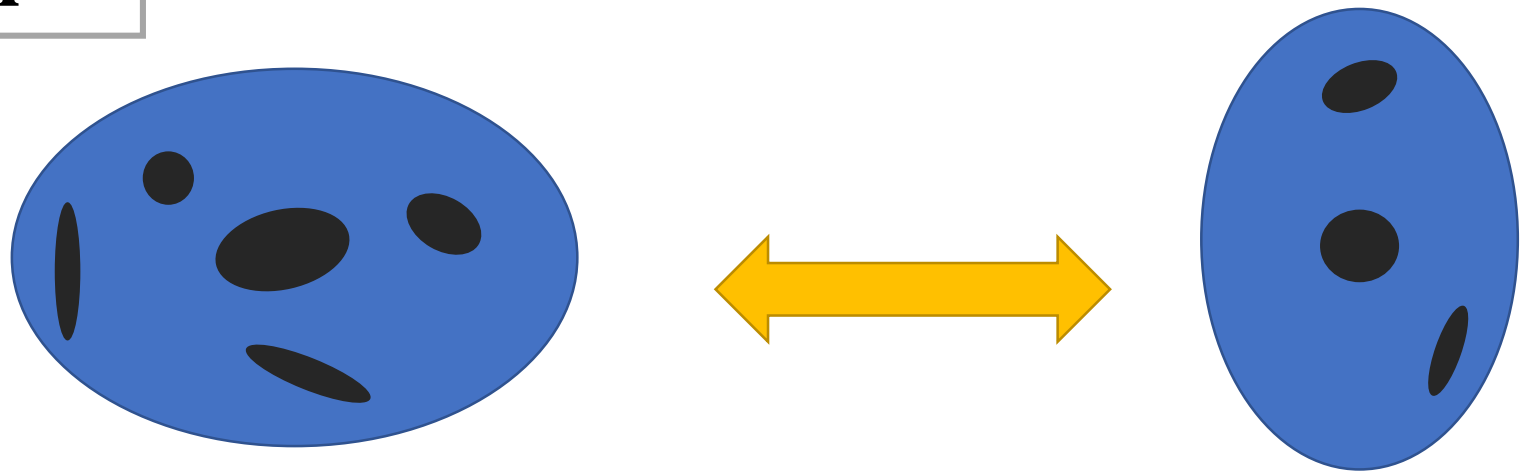

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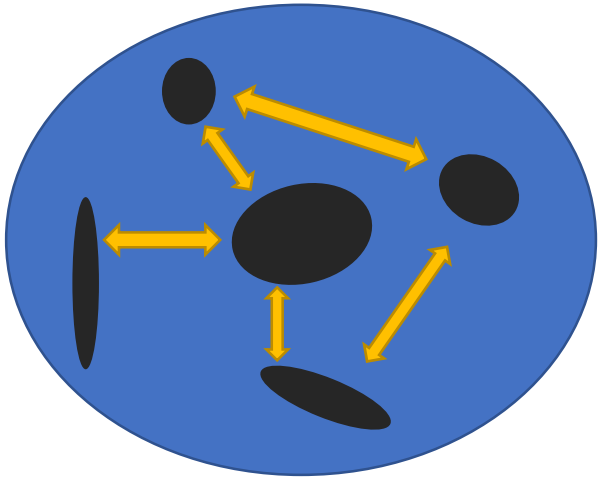

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$$\langle b_{P_e} \rangle = \int dM \frac{dn}{dM}\, b_h(M)\, E_T(M)$$

Corrections

Corrections

Halo transition regime	

Corrections

Halo transition regime	Calibrate from Simulations Takahashi et al. 2012

$$R(k) \equiv \frac{P_{\text{Halofit}}(k)}{P_{\text{halo model}}(k)}$$

Corrections

Halo transition regime	Calibrate from Simulations Takahashi et al. 2012
Star contamination	

$$R(k) \equiv \frac{P_{\text{Halofit}}(k)}{P_{\text{halo model}}(k)}$$

Corrections

Halo transition regime	Calibrate from Simulations Takahashi et al. 2012
Star contamination	Mask, Smooth scale dependence Peacock & Bilicki 2018

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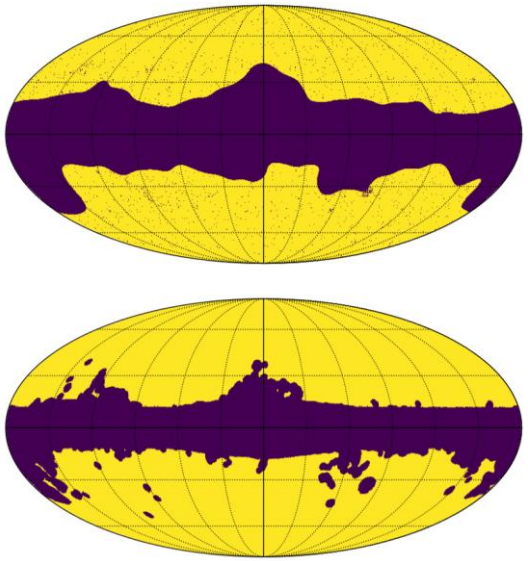

Corrections

Halo transition regime	Calibrate from Simulations Takahashi et al. 2012
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Residual star contamination	

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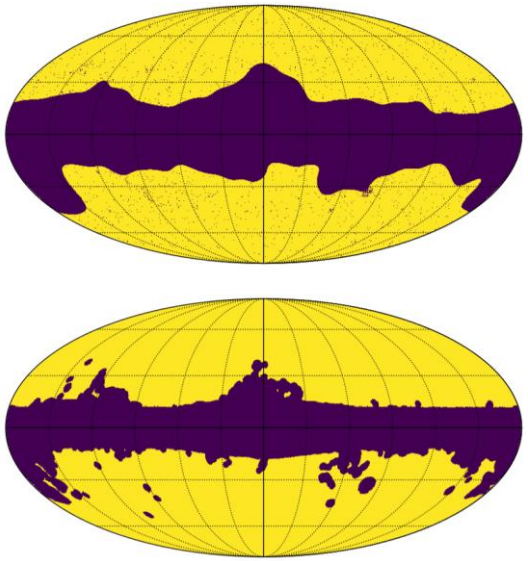

Corrections

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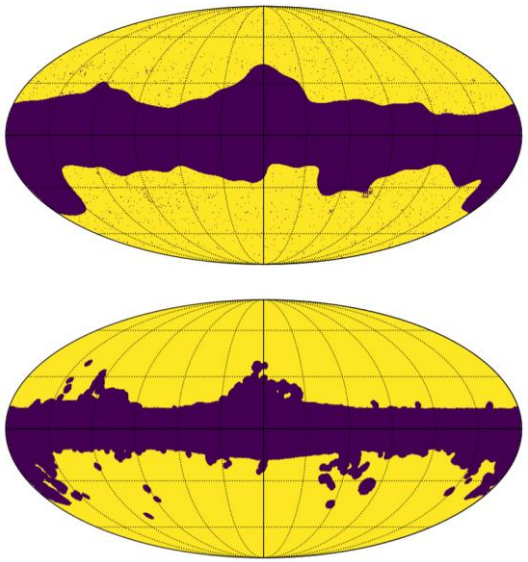

$$\boldsymbol{m}_{\text{obs}} = \boldsymbol{m}_{\text{true}} + \epsilon \boldsymbol{t}$$

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Residual star contamination	Deproject star map Elsner et al. 2017 Alonso et al. 2019
Reddening	

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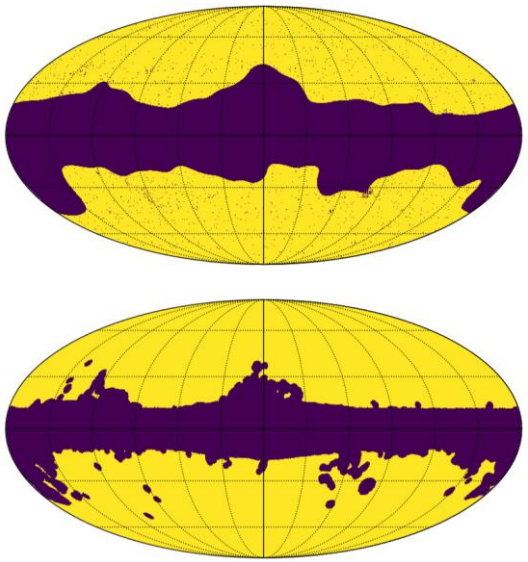

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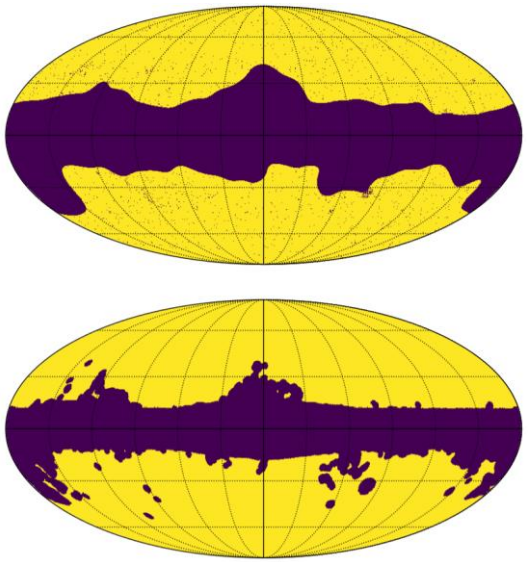

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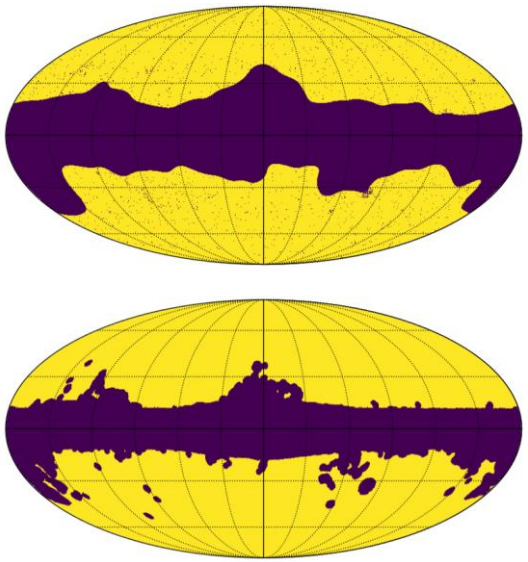
Modulation on photographic plates	

$$R(k) \equiv \frac{P_{\text{Halofit}}(k)}{P_{\text{halo model}}(k)}$$



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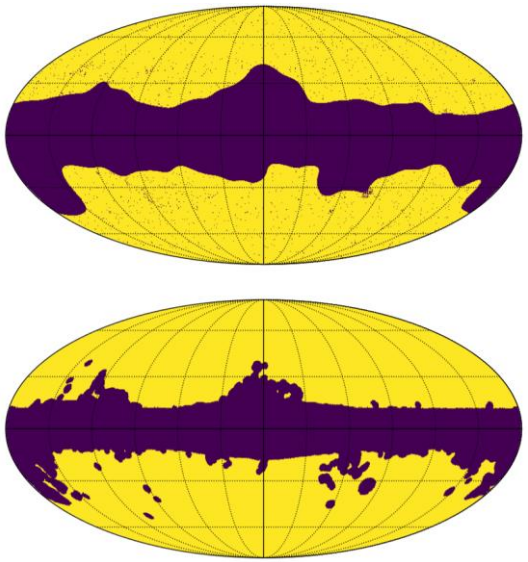
Modulation on photographic plates	Model on power spectrum

$$R(k) \equiv \frac{P_{\text{Halofit}}(k)}{P_{\text{halo model}}(k)}$$



$$\mathrm{C}_{\ell}^{\text{plate}} = \sigma_{\text{plate}}^{2}\, S_{\text{plate}} \exp\left[\left(-\ell\theta_{\text{plate}}\right)^{2}/12\right]$$

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Modulation on photographic plates	Model on power spectrum
Theoretical limitations	

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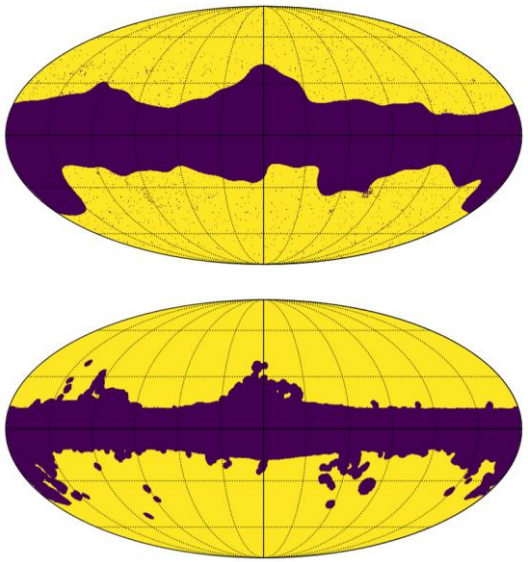

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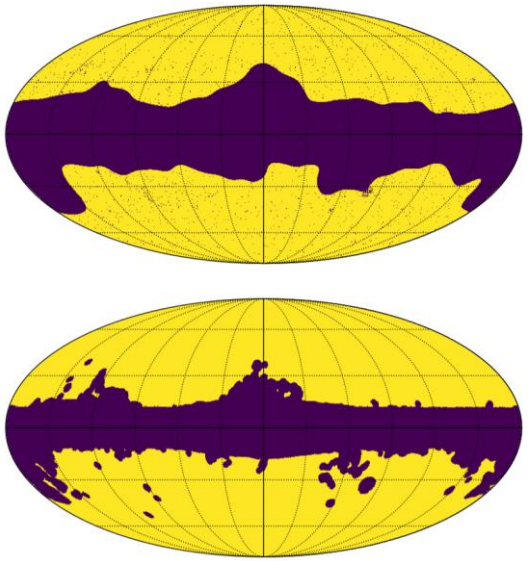
Reddening	Deproject dust map Elsner et al. 2017 Alonso et al. 2019
Modulation on photographic plates	Model on power spectrum
Theoretical limitations	Scale cuts Xavier et al. 2018

$$R(k) \equiv \frac{P_{\text{Halofit}}(k)}{P_{\text{halo model}}(k)}$$



$$\ell_{\min} = 10$$

$$\ell_{\max} = \bar{\chi} k_{\max} - {}^{1}/_{2}$$
$$k_{\max} = 1\ \text{Mpc}^{-1}$$

$$\mathrm{C}_{\ell}^{\text{plate}} = \sigma_{\text{plate}}^{2}\, S_{\text{plate}} \exp\left[\left(-\ell\theta_{\text{plate}}\right)^{2}/12\right]$$

$$\boldsymbol{m}_{\text{obs}} = \boldsymbol{m}_{\text{true}} + \epsilon \boldsymbol{t}$$

Fit parameters

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HOD parameters

$$\langle N_c(M)\rangle = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log(M/M_{\mathrm{min}})}{\sigma_{\ln M}}\right)\right]$$

$$\langle N_s(M)\rangle = \Theta(\mathrm{M} - \mathrm{M}_0)\left(\frac{\mathrm{M} - \mathrm{M}_0}{\mathrm{M}_1'}\right)^{\alpha_s}$$

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$$M_{\mathrm{min}} = M_0$$

$$10 \leq \log\frac{M_{\mathrm{min}}}{M_\odot} \leq 16$$

$$10 \leq \log\frac{M_1'}{M_\odot} \leq 16$$

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Mass bias

$$P_e(r) = P_*\, p(r/r_{500c})$$

$$P_* = 6.41\ (1.65\ \mathrm{eV\ cm^{-3}})\ h_{70}^{8/3}\left(\frac{h_{70}(1-b_H)M_{500c}}{3\times 10^{14}\ \mathrm{M}_\odot}\right)^{0.79}$$

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$$P_{UV}^{1h}(k) = \int dM\, \frac{dn}{dM}\, \langle U(k|M)\, V(k|M)\rangle$$

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$$-1 \le \rho_{yg} \le 1$$

Fit parameters

HOD parameters

$$\langle N_c(M)\rangle = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log(M/M_{\min})}{\sigma_{\ln M}}\right)\right]$$

$$\langle N_s(M)\rangle = \Theta(M - M_0)\left(\frac{M - M_0}{M_1'}\right)^{\alpha_s}$$

$$M_{\min} = M_0$$

Mass bias

$$P_e(r) = P_*\, p(r/r_{500c})$$

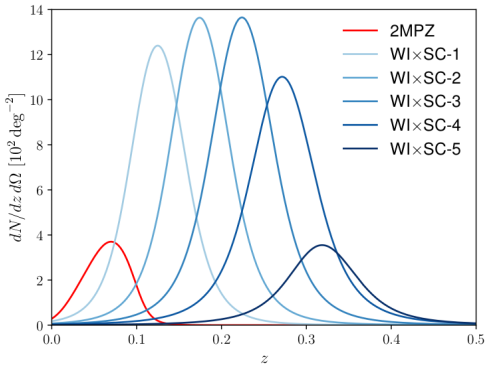
$$P_* = 6.41\ (1.65\ \mathrm{eV\ cm^{-3}})\ h_{70}^{8/3}\left(\frac{h_{70}(1-b_H)M_{500c}}{3\times 10^{14}\ \mathrm{M_\odot}}\right)^{0.79}$$

1h-covariance

$$P_{UV}^{1h}(k) = \int dM\, \frac{dn}{dM}\, \langle U(k|M)\, V(k|M)\rangle$$

$$\langle u_y(k|M)\, u_g(k|M)\rangle = (1+\rho_{yg})\langle u_g(k|M)\rangle\, \langle u_y(k|M)\rangle$$

Redshift distribution uncertainties



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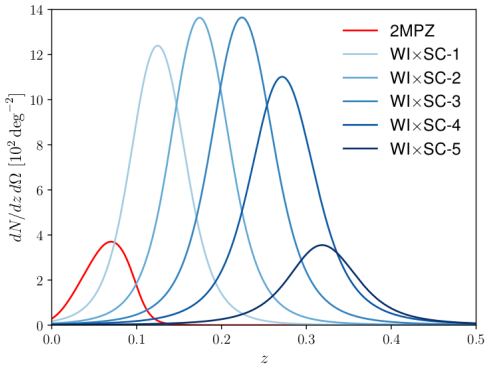

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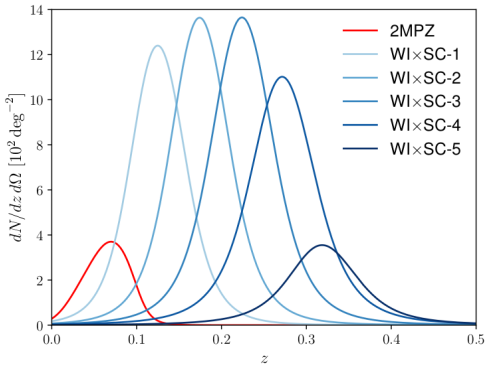

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Likelihood function

$$-2\log p(\boldsymbol{d}|\vec{\theta}) = \chi^2 \equiv \left(\boldsymbol{d} - \boldsymbol{t}(\vec{\theta})\right)^T \mathrm{Cov}^{-1}\left(\mathbf{d} - \mathbf{t}(\vec{\theta})\right)$$

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Gaussian

$$\mathrm{Cov}^{\mathrm{G}} = \delta_{\ell\ell'} \frac{C_\ell^{uw} C_\ell^{vz} + C_\ell^{uz} C_\ell^{vw}}{2\ell + 1}$$

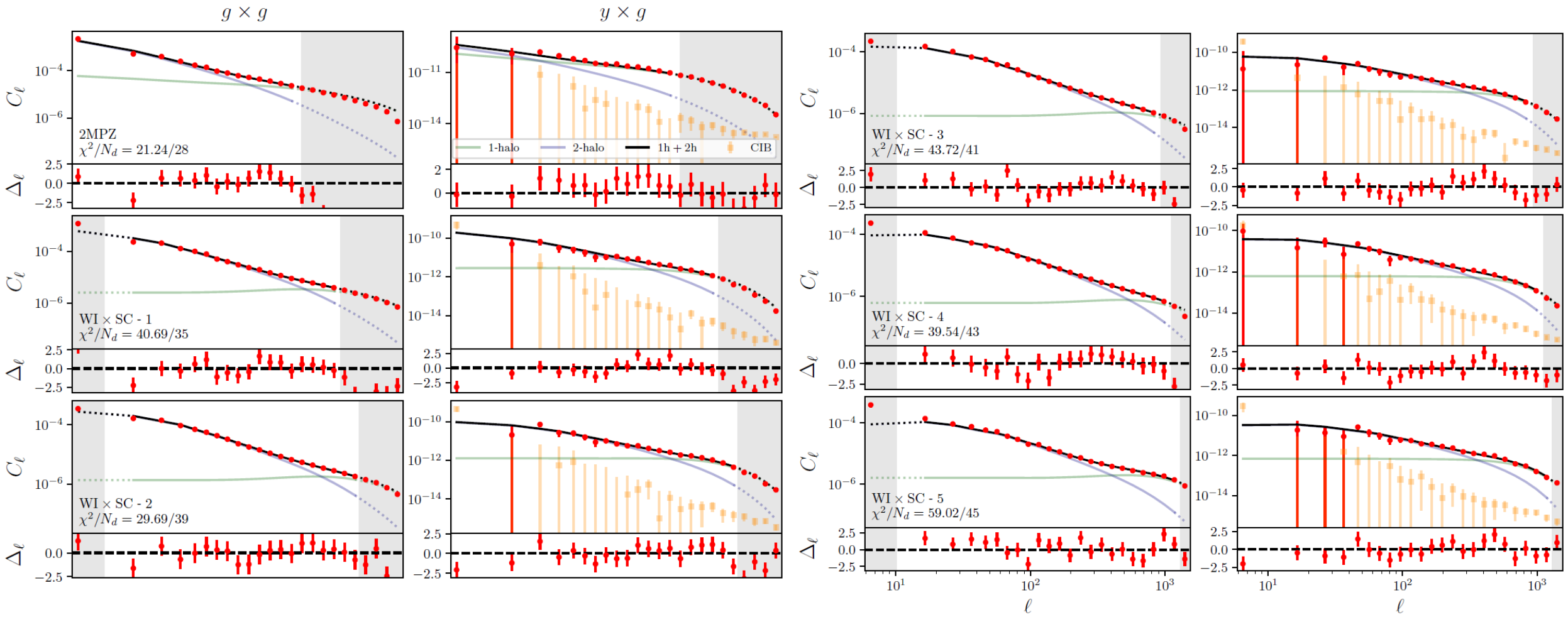
non-Gaussian

$$\mathrm{Cov}^{\mathrm{NG}} = \int d\chi \frac{W_u W_v W_w W_z}{4\pi f_{\mathrm{sky}} \chi^6} \times T_{uvwz}^{1h}$$

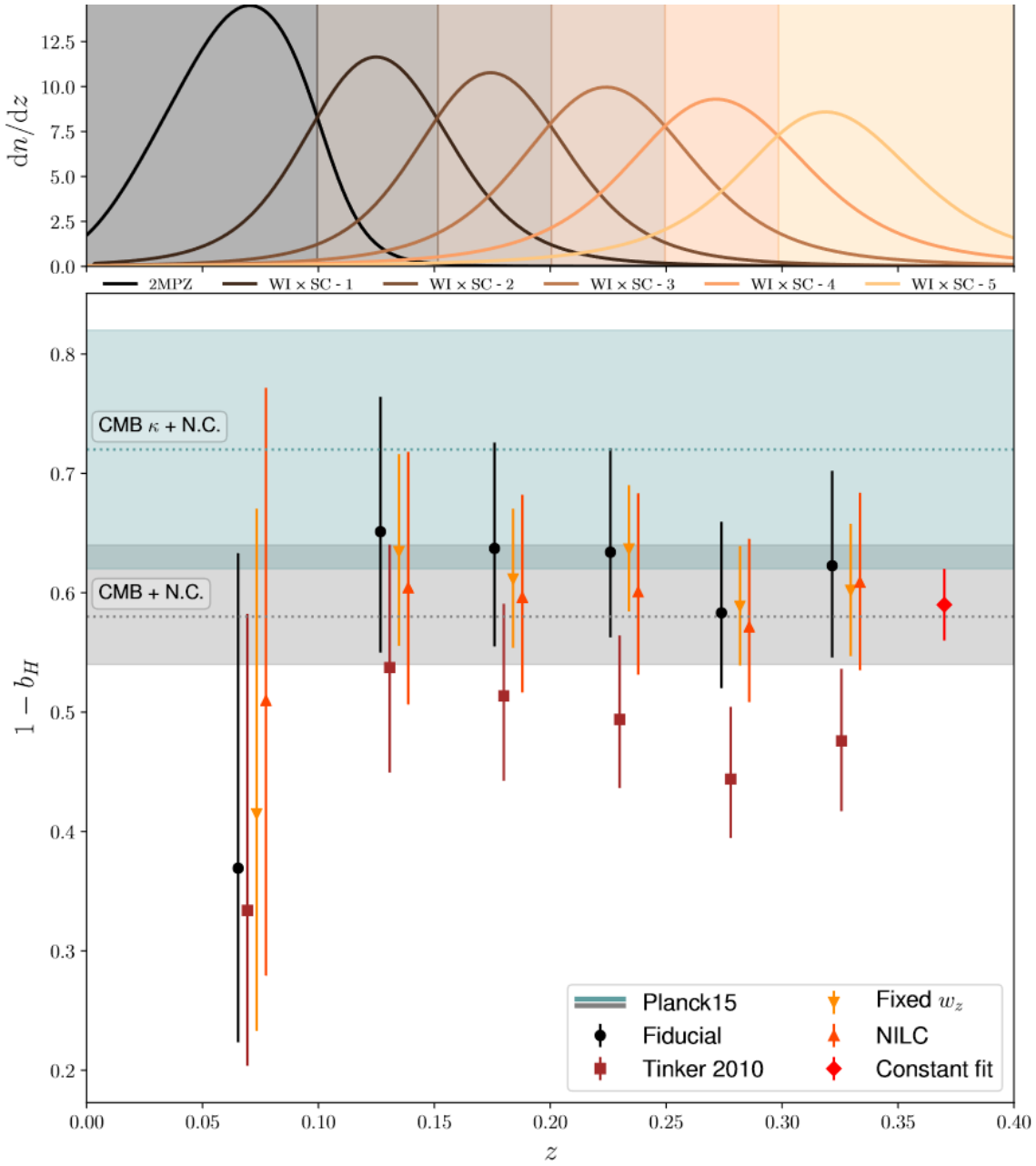
$$T_{uvwz}^{1h} = \int dM \frac{dn}{dM} \langle U(k|M)\, V(k|M)\, W(k|M)\, Z(k|M) \rangle$$

Fits

Data points: "A unified pseudo-C_ℓ framework" (Alonso et al. 2019) - **`NaMaster`**

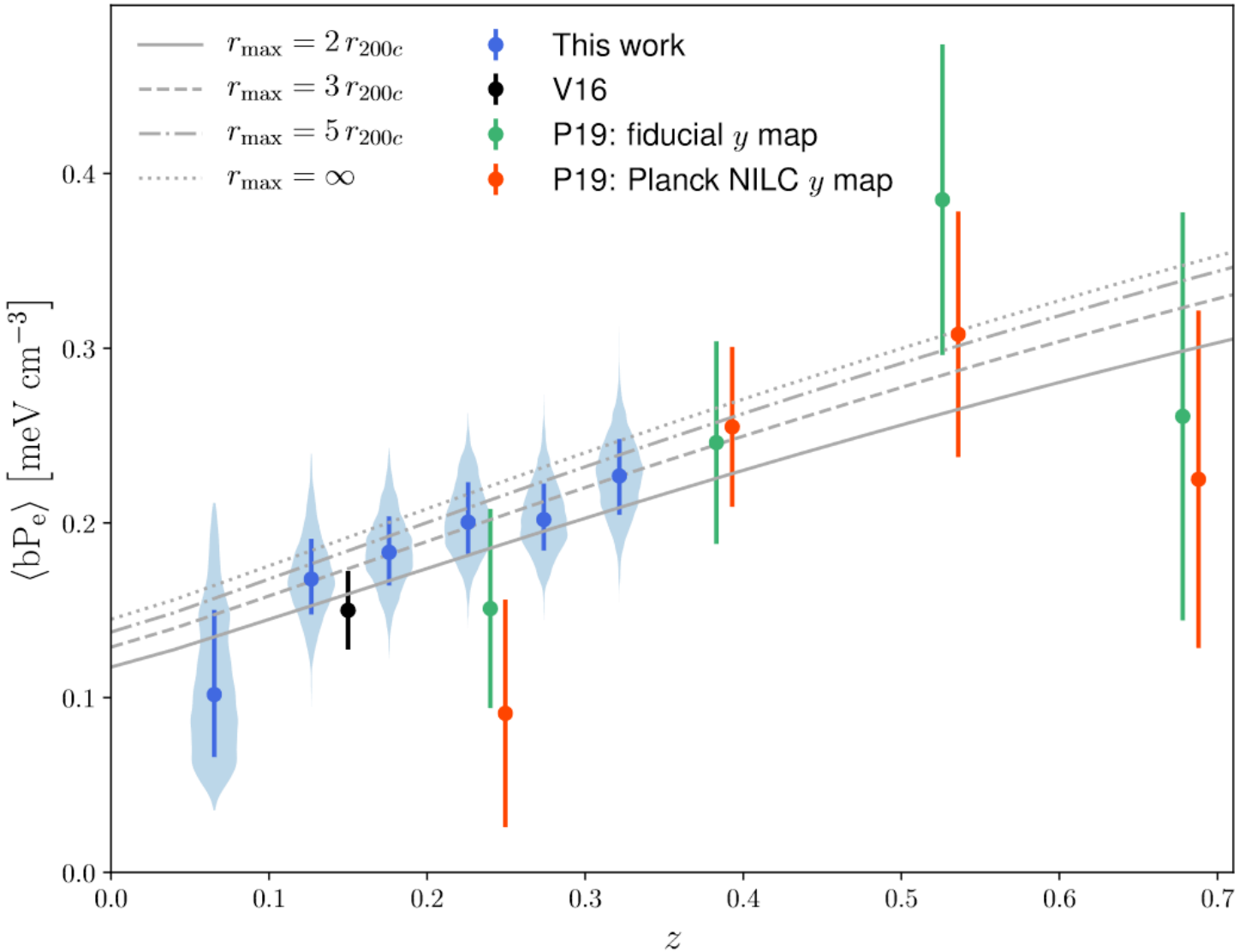


Mass Bias



Makiya et al. 2018
Salvati et al. 2019

Bias-Weighted Thermal Pressure



Vikram et al. 2017
Pandey et al. 2019
Battaglia et al. 2012

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- Future: ACT, Simons Observatory, Euclid, LSST – higher resolution y- and CMB lensing- maps, higher redshifts. Better systematics treatment.

Koukoufilippas, Alonso, Bilicki & Peacock

in preparation

Koukoufilippas, Alonso, Bilicki & Peacock

in preparation

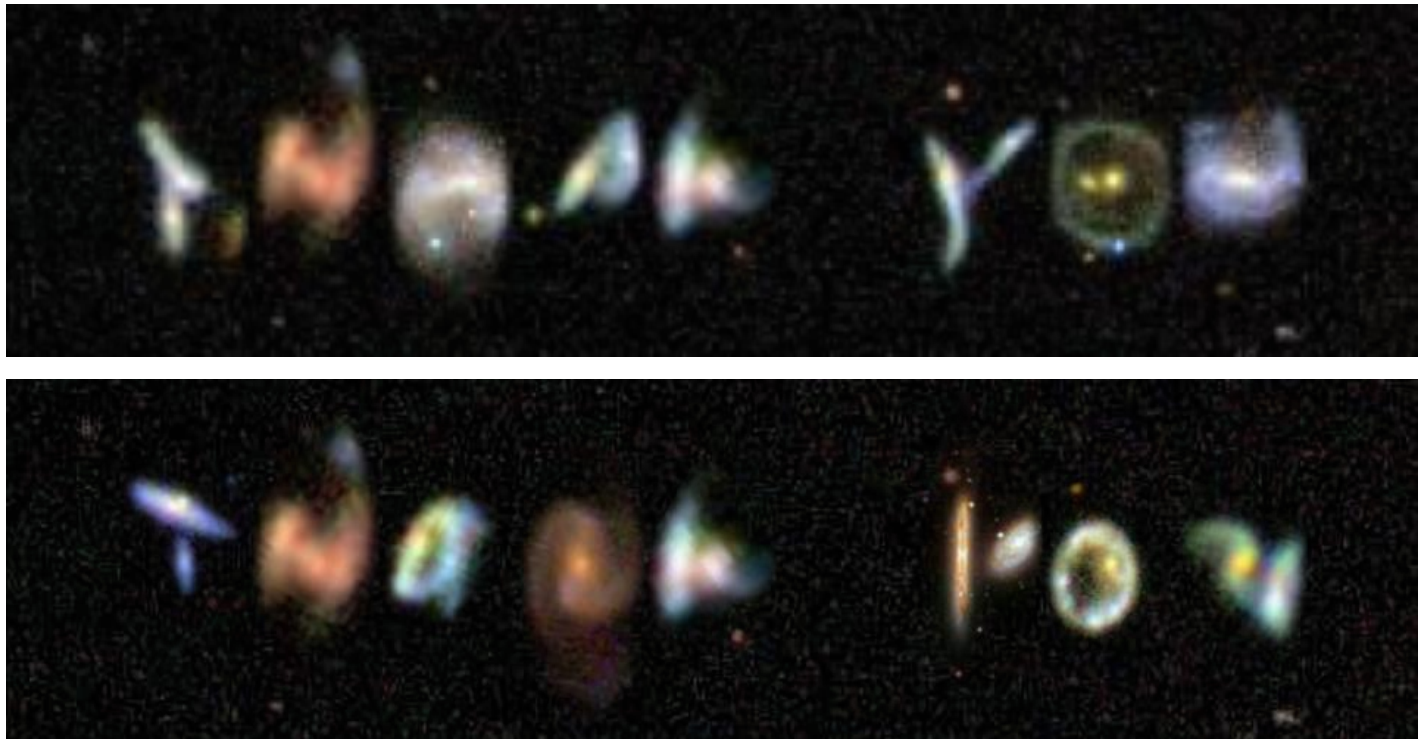
on the arXiv

Koukoufilippas, Alonso, Bilicki & Peacock

in preparation

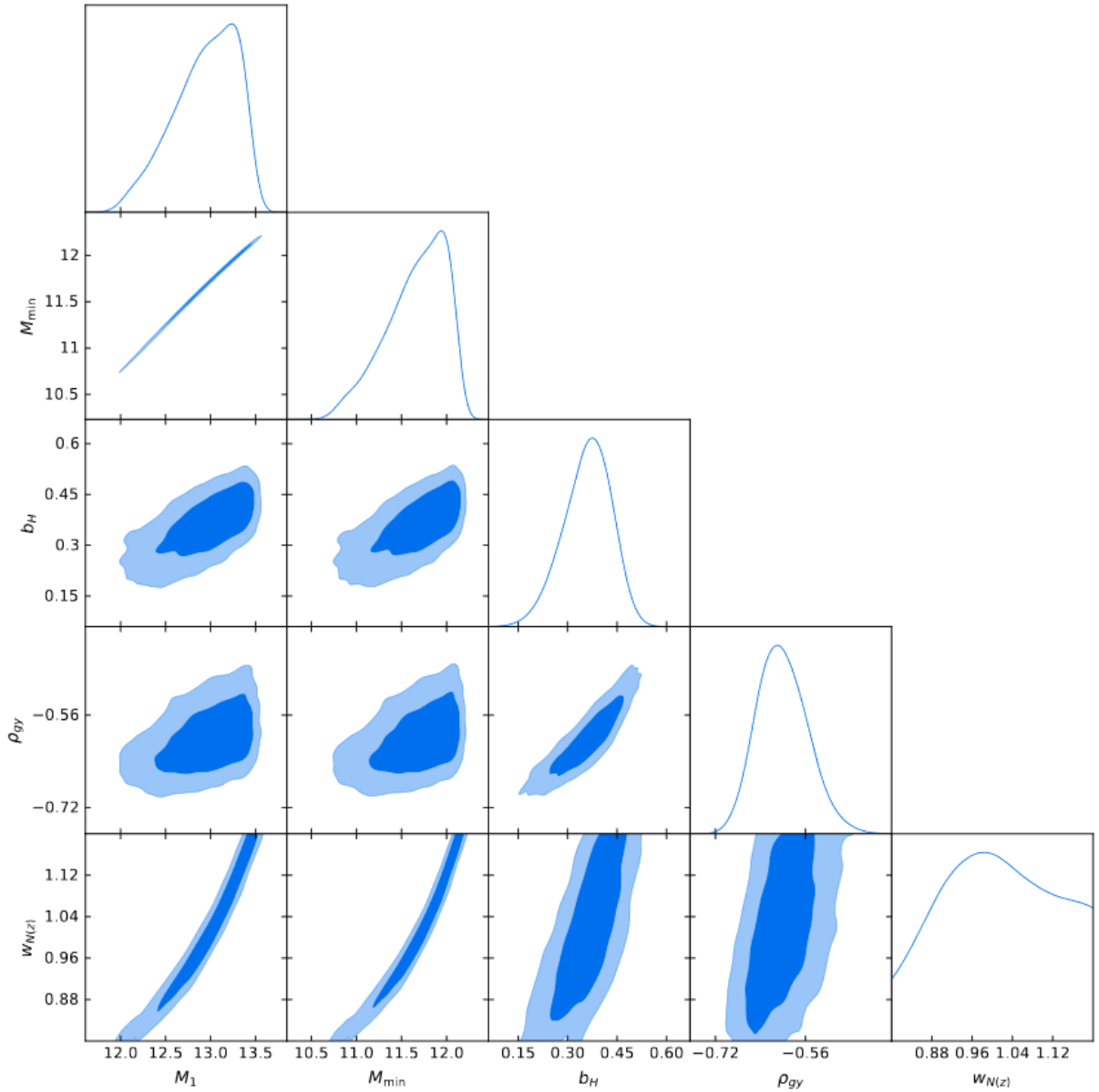
on the arXiv

soon.

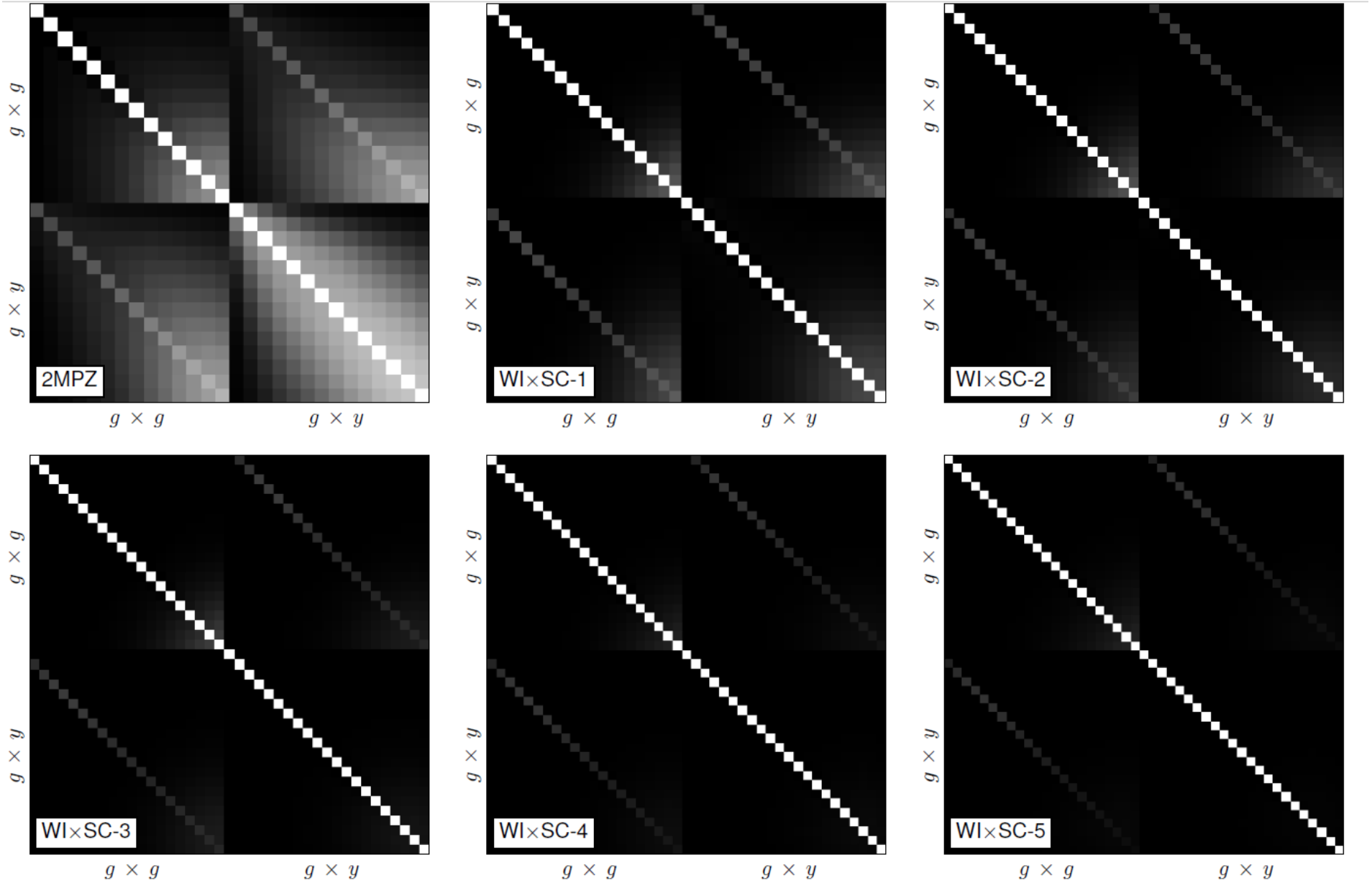


Tomographic Measurement of the Cosmic Gas Pressure

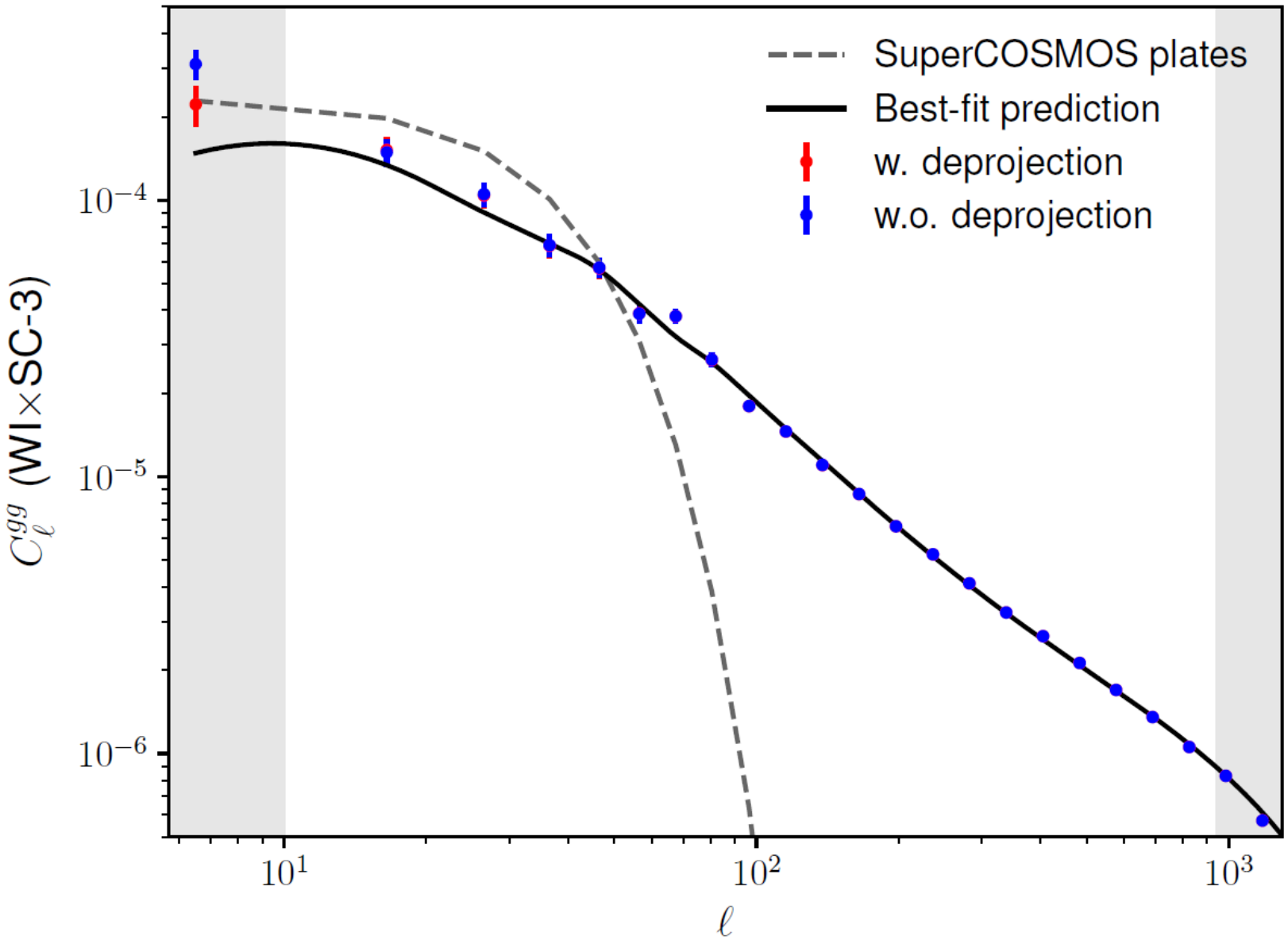
Parameter space



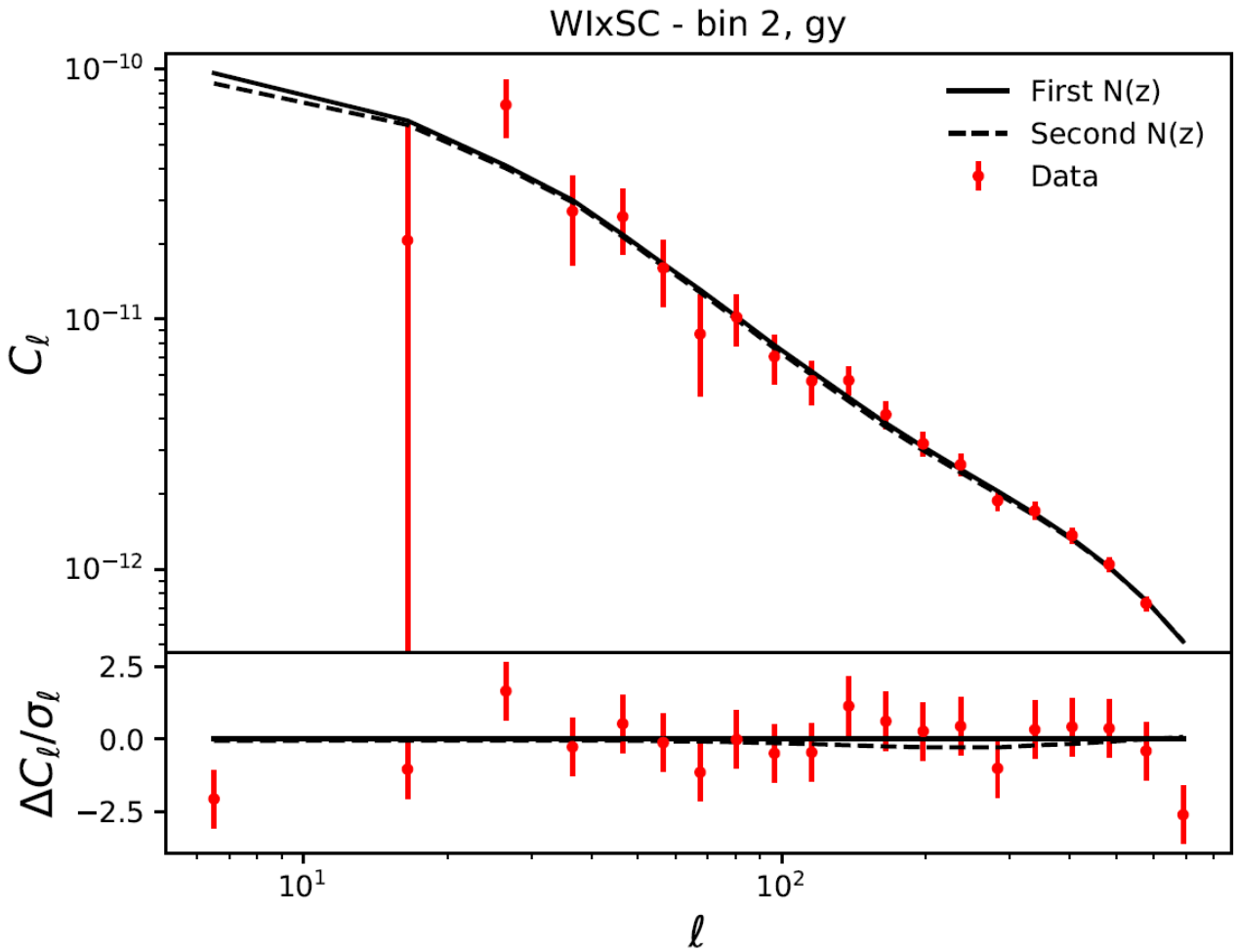
Correlation matrices

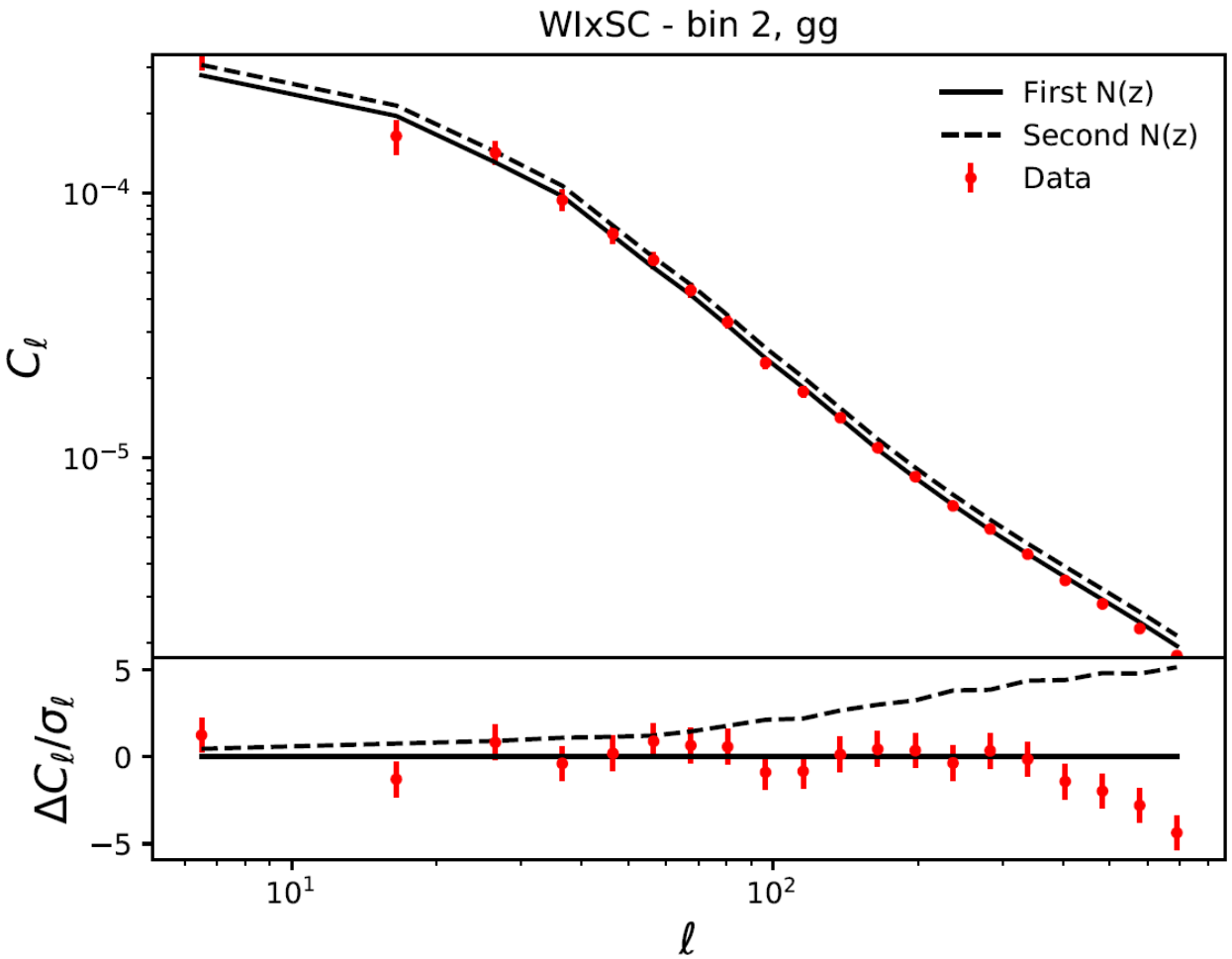


Systematics analysis

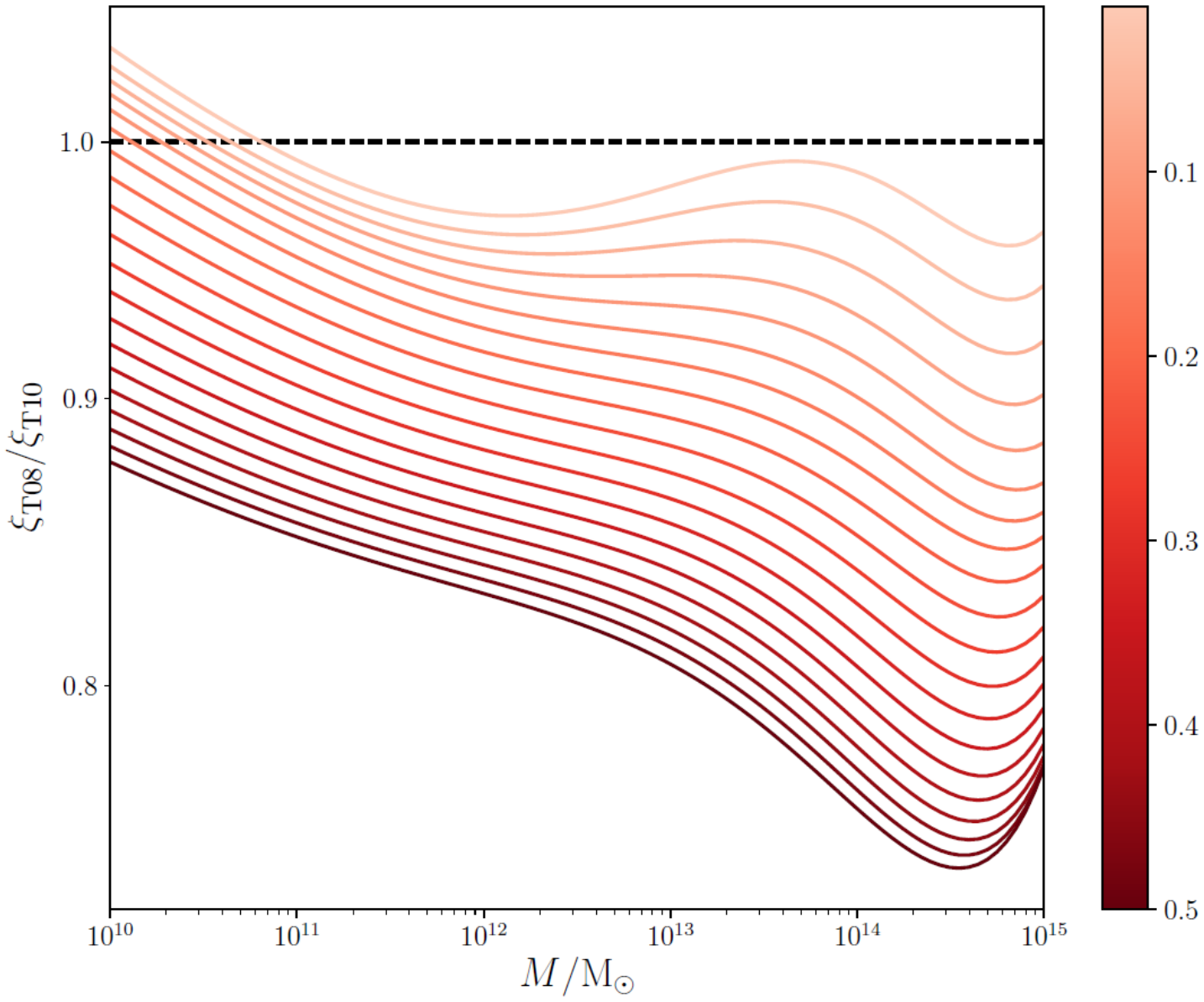


w_z motivation

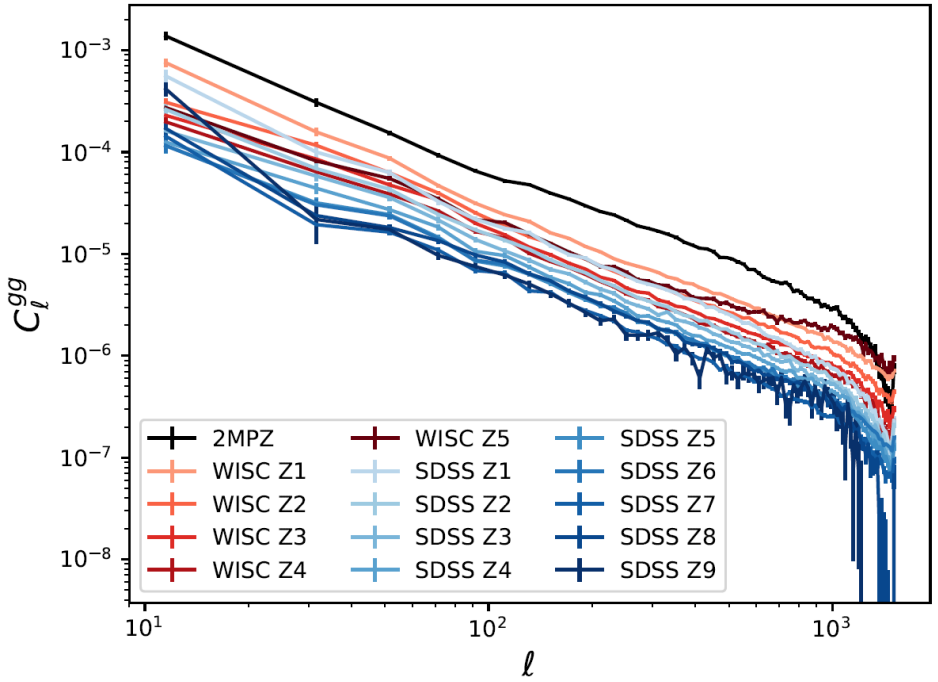




Cosmological mass functions



Data


10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
C_ℓ^{gg}
10^1
10^2
10^3
ℓ
2MPZ
WISC Z1
WISC Z2
WISC Z3
WISC Z4
WISC Z5
SDSS Z1
SDSS Z2
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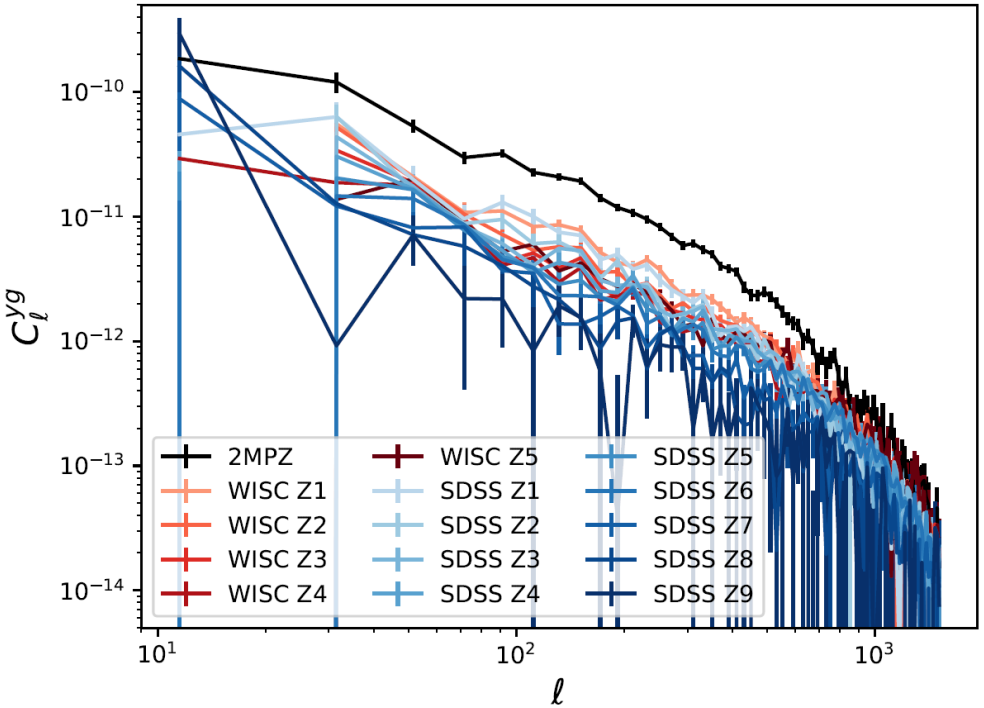
SDSS Z5
SDSS Z6
SDSS Z7
SDSS Z8
SDSS Z9


10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
C_ℓ^{yg}
10^1
10^2
10^3
ℓ
2MPZ
WISC Z1
WISC Z2
WISC Z3
WISC Z4
WISC Z5
SDSS Z1
SDSS Z2
SDSS Z3
SDSS Z4
SDSS Z5
SDSS Z6
SDSS Z7
SDSS Z8
SDSS Z9