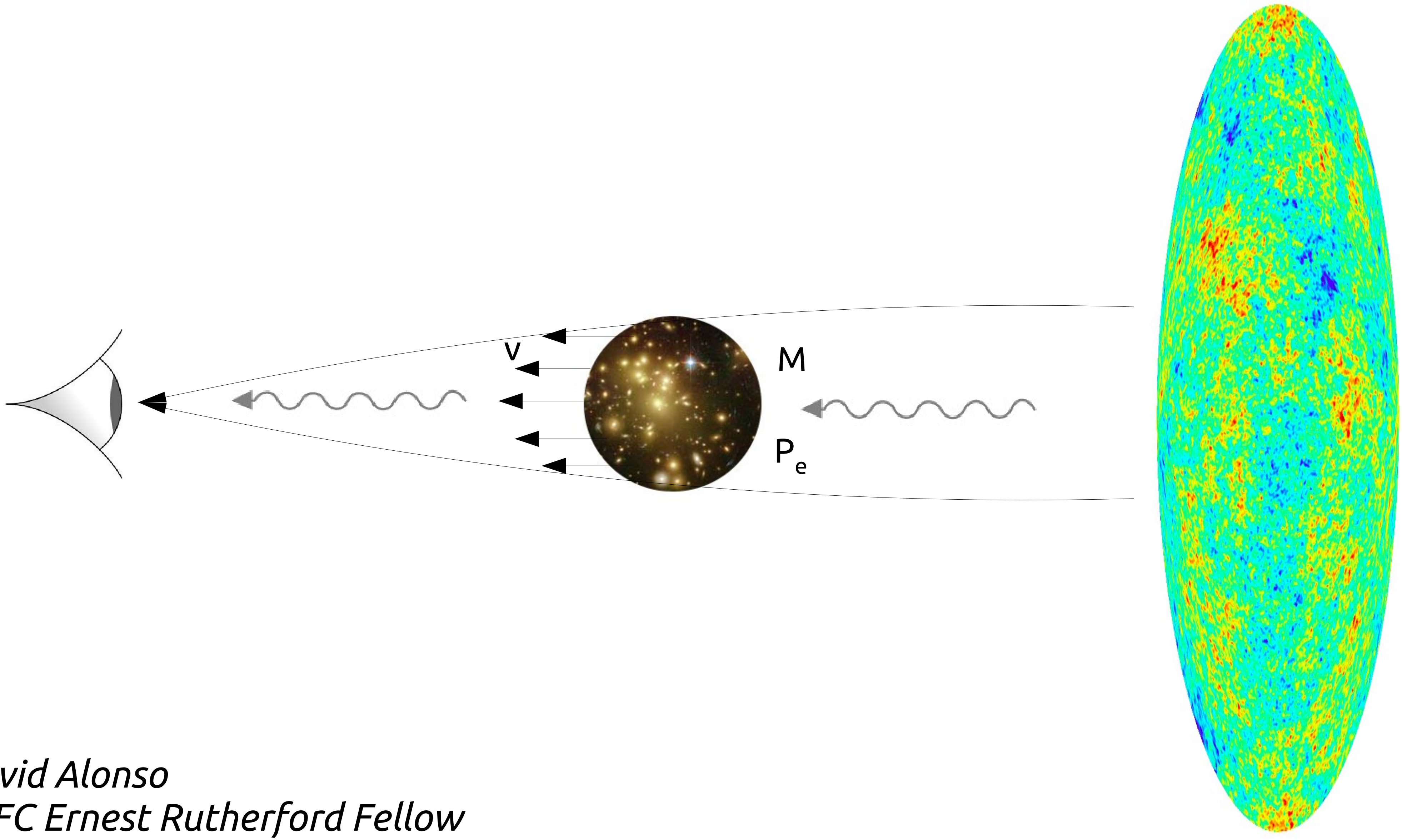
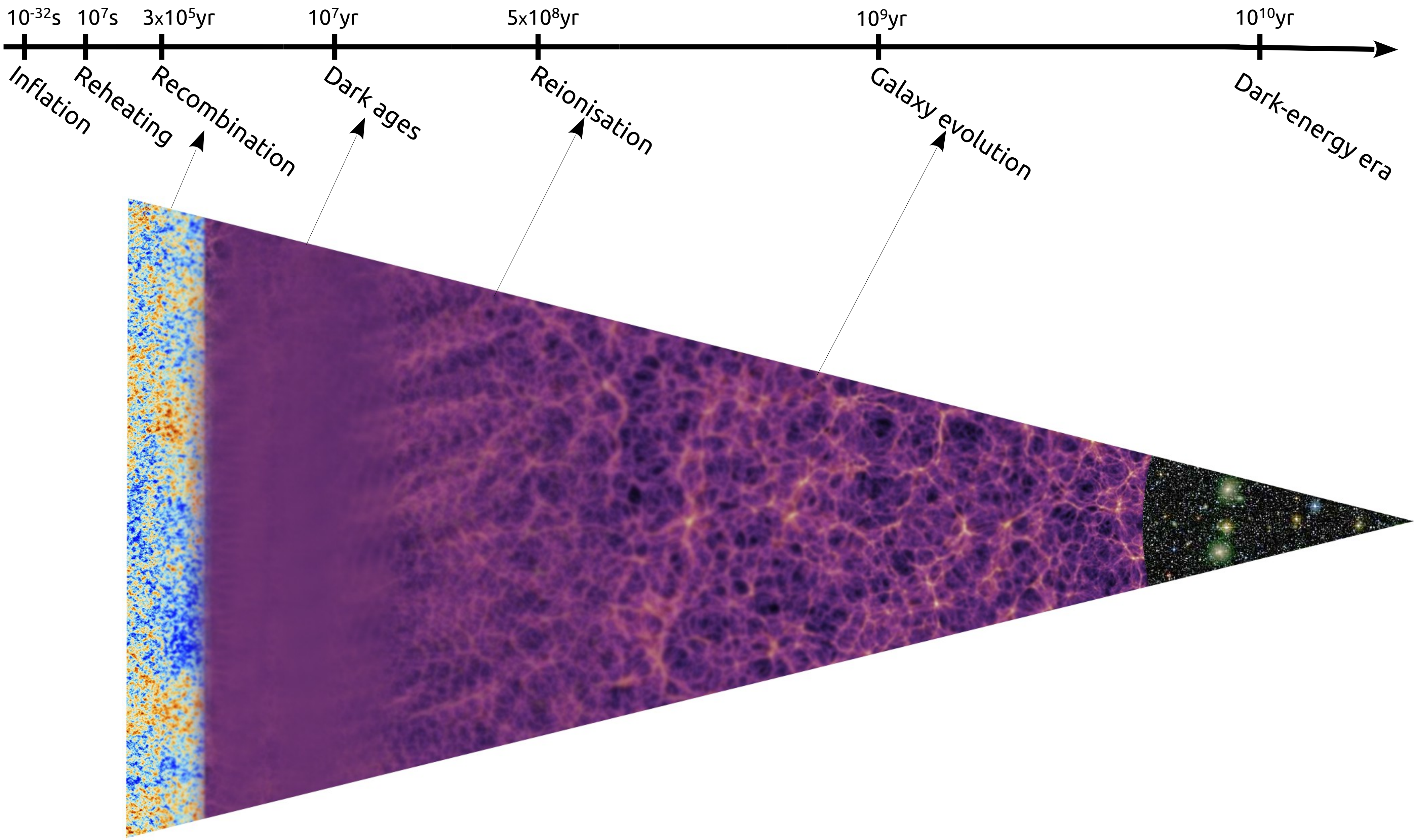
Improving large-scale structure data with CMB secondary anisotropies for cosmology



David Alonso
STFC Ernest Rutherford Fellow
University of Oxford

LAL, Orsay, Apr 1st 2019

Cosmological science questions



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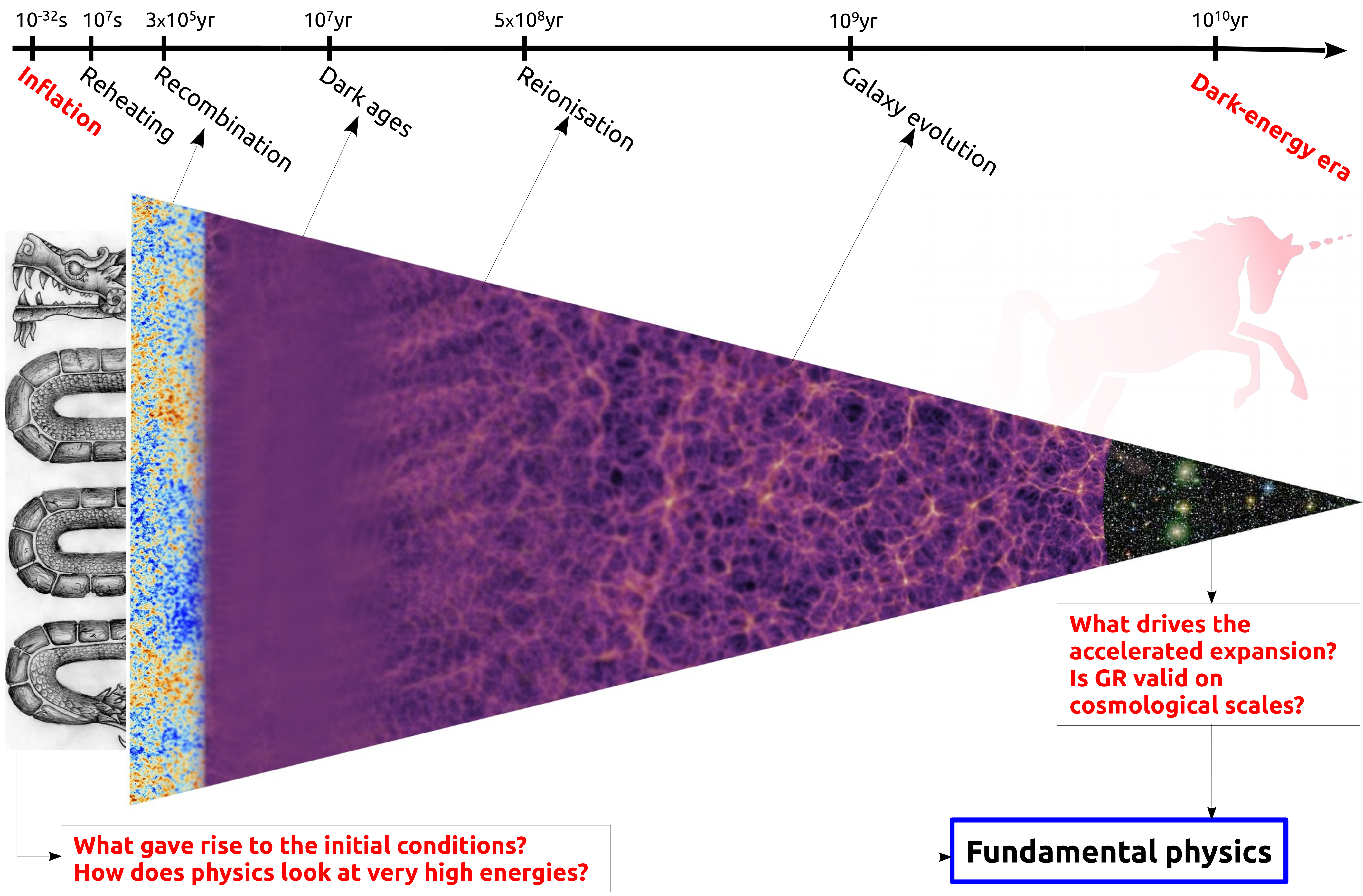

How will we go about it?

Parameters

A_s n_s
r $f_{\rm NL}$

$\Omega_{\rm DE}$ $\Omega_{\rm M}$
w_a w_0

Initial conditions
Energy components
Background evolution

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Observables

$$\Delta(\mathbf{k}, t)$$

$$\langle|\Delta(\mathbf{k}, t)|^2\rangle$$
$$\Downarrow$$
$$P(k, t)$$

Matter fluctuations
Power spectrum

Interlude: what is a power spectrum?

$$\rho(\mathbf{x}, t) \longrightarrow \Delta(\mathbf{x}, t) = \frac{\rho(\mathbf{x}, t) - \bar{\rho}(t)}{\bar{\rho}(t)}$$

Density

Overdensity

Interlude: what is a power spectrum?

$$\rho(\mathbf{x}, t) \longrightarrow \Delta(\mathbf{x}, t) = \frac{\rho(\mathbf{x}, t) - \bar{\rho}(t)}{\bar{\rho}(t)}$$

Density

Overdensity

Gaussian fields

$$p(\vec{\Delta}) = \frac{\exp\left[-\frac{1}{2}\vec{\Delta}^T\,\hat{\xi}^{-1}\vec{\Delta}\right]}{\sqrt{\det\left(2\pi\hat{\xi}\right)}}$$

$$\xi(|\mathbf{x} - \mathbf{y}|) = \langle\Delta(\mathbf{x})\Delta(\mathbf{y})\rangle$$

Interlude: what is a power spectrum?

$$\Delta(\mathbf{x}) = \int \frac{d\mathbf{k}^3}{(2\pi)^{3/2}} e^{i\mathbf{k}\mathbf{x}} \Delta(\mathbf{k}) \longrightarrow \langle |\Delta(\mathbf{k})|^2 \rangle = \frac{V}{(2\pi)^3} P(k)$$

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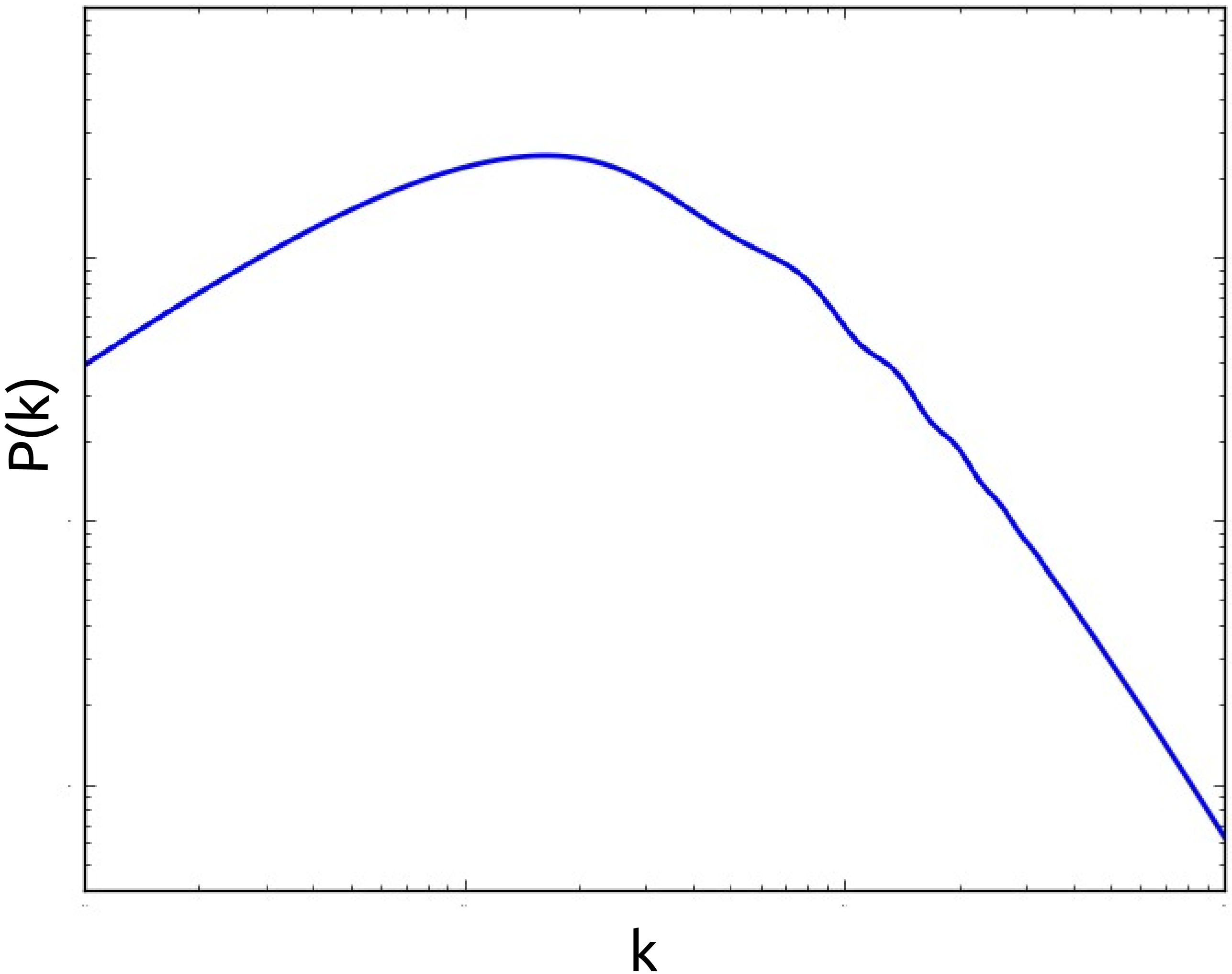

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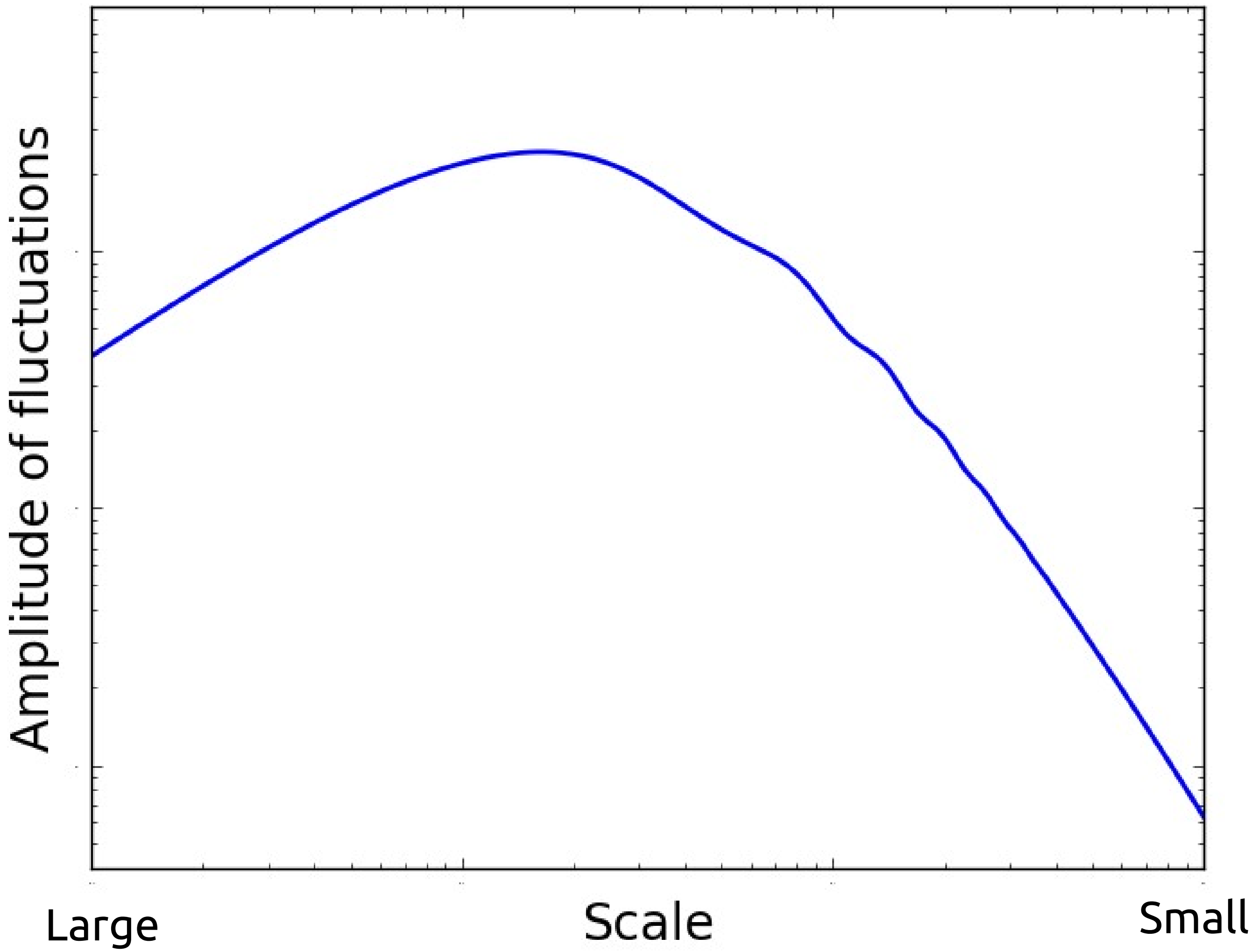

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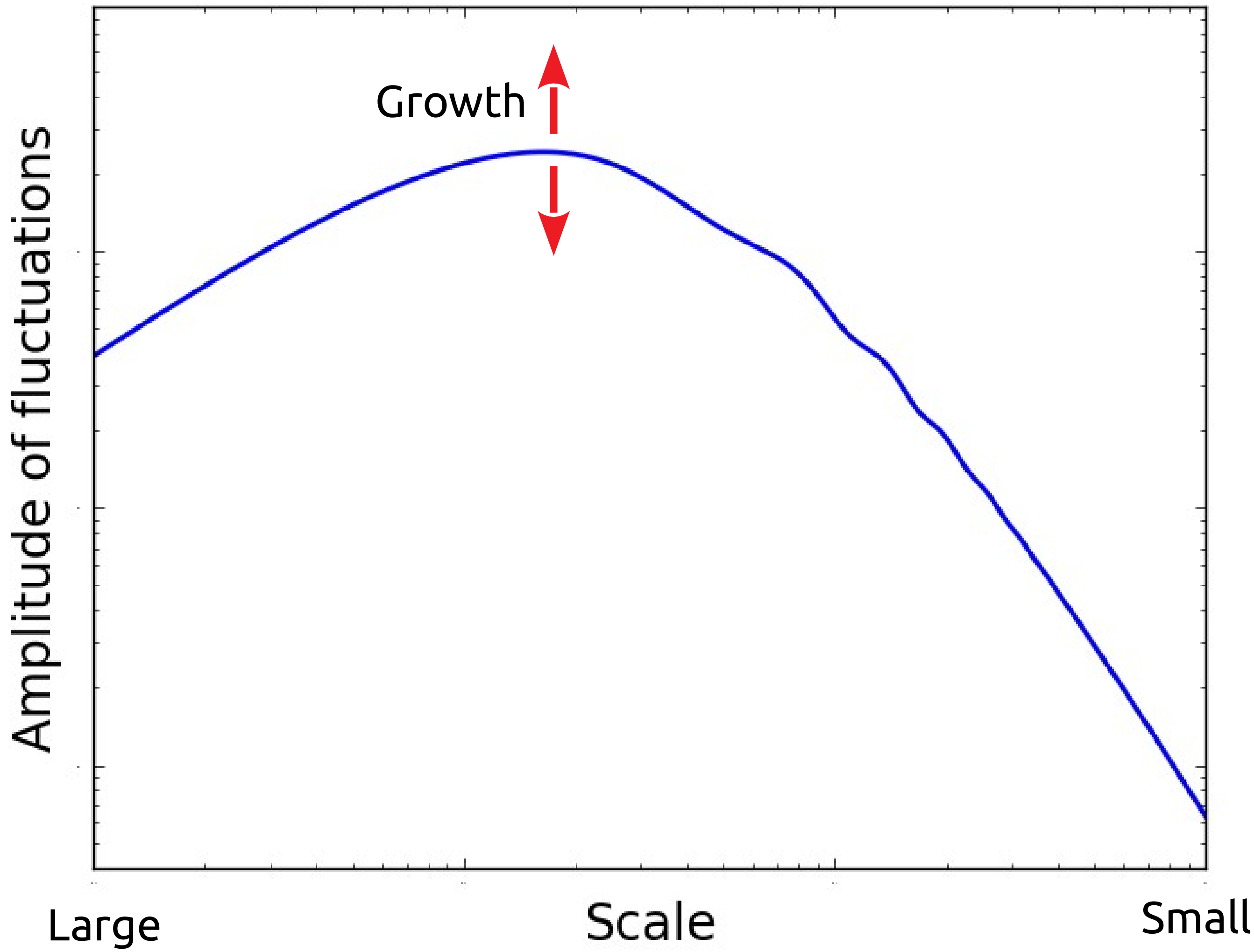

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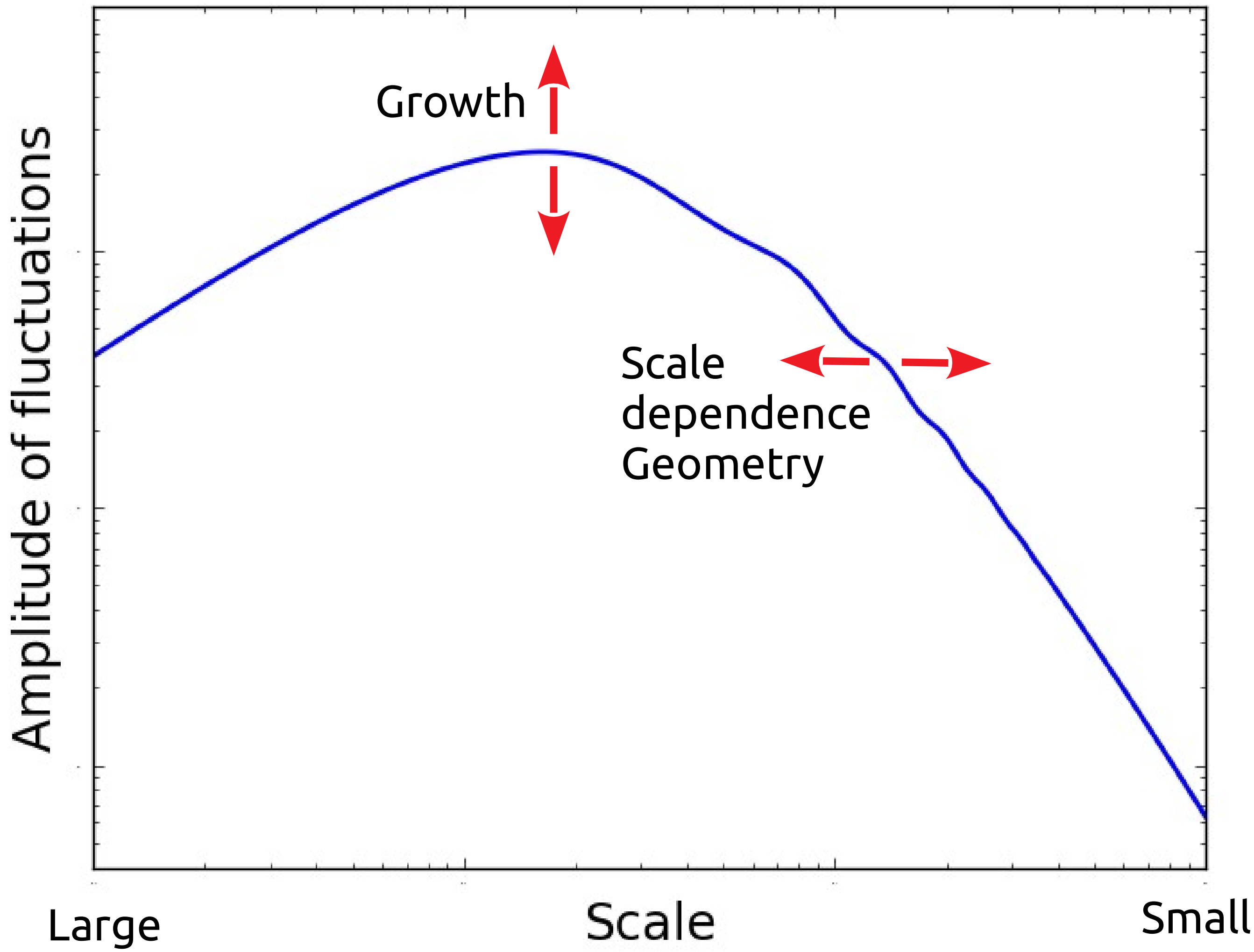

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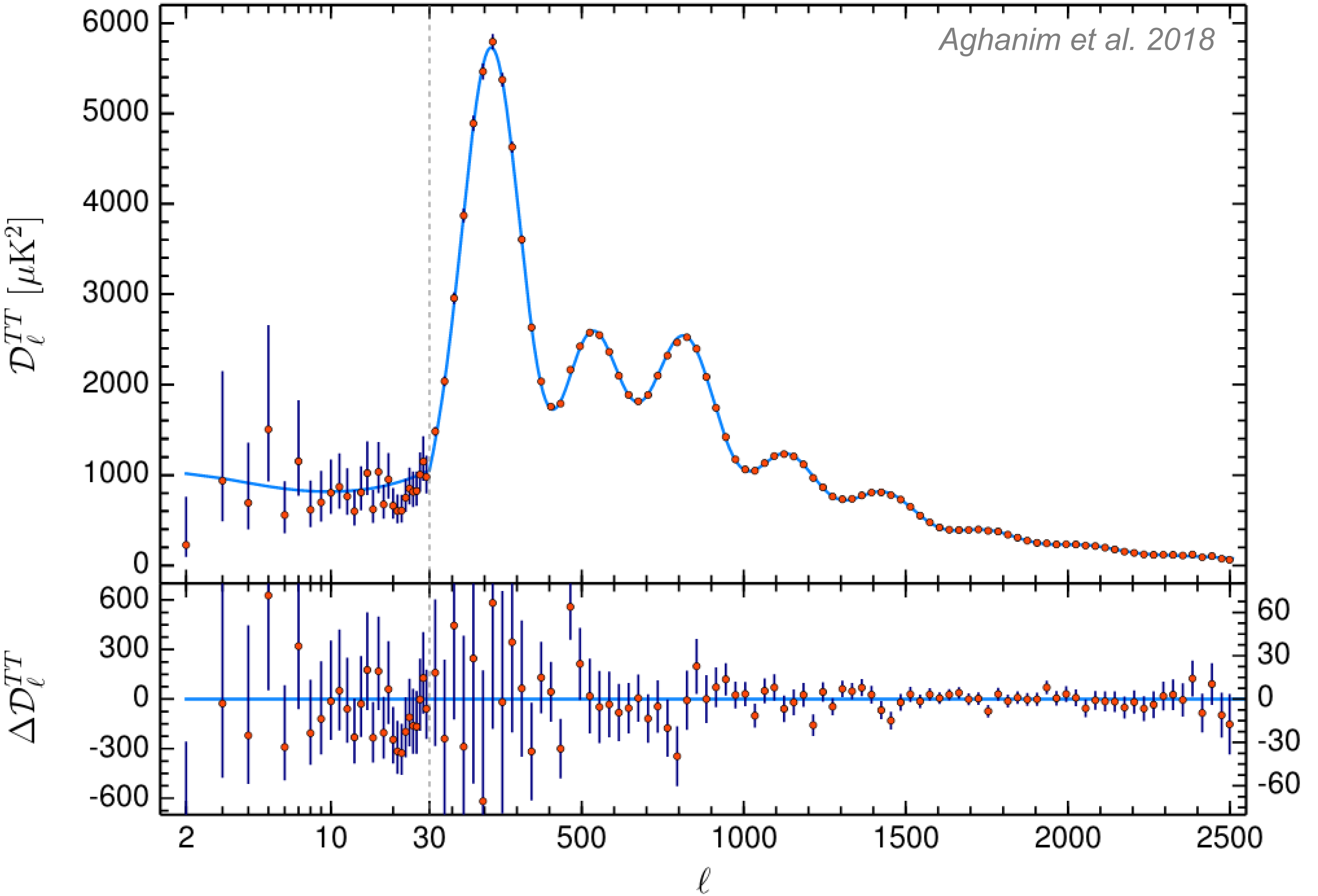
$$\delta(\theta, \varphi) = \sum_{\ell m} \delta_{\ell m} Y_{\ell m}(\theta, \phi) \qquad \left\langle \delta^{\alpha}_{\ell m} \delta^{\beta}_{\ell m}{}^{*} \right\rangle = C_\ell^{\alpha\beta}$$

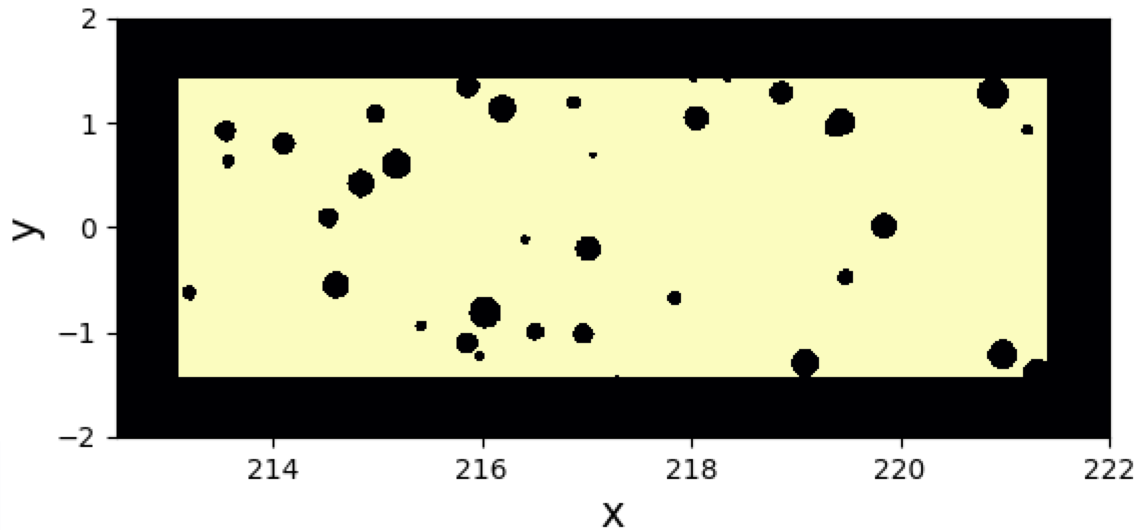
Interlude: what is a power spectrum?

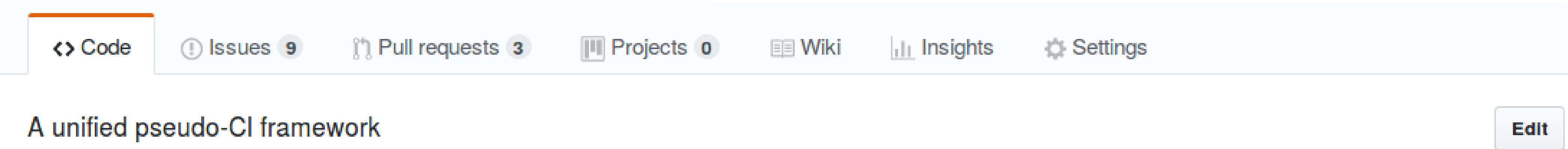


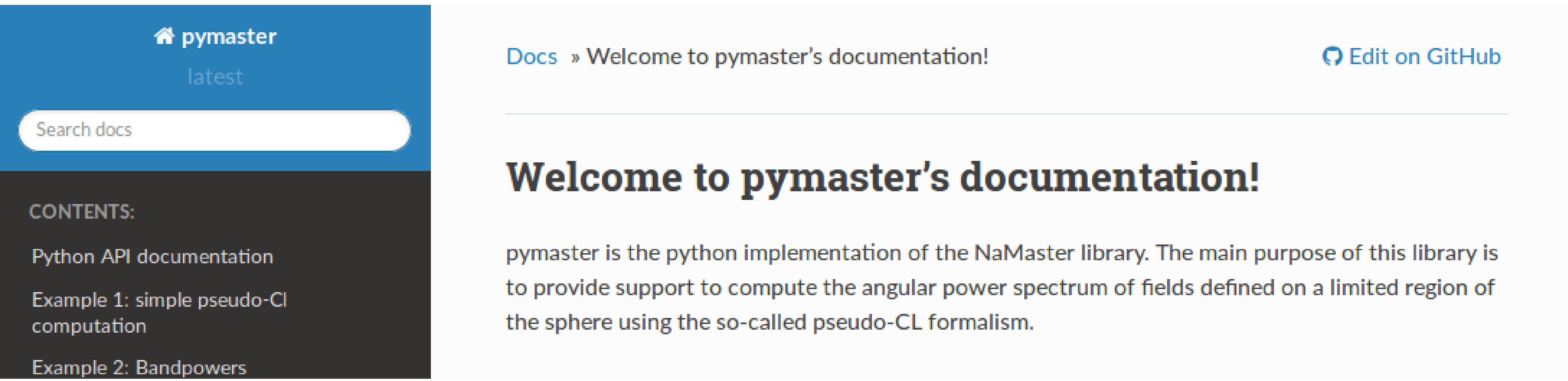
Computing power spectra

Estimating power spectra:

- Patchy sky.
- Contaminated data.
- Optimal method?
- DA et al. 1809.09603

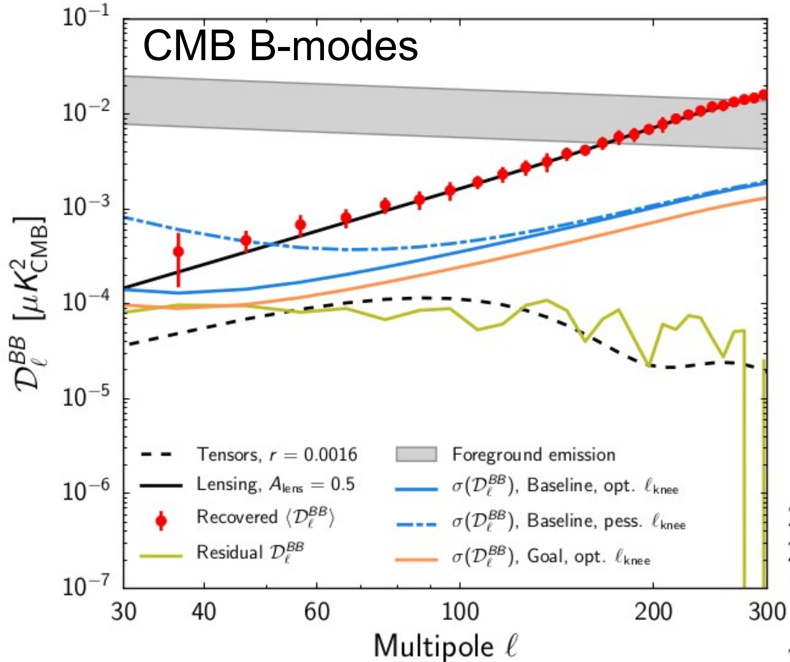






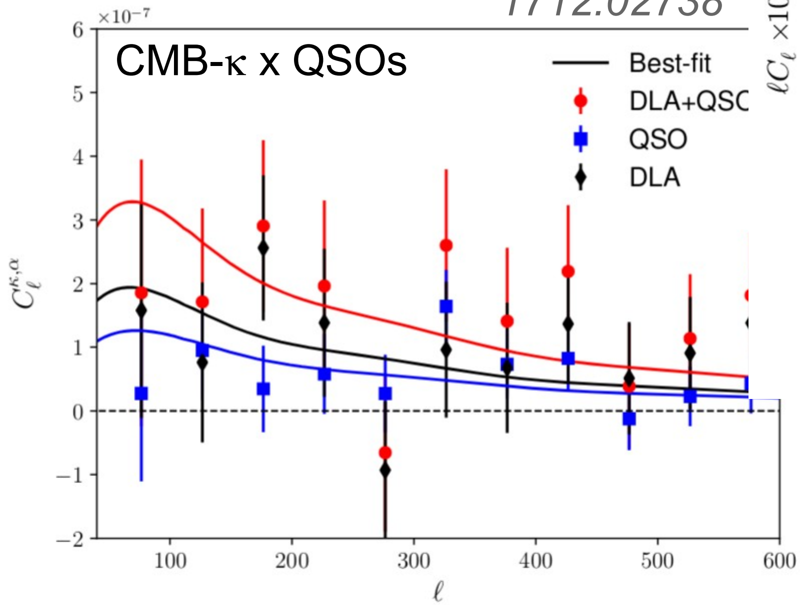
Code: https://github.com/LSSTDESC/NaMaster
Docs: https://namaster.readthedocs.io/en/latest/index.html

Computing power spectra



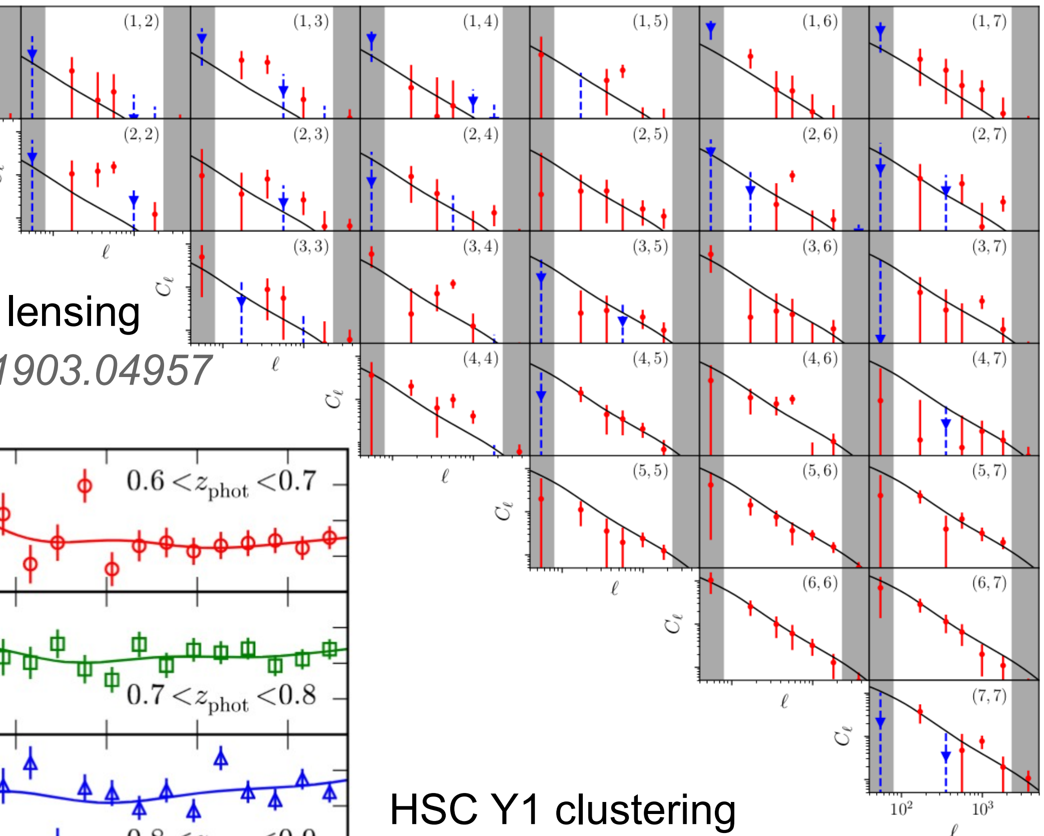
1808.07445

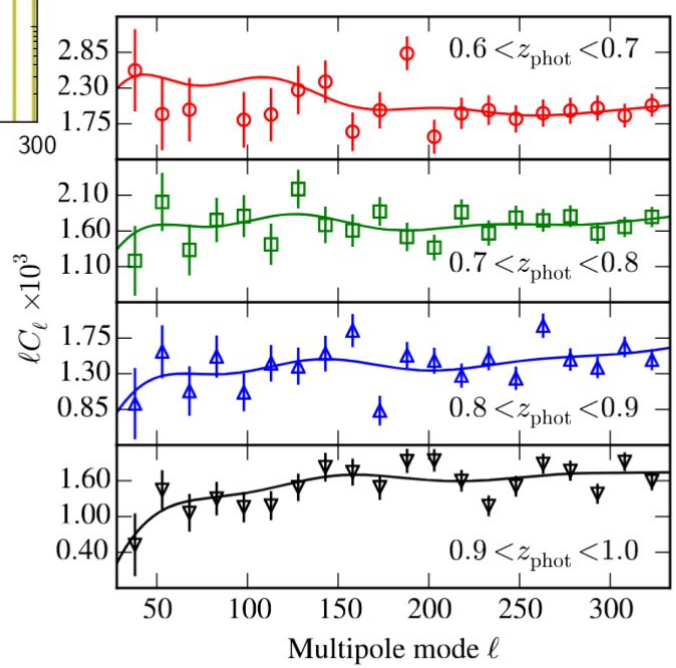
1712.02738



CFHTLenS lensing

Bellini, DA 1903.04957



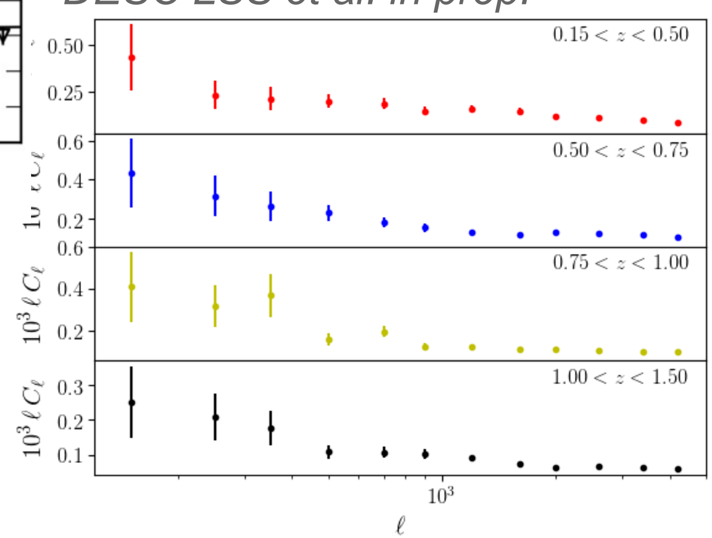


DES Y1 clustering

1807.10163

HSC Y1 clustering

DESC LSS et al. in prep.



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Power spectrum

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Parameters	(Un)observables	Observables
$A_s \quad n_s$ $r \quad f_{\rm NL}$ $\Omega_{\rm DE} \quad \Omega_{\rm M}$ $w_a \quad w_0$	$\Delta(\mathbf{k},t)$ $\langle \lvert\Delta(\mathbf{k},t)\rvert^2 \rangle$ $\Downarrow$ $P(k,t)$	$\Delta^\alpha(\theta,\phi,\lambda)$
Initial conditions Energy components Background evolution	Matter fluctuations Power spectrum	α=: CMB temperature CMB polarisation Galaxy density Galaxy shapes Lyα absorption 21cm flux ...

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How will we go about it?

Parameters	(Un)observables	Observables	Observations

Theoretical uncertainties — Astrophysical uncertainties — Instrumental noise, Inst. systematics, Selection effects

Parameters

$A_s \quad n_s$

$r \quad f_{\rm NL}$

$\Omega_{\rm DE} \quad \Omega_{\rm M}$

$w_a \quad w_0$

Initial conditions
Energy components
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(Un)observables

$$\Delta(\mathbf{k}, t)$$

$$\langle|\Delta(\mathbf{k}, t)|^2\rangle$$

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$$P(k, t)$$

Matter fluctuations
Power spectrum

Observables

$$\Delta^\alpha(\theta, \phi, \lambda)$$

α=:
- CMB temperature
- CMB polarisation
- Galaxy density
- Galaxy shapes
- Lyα absorption
- 21cm flux
- ...

Observations

$$\Delta^\alpha_{\rm obs} \equiv \Delta^\alpha + N^\alpha + S^\alpha$$

Object catalogues
Intensity maps
Spectra

Cosmology with large-scale structure

Large-Scale Structure:

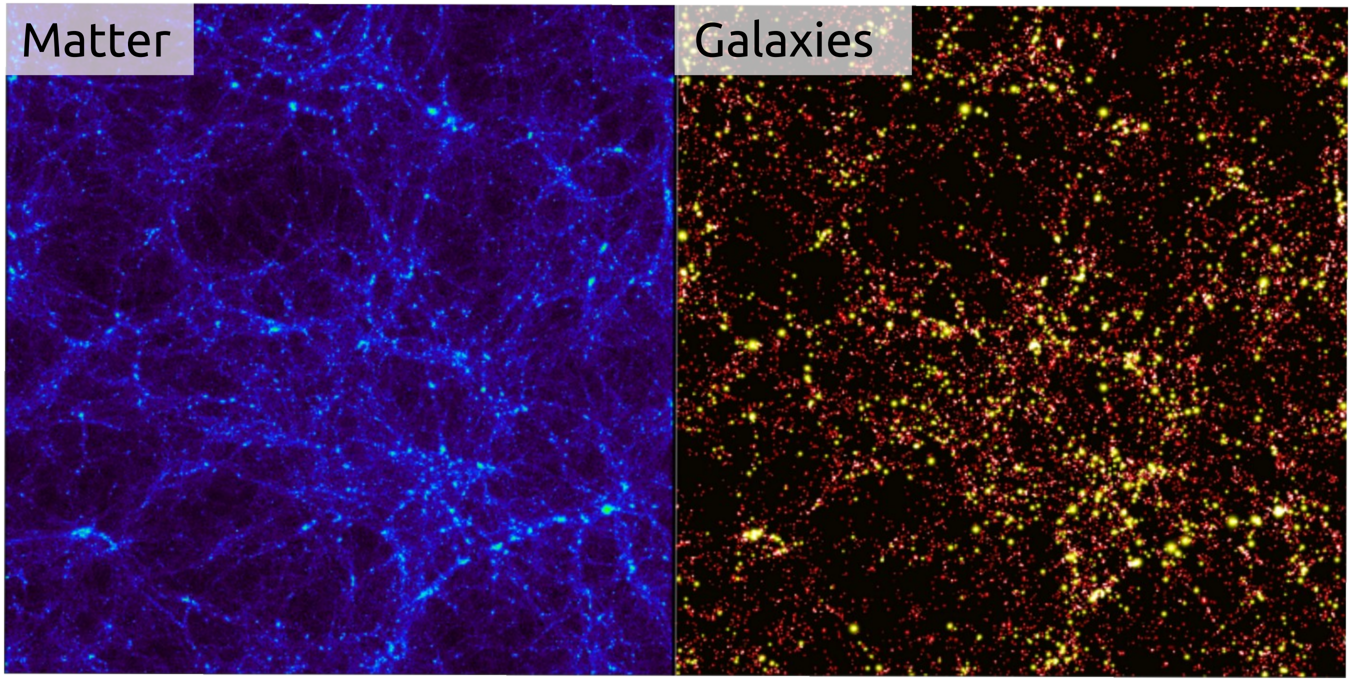
- DE affects cosmic density field
- Galaxy distribution ↔ matter density
- Main systematic → galaxy-matter connection
- In general:

$$\delta_g(x) = f[\delta_M(y)] + \varepsilon(x)$$

- On large scales:

$$\delta_g \sim b_g \, \delta_M$$

Kaiser 1984
Mo & White 1995
Sheth & Tormen 1999
McDonald & Roy 0902.0991



Credit: Herschel Space Observatory

Cosmology with large-scale structure

~~**Large-Scale Structure:**~~
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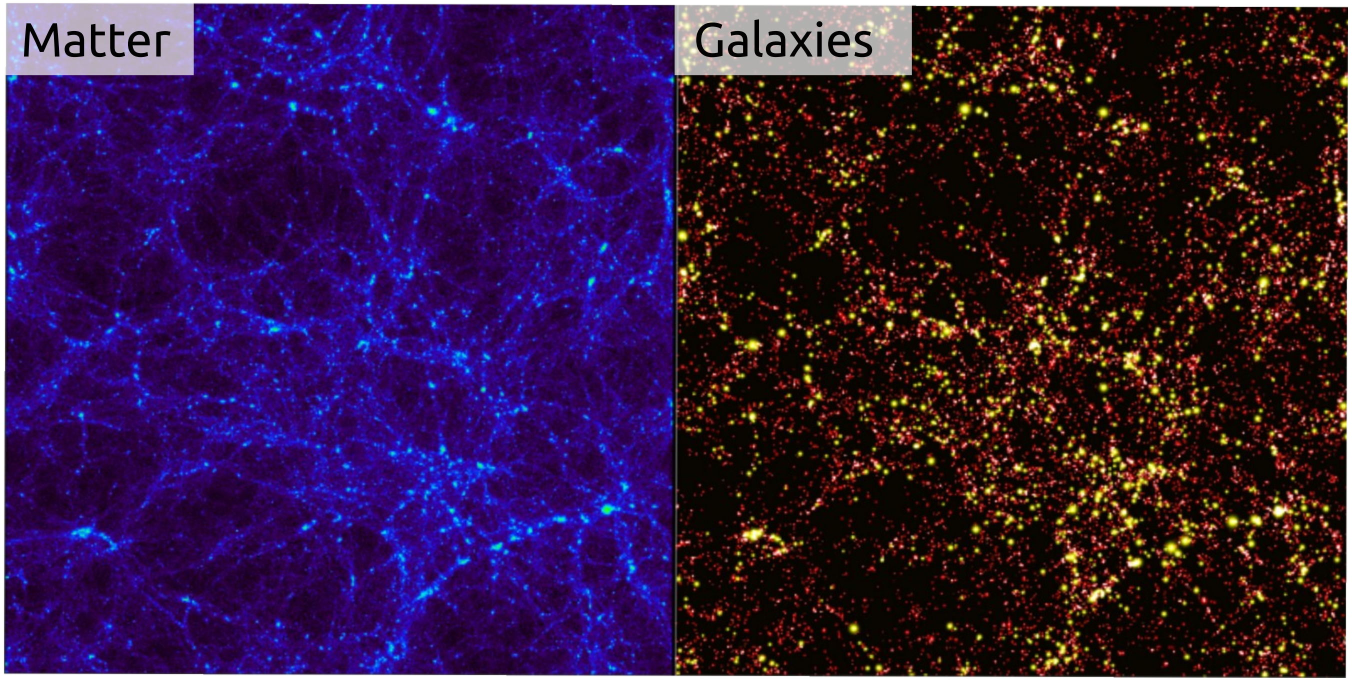

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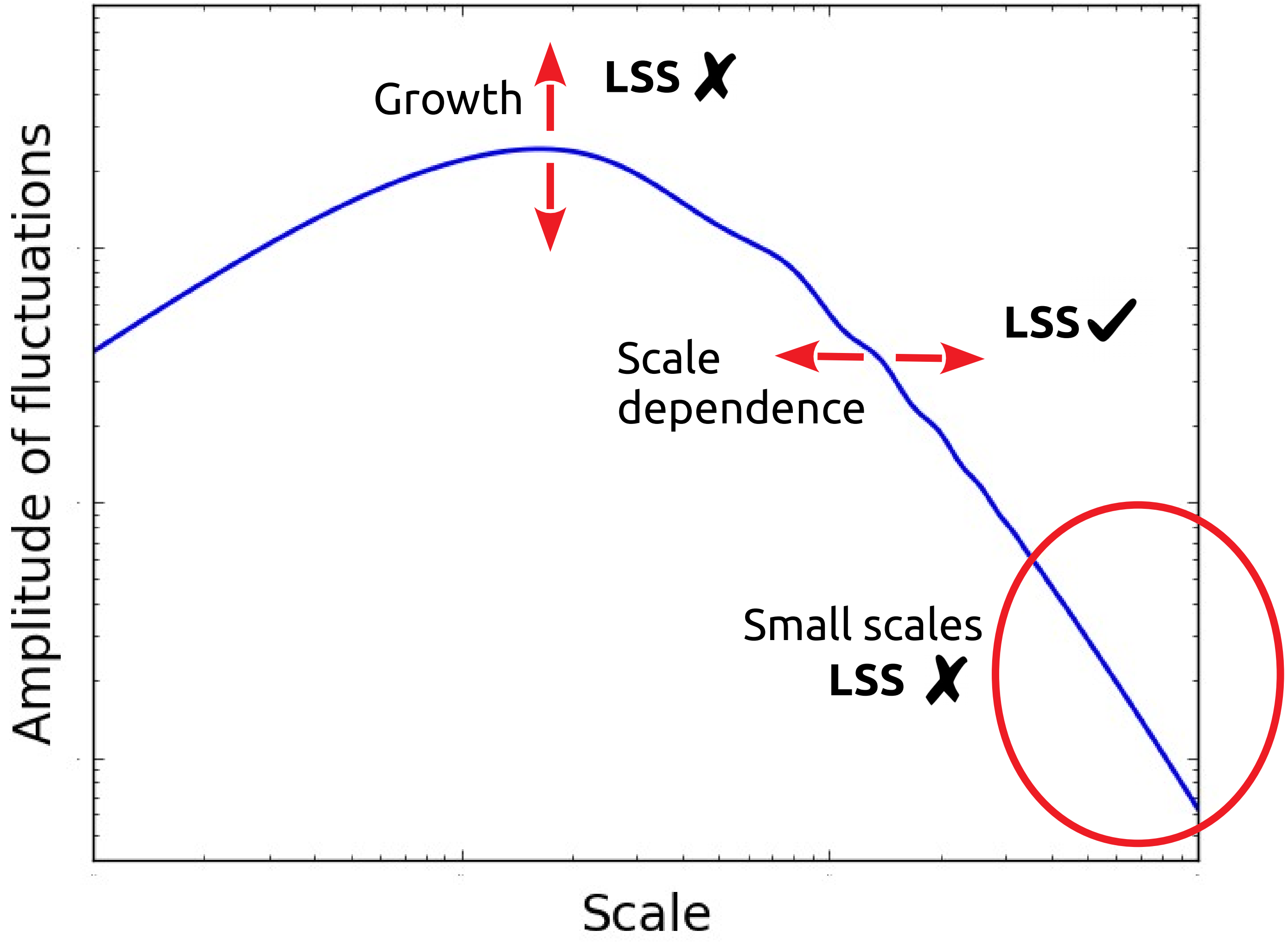
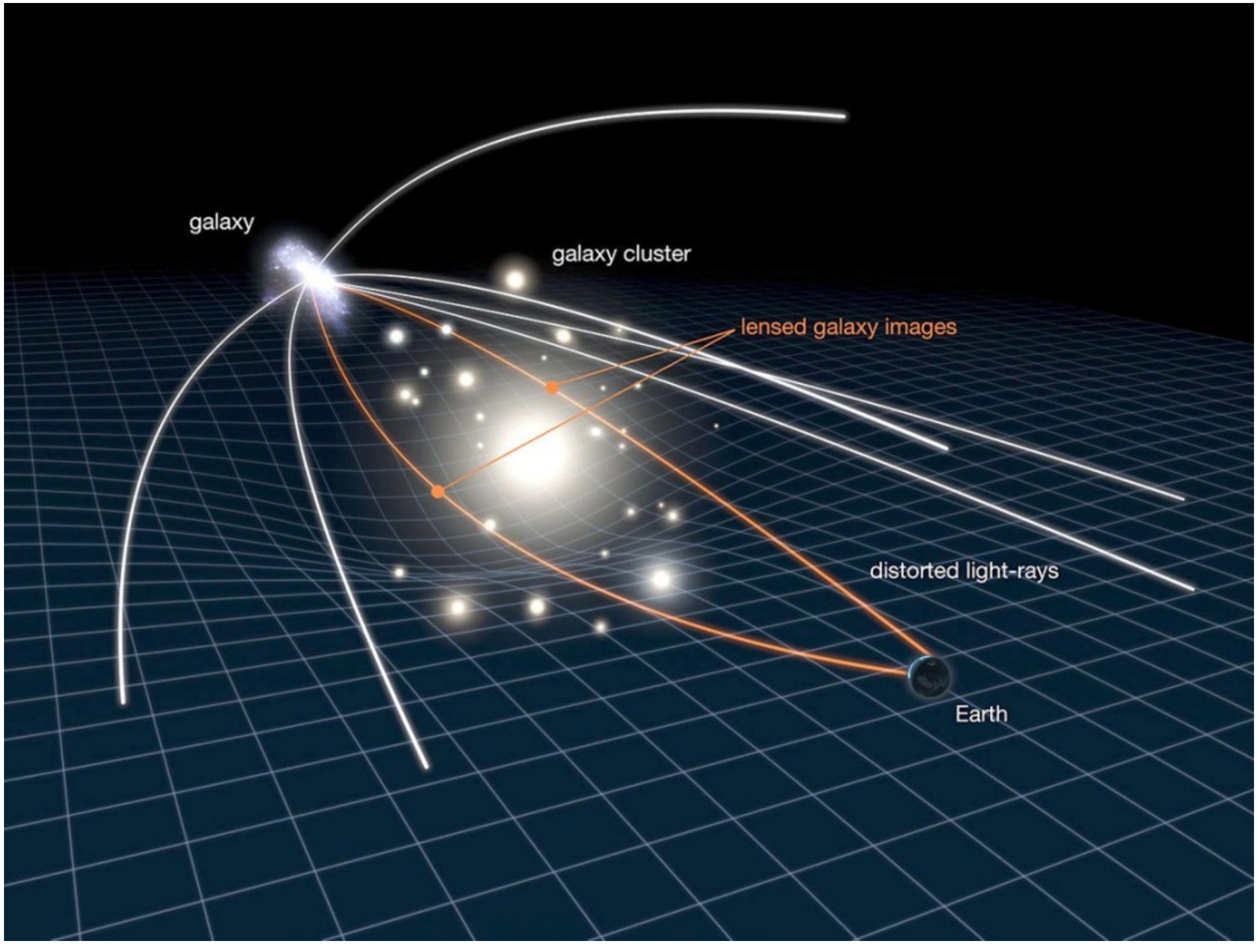
Cosmology with large-scale structure

Galaxy clustering:



Weak lensing:

- Intervening matter modifies observed galaxy shapes.
- Tracer of the true matter distribution → no bias!
- Large radial projection kernel → no scale-dependence

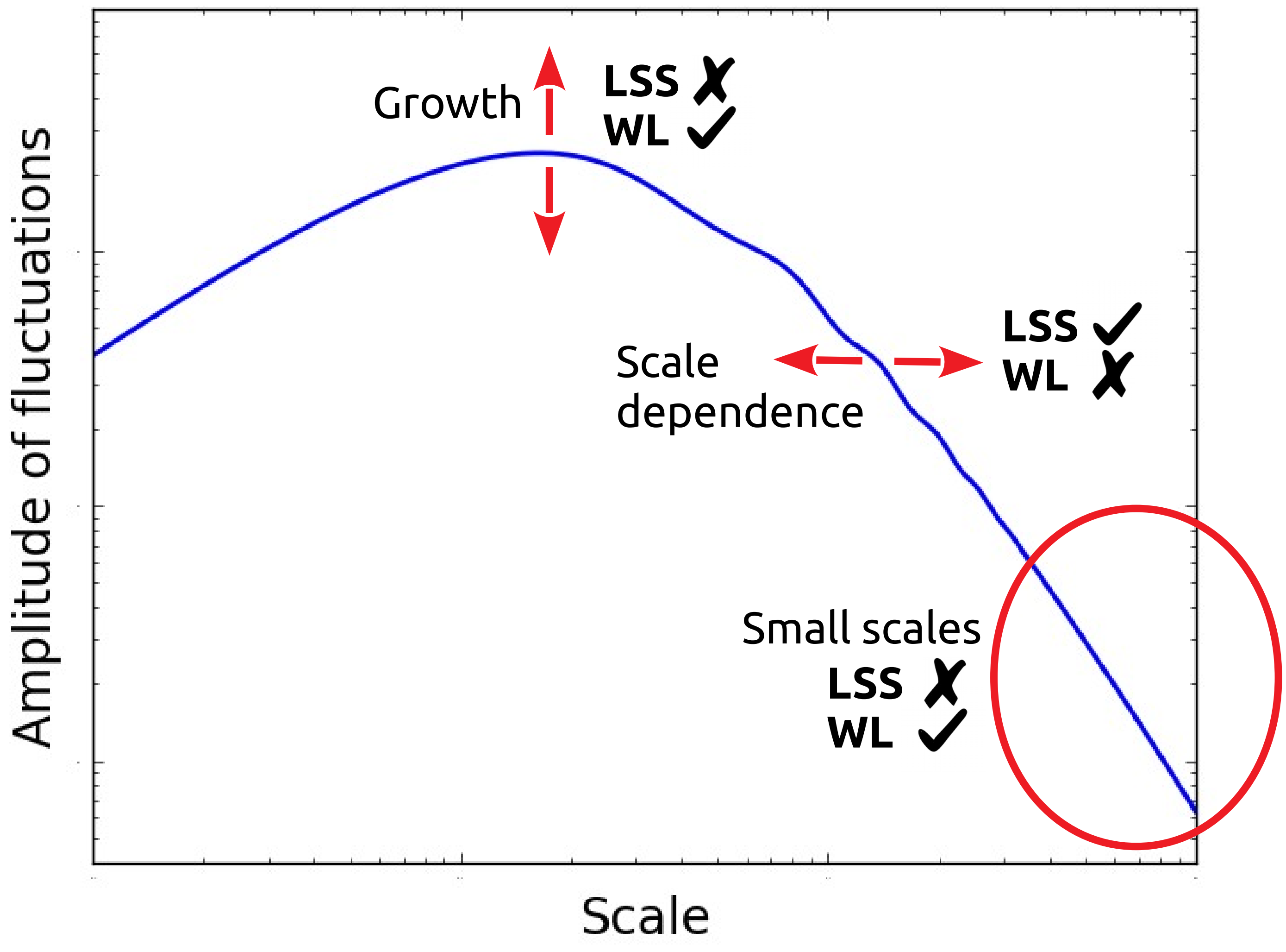


Credit: NASA/ESA

Kaiser 1992
Bartelmann & Schneider 1999

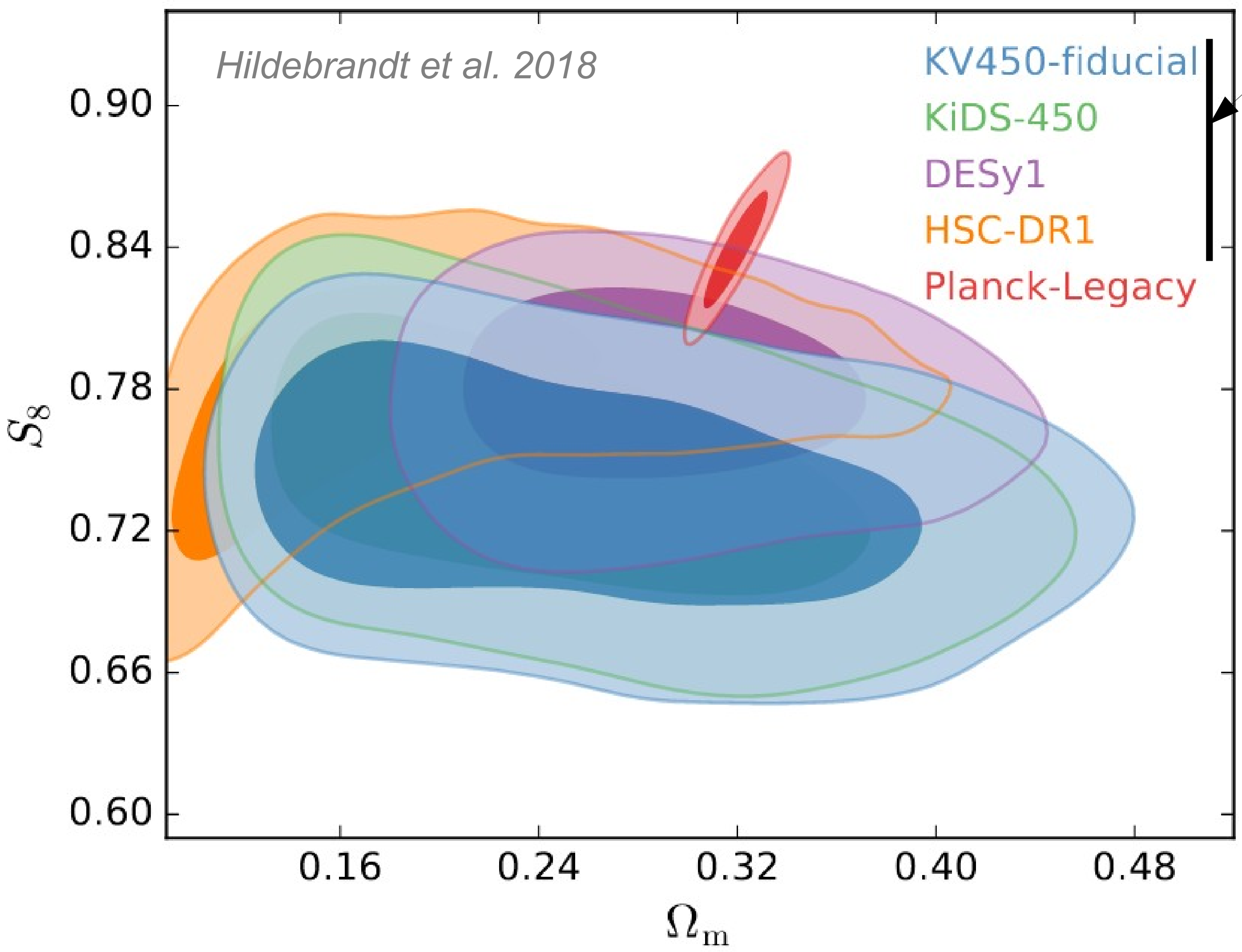
Cosmology with large-scale structure

GC-WL complementarity



Tension 1: the amplitude of fluctuations from lensing

$S_8 \rightarrow$ Overall "amplitude" of density fluctuations at late times.



WL+GC data measure this directly at late times (z<2).

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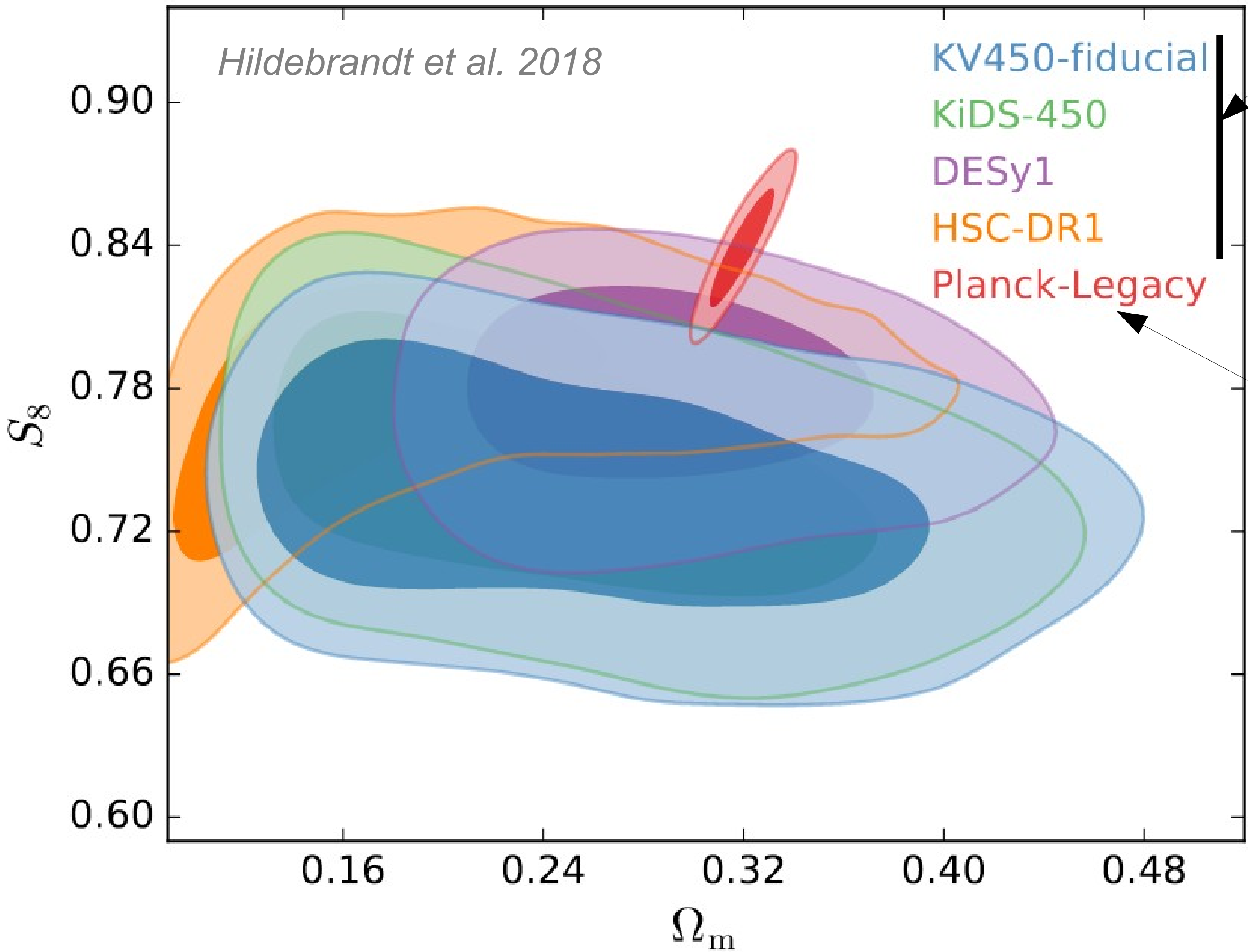

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CMB measures this at early times ($z \sim 10^3$) Then extrapolate to late times

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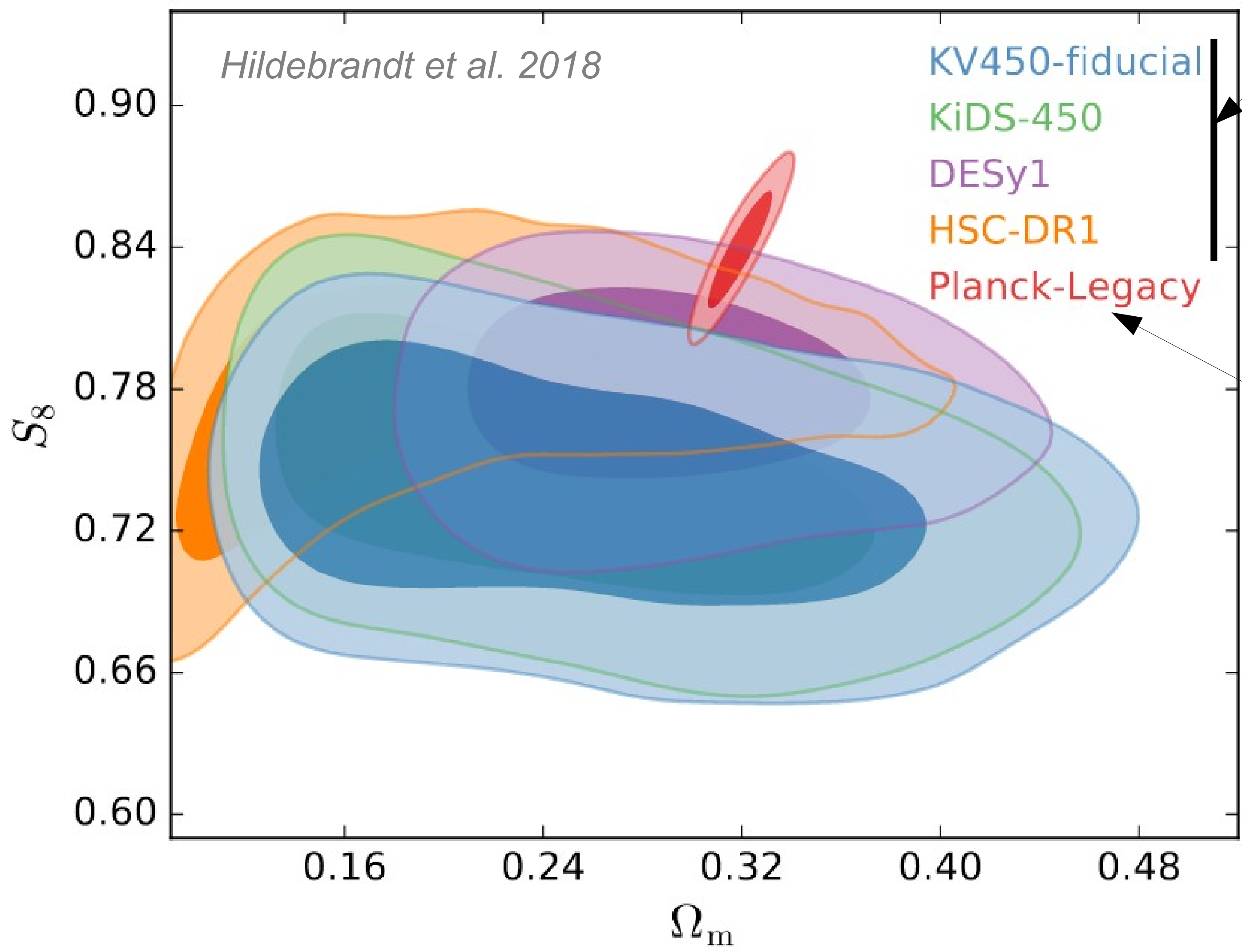

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Each lensing dataset disagrees with CMB at the 1-2σ level **in the same direction**.

Example: the LSST

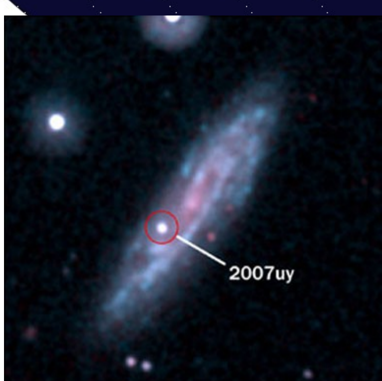
LSST

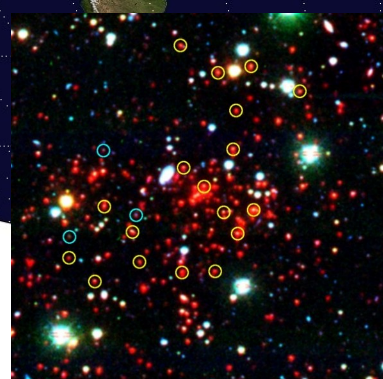
Outstanding numbers:

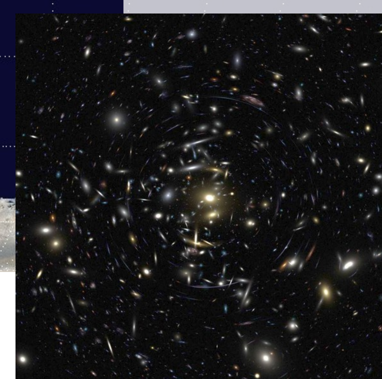
- World's largest imager
  8.4 m, 9.6 sq-deg FOV
- Wide: 20K sq-deg
- Deep: r~27
- Fast: ~100 visits per year
- Big data: ~15 TB per day

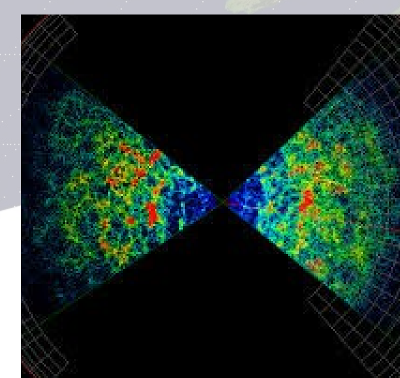
Dark Energy Science Collaboration:

- Supernovae
- Cluster science
- Strong lensing
- Weak lensing
- Large-scale structure









LSST Coll. et al. 0912.0201

Example: the LSST

Talk to Stephane, Julien, Jean-Eric, Jeremy!

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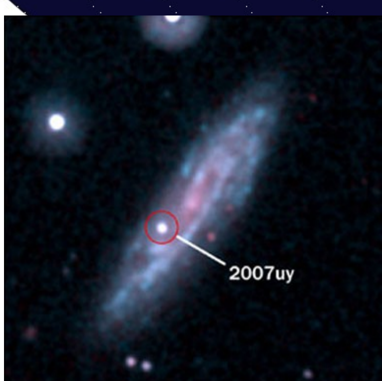

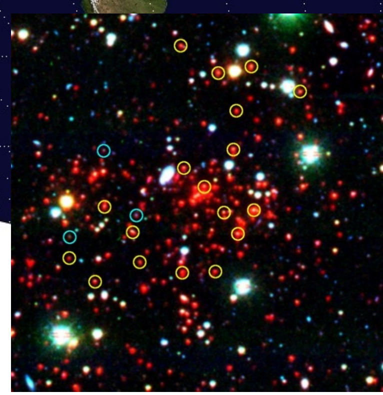

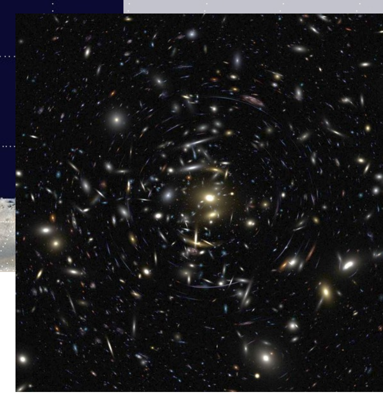

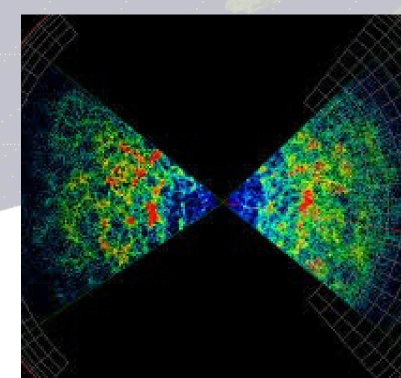

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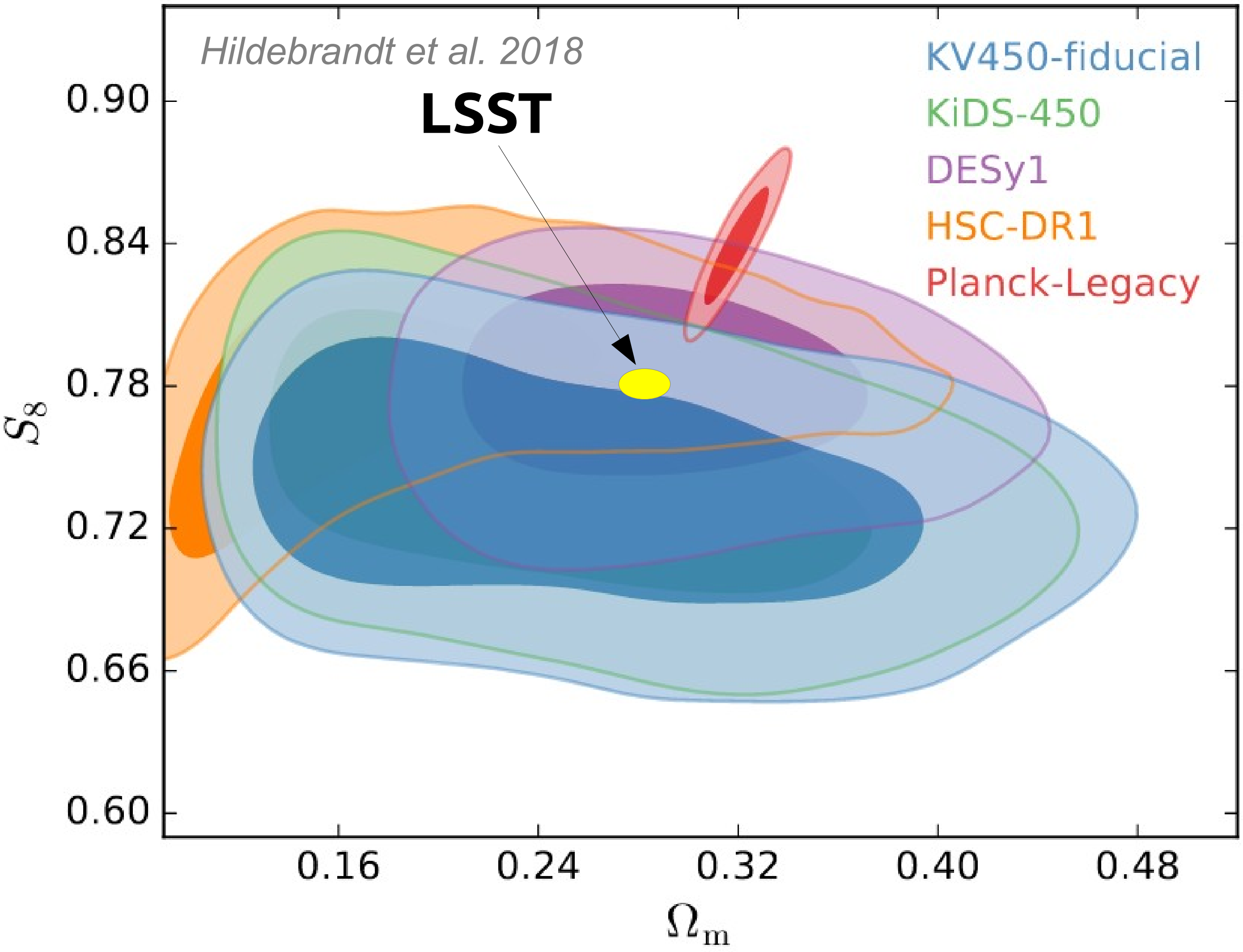
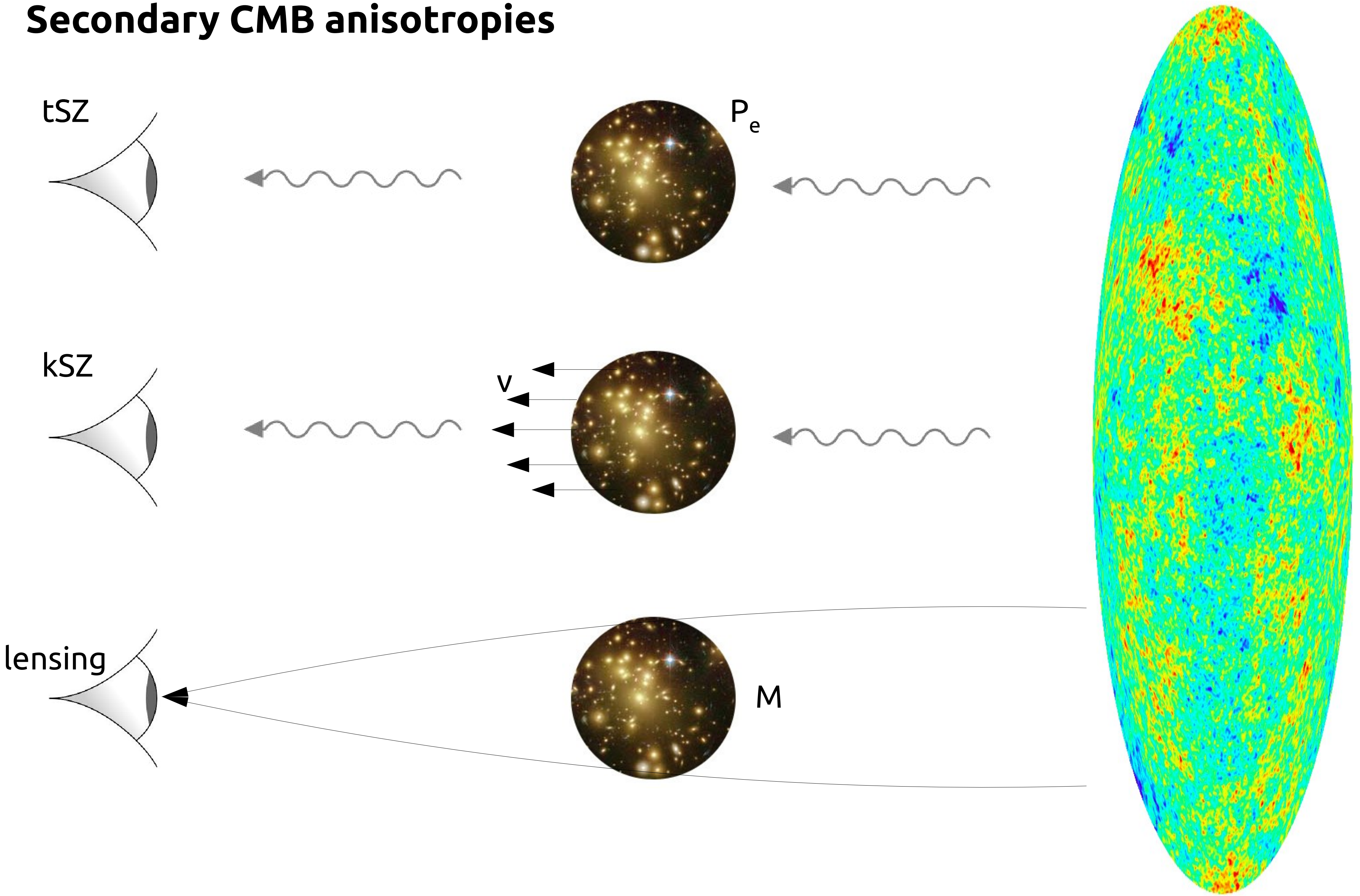


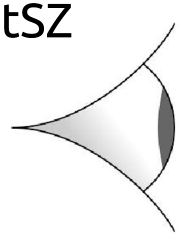
Secondary CMB anisotropies



CMB secondary anisotropies

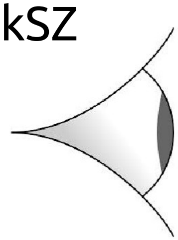
Secondary CMB anisotropies

tSZ



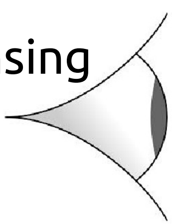
$$\left.\frac{\Delta \mathrm{T}}{\mathrm{T}}\right|_{\mathrm{tSZ}}(\nu, \hat{\mathbf{n}}) = f_{\mathrm{tSZ}}(\nu)\,\frac{\sigma_T}{m_e c^2}\int P_e(l_z, \hat{\mathbf{n}})\,dl_z$$
$$\equiv f_{\mathrm{tSZ}}(\nu)\,y(\hat{\mathbf{n}})$$

kSZ

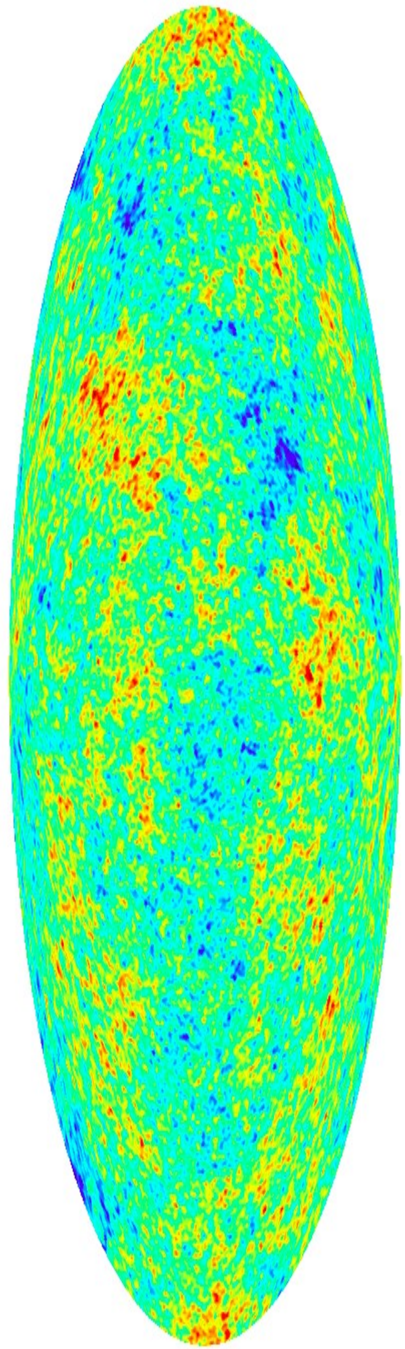


$$\left.\frac{\Delta \mathrm{T}}{\mathrm{T}}\right|_{\mathrm{kSZ}}(\hat{\mathbf{n}}) = -\sigma_T \int (\boldsymbol{\beta}\cdot\hat{\mathbf{n}})\,n_e(l_z, \hat{\mathbf{n}})\,dl_z$$
$$\equiv -\beta_r\,\tau(\hat{\mathbf{n}}),$$

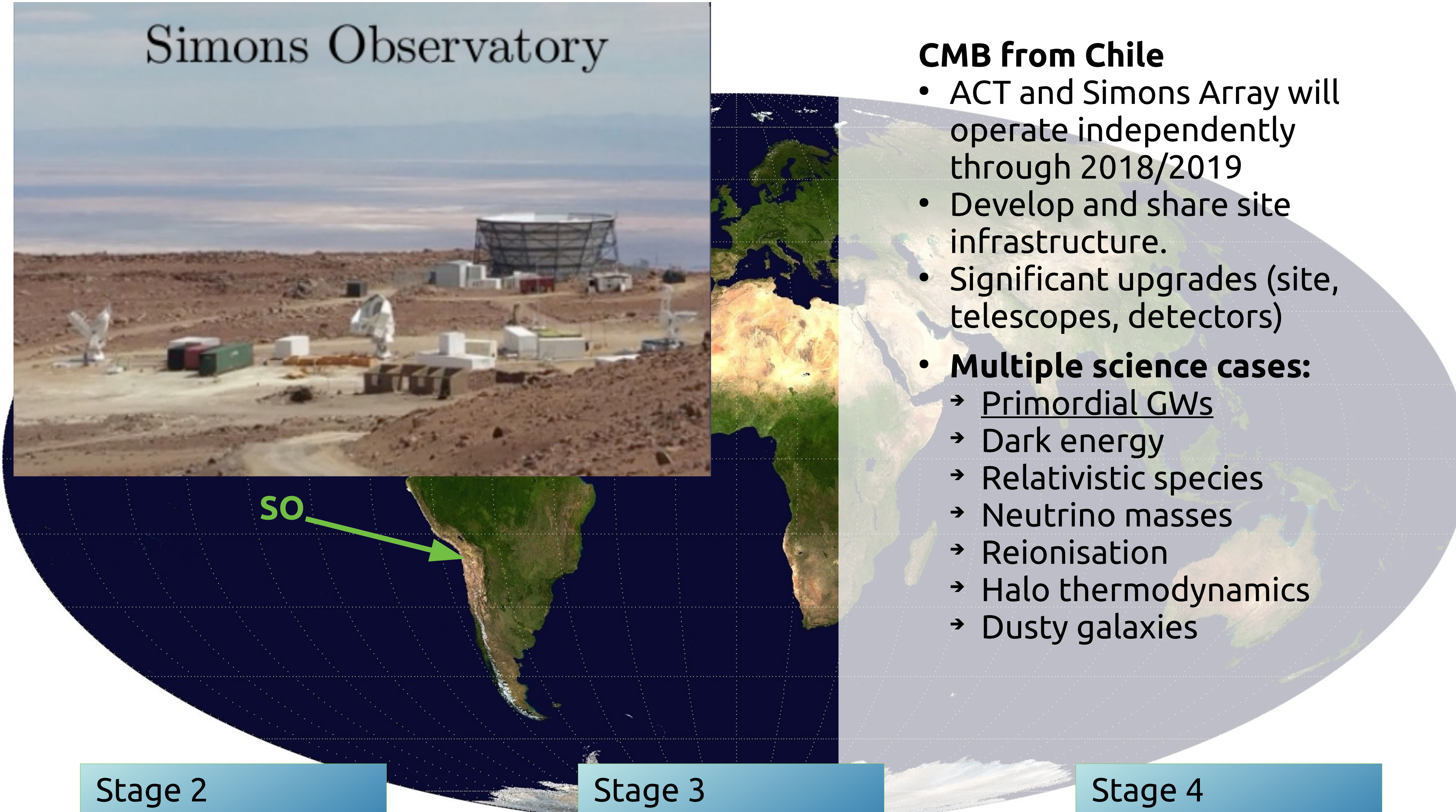
lensing



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



The Simons Observatory



CMB from Chile

- ACT and Simons Array will operate independently through 2018/2019
- Develop and share site infrastructure.
- Significant upgrades (site, telescopes, detectors)
- **Multiple science cases:**
  - → Primordial GWs
  - → Dark energy
  - → Relativistic species
  - → Neutrino masses
  - → Reionisation
  - → Halo thermodynamics
  - → Dusty galaxies

Stage 2
1000 detectors
σ(r) ~ 0.05
ACTPol, SPTPol, BICEP2
(2015 – 2016)

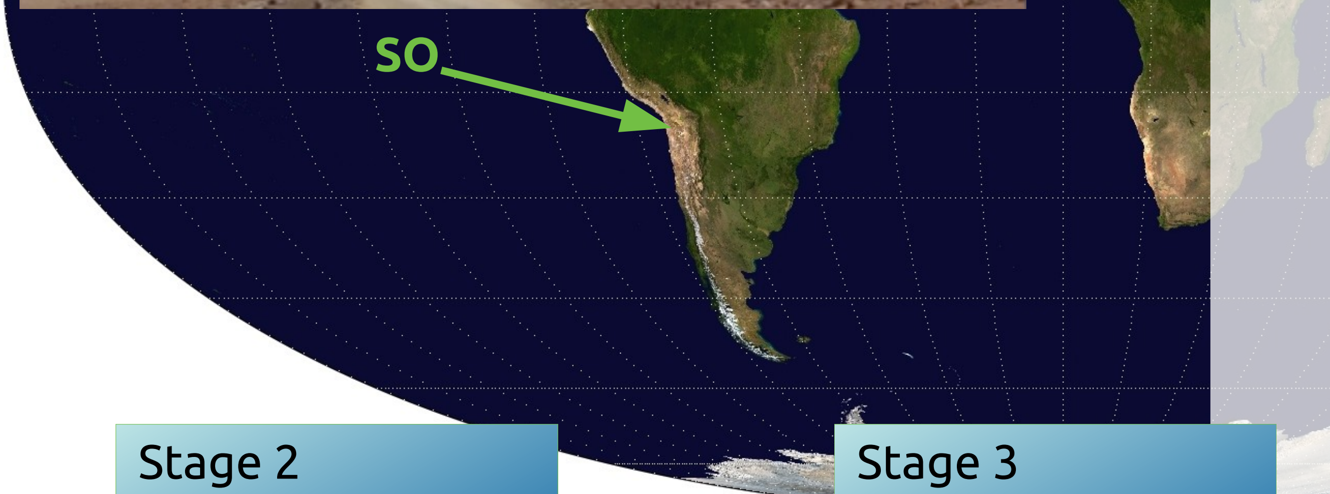
→

Stage 3
10,000 detectors
σ(r) ~ 0.006
AdvACT, SPT3G, SA
(2017 – 2020)

→

Stage 4
500,000 detectors
σ(r) ~ 0.0005
(2021 – 20**)

The Simons Observatory



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1000 detectors	10,000 detectors	500,000 detectors
σ(r) ~ 0.05	σ(r) ~ 0.006	σ(r) ~ 0.0005
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2015–2016	2017–2020	2021–20**

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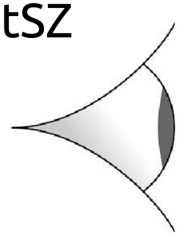

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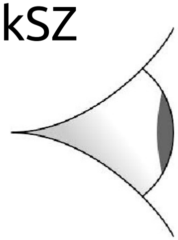
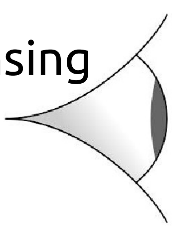
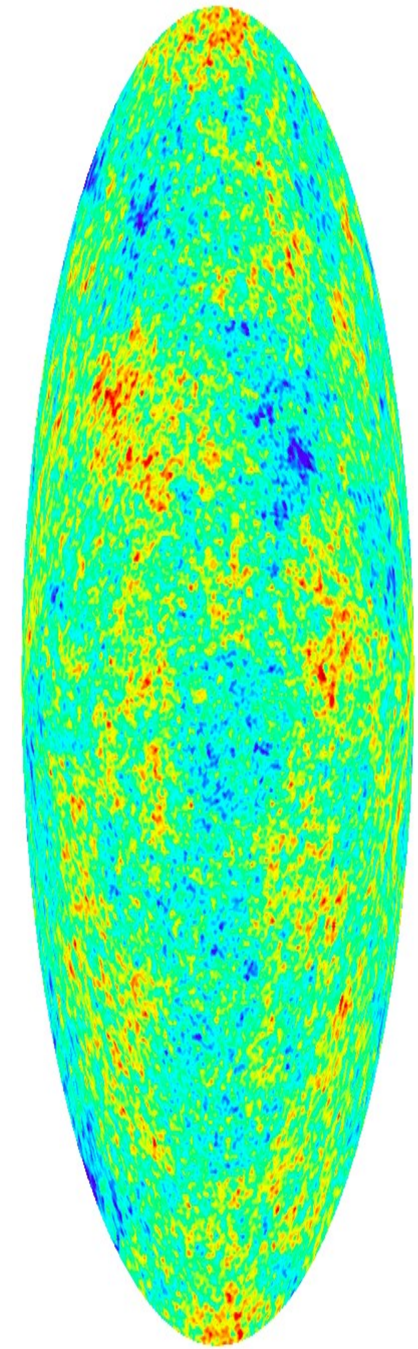


$$\left.\frac{\Delta \mathrm{T}}{\mathrm{T}}\right|_{\mathrm{kSZ}}(\hat{\mathbf{n}}) = -\sigma_T \int (\boldsymbol{\beta}\cdot\hat{\mathbf{n}})\,n_e(l_z, \hat{\mathbf{n}})\,dl_z$$
$$\equiv -\beta_r\,\tau(\hat{\mathbf{n}}),$$

lensing



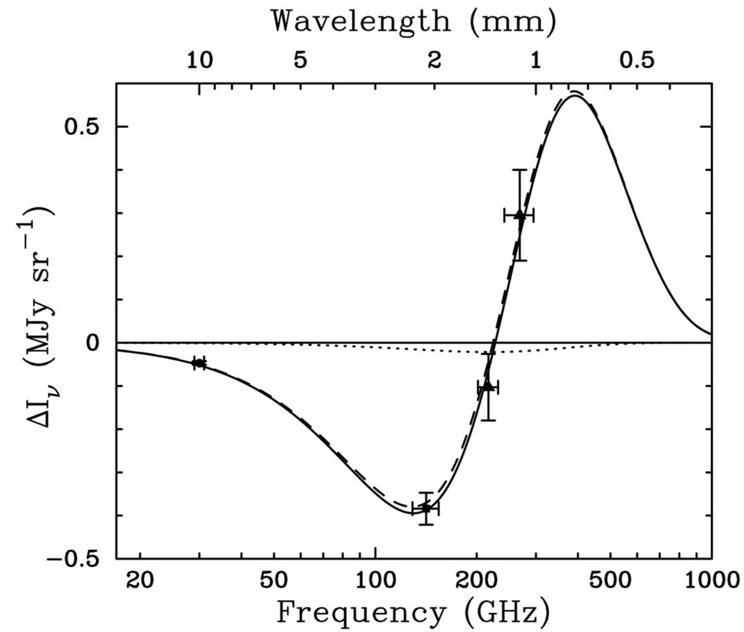
$$\kappa(\boldsymbol{x}) = \Sigma(\boldsymbol{x})/\Sigma_{\mathrm{crit}}$$
$$\Sigma(\boldsymbol{x}) \equiv \int_{-\infty}^{\infty} dl\,\rho(l, \boldsymbol{x}),\quad \Sigma_{\mathrm{crit}} \equiv \frac{c^2 d_S}{4\pi G\,d_L\,d_{LS}}$$

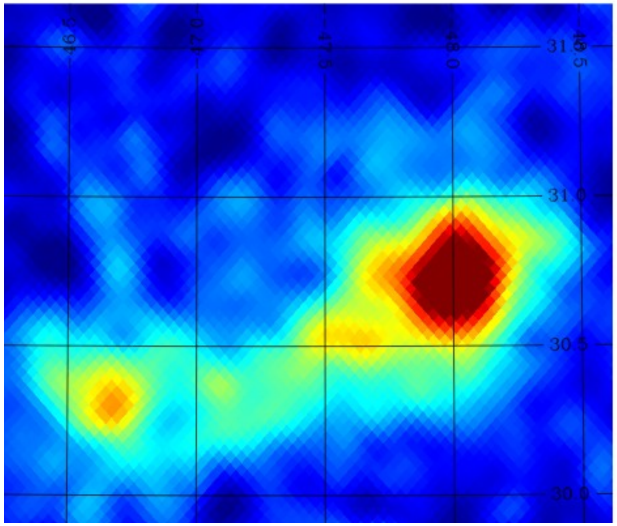


Thermal Sunyaev-Zel'dovich

Thermal Sunyaev-Zel'Dovich effect

- Scattering of CMB photons off high-energy thermal electrons.
- Characteristic SED → separable using multi-frequency.
- Direct tracer of gas pressure.
- Indirect tracer of structure.
- Good mass proxy (tight correlation with halo mass).

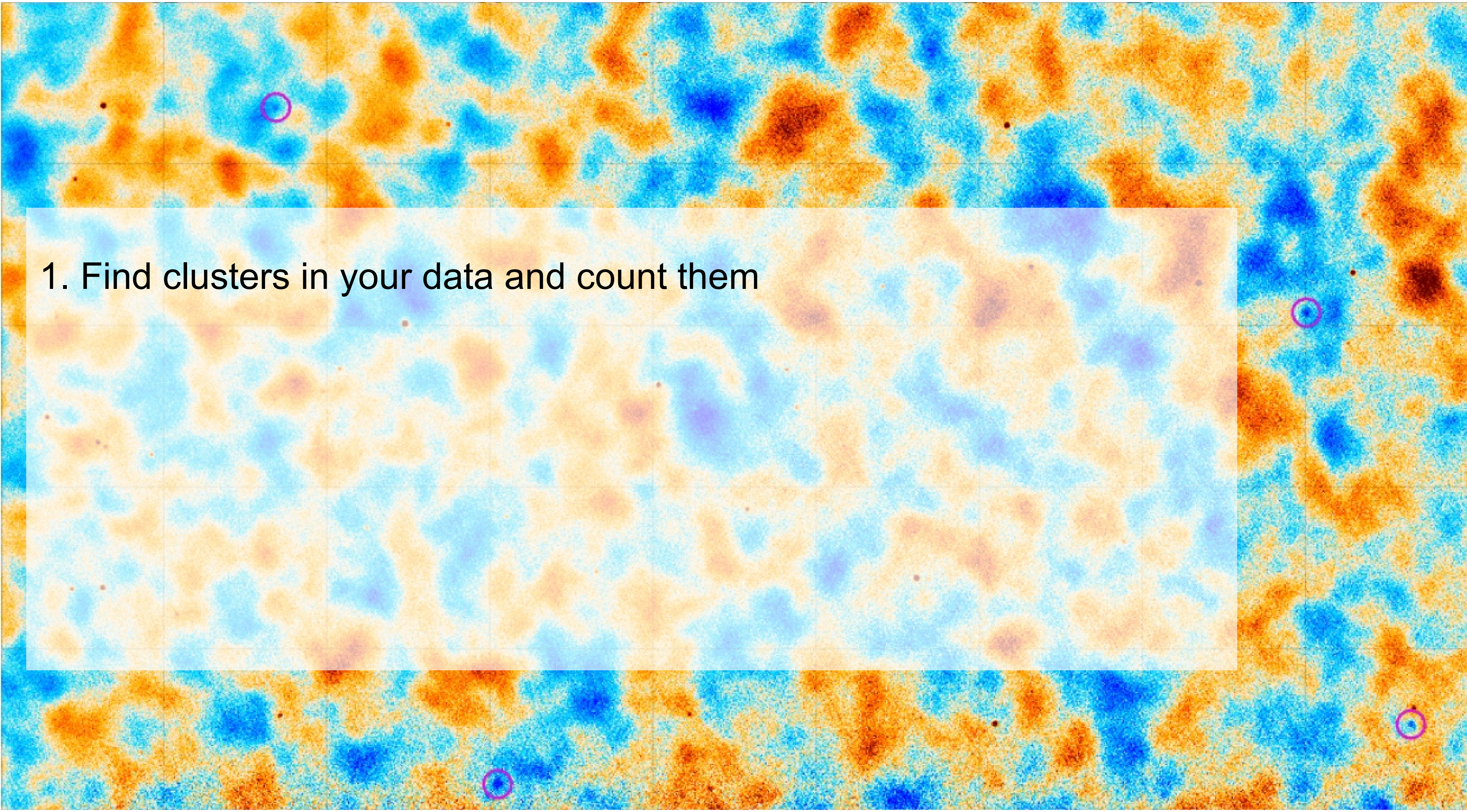




Shapley supercluster

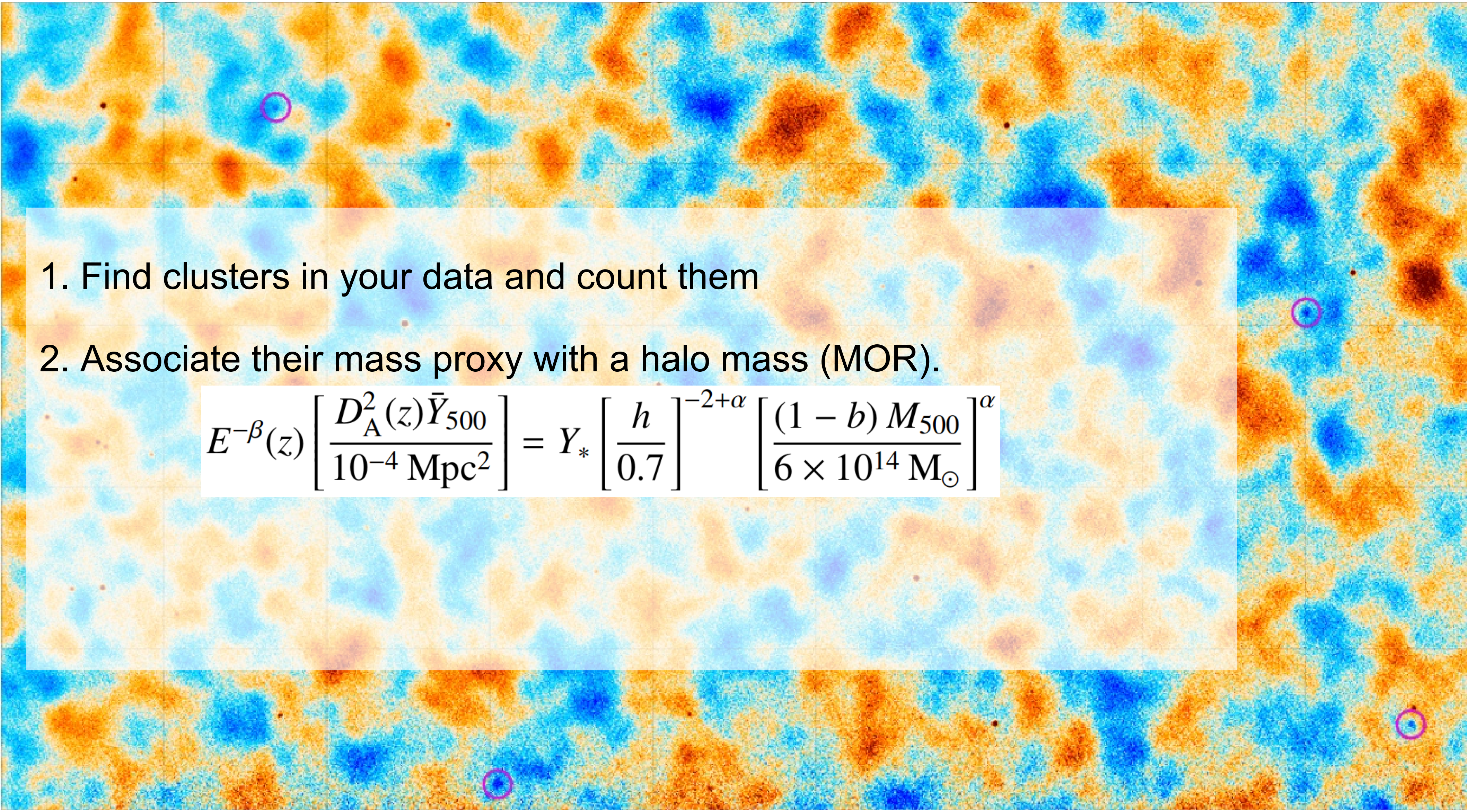
Planck Coll et al. 1502.01596

tSZ number counts



1. Find clusters in your data and count them

tSZ number counts

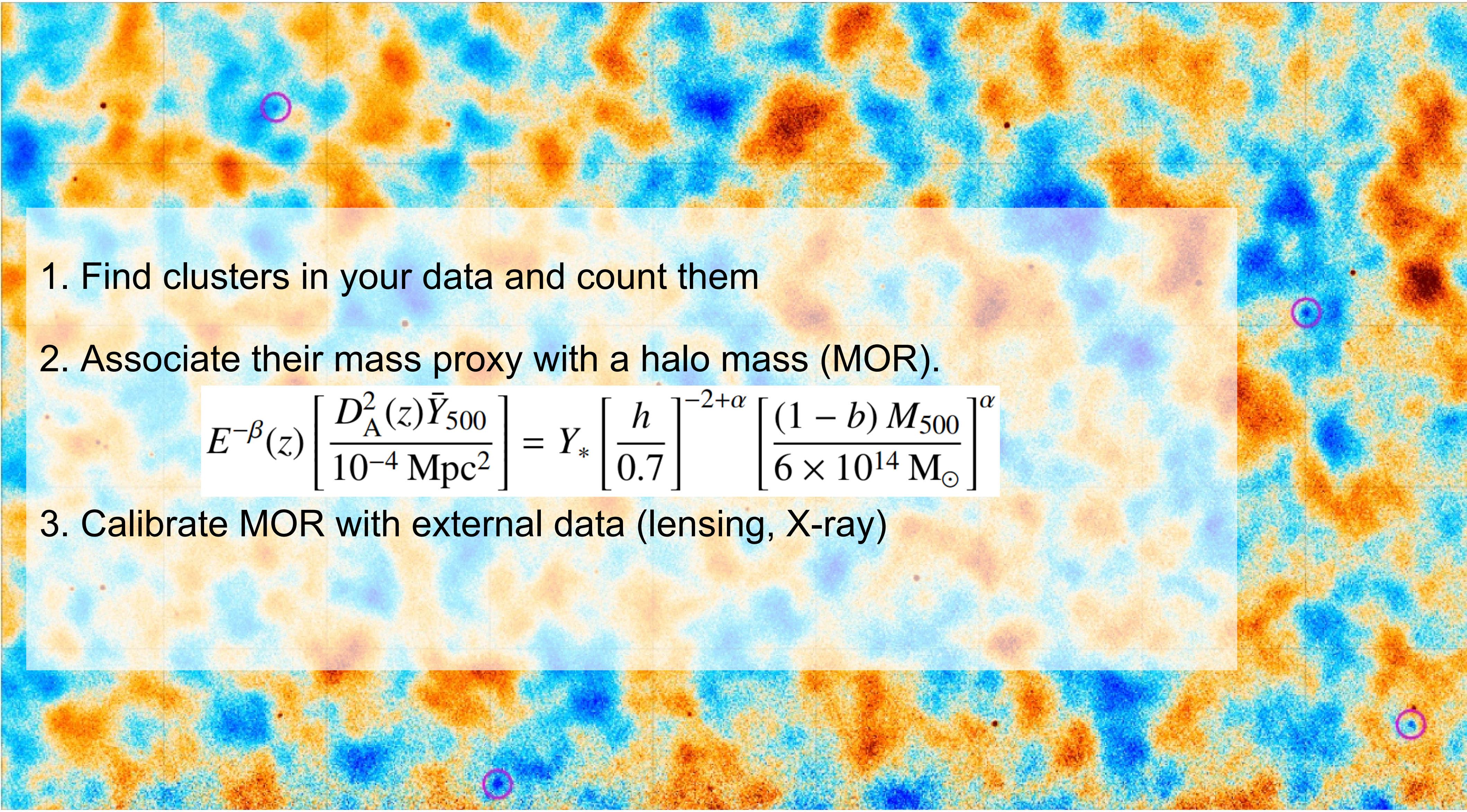


1. Find clusters in your data and count them

2. Associate their mass proxy with a halo mass (MOR).

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

tSZ number counts



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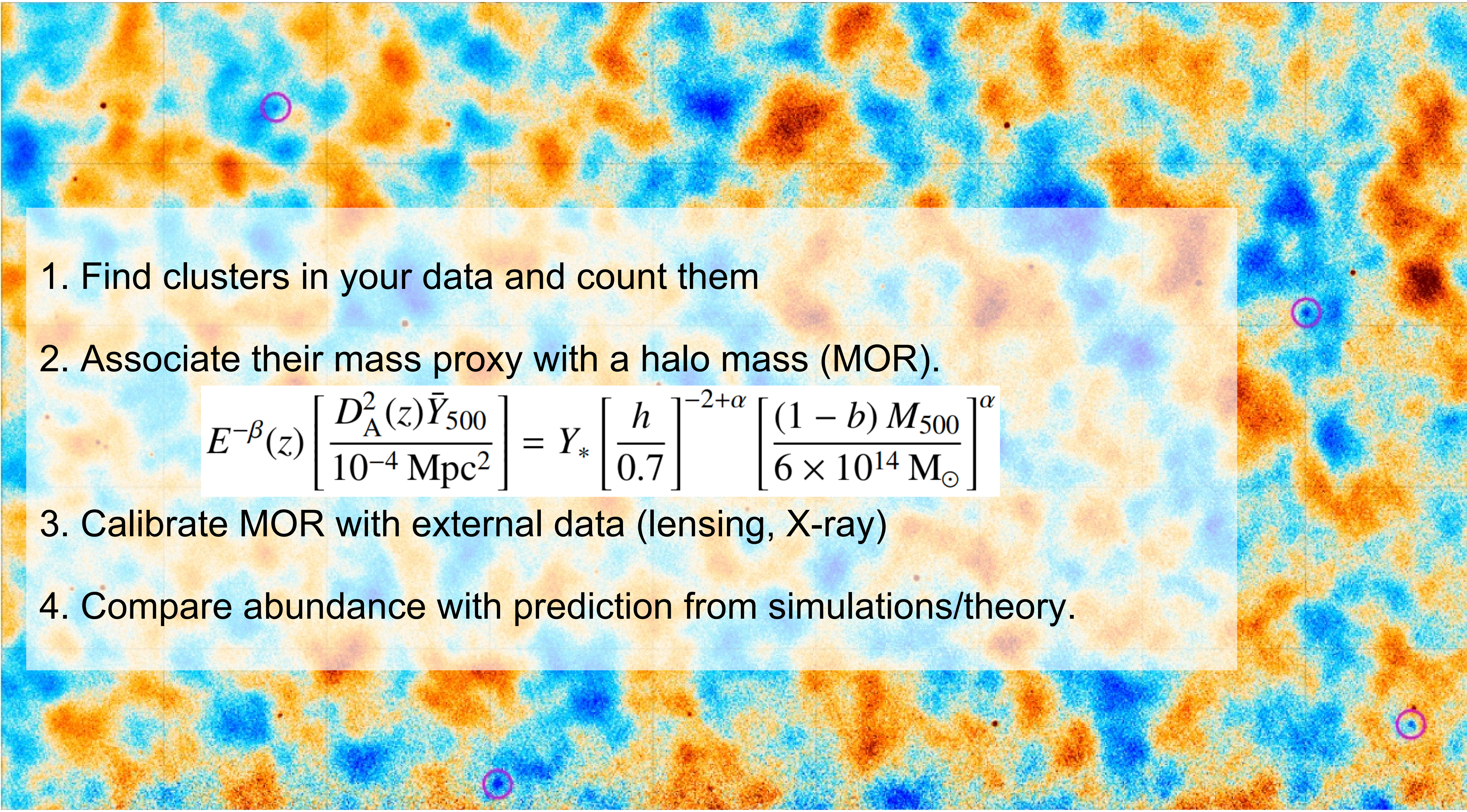
tSZ number counts



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3. Calibrate MOR with external data (lensing, X-ray)

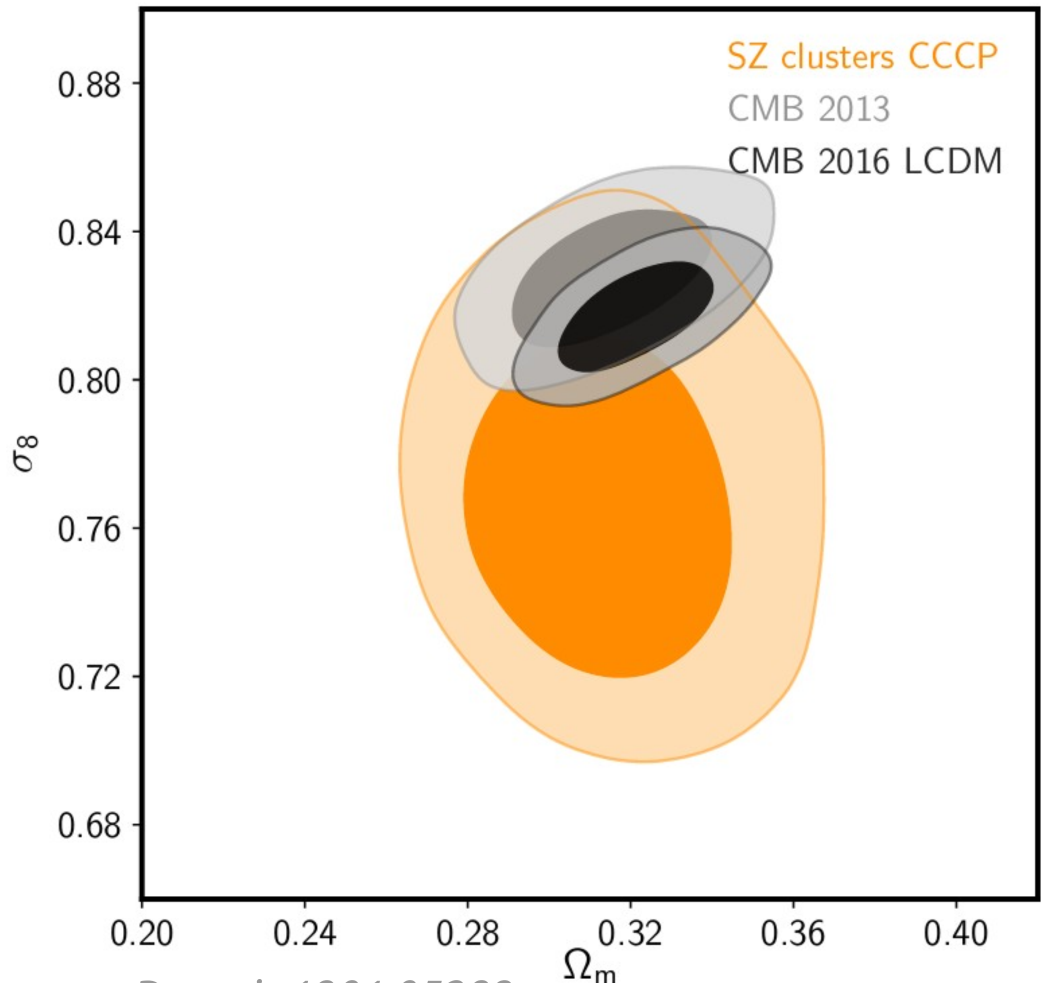
4. Compare abundance with prediction from simulations/theory.

Current tensions: the amplitude of fluctuations from clusters

Cluster cosmology:

- Imagine you had an estimate of the mass for some clusters.
- Their distribution is predicted by the mass function.
- Use the distribution to infer cosmology.

  ...
- However, you don't know the mass, only observable proxies of it.
- So first calibrate mass-observable relation.
- Then marginalize over all necessary nuisance parameters.
- Example: SZ-selected clusters.
- ~2.4σ deviation for Planck data.



Douspis 1901.05289
Planck Coll et al. 1502.01596

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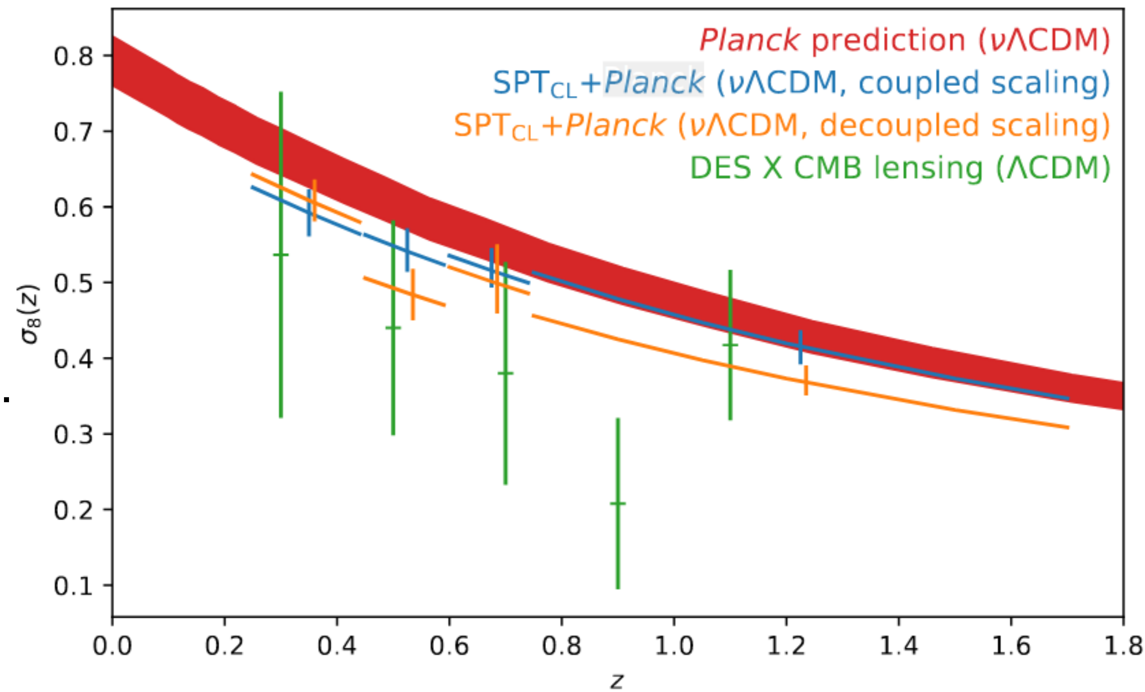

Bocquet et al. 2018

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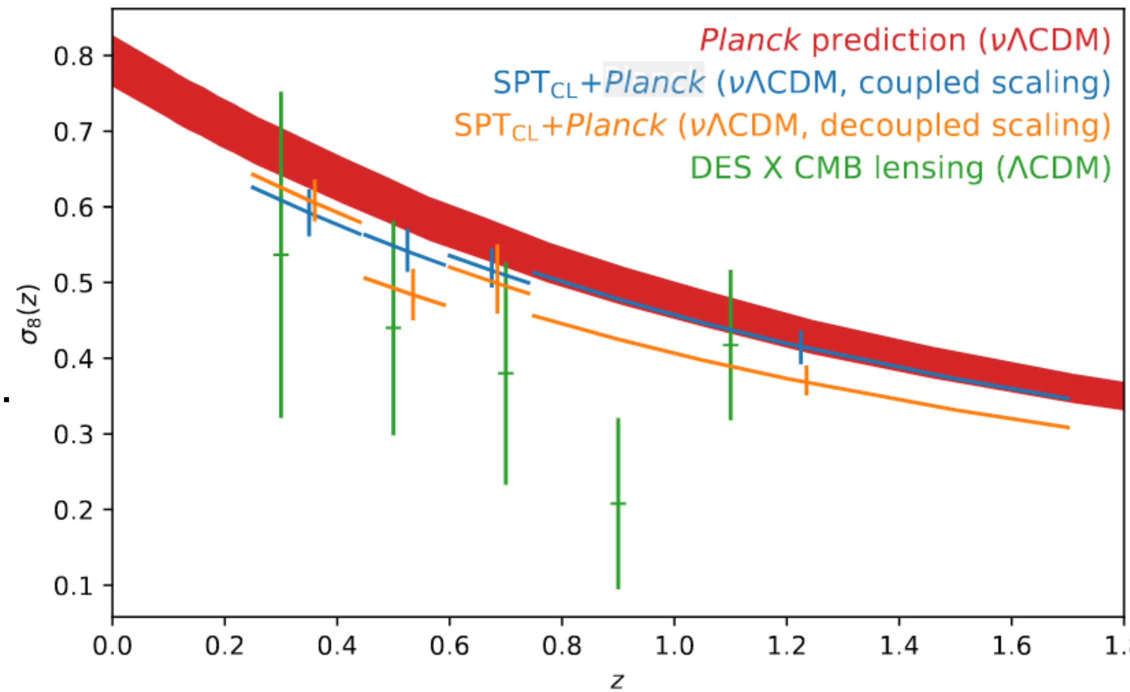
- Example: SZ-selected clusters.
- ~2.4σ deviation for Planck data.
  (similar result in SPT data)
  (in the same direction as weak lensing!)
  (similar claims with redshift-space dist.)



Bocquet et al. 2018

SZ challenges: mass calibration

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

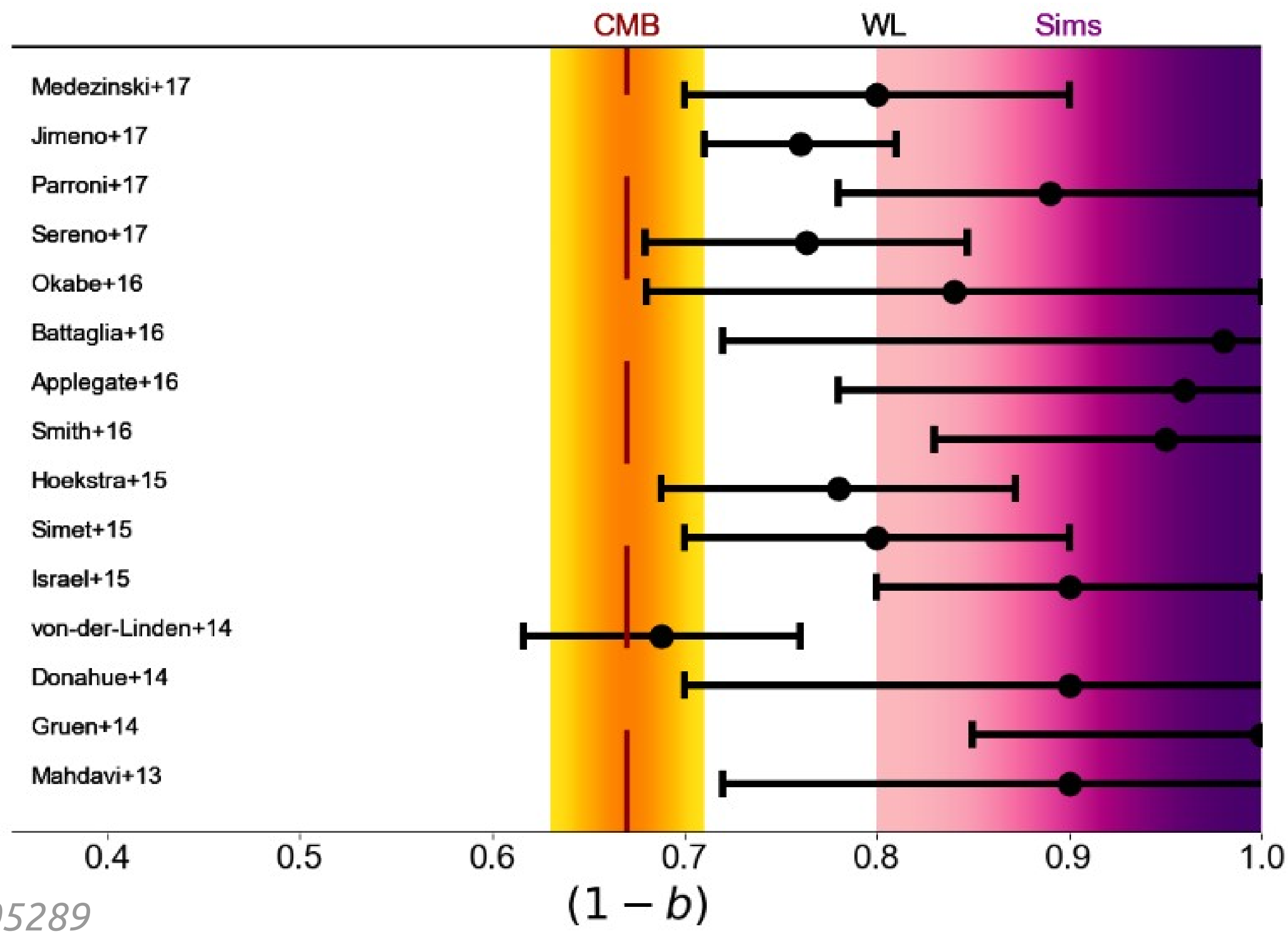
Planck Coll et al. 1502.01596

How much mass are we missing in X-ray observations?

SZ challenges: mass calibration

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

Planck Coll et al. 1502.01596



Douspis 1901.05289

Calibrating SZ masses with CMB lensing

Calibrating masses with CMB lensing

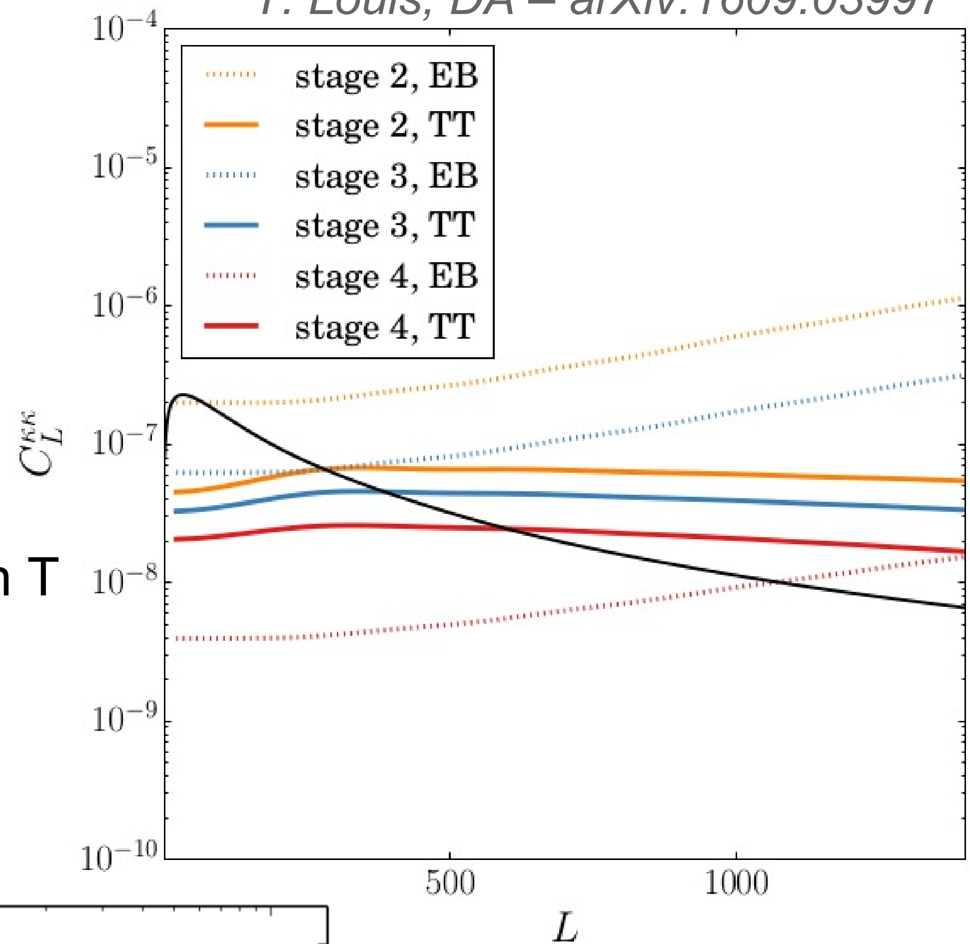
Main complication: tSZ Y_{500} ↔ halo mass

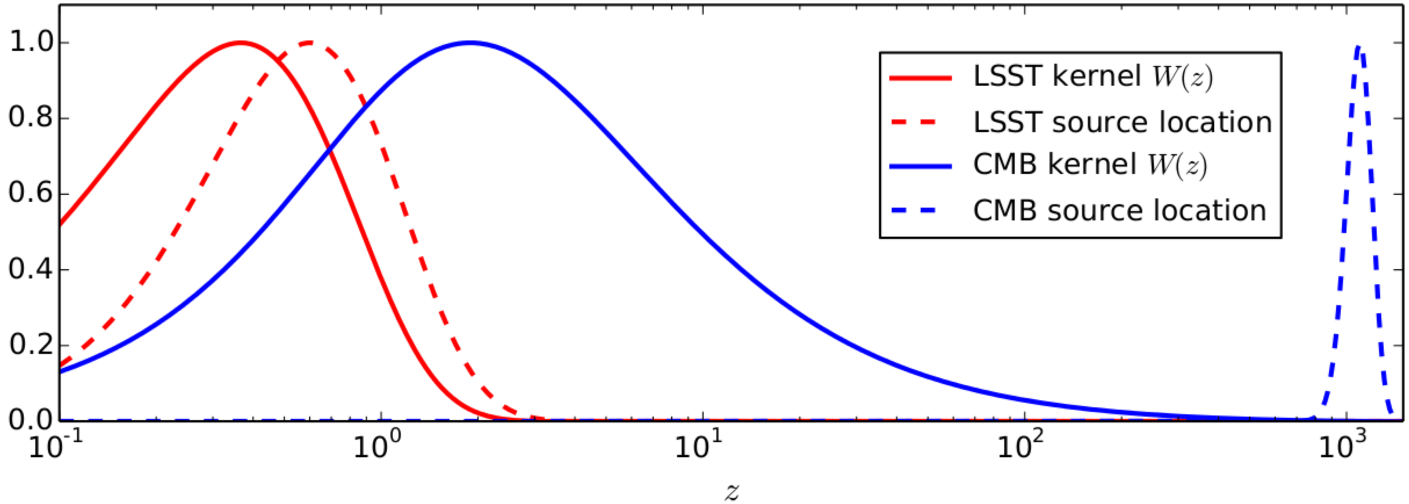
Options:

- X-ray
- Weak galaxy lensing
  - ✗ Lensing systematics?
  - ✗ High z?
- CMB lensing?
  - ✔ Potentially better systematics
  - ✔ With S4, better lensing noise with P than T (more robust against foregrounds)

Melin et al. 2015
S4 collaboration – arXiv:1610.02743
Madhavacheril et al. 2017

T. Louis, DA – arXiv:1609.03997





Calibrating SZ masses with CMB lensing

T. Louis, DA – arXiv:1609.03997

Calibrating masses with CMB lensing

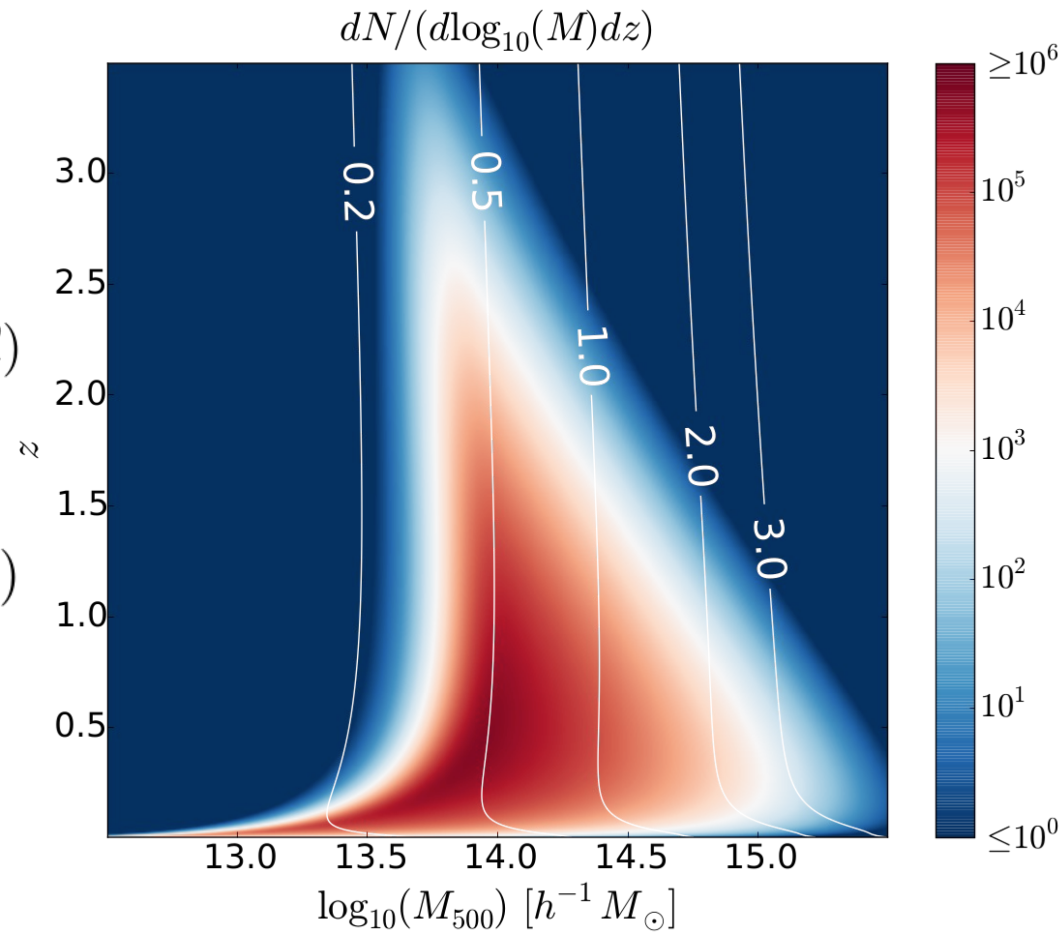
Method:

- Find clusters in temperature map from tSZ
- Reconstruct lensing convergence from polarization
- Estimate cluster mass and Compton-Y using matched filter approach in either map

$$\kappa(\boldsymbol{x}) = U_\kappa(\boldsymbol{x})\kappa_{5\theta_{500}} + n_\kappa(\boldsymbol{x})$$

$$\hat{\kappa}_{5\theta_{500}} = \sigma^2(\hat{\kappa}_{5\theta_{500}}) \int d\boldsymbol{\ell} U_\kappa^T(\boldsymbol{\ell}) N_{\kappa\kappa}^{-1}(\boldsymbol{\ell})\kappa(\boldsymbol{\ell})$$

$$\sigma^{-2}(\hat{\kappa}_{5\theta_{500}}) = \int d\boldsymbol{\ell} U_\kappa^T(\boldsymbol{\ell}) N_{\kappa\kappa}^{-1}(\boldsymbol{\ell}) U_\kappa(\boldsymbol{\ell})$$

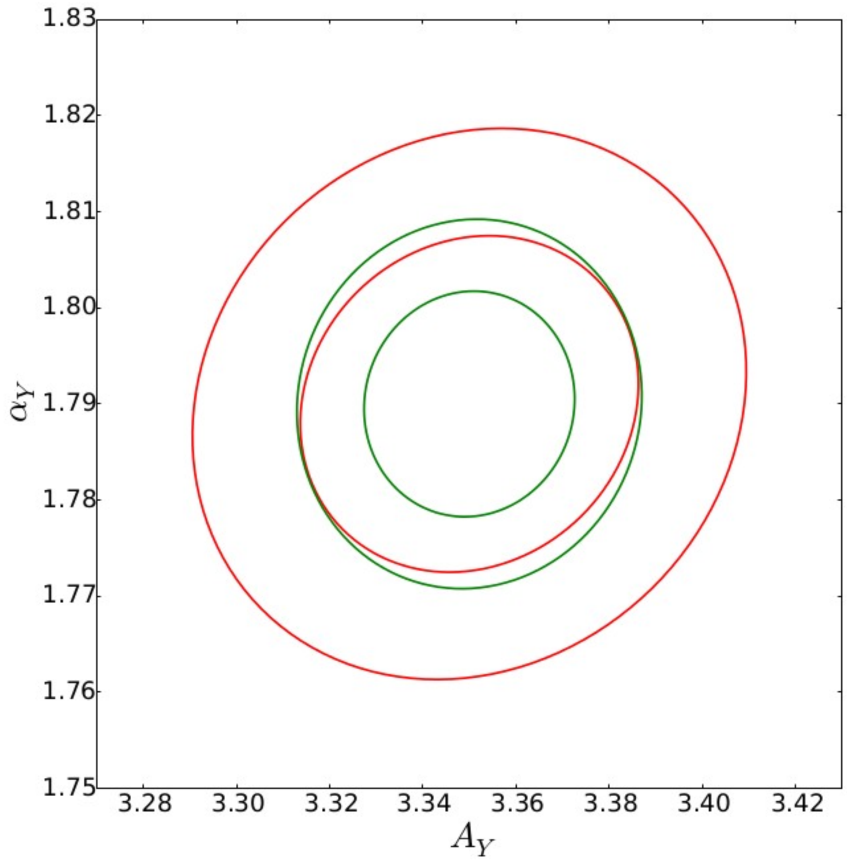


Calibrating SZ masses with CMB lensing

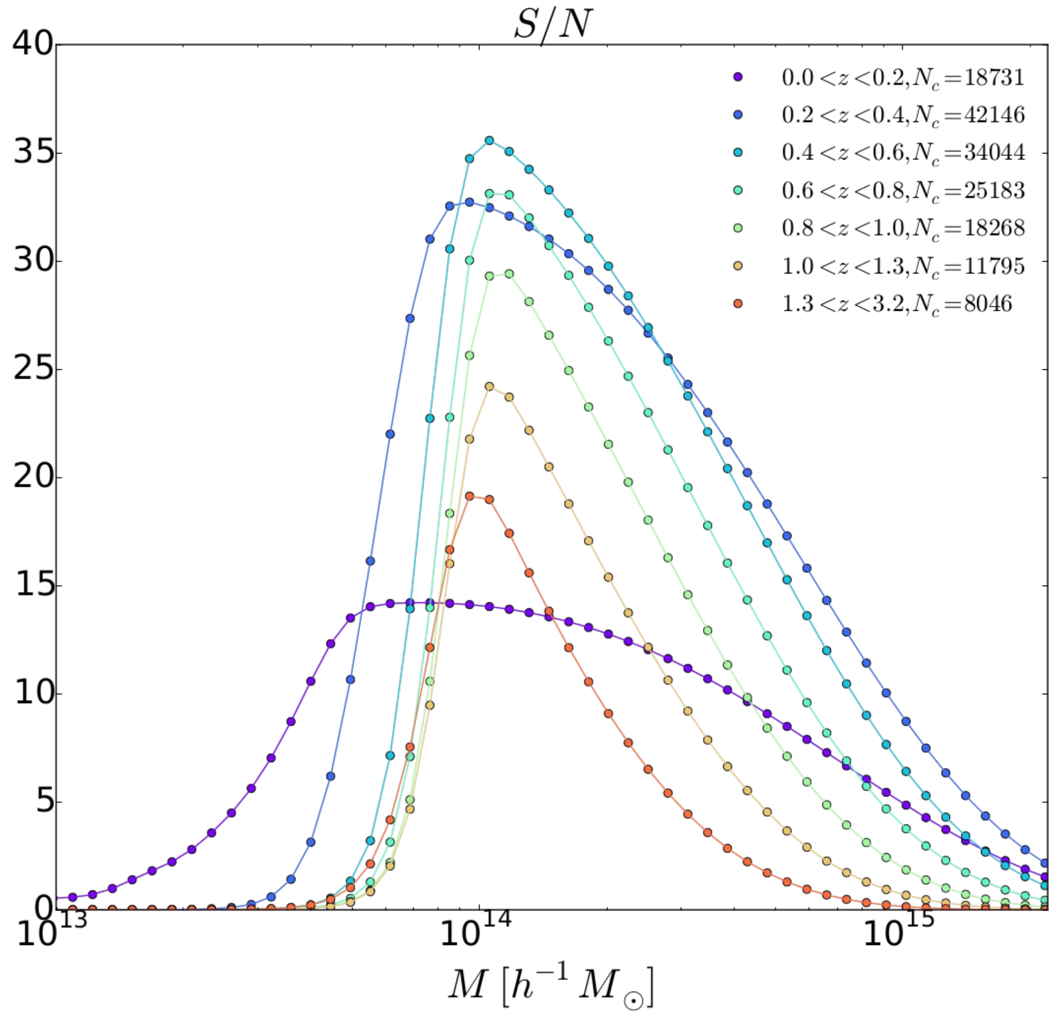
T. Louis, DA – arXiv:1609.03997

Mass calibration forecasts

Parametric



Non-parametric



~0.4% measurement of (1-b)

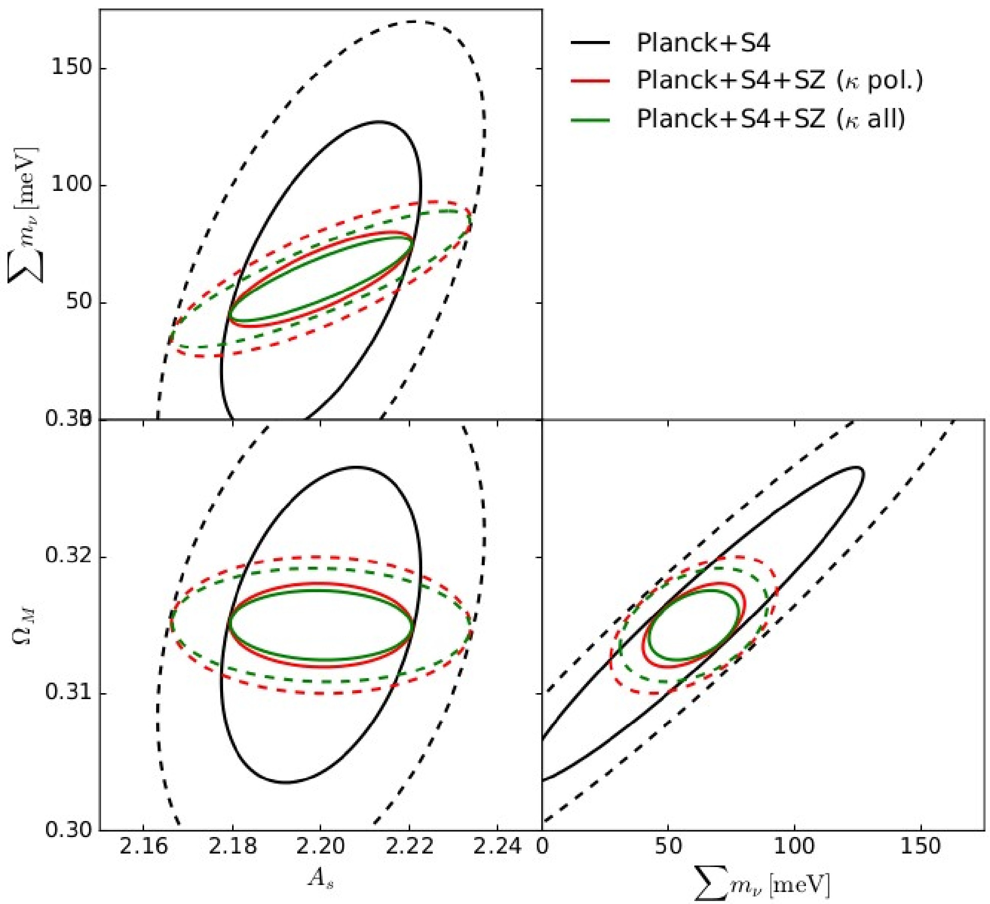
Calibrating SZ masses with CMB lensing

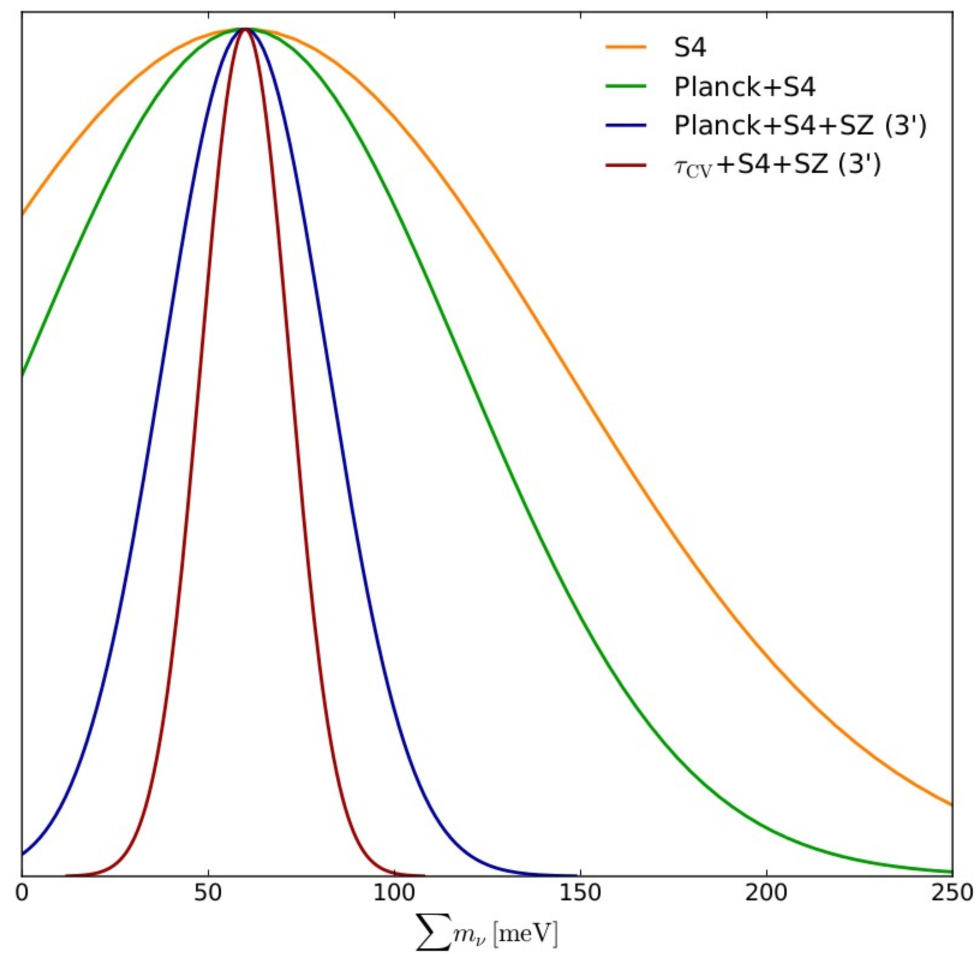
T. Louis, DA – arXiv:1609.03997

Connection with cosmological parameters

Joint tSZ+lensing likelihood
3-5σ measurement of neutrino mass

$$\frac{N(q, M_L, z)}{\Delta q_Y \, \Delta M_L \, \Delta z} \equiv \int dM dY \frac{d^3 N}{dz \, dM \, dY} P(q_Y, M_L | Y, M)$$





Mapping the tSZ effect

There is gas everywhere!
- We can estimate the tSZ flux at every pixel (not just in clusters).
- This will make us sensitive to sources below the detection level and diffuse components.
- Ideal to study warm gas and its correlation with other density tracers.

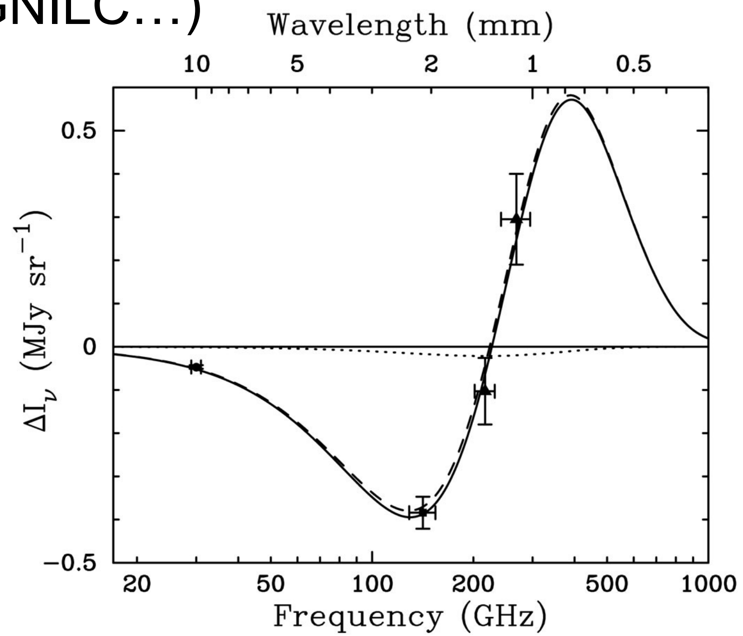
Internal Linear Combination (ILC):

tSZ has a well-known, universal SED (+ small relativistic effects).

Find the linear combination of all your frequency maps that:
- Leaves the tSZ contribution untouched.
- Minimizes the variance of the final map.

State-of-the-art methods implement further bells and whistles:
- Position- and scale-dependent ILCs (MILCA, NILC, GNILC…)
- Deprojection of contaminants with known SEDs

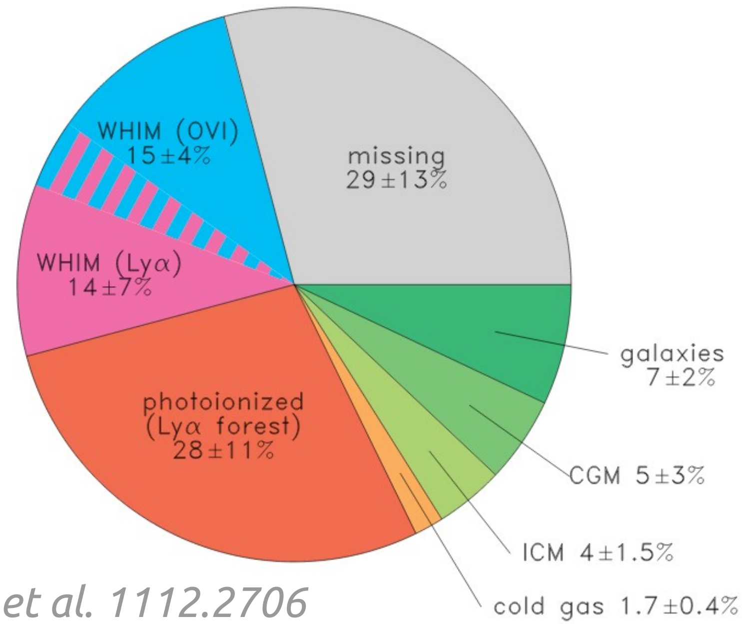
Eriksen et al. 2004
Hurier et al. 2010
Delabrouille et al. 2009
Remazeilles et al. 2011a,b



Measuring gas properties

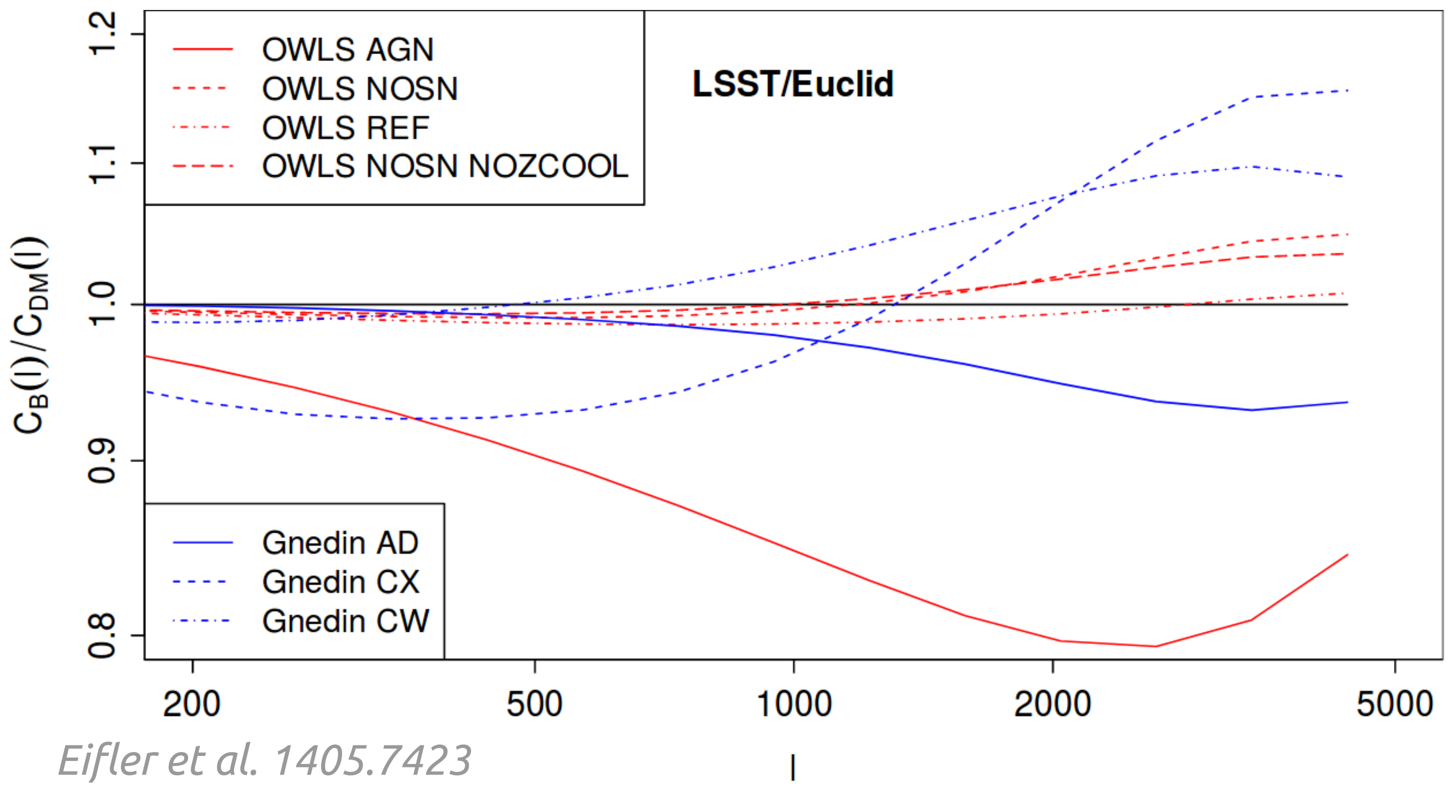
Why study gas?

1. Baryonic effects are a poorly-understood systematic for measurements of the matter power spectrum.
2. We don't have a good understanding of the diffuse gas distribution and thermodynamics ("missing baryons").
3. Uncertain temperature-density relation (e.g. Lya systematics)
4. Cluster mass uncertainties leak directly into cosmology.



Shull et al. 1112.2706

Bregman 0706.1787
Planck et al. 1504.03339
Hill et al. 1603.01608
Hill & Spergel 1312.4525
Hernandez-Monteagudo et al. 1504.04011



Eifler et al. 1405.7423

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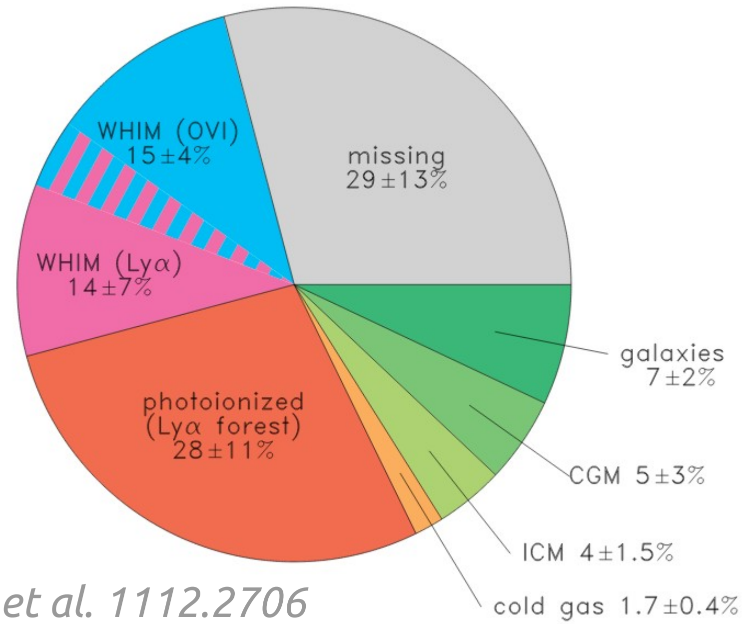

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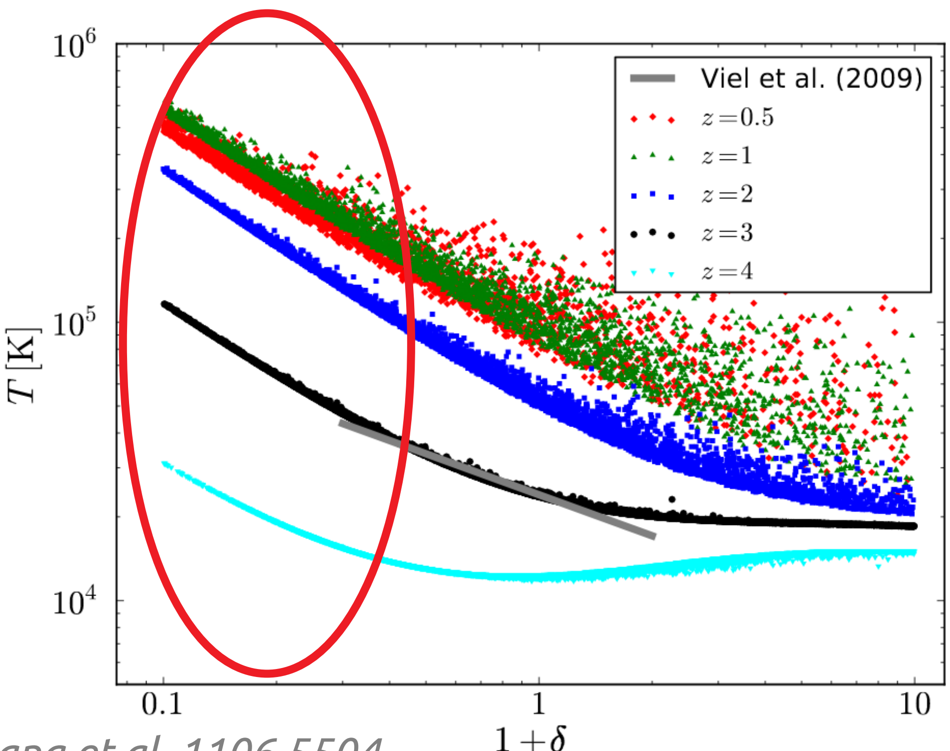
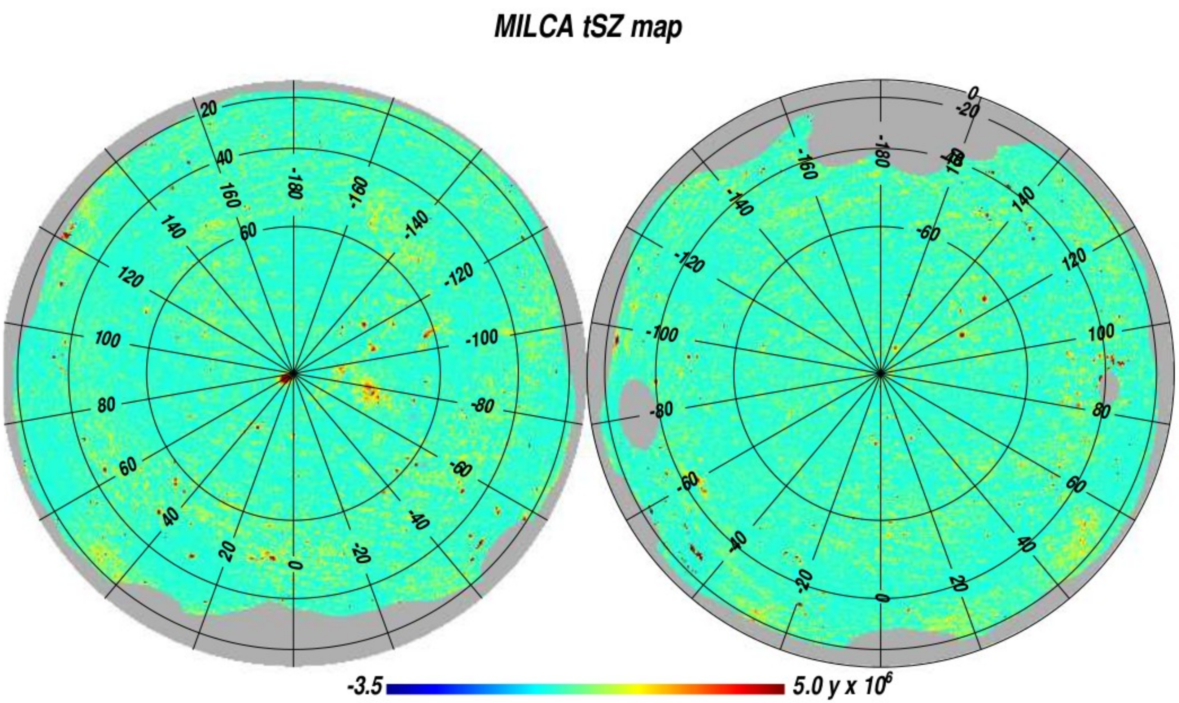


Chang et al. 1106.5504

Cross-correlation with galaxy clustering

$$y \propto (1 - b_H)^{\alpha} \qquad \delta_g \propto b_g$$



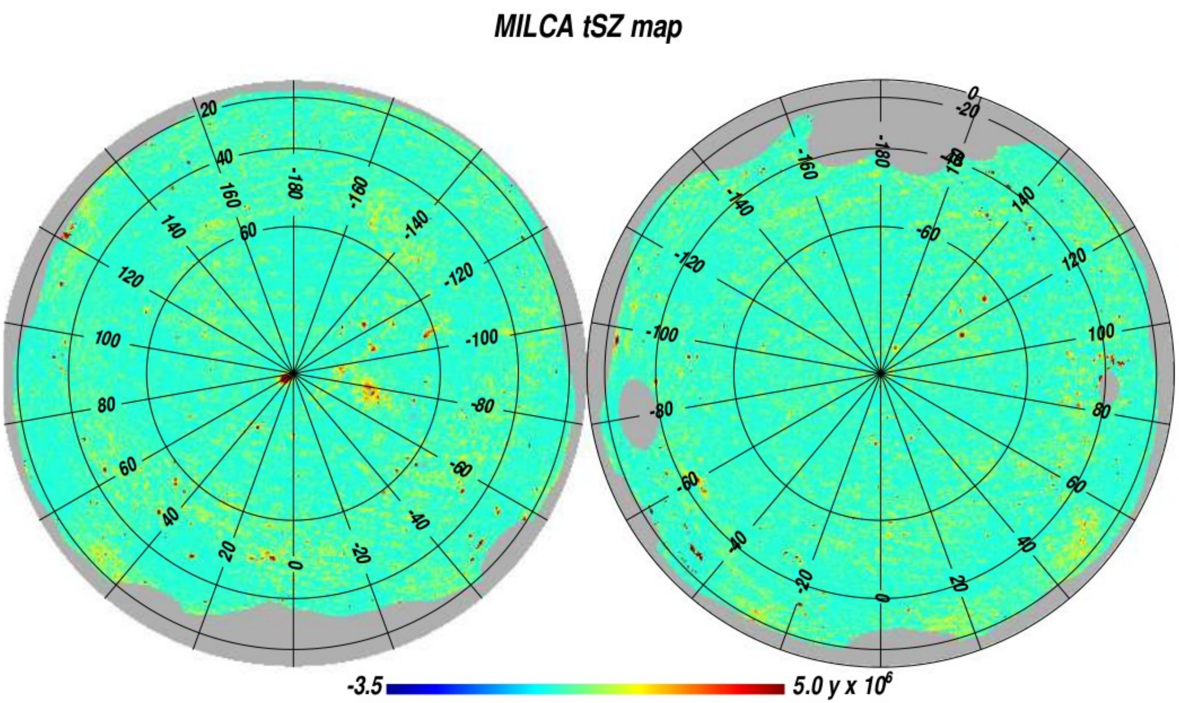
Nick Koukoufilippas

Cross-correlation with galaxy clustering

$$y \propto (1 - b_H)^{\alpha} \qquad \delta_g \propto b_g$$

$$C_\ell^{gg} \propto b_g^2$$ ← Measure galaxy bias.

$$C_\ell^{gy} \propto b_g(1 - b_H)$$ ← Use it to measure hydrostatic bias



Nick Koukoufilippas

Potential to also constrain y-λ relation.

SZ challenges: cross-correlation with galaxy clustering

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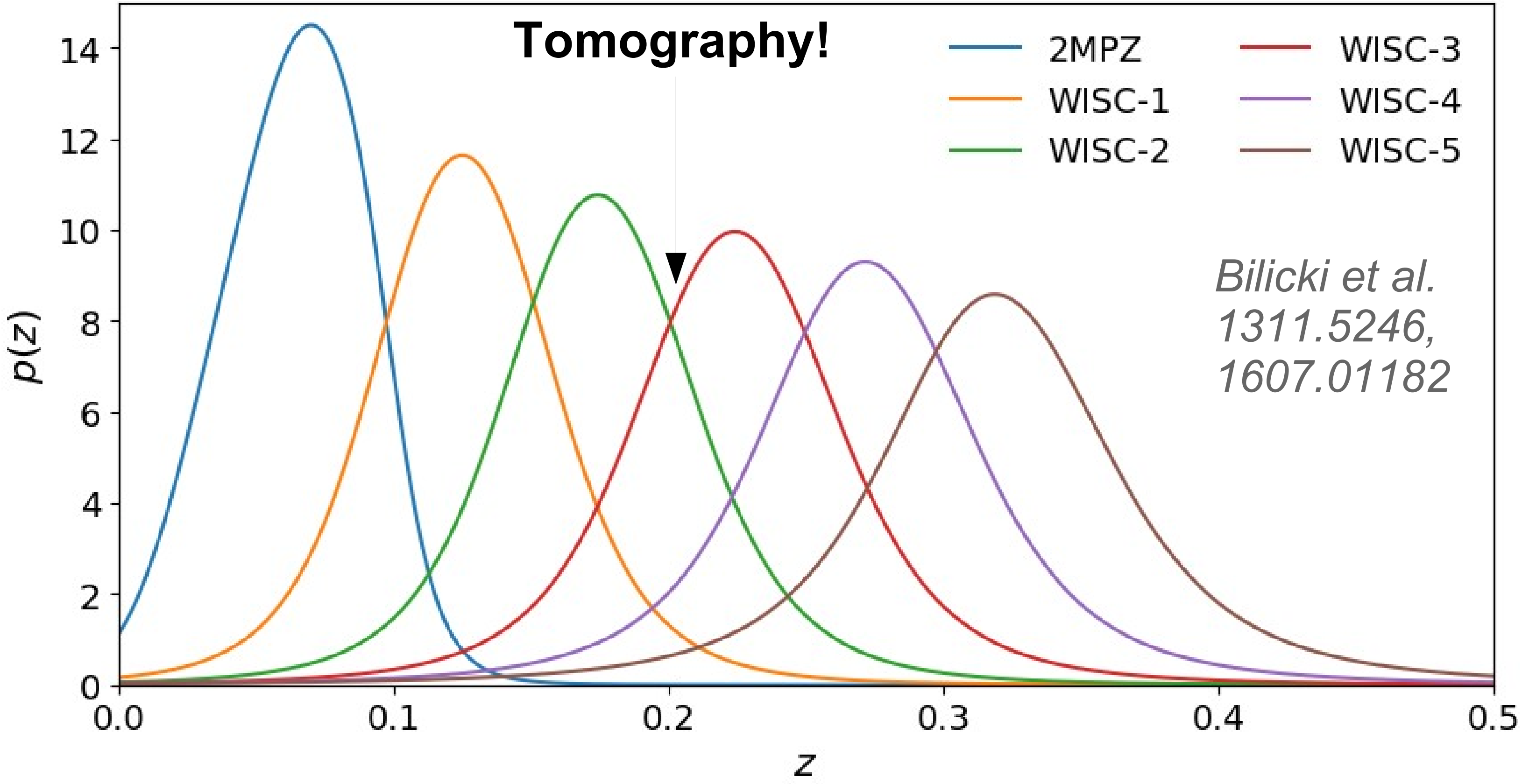
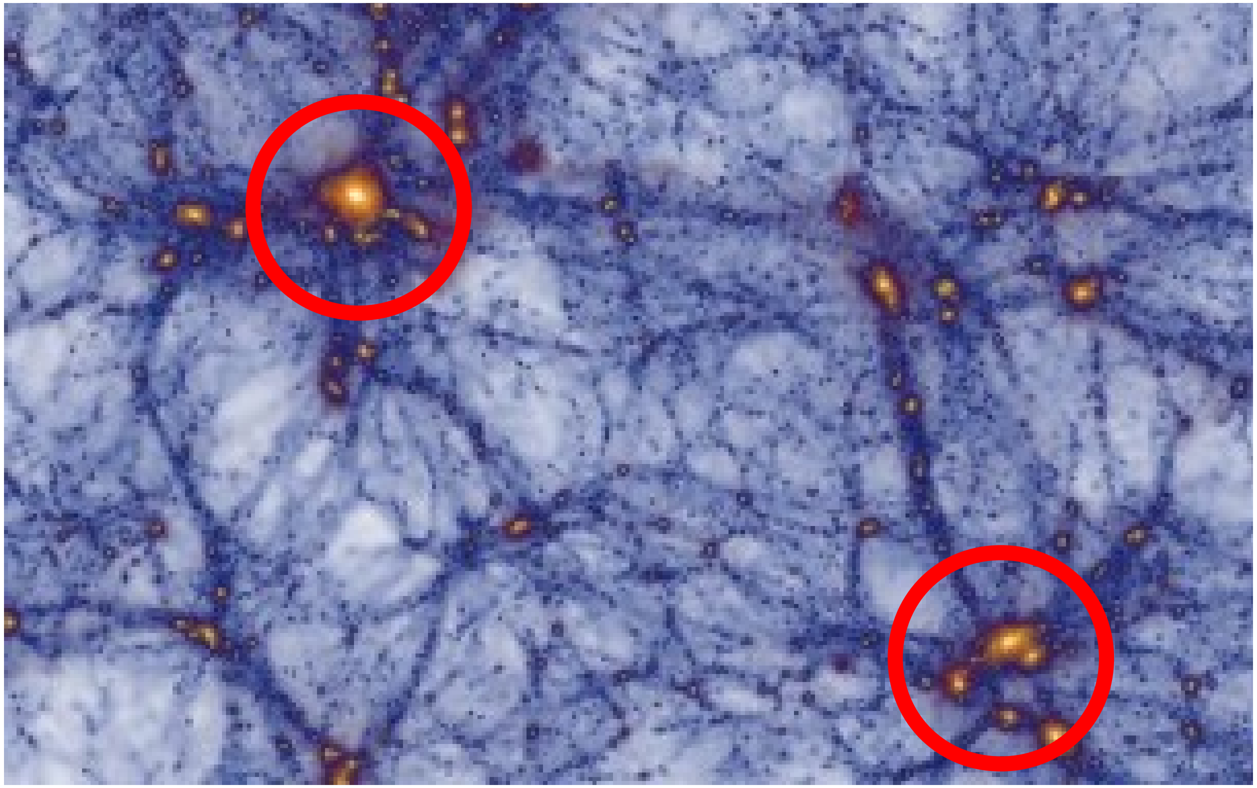
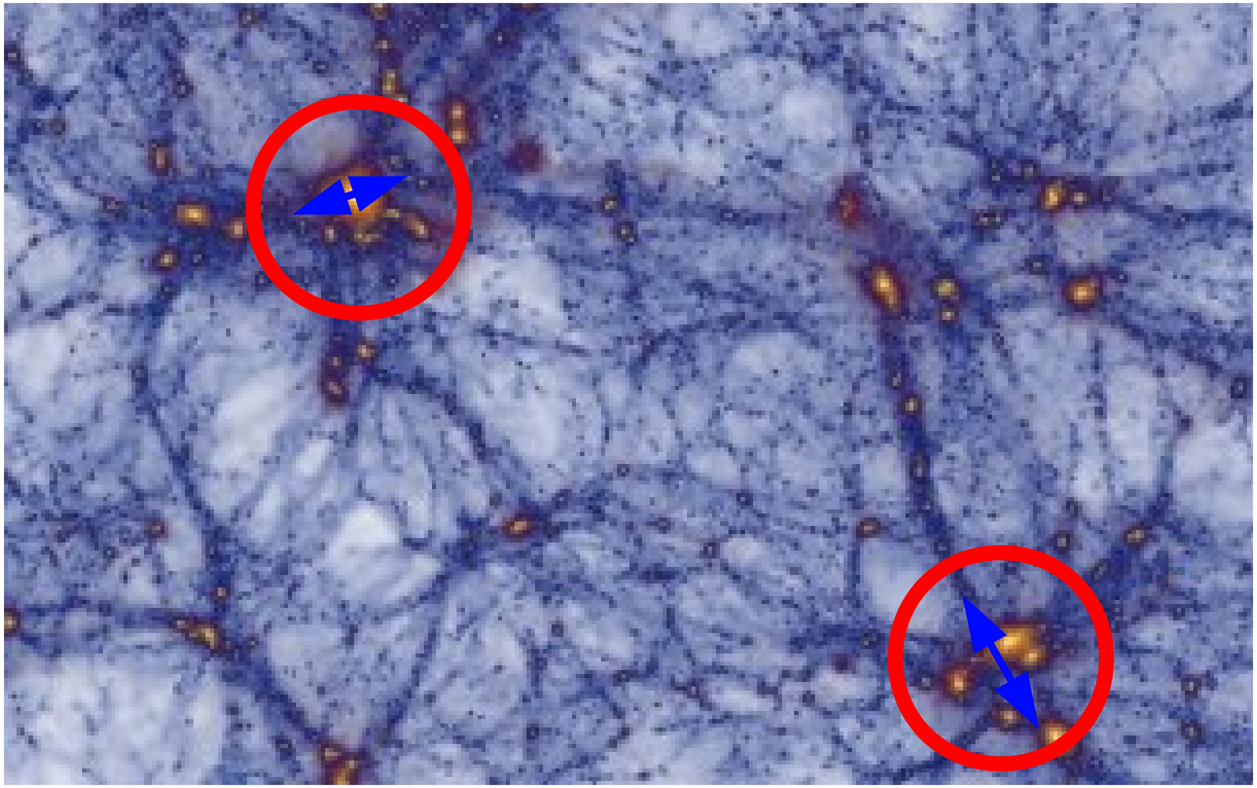


Halo-model prediction



Halo-model prediction

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



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

Halo-model prediction

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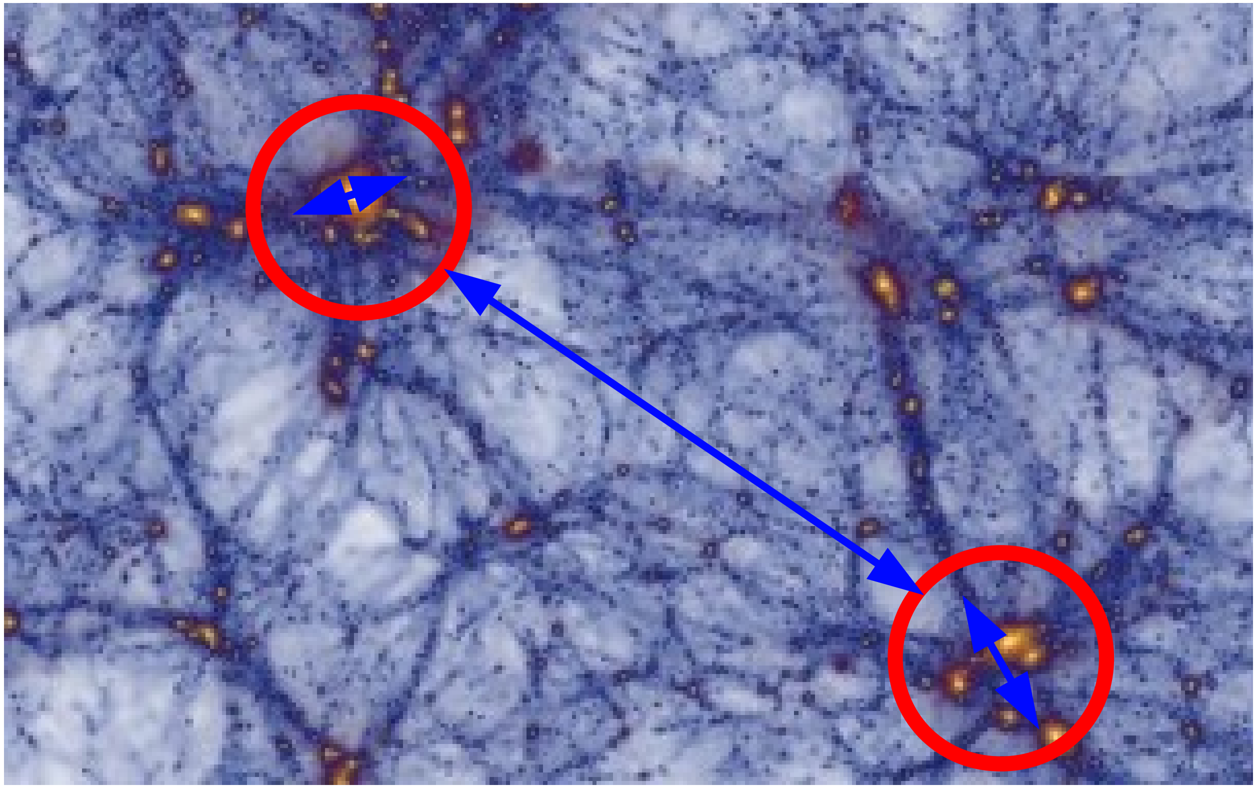

$$P_{UV}^{1h}(k) = \int dM \, \frac{dn}{dM} \, \langle U(k|M) \, V(k|M) \rangle$$

$$P_{UV}^{2h}(k) = P_L(k) \left[\int dM \frac{dn}{dM} \, b_h(M) \, \langle U(k|M) \rangle \right] \left[\int dM \frac{dn}{dM} \, b_h(M) \, \langle V(k|M) \rangle \right]$$

Halo-model prediction

Modelling the y-g cross-correlation:

- g: Halo Occupation Distribution (HOD).
  Model number of central/satellite galaxies (and their statistics) as a function of M_h.

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

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

Halo-model prediction

Modelling the y-g cross-correlation:

- g: Halo Occupation Distribution (HOD).
  Model number of central/satellite galaxies (and their statistics) as a function of M_h.
- y: generalized NFW profile (Arnaud et al. 2010).
  $(1-b_H)$ as free parameter.

$$P_e(r) = P_* \, p(r/r_{500c}) \qquad p(x) = (c_{500}x)^{-\gamma}\left[1 + (c_{500}x)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$

$$P_* = 6.41\ (1.65 \mathrm{eV\,cm}^{-3}) \left(\frac{h}{0.7}\right)^{8/3} \left(\frac{(h/0.7)\boxed{(1-b)}M_{500c}}{3\times 10^{14} M_\odot}\right)^{2/3+0.12}$$

Halo-model prediction

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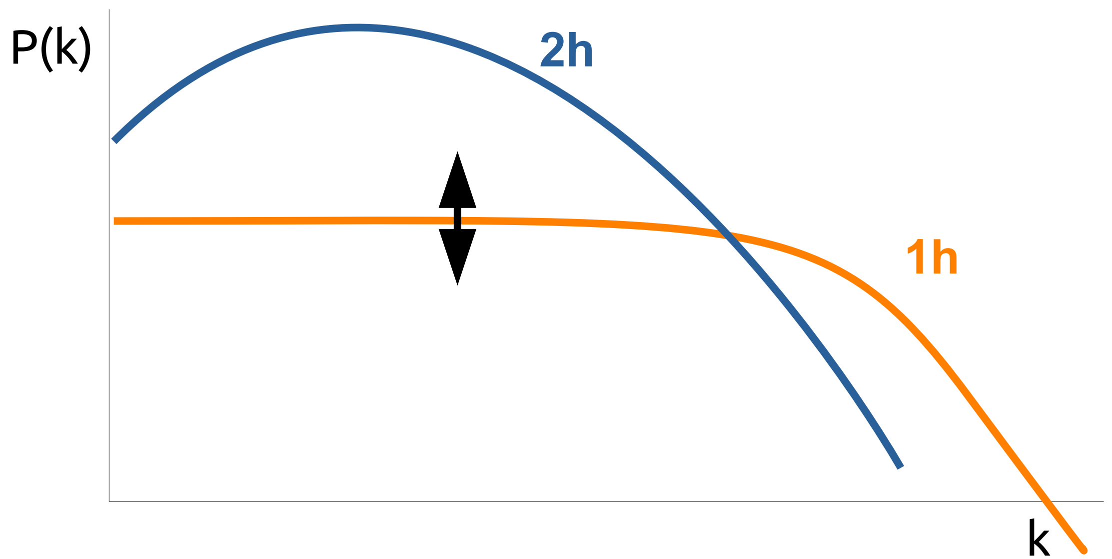
  Model number of central/satellite galaxies (and their statistics) as a function of M_h.
- y: generalized NFW profile (Arnaud et al. 2010).
  $(1-b_H)$ as free parameter.
- yxg 1-halo scatter modelled through extra parameter $\boldsymbol{\rho_{yg}}$
  Controls amplitude of 1-halo term. Degenerate with $1-b_H$ there.
  Effectively nullifies any information we can get from the 1-halo term.

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

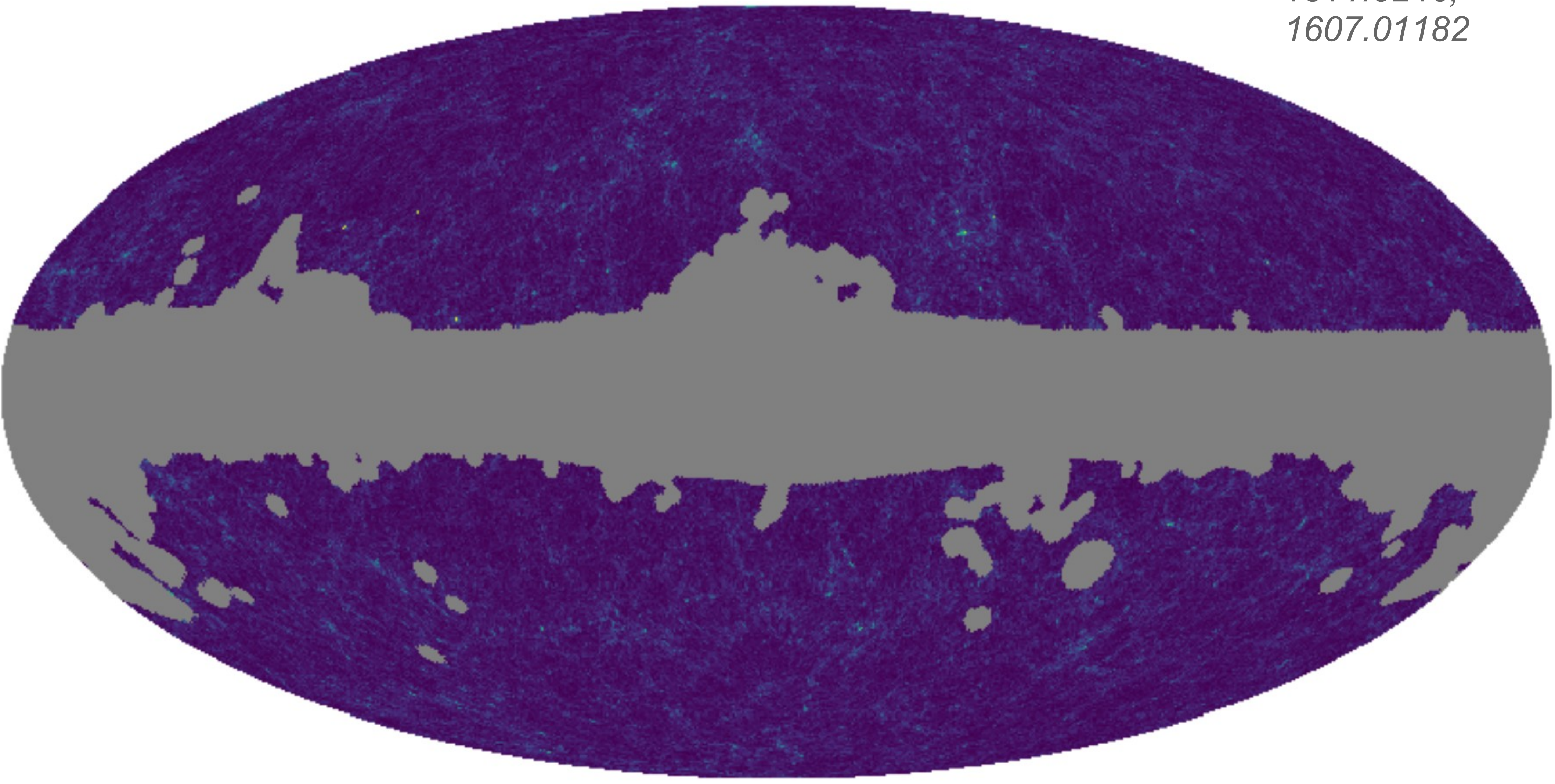


Data

Datasets:

- y: Planck maps (MILCA and NILC) *Aghanim et al. 2015*
- g: 2MPZ (2MASS + WISE + SuperCosmos, low-redshift), WISC (WISE + SuperCOSMOS, higher redshift). Full sky, photometric redshifts.

Bilicki et al. 1311.5246, 1607.01182



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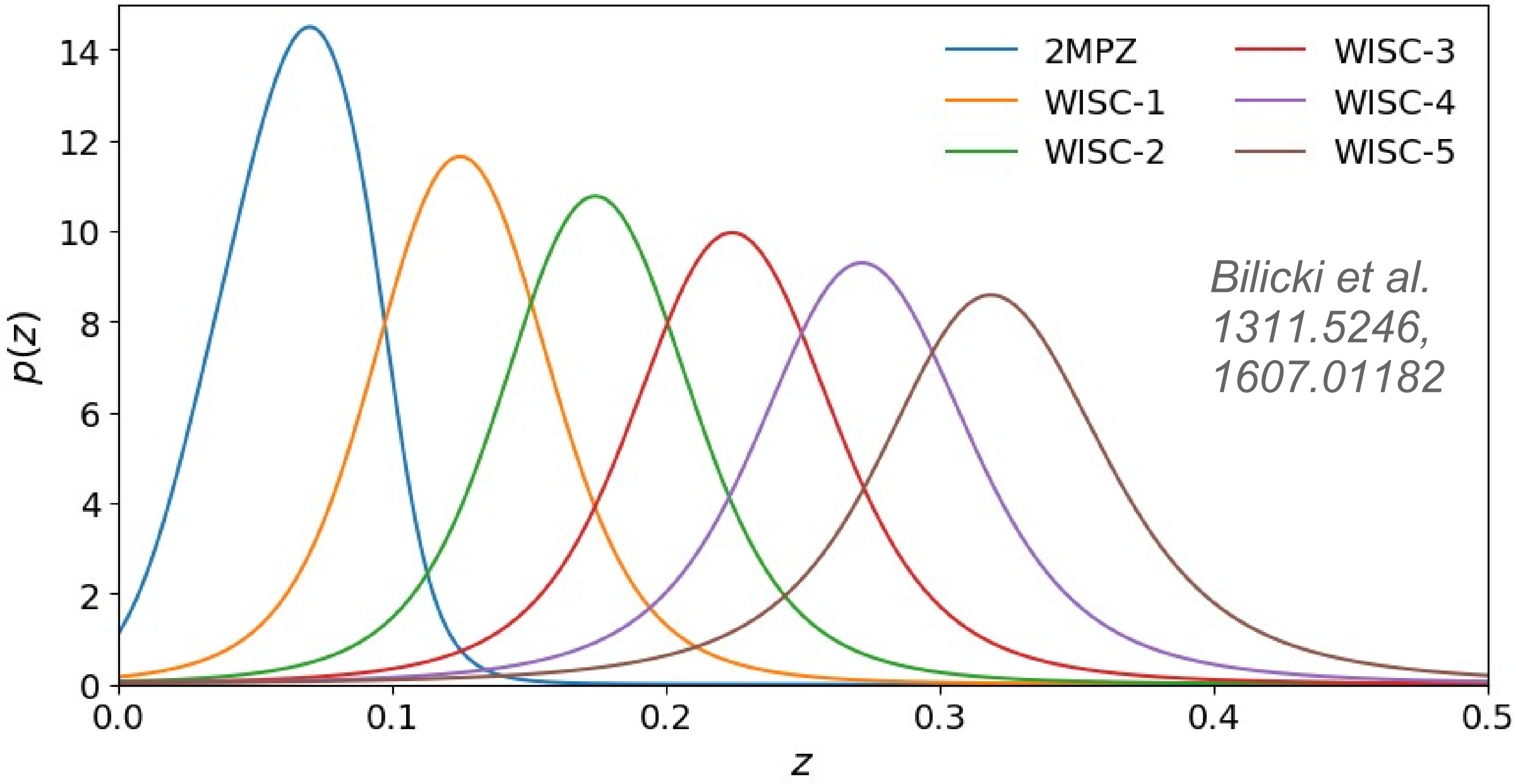
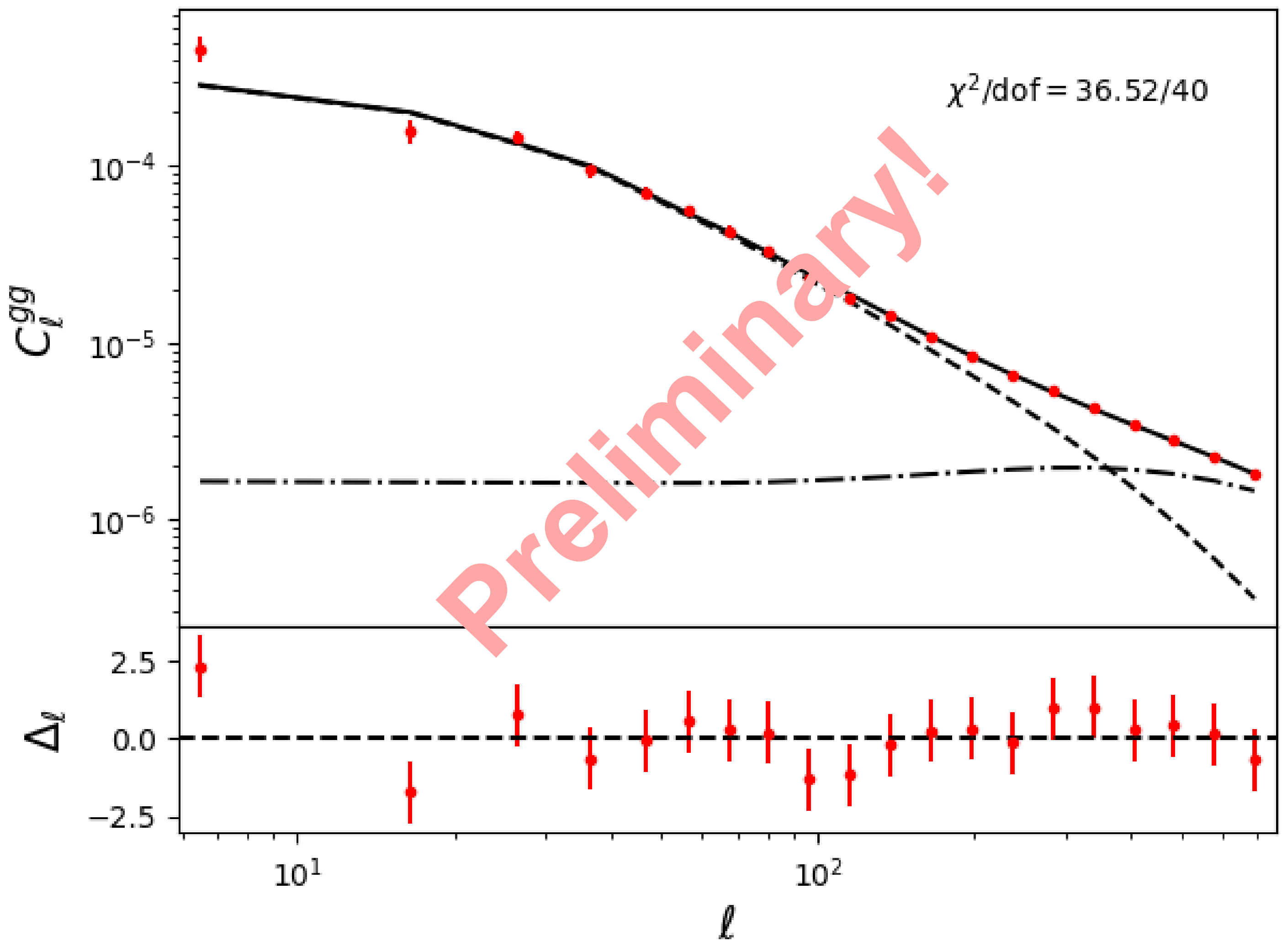


Bilicki et al. 1311.5246, 1607.01182

Results

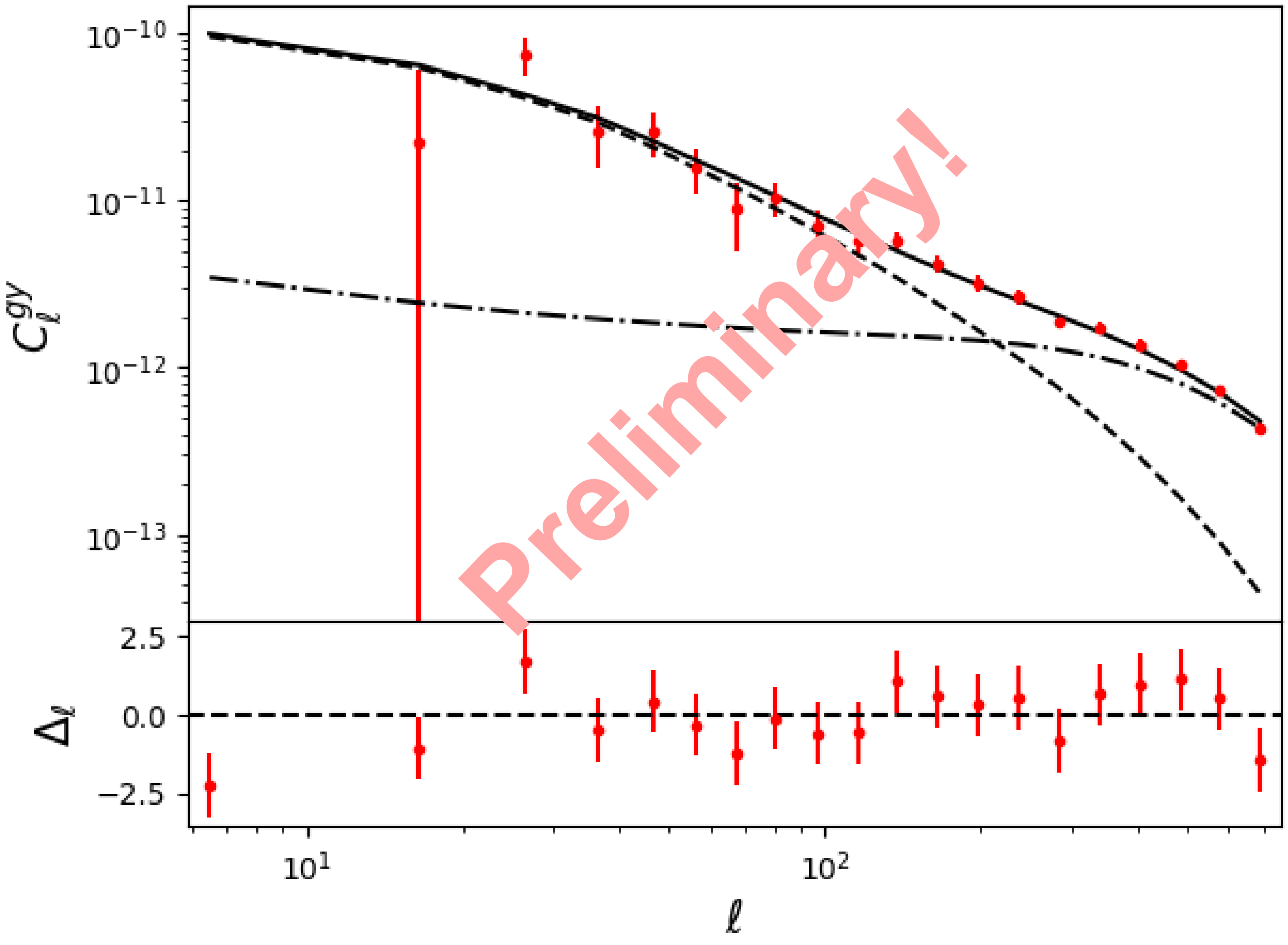
gxg



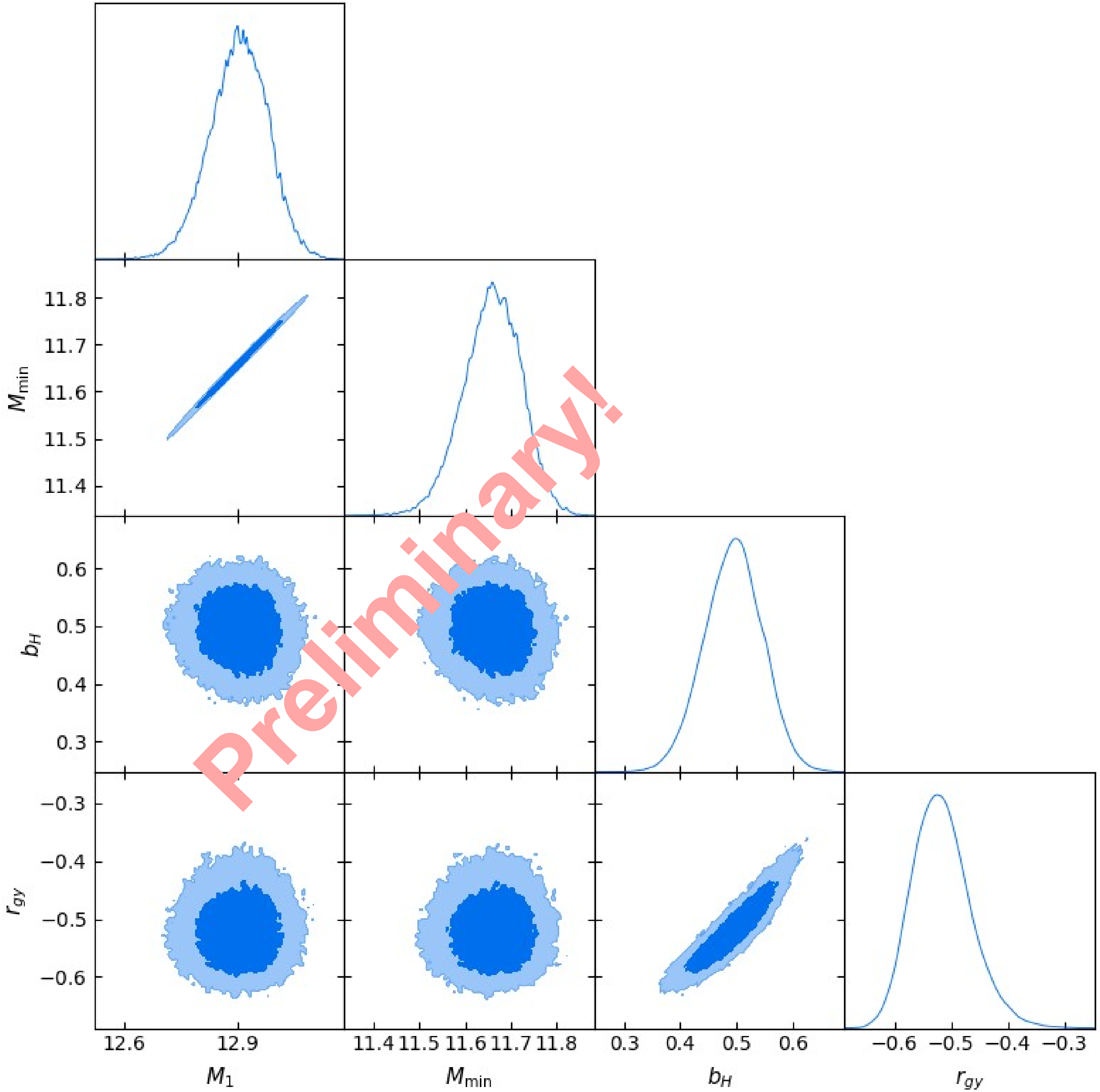
χ^2/dof = 36.52/40
Preliminary!
10^{-4}
10^{-5}
10^{-6}
C_ℓ^{gg}
2.5
0.0
−2.5
Δ_ℓ
10^1
10^2
ℓ

Results

yxg

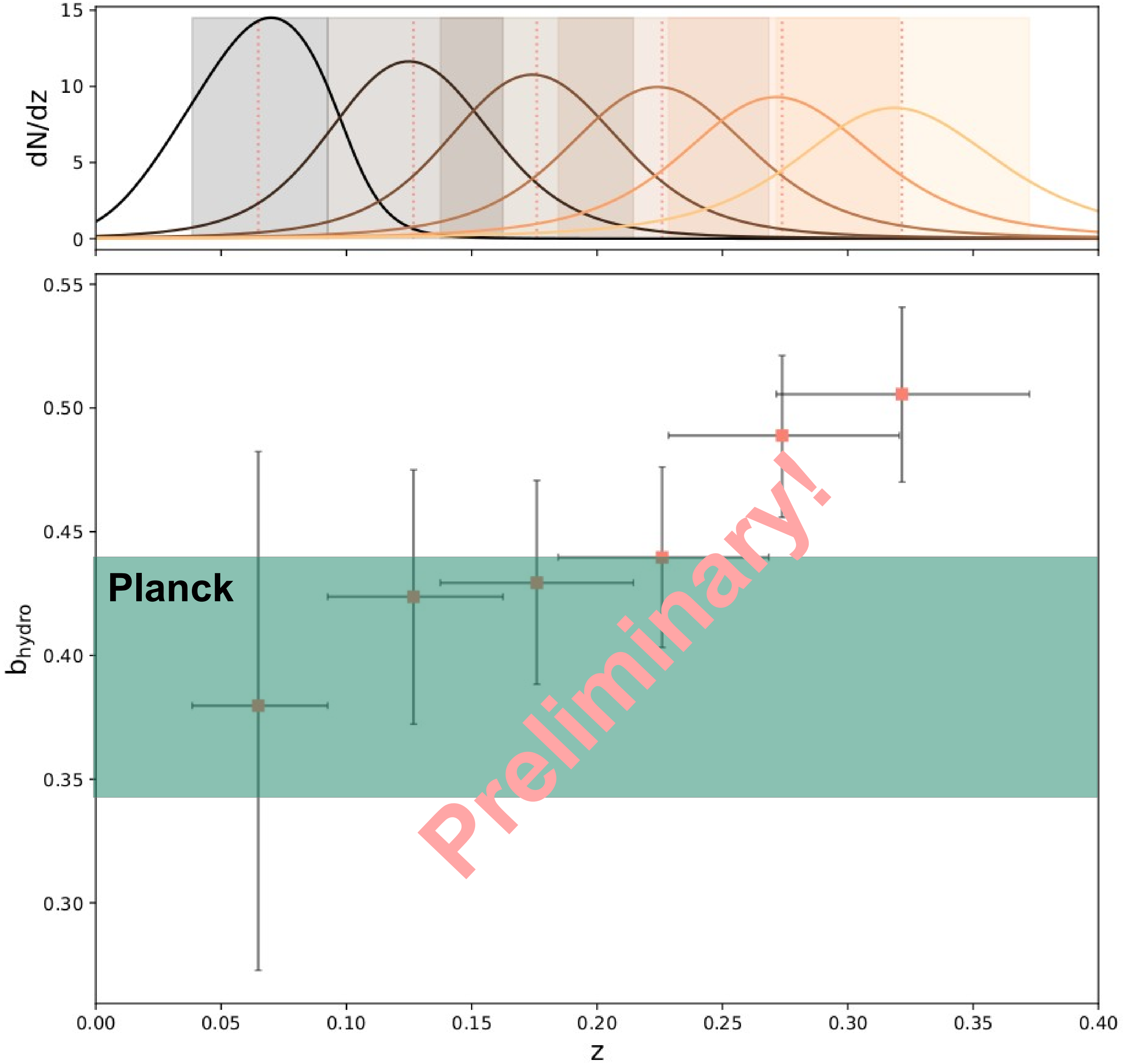

10^{-10}
10^{-11}
10^{-12}
10^{-13}
C_ℓ^{gy}
Preliminary!
2.5
0.0
−2.5
Δ_ℓ
10^1
10^2
ℓ

Results



Preliminary!
11.8
11.7
11.6
11.5
11.4
$M_{\rm min}$
0.6
0.5
0.4
0.3
b_H
−0.3
−0.4
−0.5
−0.6
r_{gy}
12.6
12.9
M_1
11.4 11.5 11.6 11.7 11.8
$M_{\rm min}$
0.3 0.4 0.5 0.6
b_H
−0.6 −0.5 −0.4 −0.3
r_{gy}

Results

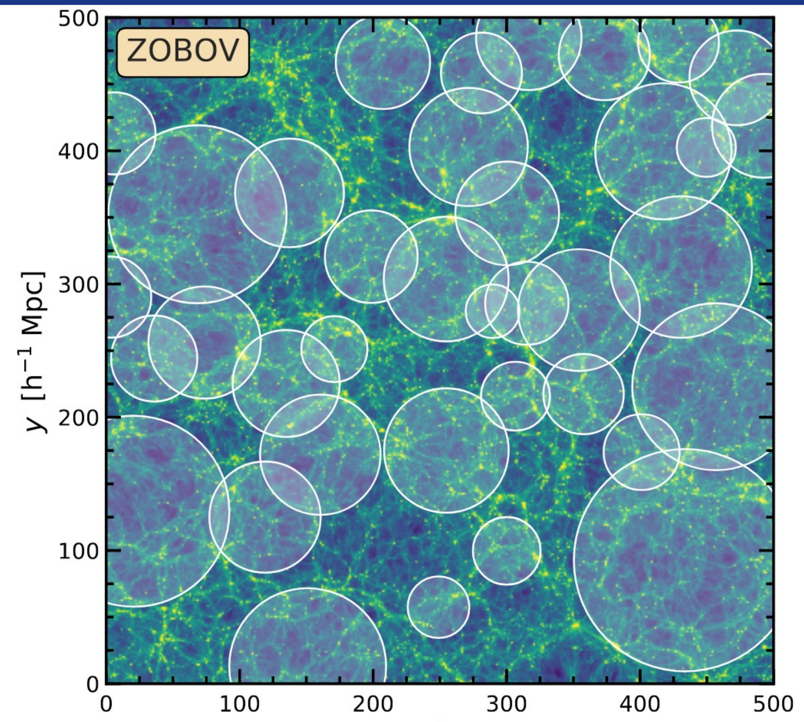


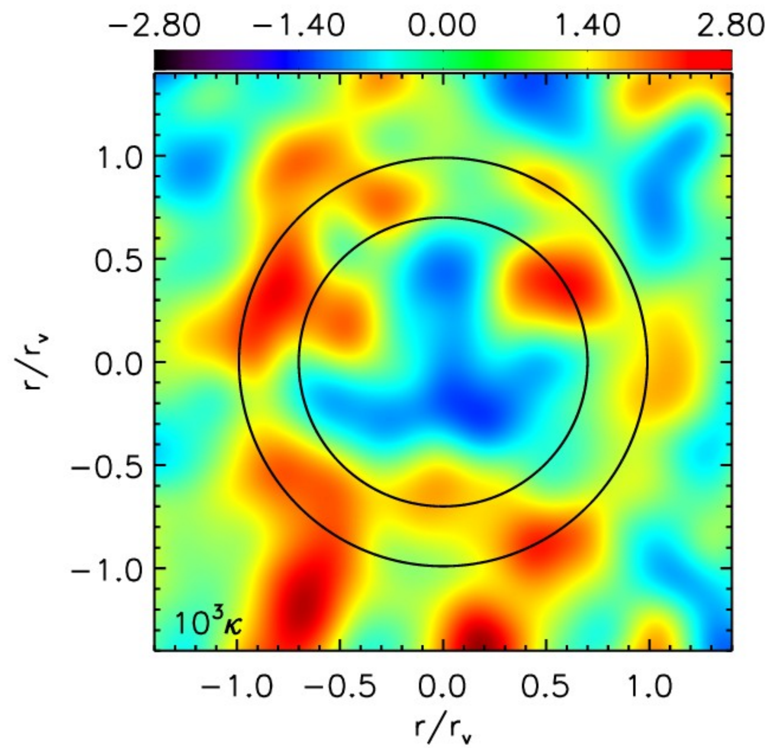
15
10
5
0
dN/dz
0.55
0.50
0.45
0.40
0.35
0.30
b_{hydro}
Planck
Preliminary!
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
z

Gas properties in underdense regions

Cosmic voids

- Large (~tens of Mpc) underdense regions.
- Main component (by volume) of the cosmic web.
- Interesting for cosmology:
  - Dominated by vacuum energy.
  - “Time-machines” to look into the future.
  - Milder growth → easier non-linearity.
- Imprint of voids on the CMB (lensing and ISW) detected at ~3σ





Cautun et al. 1710.01730
Cai et al. 1609.00301

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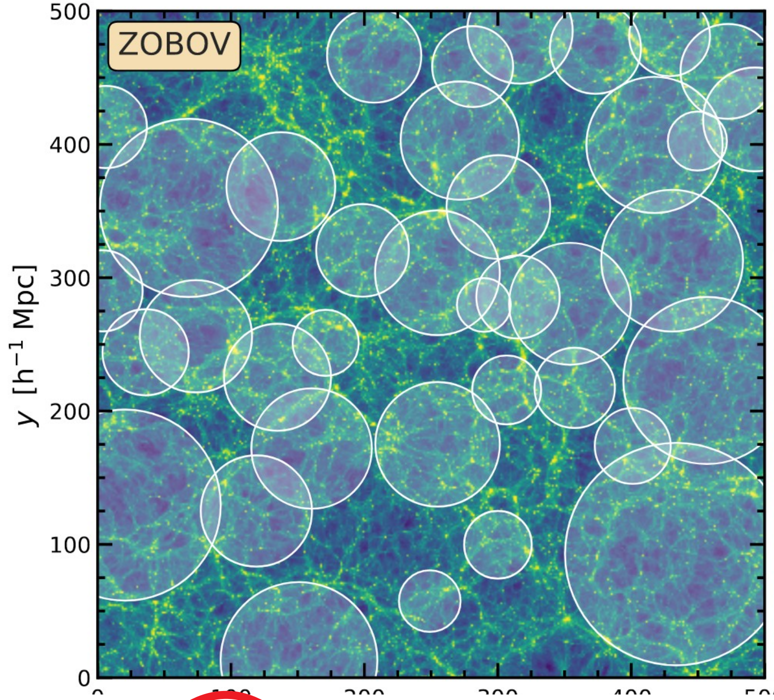
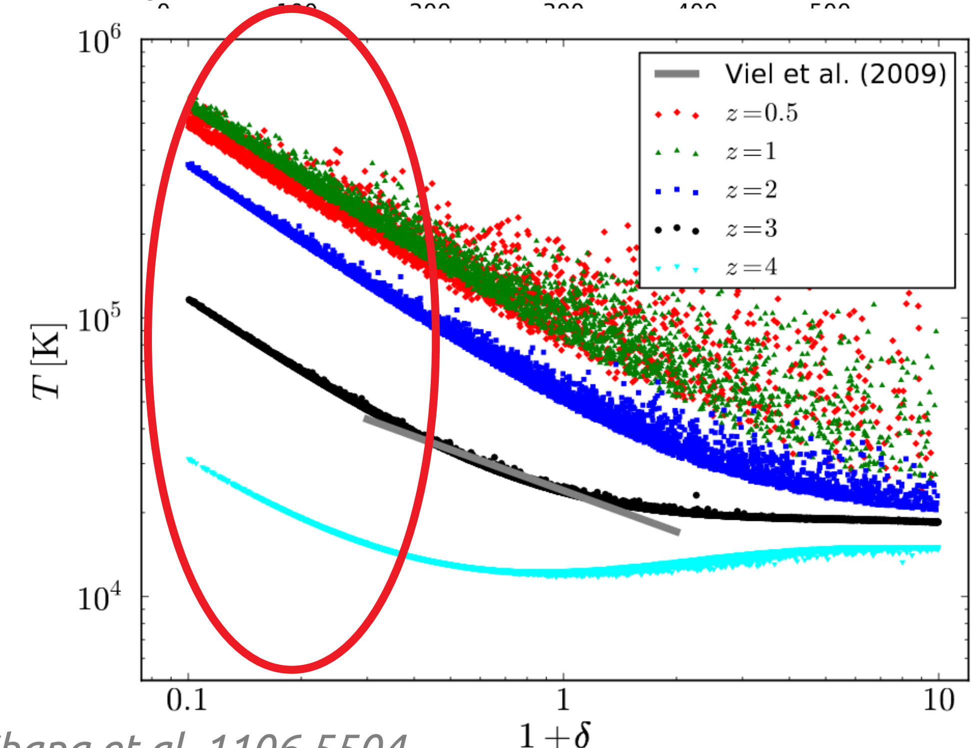
What could we learn from the tSZ in voids?

- T-ρ relation in low-density environments
- M-y relation for low-mass haloes.
- <u>Mean gas pressure!</u>
- Conditional halo mass function





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Cai et al. 1609.00301

Chang et al. 1106.5504

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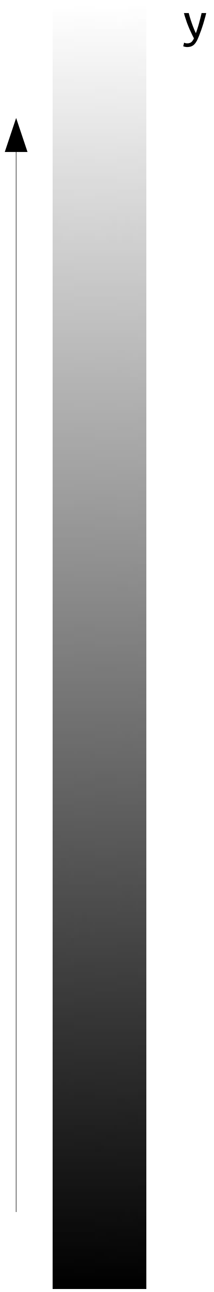
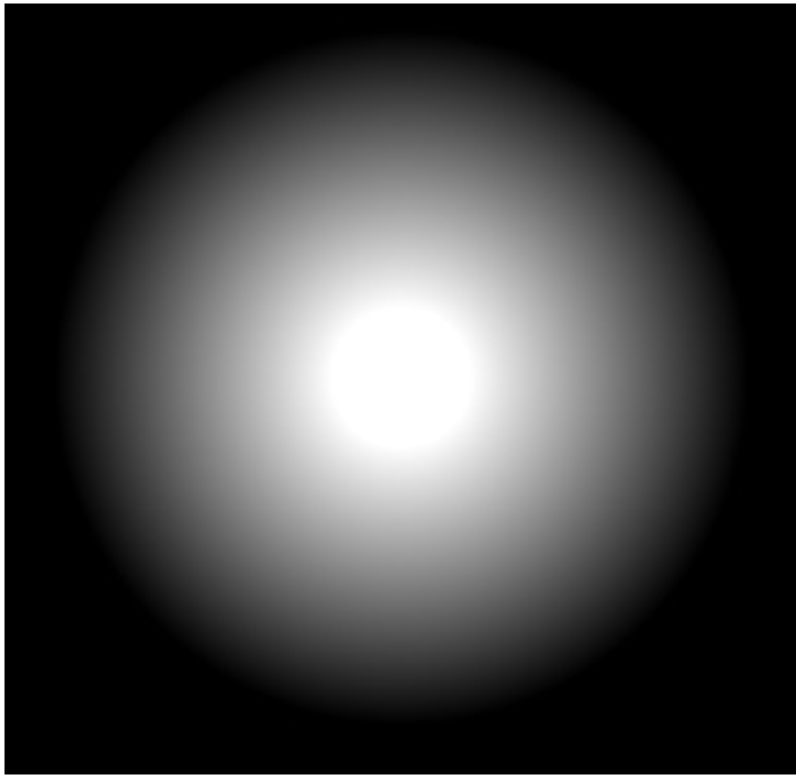


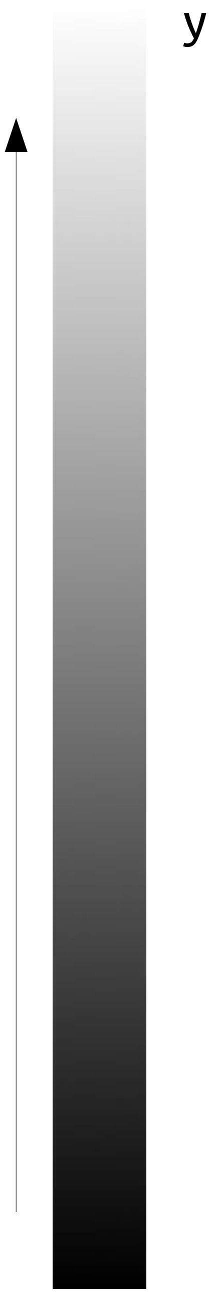
What should we expect?

or



?

Gas properties in underdense regions



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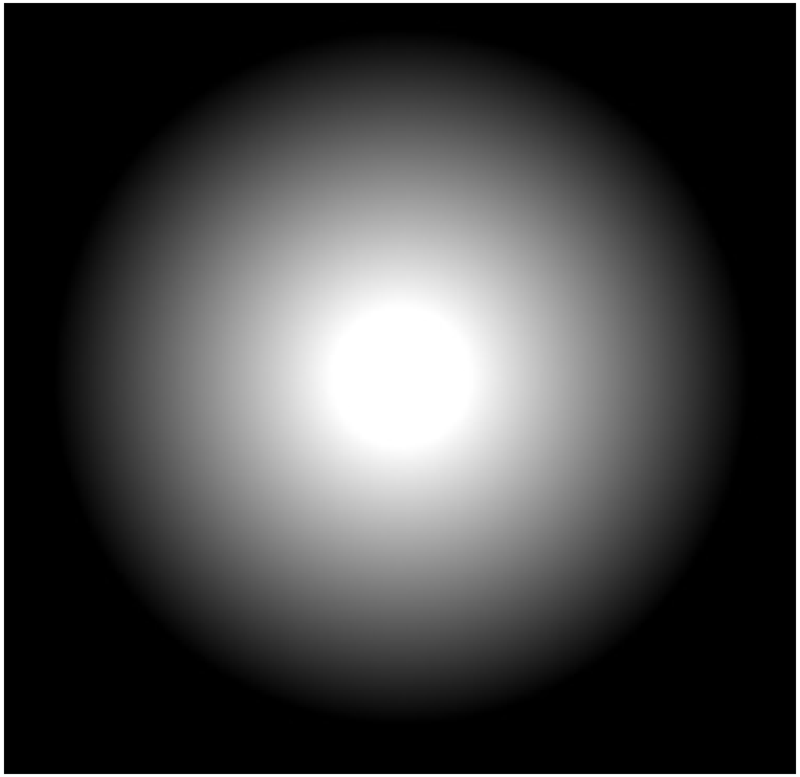

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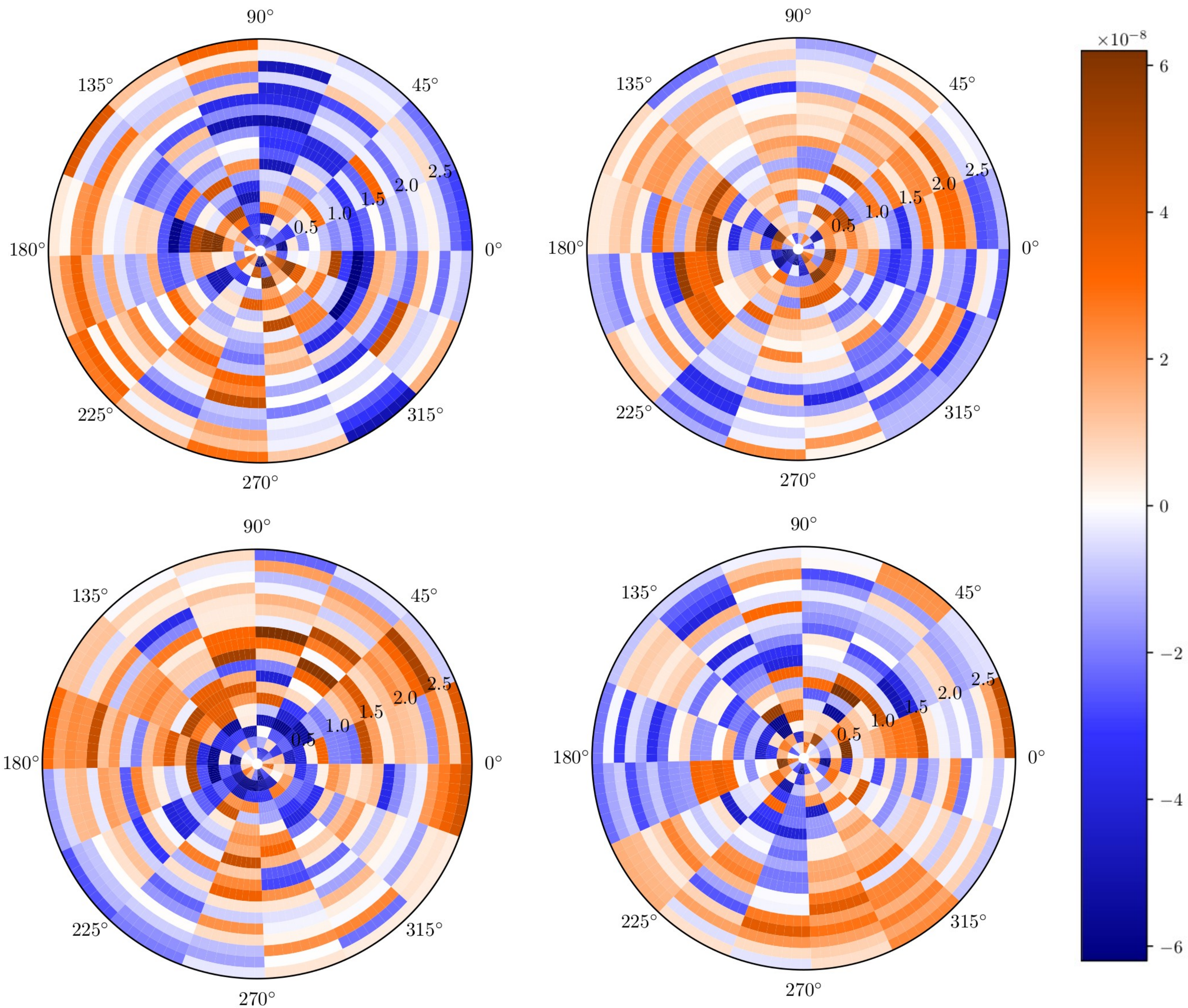
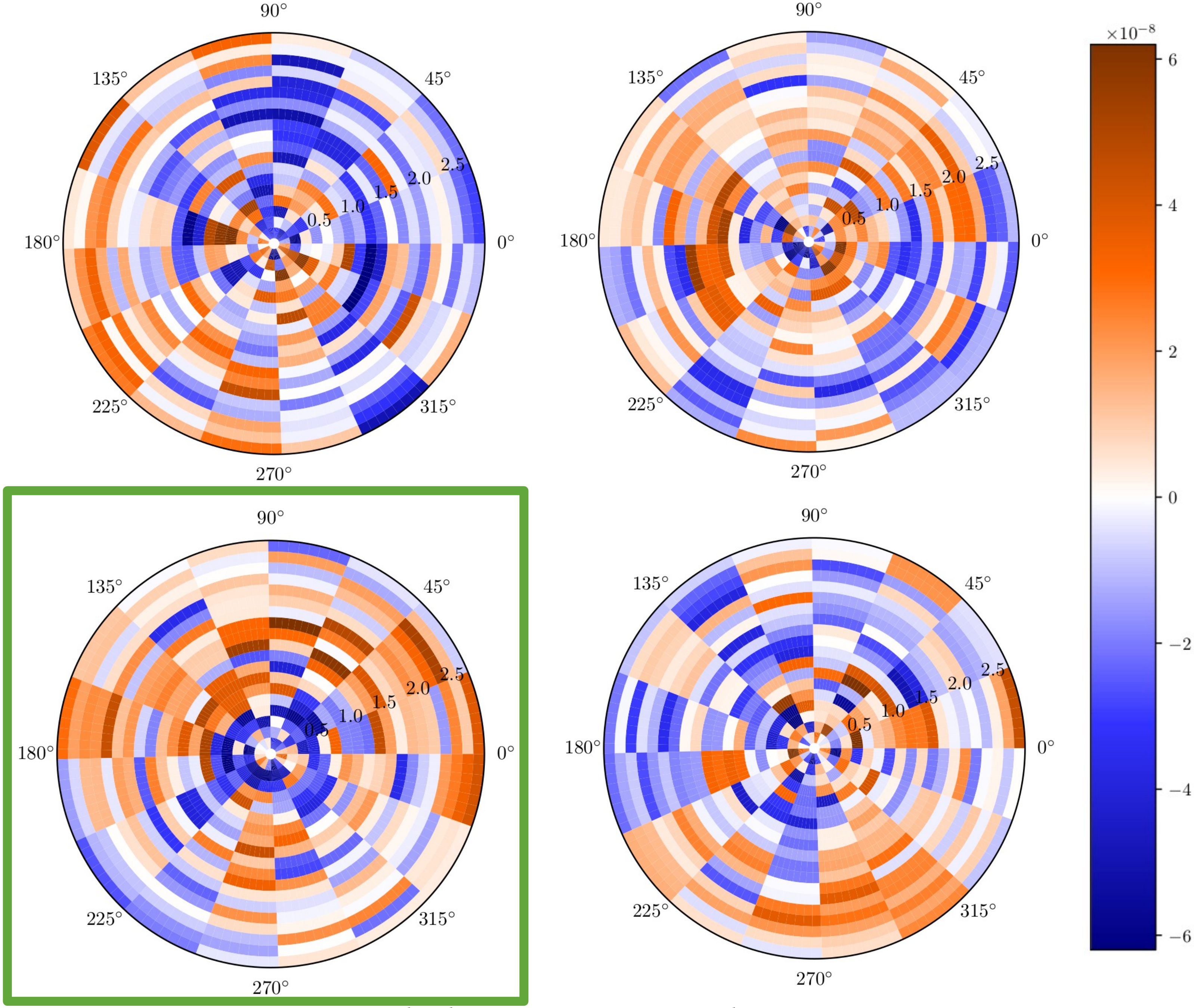
$P \sim T \cdot \rho \longrightarrow T(\rho)?$

Gas properties in underdense regions



Find the 3.4σ signal!

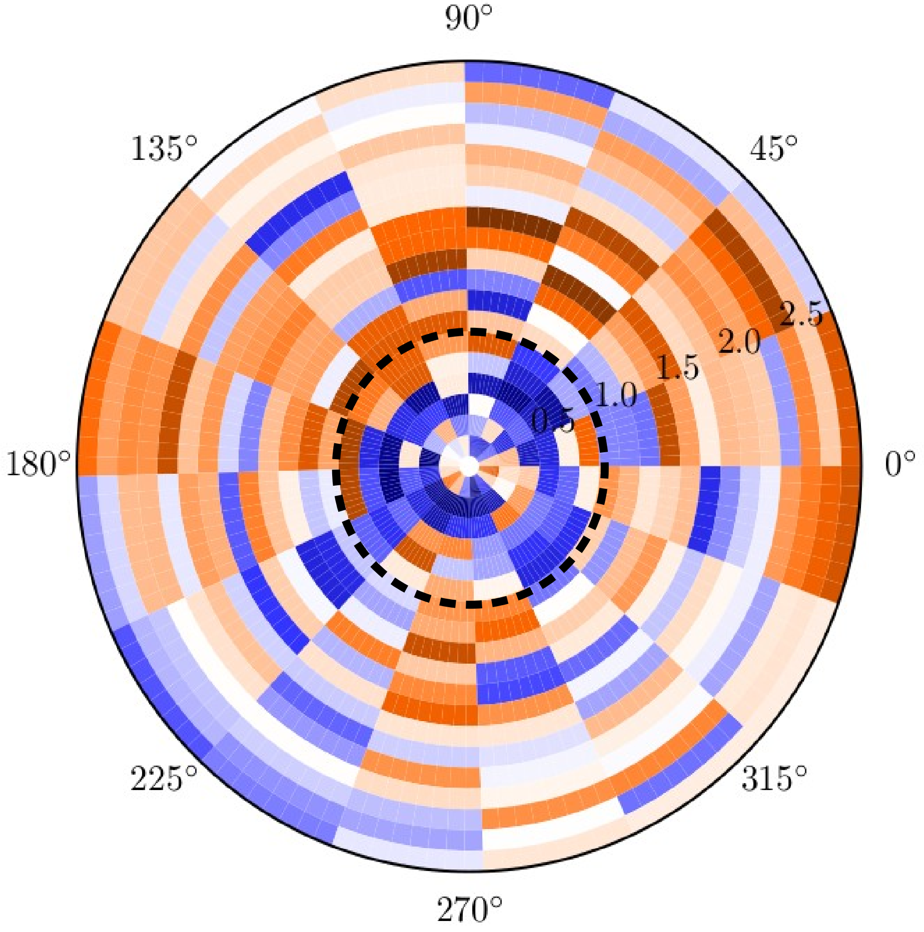
Gas properties in underdense regions



Find the 3.4σ signal!

Gas properties in underdense regions

- tSZ maps from Planck
  Planck Coll. et al. 1502.01596
- Void catalog from BOSS DR12
  Mao et al. 1602.02771
- First detection of tSZ in cosmic voids
- Thermal properties of diffuse gas.
- Constraints on T-ρ relation.
- Measurement of mean pressure!



DA et al. 1709.01489

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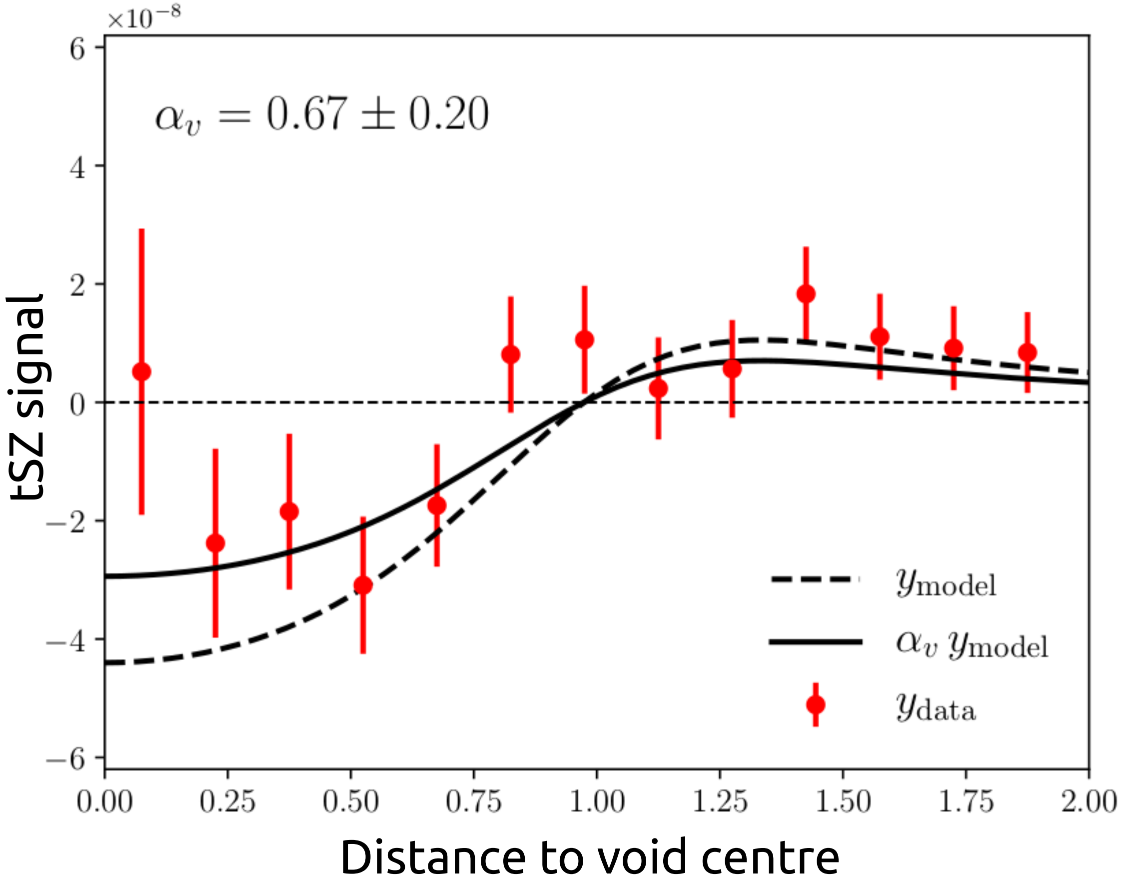

DA et al. 1709.01489

Summary

- Cosmology is in an exciting era: large upcoming and future datasets + hints of tensions in current data.
- Example: low-redshift probes measure consistently lower growth than CMB.
- Future observatories (e.g. LSST, SO) will improve constraining power massively.
- Secondary CMB anisotropies can help us understand astrophysical uncertainties through cross-correlation with LSS data.
- Mass calibration is the most important challenge for tSZ studies. Can be improved with CMB lensing.
- Cross-correlation with current low-z data shows mild redshift evolution of mass calibration parameters.
- Information about mean gas thermodynamics can be gained from cross-correlation with cosmic web elements.

Thanks!