Lentes gravitacionales en astrofísica y cosmología

Semana - 14

Parte III: lensing a nivel cosmológico

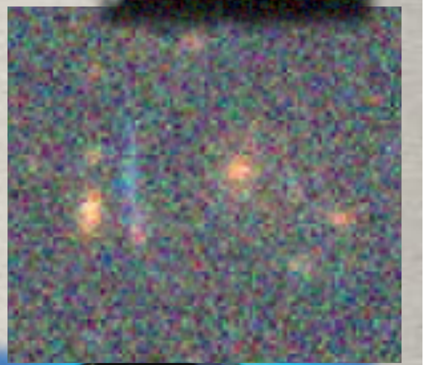
Martín Makler
ICAS/IFICI/CONICET&UNSAM y CBPF

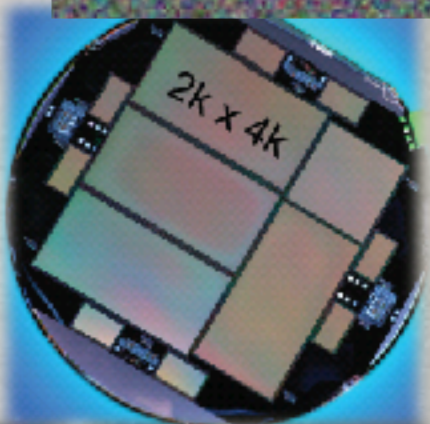
Estructura general de la materia

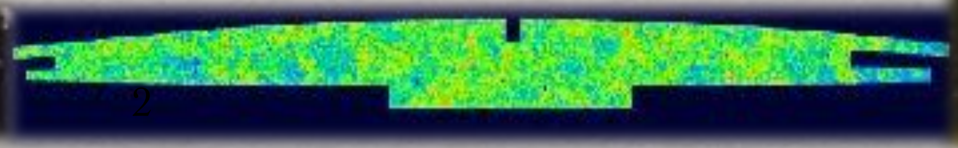
Parte III: lensing a nivel cosmológico

[perturbaciones, week lensing]

- [x] Revisión de cosmología: formación y distribución de las de estructuras en el Universo
- [x] Mas allá del plano único: lentes y estructura en gran escala
- [ ] Estadísticas de *lensing*
- [ ] Revisión de radiación cósmica de fondo
- [ ] *Lensing* de la radiación cósmica de fondo







Recapitulando

Metrica de Friedmann con perturbación escalar

$$ds^2 = a^2(\tau)\left\{(1+2\frac{\varphi}{c^2})d\tau^2 - (1-2\frac{\varphi}{c^2})\left[d\chi^2 + r^2(\chi)(d\theta^2 + \sin^2\theta d\phi^2)\right]\right\}$$

geometria del fondo (FLRW)

Propagación de la luz en el fondo homogéneo

$$\chi = \tau_0 - \tau$$

Lenteamento pela estrutura em grade escala: além da aproximação de lente fina

Métrica de Friedmann com perturbação escalar

$$ds^2 = a^2(\tau)\left\{(1+2\frac{\varphi}{c^2})d\tau^2 - (1-2\frac{\varphi}{c^2})\left[d\chi^2 + r^2(\chi)(d\theta^2 + \sin^2\theta d\phi^2)\right]\right\}$$

Equação de geodésica

$$\frac{d^2x^i}{d\lambda^2} = -g^{ik}\left(\frac{\partial g_{kl}}{\partial x^m} - \frac{1}{2}\frac{\partial g_{lm}}{\partial x^k}\right)\frac{dx^m}{d\lambda}\frac{dx^l}{d\lambda}$$

Ângulo de desvio

fonte lente

$$\theta_\sigma(\chi) = \theta^0_\sigma - \frac{2}{c^2}\int_0^{\chi}\frac{d\chi'}{r^2(\chi')}\int_0^{\chi'} d\chi''\varphi_{,\sigma}(\vec{\theta}r(\chi''),\chi'')$$

Funções de lente

Ângulo de desvio

$$\theta_\sigma(\chi) = \theta^0_\sigma - \frac{2}{c^2}\int_0^{\chi} \frac{\mathrm{d}\chi'}{r^2(\chi')}\int_0^{\chi'} \mathrm{d}\chi'' \varphi_{,\sigma}(\vec{\theta} r(\chi''), \chi'')$$

Se reduz a uma integral ao longo da trajetória do fóton

fonte lente

$$\theta_\sigma(\chi) = \theta^0_\sigma - \frac{2}{c^2}\int_0^{\chi} \mathrm{d}\chi' \varphi_{,\sigma}(\vec{\theta} r(\chi'), \chi')\frac{r(\chi-\chi')}{r(\chi)r(\chi')}$$

Potencial de lente

$$\Psi = \frac{2}{c^2 r(\chi)}\int_0^{\chi} \mathrm{d}\chi' \varphi(\vec{\theta} r(\chi'), \chi')\frac{r(\chi-\chi')}{r(\chi')}$$

Convergência

$$\kappa(\vec{\theta}) = \frac{1}{2}\nabla^2_\theta \Psi = \frac{1}{c^2}\int_0^{\chi} \mathrm{d}\chi' \nabla^2_\perp \varphi(\vec{x}_\perp, \chi')\frac{r(\chi-\chi')r(\chi')}{r(\chi)}$$

Convergencia

Usando la ecuación de Poisson para las perturbaciones

$$\nabla^2\varphi(\vec{x},\tau) = \frac{3H_0^2\Omega_m}{2a(\tau)}\delta(\vec{x},\tau)$$

Y promediando para una distribución no uniforme de fuentes

$$n(\chi) = N_{tot}^{-1}(\mathrm{d}N/\mathrm{d}\chi)$$

La convergencia se escribe como

$$\kappa(\vec{\theta}) = \frac{3H_0^2\Omega_m}{2c^2}\int_0^{\chi_H}\mathrm{d}\chi\,\delta(\vec{x}_\perp,\chi)\frac{g(\chi)}{a(\chi)}$$

Función ventana
eficiencia de lentes

donde

$$g(\chi) = r(\chi)\int_\chi^{\chi_H}\mathrm{d}\chi'\frac{r(\chi-\chi')n(\chi')}{r(\chi')}$$

Correlaciones

$$\kappa(\vec{\theta}) = \frac{3H_0^2\Omega_m}{2c^2}\int_0^{\chi_H} \mathrm{d}\chi\,\delta(\vec{x}_\perp,\chi)\frac{g(\chi)}{a(\chi)}$$

En el espacio de Fourier

$$\kappa(\vec{\ell}) = \int \mathrm{d}^2\theta\;\kappa(\vec{\theta})e^{i\vec{\ell}\cdot\vec{\theta}}$$

tenemos

$$\langle\kappa(\vec{\ell})\kappa(\vec{\ell}')\rangle = (2\pi)^2\delta^{(2)}(\vec{\ell}-\vec{\ell}')P_\kappa(\ell)$$

Espectro de potencias
de la estructura en gran escala:
dependencia cosmológica!

el espectro de potencias es dado por

$$P_\kappa(\ell) = \frac{9H_0^4\Omega_m^2}{4c^4}\int_0^{\chi_H} \mathrm{d}\chi\frac{g^2(\chi)}{a^2(\chi)}P_\delta\left(\frac{\ell}{r(\chi)},\chi\right)$$

Correlaciones

$$P_\kappa(\ell) = \frac{9H_0^4\Omega_m^2}{4c^4}\int_0^{\chi_H} \mathrm{d}\chi \frac{g^2(\chi)}{a^2(\chi)} P_\delta\left(\frac{\ell}{r(\chi)}, \chi\right)$$

Espectro de potencias
de la estructura en gran escala:
dependencia cosmológica!

Espectro de potencias

$$\begin{aligned} P_\delta(k,\tau) &= D_+(k,\tau)P_k^{\mathrm{lin}} \\ &= D_+(k,\tau)T(k)P_k \\ &= D_+(k,\tau)T(k)A_0 k^{n_s-1} \end{aligned}$$

Angular x espacial en el espacio k

$$k_\sigma = \ell_\sigma / r(\chi)$$

Tiempo conforme

$$\chi = \tau_0 - \tau$$

Cosmic Shear

- Separating into redshift bins
- Weak lensing (statistical)

Sensitive to dark energy (geometry + growth factor)

Less sensitive to baryonic physics

- large separations: linear
- Example: cosmic shear power spectrum on three photo-z slices (tomography)

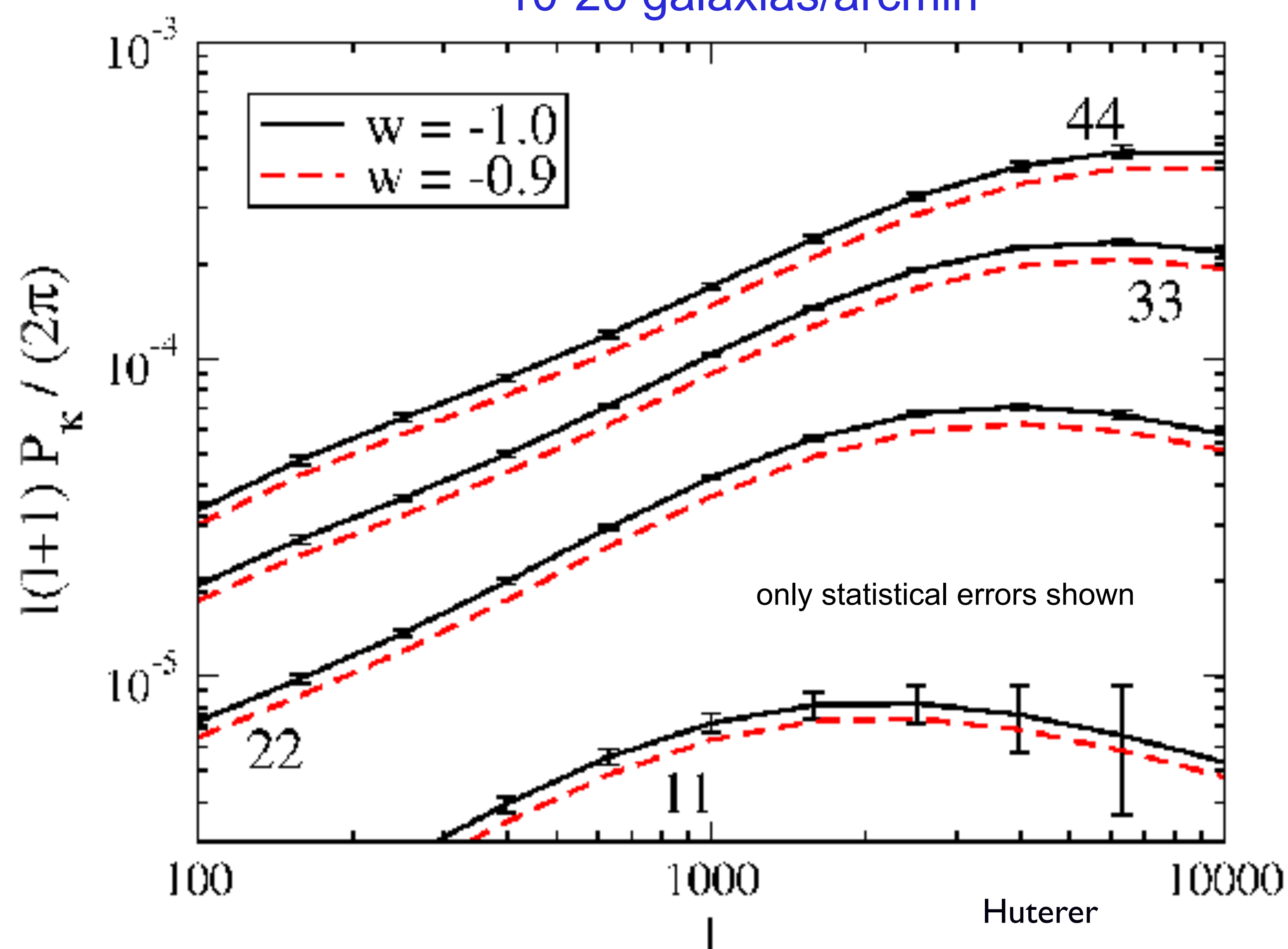
•DES:

- unique combination of area, seeing and depth
- shapes of ~ 300 million galaxies with ⟨z⟩ = 0.7

$$C_\ell^{x_a x_b} = \int dz \frac{H(z)}{D_A^2(z)} W_a(z) W_b(z) P^{s_a s_b}(k = \ell / D_A; z)$$

$$\Delta C_\ell = \sqrt{\frac{2}{(2\ell - 1) f_{sky}}} \left(C_\ell + \frac{\sigma^2(\gamma_i)}{n_{eff}} \right)$$

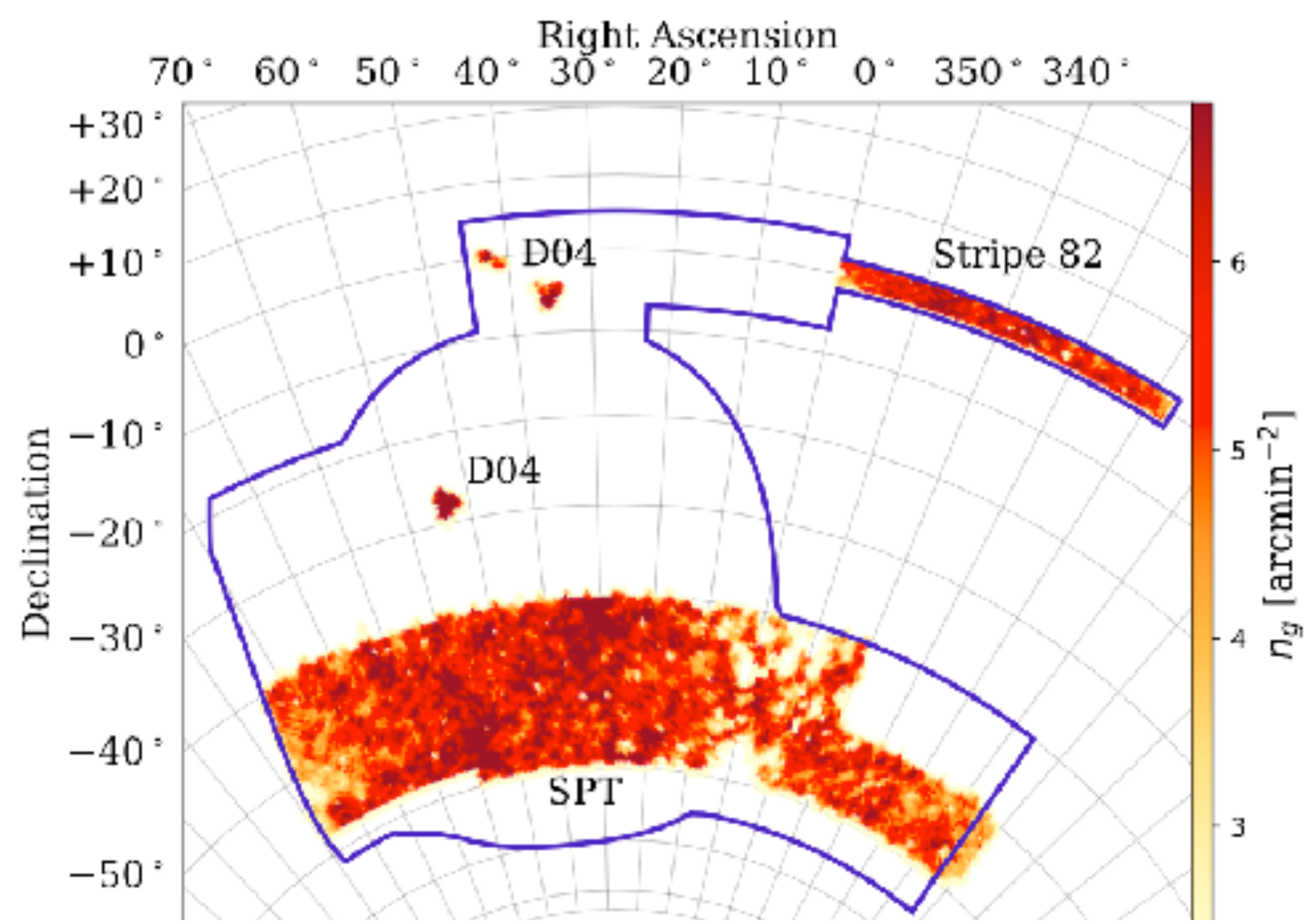
10-20 galáxias/arcmin²



Example: DES Y1 Results

- Data
  - 1321 deg^2 of g,r,i,z imaging data
  - 26 million source galaxies
  - 650,000 luminous red galaxies (redMaGIC)
- Combined analysis of 3 two-point function
  - the cosmic shear correlation function in four redshift bins
  - the galaxy angular autocorrelation function of LRGs in five redshift bins
  - the galaxy-shear cross-correlation of LRG positions and source galaxy
  - shears.
- Dark Energy Survey Year 1 Results: Cosmological Constraints from Gala
  - 10 "supporting papers" jointly sul
  - Careful analysis of systematics
  - Joint likelihoods

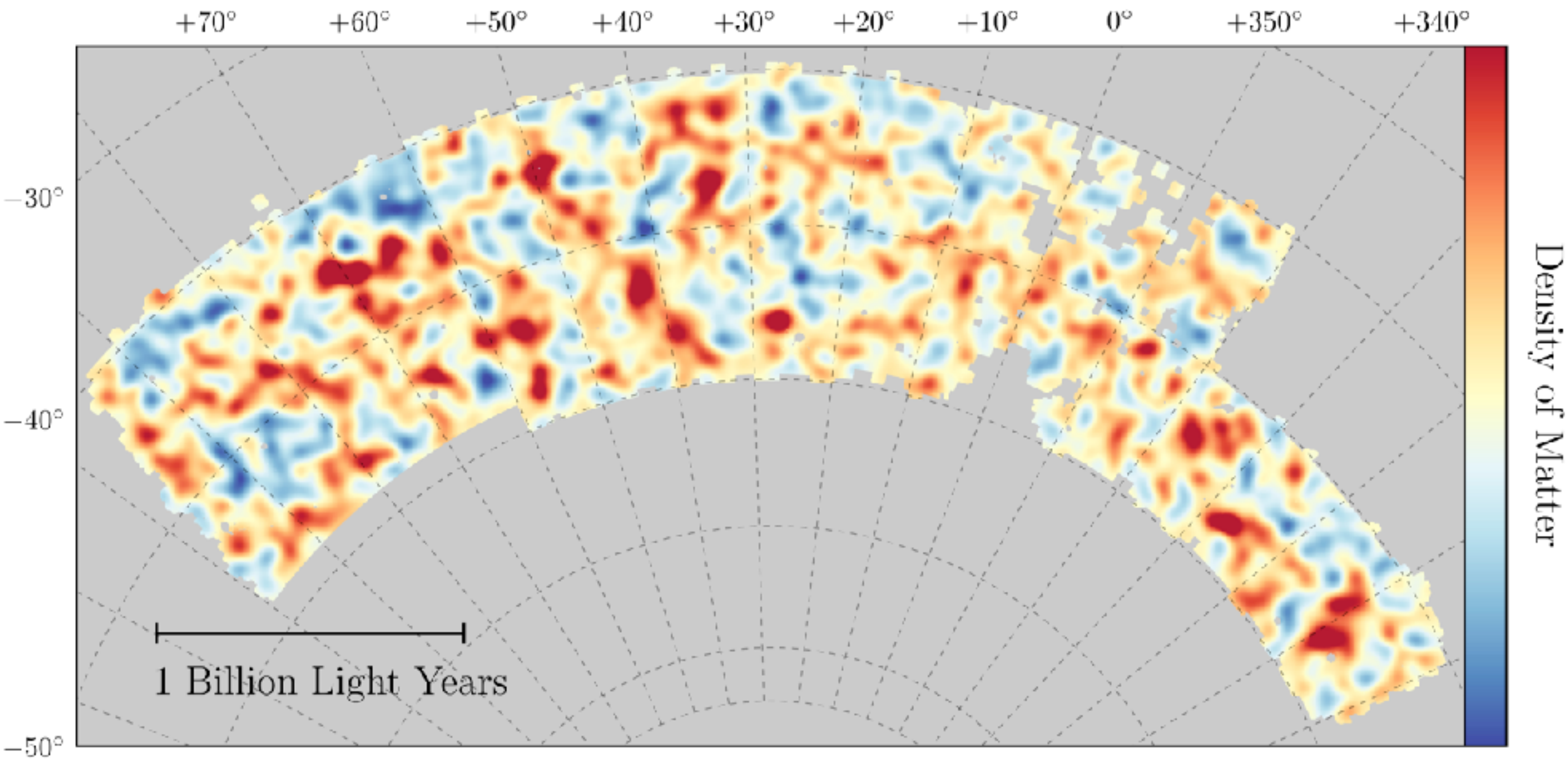
"[...] this paper presents the most stringent cosmological constraints from a galaxy imaging survey to date and, combined with external data, the most stringent constraints overall".



http://www.darkenergysurvey.org/des-year-1-cosmology-results-papers/

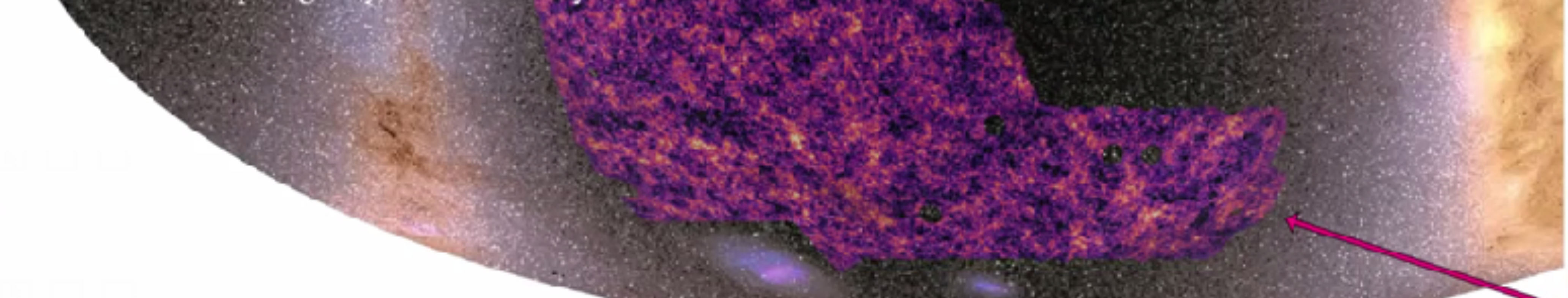
Cosmic Shear Measurements

Dark Matter Map 2.0

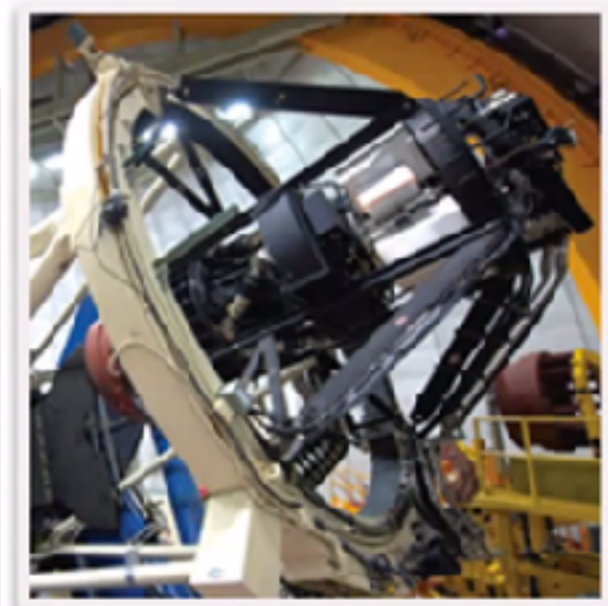


DARK ENERGY SURVEY

- **Led by Fermilab**
- **DECam**: The 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Survey Observations 2013-2019 ("Y3" means 2013-16).
- **Wide field:** 5000 sq. deg. in 5 bands. ~23 magnitude depth.
- 27 sq. deg. 5-yr SNIa survey

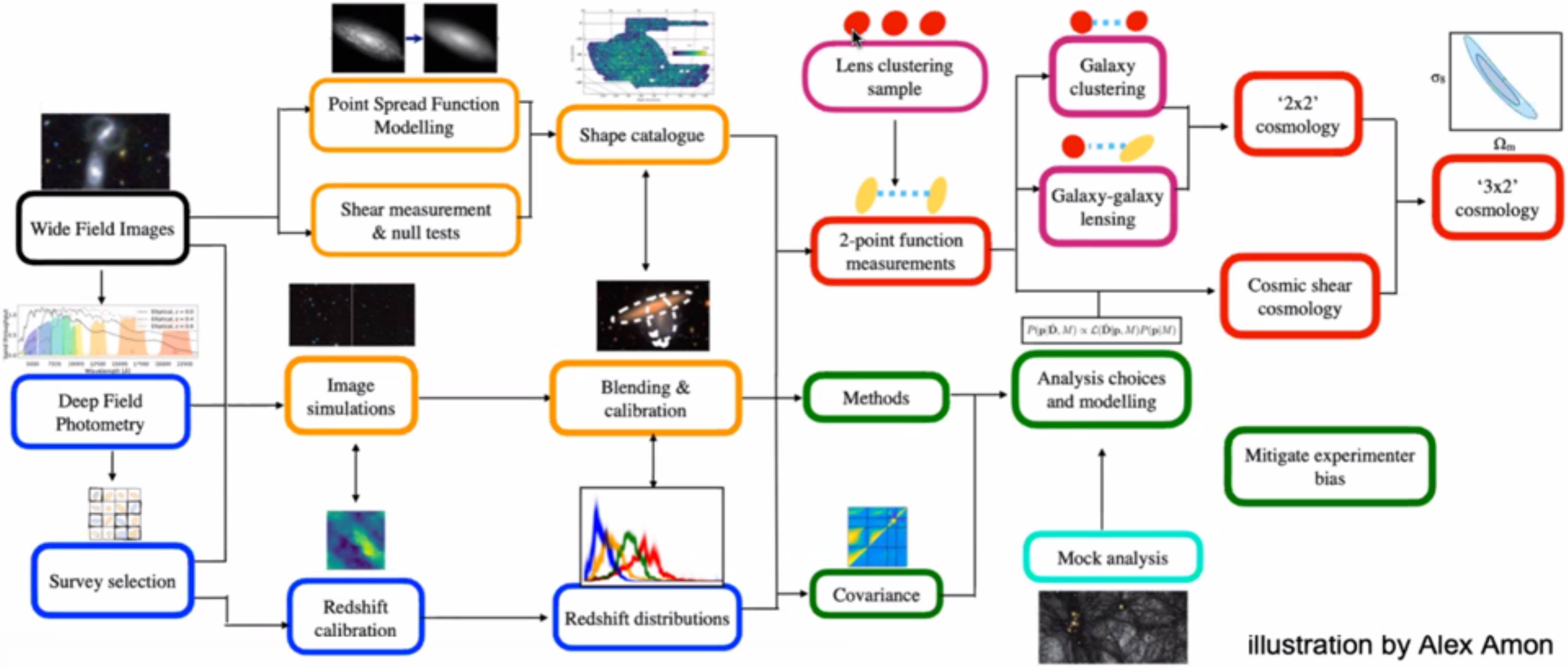


N. Jeffrey; Dark Energy Survey Collaboration



Dark Matter map from DES observations

DES Year 3: pixels to cosmology



Redshifts —— Shapes —— Clustering —— Simulations —— Theory —— Results

Estimadores estadísticos

Dark Energy Survey Year 1 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing

Galaxy–galaxy lensing: $\gamma_t(\theta)$

Cosmic shear: $\xi_{\pm}(\theta)$

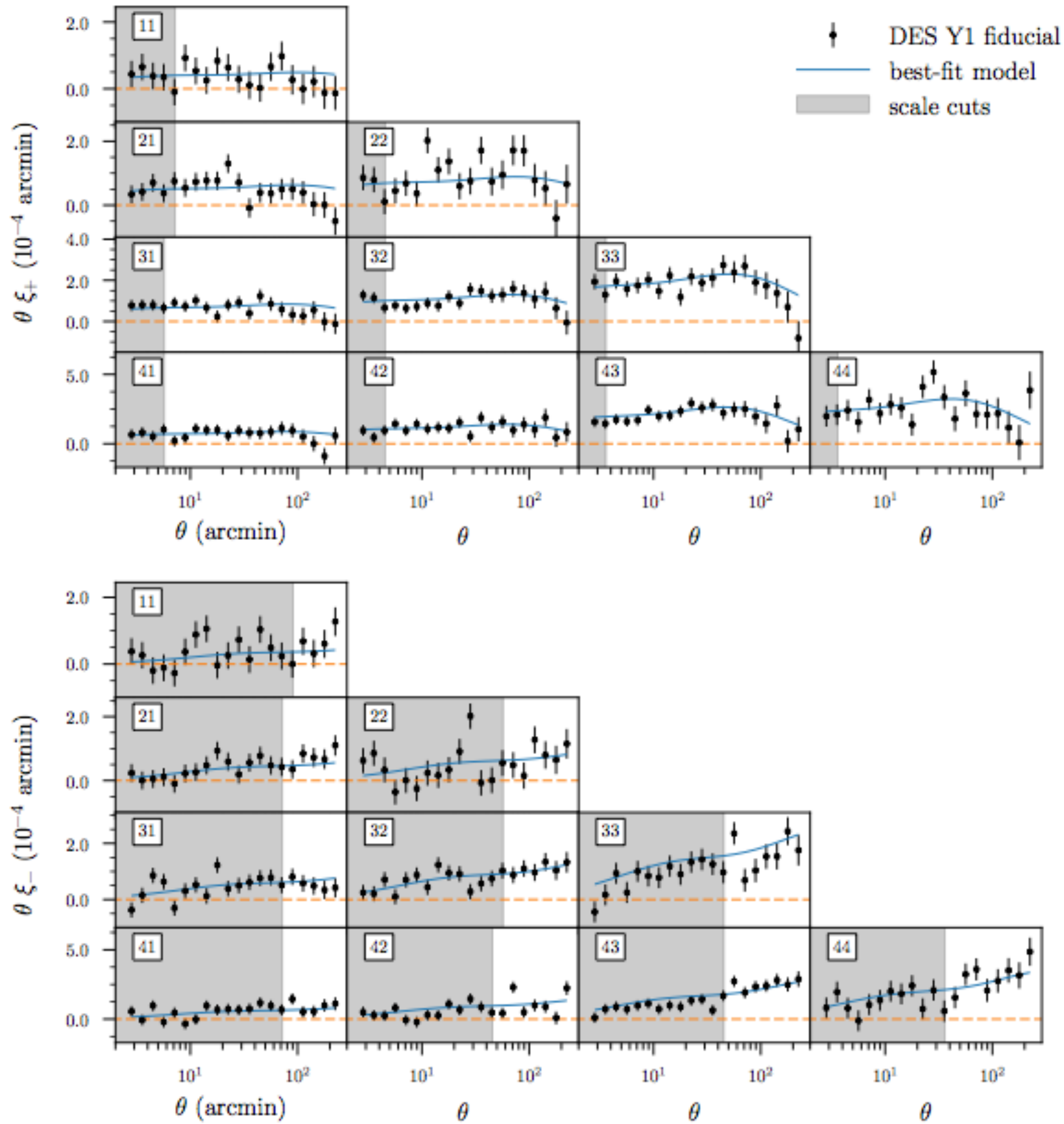
$$\xi^{ij}_{+/-}(\theta) = (1+m^i)(1+m^j) \int \frac{dl\, l}{2\pi} J_{0/4}(l\theta) \int d\chi \frac{q^i_\kappa(\chi) q^j_\kappa(\chi)}{\chi^2} P_{\rm NL}\left(\frac{l+1/2}{\chi}, z(\chi)\right)$$

$$q^i_\kappa(\chi) = \frac{3H_0^2\Omega_m}{2c^2} \frac{\chi}{a(\chi)} \int_\chi^{\chi_h} d\chi' \frac{n^i_\kappa(z(\chi'))dz/d\chi'}{\bar{n}^i_\kappa} \frac{\chi'-\chi}{\chi'}, \tag{IV.3}$$

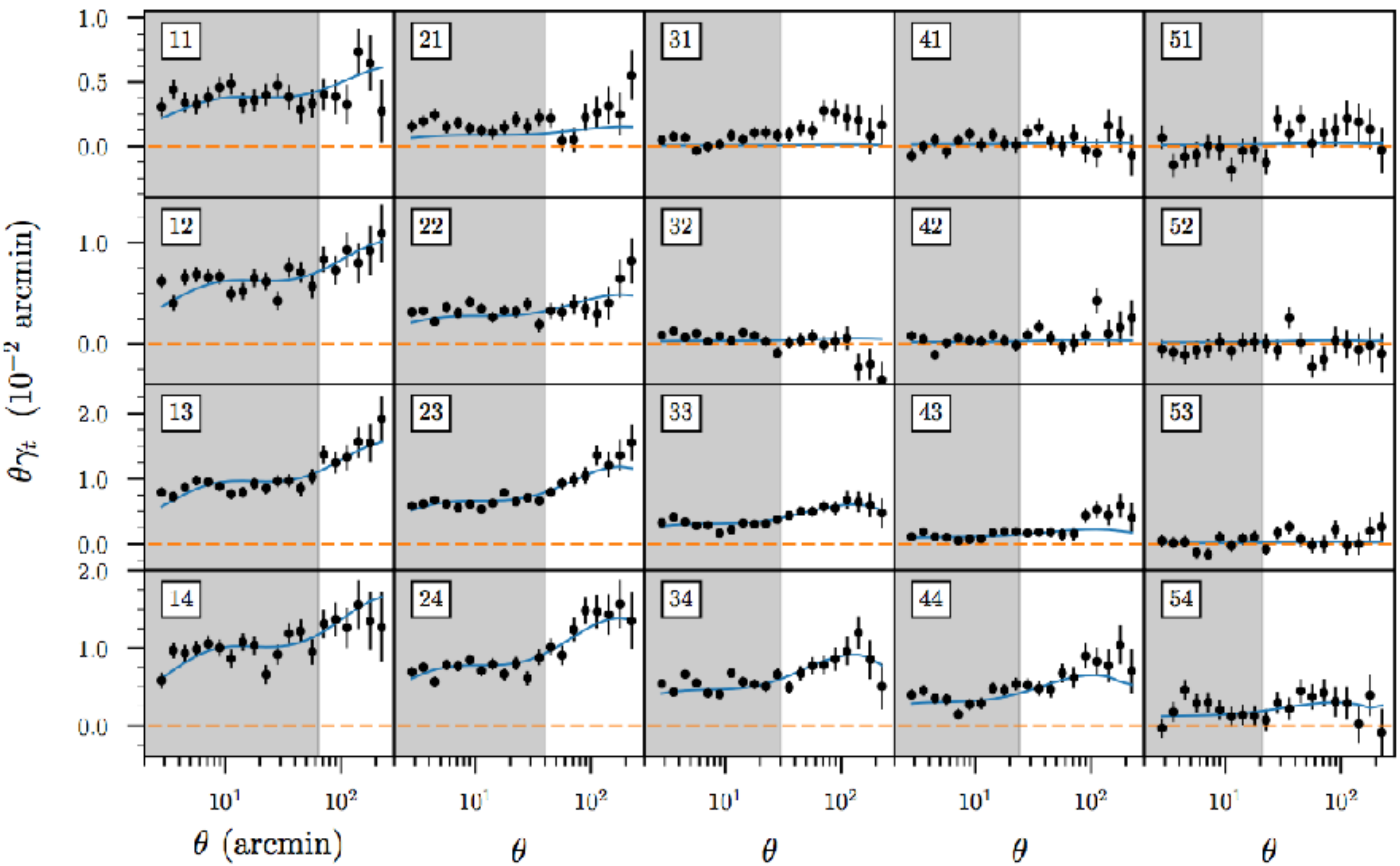
Galaxy Clustering: $w(\theta)$

$$w^i(\theta) = \int \frac{dl\, l}{2\pi} J_0(l\theta) \int d\chi \frac{q^i_{\delta_g}\left(\frac{l+1/2}{\chi}, \chi\right) q^j_{\delta_g}\left(\frac{l+1/2}{\chi}, \chi\right)}{\chi^2} \times P_{\rm NL}\left(\frac{l+1/2}{\chi}, z(\chi)\right) \tag{IV.4}$$

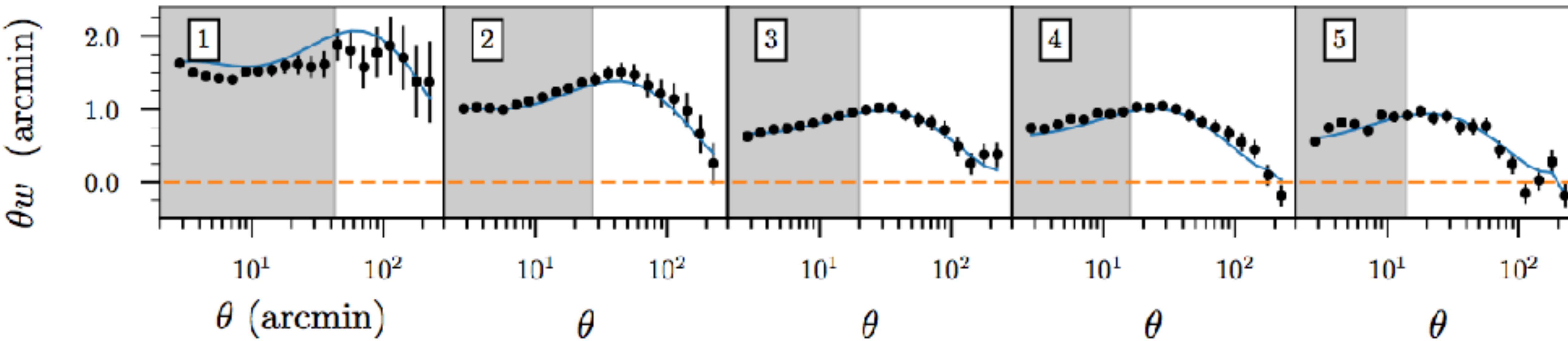
Weak Lensing Tomography



galaxy-shear correlation

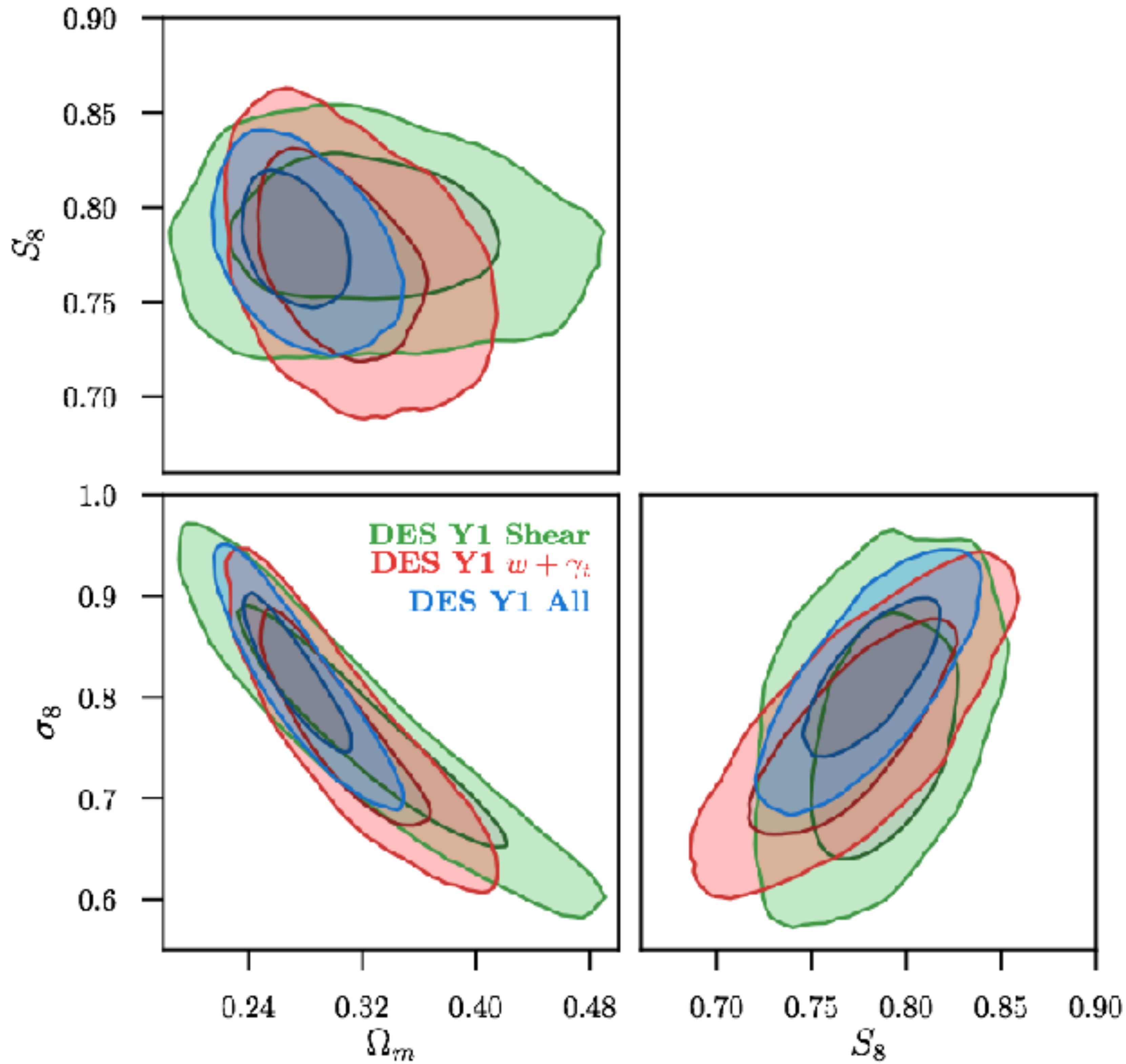


Angular Correlation Function

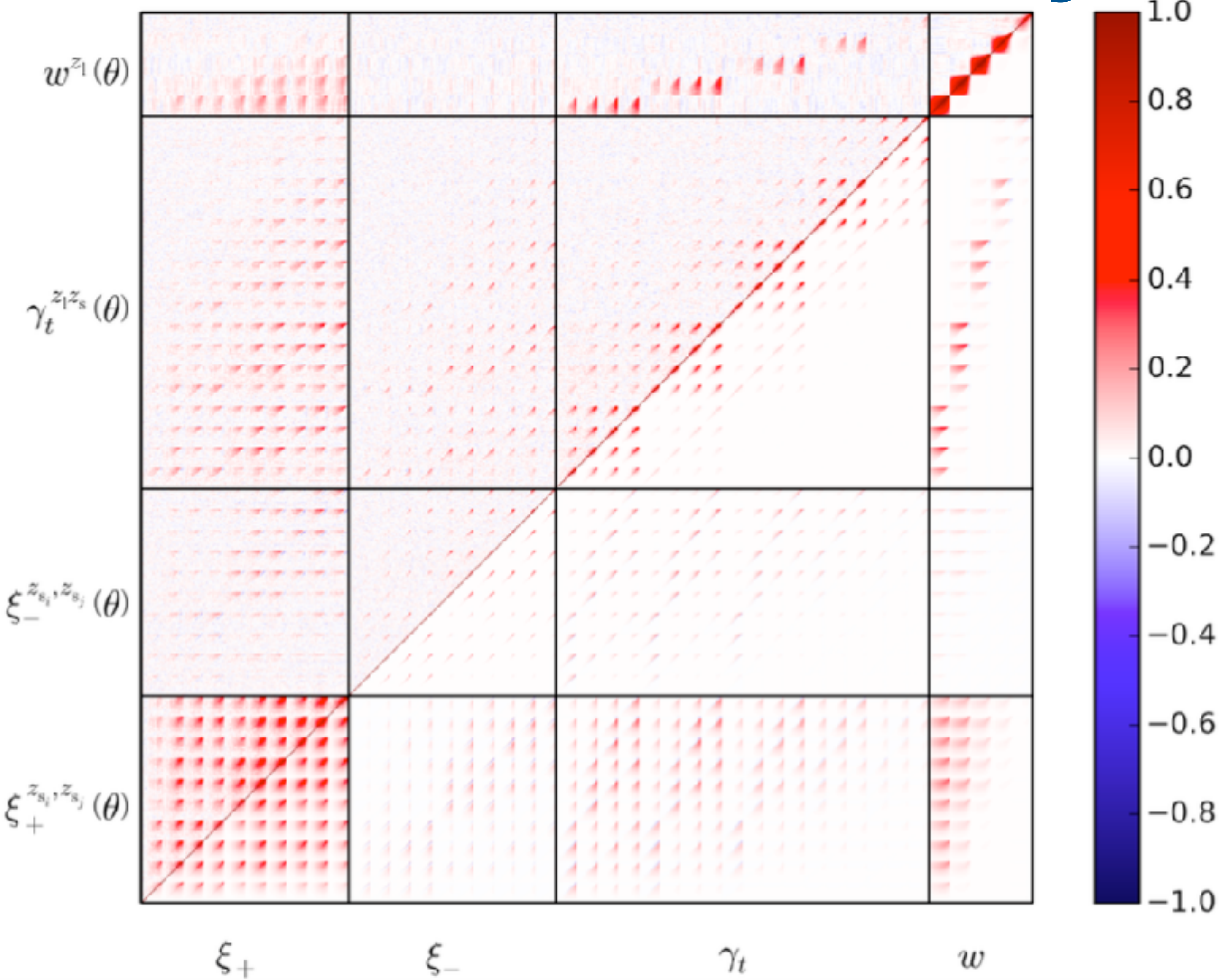


Scaled angular correlation function, θw(θ), of redMaGiC galaxies in five redshift bins

Consistency of the Probes



Combined Analysis



457 × 457 element covariance matrix!

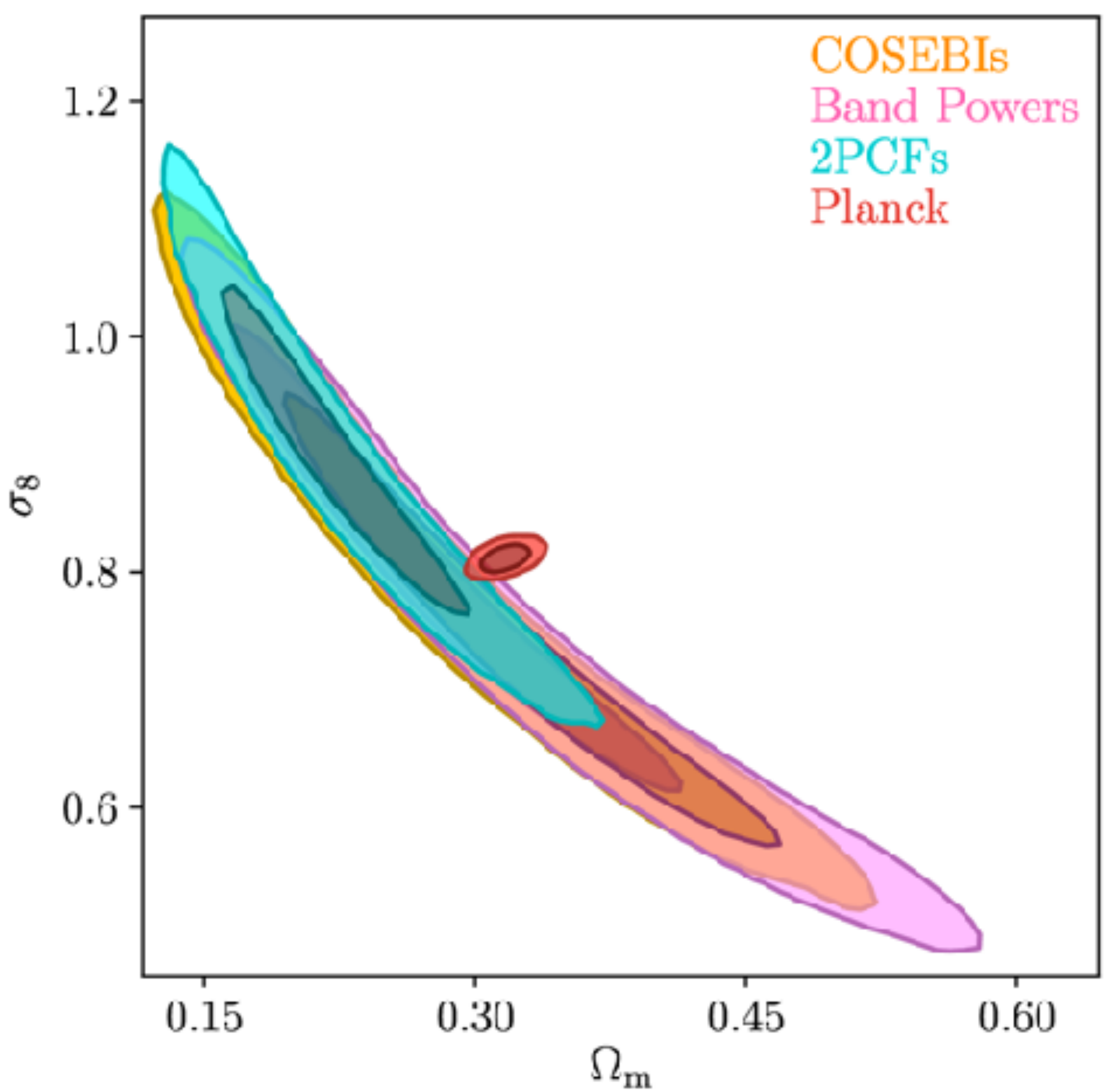
20 "nuisance parameters" + 6/7 cosmological

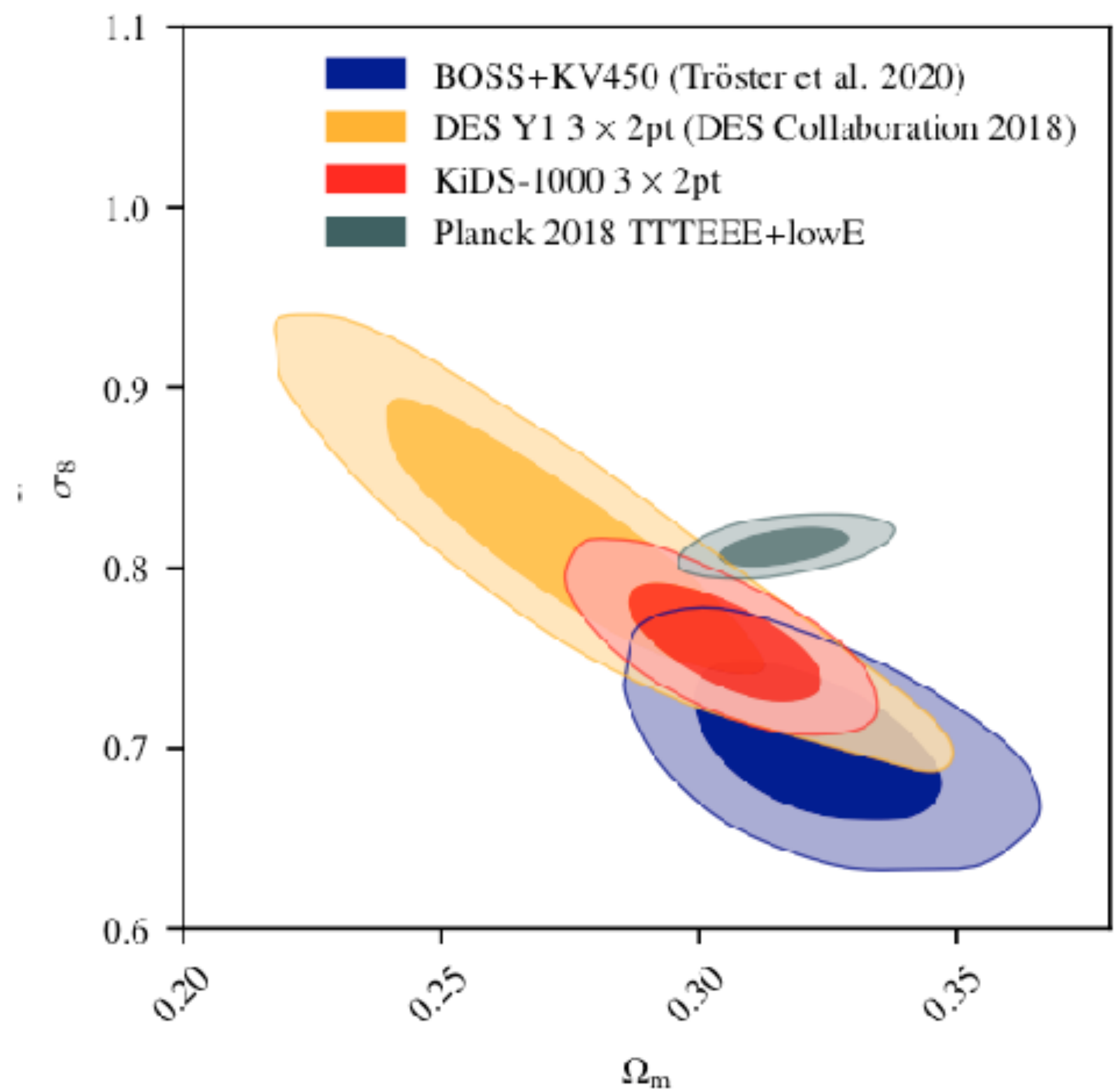
Kilo Degree Survey

KiDS: 1000 sq-deg

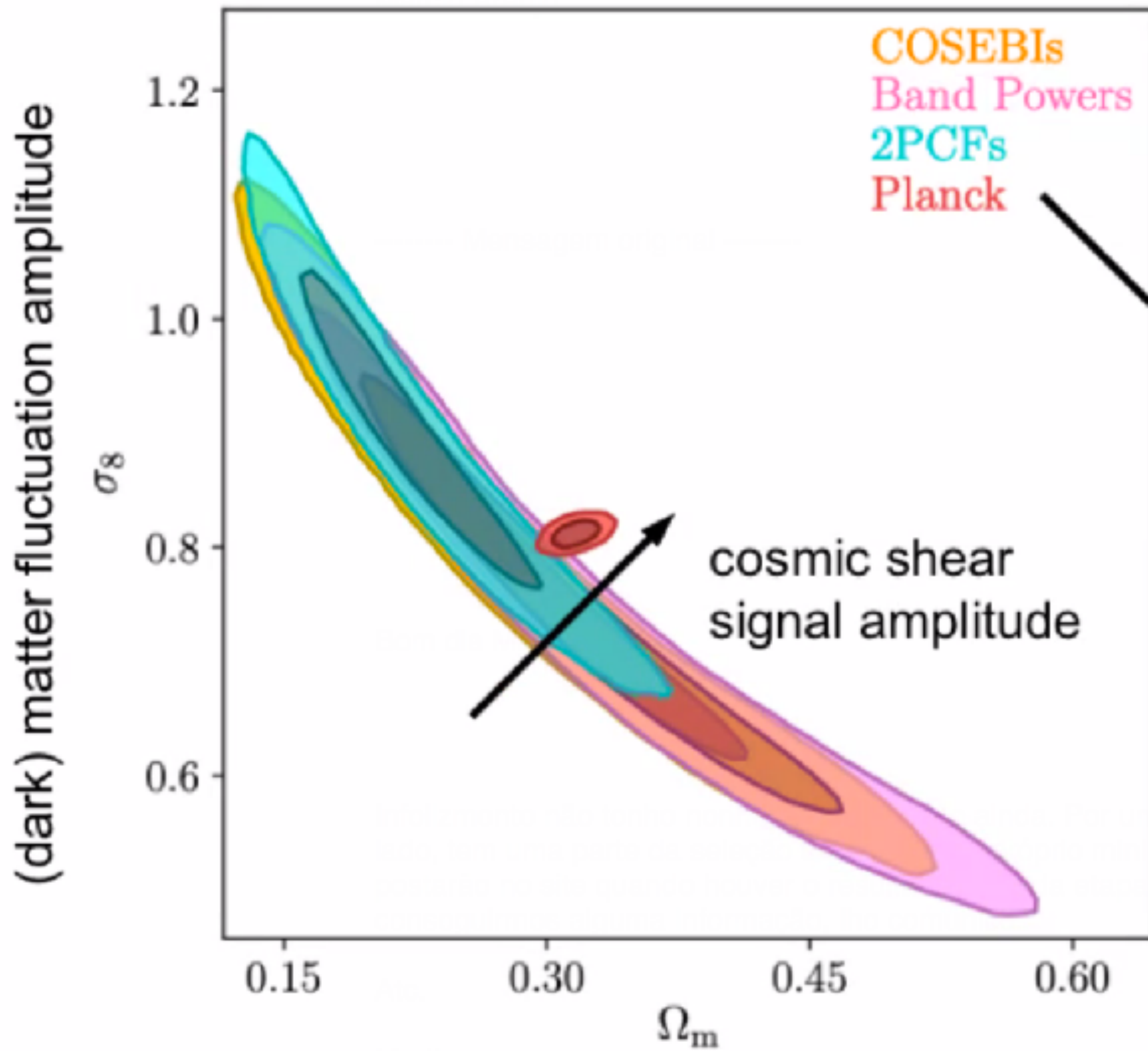
http://kids.strw.leidenuniv.nl/KiDS-1000_preprints.php

Cosmological parameter constraints from tomographic weak gravitational lensing





Cosmic shear cosmological constraints



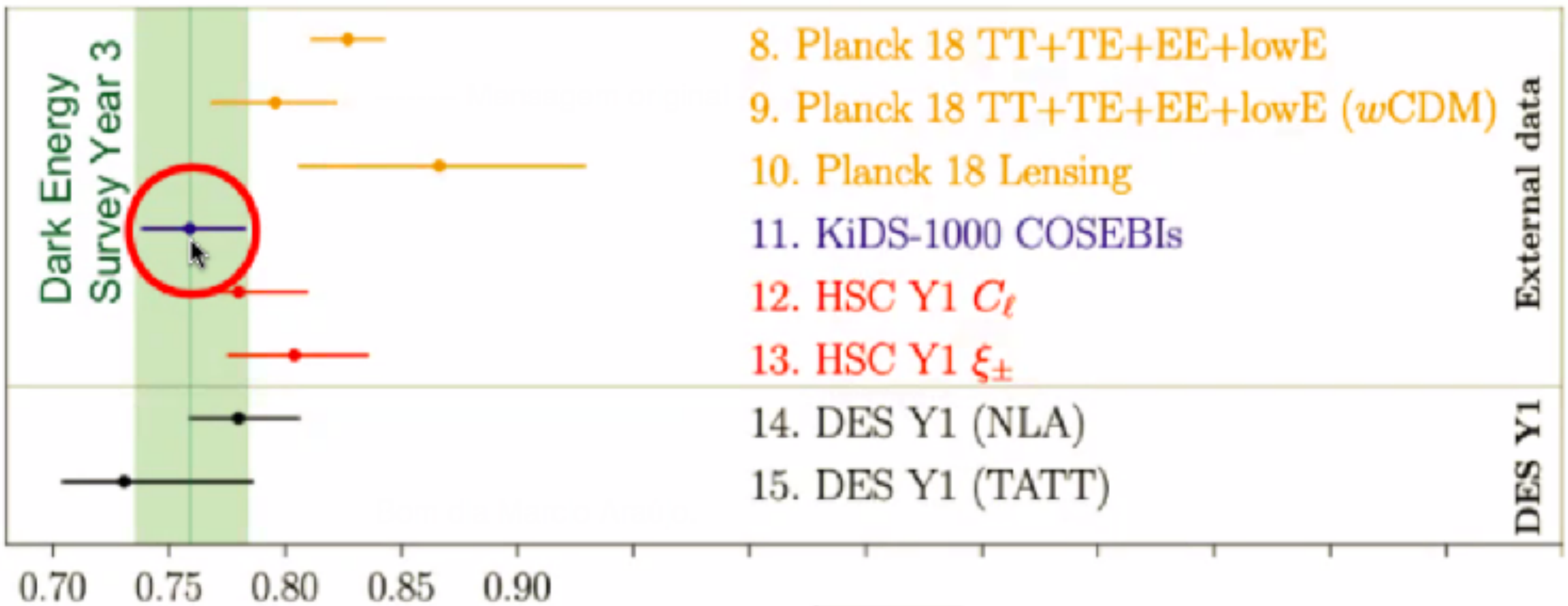
different cosmic shear statistics

cosmic microwave background constraint

(dark) matter density

Asgari, Lin, Joachimi+ (2021)

Consistency with DES

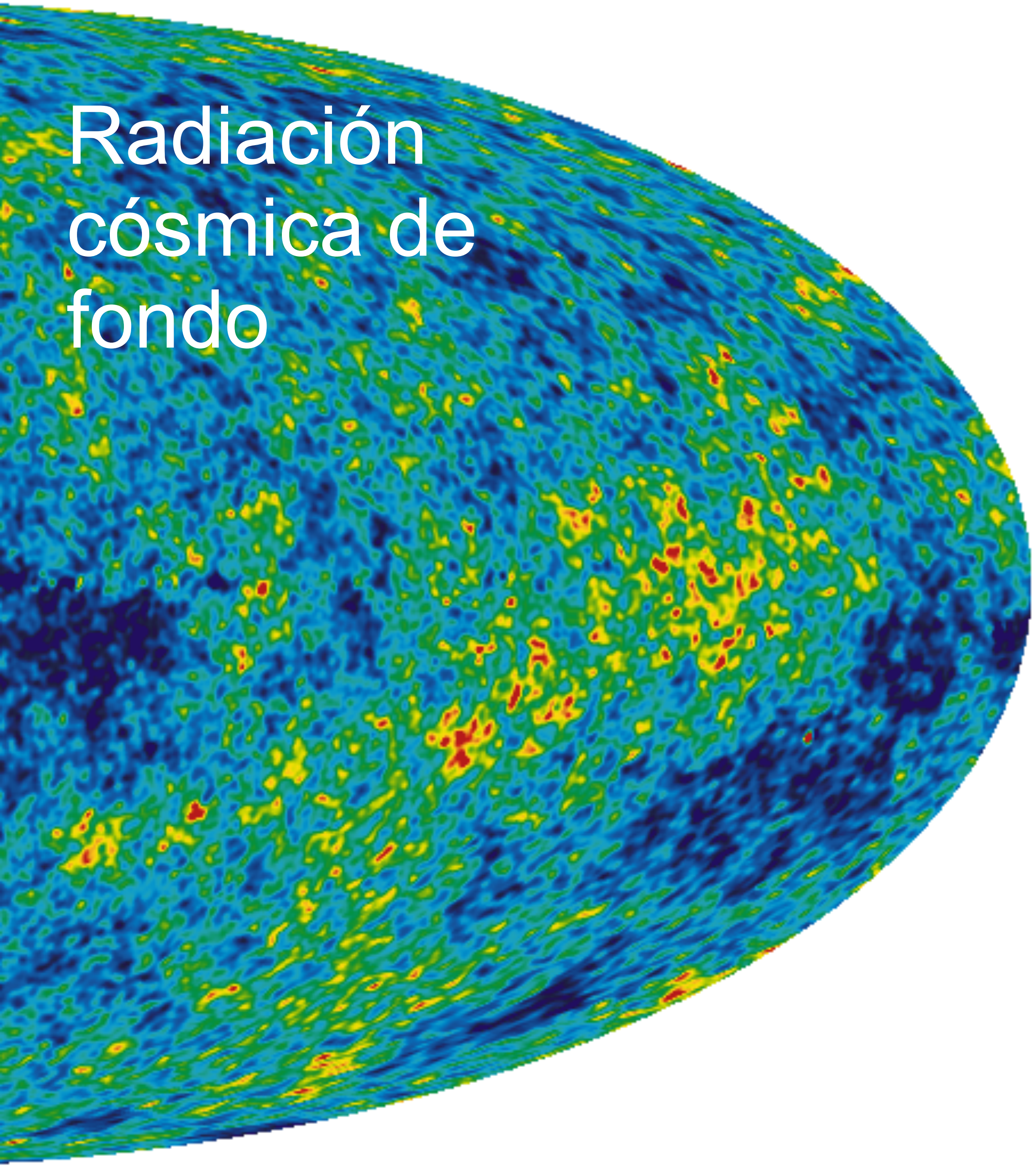


Secco+ (2021)

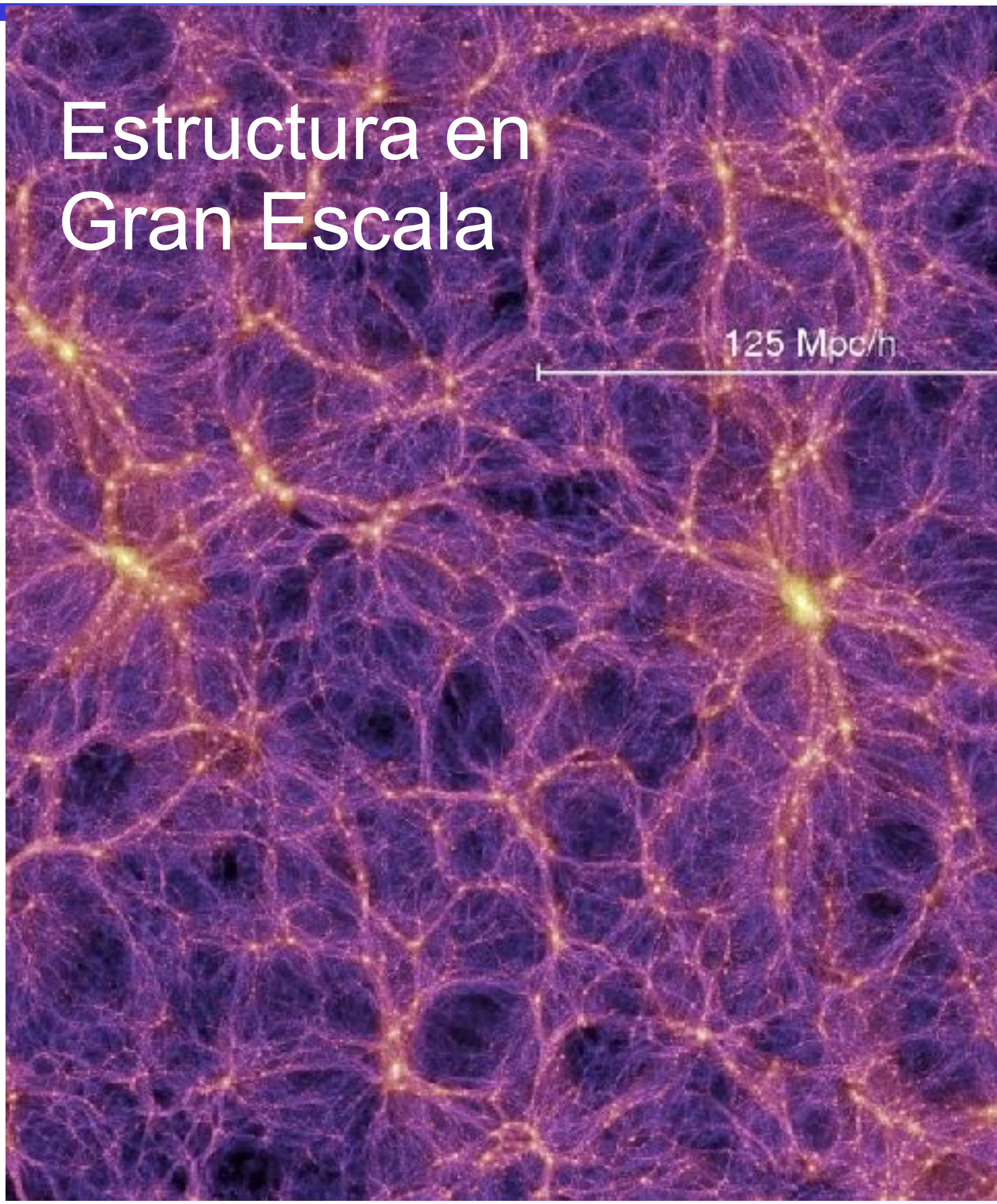
Cosmic shear agreement with nearly independent DES Year 3 results is excellent.

Problema con S_8 que se fue intensificando con el tiempo!

¿Cómo se formaron las estructuras?



Fluctuaciones ~ 10^{-4}



Fluctuaciones ~ 10^{3}

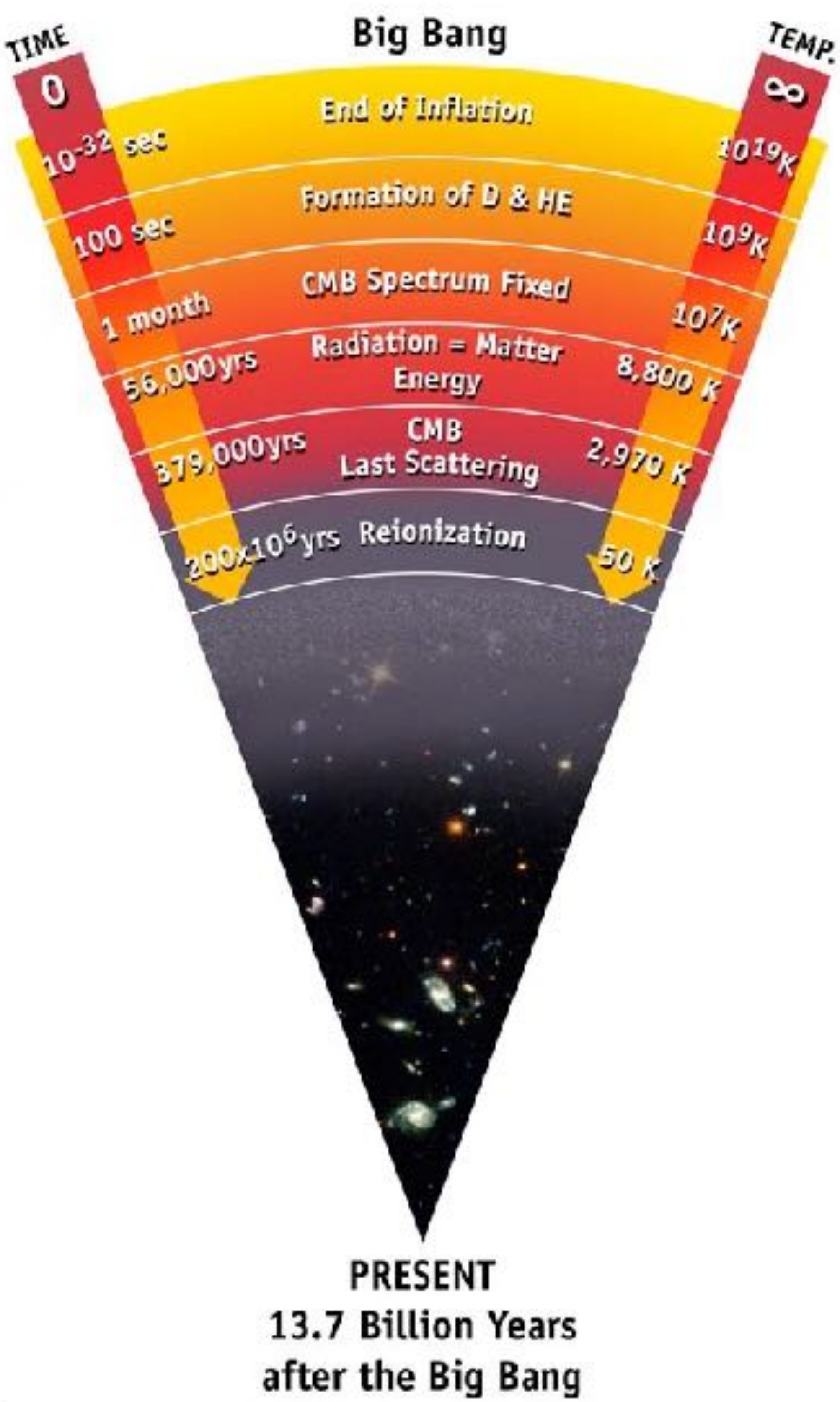
Some Milestones in the History of the Universe

energy

kT (radiation)	Event
2 x 10^{-4} eV	Today
10^{-3} eV	Galaxy formation
0.26 eV	H recombination (matter-radiation decoupling)
10 eV	Matter domination
300 keV	Formation of light elements (He^4, He^3, D e Li) (primordial nucleosynthesis)
0.5 MeV	End of leptonic era (e^+ e^- annihilation)
100 MeV	End of hadronic era and beginning of leptonic era (hadronization, annihilation hadron anti-hadron)
1000 GeV	Electroweak phase transition
10^{15} GeV	Bariosynthesis? Great Unification?
10^{19} GeV	End of quantum era? Inflation?

time

Endireitando a seta do tempo...



- Fase primordial densa e quente
  - *"Big-Bang"*
- Processos físicos:
  - inflação, PBH, quebras de simetria
  - bariogênese, leptogênese
  - Hadronização
  - Aniquilação matéria-anti-matéria...
  - Síntese dos elementos leves
  - Recombinação
  - Formação de estruturas
- Fósseis:
  - Ondas grav. primordiais, PBH
  - Fundo cósmico de neutrinos
  - Abundância primordial
  - Radiação cósmica de fundo
  - Estruturas no Universo

Recombination

When the temperature drops below 3.000K the electrons get bounded to the nuclei

- ➢ The Universe becomes transparent
- ➢ Light propagates freely

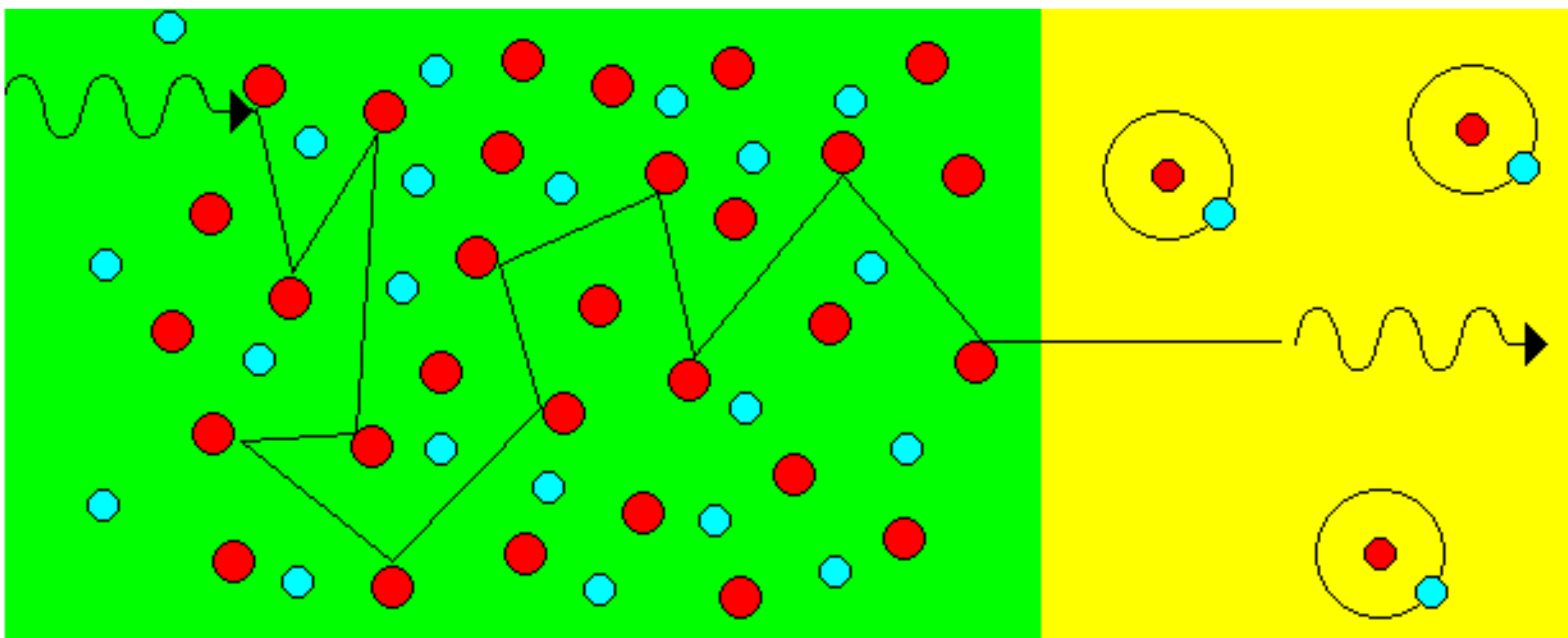
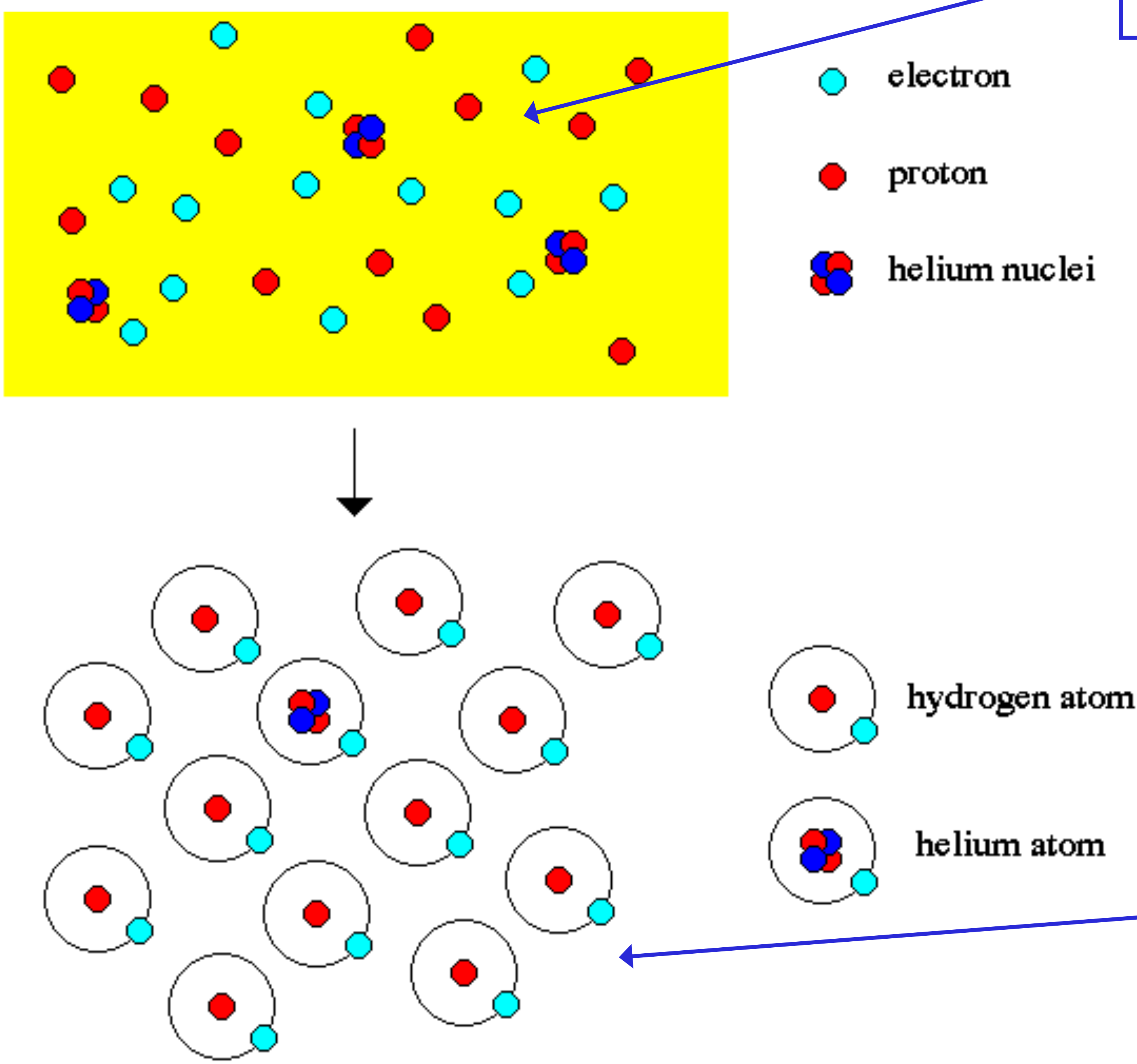


Figure from http://blueox.uoregon.edu/~karen/astro123/lectures/lec21.html

Recombination

plasma



neutral matter

Happens at 0.26eV instead of 13.6eV!

$$\eta := \frac{n_b}{n_\gamma} \simeq 6\times 10^{-10}$$

Figure from http://blueox.uoregon.edu/~karen/astro123/lectures/lec20.html

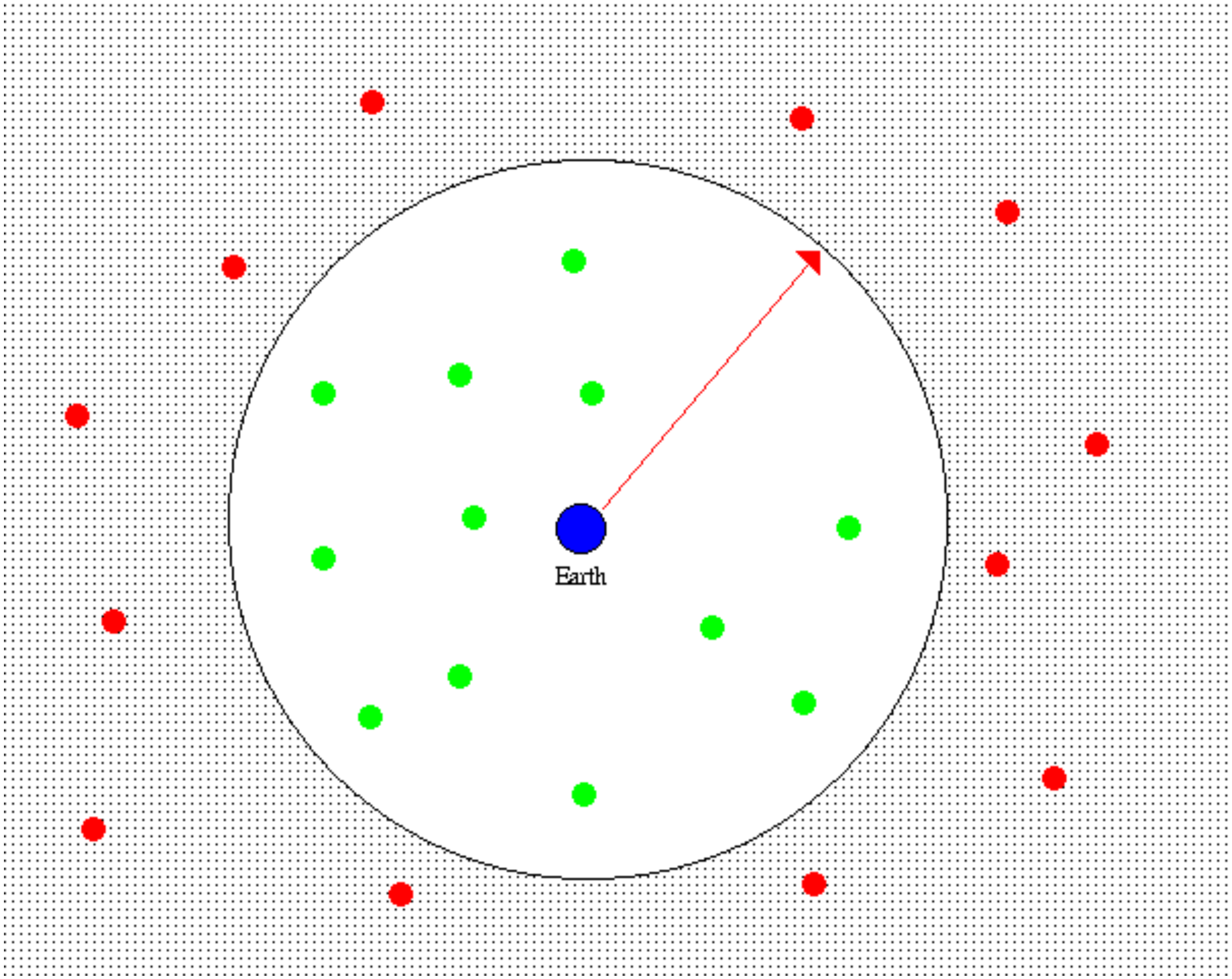
The Cosmic Microwave Background

"Photosphere" seen from our galaxy

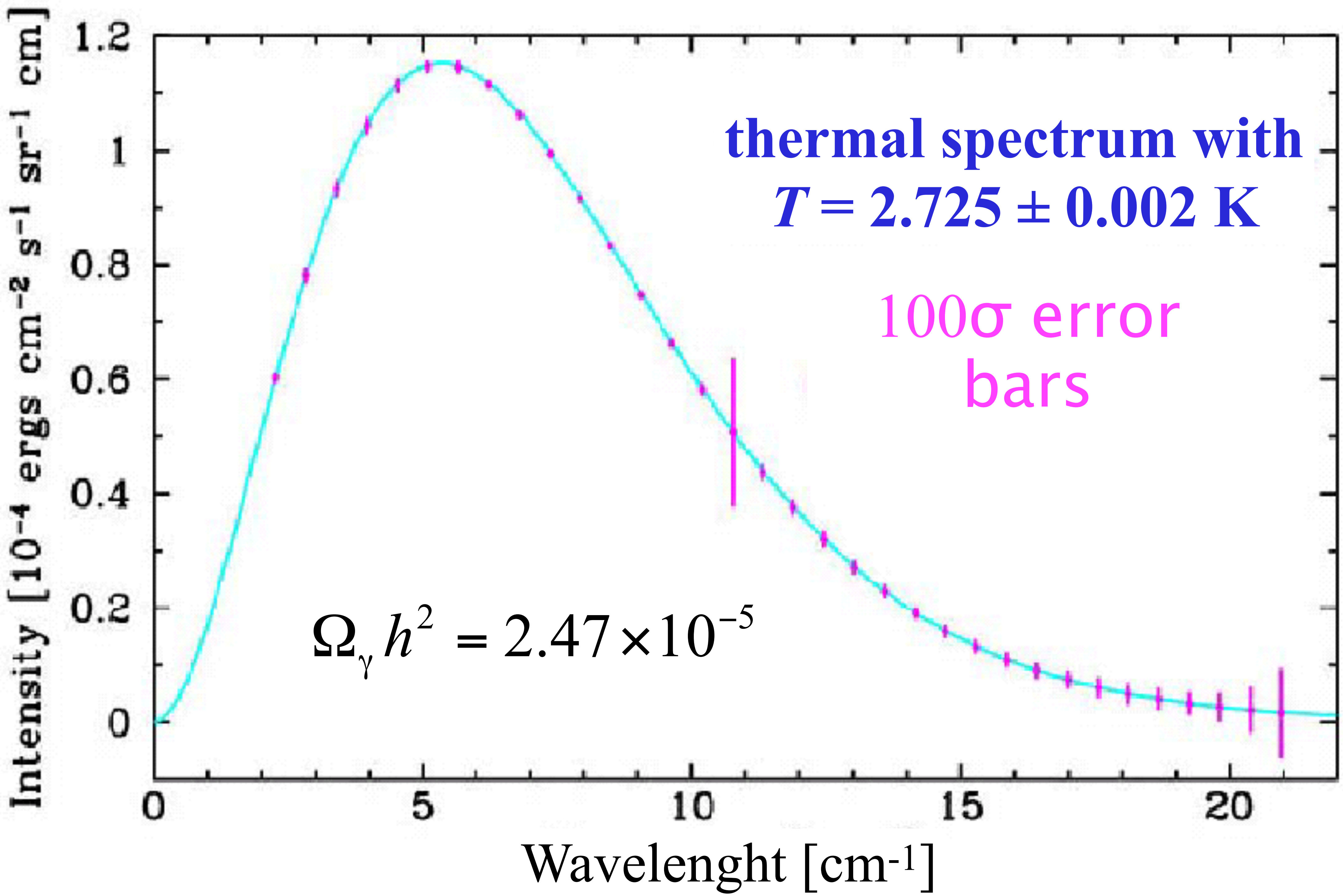
Expect to see:

Black body with redshift

$z \sim 1000$



Spectrum of the CMB

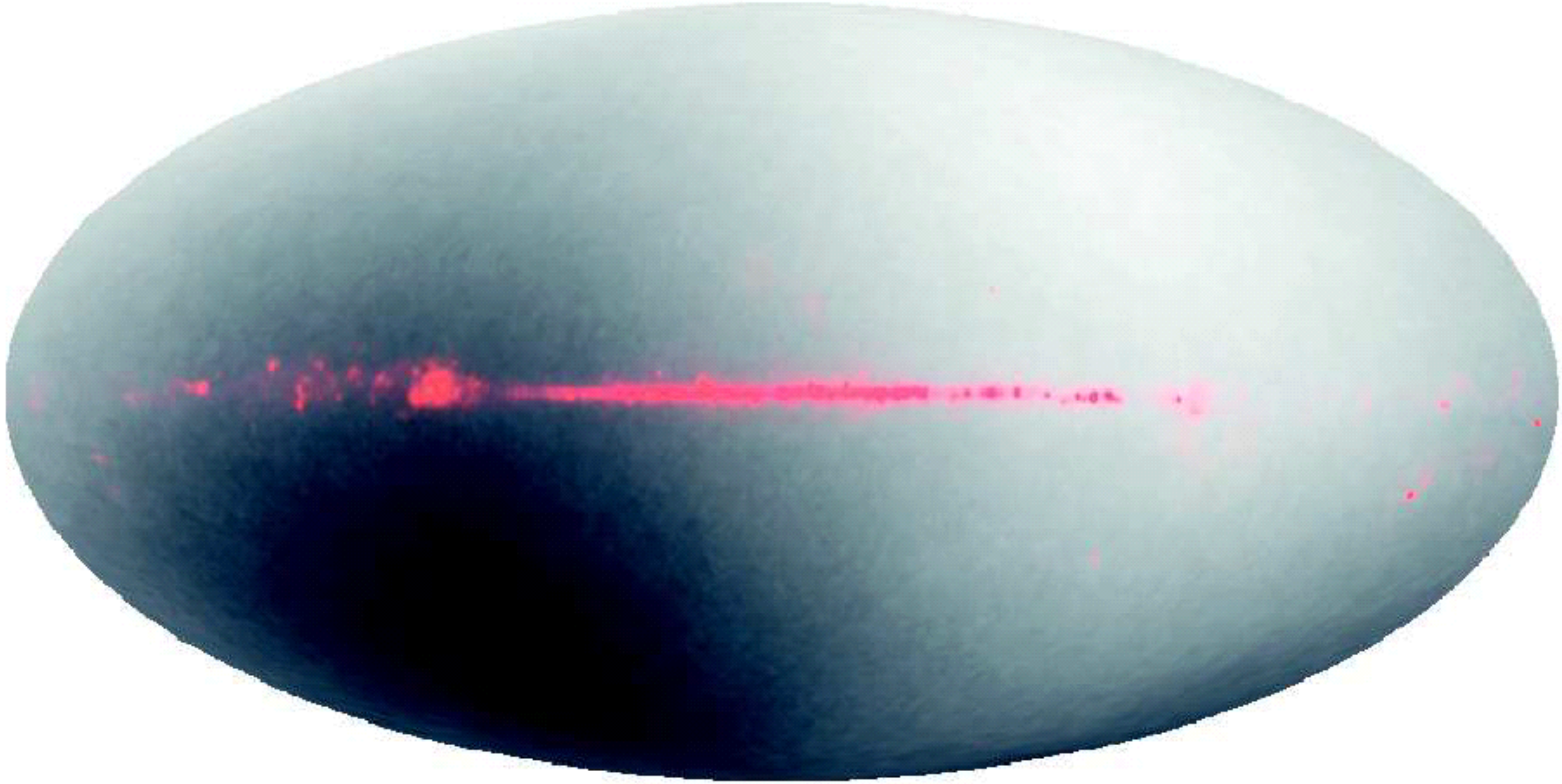


Cosmic Microwave Background I

Cosmic Microwave Background Radiation Map

Contrast: 1x 400x

- Epoch of matter and radiation decoupling (about 380.000 years after the "*Big-Bang*").
- T_0 = 2.725 ± 0.002. Redshift, $z = 1089$.
- Highly homogeneous primordial Unverse
- Dipole: ΔT = 3.346 ± 0.017 mK ➔ v_{gal} = 360 Km/s

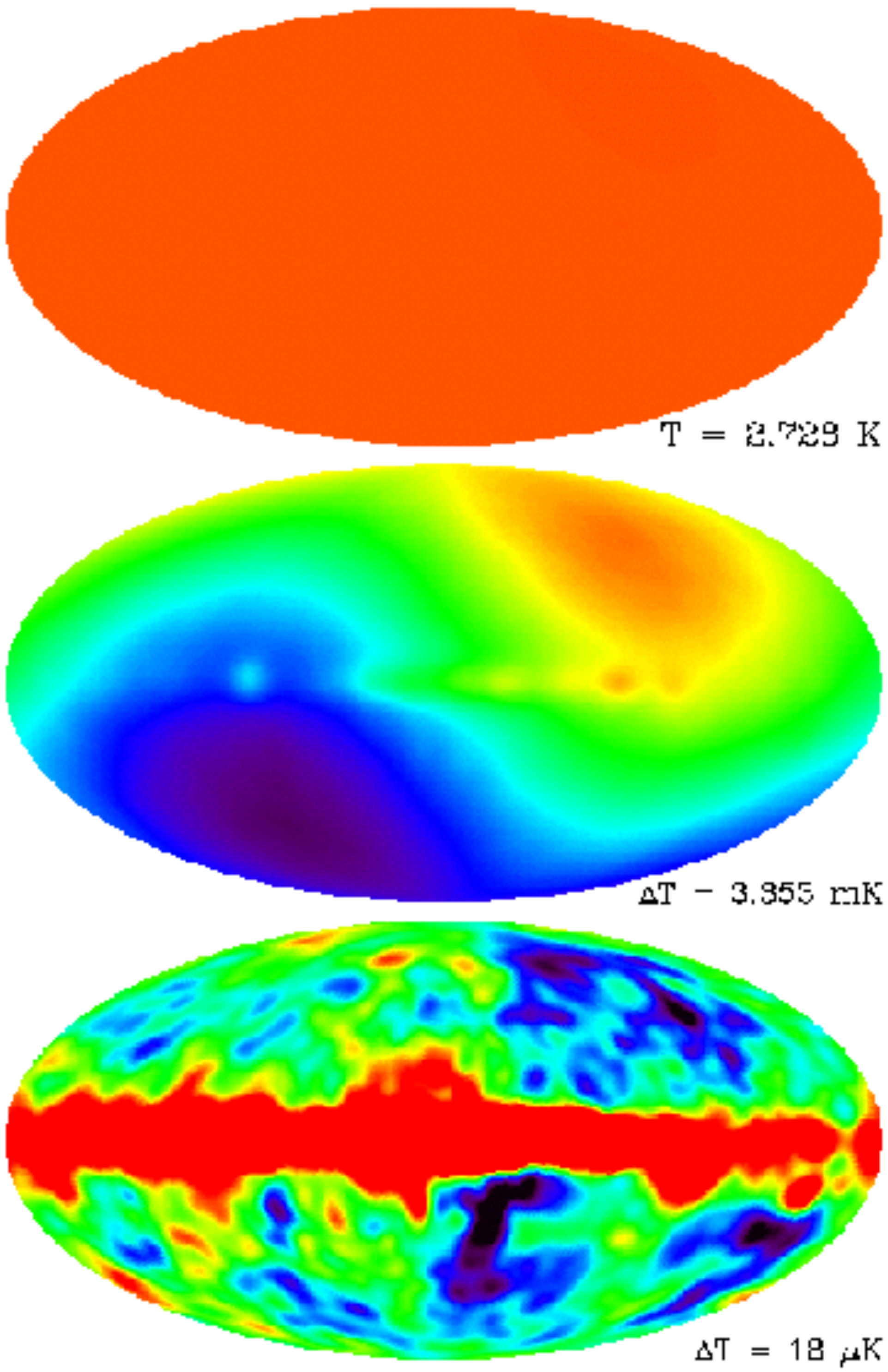


- Epoch of matter and radiation decoupling (about 380.000 years after the "*Big-Bang*").
- T_0 = 2.725 ± 0.002. Redshift, $z = 1089$.
- Highly homogeneous primordial Unverse
- Dipole: ΔT = 3.346 ± 0.017 mK ➔ v_{gal} = 360 Km/s

The Perturbed Universe

CMB anisotropies and Large-scale Structure

Anisotropies in the Cosmic Background



- T_0 = 2.725 ± 0.002.
  redshift, z = 1089
- The primordial Universe was highly homogeneous
- Dipole:
  ΔT = 3.346 ± 0.017 mK
  $\Rightarrow v_{gal}$ = 360 Km/s
- Temperature fluctuations:

$$\frac{\Delta T}{T} \approx 10^{-5}$$

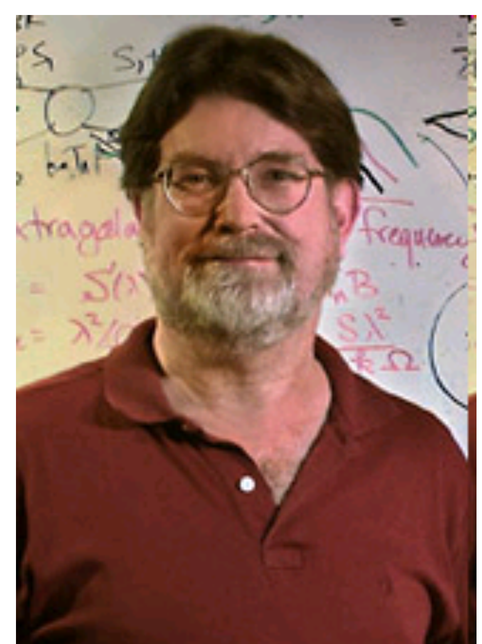
Nobel prizes: 1978, 2006

- Principais resultados do satélite COBE:
  - Corpo negro: natureza térmica da RCF
  - Anisotropias → sementes das estruturas em grandes escalas

KUNGL.
VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

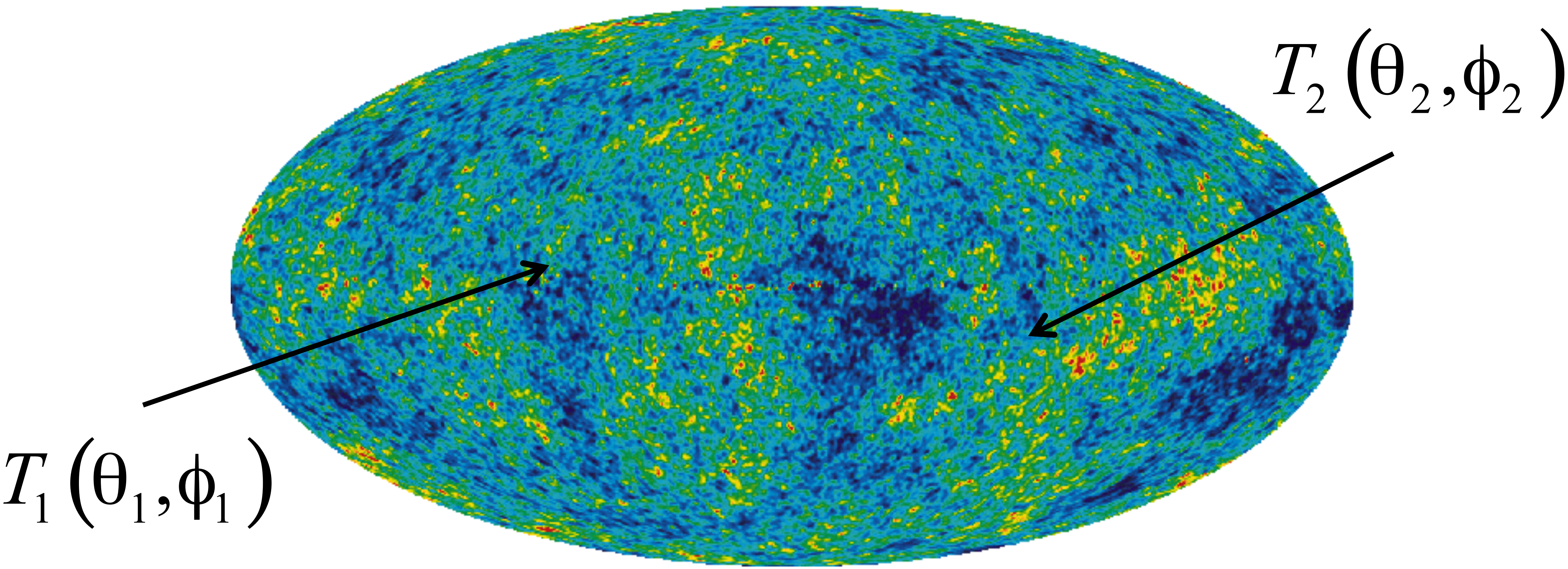
Prêmio Nobel
2006

John C. Mather



George F. Smoot

Cosmic Microwave Background Power Spectrum

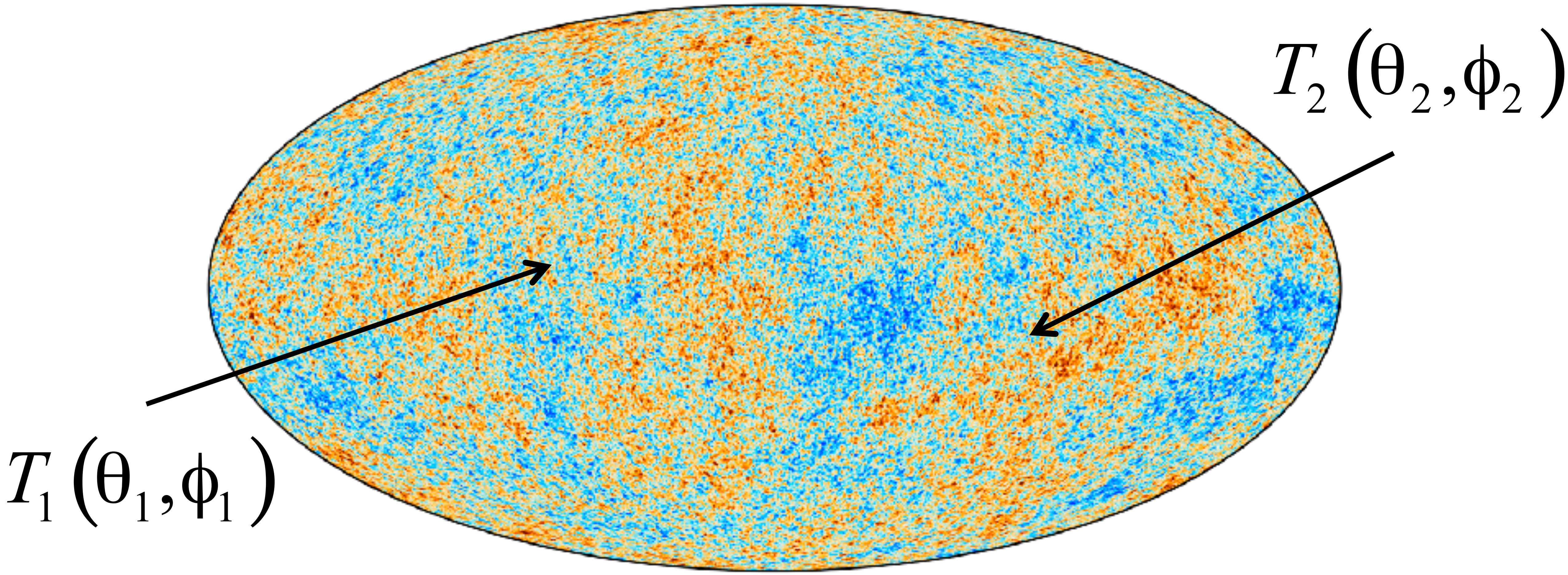


$$\langle T_1 T_2 \rangle = \sum a_{lm} Y_{lm}(\theta, \phi)$$

$$\left\langle |a_{lm}|^2 \right\rangle^{1/2} \equiv C_l$$

WMAP2008

Cosmic Microwave Background Power Spectrum



$$\langle T_1 T_2 \rangle = \sum a_{lm} Y_{lm}(\theta, \phi)$$

$$\left\langle |a_{lm}|^2 \right\rangle^{1/2} \equiv C_l$$

Planck 2015

Relativistic perturbation theory

- The starting point is the perturbed Robertson-Walker metric

$$\begin{aligned} ds^2 &= \left[g^{(0)}_{\mu\nu} + g^{(1)}_{\mu\nu}\right] dx^\mu dx^\nu \\ &= a^2(\tau)\left[-d\tau^2 + \gamma_{ij}(\vec{x})dx^i dx^j + h_{\mu\nu}(\vec{x},\tau)dx^\mu dx^\nu\right] \ , \end{aligned}$$

- At the linear level modes decouple
- Scalar perturbations:

$$\boxed{ds^2 = a^2(\tau)\left[-(1+2\Psi)d\tau^2 + (1-2\phi)\gamma_{ij}\,dx^i dx^j\right]}$$

(for a perfect fluid *Φ* = *Ψ*)

Results from the linear analysis

Need for Dark Matter

- Baryonic matter: can only cluster after decoupling $t_{\mathrm{dec}} \sim 380.000$ years

  and for $r > \lambda_J$ (Jeans length)
- Cold Dark Matter starts clustering at $t_{\mathrm{eq}} \sim 56.000$ years (matter-radiation equality)
- Baryons follow the Dark Matter potential wells
- Silk damping decreases the amplitude of baryon perturbations

CMB Anisotropies

- Primary Anisotropies

$$\frac{\Delta T}{T} = \left[\underbrace{\Psi}_{\text{Sachs-Wolfe effect}} - \underbrace{\hat{r} \cdot \vec{v}}_{\text{Doppler effect}} + \underbrace{\frac{1}{3}\delta_m}_{\text{Intrinsic temperature fluctuation}} \right]_{\eta_{ls}}$$

  - On large scales $\delta_m \simeq 2\Psi$

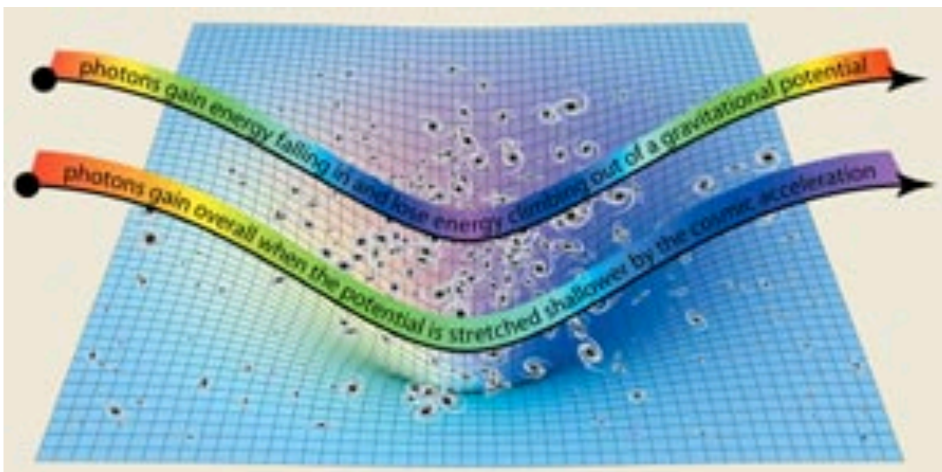
  ➔ Sachs-Wolfe plateau

  - On small scales:

  baryon acoustic oscillations

Integrated Sachs-Wolfe Effect

- Cumulative effect of gravitational shifts



http://physicsworld.com/cws/article/print/19419

$$\frac{\delta T_{ISW}}{T} = 2\int_{\tau_{dec}}^{\tau_0} \frac{\partial \phi}{\partial \tau} d\tau$$

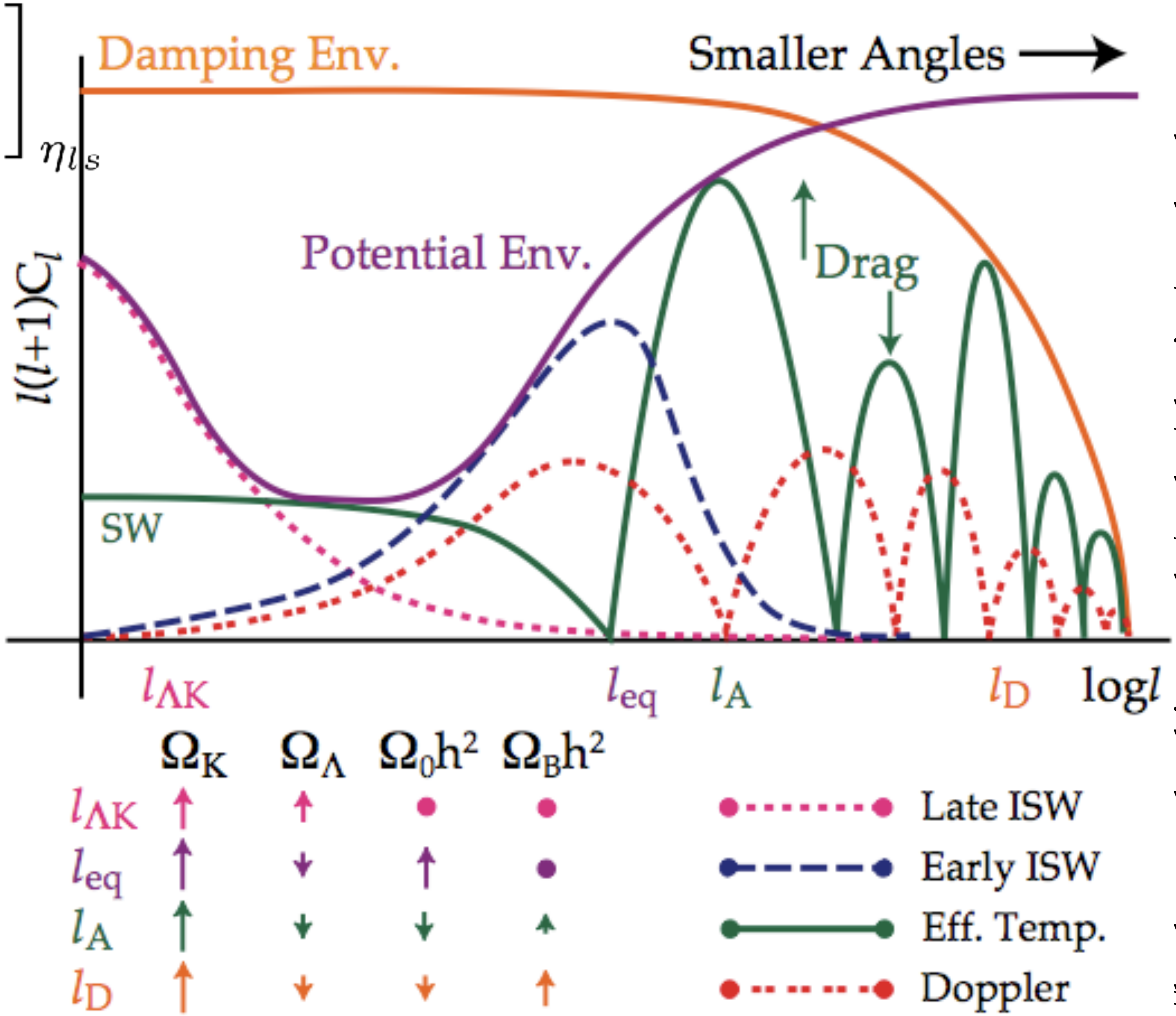
- Linear evolution, $\Omega_M = 1 \rightarrow \phi = const.$
- Late effect:
  - Correlation between the cosmic microwave background and large-scale structure!

⇨ **Dark Energy**

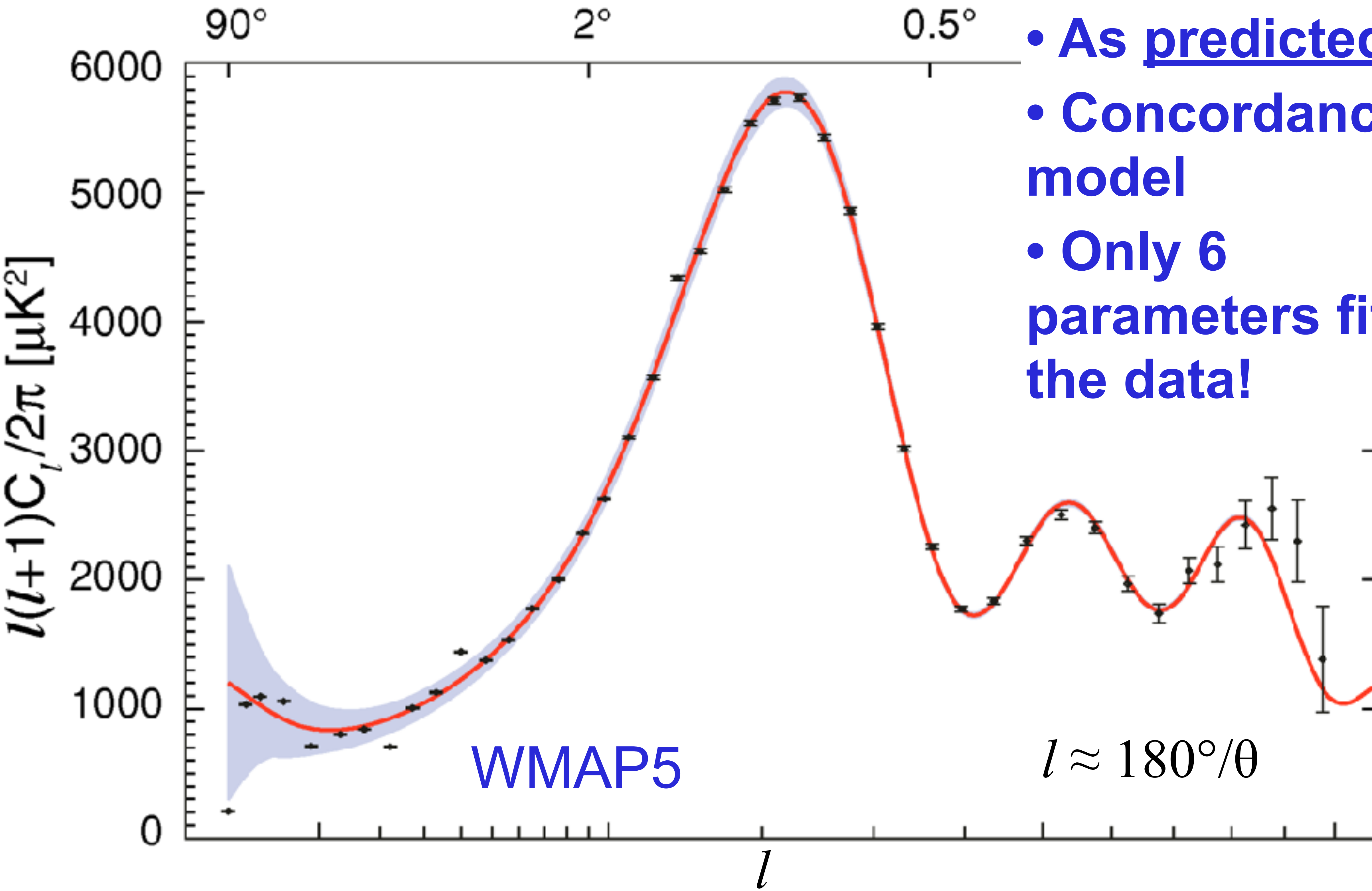
Combining the Contributions

$$\frac{\Delta T}{T} = \left[\Psi - \hat{r}\cdot\vec{v} + \frac{1}{3}\delta_m\right]_{\eta_{ls}}$$
$$+2\int_{\tau_{dec}}^{\tau_0} \frac{\partial\phi}{\partial\tau}d\tau$$

- Damping:
  - Photon diffusion in hot regions (Silk damping)
  - Finite thickness of last scattering surface

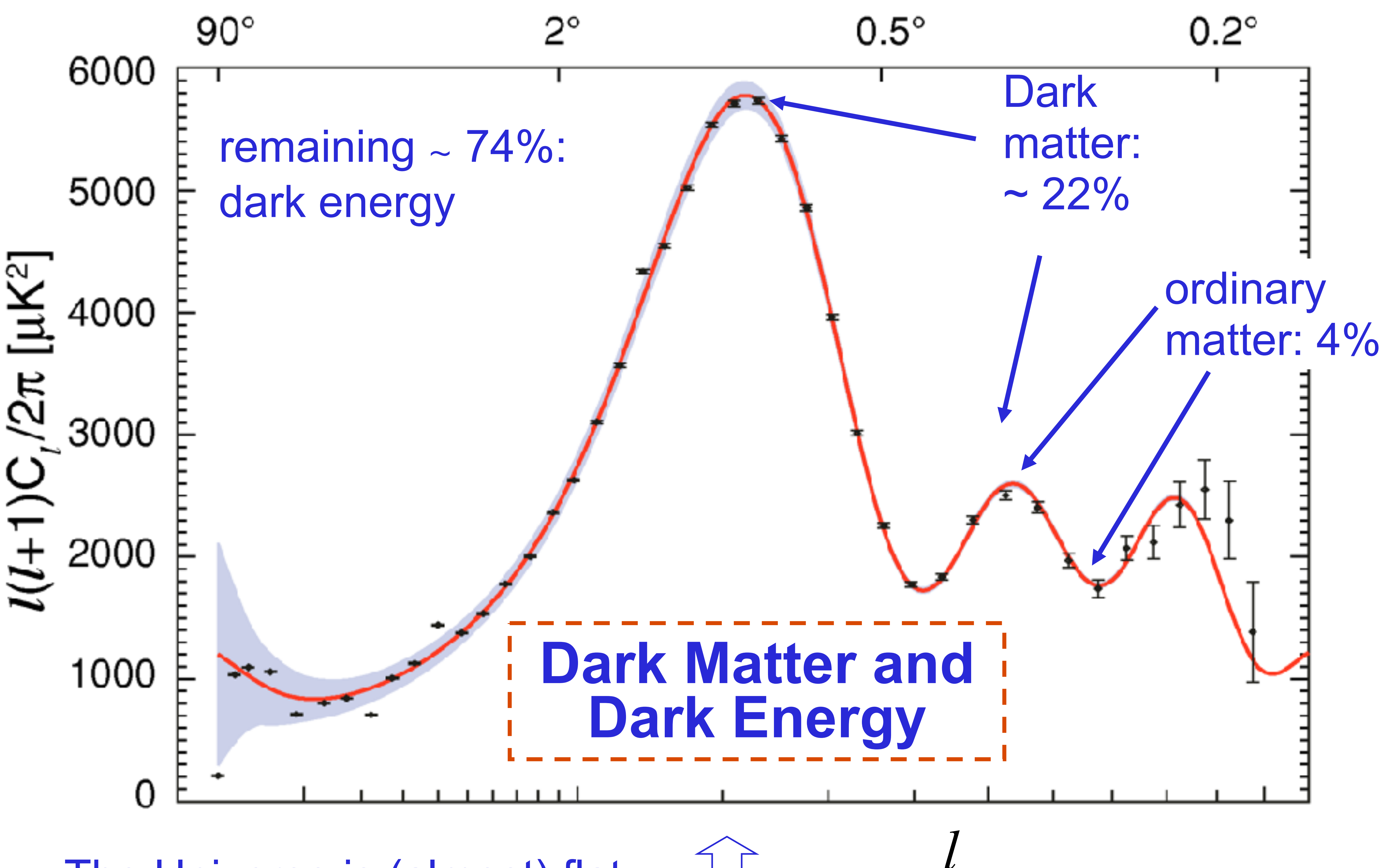


Angular Power Spectrum



- As predicted
- Concordance model
- Only 6 parameters fit the data!

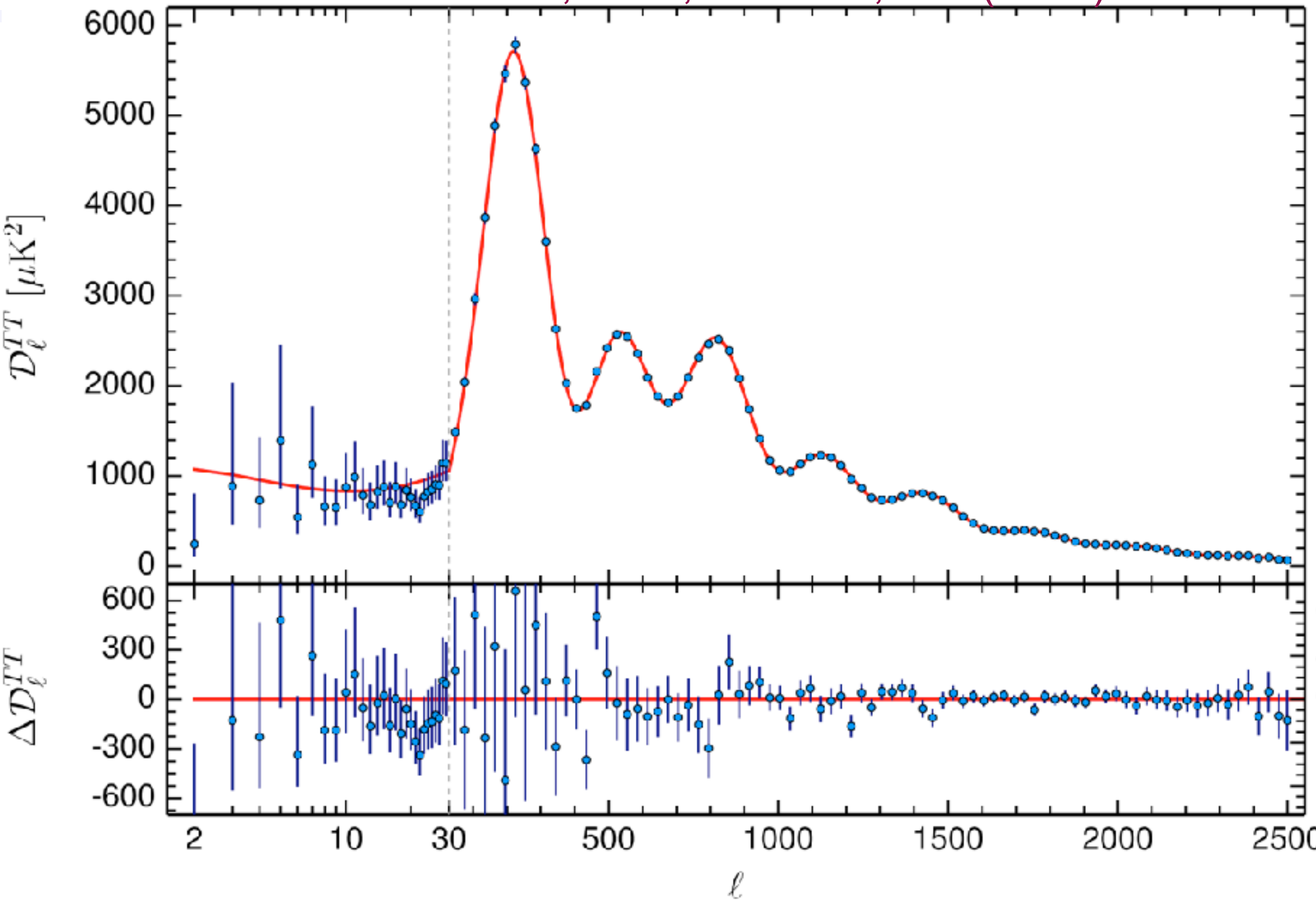
The holy grail of Cosmology



The Universe is (almost) flat

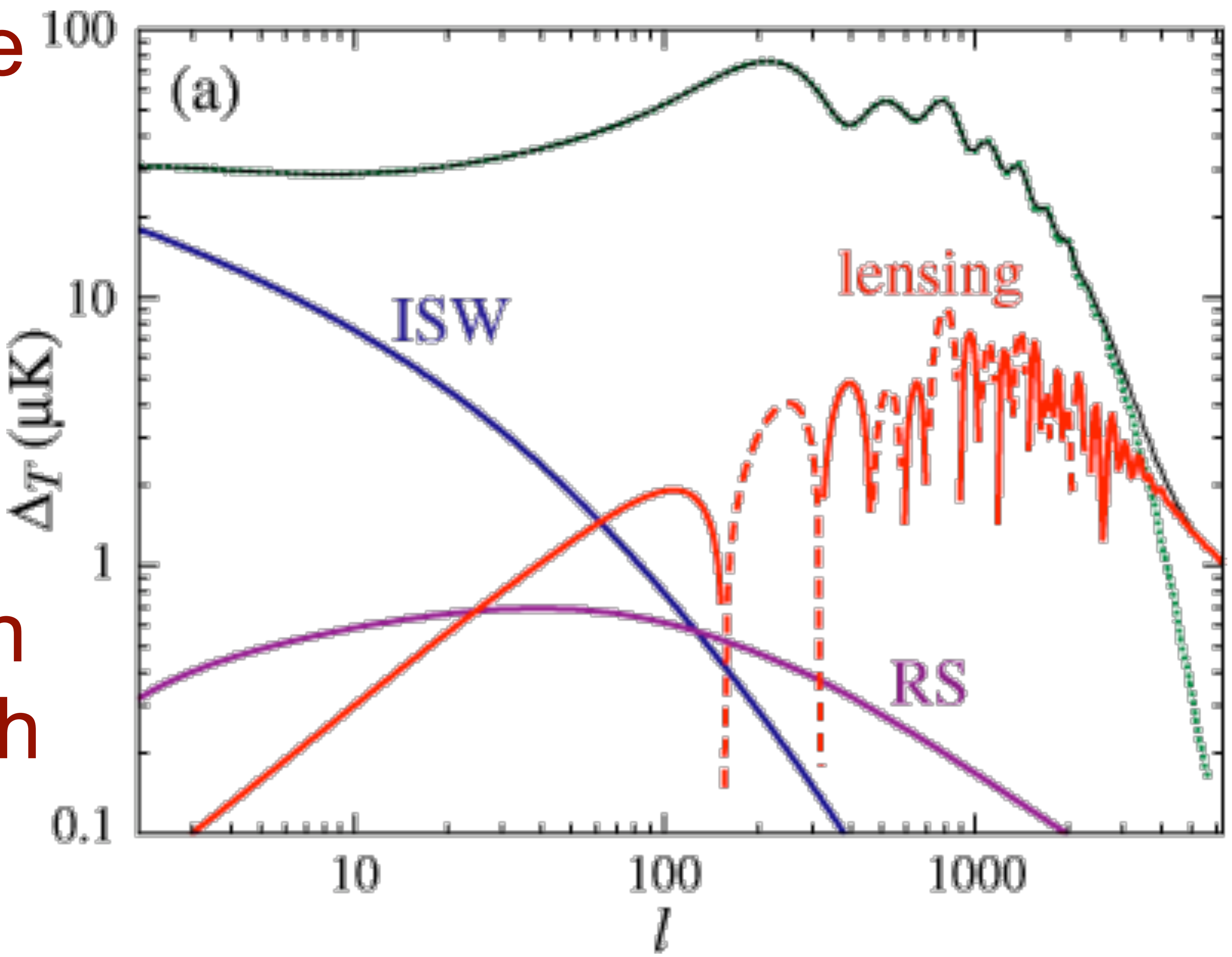
Planck 2015 power spectrum

Planck collaboration, 2016, A&A 594, A11 (2016)

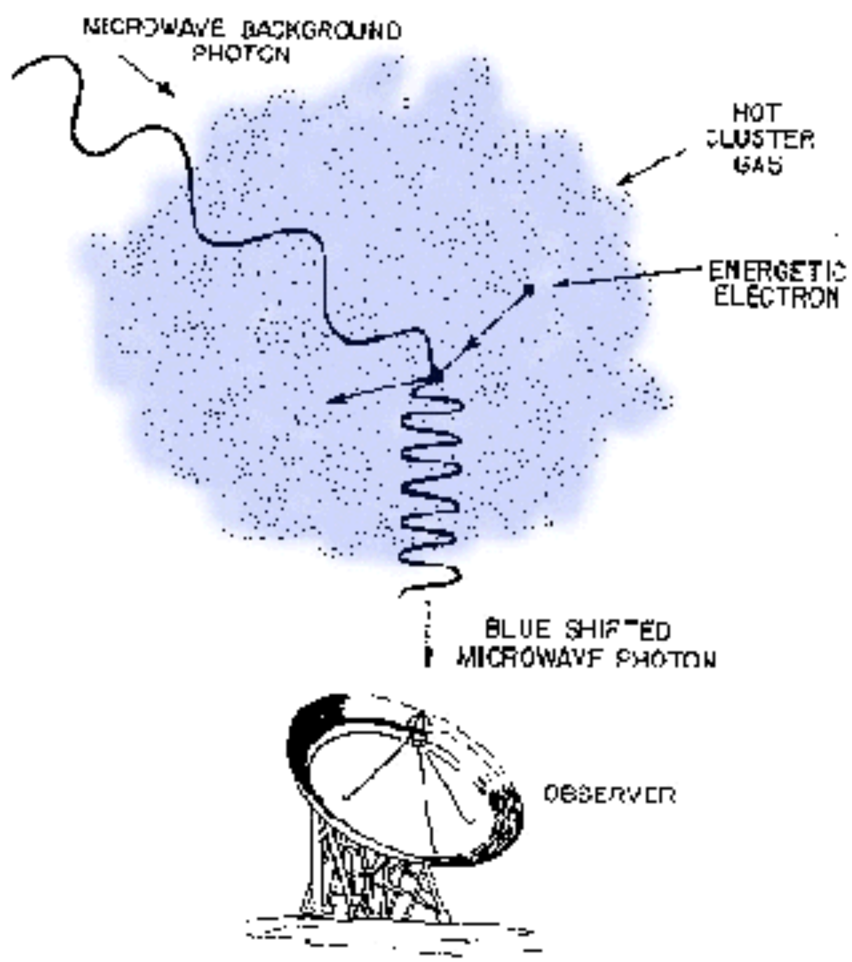


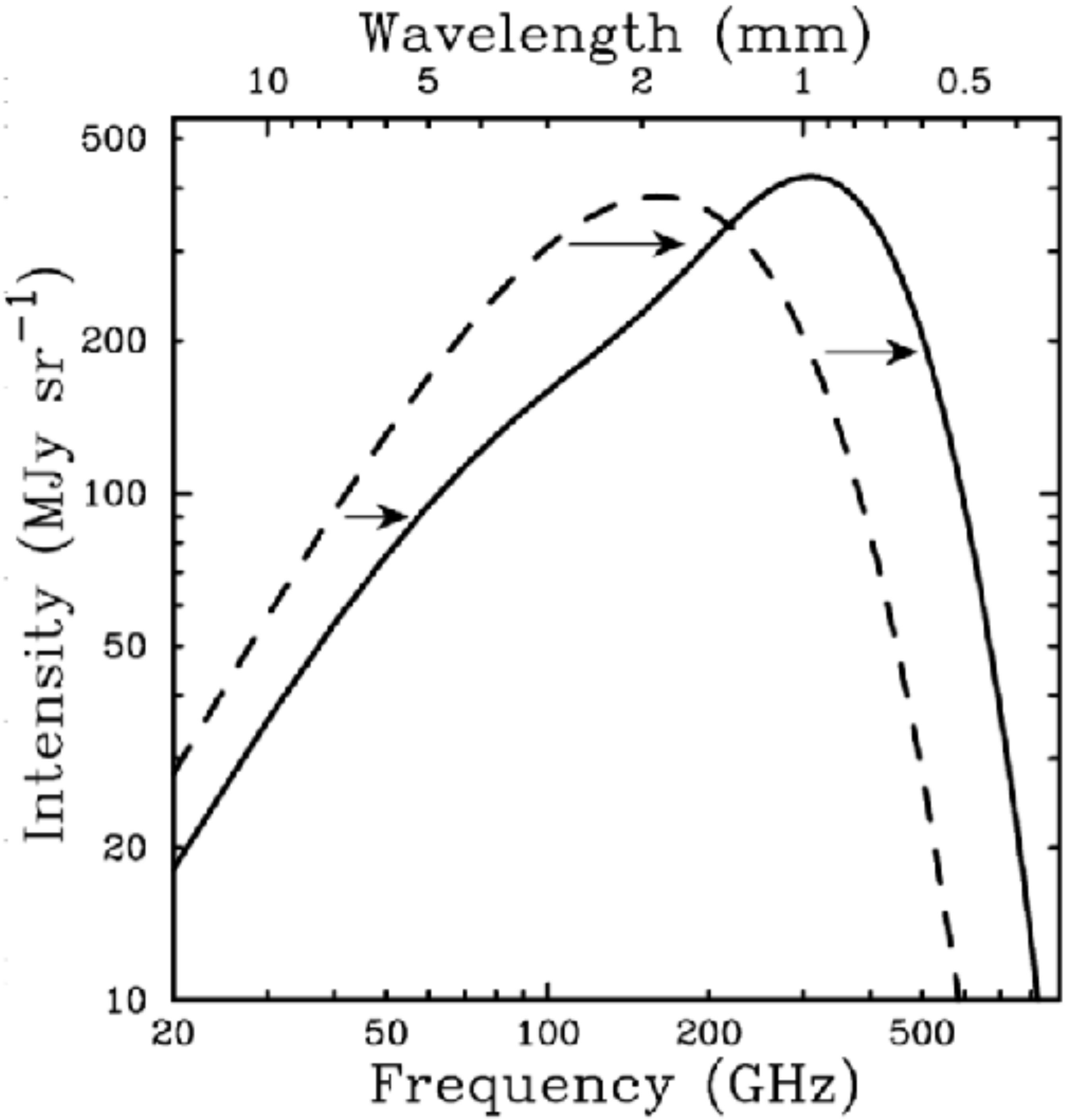
Secondary Anisotropies

- Integrated Sachs-Wolfe effect
- Gravitational Lensing
- Rees-Sciama effect
- Gravitational waves
- Scattering: reionization and Sunyaev Zel'dovich



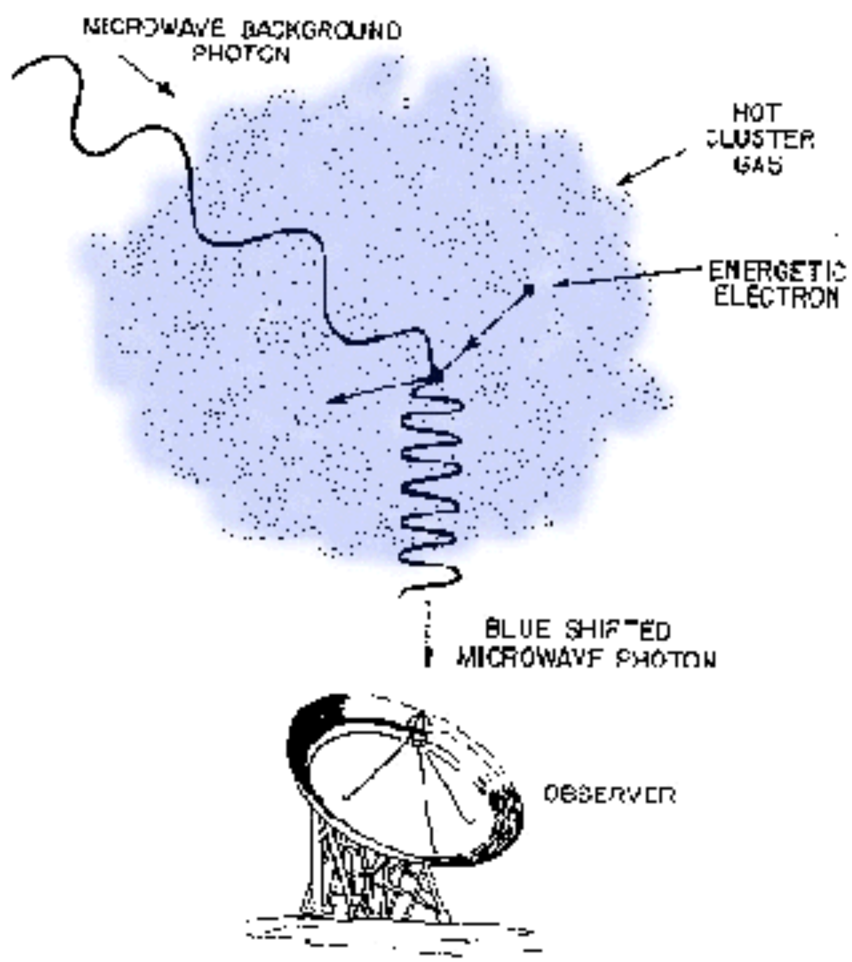
Sunyaev Zel'dovich Effect

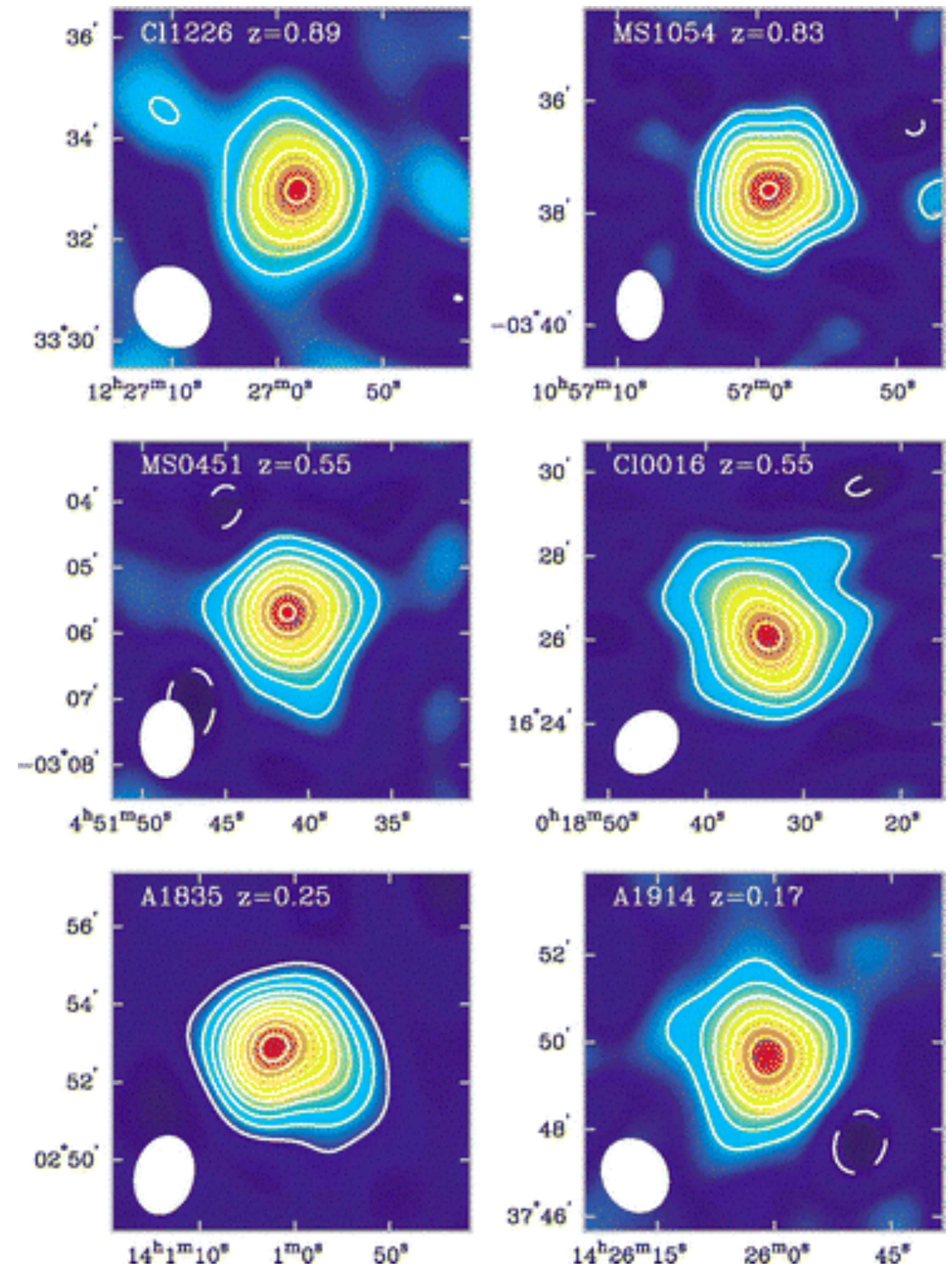




- Efeito Compton inverso
- Distorção da RCF em escalas de arcmin
- Independente de z

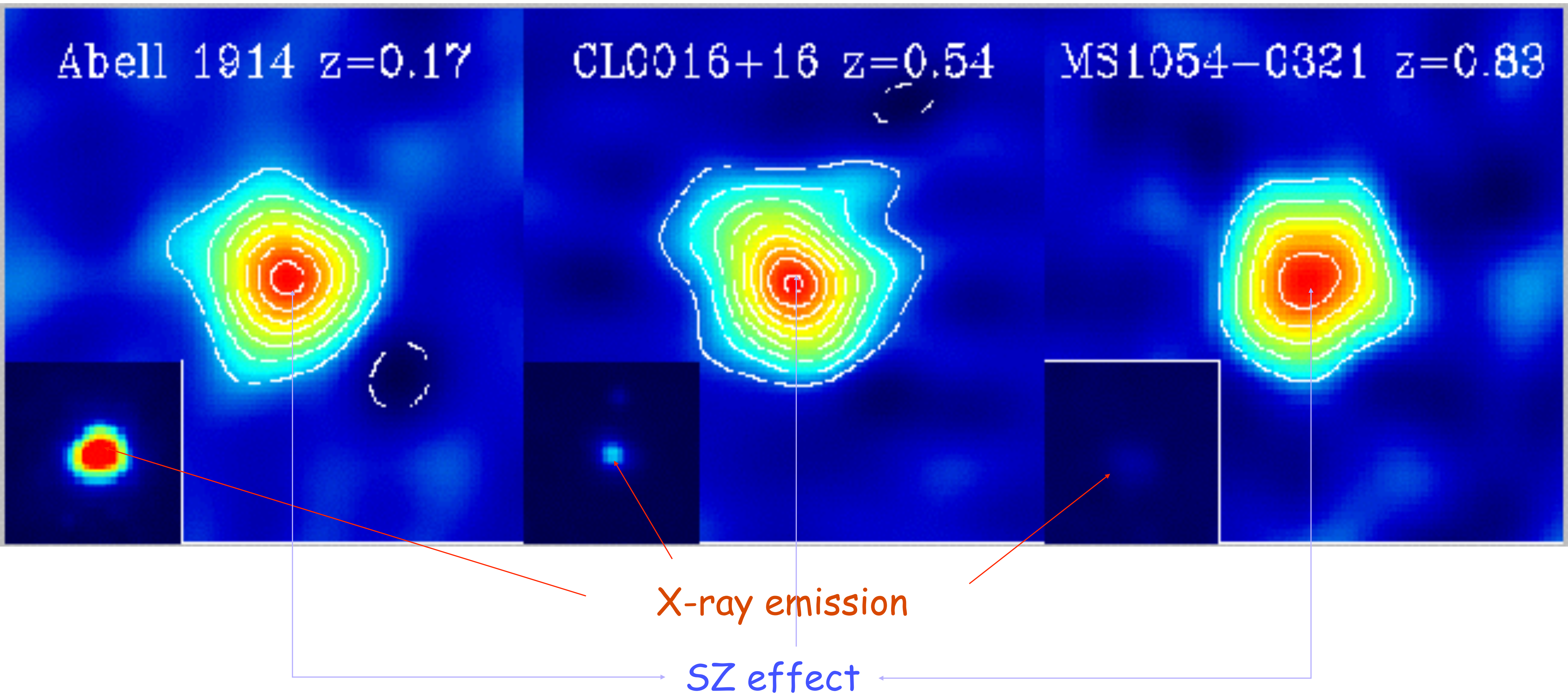
Sunyaev Zel'dovich Effect



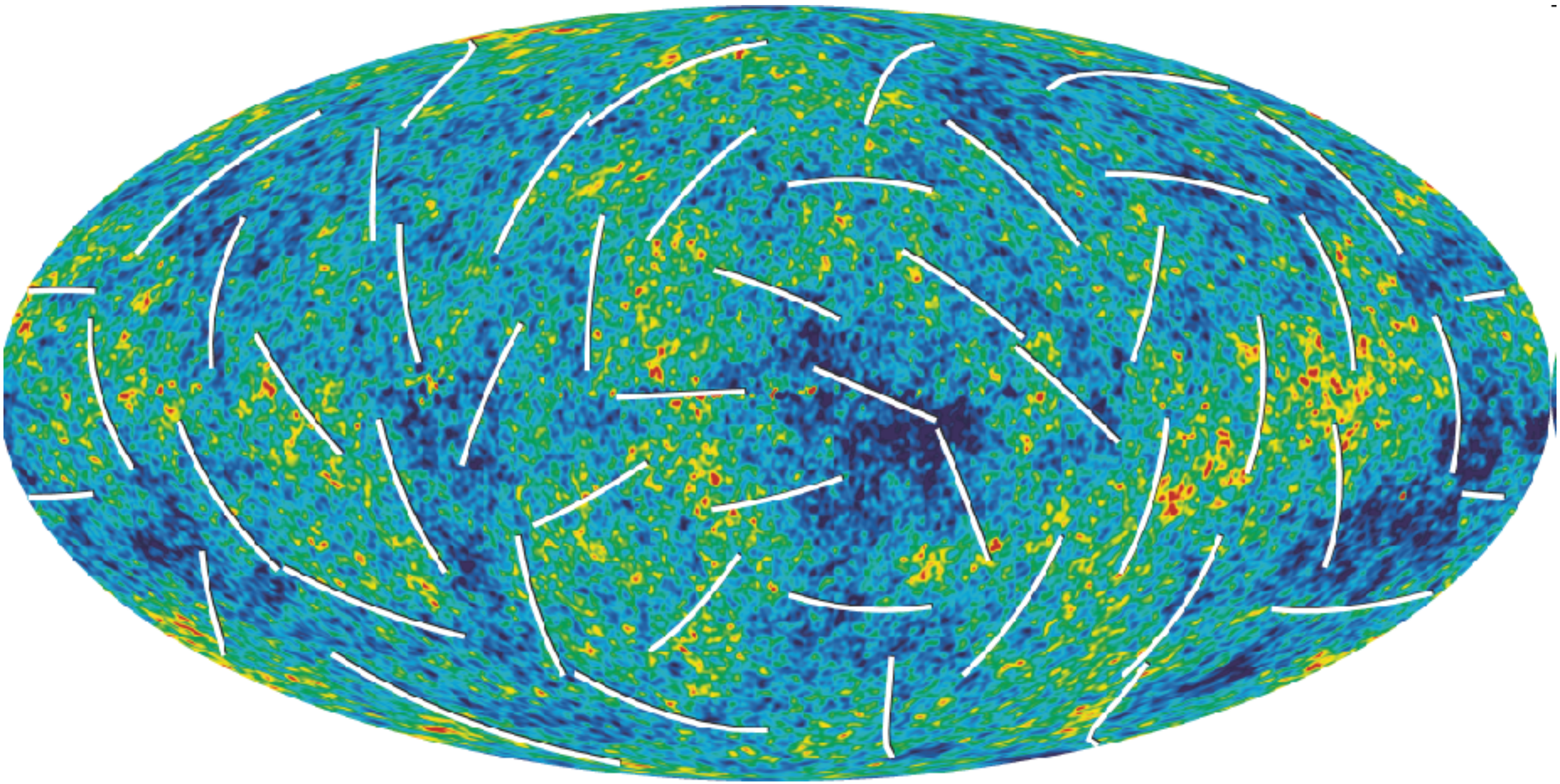


Advantage of Sunyaev Zel'dovich Effect

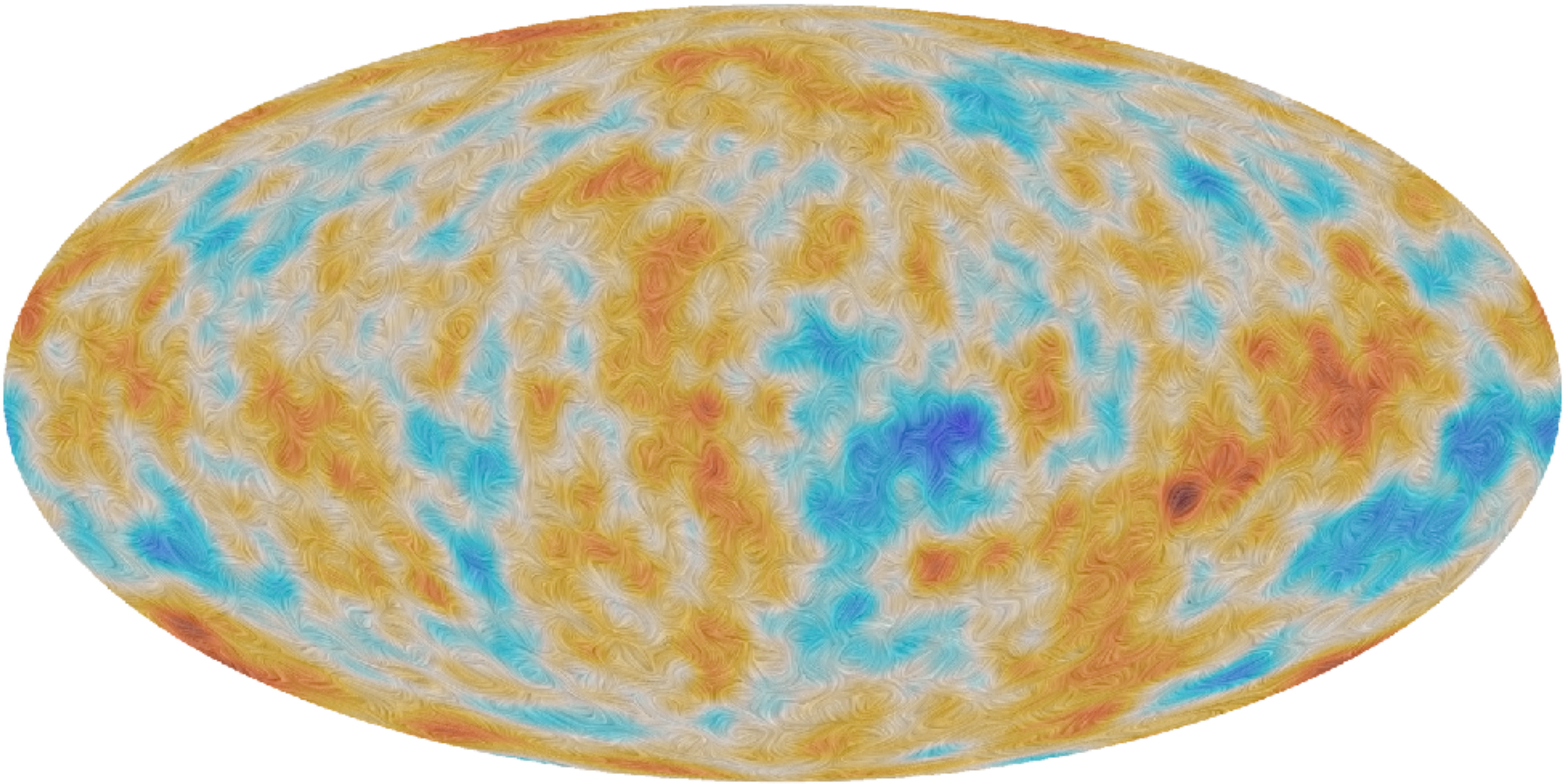
- X-ray flux drops as $(1 + z)^{-4}$
- Decrement is independent from z



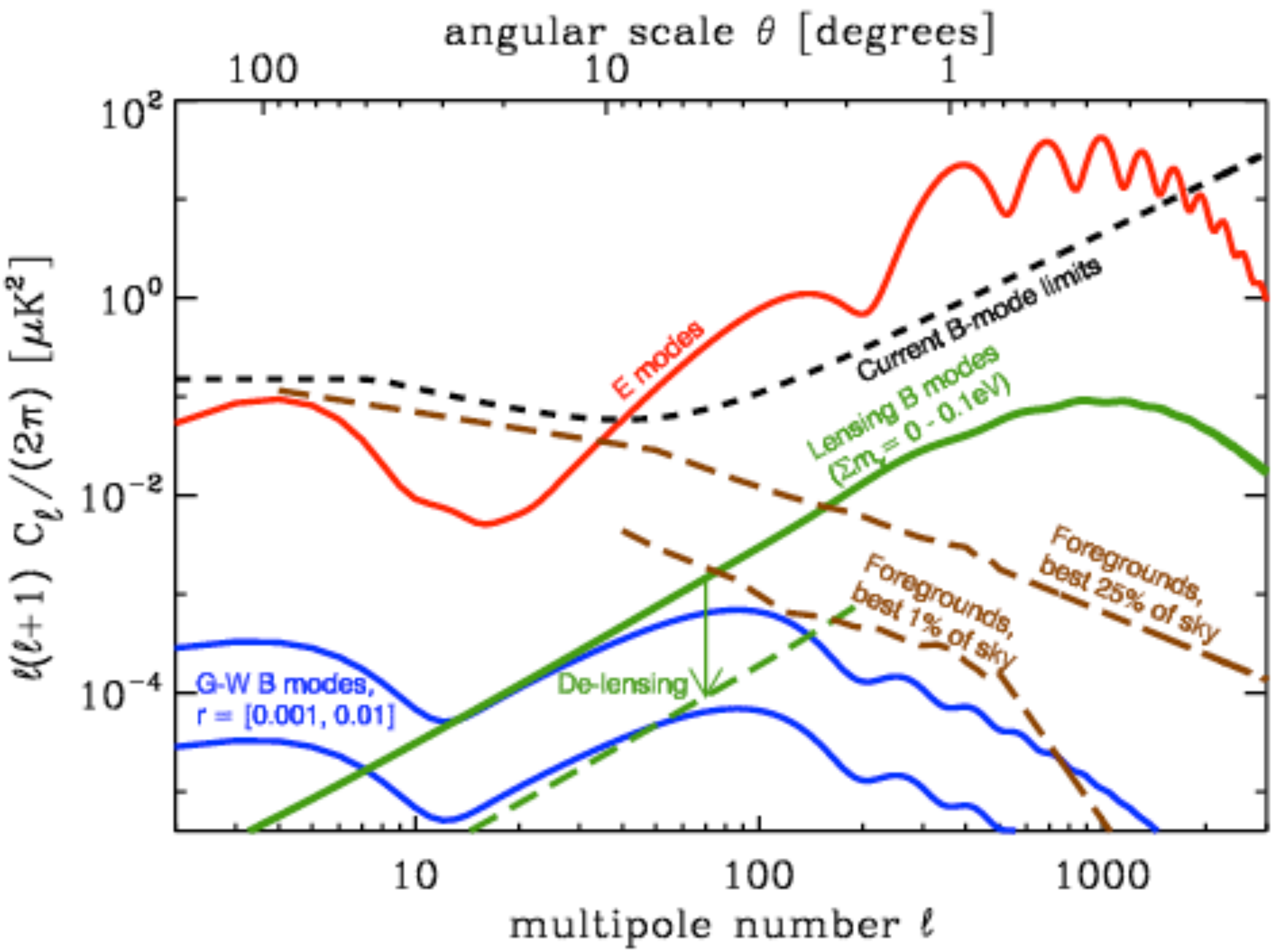
CMB Polarization



Planck Polarization Map



Espectro da Polarização



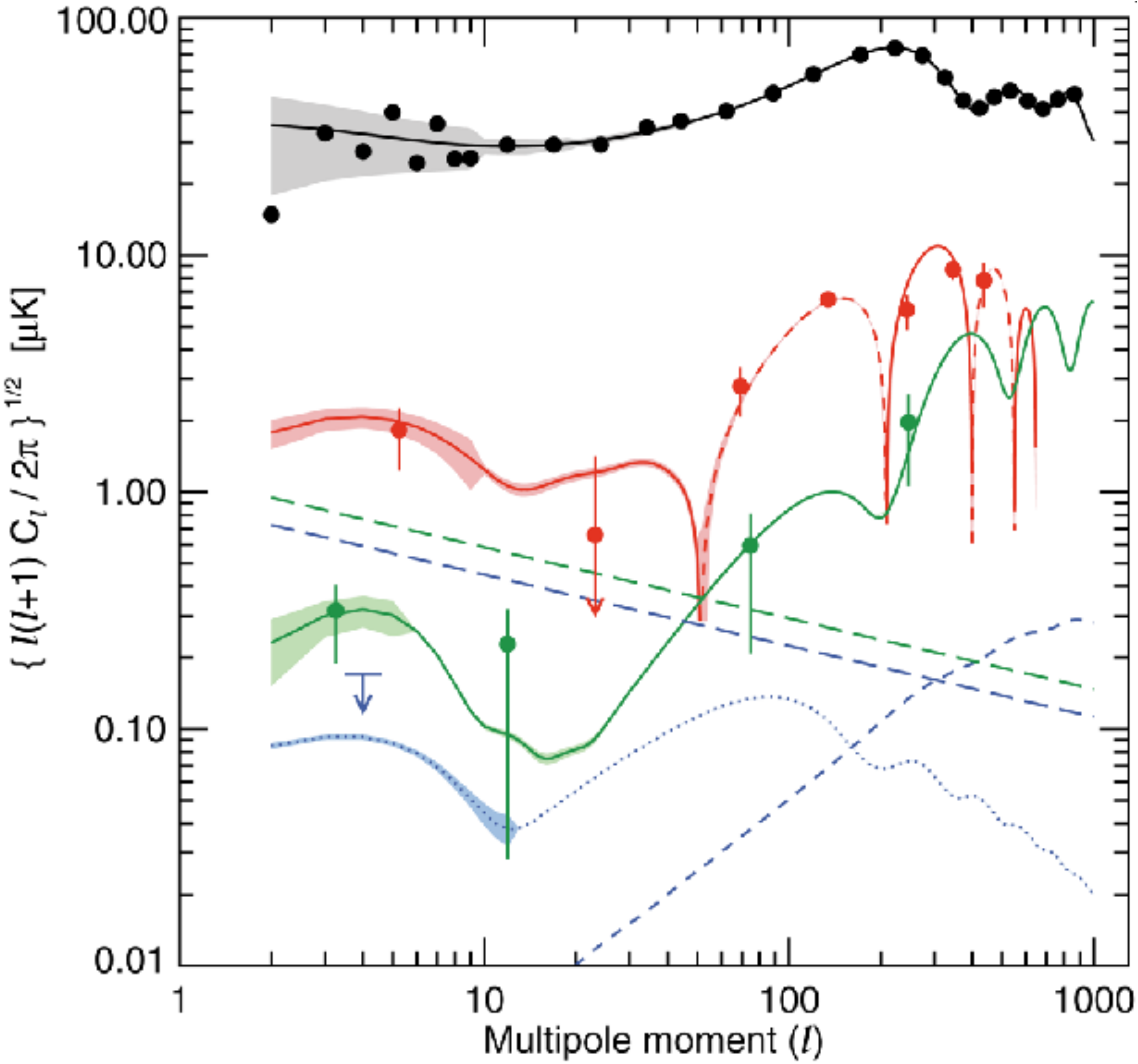
- Componentes TE e EE

  Componente BB:

  Efeito de lente + Ondas gravitacionais

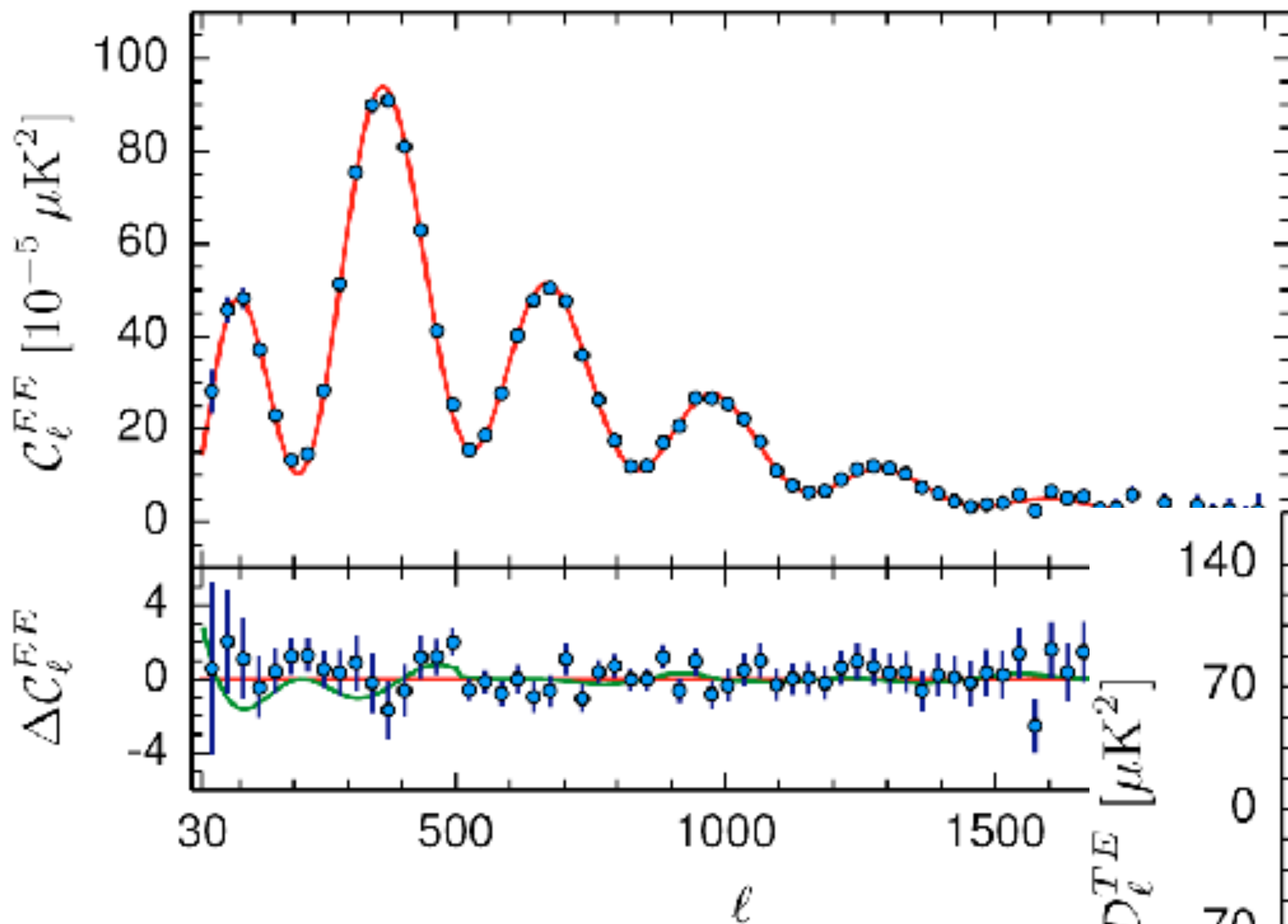
  Futuro?

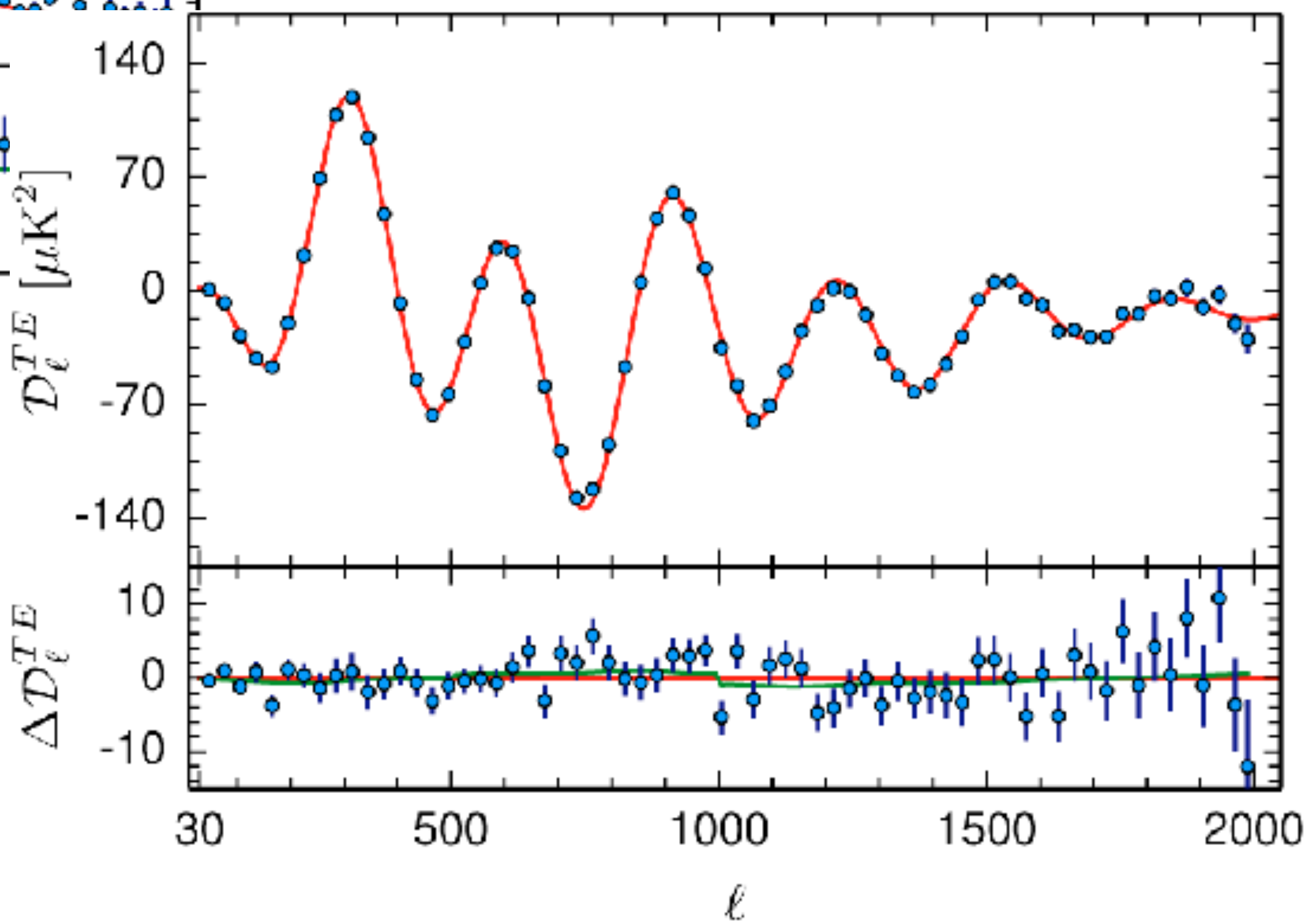
Polarization Spectrum



- TE and EE components
- BB component
- Gravitational waves

Polarization Power Spectra

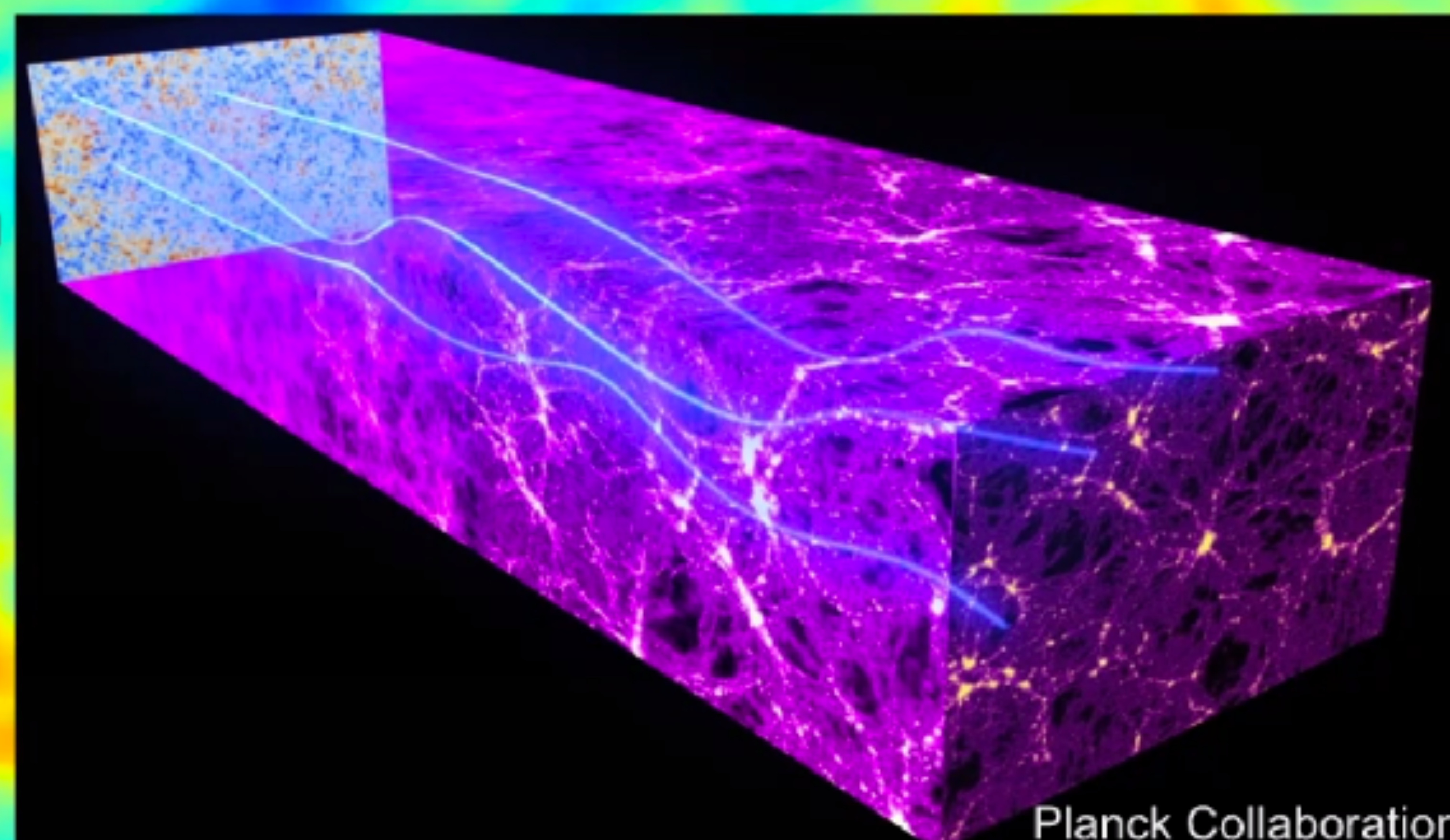




Planck 2015

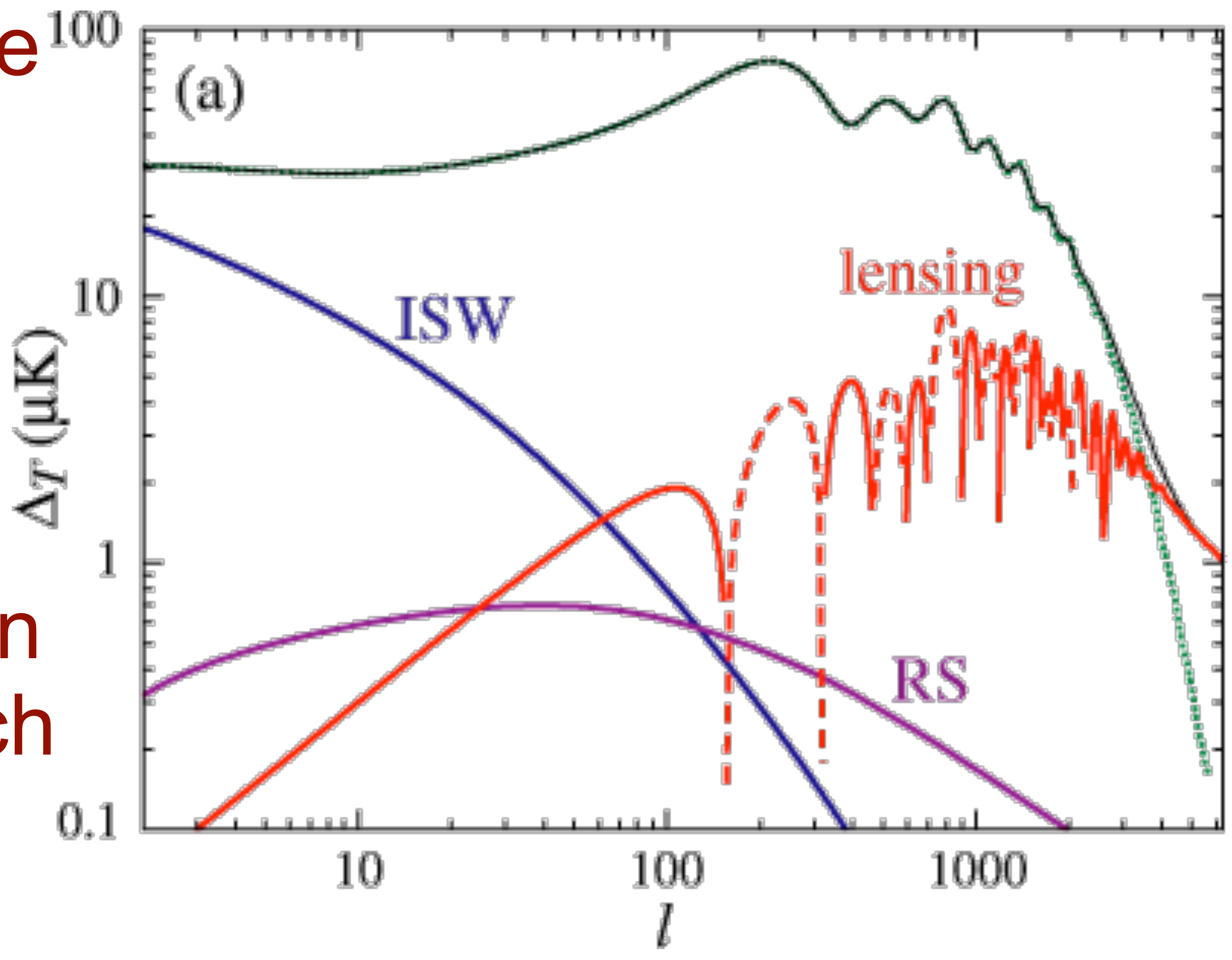
CMB as a Backlight

- Photons from the CMB are gravitationally deflected by structure
- Can reconstruct maps of the dark matter distribution
- Lensing probes the growth of structure → dark energy, $\sum m_\nu$
- Need improved temperature + polarization measurements on small angular scales across large areas of the sky

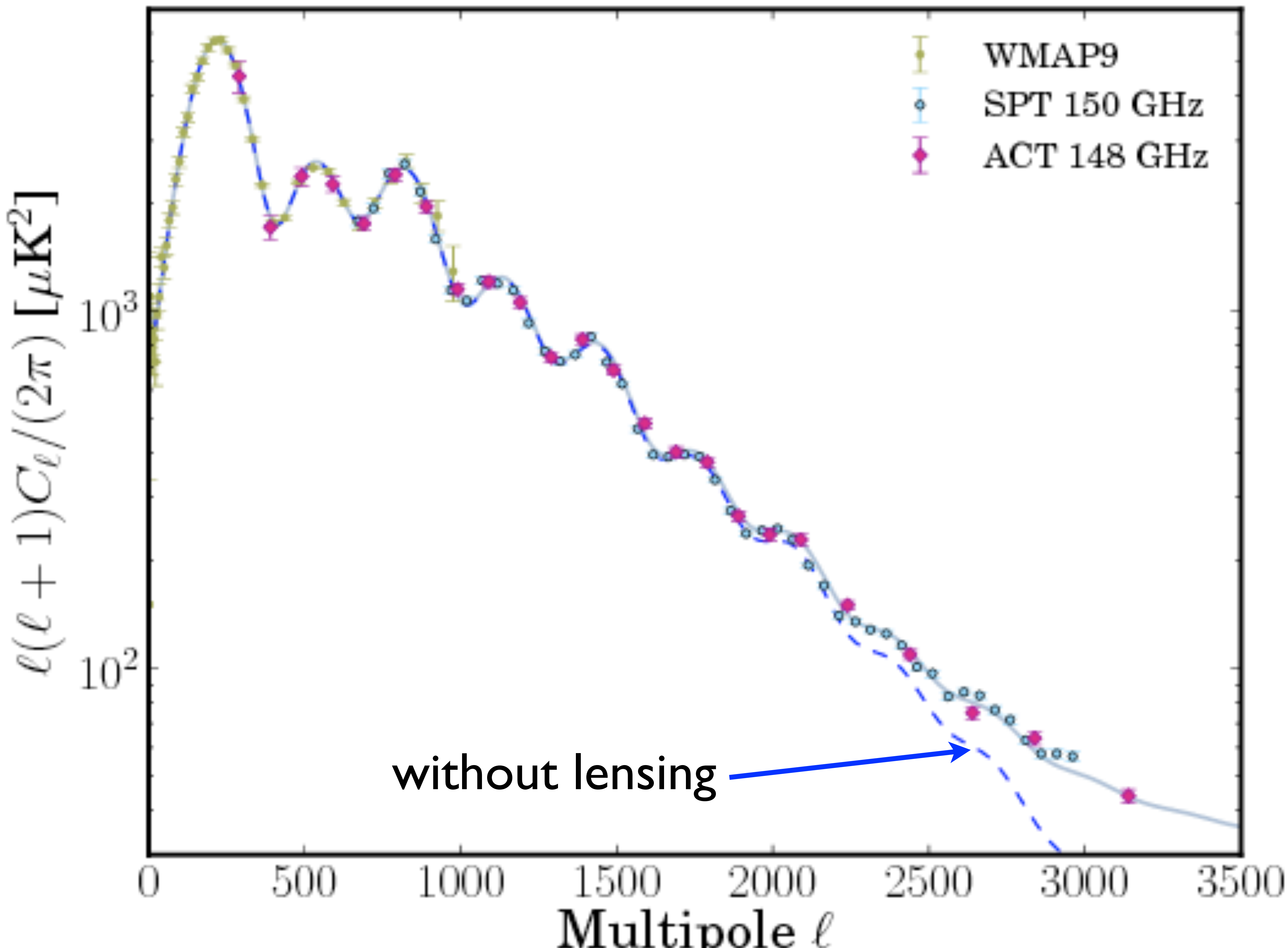


Secondary Anisotropies

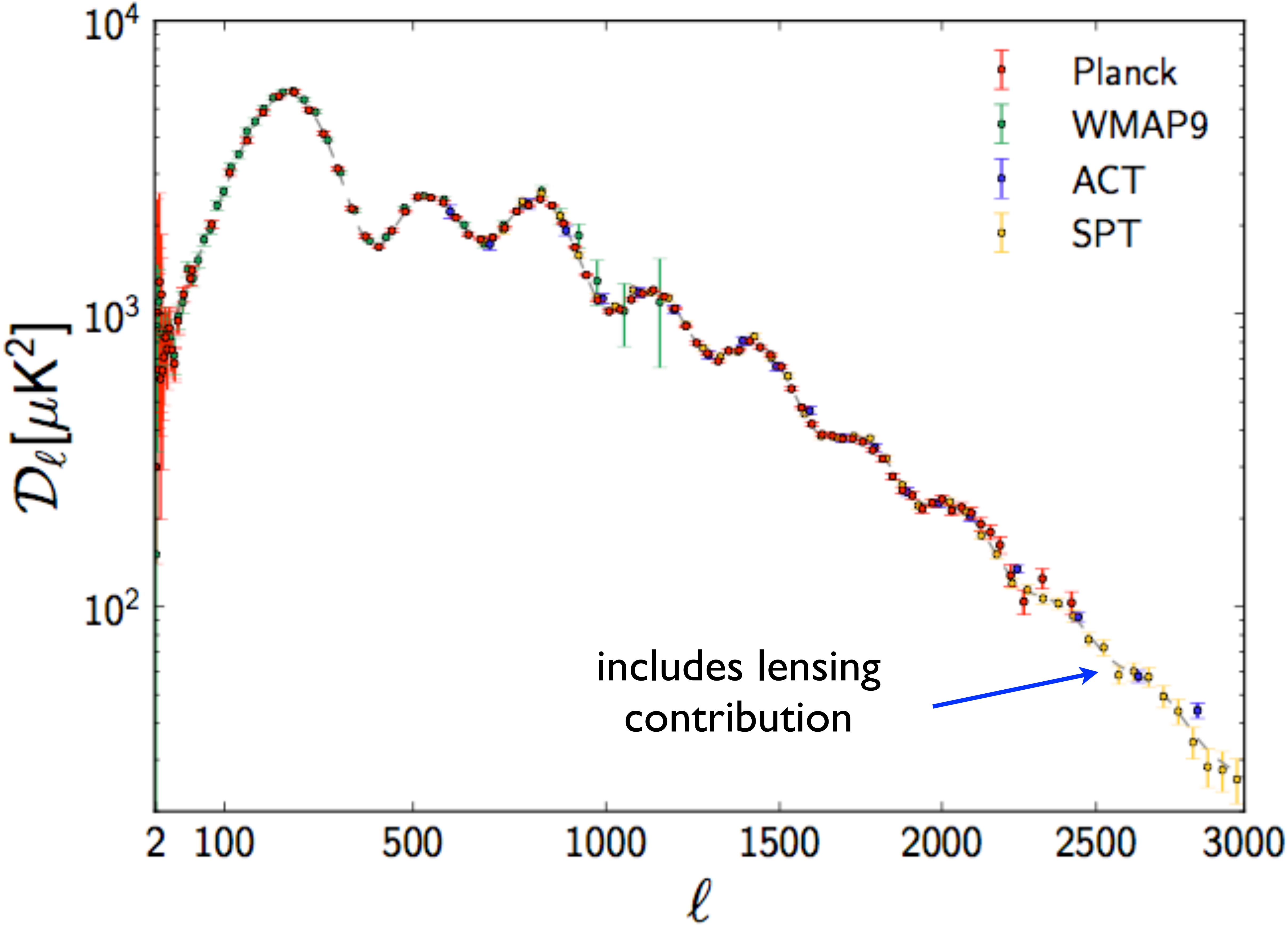
- Integrated Sachs-Wolfe effect
- Gravitational Lensing
- Rees-Sciama effect
- Gravitational waves
- Scattering: reionization and Sunyaev Zel'dovich



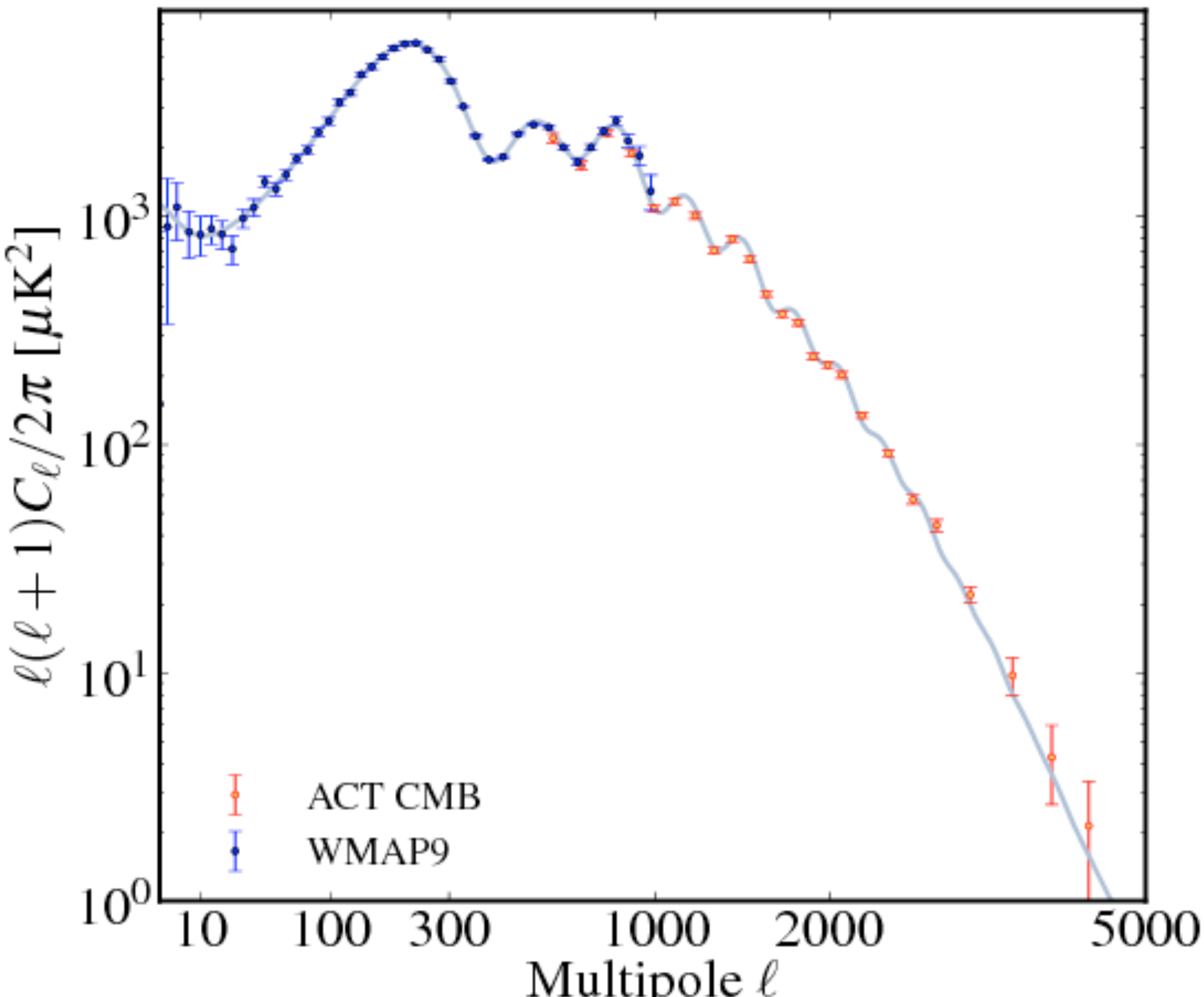
Small scale spectrum



Power spectrum @ 2013



Small scale spectrum



A&A 641, A8 (2020)
https://doi.org/10.1051/0004-6361/201833886

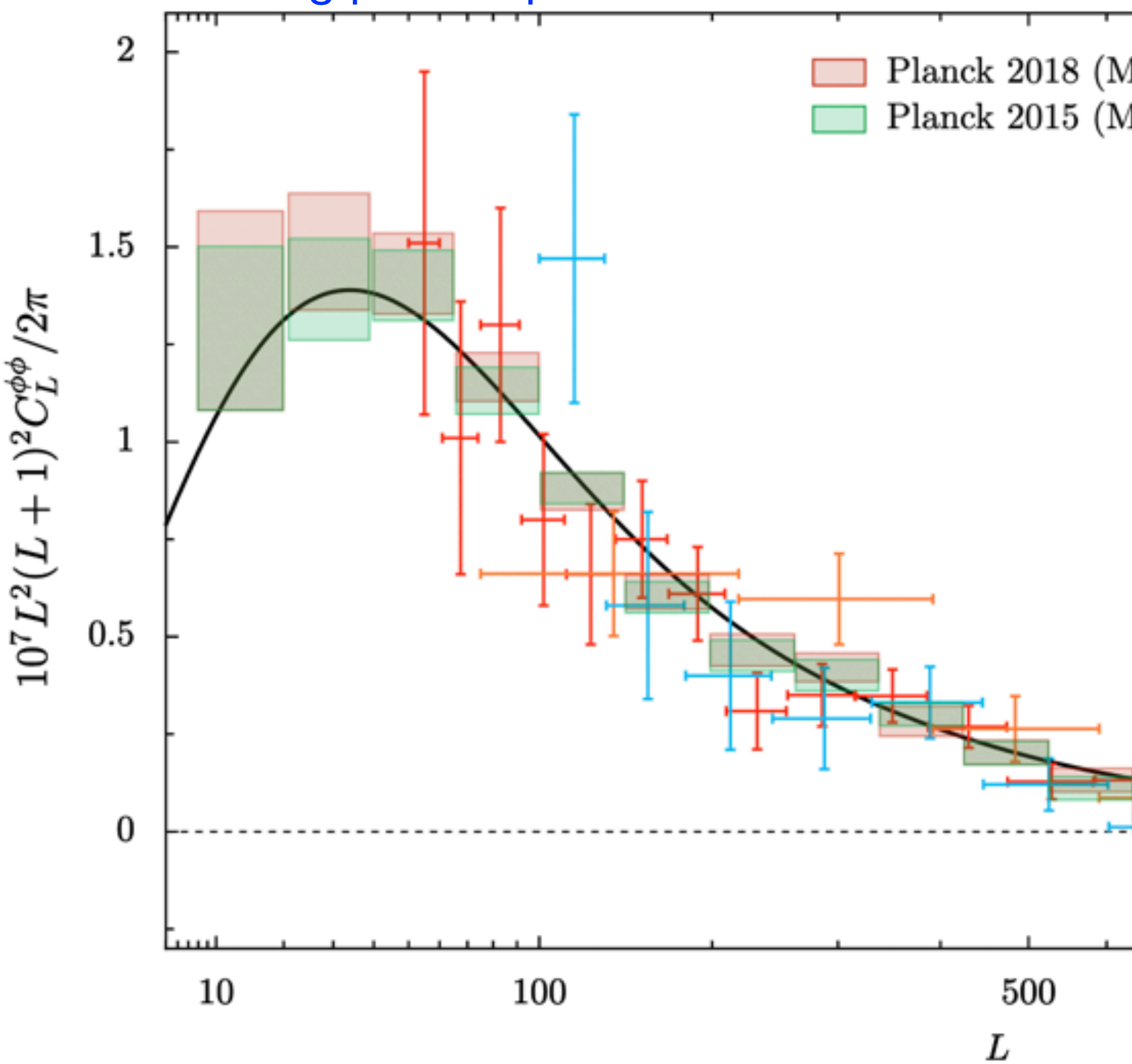
Planck 2018 results

Planck 2018 results

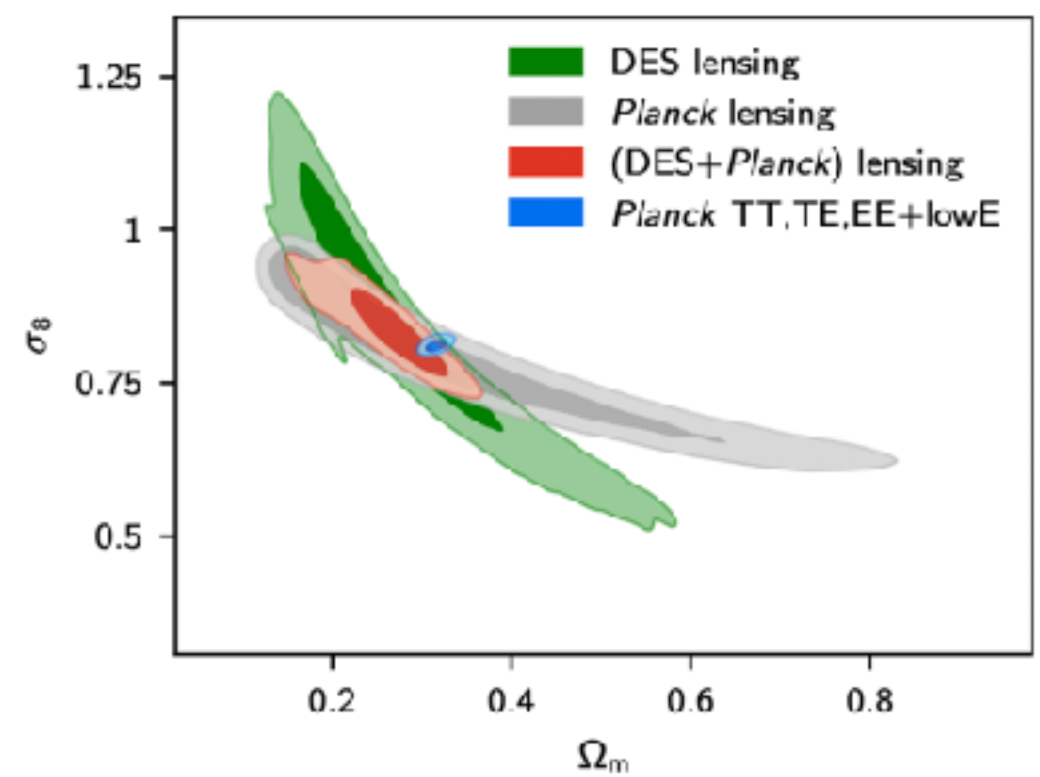
VIII. Gravitational lensing

Astronomy & Astrophysics
Special issue

Lensing power spectrum



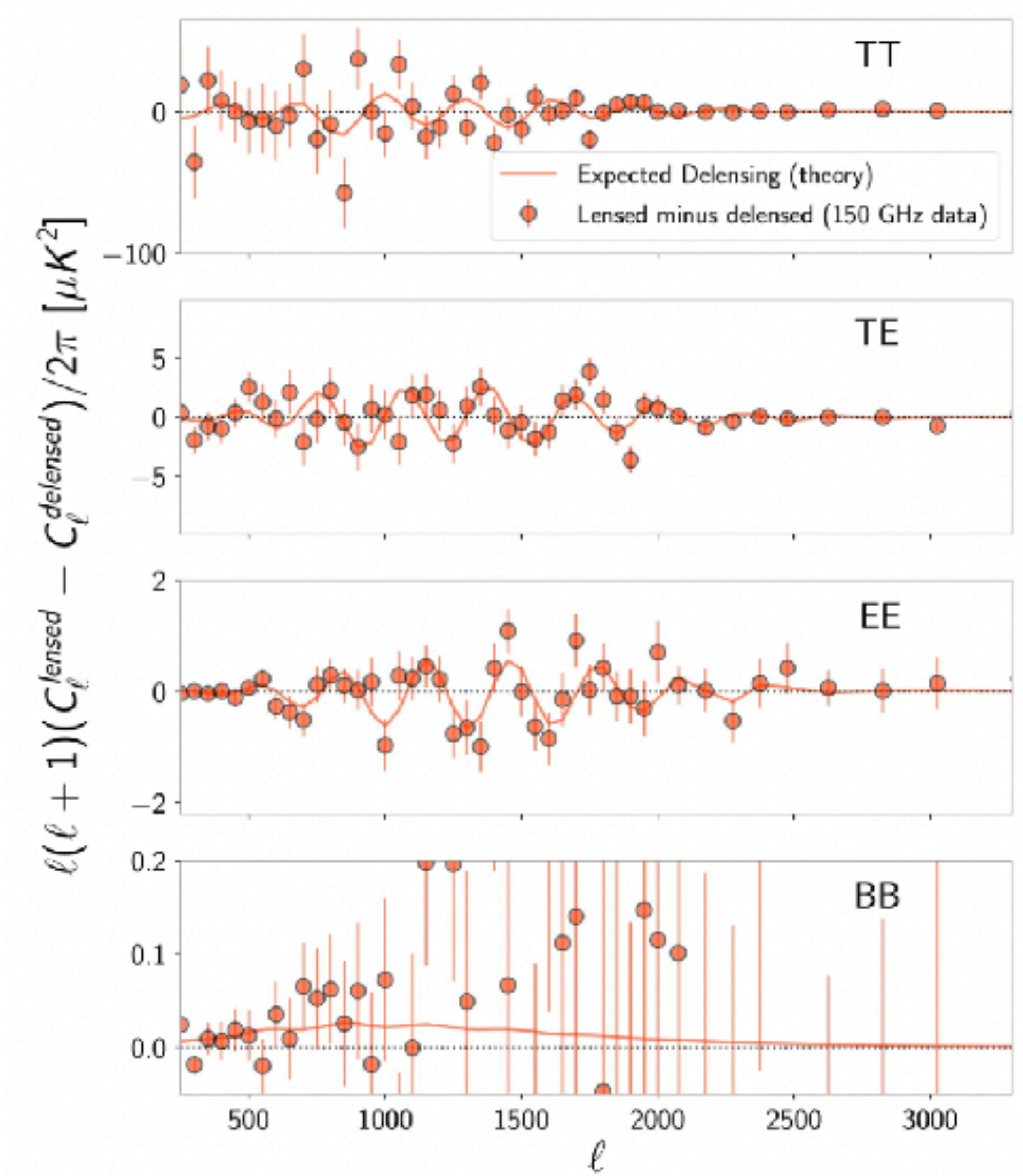
Cosmological parameters



Removiendo la señal de lentes de los espectros de potencias

The Atacama Cosmology Telescope: delensed power spectra and parameters

arXiv:2007.14405



Correlación entre grupos de galaxias y la convergencia medida en la CMB

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS 511, 3548–3560 (2022) https://doi.org/10.1093/mnras/stac138
Advance Access publication 2022 February 2

Cross-correlation of Planck cosmic microwave background lensing with DESI galaxy groups

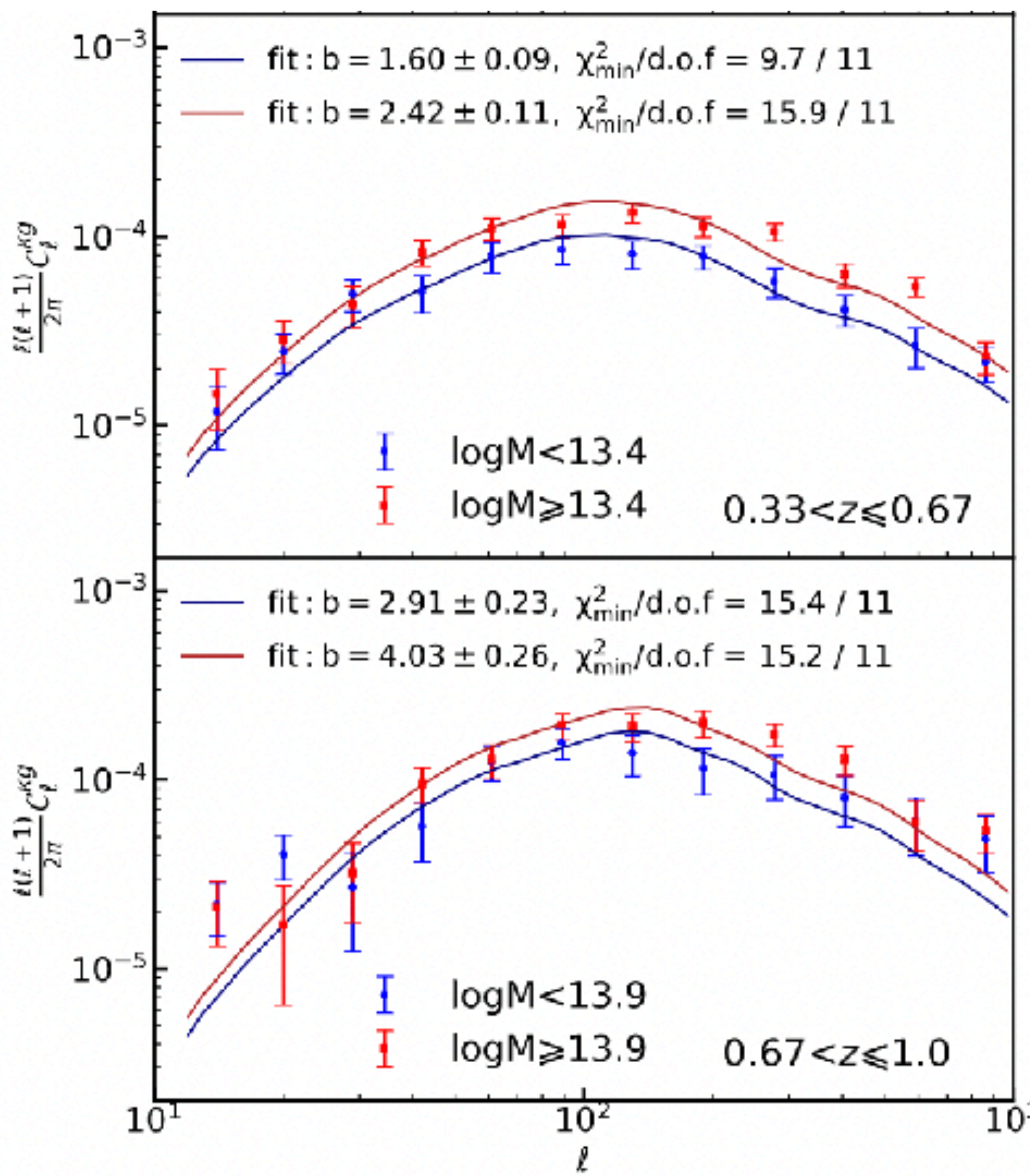
Galaxy/galaxy group overdensity δ_g and CMB lensing convergence κ are both projections of 3D density fields, expressed as line-of-sight integrals over their respective projection kernels. The angular cross-correlation power spectrum, adopting the Limber approximation (Limber 1953), is

$$C_\ell^{\kappa g} = \int \mathrm{d}\chi\, W^\kappa(\chi) W^g(\chi) \frac{1}{\chi^2} P_{mg}\left(k = \frac{\ell + 1/2}{\chi}; z\right). \quad (1)$$

The Limber approximation is inaccurate for $\ell < 10$, but such very large-scale modes are excluded from our fitting anyway, due to poor S/N. The above expression assumes spatial flatness. Here, W^κ and W^g are the projection kernels for κ and the group number density fields, respectively.

$$W^g(z) = n(z) = \frac{c}{H(z)} W^g(\chi). \quad (2)$$

$$W^\kappa(z) = \frac{3}{2c}\Omega_{m0}\frac{H_0^2}{H(z)}(1+z)\frac{\chi(\chi_* - \chi)}{\chi_*} = \frac{c}{H(z)} W^\kappa(\chi). \quad (3)$$



PHYSICAL REVIEW D
particles, fields, gravitation, and cosmology

Highlights Recent Accepted Authors Referees

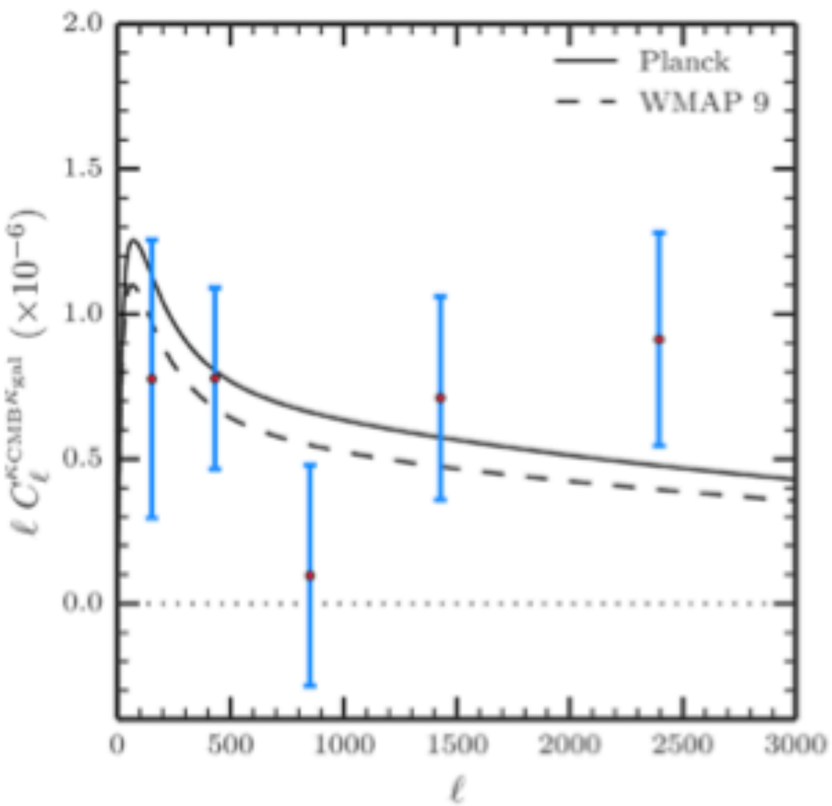
Correlation of CMB lensing with LSS lensing in CS82

Hand et al. 2015, Phys. Rev. D, 91, 062001

EDITORS' SUGGESTION

First measurement of the cross-correlation of CMB lensing and galaxy lensing

CS82 x ACT



The authors measure for the first time the cross-correlation between CMB lensing and galaxy lensing. This provides a robust test of the ΛCDM model on the largest cosmic scales, and offers powerful constraints on the evolution and nature

$$\kappa(\hat{\mathbf{n}}) = \int_0^\infty dz W^\kappa(z)\delta(\chi(z)\hat{\mathbf{n}}, z)$$

$$W^\kappa(z) = \frac{3}{2}\Omega_m H_\circ^2 \frac{(1+z)}{H(z)}\frac{\chi(z)}{c}\int_z^\infty dz_s p_s(z_s)\frac{\chi(z_s)-\chi(z)}{\chi(z_s)}$$

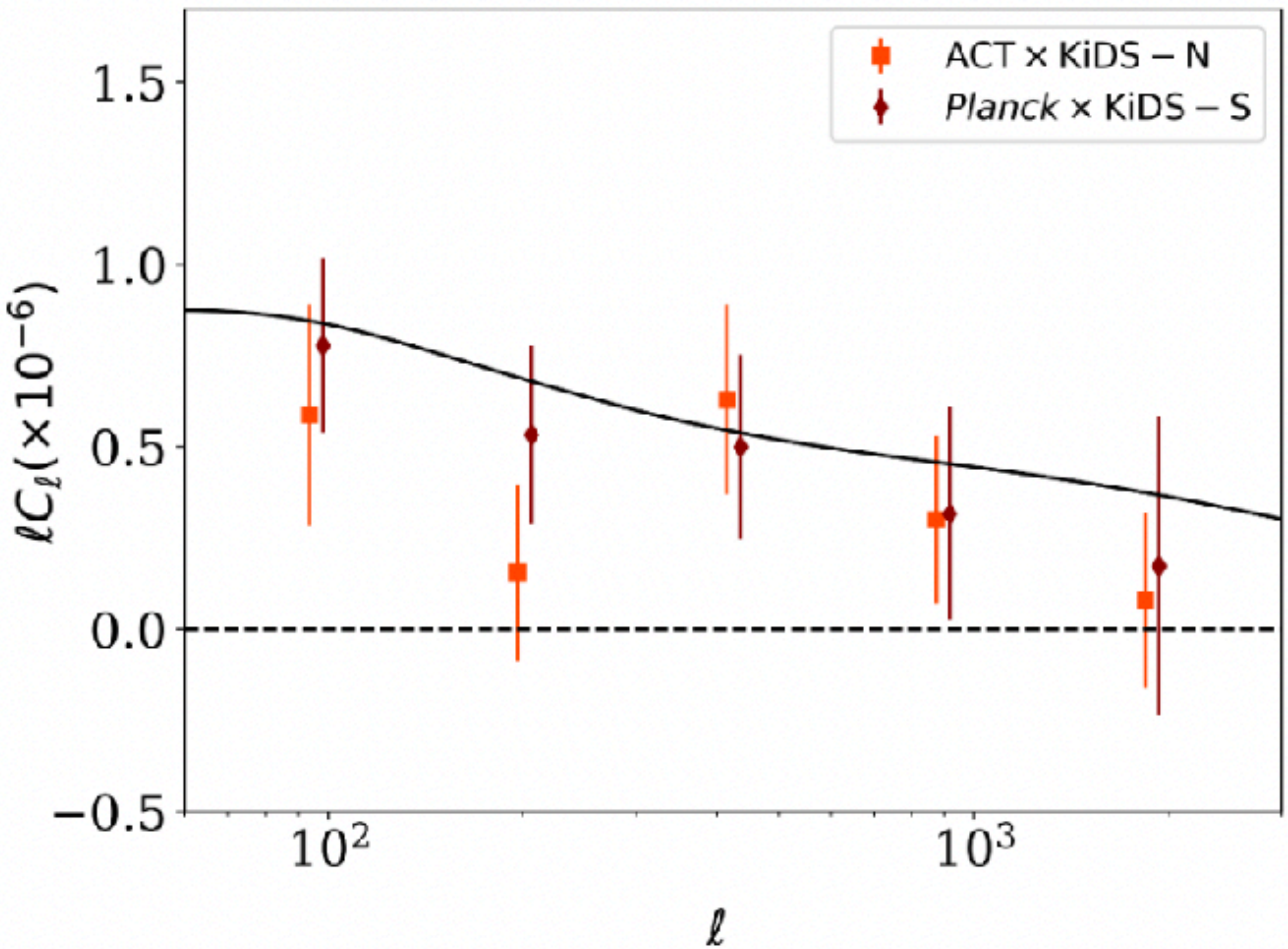
$$W^{\kappa_{\rm CMB}}(z) = \frac{3}{2}\Omega_m H_\circ^2 \frac{(1+z)}{H(z)}\frac{\chi(z)}{c}\left[\frac{\chi(z_\star)-\chi(z)}{\chi(z_\star)}\right]$$

$$C_\ell^{\kappa_{\rm CMB}\kappa_{\rm gal}} = \int_0^\infty \frac{dz}{c}\frac{H(z)}{\chi(z)^2} W^{\kappa_{\rm CMB}} W^{\kappa_{\rm gal}} P\left(k = \frac{\ell}{\chi}; z\right)$$

A&A 649, A146 (2021)
https://doi.org/10.1051/0004-6361/202039975

Astronomy & Astrophysics

Strong detection of the CMB lensing and galaxy weak lensing cross-correlation from ACT-DR4, *Planck* Legacy, and KiDS-1000



arXiv:2011.11613

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **528,** 2112–2135 (2024)
Advance Access publication 2024 January 3

https://doi.org/10.1093/mnras/stad3987

Cosmology from cross-correlation of ACT-DR4 CMB lensing and DES-Y3 cosmic shear

$$C_\ell^{\kappa_C \gamma_E} = \int_0^{z_H} dz \frac{H(z)}{\chi^2(z) c} W_\kappa^{\rm CMB}(z) W_\gamma^{\rm g}(z) P_{\delta\delta}\left(k = \frac{\ell + 0.5}{\chi(z)}, z\right)$$

$$W_\kappa^{\rm CMB}(z) = \frac{3 H_0^2 \Omega_{\rm m,0}}{2 H(z) c} \frac{\chi(z)}{a(z)} \frac{\chi(z^*) - \chi(z)}{\chi(z^*)}.$$

$$W_\gamma^{\rm g}(z) = \frac{3 H_0^2 \Omega_{\rm m,0}}{2 H(z) c} \frac{\chi(z)}{a(z)} \int_z^{z_H} dz' n(z') \frac{\chi(z') - \chi(z)}{\chi(z')}$$