COMPUTATIONAL PHYSICS FOR THEORETICAL COSMOLOGY

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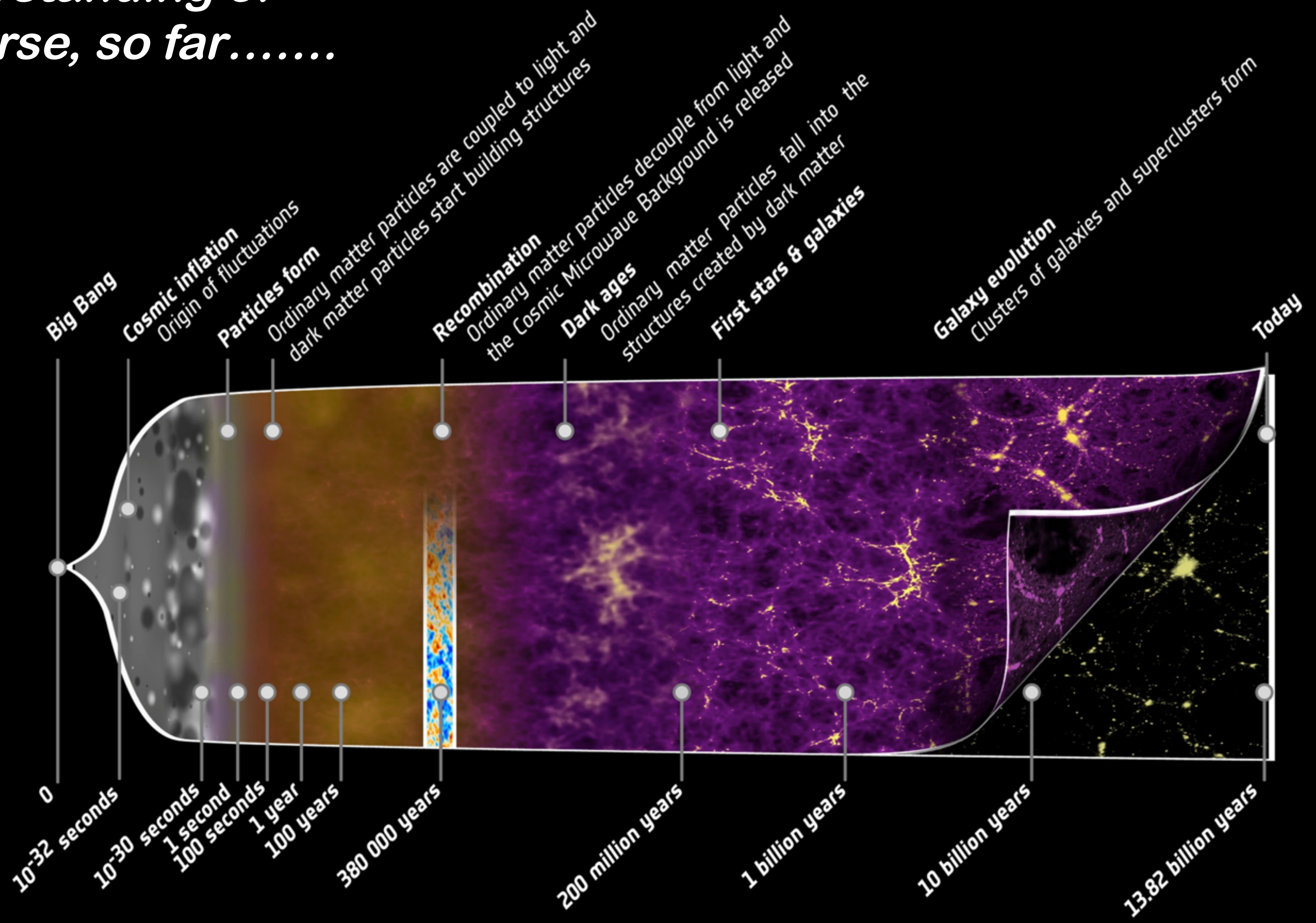
with inputs from: M. Baldi, D. Bertacca, M. Billi, M. Bortolami, N. Barbieri, N. Bartolo, L. Caloni, G. D’Amico, M. Gerbino, A. Gruppuso, M. Lembo, M. Liguori, P. Natoli, L. Pagano, D. Paoletti, N. Raffuzzi, G. Zagatti

Our understanding of the Universe, so far.......



COSMIC HISTORY

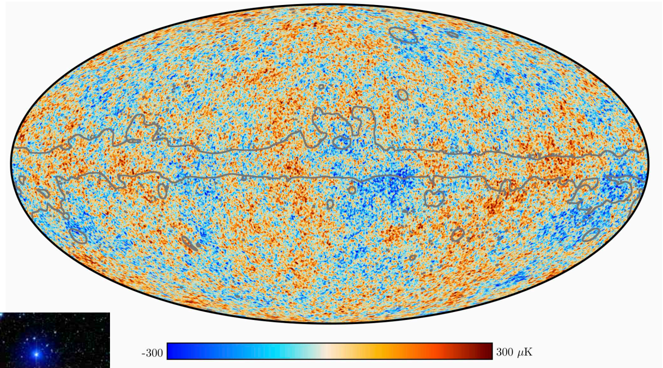
- Scalar (density) gaussian, adiabatic and nearly scale-invariant fluctuations in the metric are produced during an early phase of accelerated expansion (*inflation*) ($T<10^{17}$ GeV, $t>10^{-40}$ s)
- Tensor (GWs) metric perturbations are produced at the same time.
- Light elements are produced during Big Bang Nucleosynthesis at T~1 to 0.1 MeV, t~1 to 200s
- Neutral hydrogen is formed at T~0.3 eV (t~400kyrs). The Universe becomes transparent; baryonic matter and radiation decouple. The (polarized) radiation is free to propagate and is visible today as the cosmic microwave background (CMB), a black body at T=2.7 K. Baryons are free to collapse into the gravitational wells created by dark matter.

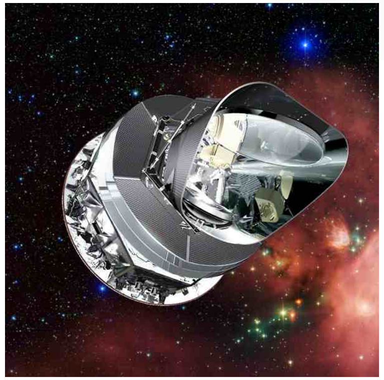
COSMIC HISTORY

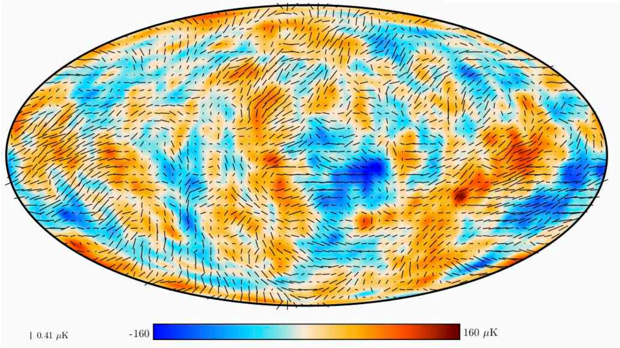
- Structures are formed through gravitational collapse. First stars and galaxies are born at t ~ few x 100 Myrs. The UV radiation from the first stars reionizes cosmic hydrogen; this generates additional CMB polarization.
- Larger cosmological structures, i.e. galaxy clusters and superclusters are formed somehow later, in a bottom-up hierarchical process.
- Cosmic acceleration due to dark energy (?) starts (basically yesterday)
- Time today: ~14 Gyrs after the end of inflation.

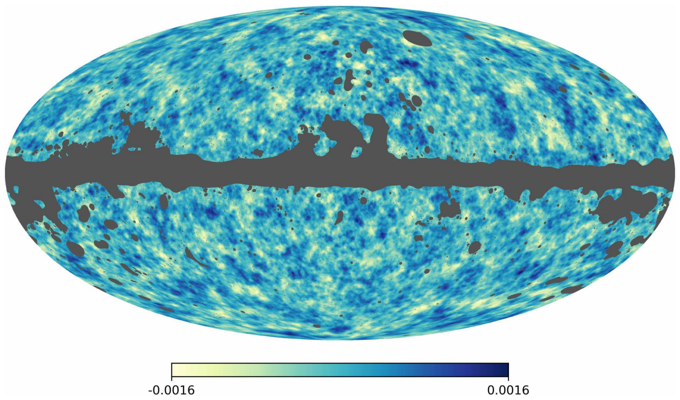
This understanding is encoded in the standard cosmological model, or **ΛCDM model**.

An example: Neutrino masses from cosmology

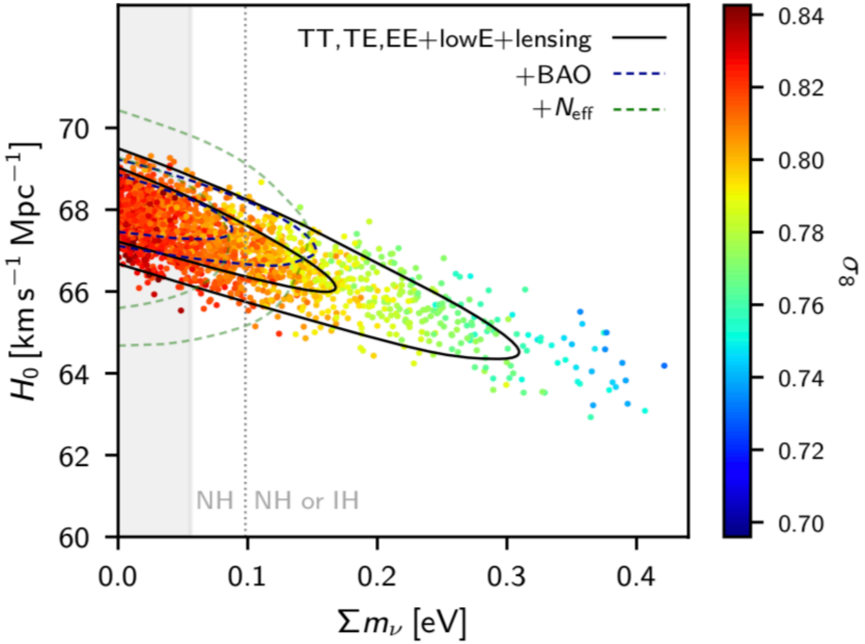








Planck 2018

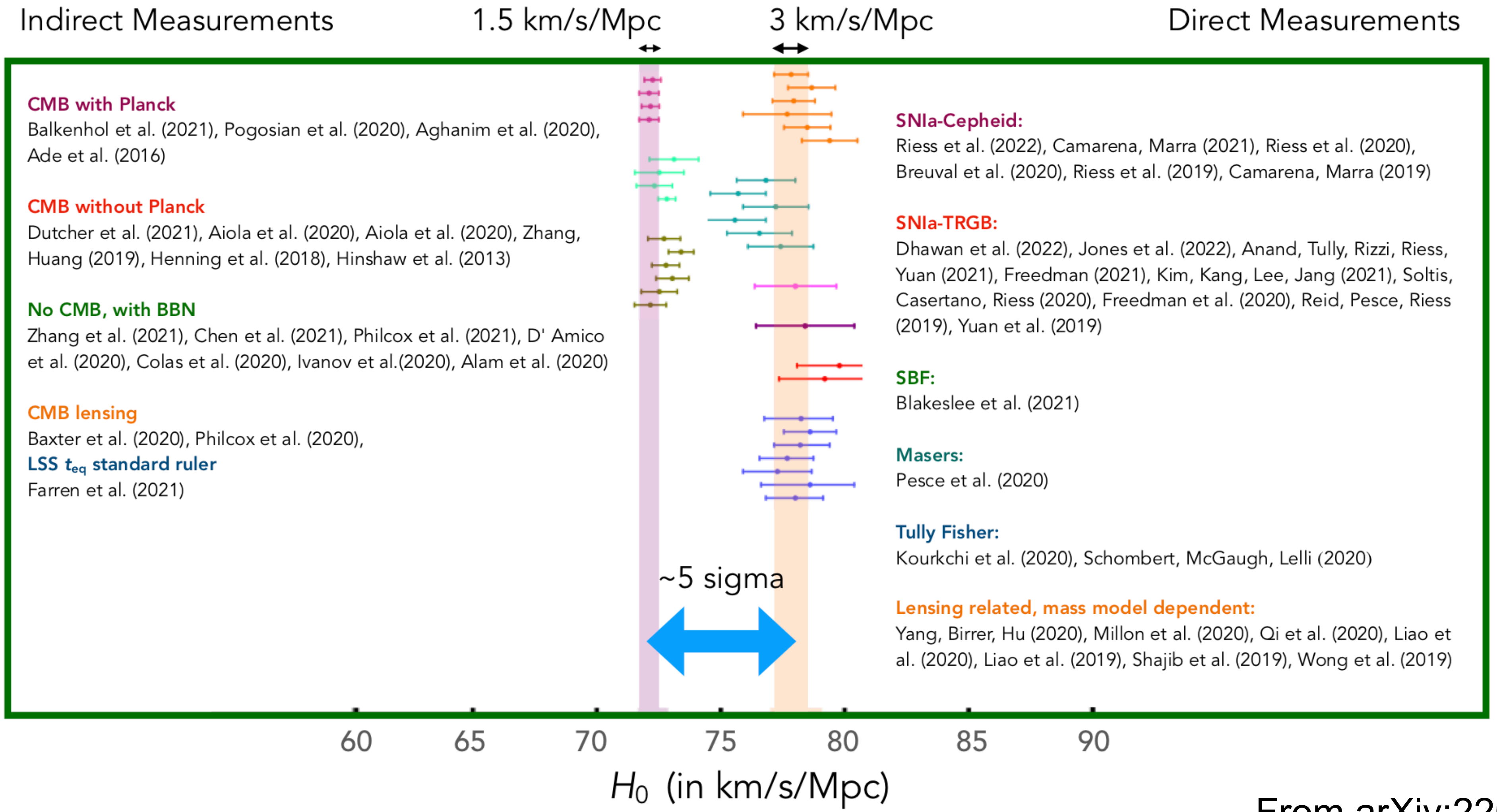


$\sum m_\nu < 0.24\,\mathrm{eV}$ (TTTEEE+lowE+lensing)

$\sum m_\nu < 0.12\,\mathrm{eV}$ (... + BAO)

(95% CL)

A CRACK IN THE MODEL?



From arXiv:2209.11726

The ΛCDM Model

The ΛCDM model is a great *phenomenological* success (although tensions have surfaced recently).

A complete understanding of the model is however still missing.

- Many predictions of inflation have been tested already (e.g. adiabatic, scale-invariant perturbations) but an actual "smoking gun" (i.e. observation of cosmological GWs) is still missing.
- What is the exact mechanism driving inflation? Is it single field, multiple field…?
- What is dark matter? Is it a single new particle, or a whole new sector? What are its properties?
- What is the origin of the baryon asymmetry?
- What is driving the acceleration today? Is it dark energy (and in case, what is it?) or a manifestation of modified gravity?
- What are the properties of light relics (e.g. active neutrinos)?

InDark

Within the INFN CSN4, research on cosmology is mainly carried on within the "InDark" (Inflation, dark matter and the large-scale structure of the Universe) project.

"Our goal is to advance in the path that goes from a simple phenomenological description of the Universe and of its evolution, to fully understanding **the nature of its constituents**, **the behaviour of gravity on cosmological scales** and the **mechanisms generating the primordial cosmological perturbations**. At the same time, this strategy will allow to **constrain models of particle physics**. Once paired with **reliable theoretical predictions**, present and forthcoming data provide a treasure trove that allows **to test with increasing accuracy, and possibly rule out, various models of the Universe, its evolution and the structures within**. "

9 nodes: BO, FE, GE, LNGS, PD, PR, RM2, TO, TS

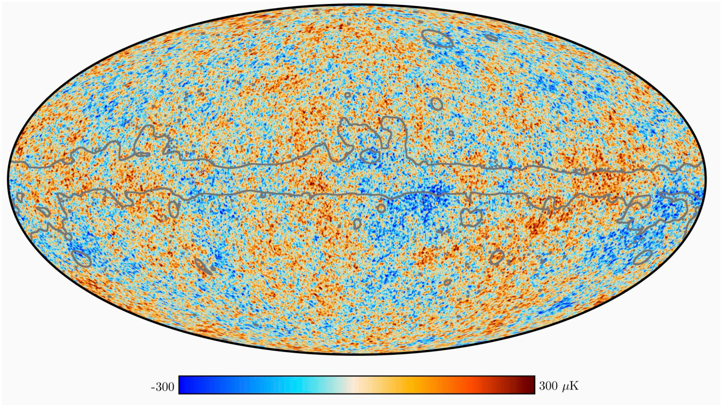
Cosmological observables

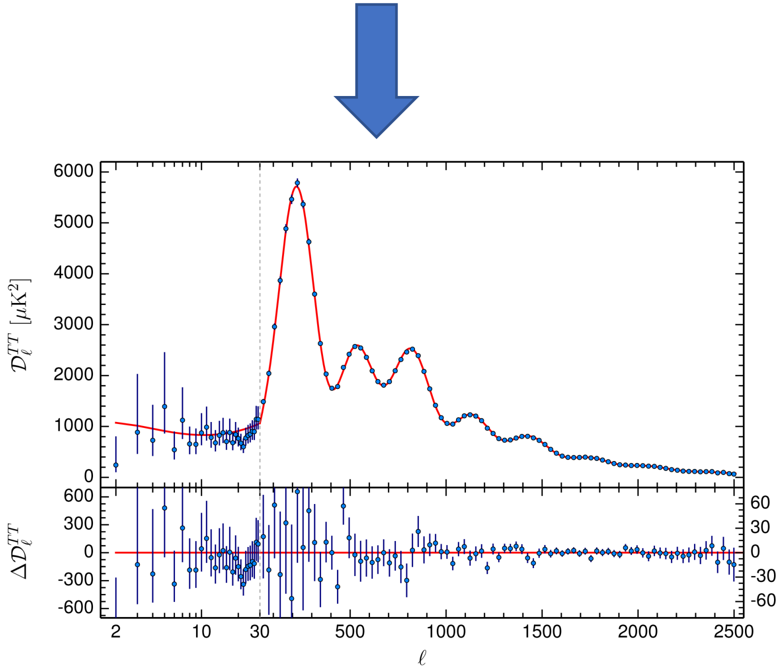
Most cosmological observations are essentially observations of cosmological fields projected on the sky (e.g. CMB temperature).

The observed fields are the "product" of stochastic initial conditions (set by inflation) and a deterministic evolution

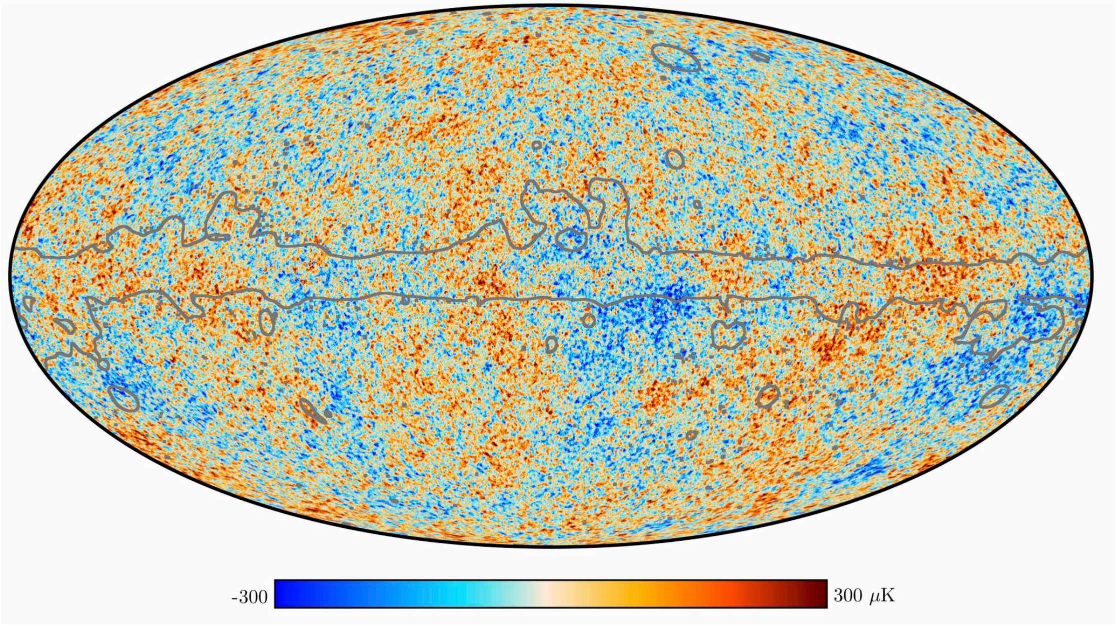
The statistical properties of the fields are encoded in their n-point statistics (starting from 2-point, i.e., the power spectrum)

Number of measured modes in a map: N ~ $(\ell_{max})^2$ where ℓ_{max} ~ 1/(angular resolution)





THE COSMIC MICROWAVE BACKGROUND

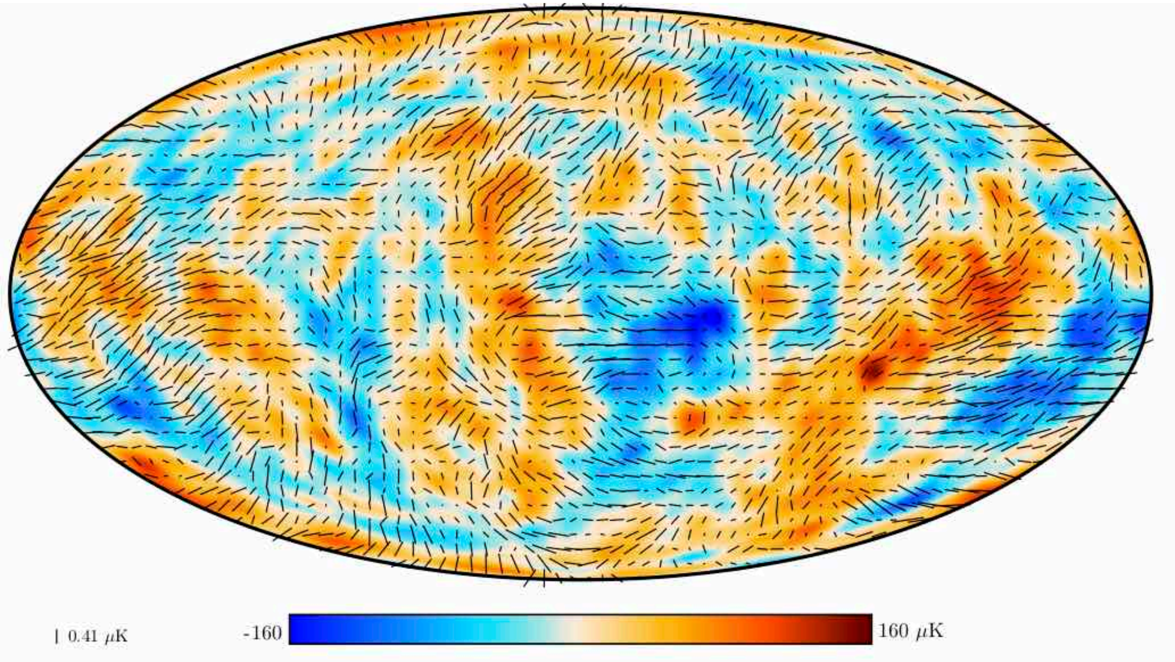


Spherical harmonic expansion:

$$T(\vec{n}) = \sum_{\ell,m} a^T_{\ell m} Y_{\ell m}(\vec{n})$$

$$\langle a^T_{\ell m} a^{T*}_{\ell' m'} \rangle = C^{TT}_\ell \delta_{\ell\ell'} \delta_{mm'}$$

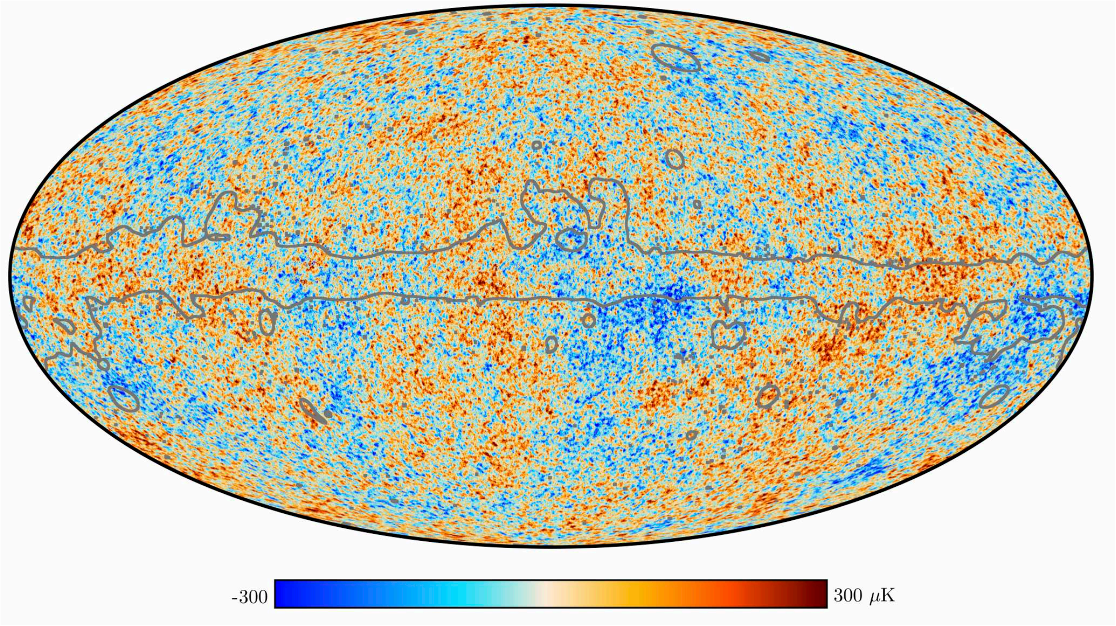
(similarly for E and B pol.)



If fluctuations are exactly gaussian, all information about the stochastic properties of the maps is contained in their (auto and cross) power spectra C_l

Temperature and polarization maps from Planck (2018)

The Cosmic Microwave Background



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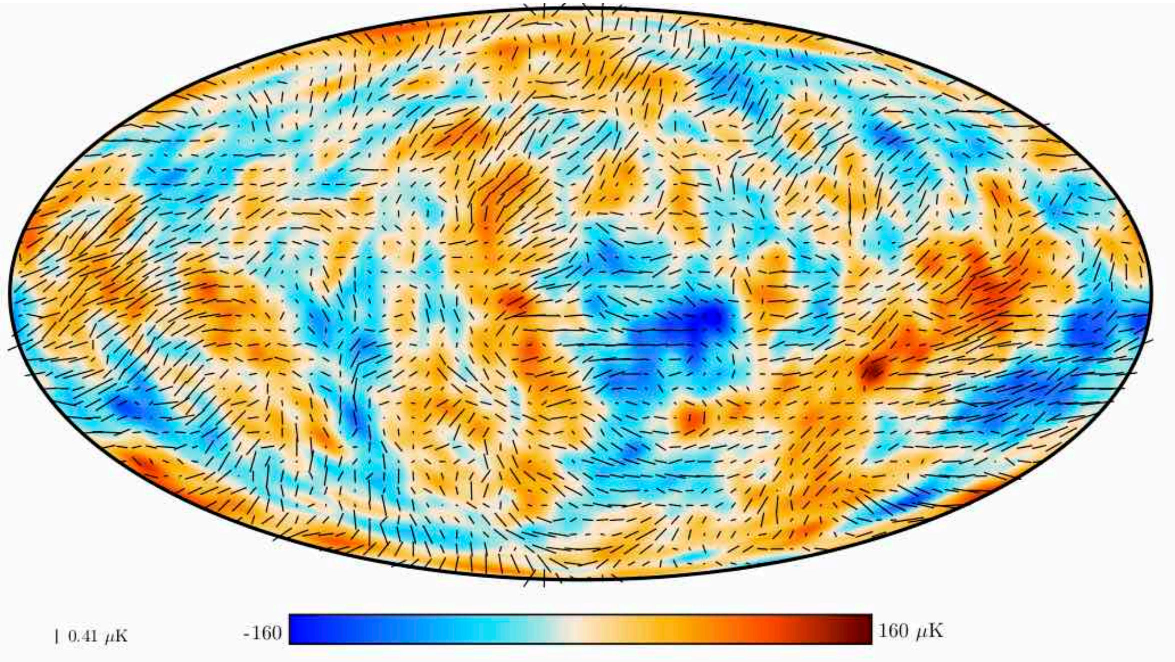
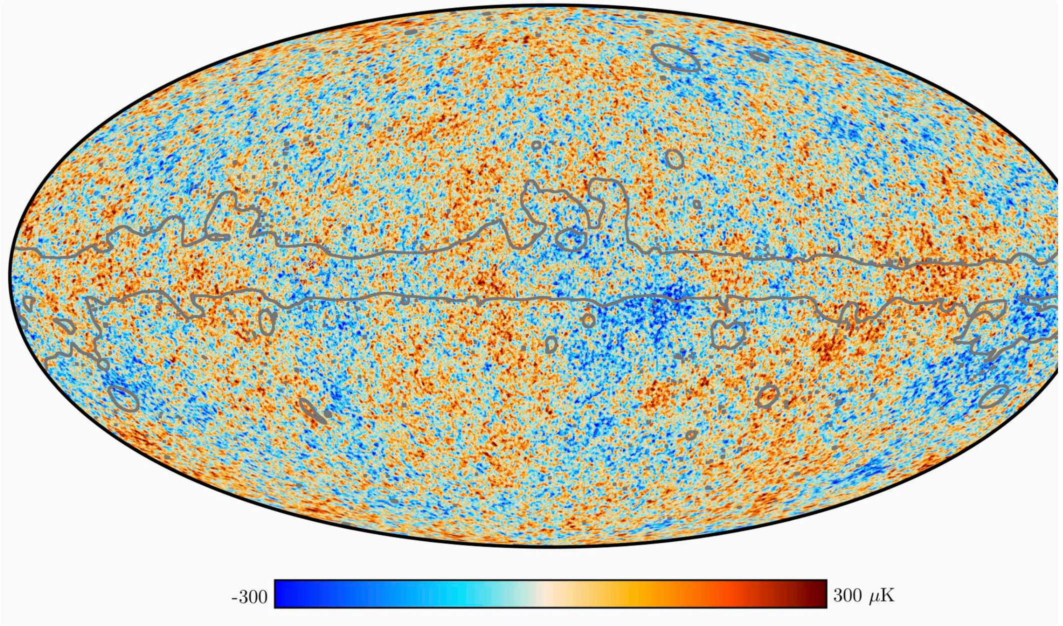


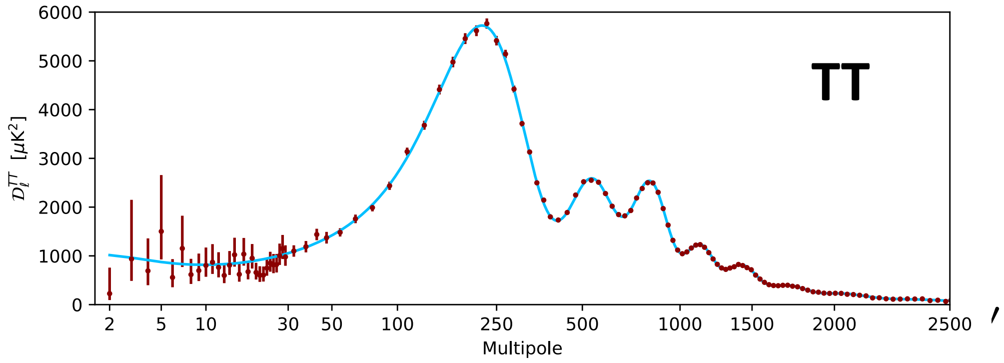
3 maps, 6 correlations: TT, EE, BB, TE, TB, EB

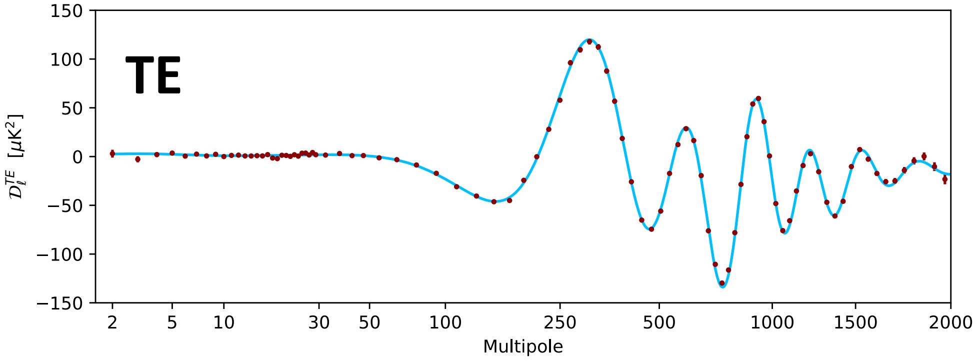
But TB,EB=0 (parity conservation)

Temperature and polarization maps from Planck (2018)

The Cosmic Microwave Background







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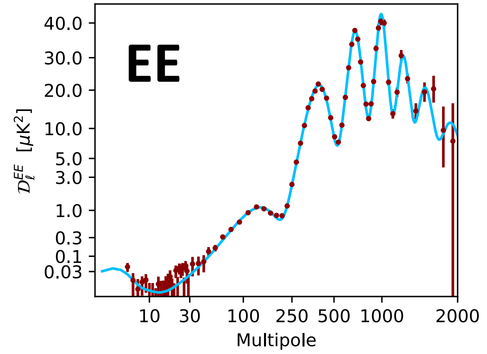
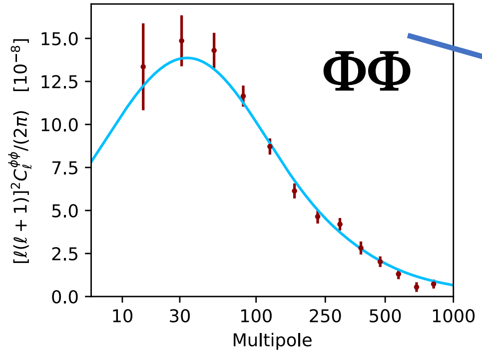


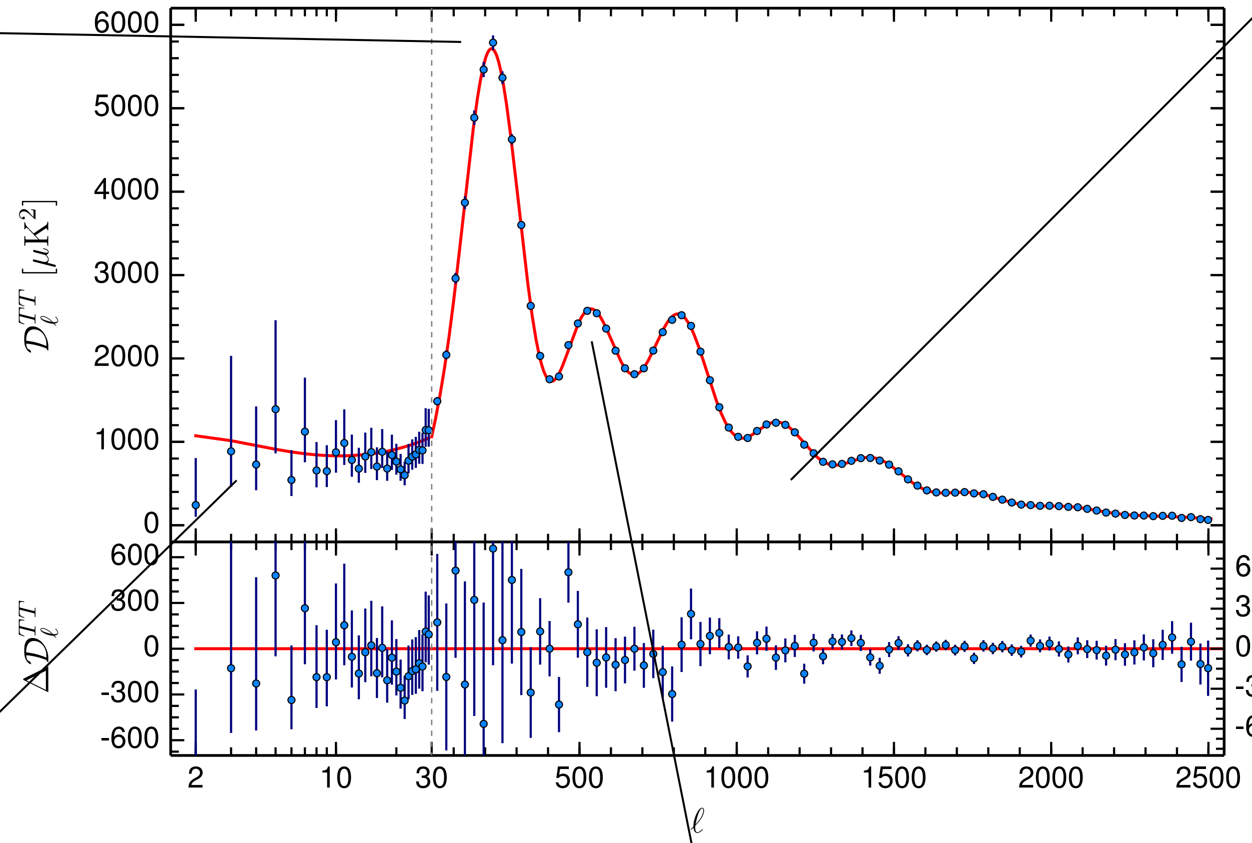


Lensing power spectrum (see below!)

Temperature and polarization maps from Planck (2018)

CMB AND COSMOLOGICAL PARAMETERS

First peak:
spatial curvature;
relative abundance of matter and radiation;
distance to the last scattering surface;
$\mathbf{H_0}$, $\mathbf{\Omega_m}$, $\mathbf{\Omega_k}$



Damping tail:
Photon diffusion length at recombination;
Slope of the primordial spectrum;
$\mathbf{N_{eff}}$, $\mathbf{\Omega_b}$, $\mathbf{Y_p}$, $\mathbf{n_s}$

+ Overall power
$\mathbf{A_s\, e^{-2\tau}}$

+ low-ell polarization (not shown)
Reionization history
τ

Large ell plateau: Primordial power spectrum; late time expansion (relative abundance of matter and dark energy);
$\mathbf{A_s}$, Ω_Λ

Relative height of first and second peak: Baryon abundance
$\mathbf{\Omega_b}$

Observations of Large-Scale Structures

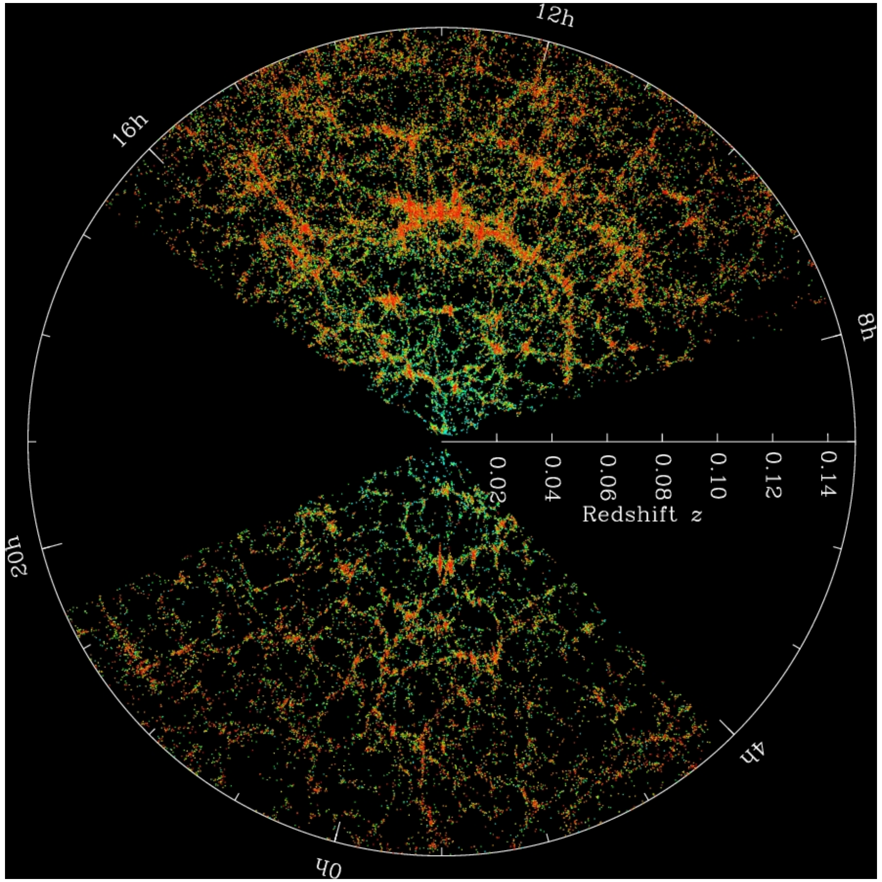


Image Credit: M. Blanton and the Sloan Digital Sky Survey.

Fractional density fluctuation:

$$\delta_m(\vec{x}, z) \equiv \frac{\rho_m(\vec{x}, z) - \overline{\rho}_m(z)}{\overline{\rho}_m(z)} = \sum \widetilde{\delta}_m(\vec{k}, z) e^{-i\vec{k}\cdot\vec{x}}$$

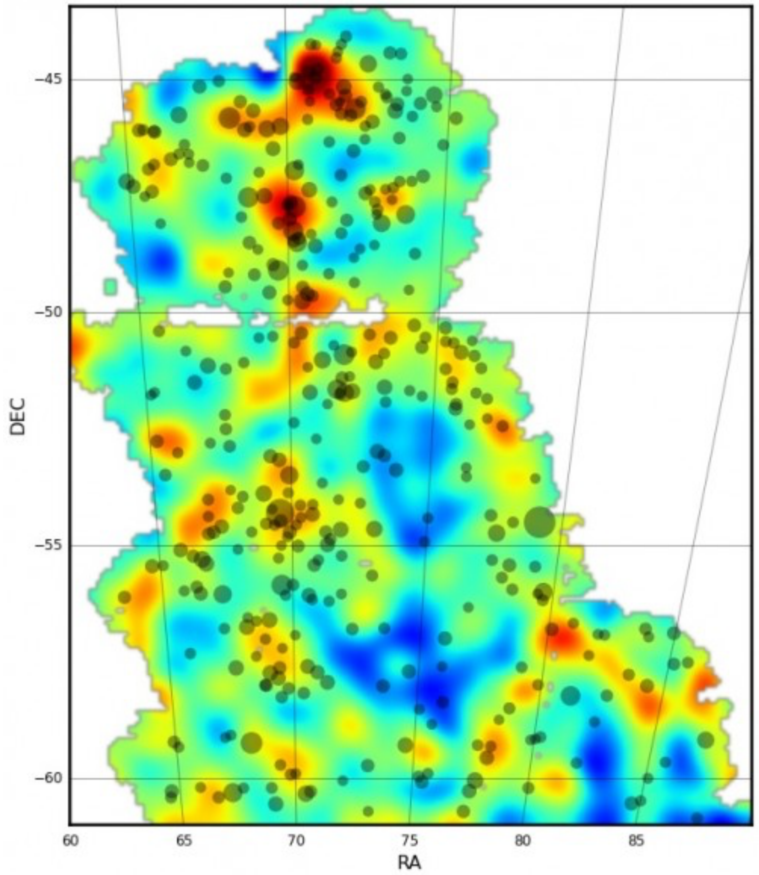
Power spectrum:

$$\left\langle \widetilde{\delta}_m(\vec{k}, z) \widetilde{\delta}_m(\vec{k}', z) \right\rangle = P_m(k, z) \delta^{(3)}\left(\vec{k} - \vec{k}'\right)$$

The power spectrum is the Fourier transform of the 2-point correlation function:

$$P_m(k) \longleftrightarrow \xi_m(r) \equiv \langle \delta_m(x) \delta_m(x + r) \rangle$$

OBSERVATIONS OF LARGE-SCALE STRUCTURES



Weak lensing convergence map from the Dark Energy Survey (DES)

Another option is to look at the distortions in galaxy shapes induced by weak gravitational lensing ("***cosmic shear***")

Cosmic shear is an observational target of future surveys (e.g. Euclid). It requires to measure distortions of order 1% in galaxy ellipticities.

$$\kappa = \frac{3}{2}\left(\frac{H_0}{c}\right)^2 \Omega_m \int_0^{r_s} dr\, \frac{\delta(r)}{a(r)} \frac{r(r_s - r)}{r_s},$$

Convergence field

This is a more direct probe of matter fluctuations than galaxy number counts, since the lensing potential is produced by all matter components, including dark matter.

However, issues with nonlinearities remain.

Weak Lensing of the CMB

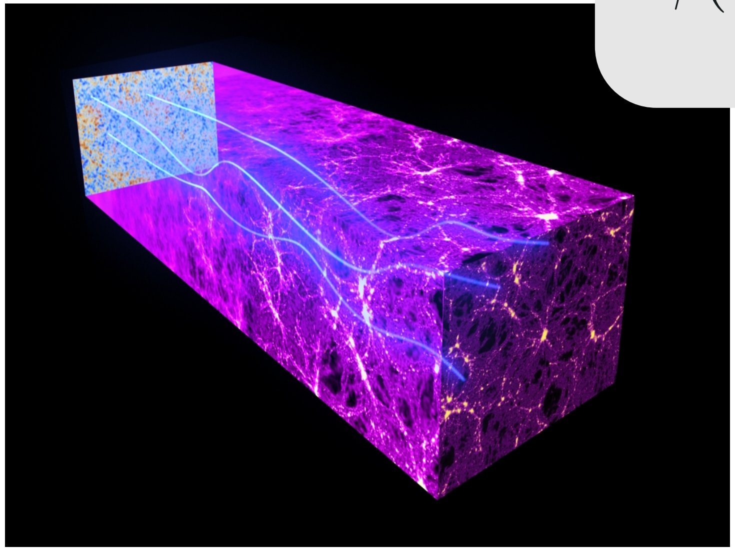
The observed CMB field T^{obs} is displaced wrt to the "unlensed" field T^{unl}, i.e. the one that would be seen in a perfectly homogeneous Universe, due to the lensing effect of intervening structures between us and the LSS:

$$T^{\rm obs}(\vec{n}) = T^{\rm unl}(\vec{n} + \vec{d})$$

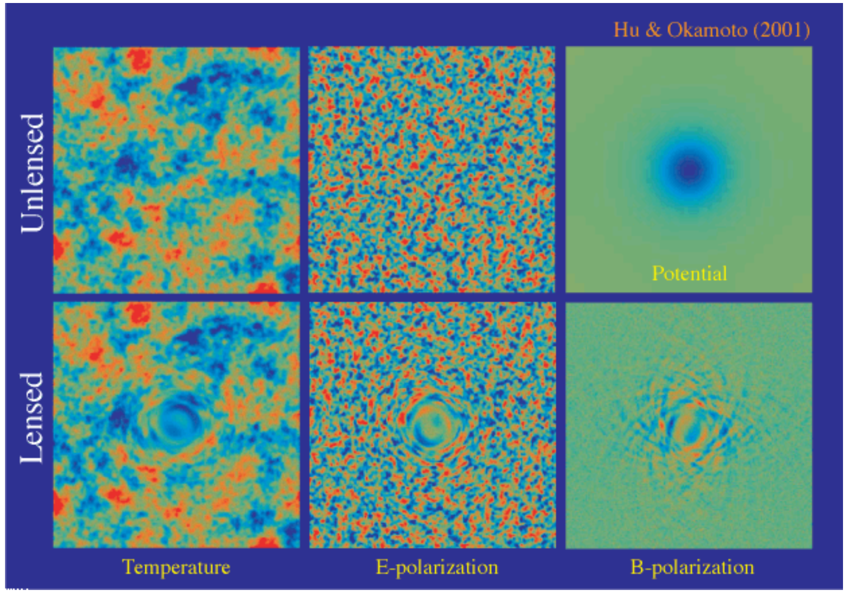
$$\vec{d} = \vec{\nabla}\phi$$ is the deflection field

Line-of-sight integral of the gravitational potentials

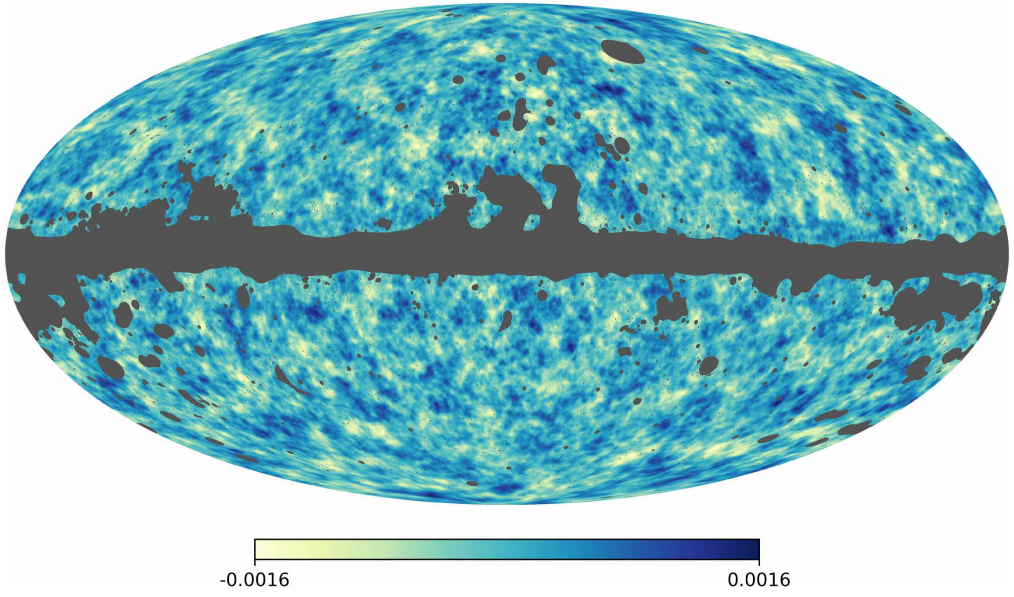
$$\phi(\hat{n}) = -\int_0^{\chi_*} d\chi \frac{\chi_* - \chi}{\chi_* \chi} (\Phi + \Psi)$$



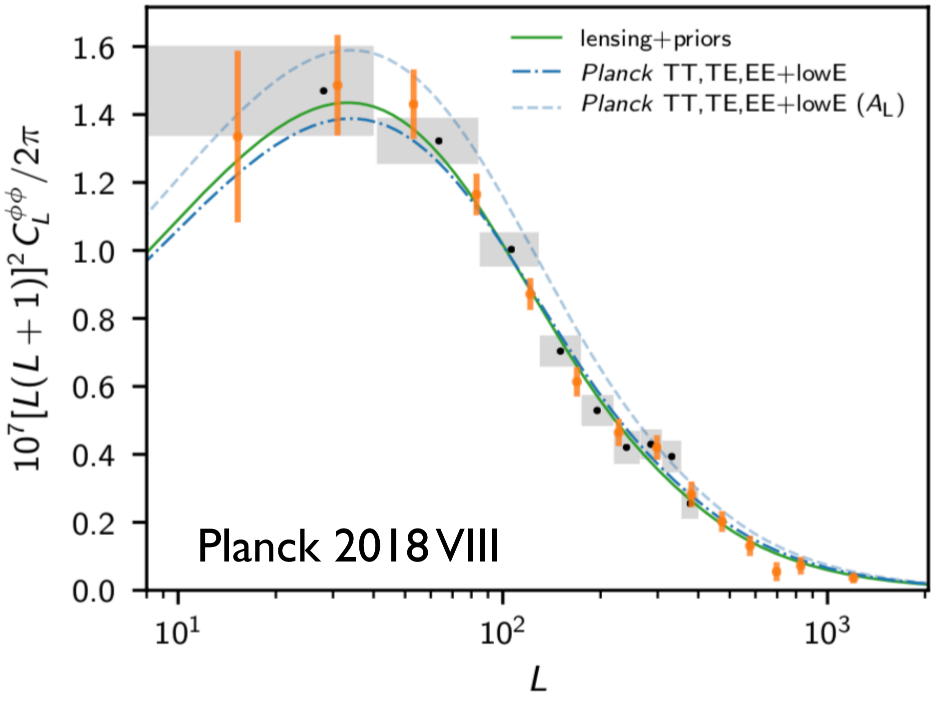
Makes CMB sensitive to the late-time density field, too….



Weak Lensing of the CMB



The induced nongaussianities can be used to reconstruct the lensing potential field



Map and power spectrum of the lensing potential estimated from the four-point correlation function of the temperature and polarization maps

FUTURE EXPERIMENTS

LSPE (2023+): Balloon borne; main target: improved polarization measurements for inflationary science.

Simons Observatory (2024+): ground-based in Chile; thousand detectors, low noise, high angular resolution; improved measurements of primary CMB in T and P; improved reconstruction of the lensing power spectrum; enhanced cluster science (detection of galaxy clusters via Sunyaev-Zeldovich effect)

CMB-S4 (2029+): ground-based, with large aperture telescope in Chile; SO successor, 10^5 detectors, lower noise, improved measurements of CMB, lensing, clusters. Ultimate CMB experiment from ground.

LiteBIRD (2029+): satellite; main target: improved polarization measurements for inflationary science and reionization. Better estimates of tau (reionization optical depth) can improve constraints on other parameters

Euclid (2022+): satellite; galaxy and weak lensing survey for the reconstruction of the matter distribution and improved measurements of the BAO scale.

DESI (2020+): ground-based, spectroscopic, BAO reconstruction.

Rubin (202x+): ground-based; galaxy and weak lensing survey

Roman (20XX+): satellite; high-z galaxy survey

SPHEREx (202x+): satellite; low-z galaxy survey, all-sky.

(INFN involvement in **red**)

HPC in InDark

The precision of data from forthcoming experiments requires us to be able to produce reliable theoretical predictions.

HPC is fundamental in allowing us to extract information from cosmological observables. In the following, I will present some examples taken from the activities of InDark associates, and related to:

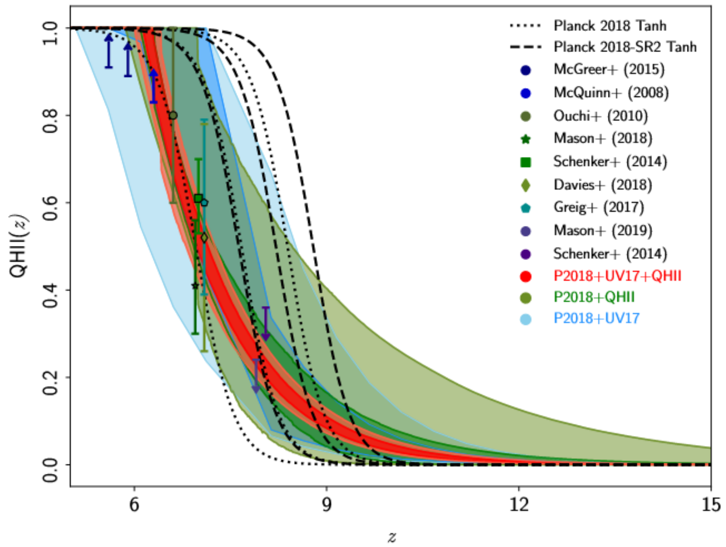
- Inference of cosmological parameters using Monte Carlo Markov Chains techniques
- Building and characterization of spectral estimators
- N-body simulations of structure formation

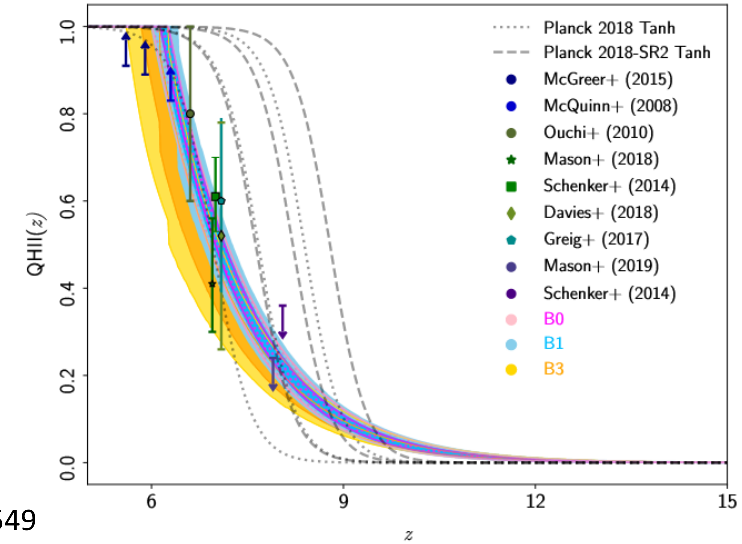
We consider several extensions of the cosmological model beyond the standard one: the reconstruction of the Epoch of reionization with the combination of CMB and astrophysical data, the study of the origin of cosmic magnetism and the study of non standard inflationary models.

RECONSTRUCTION OF THE REIONIZATION EPOCH

We perform a non-parametric reconstruction of the epoch of reionization fitting for the sources and sinks of reionization. In this approach is possibe to put together CMB with UV luminosity density data from Hubble Frontier Field and the data from quasars and gamma ray bursts.

The code fits multiple polynomials and samples up to 9 additional parameters for the reionization togehter with the standard five cosmological parameters (the optical depth in this approach is a derived parameter) and nuisance parameters from the real data likelihood. The degeneracies imply an higher number of steps in the MCMC code to reach convergencence therefore fully requiring the parametrization. Due to this factor it scales more with the number of MPI processes than openMP threads.





Slide by D. Paoletti (INAF-BO)

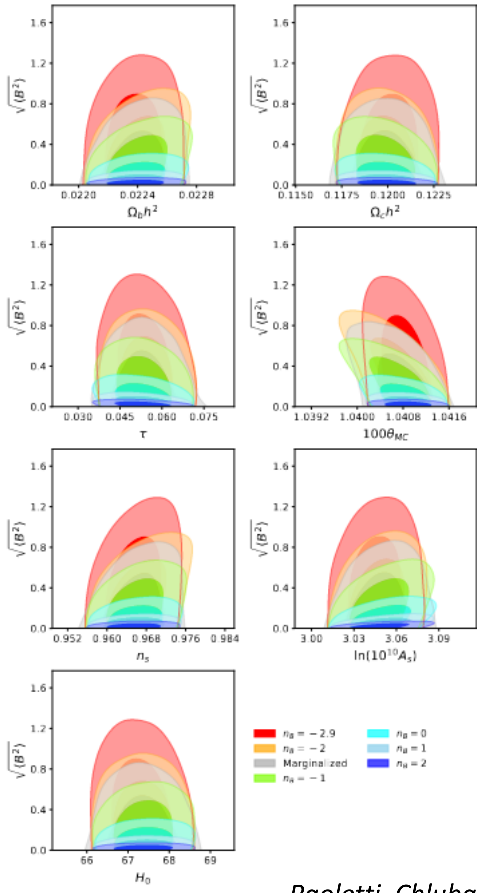
Paoletti, Hazra, Finelli, Smoot *Phys.Rev.D* 104 (2021) 12, 123549

Slide by D. Paoletti

ORIGIN OF COSMIC MAGNETISM

Primordial Magnetic Fields (PMFs) generated in the early Universe may represent the seeds that originated the magnetic fields we observe on the large scale structures and voids of the Universe. Their presence affects the entire cosmic history and leaves imprints on the CMB anisotropies which can in turn be used to provide constraints on their characteristics. In this case we consider two different effects: on the ionization history and gravitational. This activity is currently also carried out in the LiteBIRD collaboration dedicated project using also InDark HPC resources.

IONIZATION HYSTORY

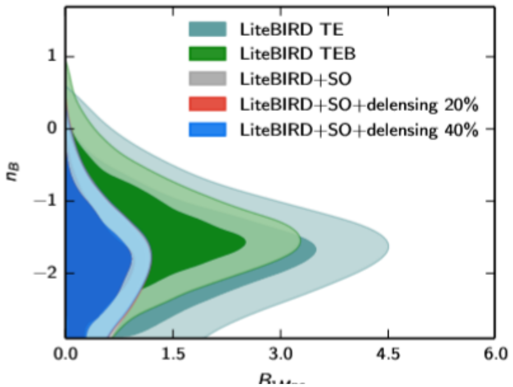


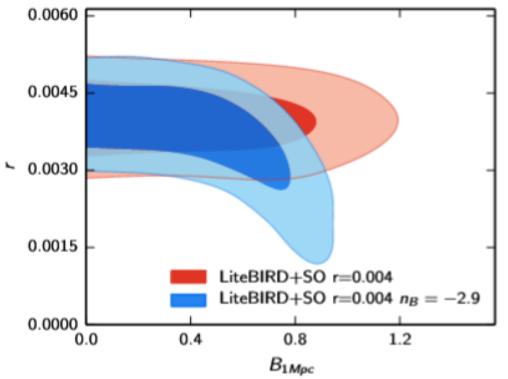
Due to the post recombination dissipation of PMFs and subsequent energy injection in the cosmological plasma.

It involves also additional c++ based code Cosmorec.
The modified camb code to overcome numerical instabilities due to the high energy injection rates requires two orders of magnitude more time samplings than original code. In this case the timing of the code is mainly related to the CPU power performing optimally on G100.

Paoletti, Chluba, Finelli, Rubino-Martin MNRAS, Volume 517, Issue 3

GRAVITATIONAL EFFECT



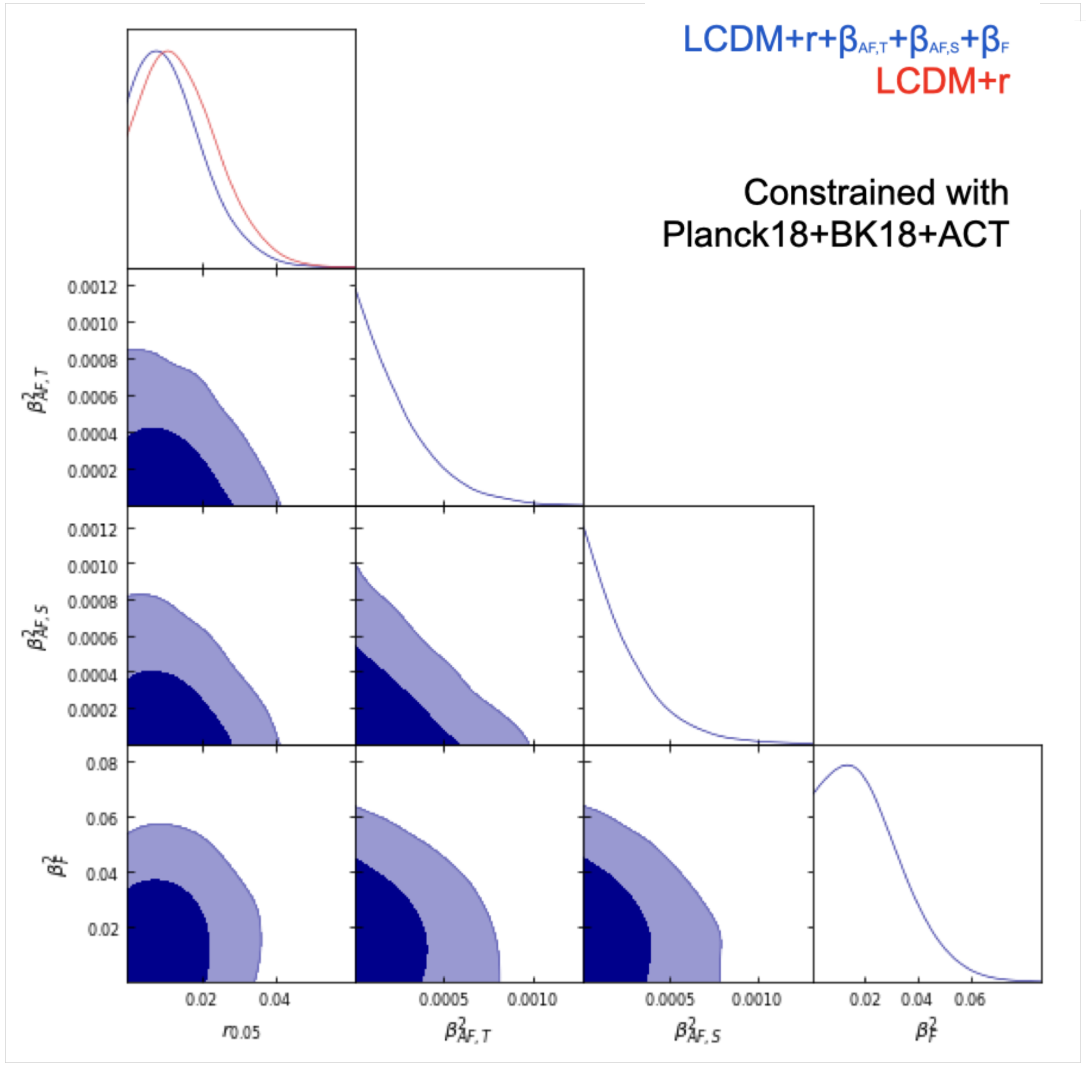


Paoletti and Finelli JCAP 11 (2019) 028

Due to the PMF energy momentum tensor contribution to the total energy of the cosmological plasma.

The modified camb code has to be performed five additional times to account for the five additional perturbative modes.
The six calls are fully parallelized on openMP.
It is one of the heaviest codes and requires the longest run time (about 1000 cpu-h)

Constraining Lorentz-violating electrodynamics with current CMB data



CPT-odd CPT-even

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\varepsilon^{\alpha\beta\mu\nu}A_\beta(k_{AF})_\alpha F_{\mu\nu} - \frac{1}{4}(k_F)^{\alpha\beta\mu\nu}F_{\alpha\beta}F_{\mu\nu}$$

Lorentz-violating electrodynamics can leave potentially detectable imprint on CMB polarization (e.g. birefringence, generation of circular polarization…..)

$\beta^2_{AF,T/S}$ are related to the time and space component of k_{AF}

β^2_F depends of the components of k_F in a non-trivial way

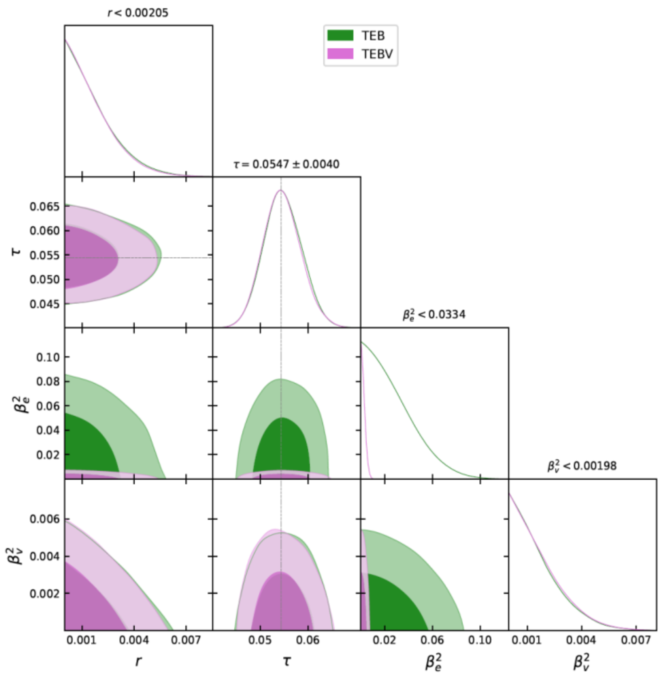
Slide by M. Lembo (UniFE)

MCMC analysis of LCDM extensions (e.g. V-modes forecast, LB reio forecast)

LCDM extensions == possible <u>new physics</u>

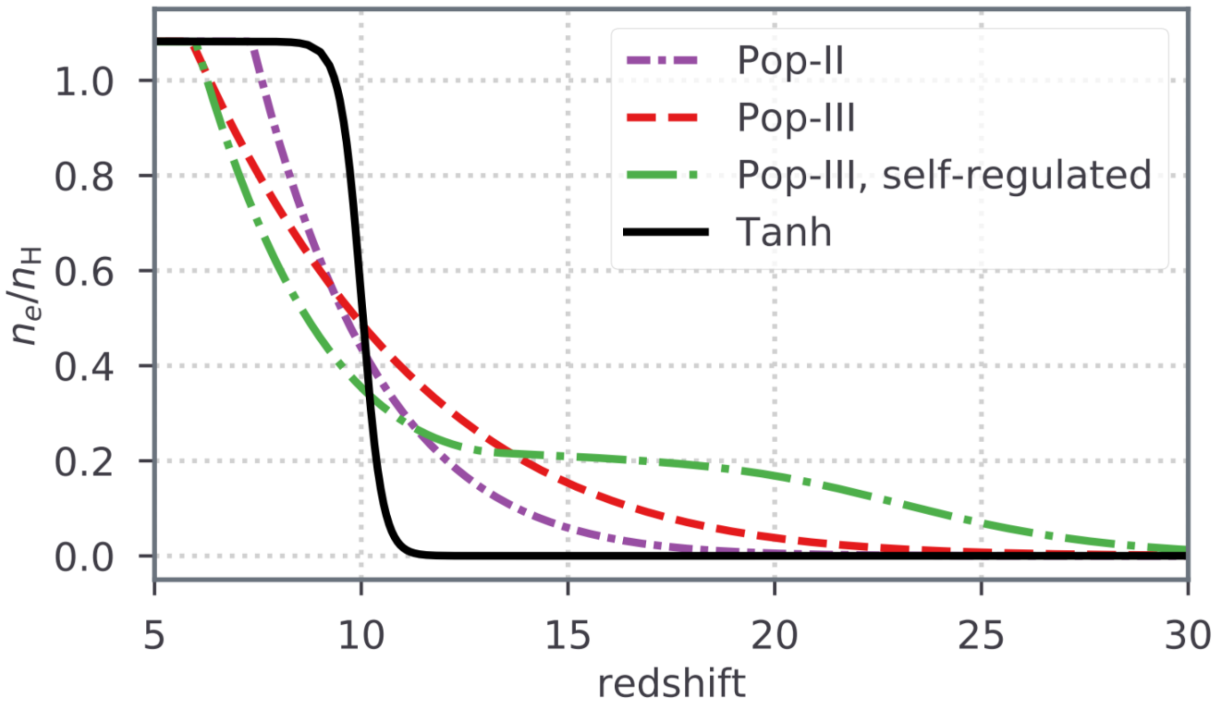
V-modes forecast: exploiting an instrumental systematic (non-ideal HWP) we are sensitive to circular polarization too, without affecting the linear polarization observation of the CMB.

Assuming a LCDM extension we can constrain parameters of nonstandard electromagnetism by using MCMC algorithms.



Reionization forecast: dropping the approximation of instantaneous cosmic reionization we want to constrain the neutrino masses and the mass ordering.

Determination of reionization parameters and their impact on the measurement of neutrino masses through MCMC sampling.



Slid by N. Barbieri (UniFE)

Bounds on axion couplings

New modified version of CAMB Boltzmann solver

AXion production rate over the qcd phase transition epoch

[D'Eramo F. Et al., Phys. Rev. Lett. **128** (2022) 152001

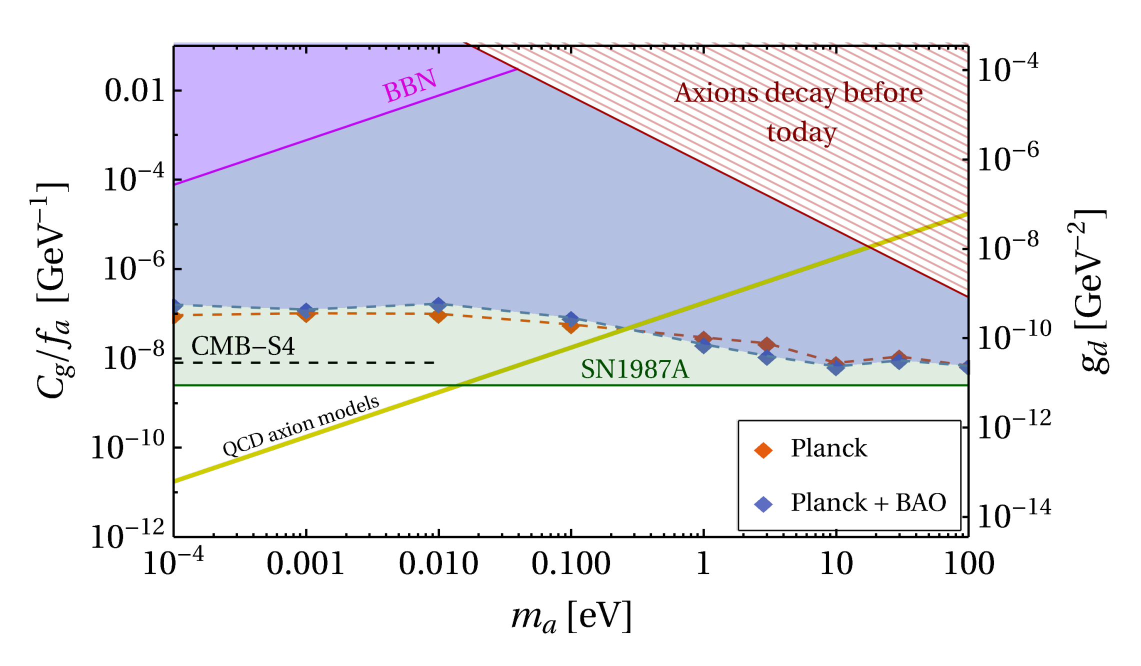
Below the energy scale f_a, the axion field is described by the effective field theory (EFT) encoded by

Soft explicit symmetry breaking mass term

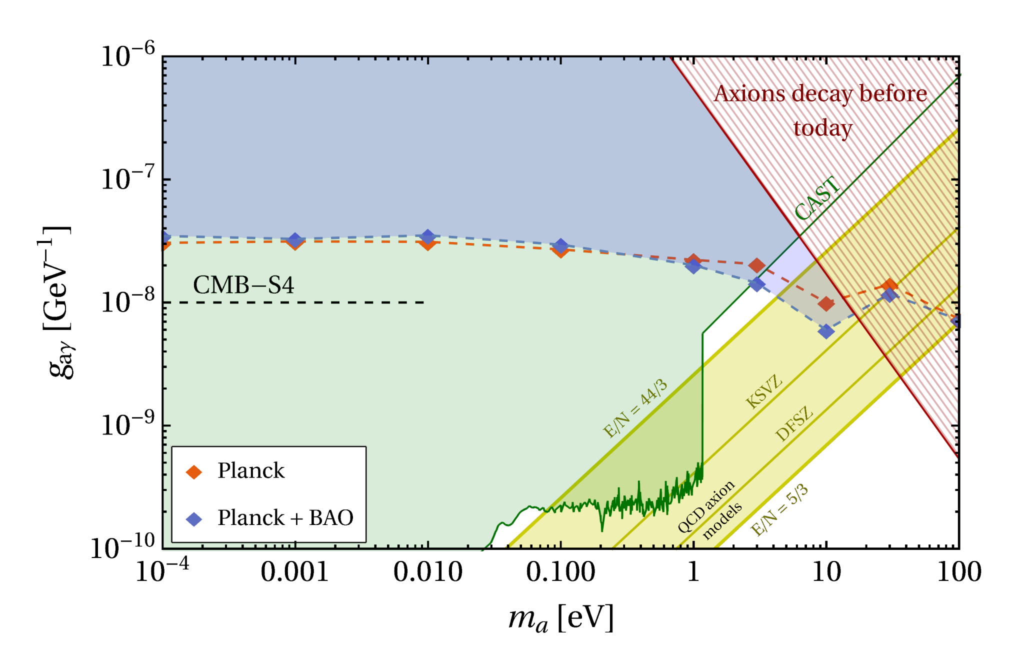
$$\mathcal{L}_{\rm EFT} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \frac{\alpha_s}{8\pi}\frac{C_g}{f_a} a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i} + \frac{1}{4}g^0_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Axion-photon coupling

Axion-gluon coupling



[Caloni L. et al., JCAP **09** 021 (2022)]



[Caloni L. et al., JCAP **09** 021 (2022)]

Beyond the power spectrum: non-Gaussianity

Does the power spectrum contain all relevant cosmological information?
(i.e., are the CMB and LSS fluctuation fields always Gaussian, at all scales?)

No, it does not

Inflation can produce small, model dependent non-Gaussianity (NG) In the primordial density field, in presence of deviations from standard single-field, slow-roll, e.g., multi-field, non-standard kinetic terms, features in the inflaton potential and more

Gravitational instability introduces non-linearity in the perturbation evolution process. When $\delta > 1$, the matter fluctuation field becomes non-Gaussian

Strong NG. Hard to model analytically at small scales

Slide by M. Liguori (UniPD)

Simulation-based inference

- One way to address the difficulty in analytically modeling the strongly non-linear regime is to rely on large sets mock realizations of the matter/halo/galaxy density field.

1. Generate tens of thousands of realizations of the density field, for a fiducial cosmological model, which should be close to the actual maximum likelihood.

2. Choose a set of summary statistics that retain as much information as possible about your parameters, while compressing the data. Extract these statistics for each realization in your simulated dataset.

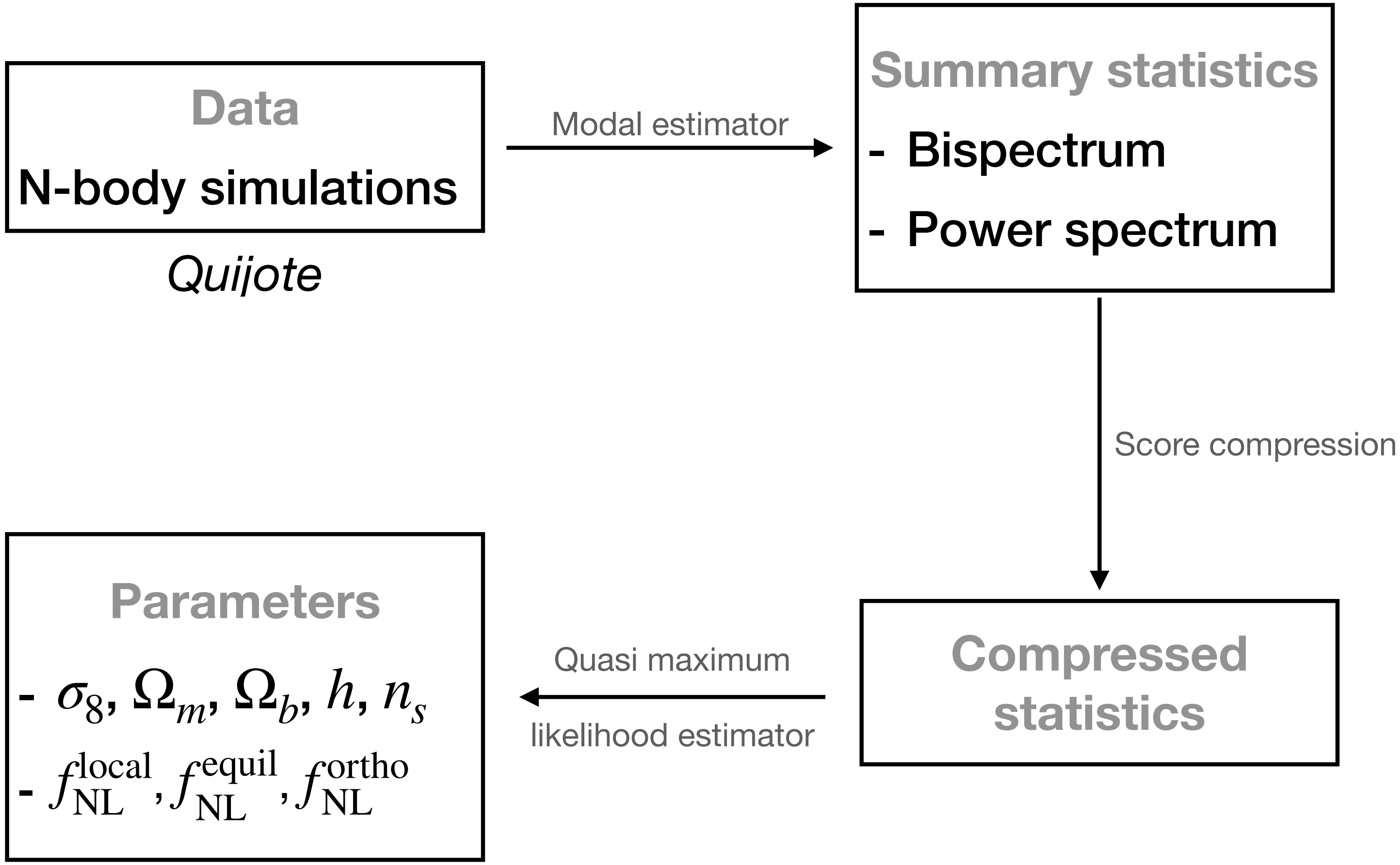
3. Compute the covariance of your summaries and the response to changes in parameters, via Monte Carlo average over the mocks.

4. Look for a further data compression scheme for your summary statistics, as lossless as possible for the parameters of interest. Typically, it is possible to compress all your starting modes into a set of N numbers, where N is the number of parameters

5. Build the covariance matrices and the find the response of your compressed statistics to changes of parameters. Use these quantities to estimate parameters.

Slide by M. Liguori (UniPD)

Joint power spectrum – bispectrum estimation of cosmological parameters



Slide by M. Liguori (UniPD)

DATA: N-BODY SIMULATIONS. QUIJOTE SUITE

- Quijote simulations, Gaussian initial conditions (f_{NL} =0)

  https://quijote-simulations.readthedocs.io/ (***F.Villaescusa Navarro***)

  - Large suite of 44000 N-body realizations with 512^3 particles in a 1 Gpc/h side box, *Planck* fiducial cosmology
  - 8000 simulations were used to compute covariances
  - different sets of 500 simulations were used to compute numerical derivatives w.r.t. cosmological parameters $(\sigma_8, \Omega_m, \Omega_b, n_s, h)$

- Quijote simulations, non-Gaussian

  - Sets of 500 simulations with primordial NG conditions: local, equilateral, orthogonal
  - Numerical derivatives $(f_{NL}^{loc}, f_{NL}^{eq}, f_{NL}^{ortho})$

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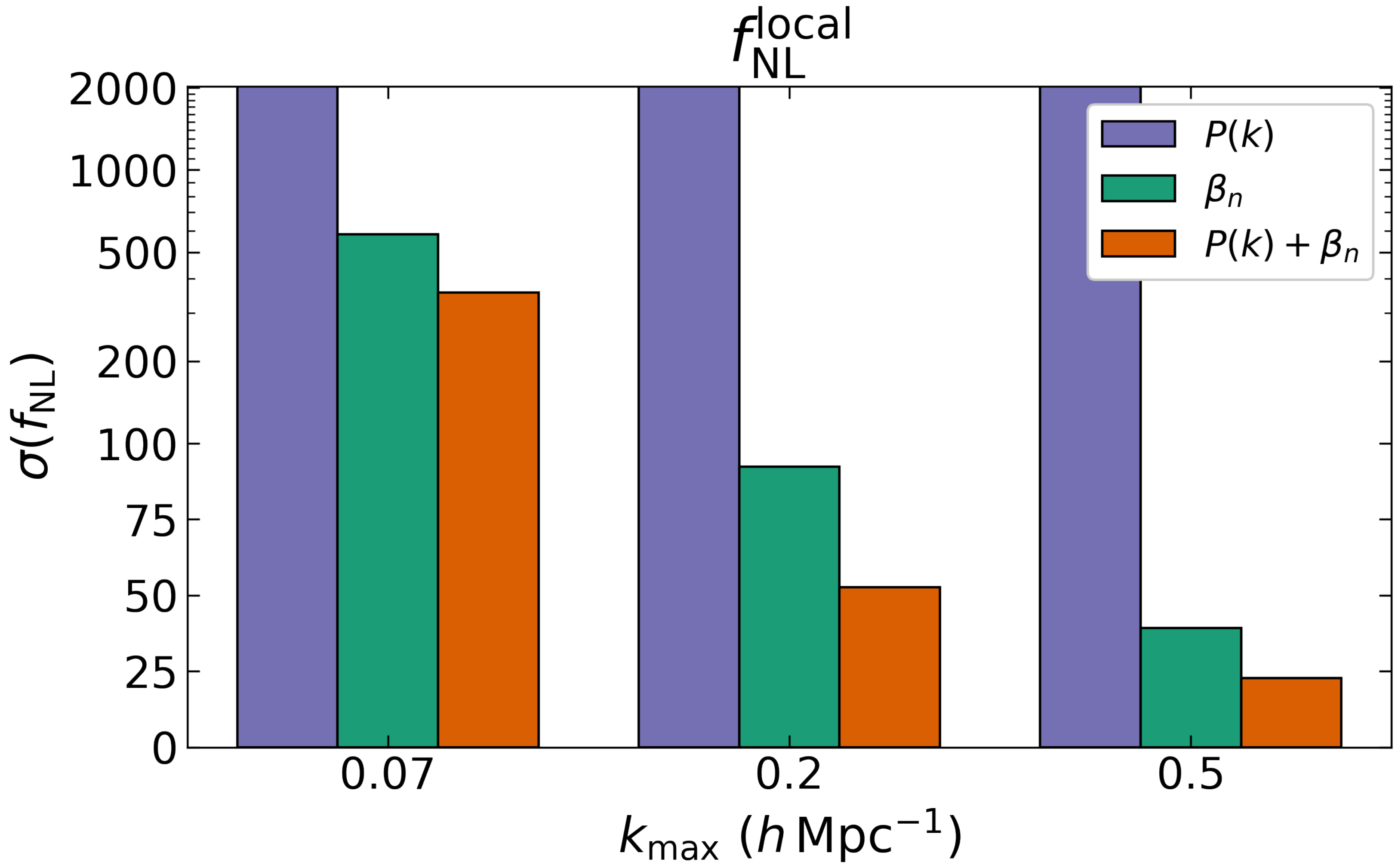

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Computational requirements

- Most of the time is spent to compute inverse FFT in the simulations boxes. Need high resolution to reach $k_{max} = 0.5 \frac{h}{Mpc}$
- For bispectrum estimation, we then need to compute all triple products of this Fourier modes ($\sim$400 triples using an efficient modal binning scheme)
- Takes $\sim$1 min and 10 GB of RAM per simulation (need to store all the Fourier modes)
- We analyze 30 simulations per node on Marconi
- Total running time for a full Quijote run (1 Gpc^3 box) is $\simeq$500 CPU hours (to be repeated for many different fiducial cosmologies and initial condition choices.

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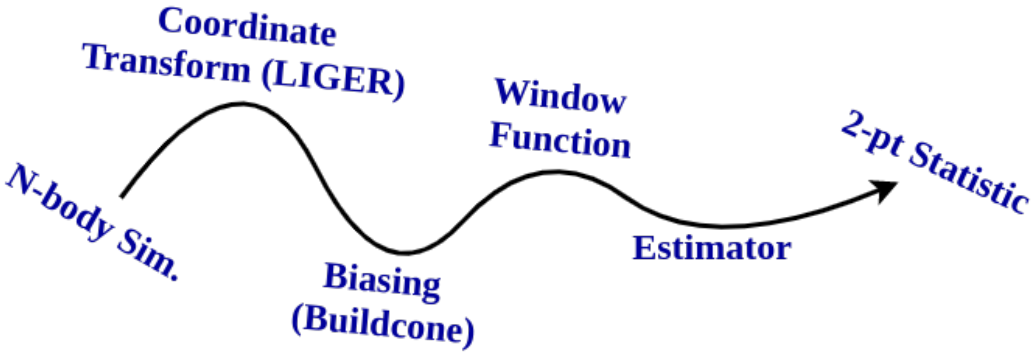
Relativistic redshift space distortions in future surveys using the LIGER method

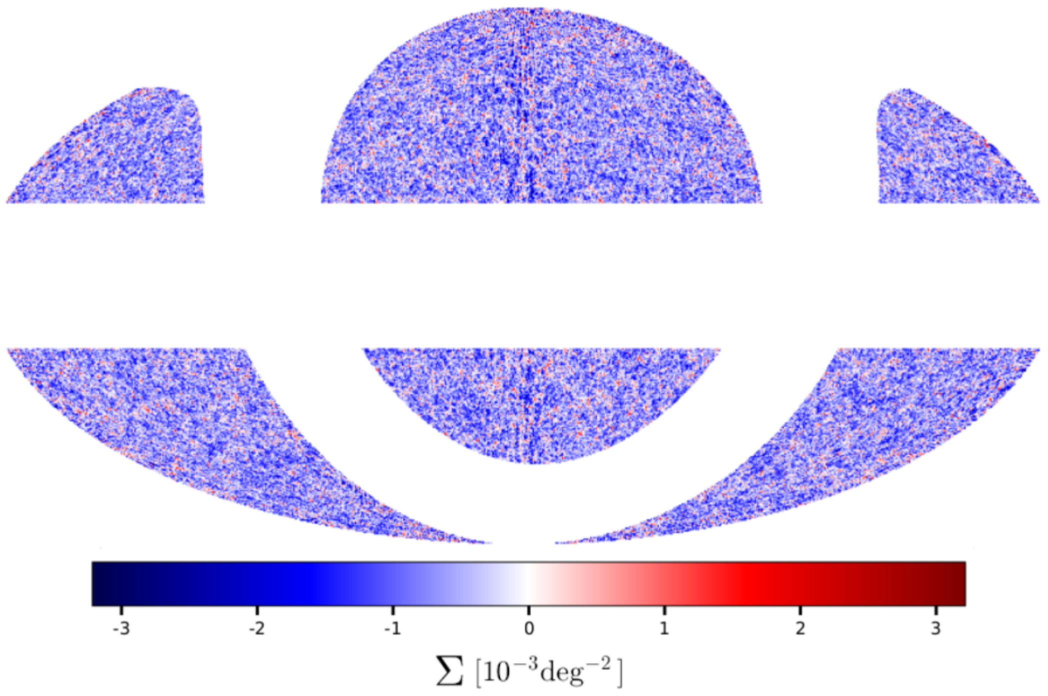
The LIGER Method

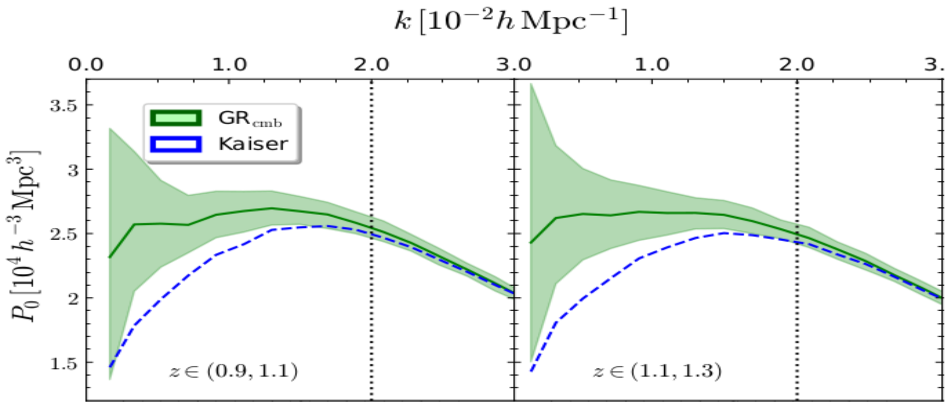
LIGER (light cones with general relativity) is a numerical technique for building mock realisations of the galaxy distribution on the past light cone of an observer accounting for relativistic corrections at linear order.



The LIGER code (available online here) postprocesses N-body simulations account for linear relativistic RSDs to produce galaxy mocks tailored to the survey properties (number density, evolution and magnification bias) of a user defined survey.

These mocks can then be used to measure any two-point statistic (2PCF , Power spectrum , etc.) with the same estimator as the one used in the future survey. This method accounts for the window function of the survey as well as noise systematics.





Slide by D. Bertacca (UniPD)

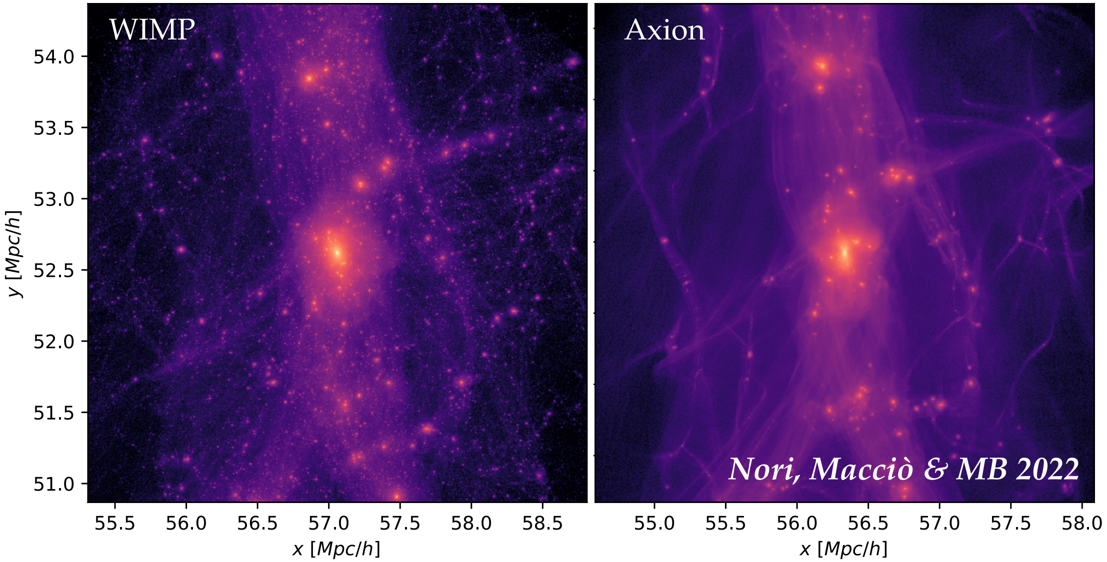
Simulating the Complexity of the Dark Sector

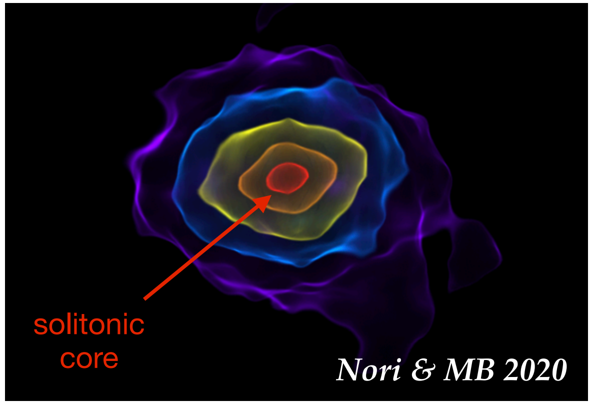
M. Baldi — Bologna University

Testing extended Dark Matter models with numerical simulations

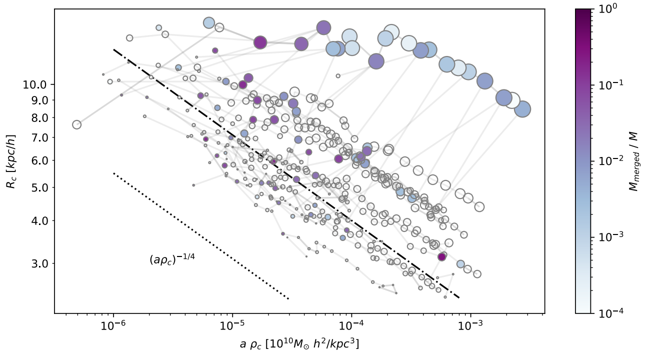
Ultra-Light scalar particles (as e.g. the Axion) provide a viable alternative to Cold Dark Matter:

- Same large-scale behaviour
- An extra **repulsive quantum force** at small scales
- Suppression of the number of small-scale structures
- Formation of **solitonic cores** in the center of halos





With the **N-body code AX-GADGET** (*Nori & MB 2018*) we can simulate statistically representative volumes of the Universe and **follow the formation and evolution of the solitonic cores** and of their **scaling relations**



Nori, Macciò & MB 2022

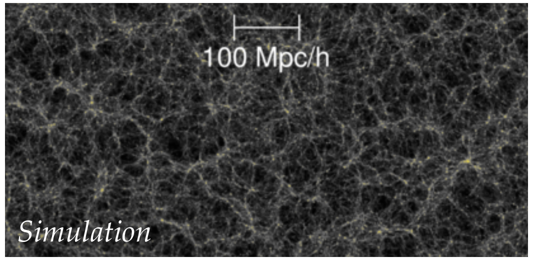
Simulating the Complexity of the Dark Sector

M. Baldi — Bologna University

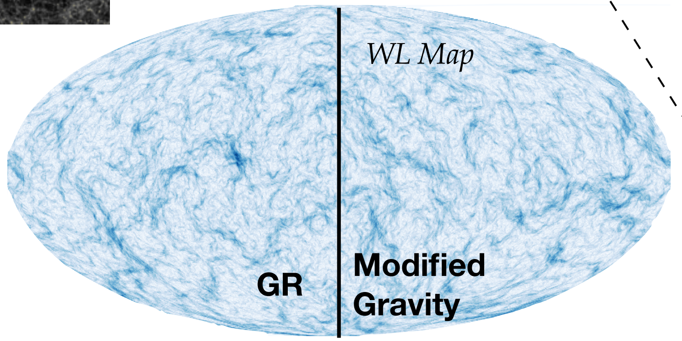
Testing Dark Energy and Modified Gravity models with numerical simulations

Cosmic Acceleration could represent the signature of **a more complex Dark Sector** or of a **modification of the laws of Gravity**

With the **MG-Gadget** N-body code (*MB et al. 2013*) we can test **extended theories of Gravity** and their predicted signatures on various cosmic observables



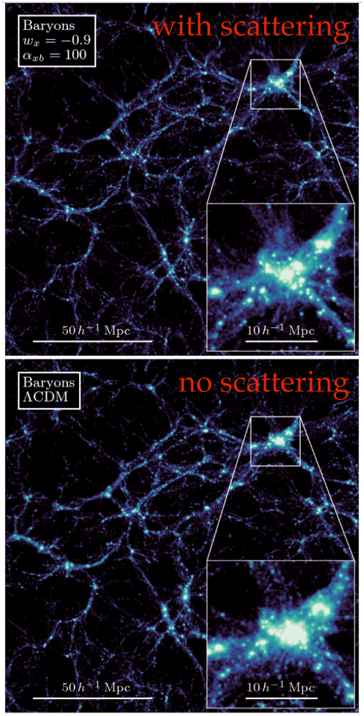
The effect of **f(R) gravity** can be detected in the **WL signal** with e.g Euclid



With the **C-Gadget** N-body code (MB et al. 2010) we can simulate the formation of cosmic structures when **Dark Energy is a new light scalar field coupled to standard or dark matter**, e.g.:

- *Coupled Quintessence (MB+ 2010, 2012, 2014, 2022, …)*
- *Dark elastic scattering (MB+ 2015, 2017, 2021, …)*
- *Growing Neutrino Quintessence (MB+ 2011)*

The effect of the elastic scattering between baryons and a Dark Energy scalar field appears in the distribution of gas particles in halos *(Ferlito et al. 2022)*

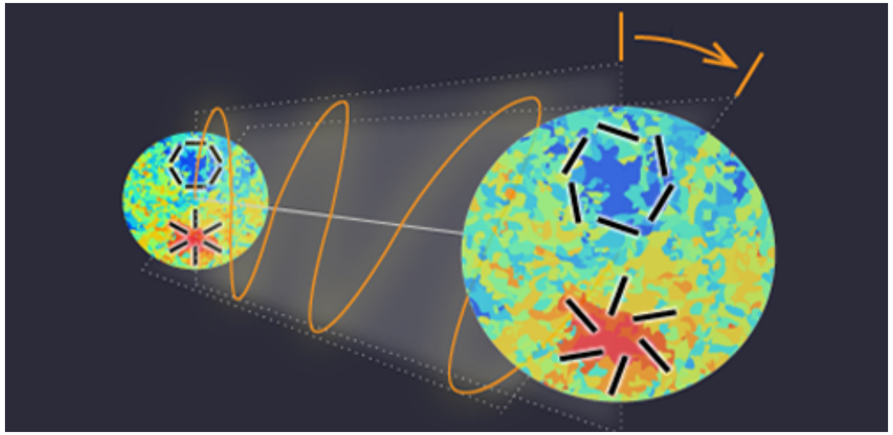


Cosmic Birefringence

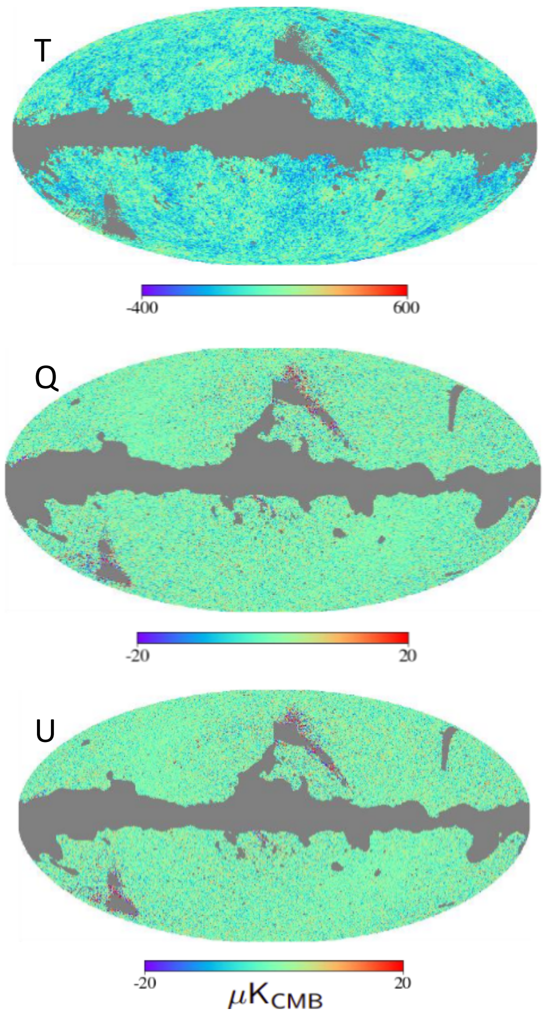
- Parity violating addition to standard EM lagrangian
- Models coupling pseudo-scalar (dark) fields to photons
- In vacuo rotation of linear polarization plane by α (CB angle)
- Linearly polarized electromagnetic radiation from distant sources: CMB

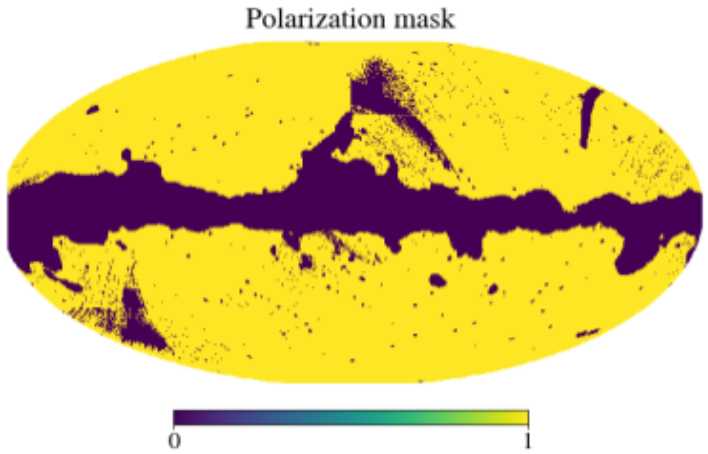
The effect can be isotropic or anisotropic.

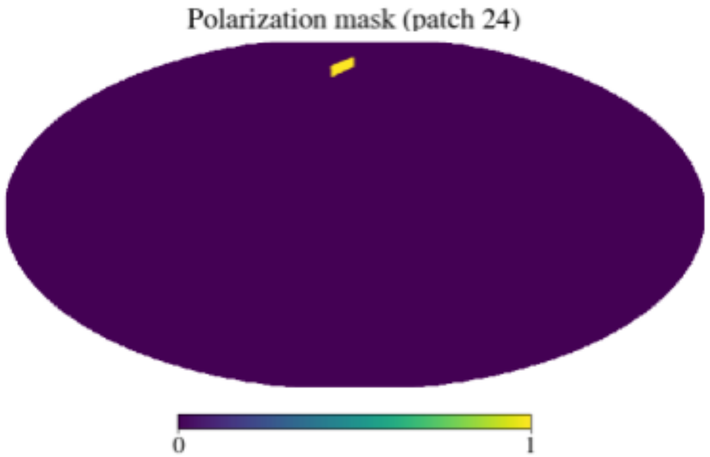
$$\mathcal{L} = -\frac{1}{4}F_{v\lambda}F^{v\lambda} - \frac{1}{2}p_{\alpha}A_{\beta}\tilde{F}^{\alpha\beta}$$



Slide by M. Bortolami (UniFE), M. Billi (UniBO), G. Zagatti (UniFE)







Idea:

- Divide the sky in small patches of equal area
- Use CMB signal in each patch to estimate the CB rotation angle
- Patches (768) are independent → massively parallel approach

Development of parallel analysis pipeline to:
select pixels → apply mask → estimate CMB spectra → estimate angle

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M. Bortolami, M. Billi, A. Gruppuso, P. Natoli, L. Pagano JCAP 09 (2022) 075

Development of pipeline to implement harmonic estimators for:

- Production of CB spectra and maps using available data from Planck satellite
- Forecasts for new experiments (LiteBIRD, CMB-S4)

$$\hat{E}^L_{(EE)} = \left(F^{LL'}\right)^{-1}\left[E^{L'}_\ell C^{EE,obs}_\ell - E^{L'}_\ell \langle C^{EE}_\ell\rangle\right] \longrightarrow \langle\hat{E}^L_{(EE)}\rangle = C^\alpha_L.$$

$$E^L_\ell = W^L_{\ell'}\left(C^{EE,obs}_{\ell'\ell}\right)^{-1}; \quad F^{LL'} = W^L_{\ell'}\left(C^{EE,obs}_{\ell'\ell}\right)^{-1} W^{L'}_\ell,$$

$$W^{L'}_\ell = \left[\tilde{H}^{L'}_{\ell\ell'}\langle C^{EE}_{\ell'}\rangle + H^{L'}_{\ell\ell',ev}\langle C^{BB}_{\ell'}\rangle\right]$$

$$\hat{\alpha}_{LM} = \frac{\sum_{ll'} \frac{(\hat{\alpha}_{LM})^{XX'}_{ll'}}{(\sigma^2_L)_{ll'}}}{\sum_{ll'} \frac{1}{(\sigma^2_L)_{ll'}}} \propto \frac{1}{\sigma_L^{-2}} \sum_{ll'mm'} X^{\text{map}}_{lm} X'^{\text{map},*}_{l'm'} K^{LM}_{ll'mm'} \qquad C^{\hat{\alpha}\hat{\alpha}}_L = \frac{1}{2L+1}\sum_M \hat{\alpha}_{LM}\hat{\alpha}^*_{LM}$$

$$\sigma_L^{-2} = \sum_{ll'}(1+\delta_{ll'})G_{ll'}\left\{\frac{\left(F^{XX'}_{ll'}\right)^2}{C^{XX,map}_l C^{X'X',\text{ map}}_{l'}}\right\} \qquad \hat{C}^{\alpha\alpha}_L = C^{\hat{\alpha}\hat{\alpha}}_L - \left(C^{\text{bias },iso}_L + C^{\text{bias },mc}_L\right)$$

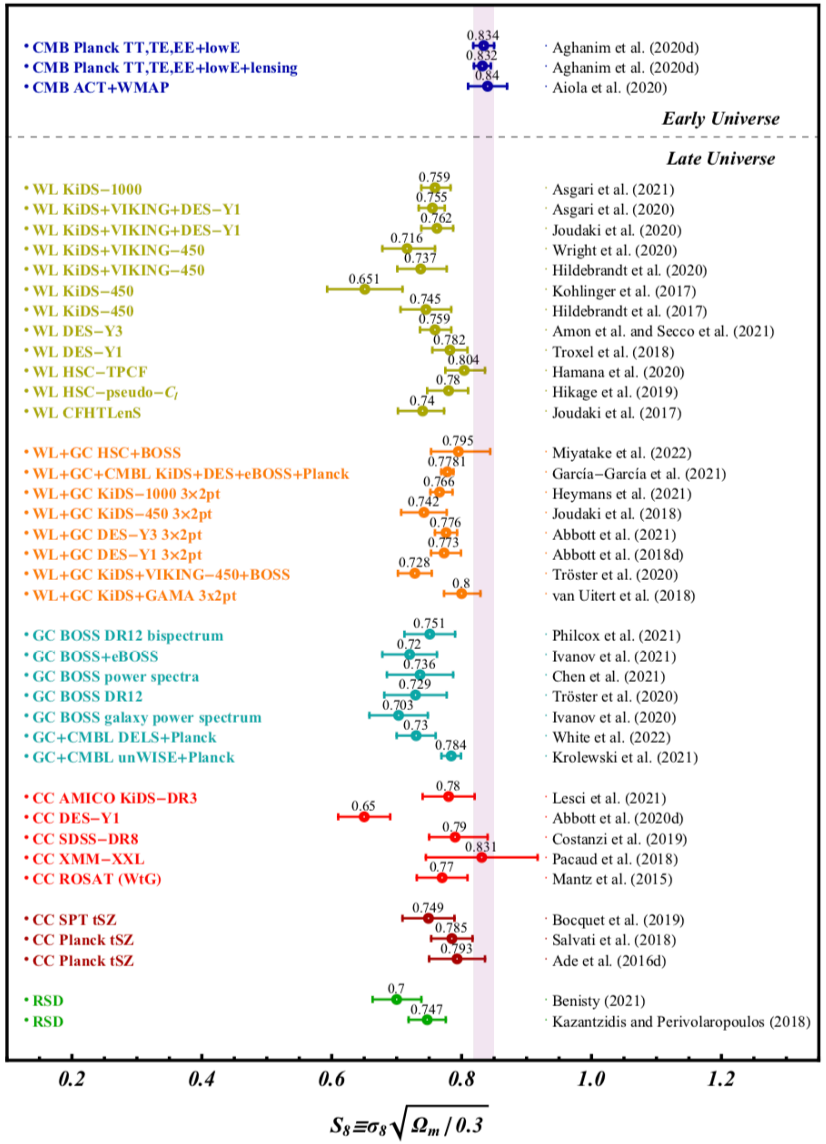
Gluscevic, Kamionkowski & Cooray, 2009

Spectra considered independent during estimation → massively parallel approach

SUMMARY

- Cosmology has, by now, become a precision science, also allowing to test fundamental physics parameters
- A concordance model has been established, that will be further tested (stressed?) by next-generation experiments
- This wealth of forthcoming data has to matched by our ability to produce reliable theoretical predictions
- HPC resources are a fundamental tool for, among others:
  - Inference problems
  - Building and testing of estimators for summary statistics
  - Studies of nonlinearities

A CRACK IN THE MODEL (2)?



From arXiv:2209.11726