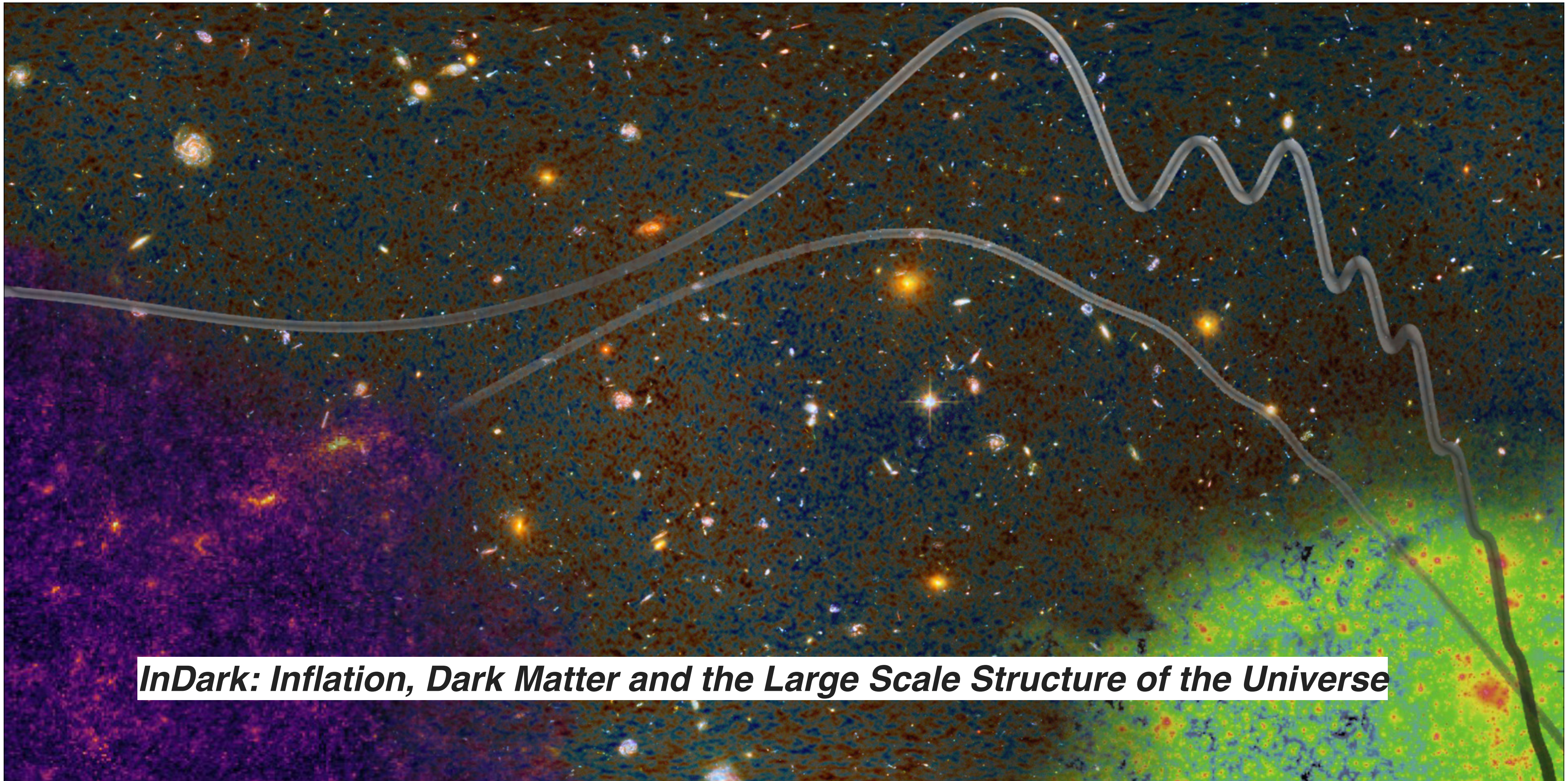


InDark: Inflation, Dark Matter and the Large Scale Structure of the Universe

Fabio Finelli

INAF OAS & INFN Bologna

Assemblea di Sezione, February 4th, 2021

InDark Bologna in a nutshell

- The *Iniziativa specifica* Inflation, Dark Matter and the Large Scale Structure of the Universe was founded in June 2001 by S. Matarrese (UniPd) as PD51

- *Iniziativa specifica* oriented to data driven theoretical cosmology with developments of advanced numerical algorithms and innovative statistical tools

- Bologna unit was introduced in 2006

- As for other InDark units, many InDark Bologna members involvement in large international collaborations in cosmology: Planck, Vipers, KiDS, Chex-MATE, Euclid, LiteBIRD, LSPE, SKA, Athena, …

- In 2014 after What Next 1st edition a collaboration with INFN CSN2 started (mainly in Bologna and Padova), mainly centred on Planck and Euclid so far.

InDark Bologna in a nutshell

- In the recent years Bologna has become a very productive unit in terms of papers and talks (e.g. 2018 65 papers, 39 talks).

- The evaluation at the national level and a good performance of the Bologna unit granted a (two-year) post-doctoral fellow in 2016 (D. K. Hazra, now permanent as lecturer at ICTS, Chennai, India)

- The proposal for 2021-2023 has 9 units:

Bologna, Ferrara, LNGS, Padova, *Parma-Milano Bicocca*,
Roma II, Roma III, Torino, Trieste

- Always good/excellent evaluations, in particular excellent evaluation (A) in all the 5 scores in the last two proposals (2018-2020, 2021-2023)

https://web.infn.it/CSN4/IS/Linea5/InDark

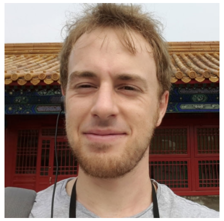
InDark Bologna


Marco Baldi
RTD B
DIFA


Matteo Braglia
Ph. D XXXIII
U. Bologna


Fabio Finelli
Senior Res.
INAF OAS


Massimo Meneghetti
Researcher
INAF OAS


Mario Ballardini
Post-Doc
DIFA


Carlo Burigana
Res. Dir.
INAF IRA


Carlo Giocoli
Researcher
INAF OAS


Lauro Moscardini
Full Prof.
DIFA


Jose R. Bermejo
Ph. D student
U. La Laguna


Sofia Contarini
Ph. D XXXIV
U. Bologna


Alessandro Gruppuso
Researcher
INAF OAS


Daniela Paoletti
Ric. TD
INAF OAS


Matteo Billi
Ph. D XXXIV
U. Bologna


Stefano Ettori
Senior Res.
INAF OAS


Federico Marulli
Prof. Ass.
DIFA


Mauro Sereno
Researcher
INAF OAS

9 Staff, 2 TD researchers, 1 Post-doc fellow, 4 PhD students (FTE=10.4)

M. Baldi, F. Finelli members of CSN2 *IS* Euclid; A. Gruppuso member of CSN2 *IS* LSPE;
F. Finelli, A. Gruppuso have been long term members of CSN4 *IS* FLAG until 2020

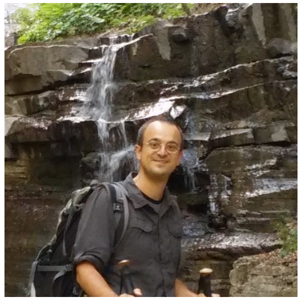
(Some) InDark Former Members

Carmelita Carbone
Researcher
INAF IASF Milano

Dhiraj Kumar Hazra
Lecturer
Institute of Mathematical Sciences
Chennai, India

Cosimo Fedeli
Data scientist and
consultant @ Oracle

Matteo Nori
Post-Doc
NYU Abu Dhabi
Abu Dhabi, United Arab Emirates

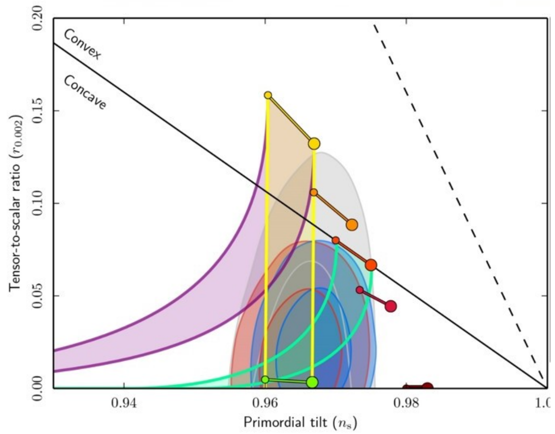


Matteo Galaverni
Associate Astronomer
Vatican Observatory

https://www.bo.infn.it/gruppo4/indark/people

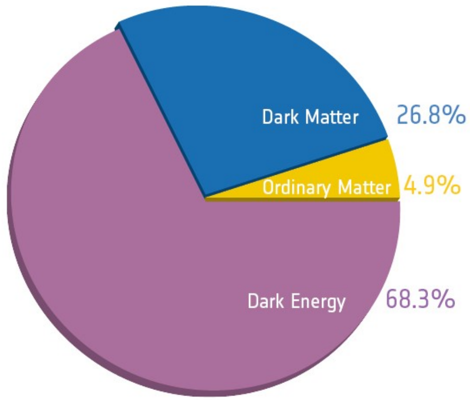
InDark Bologna Themes

Early Universe



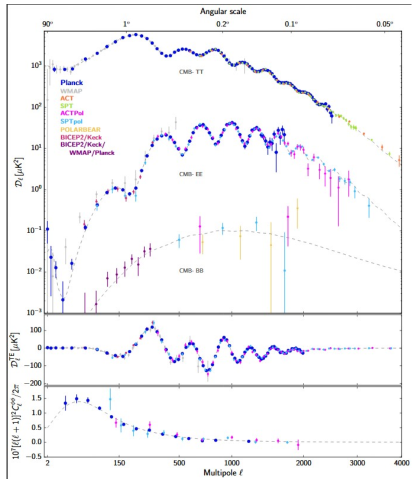
Dark Matter

Dark Energy



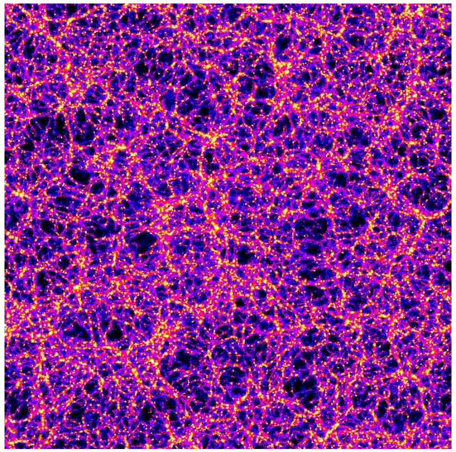
The Cosmic

Microwave Background



Large

Scale Structure



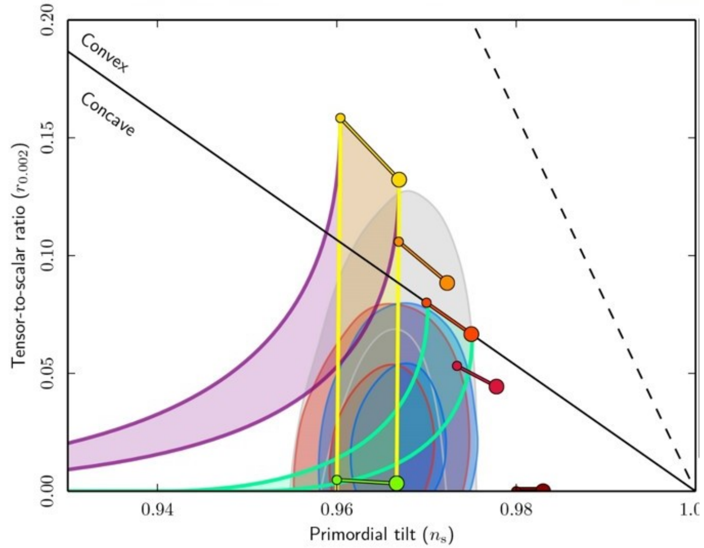
https://www.bo.infn.it/gruppo4/indark/

Early Universe

Inflationary theory

Inflation confronts CMB and LSS

Early Universe and new observations

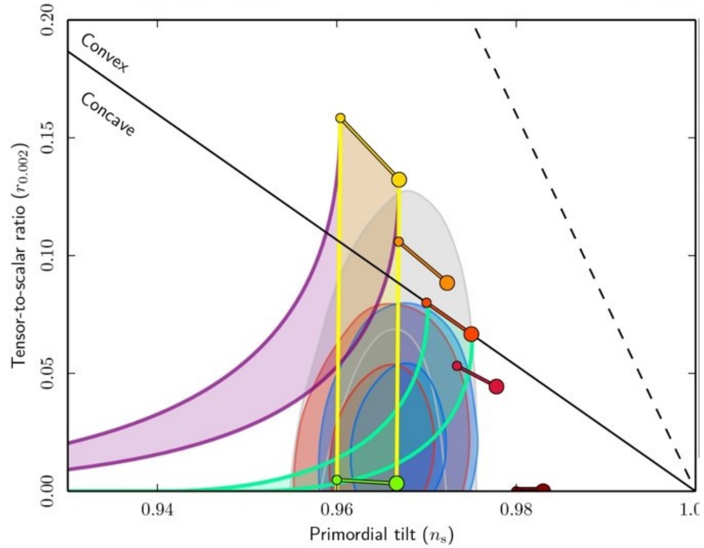


Early Universe

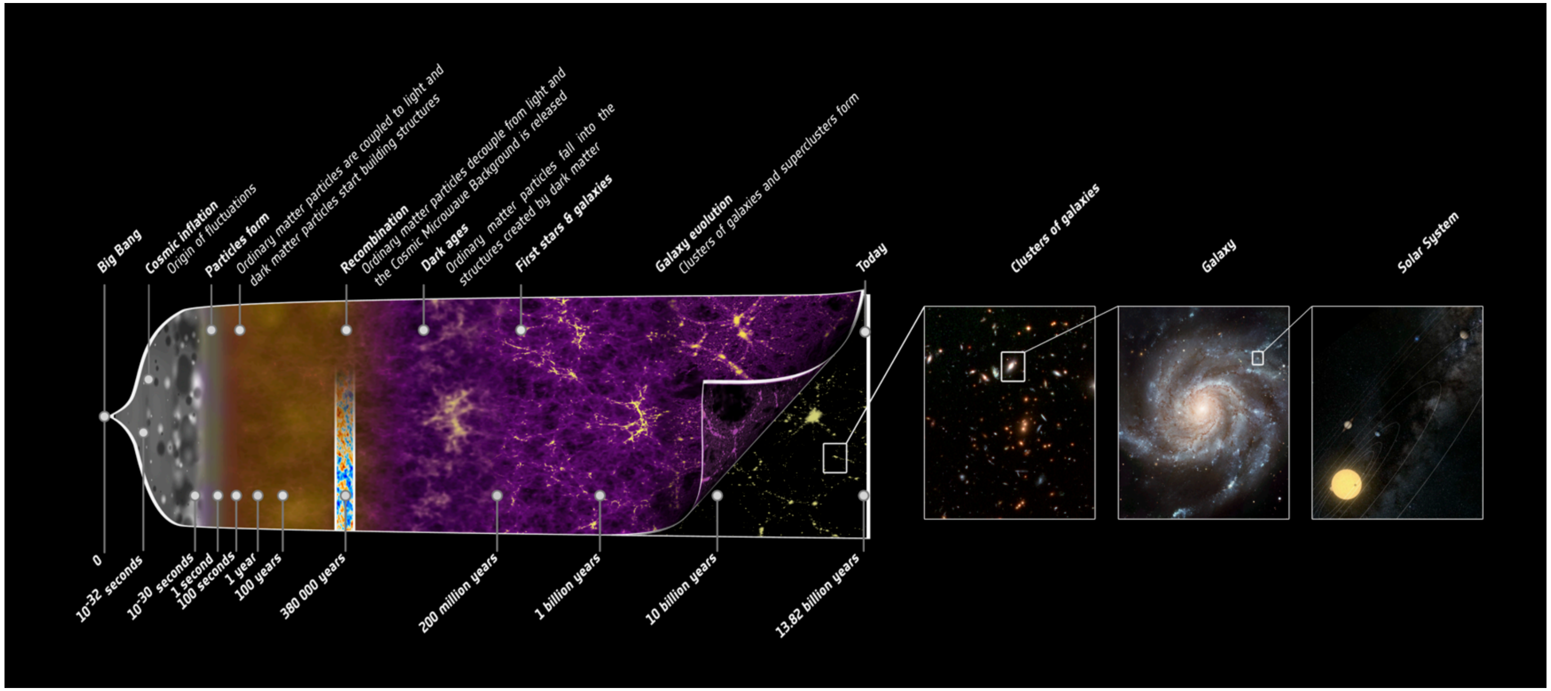
Inflationary theory

Inflation confronts CMB and LSS

Early Universe and new observations



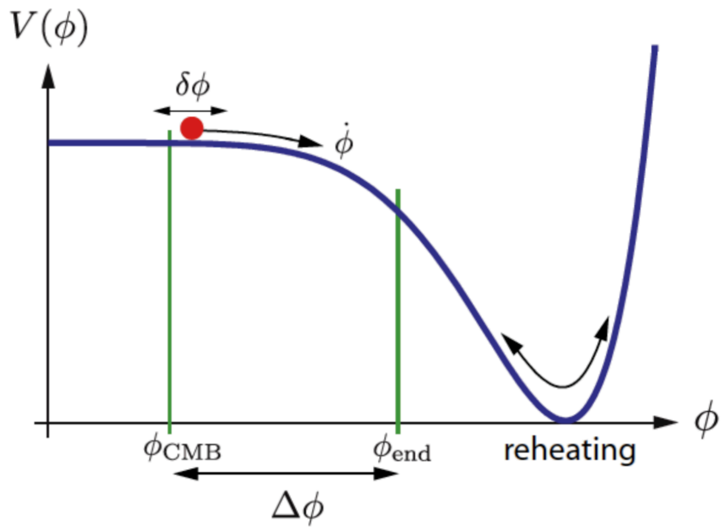
Cosmic Inflation

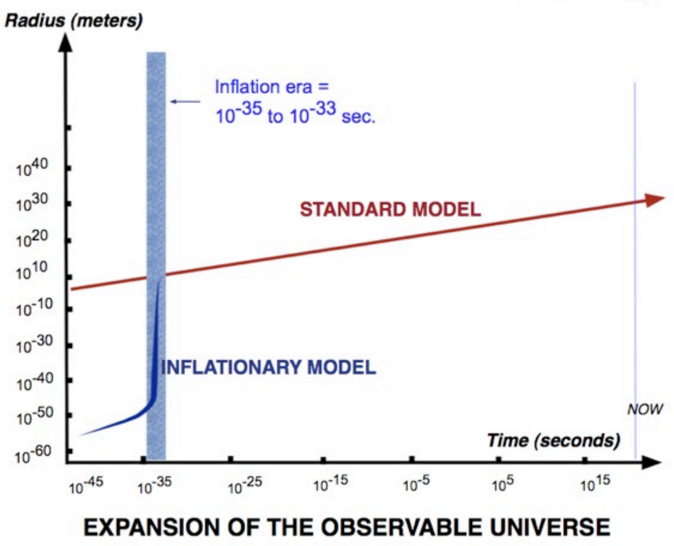


Minimal and most elegant early universe framework which solves puzzles of the Standard Hot Big Bang cosmology such as the flatness, horizon and monopole problems by postulating a nearly exponential expansion before the thermal era and at the same time provides a generation mechanism for primordial density fluctuations and gravitational waves.

INFN
Istituto Nazionale di Fisica Nucleare

Cosmic Inflation



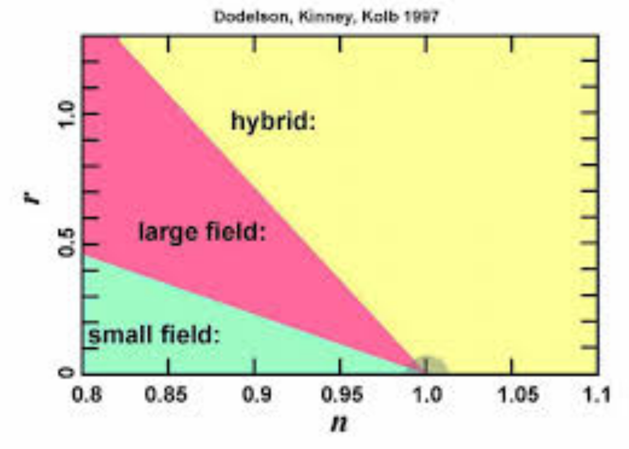


The simplest example for cosmic inflation is given by a standard scalar field which slowly rolls down a sufficiently flat potential before decaying in additional particles during the coherent oscillation stage.
The nearly exponential expansion during which the potential term dominated over the kinetic energy term is called slow-roll regime.

$$\mathcal{P}_{\mathcal{R}}(k) \simeq A_{\rm s}\left(\frac{k}{k_*}\right)^{n_{\rm s}-1} \qquad n_{\rm s}-1 \approx -3\frac{M_{\rm pl}^2 V_\phi^2}{V^2} + 2\frac{M_{\rm pl}^2 V_{\phi\phi}}{V}$$

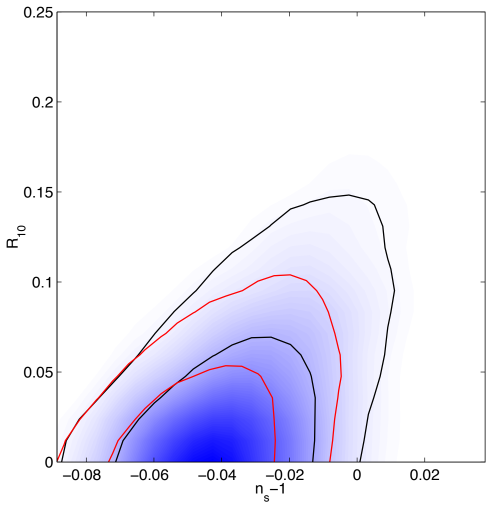
$$\mathcal{P}_{\rm t}(k) = A_{\rm t}\left(\frac{k}{k_*}\right)^{n_t} \qquad r = \frac{\mathcal{P}_{\rm t}(k_*)}{\mathcal{P}_{\mathcal{R}}(k_*)} \approx 8\frac{M_{\rm pl}^2 V_\phi^2}{V^2}$$

Cosmic Inflation



Black: WMAP 3 + SDSS

Red: WMAP 3 + CMBsmall + SDSS

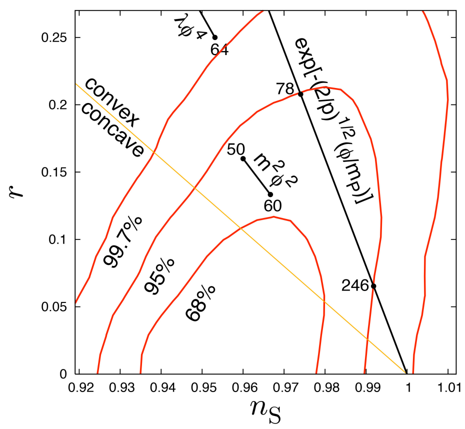


Finelli, Rianna, Mandolesi, 2006

$$n_s = 0.960 \pm 0.017 \quad (68\,\%\ \mathrm{CL})$$
$$r < 0.26 \quad (95\,\%\ \mathrm{CL})$$

$$n_s = 0.962 \pm 0.014 \quad (68\,\%\ \mathrm{CL})$$
$$r < 0.17 \quad (95\,\%\ \mathrm{CL})$$

WMAP 5 + CMBsmall + SDSS



Finelli, Hamann, Leach, Lesgourgues, 2010

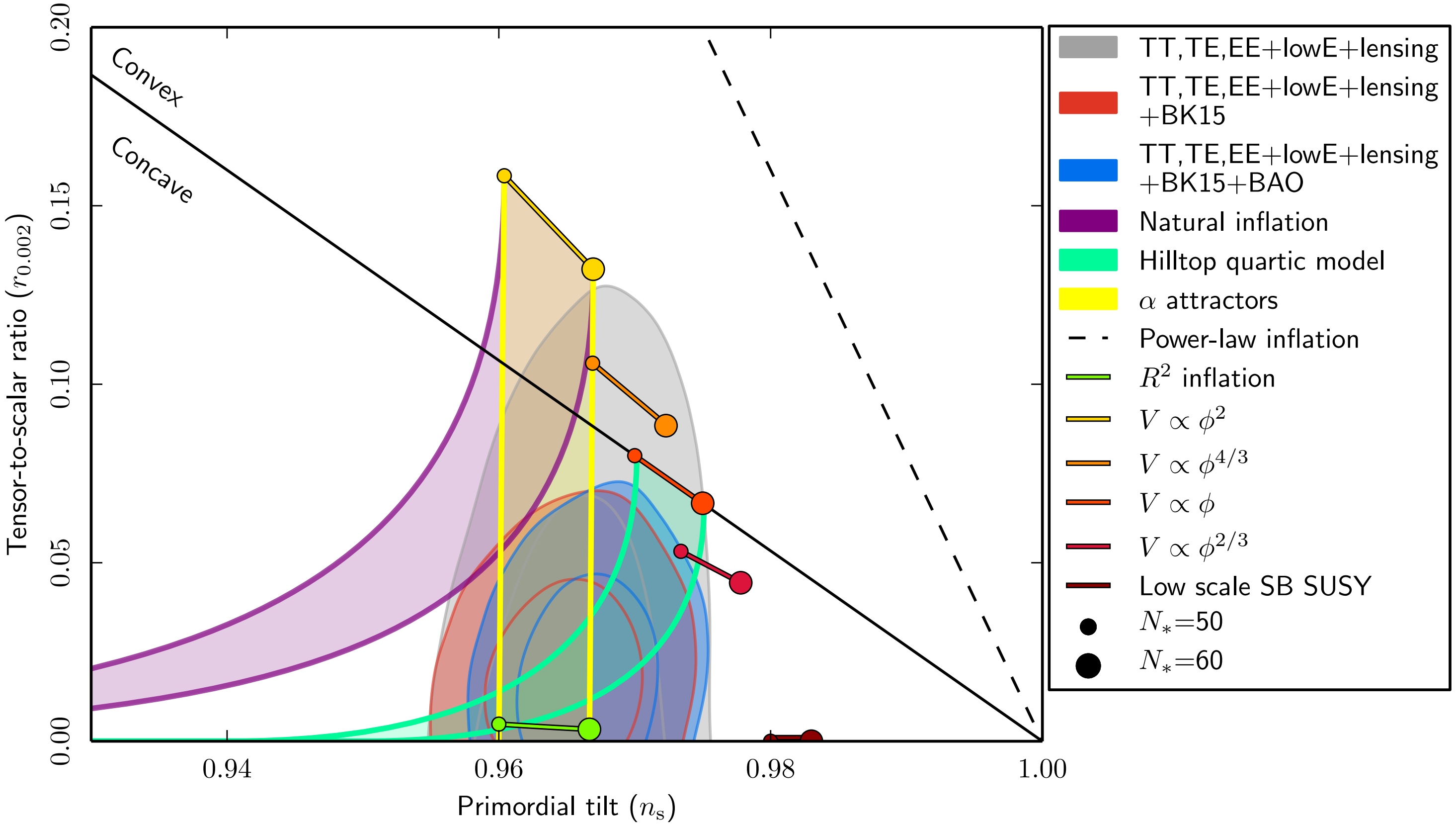
Which slow-roll simple models are best able to account the data?

Planck 2018 + BK15

$$n_s = 0.9651 \pm 0.0041 \quad (68\,\%\ \text{CL})$$

$$r < 0.056 \quad (95\,\%\ \text{CL})$$

$$V_* < (1.6 \times 10^{16}\ \text{GeV})^4 \quad (95\,\%\ \text{CL})$$



Planck 2018 results. X. Constraints on inflation

A consistent swipe of inflationary models ruling out

hybrid models,

power-law inflation,

quartic and quadratic monomial models,

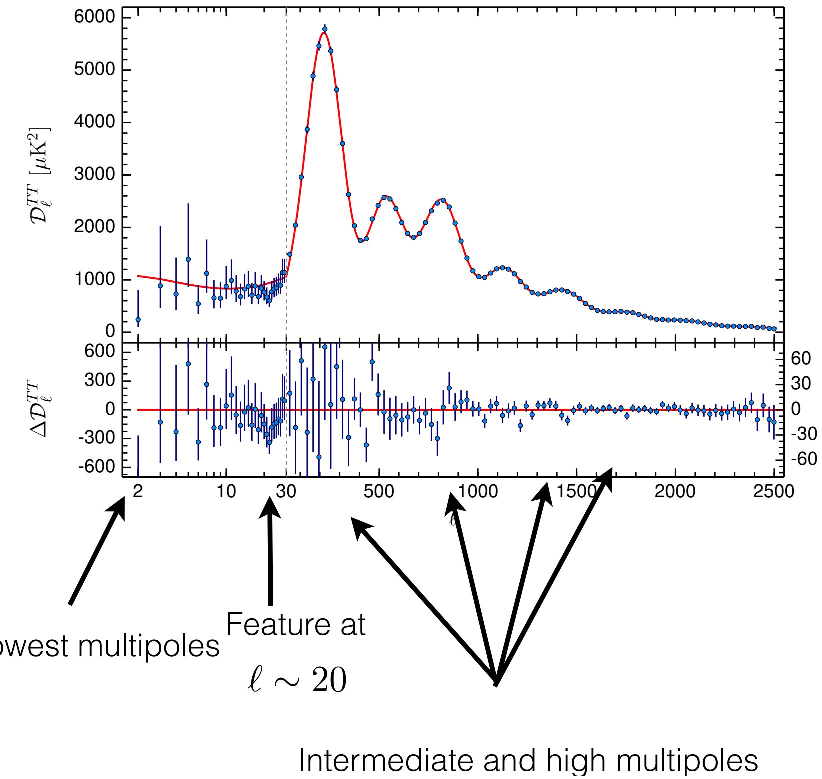
natural inflation,

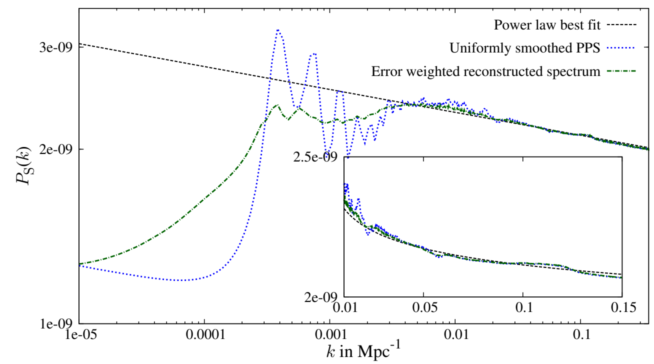
…

and suggesting at nearly statistical significant level concave potentials (V''<0).

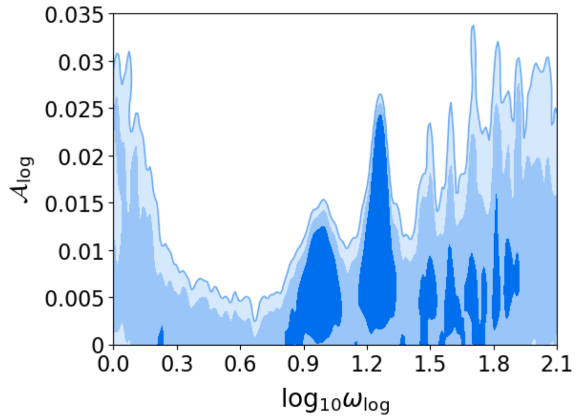
Slow-roll inflation?

Data driven approach: is slow-roll consistent with data? Yes, but there are interesting deviations which be mapped into inflation models beyond slow-roll.





Hazra et al. 2014

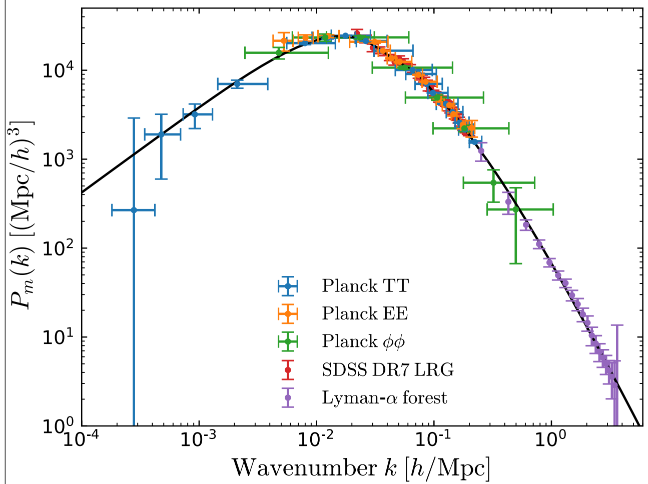


$$P_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} \left[1 + \mathcal{A}_{\log} \cos\left(\omega_{\log} \log \frac{k}{k_*} + \phi\right)\right]$$

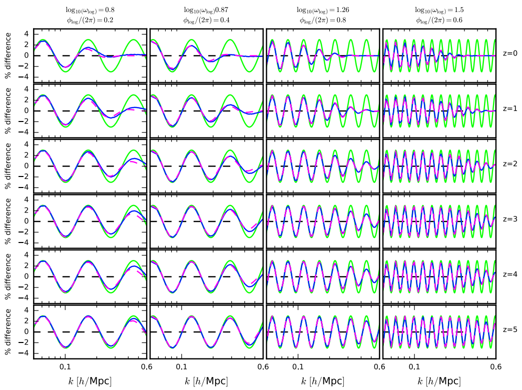
Planck 2018 results. X. Constraints on inflation

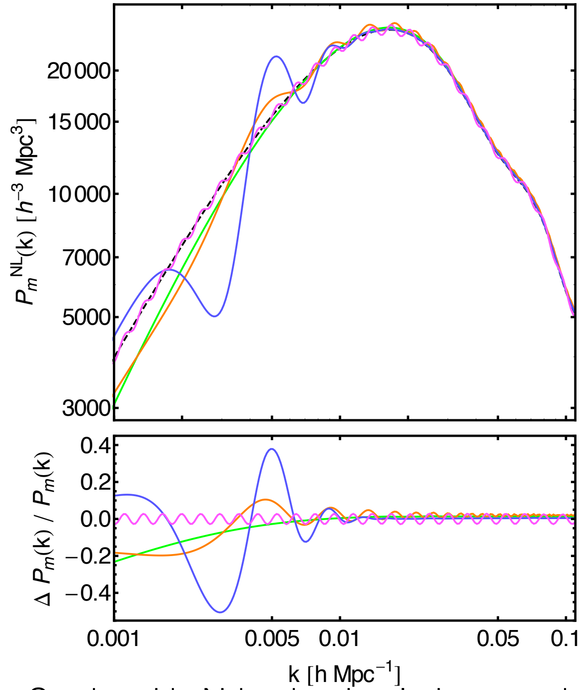
INFN
Istituto Nazionale di Fisica Nucleare

Primordial features and LSS data



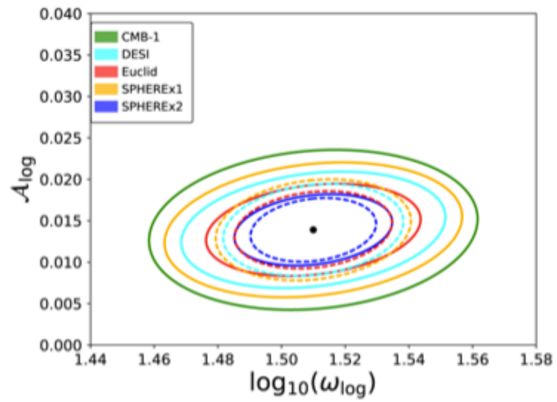
Planck 2018 results. I. Overview and the cosmological legacy of Planck





Study with N-body simulations and perturbative analytic methods primordial features in the matter power spectrum at small scales at lower redshift in order to fully exploit galaxy surveys data.

Ballardini, Murgia, Baldi, Finelli, Viel (2019)



Ballardini, Fedeli, Finelli, Moscardini (2016)

CMB + clustering forecast. Even clustering conservatively considered at linear scales, i.e. k < 0.1 Mpc^{-1}) from spectroscopic future galaxy surveys is complementary to CMB and can detect super-imposed oscillations which are hidden in Planck 2018 data.

These studies allow the use of currently available galaxy surveys data and meet the accuracy required by future surveys, e. g. Euclid.

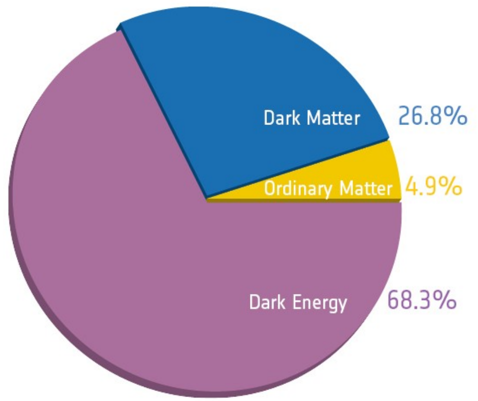
Dark Matter/Dark Energy

Non-linear structure formation by N-body simulations

Dark Matter

Dark Energy

Modified Gravity



INFN
Istituto Nazionale di Fisica Nucleare

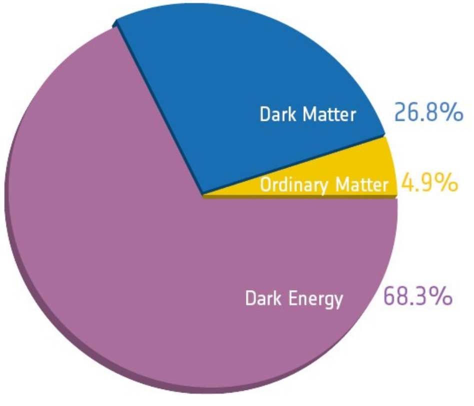
Dark Matter / Dark Energy

Non-linear structure formation by N-body simulations

Dark Matter

Dark Energy

Modified Gravity



What is the mass of dark matter ?

Baldi, Nori

Historically, CDM particles have been considered to be quite heavy, with mass $m_\chi \sim 10^{11}\, eV$, however the **decade-long lack of a direct detection** motivates the exploration of alternative scenarios that involve **lighter candidates**.

So, what if the Dark Matter was very light?

In the so called **Fuzzy Dark Matter (FDM) models**, Dark Matter is represented by a light bosonic field with $m_\chi \sim 10^{-22}\, eV$ that can show “quantum” behaviour at cosmological scales.

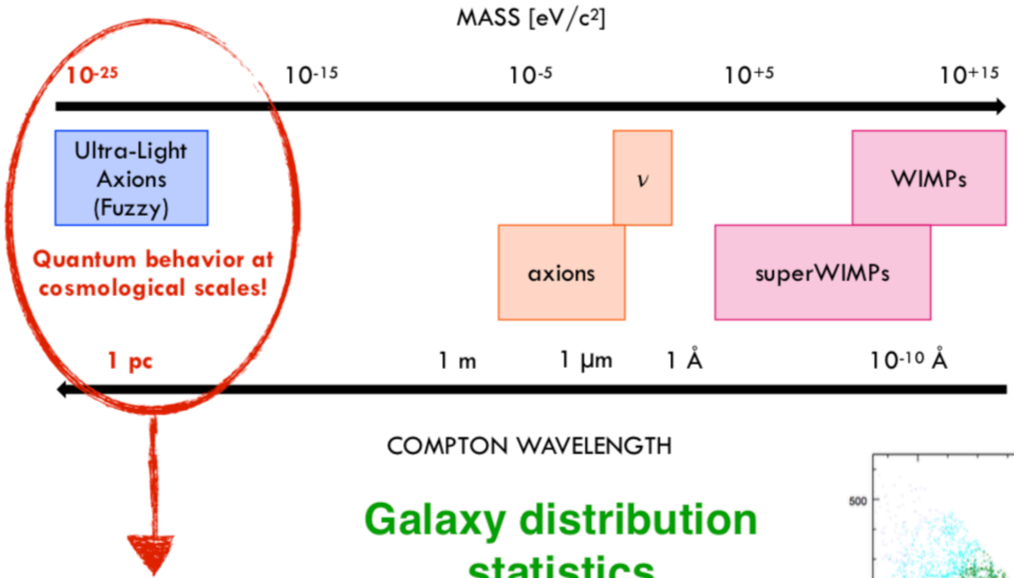
Scrödinger Equation → **Madelung Formulation** → **Quantum Navier – Stokes Equation**

$$i\frac{\hbar}{m}\partial_t\hat{\psi} = \left[-\frac{\hbar^2}{2m^2}\nabla^2 + \Phi + \lambda\left|\hat{\psi}\right|^2\right]\hat{\psi}$$

$$\partial_t\vec{v} + \left(\vec{v}\cdot\vec{\nabla}\right)\vec{v} = \frac{\hbar^2}{2m^2}\vec{\nabla}\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right) - \vec{\nabla}\Phi + \lambda\vec{\nabla}\rho$$

What is the mass of dark matter ?

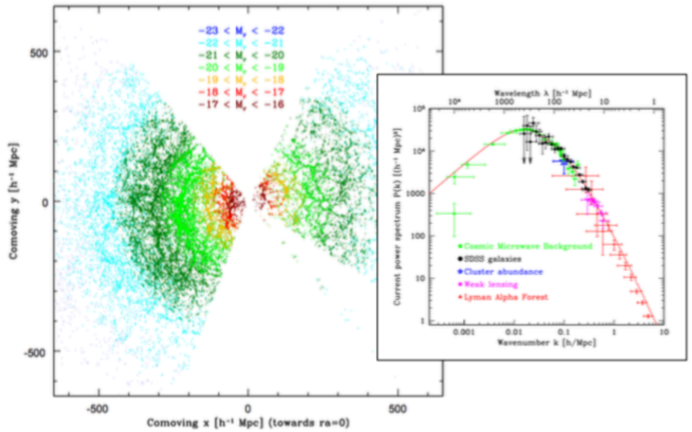
Baldi, Nori



These macroscopic quantum effects can be tested with:

Galaxy distribution statistics

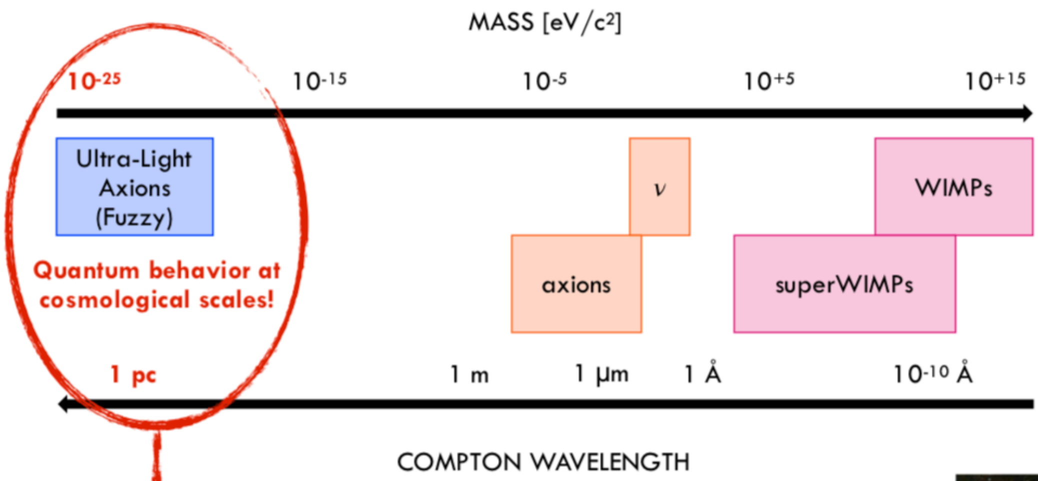
Maps of visible objects as tracer for Dar Matter distribution that is distance (thus time) dependent.



Galaxy maps and 2-point correlation function.

What is the mass of dark matter ?

Baldi, Nori



These macroscopic quantum effects can be tested with:

Geometrical distortions (Lensing)

Reconstruction of density distribution from the geometrical distortion of massive objects as predicted by General Relativity.

The massive galaxy cluster Abell 370 as seen by Hubble Space Telescope in the final Frontier Fields observations.

INFN Istituto Nazionale di Fisica Nucleare

Simulations of Fuzzy Dark Matter cosmologies

Baldi, Nori

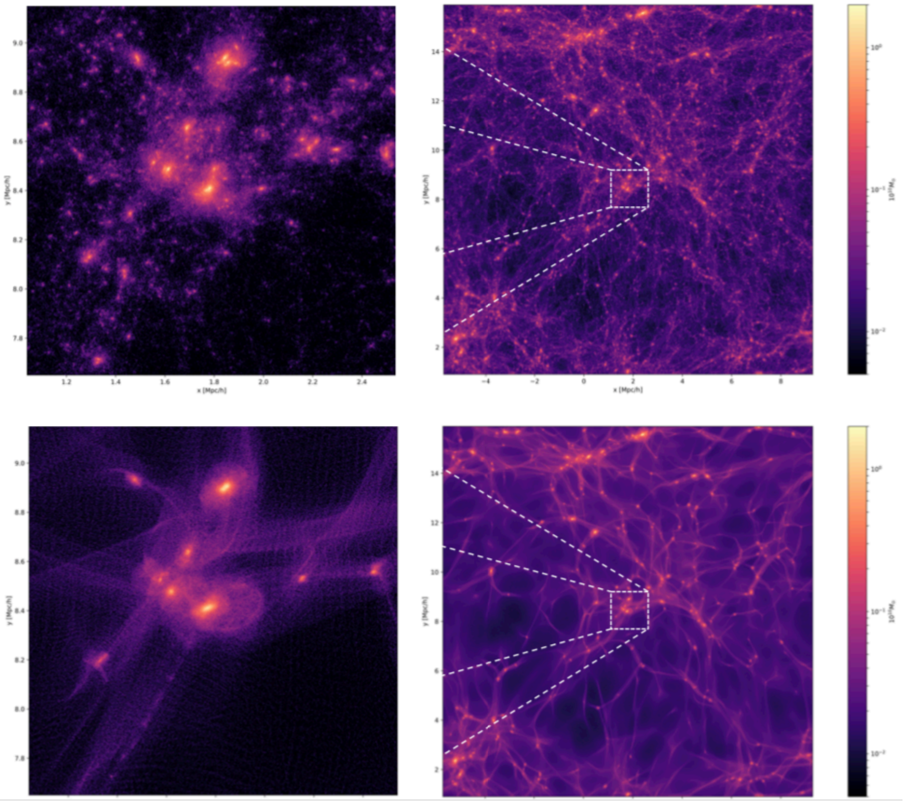
We have **developed a new code**

(AX-GADGET)

that allows to simulate the quantum properties of Fuzzy Dark Matter in the evolution of the Cosmic Web.

The effects of the quantum pressure can be seen by eye for the most extreme FDM models

Matter distribution of Cold (*above*) and Fuzzy (*below*) Dark Matter in a slice of a simulated Universe.



The Cosmic Microwave Background

Theoretical predictions for the precision of current and future CMB experiments

Interpretation of possible deviations from the concordance model in the CMB alone or in combination with other data

Cross-correlation of CMB and large scale structure

Development of algorithms

Participation to experiments: Planck (concluded), LSPE, LiteBIRD, …

The Cosmic Microwave Background

Theoretical predictions for the precision of current and future CMB experiments

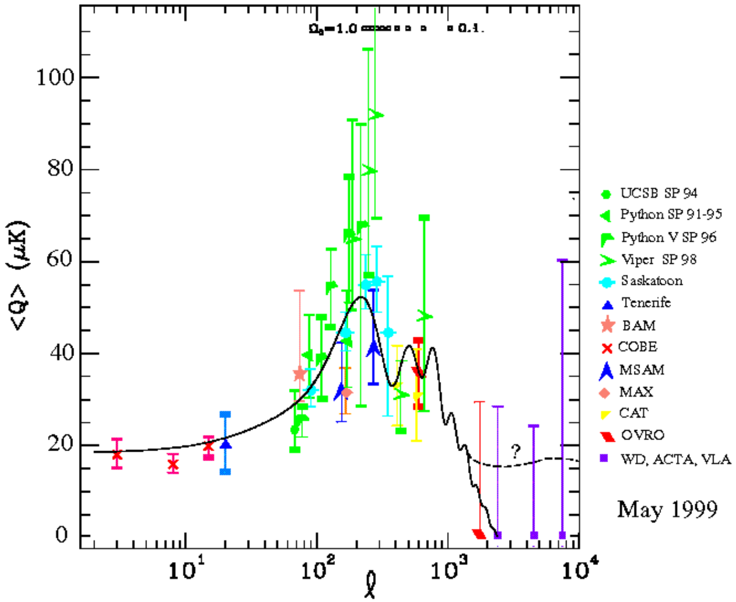
Interpretation of possible deviations from the concordance model in the CMB alone or in combination with other data

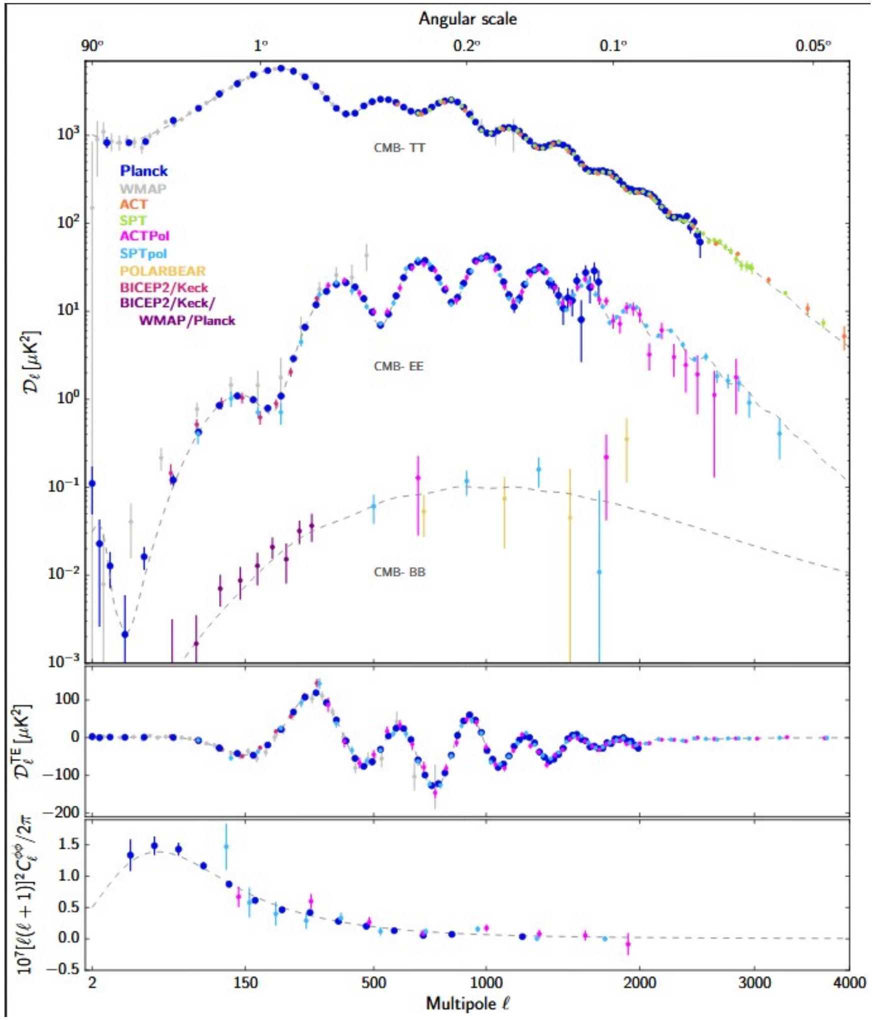
Cross-correlation of CMB and large scale structure

Development of algorithms

Participation to experiments: Planck (concluded), LSPE, LiteBIRD, …

CMB anisotropies in the last 20 yrs





InDark Bologna and Planck

F. Finelli, coordinator of the Planck papers in inflation:

Planck 2013 results. XXII. Constraints on inflation

Planck 2015 results. XX. Constraints on inflation

Planck 2018 results. X. Constraints on inflation

A. Gruppuso, coordinator of:

Planck 2015 intermediate results. XLIX. Parity-violation constraints from polarization data

D. Paoletti, coordinator of:

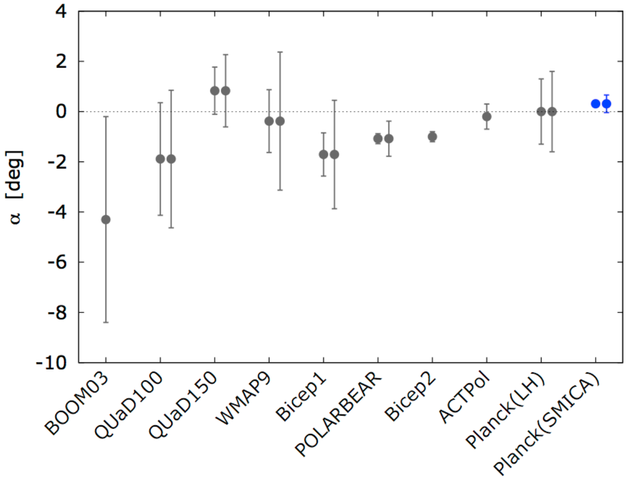
Planck 2015 results. XX. Constraints on primordial magnetic fields

INFN
Istituto Nazionale di Fisica Nucleare

Constraints on cosmic birefringence

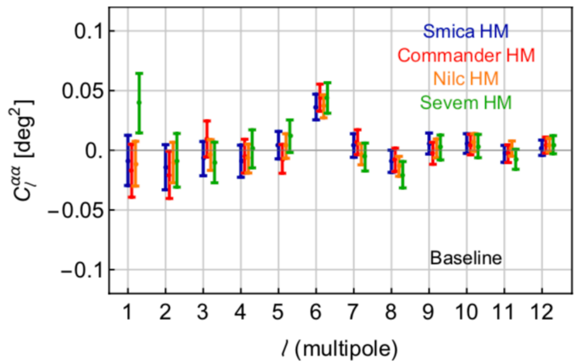
Parity violating extensions of the standard model can be tested through CMB polarised anisotropies. New coupling terms in the Maxwell Lagrangian produce an effect known as Cosmic Birefringence: the rotation of the polarisation plane of a photon (also a CMB photon since CMB is polarised). A rotation is naturally parameterised by and angle.

$$
\begin{aligned}
C_\ell^{TE,obs} &= C_\ell^{TE} \cos(2\alpha)\,, \\
C_\ell^{TB,obs} &= C_\ell^{TE} \sin(2\alpha)\,, \\
C_\ell^{EE,obs} &= C_\ell^{EE} \cos^2(2\alpha) + C_\ell^{BB} \sin^2(2\alpha)\,, \\
C_\ell^{BB,obs} &= C_\ell^{BB} \cos^2(2\alpha) + C_\ell^{EE} \sin^2(2\alpha)\,, \\
C_\ell^{EB,obs} &= \frac{1}{2}\left(C_\ell^{EE} - C_\ell^{BB}\right) \sin(4\alpha)\,,
\end{aligned}
$$



Planck 2015 results. XLIX. Parity-violation constraints from polarization data

In case of anisotropic birefringence, as due to fluctuations in a cosmological pseudo-scalar field

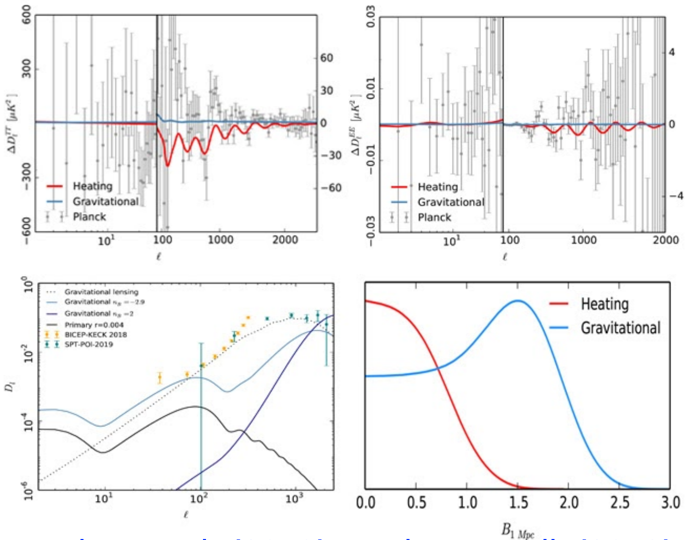


Gruppuso et al. (2020)

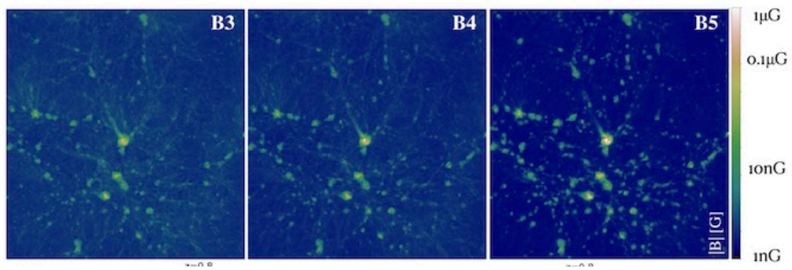
Constraints on primordial magnetic fields

While cosmic magnetic fields are ubiquitous in our Universe, their origin is still a mystery. They are routinely detected at high statistical significance in galaxies and galaxy clusters, but their measurements in the remaining >99% of the cosmic volume, comprising filaments, sheets and voids have larger uncertainties. One possible scenario is that they originated from **primordial magnetic seeds** generated before cosmological recombination and later amplified by structure formation.

The primordial hypothesis is mostly constrained by the measurements of CMB anisotropies, through a variety of effects, such as the contribution to scalar, vector, tensor cosmological perturbations, heating of the pre and post-recombination plasma, non-Gaussianity, Faraday rotation, non-vanishing parity-odd CMB TB, EB power spectra due to non-zero helicity.



Paoletti et al. (2019); Paoletti, Finelli (2019).

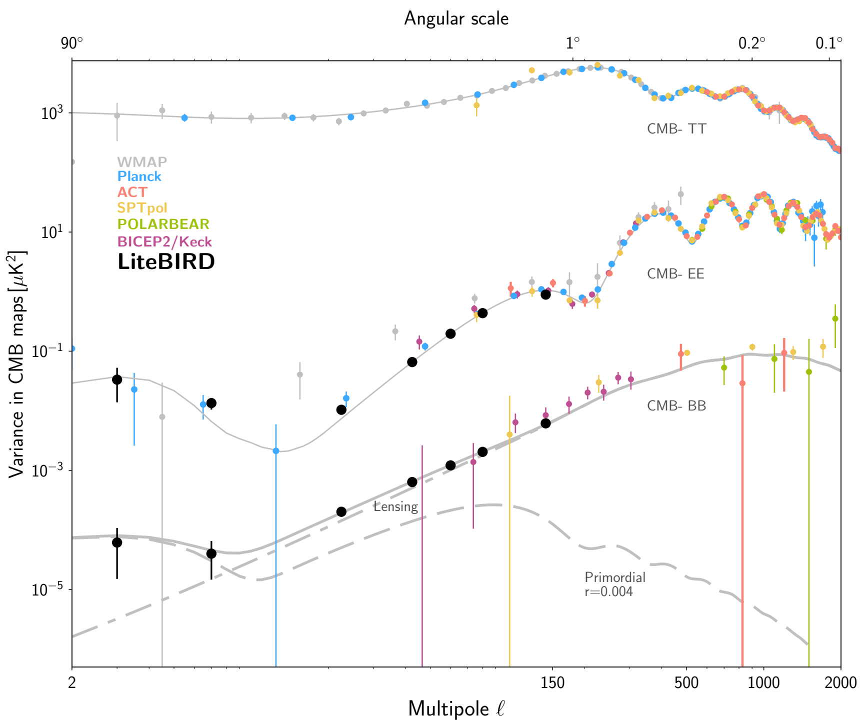


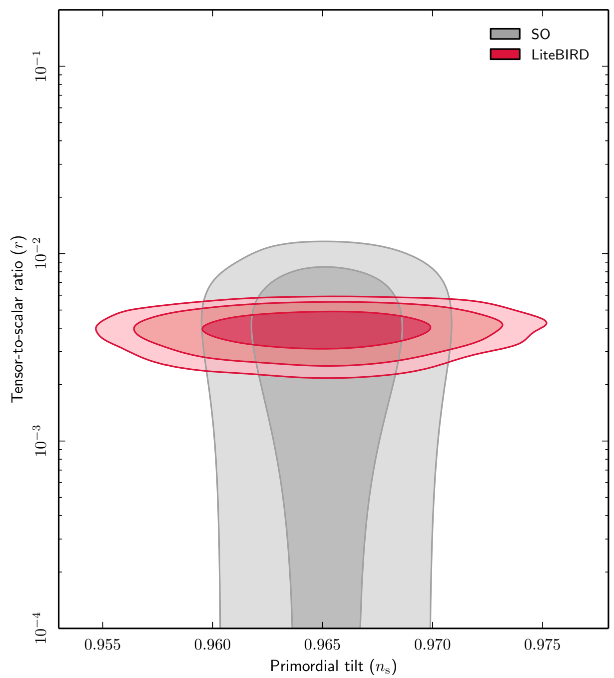
A direct link between primordial seeds constrained by CMB and the observable properties of cosmic magnetism at low redshift by accurate N-body simulations.

Vazza, Paoletti et al. (2021)

Contribution to future CMB programs

By capitalising on the Planck experience we have contributed to several proposals for post-Planck CMB experiments: CMBpol, Bpol, CORE, PRISM, CORE+, CORE, **LSPE, LiteBIRD**, Pristine, ESA call for ideas Voyage 2050 …





M. Hazumi et al. (incl. F. Finelli, A. Gruppuso, D.Paoletti) (2021)

Large Scale Structure

Clusters of galaxies

New tracers from current and future galaxy surveys

Development of algorithms

Participation to experiments: Vipers (concluded), KiDS, XXL, Euclid, SKA.

Large Scale Structure

Clusters of galaxies

New tracers of density perturbations from current and future galaxy surveys

Development of algorithms

Participation to experiments: Vipers (concluded), Kids, XXL, Euclid, SKA.

Cosmology with galaxy clusters

Marulli, Moscardini

Galaxy clusters are the **largest virialized objects** in the Universe

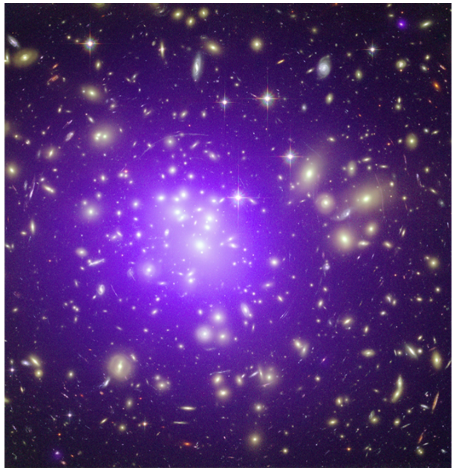
Mass: $10^{13}\ M_{\odot} < M < 10^{15}\ M_{\odot}$

Radius: 1 Mpc < R < 5 Mpc

Detection:

lensing, NIR-optical, X-rays,

thermal Sunyaev-Zel'dovich (tSZ) effect



Abell 1689, HST-Chandra X-ray observatory composite image

The number of clusters in ongoing (eRosita) and future (Euclid, …) observations are expected to increase significantly and so the scientific capability of cluster cosmology.

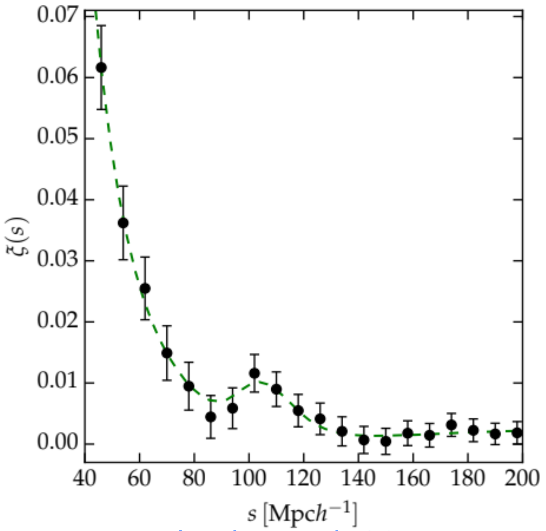
Cosmology with galaxy clusters

Marulli, Moscardini

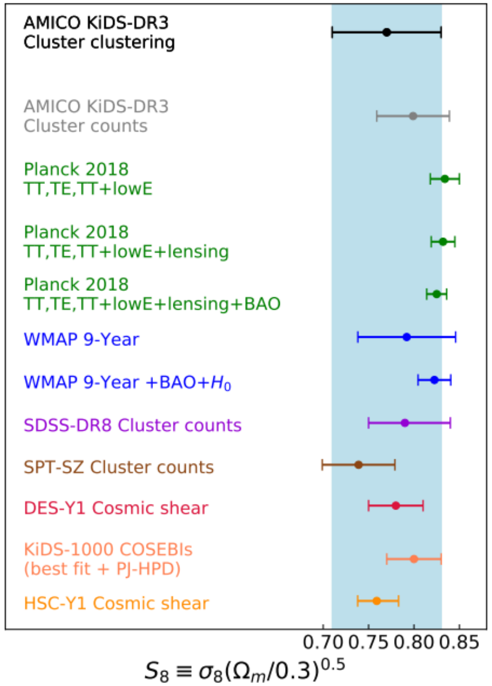
Galaxy clusters are powerful cosmological probes to constrain cosmological parameters and test the gravity theory.

The main galaxy cluster statistics for cosmological use are:
number counts, lensing profiles, two-point and three-point correlation functions.

The galaxy cluster samples analyzed by our group are:
the SDSS spectroscopic cluster catalogue;
the XXL catalogue;
the AMICO KiDS-DR3 photometric catalogue.



Veropalumbo et al. 2015



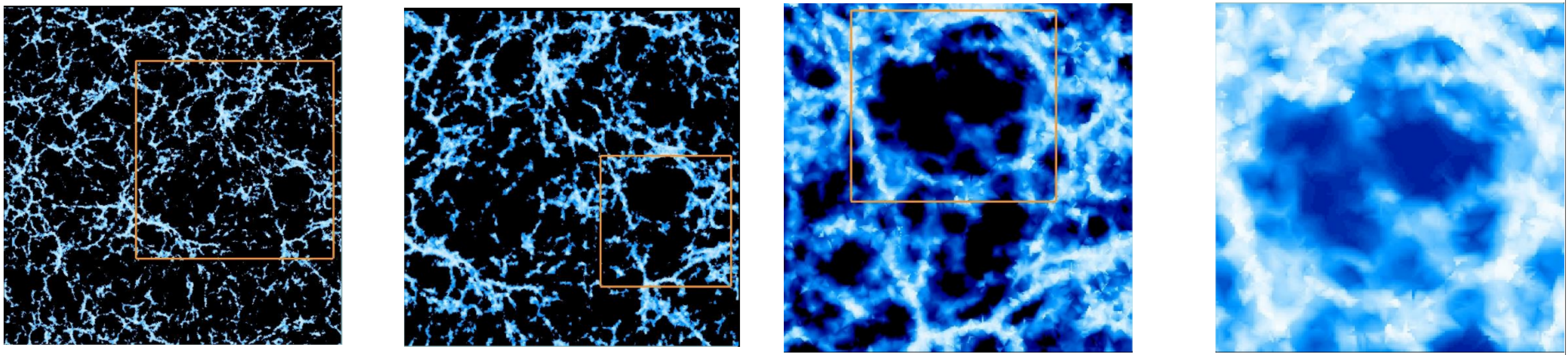
Lesci et al. 2020

New tracers: cosmology with voids

Cosmic voids are **large and underdense regions**, filling most of the volume of the Universe

They originate from the evolution of **underdensities** in the primordial matter density field

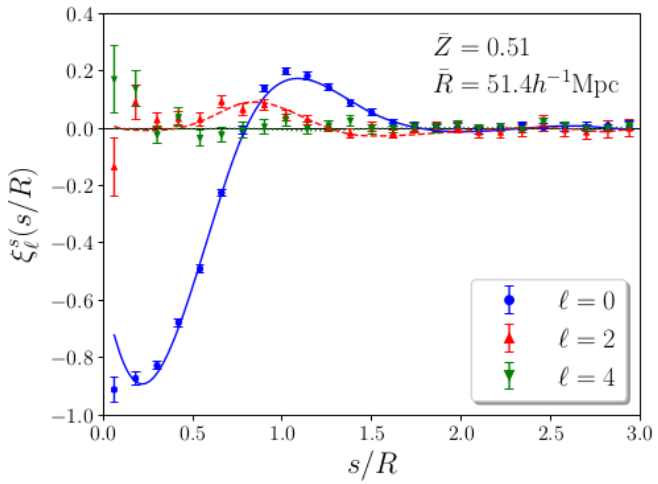
Isolated voids tend to become **more spherical** as they evolve, remaining **mildly non-linear** objects



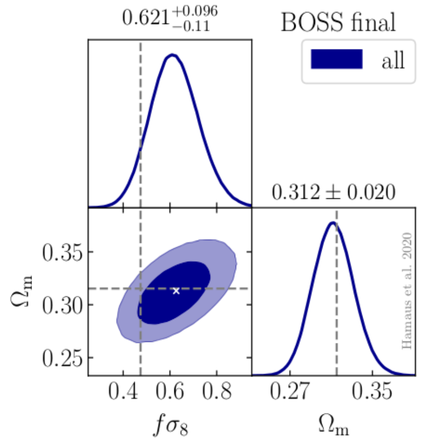
Istituto Nazionale di Fisica Nucleare

New tracers: cosmology with voids

Easy to **model** thanks to their simple shape and evolution



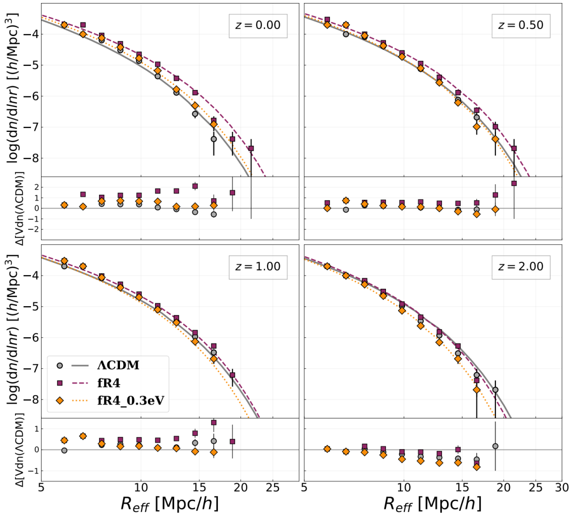
Very **sensitive** to cosmological parameters



Istituto Nazionale di Fisica Nucleare

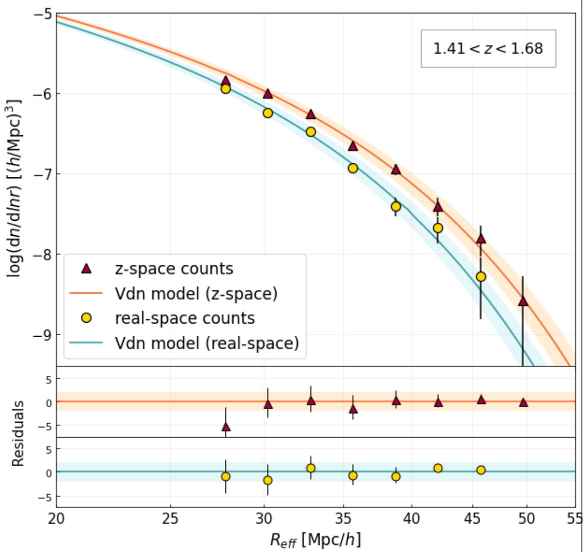
New tracers: cosmology with voids

S. Contarini, F. Marulli, L. Moscardini et al. 2019



Disentangling the degeneracies between **modified gravity** and **neutrino mass**

Euclid: cosmological forecasts from void abundance
(S. Contarini and the Euclid Team, in preparation)



Powerful cosmological probes
In the perspectives of forecoming **wide sky surveys**

A current snapshot of InDark @ BO in Euclid science coordination: **L. Moscardini** (co-lead SWG CL), **M. Meneghetti** (lead SWG SL), **C. Giocoli** (co-lead IST:NL, SWG CS Cluster, WL WPs, SWG CL Cluster simulations WP, SWG SL Theory WP, SWG WL Cosmological simulations WP), **M. Baldi** (co-lead TH simulations WP), **S. Ettori** (lead CL Astrophysics of Galaxy Clusters WP), **F. Finelli** (co-lead TH initial conditions WP), **F. Marulli** (co-lead di OU-LE3 2PCF-GC, 2PCF-CL, 3PCF-CL, PK-CL, BK-CL; co-lead CL Statistics of the cluster sample WP), **M. Sereno** (co-lead CL Mass Modelling WP), …

INFN
Istituto Nazionale di Fisica Nucleare

Thanks for your attention