Title: Fundamental Physics from Galaxy Surveys

Speakers: Mikhail Ivanov

Series: Cosmology & Gravitation

Date: March 26, 2024 - 11:00 AM

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Abstract: Elucidating the nature of dark matter, dark energy, and dynamics of the early universe stand as major challenges of modern cosmology and particle physics. I will present a new program of addressing these challenges with galaxy surveys. This program builds on theoretical particle physics tools and allows for sub-percent precision analytic understanding of galaxy clustering on large scales. I will share some results of this program that include new measurements of fundamental cosmological parameters and constraints on new physics beyond the standard models of particles and cosmology.

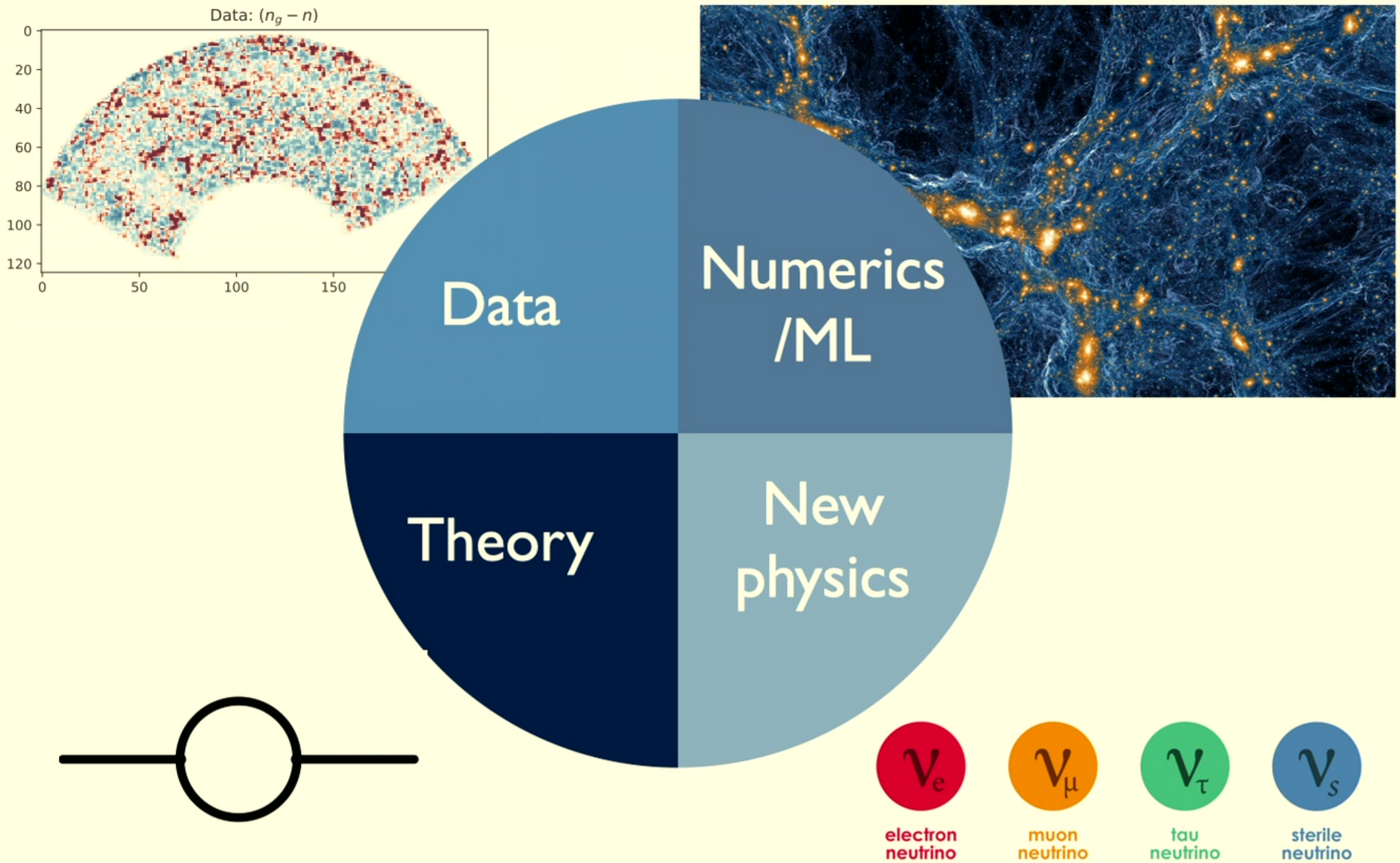
Zoom link

Fundamental Physics from Galaxy Surveys

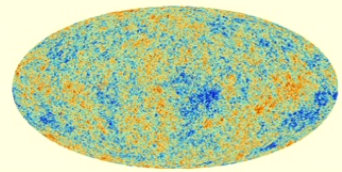
Mikhail (Misha) Ivanov
MIT

PI Cosmology Seminar, 03/26/2024

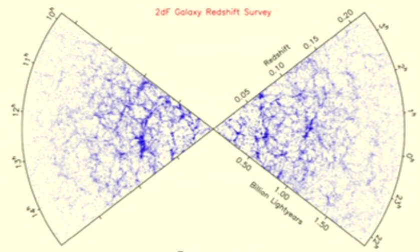
Large-Scale Structure Cosmology



Cosmology



CMB



galaxies

inflation

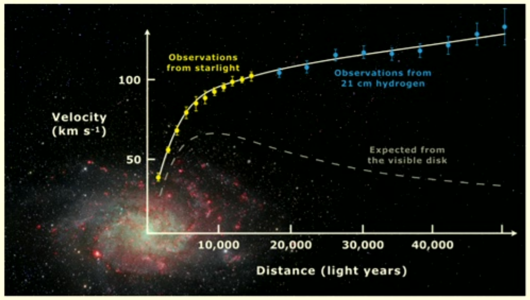
$E \lesssim 10^{16}\ \mathrm{GeV}$

$\Lambda\mathrm{CDM}$: Inflation, Cold Dark Matter, Lambda

Known Unknowns:
What was inflation, exactly?
DM? etc.

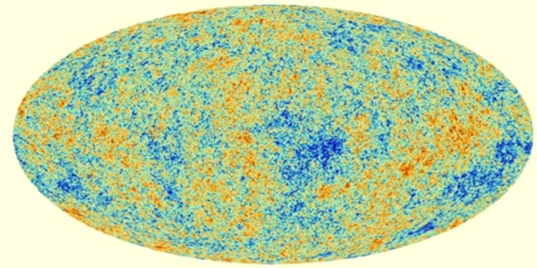
Unkown Unknowns:
Surprises ?

Dark Matter



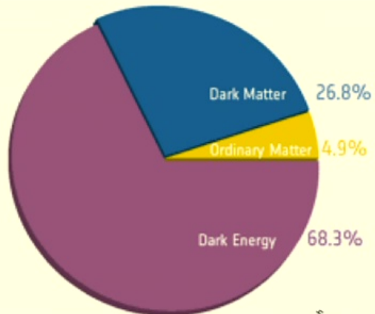
© Wikipedia

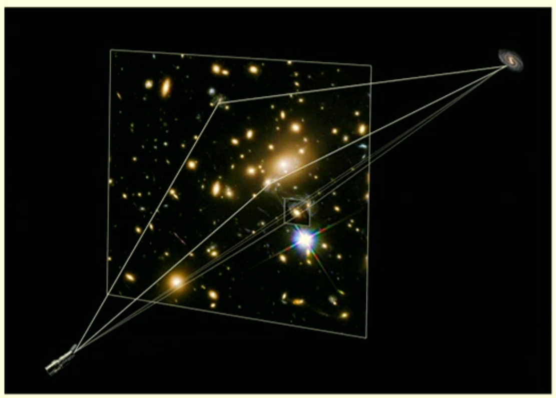
Rotation curves



Planck'18

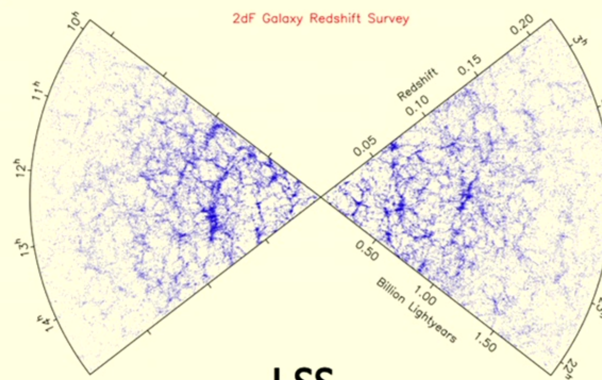
CMB





Lensing

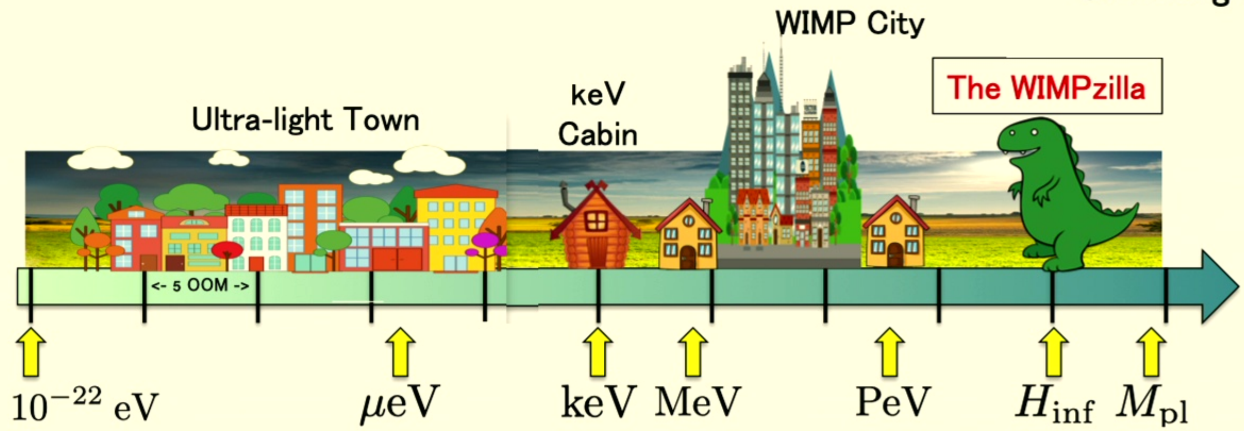
© NASA+ESA



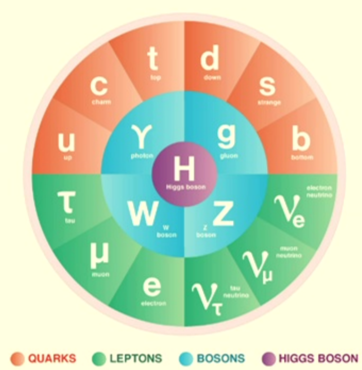
LSS

Dark Matter

© A. Long @LWD



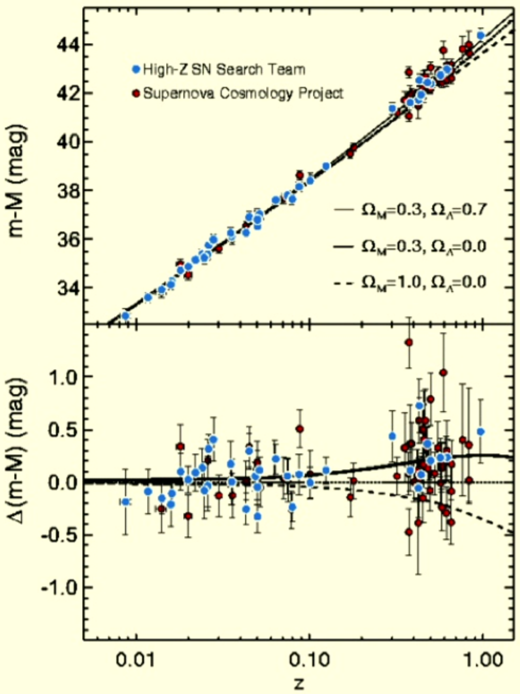
- DM gravitates like usual matter, but does not shine
- Particles beyond SM, primordial BH's, modified gravity, etc…



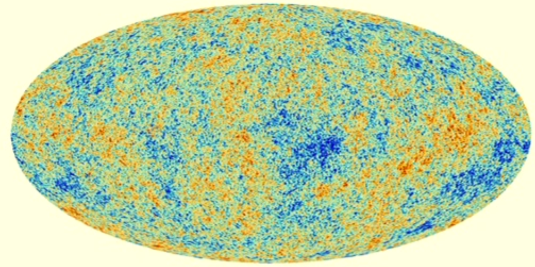
+ SUSY/ axions/ sterile neutrinos, PBHs, … ?

Dark Energy

Supernovae

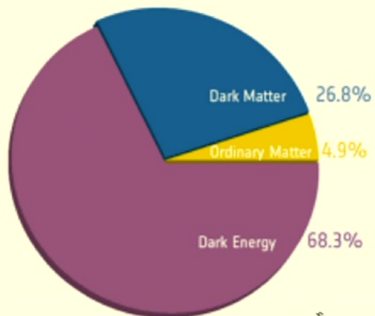


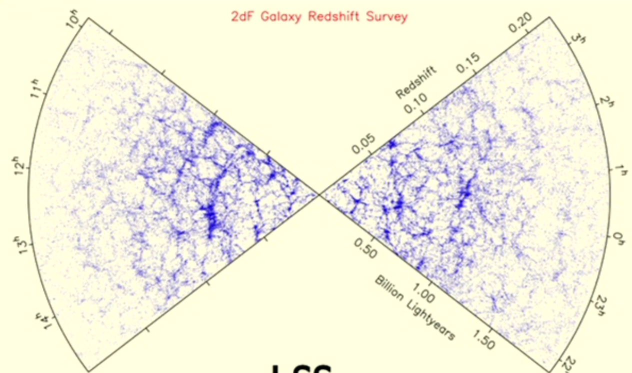
O'Raifeartaig++'17



Planck'18

CMB





LSS

Dark Energy - Cosmological Constant ?

$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} + \Lambda \, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

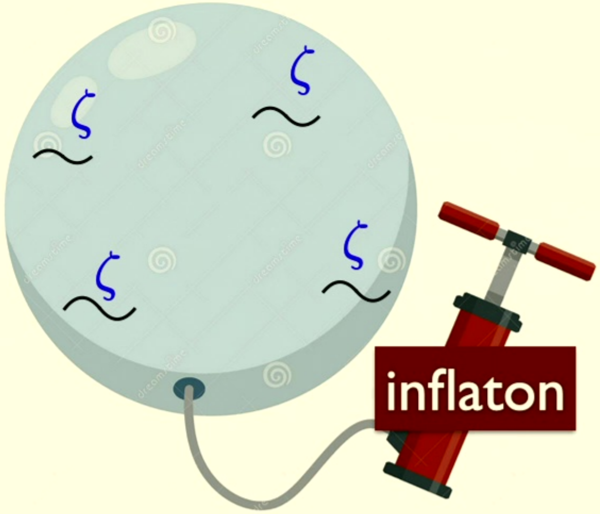
- DE can be a CC
- If DE is not a CC,
  even more questions …

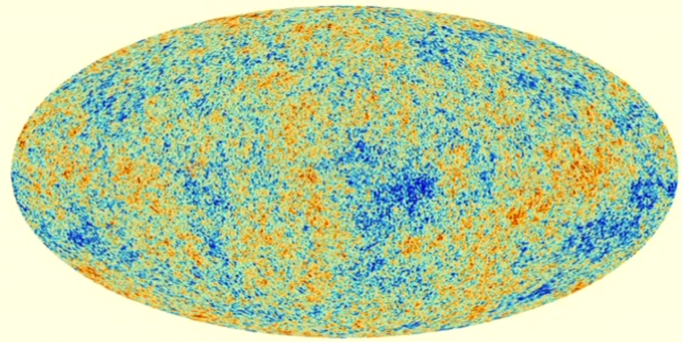
- Verification that DE is CC:

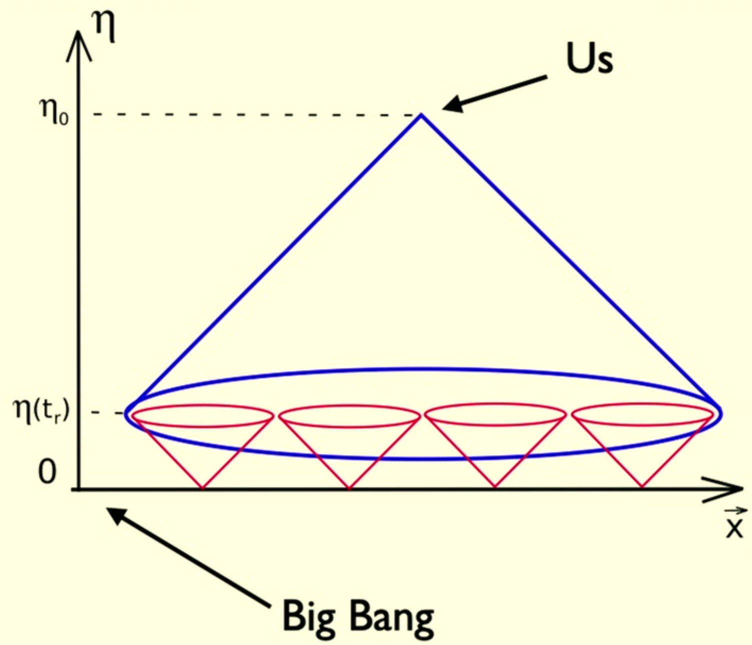
DARK ENERGY SURVEY

+ LSST, etc

Cosmic inflation



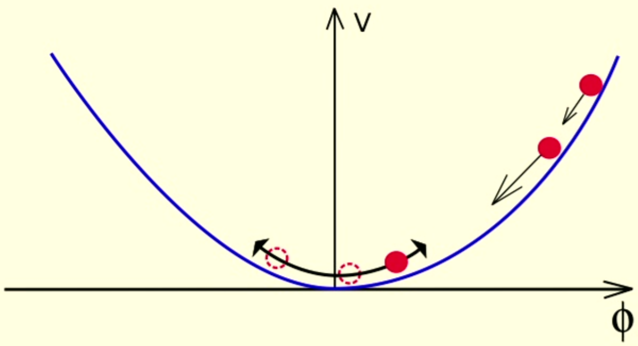




- Primordial accelerated expansion prior to BB

A. Guth (1981)
Starobinsky, Linde, Albrecht, Steinhardt, ++

Cosmic inflation: slow roll and beyond



$$3M_P^2 H^2 \approx V \approx \text{const}$$

- Mechanism is understood
- Particle Physics realization?

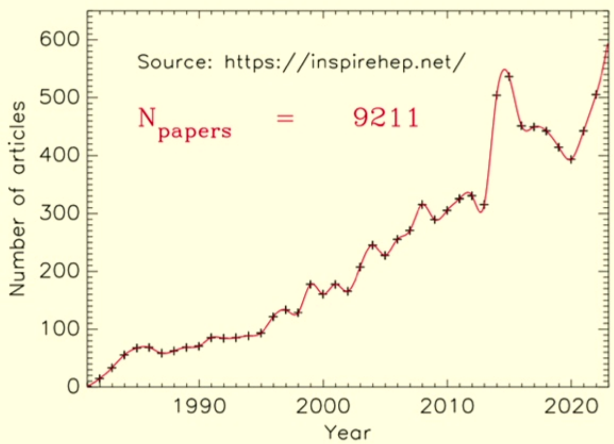
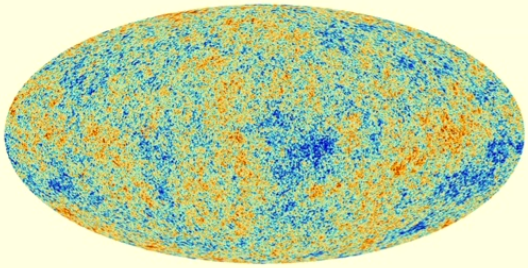


Figure 1. Number of articles containing the word "inflation" and its variations (i.e. "inflating", "inflationary", etc ...) in its title published each year since the advent of inflation. The total number exceeds 9200 papers.

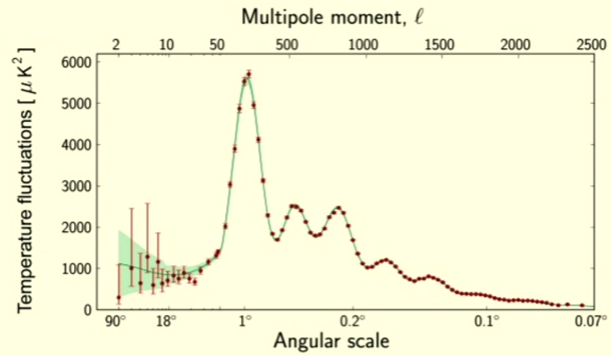
Encyclopædia Inflationaris : over 120 models

G. Martin++(1303.3787)

Cosmic Microwave Background

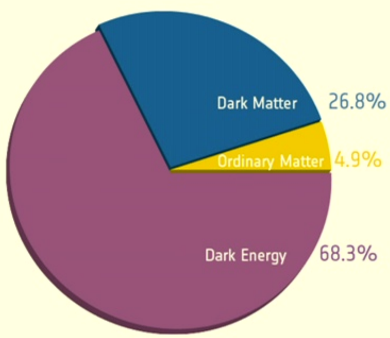


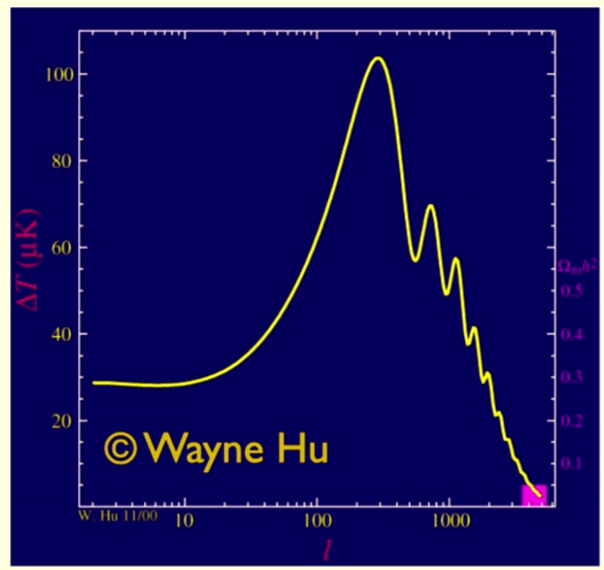
Planck'18



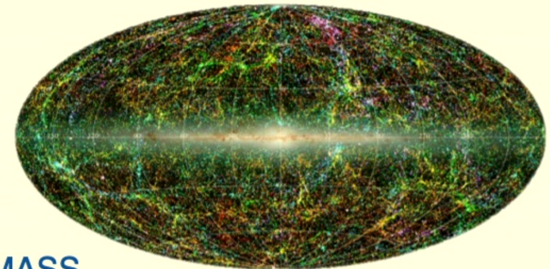
$$C_\ell \sim \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle, \quad \ell \sim \frac{1}{\theta}$$

$$\{\Omega_m, \Omega_b, H_0, \tau, A_s, n_s\}$$





Large-Scale Structure



(c) 2MASS

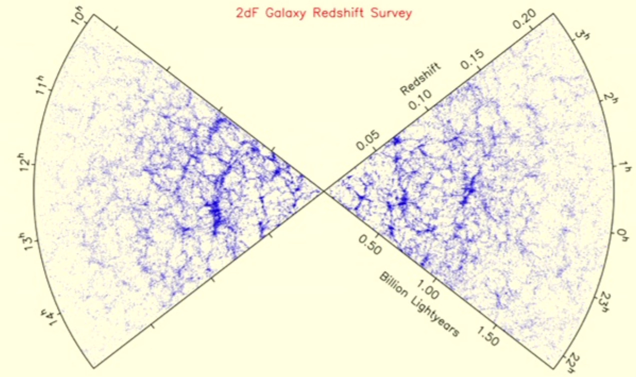
$$\delta = \frac{\delta\rho}{\rho}$$

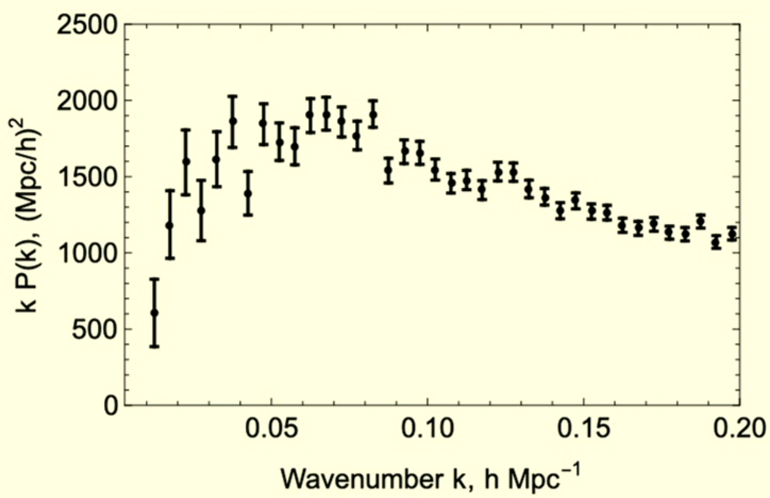
ex: SDSS, DESI,
Euclid, Roman, …

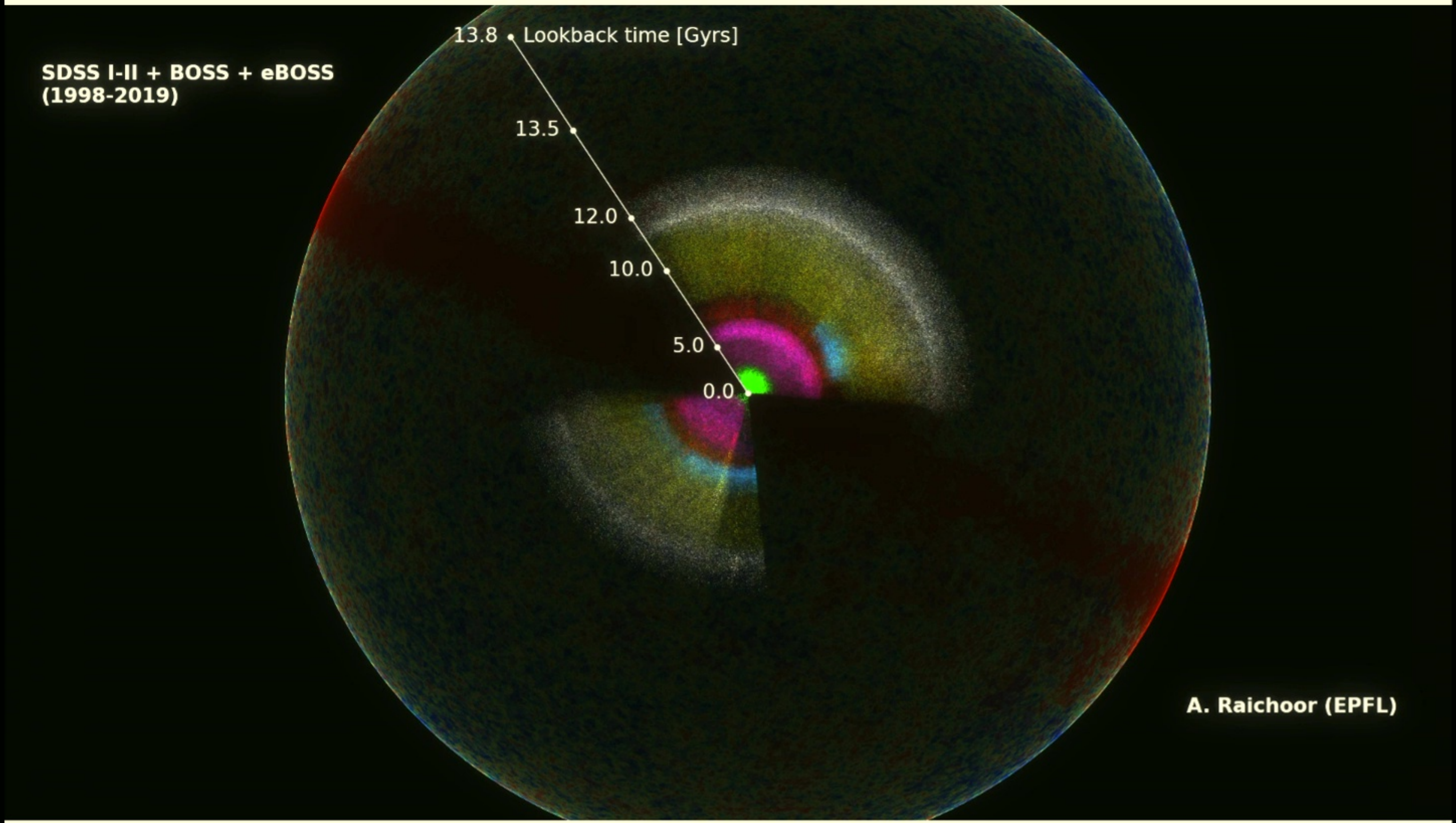
$$\langle\delta^2\rangle \to P(k)$$

$$\langle\delta^3\rangle, \ldots$$

$$k = \frac{2\pi}{\lambda}$$



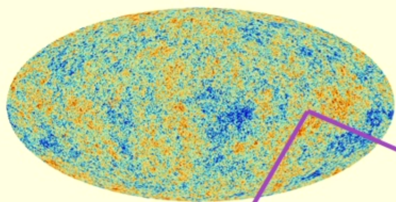



SDSS I-II + BOSS + eBOSS
(1998-2019)
13.8
Lookback time [Gyrs]
13.5
12.0
10.0
5.0
0.0
A. Raichoor (EPFL)

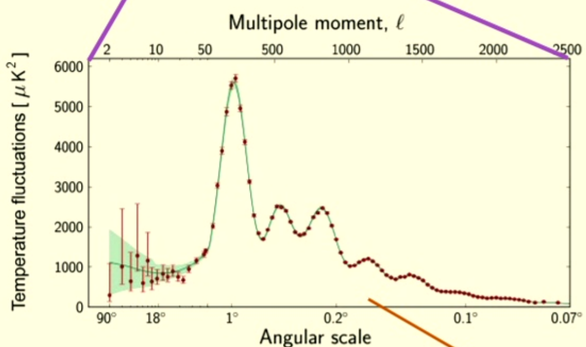
© eBOSS (2021)

Full-shape analysis

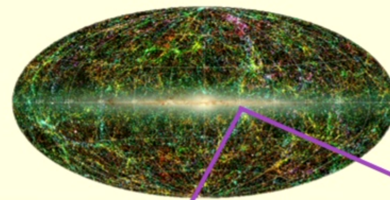
CMB:



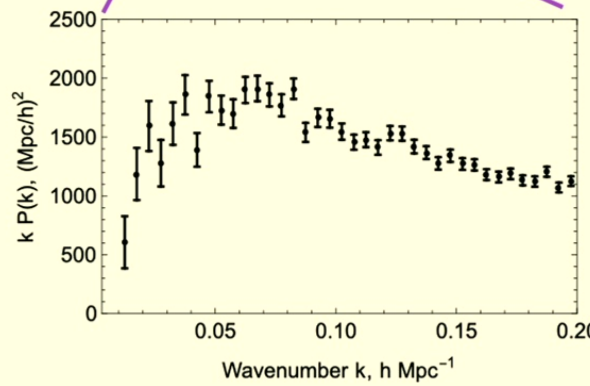
$$\frac{\delta T}{T}$$



LSS:



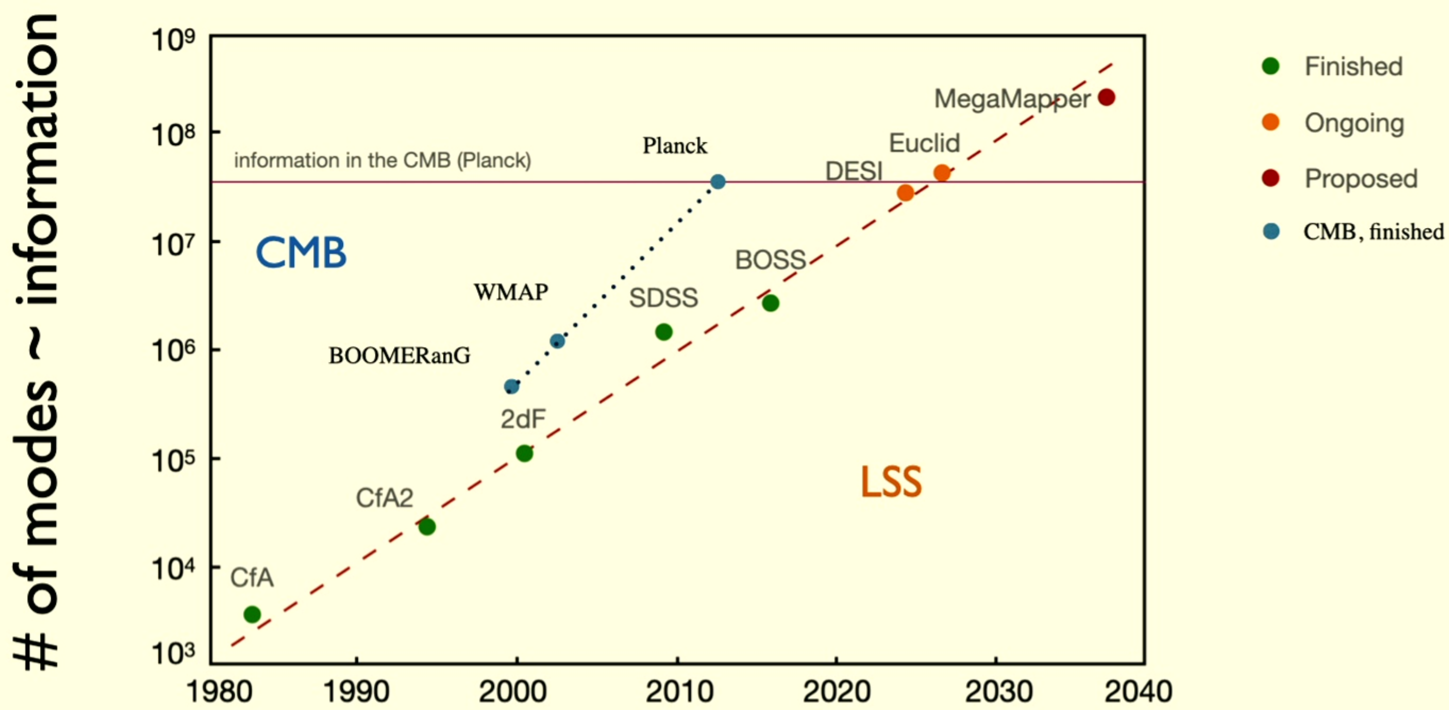
$$\frac{\delta \rho}{\rho}$$



Parameters: $\rho_{\rm dm}, \dots$

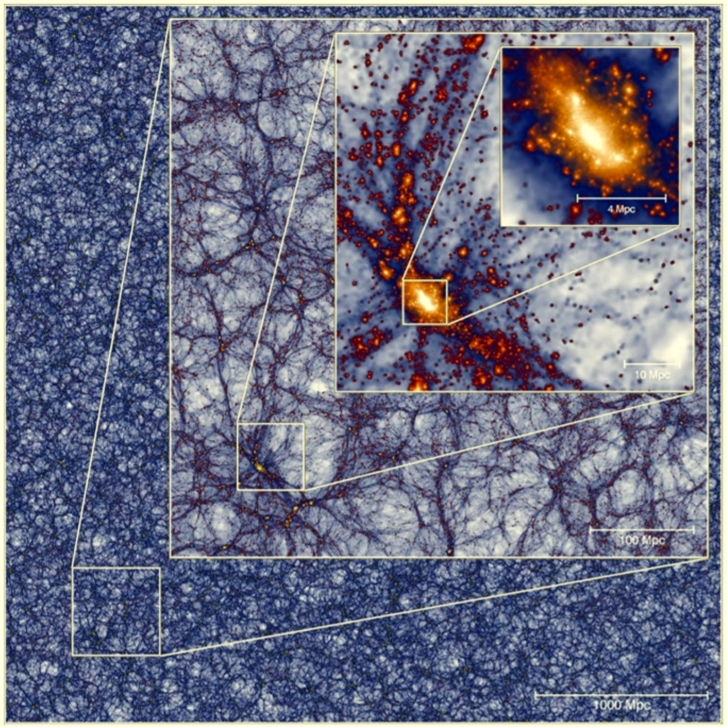
- CMB and LSS probe different scales, different epochs (redshifts) different physics !
- LSS is 3d —> contains orders of magnitude more information

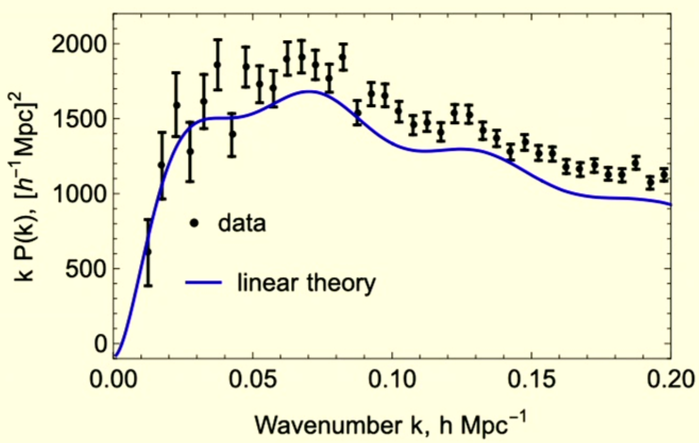
Mode counting



At face values this means a revolution!

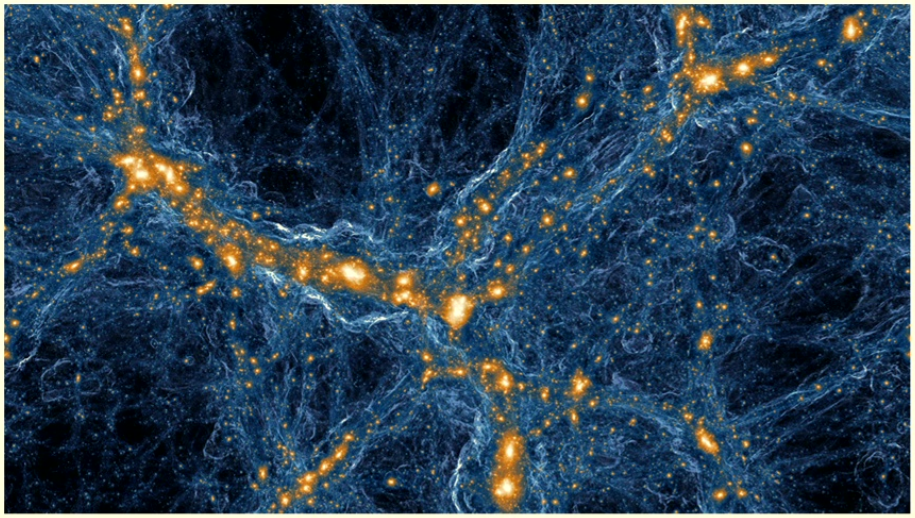
The big problem





- non-linearity = non-Gaussianity
- any optimal analysis must include NG statistics

Sources of non-linearity



IllustrisTNG

- Clustering of dark matter
- Galaxy - DM connection
- Baryonic feedback
- Redshift space distortions

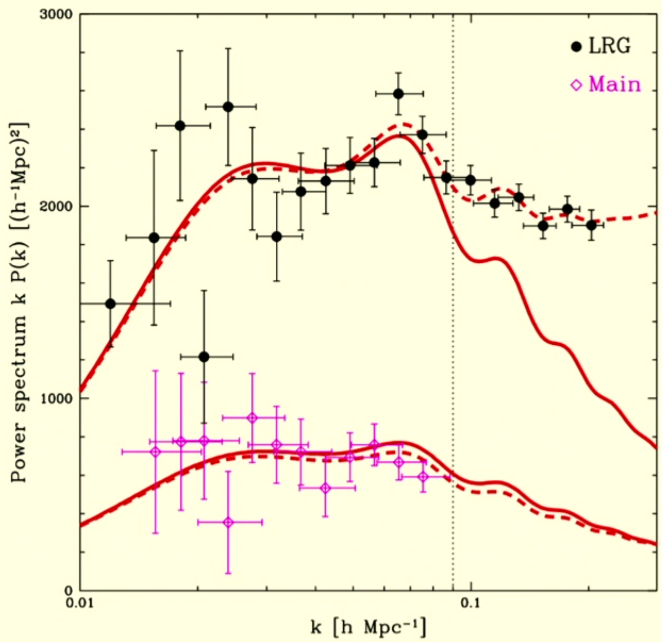
$$\delta_g = b_1\delta + b_2\delta^2 + b_{\mathcal{G}_2}(\nabla_{\langle i}\nabla_{j\rangle}\Phi)^2 + \dots$$

McDonald, Roy (2009), ++

Desjacques, Jeong, Schmidt (2016)

Nuisance parameters: $b_1, b_2, b_{\mathcal{G}_2}, \dots$

Ways to analyse LSS:



Tegmark++, SDSS analysis (2006)

- $\sigma_{\mathrm{theory}} \gg \sigma_{\mathrm{data}}$
- "standard" approach until recently: focus on observables that are approximately stable w.r.t. non-linear effects: Baryon Acoustic Oscillations + RSD
- Discard shape information
- Can't really measure cosmological parameters

Cosmological parameters: CMB vs LSS

Planck 2013 results. XVI. Cosmological parameters

Abstract: This paper presents the first cosmological results based on *Planck* measurements of the cosmic microwave background (CMB) temperature and lensing-potential power spectra. We find that the *Planck* spectra at high multipoles ($\ell \gtrsim 40$) are extremely well described by the standard spatially-flat six-parameter ΛCDM cosmology with a power-law spectrum of adiabatic scalar perturbations. Within the context of this cosmology, the *Planck* data determine the cosmological parameters to high precision: the angular size of the sound horizon at recombination, the physical densities of baryons and cold dark matter, and the scalar spectral index are estimated to be $\theta_* = (1.04147 \pm 0.00062) \times 10^{-2}$, $\Omega_b h^2 = 0.02205 \pm 0.00028$, $\Omega_c h^2 = 0.1199 \pm 0.0027$, and $n_s = 0.9603 \pm 0.0073$, respectively (Note that in this abstract we quote 68% errors on measured parameters and 95% upper limits on other parameters.) For this cosmology, we find a low value of the Hubble constant, $H_0 = (67.3 \pm 1.2)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, and a high value of the matter density parameter, $\Omega_m = 0.315 \pm 0.017$. These values are in tension with recent direct measurements of H_0 and the magnitude-

The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: Baryon Acoustic Oscillations in the Data Release 10 and 11 Galaxy Samples

ABSTRACT

We present a one per cent measurement of the cosmic distance scale from the detections of the baryon acoustic oscillations in the clustering of galaxies from the Baryon Oscillation Spectroscopic Survey (BOSS), which is part of the Sloan Digital Sky Survey III (SDSS-III). Our results come from the Data Release 11 (DR11) sample, containing nearly one million galaxies and covering approximately 8 500 square degrees and the redshift range $0.2 < z < 0.7$. We also compare these results with those from the publicly released DR9 and DR10 samples. Assuming a concordance ΛCDM cosmological model, the DR11 sample covers a volume of $13\,\mathrm{Gpc}^3$ and is the largest region of the Universe ever surveyed at this density. We measure the correlation function and power spectrum, including density-field reconstruction of the baryon acoustic oscillation (BAO) feature. The acoustic features are detected at a significance of over $7\,\sigma$ in both the correlation function and power spectrum. Fitting for the position of the acoustic features measures the distance relative to the sound horizon at the drag epoch, r_d, which has a value of $r_{d,\mathrm{fid}} = 149.28$ Mpc in our fiducial cosmology. We find $D_V = (1264 \pm 25\,\mathrm{Mpc})(r_d/r_{d,\mathrm{fid}})$ at $z = 0.32$ and $D_V = (2056 \pm 20\,\mathrm{Mpc})(r_d/r_{d,\mathrm{fid}})$ at $z = 0.57$. At 1.0 per cent, this latter measure is the most precise distance constraint ever obtained from a galaxy survey. Separating the clustering along and transverse to the line-of-sight yields measurements at $z = 0.57$ of $D_A = (1421 \pm 20\,\mathrm{Mpc})(r_d/r_{d,\mathrm{fid}})$ and $H = (96.8 \pm 3.4\,\mathrm{km/s/Mpc})(r_{d,\mathrm{fid}}/r_d)$. Our measurements of the distance scale are in good agreement with previous BAO measurements and with the predictions from cosmic microwave background data for a spatially flat cold dark matter model with a cosmological constant.

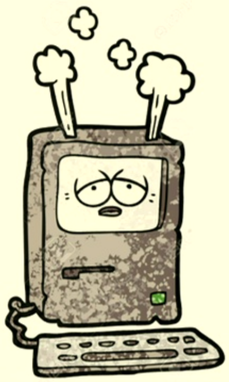
- BAO have been foundational
- Can we get more information from the shape?

Understand non-linearities !

Numerics/Analytics

Simulations

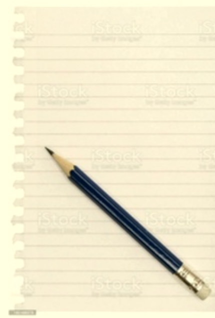
- ✓ matter clustering
- ✓ unlimited range
- ✗ galaxy formation
- ✗ time-consuming



credit: lineartestpilot

Perturbation theory

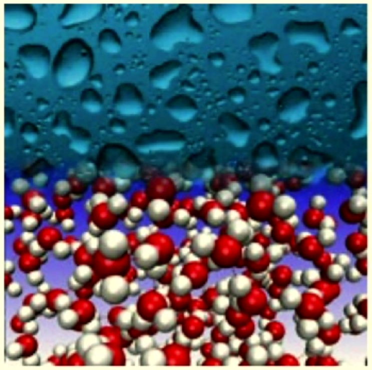
- ✗ limited range
- ✓ precision & accuracy
- ✓ fast/ cheap - beyond LCDM
- ✓ marg. over gastrophysics



State-of-the-art equipment
for theoretical physicist

credit: CartoonStock

Why do formulas work?



$\longleftrightarrow$

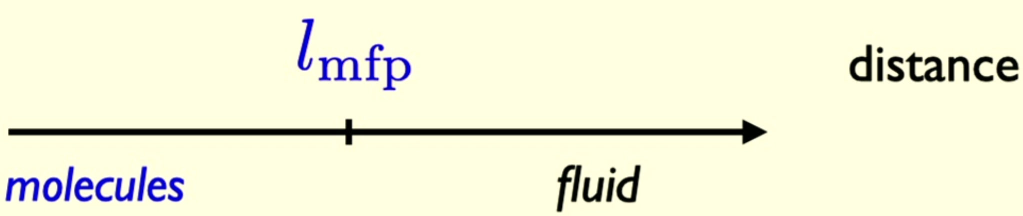
l_{mfp}

- Coarse-grained (large-scale) fields:

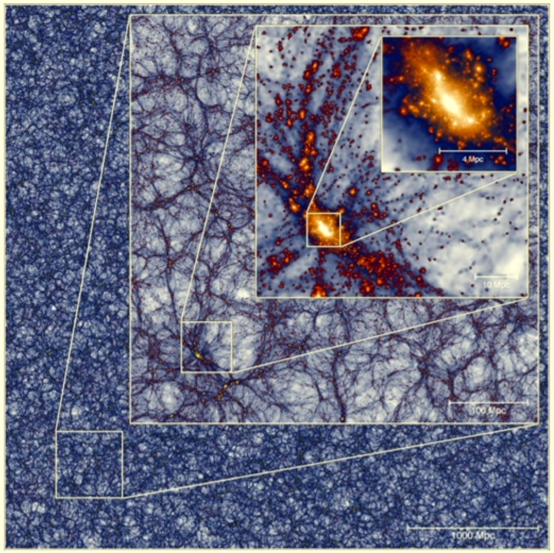
$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\mathbf{u} + \ldots + \nu_2\nabla^4\mathbf{u}$$

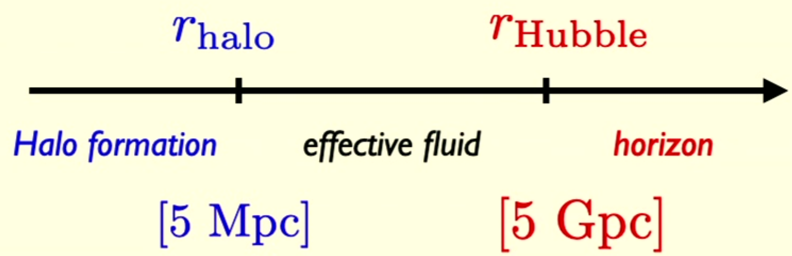
- Convergent gradient expansion:

$$\frac{\nu_2\nabla^4\mathbf{u}}{\nu\nabla^2\mathbf{u}} \sim \frac{l_{\mathrm{mfp}}^2}{\lambda^2} \ll 1$$



Large-scale structure theory





- **EFT of Large Scale Structure:**

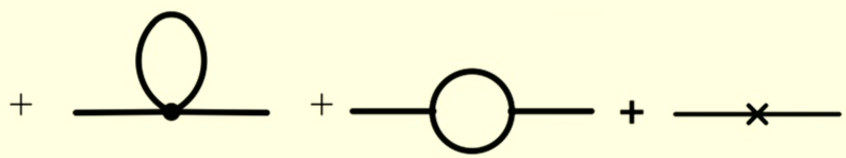
  Baumann (2012), Carrasco, Senatore, Zaldarriaga, White, Chen, Vlah, Schmidt, Pajer, Hertzberg+++

- **TSPT helps me get $\sim 0.1\%$ understanding**

Time-sliced perturbation theory (TSPT)

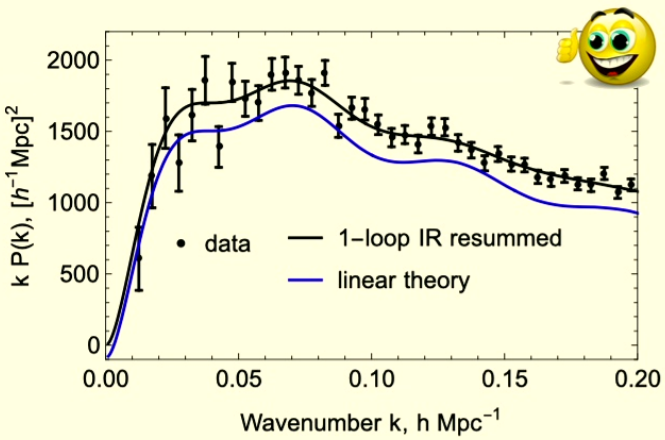
Path Integral Formulation of EFT of Large-Scale Structure

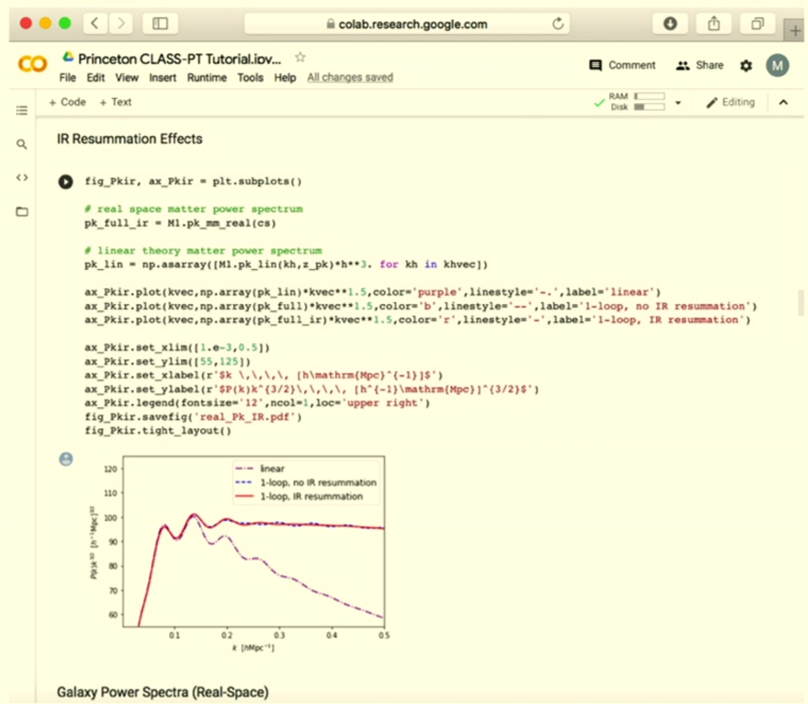
Blas, Garny, MI, Sibiryakov (2015)



It works!

https://github.com/Michalychforever/CLASS-PT





2-loop, 3-loop ….

3-point function, 4-pf, …

caveat: nuisance parameters

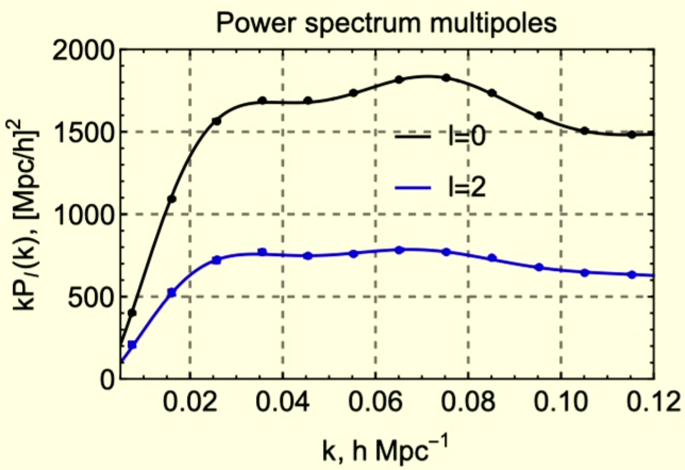
~Wilson coeff's

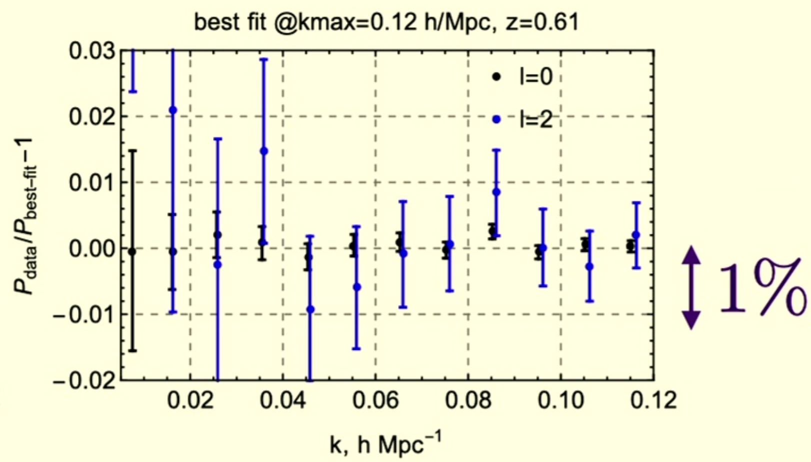
see also FAST-PT, Velocilaptor, Spinosourus, PiBird, CLASS-1loop, etc.

Blind Perturbation Theory Challenge

Large N-body sims

~ the observable Universe
100x actual data



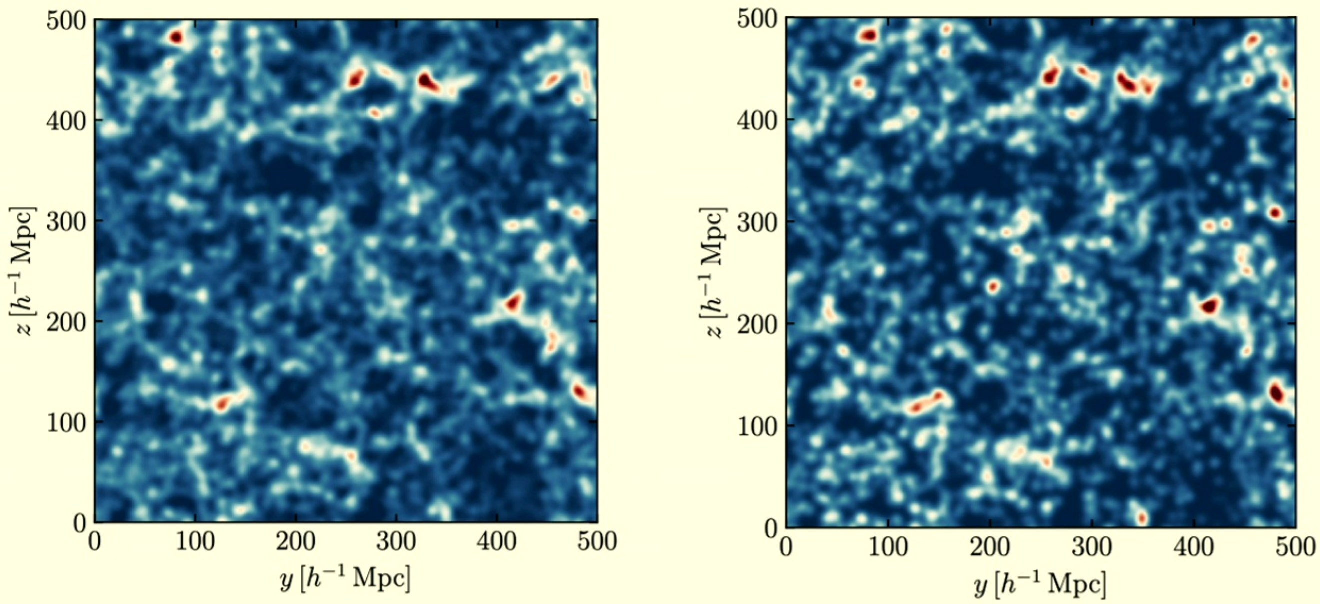


True cosmology recovered with ~0.5% accuracy

Nishimichi, Takada, MI, Simonovic, Zaldarriaga, D'Amico, ++(2020)

N. B. tested in more blind challenges after

Field-level comparison



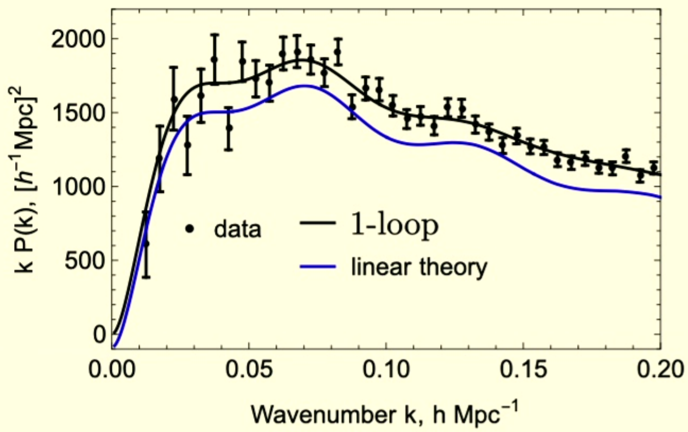
MI, Cuesta-Lazaro, ++'24

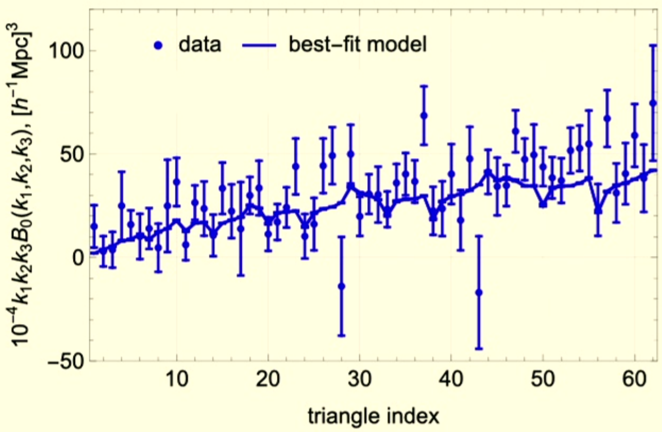
Schmittfull, Simonovic, MI++'20

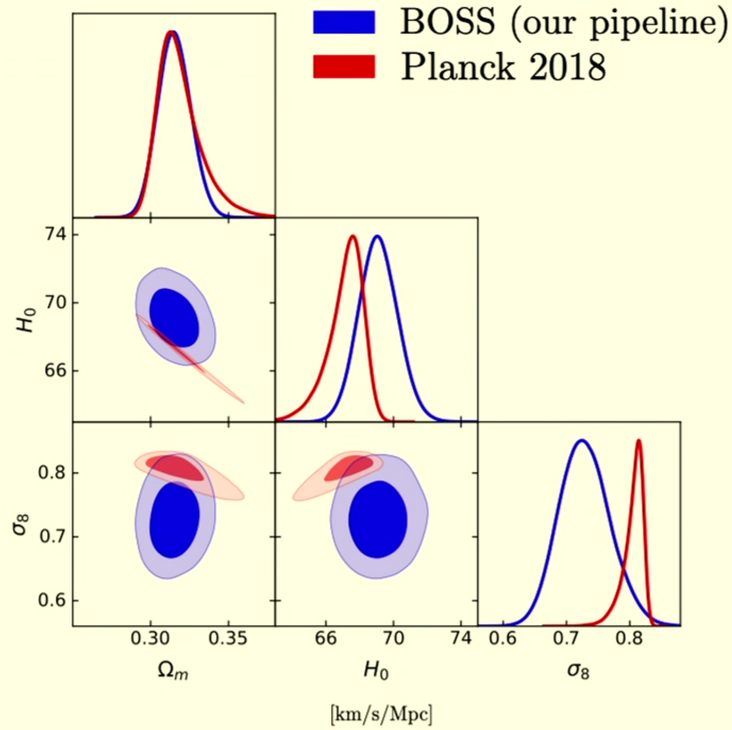
Schmittfull++'18

Large-scale structure: re-analysis of BOSS data

Our pipeline:





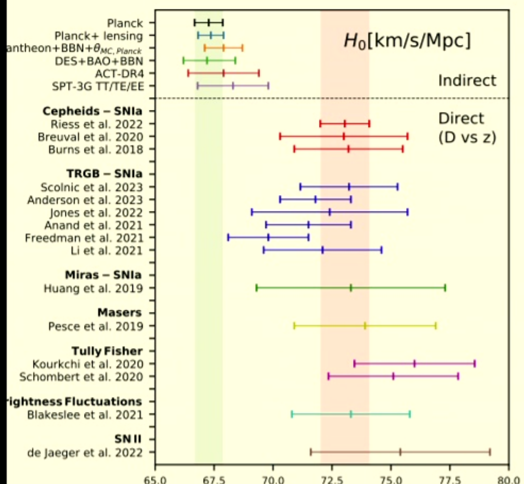


MI, Simonovic, Zaldarriaga (2019), Philcox, MI (2021) ++
D'Amico, Kokron++(2019), Chen, White, Vlah (2021)

Ask me about tensions!

Applications

testing LCDM:



w/ O.Philcox, A. Chudaykin, K. Dolgikh

Dark Sectors

w/ M. Toomey, C. Hill, K. Rogers, A. He, R. An, V. Gluscevic

Testing inflation

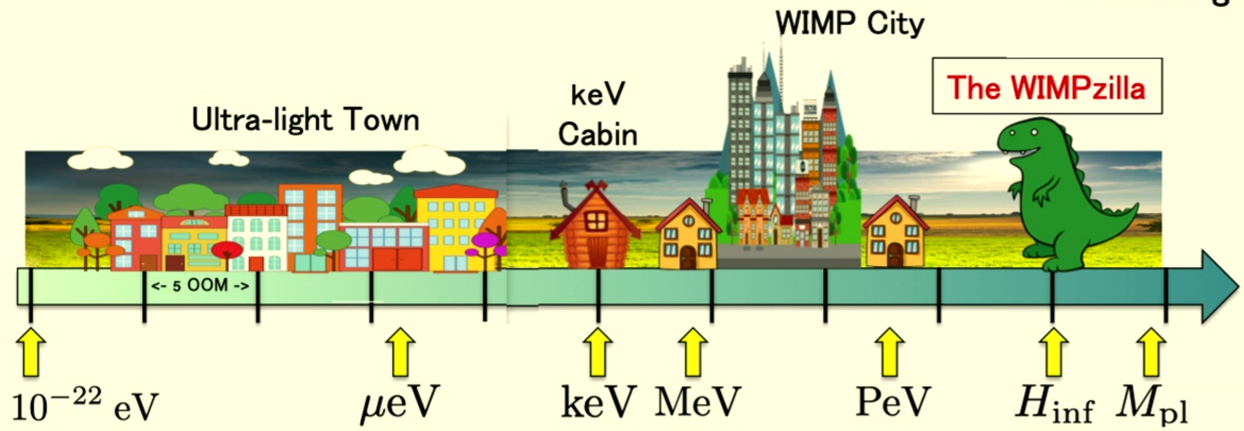
Ghost inflation!

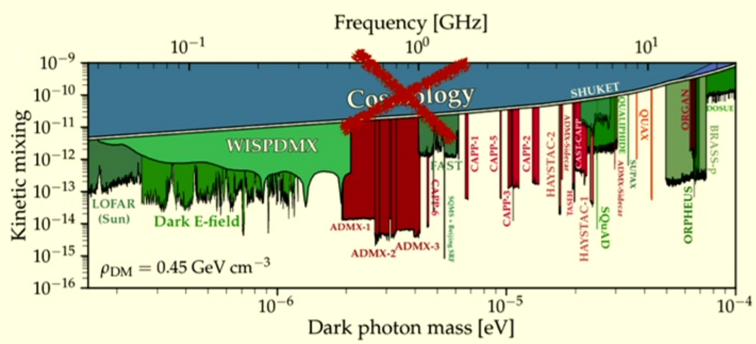
© Philcox w/Midjourney

w/ O.Philcox, G. Cabass

What if there are many DMs ?

© A. Long @LWD

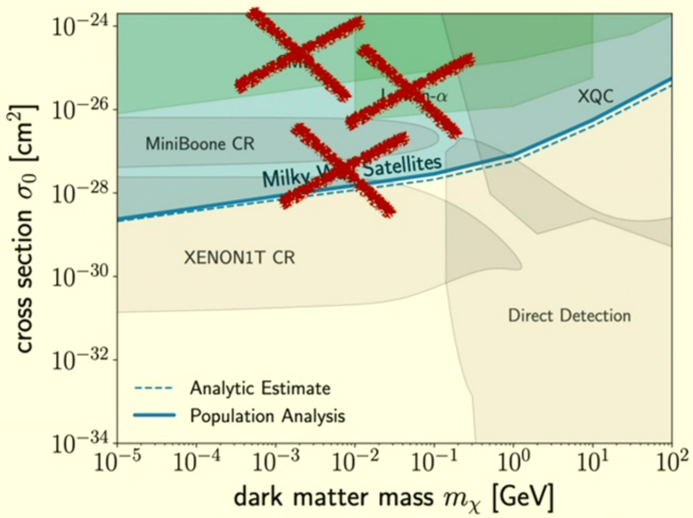




https://cajohare.github.io/AxionLimits/

ex: Axiverse

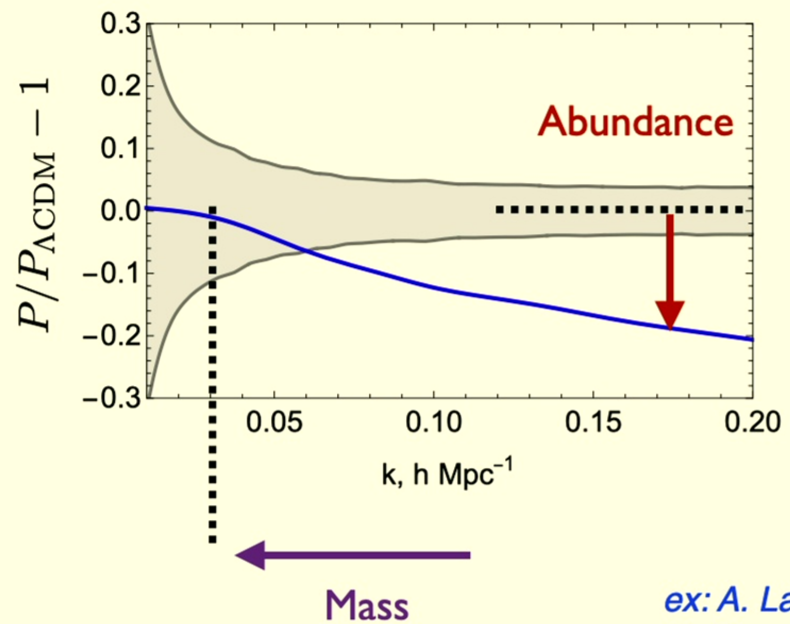
Arvanitaki++ (2009)



Nadler ++ (2020)

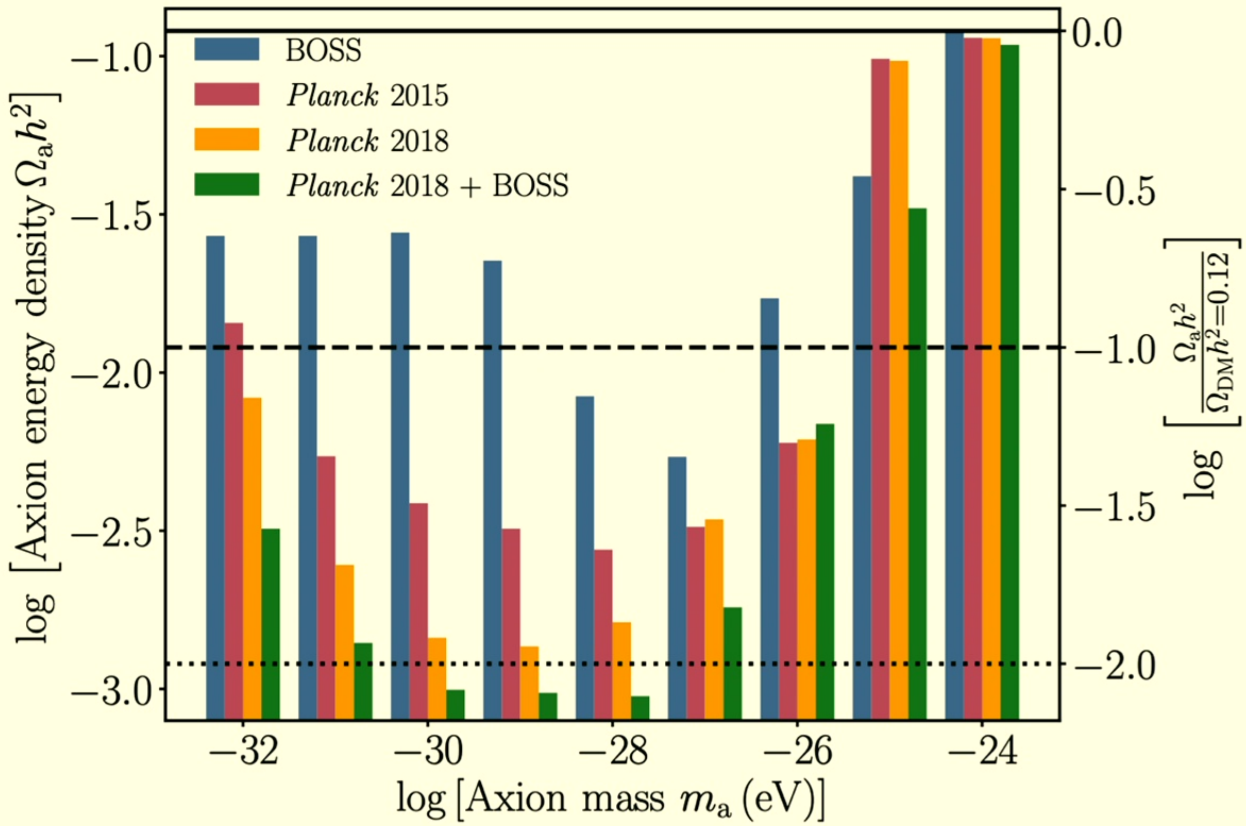
We can do better with Galaxies!

- Imagine two DM components, one is not exactly cold
- ~ there's a Jeans scale beyond which it won't cluster!



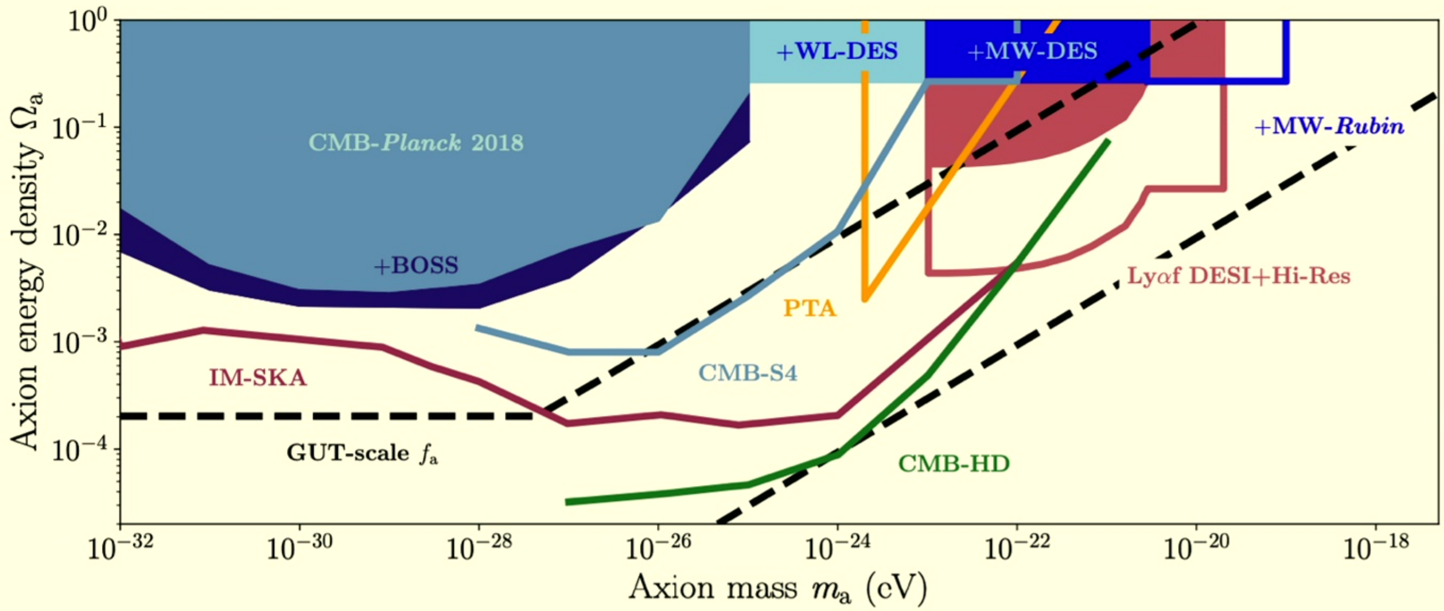
ex: A. Laguë++'21,
K. Rogers, Laguë, MI++'21

Axion Dark Matter constraints



Rogers, Lague, MI ++ (2023)

Axion Dark Matter constraints



Rogers, Lague, MI ++ (2023)

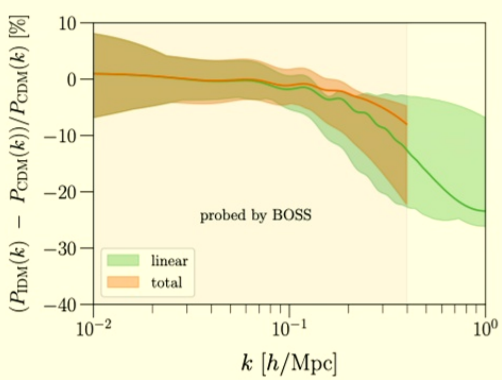
DM - baryon interactions: apparent evidence ?

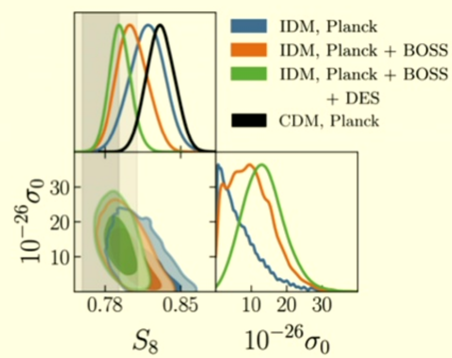
- motivated by direct detections

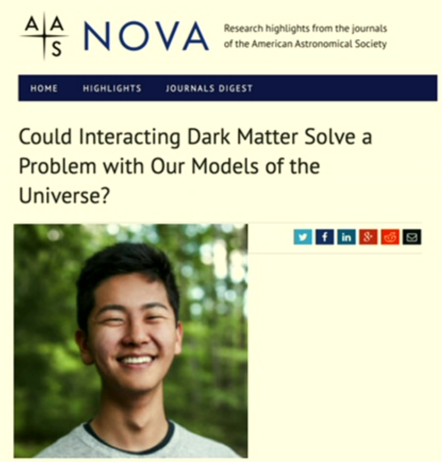
Dvorkin, Blum, Kamionkowski ++ (2014)
Gluscevic, Boddy (2018)
Slatyer, Wu (2018)

$\sim 10\%$ of DM ~ $m_\chi \sim 1$ MeV interacts w/ baryons

$$\sigma_0 = 1.34^{+0.51}_{-0.67} \times 10^{-25}\ \mathrm{cm}^2$$







Adam He, MI, Rui, Gluscevic (2023)

First Constraints on Single-Field Inflation

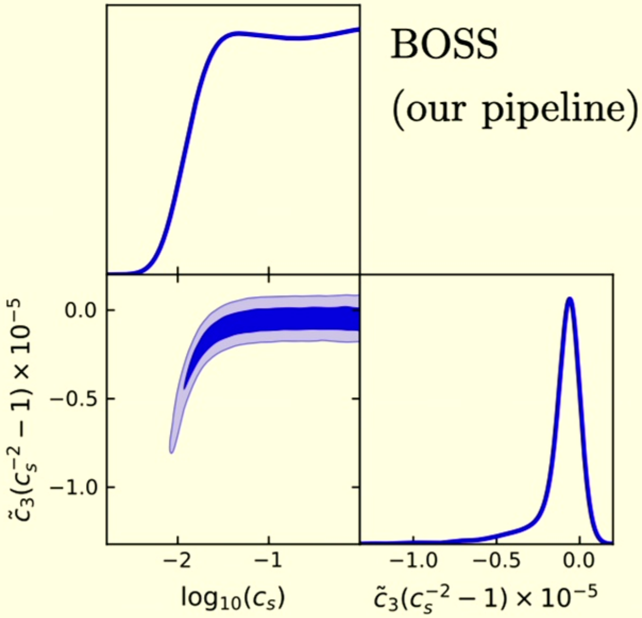
- **Effective Lagrangian**

Cheung, Creminelli, ++ (2007)

$$S_{\rm EFT} = \int d^4x\sqrt{-g}\left[\frac{M_P^2|\dot H|}{c_s^2H^2}\left(\dot\zeta^2 - c_s^2\frac{(\nabla\zeta)^2}{a^2}\right) + \frac{M_P^2|\dot H|}{c_s^2H^3}(1-c_s^2)\left(\frac{\dot\zeta(\nabla\zeta)^2}{a^2} - \left(1+\frac{2}{3}\frac{\tilde c_3}{c_s^2}\right)\dot\zeta^3\right)\right]$$

$$c_s \geq 0.013 \text{ at } 95\% \text{ CL}$$

Cabass, MI, Philcox ++(2022a, 2022b)



+ multi-field models
i.e. cosmo collider

Summary

- EFT - robust *analytic* tool for LSS
- Cosmo. parameters competitive with CMB
- Novel ways to test new physics
- Huge improvements in the future
- Many O(1) question on inflation, DM will be answered

Thank you!