Probing Cosmic Inflation and Dark Matter with Galaxy Surveys

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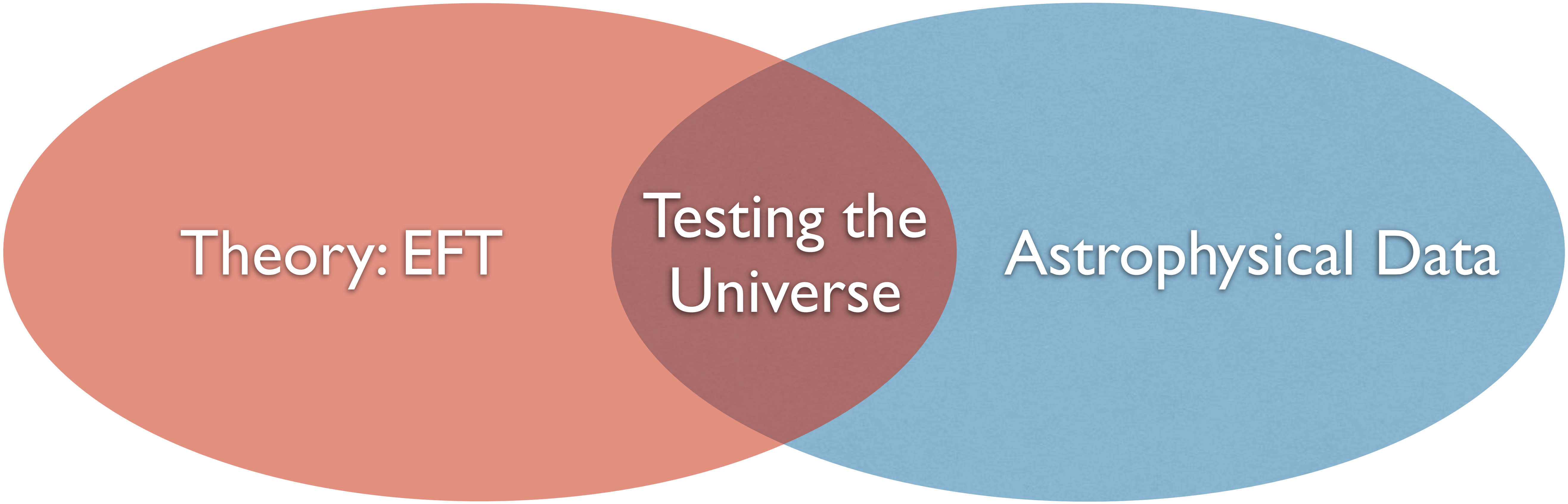
LBNL cosmology seminar, 01/17/2023

Intro



- Goal: understand dark matter, inflation, the origin of spacetime
- Method: effective field theory

Examples:

in this talk:

- Large-scale structure theory and data analysis

  Large-scale structure theory

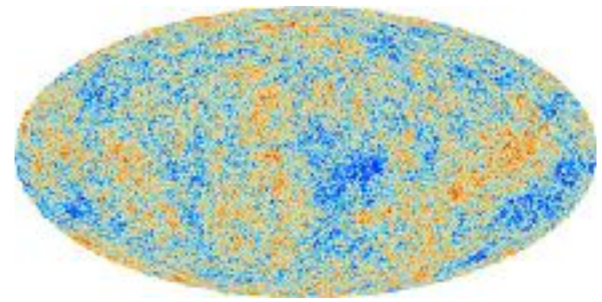
  New pipeline for galaxy surveys

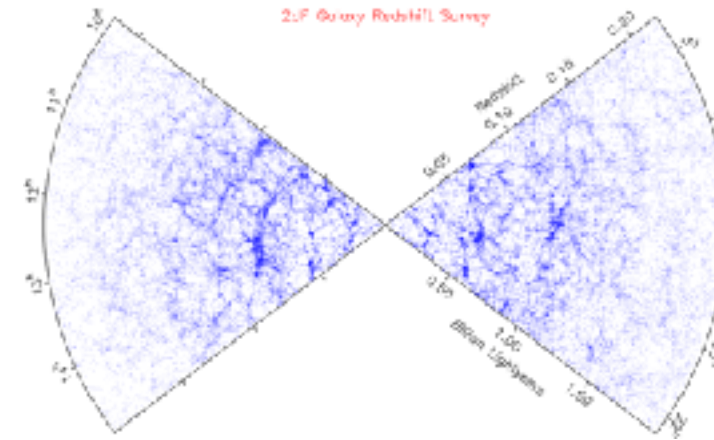
  Constraints on fundamental cosmology

NOT in this talk:

- Gravitational waves, black hole Love numbers

Cosmology



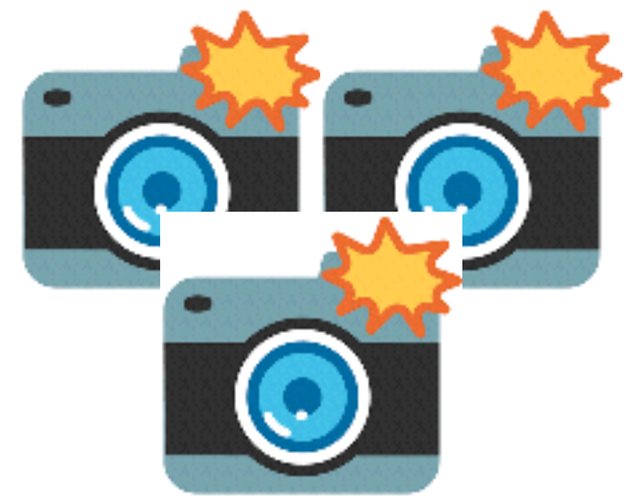


CMB

galaxies

inflation

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



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

Known Unknowns:

What was inflation, exactly?

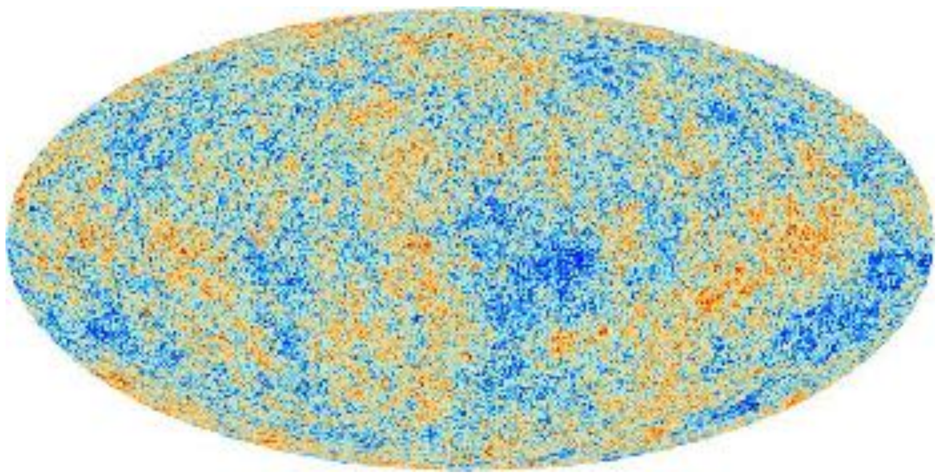
Is DM really cold?

etc.

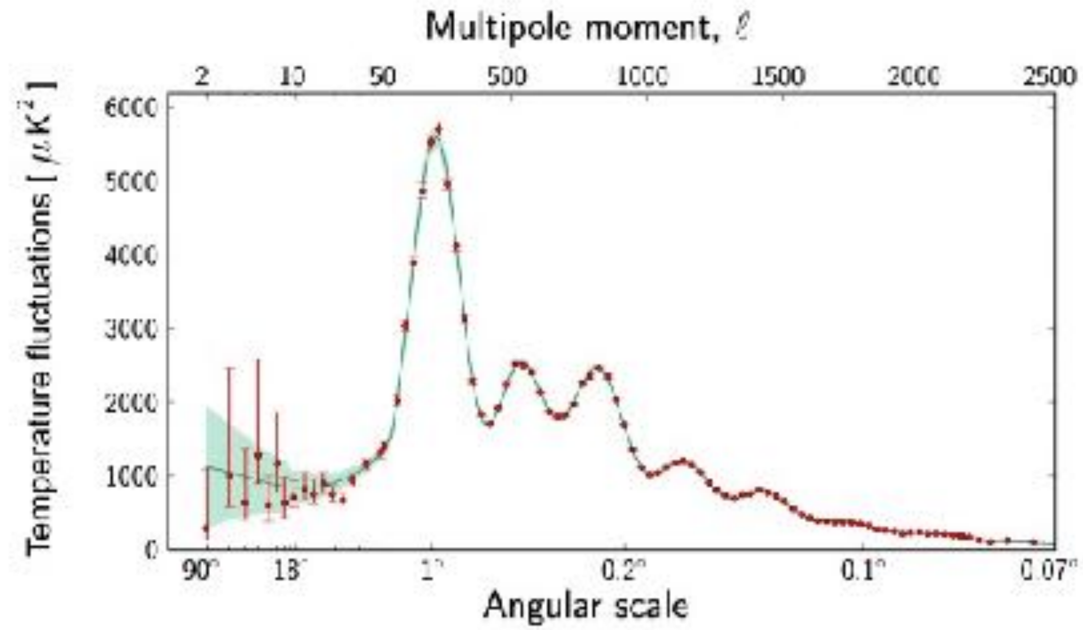
Unkown Unknowns:

Surprises ?

Cosmic Microwave Background

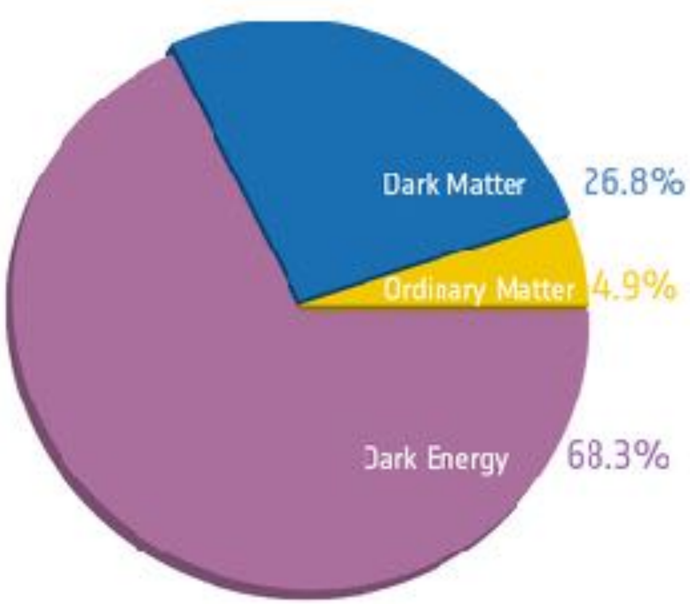


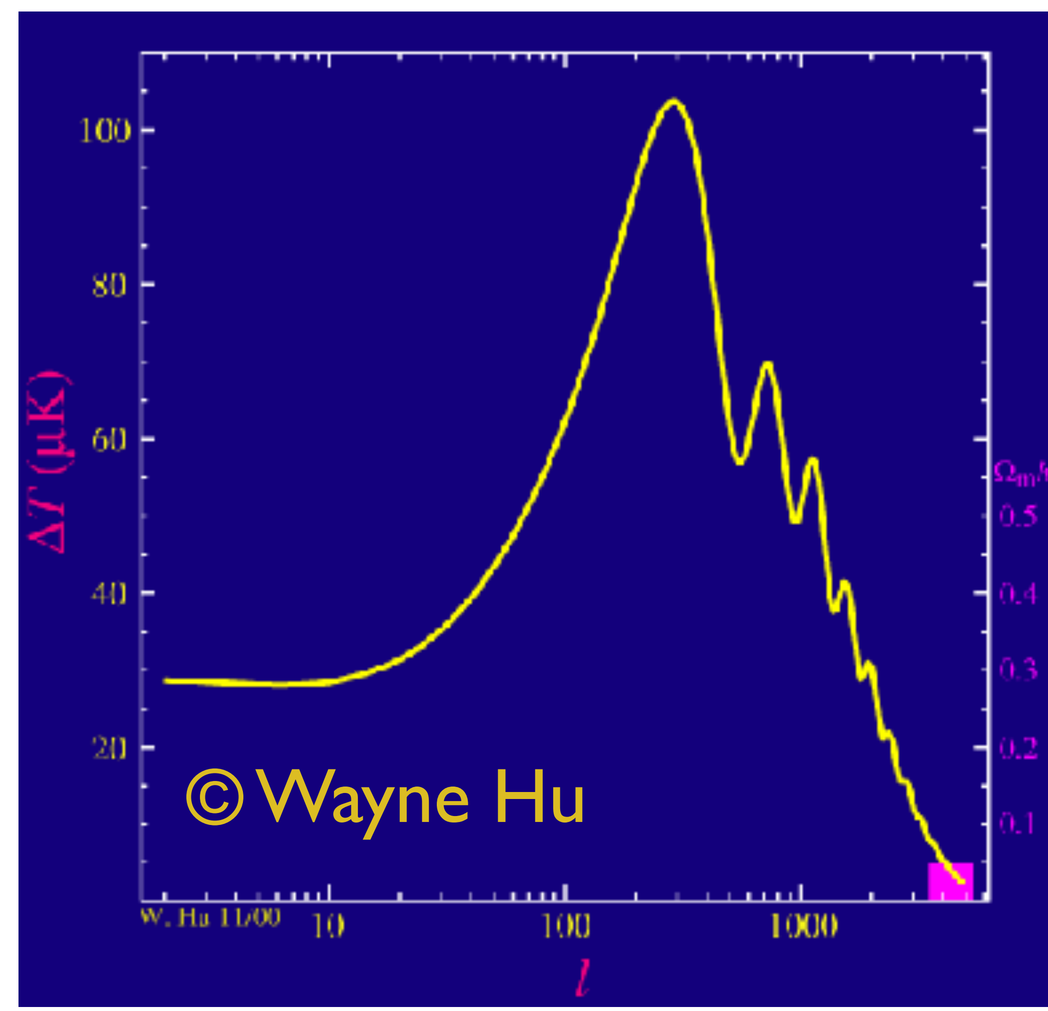
Planck'18



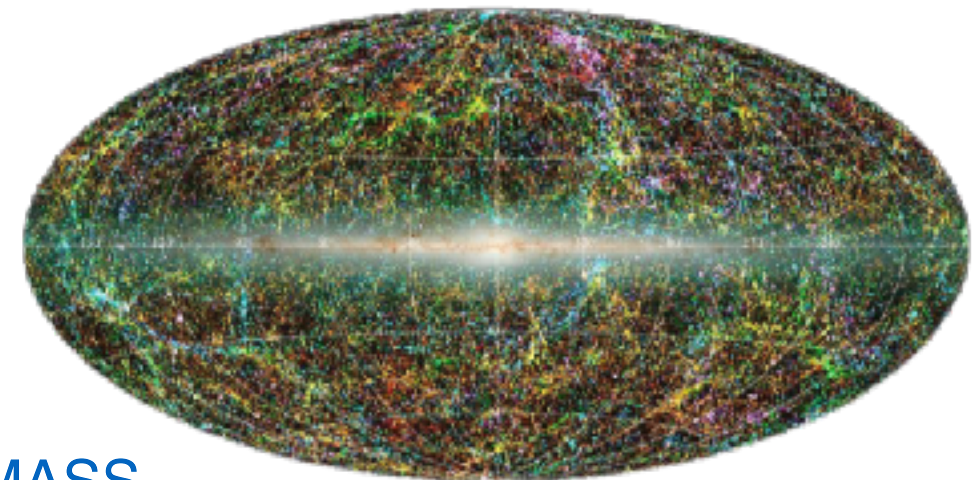
$$C_\ell \sim \left\langle \left(\frac{\delta T}{T} \right)^2 \right\rangle, \quad \ell \sim \frac{1}{\theta}$$

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





Large-Scale Structure



(c) 2MASS

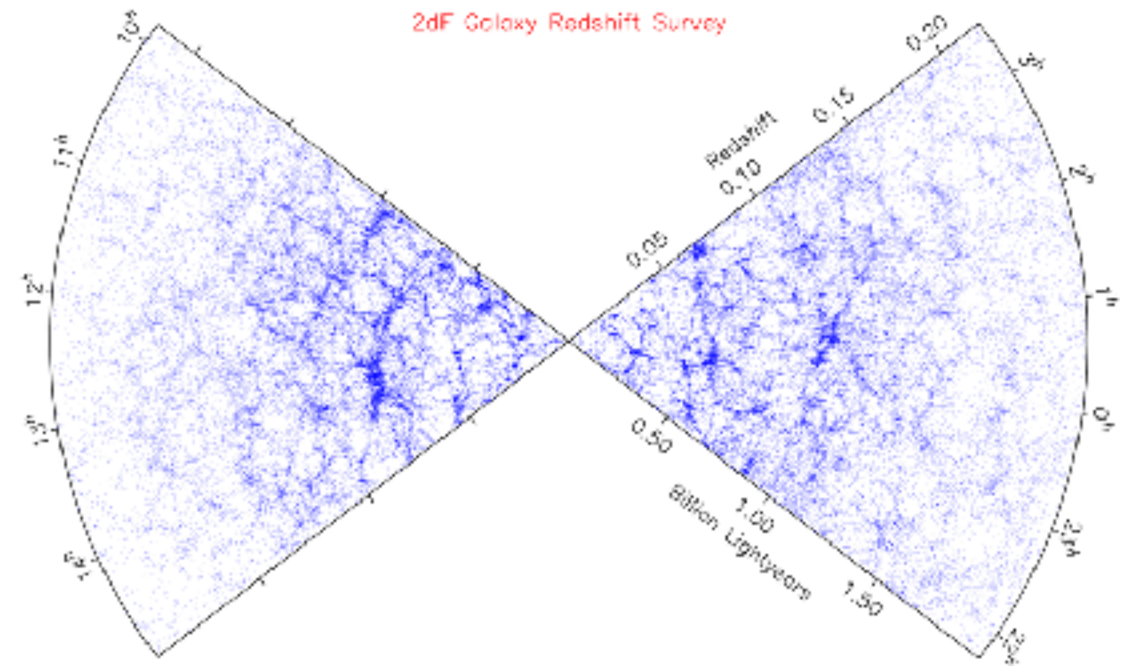
$$\delta = \frac{\delta\rho}{\rho}$$

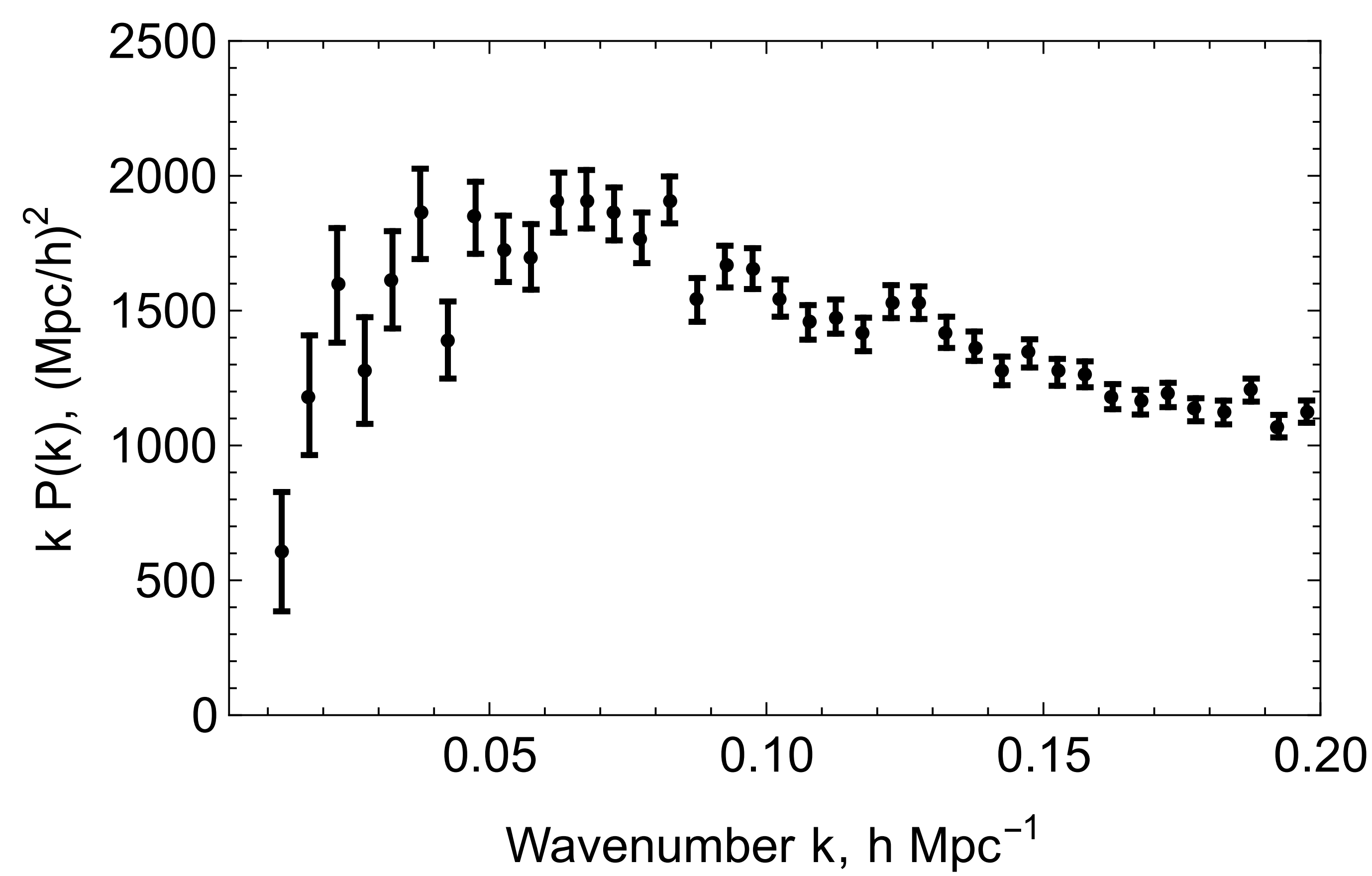
ex: SDSS, DESI, Euclid, Roman, …

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

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

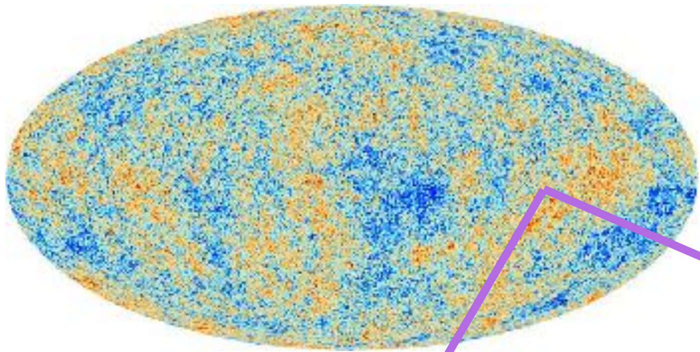
$$k = \frac{2\pi}{\lambda}$$



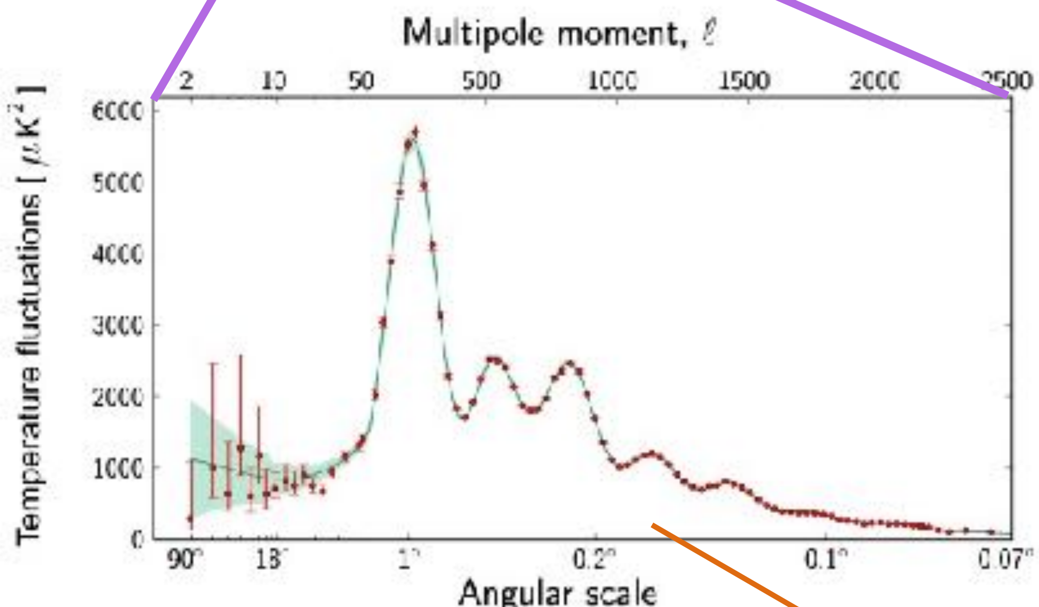


Full-shape analysis

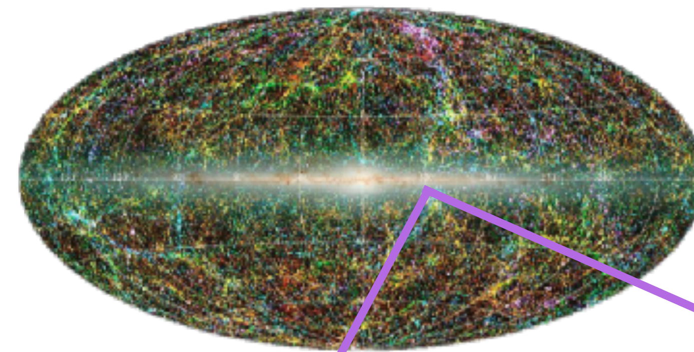
CMB:



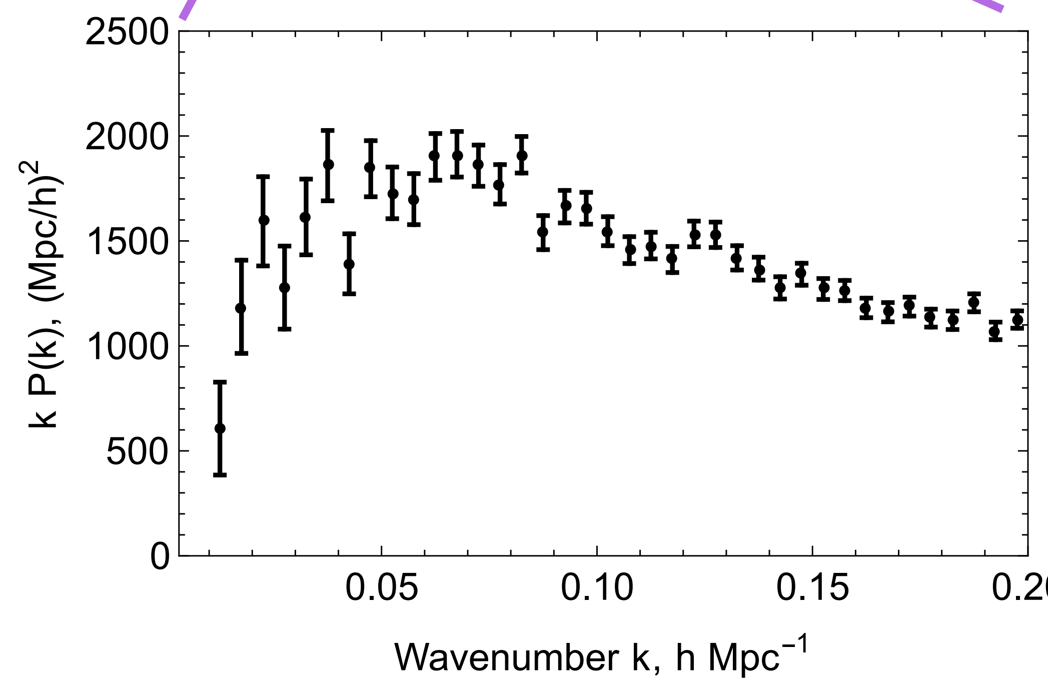
$$\frac{\delta T}{T}$$



LSS:



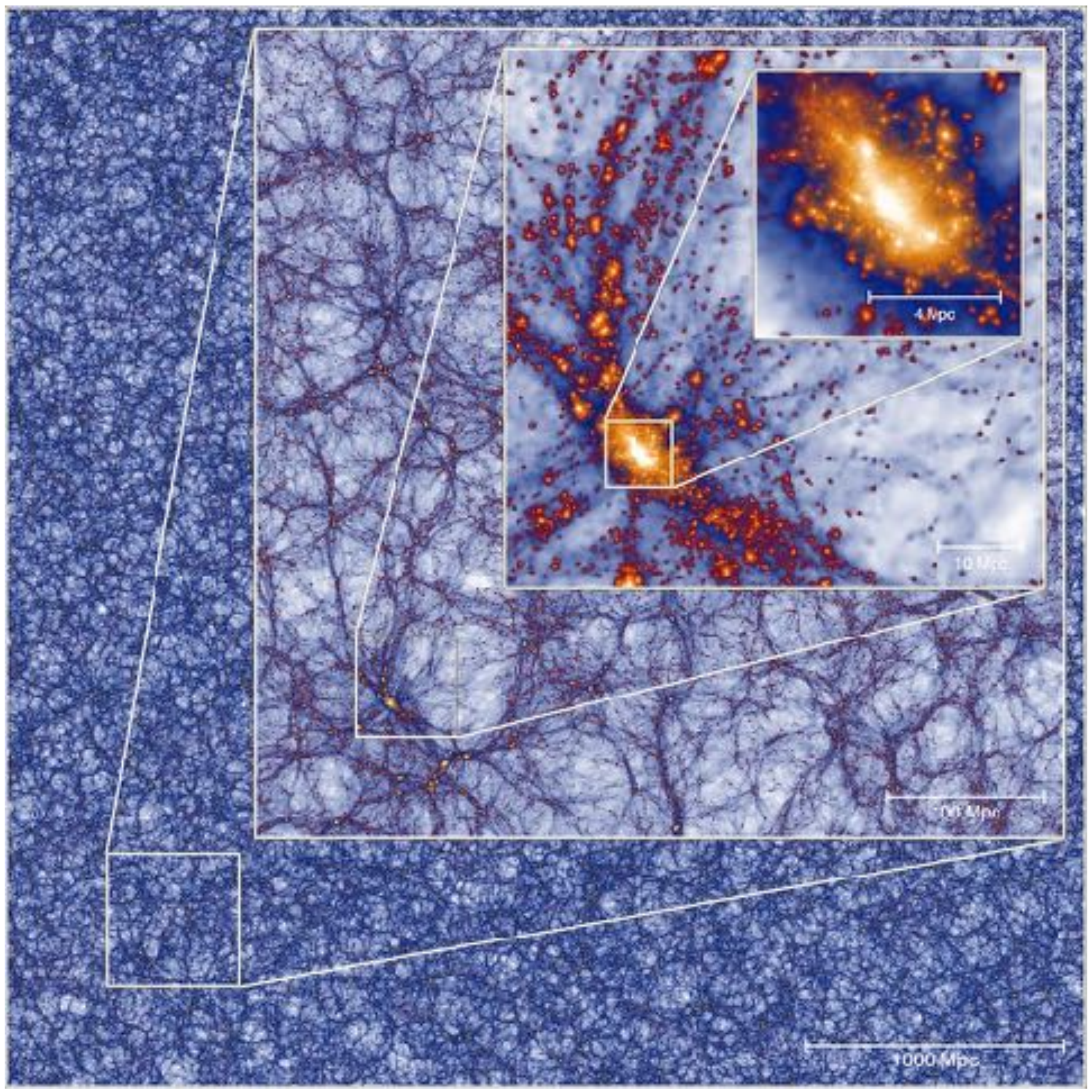
$$\frac{\delta\rho}{\rho}$$

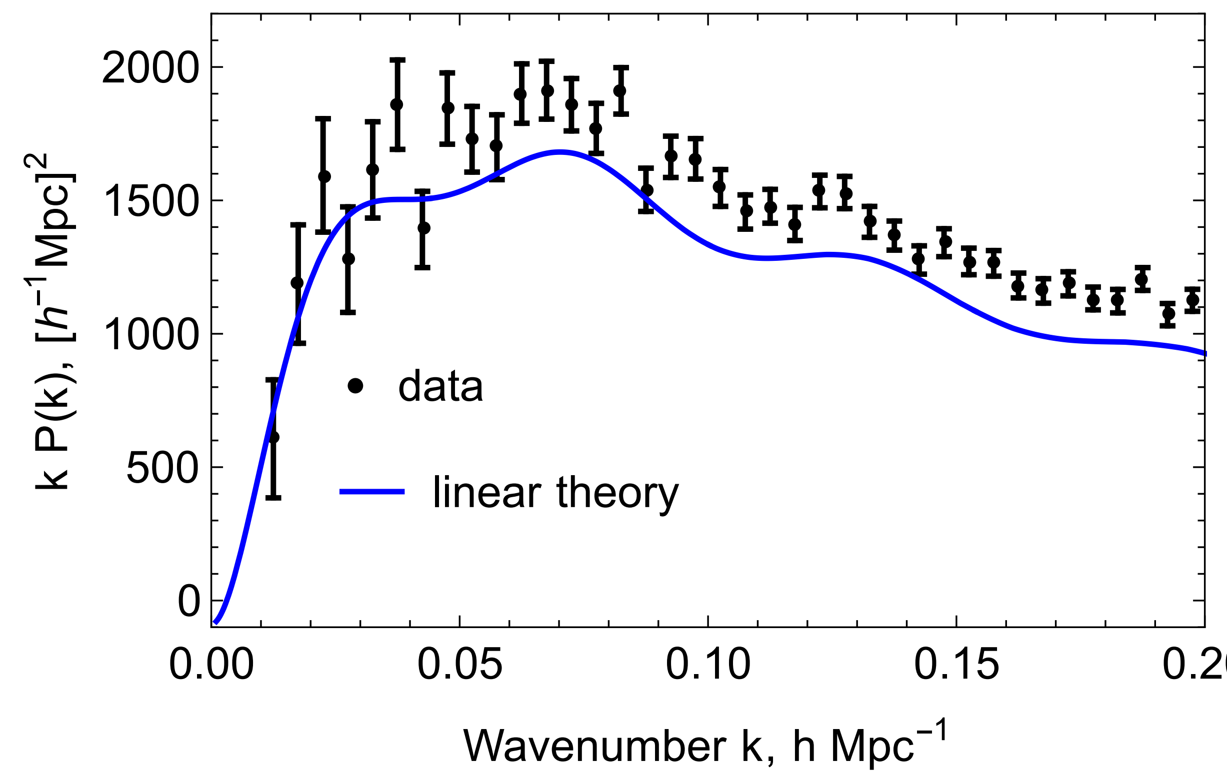


Parameters: $\rho_{\rm dm}, \cdots$

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

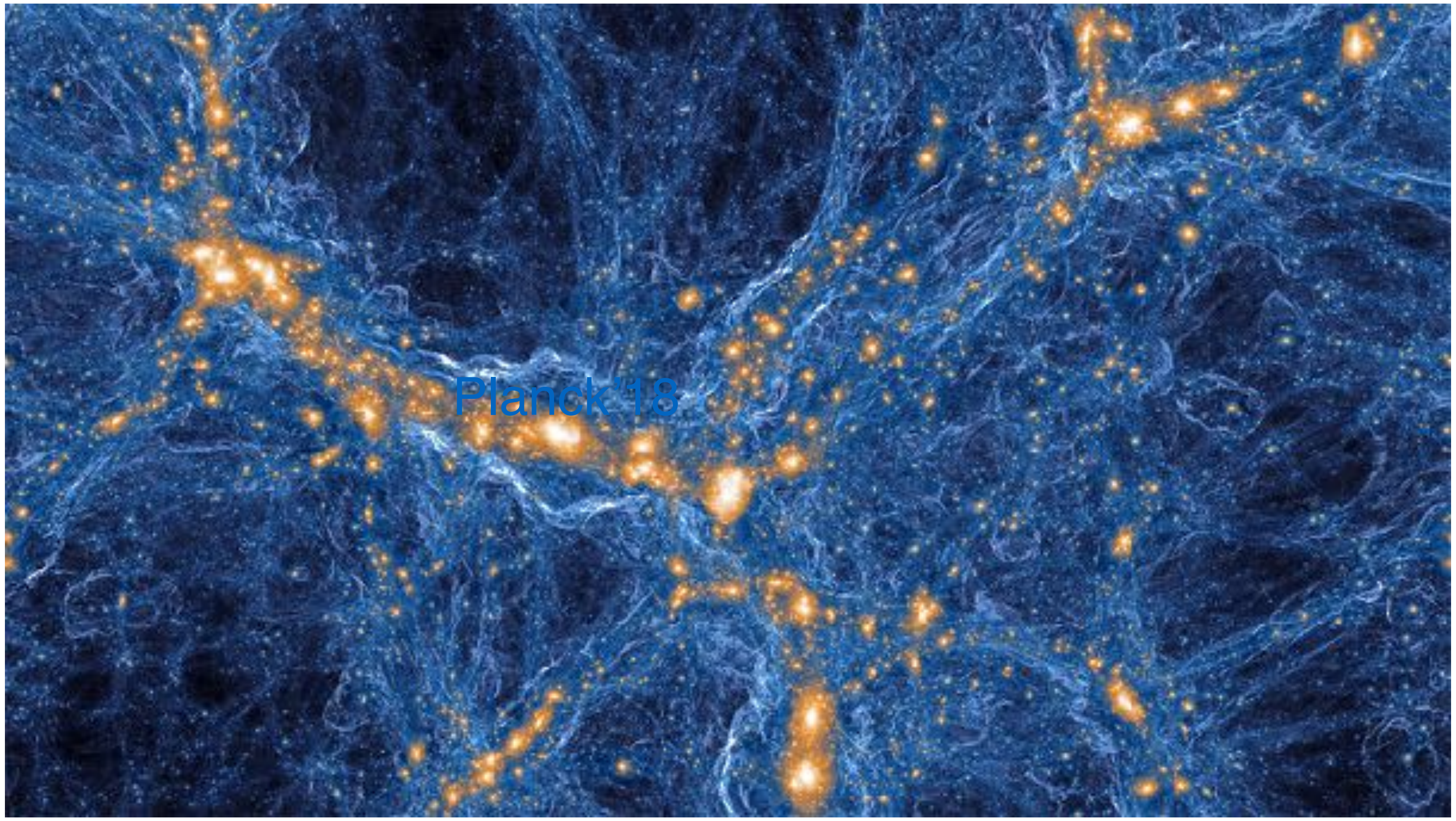
The big problem





- non-linearity = non-Gaussianity

Secondary sources of non-linearity



IllustrisTNG

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

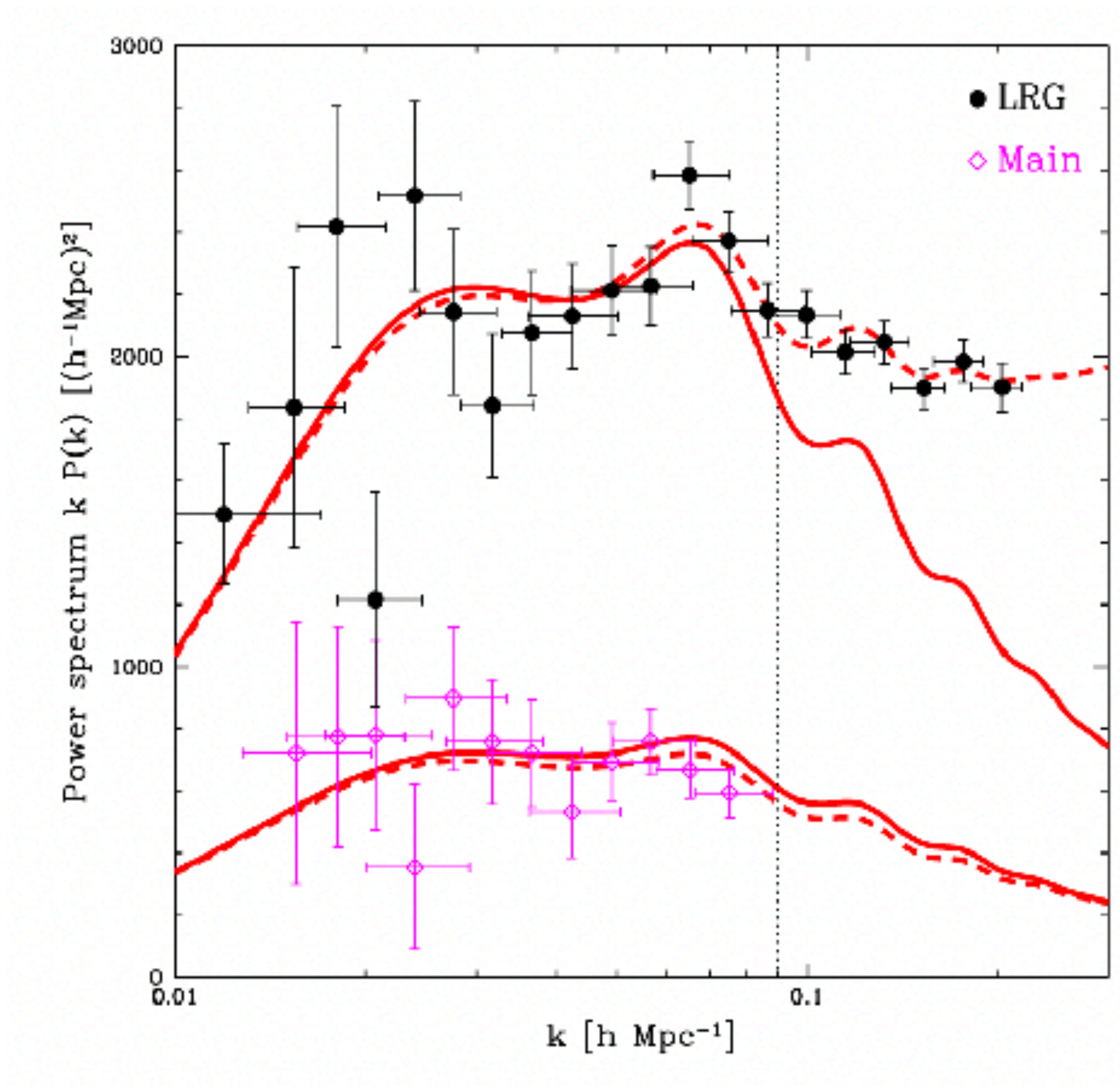
$$\delta_{\rm g} = b_1\delta + b_2\delta^2 + b_{\mathcal{G}_2}(\nabla_{\langle i}\nabla_{j\rangle}\Phi)^2 + \ldots$$

McDonald, Roy (2009), ++

Desjacques, Jeong, Schmidt (2016)

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

Ways to analyse LSS:



Tegmark++, SDSS analysis (2006)

- $\sigma_{\text{theory}} \gg \sigma_{\text{data}}$
- "standard" approach until recently: focus on observables that are approximately stable w.r.t. non-linear effects (distance + growth amplitude)
- Discard shape information

We can do much better!

Understand non-linearities

Analytics vs. Numerics (simulations)

Numerics/Analytics

Simulations

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

Perturbation theory

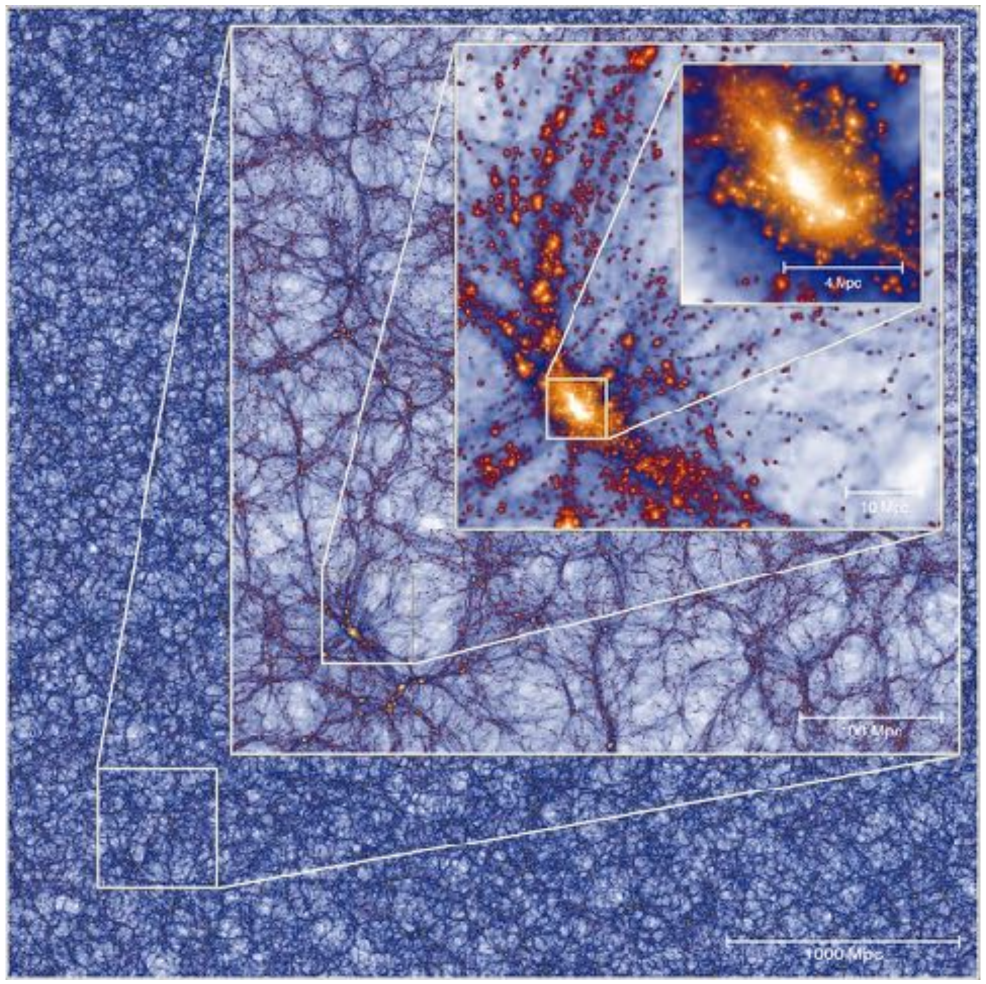
- ✗ limited range
- ✓ precision & accuracy
- ✓ fast/ cheap - beyond LCDM
- ✓ marg. over gastrophysics

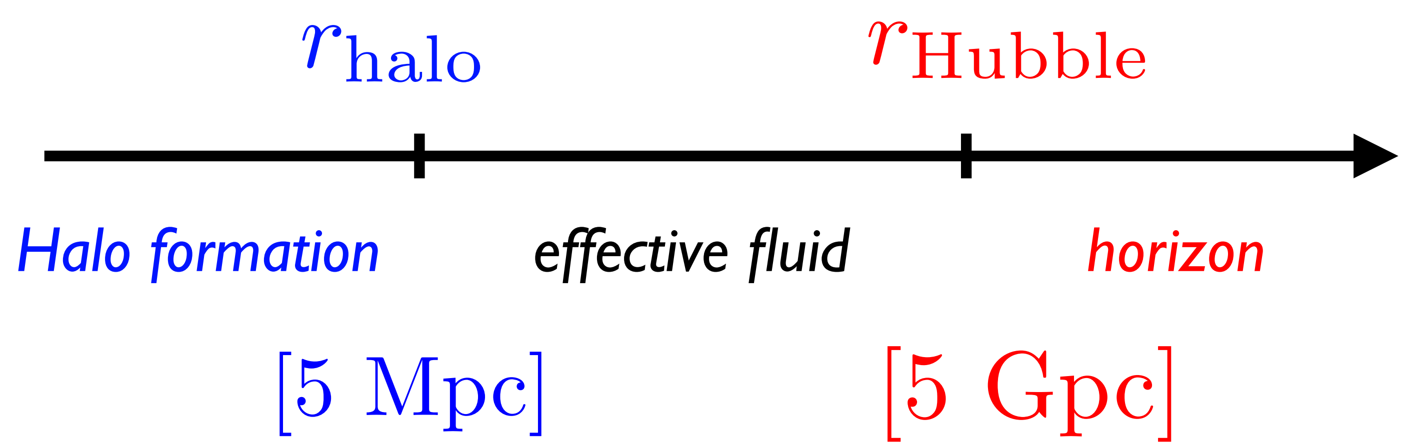
credit: lineartestpilot

State-of-the-art equipment
for theoretical physicist

credit: CartoonStock

Large-scale structure theory





- EFT of Large Scale Structure:

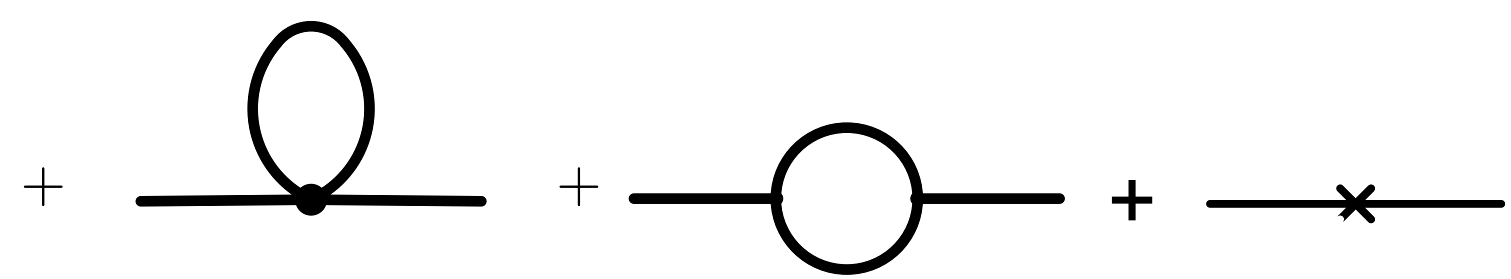
  Baumann (2012), Carrasco, Senatore, Zaldarriaga,
  White, Chen, Vlah, *Schmidt, Pajer, Baldauf, Hertzberg+++*

- TSPT allows me to get $\sim 0.1\%$ understanding

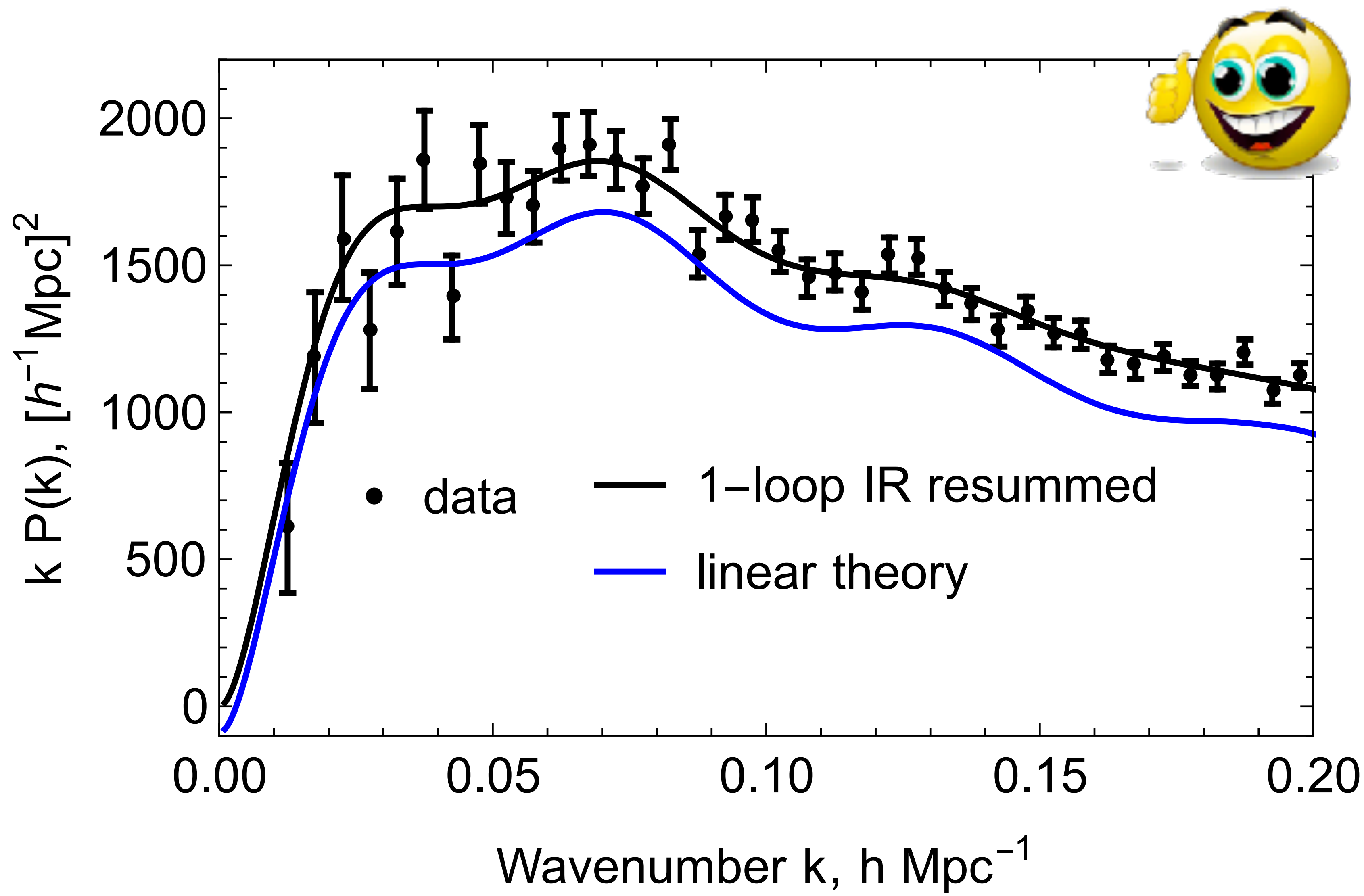
Time-sliced perturbation theory (TSPT)

Path Integral Formulation of EFT of Large-Scale Structure

Blas, Garny, MI, Sibiryakov (2015)



It works!



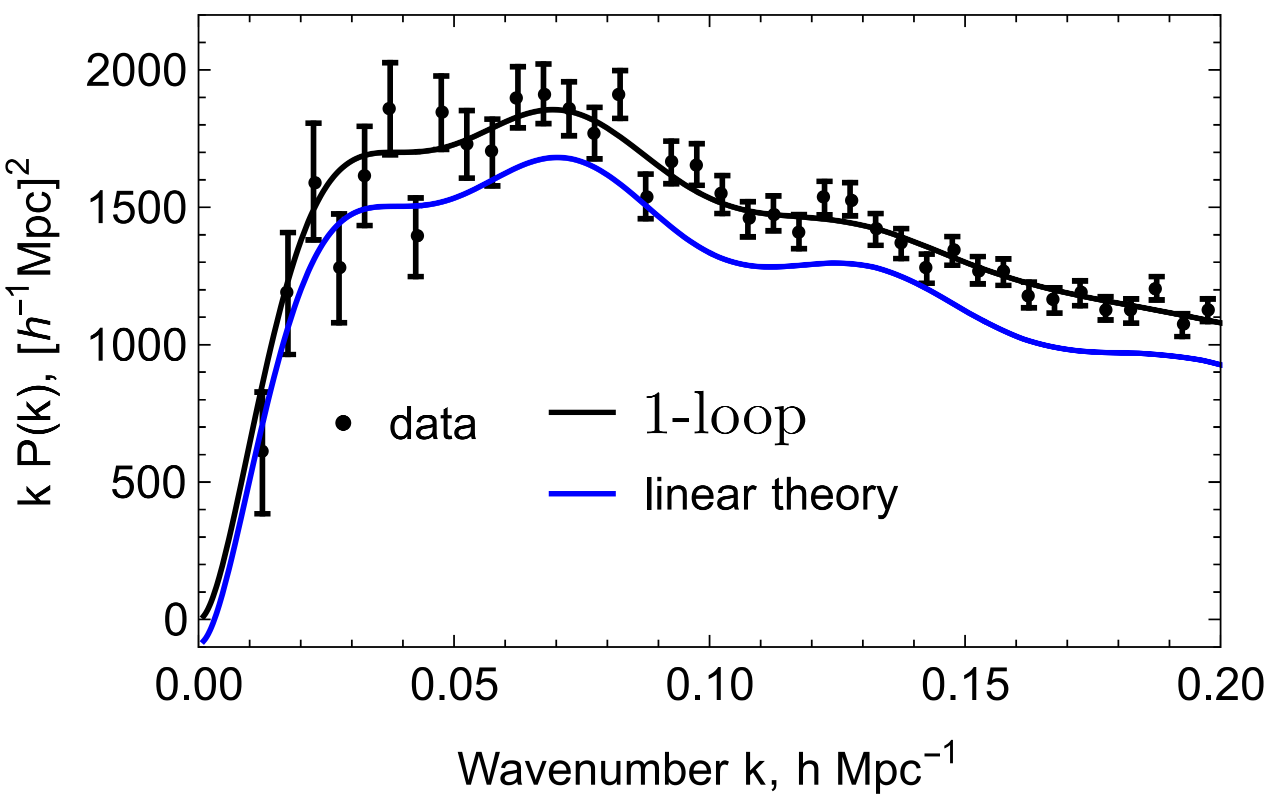
2-loop, 3-loop ….

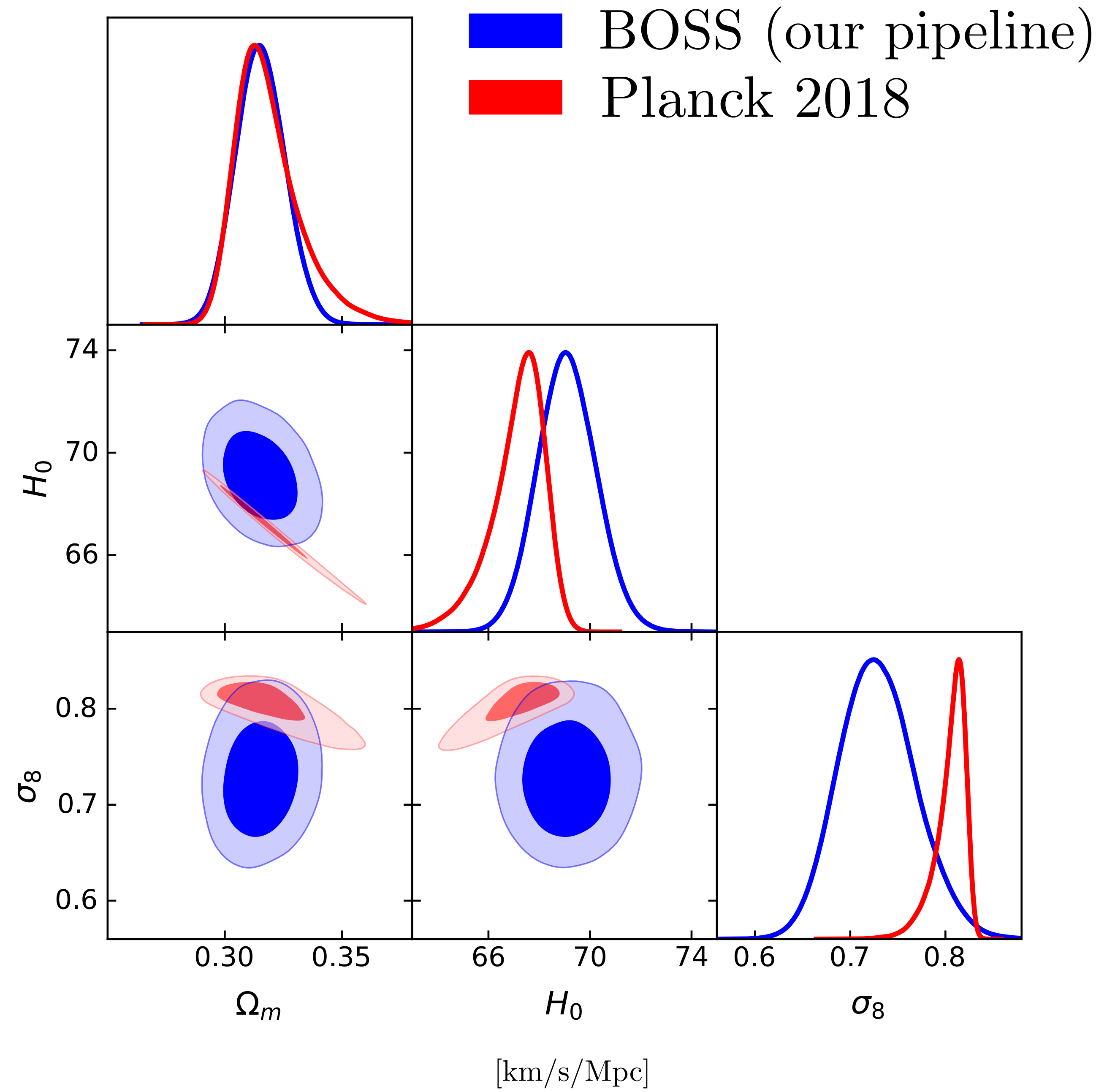
3-point function (bispectrum), 4-pf, …

caveat: nuisance parameters appear (~Wilson coeff's)

Large-scale structure: from theory to data

Our pipeline:





Similar results by M.White's group !

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

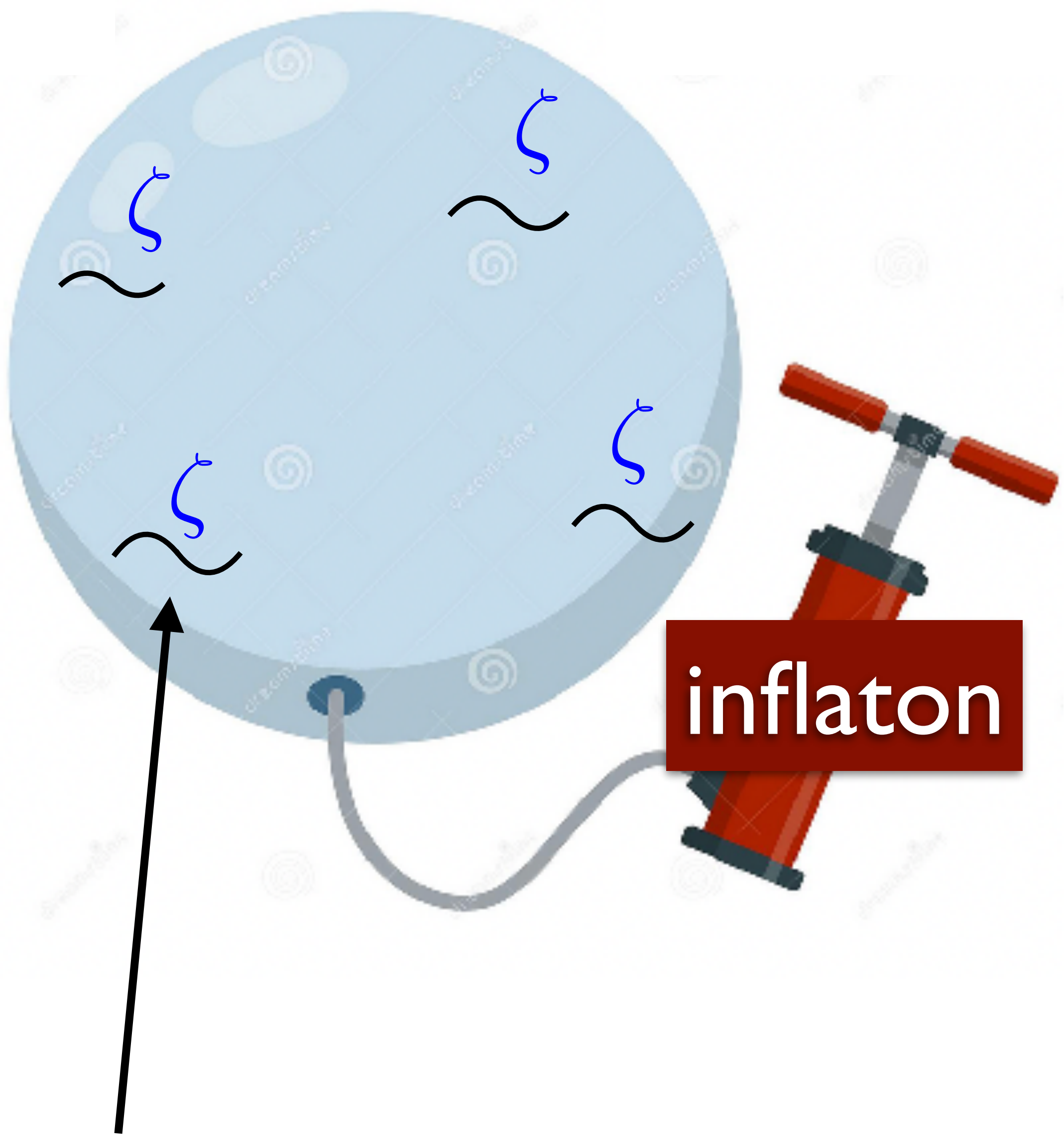
Non-standard scenarios

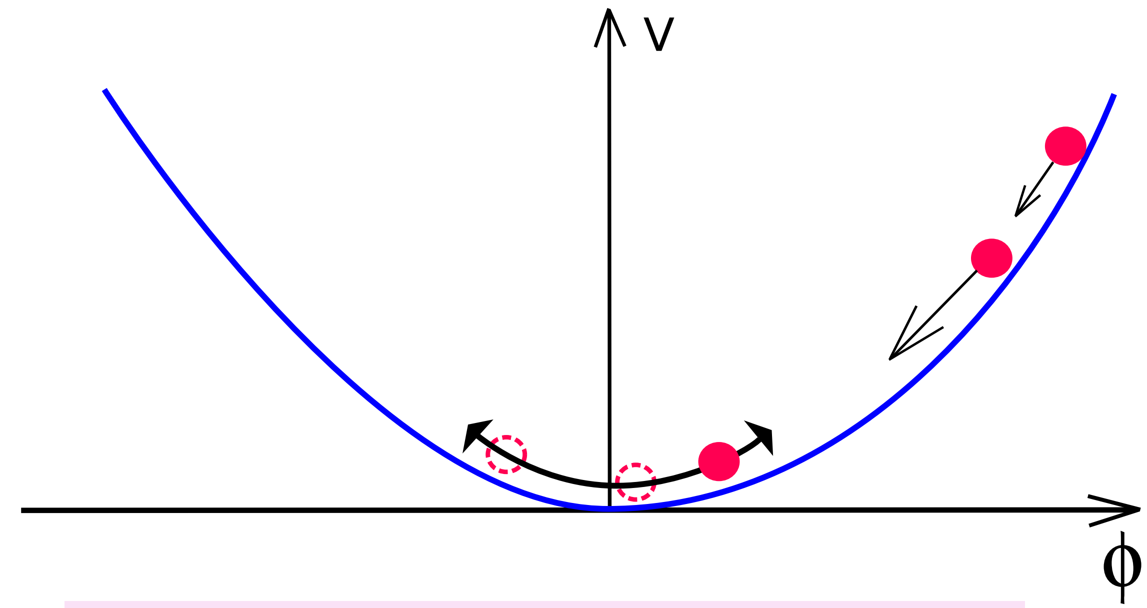
- ✓ Can efficiently explore beyond-LCDM:

- Hubble tension, Early Dark Energy
- Dynamical Dark Energy
- …

- Inflation / Primordial non-Gaussianity
- Dark Matter

Slow Roll Inflation





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

$$\varepsilon \equiv -\frac{\dot{H}}{H^2}\,, \qquad \eta \equiv \frac{\dot{\varepsilon}}{H\varepsilon}$$

$$g_{ij} = a^2(t)e^{2\zeta}\delta_{ij}$$

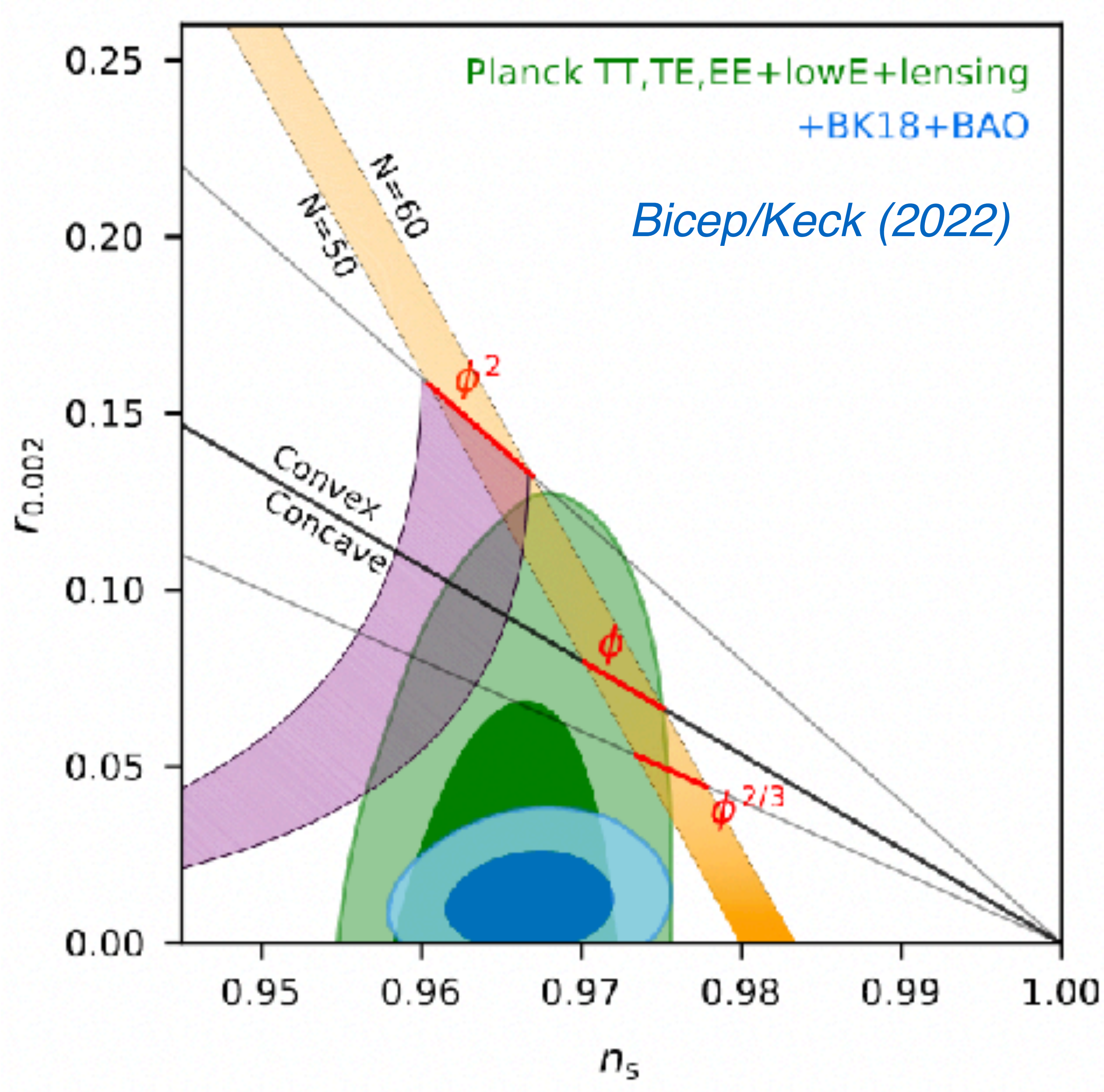
$$k^3 P_\zeta \sim \langle \zeta^2 \rangle \sim A_s k^{n_s - 1}$$

$$\zeta \sim \frac{H}{\dot{\phi}}\delta\phi$$

$$n_s - 1 = 2\eta - 6\epsilon$$

$$r = \frac{P_h}{P_\zeta} = 16\epsilon$$

Inflation



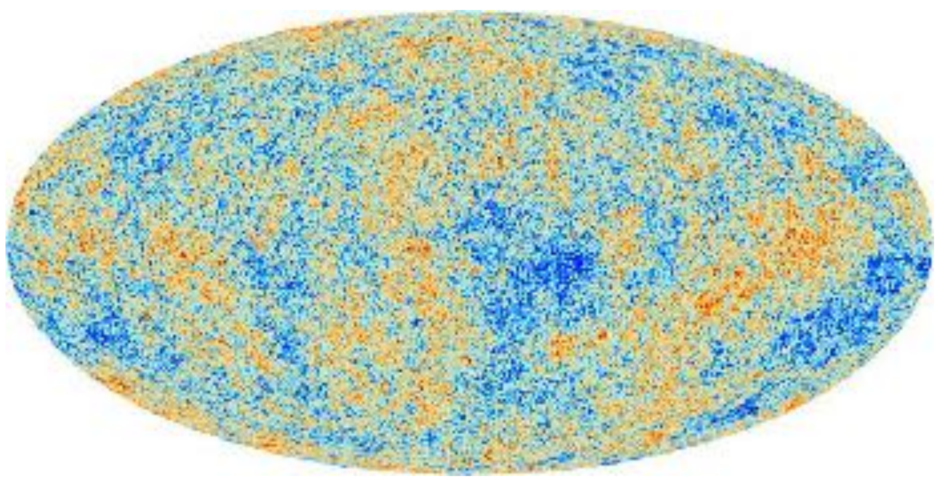
- Energy scale - ? Primordial GW
- How many degrees of freedom ?
- How fast did they propagate?
- Did they have any interaction?

In this talk!

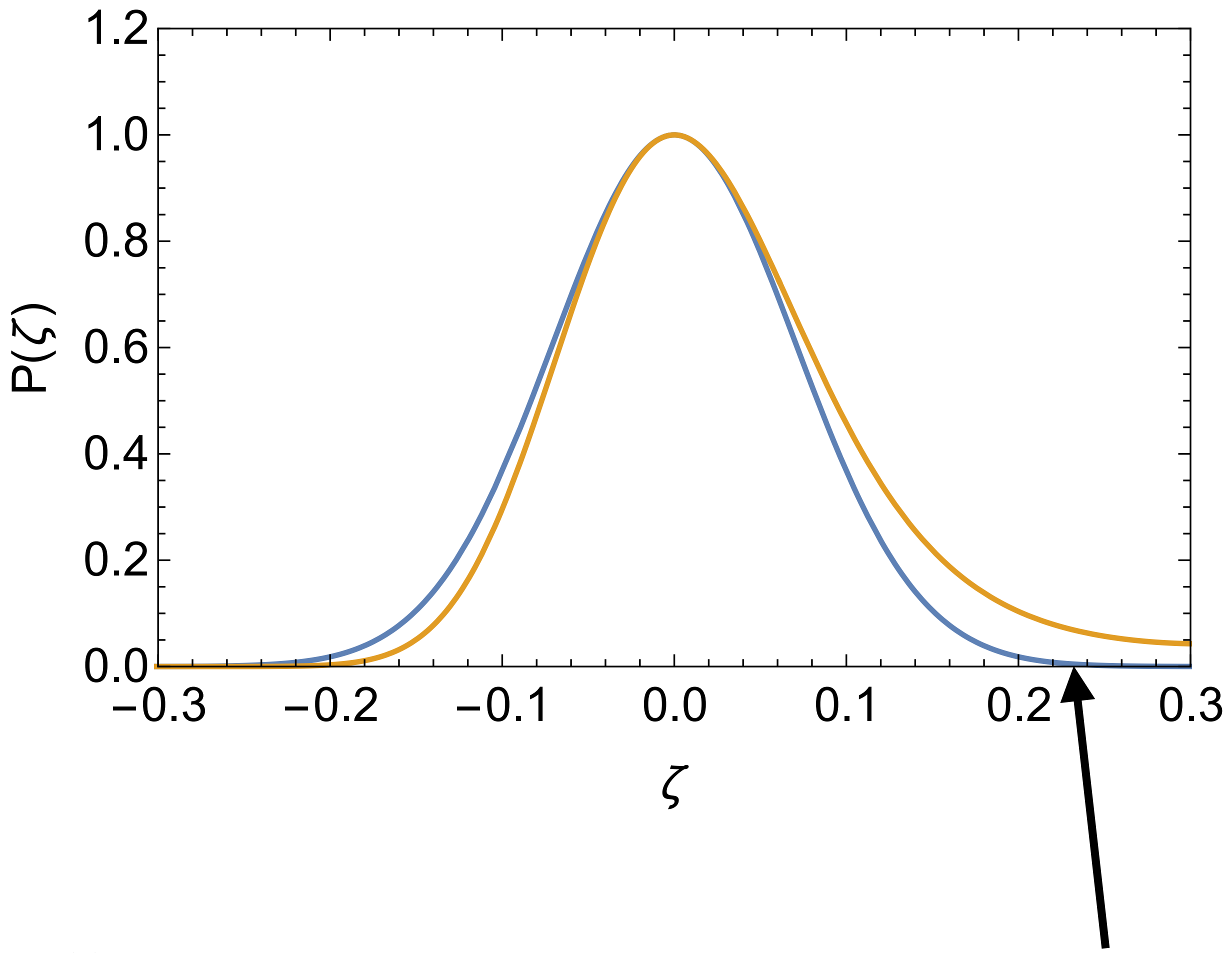
$$A_s \sim \frac{H^2}{M_P^2 \epsilon} \sim 10^{-10}$$

Primordial non-Gaussianity

- Spectrum of fluctuations is nearly Gaussian, … but


Planck'18

- interactions do produce primordial non-Gaussianity (PNG)



$$f_{\rm NL} = 10^5$$

Skewness: $$\frac{\langle \zeta^3 \rangle}{\langle \zeta^2 \rangle^{3/2}} \sim 10^{-5} f_{\rm NL}$$

Local PNG

- ex: Modulated reheating, decay rate is controlled by a field

$$\Gamma = \Gamma_0 + \Gamma_1 \sigma(t, \mathbf{x}) + \Gamma_2 \sigma^2(t, \mathbf{x}) + ...$$

- This gives the curvature fluctuation

$$\zeta(t, \mathbf{x}) = \zeta_G(t, \mathbf{x}) + f_{\rm NL}^{\rm local} \zeta_G^2(t, \mathbf{x}) + ...$$

- Primordial skewness (bispectrum): $B_\zeta \sim \langle \zeta^3 \rangle \sim f_{\rm NL}^{\rm local} P_\zeta^2$

$$\frac{\langle \zeta^3 \rangle}{\langle \zeta^2 \rangle^{3/2}} \sim 10^{-5} f_{\rm NL}$$

Local PNG

$$\zeta(t,\mathbf{x}) = \zeta_G(t,\mathbf{x}) + f_{\rm NL}^{\rm local}\zeta_G^2(t,\mathbf{x}) + \ldots$$

- Generated by local physics after horizon crossing

  multi-field,
  curvaton,
  modulated reheating, etc.

- Theoretical target: $f_{\rm NL}^{\rm local} \sim 1 \div 10$
- Detection of $f_{\rm NL}^{\rm local}$ = rule out single field models
- *Maldacena (2002)*

  ~~$\zeta(t,\mathbf{x}) = \zeta_G(t,\mathbf{x}) + f_{\rm NL}^{\rm local}\zeta_G^2(t,\mathbf{x}) + \ldots$~~

Non-Gaussianity from Cubic Interactions

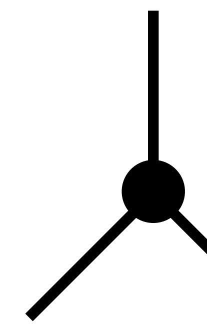
- Vanilla single field:

$$S_\phi = \frac{1}{2}\int d^4x\; a^3\left[\dot\phi^2 - \frac{(\partial_i\phi)^2}{a^2} + \mathcal{O}(\epsilon)\right]$$

$$ds^2 = -dt^2 + a(t)^2 d\mathbf{x}^2$$

- Interactions:

$$S_\phi = \frac{1}{2}\int d^4x\; a^3\left[\dot\phi^2 - \frac{(\partial_i\phi)^2}{a^2} + \frac{\dot\phi^3}{M^2} + \ldots\right]$$



$\dot\phi^3$

- Effective field theory of inflation: write all interactions consistent with symmetries

$$B_\zeta(k,k,k) \sim f_{\rm NL}(P_\zeta(k))^2$$

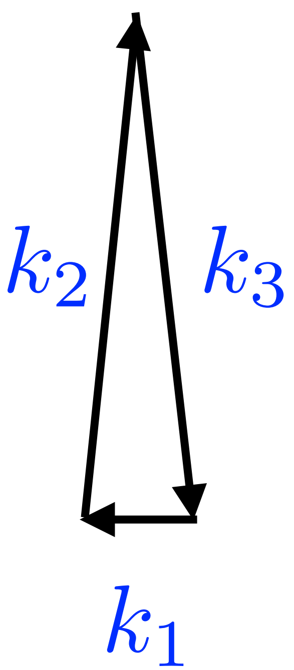
- Theoretical target: $f_{\rm NL}^{\text{non-local}} \sim 1 \div 100$

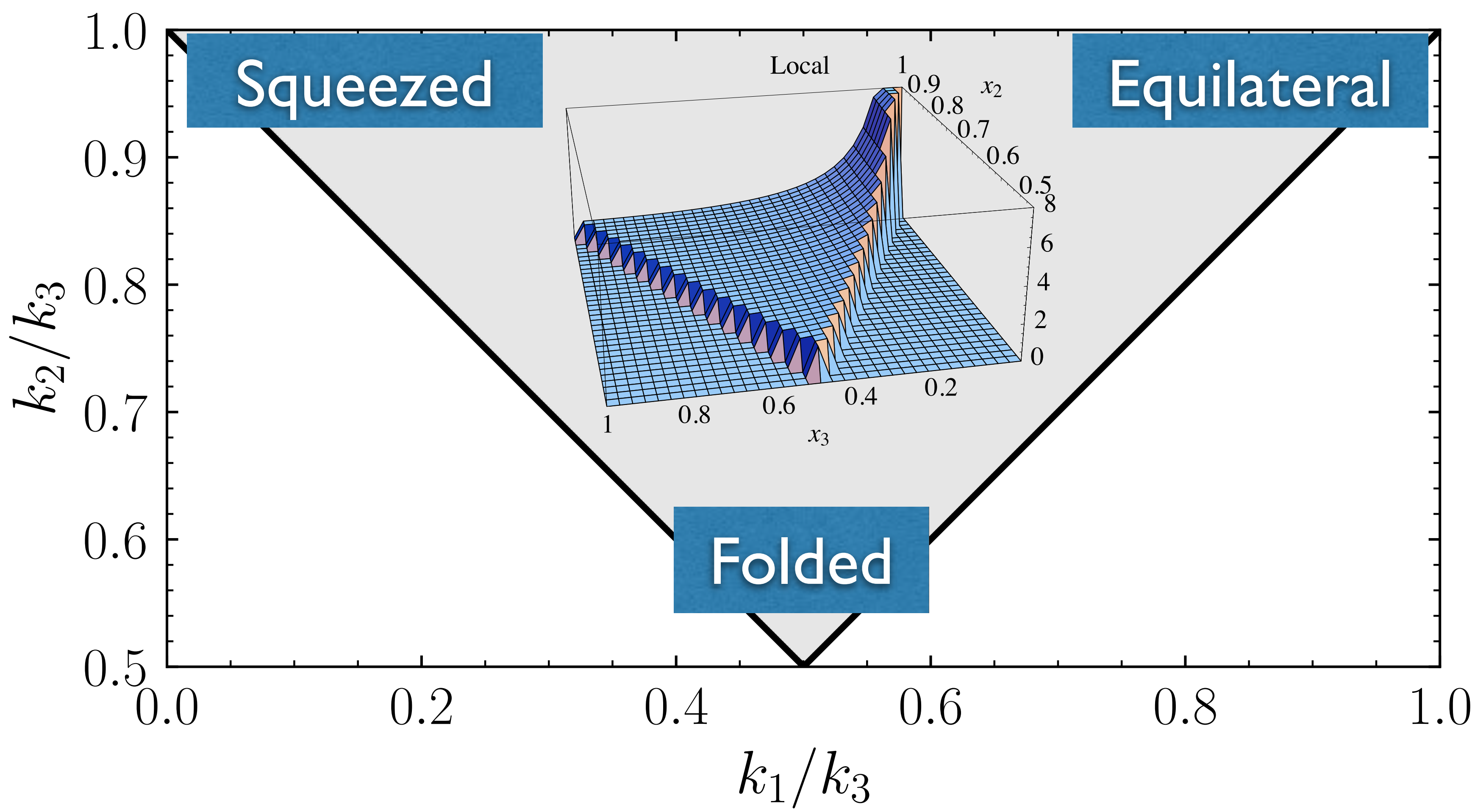
Shapes of non-Gaussianity

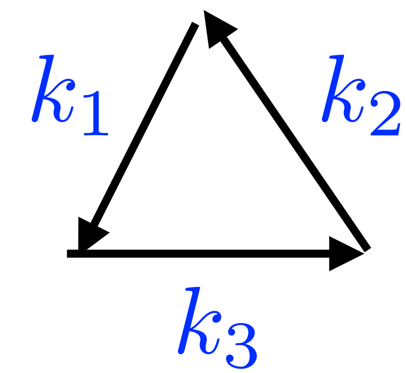
$$S(k_1, k_2, k_3) = k_1^2 k_2^2 k_3^2 B_\zeta(k_1, k_2, k_3)$$

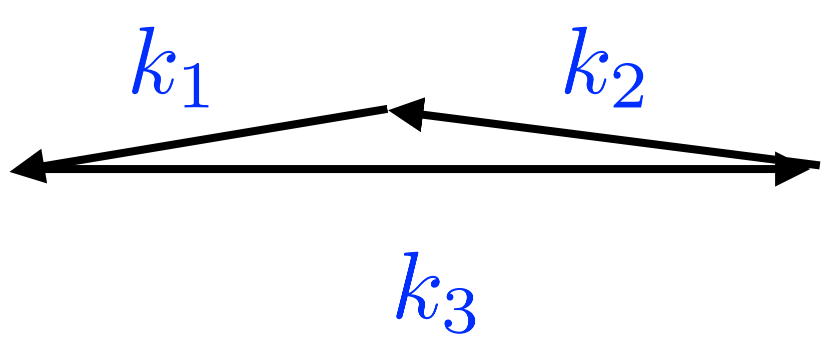
Local (multi-field)

Equilateral (single field)







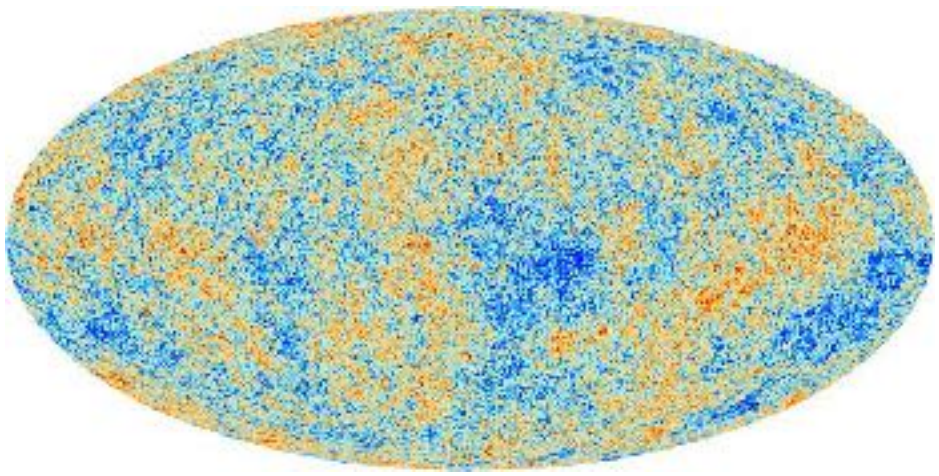


Orthogonal (single field)

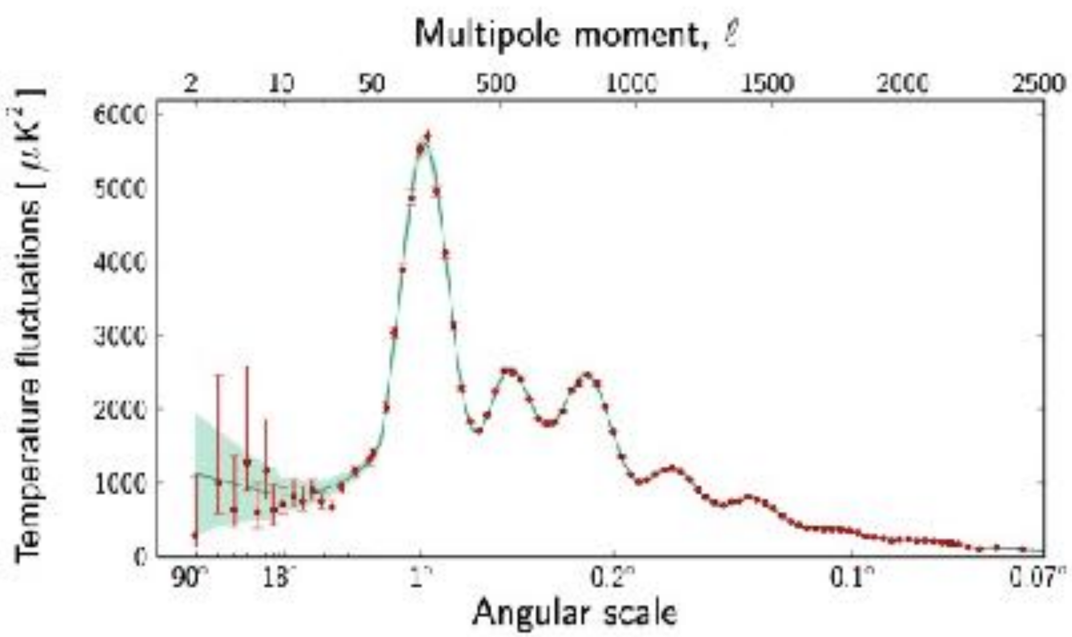
Babich, Creminelli, Zaldarriaga'04

Senatore, Smith, Zaldarriaga'09

Planck constrains on PNG



Planck'18



cf. Planck 2018:

$$f_{\rm NL}^{\rm equil} = -26 \pm 47$$

$$f_{\rm NL}^{\rm ortho} = -38 \pm 24$$

$$f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$$

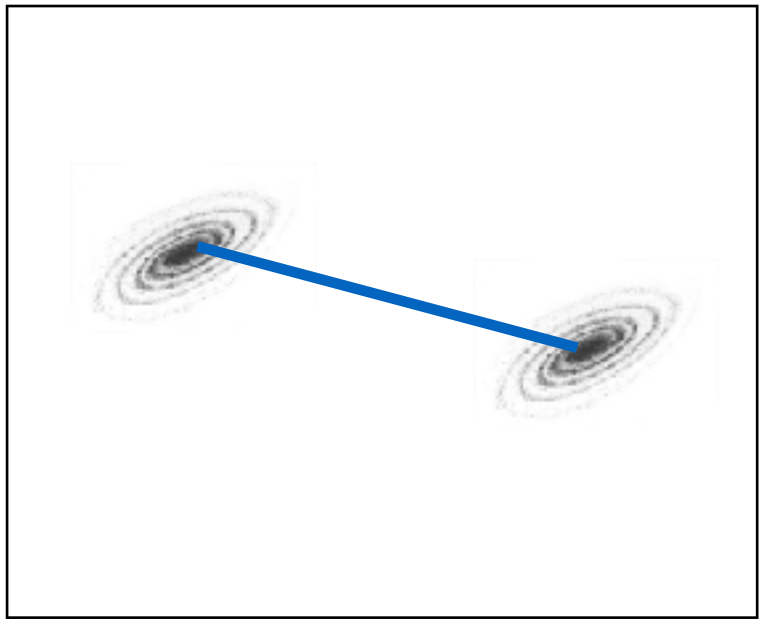
- CMB cannot improve by more than 2x

Ade et al., Simons observatory forecast (2018)

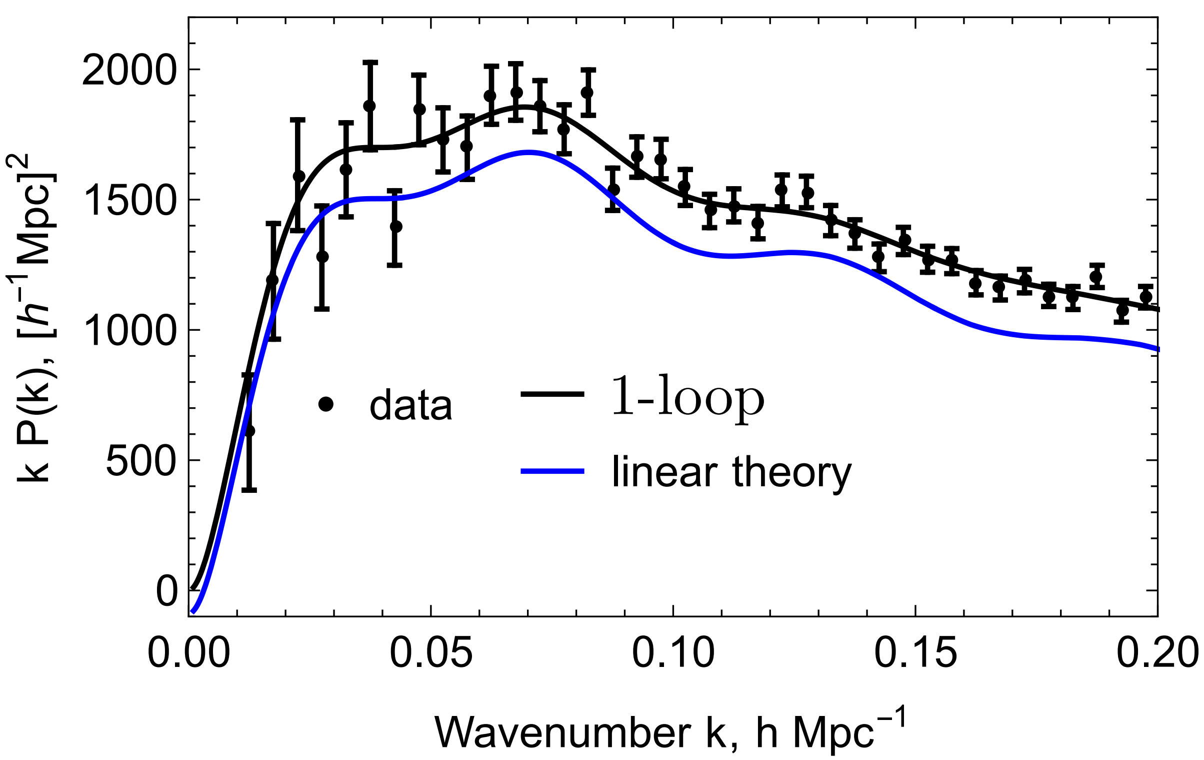
- Limited by the number of modes!

Non-Gaussianity: correlation functions

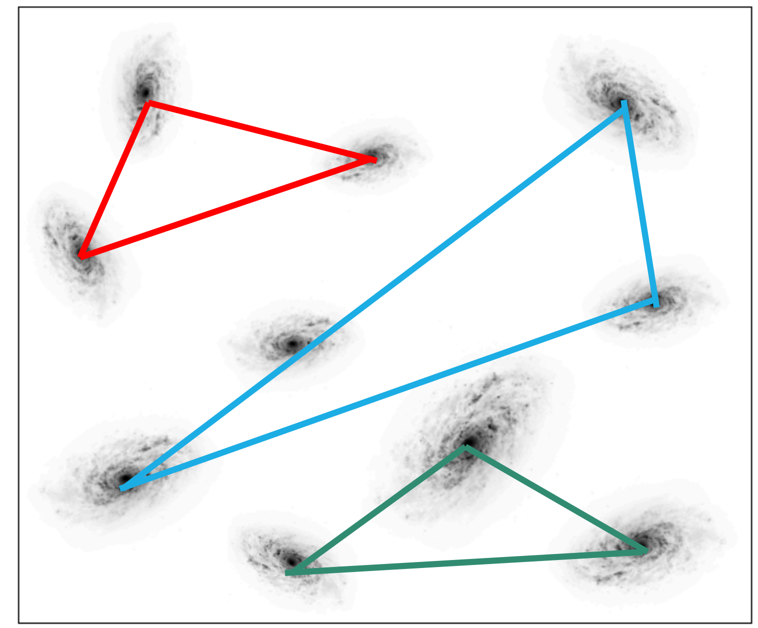
Power spectrum



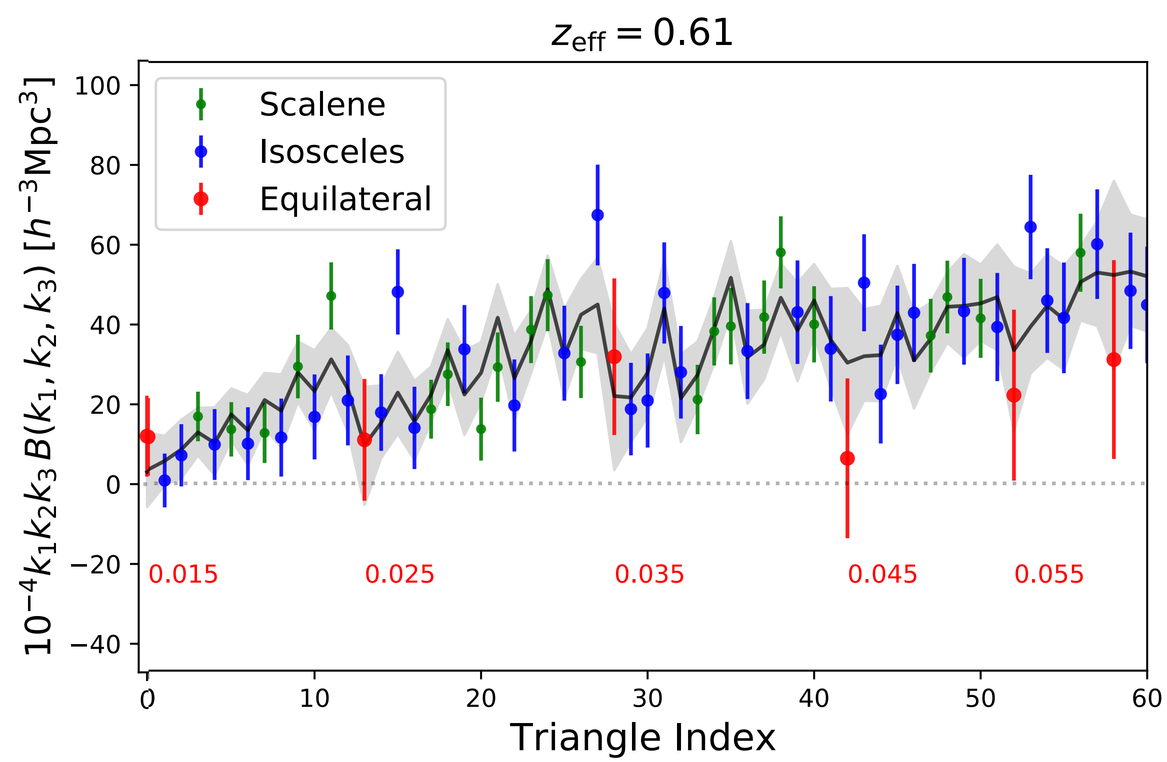
$$P(k) = \langle \delta(\mathbf{k}) \delta(\mathbf{k}') \rangle'$$



Bispectrum



$$B_g(k_1, k_2, k_3) = \langle \delta_g(\mathbf{k}_1) \delta_g(\mathbf{k}_2) \delta_g(\mathbf{k}_3) \rangle'$$

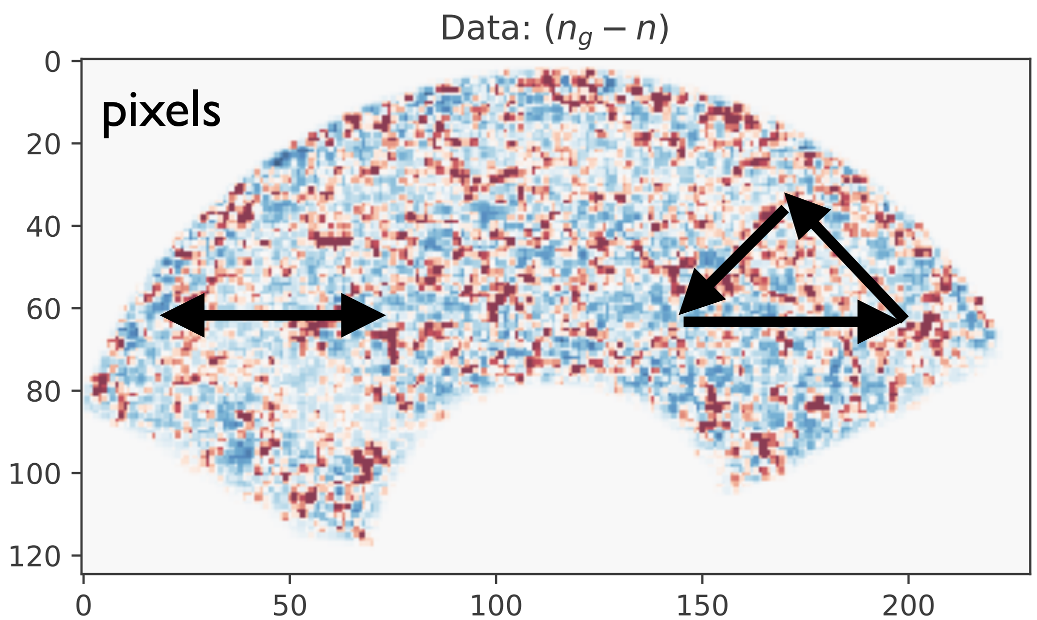


Cosmology with the Bispectrum

The bispectrum data was not systematically explored before

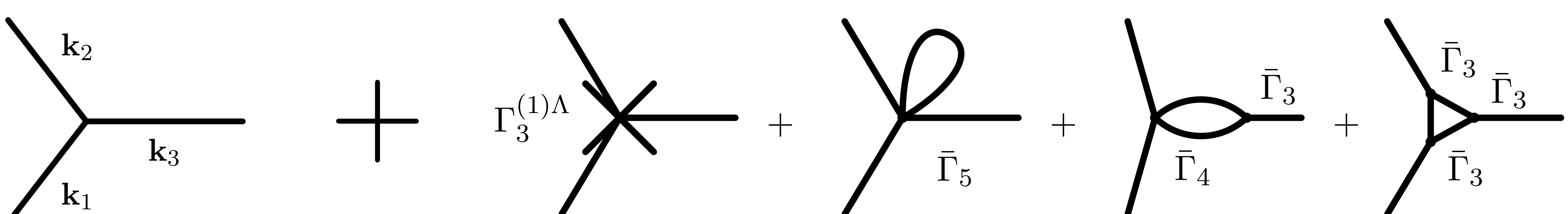
New pipeline:

Measure B from the BOSS data (mask-free)

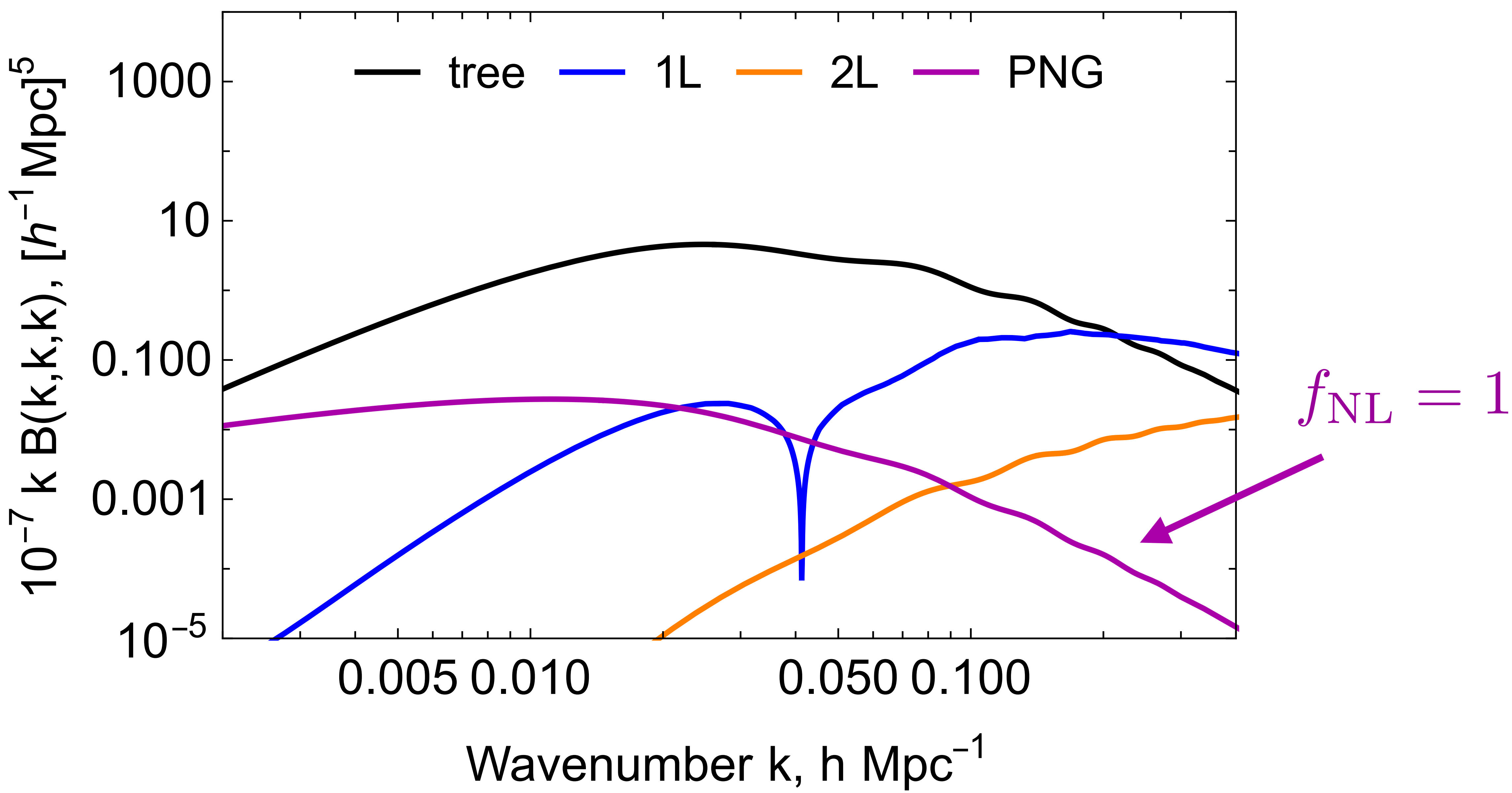


Philcox (2021)
Philcox, MI (2021)
MI ++ (2021)
Philcox, MI ++ (2022)

Systematic theory model: tree-level and one-loop EFT



Theoretical challenge



- $f_{\rm NL} \sim 1 \div 10$ is equivalent to 0.1% precision
- Only EFT can guarantee this precision!

New constraints on PNG from BOSS

BOSS constrains:

$$f_{\rm NL}^{\rm equil} = 260 \pm 300$$

$$f_{\rm NL}^{\rm ortho} = -23 \pm 120$$

$$f_{\rm NL}^{\rm local} = -33 \pm 28$$

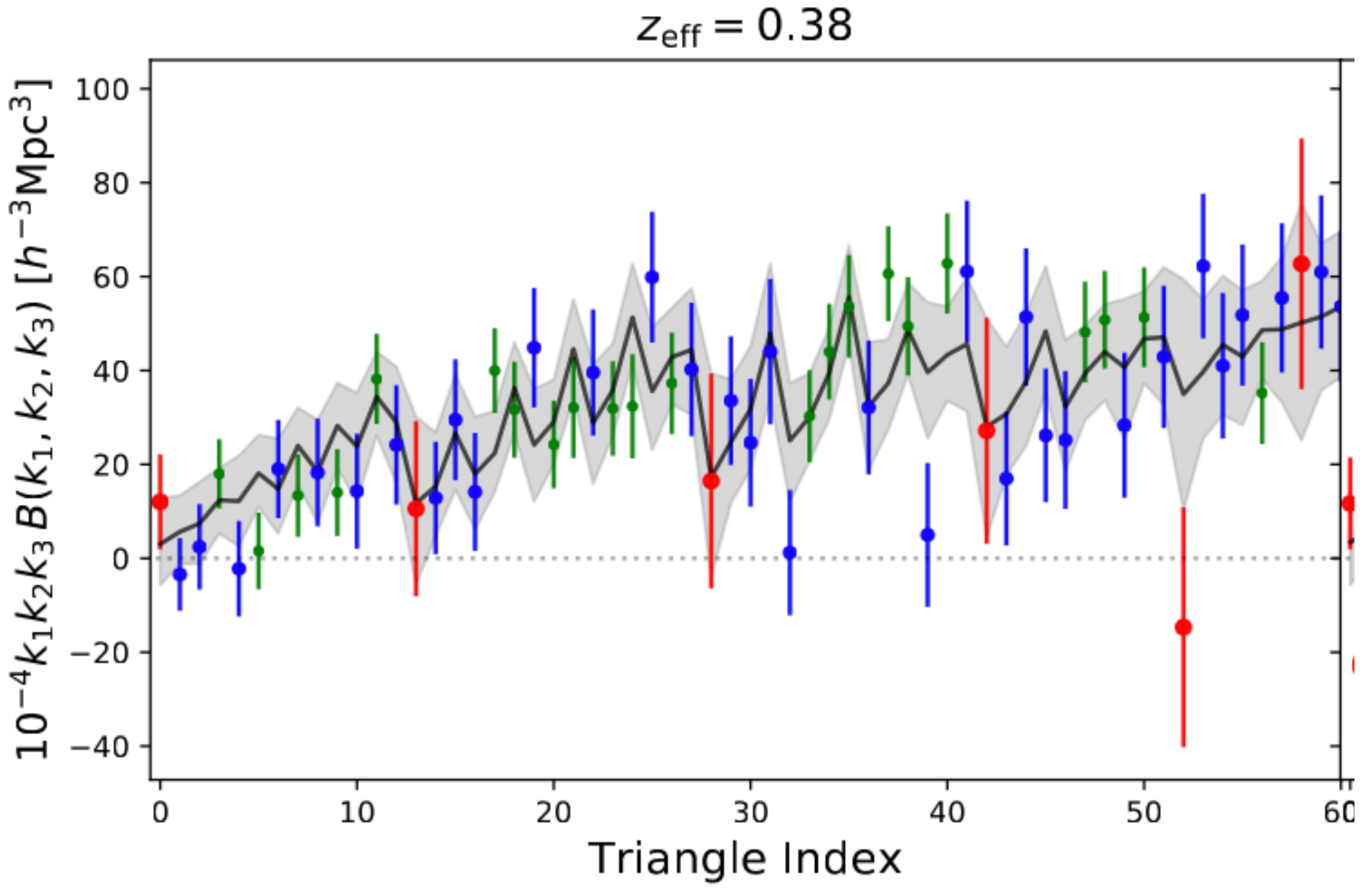
Cabass, MI ++ (2022a, 2022b)

cf. Planck 2018:

$$f_{\rm NL}^{\rm equil} = -26 \pm 47$$

$$f_{\rm NL}^{\rm ortho} = -38 \pm 24$$

$$f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$$

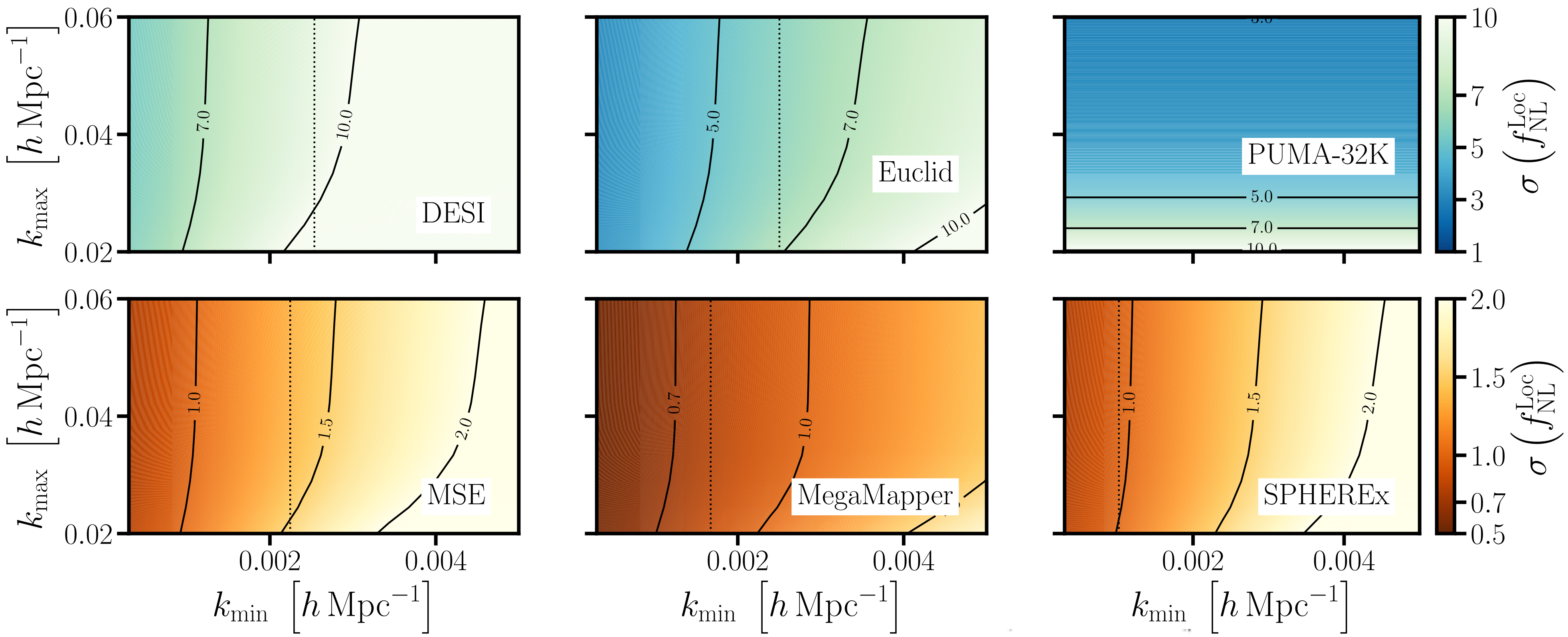


$f_{\rm NL}^{\rm equil} \sim c_s^{-2}$. $c_s \geq 0.013$ at 95% CL

Future constraints:

- $f_{\rm NL}^{\rm local}$

Sailer et al (2021)

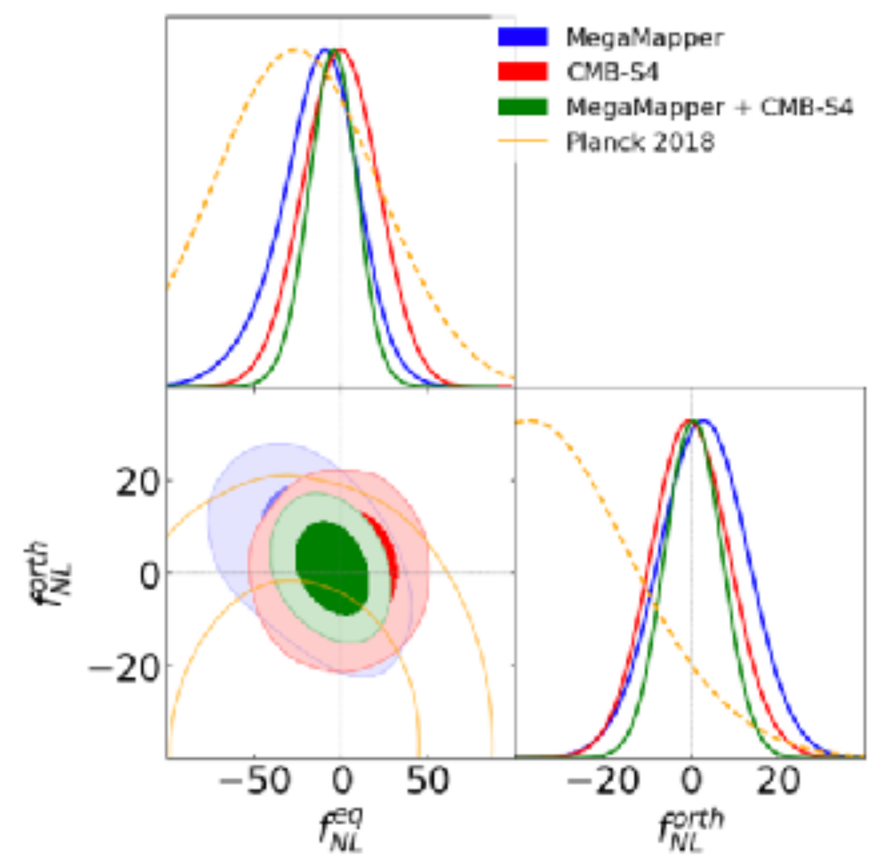


- $f_{\rm NL}^{\rm eq,orth}$

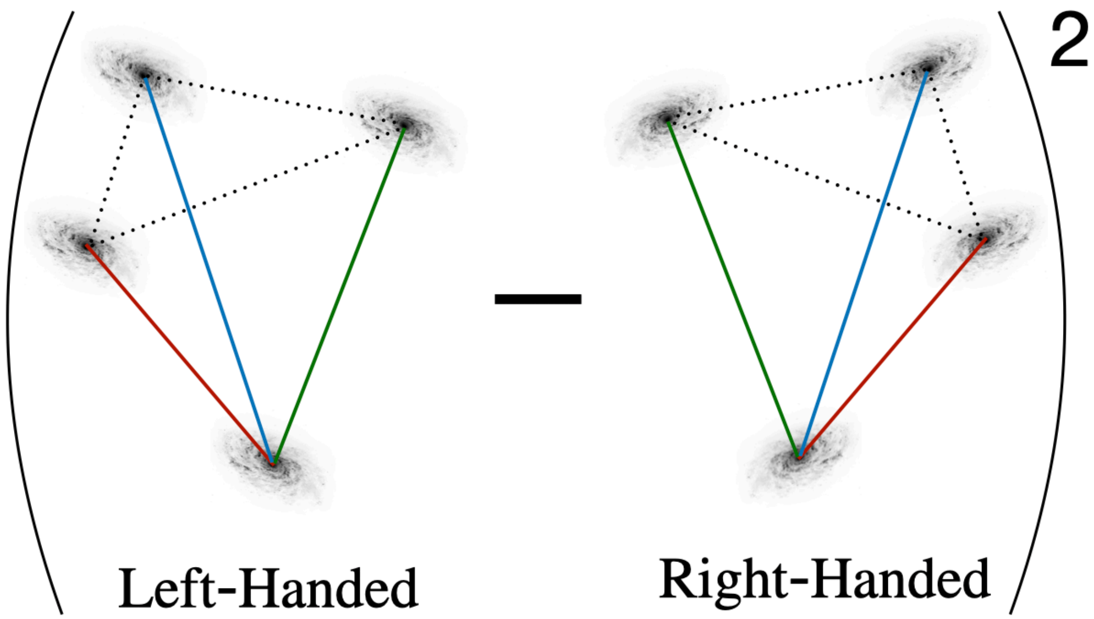
Philcox, MI, ++(2022)

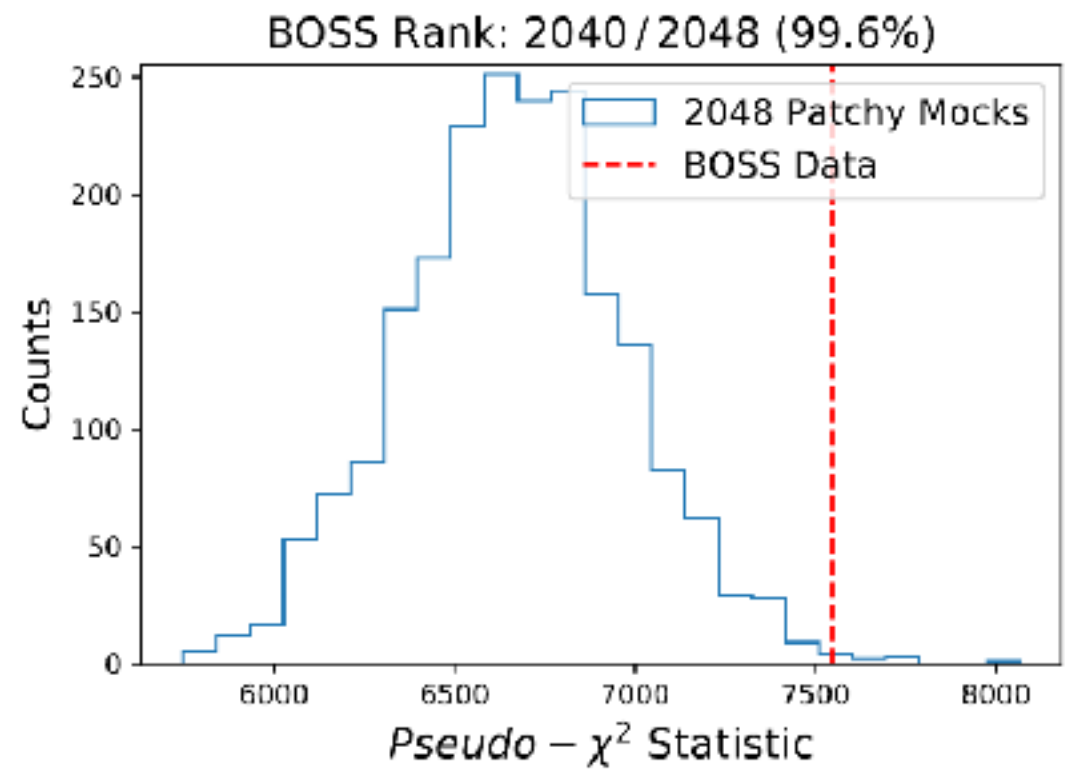
Megamapper+CMB S4

$$\sigma(f_{\rm NL}^{\rm local}) = 0.5$$
$$\sigma(f_{\rm NL}^{\rm eq}) = 14$$
$$\sigma(f_{\rm NL}^{\rm orth}) = 7$$



Unknown unknown: Parity Violation with 4-pf





- Detection of parity violation! *Cahn et al. (2021)*

  $$@ \ (2.9 \div 7)\sigma$$

  Philcox (2022) *Hou et al. (2022)*

- Cannot be generated by non-linear clustering!

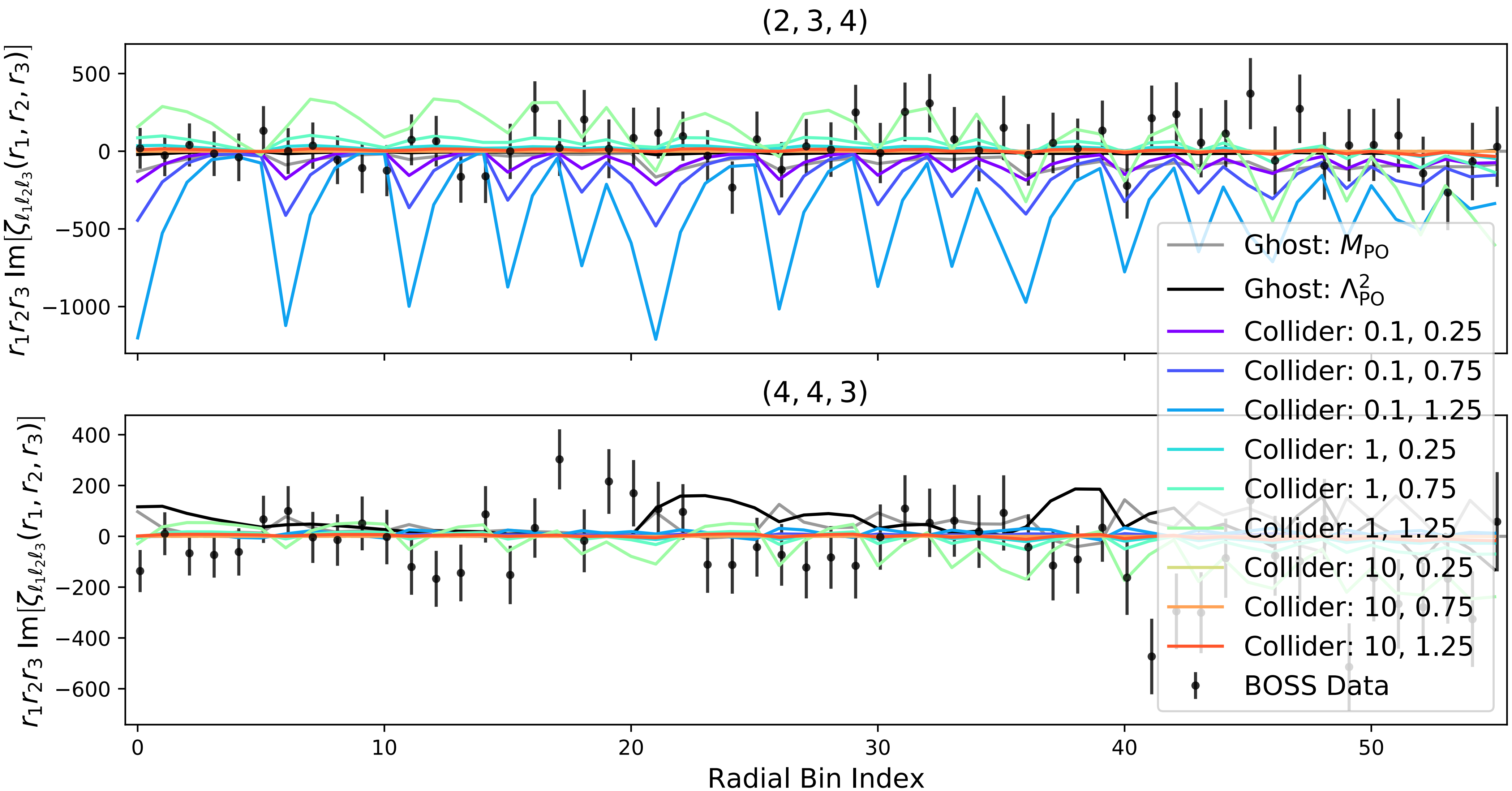
- If true, must be primordial

Parity Violation in Inflation

- **EFT of Inflation:** *Cabass, MI, Philcox (2022)*

$$S_{\pi\pi\pi\pi}^{(\mathrm{LO})} = \frac{1}{M_{\mathrm{PO}}} \int \mathrm{d}^4x\, \sqrt{-g}\, a^{-9} \epsilon_{ijk} \partial_m \partial_n \pi \partial_n \partial_i \pi \partial_m \partial_l \partial_j \pi \partial_l \partial_k \pi$$

- **Not supported by data:**



Dark Matter

- Currently: CDM
- small scale problems (caveat: baryons)
- $\Omega_{dm}/\Omega_b \sim 5$ **(???)**
- DM not cold (fraction) - ?
- LSS is more sensitive than CMB !

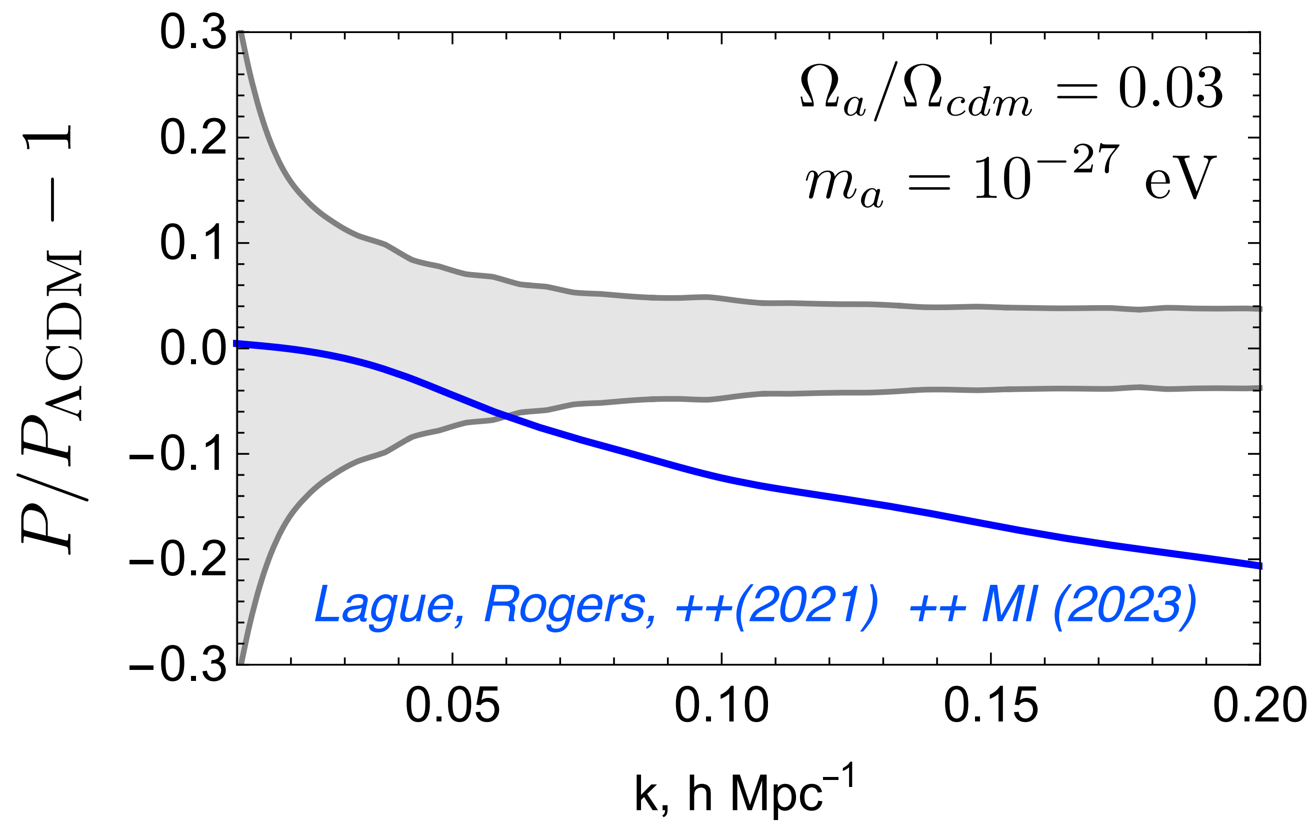
Example: **Axions**

$$\Box\phi - m_{\rm a}^2\phi = 0$$

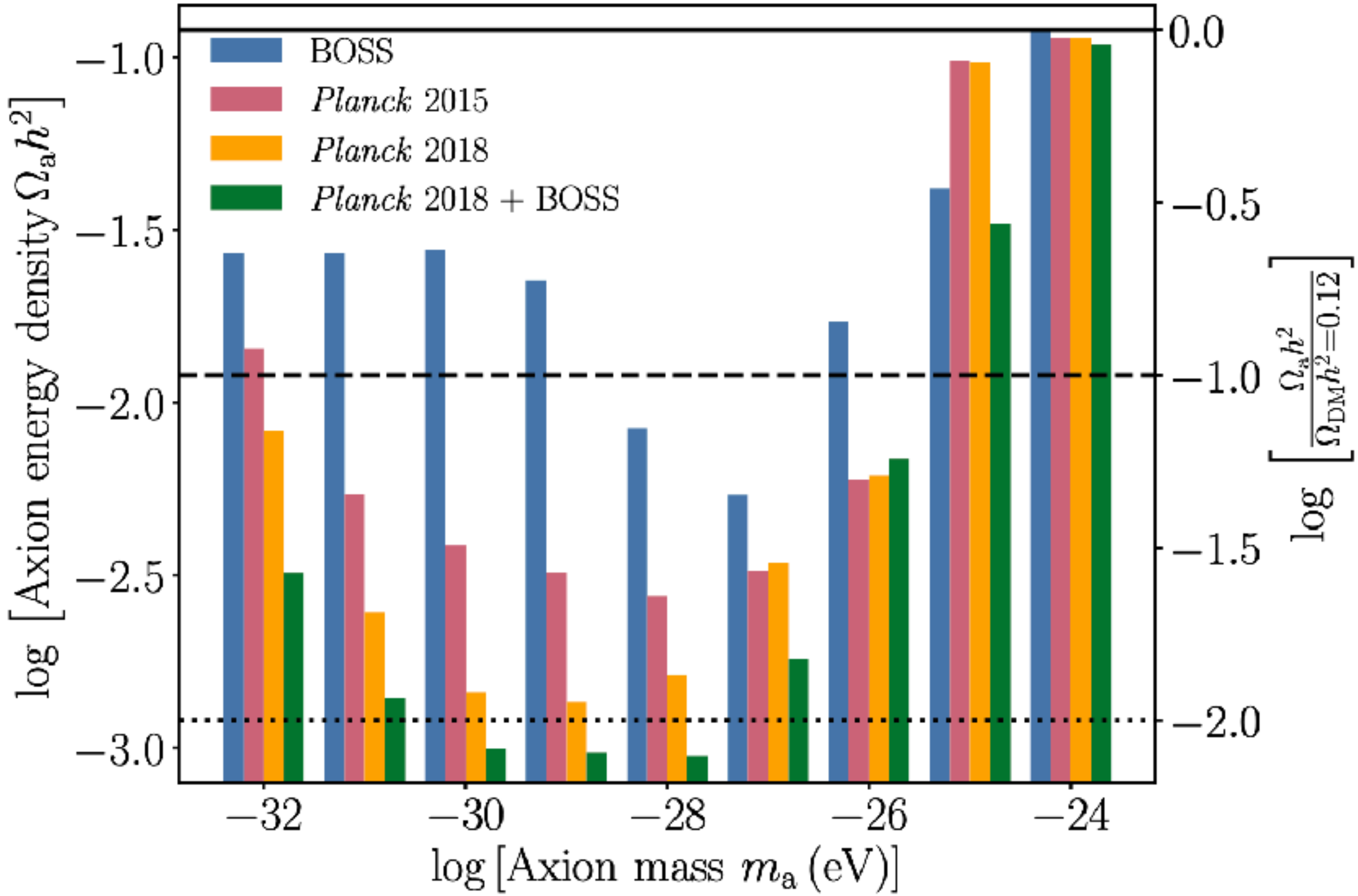
Hu, Barkana, Gruzinov (2000)

$$\dot{\boldsymbol{v}} + H\boldsymbol{v} + \frac{1}{a}(\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = -\frac{1}{a}\nabla\Phi - \frac{\hbar^2}{2m^2a^3}\nabla p$$

$$p \equiv -\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}$$

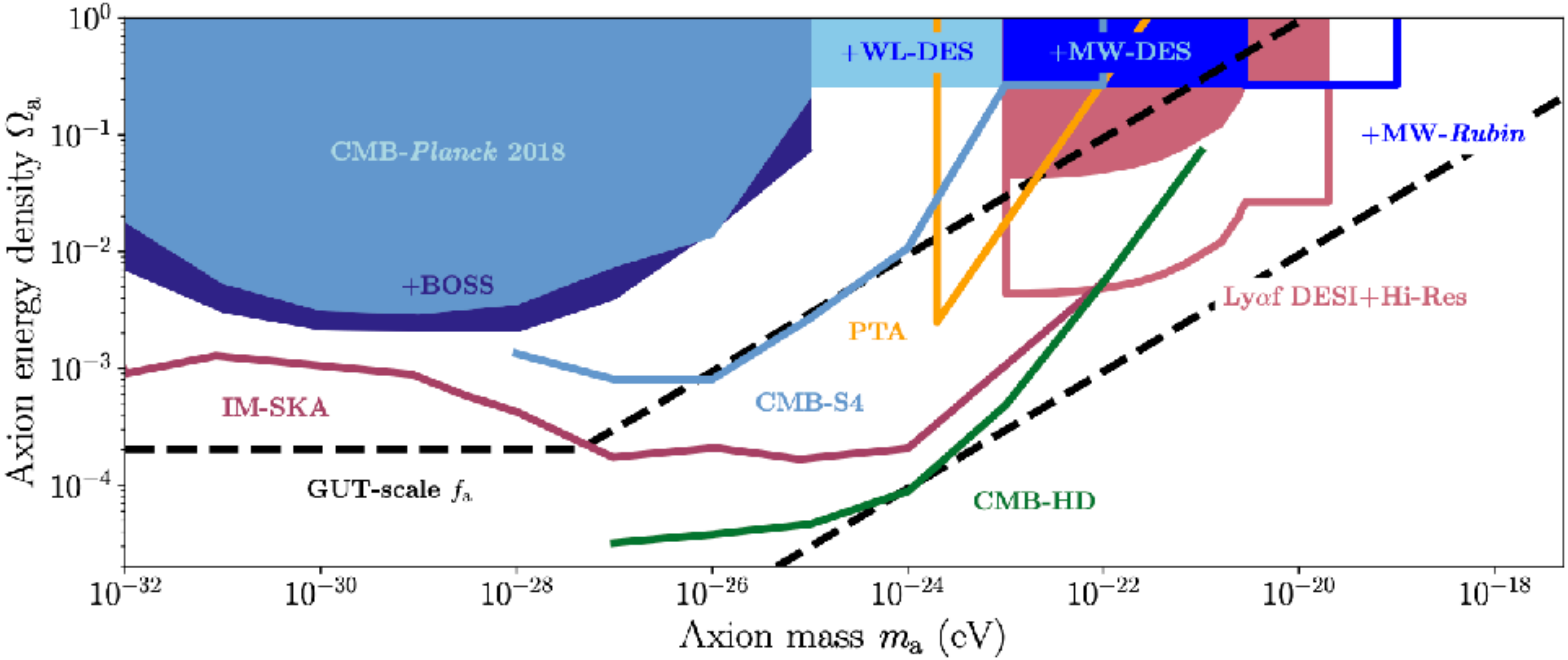


Axion Dark Matter constraints



Rogers, Lague, MI ++(to appear)

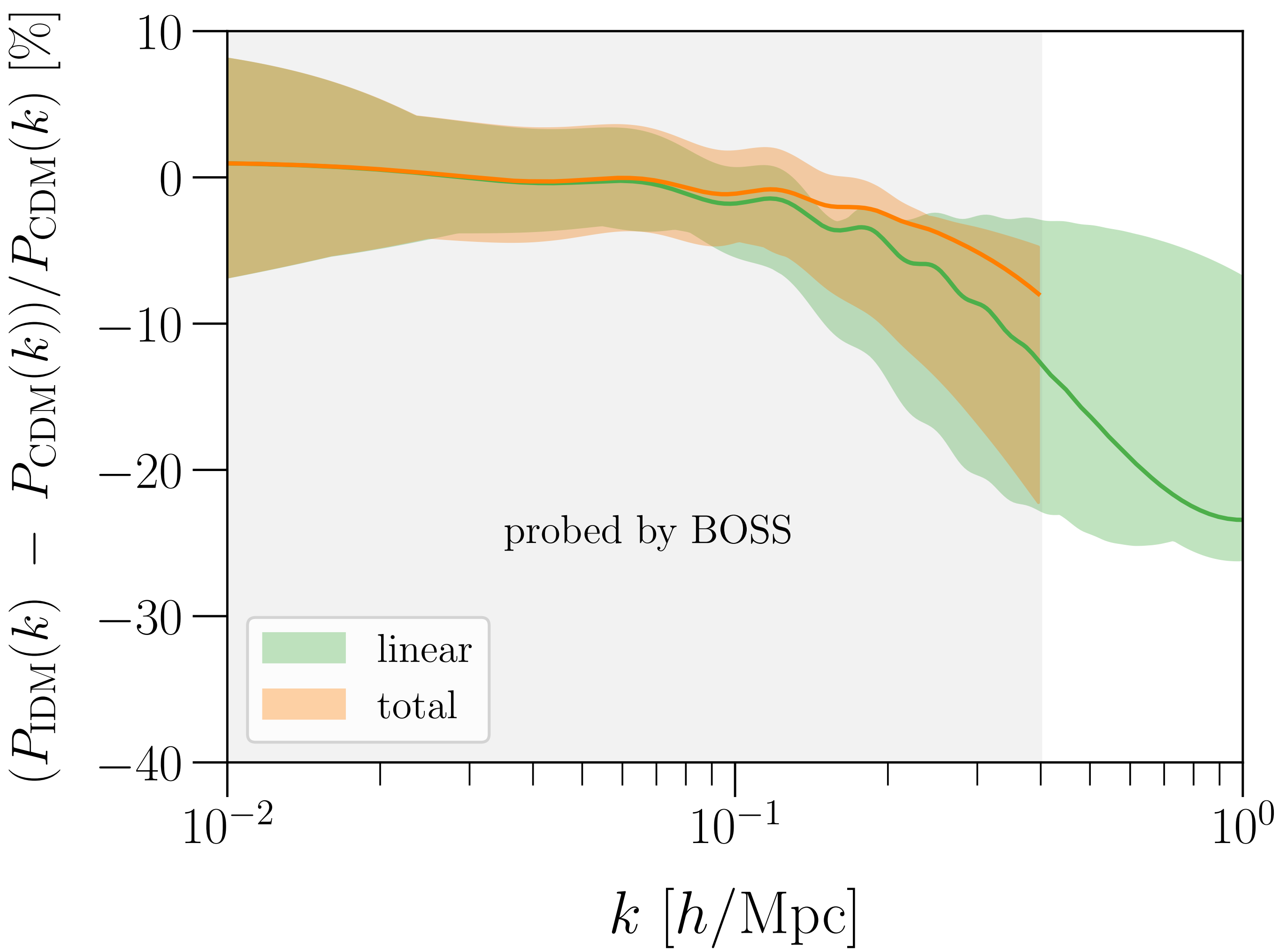
Axion Dark Matter constraints

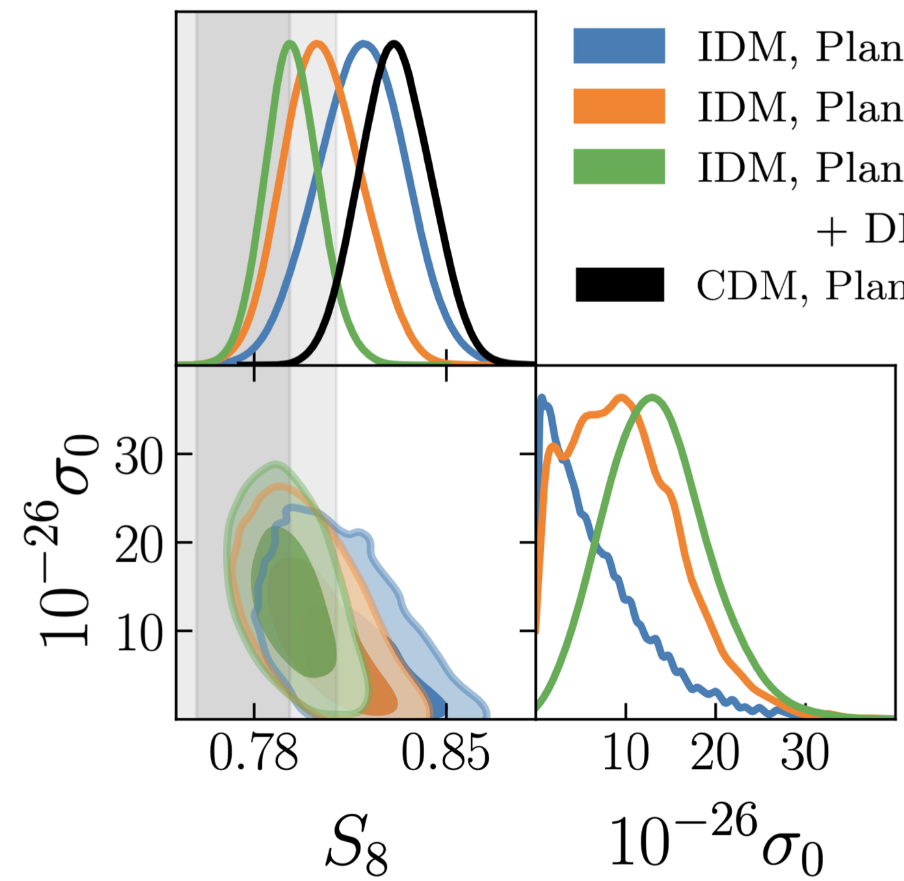


Rogers, Lague, MI ++(to appear)

DM - baryon interactions

- motivated by direct detection





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

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

Dvorkin ++ (2014)
Glusevic, Boddy (2018)
Slatyer, Wu (2018)
He, MI ++(to appear)

Future

- LSS results will improve by ~5-10 in ~5-10 years

euclid consortium

DARK ENERGY SPECTROSCOPIC INSTRUMENT

VERA C. RUBIN OBSERVATORY

Summary

- PT (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 DM, inflation will be answered

Thank you!