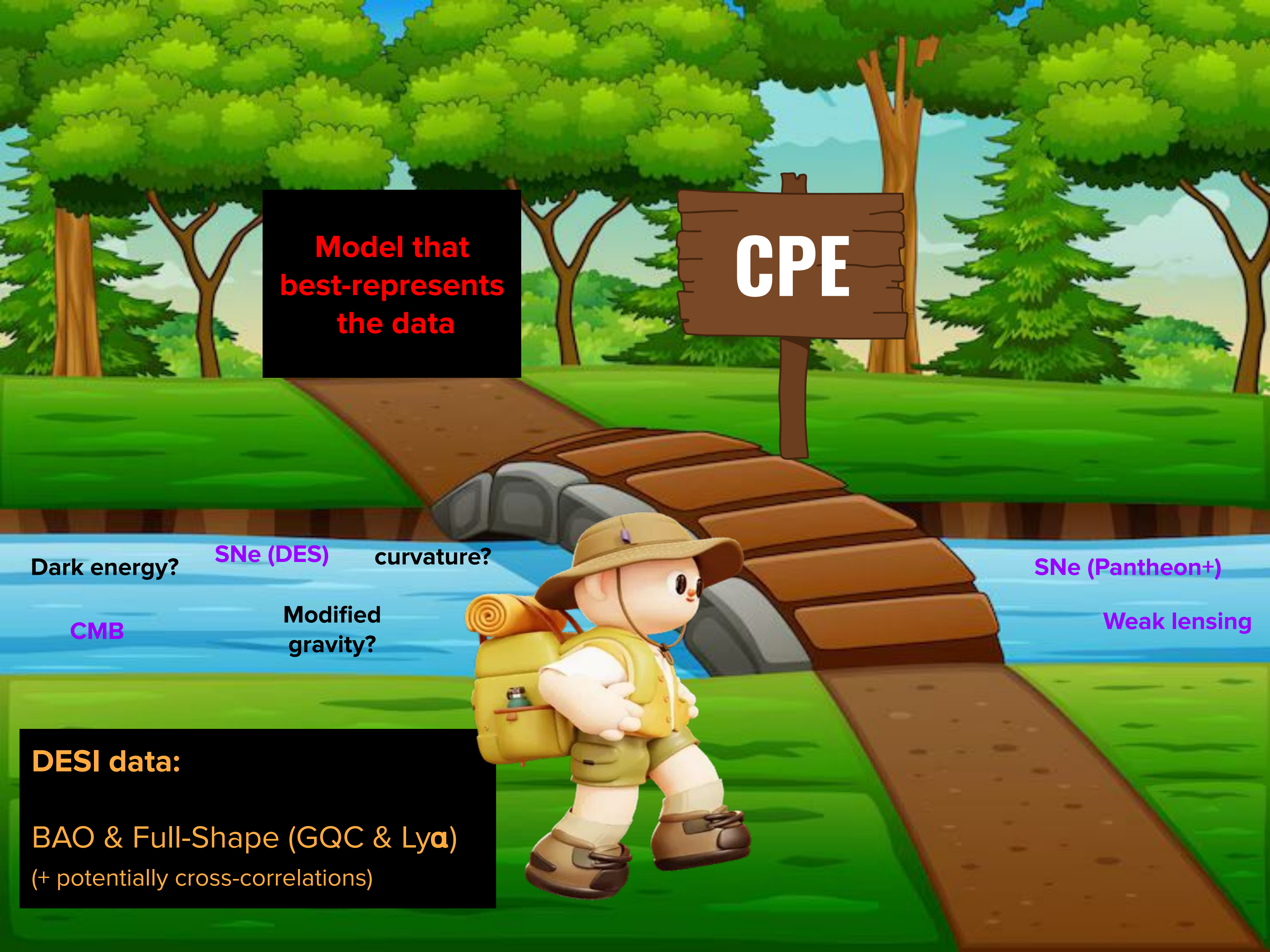
Science Lecture:

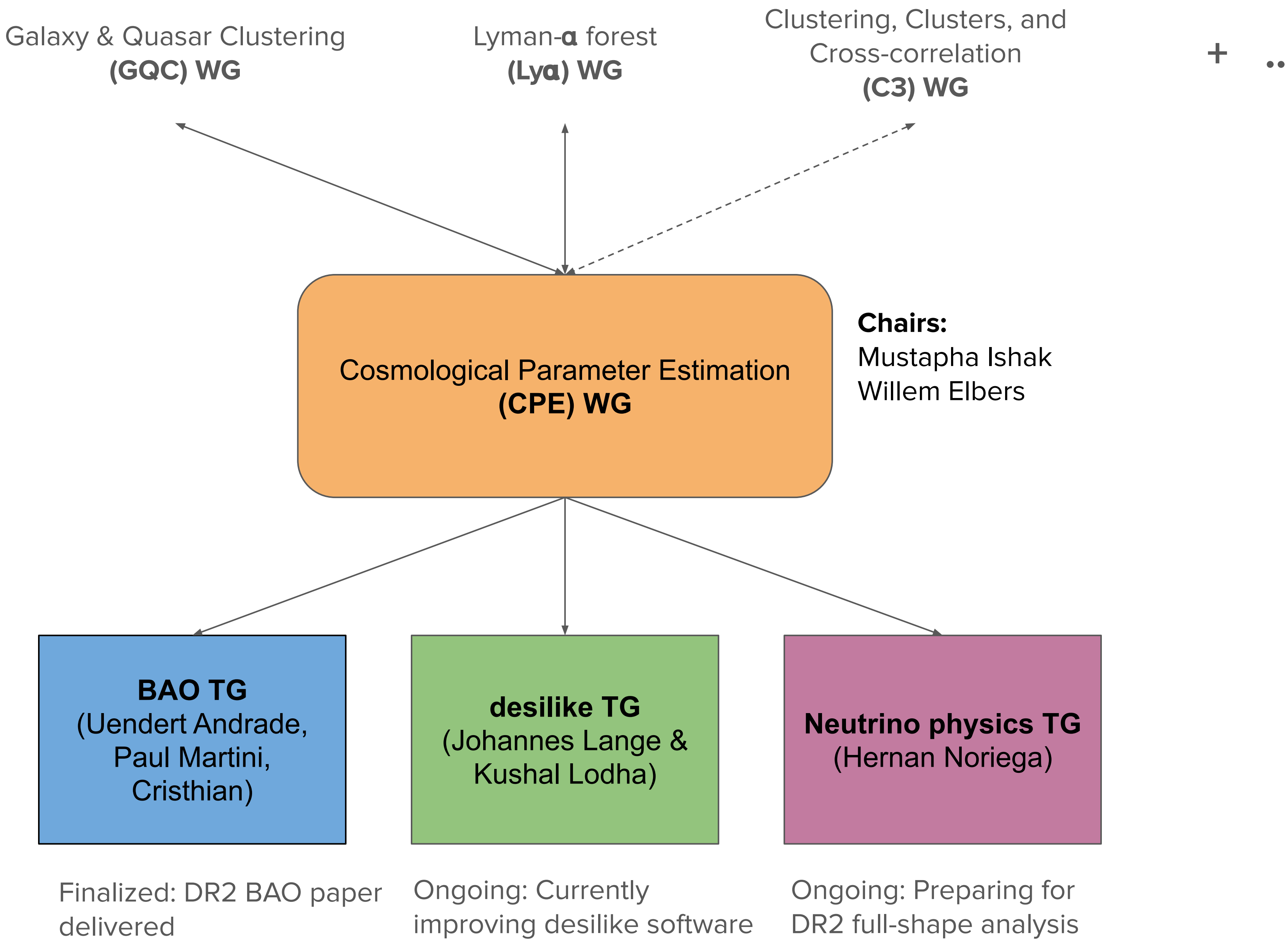
CPE work within DESI

Cristhian Garcia-Quintero
&
Hernan Noriega

Part 1:

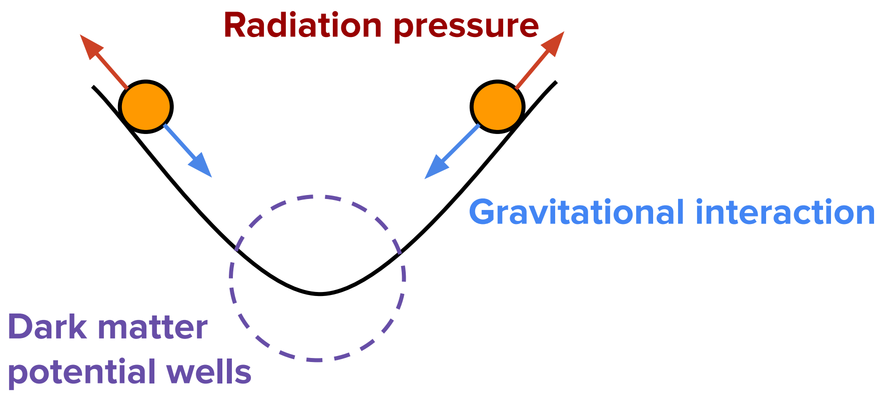
CPE work for BAO DR2 & future perspective


Model that best-represents the data
CPE
Dark energy?
SNe (DES)
curvature?
SNe (Pantheon+)
CMB
Modified gravity?
Weak lensing
DESI data:
BAO & Full-Shape (GQC & Lyα)
(+ potentially cross-correlations)

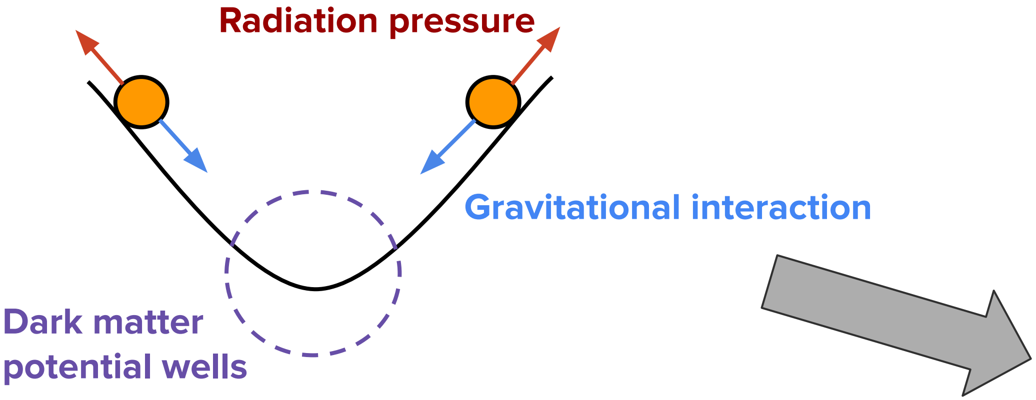


Galaxy & Quasar Clustering
(GQC) WG
Lyman-α forest
(Lyα) WG
Clustering, Clusters, and
Cross-correlation
(C3) WG
+ ...
Cosmological Parameter Estimation
(CPE) WG
Chairs:
Mustapha Ishak
Willem Elbers
BAO TG
(Uendert Andrade,
Paul Martini,
Cristhian)
desilike TG
(Johannes Lange &
Kushal Lodha)
Neutrino physics TG
(Hernan Noriega)
Finalized: DR2 BAO paper
delivered
Ongoing: Currently
improving desilike software
Ongoing: Preparing for
DR2 full-shape analysis

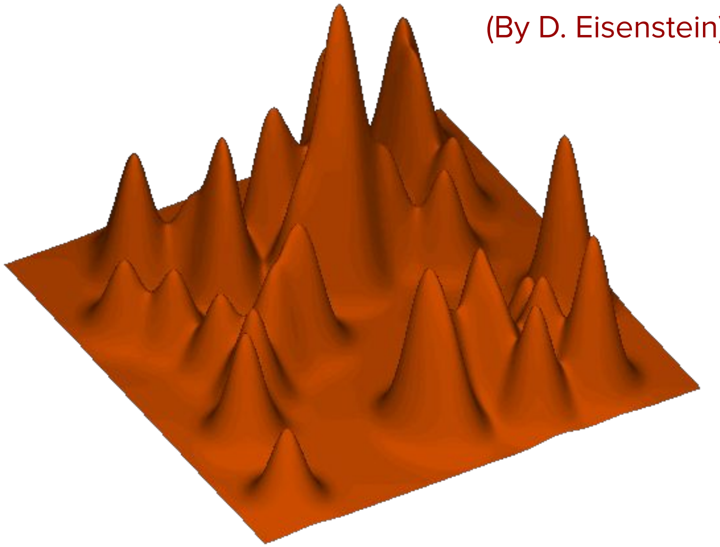
Baryon Acoustic Oscillations (BAO)



Baryon Acoustic Oscillations (BAO)



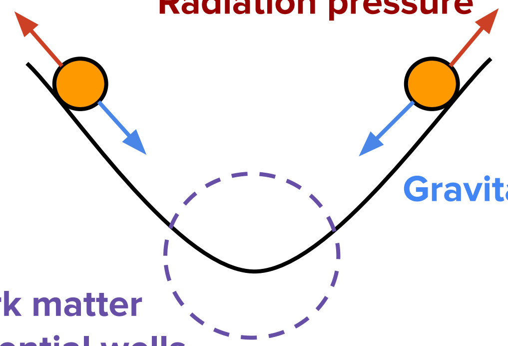
Baryonic Acoustic Oscillations in the fluid



Sound waves propagating in the plasma at around 57% the speed of light.

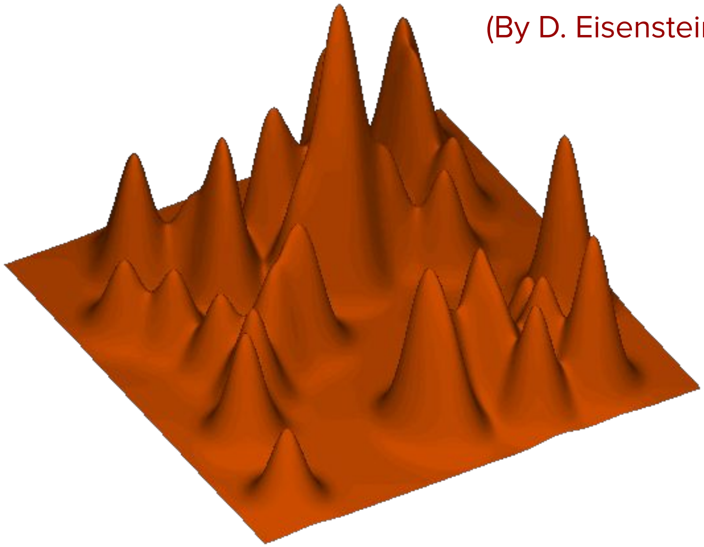
$$c_s(z) = 3^{-1/2} c \left[1 + \tfrac{3}{4}\rho_b(z)/\rho_\gamma(z)\right]^{-1/2}$$

Baryon Acoustic Oscillations (BAO)

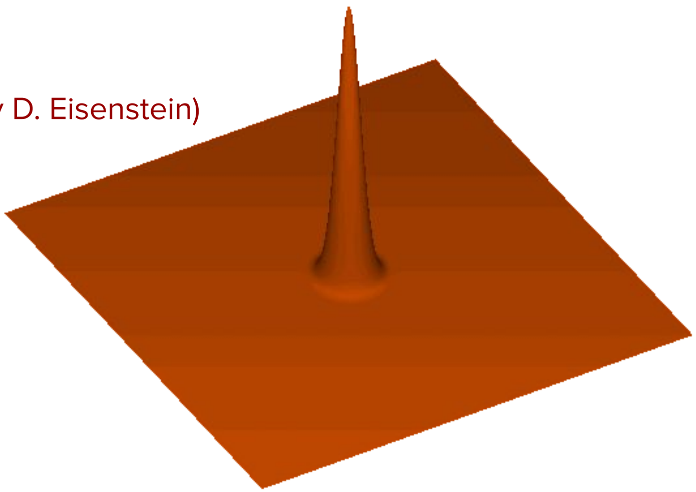


Baryonic Acoustic Oscillations in the fluid

(By D. Eisenstein)



(By D. Eisenstein)

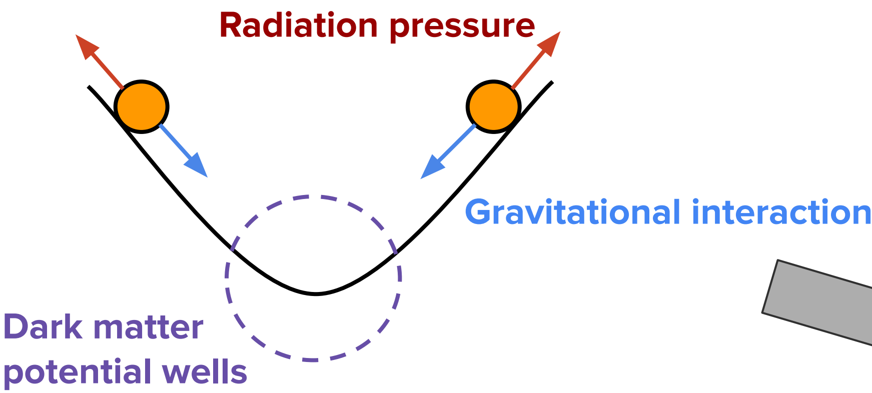


Longest oscillation, from big bang until ~ time of recombination

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$

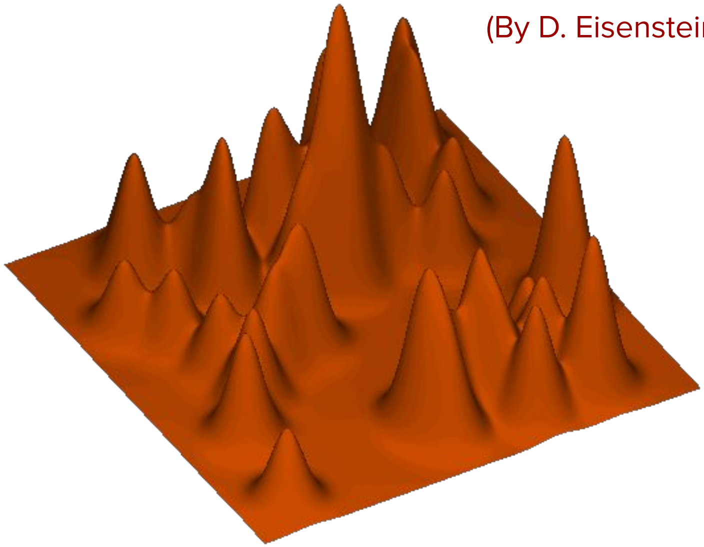
$$c_s(z) \; = \; 3^{-1/2} c \left[1 + \tfrac{3}{4}\rho_b(z)/\rho_\gamma(z)\right]^{-1/2}$$

Baryon Acoustic Oscillations (BAO)

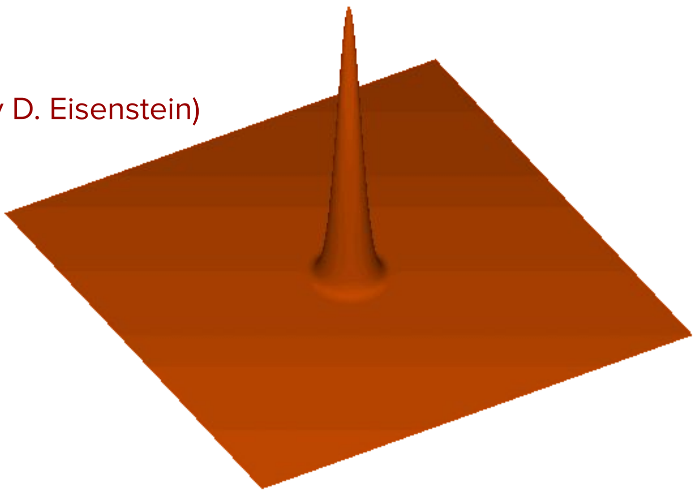


Baryonic Acoustic Oscillations in the fluid

(By D. Eisenstein)

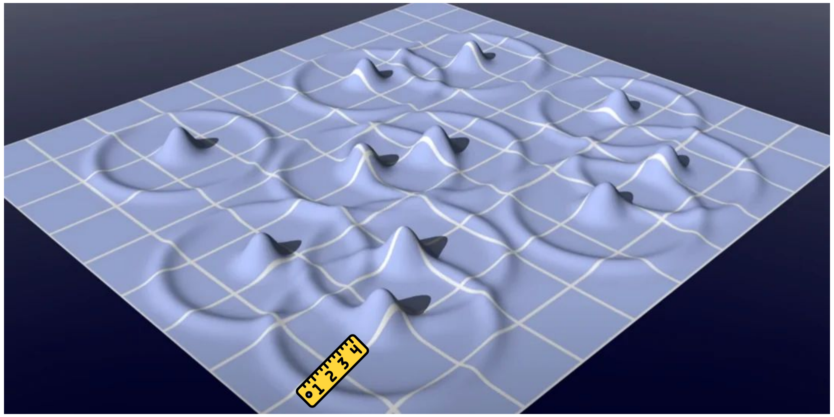


(By D. Eisenstein)



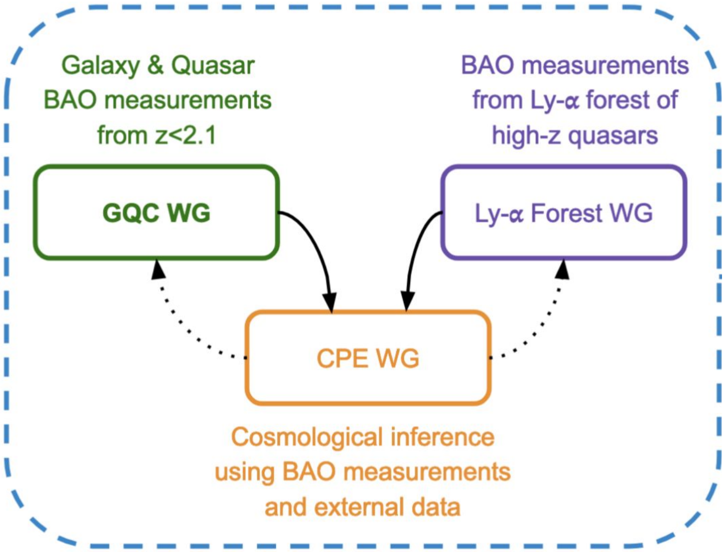
Longest oscillation, from big bang until ~ time of recombination

Such oscillation is present throughout the Universe

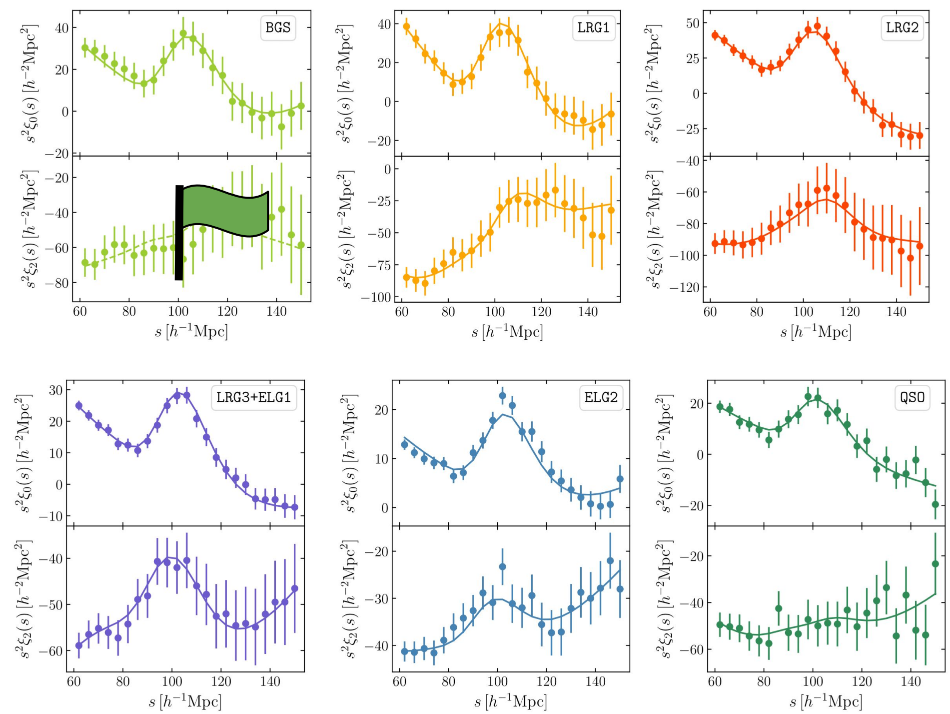


Baryon Acoustic Oscillations measurements

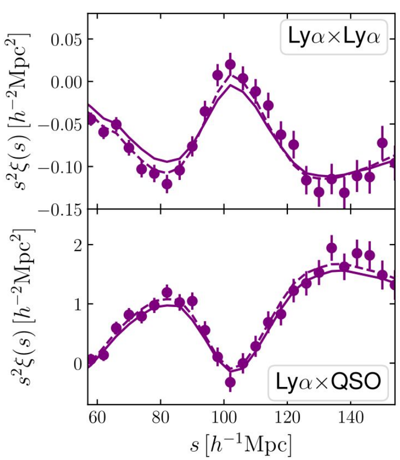
Galaxy & Quasar, Lya BAO and Cosmological Interpretation



GQC



Lyα

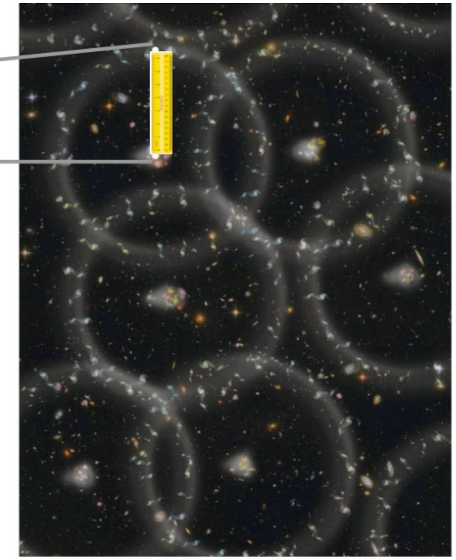


Cosmology parameters from BAO (ΛCDM example)

$$\theta_{\mathrm{BAO}} = r_{\mathrm{d}}/D_{\mathrm{M}}(z)$$

sound horizon r_{d}

transverse comoving distance



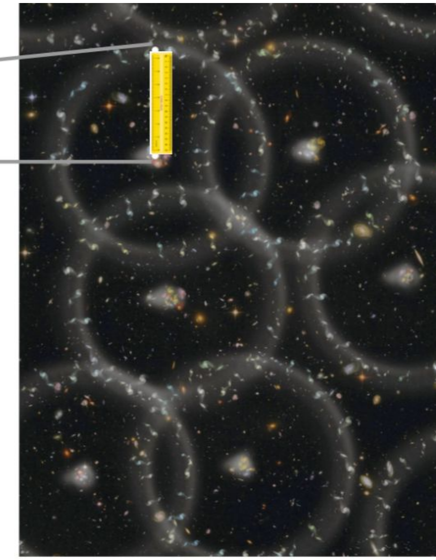
distribution of galaxies (cartoonish)

Cosmology parameters from BAO (ΛCDM example)

$$\theta_{\rm BAO} = r_{\rm d}/D_{\rm M}(z)$$

sound horizon $r_{\rm d}$

transverse comoving distance



distribution of galaxies (cartoonish)

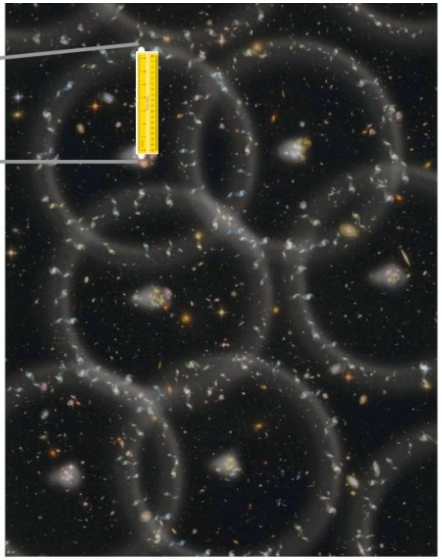
$$\theta_{\rm BAO} = \frac{r_{\rm d}}{D_{\rm M}} = r_{\rm d}\left[\frac{c}{H_0}\int_0^z dz\,\frac{H_0}{H(z)}\right]^{-1}$$

Cosmology parameters from BAO (ΛCDM example)

$$\theta_{\mathrm{BAO}} = r_{\mathrm{d}} / D_{\mathrm{M}}(z)$$

sound horizon r_{d}

transverse comoving distance



distribution of galaxies (cartoonish)

$$\frac{H^2(z)}{H_0^2} = \Omega_r (1+z)^4 + \Omega_m (1+z)^3 + \Omega_\Lambda + \Omega_k (1+z)^2$$

$\Omega_r \approx 0$

$\Omega_k = 0$

$\Omega_\Lambda \approx 1 - \Omega_m$

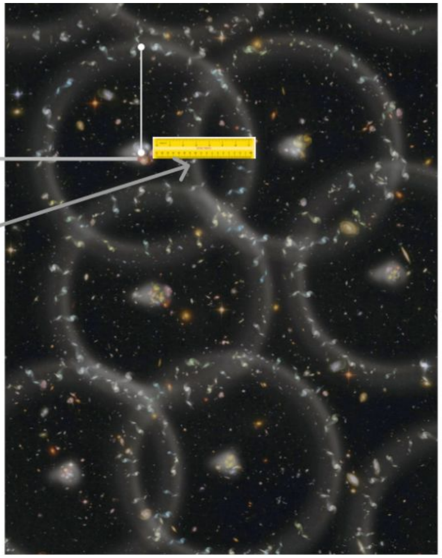
$$\theta_{\mathrm{BAO}} = \frac{r_{\mathrm{d}}}{D_{\mathrm{M}}} = r_{\mathrm{d}} \left[\frac{c}{H_0} \int_0^z dz \frac{H_0}{H(z)} \right]^{-1} = \frac{H_0 r_{\mathrm{d}}}{c} \left[\int_0^z \sqrt{\Omega_{\mathrm{m}}(1+z)^3 + \Omega_\Lambda} dz \right]^{-1}$$

Cosmology parameters from BAO (ΛCDM example)

$$\Delta z_{\rm BAO} = r_{\rm d}/D_{\rm H}(z)$$

sound horizon $r_{\rm d}$

Hubble distance



distribution of galaxies
(cartoonish)

Cosmology parameters from BAO (ΛCDM example)

$$\Delta z_{\rm BAO} = r_{\rm d}/D_{\rm H}(z)$$

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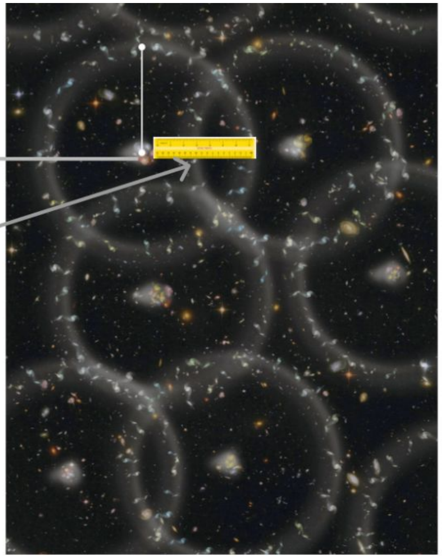
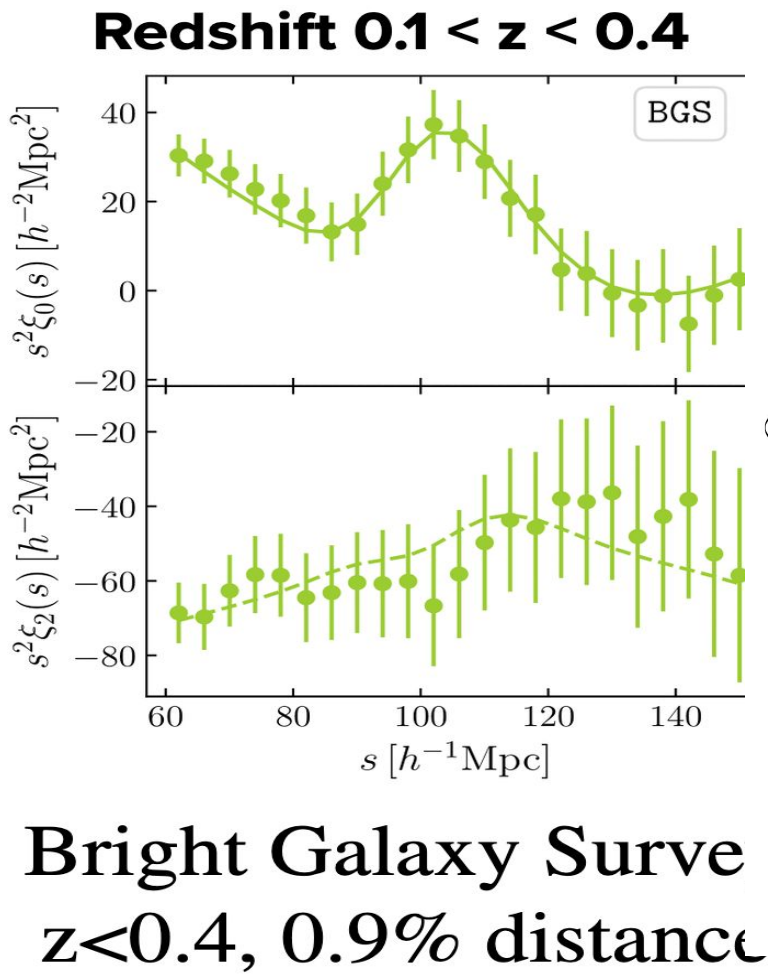
Hubble distance

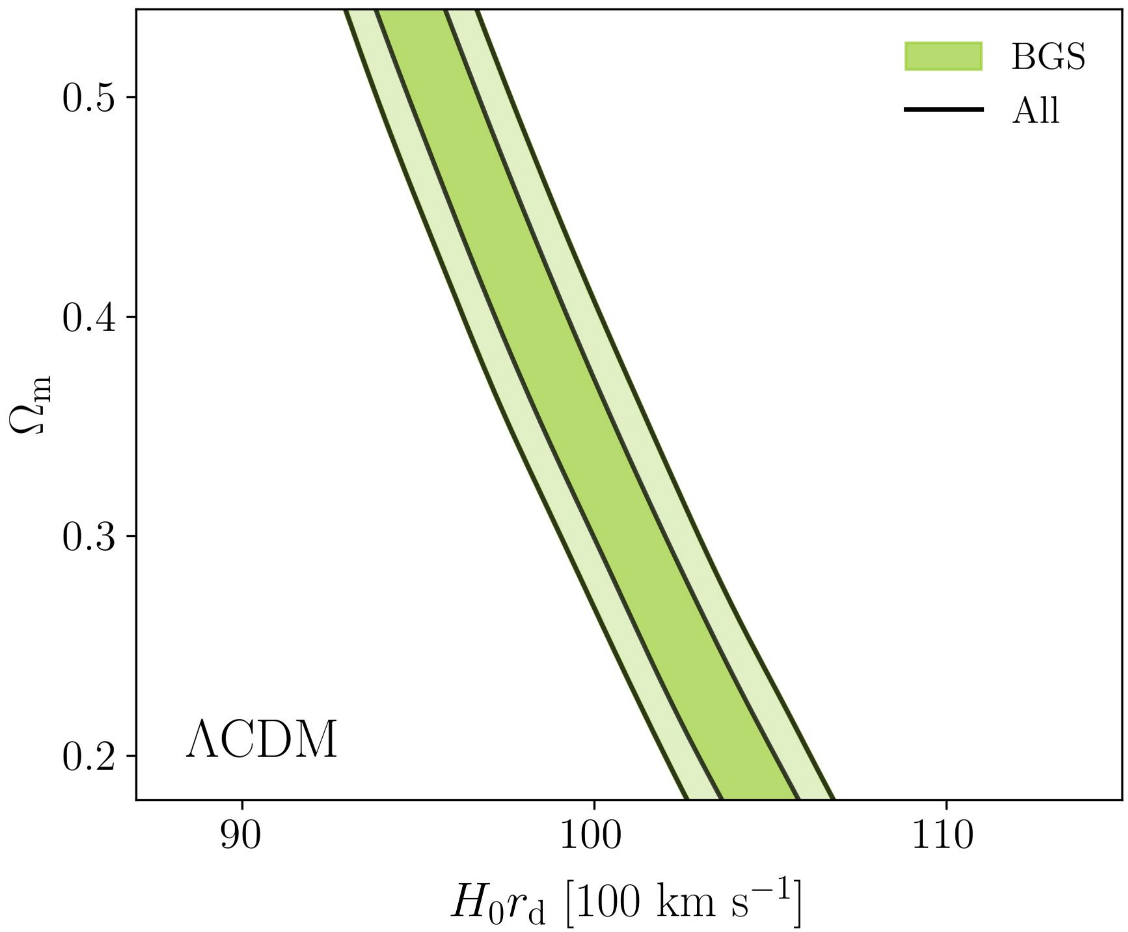


distribution of galaxies (cartoonish)

$$\delta z_{\rm BAO} = r_{\rm d}\frac{H(z)}{c} = \frac{H_0 r_{\rm d}}{c}\sqrt{\Omega_{\rm m}(1+z)^3+\Omega_\Lambda}$$

Cosmology parameters from BAO





Error bars reduction by factor of ~2

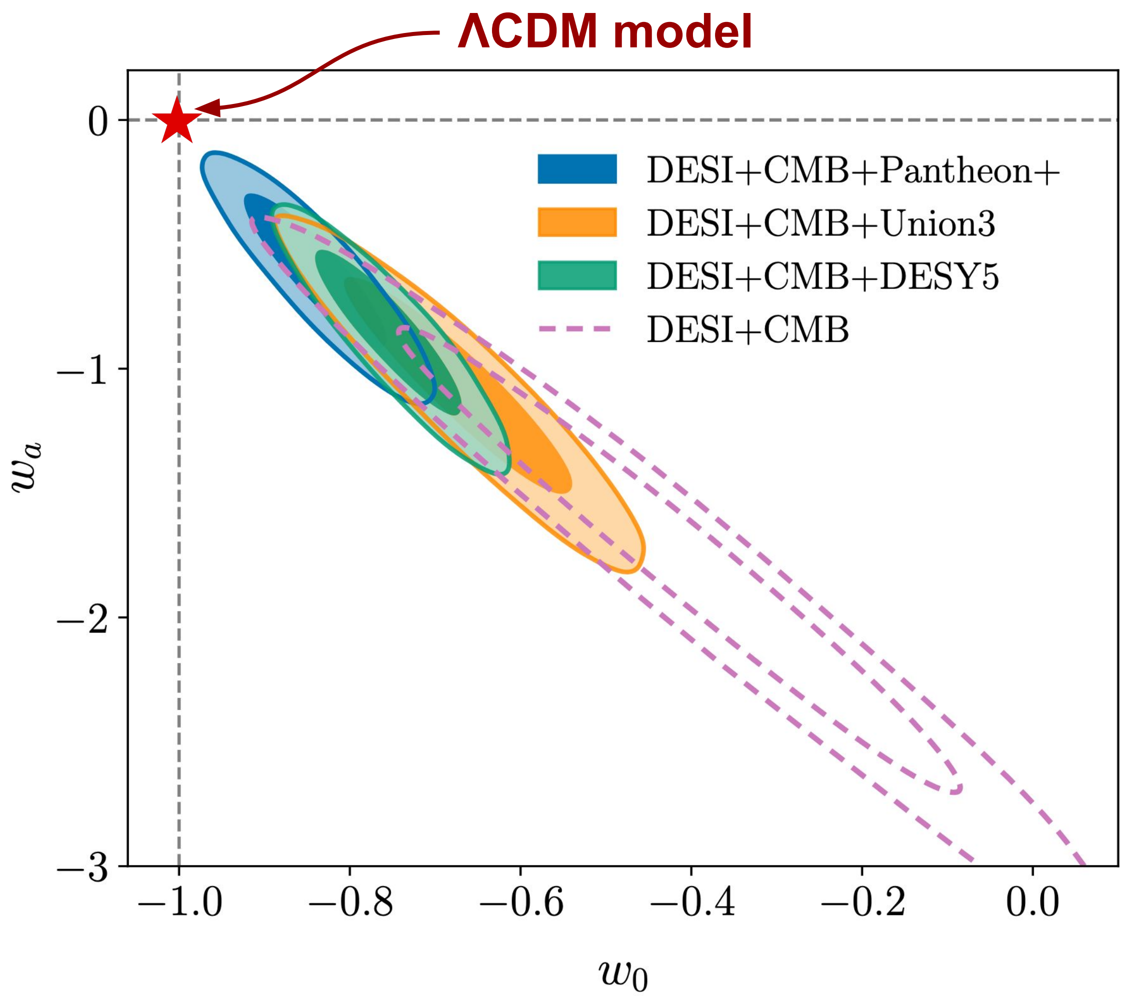
Tension with SDSS in LRG1 reduced to 2.6σ

LRG+ELG provides the most precise isotropic distance scale measurement: 0.45% (nearly 15σ!)

We now have 2D BAO measurements for QSO

Slight disagreement with DESI and Planck best-fit ΛCDM models.

Hints for evolving dark energy



DESI+CMB: 3.1σ
(Planck PR4)

* The current status of this tension is 3.2σ as reported by the SPT collaboration using a combination SPT+Planck+ACT

(See ArXiv: 2506.20707)

+ Pantheon+ SNe Ia: 2.8σ
(Scolnic et al. 2022)

+ Union3 SNe Ia: 3.8σ
(Rubin et al. 2024)

+ DES-SN5YR SNe Ia: 4.2σ
(Davis & DES collaboration 2024)

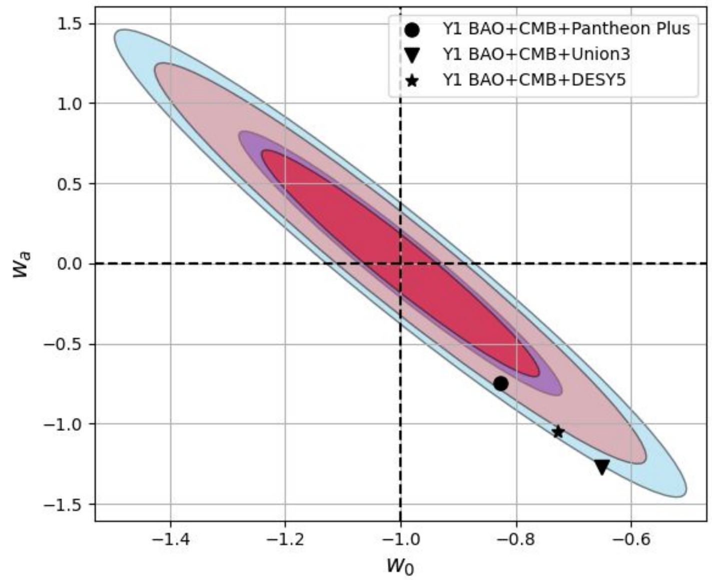
CPE dark energy supporting paper:
K. Lodha et al. 2025
ArXiv: 2503.14743

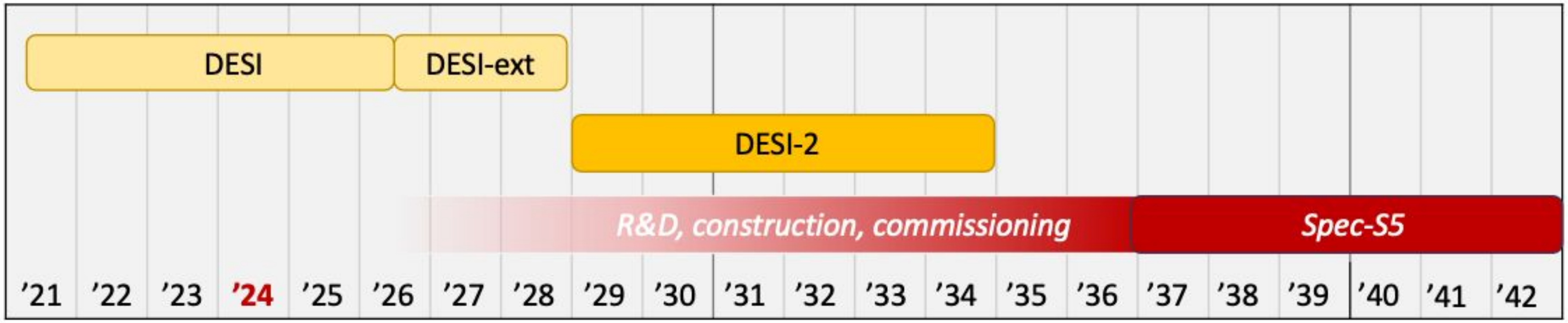
CPE neutrinos supporting paper:
W. Elbers et al. 2025
ArXiv: 2503.14744

Plans ahead

Any plans for DR3? Still need to wait and define what the DR3 batch would be, in the meantime, we have DR2 full shape results on the way.

- **DESI (primarily z<1.5)**
  - Five year survey + 2.5 year extension aimed at Dark Energy with BAO and RSD measurements
- **DESI-II (primarily z>2)**
  - As powerful as DESI, but focused on z>2. Aim for a six year survey with some instrument upgrades
- **Spec-S5 (Spectroscopic Stage 5, where DESI is 'Stage 4")**
  - New facility or facilities and new instrumentation

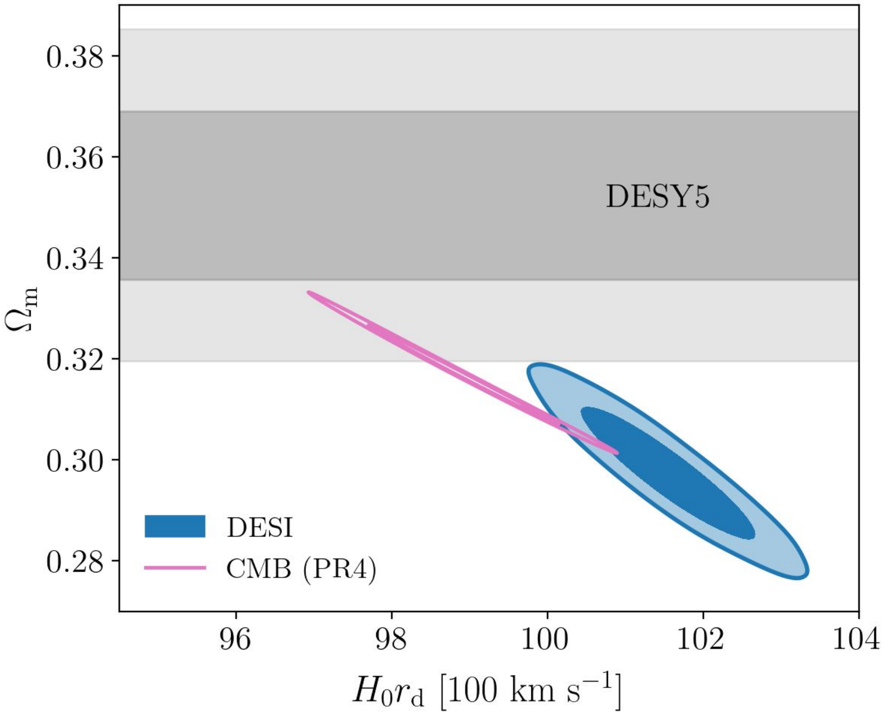




Things to keep in mind for further analyses with DR2 or DR3:

- Cosmological tensions

Cosmological tensions within ΛCDM

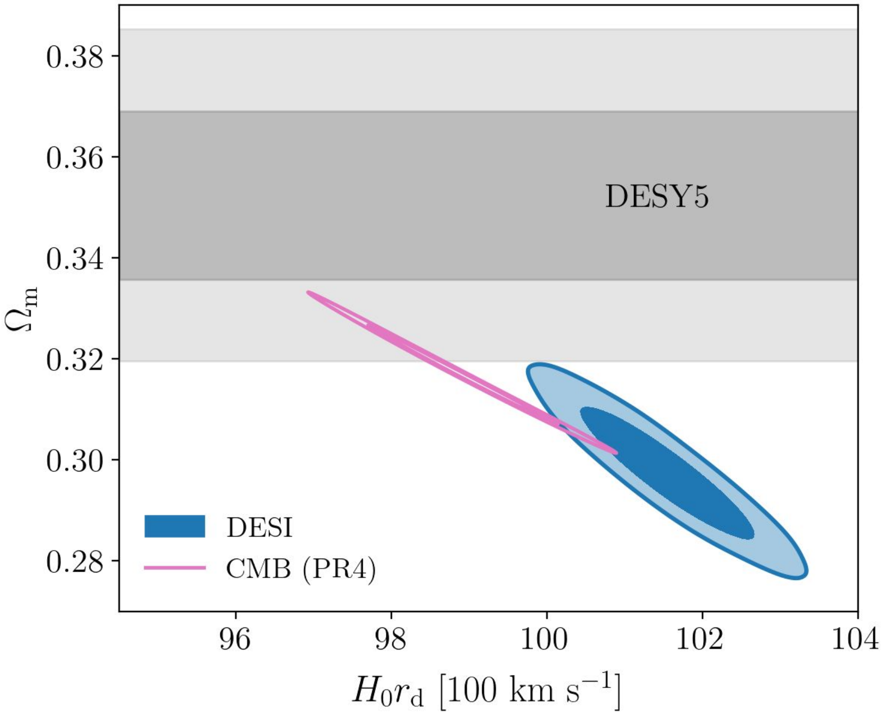


Discrepancy between DESI and SNe ranges from 1.7 σ to 2.9σ.

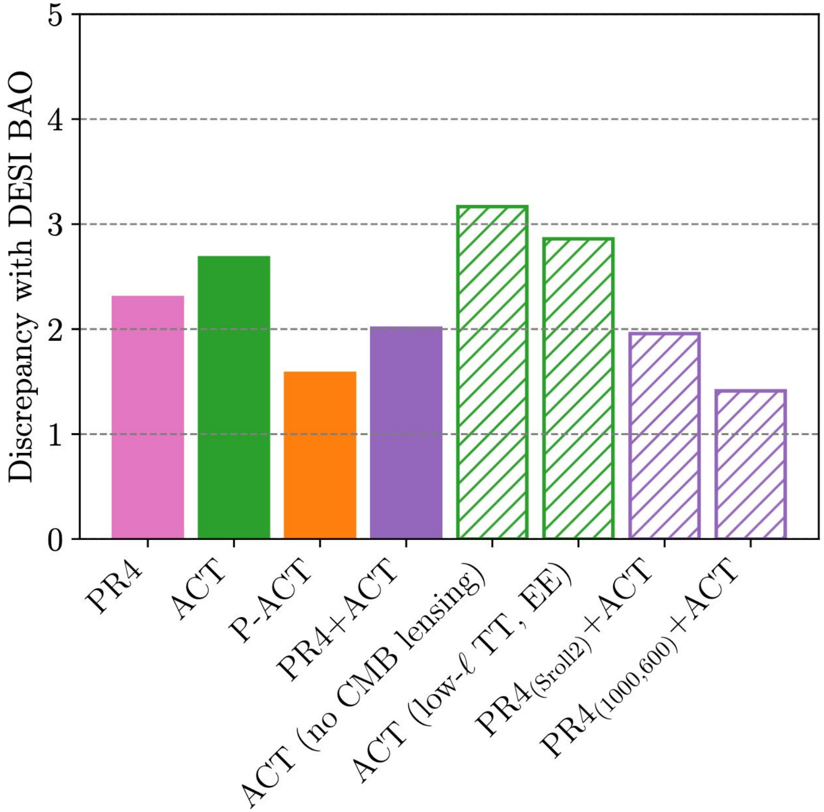
Discrepancy between DESI and Planck is 2.3σ.

Cosmological tensions within ΛCDM

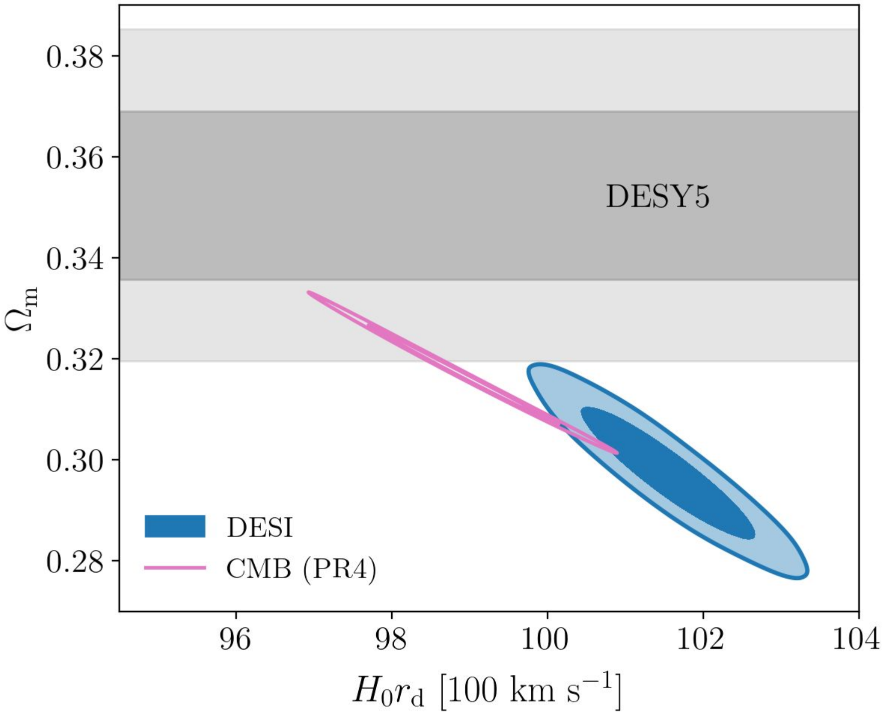
New CMB data from ACT got available

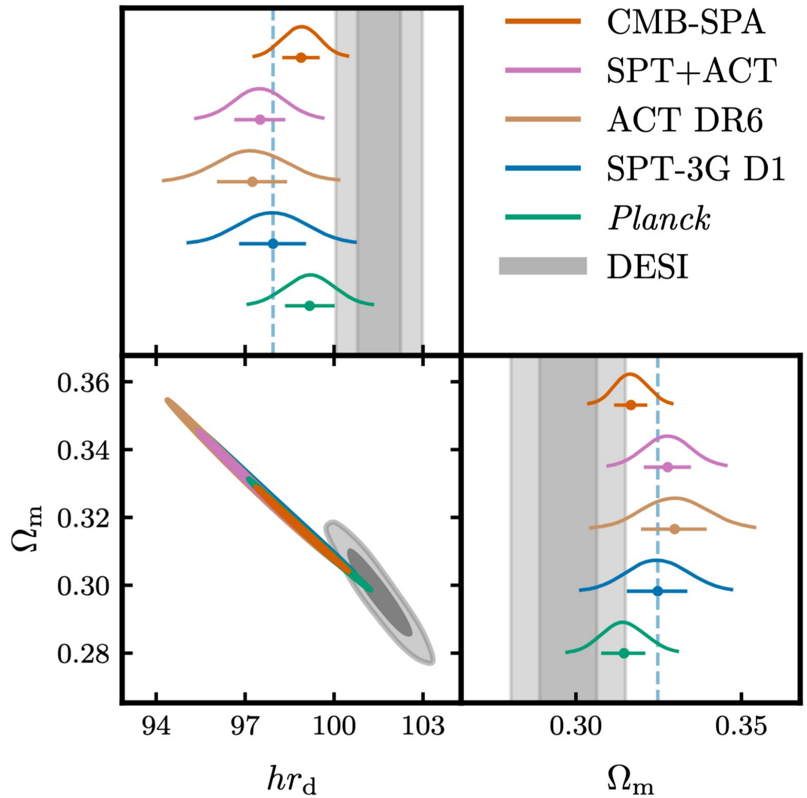


C. Garcia-Quintero et al.
ArXiv: 2504.18464



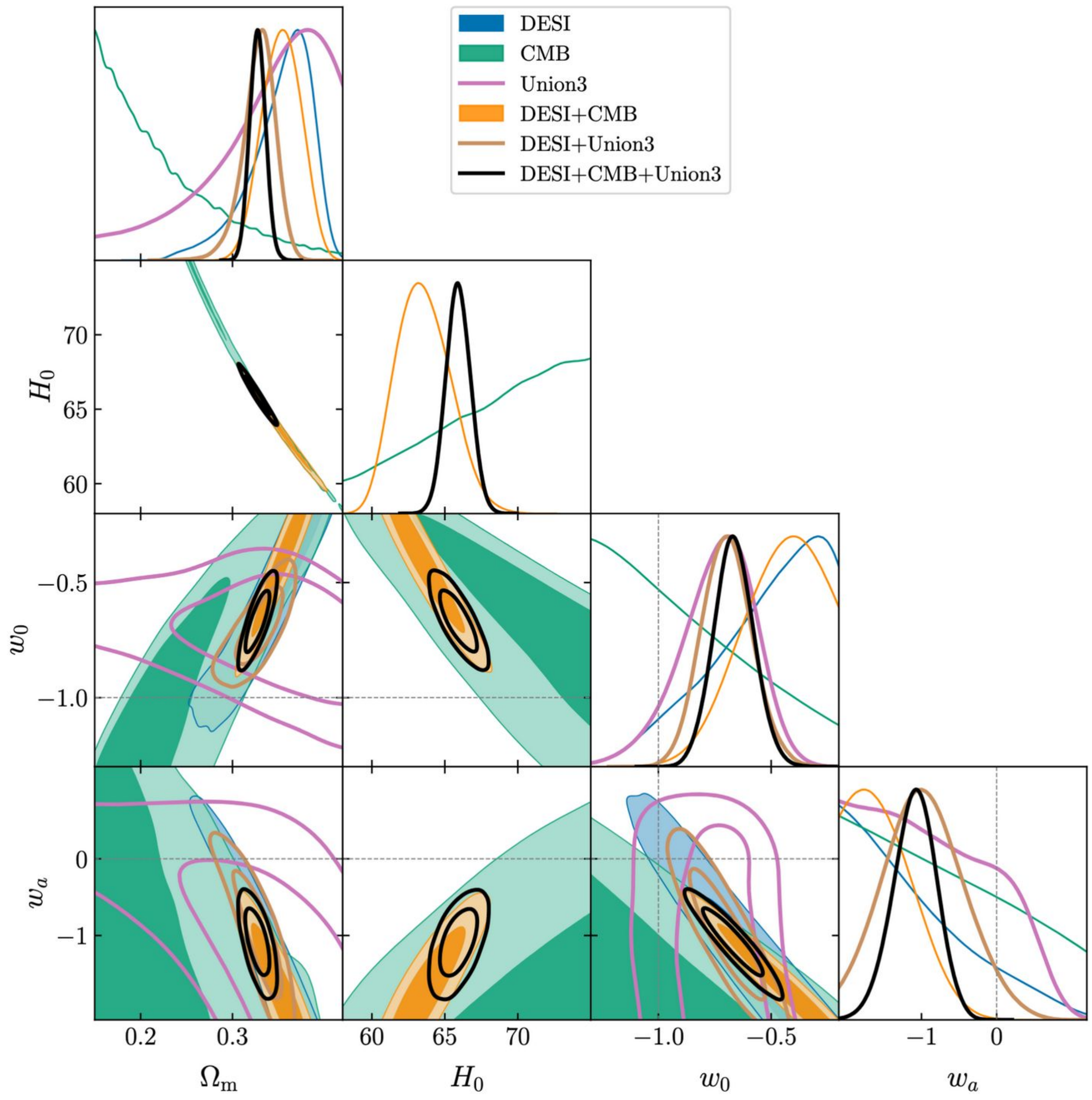
Even better, now we have SPT and a 'consolidated' CMB dataset, currently in a 2.8σ discrepancy with DESI BAO DR2.





Latest SPT results
ArXiv: 2506.20707

Cosmological tensions within ΛCDM



By Sesh N.

Things to keep in mind for further analyses with DR2 or DR3:

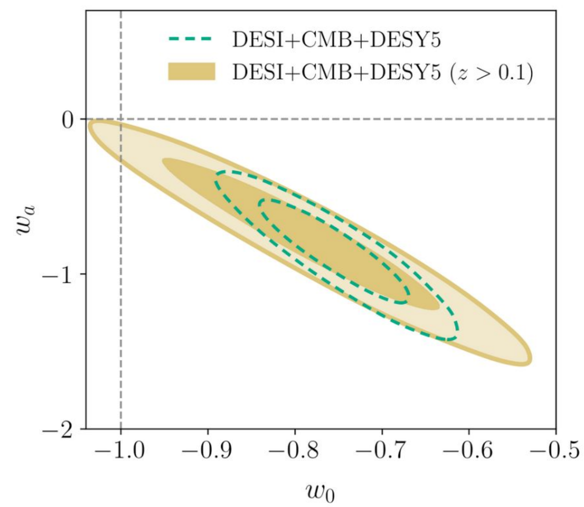
- Cosmological tensions
- Systematics in the data?

Systematics in SNe Ia data?

- Systematics in the SNe data?

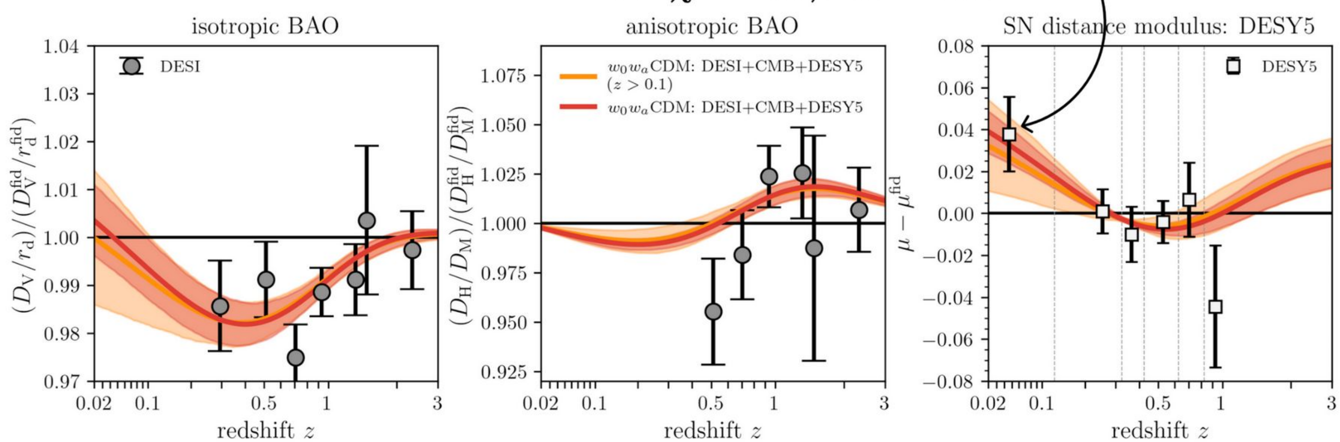
- We may need to wait for ZTF, Rubin, or other reanalyses
- Removing low-redshift data effects the significance of the hints, but do not change the best-fit model drastically

Removing low-z SN



assuming $z > 0.1$ fit, including the $z < 0.1$ SN data

$$\Rightarrow \Delta\chi^2 = 186, \text{ndof} = 197$$

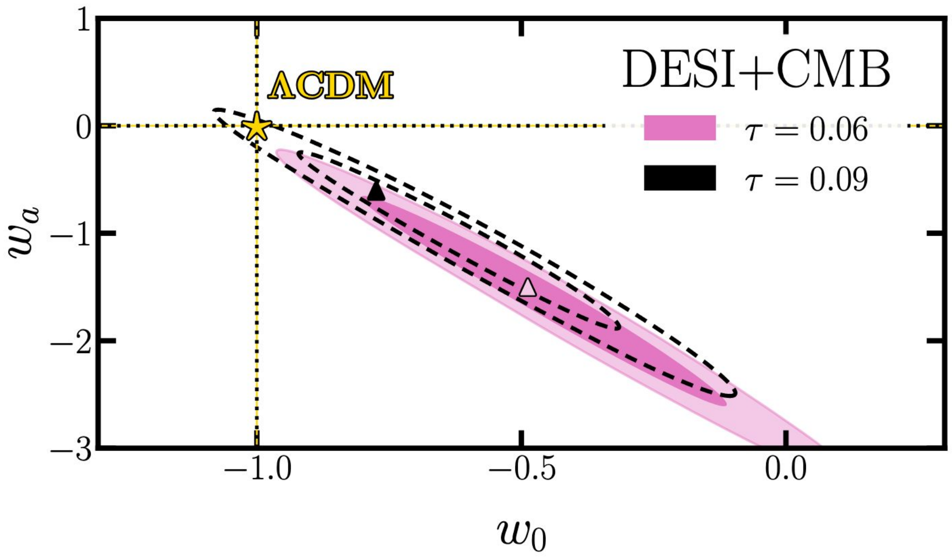


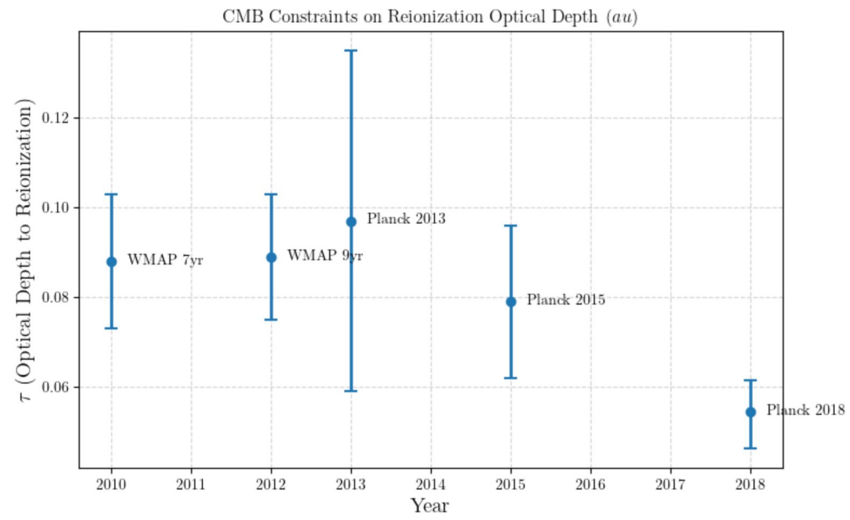
full DESY5 best χ^2 barely changes between $z > 0.1$ and full fit

Systematics in CMB data?

- **Systematics in the CMB data?**
    - Potential issues with τ-reionization?

N. Sailor et al.
ArXiv: 2504.16932

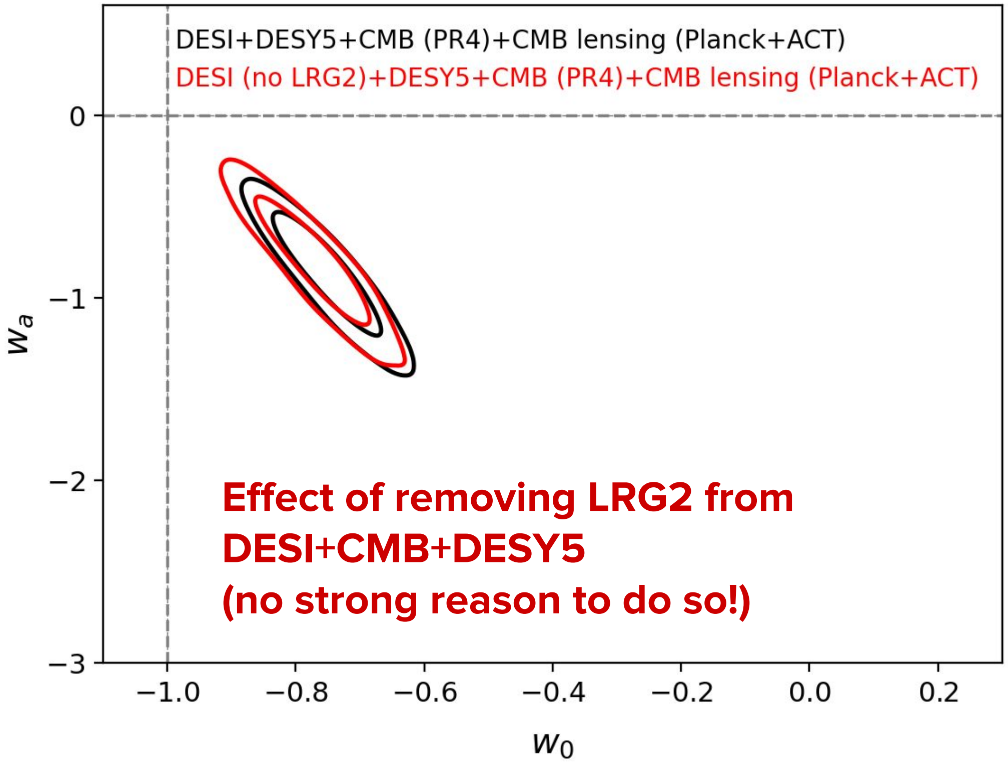




Systematics in the BAO data?

- Systematics in the BAO data? I personally do not expect so.

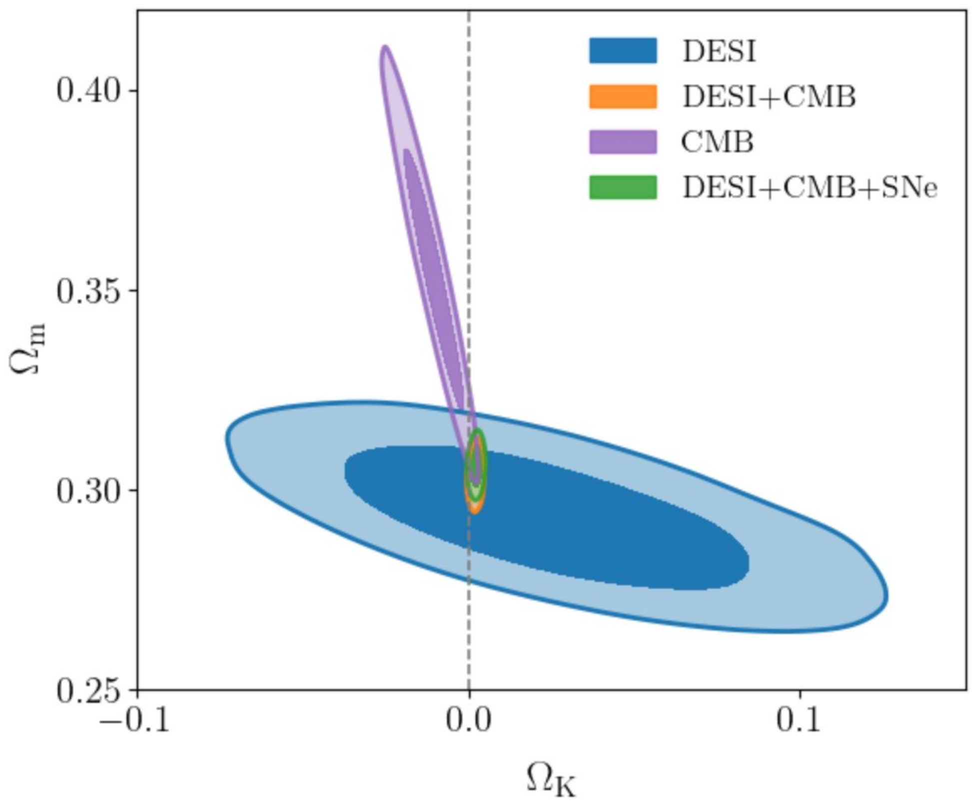
- Replacing some DESI BAO data points with the SDSS ones does not solve the *tension* (ArXiv: 2404.03002)
- Using alternative BAO measurements, e.g. DES, still shows some departures when combined with SNe (see ArXiv: 2503.06712)
- A coherent error in our BAO estimates would need a shift 10X more than allowed given our systematic error budget (see ArXiv: 2503.14738)



Things to keep in mind for further analyses with DR2 or DR3:

- Cosmological tensions
- Systematics in the data?
- Keep checking on other parameters

Other parameters to keep track of? Curvature, modified gravity, etc



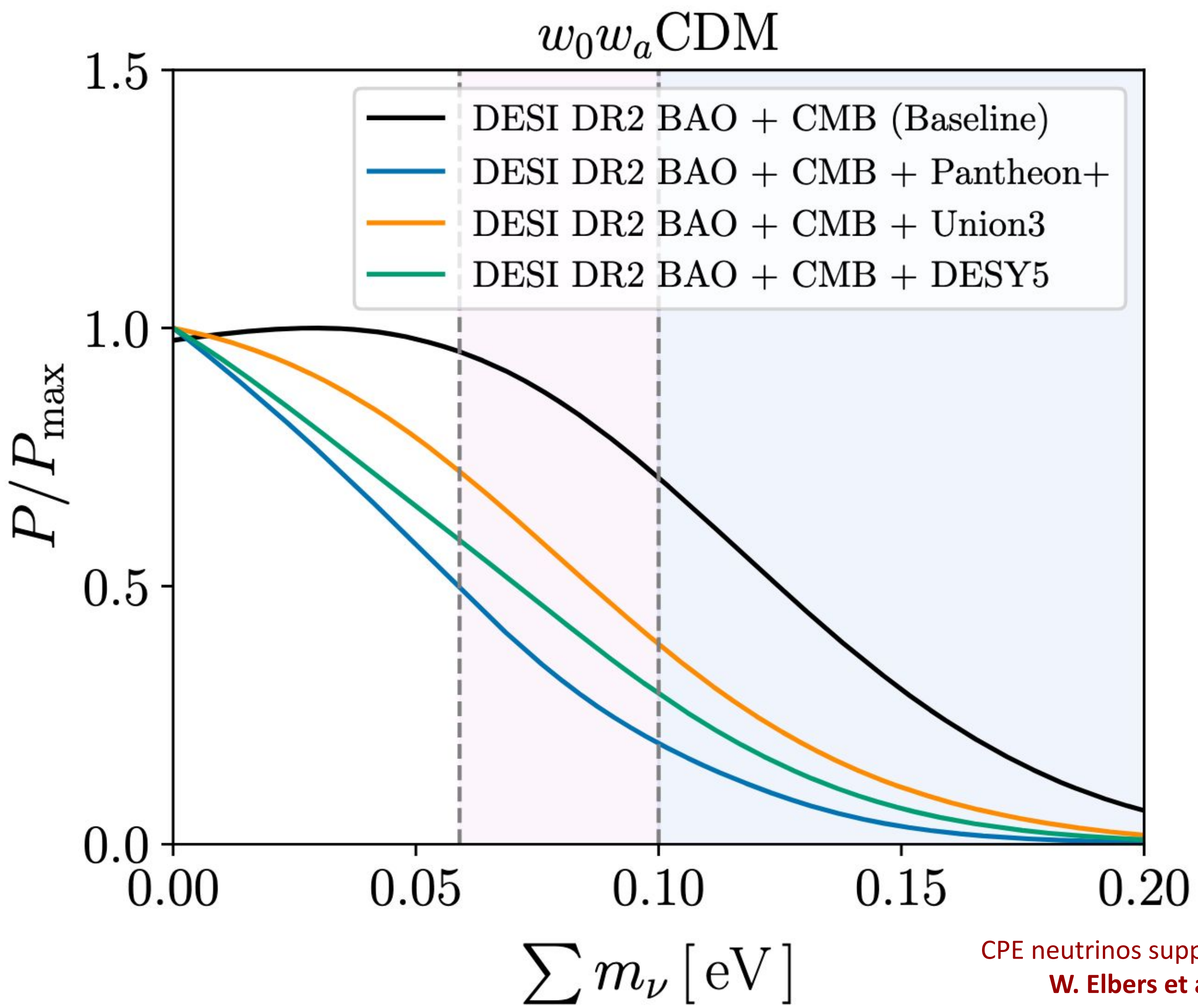
DESI+CMB+DESY5 gives a 2.3σ preference for curvature
(See also ArXiv: 2505.00659)

CMB same as used in DR2 paper.

Things to keep in mind for further analyses with DR2 or DR3:

- Cosmological tensions
- Systematics in the data?
- Keep checking on other parameters
- Keep an eye on neutrino mass

Monitor how the neutrino mass constraints behave with more data



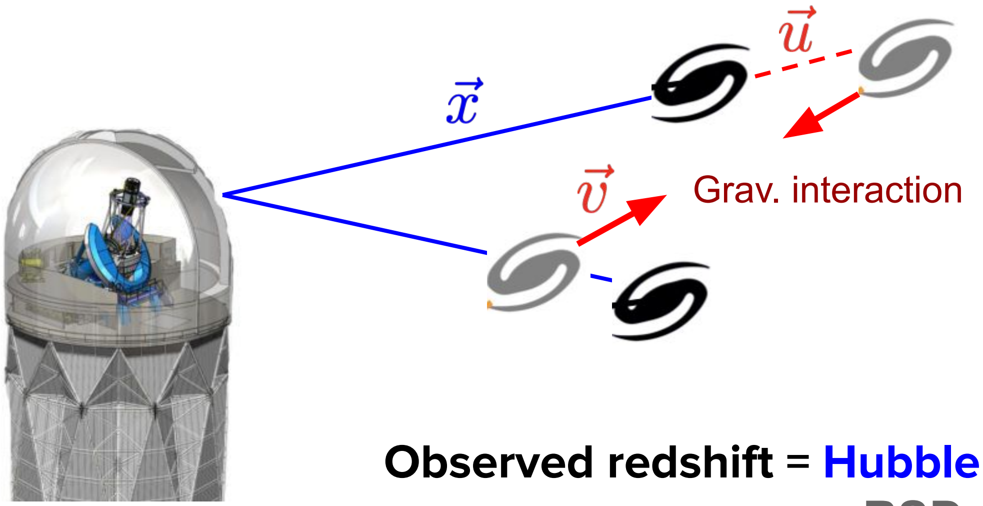
CPE neutrinos supporting paper:
W. Elbers et al. 2025
ArXiv: 2503.14744

Part 2:

CPE and work towards DR2 full-shape

Work done for DR1 & perspectives for DR2

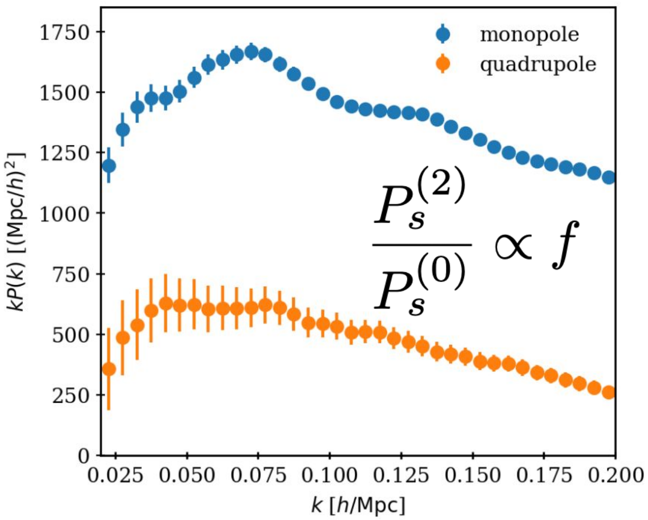
Galaxy Full Shape in a nutshell



$$\vec{s} = \vec{x} + \hat{x}\,\frac{\overbrace{\vec{v}\cdot\hat{x}}^{\vec{u}}}{aH}$$

Observed redshift = Hubble flow + peculiar velocities

RSD (redshift space distortions)

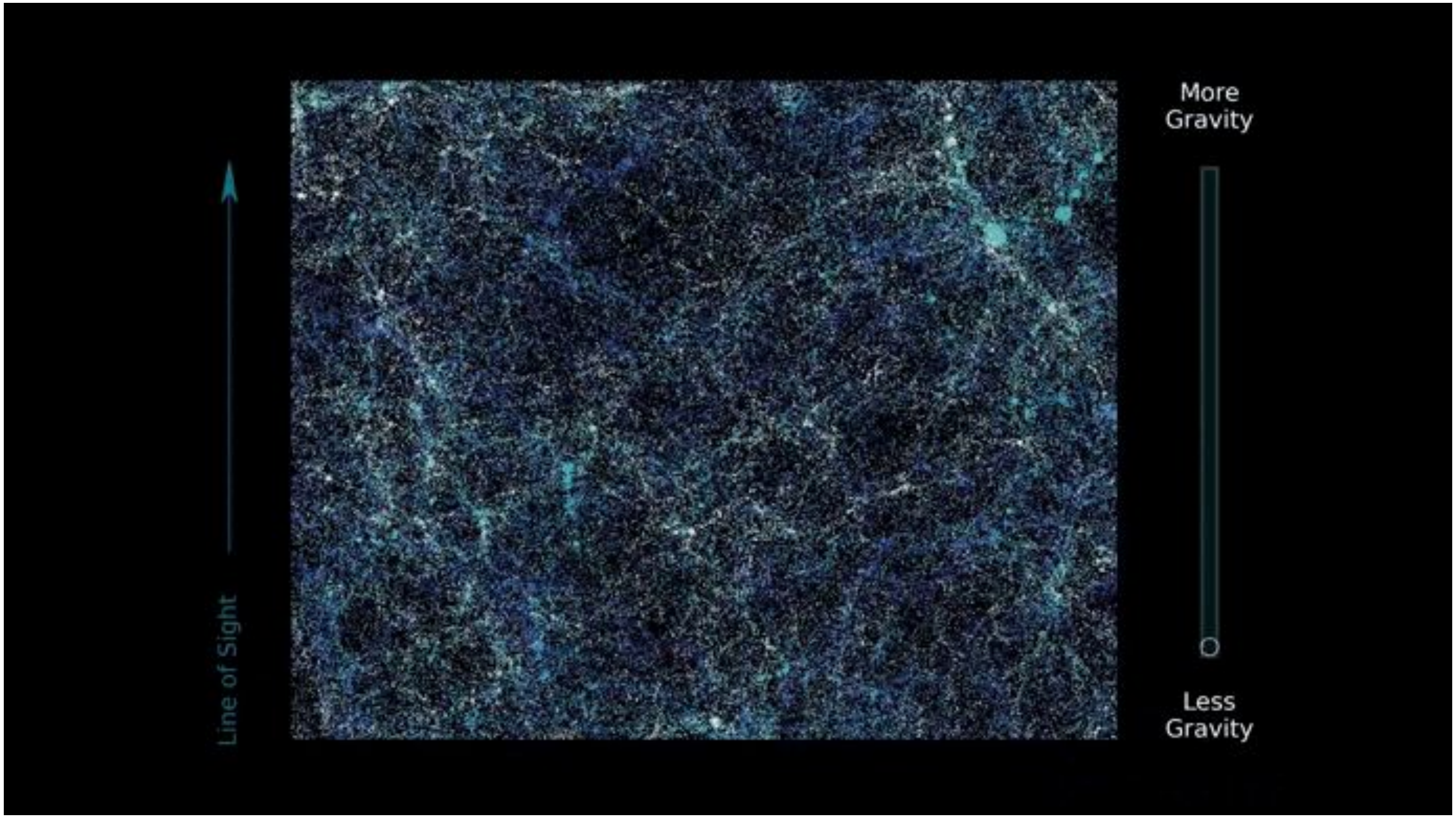


We model galaxy clustering in redshift space using full-shape of the galaxy power spectrum. Introduces **anisotropy** but **enables to:**

- probe the **growth of structures $f\sigma_8$**
- **test the theory of gravity and dark energy**
- **constrain the sum of neutrino masses**

Galaxy Full Shape in a nutshell

Credit: Claire Lamman and Michael Rashkovetskyi / DESI collaboration



$$\delta_s(\mathbf{k}) = (1 + f\mu^2)\delta(\mathbf{k})$$

Where **μ** the **cosine of the angle** between the **line-of-sight** and the **wave-vector *k***.

Linear order: Kaiser power spectrum

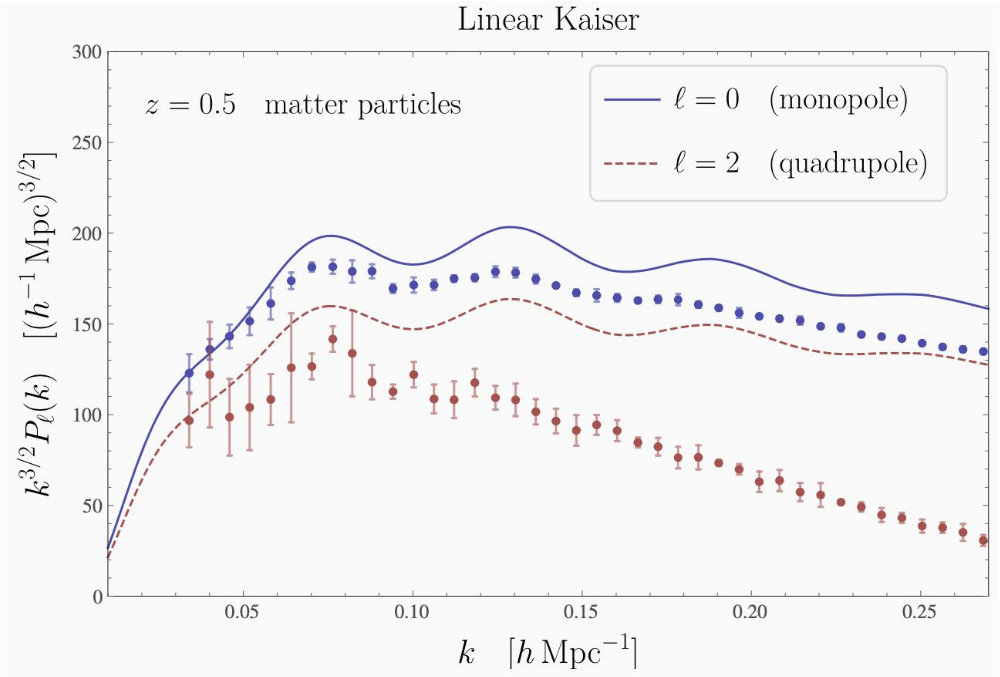
$$P_s^K(k,\mu) = (1+\beta\mu^2)^2 b_1^2 P_L(k), \quad \text{with} \quad \beta = \frac{f}{b_1}$$

Multipoles:

$$P_0^K(k) = \left(1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2\right) b_1^2 P_L(k)$$

$$P_2^K(k) = \left(\frac{4}{3}\beta + \frac{4}{7}\beta^2\right) b_1^2 P_L(k)$$

ratio!



To better describe the galaxy clustering, **we need to consider**:

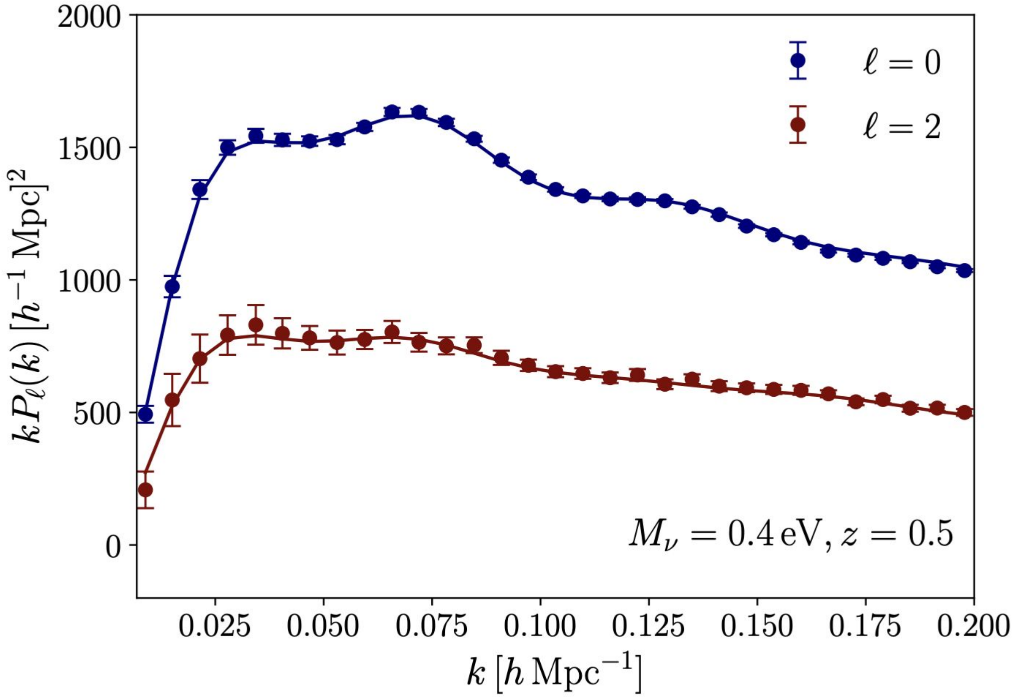
- **nonlinear terms (1-loop correction);**
- **EFT counterterms**
- **IR resummations**
- **nonlinear biasing**
- **stochastic terms**

Full Shape power spectrum

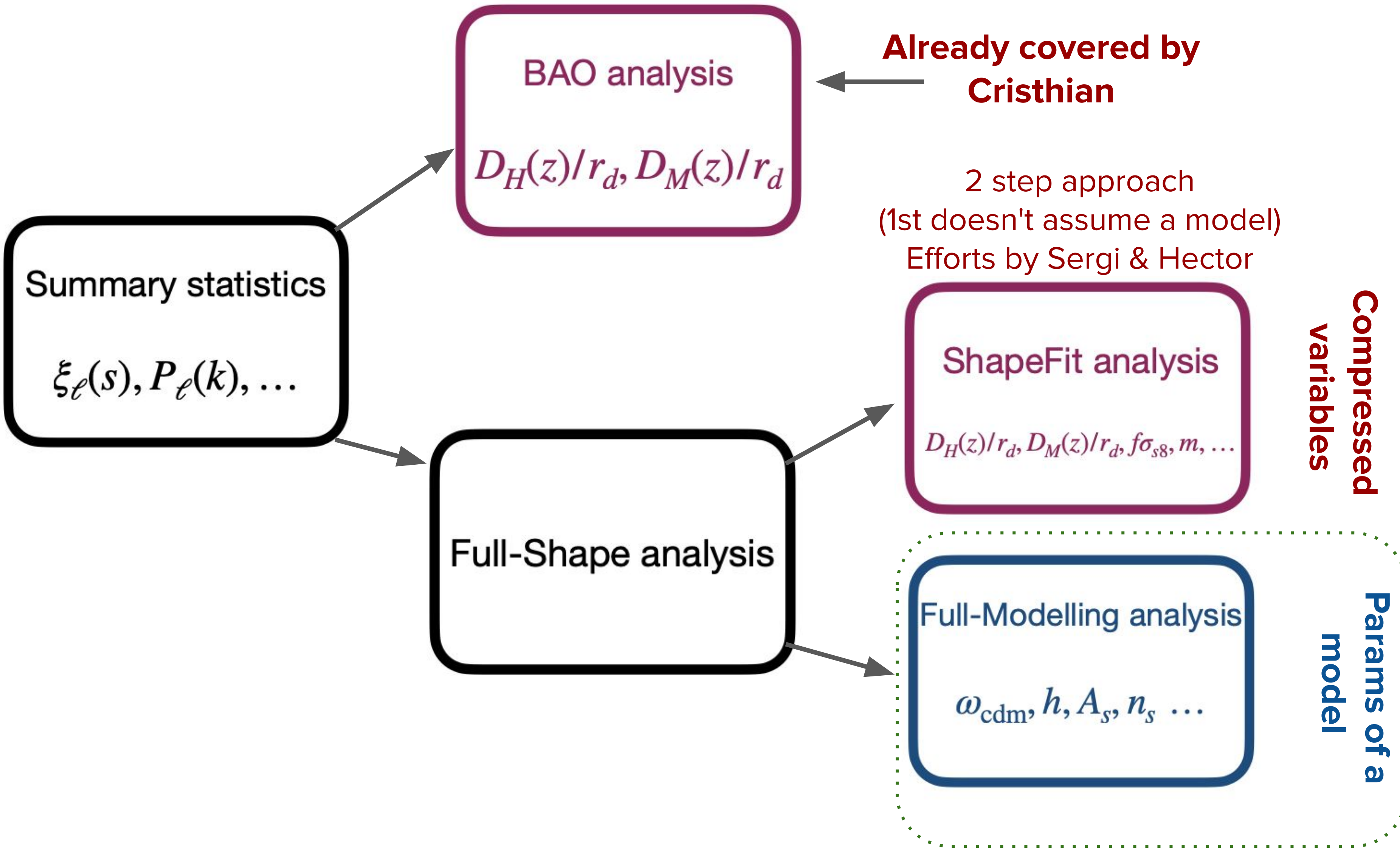
$$P_s(k,\mu) = P_s^{\rm PT}(k,\mu) + (\alpha_0 + \alpha_2\mu^2 + \alpha_4\mu^4)k^2 P_L + ({\rm SN}_0 + {\rm SN}_2 k^2\mu^2 + {\rm SN}_4 k^4\mu^4)$$

1-loop PT | **EFT counterterms** | **Stochastic-terms**

\+ **IR resummations**

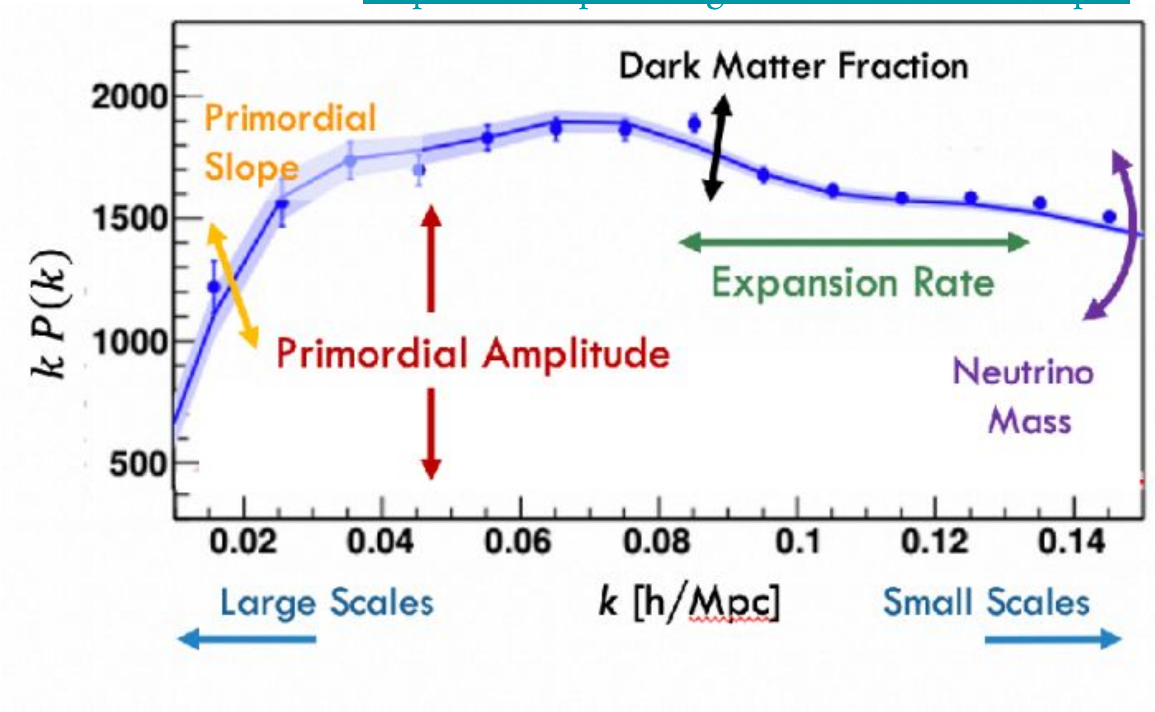


Full Shape analysis



Direct fitting approach: Full-Modeling

Taken from https://oliverphilcox.github.io/files/cotb24.pdf

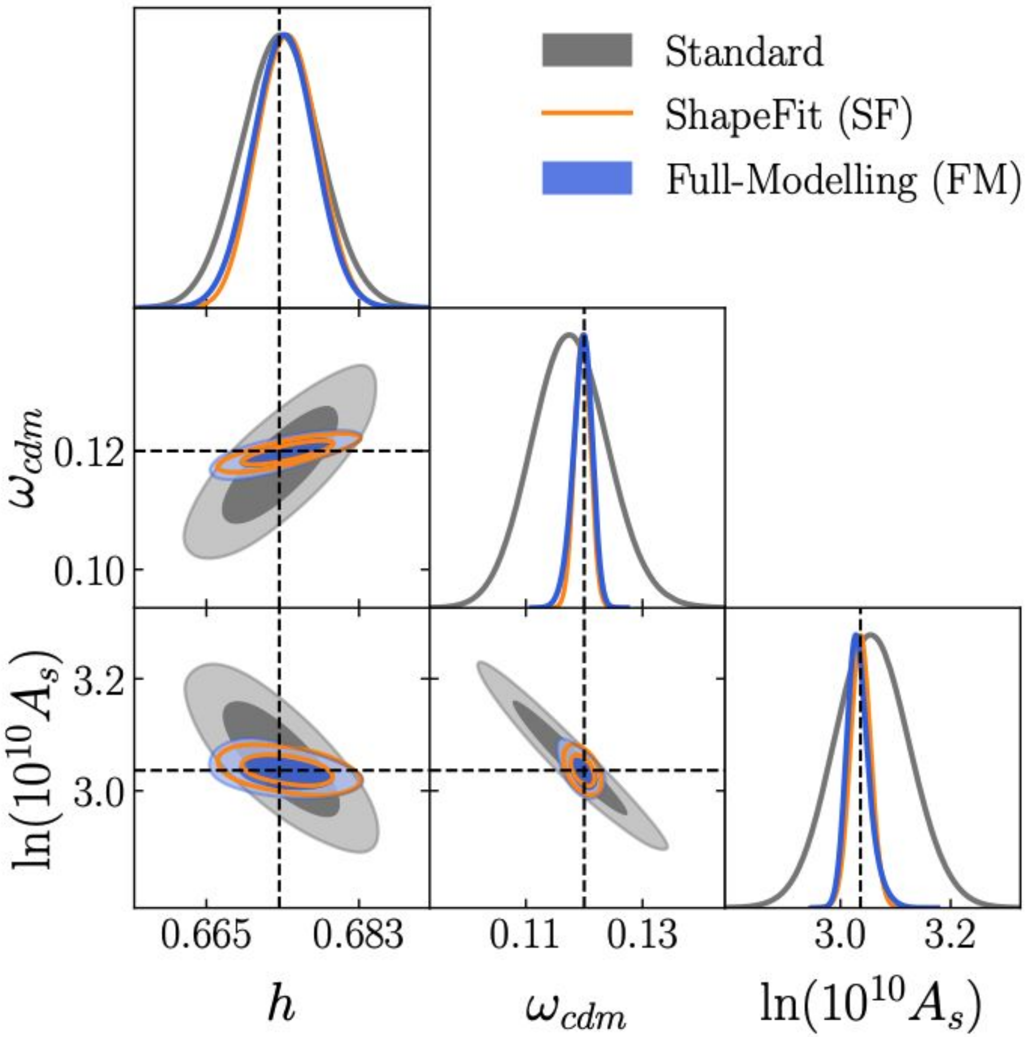


Cosmological parameters are **vary directly** for a **given cosmological model**

(as it is done for CMB)

Comparison of Compressed vs Full-Modeling

ΛCDM



Noriega et al 2024a.

Models and codes employed in DR1

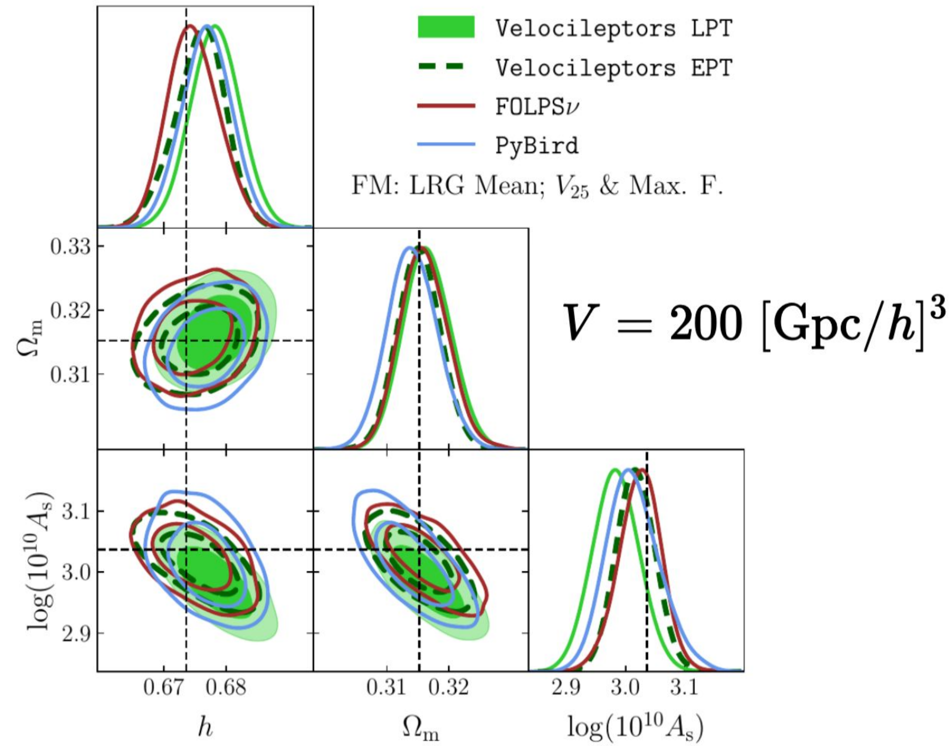
Three **power spectrum Effective Field Theory** models considered:

- **Velocileptors** Maus et al. 2024
- **Folps** Noriega et al. 2024
- **Pybird** Lai et al. 2024

One **configuration-space** model:

- **EFT-GSM** Ramirez et al. 2024

One comparison paper: Maus et al. 2024



Credit: Mark Maus, Hernan Noriega, Yan Lai, Sadi Ramirez

KP5 paper: DESI 2024 V

Hector & Pauline, +++

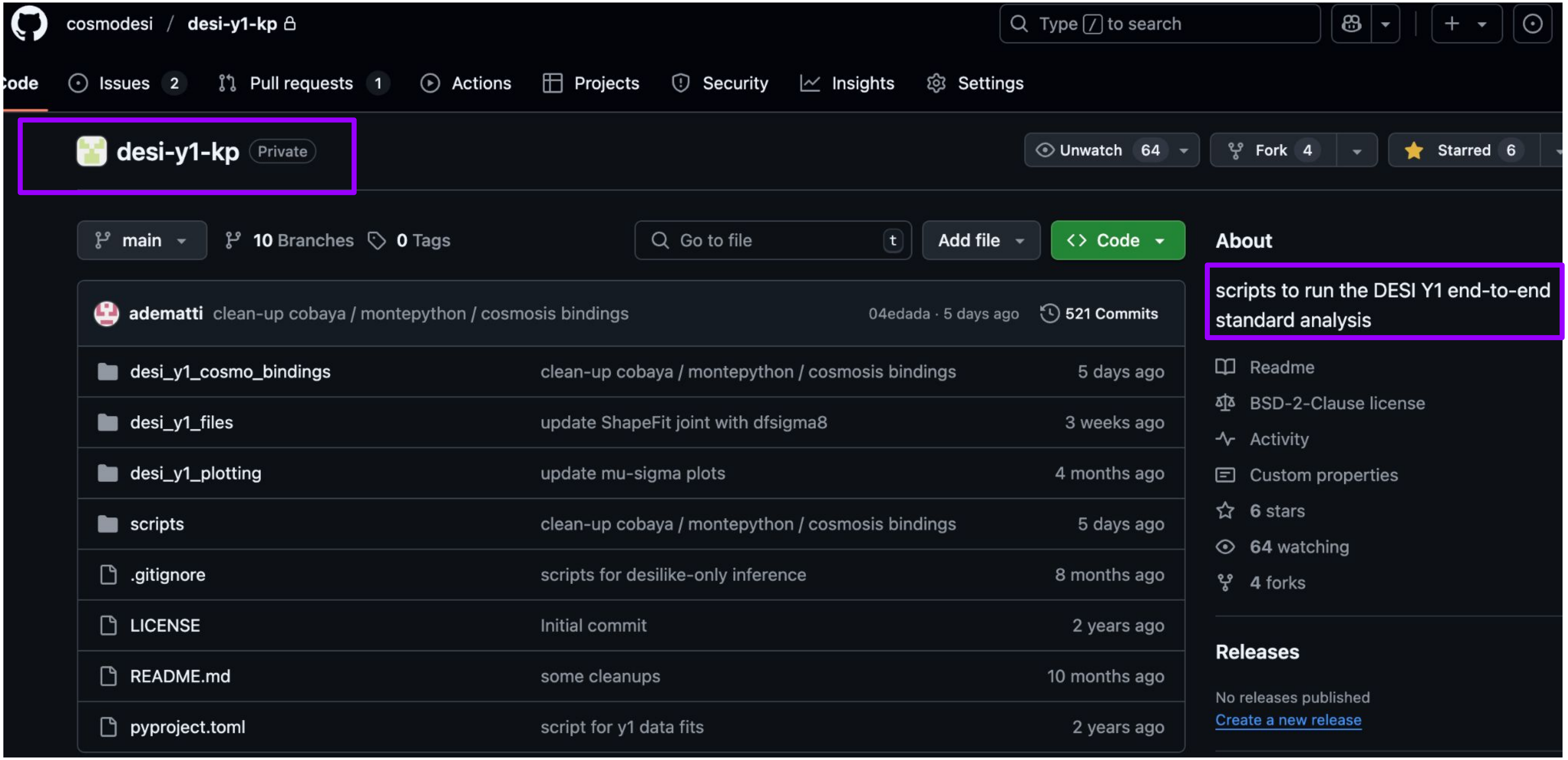
FS key paper: DESI 2024 VII

Dragan, Eva, Mustapha, +++

Models and codes used in DR1

You can **reproduce Y1 full shape results** using

https://github.com/cosmodesi/desi-y1-kp



Results DR1
Full Shape

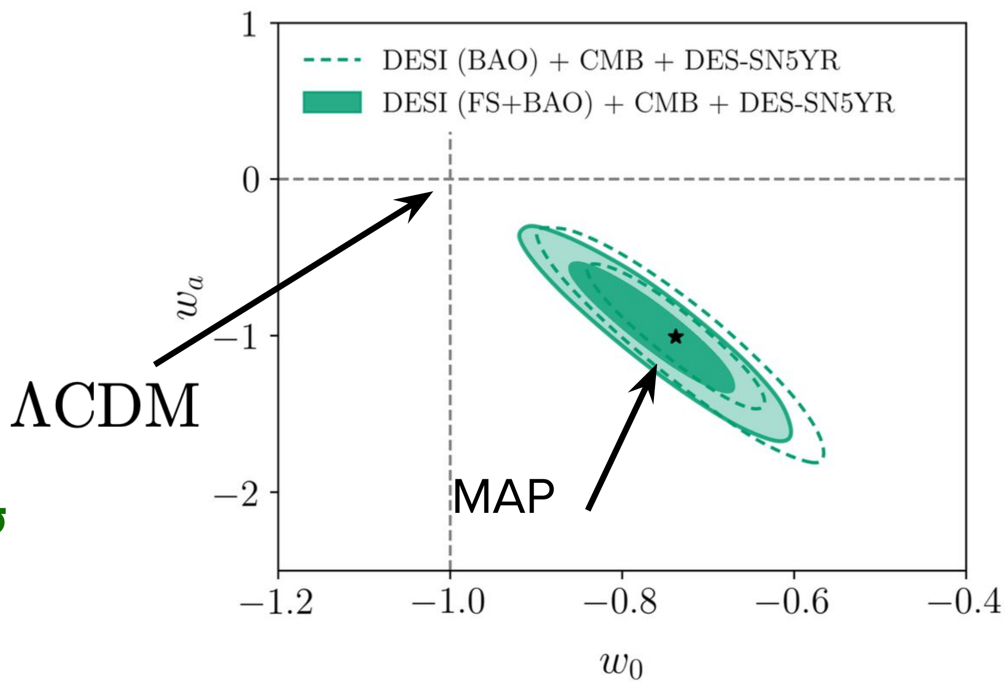
DR1 Full-Shape: Dark Energy constraints

Combining all DESI + CMB + SN

DESI + CMB + Pantheon+: **2.5σ**
(BAO: 2.5σ)

DESI + CMB + Union3: **3.4σ**
(BAO: 3.5σ)

DESI + CMB + DES-SNY5R: **3.8σ**
(BAO: 3.9σ)



20% tighter constraints than **BAO-only**, same preference for w0 >–1, wa <0

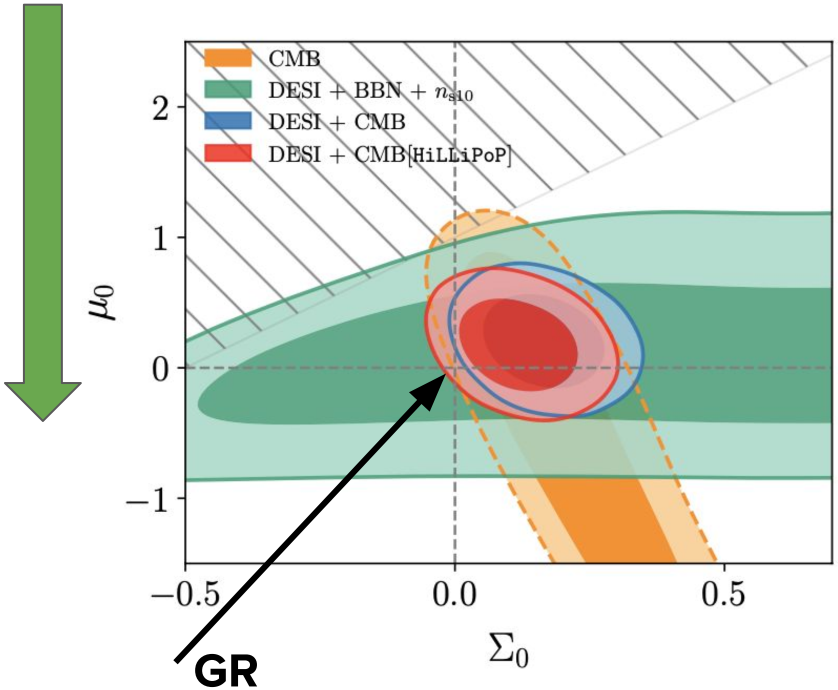
DR1 Full-Shape: Modified Gravity (time-dependent)

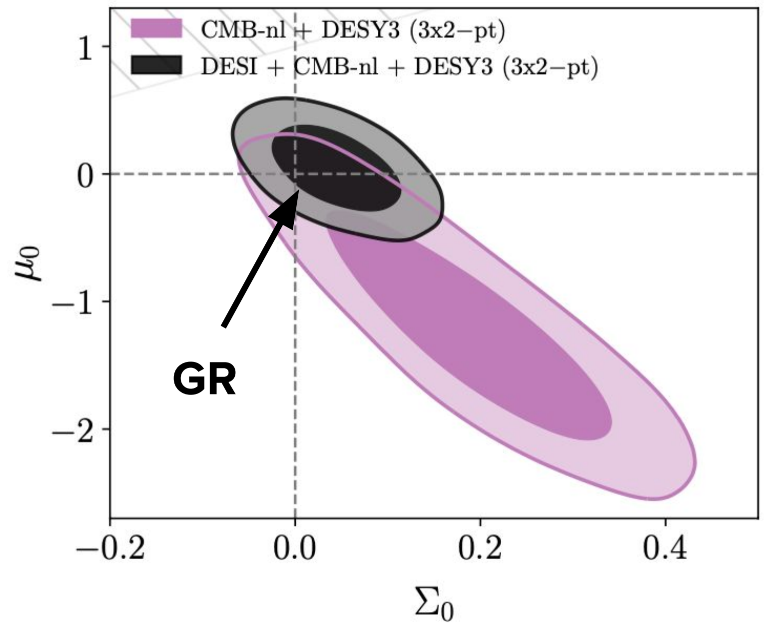
Phenomenological parameters to test deviations from **GR**

(mass trajectories) $$k^2\Psi = -4\pi G a^2 \mu(a,k) \sum_i \rho_i \Delta_i$$

(photon trajectories) $$k^2(\Phi + \Psi) = -8\pi G a^2 \Sigma(a,k) \sum_i \rho_i \Delta_i$$

Time-dependent parametrization:
Info mainly from fsimga8





$$\mu_0 = 0.11^{+0.45}_{-0.54}$$

(DESI (FS+BAO)+BBN+n_{s10})

$$\left.\begin{aligned}\mu_0 &= 0.04 \pm 0.22,\\ \Sigma_0 &= 0.044 \pm 0.047,\end{aligned}\right\}$$ DESI (FS+BAO)+CMB-nl+ DESY3 (3×2-pt).

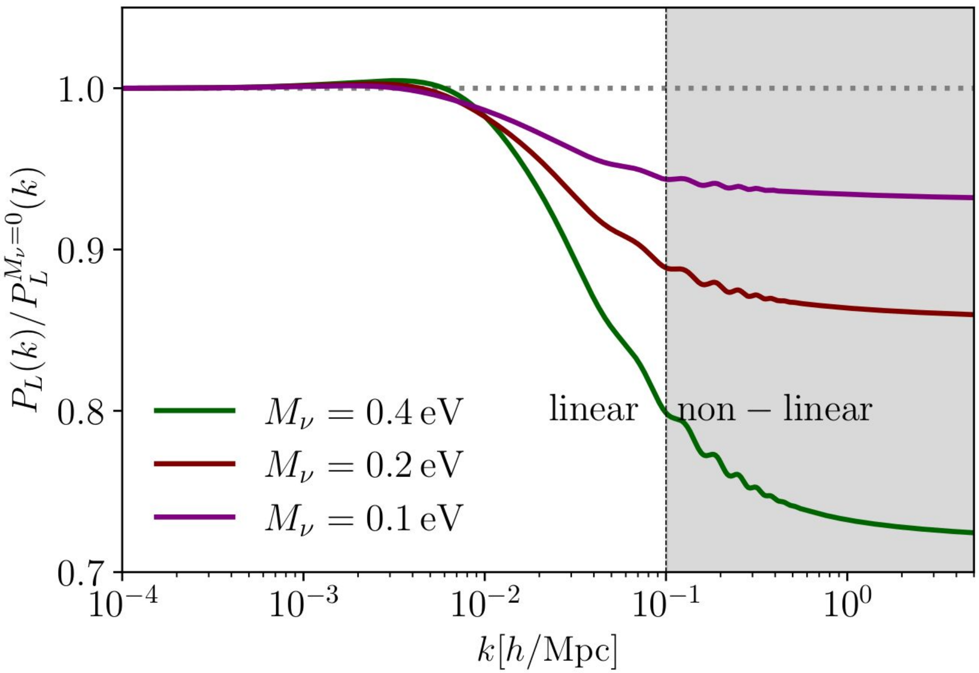
Massive neutrinos impact:

i) the expansion history of the Universe

Transition from relativistic to nonrelativistic

ii) the growth of structure:

Large thermal velocities washout structure formation on small scales

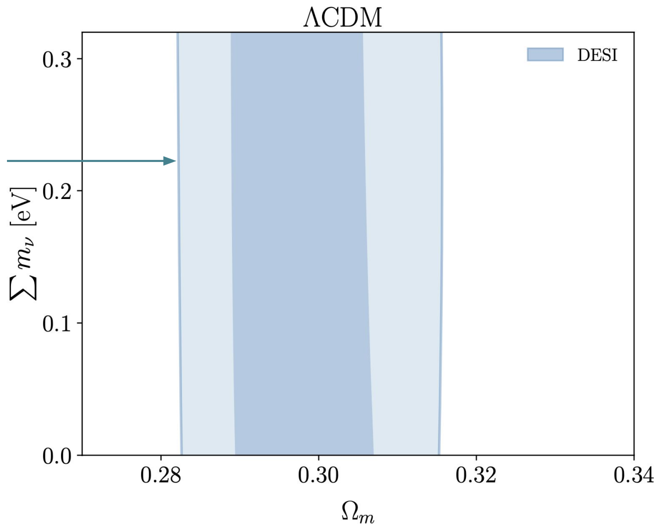


$$\frac{\Delta P}{P} = -8 f_\nu$$

DR1 Full-Shape: Neutrino mass constraints

Assuming $\sum m_\nu > 0\,\mathrm{eV}$ ← **Constraints depends on the prior!**

BAO-alone can NOT constrain neutrino mass



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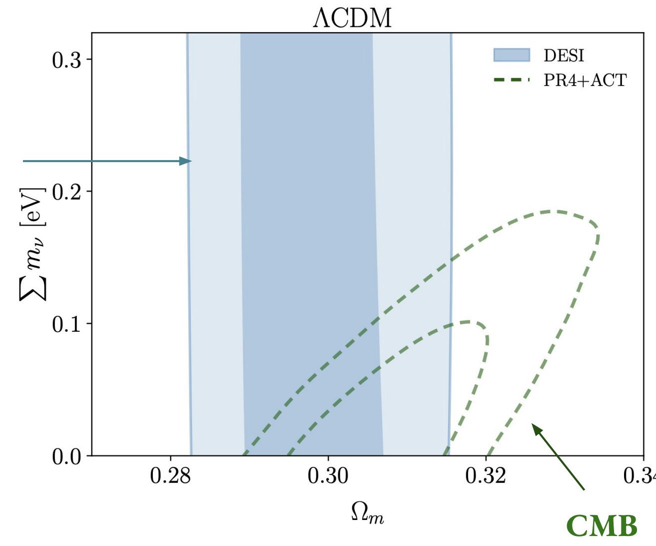

DR1 Full-Shape: Neutrino mass constraints

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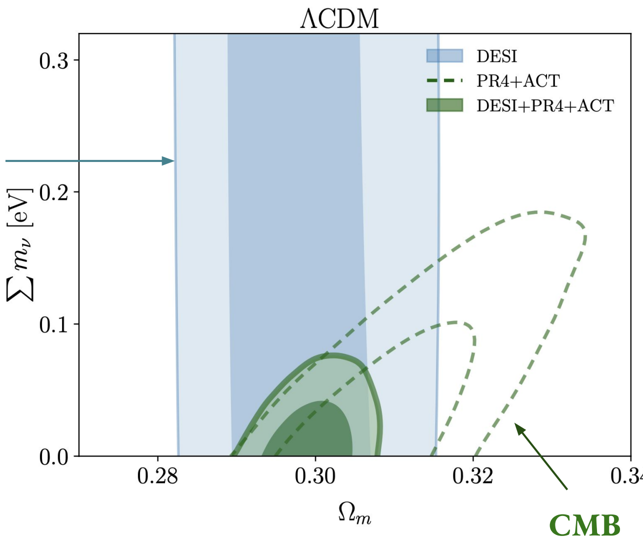


For Year 1 we got

$$\underbrace{\sum m_\nu < 0.071\,\mathrm{eV}\ (95\%)}_{\mathrm{DESI + CMB}}$$

(15% better than BAO-only: $0.082\,\mathrm{eV}$)

The very tight **constraints** on the **total neutrino mass** mainly come from **geometry***

how the degeneracy is broken: strongly affect neutrino constraints

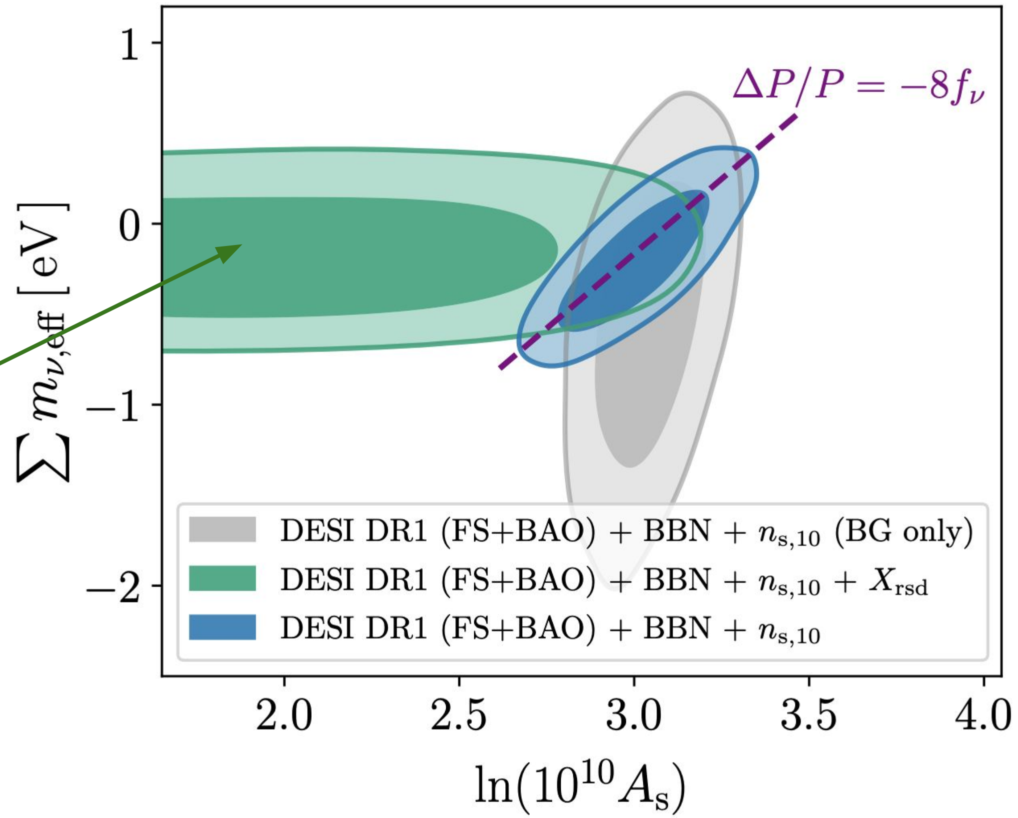
* except for lensing

DR1 Full-Shape: Neutrino mass constraints

DESI is able to get neutrino constraints **without including CMB data**

$$\text{DESI DR1 (FS+BAO)} + \text{BBN} + n_{\mathrm{s},10}: \quad \sum m_\nu < 0.409\,\mathrm{eV} \quad (95\%).$$

In this mass range, **information on Mnu** derives from the **free-streaming effect on the shape of the power spectrum** rather than from the amplitude or **background**



Elbers et al 2503.14744

Perspectives for DR2

Full-shape modeling
Modified gravity constraints
Neutrinos

Perspectives for DR2 Full-Shape: Bispectrum

Beyond 2-point

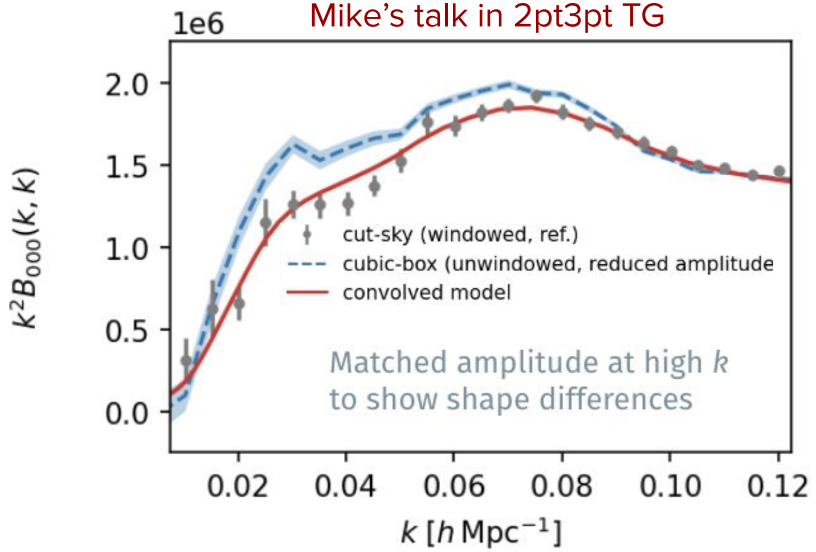
$$B(k_1, k_2, k_3) = \langle \delta(k_1)\, \delta(k_2)\, \delta(k_3) \rangle'$$

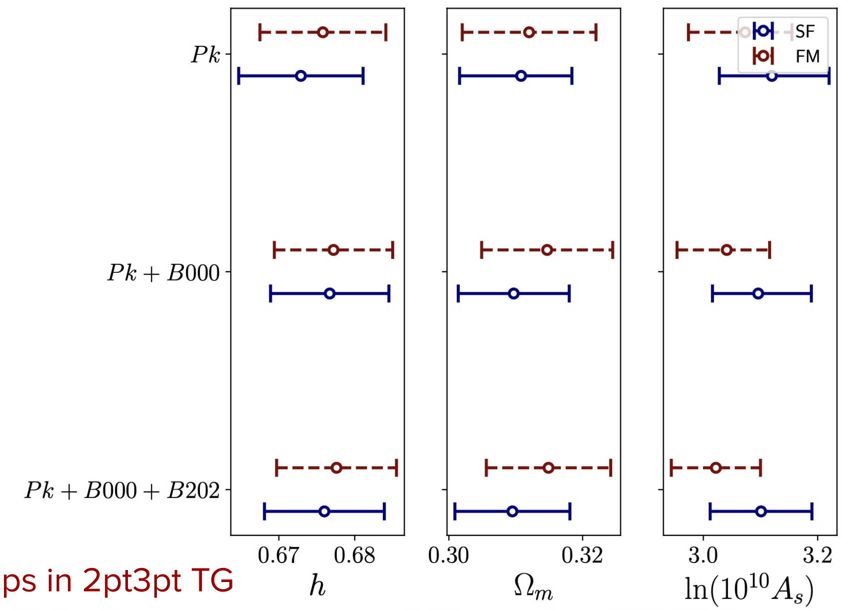
- At large scales, the bispectrum **constrains second-order biases b2** and **bs**.
- Helps **break degeneracies** between **nuisance** and **cosmological** parameters.
- Mainly **improves constraints** on **As** and **Mnu**

Different implementations:
Sugiyama, Scoccimarro,...

ShapeFit (SF)
Full-Modeling (FM)

Mike's talk in 2pt3pt TG





Folps in 2pt3pt TG

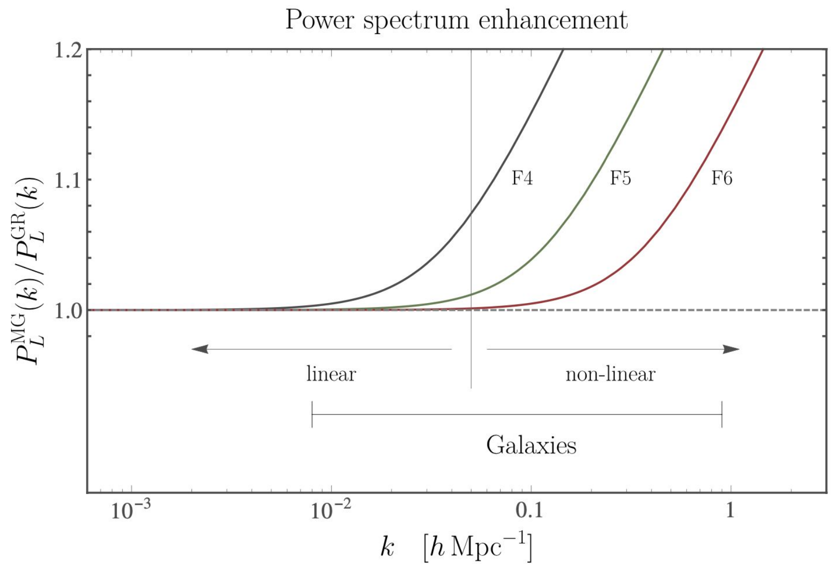
Perspectives for DR2 Full-Shape: Scale-dependent MG

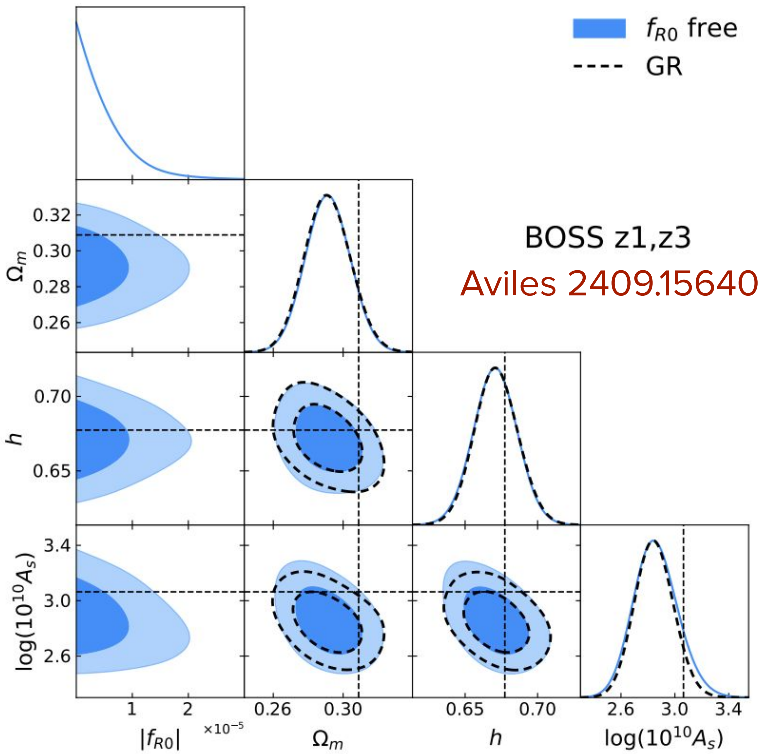
Exploit scale-dependent MG models, which affects the spectra a certain scales

Certain scales -> MG

Large scales -> GR

fifth-force, or **Yukawa potential** with **fine range**





BOSS z1,z3
Aviles 2409.15640

For these models, **constraints** are obtained from **fσ8** and the **full shape of the spectra**;

this is essentially what full-shape analysis is designed to do

Perspectives for DR2 Full-Shape: Neutrinos

SPT paper 2506.20707

$$\Sigma m_\nu < 0.081\,\mathrm{eV} \text{ for SPT-3G D1} + \text{DESI},$$
$$\Sigma m_\nu < 0.048\,\mathrm{eV} \text{ for CMB-SPA} + \text{DESI}.$$

CMB-SPA + DESI, rule out **NH** at **97.9%**, and **IH** at **99.9%**

Exploit alternative probes of neutrino mass that are less sensitive to background evolution (which is degenerate with neutrinos).

Systematics in CMB?

tau ~ 0.09 reconciles LCDM and neutrino mass constraints

N. Sailor et al. ArXiv: 2504.16932
Tanisha et al. ArXiv: 2504.21813