Large-scale structure

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ISAPP 2024: Particle Candidates for Dark Matter

Lecture 4

Biased tracers and redshift space

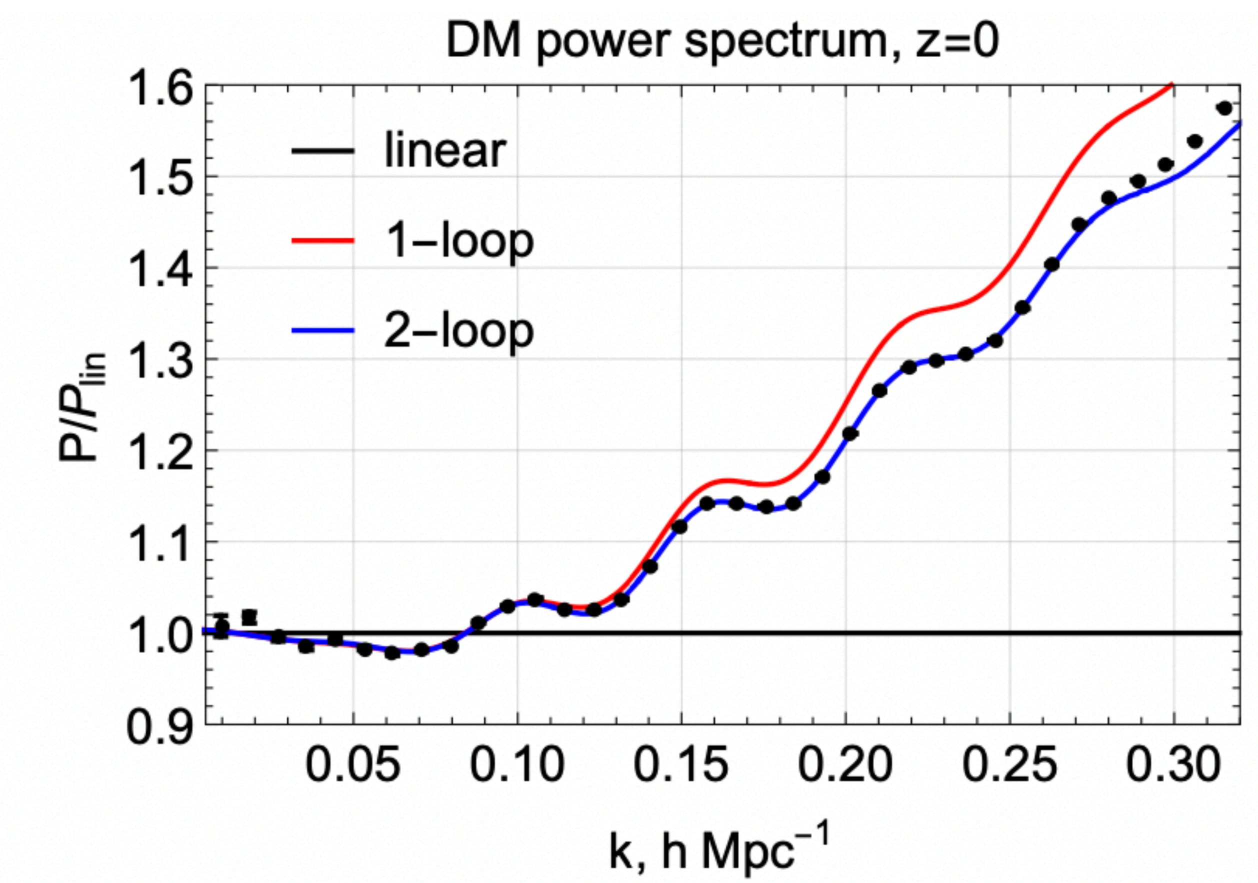
One-loop galaxy power spectrum

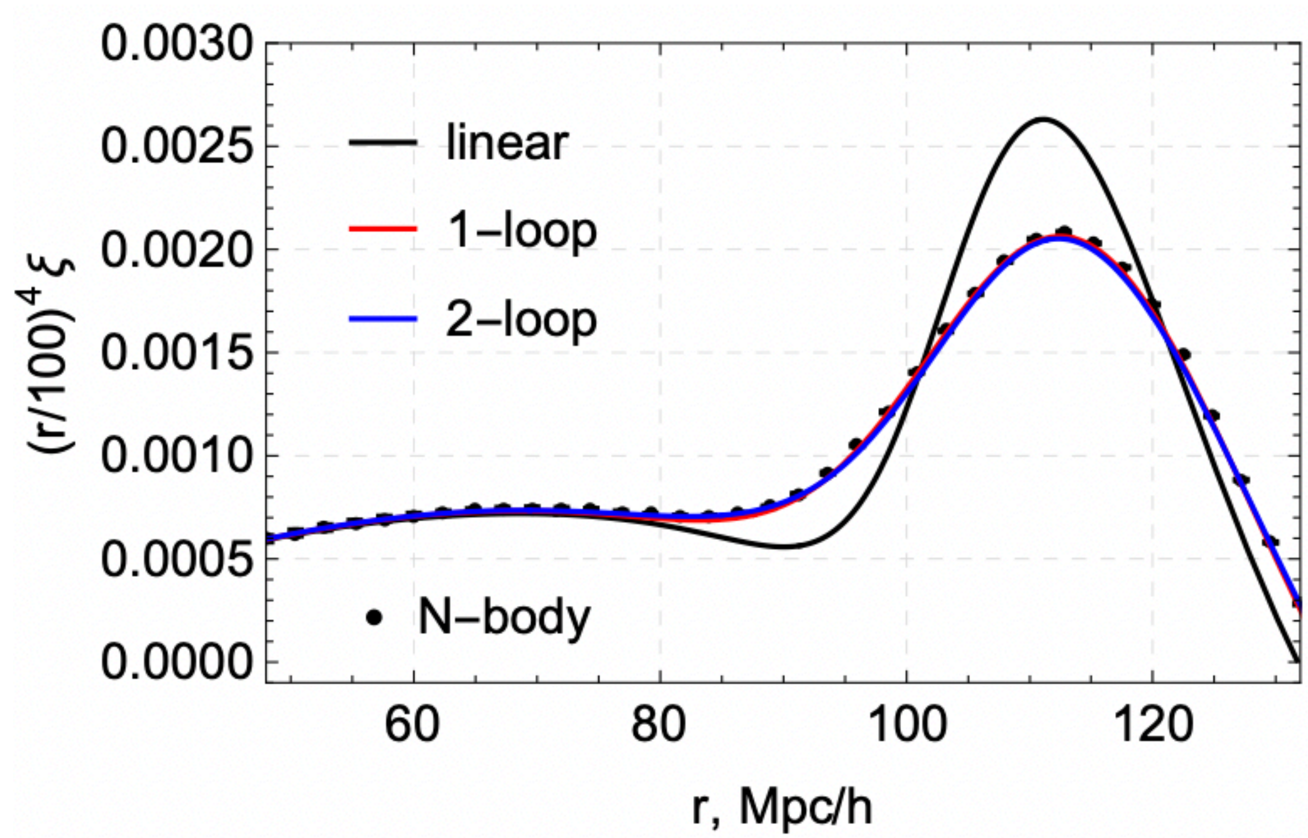
Exploring DM with LSS

IR resummed 2-loop power spectrum

1% precision up to $k \approx 0.25\ h/\mathrm{Mpc}$

Perfect description of the BAO peak

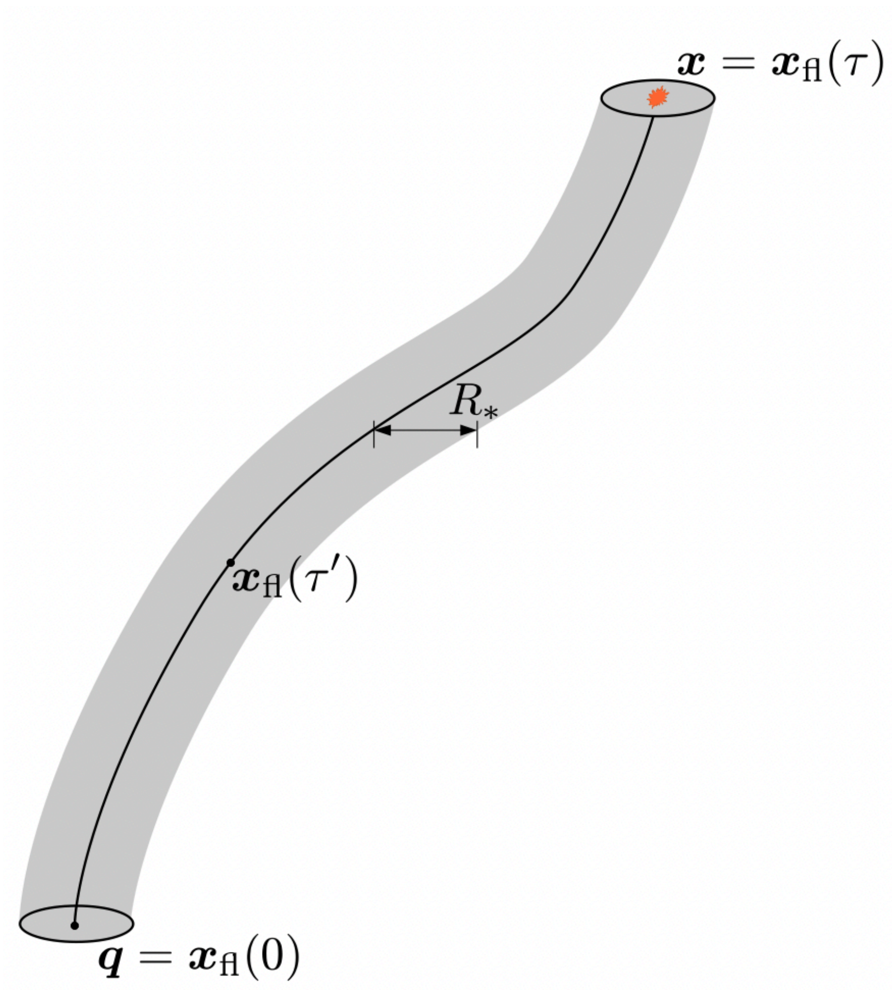




The same principles hold for galaxies

Galaxies as a biased tracer od DM

$$\delta_g(\boldsymbol{x},\tau) = \int_0^{\tau} d\tau' F[\partial_i\partial_j\Phi(\boldsymbol{x}_{\rm fl}(\tau'),\tau'), \mathrm{ICs}, \Omega_b, H_0, \ldots, \mathrm{SFR}(\tau,\tau'),\ \mathrm{AGN}(\tau,\tau'), \ldots]$$



Galaxies as a biased tracer od DM

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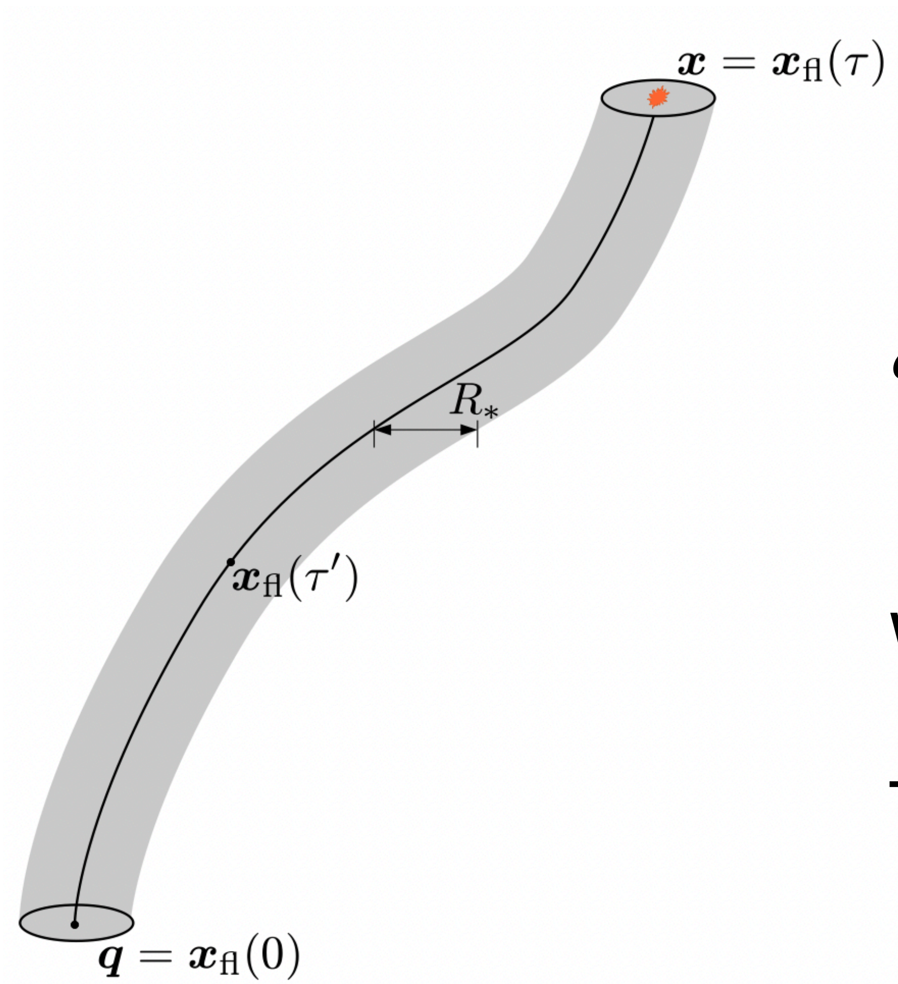
local in space!



$$\delta_{g,l}(\boldsymbol{x},\tau) = \sum_n \int_0^\tau d\tau' c_n(\tau,\tau')\mathcal{O}_n[\partial_i\partial_j\Phi(\boldsymbol{x}_{\rm fl}(\tau'),\tau')] + \epsilon(\tau)$$

We can perturbatively solve for $\partial_i\partial_j\Phi(\boldsymbol{x}_{\rm fl}(\tau'),\tau')$

The noise contribution $\epsilon(\tau)$ has to be modelled

Galaxies as a biased tracer od DM

Along the fluid element:

$$\mathcal{O}(\boldsymbol{x}_{\text{fl}}(\tau'), \tau') = \mathcal{O}(\boldsymbol{x}, \tau) + (\tau' - \tau)\frac{D}{D\tau}\mathcal{O}(\boldsymbol{x}, \tau) + \cdots \qquad \frac{D}{D\tau} \equiv \frac{\partial}{\partial \tau} + v^i \nabla_i$$

This allows us to integrate in time

$$\delta_{g,l}(\boldsymbol{x}, \tau) = b_1(\tau)\delta(\tau) + \frac{b_2(\tau)}{2}\delta^2(\tau) + b_t(\tau)(\partial_i\partial_j\Phi(\tau))^2 + \cdots + P_{\text{shot}}$$

Bias parameters $b_i(\tau)$ encode all small scale physics of galaxy formation!

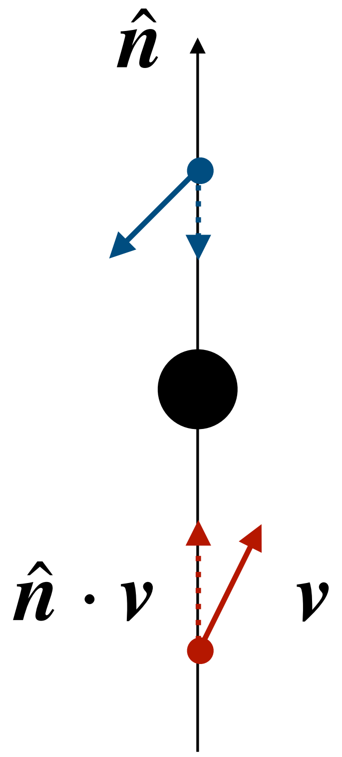
On large scales P_{shot} is approximately constant and given by $P_{\text{shot}} \approx \frac{1}{n}$

Redshift space distortions

$$s_i = x_i + \frac{\hat{\boldsymbol{n}} \cdot \boldsymbol{v}}{\mathcal{H}} \hat{n}_i$$

$$\rho_g(\boldsymbol{s}) d^3\boldsymbol{s} = \rho_g(\boldsymbol{x}) d^3\boldsymbol{x}$$

$$(1 + \delta_g(\boldsymbol{s})) d^3\boldsymbol{s} = (1 + \delta_g(\boldsymbol{x})) d^3\boldsymbol{x}$$



$$\delta_{g,s}(\boldsymbol{k}) = \int d^3\boldsymbol{x} (1 + \delta_g(\boldsymbol{x})) e^{-i\boldsymbol{k}\cdot\boldsymbol{s}} - \int d^3\boldsymbol{x} \left| \frac{\partial \boldsymbol{s}}{\partial \boldsymbol{x}} \right| e^{-i\boldsymbol{k}\cdot\boldsymbol{s}}$$

We can perturbatively expand this formula in velocities to any order we need

1-loop galaxy power spectrum

$$P_{\rm gg,RSD}(z,k,\mu) = Z_1^2(\mathbf{k})P_{\rm lin}(z,k) + 2\int_{\mathbf{q}} Z_2^2(\mathbf{q},\mathbf{k}-\mathbf{q})P_{\rm lin}(z,|\mathbf{k}-\mathbf{q}|)P_{\rm lin}(z,q)$$
$$+ 6Z_1(\mathbf{k})P_{\rm lin}(z,k)\int_{\mathbf{q}} Z_3(\mathbf{q},-\mathbf{q},\mathbf{k})P_{\rm lin}(z,q)$$
$$+ P_{\rm ctr,RSD}(z,k,\mu) + P_{\epsilon\epsilon,\rm RSD}(z,k,\mu)\,,$$

contain galaxy formation physics

$$Z_1(\mathbf{k}) = b_1 + f\mu^2\,,$$
$$Z_2(\mathbf{k}_1,\mathbf{k}_2) = \frac{b_2}{2} + b_{\mathcal{G}_2}\left(\frac{(\mathbf{k}_1\cdot\mathbf{k}_2)^2}{k_1^2k_2^2} - 1\right) + b_1F_2(\mathbf{k}_1,\mathbf{k}_2) + f\mu^2G_2(\mathbf{k}_1,\mathbf{k}_2)$$
$$+ \frac{f\mu k}{2}\left(\frac{\mu_1}{k_1}(b_1+f\mu_2^2) + \frac{\mu_2}{k_2}(b_1+f\mu_1^2)\right)\,,$$

Infrared resummation

$$\Sigma^2(z) \equiv \frac{1}{6\pi^2}\int_0^{k_S} dq\, P_{\rm nw}(z,q)\left[1 - j_0\left(\frac{q}{k_{osc}}\right) + 2j_2\left(\frac{q}{k_{osc}}\right)\right]$$

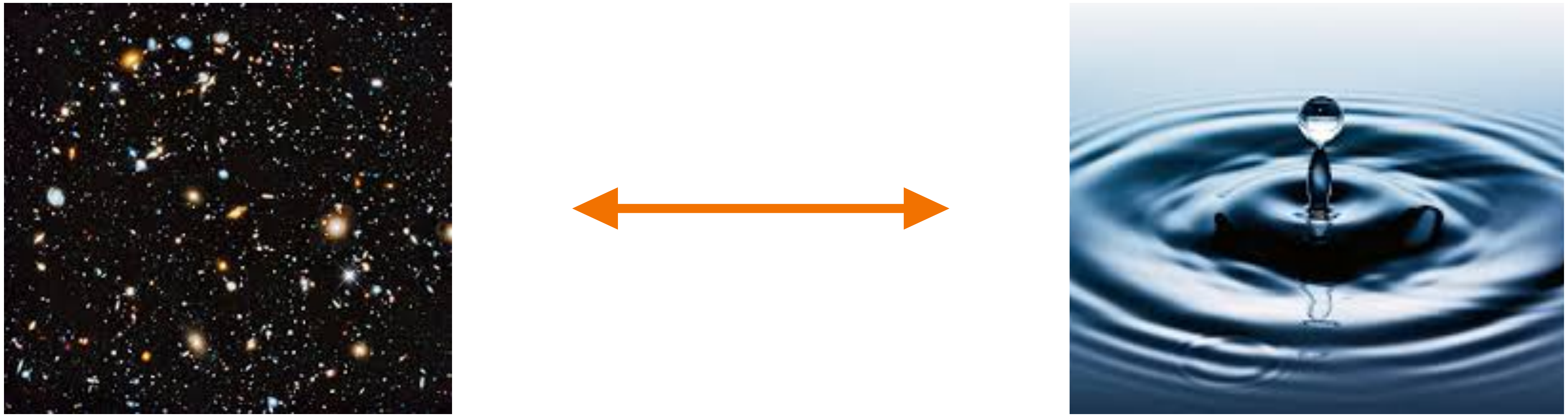
$$\delta\Sigma^2(z) \equiv \frac{1}{2\pi^2}\int_0^{k_S} dq\, P_{\rm nw}(z,q)j_2\left(\frac{q}{k_{osc}}\right)$$

$$\Sigma^2_{\rm tot}(z,\mu) = (1 + f(z)\mu^2(2+f(z)))\Sigma^2(z) + f^2(z)\mu^2(\mu^2-1)\delta\Sigma^2(z)$$

$$P_{\rm gg}(z,k,\mu) = (b_1(z)+f(z)\mu^2)^2\left(P_{\rm nw}(z,k) + {\rm e}^{-k^2\Sigma^2_{\rm tot}(z,\mu)}P_{\rm w}(z,k)(1+k^2\Sigma^2_{\rm tot}(z,\mu))\right)$$
$$+ P_{\rm gg,\ nw,\ RSD,\ 1\text{-}loop}(z,k,\mu) + {\rm e}^{-k^2\Sigma^2_{\rm tot}(z,\mu)}P_{\rm gg,\ w,\ RSD,\ 1\text{-}loop}(z,k,\mu)\,.$$

Parameters: $(\omega_{\rm b}, \omega_{\rm cdm}, h, A^{1/2}, n_s, m_\nu) \times (b_1A^{1/2}, b_2A^{1/2}, b_{\mathcal{G}_2}A^{1/2}, P_{\rm shot}, c_0^2, c_2^2, \tilde{c})$

Some literature



Lecture notes:

Baldauf, Les Houches Lecture Notes 108 (2020)

Senatore, https://indico.ictp.it/event/8317/session/15/contribution/61/material/2/0.pdf

Reviews:

Ivanov: 2212.08488

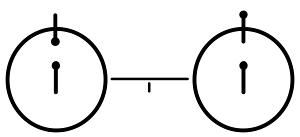
Desjacques, Jeong, Schmidt: 1611.09787

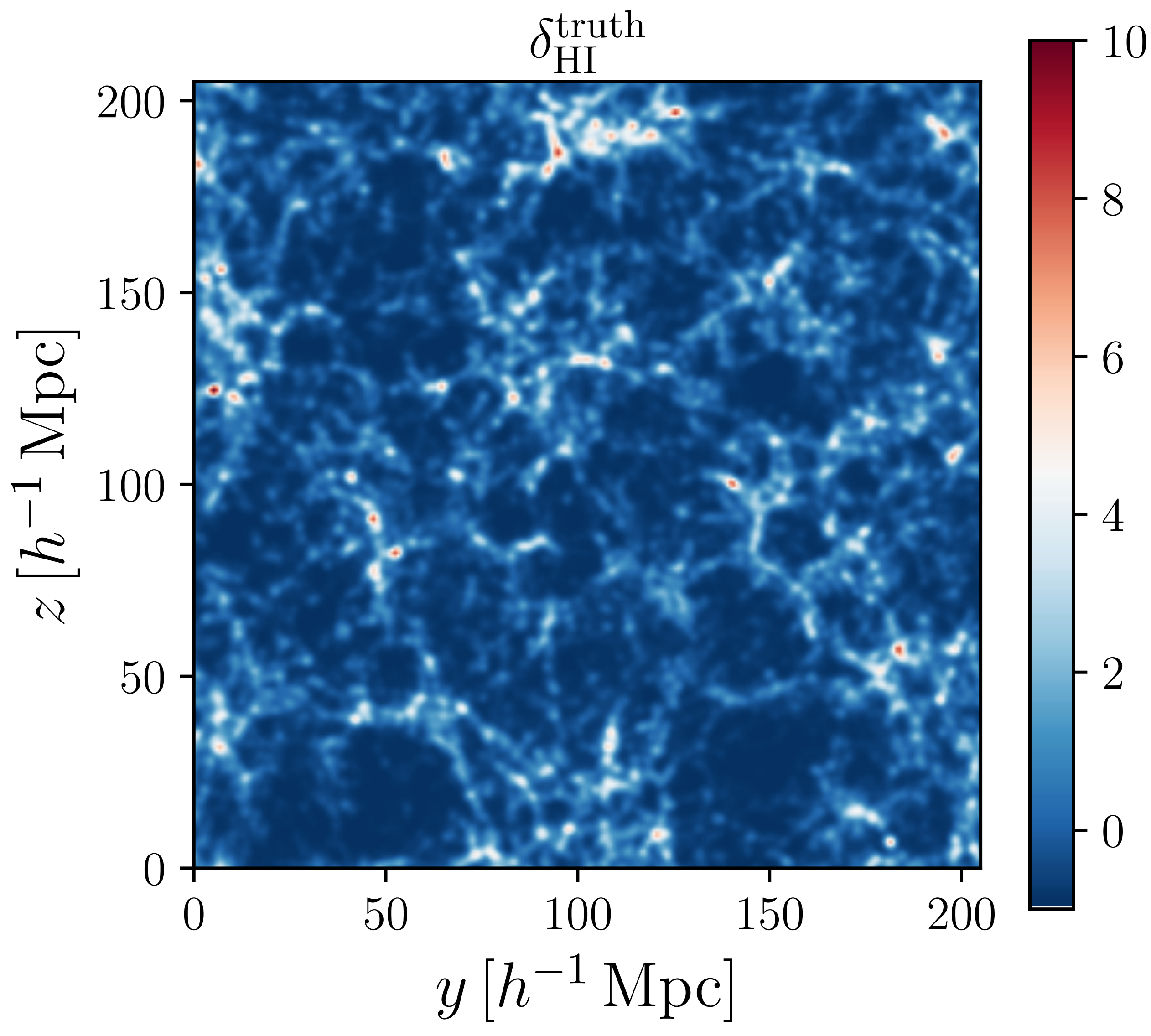
Cabas, Ivanov, Lewandowski, Mirbabayi, Simonovic: 2203.08232

How well does PT work?

Obuljen, MS, Schneider, Feldmann (2022)

Differences wrt the truth compatible with the shot noise





Hydro code

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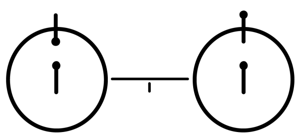
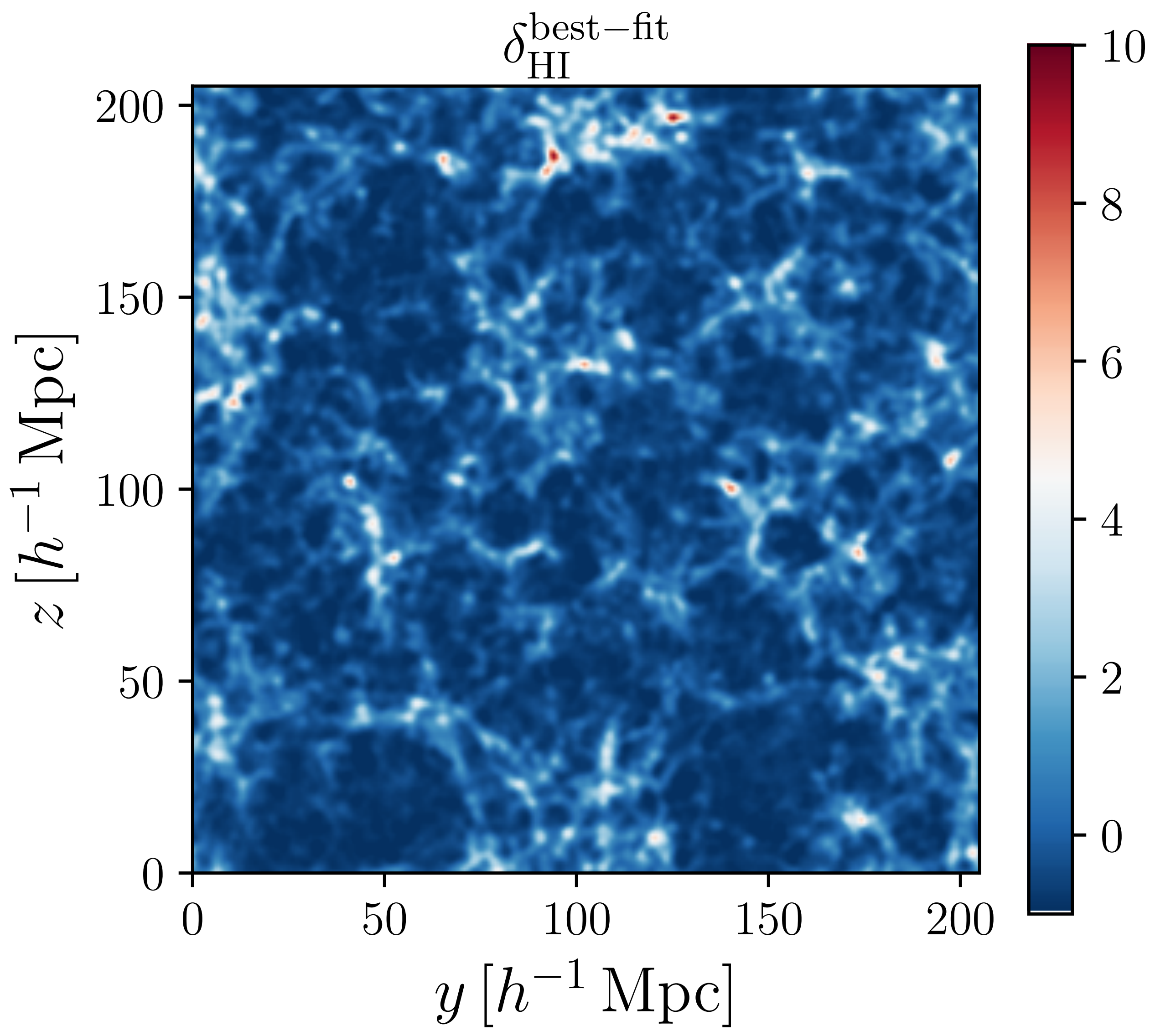


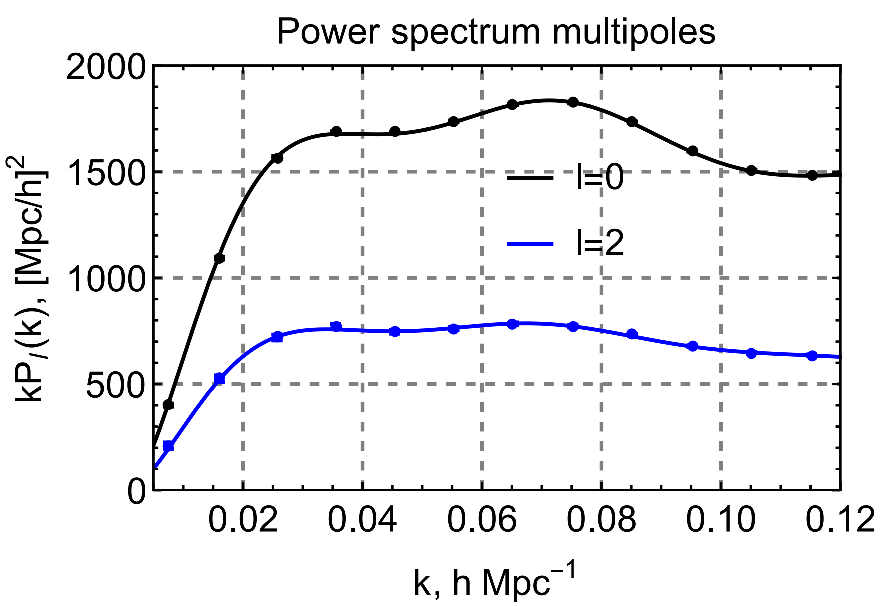


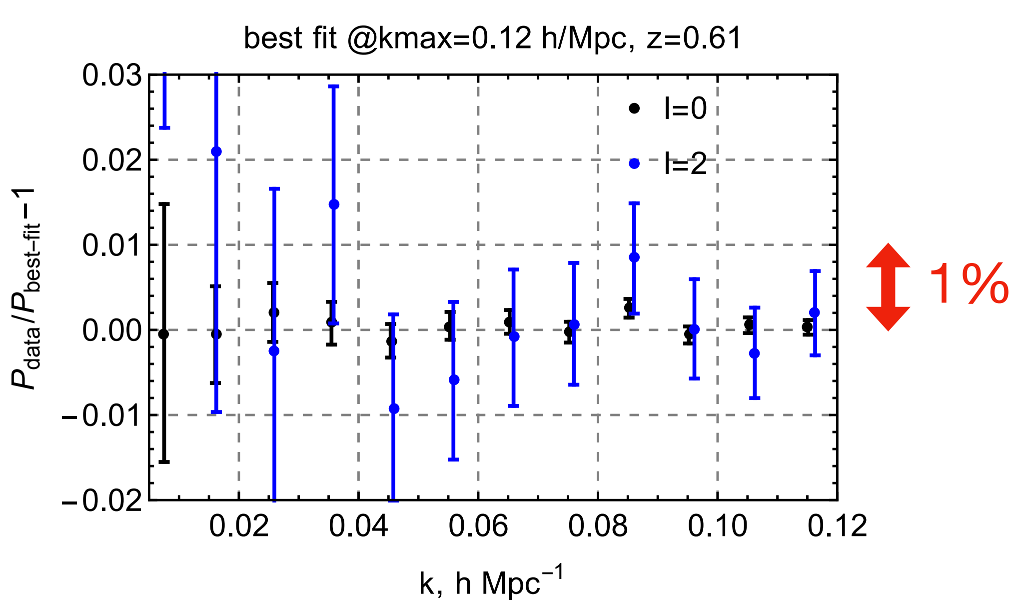
PT map

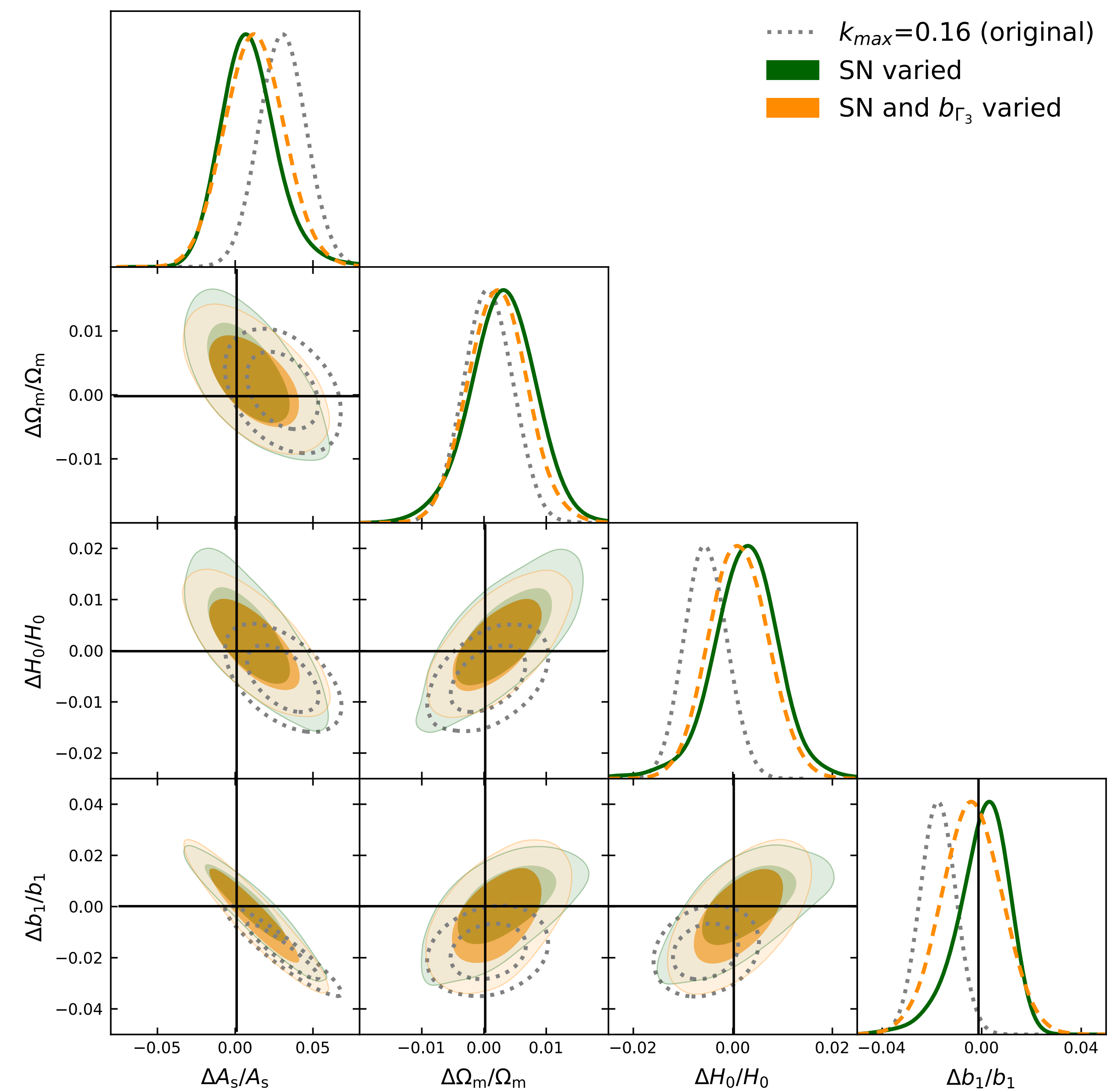
How well does PT work?

Nishimichi et al. (2020)

Blind analysis, very large volume ~ 600 $(Gpc/h)^3$), realistic galaxies

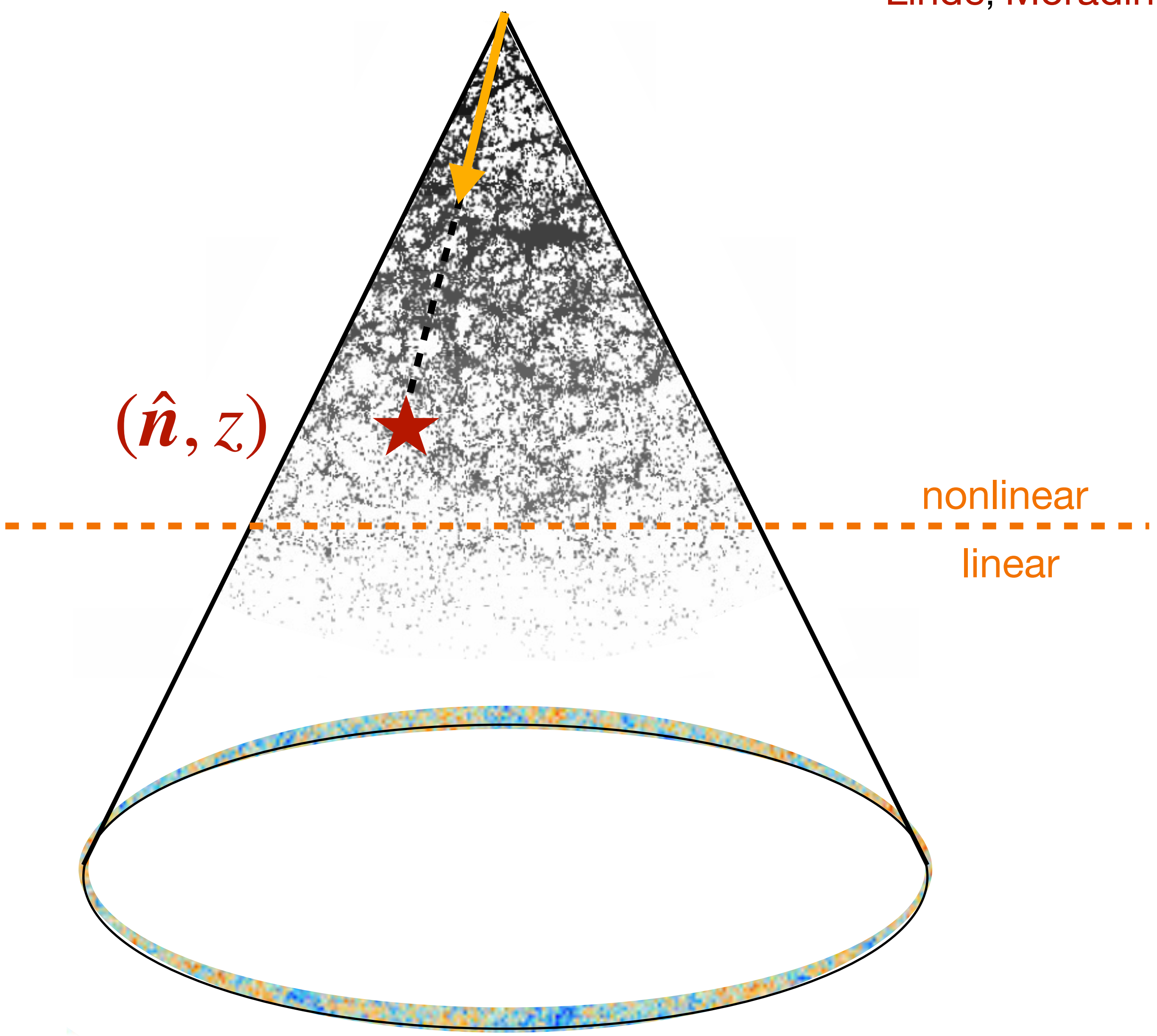






A new era in cosmology

Chudaykin, Ivanov, Philcox, MS (2019)
D'Amico, Senatore, Zhang (2019)
Chen, Vlah, Castorina, White (2020)
Linde, Moradinezhad Dizgah, Radermacher, Casas, Lesgourgues (2024)



CLASS-PT
PyBird
velocileptors
CLASS-OneLoop

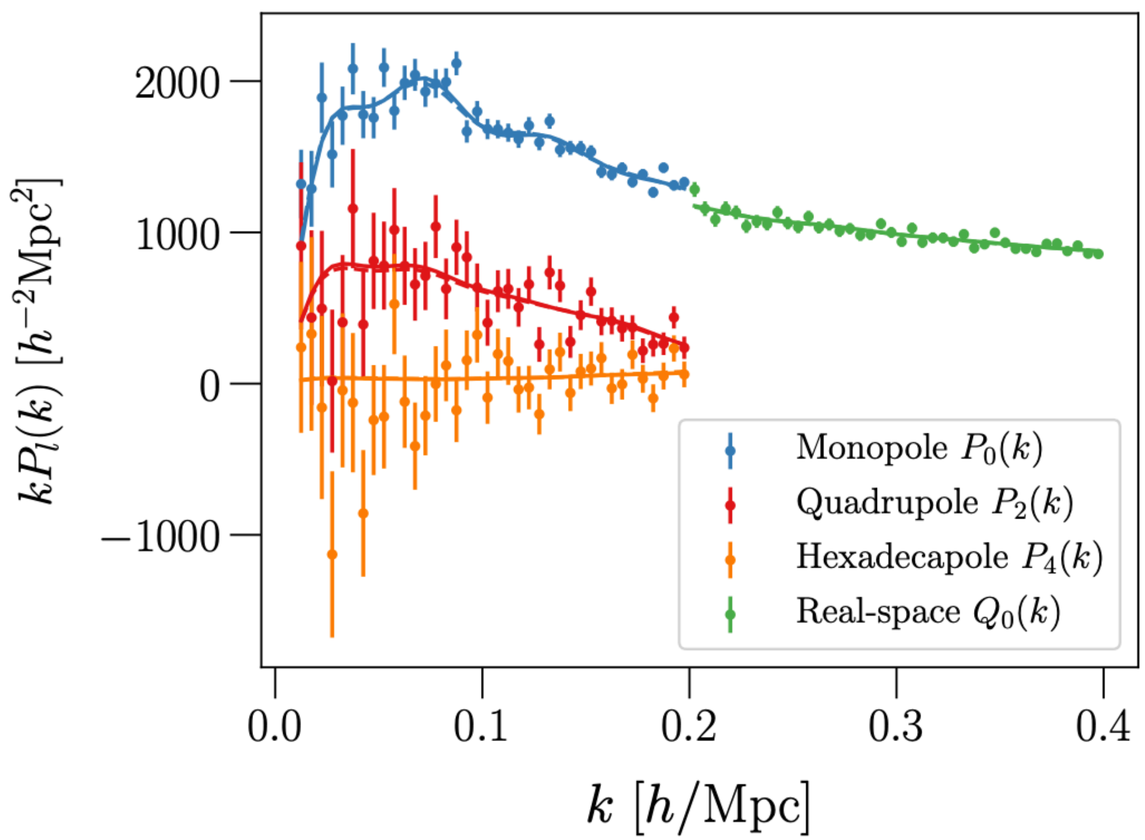
CMBFAST
CAMB
CLASS

Evolution of the vacuum state from inflation to redshift zero

Application to BOSS data

Galaxy map

BOSS data
~ few x 10^6 galaxies
~ 6 (Gpc/h)^3



Full-shape analysis

Similar to CMB, directly measures “shape” parameters

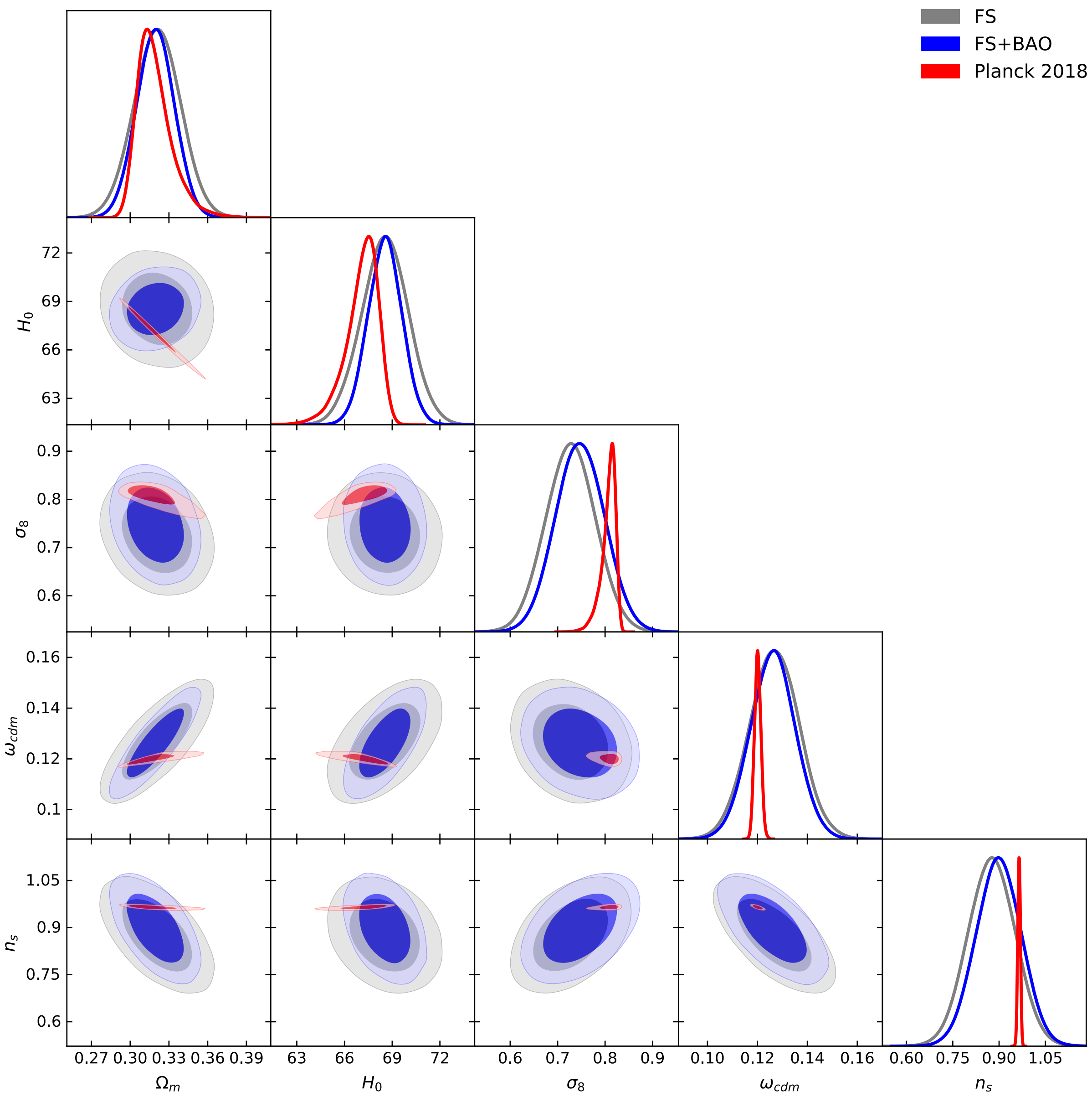
all cosmological parameters
no CMB input needed

Application to BOSS data

Ivanov, MS, Zaldarriaga (2019)

d'Amico, Gleyzes, Kokron, Markovic, Senatore, Zhang, Beutler, Gil Marin (2019)

Philcox, Ivanov, MS, Zaldarriaga (2020)



Using BBN prior on ω_b

$H_0 = 68.6 \pm 1.1$ km/s/Mpc

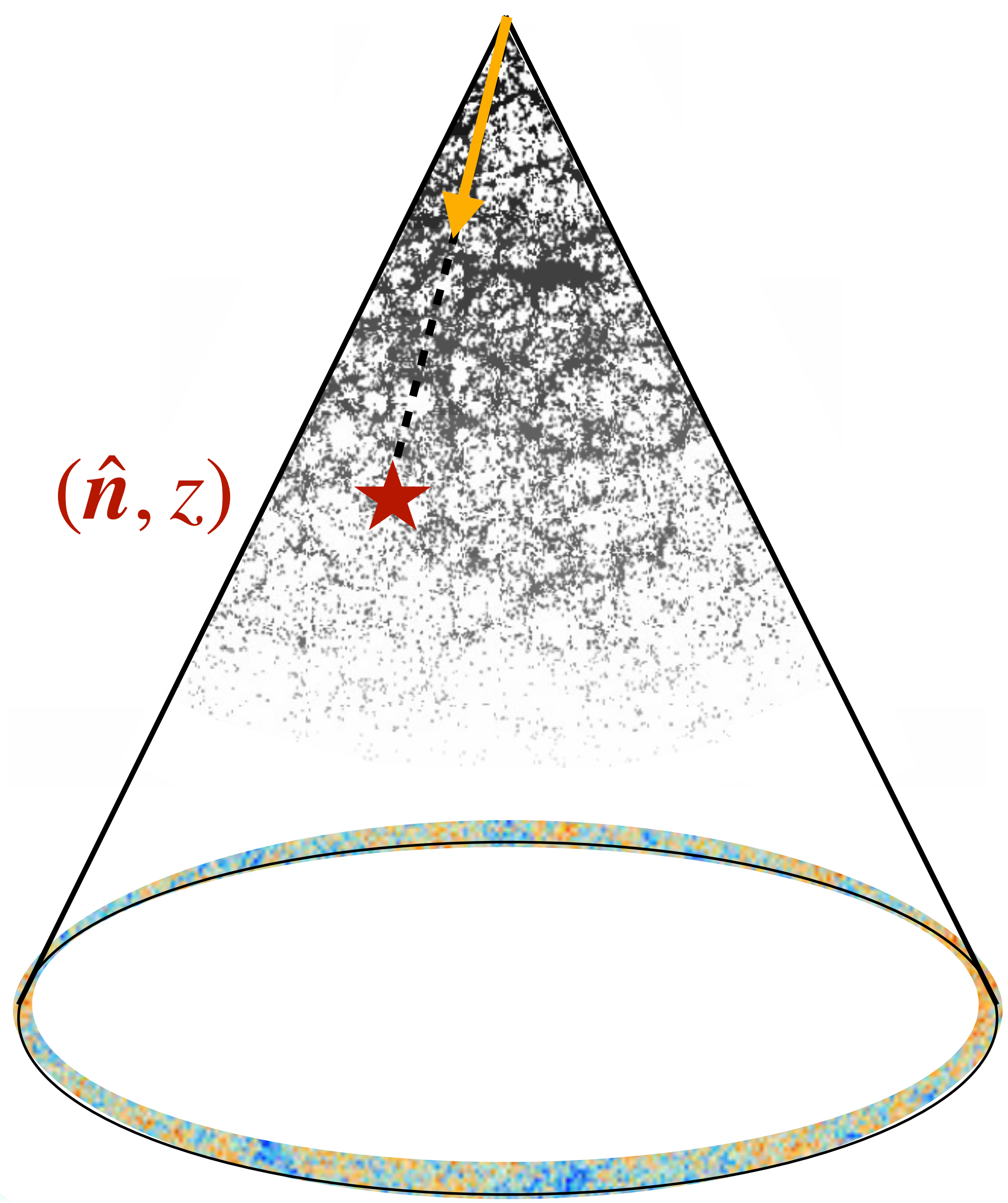
$H_0 = 67.8 \pm 0.7$ km/s/Mpc (fixing the tilt)

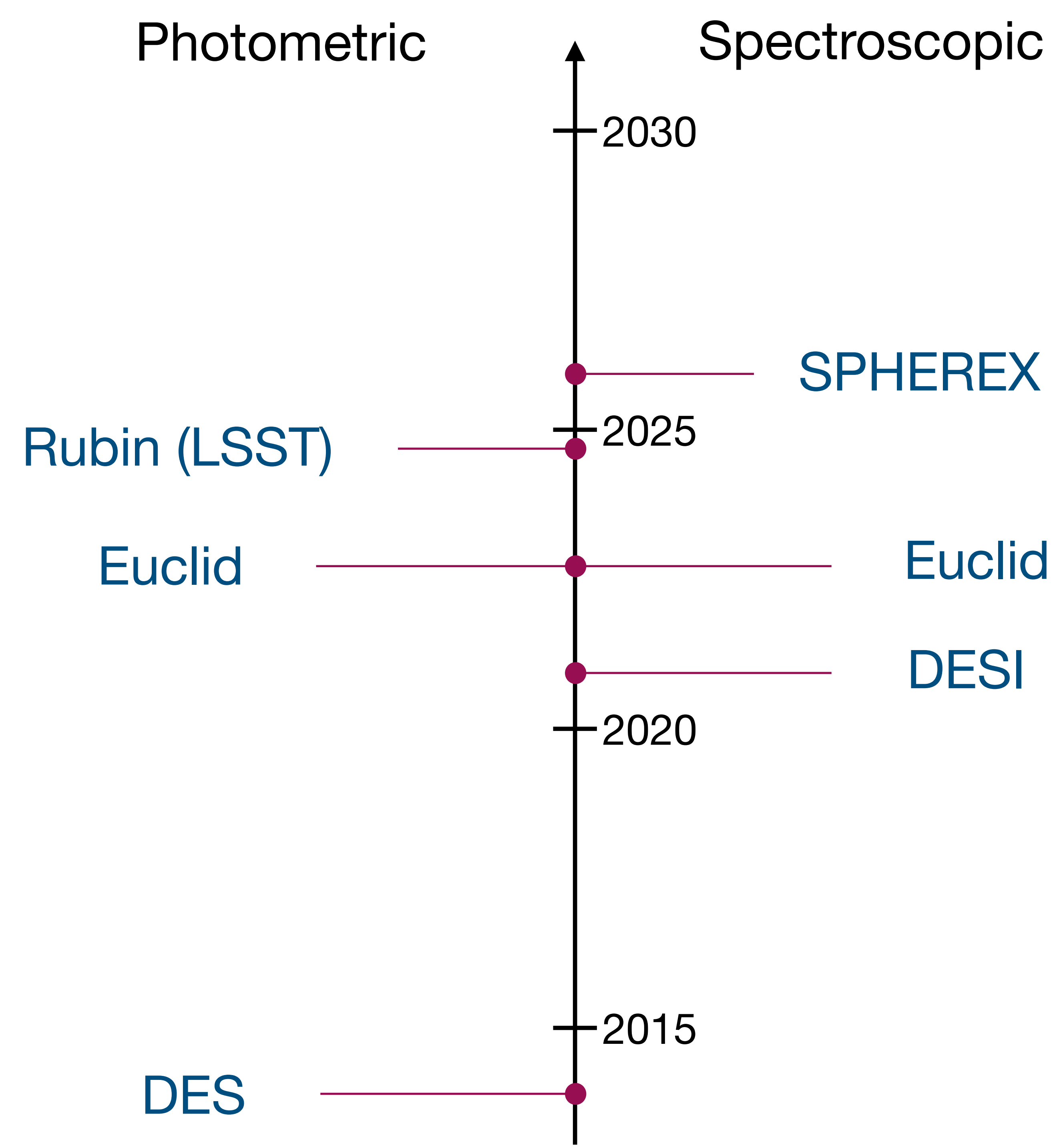
Naive rescaling to DESI Y1

$\Delta H_0 \approx 0.6(0.4)$ km/s/Mpc

What comes next?

Image billions and take spectra of ~100 million of objects up to z<5





Beyond ΛCDM - exotic dark matter

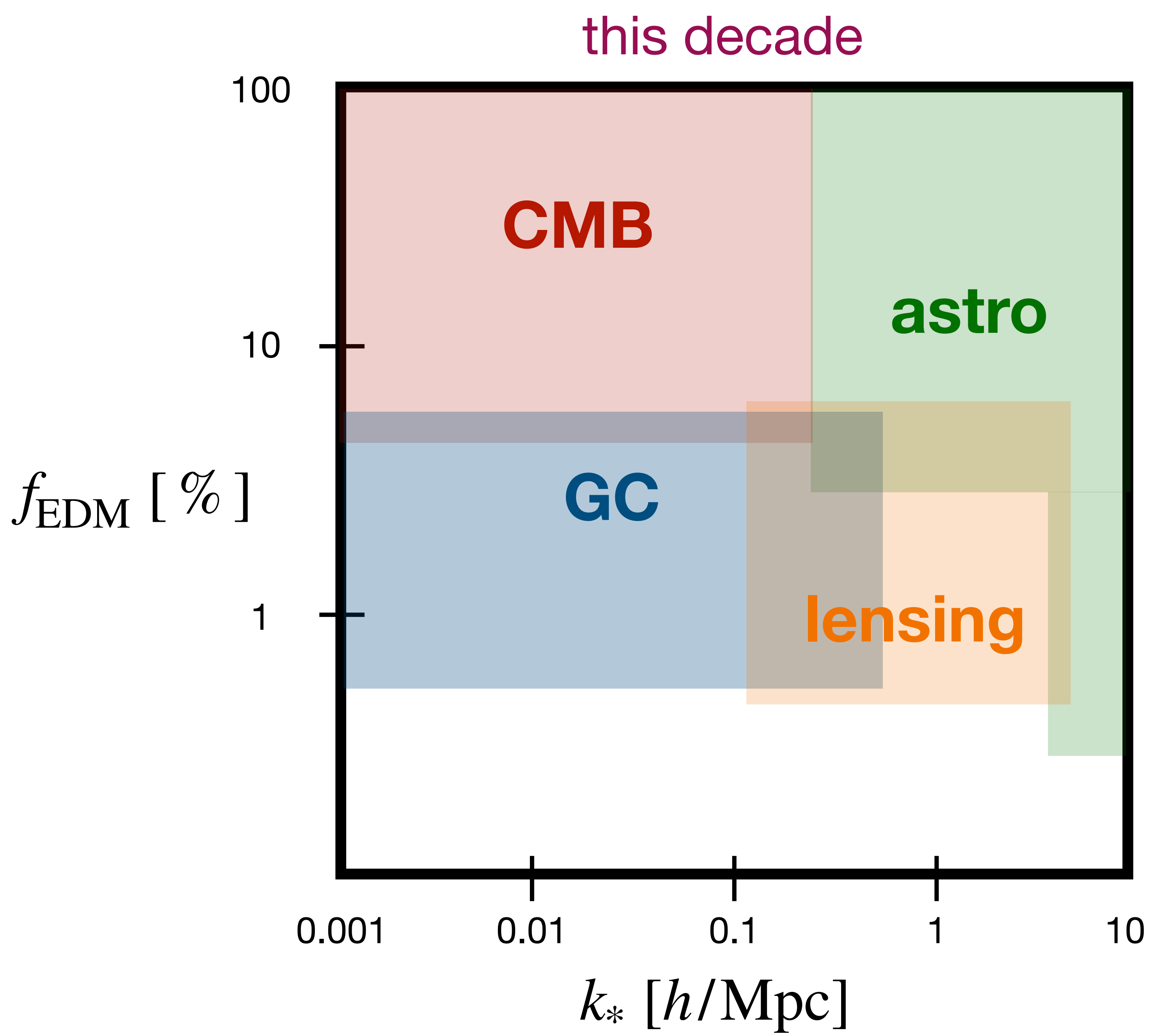
A fraction of DM is exotic: $f_{\mathrm{EDM}} = \Omega_{\mathrm{EDM}}/\Omega_d$

Imprints a characteristic scale k_* on the matter power spectrum

Use gravity only!

ULA
Baryon-DM interactions
LiMRs
Long-range forces
SIDM
…

What are the odds?



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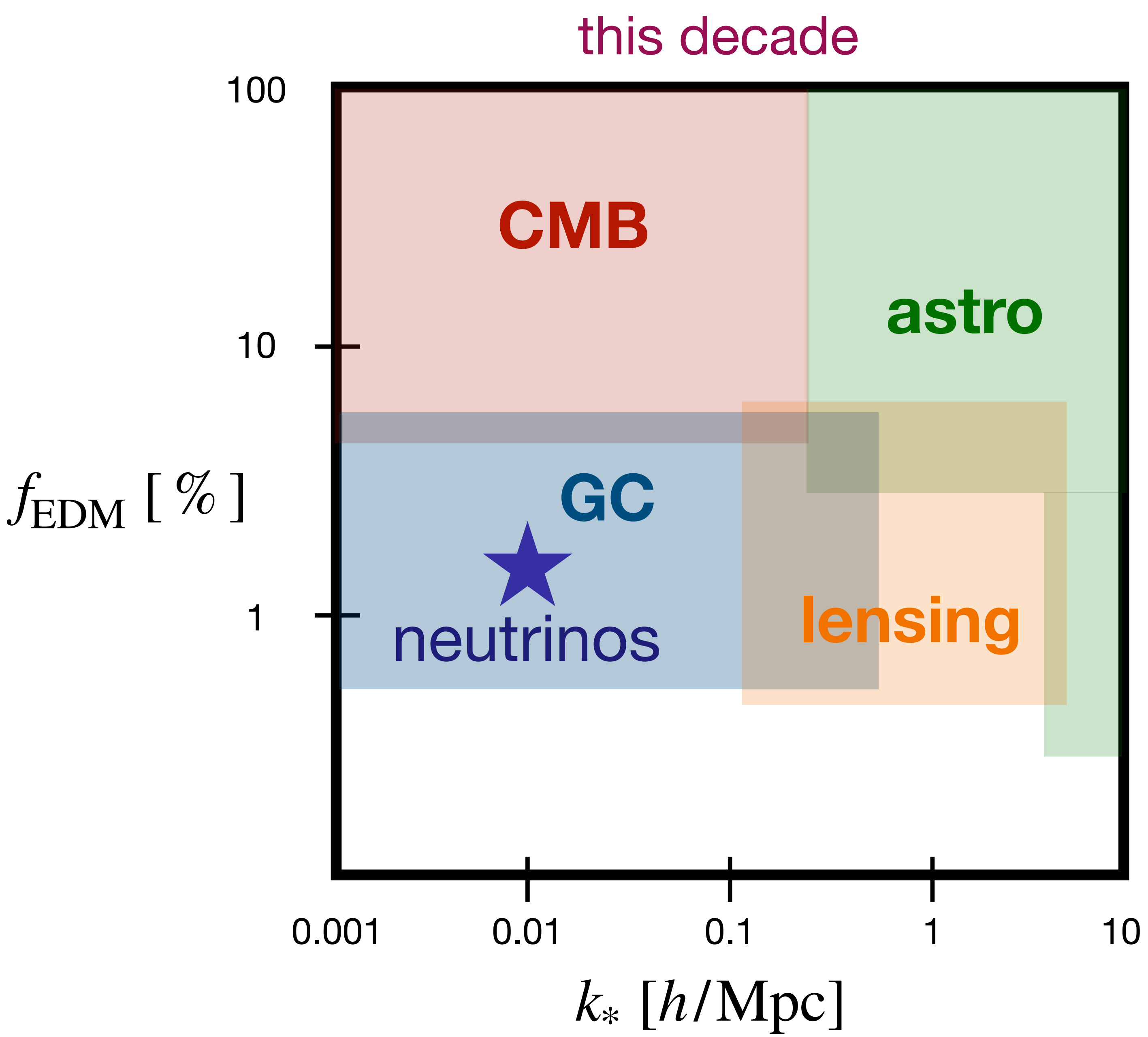
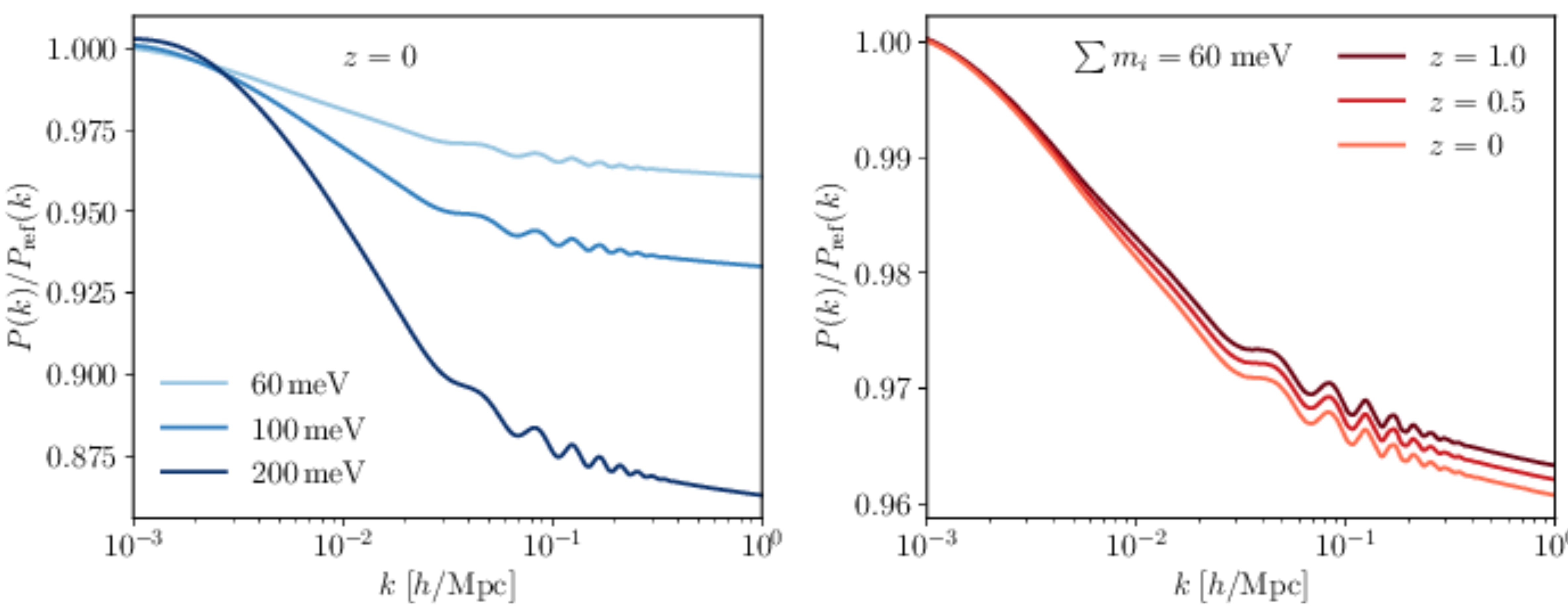
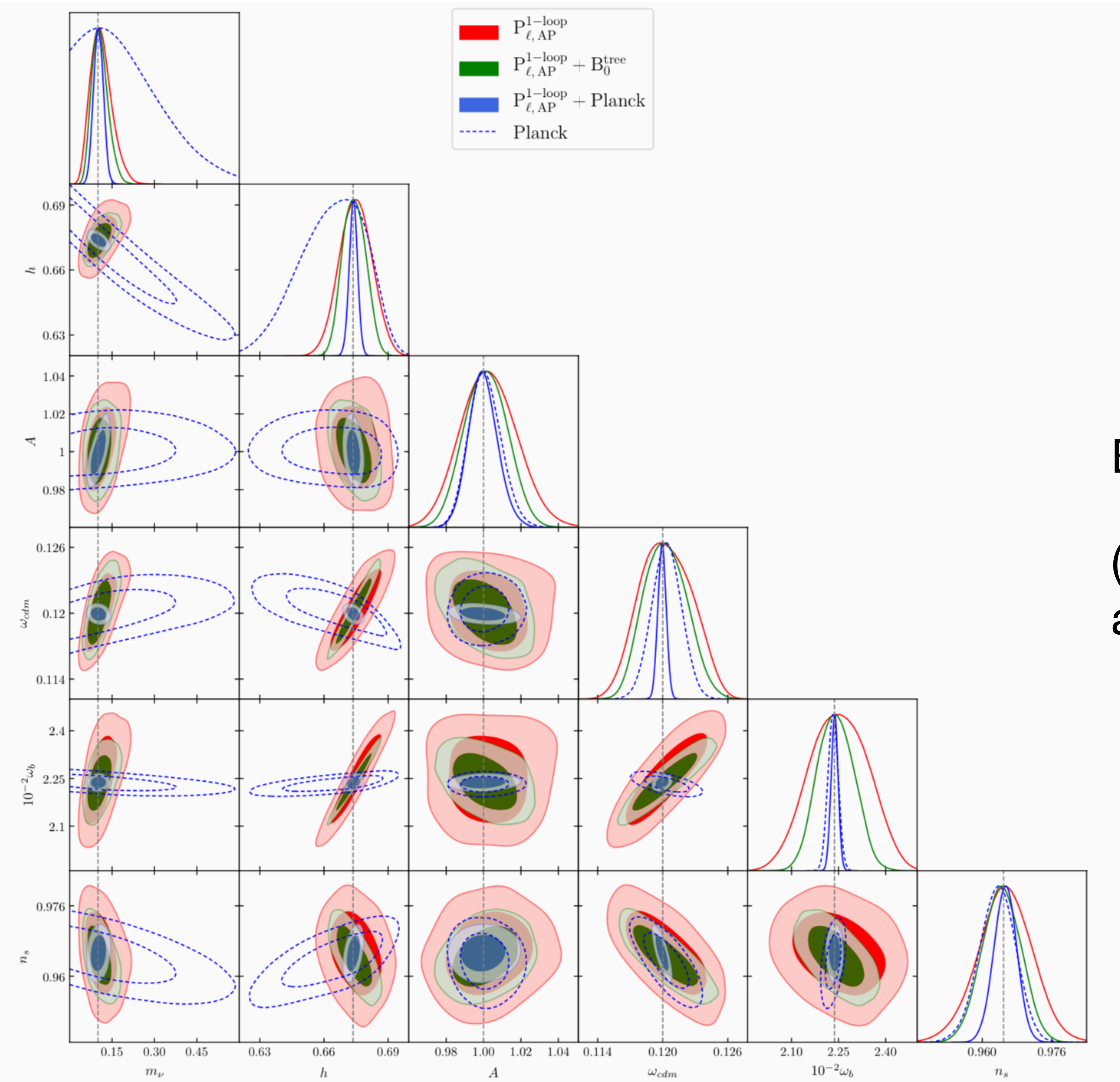


Beyond ΛCDM - neutrinos

Free-streaming neutrinos cause scale-dependent suppression of structure



Beyond ΛCDM - neutrinos



Chudaykin, Ivanov (2019)

Euclid/DESI-like survey

(galaxies only, no Lya and quasars)

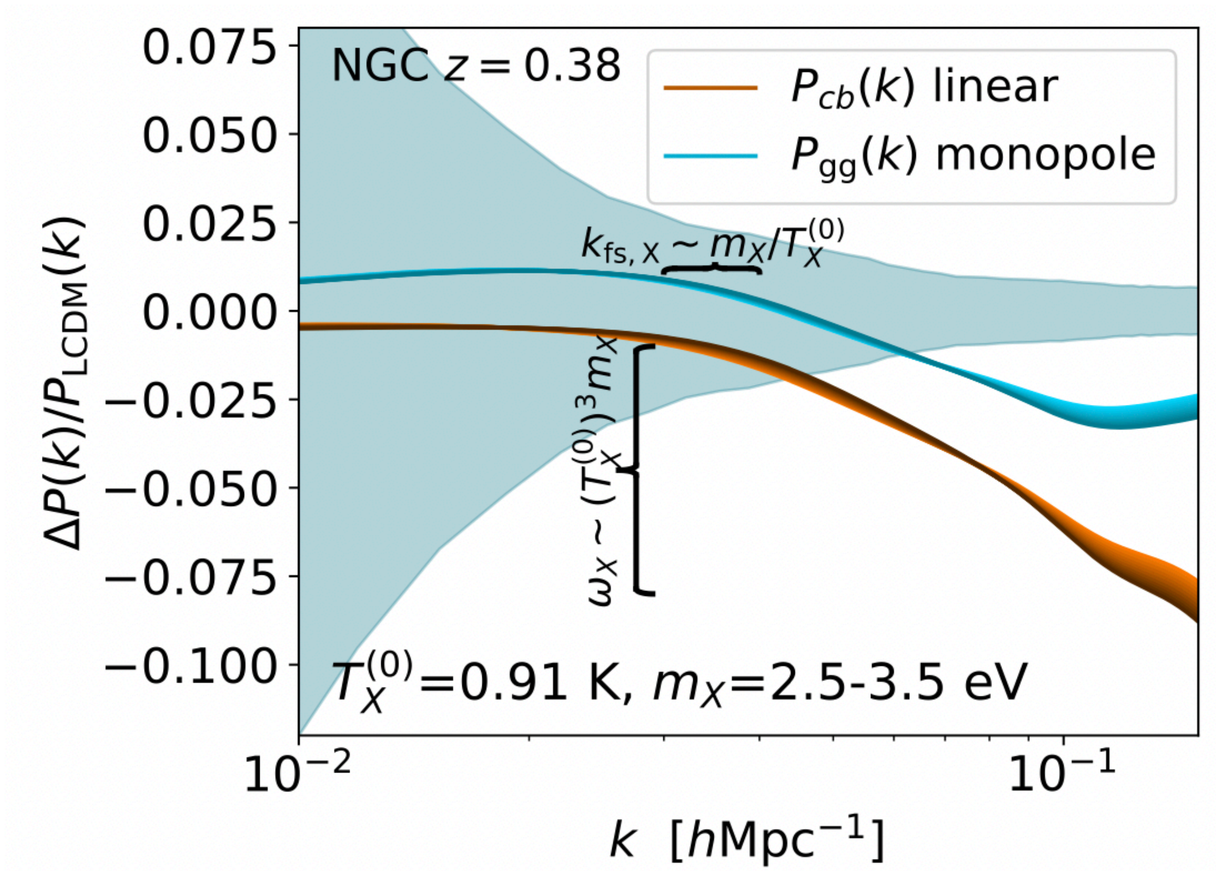
Beyond ΛCDM - LiMRs

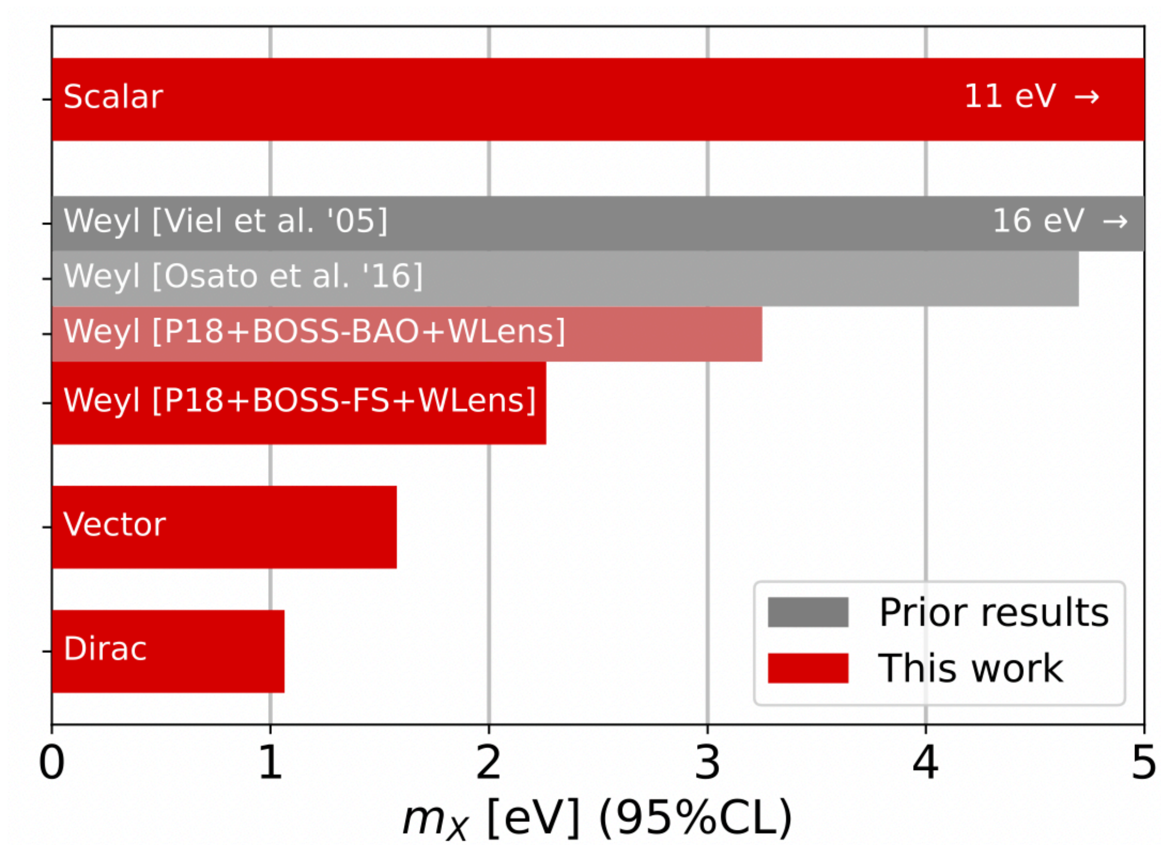
There can be other dark light but massive relics (LiMRs)

Physics is similar to neutrinos

An example: thermal production of QCD axion in the early universe

Xu, Muñoz, Dvorkin (2022)





Beyond ΛCDM - ultralight ALP

Fuzzy dark matter

Hu, Barkana, Gruzinov (2000)
Hui, Ostriker, Tremaine, Witten (2016)

$$\sim \frac{\hbar}{m_a v}$$

$$k_* \sim m_a v$$

$$\Delta x \cdot \Delta(m_a v) = \hbar/2$$

The whole of DM ULA, $m_a > 10^{-19}\,\mathrm{eV}$

Galaxy clustering probes $10^{-32} - 10^{-24}\,\mathrm{eV}$
where ULA can be just a fraction of DM

Beyond ΛCDM - ultralight ALP

Fuzzy dark matter

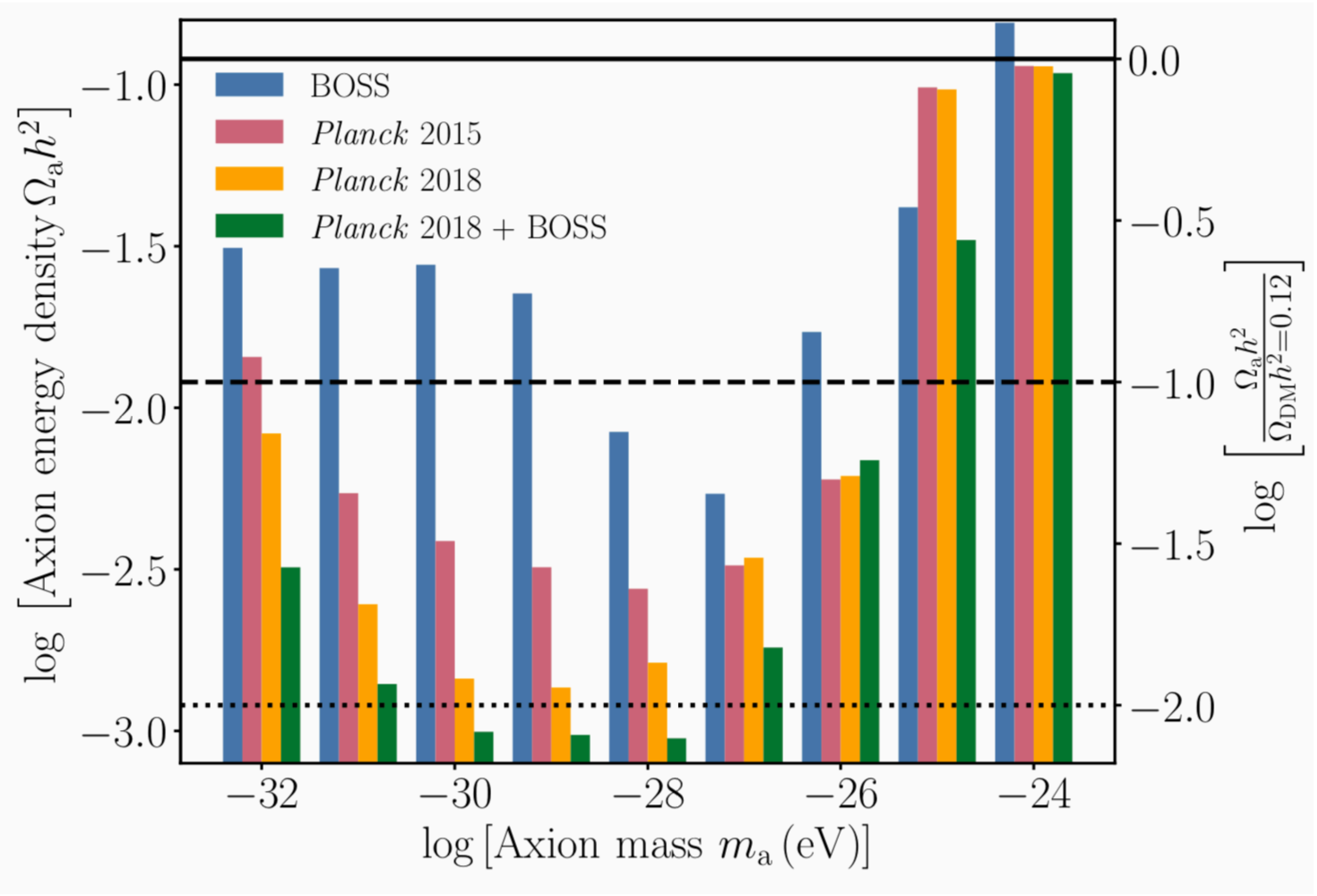
Hu, Barkana, Gruzinov (2000)
Hui, Ostriker, Tremaine, Witten (2016)

String-theory “inspired” target:

$$\frac{\Omega_a}{\Omega_d} \sim 0.1 \left(\frac{F}{M_{\rm pl}}\right)^2 \left(\frac{m_a}{10^{-28}\,{\rm eV}}\right)^{1/2}$$

LSS constraints will improve ~ 5x

Laguë, Bond, Hložek, Rogers, Marsh, Grin (2021)
Rogers et. al. (2023)

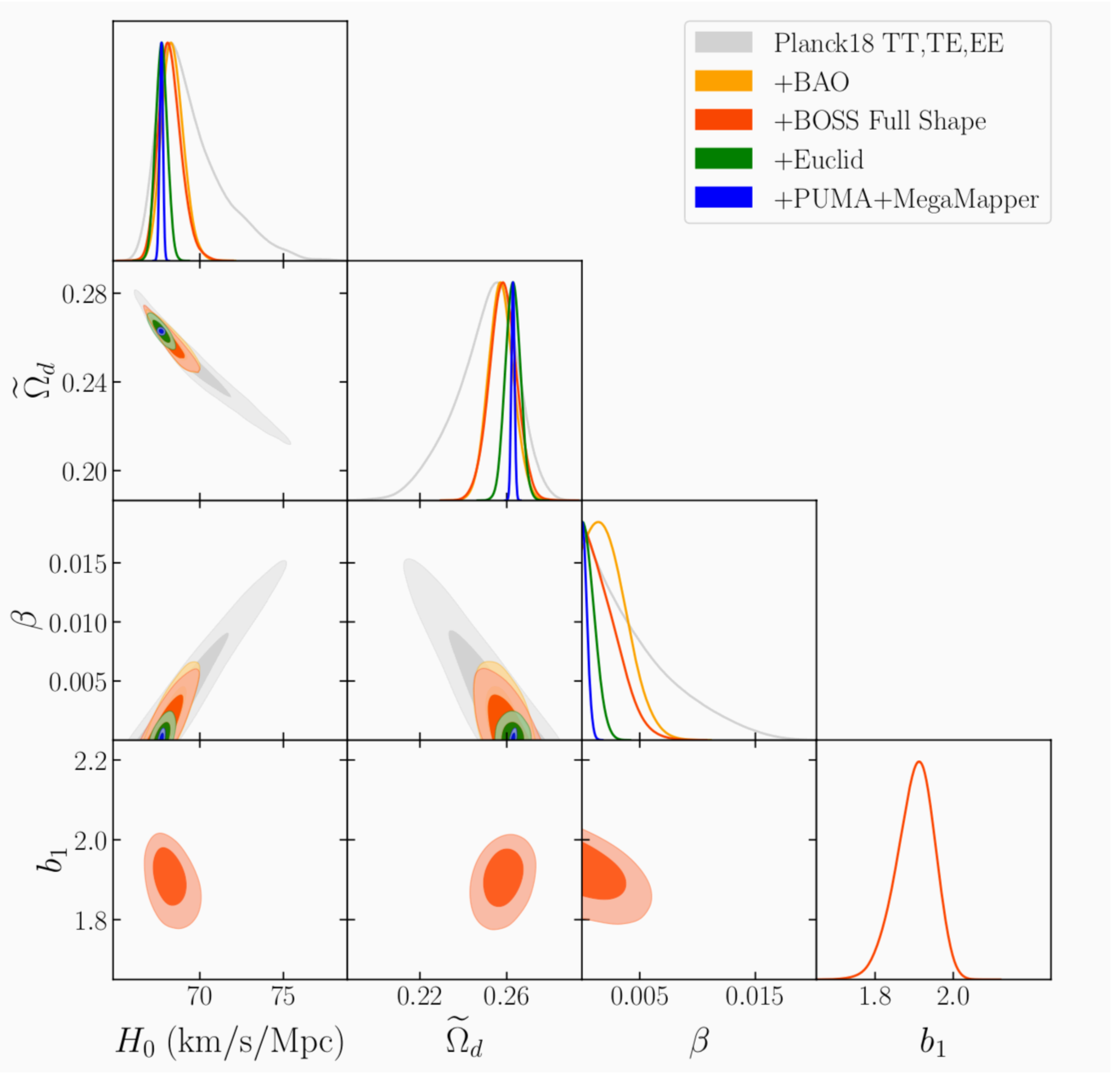


Beyond ΛCDM - DM long range force

Bottaro, Castorina, Costa, Redigolo, Salvioni (2023)

Additional long-range force mediated by a massless scalar

Appears as “modified gravity” for DM

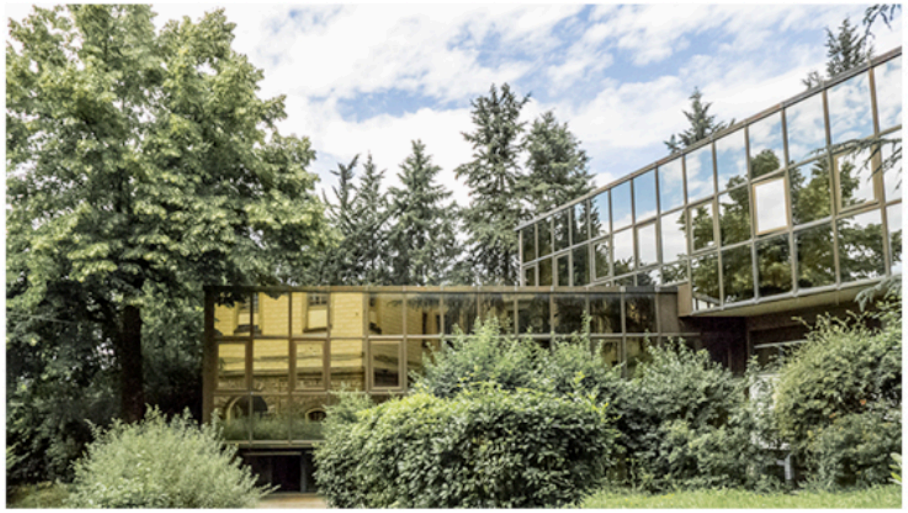


Beyond ΛCDM and beyond SM

The Galileo Galilei Institute For Theoretical Physics

Centro Nazionale di Studi Avanzati dell'Istituto Nazionale di Fisica Nucleare

Arcetri, Firenze



Home > Workshops

Workshops at Galileo Galilei Institute

Aug 25, 2025 - Oct 03, 2025	**New Physics from Galaxy Clustering at GGI** **Training Week** (Aug 25, 2025 - Aug 29, 2025) **Focus Week** (Sep 15, 2025 - Sep 19, 2025) **Conference** (Sep 29, 2025 - Oct 03, 2025)