Constraining mixed dark matter with galaxy clustering

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Which Dark Matter with galaxy clustering

What kind of new physics can we look for with galaxy clustering?

$$P(k,a) \sim \underline{D^2(a)T^2(k)}\; \underline{P_0(k)}$$

Dynamics of the Dark Sector

Primordial features

Dynamics already constrained by larger and smaller scales (CMB, Lyman-α,...)

+

galaxy clustering data getting to unprecedented precisions

$\Downarrow$

<u>ideal place to look for small deviations from CDM</u>

$$D(a)T(k) \sim aT_{\rm CDM}(k)\,(1+\boxed{\Delta_{\rm NP}})$$

Promising opportunity to constraints BSM scenarios.
If the dark sector is really dark, might be a unique window!

Why mixed models

In many scenarios DM is CDM + something else (ultra-light axions [Lagüe et al 22, Rogers et al 23], warm thermal relics [Xu et al 21, Çelik&Schmidt 25], subcomponent with strong self-interactions [Garani et al 22], ...)

So, the DM is CDM+χ. How strange can it be? Assuming that e.g. like neutrinos

1. χ non-relativistic
2. χ decoupled

$\Rightarrow$ fluid description [Shoji&Komatsu 10]

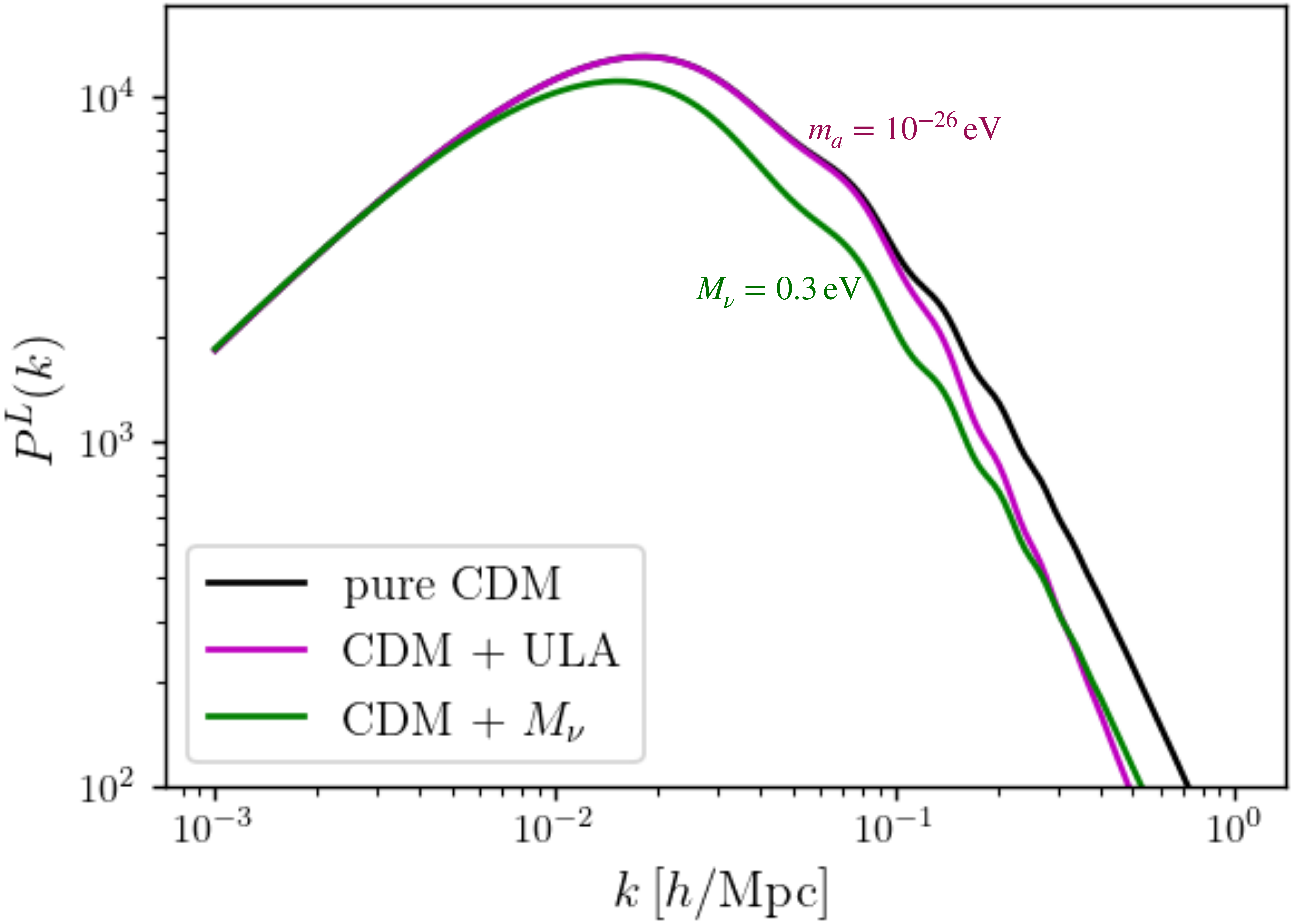
$$\ddot{\delta}_c + \mathcal{H}\dot{\delta}_c - \frac{3}{2}\mathcal{H}^2\delta_m = 0$$

the deviation from CDM ends up in this term

$$\ddot{\delta}_\chi + \mathcal{H}\dot{\delta}_\chi - \frac{3}{2}\mathcal{H}^2\delta_m + c_s^2 k^2 \delta_\chi = 0$$

Phenomenologically, two new parameters $\left(f_\chi, \quad k_J \sim \frac{\mathcal{H}(a)}{c_s(a)} \right)$

Linear perturbations



Linear result: $\sim$ suppression below k_J

$\Rightarrow$ full-shape analysis seems the ideal tool to probe these scenarios

! Nonlinearities are relevant

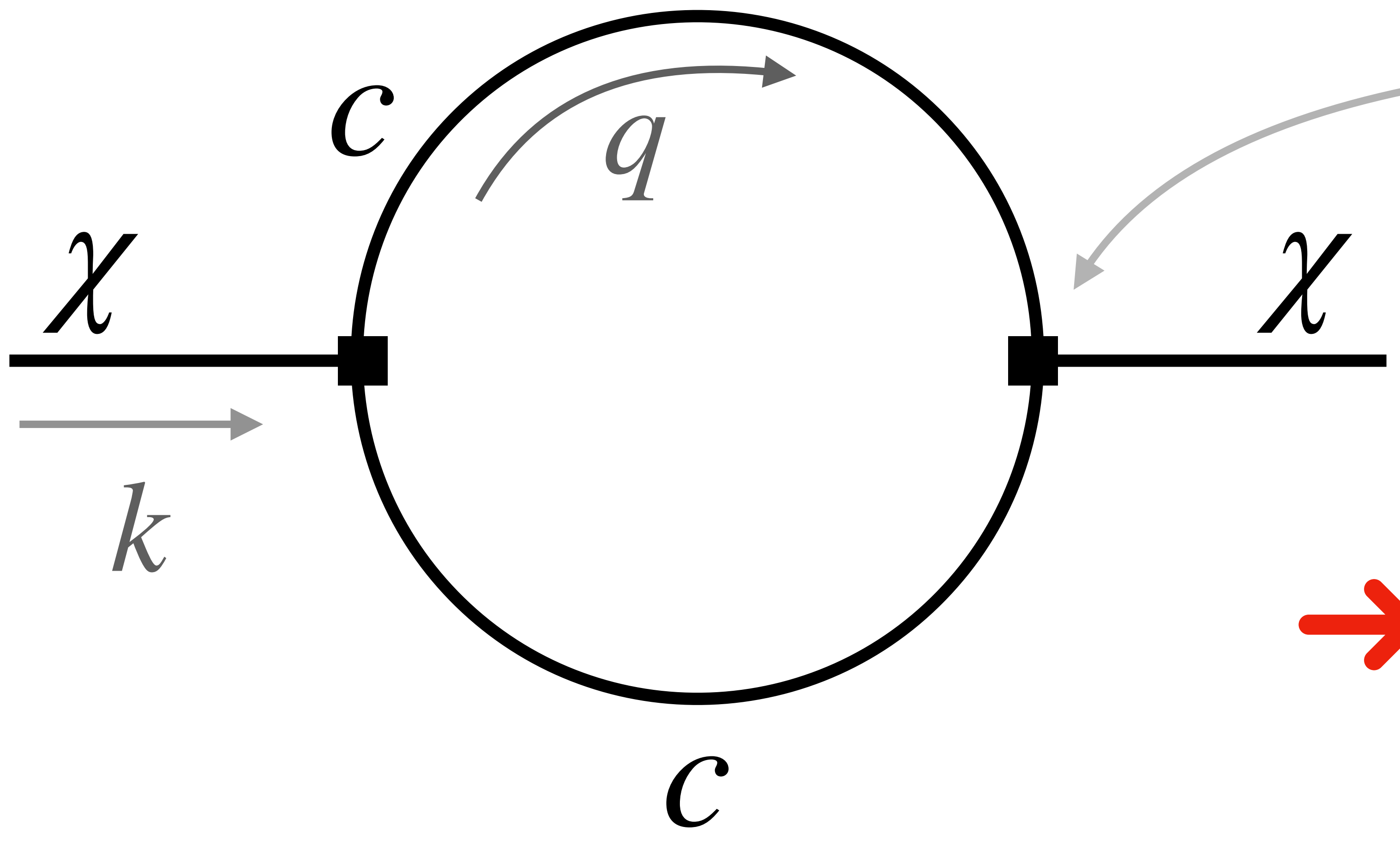
Hence:

1. Theory study of NL
2. Constraints from full-shape BOSS

Nonlinear Perturbation Theory with two components

Nonlinearity couples the modes: all the scales are affected. In SPT approach

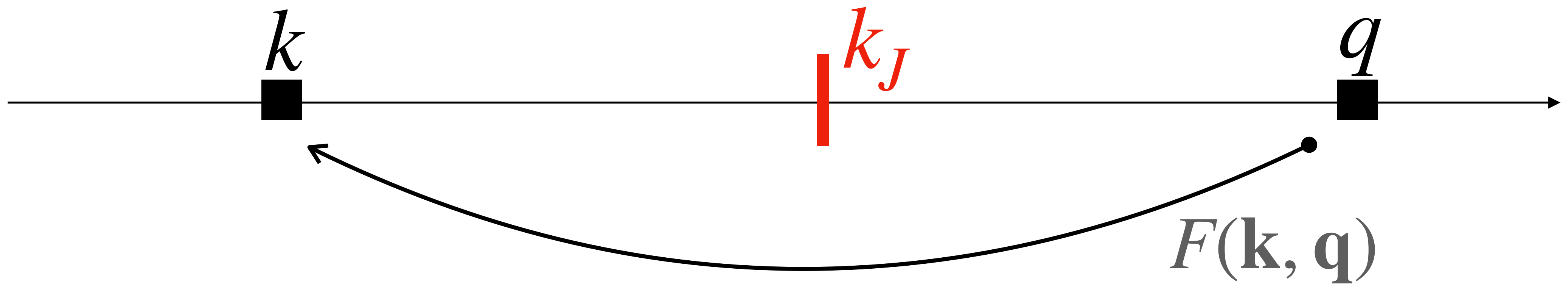
$$\delta(k) = \delta^L(k) + \int d^3q\, F_a^{[2]}(\mathbf{q},\mathbf{k}-\mathbf{q})\delta^L(\mathbf{q})\delta^L(\mathbf{k}-\mathbf{q}) + \cdots$$



PT Kernels (mode coupling)

For CDM is known, but for χ?

➜ The difficulty: additional scale involved



We can study the limits $\gg k_J$, $\ll k_J$ analytically, or solve the integrals fully numerically

Nonlinear Perturbation Theory with two components

Turns out that the symmetries are so constraining that kernels are very similar to the CDM ones

$$\int F_\chi^{[2]} \delta^L \delta^L \approx \int F_2\, \delta_\chi^L \delta_\chi^L$$ or, in other words $$\delta_\chi^{[n]}(\mathbf{k}) \simeq \frac{\mathcal{T}_\chi(k)}{\mathcal{T}_c(k)} \delta_c^{[n]}(\mathbf{k})$$

- ✦ This holds for velocity field Θ as well, respecting IR cancellation for all 1-loop integrals
- ✦ Works better than 1% (with $f_\chi = 10\,\%$) for smallest scales of matter power spectrum

  $\Rightarrow$ probably fine for all the realistic survey volumes!

- ✦ **Incredible advantage for code implementation**: can recycle the FFTLog routines to compute 1-loop contributions

Towards the analysis: bias and full-shape template

Start from the CDM-only "EFTofLSS" template for full-shape

$$P_g(k) = P_g^L(k) + P_g^{1-\mathrm{loop}}(k) + P_g^{\mathrm{ctr}}(k) + P_g^{\mathrm{noise}}(k)$$

⇒we allow galaxies trace also δ_χ

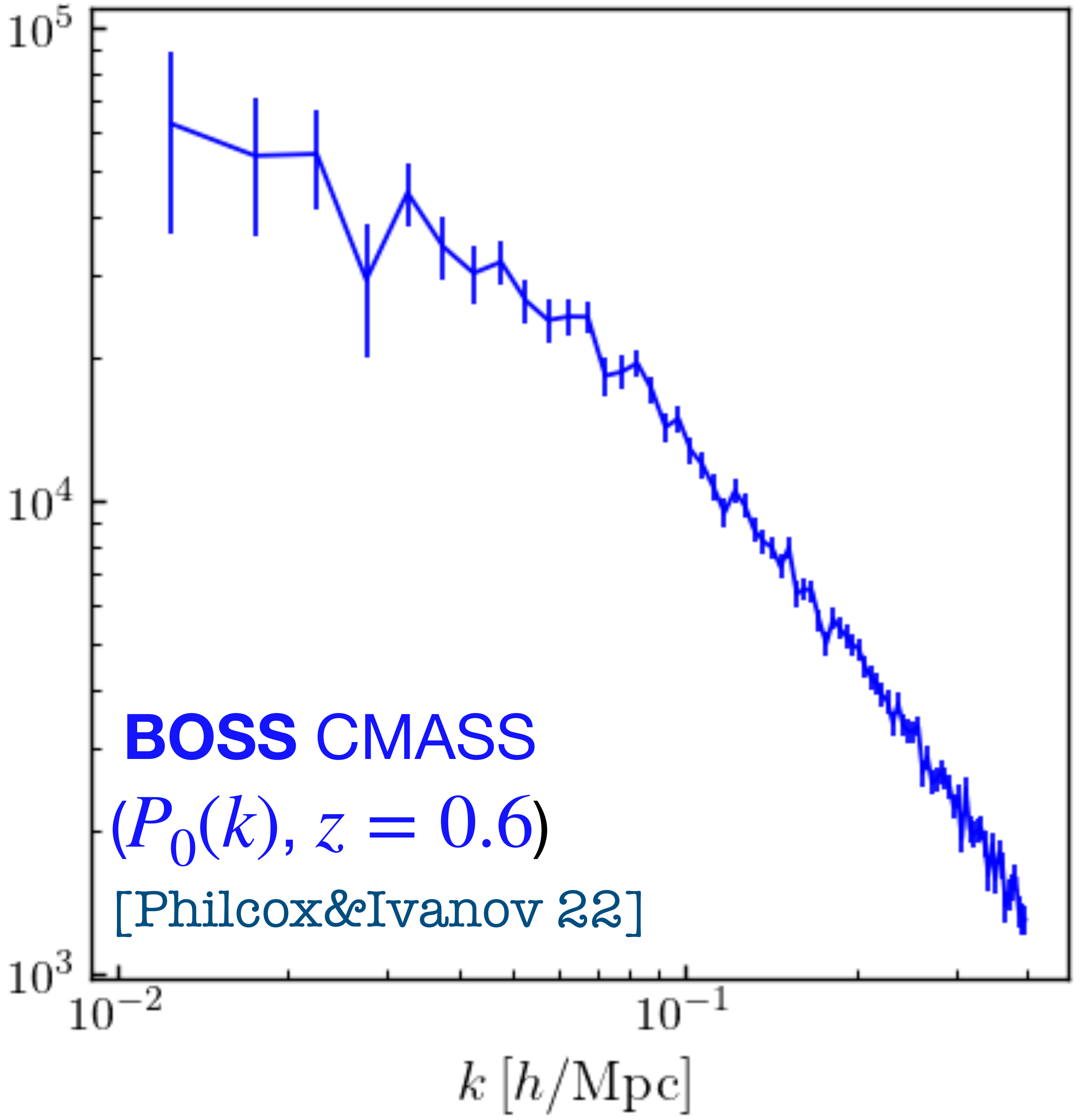
$$\delta_g = b_1\delta_c + b_\chi\delta_\chi + \cdots$$

Actually, the other modes can appear: for a proper treatment (see [Çelik&Schmidt 25])
Nonlinear biases? The number of operator explodes (see eg [Bottaro et al 23])

⇒ modify the code to implement new bias, nonlinearities, counterterms…

$$P_g^{\mathrm{ctr}} \simeq -2c_c k^2 P_{cc} - 2c_\chi k^2 P_{c\chi} + \cdots$$

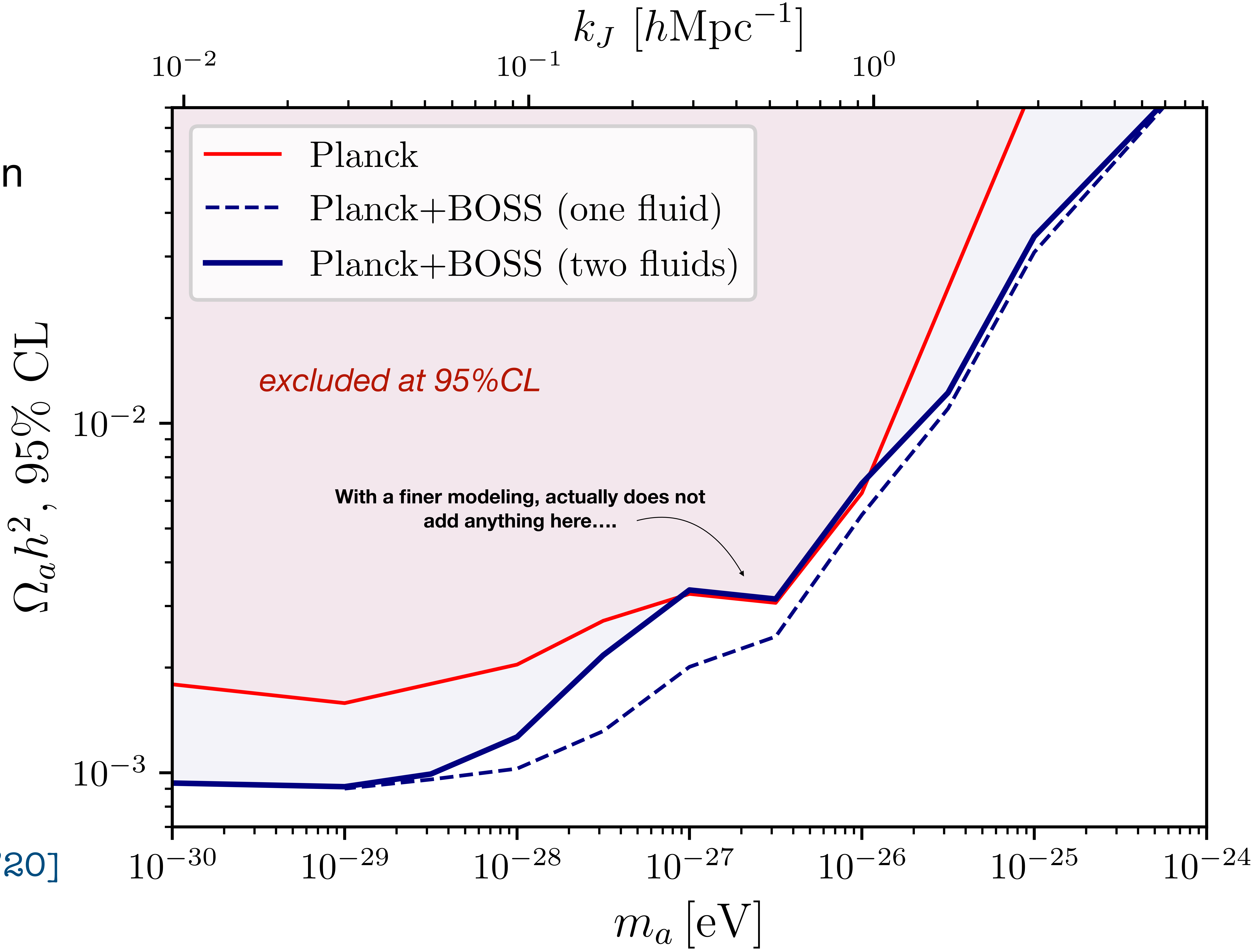
⇒ finally, fit data!



Results: ULAs

We scan on m_a and then constraint $\Omega_a h^2$

[as Rogers et al. '23]



AxiCLASS [Smith et al. '20]

PBJ [Moretti et al. '23]

Hidden: the importance of Q_0 for BSM

P_ℓ up to $k_{\max} = 0.2h\mathrm{Mpc}^{-1}$

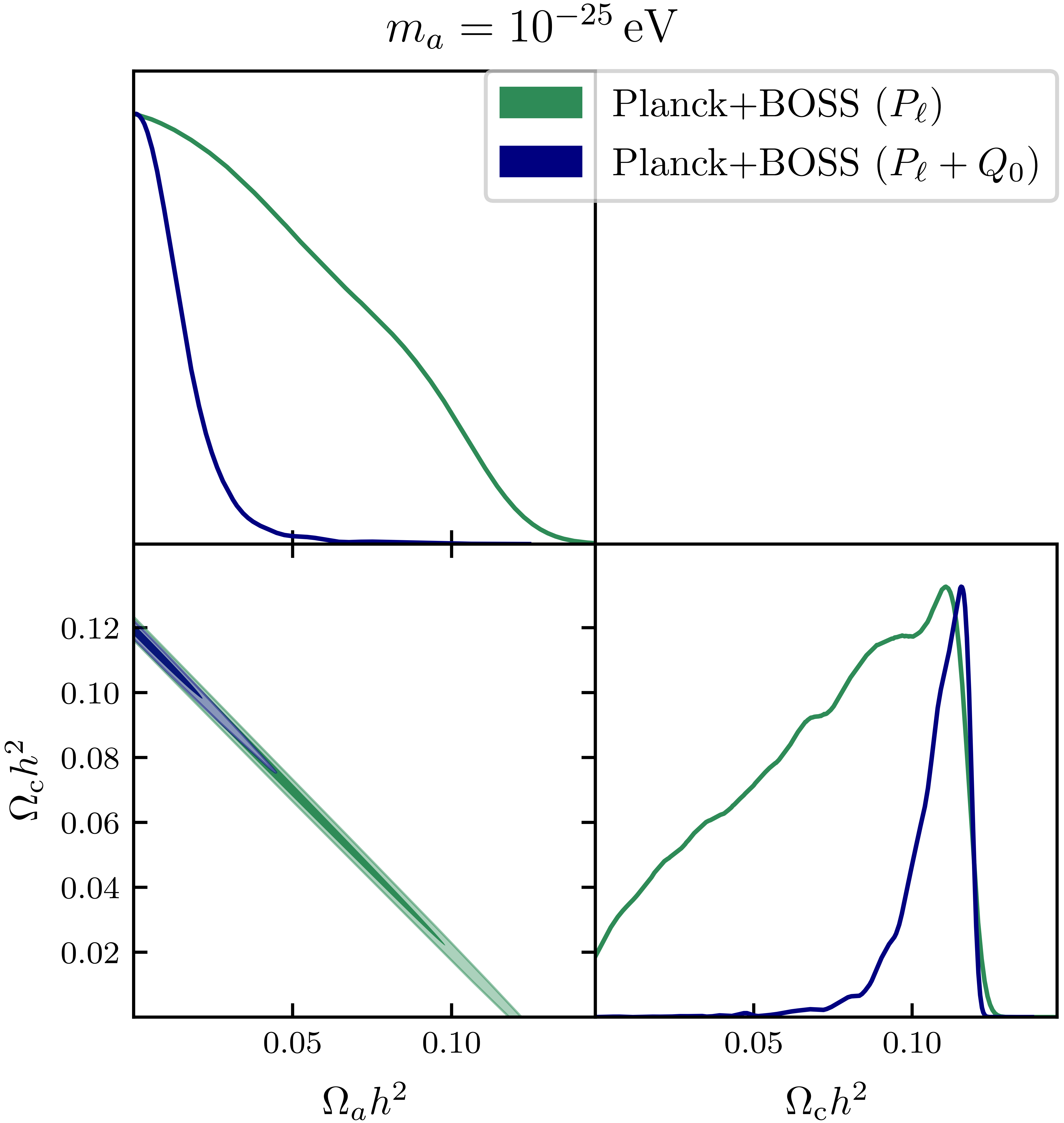
$Q_0 = P_0 - \frac{1}{2}P_2 + \frac{3}{8}P_4$ *free from RSDs*

fit up to $k_{\max} = 0.4h\mathrm{Mpc}^{-1}$

[Ivanov et al. 22]

The information is really coming from the shape suppression!

Full-shape analysis particularly beneficial for probing BSM!



Some outlooks

- CMB + LSS already very powerful in constraining, even $\Omega_a \lesssim 0.01\Omega_m$!

- Theoretical modeling is important for controlled results. In constraining, not to overestimate [Çelik&Schmidt 25]. With a detection, totally new perspective.

- **Sims**: Observables computed purely from theory. But we know more than this: priors on the bias/counterterms from simulations?

- **BSM**: More particle physics scenarios to explore?

Thanks