Constraining mixed scenarios 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?

$$P(k,a) \sim \underbrace{D^2(a)T^2(k)}_{\text{Dynamics of the Dark Sector}}\ \underbrace{P_0(k)}_{\text{Primordial features}}$$

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

$\Downarrow$

ideal place to look for small deviations from CDM

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

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

1. χ non-relativistic
2. χ non-interacting

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

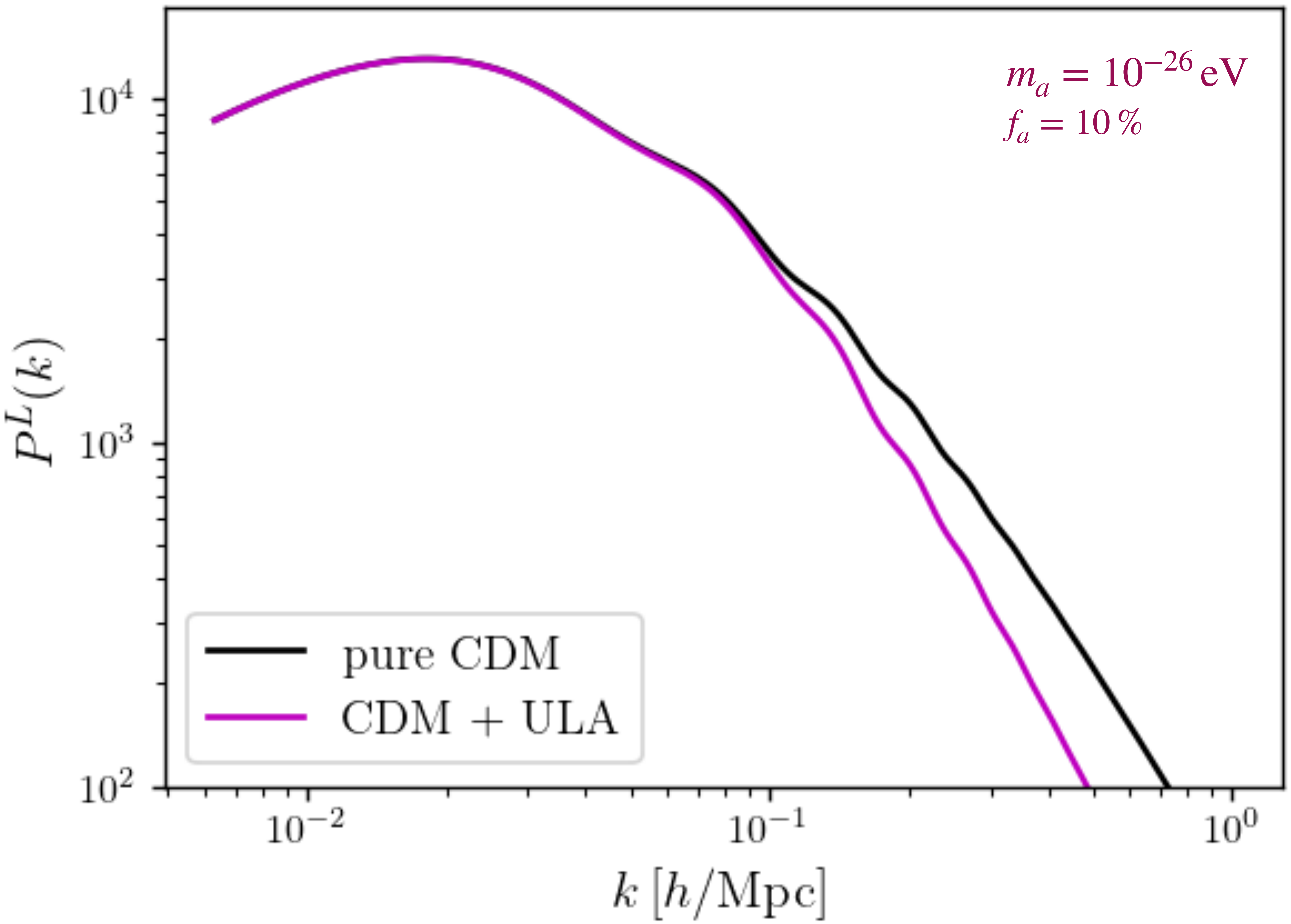
$$\ddot{\delta}_c + \mathcal{H}\dot{\delta}_c - \frac{3}{2}\mathcal{H}^2\delta_m = 0$$

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

the deviation from CDM ends up in this term

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

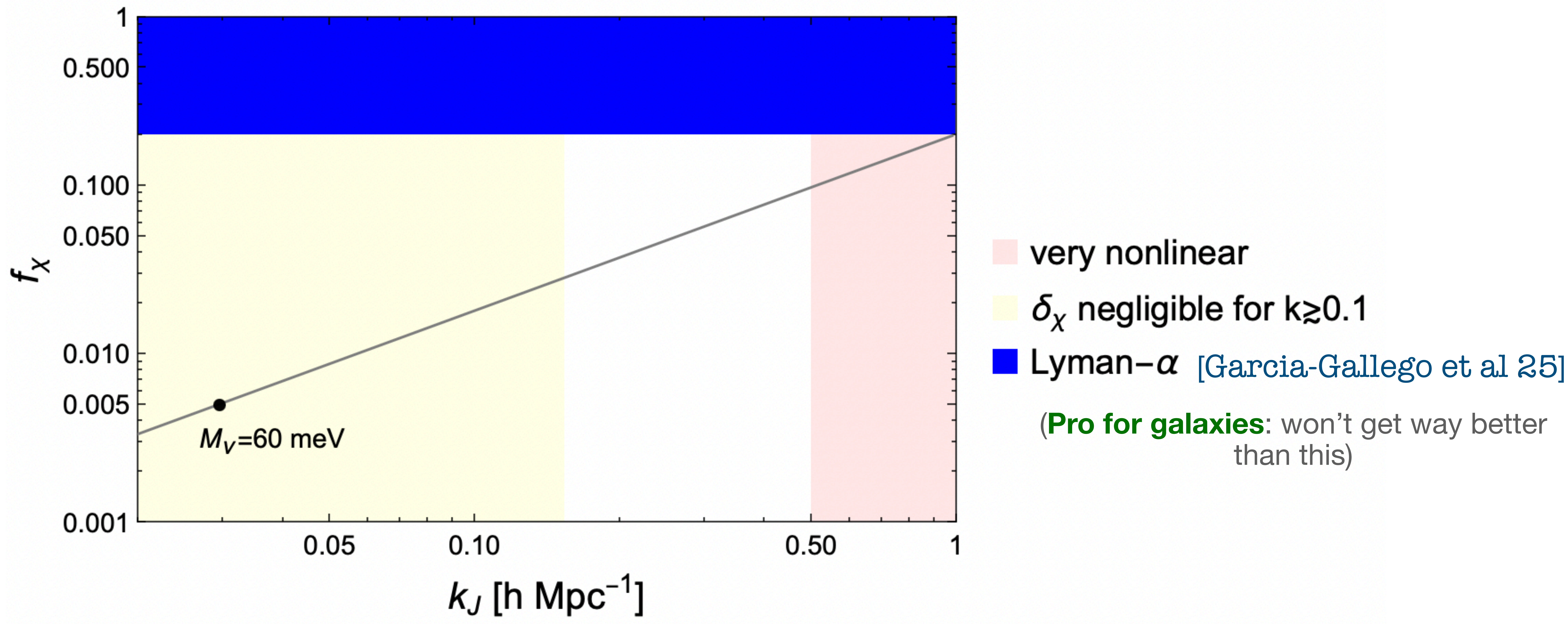
The growth of linear perturbations



⇒ full-shape analysis seems the ideal tool to probe these scenarios

Full-shape analysis seems the tool to probe these scenarios. Is it?

- **Motivation for the theoretical effort**: having a *first-principles*, robust, *controlled* computation
- How hard is the theoretical study? How hard is it to implement in a LSS inference code?
- Results would be generic or very model-dependent?
- By construction, marginalizing over unknowns (bias, counterterms…) Is there really a gain in constraining power after this?



(**Pro for galaxies**: won't get way better than this)

- The fractions we can test is already small (helps theory)
- The "nontrivial" case reduces to $k \ll k_J$ [Çelik&Schmidt 25]

(**Stretch goal**: report generic constraints in this plot, and then read the corresponding particle physics model. Unfortunately it is not that trivial…)

The steps one needs to take for a full, proper, EFTofLSS 1-loop analysis:

1. Have the BSM model implemented in an Einstein-Boltzmann solver

2. Study nonlinearities with perturbation theory

3. Bias expansion with two fluids

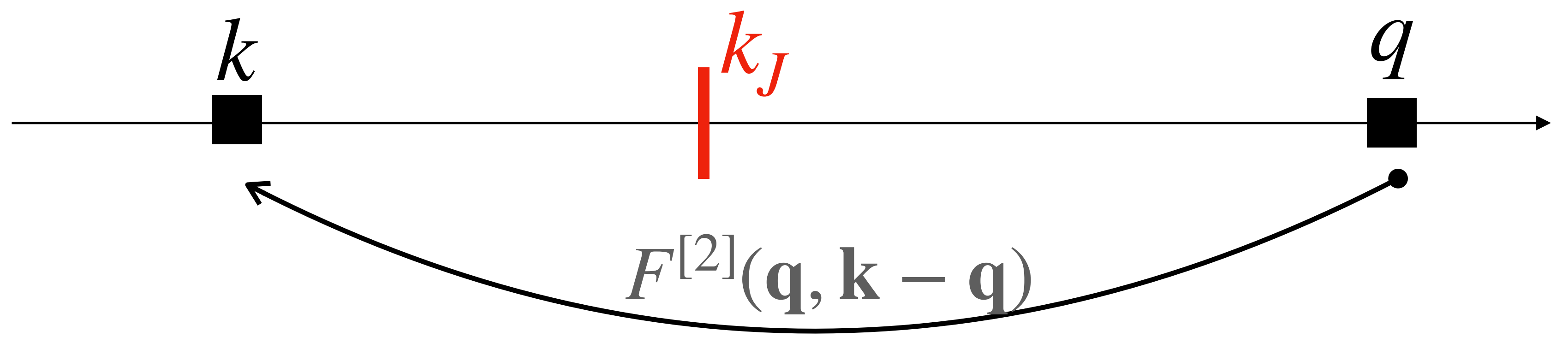
4. Include redshift-space distortions

5. Add this (at least in an approximate way) to an LSS code

Nonlinear Perturbation Theory with two components

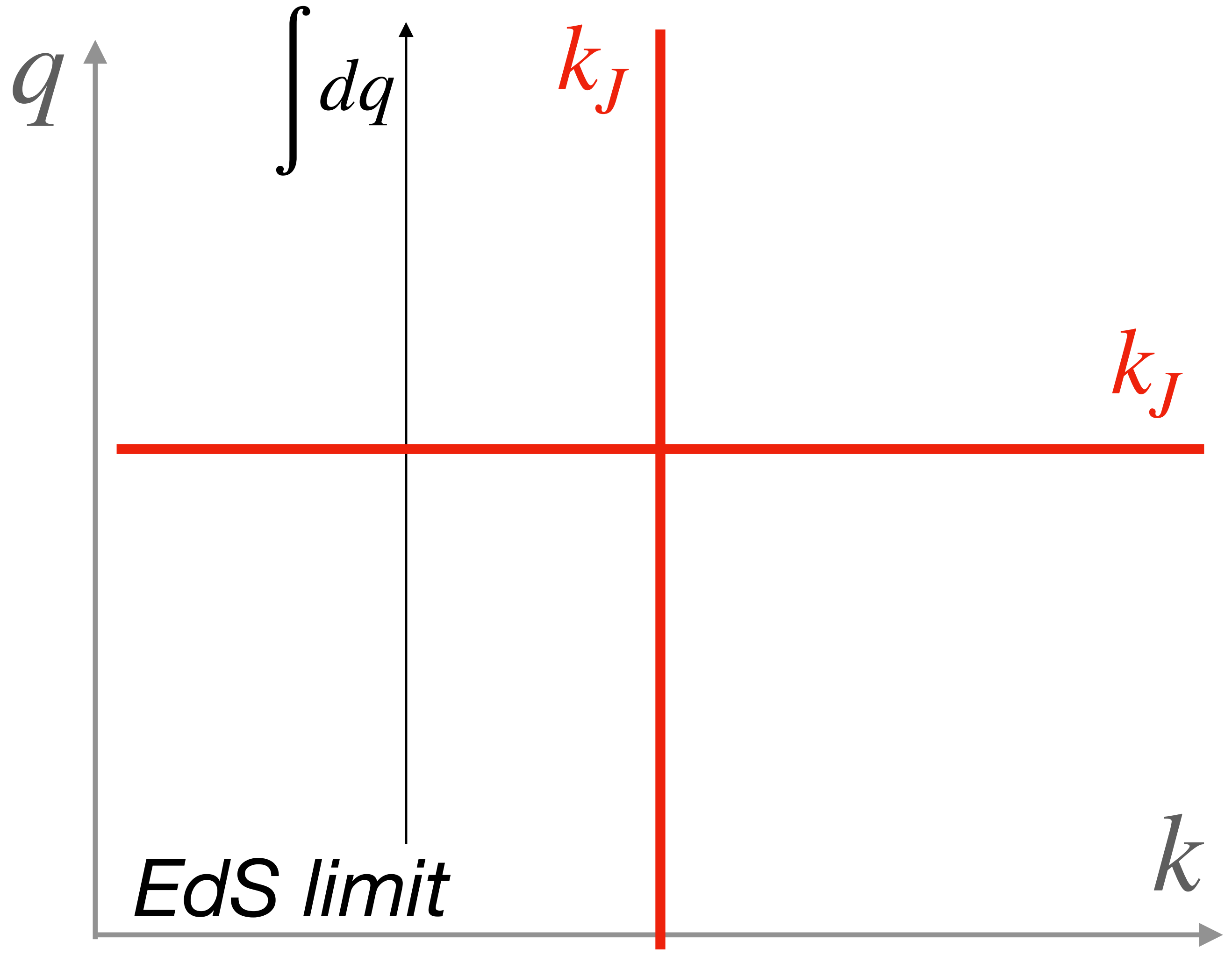
Nonlinearity couples the modes: all the scales are affected. In SPT approach

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



PT Kernels (mode coupling)
For CDM is known, but for χ?

Our approach: we can work in an $f_\chi \ll 1$ expansion. The problem is actually 2D now:



We can study analytically the 4 limits. We see that IR cancellation happens exactly as in EdS (even for $k \gg k_J$)

Could be guessed from first principles? [D'Amico et al 21]

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 $$\delta_\chi^{[n]}(\mathbf{k}) \simeq \frac{\mathcal{T}_\chi(k)}{\mathcal{T}_c(k)} \delta_c^{[n]}(\mathbf{k})$$

As already assumed in M_ν PT studies [Aviles et al 21]

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

Side note: some claims on effects in the squeezed bispectrum [Nascimento&Loverde 23, Kamalinejad&Slepian 20, Zhu&Castorina 20]. In this fluid description, we find none: are we missing something?

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_a

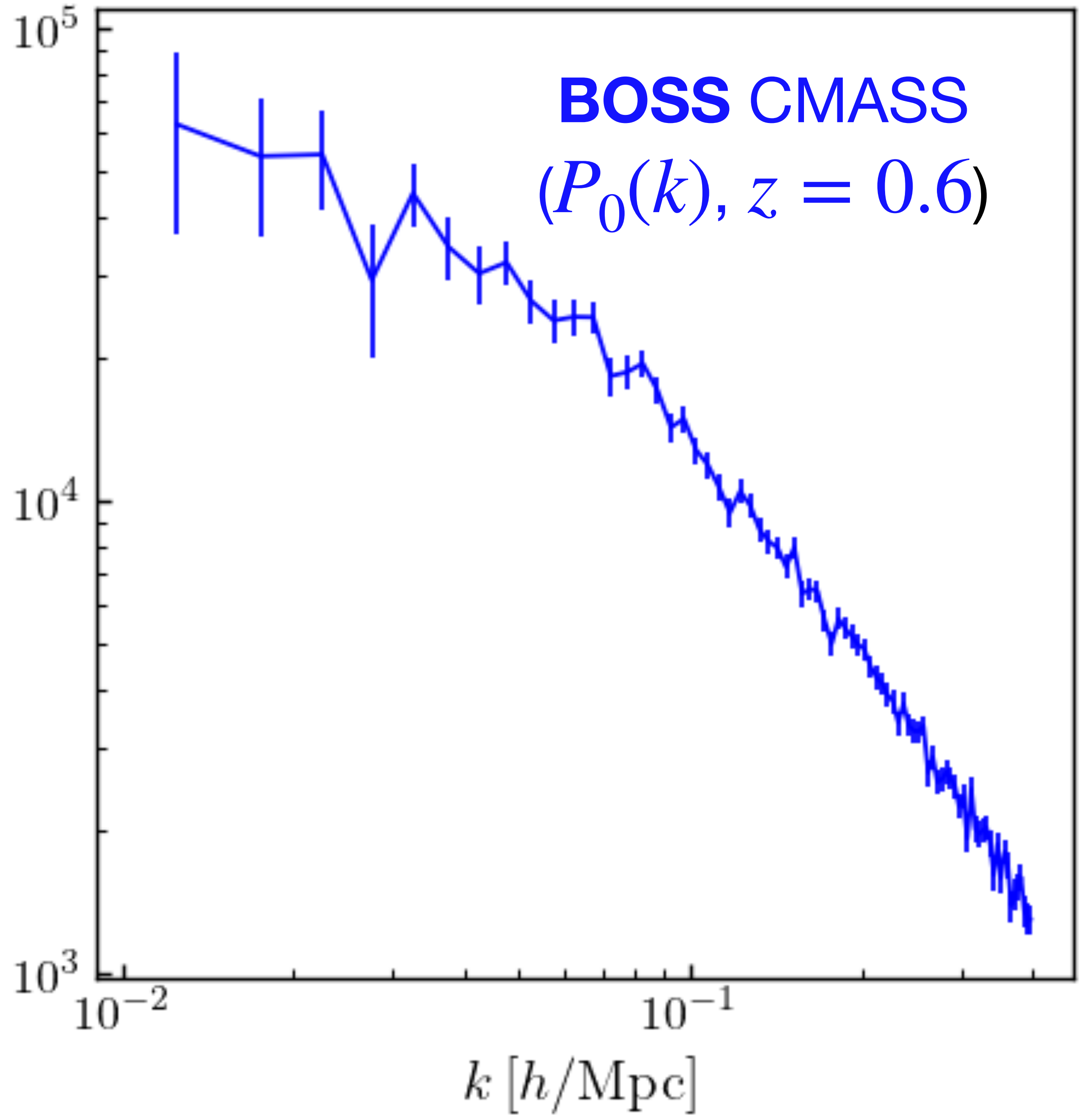
$$\delta_g = b_1\delta_c + b_a\delta_a + \cdots$$

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…

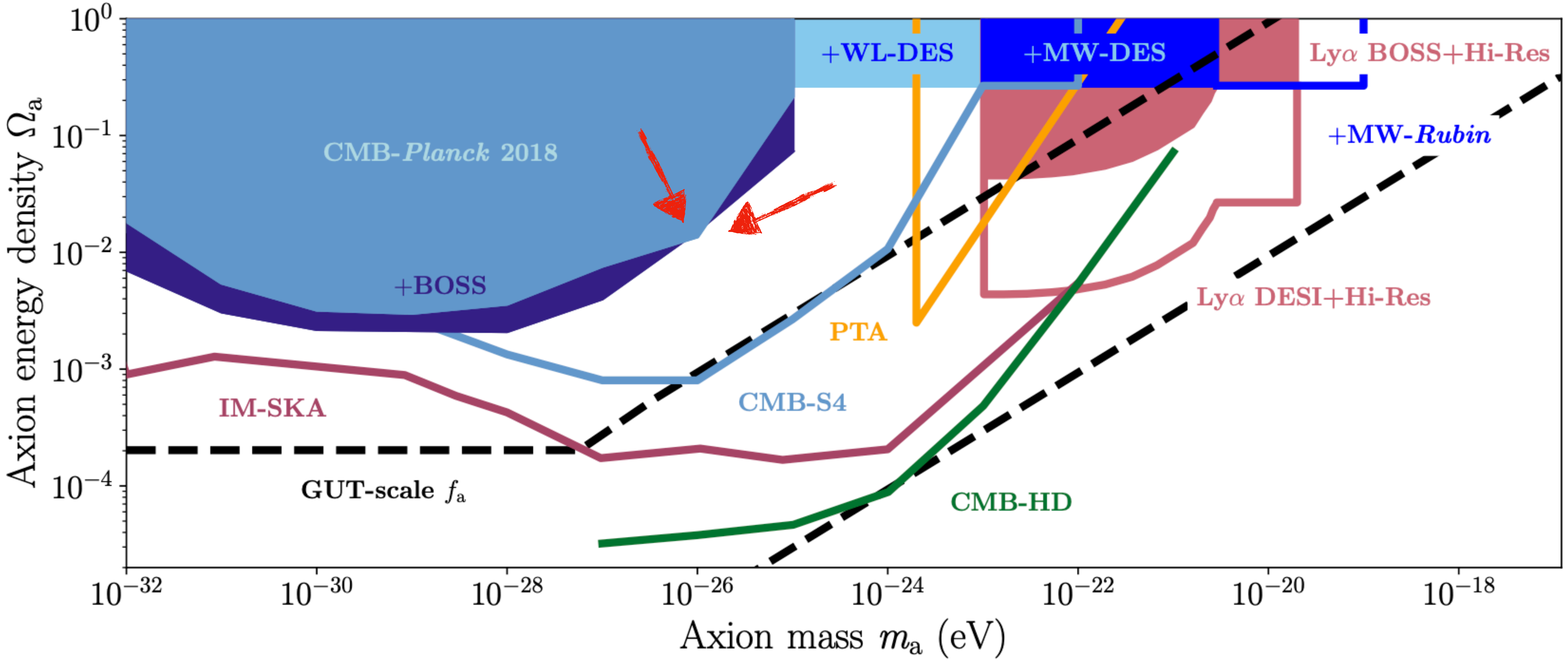
$$P_g^{\mathrm{ctr}} \simeq -2c_c k^2 P_{cc} - 2c_a k^2 P_{ca} + \cdots$$

⇒ finally, fit data!

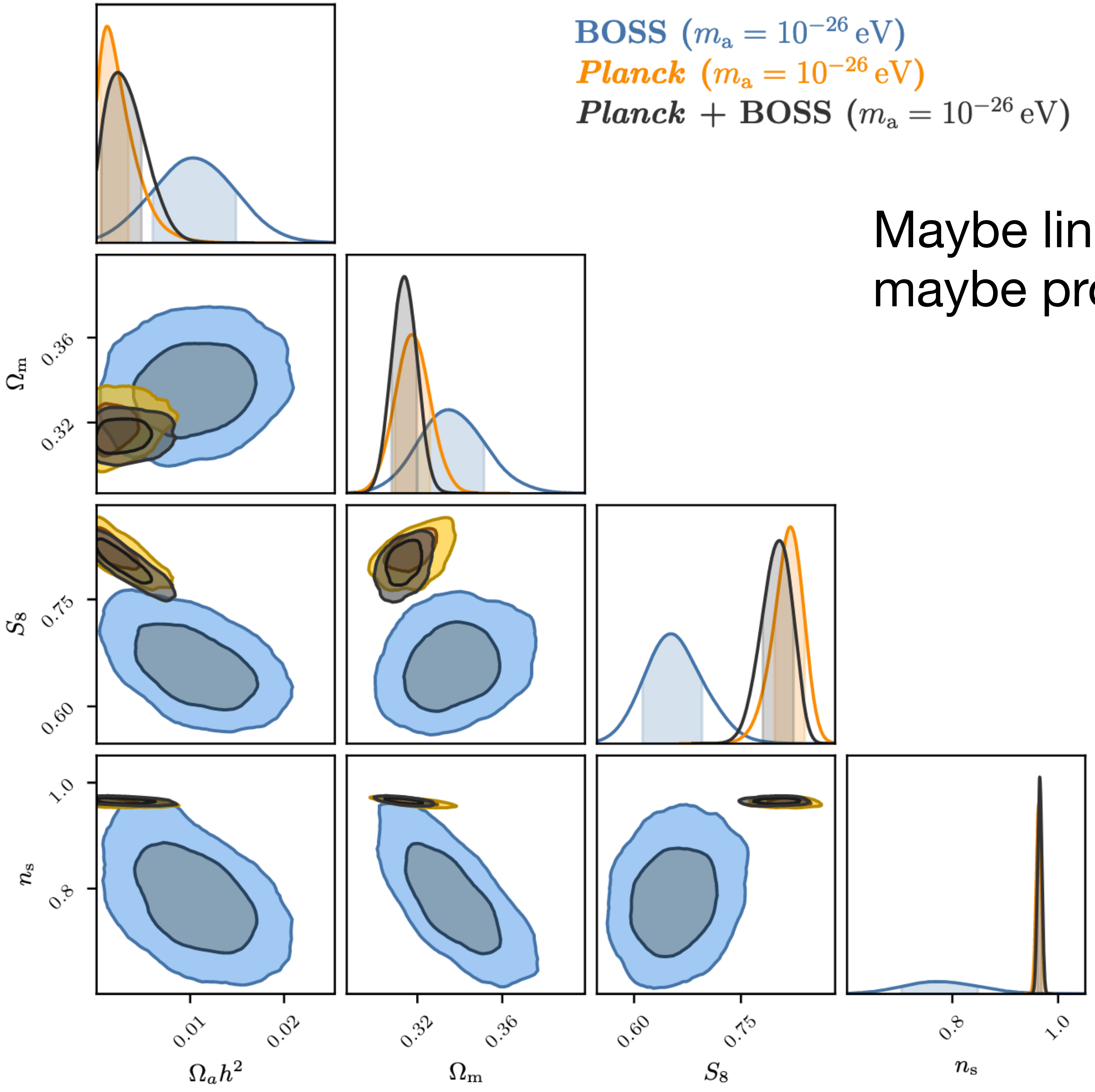


Our reference for ULAs

[Rogers et al. 23]



[Rogers et al. 23]



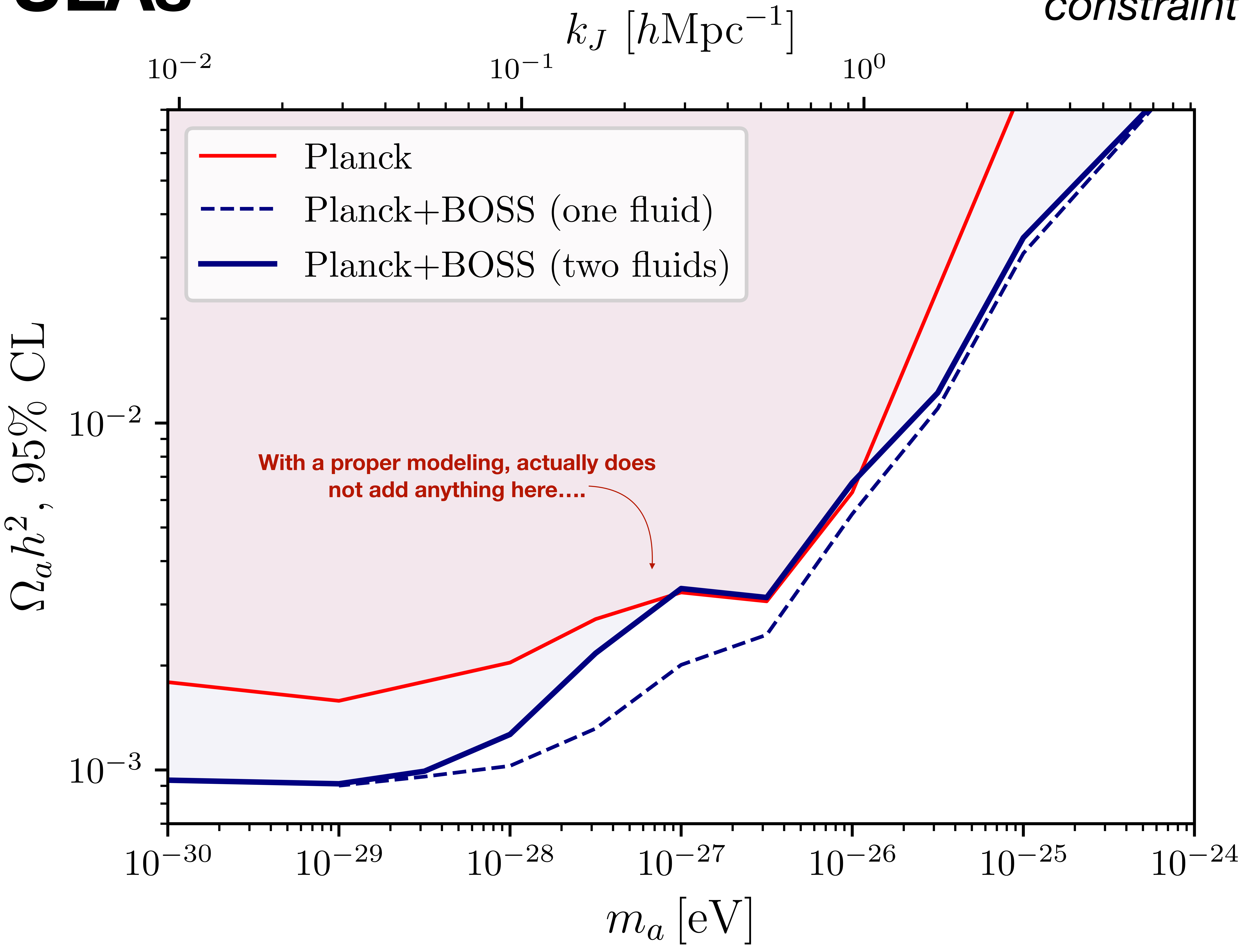
Maybe linked to the S_8 tension in BOSS, maybe projection effects

What we are after to, changes a lot the perspective:
just excluding, or do we have a detection?

In the latter case, proper modeling is imperative

Results: ULAs

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

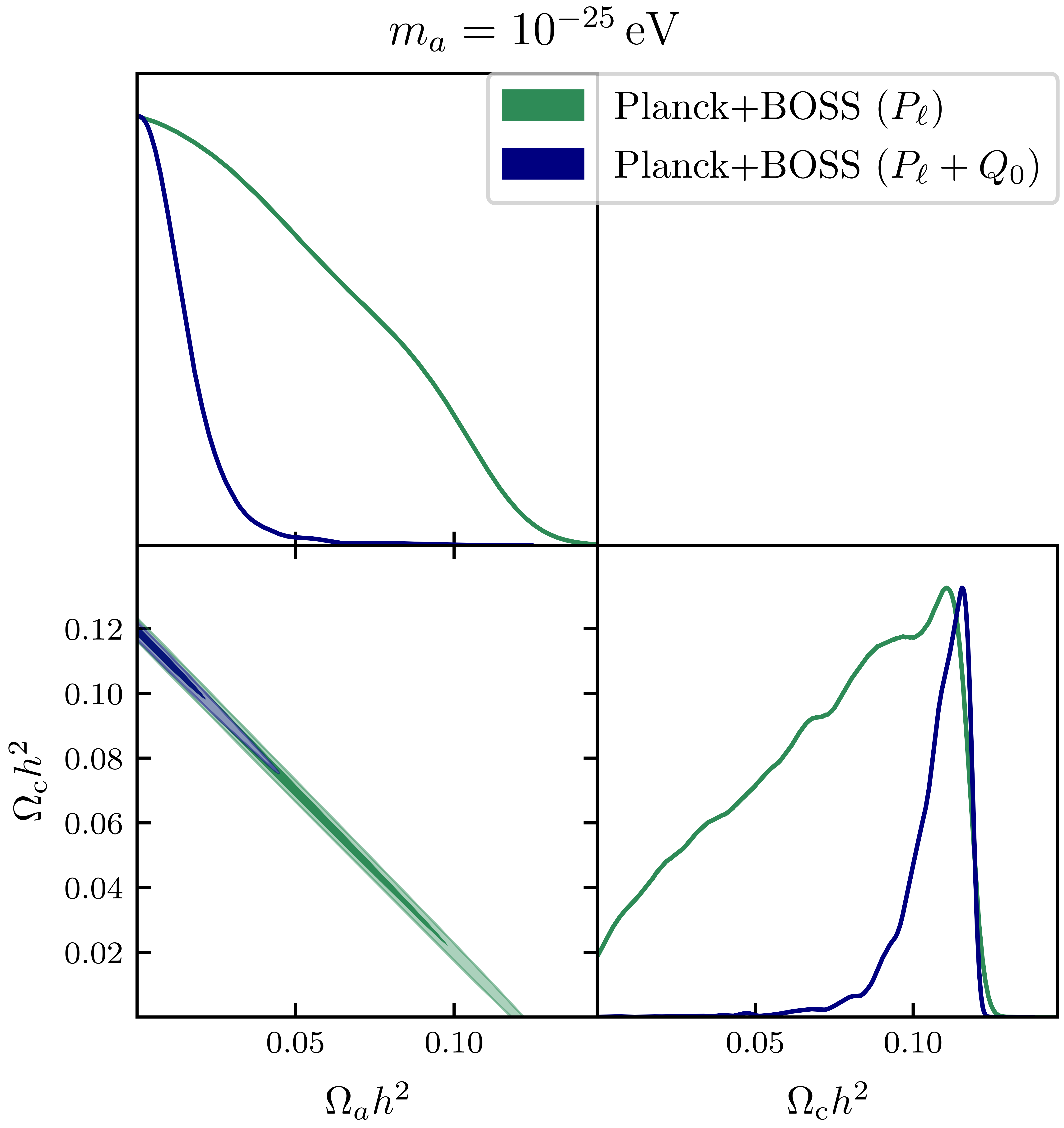


Hidden: the importance of Q_0 for BSM

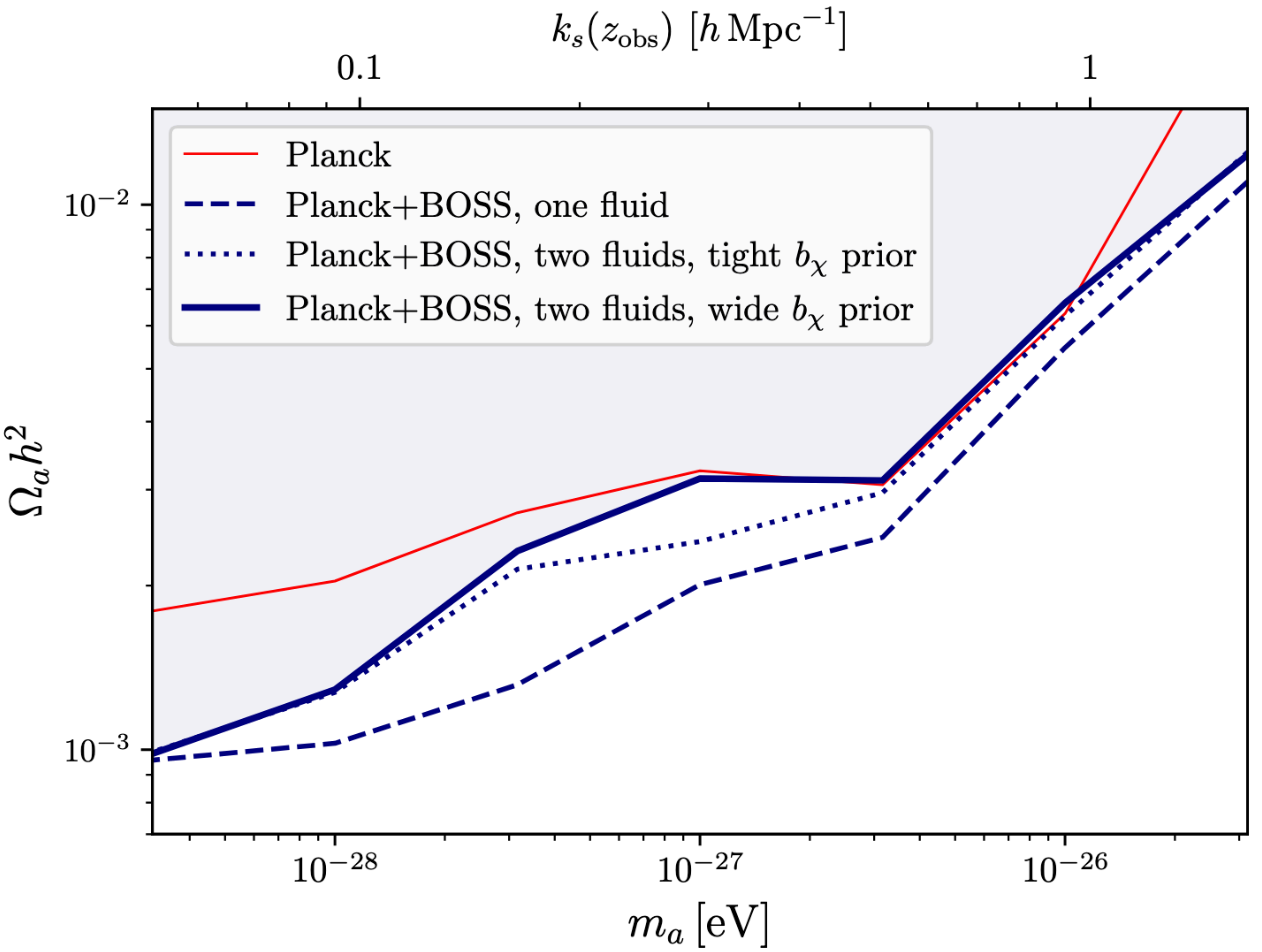
$$\check{Q}_0(k_i) = \check{P}_0 - \frac{1}{2}\check{P}_2 + \frac{3}{8}\check{P}_4$$

Being free from RSDs, one can push the fit up to $k_{\rm max} = 0.4h{\rm Mpc}^{-1}$ [Ivanov et al. 22]

Particularly beneficial for probing BSM suppression!



Do we know something more? For instance, $b_\chi \sim \mathcal{O}(f_\chi)$ [Çelik&Schmidt 25]



Some outlooks

- CMB + LSS is 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
- The $(f_\chi,\, k_J)$ plot is not generic, but background dependent
- Not very clear how much information coming from background or shape suppression (neither for massive neutrinos, see [Elbers et al 25])