Hints of dark matter-neutrino interactions in Lyman-α data

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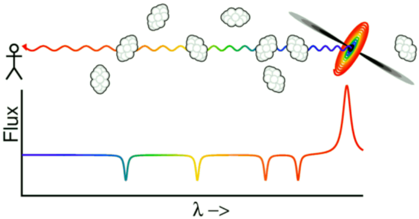
Presentation for the IRN Terascale meeting 2022

Based on
Hooper & Lucca 2021 [2110.04024]

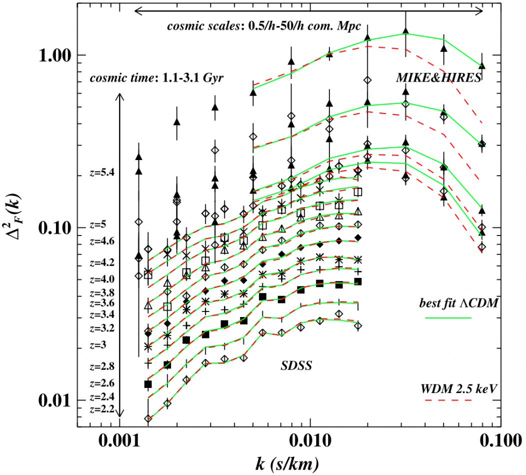
The Lyman-α flux power spectrum

- Photons from quasars 1) travel through H clouds, 2) get absorbed and 3) re-emitted in other direction
- Since clouds are at lower redshifts than source, features are shifted towards lower wavelengths $\rightarrow$ Lyα forest
- Density and temperature of clouds determine depth and width of absorption features



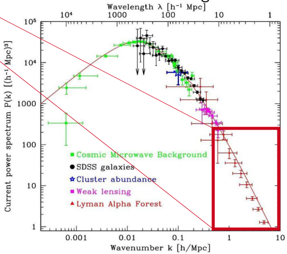
Adapted from `www.astro.ucla.edu`

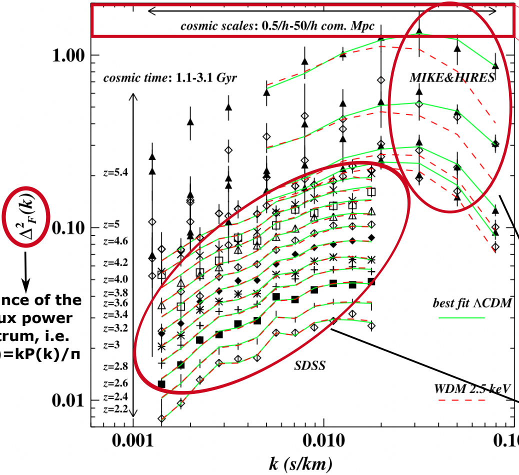
- Calculate normalized "transmission", Fourier transform, ensemble average, get flux PS and its variance



Adapted from Viel et al. 2013

Adapted from Tegmark et al. 2004





Variance of the 1D flux power spectrum, i.e. $\Delta^2(k)=kP(k)/\pi$

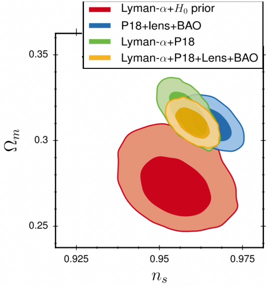
Small scales sensitive to astro parameters and DM properties

Large scales sensitive to cosmo parameters such as Ω_m, σ_8 and n_s

Adapted from Viel et al. 2013

State-of-the-art at large scales:

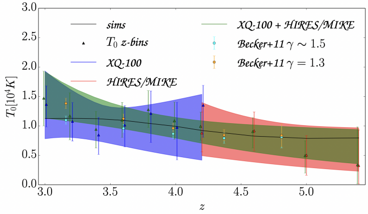
- Overall good agreement with WL
- $2-3\sigma$ tension with early-time probes in tilt of the PS



State-of-the-art at small scales:

- Suppression at small scales is caused by 1) gas pressure and 2) thermal broadening
- If the gas is colder one has less suppression (and vice versa)

$\rightarrow$ Possible to determine the temperature evolution!

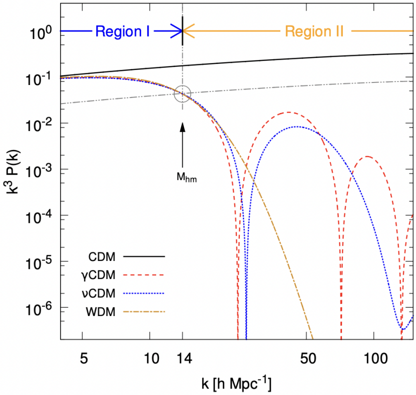


Adapted from
Palanque-delabrouille et al. 2019 (top)
Irsic et al. 2017 (bottom)

Lyman-α as a tool to constrain dark matter

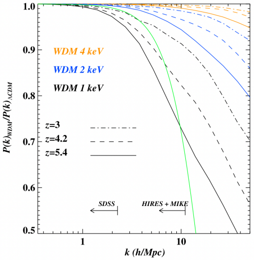
Generalities on the role of (light/warm and interacting) DM:

- If the DM is 1) light/warm ($m_{\rm DM} \simeq \mathcal{O}$(few keV)) or 2) interacting (with e.g. baryons, γ, ν and dark radiation)
- High velocity dispersion/ interactions act as pressure/dragging effect countering the gravitational collapse
- Shape of the suppression encapsulates the model dependence

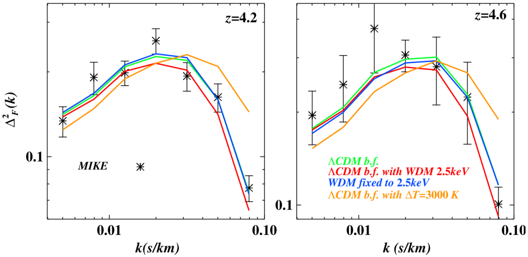


Adapted from Schewtschenko et al. 2014

- Although this is true at the level of the *matter* PS, the true observable is still the *flux* PS
- In that case, the suppression can be (at least partially) compensated by modifications to $T(z)$ (which becomes model-dependent)
  $\rightarrow$ This needs to be taken into account!



vs.



WDM clearly excluded, right? ... Not so much!

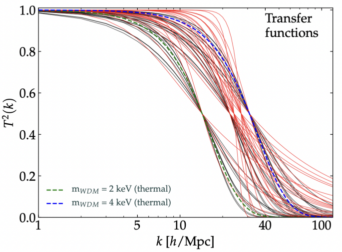
Adapted from Viel et al. 2013

However, CLASS/CAMB can only give you the *matter* PS! So how to perform MCMCs without the need of very expensive N-body simulations?
$\rightarrow$ One option is to (see e.g. Murgia et al. 2017, 2018, Archidiacono et al. 2019)

1. express the suppression of the matter PS in terms of the transfer function $T^2(k) = P(k)/P_{\Lambda CDM(k)} = [1 + (\alpha k)^\beta]^\gamma$,
2. create a grid of $\{\alpha, \beta, \gamma\}$ combinations (also with $\{n_s, \sigma_8, z_{\rm reio}\}$),
3. for each combination calculate the *flux* PS (with $T(z)$ effects!),

and (after the grid is ready) given a model's prediction for $\{\alpha, \beta, \gamma\}$

4. interpolate the pre-computed grid,
5. get the corresponding flux, χ^2, constraints, etc.



Adapted from Murgia et al. 2017

Only MIKE/HIRES lkl exists so far (Archidiacono et al. 2019)

The curious case of ... dark matter-neutrino interactions

For the specific case of DM-ν interactions, we assume

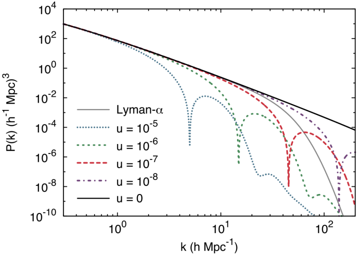
1. that the neutrinos are massive (non-trivial, more on this next),
2. that they interact with the DM via a Thompson-like scattering process (i.e. $m_{\rm DM} \gg m_\nu$) with the CS

$$\sigma_{{\rm DM}\nu} = \sigma_0 \left(\frac{m_{\rm DM}}{1 \text{ GeV}}\right) = u_{{\rm DM}\nu}\sigma_{\rm T} \left(\frac{m_{\rm DM}}{100 \text{ GeV}}\right) ,$$

   where $u_{{\rm DM}\nu}$ is just a dimensionless reformulation of σ_0,
3. that the interaction strength is the same for all 3 neutrino species,
4. that the total DM content of the universe is interacting, and
5. that the neutrino masses follow the normal hierarchy (with a lower limit on $\sum m_\nu$ of 0.06 eV)

State-of-the-art before our paper:

1. Wilkinson et al. 2014 reformulated previous WDM constraints (from Viel et al. 2013) assuming massless neutrinos



$\rightarrow$ obtaining $u_{\mathrm{DM}\nu} < 1 \times 10^{-7}$

2. Mosbech et al. 2020 accounted for m_ν (“massive” work!), tested the model against P18+BAO and found that the model can solve the S_8 tension (they also made their CLASS code public!)

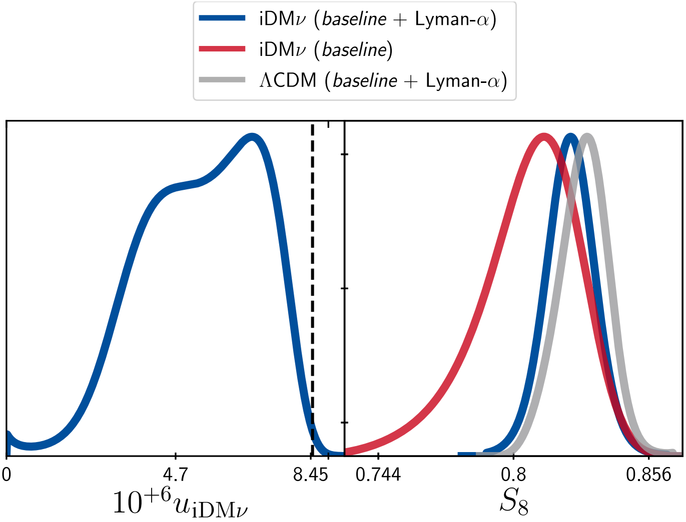
Straightforward goals of our paper:

1. Update Wilkinson at al. by
   1.1 accounting for m_ν (using Mosbech et al.'s code) and
   1.2 confronting the model with real Lyman-α data (using Archidiacono et al.'s likelihood)
2. Check if the model can still solve the σ_8 tension after the inclusion of Lyman-α

Expected timeline:

1. set up the runs
2. check 2 weeks later to find clean upper bounds on $u_{\mathrm{DM}\nu}$
3. write a quick paper
4. celebrate the victory

10 months later


iDMν (*baseline* + Lyman-α)
iDMν (*baseline*)
ΛCDM (*baseline* + Lyman-α)
0
4.7
8.45
$10^{+6}u_{\mathrm{iDM}\nu}$
0.744
0.8
0.856
S_8

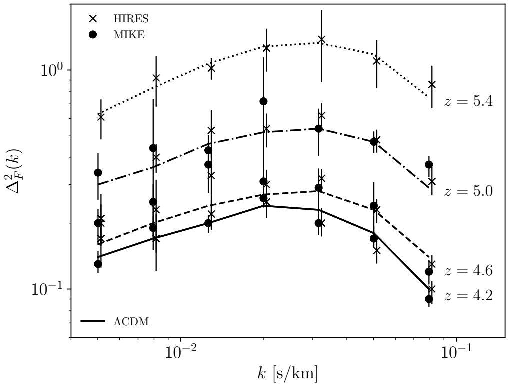
Two main possible origins for the presence of this preference:

1. Numerical
   - On the CLASS side: no error here
   - On the MP side: validity of the lkl pushed to its limits (more tests on-going) although all sanity checks are formally passed

   So let us assume the numerical side can be trusted

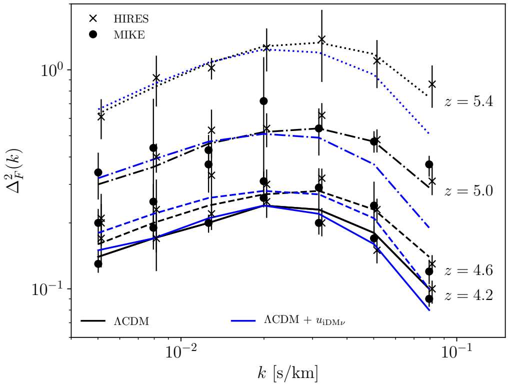
2. Physical

- ΛCDM shows deficit at large scales and excess at small scales $\rightarrow$ additional tilt needed (in agreement with SDSS analysis)



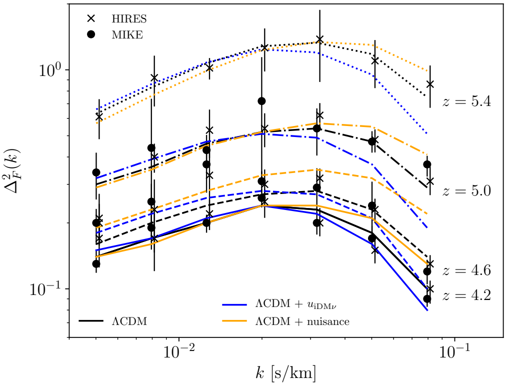
2. Physical

- DM-ν interactions can correctly increase the tilt at large scales, but with a too large suppression at small scales



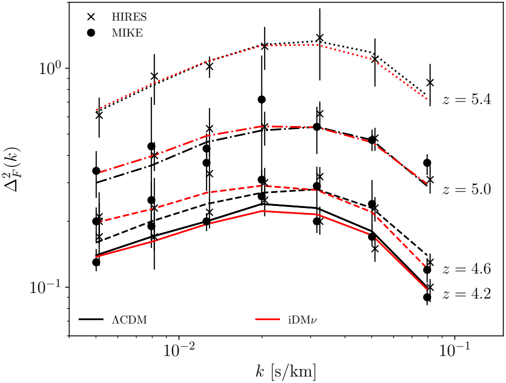
2. Physical

- Remember however that a lower gas temperature can enhance the spectrum at small scales



2. Physical

- The two contributions perfectly compensate to fit the data better than ΛCDM ($\Delta\chi^2 = -8$ for MIKE/HIRES, approx. 3σ)!



It is at this point fair to ask: why hasn't this been seen for other models?

- WDM does not enhance large scales (i.e. it does not *tilt* the overall spectrum, but only suppresses it)
- The same is also true for many other models such as inter. DM-DR

Also:

- In many cases, constraints "recycled" from WDM bounds instead of being directly derived from the data
  $\rightarrow$ "good" models might have been gone undetected
- This is precisely the case for the Wilkinson et al. results obtained in the context of DM-(massless) ν interactions (as we find explicitly)

$\rightarrow$ So, there is nothing special about this model *per se*: it just tilts the spectrum in the right way (not so easy though)

Final thoughts and take-home message

- There is a $2-3\sigma$ tension in the determination of the matter/flux PS tilt between early-time inference and direct Lyman-α measurements
- Many DM models predict a suppression of the matter/flux PS at Lyman-α scales, but only few can correctly adjust the spectrum's tilt
- DM-ν interactions are one such example, leading to a 3σ preference for a non-zero interaction strength
- Future work fundamental to test the validity of method and results