How dark is dark matter?

Pushing the Boundaries – Standard Model and Beyond at LHC
Durham, 18/09/19

Julia Stadler, University of Durham
based on work with Céline Bœhm and Olga Mena

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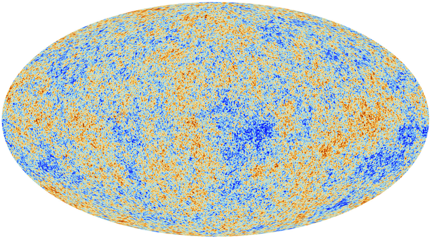
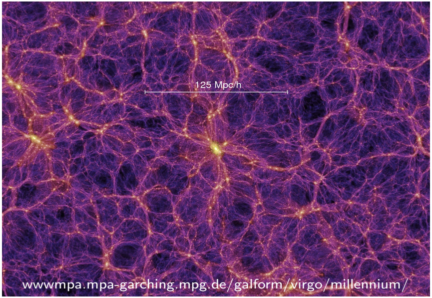
The Success of ΛCDM



www.esa.int/spaceinimages/Images/2013/03/Planck_CMB



wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/

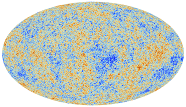
chandra.harvard.edu/photo/2006/1e0657/index.html

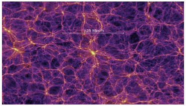
www.esa.int/spaceinimages/Images/2013/11/Milky_Way

Being agnostic about DM properties

Cosmological and astrophysical observations provide most of the present konwledge about DM properties.

$\Rightarrow$ ΛCDM assumes a **single**, **collsionless** fluid w/ **zero velocity**.






Cold-DM
But how cold?

- Warm dark matter
- Ultralight dark matter
- ...

C-**Dark**-M
But how dark?

- Self interacting DM
- DM-baryon scattering
- DM-DR scattering
- DM-γ scattering
- DM-ν scattering
- ...

Being agnostic about DM properties

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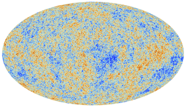

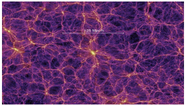
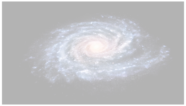

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- **DM-γ scattering** 1
- **DM-ν scattering** 3
- ...

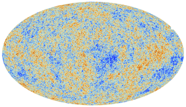
DM-γ elastic scattering

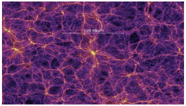
Cosmological
konwledge ab
$\Rightarrow$ ΛCDM as

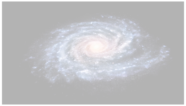
$$\theta'_{\rm dm} = -\mathcal{H}\theta_{\rm dm} + k^2\psi - \frac{4\rho_\gamma}{3\rho_{\rm dm}}\kappa'_{\gamma{\rm dm}}\left(\theta_{\rm dm} - \theta_\gamma\right)$$

$$\theta'_\gamma = -k^2\left(\frac{\delta_\gamma}{4} - \sigma_\gamma\right) + k^2\psi + \kappa'_{\gamma{\rm b}}\left(\theta_{\rm b} - \theta_\gamma\right) + \kappa'_{\gamma{\rm dm}}\left(\theta_{\rm dm} - \theta_\gamma\right)$$

[Wilkinson et al. (2014)]







Cold-DM
But how cold?

Ultralight dark matter

Scattering rate: $\kappa'_{\gamma{\rm dm}} = a\, n_{\rm dm}\, \sigma_{\gamma{\rm dm}}$

$$\Rightarrow u_{\gamma{\rm dm}} = \frac{\sigma_{\gamma{\rm dm}}}{\sigma_{\rm Th}}\left(\frac{m_{\rm dm}}{100\,{\rm GeV}}\right)^{-1}$$

[Bœhm et al. (2001, 2004)]

C-**Dark**-M
But how dark?

DM-DR scattering

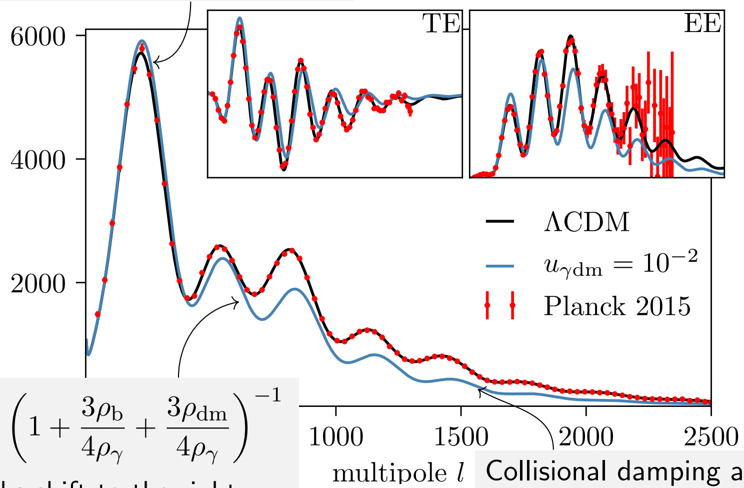
DM-γ scattering

DM-ν scattering

...

DM-γ scattering: effect on the CMB

Decreased photon diffusion length.
$\Rightarrow$ Increase of the first peak.



$$c_\mathrm{s}^2 = \frac{1}{3}\left(1 + \frac{3\rho_\mathrm{b}}{4\rho_\gamma} + \frac{3\rho_\mathrm{dm}}{4\rho_\gamma}\right)^{-1}$$

$\Rightarrow$ Peaks shift to the right.

Collisional damping at the DM-γ last scattering surface.

Constraints from Planck 2015

JS, C. Bœhm [1802.06589]

→ Computation of CMB spectra with `CLASS` [Blas, Lesgourgues, Tram (2011)]

→ MCMC sampling with `MontePython` [Audren, Lesgourgues et al. (2012)]

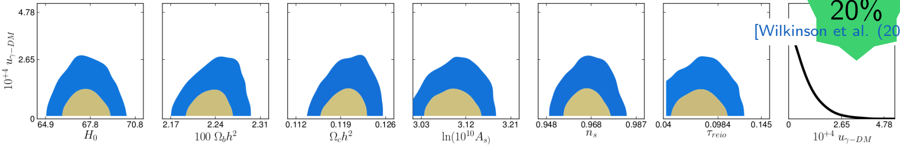
→ Parameter Space:

$$H_0 \;|\; \Omega_b h^2 \;|\; \Omega_{\rm dm} h^2 \;|\; \ln\left(10^{10} A_s\right) \;|\; n_s \;|\; \tau_{\rm reio} \;|\; u_{\gamma{\rm dm}}$$

"Planck TT + lowTEB": $\sigma_{\gamma{\rm dm}} < 1.5 \times (m_{\rm dm}/{\rm GeV})\;\;{\rm fm}^2$

20%

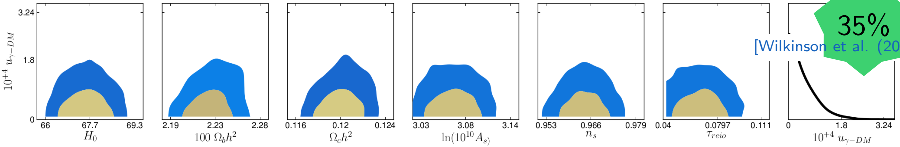
[Wilkinson et al. (2014)]



"Planck TTTEEE + lowTEB + lensing": $\sigma_{\gamma{\rm dm}} < 1.0 \times (m_{\rm dm}/{\rm GeV})\;\;{\rm fm}^2$

35%

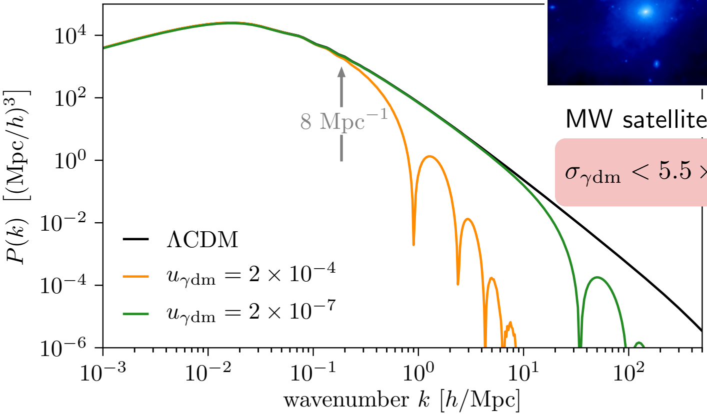
[Wilkinson et al. (2014)]

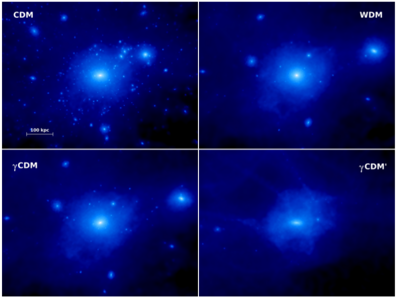


DM-γ scattering: matter power spectrum

$$\theta'_{\rm dm} = -\mathcal{H}\theta_{\rm dm} + k^2\psi - \frac{4\rho_\gamma}{3\rho_{\rm dm}}\kappa'_{\gamma{\rm dm}}\left(\theta_{\rm dm} - \theta_\gamma\right)$$

- damped acoustic oscillations
- small-scale power suppression





MW satellite counts:

$$\sigma_{\gamma{\rm dm}} < 5.5 \times 10^{-9}\,\sigma_{\rm Th}\left(\frac{m_{\gamma{\rm dm}}}{\rm GeV}\right)$$

[Bœhm et al. (2014)]

DM-γ scattering: sound speed

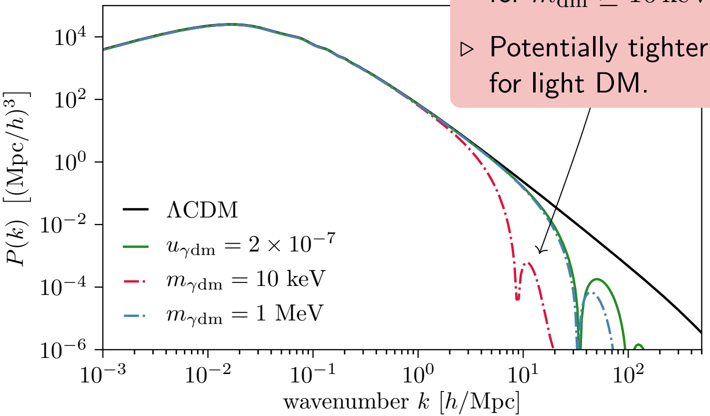
JS, C. Bœhm [1802.06589]

$$\theta'_{\rm dm} = -\mathcal{H}\theta_{\rm dm} + k^2\psi - \frac{4\rho_\gamma}{3\rho_{\rm dm}}\kappa'_{\gamma{\rm dm}}\left(\theta_{\rm dm} - \theta_\gamma\right) + k^2 c^2_{\rm dm}\delta_{\rm dm}$$

$$c^2_{\rm dm} = \frac{k_{\rm B}\,T_{\rm dm}}{m_{\rm dm}}\left[1 - \frac{1}{3}\frac{\partial \ln T_{\rm dm}}{\partial \ln a}\right]$$

Dark matter sound speed

- Negligible impact on CMB spectra for $m_{\rm dm} \geq 10\,{\rm keV}$
- Potentially tighter limits from LSS for light DM.

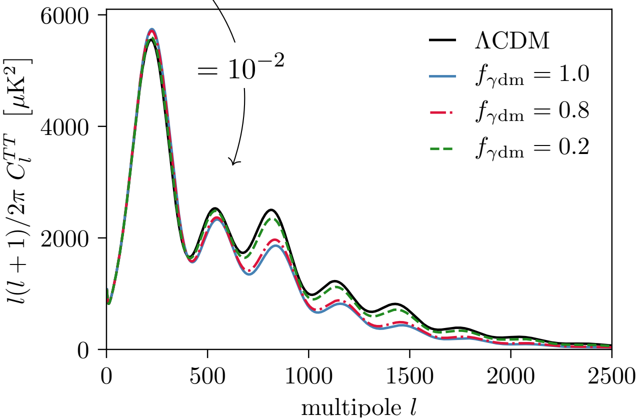


Two dark matter components:
- ∘ collisionless CDM
- ∘ DM scattering elastically with photons

$$u_{\gamma\rm dm} = \frac{\sigma_{\gamma\rm dm}}{\sigma_{\rm Th}} \left(\frac{m_{\rm dm}}{100\,\rm GeV}\right)^{-1}$$

$$f_{\gamma\rm dm} = \frac{\text{interacting DM}}{\text{total DM}}$$

$= 10^{-2}$



Two dark matter components:
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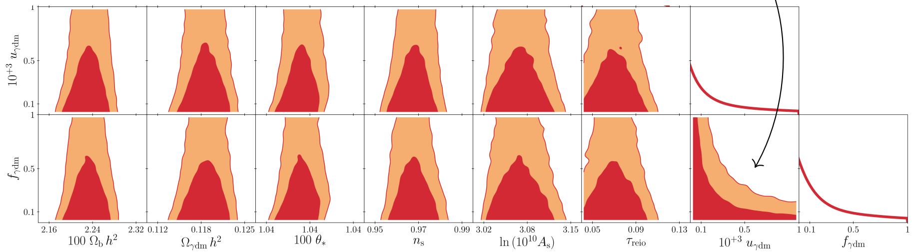
CMB constraints show a degeneracy w.r.t the new parameters!

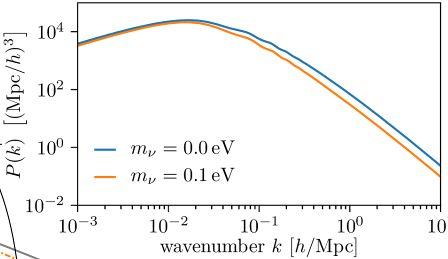


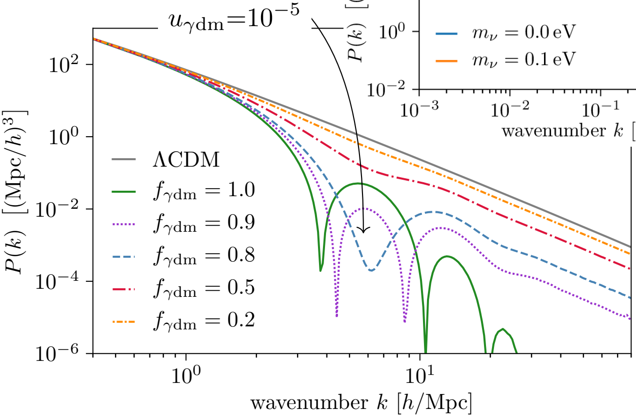
Mixed DM: the matter power spectrum

Large interacting DM fraction:
perturbations in the dark matter components cancel.

$\Rightarrow$ Additional power suppression on intermediate scales.

Small interacting DM fraction:
similar signature as heavy neutrinos!





Mixed DM: DESI forecast

JS, C. Bœhm, O. Mena [1807.10034]

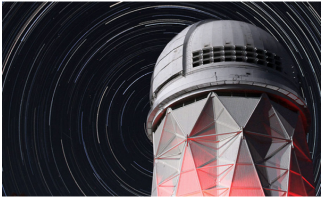
Dark Energy Spectroscopic Instrument (DESI)

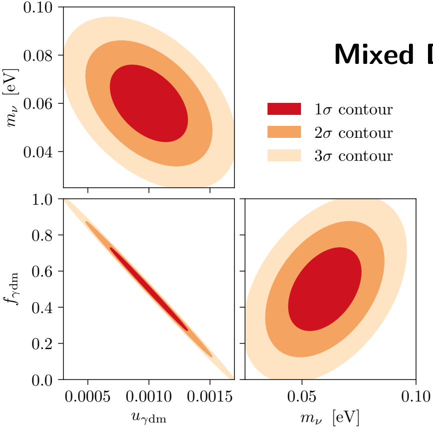
→ ground based LSS survey

→ First light planned for 2020.

→ Expected sensitivity $\delta m_\nu = 0.02\,\mathrm{eV}$.

[Font-Ribera et al. (2014)]





Mixed DM Fisher forecast

→ The mixed DM parameters are strongly degenerate.

→ Both parameters show a degeneracy with m_ν.

→ The expected error on m_ν increases **at least** by a factor of 2.

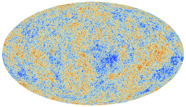
DM-ν elastic scattering

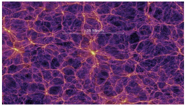
Cosmological and astrophy
konwledge about DM prop
$\Rightarrow$ ΛCDM assumes a **sing**

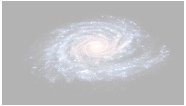
$$\theta'_\nu = k^2\left(\frac{\delta_\nu}{4} - \sigma_\nu\right) + k^2\psi - \kappa'_{\nu\mathrm{dm}}\left(\theta_\nu - \theta_{\nu\mathrm{dm}}\right)$$

$$\theta'_{\mathrm{dm}} = k^2\psi - \mathcal{H}\theta_{\mathrm{dm}} - \frac{3\rho_\nu}{4\rho_{\mathrm{dm}}}\kappa'_{\nu\mathrm{DM}}\left(\theta_{\mathrm{dm}} - \theta_\nu\right)$$

[Wilkinson et al. (2014)]
[Bœhm et al. (2004)]







Scattering rate: $\kappa'_{\nu\mathrm{dm}} = a\, n_{\mathrm{dm}}\, \sigma_{\nu\mathrm{dm}}$

$$\Rightarrow u_{\nu\mathrm{dm}} = \frac{\sigma_{\nu\mathrm{dm}}}{\sigma_{\mathrm{Th}}}\left(\frac{m_{\mathrm{dm}}}{100\,\mathrm{GeV}}\right)^{-1}$$

Planck '15: $u_{\nu\mathrm{dm}} \leq 2.14 \times 10^{-4}$
[Diacoumis, Wong (2019)]

Planck '13 & Lyα: $u_{\nu\mathrm{dm}} \leq 1.5 \times 10^{-7}$
[Wilkinson (2014)]

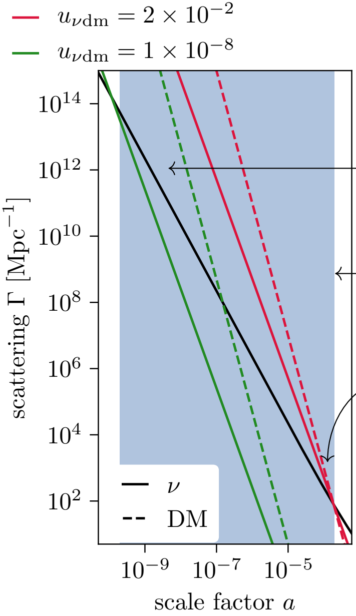
C-**Dark**-M
But how dark?

DM-γ scattering

DM-ν scattering

...

JS, C. Bœhm, O. Mena [1093.00540]



$$\Gamma_{\mathrm{dm}-\nu} \quad = \quad \frac{4\rho_\nu}{3\rho_{\mathrm{dm}}}\Gamma_{\nu-\mathrm{dm}}$$

Both species do not decouple simultaneously!

DM decouples when νs free stream.
$\Rightarrow$ **Mixed damping.**

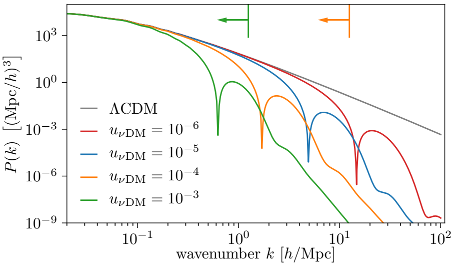
DM decouples when νs are collisional.
$\Rightarrow$ **Collisional damping.**

DM and ν decouple simultaneously if

$$u_{\nu\mathrm{dm}} \simeq 2 \times 10^{-2}$$

Mixed damping is important for present constraints!

Mixed damping – analytically



Prerequisites

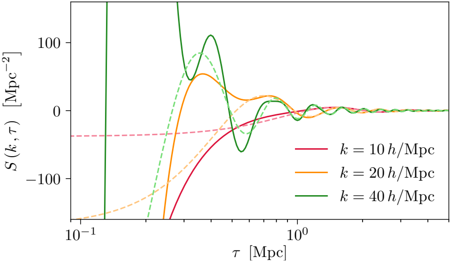
- $(3\rho_\nu)\,/\,(4\rho_{\mathrm{dm}}) < 1$ radiation domination.
- Neutrinos are free streaming.

$$(3\rho_\nu)\,/\,(4\rho_{\mathrm{dm}})\,\kappa'_{\nu\mathrm{DM}} = C_\kappa/\tau^3 \longrightarrow S(\tau) = 3\phi'' + \frac{3}{\tau} - k^2\psi + \frac{C_\kappa}{\tau}\left(3\phi' - \theta_\nu\right)$$

$$\uparrow$$

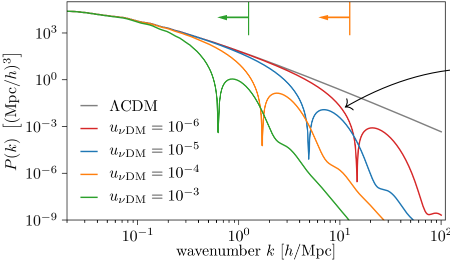
$$\delta''_{\mathrm{dm}} + \left(\frac{1}{\tau} + \frac{C_\kappa}{\tau^2}\right)\delta'_{\mathrm{dm}} = S(k\,,\tau)$$

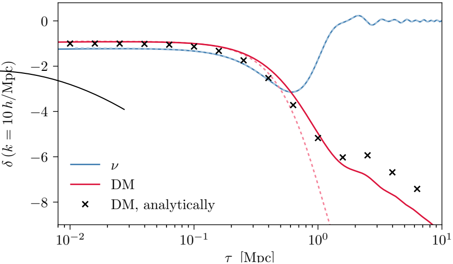
$$\delta^{\mathrm{late}}_{\mathrm{dm}} \propto 2\left(\int_0^\tau d\tau' S(\tau')\,\frac{\tau'}{2} e^{-\frac{C_\kappa}{2\tau'^2}}\right)\ln\tau$$



Mixed damping – analytically

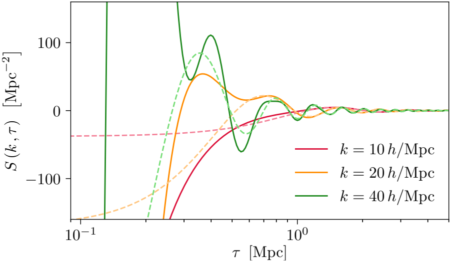
JS, C. Bœhm, O. Mena [1093.00540]





$$\delta''_{\mathrm{dm}} + \left(\frac{1}{\tau} + \frac{C_\kappa}{\tau^2}\right)\delta'_{\mathrm{dm}} = S\,(k\,,\tau)$$

$$\delta_{\mathrm{dm}}^{\mathrm{late}} \propto 2\left(\int_0^\tau d\tau' S\,(\tau')\;\frac{\tau'}{2}e^{-\frac{C_\kappa}{2\tau'^2}}\right)\ln\tau$$



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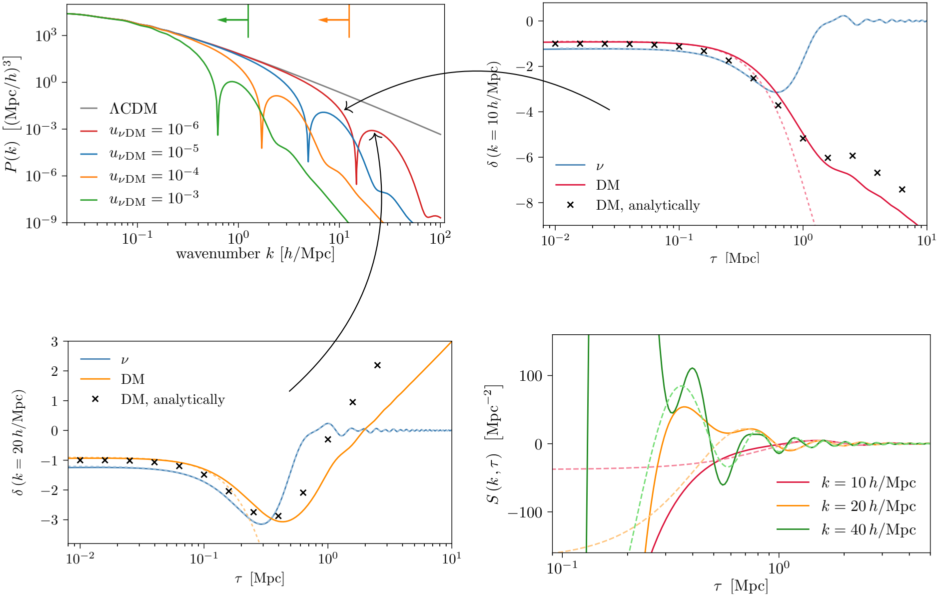

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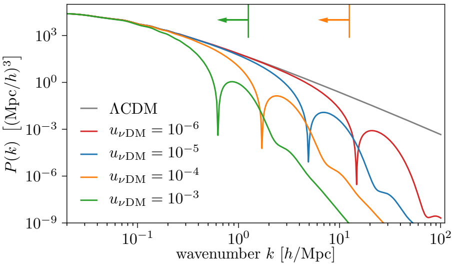

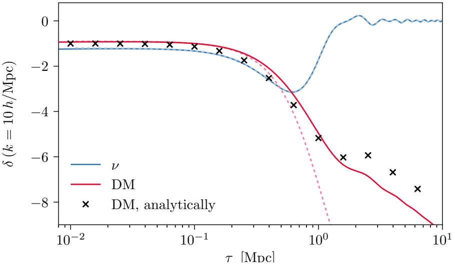

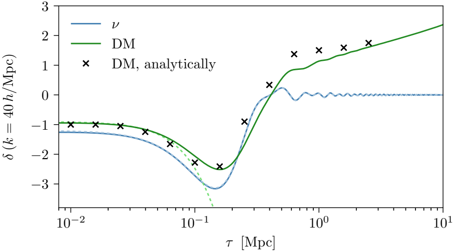

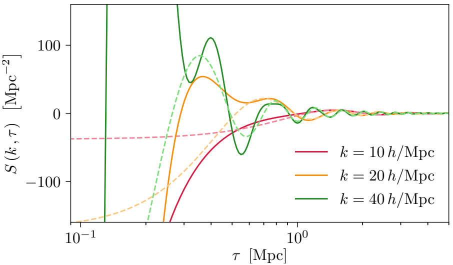

Conclusions

- Cosmology can constrain the particle physics properties of DM.
- Limits are very complementary to collider searches and direct detection attempts.
- Updated CMB limits on **DM**-γ interactions.
- An **admixture** of interacting and non-interacting DM is hard to detect and can affect neutrino mass measurements.
- In **DM**-$\boldsymbol{\nu}$ interactions the predominant effect is due to mixed damping, in contrast to the canonical collisional damping.