# Non-minimally coupled scalar field as cold dark matter

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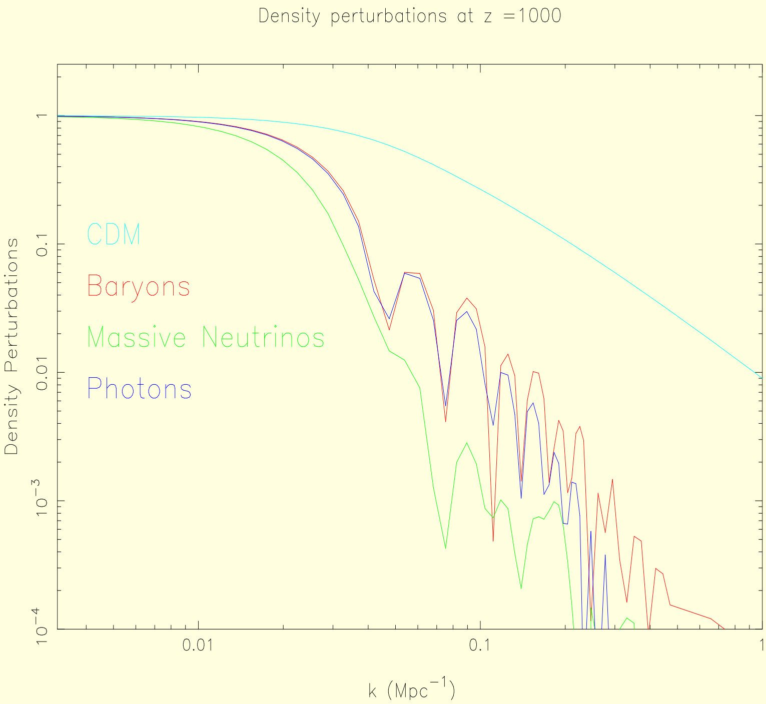
# 1. Evolution of Density perturbations: $z = 1000$



## 2. Scales in the problem

- **Matter-radiation equality**:

$$k_{\rm eq} \simeq 0.2\,\Omega_{\rm m} h^2\,{\rm Mpc}^{-1} \tag{1}$$

  Determines the shape of CDM perturbations

- **Sound velocity of baryon-photon fluid**: $c_s \simeq c/\sqrt{3}$. At $z \simeq 1000$:

$$k_{\rm sound} \simeq \sqrt{3}H(z) \simeq 0.02(\Omega_m h^2)^{1/2}\,{\rm Mpc}^{-1} \tag{2}$$

- **Silk damping**: The damping scale of baryon-photon fluid owing to viscosity. $l_s^2 \simeq H^{-1} l_{\rm mf}$:

$$k_s \simeq 0.5 \left(\frac{\Omega_b h^2}{0.022}\right)^{1/2} (\Omega_m h^2)^{1/4}\,{\rm Mpc}^{-1} \tag{3}$$

- **Free streaming of massive neutrino**: Roughly $H^{-1}$ at $T \simeq m_\nu$, e.g. for $m_\nu \simeq 0.2\,{\rm eV}$, $k_{\rm fs} \simeq 0.01\,{\rm Mpc}^{-1}$

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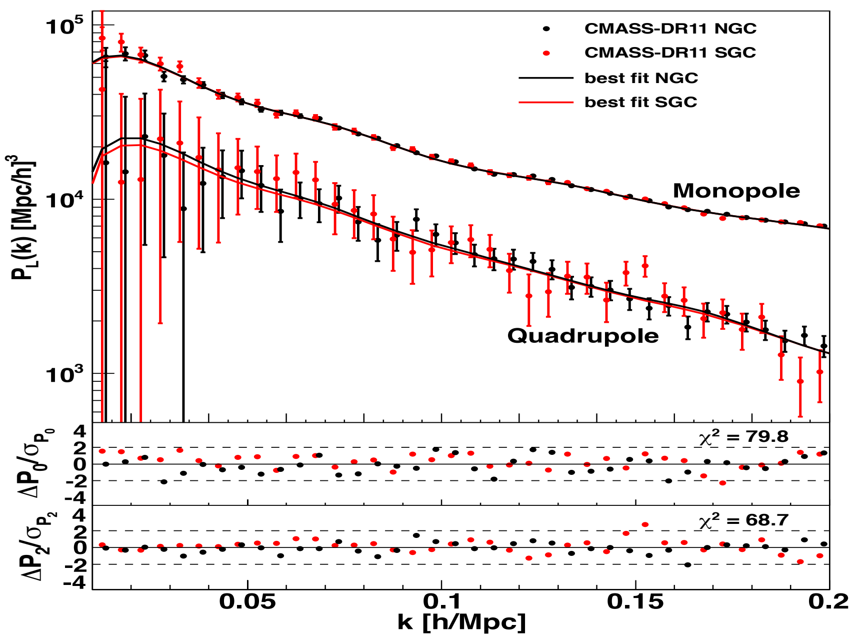
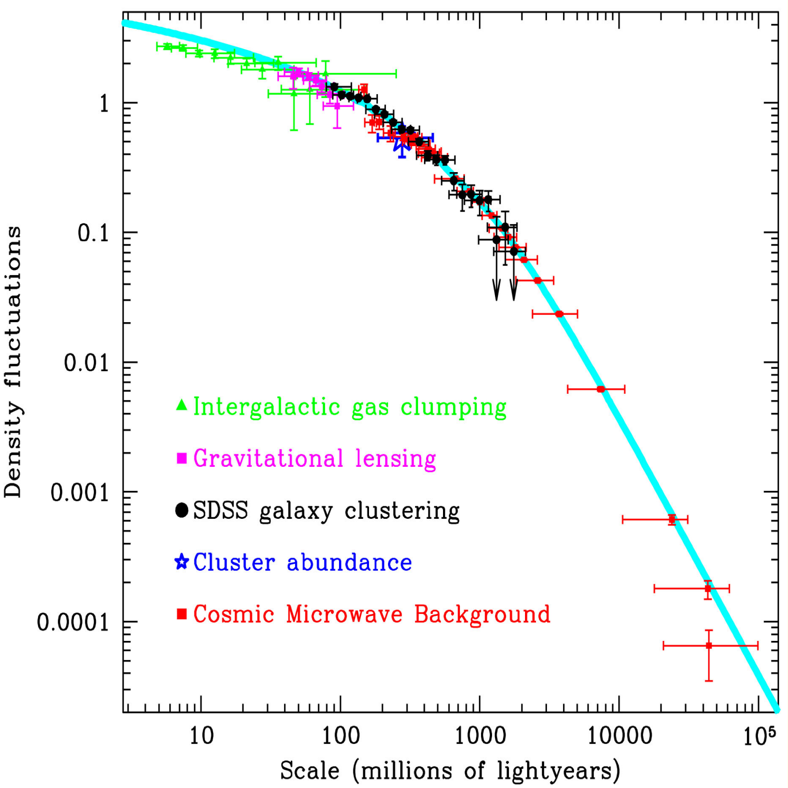
# 3. SDSS results: power spectrum



(Beutler et al. 2013)

# 4. Probes of matter Power Spectrum



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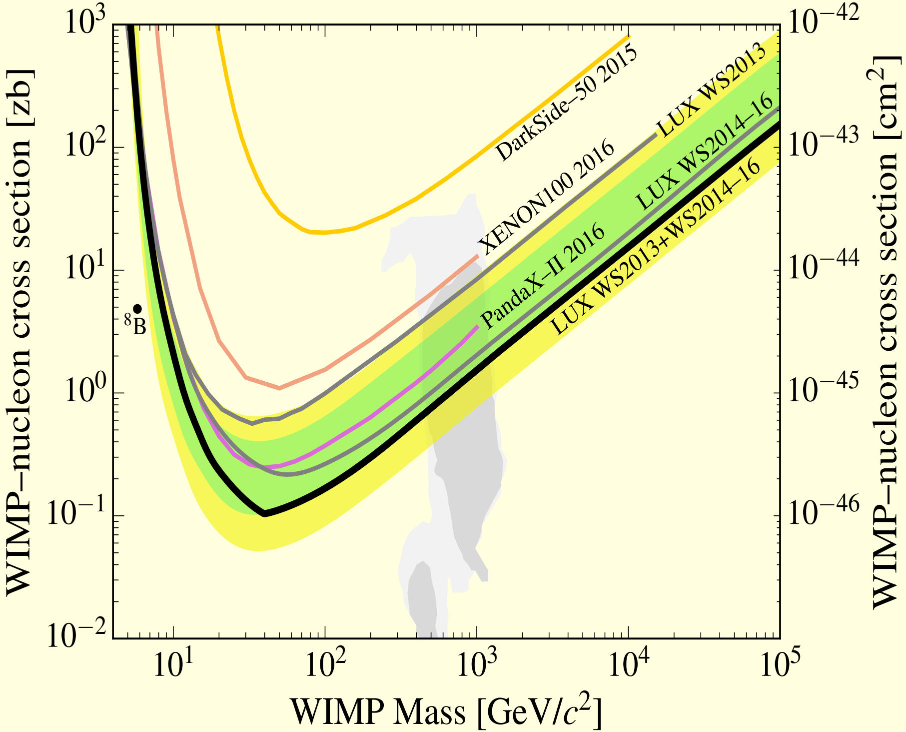
# 5. Determining the nature of Dark matter: Planck results

- `Primordial perturbations`: scalar spectral index, $n_s = 0.9652 \pm 0.0062$
- `Baryons`: $\Omega_B h^2 = 0.022 \pm 0.00023$
- `Nonrelativistic component of the dark matter`: $\Omega_{cdm} h^2 = 0.1199 \pm 0.0022$
- `Hubble's constant`: $H_0 = 67.26 \pm 0.98$, the most precise measurement of Hubble's constant
- `Massive neutrinos`: $\sum m_\nu < 0.23\,\mathrm{eV}$, $\Rightarrow \Omega_\nu < 0.005$ (particle physics data gives: $\Omega_\nu > 0.001$)
- `Massless neutrinos`: $N_{\mathrm{eff}} = 3.15 \pm 0.23$
- `Total matter content`: Consistent with spatially flat universe $\Omega_{\mathrm{total}} = 1 \pm 0.005$

## 6. Does CDM work at sub-galactic scales?

- *Missing sub-haloes of Milky Way*: Simulation reproduce adequately substructures of clusters but predict up to 25 times more dwarf spheroidals than detectable in Milky Way. Less power at small scales?
- *Cuspy profiles*: Simulations suggest cuspy profiles in the center of galaxies, yet observations suggest flat profiles. Interacting dark matter?
- *Too big to fail conundrum*: Simulations suggest substructures of Milky Way are too big or they should have hosted baryonic structures.

# 7. Dark matter detection experiments



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# 8. Alternative dark matter models

- **Warm Dark Matter**: massive particle of $m_{\rm wdm} \simeq$ keV free streams and suppresses density perturbations at cosmological scales.

- **Late Forming Dark matter**: The dark matter forms due to a phase transition at $z = z_f$, inheriting the initial conditions of massless neutrinos. Power suppressed at scales inside the horizon for $z < z_f$.

- **Ultra-Light Axion (ULA)**: Dark matter is a scalar field with non-zero effective mass, $m_a$, and sound velocity. Density perturbations at scales smaller than the sound horizon cannot grow.

- **Decaying Charged particle**: A charged particle decays into a neutral particle and an electron at $z = z_{\rm decay}$, impacting scales below horizon for $z < z_{\rm decay}$.

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## 9. Classical scalar field (ULA) as cold dark matter

- *Background evolution*: The field behaves like cosmological constant at early time $m_a \ll H$, but oscillates and on average behaves as matter $\rho_\phi \simeq 1/a^3$ at late times.
- *Perturbation theory*: The effective sound speed:

$$c_s^2 = \frac{k^2/(m_a^2 a^2)}{(1 + k^2/(m_a^2 a^2))} \tag{4}$$

- *Early times*: $c_s^2 \Longrightarrow 1$, but scalar field has little impact on the gravitational potential.
- *Late times: scalar field energy density comparable to radiation*: For normal CDM, the density contrast increases as either $\log(a)$ or $a$, but for scalar field, finite sound speed prevents growth.
- *Very late times*: $c_s \Longrightarrow 0$ and scalar field behaves as pressureless CDM.

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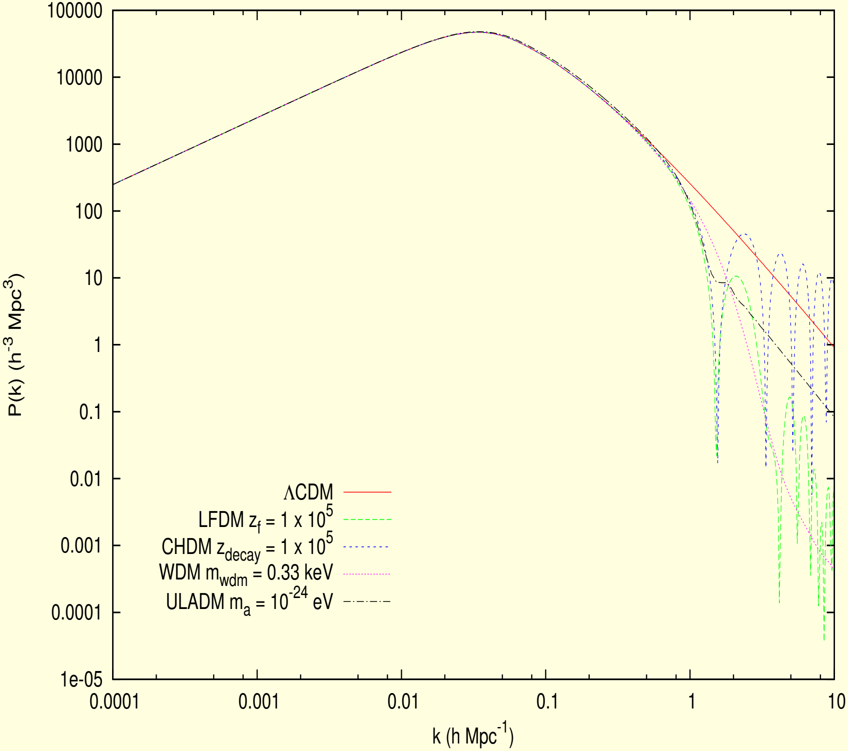
# 10. Matter power spectra



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# 11. Cosmological observables at small scales

- *Lyman-$\alpha$ clustering*: Probes nearly non-linear density perturbations at scales up to $k \simeq 4\,\mathrm{Mpc}^{-1}$ (Sarkar et al. 2021)

- *Epoch of reionization*: Halo population decreases for alternative dark matter models, leading to different reionization histories and the neutral hydrogen (HI) signal. Scales $k \simeq 5$–$25\,\mathrm{Mpc}^{-1}$.

- *Collapsed fraction of matter at high redshifts*: Average HI mass density upto $z \simeq 5$ is known from damped Lyman-$\alpha$ studies. This is extremely sensitive to the matter power spectrum at scales $k \simeq 5\,\mathrm{Mpc}^{-1}$.

- *CMB spectral distortion from Silk damping*: Viscous damping damps scales in the range $0.3 < k < 10^4\,\mathrm{Mpc}$ in pre-recombination era. This is the only linear probe of such a range of scales (Sarkar et al. 2017).

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# 12. Non-minimally coupled scalar field

- *Lagrangian*:

$$\mathcal{L}_\phi = -\frac{1}{2}\sqrt{-g}[g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + m_\phi^2\phi^2 + \xi R\phi^2]. \quad (5)$$

  $\xi$ is a dimensionless coupling constant.

- *Background evolution*: Owing to the $R^2$ term, the background evolution of the scalar field changes substantially at early times. In particular, the scalar field might not behave as cosmological constant at early times.

- *Evolution of first order perturbation*: The anisotropic stress is non-zero which can impact the small scales. The 'sound velocity' of the scalar field is non-singular in this case, which has a bearing on all scales.

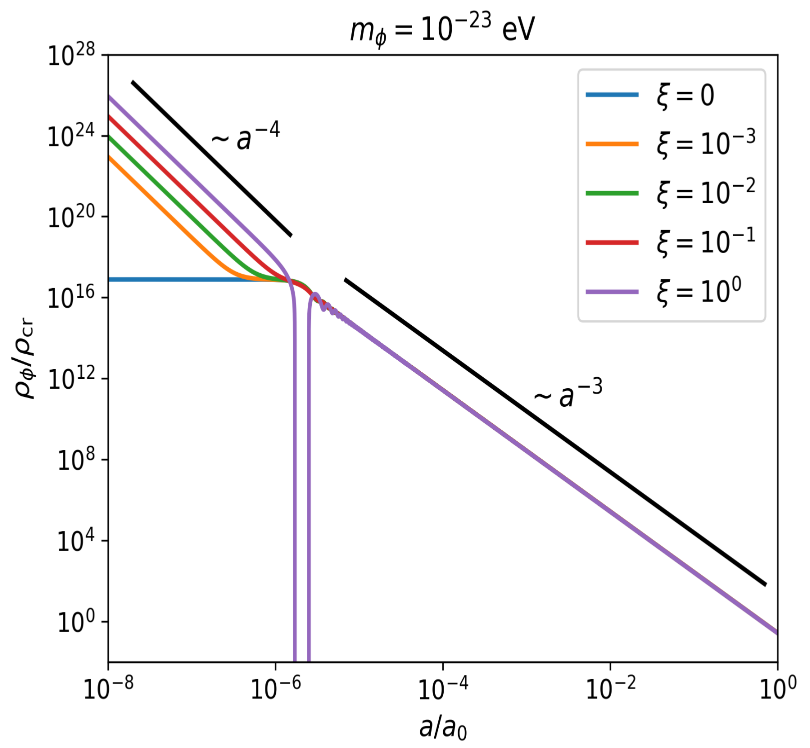
# 13. The multi-component fluid: the usual case

- *Early times*: Both the background and the first order evolution (at both sub- and super-horizon scales) is dominated by photons and neutrinos at early times.

- *Intermediate times*: $10^6 < z < 10^3$. The scalar field makes a transition to the matter phase $\langle \rho_\phi \rangle \propto 1/a^3$ and dominates the energy density after the matter-radiation equality. Photons and baryons are still tightly coupled

- *post-recombination era*: The photons and baryons decouple. The energy density is dominated by scalar field with baryons contributing around 16% of the energy density.

# 14. Background evolution: non-minimal case



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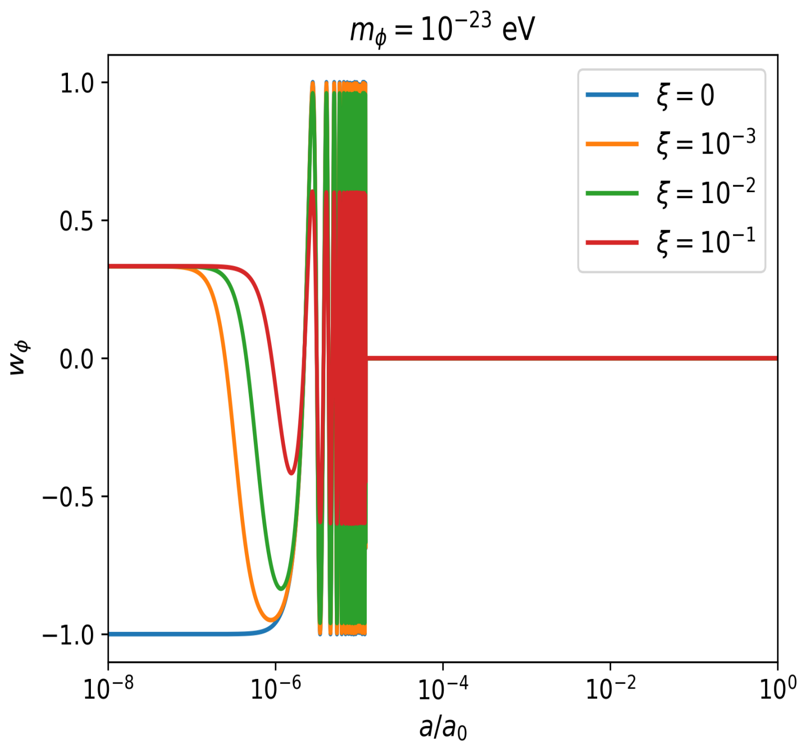
# 15. Background evolution: equation of state



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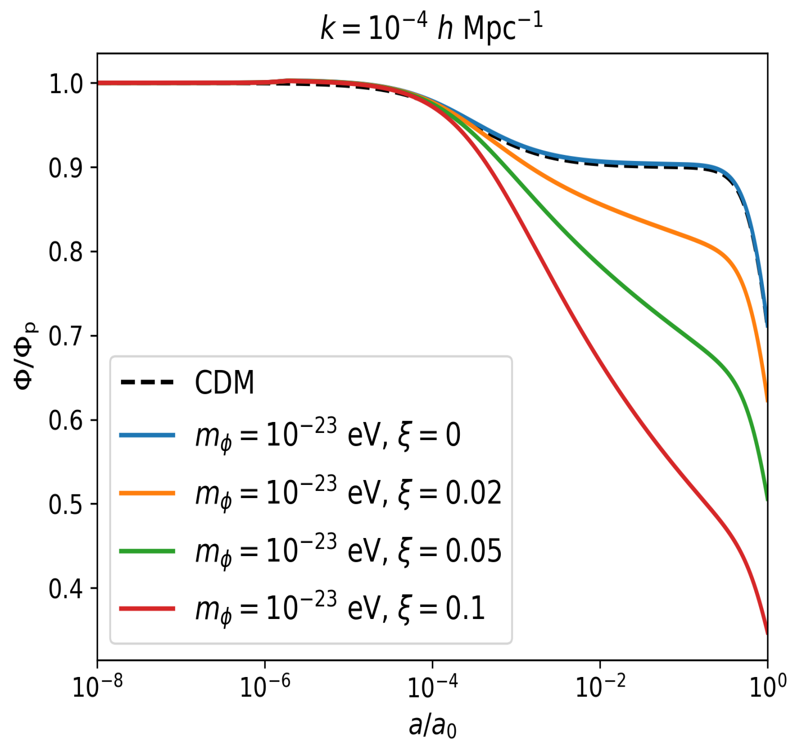
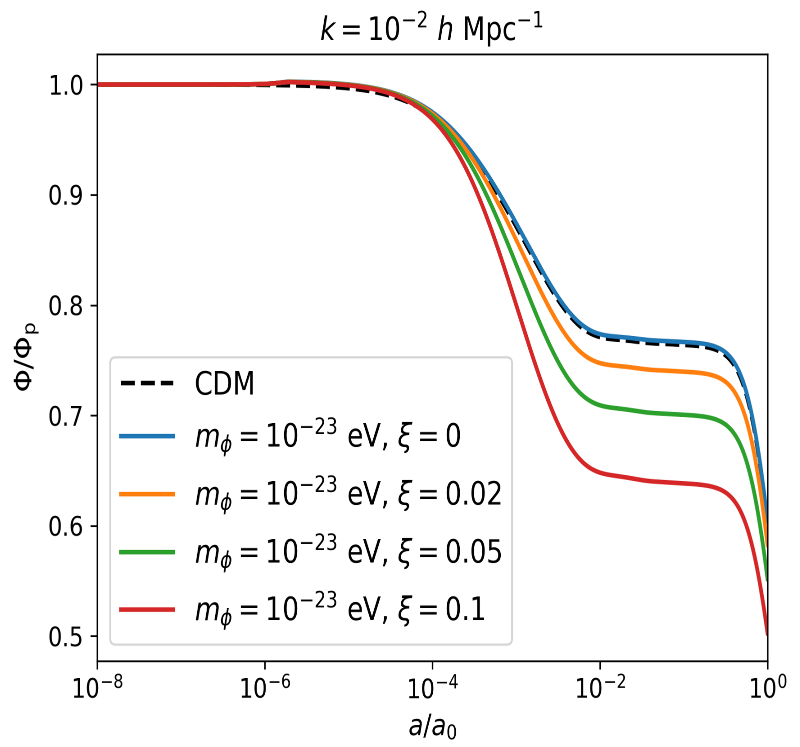
# 16. Large scale gravitational potential



# 17. Gravitational potential: intermediate scales



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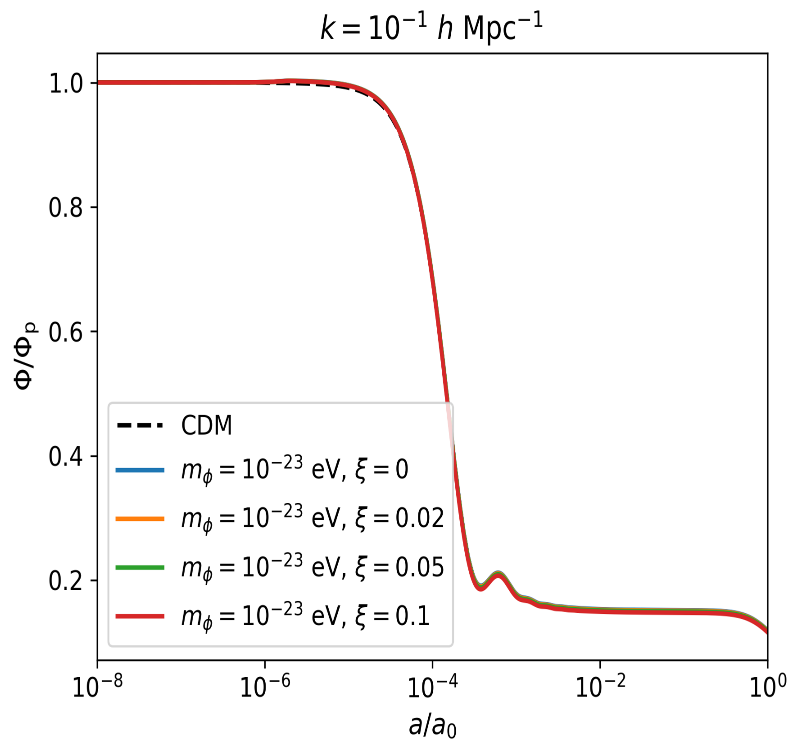
# 18. Gravitational potential: small scales



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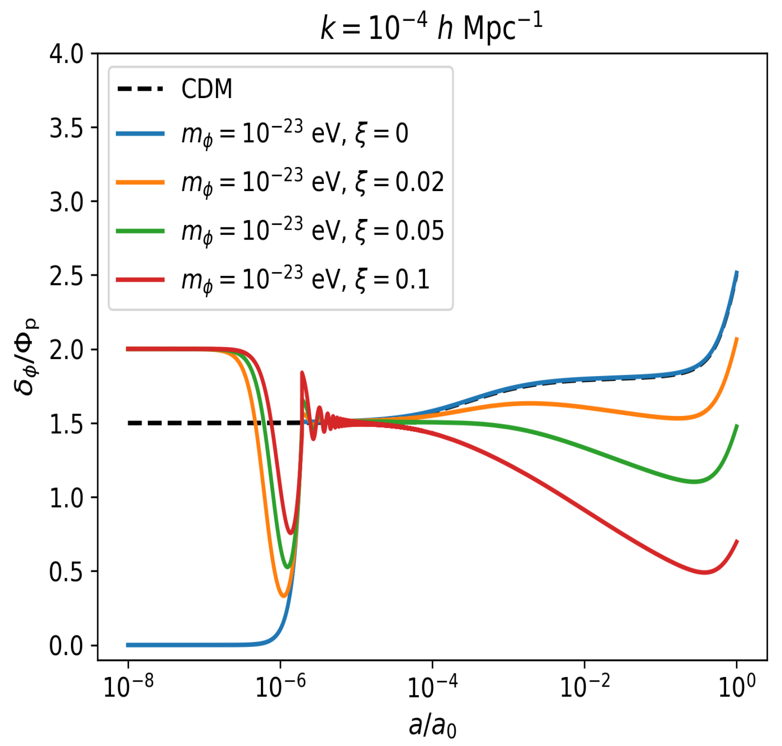
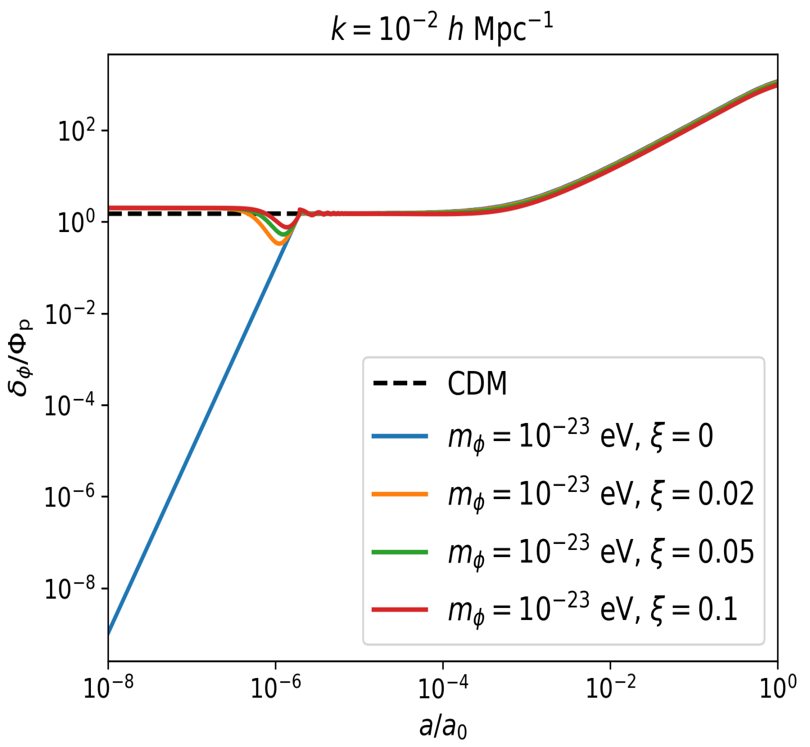
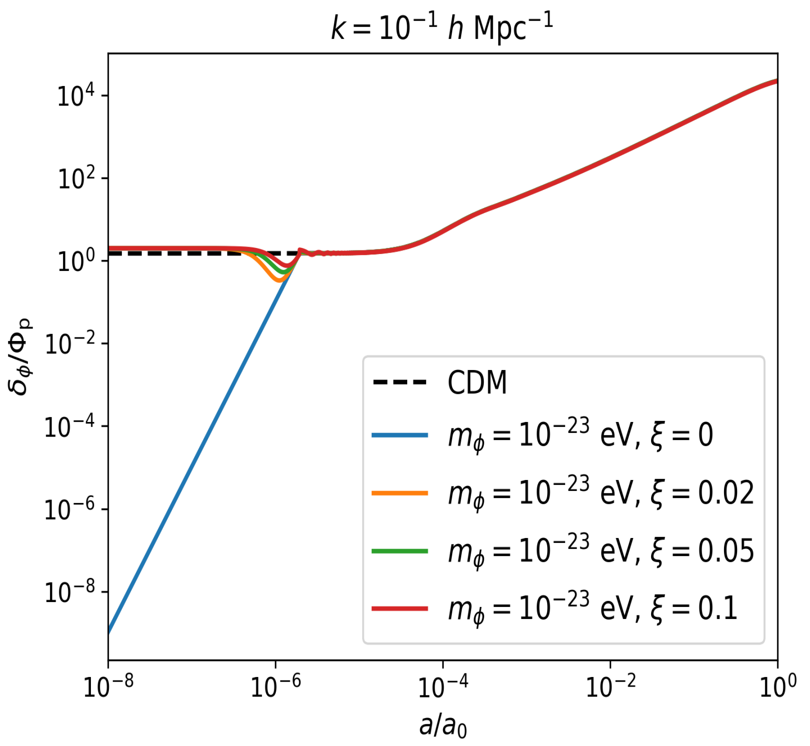
# 19. Large scale density contrast



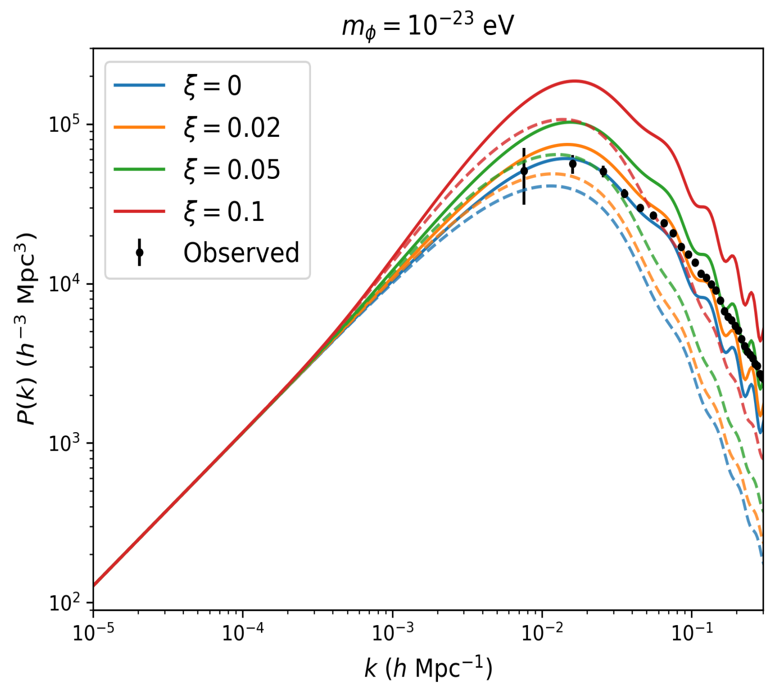
# 20. Density contrast: Intermediate scales



# 21. Density contrast: Small scales



# 22. Matter power spectrum: adiabatic and isocurvature modes



# 23. Summary and future prospects

- The nature of dark matter is still unknown, in spite of the success of ΛCDM model. Experimental searches have failed so far and there are issues with the model at small scales.

- Many cosmological observables at small scales constrain alternative dark matter models, e.g. Lyman-$\alpha$ data, collapsed fraction of HI at high redshifts.

- A classical scalar field can act as cold dark matter. In addition, it might result in suppression of small scale power which might be preferred by observations.

- A non-minimally coupled scalar field introduces new features at large scale which can be measured by large scale and CMB observation.