Setting up and diagnosing an exotic cosmological simulation

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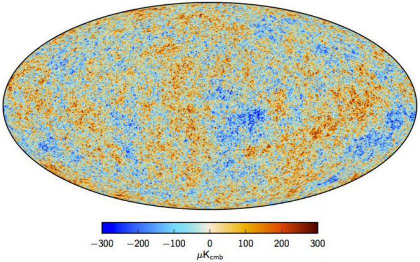
Introduction : the standard cosmological model ΛCDM

- Gravitation described by general relativity.
- Components of the model : baryons + cosmological constant (Λ) + cold dark matter (CDM) + radiation (photons and neutrinos)
- Universe homogeneous and isotropic
- Universe in expansion : $r(t) = a(t) \times L$, redshift $z = \frac{1}{1+a}$ with $r(t)$ the comoving distance and L the physical distance

Introduction : the standard cosmological model ΛCDM

- Universe homogeneous at large scale : Matter density contrast $\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \overline{\rho(\mathbf{x})}}{\overline{\rho(\mathbf{x})}} \ll 1$

$\overline{T} = 2.7$ K (today)



Credits : ESA

- The small inhomogeneities will be amplified by gravitation during ≈ 14 Gyr and lead to structure formation.

The development of gravitational instabilities

- Continuity equation :

$$\dot{\delta} + \frac{1}{a}\nabla\left((1+\delta)\mathbf{v}\right) = 0$$

- Euler equation :

$$\dot{\mathbf{v}} + H\mathbf{v} + \frac{1}{a}(\mathbf{v}\nabla)\mathbf{v} + \frac{1}{a}\nabla\phi = 0$$

- Poisson equation :

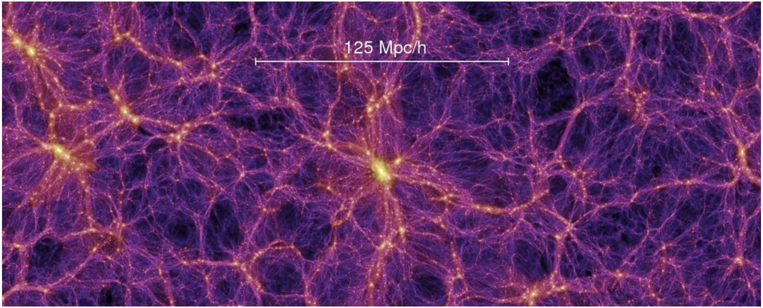
$$\Delta\phi - 4\pi G\overline{\rho}a^2\delta = 0$$

with $\mathbf{v}$ the speed of the dark matter fluid, ϕ the gravitational potential and $H = \frac{\dot{a}}{a}$ the Hubble constant

Order of magnitudes

- 1 parsec (pc) $\approx 10^{16}$ m,
- Galaxy $\approx$ 30 kpc,
- Cluster of galaxies $\approx$ 10 Mpc,
- Observable Universe $\approx$ 30 Gpc.

Here we are interested in scales between 10 and 500 Mpc.



Credits : Springel et. al (2005)

Cosmological observables

- Correlation function : $\zeta(r) = \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r})\rangle$
- Power spectrum : Fourier transform of the correlation function (measures the variance of δ)

$$P(k) = \int d^3\mathbf{r}\zeta(r)\exp(i\mathbf{k}\cdot\mathbf{r})$$

- σ_8 : dispersion of the density contrast in a sphere of radius $R_8 = 8\ h^{-1}$ Mpc* :

$$\sigma_8 = \left\langle \left(\frac{3}{4\pi R_8^3} \int_{|\mathbf{x}|<R_8} \delta(\mathbf{x}) \mathrm{d}^3\mathbf{x} \right)^2 \right\rangle^{1/2}$$

* : $h = \frac{H_0}{100 \text{ km/s/Mpc}} \approx 0.67$ is the reduced Hubble constant [Aghanim, 2020]

The S_8 tension [Abdalla, 2022]

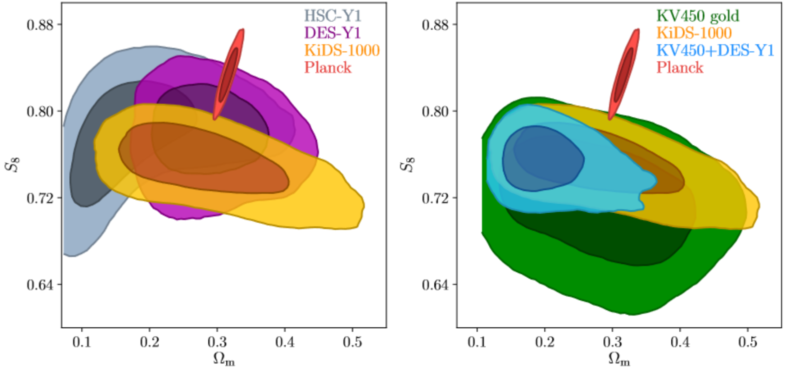
Study the distribution of matter in the Universe : measure $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$. Different methods :

- Cosmological microwave background : $S_8 = 0.84 \pm 0.030$ [Aiola, 2020],
- Large scale structure catalogs (count of galaxy clusters) : $S_8 = 0.789 \pm 0.012$ [Pratt, 2019]
- Gravitational lensing. $S_8 \approx 0.7781 \pm 0.0094$ [García-García, 2021]

These measures depend on the cosmological model used to interpret the data

The S_8 tension

$$S_8 = \sigma_8 \sqrt{\Omega_m/0.3}$$



Comparison of S_8 values using different methods [Asgari, 2021]

Goal of the internship

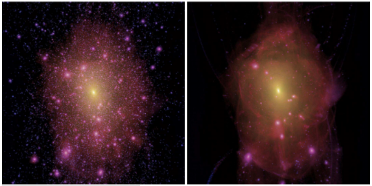
- The S_8 tension may suggest that some additional physics should be added to the ΛCDM model
- We will investigate exotic ingredients that modify small scale structures but leave the large scale structure invariant
- For scales smaller than ≈ 10 Mpc, we cannot linearize the equations of motion : numerical simulations
- Originality of our approach : We combine more than one extension of ΛCDM. These extensions are mutually not exclusive but are rarely tried together

Methodology

- N-body code RAMSES [Teyssier, 2002] to solve the equations of motion (total CPU time : 2400 hours)
- Initial conditions generated with the code MONOFONIC [Hahn, 2020]
- Box of 500 Mpc/h with a resolution of 256^3 pixels
- We assume baryons are collisionless (no hydrodynamics)
- Simulation of ΛCDM used as a reference to interpret the power spectra and the S_8 value of the exotic models.

Exotic Ingredient 1 : Warm dark matter

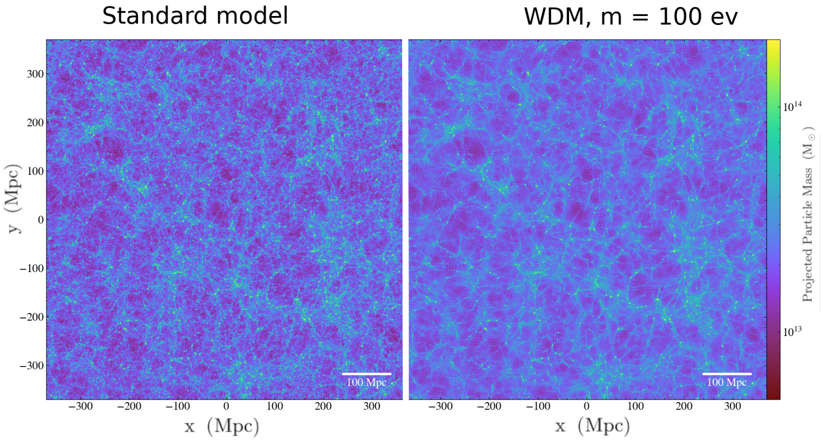
- Warm dark matter : dark matter that has an initial velocity after recombination, that depends of its mass [Bode, 2001].
- It will escape more easily gravitational potential wells : less small scale structures
- Characteristic size of suppressed structures [Peter, 2009] : $R \approx 0.2\ (\Omega_m h^2)^{1/3}\ (m/1\ \mathrm{keV})^{-4/3}$ Mpc
- Observational constraints :
  $m > 5{,}3$ keV
  [Palanque, 2020]



Credits : Angulo, 2021

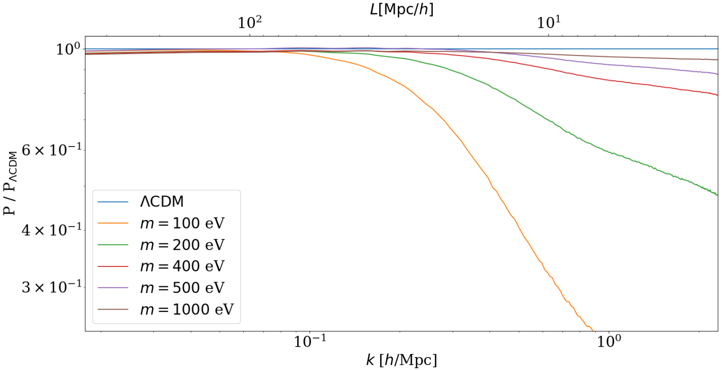
Exotic Ingredient 1 : Warm dark matter

Visualization at z = 0 :



Exotic Ingredient 1 : Warm dark matter

The lower the mass of warm matter, the more it reduces the power spectrum (z = 1 / 7 Gyr ago)



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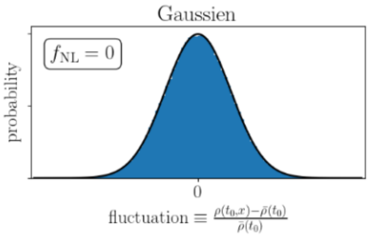
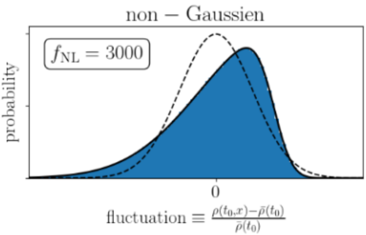
Exotic Ingredient 2 : Primordial non gaussianities





ΛCDM : the distribution of δ is assumed to be gaussian. Here we add a corrective term [Stahl, 2024] :

$$\Phi(\mathbf{k}) = \Phi_G(\mathbf{k}) + f_{NL}(\Phi_G^2(\mathbf{k}) - < \Phi_G^2 >),$$

$$\text{with } f_{NL}(k) = \frac{f_{NL}^0}{2\left(1 + \tanh\frac{k_{min}}{\sigma}\right)}\left(\tanh\frac{k_{min}}{\sigma} + \tanh\left(\frac{k - k_{min}}{\sigma}\right)\right)$$

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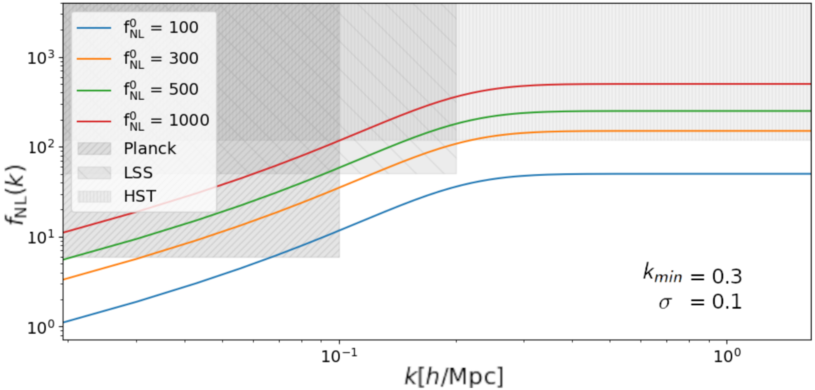
Exotic Ingredient 2 : Primordial non gaussianities

$$f_{NL}(k) = \frac{f_{NL}^0}{2\left(1 + \tanh\frac{k_{min}}{\sigma}\right)}\left(\tanh\frac{k_{min}}{\sigma} + \tanh\left(\frac{k - k_{min}}{\sigma}\right)\right)$$



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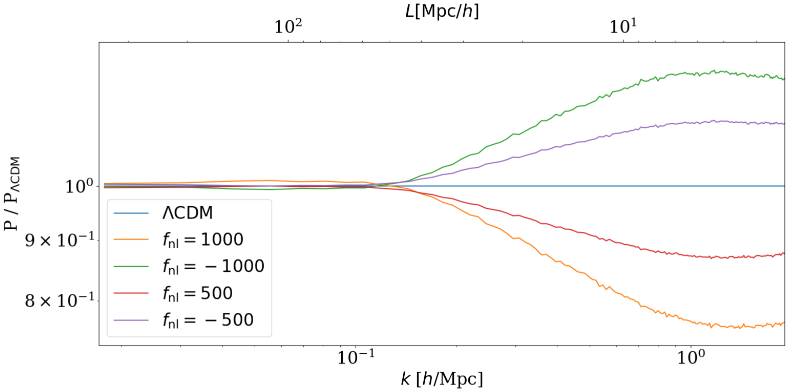
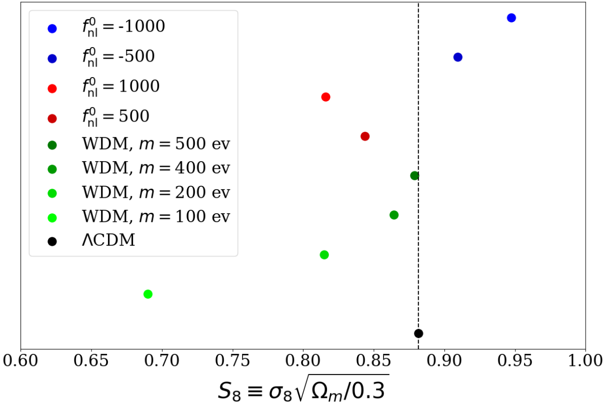
Exotic Ingredient 2 : Primordial non gaussianities

Different values of f_{NL}^0 favor over- or under-densities (z = 1)



S_8 estimation

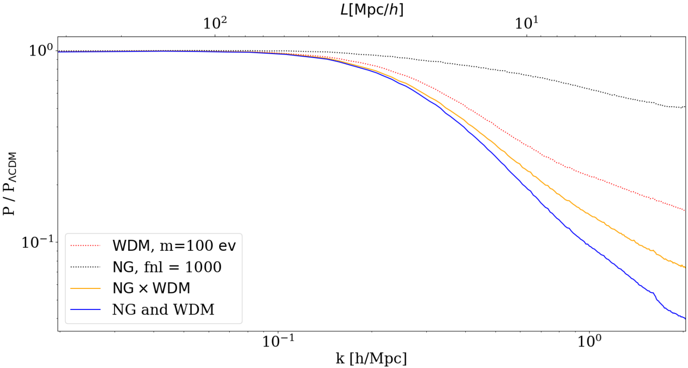
WDM decreases S_8, PNG can increase or decrease S_8 (z = 1)



Our original approach : WDM and PNG together

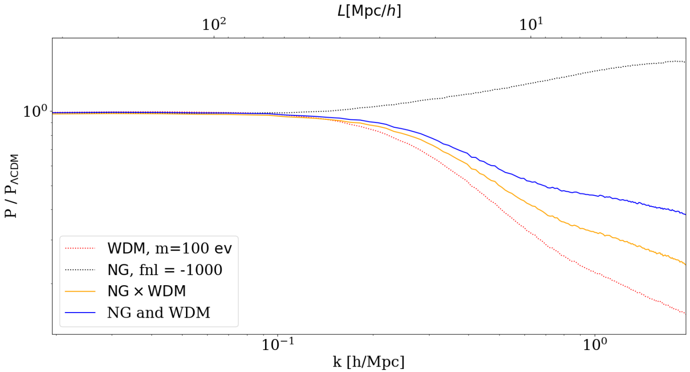
Combining the two parameters doesn't produce a linear response :
$P_{NG} \times P_{WDM} \neq P_{NG \text{ and } WDM}$

$m = 100$ eV, $f_{\rm NL}^{0} > 0$: non linearities accentuate structure suppression : "snowball effect"



Our original approach : WDM and PNG together

$m = 100$ eV, $f_{\rm NL}^0 < 0$: non linearities favorize the effect of non gaussianities over WDM



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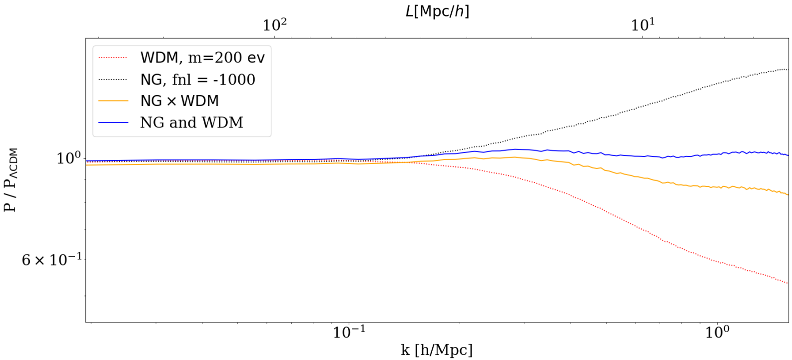
Our original approach : WDM and PNG together

$m = 200$ eV, $f_{\mathrm{NL}}^{0} < 0$: Power spectrum very similar to ΛCDM.



Conclusions

- Tensions such as S_8 are challenging the ΛCDM model and may be calling for new physics (warm dark mtter, primordial non gaussianities...)
- Using numerical simulations, we investigated the combined effect of WDM and PNG on structure formation
- Combining several extensions has not extensively been tried and may prove fruitful. In particular, constraints on warm dark matter may be overestimated
- We showed, when combining the two, that the non-linearities always tend to accentuate the effect of primordial non gaussianities over WDM.

References I

- Abdalla (2022).
  Cosmology intertwined : A review of the particle physics, astrophysics, and cosmology associated with the cosmological tensions and anomalies.
  Journal of High Energy Astrophysics.
- Aghanim (2020).
  Planck 2018 results-vi. cosmological parameters.
  Astronomy & Astrophysics.
- Aiola (2020).
  The atacama cosmology telescope : Dr4 maps and cosmological parameters.
  Journal of Cosmology and Astroparticle Physics, 2020.
- Asgari (2021).
  Kids-1000 cosmology : Cosmic shear constraints and comparison between two point statistics.
  Astronomy & ; Astrophysics.
- Bode (2001).
  Halo formation in warm dark matter models.
  The Astrophysical Journal.
- García-García (2021).
  The growth of density perturbations in the last 10 billion years from tomographic large-scale structure data.
  Journal of Cosmology and Astroparticle Physics.
- Hahn (2020).
  Music2-monofonic : 3lpt initial condition generator.
  Astrophysics Source Code Library.
- Palanque (2020).
  data.

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References II

- Peter (2009).
  Primordial cosmology.
  Oxford University Press.
- Pratt (2019).
  The galaxy cluster mass scale and its impact on cosmological constraints from the cluster population.
  Space Science Reviews.
- Stahl (2024).
  Scale-dependent local primordial non-gaussianity as a solution to the s_8 tension.
  arXiv preprint arXiv :2404.03244.
- Teyssier, R. (2002).
  Cosmological hydrodynamics with adaptive mesh refinement-a new high resolution code called ramses.
  Astronomy & Astrophysics.