Ultralight dark matter

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Cosmology 2018 in Dubrovnik

Outline

- Introduction
  - Coherent bosons in cosmology:
    Models for dark matter, dark energy, inflation,…
- Background evolution
  - Scalar fields
  - Vector fields
  - Spin-2 fields
- Dark graviton Phenomenpology:
  - Fifth-force experiments
  - Astrophysical constraints
  - Collider analysis
  - Cosmological signatures
- Conclusions

Scalar fields in cosmology

Coherent scalar fields are the standard candidates for solving cosmological unresolved questions as:

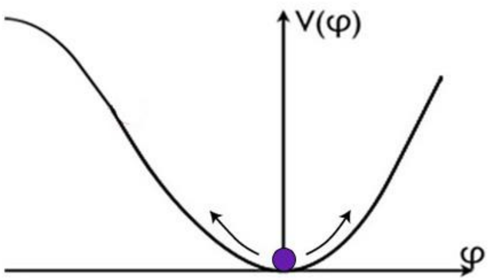
- Inflation: Inflaton.
- Dark matter: Axion and axion-like particles.
- Dark energy: quintessence, scalar-tensor theories of gravity,...

Simalar results can be provided by any bosonic field. Vector fields, and new vectors are maybe the best motivated theoretically.

Background evolutions

Scalar field DM

Homogeneous field (M. S. Turner, Phys. Rev. D 28 (1983) 6.)



$$V(\phi) = a\phi^n$$

$$\omega = \frac{n-2}{n+2}$$

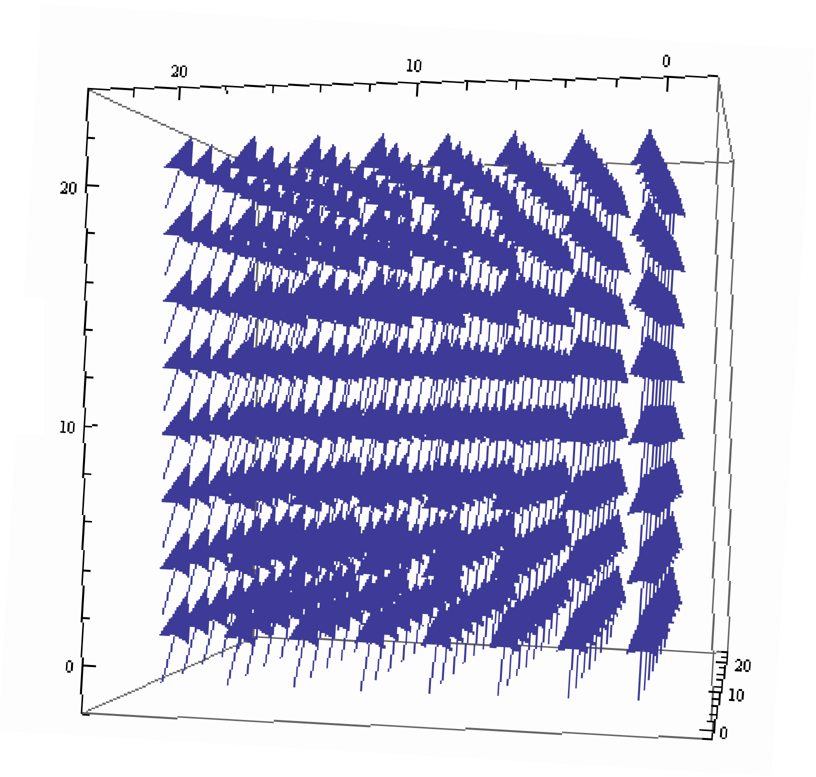
Average eq. of state

$n = 2$ matter

$n = 4$ radiation

The anisotropy problem

However, higher spin coherent oscillations are generally anisotropic. This fact can be in contradiction with the large isotropy of the universe as shown by the cosmic microwave background (CMB).



The anisotropy problem

There are different solutions in the literature:

- Using the scalar degree of freedom $\mathbf{A_0}$.

Beltran Jimenez, Maroto,   Phys. Rev. D78, 063005 (2008)

Beltran Jimenez, Maroto, JCAP 0903, 016 (2009)

- Particular solutions: Triads of orthogonal vectors.

H.H. Soleng, Astron. Atrophys. 237, 1 (1990)

Bento, Bertolami, Moniz, Mourao, Sa, Class. Quant. Grav. 10, 285 (1993)

- Large number, N, of **randomly oriented fields**. Reducing anisotropy in $\sqrt{N}$.

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- **Average isotropy** for a linear polarized Abelian vector coherent oscillation with potential $A_\mu A^\mu$.

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Isotropy theorem for Abelian vector fields

Abelian vector fields described by the action:

$$S = \int d^4x \sqrt{g} \left(-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V\left(A_\mu A^\mu\right) \right)$$

If the **field evolves rapidly** and $\boldsymbol{A_i}$ **,** $\boldsymbol{\dot{A}_i}$ **are bounded** during its evolution:

1.- **The energy momentum tensor is diagonal and isotropic in average.**

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Similar argument than for the Virial theorem in classical mechanics:

(for a FLRW background) ⟹

$$0 = \frac{G_{ij}(T) - G_{ij}(0)}{T} = \left\langle 2V'(A^2)\frac{A_i A_j}{a^2} \right\rangle + \left\langle \frac{\dot{A}_i \dot{A}_j}{a^2} \right\rangle$$

$$G_{ij} = \frac{\dot{A}_i A_j}{a^2}, \quad i, j = 1, 2, 3$$

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If the **field evolves rapidly** and $\boldsymbol{A_i}$ **,** $\boldsymbol{\dot{A}_i}$ **are bounded** during its evolution:

1.- **The energy momentum tensor is diagonal and isotropic in average.**

2.- **Under power law potentials, the equation of state parameter is constant:**

$$V = \lambda (A_\mu A^\mu)^n \quad \longrightarrow \quad \omega = \frac{\langle p \rangle}{\langle \rho \rangle} = \frac{n-1}{n+1}$$

JARC, Hallabrin, Maroto, Nunez Jareno, Phys. Rev. D86 (2012)

Isotropy theorem for Yang-Mills theories

Yang-Mills theories associated with semi-simple groups described by the action:

$$S = \int d^4x \sqrt{g} \left(-\frac{1}{4} F^a{}_{\mu\nu} F^{a\,\mu\nu} - V\left(A^a{}_\mu A^{a\,\mu}\right) \right)$$

If the **field evolves rapidly** and $\boldsymbol{A^a{}_i}$ **,** $\boldsymbol{\dot{A}^a{}_i}$ **are bounded** during its evolution,

1.- **The energy momentum tensor is diagonal and isotropic in average.**

2.- **Without potential, the equation of state parameter is w = 1/3 , i.e. it behaves as radiation.**

JARC, Maroto, Nunez Jareno, Phys. Rev. D87 (2013) 043523

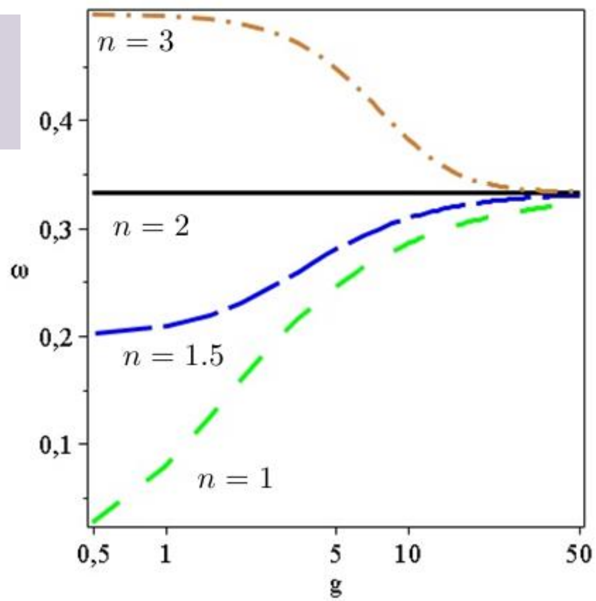
Example I: SU(2) theory

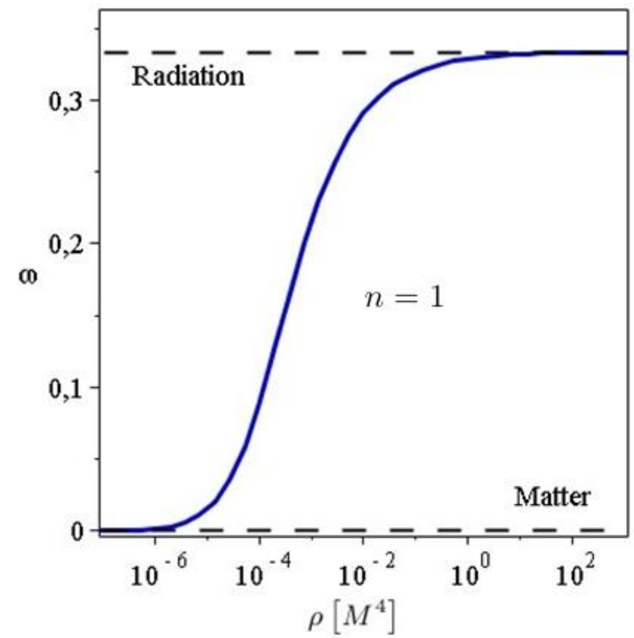
The self-interaction for non-Abelian theories changes the average equation of state. For high energy densities or large coupling constants it will behave as radiation, in the opposite limit, the Abelian behavior is recovered.

$$V = \frac{1}{2}(-M^2 A^a_\rho A^{a\ \rho})^n$$

$$\boldsymbol{g \downarrow,\ \rho \downarrow}$$
$$\boldsymbol{\omega = \frac{n-1}{n+1}}$$

$$\boldsymbol{g \uparrow,\ \rho \uparrow}$$
$$\boldsymbol{\omega = \frac{1}{3}}$$





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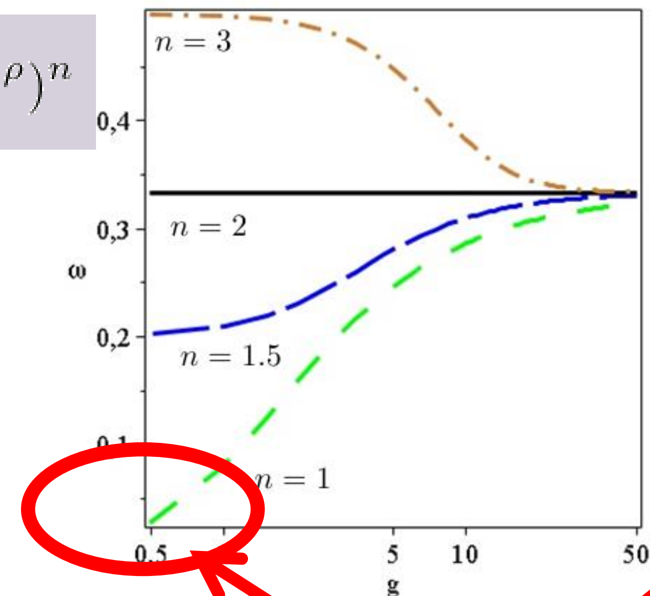
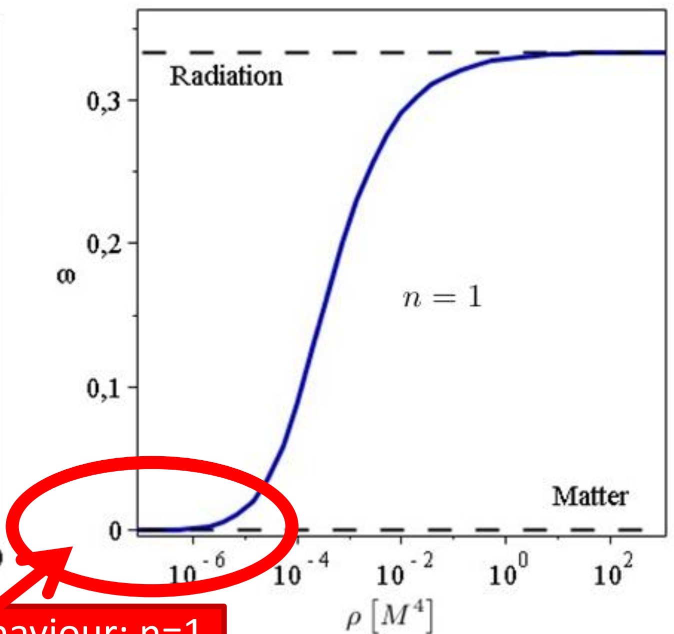




DARK MATTER behaviour: n=1

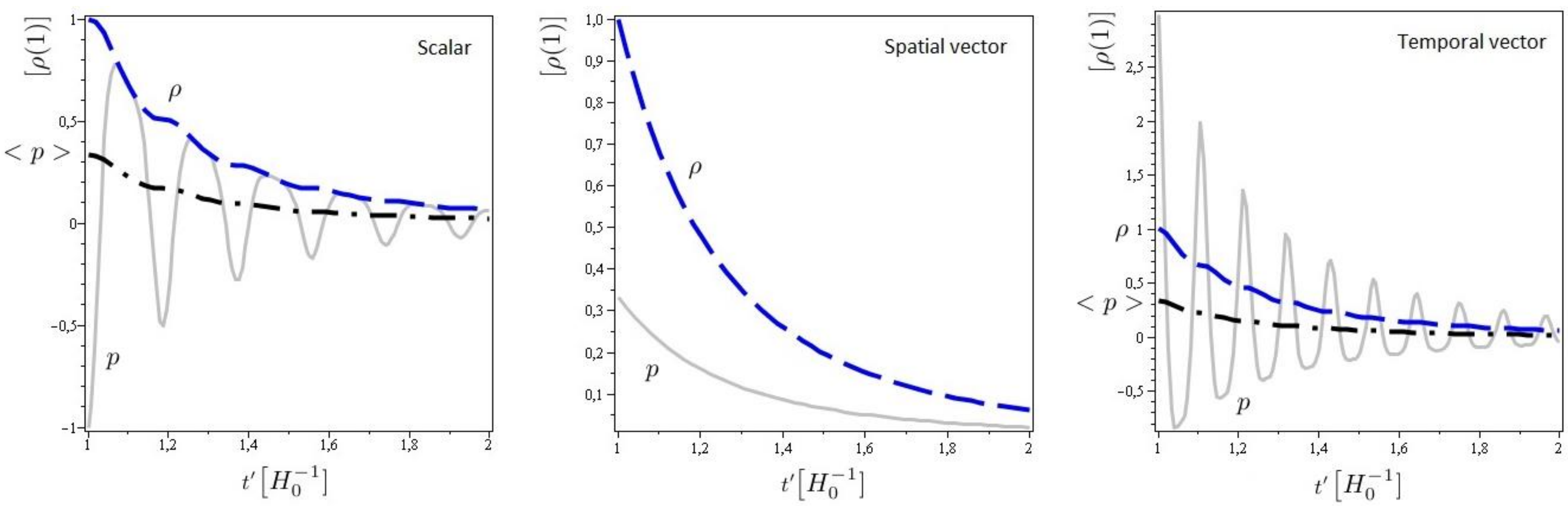
JARC, Maroto, Nunez Jareno, Phys. Rev. D87 (2013) 043523

Example II: n=2

For a power law potential, the equation of state of the average energy is the same for: scalar, Abelian vectors, spatial and temporal Non-Abelian vector components (by assuming a negligible self-interactions).

$$V = \frac{1}{2}(-M^2 A_\rho A^\rho)^n \longrightarrow \omega = \frac{n-1}{n+1}$$

Although their evolutions are very different:



JARC, Maroto, Nunez Jareno, Phys. Rev. D87 (2013) 043523

Isotropy theorem (arbitrary spin)

Rapid evolving coherent fields do not suffer from constraining requirements from cosmological isotropy.

Isotropy Theorem: The average Energy-Momentum tensor of a field of any spin minimally coupled to gravity is diagonal and isotropic if

1.- the field evolves rapidly:

with respect to the background metric evolution.

with respect to spatial variations.

2.- $\phi^a{}_i$ and $\dot{\phi}^a{}_i$ remain bounded during the evolution

JARC, Hallabrin, Maroto, Nunez Jareno, Phys. Rev. D86 (2012)

JARC, Maroto, Nunez Jareno, Phys. Rev. D87 (2013) 043523

General Results (spin independent)

Homogeneous field (J.A.R. Cembranos, A.L.M., S.J. Núñez Jareño, JCAP 1403 (2014) 042)

Homogeneous fields with non-zero spin break isotropy, but:

$$\mathcal{L} \equiv \mathcal{L}\left[\phi^A, \partial_\mu \phi^A\right]$$

ϕ_A and $\dot{\phi}_A$ bounded

$$\omega_A^{-1} \ll T \ll H^{-1}$$

For **rapidly oscillating fields**, virial theorem ensures diagonal and isotropic energy-momentum tensor in average

Power-law theories:

$$\mathcal{H} = \left(\lambda^{AB} g_{00} \Pi_A^0 \Pi_B^0\right)^{n_T} + \left(M_{AB}\phi^A\phi^B\right)^{n_V}$$

Average equation of state:

$$\omega = \frac{2\, n_V}{1 + \frac{n_V}{n_T}} - 1$$

Spin-2 Fields

Massive gravitons appear naturally in theories with large extra dimensions and other modications of gravity:

- Arkani-Hamed-Dimopoulos-Dvali (ADD) model.
- Randall-Sundrum model.
- Bimetric gravity.

$$\begin{matrix}\text{GR} \\ \text{(Einstein-Hilbert)}\end{matrix} \quad + \quad \begin{matrix}\text{Massive spin 2} \\ \text{(Fierz-Pauli)}\end{matrix}$$

Dark Gravitons

Example: **Spin 2 DM**

Spin 2. Massive gravitons as wave DM
(Cembranos, A.L.M., Núñez Jareño, JCAP 1403 (2014) 042)

Fierz-Pauli Lagrangian

$$\mathcal{L} = \frac{M_{Pl}^2}{8}\Big[\nabla_\alpha h^{\mu\nu}\nabla^\alpha h_{\mu\nu} - 2\nabla_\alpha h^\alpha_\mu \nabla_\beta h^{\mu\beta} + 2\nabla_\alpha h^\alpha_\mu \nabla^\mu h^\beta_\beta - \nabla_\alpha h^\mu_\mu \nabla^\alpha h^\nu_\nu - m_g^2\left(h_{\mu\nu}h^{\mu\nu} - \left(h^\mu_\mu\right)^2\right)\Big] .$$

Average equation of state:

$$\omega = \frac{2n_V}{1+\frac{n_V}{n_T}} - 1 = 0$$

Higher-spin DM

Example: **Spin 2 DM**

Spin 2. Massive gravitons as wave DM
(Cembranos, A.L.M., Núñez Jareño, JCAP 1403 (2014) 042)

Fierz-Pauli Lagrangian

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Condensate of massive graviton and dark matter, K. Aoki and K. Maeda, arXiv:1707.05003 [hep-th]

Oscillating spin-2 Dark Matter, L. Marzola, M. Raidal, and F. R. Urban, arXiv:1708.04253 [hep-ph]

Dark Graviton Phenomelogy

- Fith-force experiments
- Astrophysical constraints
- Collider analysis
- Cosmological signatures

Fith-force Experiments

$$\mathcal{L} = \frac{1}{2} h^{\mu\nu} \mathcal{O}^{\alpha\beta}{}_{\mu\nu} h_{\alpha\beta} + \kappa h_{\mu\nu} T^{\mu\nu} \ ,$$

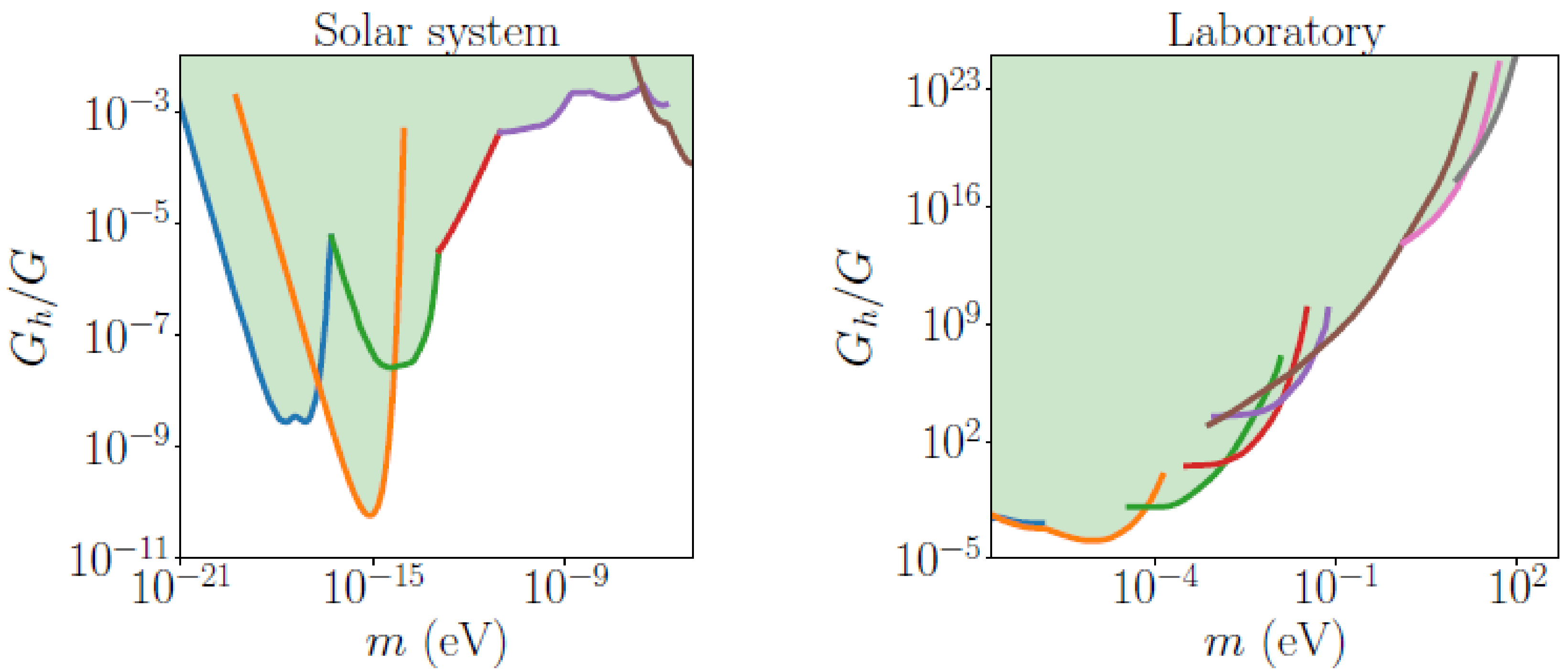
Fifth-force between two non-relativistic sources

$$V = -\frac{4}{3}\kappa^2 M_1 M_2 \frac{\mathrm{e}^{-mr}}{8\pi r}, \qquad r = |\mathbf{x}_1 - \mathbf{x}_2| \ .$$

Total gravitational force = GR + Fierz-Pauli

$$V(r) = -\frac{G M_1 M_2}{r}\left(1 + \frac{4}{3}\frac{G_h}{G}\mathrm{e}^{-mr}\right) , \qquad \kappa \equiv 1/M_h \equiv \sqrt{8\pi G_h}$$

Fith-force Experiments



$$V(r) = -\frac{GM_1M_2}{r}\left(1 + \alpha e^{-r/\lambda}\right), \qquad \alpha = \frac{4}{3}\frac{G_h}{G}, \ \lambda = 1/m$$

Astrophysical Constraints

New light, weakly interacting particle $\rightarrow$ Modified energy-loss rate

Fruitfully applied to

- Axions
- Hidden photons
- ADD gravitons
- ...

Approach

1. Choose interaction and identify relevant processes.
2. Compute the matrix element for each process using QFT.
3. Compute the energy-loss rate using the Boltzmann equation.
4. Apply the results to the stellar-medium conditions.

Astrophysical Constraints

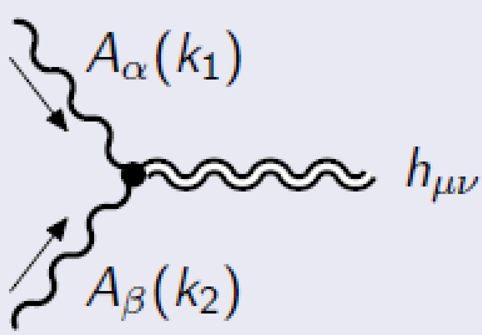
Coupling of the hidden gravitons $h_{\mu\nu}$ to the plasma through the QED energy-momentum tensor

$$\mathcal{L}_{\rm QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(\mathrm{i}\not{D} - m)\psi \ , \qquad D_\mu = \partial_\mu + \mathrm{i}qA_\mu \ ,$$

$$T^{\rm QED}_{\mu\nu} = F_{\mu\alpha}F_\nu{}^\alpha + \frac{\mathrm{i}}{2}\left[\bar{\psi}\gamma_{(\mu}D_{\nu)}\psi - (D_{(\mu}\bar{\psi})\gamma_{\nu)}\psi\right] + \eta_{\mu\nu}\mathcal{L}_{\rm QED} \ ,$$

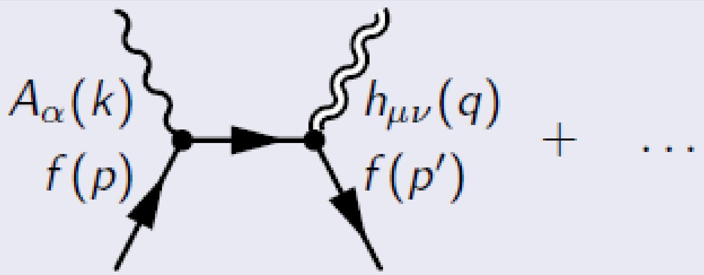
The simplest process is

$\gamma + \gamma \to G$

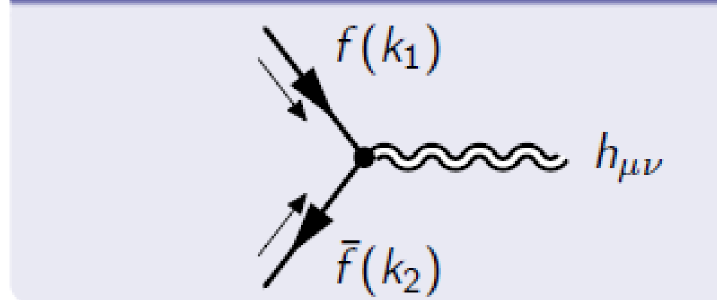


Astrophysical Constraints

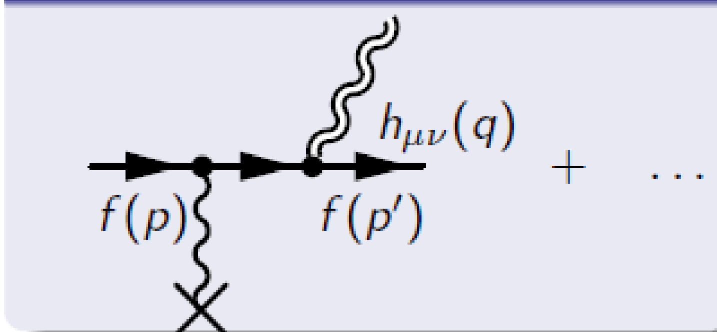
$\gamma + e^- \to G + e^-$



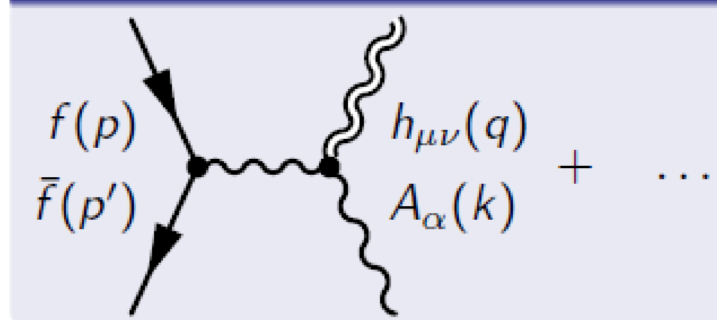
$e^- + e^+ \to G$



$e^- + \text{EF} \to e^- + G$



$e^- + e^+ \to \gamma + G$



+ Nucleon-nucleon bremsstrahlung, $NN \to NN + G$

Astrophysical Constraints

Additional channels of energy loss modify the evolution of different sources.

Limits on the emissivity $\epsilon \equiv Q/\rho$,

- *Sun* ($T = 1.3$ keV). Modification of the age of the Sun

$$\epsilon < 1 \text{ erg g}^{-1} \text{ s}^{-1}$$

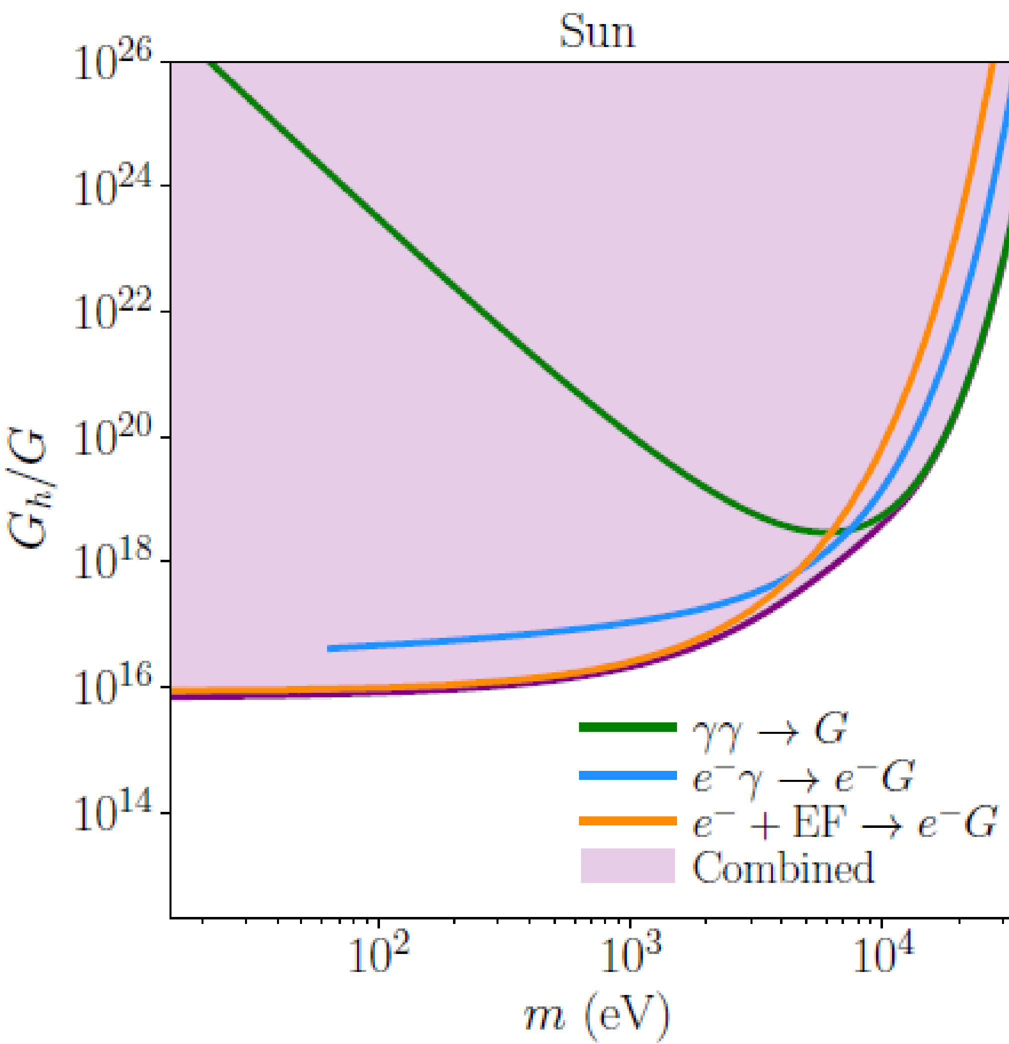
- *Red Giants* ($T = 8.6$ keV). Delay of the ignition of helium

$$\epsilon < 10 \text{ erg g}^{-1} \text{ s}^{-1}$$

- *Supernova 1987A* ($T = (40 - 60)$ MeV). Shortening of the neutrino signal

$$\epsilon < 10^{19} \text{ erg g}^{-1} \text{ s}^{-1}$$

Astrophysical Constraints



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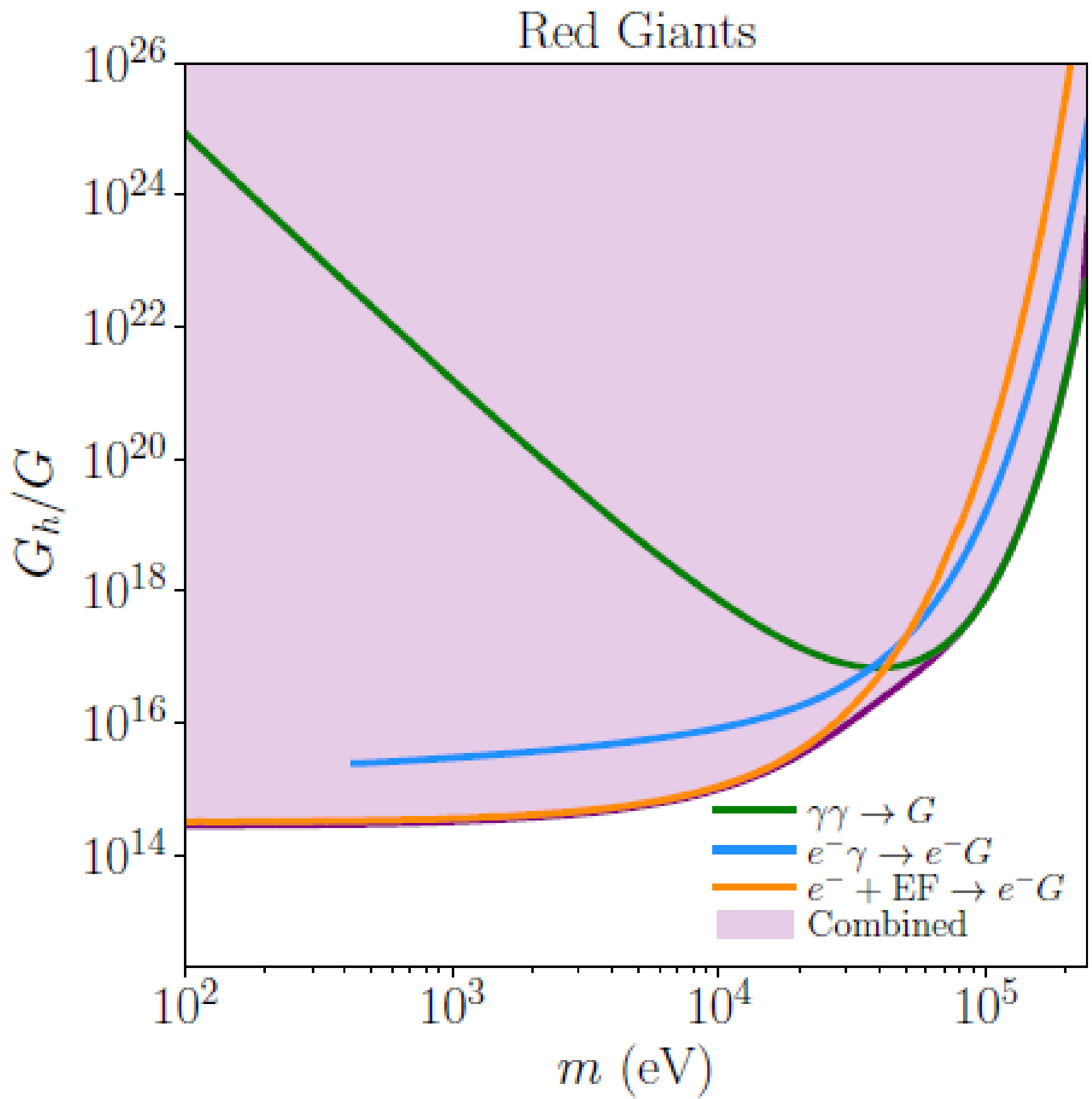

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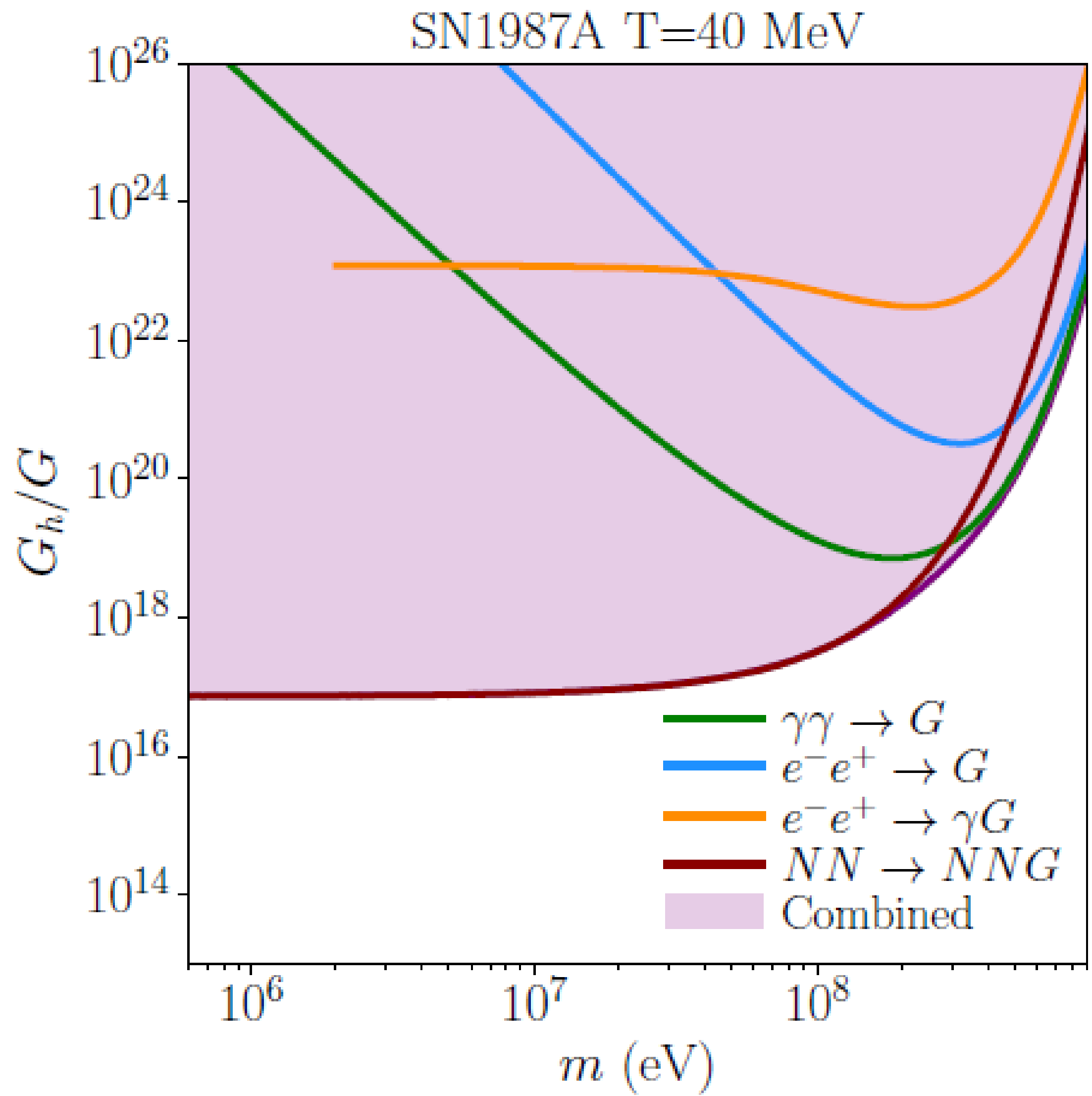
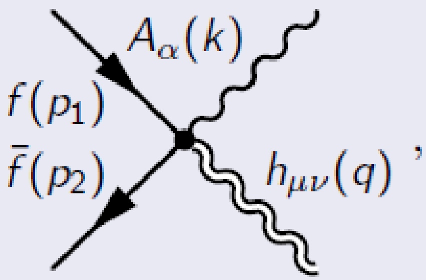


Collider Analyses

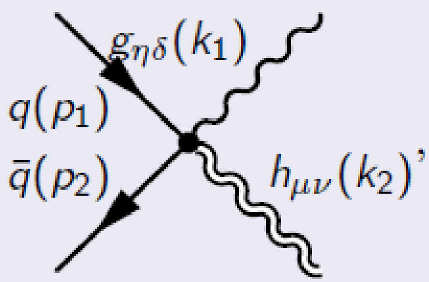
- We consider LHC processes with an energetic jet + large missing transverse momentum.
- Looking for the generation of gravitons through the processes:

$f\bar{f} \to \gamma G$



$$\frac{d\sigma}{dt} = \frac{\alpha Q_f^2}{16 N_f} \frac{1}{s M_h^2} F_1(t/s, m^2/s)$$

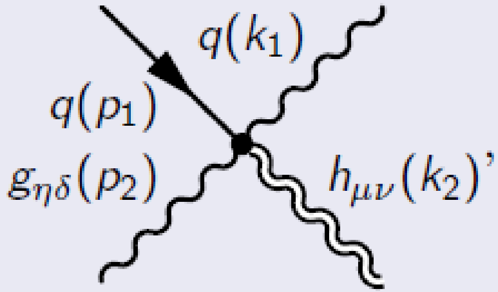
$q\bar{q} \to gG$



$$\frac{d\sigma}{dt} = \frac{\alpha_s}{36} \frac{1}{s M_h^2} F_1(t/s, m^2/s)$$

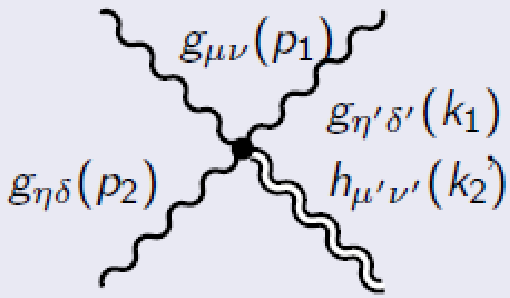
Collider Analyses

$q\bar{g} \rightarrow qG$



$$\frac{d\sigma}{dt} = \frac{\alpha_s}{96}\frac{1}{sM_h^2}F_2(t/s, m^2/s)$$

$gg \rightarrow gG$



$$\frac{d\sigma}{dt} = \frac{\alpha_s}{16}\frac{1}{sM_h^2}F_3(t/s, m^2/s)$$

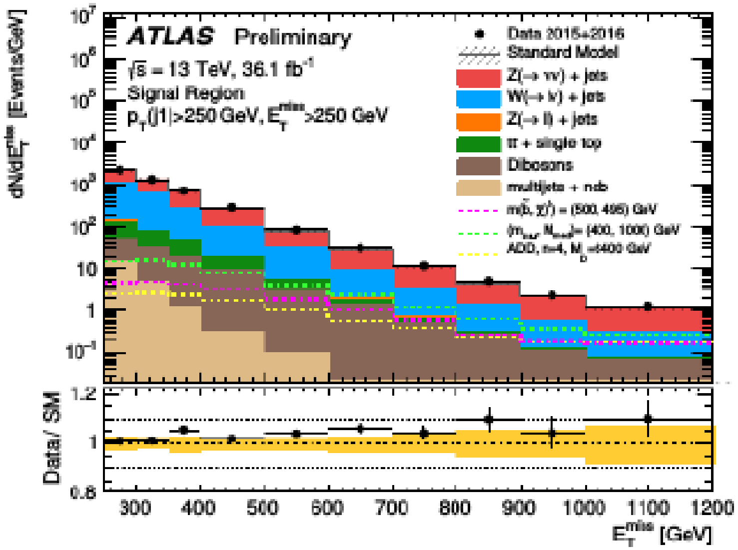
Collider Analyses

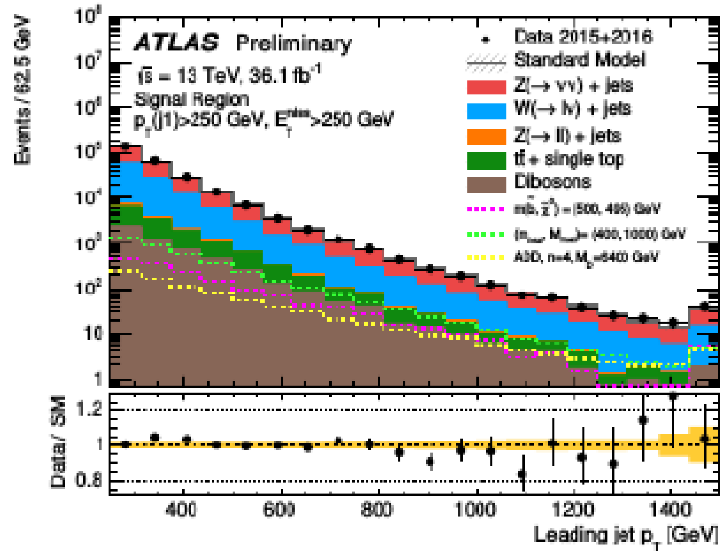
- ATLAS refs.: CERN-EP-2016-075, ATLAS-CONF-2017-060. Search for DM models and exotica.
- Experimental cuts:
  - $\mathcal{L} = 36.1\,\mathrm{fb}^{-1}$
  - $E_T^{\mathrm{miss}} > 250\,\mathrm{GeV}$
  - Leading jet: $p_t > 250\,\mathrm{GeV}$, $|\eta| < 2.4$
  - Max. 4 jets with $p_t > 30\,\mathrm{GeV}$, $|\eta| < 2.8$
  - $\Delta\phi(\mathrm{jet}, \vec{p}_T^{\,\mathrm{miss}}) > 0.4$ for the selected jets.
- PYTHIA 8+DELPHES+ROOT, used for simulating this analysis.

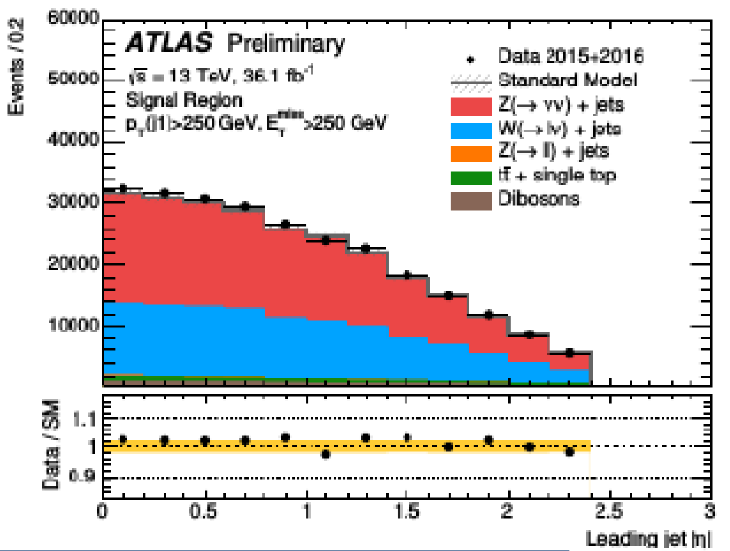
Table 1: Inclusive (IM1–IM10) and exclusive (EM1–EM10) signal regions with increasing $E_{\mathrm{T}}^{\mathrm{miss}}$ thresholds from 250 GeV to 1000 GeV. In the case of IM10 and EM10, both signal regions contain the same selected events in data. In the case of the IM10, the background predictions are computed considering only data and simulated events with $E_{\mathrm{T}}^{\mathrm{miss}} > 1$ TeV, whereas the EM10 background prediction is obtained from fitting the full $E_{\mathrm{T}}^{\mathrm{miss}}$ shape in data and simulation (see Section 6).

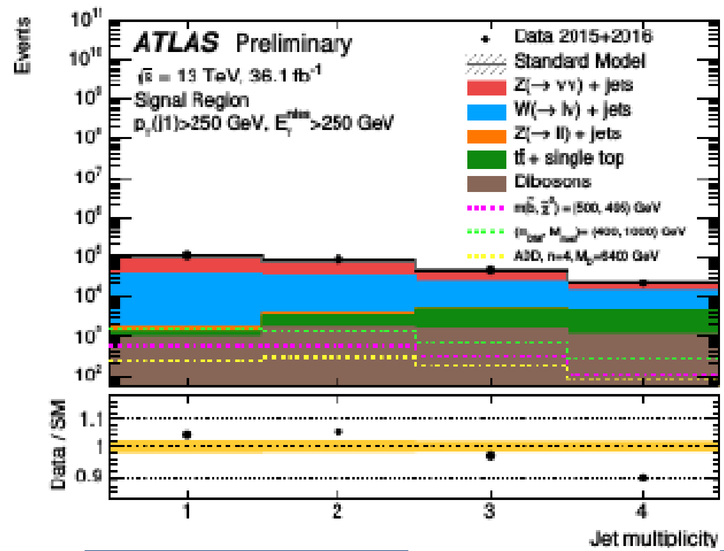
Inclusive (IM)	IM1	IM2	IM3	IM4	IM5	IM6	IM7	IM8	IM9	IM10
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	>250	>300	>350	>400	>500	>600	>700	>800	>900	>1000
Exclusive (EM)	EM1	EM2	EM3	EM4	EM5	EM6	EM7	EM8	EM9	EM10
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	250–300	300–350	350–400	400–500	500–600	600–700	700–800	800–900	900–1000	>1000

Collider Analyses

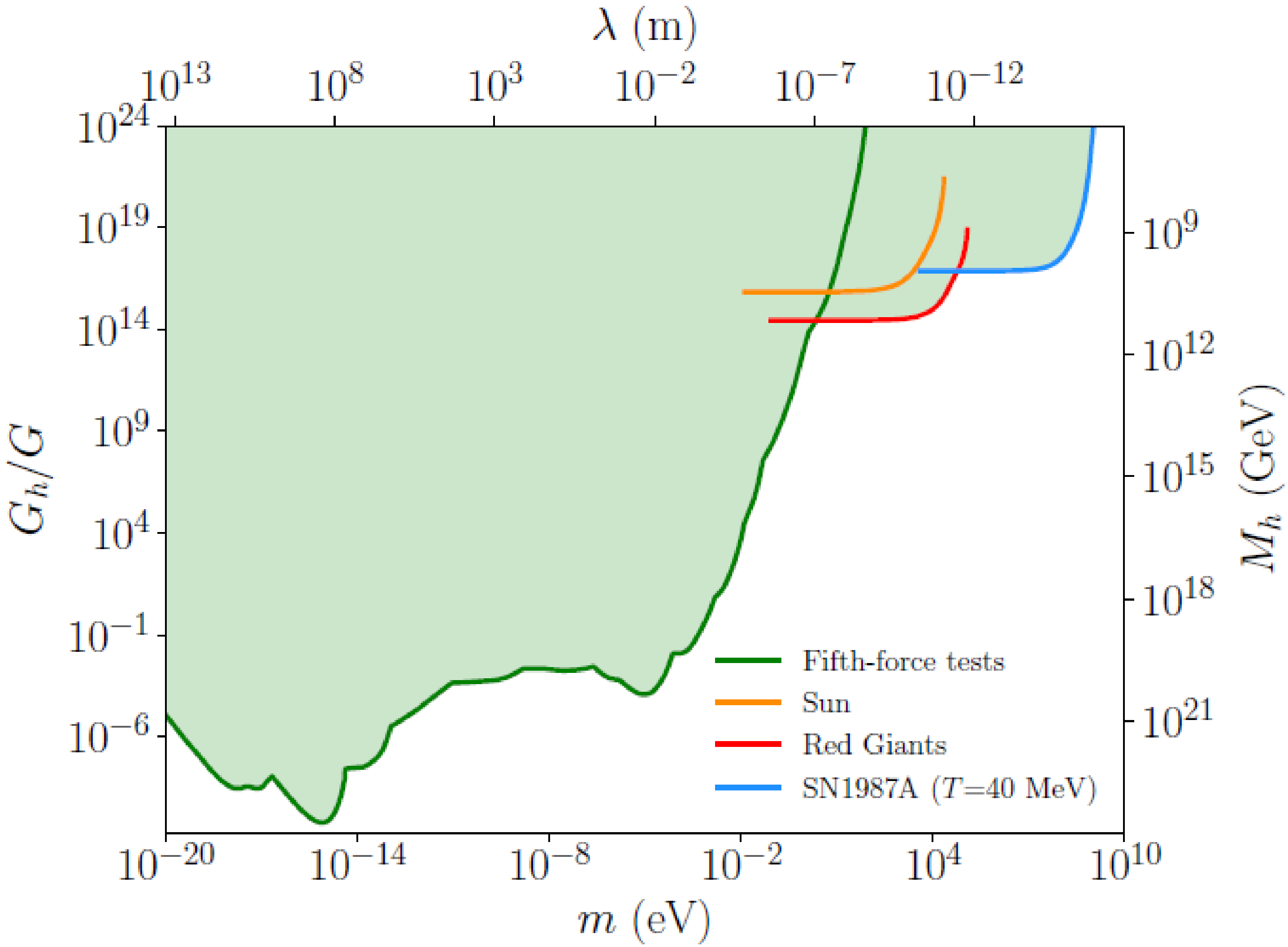






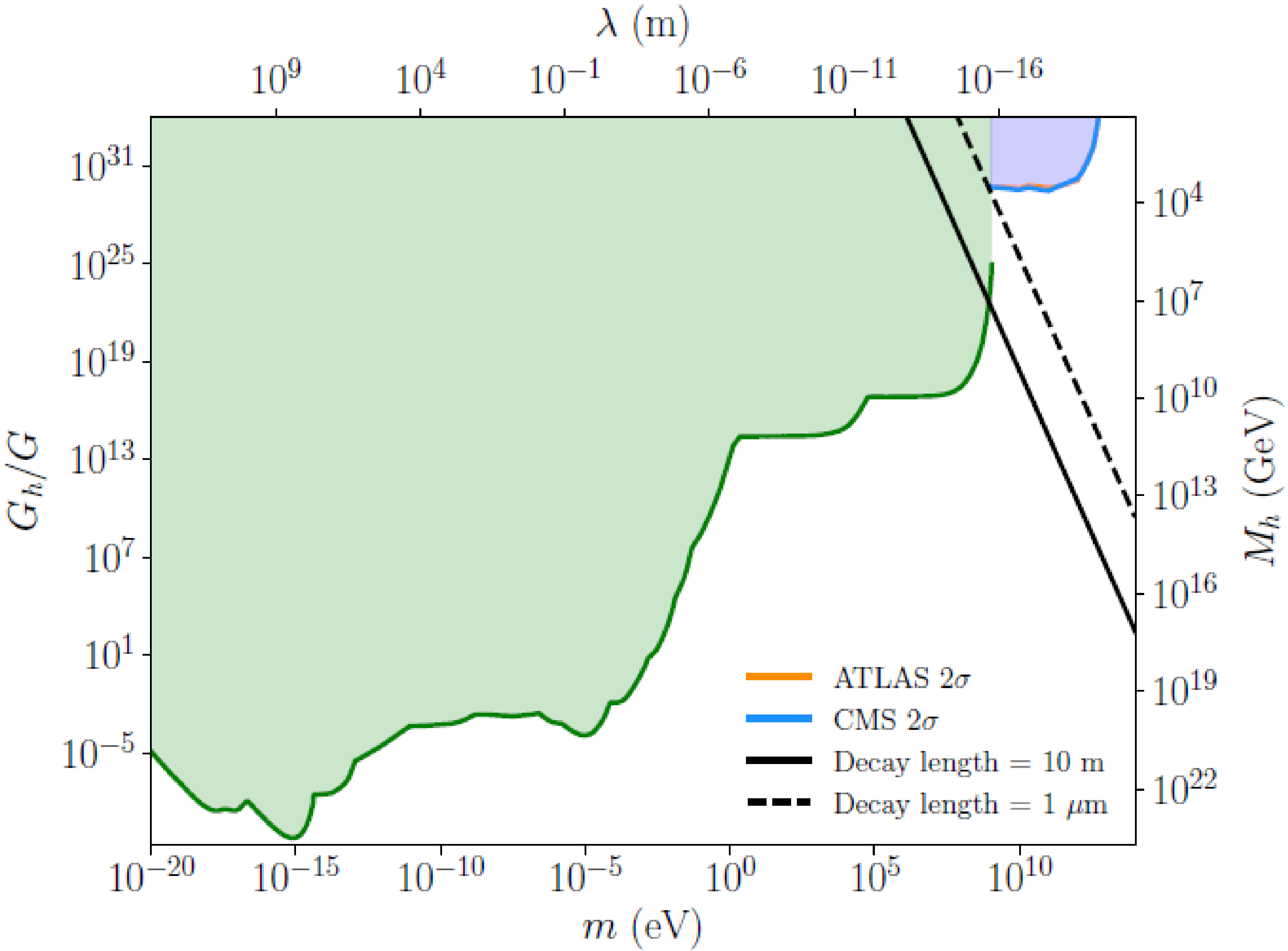


Results



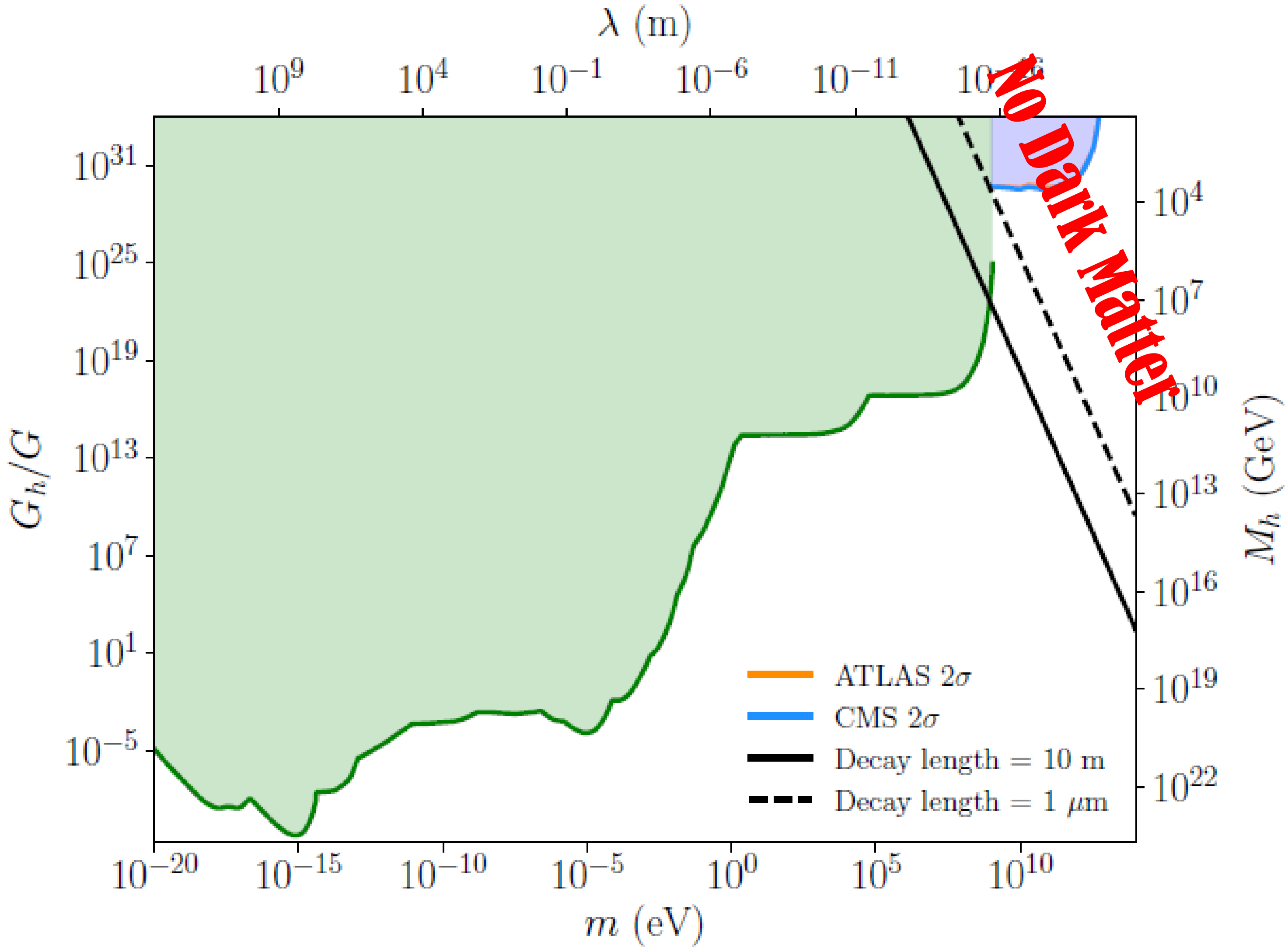
λ (m)
10^{13}
10^{8}
10^{3}
10^{-2}
10^{-7}
10^{-12}
10^{24}
10^{19}
10^{14}
10^{9}
10^{4}
10^{-1}
10^{-6}
G_h/G
10^{9}
10^{12}
10^{15}
10^{18}
10^{21}
M_h (GeV)
Fifth-force tests
Sun
Red Giants
SN1987A (T=40 MeV)
10^{-20}
10^{-14}
10^{-8}
10^{-2}
10^{4}
10^{10}
m (eV)

Results



λ (m)
10^9
10^4
10^{-1}
10^{-6}
10^{-11}
10^{-16}
G_h/G
10^{31}
10^{25}
10^{19}
10^{13}
10^7
10^1
10^{-5}
M_h (GeV)
10^4
10^7
10^{10}
10^{13}
10^{16}
10^{19}
10^{22}
ATLAS 2σ
CMS 2σ
Decay length = 10 m
Decay length = 1 μm
10^{-20}
10^{-15}
10^{-10}
10^{-5}
10^0
10^5
10^{10}
m (eV)

Results



λ (m)
10^9
10^4
10^{-1}
10^{-6}
10^{-11}
10^{-16}
No Dark Matter
G_h/G
10^{31}
10^{25}
10^{19}
10^{13}
10^7
10^1
10^{-5}
M_h (GeV)
10^4
10^7
10^{10}
10^{13}
10^{16}
10^{19}
10^{22}
ATLAS 2σ
CMS 2σ
Decay length = 10 m
Decay length = 1 μm
10^{-20}
10^{-15}
10^{-10}
10^{-5}
10^0
10^5
10^{10}
m (eV)

Cosmological signatures: Perturbations

$$ds^2 = a(\eta)^2 \left[(1 + 2\Phi(\eta, \vec{x}))\, d\eta^2 - ((1 - 2\Psi(\eta, \vec{x}))\, \delta_{ij} + h_{ij}(\eta, \vec{x}))\, dx^i dx^j - 2Q_i(\eta, \vec{x}) d\eta dx^i \right]$$

Small Scale Structure

- Most of the DM models based on a **particle** description of the DM candidates

- Small-scale "issues" :

  a) missing satellite, b) too-big-to-fail, c) cusp-core

- Solutions proposed: a) baryonic physics effects,

  b) alternative DM models: warm, self-interacting, decaying DM,…

- Another solution **wave dark matter ΨDM** (Sin, PRD 50, 3650 (1994), Guzmán-Matos, CQG 17, L9 (2000)) also known as **fuzzy DM** (Hu et al, PRL85, 1158 (2000))

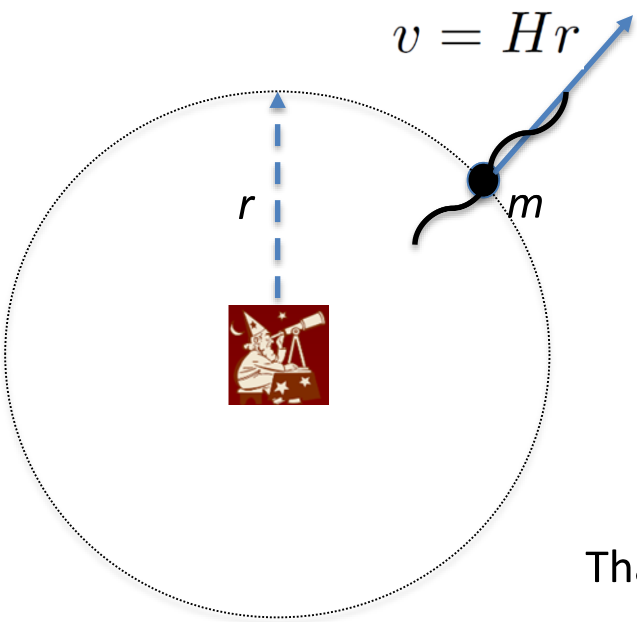
- Existing wave DM models based on ultralight axions or axion-like particles ($m_a \sim 10^{-22}$ eV). What about higher-spin wave DM?

Particle DM vs. Wave DM

Heuristic interpretation (Hu et al, PRL85, 1158 (2000), Hlozek et al, PRD 91 103512 (2015))

Consider a particle of mass *m* << 1 eV moving with the Hubble flow *H*

Important quantum effects at small scales for very light particles



The corresponding de Broglie wavelength:

$$\lambda_{\mathrm{dB}} = \frac{1}{mv} = \frac{1}{mHr}$$

Thus, the particle can be localized only in a sphere with radius:

$$r \geq \lambda_{\mathrm{dB}} \Longrightarrow r \geq \frac{1}{\sqrt{Hm}}$$

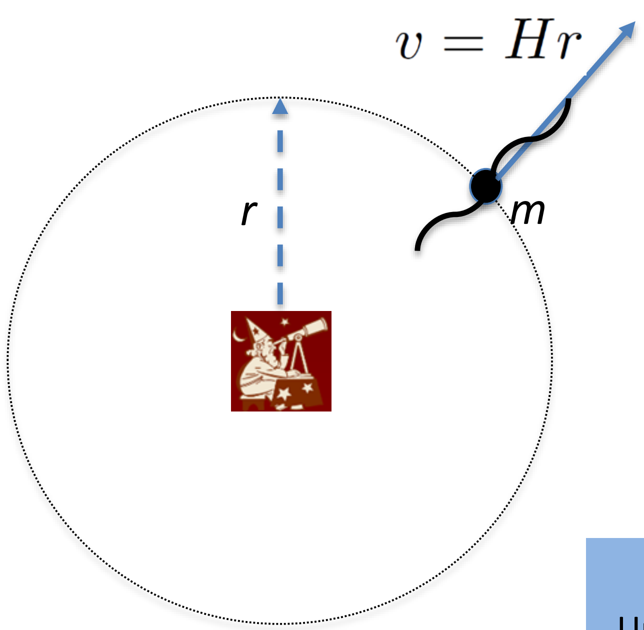
That corresponds to a (physical) wavenumber k=π/r

$$k_{\star} = \pi\sqrt{mH}$$

Particle DM vs. Wave DM

Heuristic interpretation (Hu et al 2000, Hlozek et al, PRD 91 103512 (2015))

Consider a particle of mass *m* << 1 eV moving with the Hubble flow *H*



Thus, we have:

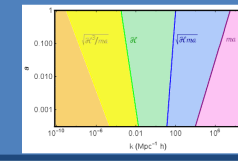
$$k < \pi\sqrt{Hm}$$ particle-like behaviour

$$k > \pi\sqrt{Hm}$$ wave-like behaviour

Jeans scale = de Broglie wavelength

Uncertainty principle modifies small-scale structure formation

Perturbations



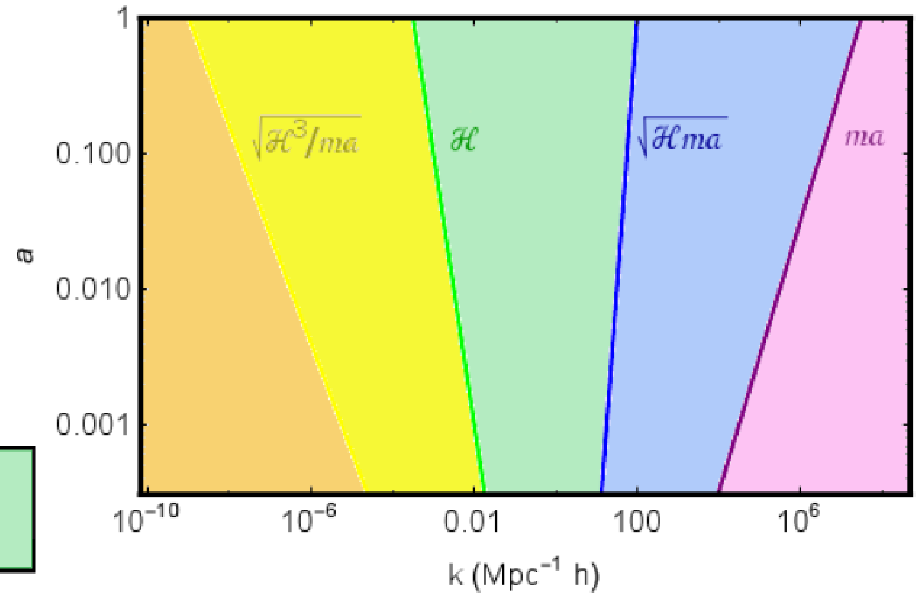
CDM	$\Psi = \Phi \sim$ const. $\delta\rho \sim a^{-3}$ $Q \sim a^{-2}$		$\Psi = \Phi \sim$ const. $\delta\rho \sim a^{-2}$ $Q \sim a^{-2}$		

Particle Regime ← | → Wave Regime

Scalar	$\Psi = \Phi \sim$ const. $\delta\rho \sim a^{-3}$ $\delta\phi \sim$ const.		$\Psi = \Phi \sim$ const. $\delta\rho \sim a^{-2}$ $\delta\phi \sim$ const.	$\Psi = \Phi \sim a^{-1}$ $\delta\rho \sim a^{-3}$ $\delta\phi \sim a^{-3/2}$ Oscillating k^2/maH	**Cut-off**
Vector	Averaging fails	$\Psi = \Phi \sim$ const. $\frac{\Psi - \Phi}{\Psi} = 0$ $\delta\rho \sim a^{-3}$ $\delta A_a \sim a$ $Q \sim a^{-2}$ $h_{ij} = 0$	$\Psi = \Phi \sim$ const. $\frac{\Psi - \Phi}{\Psi} = 0$ $\delta\rho \sim a^{-2}$ $\delta A_a \sim a$ $Q \sim a^{-2}$ $h_{ij} = 0$	$\Psi \sim \Phi \sim a^{-1}$ $\frac{\Psi - \Phi}{\Psi} \sim a^{-2}$ $\delta\rho \sim a^{-3}$ $\delta A_a \sim a^{-1/2}$ $Q \sim a^{-2}$ $h_{ij} \sim a^{-1}$ Oscillating k^2/maH	**Cut-off**
k^2	0	$\mathcal{H}^3/ma$	$\mathcal{H}^2$	$\mathcal{H}ma$	m^2a^2

JARC, A.L.Maroto, Núñez Jareño, JHEP 1702 (2017) 064

Perturbations



CDM	$\Psi = \Phi \sim$ const. $\delta\rho \sim a^{-3}$ $Q \sim a^{-2}$		$\Psi = \Phi \sim$ const. $\delta\rho \sim a^{-2}$ $Q \sim a^{-2}$		
		Particle Regime ←		→ Wave Regime	
Scalar	$\Psi = \Phi \sim$ const. $\delta\rho \sim a^{-3}$ $\delta\phi \sim$ const.		$\Psi = \Phi \sim$ const. $\delta\rho \sim a^{-2}$ $\delta\phi \sim$ const.	$\Psi = \Phi \sim a^{-1}$ $\delta\rho \sim a^{-3}$ $\delta\phi \sim a^{-3/2}$ Oscillating k^2/maH	Cut-off
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k^2	0	$\mathcal{H}^3/ma$	$\mathcal{H}^2$	$\mathcal{H}ma$	m^2a^2 →

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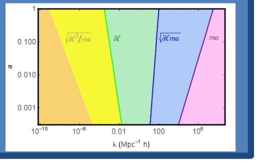
Perturbations



Particle Regime ⟵ | ⟶ Wave Regime

CDM	$\Psi = \Phi \sim$ const. $\delta\rho \sim a^{-3}$ $Q \sim a^{-2}$		$\Psi = \Phi \sim$ const. $\delta\rho \sim a^{-2}$ $Q \sim a^{-2}$		
Scalar	$\Psi = \Phi \sim$ const. $\delta\rho \sim a^{-3}$ $\delta\phi \sim$ const.		$\Psi = \Phi \sim$ const. $\delta\rho \sim a^{-2}$ $\delta\phi \sim$ const.	$\Psi = \Phi \sim a^{-1}$ $\delta\rho \sim a^{-3}$ $\delta\phi \sim a^{-3/2}$ Oscillating k^2/maH	Cut-off
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k^2	0	$\mathcal{H}^3/ma$	$\mathcal{H}^2$	$\mathcal{H}ma$	m^2a^2

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Perturbations: scalar field

$$V(\phi)=a\phi^n$$

$n = 2$

$$c^2_{\rm eff}(k) \equiv \frac{\langle\delta p_k\rangle}{\langle\delta\rho_k\rangle} \begin{cases} \frac{n-2}{n+2} = 0 \\ = \frac{k^2}{4m^2a^2} \end{cases}$$

$$V(\phi)=m^2\phi^2/2$$

$$c^2_{\rm eff}(k) \equiv \frac{\langle\delta p_k\rangle}{\langle\delta\rho_k\rangle} \begin{cases} = \frac{k^2}{4m^2a^2} \\ \end{cases}$$

J.A.R. Cembranos, A.L.M., S.J. Núñez Jareño, JHEP 1603 (2016) 013

Perturbations: scalar field

$$V(\phi)=a\phi^n$$

$$c_{\rm eff}^2(k) \equiv \frac{\langle \delta p_k \rangle}{\langle \delta \rho_k \rangle} \begin{cases} \dfrac{n-2}{n+2} & n = 2 \quad = 0 \\ = \dfrac{k^2}{4m^2a^2} \end{cases}$$

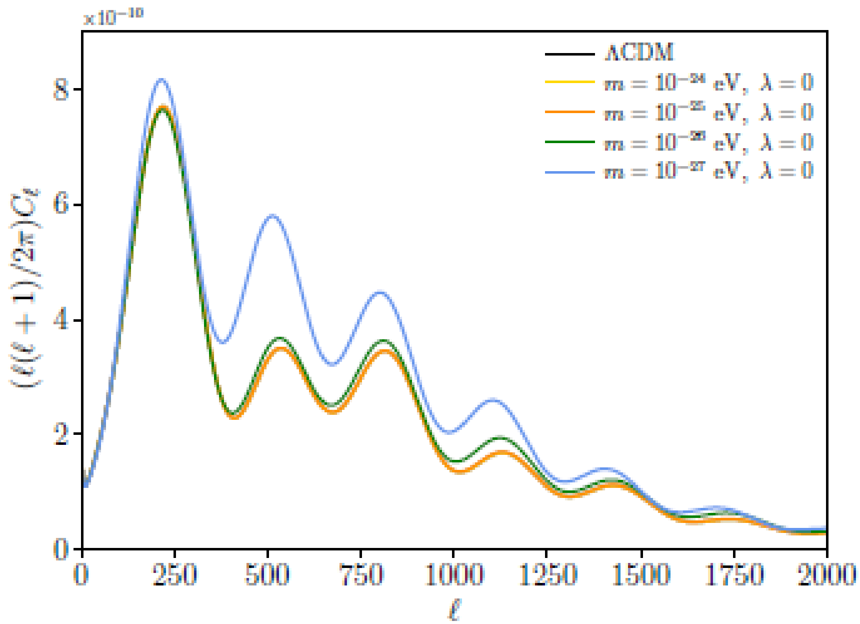
$$V(\phi)= m^2\phi^2/2+\lambda\phi^l/l$$

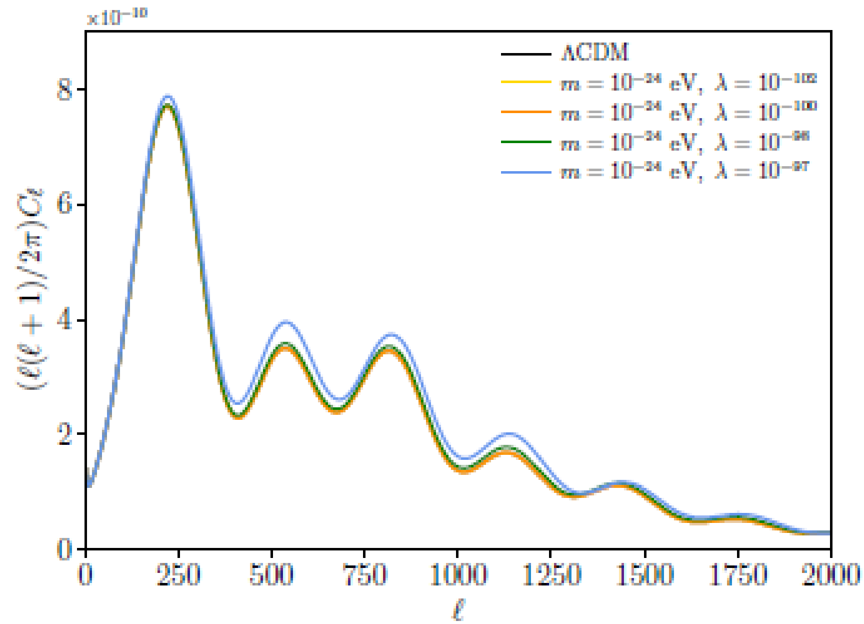
$$c_{\rm eff}^2(k) \equiv \frac{\langle \delta p_k \rangle}{\langle \delta \rho_k \rangle} \begin{cases} = \dfrac{k^2}{4m^2a^2} \\ l = 2p \quad = \dfrac{k^2}{4m^2a^2} + \dfrac{(p-1)}{2^{2p}} \begin{pmatrix} 2p \\ p \end{pmatrix} \dfrac{\lambda \phi_c^{2p-2}}{m^2 a^{3(p-1)}} + \mathcal{O}(\epsilon) \end{cases}$$

J.A.R. Cembranos, A.L.M., S.J. Núñez Jareño, JHEP 1603 (2016) 013

Perturbations: $V(\phi) = m^2\phi^2/2 + \lambda\phi^l/l$ $l=4$

Simulations (CLASS):

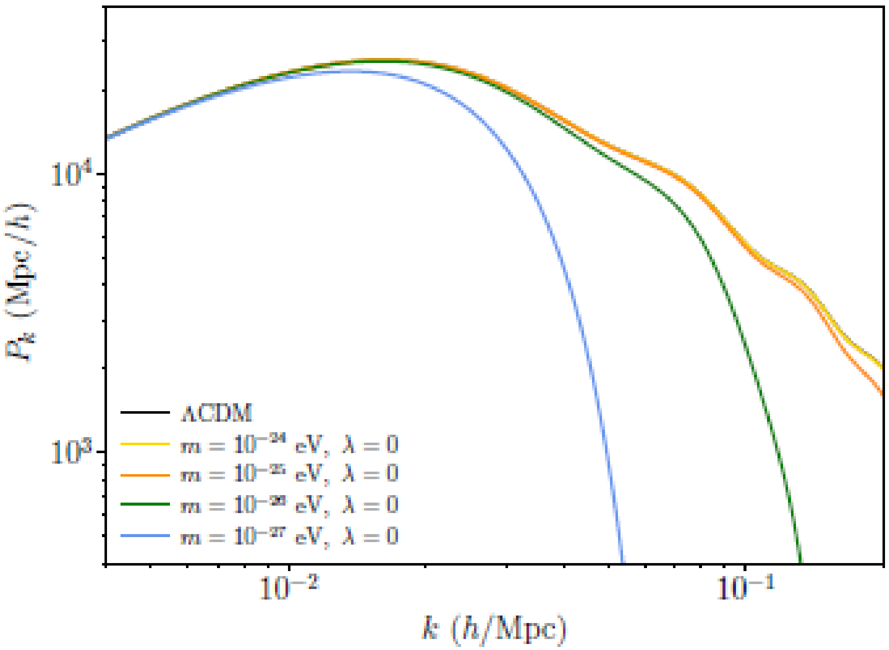


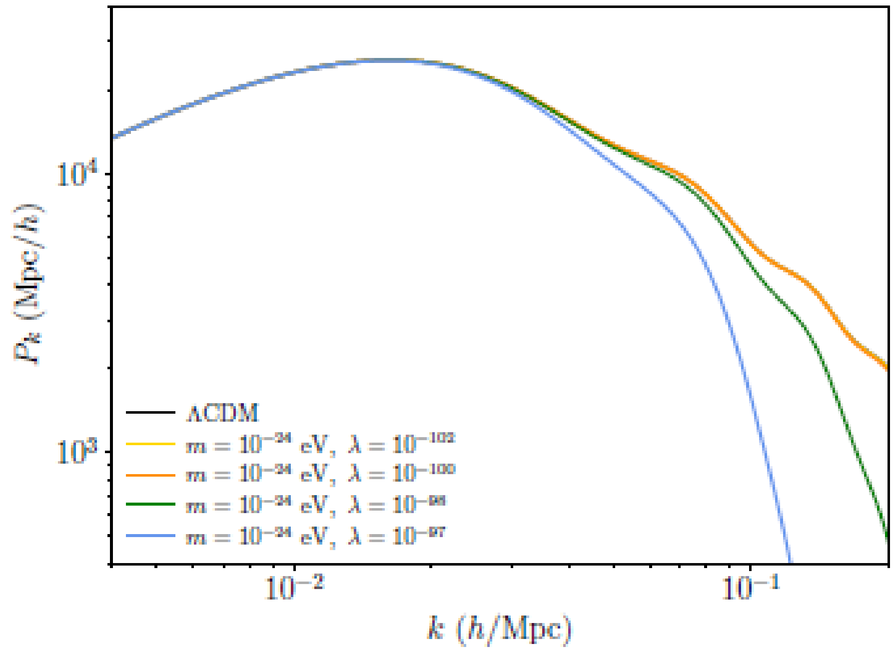


JARC, A.L.Maroto, S.J. Nuñez Jareño, H. Villarrubia, JHEP 1808 (2018) 073

Perturbations: $V(\phi) = m^2\phi^2/2 + \lambda\phi^l/l$ $l=4$

Simulations (CLASS):





JARC, A.L.Maroto, S.J. Nuñez Jareño, H. Villarrubia, JHEP 1808 (2018) 073

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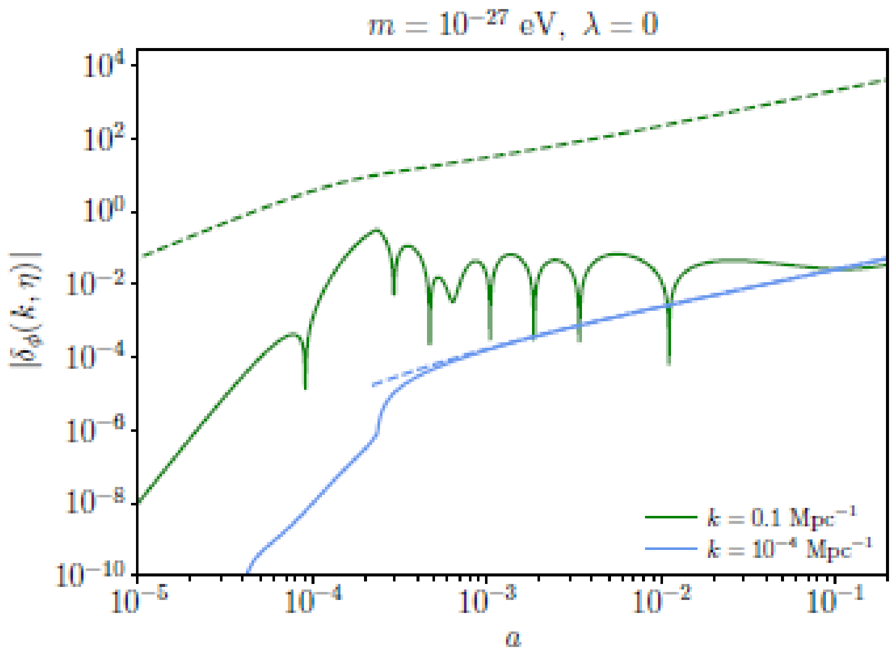

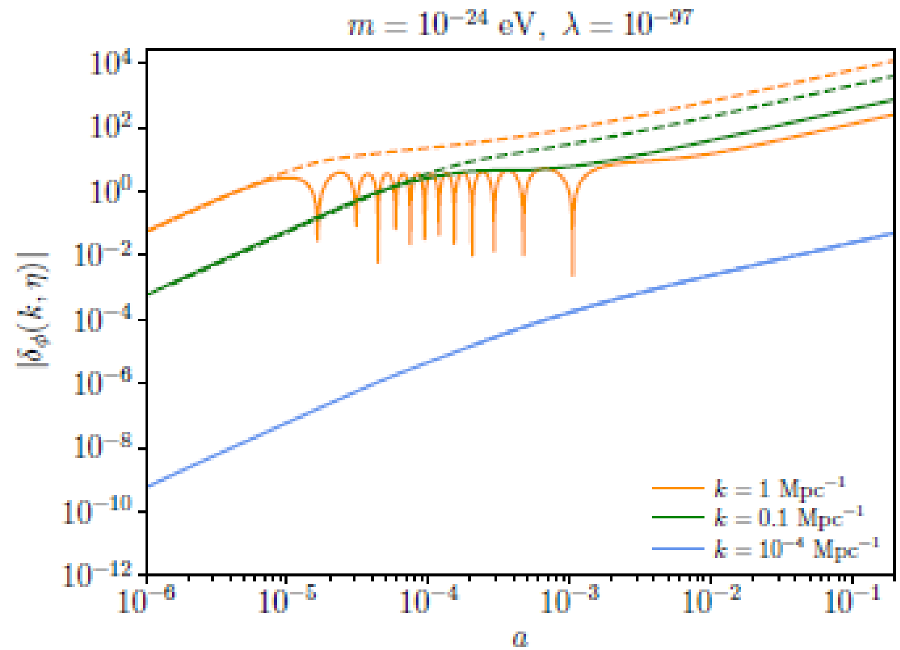

JARC, A.L.Maroto, S.J. Nuñez Jareño, H. Villarrubia, JHEP 1808 (2018) 073

Perturbations: $V(\phi) = m^2\phi^2/2 + \lambda\phi^l/l$ $l=4$

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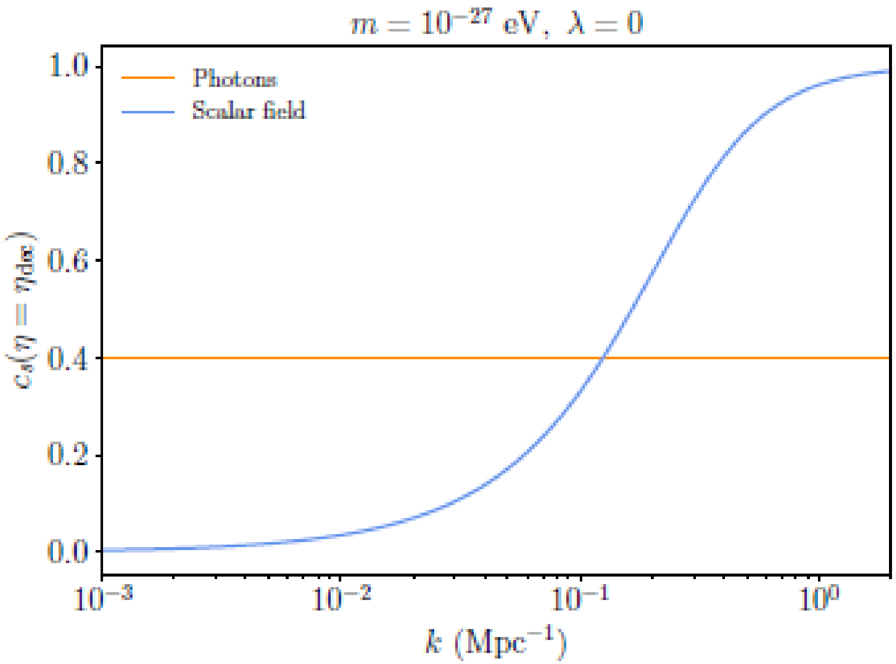

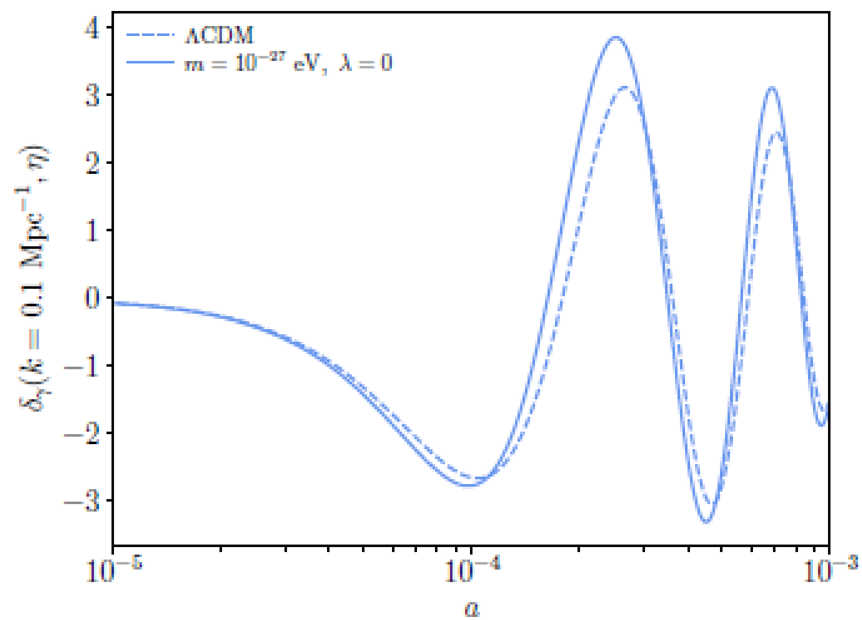

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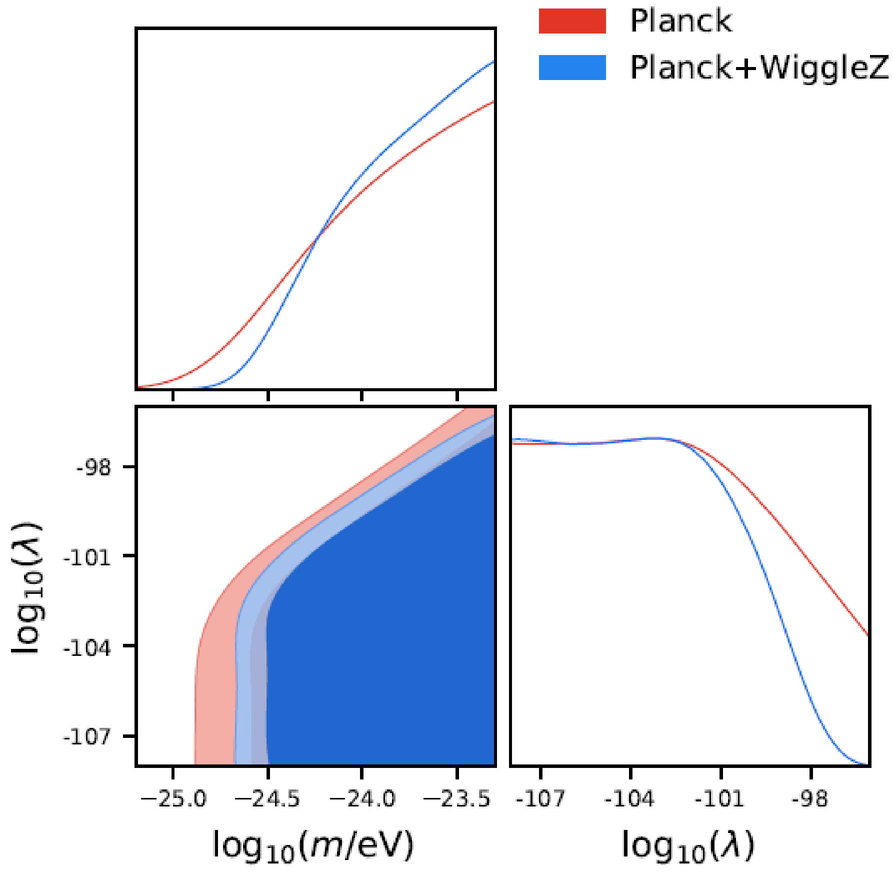
Results from simulations:



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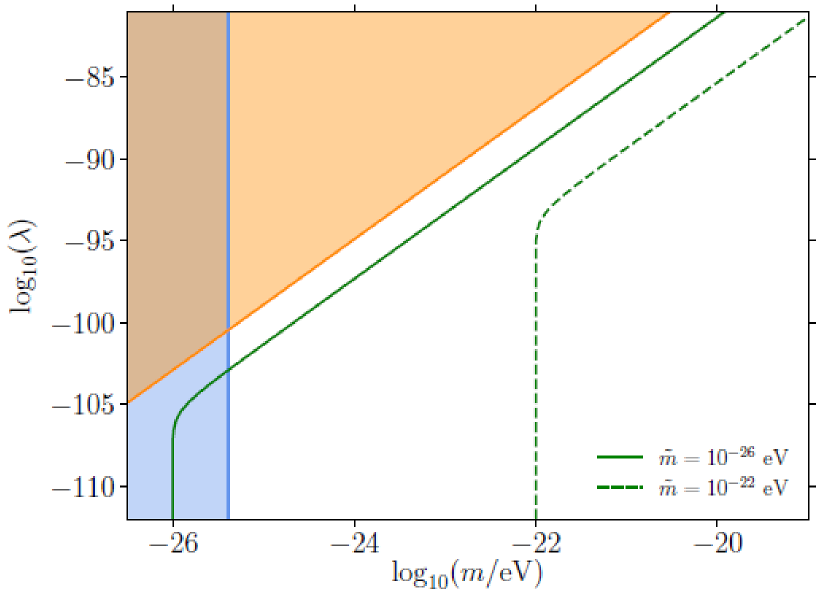

Apporximated sound speed:

$$c_s^2 \simeq \frac{k^2}{4m^2a^2} + \frac{3}{4}\frac{\lambda}{m^4}\rho_\phi \ .$$

By assuming same Jeans scale at matter-radiation equality:

$$\lambda = 4.96 \times 10^{-100} \left(\frac{\tilde{m}}{10^{-24}\ \mathrm{eV}}\right)^3 \left(\frac{1-r^2}{r^4}\right) , \qquad r \equiv \frac{\tilde{m}}{m} \ .$$

JARC, A.L.Maroto, S.J. Nuñez Jareño, H. Villarrubia, JHEP 1808 (2018) 073

Higher-spin wave DM

Perturbations: **Spin 1**

Dark photons

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{m^2}{2}A_\mu A^\mu \, .$$

$$A_\mu \;=\; \left(\delta A_0(\eta,\vec{x}),\; \vec{A}(\eta) + \delta\vec{A}(\eta,\vec{x})\right)$$

3 independent perturbations (δA_0 is fixed)

$$ds^2 \;=\; a(\eta)^2\left[(1+2\Phi(\eta,\vec{x}))\,d\eta^2 - ((1-2\Psi(\eta,\vec{x}))\,\delta_{ij} + h_{ij}(\eta,\vec{x}))\,dx^i dx^j - 2Q_i(\eta,\vec{x})d\eta dx^i\right]$$

S-V-T mixing

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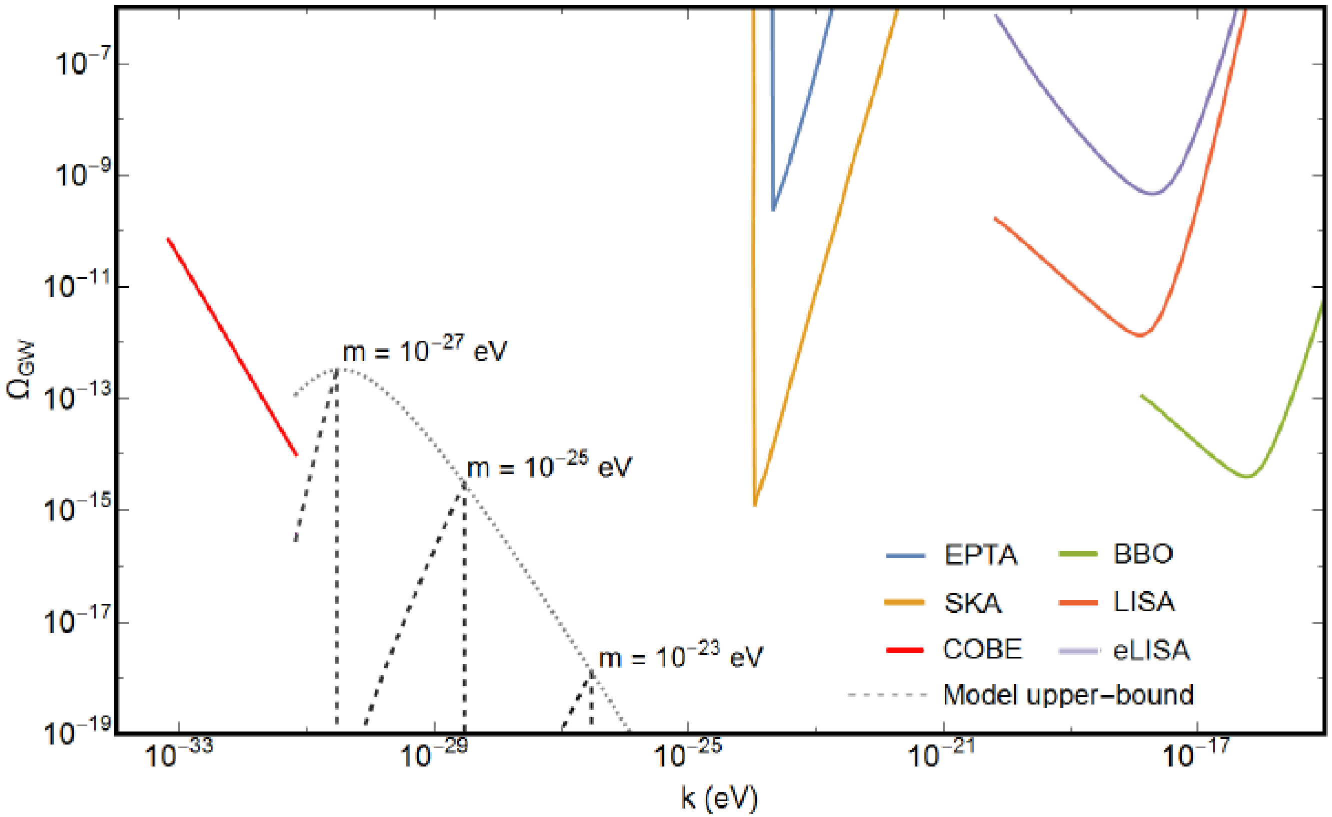
Vector DM

Tensor perturbations: Gravitational waves



JARC, A.L.Maroto, Núñez Jareño, JHEP 1702 (2017) 064

Conclusions

- Coherent scalars are interesting DM (in addition to DE and inflaton) candidates with difference cosmological perturbation dynamics. For example, ultralight DM models modify the small scale structure formation (wave DM).

- Higher-spin fields can also play the same roles. (No isotropy problem: isotropic average energy-momentum).

- Arbitrary-spin fields with power-law Hamiltonians behave as perfect fluids with average equation of state:

$$\omega = \frac{2\, n_V}{1 + \frac{n_V}{n_T}} - 1$$

- Dark photons and gravitons arises in well-motivated theoretical frameworks and present a rich and distinctive phenomenology.