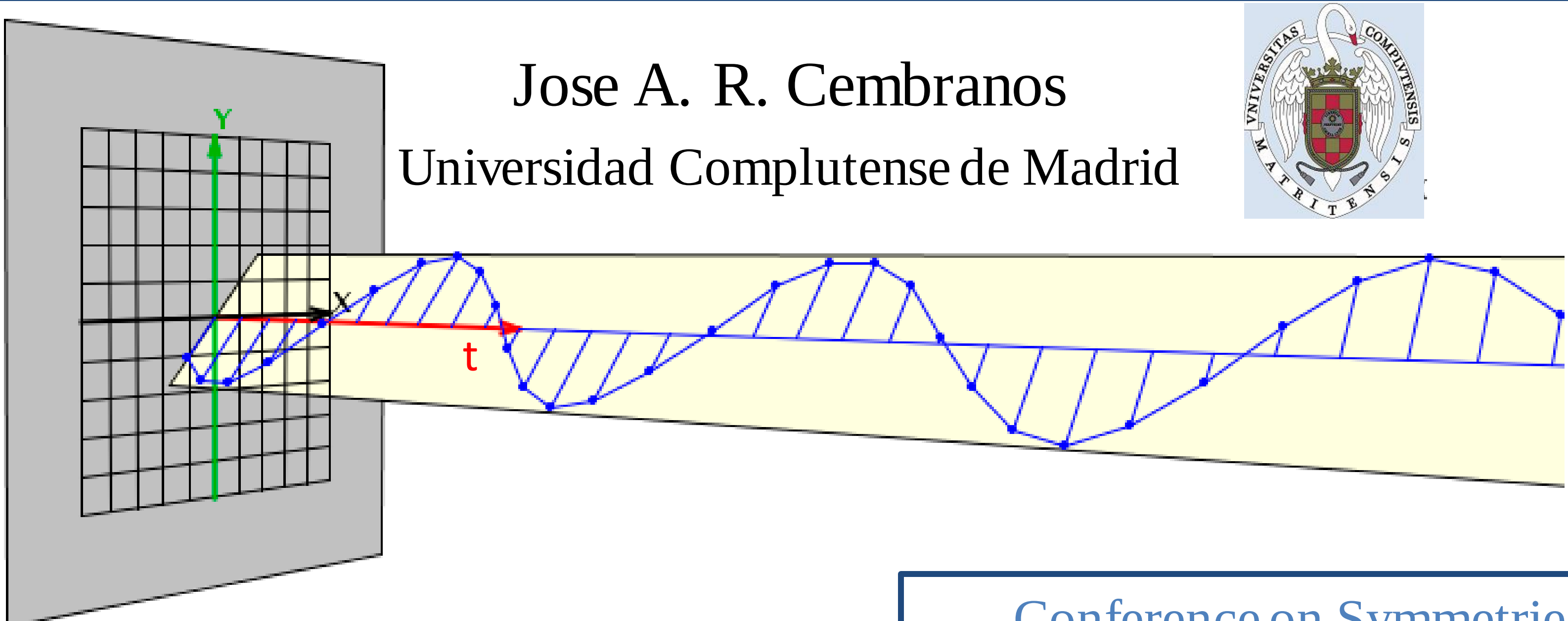
# Isotropy theorem in expanding geometries





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Conference on Symmetries, Geometry and Quantum Gravity

18-22 June 2018, Primosten, Croatia

Collaboration with A.L. Maroto, S.J. Núñez Jareño and H. Villarrubia

# Outline

- Introduction
  - Coherent bosons in cosmology:
    Models for dark matter, dark energy, inflation,…
- Background evolution
  - Scalar fields
  - Isotropy theorem for
    Abelian vector fields
    Non-Abelian vector fields
    General case: Spin 2 fields
- Perturbations:
  - Scalar fields
  - Vector fields
- Conclusions

# Introduction

- 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 $\Psi$DM** (Sin, PRD 50, 3650 (1994), Guzmán-Matos, CQG 17, L9 (2000)) also known as **fuzzy DM** (Hu et al, PRL85, 1158 (2000))

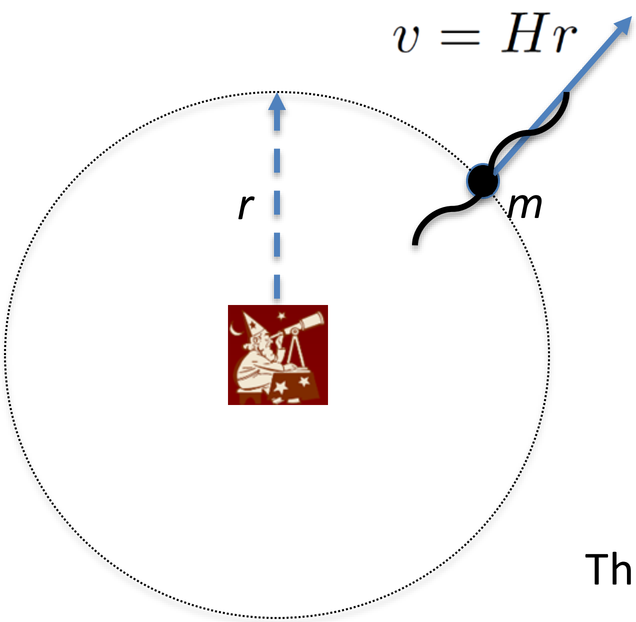
- Existing wave DM models based on ultralight axions or axion-like particles ($m_a \sim 10^{-22}$ eV). What about higher-spin wave DM?

# 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:

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

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

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

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

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

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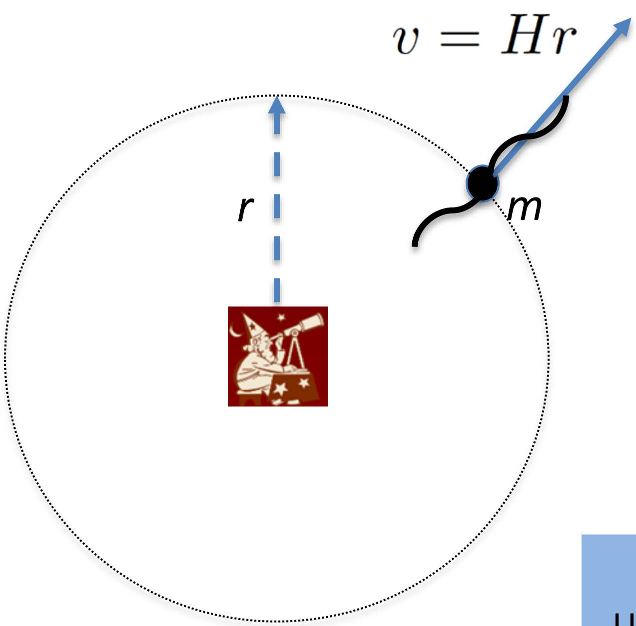



Thus, we have:

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

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

**Jeans scale = de Broglie wavelength**

Uncertainty principle modifies small-scale structure formation

# Scalar fields in cosmology

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

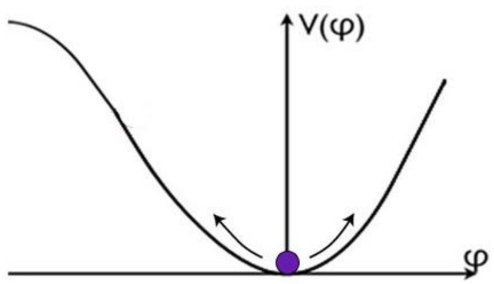
- Inflation: Inflaton.
- Dark matter: Axion and axion-like particles.
- Dark energy: quintessence, scalar-tensor theories of gravity,…

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.)




$$\boxed{V(\phi)=a\phi^n}$$

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

Average eq. of state

$$\begin{cases} n = 2 & \text{matter} \\ n = 4 & \text{radiation} \end{cases}$$

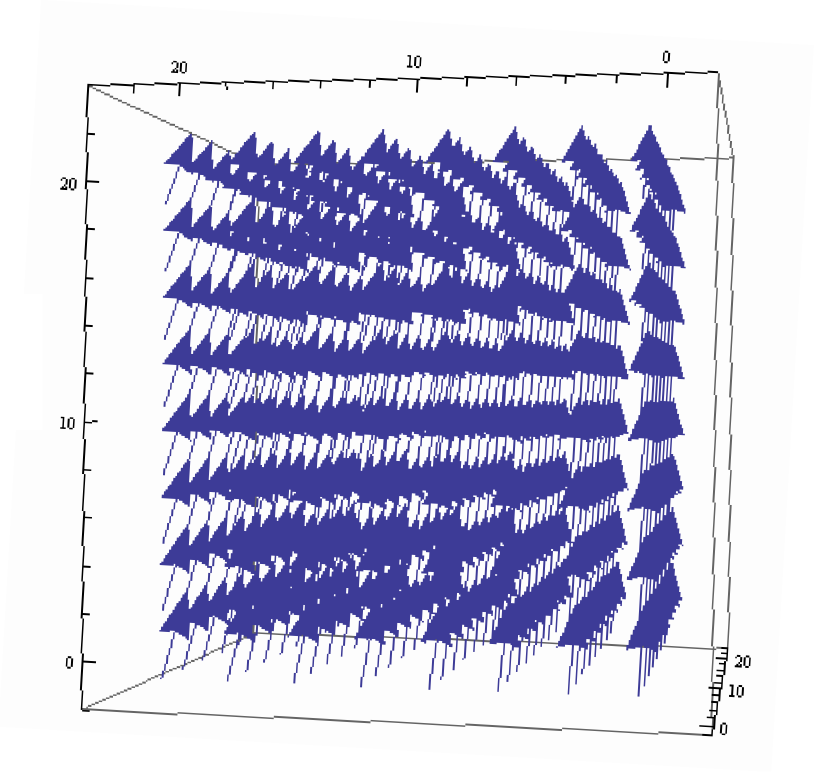
# Theoretical frameworks for vector fields

New vector fields appear in many theoretical extensions of General Relativity or the Standard Model interactions:

- **GUT** P. Langacker, Phys. Rep. 72 C, 185 ( 1981)
- **SUSY** S. Weinberg, Phys. Rev. D 26, 287 (1982); P. Fayet, Nucl. Phys. B 187, 184 (1981)
- **Fith force extensions** E. D. Carlson, Nucl. Phys. B 286, 378 ( 1987)
- **Paraphoton models** L. B. Okun, Sov. Phys. JETP 56, 502 (1982) [Zh. Eksp. Teor. Fiz. 83, 892 (1982)]
- **Superstring compactifications** J. Ellis et al., Nucl. Phys. B 276, 14 (1986) M. Goodsell, A. Ringwald, Fortsch. Phys. 58, 716 (2010)

# The anisotropy problem

However, vector 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 **$A_0$** .

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:

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

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) $\Longrightarrow$

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

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

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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.

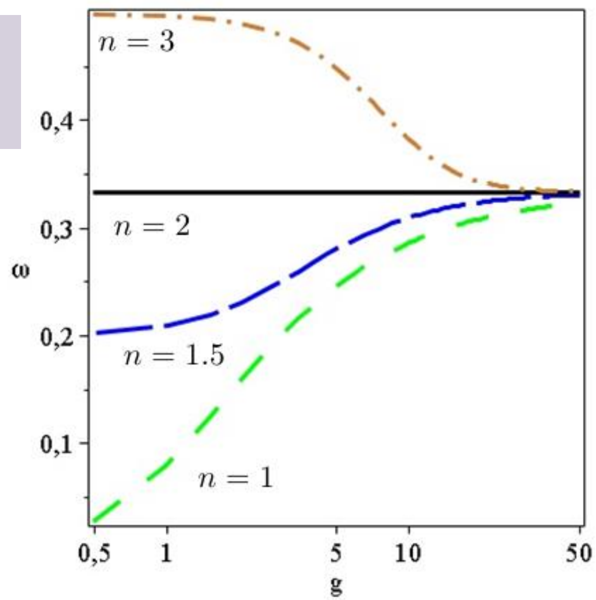
$$V = \frac{1}{2}(-M^2 A^a_\rho A^{a\,\rho})^n$$

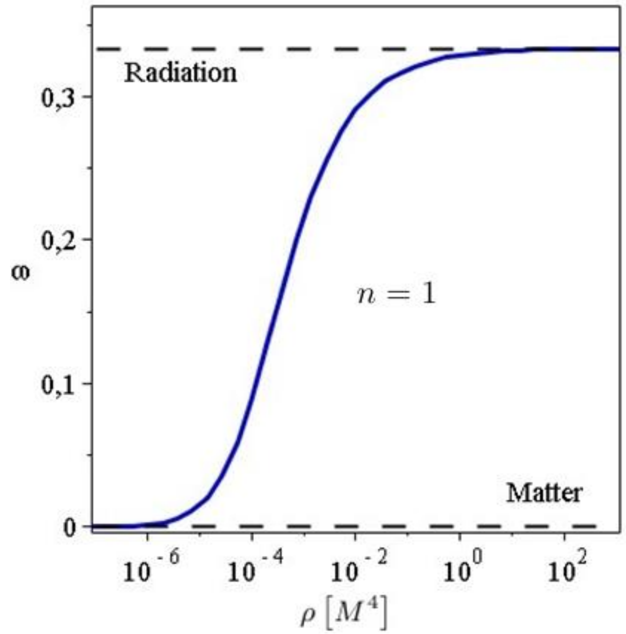
$g \downarrow,\ \rho \downarrow$

$$\omega = \frac{n-1}{n+1}$$

$g \uparrow,\ \rho \uparrow$

$$\omega = \frac{1}{3}$$

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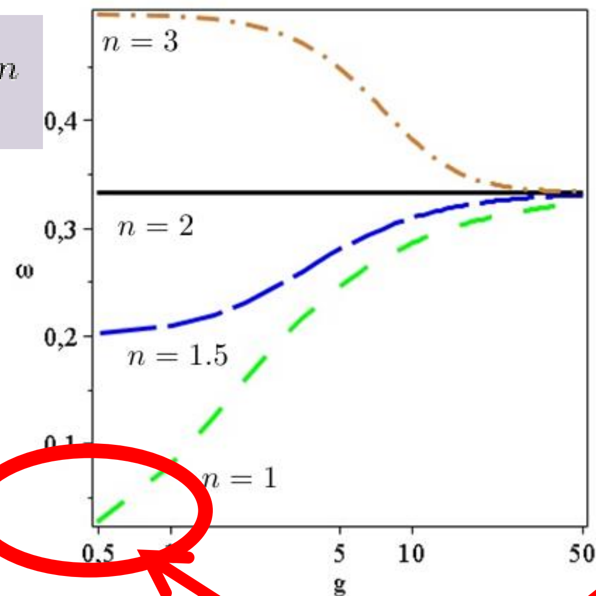
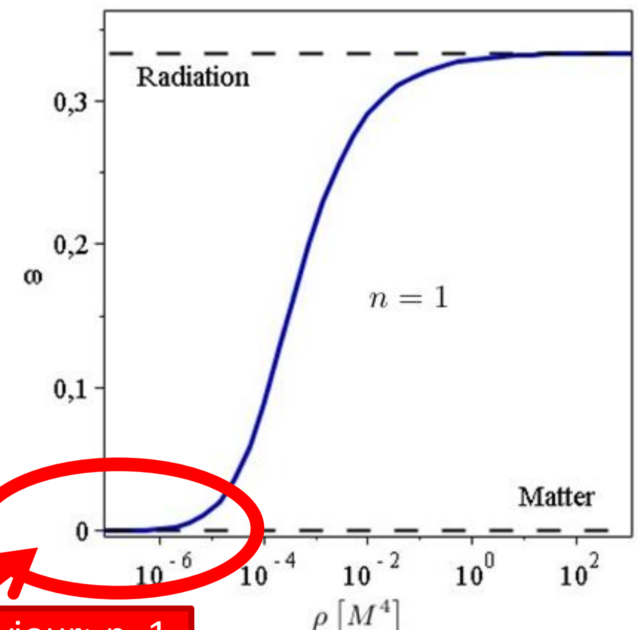



DARK MATTER behaviour: n=1

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

# Gauge fixing term

The previous results can be extended to actions completed with the gauge fixing term:

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\ \mu\nu} + \frac{\xi}{2}(\nabla_\rho A^{a\ \rho})^2 - V(M_{ab}A^a_\rho A^{b\rho})$$

The result is the same, if the **field evolves rapidly** and $A^a{}_i$ , $\dot{A}^a{}_i$ **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.**

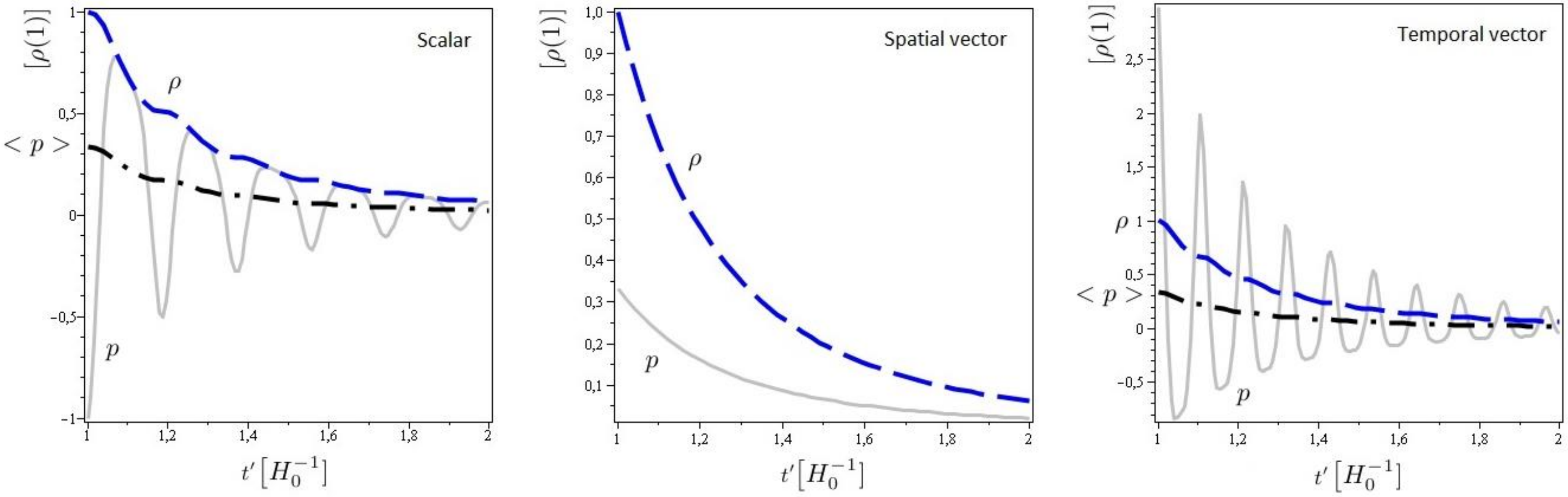
JARC, Maroto, Nunez Jareno, Phys. Rev. D87 (2013) 043523

# Example 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

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

**Isotropy Theorem:** The average Energy-Momentum tensor of a vector field is diagonal and isotropic if

1.- its action is

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\ \mu\nu} + \frac{\xi}{2}(\nabla_\rho A^{a\ \rho})^2 - V(M_{ab}A^a_\rho A^{b\rho})$$

2.- The vector field evolves rapidly:

with respect to the background metric evolution.

with respect to spatial variations.

3.- $A^a{}_i$ and $\dot{A}^a{}_i$ remain bounded during its evolution

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

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

# Isotropy theorem for higher-spin fields

## 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:

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

$\phi_A$ 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:

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

# 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

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

Average equation of state:

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

# Higher-spin DM

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**Spin 2**. Massive gravitons as wave DM
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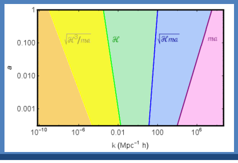
Condensate of massive graviton and dark matter, K. Aoki and K. Maeda, arXiv:1707.05003 [hep-th]

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

# Perturbations

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

# Perturbations



| | | | | | |
|---|---|---|---|---|---|
| **CDM** | $\Psi = \Phi \sim$ const.<br>$\delta\rho \sim a^{-3}$<br>$Q \sim a^{-2}$ | | $\Psi = \Phi \sim$ const.<br>$\delta\rho \sim a^{-2}$<br>$Q \sim a^{-2}$ | | |
| | | | Particle Regime ← | → Wave Regime | |
| **Scalar** | $\Psi = \Phi \sim$ const.<br>$\delta\rho \sim a^{-3}$<br>$\delta\phi \sim$ const. | | $\Psi = \Phi \sim$ const.<br>$\delta\rho \sim a^{-2}$<br>$\delta\phi \sim$ const. | $\Psi = \Phi \sim a^{-1}$<br>$\delta\rho \sim a^{-3}$<br>$\delta\phi \sim a^{-3/2}$<br>Oscillating $k^2/maH$ | Cut-off |
| **Vector** | Averaging fails | $\Psi = \Phi \sim$ const.<br>$\frac{\Psi - \Phi}{\Psi} = 0$<br>$\delta\rho \sim a^{-3}$<br>$\delta A_a \sim a$<br>$Q \sim a^{-2}$<br>$h_{ij} = 0$ | $\Psi = \Phi \sim$ const.<br>$\frac{\Psi - \Phi}{\Psi} = 0$<br>$\delta\rho \sim a^{-2}$<br>$\delta A_a \sim a$<br>$Q \sim a^{-2}$<br>$h_{ij} = 0$ | $\Psi \sim \Phi \sim a^{-1}$<br>$\frac{\Psi - \Phi}{\Psi} \sim a^{-2}$<br>$\delta\rho \sim a^{-3}$<br>$\delta A_a \sim a^{-1/2}$<br>$Q \sim a^{-2}$<br>$h_{ij} \sim a^{-1}$<br>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, arXiv: 1611.03793

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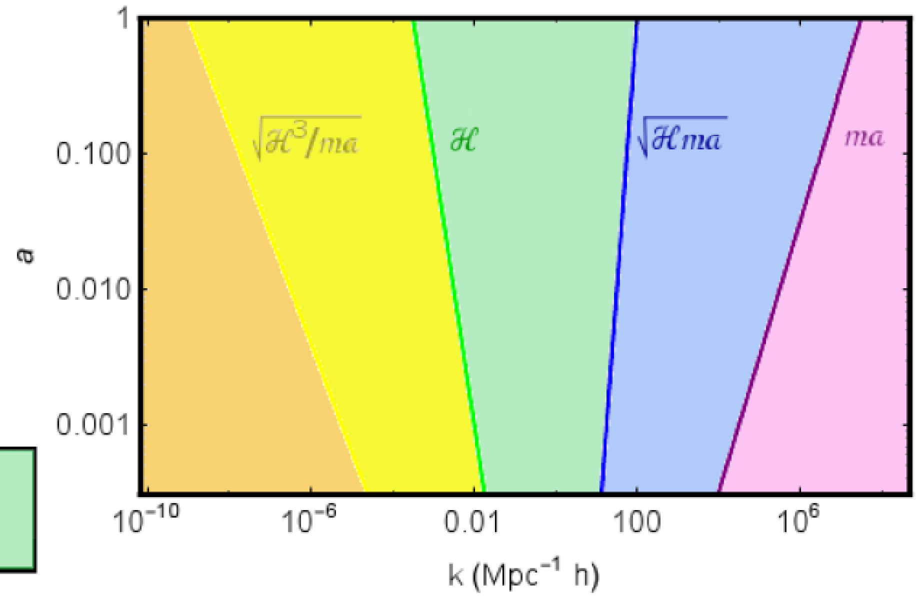


Particle Regime ← → Wave Regime

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| $\mathbf{k^2}$ | 0 | $\mathcal{H}^3/ma$ | $\mathcal{H}^2$ | $\mathcal{H}ma$ | $m^2a^2$ |

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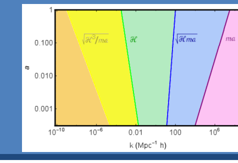

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| **$k^2$** | 0 — $\mathcal{H}^3/ma$ | $\mathcal{H}^3/ma$ — $\mathcal{H}^2$ | $\mathcal{H}^2$ — $\mathcal{H}ma$ | $\mathcal{H}ma$ — $m^2a^2$ | $m^2a^2$ → |

JARC, A.L.Maroto, Núñez Jareño, arXiv: 1611.03793

# Perturbations: scalar field

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

$$c^2_{\rm eff}(k) \equiv \frac{\langle \delta p_k \rangle}{\langle \delta \rho_k \rangle} \begin{cases} \dfrac{n-2}{n+2} \\[2em] \end{cases}$$

$\boxed{n = 2}$

$= 0$

$$= \frac{k^2}{4m^2a^2}$$

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

$$= \frac{k^2}{4m^2a^2}$$

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

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

# Perturbations: scalar field

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

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

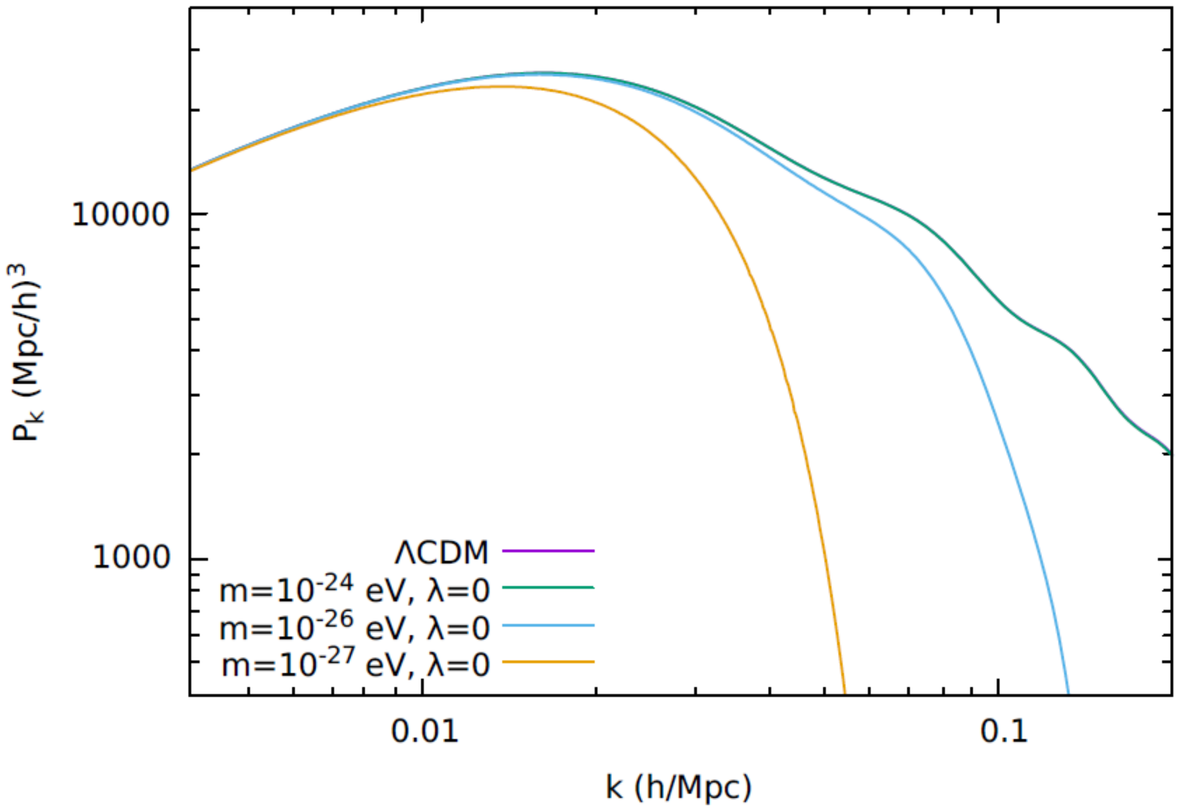
$$V(\phi) = m^2\phi^2/2 + \lambda\phi^l/l$$

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

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, arXiv:1805.08112

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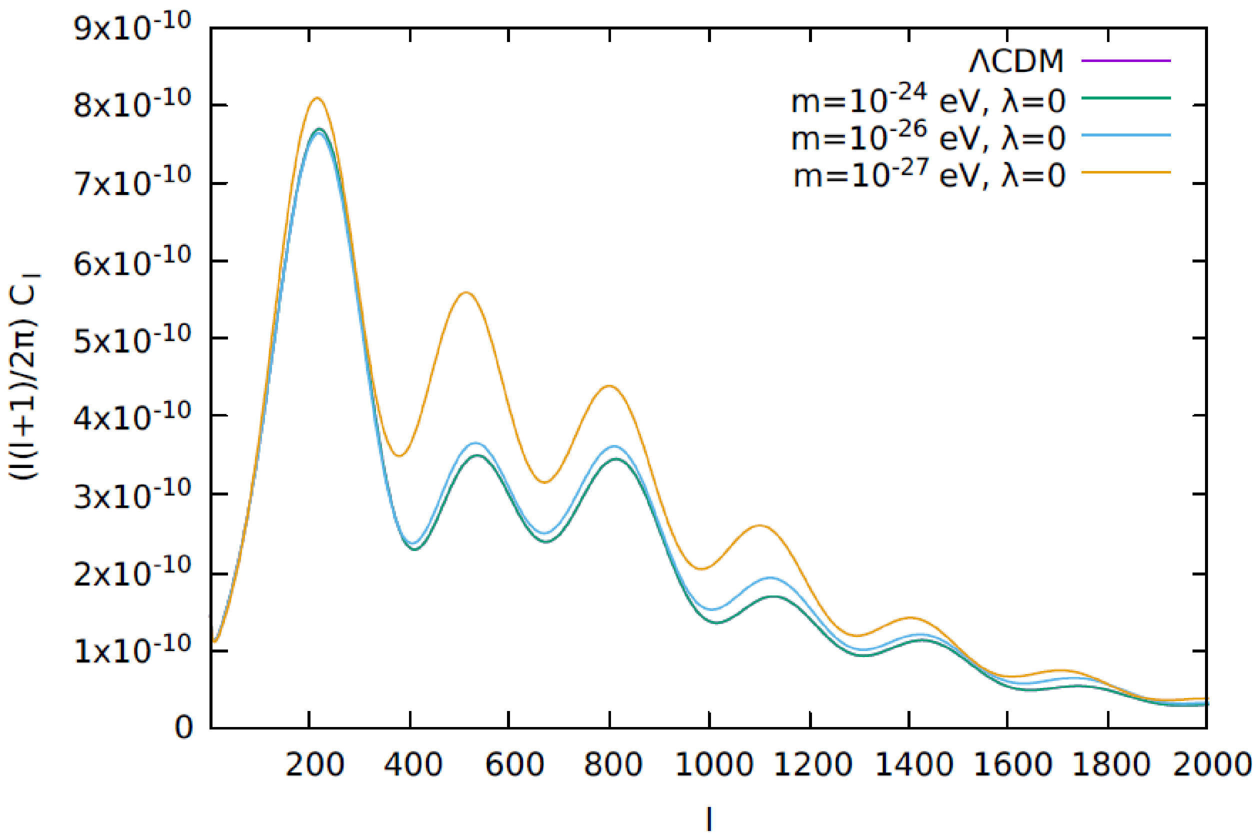


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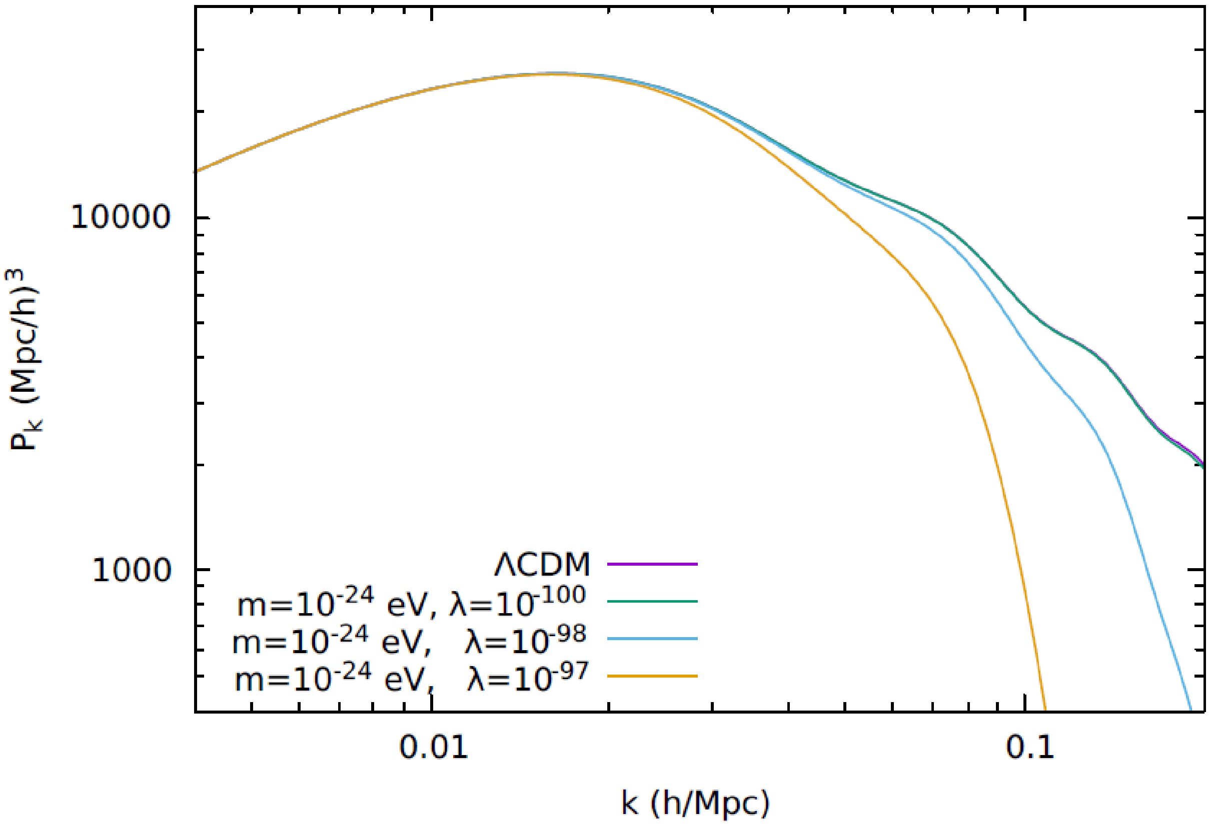


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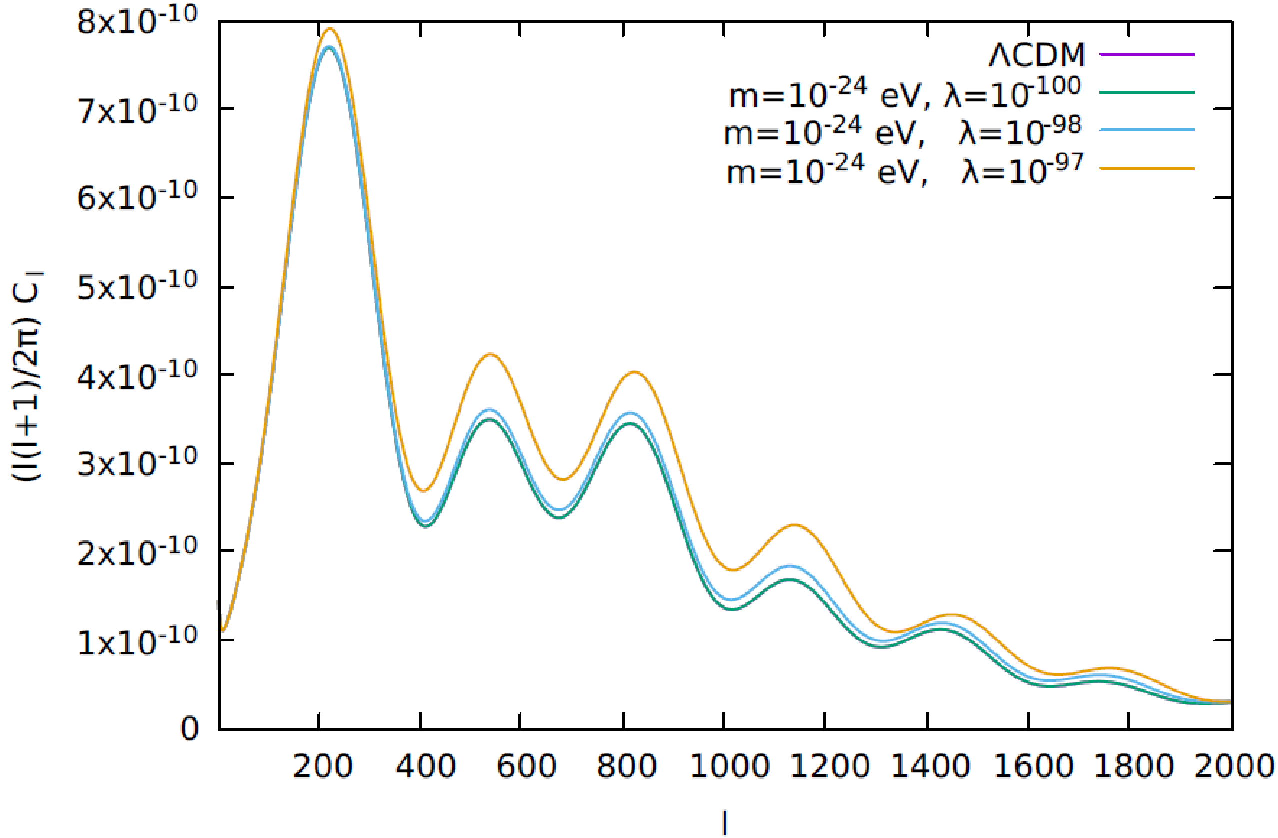


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# Higher-spin wave DM

## 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 ($\delta A_0$ is fixed)

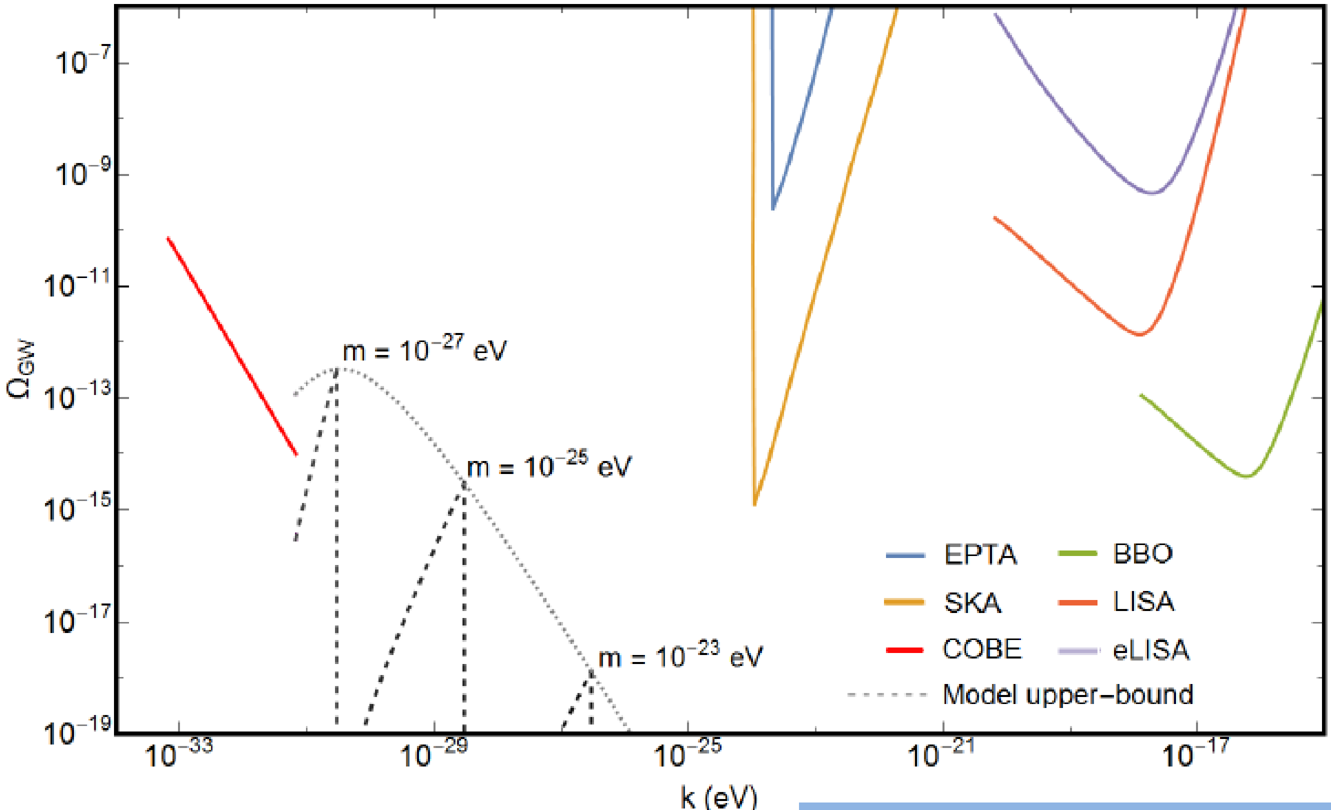
$$ds^2 = a(\eta)^2 \left[ (1 + 2\Phi(\eta, \vec{x})) \, d\eta^2 - ((1 - 2\Psi(\eta, \vec{x})) \, \delta_{ij} + h_{ij}(\eta, \vec{x})) \, dx^i dx^j - 2Q_i(\eta, \vec{x}) d\eta dx^i \right]$$

S-V-T mixing

JARC, A.L.Maroto, Núñez Jareño, arXiv: 1611.03793

# Vector DM

Tensor perturbations: Gravitational waves




JARC, A.L.Maroto, Núñez Jareño, arXiv: 1611.03793

# Conclusions

- Coherent scalars are interesting DE, DM or 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:

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

- Ultralight vectors are indistinguishable from scalars in the particle regime, however in the wave regime they generate scalar-vector-tensor mixing, anisotropic stress and GW.