Ultra-light dark matter and interferometers

Federico Urban

CEICO

Institute of Physics
Czech Academy of Sciences
Prague

LISA CZ meeting
Prague – Czech Republic

Sep 23, 2024

Co-funded by
the European Union

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

:: outline ::

:: outline ::

- Dark Matter

:: outline ::

- Dark Matter ...or modified gravity?

:: outline ::

- Dark Matter ...or modified gravity?
- Why spin-2? Why ultra-light?

:: outline ::

- Dark Matter ...or modified gravity?
- Why spin-2? Why ultra-light?
- Continuous Gravitational Waves

:: outline ::

- Dark Matter ...or modified gravity?
- Why spin-2? Why ultra-light?
- Continuous Gravitational Waves
- Results: coming full circle

:: outline ::

- Dark Matter ...or modified gravity?
- Why spin-2? Why ultra-light?
- Continuous Gravitational Waves
- Results: coming full circle

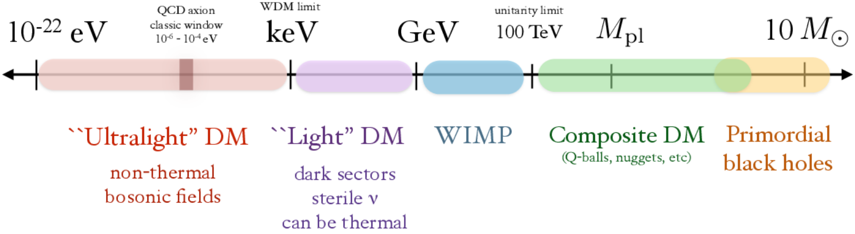
JCAP 04 (2021) 053 and arXiv:2012.13997 [astro-ph.CO]

...and work in progress...

dark matter

Mass scale of dark matter

(not to scale)



:: ultra-light ::

:: ultra−light ::

Dynamics of the zero mode: $\ddot{\Phi} + 3H\dot{\Phi} + m^2\Phi = 0$

:: ultra−light ::

Dynamics of the zero mode: $\ddot{\Phi} + 3H\dot{\Phi} + m^2\Phi = 0$

1. At early times $m << H$ the field is frozen: $\Phi \sim \text{const}$

:: ultra—light ::

Dynamics of the zero mode: $\ddot{\Phi} + 3H\dot{\Phi} + m^2\Phi = 0$

1. At early times $m << H$ the field is frozen: $\Phi \sim \mathrm{const}$
2. As soon as $H \lesssim m$ the field feels the potential: $\Phi \sim a^{-3/2}\cos(mt)$

:: ultra–light ::

Dynamics of the zero mode: $\ddot{\Phi} + 3H\dot{\Phi} + m^2\Phi = 0$

1. At early times $m << H$ the field is frozen: $\Phi \sim \mathrm{const}$
2. As soon as $H \lesssim m$ the field feels the potential: $\Phi \sim a^{-3/2}\cos(mt)$
3. The energy density is $\rho \sim a^{-3}$

:: ultra–light ::

Dynamics of the zero mode: $\ddot{\Phi} + 3H\dot{\Phi} + m^2\Phi = 0$

1. At early times $m << H$ the field is frozen: $\Phi \sim \text{const}$
2. As soon as $H \lesssim m$ the field feels the potential: $\Phi \sim a^{-3/2}\cos(mt)$
3. The energy density is $\rho \sim a^{-3} \Rightarrow$ Scales like dust

:: ultra−light ::

Dynamics of the zero mode: $\ddot{\Phi} + 3H\dot{\Phi} + m^2\Phi = 0$

1. At early times $m << H$ the field is frozen: $\Phi \sim$ const
2. As soon as $H \lesssim m$ the field feels the potential: $\Phi \sim a^{-3/2}\cos(mt)$
3. The energy density is $\rho \sim a^{-3} \Rightarrow$ Scales like dust
4. The pressure density is $P \sim a^{-3}\cos(2mt)$

:: ultra–light ::

Dynamics of the zero mode: $\ddot{\Phi} + 3H\dot{\Phi} + m^2\Phi = 0$

1. At early times $m << H$ the field is frozen: $\Phi \sim \text{const}$
2. As soon as $H \lesssim m$ the field feels the potential: $\Phi \sim a^{-3/2}\cos(mt)$
3. The energy density is $\rho \sim a^{-3} \Rightarrow$ Scales like dust
4. The pressure density is $P \sim a^{-3}\cos(2mt) \Rightarrow$ Not cool?

:: ultra−light ::

Dynamics of the zero mode: $\ddot{\Phi} + 3H\dot{\Phi} + m^2\Phi = 0$

1. At early times $m << H$ the field is frozen: $\Phi \sim$ const
2. As soon as $H \lesssim m$ the field feels the potential: $\Phi \sim a^{-3/2}\cos(mt)$
3. The energy density is $\rho \sim a^{-3} \Rightarrow$ Scales like dust
4. The pressure density is $P \sim a^{-3}\cos(2mt) \Rightarrow$ Not cool?
5. On cosmological times $P \approx 0 + \mathcal{O}(H/m) \ll 1$

:: ultra–light ::

Dynamics of the zero mode: $\ddot{\Phi} + 3H\dot{\Phi} + m^2\Phi = 0$

1. At early times $m << H$ the field is frozen: $\Phi \sim$ const
2. As soon as $H \lesssim m$ the field feels the potential: $\Phi \sim a^{-3/2}\cos(mt)$
3. The energy density is $\rho \sim a^{-3} \Rightarrow$ Scales like dust
4. The pressure density is $P \sim a^{-3}\cos(2mt) \Rightarrow$ Not cool?
5. On cosmological times $P \approx 0 + \mathcal{O}(H/m) \ll 1$ Cool enough!

:: the ſcaleſ ::

:: the scales ::

- Persistent: coherence time is
  $t_{\rm coh} := 4\pi/mv^2 \sim 10^6/f \sim 65\ \mathrm{y}\ (10^{-18}\mathrm{eV}/m)$

:: the ſcaleſ ::

- Persistent: coherence time is
  $t_{\rm coh} := 4\pi/mv^2 \sim 10^6/f \sim 65\ \mathrm{y}\ (10^{-18}\mathrm{eV}/m)$

- Homogeneous: de Broglie wavelength is
  No gradients within $\lambda_{\rm dB} := 2\pi/mv \sim 10^3/f \sim 0.1\mathrm{pc}\ (10^{-18}\ \mathrm{eV}/m)$

:: the ſcaleſ ::

Persistent: coherence time is
$t_{\rm coh} := 4\pi/mv^2 \sim 10^6/f \sim 65\ \mathrm{y}\ (10^{-18}\mathrm{eV}/m)$

Homogeneous: de Broglie wavelength is
No gradients within $\lambda_{\rm dB} := 2\pi/mv \sim 10^3/f \sim 0.1\mathrm{pc}\ (10^{-18}\ \mathrm{eV}/m)$

Rapidly oscillating: frequency is
$f := m/2\pi \sim 1\mathrm{h}^{-1}\ (m/10^{-18}\ \mathrm{eV})$

:: the ſcaleſ ::

Persistent: coherence time is
$t_{\rm coh} := 4\pi/mv^2 \sim 10^6/f \sim 65\ \mathrm{y}\ (10^{-18}\mathrm{eV}/m)$

Homogeneous: de Broglie wavelength is
No gradients within $\lambda_{\rm dB} := 2\pi/mv \sim 10^3/f \sim 0.1\mathrm{pc}\ (10^{-18}\ \mathrm{eV}/m)$

Rapidly oscillating: frequency is
$f := m/2\pi \sim 1\mathrm{h}^{-1}\ (m/10^{-18}\ \mathrm{eV})$

Classical: occupation number is
$\mathcal{N} \sim 10^{76}(10^{-18}\ \mathrm{eV}/m)^4$

:: variety ::

:: variety ::

Spin 0. $\mathcal{L} = \frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}m^2\Phi^2$

:: variety ::

Spin 0. $\mathcal{L} = \frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}m^2\Phi^2$

Spin 1. $\mathcal{L} = -\frac{1}{4}F^2 + \frac{1}{2}m^2A^2$

:: variety ::

Spin 0. $\mathcal{L} = \frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}m^2\Phi^2$

Spin 1. $\mathcal{L} = -\frac{1}{4}F^2 + \frac{1}{2}m^2A^2$

Spin 2. $\mathcal{L} = M_{ij}\mathcal{E}^{ijkl}M_{kl} - \frac{1}{2}m^2(M_{ij}M^{ij} - M^2)$

:: variety ::

Spin 0. $\mathcal{L} = \frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}m^2\Phi^2$

Spin 1. $\mathcal{L} = -\frac{1}{4}F^2 + \frac{1}{2}m^2A^2$

Spin 2. $\mathcal{L} = M_{ij}\mathcal{E}^{ijkl}M_{kl} - \frac{1}{2}m^2(M_{ij}M^{ij} - M^2)$

The field is a stack of waves

$$\Phi \sim \frac{\sqrt{\rho_{\rm DM}}}{m}\sum_i \cos\left[m(1+\frac{v_i^2}{2})t + \vec{k}_i\cdot\vec{x} + \Upsilon_i\right]$$

:: variety ::

Spin 0. $\mathcal{L} = \frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}m^2\Phi^2$

Spin 1. $\mathcal{L} = -\frac{1}{4}F^2 + \frac{1}{2}m^2A^2$

Spin 2. $\mathcal{L} = M_{ij}\mathcal{E}^{ijkl}M_{kl} - \frac{1}{2}m^2(M_{ij}M^{ij} - M^2)$

The field is a stack of waves

$$\Phi \sim \frac{\sqrt{\rho_{\rm DM}}}{m}\sum_i \cos\left[m(1+\frac{v_i^2}{2})t + \vec{k}_i\cdot\vec{x} + \Upsilon_i\right]$$

Distinguishing the spin with...

:: variety ::

Spin 0. $\mathcal{L} = \frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}m^2\Phi^2$

Spin 1. $\mathcal{L} = -\frac{1}{4}F^2 + \frac{1}{2}m^2A^2$

Spin 2. $\mathcal{L} = M_{ij}\mathcal{E}^{ijkl}M_{kl} - \frac{1}{2}m^2(M_{ij}M^{ij} - M^2)$

The field is a stack of waves

$$\Phi \sim \frac{\sqrt{\rho_{\rm DM}}}{m}\sum_i \cos\left[m(1+\frac{v_i^2}{2})t + \vec{k}_i\cdot\vec{x} + \Upsilon_i\right]$$

Distinguishing the spin with...

PTAs Armaleo, López Nacir and FU JCAP2020 and Unal, FU and Kovetz PLB2024

:: variety ::

Spin 0. $\mathcal{L} = \frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}m^2\Phi^2$

Spin 1. $\mathcal{L} = -\frac{1}{4}F^2 + \frac{1}{2}m^2A^2$

Spin 2. $\mathcal{L} = M_{ij}\mathcal{E}^{ijkl}M_{kl} - \frac{1}{2}m^2(M_{ij}M^{ij} - M^2)$

The field is a stack of waves

$$\Phi \sim \frac{\sqrt{\rho_{\rm DM}}}{m}\sum_i \cos\left[m(1+\frac{v_i^2}{2})t + \vec{k}_i\cdot\vec{x} + \Upsilon_i\right]$$

Distinguishing the spin with...

PTAs Armaleo, López Nacir and FU JCAP2020 and Unal, FU and Kovetz PLB2024

GWIs Armaleo, López Nacir and FU JCAP2021

:: fifth force ::

The ripples in the fabric caused by the ULDM are enough to perturb the system.

:: fifth force ::

The ripples in the fabric caused by the ULDM are enough to perturb the system.
However, things are much more fun if Dark Matter carries a fifth force...

:: fifth force ::

The ripples in the fabric caused by the ULDM are enough to perturb the system.
However, things are much more fun if Dark Matter carries a fifth force...

- Scalar: $L_I = m_A^{\phi}[1 + v_A^2/2] + m_B^{\phi}[1 + v_B^2/2] + G m_A^{\phi} m_B^{\phi}/r$

:: fifth force ::

The ripples in the fabric caused by the ULDM are enough to perturb the system.
However, things are much more fun if Dark Matter carries a fifth force...

- Scalar: $L_I = m_A^\phi[1 + v_A^2/2] + m_B^\phi[1 + v_B^2/2] + G m_A^\phi m_B^\phi / r$

  Linear coupling: $m_i^\phi = m_i[1 + \boldsymbol{\alpha}\Phi]$

  Quadratic coupling: $m_i^\phi = m_i[1 + \boldsymbol{\beta}\Phi^2/2]$

  López Nacir et al PRL2017 and PRD2020

:: fifth force ::

The ripples in the fabric caused by the ULDM are enough to perturb the system.
However, things are much more fun if Dark Matter carries a fifth force...

- Scalar: $L_I = m_A^{\phi}[1 + v_A^2/2] + m_B^{\phi}[1 + v_B^2/2] + G m_A^{\phi} m_B^{\phi}/r$

  Linear coupling: $m_i^{\phi} = m_i[1 + \boldsymbol{\alpha}\Phi]$

  Quadratic coupling: $m_i^{\phi} = m_i[1 + \boldsymbol{\beta}\Phi^2/2]$

  López Nacir et al PRL2017 and PRD2020

- Vector: $L_I = q_A v_A^i \mathrm{A}_i + q_B v_B^i \mathrm{A}_i$

:: fifth force ::

The ripples in the fabric caused by the ULDM are enough to perturb the system.
However, things are much more fun if Dark Matter carries a fifth force…

Scalar: $L_I = m_A^\phi[1 + v_A^2/2] + m_B^\phi[1 + v_B^2/2] + Gm_A^\phi m_B^\phi/r$

Linear coupling: $m_i^\phi = m_i[1 + \boldsymbol{\alpha}\Phi]$

Quadratic coupling: $m_i^\phi = m_i[1 + \boldsymbol{\beta}\Phi^2/2]$

López Nacir et al PRL2017 and PRD2020

Vector: $L_I = q_A v_A^i \mathrm{A}_i + q_B v_B^i \mathrm{A}_i$

For example, $(B - L)$ charge: $q_i = \boldsymbol{g} c_i m_i/m_n$

López Nacir and FU JCAP2018

:: fifth force ::

The ripples in the fabric caused by the ULDM are enough to perturb the system.
However, things are much more fun if Dark Matter carries a fifth force...

Scalar: $L_I = m_A^\phi[1 + v_A^2/2] + m_B^\phi[1 + v_B^2/2] + G m_A^\phi m_B^\phi / r$

Linear coupling: $m_i^\phi = m_i[1 + \boldsymbol{\alpha}\Phi]$

Quadratic coupling: $m_i^\phi = m_i[1 + \boldsymbol{\beta}\Phi^2/2]$

López Nacir et al PRL2017 and PRD2020

Vector: $L_I = q_A v_A^i \mathrm{A}_i + q_B v_B^i \mathrm{A}_i$

For example, $(B - L)$ charge: $q_i = \boldsymbol{g} c_i m_i / m_n$

López Nacir and FU JCAP2018

Tensor: $L_I = \lambda m_A v_A^i v_A^j \mathrm{M}_{ij} + \lambda m_B v_B^i v_B^j \mathrm{M}_{ij}$

:: fifth force ::

The ripples in the fabric caused by the ULDM are enough to perturb the system. However, things are much more fun if Dark Matter carries a fifth force…

Scalar: $L_I = m_A^\phi[1 + v_A^2/2] + m_B^\phi[1 + v_B^2/2] + G m_A^\phi m_B^\phi / r$

Linear coupling: $m_i^\phi = m_i[1 + \boldsymbol{\alpha}\Phi]$

Quadratic coupling: $m_i^\phi = m_i[1 + \boldsymbol{\beta}\Phi^2/2]$

López Nacir et al PRL2017 and PRD2020

Vector: $L_I = q_A v_A^i \mathrm{A}_i + q_B v_B^i \mathrm{A}_i$

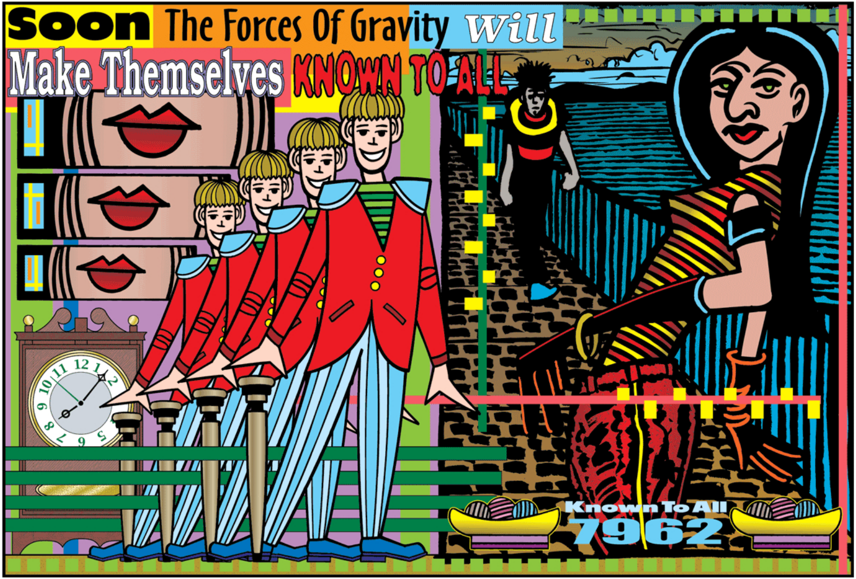
For example, $(B - L)$ charge: $q_i = \boldsymbol{g} c_i m_i / m_n$

López Nacir and FU JCAP2018

Tensor: $L_I = \lambda m_A v_A^i v_A^j \mathrm{M}_{ij} + \lambda m_B v_B^i v_B^j \mathrm{M}_{ij}$

In bigravity the universal coupling is $\alpha = \boldsymbol{\lambda}/m_{\mathrm{pl}}$

Armaleo, López Nacir and FU JCAP2020a


Soon The Forces Of Gravity Will
Make Themselves KNOWN TO ALL
Known To All
7962

:: perturb ::

The dark matter field is described by

$$M_{ij}(t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m} \cos\left(mt + \Upsilon\right) \varepsilon_{ij}(\mathrm{r})$$

:: perturb ::

The dark matter field is described by

$$M_{ij}(t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m}\cos\left(mt + \Upsilon\right)\varepsilon_{ij}(\mathsf{r})$$

from which one finds the curvature perturbations

$$h_{ij}(t) = \frac{\alpha}{M_{\mathrm{Pl}}}M_{ij}(t) = \frac{\alpha\sqrt{2\rho_{\mathrm{DM}}}}{mM_{\mathrm{Pl}}}\cos\left(mt + \Upsilon\right)\varepsilon_{ij}(\mathsf{x})$$

:: perturb ::

The dark matter field is described by

$$M_{ij}(t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m} \cos(mt + \Upsilon)\varepsilon_{ij}(\mathrm{r})$$

from which one finds the curvature perturbations

$$h_{ij}(t) = \frac{\alpha}{M_{\mathrm{Pl}}} M_{ij}(t) = \frac{\alpha\sqrt{2\rho_{\mathrm{DM}}}}{m M_{\mathrm{Pl}}} \cos(mt + \Upsilon)\varepsilon_{ij}(\mathrm{x})$$

This looks like a continuous gravitational wave

gravitational waves

:: continuous gravitational waves ::

:: continuous gravitational waves ::

Persistent

The coherence time is $t_{\text{coh}} := 4\pi/mv^2 = 2/fv^2 \sim 10^6/f$

:: continuous gravitational waves ::

Persistent

The coherence time is $t_{\rm coh} := 4\pi/mv^2 = 2/fv^2 \sim 10^6/f$

Quasi-monochromatic

The frequency is the same within $\lambda_{\rm dB} := 2\pi/mv = 1/fv \sim 10^3/f$

:: continuouſ gravitational waveſ ::

- Persistent
  The coherence time is $t_{\rm coh} := 4\pi/mv^2 = 2/fv^2 \sim 10^6/f$

- Quasi-monochromatic
  The frequency is the same within $\lambda_{\rm dB} := 2\pi/mv = 1/fv \sim 10^3/f$

- Continuous waves can be detected at much smaller sentitivity
  Thanks to a longer integration time and $h_0 \propto T_{\rm obs}^{-1/2} \sim T_{\rm obs}^{-1/4} T_{\rm chunk}^{-1/4}$

:: continuous gravitational waves ::

- Persistent

  The coherence time is $t_{\rm coh} := 4\pi/mv^2 = 2/fv^2 \sim 10^6/f$

- Quasi-monochromatic

  The frequency is the same within $\lambda_{\rm dB} := 2\pi/mv = 1/fv \sim 10^3/f$

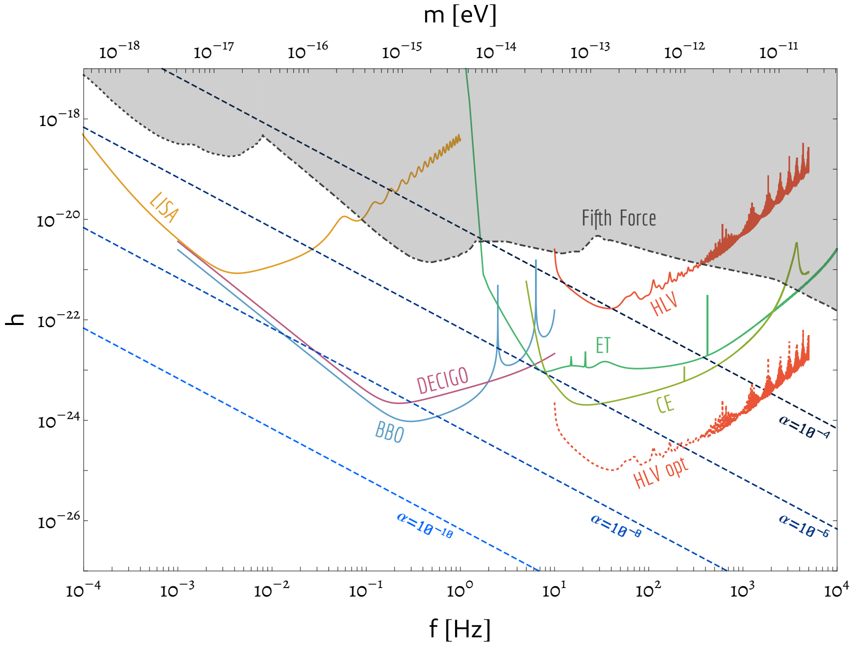
- Continuous waves can be detected at much smaller sentitivity

  Thanks to a longer integration time and $h_0 \propto T_{\rm obs}^{-1/2} \sim T_{\rm obs}^{-1/4} T_{\rm chunk}^{-1/4}$

- The overall magnitude scales as $1/m$ thanks to α

  C.f. the $1/m^2$ for spin-0 and spin-1 (without fifth forces)

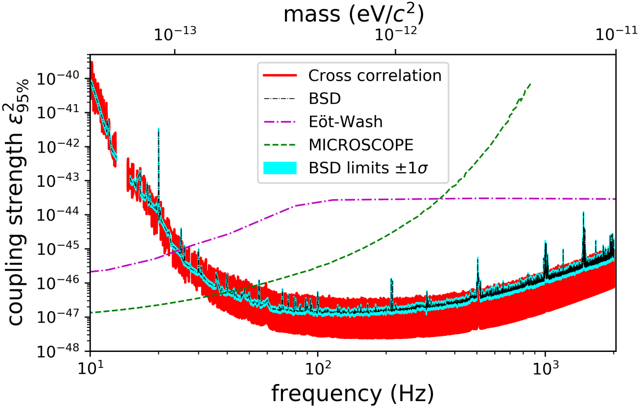
results



m [eV]
h
f [Hz]
LISA
DECIGO
BBO
Fifth Force
HLV
ET
CE
HLV opt
α=10⁻⁴
α=10⁻⁶
α=10⁻⁸
α=10⁻¹⁰

:: spin one ::

$$\mathcal{L}_{\text{int}} = \varepsilon e J^{\mu} A_{\mu}$$



for spin-2: work in progress!

:: ſummary ::

:: ſummary ::

Dark Matter remains a **mystery** in cosmology

:: summary ::

Dark Matter remains a **mystery** in cosmology

Ultra-light dark matter is an **especially interesting** candidate

:: ſummary ::

Dark Matter remains a **mystery** in cosmology

Ultra-light dark matter is an **especially interesting** candidate

Spin-2 ULDM is special because the action is **unique** and non-negotiable

:: ſummary ::

Dark Matter remains a **mystery** in cosmology

Ultra-light dark matter is an **especially interesting** candidate

Spin-2 ULDM is special because the action is **unique** and non-negotiable

The metric perturbations look like a **continuous** gravitational wave

:: summary ::

Dark Matter remains a **mystery** in cosmology

Ultra-light dark matter is an **especially interesting** candidate

Spin-2 ULDM is special because the action is **unique** and non-negotiable

The metric perturbations look like a **continuous** gravitational wave

We are sensitive to $\alpha \sim 10^{-6}$ **or less** with HLV at $m \sim 10^{-13}$ eV

:: ſummary ::

Dark Matter remains a **mystery** in cosmology

Ultra-light dark matter is an **especially interesting** candidate

Spin-2 ULDM is special because the action is **unique** and non-negotiable

The metric perturbations look like a **continuous** gravitational wave

We are sensitive to $\alpha \sim 10^{-6}$ **or less** with HLV at $m \sim 10^{-13}$ eV

We will be sensitive to $\alpha \sim 10^{-8}$ **or less** with LISA at $m \sim 10^{-137}$ eV

:: ſummary ::

Dark Matter remains a **mystery** in cosmology

Ultra-light dark matter is an **especially interesting** candidate

Spin-2 ULDM is special because the action is **unique** and non-negotiable

The metric perturbations look like a **continuous** gravitational wave

We are sensitive to $\alpha \sim 10^{-6}$ **or less** with HLV at $m \sim 10^{-13}$ eV

We will be sensitive to $\alpha \sim 10^{-8}$ **or less** with LISA at $m \sim 10^{-137}$ eV

Maybe, after all, Dark Matter arises as an **extension** of General Relativity

:: ſummary ::

Dark Matter remains a **mystery** in cosmology

Ultra-light dark matter is an **especially interesting** candidate

Spin-2 ULDM is special because the action is **unique** and non-negotiable

The metric perturbations look like a **continuous** gravitational wave

We are sensitive to $\alpha \sim 10^{-6}$ **or less** with HLV at $m \sim 10^{-13}$ eV

We will be sensitive to $\alpha \sim 10^{-8}$ **or less** with LISA at $m \sim 10^{-137}$ eV

Maybe, after all, Dark Matter arises as an **extension** of General Relativity

Armaleo, López Nacir, FU arXiv:2012.13997 [astro-ph.CO] — JCAP (2021)

...and work in progress (with LIGO/Virgo (and LISA?) working groups)