Dark Matter Production from Bubbles

Gravitational Wave Signals in Different Dark Matter Models

Montpellier-Sète 10/09/2025 – 12/09/2025

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Cofinanciado por la Unión Europea

AGENCIA ESTATAL DE INVESTIGACIÓN

MultiDark
Multimessenger Approach for Dark Matter Detection

IPARCOS

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Jose A. R. Cembranos
IPARCOS
Universidad Complutense de Madrid

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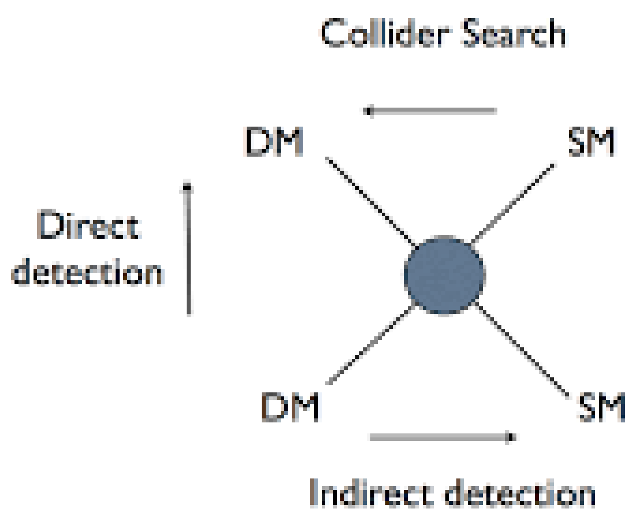
Dark Matter Searches

1. It became standard to talk about:

1.a. Particle Production (Colliders)

1.b. Direct Detection

1.c. Indirect Detection (Cosmic rays)



Dark Matter Searches

2. Other indirect searches:

- **2.a. Cosmological signatures:**
  - 2.a.1. Structure formation
  - 2.a.2. Primordial abundances
  - 2.a.3. Anomalies in the CMB
- **2.b. Astrophysical signatures:**
  - 2.b.1. Cooling of stellar objects
- **2.c. Laboratory signatures:**
  - 2.c.1. Electroweak precision observables.
  - 2.c.2. anomalous magnetic moments (muon g-2).
  - 2.c.3. Torsion balance experiments.

Gravitational waves as an evidence of Dark Matter

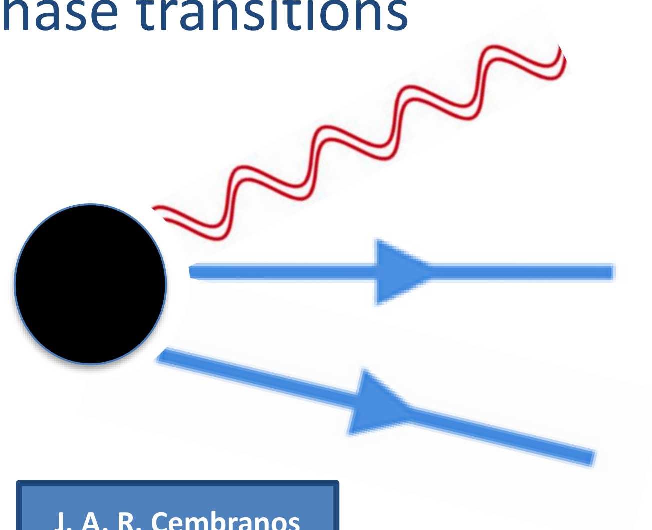
1. Gravitational waves as a proof of the Dark Matter framework

1.a. Proof of the Dark Matter production mechanism:

1.a.1. Freeze-in mechanism

1.a.2. Gravitational production

1.a.3. First order phase transitions



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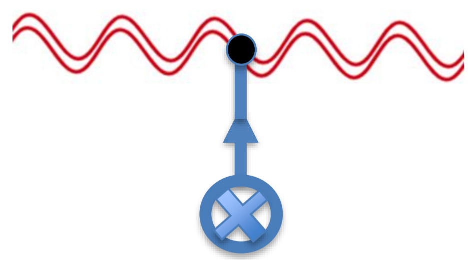
2. Gravitational waves directly associated with Dark Matter

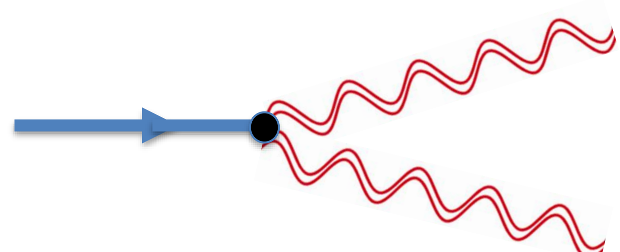
2.a. Gravitational waves modified by Dark Matter:

2.a.1. Ultralight Dark Matter



2.b. GW produced by Dark Matter:

2.b.1. Gravitational radiation or decays of Dark Matter



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JARC, Mindaugas Karciauskas, 2311.00378 [hep-ph]

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JARC, L. J. Garay, A. Parra-López, J.M. Sánchez Velázquez, 2310.07515 [gr-qc]

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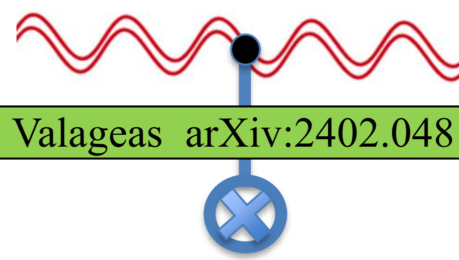

JARC, P. Brax, C. Burrage, P. Valageas arXiv:2402.04819 [astro-ph.CO]

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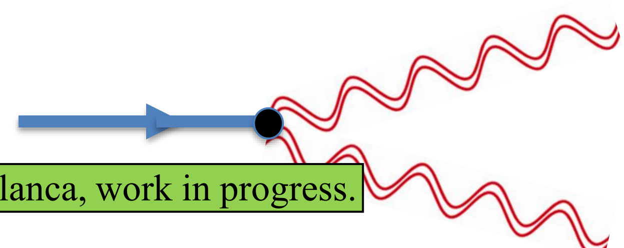

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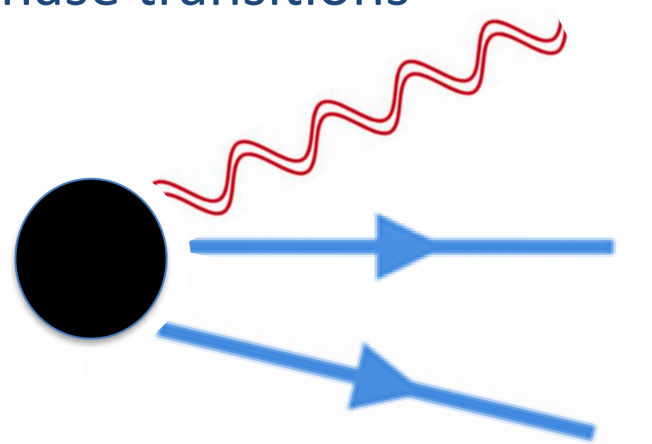

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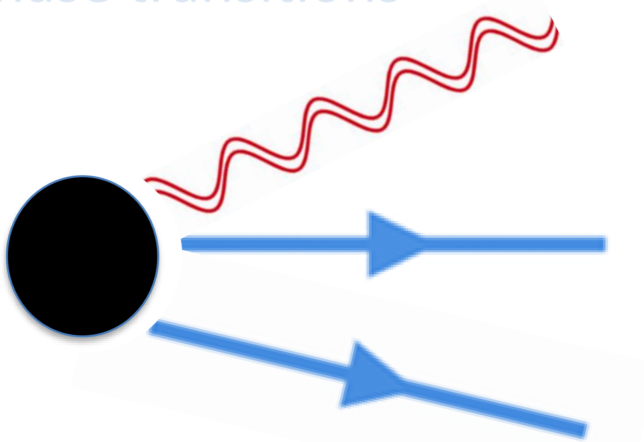

“Freeze-in” production and inflationary models

Botzmann equation:

$$\frac{d}{dt}n + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\mathrm{EQ}}^2),$$

By assuming that all the DM has been produced during reheating and by modelling this stage with the following evolution:

$$H = H_R \left(\frac{a}{a_R}\right)^{\beta}, \qquad T = T_R \left(\frac{a}{a_R}\right)^{\alpha},$$

1. “Standard” reheating: $\alpha = -3/8 \quad \beta = -3/2$

2. Kinaton reheating: $\alpha = -1 \quad \beta = -3$

JARC, Mindaugas Karciauskas, 2311.00378 [hep-ph]

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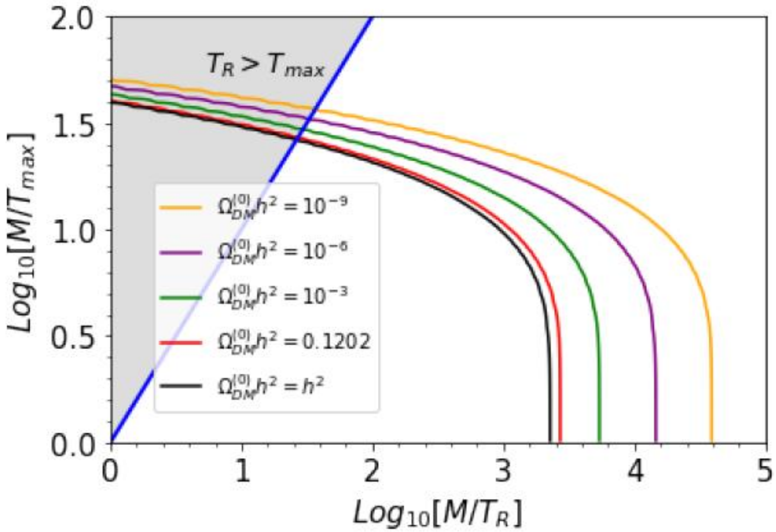
$$H = H_R \left(\frac{a}{a_R}\right)^{\beta}, \qquad T = T_R \left(\frac{a}{a_R}\right)^{\alpha},$$

Effective evolution for a model with radiation, inflaton and DM:

$$\begin{aligned}
\dot{\rho_\phi} + 3H\rho_\phi + \Gamma_\phi \rho_\phi = 0,\\
\dot{\rho_\gamma} + 4H\rho_\gamma - (1 - B_\chi)\Gamma_\phi\rho_\phi - \\
-\frac{\langle\sigma|v|\rangle}{m_\chi}\left[\rho_\chi^2 - (\rho_\chi^{\mathrm{EQ}})^2\right] - \Gamma_\chi(\rho_\chi - \rho_\chi^{\mathrm{EQ}}) = 0,\\
\dot{\rho_\chi} + 3H\rho_\chi - B_X\Gamma_\phi\rho_\phi + \\
+\frac{\langle\sigma|v|\rangle}{m_X}\left[\rho_\chi^2 - (\rho_\chi^{\mathrm{EQ}})^2\right] + \Gamma_\chi(\rho_\chi - \rho_\chi^{\mathrm{EQ}}) = 0.
\end{aligned}$$



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\dot{\rho_\chi} + 3H\rho_\chi - B_X \Gamma_\phi \rho_\phi &+ \\
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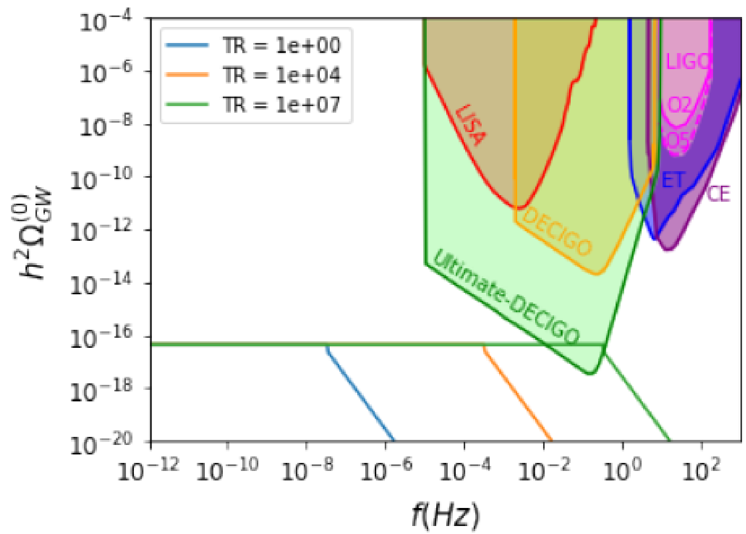

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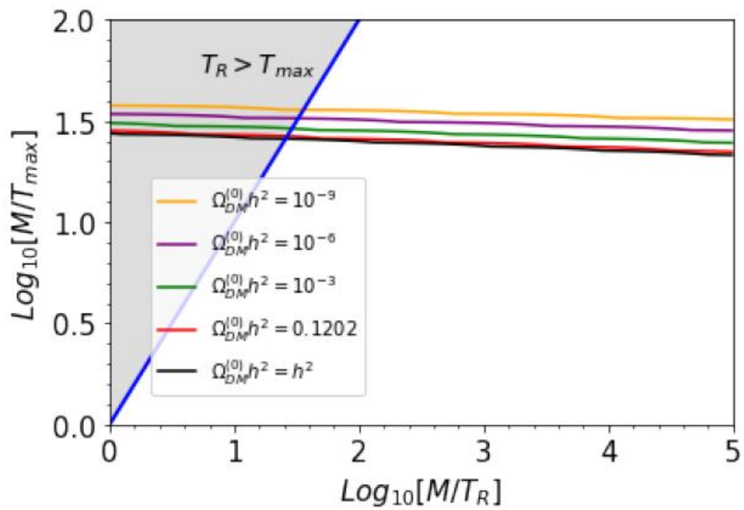
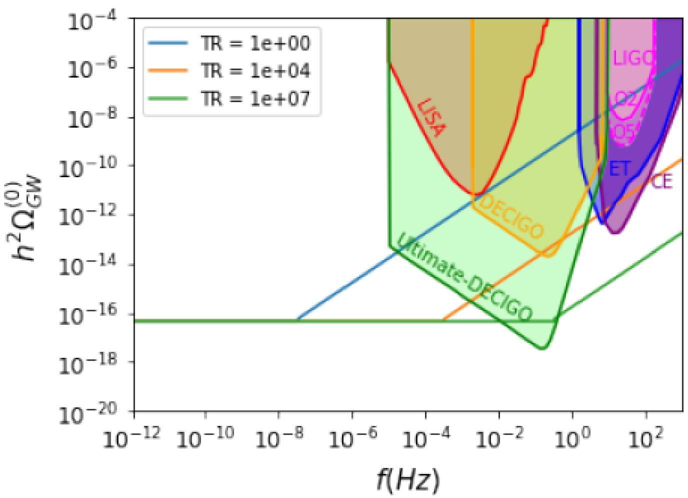
“Freeze-in” production and inflationary models

2. Kinaton reheating: $\alpha = -1 \qquad \beta = -3$

$$H = H_R \left(\frac{a}{a_R}\right)^{\beta}, \qquad T = T_R \left(\frac{a}{a_R}\right)^{\alpha},$$

Inflation followed by a kinaton dominated stage, radiation and DM.





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"Freeze-in" production and inflationary models

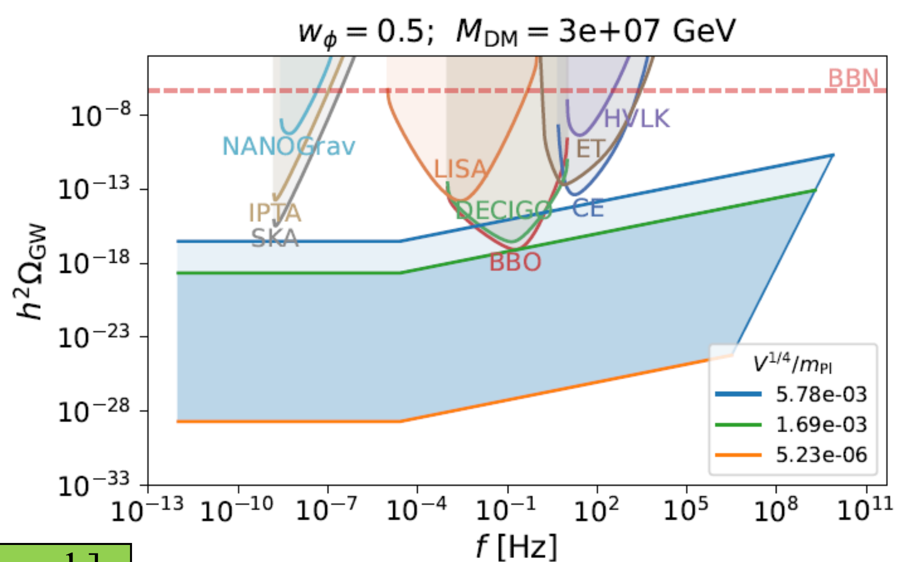
3. Between scenario 1. and 2., there are reheating models with power law minima for the inflaton:

$$V(\phi) \propto \phi^{2n}, \qquad w_\phi = \frac{n-1}{n+1}.$$

$$\Omega_{\rm GW} h^2(f) \simeq \Omega_{\rm GW}^{\rm rd} h^2 \times \begin{cases} 1 & f < f_{\rm reh} \\ \mathcal{A}_{\rm s}\left(\frac{f}{f_{\rm reh}}\right)^{-2\frac{1-3w_\phi}{1+3w_\phi}} & f > f_{\rm reh} \end{cases},$$

In general:

$$H \simeq H_{\rm I}\left(\frac{a}{a_{\rm I}}\right)^{-\frac{3}{2}(1+w_\phi)}$$



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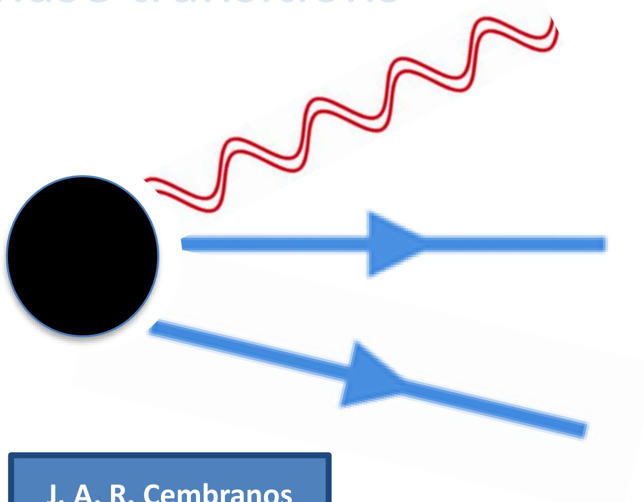
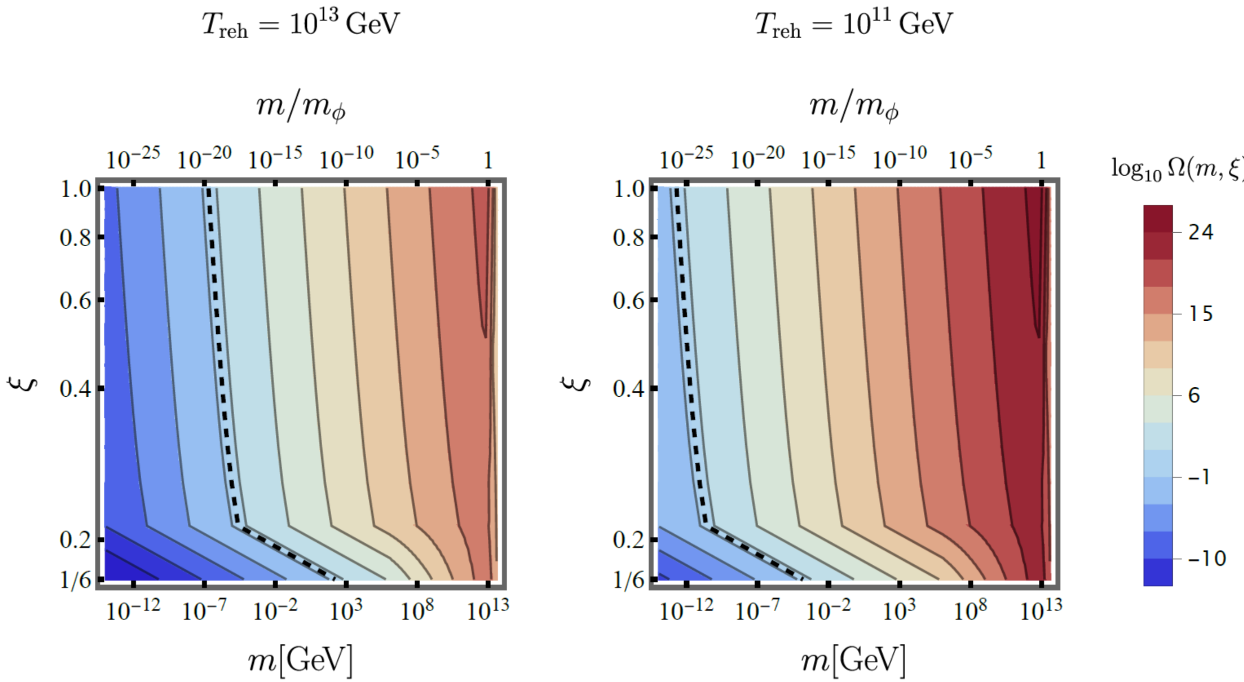


Gravitational production of Scalar DM

Non-interacting scalar field with action

$$S = -\frac{1}{2}\int d^4x\sqrt{-g}[\partial_\mu\varphi\partial^\mu\varphi + (m^2 + \xi R)\varphi^2]$$

Non-minimal coupling to the curvature



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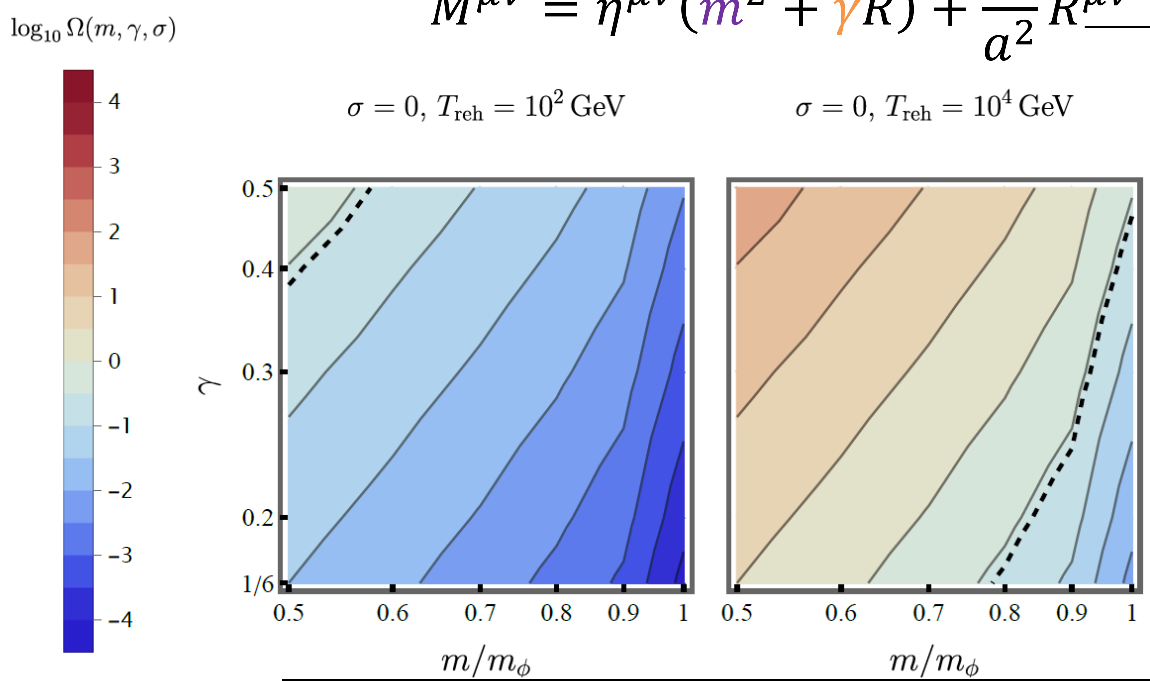
Gravitational production of vector DM

Non-interacting vector field with action

$$S = -\frac{1}{2}\int d^4x\, [\frac{1}{2}F^{\mu\nu}F_{\mu\nu} + a^2 M^{\mu\nu}A_\mu A_\nu]$$

Effective tensor with couplings γ and σ

$$M^{\mu\nu} = \eta^{\mu\nu}(m^2 + \gamma R) + \frac{\sigma}{a^2}\tilde{R}^{\mu\nu} \longrightarrow \tilde{R}^{\mu\nu} = R^{\mu\nu} - g^{\mu\nu}R/4$$



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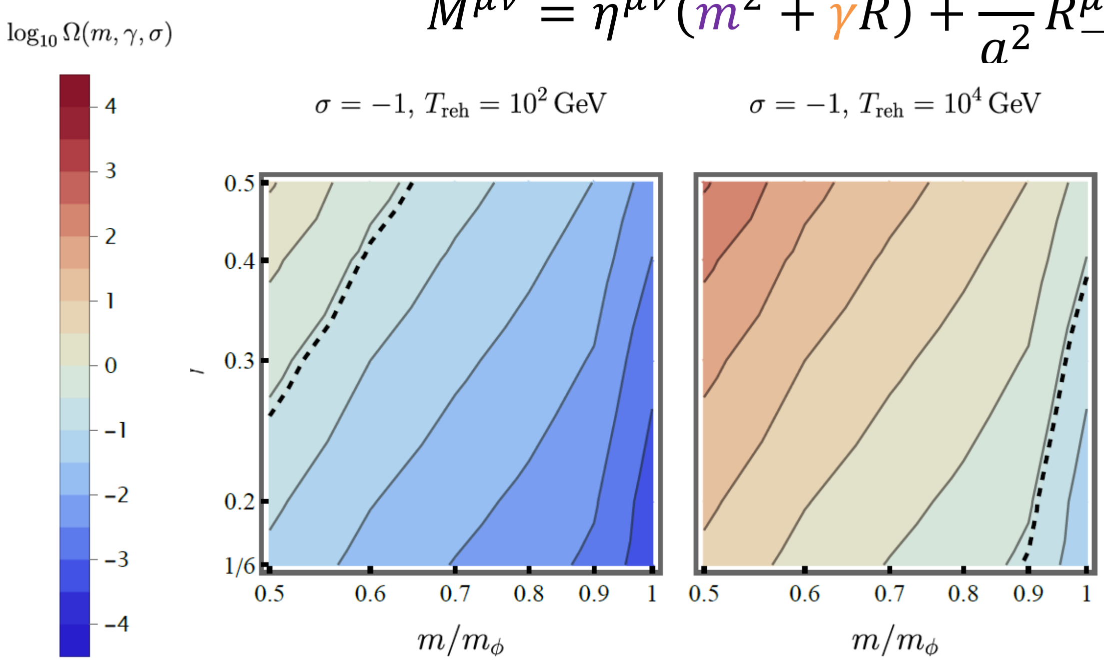

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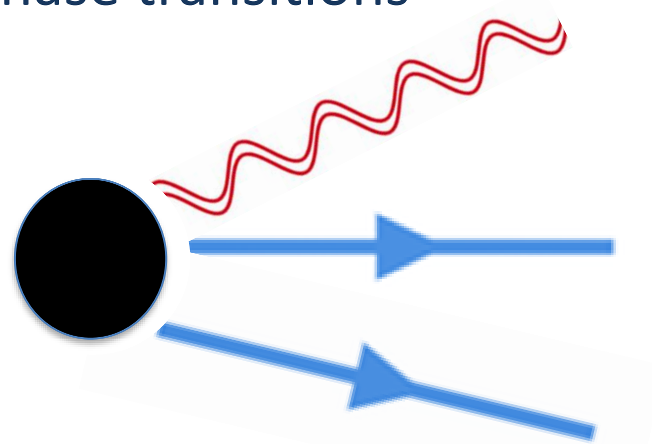
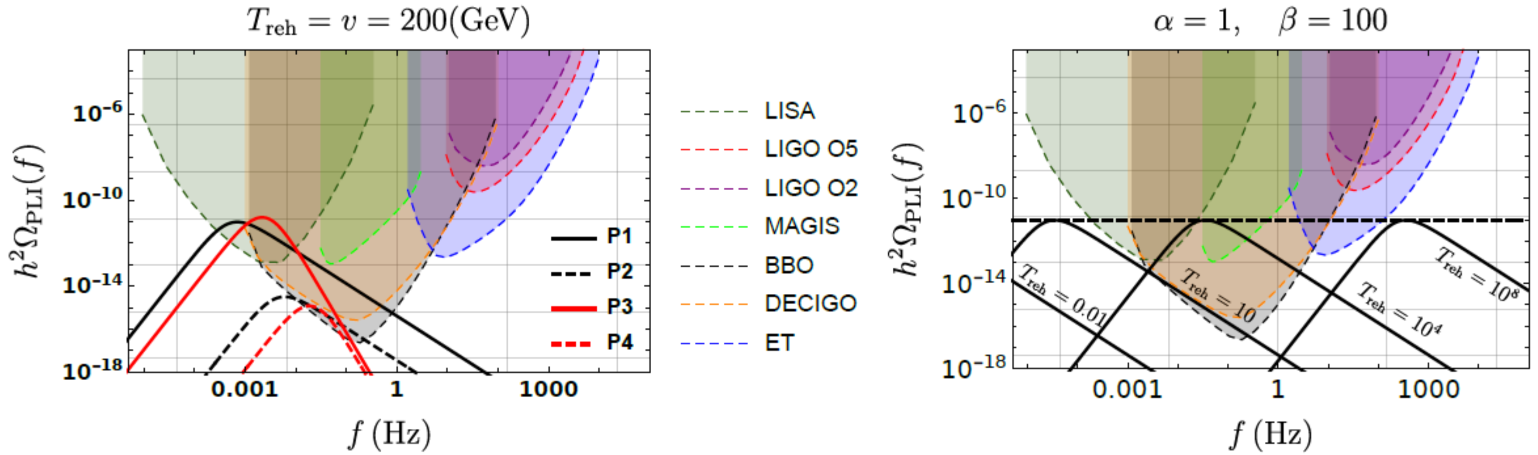


Production in first order phase transitions

Dark Matter production by bubble expansion

In this regimen, efficient production of particles with mass: $M \sim \sqrt{\gamma_w} T_{\rm nuc}$,

This mechanism dominates the one associated to bubble collisions in large portion of parameter space



A. Azatova, M. Vanvlasselaera, W. Yind, JHEP 288 (2021)

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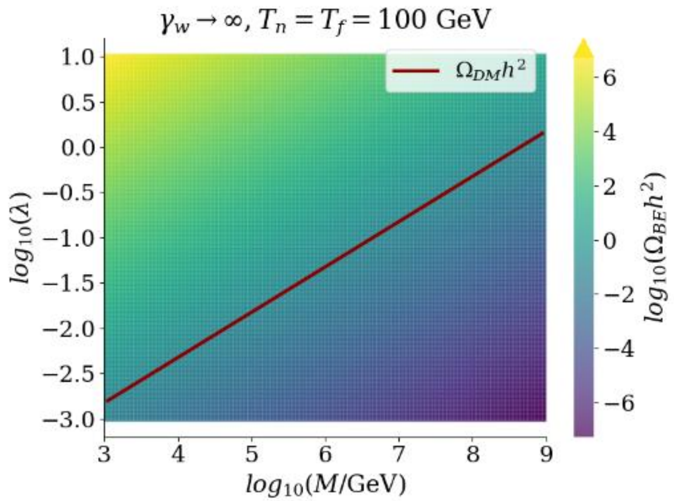
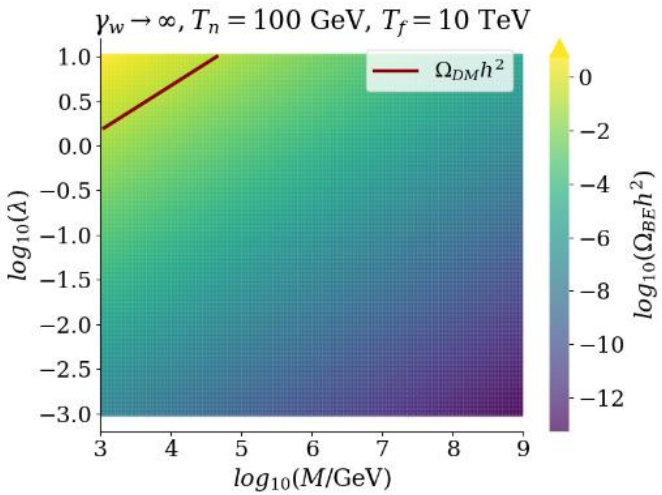
$$\mathcal{L}_{int} = -\lambda h^2 \phi^2 / 2$$

$$\Omega^0_{BE} h^2 = 1,35 \cdot 10^5 \frac{\lambda^2}{g_{\star s}} \frac{v^2}{M_\phi GeV} \left(\frac{T_{nuc}}{T_{reh}} \right)^3$$





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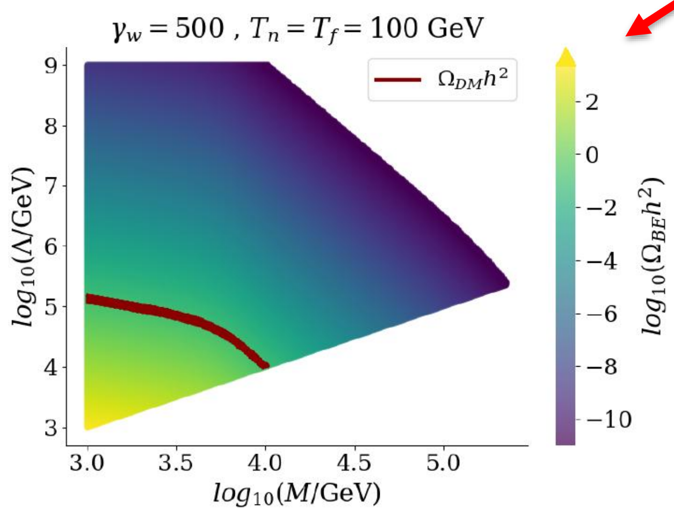
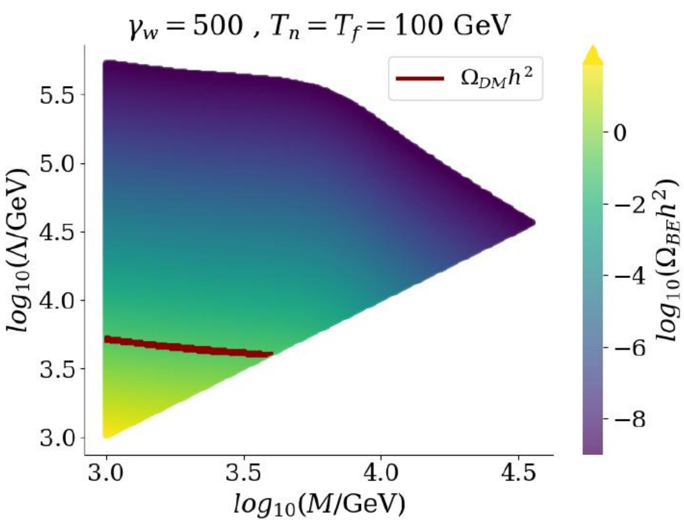
n = 3 *n = 4*





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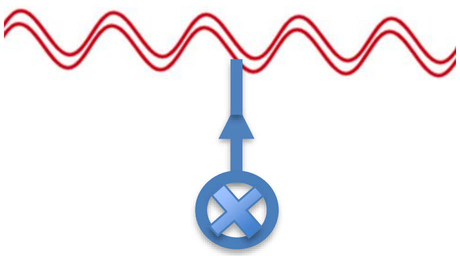
2. Gravitational waves directly associated with Dark Matter

2.a. Gravitational waves modified by Dark Matter:

2.a.1. Ultralight Dark Matter



2.b. GW produced by Dark Matter:

2.b.1. Gravitational decays of Dark Matter

Ultralight dark matter

Ultralight Dark Matter related to coherent scalar fields form high density structures (solitons).

These scalar fields oscillates rapidly with a frequency associated to their mass: $\phi(\vec{x},t) = A(\vec{x},t)\ \cos[m_\phi t + \alpha(\vec{x},t)].$

Binary systems allow to prove these DM structures by inducing variations in the frequency of the gravitational waves related to a similar effect to the well-known Sachs-Wolfe of the CMB:

$$\frac{\Delta f}{f} = \Psi_N(\vec{x},t) - \Psi_N(\vec{x}_e,t_e),$$

Ultralight DM modifies the Newtonian potential as

$$\Psi_N(\vec{x},t) = \Psi_0(\vec{x}) + \Psi_{\rm osc}(\vec{x})\cos[\omega t + 2\alpha(\vec{x})], \qquad \omega = 2m_\phi.$$

JARC, P. Brax, C. Burrage, P. Valageas arXiv:2402.04819 [astro-ph.CO]

Ultralight dark matter

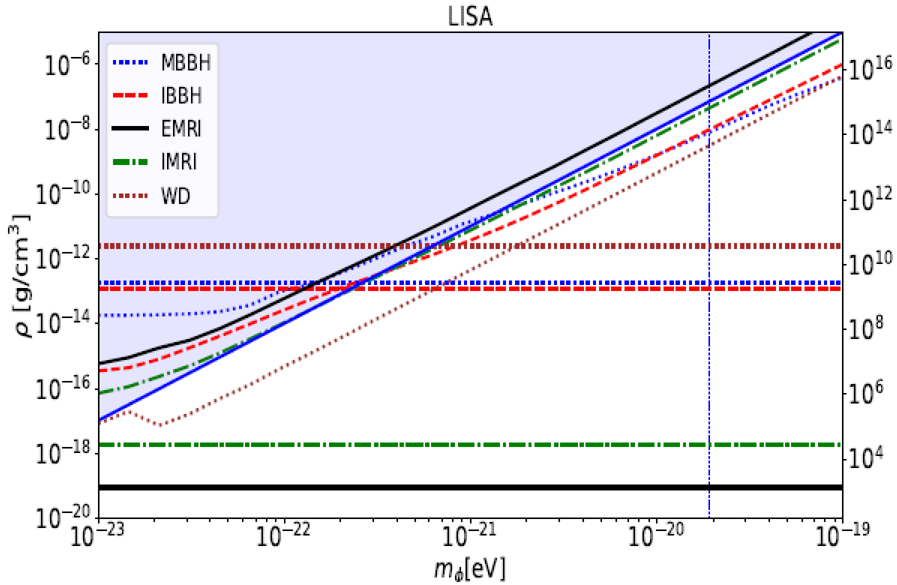
Ultralight Dark Matter related to coherent scalar fields form high density structures (solitons).

Identified backgrounds for this signal:

- Impact of the DM halo
- Mass increase effect of compact objects
- Gravitational friction

B. LISA

	m_1 ($M_\odot$)	m_2 ($M_\odot$)	SNR
MBBH	10^6	5×10^5	3×10^4
IBBH	10^4	5×10^3	708
IMRI	10^4	10	64
EMRI	10^5	10	22
WD	0.4	0.3	7



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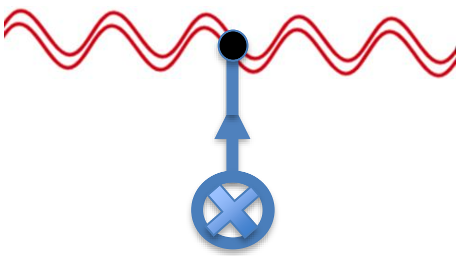

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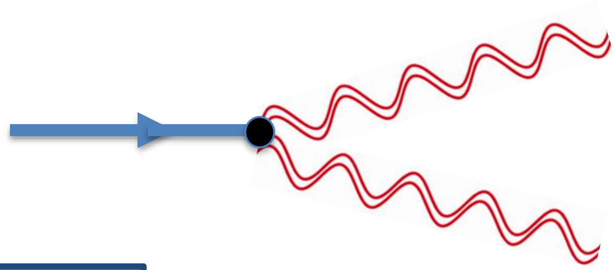


Instable DM decaying into gravitons

Assumptions:

- Instable DM
- Main decay channel produce gravitons

  Example: $\phi \to 2h$ (monochromatic GWs: $m_\phi/2$)
- General study in terms of

  m_ϕ: mass of the particle

  τ : DM lifetime
- Limits:
  - $m_\phi > 10^{-22}$ eV.
  - $\tau > t_0$.

Contributions:

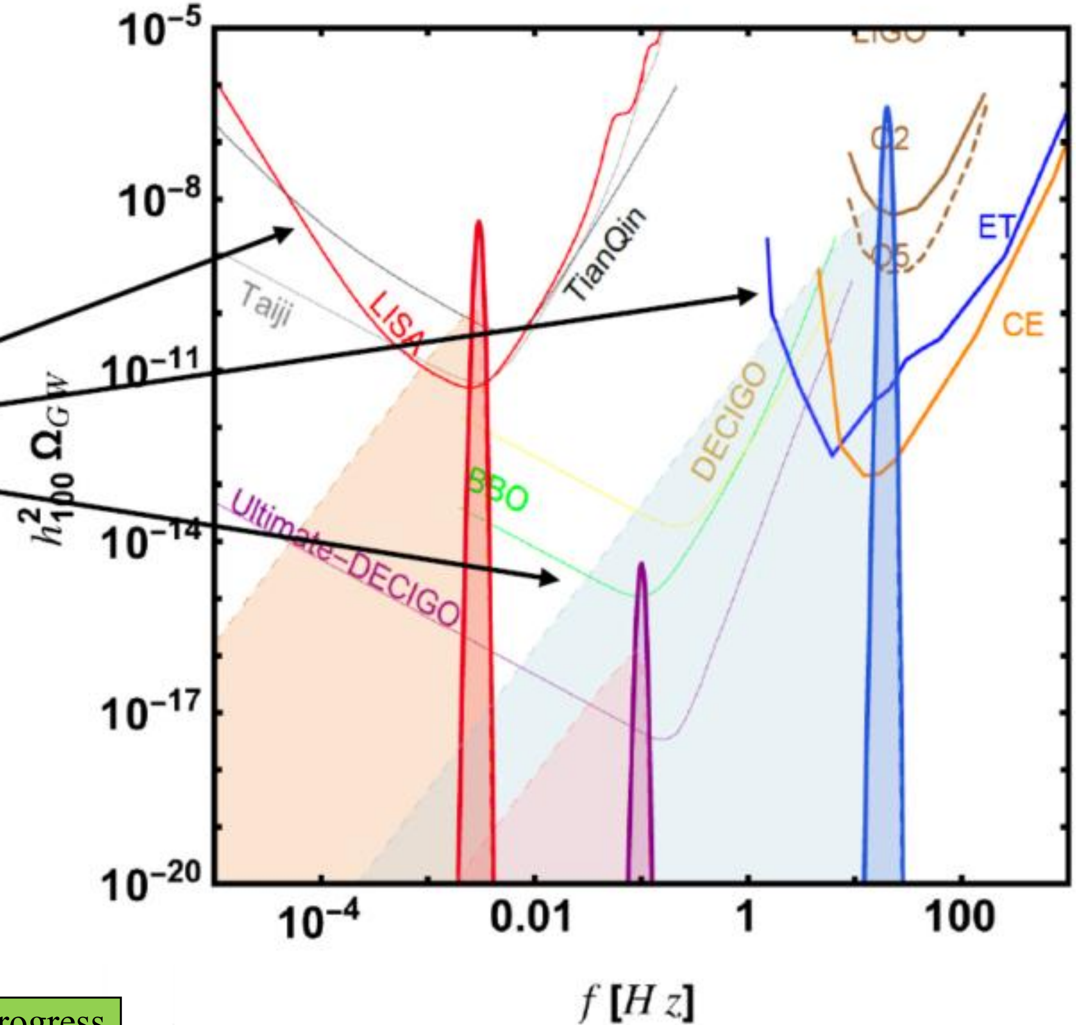
- Extragalactic contribution
- Local contribution

JARC , A. Cendal, I. Mariblanca, work in progress.

Instable DM decaying into gravitons

$$h_{100}^2 \Omega_{GW} \propto f^2 \frac{d\Phi}{dE}$$

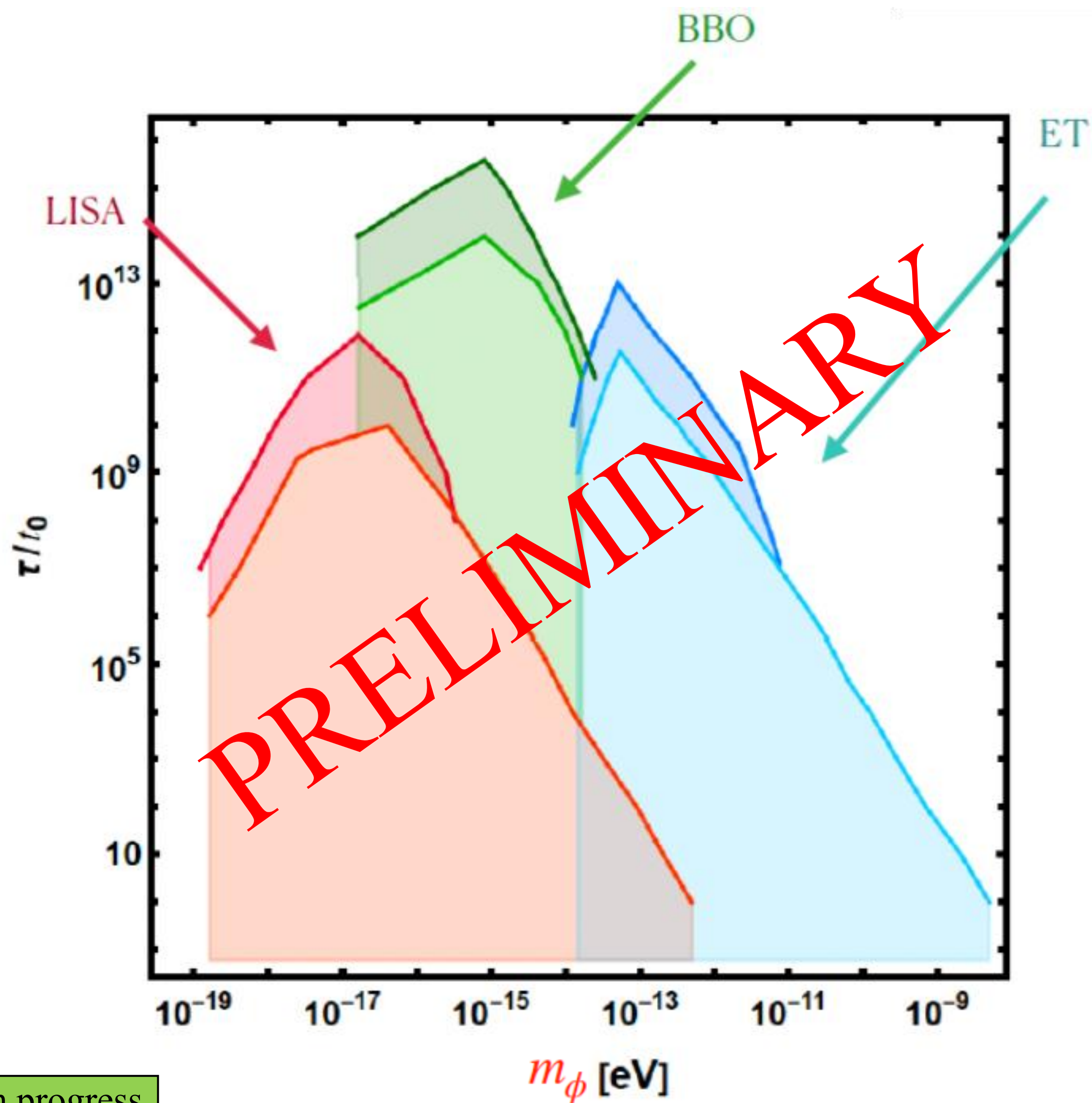
Sensitivity curves



JARC , A. Cendal, I. Mariblanca, work in progress.

Instable DM decaying into gravitons

Range of parameters that allow indirect detection of dark matter with gravitational wave telescopes



JARC , A. Cendal, I. Mariblanca, work in progress.

Conclusions

We have discussed the connection between different dark matter models and their gravitational signatures. In particular, they can help to determine features of the dark matter:

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