SEARCHING FOR ULTRALIGHT DARK MATTER WITH GWS

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Based on arXiv:2409xxx

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INTRODUCTION TO ULTRALIGHT DARK MATTER (ULDM)

Dark Matter (DM)

Number density: $n_{gal} = \frac{N}{V_{gal}} \sim \frac{M_{gal}}{m} \times \frac{1}{V_{gal}} \sim \frac{1}{m} \times \frac{10^{12} M_{\odot}}{(30\ kpc)^3}$

De Broglie Wavelength: $\lambda_{db} \sim 0.5\ kpc \left(\frac{10^{-22} eV}{m}\right)\left(\frac{250\ km\ s^{-1}}{v}\right)$

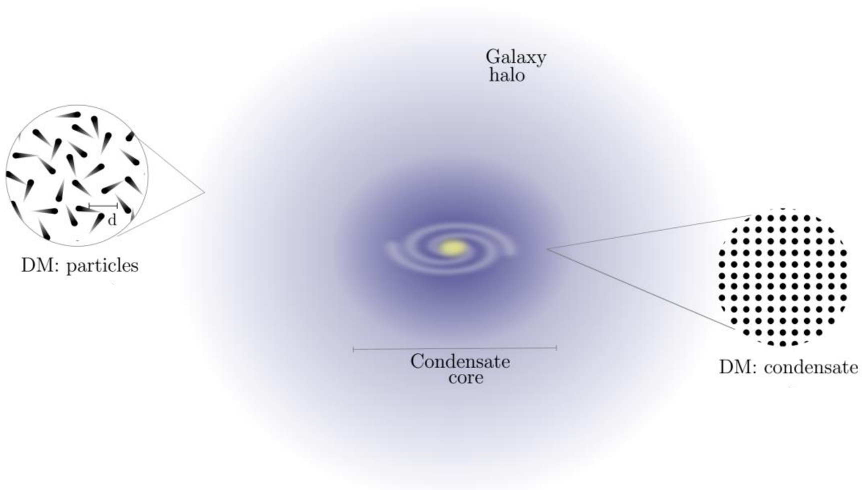
Occupation number : $\mathcal{N} = n\, \lambda_{db}^3 \sim 10^{92} \times \left(\frac{10^{-22} eV}{m}\right)^4$

Given $\mathcal{N} \gg 1$ for $m \ll O(10) eV$ DM can be described by a classical field with

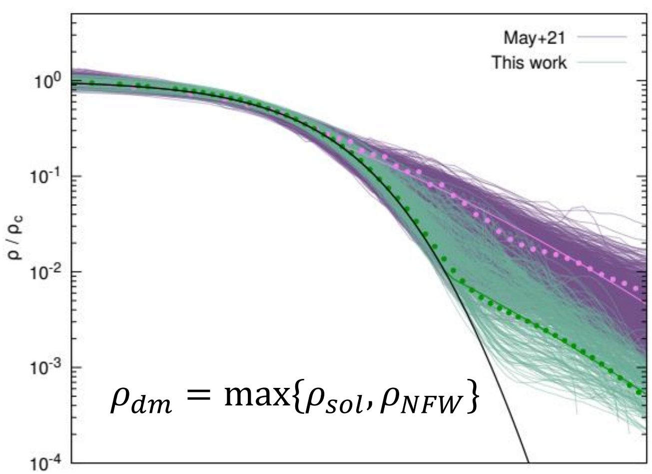
EOM: $\Box\phi + m^2\phi = 0$

Homogeneous solution are given by an oscillating field with frequency $\omega = m$

ULDM FIELD AT GALACTIC SCALE



Ferreira 2005.03254 & Chan 2110.11882



Parametrizing the space dependent part of the field $\phi = \frac{(\psi e^{imt} + \psi^* e^{-imt})}{\sqrt{2m}}$ and the metric

$$g_{\mu\nu} dx^\mu dx^\nu \approx -(1 - 2\Phi) dt^2 + (1 + 2\Psi)\delta_{ij} dx^i dx^j$$

Schrodinger-Poisson (SP) system of equations:

$$\mathrm{i}\,\partial_t \psi = -\left\{\frac{\nabla^2}{2\,m} + m\left[\langle\Phi\rangle + \frac{\rho_{dm}}{8\,\mathrm{m}^2 f^2}\right]\right\}\psi$$

$$\nabla^2\langle\Phi\rangle = -\,4\,\pi\,(\rho_{dm} + \rho_m)$$

Numerical simulations show always the formation of a dense coherent structure, i.e. **soliton**, at the centre of the galactic halo.

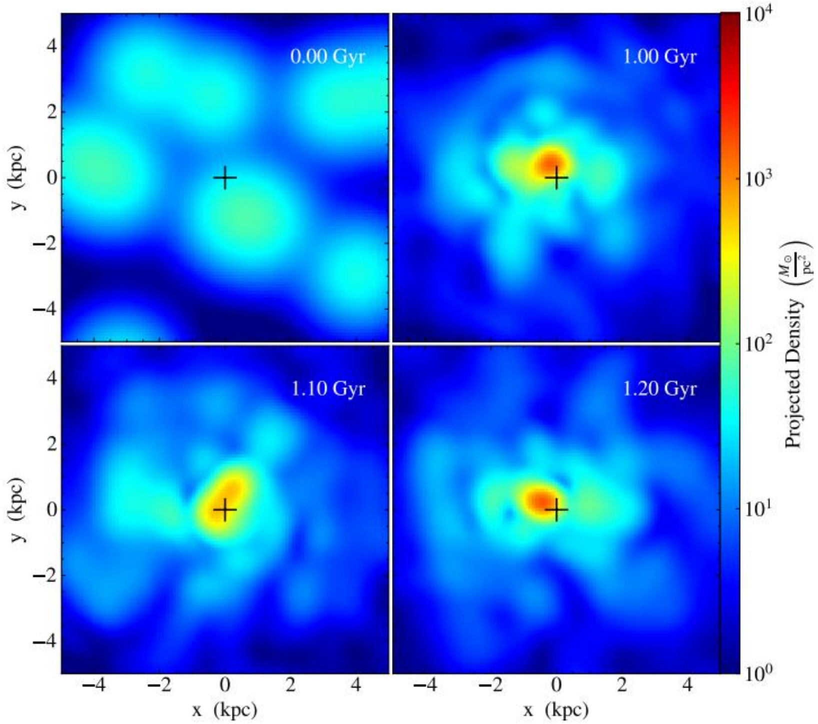
The soliton is a stationary solution of the SP equations (non-relativistic limit) with density profile

$$\rho_{sol} = \frac{\rho_0}{\left(1 + 0.091\left(\frac{r}{r_c}\right)^2\right)^8}$$ with core radius

$$r_c \sim 0.2\,kpc\left(\frac{10^{-22} eV}{m}\right)^2\left(\frac{10^9 M_\odot}{M_{sol}}\right) \sim 0.4\,\lambda_{db}$$

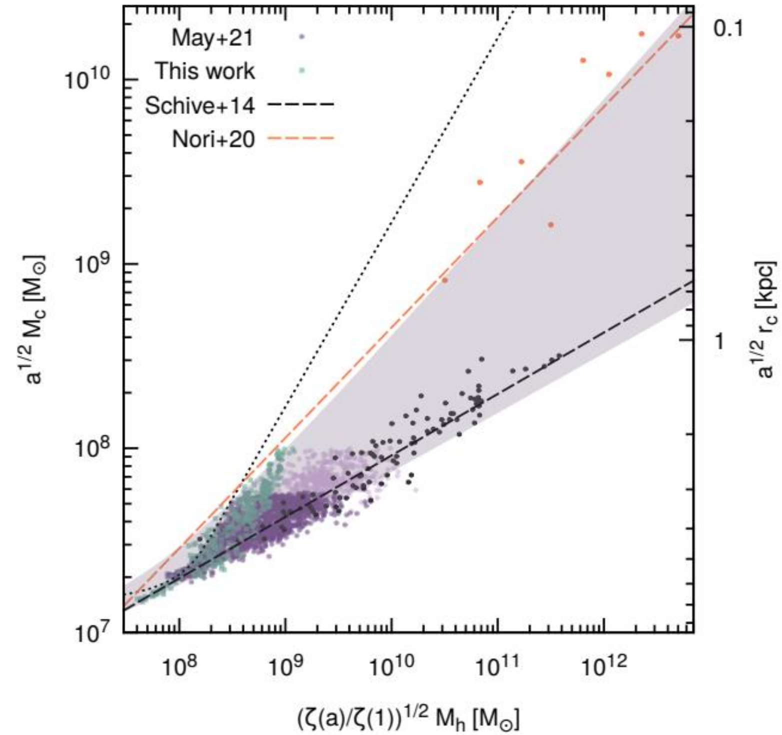
HALO AND SOLITON FORMATION

Hui 2101.11735



Different ideas to test this model ↦ we focus on the effect of propagation of radiation in this DM environment

Ferreira 2005.03254

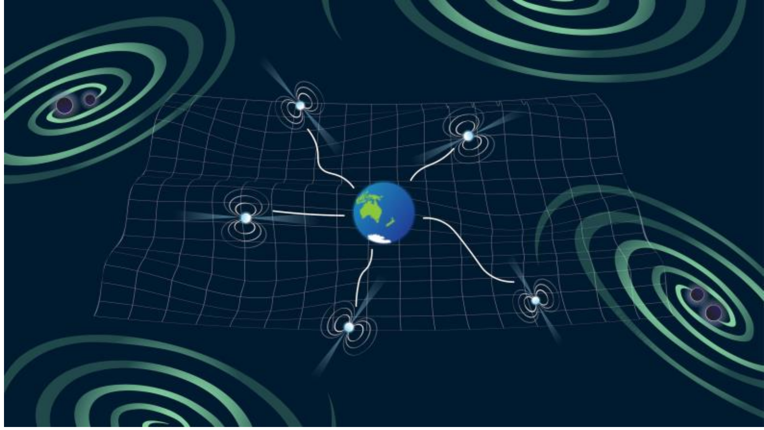


The mass of the soliton is related to the mass of the DM halo where it is formed. Schive 1407.7762

$$M_{sol} \approx 1.4 \times 10^9 \left(\frac{10^{-22} eV}{m_{dm}}\right)\left(\frac{\mathrm{M_{halo}}}{10^{12}\mathrm{M_\odot}}\right)^{\frac{1}{3}}$$

But some dispersion is observed in the literature

GRAVITATIONAL REDSHIFT



Because of the inhomogeneities of the gravitational background along the line of sight a signal experiences gravitational redshift

$$\frac{\Delta\omega_e}{\omega_e} \simeq \Phi|_e^r + n^i\, v_i|_e^r - I_{ISW} \text{ where}$$

$$I_{ISW} = (\Phi+\Psi)|_e^r + n^i \int_e^r \partial_i(\Phi+\Psi)\, d\lambda$$

The DM background oscillates, then the gravitational potentials also oscillate.

Decomposing $\Psi = \langle\Psi\rangle + \delta\Psi\cos(\omega_\delta t)$ as well as for Φ, from Einstein equations one finds

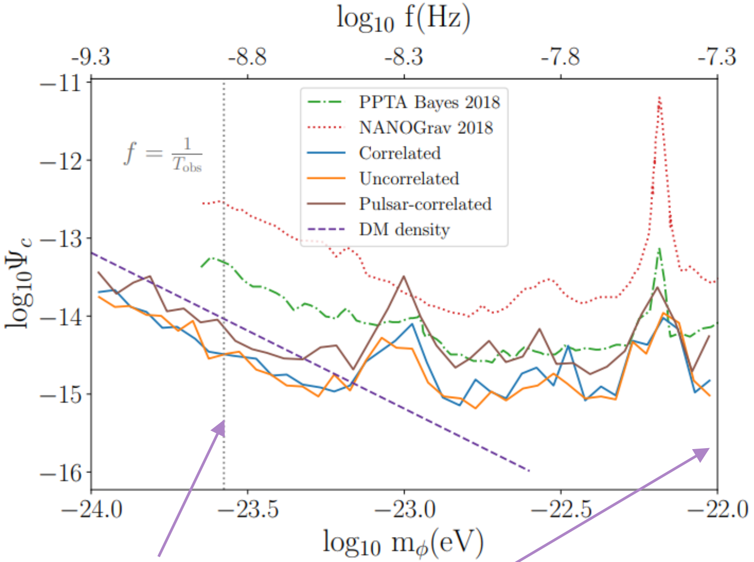
Khmelnitsky & Rubakov 1309.5888

$$\delta\Psi = -\frac{\pi\rho}{m^2} \text{ and } \omega_\delta = 2m$$

Periodic modulation in the time of arrival residuals of millisecond Pulsars

$$\Delta t \simeq -\int_0^t \frac{\Delta\omega_e(t')}{\omega_e}\, dt' \simeq -\int_0^t (\Psi_e - \Psi_r)\, dt'$$

Clemente et al. 2023, 2306.16228



$$f_{low} = \frac{1}{T_{obs}} \qquad f_{high} = \frac{1}{\delta t_{obs}}$$

$$T_{obs} \sim 25\ years \qquad \delta t_{obs} \sim 3\ weeks$$

CASE OF GRAVITATIONAL WAVES

Look at María José Bustamante-Rosell 2021

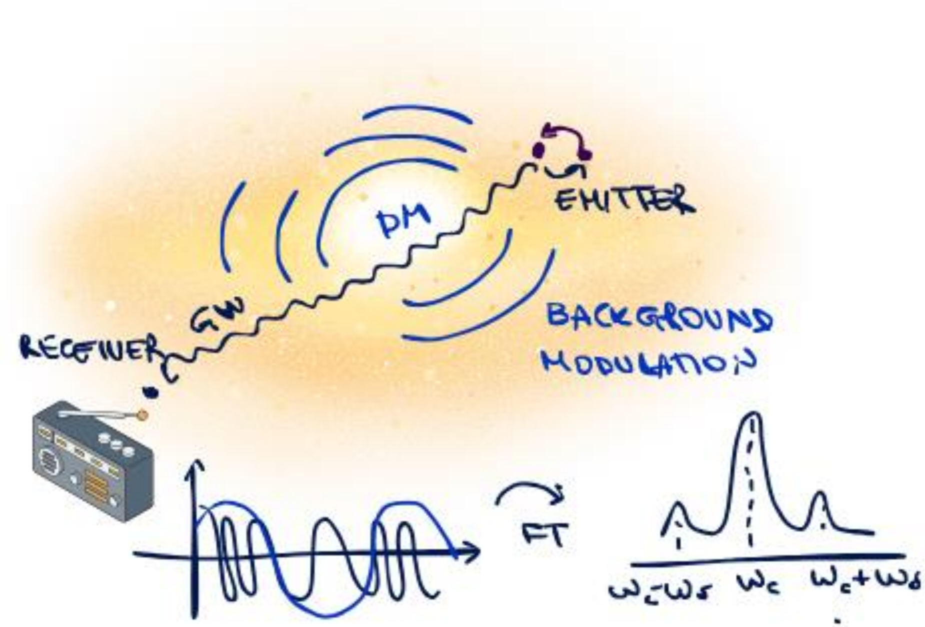
The same as for Pulsars will happen for any radiation at a fixed frequency $\omega_e \Rightarrow$ GW will experience frequency modulation. First, let's consider a monochromatic GW:

$$h_{GW} = A\cos\left(\omega_e u + \varphi\right) + A\frac{\omega_e}{\omega_\delta}\Upsilon|_e \sin[(\omega_e \pm \omega_\delta)\, u + \varphi)]$$

carrier frequency

modulation frequency

- GW emitters could come from inside the soliton (not contaminated by dust in the GC)
- Could be more abundant than Pulsars in PTA
- No limitation on observation time (higher frequency could be reached)
- Signal from other Galaxies



Signal-to-Noise-Ratio (SNR) of sidebands:

$$SNR_\delta = \frac{1}{\sqrt{2}}\frac{\omega_e}{\omega_\delta}\Upsilon(\rho_0, m, x_e) SNR_h$$

Amplitude of the modulation

of the carrier

AMPLITUDE OF THE MODULATION Υ

- Minimal coupling: pure gravitational interaction

With $\delta\Phi = \Phi_2 \cos(2mt)$ and $V = \frac{1}{2} m^2 \phi^2 (1 - \frac{1}{12}\frac{\phi^4}{f^4})$

Solutions are given by 2^{nd} order Einstein equations

$$\nabla^2 \left[\Psi_2 + \frac{\pi\rho}{m^2}\right] = -\frac{\pi}{6 f^2 m^2}\,\rho^2$$

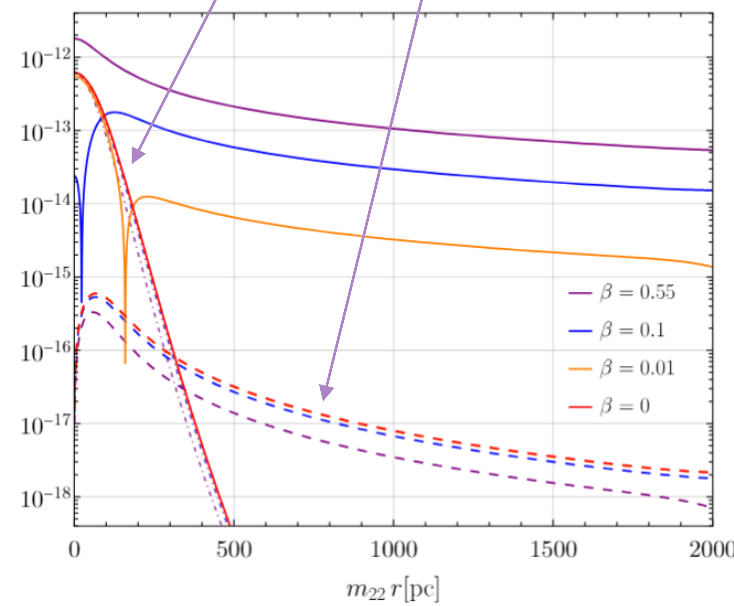
$$\nabla^2 \Phi_2 = 8\pi\,[5\langle\Phi\rangle + \gamma - \frac{\rho}{12 f^2 m^2}]\,\rho$$

- Direct coupling: ULDM directly coupled to SM (e.g. $m_\chi \frac{\phi}{\Lambda_1}\bar{\chi}\chi$ or $m_\chi \frac{\phi^2}{\Lambda_2^2}\bar{\chi}\chi$), under a conformal transformation to the Jordan-Fierz metric:

$\widetilde{g_{\mu\nu}} = A^2(\phi) g_{\mu\nu}$, with $A \simeq 1 + \frac{\phi}{\Lambda_1}$ or $A \simeq 1 + \frac{\phi^2}{\Lambda_2}$

$$\Rightarrow \Upsilon = \frac{\sqrt{2}}{\Lambda_1}\left(\frac{\rho}{m^2}\right)^{1/2}\Big|_e \text{ and } \Upsilon = \frac{1}{\Lambda_2^2}\left(\frac{\rho}{m^2}\right)\Big|_e$$

$$\Upsilon = \Psi_2 - \frac{2}{\omega_\delta} n^i \partial_i \Phi_2 \Big|_e$$



$$\beta \simeq \frac{0.024}{m_{22}}\left(\frac{10^{16} Gev}{f_\phi}\right)^2 \sqrt{\frac{\rho_0}{10^3 M_\odot pc^{-3}}}$$

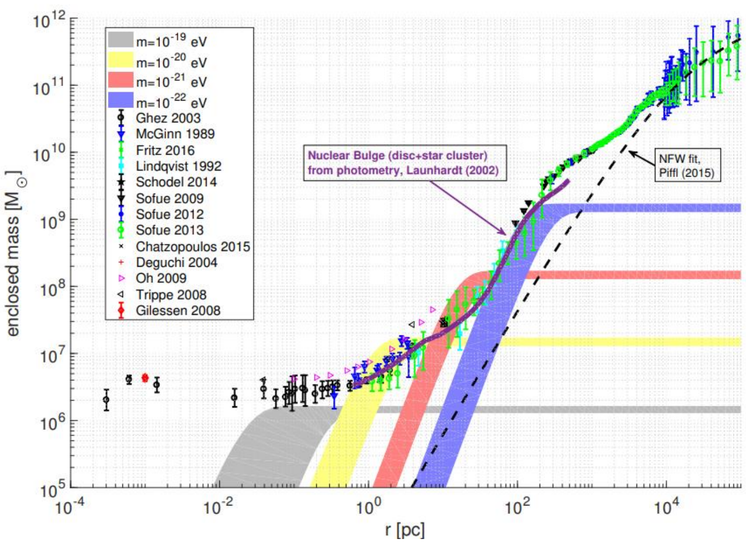
Self-interaction increases the effect at larger radius

RESULTS FOR THE MILKY WAY

- Observational constraints:

kinematic data show a preference of a for an inner cored profile in the bulge with mass

$M_{core} \leq 6 \times 10^9 M_\odot$ within $r_c \sim 0.25\ kpc$, average density of $\rho_0 \sim 10^3 M_\odot pc^{-3}$ compatible with a ULDM soliton



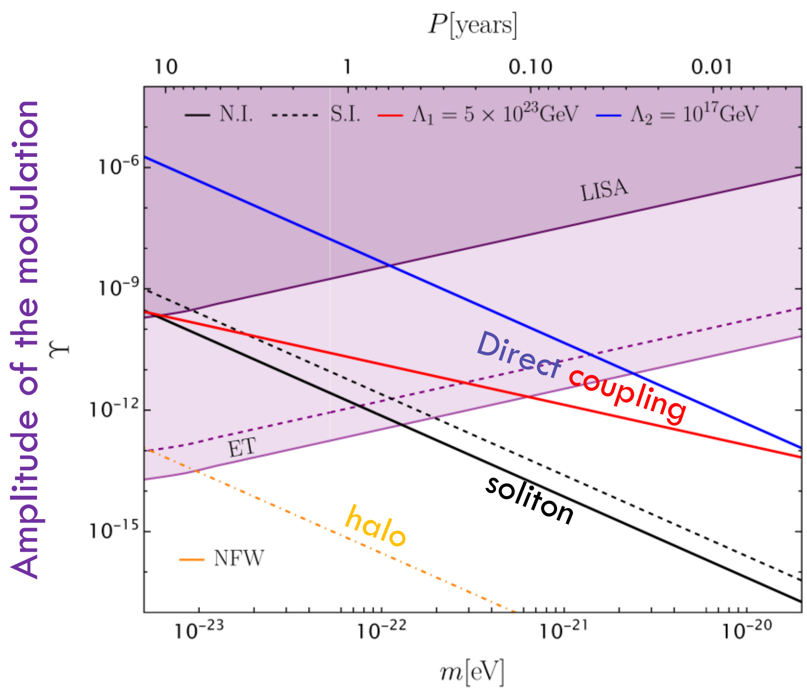
- Astrophysical populations of galactic monochromatic GW sources:
  - White Dwarfs/ X-MRIS $\longrightarrow\ f_e \sim mHz$ (detectable by LISA, TianQin, Taiji)
  - Deformed Spinning Neutron Stars $\longrightarrow\ f_e \sim kHz$ (detectable ET/CE)

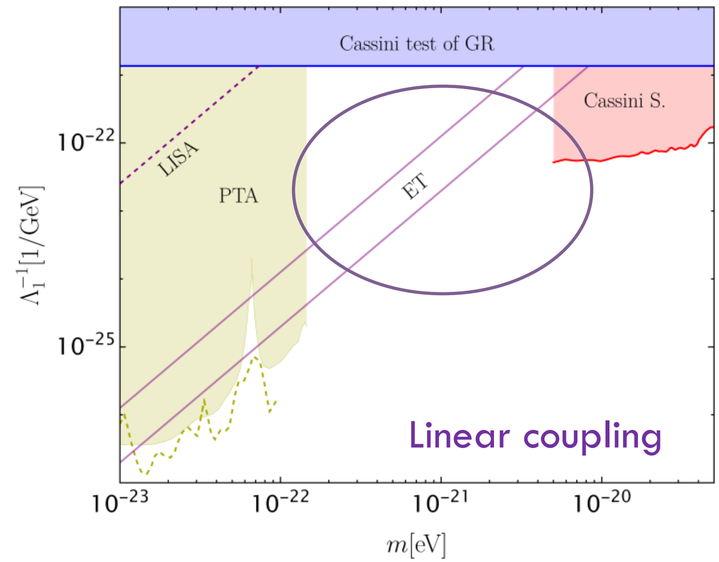
Expected/Simulated values for the calculation of the sensitivity from different astrophysical populations (N carriers)

$$SNR_\delta = \frac{1}{\sqrt{2}} \frac{\omega_e}{\omega_\delta} \Upsilon(\rho_0, m, x_e) \sqrt{N}\, SNR_h$$

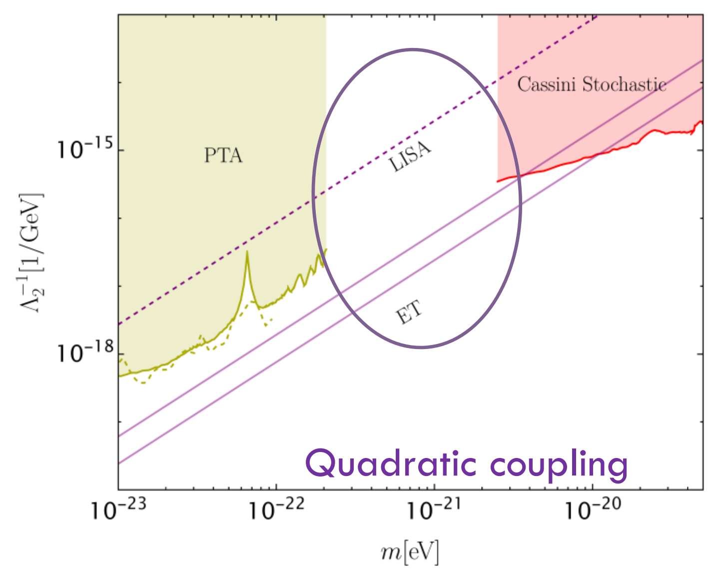
	N	$\langle \mathrm{SNR}_h \rangle$	$\sqrt{N}\langle \mathrm{SNR}_h \rangle \langle f_e \rangle [\mathrm{Hz}]$	
	Double White Dwarfs			
LISA	$5.5(1.6) \times 10^3$	37(38)	7.8(4.3)	
TianQin	$2.5(0.7) \times 10^3$	37(37)	5.1(2.9)	
Taiji	$5.8(1.7) \times 10^3$	59(60)	13(6.8)	
μAres	$504(148) \times 10^3$	49(48)	97(52)	
	X-MRIs			
LISA	$\mathcal{O}(5)$	$\sim 10^3$	~ 10	1903.10871
	Spinning NSs			
ET/CE	$\mathcal{O}(200)$	~ 30	$\sim 10^5$	2303.04714

SENSITIVITIES TO ULDM IN THE MW





Great prospects for direct coupling: ET and LISA can probe the uncover window at masses $2 \times 10^{-22}\ eV \leq m \leq 3 \times 10^{-21}\ eV$



Spinning NS in ET outperform compared to LISA binaries

Not possible to probe NFW profile for $m > 10^{-23} eV$

ET could probe the ULDM soliton for the minimal coupling for masses $m \leq 2 \times 10^{-22}\ eV$

RESULTS FOR OTHER GALAXIES

With GWs we can probe the ULDM environment of other galaxies (more massive soliton).

We consider four case-examples of binaries:

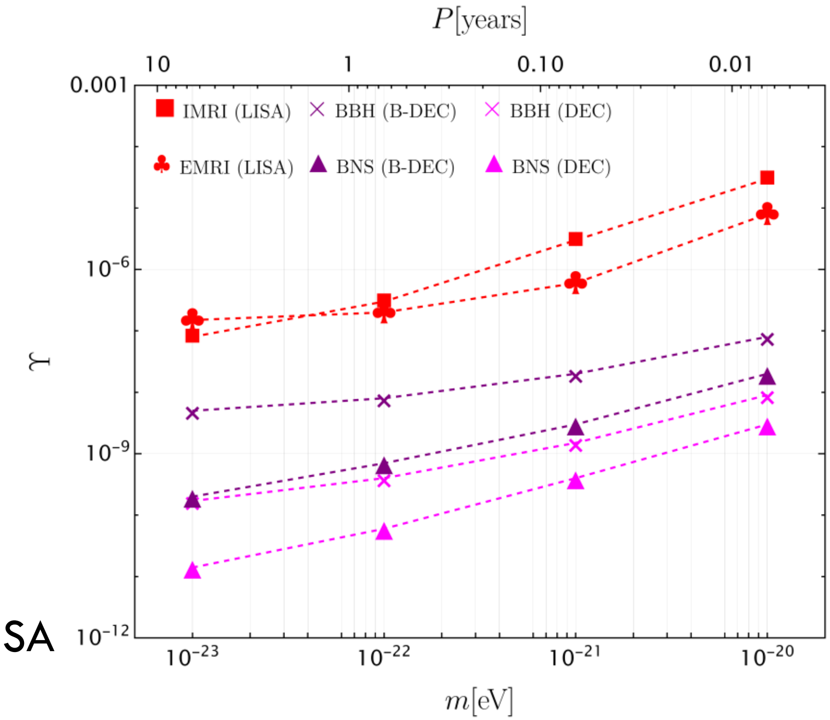
- EMRI: $(m_1, m_2) = \left(10^6 M_\odot, 60 M_\odot\right)$ at Gpc
- IMRI: : $(m_1, m_2) = \left(10^4 M_\odot, 10 M_\odot\right)$ at Gpc
- BBH: GW170608-like event
- BNS: GW170817-like event

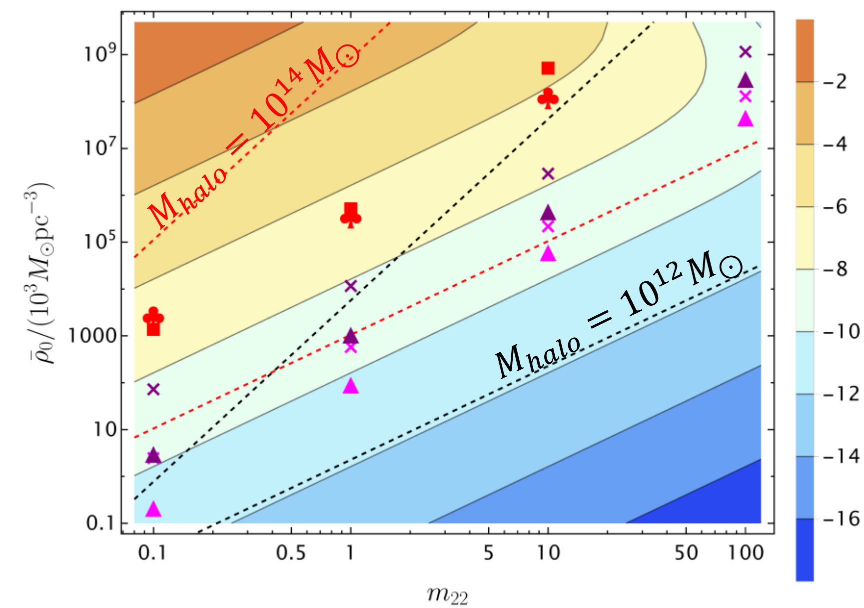
} LISA (EMRI, IMRI)

} (B-)DECIGO (BBH, BNS)

These sources are chirping, the correction to the phase of the GW is more complicated and we cannot easily isolate its SNR ⟶ we compute he uncertainty on Υ through a Fisher matrix and define the threshold when $\sigma_\Upsilon \leq \Upsilon$

Also look at J. Stegmann et al. 2023 2311.06335 and P. Brax et al 2024 2402.04819



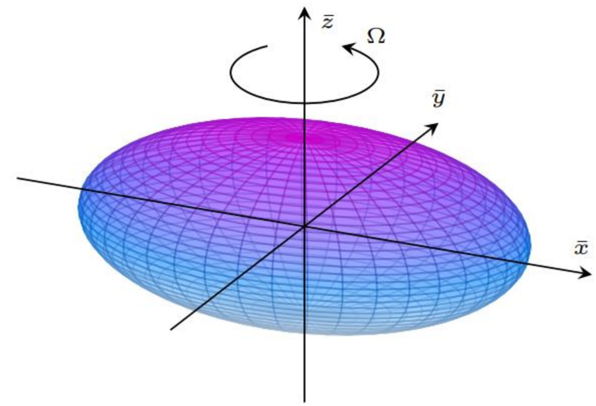


CONCLUSION AND FUTURE DIRECTIONS

- Imprint the ULDM oscillations in the phase of GWs (minimal and direct coupling)
- Extend previous computations to solitons and with self-interaction
- The SNR of the effect in terms of the carrier SNR, the amplitude Υ and the ratio ω_e/ω_δ
- Sensitivity of different astrophysical population for the MW $\Rightarrow$ Spinning NS detectable with ET/CE have optimal prospects
- LISA sources could fill the gap in the $2 \times 10^{-22}\ eV \leq m \leq 3 \times 10^{-21}\ eV$ mass window
- Extragalactic (chirping) sources could probe ULDM over densities in other Galaxies

GWS FROM SPINNING NS

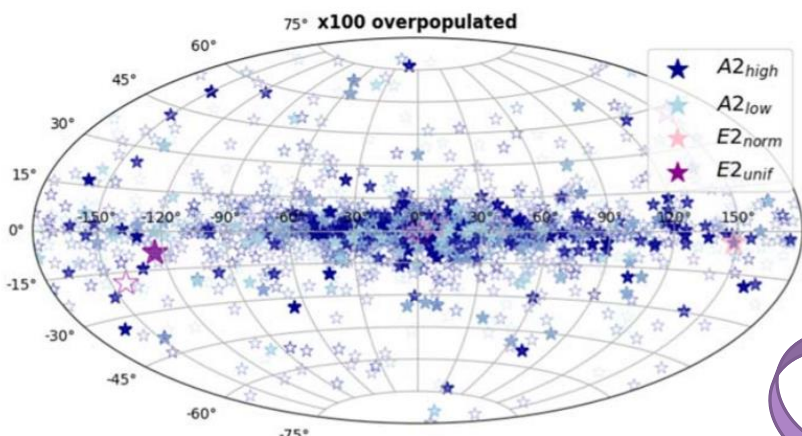
Reviews e.g Gittins 2401.01670,
Piccinni 2202.01088



Rotating NS can support long-lived, non-axisymmetric deformations known as mountains ⇒ potential sources of continuous GW

$$h_0 = \frac{4G}{c^4}\frac{\epsilon I_3 \Omega^2}{d} \approx 10^{-25}\left(\frac{10\,\mathrm{kpc}}{d}\right)\left(\frac{\epsilon}{10^{-6}}\right)\left(\frac{I_3}{10^{45}\,\mathrm{g\,cm^2}}\right)\left(\frac{\nu}{500\,\mathrm{Hz}}\right)^2$$

Ellipticity parameter $\epsilon = (I_2 - I_1)/I_3$



Average number of detectable sources from 2303.04714

Model	$\bar{n}$	
	ET	CE
$A2_{low}$	231.9 ± 14.6	338.1 ± 16.8
$A2_{high}$	387.2 ± 19.4	524.3 ± 22.6
$E2_{norm}$	0.5 ± 0.6	2.0 ± 1.4
$E2_{unif}$	1.7 ± 1.3	5.2 ± 2.2

Great uncertainty on the detection prospects

CHIRPING CASE

- Gravitational redshift $\chi = \Phi|_e^r + n^i\, v_i|_e^r - I_{iSW}$
- Relative phase correction $\eta = \frac{\int \omega_e \chi}{\int \omega_e}$
- Quadrupolar result for the GW frequency

$$f_e = \frac{1}{\pi}\left(\frac{2GM}{c^3}\right)^{-\frac{5}{8}}\left(\frac{5}{256\tau}\right)^{3/8}$$

$$\eta_r(\tau_r) = -\frac{|\Upsilon|}{13}\left(13\,{}_1F_2\left(\frac{5}{16};\frac{1}{2},\frac{21}{16};-\frac{1}{4}\tau^2\omega_\delta^2\right)\cos\Theta + 5\tau\omega_\delta\,{}_1F_2\left(\frac{13}{16};\frac{3}{2},\frac{29}{16};-\frac{1}{4}\tau^2\omega_\delta^2\right)\sin\Theta\right) + \Theta_c$$