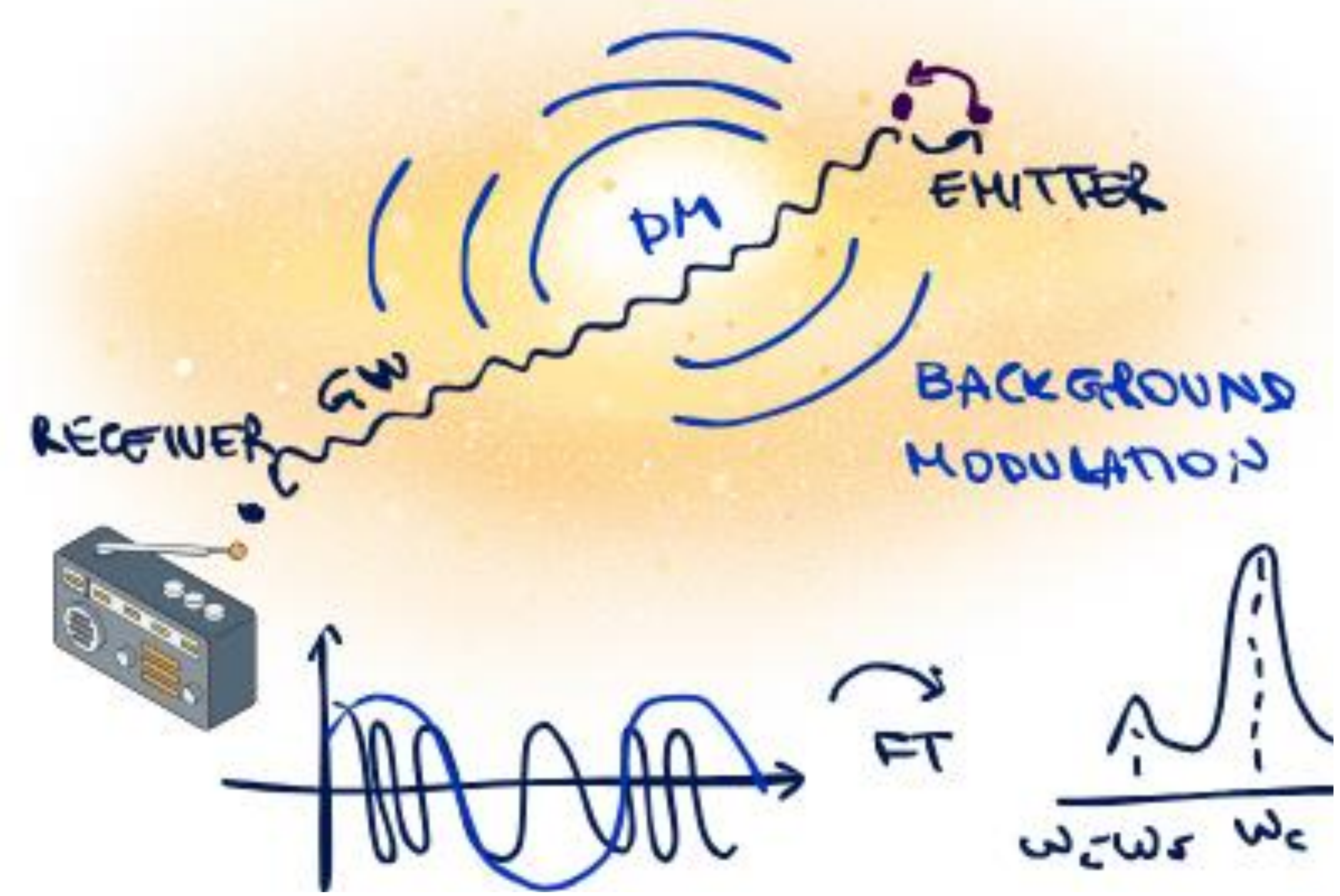

Ultra light dark matter searches with LISA binaries

Diego Blas
w/ Silvia **Gasparotto** & Rodrigo Vicente

e-Print: 2410.07330 [hep-ph]

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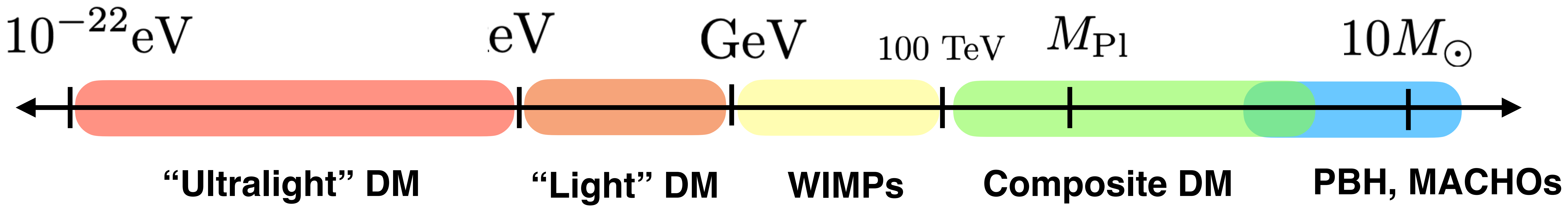
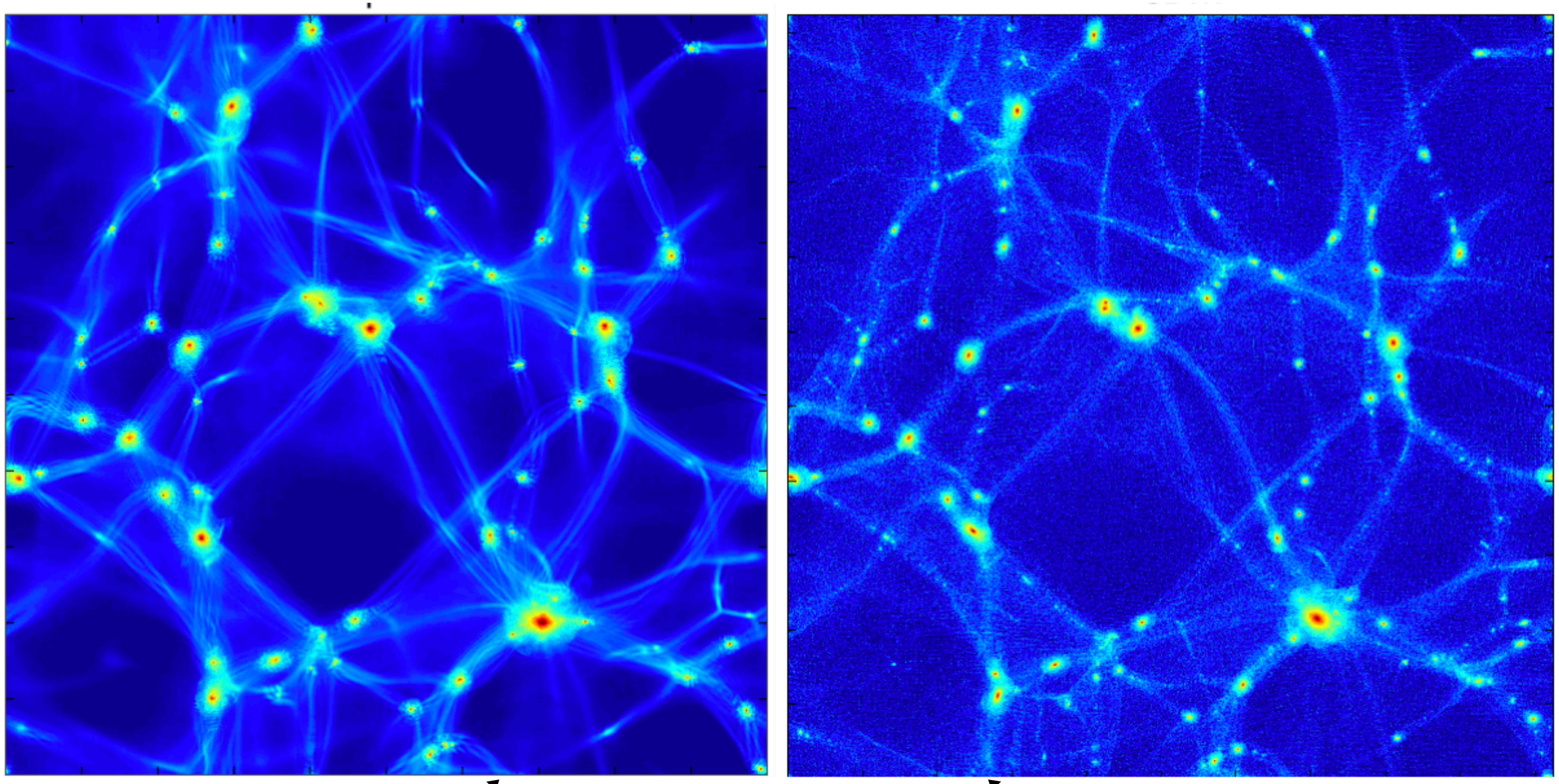
Dark Matter: where to look?



Similar behaviour at large-scales

$m \sim 10^{-22}\,\mathrm{eV}$

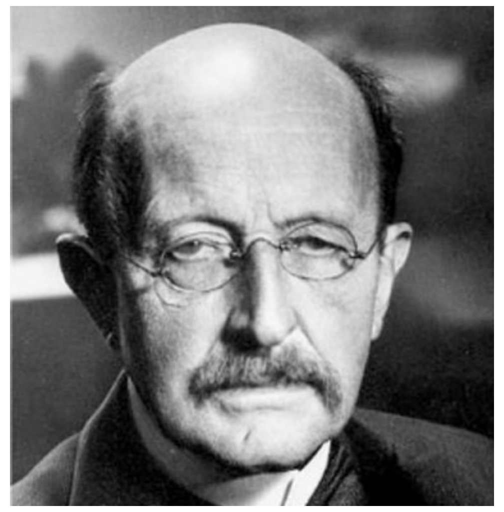
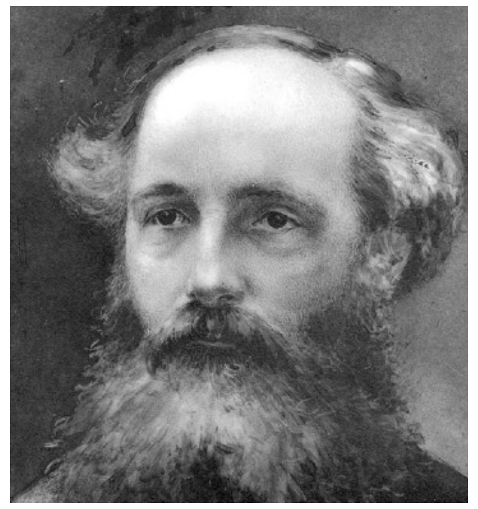
Scale of ~30 Mpc, Schive et al. 1406.6586



We see differences at small scales

(U)LDM **does not** behaves as CDM at small-scales

Description as a particle, as a classical field or as DF?

$\hbar\omega$    $F_{\mu\nu}$

e.g. Milky way DM halo

i) typical **distance** between particles $d \sim n^{-1/3} \sim (M/(mV))^{-1/3} \sim 20\ \mathrm{kpc}/(10^9\ M_\odot)^{1/3} m^{1/3}$

ii) typical **size** of particle wavepacket in the halo $L \gtrsim 1/(m v_{\rm esc}) \approx 190 \left(\frac{m}{10^{-22}\mathrm{eV}}\right)^{-1} \mathrm{pc}$

particles overlap for $d \lesssim L$

$m_{MW} \sim 1\,\mathrm{eV}$

fermions

become degenerate close to this limit

a $m_f \gtrsim \mathrm{keV}$ Tremaine-Gunn bound

b ‘condensed dark matter’ Bar et al 2102.11522 Garani et al 2207.06928

bosons

field theory description

c $\mathcal{L} = \frac{1}{2}\left[(\partial_\mu \phi)^2 - m^2\phi^2\right]$ + gravity

(spin 0, 1 or 2)

ULDM summary

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

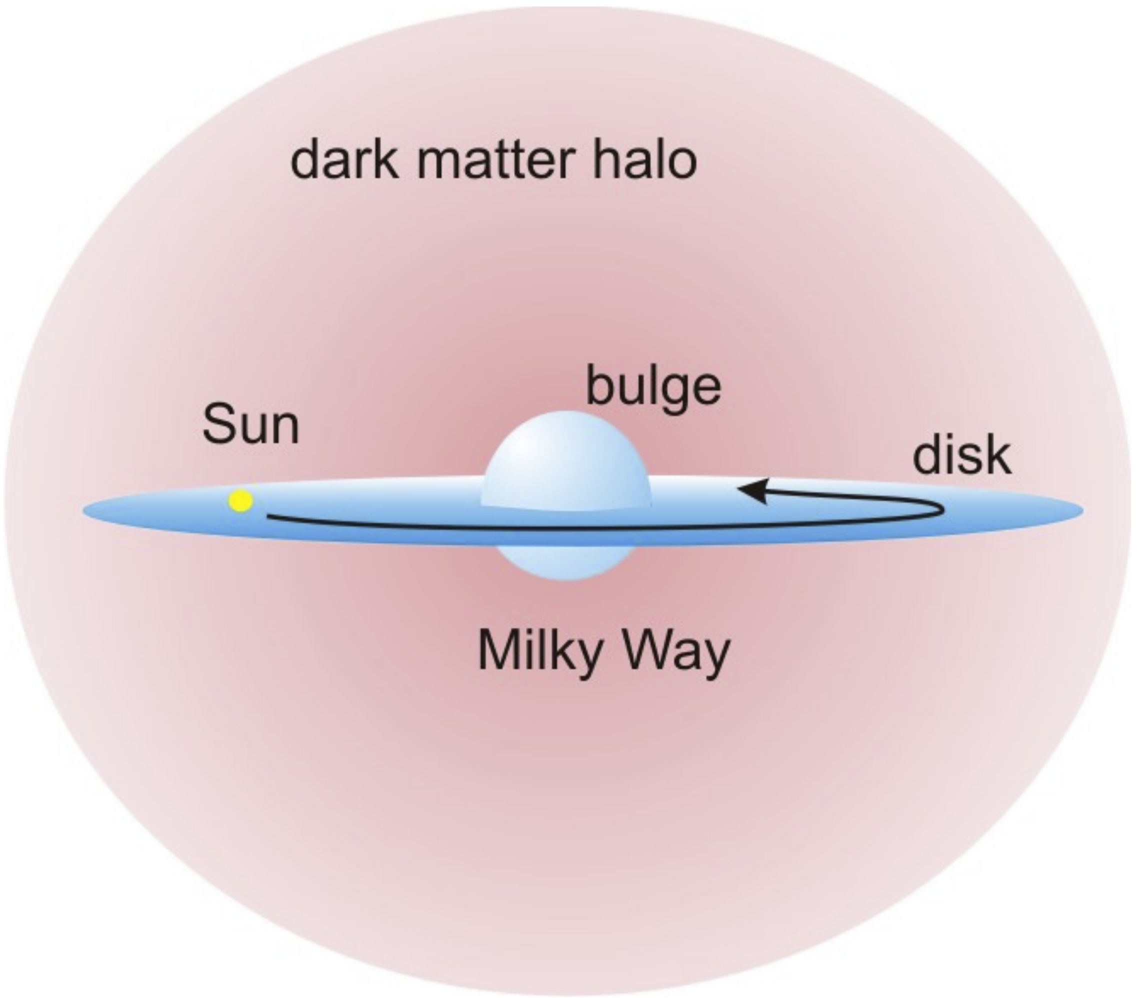
Occupation number : $\mathcal{N} = n\ \lambda_{db}^3 \sim 10^{92} \times \left(\frac{10^{-22} eV}{m}\right)^4$

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 **does not** behaves like CDM at small-scales



$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu \phi)^2 - m^2\phi^2\right] \quad + \text{gravity}$$

$$\lambda_{\rm dB} \sim \frac{10^{-22}\text{eV}}{m}\frac{10^{-3}}{v}\text{kpc}$$

$$\phi_k \sim e^{i(\omega t - kx)}$$

Virialized configuration: collection of waves with distribution determined by properties from the galaxy

$$\phi \propto \int_0^{v_{max}} \mathrm{d}^3 v\, e^{-v^2/\sigma_0^2} e^{i\omega_v t} e^{-im\vec{v}\cdot\vec{x}} e^{if_{\vec{v}}} + c.c.$$

$\sigma_0 \sim 10^{-3} c$ in the MW

free wave

The DM potential has coherent oscillations in λ_{db}

$$t \sim \frac{10^6}{m}\left(\frac{10^{-6}}{\sigma_0^2}\right)$$

Close to λ_{db}

In terms of **fluid variables (e.g. $\rho \propto m^2\phi^2$):**

gravitational potential

$$\dot{\rho} + 3H\rho + \frac{\nabla}{a}(\rho\,\vec{v}) = 0$$

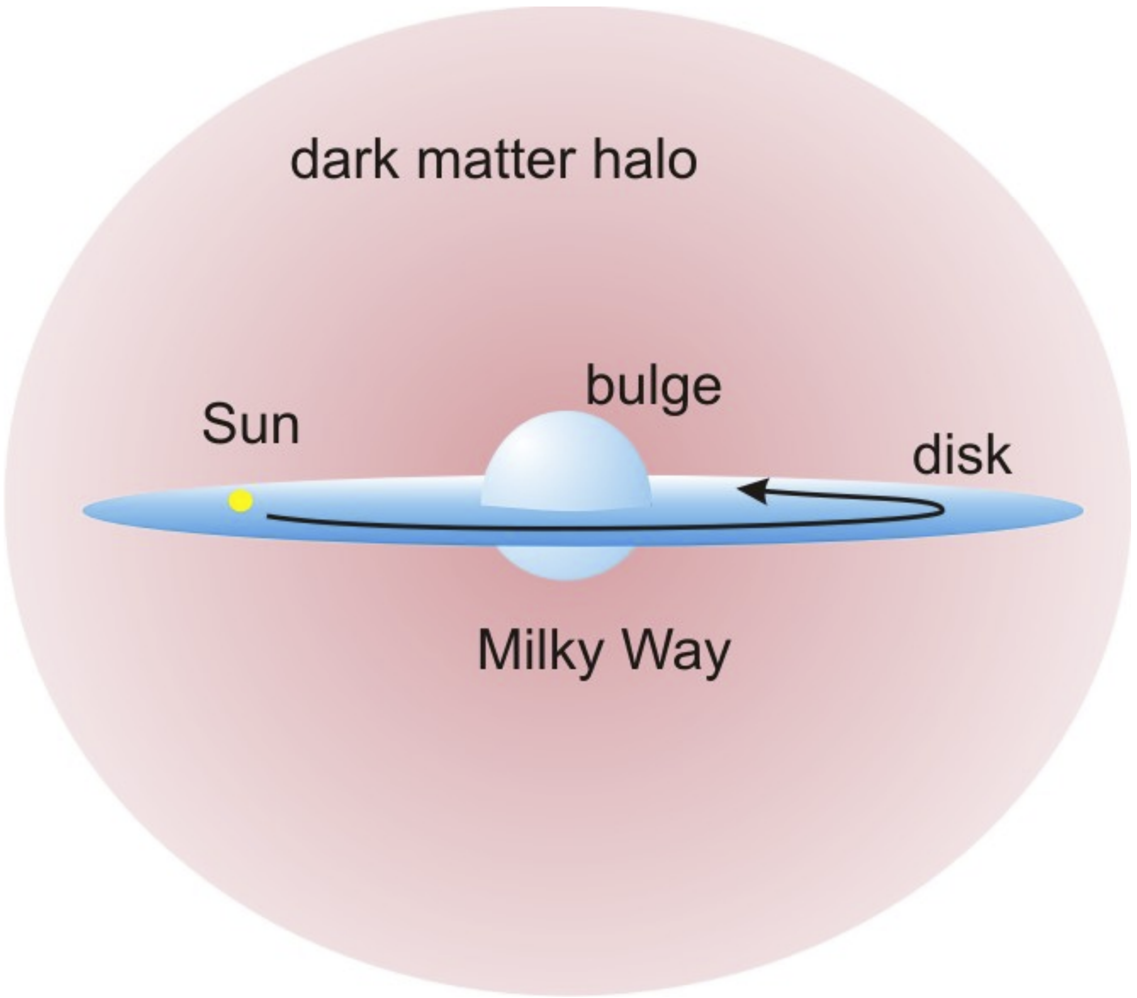
$$\dot{\vec{v}} + H\vec{v} + \left(\vec{v}\cdot\frac{\nabla}{a}\right)\vec{v} = -\frac{\nabla}{a}\left(V - \frac{1}{2m^2a^2}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

pure CDM part

new phenomena at small scales!
(repulsive effect: “quantum pressure”)

$$\lambda_{\rm dB} \sim \frac{10^{-22}\text{eV}}{m}\frac{10^{-3}}{v}\text{kpc}$$

ULDM **does not** behaves like CDM at small-scales



$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu \phi)^2 - m^2\phi^2\right]$$ + gravity

$$\lambda_{\rm dB} \sim \frac{10^{-22}{\rm eV}}{m}\frac{10^{-3}}{v}{\rm kpc}$$

$$\phi_k \sim e^{i(\omega t - kx)}$$

Virialized configuration: collection of waves with distribution determined by properties from the galaxy

$$\phi \propto \int_0^{v_{max}} {\rm d}^3 v\, e^{-v^2/\sigma_0^2} e^{i\omega_v t} e^{-im\vec{v}\cdot\vec{x}} e^{if_{\vec{v}}} + c.c.$$

$\sigma_0 \sim 10^{-3}c$ in the MW

free wave

The DM potential has coherent oscillations in λ_{db}

A) coherent oscillations +
B) stochastic 'narrow' piece

Close to λ_{db}
In terms of **fluid variables (e.g.** $\rho \propto m^2\phi^2$**):**

gravitational potential

$$\dot{\rho} + 3H\rho + \frac{\nabla}{a}(\rho\,\vec{v}) = 0$$

$$\dot{\vec{v}} + H\vec{v} + \left(\vec{v}\cdot\frac{\nabla}{a}\right)\vec{v} = -\frac{\nabla}{a}\left(V - \frac{1}{2m^2a^2}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

pure CDM part

new phenomena at small scales!
(repulsive effect: "quantum pressure")

C) changes dynamics at smaller scales $\frac{10^{-3}}{v}{\rm kpc}$

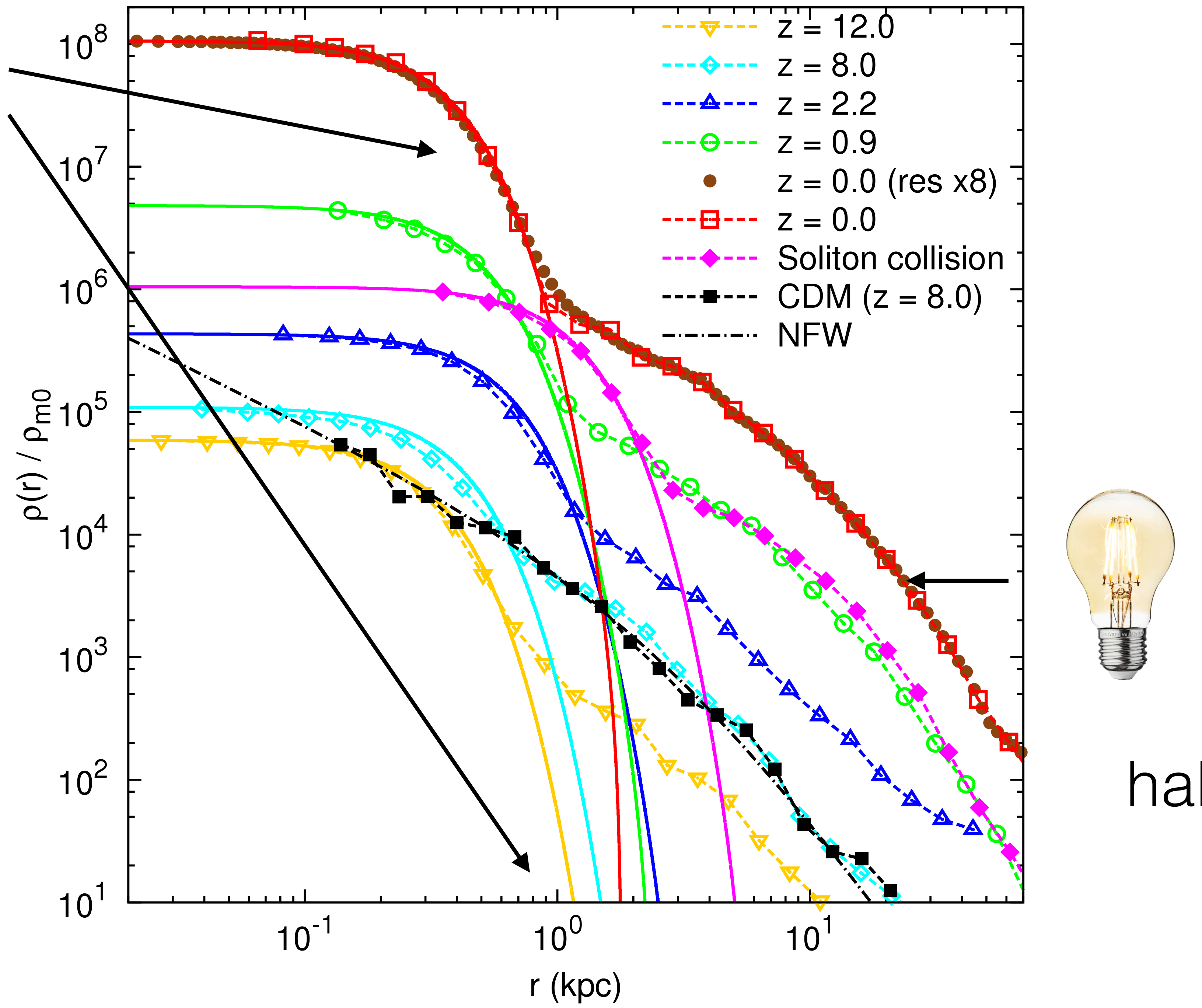
New phenomenology from ULDM

DM small scale dynamics

C) changes dynamics at smaller scales

Schive et al.1407.7762

soliton



halo

$$\dot{\rho} + 3H\rho + \frac{\nabla}{a}(\rho\,\vec{v}) = 0$$

$$\dot{\vec{v}} + H\vec{v} + \left(\vec{v}\cdot\frac{\nabla}{a}\right)\vec{v} = -\frac{\nabla}{a}\left(V - \frac{1}{2m^2a^2}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

gravitational potential

pure CDM part

repulsive term

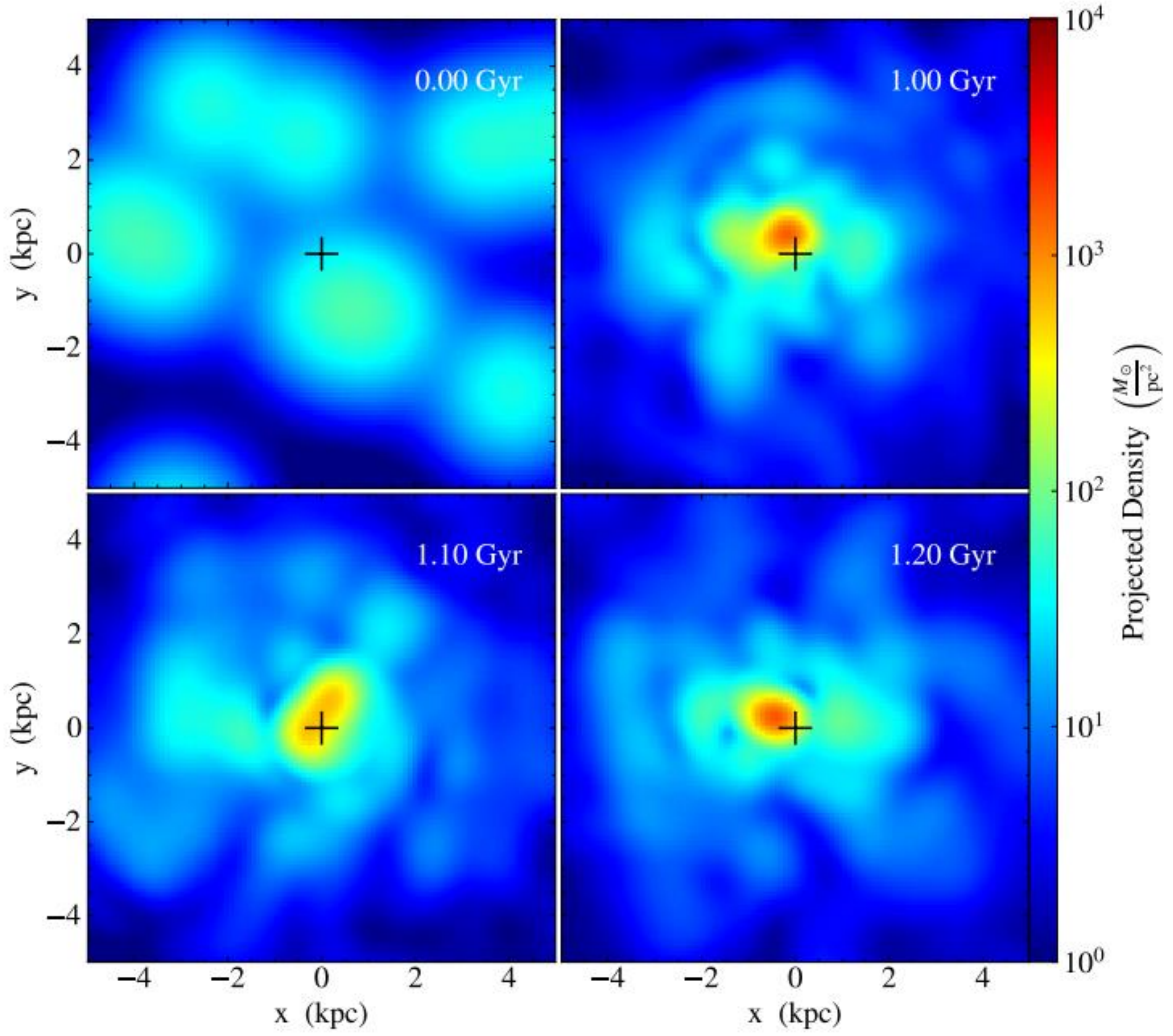
$$\phi(x,t) = \frac{M_{pl}}{2\sqrt{2\pi}}e^{-imt}e^{-i\gamma t}\chi(x) + h.c.$$

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

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

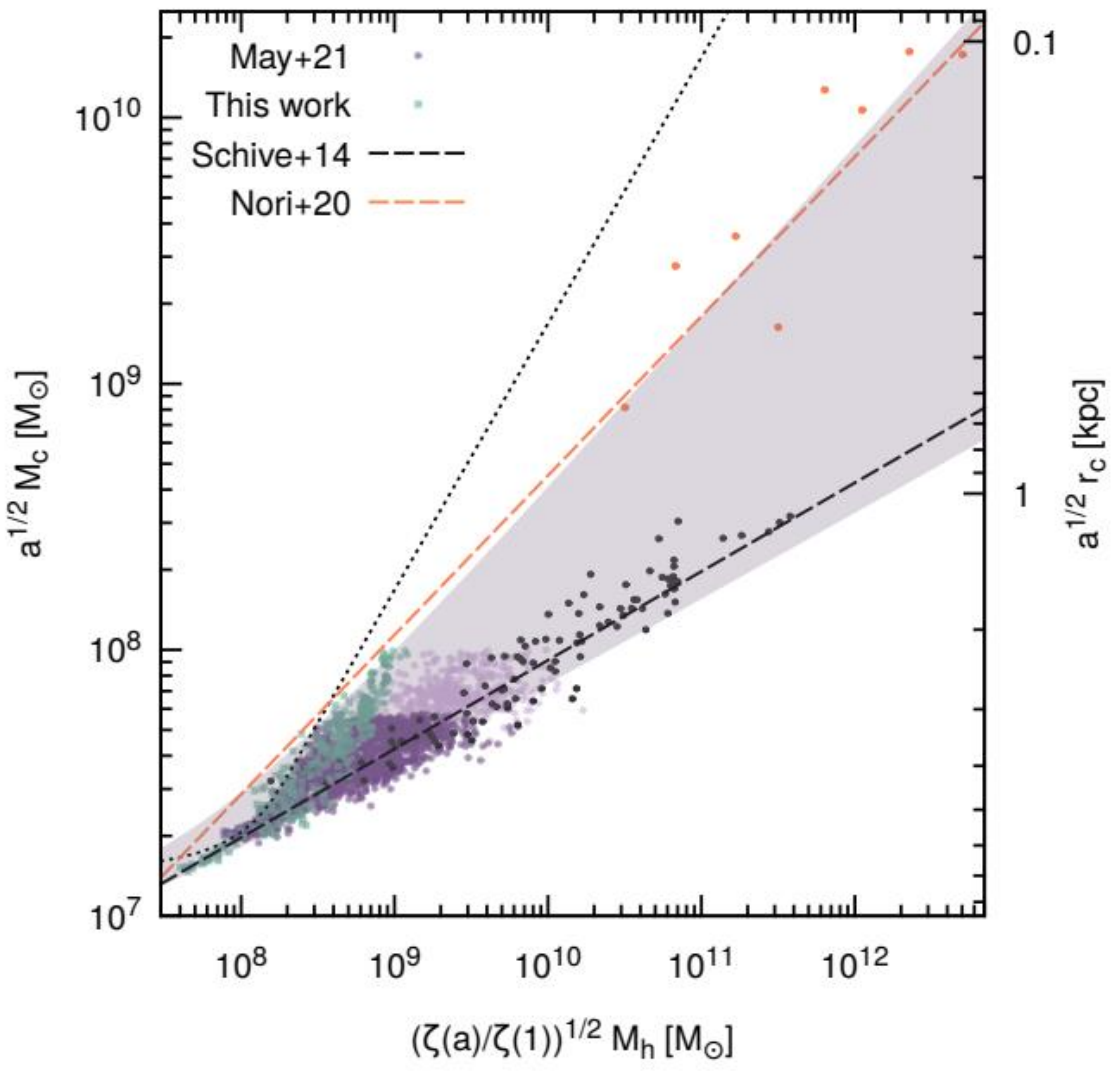
HALO AND SOLITON FORMATION

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

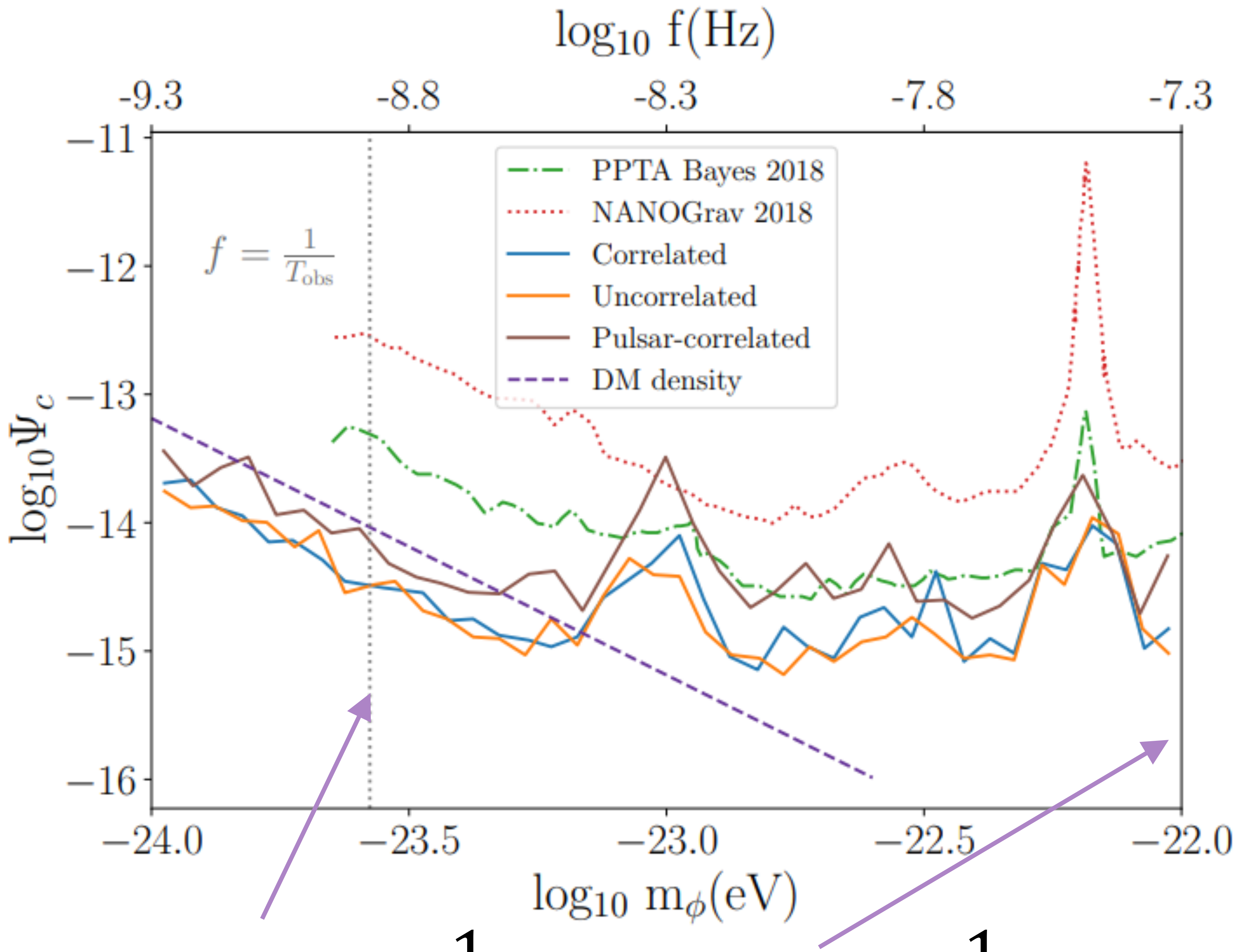
Khmelnitsky & Rubakov 1309.5888

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

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



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

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

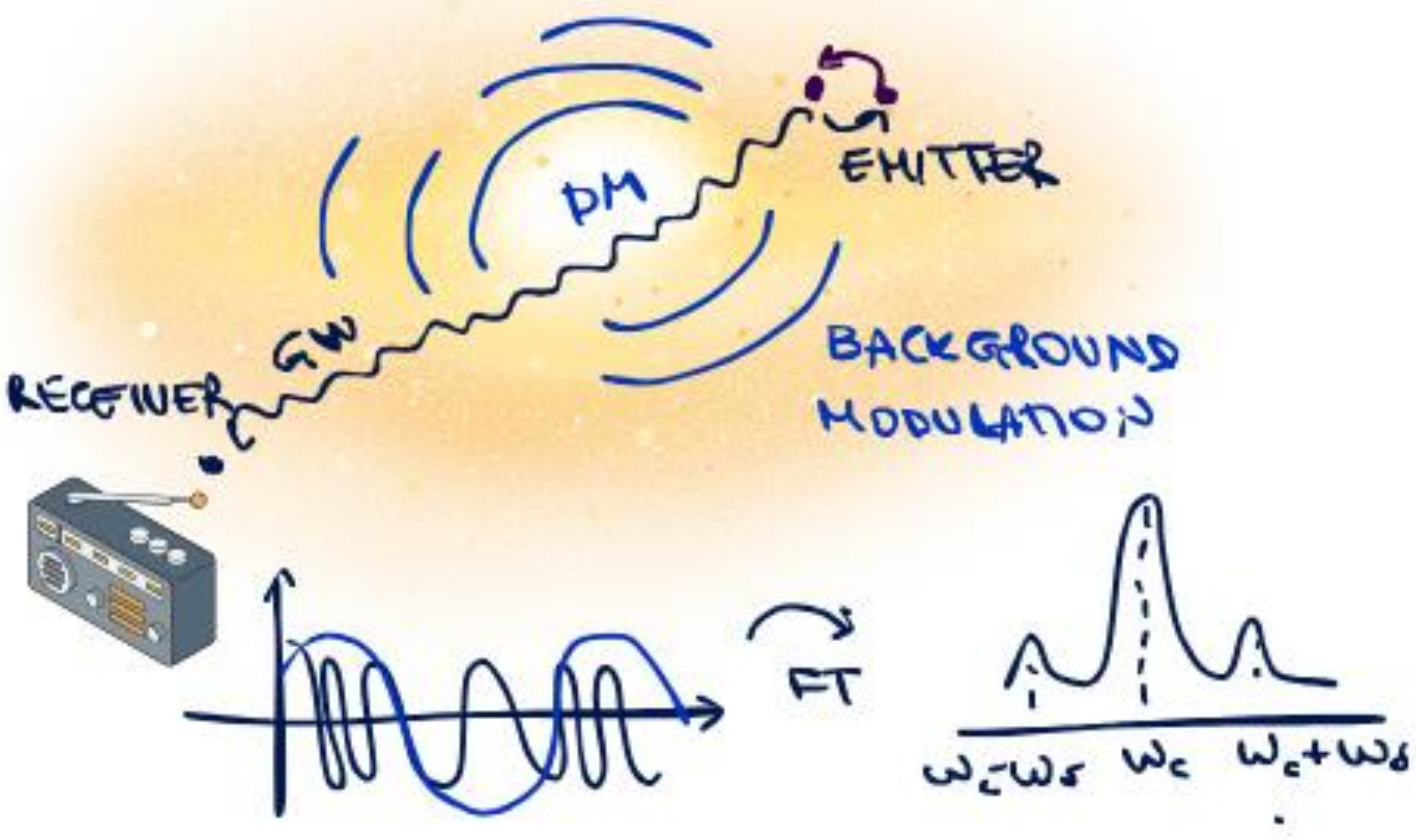
ULDM modulates GWs

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:

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

$\frac{\omega_e}{\omega_\delta} \gg 1$

Amplitude of the modulation

of the carrier

Which potential?

• 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

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

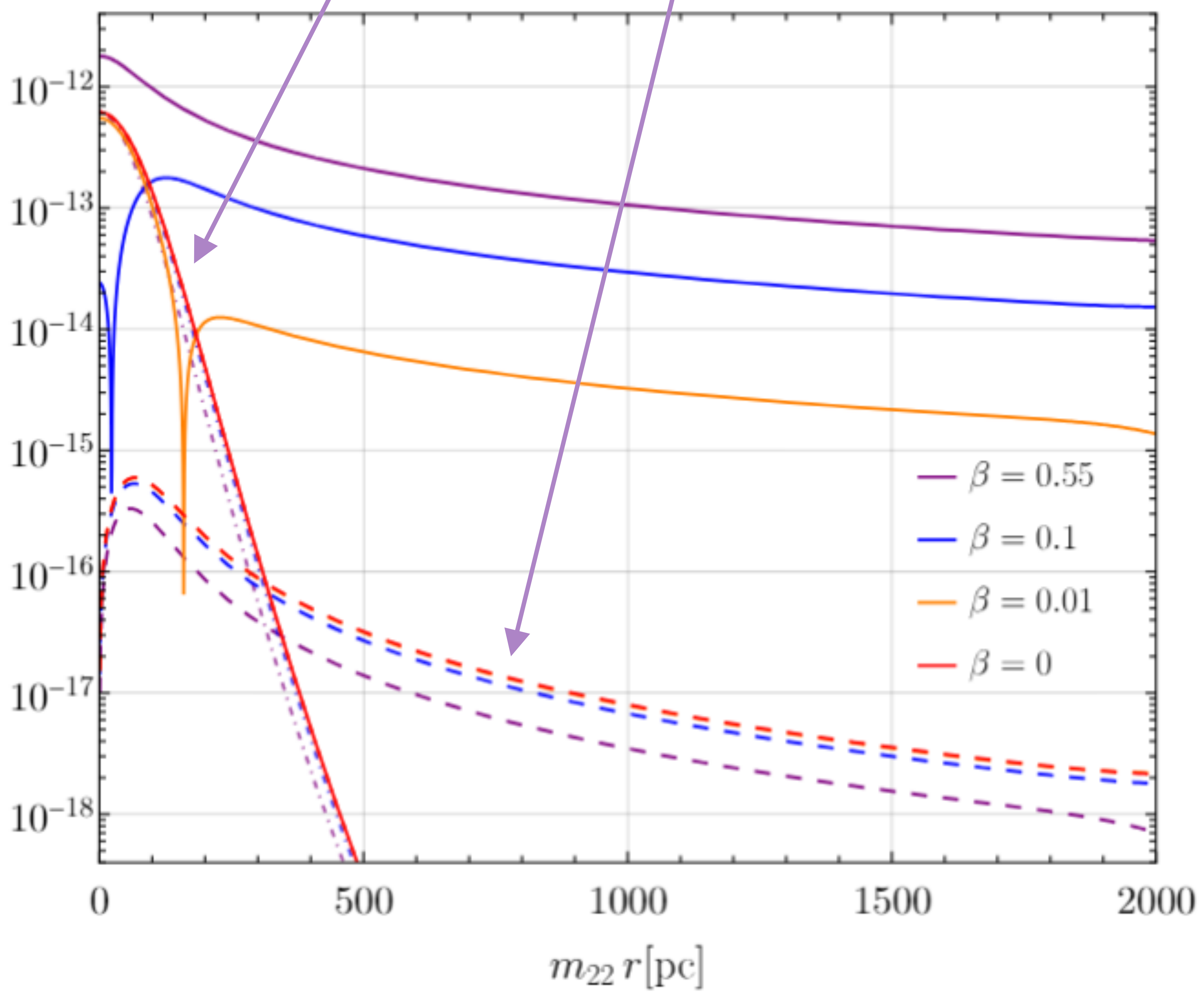
$$\nabla^2 \Phi_2 = 8\pi \left[5\langle\Phi\rangle + \gamma - \frac{\rho}{12 f^2 m^2}\right]\rho$$

•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

Galactic sources

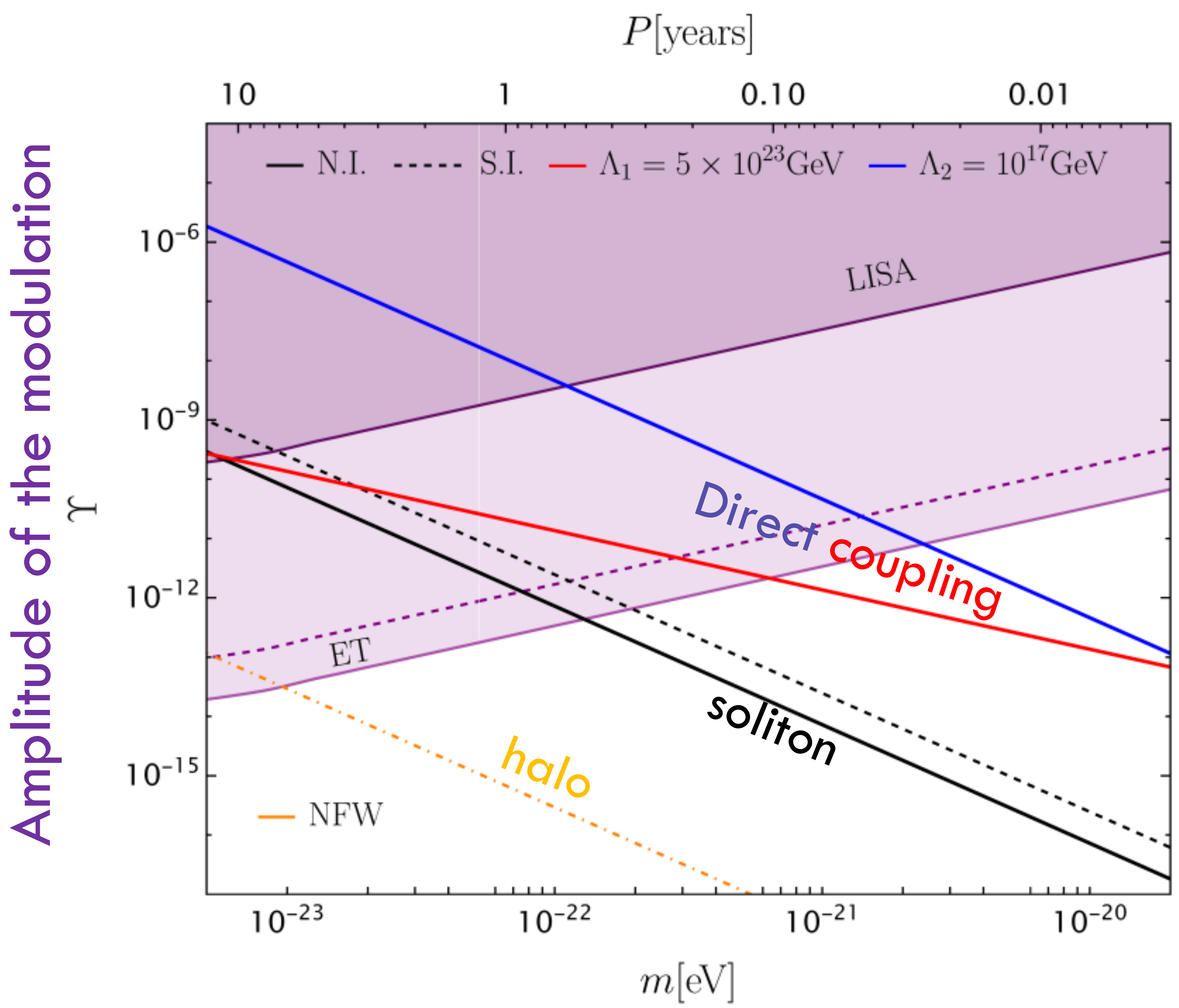
- Astrophysical populations of galactic monochromatic GW sources:
  - White Dwarfs/ X-MRIS $\longrightarrow \quad f_e \sim mHz$ (detectable by LISA, TianQin, Taiji)
  - Deformed Spinning Neutron Stars $\longrightarrow \quad f_e \sim kH.$ (detectable ET/CE)

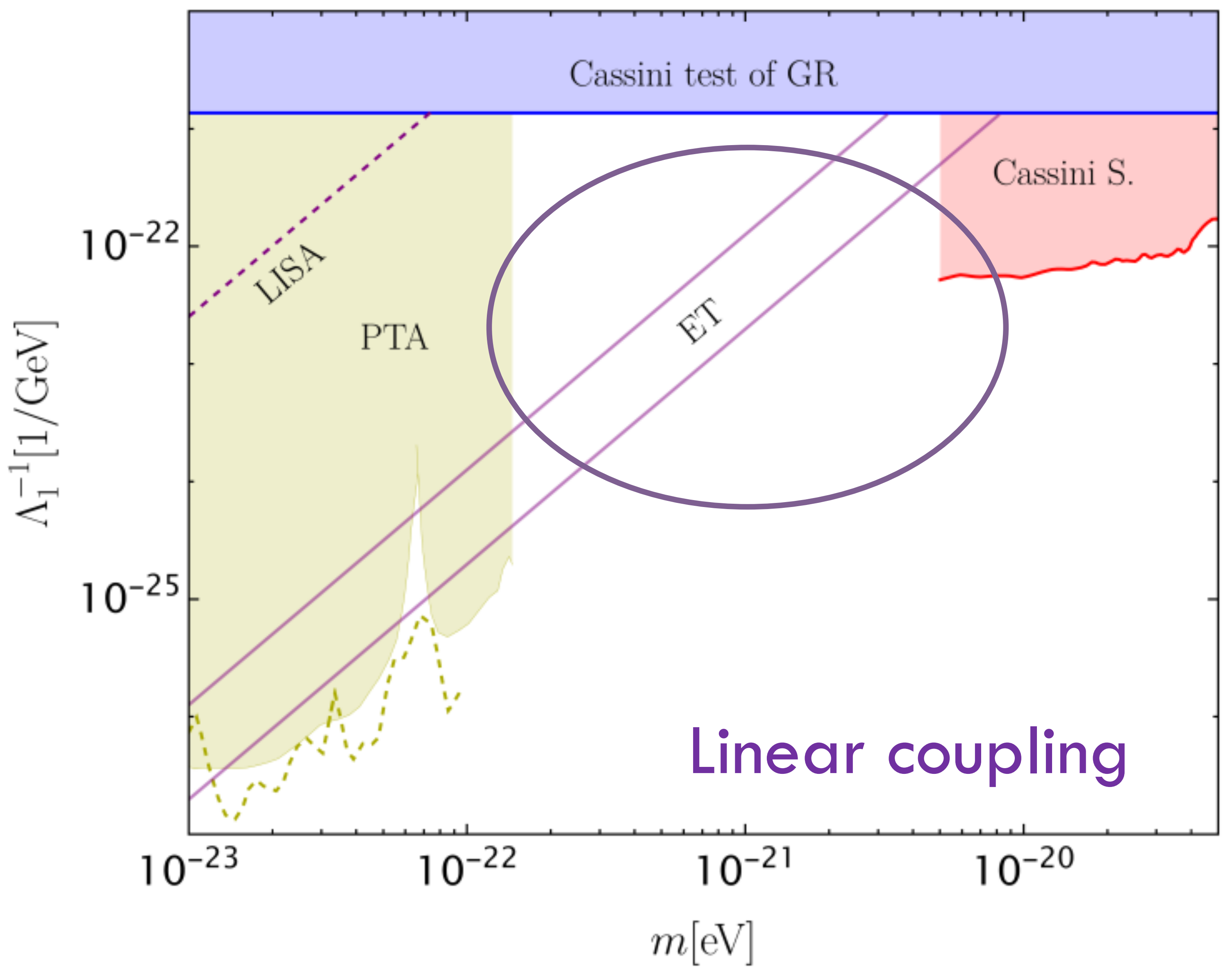
Expected/Simulated values for the calculation of the sensitivity from different astrophysical populations (N carriers)

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

	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



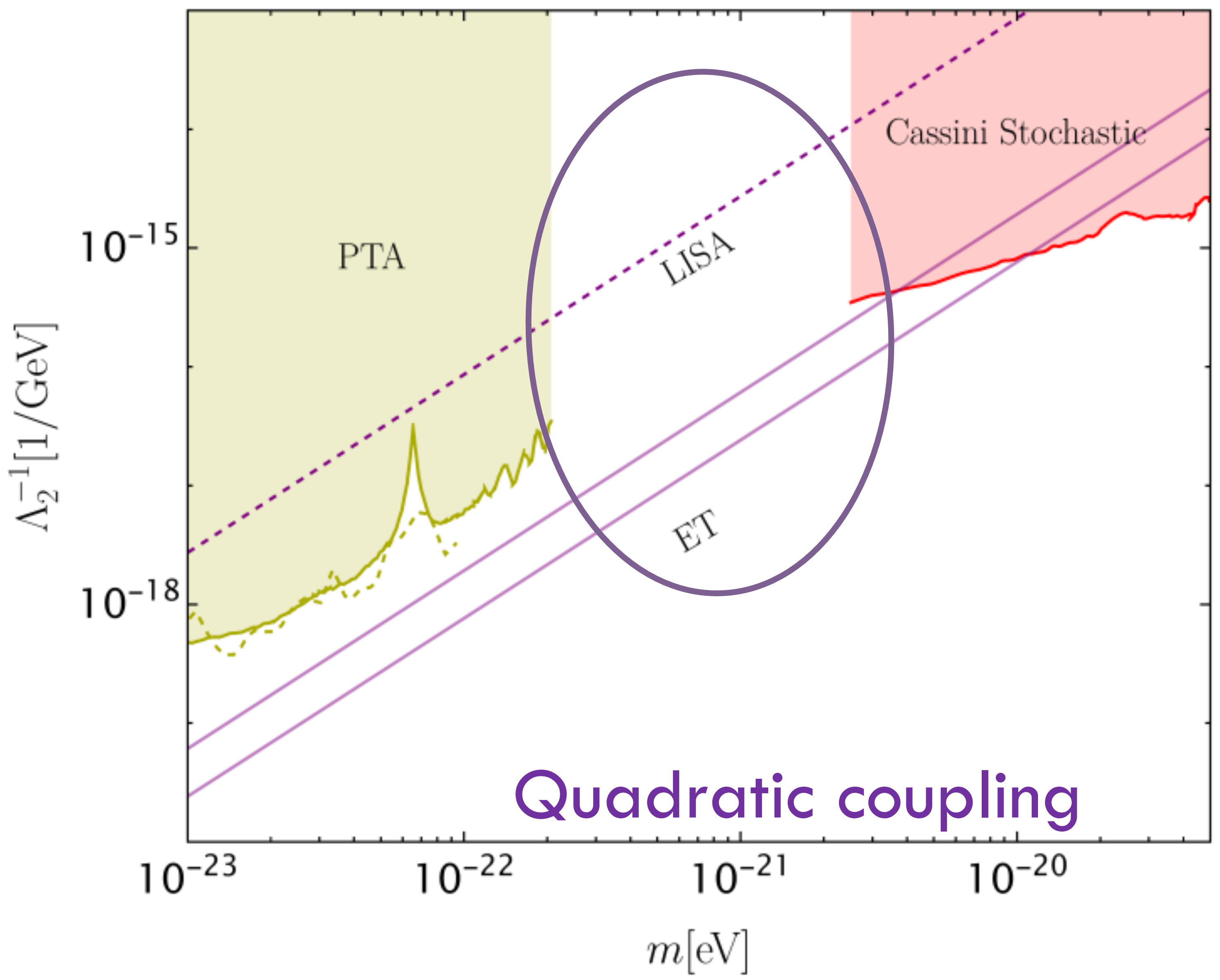


Great prospects for direct coupling: ET and LISA can probe the uncover window at masses $2 \times 10^{-22}\ eV \leq m \leq 3 \times 10^{-21}\ eV$

Spinning NS in ET outperform compared to LISA binaries

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

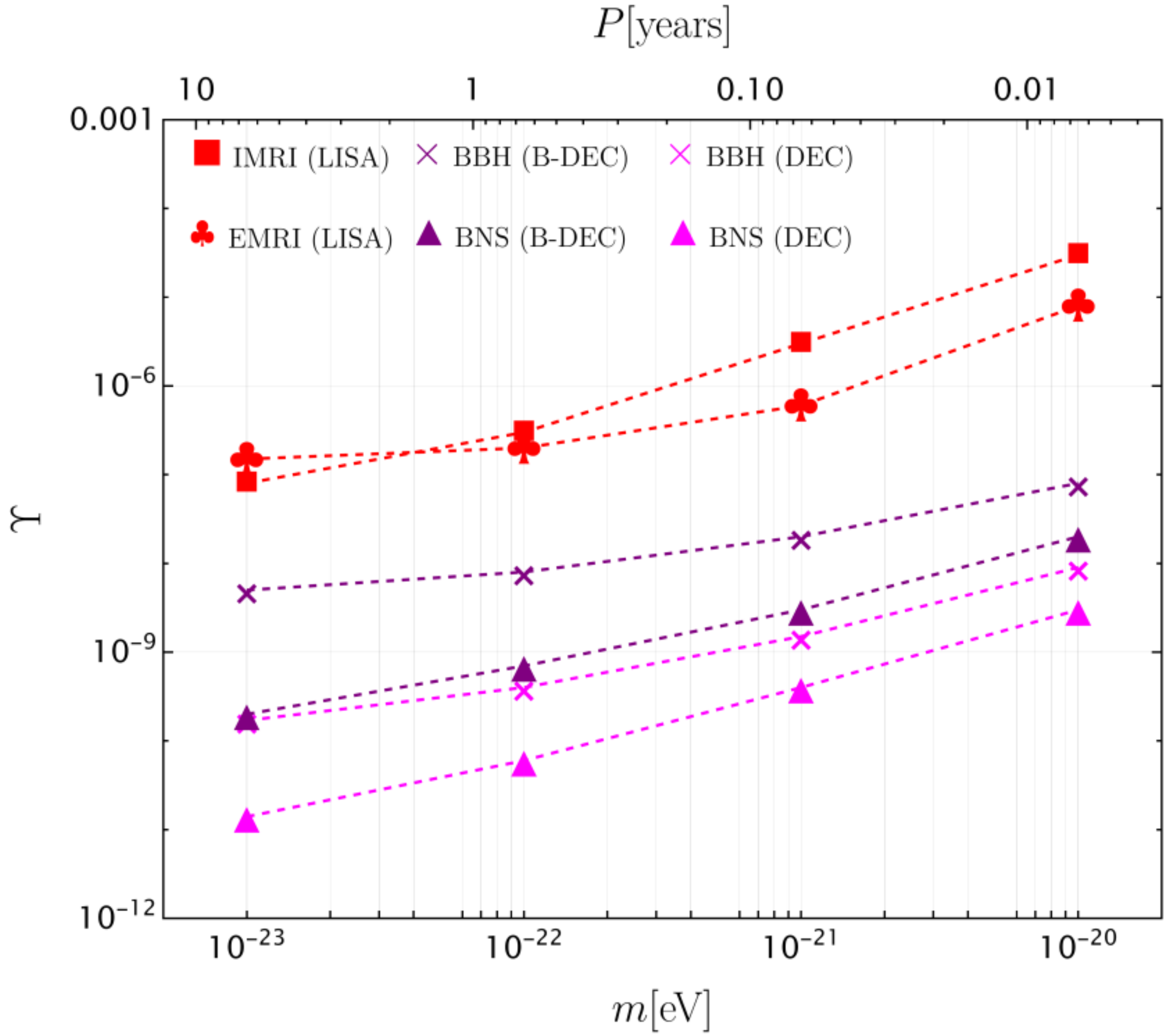
ET could probe the ULDM soliton for the minimal coupling for masses $m \leq 2 \times 10^{-22}\ eV$

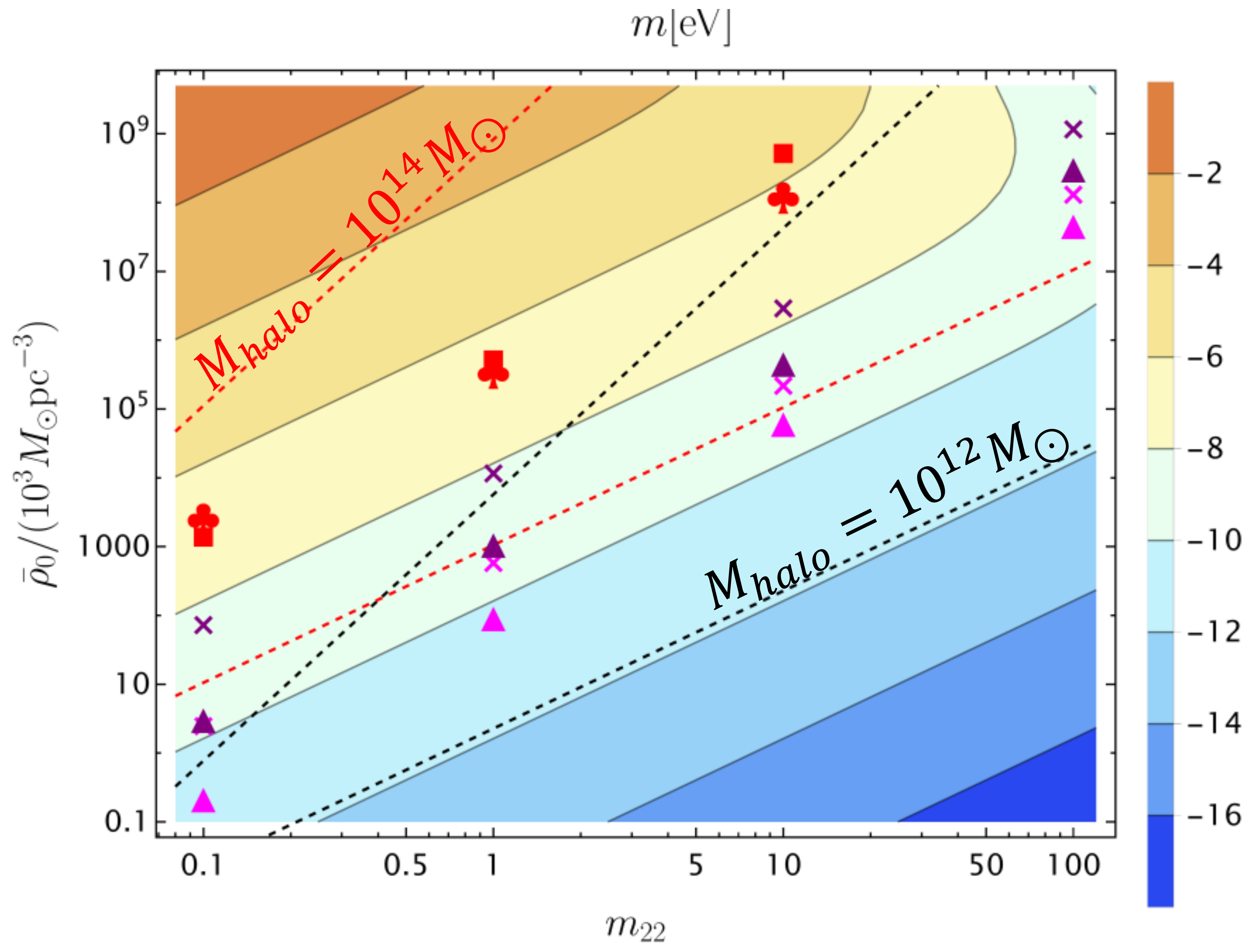


Extra galactic sources

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

(B-)DECIGO



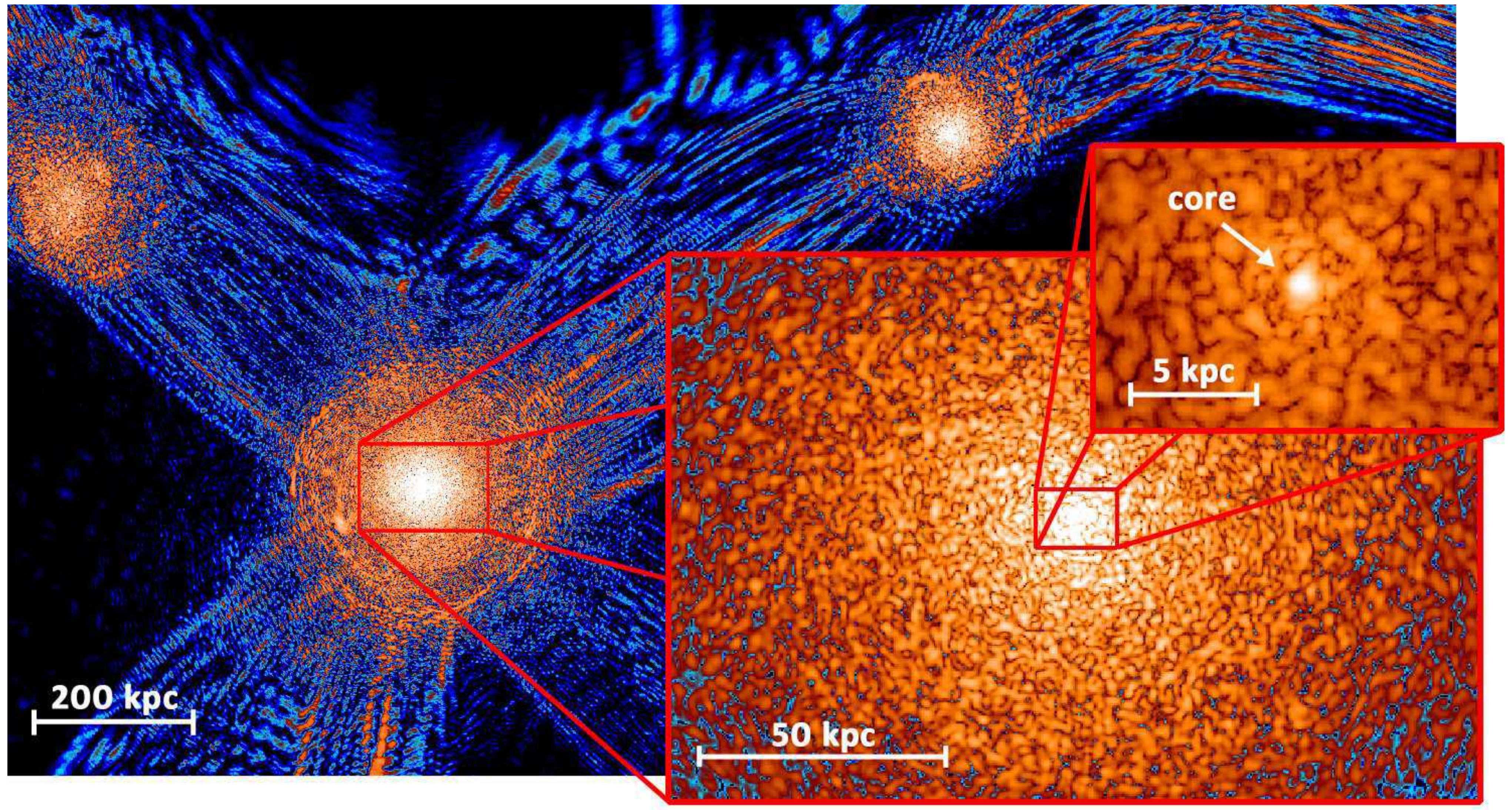


Conclusions

e-Print: 2410.07330 [hep-ph]

Ultra-light bosonic DM

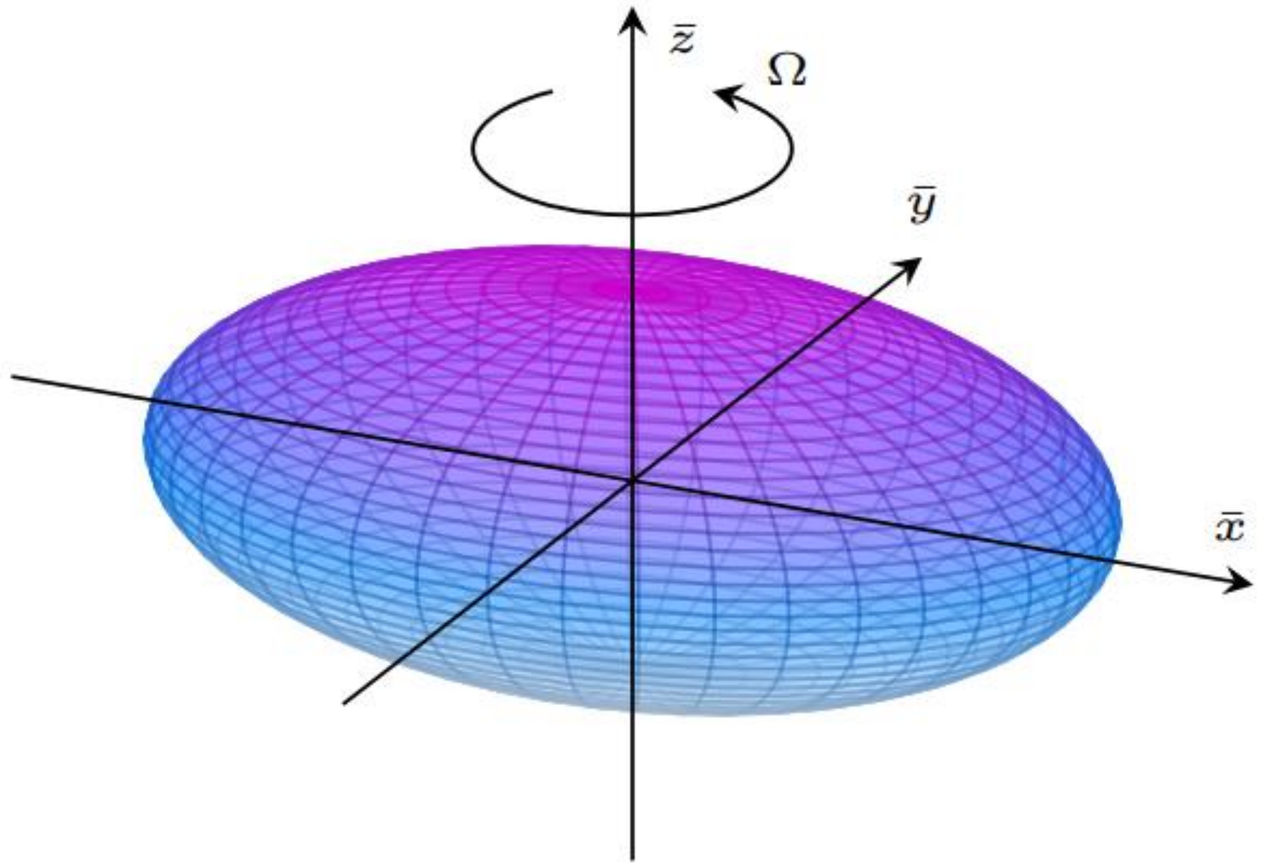
C) changes dynamics at smaller scales



- Generate over densities at galactic centers that oscillate coherently
- ULDM oscillations get imprinted in the phase of GWs
- LISA 'coherent' sources may detect this effect (SNR~ $\frac{\omega_e}{\omega_\delta} \Upsilon(\rho_0, m, x_e) SNR_h \sqrt{N}$)
  $\omega_e \to 1$
- LISA galactic sources opening $2 \times 10^{-22}\ eV \leq m \leq 3 \times 10^{-21}\ eV$ mass window
- Extragalactic (chirping) sources could probe ULDM over densities in other Galaxies

GWS FROM SPINNING NS

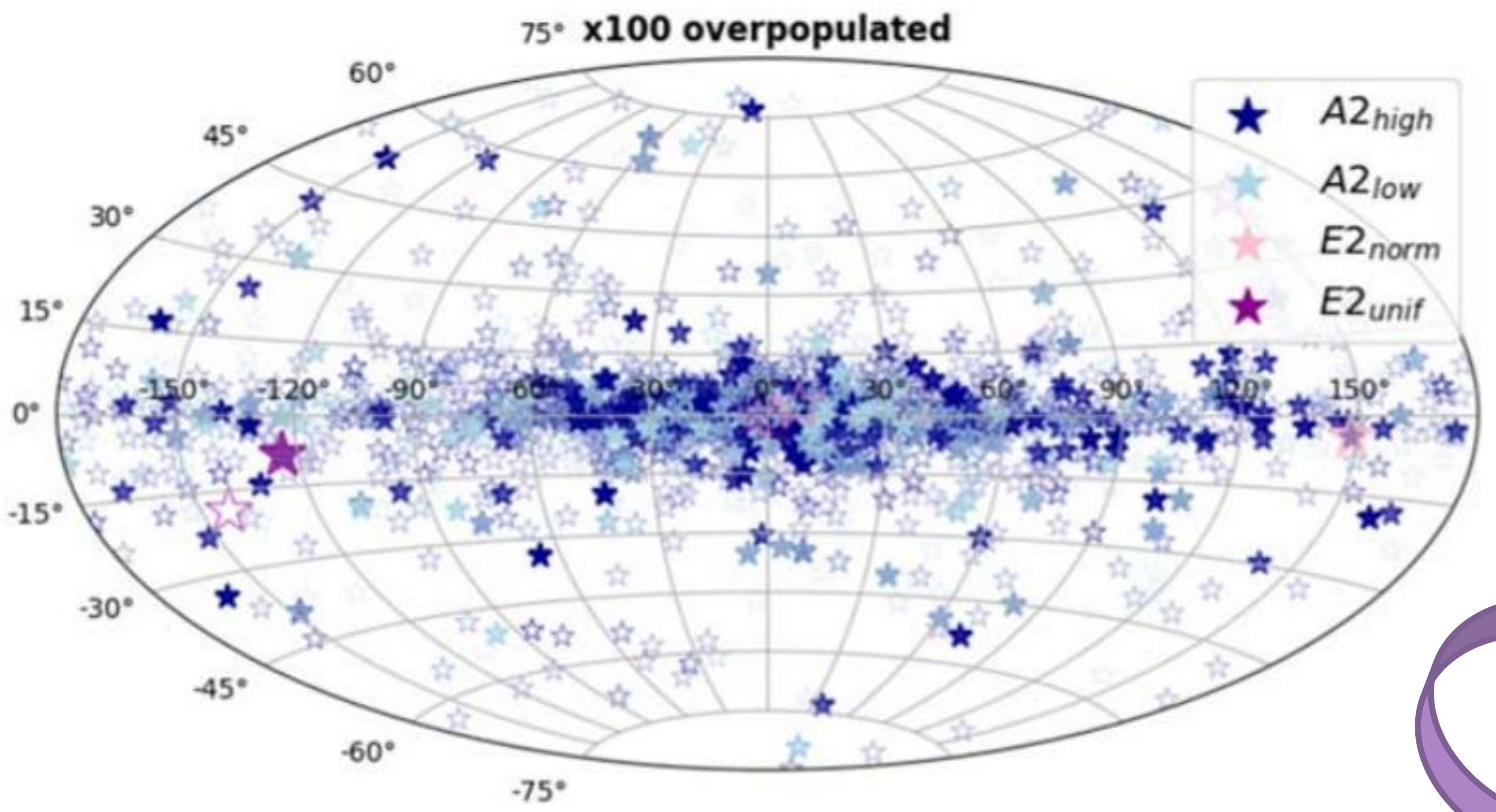
Reviews e.g Gittins 2401.01670,
Piccinni 2202.01088



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

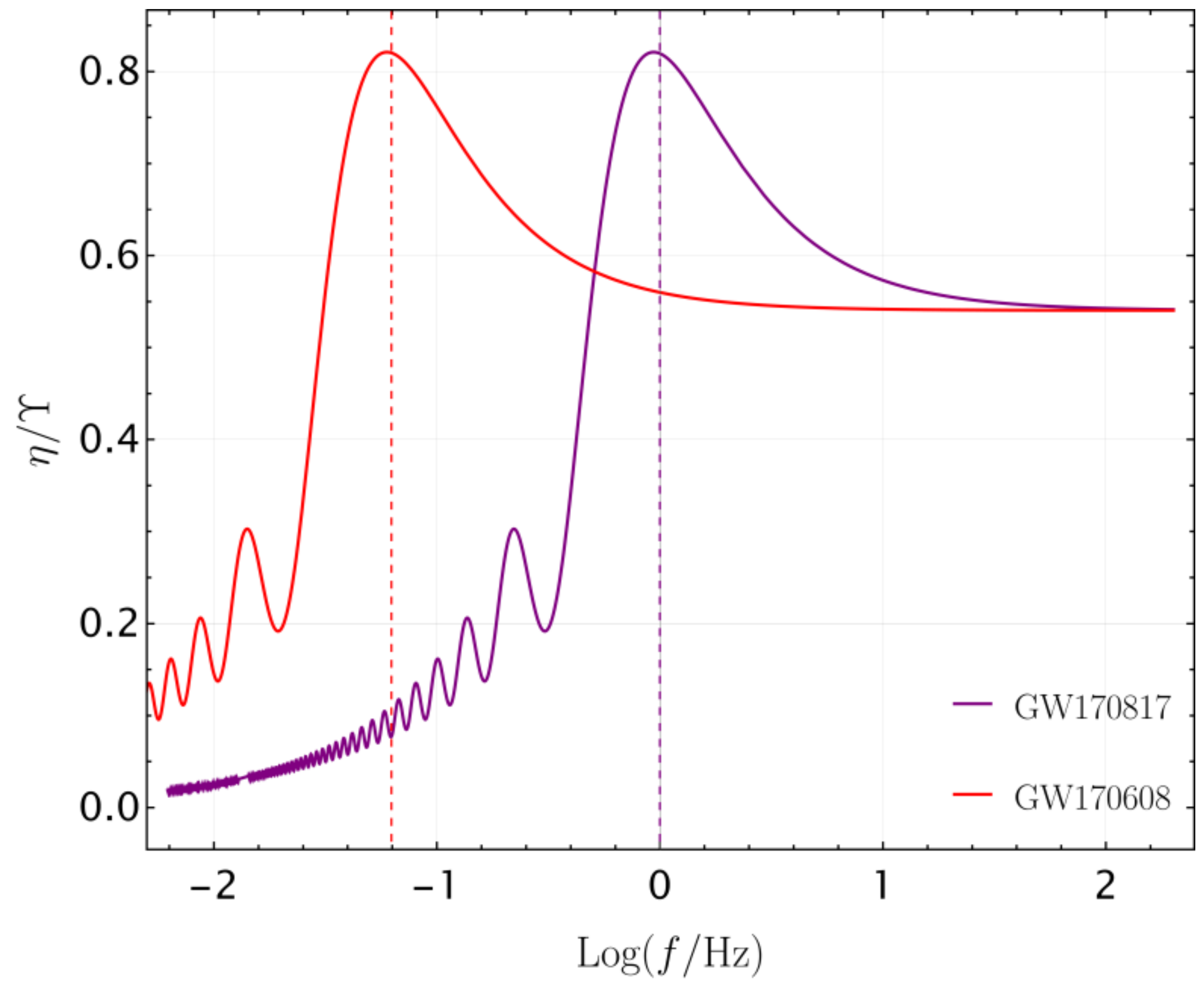
CHIRPING CASE

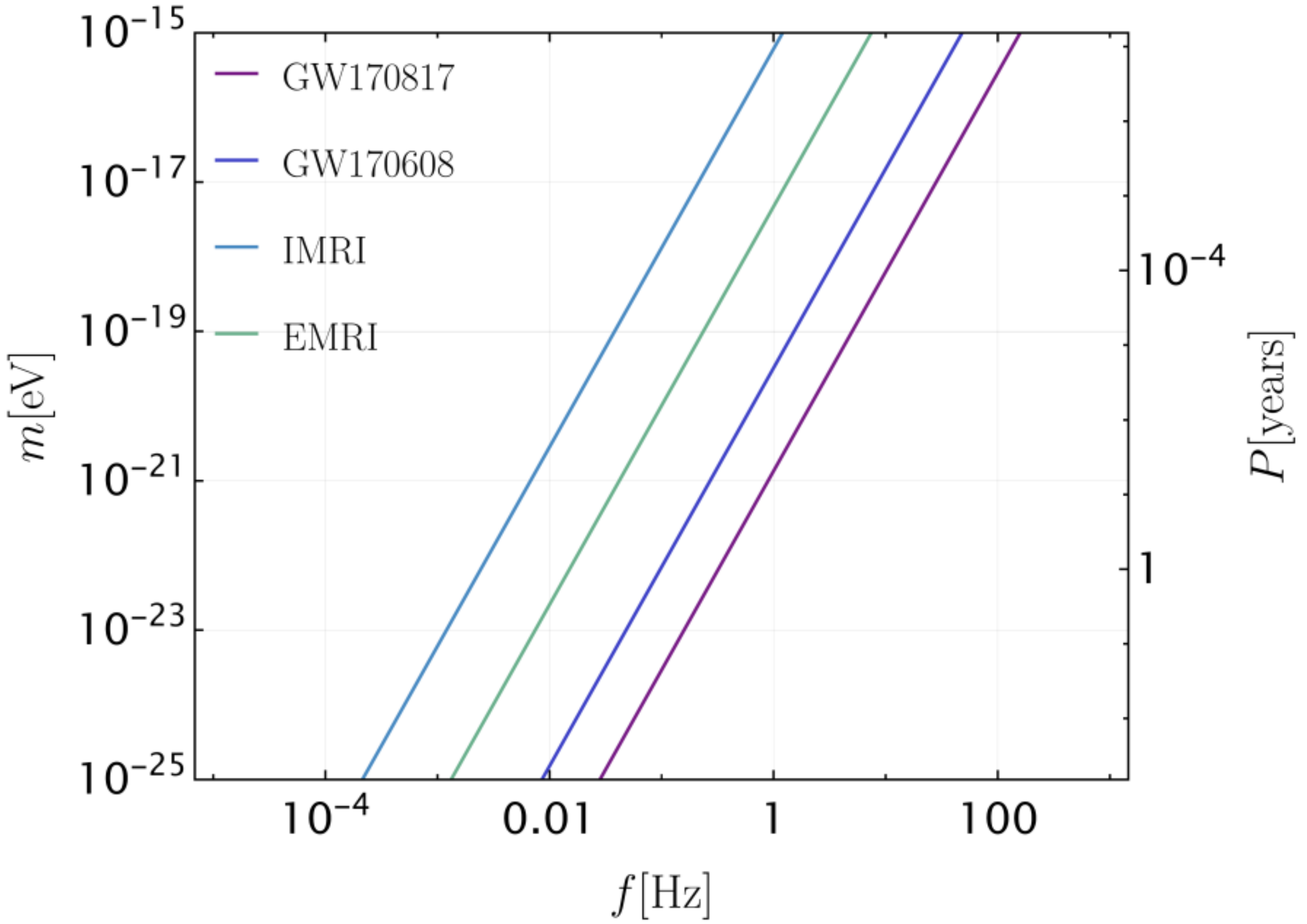
- Gravitational redshift $\chi = \Phi|_e^r + n^i\, v_i|_e^r - I_{iSW}$
- Relative phase correction $\eta = \frac{\int \omega_e \chi}{\int \omega_e}$
- Quadrupolar result for the GW frequency

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

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

$$\left.+5\tau\omega_\delta\,{}_1F_2\left(\frac{13}{16};\frac{3}{2},\frac{29}{16};-\frac{1}{4}\tau^2\omega_\delta^2\right)\sin\Theta\right)+\Theta_c$$



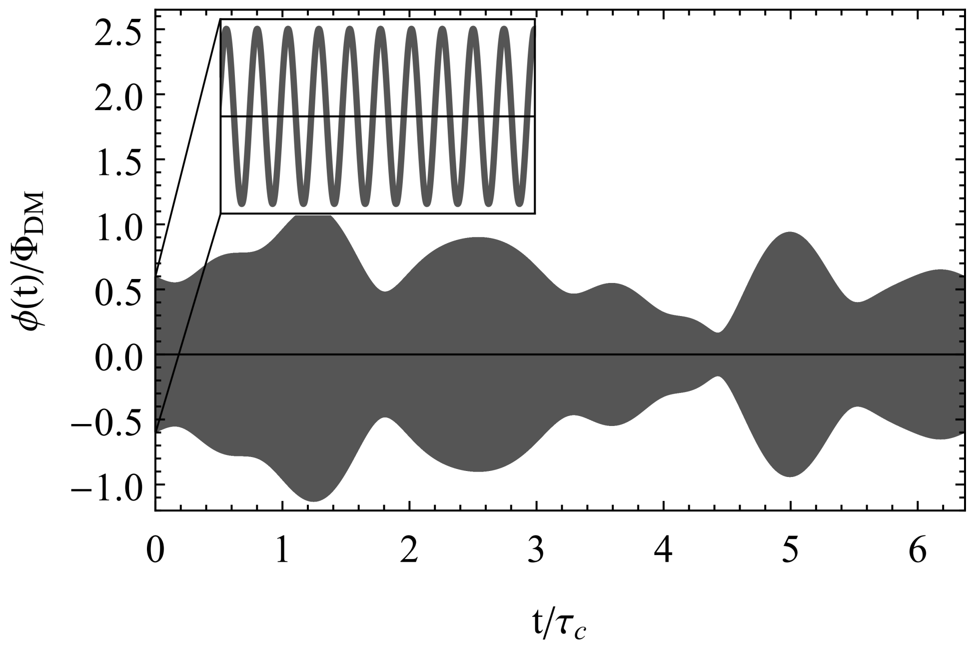


New phenomenology from ULDM

Centers et al 19

DM halo

$$\phi \propto \int_0^{v_{max}} \mathrm{d}^3 v\, e^{-v^2/\sigma_0^2} e^{i\omega_v t} e^{-im\vec{v}\cdot\vec{x}} e^{if_{\vec{v}}} + c.c.$$



A) coherent oscillations

$$\omega \sim m \approx \frac{m}{10^{-22}\,\mathrm{eV}} \frac{1}{76\ \mathrm{days}} \qquad t \sim \frac{10^6}{m}\left(\frac{10^{-6}}{\sigma_0^2}\right)$$

$$\phi \approx \phi_0 \cos(\omega t + \psi_0)$$

SM-DM interactions

$$\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$
$$m_{\rm SM}\phi\, \psi_{\rm SM}^2$$

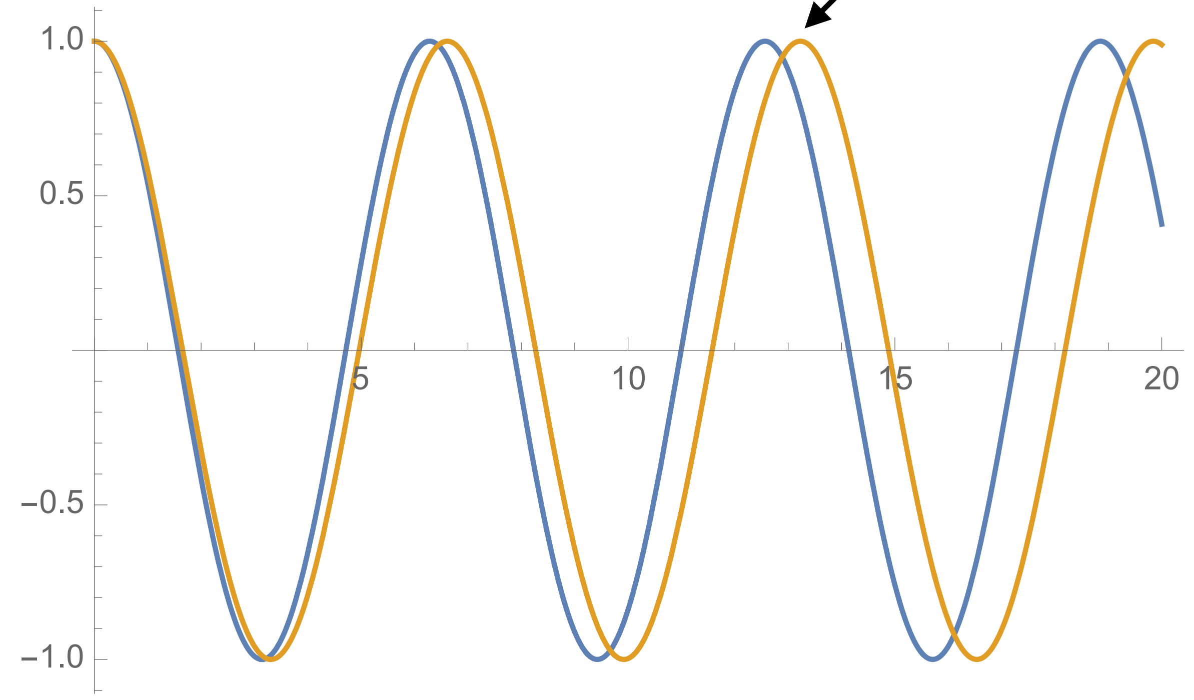
B) stochastic 'narrow' piece

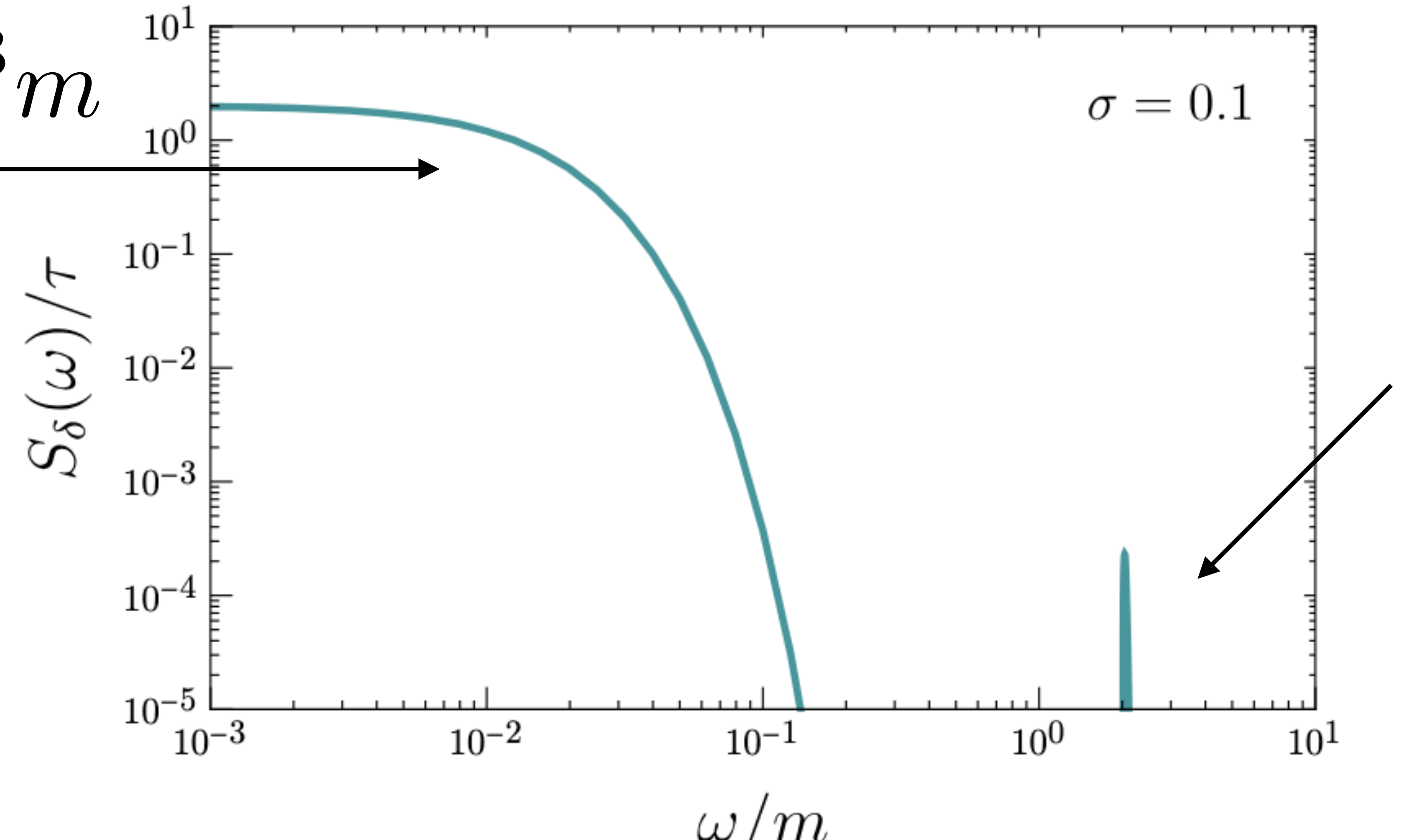
$$\sim \langle \phi^* \phi \rangle$$

these fluctuations heat, decorrelate (interf), friction

Kim 2306.13348
Ban-Or et lal 19

$$\delta\omega \approx 10^{-3} m$$





$$\omega = 2m$$

Marsh, Niemeyer 18
Dalal , Kravtsov 22
Ban-Or et lal 19
Bar-Or et al 1809.07673

Properties of the soliton

$$\phi(x,t) = \frac{1}{\sqrt{2m}} e^{-imt}\psi(x,t) + c.c.$$

$v \ll c,\ \omega \ll m$

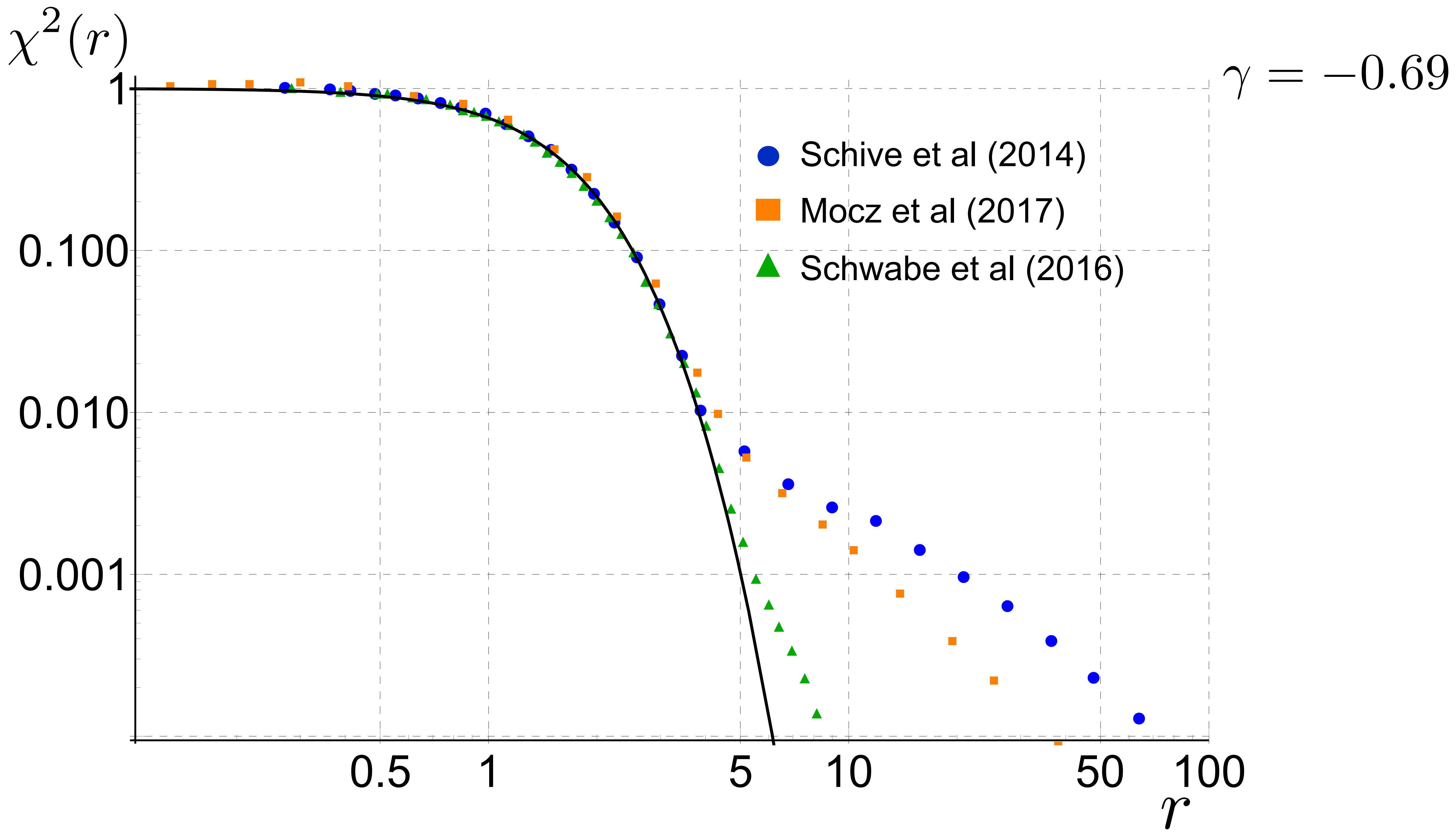
$$i\partial_t \psi = -\frac{1}{2m}\Delta\psi + m\Phi_N\psi$$

$$\Delta\Phi_N = 4\pi G|\psi|^2$$

spherically symmetric stationary, non-relativistic solution:

e.g. Bar, DB, Blum, Sibiryakov 18

$$\phi(x,t) = \frac{M_{pl}}{2\sqrt{2\pi}} e^{-imt} e^{-i\gamma t}\chi(x) + h.c.$$



scaling solution

$$\chi_\lambda(r) = \lambda^2 \chi_1(\lambda r)$$

$$x_{c\lambda} = \lambda^{-1} x_{c1}$$

$$M_\lambda = \lambda M_1$$

$$\gamma_\lambda = \lambda^2 \gamma$$

$$\rho_{c\lambda} = \lambda^4 \rho_{c1}$$

What fixes γ?