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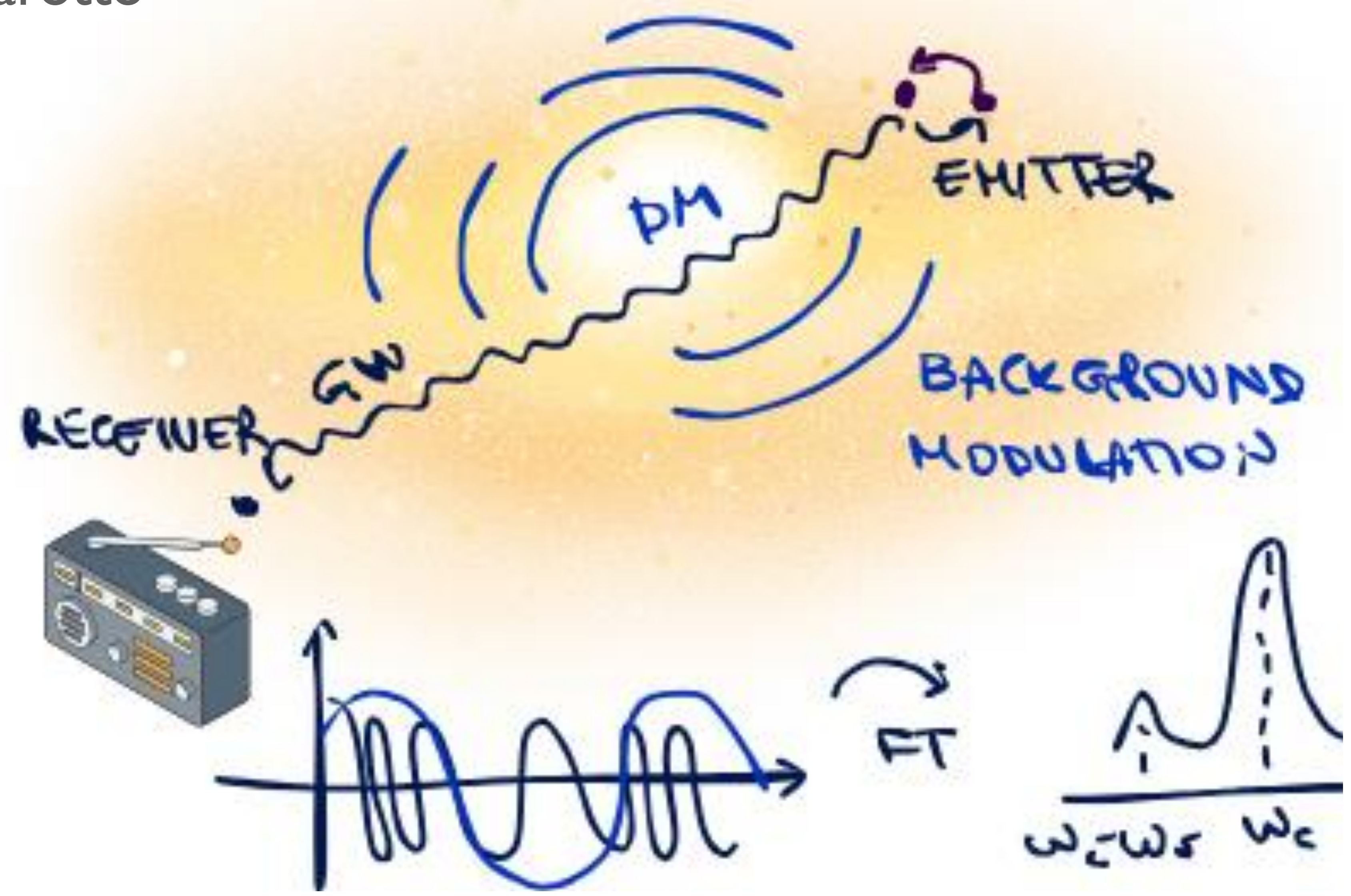

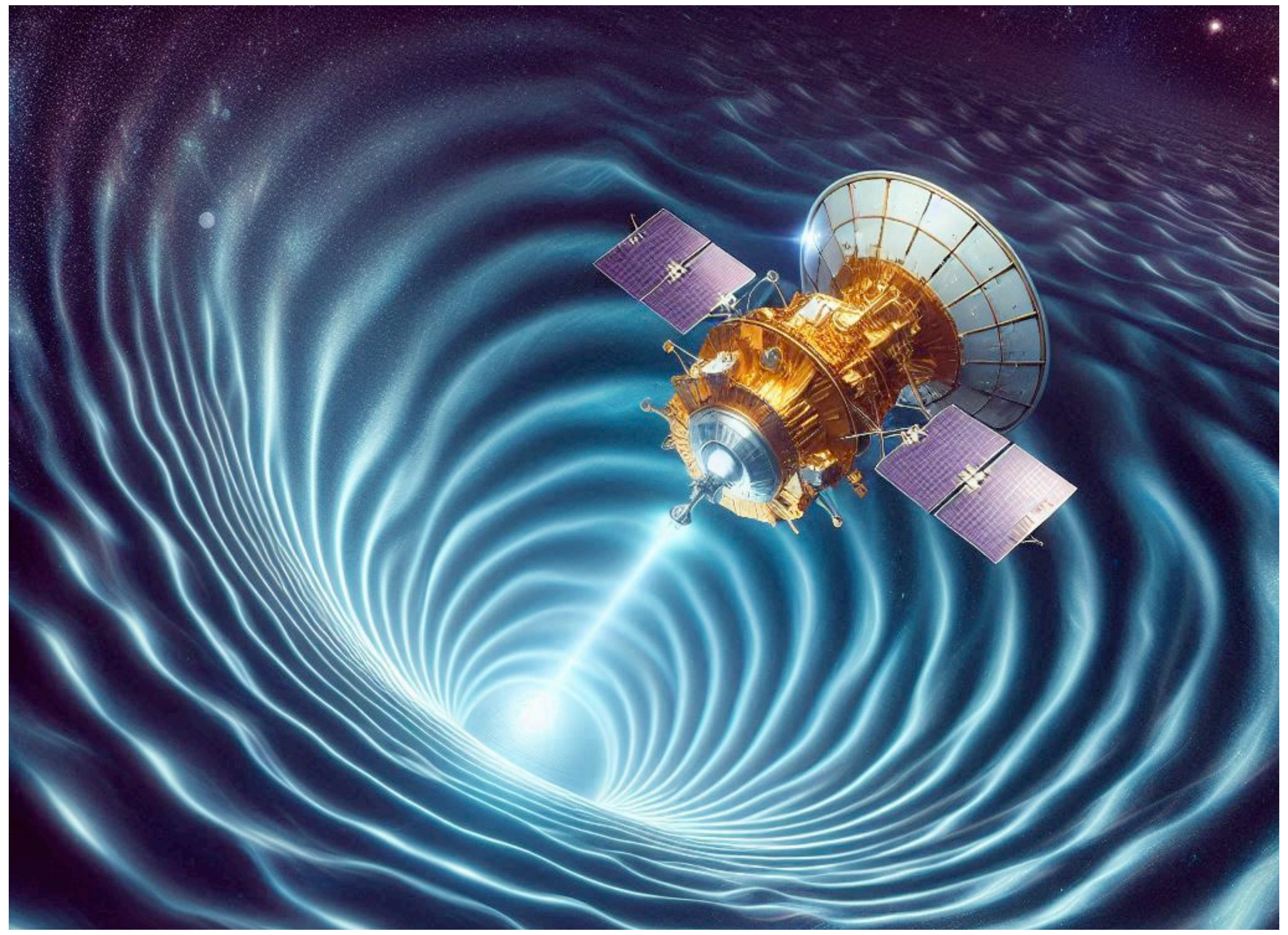

New ideas to find ultralight dark matter in astrophysical data

Diego Blas

w/ **S. Gasparotto** & R.Vicente

e-Print: 2410.07330 [hep-ph]

w/ **L. Zwick,** D. Soyuer, D. J. D'Orazio, D. O'Neill, A. Derdzinski, P. Saha, A. C. Jenkins, Z. Kelley

e-Print: 2406.02306 [astro-ph.HE]

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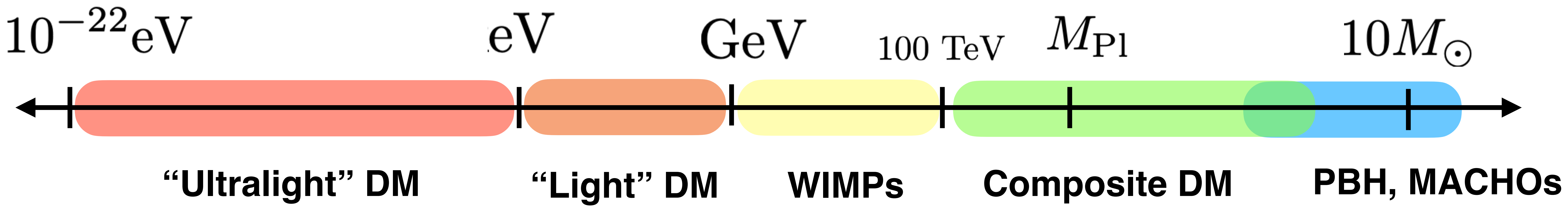
Dark Matter: where to look?



“Ultralight” DM

“Light” DM

WIMPs

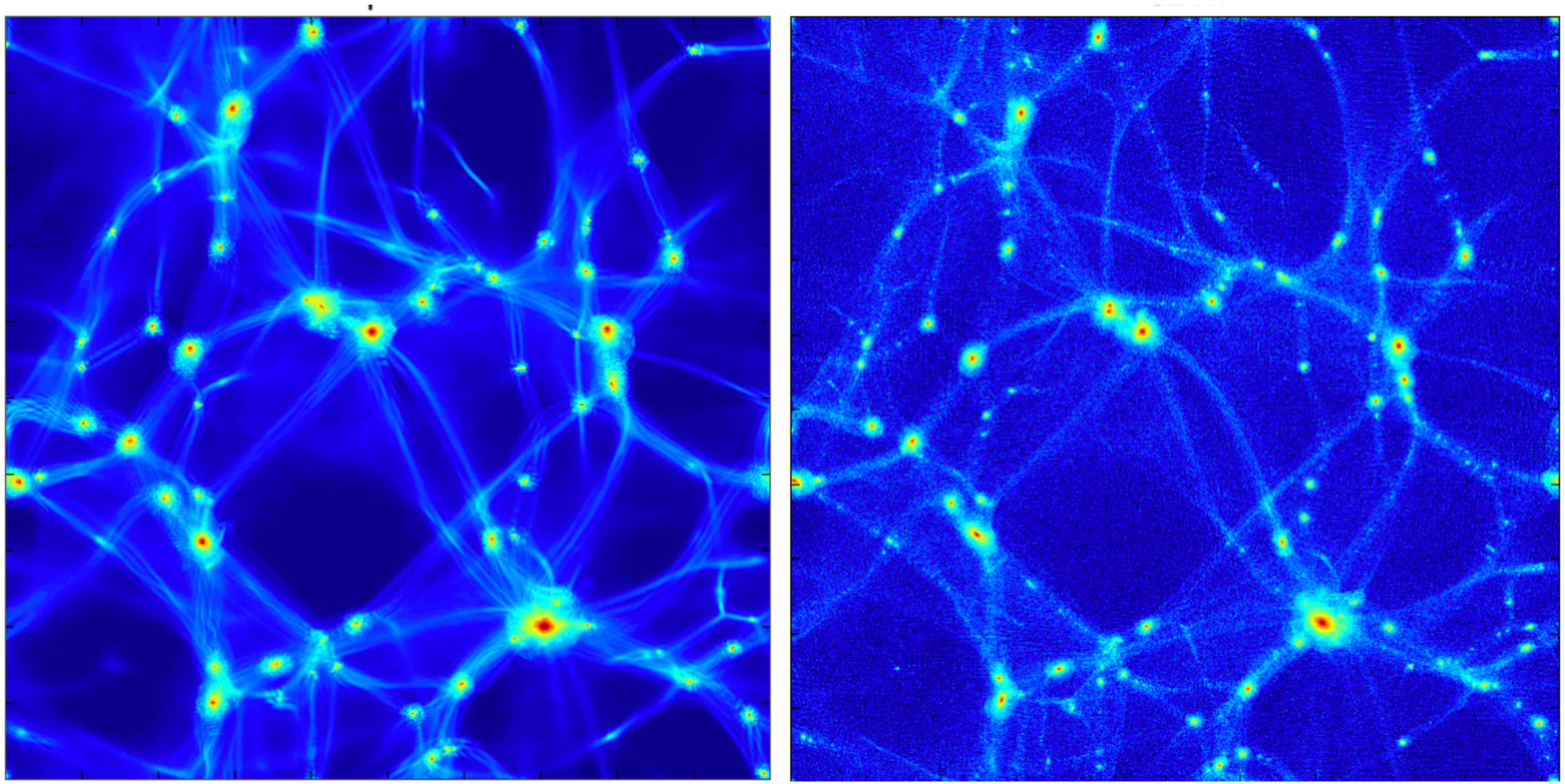
Composite DM

PBH, MACHOs

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 $L \gtrsim 1/(m v_{\mathrm{esc}}) \approx 190 \left(\frac{m}{10^{-22}\mathrm{eV}}\right)^{-1}\ \mathrm{pc}$

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

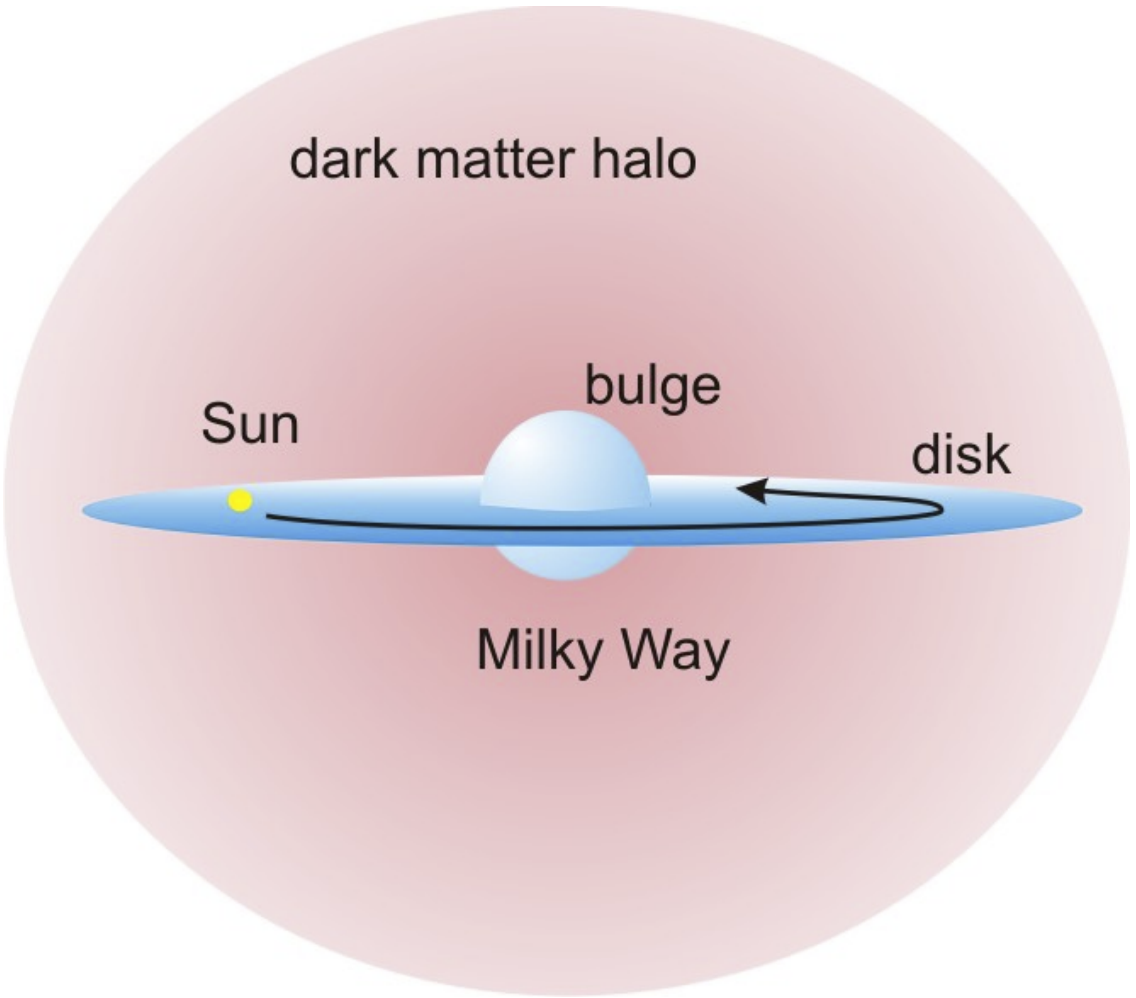
Occupation number : $\mathcal{N} = n\, \lambda_{db}^3 \sim 10^{92} \times \left(\frac{10^{-22} eV}{m}\right)^4$

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



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

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

Close to λ_{db}

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

gravitational potential

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

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

pure CDM part

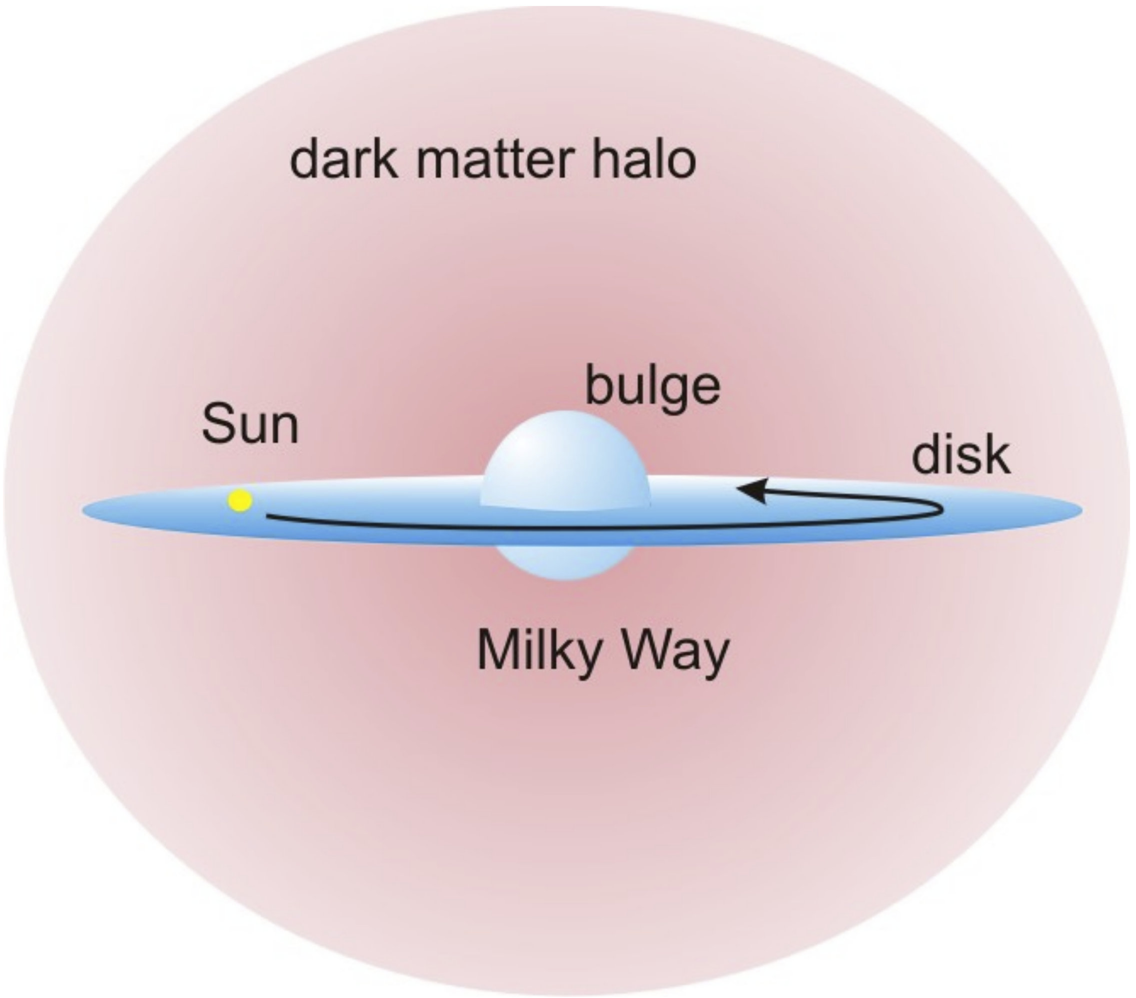
new phenomena at small scales!
(repulsive effect: “quantum pressure”)

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

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

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



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

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

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

free wave

The DM potential has coherent oscillations in λ_{db}

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

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

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

pure CDM part

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

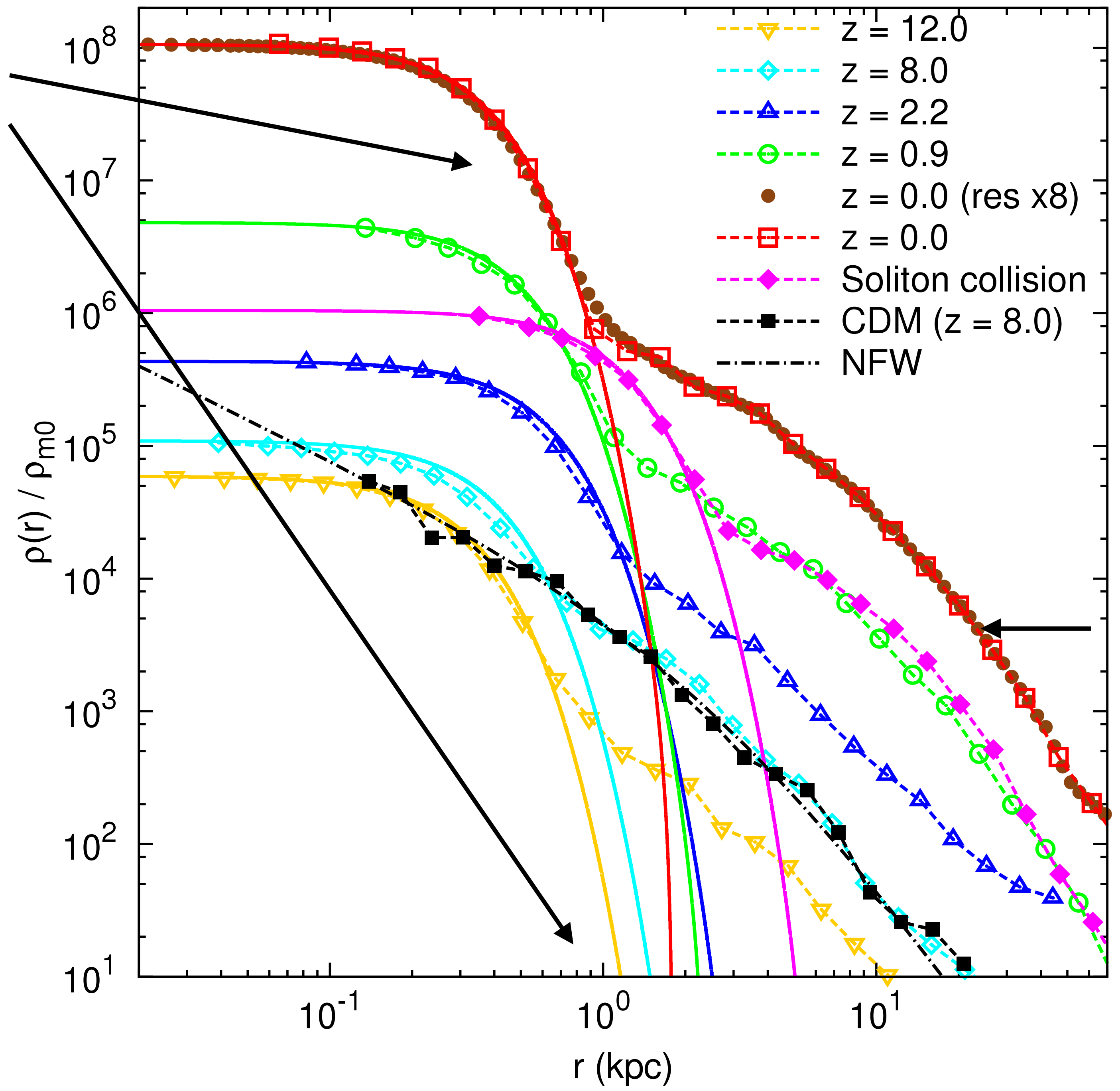
C) changes dynamics at smaller scales $\frac{10^{-3}}{v}$kpc

New phenomenology from ULDM

DM small scale dynamics

C) changes dynamics at smaller scales

Schive et al.1407.7762



soliton

halo

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

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

gravitational potential

pure CDM part

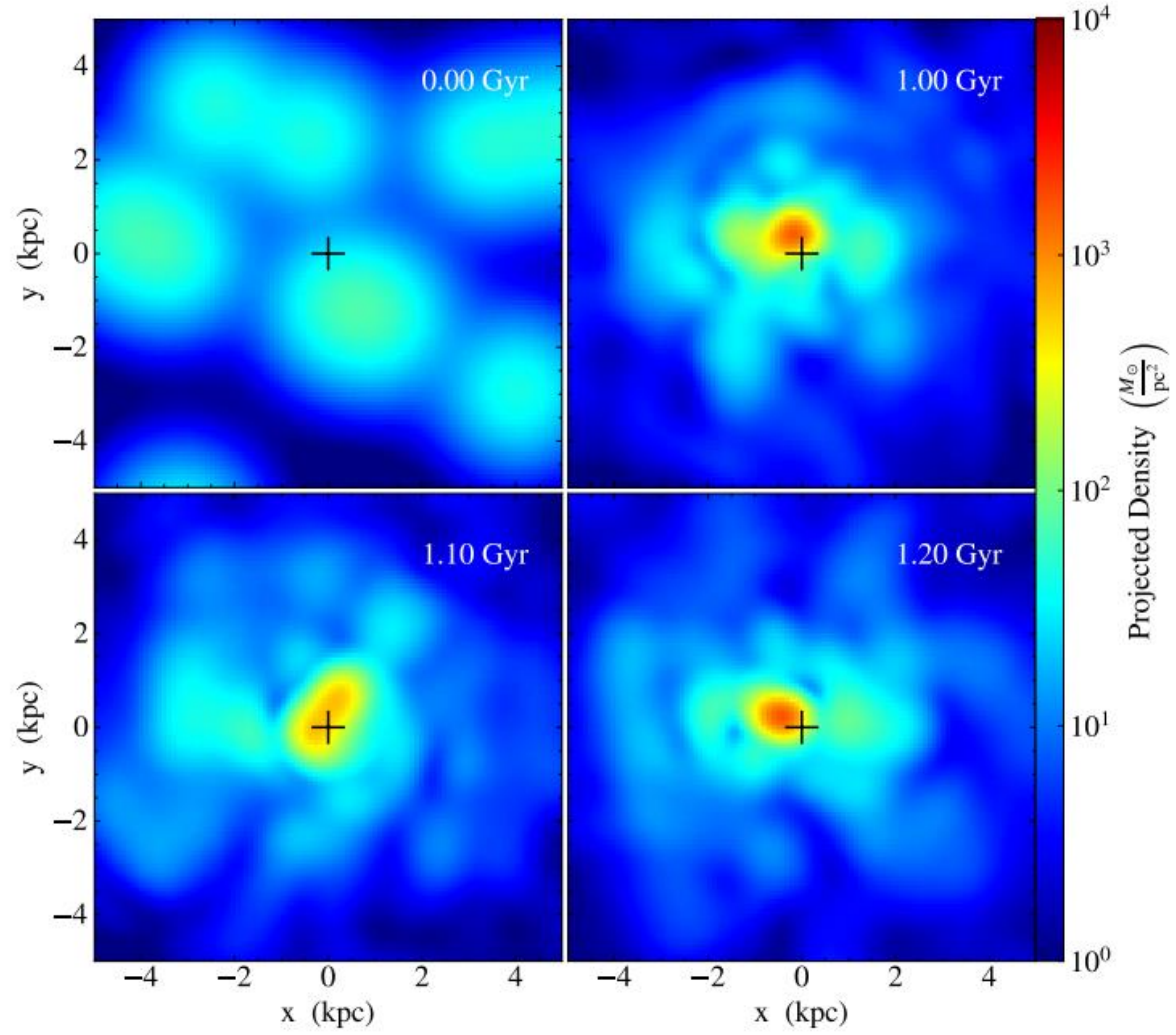
repulsive term

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

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

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

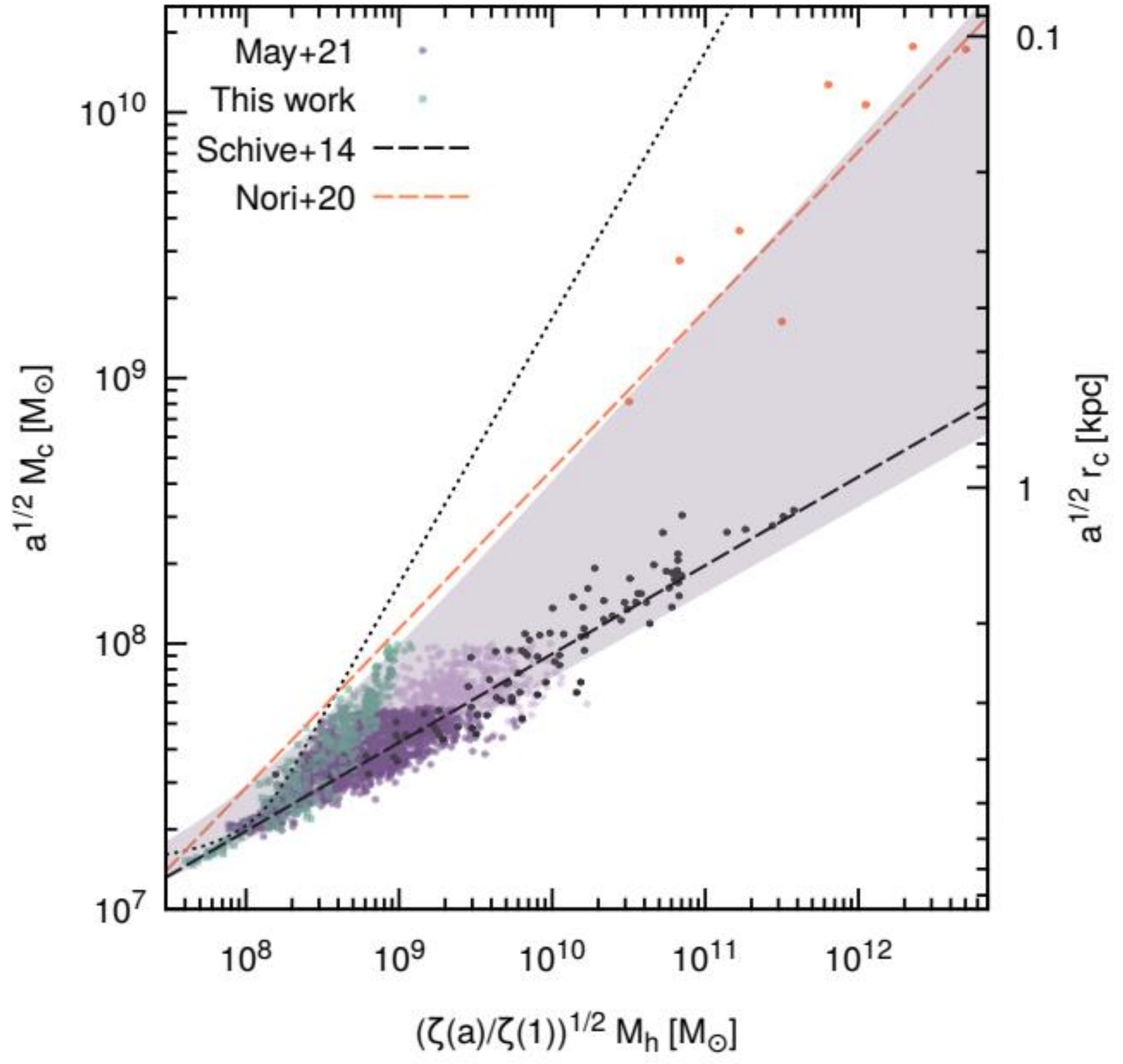
HALO AND SOLITON FORMATION



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

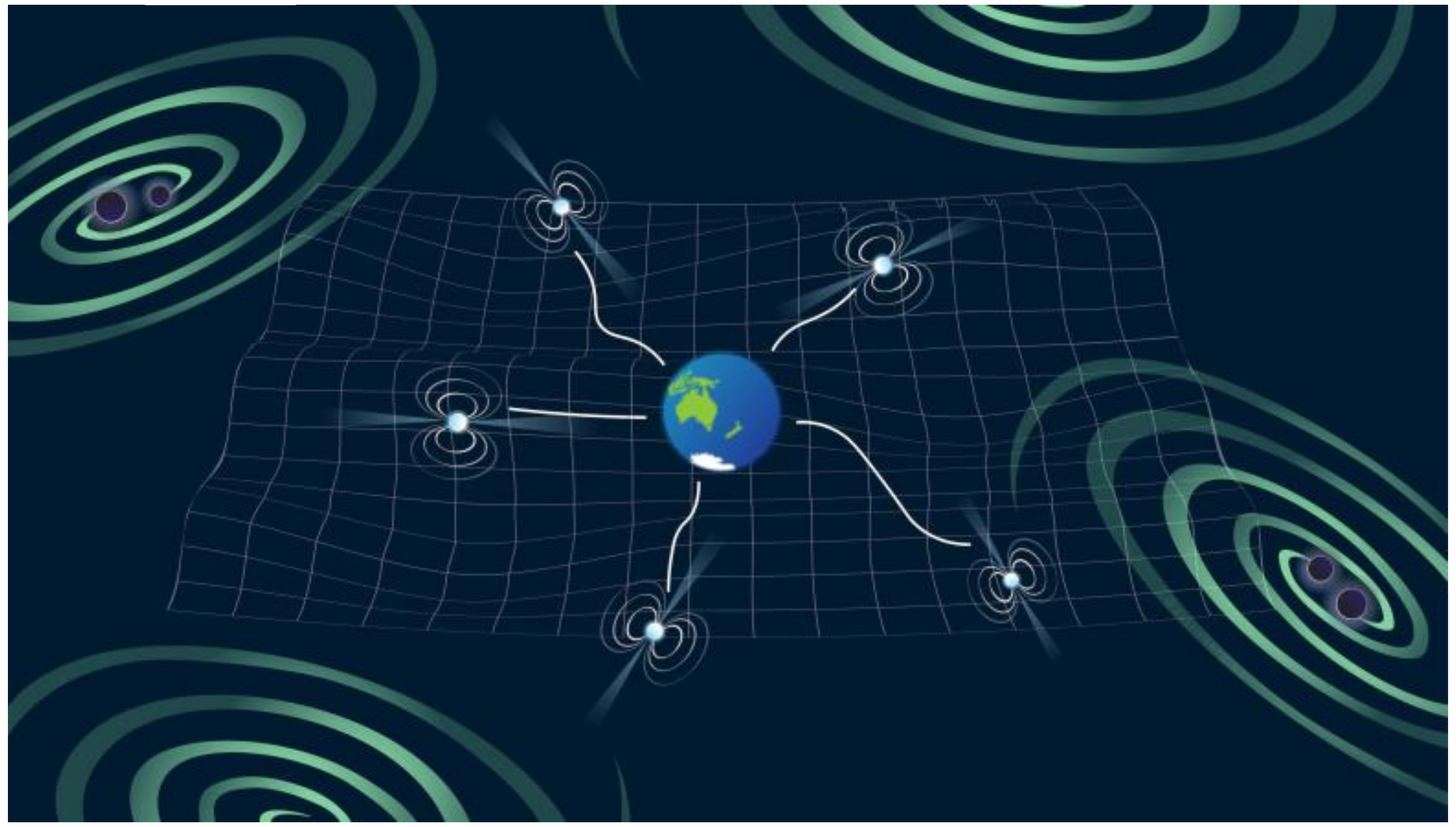


The mass of the soliton is related to the mass of the DM halo where it is formed. Schive 1407.7762

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

But some dispersion is observed in the literature

Waves propagating in ‘Newtonian’ metric



$$g_{\mu\nu}\mathrm{d}x^{\mu}\mathrm{d}x^{\nu} \approx -(1-2\Phi)\mathrm{d}t^2 + (1+2\Psi)\delta_{ij}\ \mathrm{d}x^i\ \mathrm{d}x^j,$$

$$\frac{\Delta\omega_e}{\omega_e} \simeq \Phi\Big|_e^r + n^i v_i\Big|_e^r - I_{iSW}$$

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

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

$$\Longrightarrow$$

$$\Phi = \bar{\Phi} + \delta\Phi$$

$$\Psi = \underset{\uparrow}{\bar{\Psi}} + \underset{\uparrow}{\delta\Psi}$$

stationary oscillating

$$\Longrightarrow$$

leading term

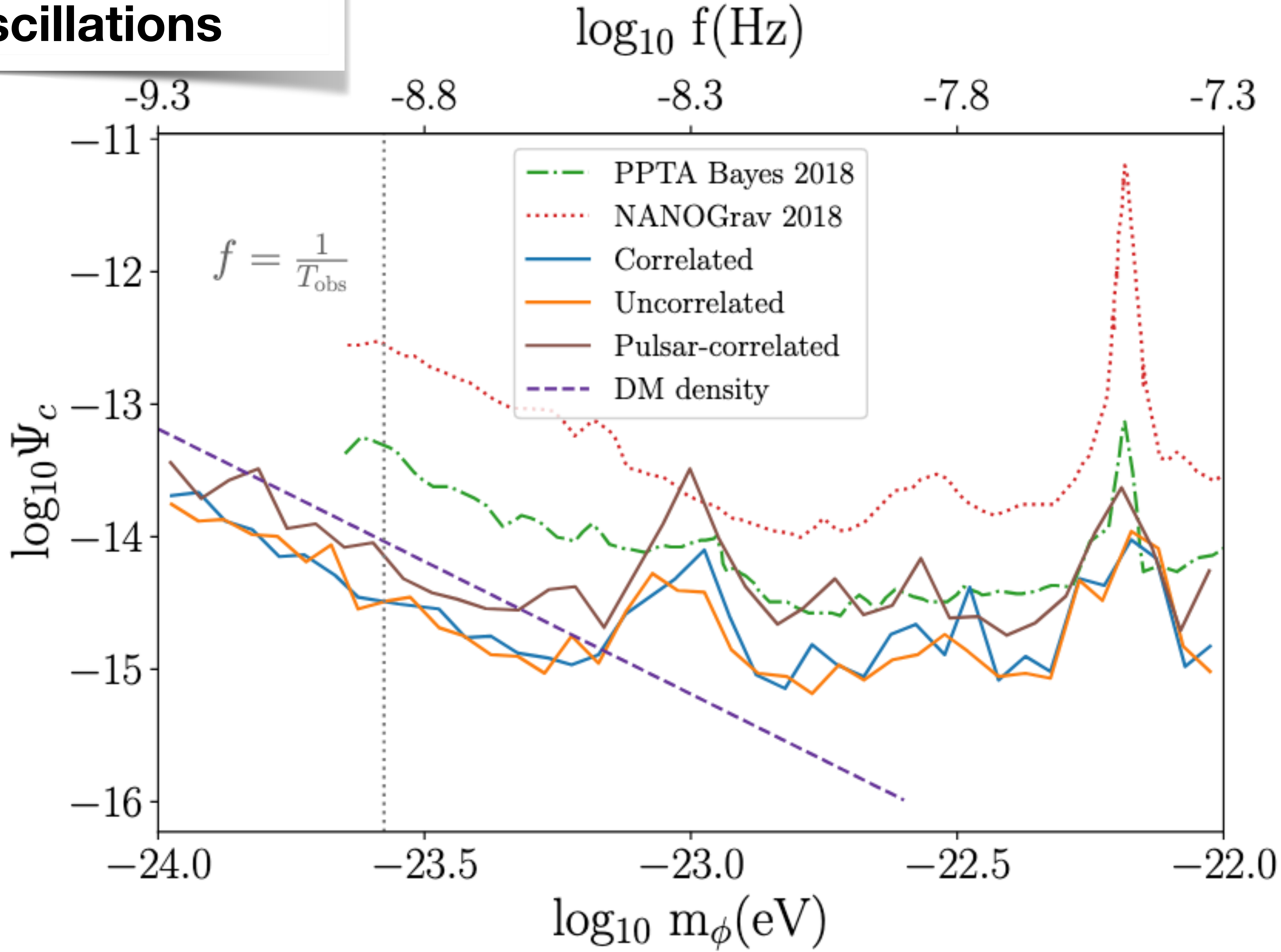
$$\delta\Psi \equiv \frac{\pi}{m^2}\bar{\rho}_\phi \cos(2mt)$$

Changes in time of arrival (PTA!)

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

ULDM in PTA searches

A) coherent oscillations

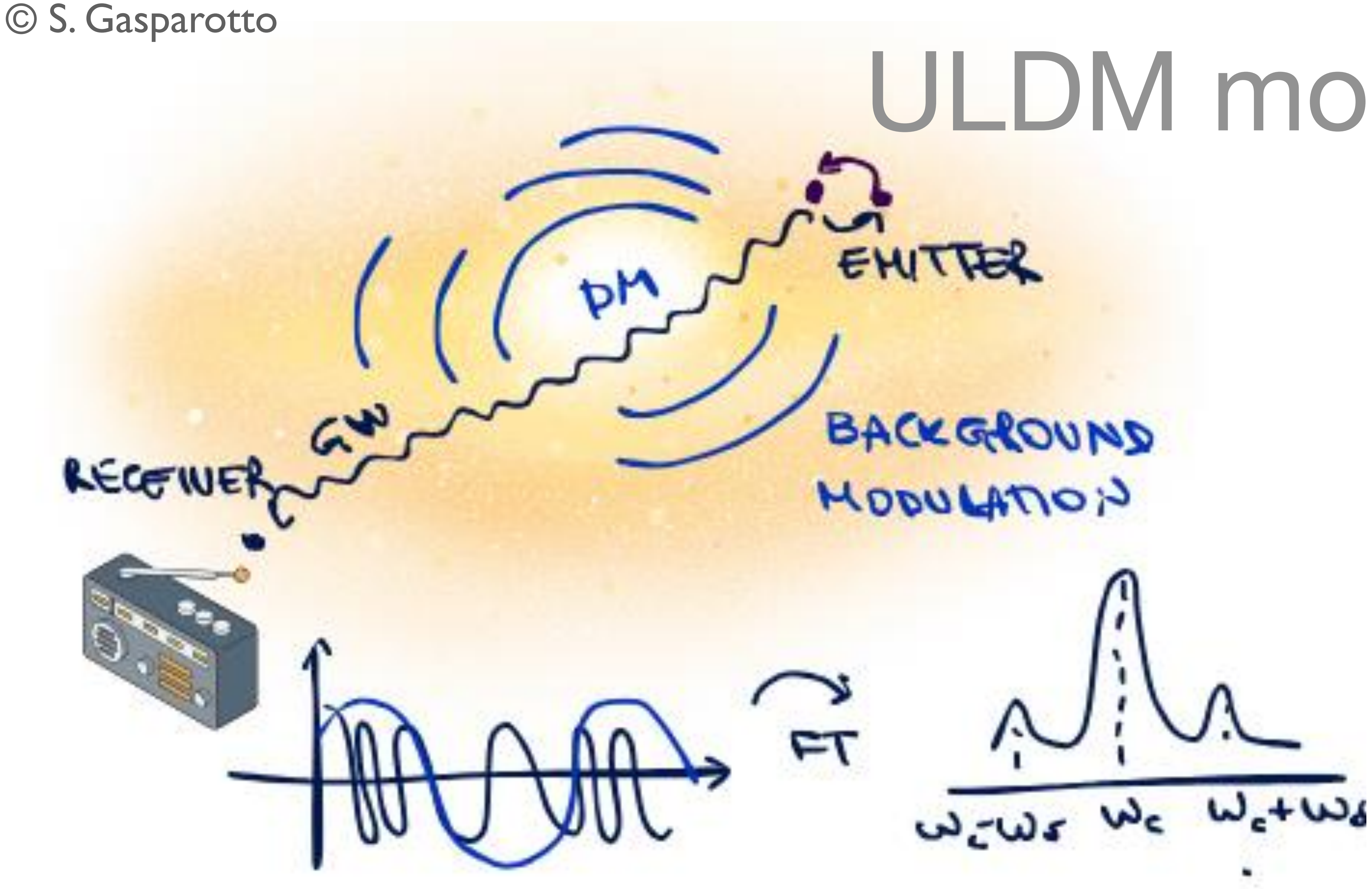


Smarra et al
2306.16228 [astro-ph.HE]

$$f_{\rm low} = \frac{1}{T_{\rm obs}}, \quad f_{\rm high} = \frac{1}{\delta t_{\rm obs}}$$

ULDM modulates GWs

DB, Gasparotto, Vicente, 2410.07330



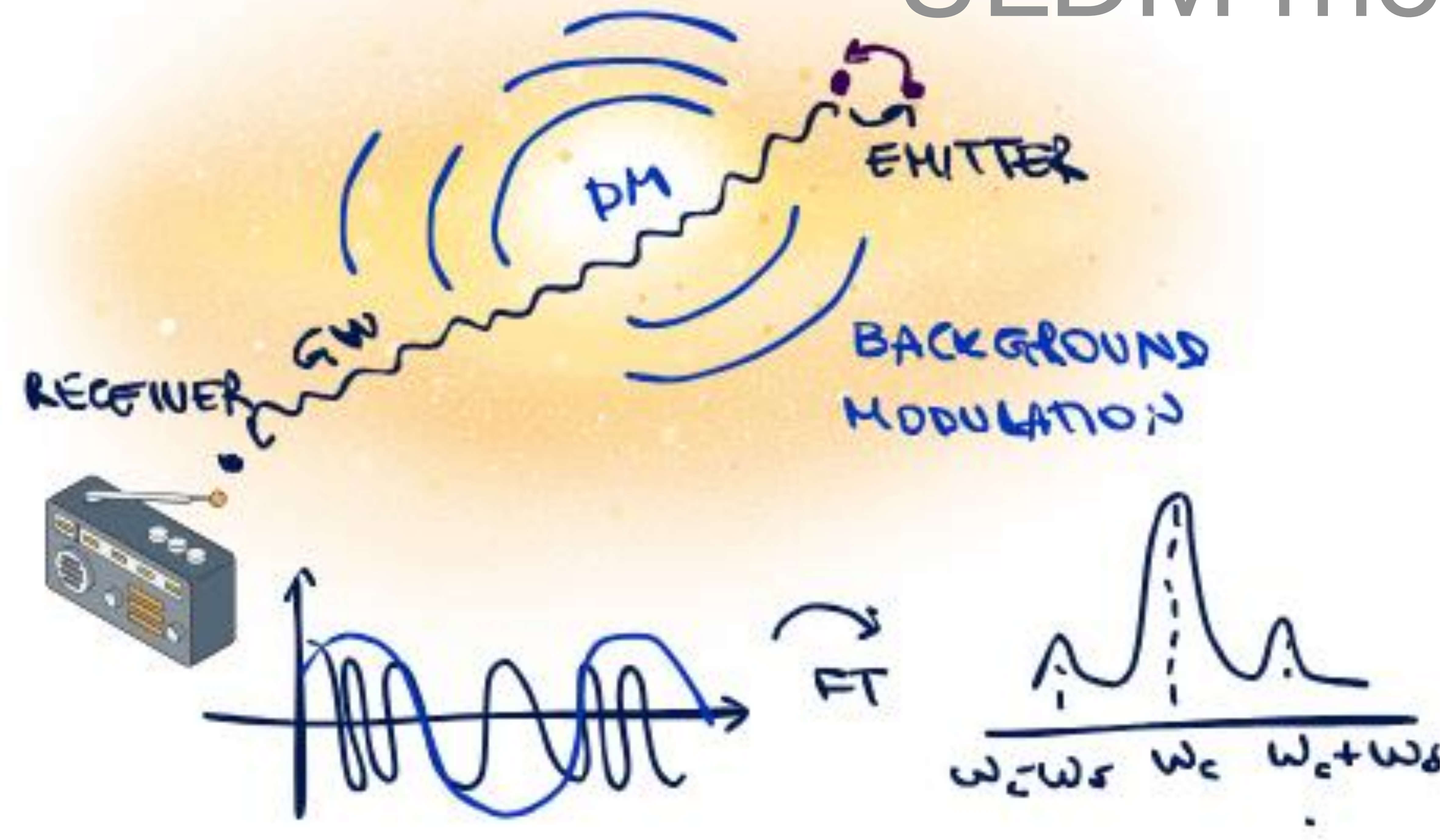
$$\Upsilon = \underset{\frac{\pi}{m^2}\bar{\rho}_\phi}{\underset{\uparrow}{\Psi_2}} - \frac{2}{\omega_\delta} n^i \partial_i \Phi_2 \Big|_e$$

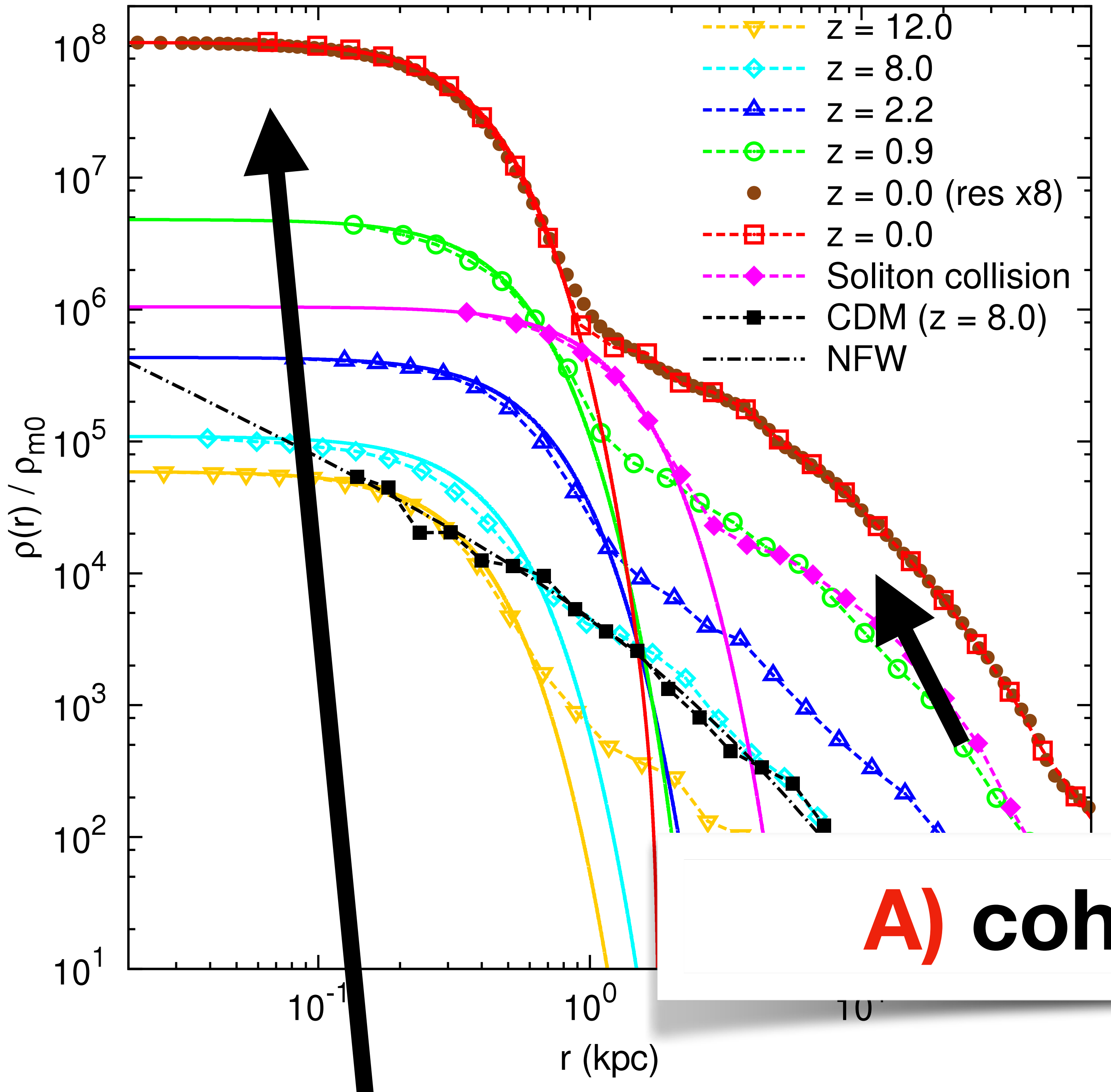
$$\omega_\delta = 2m$$

$$h_{GW} = \overset{\text{primary wave}}{\boxed{A\cos\left(\omega_e u + \varphi\right)}} + A\frac{\omega_e}{\omega_\delta}\Upsilon\Big|_e \sin\left[\left(\omega_e \pm \underset{\swarrow}{}\omega_\delta\right) u + \varphi)\right]$$

$$\boxed{SNR_\delta = \frac{1}{\sqrt{2}}\frac{\omega_e}{\omega_\delta}\Upsilon\sqrt{N}SNR_h}$$

ULDM modulates GWs





A) coherent oscillations

C) changes dynamics at smaller scales

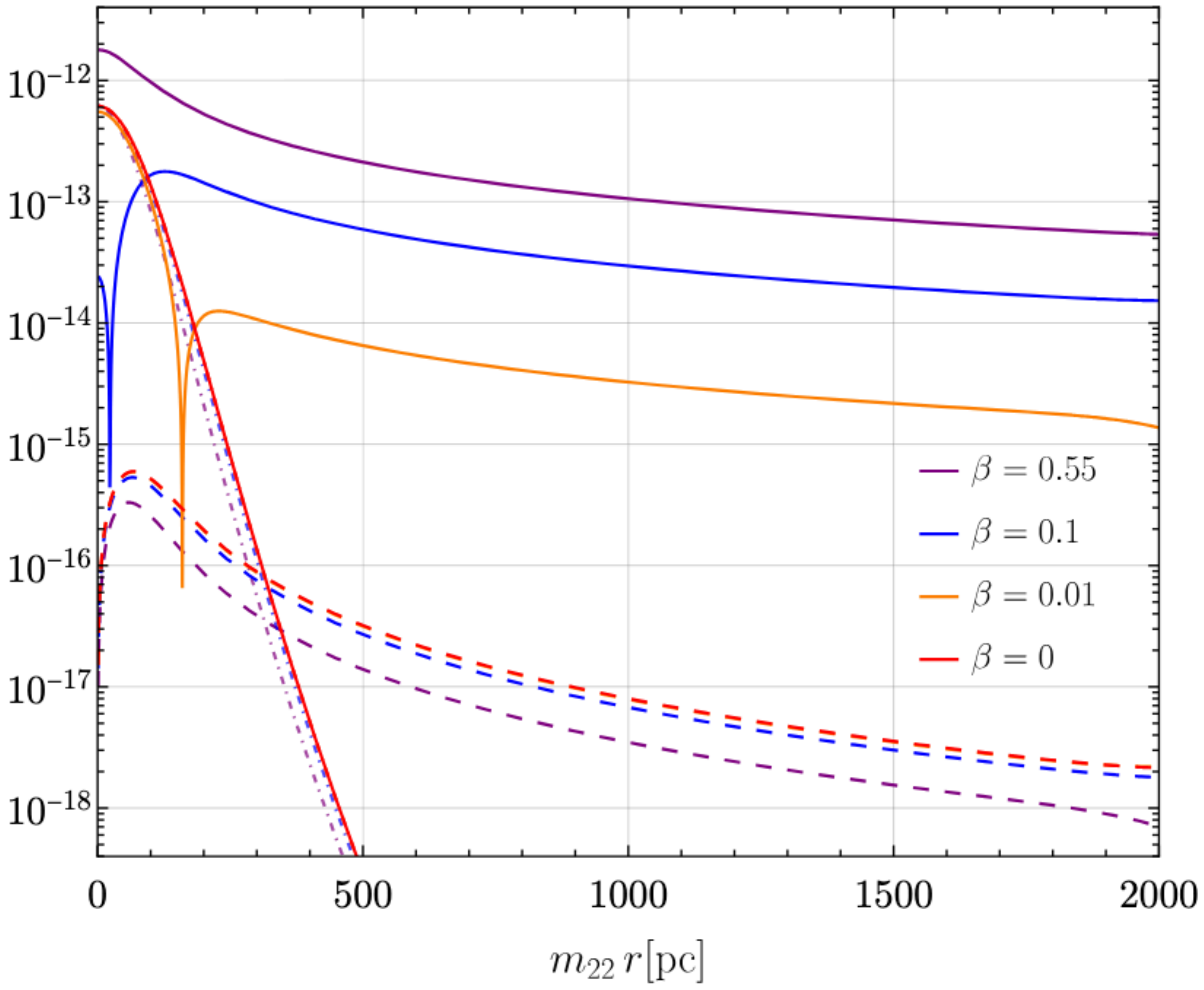
$$SNR_\delta = \frac{1}{\sqrt{2}}\frac{\omega_e}{\omega_\delta}\Upsilon\sqrt{N}SNR_h$$

many sources of GWs of **high** ω_e
at the **galactic center:** we may beat PTA

Which potential?

DB, Gasparotto, Vicente, 2410.07330

$$\mathcal{V}[\phi] = \frac{1}{2}(m\phi)^2\left[1 - \frac{1}{12}(\phi/F)^2\right], \qquad \beta \equiv \frac{\sqrt{\bar{\rho}_0/\pi}}{16\,(F^2 m)}$$



Ψ_2

$m^{-1}\partial_r\Phi_2$

Galactic sources

DB, Gasparotto, Vicente, 2410.07330

$$SNR_\delta = \frac{1}{\sqrt{2}}\frac{\omega_e}{\omega_\delta}\Upsilon\sqrt{N}SNR_h$$

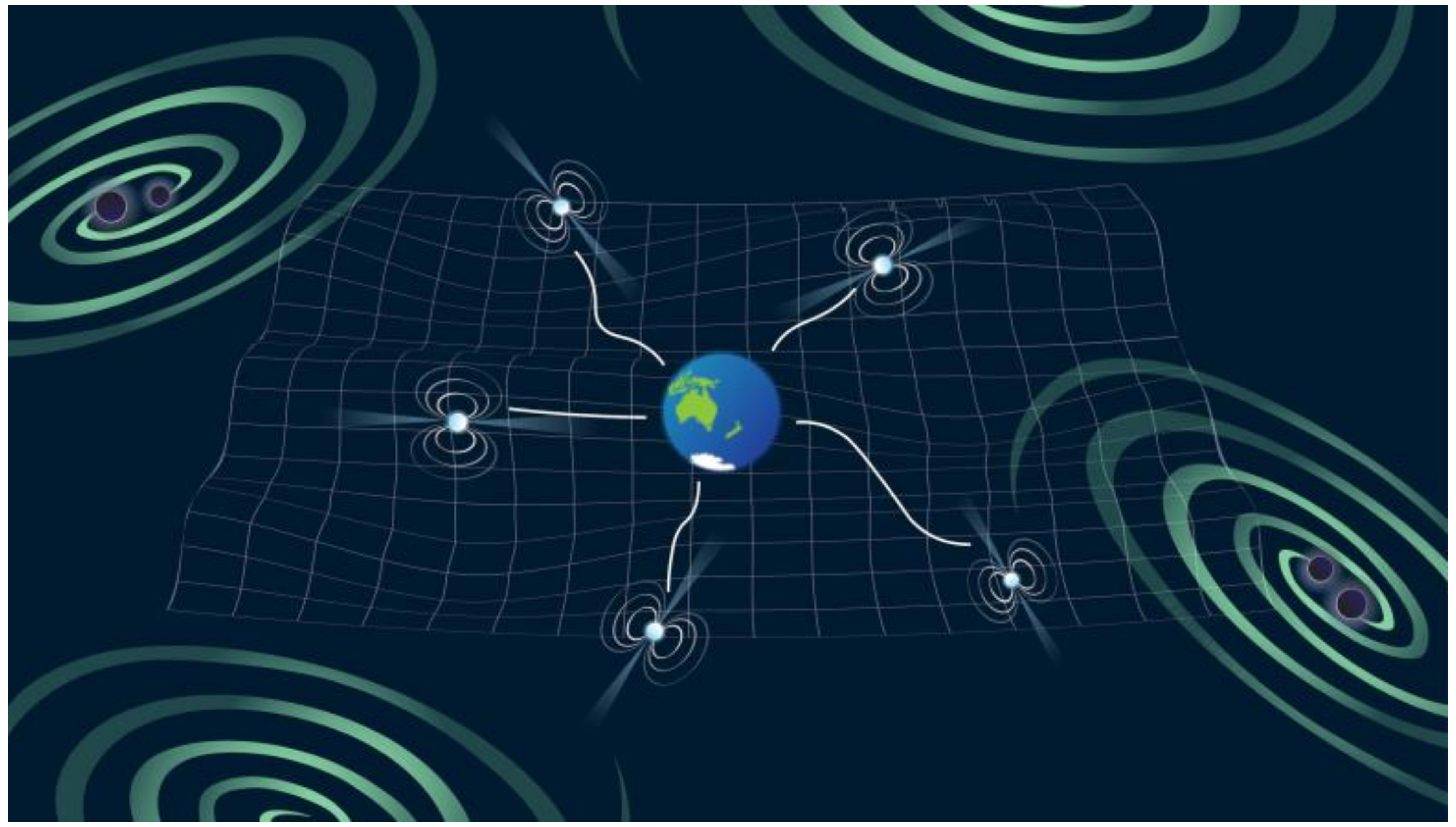
	N	$\langle \mathrm{SNR}_h \rangle$	$\sqrt{N}\langle \mathrm{SNR}_h \rangle \langle f_e \rangle [\mathrm{Hz}]$
	Double White Dwarfs		
LISA	$5.5(1.6) \times 10^3$	37(38)	7.8(4.3)
TianQin	$2.5(0.7) \times 10^3$	37(37)	5.1(2.9)
Taiji	$5.8(1.7) \times 10^3$	59(60)	13(6.8)
μAres	$504(148) \times 10^3$	49(48)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

$f_e \sim \mathrm{mHz}$

$f_e \sim \mathrm{kHz}$

Models with ULDM coupled to baryons

DB, Gasparotto, Vicente, 2410.07330



$$g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu \approx -(1-2\Phi)\mathrm{d}t^2 + (1+2\Psi)\delta_{ij}\ \mathrm{d}x^i\ \mathrm{d}x^j,$$

if all fields couple as

$$\mathcal{L}_\mathrm{m} = \mathcal{L}_\mathrm{m}\left[\boldsymbol{\chi}^i, A^2(\phi)\boldsymbol{g}\right]$$

all effects are the same with the effective metric

$$\widetilde{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu}$$

this is more generic that it seems, as it accounts for contributions of the form

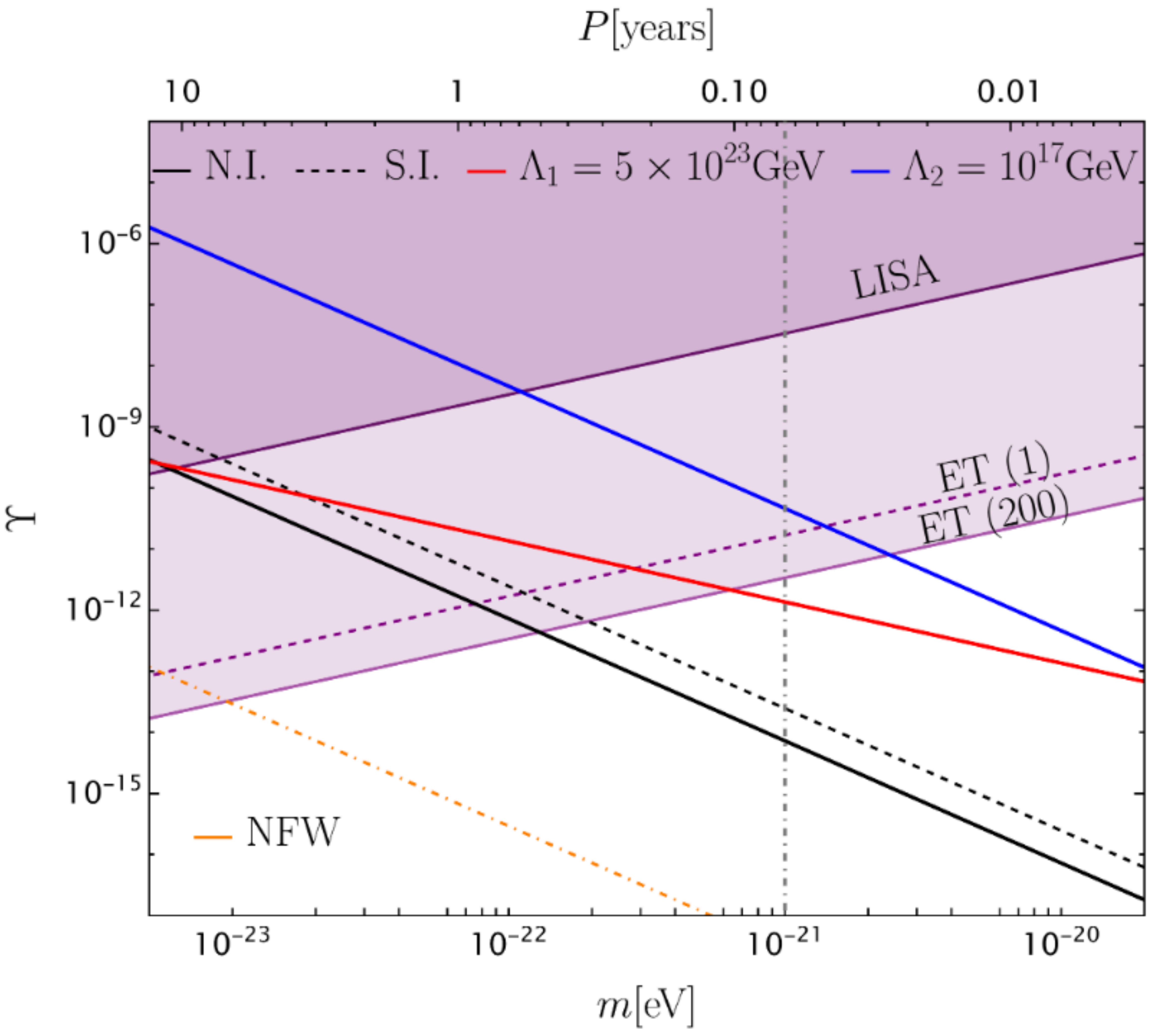
$$A \approx 1 + \phi/\Lambda_1 \text{ and } A \approx 1 + \phi^2/\Lambda_2^2$$

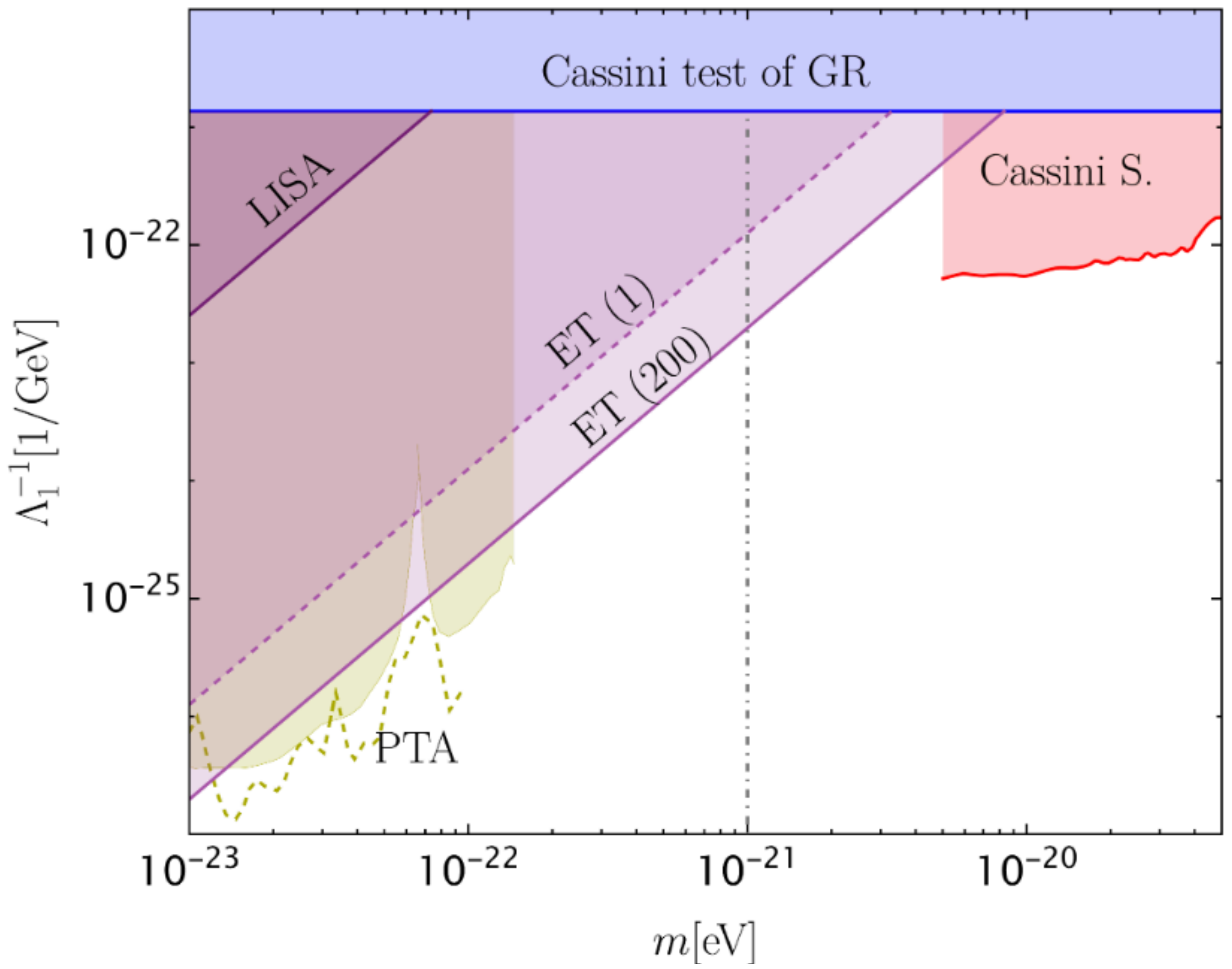
$$SNR_\delta = \frac{1}{\sqrt{2}}\frac{\omega_e}{\omega_\delta}\Upsilon\sqrt{N} SNR_h$$

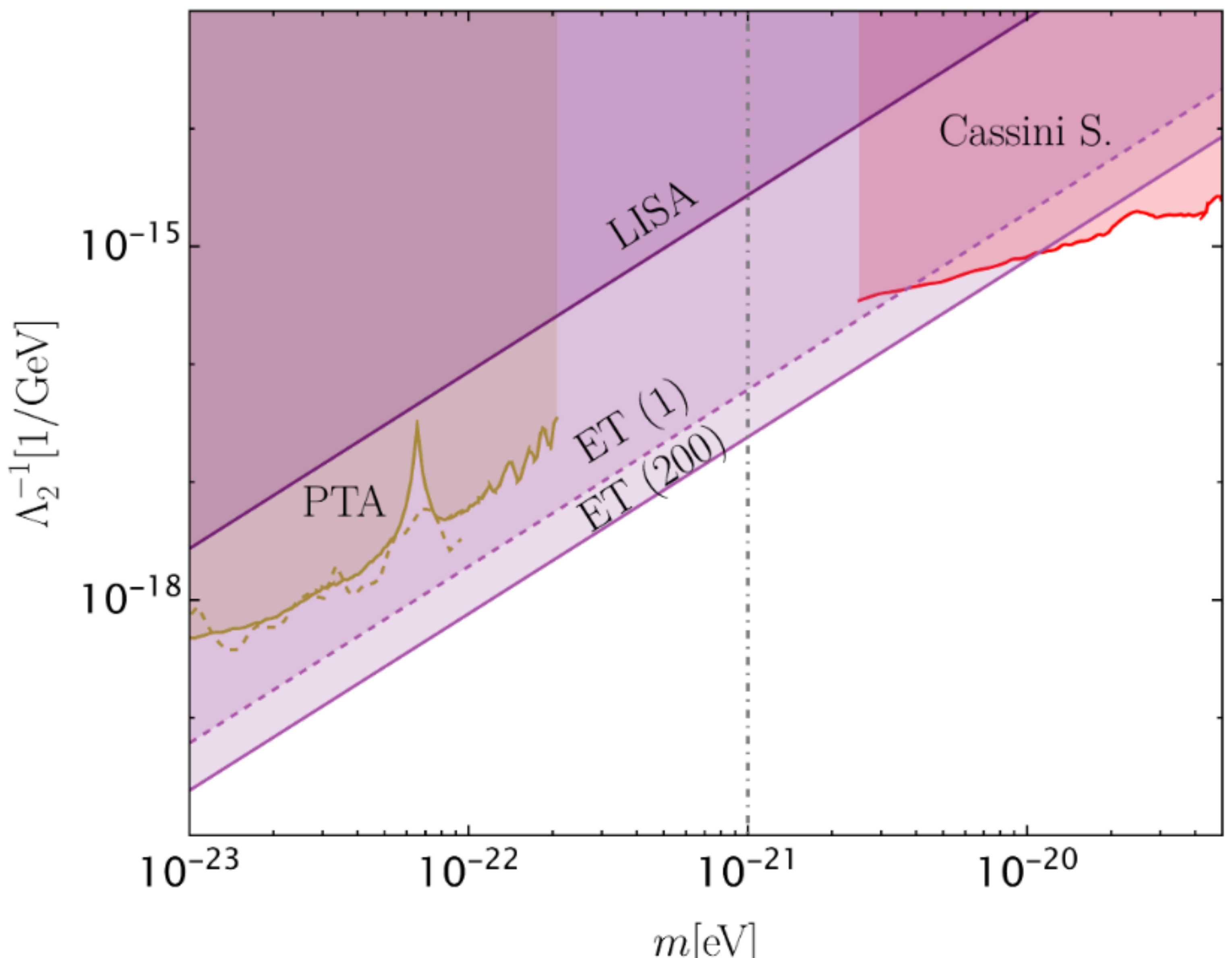
$$\Upsilon \equiv \begin{cases} \left[\Psi_2 - \frac{2}{\omega_\delta} n^i \partial_i \Phi_2\right]_{x_\mathrm{e}^i}, & \text{(minimal)} \\ \frac{\sqrt{2}}{\Lambda_1}\left(\frac{\bar{\rho}_\phi(x_\mathrm{e}^i)}{m^2}\right)^{1/2}, & \text{(direct linear)} \\ \frac{1}{\Lambda_2^2}\frac{\bar{\rho}_\phi(x_\mathrm{e}^i)}{m^2}, & \text{(direct quadratic)} \end{cases}$$

Sensitivity to ULDM from MW sources

DB, Gasparotto, Vicente, 2410.07330





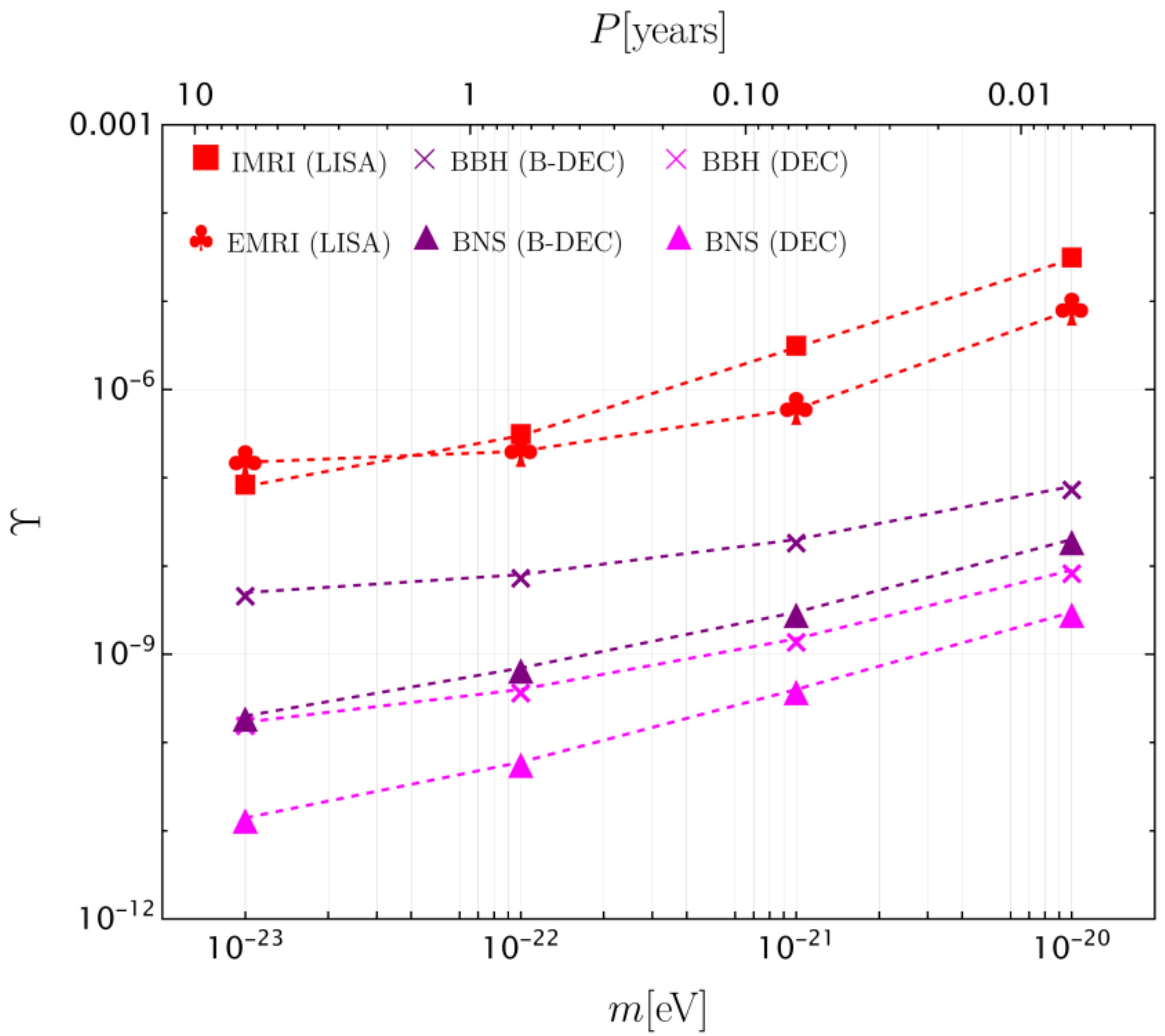


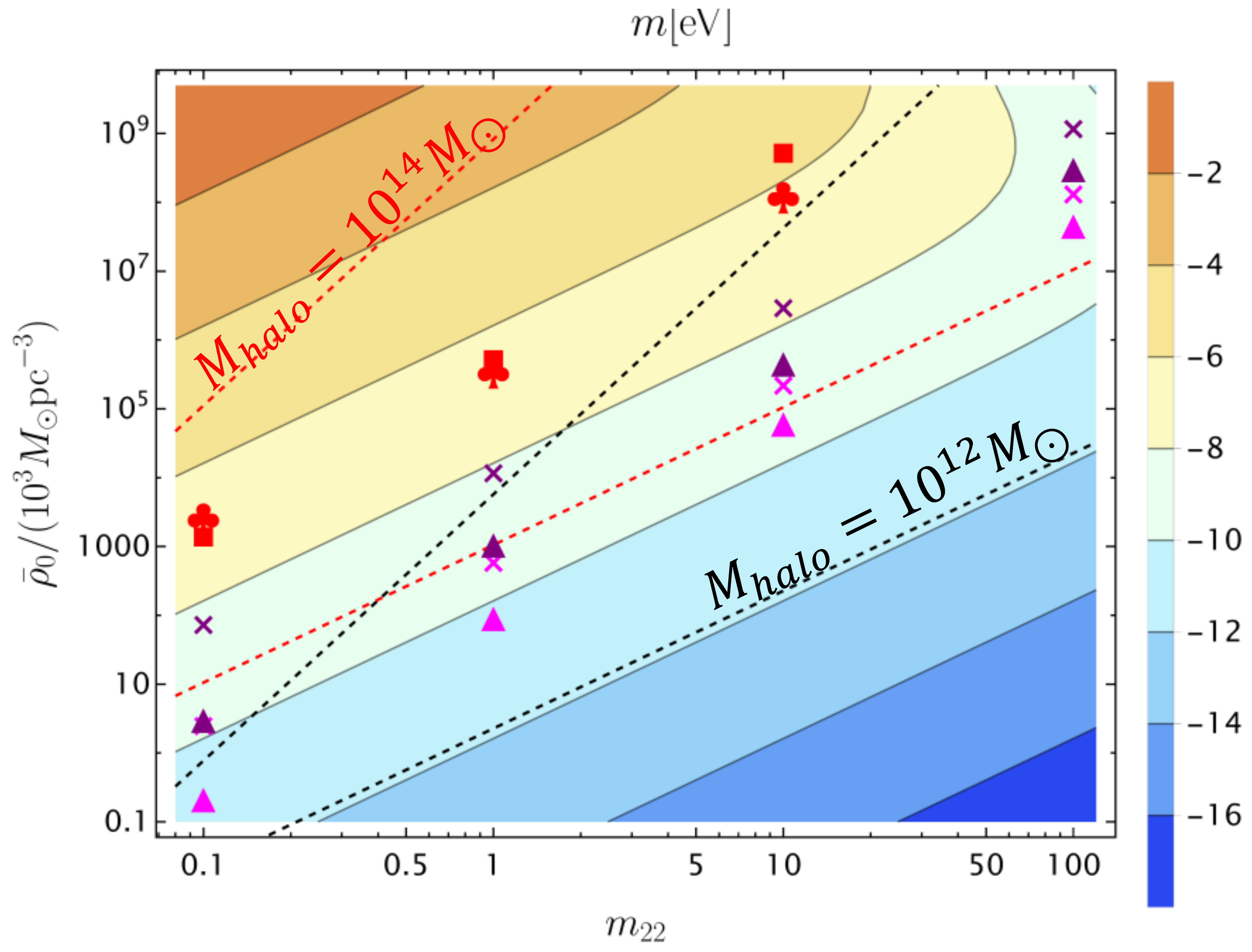
Extra galactic sources

DB, Gasparotto, Vicente, 2410.07330

- 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

(B-)DECIGO



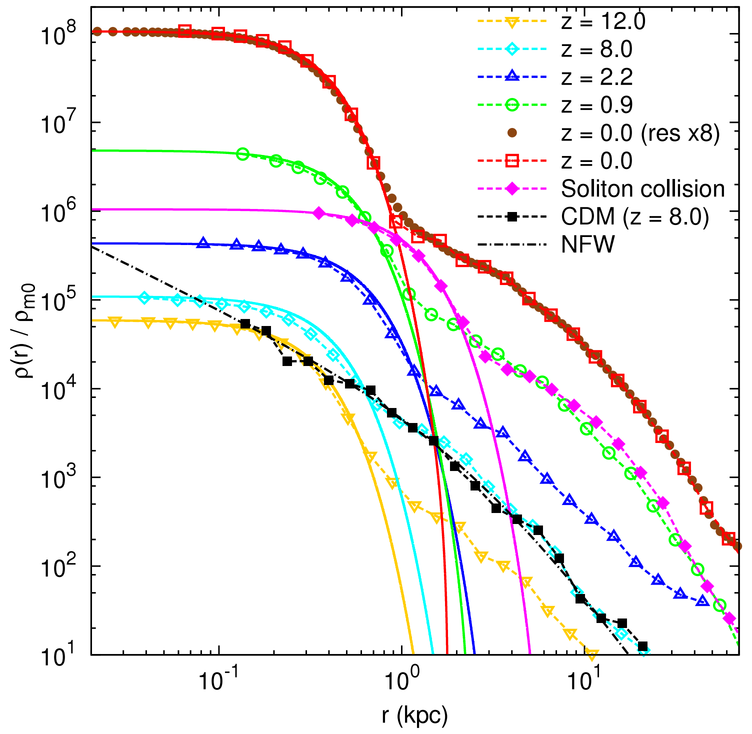


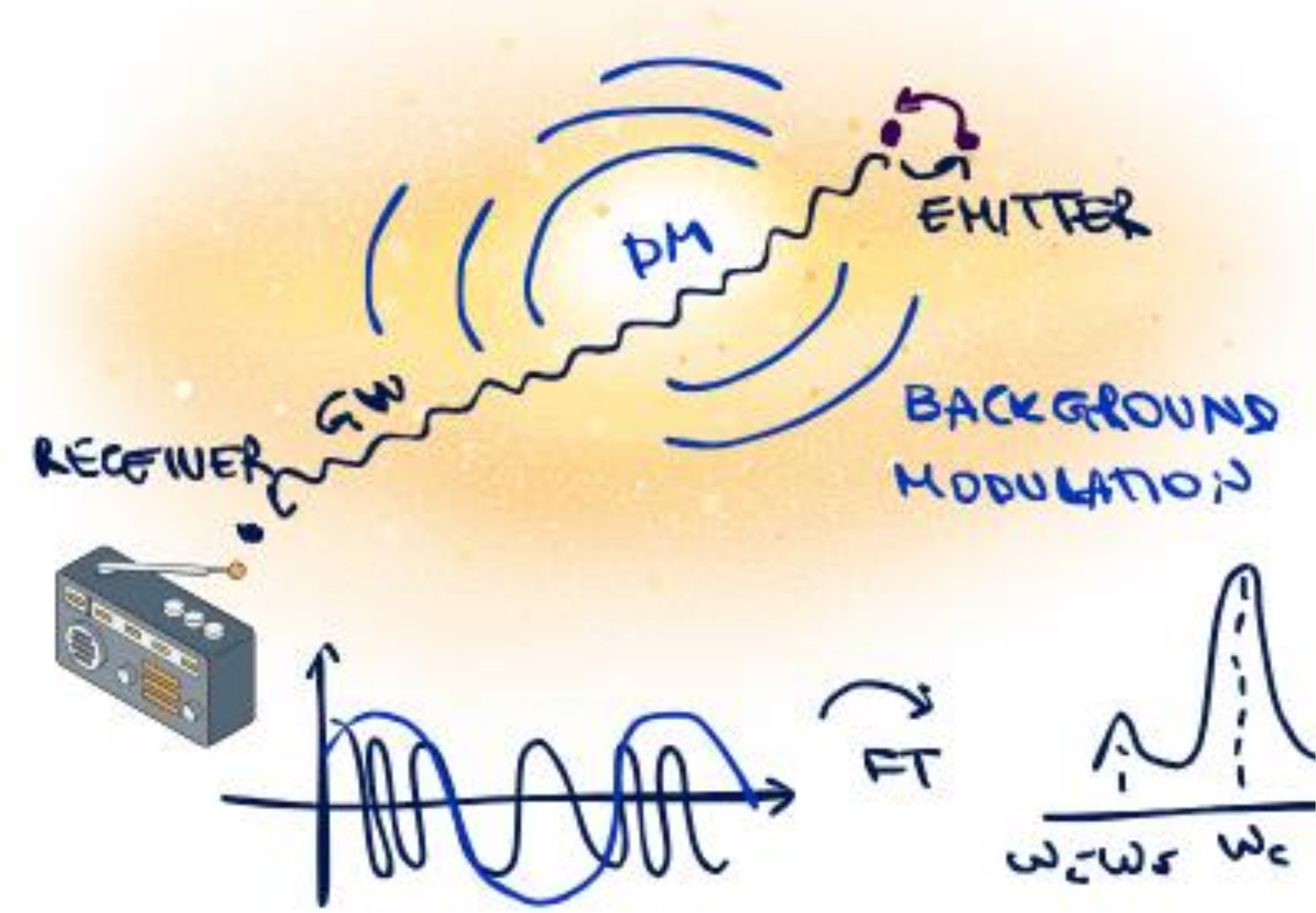
Conclusions part I

DB, Gasparotto, Vicente, 2410.07330

Ultra-light bosonic DM

- Generate over densities at galactic centers that oscillate coherently





- ULDM oscillations get imprinted in the phase of GWs

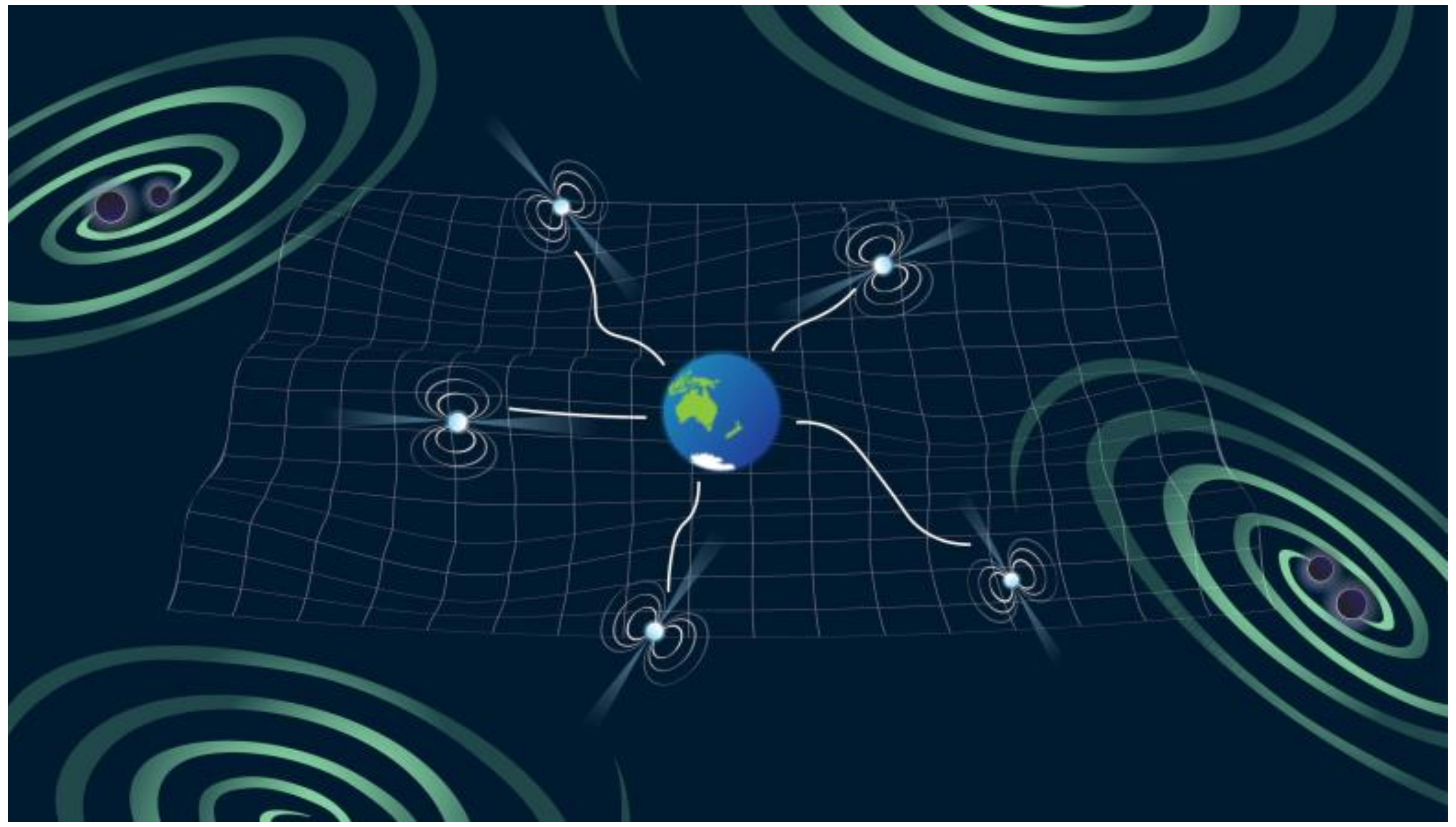
- 'Coherent' sources may detect this effect (high frequency, numbers and in GC)

$$SNR_\delta = \frac{1}{\sqrt{2}}\frac{\omega_e}{\omega_\delta}\Upsilon\sqrt{N}SNR_h$$

- Galactic sources opening 2×10^{-22} eV $\leq m \leq 3 \times 10^{-21}$ eV mass window

- Extragalactic (chirping) sources could probe ULDM over densities in other Galaxies

Waves propagating in ‘Newtonian’ metric



$$g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu \approx -(1-2\Phi)\mathrm{d}t^2 + (1+2\Psi)\delta_{ij}\ \mathrm{d}x^i\ \mathrm{d}x^j,$$

$$\frac{\Delta\omega_e}{\omega_e} \simeq \Phi\Big|_e^r + n^i v_i\Big|_e^r - I_{iSW}$$

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

$$\phi_k \sim e^{i(\omega t - kx)} \quad \Longrightarrow \quad \begin{aligned} \Phi &= \bar{\Phi} + \delta\Phi \\ \Psi &= \underset{\substack{\uparrow \\ \text{stationary}}}{\bar{\Psi}} + \underset{\substack{\uparrow \\ \text{oscillating}}}{\delta\Psi} \end{aligned} \quad \Longrightarrow$$

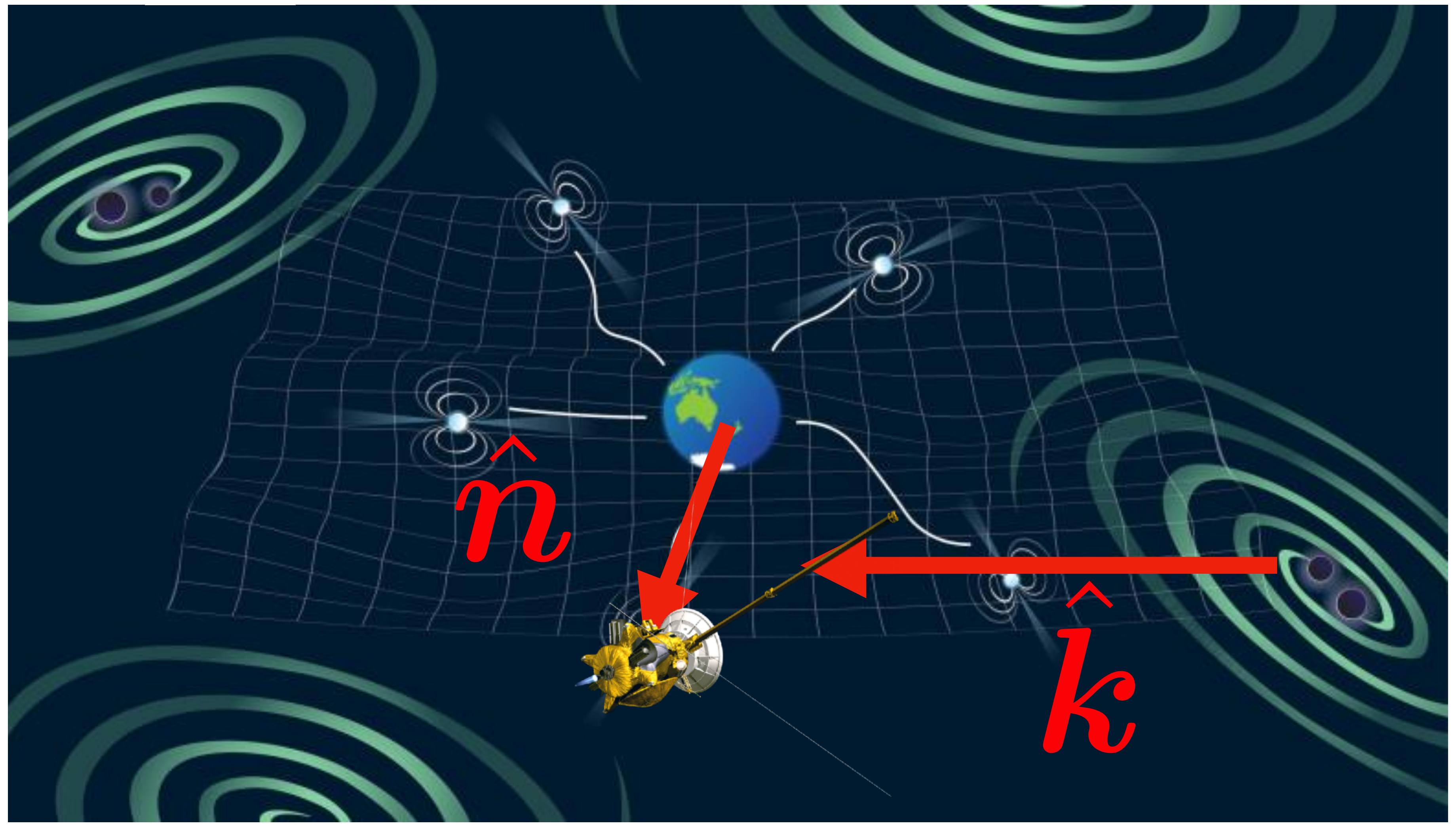
leading term

$$\delta\Psi \equiv \frac{\pi}{m^2}\bar{\rho}_\phi \cos(2mt)$$

Changes in time of arrival (PTA!)

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

Tracked space-craft in weak metric



Armstrong, J.W. , Living Reviews in Relativity, 9, 1, doi: 10.12942/lrr-2006-1

$$\frac{\Delta\nu}{\nu_0}(t)\bigg|^{\mathrm{GW}} = \frac{\mu-1}{2}\bar{\Psi}(t) - \mu\bar{\Psi}\left(t - \frac{\mu+1}{2}T_2\right) + \frac{\mu+1}{2}\bar{\Psi}\left(t - T_2\right)$$

$$\bar{\Psi}(t) = (\hat{\boldsymbol{n}}\cdot\mathbf{h}(t)\cdot\hat{\boldsymbol{n}})/\left(1-\mu^2\right) \qquad \mu = \hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{n}}$$

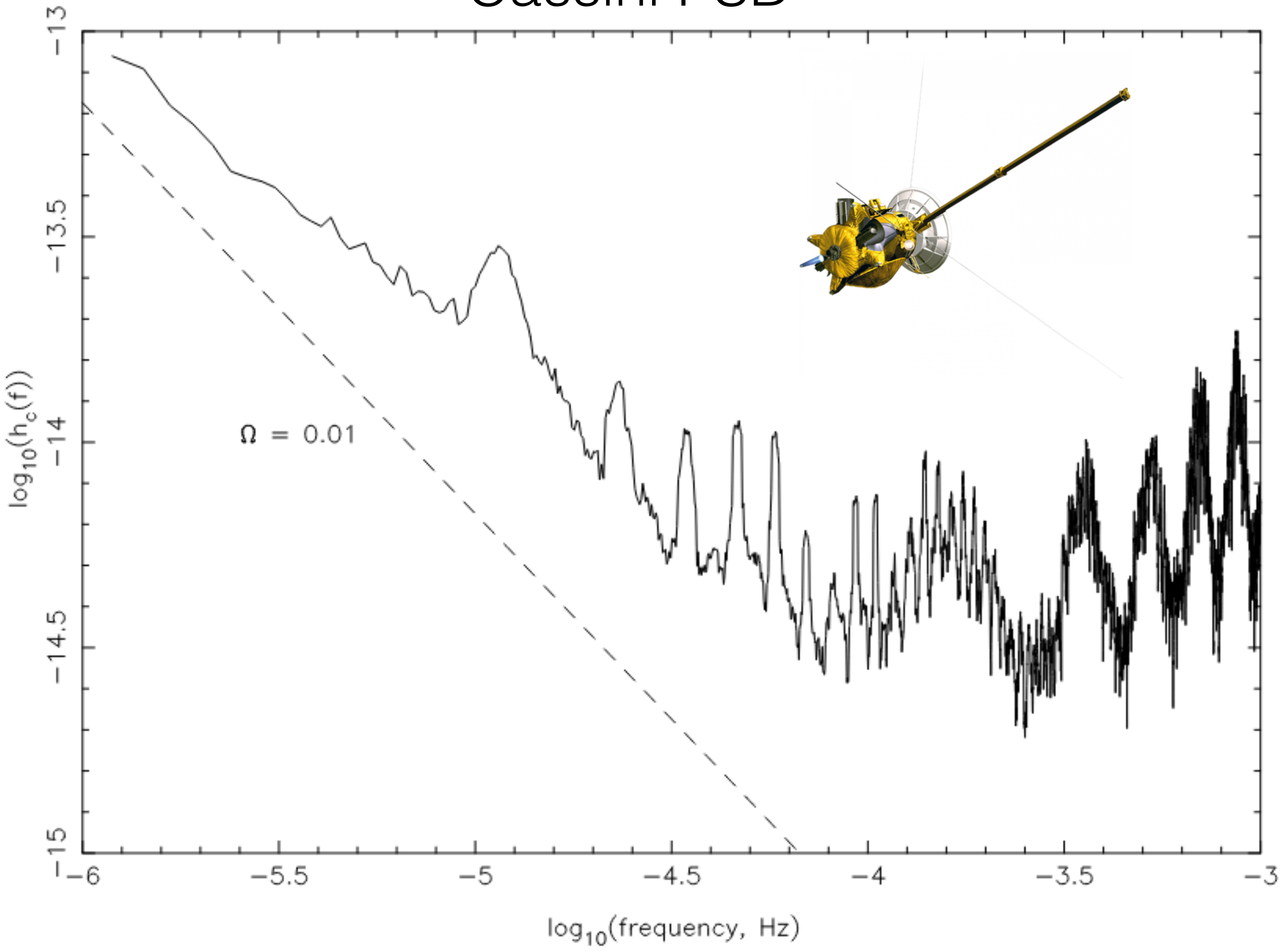
Zwick, DB et al 2406.02306 [astro-ph.HE]
Khmelnitsky, Rubakov 1309.5888 [astro-ph.CO]

$$\frac{\Delta\nu}{\nu_0}(t)\bigg|^{\mathrm{ULDM}} = -\Psi(t) + \Psi\left(t - T_2\right).$$

GWs and ULDM searches w/ Doppler tracking

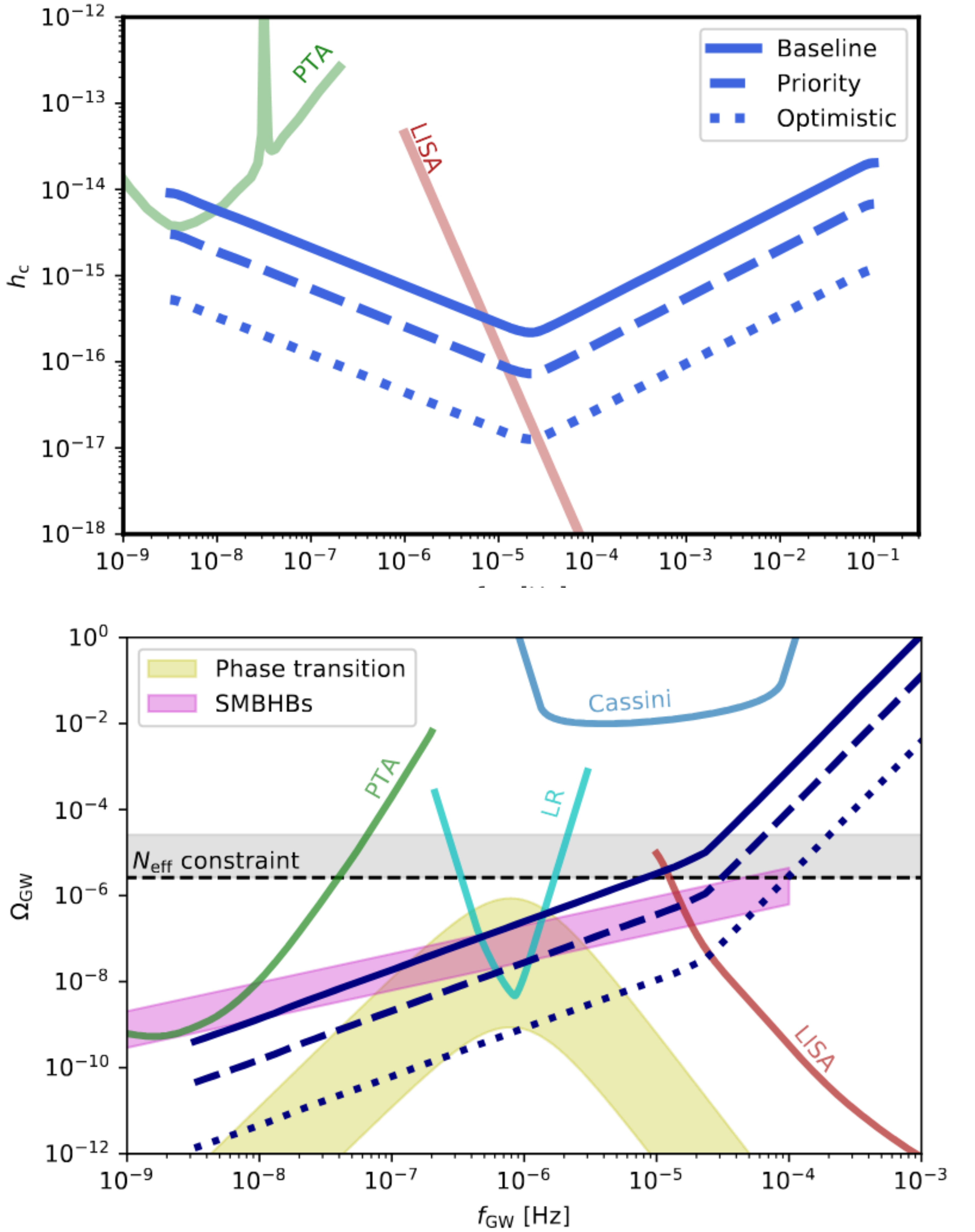
Zwick, DB et al 2406.02306 [astro-ph.HE]

Cassini PSD



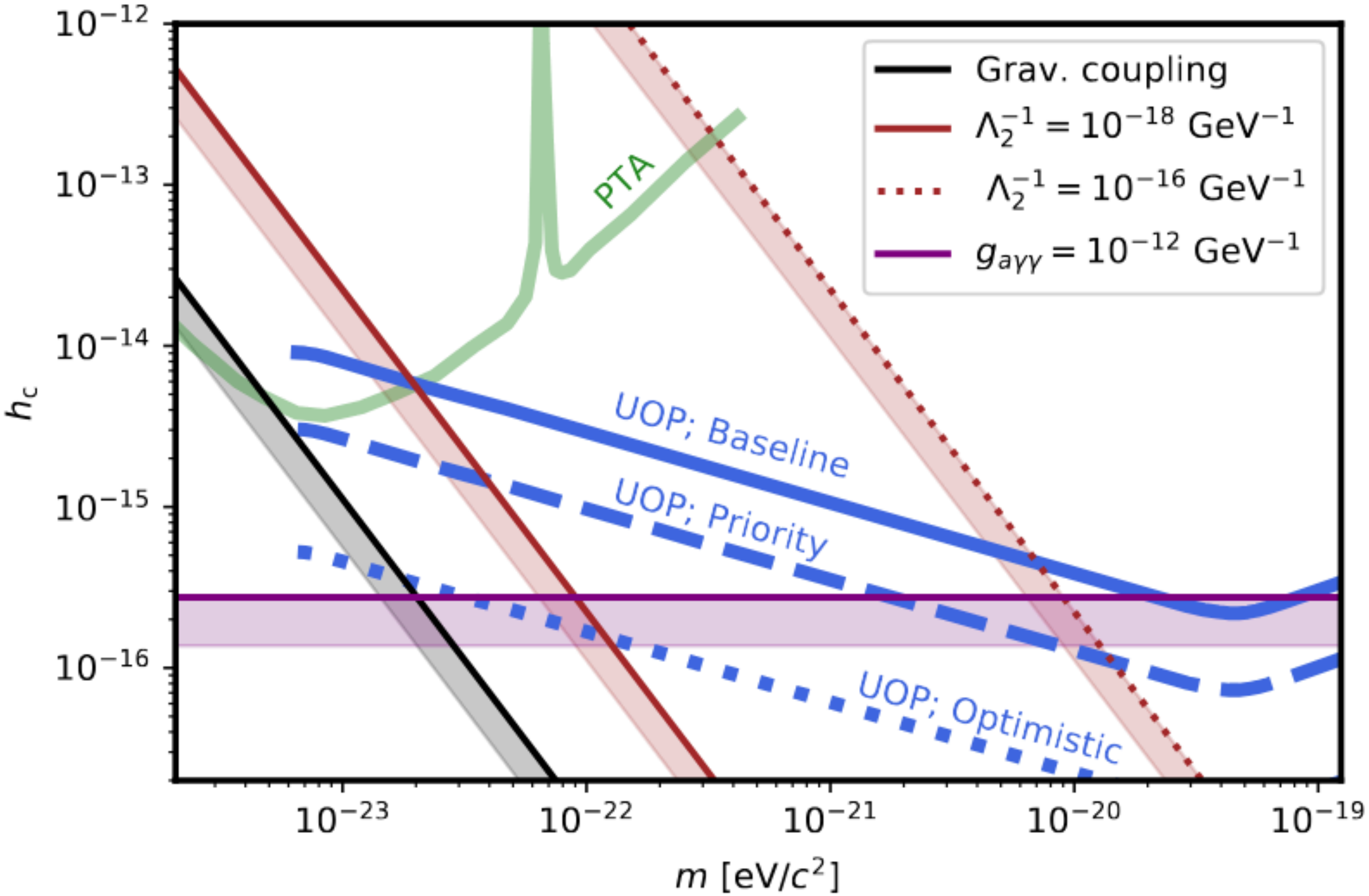
Bertotti, B., Vecchio, A., & Iess, L. 1999, Phys. Rev. D, 59, 082001

Uranus Orbiter and Probe



GWs and **ULDM** searches w/ Doppler tracking

Zwick, DB et al 2406.02306 [astro-ph.HE]

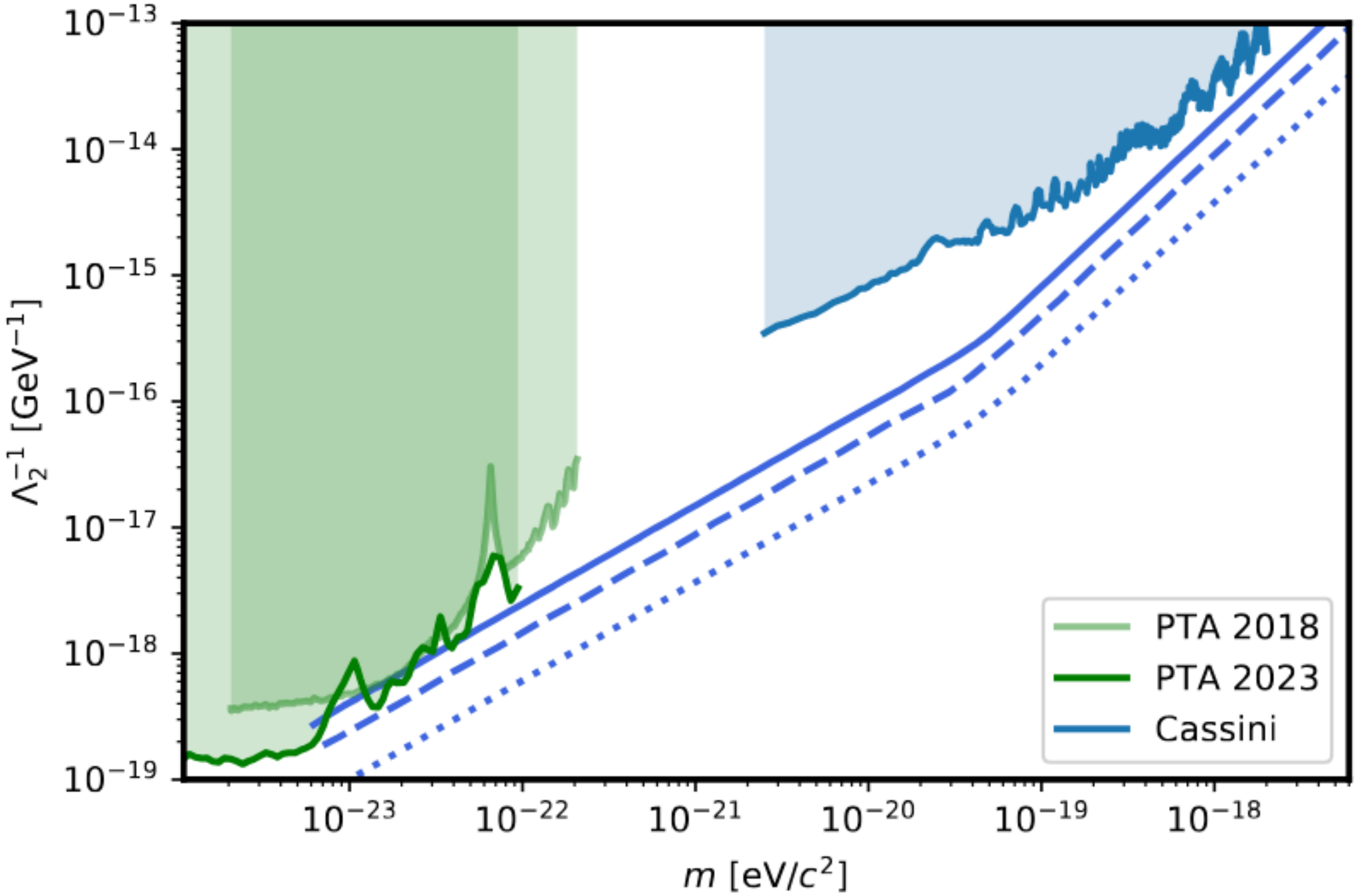


GWs and **ULDM** searches w/ Doppler tracking

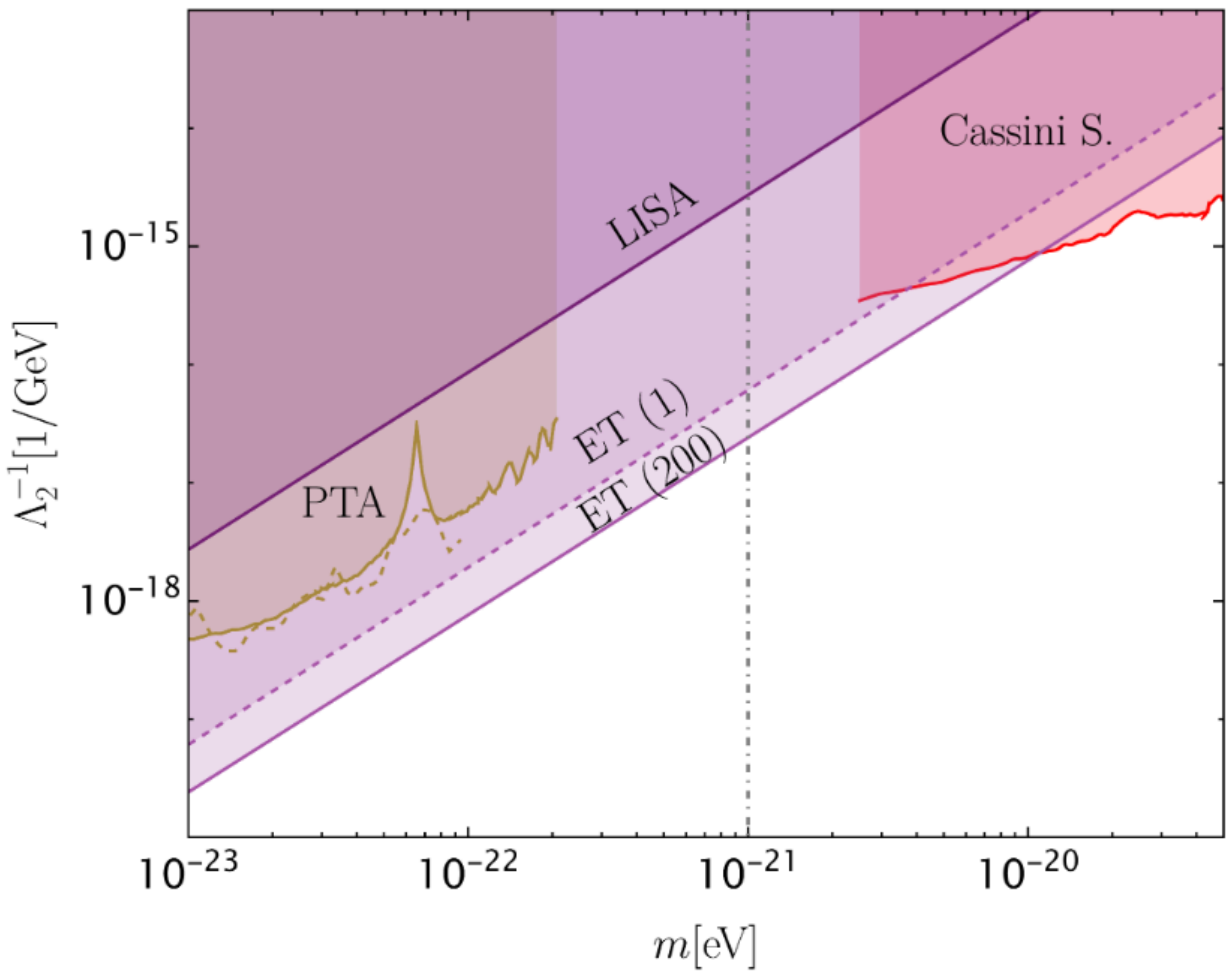
Zwick, DB et al 2406.02306 [astro-ph.HE]

Case with direct coupling $\tilde{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu}$ with $A \approx 1 + \phi^2/\Lambda_2^2$

UOP (in the Solar System)



ET Binaries (at MW center)



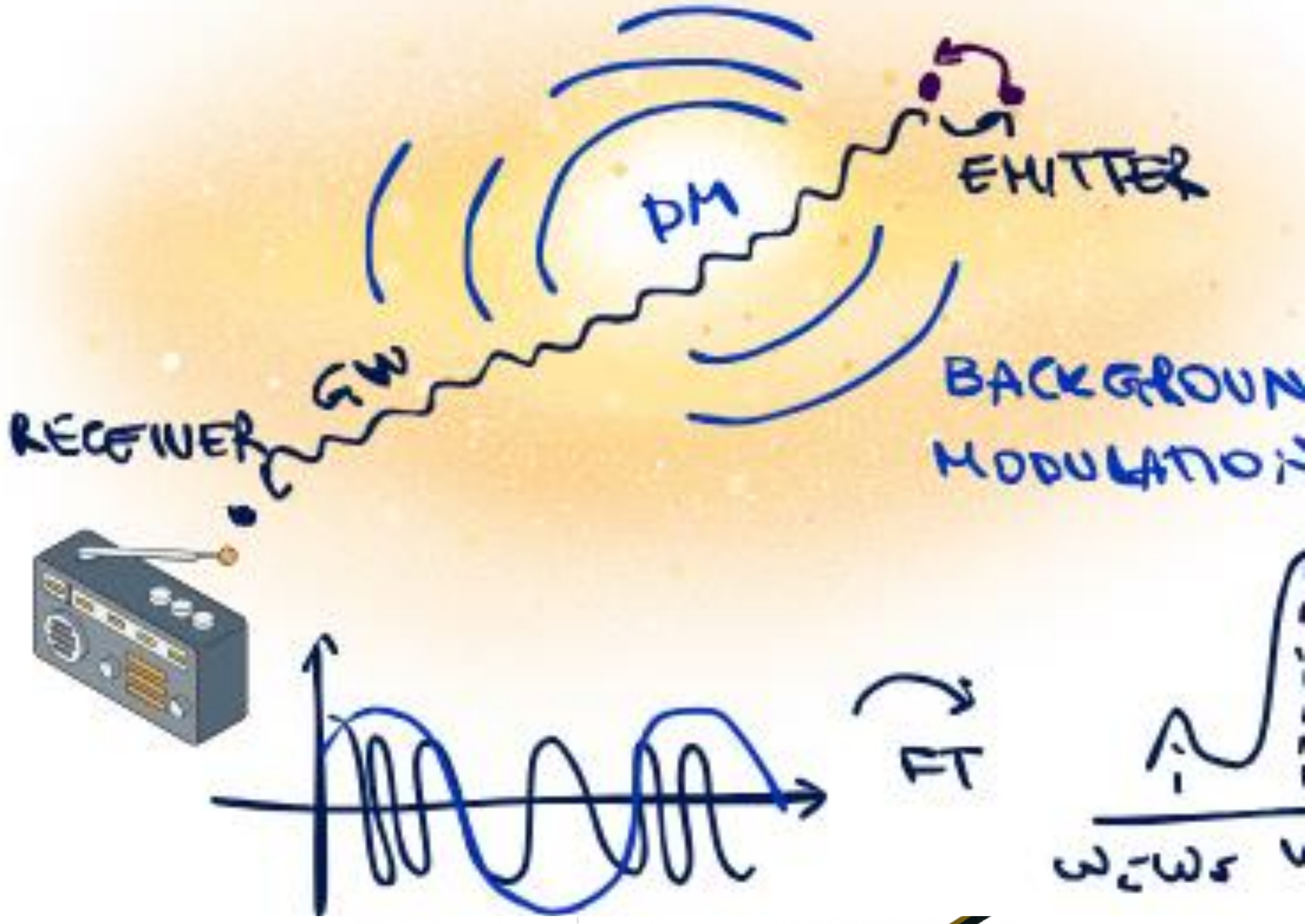
Conclusions part II

Zwick, DB et al 2406.02306 [astro-ph.HE]

Ultra-light bosonic DM

- Generates fluctuating stationary galactic gravitational potentials
- ULDM oscillations get imprinted in the frequency of tracking radar signals
- Cassini data can be directly translated into constraints for ULDM
- A future mission to Uranus, if ranged, would generate constraints/detections at 2×10^{-23} eV $\leq m \leq 3 \times 10^{-18}$ eV mass window

Outlook



Part I

- Currently working on it with O. Piccinni (expert on coherent sources of GW)
    - Possible degeneracies? New strategies? Folding?

Part II

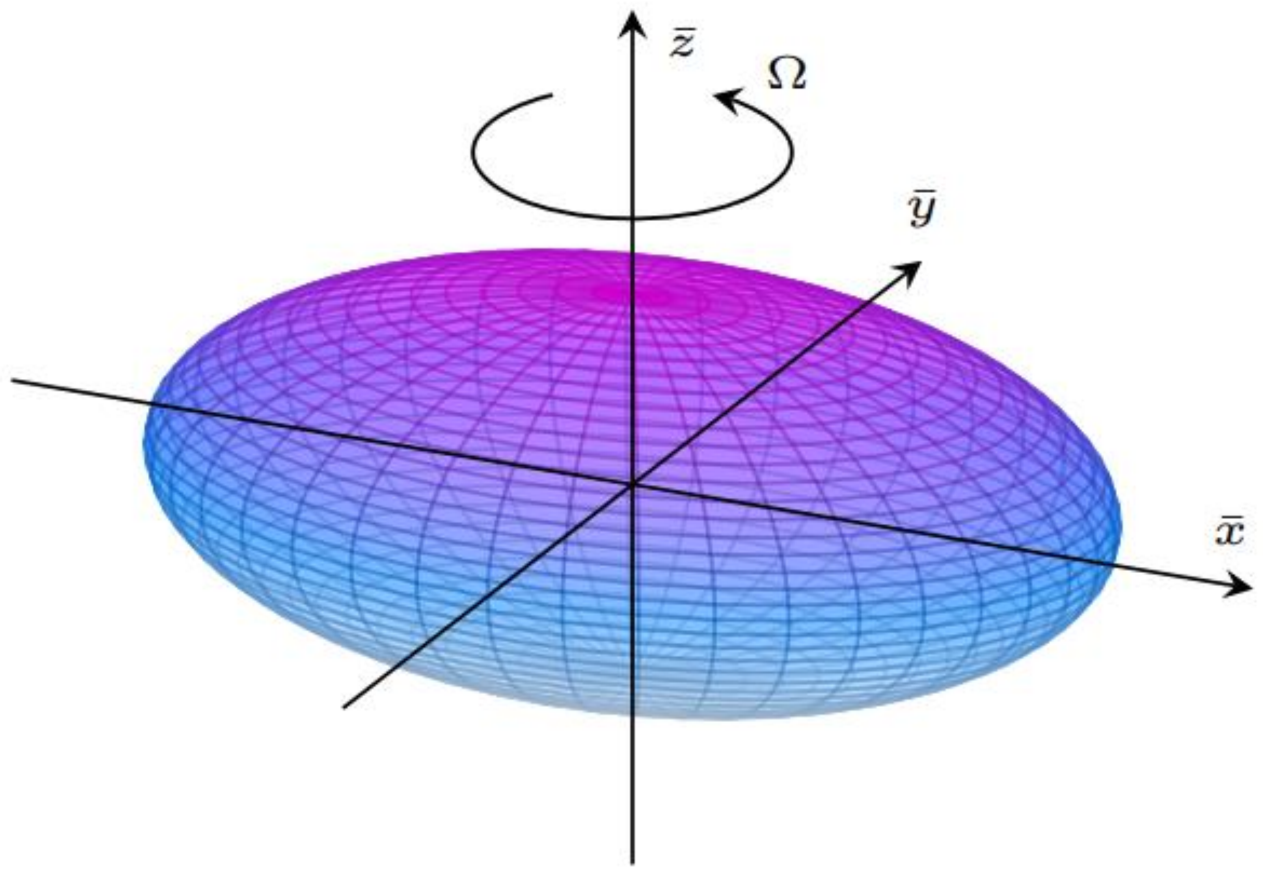
- A lot of uncertainties. So far we want to better understand the noise

In general…

- Other precise orbit information may be also impacted (e.g. SLR, LLR, GNSS…)
- working on Hyungjin Kim's idea for the stochastic part.

GWS FROM SPINNING NS

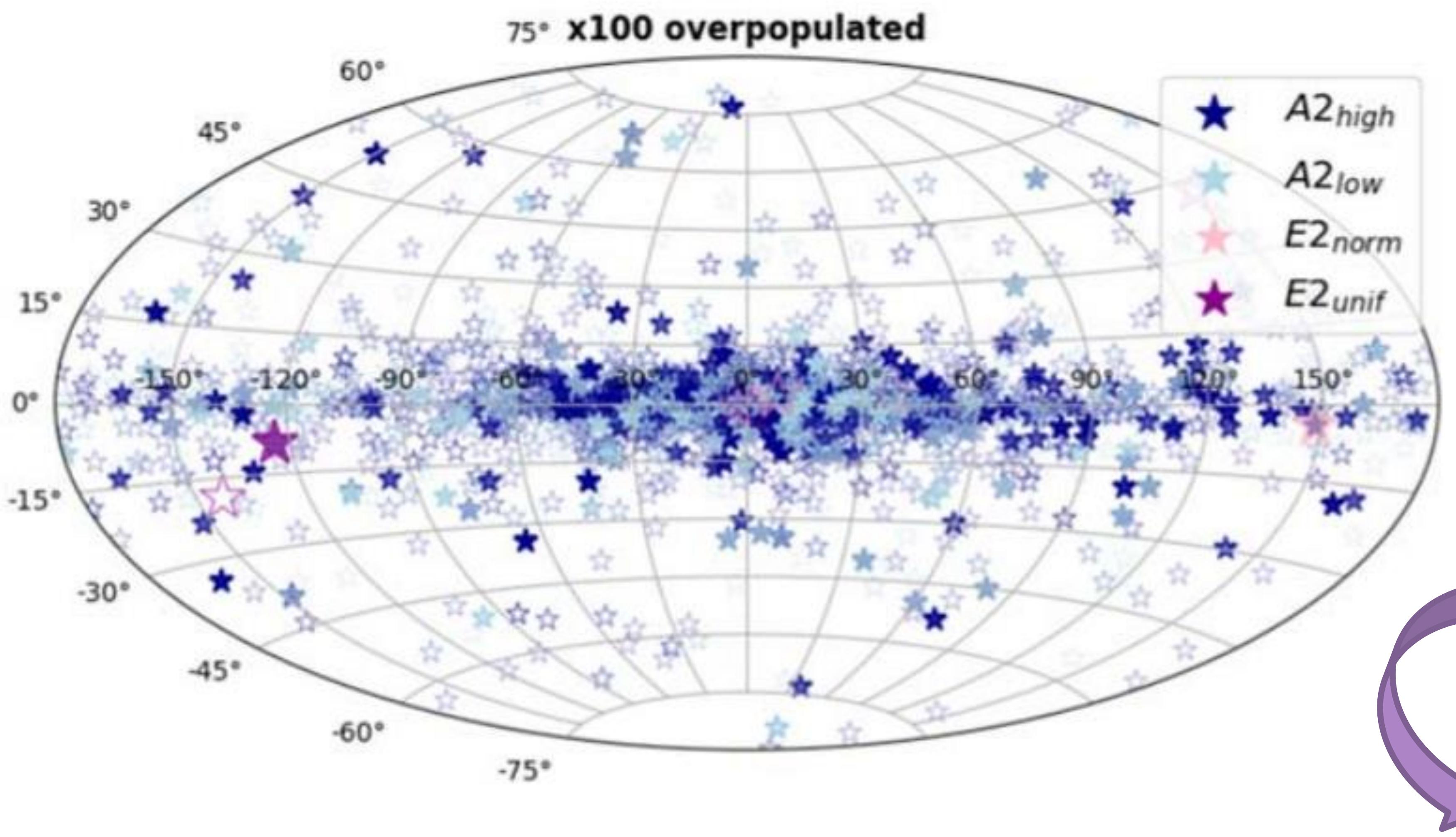
Reviews e.g Gittins 2401.01670,
Piccinni 2202.01088



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

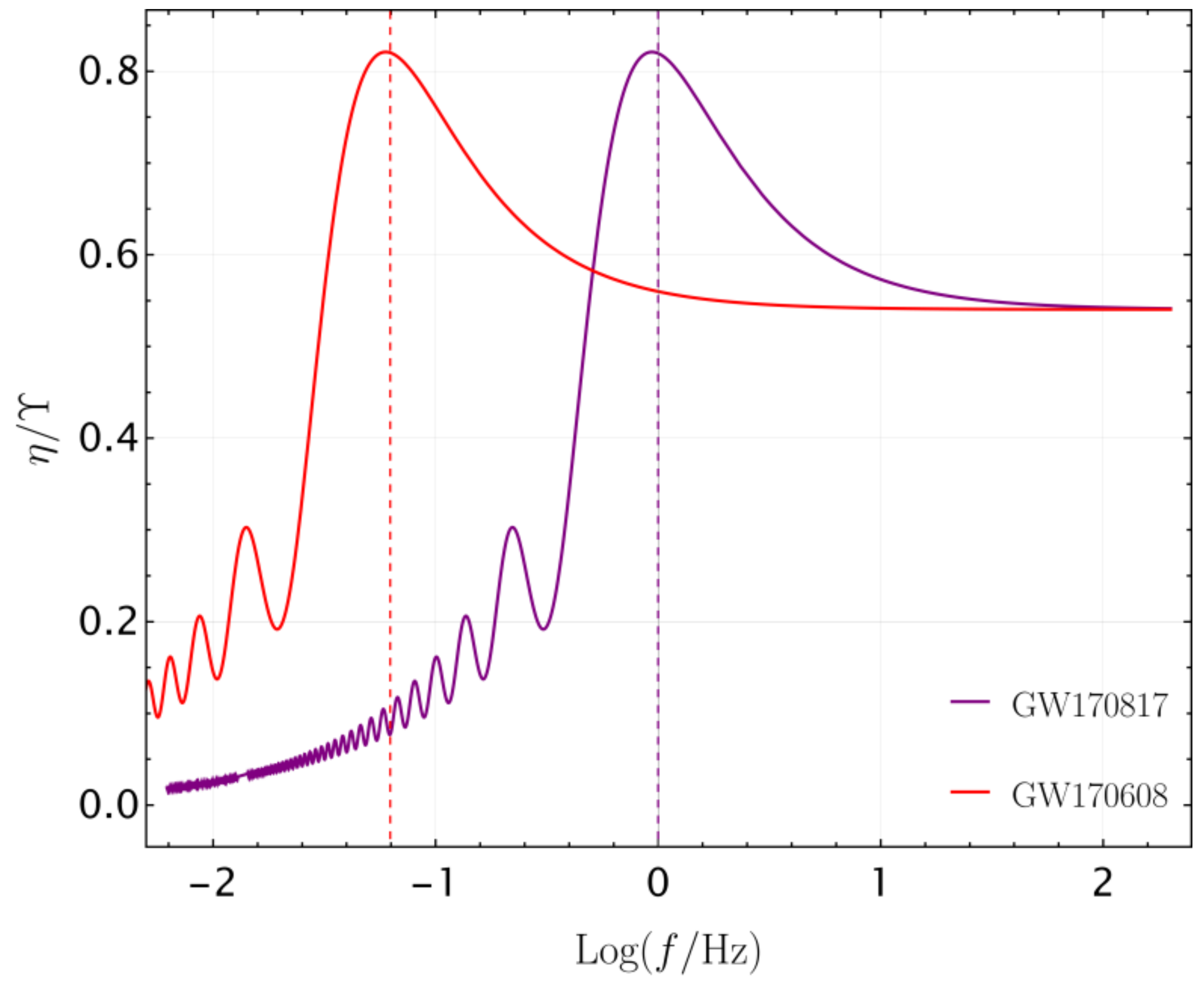
Great uncertainty on the detection prospects

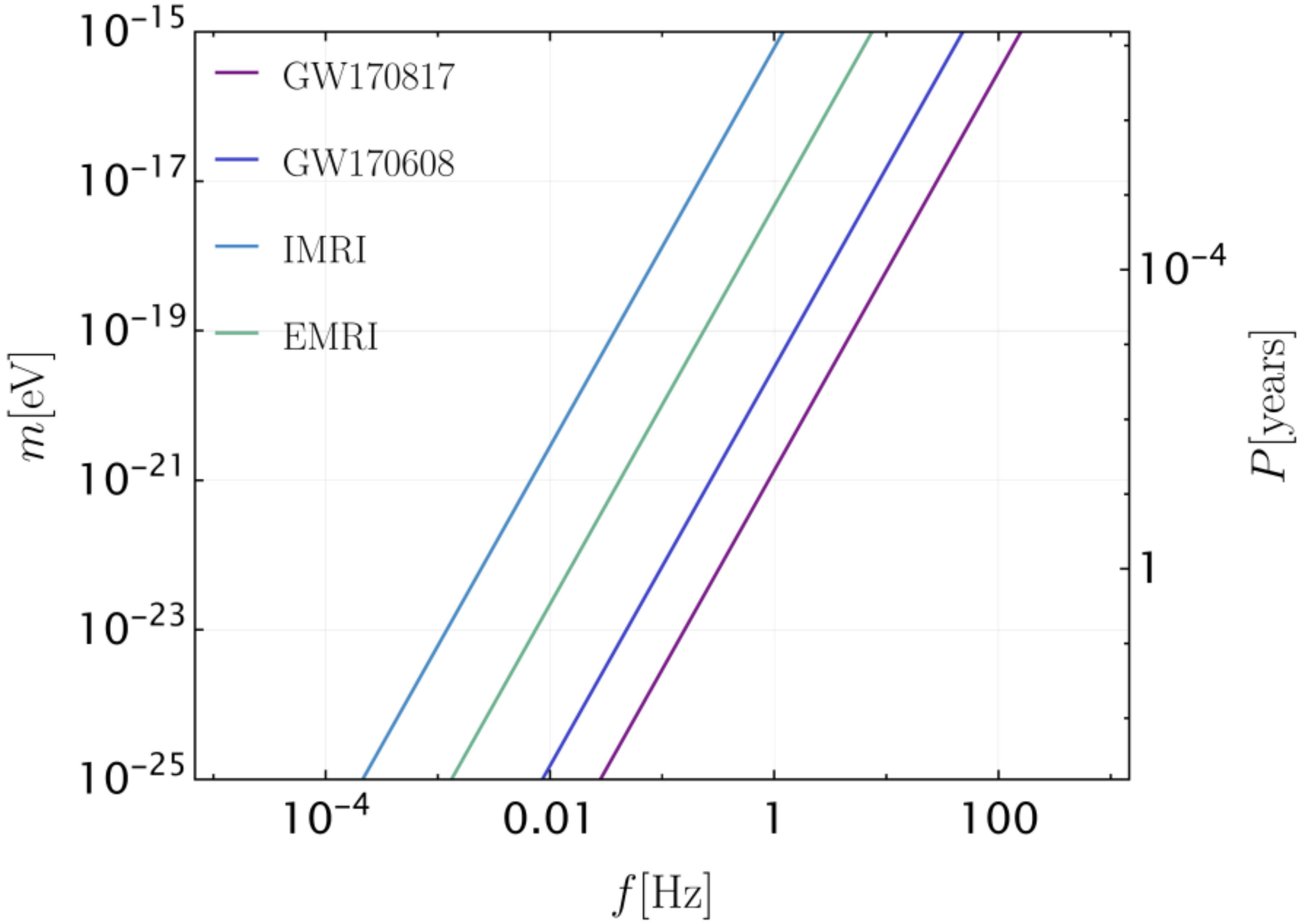
CHIRPING CASE

- 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

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

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





New phenomenology from ULDM

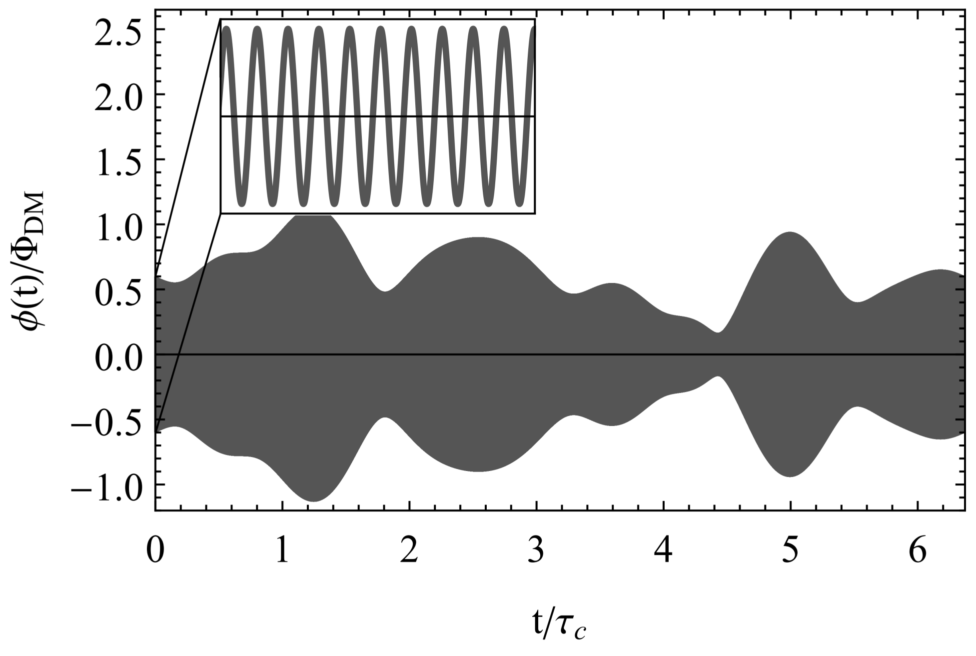
Centers et al 19

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

$$\phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$m_{\rm SM} \phi\, \psi_{\rm SM}^2$$

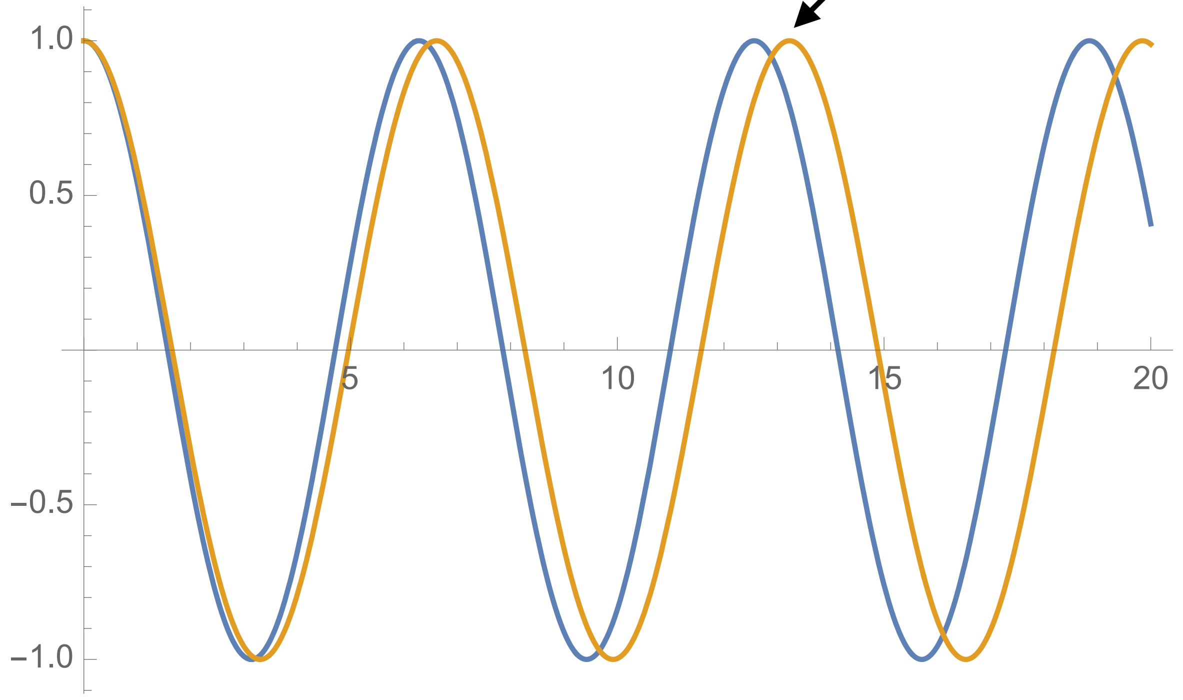
B) stochastic 'narrow' piece

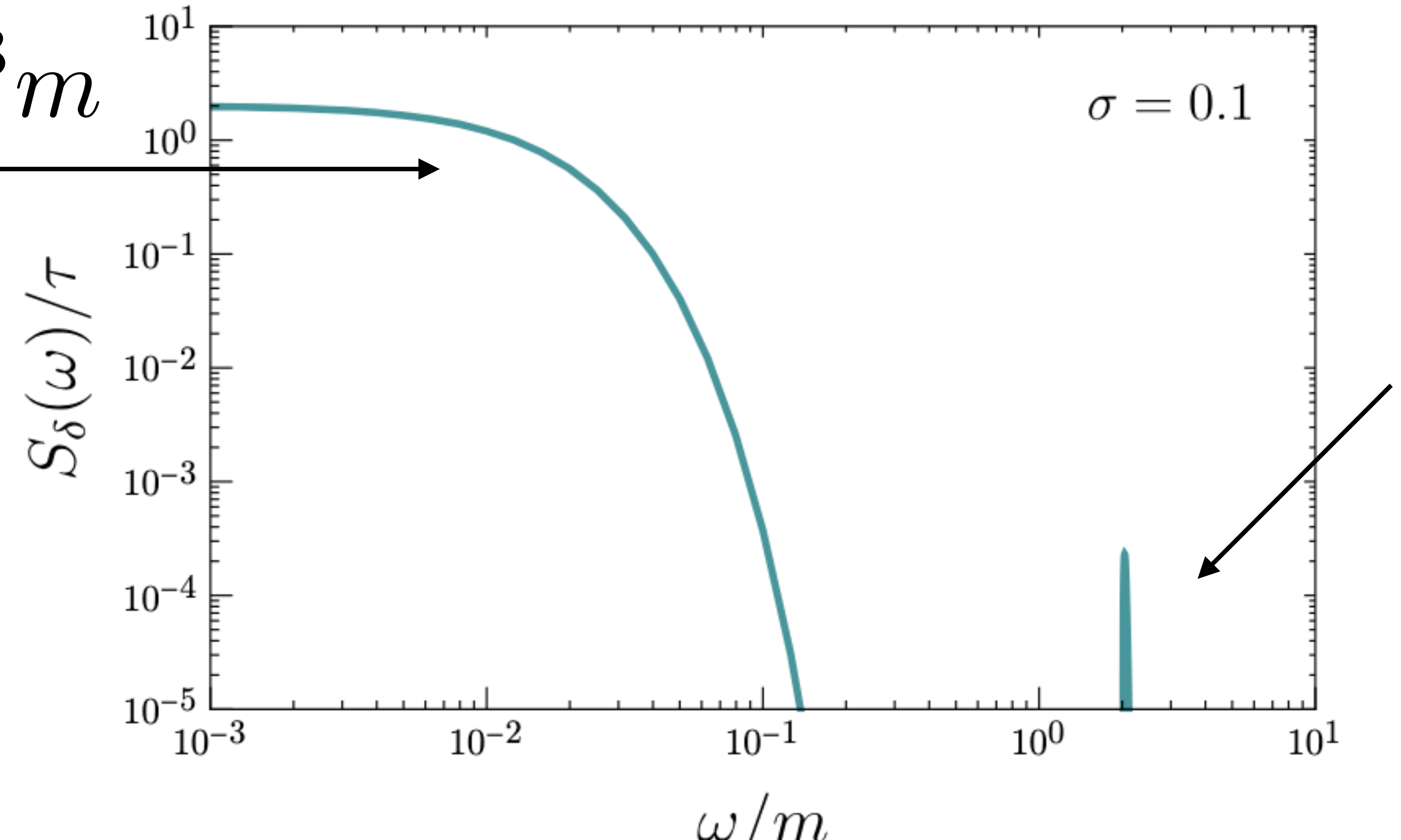
$$\sim \langle \phi^* \phi \rangle$$

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

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

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

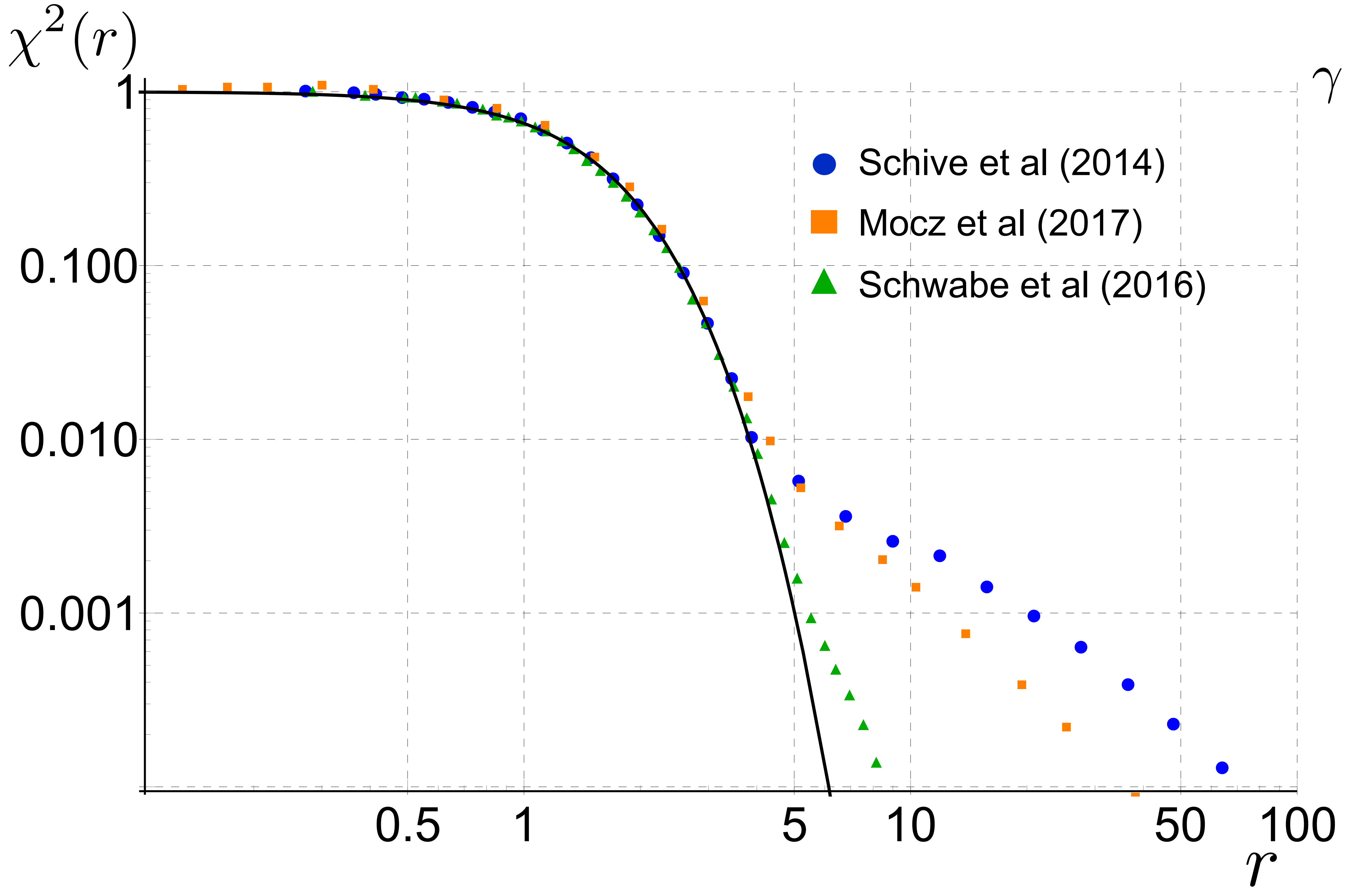
$$i\partial_t\psi = -\frac{1}{2m}\Delta\psi + m\Phi_N\psi$$

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

spherically symmetric stationary, non-relativistic solution:

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

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



$\gamma = -0.69$

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?