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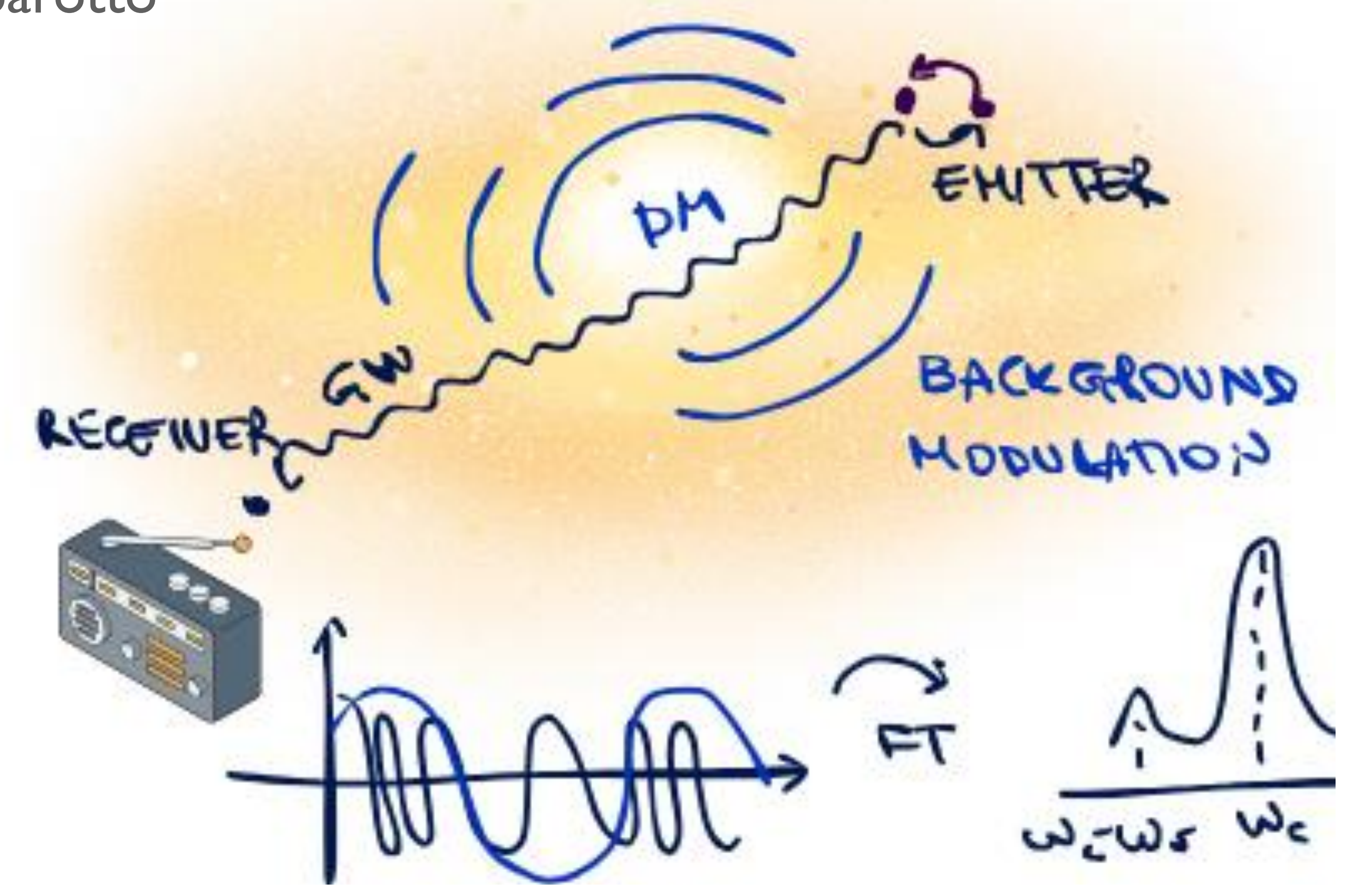

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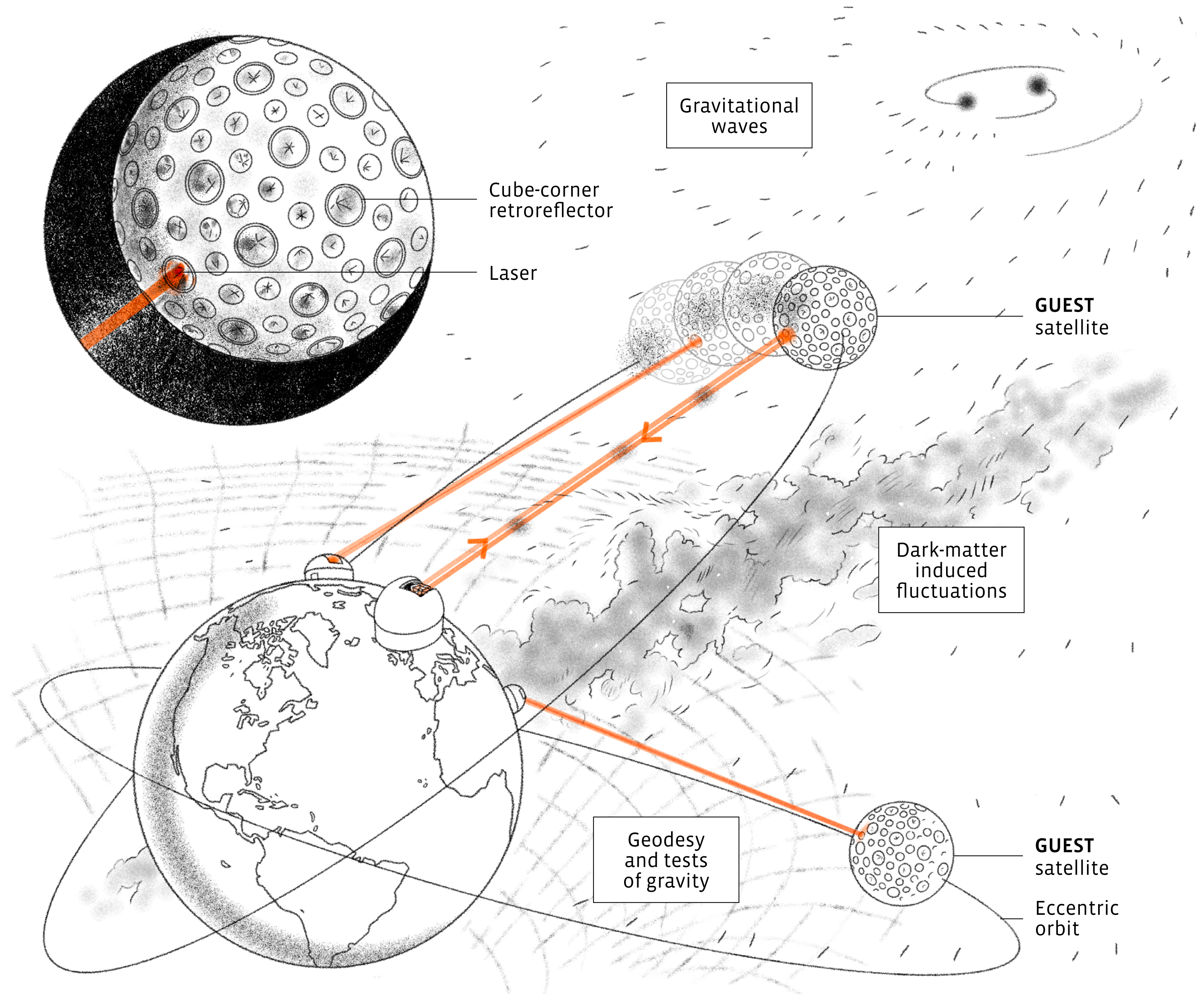

New ideas to find ultralight dark matter in astrophysical data

Diego Blas

w/ Gasparotto & Vicente
e-Print: 2410.07330 [hep-ph]

w/ Bourguin, Foster, Hees, Herrero, Jenkins, Xue
e-Print: arXiv: 2504.15334 [astro-ph.CO], arXiv:2504.16988 [gr-qc], 2506.11802 [gr-qc]

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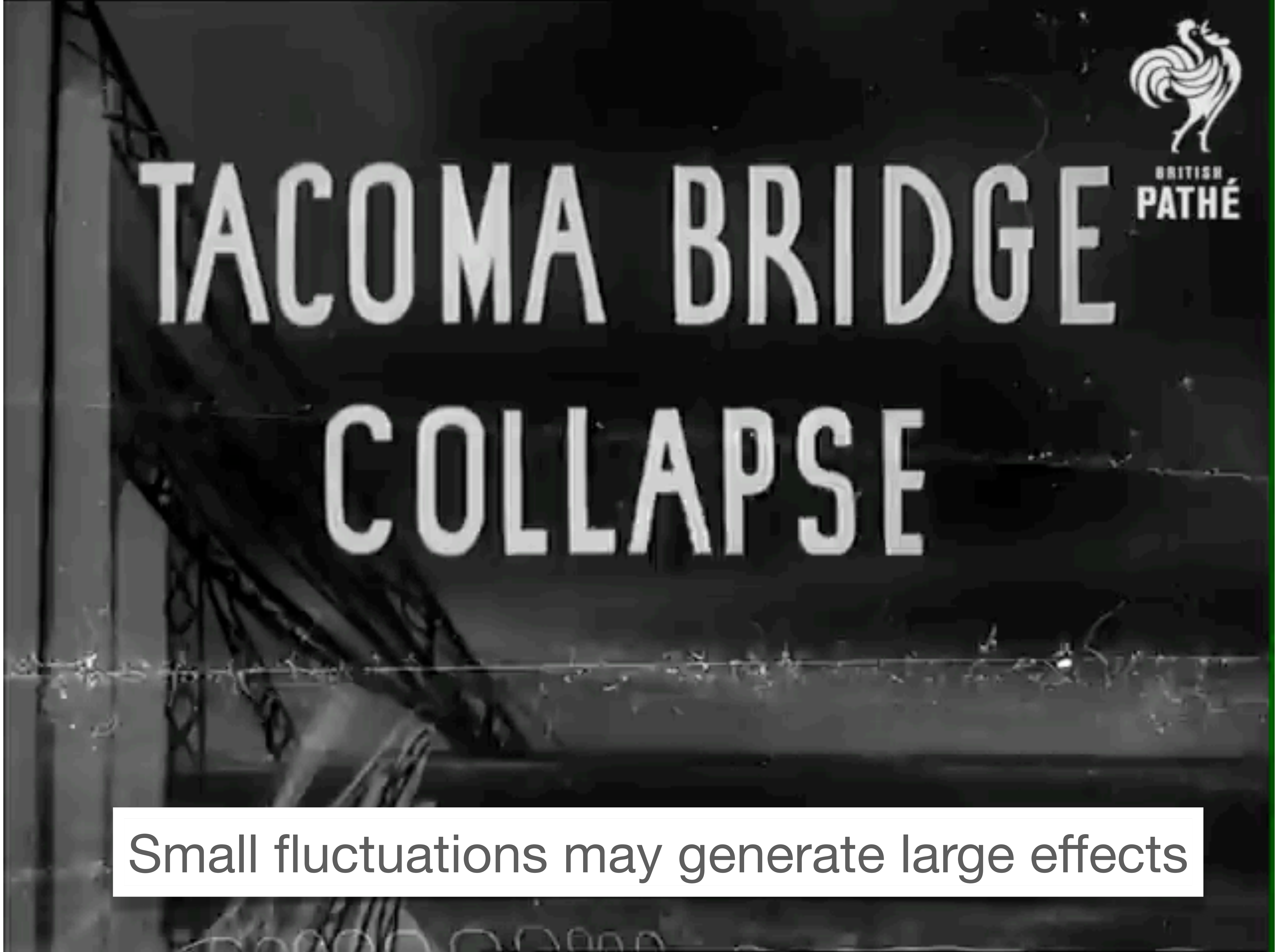
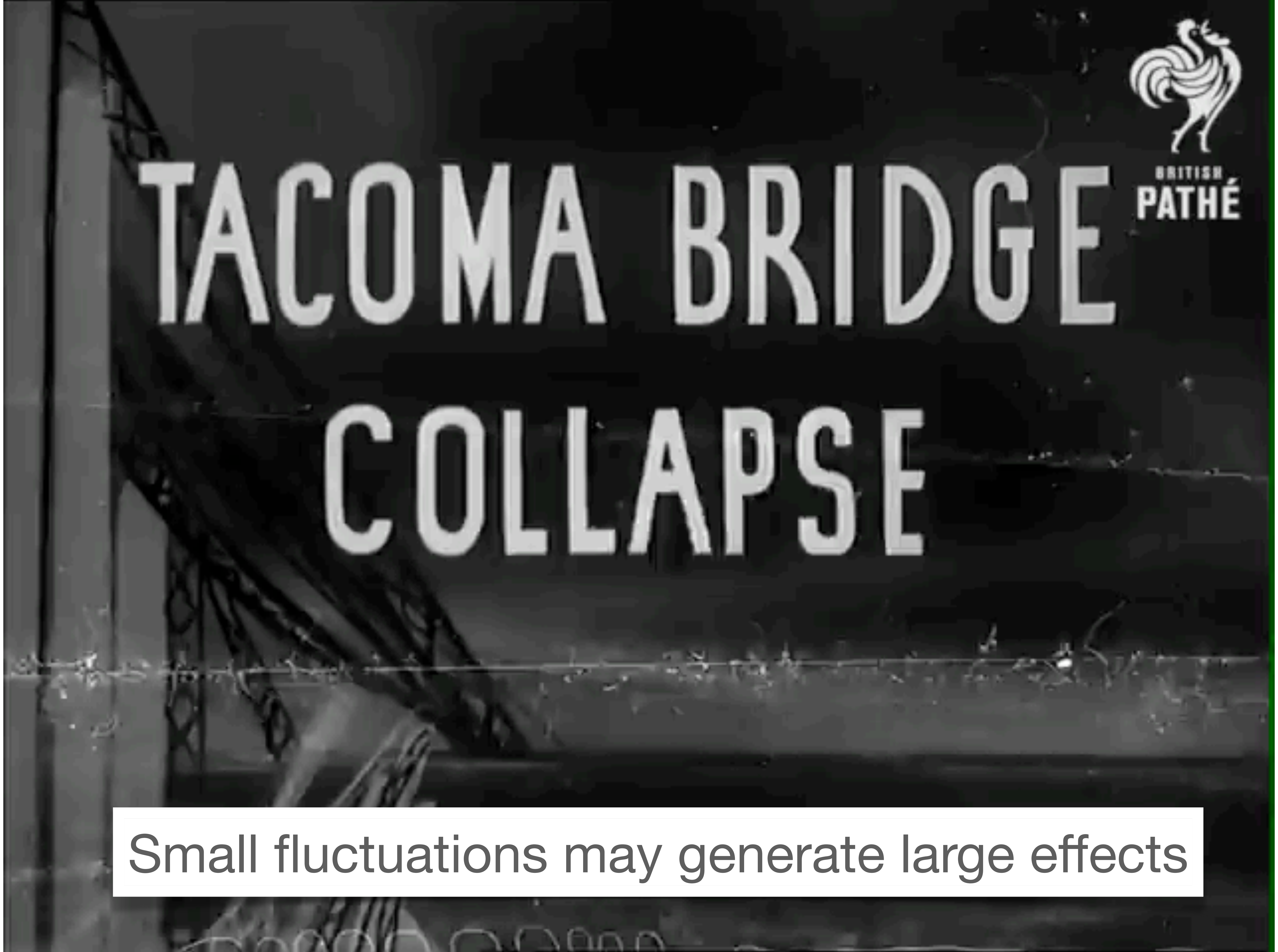
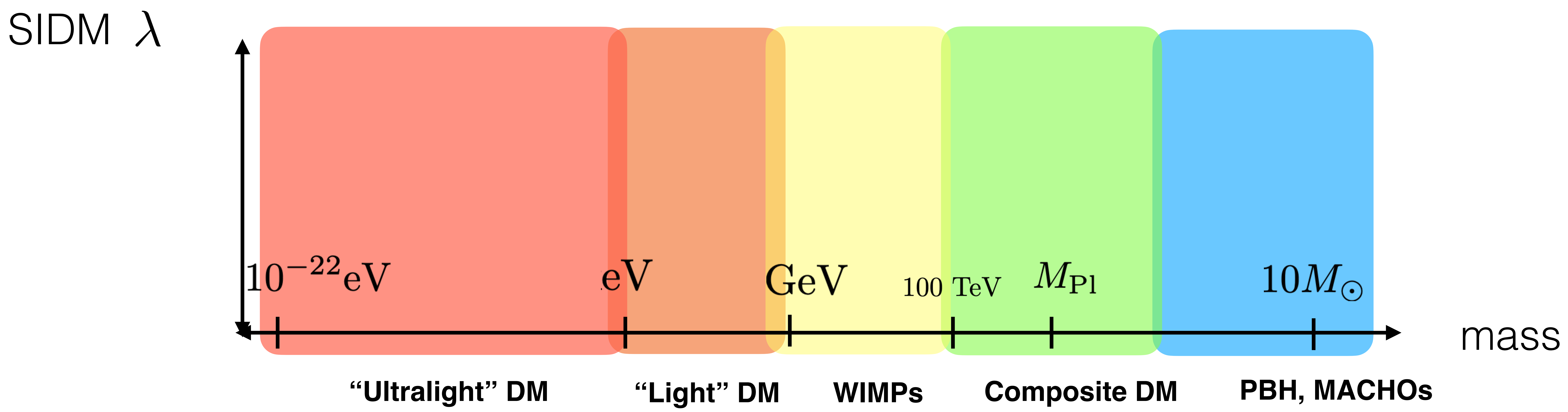


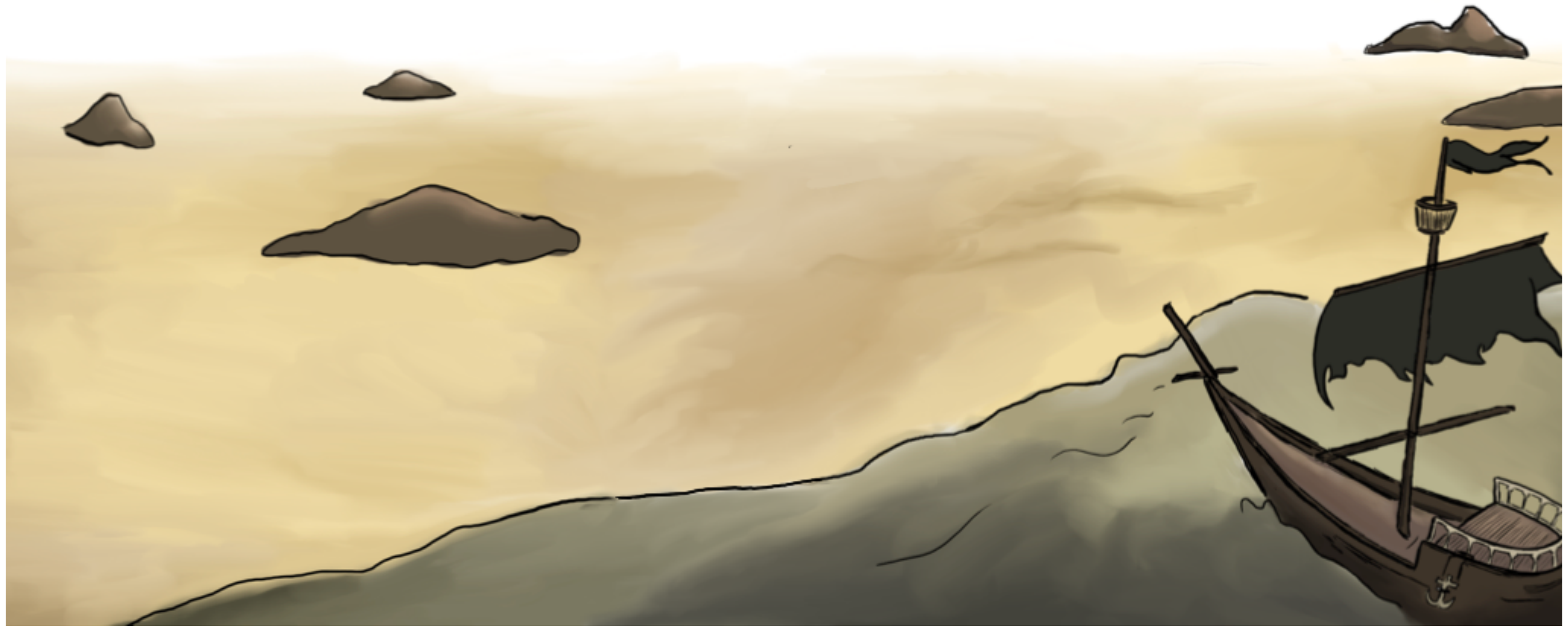
Small fluctuations may generate large effects



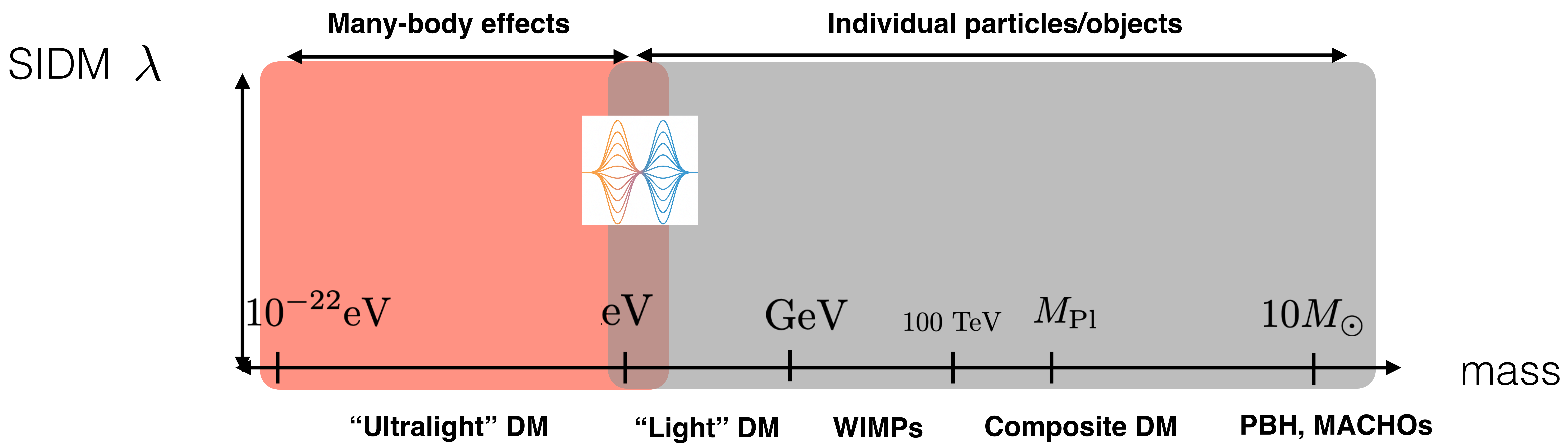
Small fluctuations may generate large effects

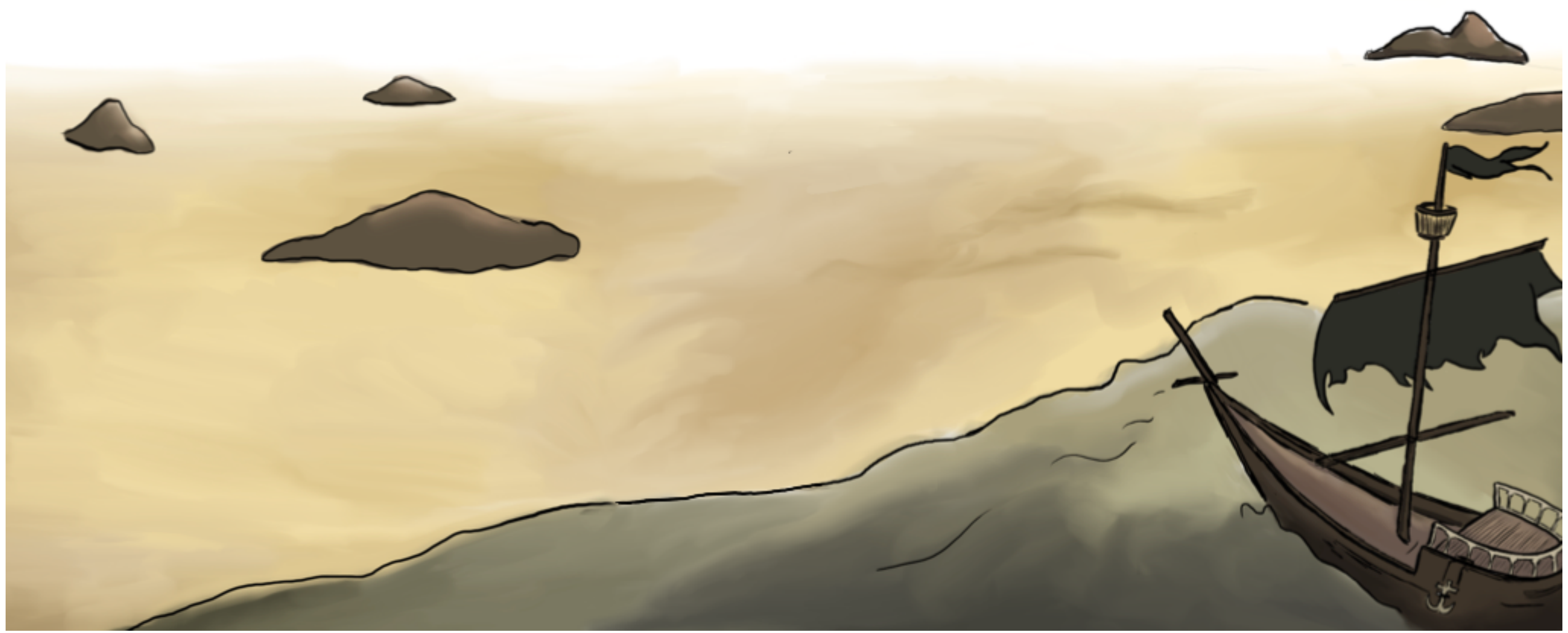
Dark Matter: where to look?



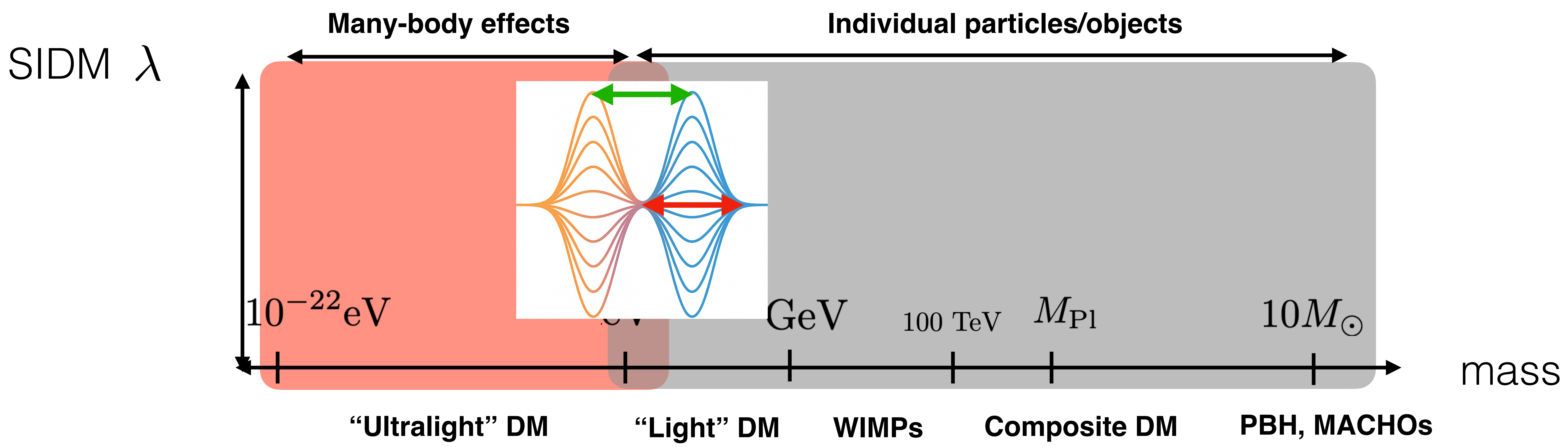


Dark Matter: where to look?





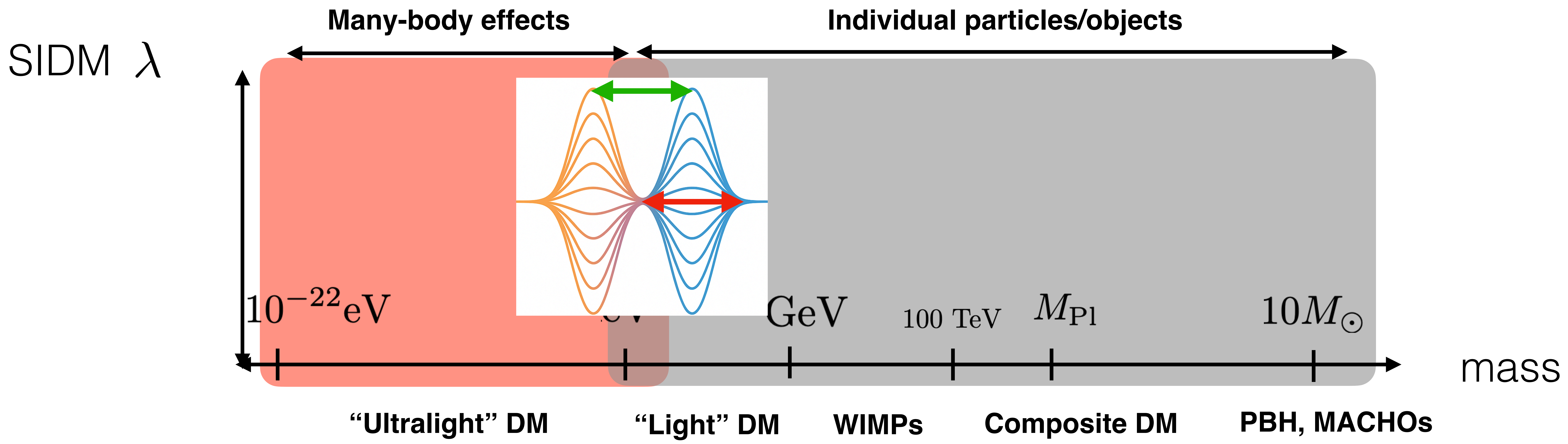
Dark Matter: where to look?



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

Dark Matter: where to look?



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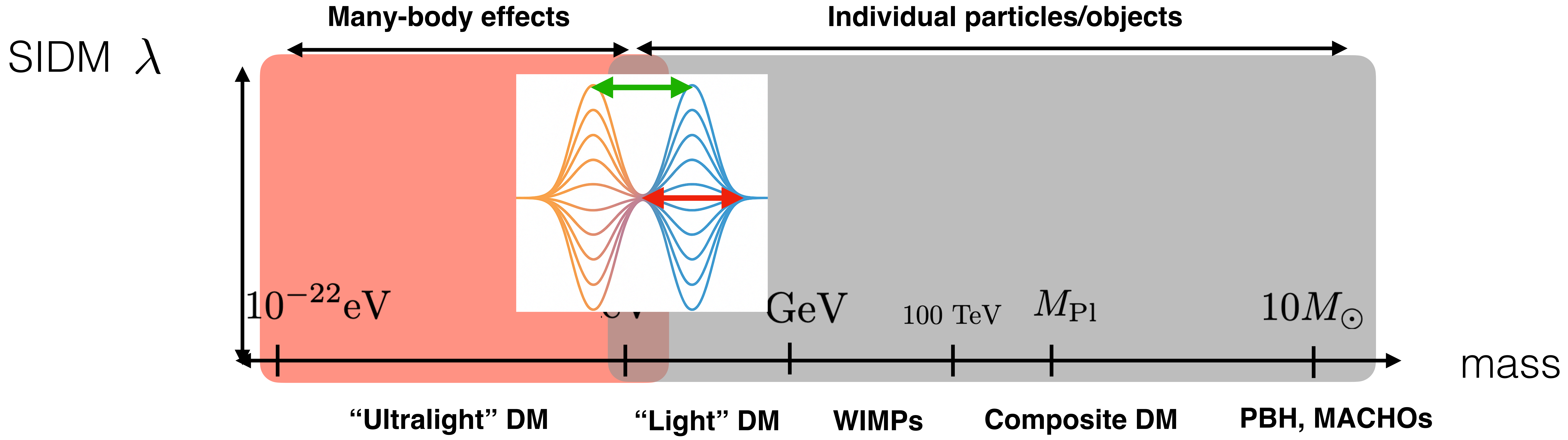
bosons ← particles overlap for $d \lesssim L$ → **fermions**

Dark Matter: where to look?



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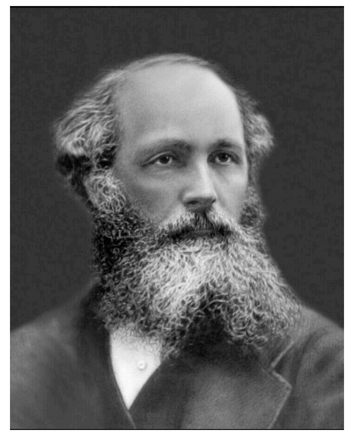


bosons

field theory description

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

fermions

become degenerate

* $m_f \gtrsim \text{keV}$ Tremaine-Gunn bound

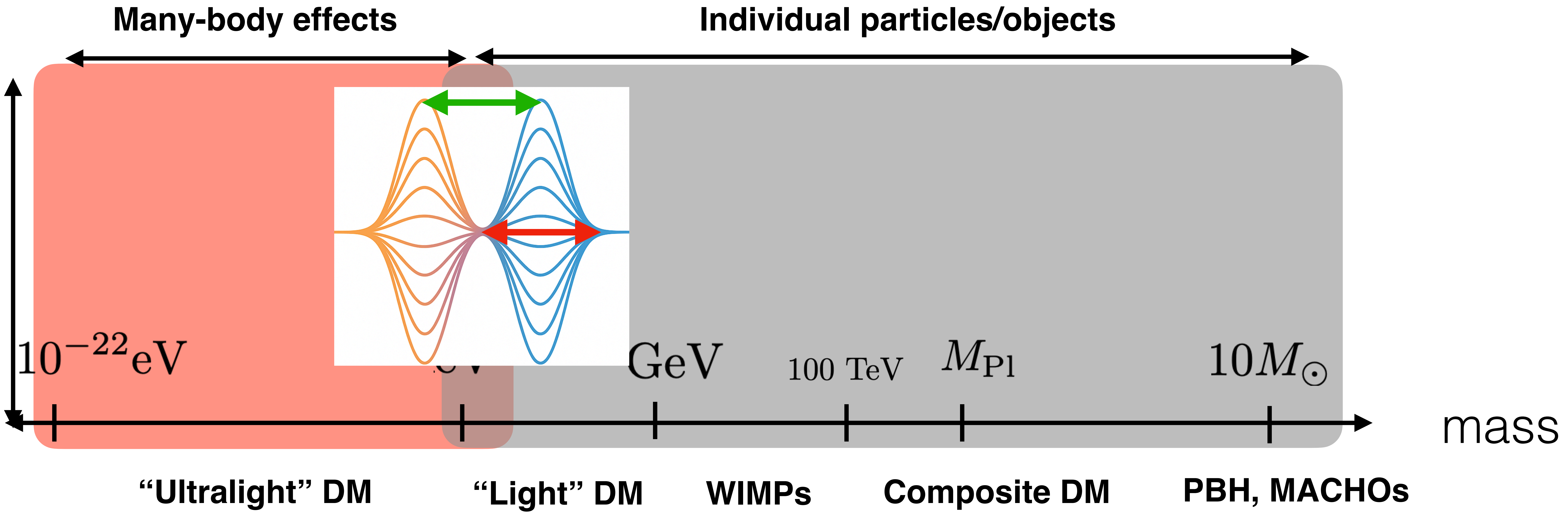
* ‘condensed dark matter’

Bar et al 2102.11522

Garani et al 2207.06928

Dark Matter: where to look?

SIDM λ



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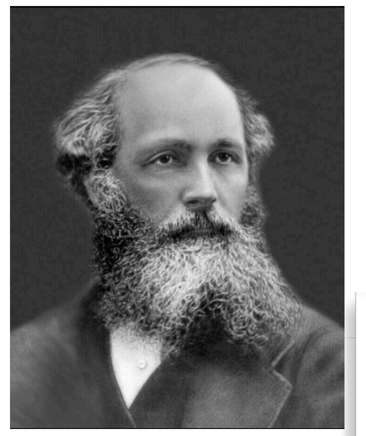


IN BOTH CASES:
"SMALL SCALE" (cold and/or dense) DYNAMICS MODIFIED

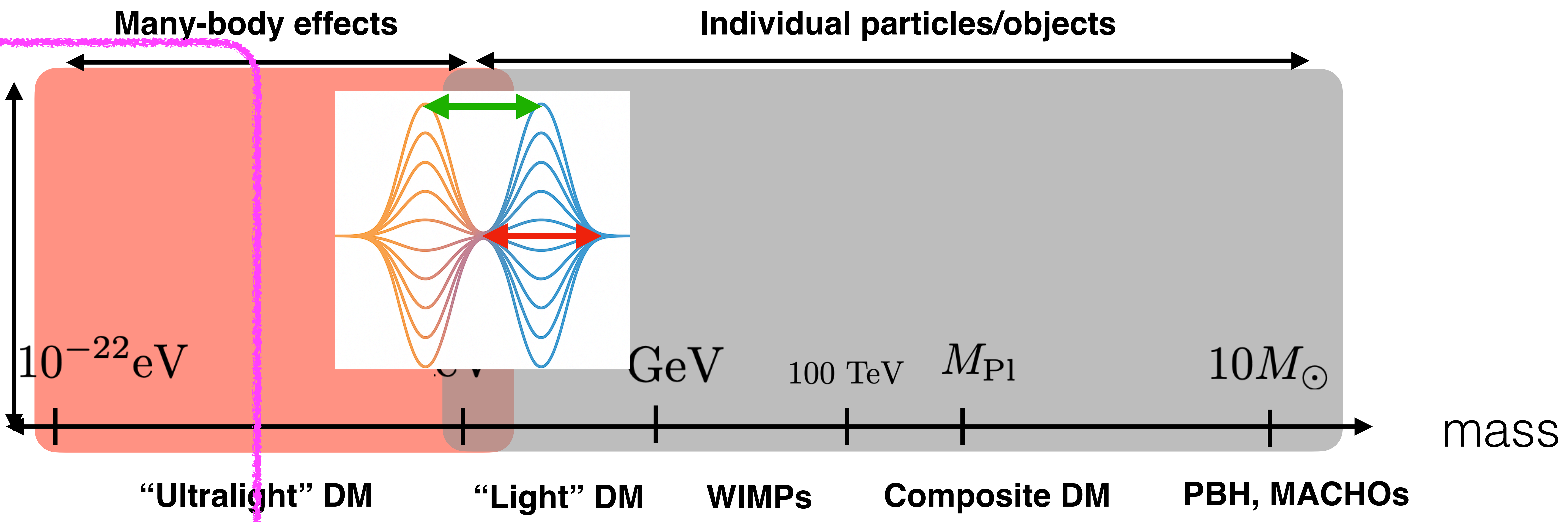
* $\mathcal{L}$

11522
Garani et al 2207.06928

Dark Matter: where to look?

This talk

SIDM λ



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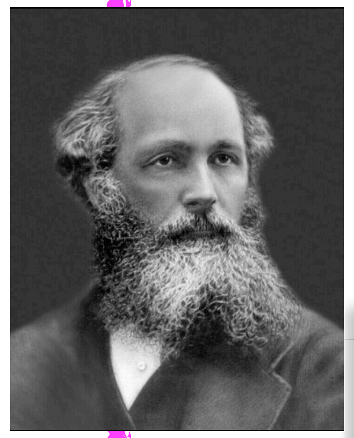

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IN BOTH CASES:

"SMALL SCALE" (cold and/or dense) DYNAMICS MODIFIED

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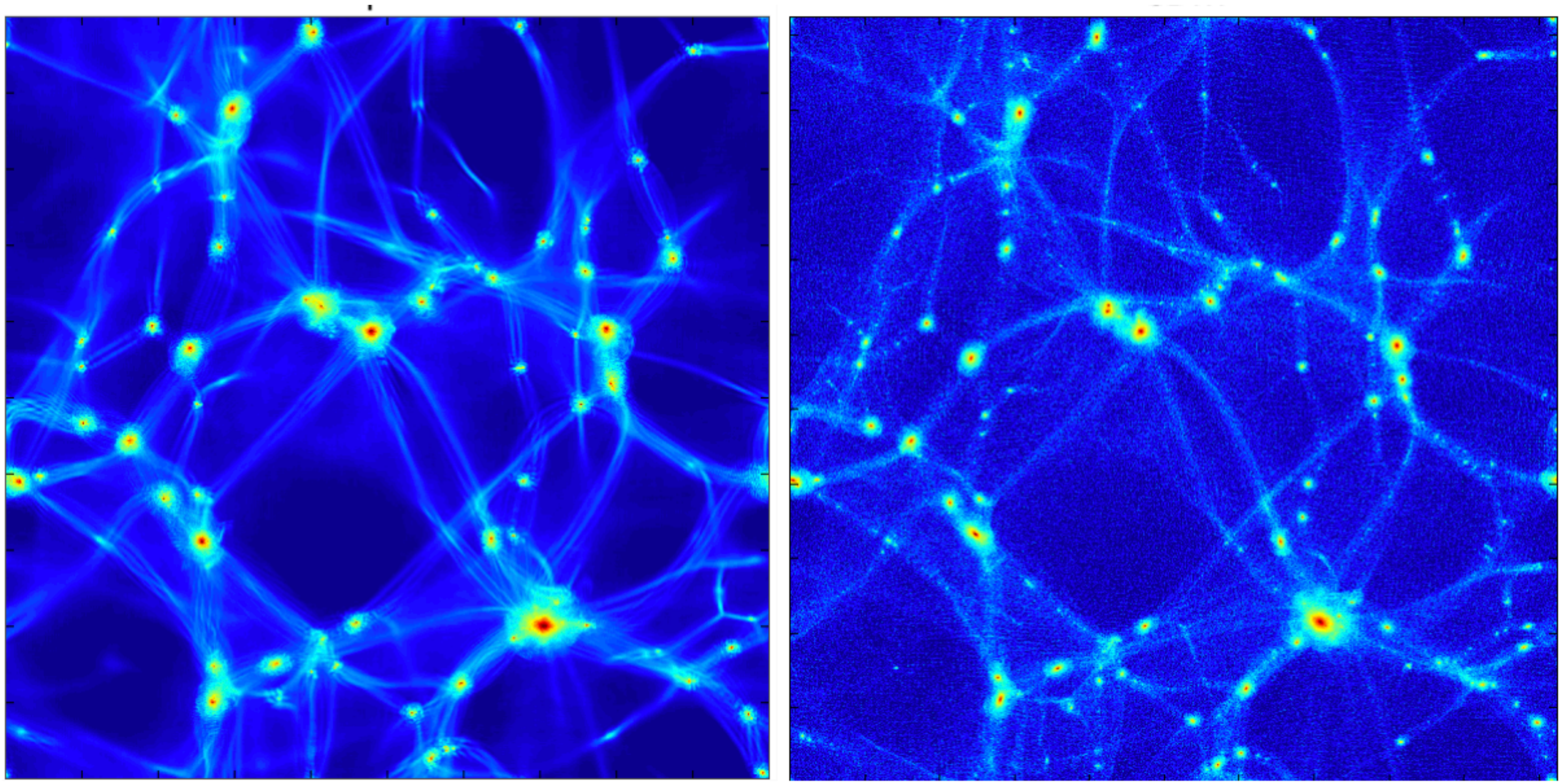
11522

Garani et al 2207.06928

ULDM and CDM similar at large-scales

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

Scale of ~30 Mpc, Schive et al. 1406.6586



ULDM **differs** from CDM at small-scales

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

Halo (free waves)

Virialized configuration: collection of waves with distribution determined by virialization in the galaxy

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

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

$\omega_v \approx m(1 + v^2/2)$ Non-relativistic

The DM potential has coherent oscillations at

$$\omega \approx \frac{1}{76\,\mathrm{d}}\left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)$$

coherent over regions of size $\lambda_{\mathrm{dB}} \sim \frac{10^{-22}\mathrm{eV}}{m}\frac{10^{-3}}{v}\mathrm{kpc}$

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

When vorticity can be neglected

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")

Relevant if $d \lesssim \lambda_{\mathrm{dB}}$

Changes in DF, relaxation, etc.

+ other interactions λ

New handles to find the nature of DM

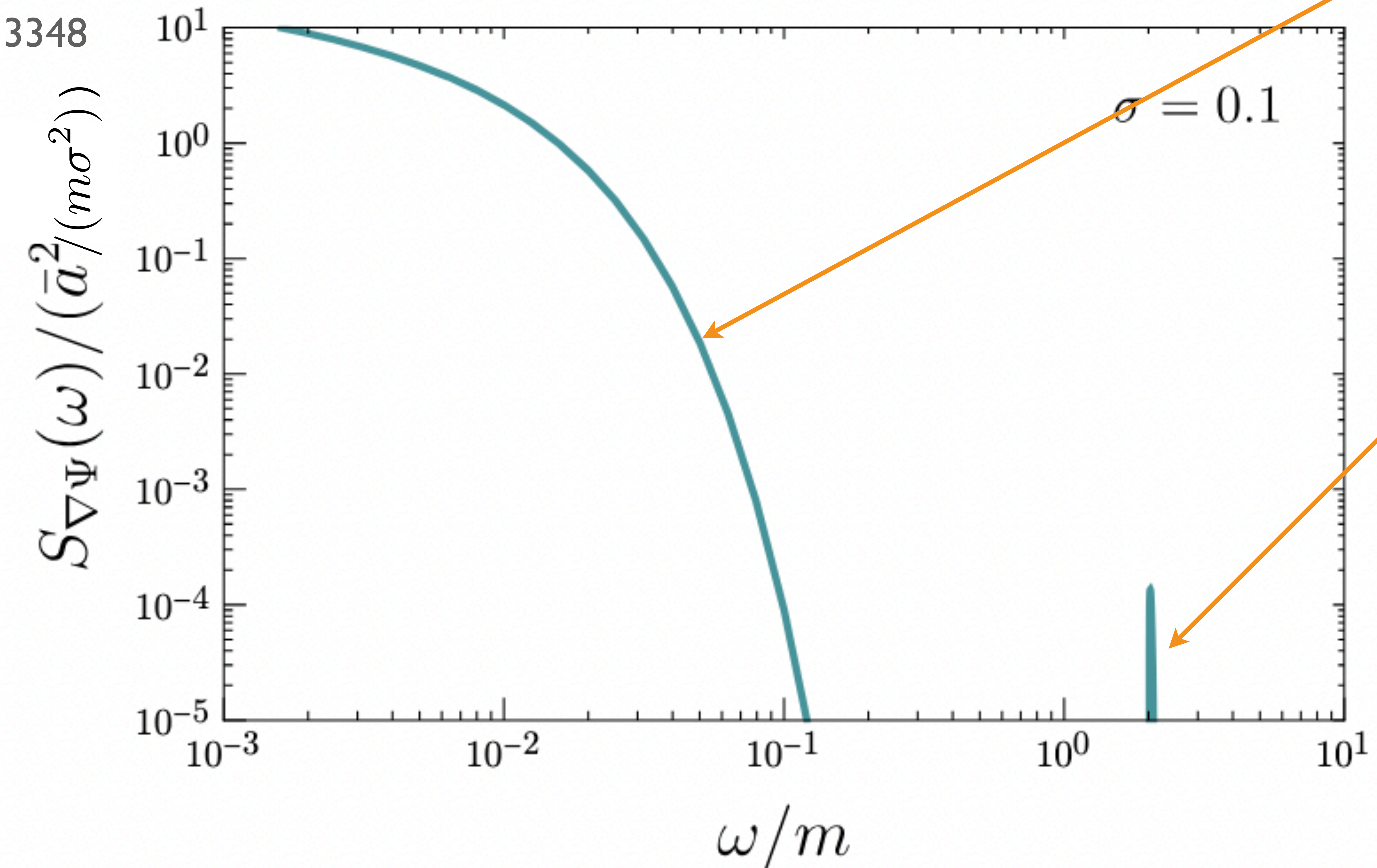
Halo (free waves)

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

$$\Delta\Psi \propto \rho \propto \phi^2 \propto \cos(m(1+v_1)t)\cos(m(1+v_2)t) \propto (\cos(m(v_1 - v_2)t) + \cos(2mt))$$

Gravitational field also oscillates

Kim 2306.13348



These oscillations **inject heat** in any dynamical situation (may be resonantly absorbed)

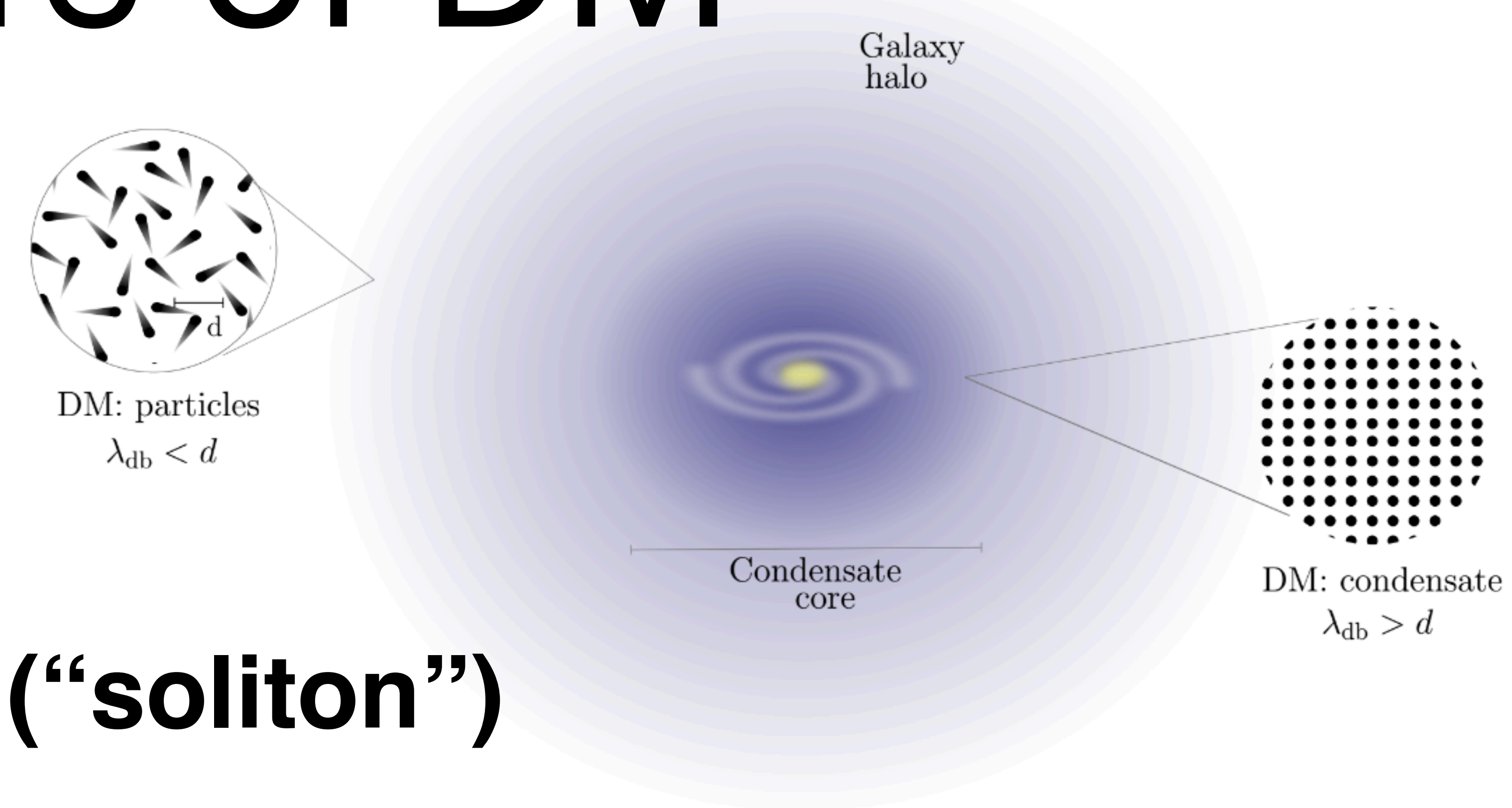
Affect streams, binaries, halo more prone to collapse, splashback radius …

SIDM may add extra phenomena

$$\lambda_{\rm dm-sm}\phi^n \bar{\psi}\psi \Rightarrow f(t,k)\bar{\psi}(p)\psi(p-k)$$

Mass fluctuates!

New handles to find the nature of DM



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

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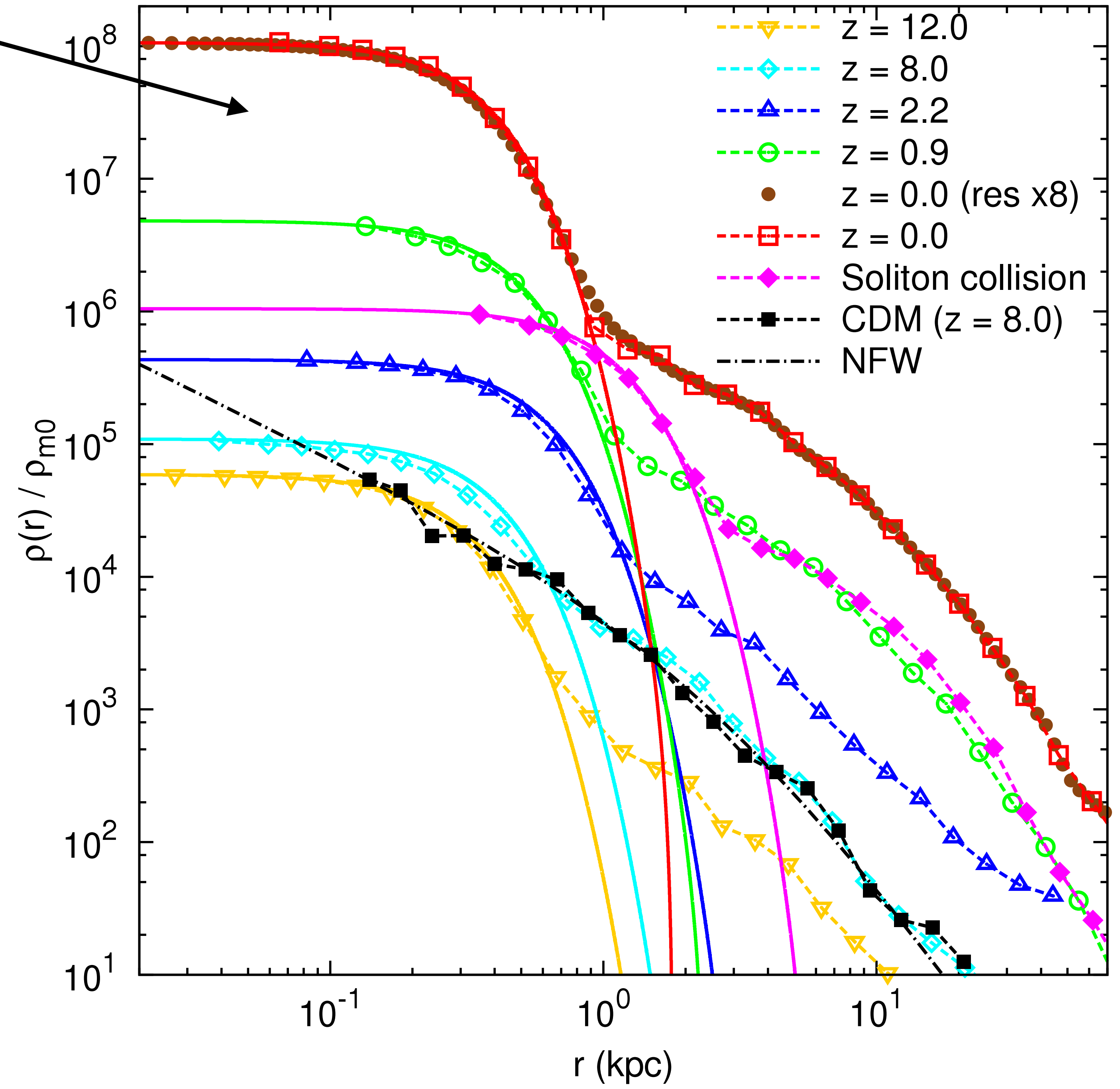
gravitational potential

pure CDM part

repulsive term

core structure ("soliton")



halo

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

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

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

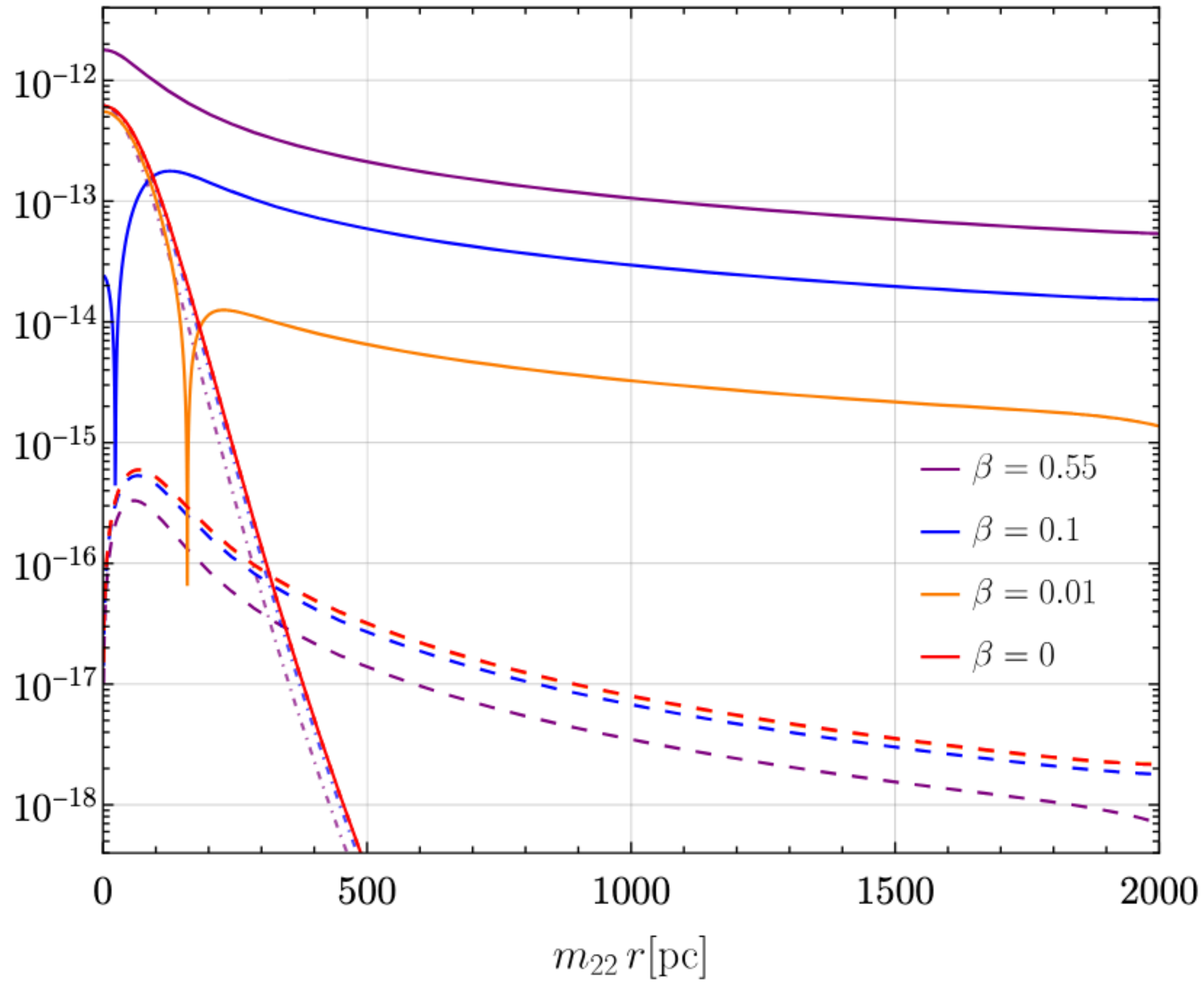
there is some scattering

Hui et al 2101.11735
Chan et al 2110.11882

SIDM and solitons

DB, Gasparotto, Vicente, 2410.07330

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

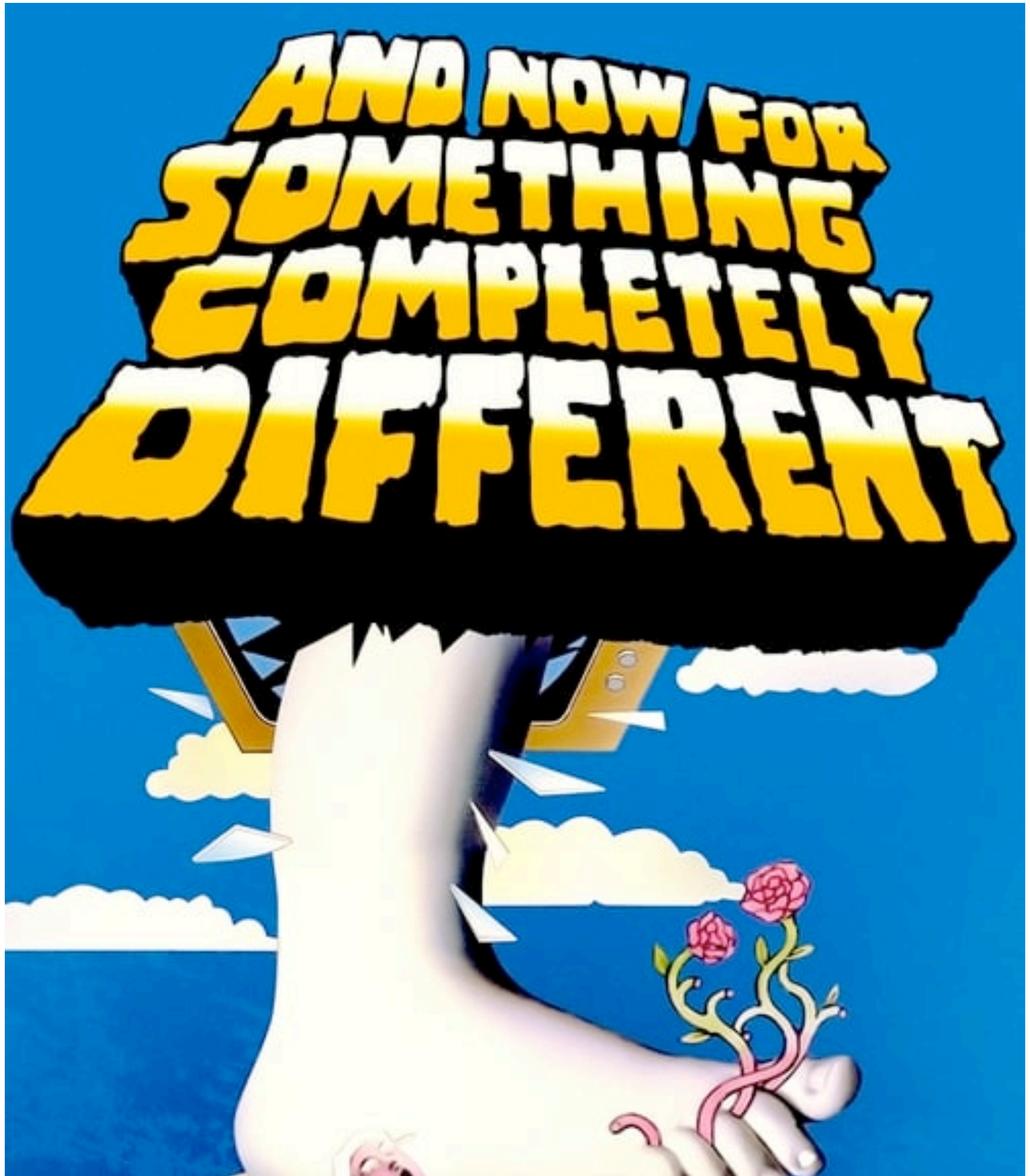


Ψ_2

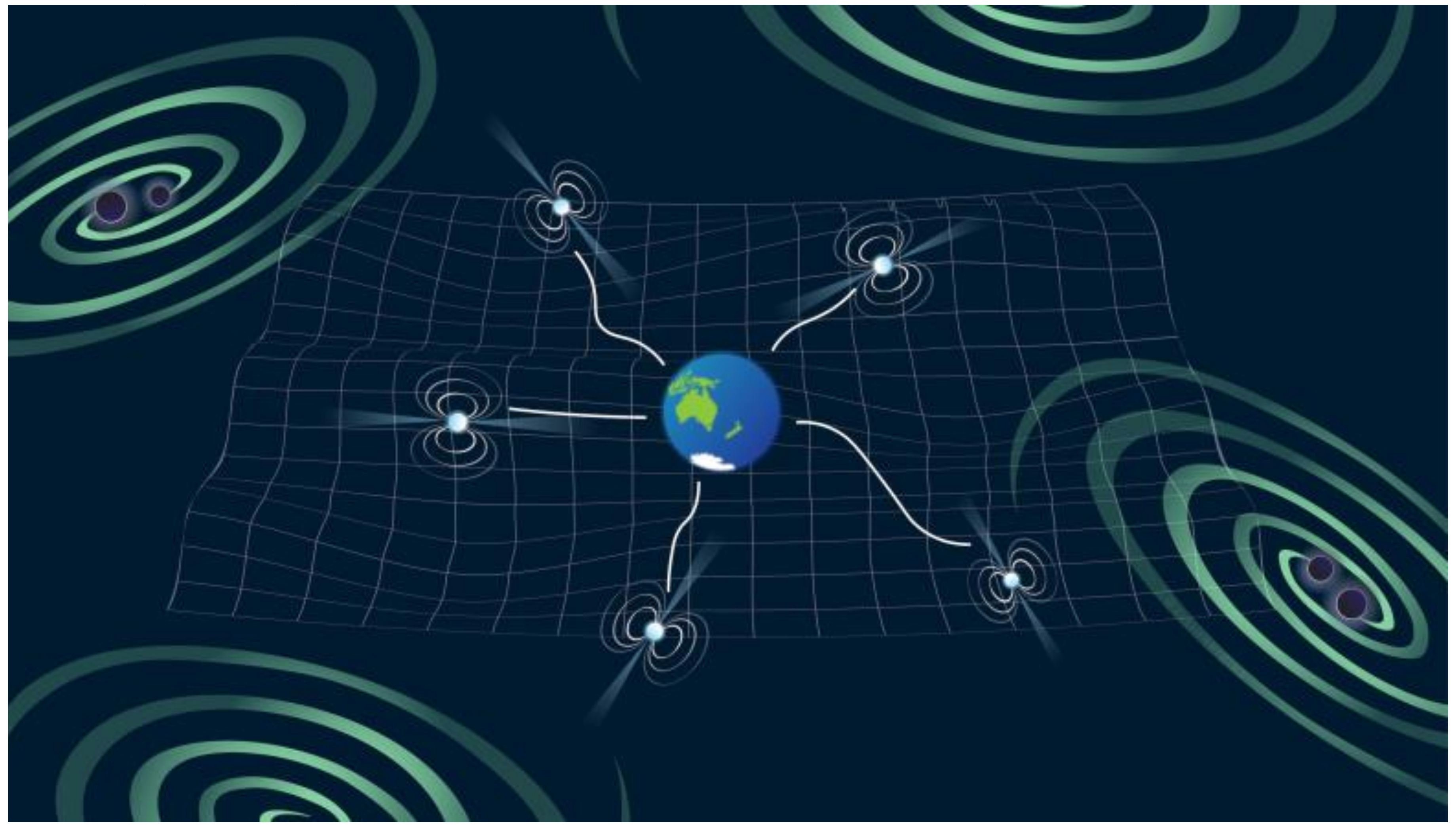
$m^{-1}\partial_r \Phi_2$

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

Where to look for these features?



New ULDM handle I: propagation of signals



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

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

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

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

⇨

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

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

↑ stationary ↑ oscillating

⇨

leading term

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

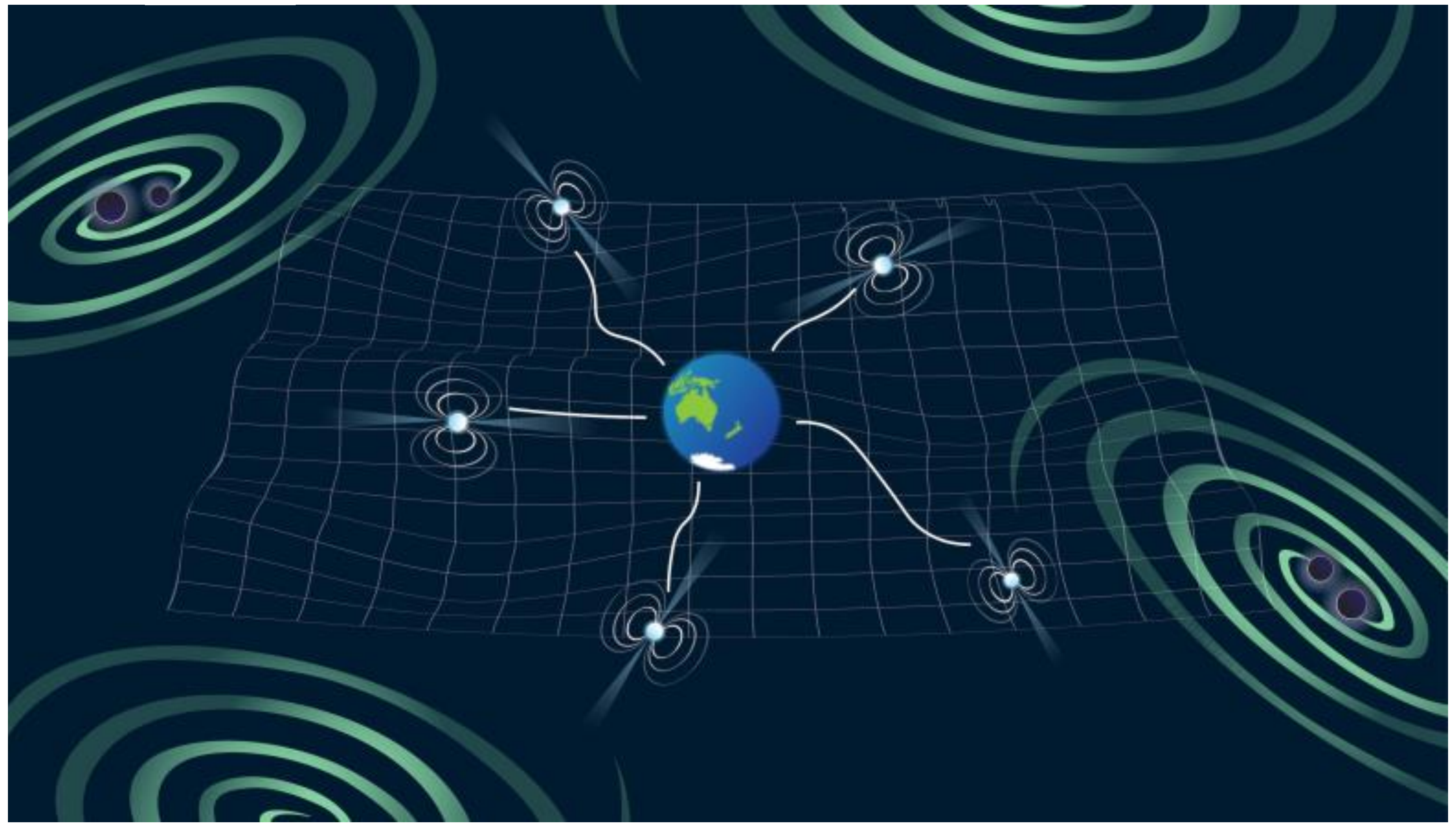
Changes in time of arrival

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

G=1

Models with ULDM coupled to SM (& SIDM)

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 $\lambda_{\mathrm{dm-sm}}\phi^n\bar{\psi}\psi$

- Linear $\phi/\Lambda_1\ \bar{\psi}\psi + (\phi/\Lambda_1)F^2$
- Quadratic $\phi^2/\Lambda_2^2\ \bar{\psi}\psi + (\phi/\Lambda_2)^2 F^2$

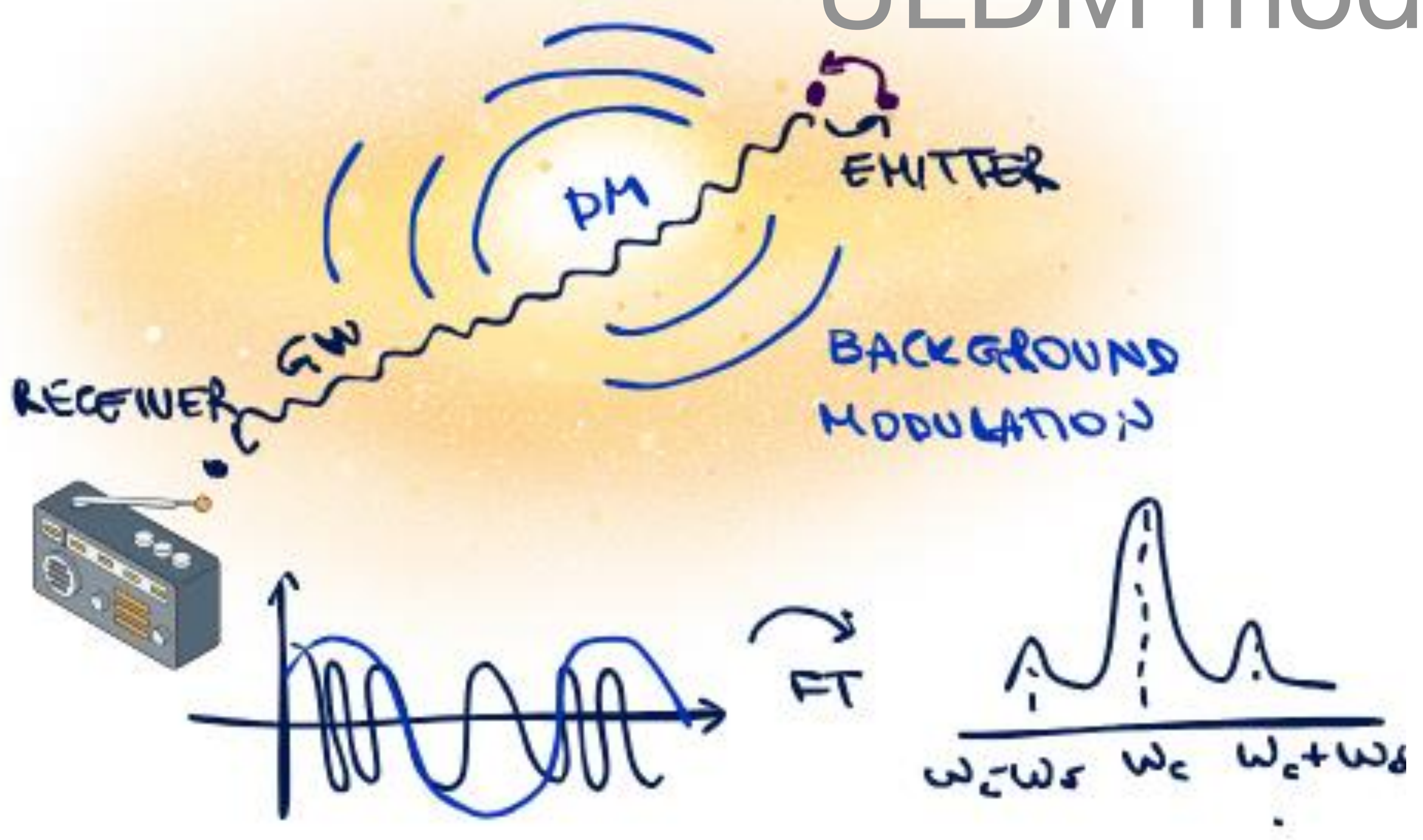
Effective amplitude of the fluctuations

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

G=1

ULDM modulates signals

DB, Gasparotto, Vicente, 2410.07330



Effective amplitude of the fluctuations

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

$$\omega_\delta = 2m$$

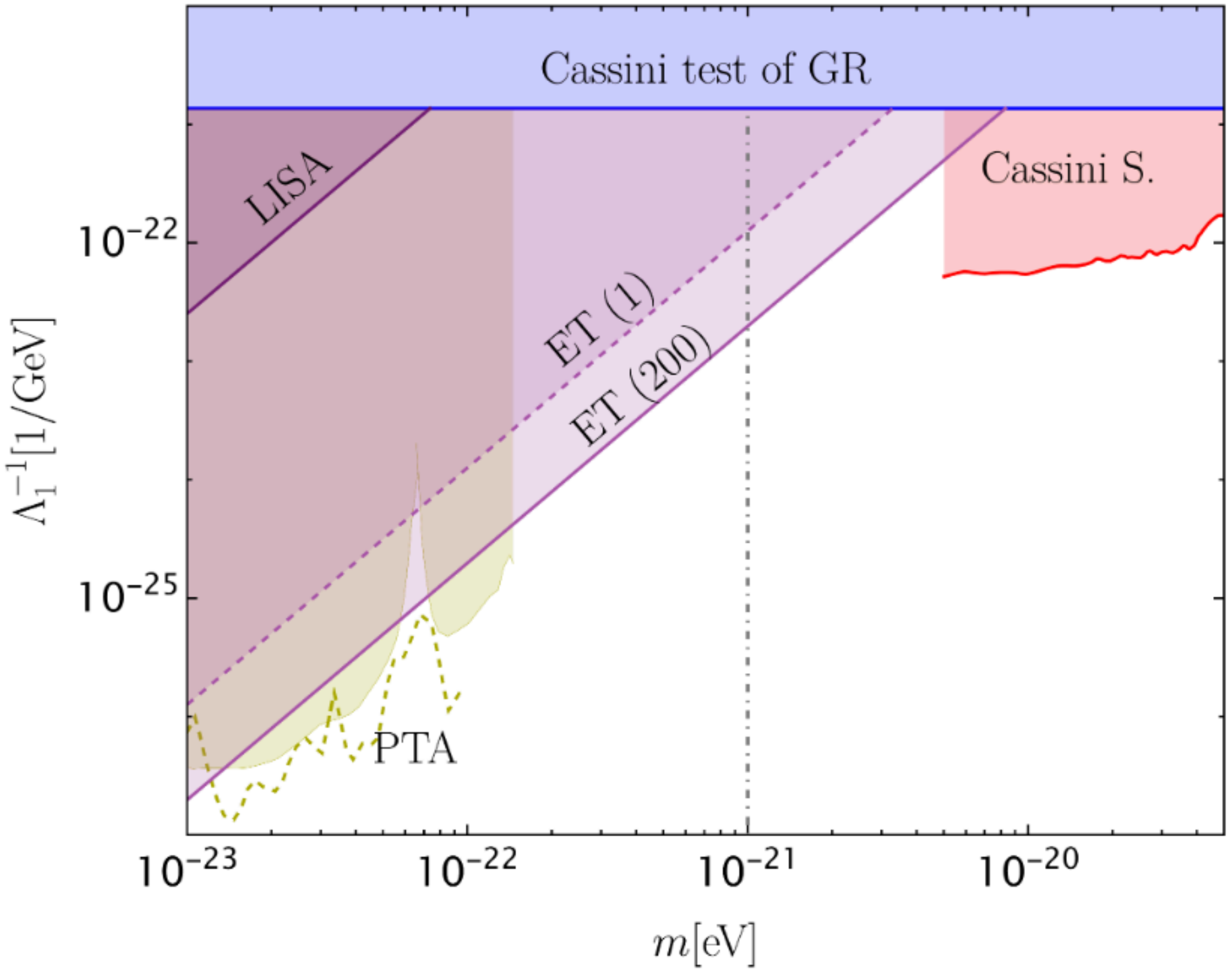
primary wave

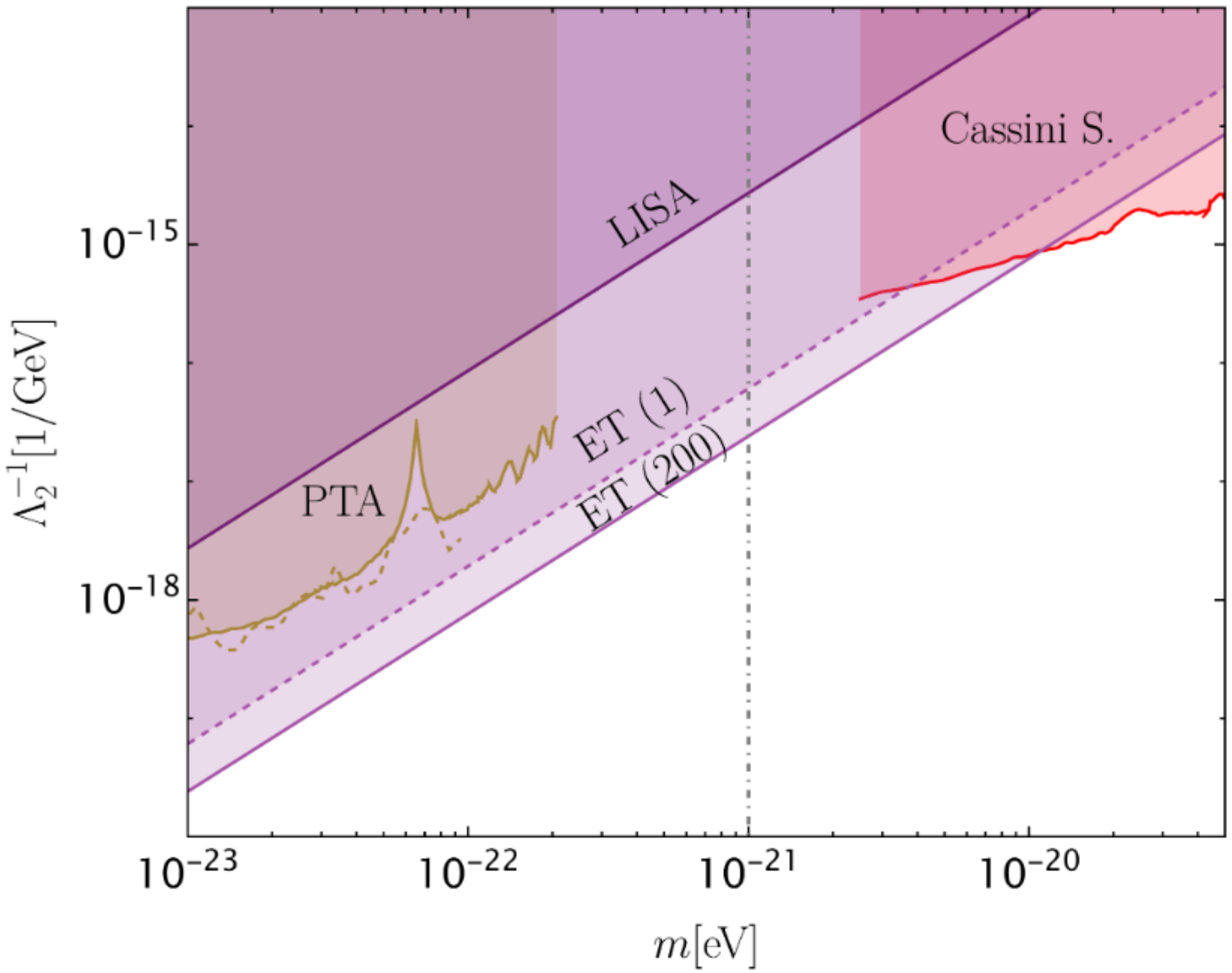
$$h \approx \mathcal{A}\Big[\cos(\omega_e u + \alpha_0') + \pm \frac{\omega_e}{2\omega_\delta} \Upsilon\Big|_{r_e} \cos[(\omega_e \pm \omega_\delta)u + \alpha_0' \pm \varphi_\delta]\Big]$$

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

ULDM modulation of gravitational waves

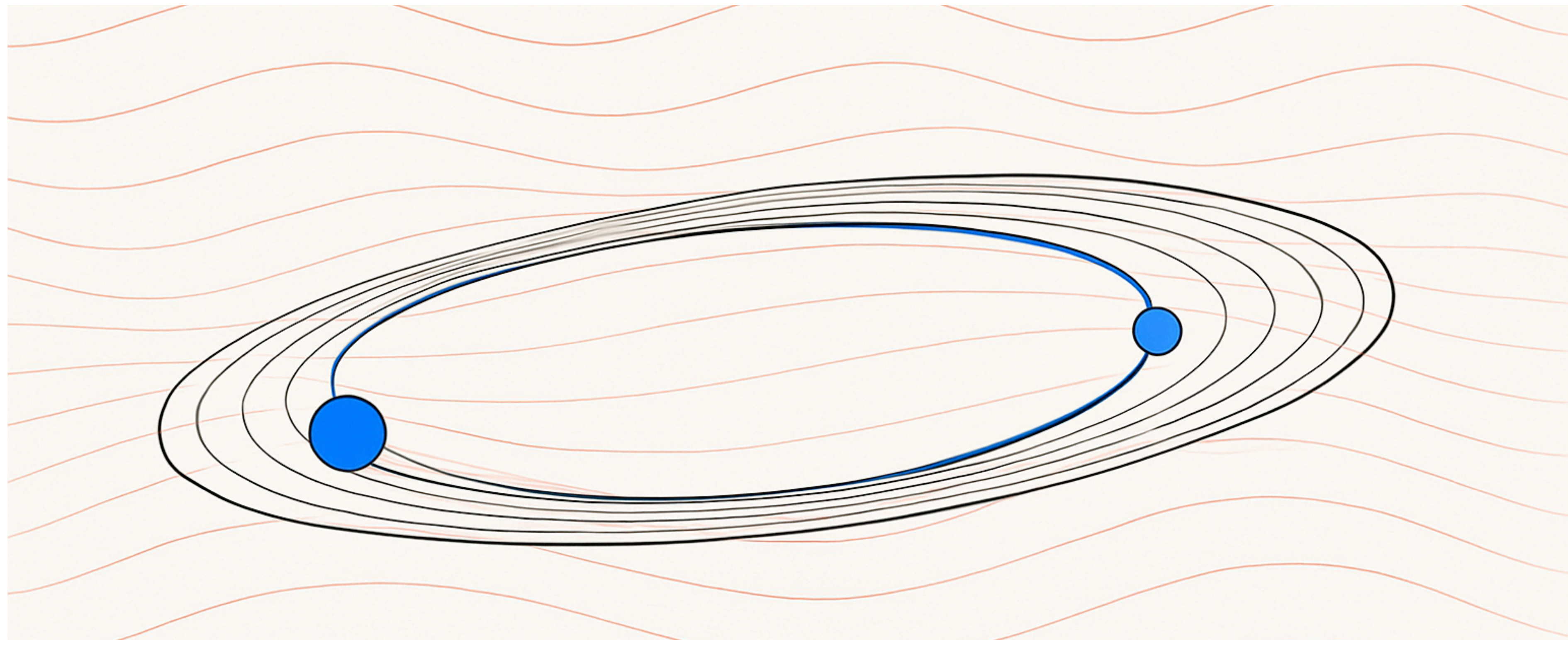
DB, Gasparotto, Vicente, 2410.07330





New ULDM handle II: resonant absorption (binaries)

fluctuating gravitational potentials affect gravitationally bound systems



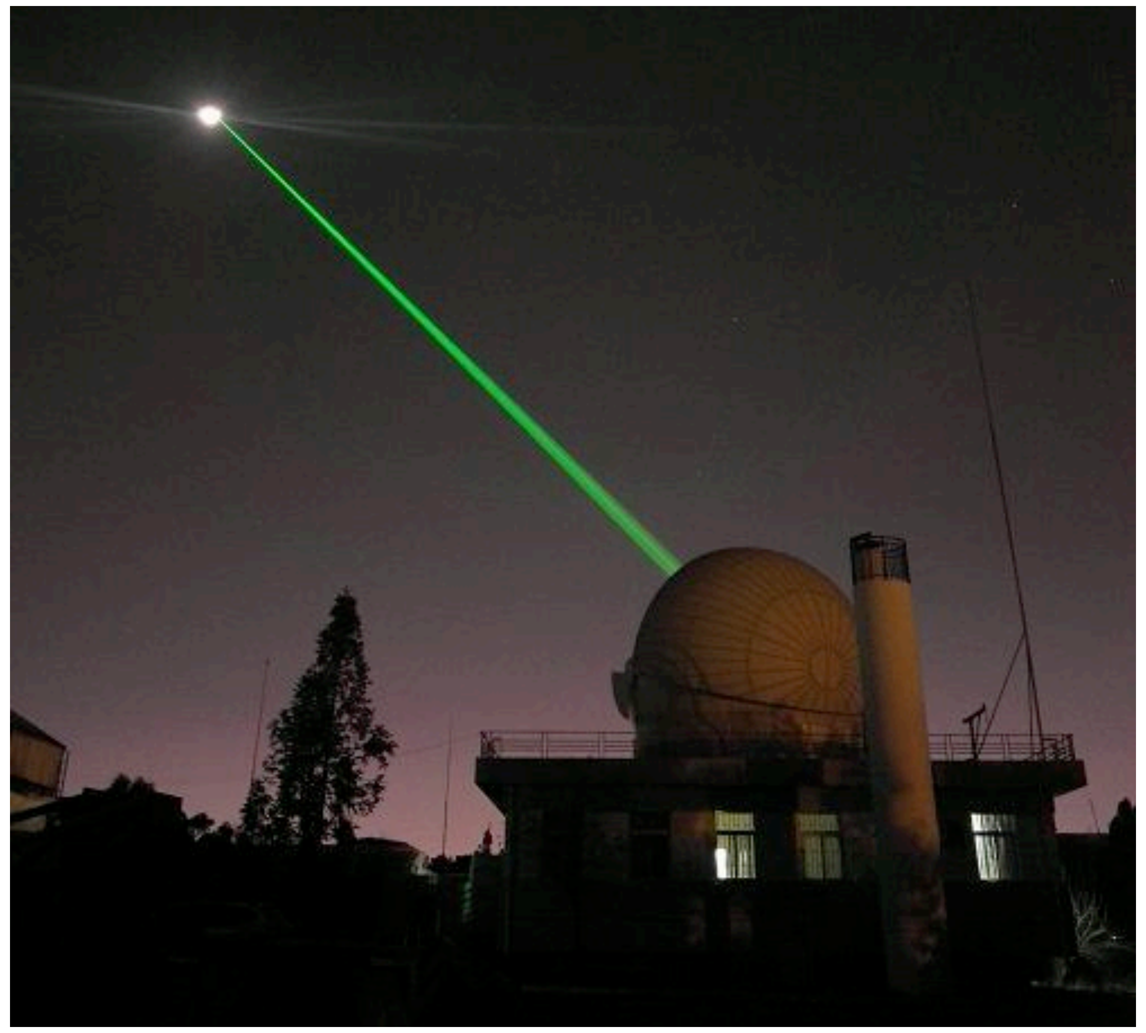
$$\ddot{r}_i + \frac{GM}{r^3} r_i = \boxed{-\ddot{\psi}\, r_i}$$

External Gravitational Potential

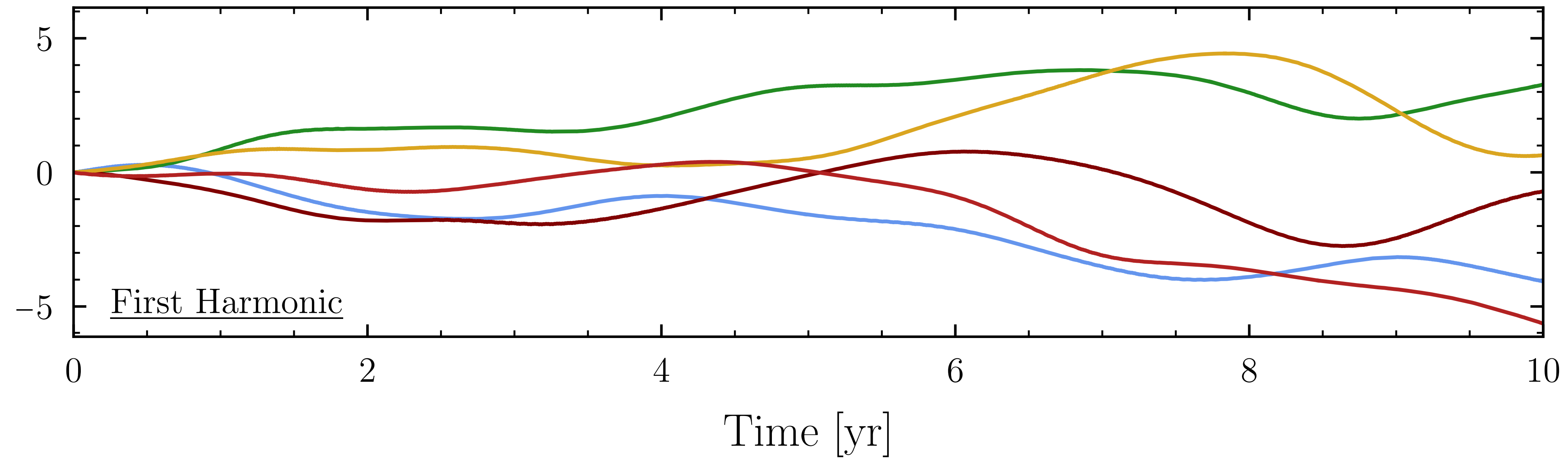
Newtonian Potential

$h \sim \cos(2\pi f t)$
$r \sim e \cos(2\pi t/P)$
possible resonances at *f=n/P*

New ULDM handles II: resonant absorption



Moon's orbit
Δr (cm)



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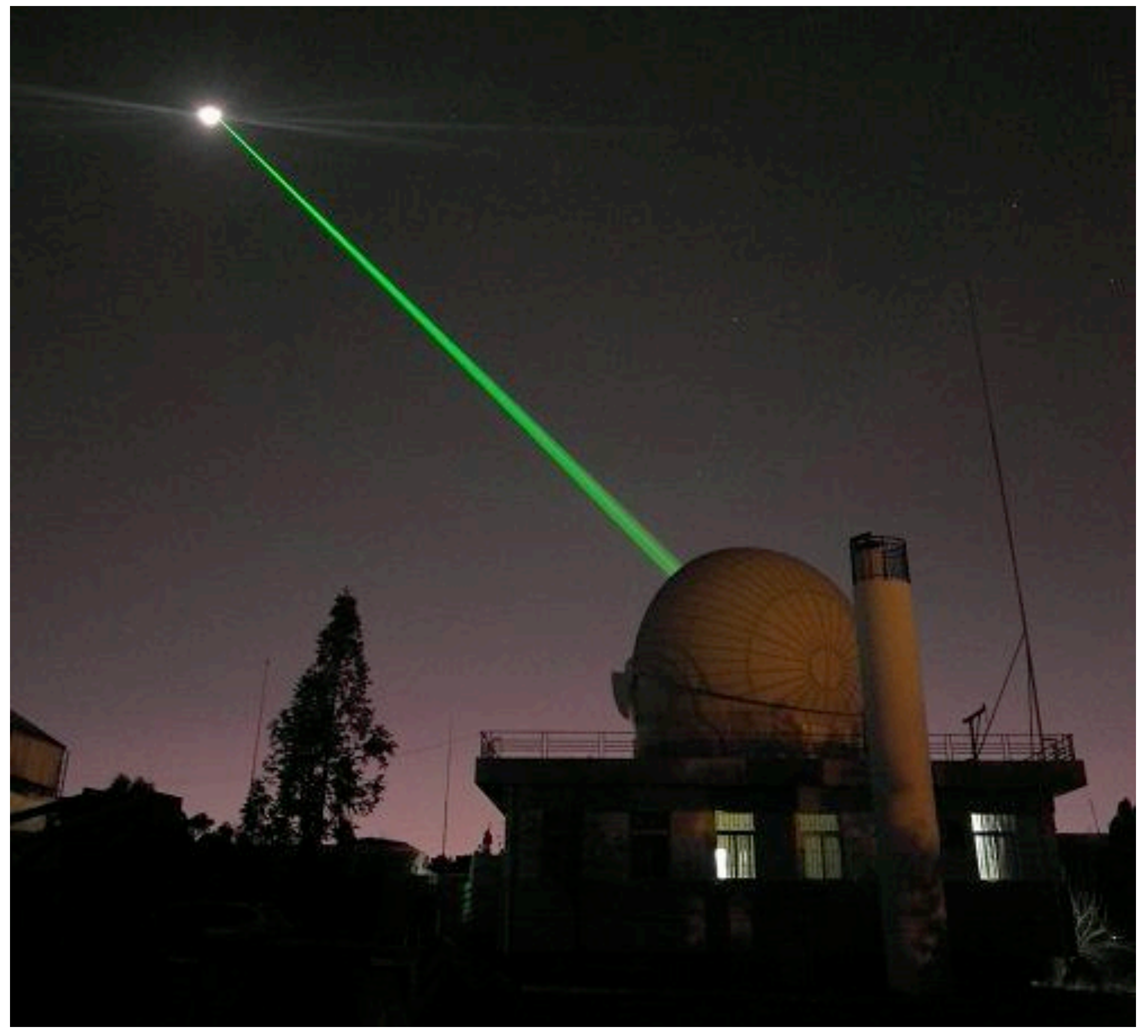

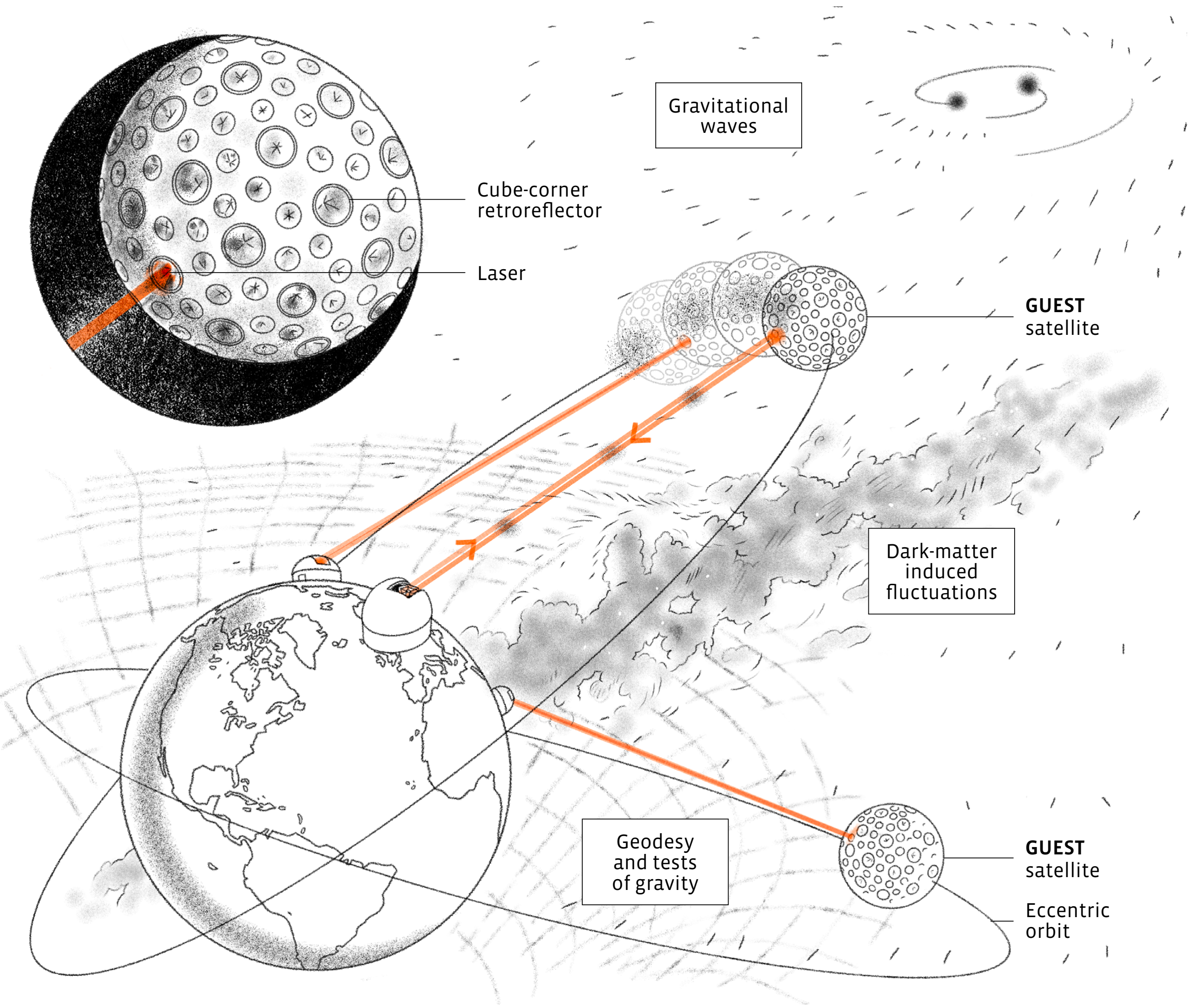

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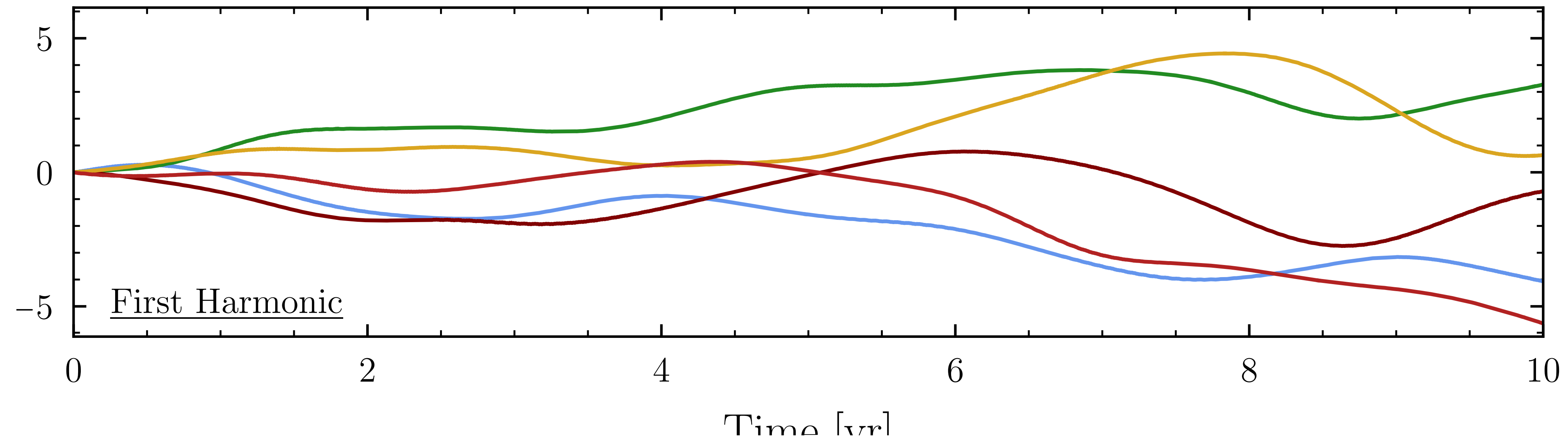
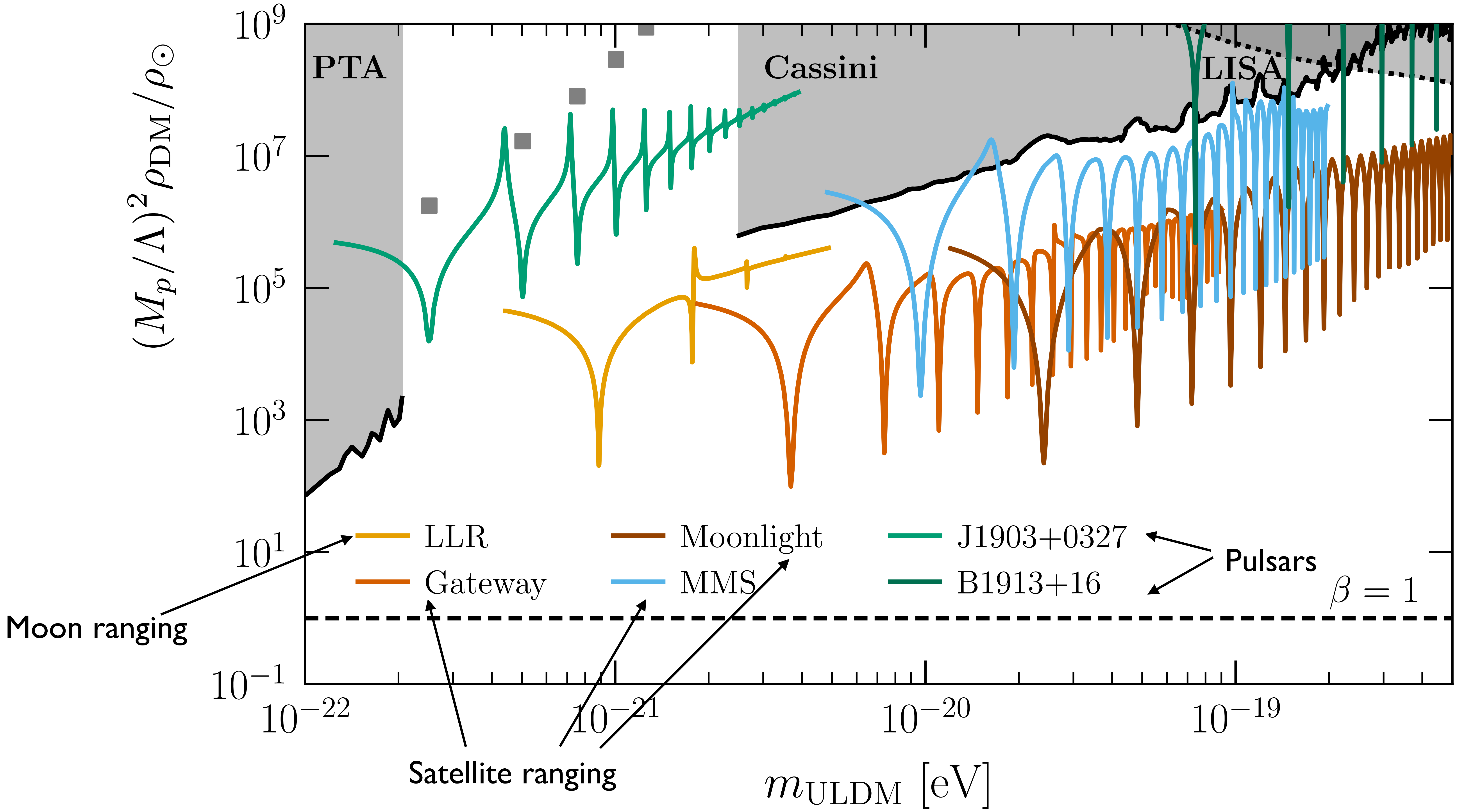
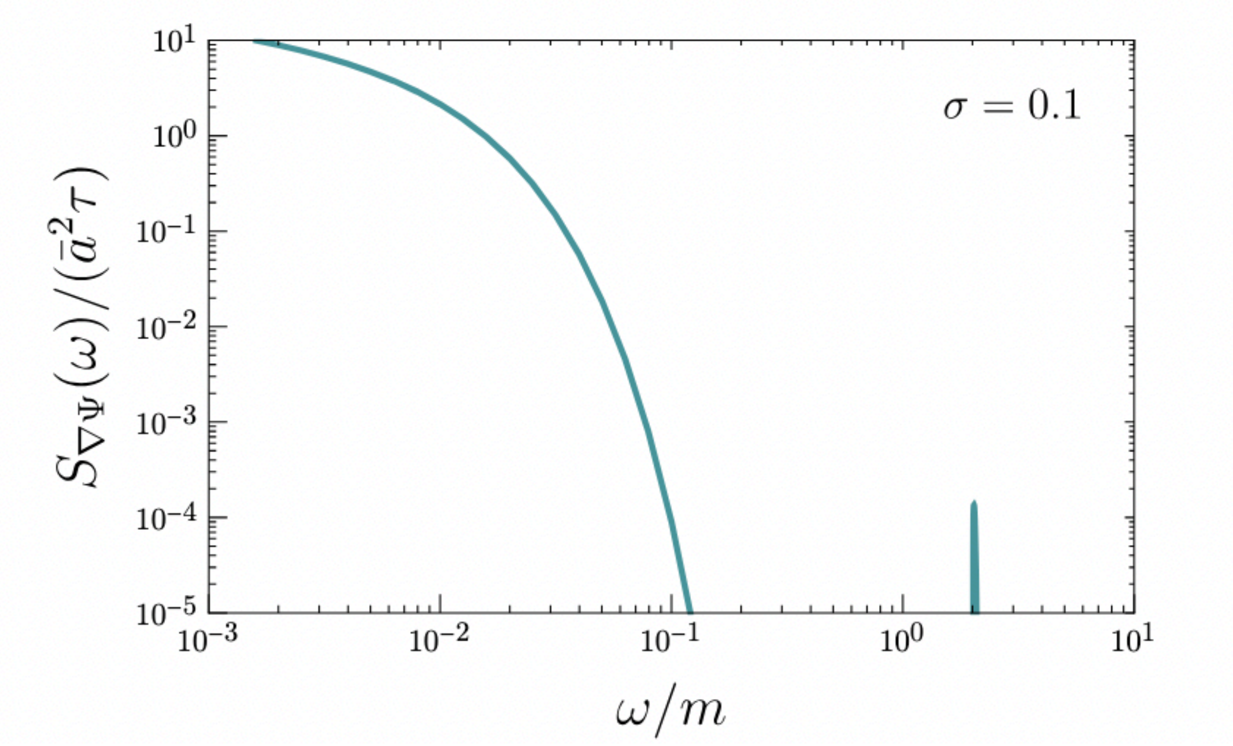
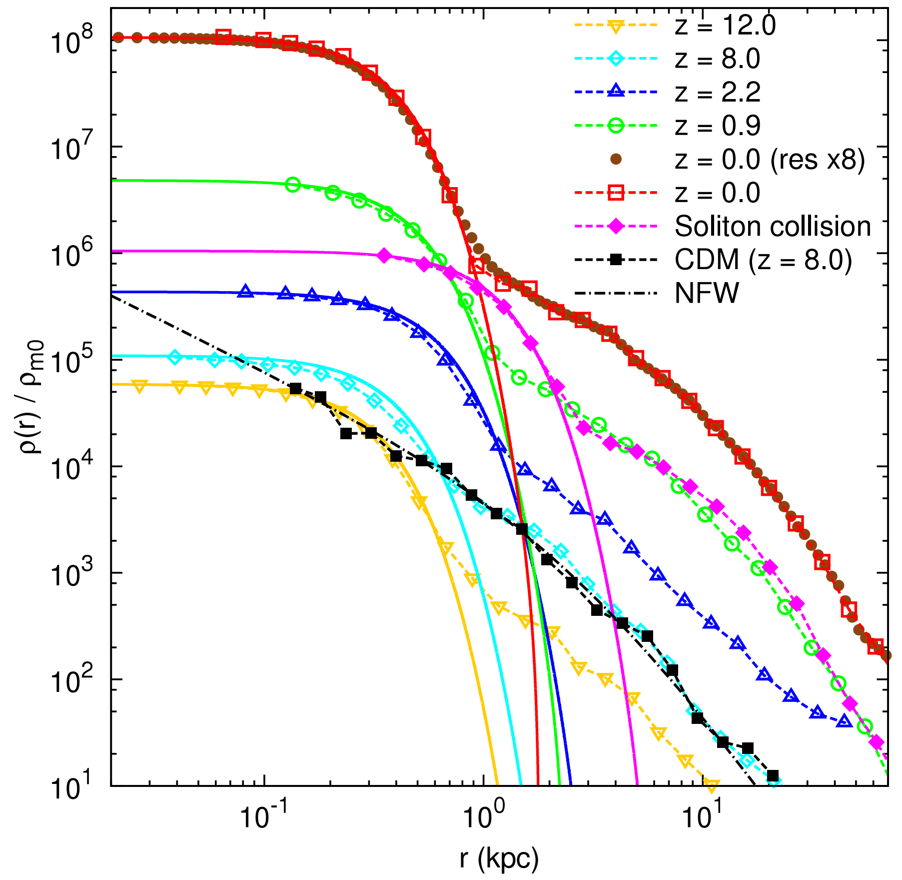




Conclusions

- Generates fluctuating **fields** and stationary **galactic gravitational potentials**
- Generates coherent **cores** at high density (solitons)

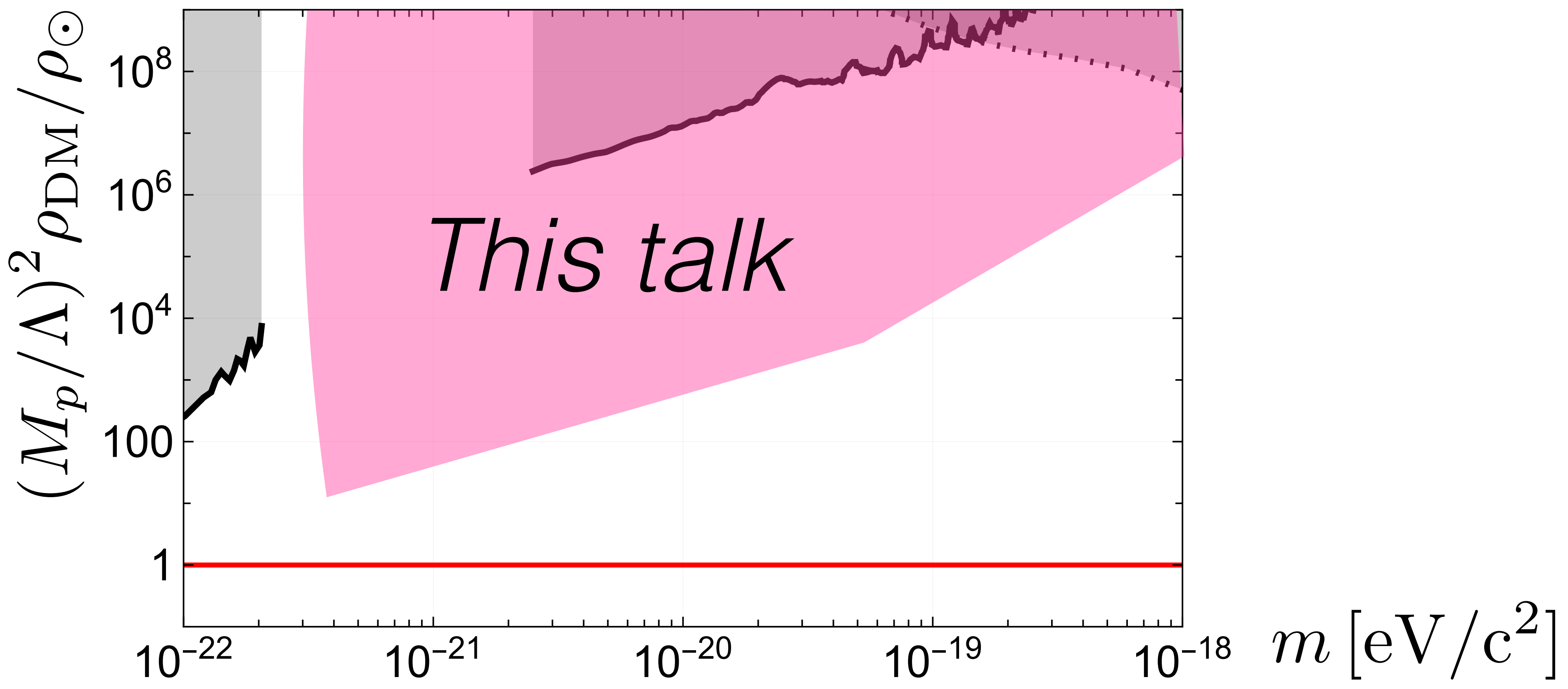




- These fluctuations affect all motion (gravitational dynamics)
- SIDM: extended cores, direct effect in the bodies

ULDM

- Modulates the phase of GWs
- Gets absorbed in binary systems



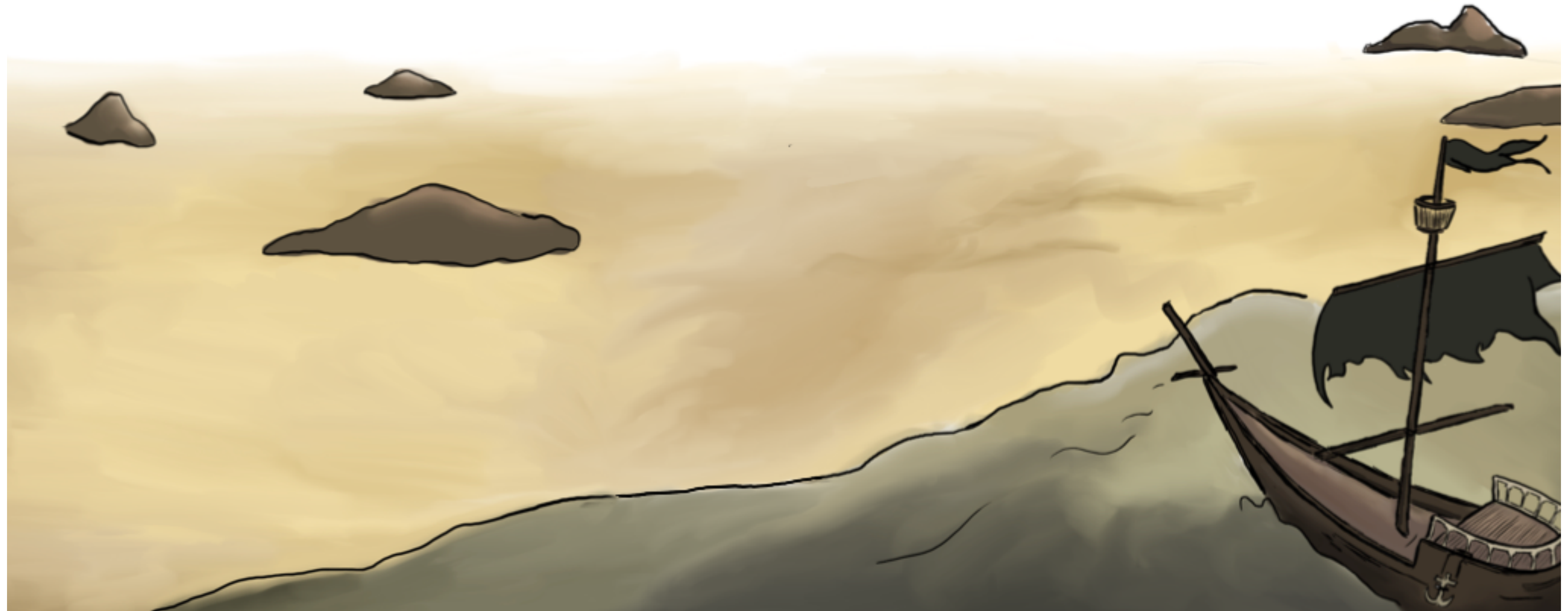
10^{-22}eV ⟷ eV

Outlook

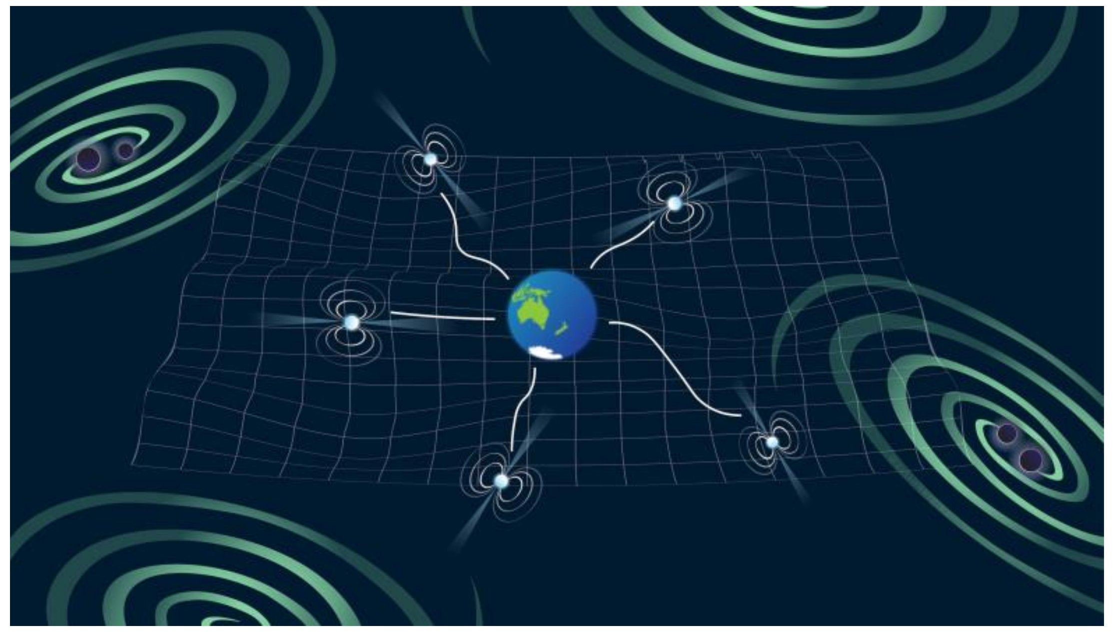
- Generates fluctuating **fields** and stationary **galactic gravitational potentials**
- Generates coherent **cores** at high density (solitons)

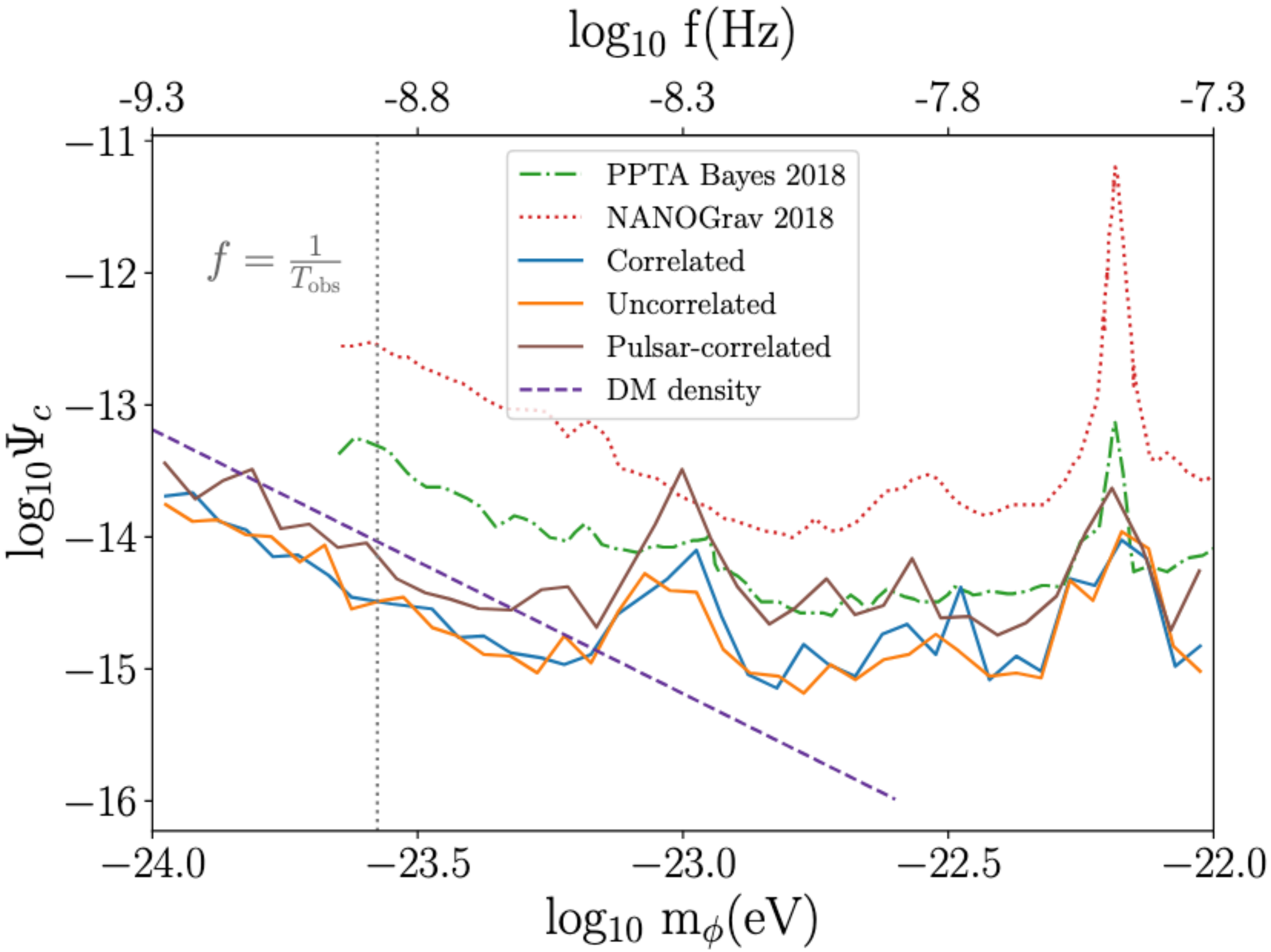
  - These fluctuations affect all motion (gravitational dynamics)
  - SIDM: extended cores, direct effect in the bodies

What do they do for very cold, dense, balanced, resonating…
configurations in **your** simulations?



ULDM modifies time of arrival in **pulsar** signals





Smarra et al
2306.16228 [astro-ph.HE]

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

Properties of the soliton

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

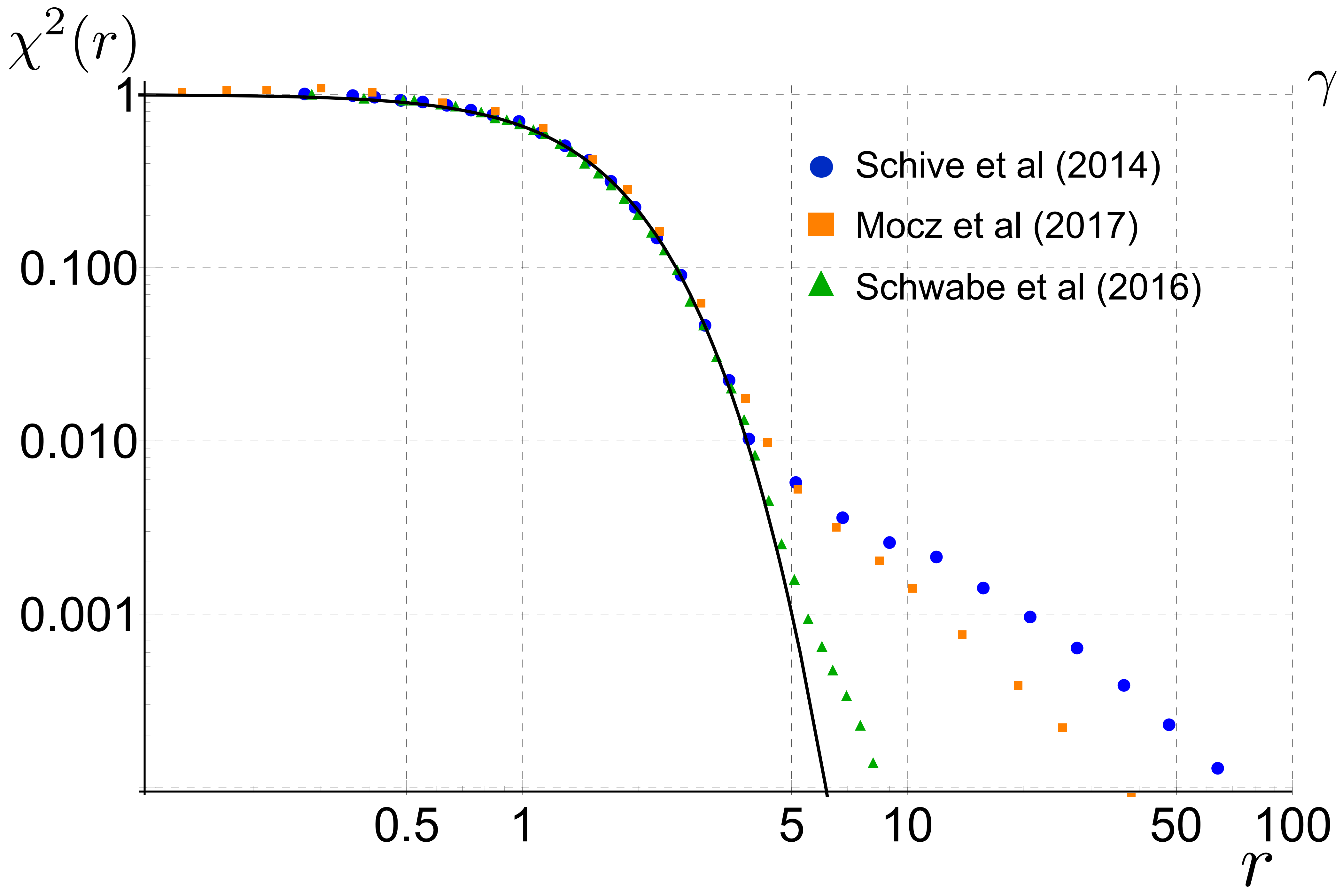
$v \ll c,\ \omega \ll m$

$$i\partial_t \psi = -\frac{1}{2m}\Delta\psi + m\Phi_N\psi$$
$$\Delta\Phi_N = 4\pi G|\psi|^2$$

spherically symmetric stationary, non-relativistic solution:

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

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



$\gamma = -0.69$

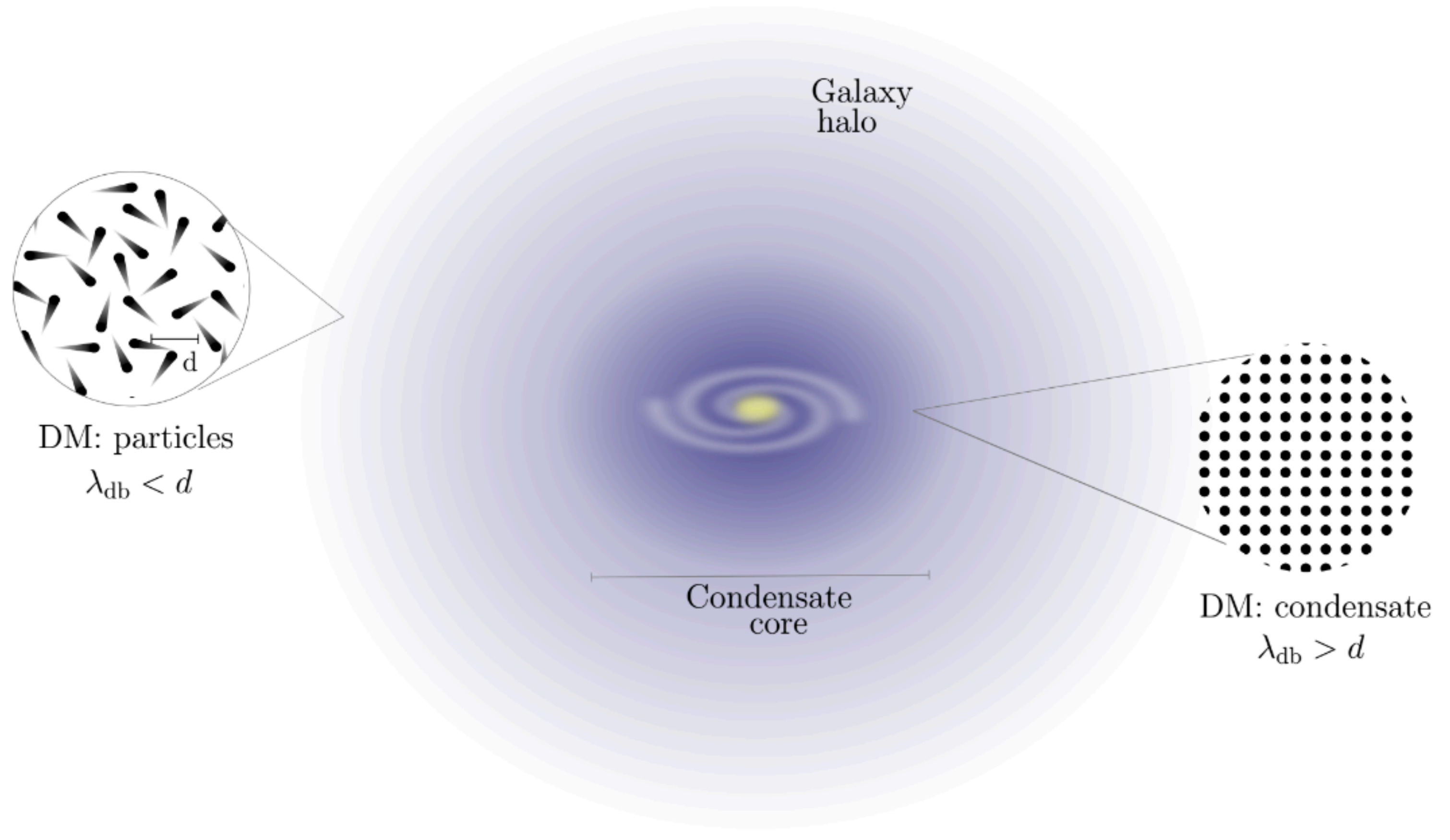
scaling solution

$$\chi_\lambda(r) = \lambda^2 \chi_1(\lambda r)$$
$$x_{c\lambda} = \lambda^{-1} x_{c1}$$
$$M_\lambda = \lambda M_1$$
$$\gamma_\lambda = \lambda^2 \gamma$$
$$\rho_{c\lambda} = \lambda^4 \rho_{c1}$$

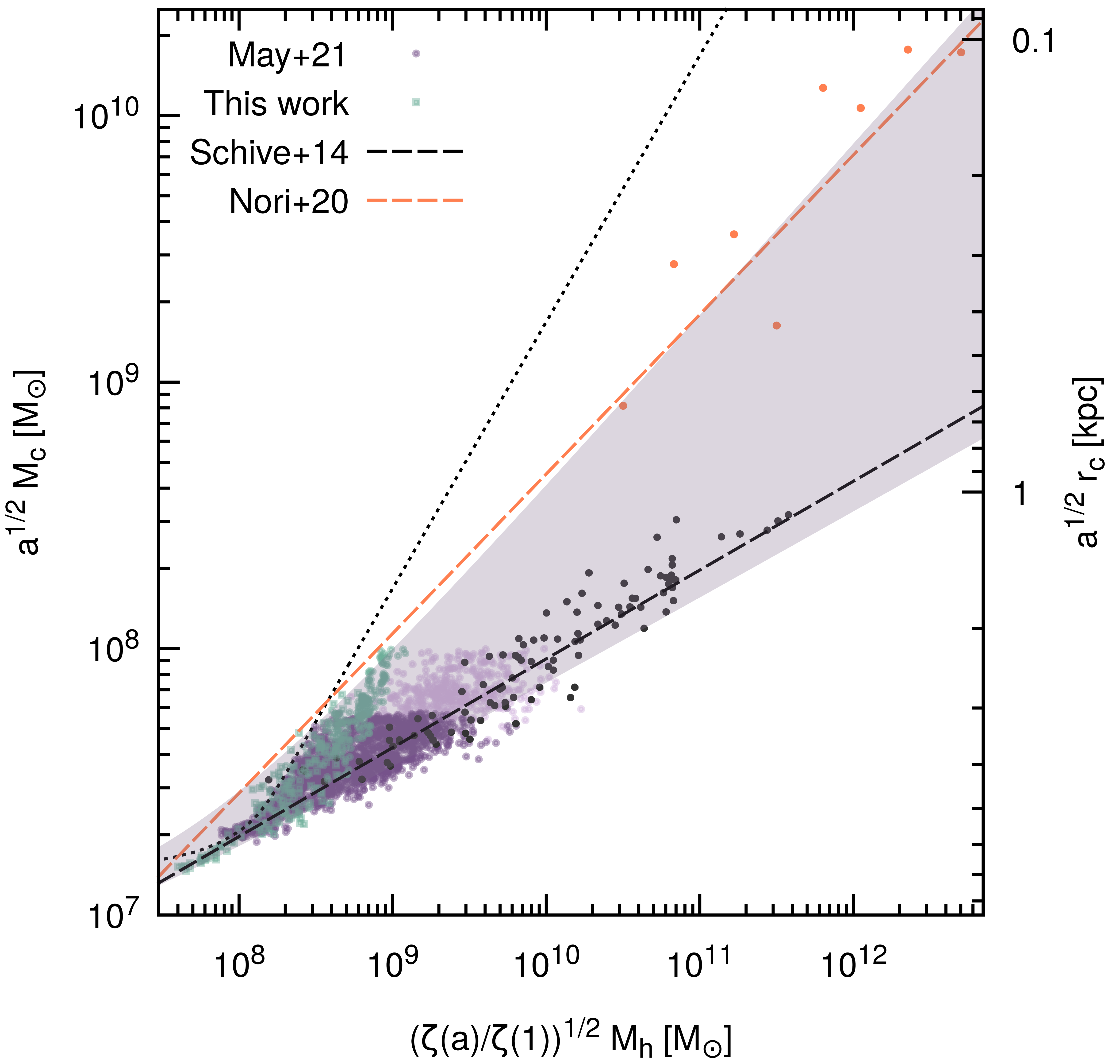
What fixes γ?

Scattering in halo-soliton relation

Ferreira et al 2005.03254
Chan et al 2110.11882



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



Our estimates from 2025 for 2025

Foster, DB et al., arXiv: 2504.15334 [astro-ph.CO]
Foster, DB et a., arXiv:2504.16988 [gr-qc]