Aspects of **ultralight dark matter** for **astrophysical observations**

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GOBIERNO DE ESPAÑA

MINISTERIO DE CIENCIA E INNOVACIÓN

Generalitat de Catalunya
Departament de Recerca i Universitats

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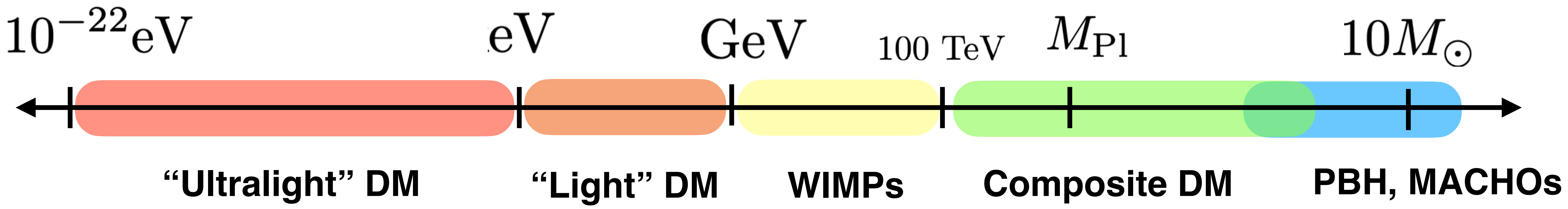
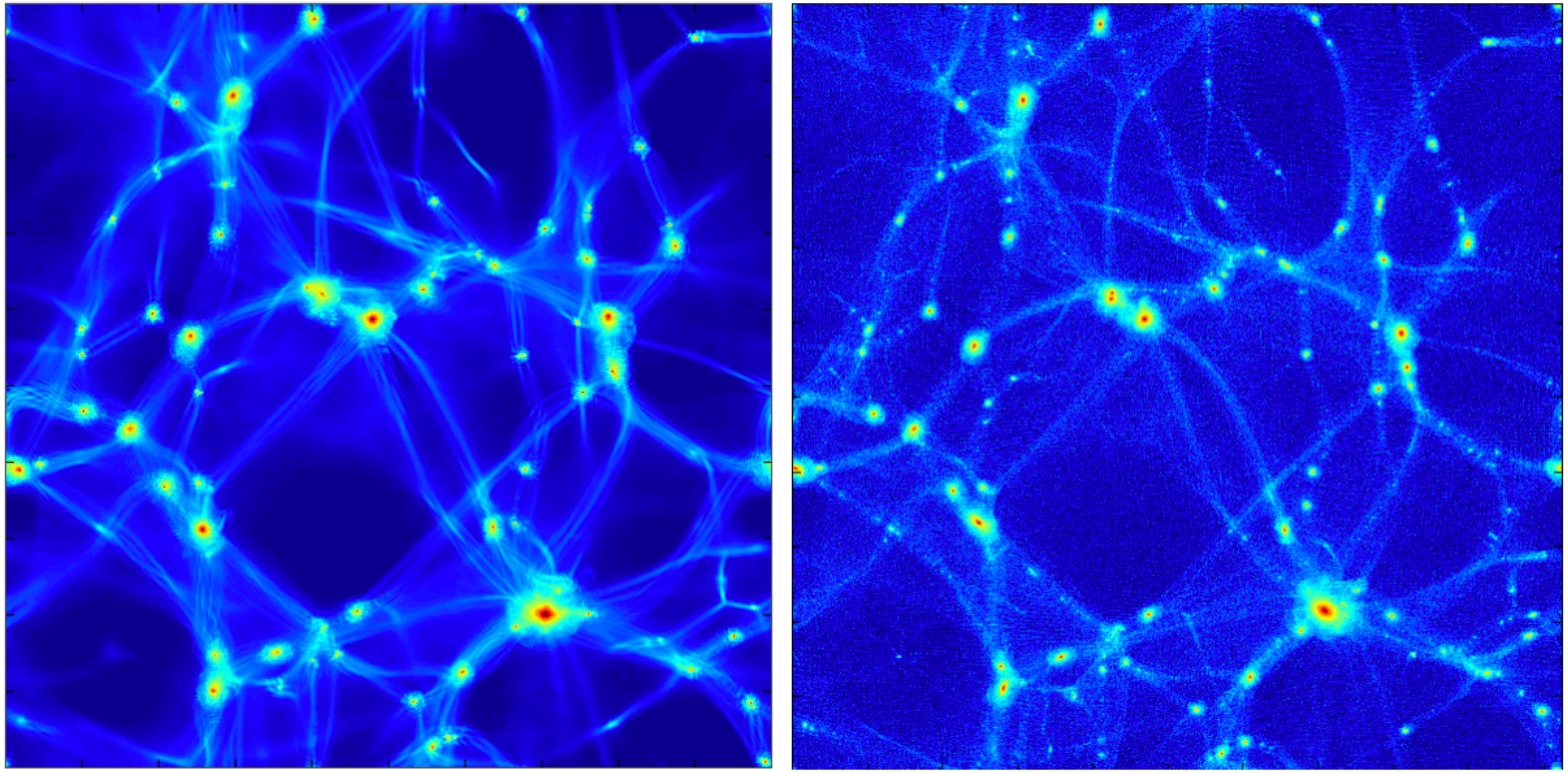
Dark Matter: where to look?



Similar behaviour at large-scales

Scale of ~30 Mpc, Schive et al. 1406.6586



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

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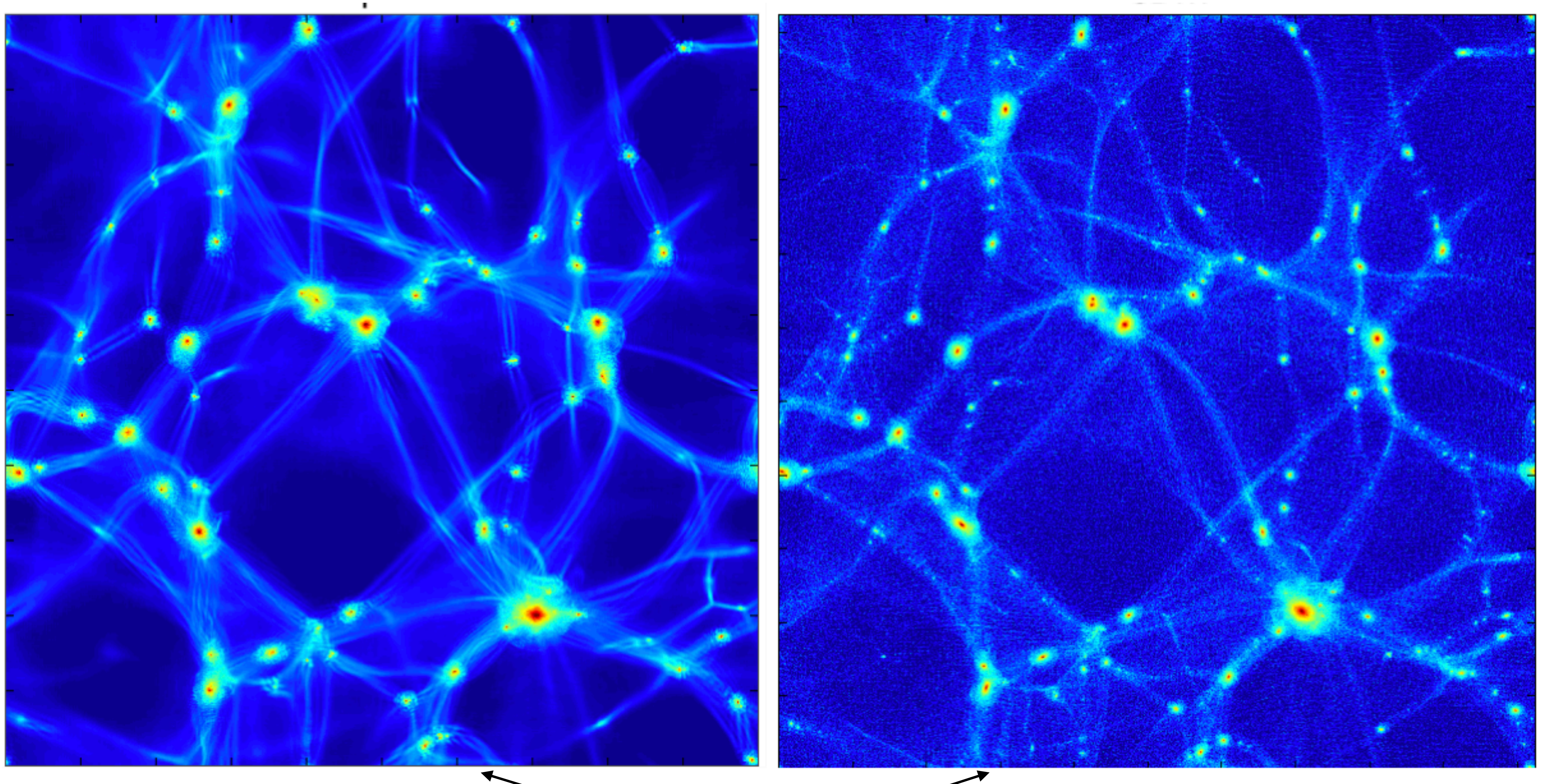


We see differences at small scales

What can we look for

DM

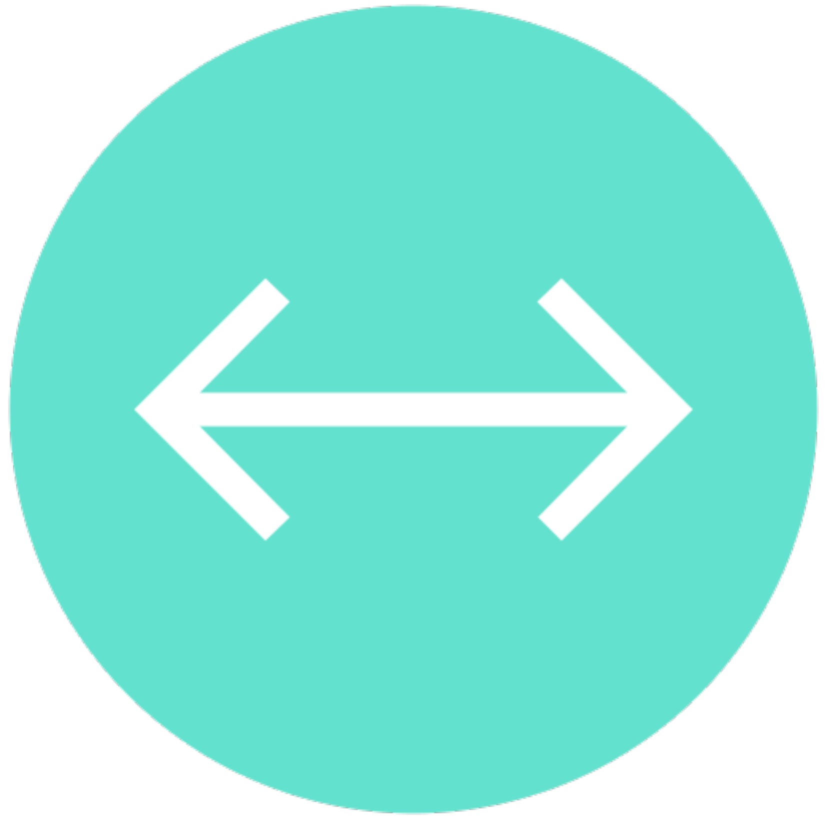
particle vs compact object

mass

spin

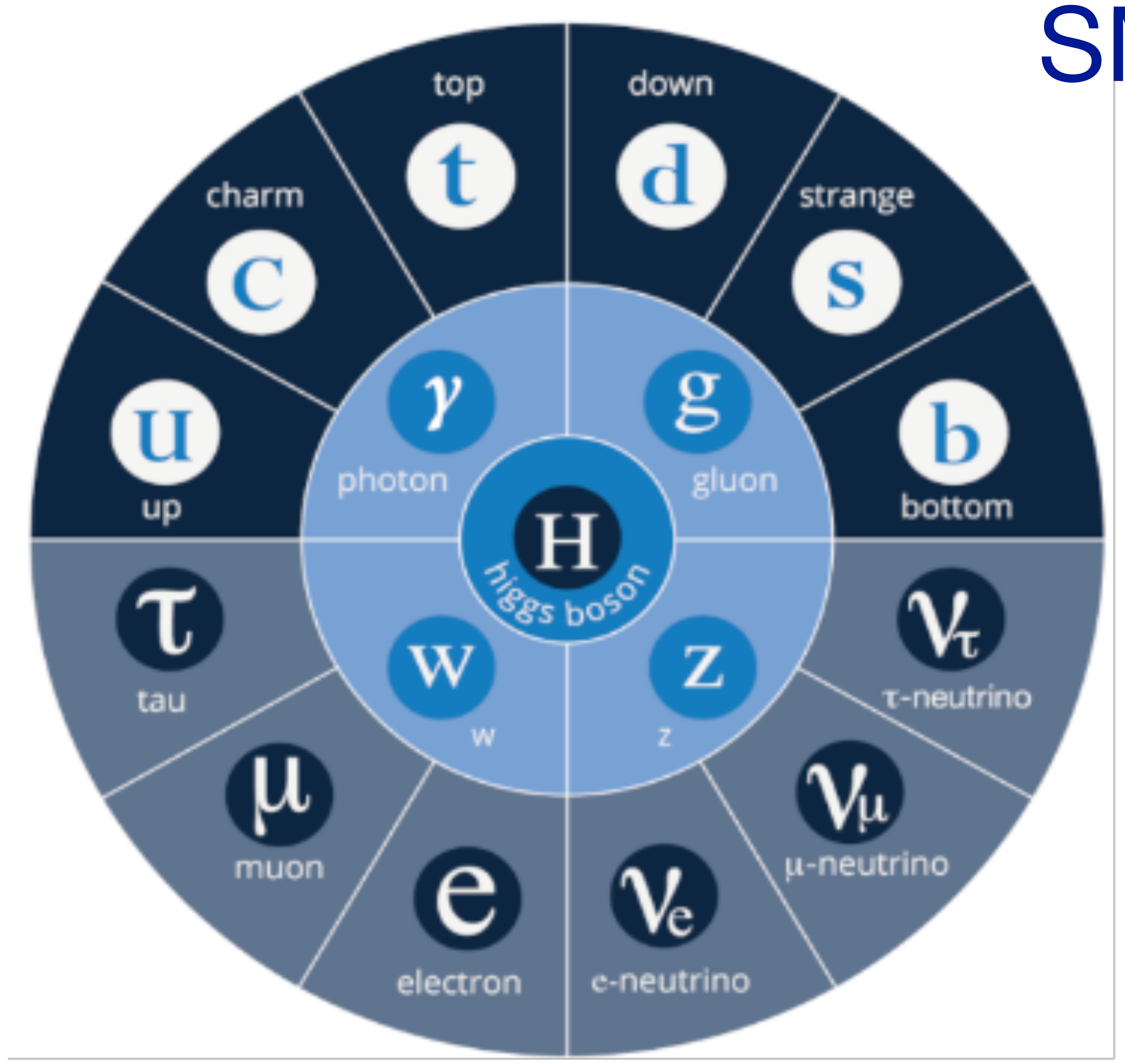
self-interactions

complexity



SM-DM interactions

SM



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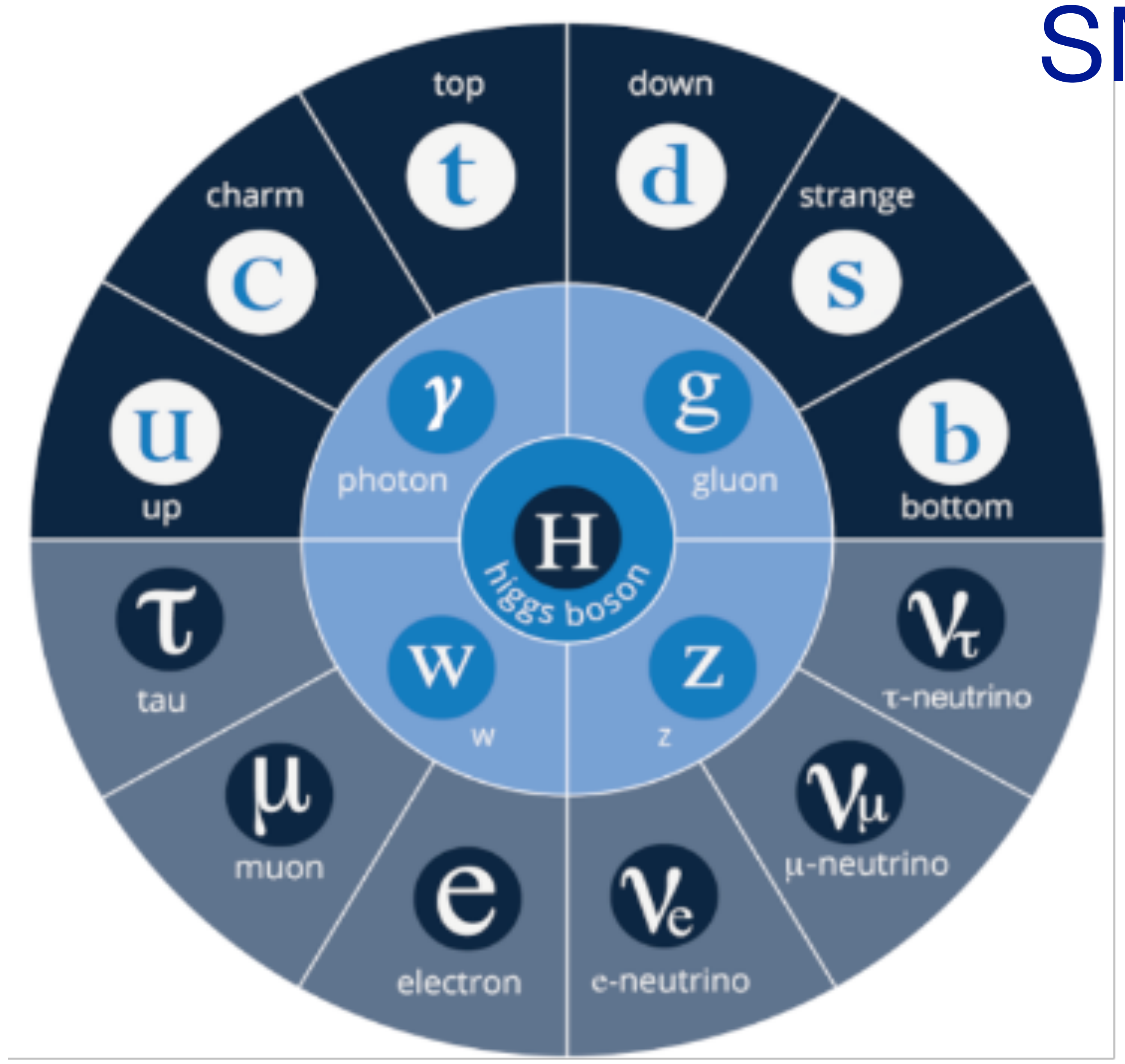

On top this, there are wishful properties (‘miracles’)

1. does it help in astrophysical observation?
2. is it ‘naturally’ produced in the early Universe?
3. is it theoretically motivated by other ‘principles’/theory concerns?
4. can we detect it in the laboratory?
5. can we single it out in astrophysical data?

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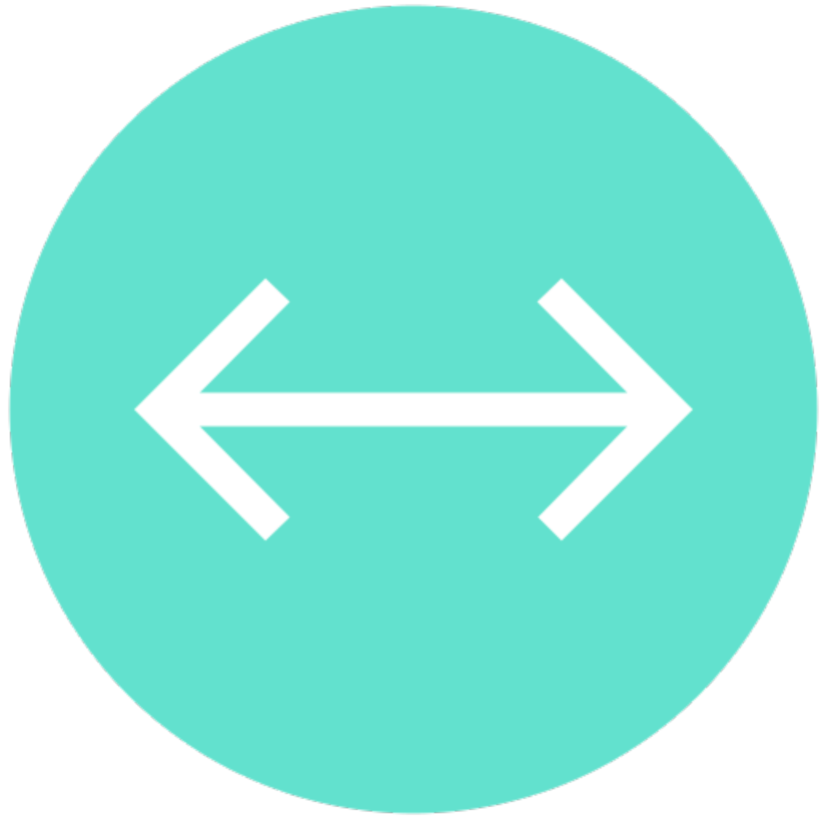

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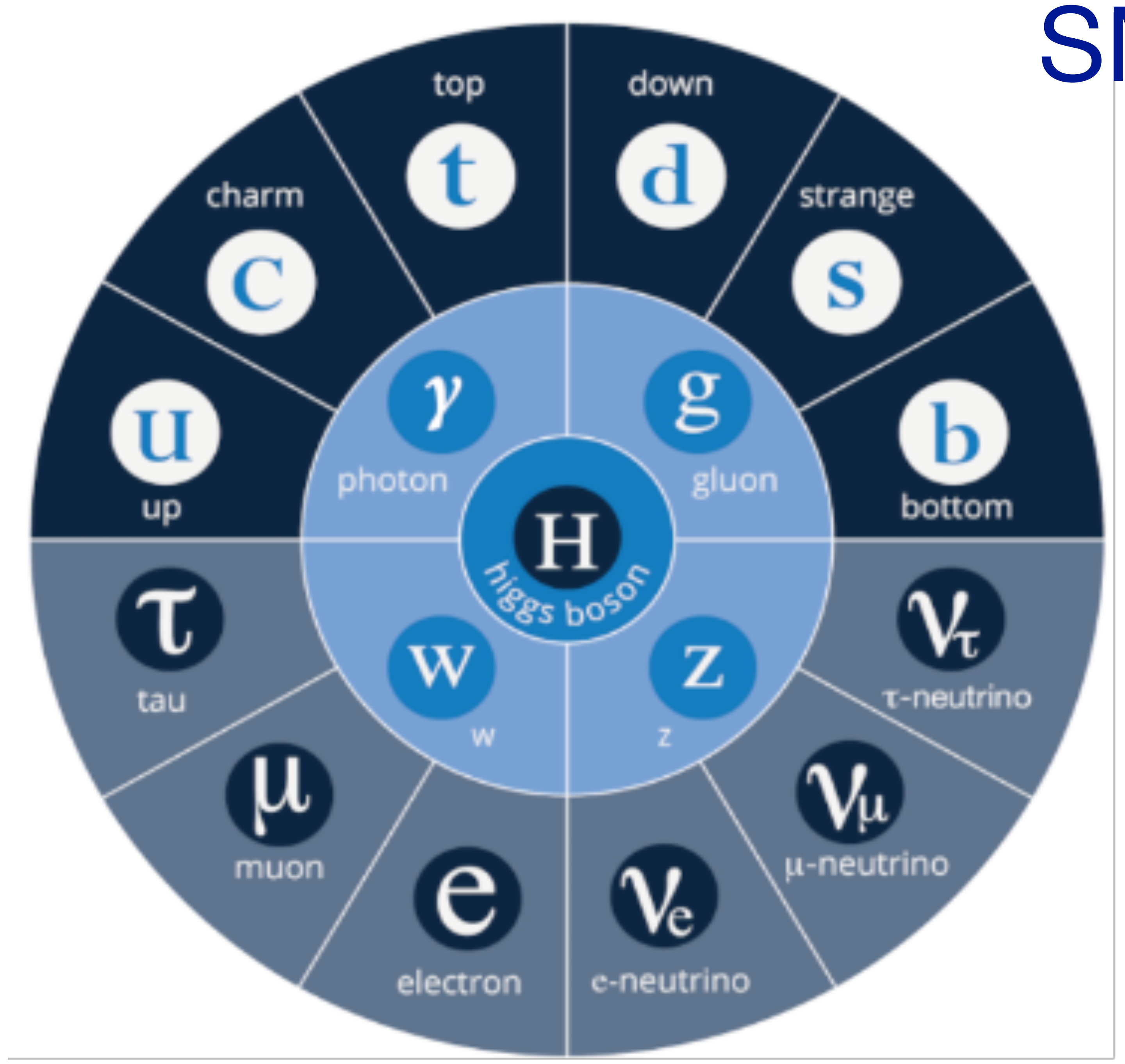

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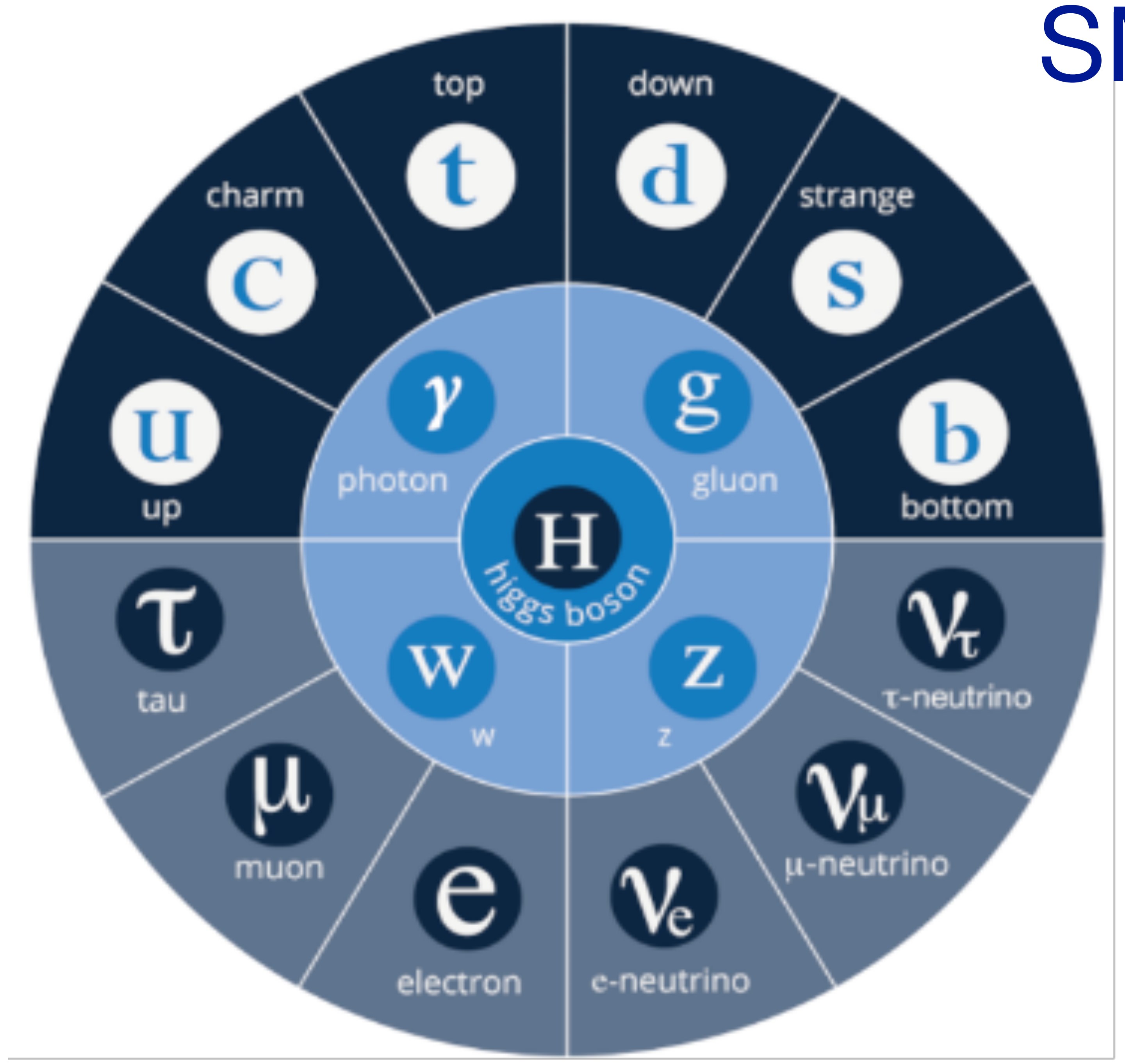

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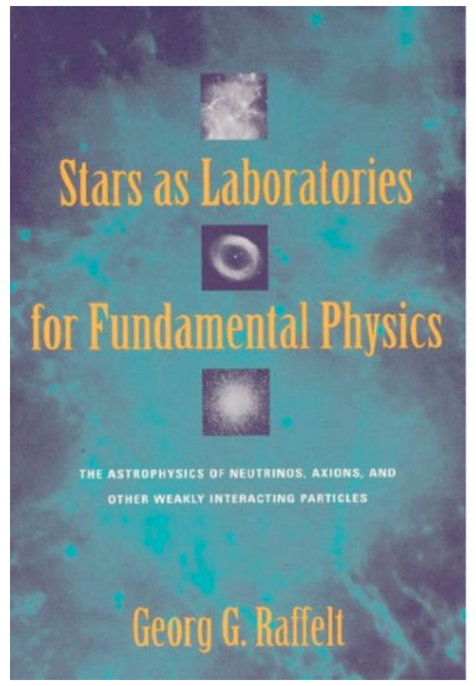

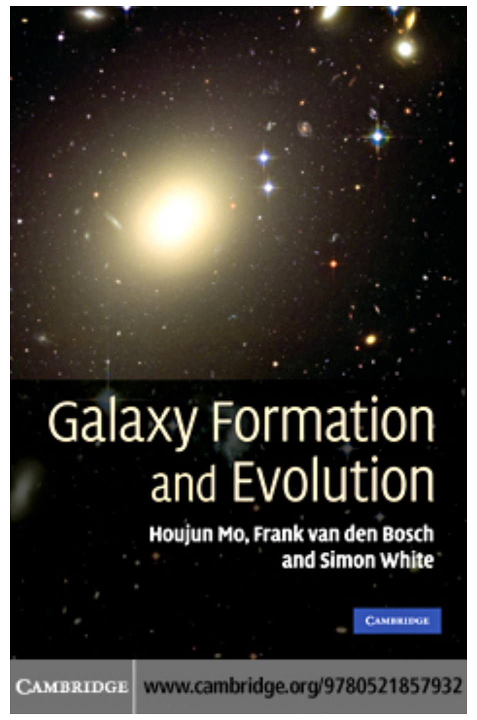

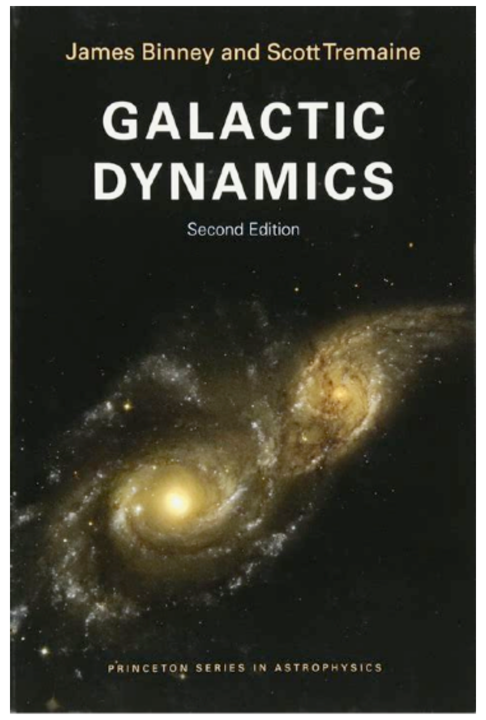

‘Try to extend the diversity
of DM models
to astrophysical modelling’

What can we look for

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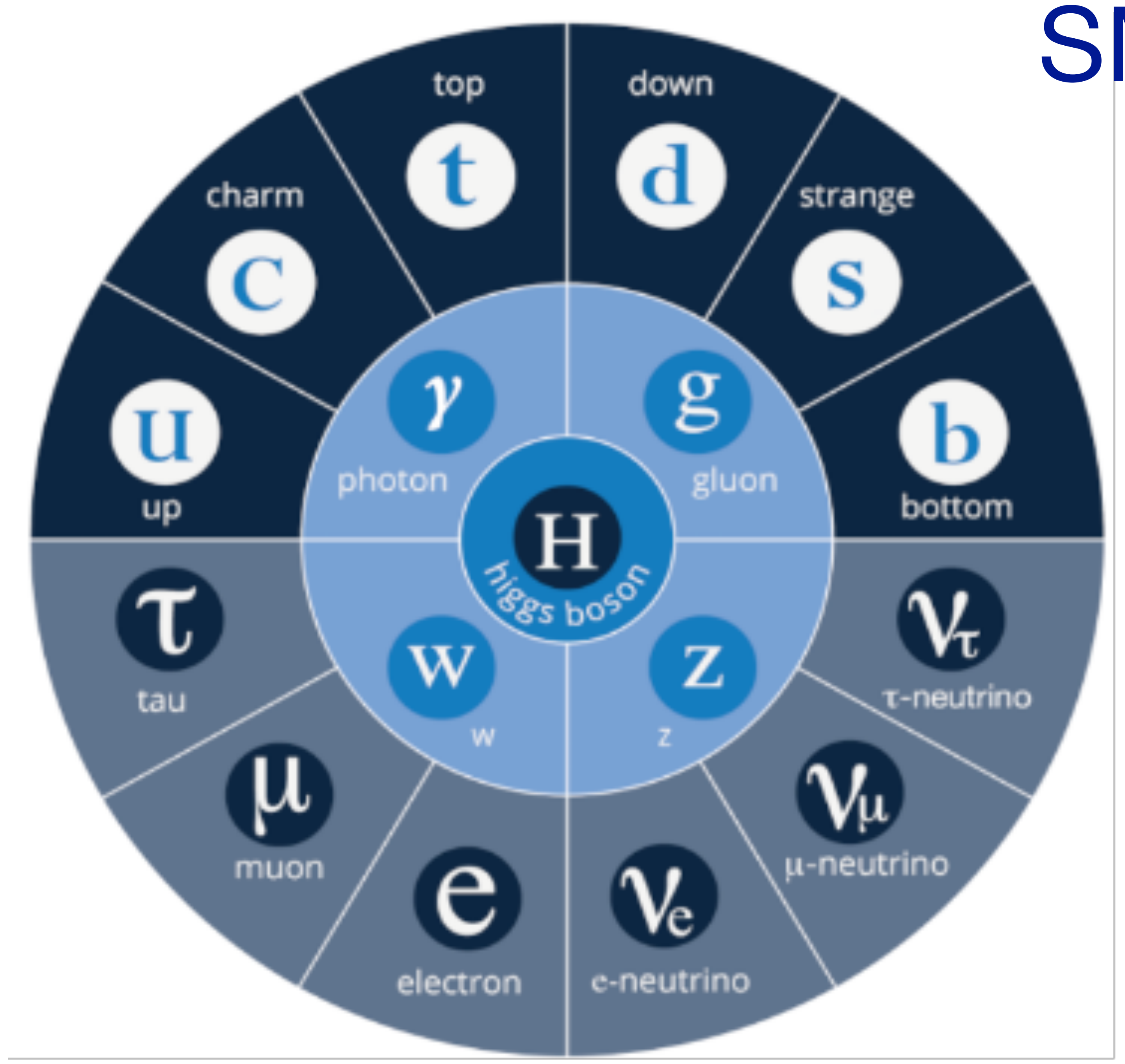

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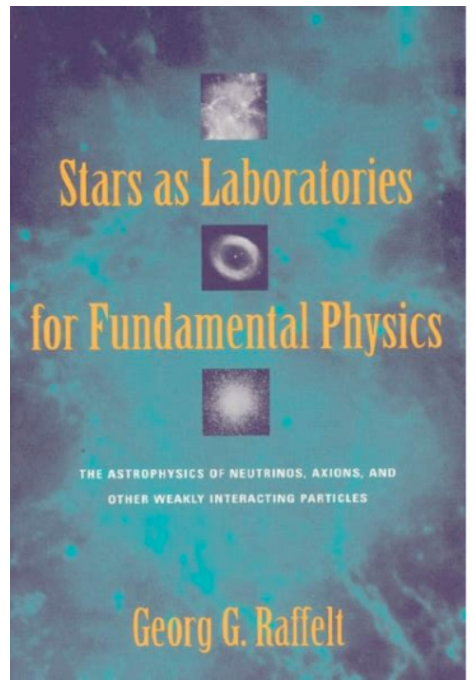
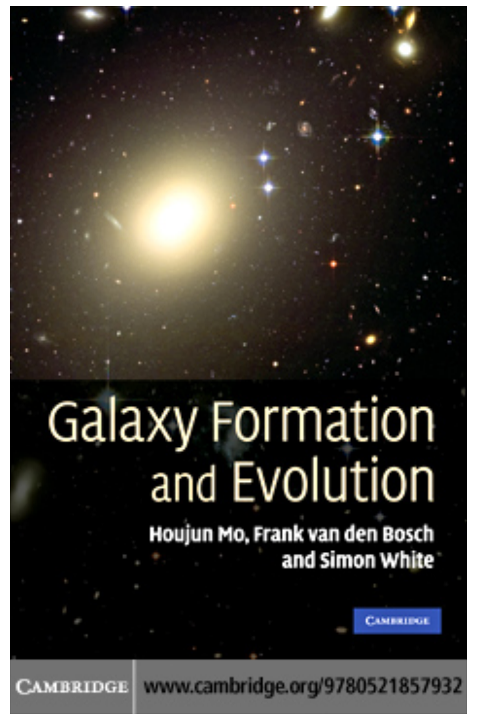
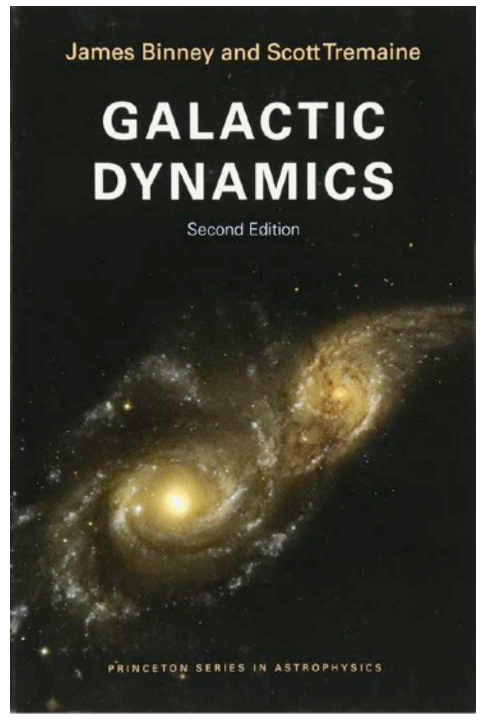
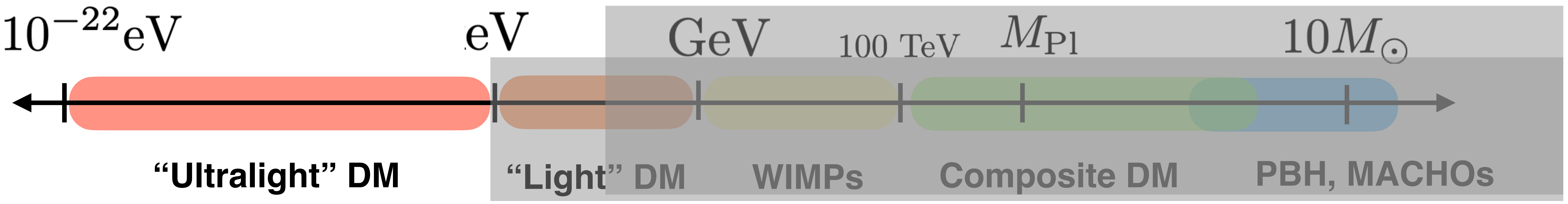






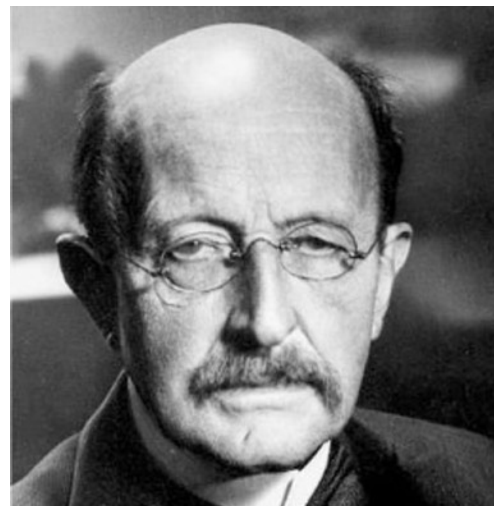
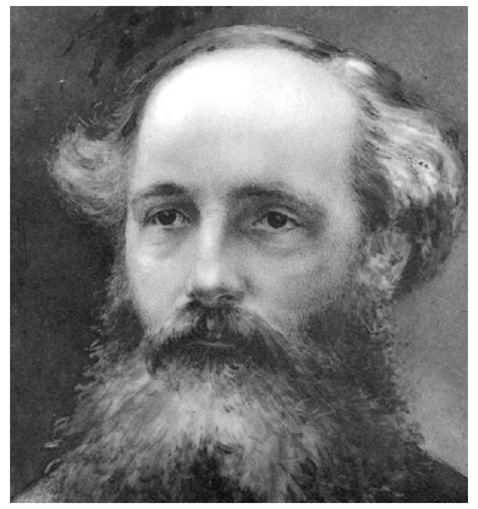
‘Try to extend the diversity of DM models to astrophysical modelling’

2 natural barriers: ULDM and Tremaine-Gunn



(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)

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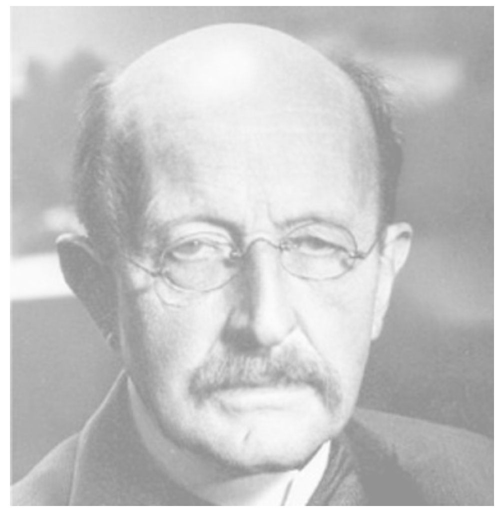
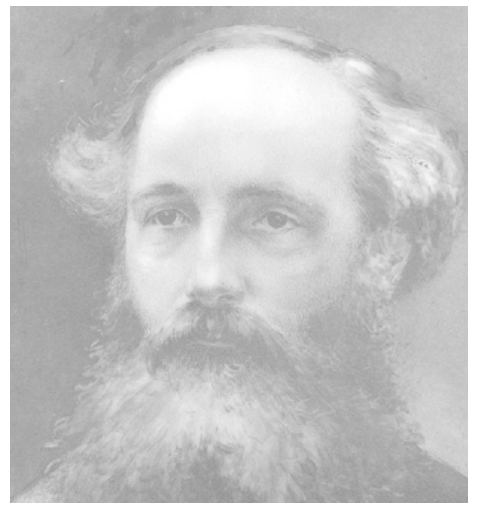
$\hbar\omega$    $F_{\mu\nu}$

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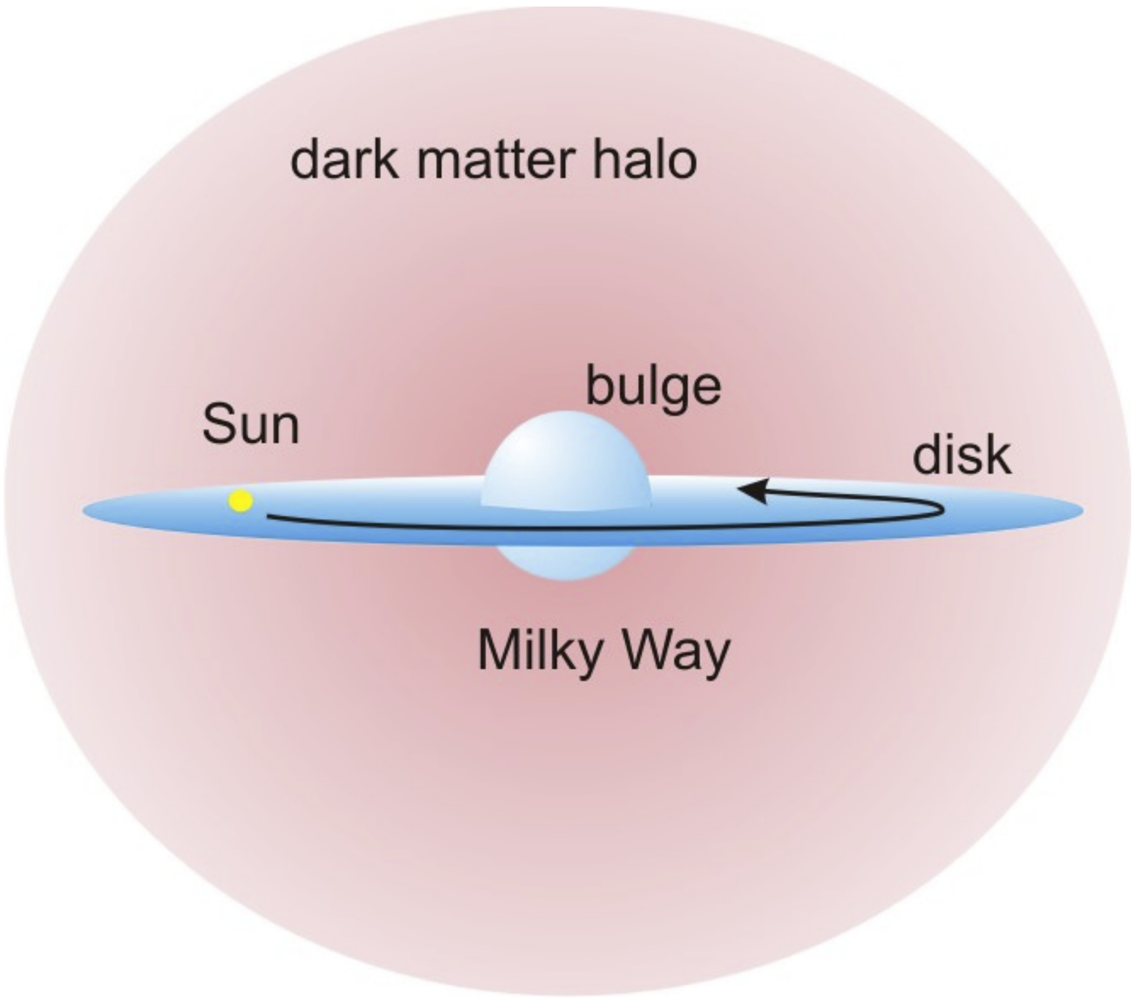

$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu \phi)^2 - m^2\phi^2\right] \quad + \text{ gravity}$$

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

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

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

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

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

pure CDM part

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

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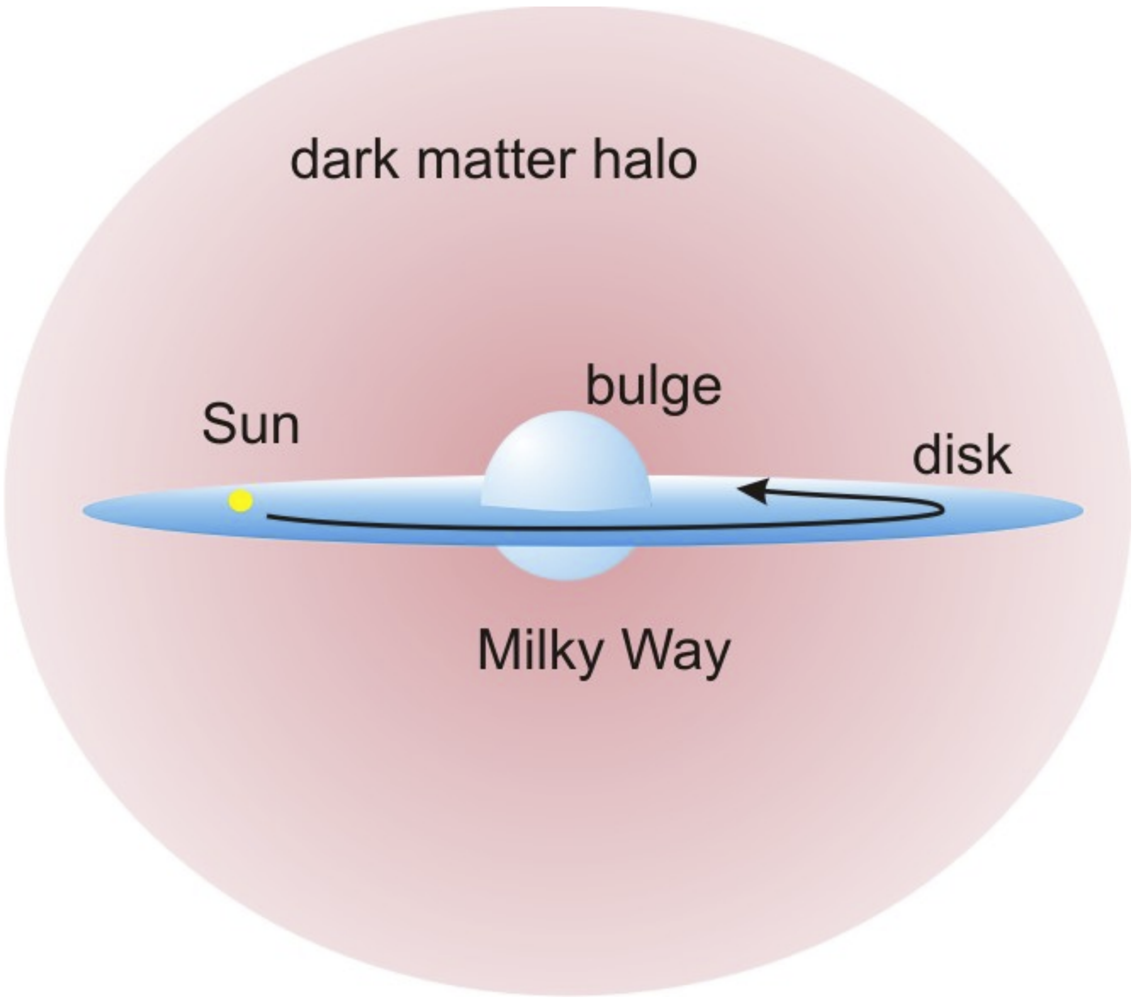

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A) coherent oscillations +
B) stochastic 'narrow' piece

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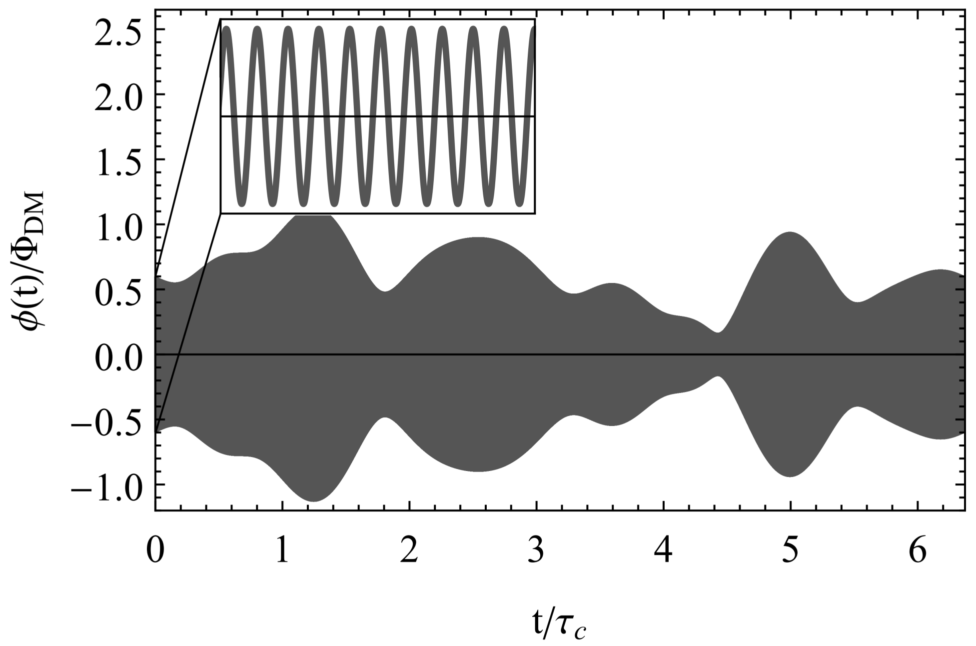
C) changes dynamics at smaller scales $\frac{10^{-3}}{v}$kpc

New phenomenology from ULDM

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

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

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

SM-DM interactions

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

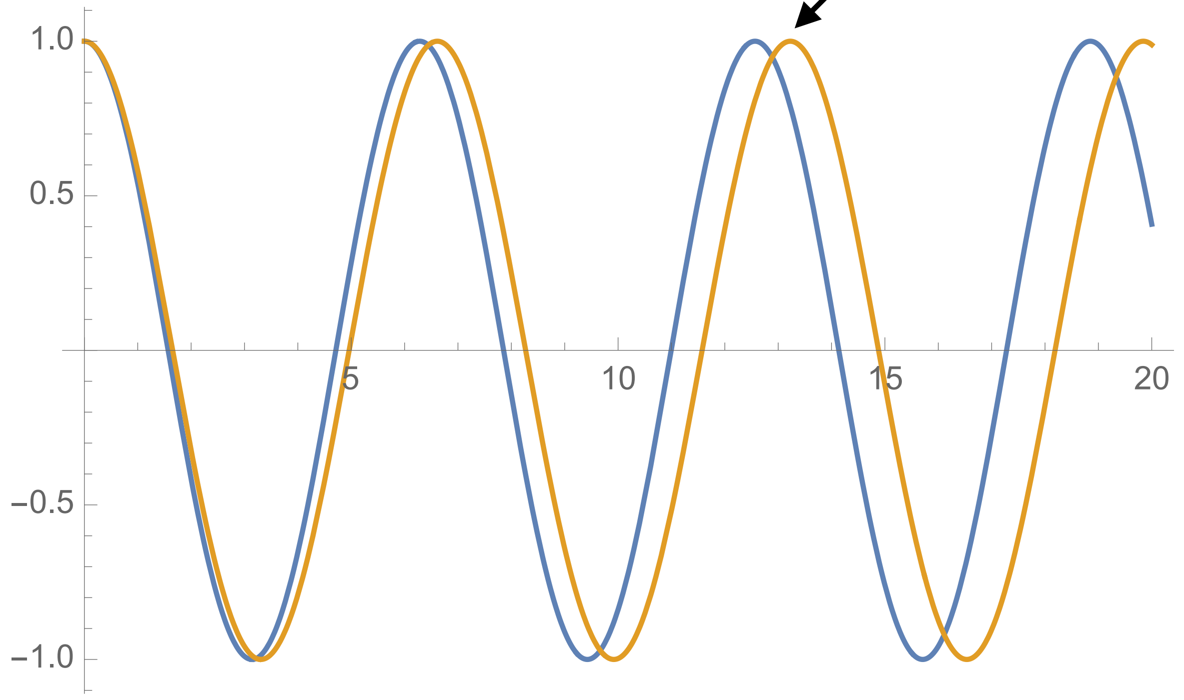
$$m_{\mathrm{SM}}\phi\,\psi_{\mathrm{SM}}^2$$

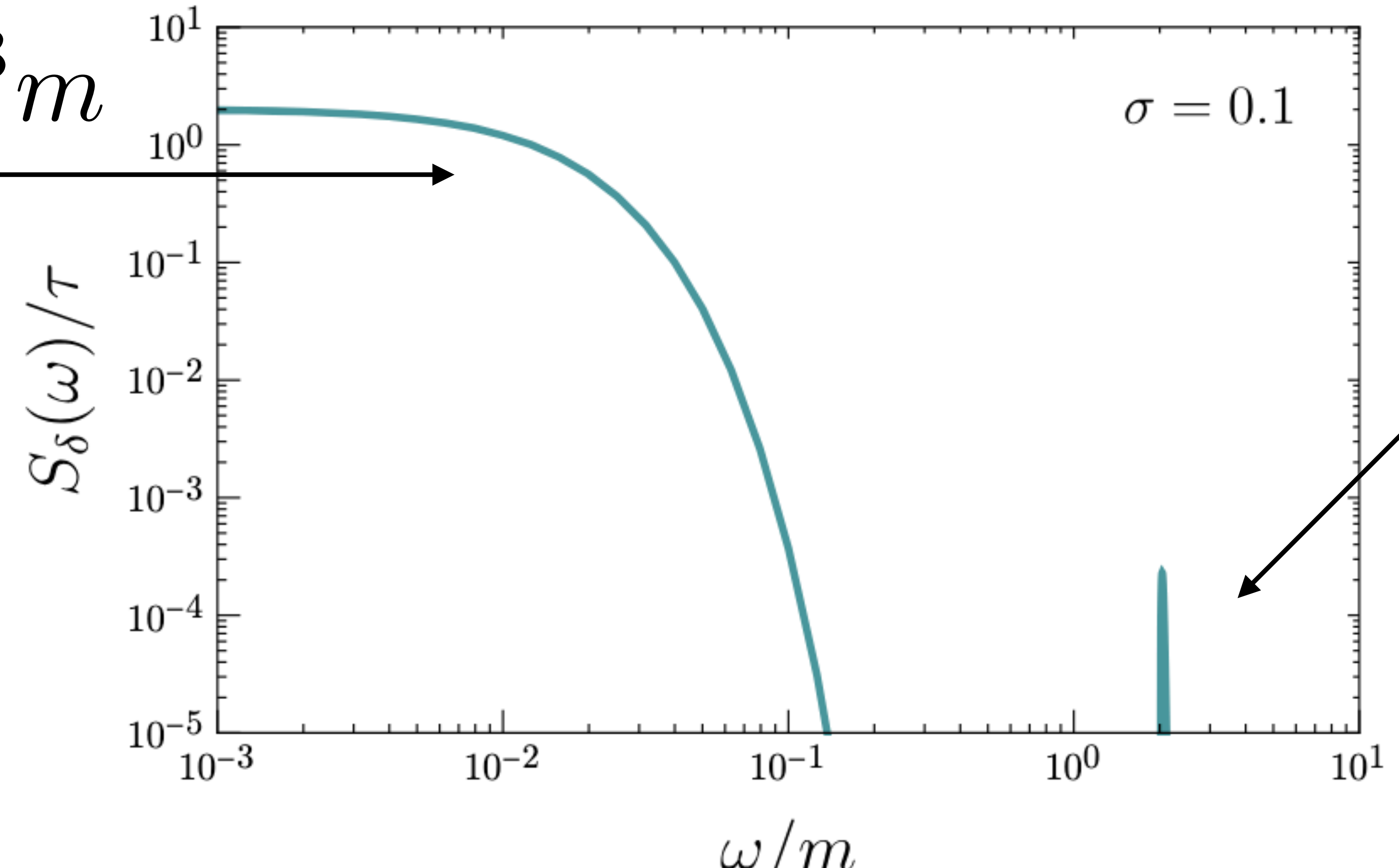
B) stochastic 'narrow' piece

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

Kim 2306.13348
Ban-Or et lal 19

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





these fluctuations heat, decorrelate (interf), friction

$$\omega = 2m$$

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

New phenomenology from ULDM

DM small scale dynamics

C) changes dynamics at smaller scales

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

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gravitational potential

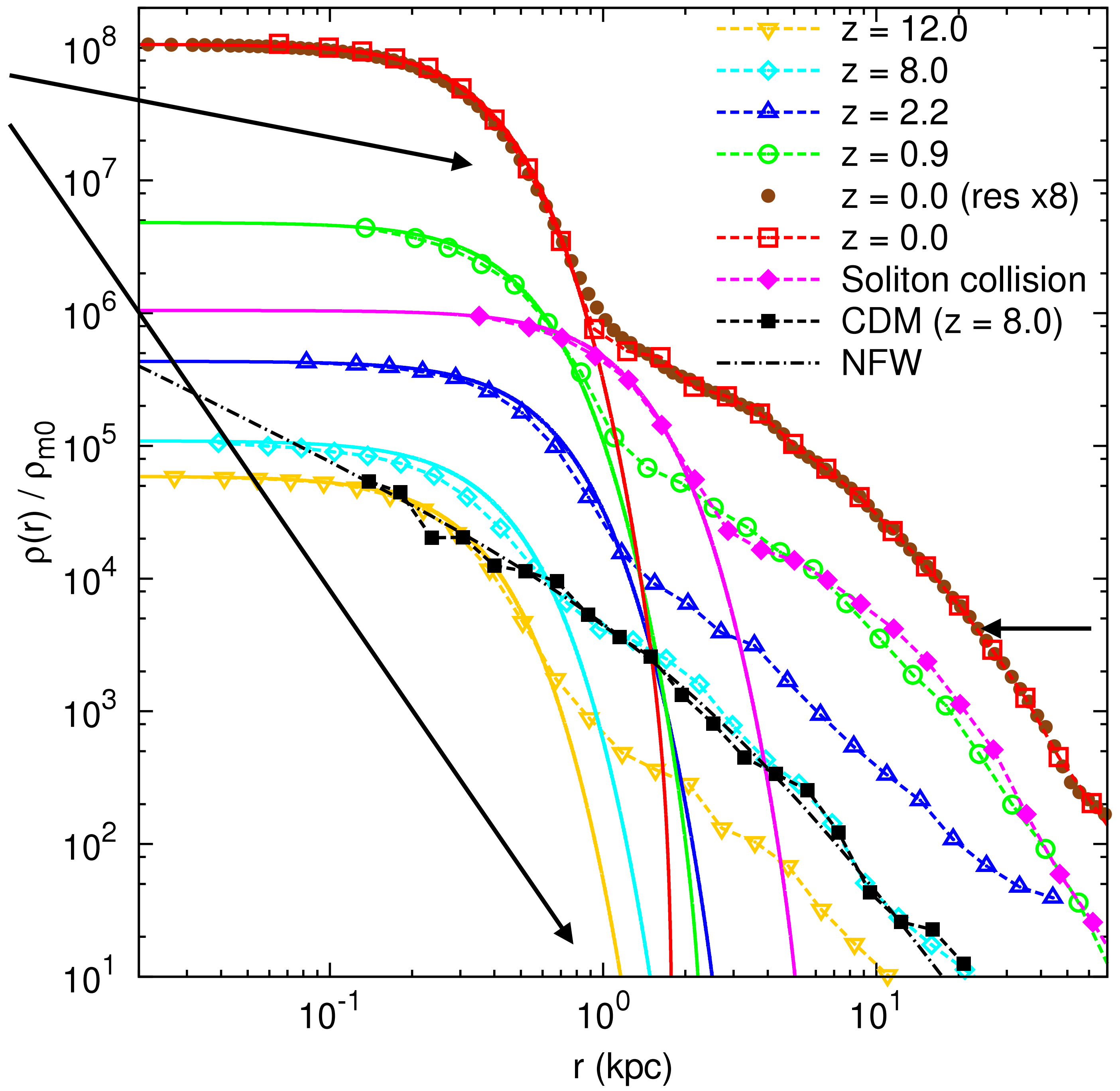
pure CDM part

repulsive term

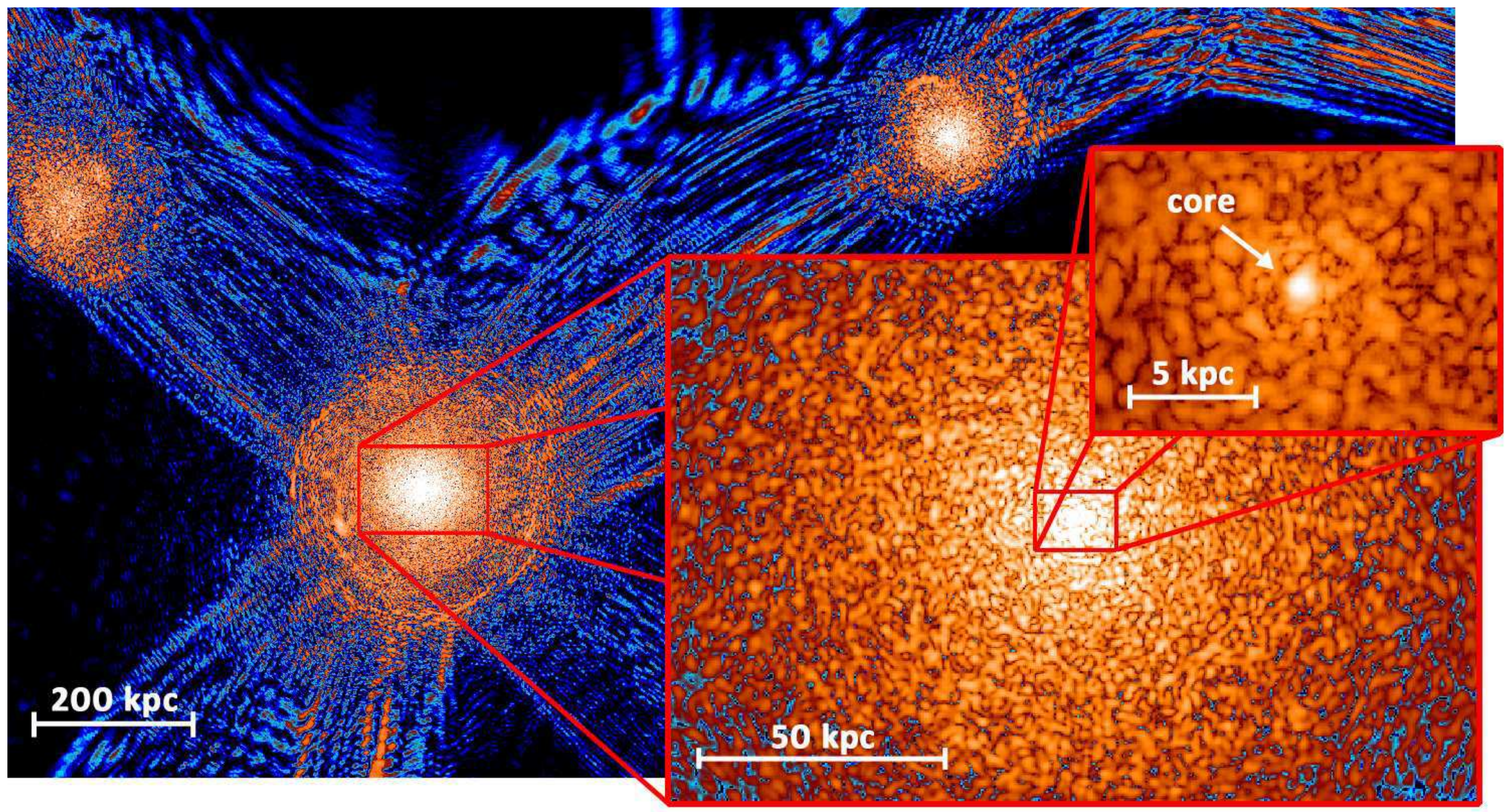
$$\phi(x,t) = \frac{M_{pl}}{2\sqrt{2\pi}}e^{-imt}e^{-i\gamma t}\chi(x) + h.c.$$

Schive et al.1407.7762

soliton



halo



New phenomenology from ULDM: 3 examples

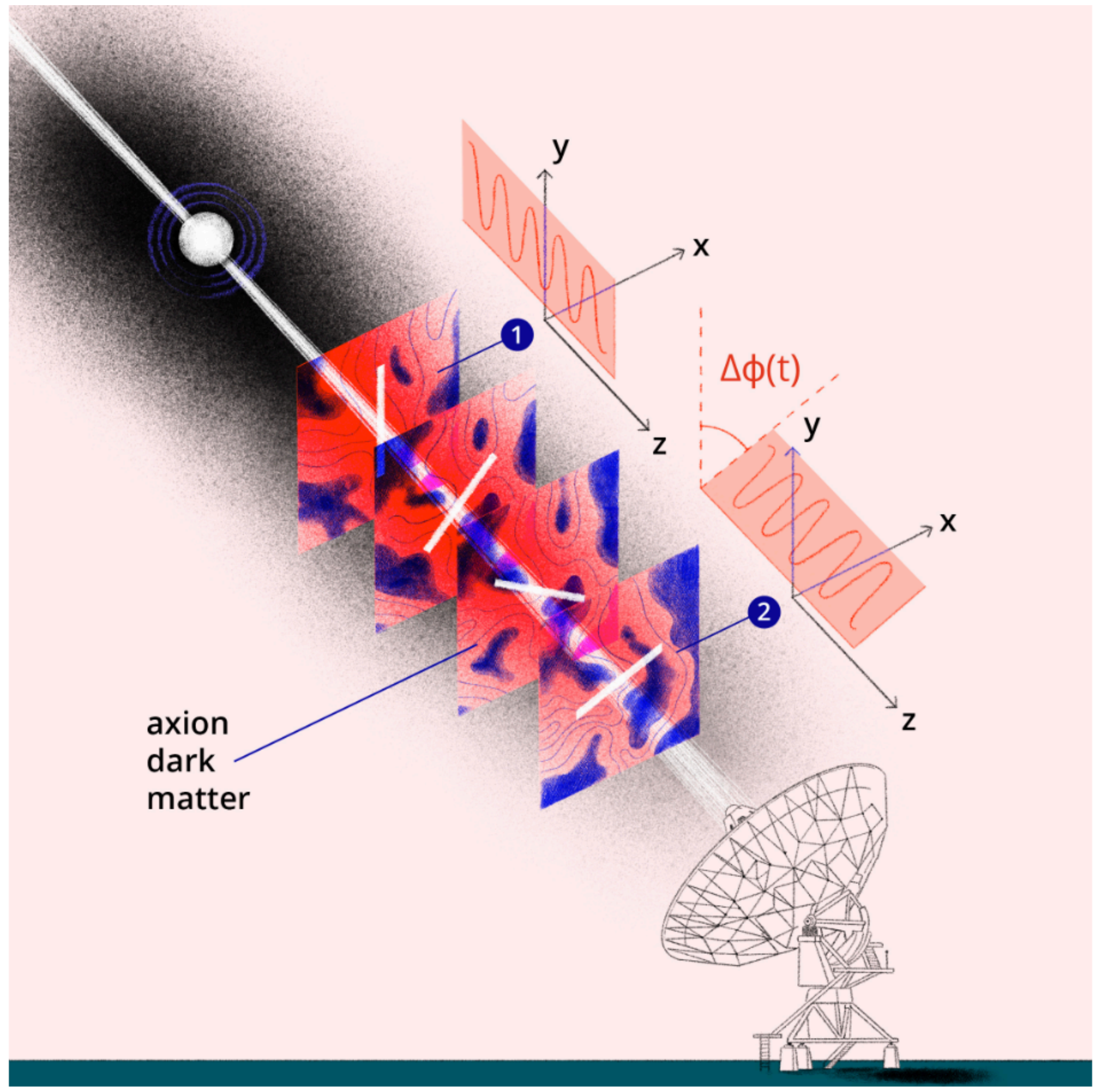
A) coherent oscillations

$$\mathcal{L} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{g_{a\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\left(\partial_\mu a \partial^\mu a - m_a^2 a^2\right)$$

Searching for dark-matter waves with PPTA and QUIJOTE pulsar polarimetry

Andrés Castillo (Laguna U., Tenerife), Jorge Martin-Camalich (Laguna U., Tenerife), Jorge Terol-Calvo (Laguna U., Tenerife), Diego Blas (Barcelona, Autonoma U. and Barcelona, IFAE), Andrea Caputo (Tel Aviv U. and Weizmann Inst.) et al. (Jan 10, 2022)

$$a = a_0 \cos(mt + \psi_0)$$



Huge landscape of possibilities

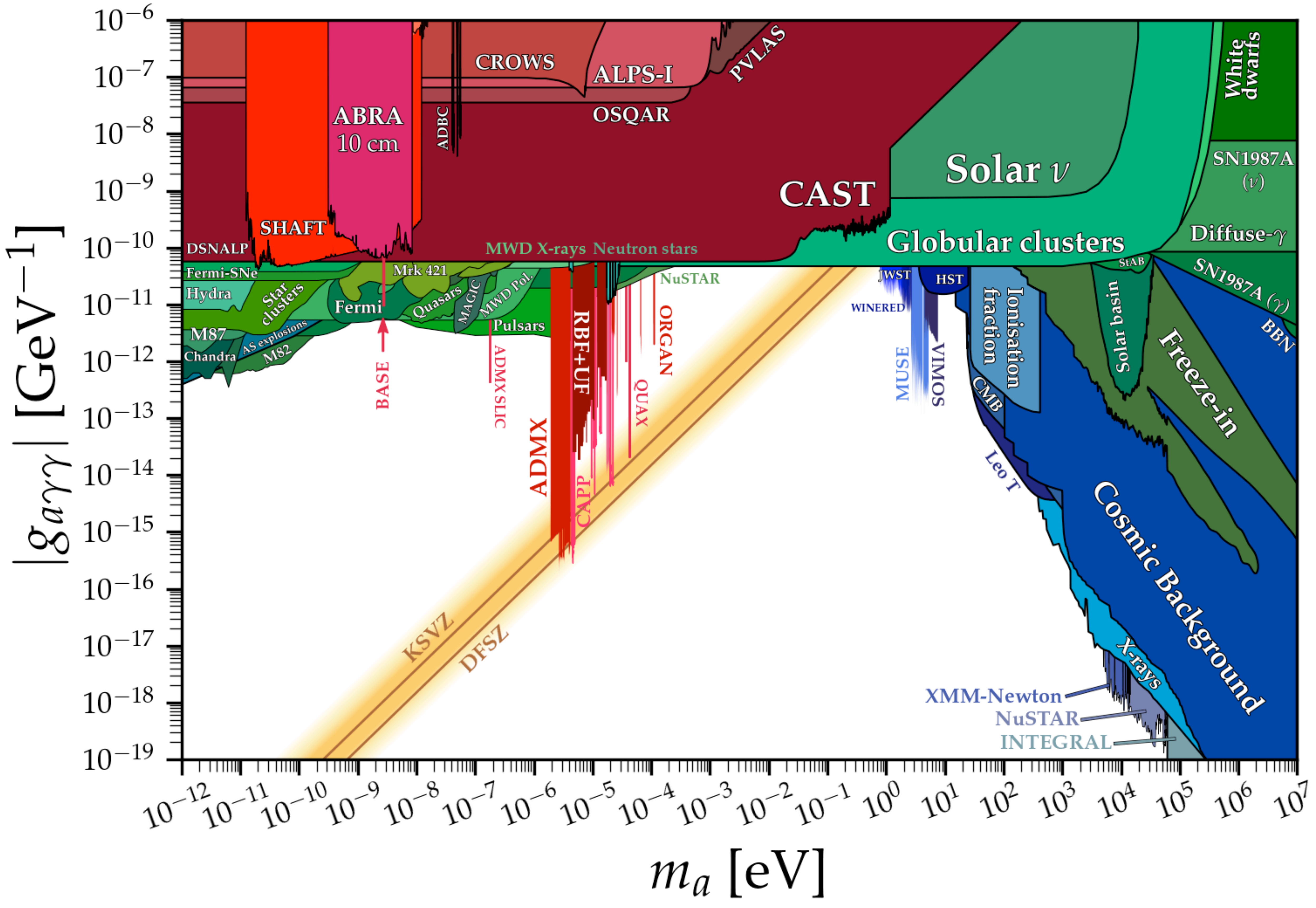
$$\mathcal{L}_{\rm int} = \frac{\phi}{\sqrt{2}}\left(\frac{d_e}{4\mu_0}F_{\mu\nu}F^{\mu v} - \frac{d_g\beta_3}{2g_3}G^a_{\mu\nu}G^{a\mu v} - \sum_{i=e,u,d}\left(d_{m_i} + \gamma_{m_i}d_g\right)m_i\bar{\psi}_i\psi_i\right),$$

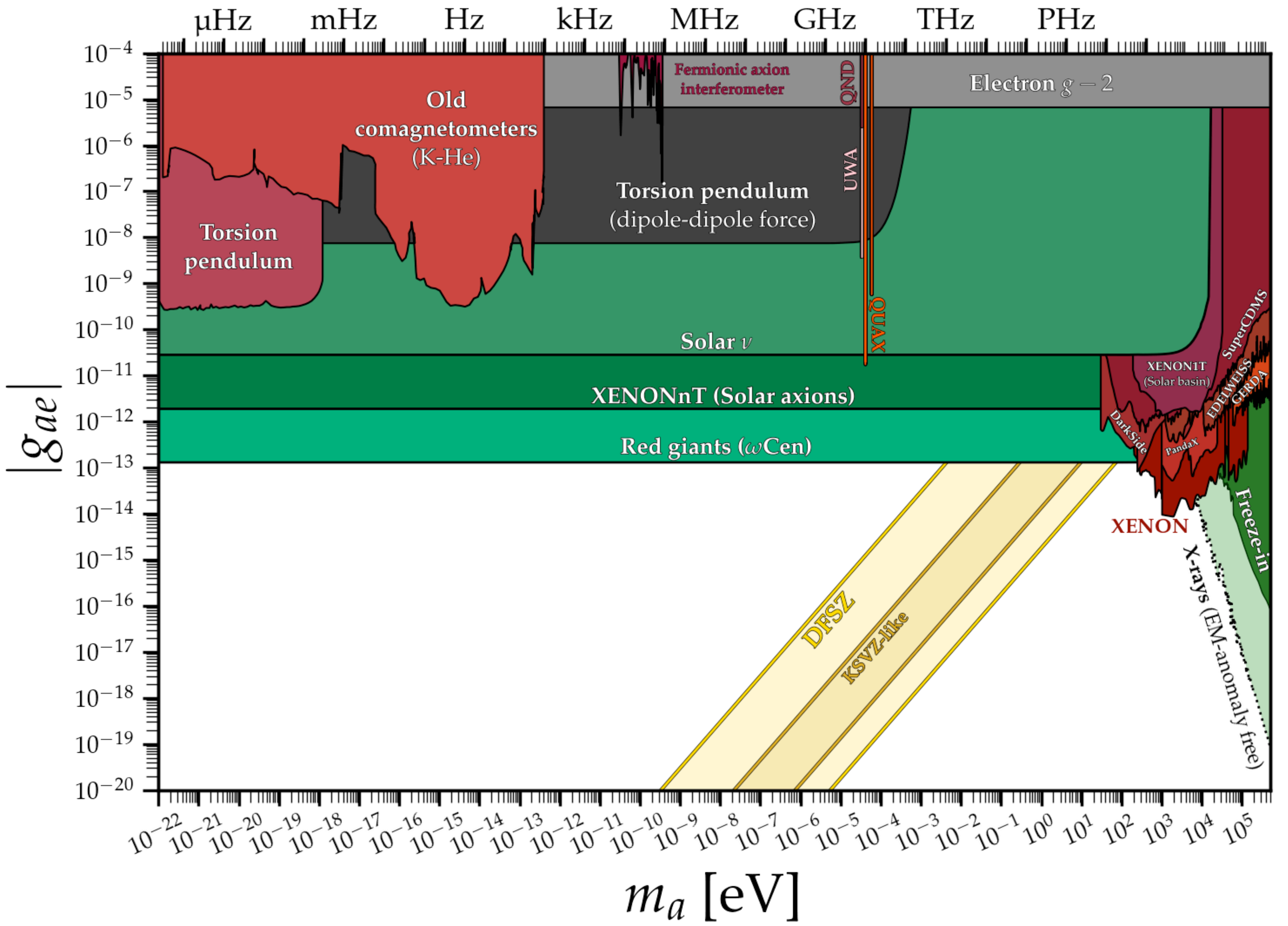
New phenomenology from ULDM: 3 examples

A) coherent oscillations

https://cajohare.github.io/AxionLimits/

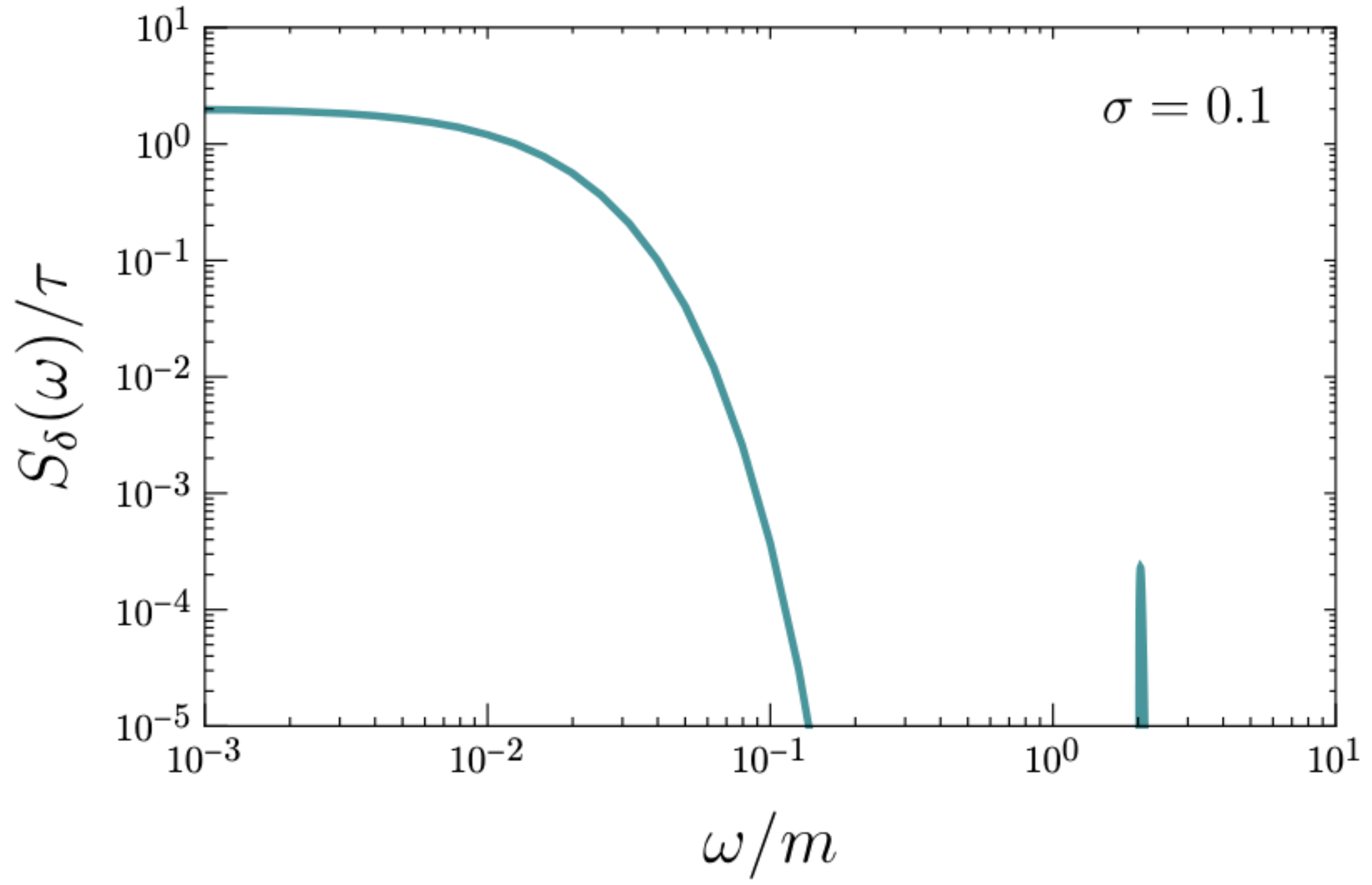
Huge landscape of possibilities





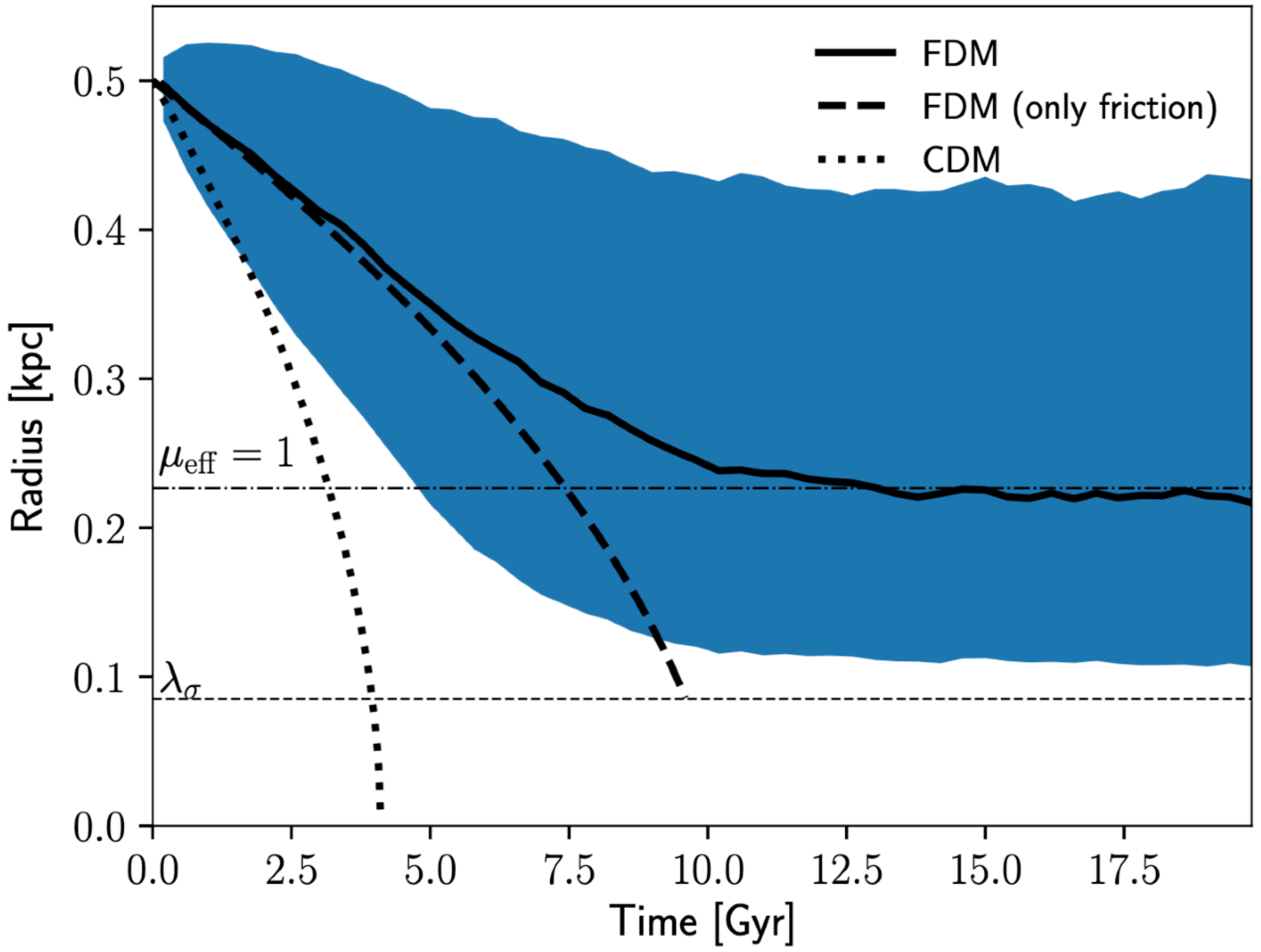
New phenomenology from ULDM: 3 examples

B) stochastic 'narrow' piece



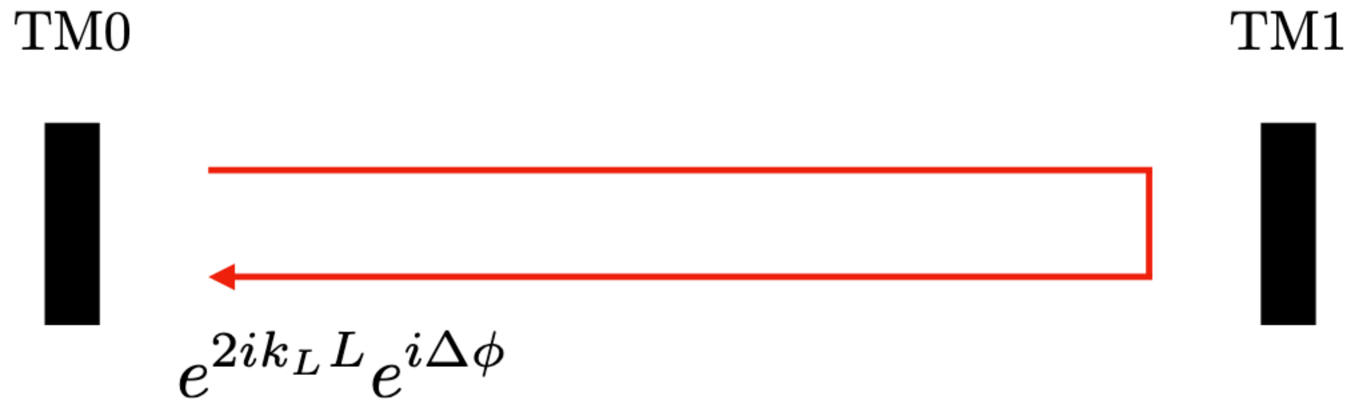
Bar-Or et al 1809.07673

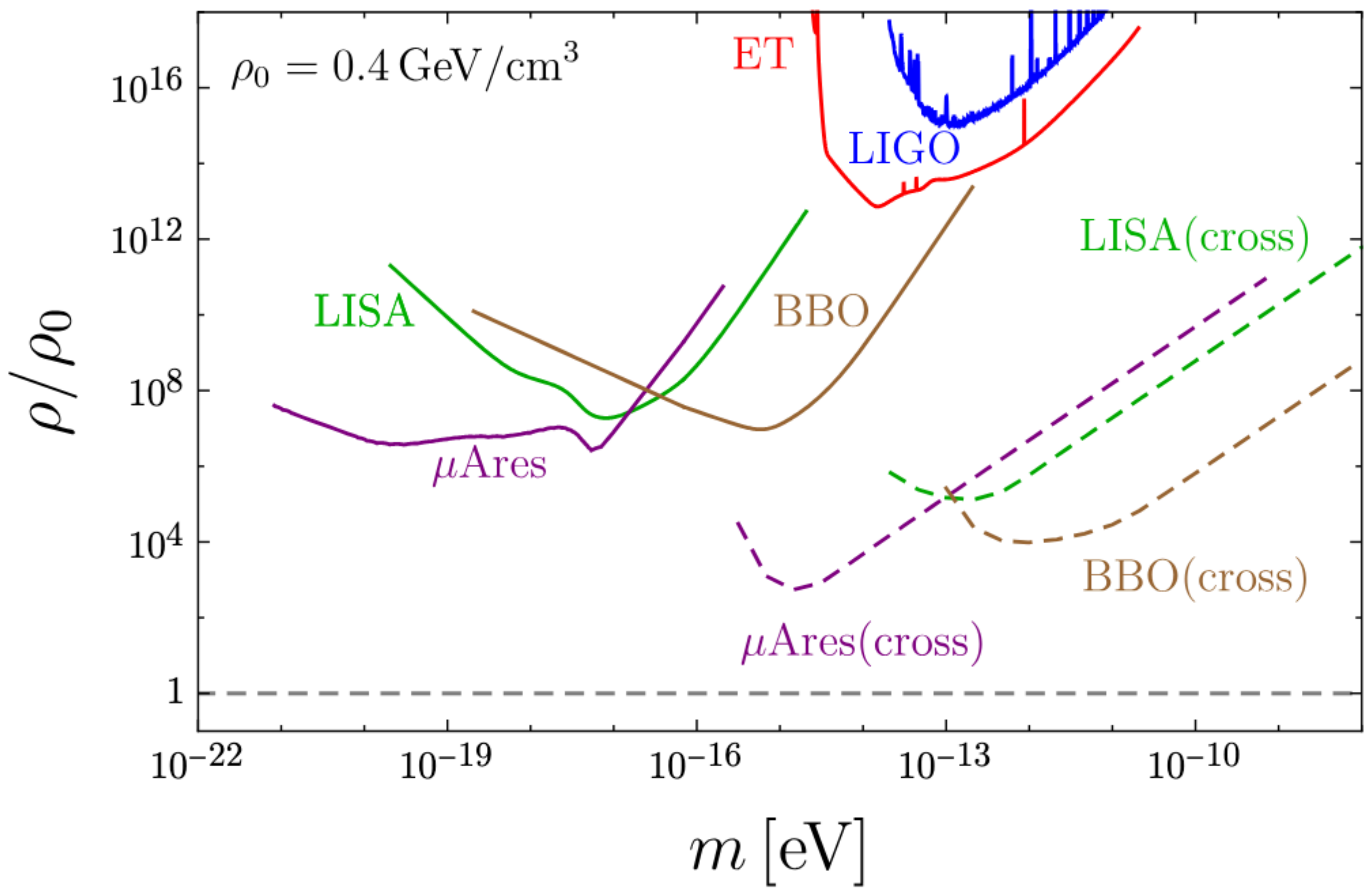
Stalling of dynamical friction



Kim 2306.13348

Impact on interferometers

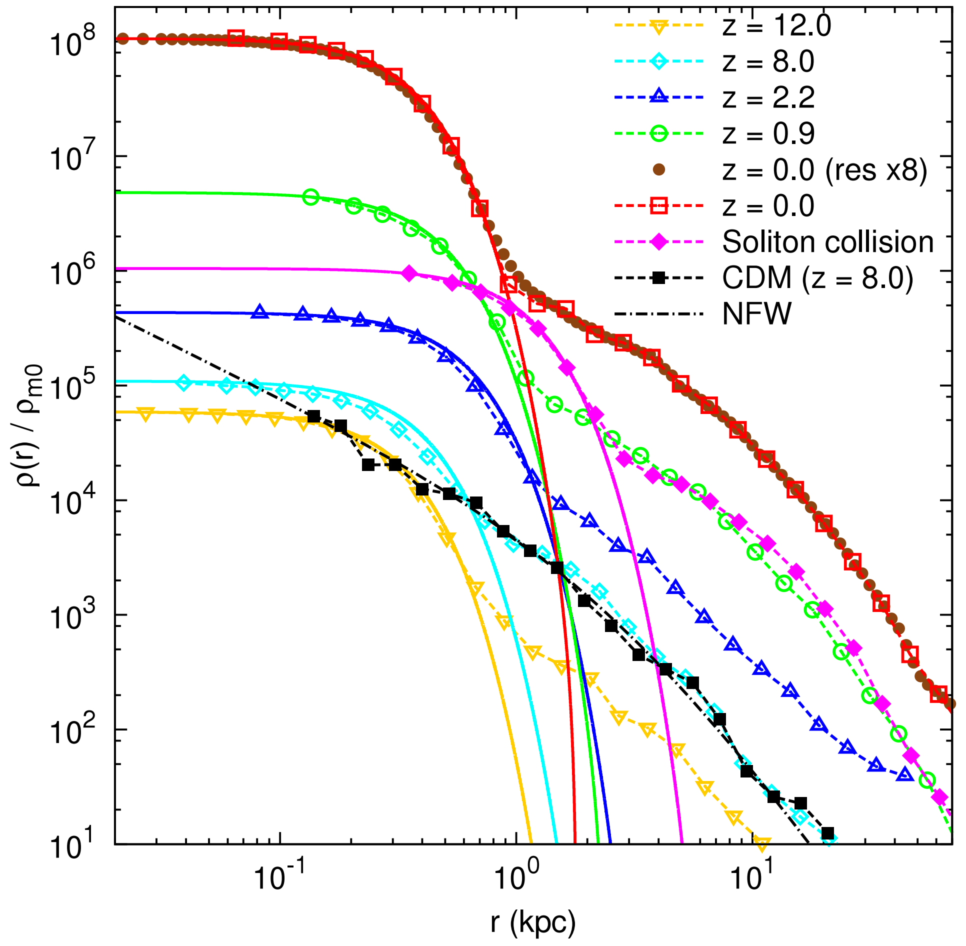


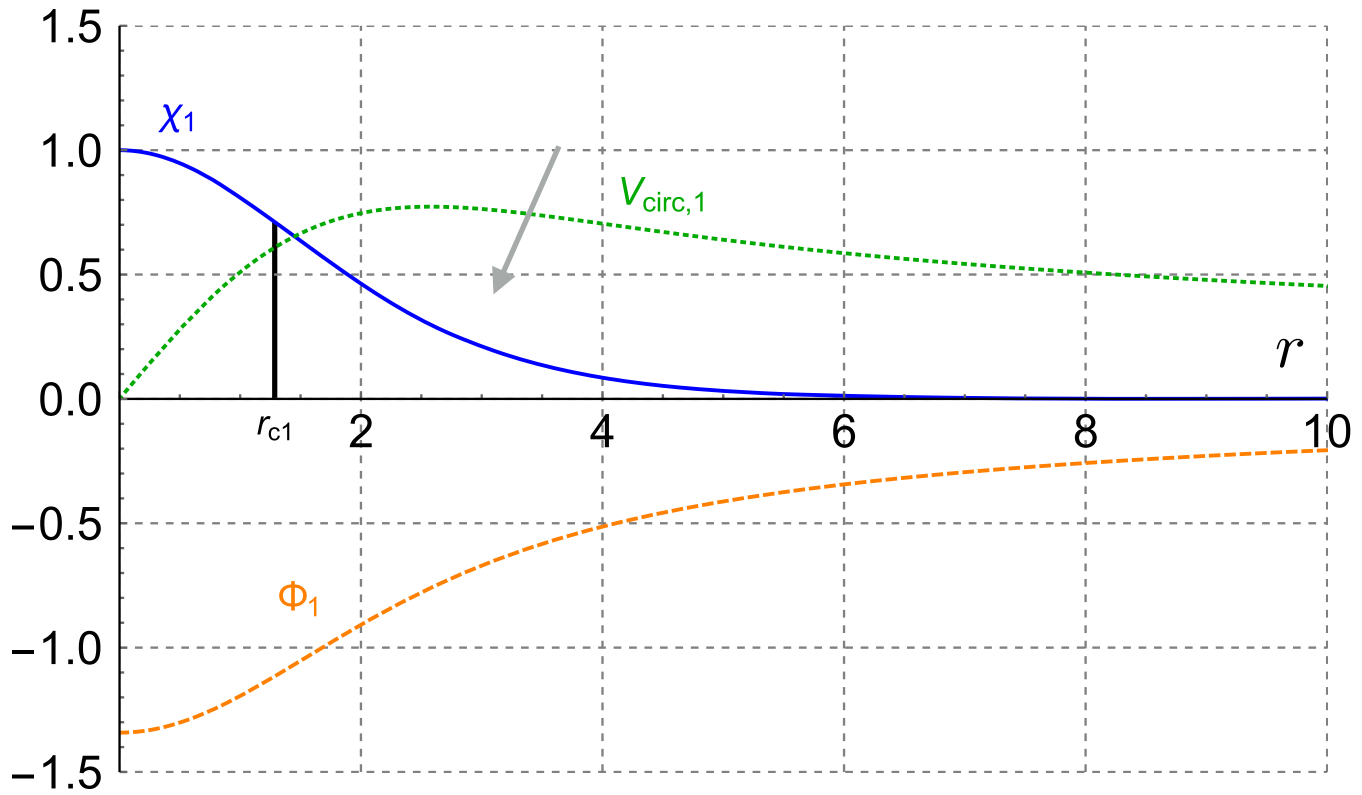


New phenomenology from ULDM: 3 examples

C) changes dynamics at smaller scales

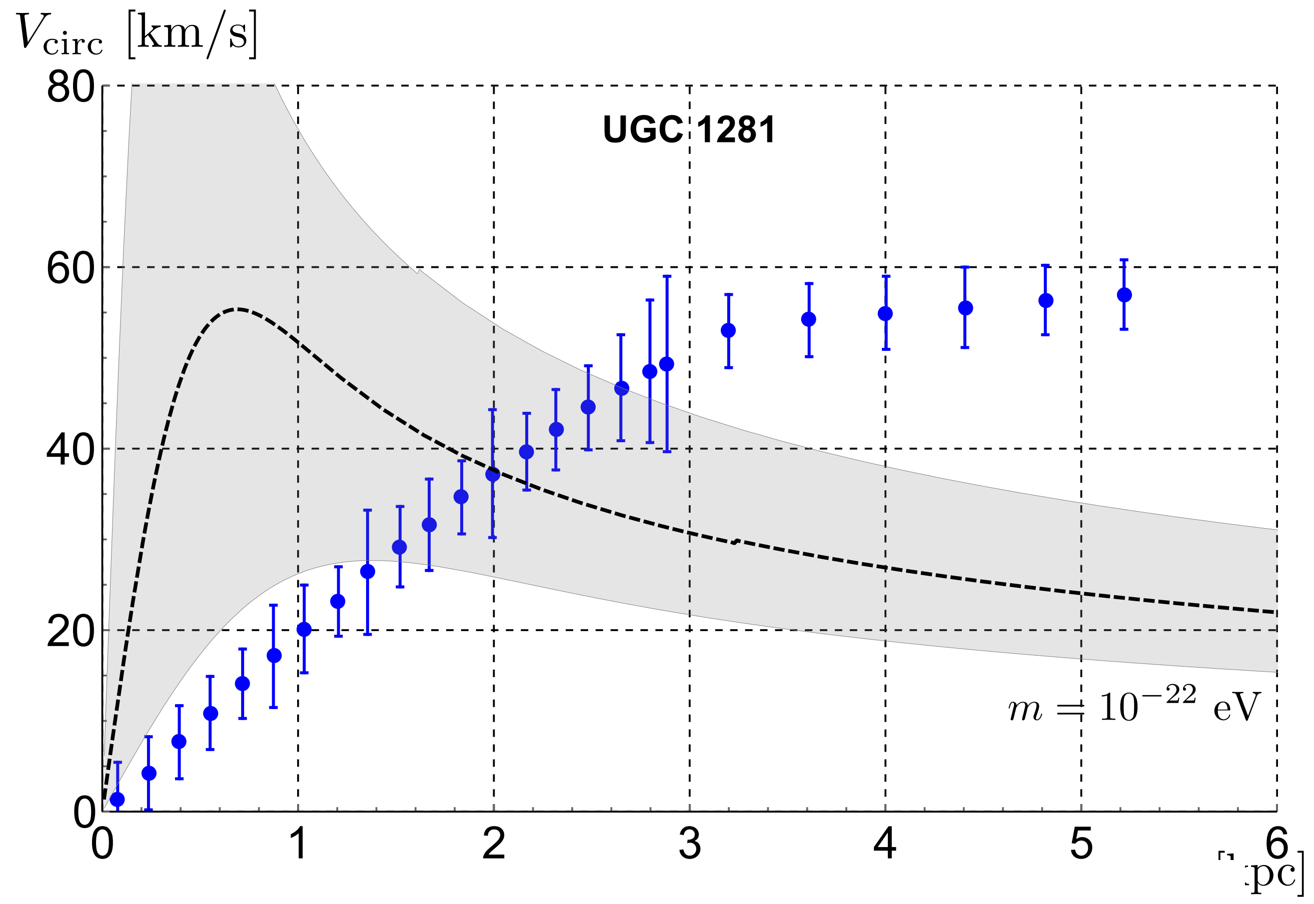
Velocity curves in the presence of solitons





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

Bar, DB, Blum, Sibiryakov 1805.00122



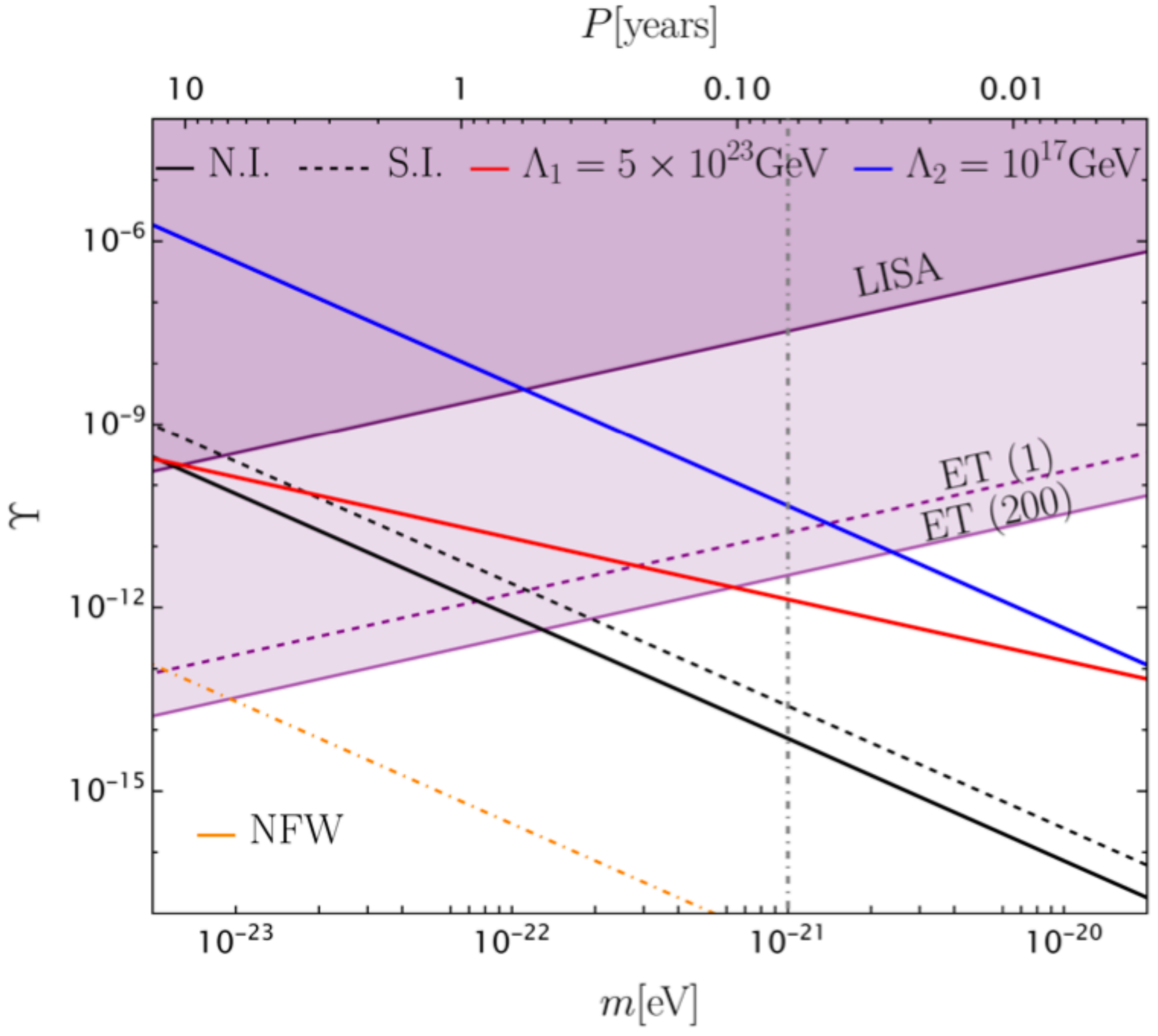
Modulation of signals of known spectrum

Time depending gravitational redshift

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

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

Sources at the center include **LISA** binaries!



DB, Gasparotto, Vicente 24

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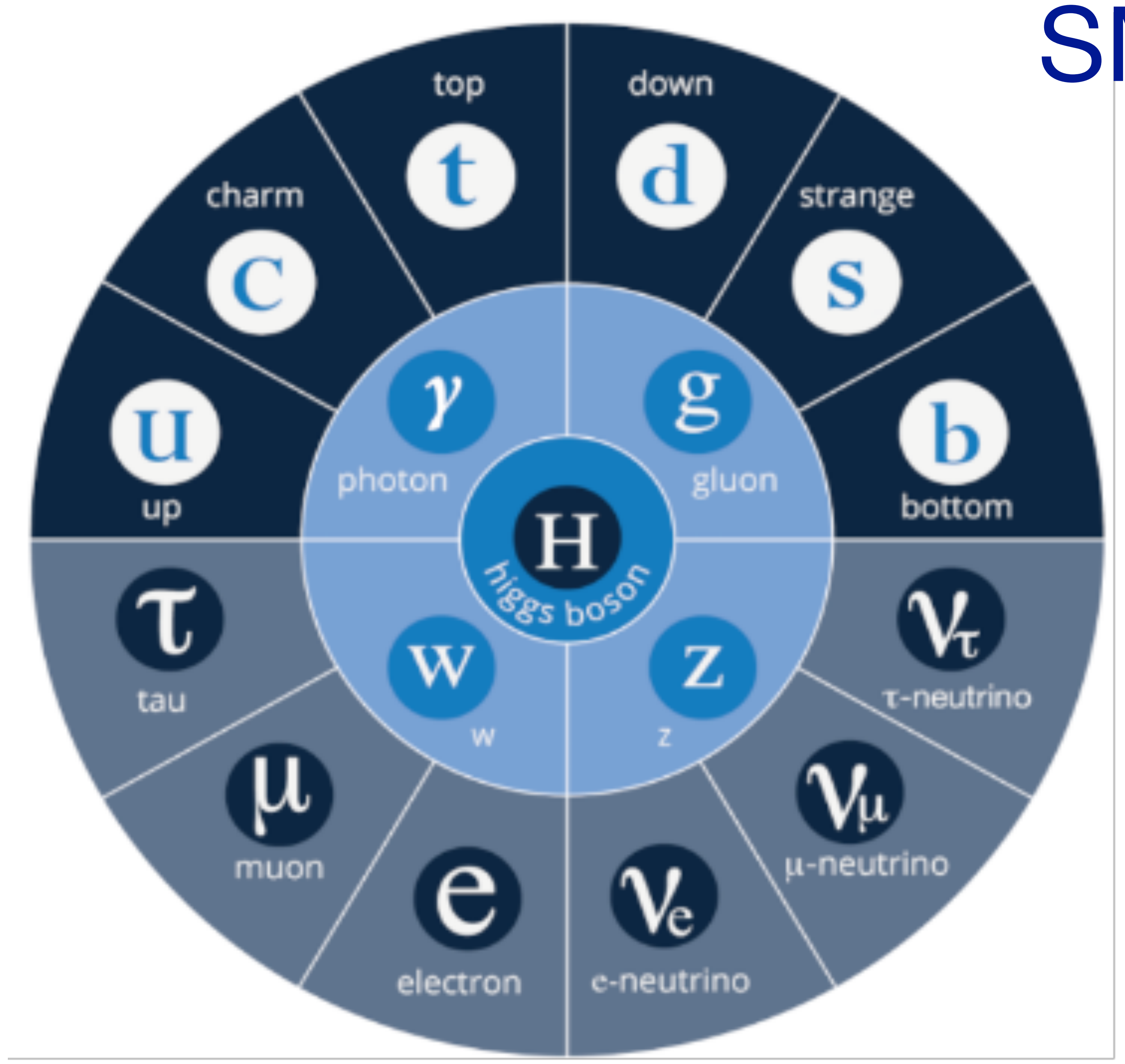

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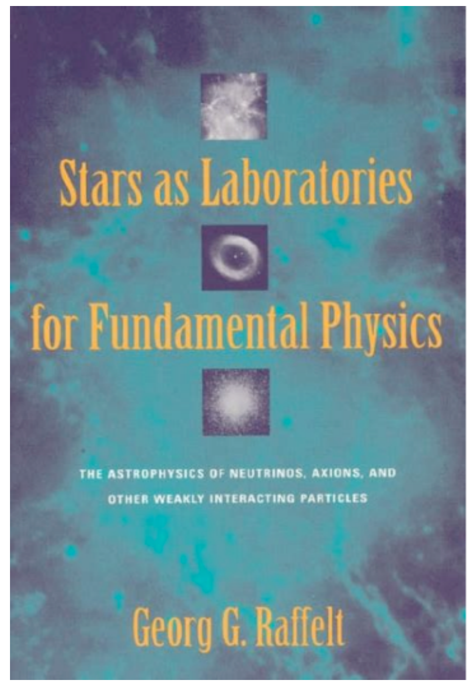
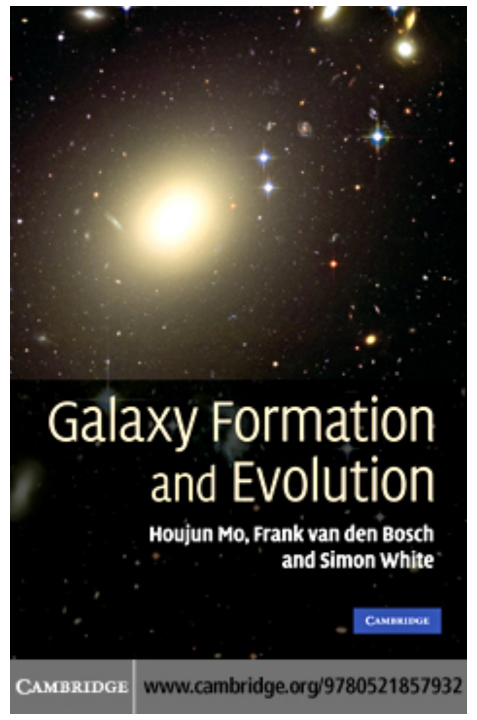
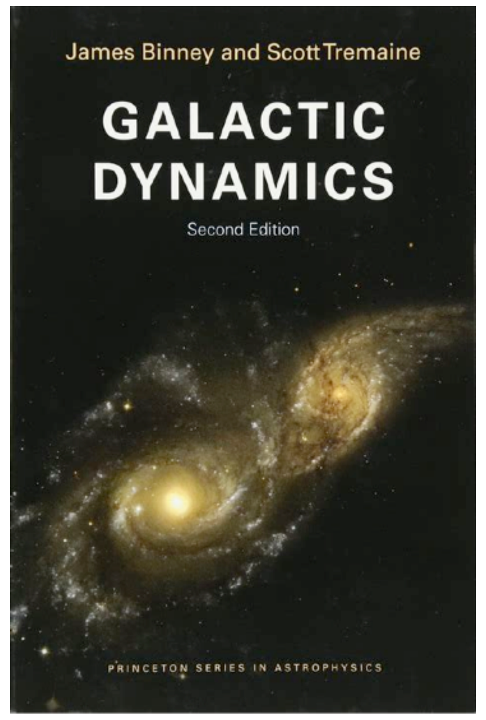
UNDARK







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to astrophysical modelling’

Conclusions

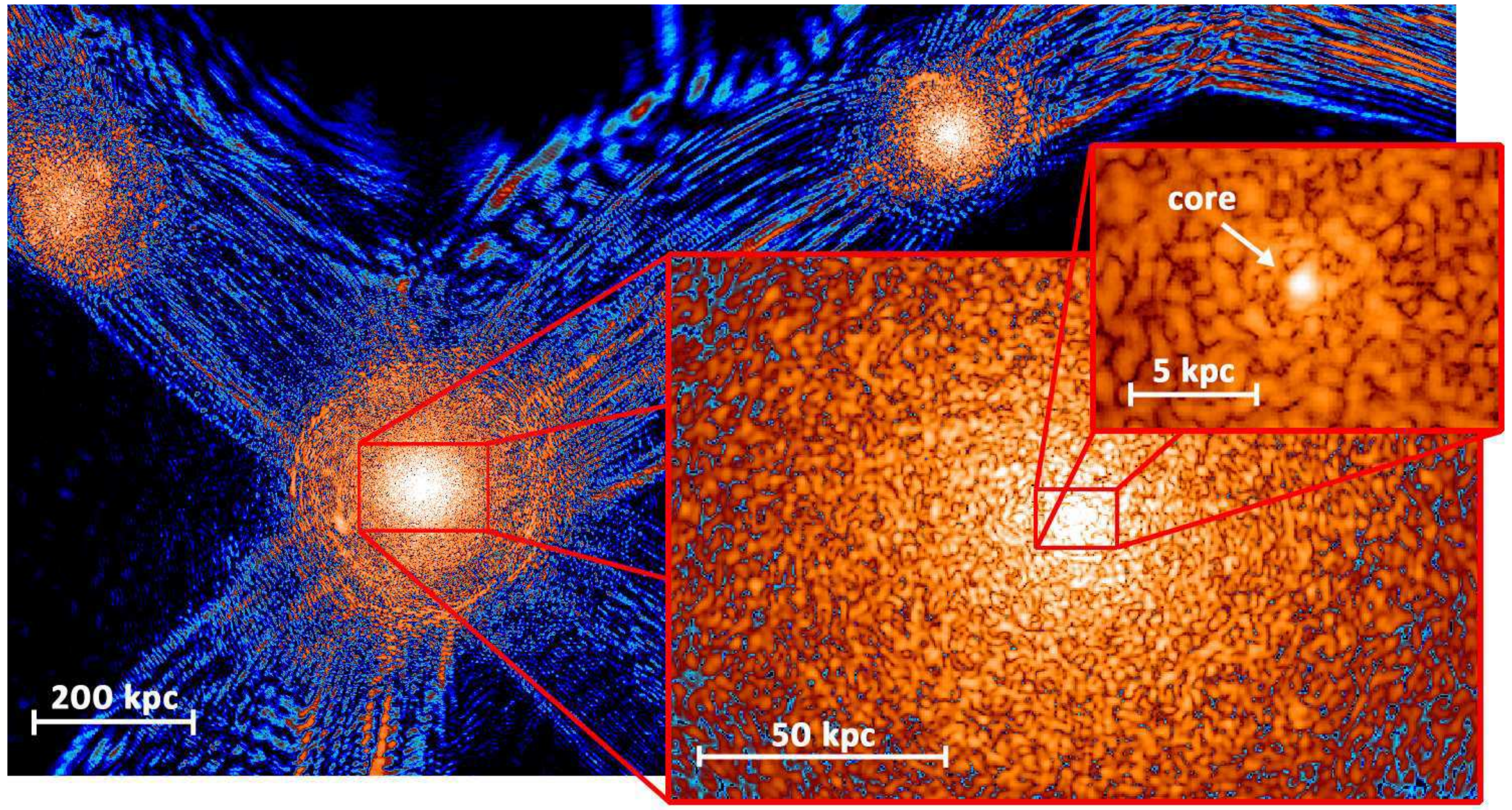
Ultra-light bosonic DM (or light fermionic DM)

- Includes new dynamics that open new phenomenological windows
- Two directions
  - explore all possible masses, with different time scales
  - explore direction of possible couplings

A) coherent oscillations

B) stochastic 'narrow' piece

C) changes dynamics at smaller scales



Properties of the soliton

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

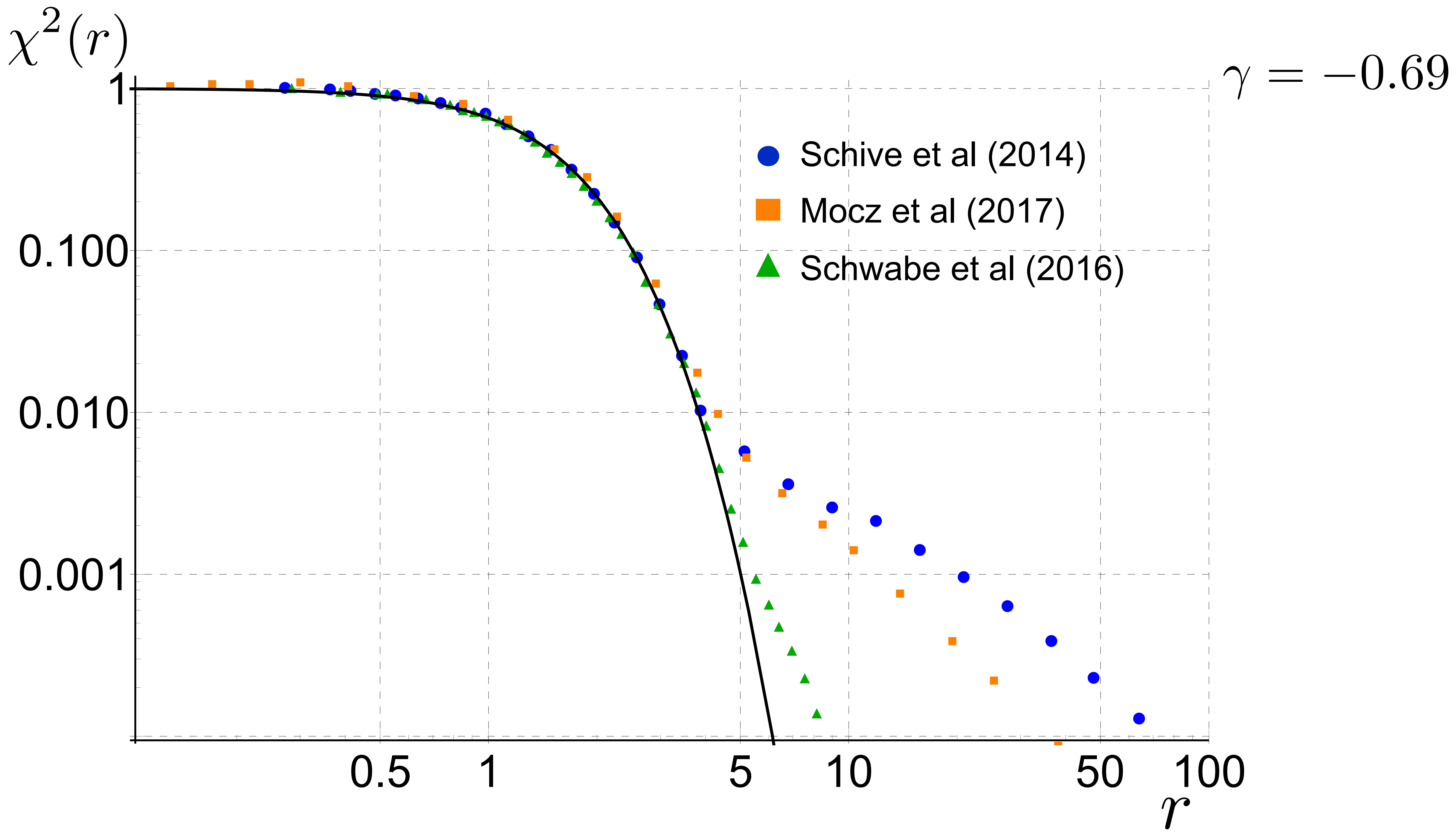
$v \ll c,\ \omega \ll m$

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

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?