Ultralight New Physics:
From Astrophysical Frontiers to Laboratory Discoveries

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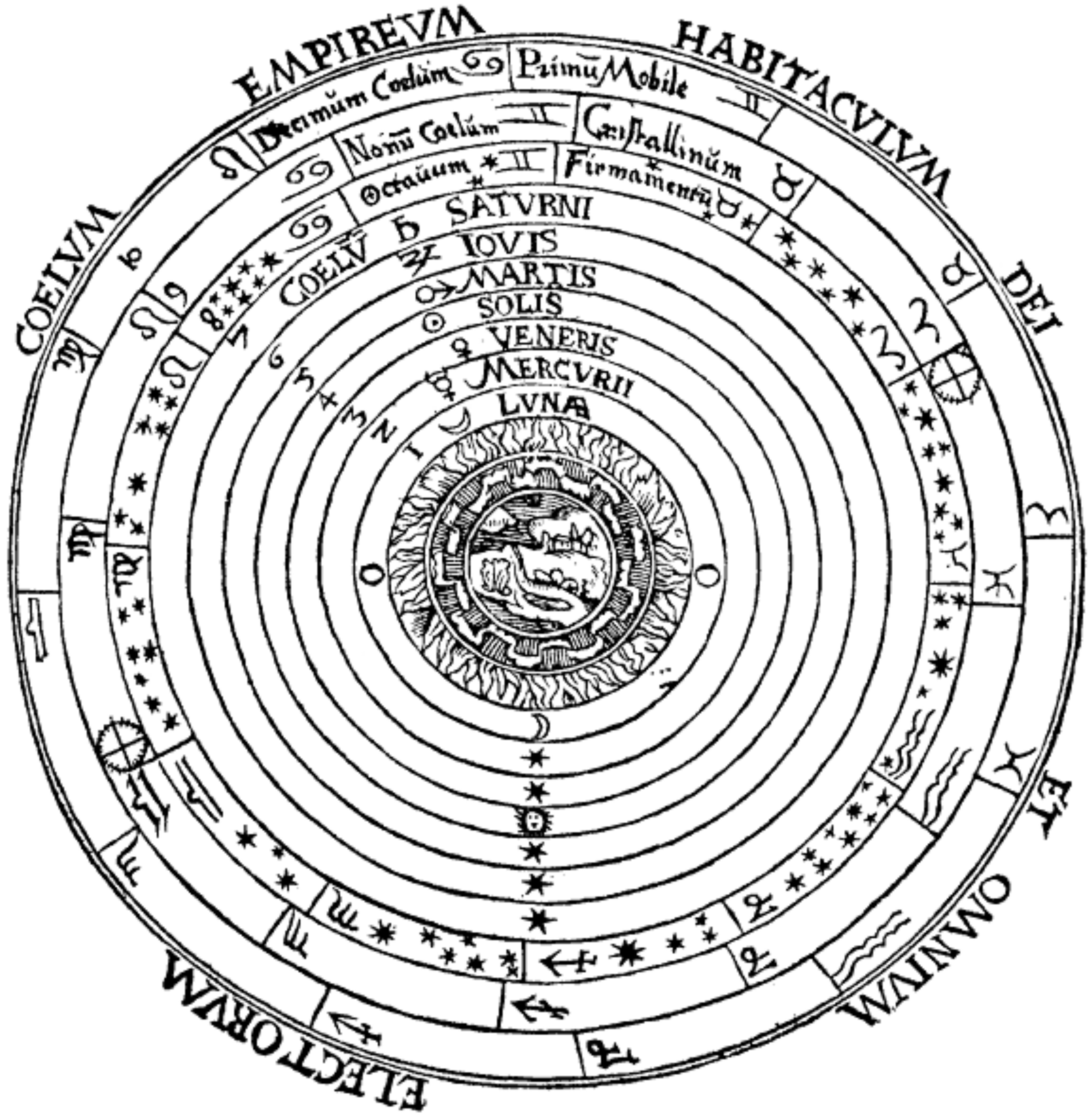
DESY Particle and Astroparticle Physics Colloquium
30 September 2025

Old Standard Model of the Solar System:



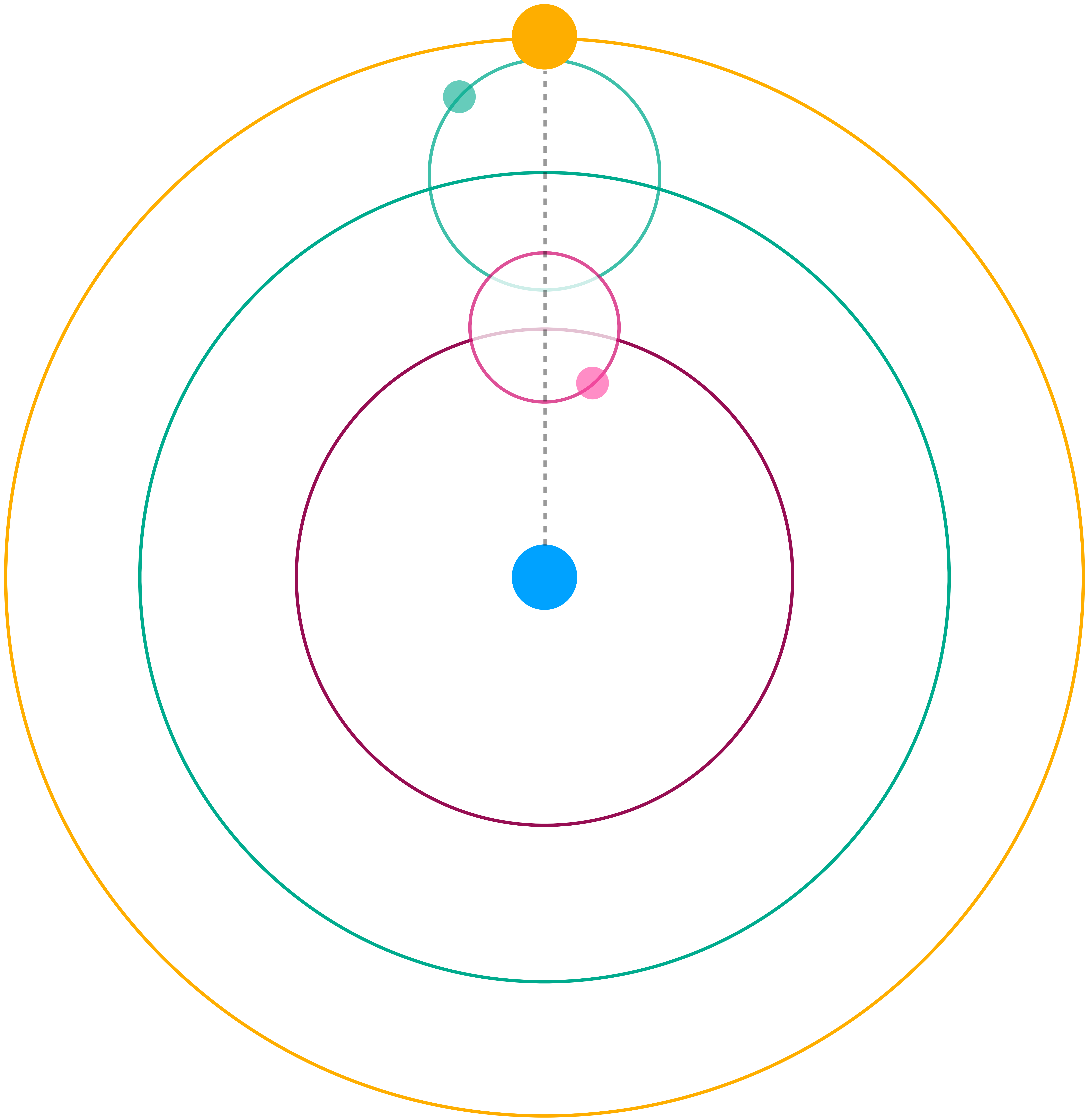
Geocentric model

it works quite well

but it has some **‘fine-tuning’ problems**

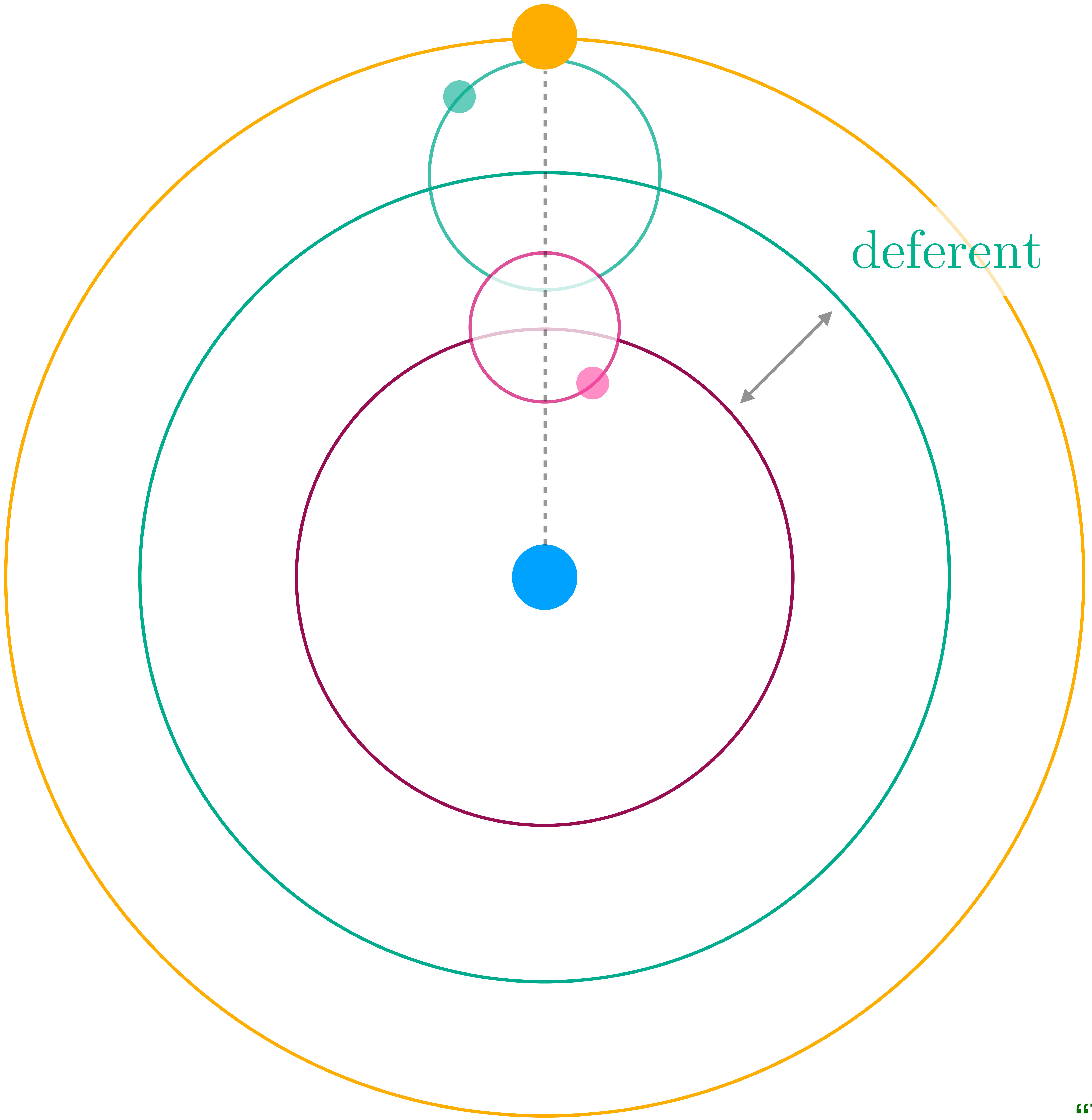
I

the center of epicycle of inner planets
always aligned with Earth-Sun



II

arbitrariness in
order of deferent



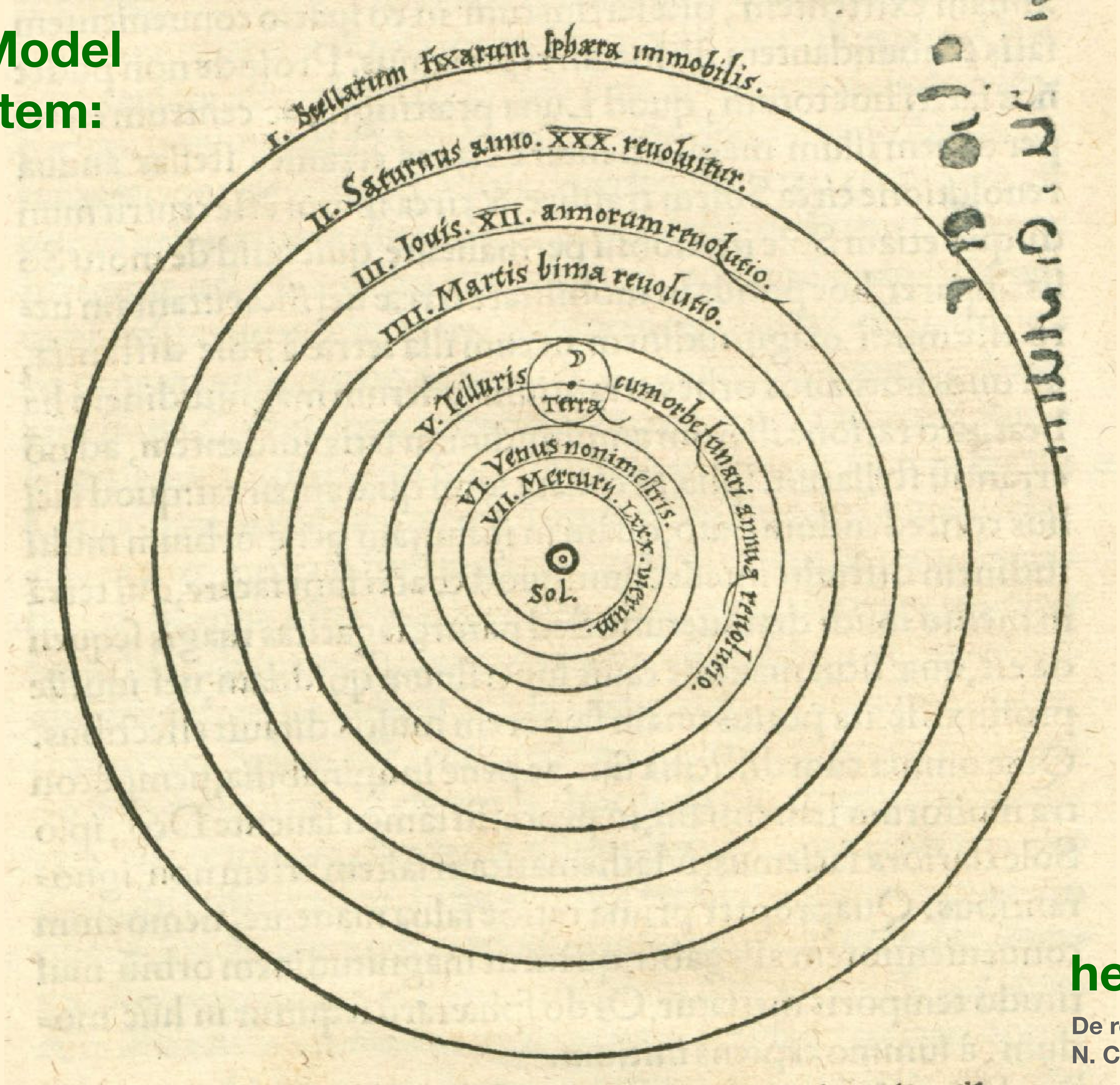
for more examples

S. Weinberg

“To Explain the World” (2015)

a more **natural** model

New Standard Model of the Solar System:



heliocentric model

De revolutionibus orbium coelestium
N. Copernicus (1543)

Heliocentric model (1543)

asthetically more pleasing / predictive

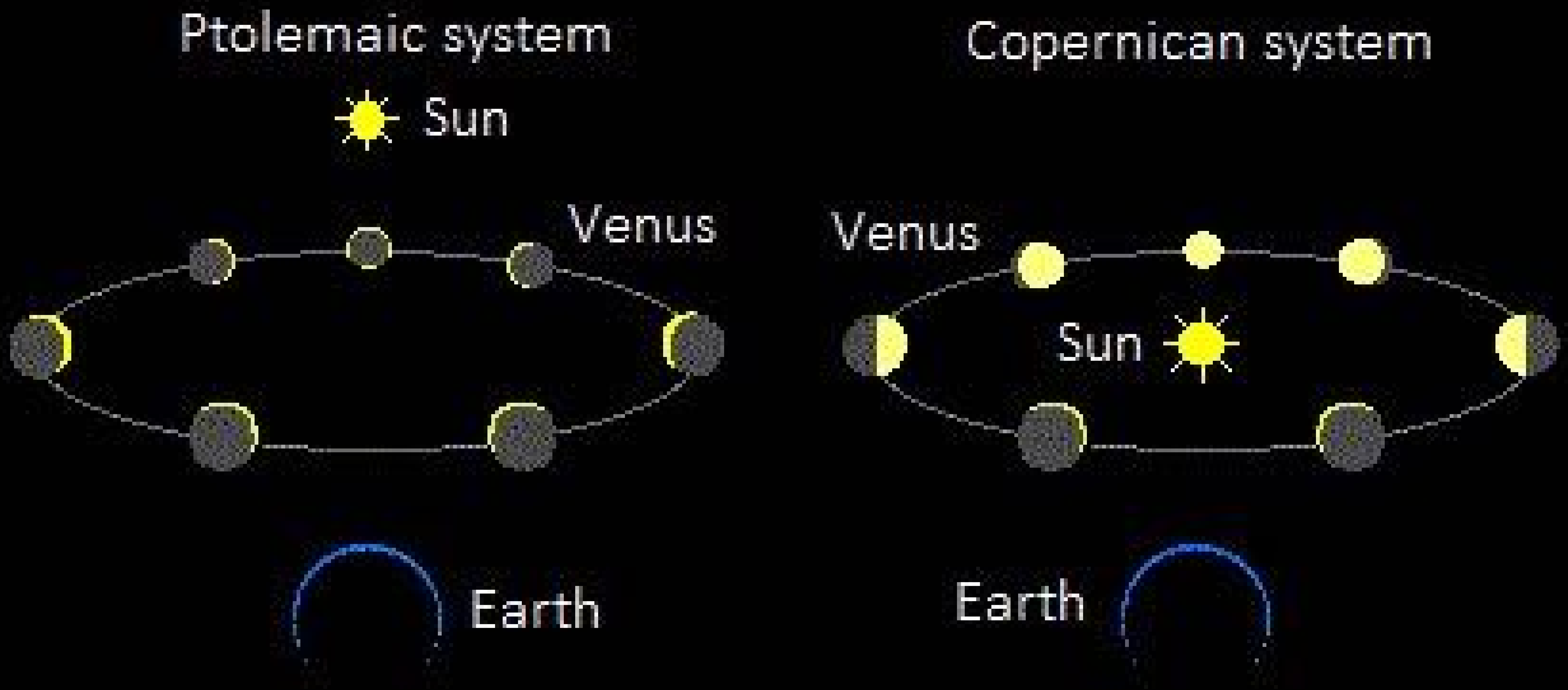
not particularly data-driven (!)

the first evidence

from the observation of Venus

by Galilei (1640)

VENUS 2002
Photographed at the TBGS Observatory
by Chris Proctor


Ptolemaic system
Sun
Venus
Earth
Copernican system
Venus
Sun
Earth

concrete mathematical formulation

by Newton (1687)

$$S = \int d^4x \, \mathcal{L}_{\mathrm{SM}}$$

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi \\
& + \psi_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

reasons to believe that

there are more than just the standard model

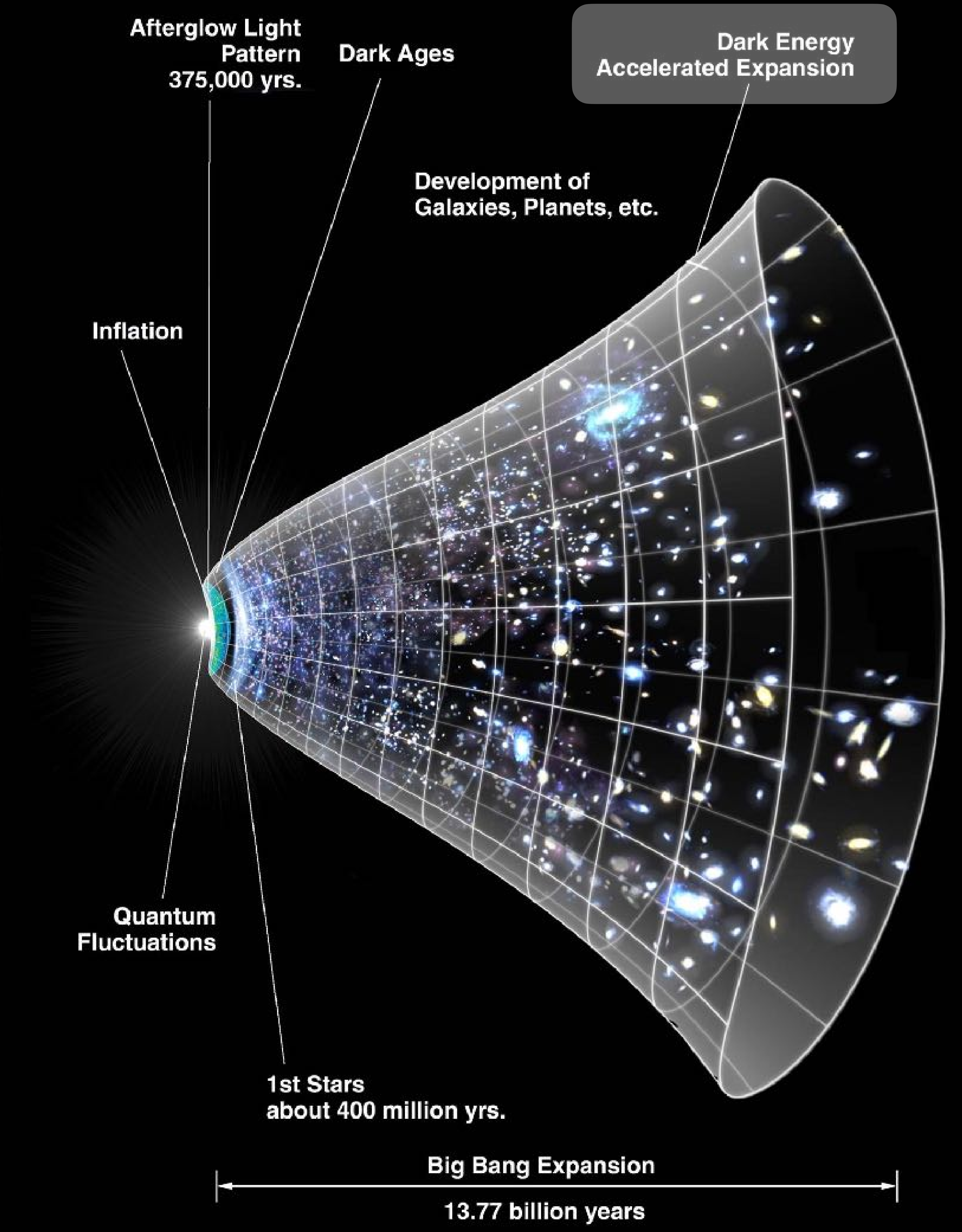
Observations
from starlight
Observations from
21 cm hydrogen
Velocity
(km s-1)
100
50
Expected from
the visible disk
10,000
20,000
30,000
40,000
Distance (light years)

it is often unclear
where new physics is hiding

‘curse of dimensionality’
in high energy physics

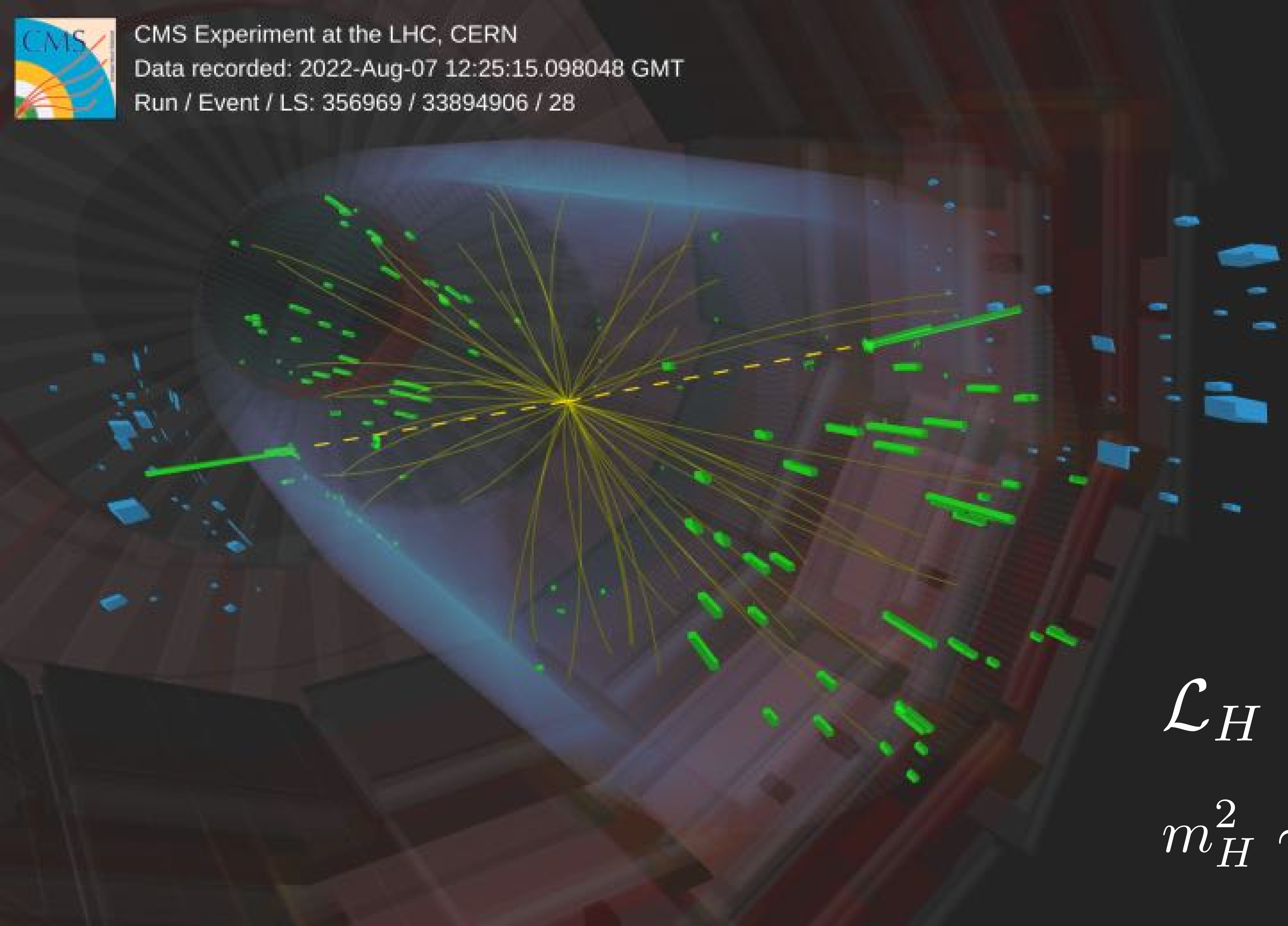
fine-tuning problems of
the Standard Model of particle physics

$$\mathcal{L}_{\mathrm{SM}} = \Lambda^4 + m_H^2 |H|^2 + \theta G\widetilde{G} + \cdots$$



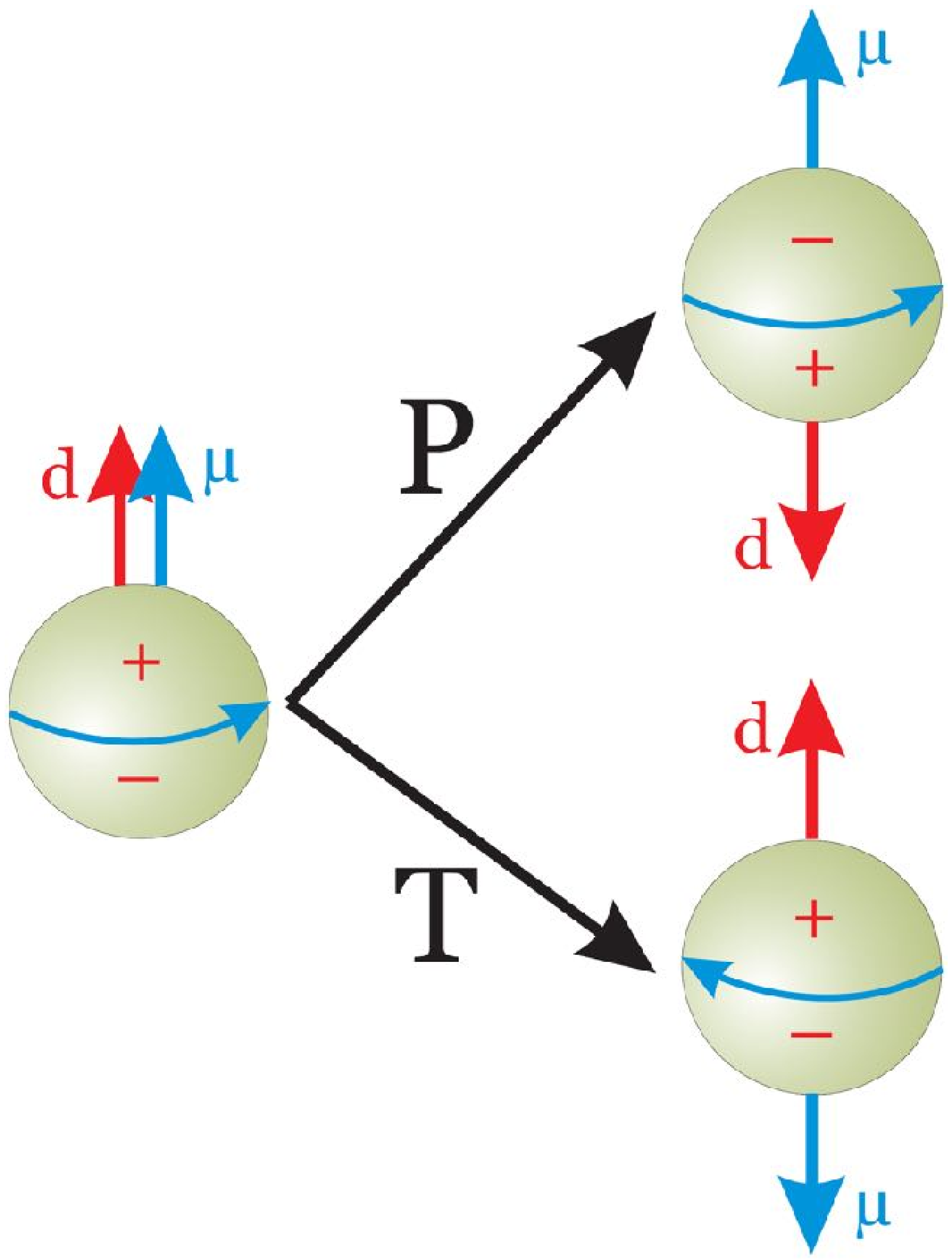
$$\mathcal{L}_{\rm cc} = \Lambda^4$$

$$\Lambda = {\rm meV}$$



$$\mathcal{L}_H = m_H^2 |H|^2$$

$$m_H^2 \sim (100\text{GeV})^2$$



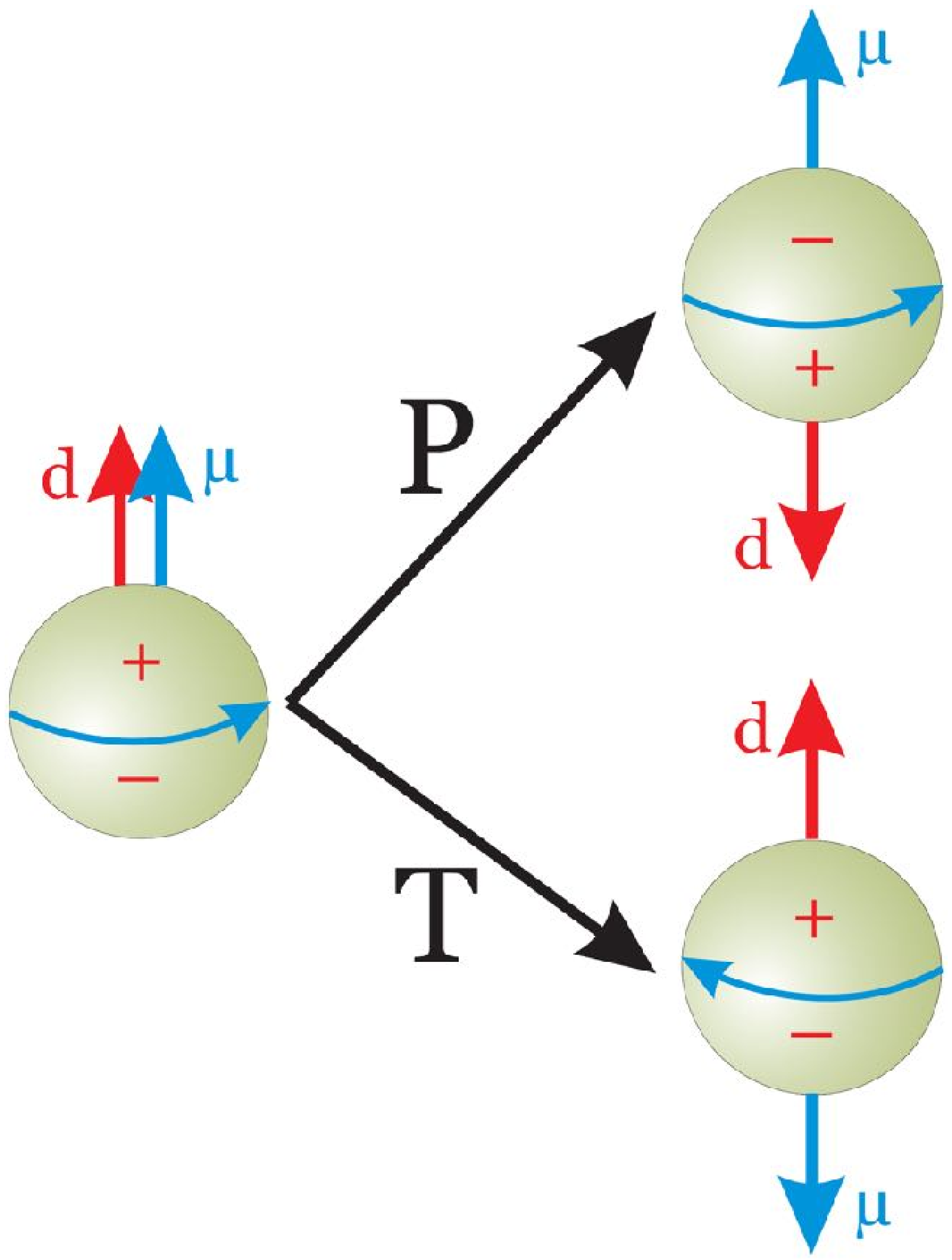
$$\mathcal{L} = \theta G \widetilde{G}$$

neutron electric dipole moment

$$d_n \sim 10^{-16} \theta \, \mathrm{e} \cdot \mathrm{cm}$$

$$\lesssim 10^{-26} \, \mathrm{e} \cdot \mathrm{cm}$$

Abel et al (20)



$$\mathcal{L} = \theta G \widetilde{G}$$

$$\theta < 10^{-10}$$

Ultralight New Physics:

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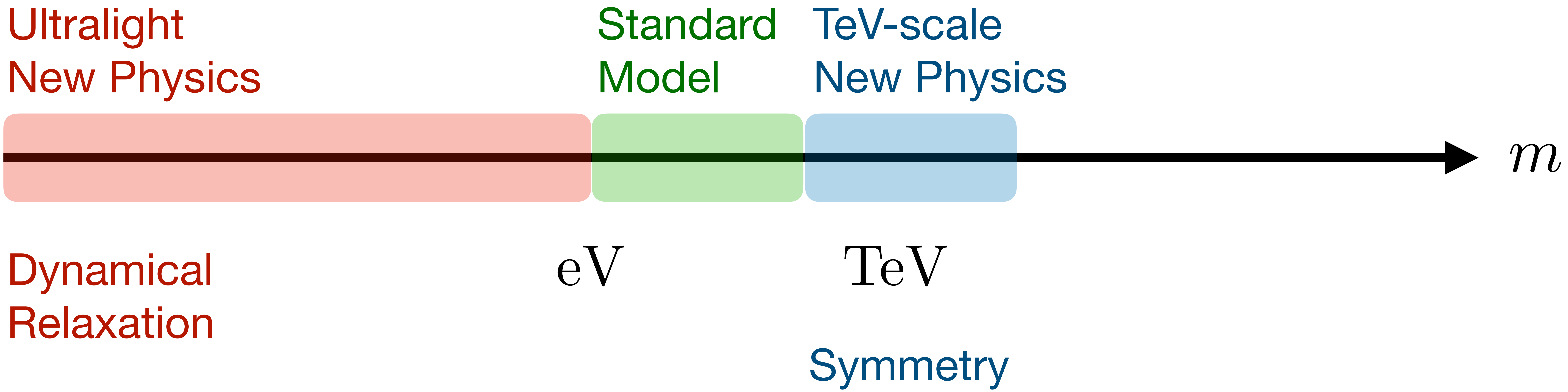
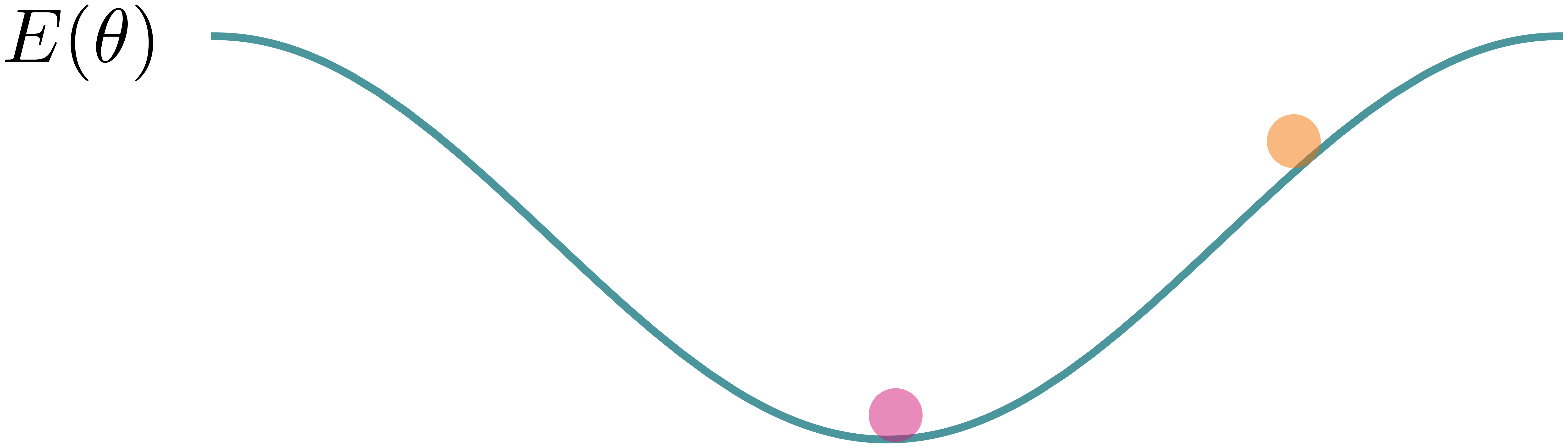


Ultralight
New Physics
Standard
Model
TeV-scale
New Physics
m
Dynamical
Relaxation
eV
TeV
Symmetry

$$\mathcal{L} = \theta G \widetilde{G}$$

QCD vacuum energy depends on θ



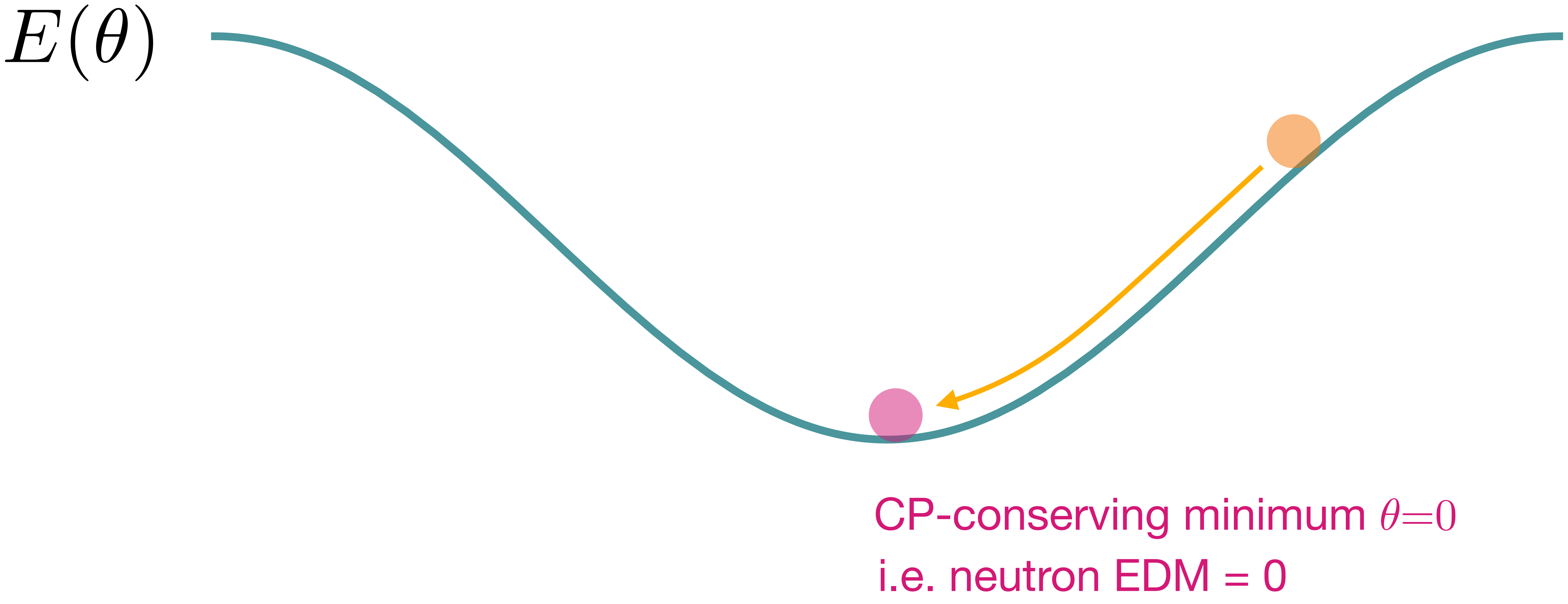
CP-conserving minimum $\theta=0$

i.e. neutron EDM = 0

$$\mathcal{L} = \theta G\widetilde{G}$$

if θ were a dynamical degree of freedom

the strong CP angle dynamically relaxes to minimum



$$\mathcal{L} = \theta G\widetilde{G}$$

if θ were a dynamical degree of freedom

the strong CP angle dynamically relaxes to minimum

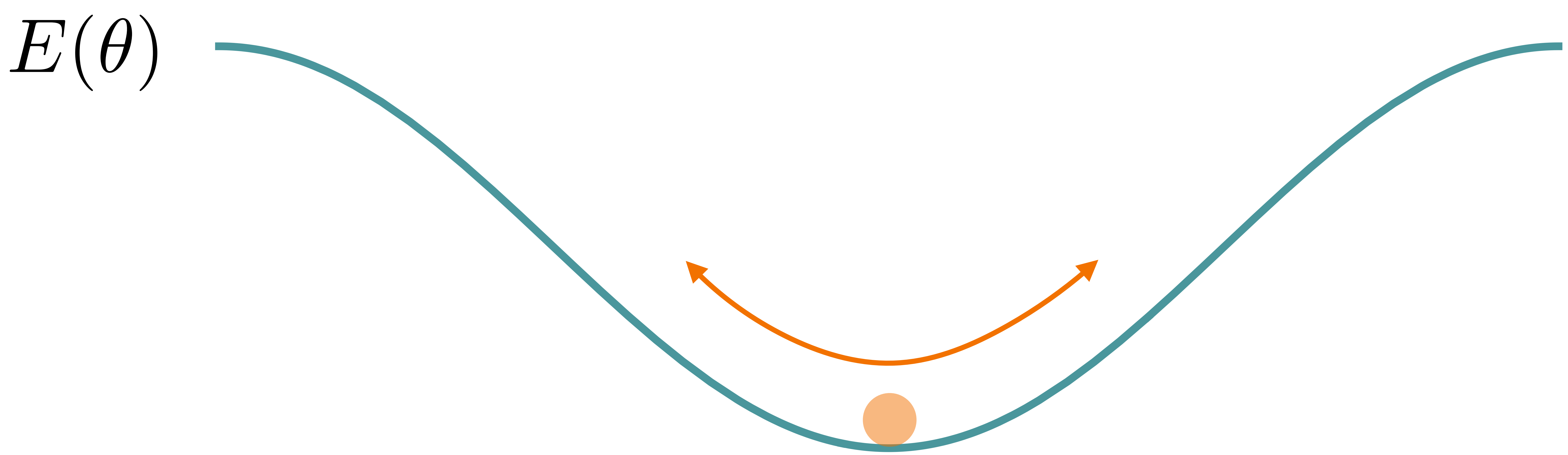
QCD Axion solution

CP-conserving minimum θ=0

i.e. neutron EDM = 0

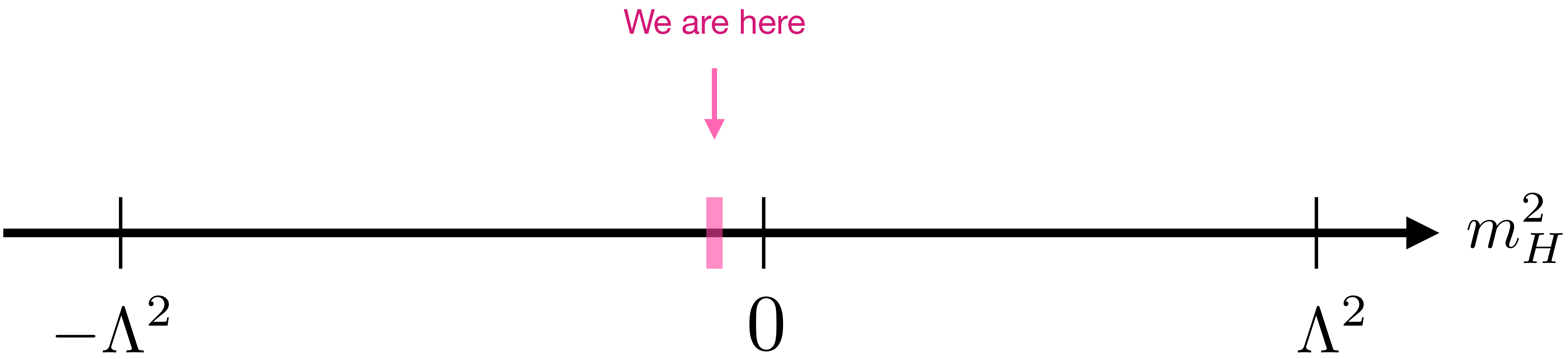
it oscillates around the minimum

oscillation around minimum behaves as **cold dark matter**



what about

$$\mathcal{L} = m_H^2 |H|^2$$



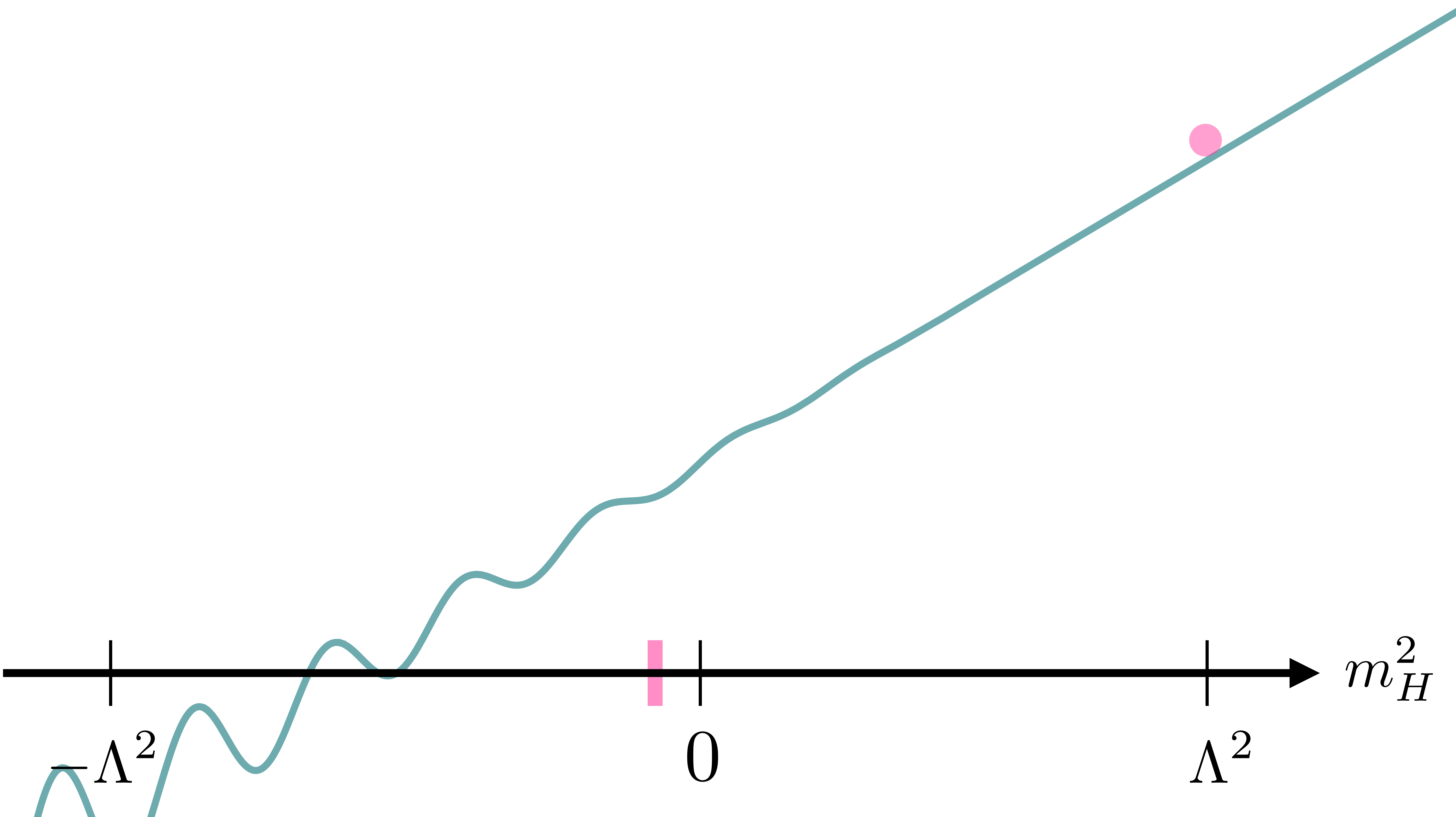
We are here
m_H^2
$-\Lambda^2$
0
Λ^2

$$\mathcal{L} = m_H^2 |H|^2$$

$$\downarrow$$

$$\mathcal{L} = m_H^2(\theta)|H|^2 + f^2(\partial\theta)^2 - V(\theta)$$

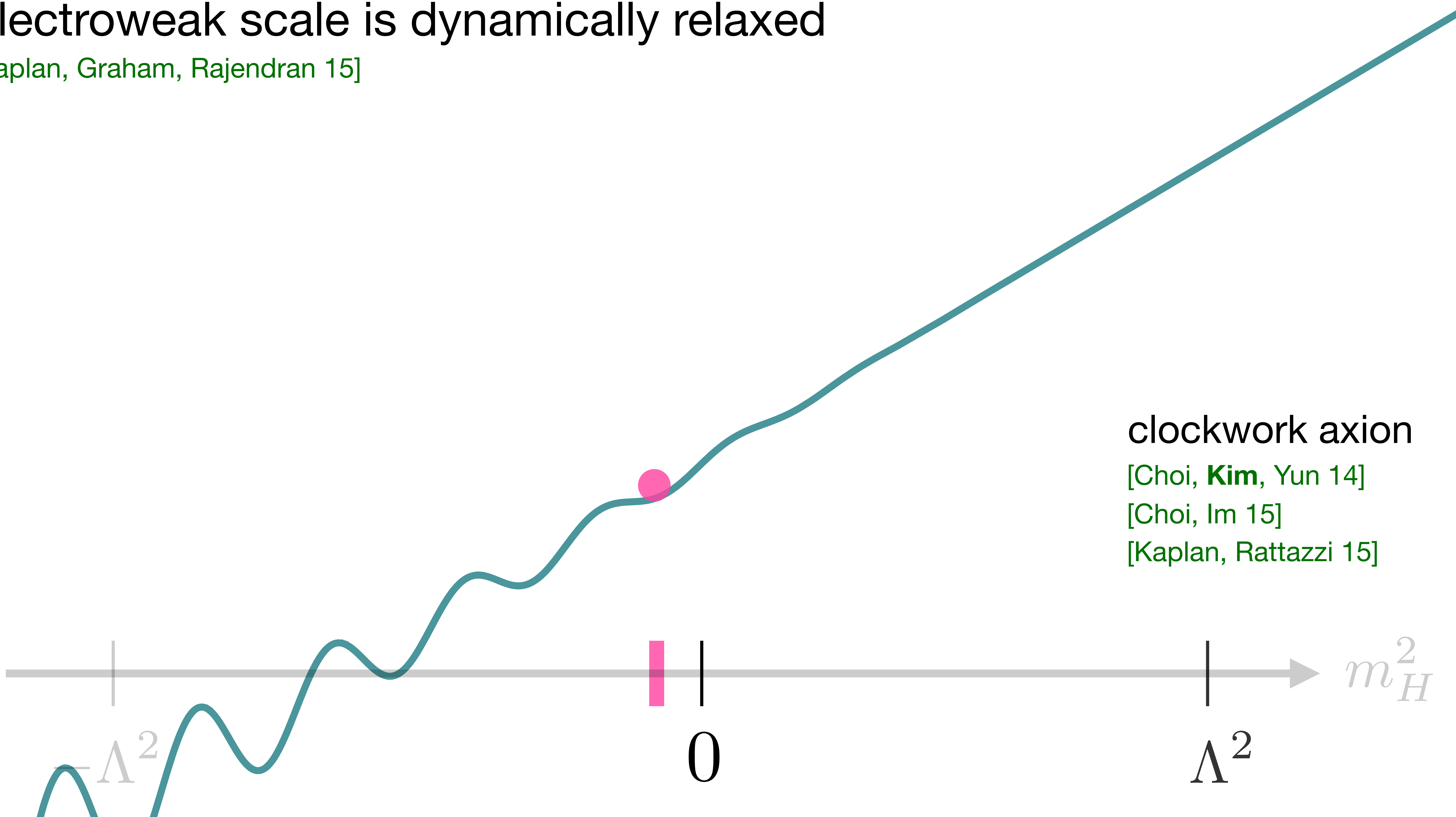
$$V(\theta) = \Lambda_{\rm UV}^4 \cos(\theta) + \Lambda_{\rm br}^4 \cos(c\theta)$$



m_H^2
$-\Lambda^2$
0
Λ^2

Electroweak scale is dynamically relaxed

[Kaplan, Graham, Rajendran 15]



clockwork axion

[Choi, **Kim**, Yun 14]

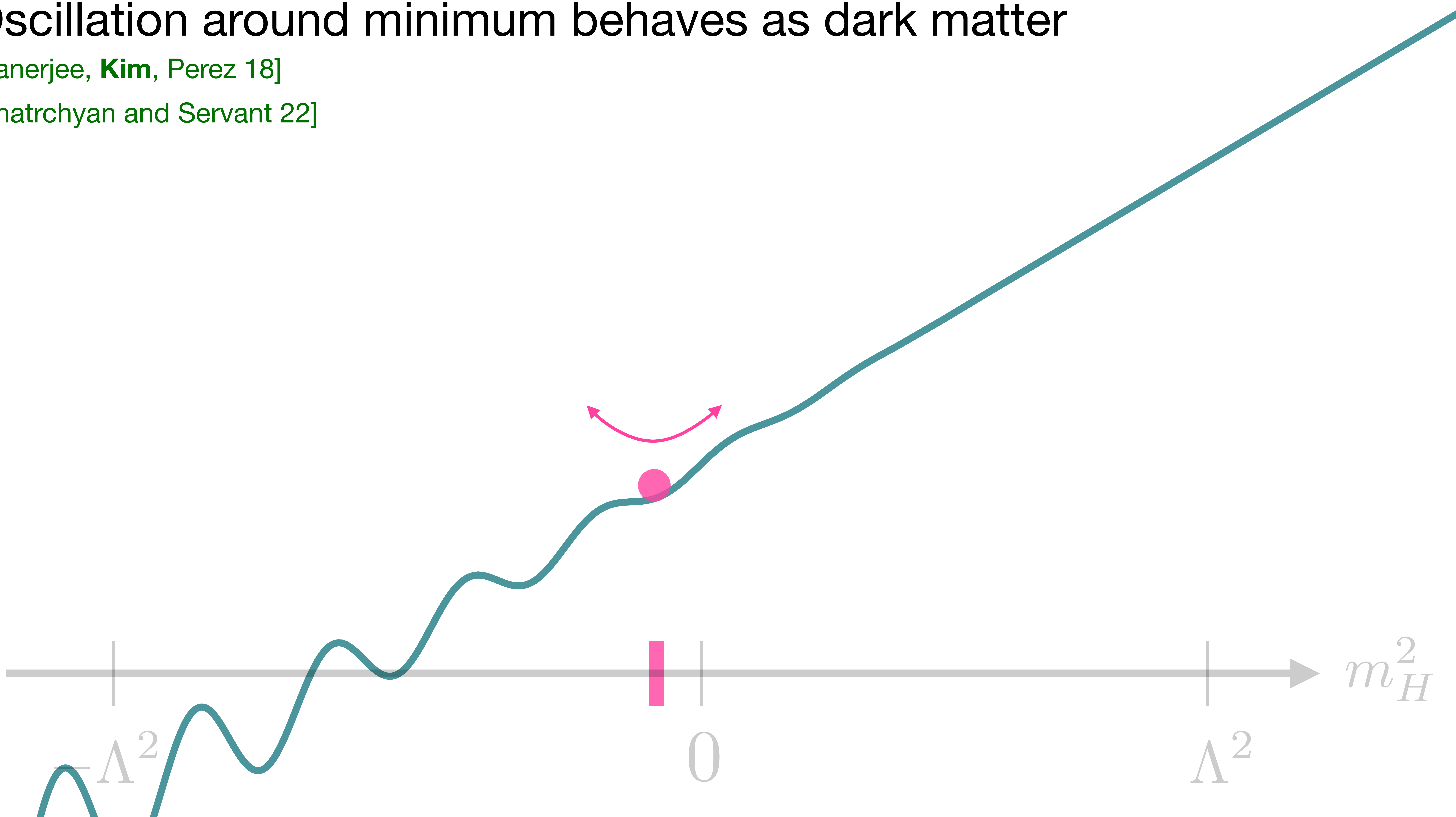
[Choi, Im 15]

[Kaplan, Rattazzi 15]

Oscillation around minimum behaves as dark matter

[Banerjee, **Kim**, Perez 18]

[Chatrchyan and Servant 22]



Ultralight new physics could explain
fine-tuning problems dynamically

at the same time
it could be dark matter in the universe

Ultralight New Physics:

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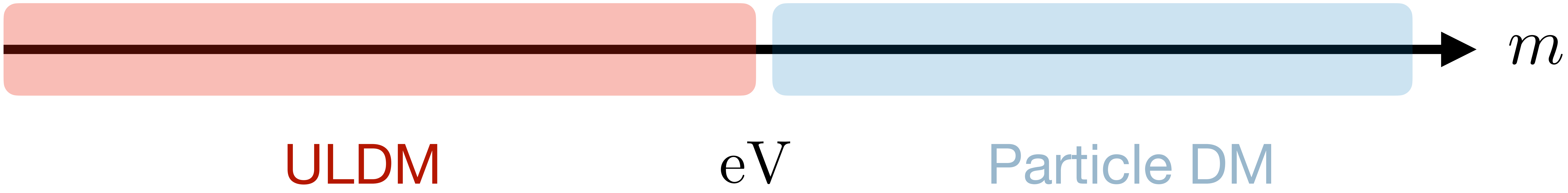
Astrophysical Frontiers

(gravitationally)

I will assume ultralight particles
to be dark matter in the present universe

Ultralight dark matter (ULDM)

as bosonic DM candidates with $\mathrm{m} < \mathrm{eV}$



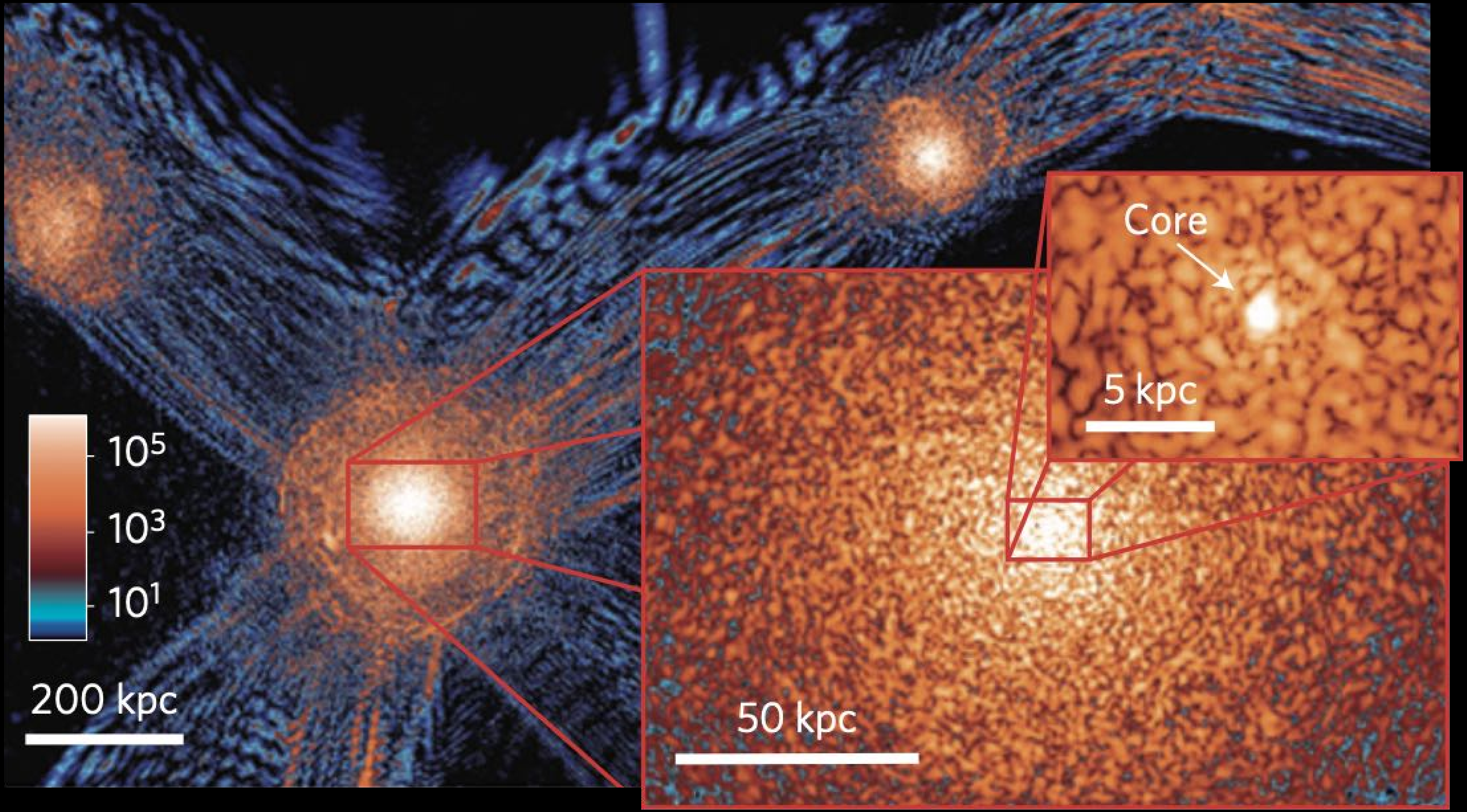
Ultralight dark matter

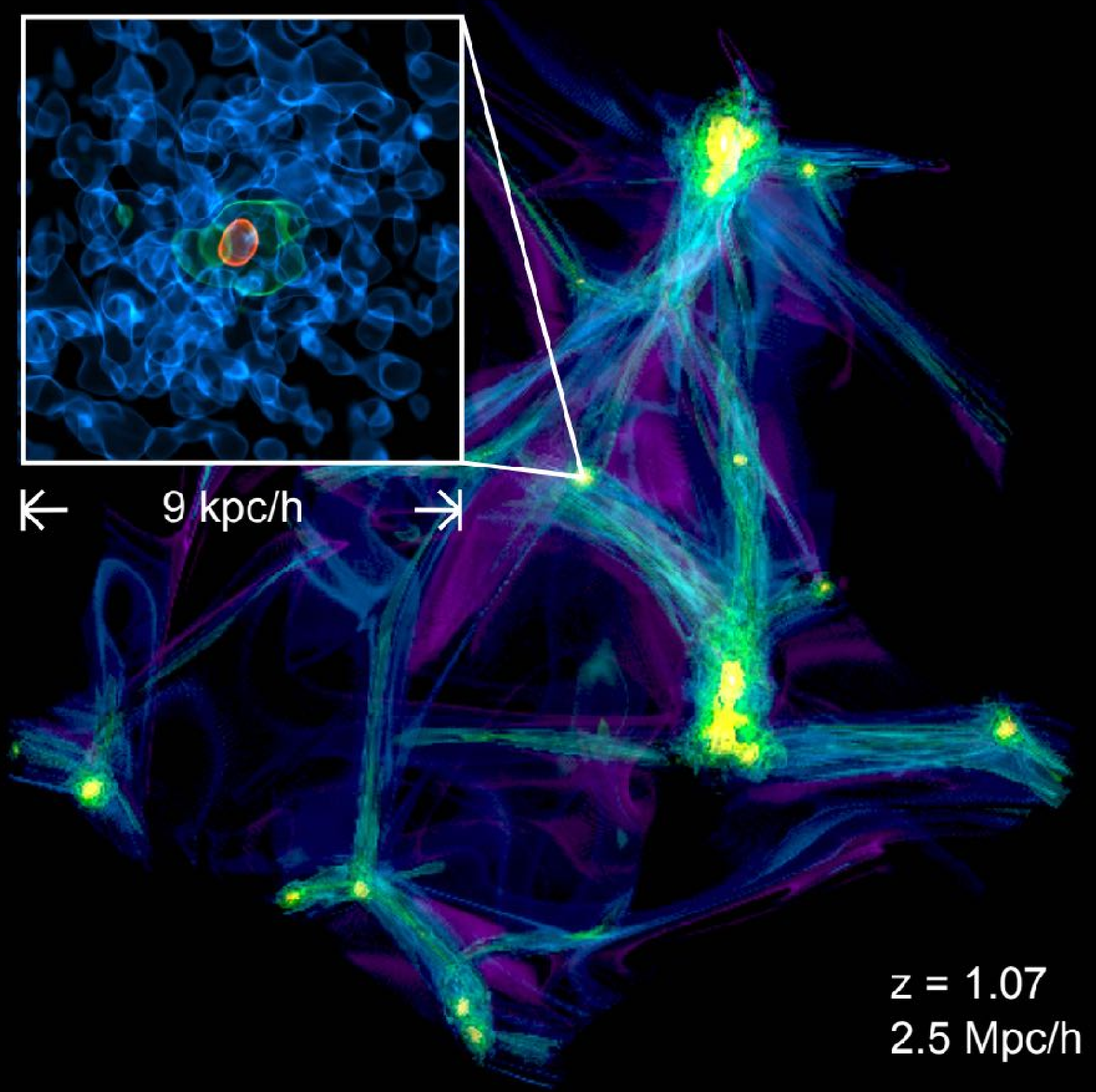
as bosonic DM candidates with $\mathrm{m} < \mathrm{eV}$

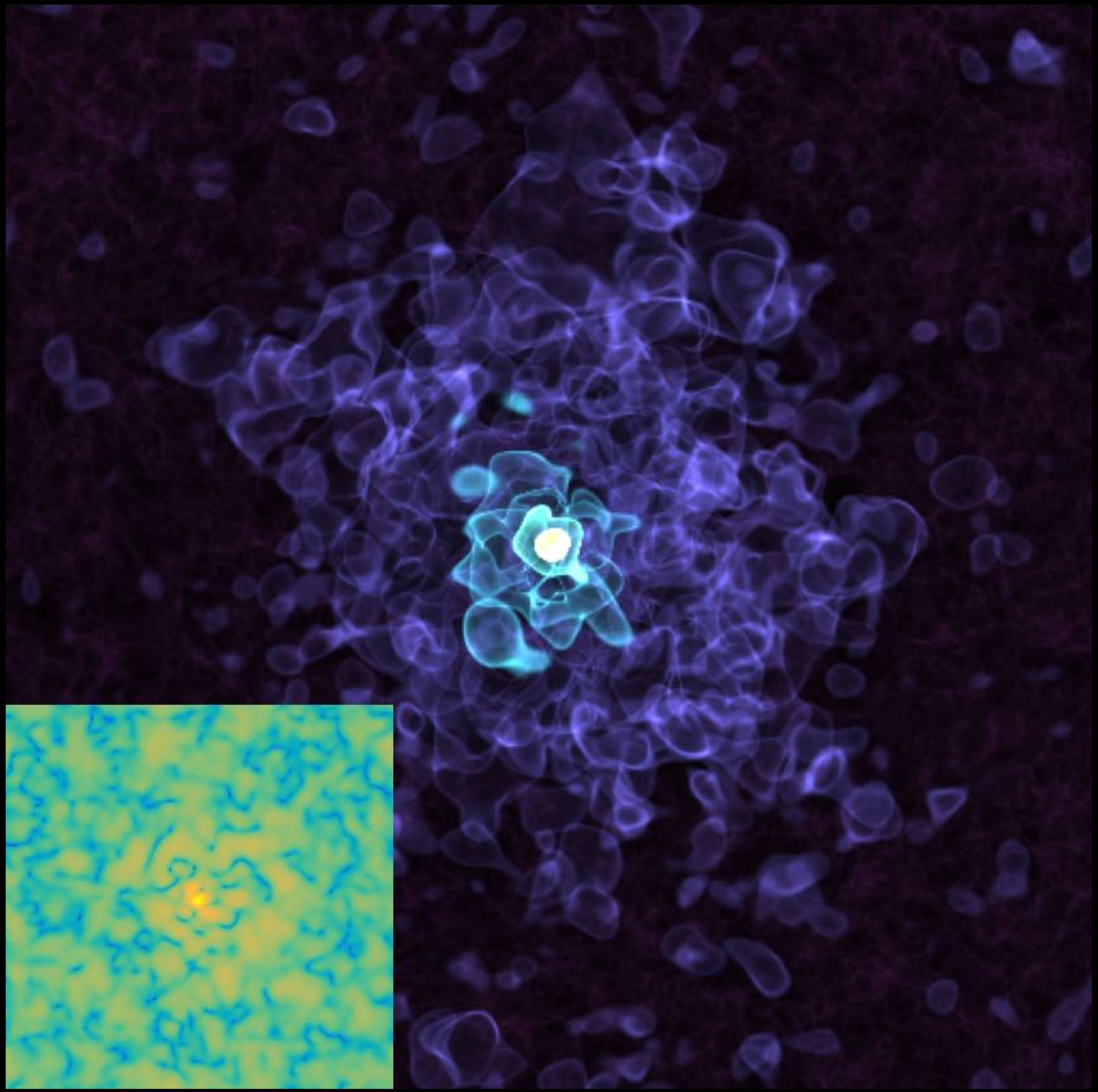
$$m \lesssim 10\,\mathrm{eV}$$

$$N_{\mathrm{occ}} \sim n_{\mathrm{dm}} \lambda^3 \sim \left(\frac{10\,\mathrm{eV}}{m}\right)^4$$

Schive, Chiueh, Broadhurst (14)





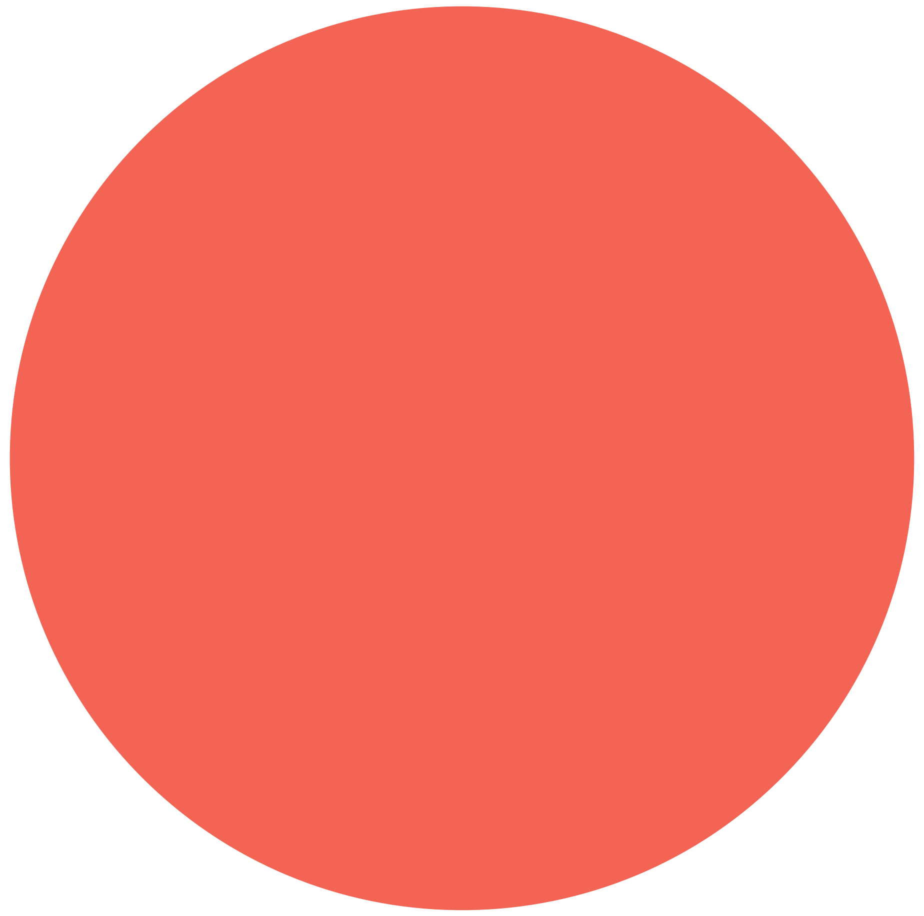


Veltmaat, Niemeyer, Schwabe (18)

An intuitive understanding of the granule structure:

[Hui et al 17]

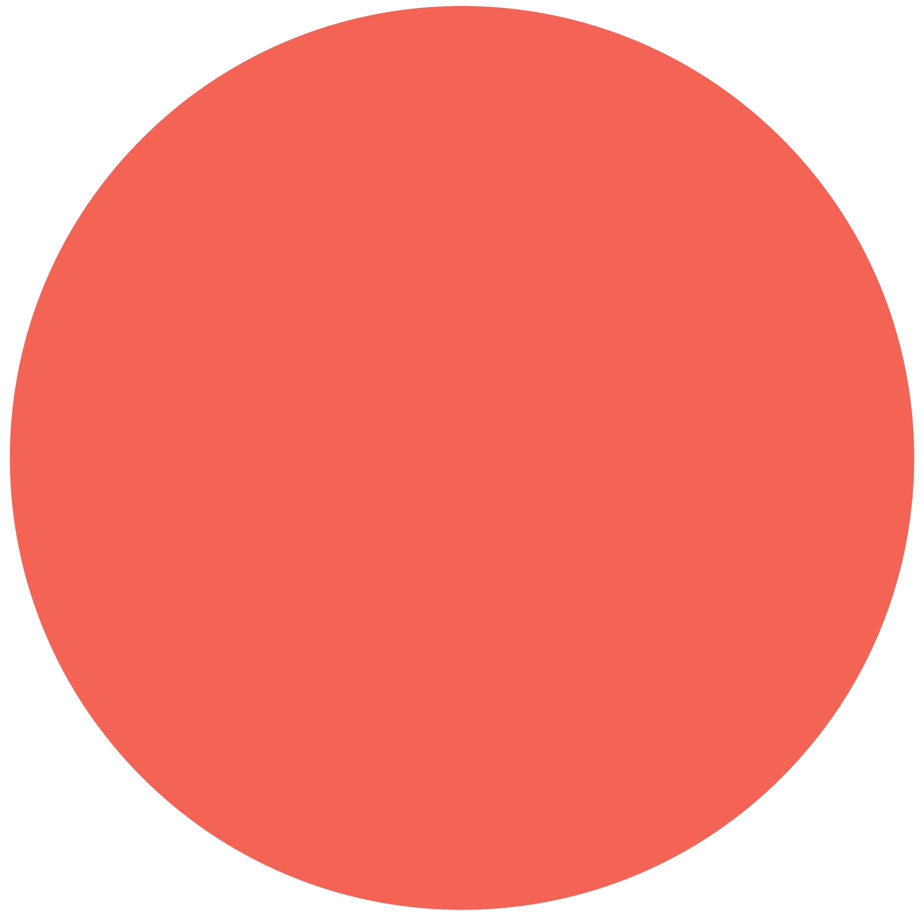
Quasiparticle



$$\ell \sim \lambda = \frac{1}{mv}$$

$$m_{\rm eff} \sim \rho_{\rm DM}\ell^3$$

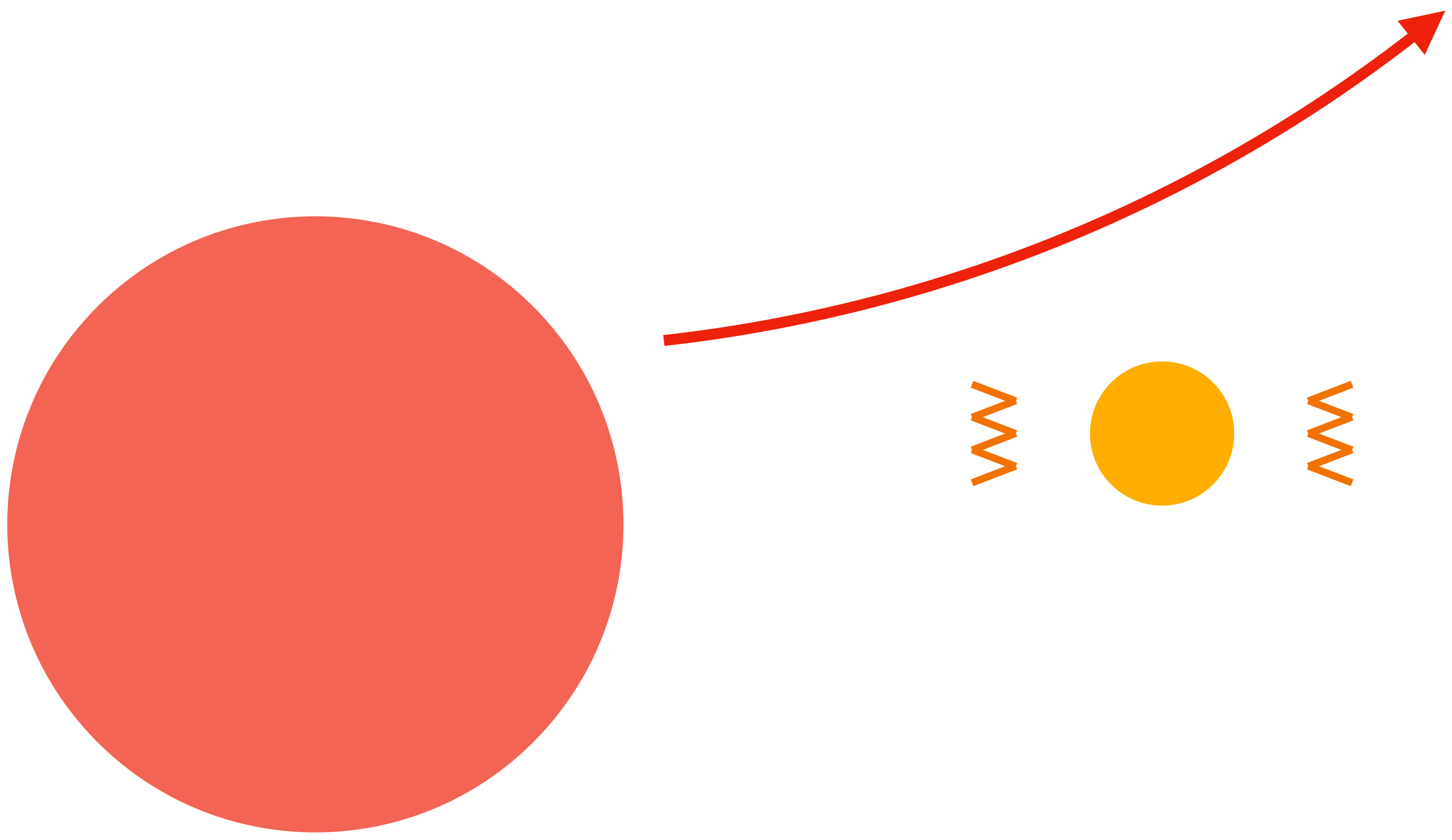
the size and mass of them could be astronomical



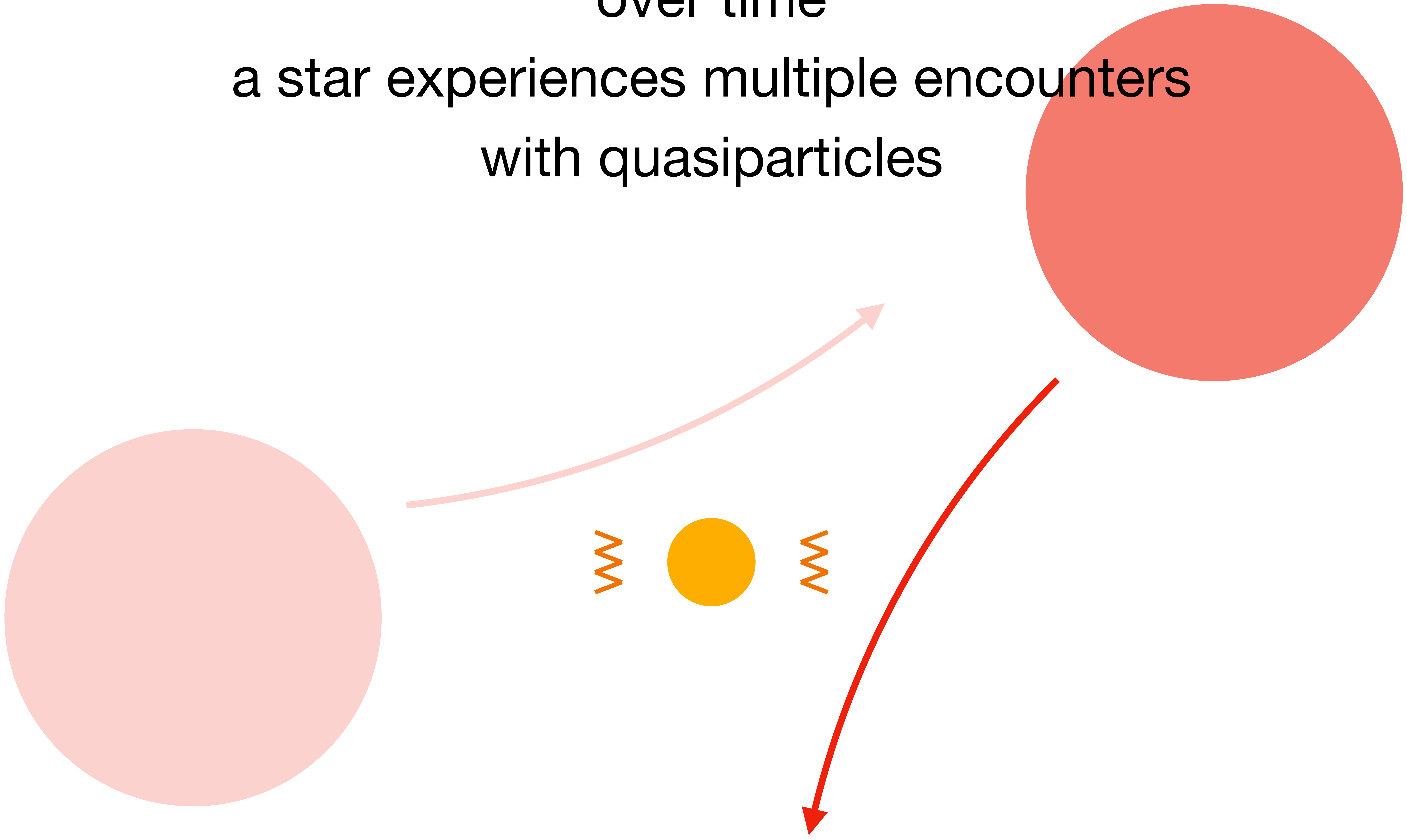
$$\ell \sim \lambda = \frac{1}{mv} \sim 10\,\mathrm{AU} \times \left(\frac{10^{-16}\,\mathrm{eV}}{m}\right)$$

$$m_{\mathrm{eff}} \sim \rho_{\mathrm{DM}} \ell^3 \sim 10^{15}\,\mathrm{kg} \times \left(\frac{10^{-16}\,\mathrm{eV}}{m}\right)^3$$

being that massive
it may engage in interaction with stars
and significantly perturb the motion of them



over time
a star experiences multiple encounters
with quasiparticles



over time

a star experiences multiple encounters

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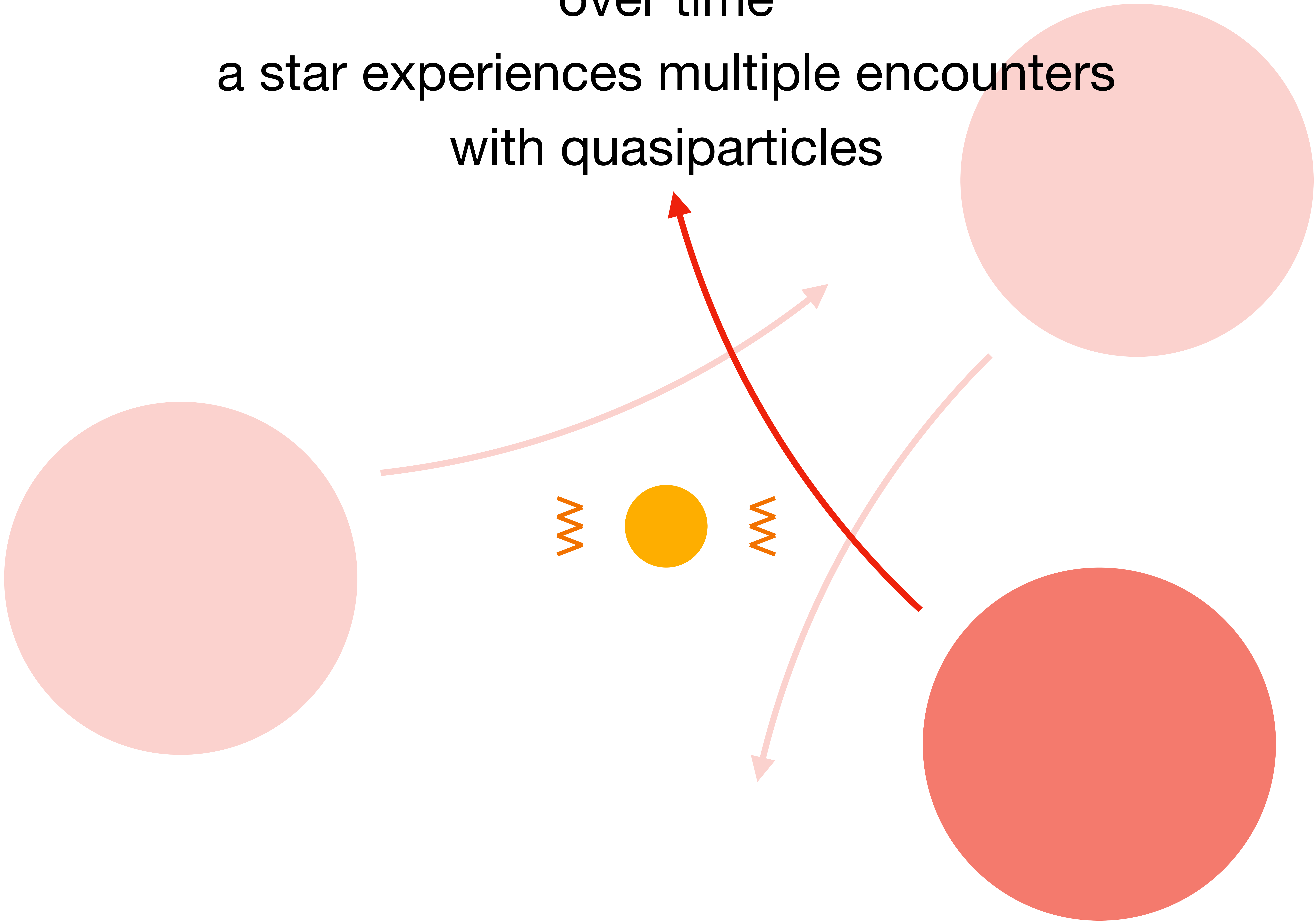
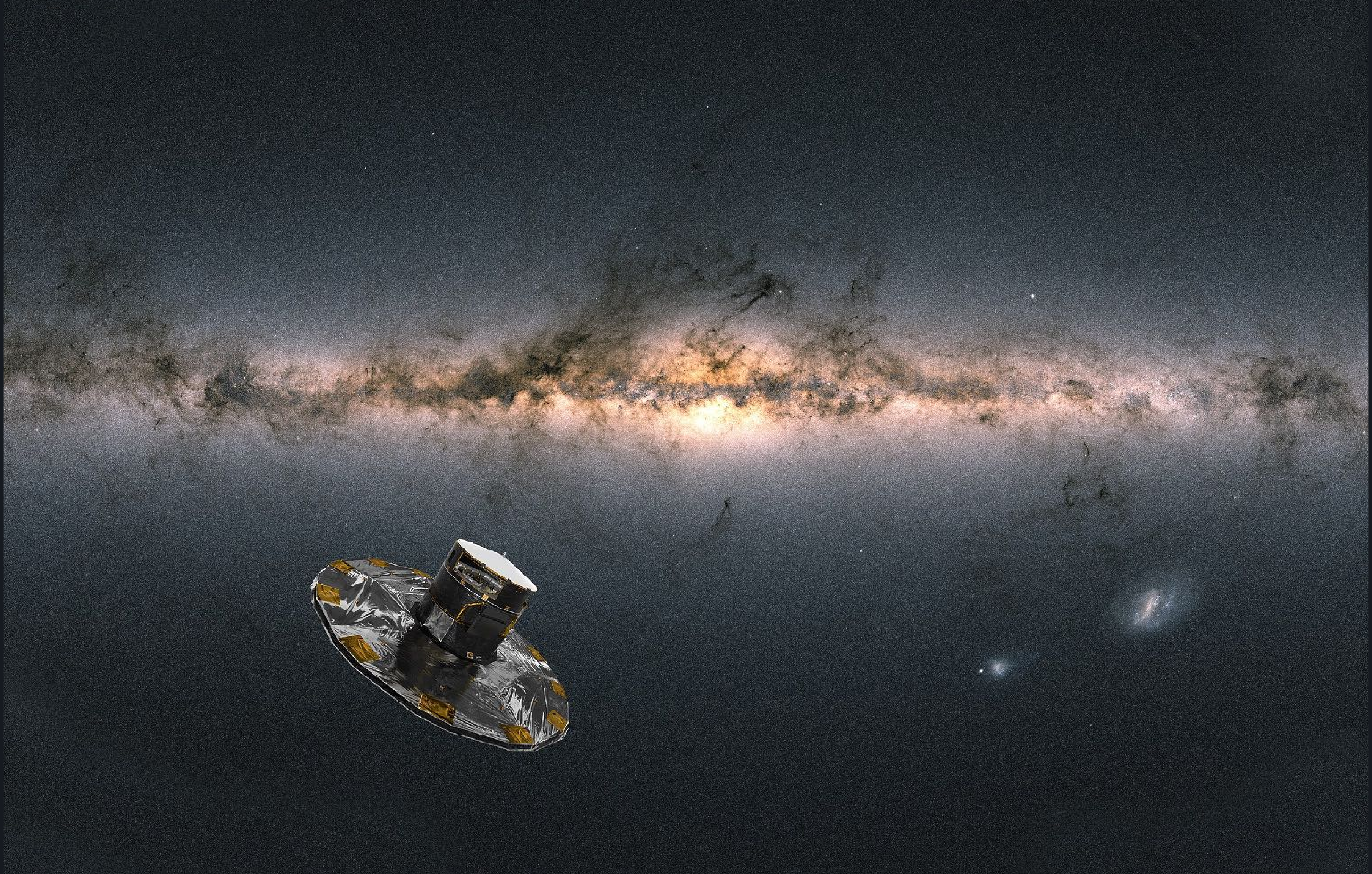


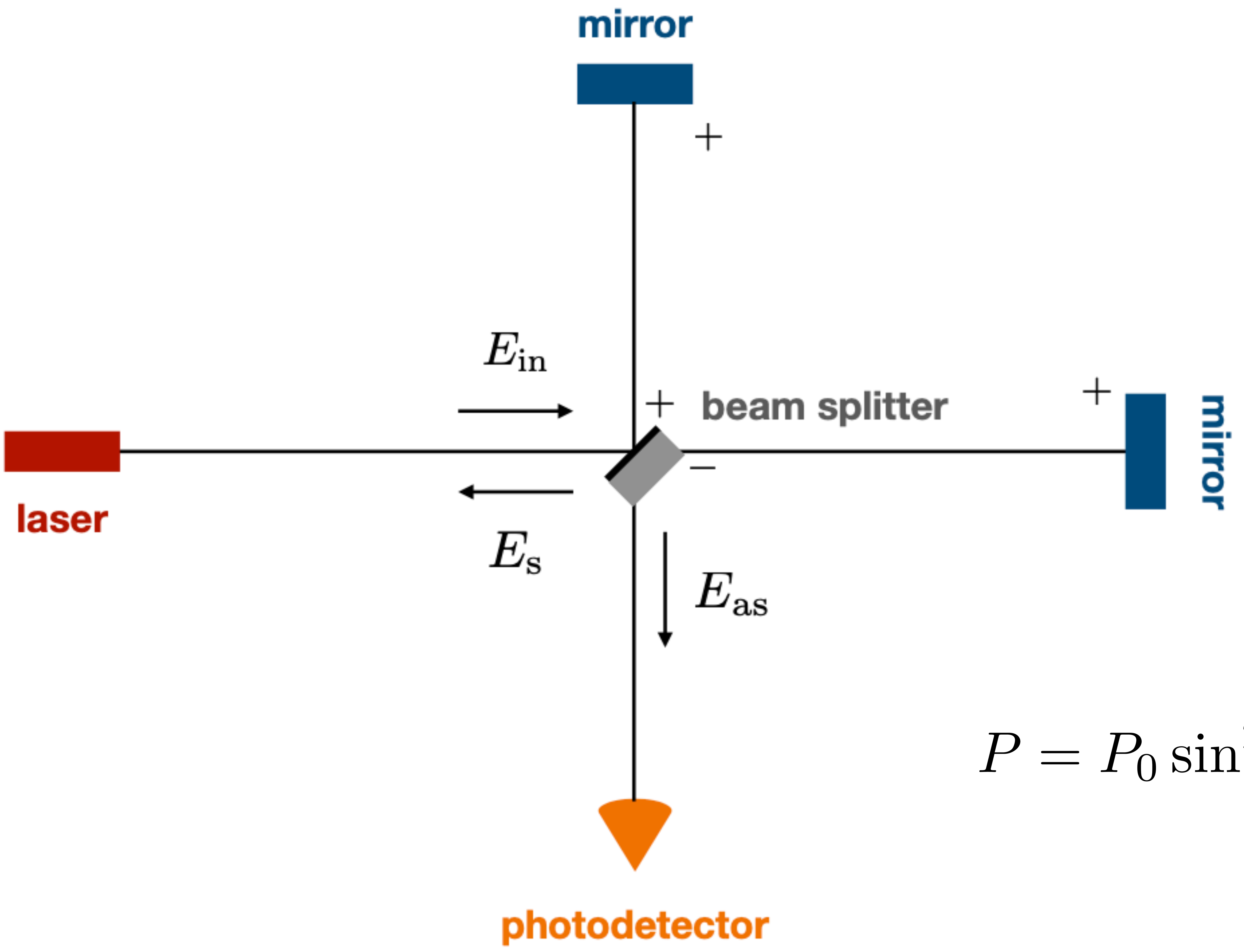
quasiparticles *bombards* normal matters
leaving distinctive stochastic signals
in gravitational wave detectors


Interferometry

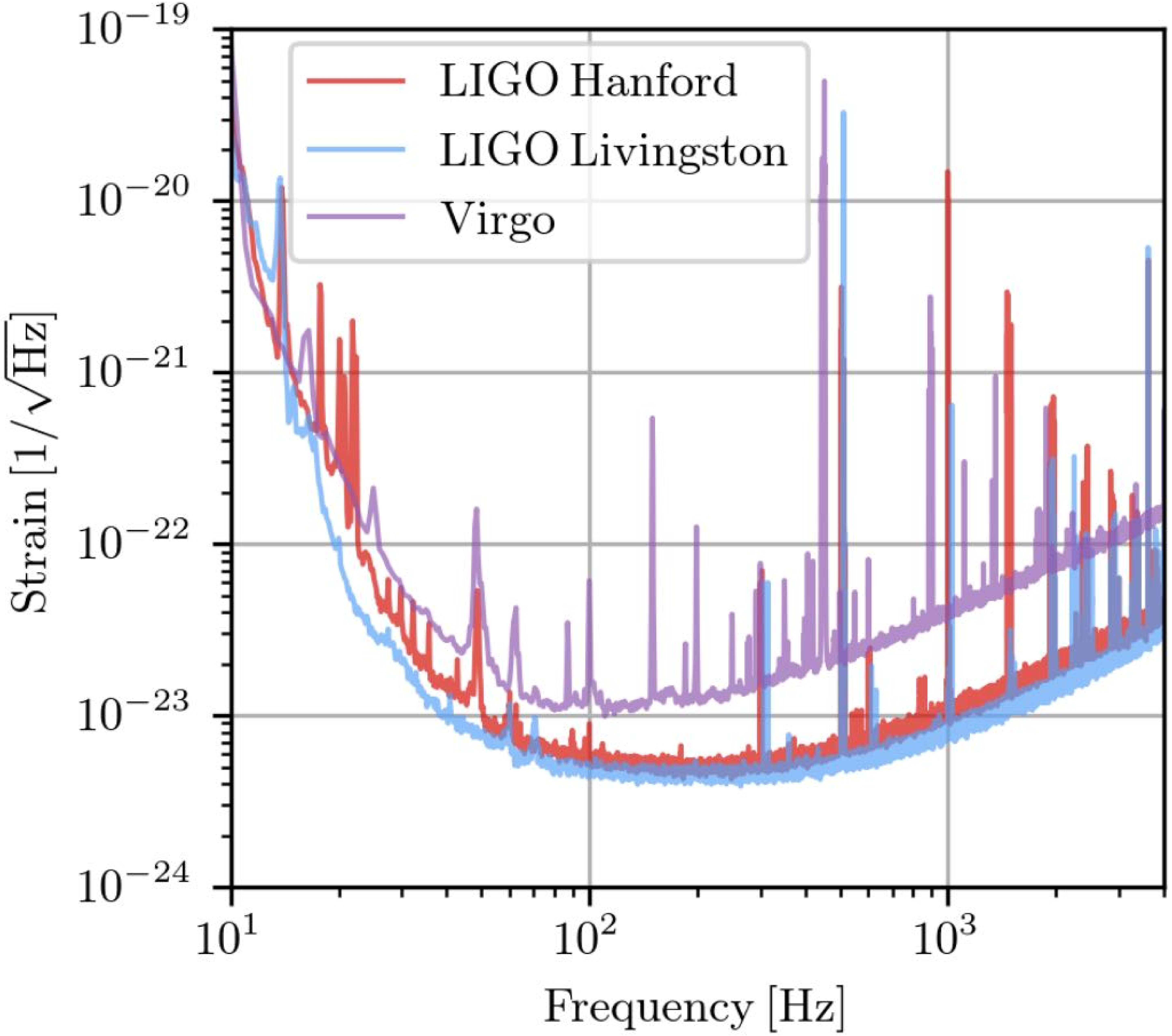
Pulsar Timing Array

Astrometry

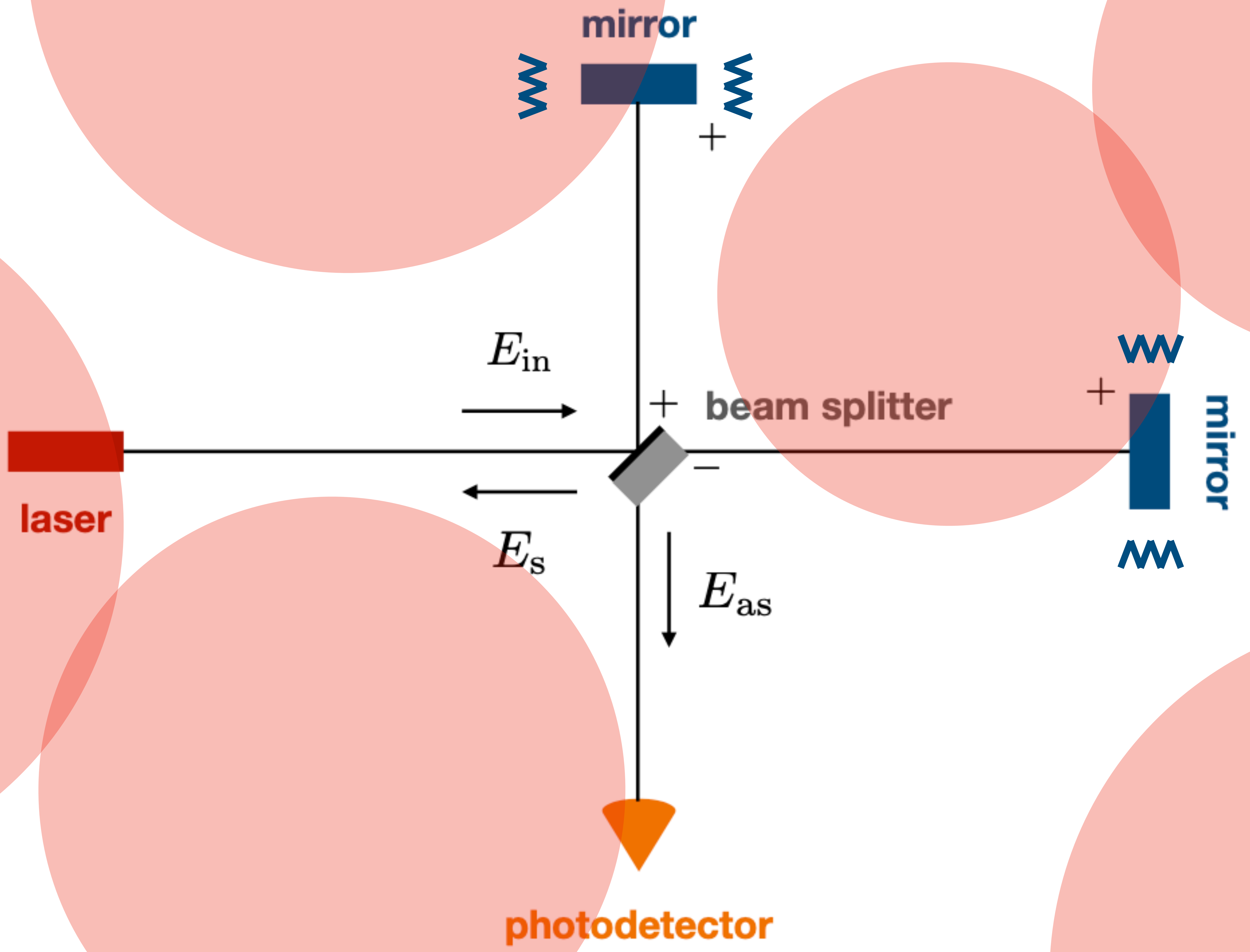




$$P = P_0 \sin^2(k\Delta L)$$



LIGO Hanford
LIGO Livingston
Virgo
Strain [1/√Hz]
Frequency [Hz]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}



mirror
$E_{\rm in}$
beam splitter
mirror
laser
$E_{\rm s}$
$E_{\rm as}$
photodetector

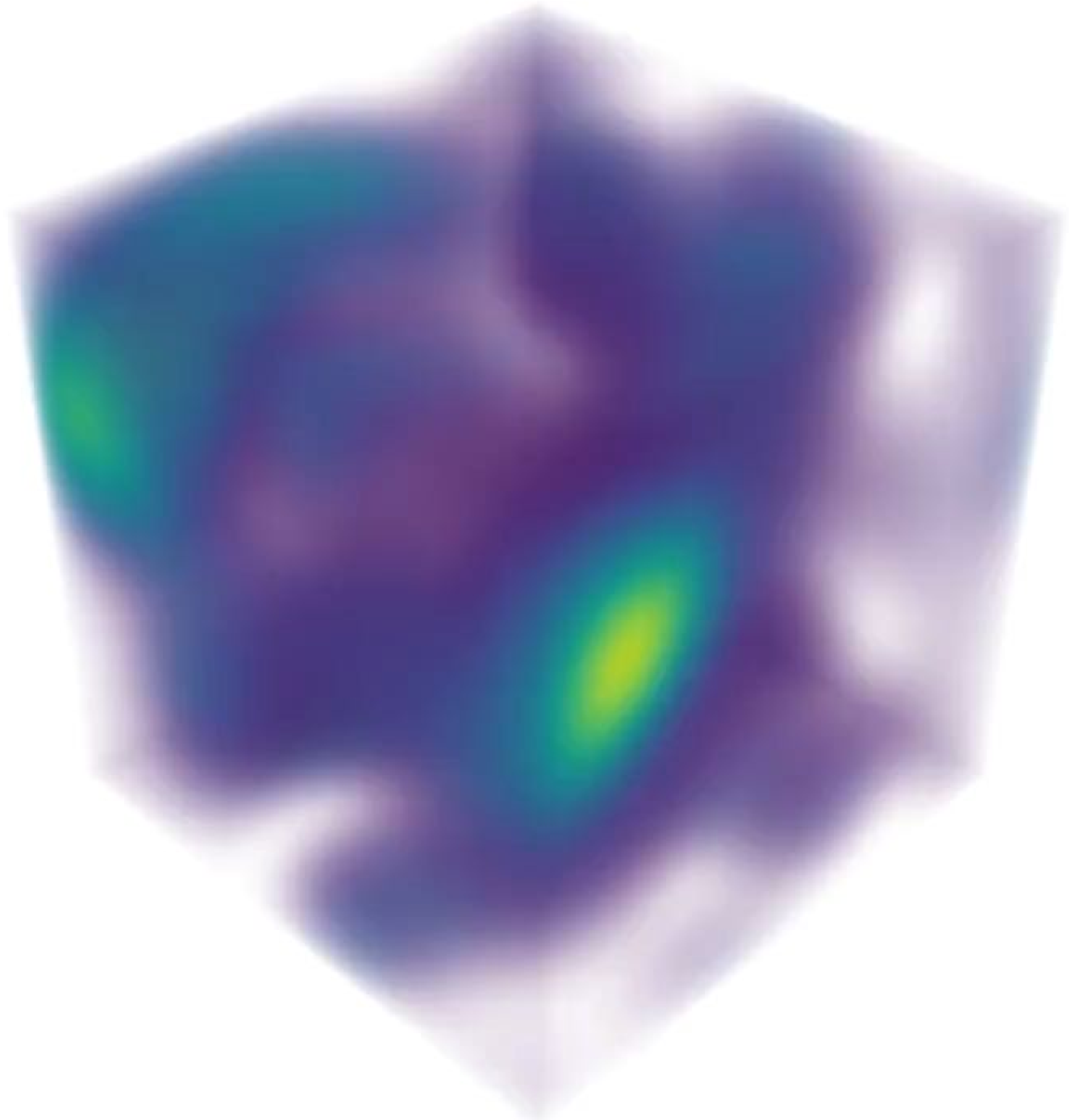
can we actually measure that?

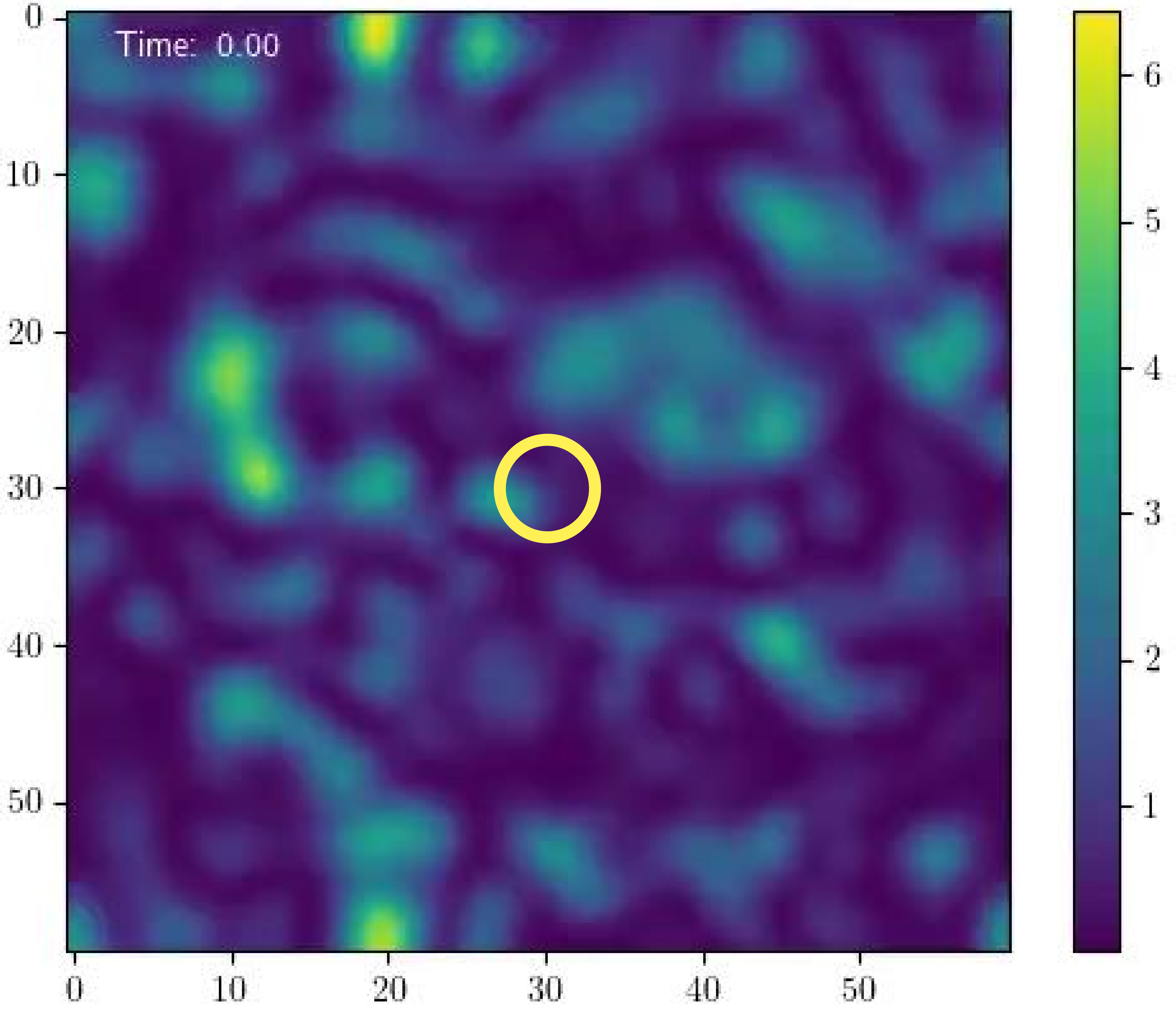
$$\ddot{x} = -\nabla\Phi$$

$$\nabla^2\Phi = 4\pi G\rho$$

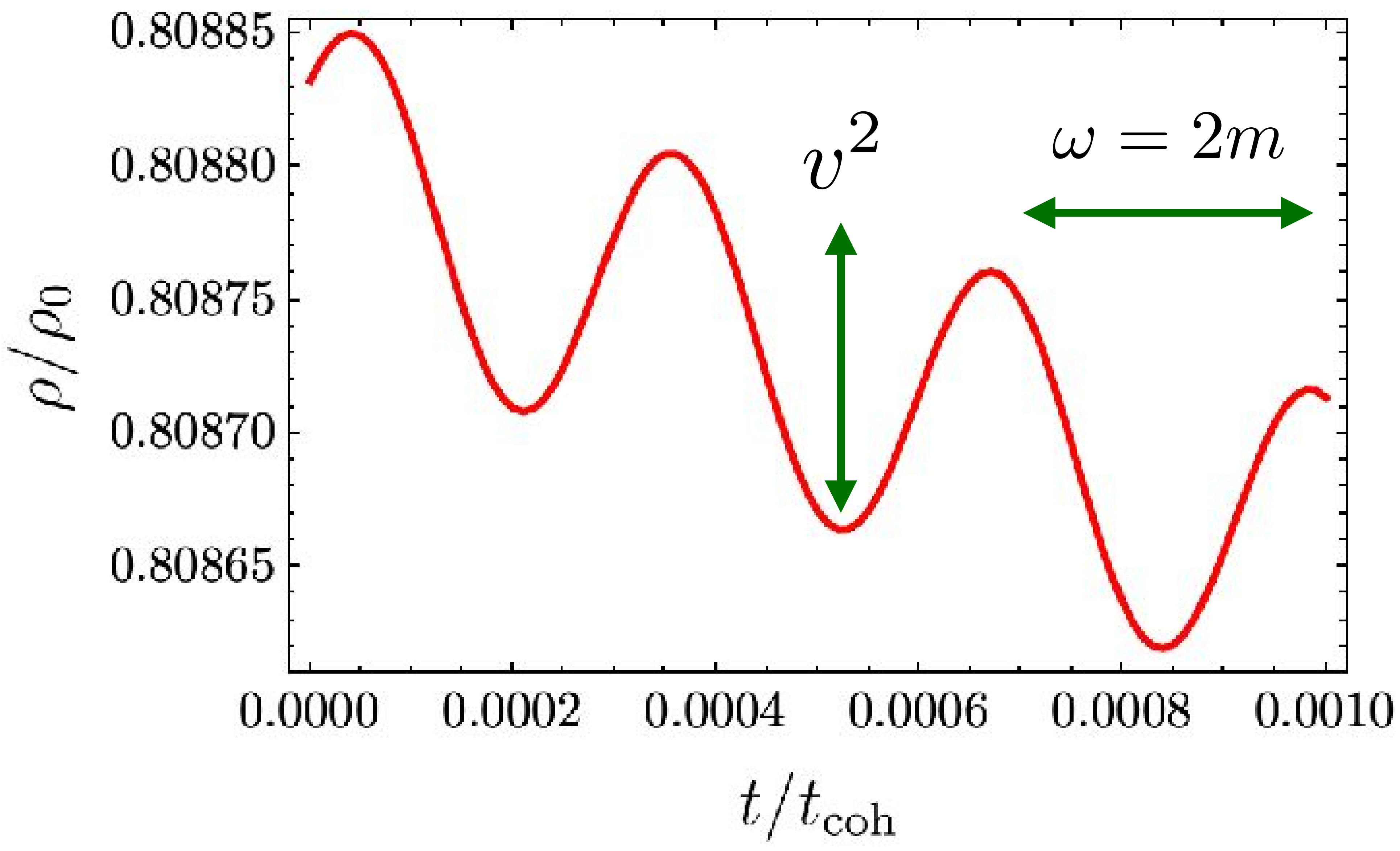
what is reflected in *detector observables*

is the *statistical properties* of density fluctuations of ULDM

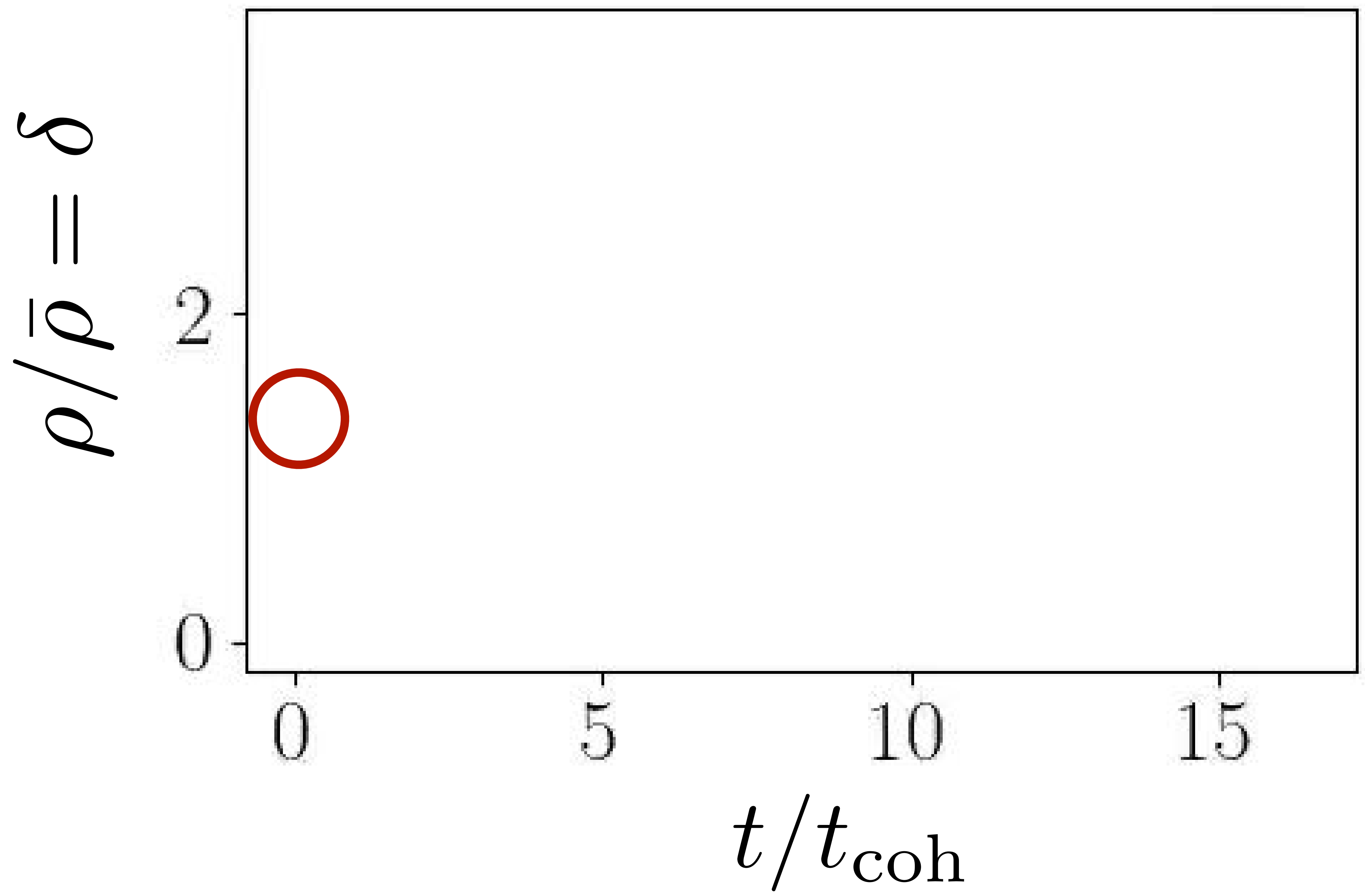




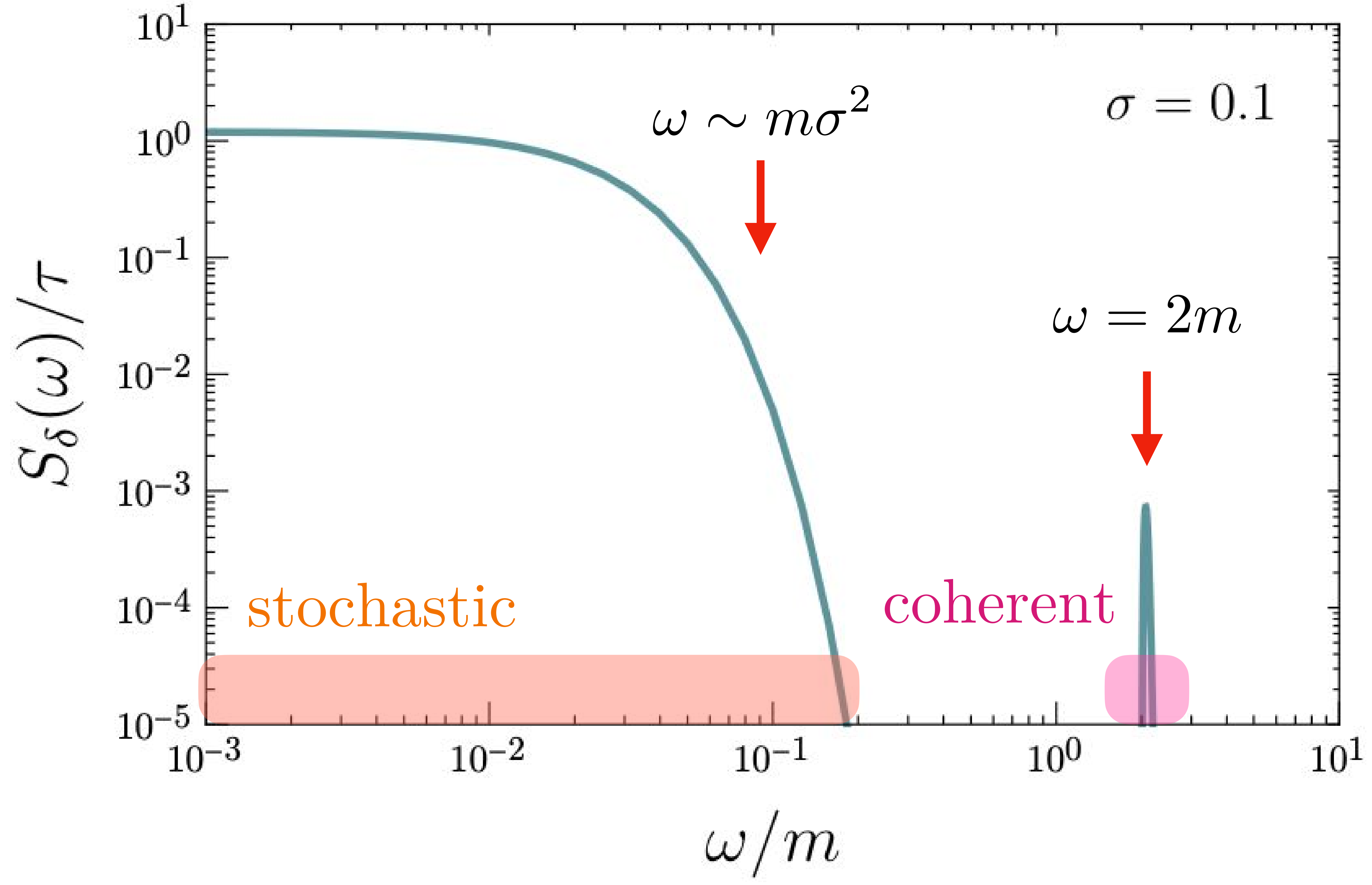
Time: 0.00

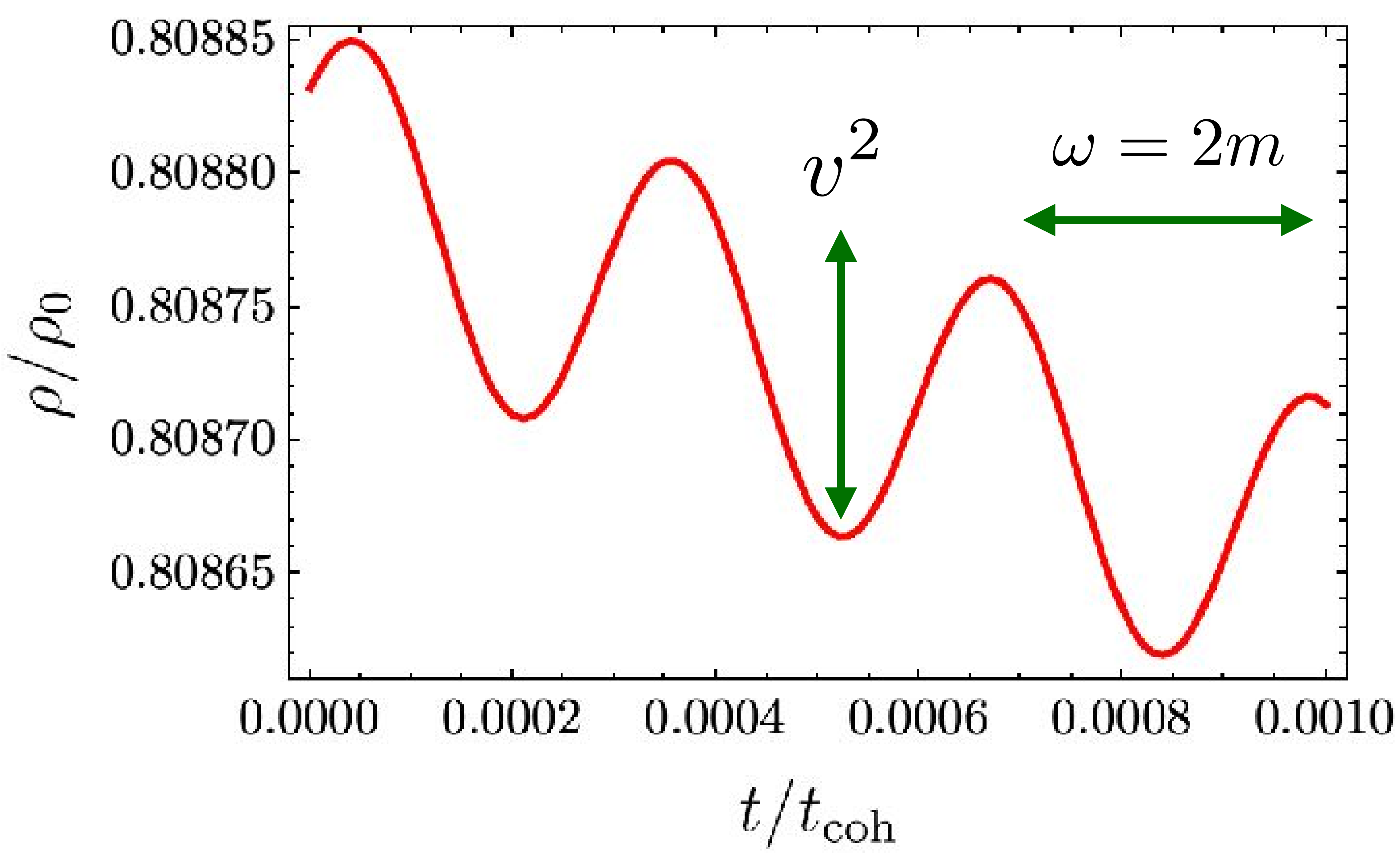


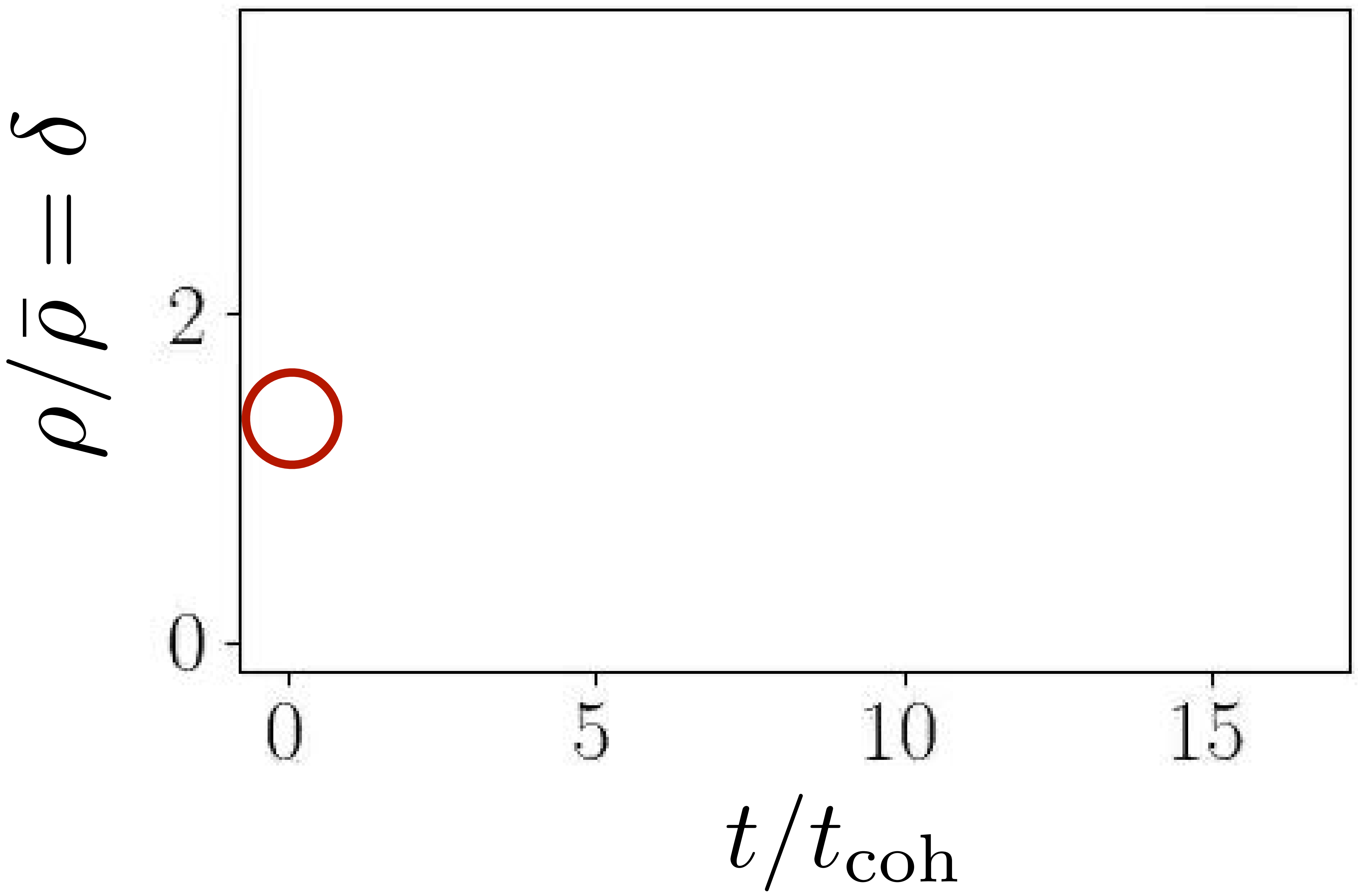
ρ/ρ_0
v^2
$\omega = 2m$
$t/t_{\rm coh}$



$\rho/\bar{\rho} = \delta$
$t/t_{\rm coh}$

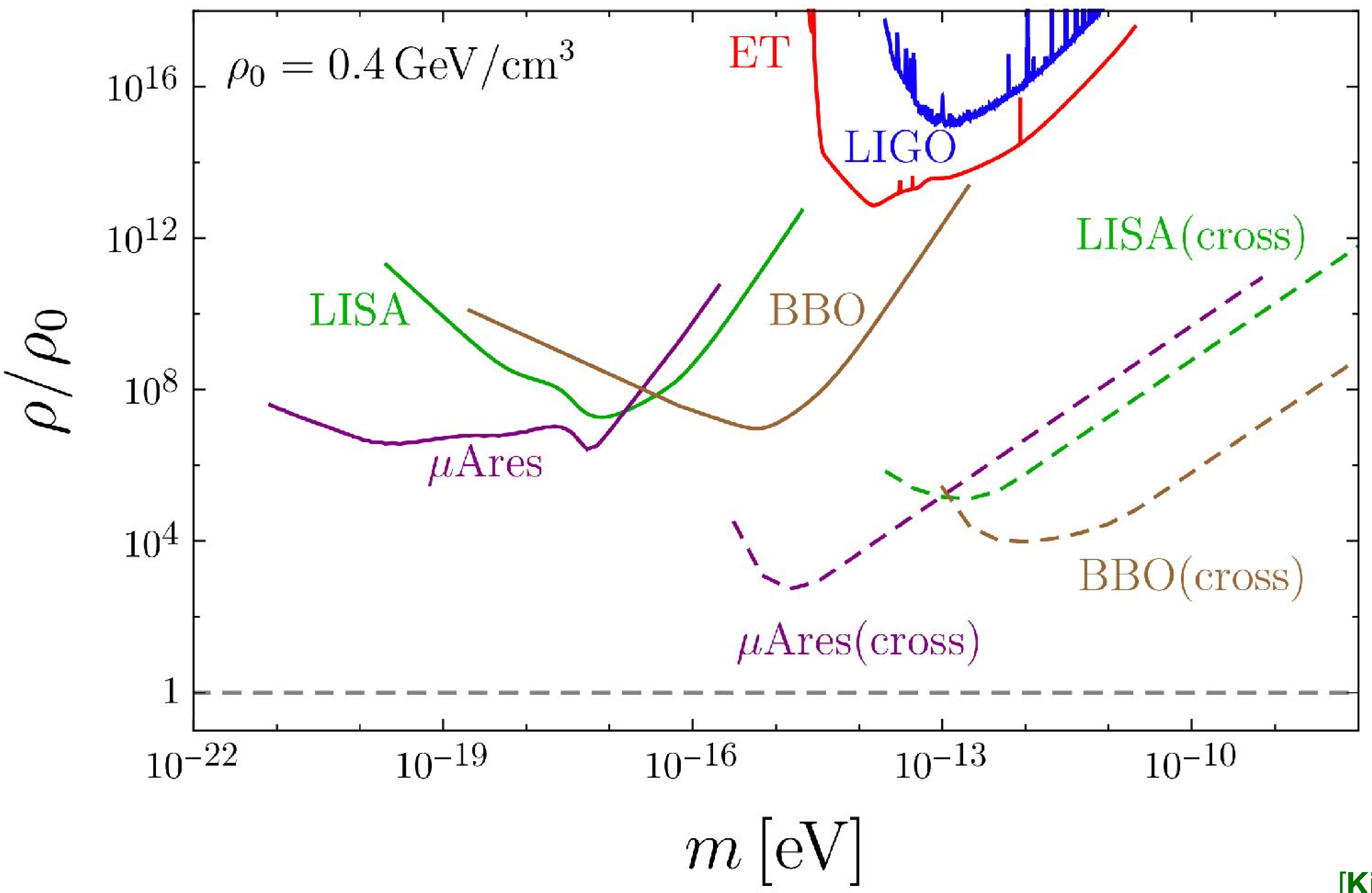






[**Kim** 2306.13348]

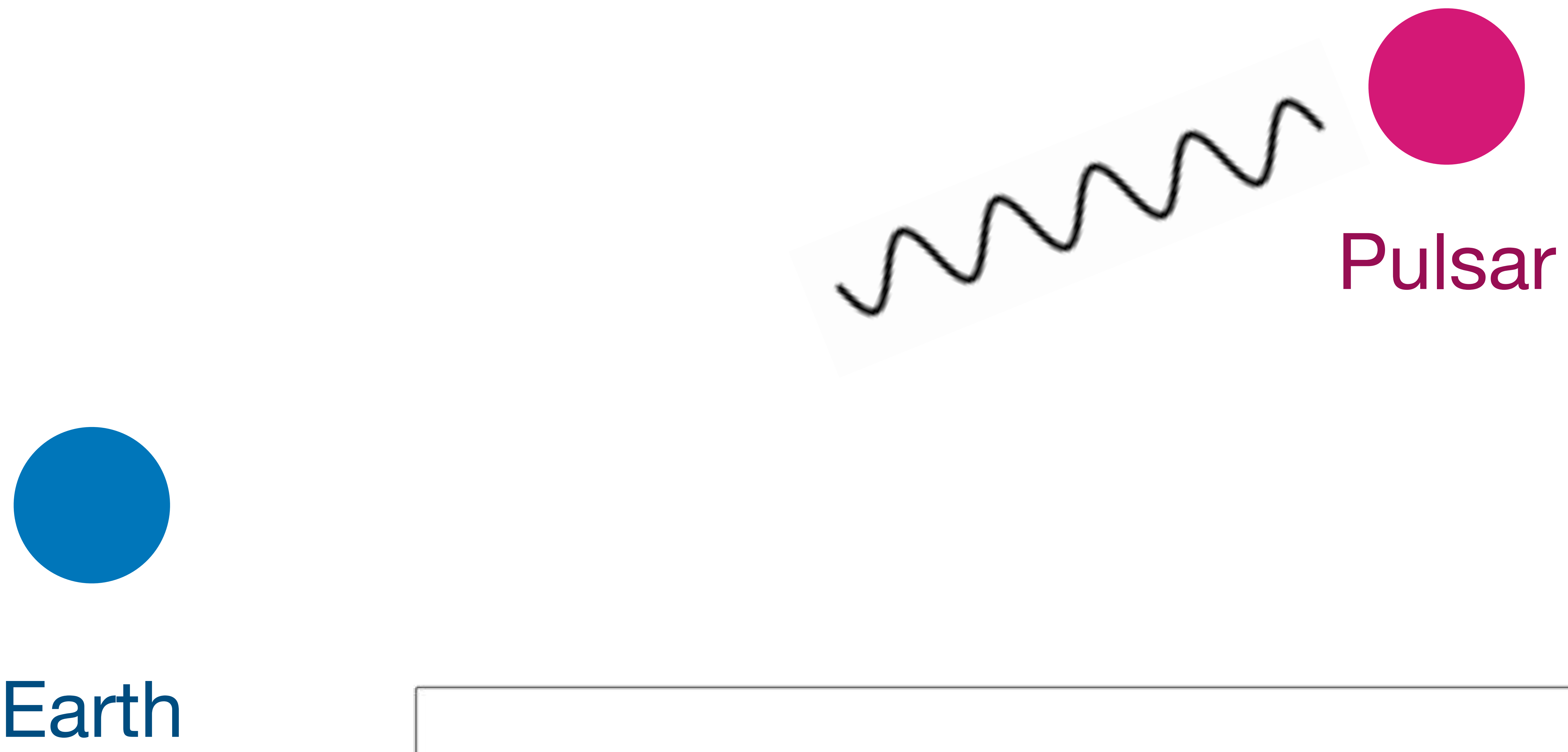
[**Kim**, Lenoci, Perez, Ratzinger, 2307.14962]

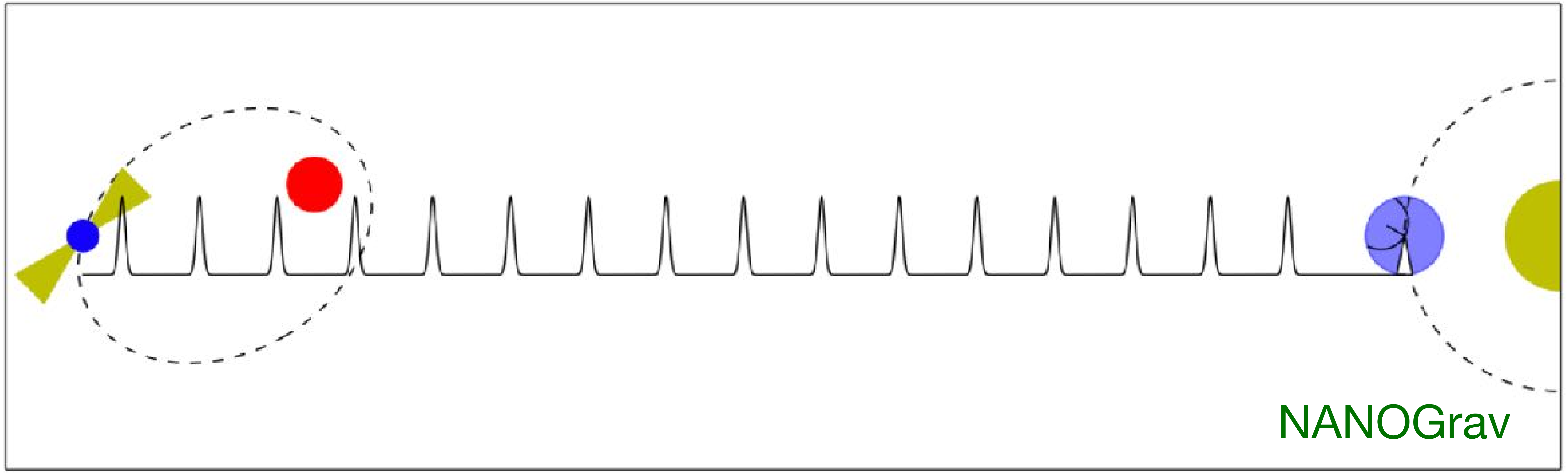


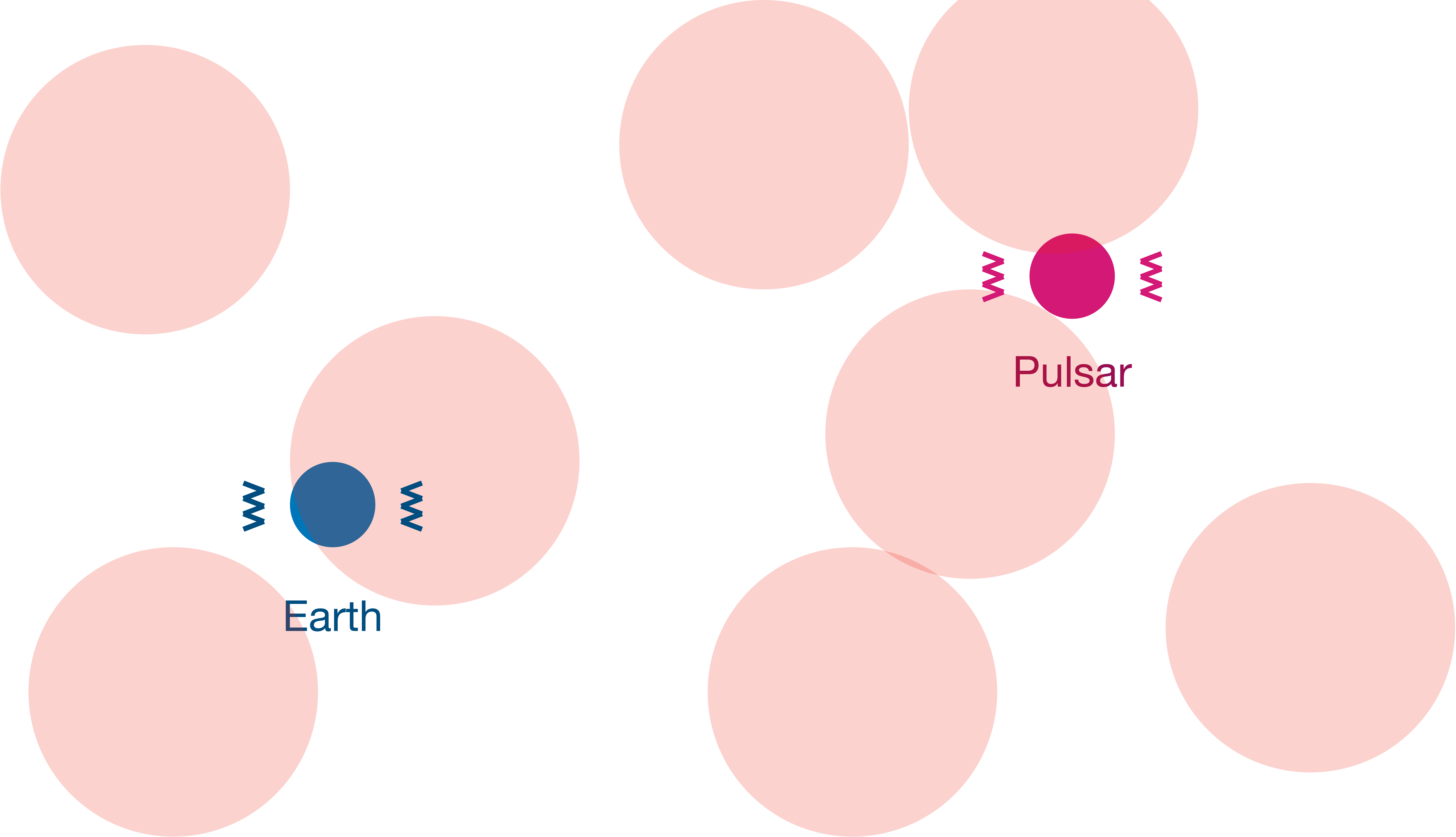
[**Kim** 2306.13348]

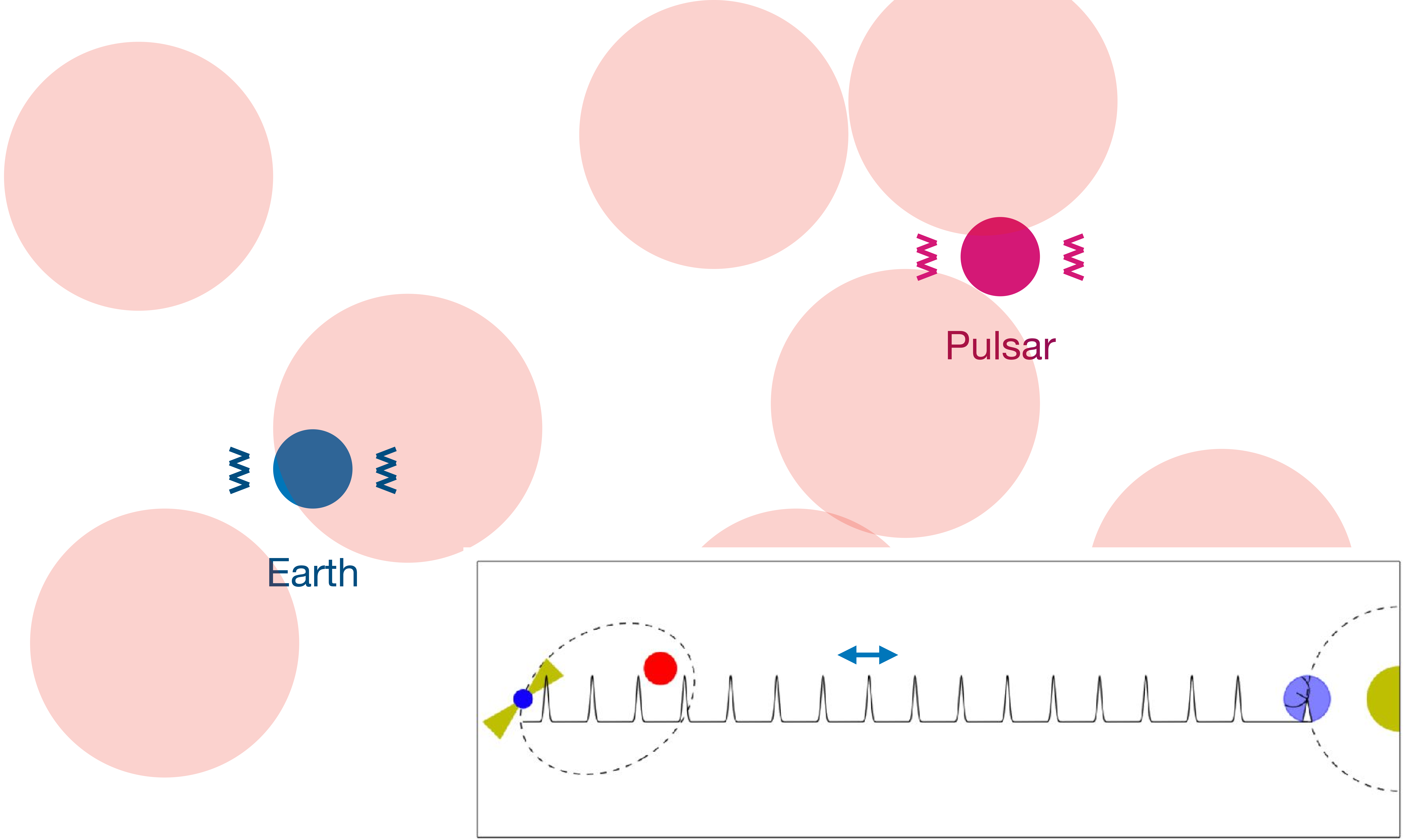
another example:

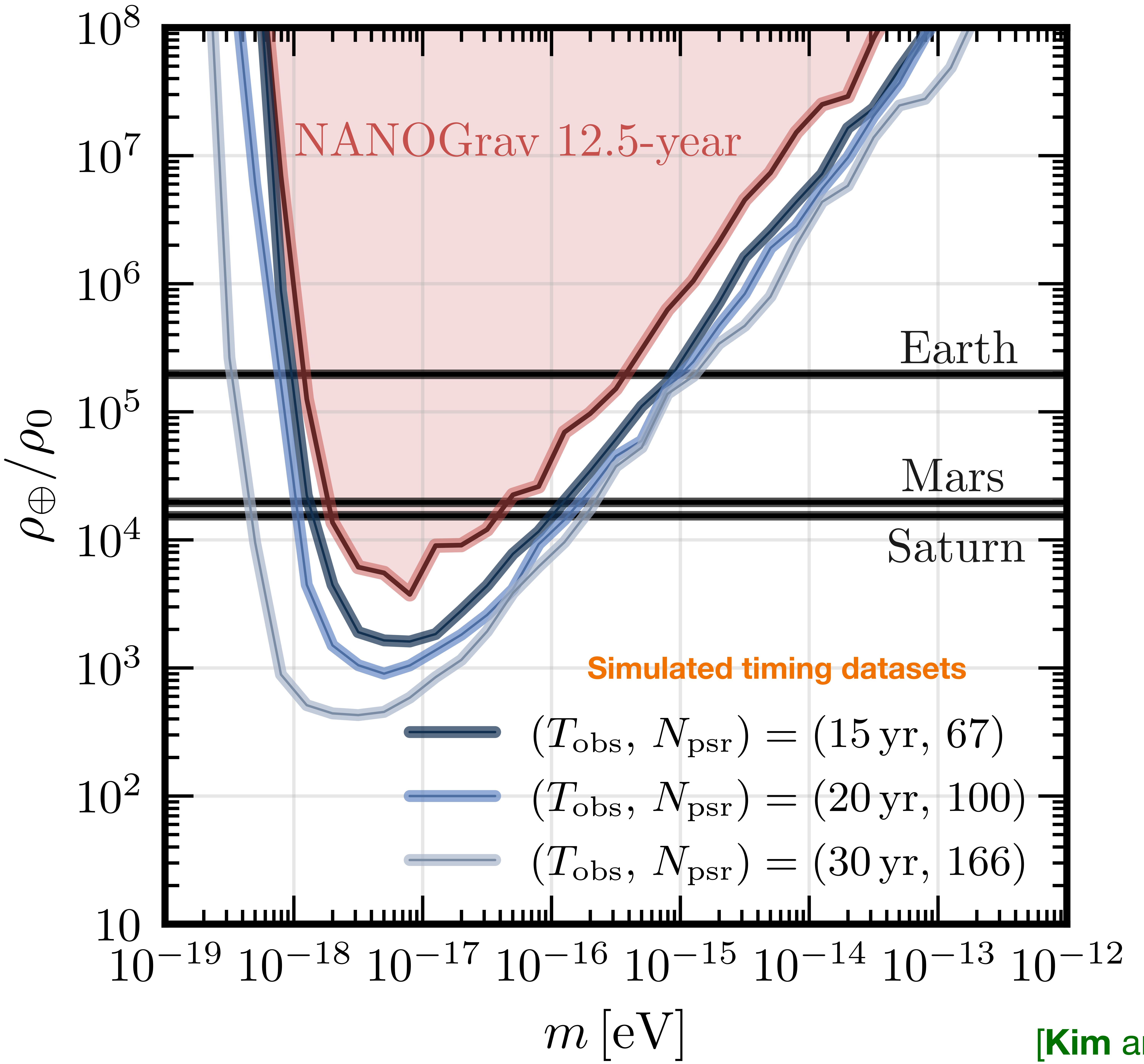
Pulsar Timing Array


Pulsar
Earth


NANOGrav


Pulsar
Earth


Pulsar
Earth



[**Kim** and Mitridate 2312.12225]

one last example:

Astrometry

astrometry involves
precision measurements of
positions / velocities of stars

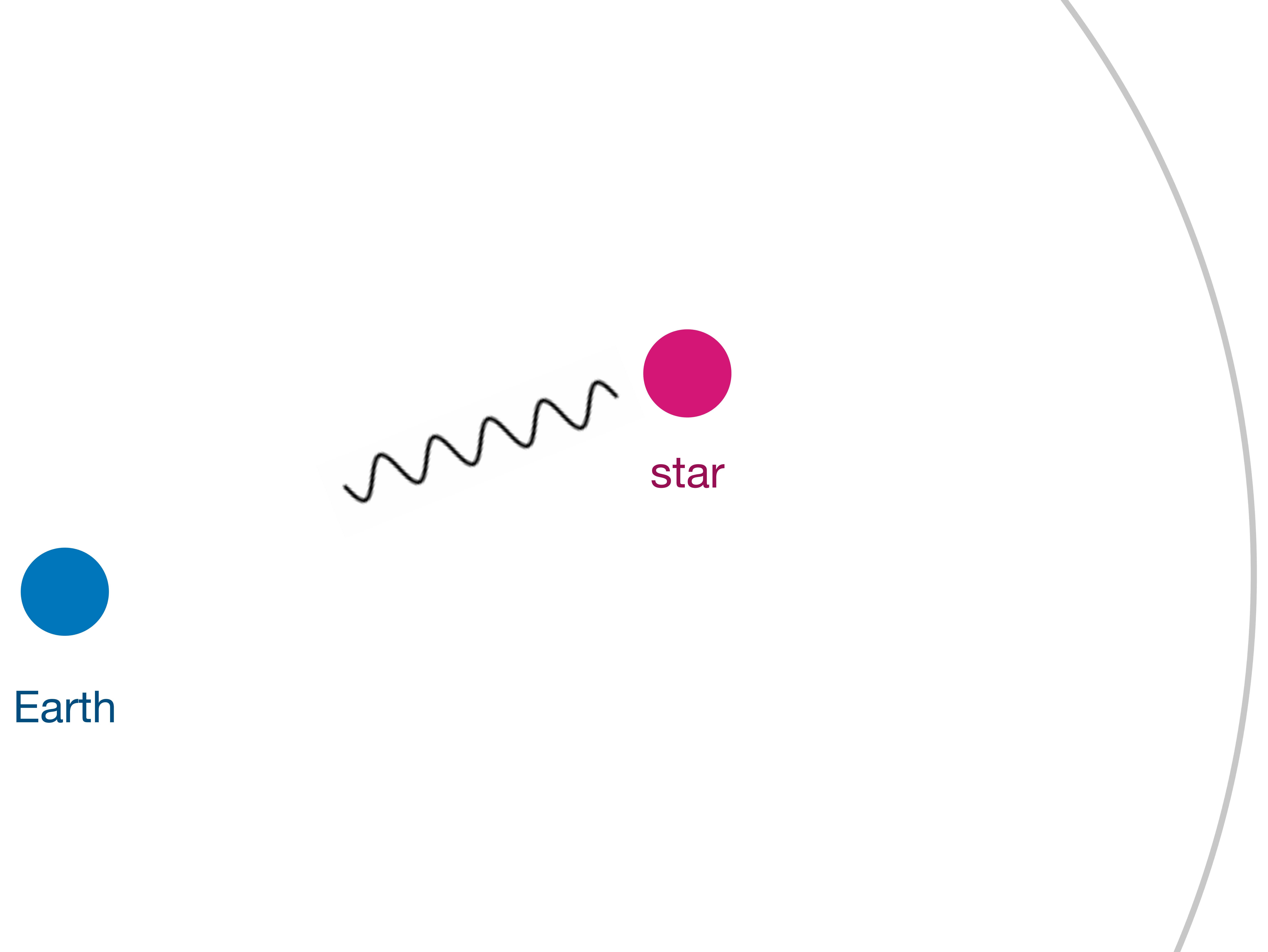
current/future astrometry missions measure

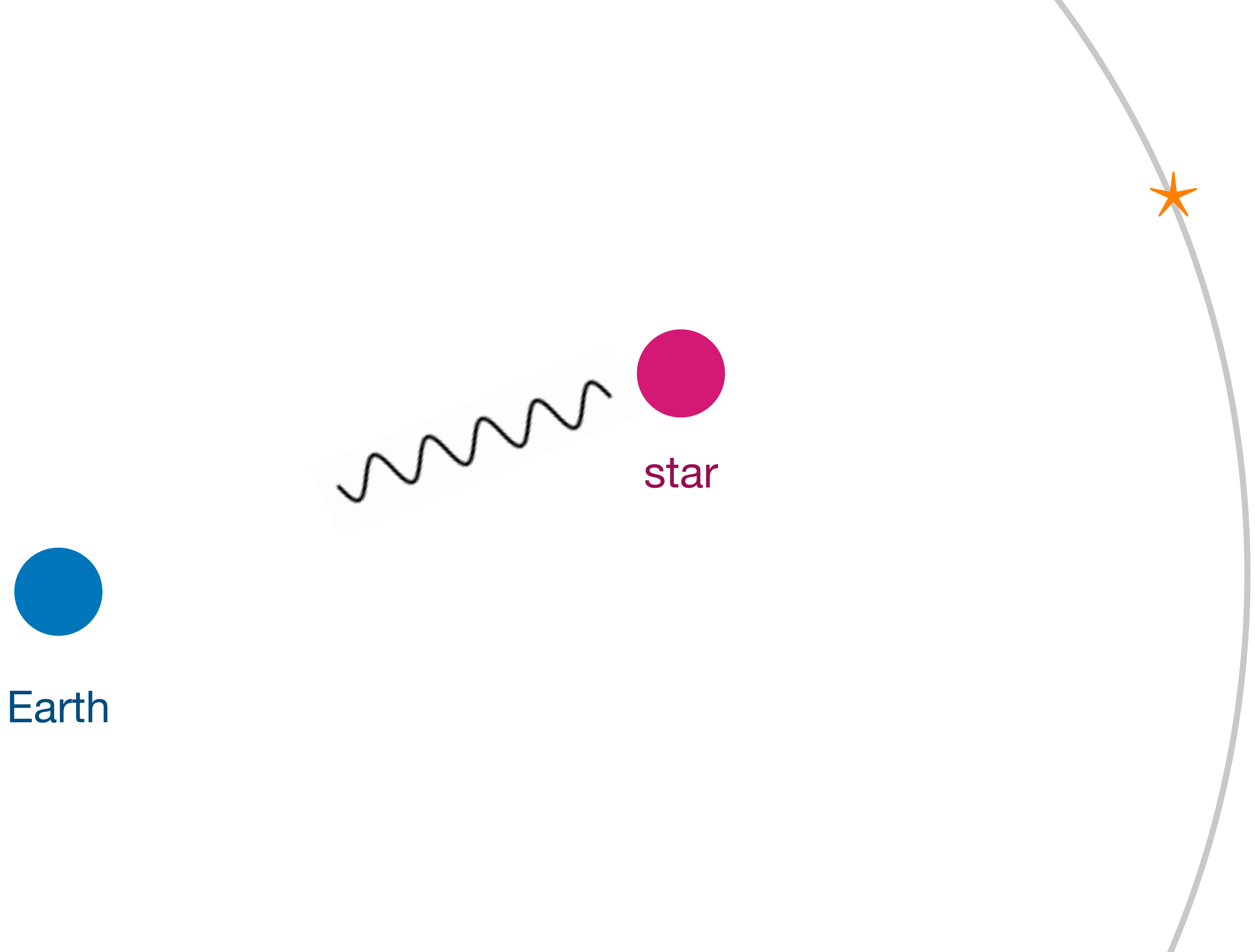
$$N_\star = 10^8 - 10^9$$

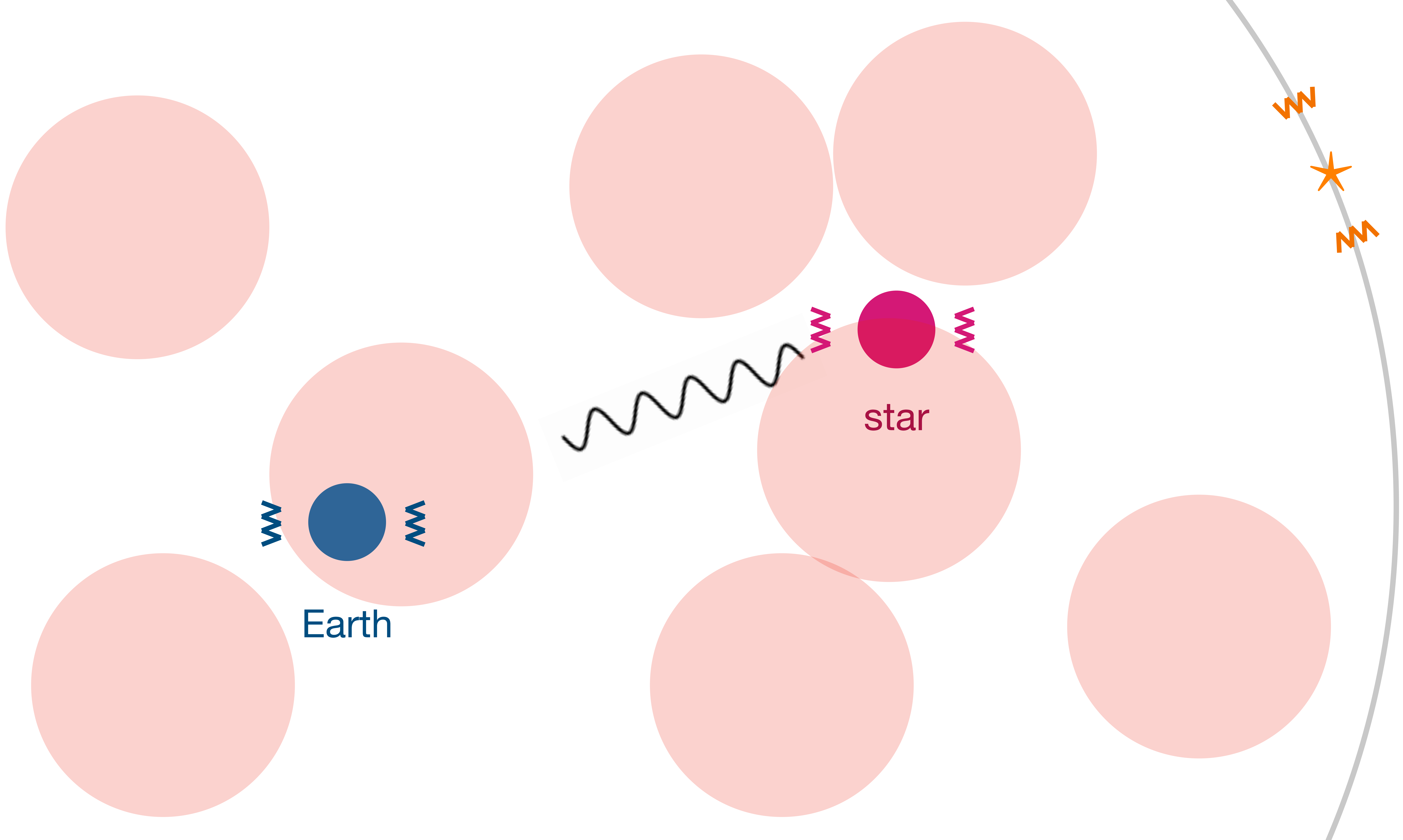
at the precision of

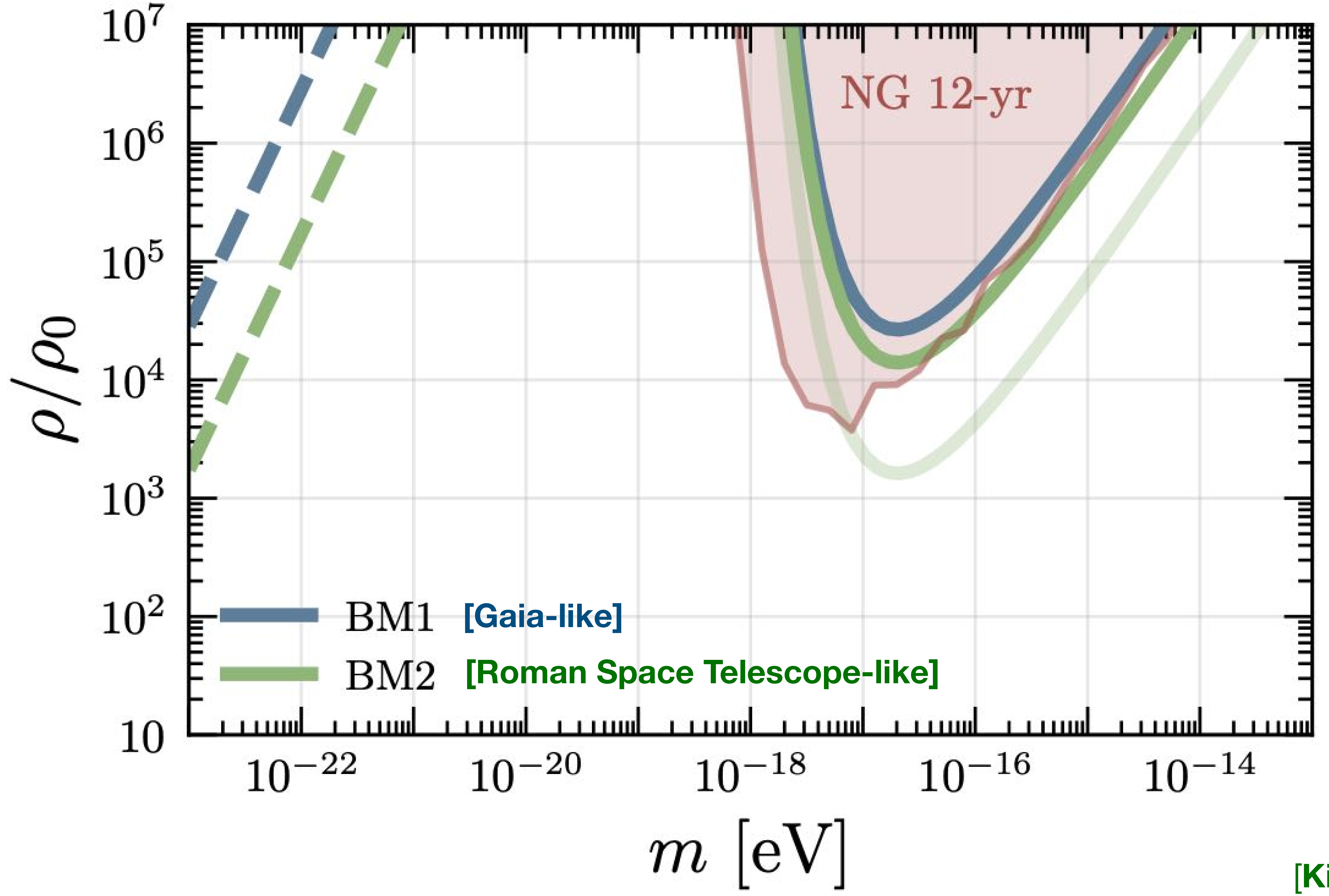
$$\Delta\theta \sim \mathcal{O}(10^2)\mu\text{as}$$

$\mu\text{as} = 5 \times 10^{-12}\,\text{rad}$


star
Earth


star
Earth


star
Earth



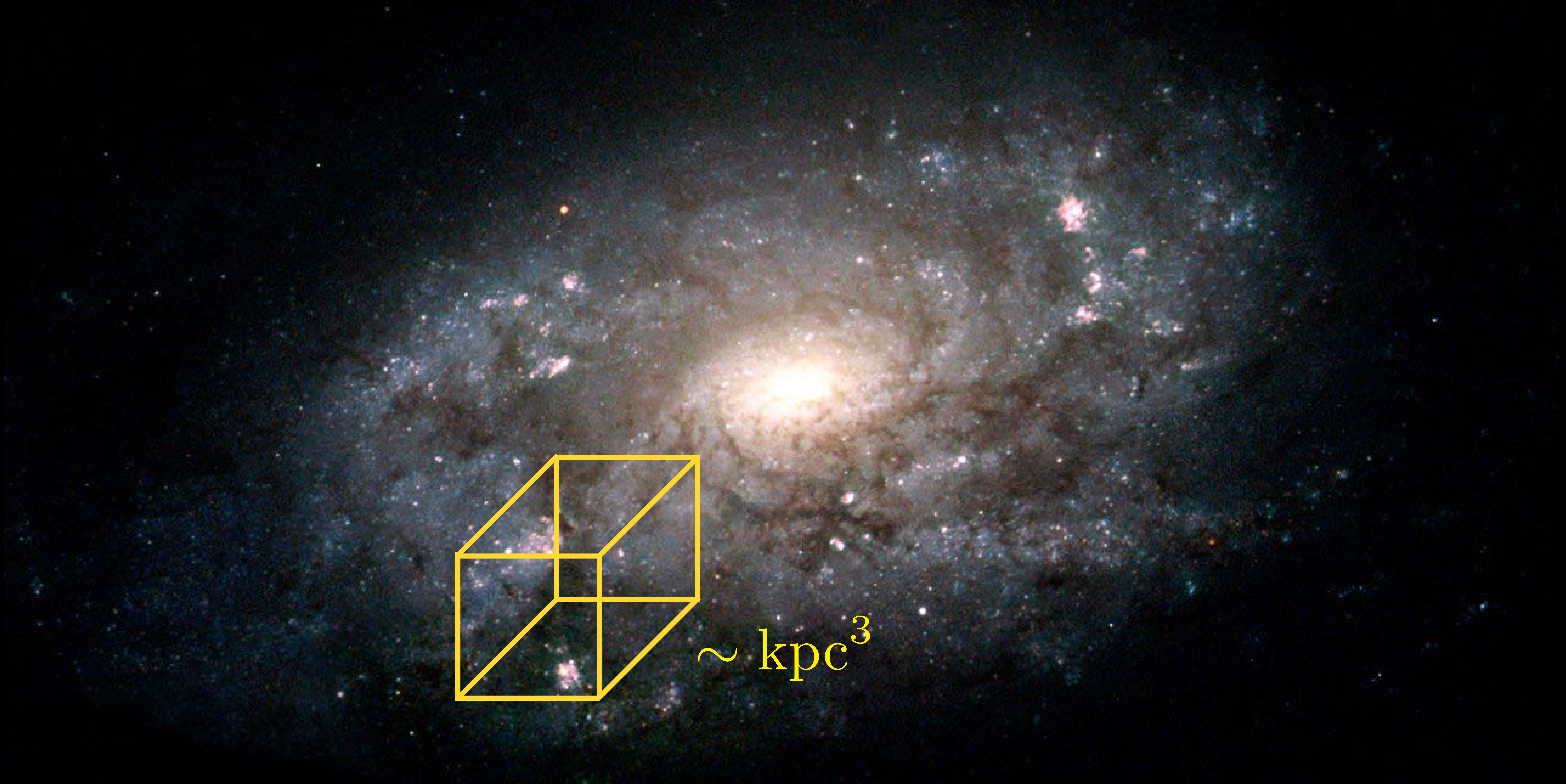
[**Kim** 2406.03539]

Remark

all of the results shown here are sensitive to

ULDM density around/within the solar system

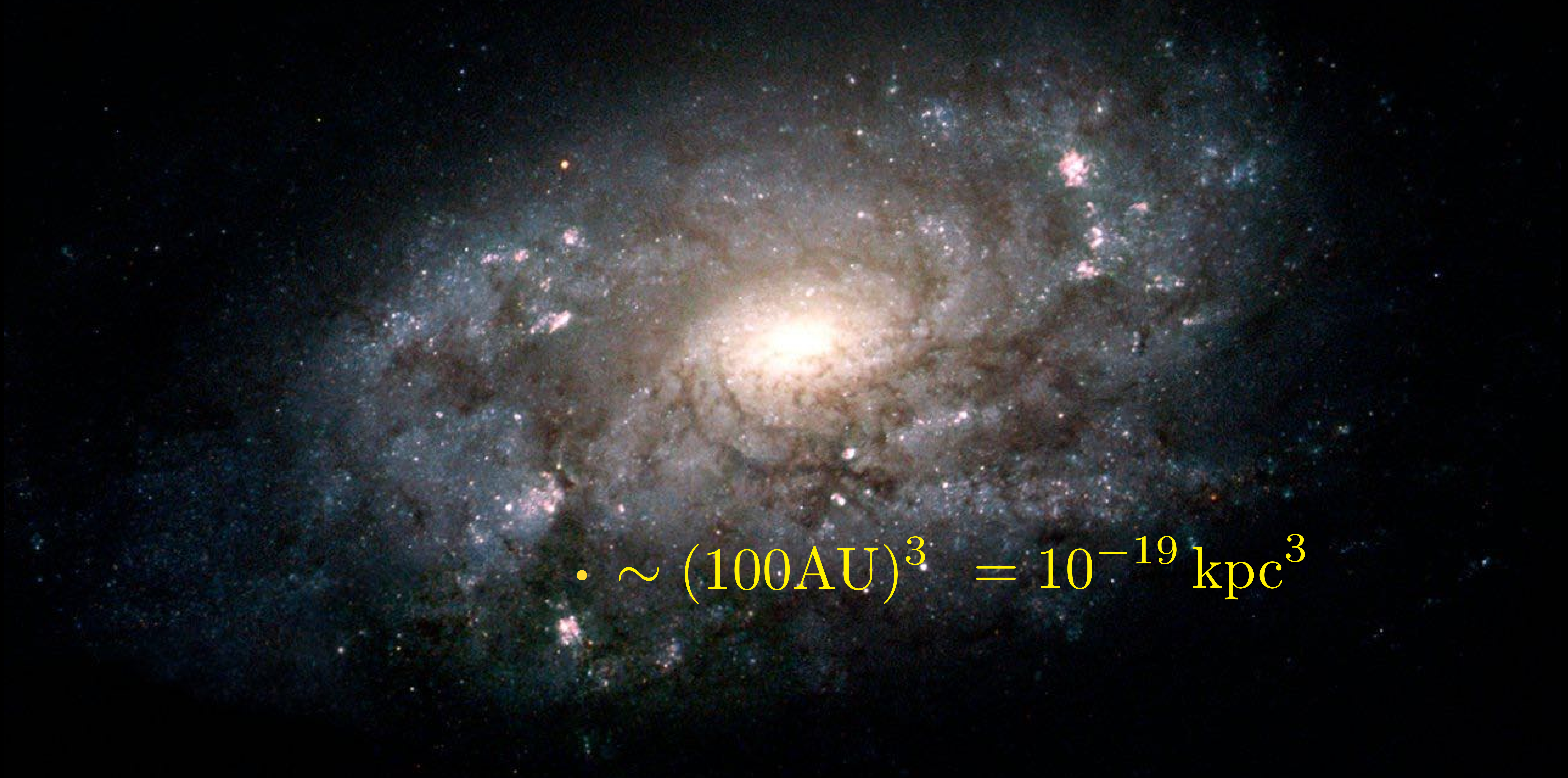
local dark matter density is often derived over kpc scales



$$\rho_0 = 0.4\,\mathrm{GeV/cm^3}$$

is an ***average density over the volume of kpc*** what we are probing is

(or what matters for all terrestrial DM detector is)



- $\sim (100\mathrm{AU})^3 \;= 10^{-19}\,\mathrm{kpc}^3$

currently no measurement on this scale exists only constraints exist

$$\rho/\rho_0 \lesssim 10^{11}$$

From geodetic satellite and LLR [Adler (08)]

$$\rho/\rho_0 \lesssim 6 \times 10^6$$

From asteroids in the solar system [Tsai et al (22)]

$$\rho/\rho_0 \lesssim 2 \times 10^4$$

From solar system ephemerides [Pitjev, Pitjeva (13)]

GW detectors will provide

one of the strongest probes of ULDM density

within/around the solar system

Laboratory Discoveries

(non-gravitationally)

ULDM may communicate with SM
via non-gravitational interaction

$$\mathcal{L} = h(\theta)\mathcal{O}_{\rm SM}$$

$$\mathcal{O}_{\rm SM} = \{\alpha^{-1}FF,\, m_\psi\bar{\psi}\psi,\, \cdots\}$$

ULDM may communicate with SM
via non-gravitational interaction

$$\mathcal{L} = h(\theta)\mathcal{O}_{\mathrm{SM}}$$

$h(\theta) = \theta$ Relaxation-type [Banerjee, **Kim**, Perez 2017] [Banerjee, **Kim** et al 2020]

$= \theta^2$ QCD Axion [**Kim** and Perez 2022] [**Kim** et al 2024] [Beadle et al 2004]

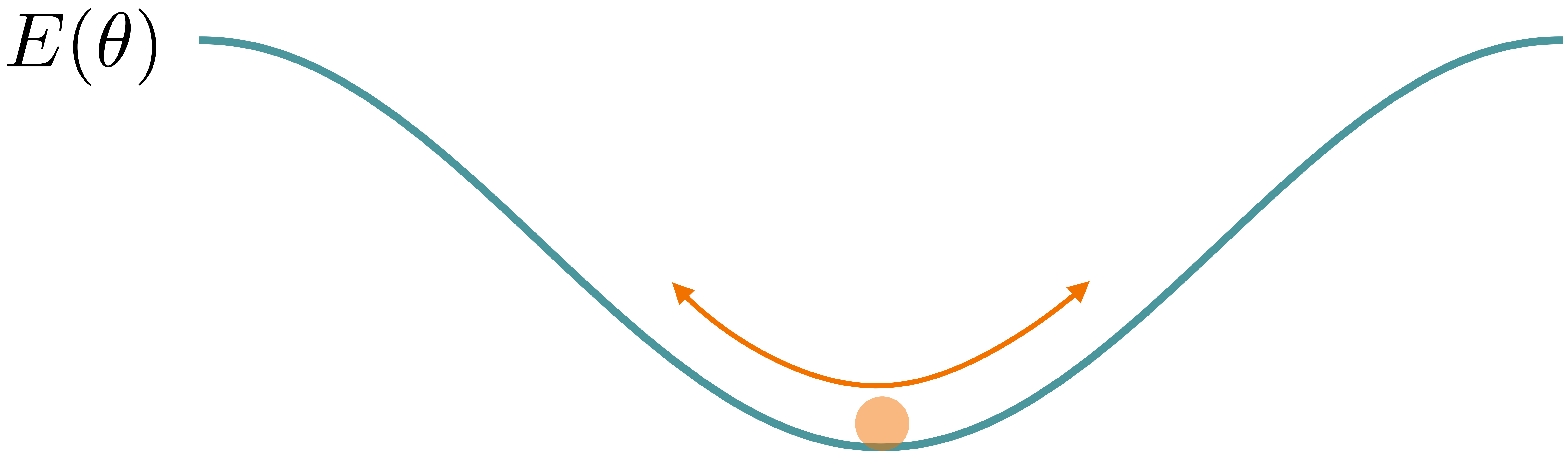
$$\mathcal{L} = \frac{1}{\alpha_0}\left(1 + g\theta^n\right)FF \equiv \frac{1}{\alpha}FF$$

$$\downarrow$$

$$\alpha(t) = \alpha_0\left[1 - g\theta^n(t)\right]$$

$$\delta\alpha/\alpha = -g\theta^n(t)$$

as it oscillates around the minimum

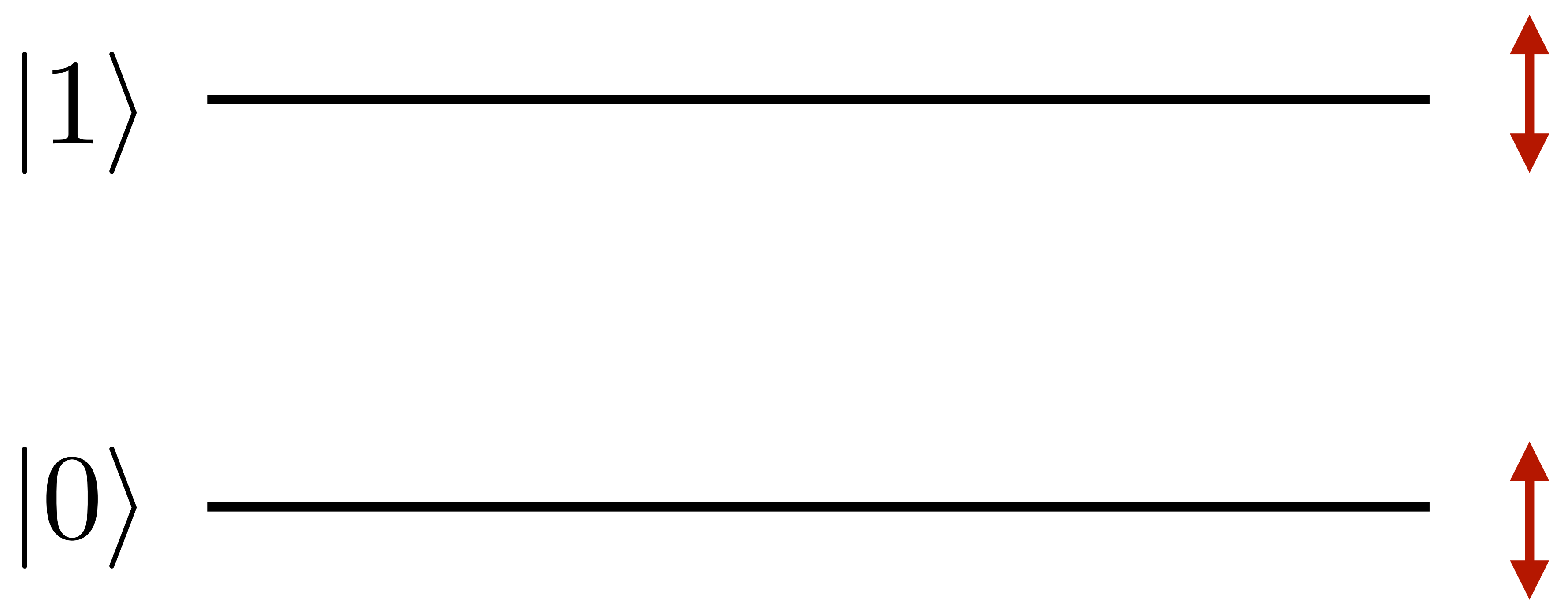


fundamental constants also oscillates in time

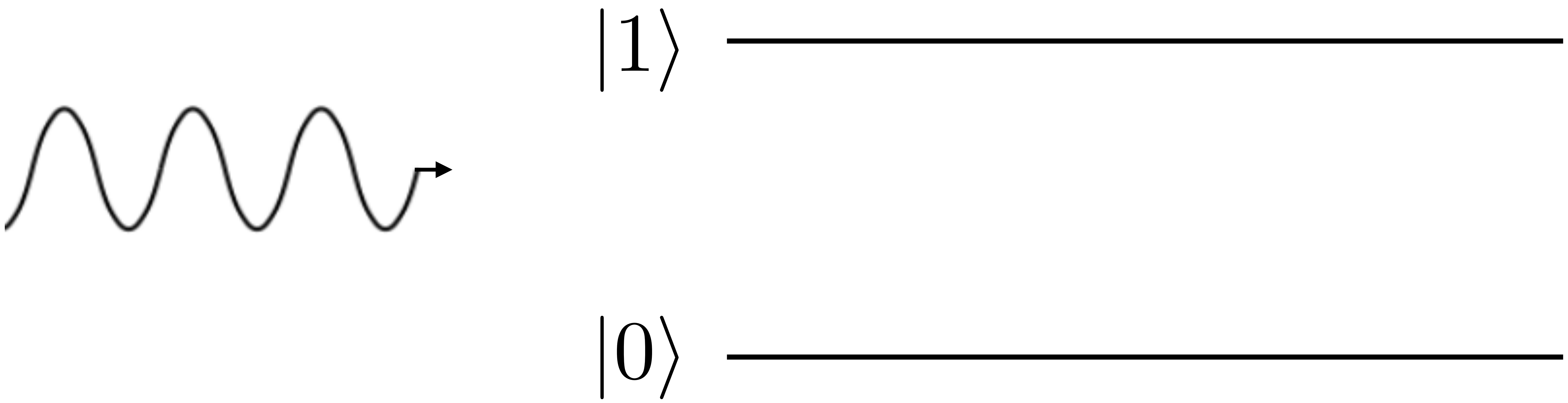
$$\alpha(t) = \alpha_0 [1 - g\theta^n(t)]$$

A new probe of ULDM

Time-oscillation of atomic energy levels

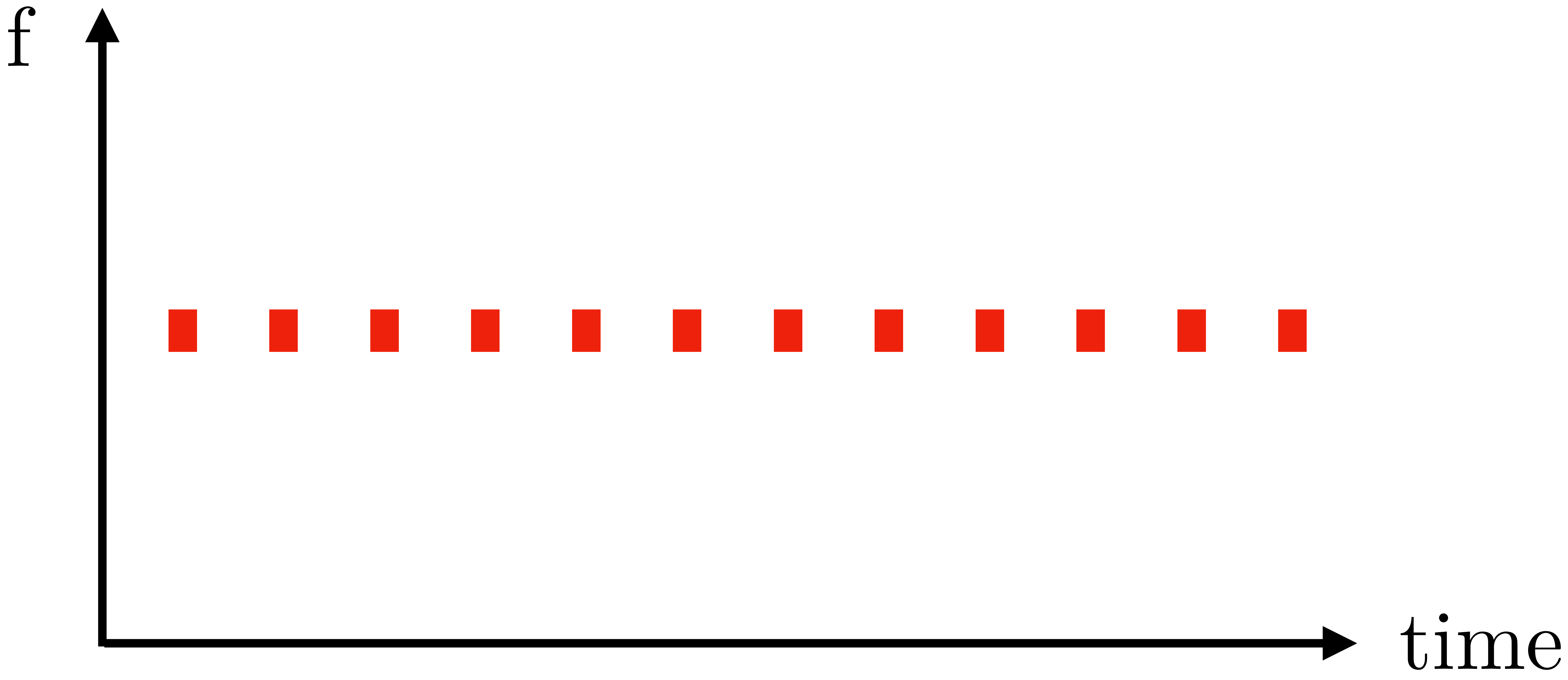


interrogate two-level system regularly

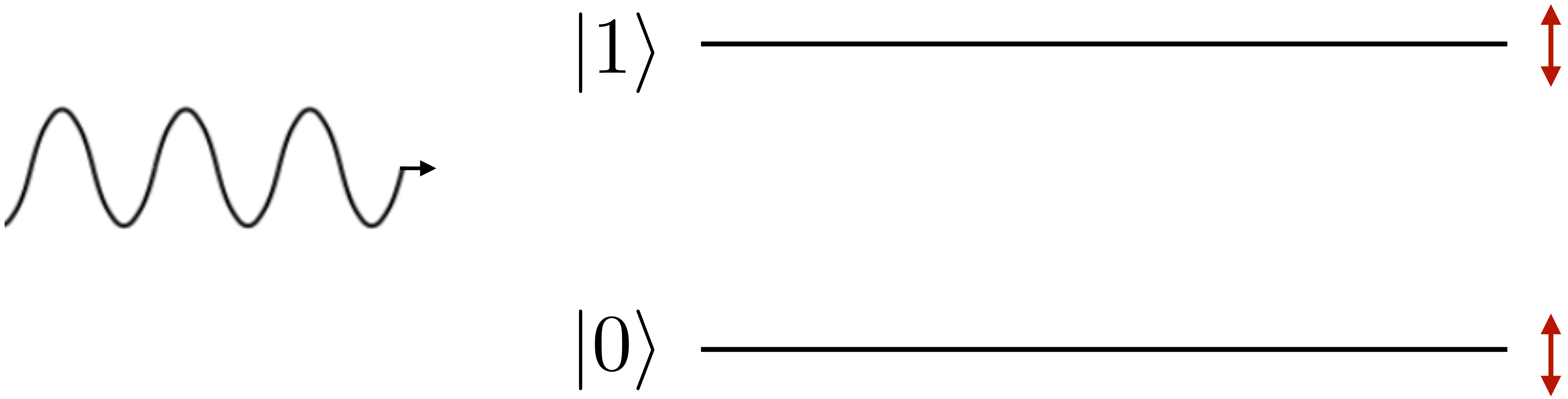


measure the level splitting

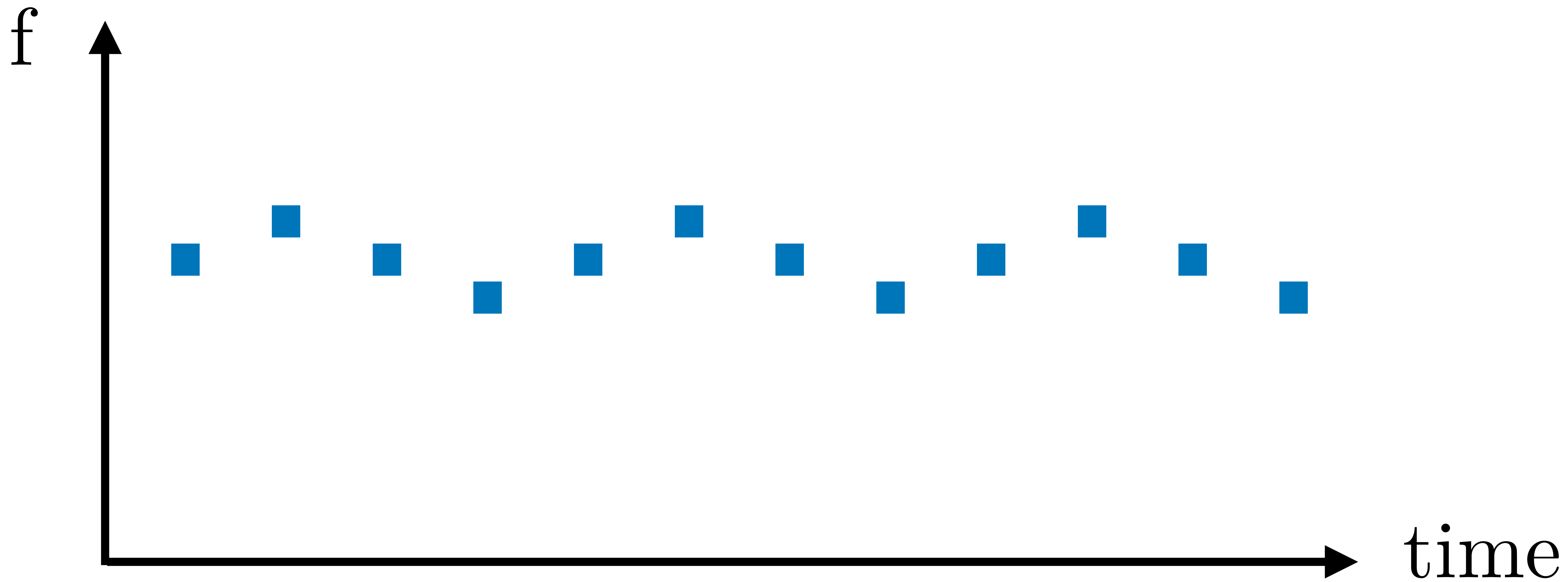
without axion, this would give us



Now the same experiment
but with ultralight dark matter

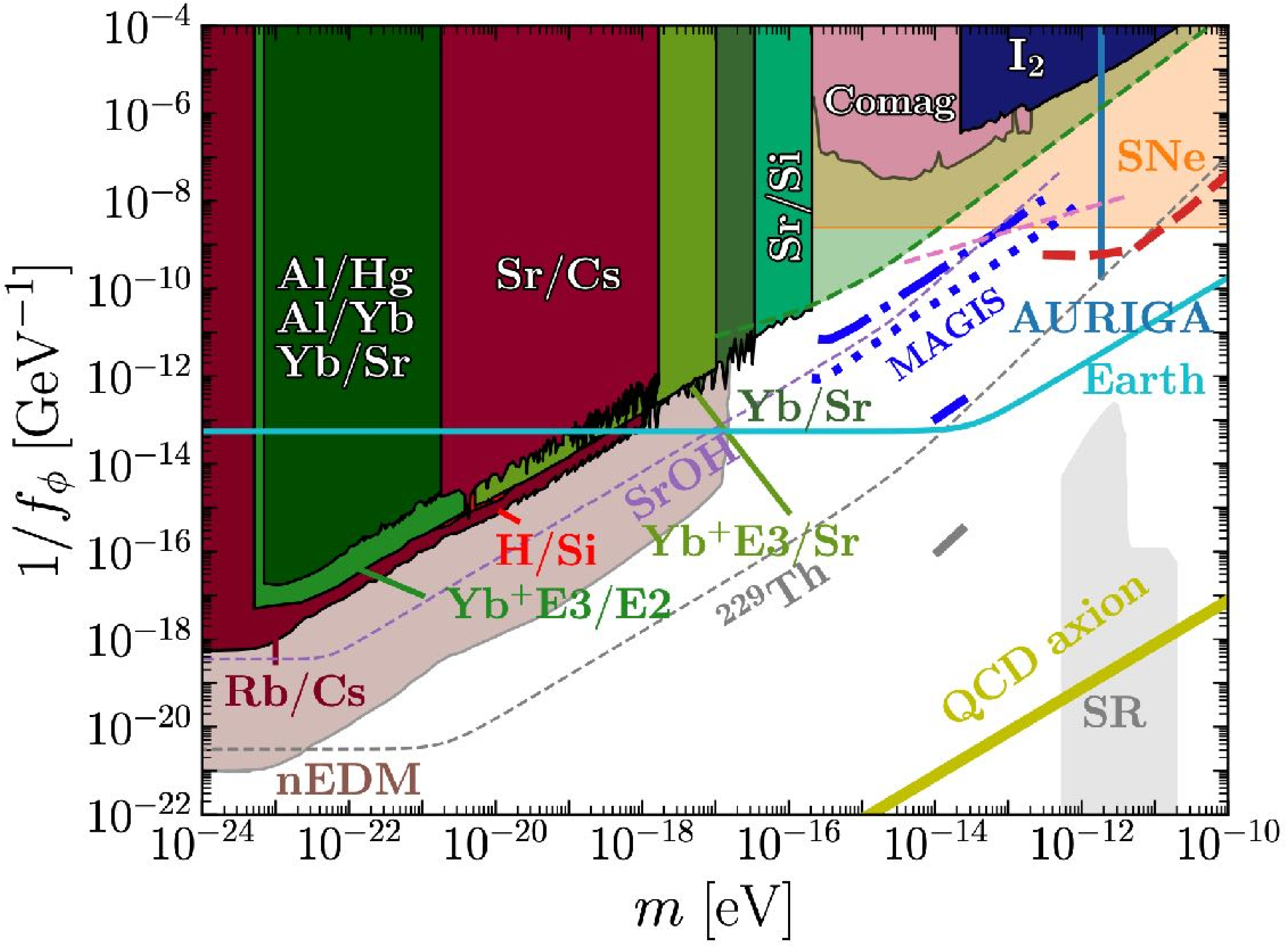


this time, the result would look like



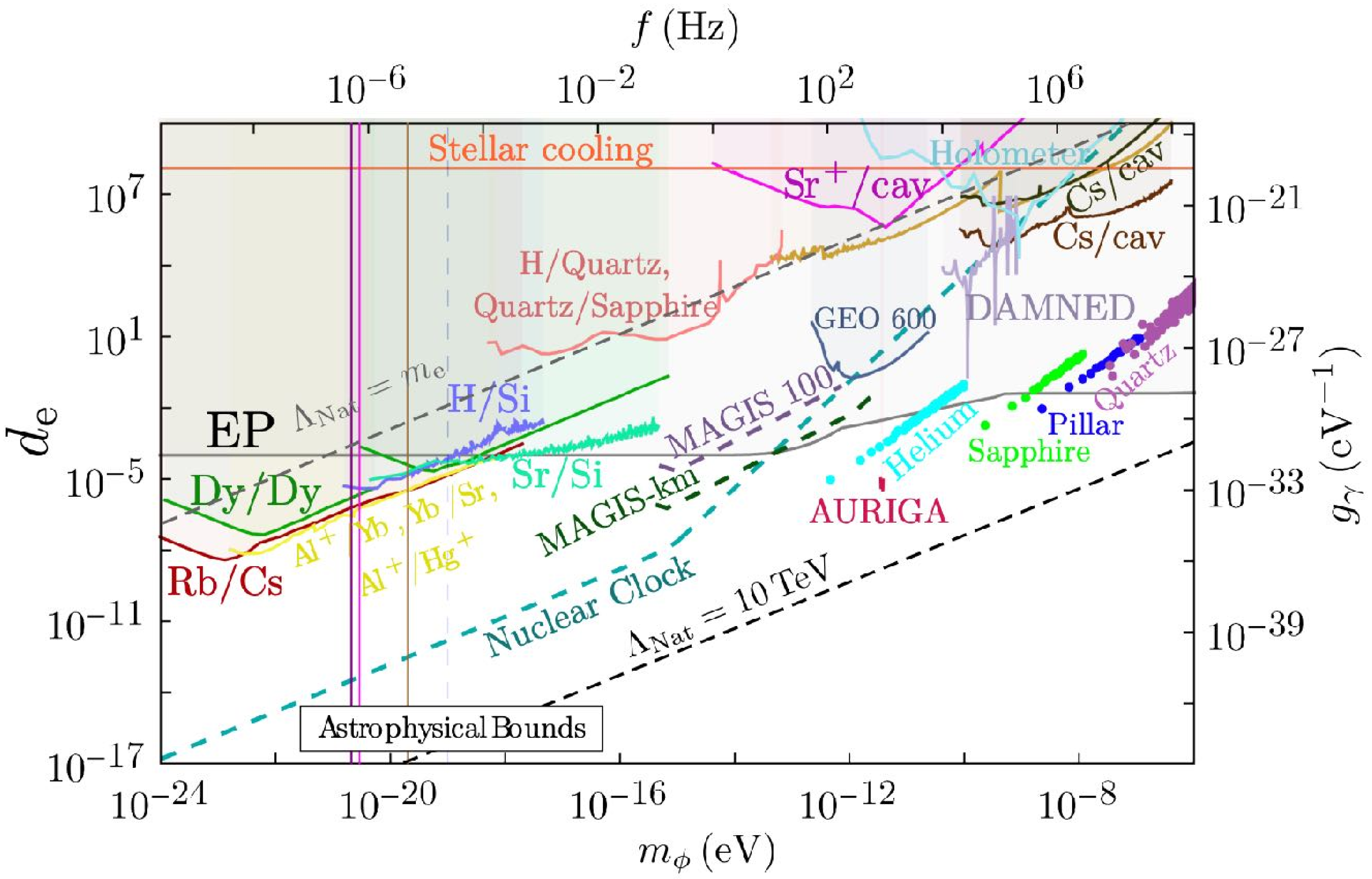
by looking for ULDM-induced signal
oscillations of energy level could be probed

$$h(\theta) = \theta^2$$



[**Kim**, Lenoci, Perez, Ratzinger (23)]
[**Kim** and Perez (22)]

$$h(\theta) = \theta$$



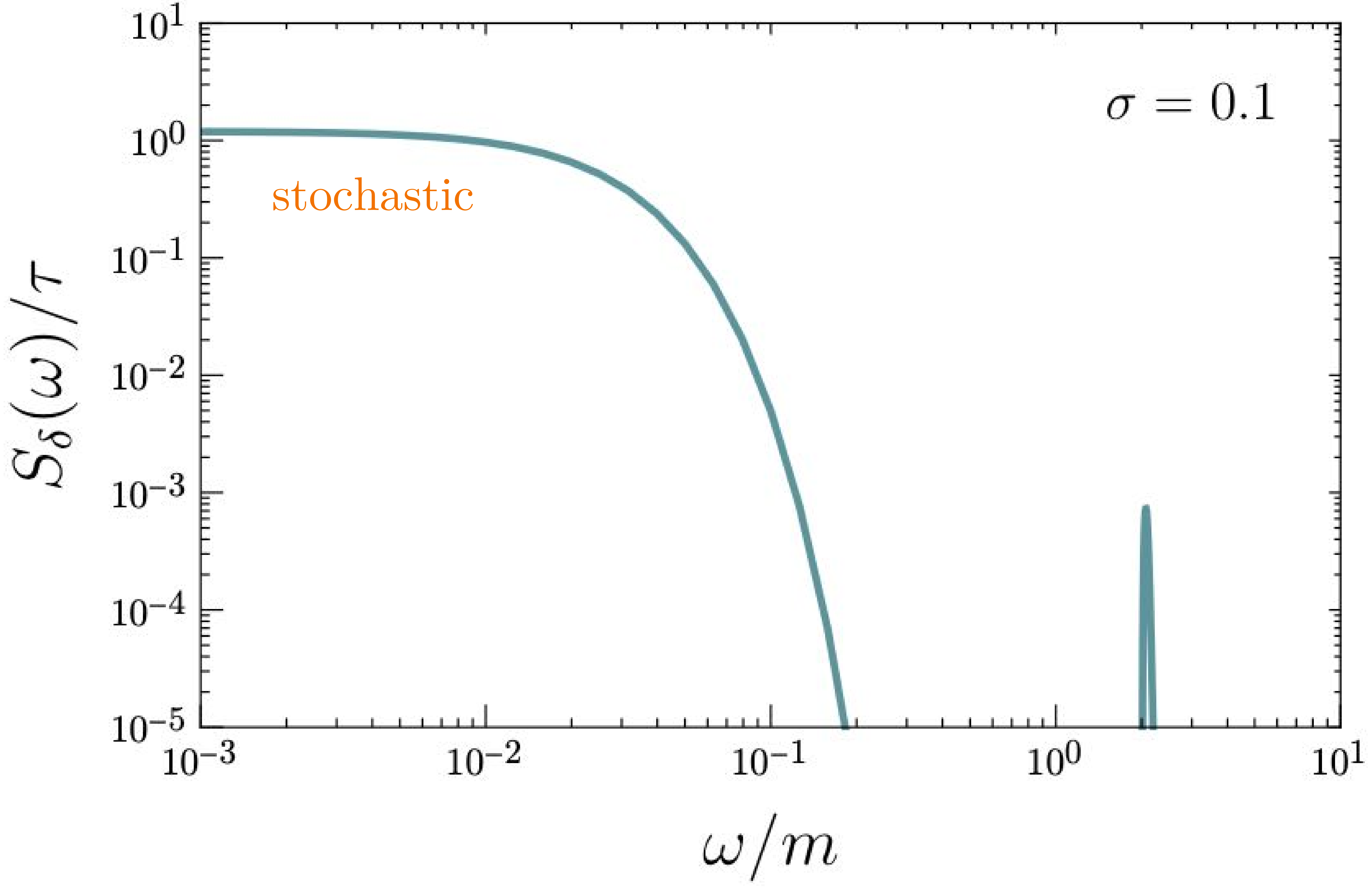
[Snowmass, Budker et al, (22)]
[Banerjee, **Kim**, et al (20)]

now what?

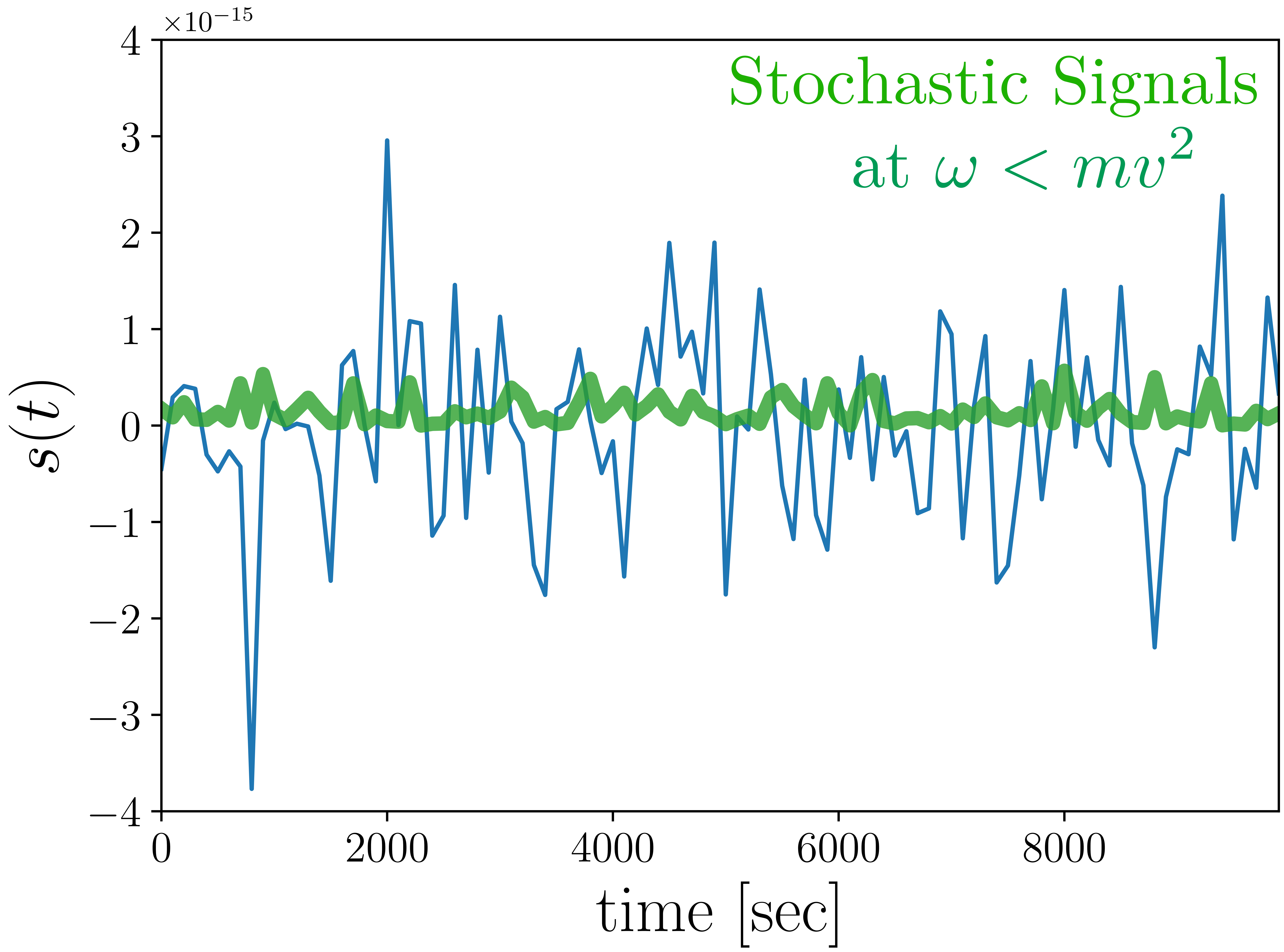
I

cross-correlation of
a network of detectors

$$s(t) = \phi^{2n}(t)$$

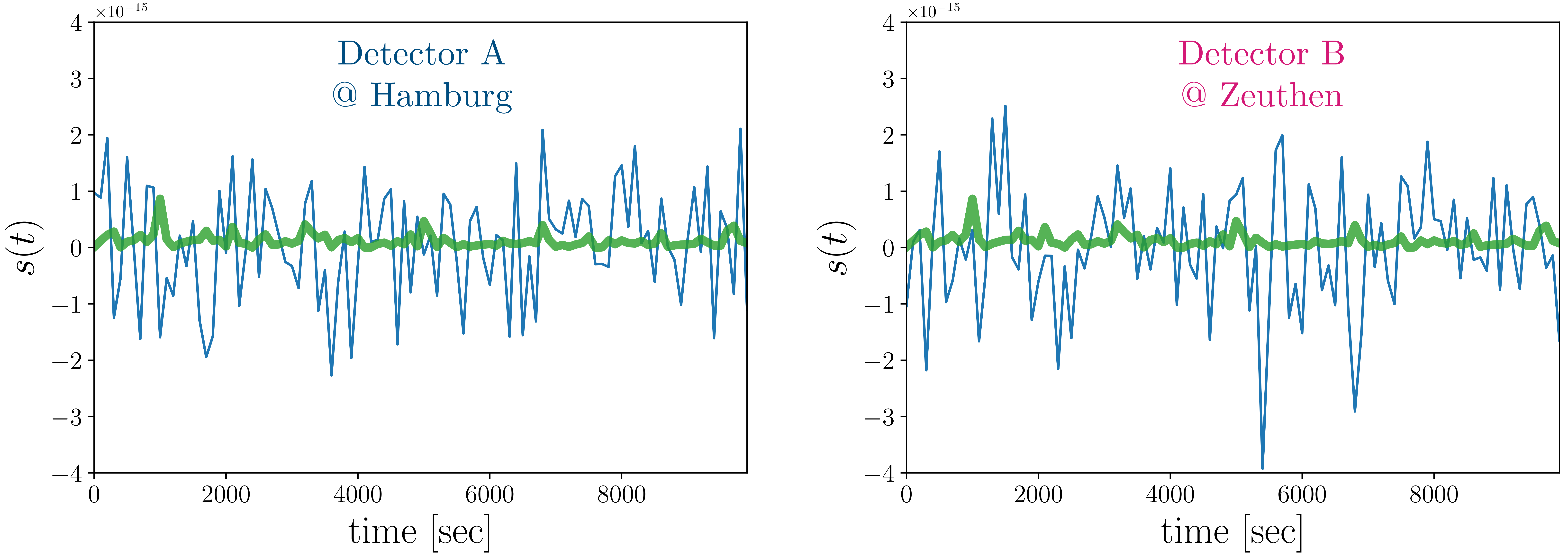


$\sigma = 0.1$
stochastic
$S_\delta(\omega)/\tau$
ω/m
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}



$\times 10^{-15}$
4
3
2
1
0
−1
−2
−3
−4
0
2000
4000
6000
8000
$s(t)$
time [sec]
Stochastic Signals
at $\omega < mv^2$

As long as $m < 10^{-9}$ eV
two detectors are well within the wavelength



stochastic signals would be correlated
while noises are uncorrelated

[Gong, Luo, Wang, Nat. Astron (21)]

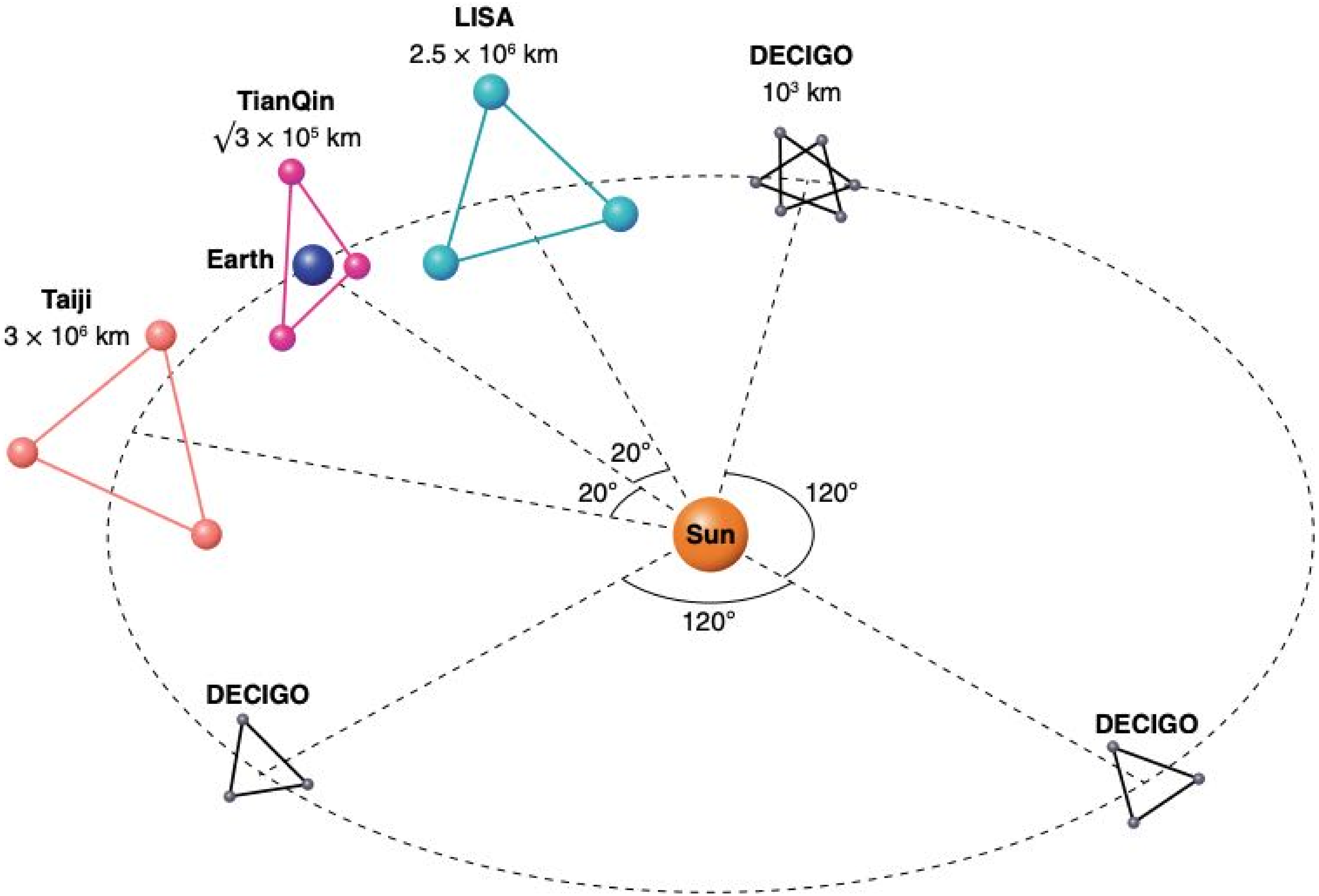
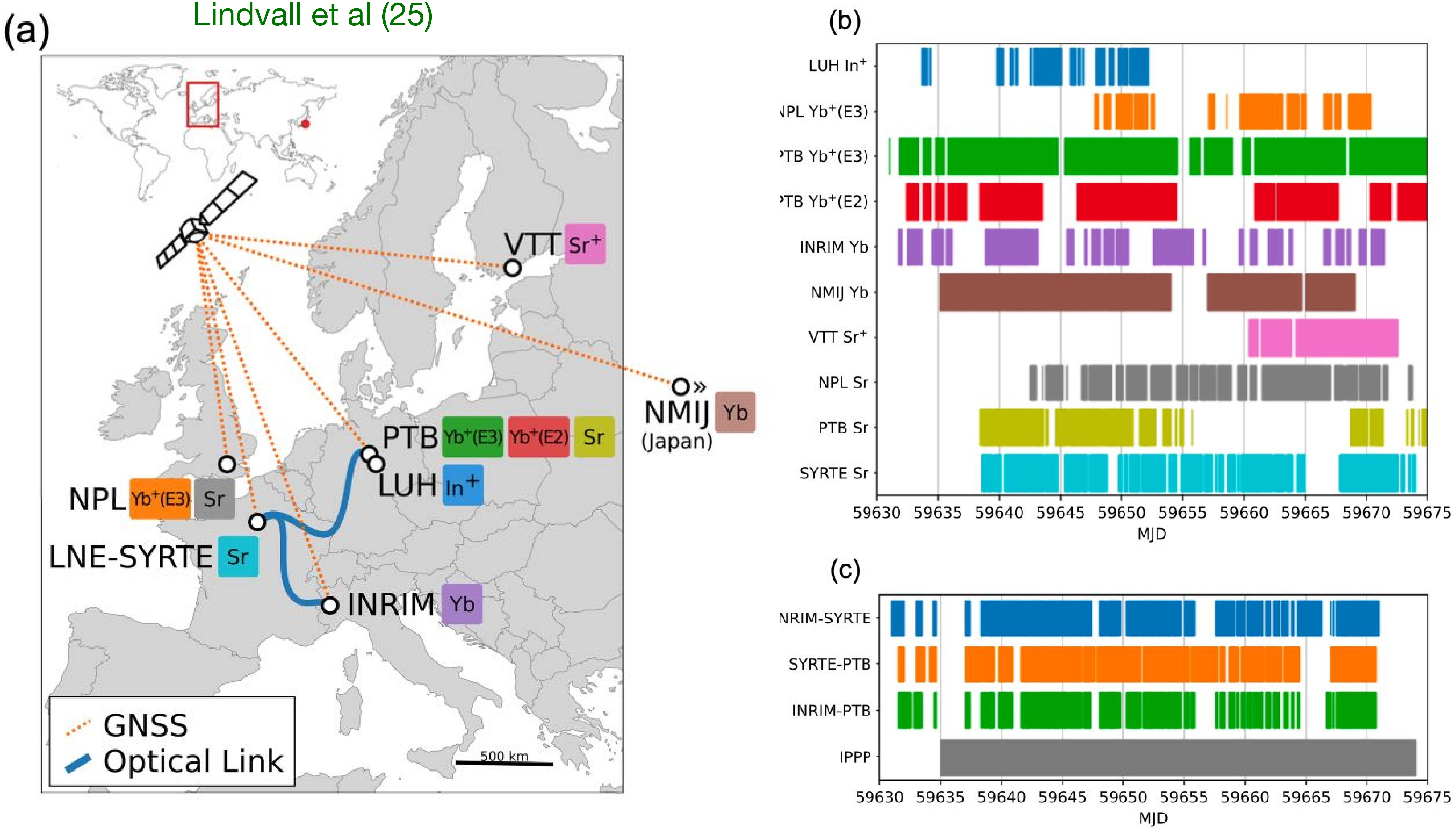


Fig. 1 | Schematic of space-based GW detector constellations. The detector plane of TianQin points to the calibration source RX J0806.3+1527 and DECIGO has four clusters.

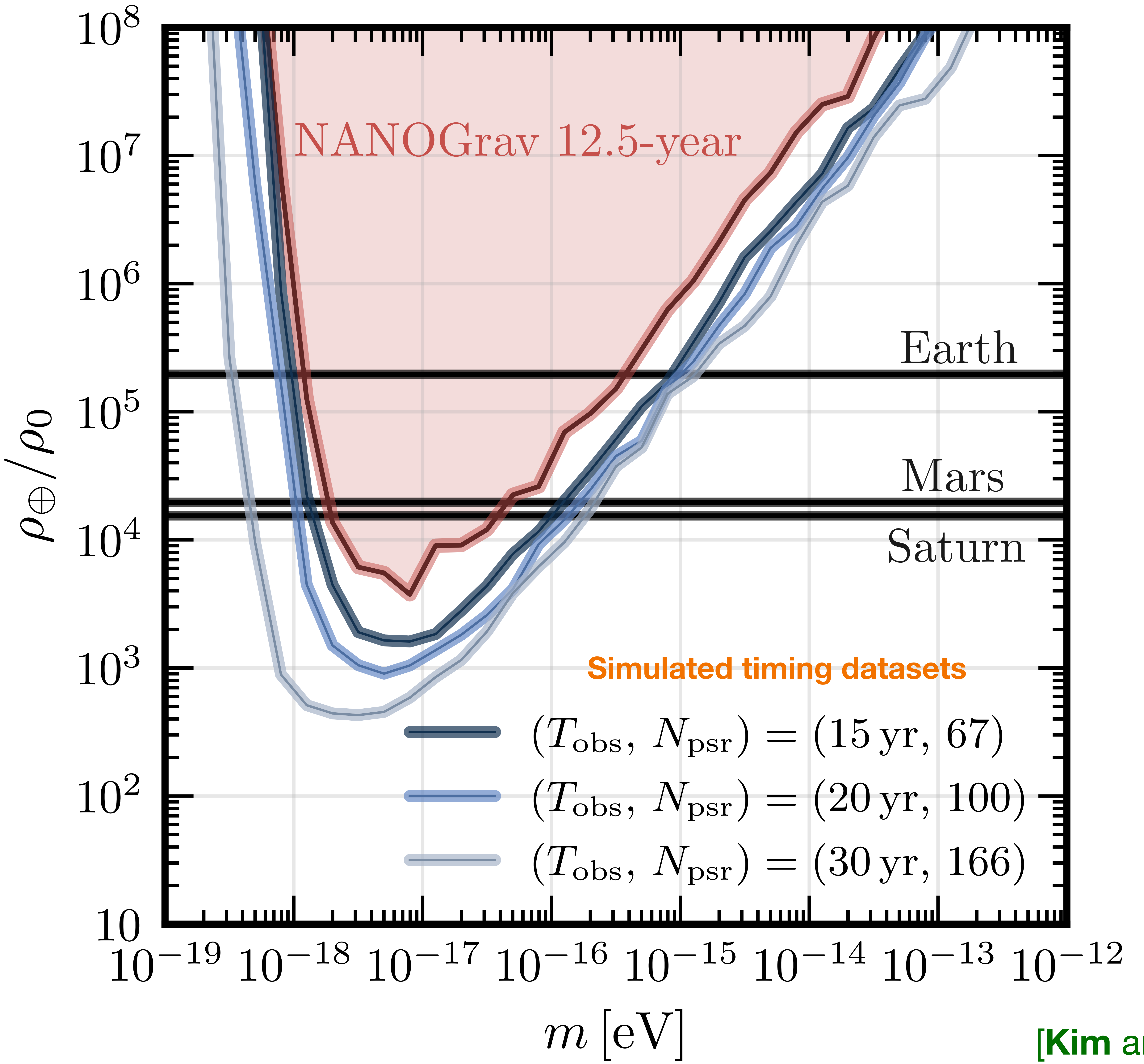
Lisdat et al, Nat. Comm. (16)

Lindvall et al (25)



II

prospects of gravitational probes



[**Kim** and Mitridate 2312.12225]

Next International Pulsar Timing Array (IPTA) data release
is expected to include

$$N_{\rm psr} \sim 100$$

$$T_{\rm obs} = 20^{+}\,{\rm yr}$$

with next-gen ratio telescope (e.g. Square Kilometer Array)
an order of magnitude or more improvement might be feasible

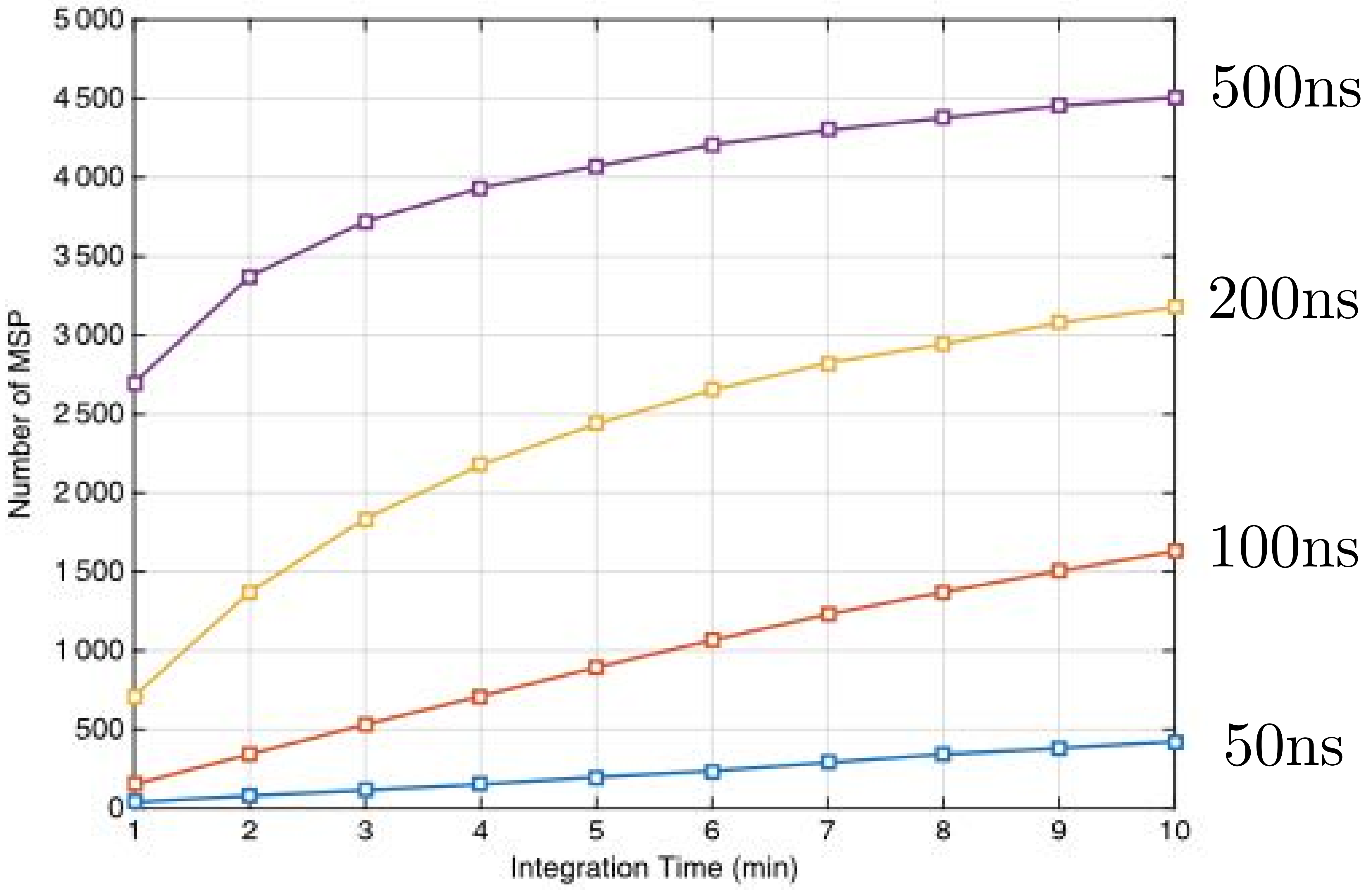
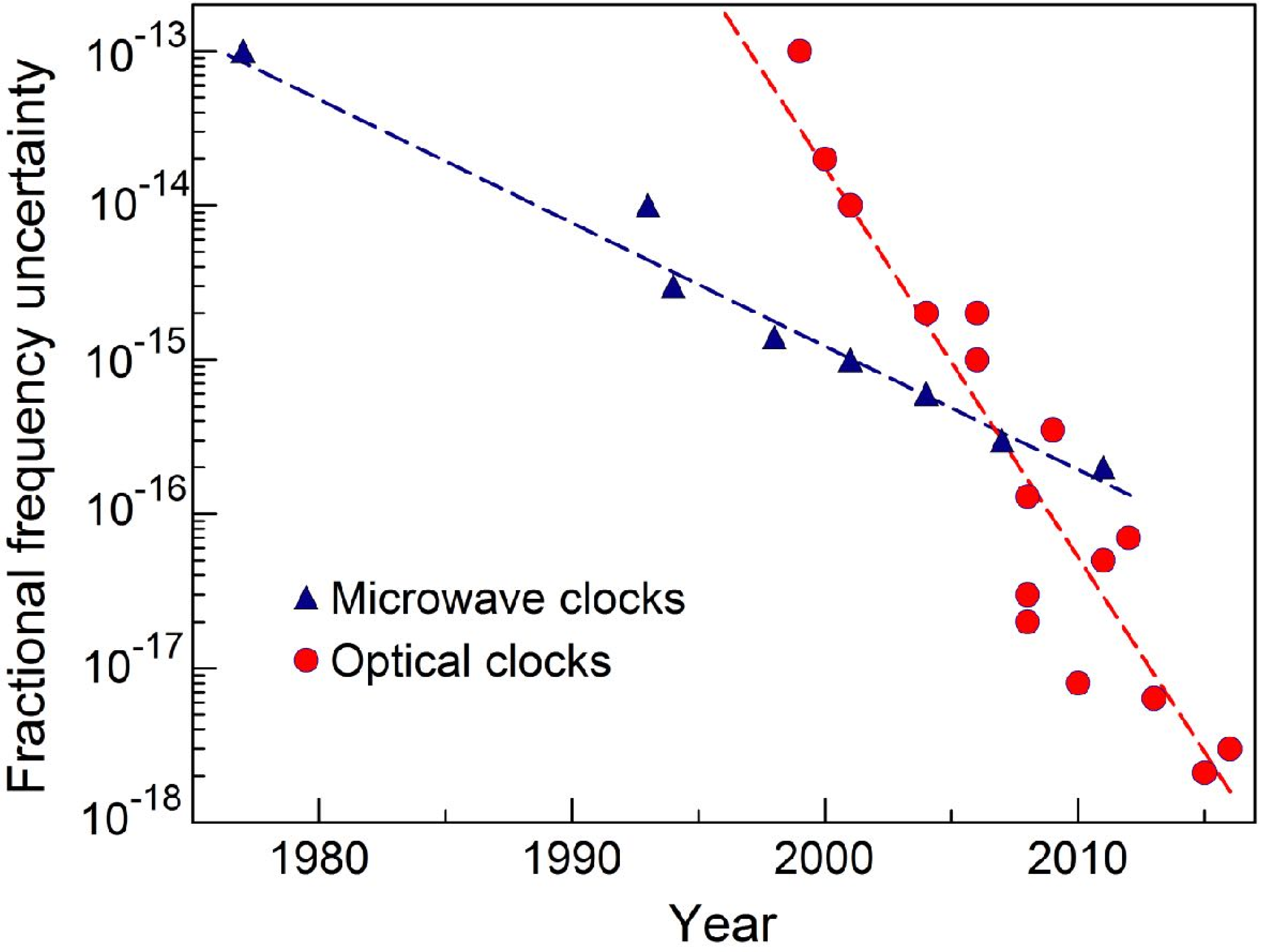


Figure 10. Numbers of MSPs that can archive a certain RMS noise level (or better) with varying integration time. Colour lines indicate different RMS noise levels (from bottom to top): 50 ns (blue), 100 ns (red), 200 ns (yellow), and 500 ns (purple).

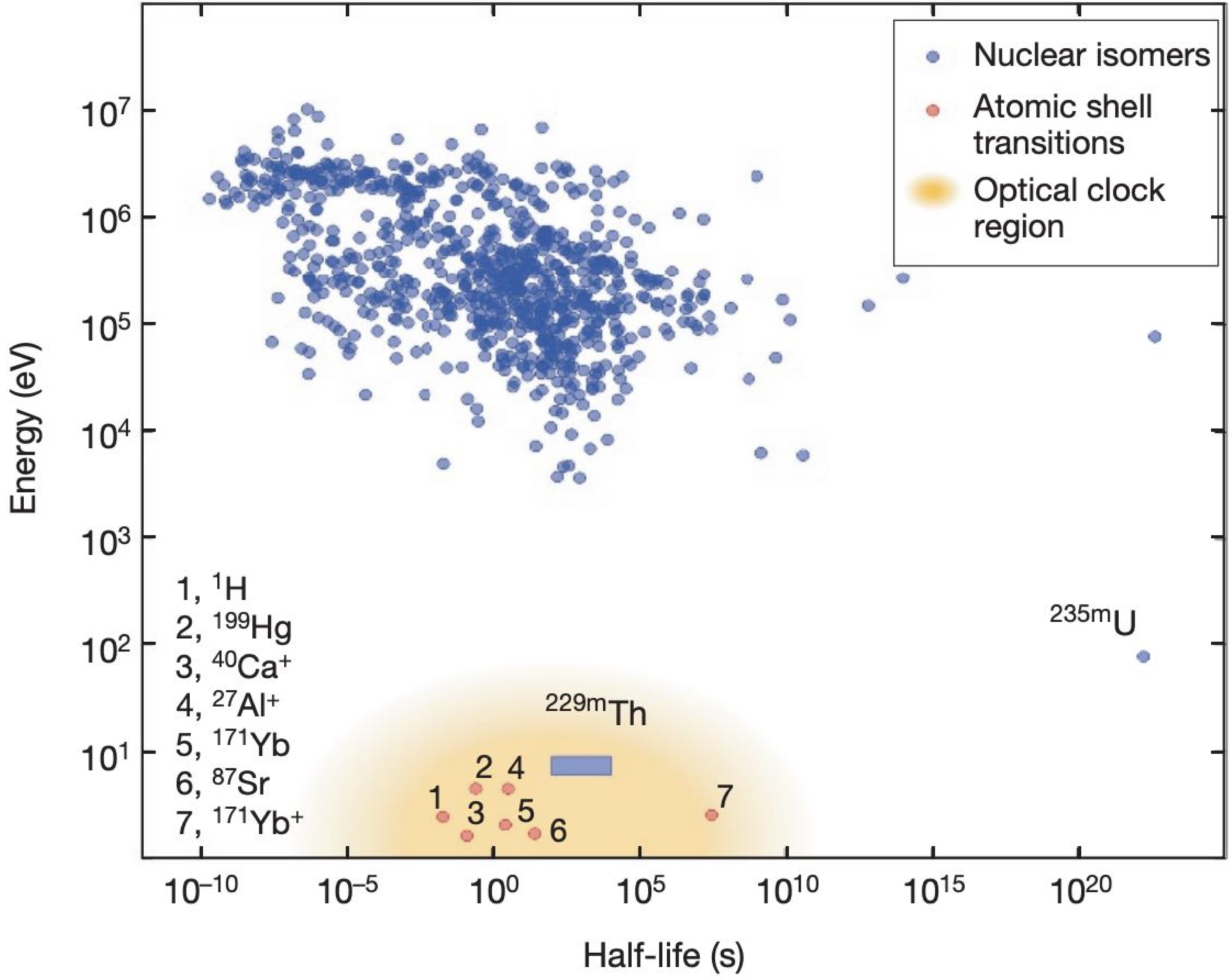
[SKA, Weltman et al (20)]

III

prospects of non-gravitational probes



[Safronova et al (18)]



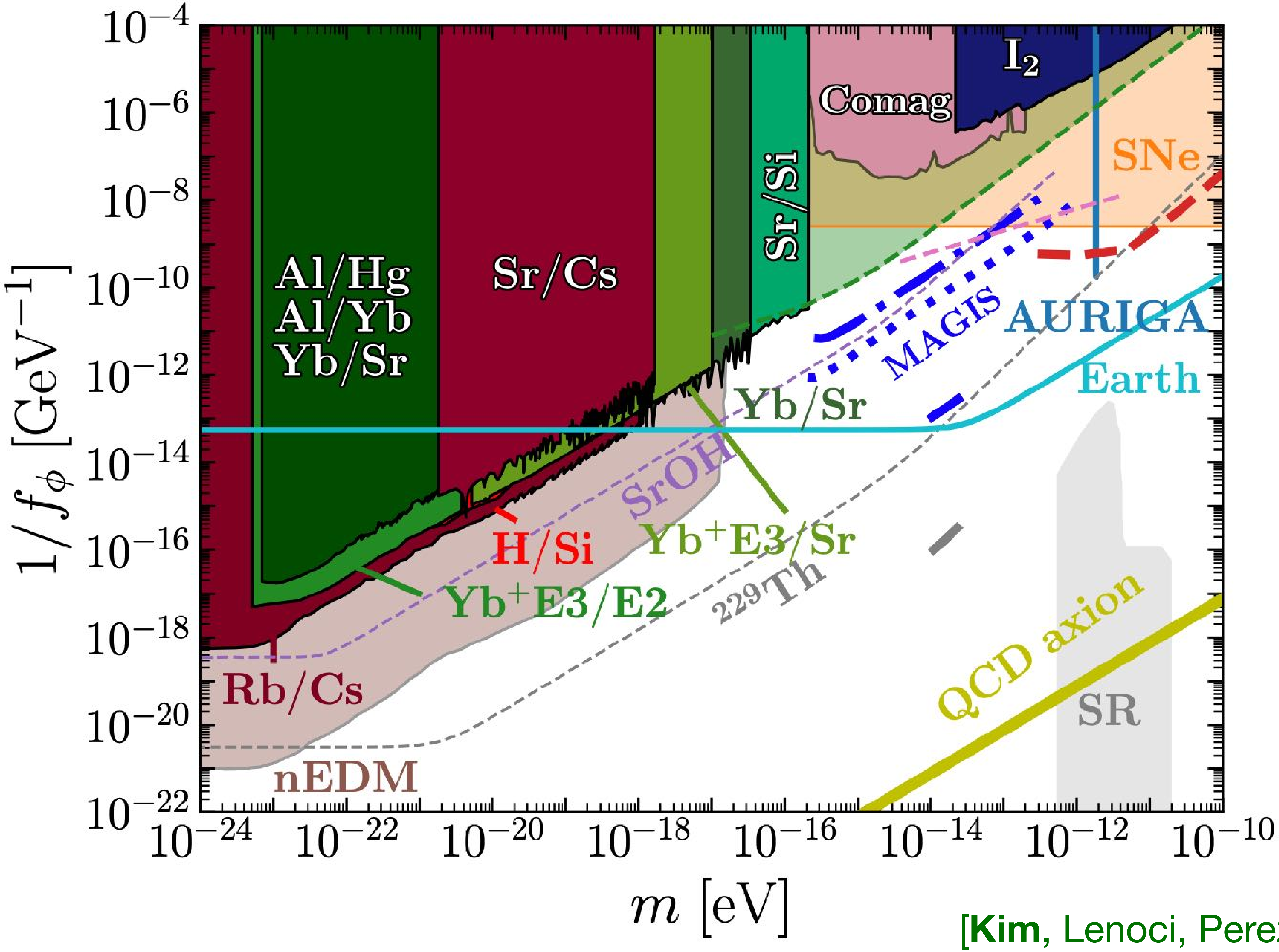
Nuclear isomers
Atomic shell transitions
Optical clock region
Energy (eV)
10^7
10^6
10^5
10^4
10^3
10^2
10^1
Half-life (s)
10^{-10}
10^{-5}
10^0
10^5
10^{10}
10^{15}
10^{20}
1, ^1H
2, ^{199}Hg
3, $^{40}Ca^+$
4, $^{27}Al^+$
5, ^{171}Yb
6, ^{87}Sr
7, $^{171}Yb^+$
^{235m}U
^{229m}Th

progress is rapid

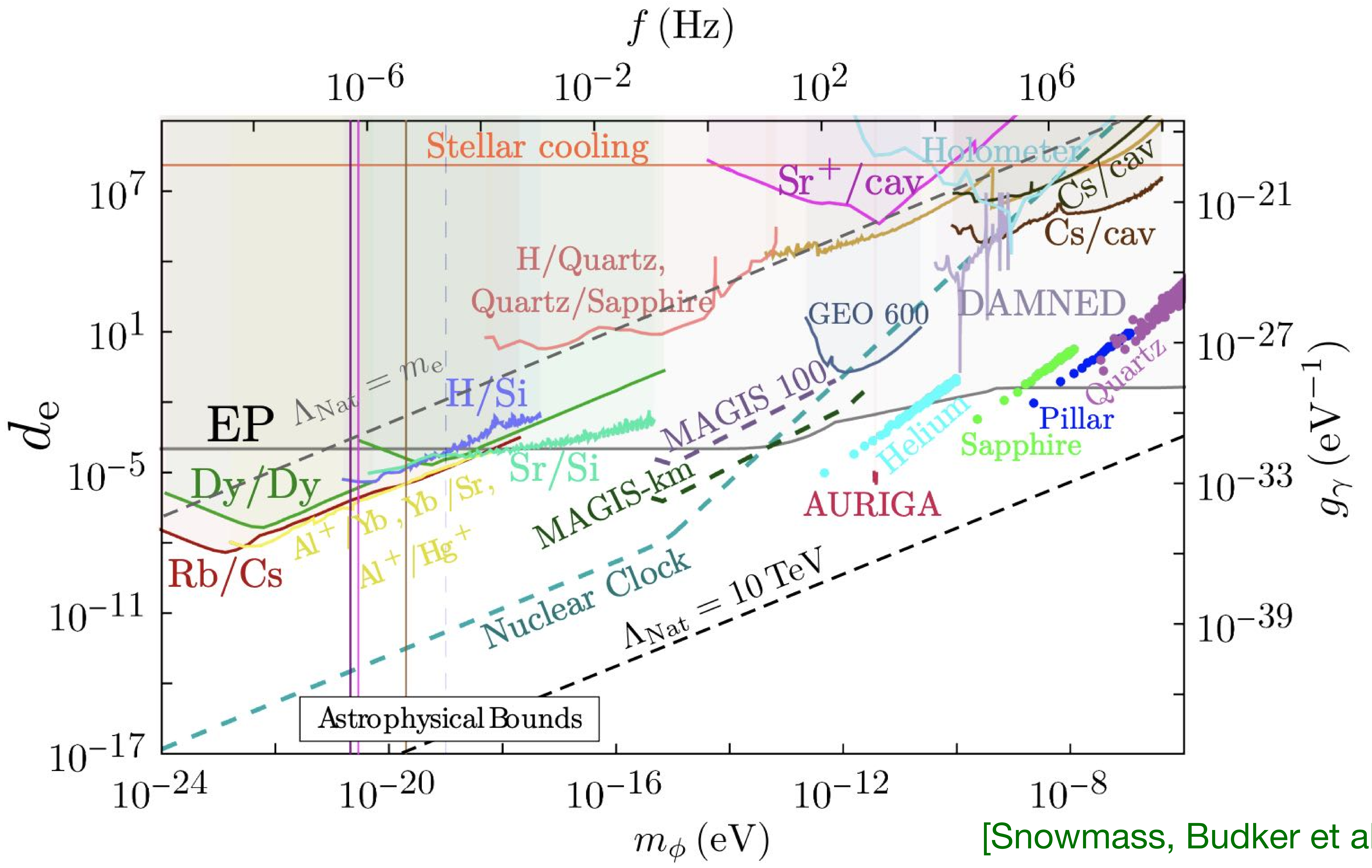
precision in the energy level has improved as

$$\delta f / f$$

[Seiferle et al, Nature] [Masuda et al, Nature]	[Kraemer et al, Nature]	[Tiedau et al, PRL] [Elwell et al, PRL]	[Zhang et al, Nature]
0.01	0.001	10^{-6}	10^{-12}
(2019)	(2023)	(2024)	(2024)
		April	June



[**Kim**, Lenoci, Perez, Ratzinger (23)]
[**Kim** and Perez (22)]



[Snowmass, Budker et al, (22)]

[Banerjee, **Kim**, et al (20)]