Gravitational Sensing of Ultralight Dark Matter

Hyungjin Kim (DESY)

Quantum Sensing for Fundamental Physics
20 Nov 2024

What do we know about

Dark Matter Density

around the solar system?

$$\rho \stackrel{?}{=} 0.4\,\mathrm{GeV}/\mathrm{cm}^3$$

only over ***kpc-scale***

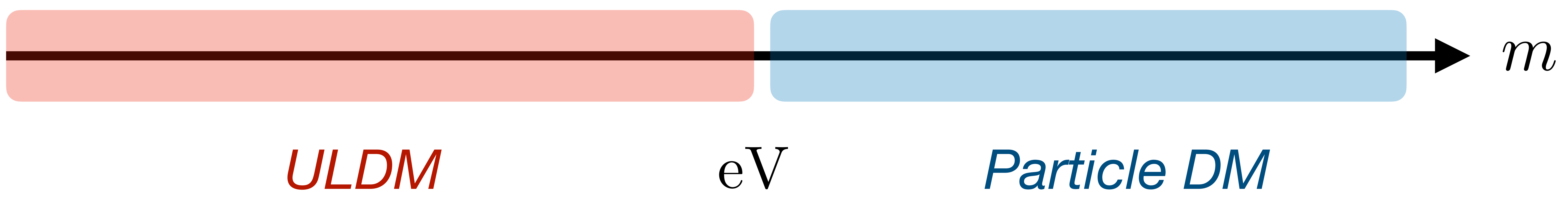
near the solar system

$$\rho \lesssim \mathcal{O}(1) \times 10^4\,\mathrm{GeV/cm^3}$$

Probing ultralight DM with GW detectors

Ultralight Dark Matter

we define *ultralight dark matter (ULDM)*
as *bosonic DM candidates with* $\mathrm{m} < \mathrm{eV}$

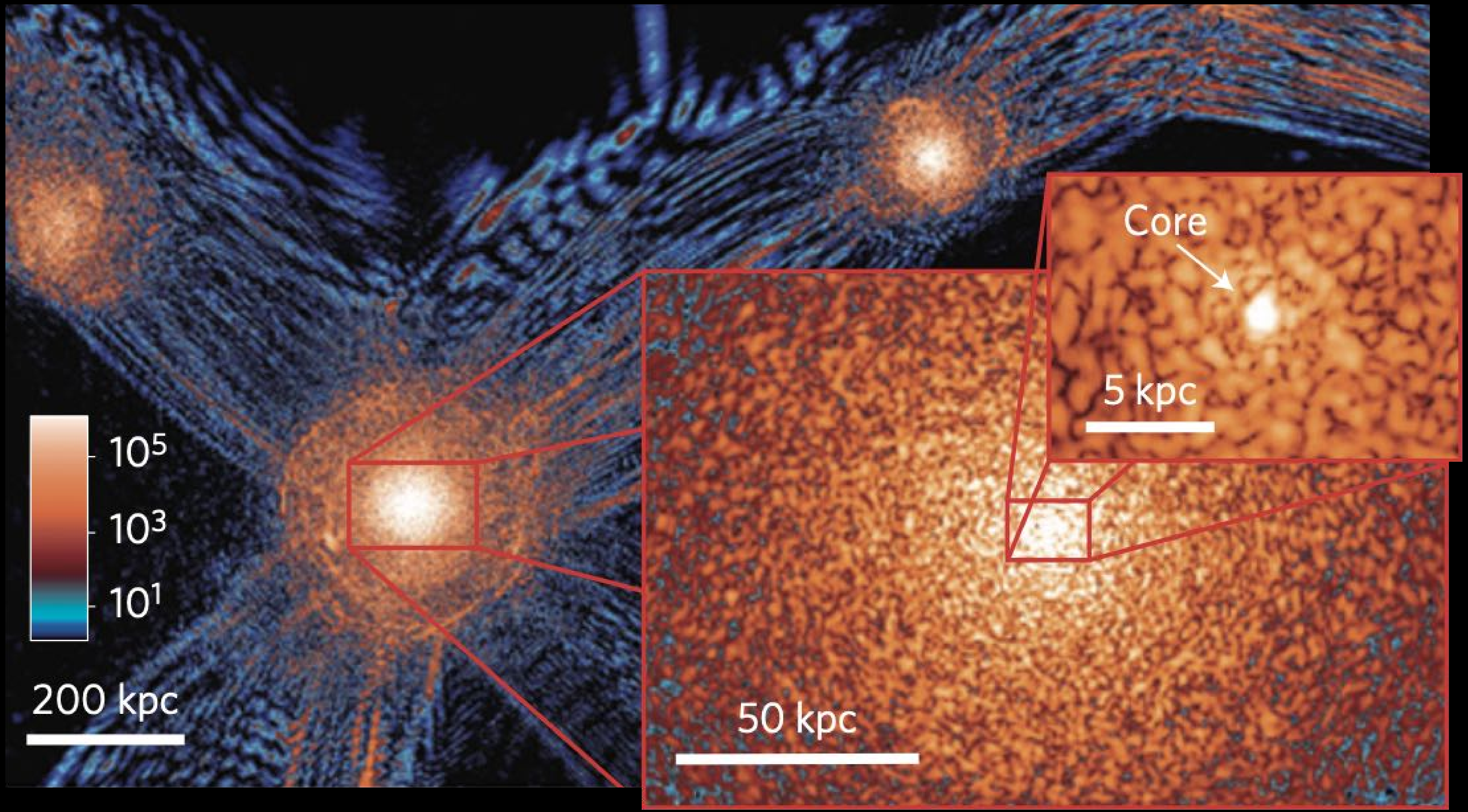


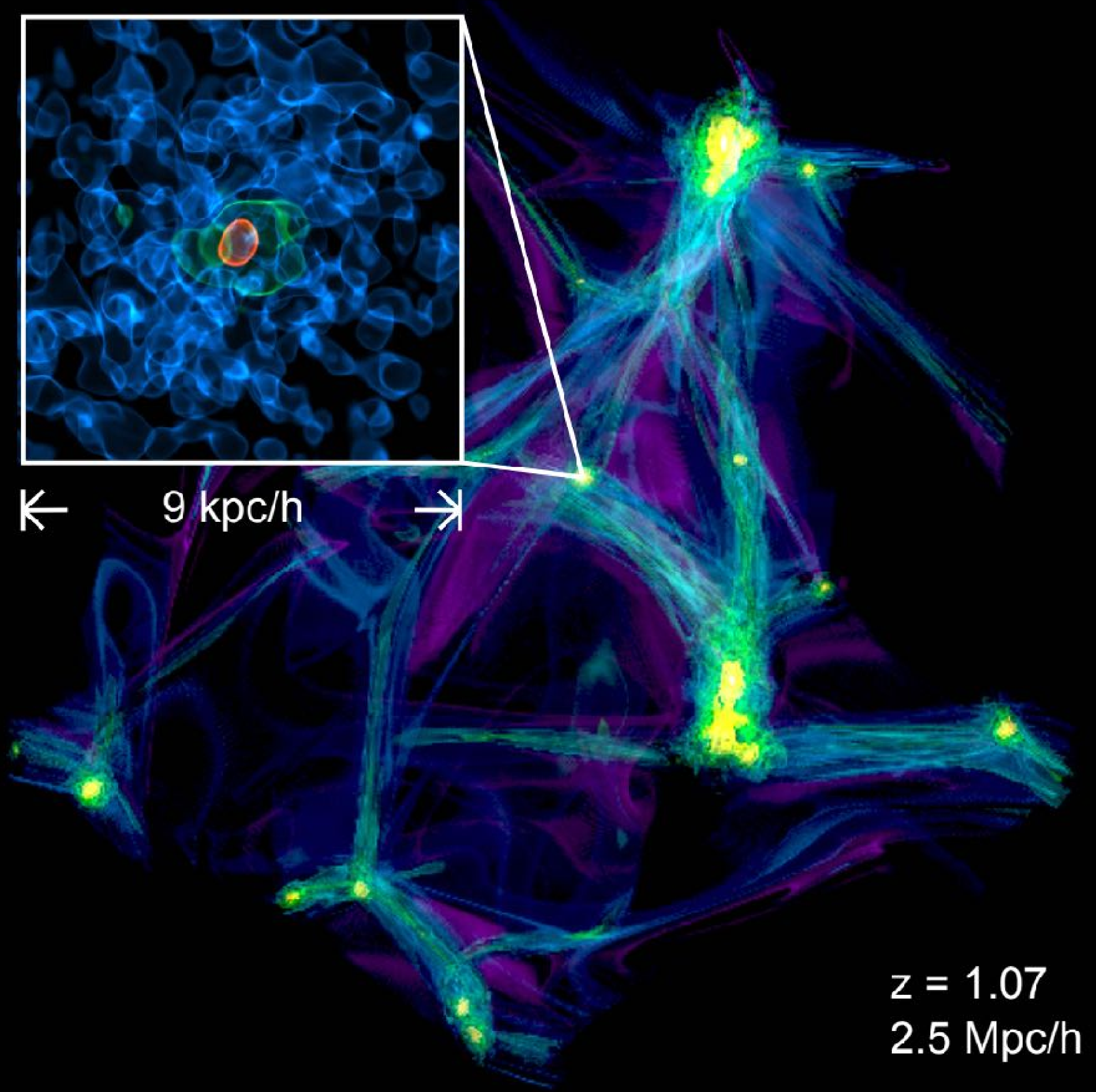
we define *ultralight dark matter (ULDM)*
as *bosonic DM candidates with* $\mathrm{m} < \mathrm{eV}$

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

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

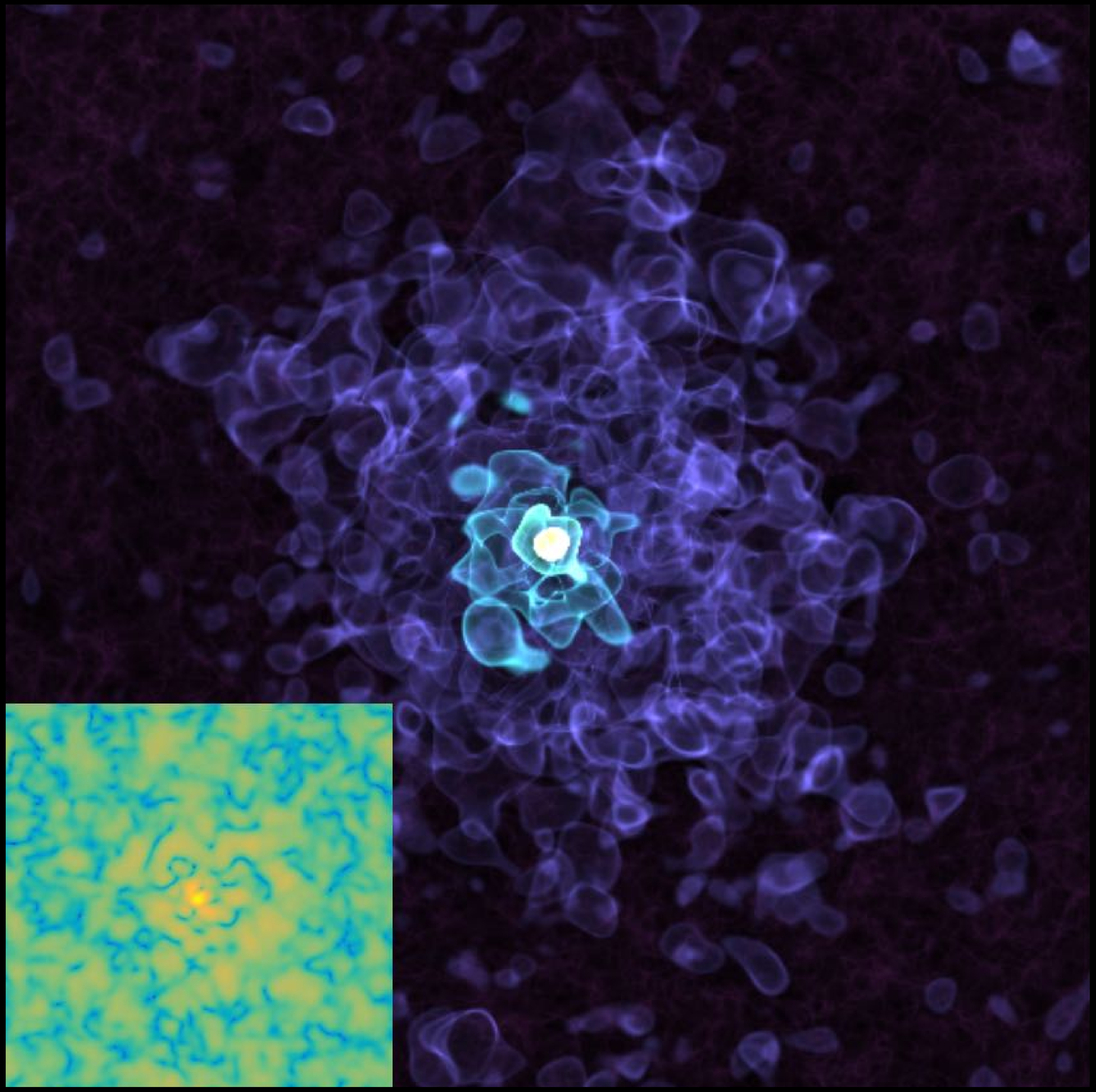
Schive, Chiueh, Broadhurst (14)





Veltmaat, Niemeyer, Schwabe (18)

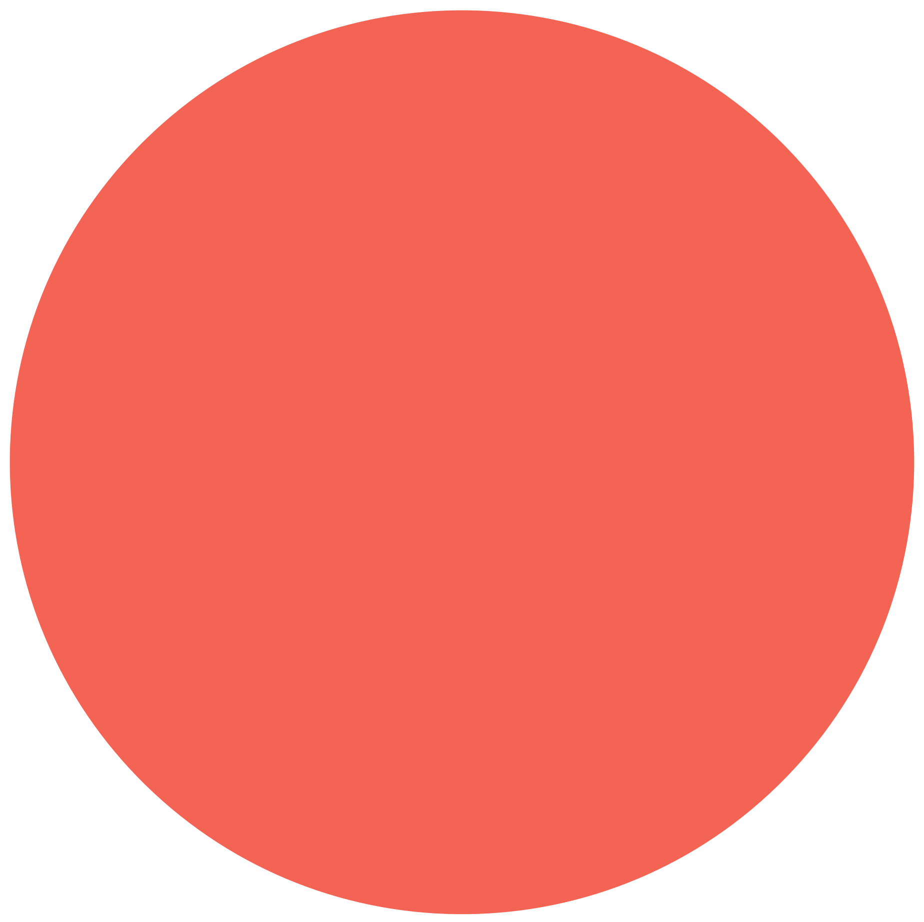
Mocz et al (17)



An intuitive understanding of the granule structure:

[Hui et al 17]

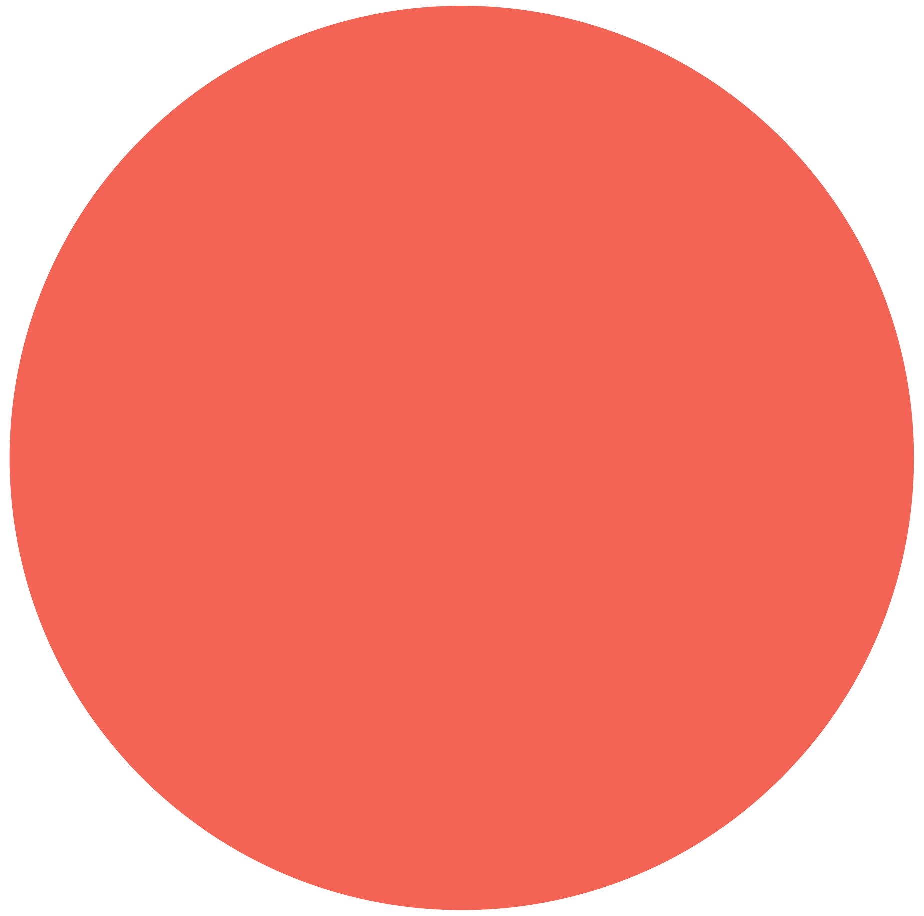
Quasiparticle



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

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

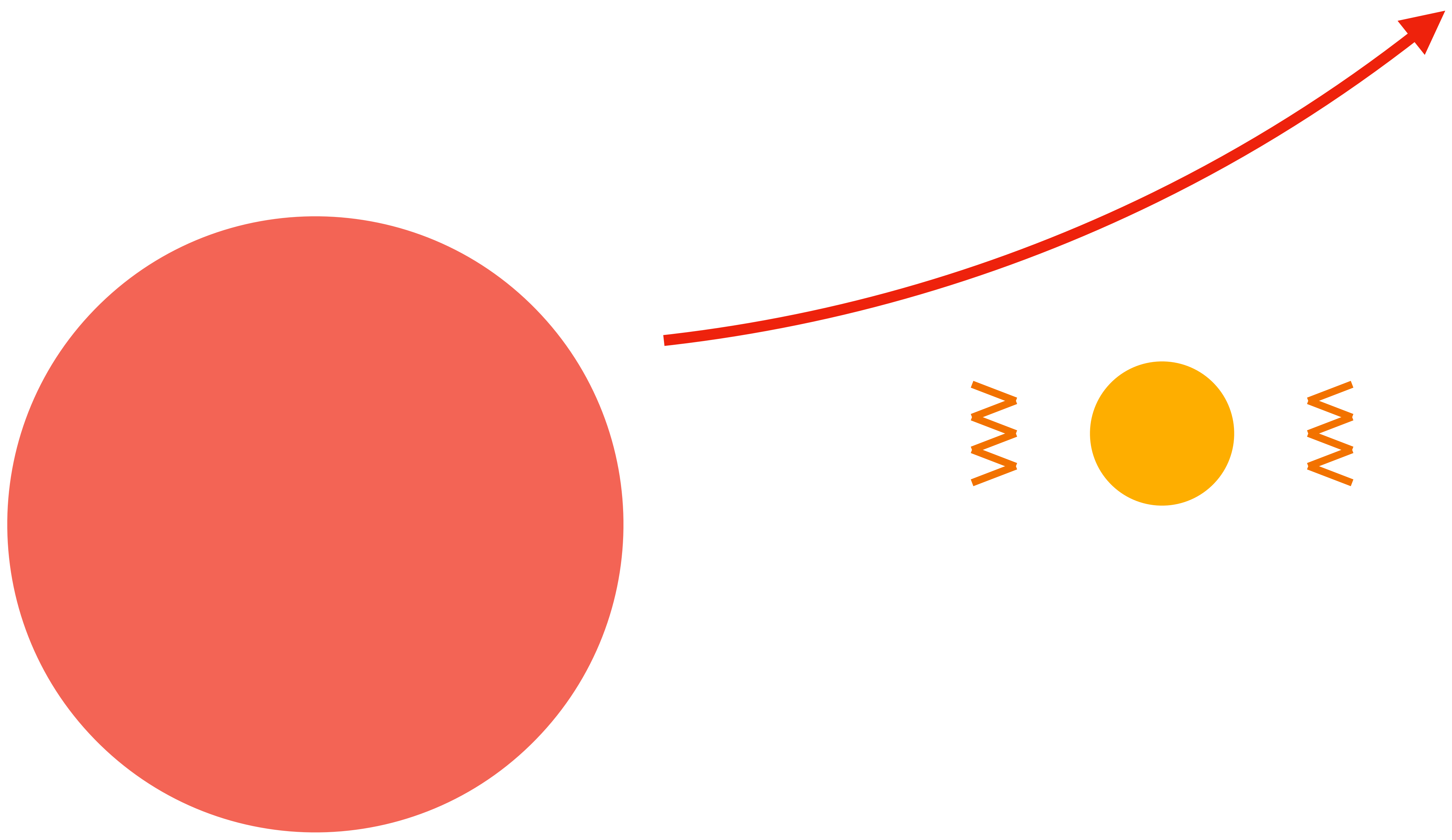
the size and mass of them could be astronomical



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

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

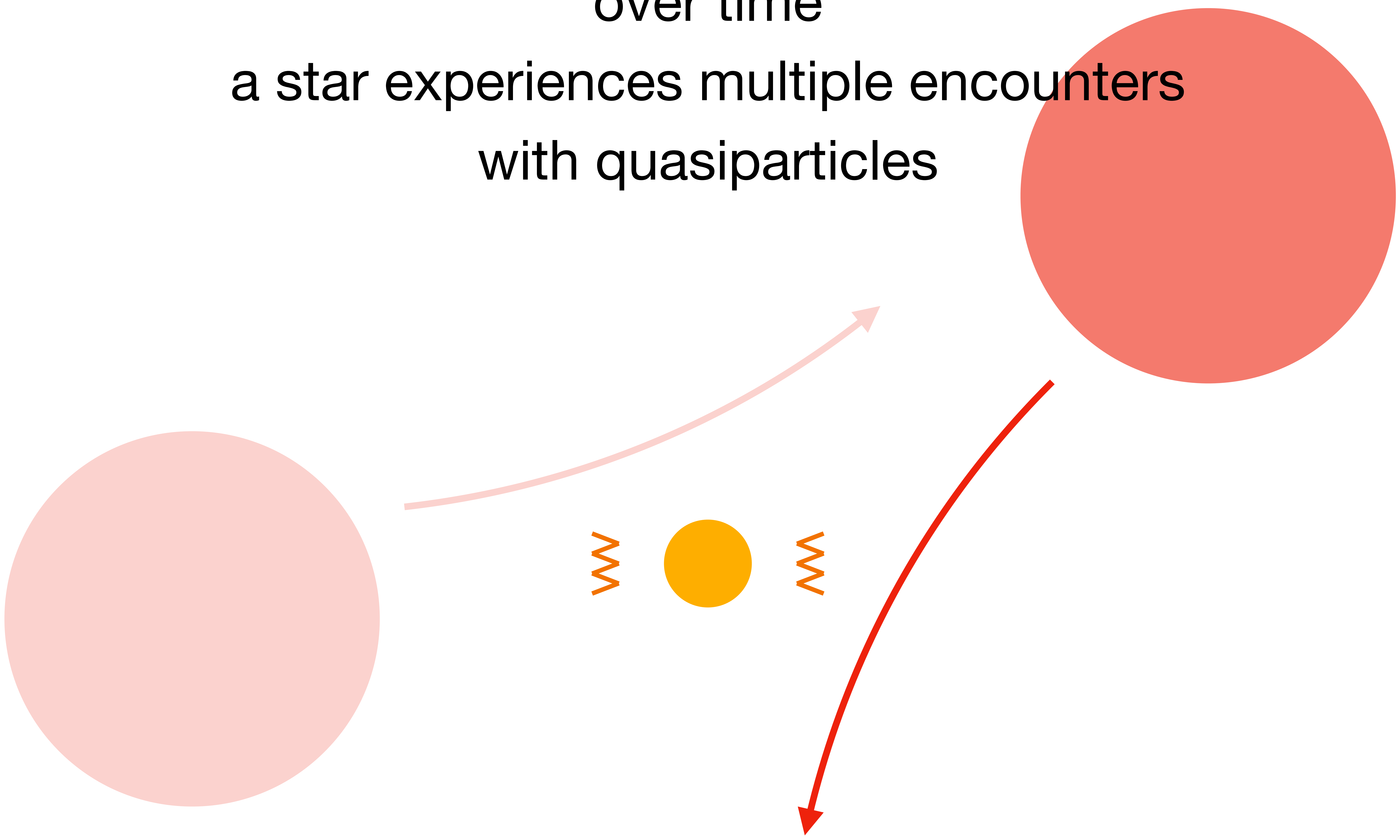
being that massive
it may engage in interaction with stars
and significantly perturb the motion of them



over time

a star experiences multiple encounters

with quasiparticles



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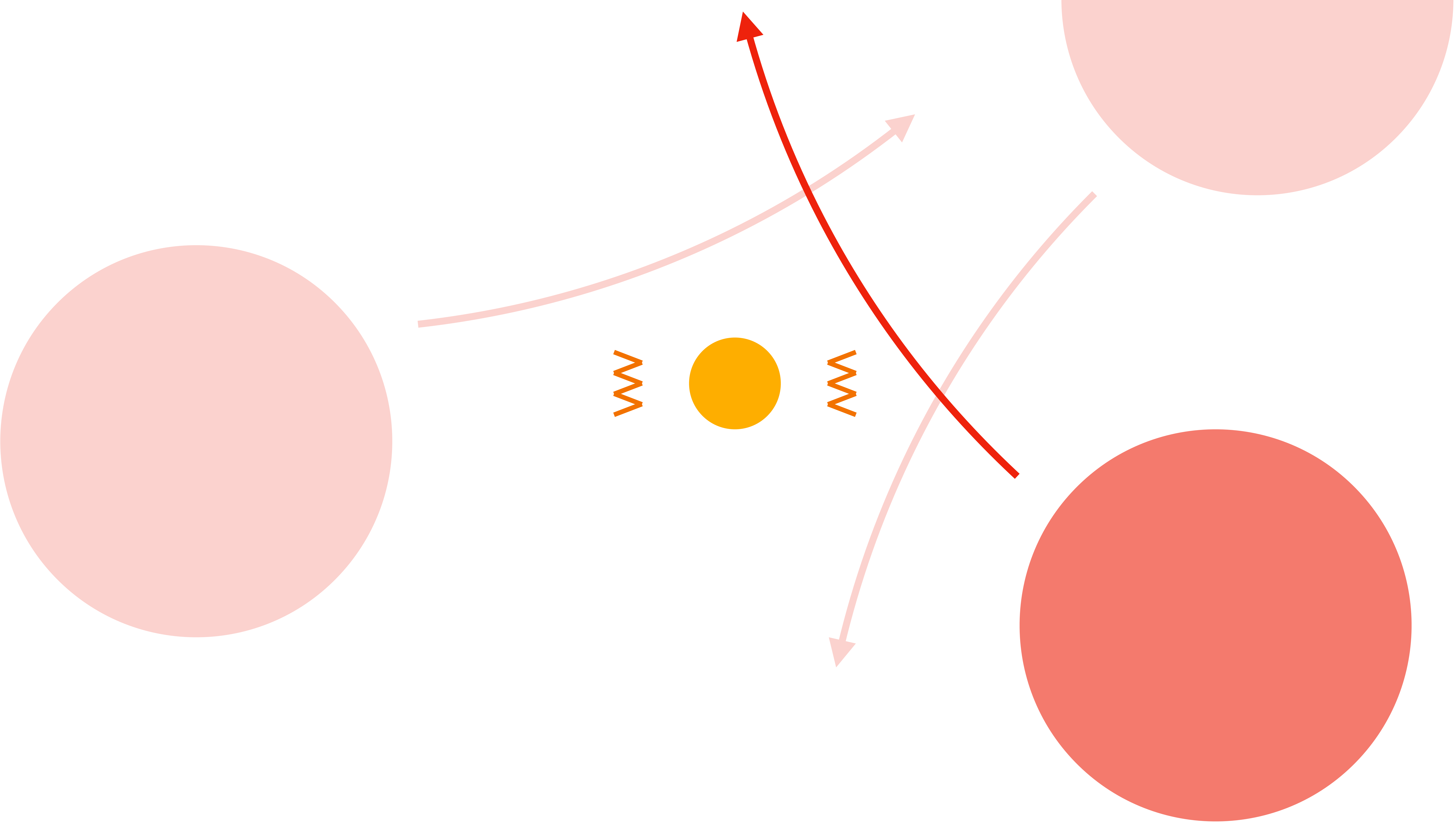

so what?

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quasiparticles *bombards* normal matters,
leaving *distinctive stochastic signals* in *GW detectors*

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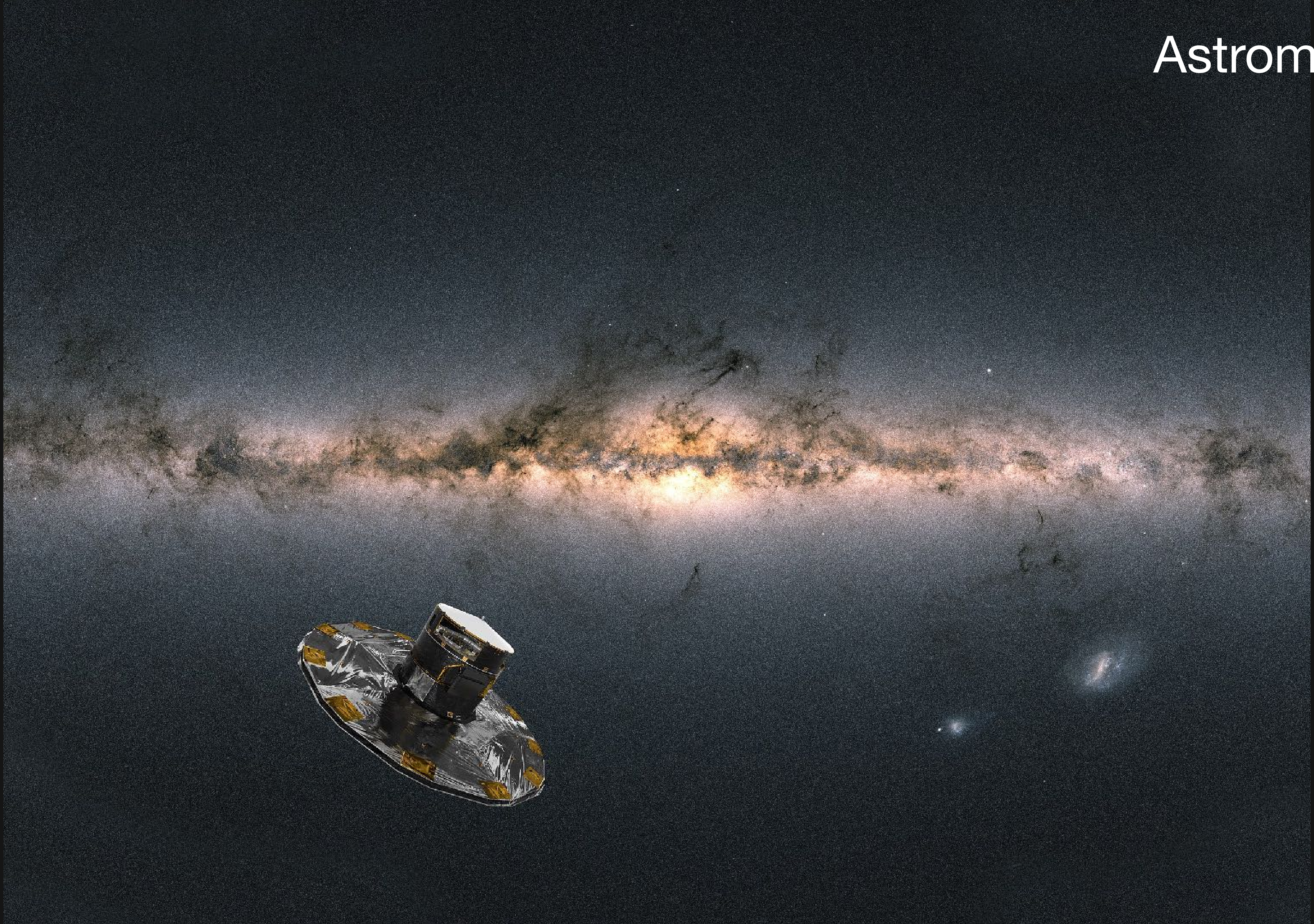
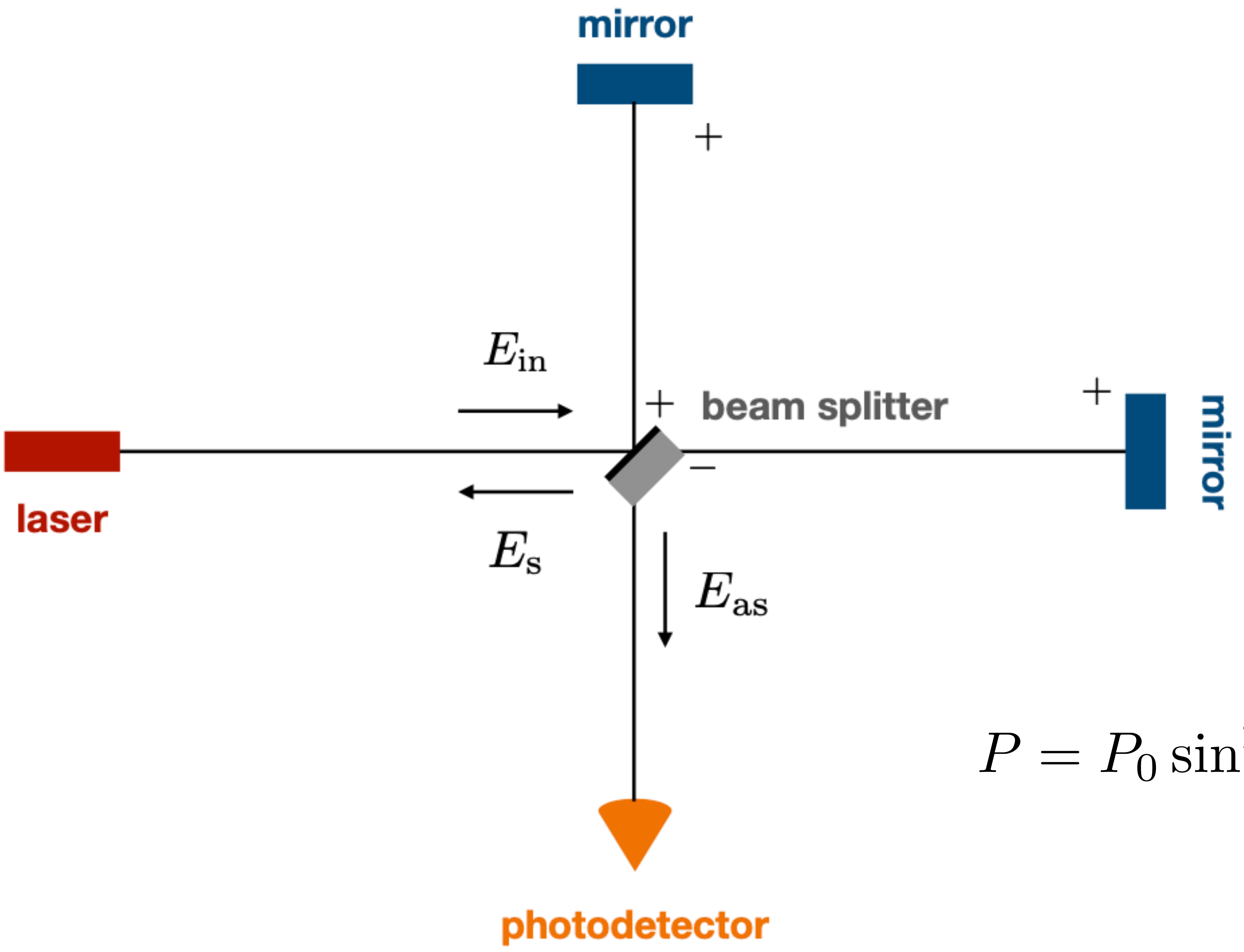
Interferometry

Pulsar Timing Array

Astrometry

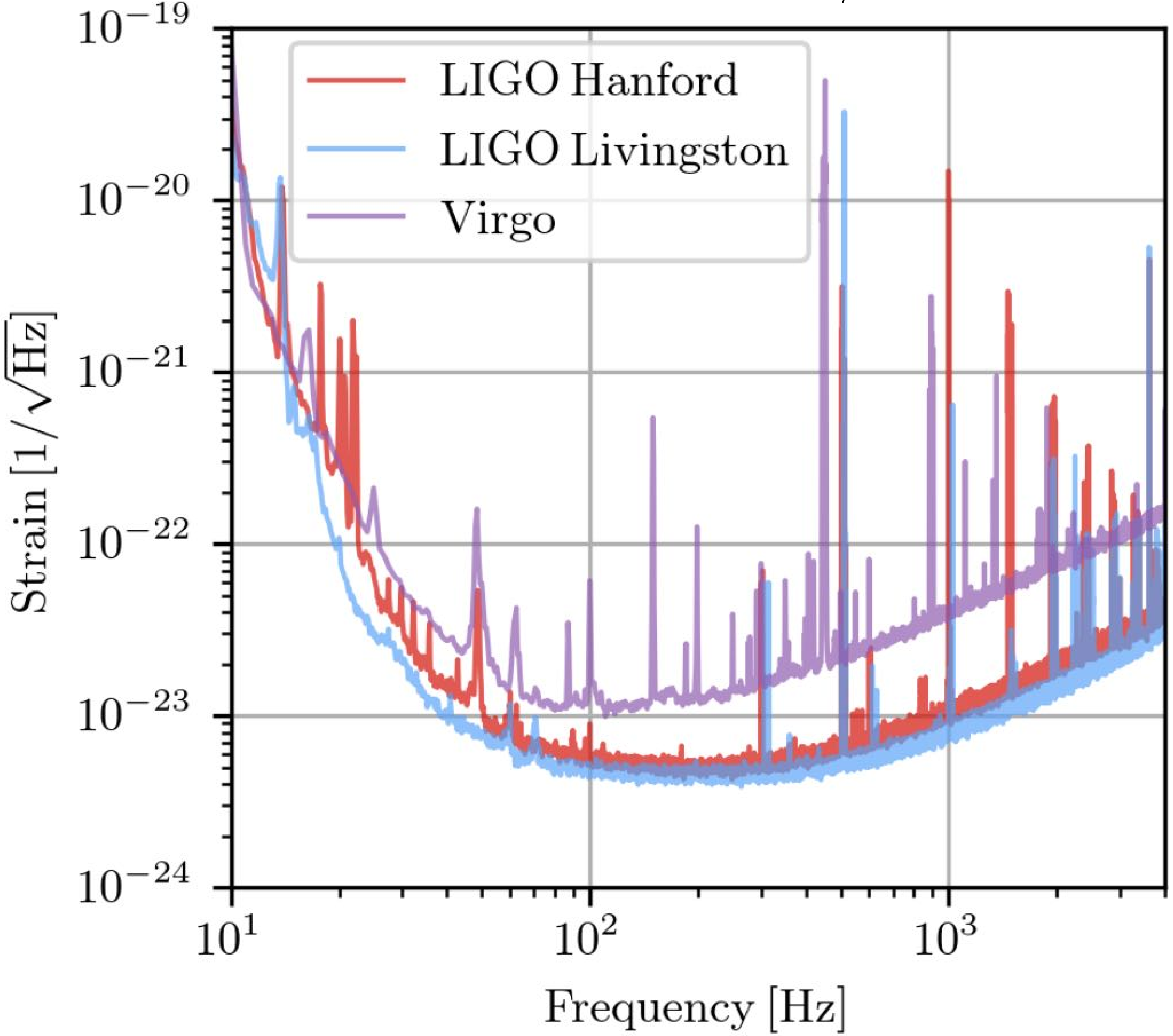


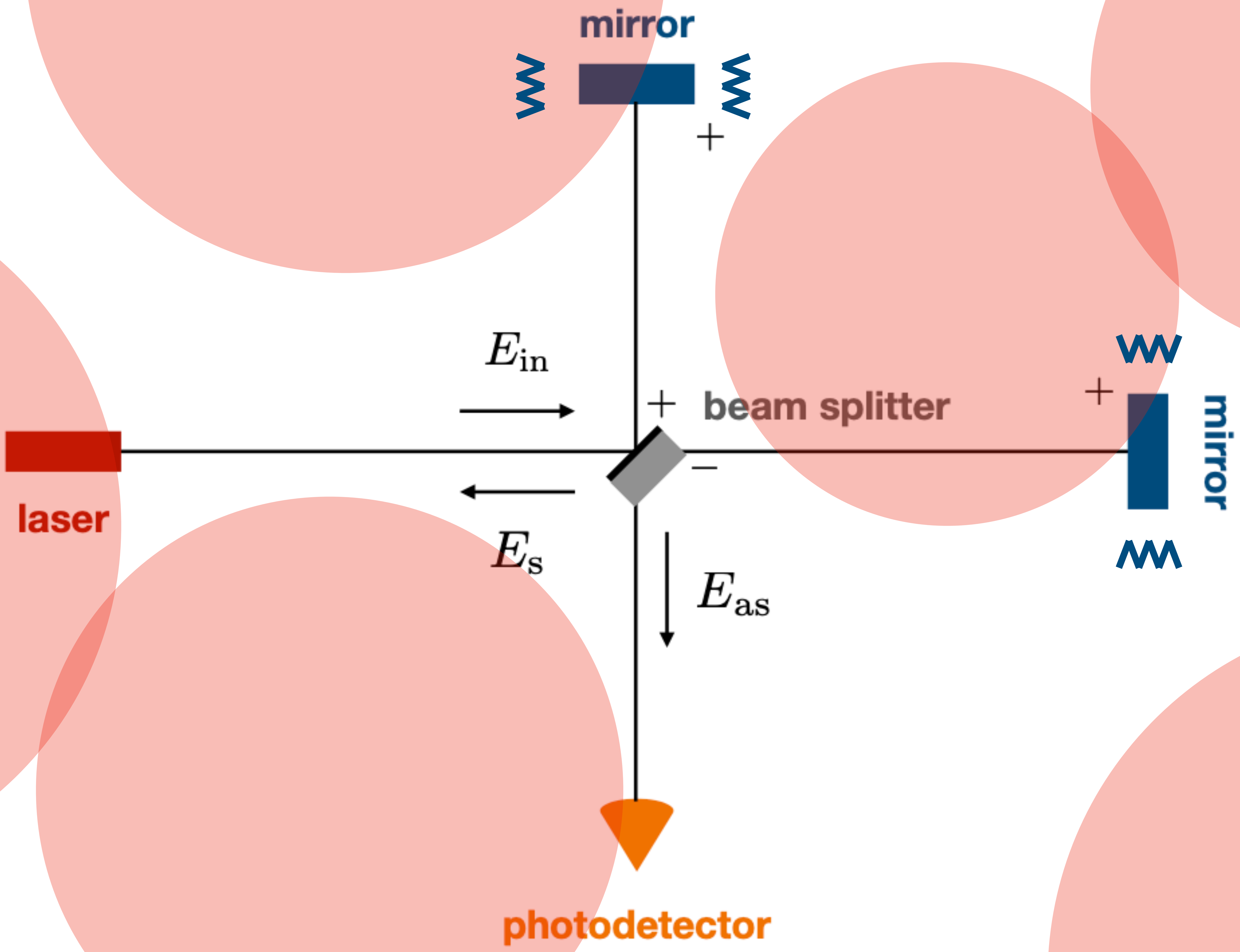


$$P = P_0 \sin^2(k\Delta L)$$

$$S_n^{1/2}(f) \sim S_{\Delta L/L}^{1/2}(f)$$

$$\langle x^2 \rangle = \int df \, S_x(f)$$



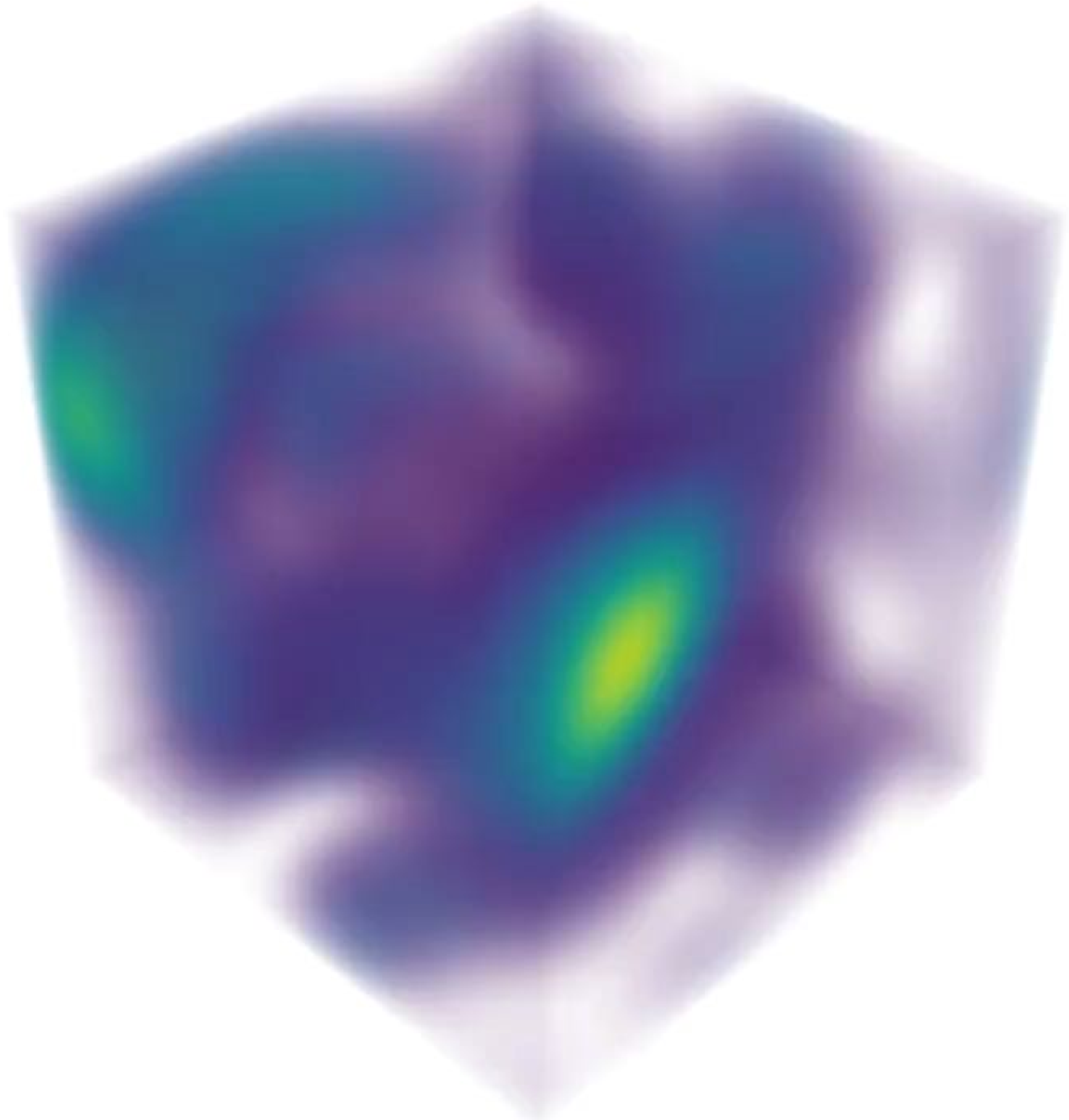

mirror
+
$E_{\rm in}$
+
beam splitter
+
mirror
−
laser
$E_{\rm s}$
$E_{\rm as}$
photodetector

can we actually measure
ULDM signals with GW interferometers?

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

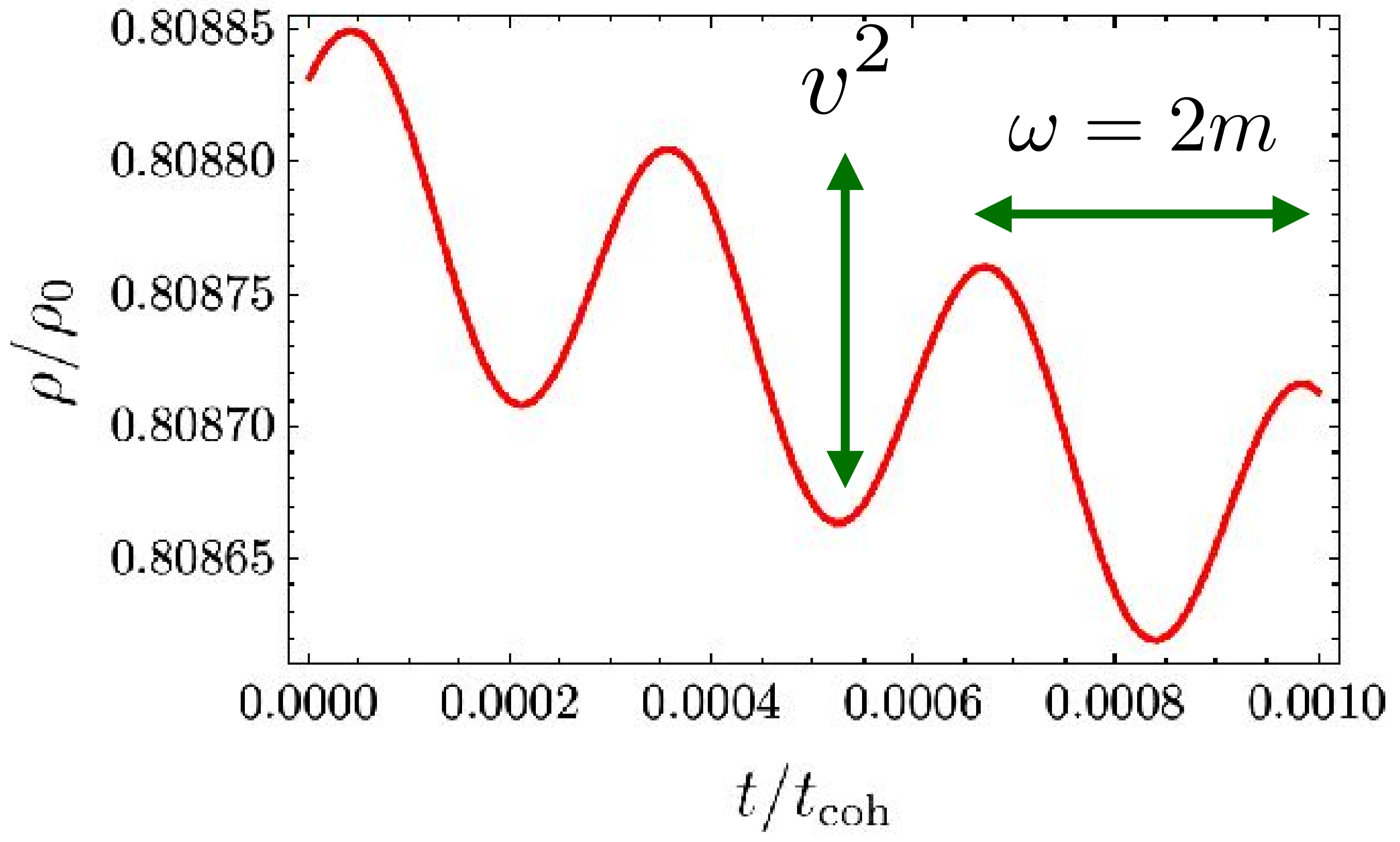
$$\nabla^2\Phi = 4\pi G\rho$$

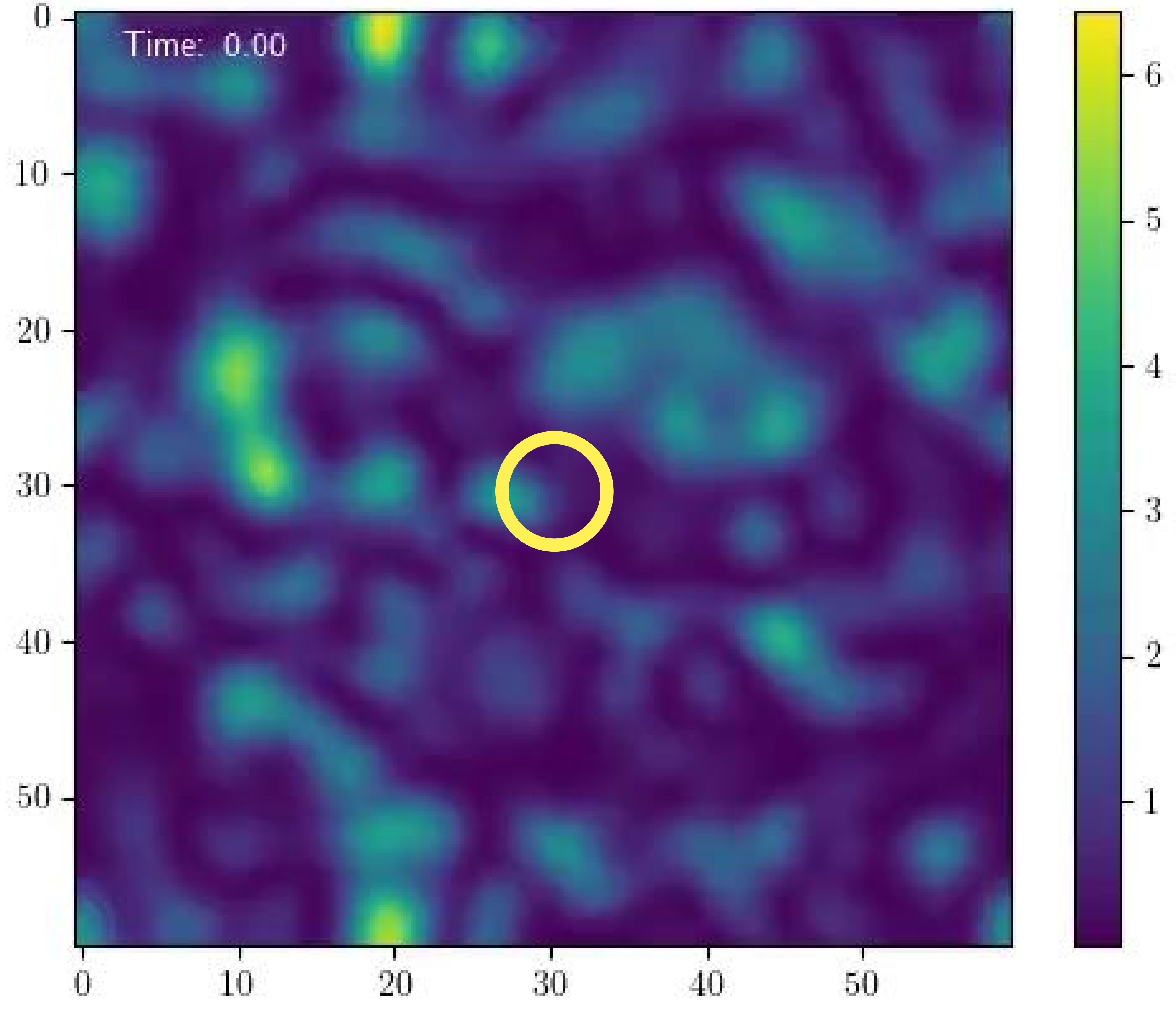
what is reflected in *detector observables*
is the *statistical properties* of
density fluctuations of ULDM

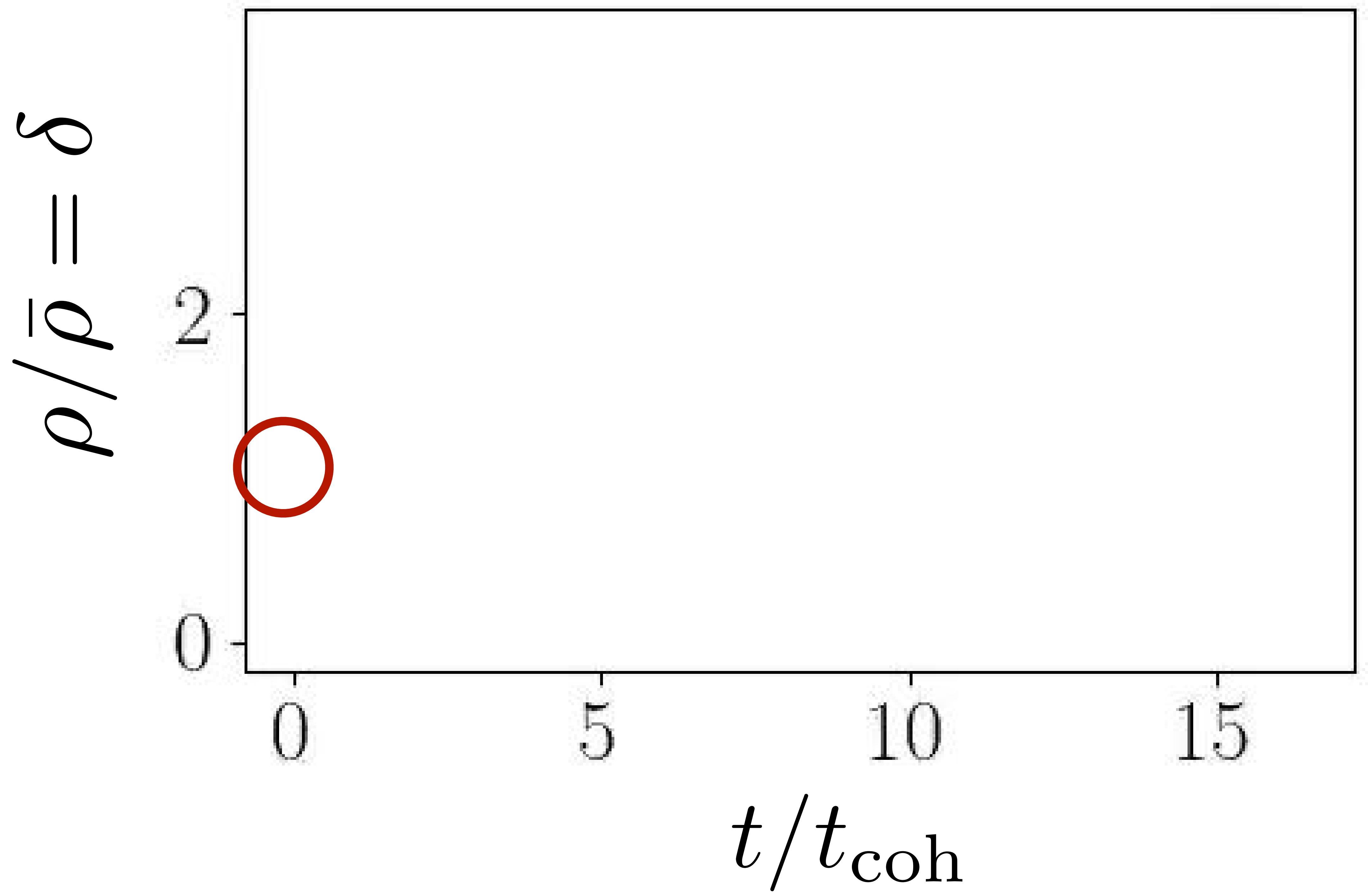


the density-density correlator at the same position is

$$\langle \delta(x)\delta(x) \rangle = \int \frac{d\omega}{2\pi} S_\delta(\omega)$$







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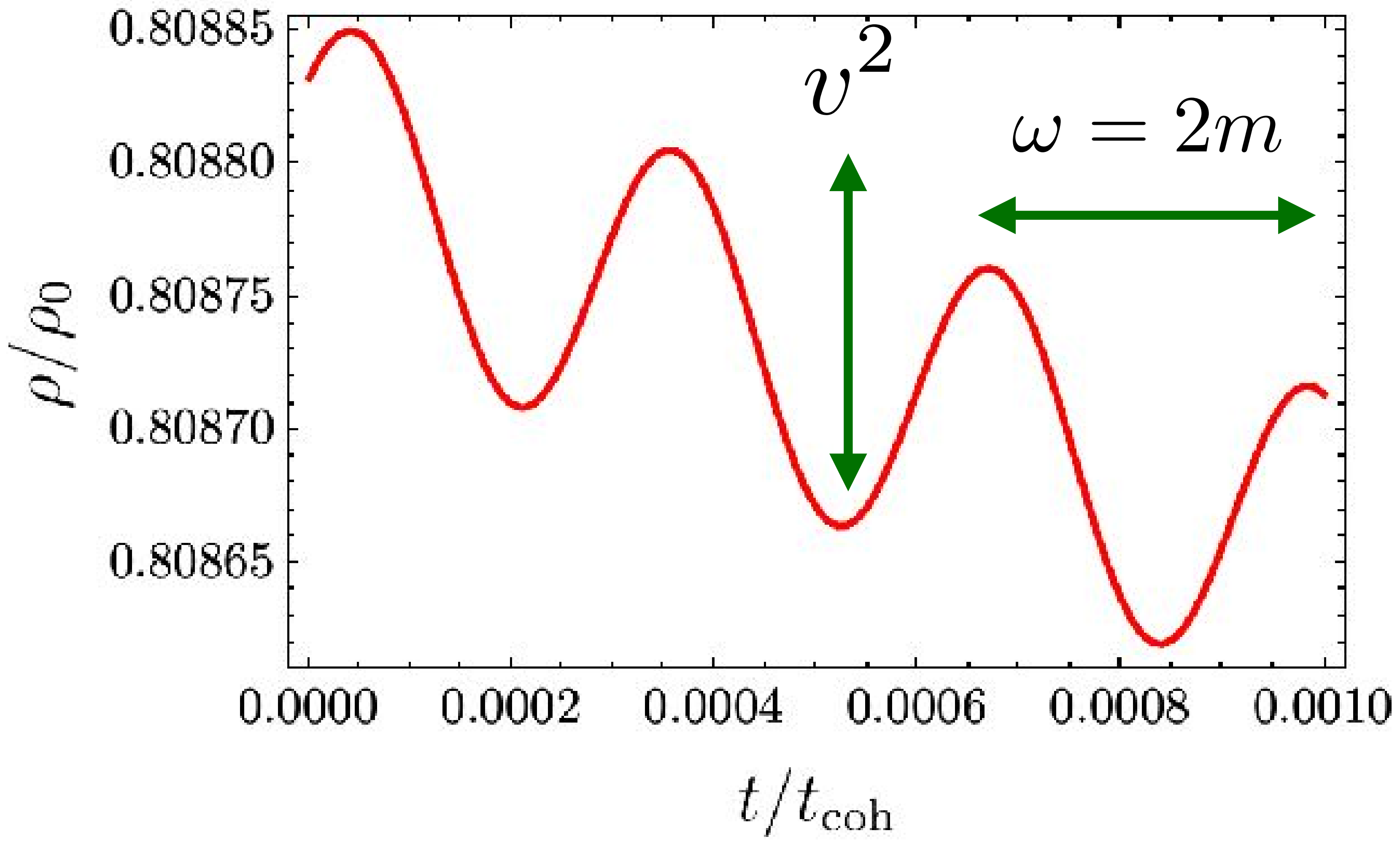
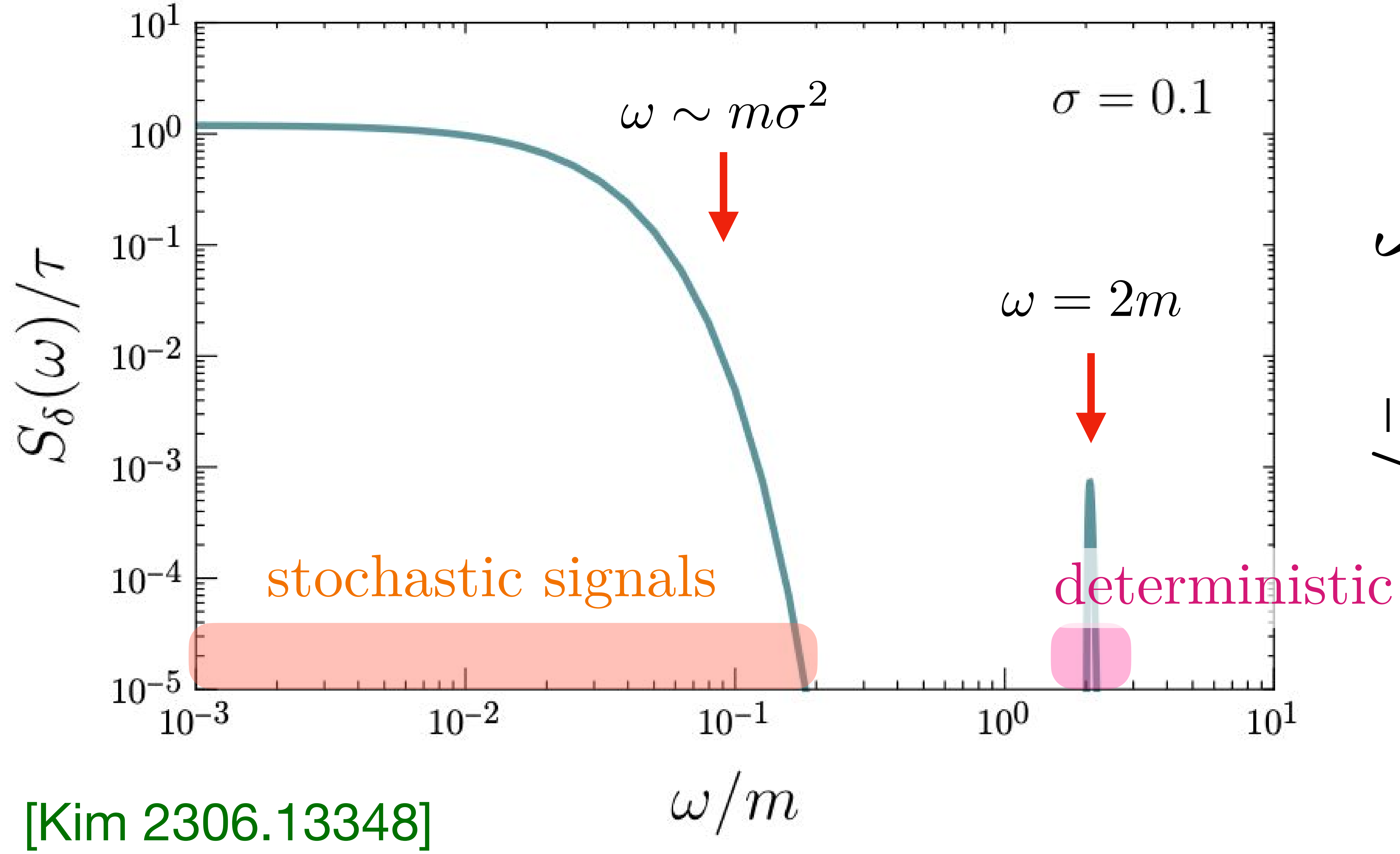
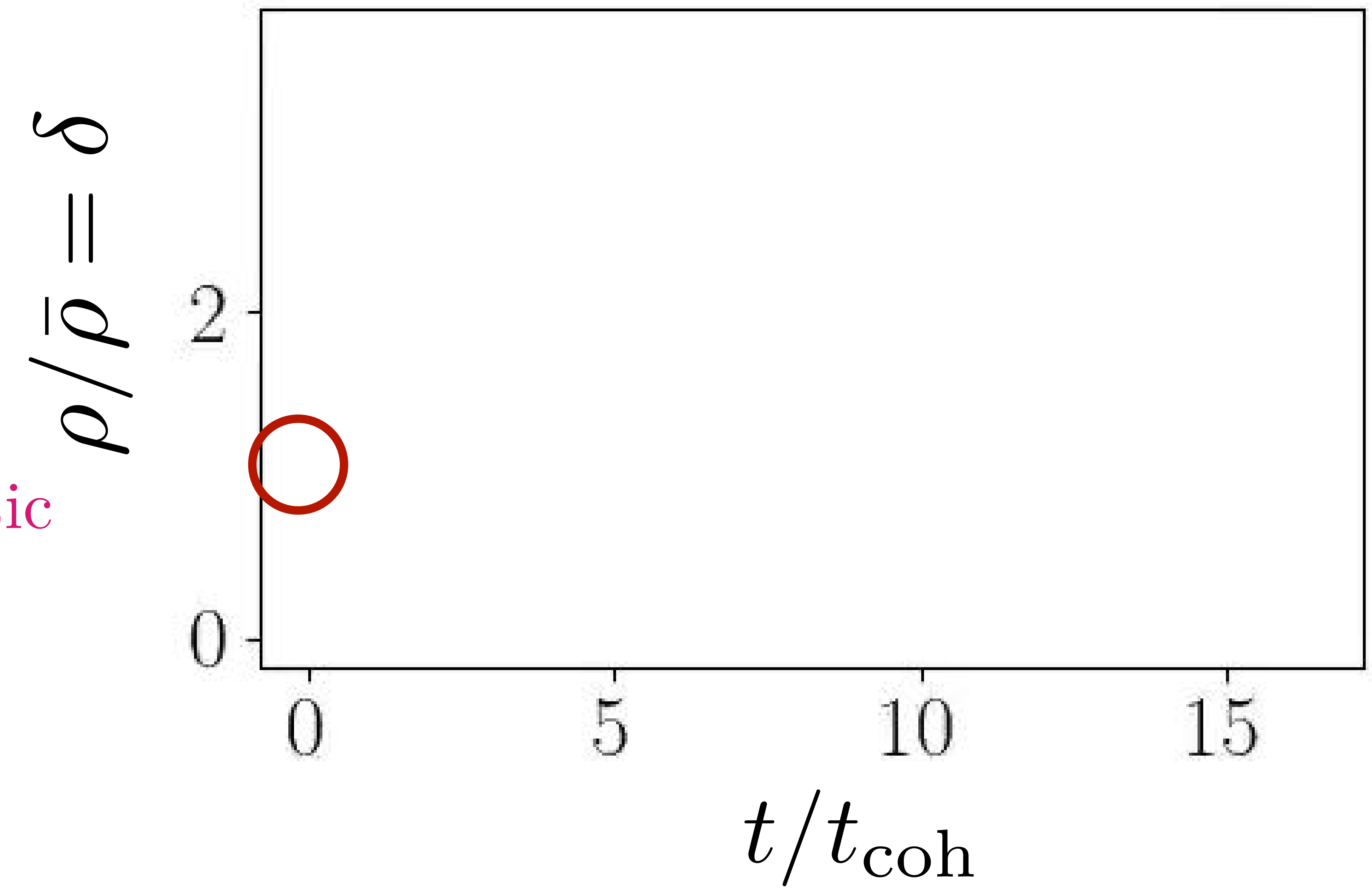


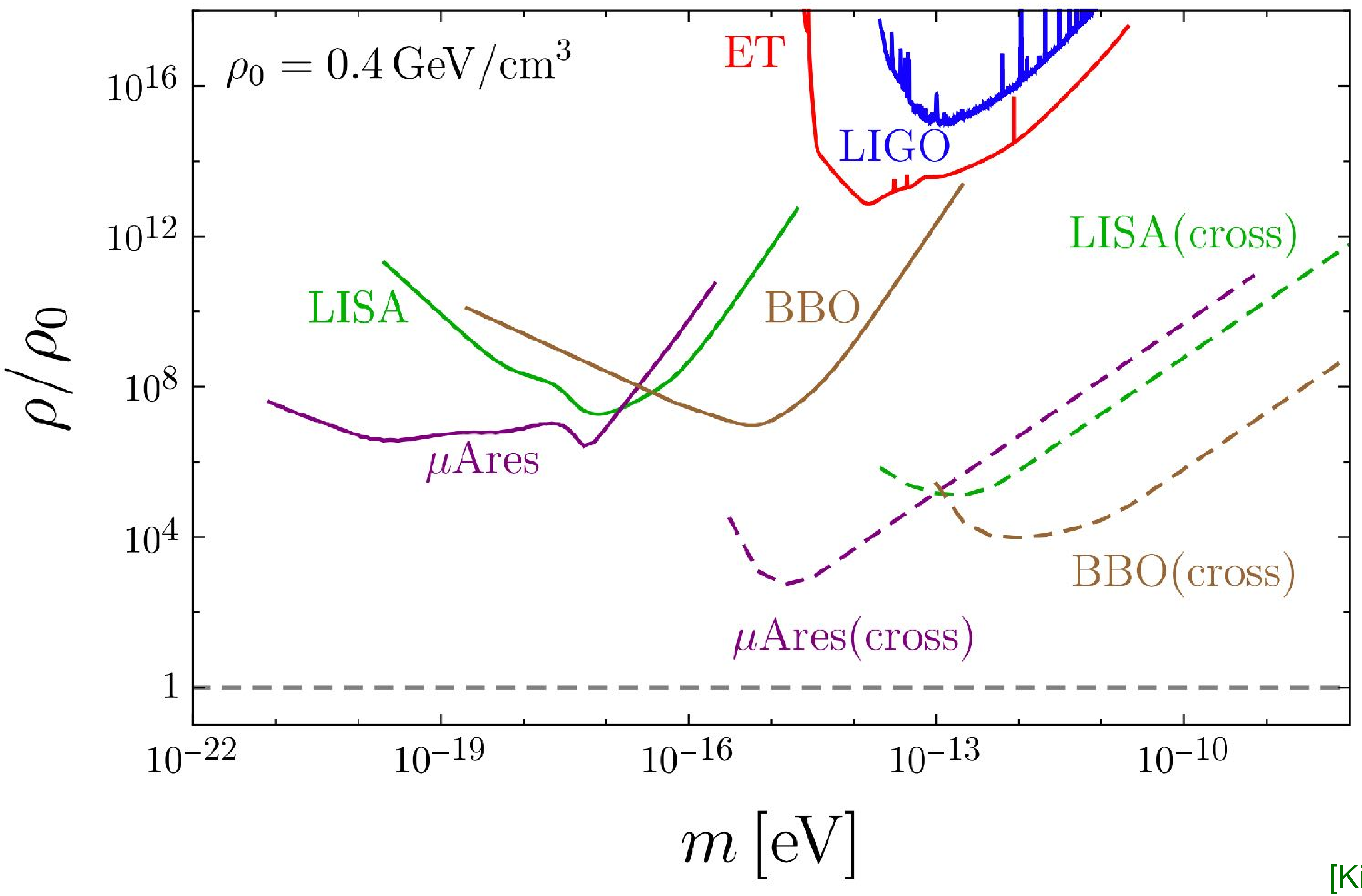
$$S_\delta(\omega) = \tau[\sigma^4 A_\delta(\omega) + B_\delta(\omega)]$$





[Kim 2306.13348]

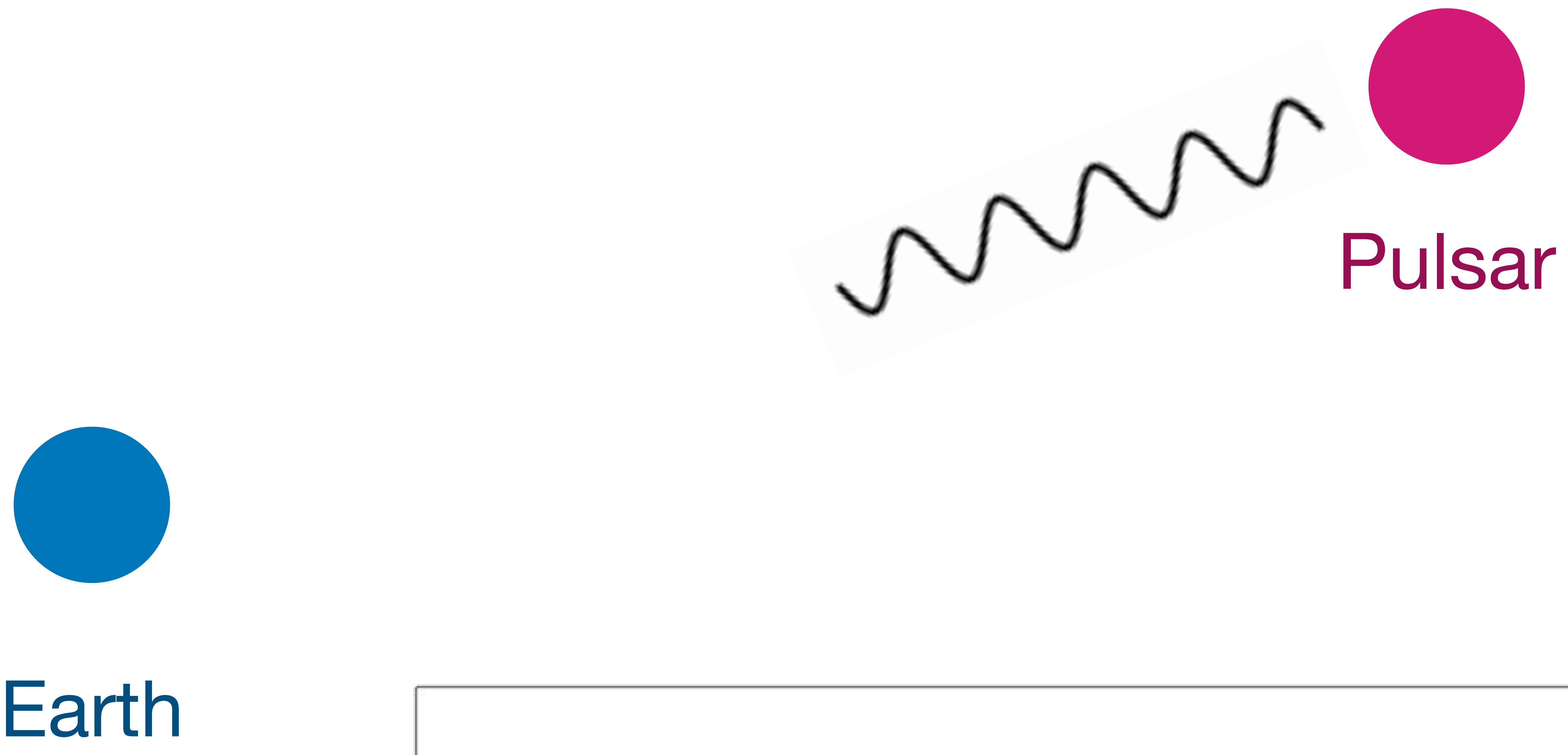
[Kim, Lenoci, Perez, Ratzinger, 2307.14962]

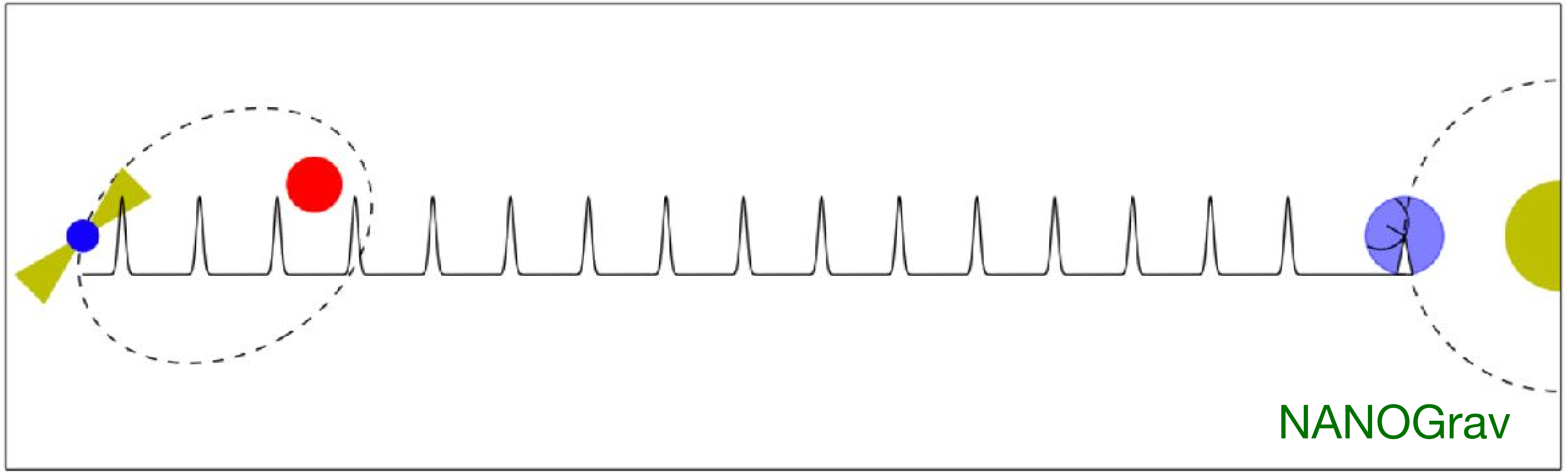


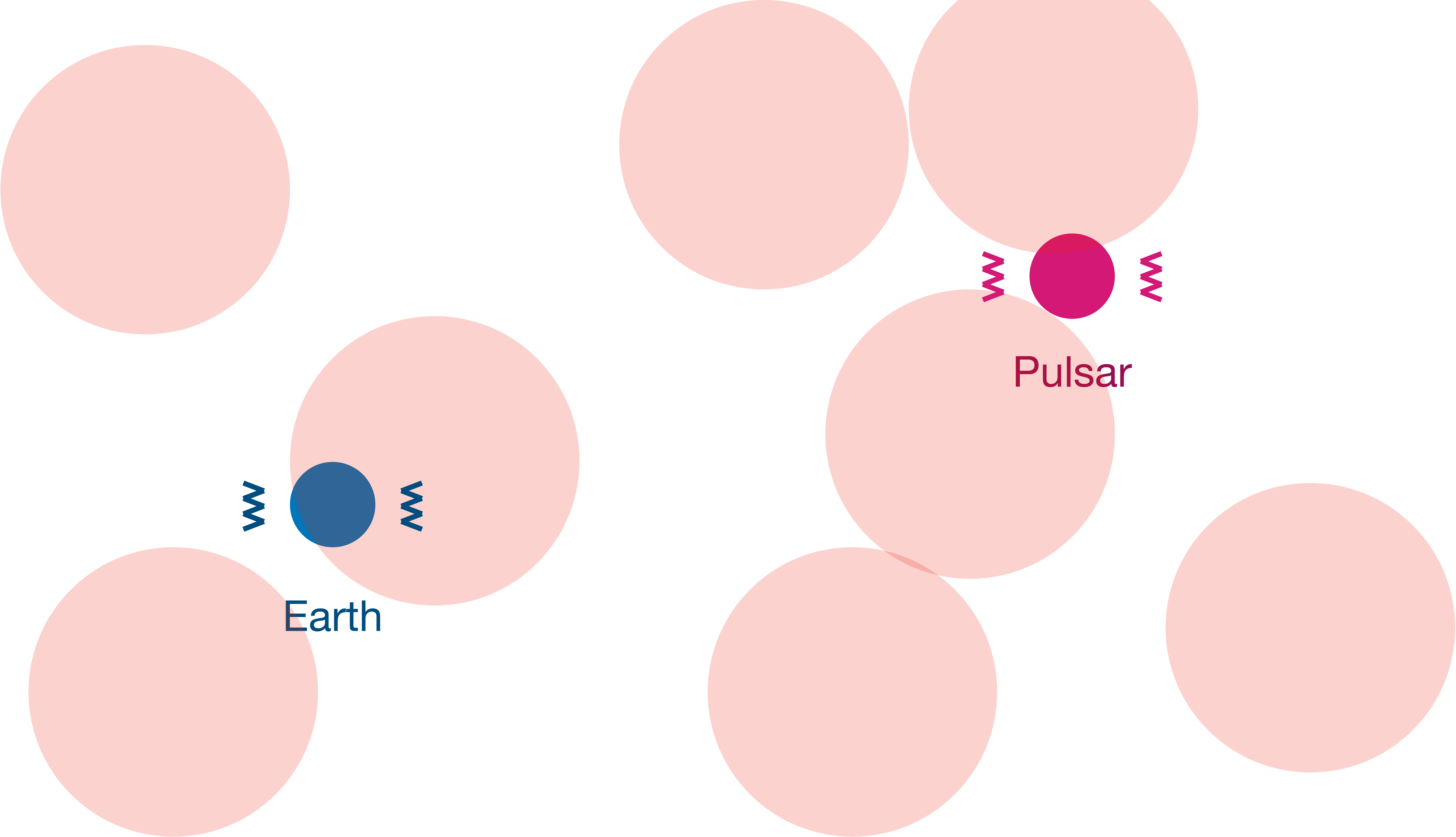
[Kim 2306.13348]

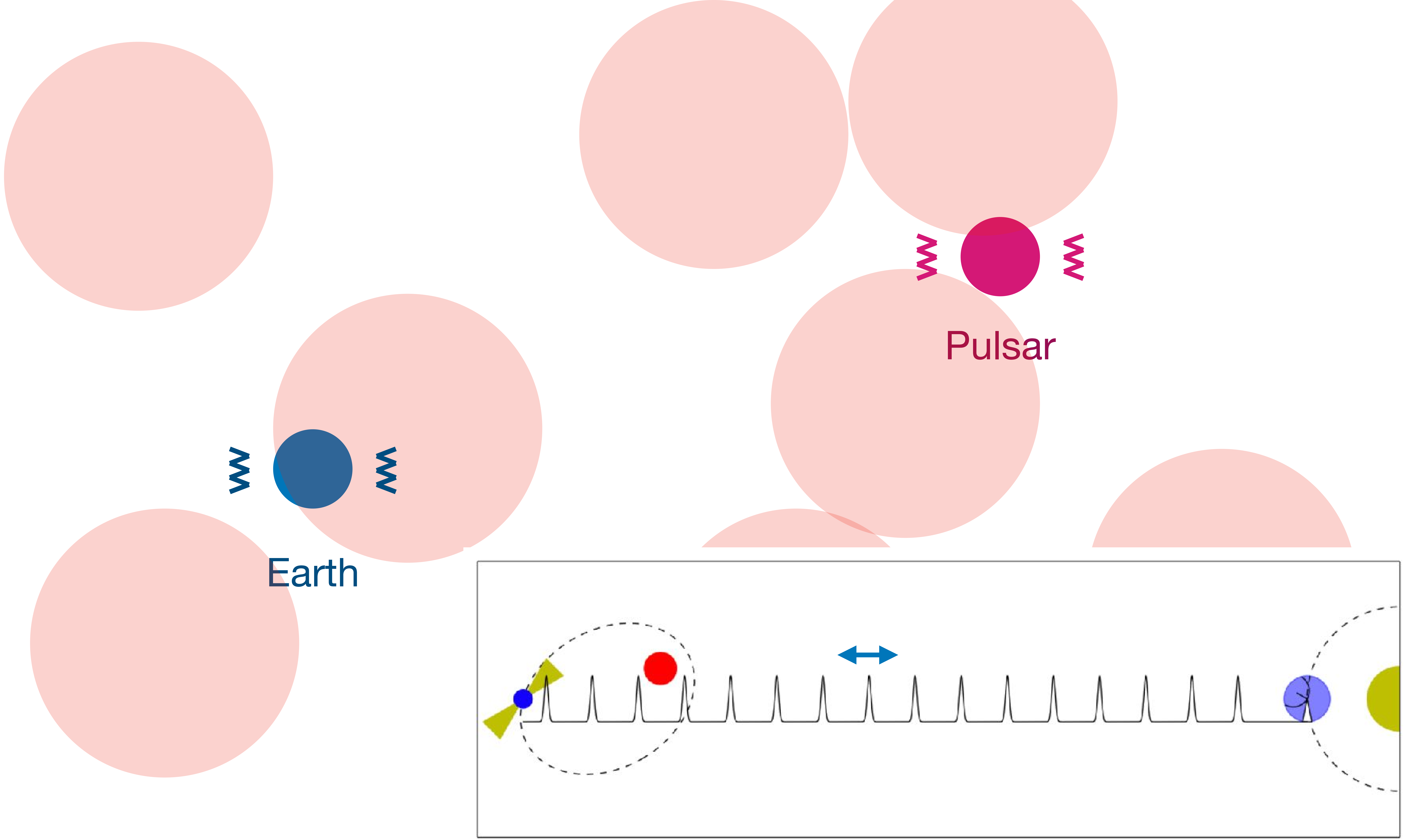
another example:

Pulsar Timing Array


Pulsar
Earth


NANOGrav


Pulsar
Earth

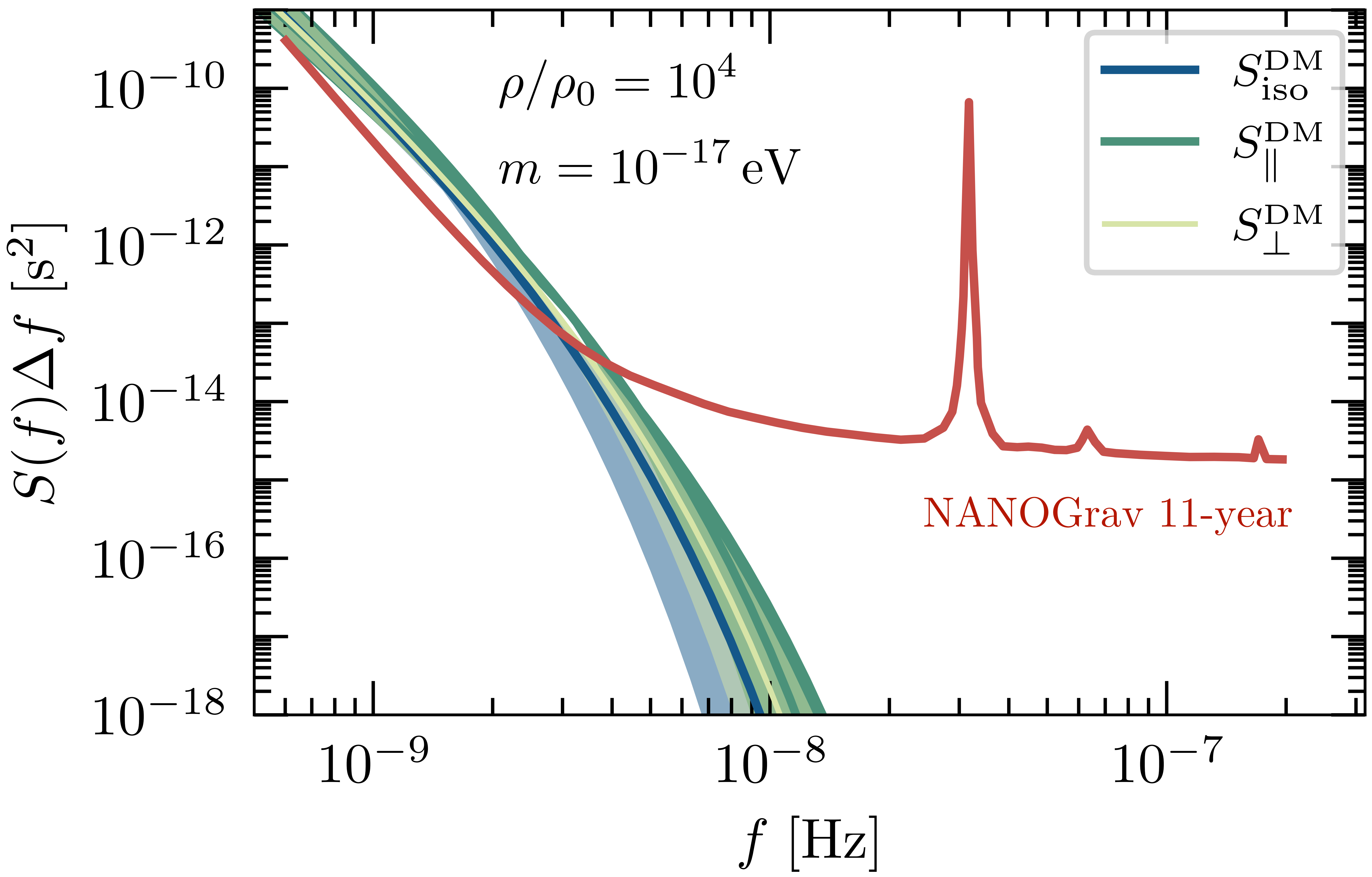


Pulsar
Earth

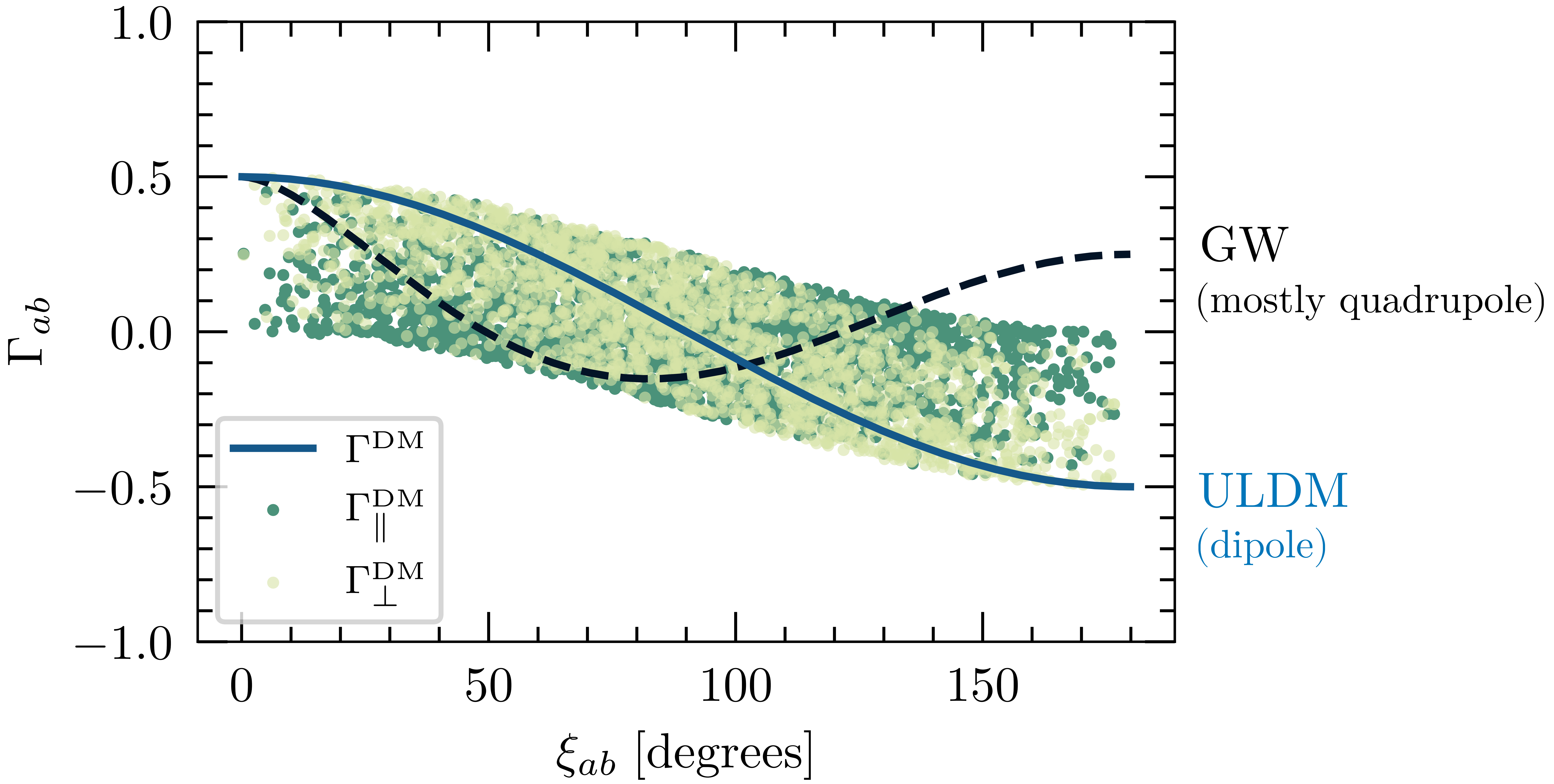
ultralight dark matter signal is characterised by

spectrum and ***correlation***

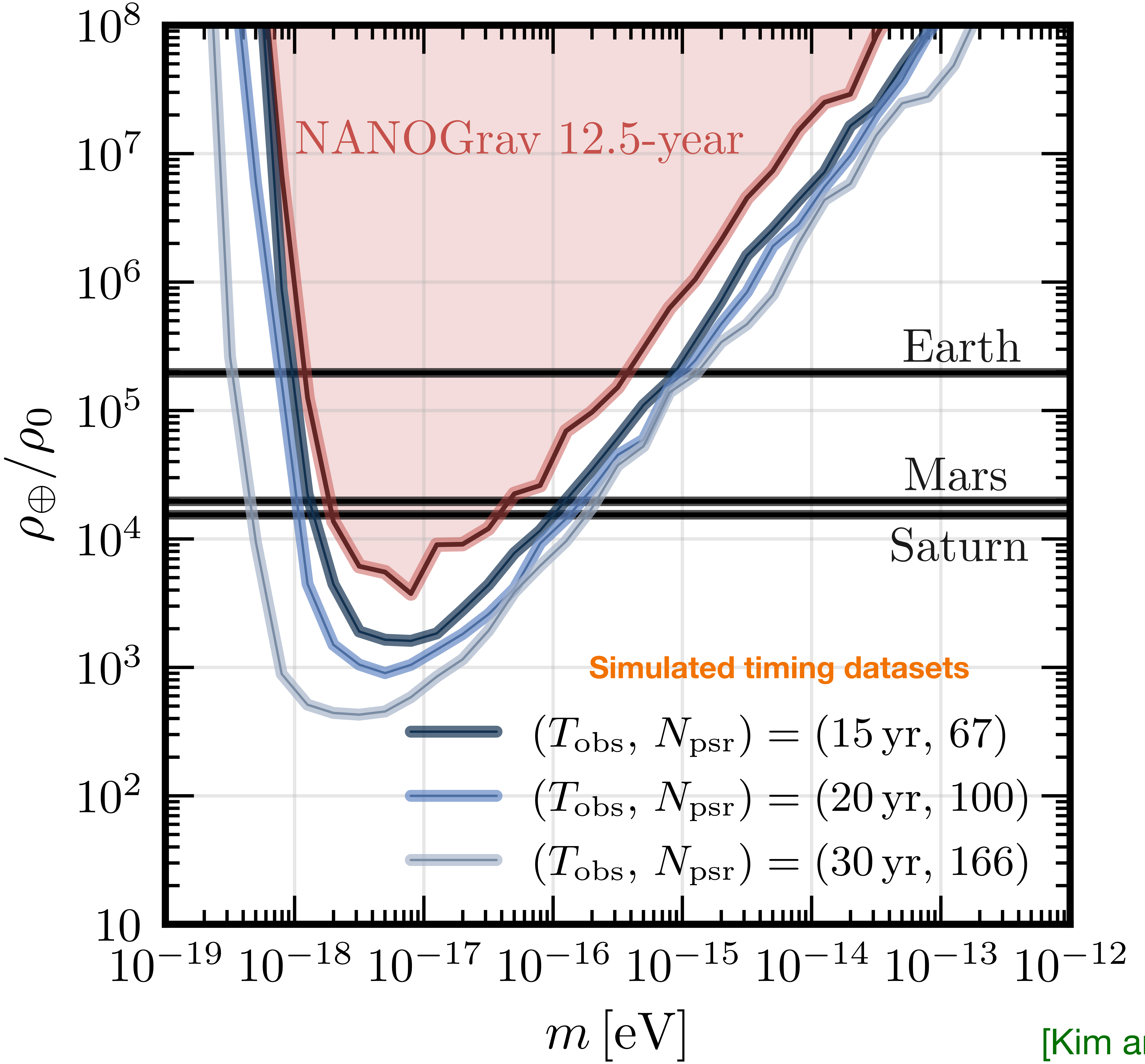
$$\langle \delta t_a \delta t_b \rangle = \int df \, \Gamma_{ab}^{\mathrm{ULDM}} S_{\delta t}^{\mathrm{ULDM}}(f)$$



[Kim and Mitridate 2312.12225]



[Kim and Mitridate 2312.12225]



[Kim and Mitridate 2312.12225]

one last example:

Astrometry

astrometry involves
precision measurements of
positions / velocities of stars

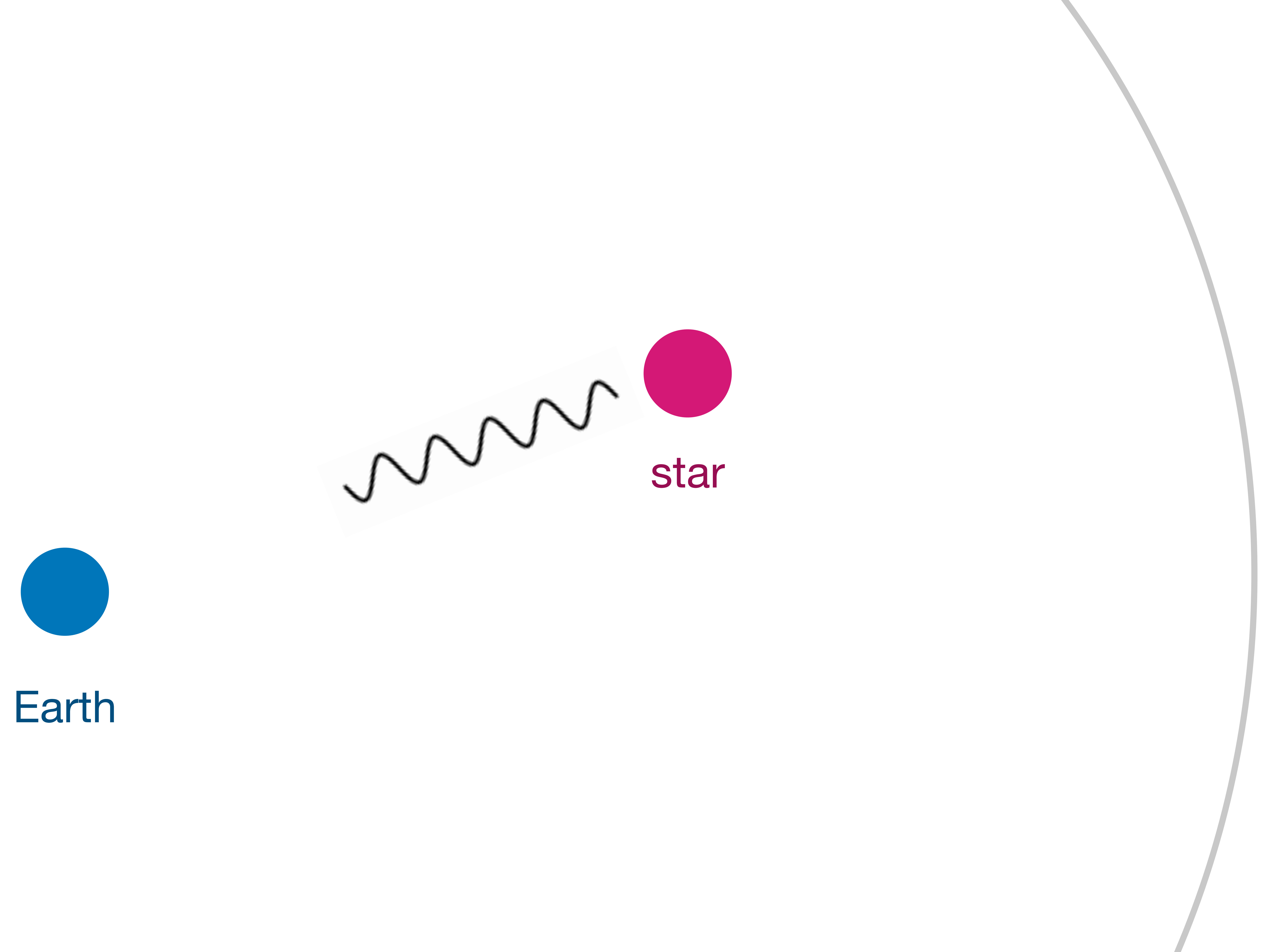
current/future astrometry missions measure

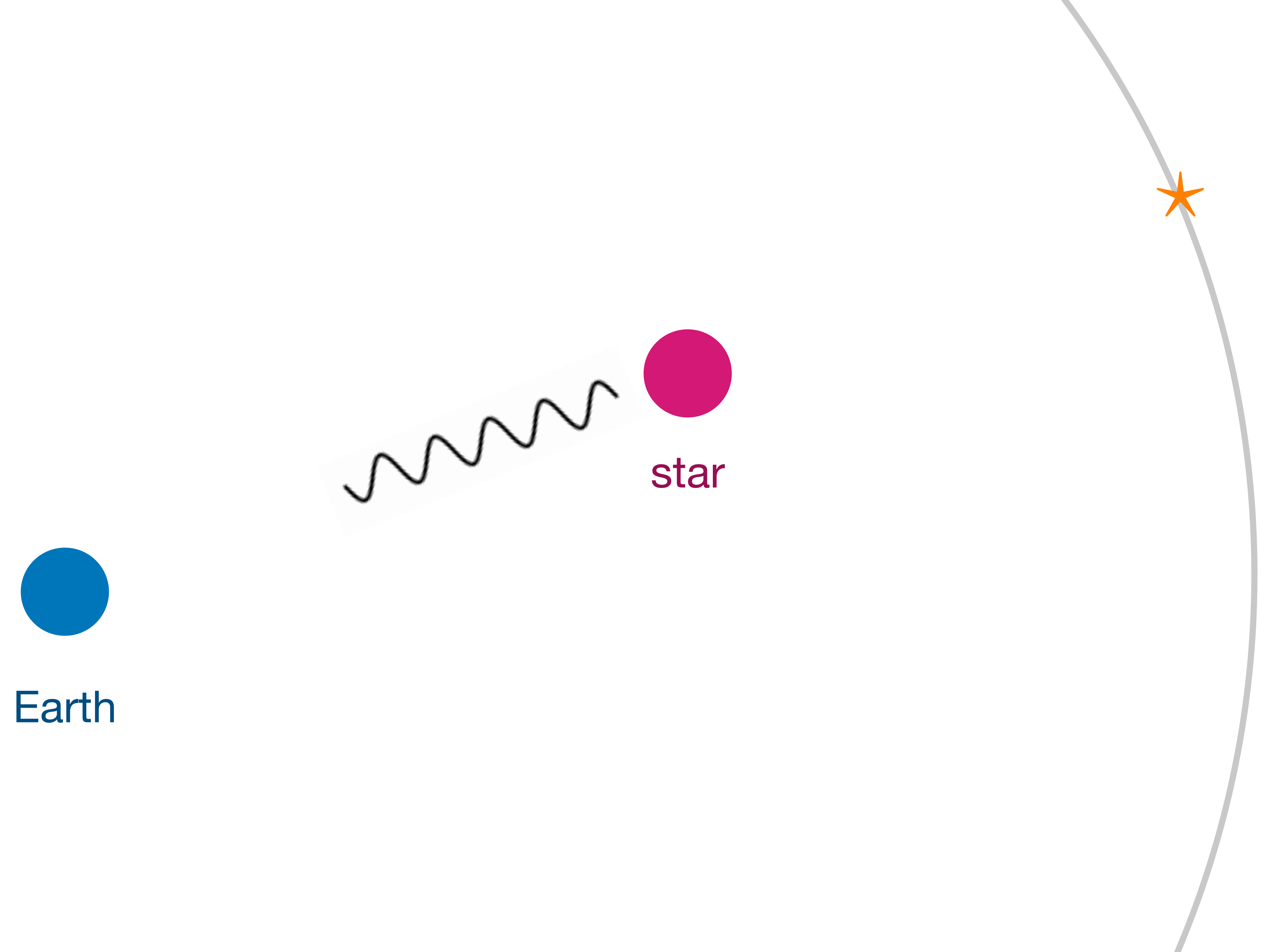
$$N_\star = 10^8 - 10^9$$

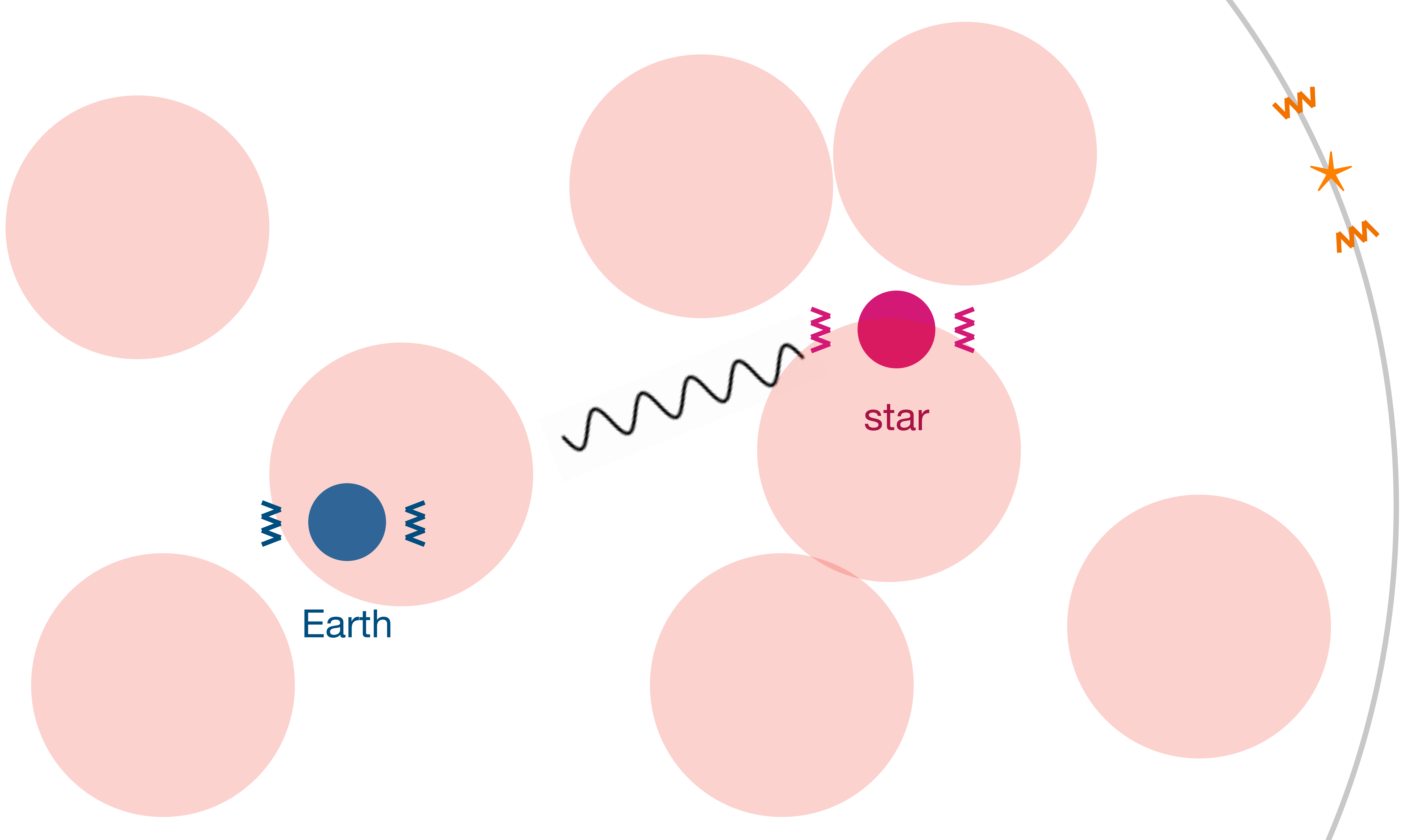
at the precision of

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

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


star
Earth


star
Earth


star
Earth

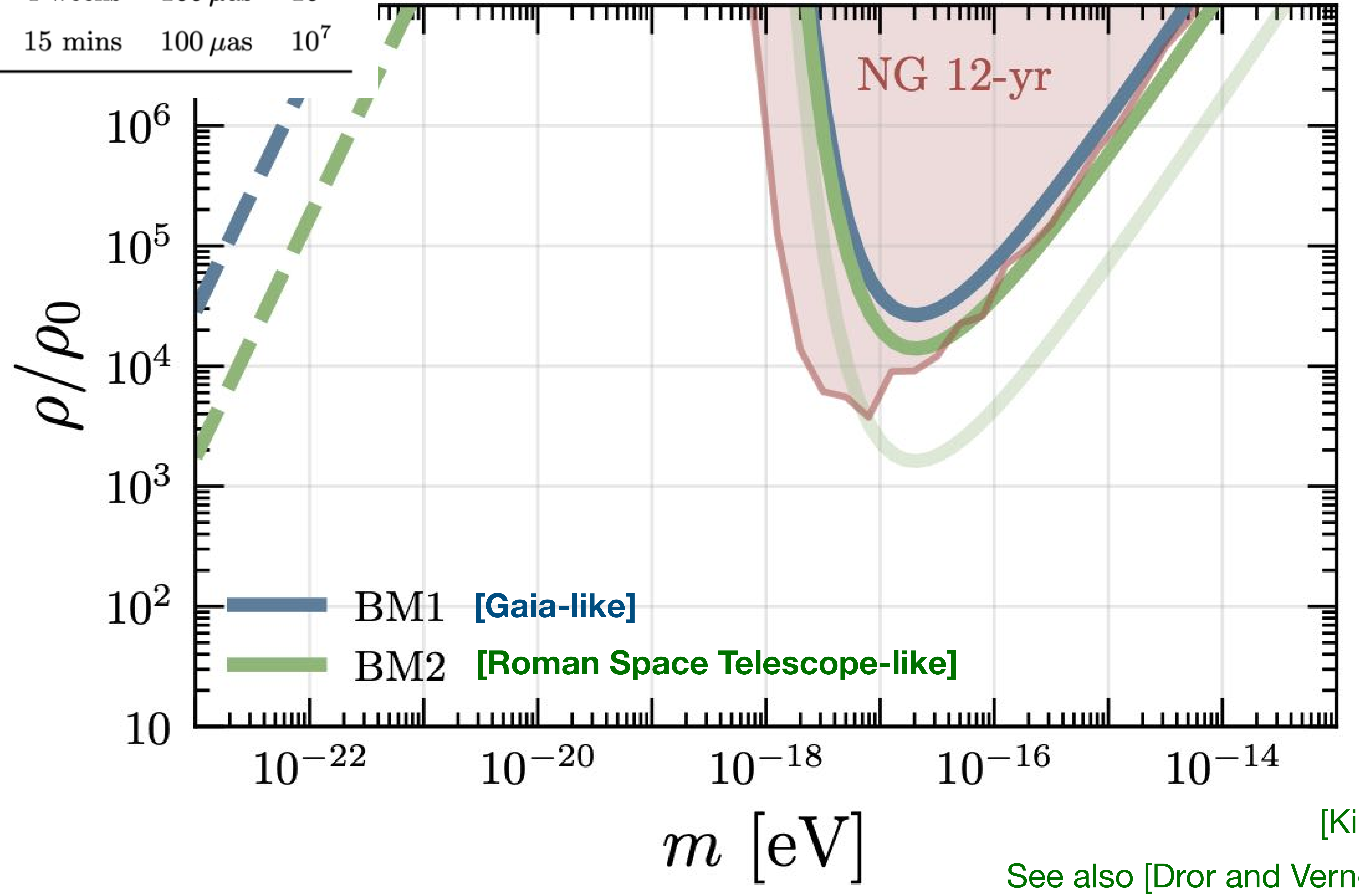
similarly

the signal is characterised by spectrum and correlation

$$\langle \delta n_a^i(t)\delta n_b^j(t')\rangle = \int df\, \Gamma_{ab}^{ij} S(f) \cos[2\pi f(t-t')]$$

[Kim 2406.03539]

	T	Δt	σ_r	$N_\star$
BM1	10-yr	4 weeks	100 μas	10^8
BM2	10-yr	15 mins	100 μas	10^7



[Kim 2406.03539]

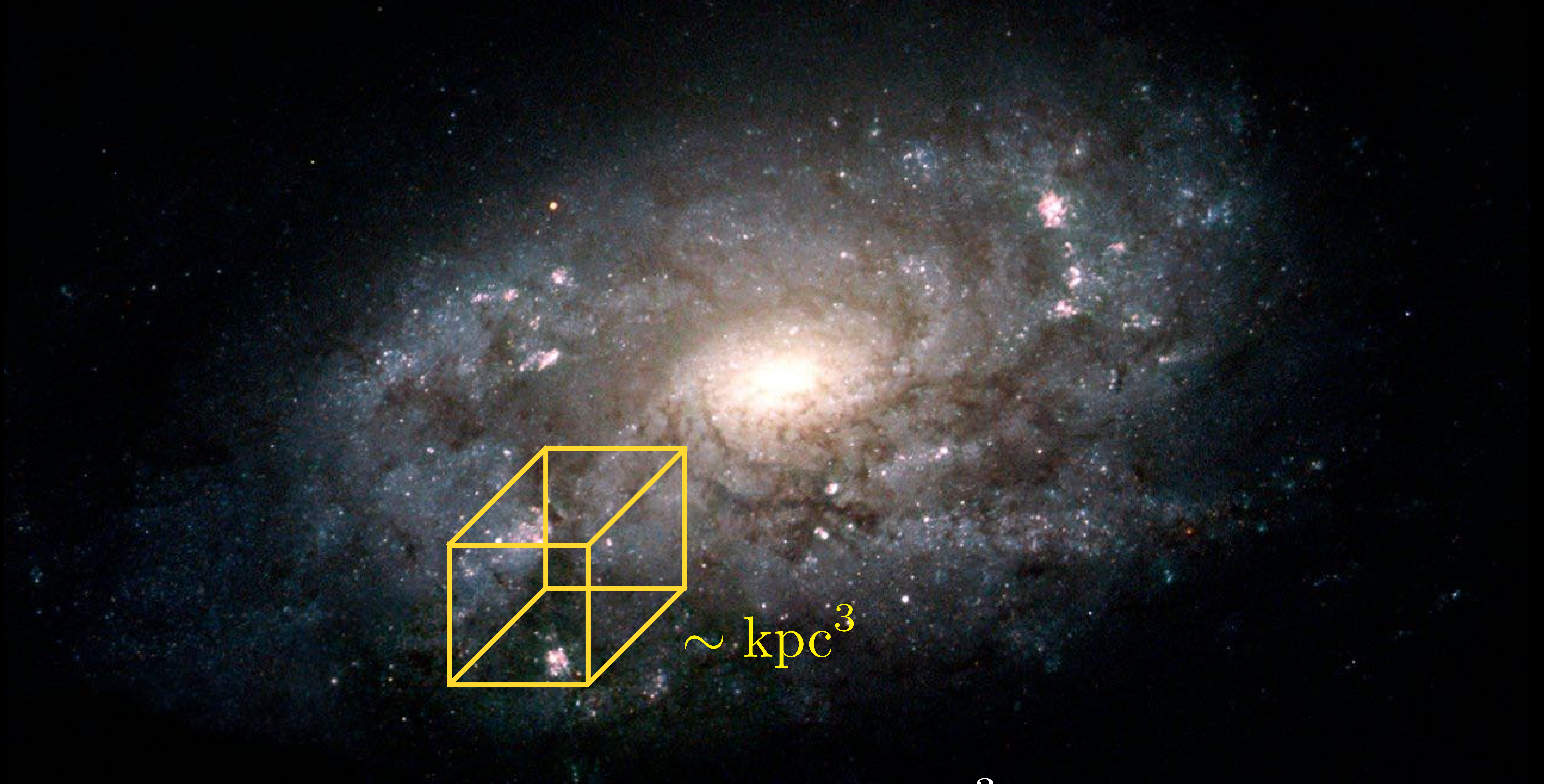
See also [Dror and Verner 2406.03526]

Remark I

all of the results shown here are sensitive to

ULDM density around/within the solar system

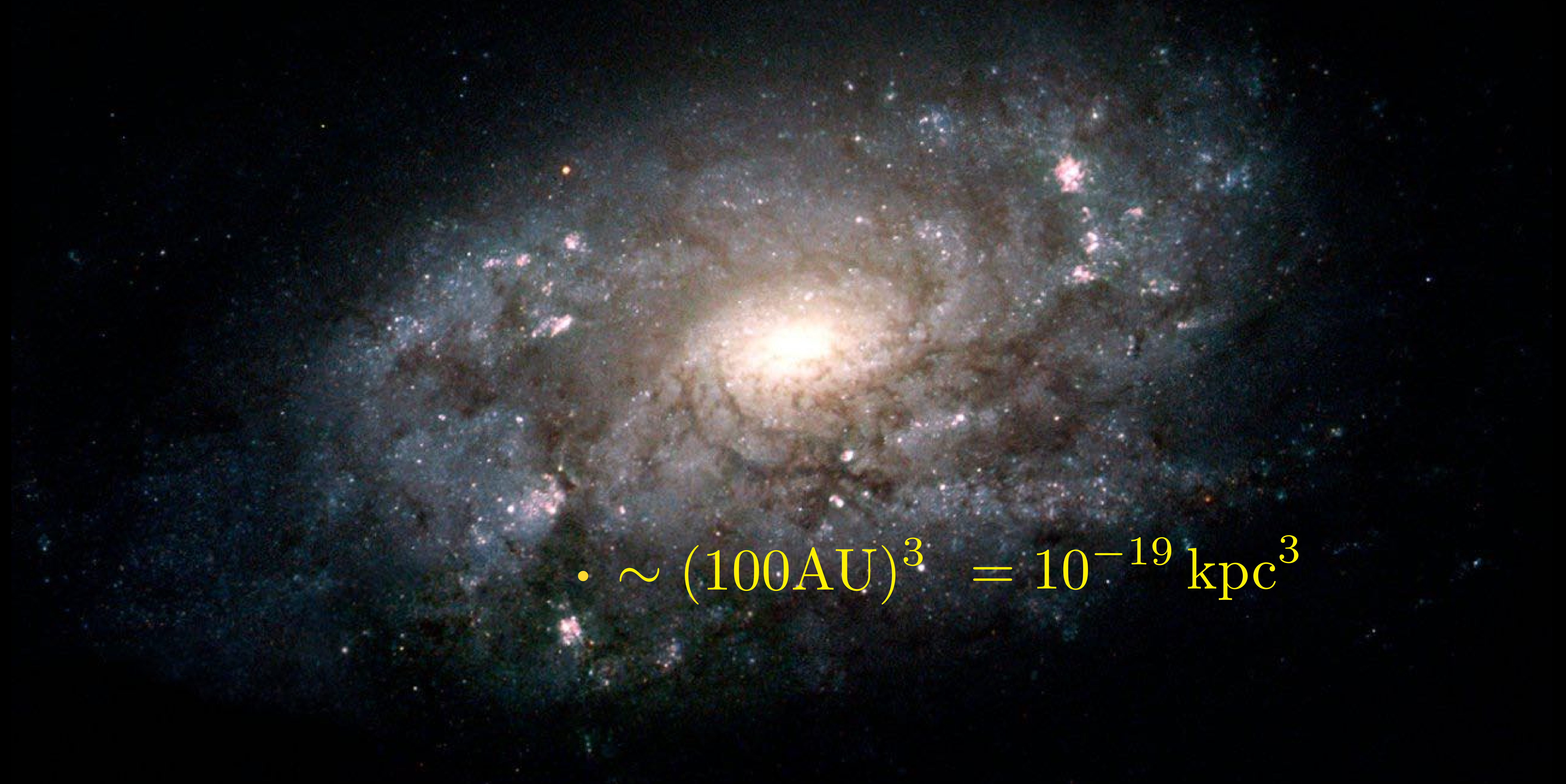
local dark matter density is often derived over kpc scales



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

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, Eby et al (22)]

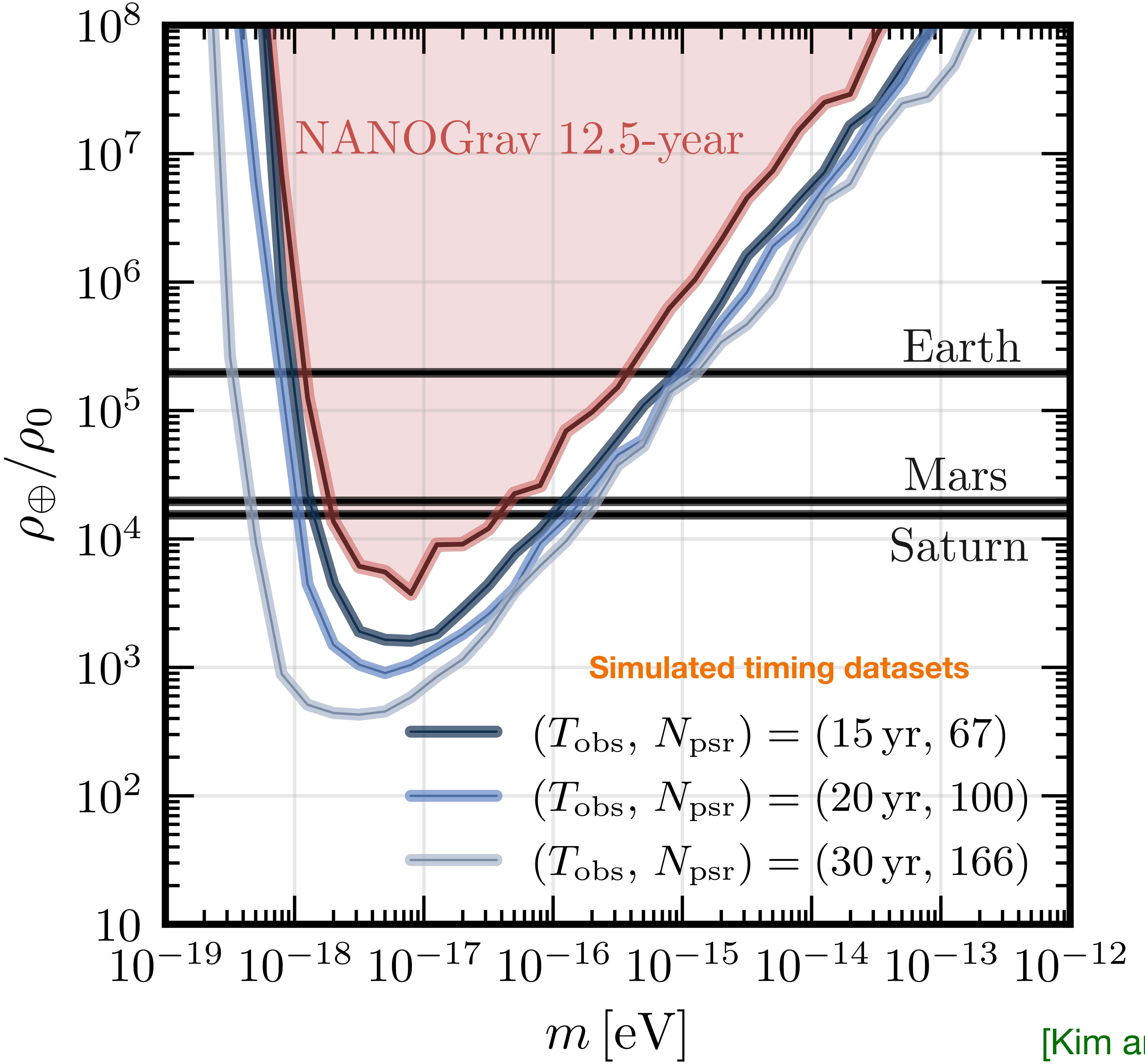
$$\rho/\rho_0 \lesssim 2 \times 10^4$$

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

GW detectors will provide
one of the strongest probes of ULDM density
within/around the solar system

Remark II

prospects of pulsar timing array

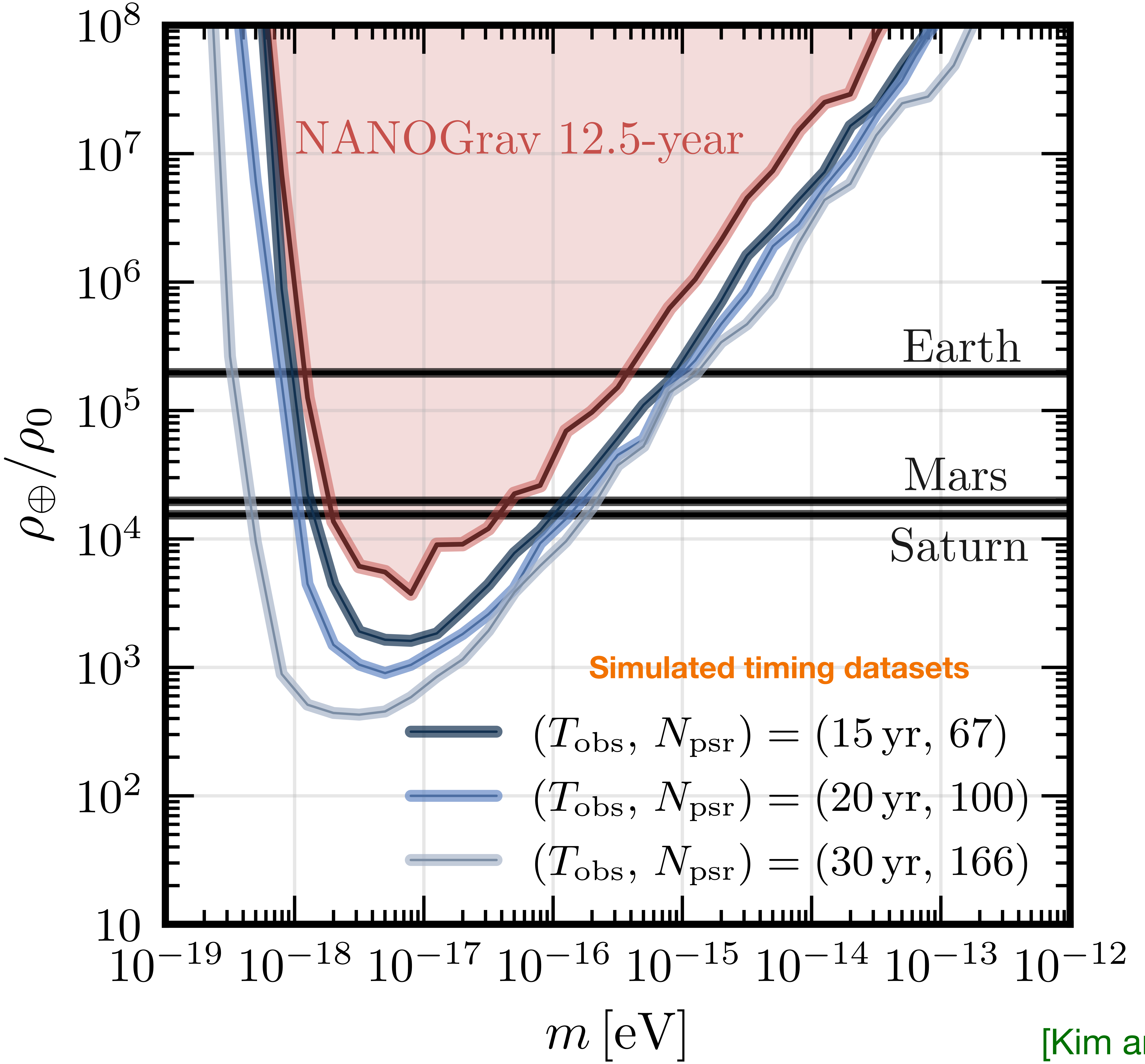


[Kim and Mitridate 2312.12225]

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

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

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



[Kim and Mitridate 2312.12225]

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

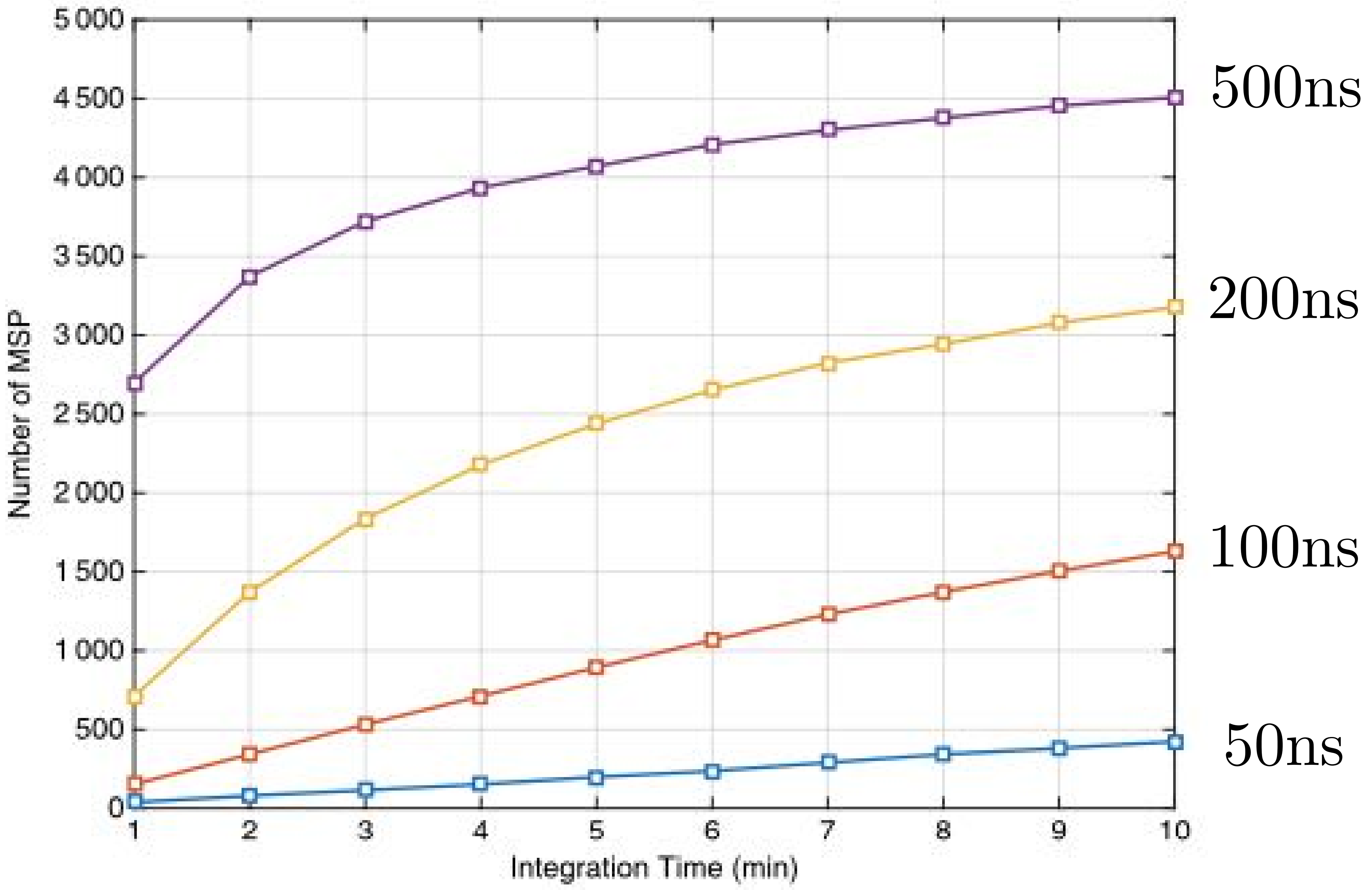


Figure 10. Numbers of MSPs that can archive a certain RMS noise level (or better) with varying integration time. Colour lines indicate different RMS noise levels (from bottom to top): 50 ns (blue), 100 ns (red), 200 ns (yellow), and 500 ns (purple).

[SKA, Weltman et al (20)]