Astrometric Search for Ultralight Dark Matter

Hyungjin Kim (DESY)

A Future Space Mission with Very High Precision Astrometry
12 Sep 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***

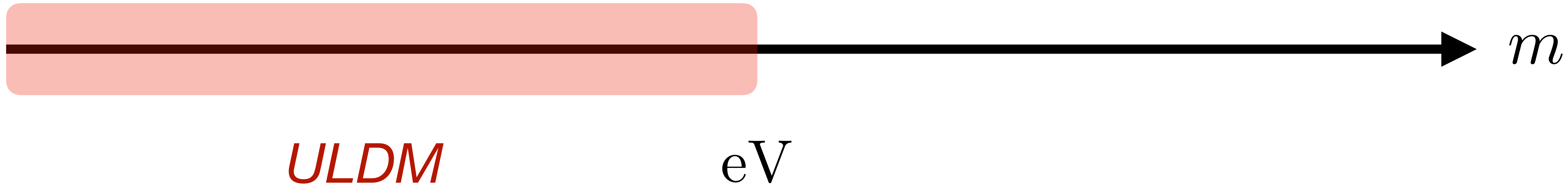
near the solar system

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

Astrometric Search (GW detectors) for Ultralight Dark Matter

Ultralight Dark Matter

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



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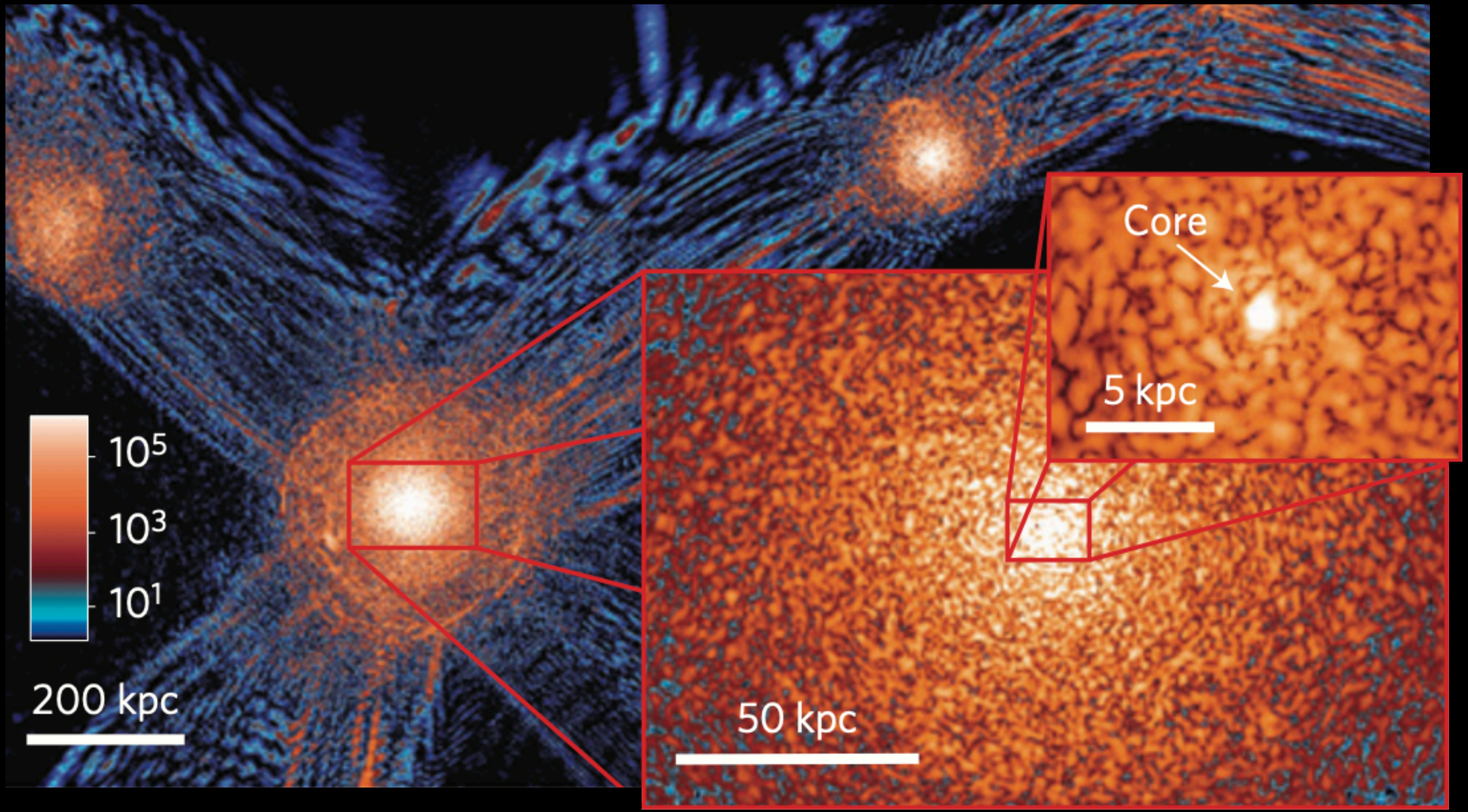
as *bosonic DM candidates with* $\mathrm{m} < \mathrm{eV}$

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

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

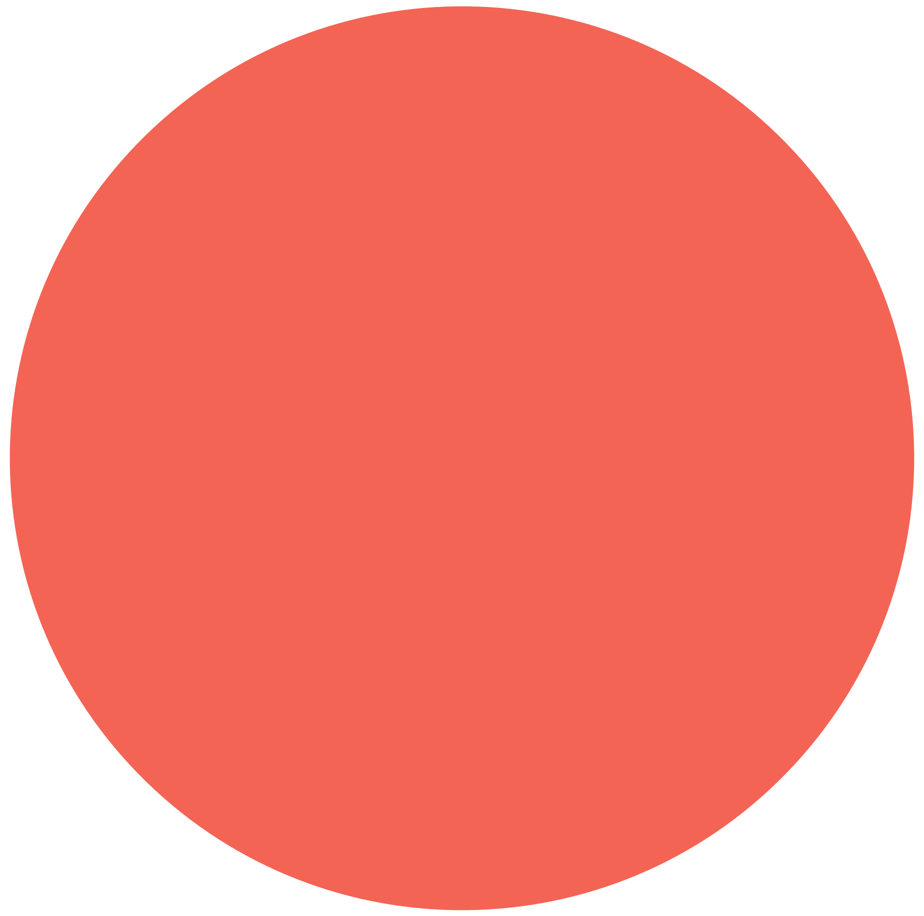
Schive, Chiueh, Broadhurst (14)



An intuitive understanding of the granule structure:

[Hui et al 17]

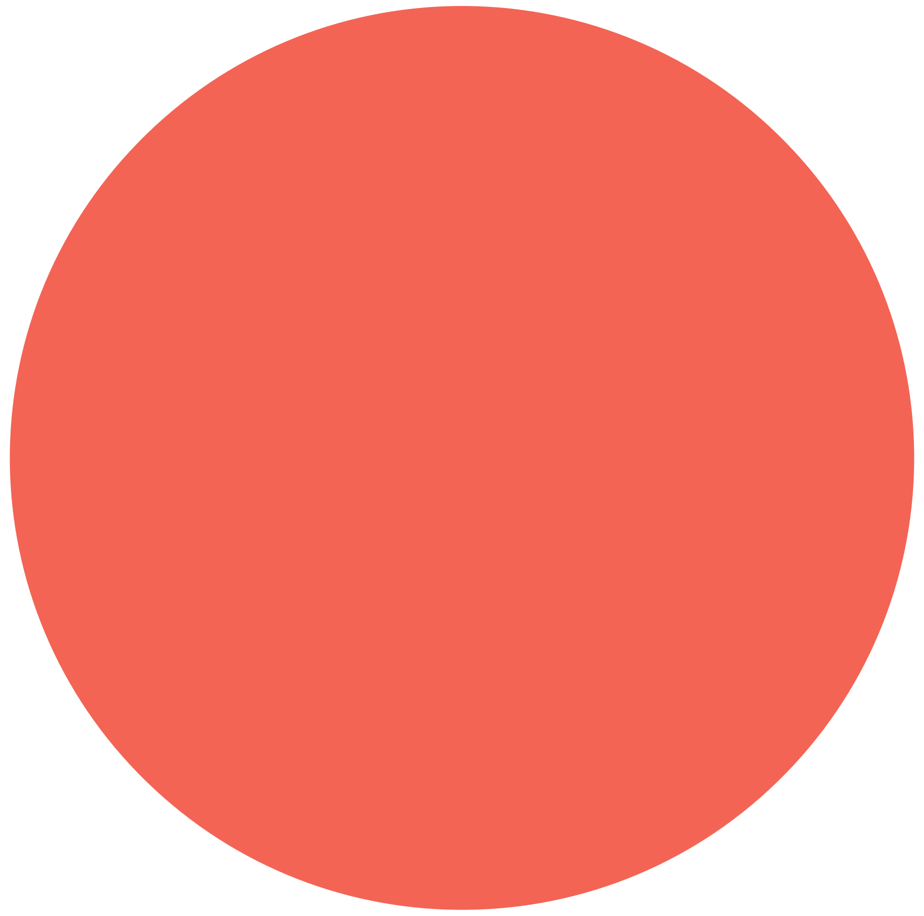
Quasiparticle



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

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

the size and mass of them could be astronomical



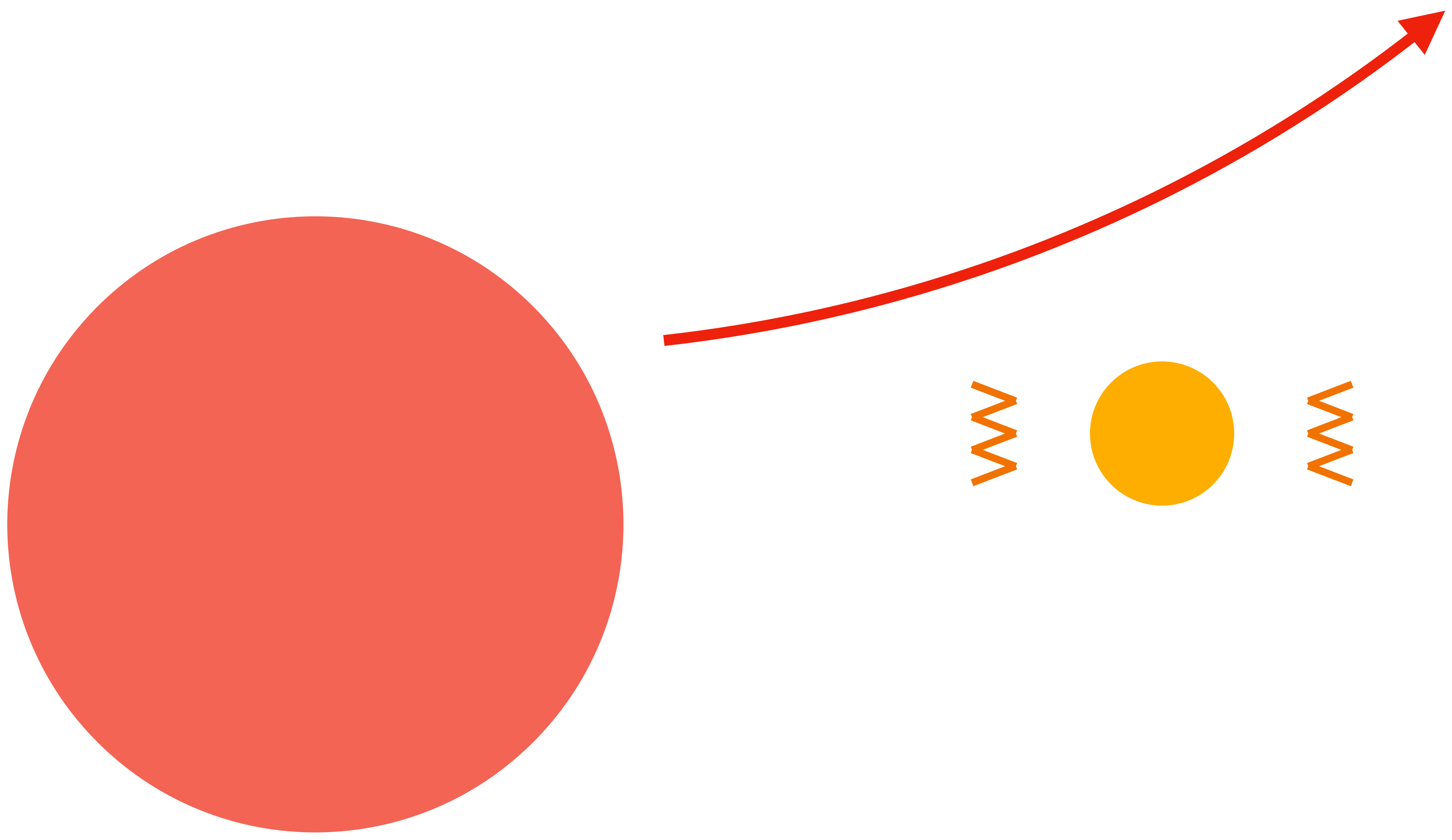
$$\ell \sim \lambda = \frac{1}{mv} \sim 10\,\mathrm{AU} \times \left(\frac{10^{-16}\,\mathrm{eV}}{m}\right)$$

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

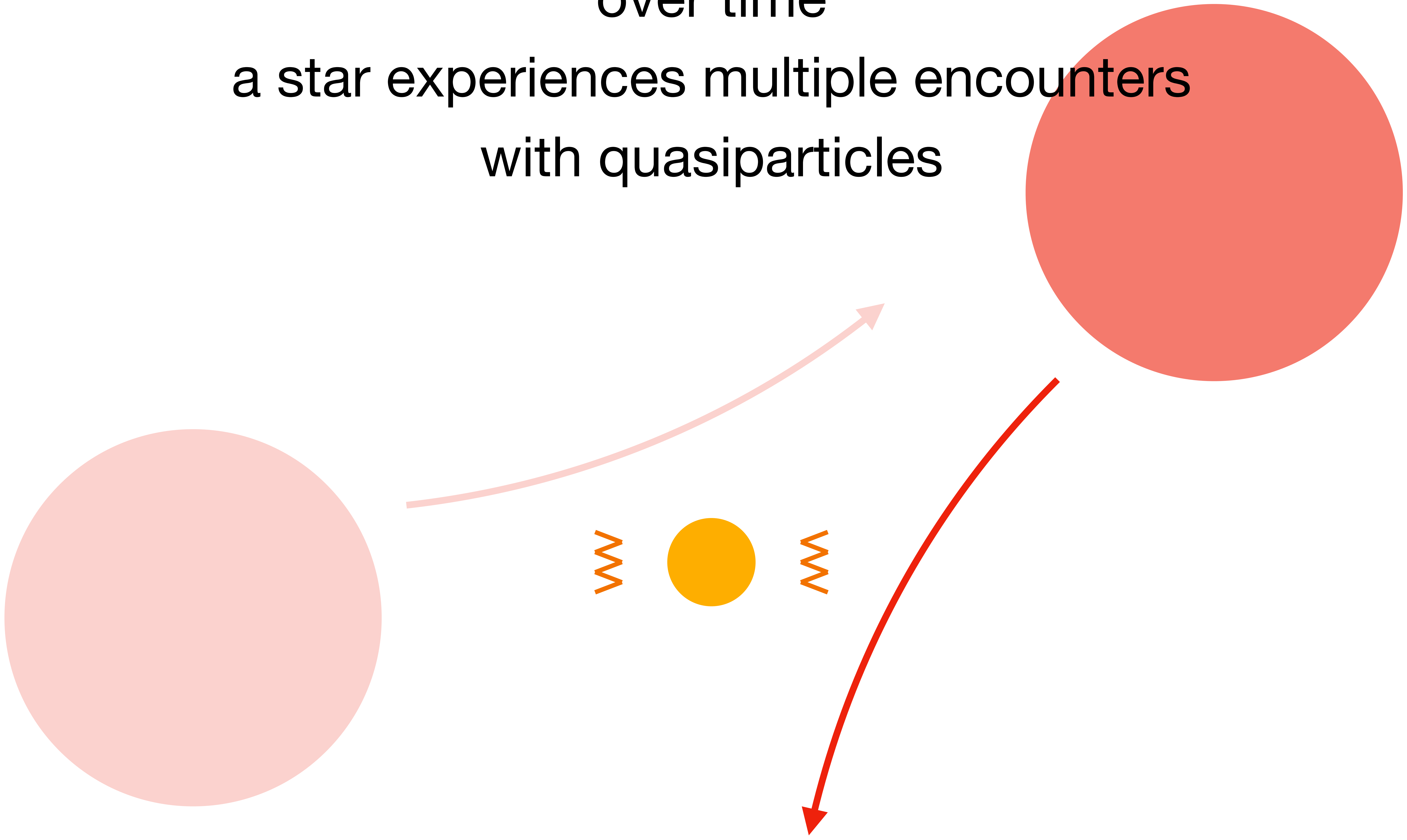
being that massive

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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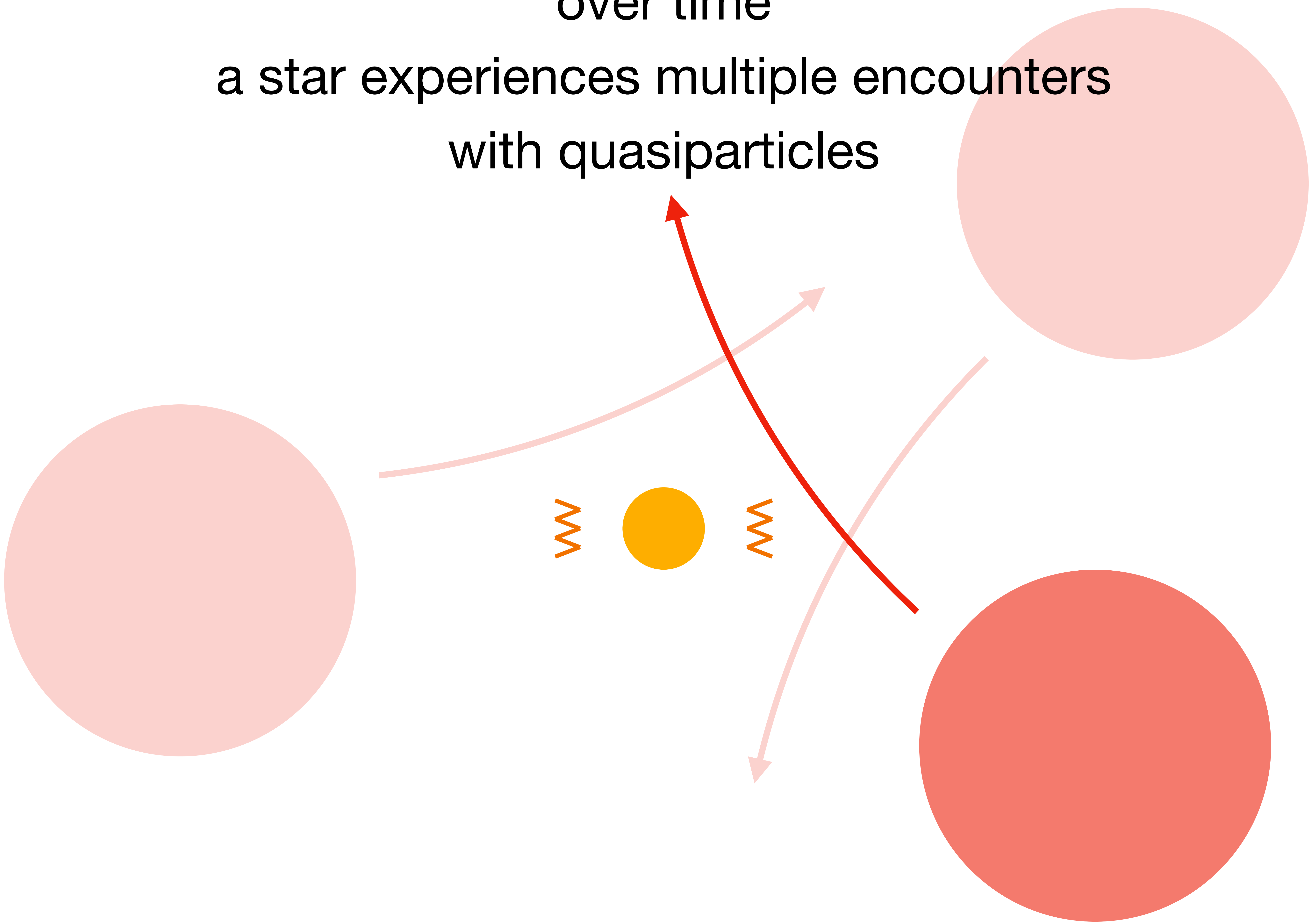


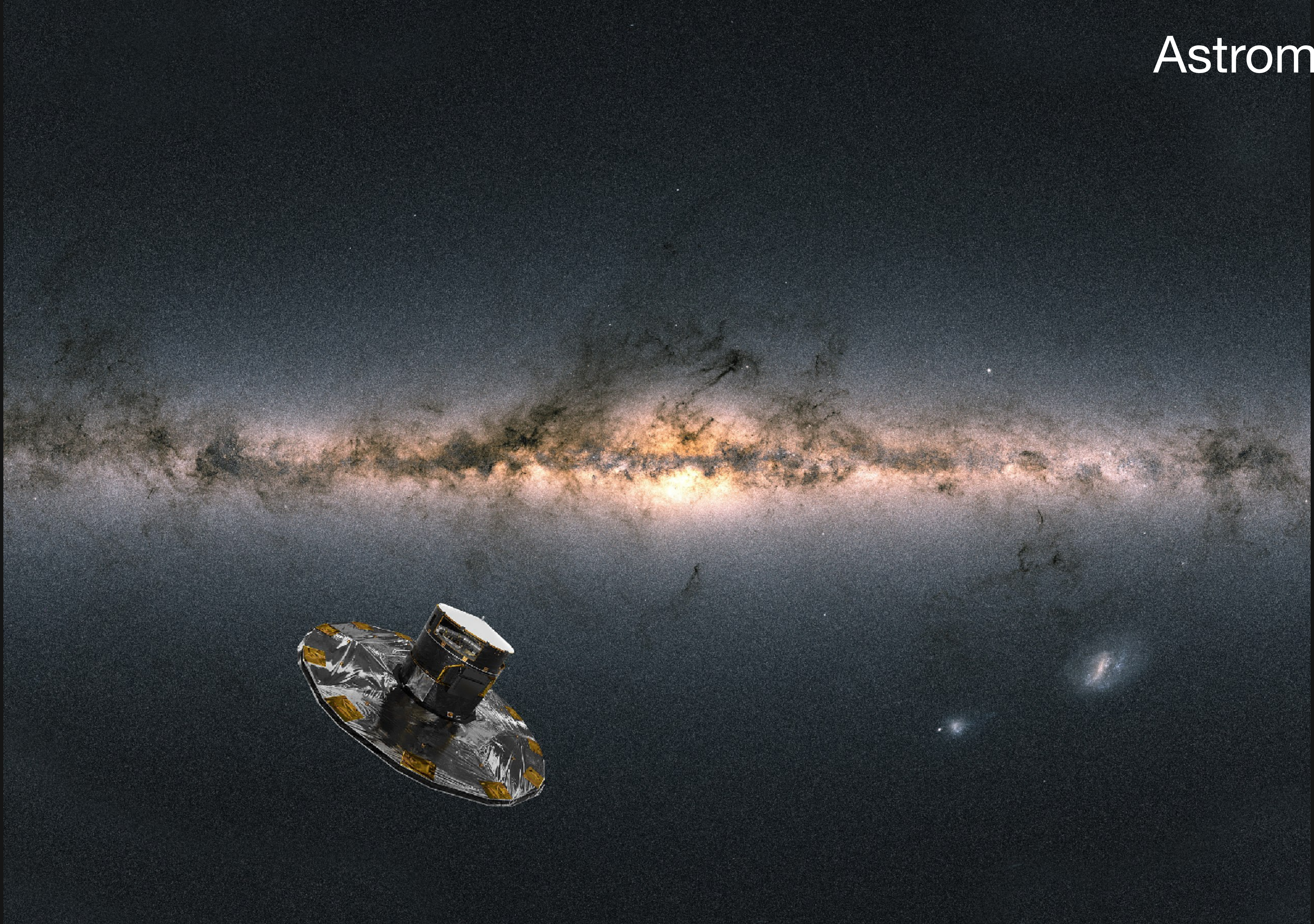
so what?

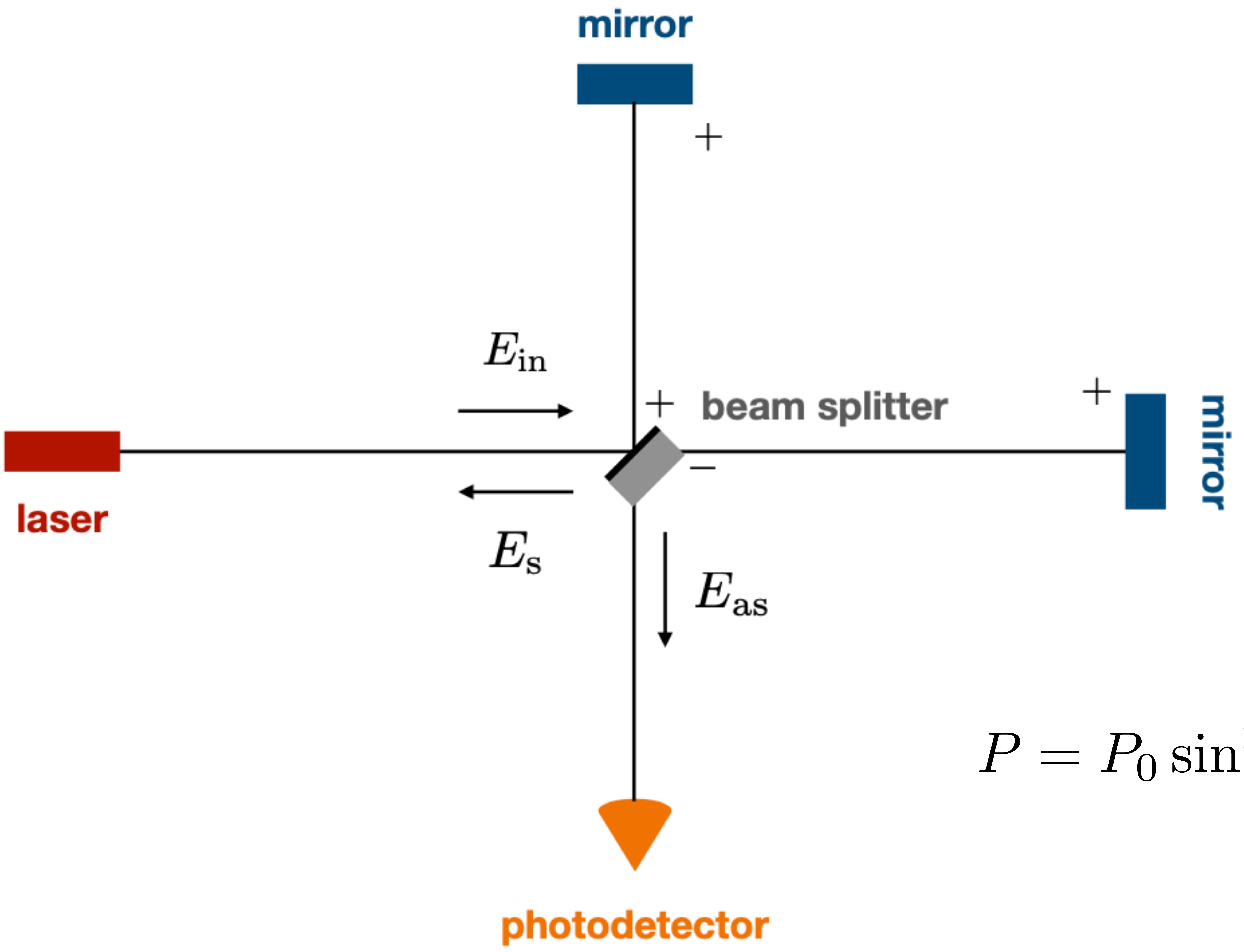
so what?

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

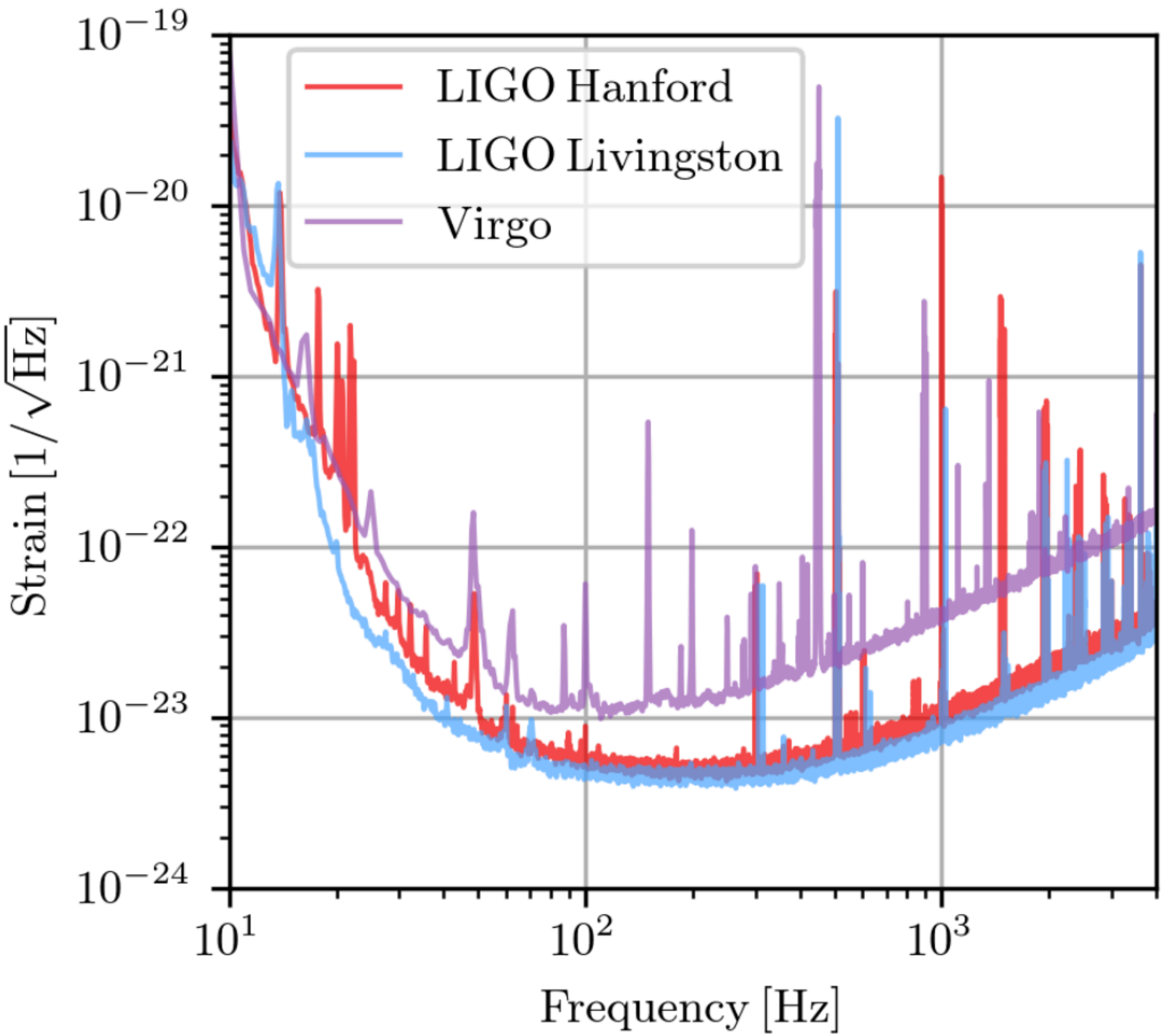
Interferometry

Pulsar Timing Array

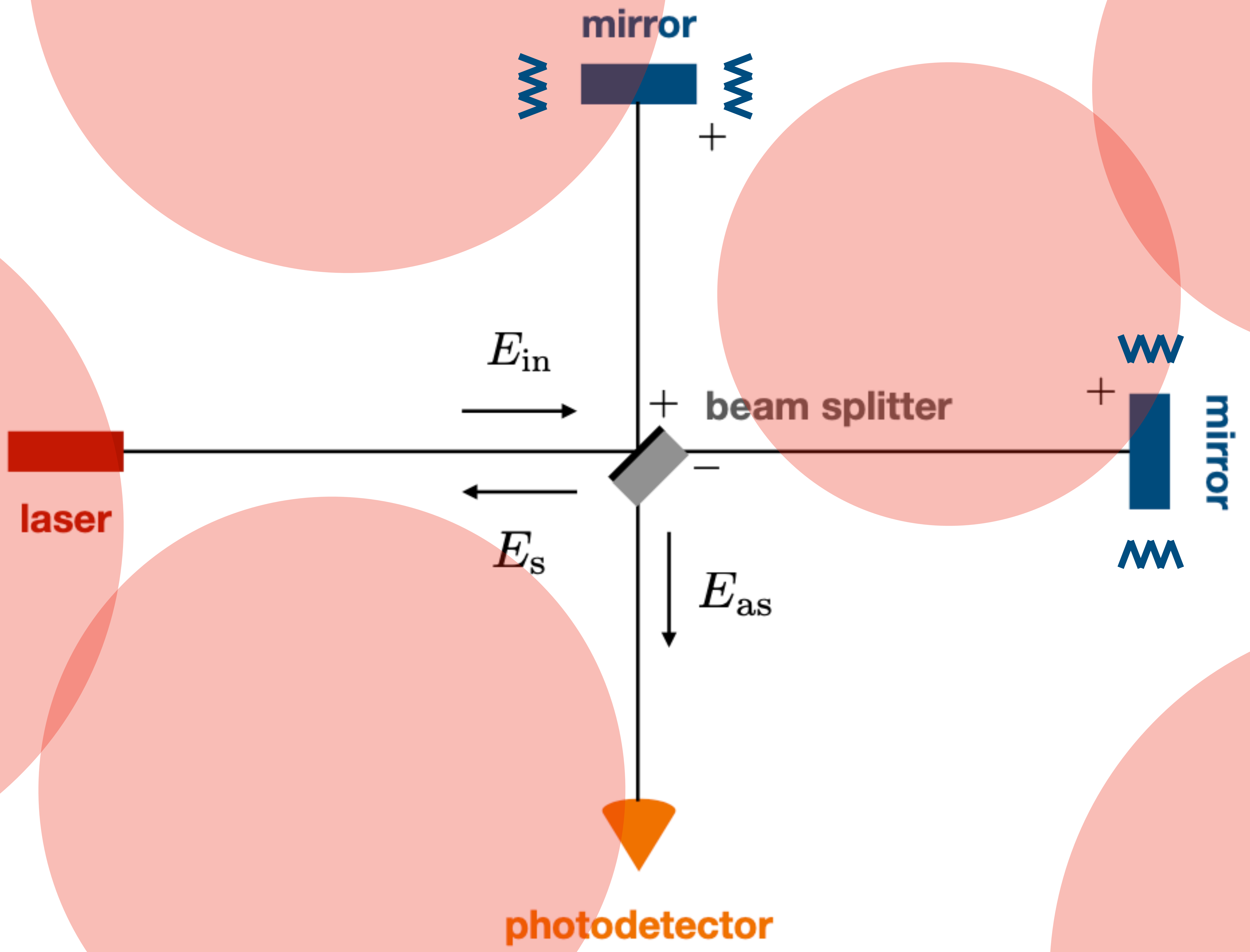

Astrometry



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



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

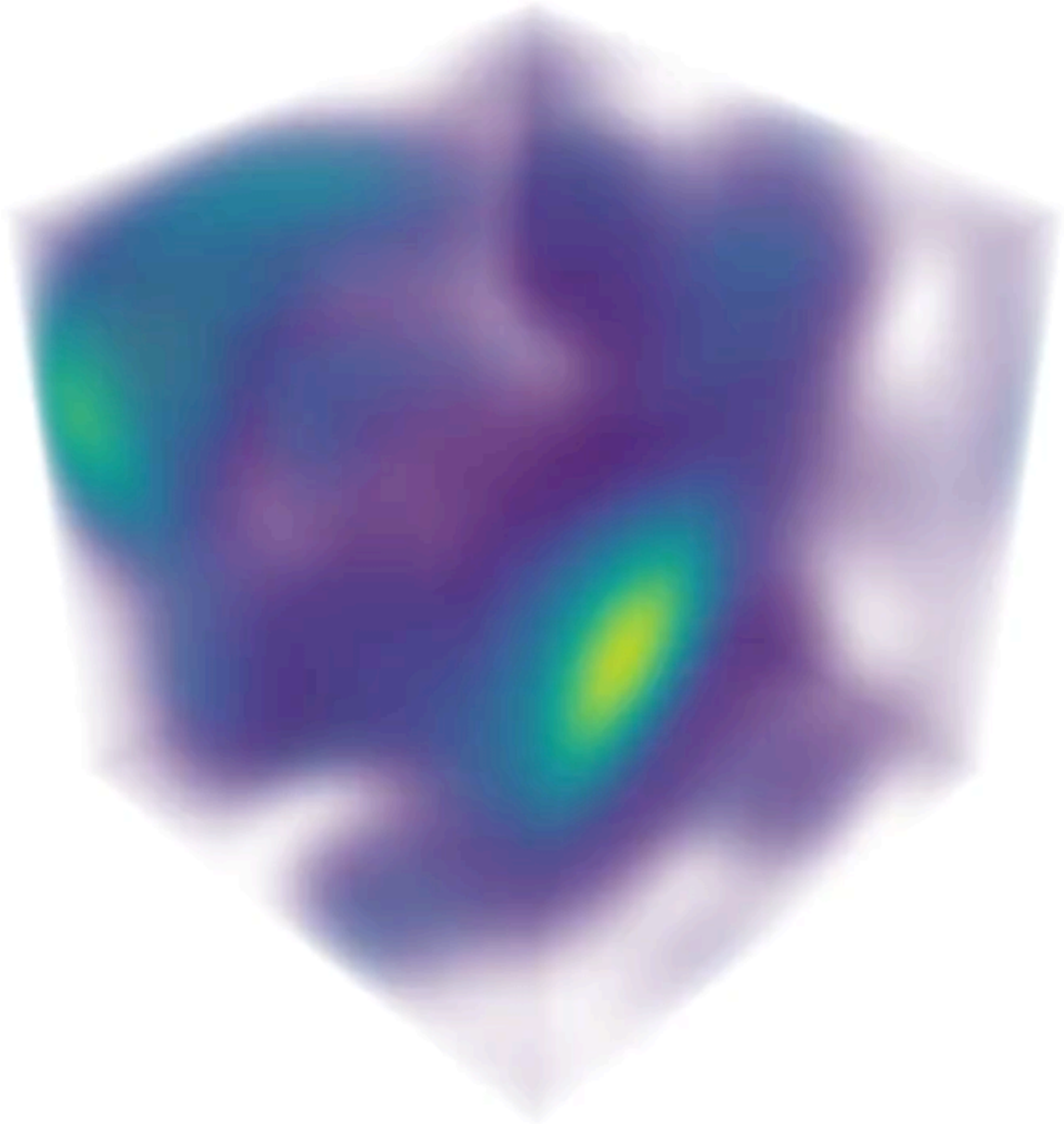


mirror
+
$E_{\rm in}$
+
beam splitter
+
mirror
laser
−
$E_{\rm s}$
$E_{\rm as}$
photodetector

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

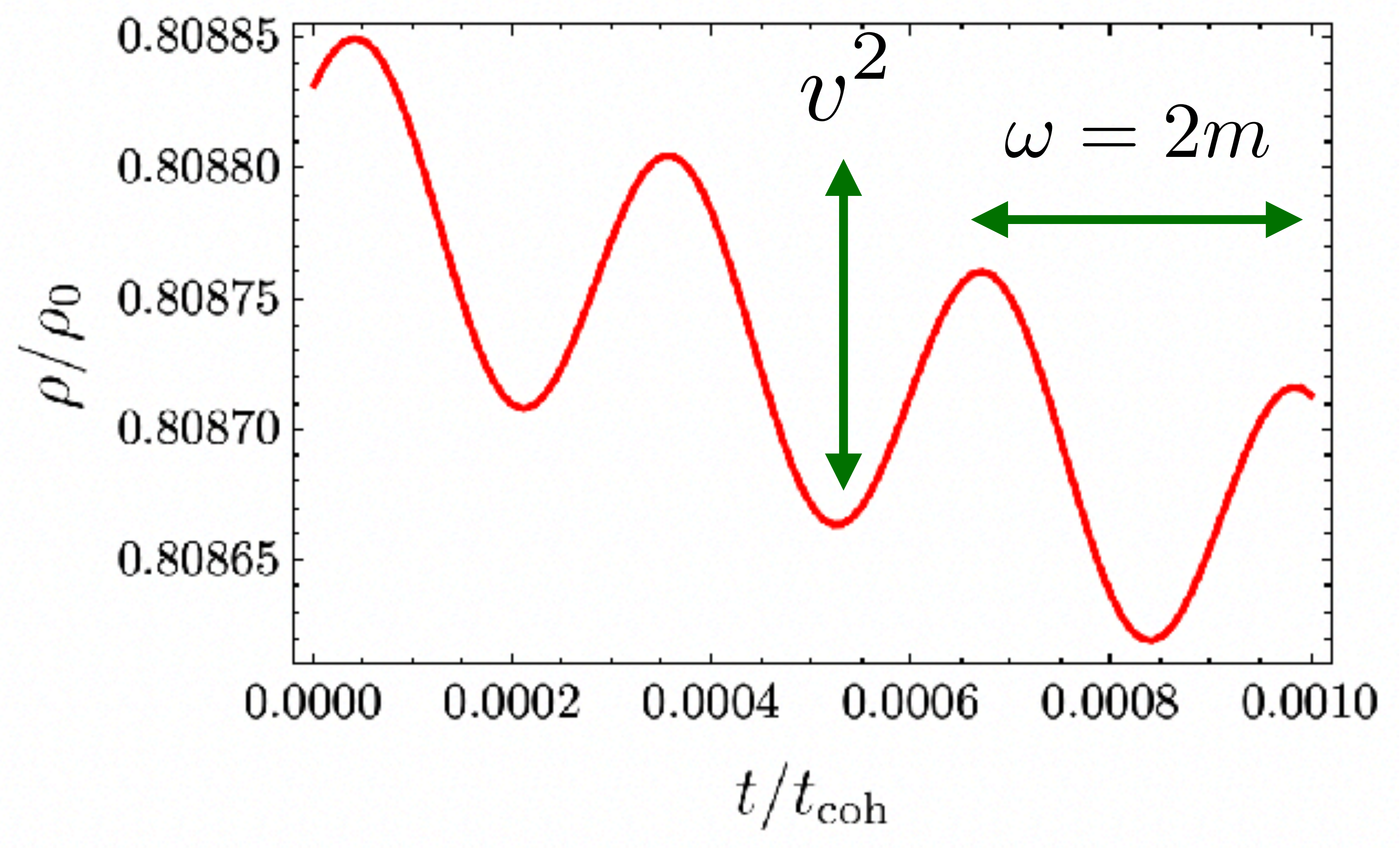
$$\nabla^2\Phi = 4\pi G\rho$$

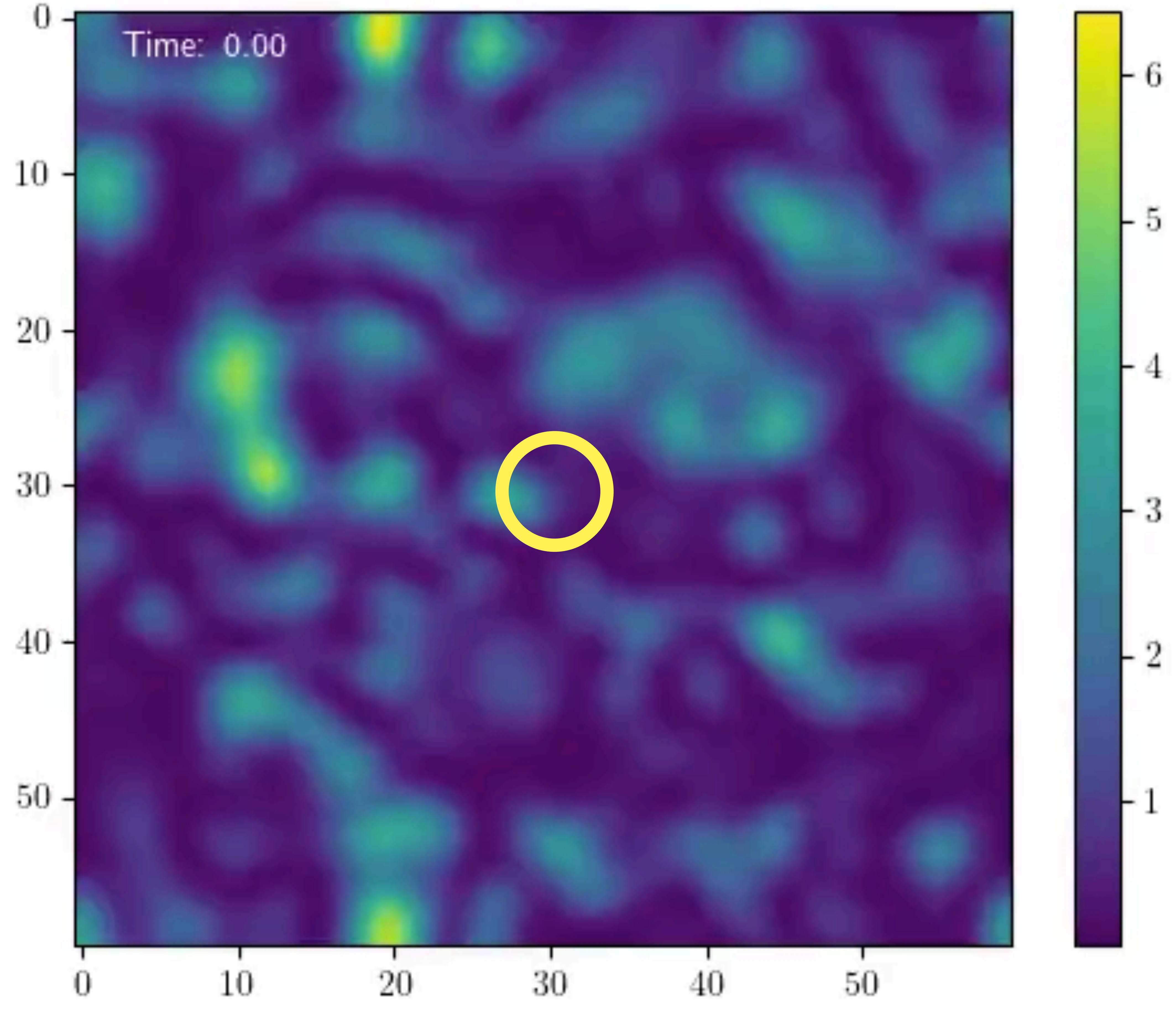
what is reflected in *detector observables*
is the *statistical properties* of
density fluctuations of ULDM

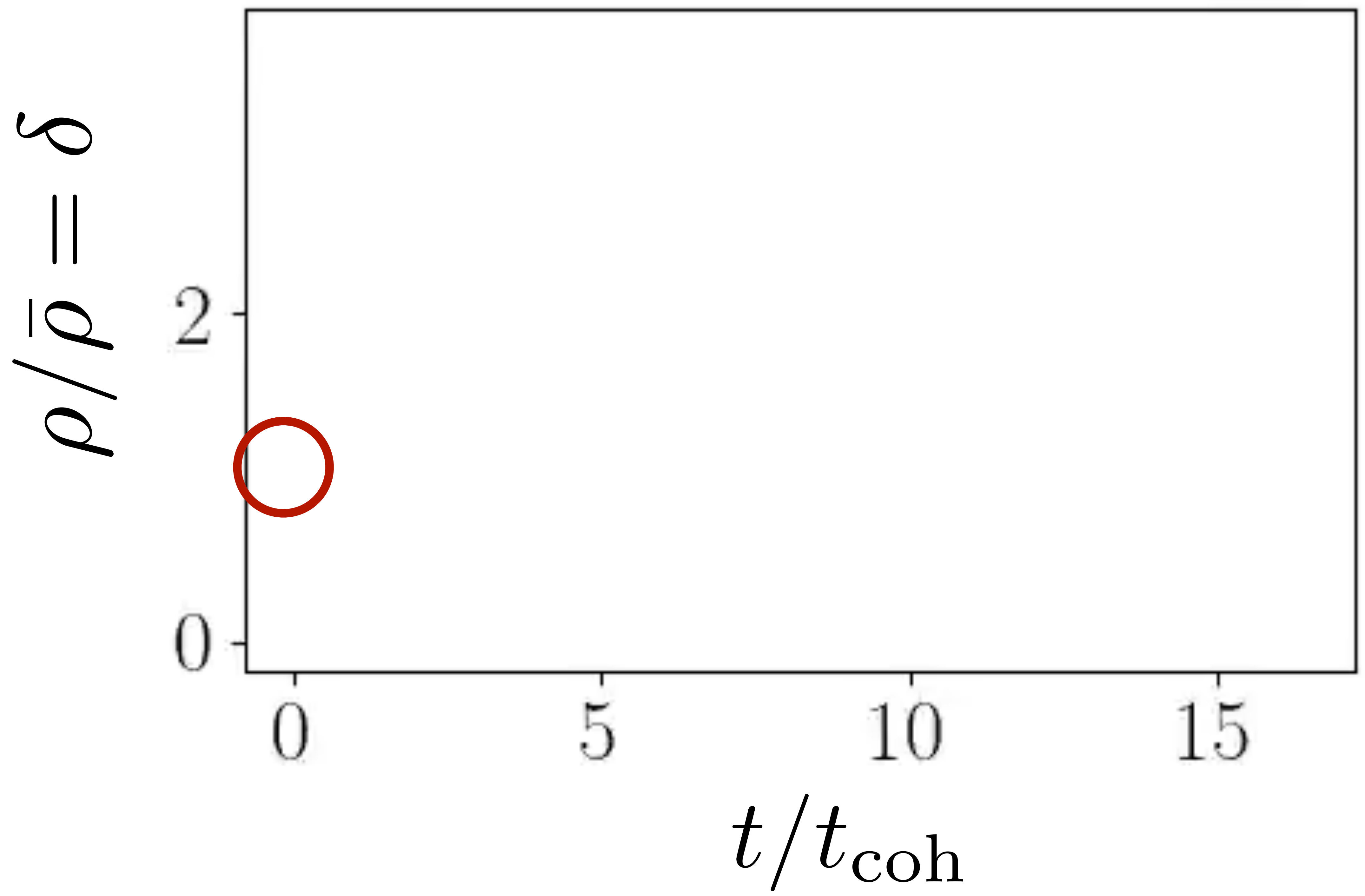


the density-density correlator at the same position is

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







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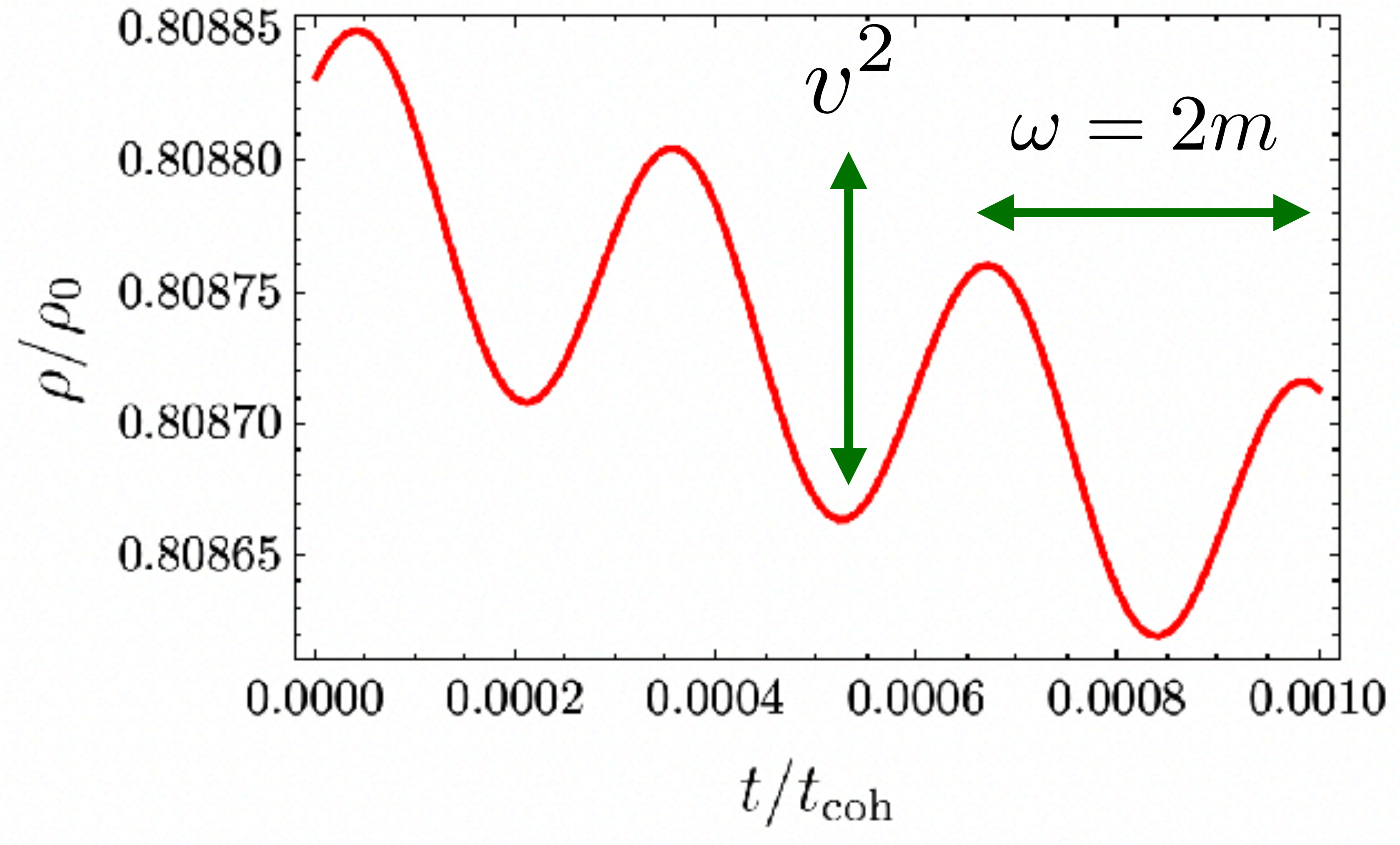
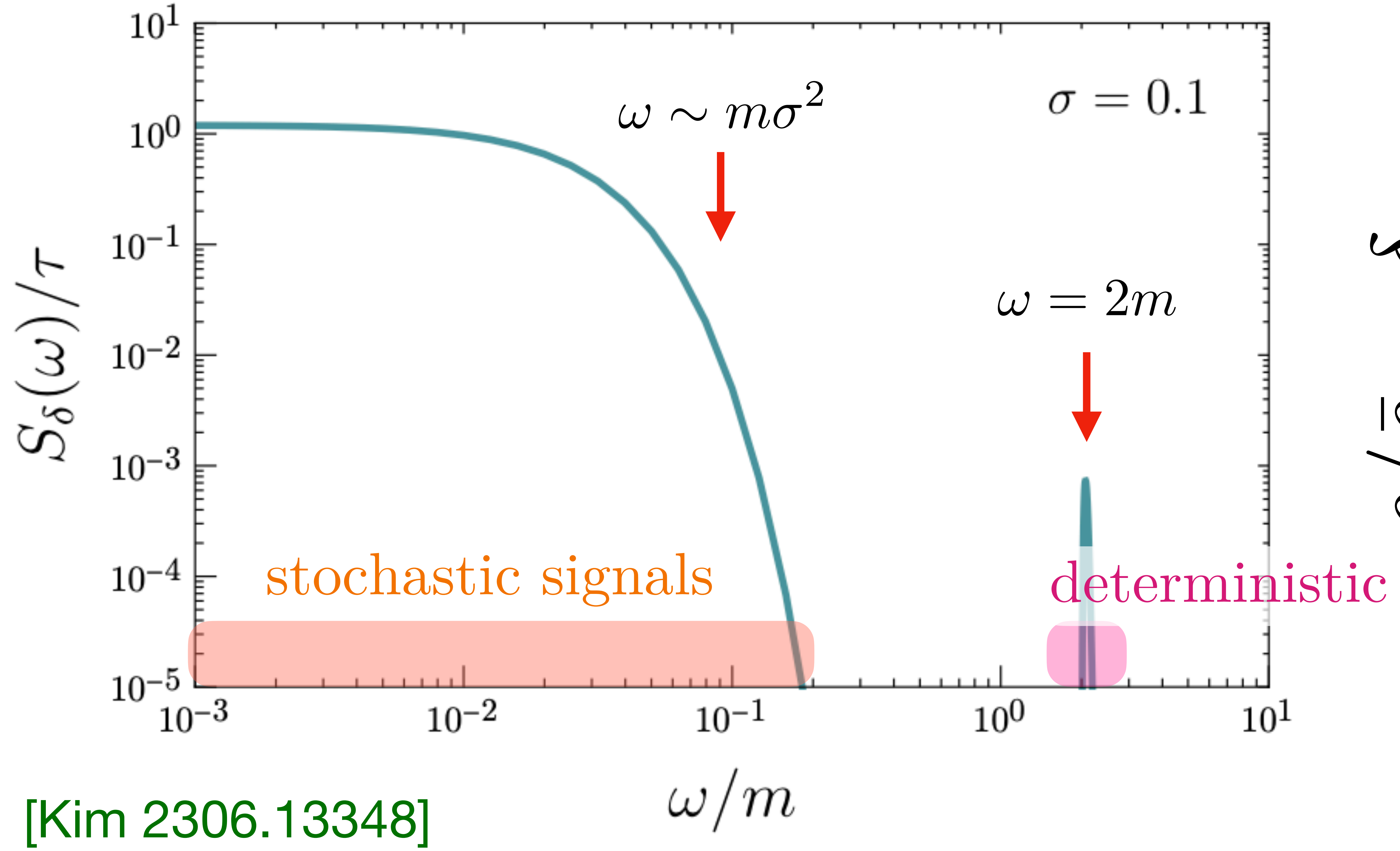
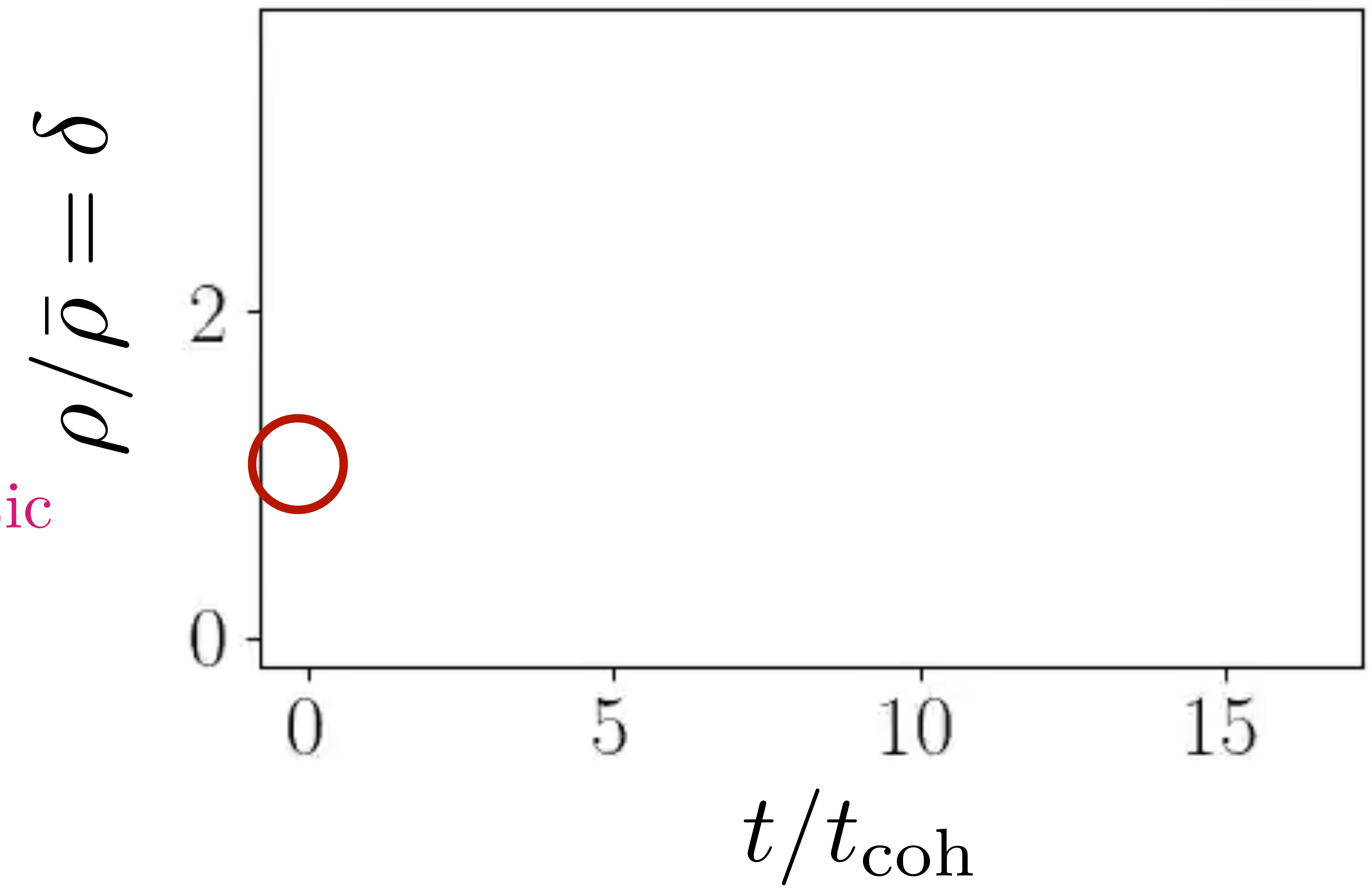


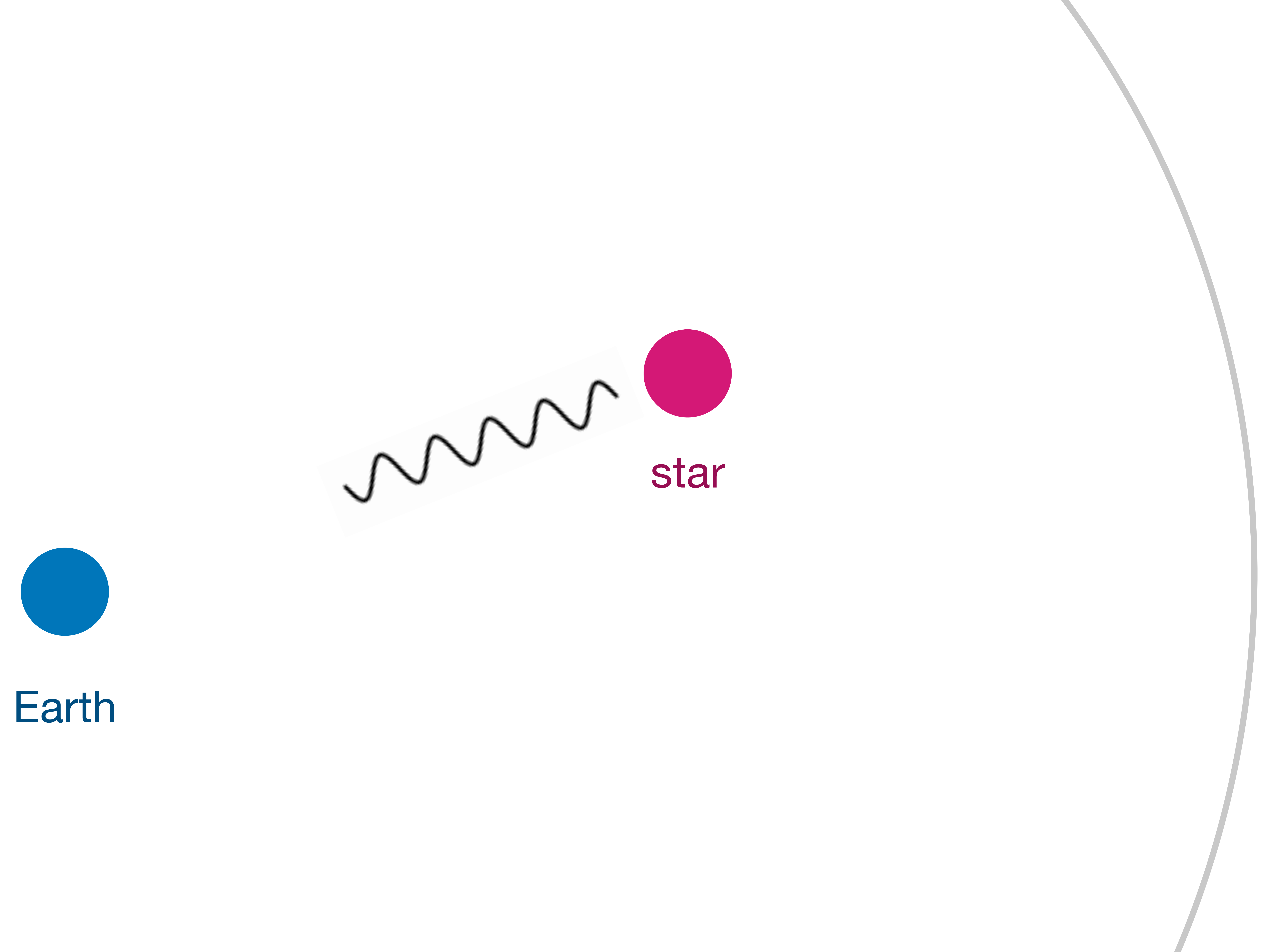
$$S_\delta(\omega) = \tau[\sigma^4 A_\delta(\omega) + B_\delta(\omega)]$$

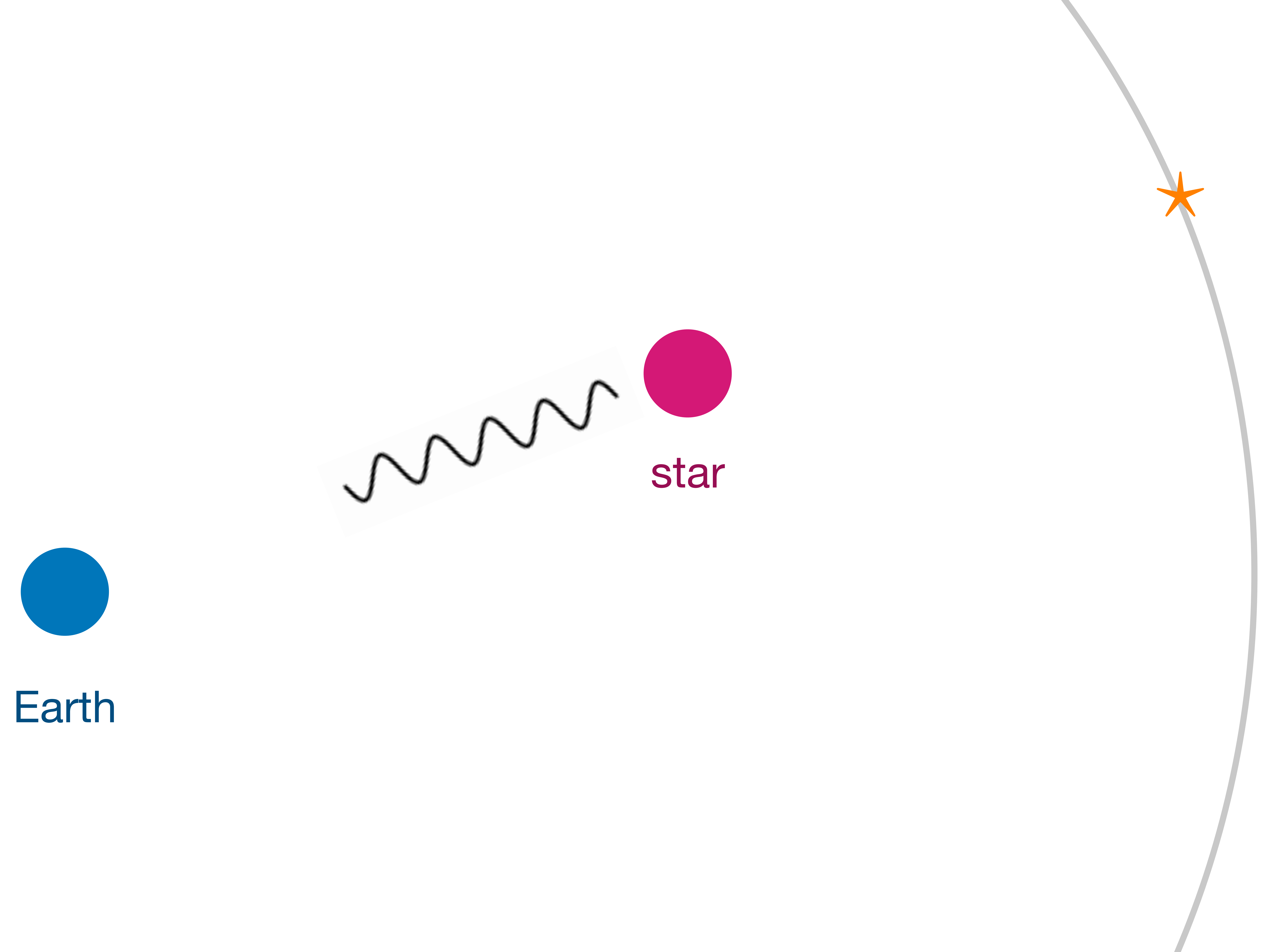


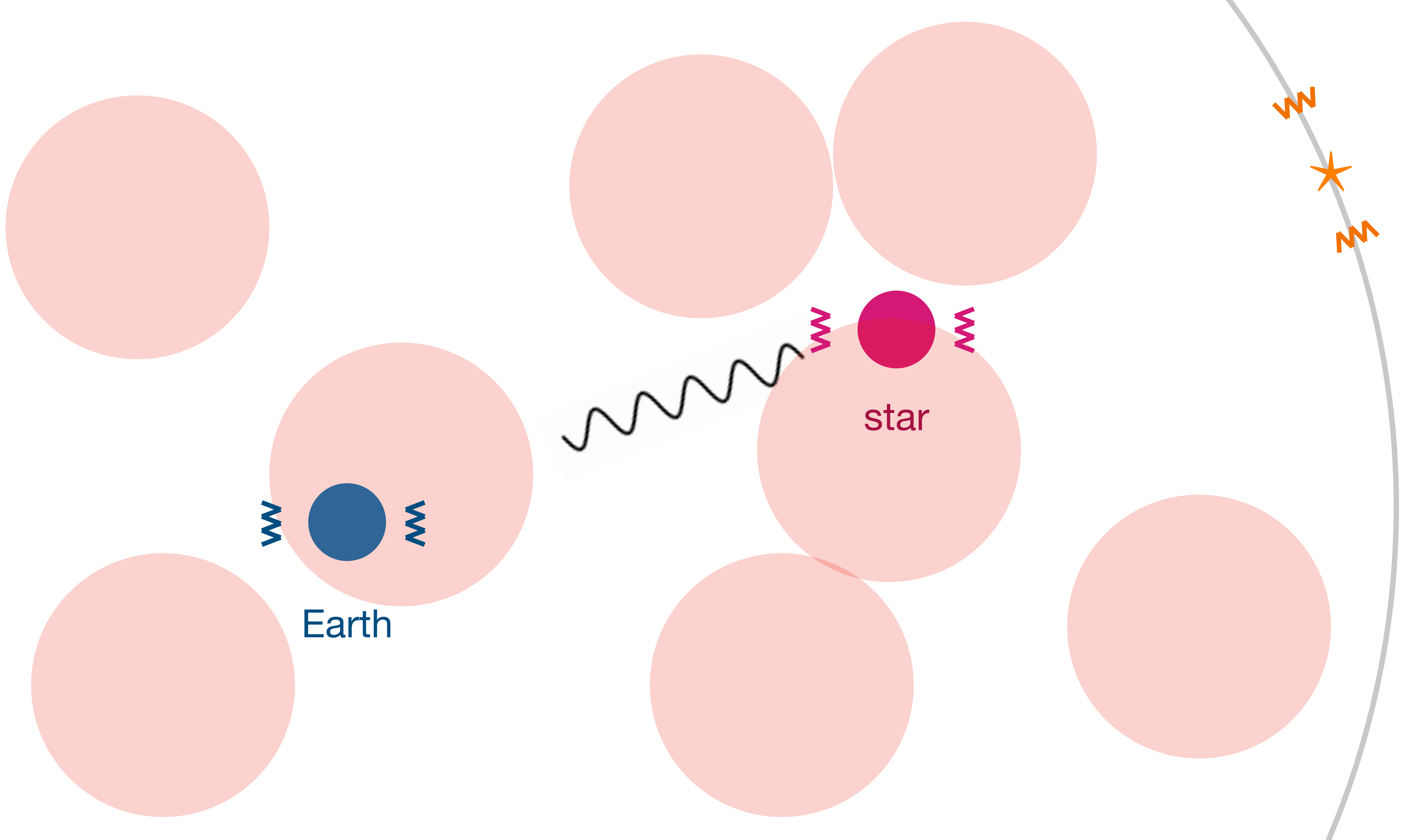


[Kim 2306.13348]

[Kim, Lenoci, Perez, Ratzinger, 2307.14962]


star
Earth


star
Earth

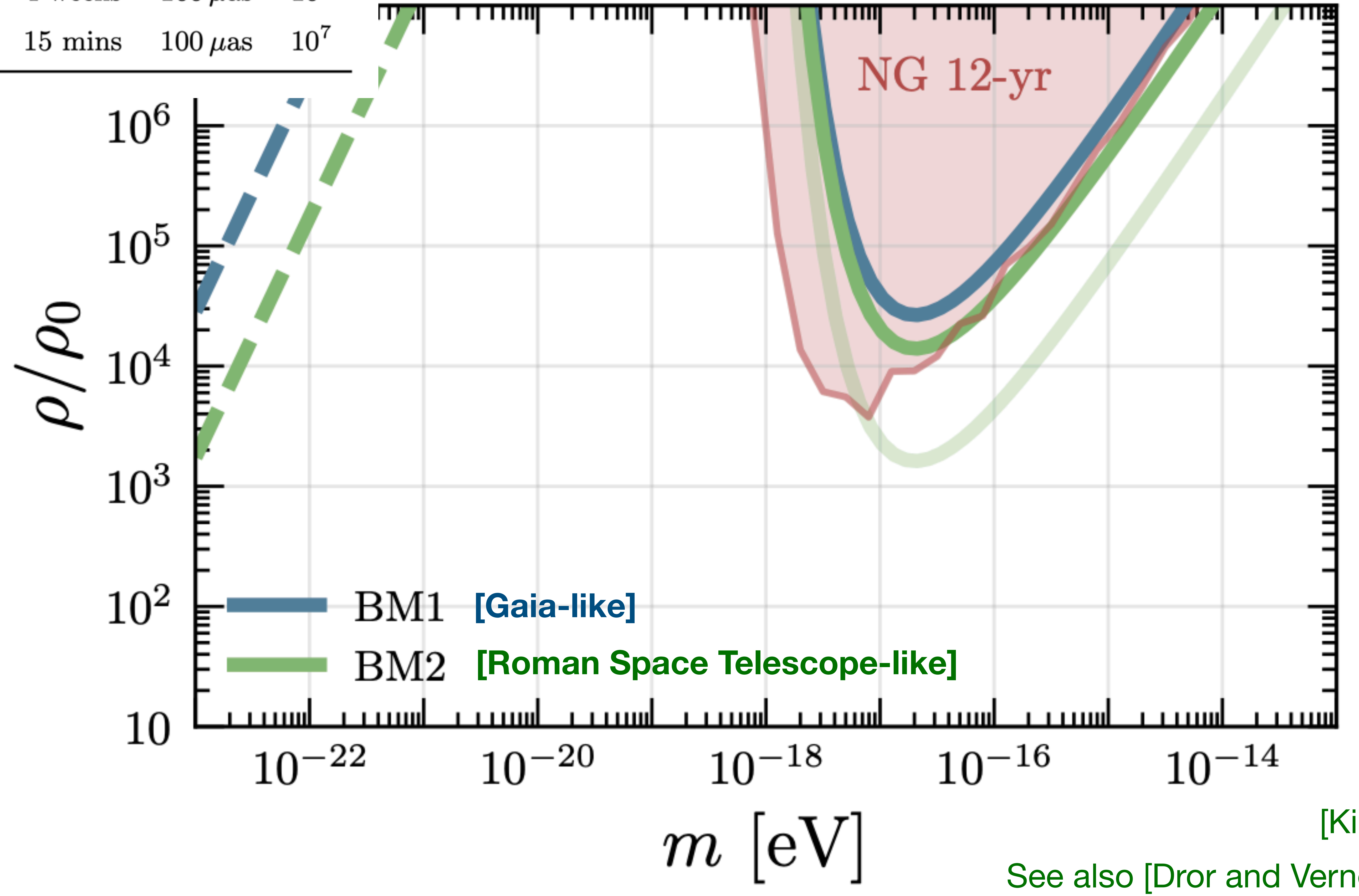

star
Earth

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]

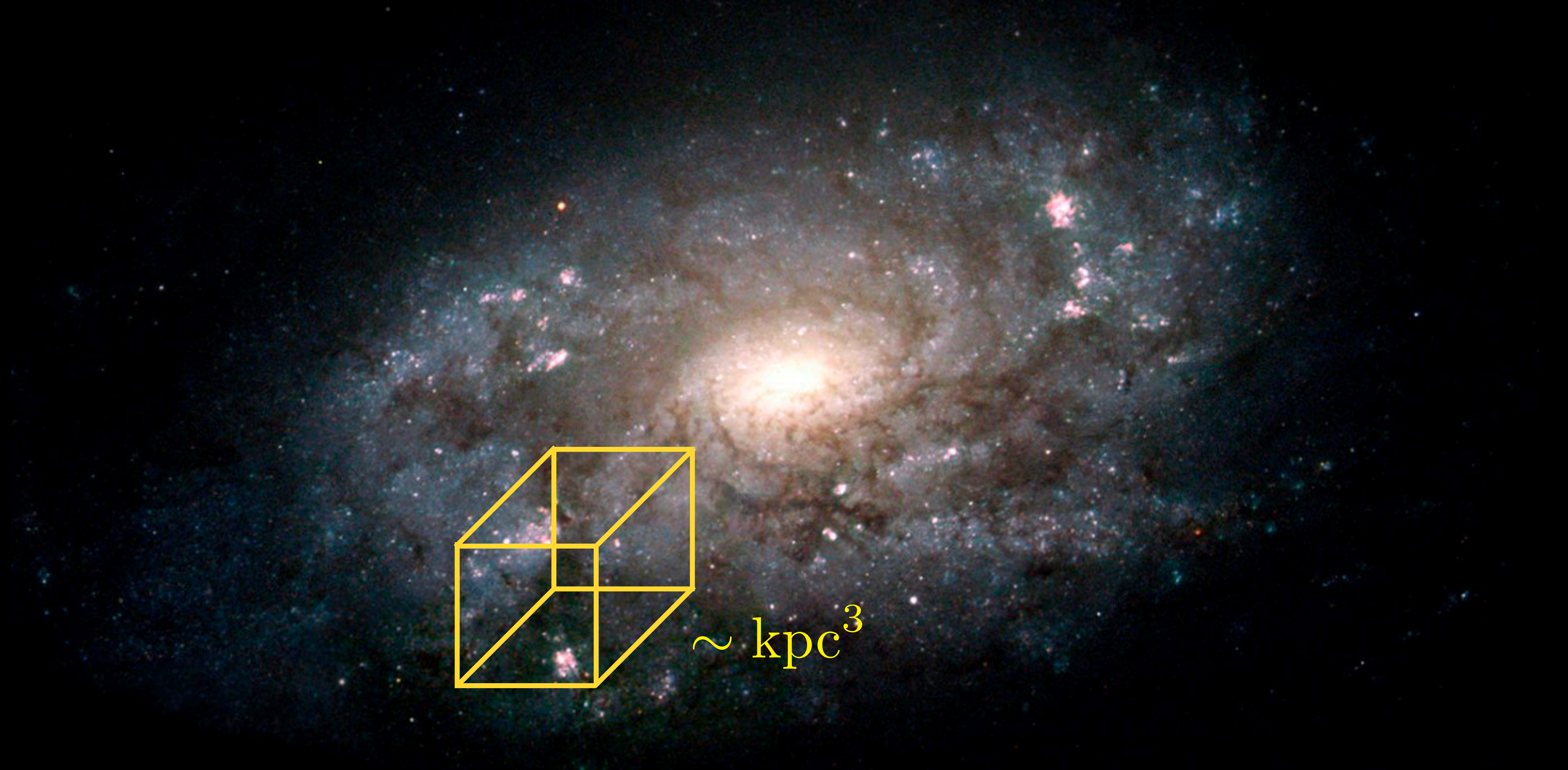
See also [Dror and Verner 2406.03526]

Remark

the result shown here is sensitive to

ULDM density around/within the solar system

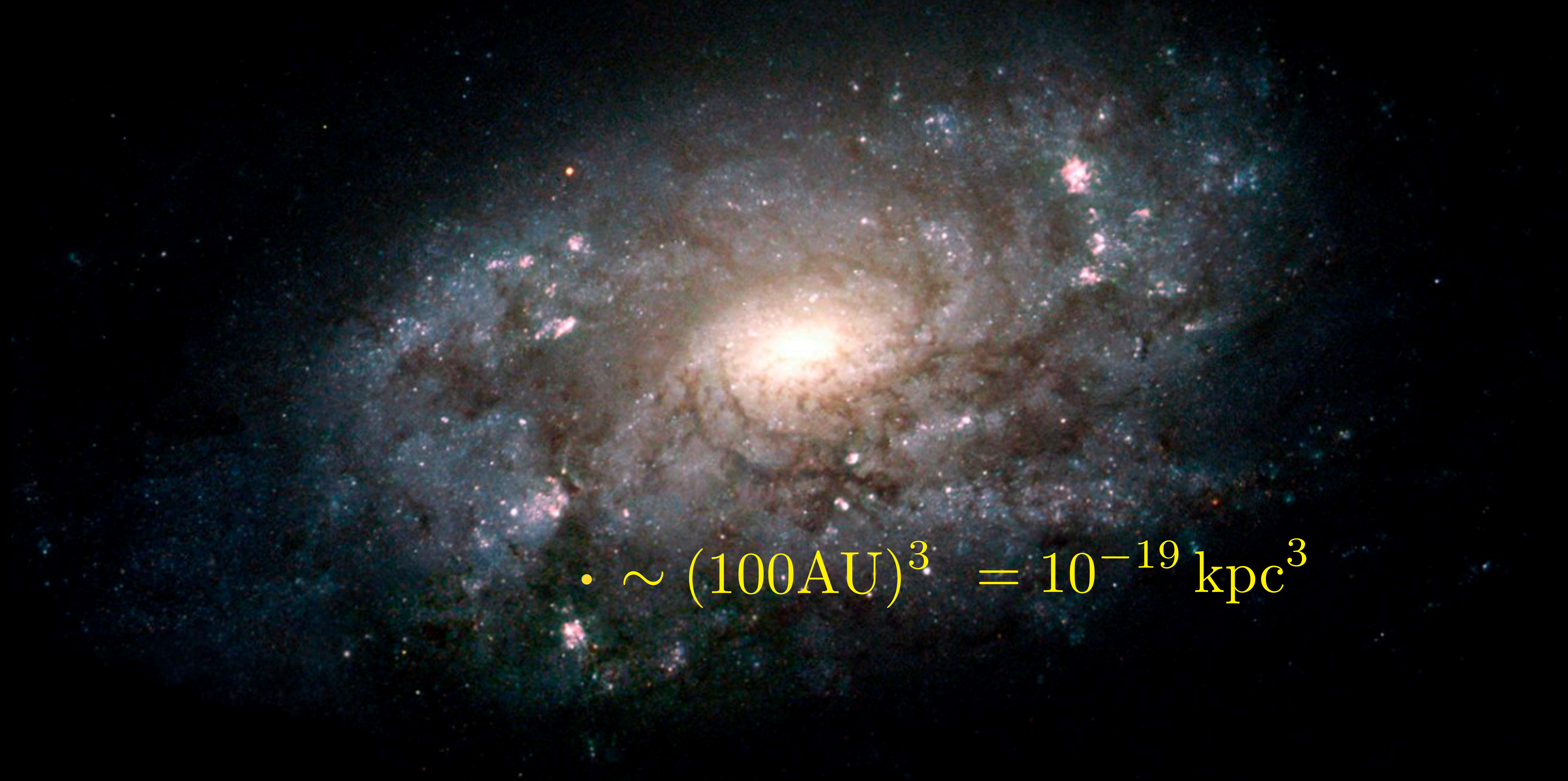
local dark matter density is often derived over kpc scales



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

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)]

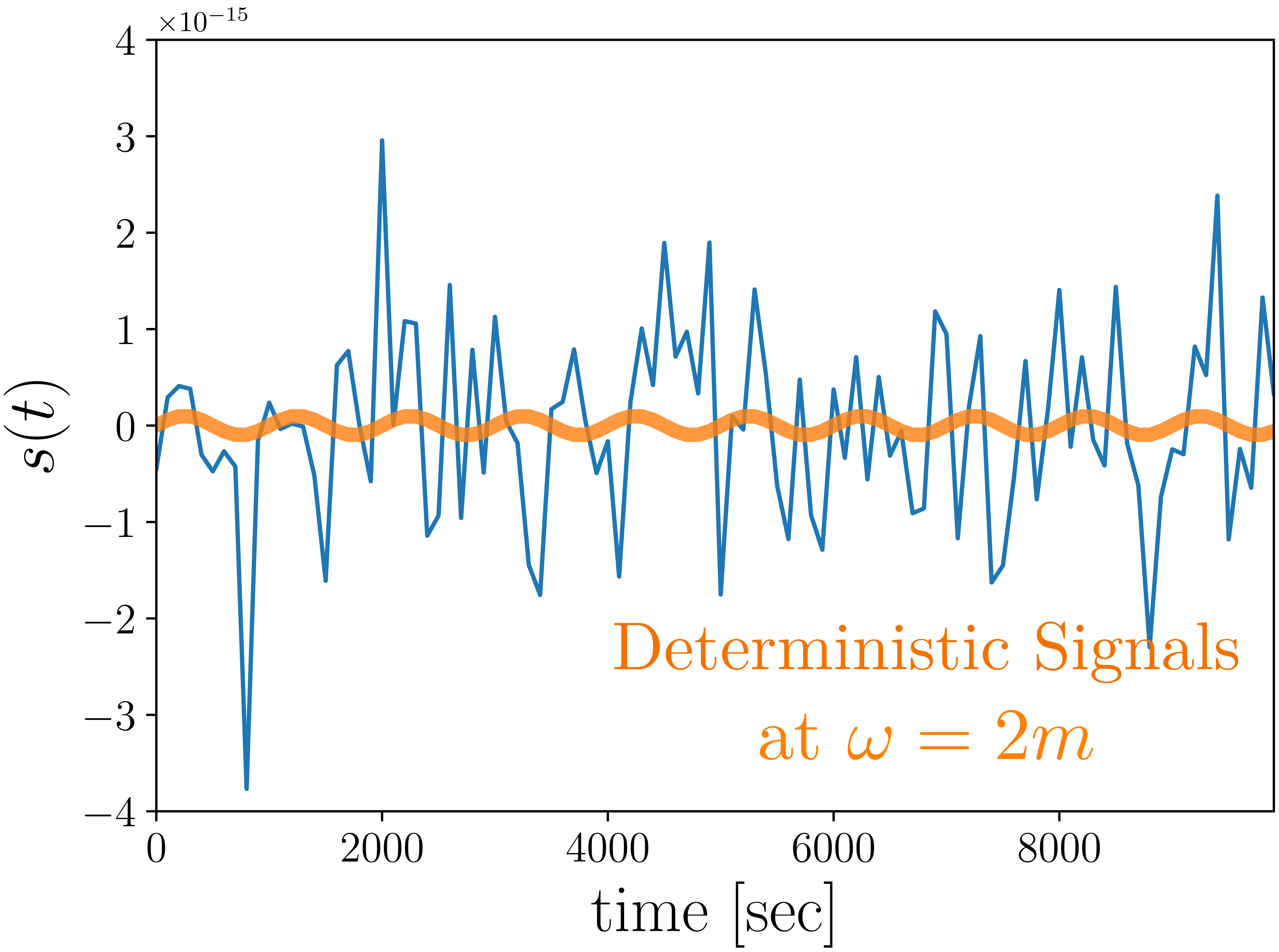
$$\rho/\rho_0 \lesssim 2 \times 10^4$$

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

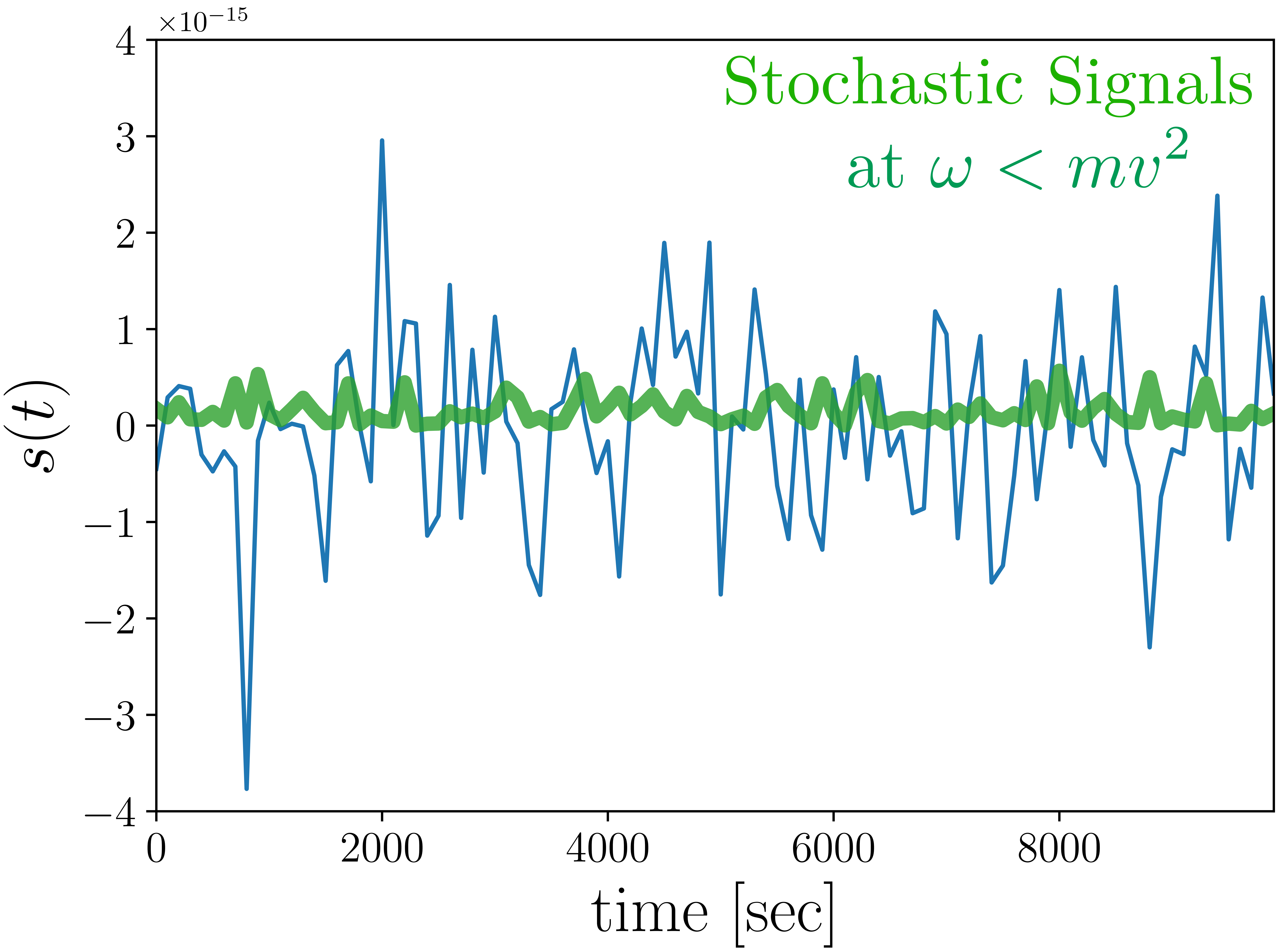
Astrometry will provide

one of the strongest probes of ULDM density

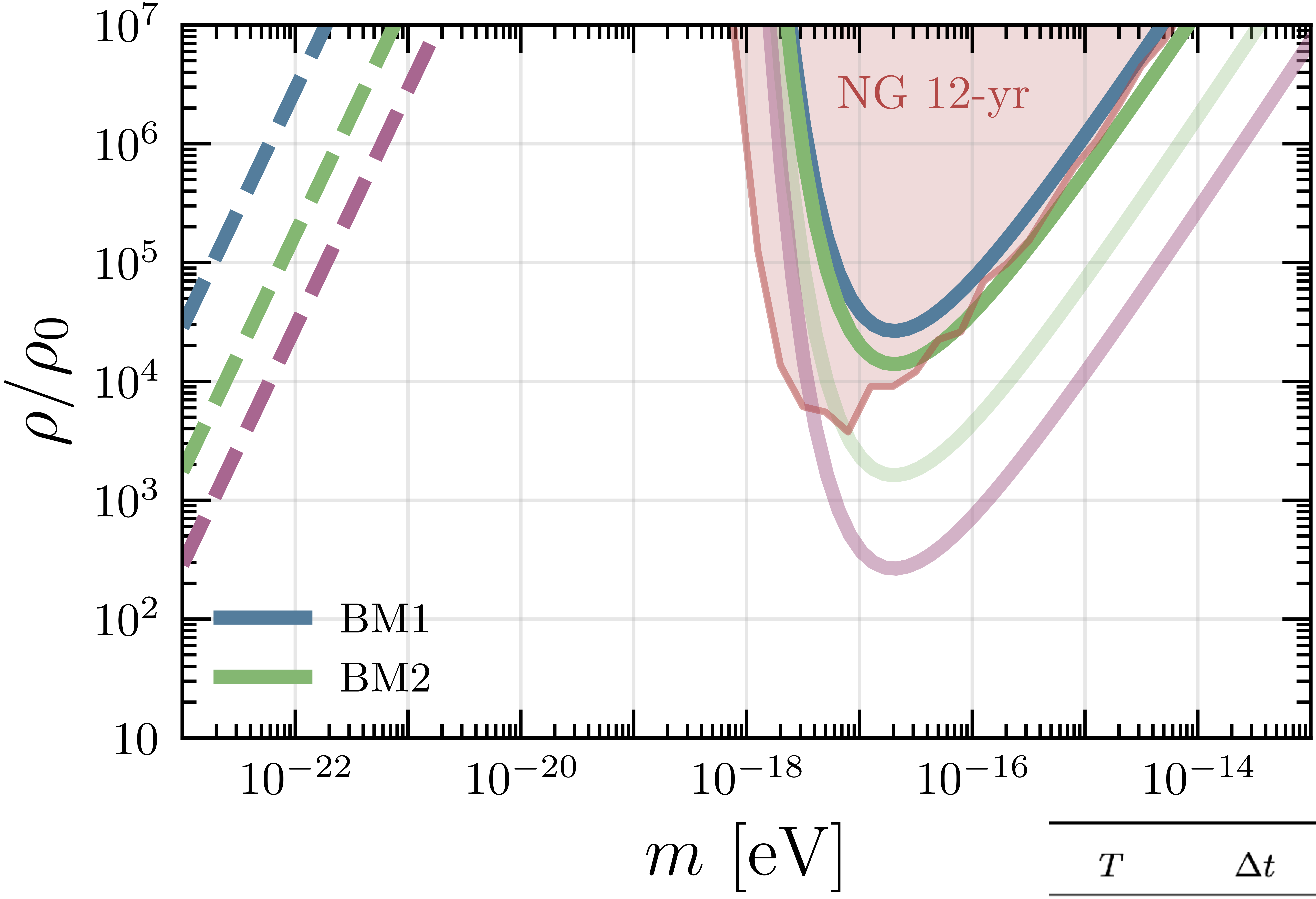
within/around the solar system



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



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



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