Probing Ultralight Dark Matter in Gravity Wave Detectors

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58th Rencontres de Moriond 2024
March 28, 2024

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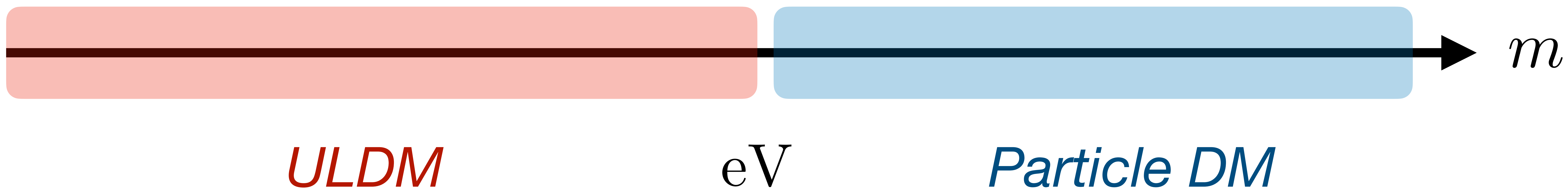
Ultralight Dark Matter

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

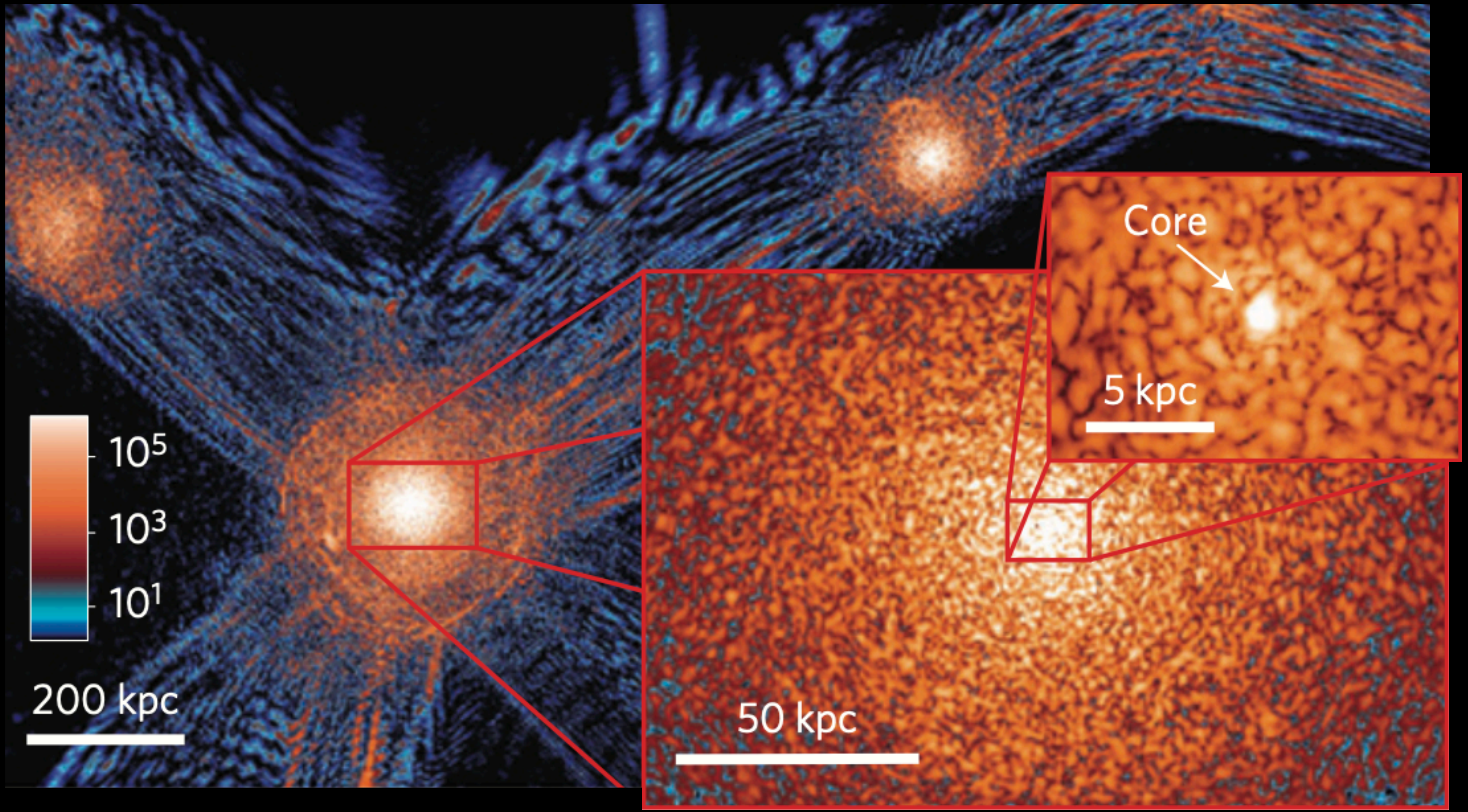


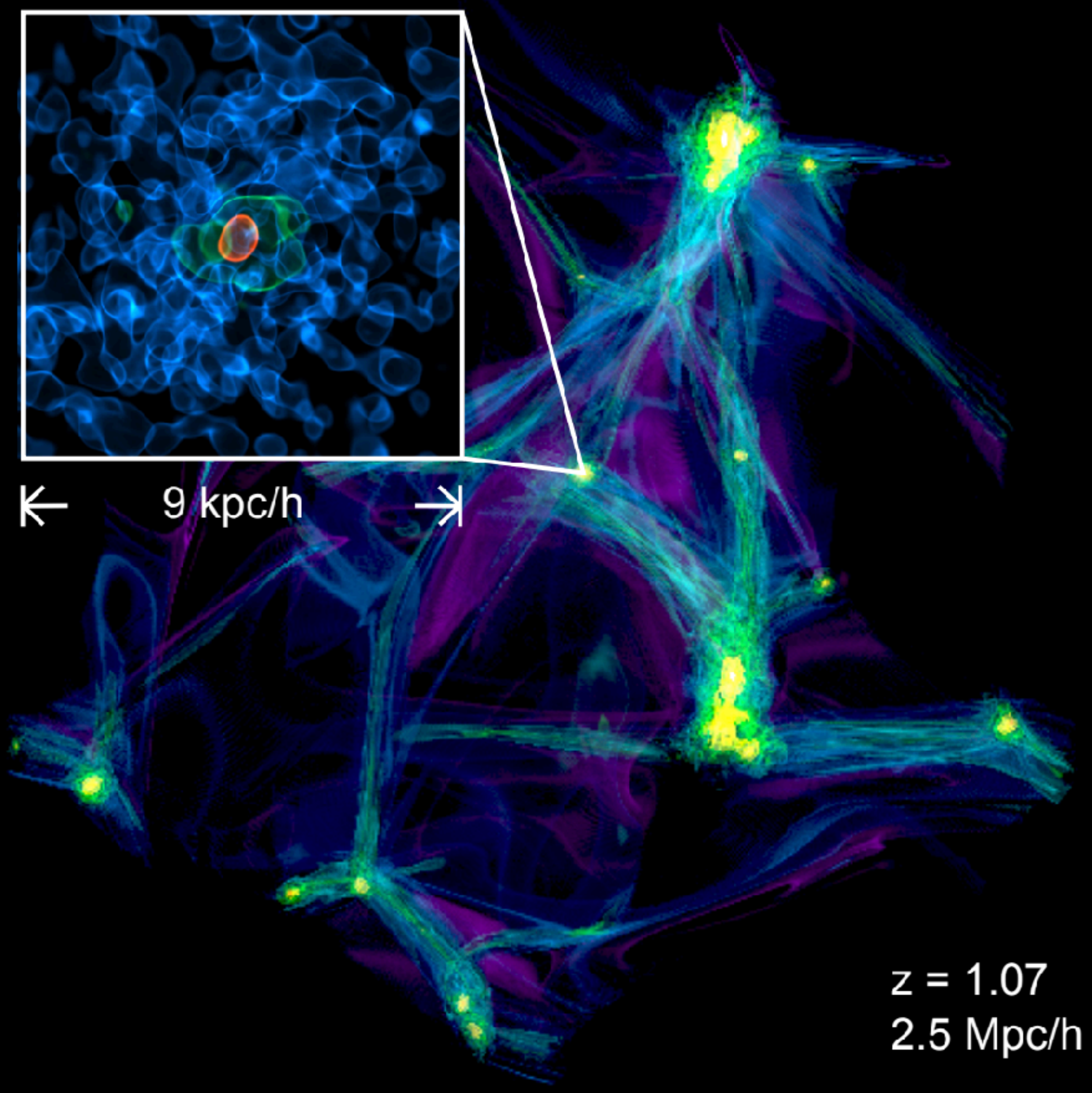
we define *ultralight dark matter (ULDM)*
as *bosonic DM candidates with* $\mathrm{m} < \mathrm{eV}$

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

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

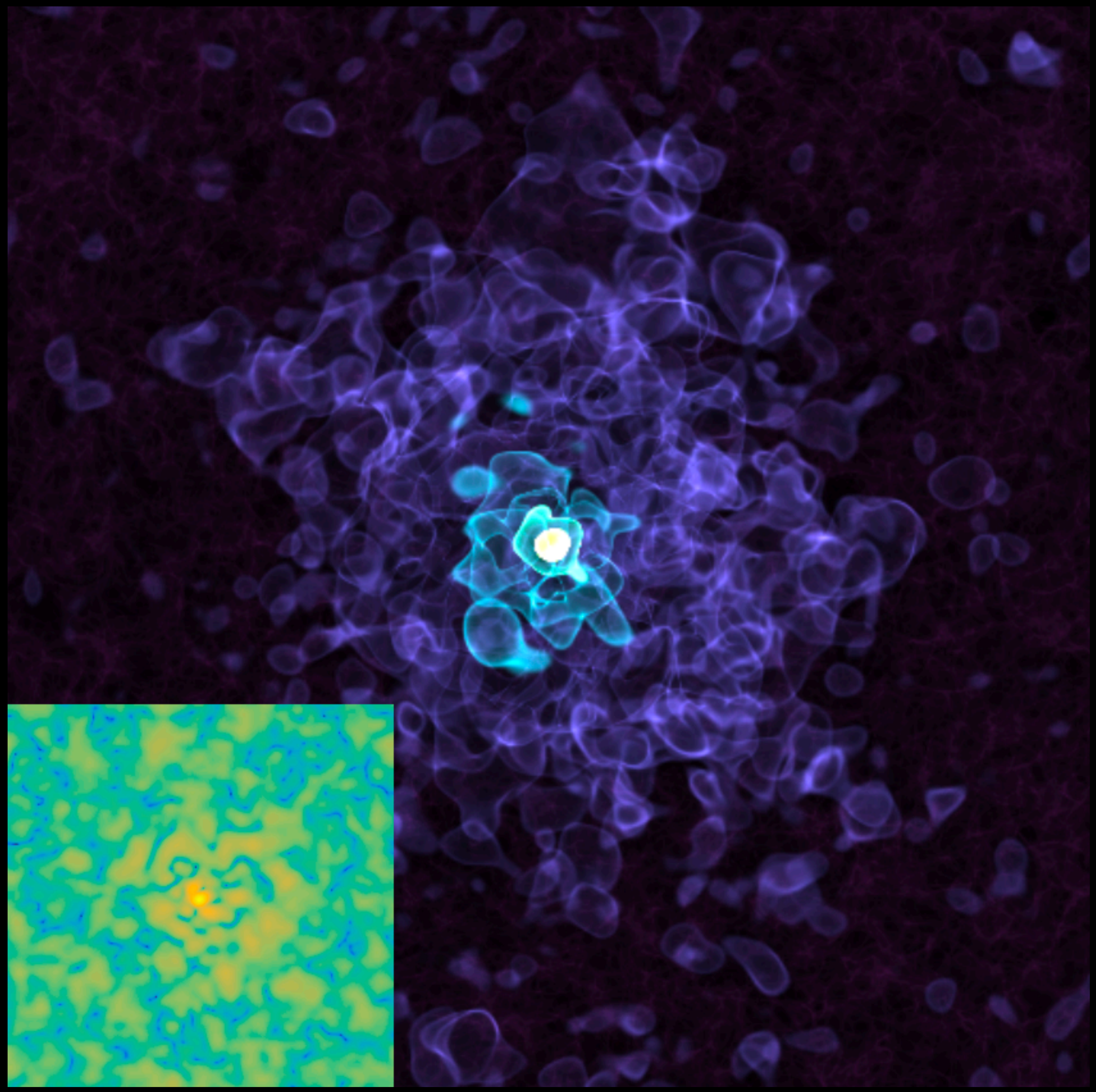
Schive, Chiueh, Broadhurst (14)





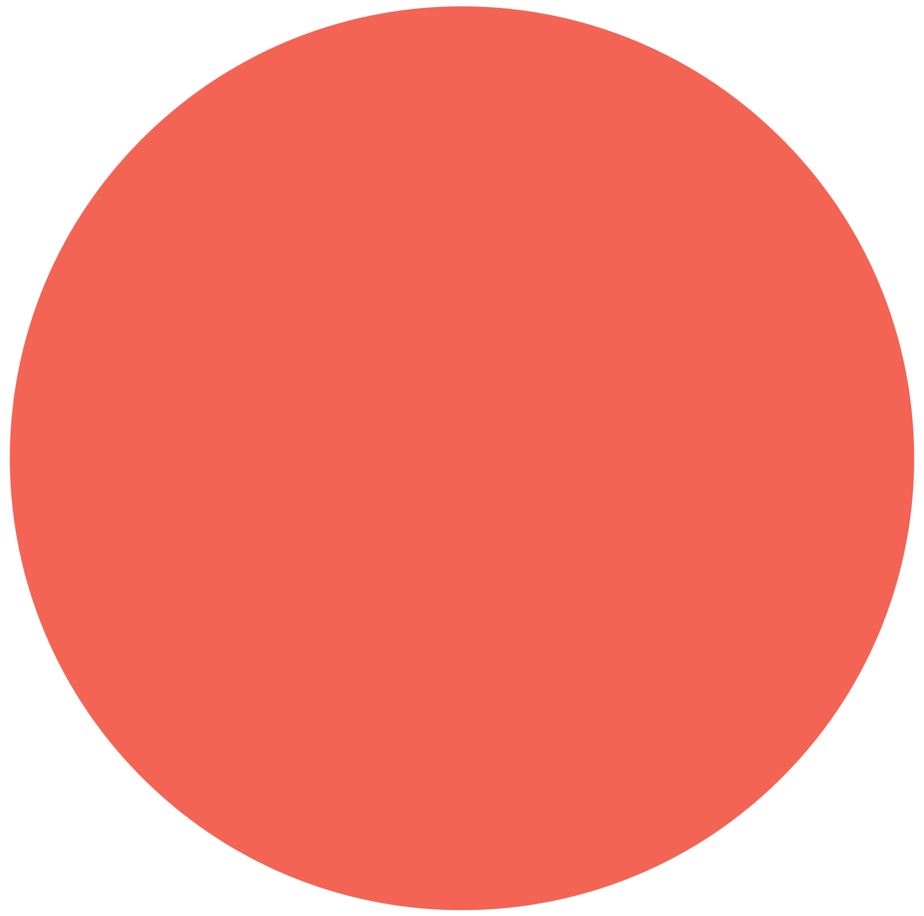
Veltmaat, Niemeyer, Schwabe (18)

Mocz et al (17)



An intuitive understanding of the granule structure:

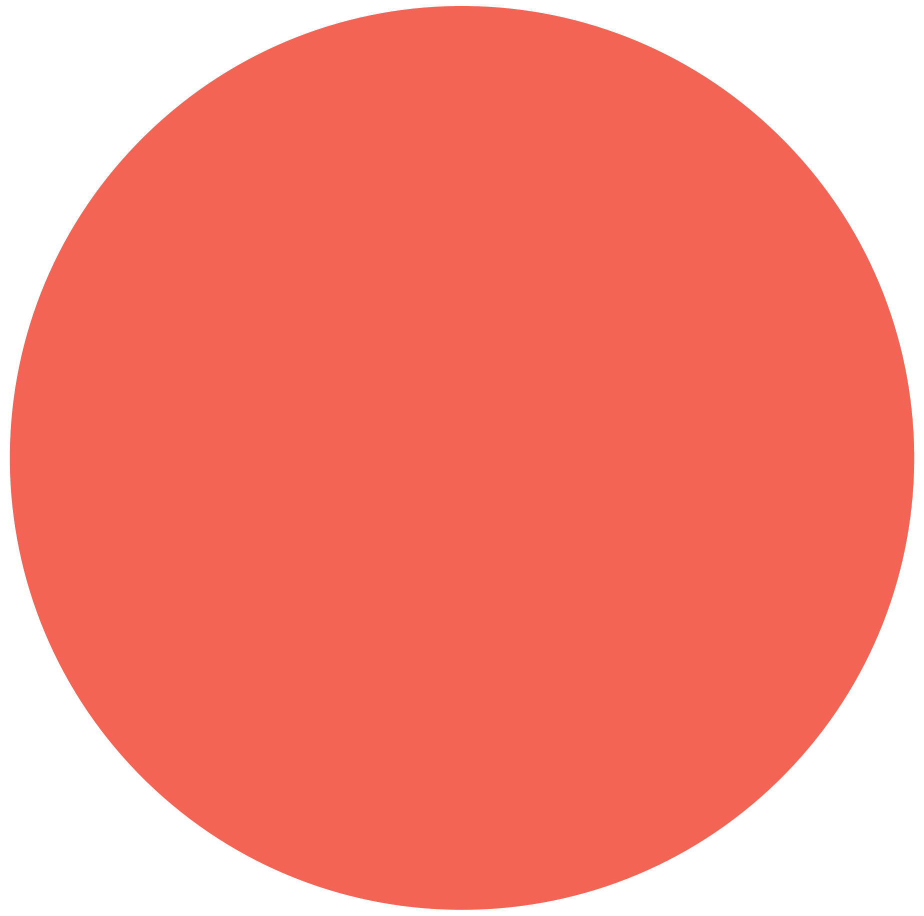
Quasiparticle



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

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

the size and mass of them could be astronomical



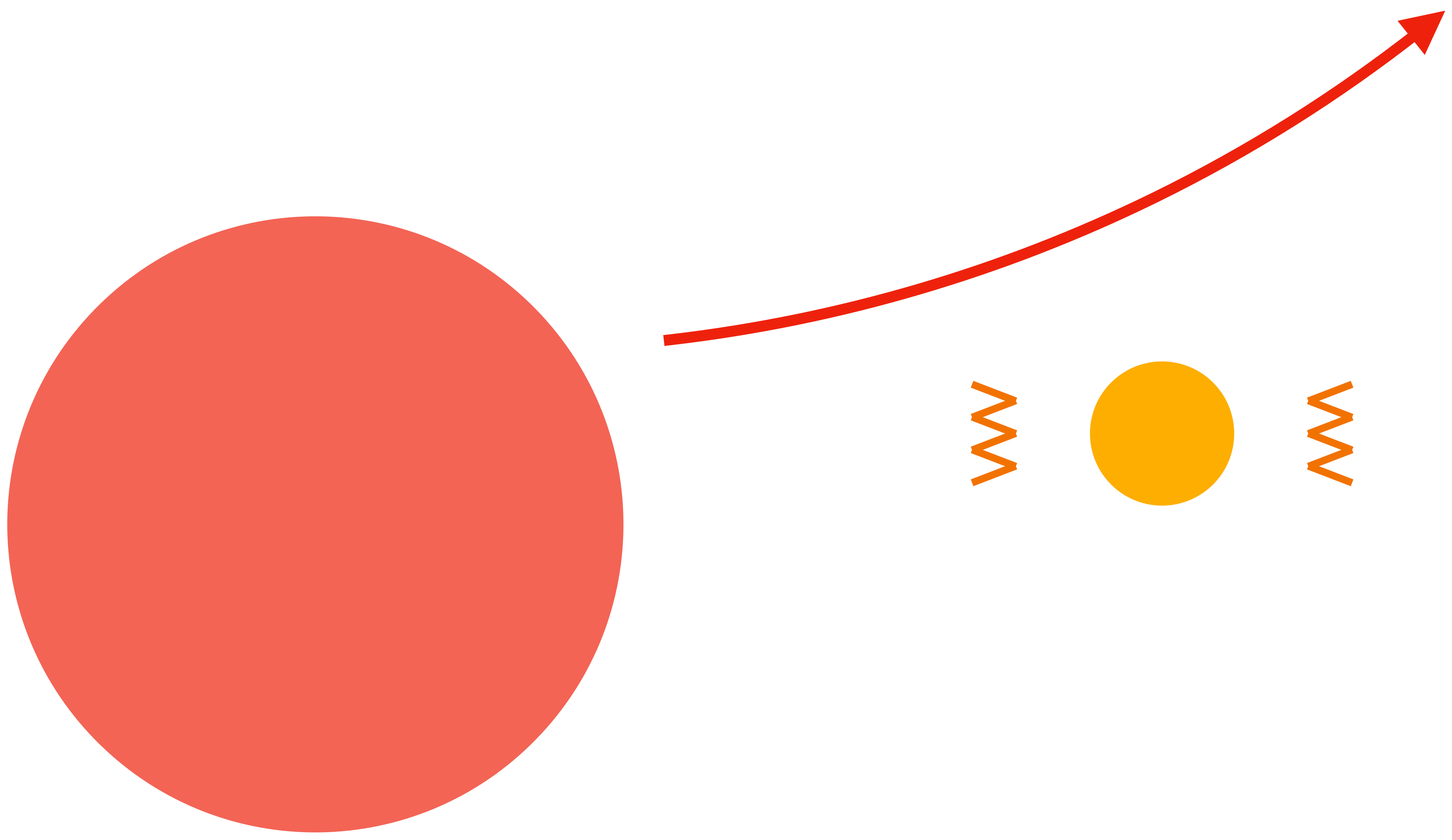
$$\ell \sim \lambda = \frac{1}{mv} \sim 10\,\mathrm{AU} \times \left(\frac{10^{-16}\,\mathrm{eV}}{m}\right)$$

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

being that massive

it may engage in interaction with stars

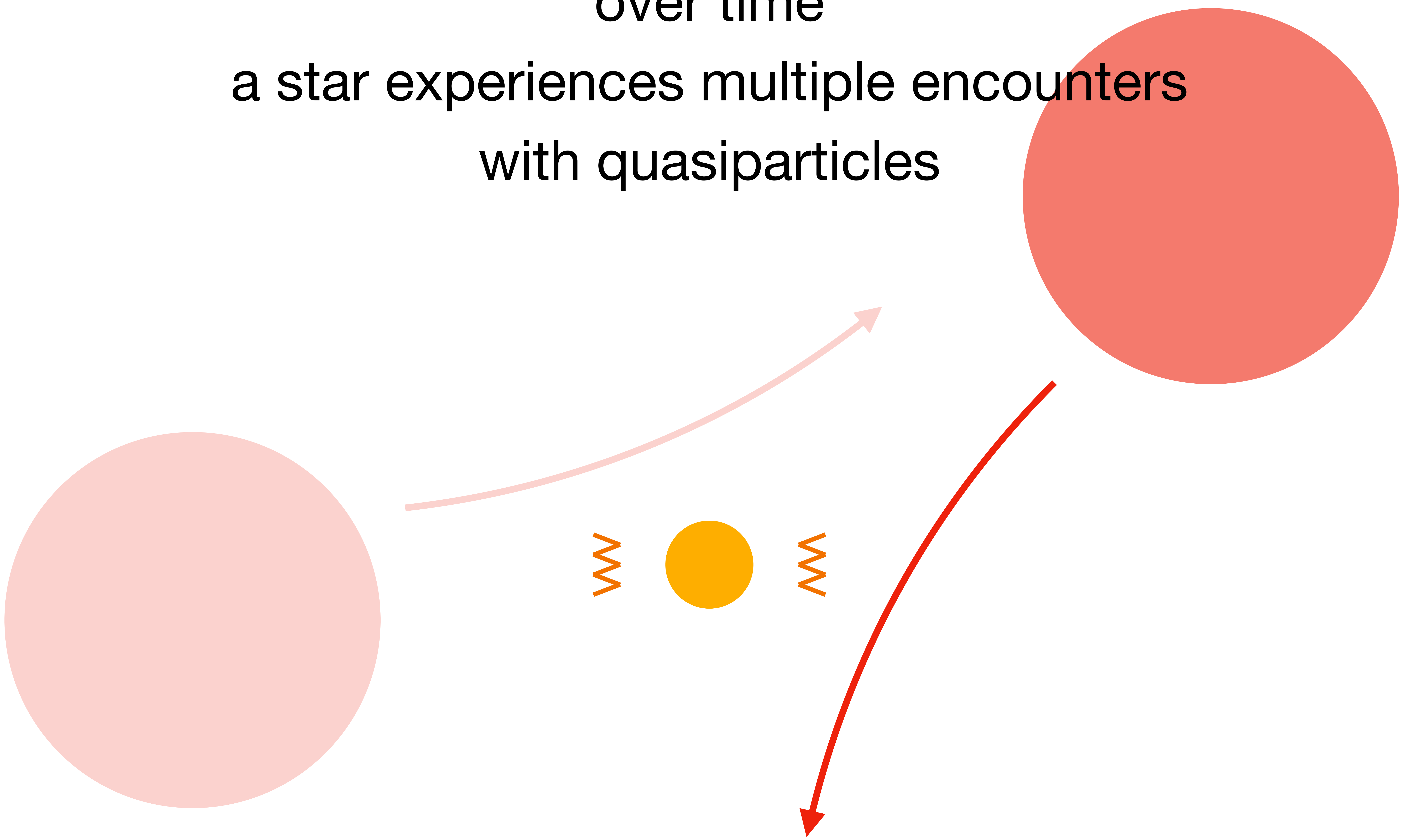
and significantly perturb the motion of them



over time

a star experiences multiple encounters

with quasiparticles



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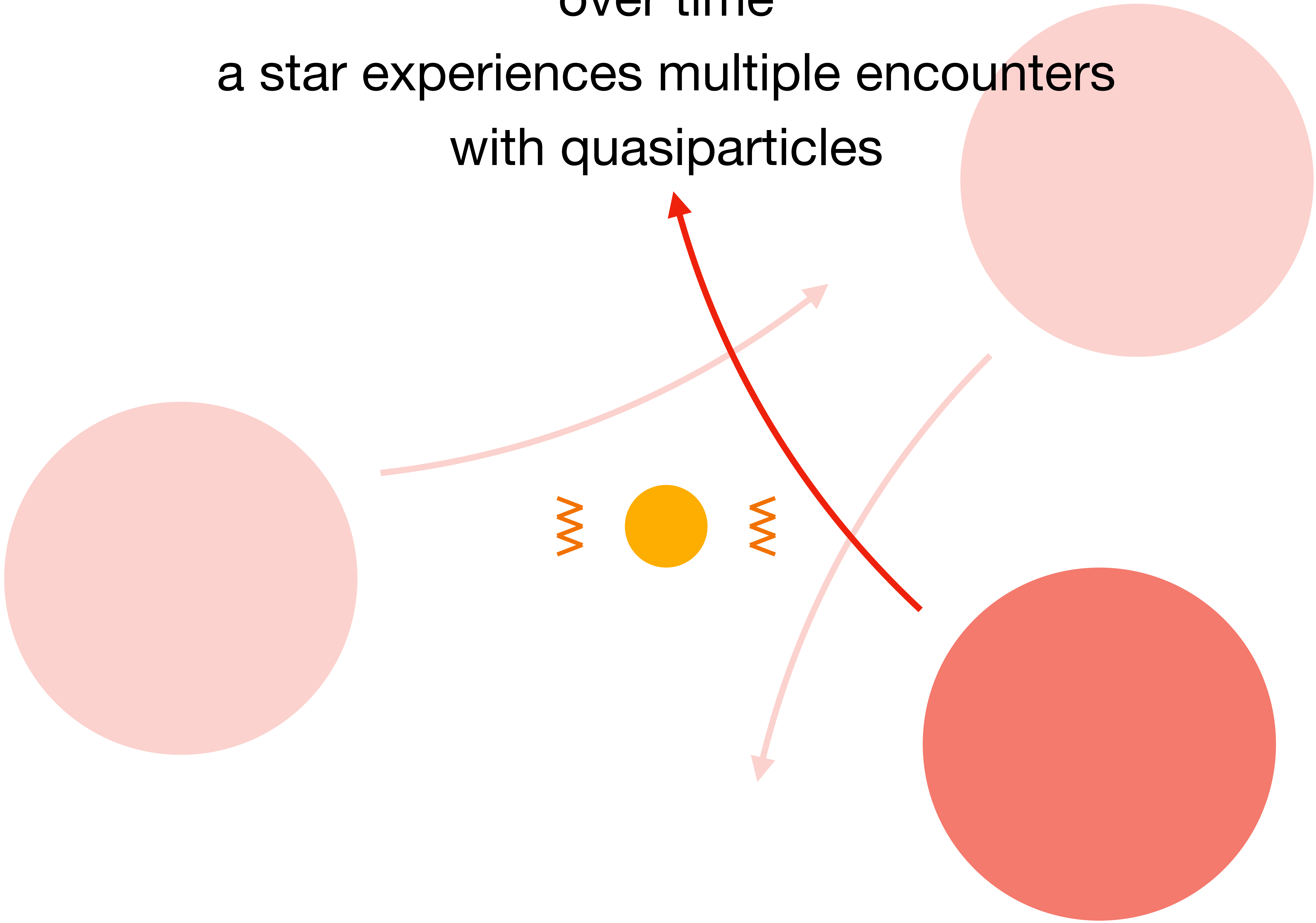


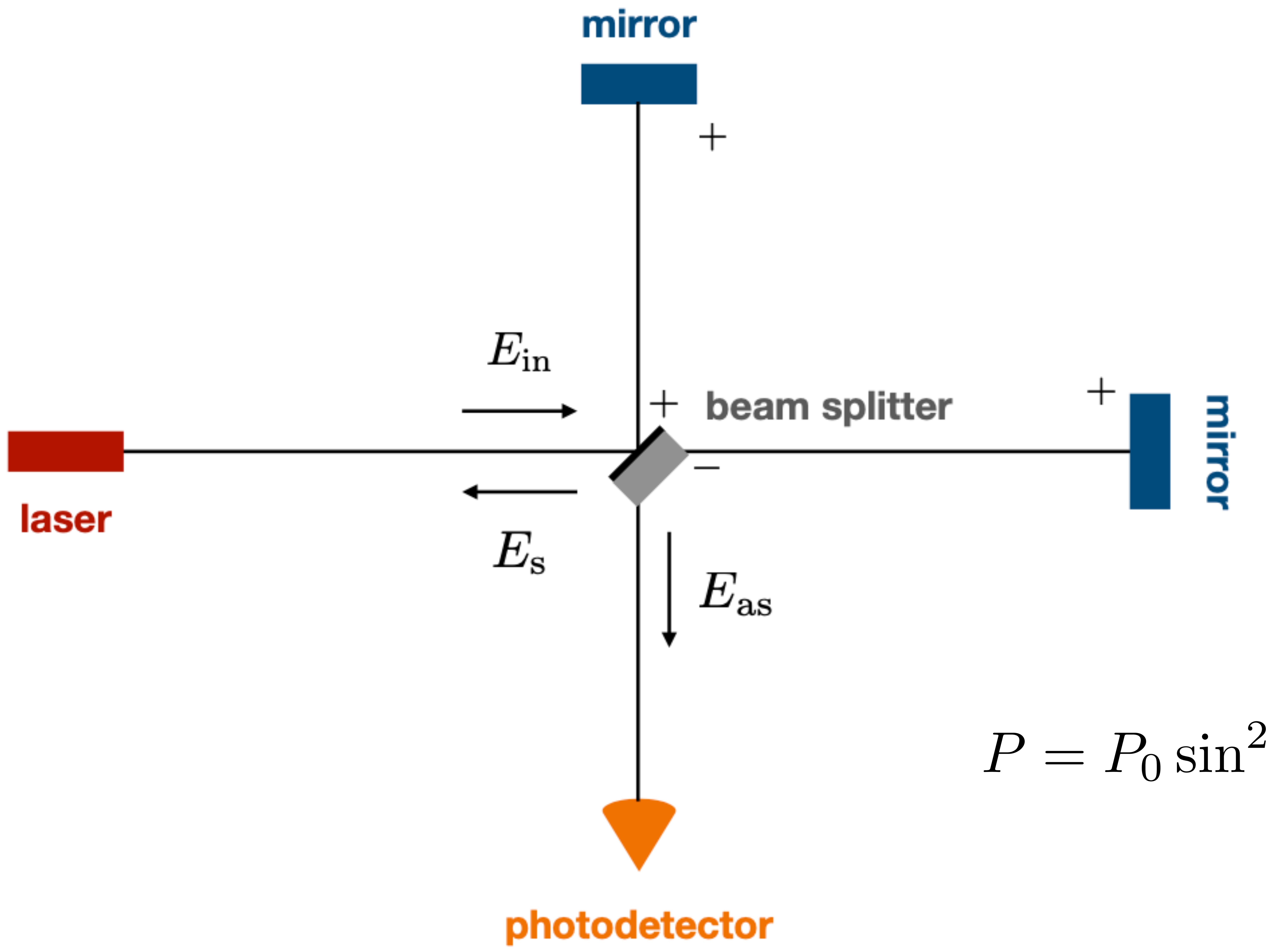
so what?

so what?

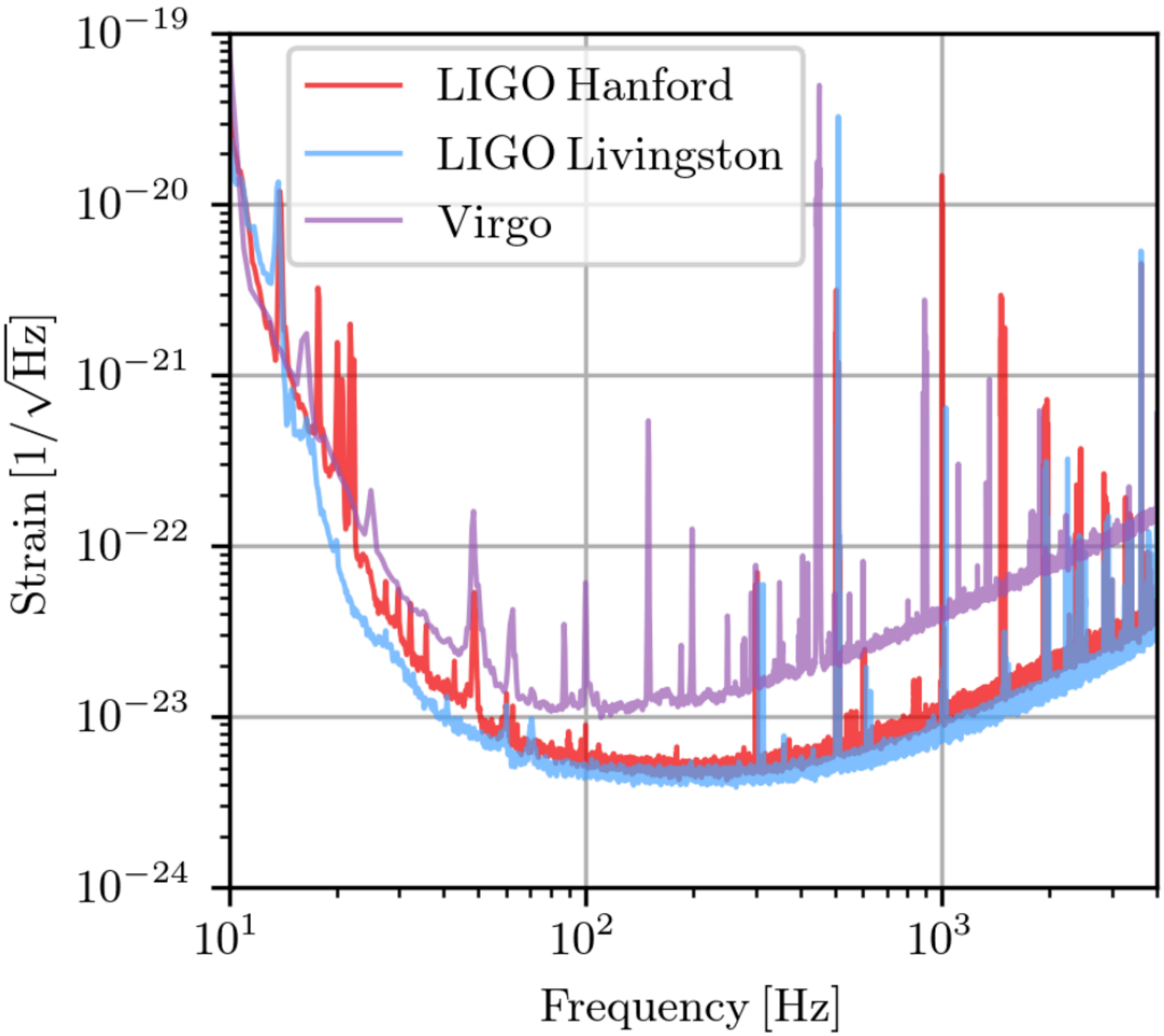
quasiparticles *bombards*

normal matters, leaving *distinctive stochastic signals*

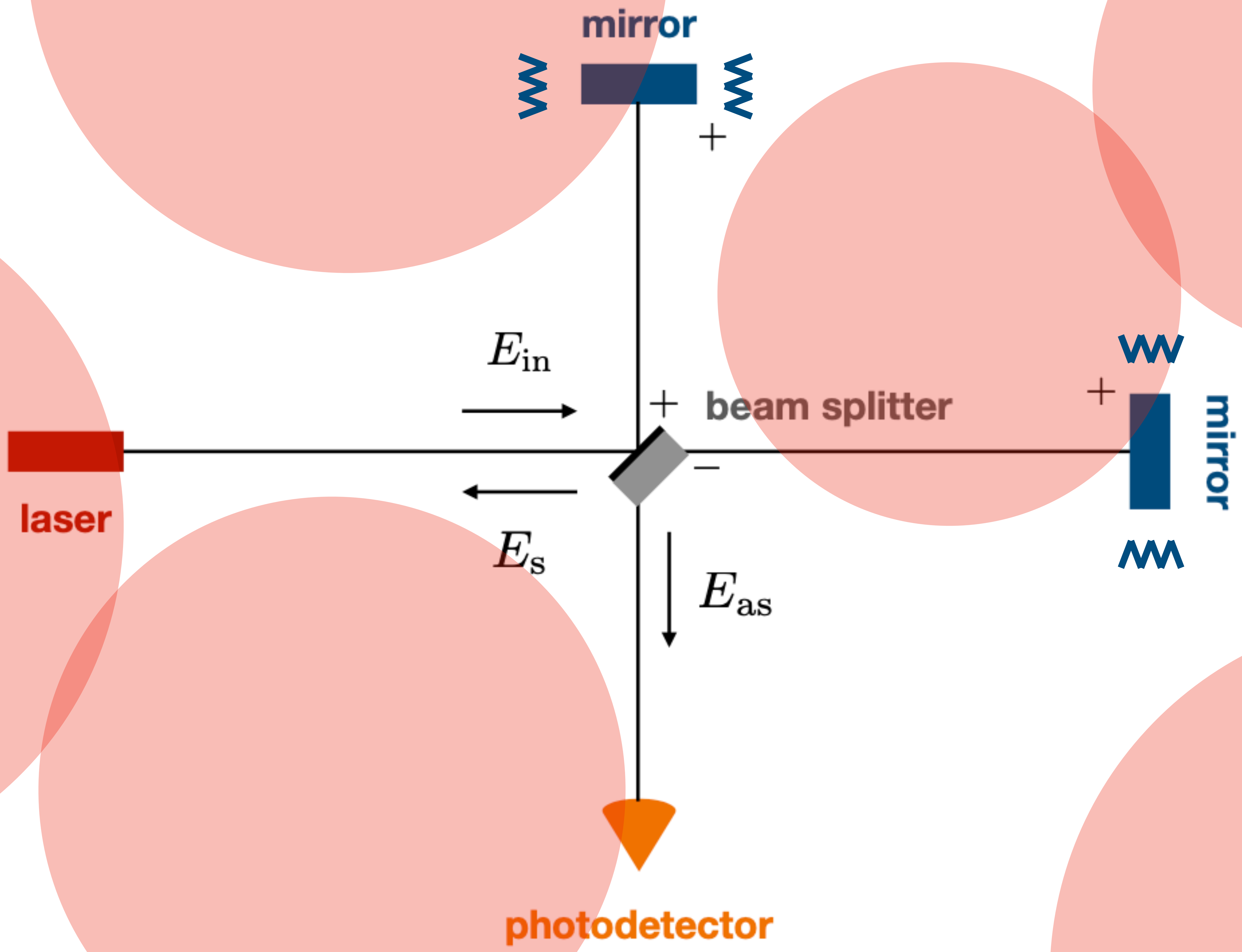
in *gravity wave detectors*



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



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


mirror
E_{in}
beam splitter
laser
E_s
E_{as}
mirror
photodetector

Can we actually measure
ULDM signals with GW interferometers?

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

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

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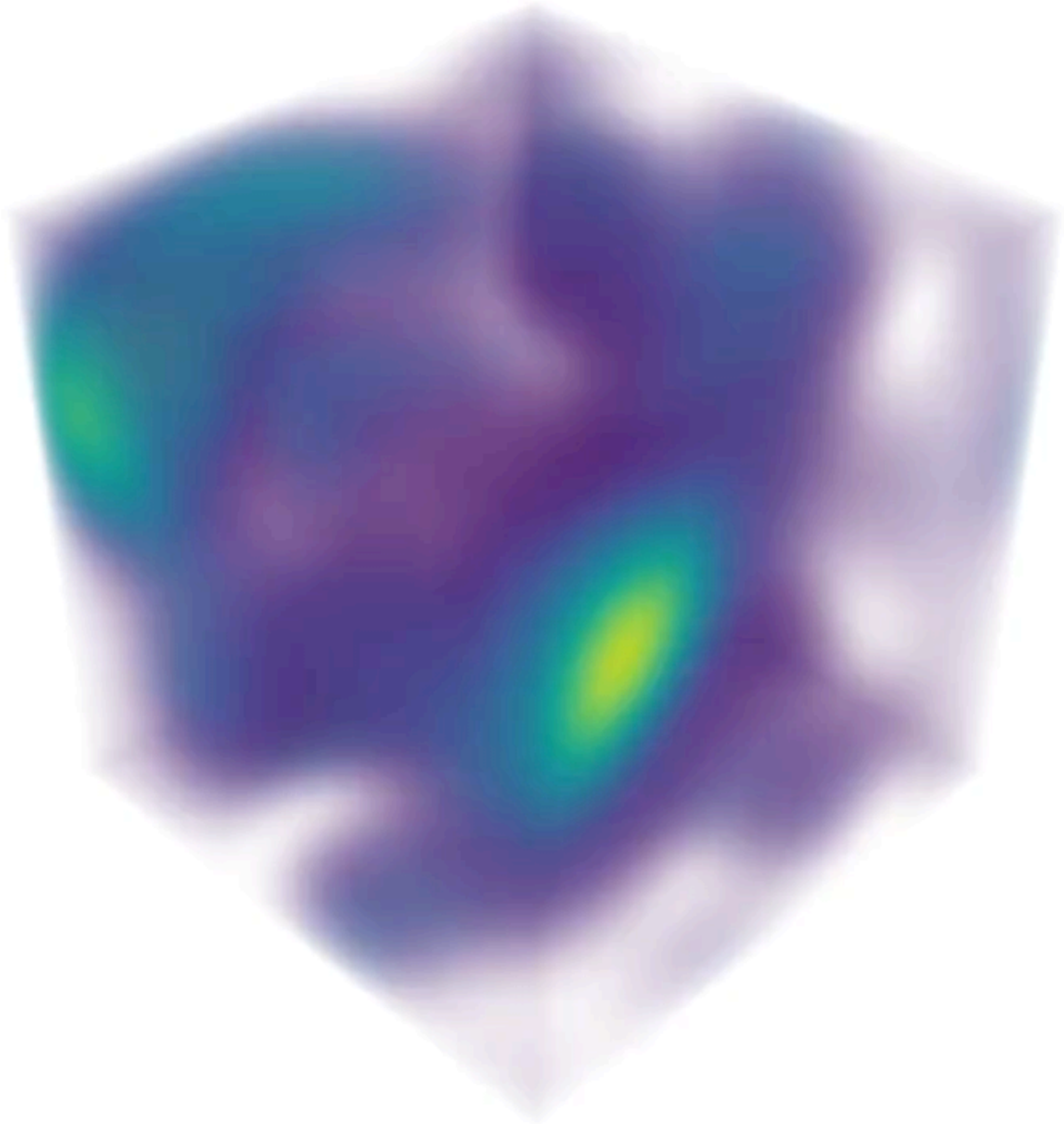
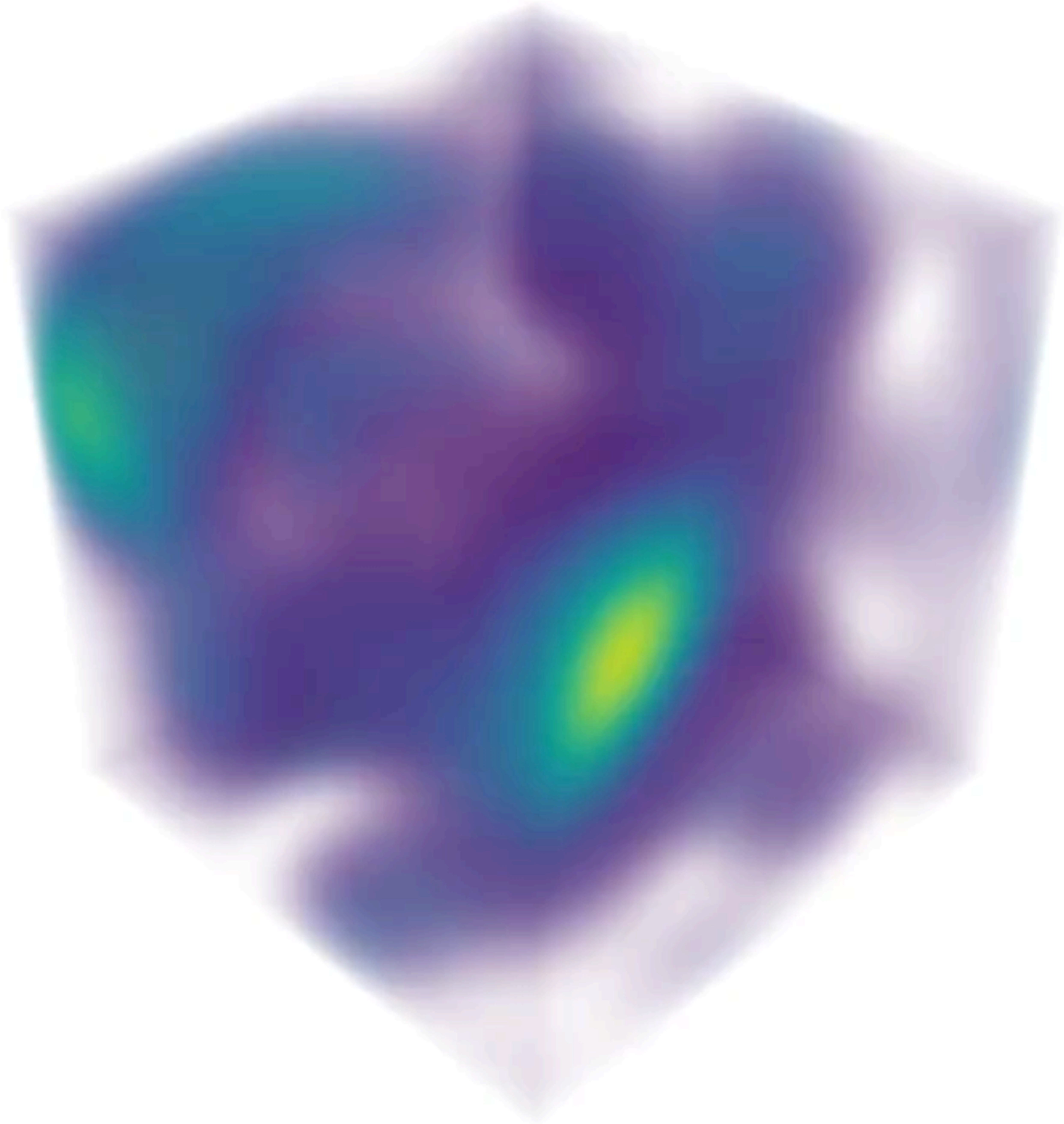
$$\nabla^2\Phi = 4\pi G\rho$$

what is reflected in *detector observables*

is the *statistical properties* of

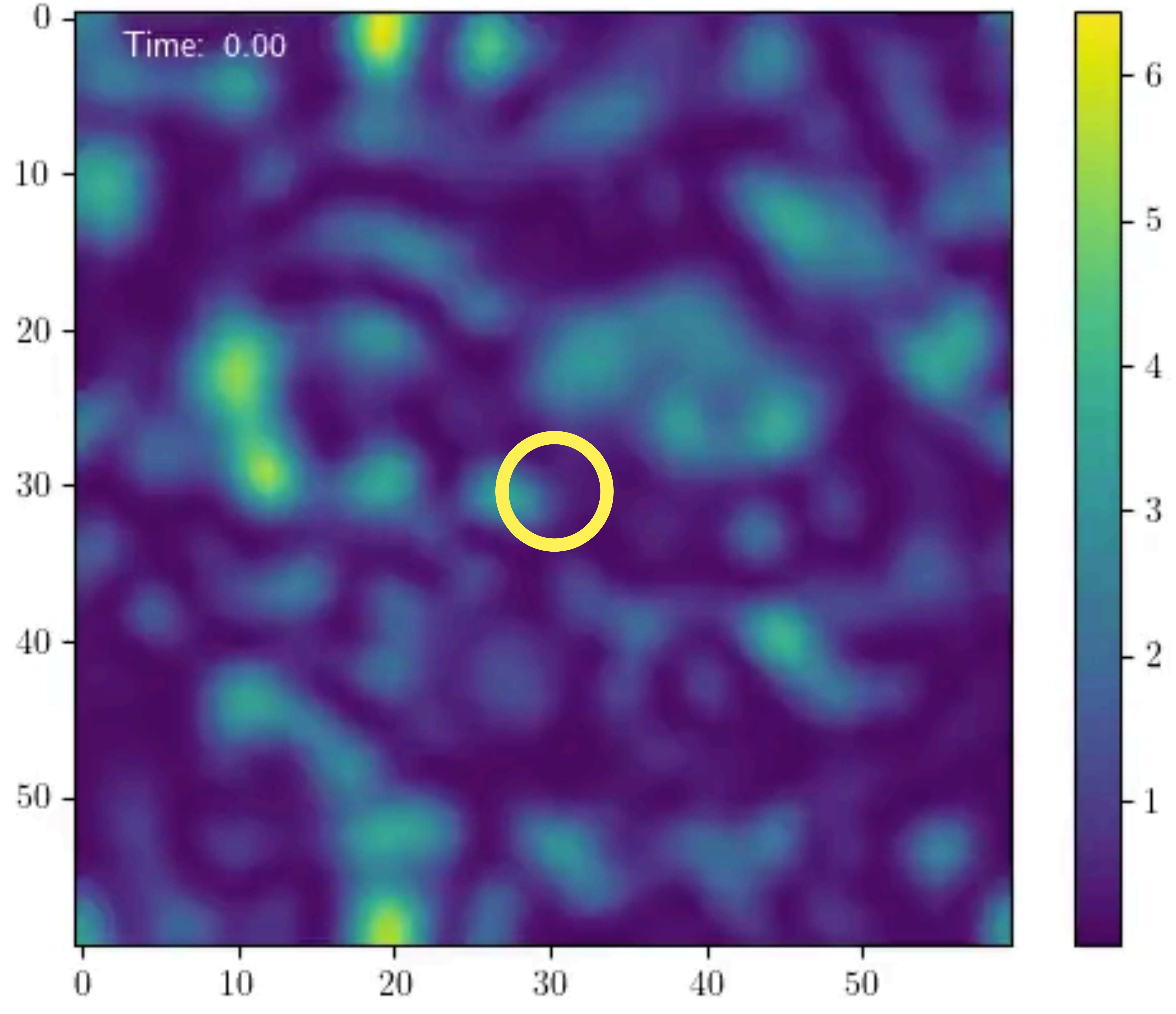
density fluctuations of ULDM





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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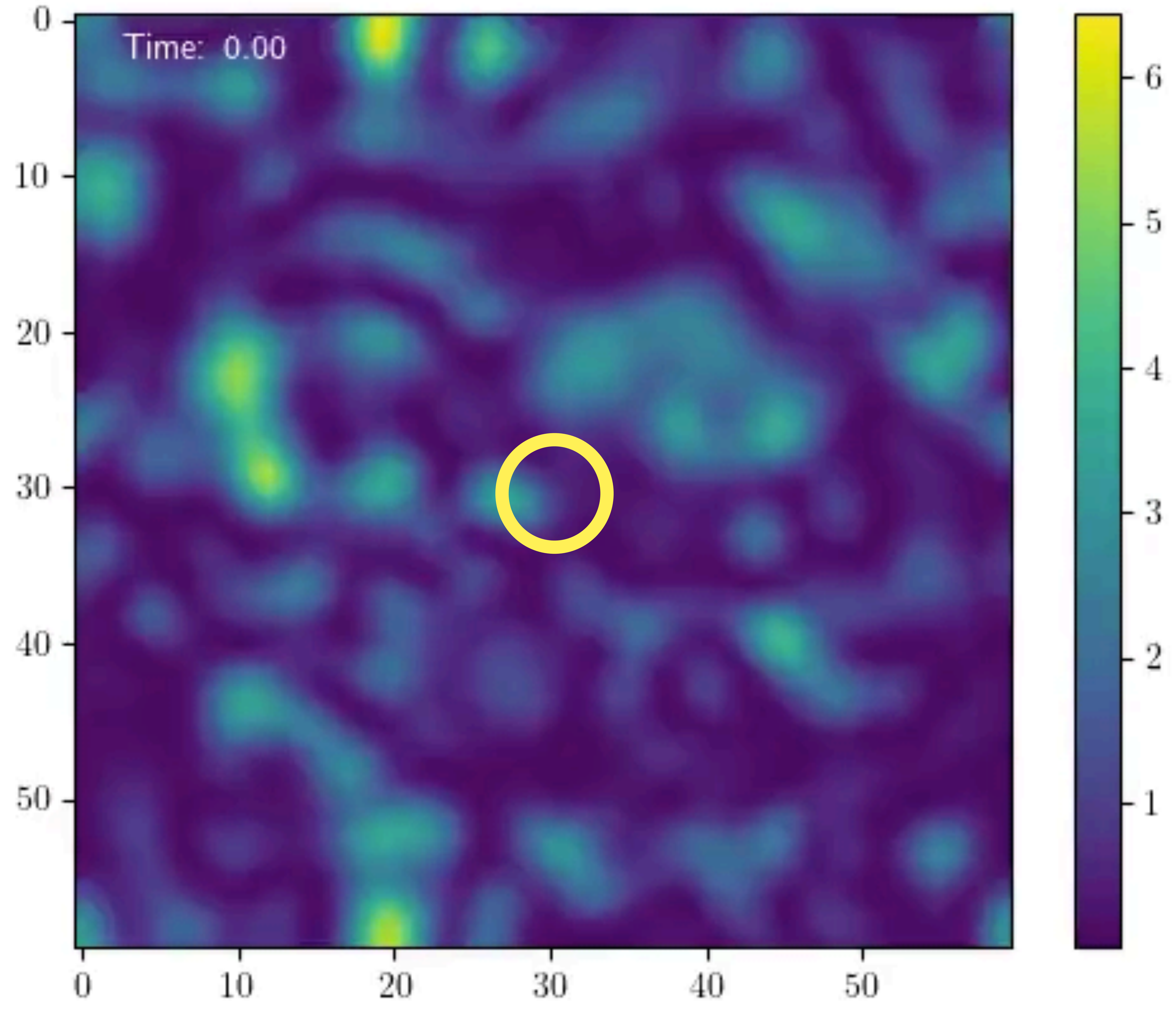

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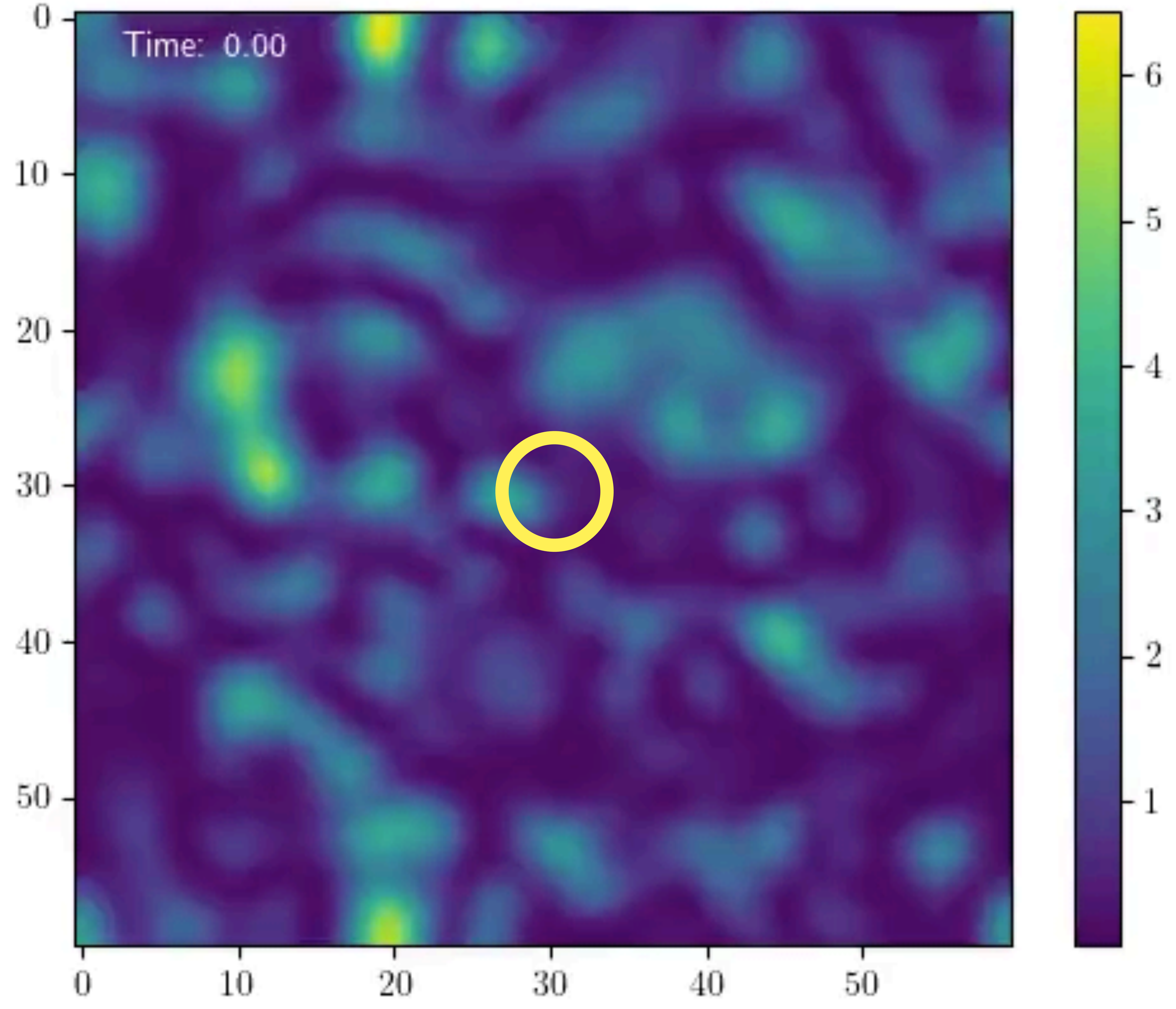

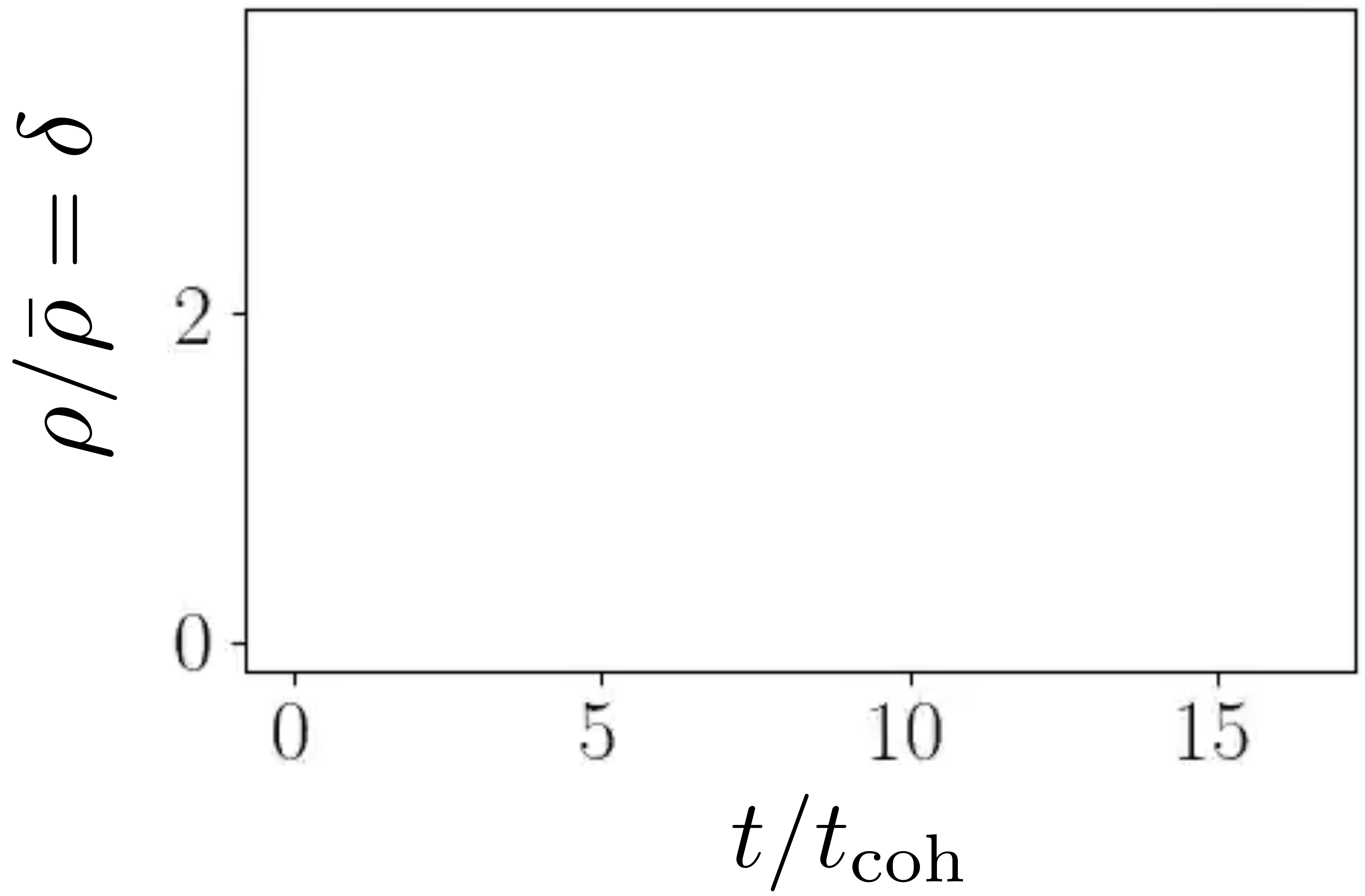

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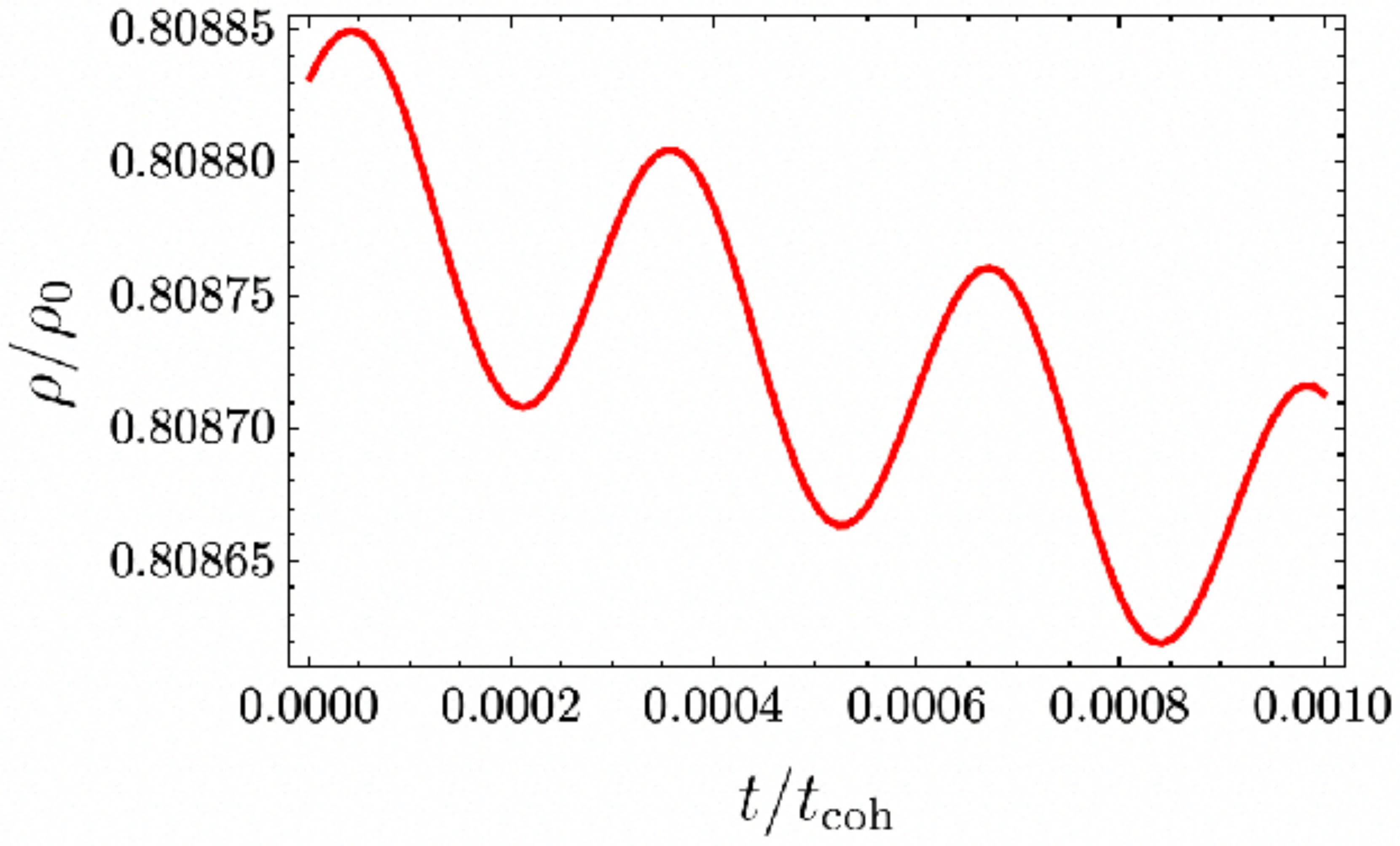

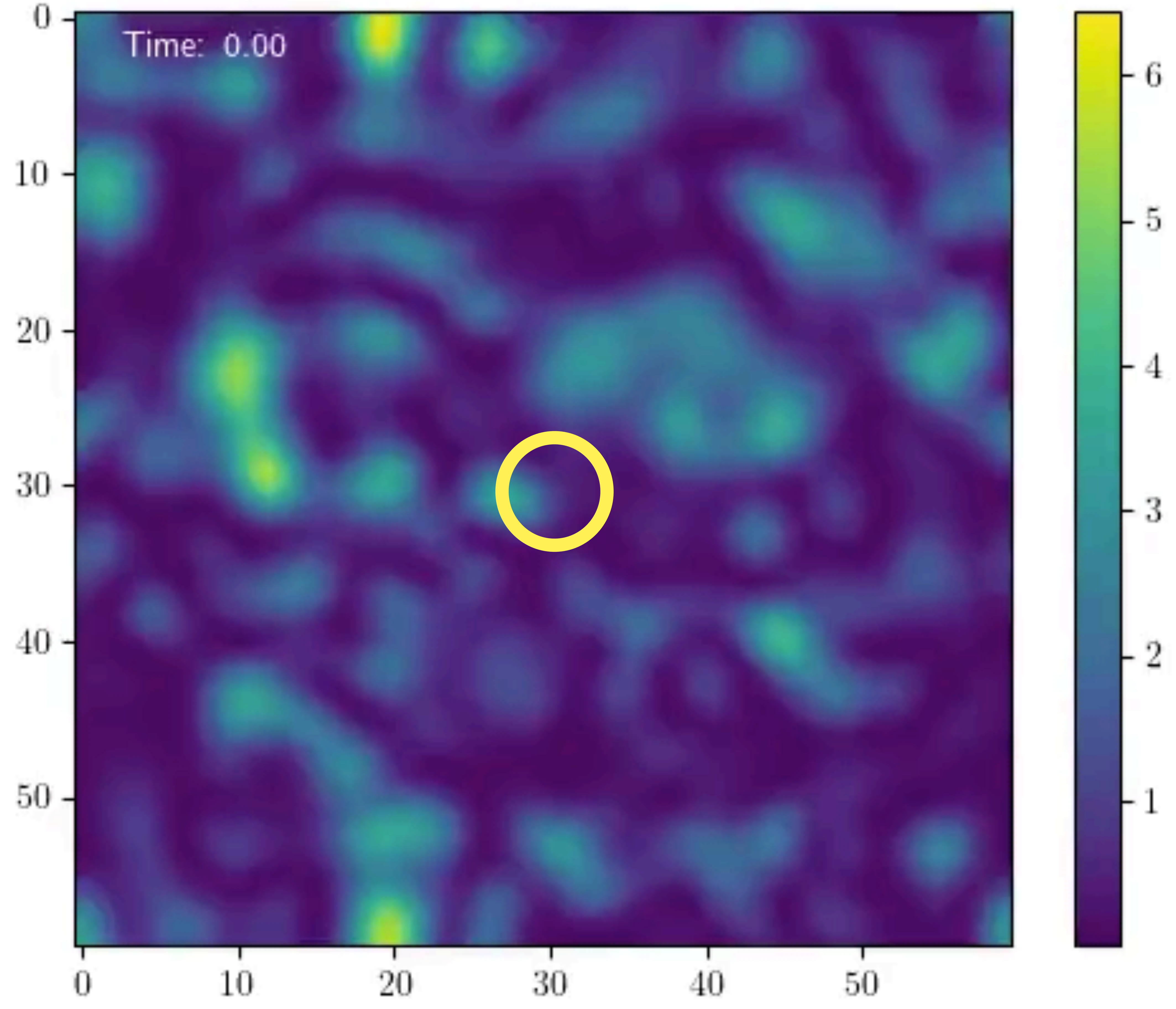

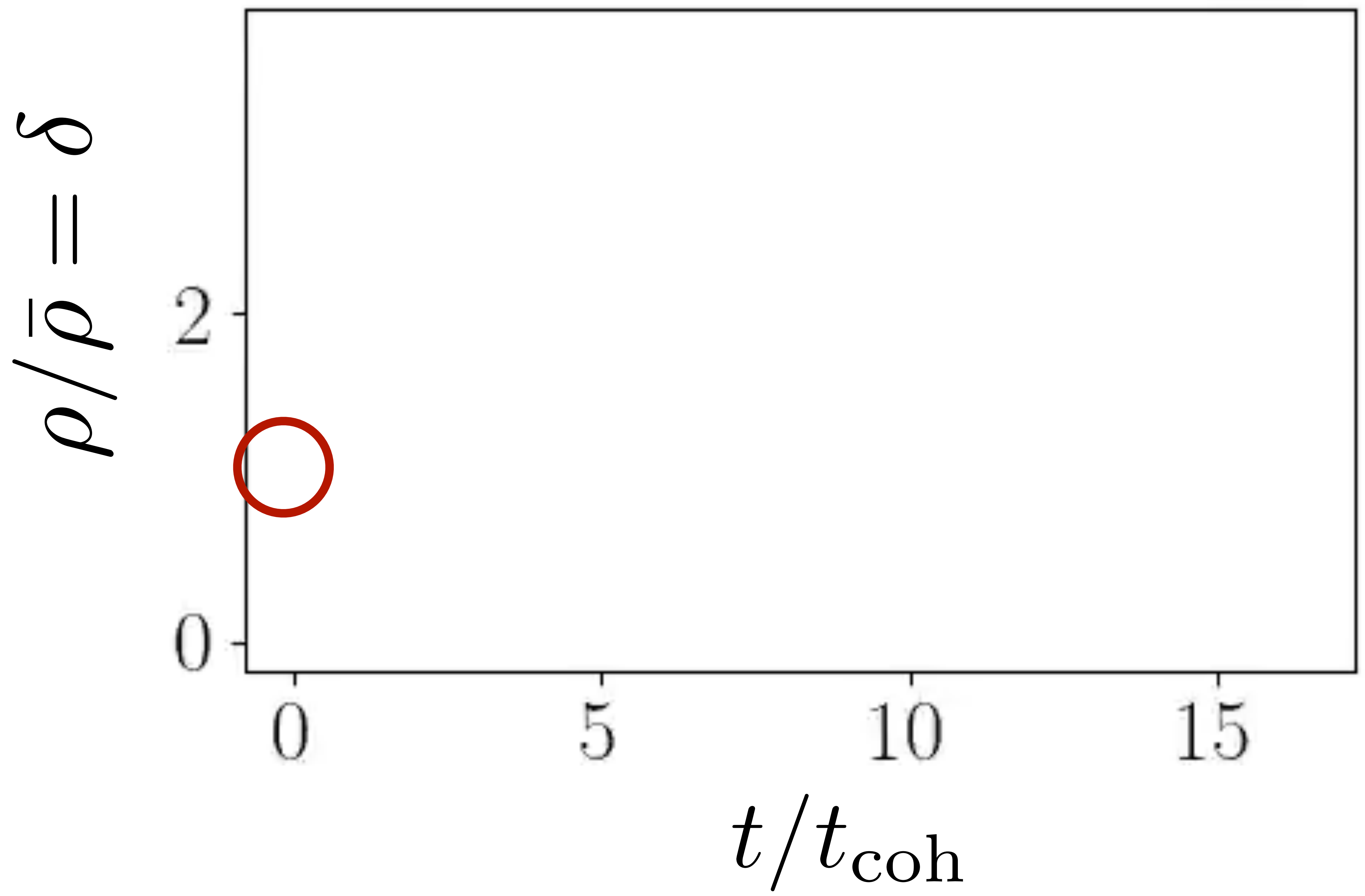

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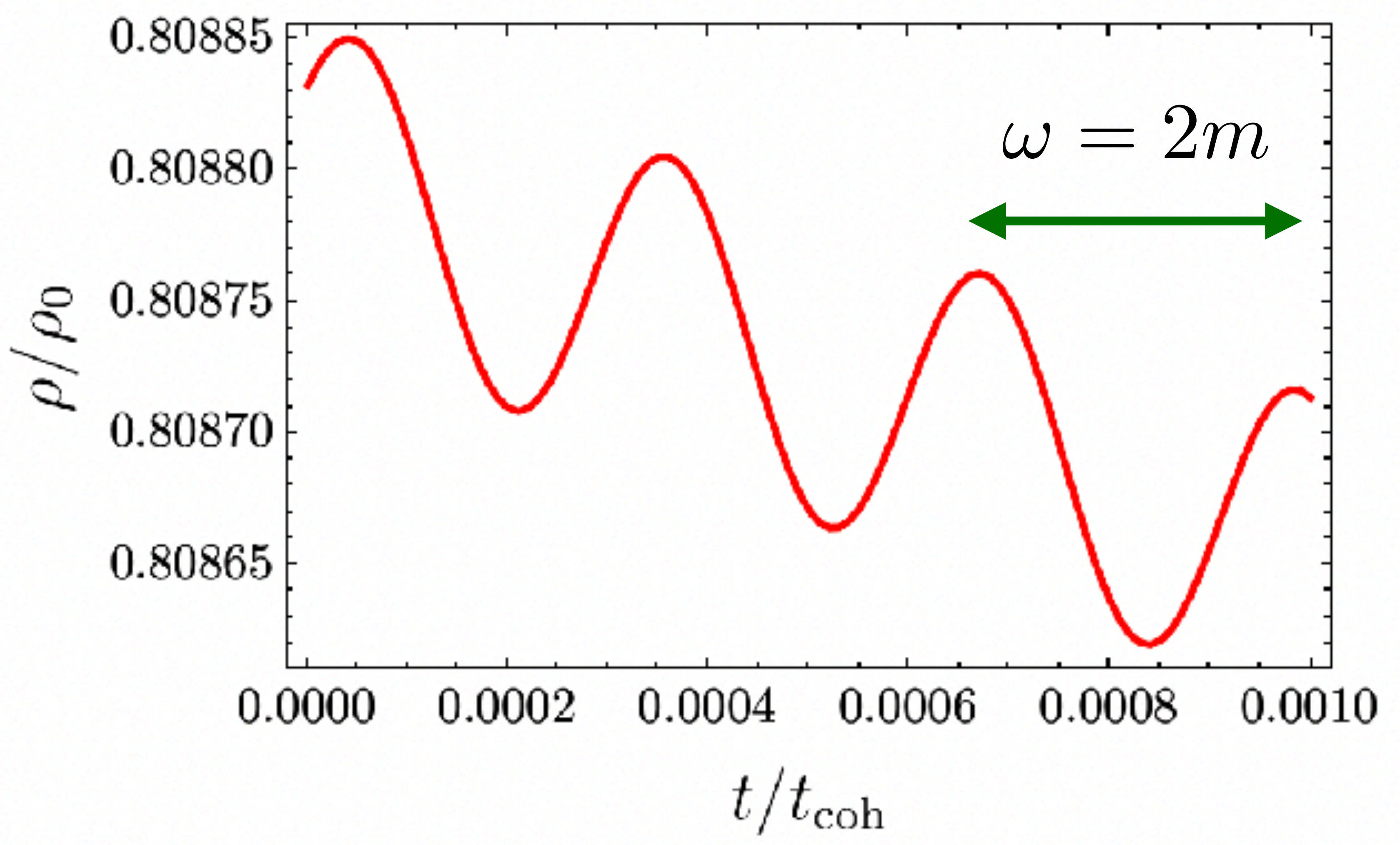

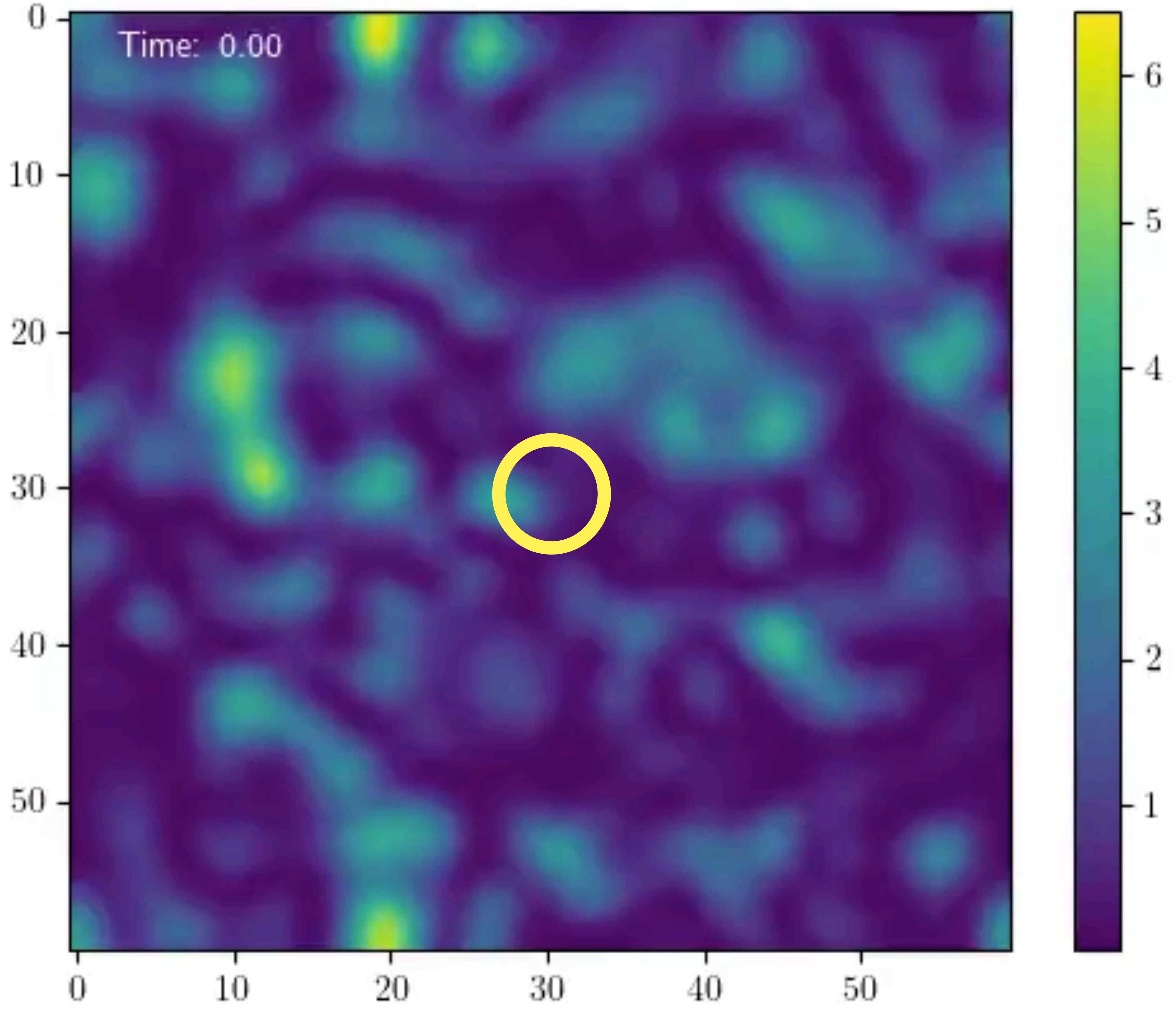

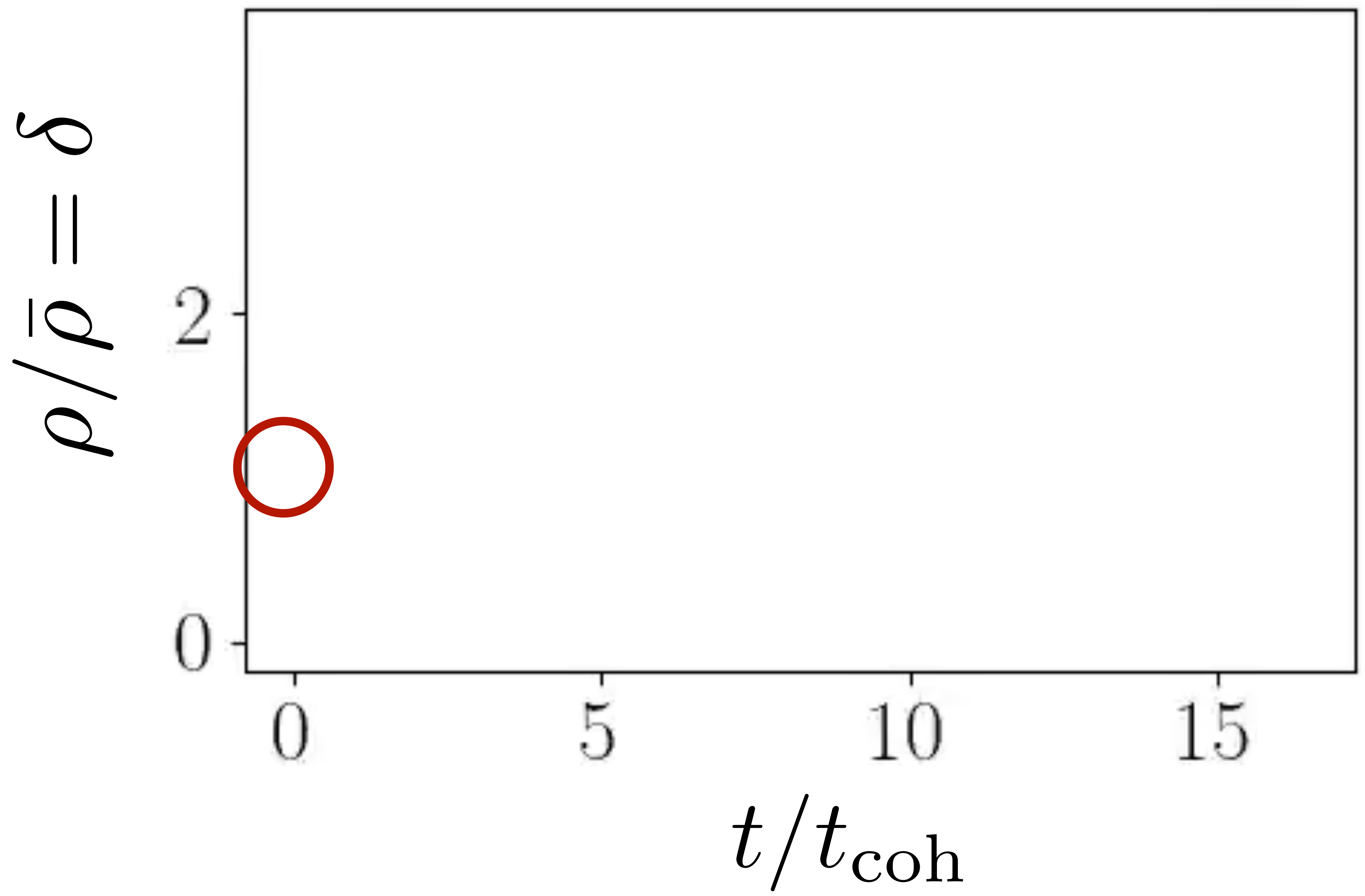

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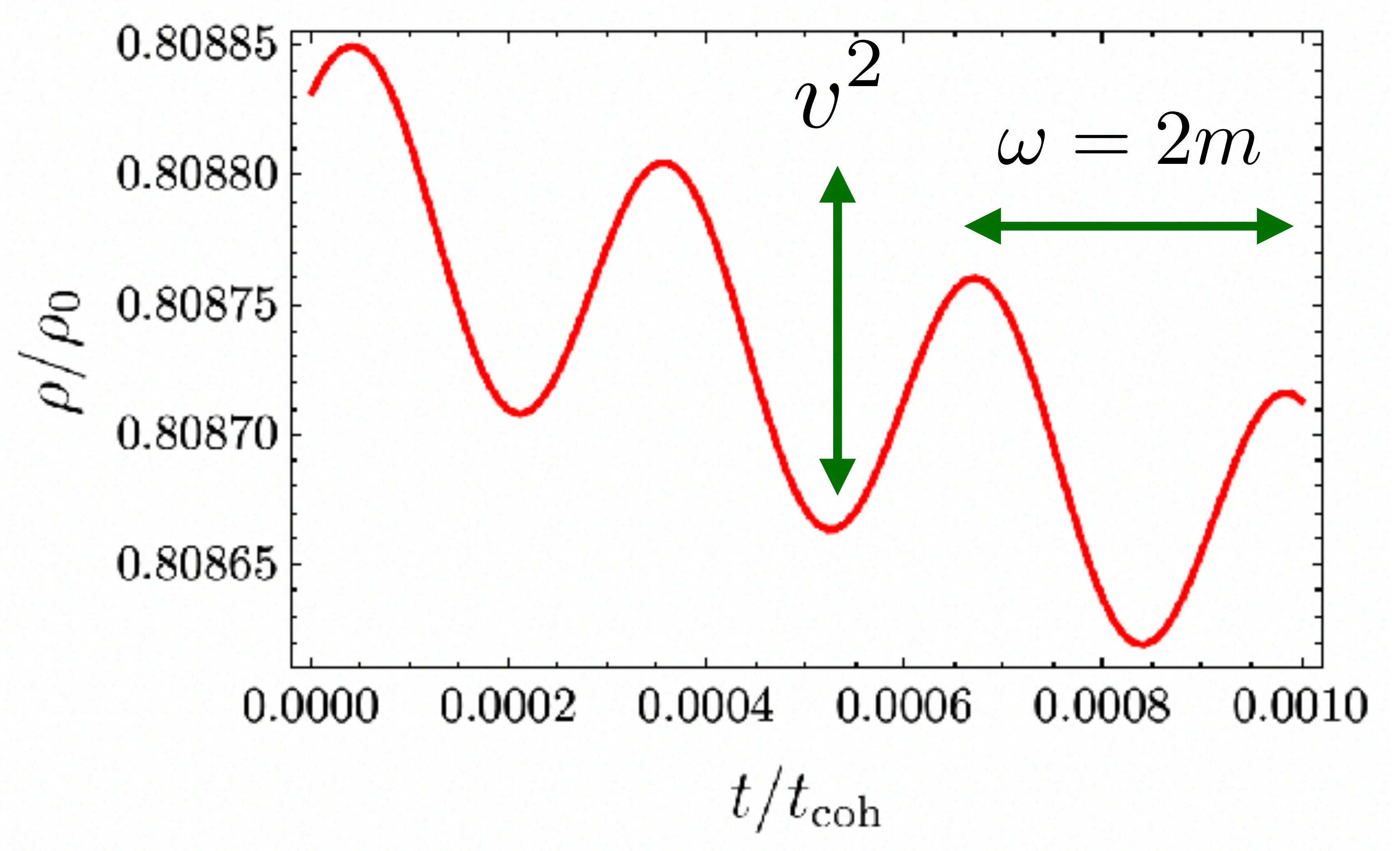

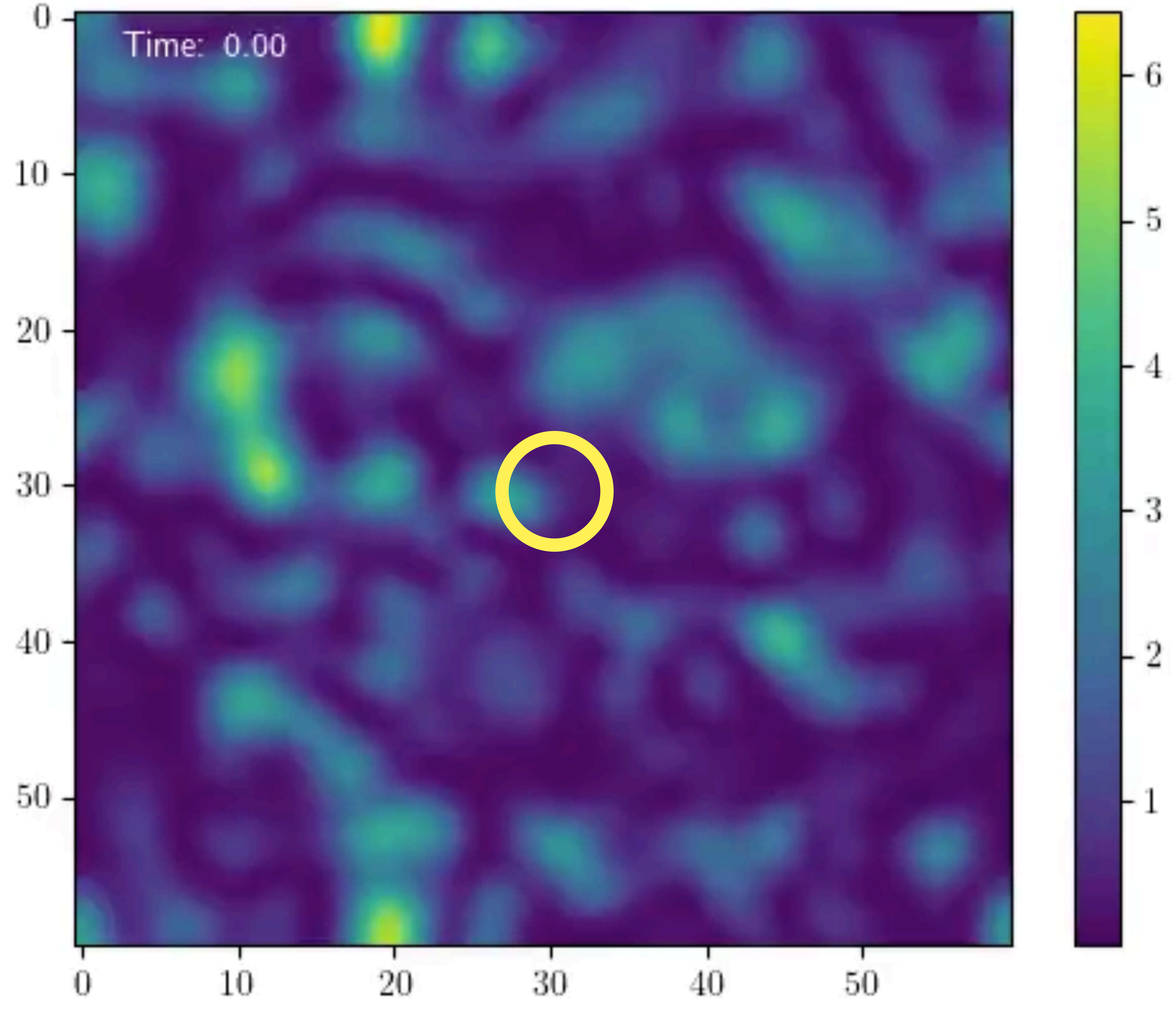

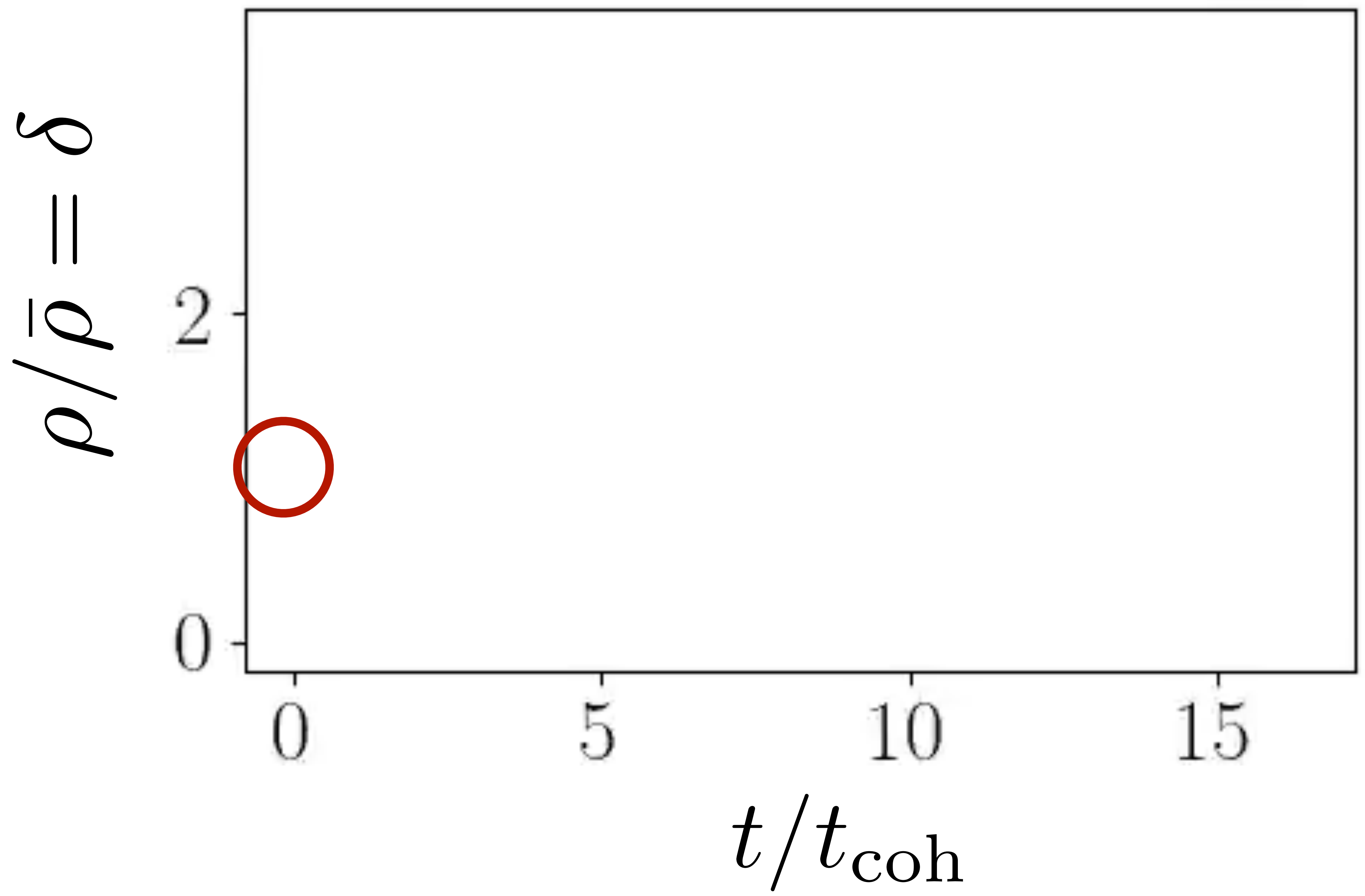

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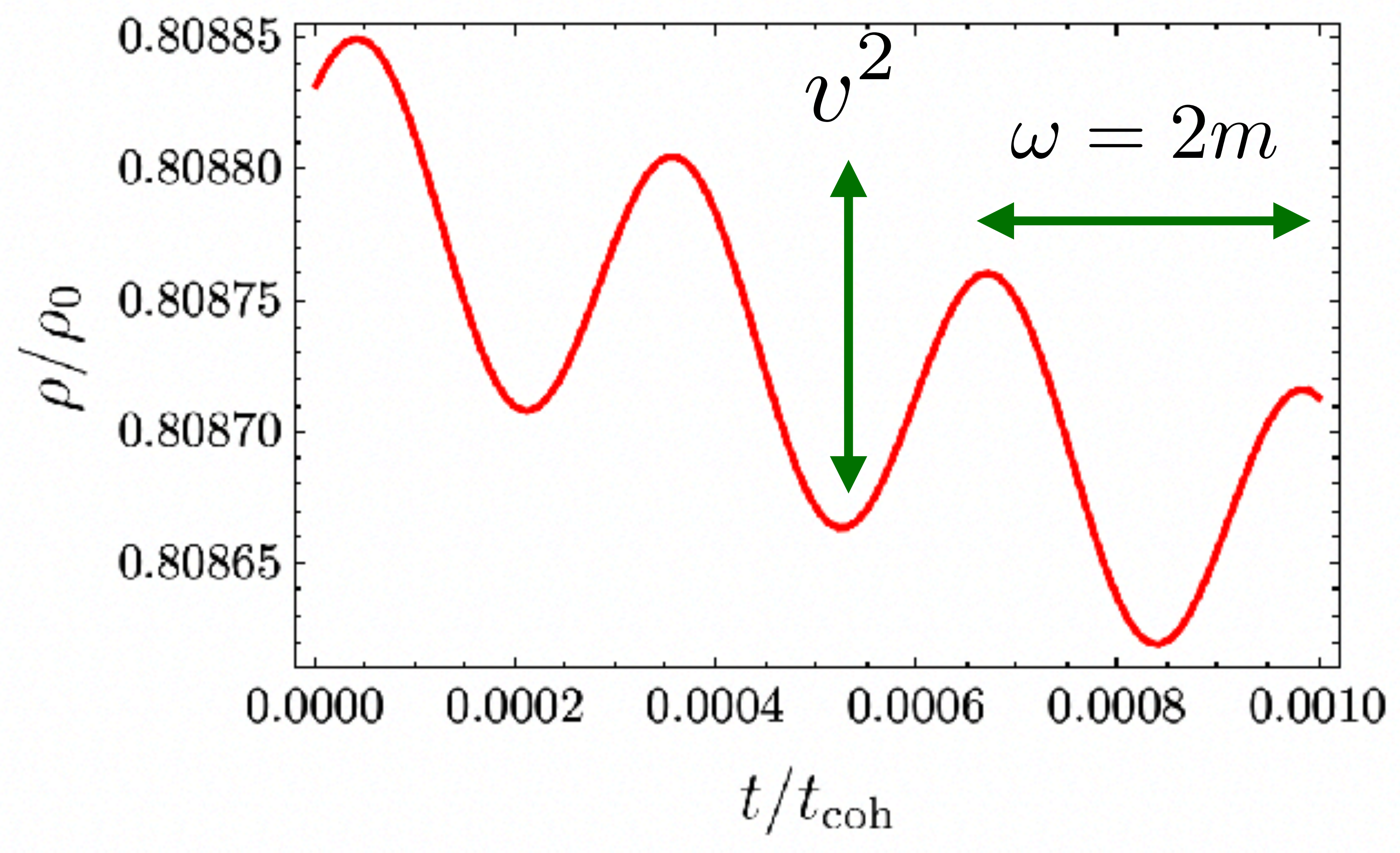
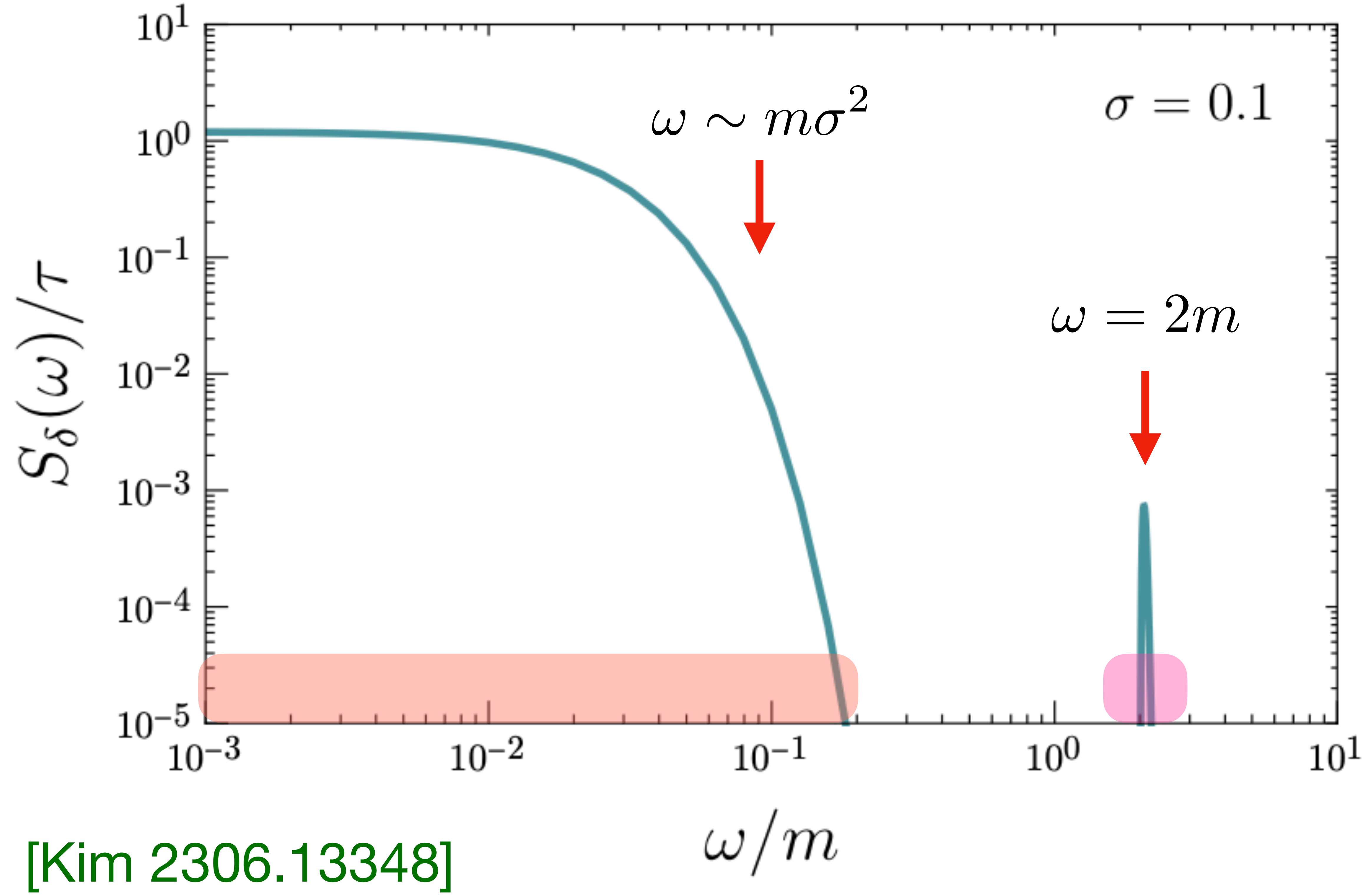
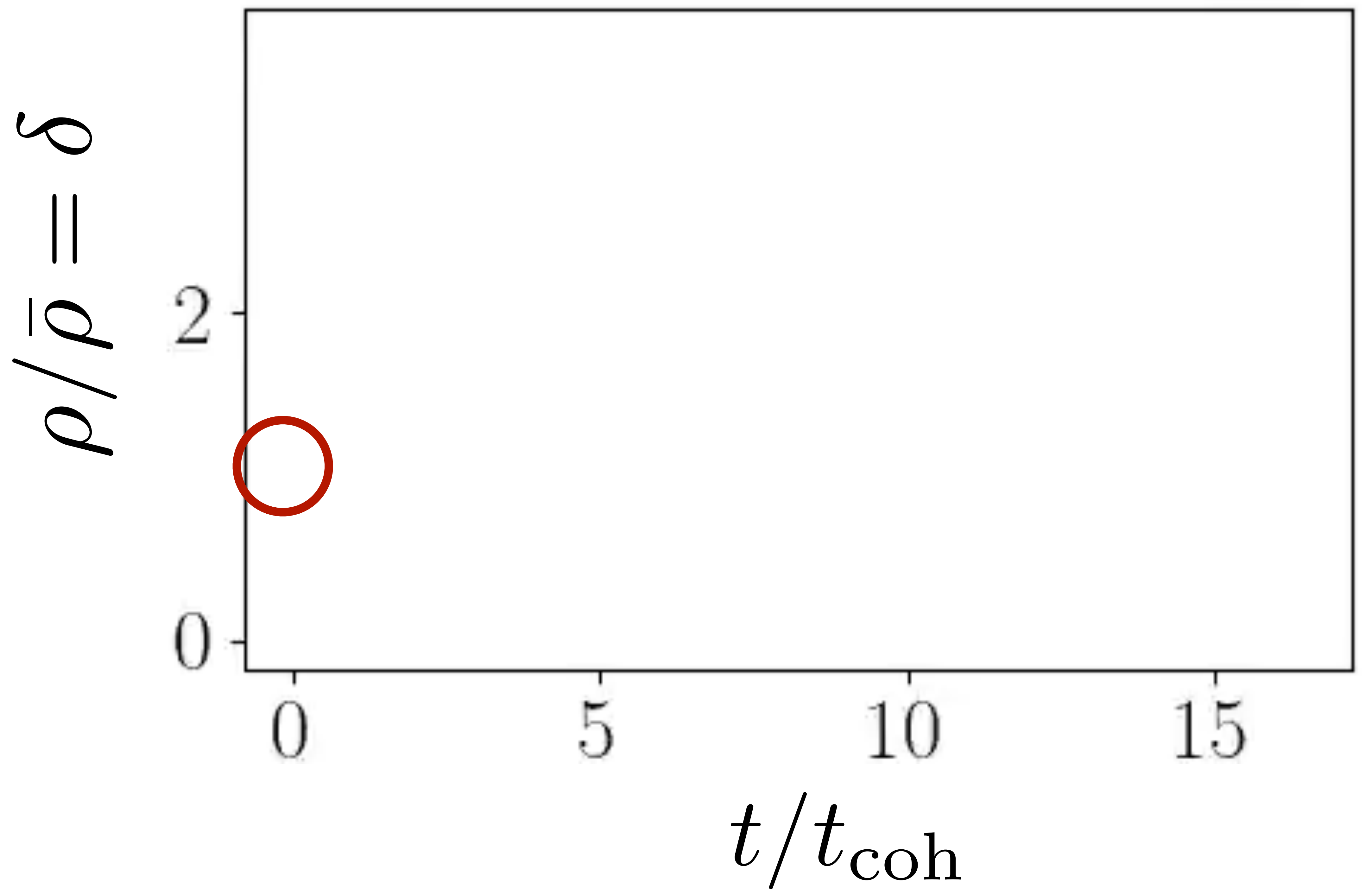


$$S_\delta(\omega) = \tau[\sigma^4 A_\delta(\omega) + B_\delta(\omega)]$$





[Kim 2306.13348]

[Kim, Lenoci, Perez, Ratzinger, 2307.14962]

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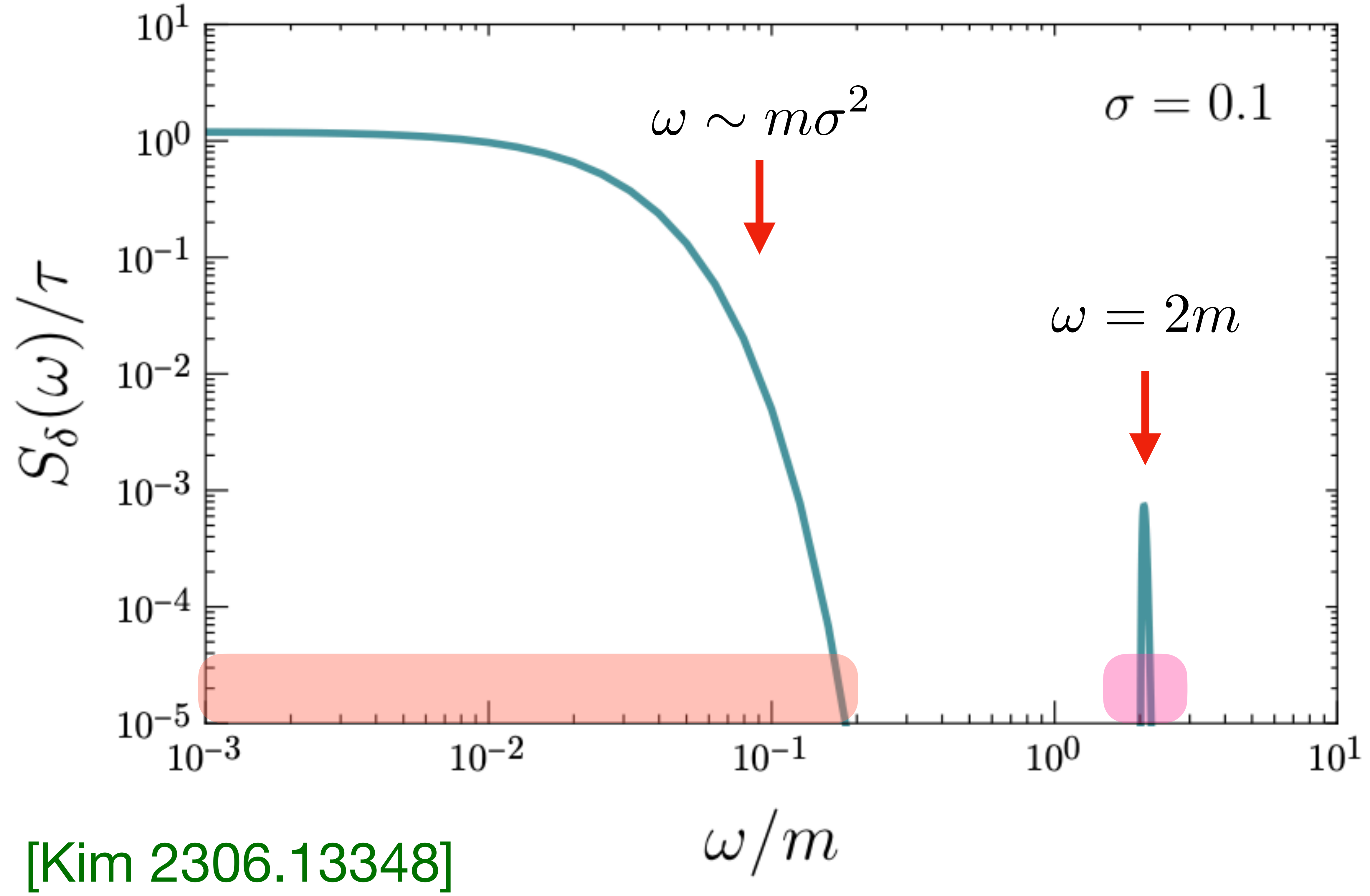

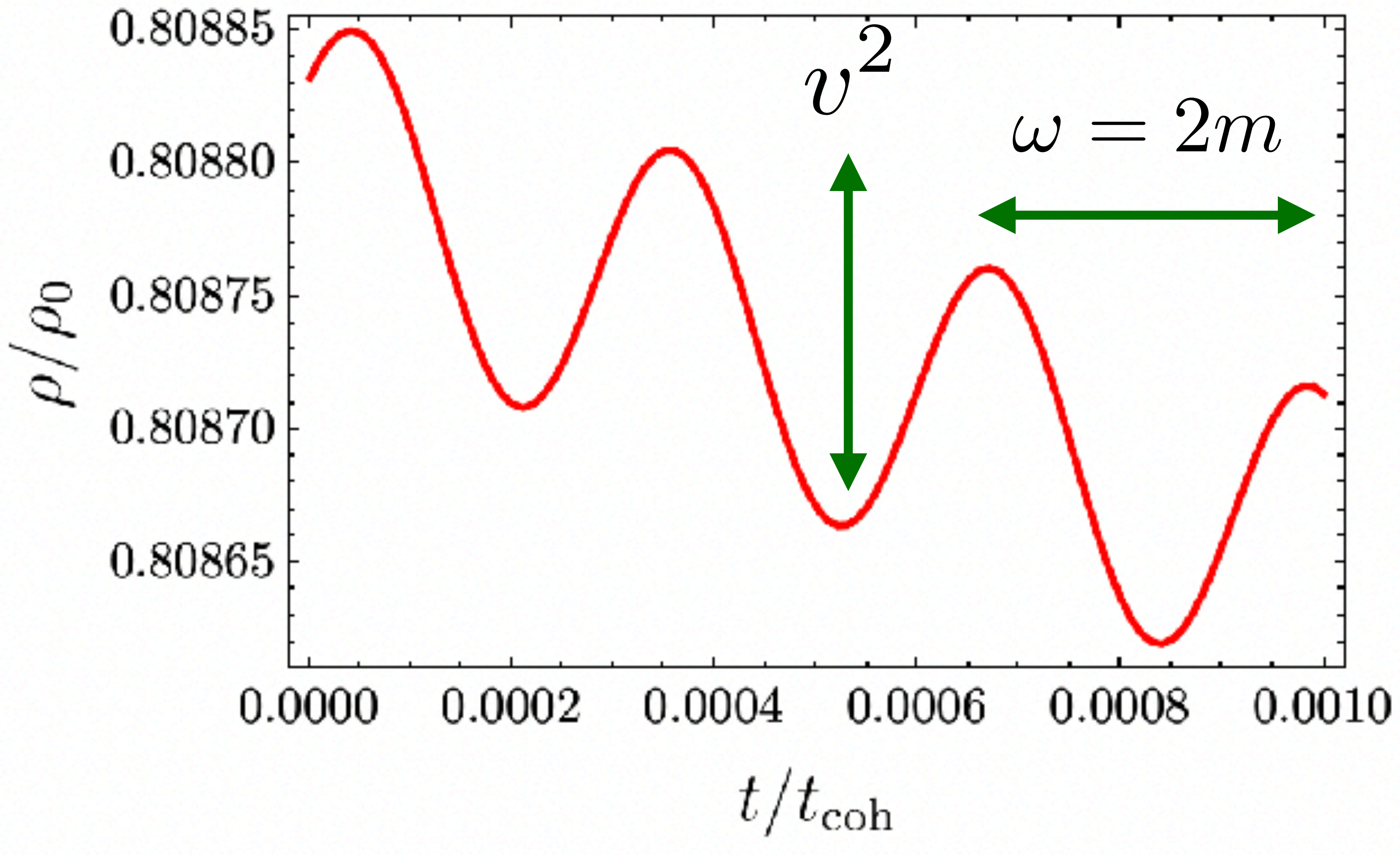

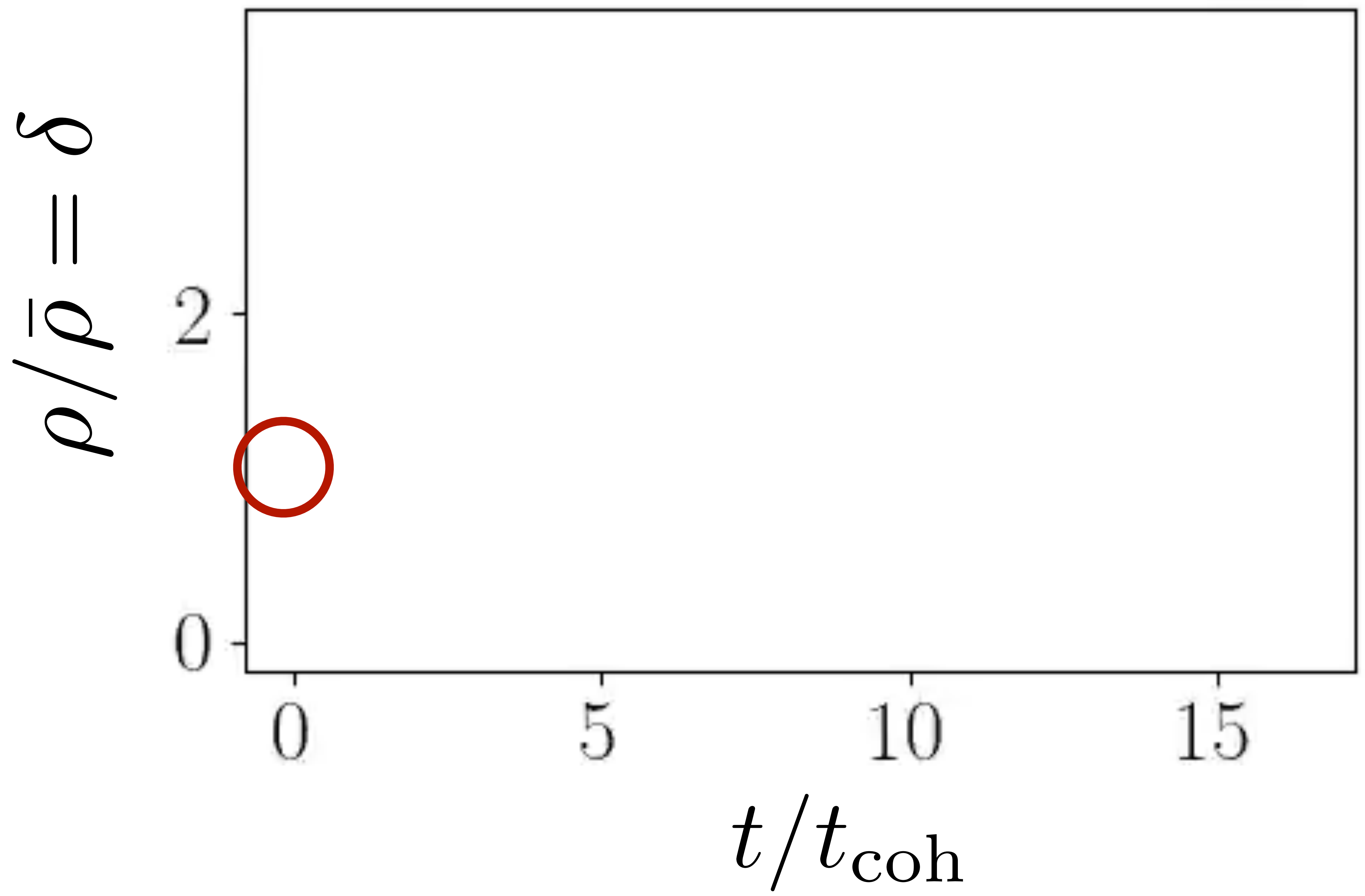

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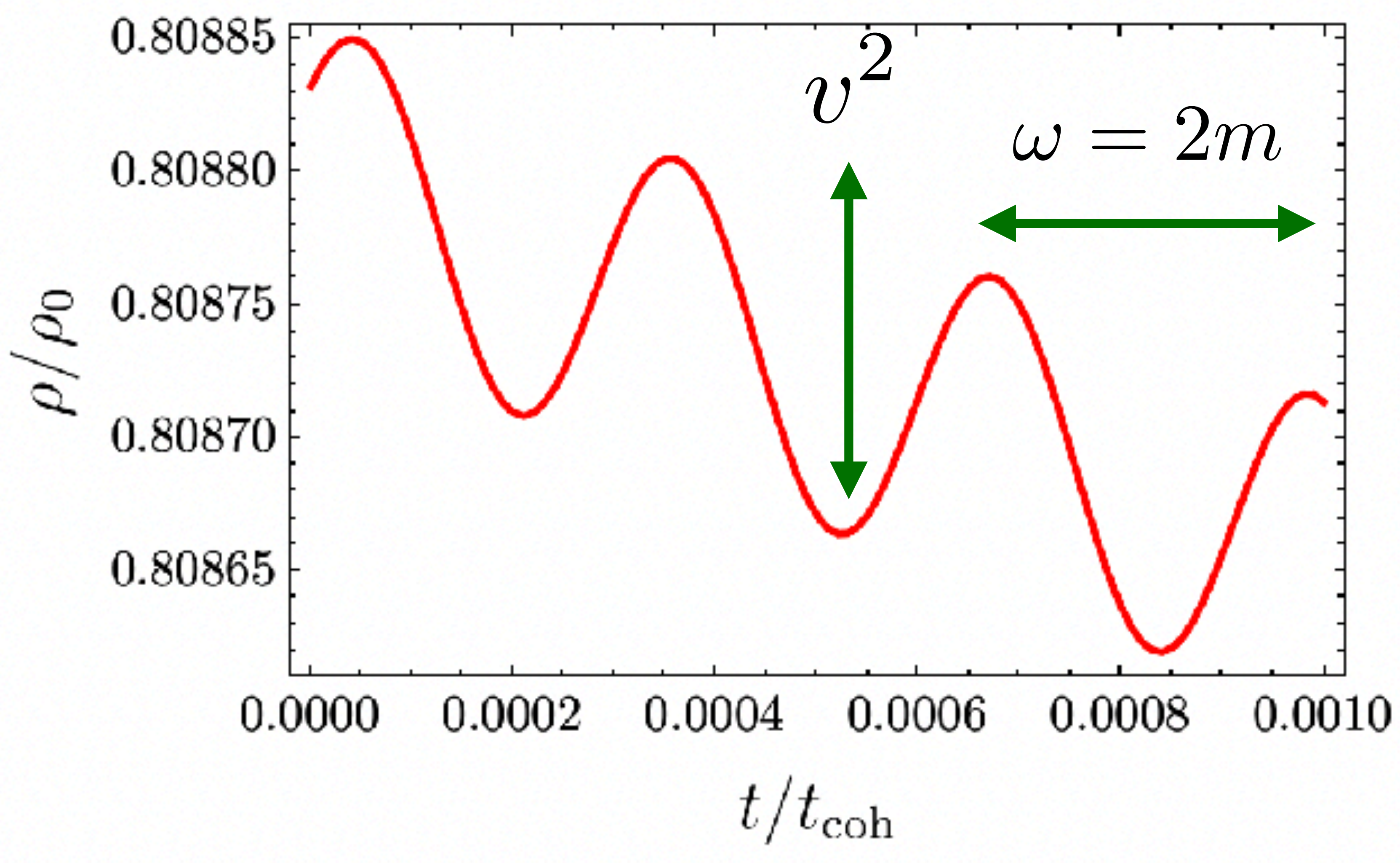

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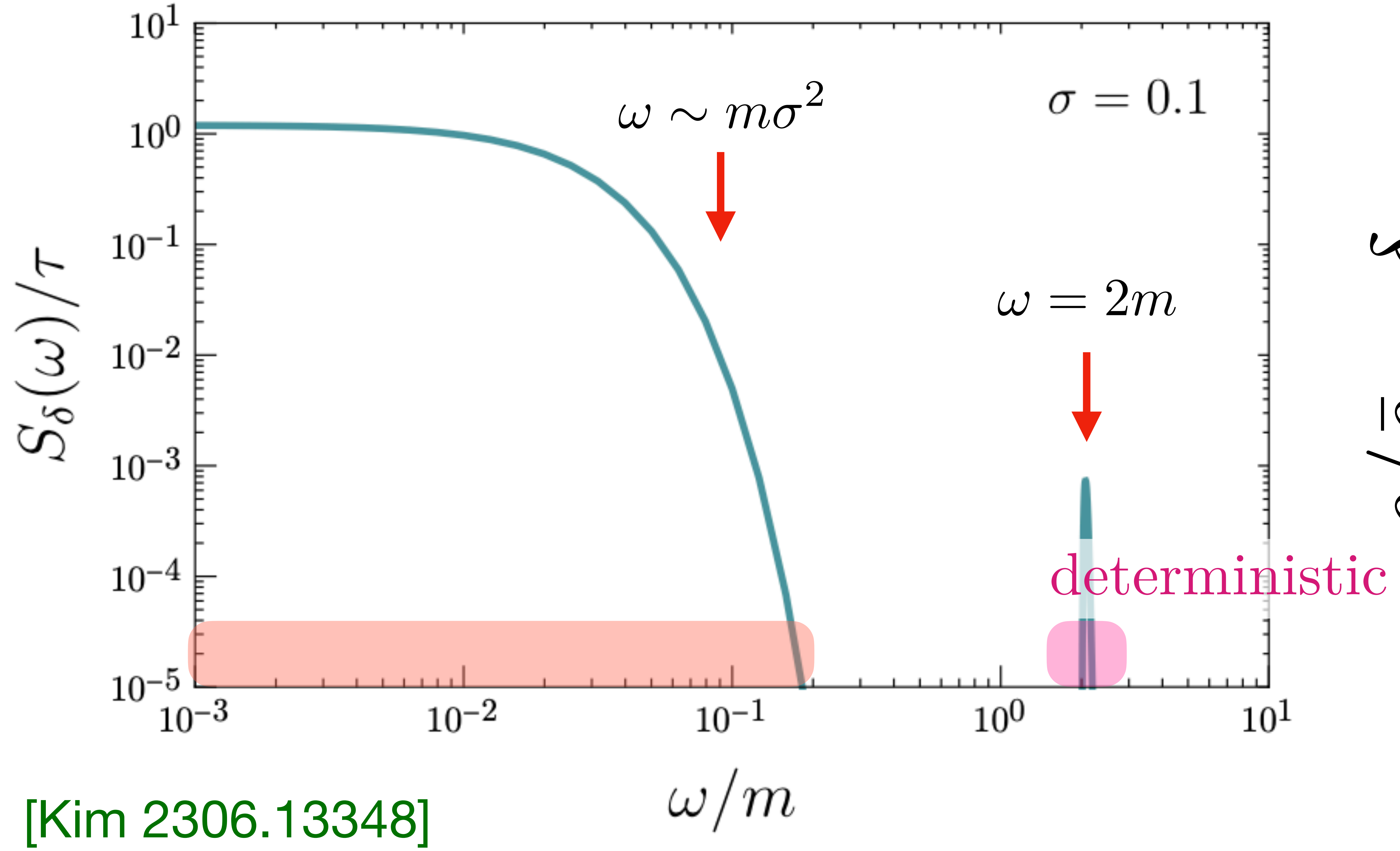

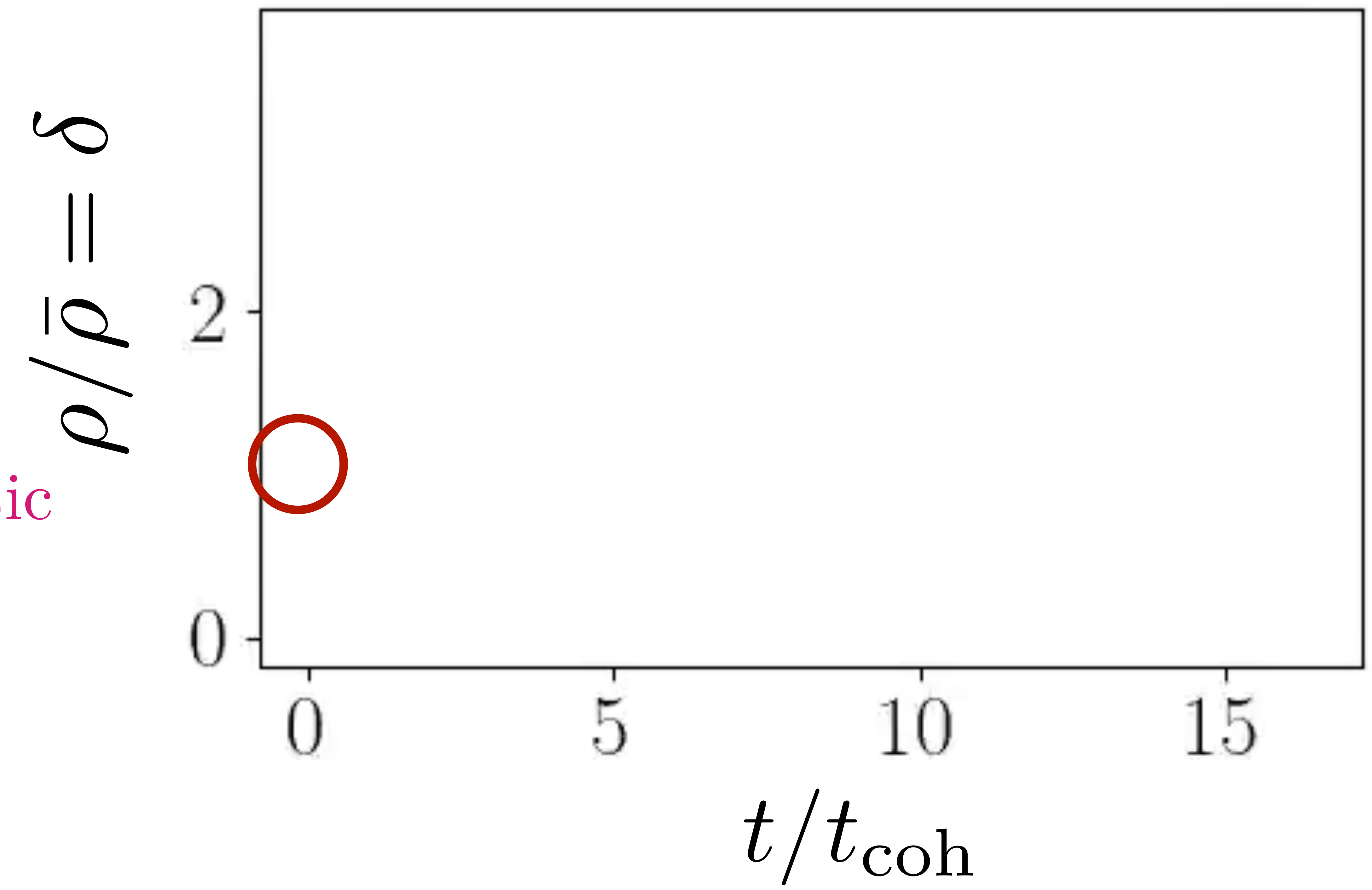

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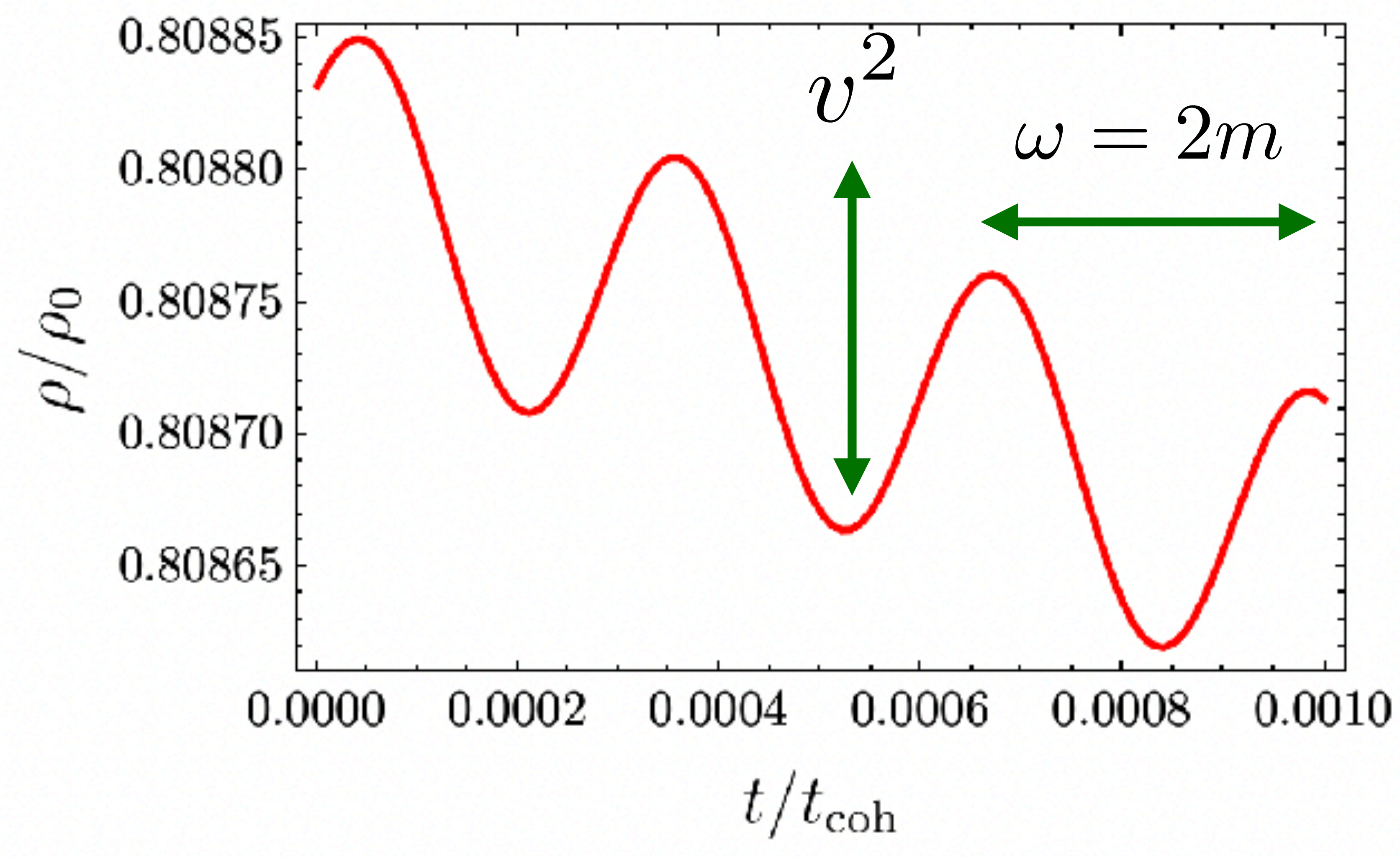

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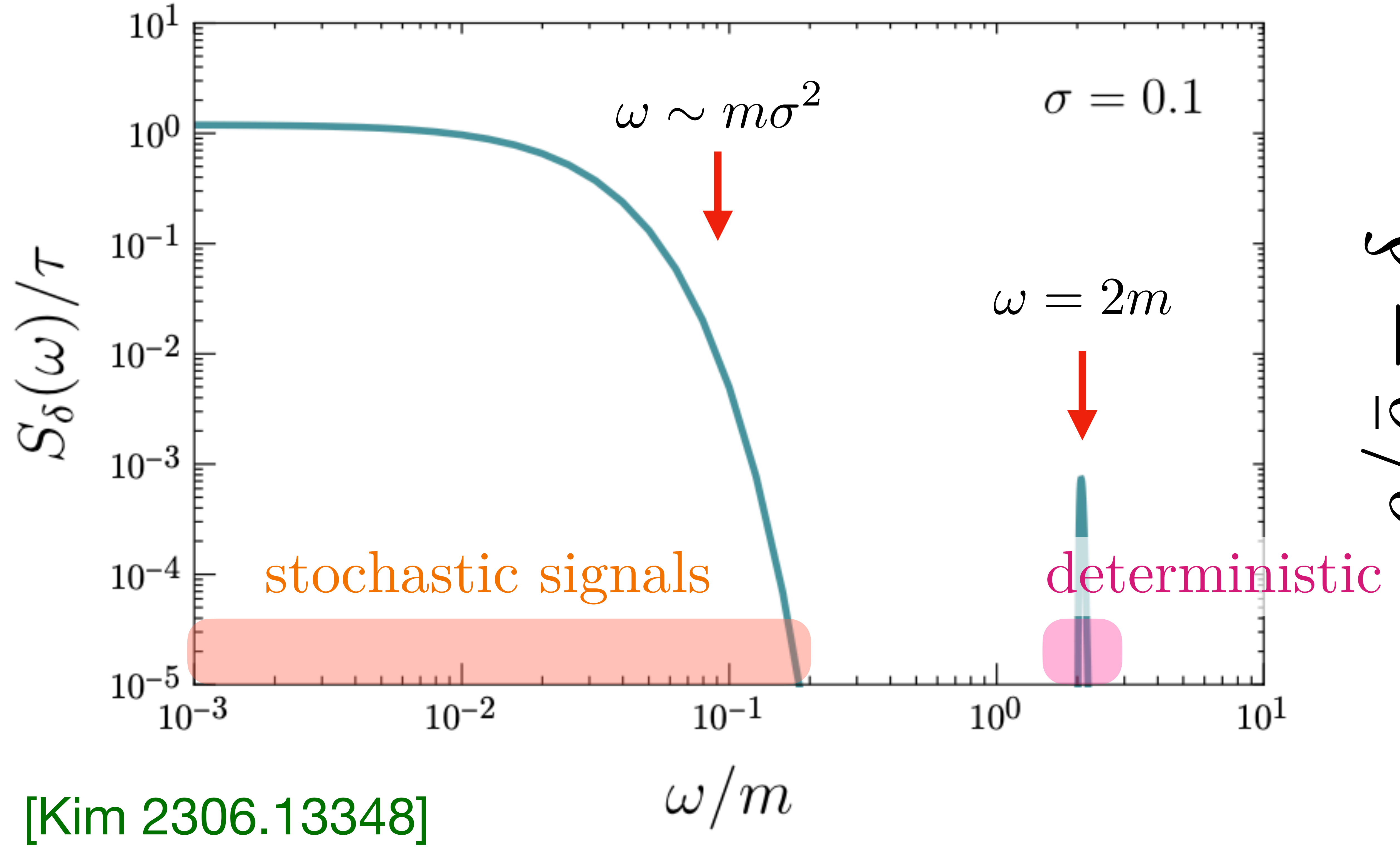

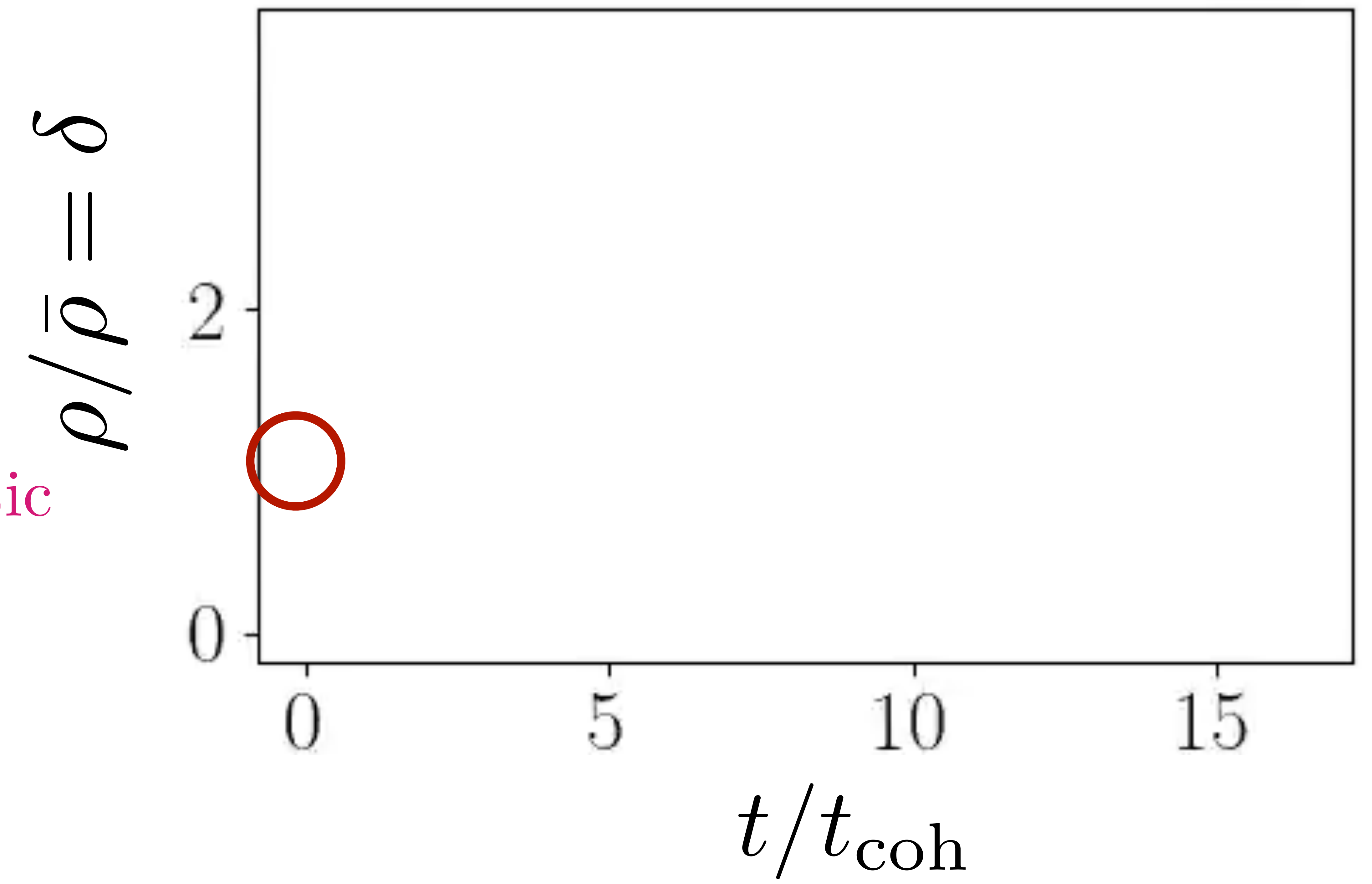

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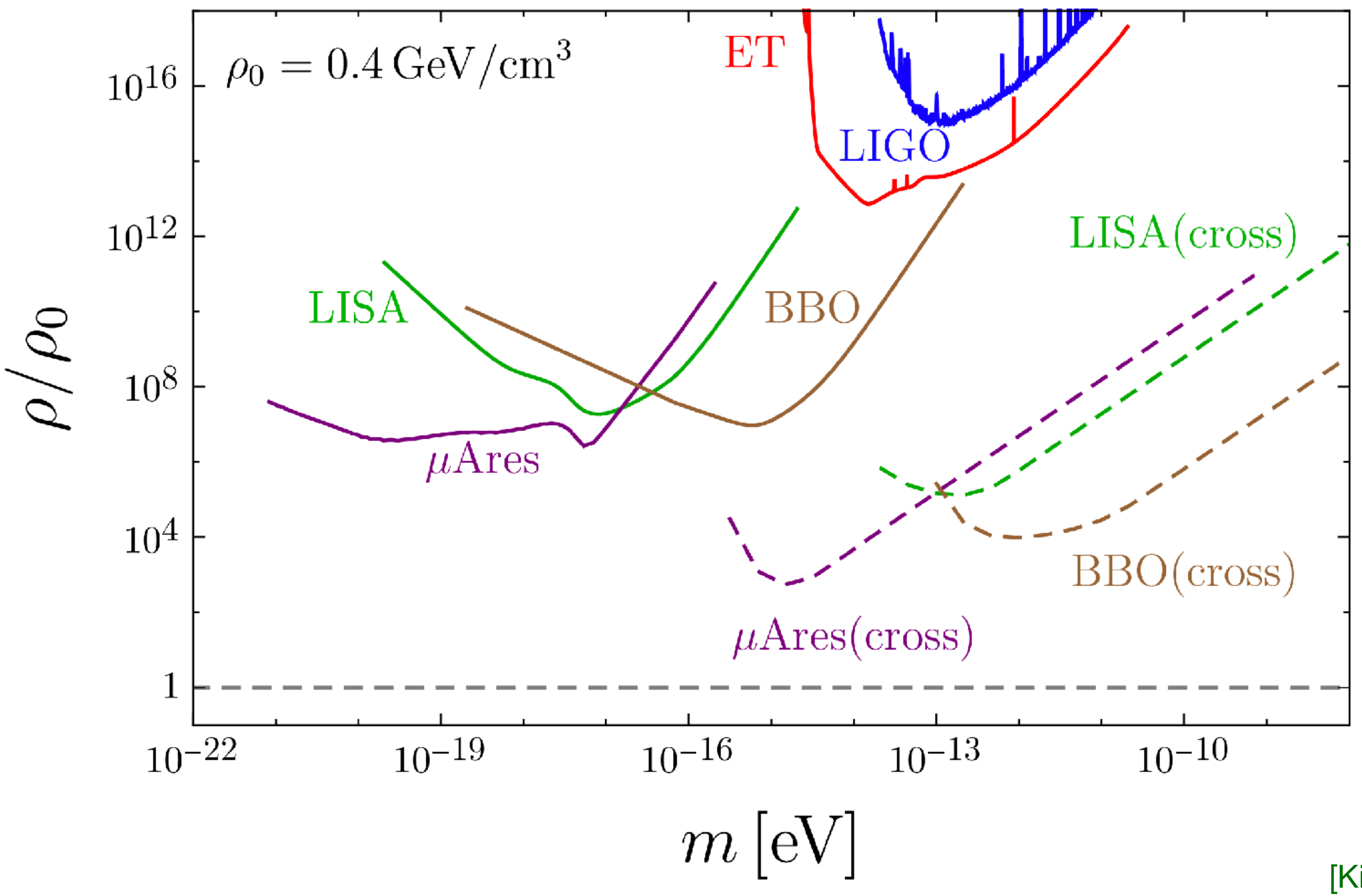
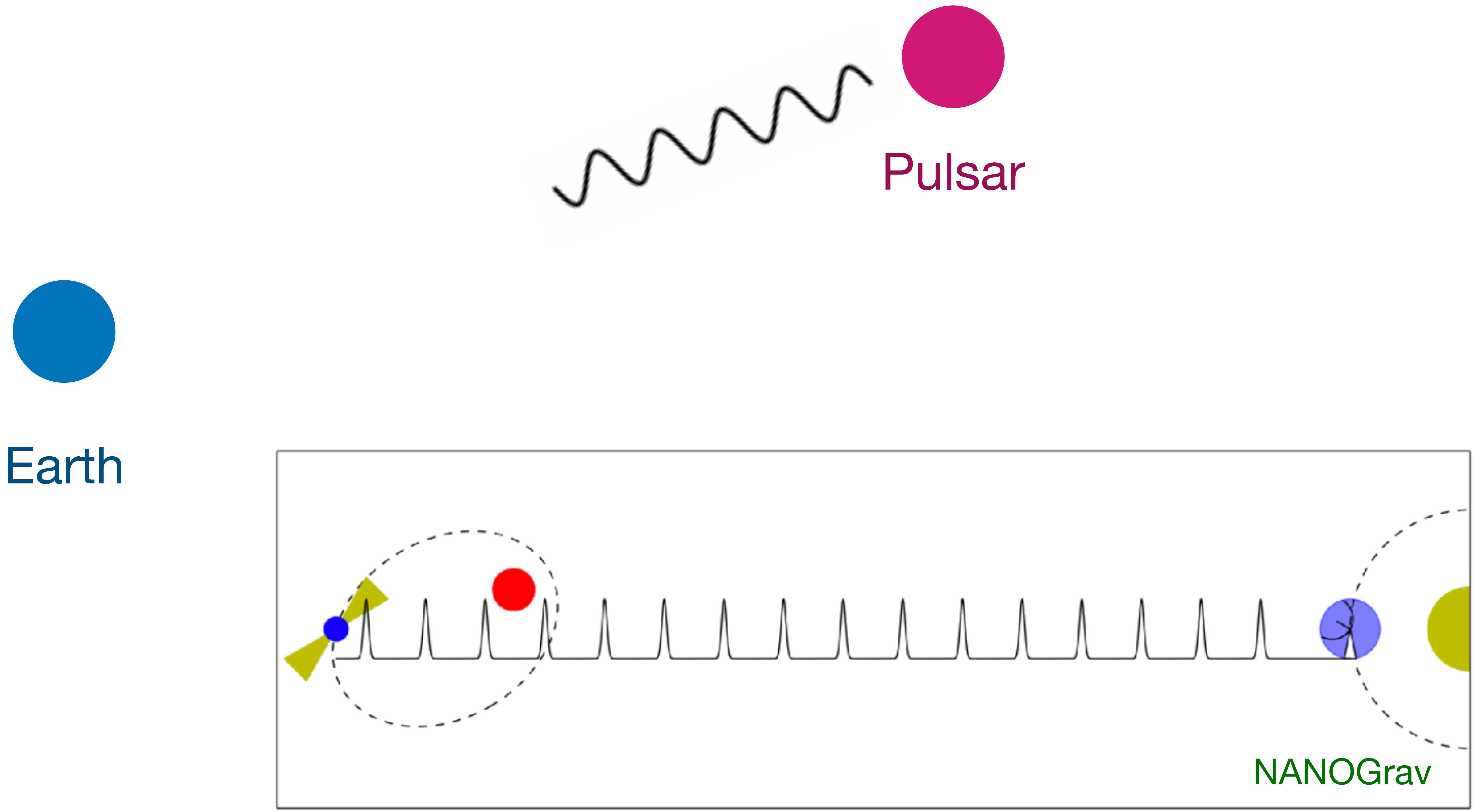
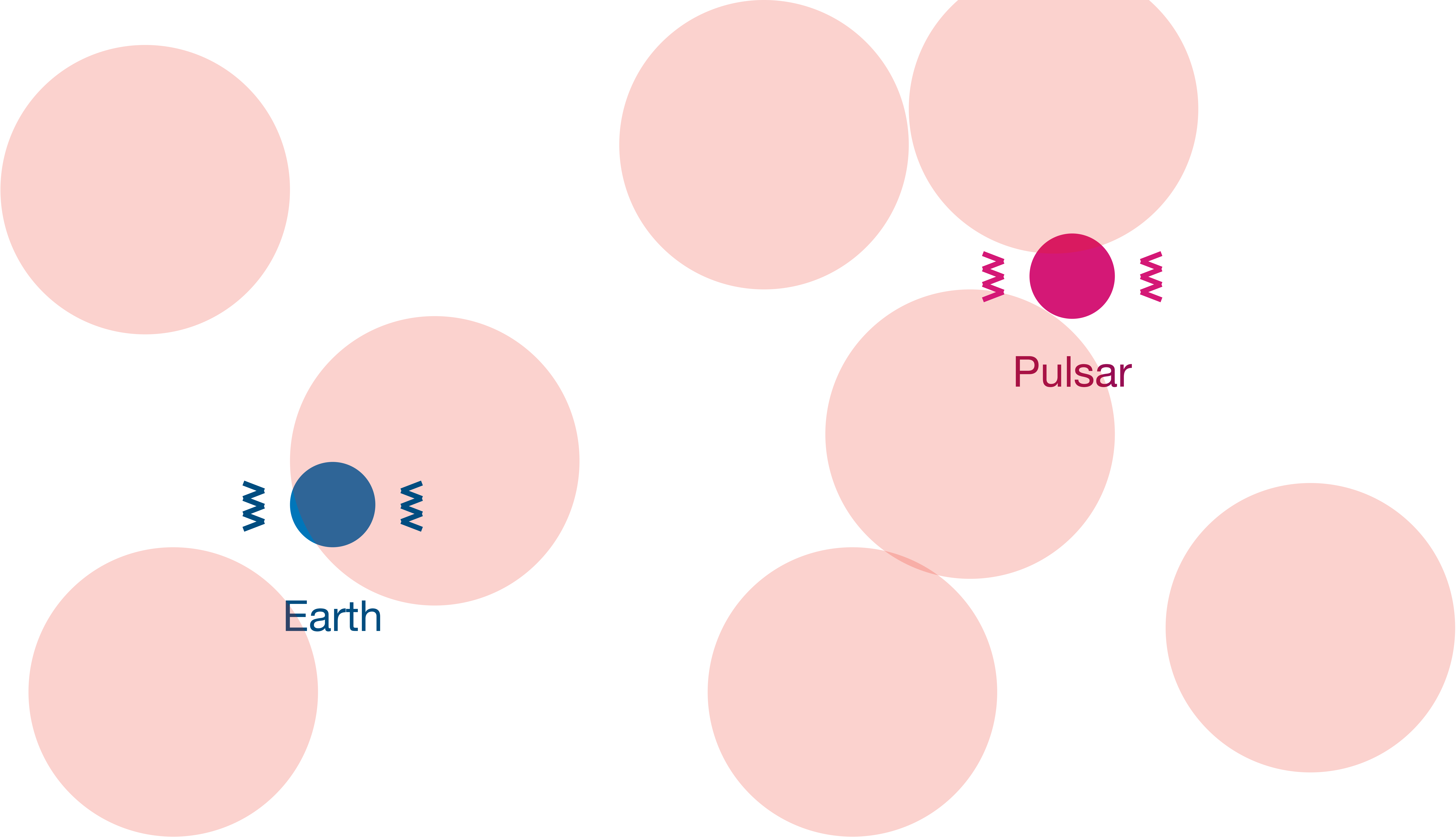


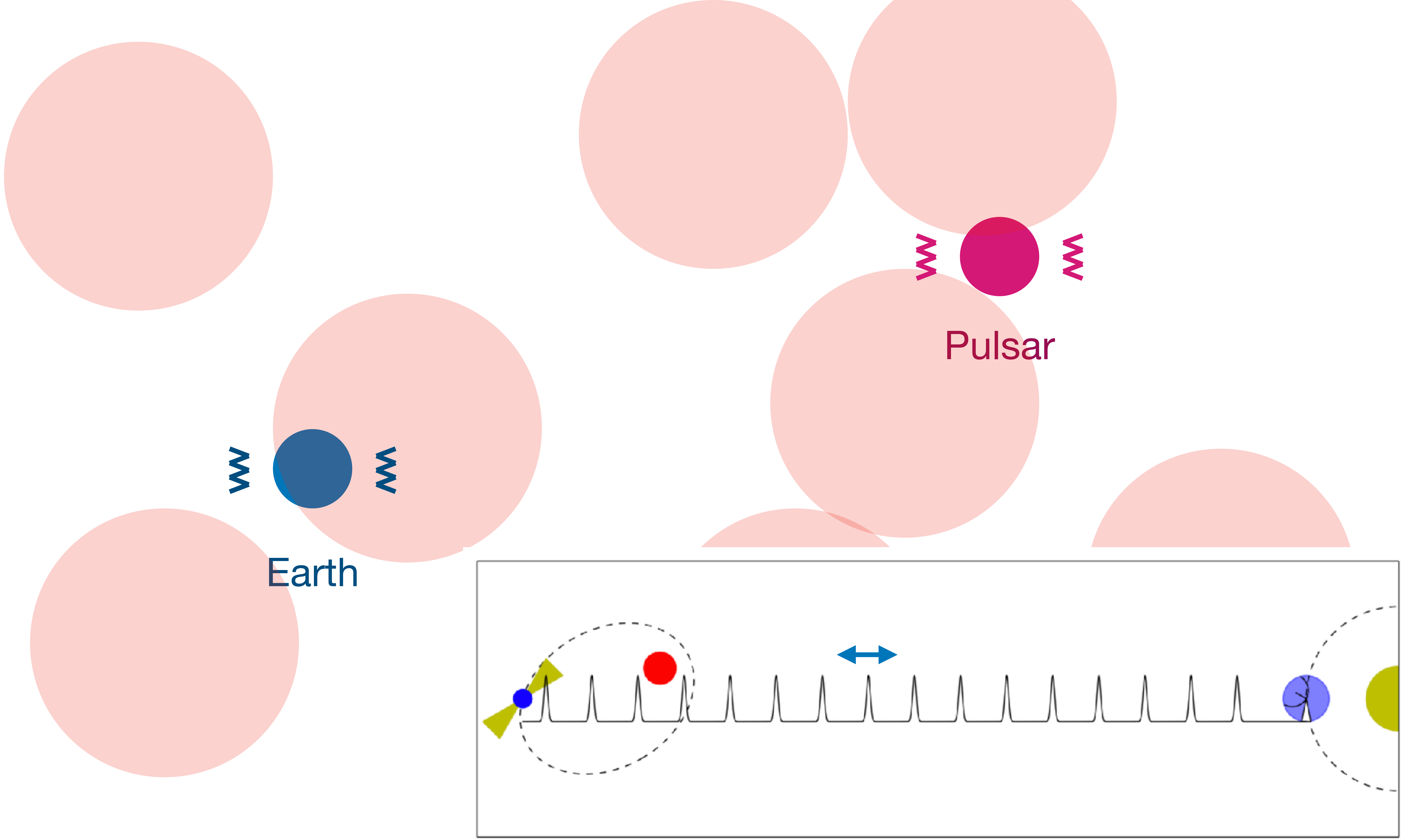
[Kim 2306.13348]

one more example:

Pulsar Timing Array


Pulsar
Earth
NANOGrav


Pulsar
Earth


Pulsar
Earth

to fully explore the capacity of PTA for ULDM searches
following questions need to be addressed

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

to fully explore the capacity of PTA for ULDM searches
following questions need to be addressed

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

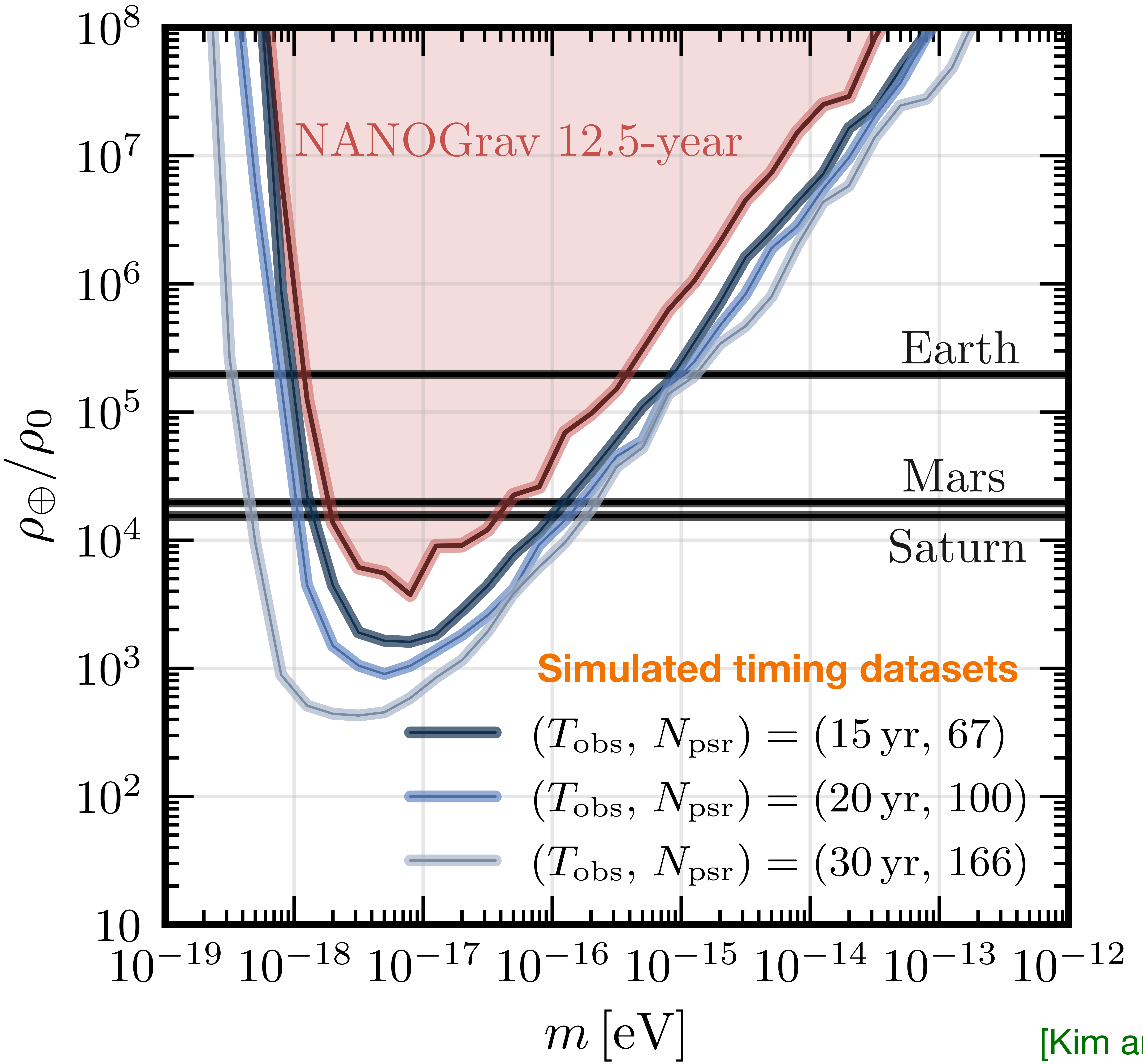
*what's the **spectrum**?*

to fully explore the capacity of PTA for ULDM searches
following questions need to be addressed

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

*what's the **spectrum**?*

*what is the **correlation** of timing residual?*



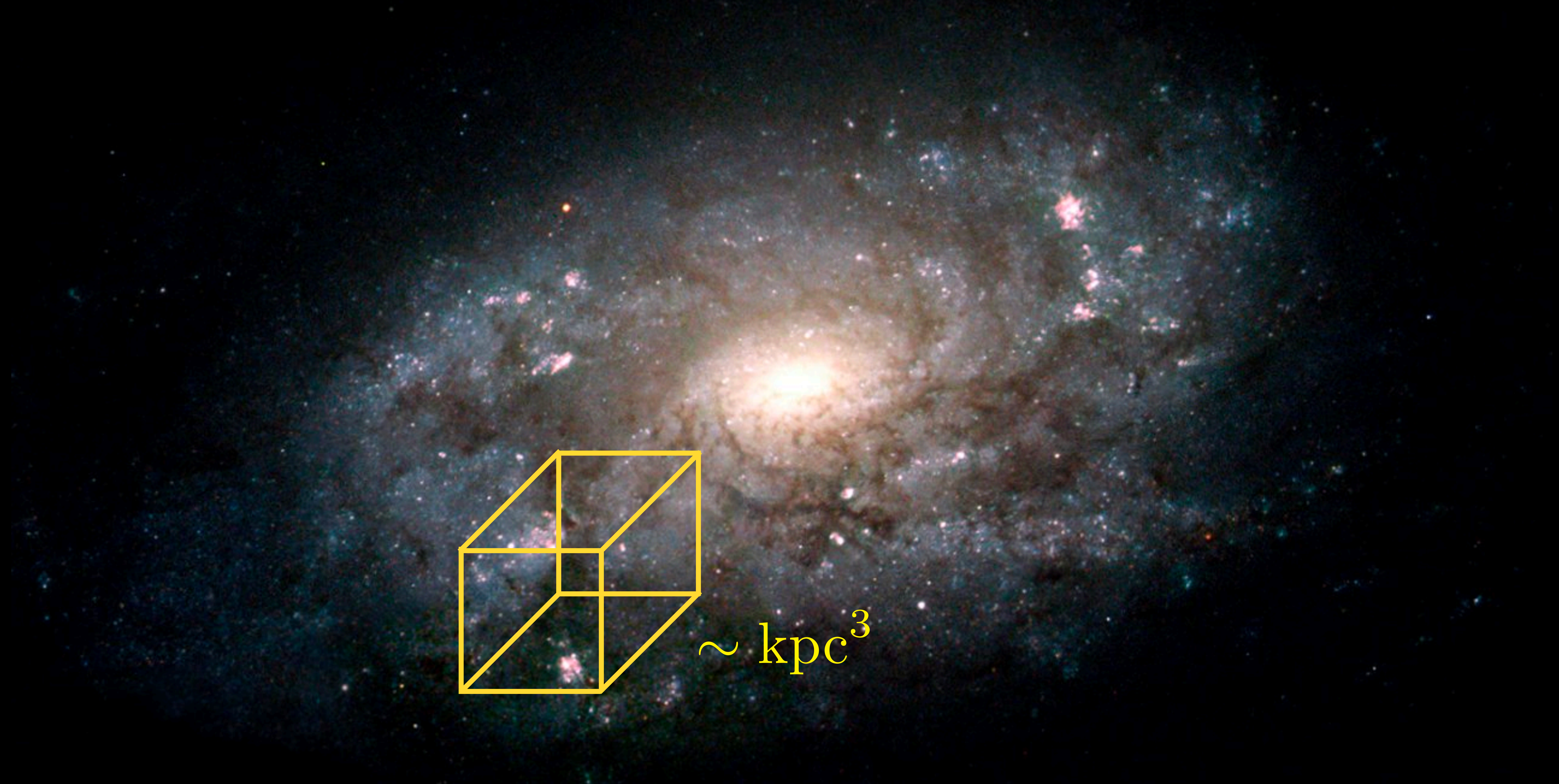
[Kim and Mitridate 2312.12225]

Remark I

all of the results shown here are sensitive to

ULDM density around/within the solar system

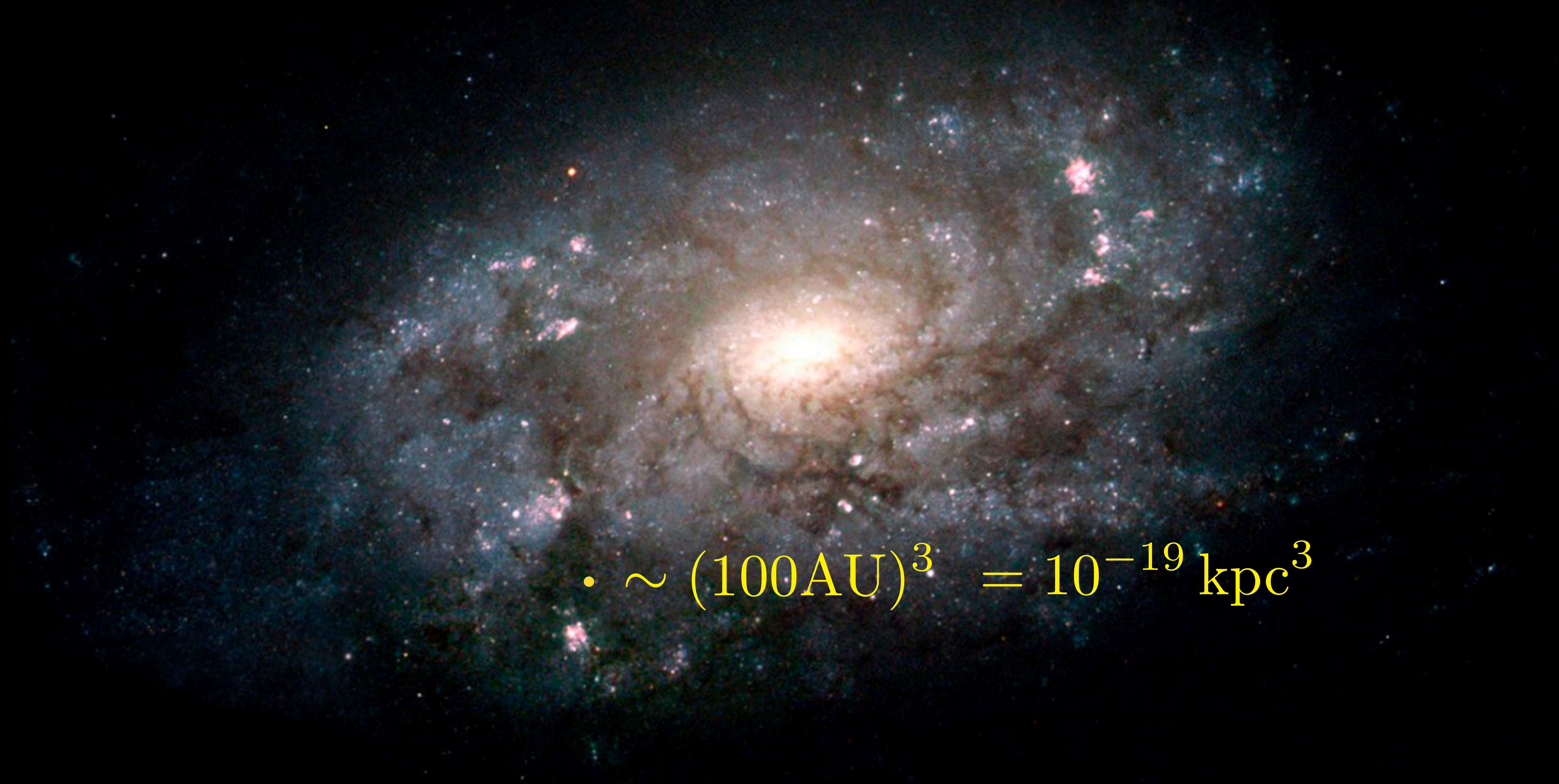
local dark matter density is often derived over kpc scales



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

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

only constraints exist

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

From geodetic satellite and LLR [Adler (08)]

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)]

only constraints exist

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From asteroids in the solar system
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$$\rho/\rho_0 \lesssim 2 \times 10^{4}$$

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

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

Remark II

PTA might reach to a factor few times local DM density
in next decades

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

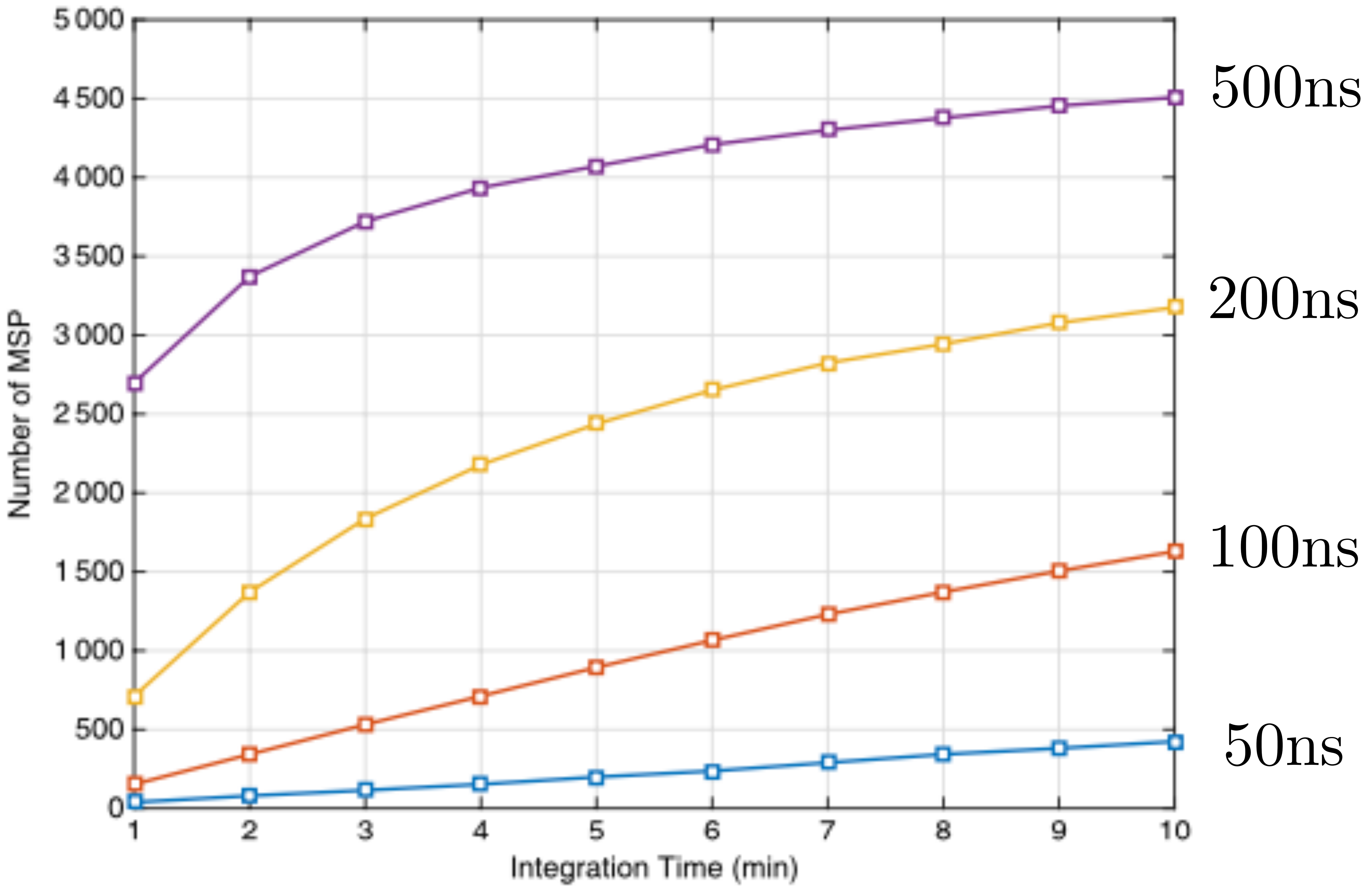

Figure 10. Numbers of MSPs that can archive a certain RMS noise level (or better) with varying integration time. Colour lines indicate different RMS noise levels (from bottom to top): 50 ns (blue), 100 ns (red), 200 ns (yellow), and 500 ns (purple).

[SKA, Weltman et al (20)]