

Gravitational Probes of Ultralight Dark Matter

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**What do we know about
Dark Matter Density
around the solar system?**

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

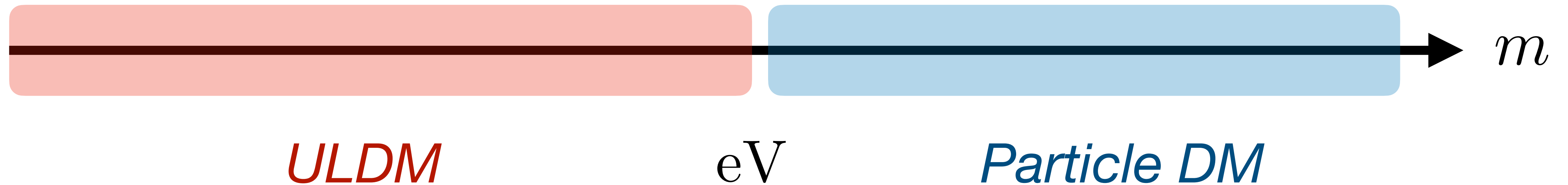
only over ***kpc-scale***

near the solar system

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

Ultralight Dark Matter

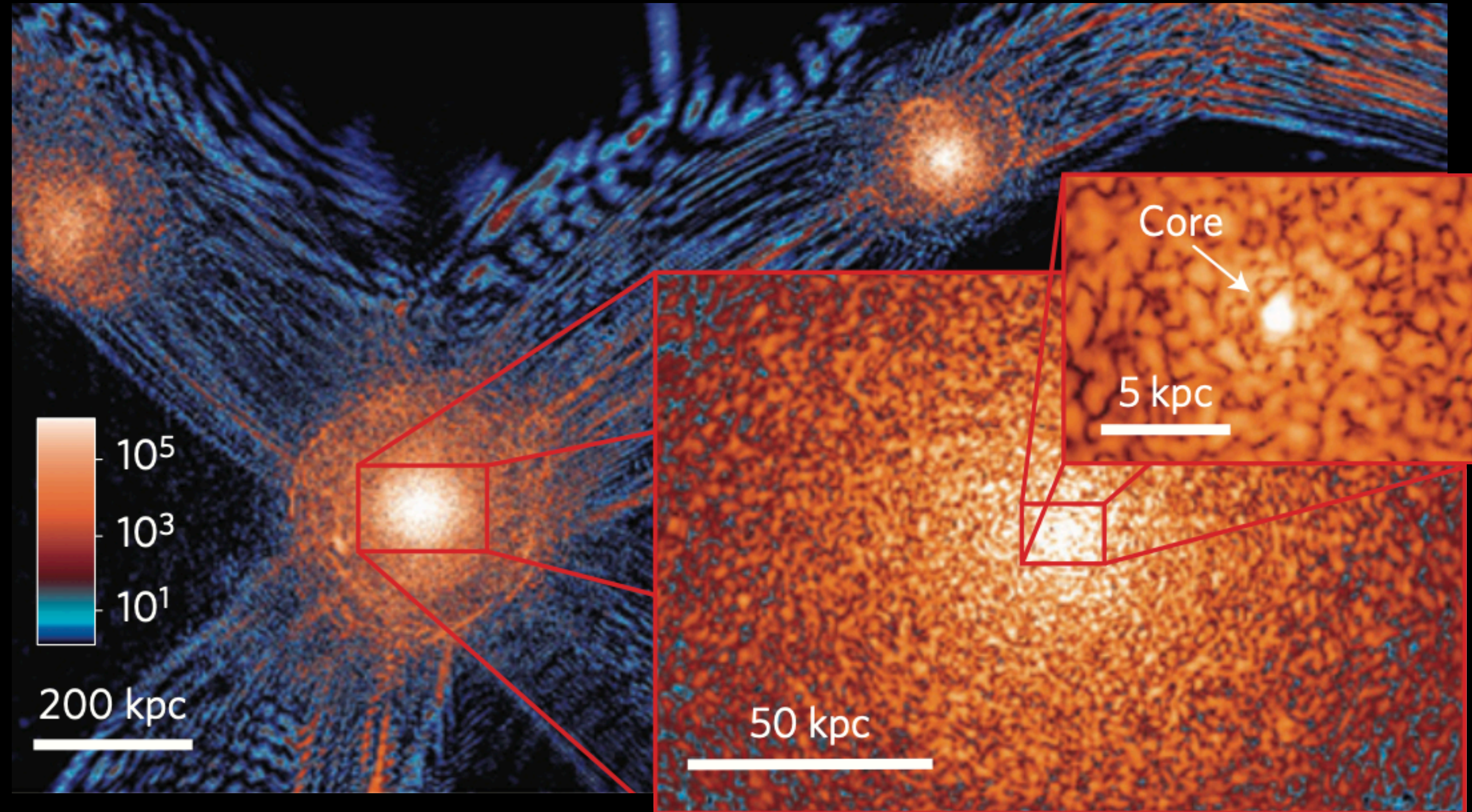
we define *ultralight dark matter (ULDM)*
as *bosonic DM candidates with* $m < \text{eV}$



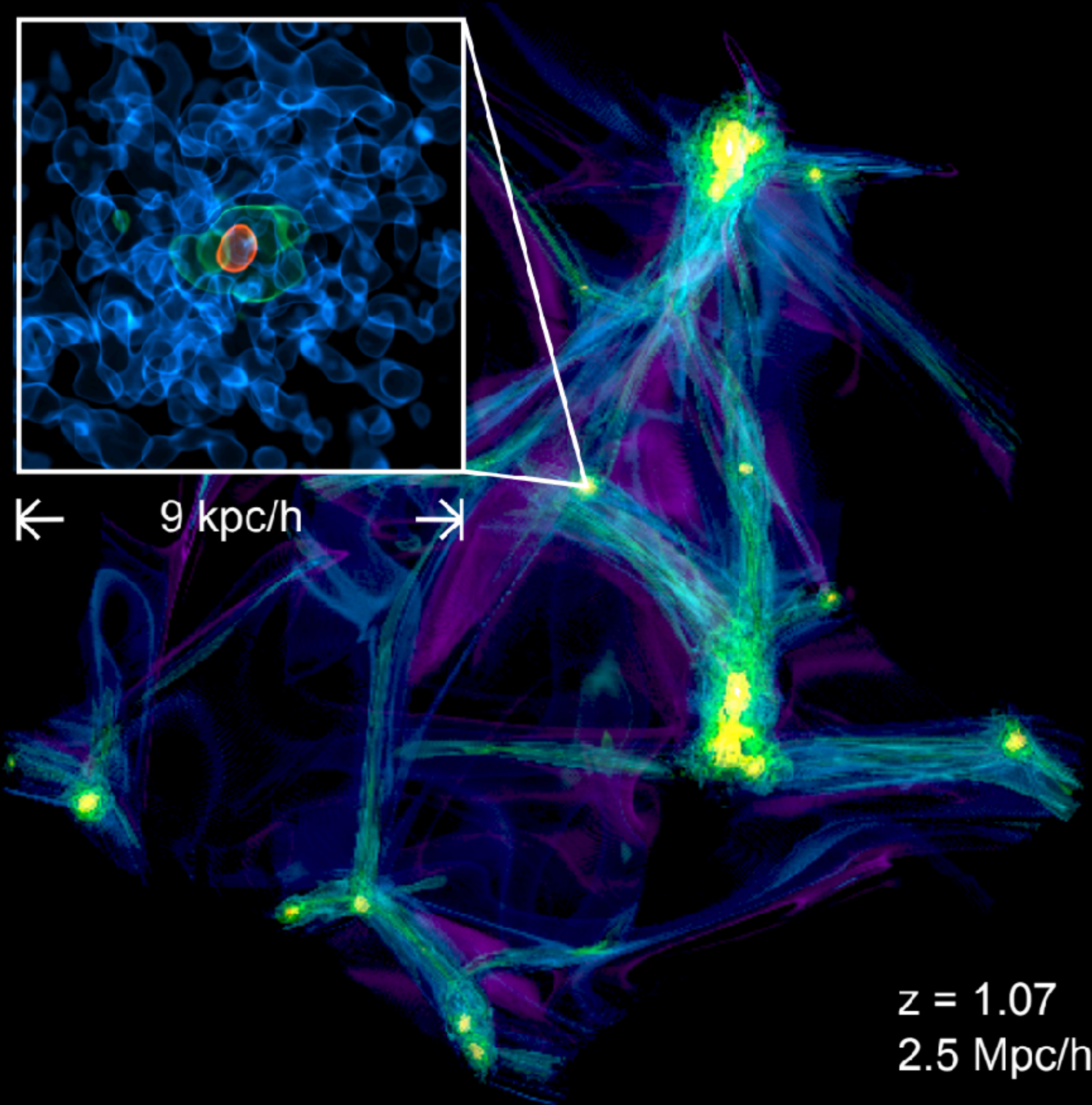
we define *ultralight dark matter (ULDM)*
as *bosonic DM candidates with* $m < \text{eV}$

$$m \lesssim 10 \text{ eV}$$

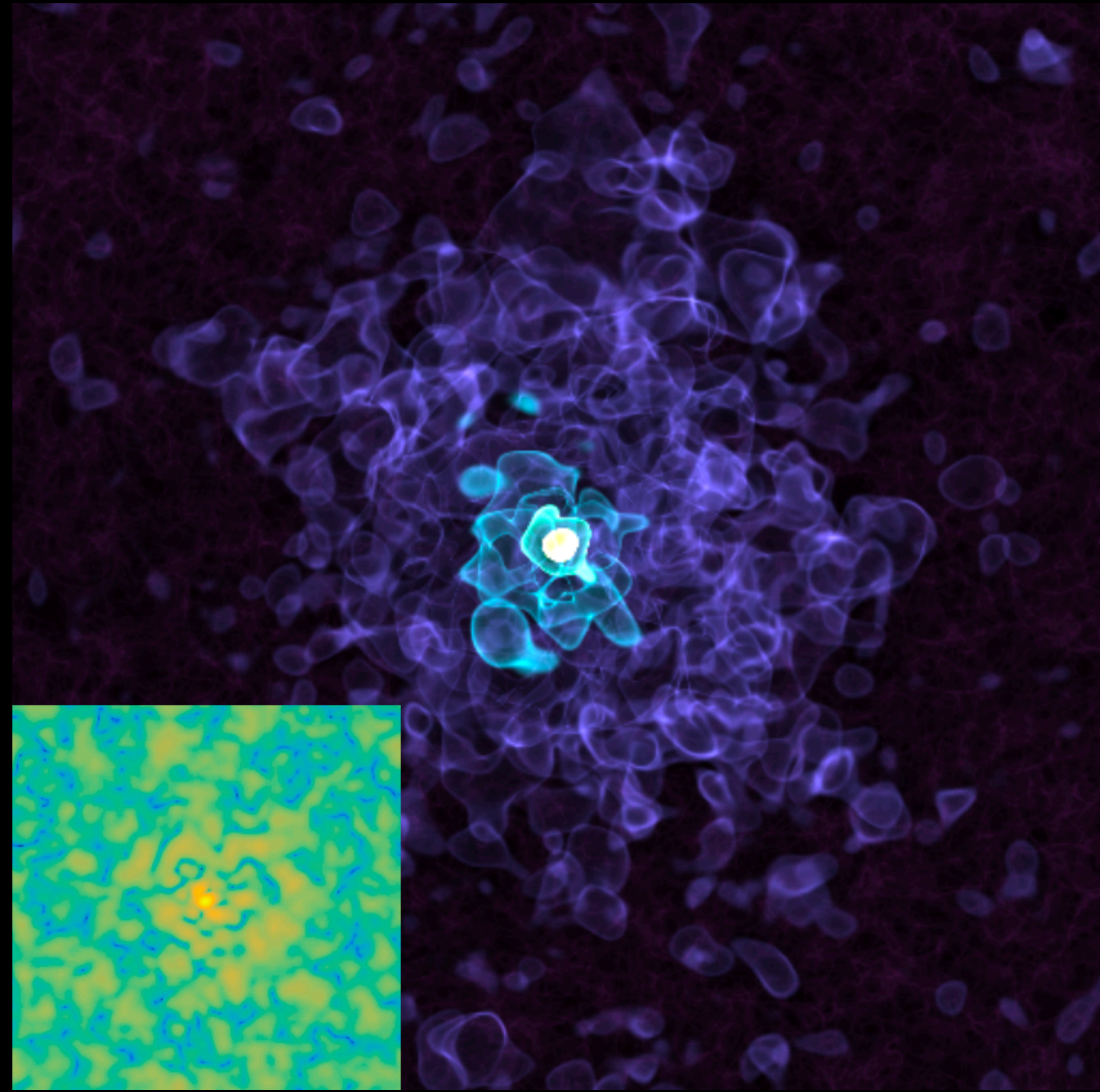




Mocz et al (17)



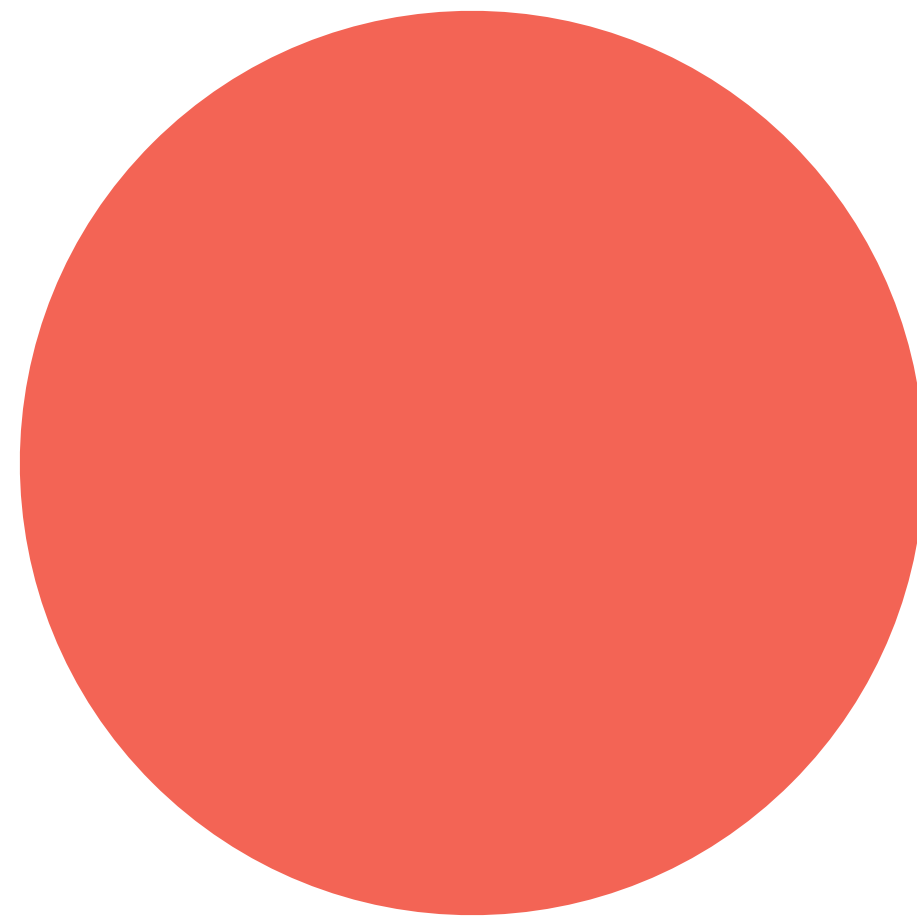
Veltmaat, Niemeyer, Schwabe (18)



An intuitive understanding of the granule structure:

Quasiparticle

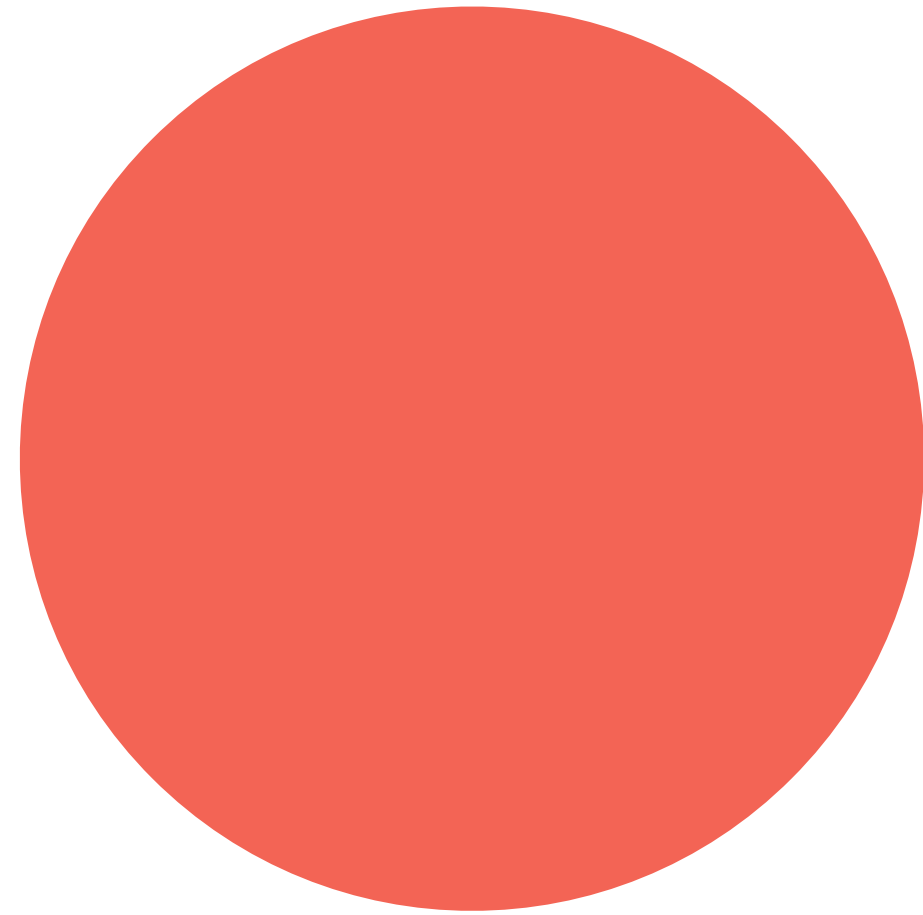
[Hui et al 17]



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

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

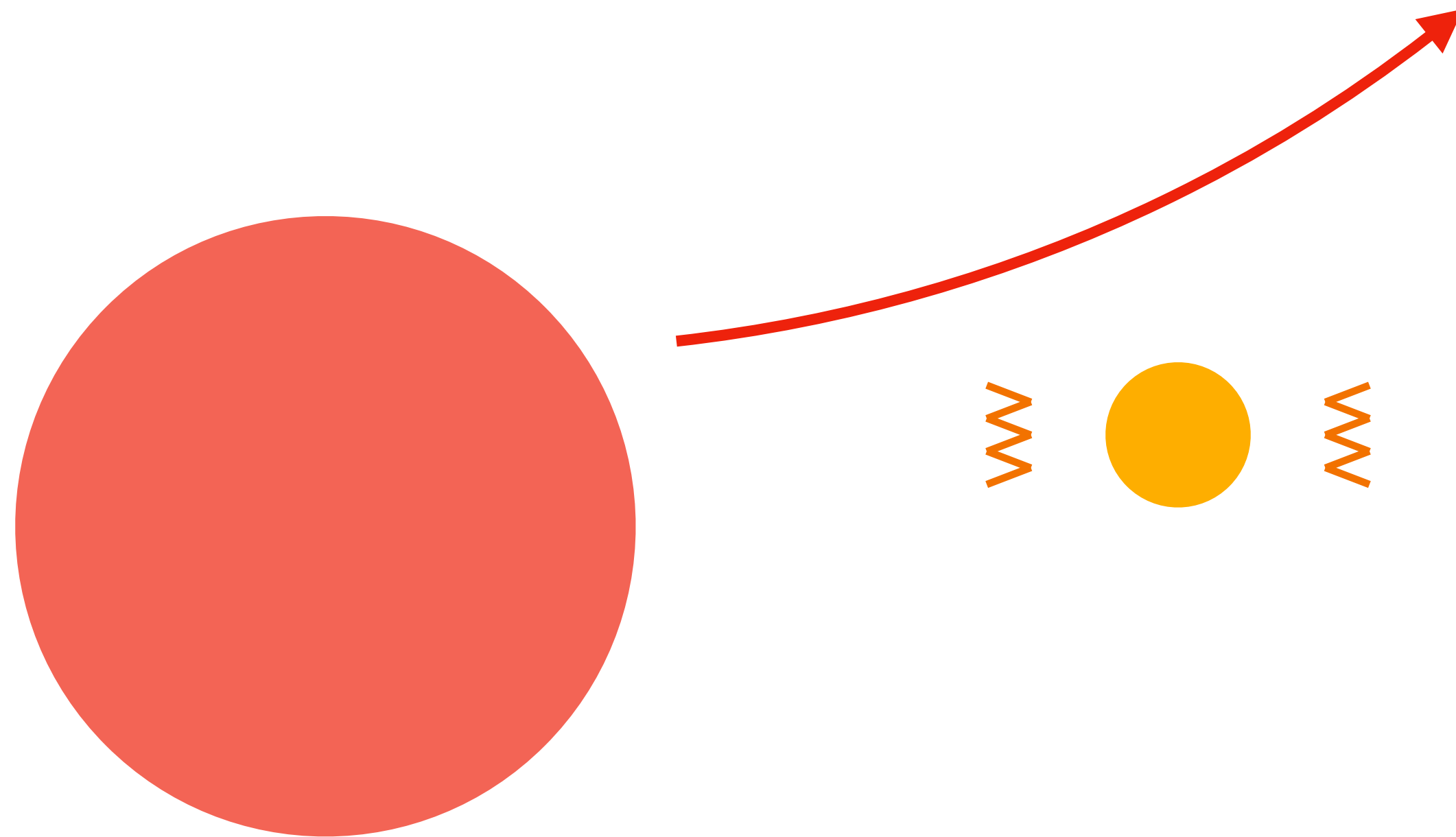
the size and mass of them could be astronomical



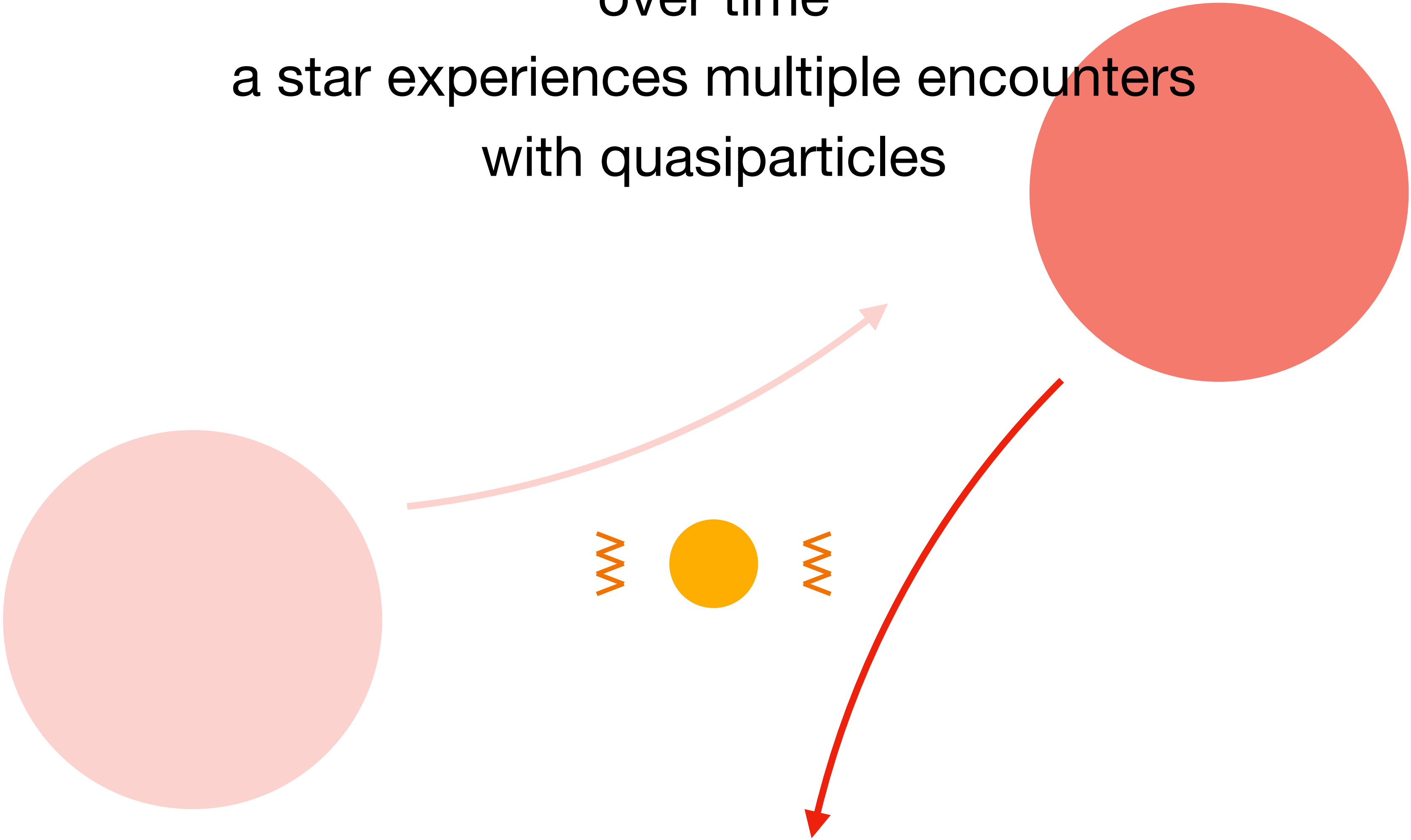
$$\ell \sim \lambda = \frac{1}{mv} \sim 10 \text{ AU} \times \left(\frac{10^{-16} \text{ eV}}{m} \right)$$

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

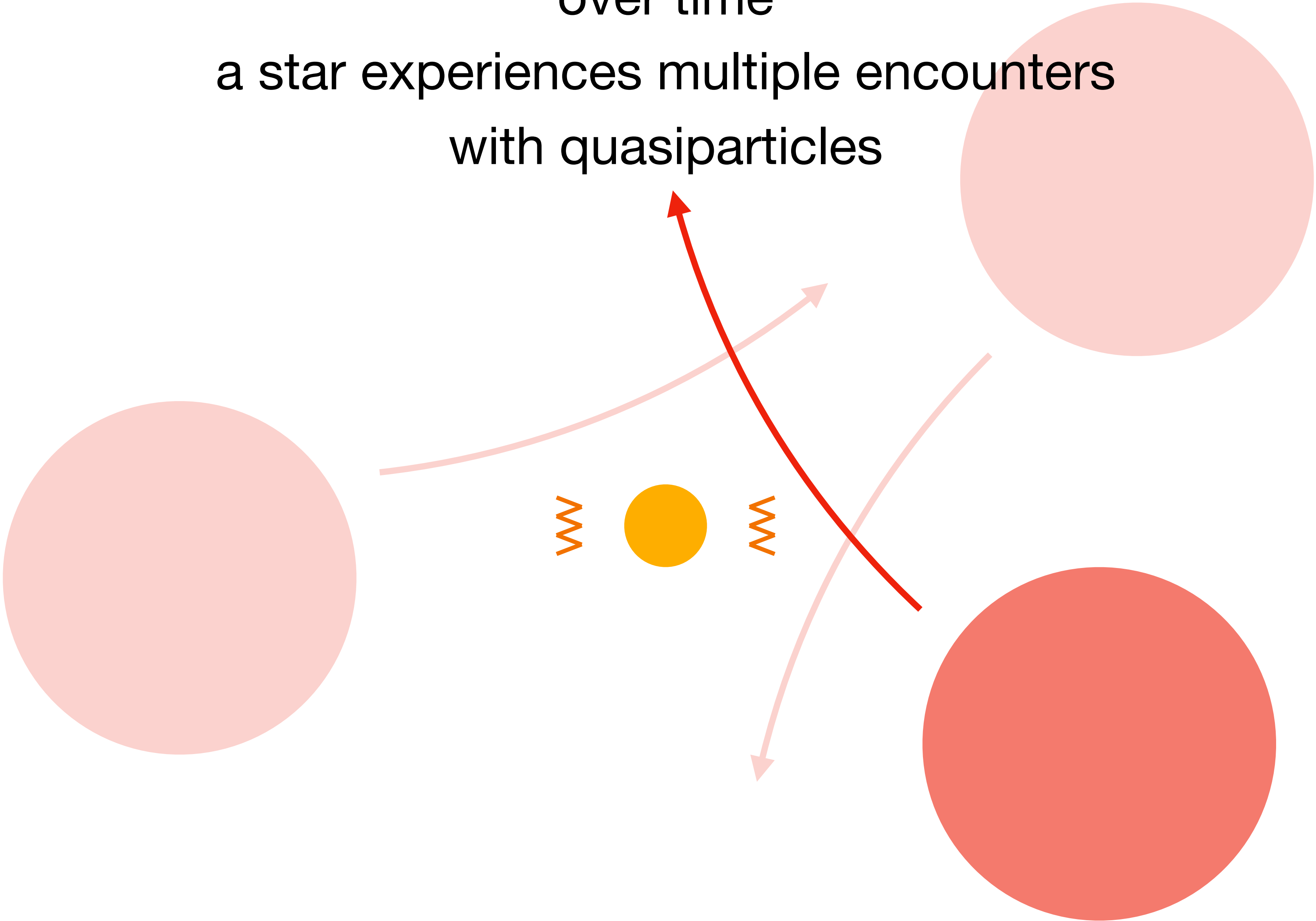
being that massive
it may engage in interaction with stars
and significantly perturb the motion of them



over time
a star experiences multiple encounters
with quasiparticles



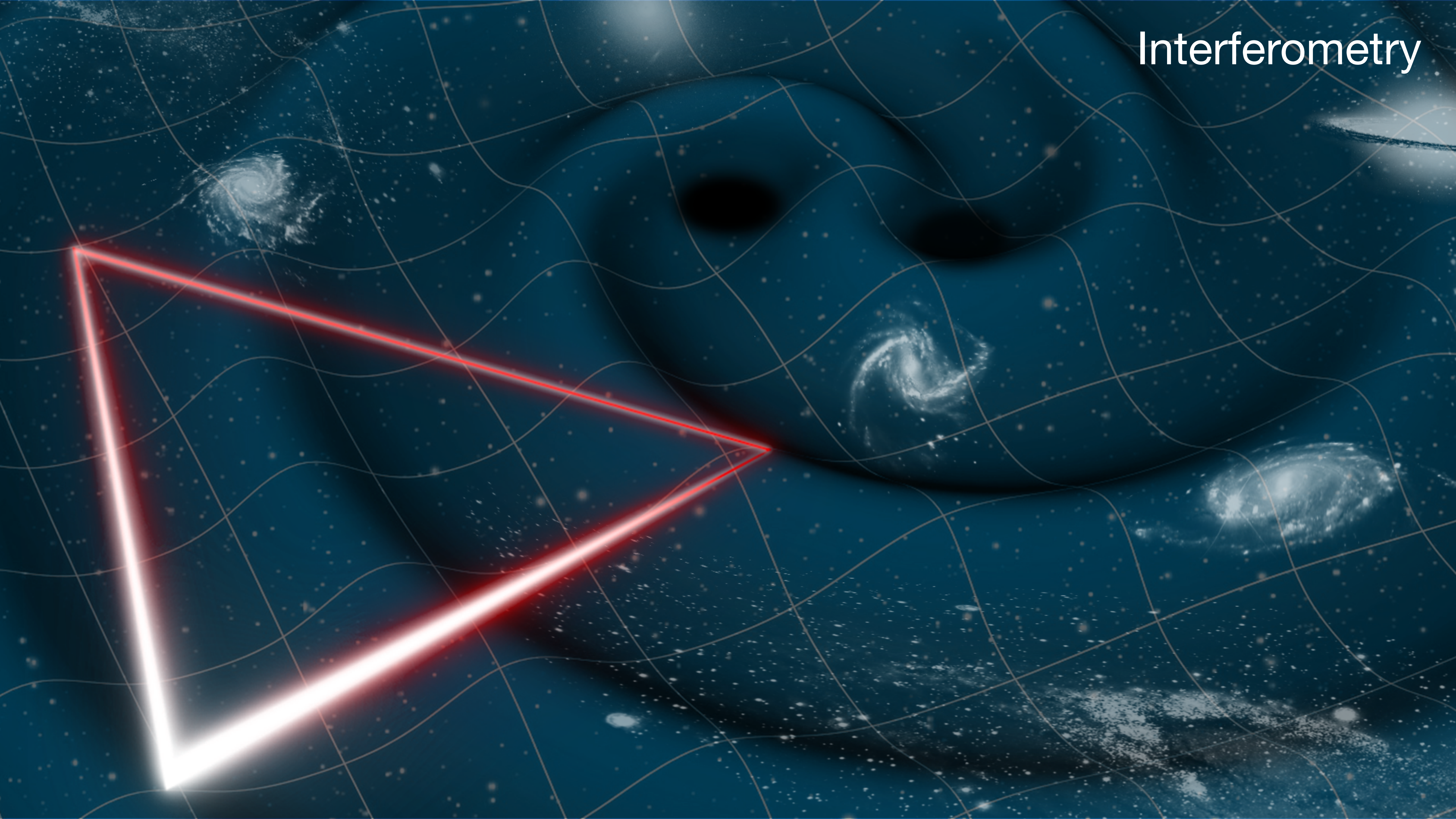
over time
a star experiences multiple encounters
with quasiparticles



so what?

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

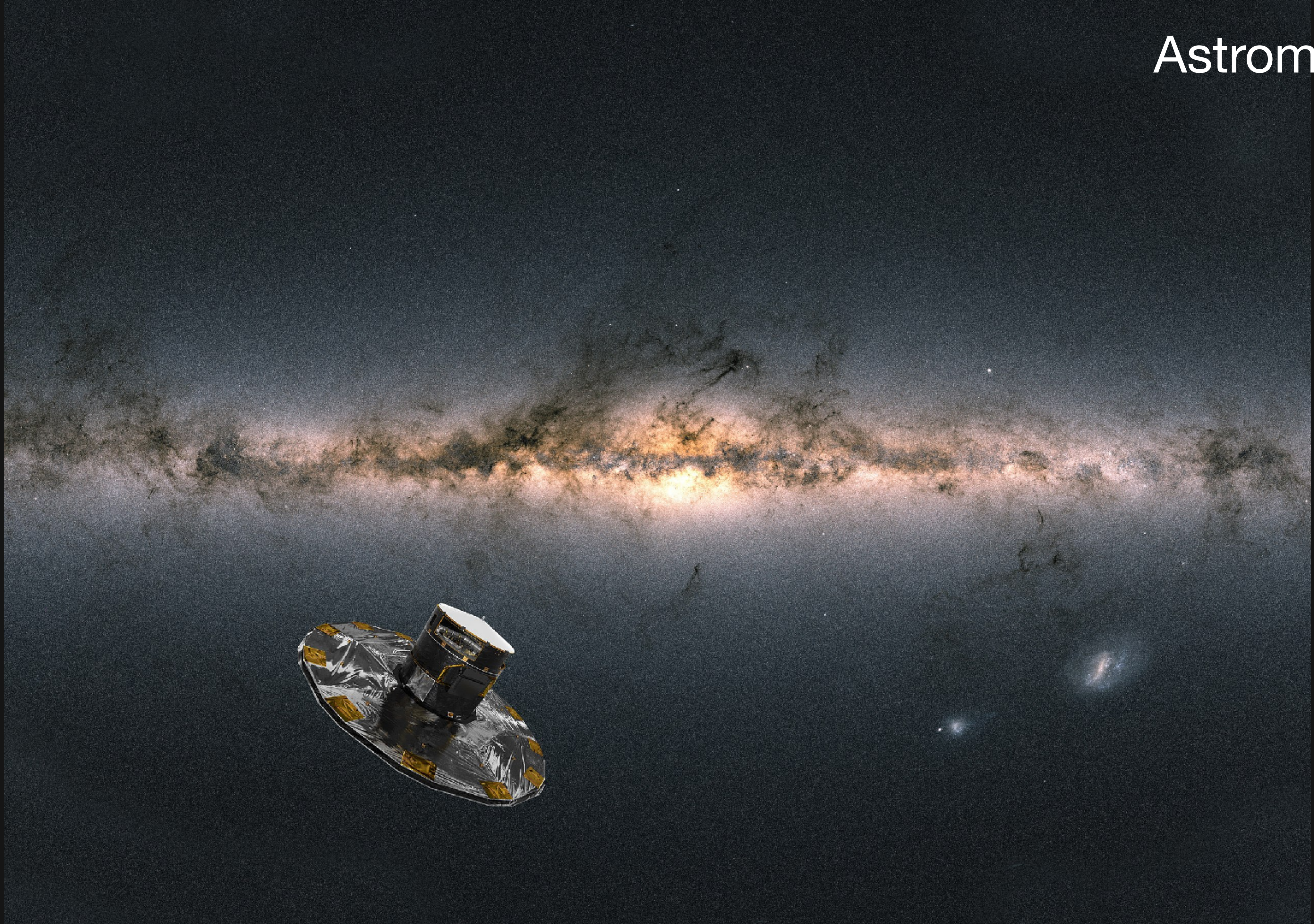
Interferometry



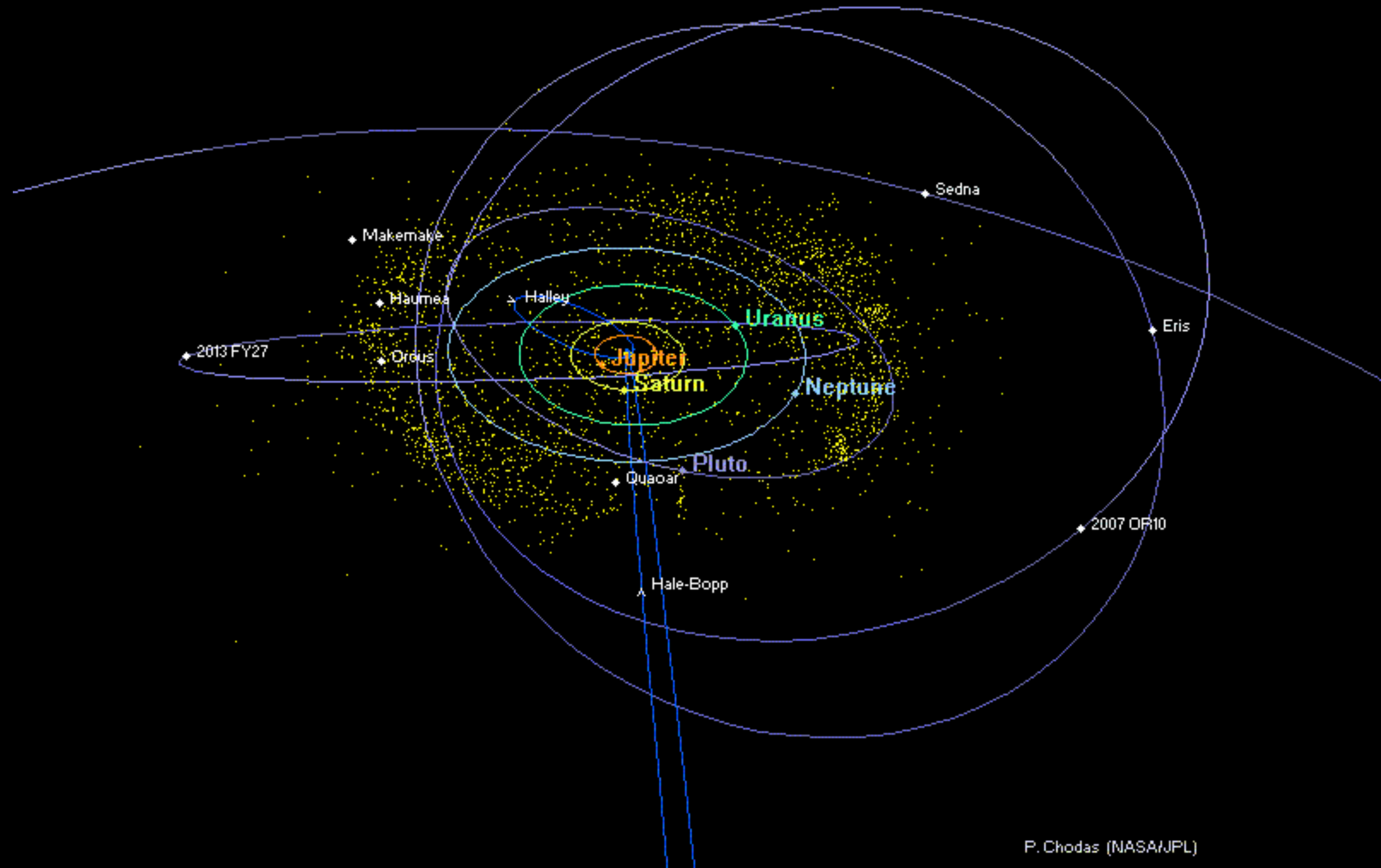
Pulsar Timing Array

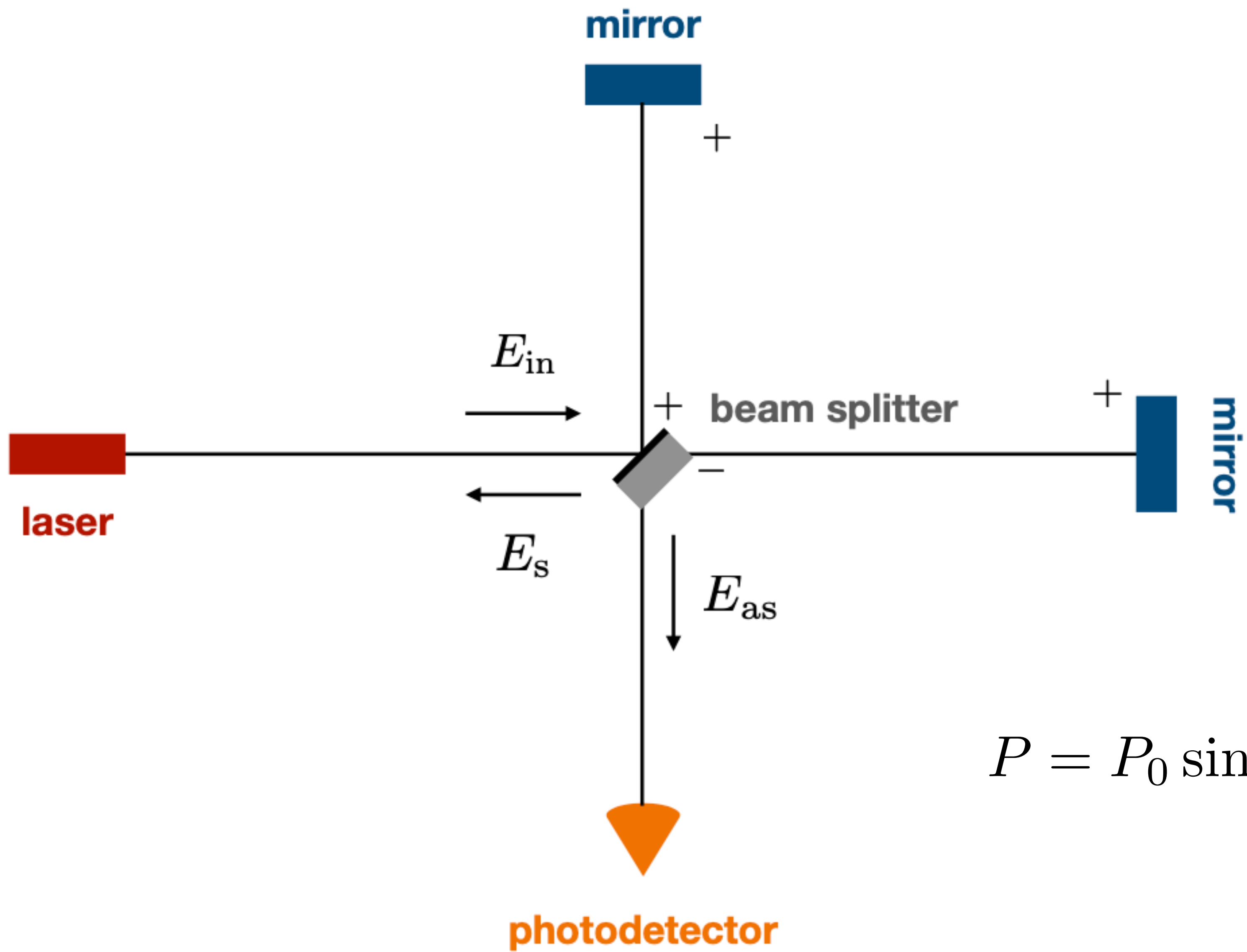


Astrometry



Solar system ephemerides



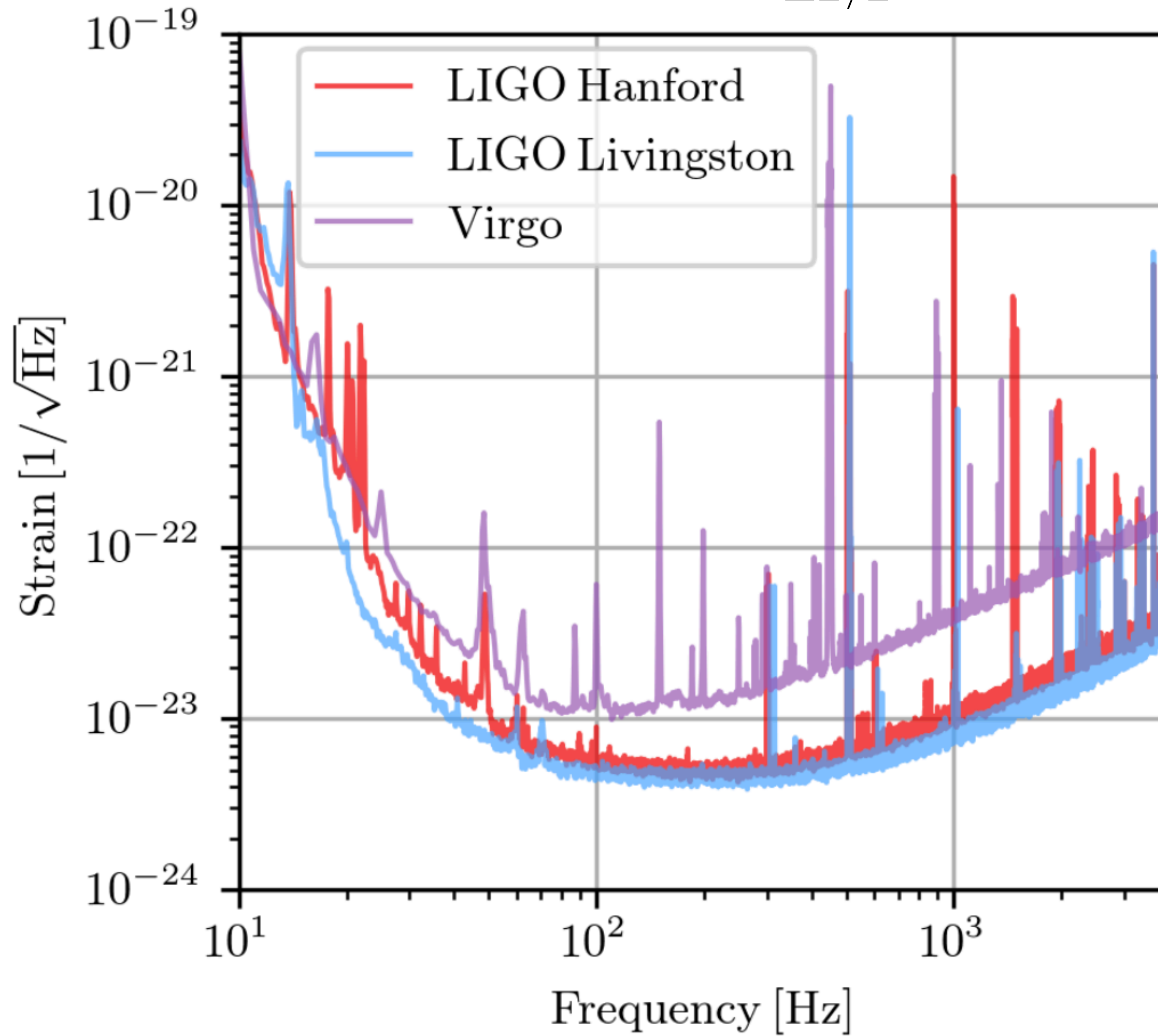


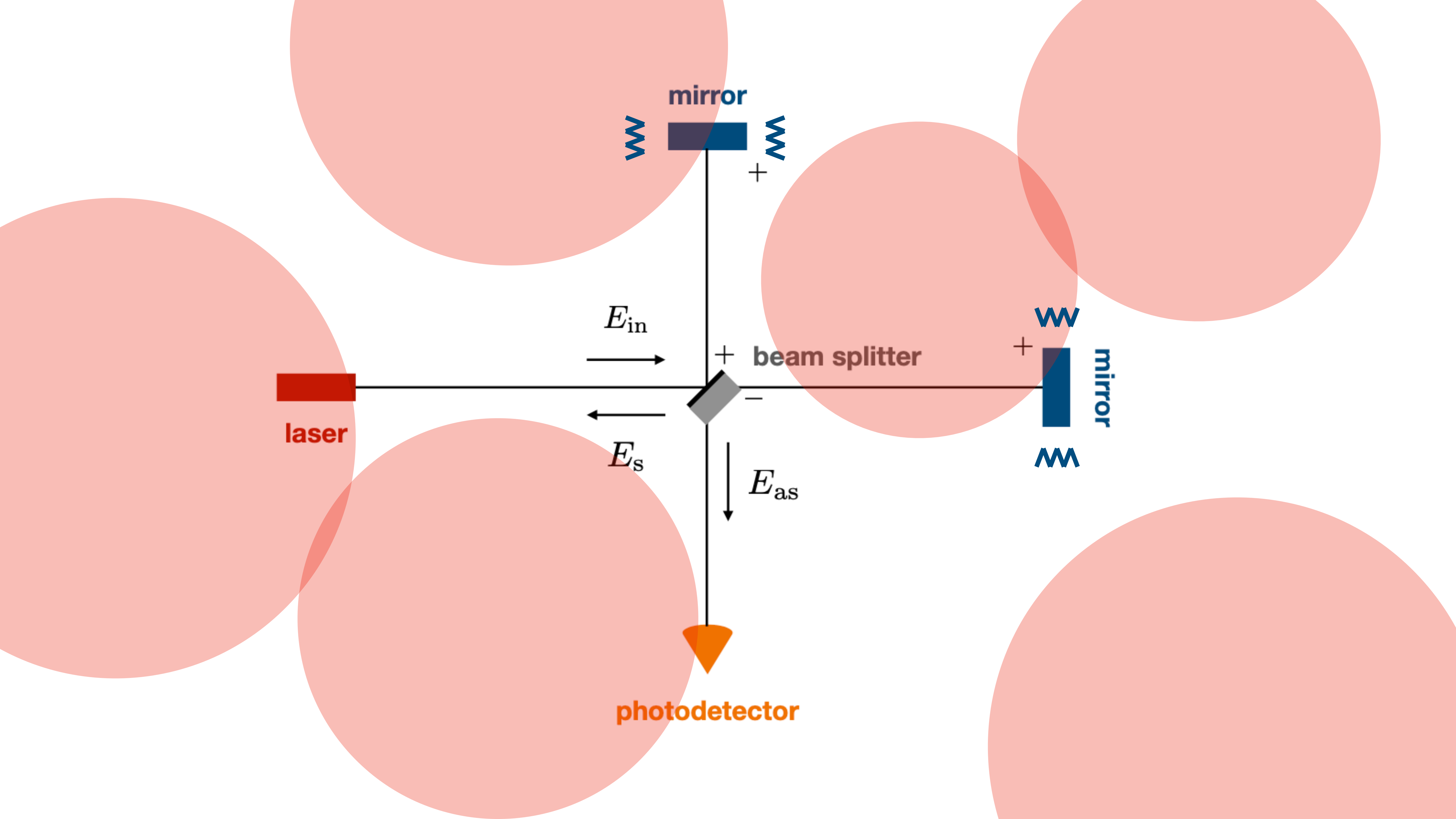
$$P = P_0 \sin^2(k\Delta L)$$



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

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





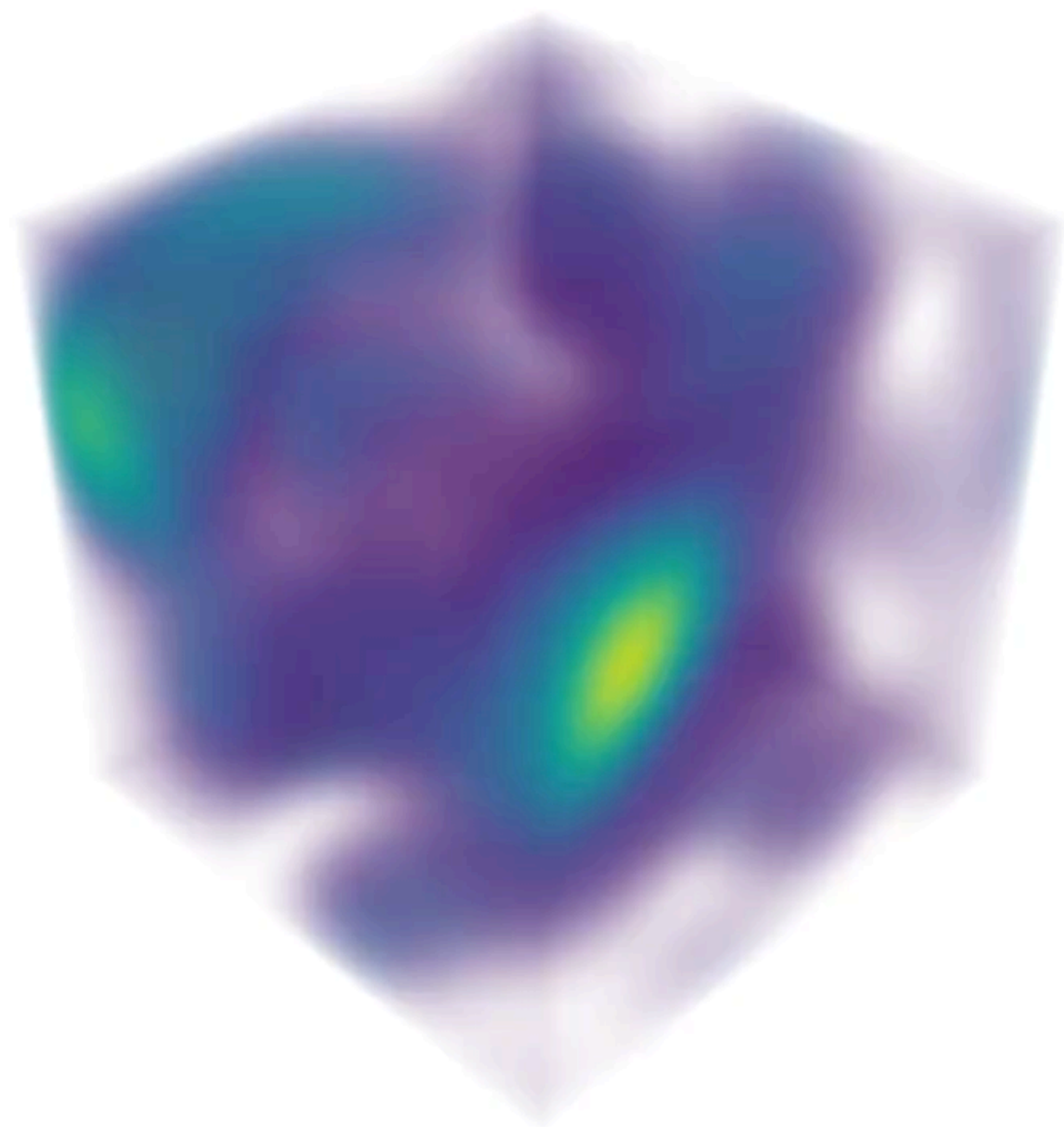
can we actually measure it?

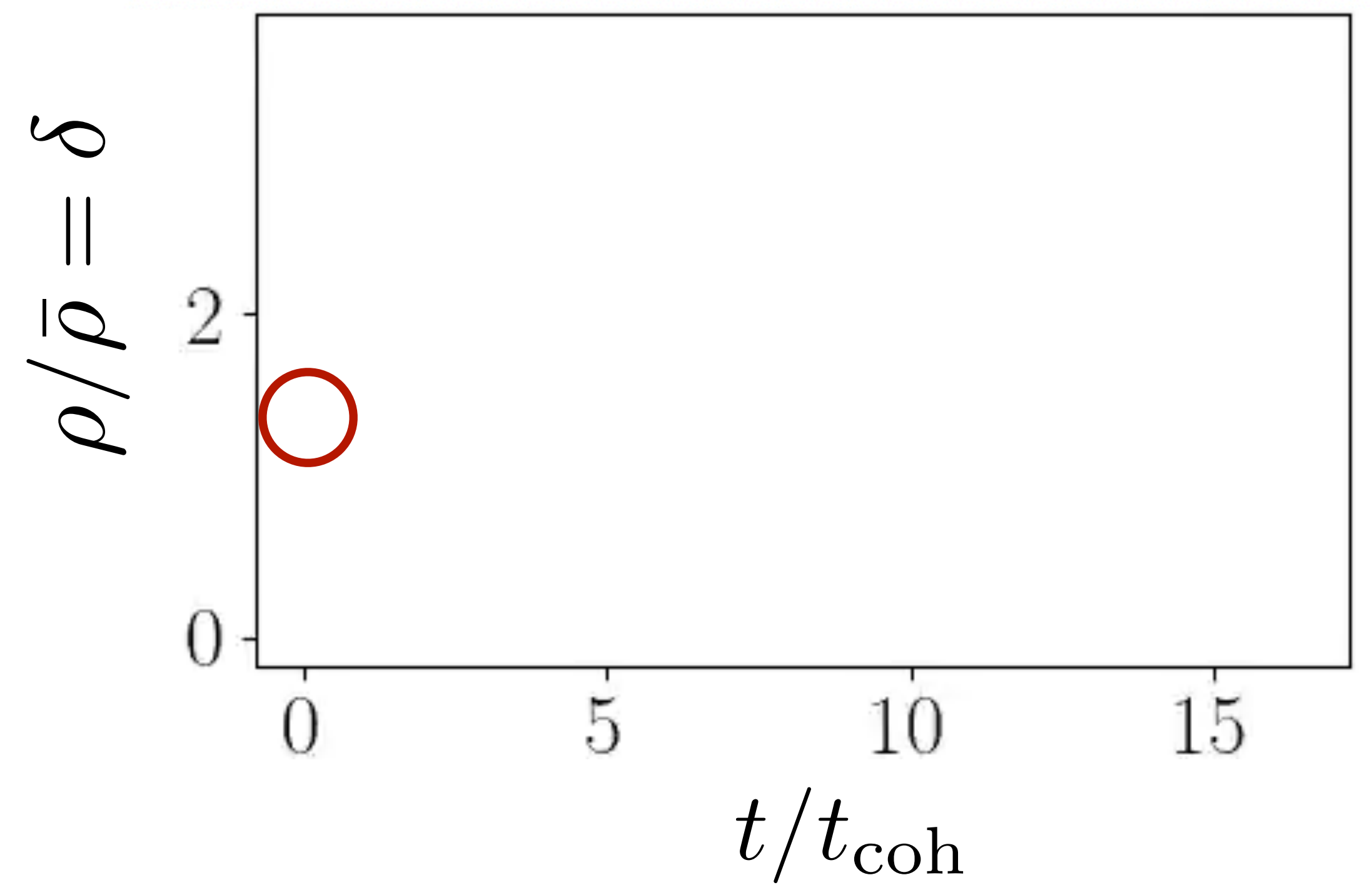
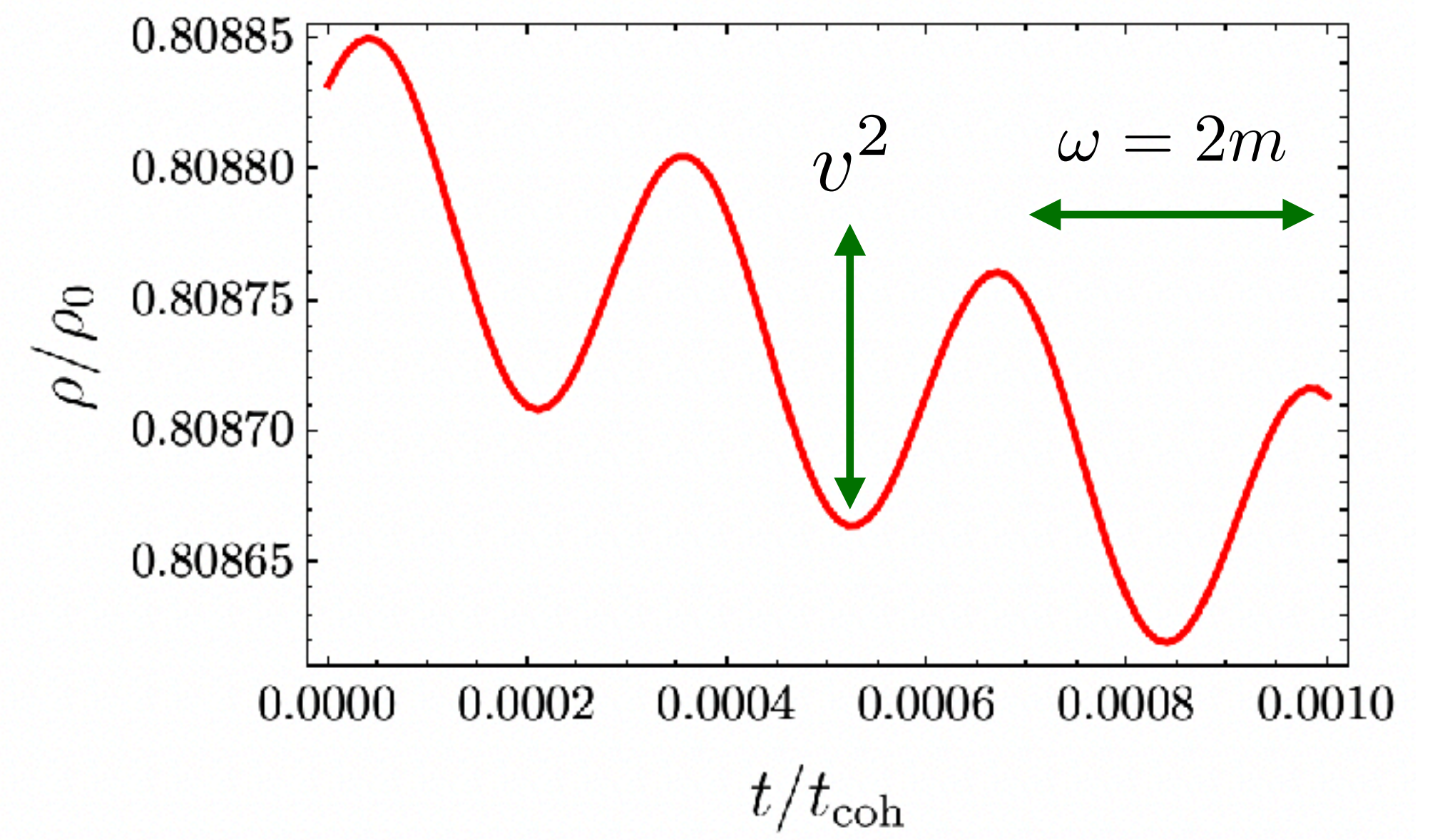
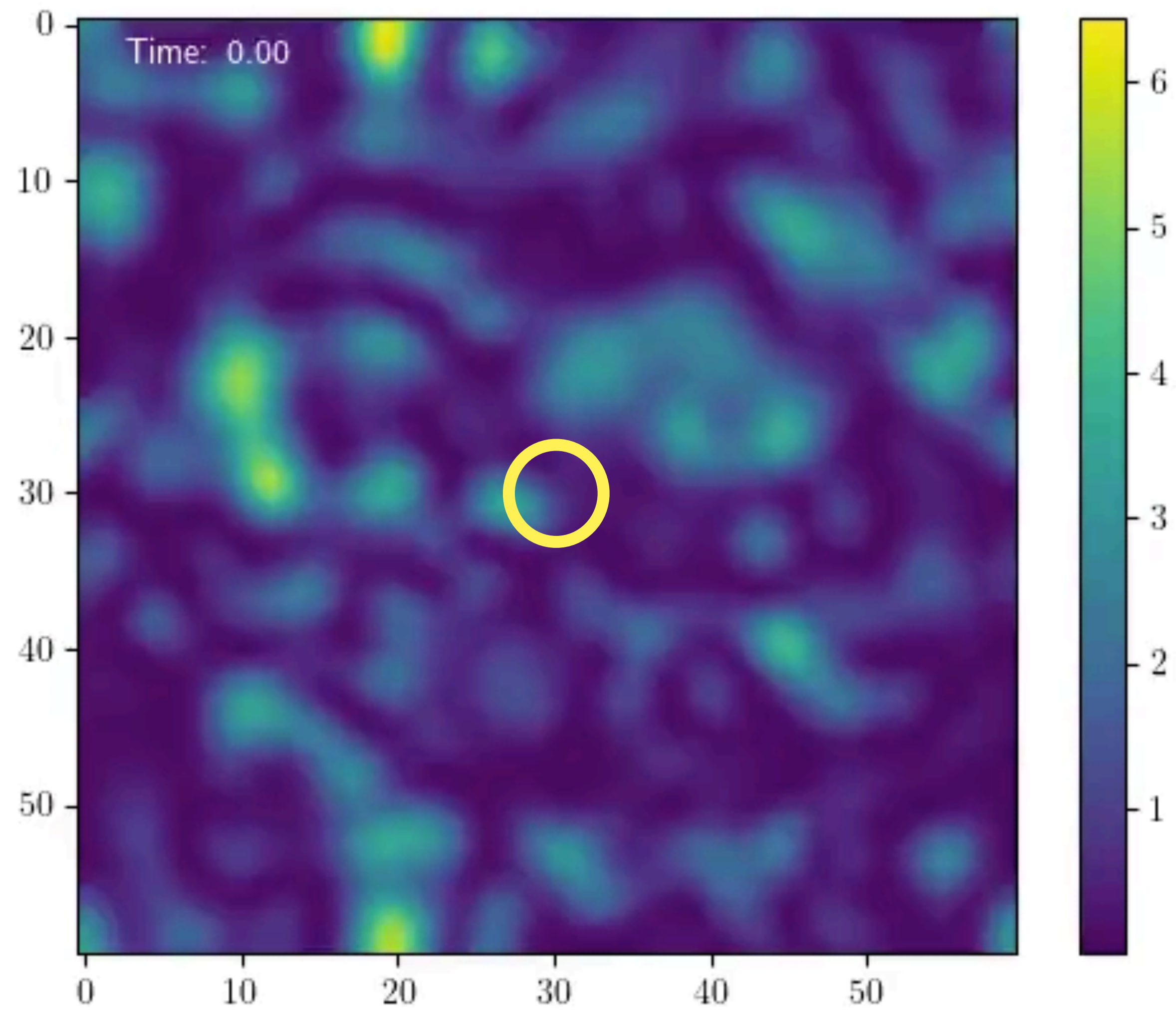
$$\ddot{x} = -\nabla\Phi$$

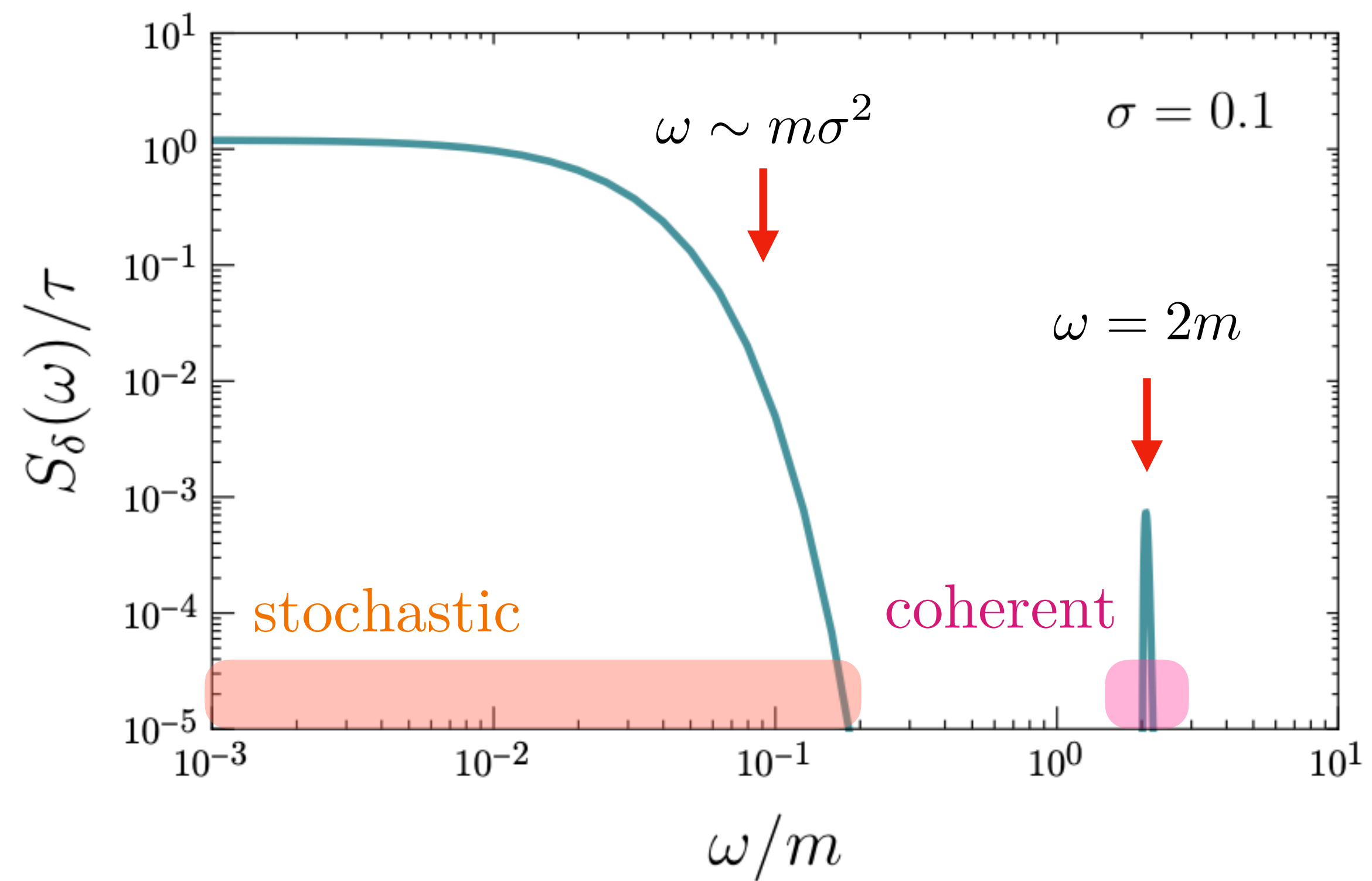
$$\nabla^2\Phi = 4\pi G\rho$$



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

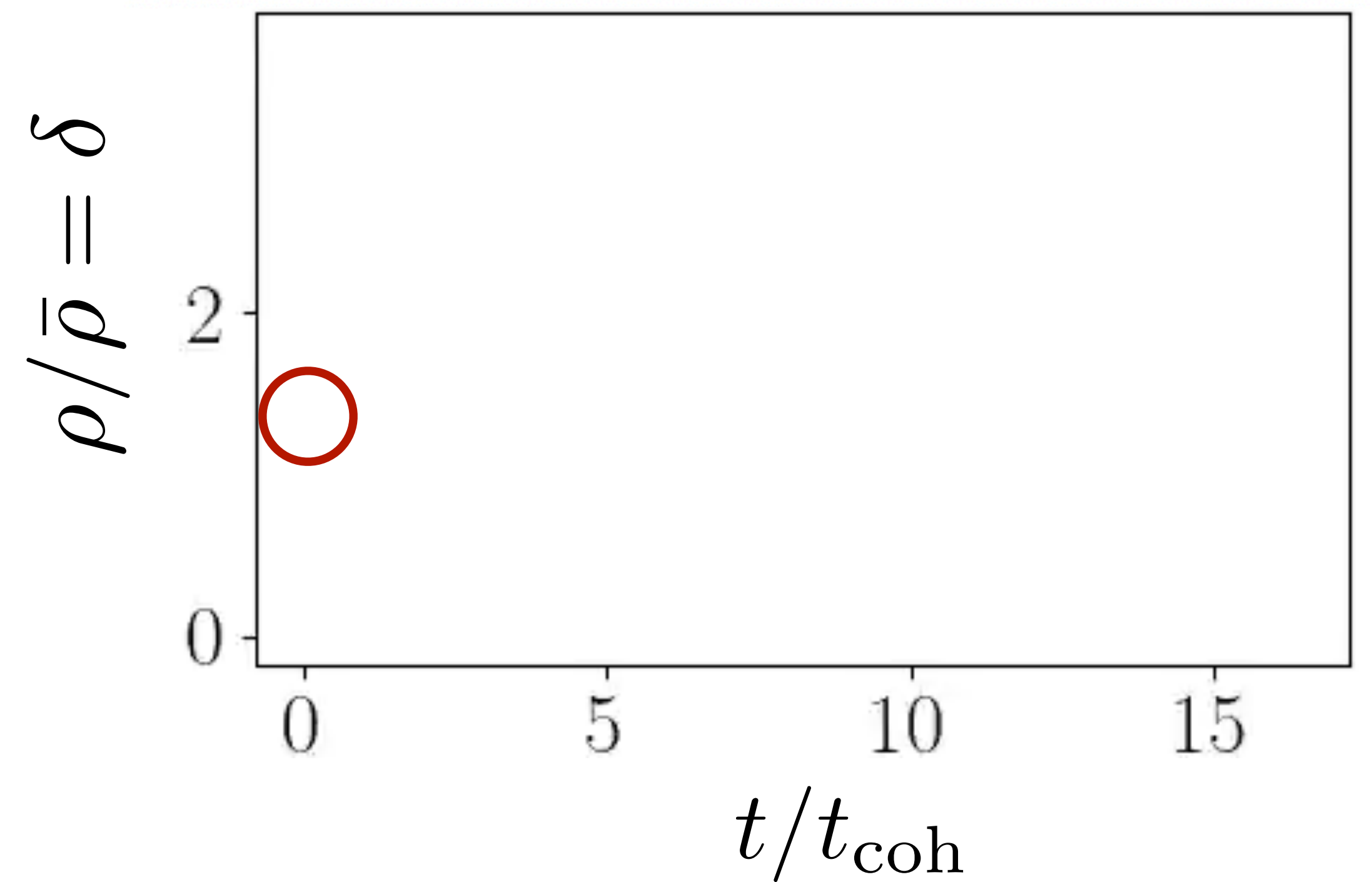
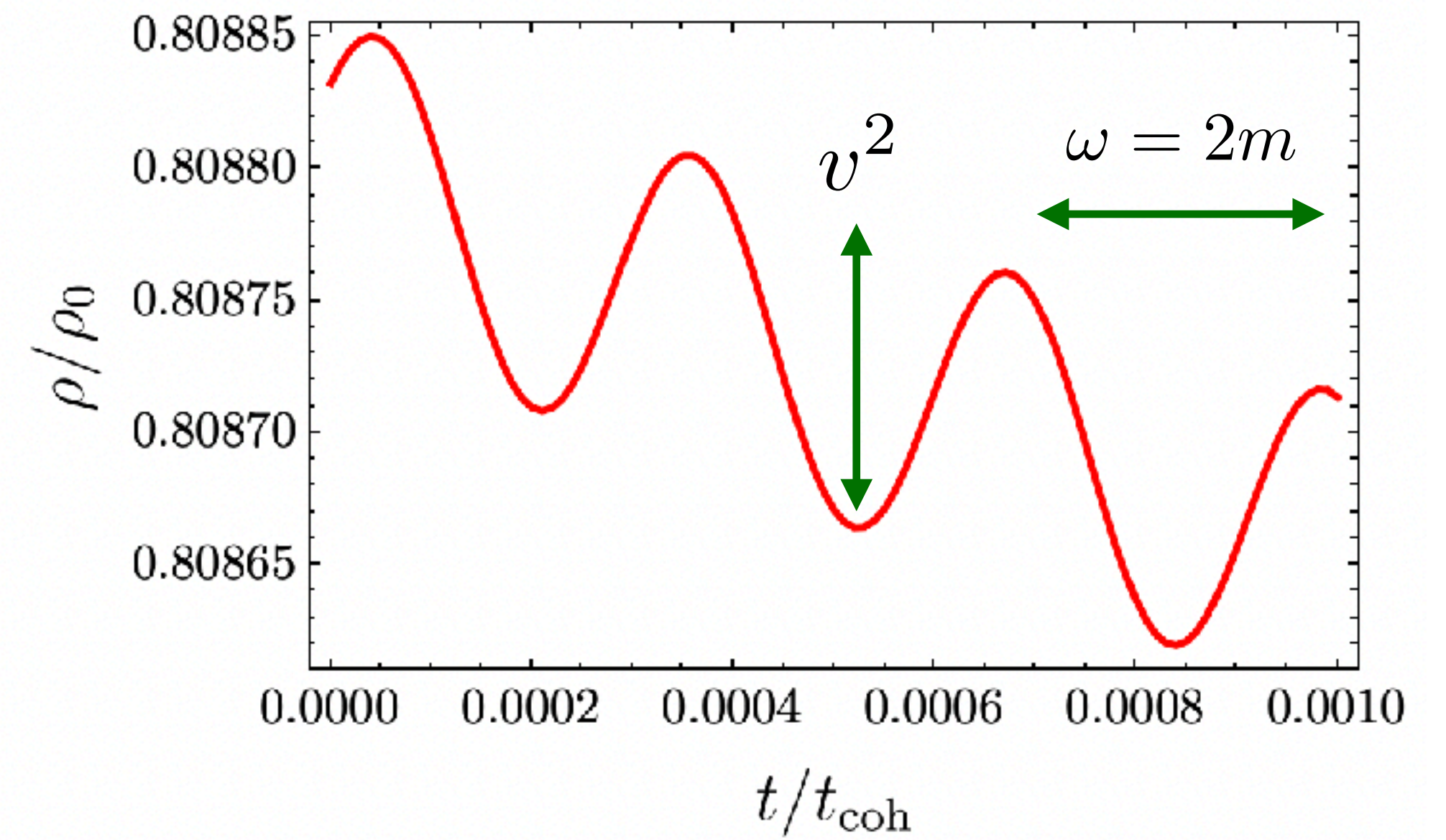


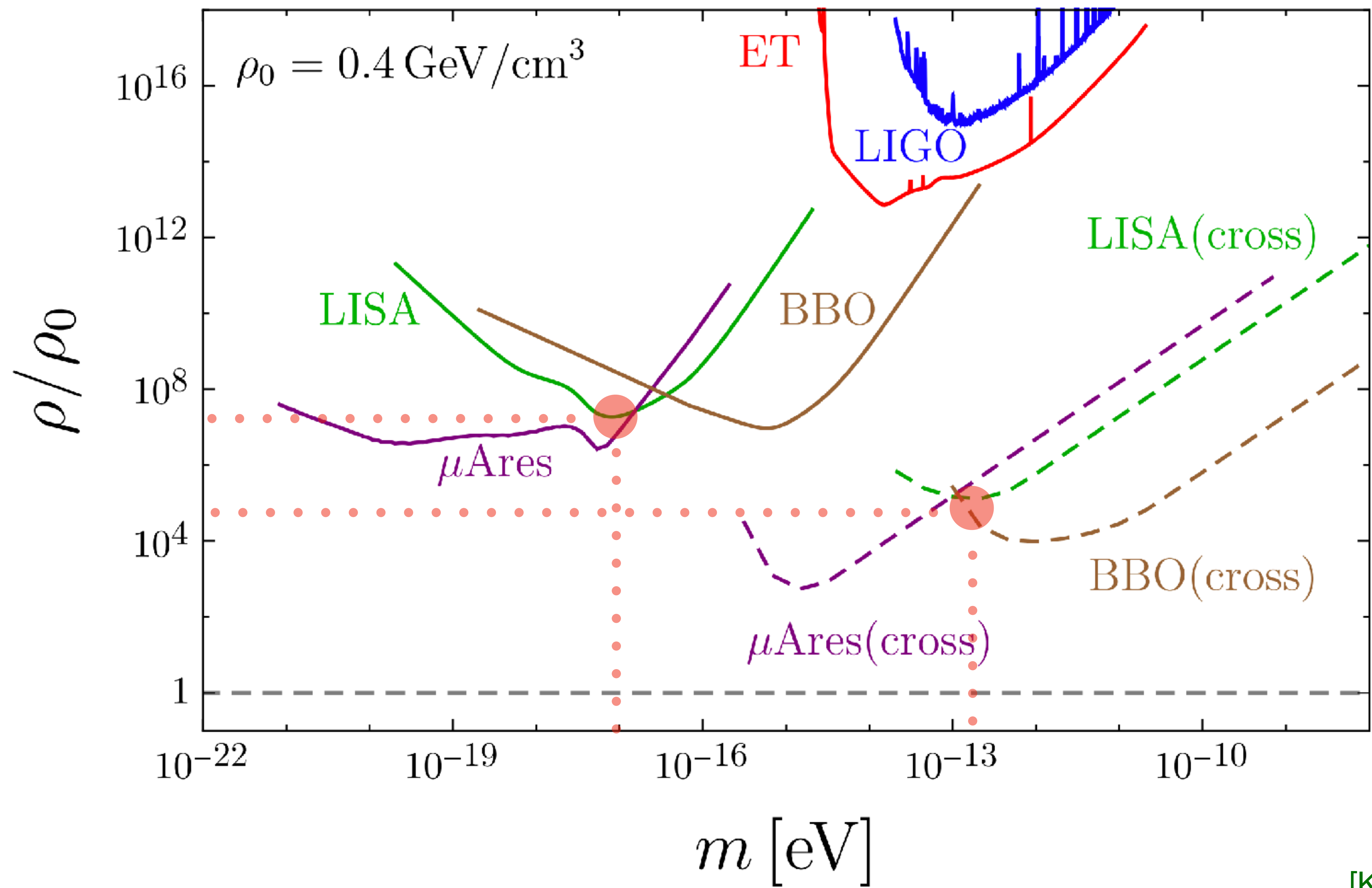




[Kim 2306.13348]

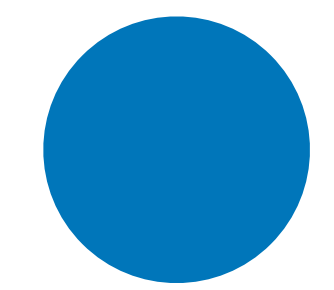
[Kim, Lenoci, Perez, Ratzinger, 2307.14962]



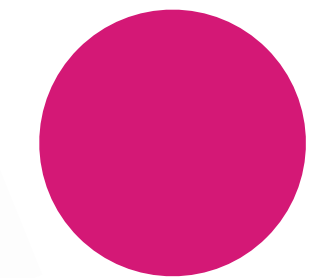


another example:

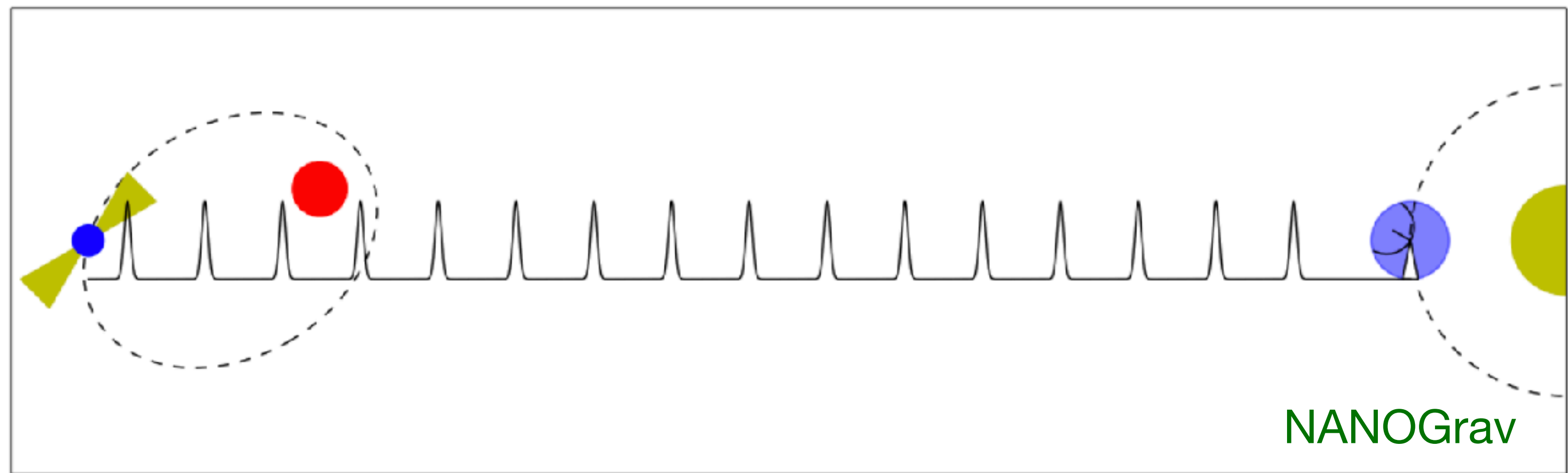
Pulsar Timing & Astrometry

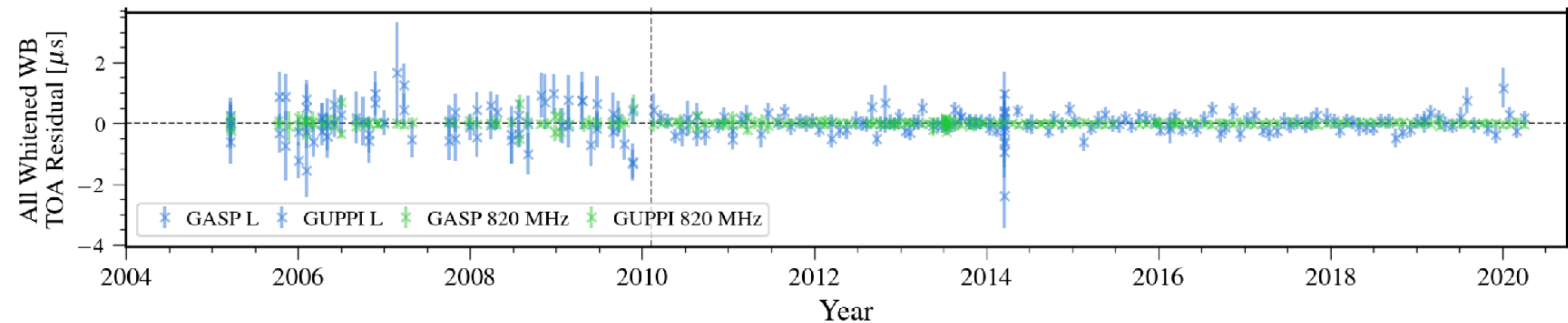
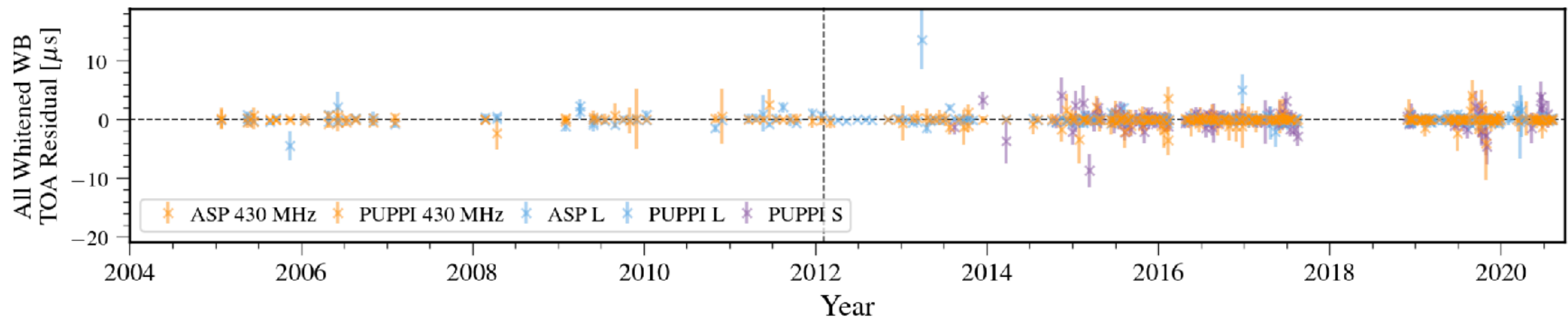
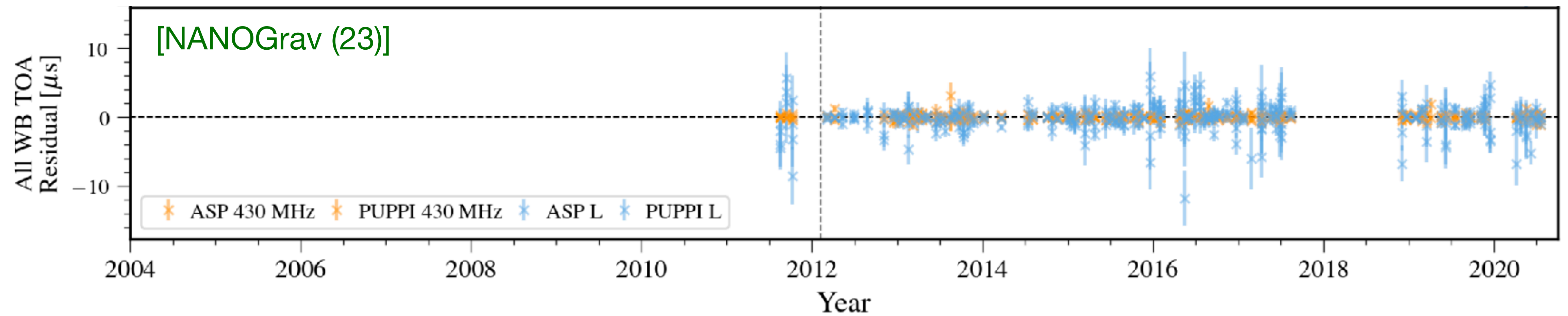


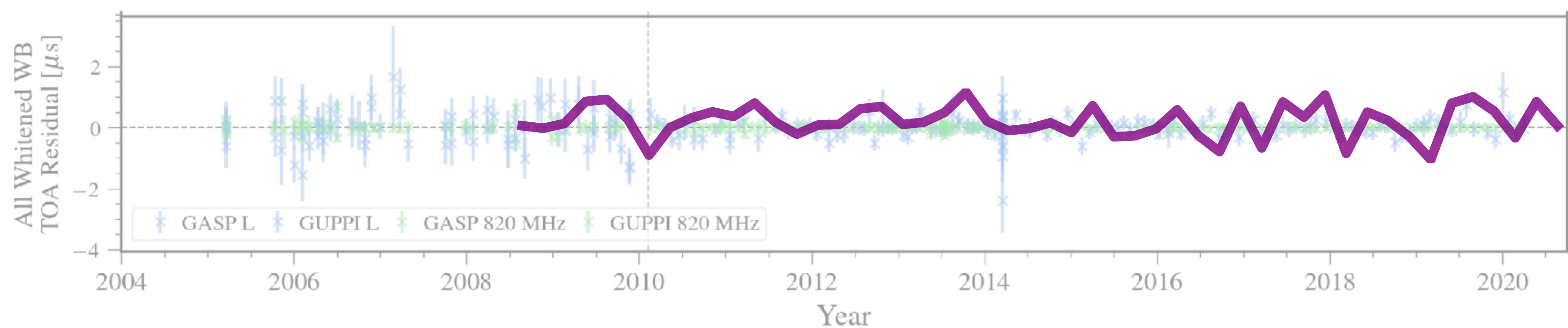
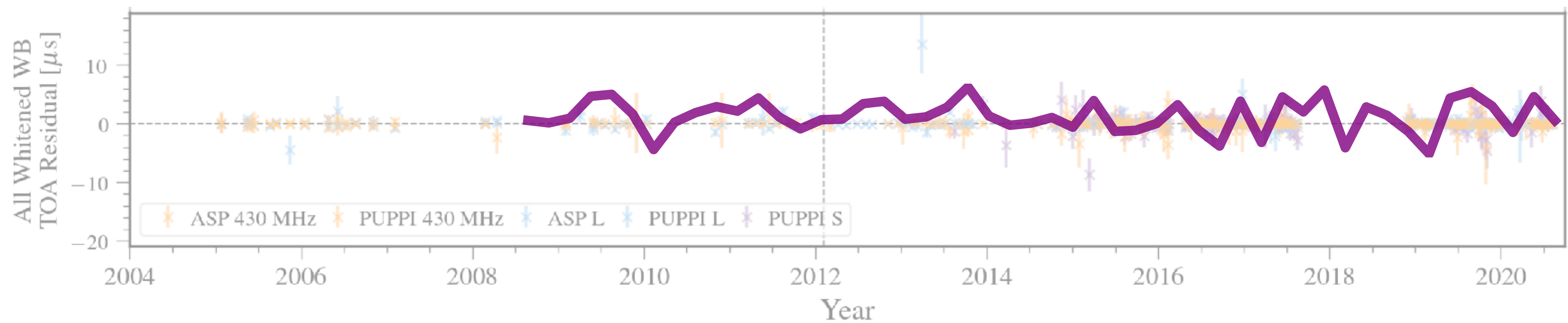
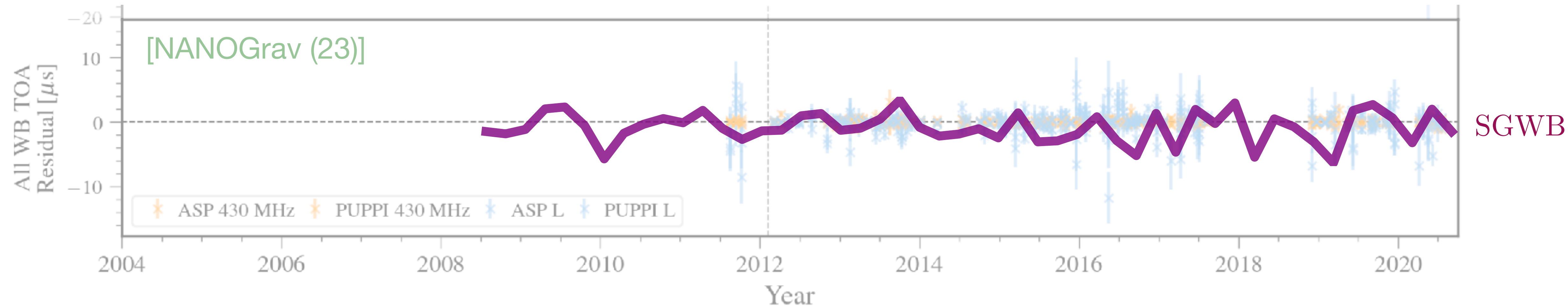
Earth

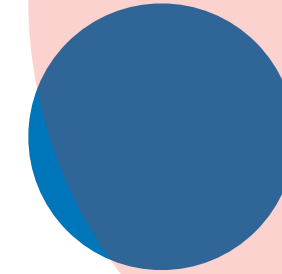
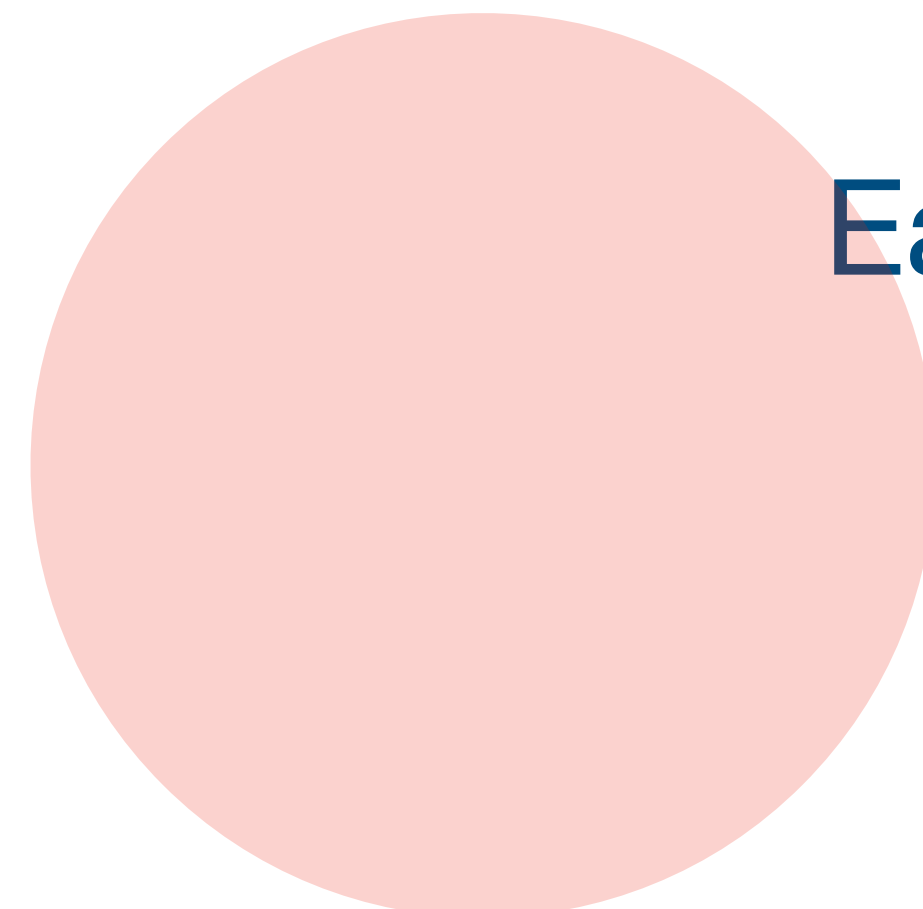
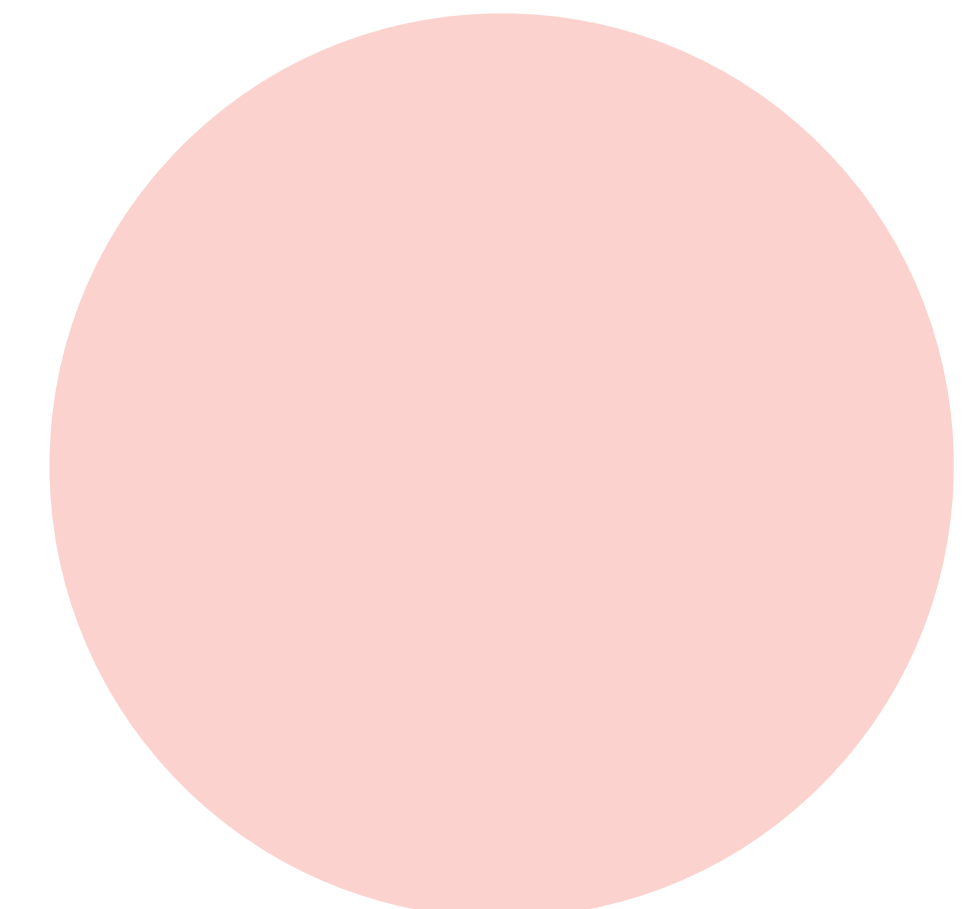
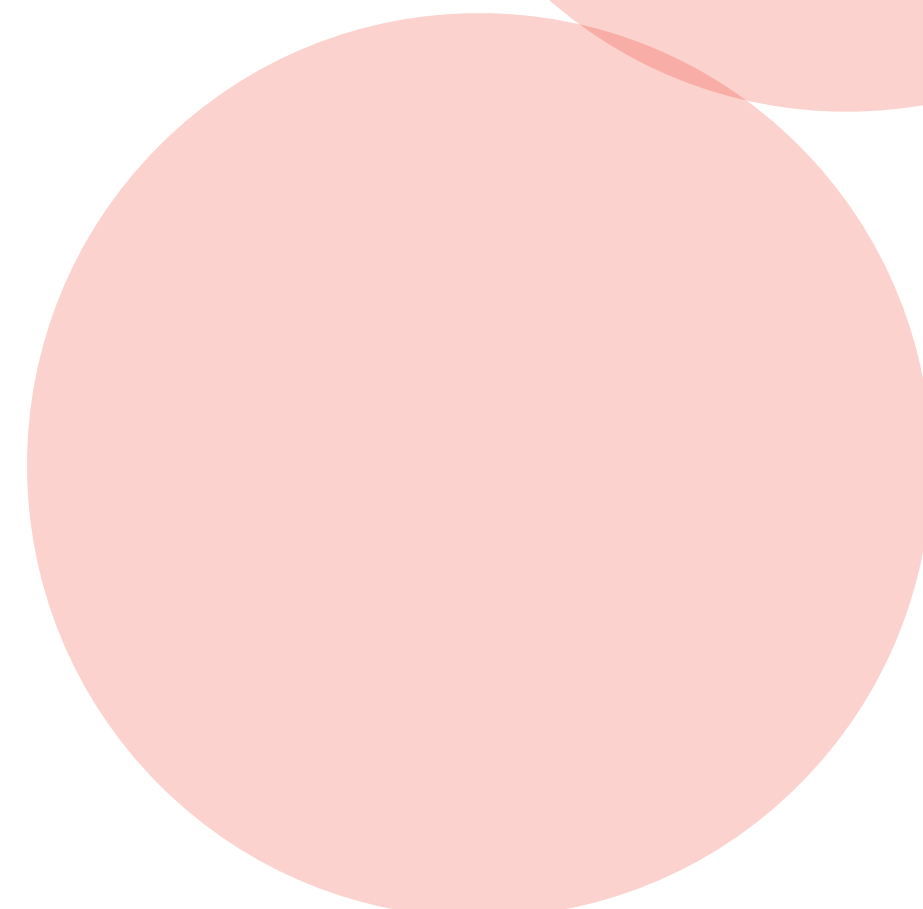
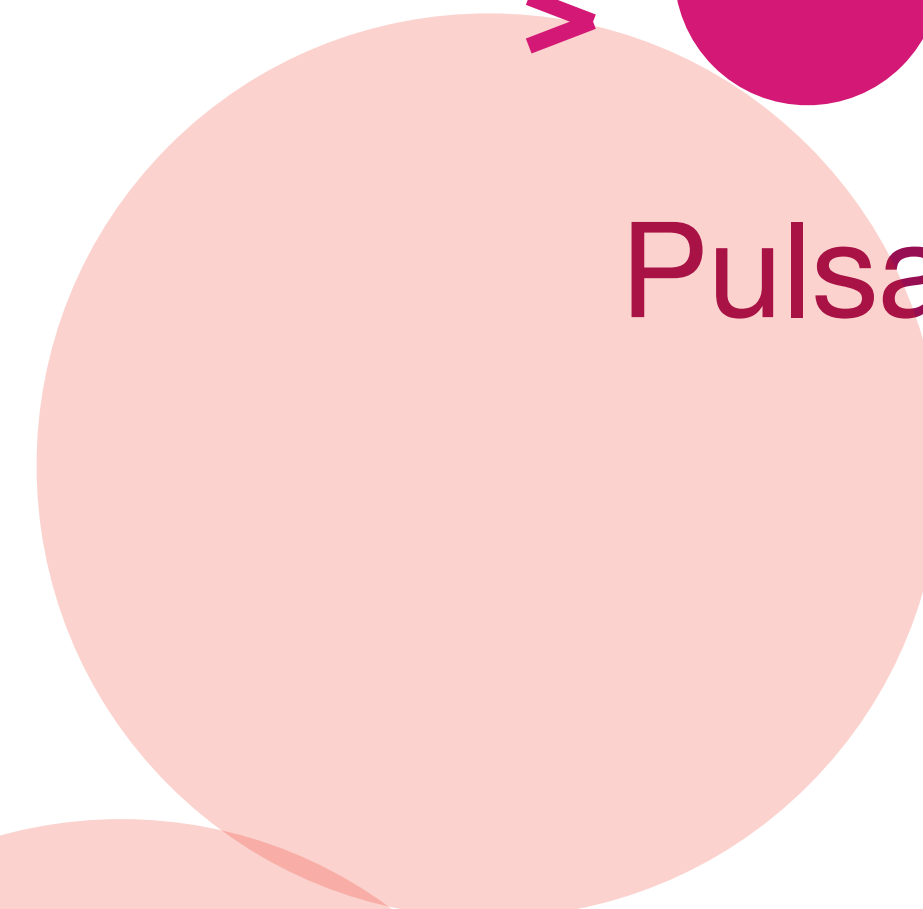
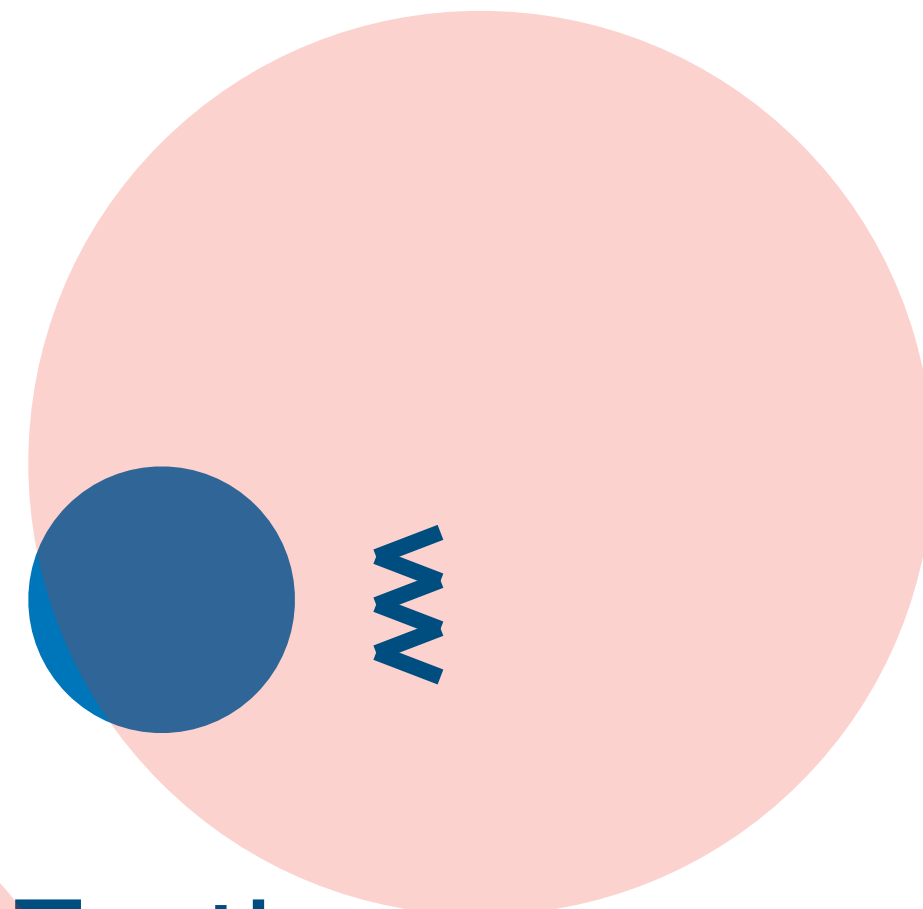
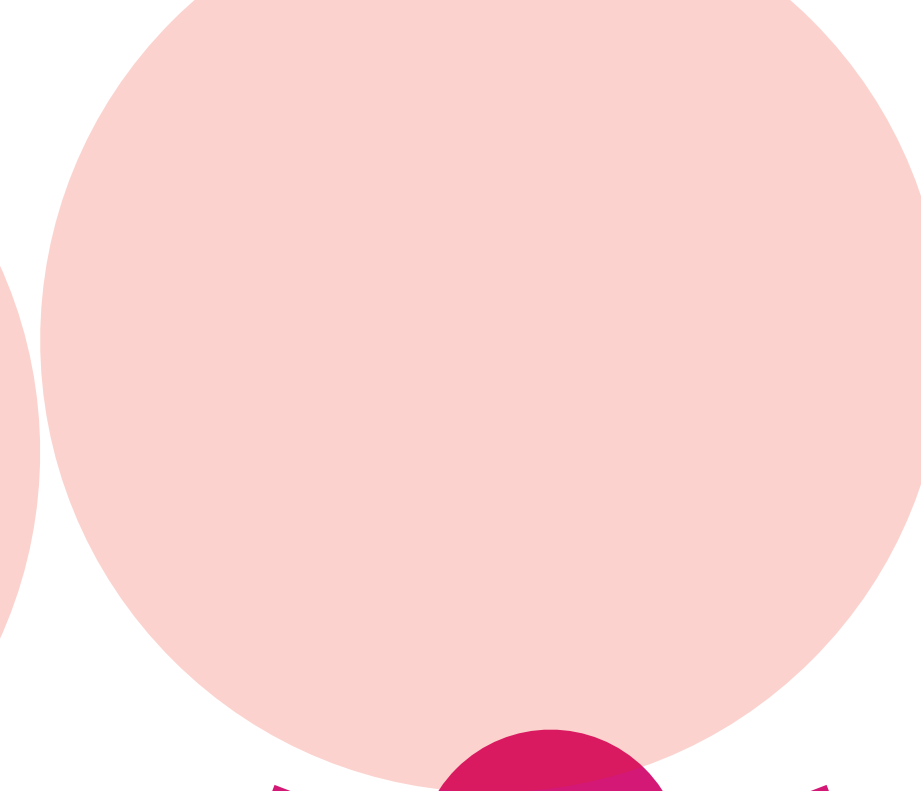
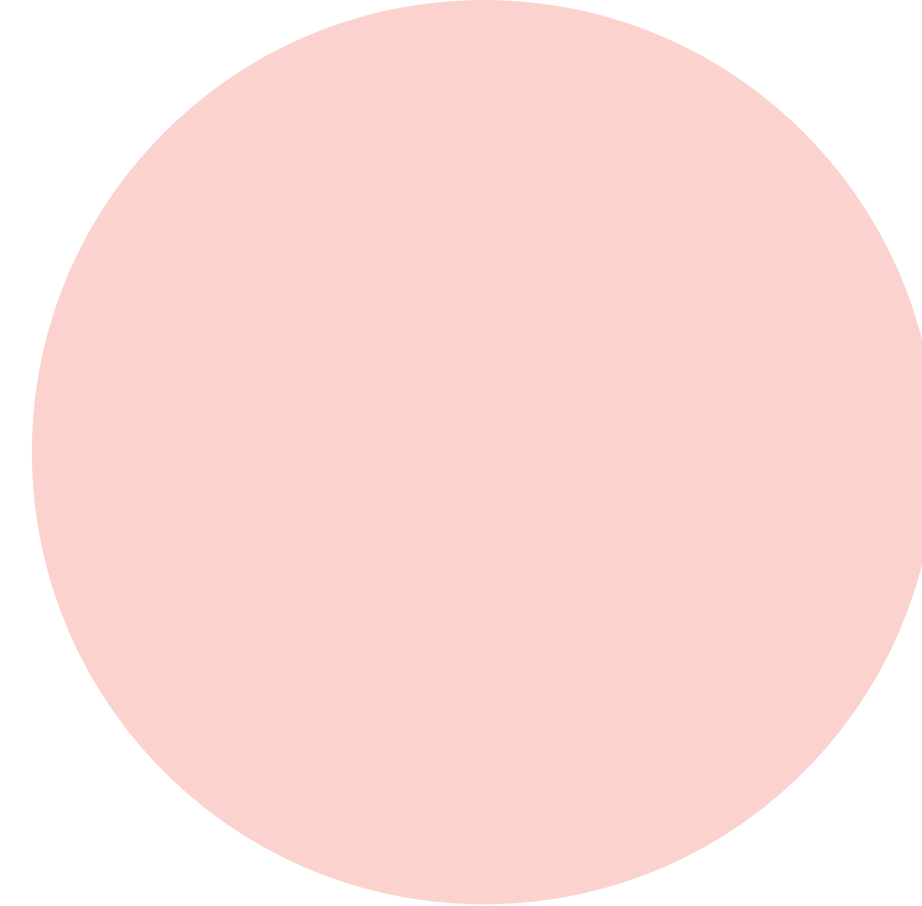
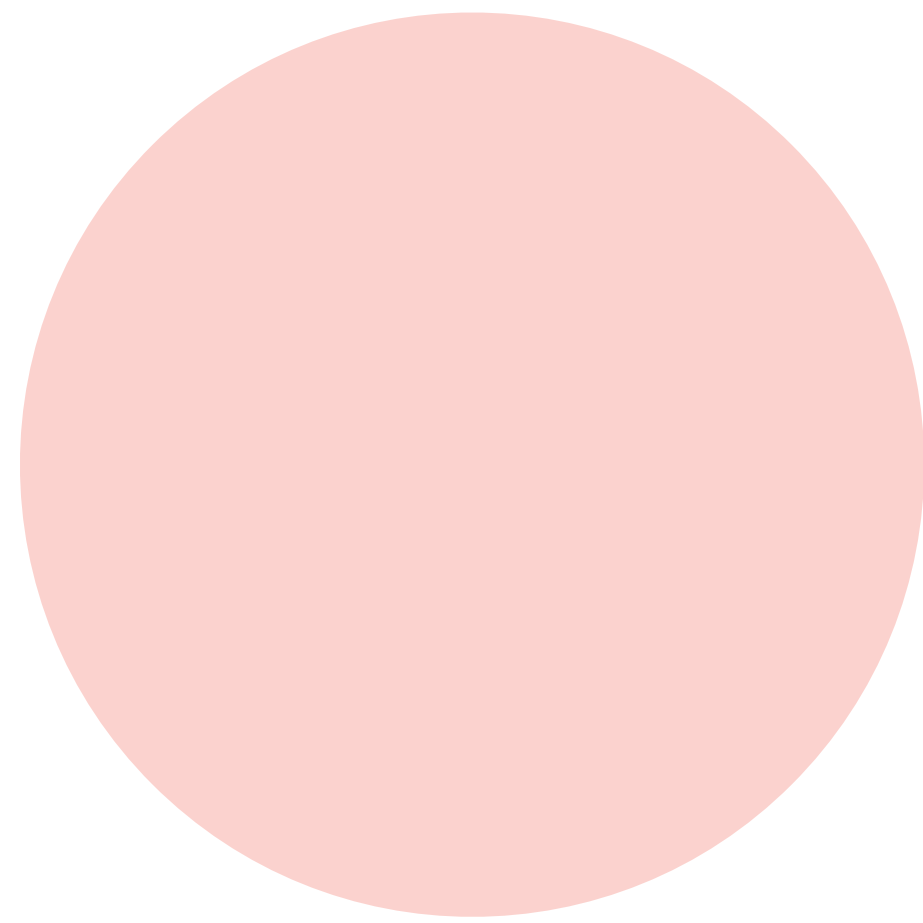


Pulsar

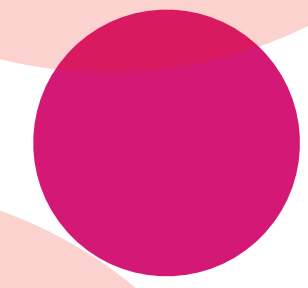




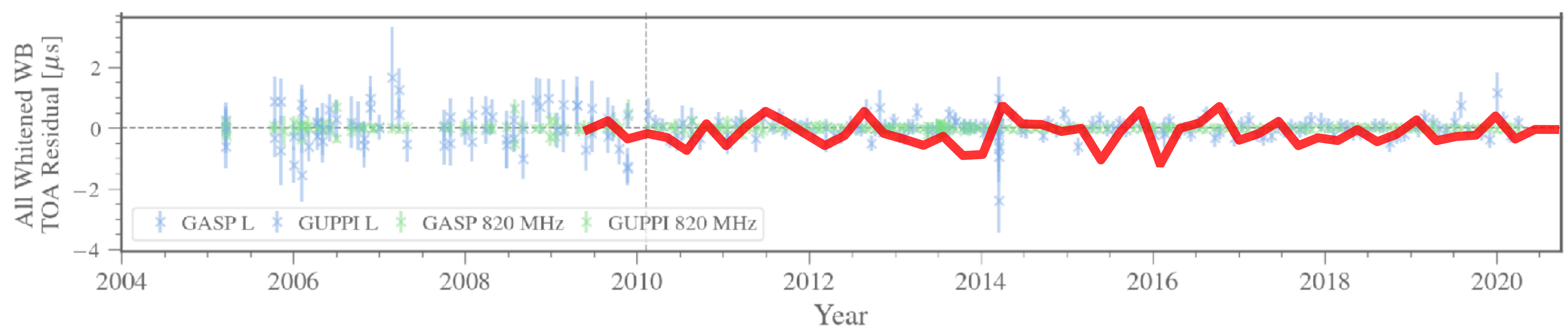
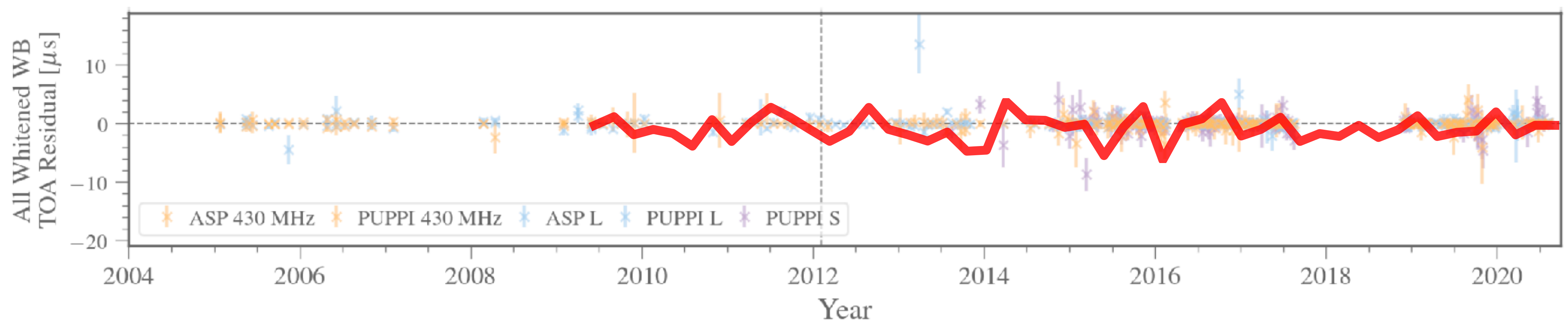
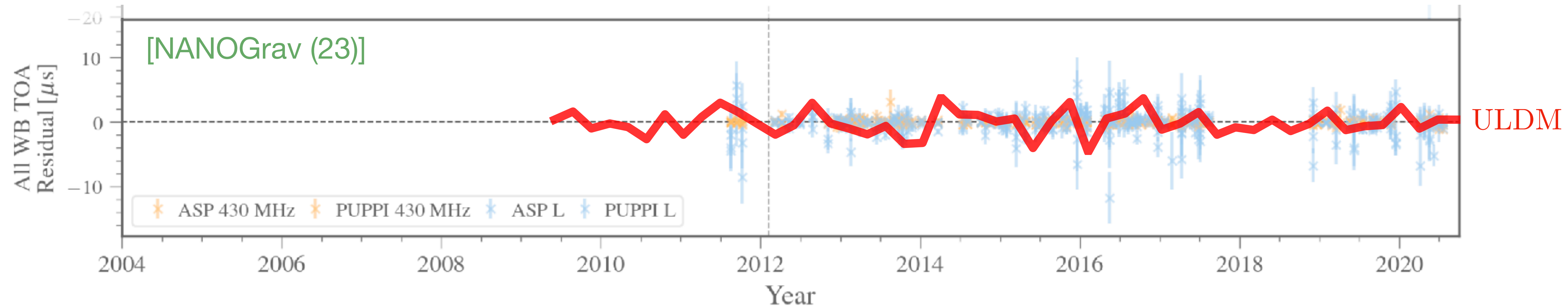


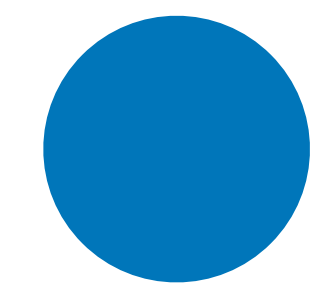


Earth

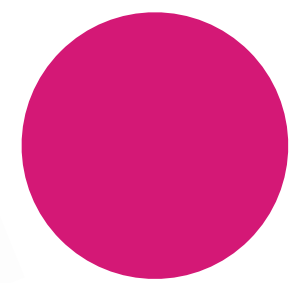


Pulsar



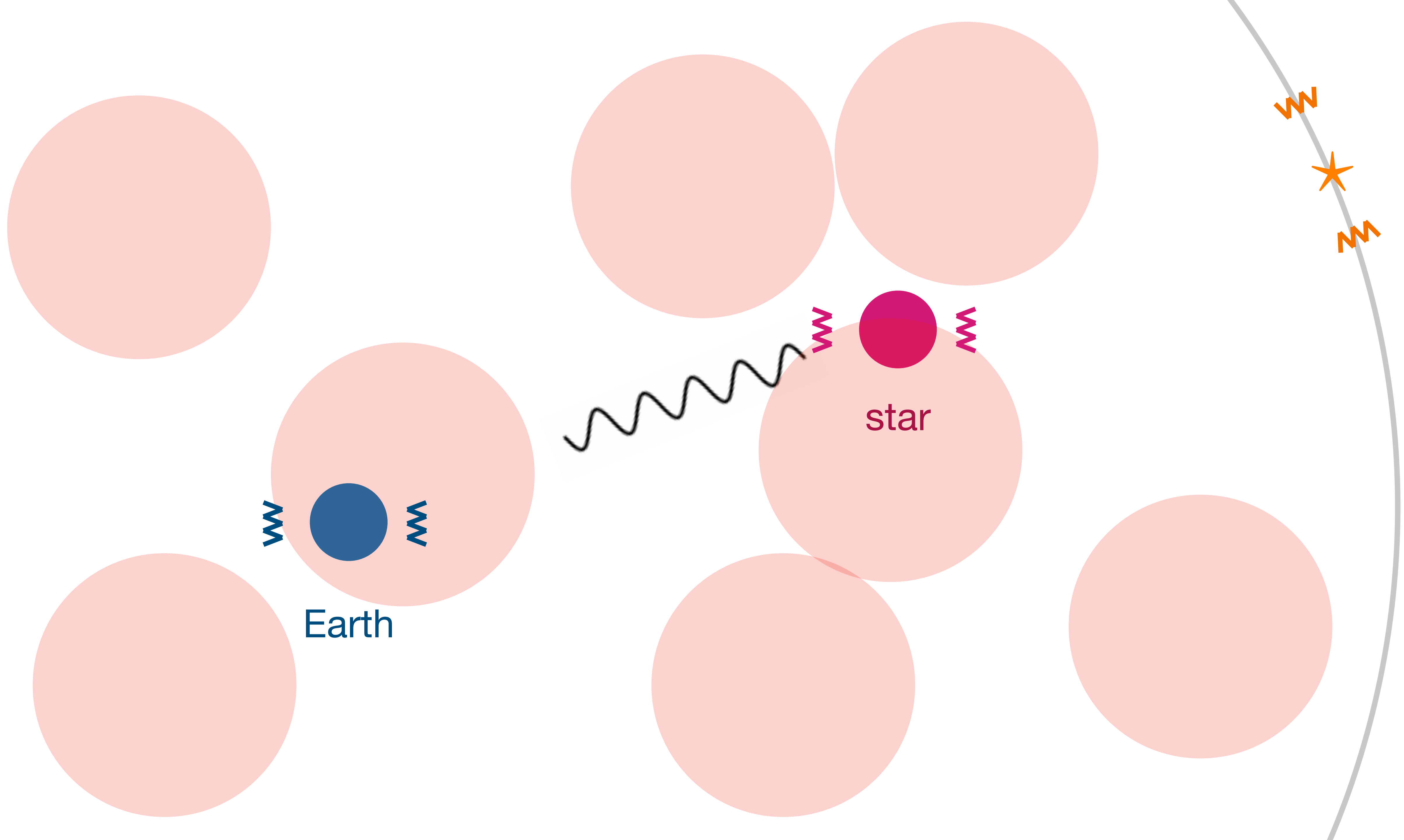


Earth



star





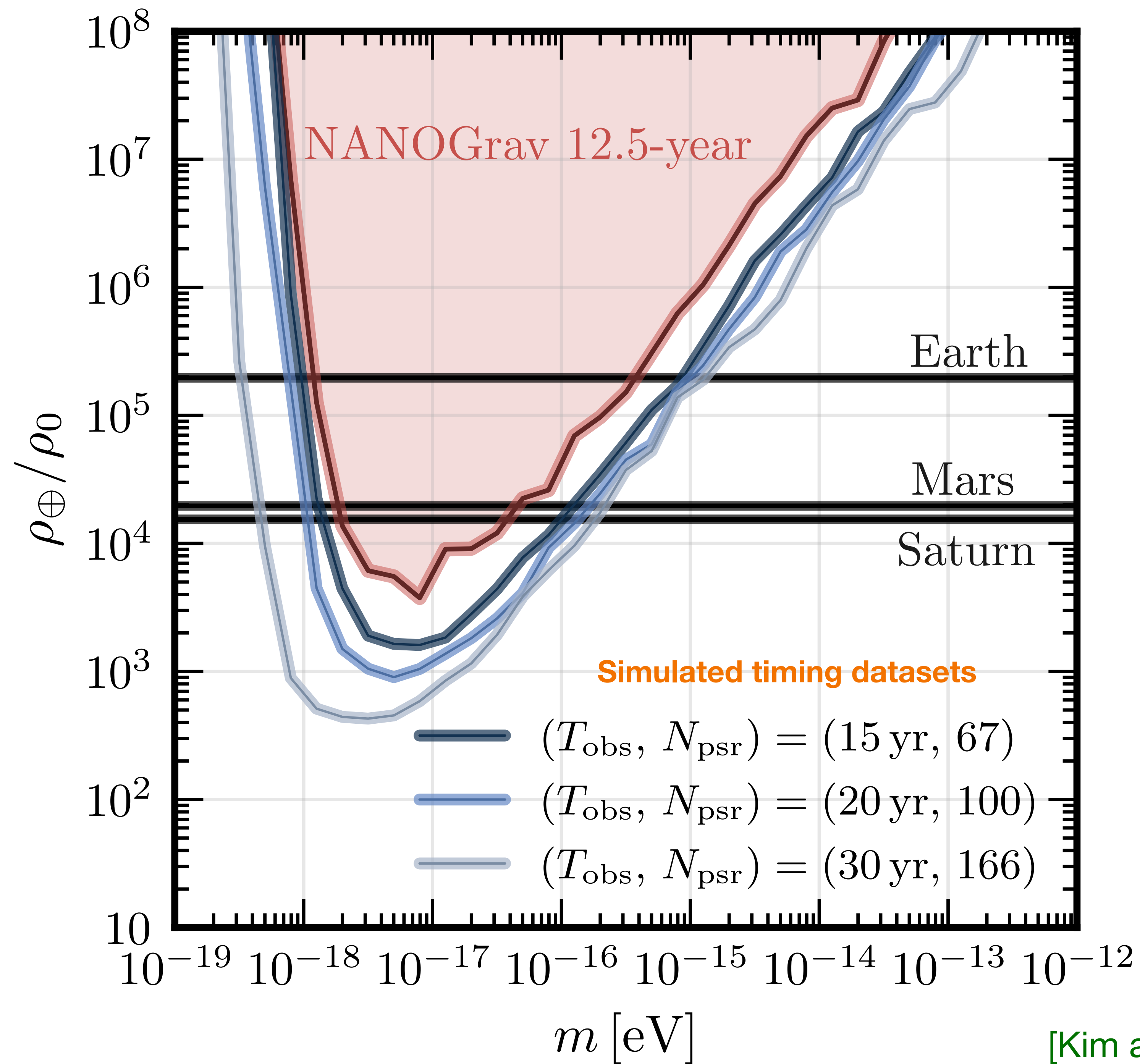
$$\langle \delta t_a \delta t_b \rangle = \int df \, \Gamma_{ab}^{\text{ULDM}} S_{\delta t}^{\text{ULDM}}(f)$$

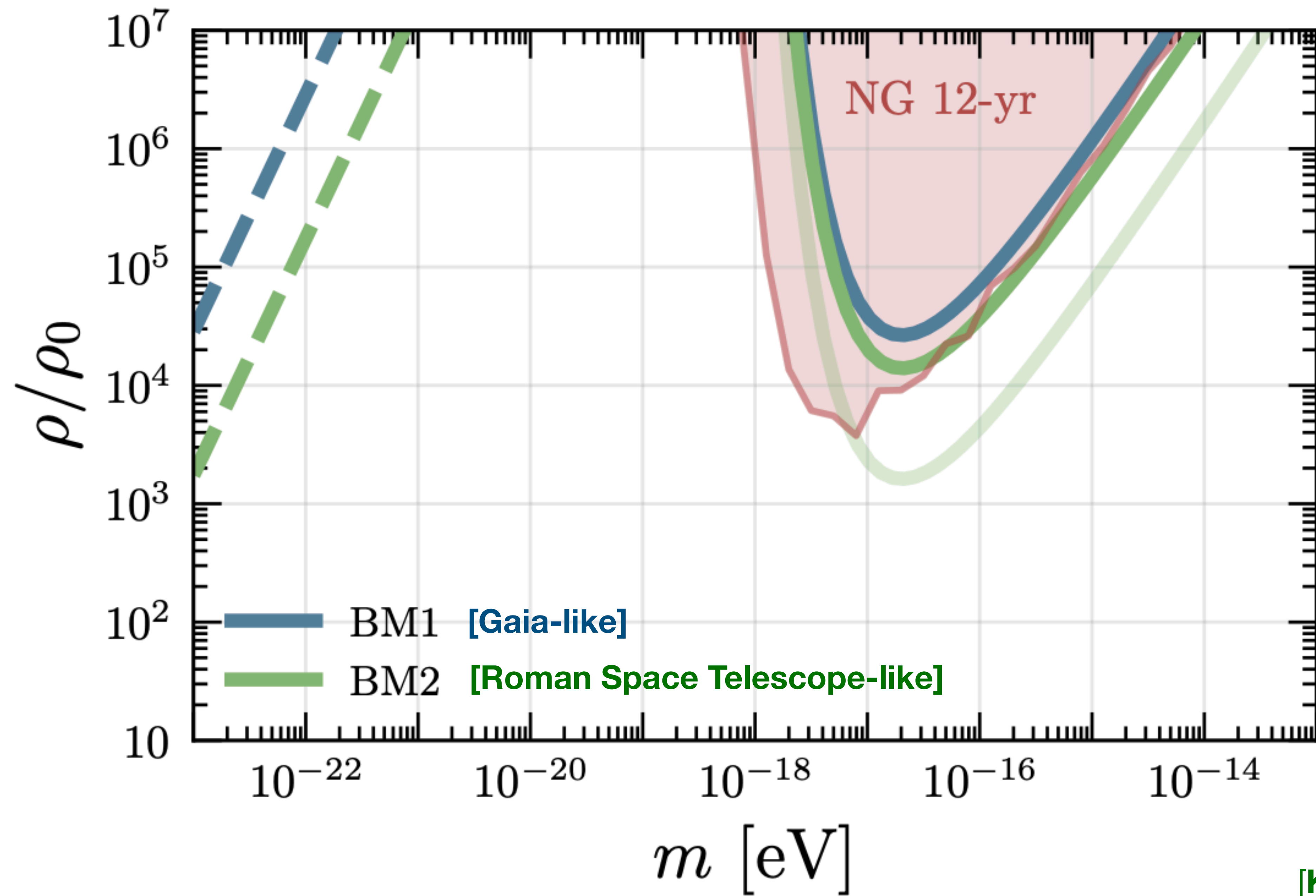
$$\langle \delta t_a \delta t_b \rangle = \int df \Gamma_{ab}^{\text{ULDM}} S_{\delta t}^{\text{ULDM}}(f)$$

for isotropic DM distribution

$$\Gamma_{ab} = \frac{1}{2} [\delta_{ab} + \hat{n}_a \cdot \hat{n}_b]$$

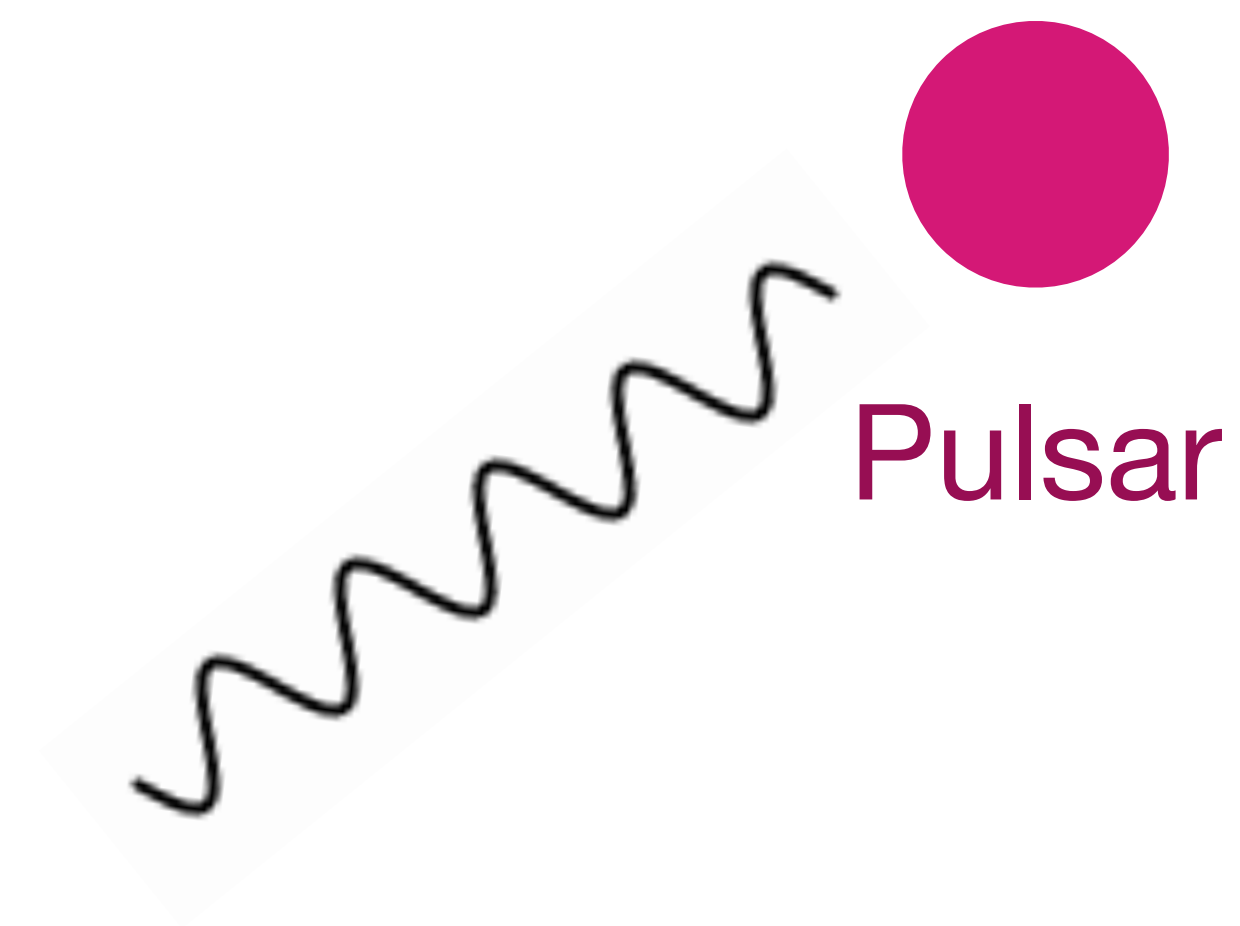
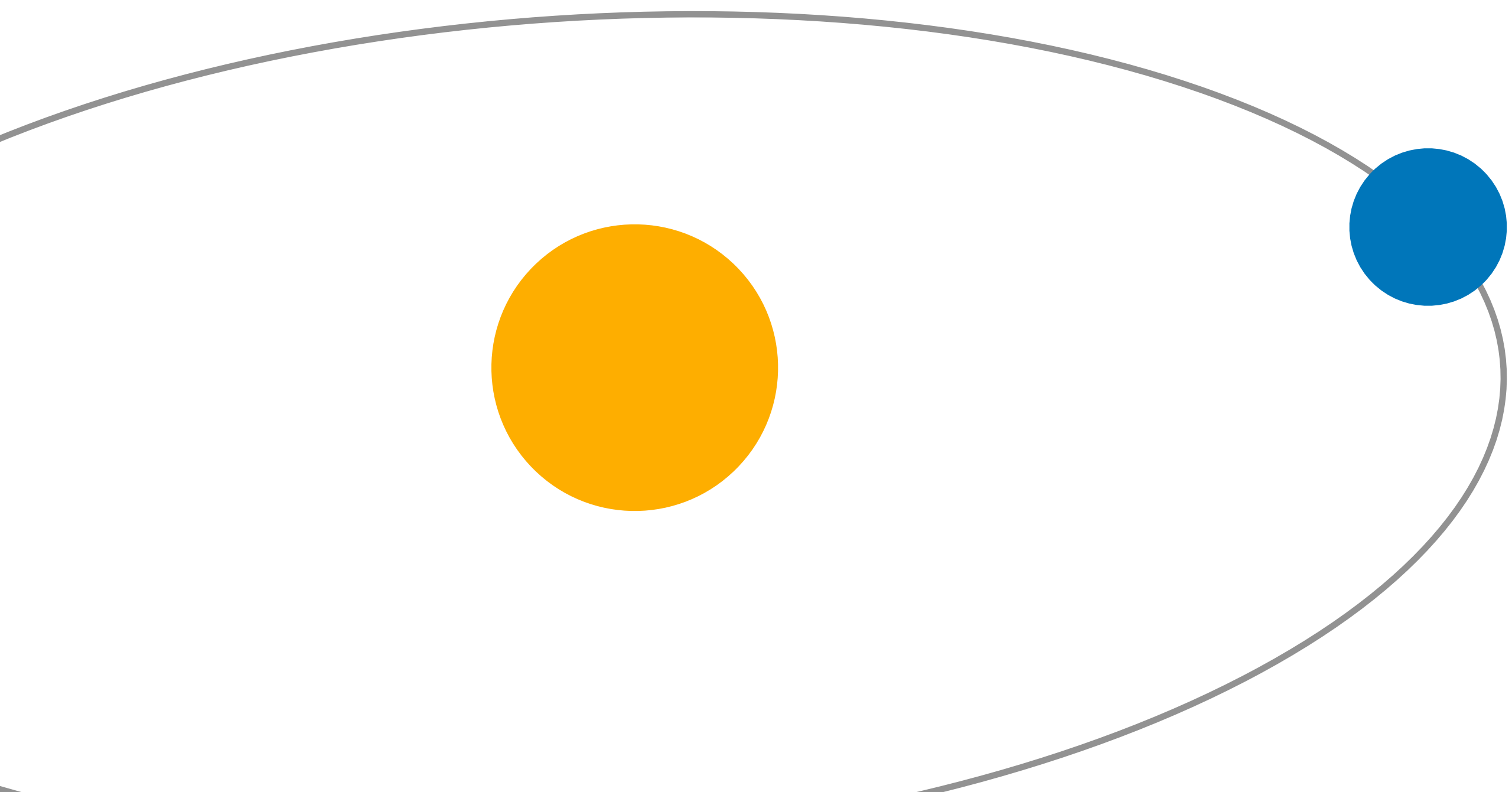
$$S_{\delta t}(f) = \frac{a^2 \tau}{(2\pi f)^4} \left[\frac{64}{3\pi} K_0(\omega/m\sigma^2) \right]$$



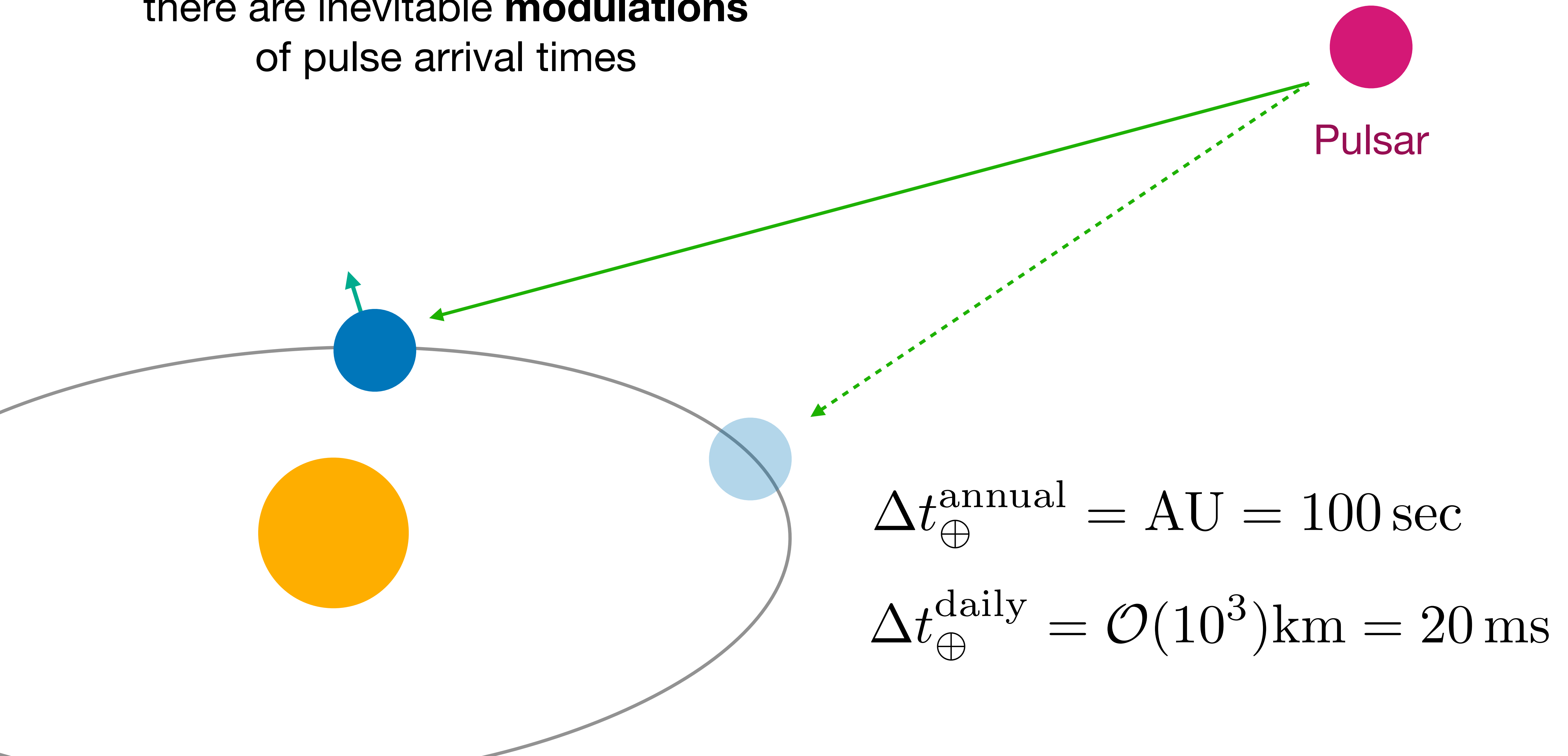


one last example:

Solar system dynamics



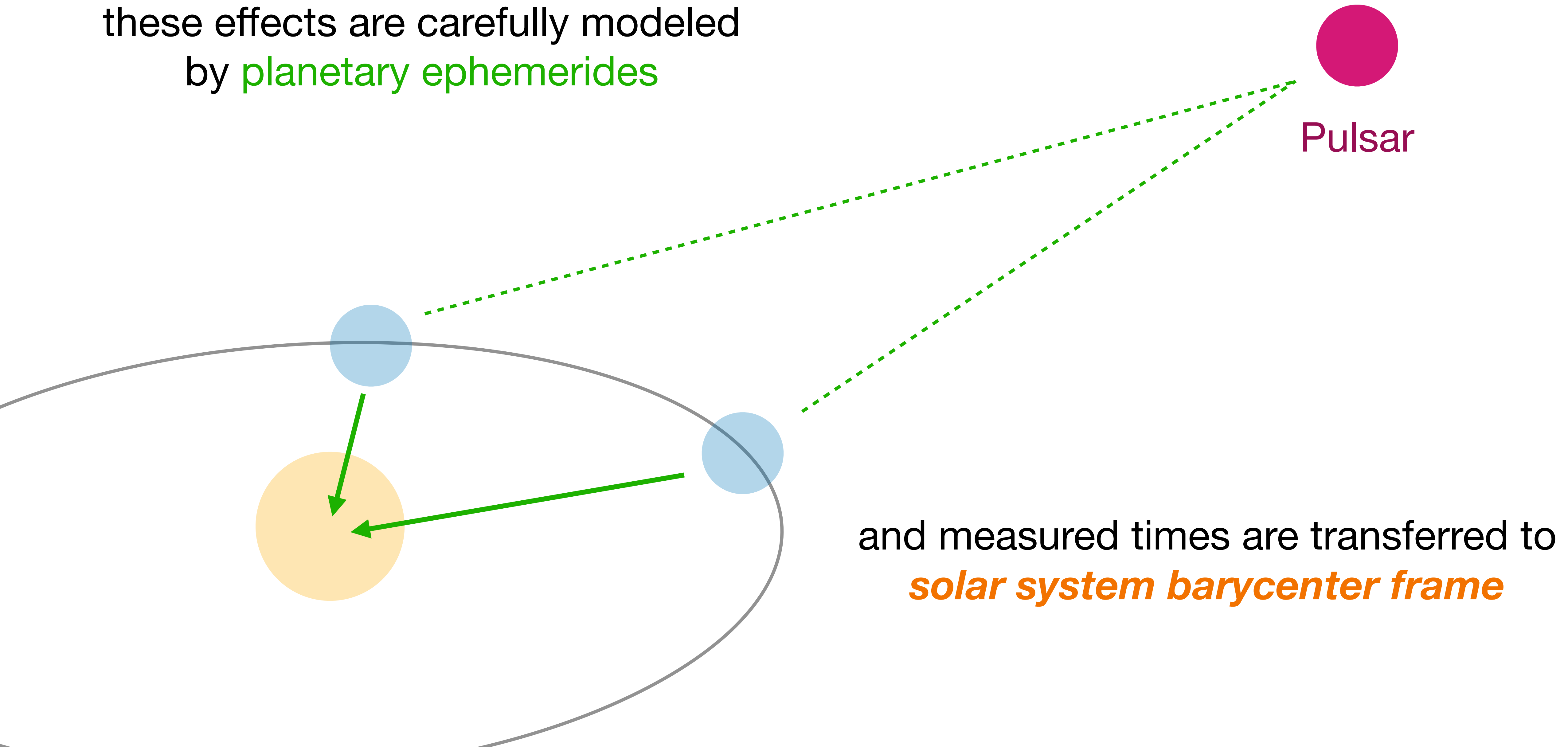
due to the motion of Earth
there are inevitable **modulations**
of pulse arrival times



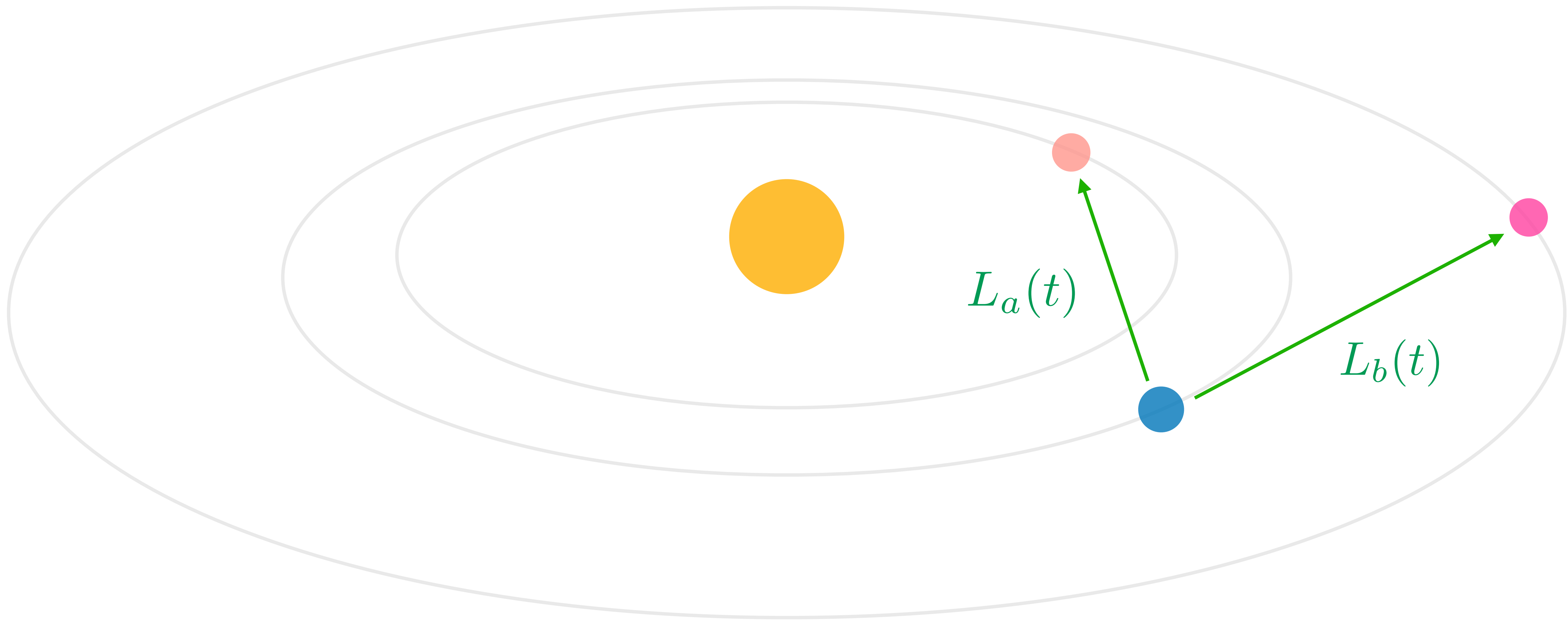
$$\Delta t_{\oplus}^{\text{annual}} = \text{AU} = 100 \text{ sec}$$

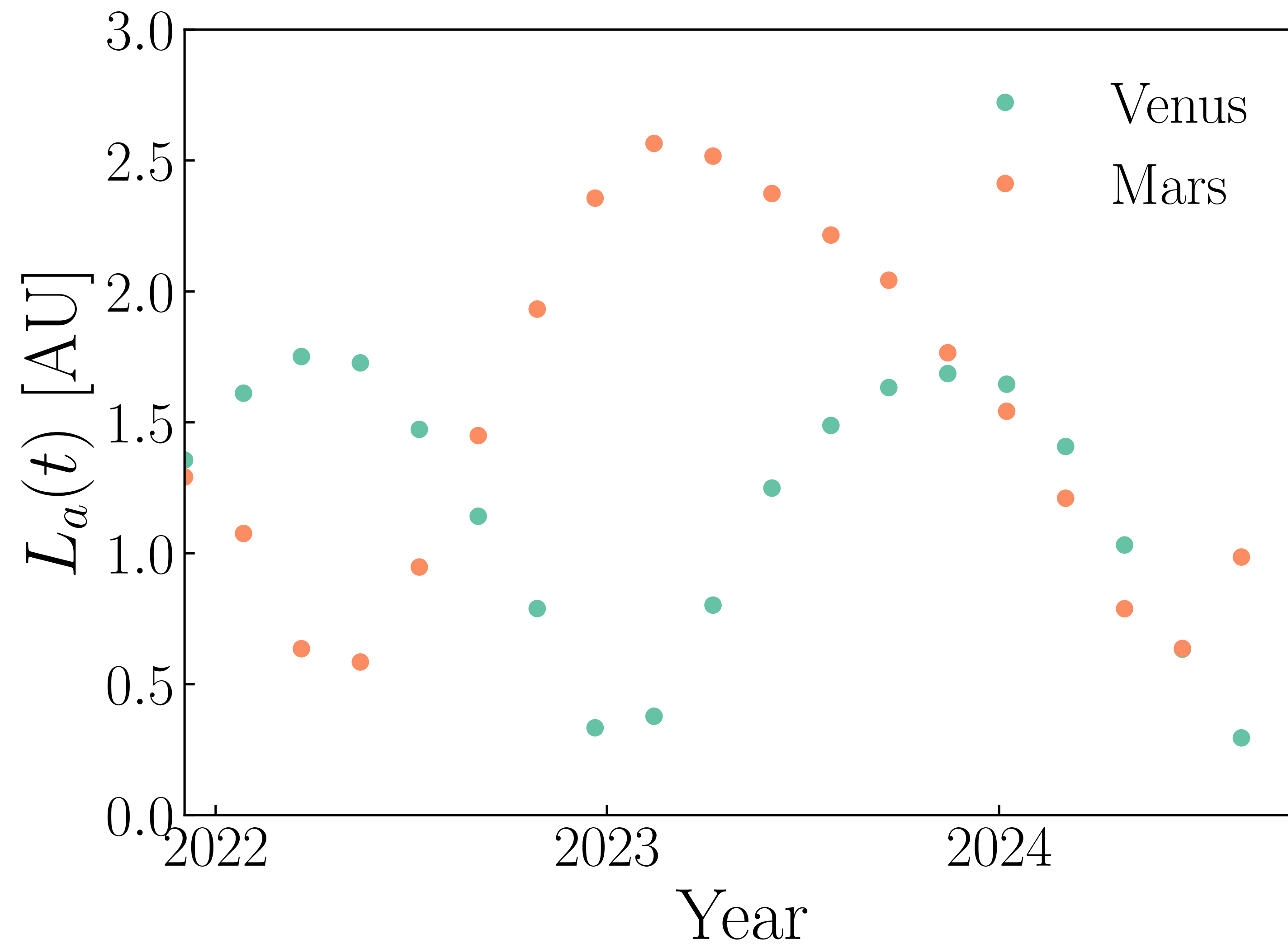
$$\Delta t_{\oplus}^{\text{daily}} = \mathcal{O}(10^3) \text{ km} = 20 \text{ ms}$$

these effects are carefully modeled
by **planetary ephemerides**

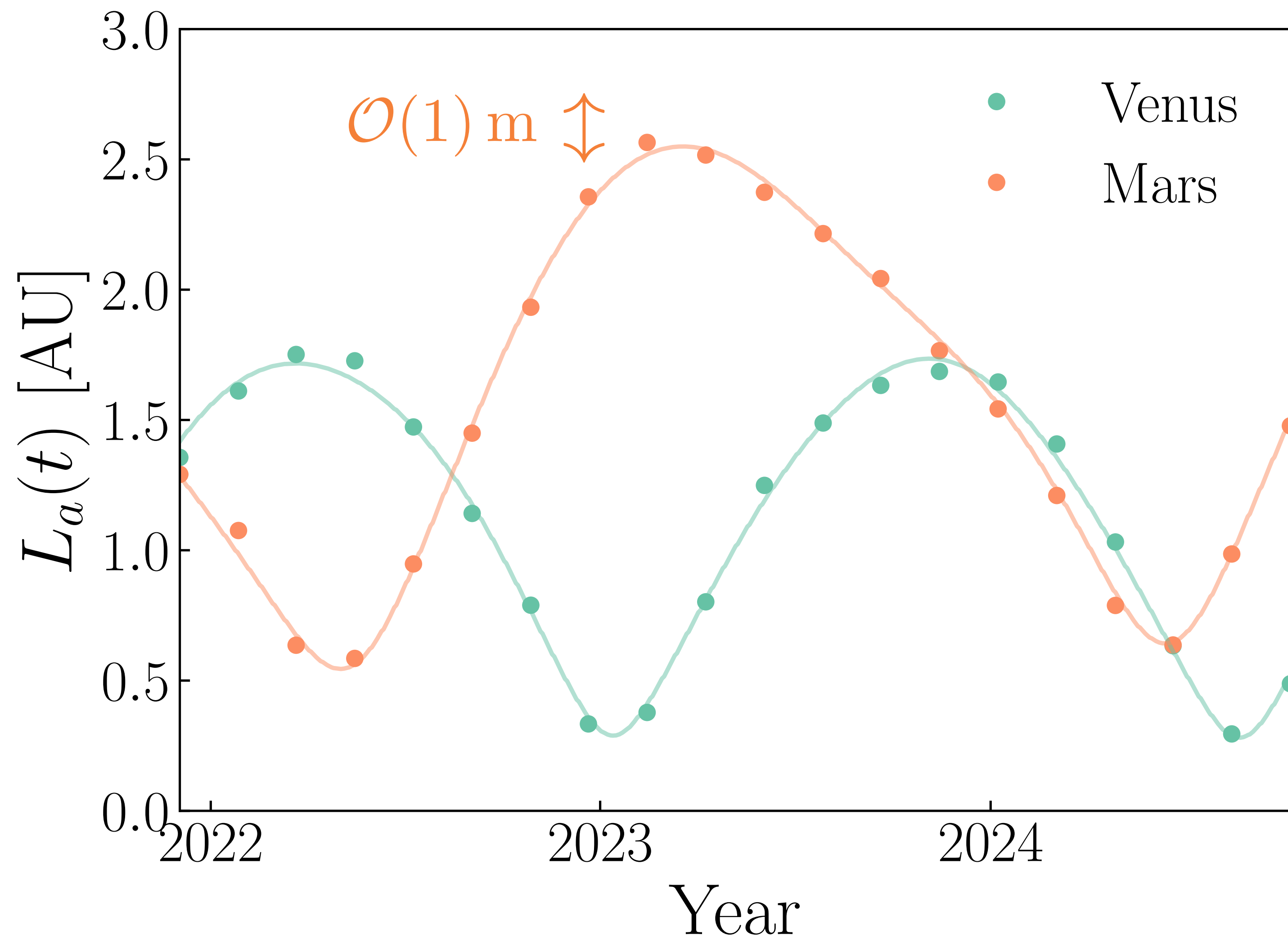


and measured times are transferred to
solar system barycenter frame





$$L_a(t) = L_a^{\text{model}}(t; \boldsymbol{\theta}_{\text{model}}) + n_a(t)$$



$$\Delta L_a(t) = L_a(t) - L_a^{\text{model}}(t; \boldsymbol{\theta}_{\text{fit}})$$

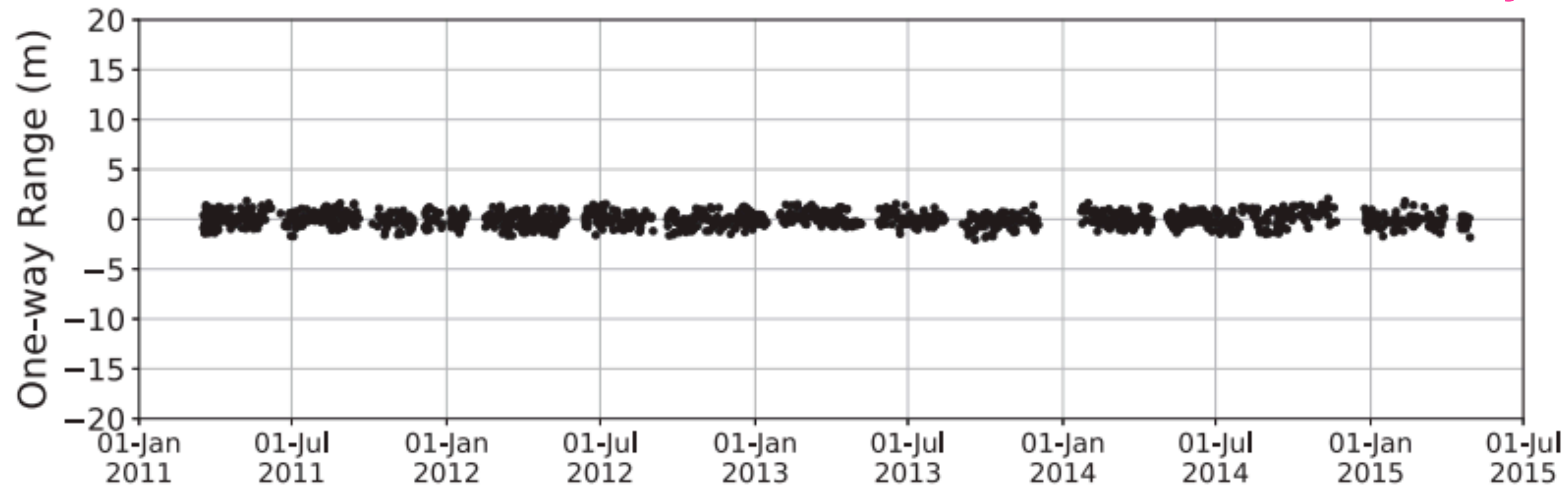


Figure 5. Residuals of the MESSENGER range data against DE440. The rms residual of the MESSENGER ranges is about 0.7 m.

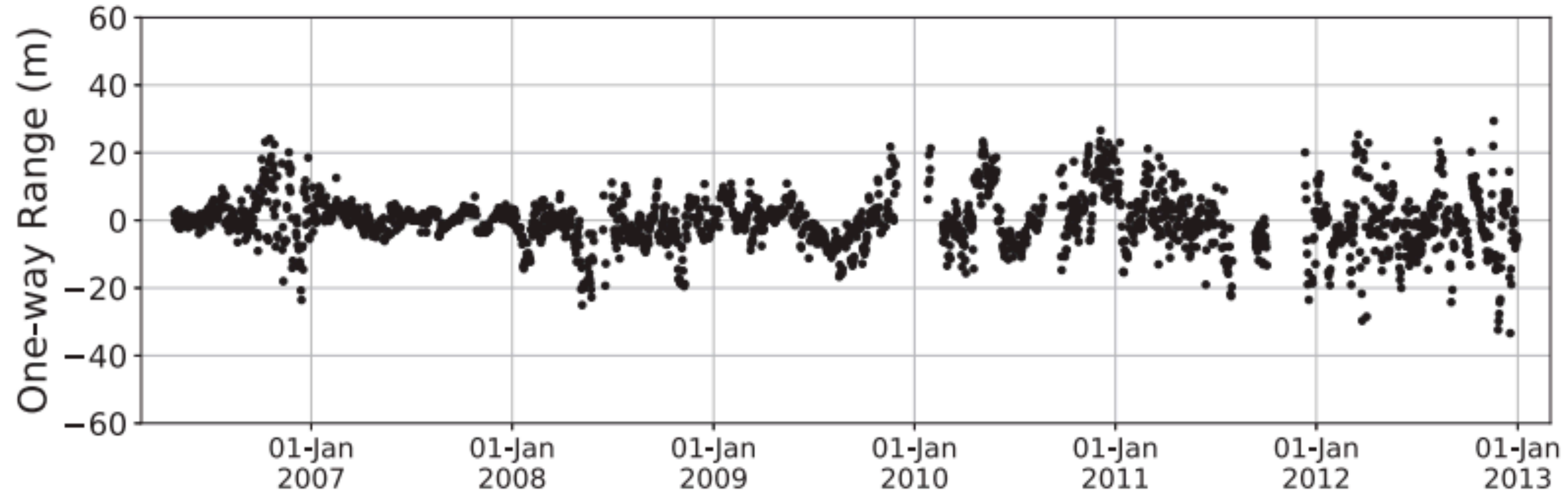
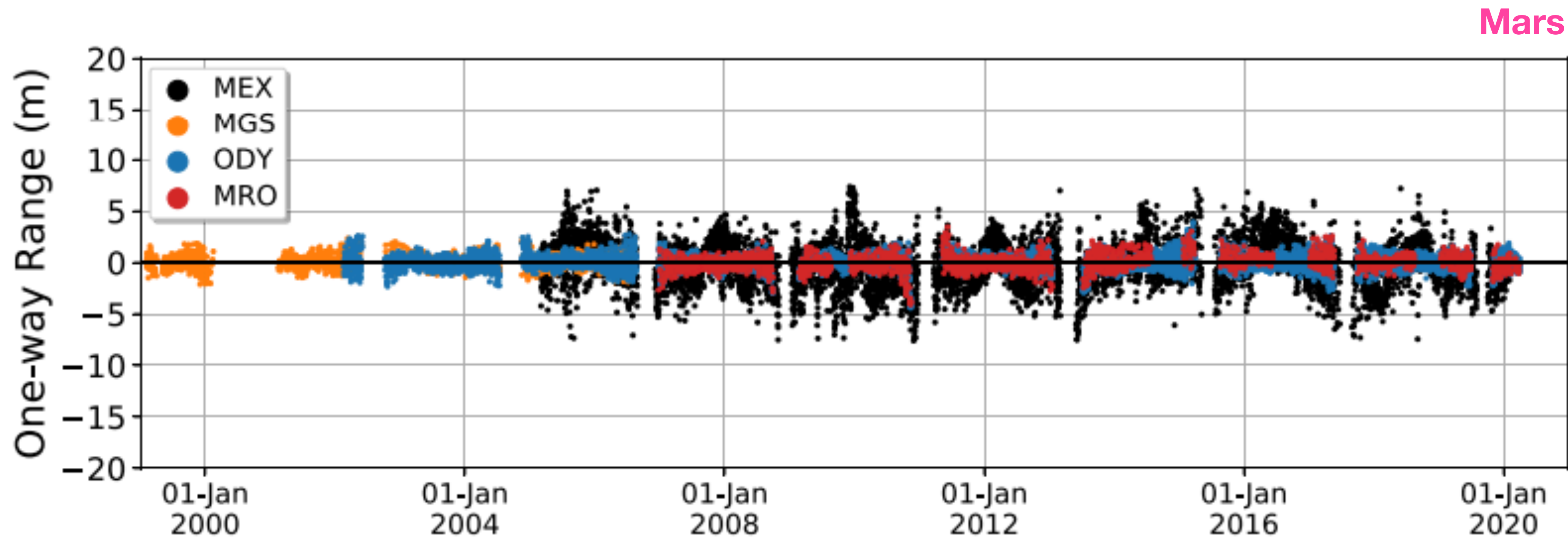
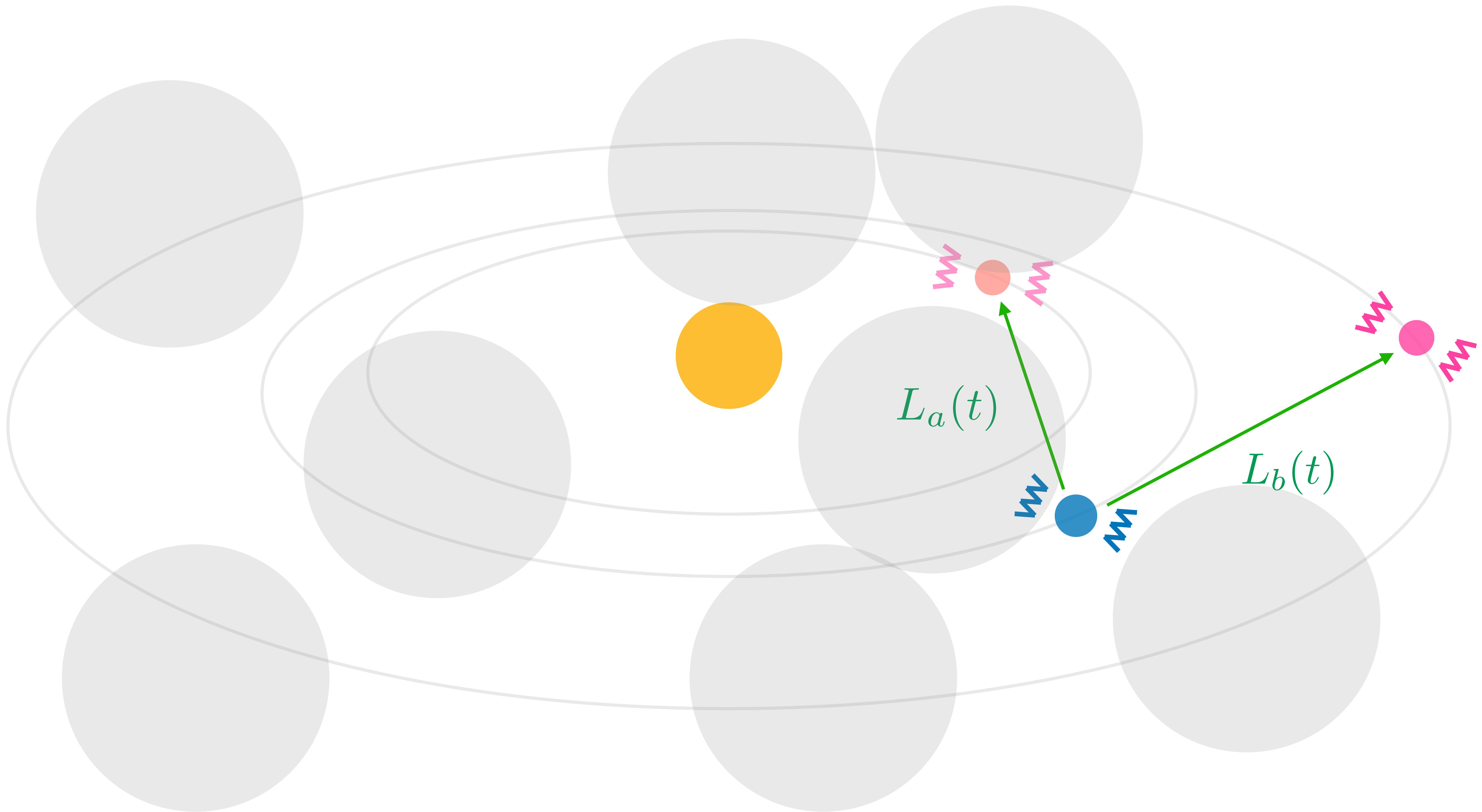


Figure 6. Residuals of the Venus Express range data against DE440. The rms residual of the Venus Express ranges is about 8 m.





signal is similarly characterized by
two-point function

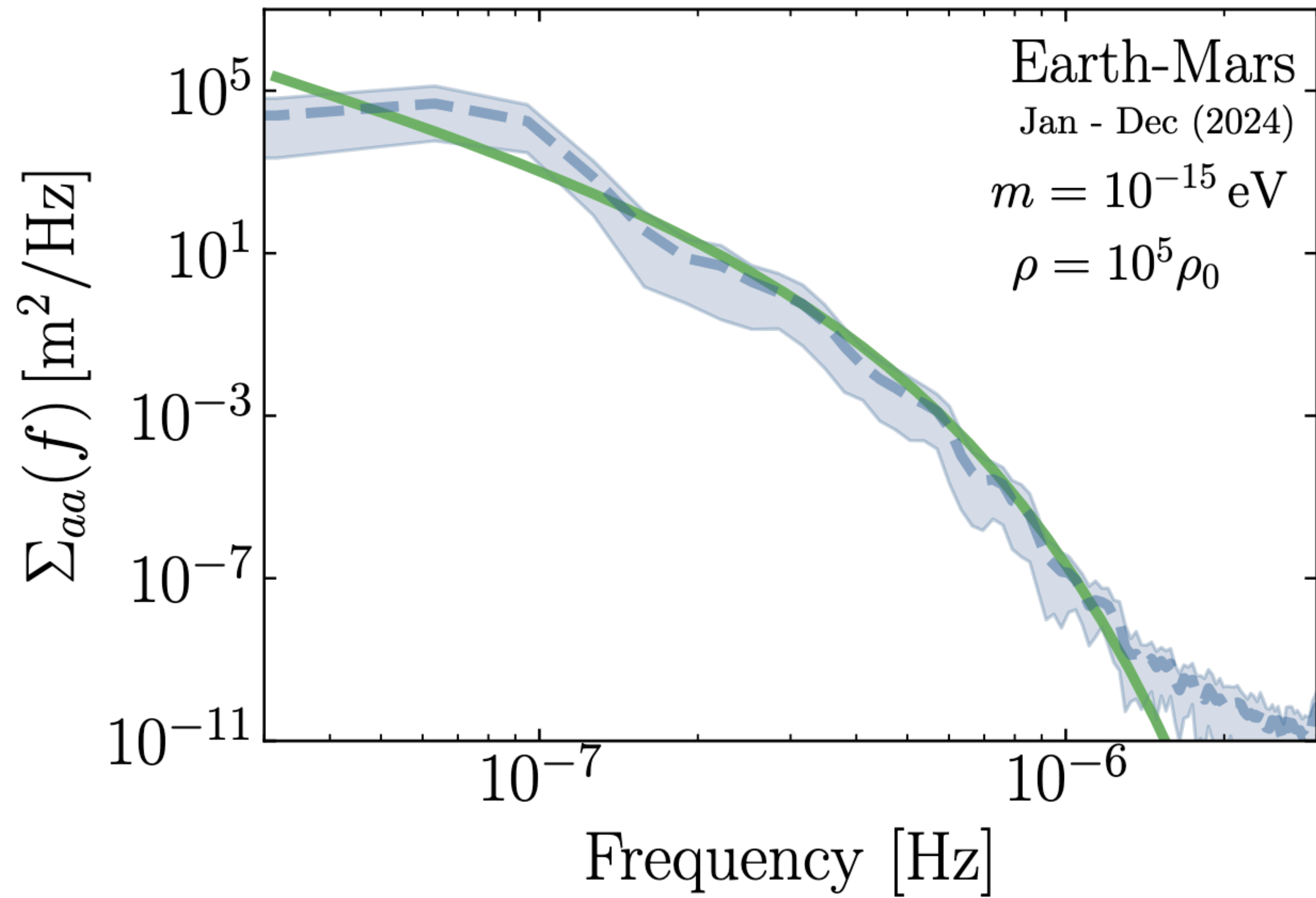
$$\left\langle \widetilde{\Delta L}_a(f) \widetilde{\Delta L}_b(f') \right\rangle = \frac{1}{2} \delta(f - f') S_{aa}(f) \Gamma_{ab}(f, \mathbf{L}_a, \mathbf{L}_b)$$

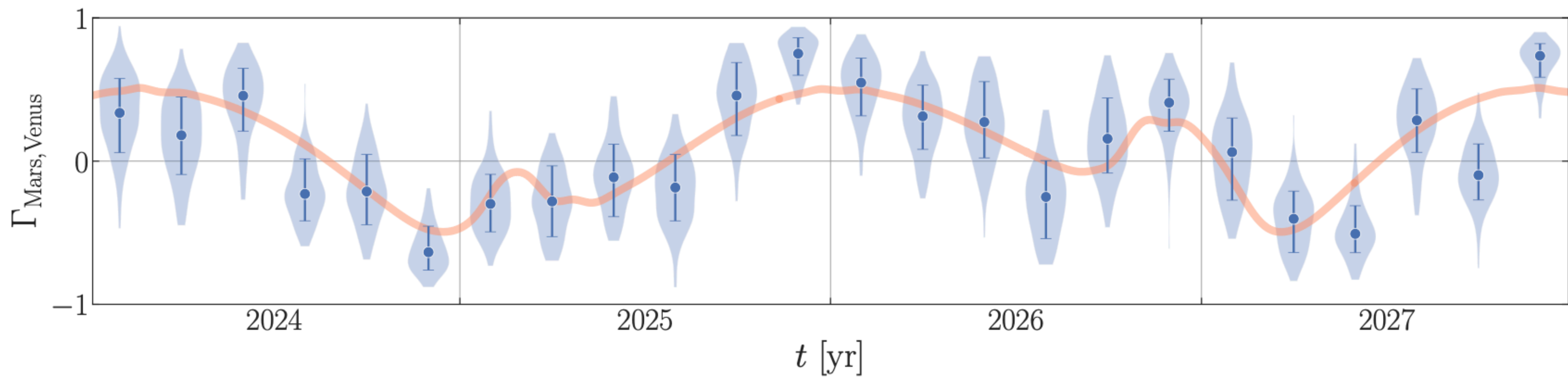
both quantities are analytically calculable
assuming nominal separations are *constant*

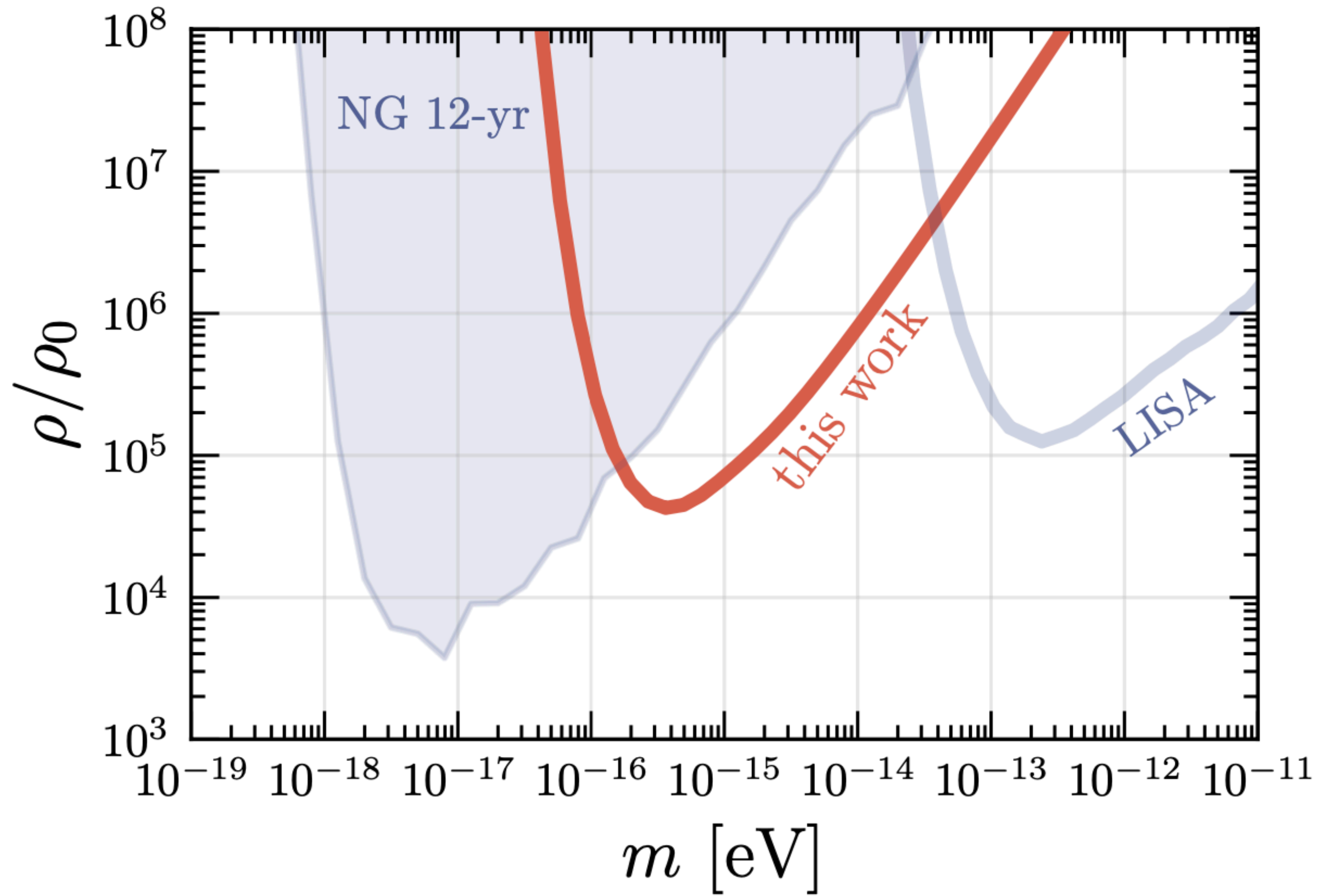
one crucial difference is that
the nominal separation changes over time

$$\left\langle \widetilde{\Delta L}_a(f) \widetilde{\Delta L}_b(f') \right\rangle = \frac{1}{2} \delta(f - f') S_{aa}(f) \Gamma_{ab}(f, \mathbf{L}_a, \mathbf{L}_b)$$

the spectrum and reduction function are
time-dependent







A remark

all of the results shown here are sensitive to
ULDM density around/within the solar system

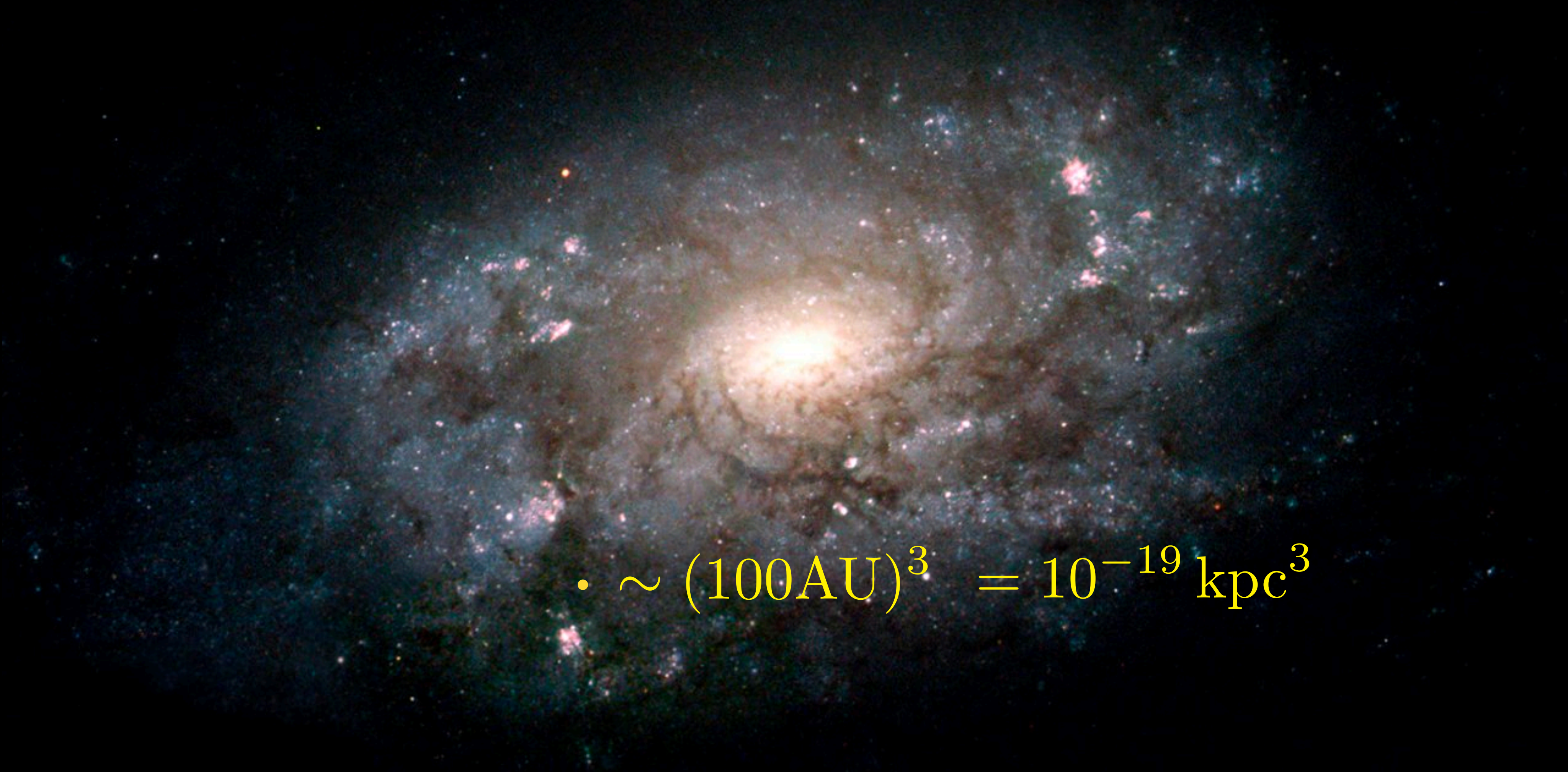
local dark matter density is often derived over kpc scales



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

is an ***average density over the volume of kpc***

what we are probing is
(or what matters for all terrestrial DM detector is)



• $\sim (100\text{AU})^3 = 10^{-19} \text{ kpc}^3$

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)]

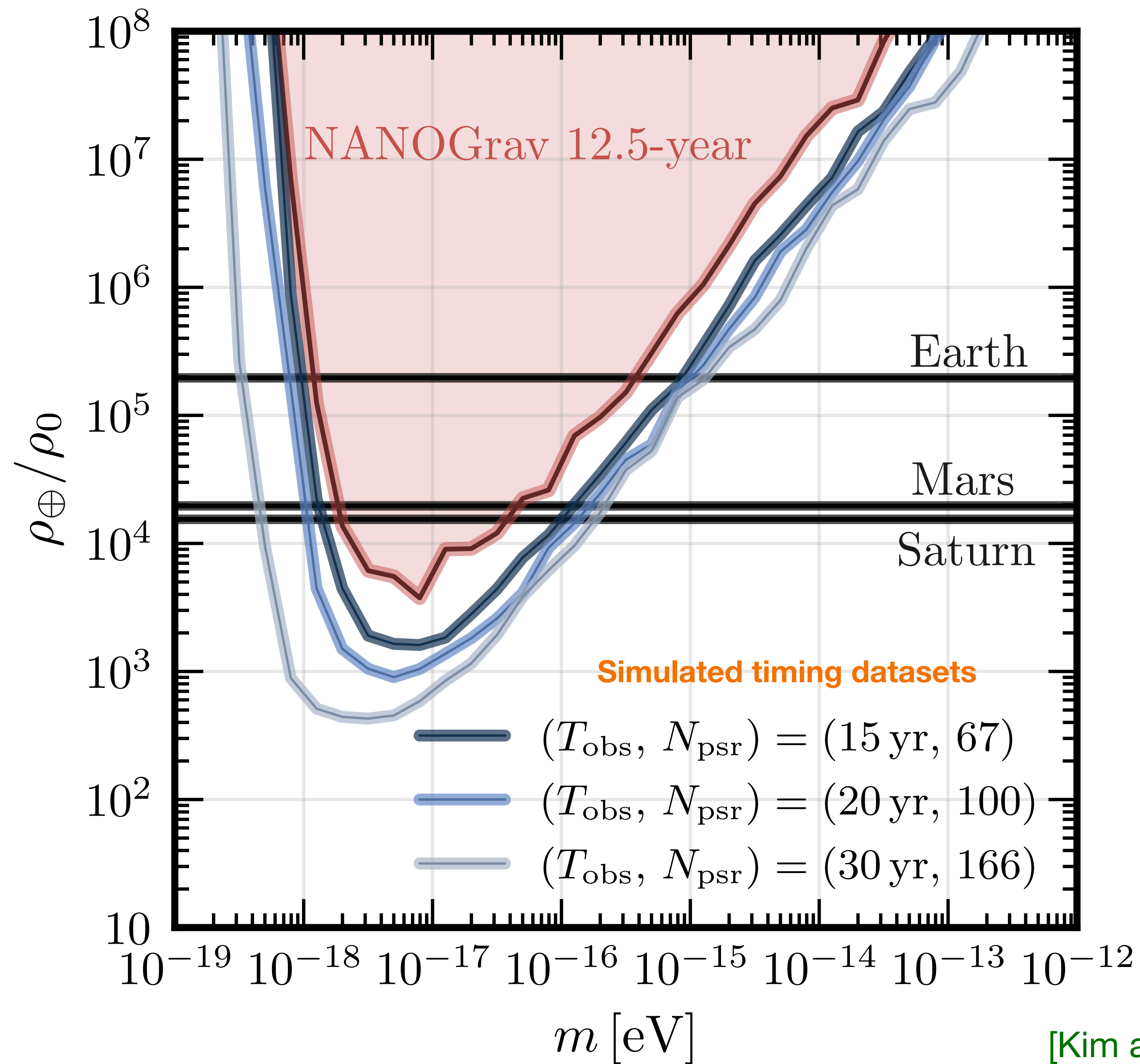
$$\rho/\rho_0 \lesssim 2 \times 10^4$$

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

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

Another remark

prospects of gravitational probes



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

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

$$T_{\text{obs}} = 20^+ \text{ yr}$$

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

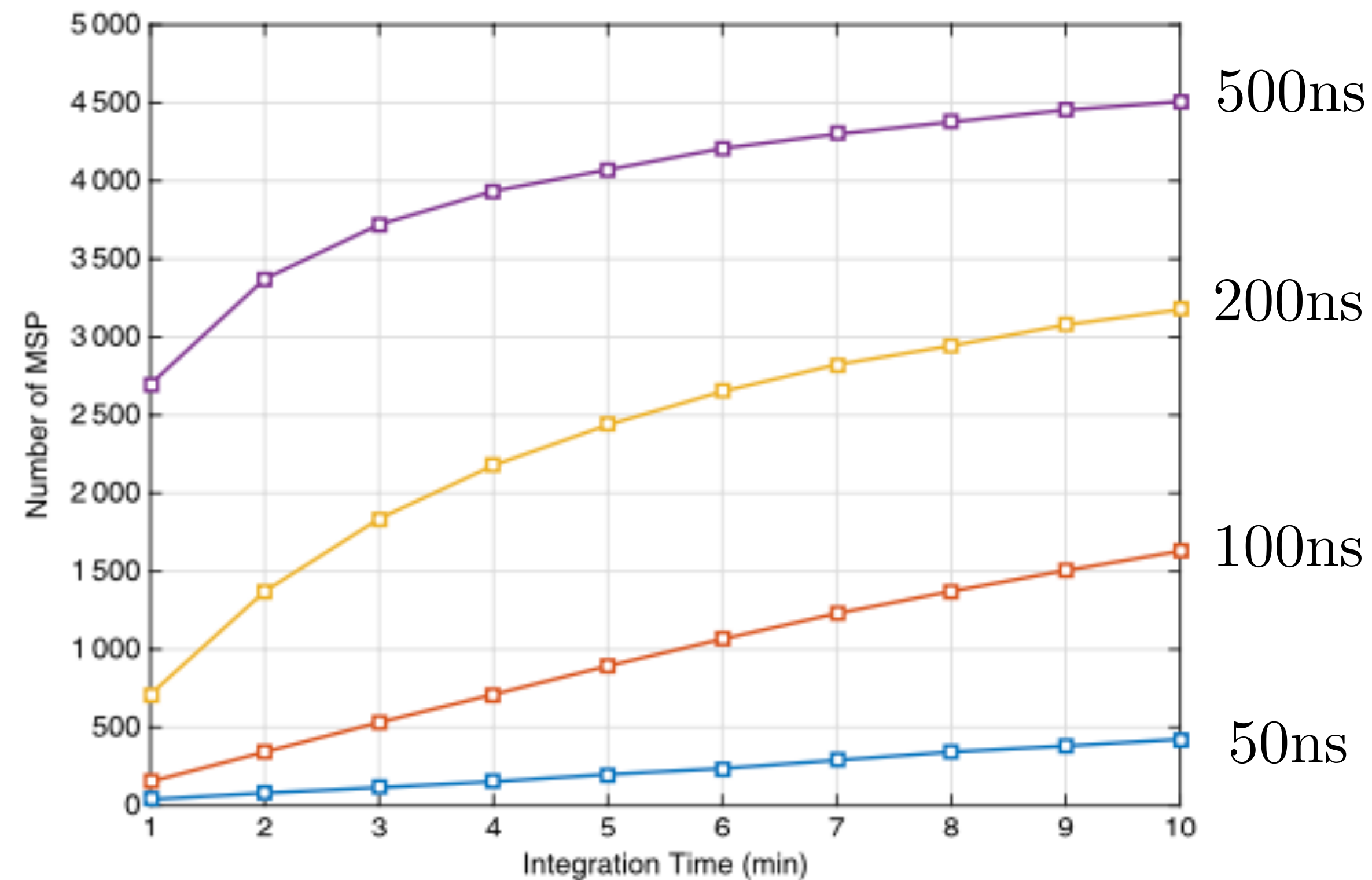


Figure 10. Numbers of MSPs that can archive a certain RMS noise level (or better) with varying integration time. Colour lines indicate different RMS noise levels (from bottom to top): 50 ns (blue), 100 ns (red), 200 ns (yellow), and 500 ns (purple).

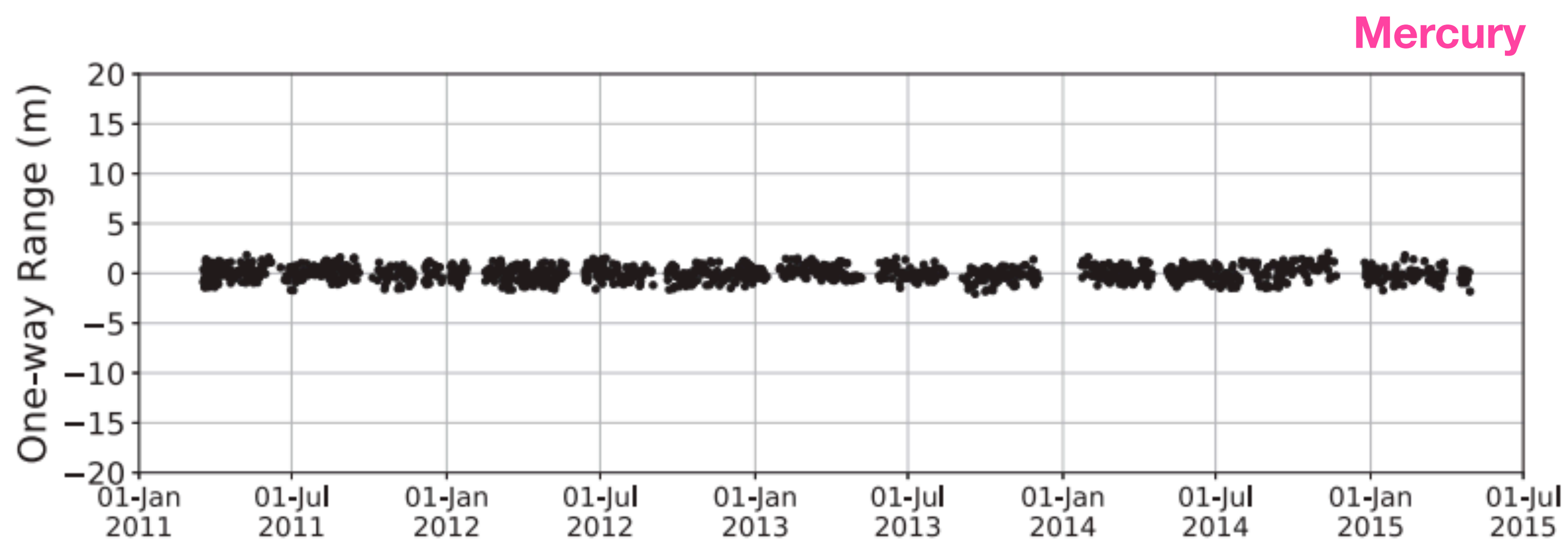


Figure 5. Residuals of the MESSENGER range data against DE440. The rms residual of the MESSENGER ranges is about 0.7 m.

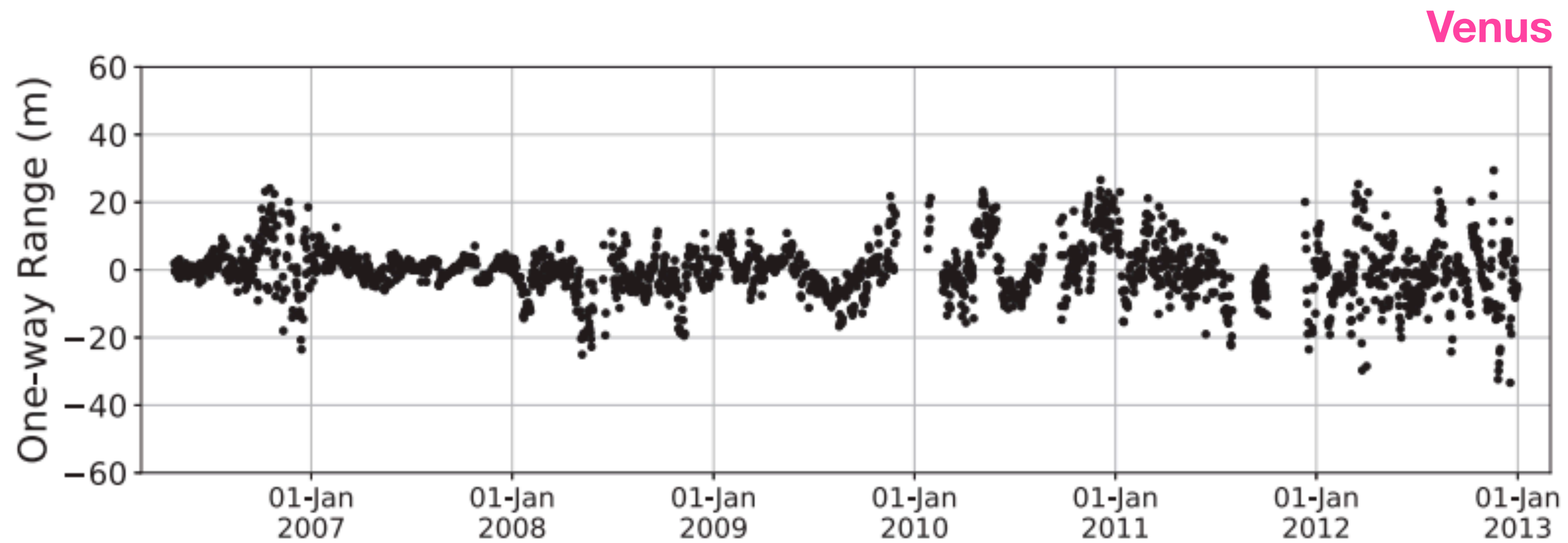


Figure 6. Residuals of the Venus Express range data against DE440. The rms residual of the Venus Express ranges is about 8 m.

BepiColombo: Exploring Mercury

The European Space Agency's mission to Mercury will travel 8,524,000,000 km in seven years to reach the planet closest to the Sun. Upon arrival, the European and Japanese spacecraft will separate and each enter their own orbits around the planet.

MMO

The Mercury Transfer Module (MTM), carries the interplanetary propulsion system. It is jettisoned on arrival.

Mercury

MPO Orbit: 480 – 1,500 km

MPO

The Mercury Planetary Orbiter (MPO) will focus on the surface and interior science of Mercury with instruments that will point continuously at the planet.

As prime contractor for ESA, Airbus is responsible for designing and building all of the European spacecraft hardware.

The Heat shield (MOSIF) protects the Japanese orbiter MMO during the long journey. It is jettisoned at Mercury.

The Mercury Magnetospheric Orbiter (MMO) is the only part of the mission supplied by the Japanese space agency JAXA. It will focus on exploring Mercury's magnetic environment.

MMO Orbit: 590 – 11,640 km

AIRBUS