Detecting ultralight bosonic dark matter with high-precision astronometry

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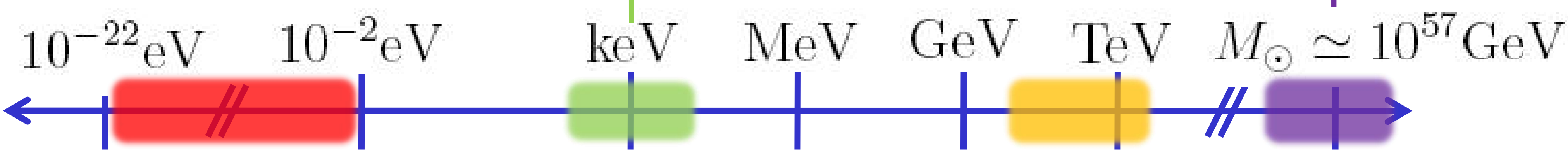
Dark matter candidates

Sterile neutrinos
Neutrino oscillation
X-ray astronomy

Black holes (MACHOs):
Astrophysical detection

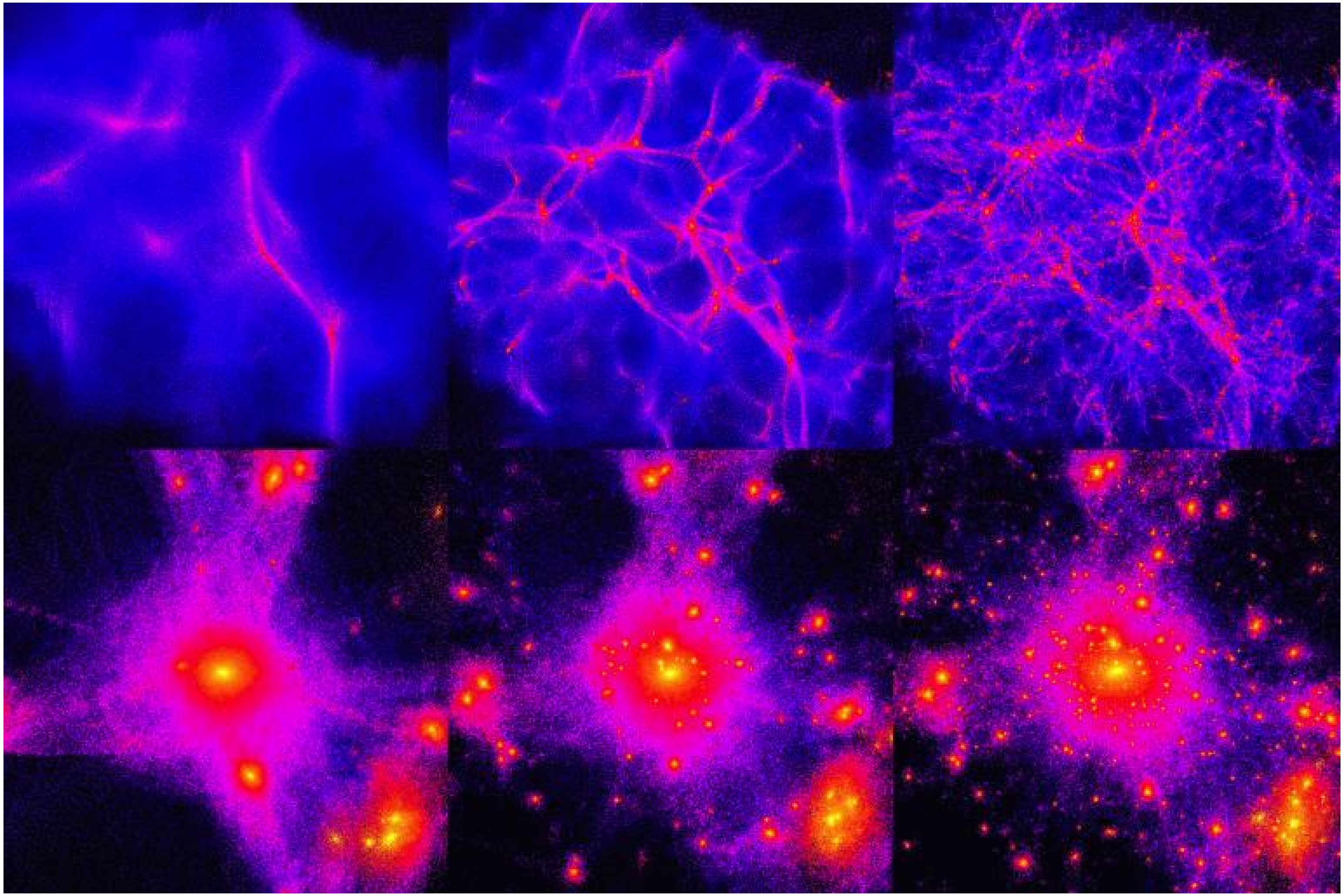


Very light dark matter
Axion, ALP, dark photon ...

WIMPs:
direct detection,
indirect detection,
collider detection

Dark matter should be cold, but not that cold

Courtesy ITC @ University of Zurich



Early

z=0

Hot Warm Cold

Ultralight (fuzzy) dark matter

- Ultralight, bosonic dark matter can form Bose-Einstein condensation and serve as cold DM

- Ultralight DM (~10^{-22} eV) appear like a coherent wave with wavelength comparable to a dwarf galaxy, which may solve the cusp-core problem of cold DM (Hu et al., 2000)

$$i(\partial_t + \frac{3}{2}\frac{\dot{a}}{a})\psi = (-\frac{1}{2m}\nabla^2 + m\Psi)\psi$$

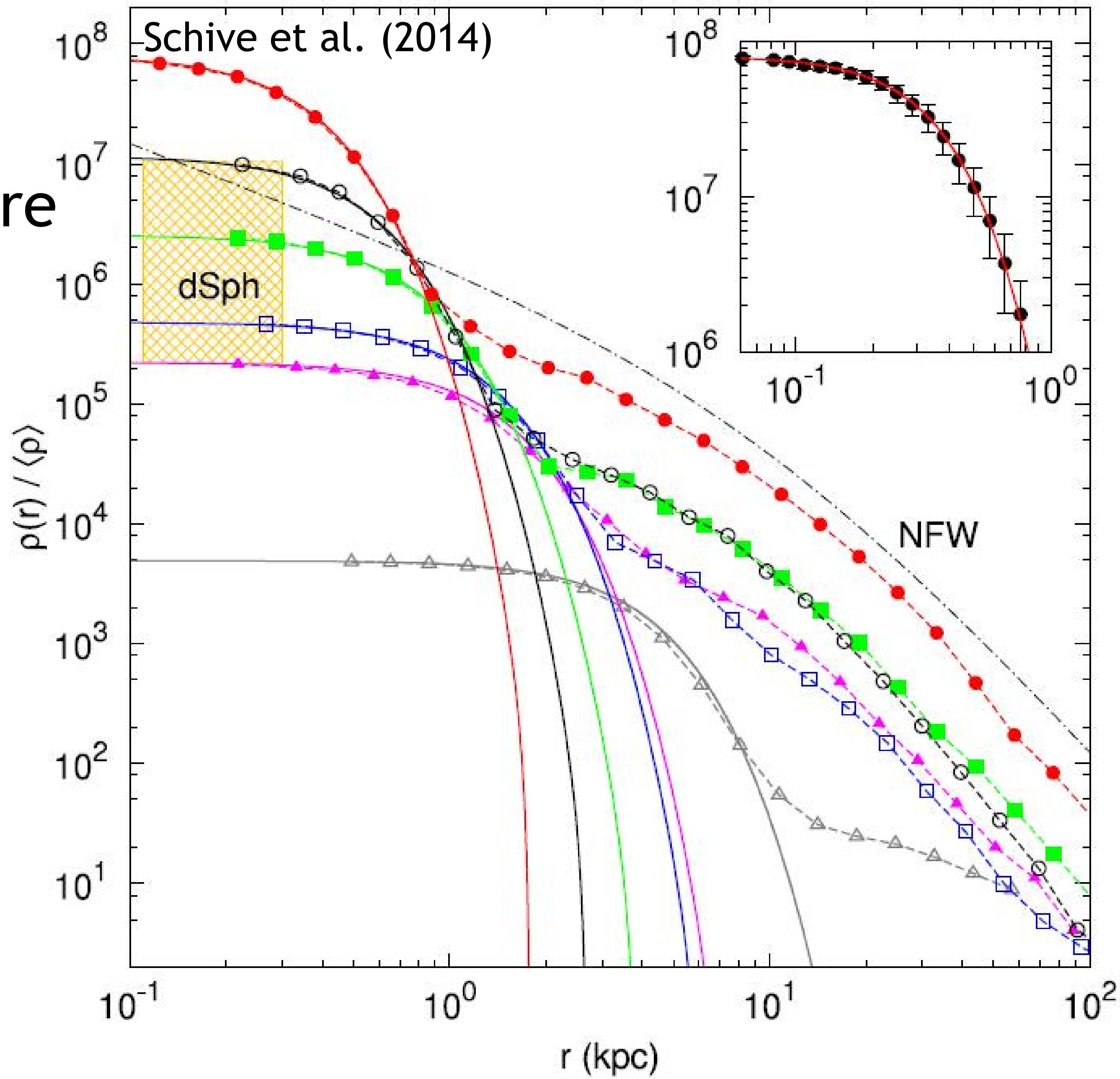
$$i\partial_t\psi = (-\frac{1}{2m}\nabla^2 + m\Psi)\psi\,, \quad \nabla^2\Psi = 4\pi G\delta\rho$$

$$r_{J\mathrm{h}} \sim 3.4(c_{10}/f_{10})^{1/3} m_{22}^{-2/3} M_{10}^{-1/9} (\Omega_m h^2)^{-2/9} \mathrm{kpc}$$

Jeans scale: below which perturbation is stable and above which behaves like CDM

Ultralight (fuzzy) dark matter

Soliton core



Detection of ultralight (fuzzy) DM

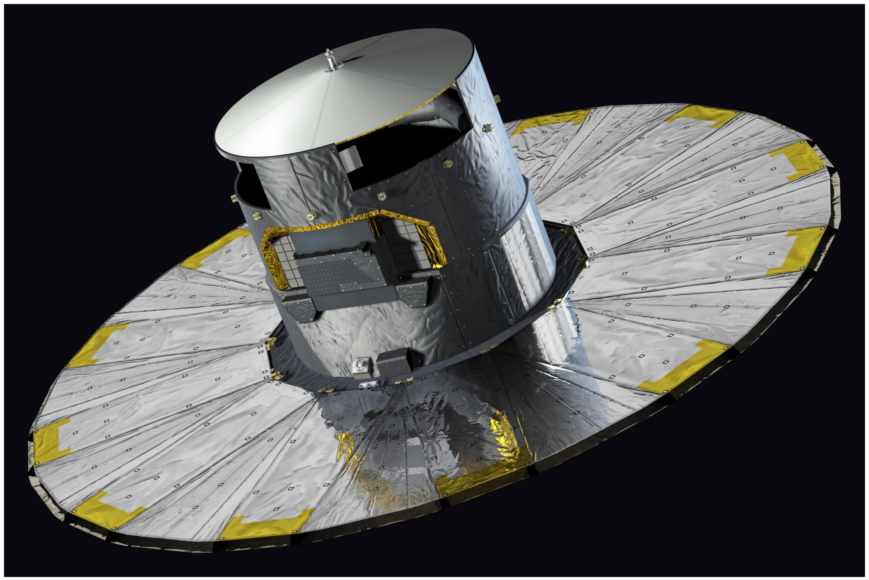
- Due to its very small mass, it is very difficult to detect them with conventional particle detector

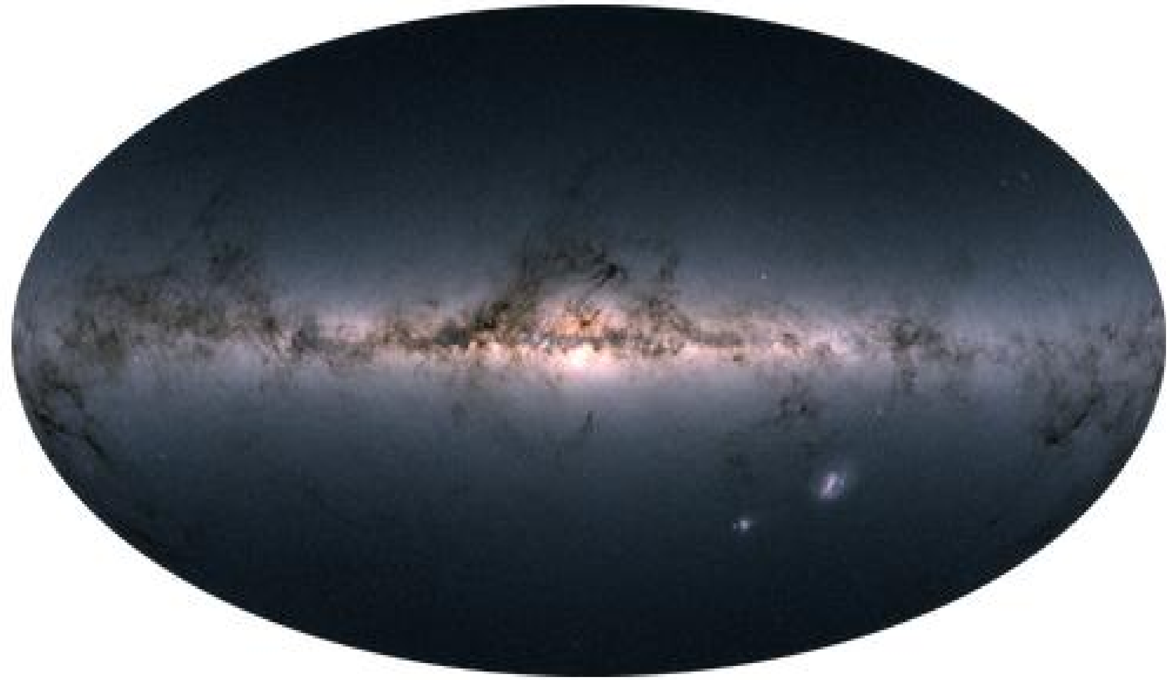
- Astronomical method to try to detect a cumulative effect of such dark matter is a possible way

- Timing measurements (by PTA) of highly stable pulsars

- Astrometry observations (by Gaia) of positions of large number of stars

High-precision astrometry by Gaia

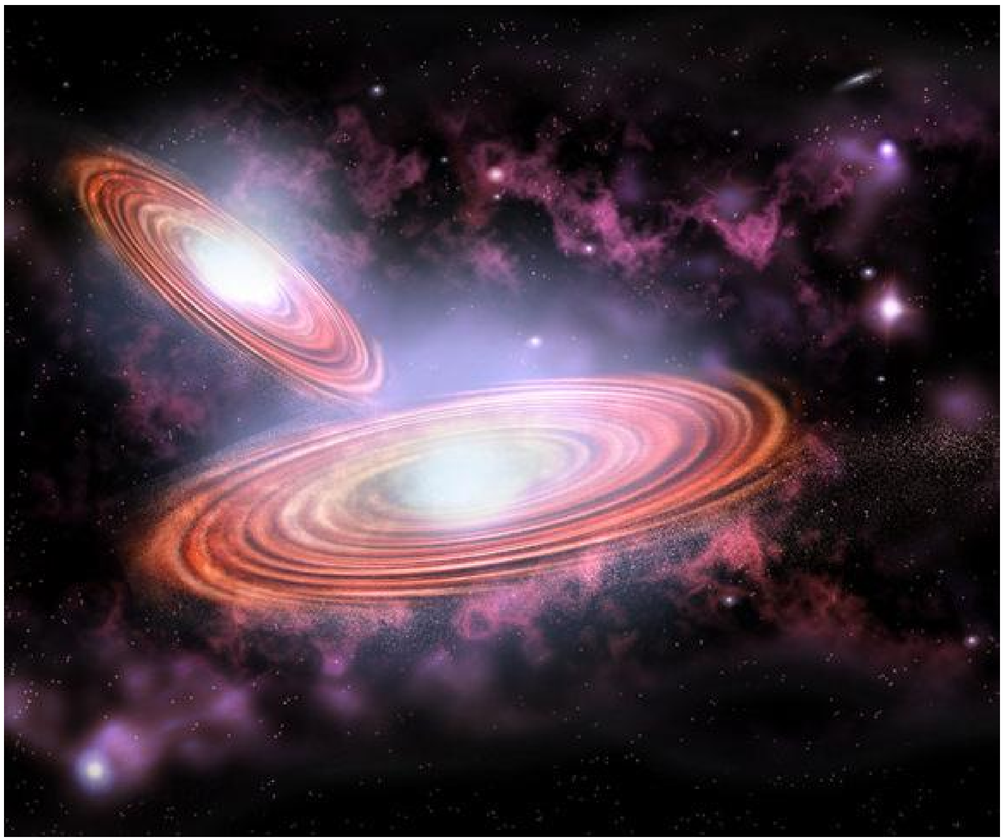




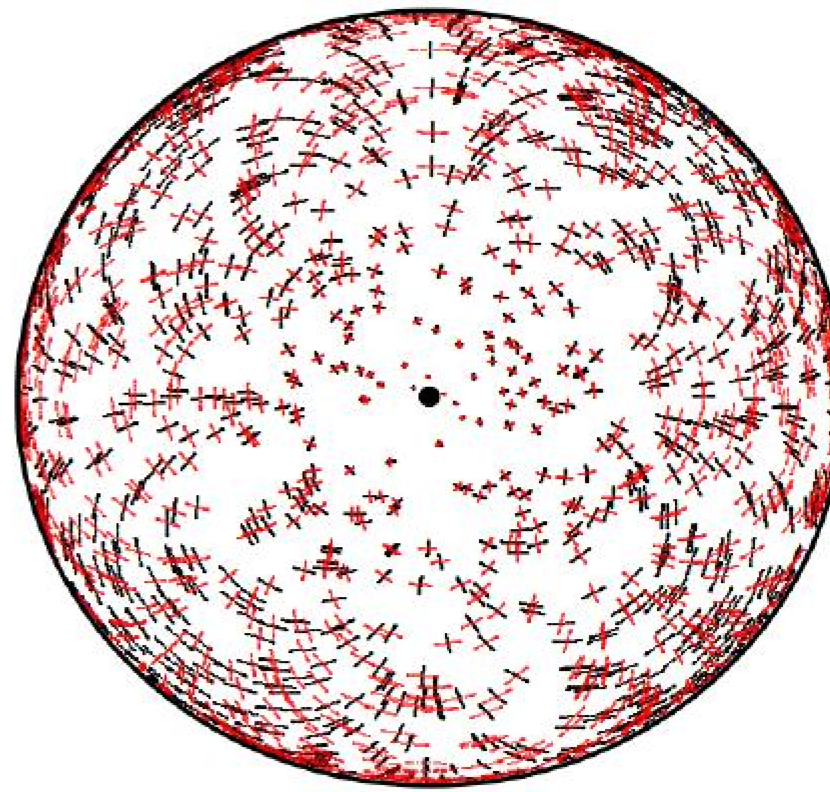
- Very high precision of location measurements (~100 μas) of large amount of stars (~10^9)
- A revolution in probing structure and dynamics of the Milky Way, stellar physics, exoplanets, and fundamental physics
- 2nd data release in 2018, with astrometry (location, movements) and astrophysical (temperature, variability etc.) data of a large number of stars

Detecting gravitational wave with Gaia

Binary supermassive black hole inspiral: T (yr), h(1e-15)



$$\delta n_i = \frac{n_i - q_i}{2(1 - \vec{q}\cdot\vec{n})} h_{jk}(\mathrm{E}) n^j n^k - \frac{1}{2} h_{ij}(\mathrm{E}) n^j$$



Moore et al. (2017)

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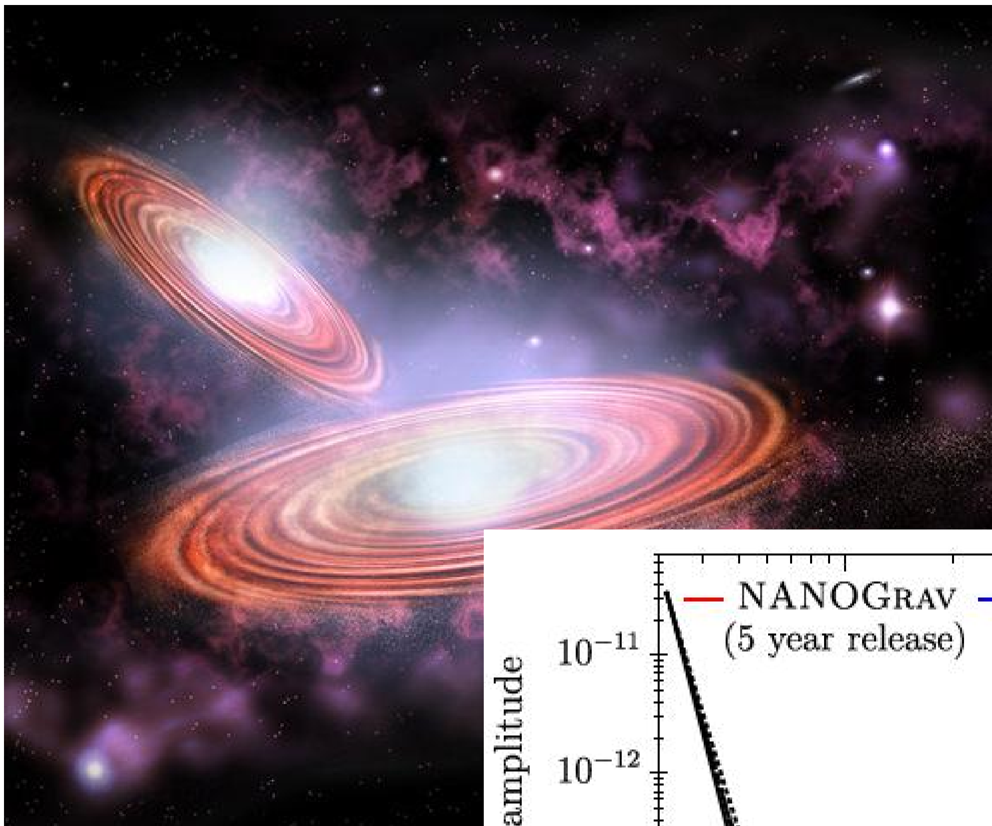
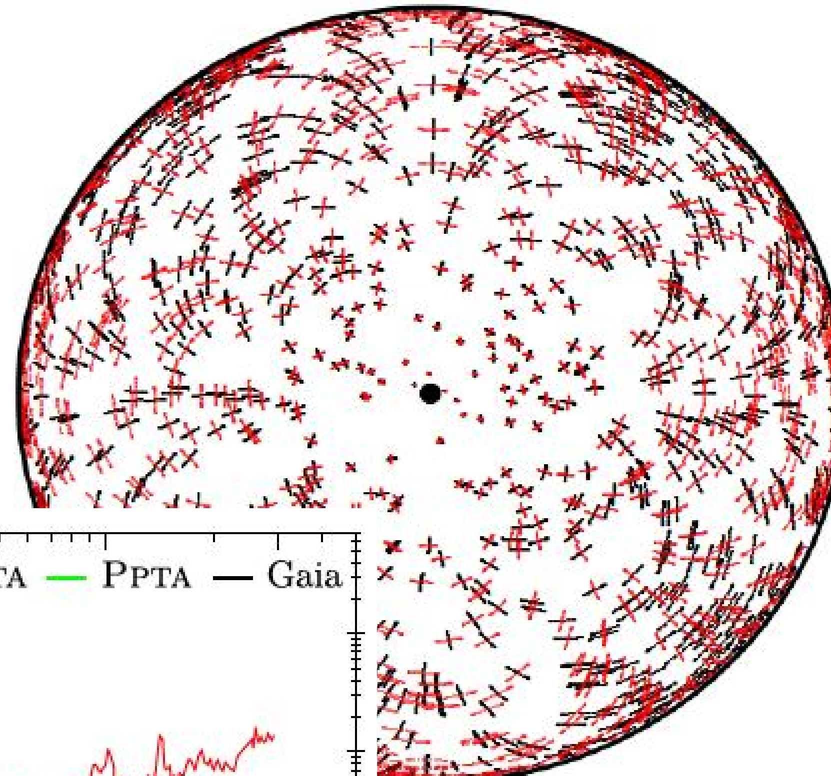
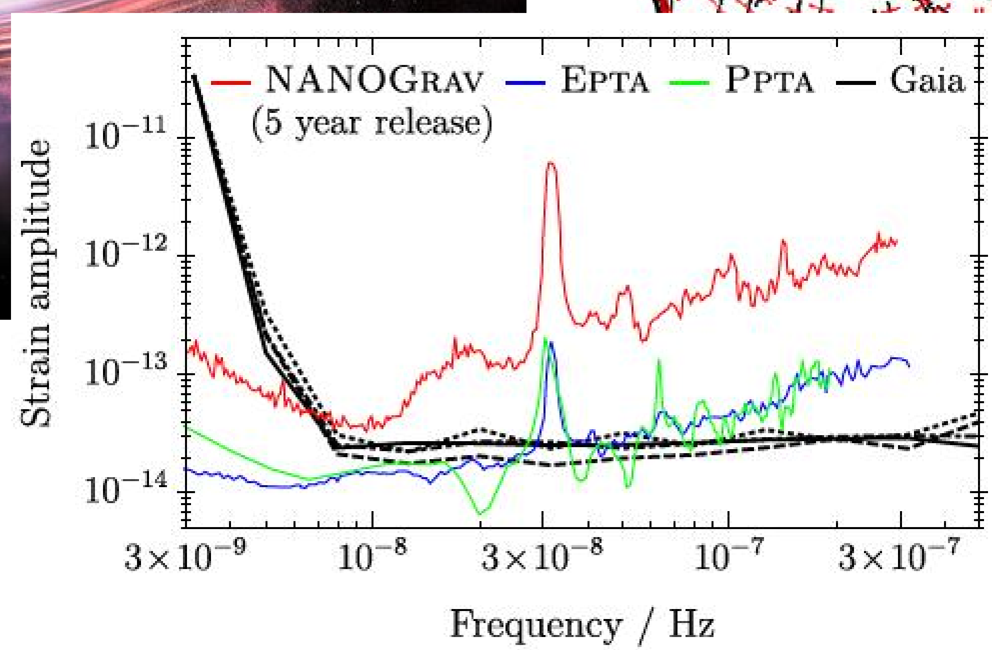






Moore et al. (2017)

Astronomical detection of ultralight dark photon dark matter (DPDM)

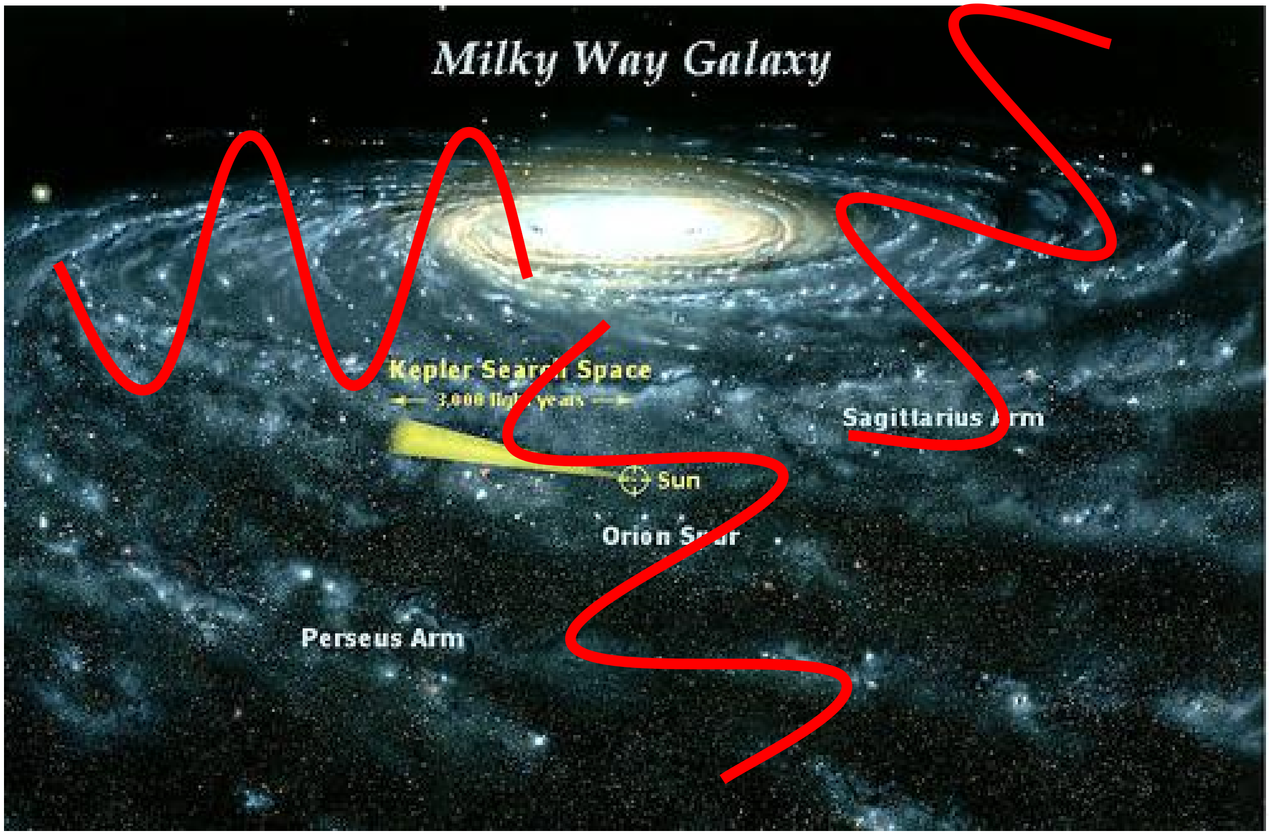
- A hypothetical hiden-sector particle proposed as a force carrier similar to photon

- Considering a special class of dark photon which is the gauge boson of the $U(1)_B$ or $U(1)_{B-L}$ group: it would interact with any object with B or (B-L) number (“dark charge”)

- A good candidate of (fuzzy) dark matter (DPDM)

- If its mass is very small (10^{-22} eV), the dark photon behaves like an oscillating background, drives displacements for particles with “dark charge”

Ultralight DPDM



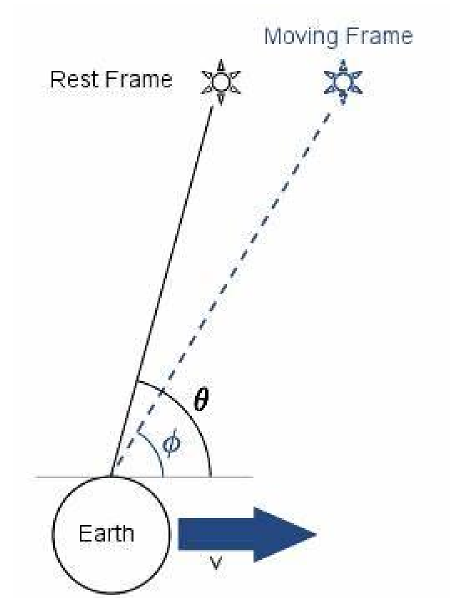
- Coherence length:
  $l \sim 0.4 (m_A/10^{-22}\,\mathrm{eV})^{-1}\,\mathrm{kpc}$
- Coherent time: $(m_A/10^{-22}\mathrm{eV})$ Myr
- Frequency: 30 nHz$\times(m_A/10^{-22}\mathrm{eV})$
- Within the reach of Gaia: 5-10 yrs of operation

Detecting DPDM with astrometry

- A test body (e.g., the Gaia satellite) with the "dark charge" would feel a force due to the coupling with the dark photon background, generating an additional oscillation

$$\boldsymbol{a}(t,\boldsymbol{x}) \simeq \epsilon e \frac{q}{m} m_A \boldsymbol{A_0} \cos(m_A t - \boldsymbol{k}\cdot\boldsymbol{x})$$

- The aberration of light leads to variation of apparent locations of stars

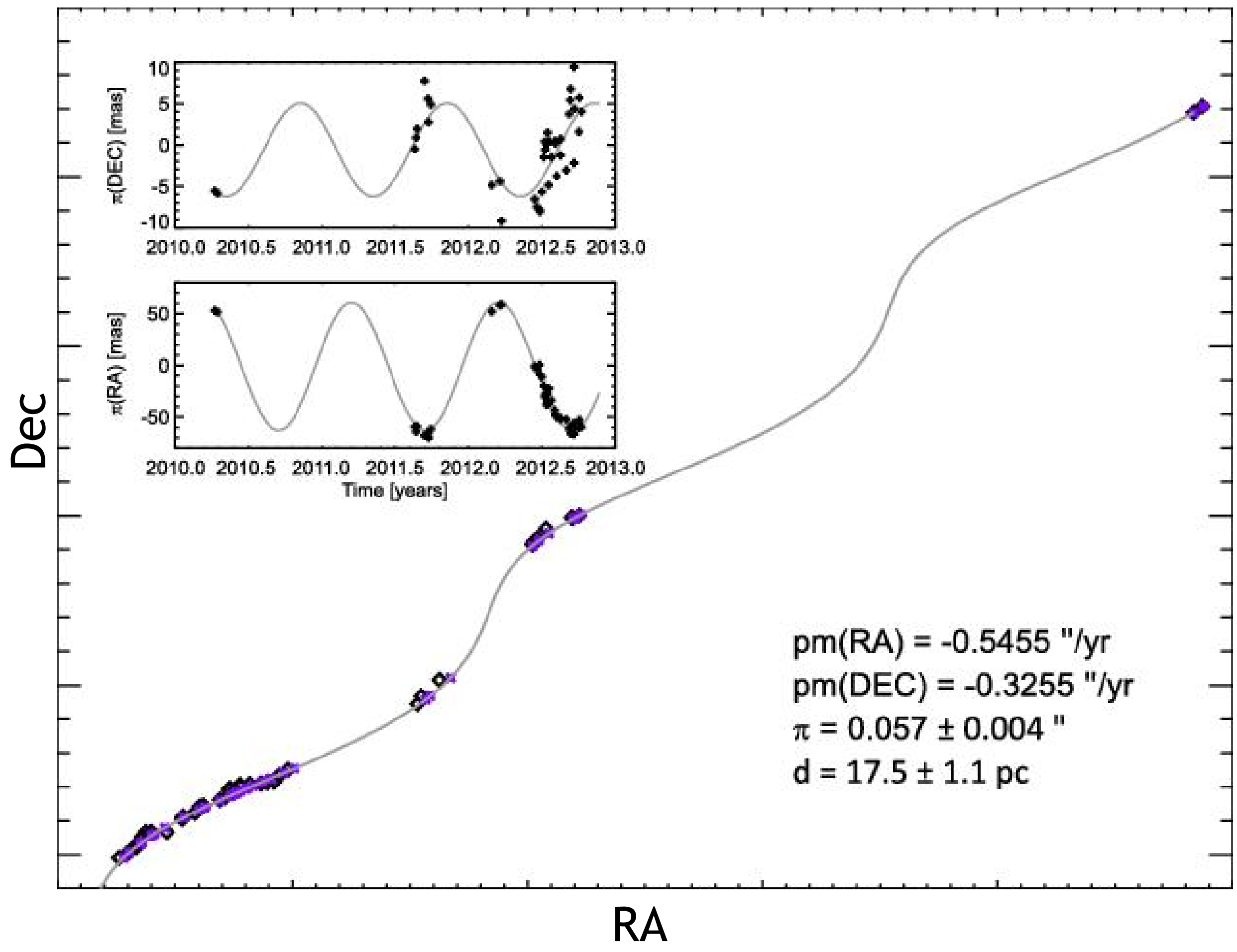


$$\Delta \boldsymbol{v}(t,\boldsymbol{x}) \simeq \epsilon e \frac{q}{m} \boldsymbol{A_0} \sin(m_A t - \boldsymbol{k}\cdot\boldsymbol{x}). \qquad \Delta\theta \simeq -\Delta v \, \sin\theta$$

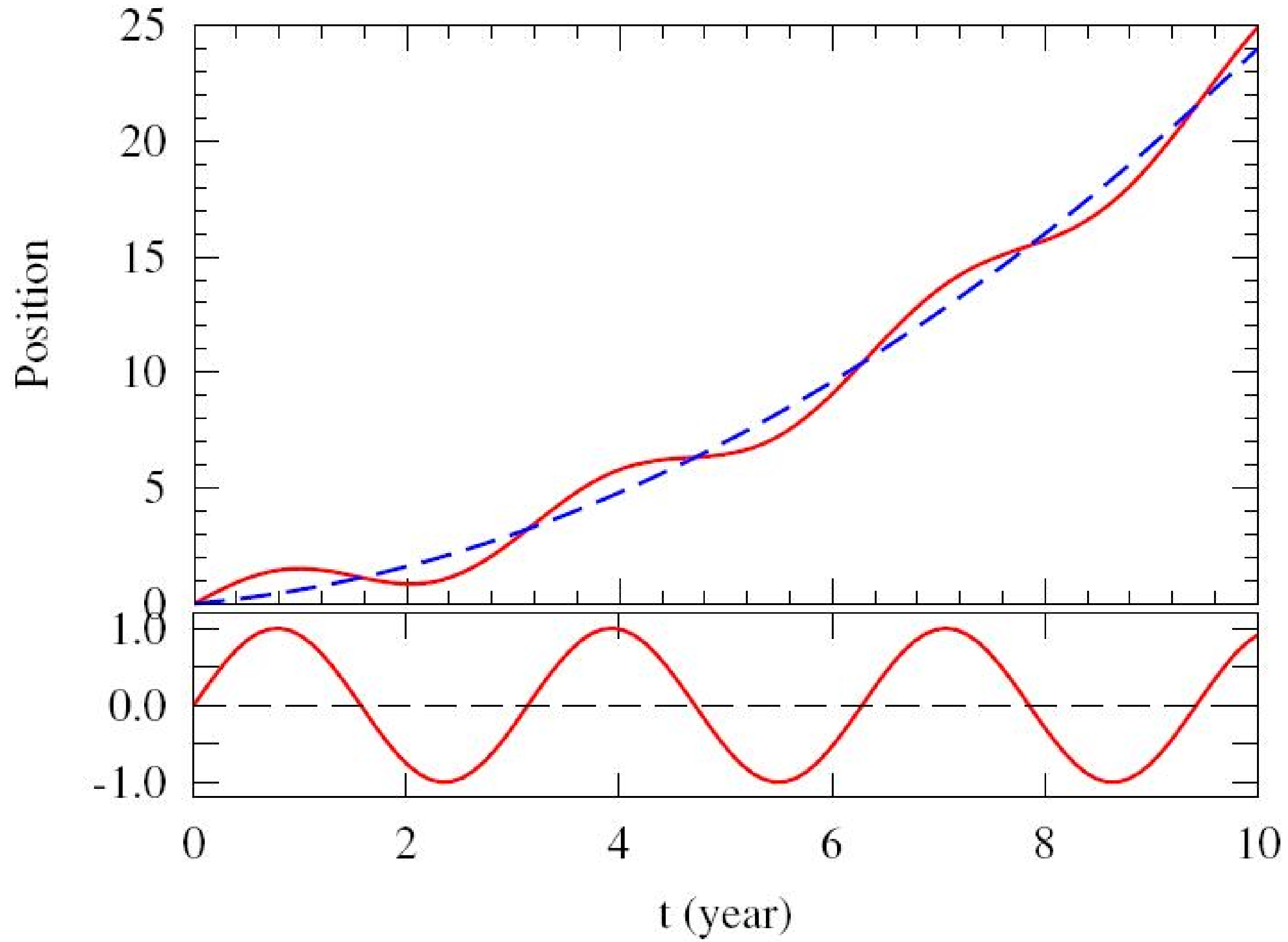
- Many stars show a pattern of their location variations

Background

- Parallax (satellite's orbiting around the earth and the earth's orbiting around the sun)
- Abberation of light (motion of the satellite, the earth, and the sun)
- Proper motion of the star itself

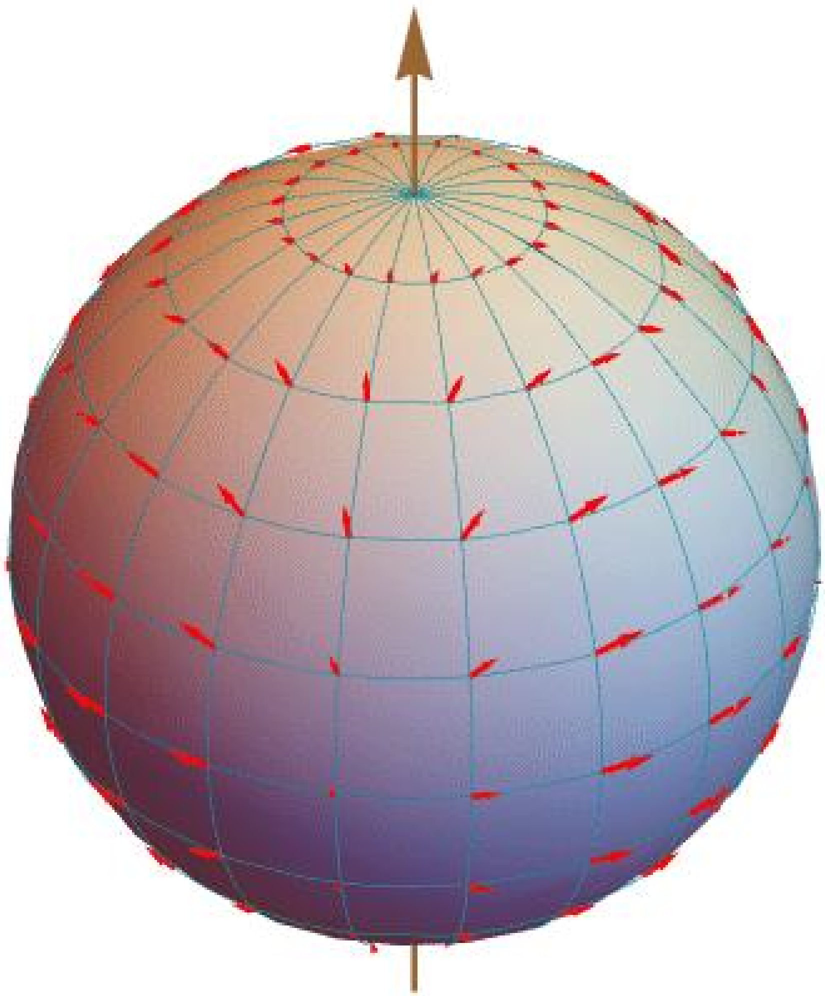


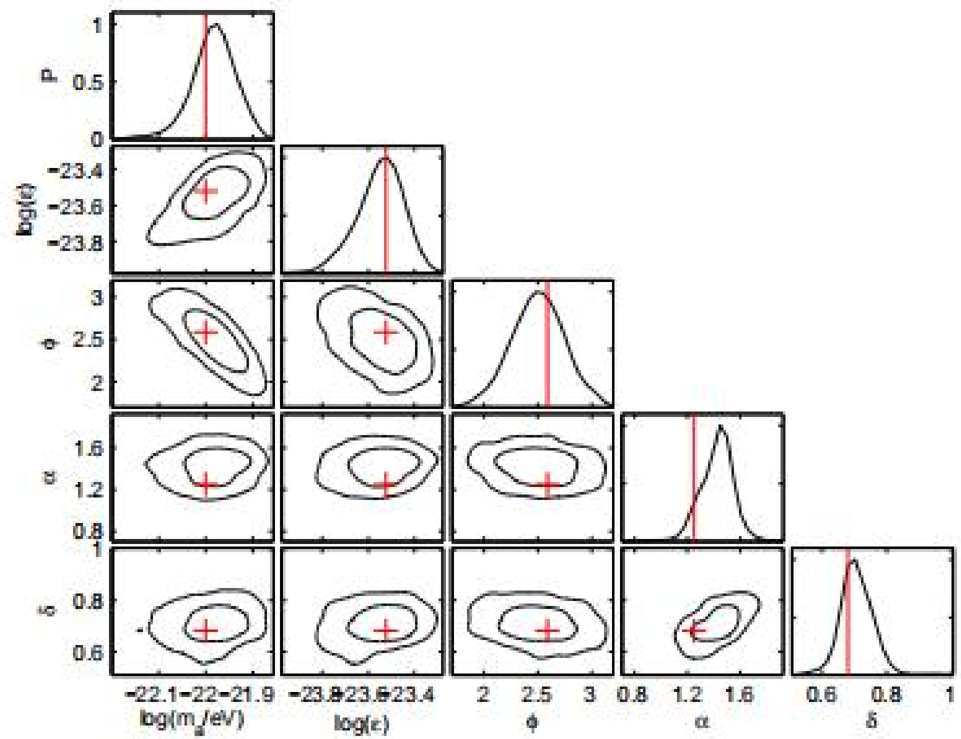
Background subtraction



- Assuming the satellite's and earth's orbits are precisely known
- Using a quadratic function to model the proper motion
- Simulate the proper motion and subtracted through a fitting

Simulation and reconstruction



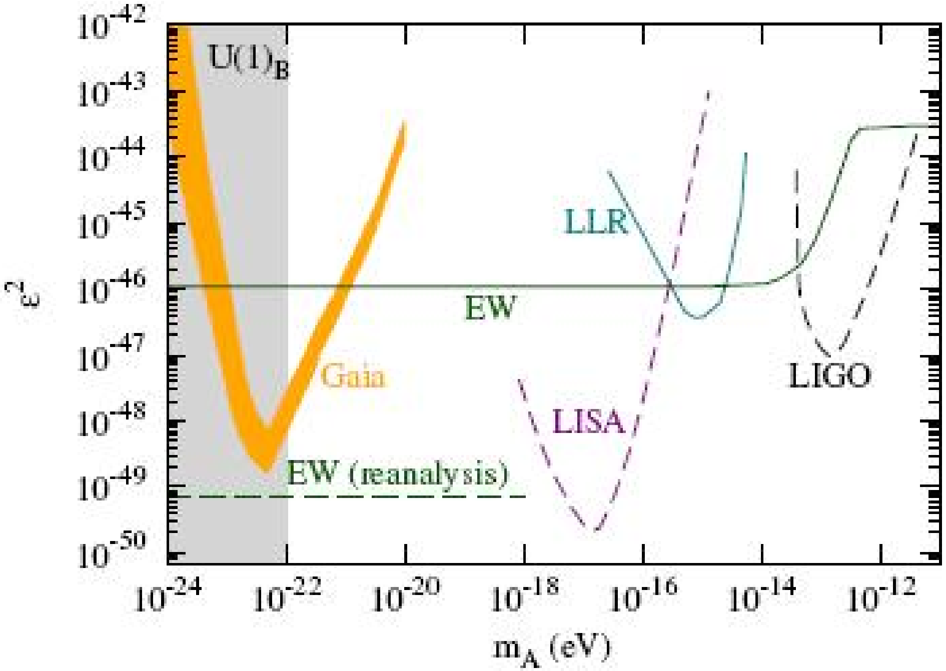


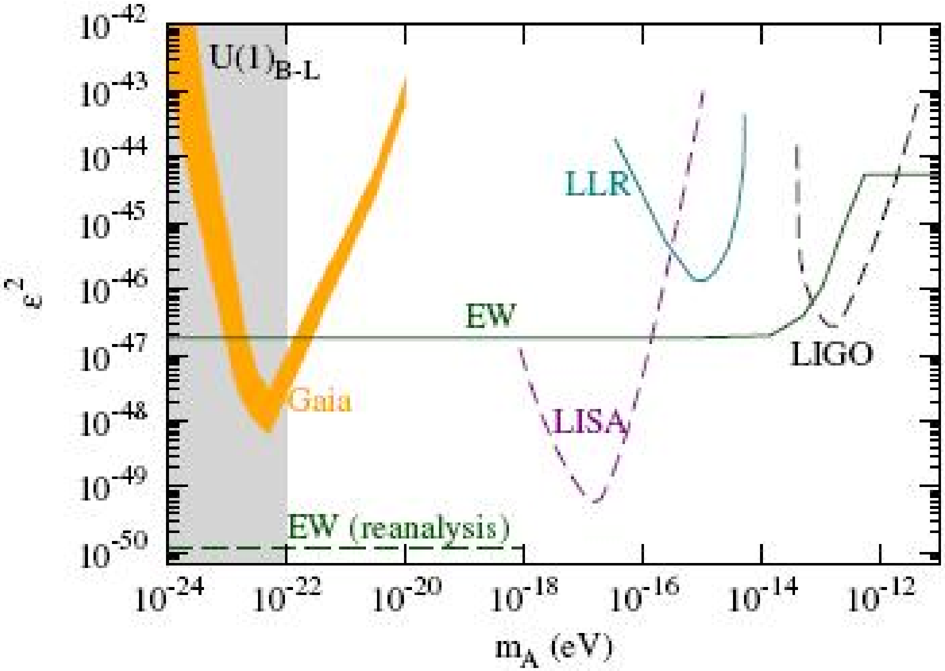
$$(m_A, \epsilon, \phi, \alpha, \delta) = (10^{-22}\ \mathrm{eV}, 3\times 10^{-24}, 2.59, 1.25, 0.68)$$

Oscillation pattern

Sensitivities on dark photon couplings

1902.05962





- Reach the best sensitivities for $m_A<10^{-21}$ eV
- Sensitivities become worse when $m_A<10^{-22}$ eV due to that the subtraction of background motion also removes part of the signal

Summary

- Bosonic dark matter with ultra-small mass is a well motivated candidate for dark matter

- Its wave nature would results in coherent oscillation of objects (either the detectors or the targets) located in this dark matter background

- High-precision astrometry observations (by e.g., CSST) can effectively probe such kind of ultralight dark matter which is, however, difficult to be detected by other ways

Thanks for your attention!