Detecting ultralight bosonic dark matter with high-precision astronometry and timing

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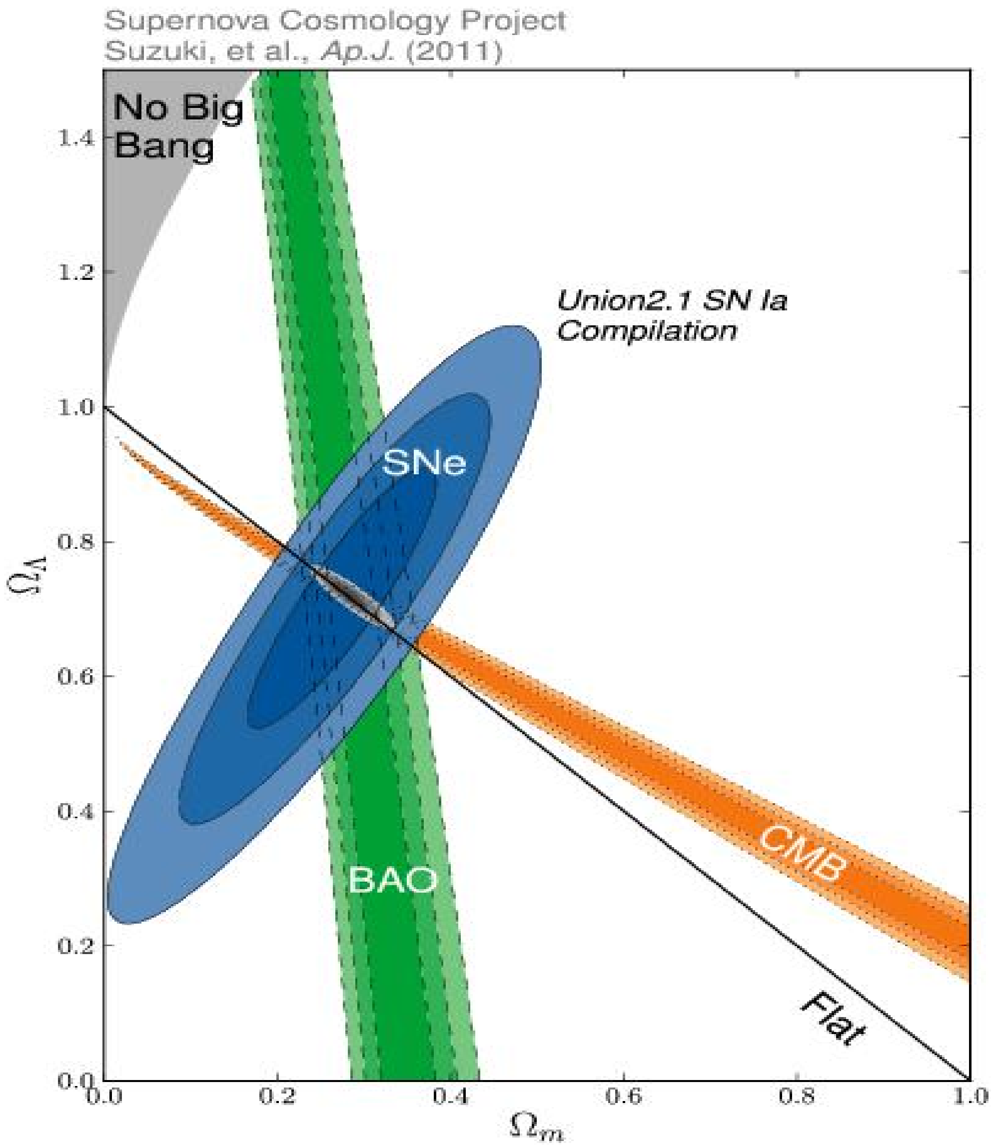
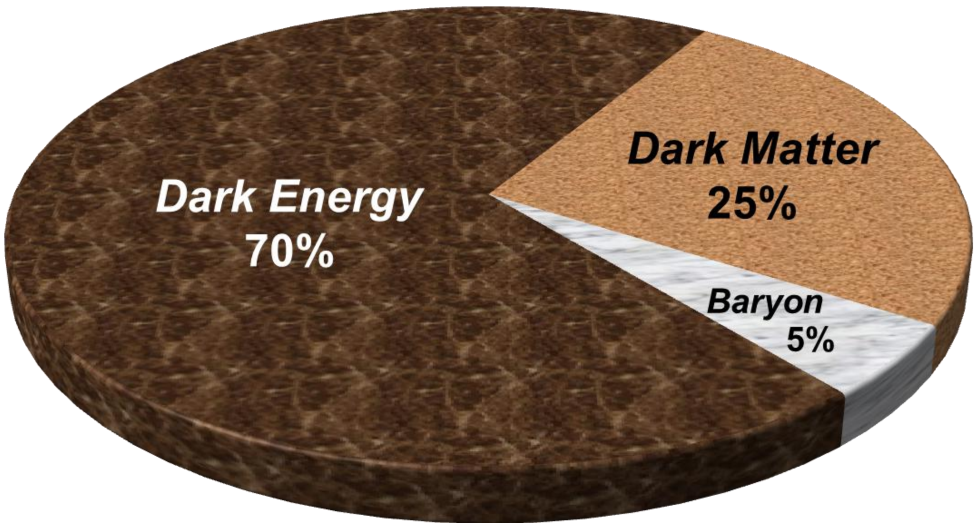
With Huaike Guo, Yingqi Ma, Jing Shu, Xiao Xue, and Yue Zhao (arXiv:1902.05962)

2nd TDLI Mini-Workshop on "New Physics at the Tera Scale", Shanghai, 2019.8.3-5

Standard model of cosmology

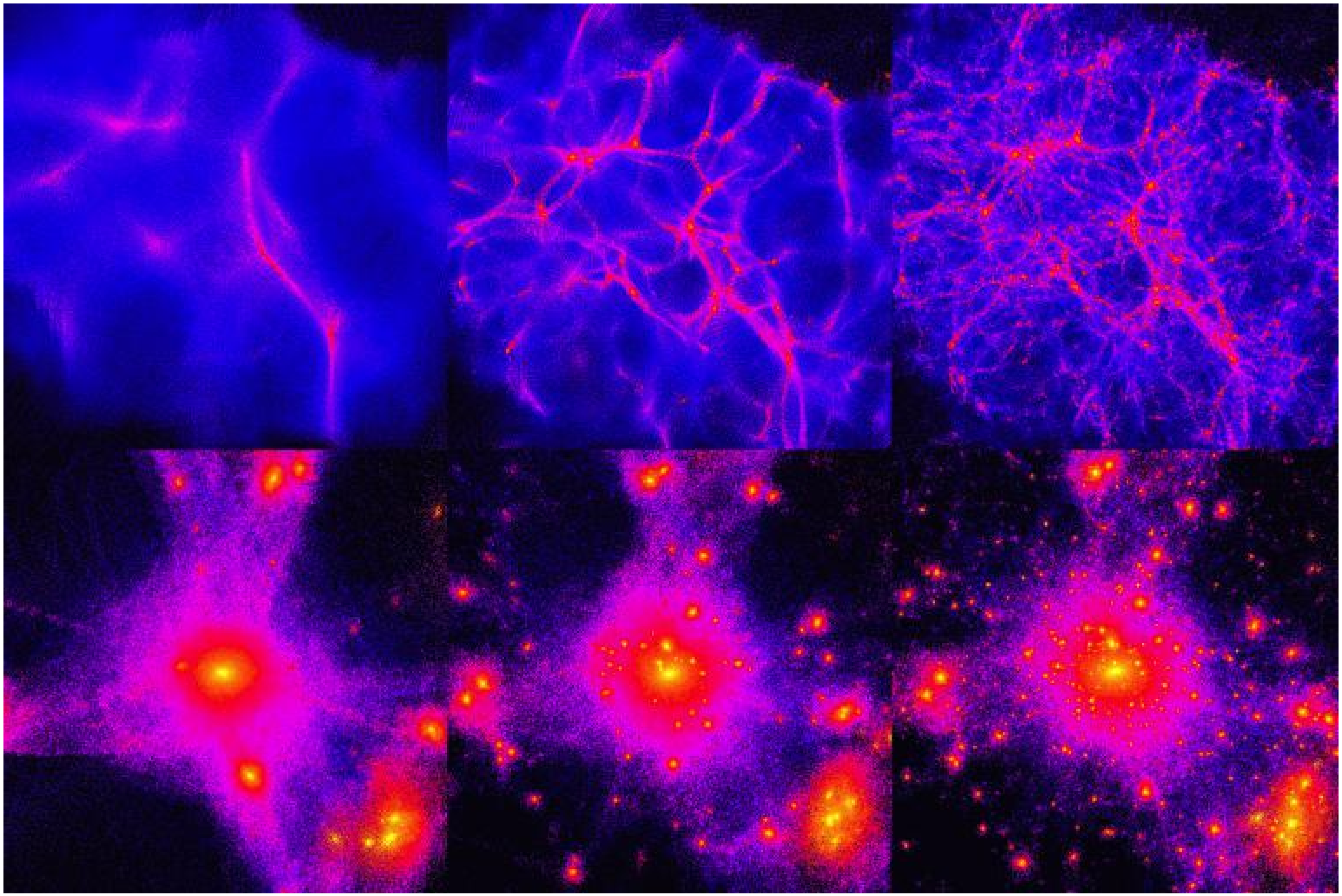




- The universe is made up of 70% dark energy, 25% dark matter and 5% ordinary matter
- We know little about the Universe!

Dark matter should be cold, but not that cold

Courtesy ITC @ University of Zurich



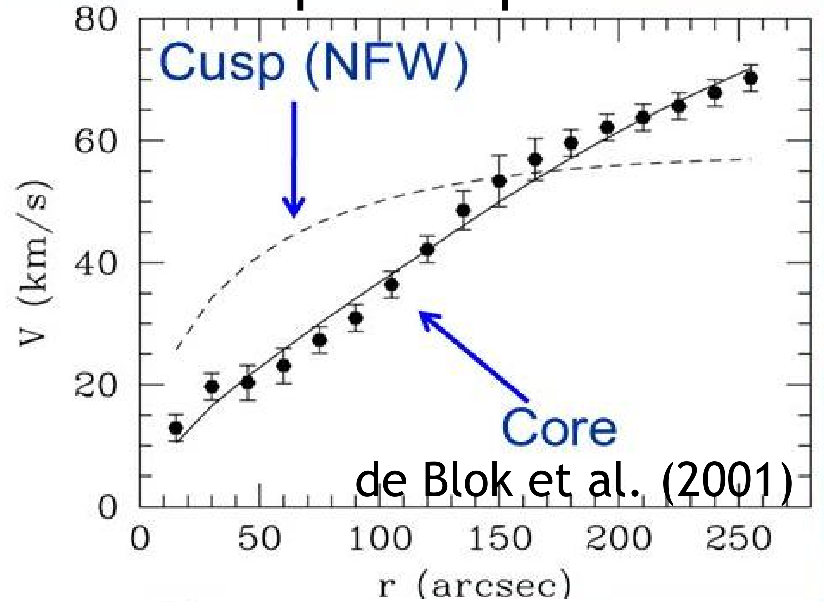
Early

z=0

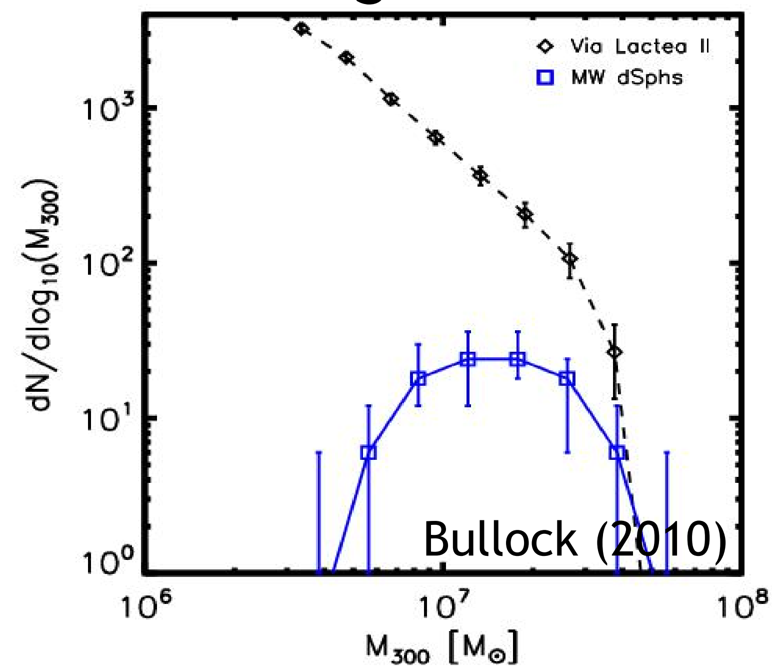
Hot　　Warm　　Cold

Small-scale problems of cold dark matter

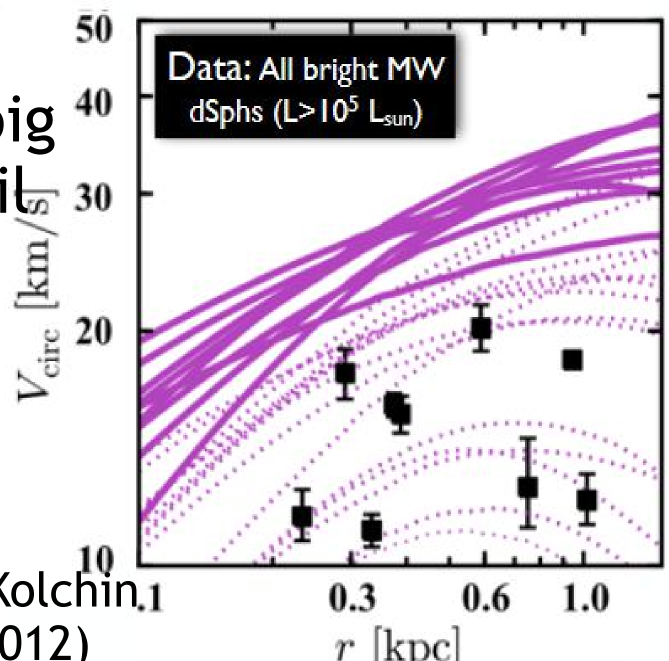
cusp-core problem



missing satellites



too big to fail



Boylan-Kolchin et al. (2012)

- Some may not be real problems
- Baryon effect
- Dark matter properties (warm, self-interaction, ...)

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)

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

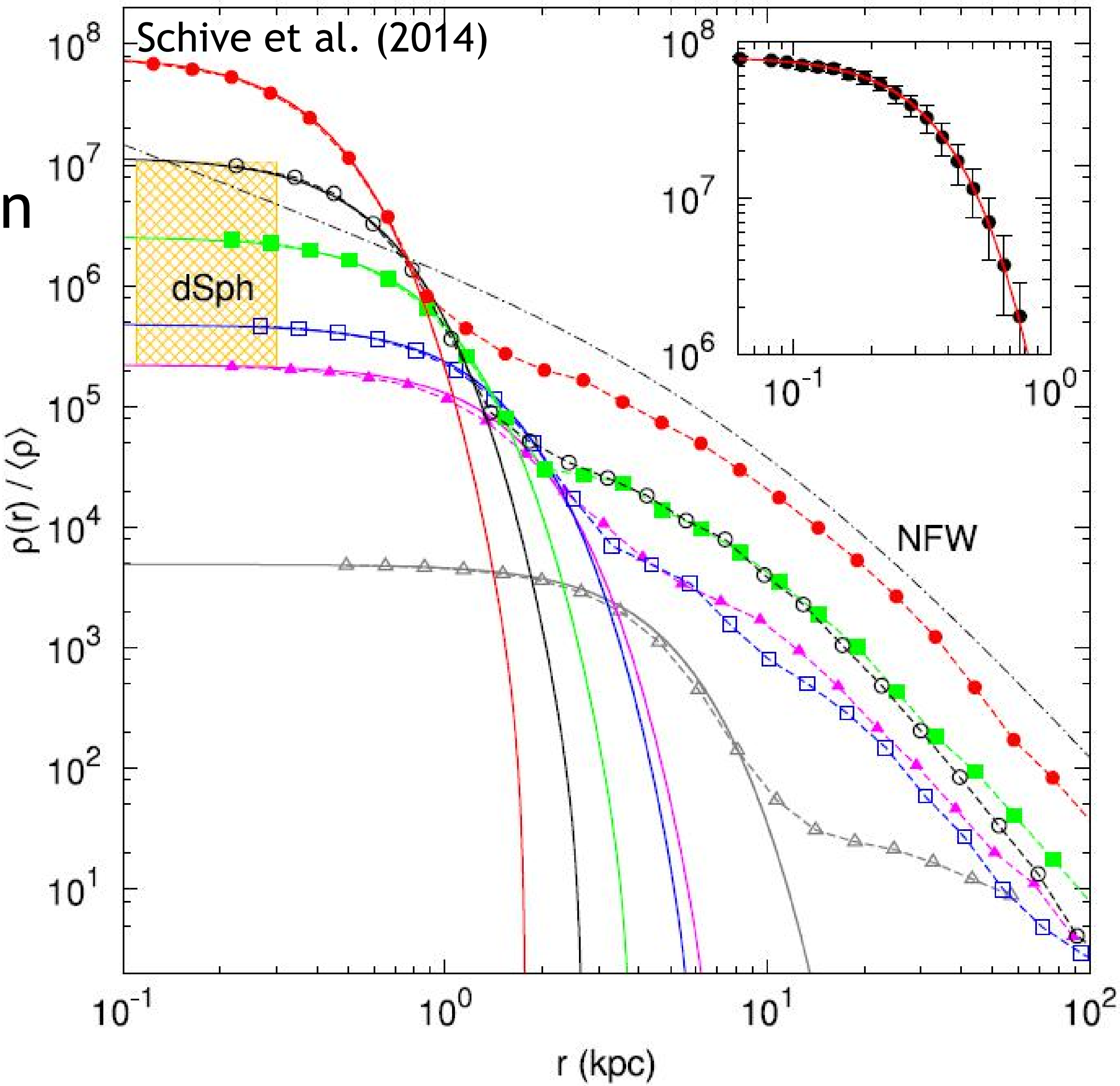
$$i\partial_t\psi = (-\frac{1}{2m}\nabla^2 + m\Psi)\psi\,, \quad \nabla^2\Psi = 4\pi G\delta\rho$$

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

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

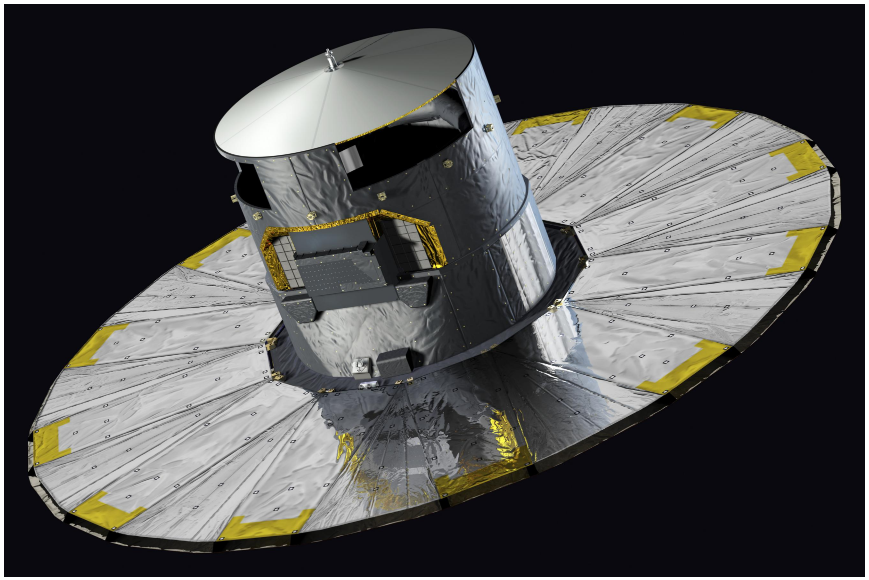
- Astronomical method to try to detect a cumulative effect of such dark matter is a possible way

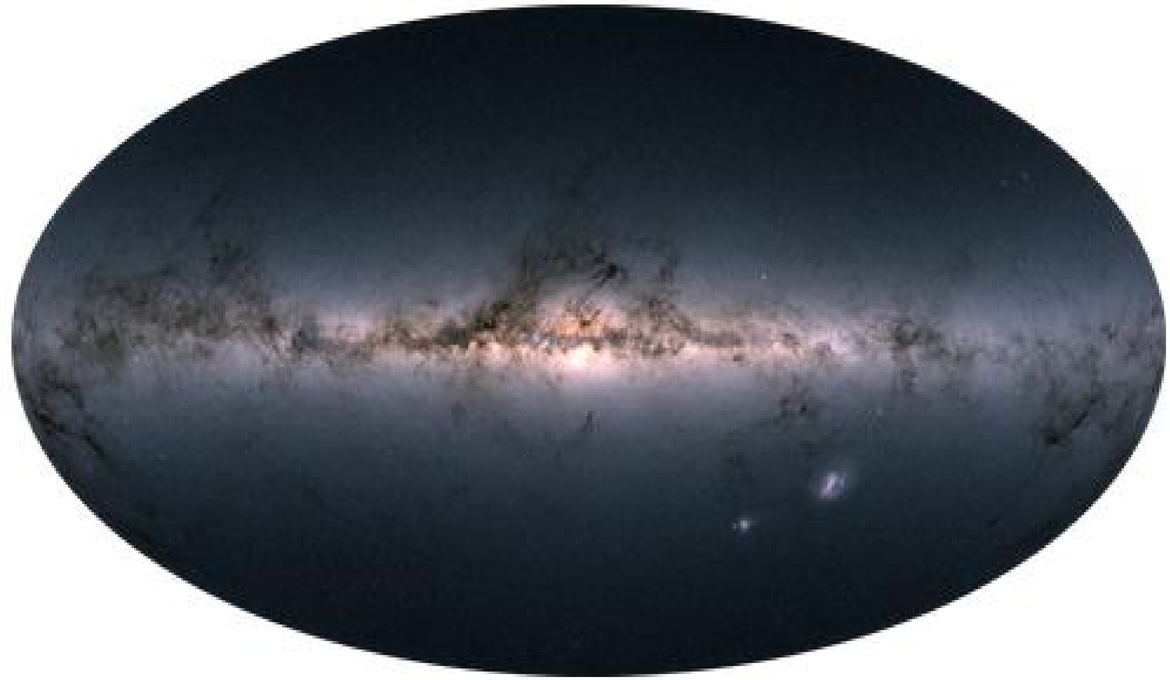
H. Fukuda, S. Matsumoto, T. Yanagida (2019), solar system body ephemeris

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

- Timing measurements (by PTA) of highly stable pulsars

High-precision astrometry by Gaia



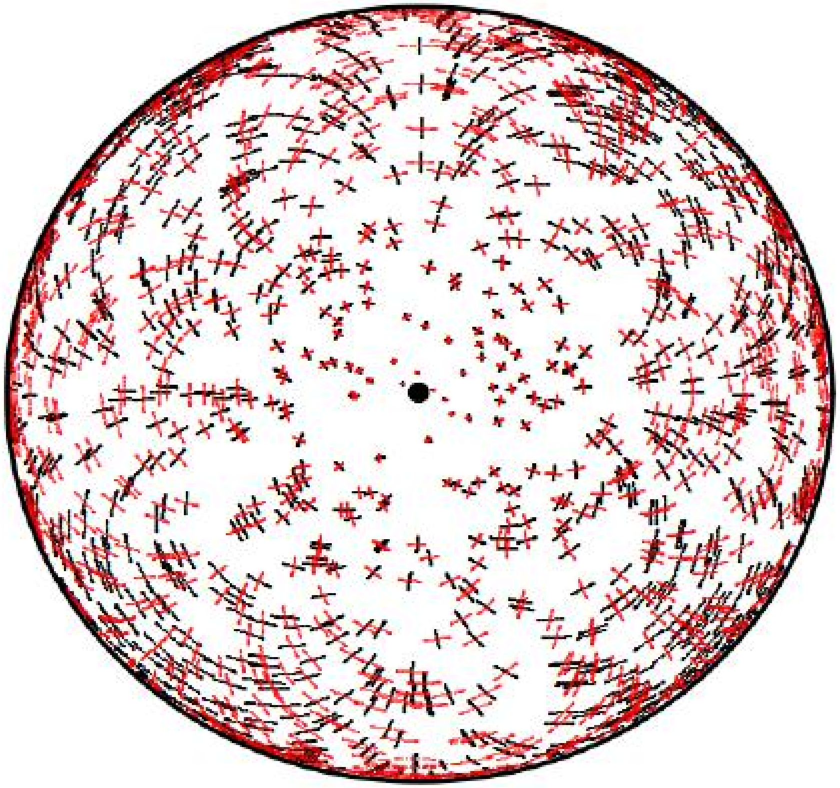


- Very high precision of location measurements (~100 μas) of large amount of stars (~10^9)
- A revolution in probing structure and dynamics of the Milky Way, stellar physics, exoplanets, and fundamental physics
- 2nd data release in 2018, with astrometry (location, movements) and astrophysical (temperature,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

Detecting gravitational wave with Gaia

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

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



Moore et al. (2017)

Detecting gravitational wave with Gaia

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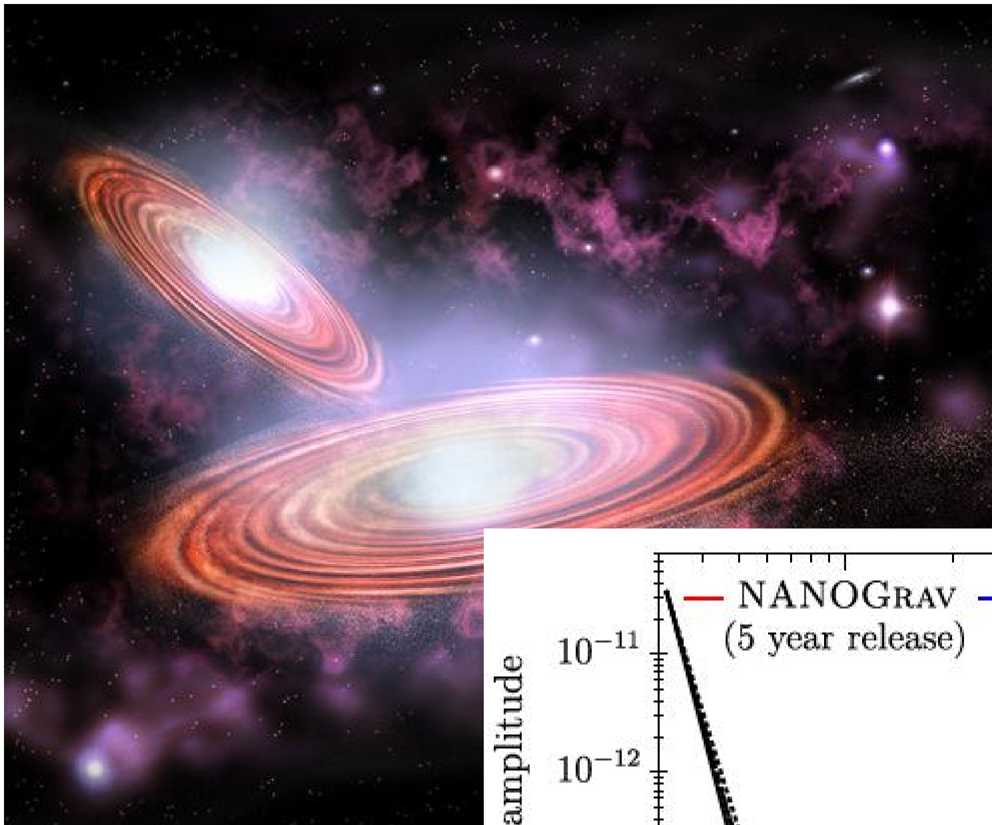
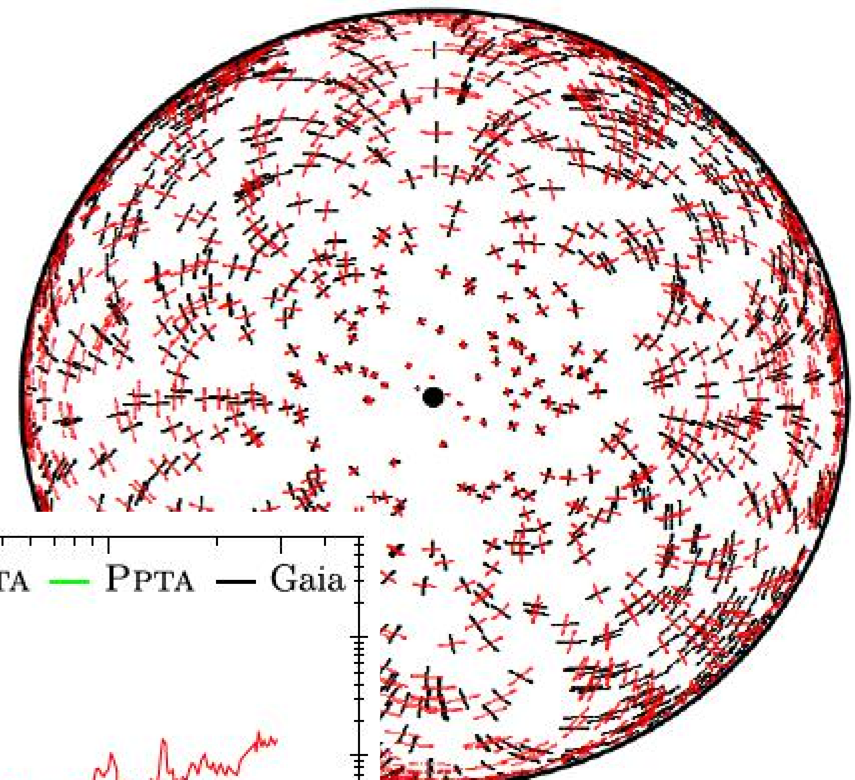
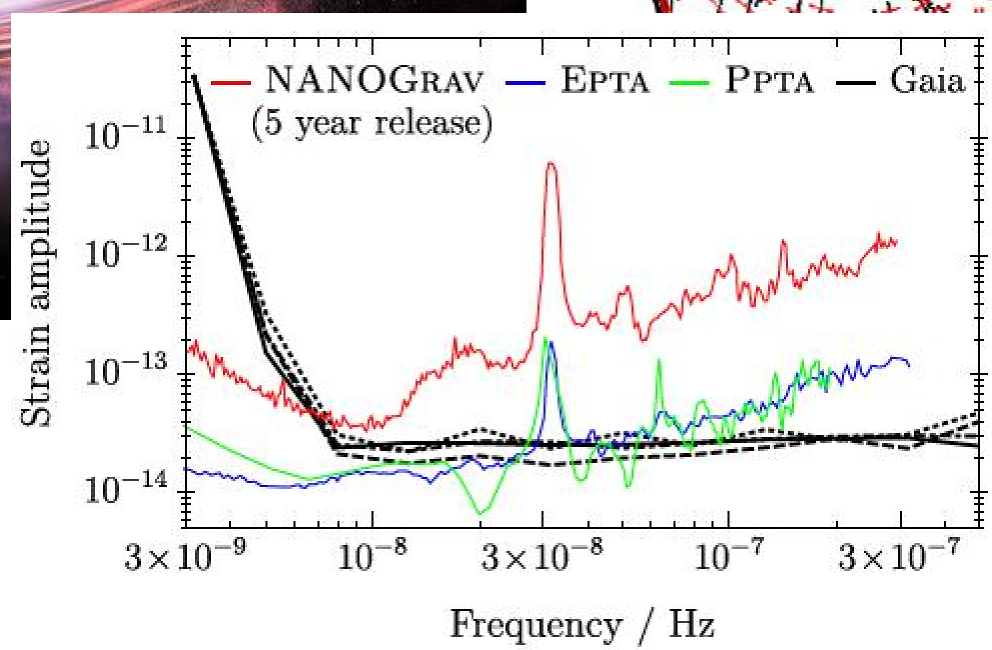






Moore et al. (2017)

(Ultralight) dark photon

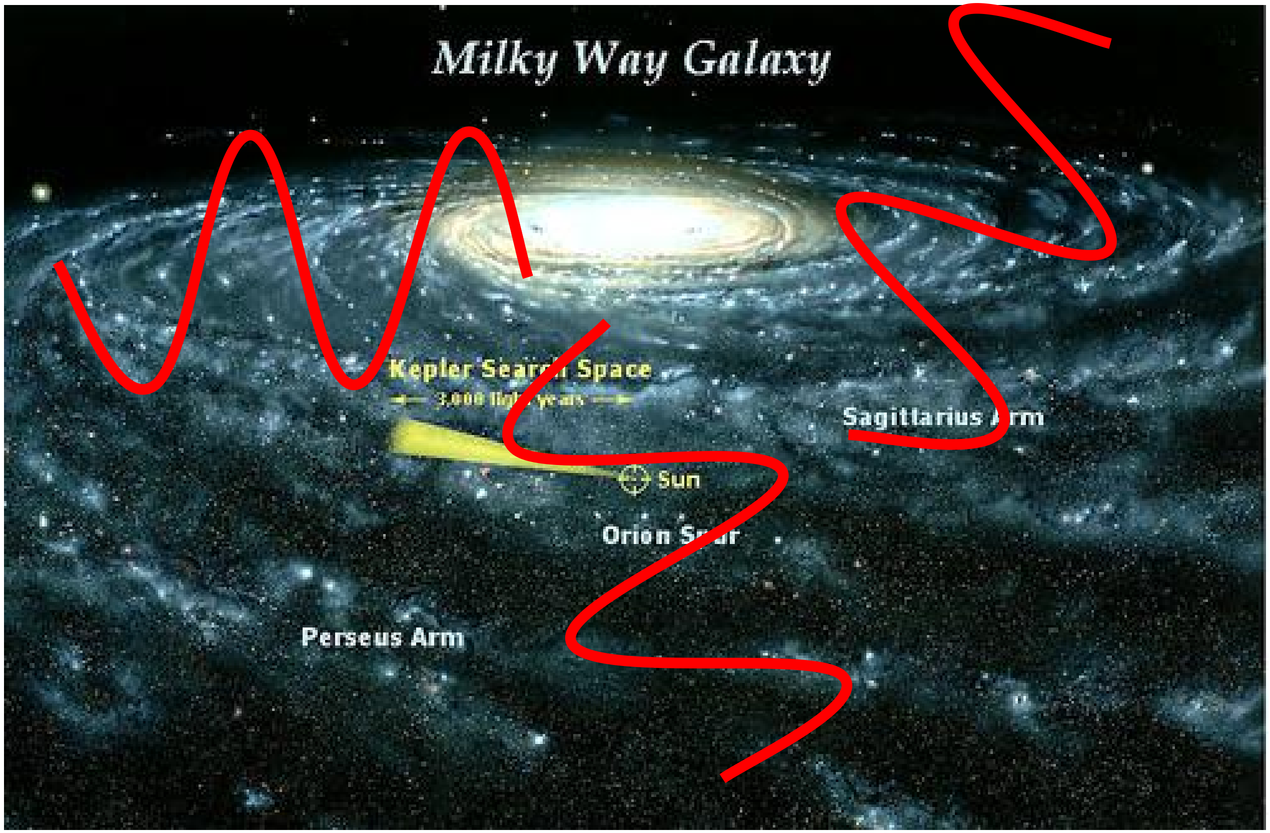
- A hypothetical hiden-sector particle proposed as a force carrier similar to photon

- 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

- 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) dark photon



- 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

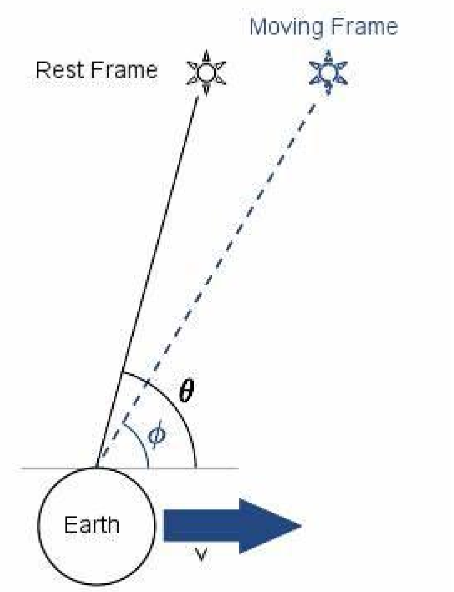
Detecting dark photon DM with astrometry

- 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

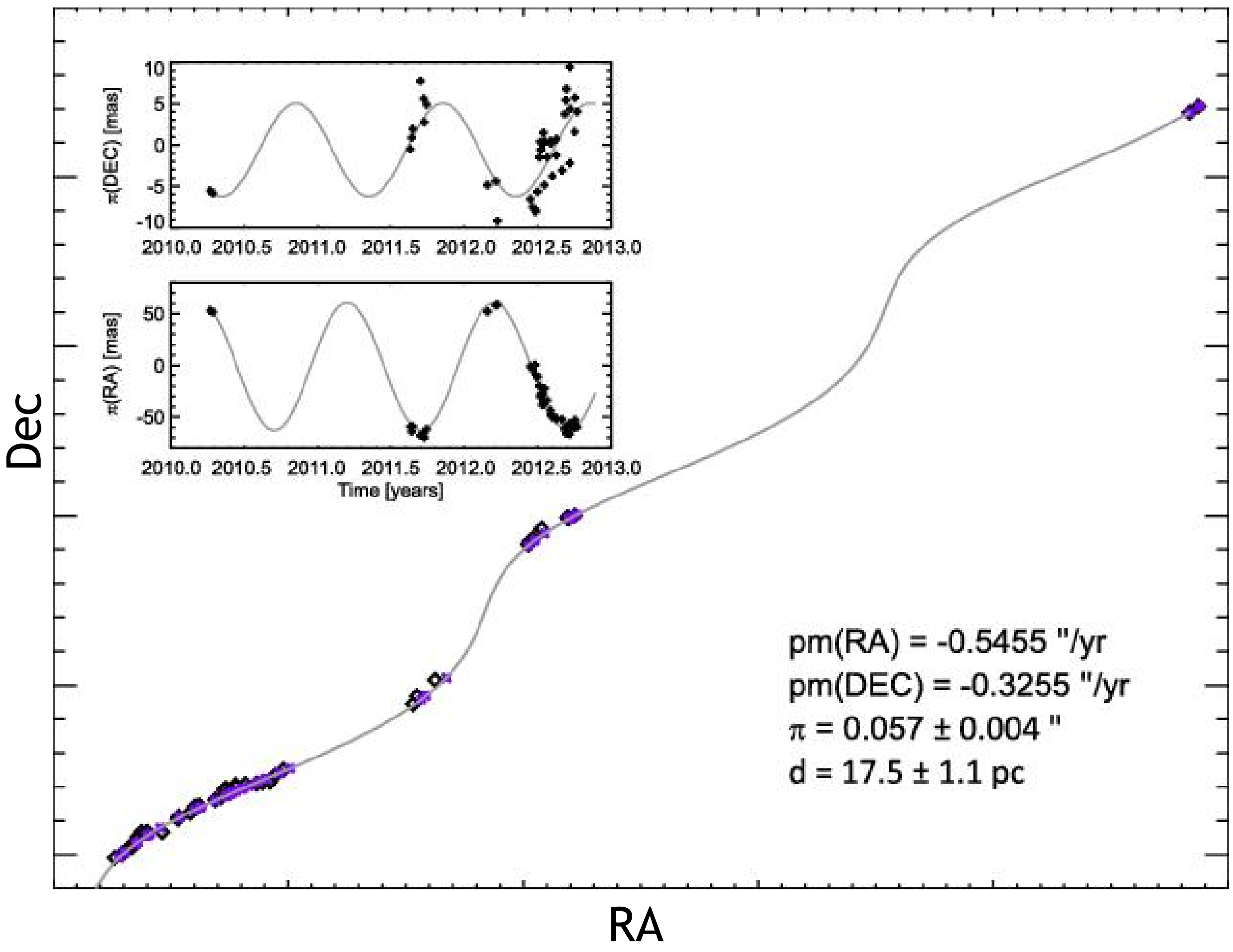
$$\Delta \boldsymbol{v}(t, \boldsymbol{x}) \simeq \epsilon e \frac{q}{m} \boldsymbol{A_0} \sin(m_A t - \boldsymbol{k} \cdot \boldsymbol{x}). \qquad \Delta\theta \simeq -\Delta v \, \sin\theta$$



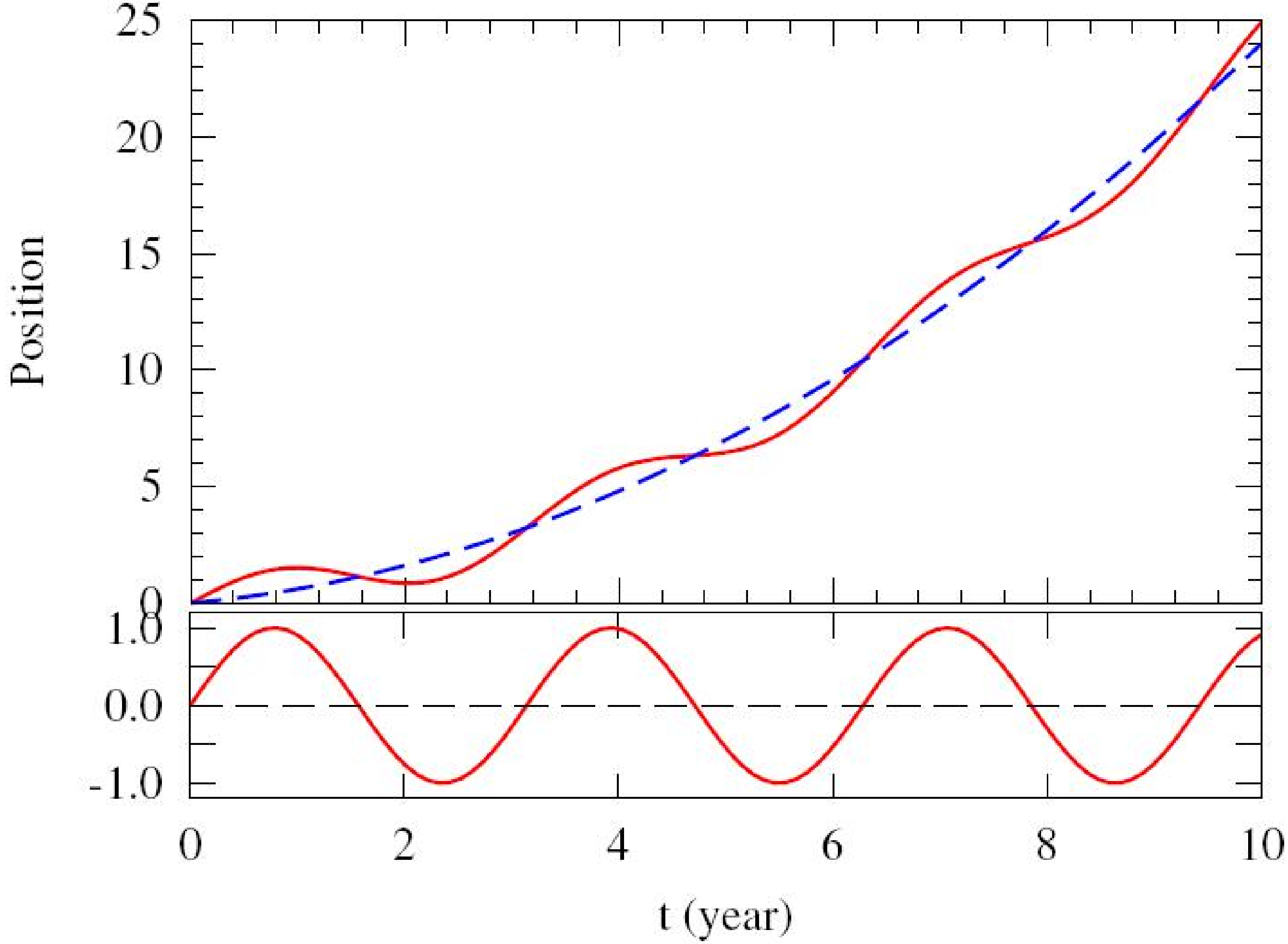
- Many stars show a pattern of their location variations

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

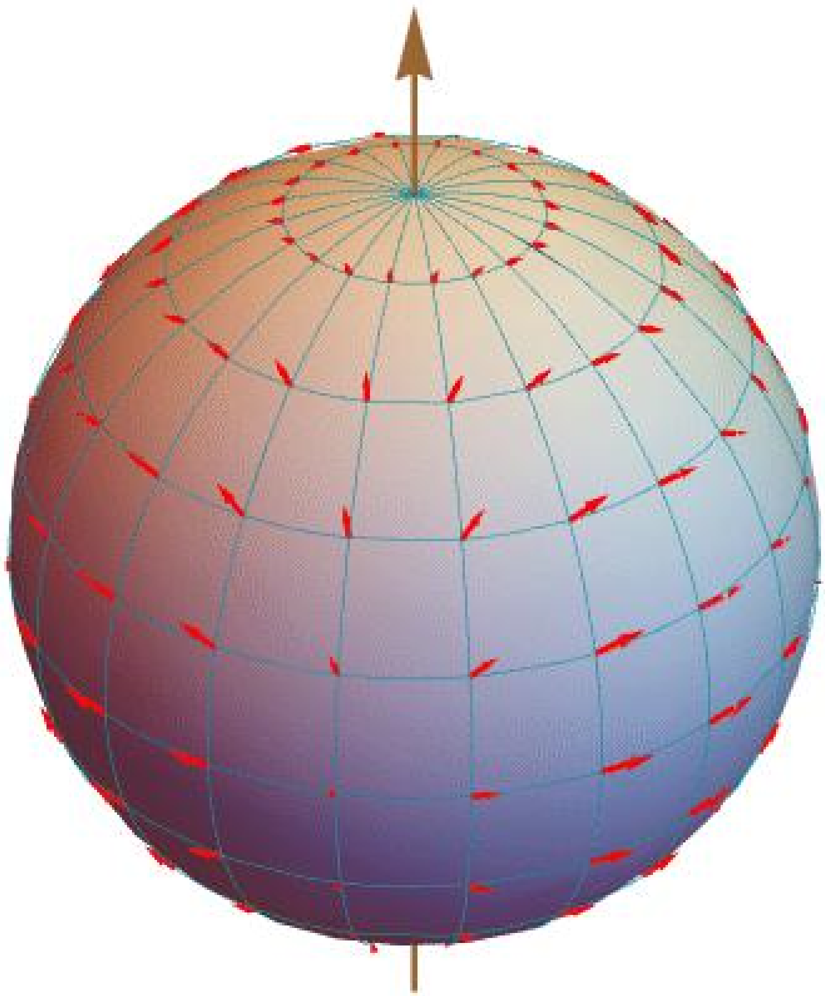


Background subtraction

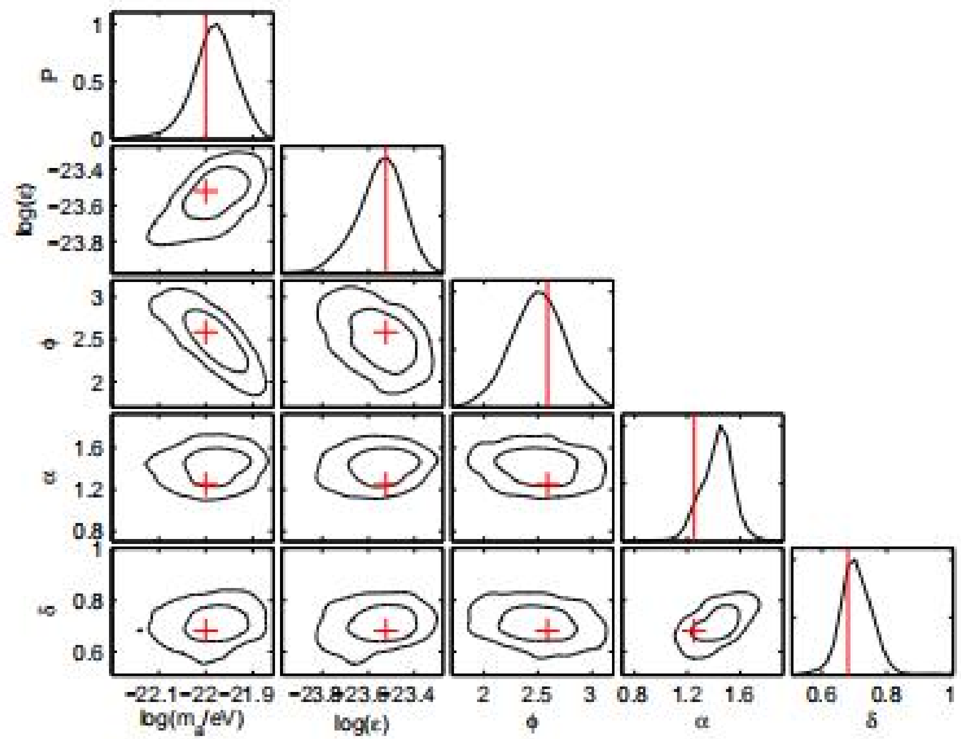


- Assuming the satellite's and earth's orbits are precisely known
- Using a quadratic function to model the proper motion
- Simulate the proper motion and subtracted through a fitting

Simulation and reconstruction



Oscillation pattern



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

Sensitivities on dark photon couplings

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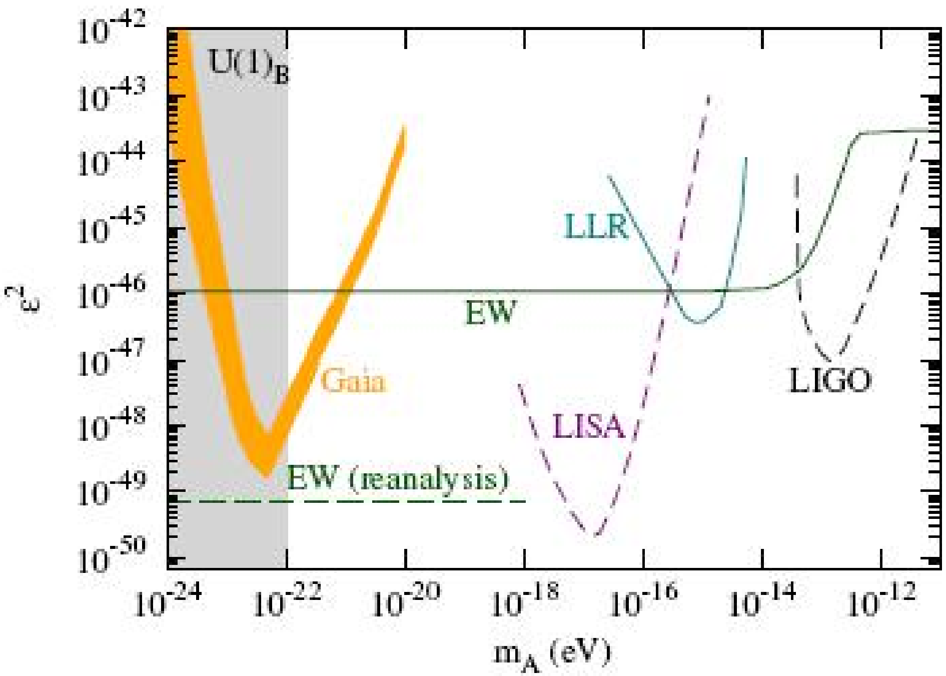
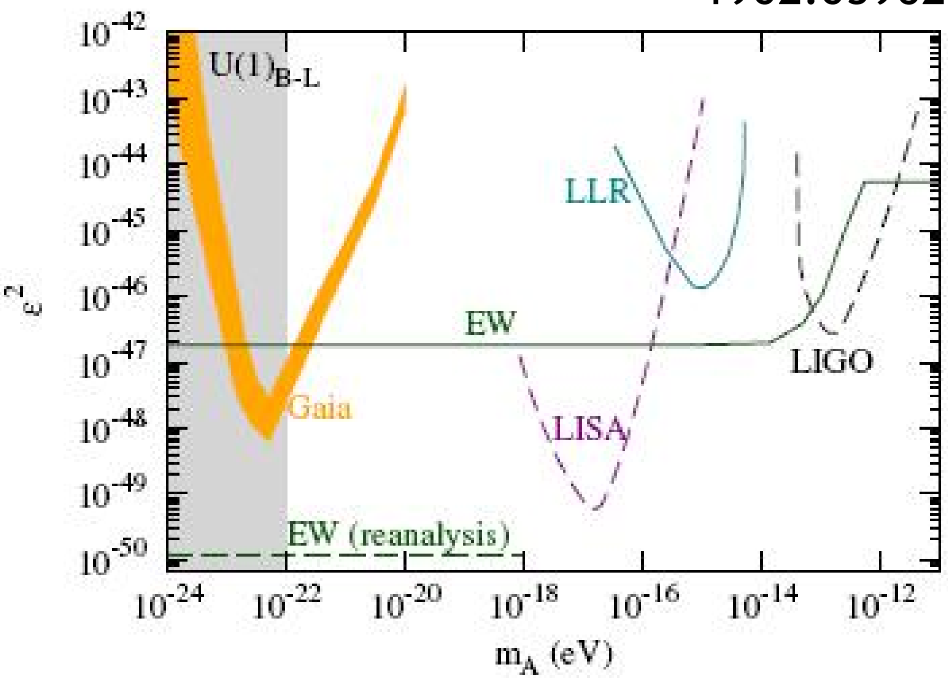
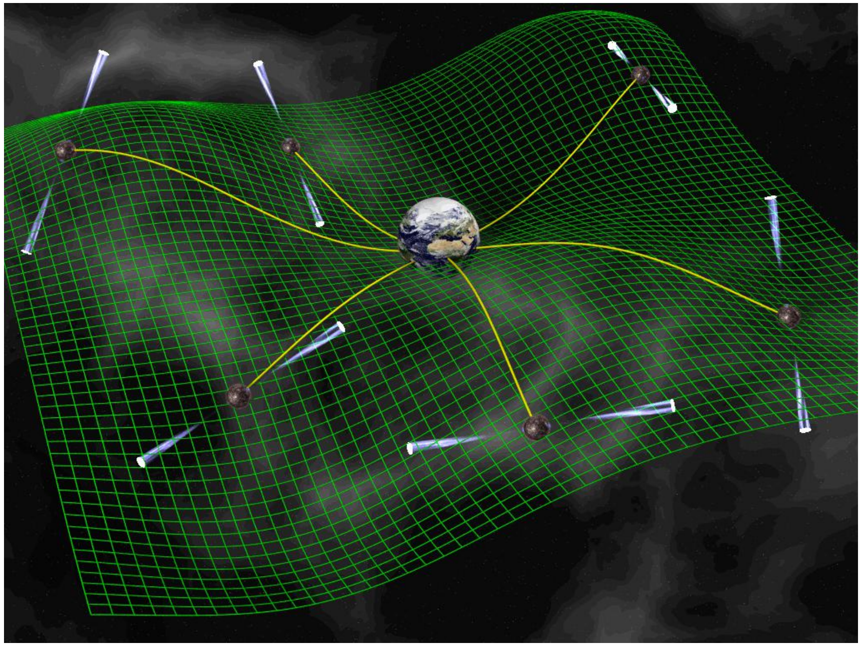
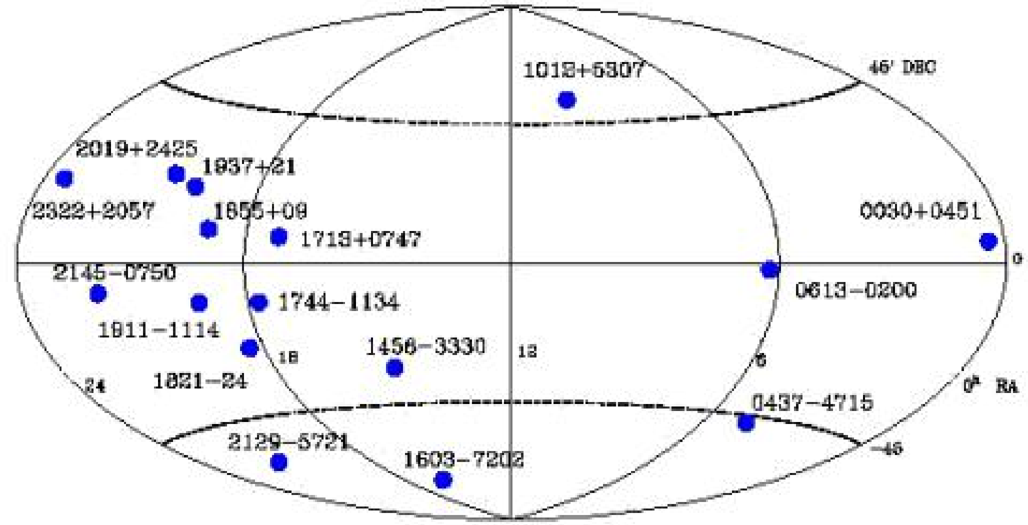


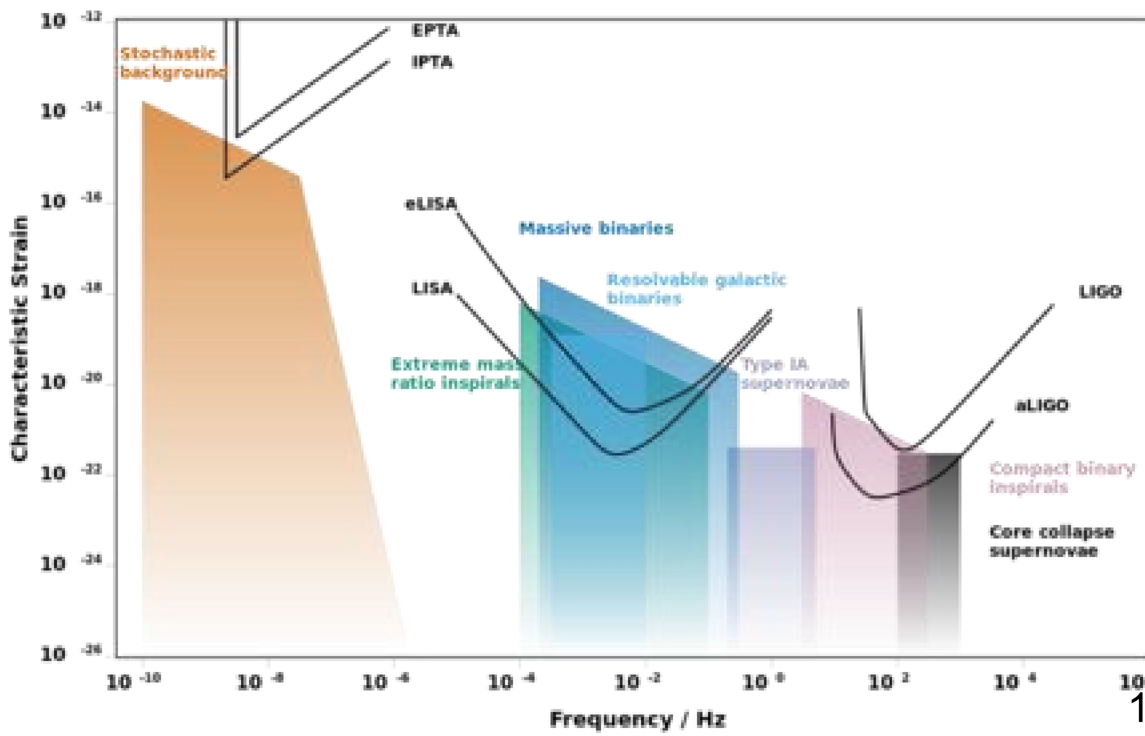


- Reach the best sensitivities for $m_A<10^{-21}$ eV
- Sensitivities become worse when $m_A<10^{-22}$ eV due to that the subtraction of background motion also removes part of the signal

Pulsar timing array







- Proposed for nHz GW detection (binary SMBHs)
- PPTA, EPTA, IPTA, NanoGrav, ...
- Can also be used for many other sciences (DM, PBH, small bodies)

PPTA search for scalar fuzzy DM

Parkes Pulsar Timing Array constraints on ultralight scalar-field dark matter

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(The PPTA Collaboration)

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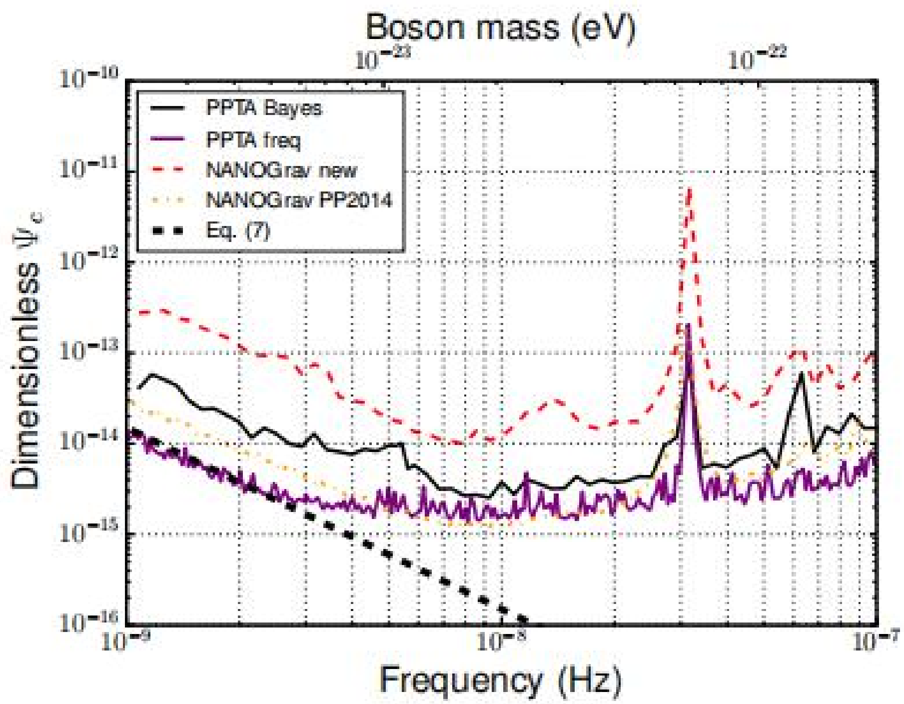
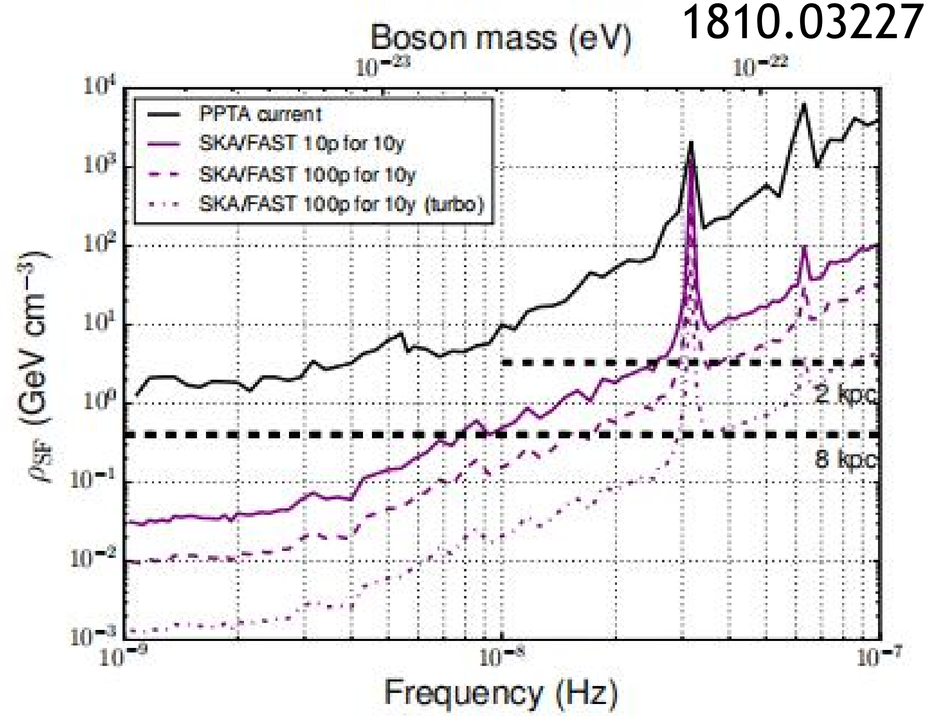




PTA search for dark photon dark matter

Both the pulsar and the earth would oscillate in the dark photon background, resulting in time residuals of pulses

$$\delta \boldsymbol{x}_{e,p}(t) \simeq -\frac{\epsilon e q}{m_A m} \boldsymbol{A_0}^{e,p} \cos\left[m_A(t-t_0)+\alpha_{e,p}\right]$$

$$\Delta t_r^d(t) = \frac{\left|\boldsymbol{d}+\delta \boldsymbol{x}_p\left(t-\frac{|\boldsymbol{d}|}{v(t)}\right)-\delta \boldsymbol{x}_e(t)\right|-|\boldsymbol{d}|}{v(t)} \simeq \frac{\boldsymbol{n}_p \cdot \Delta \boldsymbol{x}(t)}{v(t)},$$

Parkes PTA (ongoing)

FAST PTA?

PTA search for dark photon dark matter

$$t^{obs} = t^{det}(\xi_A) + n(\xi_B) + t^{signal}(\xi_C)$$

Terms	Meaning	Parameter ξ_i	
t^{obs}	the observed TOA		
$t^{det}(\xi_A)$	The deterministic modeled TOA	Including the pulsar sky location (RAJ and DecJ), spin frequency and spin-down rate, dispersion measure, proper motion, parallax and (when applicable) binary orbital parameters etc.	Parameters will be fitted by TEMPO2.
$n(\xi_B)$	The random noise	Including red noise parameters (including gravitational wave signals) and additional white noise parameters.	Bayesian or Frequentist analysis.
$t^{signal}(\xi_C)$	The signal	Including continuous wave signal parameters, and BayesEphem parameters.	

Fitting timing residuals

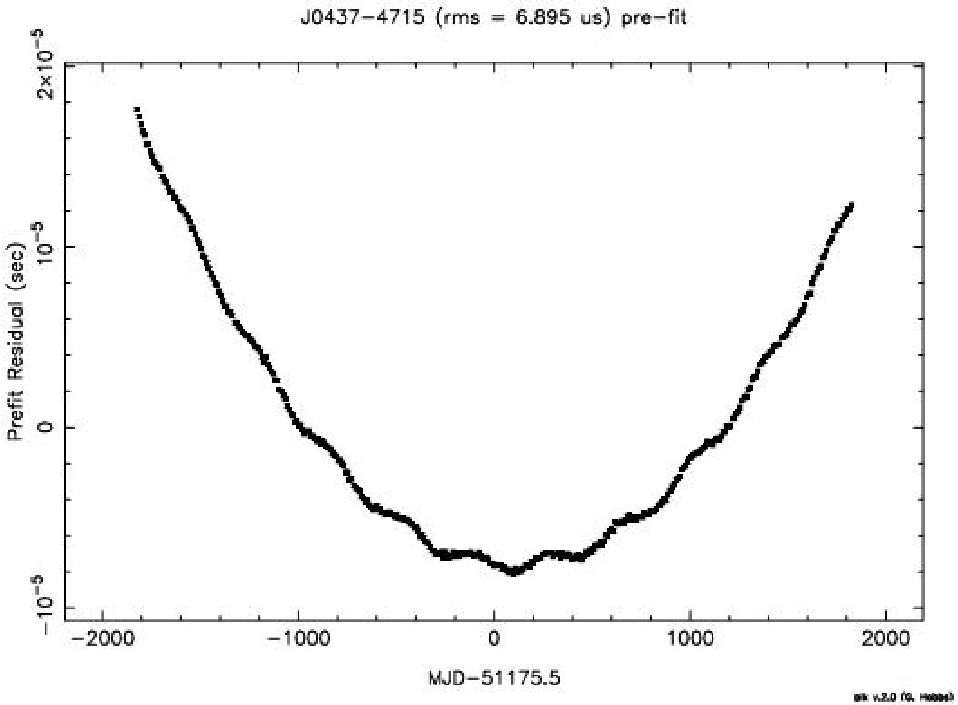
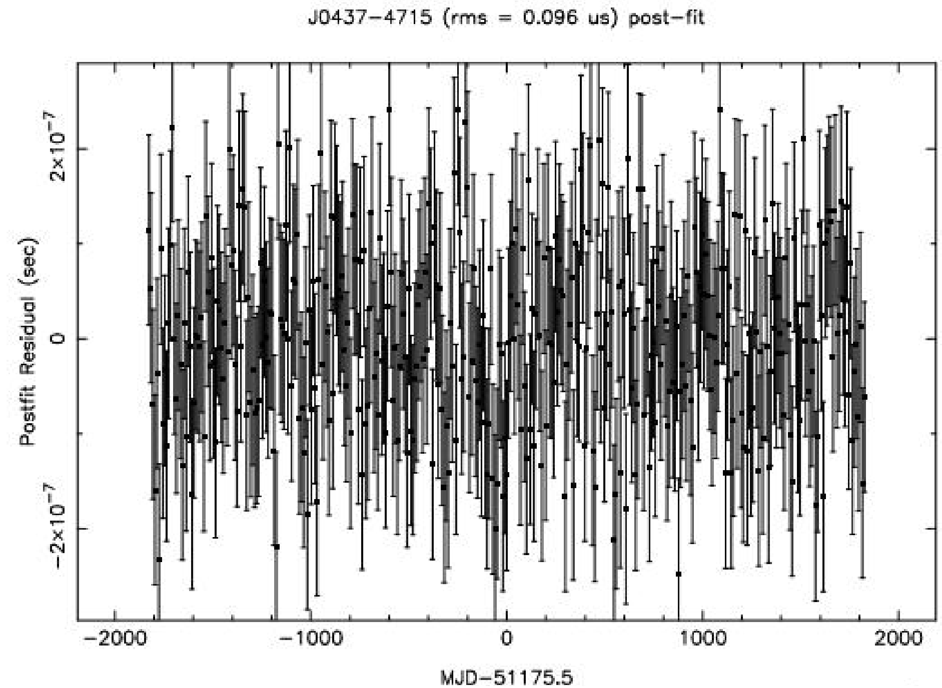
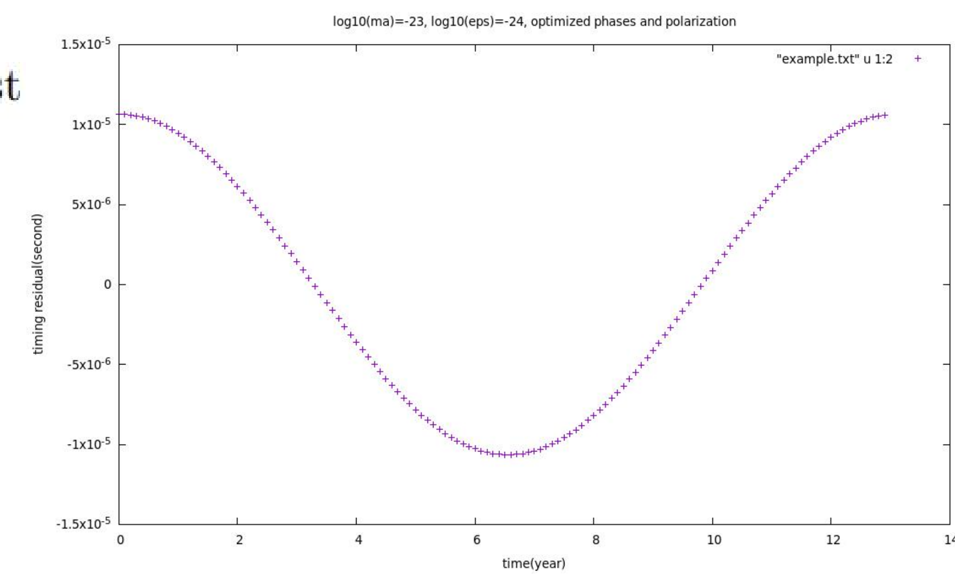


Figure 1: a) pre-fit timing residuals for the test





Summary

- Bosonic dark matter with ultra-small mass is a well motivated candidate for cold 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 and/or timing observations can effectively probe such kind of ultralight dark matter which is, however, difficult to be detected by other ways

Thanks for your attention!

Ultra-light DM – Dark Photon

- Mass

W/Z bosons get masses through the Higgs mechanism.

A dark photon can also get a mass by a dark Higgs,
or through the Stueckelberg mechanism.

a special limit of the Higgs mechanism
unique for U(1) gauge group

- Relic abundance (non-thermal production)

Misalignment mechanism

Light scalar decay

Production from cosmic string

Ultra-light dark photon can be a good candidate of cold dark matter!

by Y. Zhao

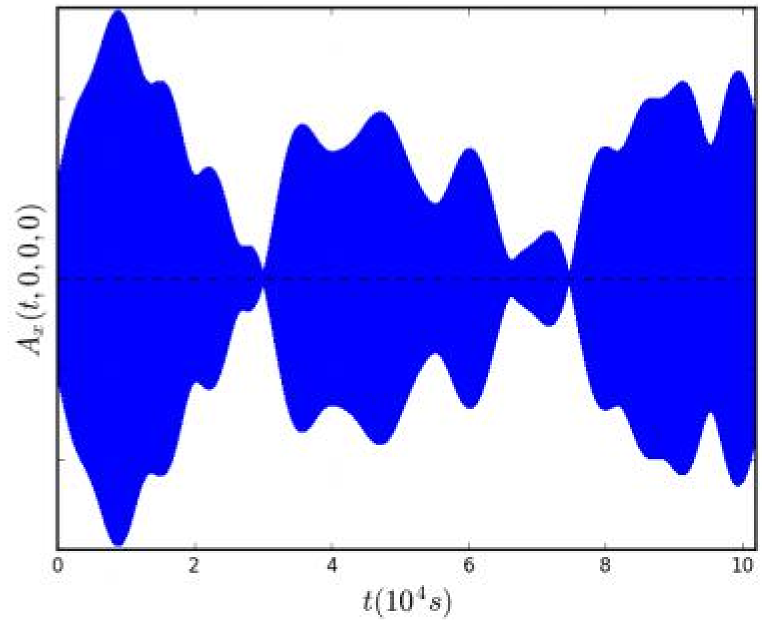
Simulating the DPDM background

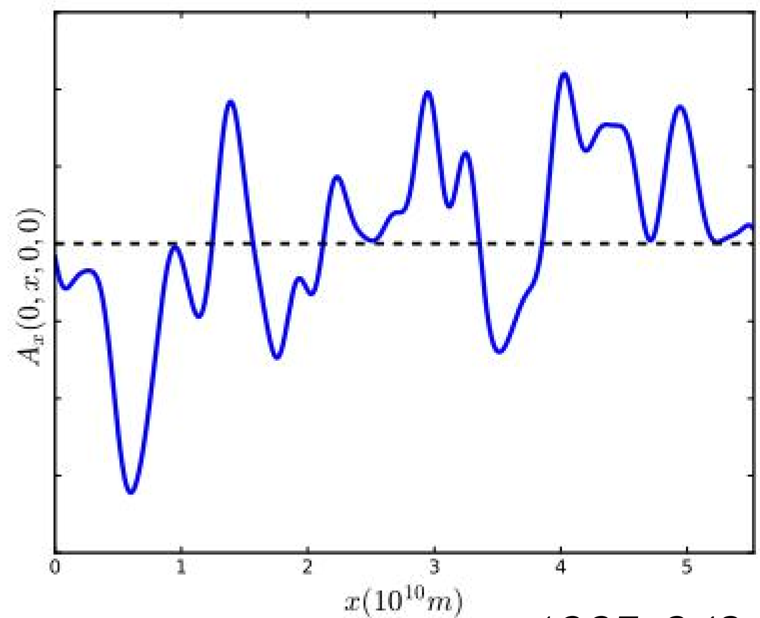
$$\vec{A}_i(t, \mathbf{x}) \equiv \vec{A}_{i,0} \sin(\omega_i t - \vec{k}_i \cdot \vec{x} + \phi_i),$$

$$\vec{A}_{total}(t, \mathbf{x}) = \sum_{i=1}^{N} \vec{A}_{i,0} \sin(\omega_i t - \vec{k}_i \cdot \vec{x} + \phi_i),$$

$$A_\mu \simeq A_{\mu,0} \cos[m_A t - \vec{k} \cdot \vec{x} + \theta]$$

$$|\vec{A}_0| \simeq \sqrt{2\rho_{DM}}/m_A$$





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