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AGENCIA
ESTATAL DE
INVESTIGACIÓN

# Astrometric and (some) PTA probes of dark matter

**Speaker: Xiao Xue (IFAE Barcelona)**

Beyond WIMPs | Oxford, UK | April 09 2025

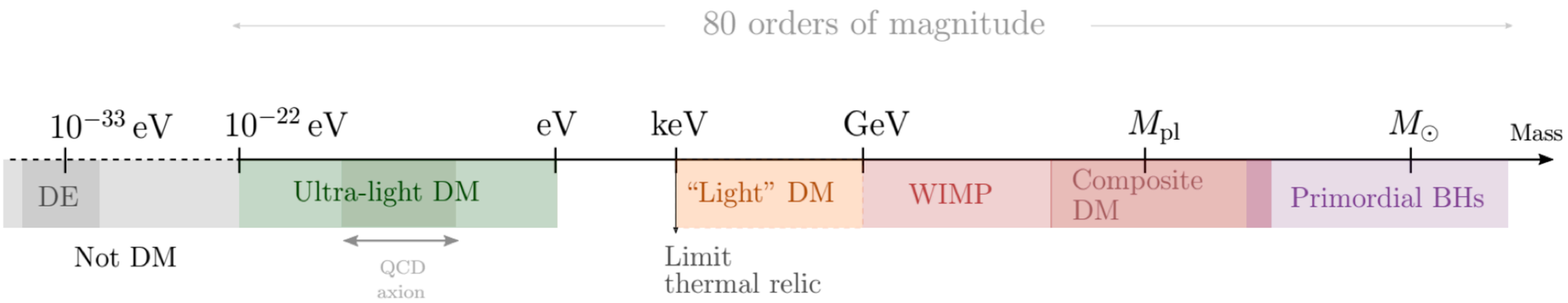
# Galaxy rotation curve

- Rubin, V. C., & Ford, W. K. Jr. (1970). ApJ, 159, 379.
- More galaxies:
- Rubin, V. C., Ford, W. K., & Thonnard, N. (1978), ApJ, 225, L107. https://doi.org/10.1086/182804
- Rubin, V. C., Thonnard, N., & Ford, W. K. (1980), ApJ, 238, 471. https://doi.org/10.1086/158003 **(21 galaxies)**

Author: Ingo Berg
Link: https://beltoforion.de/en/spiral_galaxy_renderer/

# Dark matter “candidates”

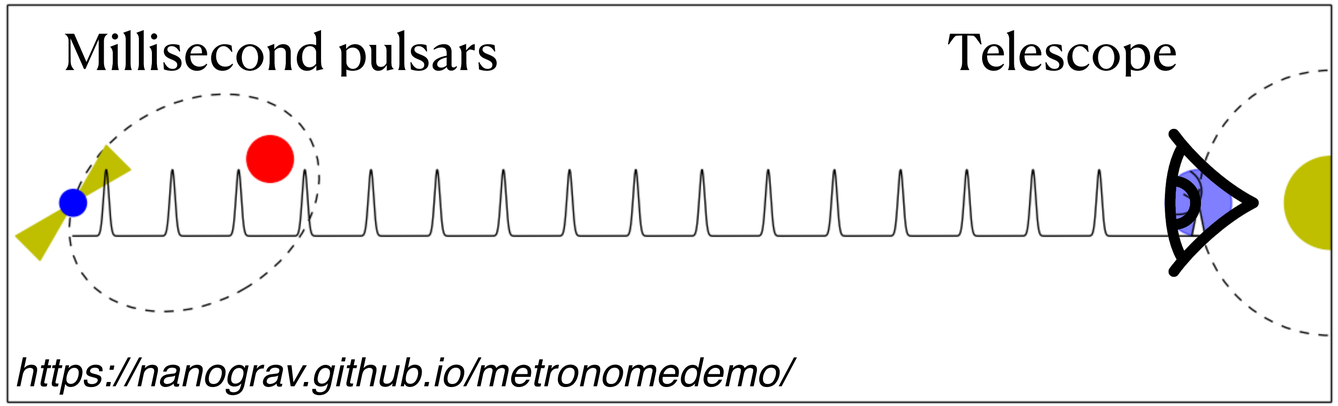
- From the point of view of particle physcists




Ultra-light dark matter, Elisa G.M. Ferreira, Astron.Astrophys.Rev. 29 (2021) 1, 7

# PTA and astrometric surveys

- Hewish, A., Bell, S. J., Pilkington, J. D. H., Scott, P. F., & Collins, R. A. (1968). Observation of a rapidly pulsating radio source. Nature, 217(5130), 709–713.
- Hulse, R. A., & Taylor, J. H. (1975). (Nobel Prize 1993) Discovery of a pulsar in a binary system. *The Astrophysical Journal, 195*, L51–L53
- First evidence of stochastic gravitational wave background (2023)




# PTA and astrometric surveys

**Surveys**

- Sloan Digital Sky Survey (SDSS)
- LSST
- LAMOST
- DES
- Hipparcos
- Gaia
- ...
- Kepler (relative astrometry)
- Roman (relative astrometry)

**Target**

Galaxies

Quasars

Stars

Dwarfs

Exoplanets

**Information**

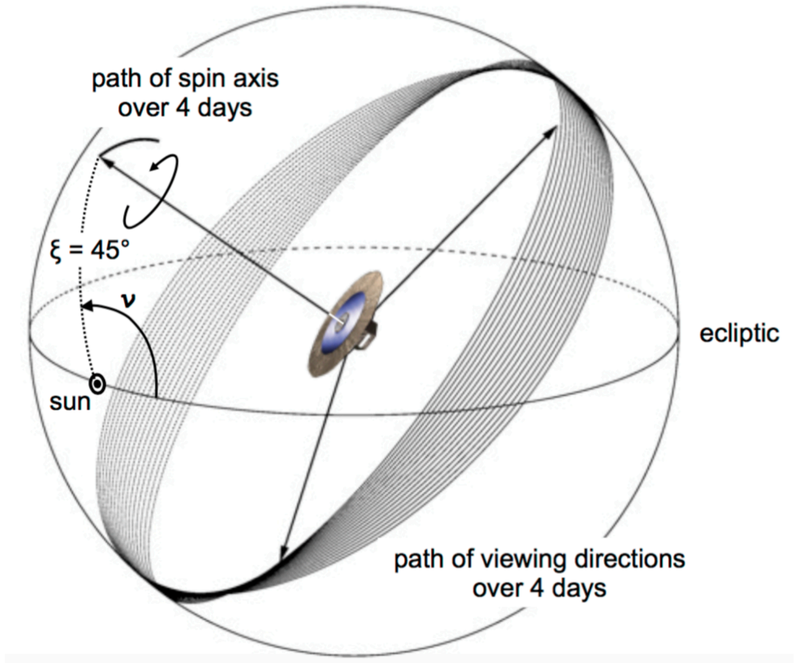
Astrometry (sky location)

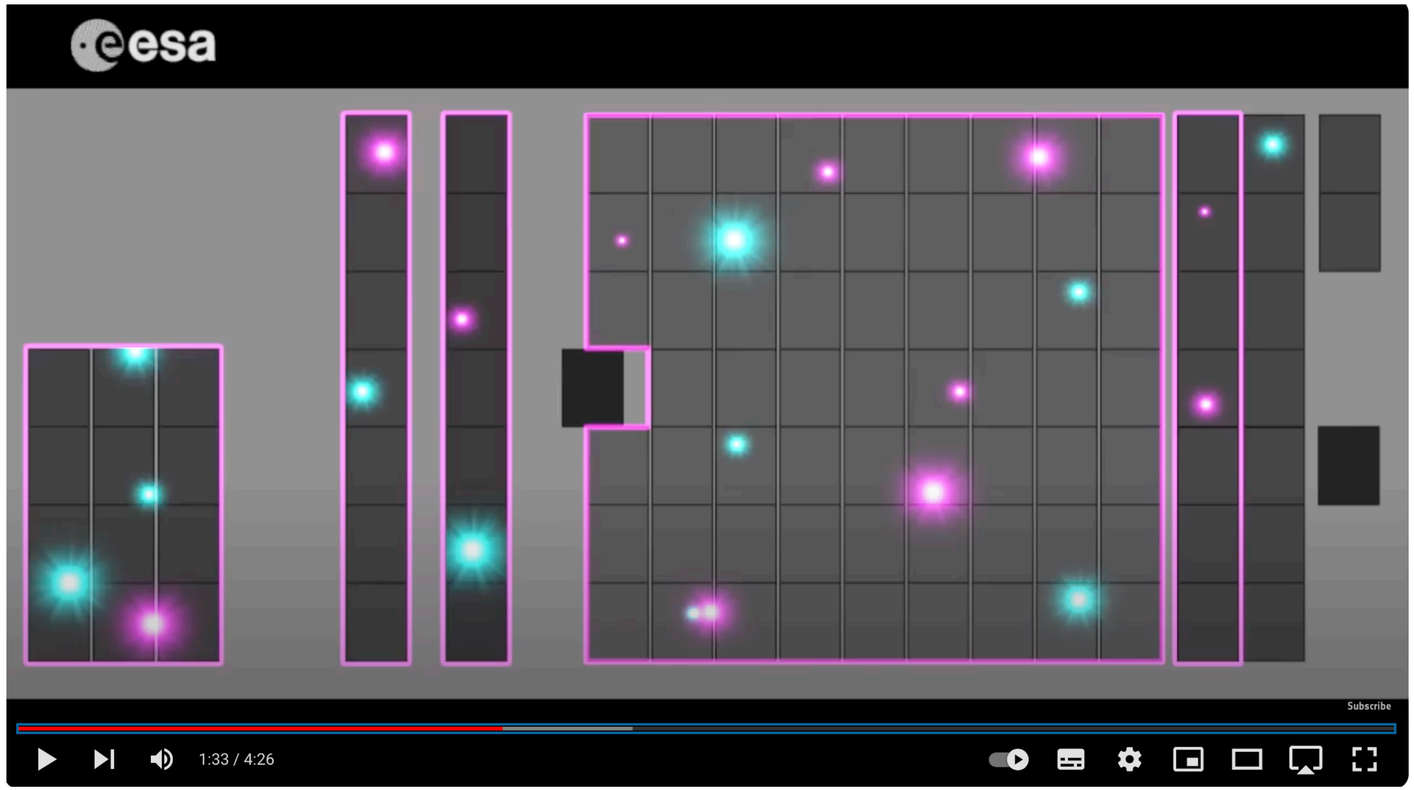
Photometry (brightness)

Spectroscopy (spectrum)

# PTA and astrometric surveys

## Gaia survey (Global astrometry)



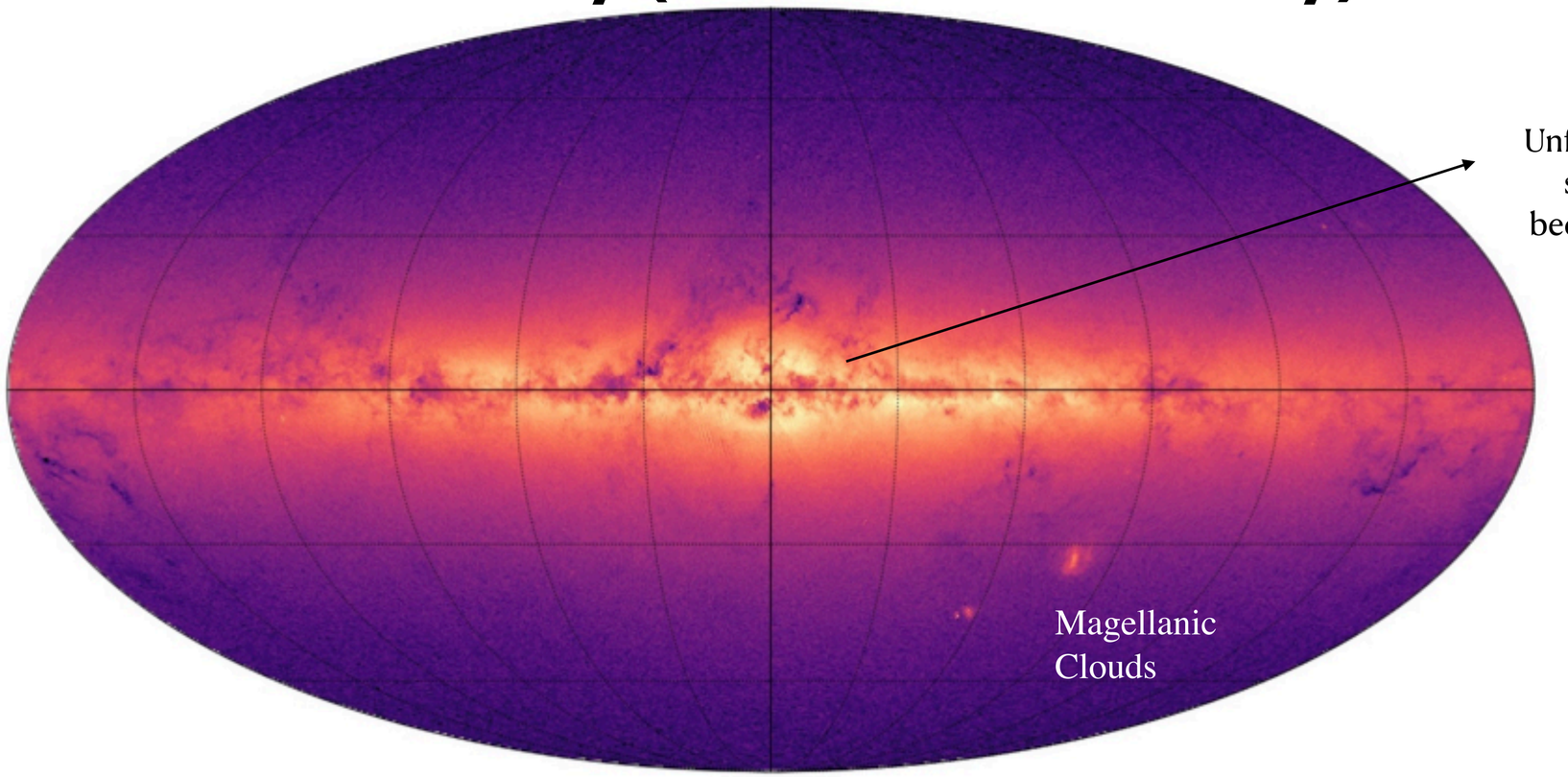




https://www.youtube.com/watch?v=bbfb8VhH7Lo

~1 Billion stars
Resolution: ~ 100 micro arcsecond
From 2014 to now
Up to data release 3

# PTA and astrometric surveys

## Gaia survey (Global astrometry)




Unfortunately, we can't see many stars in the Galactic center, because their light is blocked by the galactic disk.


~1 Billion stars
Resolution: ~ 100 micro arcsecond
From 2014 to now
Up to data release 3

# Content

- Milky Way dark matter profile
- Dark matter substructure / primordial BHs
- **Ultralight dark matter ( scalar, vector )**
  - Gravitational effect
  - With additional interactions
- **Binary evolution**

# Dark matter density profile

## Vertical velocity measurement


- Bovy, J., & Tremaine, S. (2012), ApJ, 756, 89.
- Read, J. I. (2014), J. Phys. G: Nucl. Part. Phys., 41, 063101.
- McKee, C. F., Parravano, A., & Hollenbach, D. J. (2015), ApJ, 814, 13.
- Sivertsson, S., et al. (2018), MNRAS, 478(2), 1677–1693.
- (Not the full list)

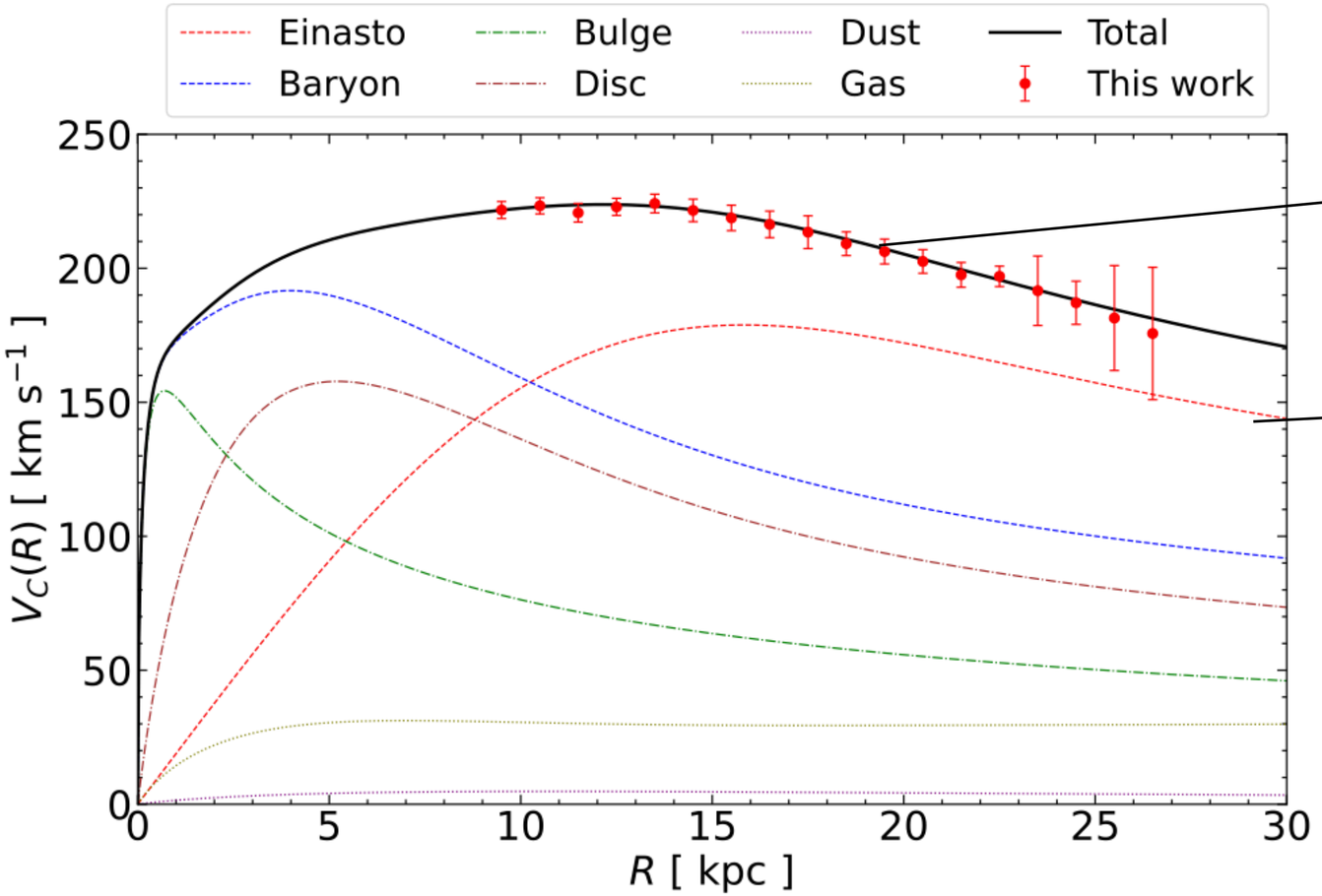

Steady state vertical Jean's equation

$$\frac{1}{\nu}\frac{\partial(\nu\sigma_z^2)}{\partial z} + \frac{1}{R\nu}\frac{\partial(R\nu\sigma_{Rz})}{\partial R} = -\frac{\partial\Phi}{\partial z}$$

$$\rho_{\rm DM} \simeq 0.4\frac{\rm GeV}{\rm cm^3} \simeq 0.01\frac{M_\odot}{\rm pc^3}$$

# Dark matter density profile

## Milky Way rotation curve




Keplerian decline

$$\rho \simeq 0.02 M_\odot / \mathrm{pc}^3 e^{-(r/11.41\mathrm{kpc})^{1/0.43}}$$

Jiao, Yongjun, et al. "Detection of the Keplerian decline in the Milky Way rotation curve." Astronomy & Astrophysics 678 (2023): A208.

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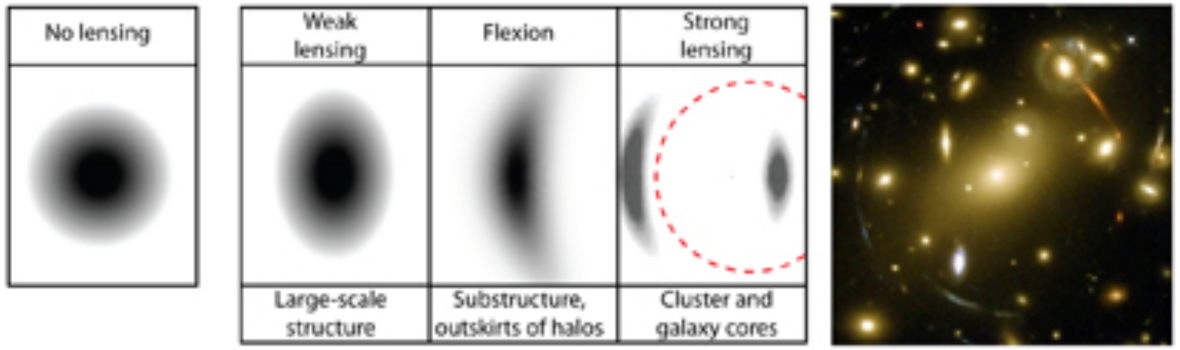
# Substructure: weak lensing

## Results from Gaia




https://sci.esa.int/web/euclid/-/46675-weak-lensing-effects

$$\Delta\boldsymbol{\theta}_i = -\frac{4GM_l}{c^2 r_l}\frac{\widetilde{M}_l(\beta_{li})}{\beta_{li}/\beta_l}\hat{\boldsymbol{\beta}}_{li},$$

**Proper motion**

**Acceleration**

**Smaller the size, Stronger the lensing**

$r_l$ : physical size of the lens

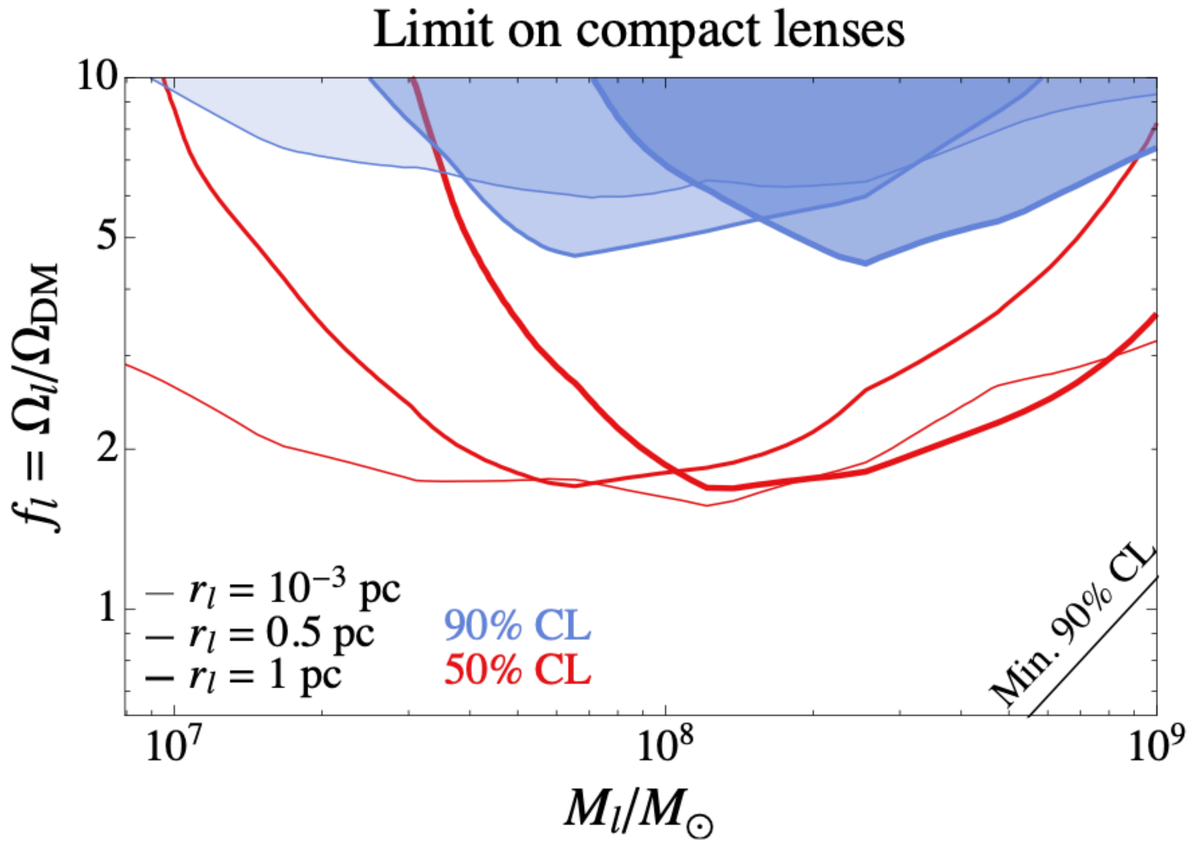
$\beta_l$ : angular size of the lens

$M_l$: mass of the lens

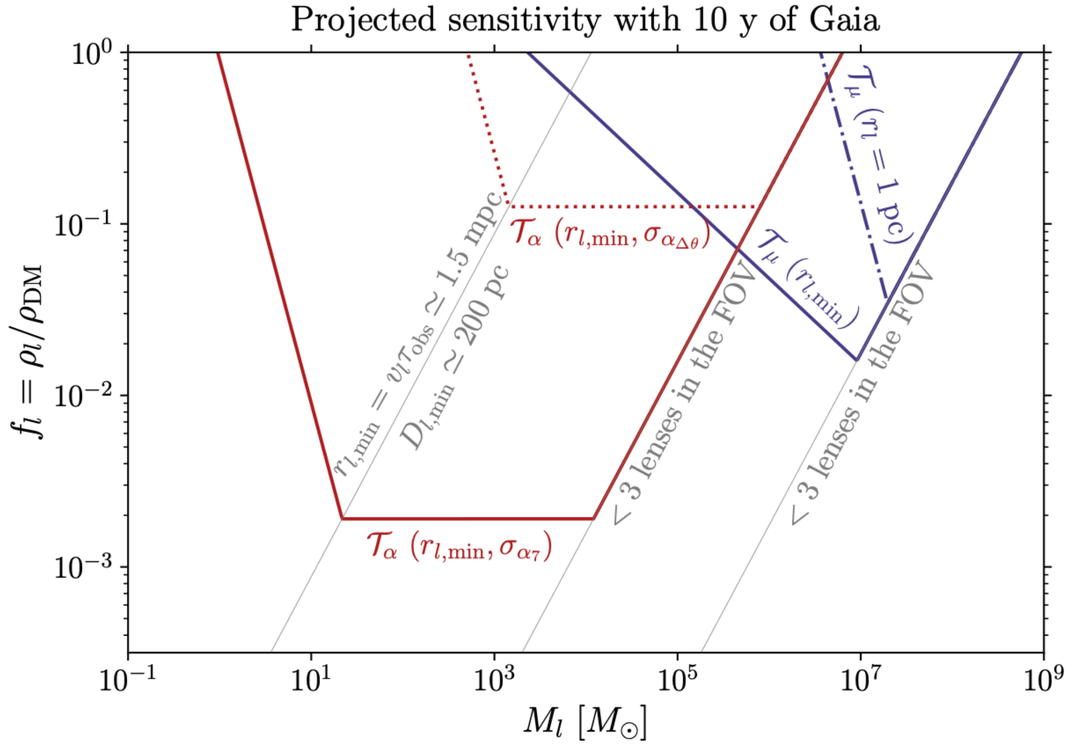
$\beta_{li}$: angular difference between lens and source

# Substructure: weak lensing

## Results from Gaia



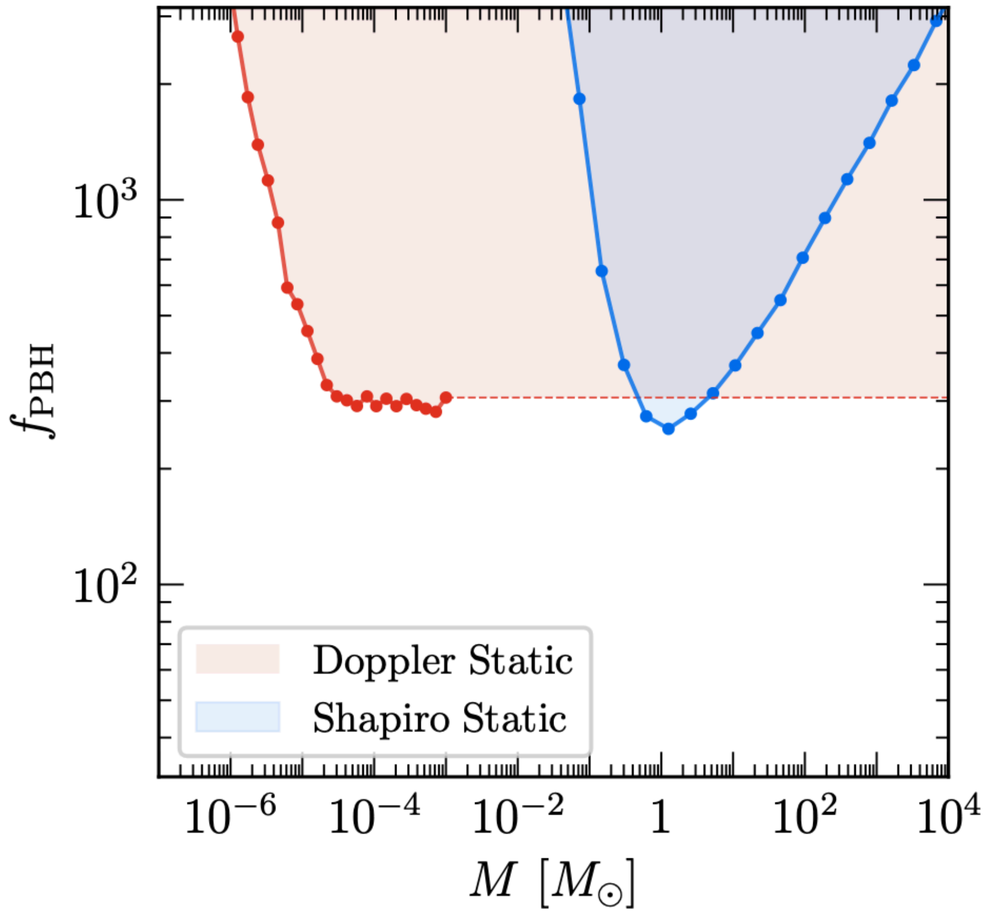

Mondino, Cristina, et al. (22 months Gaia data)
*PRL* 125.11 (2020): 111101.




Red: Accretion template
Blue: Proper motion template
$\sigma_\alpha$: acceleration dispersion
Mondino, Cristina, et al.
*MNRAS* 531.1 (2024): 632-648.

# Substructure: Shapiro delay | Doppler effect

## Results from PTA




$$h_{D,\rm dyn}(t) = A_{D,\rm dyn}(t - t_0)\Theta(t - t_0),$$

$$h_{D,\rm sta}(t) = \frac{A_{D,\rm sta}}{\rm vr^2}\, t^3,$$

$$h_{S,\rm sta}(t) = \frac{A_{S,\rm sta}}{\rm yr^2}\, t^3,$$

Afzal, Adeela, et al. "The NANOGrav 15 yr data set: Search for signals from new physics." *The Astrophysical Journal Letters* 951.1 (2023): L11.

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# Ultralight dark matter

## Gravitational effect

Scalar dark matter:

$$T_{\mu\nu} = \boxed{\partial_\mu a \partial_\nu a} - \eta_{\mu\nu}\left(\frac{1}{2}\eta^{\sigma\rho}\partial_\sigma a \partial_\rho a + \frac{1}{2}m^2 a^2\right)$$

suppressed by $v_{\rm vir}$

Vector (Dark photon) dark matter:

$$T_{\mu\nu}(t,\boldsymbol{x}) = \eta_{\mu\nu}\left(-\frac{1}{4}F_{\rho\sigma}F^{\rho\sigma} - \frac{1}{2}m^2 A^\rho A_\rho\right) + \eta^{\rho\sigma}F_{\mu\sigma}F_{\nu\rho} + \boxed{m^2 A_\mu A_\nu}$$

No suppression from $v_{\rm vir}$

# Ultralight dark matter

## Gravitational effect

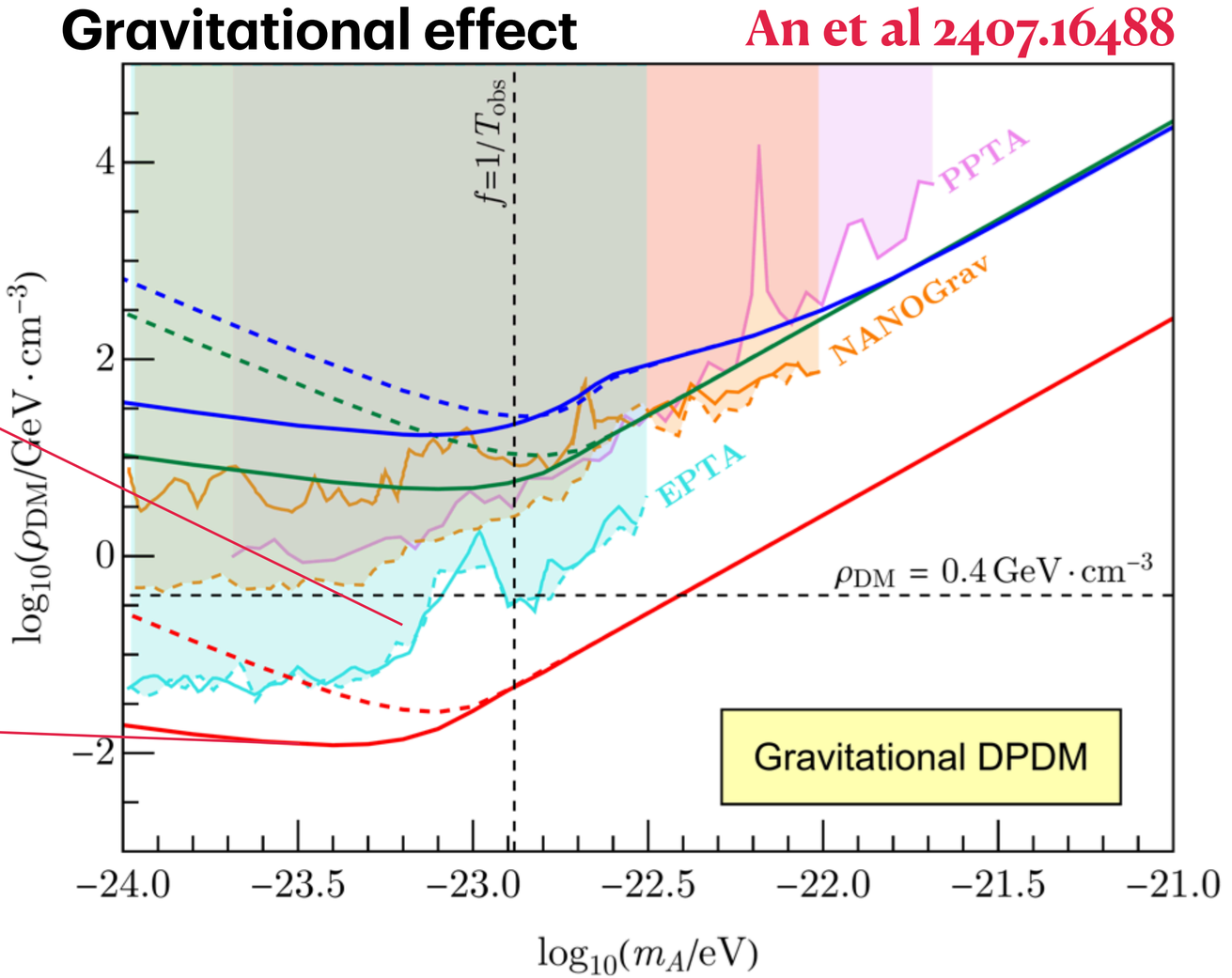
| | Scalar | Vector |
|---|---|---|
| diagonal term (For PTA) | $\propto \sqrt{\rho_{\rm DM}}$ | $\propto \sqrt{\rho_{\rm DM}}$ |
| Non-diagonal term (For Astrometry) | $\propto 10^{-3}\sqrt{\rho_{\rm DM}}$ | $\propto \sqrt{\rho_{\rm DM}}$ |

An et al 2407.16488

# Ultralight dark matter

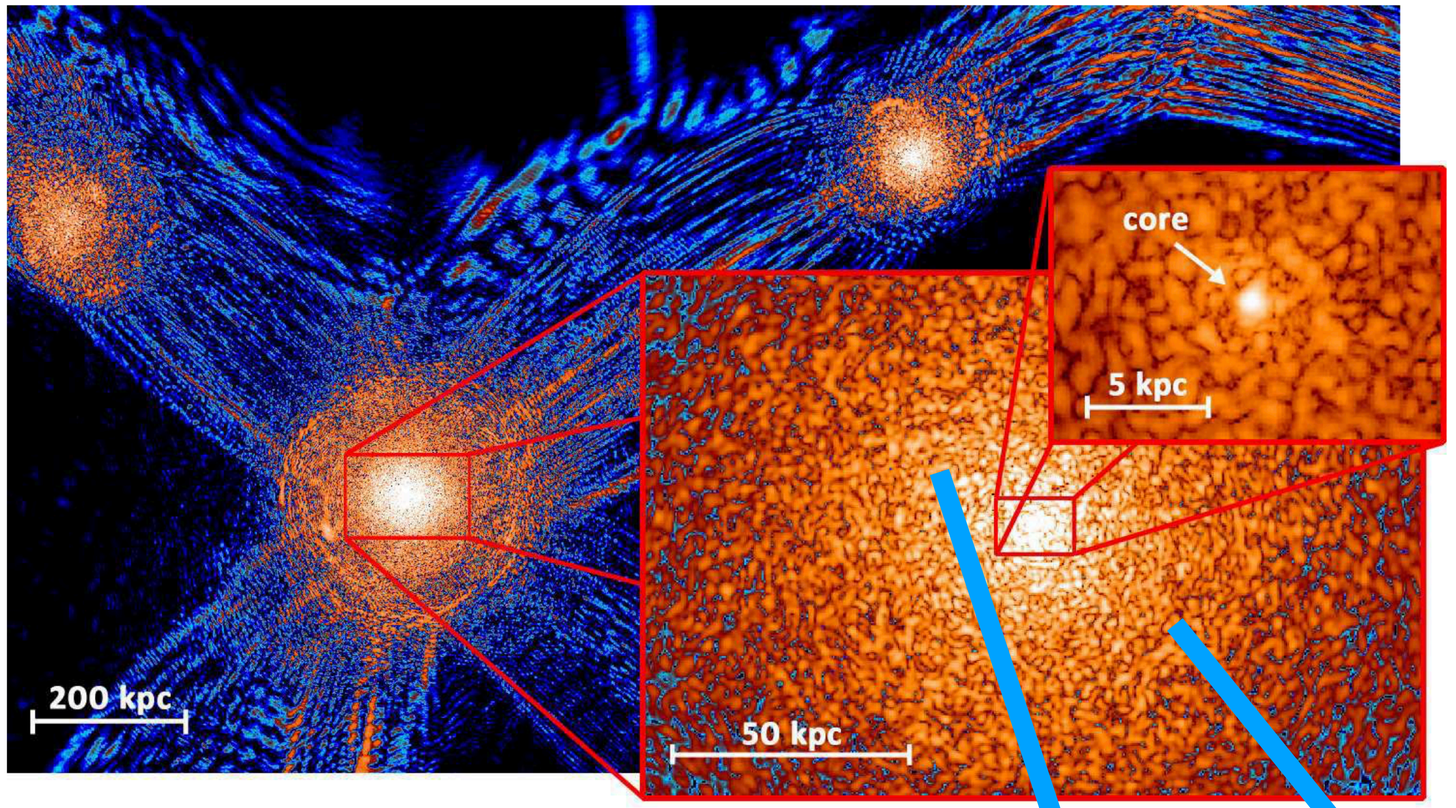
PTA:
Timing residual
$\delta t \propto m^{-3}$

Astrometry:
Angular deflection
$\delta n \propto m^{-2}$



# Ultralight dark matter

Schive, Chiueh, Broadhurst, 14’




Multivariate
Normal distribution

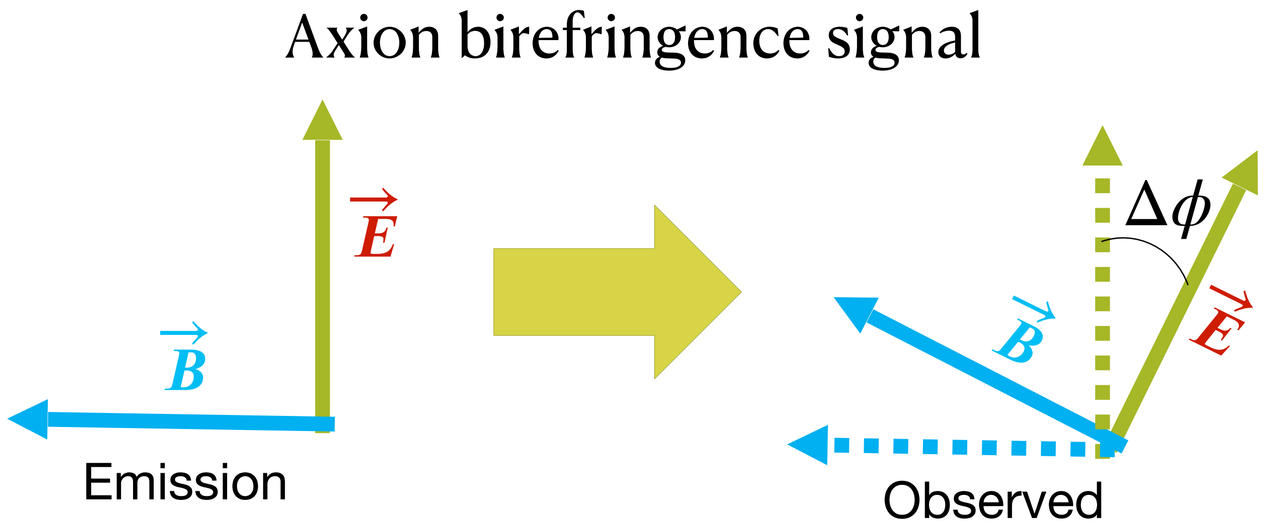
Correlation
Monopole Earth term +
inter-pulsar/Earth terms

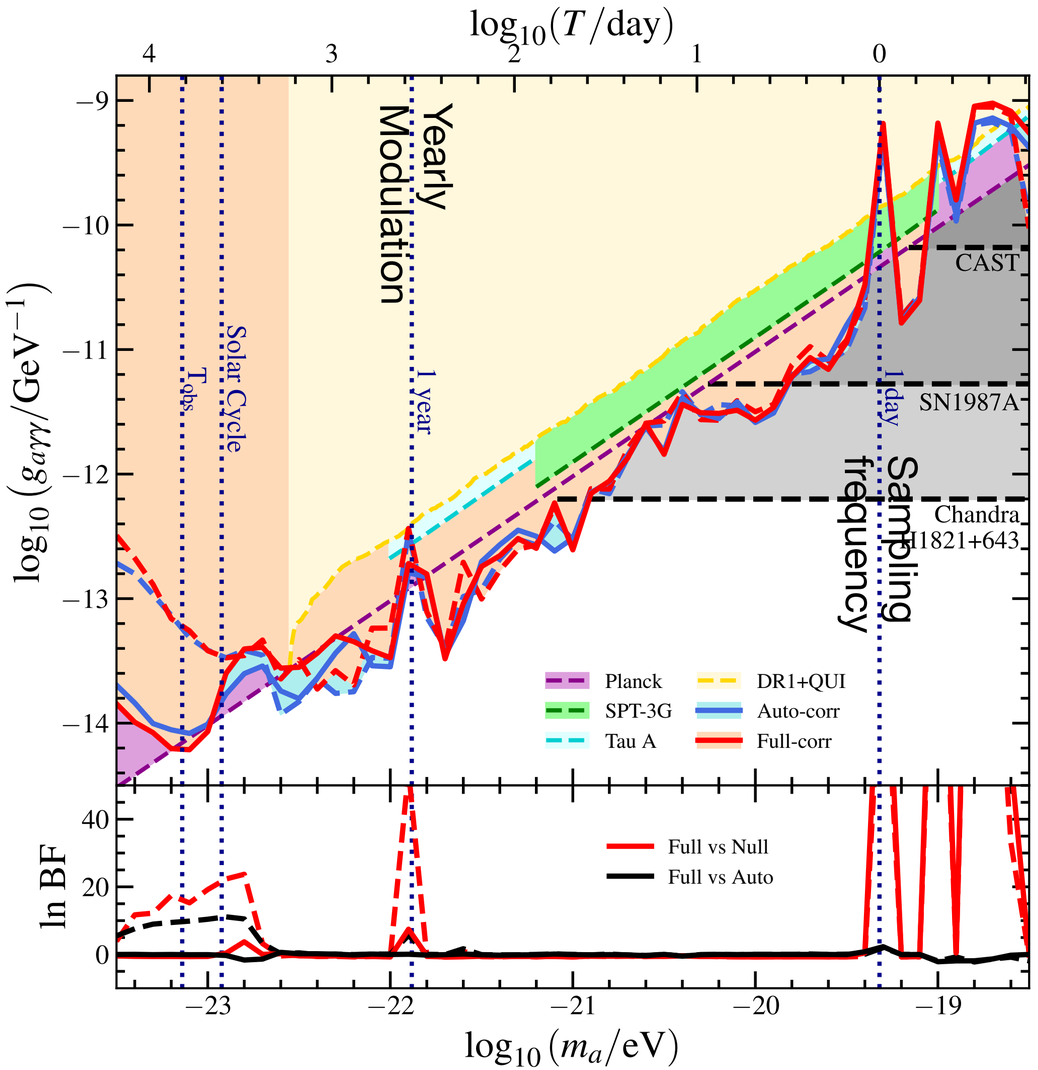
$$P\left(a(t_1,\vec{x}_1), a(t_2,\vec{x}_2), \ldots, a(t_n,\vec{x}_n)\right) = \mathcal{N}(\vec{0}, \boldsymbol{C}')$$

Foster, Kahn, Nguyen, Rodd, Safdi, 20’

# Ultralight dark matter

## Pulsar polarization array




**First Pulsar Polarization Array Limits on Ultralight Axion-like Dark Matter** #1

Xiao Xue (Barcelona, IFAE and Hamburg U., Inst. Theor. Phys. II and DESY), Shi Dai (Australia, CSIRO, Epping), Hoang Nhan Luu (Basque U., Bilbao), Tao Liu (Hong Kong U. Sci. Tech.), Jing Ren (Beijing, Inst. High Energy Phys. and Peking U., CHEP) et al. (Dec 3, 2024)

e-Print: 2412.02229 [astro-ph.HE]

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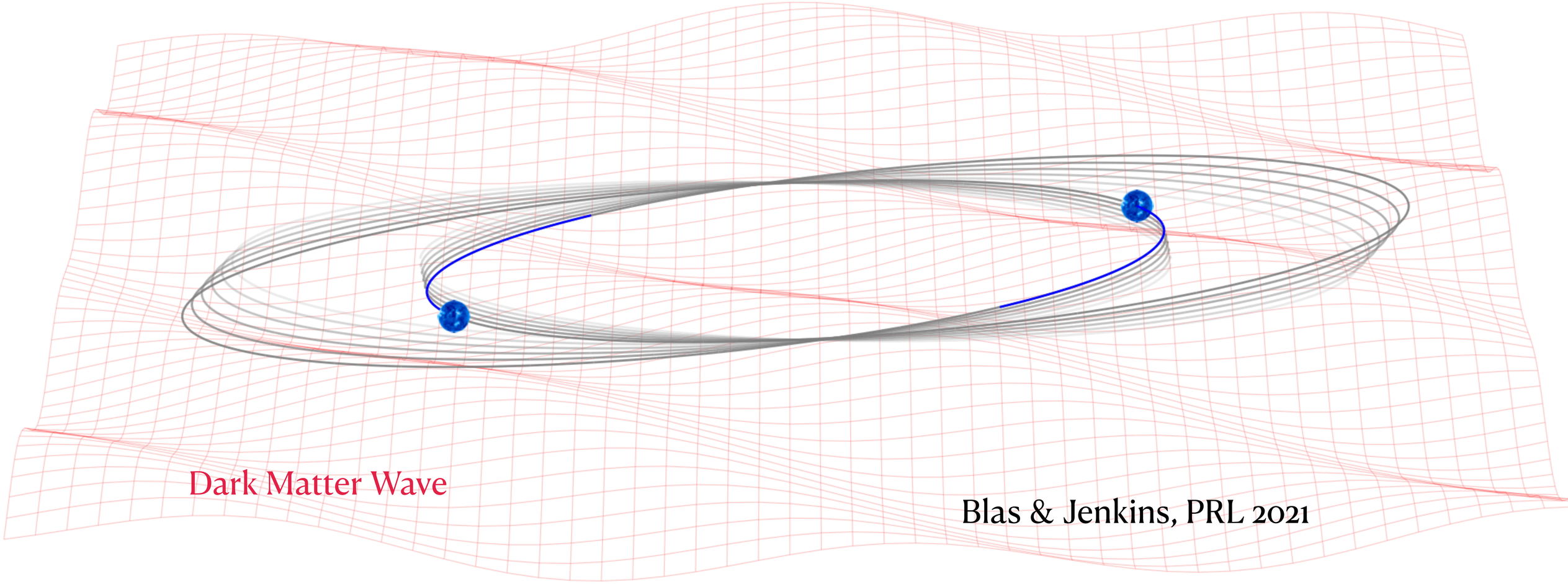
# Binary evolution




Blas & Jenkins, PRL 2021

# Binary evolution

$$\vec{a} = -\ddot{\Phi}\vec{r}$$

Diego Blas, Diana Lopez Nacir, and Sergey Sibiryakov, Phys. Rev. Lett. 118, 261102 (2017), arXiv:1612.06789

**Pure gravitational effect**

**To appear on arXiv soon!**

- Not mentioned in this talk:
  - Dark matter / dark sector imprints on GW
  - Various couplings between DM and SM
  - Wide band DM spectrum
- Future work with NANOGrav
- Binary evolution
  - Improved theory paper
  - Data analysis paper