The Kavli Institute for Astronomy and Astrophysics at Peking University
北京大学科维理天文与天体物理研究所

Workshop on Very Light Dark Matter 2021

Bounding long-range force from dark matters with binary pulsars

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Shao, Wex, & Kramer 2018, PRL 120:241104

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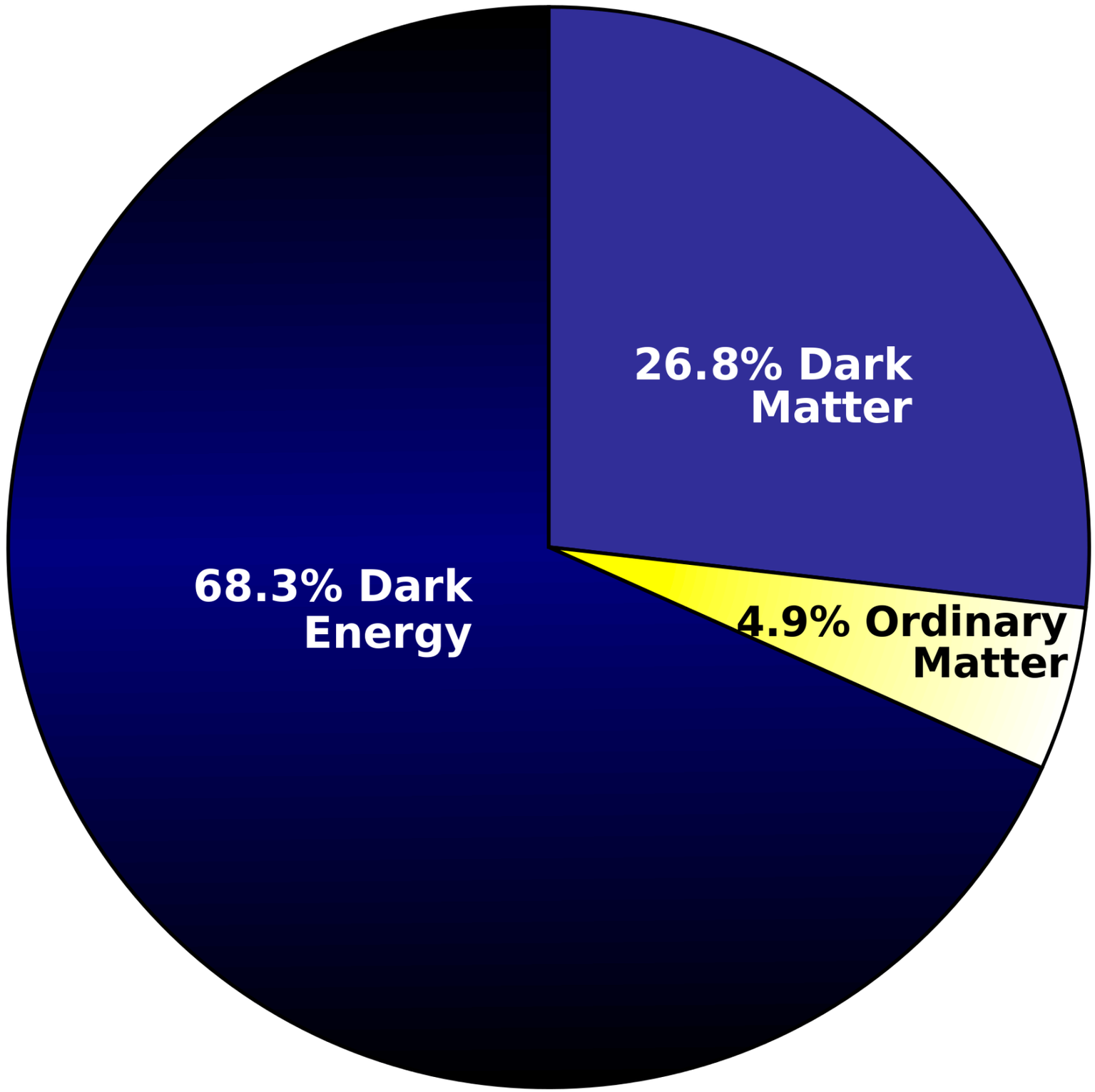
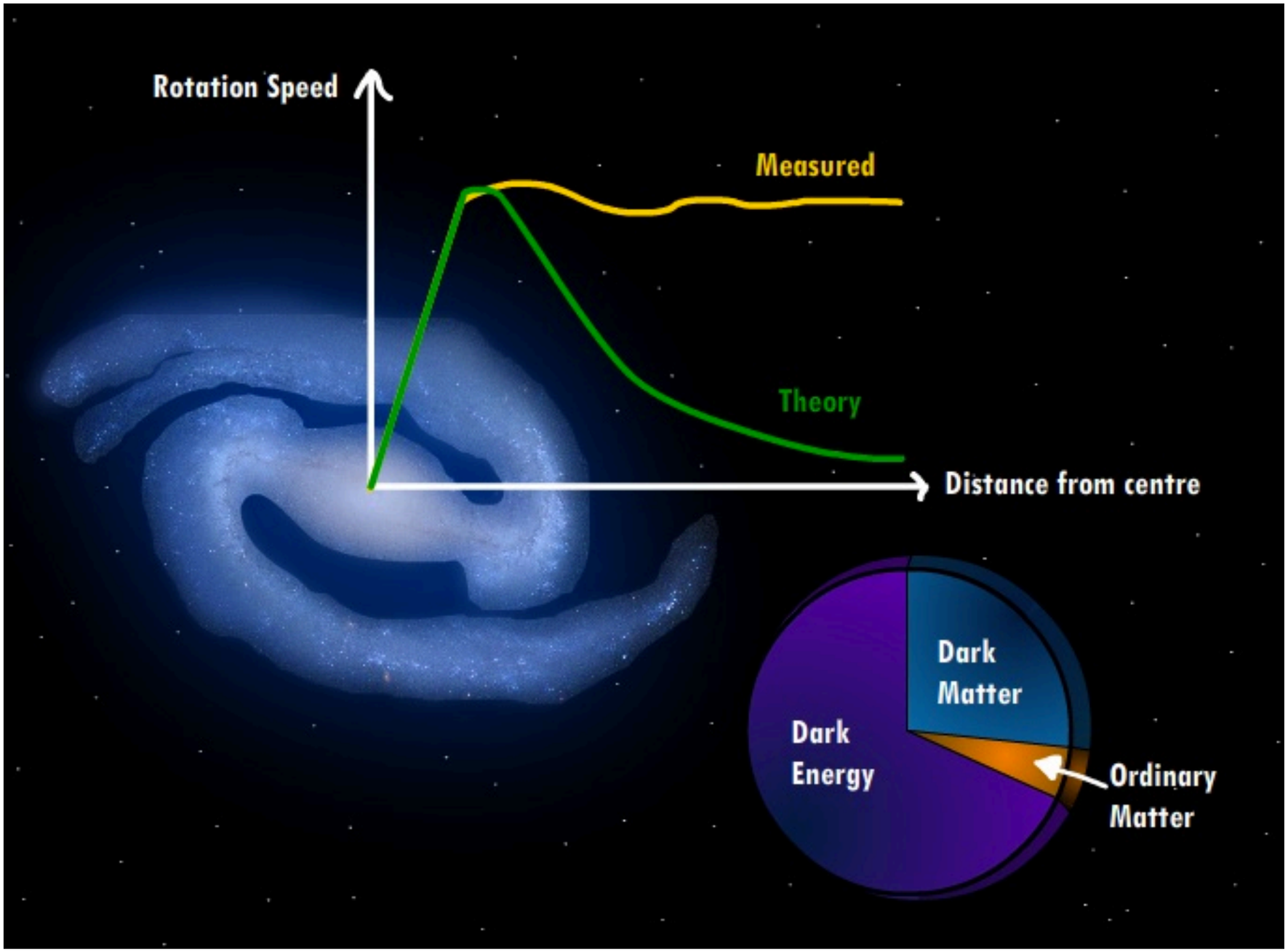
Universe

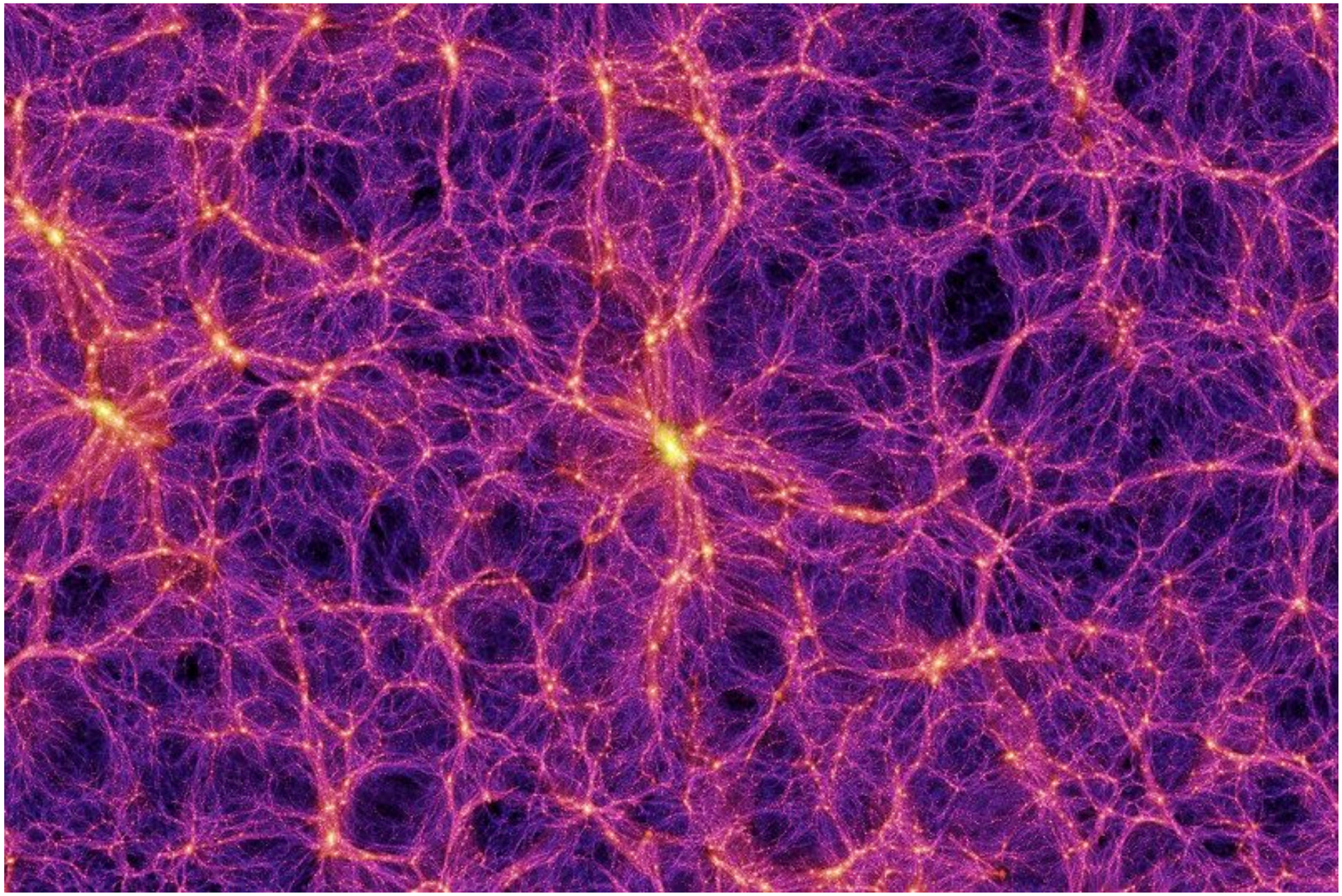


Rotation curves



Originally, the idea of dark matter came from the “anomaly” of rotation curves

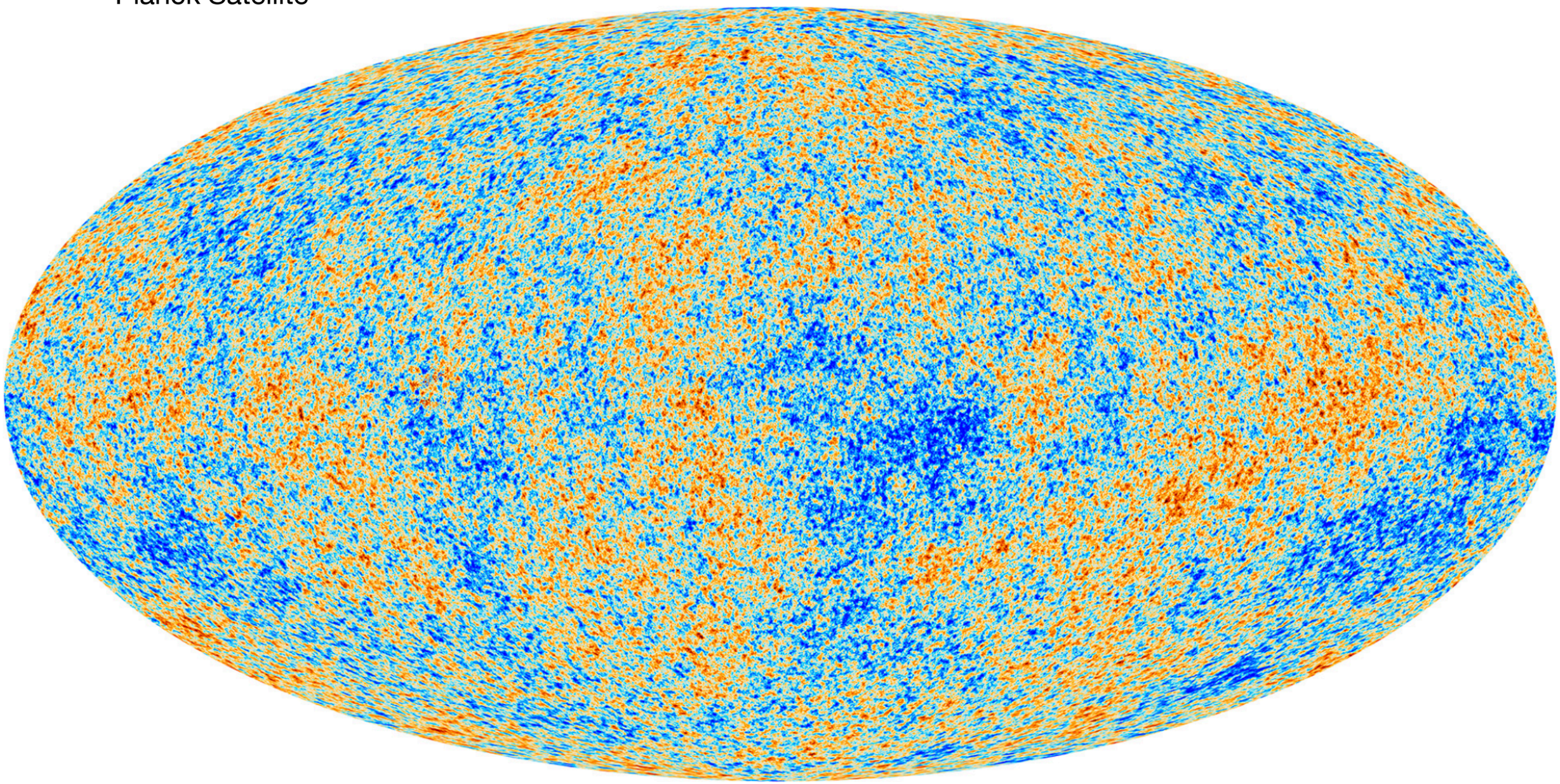
Large-scale structure



The particular property also influences the formation of large-scale structures of our Universe

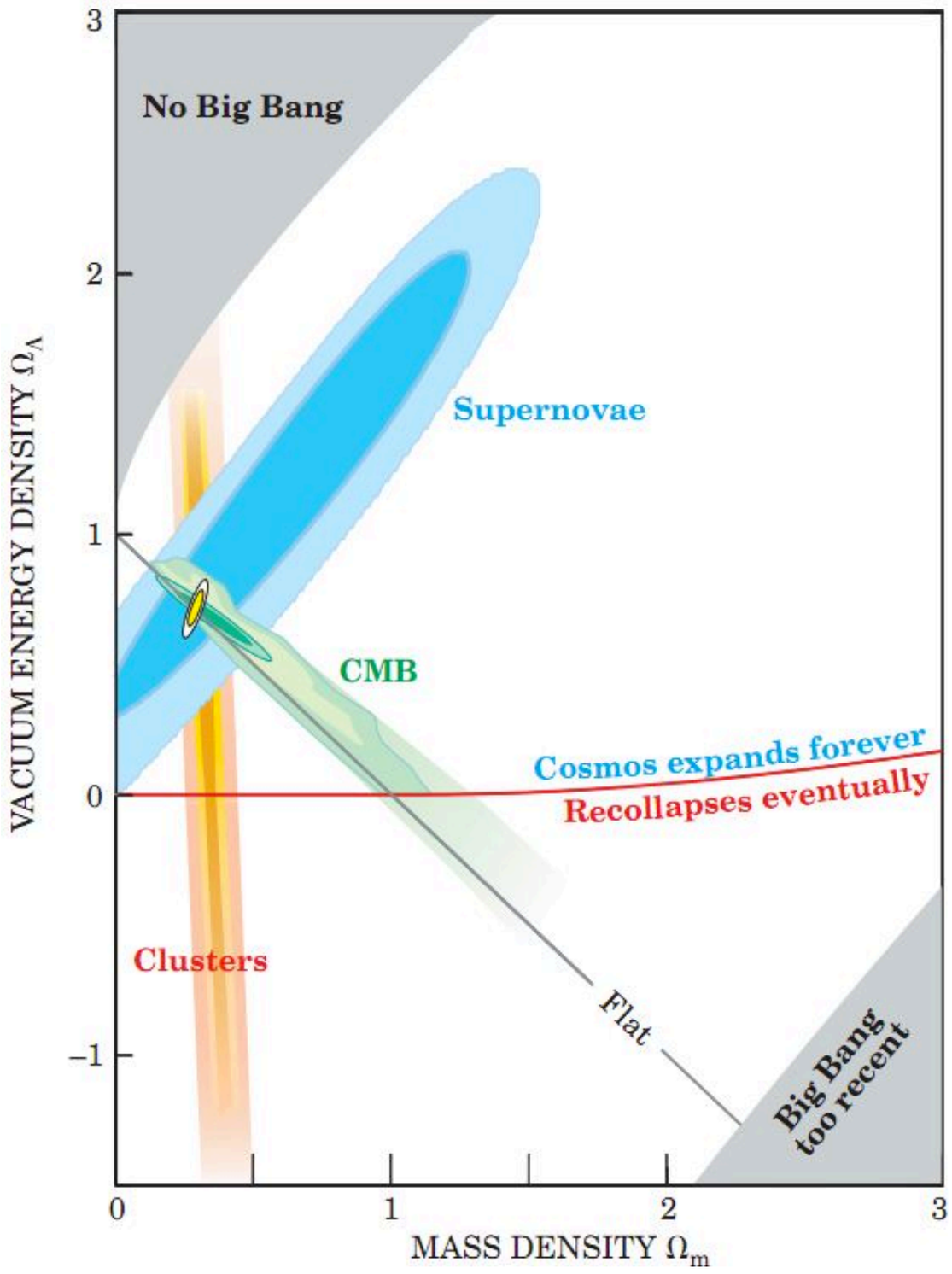
Cosmic microwave background

Planck Satellite



Dark matters also leave imprints on the cosmic microwave background

ΛCDM cosmology



- ΛCDM is a parametrization of the Big Bang cosmology, in which the universe contains a cosmological constant **Λ**, and cold dark matter, **CDM**

  - ✓ **Λ: associated with dark energy**
  - ✓ **CDM: cold dark matter**

- It is frequently referred to as the **standard model** of Big Bang cosmology

Searches for dark matters

“Search” means looking for interactions….

Nothing found yet!

What are dark-matter “particles/fields”?

Another question

Is there a long-range force between dark matter and ordinary matter other than the gravity?

What QFT tells us…

- **In quantum field theory, scalar (-) or vector boson (+) exchange introduces a spin-independent potential between a test mass A and DM** Adelberger et al. 2009

$$V(r) = \mp g_5^2 \frac{q_5^{(A)} q_5^{\mathrm{DM}}}{4\pi r} e^{-r/\lambda}$$

- **An *apparent* violation of the equivalence principle**

Eötvös parameter

$$\eta_{\mathrm{DM}}^{(A,B)} = \pm \frac{g_5^2}{4\pi G u^2} \frac{q_5^{\mathrm{DM}}}{\mu_{\mathrm{DM}}} \left(\frac{q_5^{(A)}}{\mu_A} - \frac{q_5^{(B)}}{\mu_B} \right)$$

$$\eta^{(A,B)} \equiv \frac{a_A - a_B}{\frac{1}{2}\left(a_A + a_B\right)}$$

$$\lambda = \infty$$

$\left(q_5/\mu\right)$ **is an object's charge per atomic mass unit *u***

✦ A generic parameterization

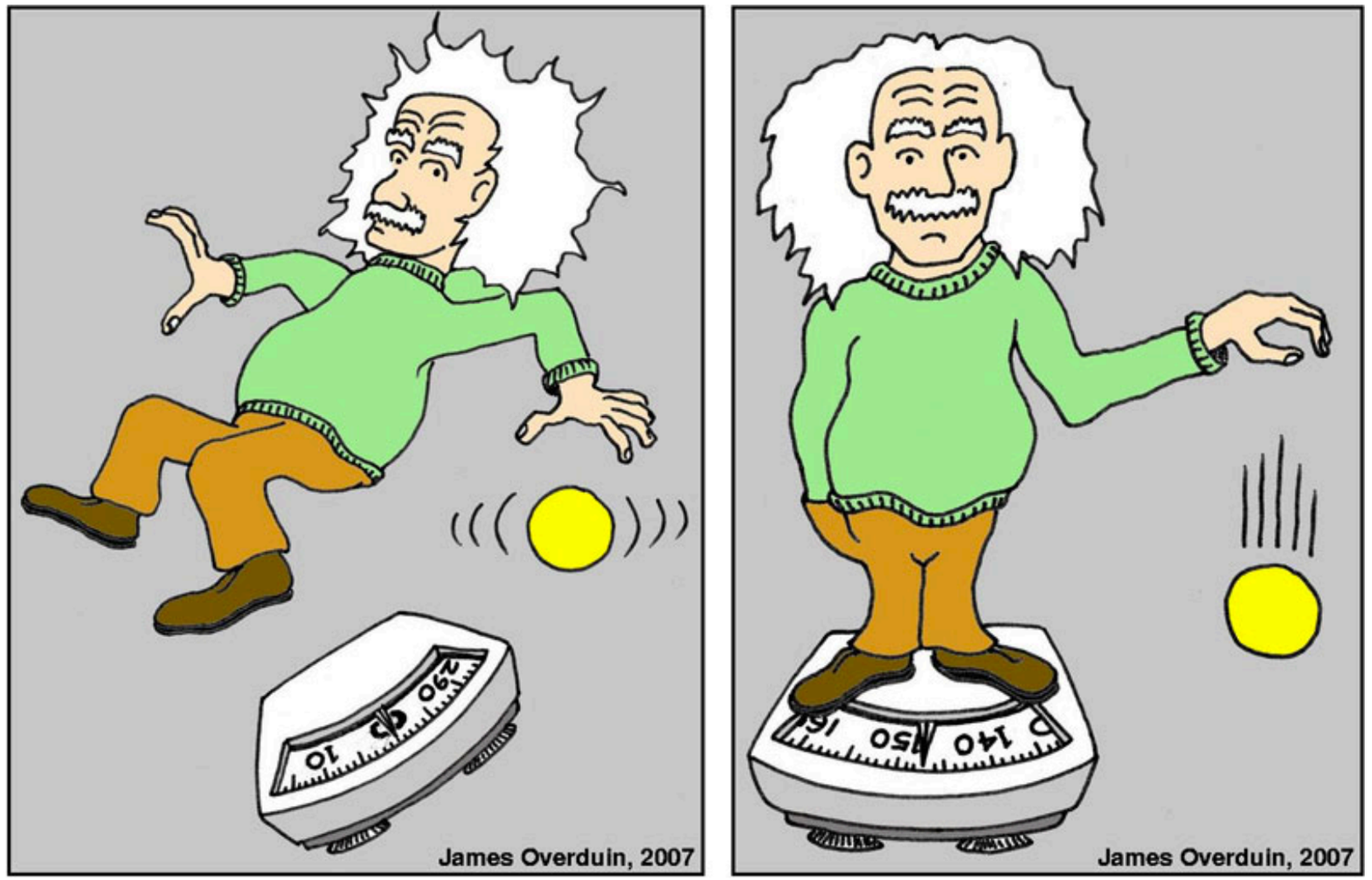
$$\left(\frac{q_5}{\mu}\right) = \left(\frac{Z}{\mu}\right)\cos\psi + \left(\frac{N}{\mu}\right)\sin\psi$$

$$\tan\psi = \frac{q_5^{(n)}}{q_5^{(p)} + q_5^{(e)}}$$

The most general expression for vector charges and a reasonable tree-level approximation for scalar charges

Adelberger et al. 2009

Equivalence principle in GR



The gravitational “force” as experienced locally while standing on a massive body (such as the Earth) is the same as the pseudo-force experienced by an observer in a non-inertial (accelerated) frame of reference.

Mass deficit

- **Nuclear binding, electromagnetic binding, etc**

$$\left(\frac{B}{\mu}\right) = \left(\frac{Z}{\mu}\right) + \left(\frac{N}{\mu}\right) = 1 + \mathcal{O}\left(10^{-3}\right)$$

- **Gravitational binding for neutron stars**

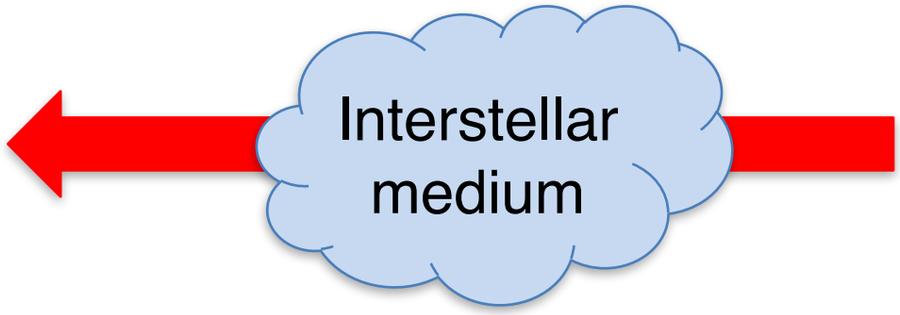
$$\left(\frac{B}{\mu}\right) = 1 + \mathcal{O}\left(10^{-1}\right)$$

Shao et al. 2018

	Z/μ	N/μ	B/μ
Be	0.443 84	0.554 80	0.998 65
Al	0.481 81	0.518 87	1.000 68
Ti	0.459 61	0.541 47	1.001 08
Pt	0.399 84	0.600 34	1.000 18
Earth	0.49	0.51	1.00
Moon	0.50	0.50	1.00
NS (1.33 $M_\odot$)	$\simeq$0	$\simeq$1.19	$\simeq$1.19
WD (0.290 $M_\odot$)	$\simeq$0.5	$\simeq$0.5	$\simeq$1.0

Mass deficit sets the “sensitivity” to different kinds of energy

Pulsar timing



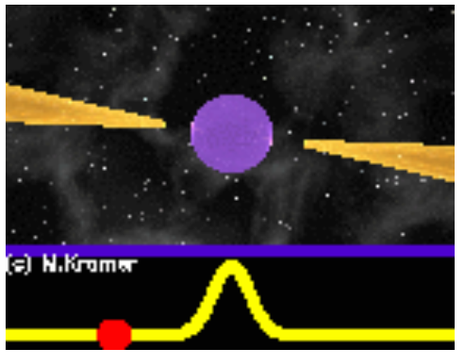
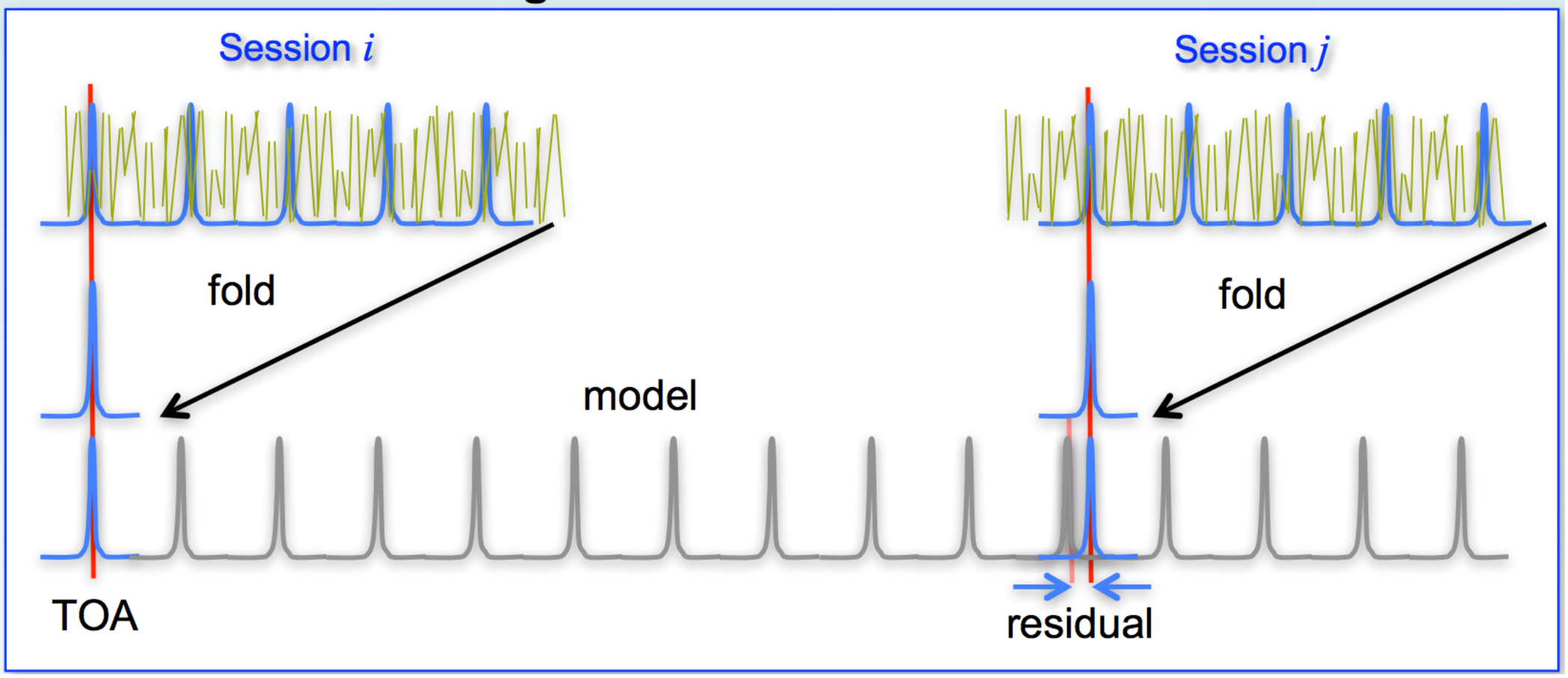


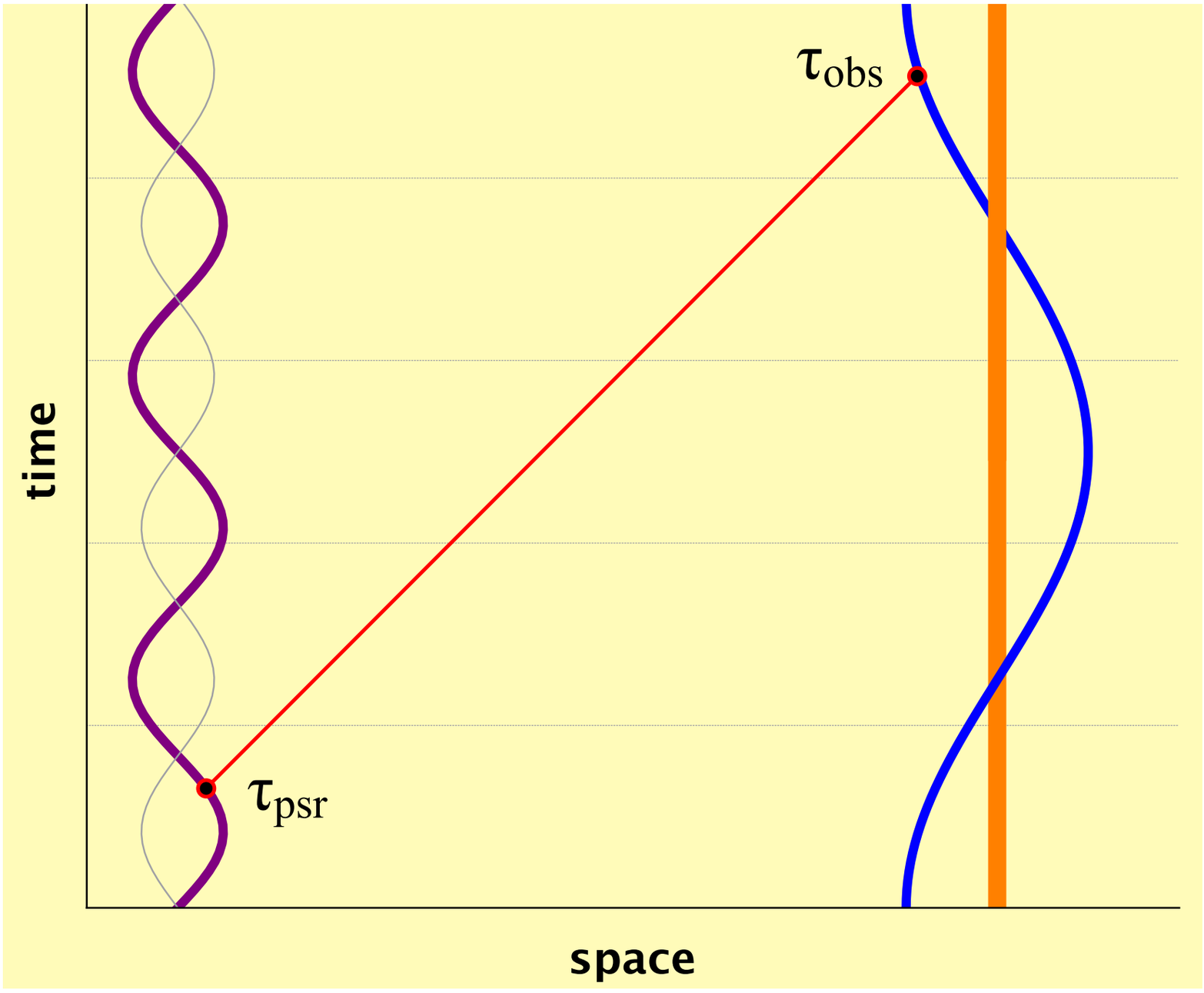
Figure Credit: M. Kramer

Phase-connected timing solution:

Credit: N. Wex



Timing model



©N. Wex

State-of-the-art equivalence principle

Shao et al. 2018

see also MICROSCOPE'2017

test bodies

measurement precision

$$\eta_{\oplus}^{(A,B)} \equiv \frac{a_A - a_B}{\frac{1}{2}(a_A + a_B)}$$

attractor

driving force

~ 10^{-2} m s^{-2}

$$\eta < 10^{-13}$$

State-of-the-art equivalence principle

Shao et al. 2018

test bodies

measurement precision

$$\eta^{(A,B)}_{\mathrm{DM}} \equiv \frac{a_A - a_B}{\frac{1}{2}(a_A + a_B)}$$

attractor

driving force

~ 10^{-10} m s^{-2}

$\eta_{\mathrm{DM}} < 10^{-5}$

Testing equivalence principle with pulsars

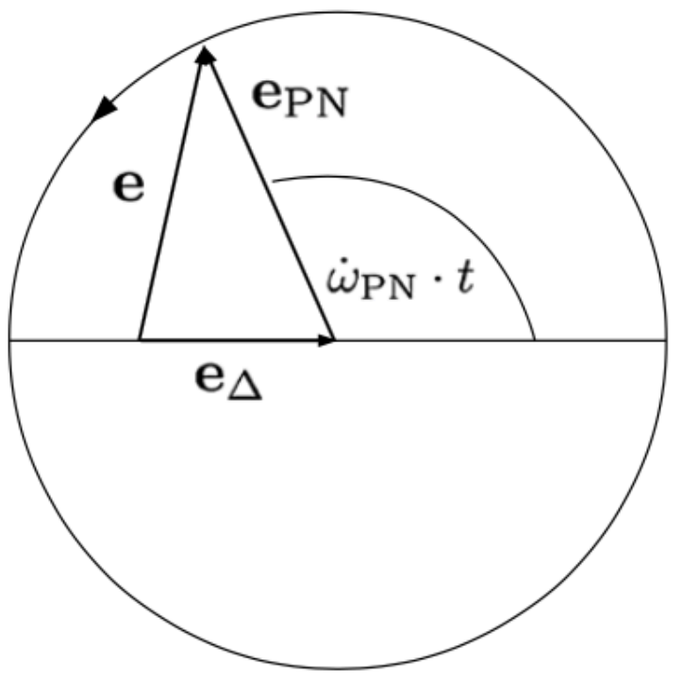
EP violation "polarises" a binary orbit

Nordtvedt 1968
Damour & Schaefer 1991
Zhu et al. 2019

$\eta < 10^{-3}$

Eccentricity vector

$$\mathbf{e} \equiv e\hat{\mathbf{a}}$$



$g \sim 2 \times 10^{-10}$ m s^{-2}

$\mathbf{g}_{\perp}$

see Freire, Kramer, Wex 2012 for details

PSR J1713+0747

1.33 $M_\odot$ NS

0.29 $M_\odot$ WD

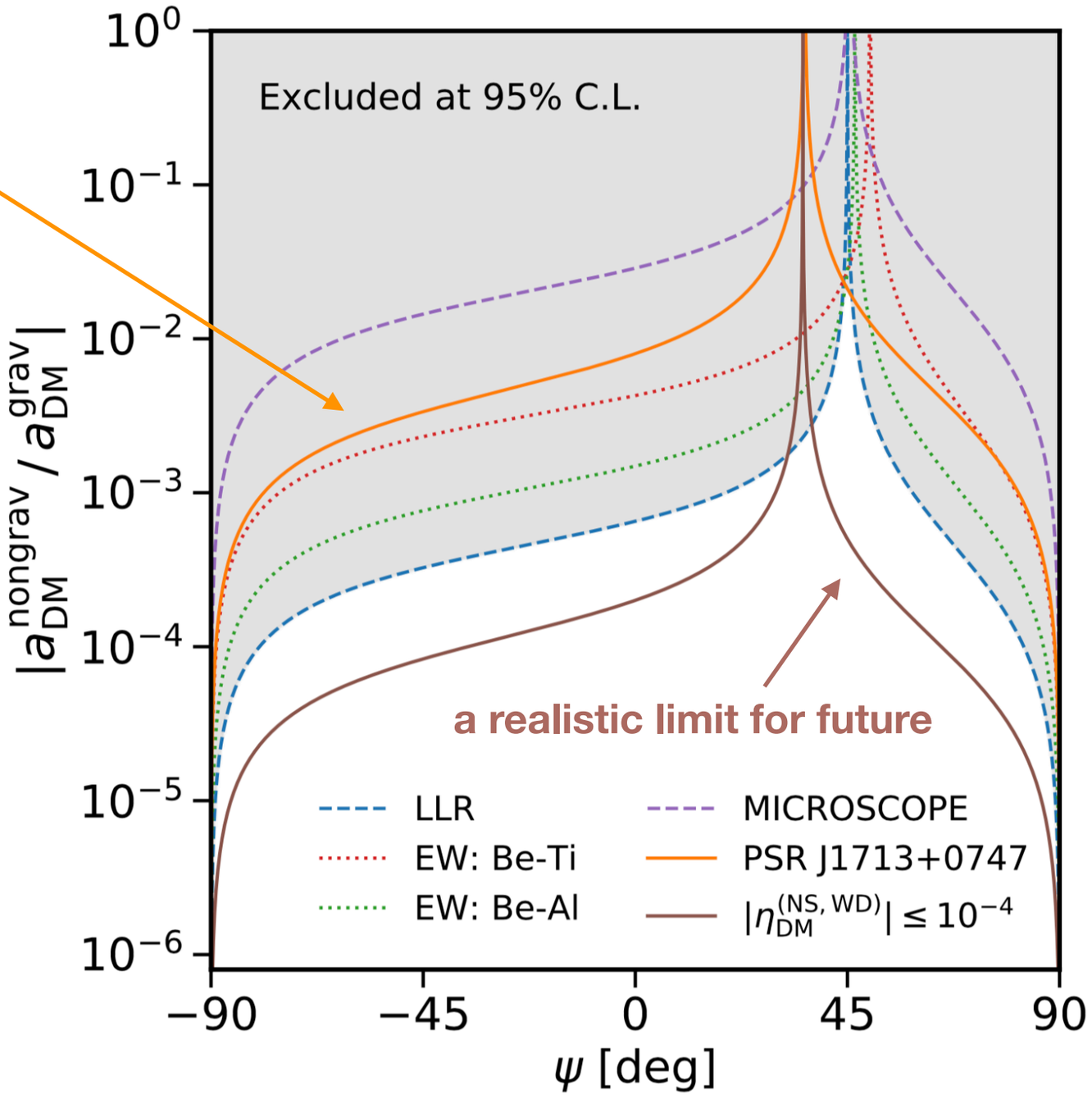
Credit: B. Saxton (NRAO/AUI/NSF)

Non-gravitational force from dark matter

PSR J1713+0747: $\eta_{DM} < 0.004$

Zhu et al. 2019

- **Large material difference in test-body pairs (NS vs WD)**
- **Significant gravitational binding energy ~0.2**
- **Improve continuously with timing baseline: $T^{-3/2}$**

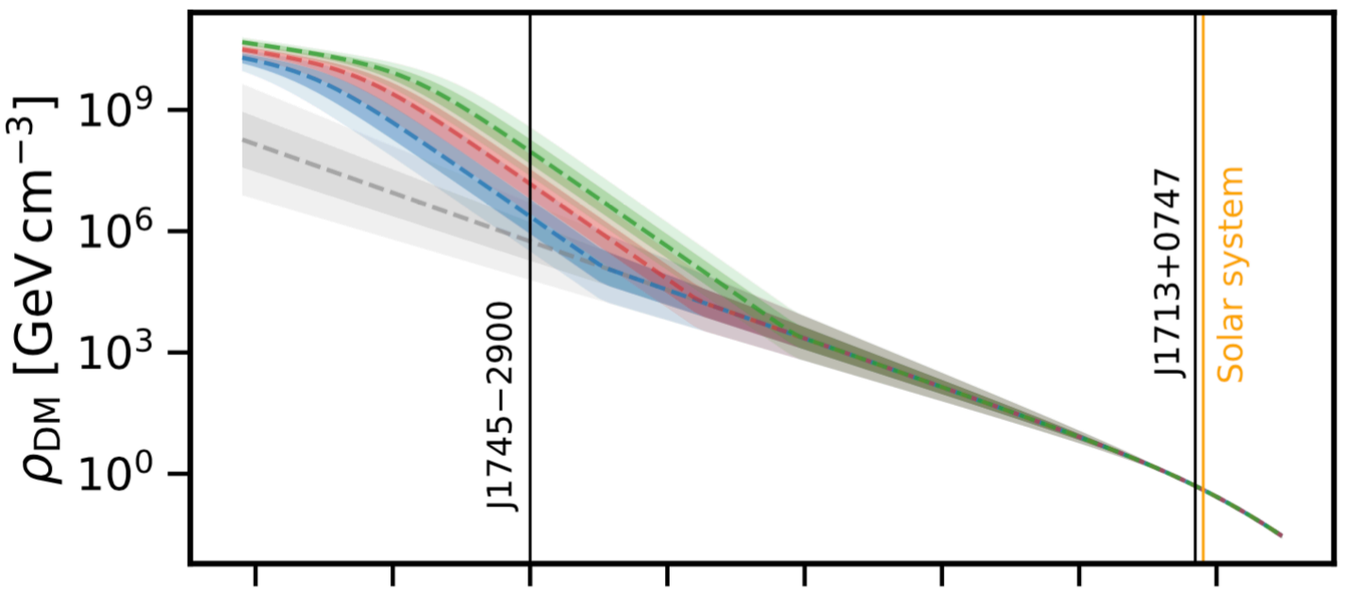


Shao et al. 2018

Pulsar survey towards Galactic center

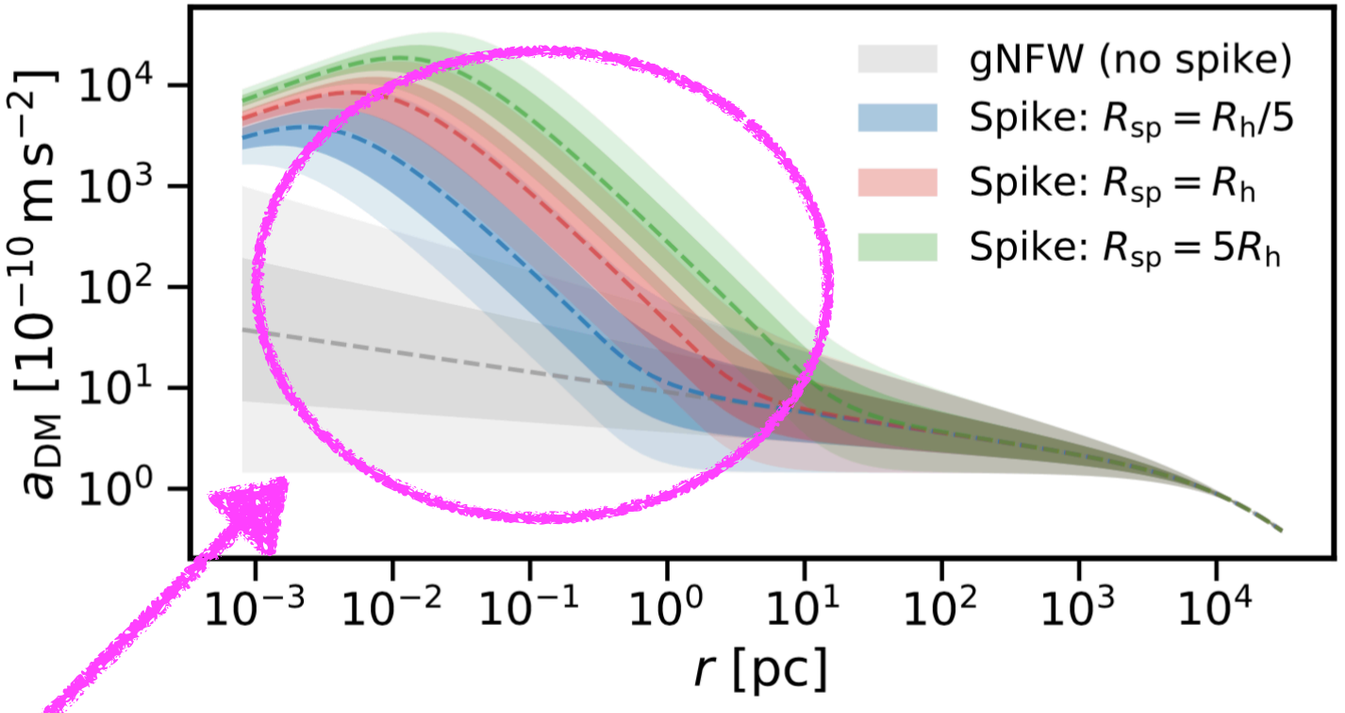
✦ **In response to the adiabatic growth of Sgr A*, a dark matter spike is expected close to the BH**

Gondolo & Silk 1999



✦ **Binary pulsars within about 10 pc from the Galactic centre will be extremely helpful in the test**

Eatough et al. 2015
BalckHoleCam project



Driving force larger by orders of magnitude

Summary

- **Is there a long-range force between dark matter and ordinary matter other than the gravity?**

- **PSR J1713+0747 shows that, the non-gravitational force between "dark matter" and ordinary matter is <1% of the gravity**

- **Solar-system orbital dynamics** [Sun, Cao, Shao, PRD100:084030 (2019)]

- **Future pulsar surveys towards the Galactic center will do even better**

Thank you!