



Testing the Universality of Free Fall towards Dark Matter with Pulsars

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Outline

◆ Equivalence Principles

◆ Pulsar Timing

◆ “Dark Matters”

◆ Glue Everything Together

✓ “Testing the Universality of Free Fall towards Dark Matter with Pulsar Timing”

Equivalence Principles

Equivalence Principle: Universality of Free Fall

(famous “rumor”)



(real-life demonstration)



Gravitational mass = Inertial mass

$$m_g = m_I$$

Equivalence Principle: Universality of Free Fall

(famous “rumor”)



(real-life demonstration)

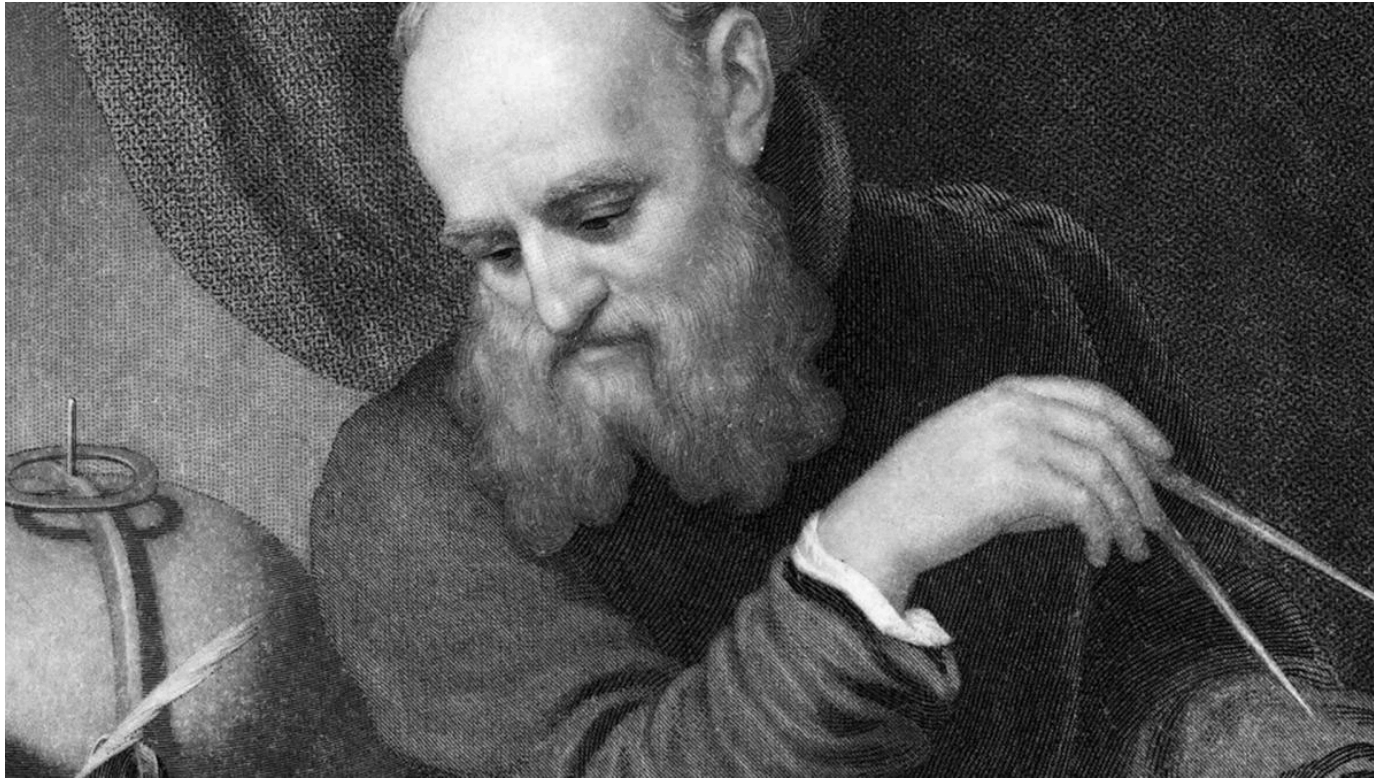


Free drops: errors in initial conditions

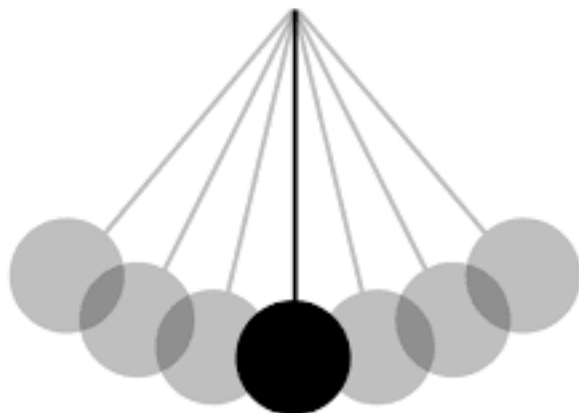
It was not picked, even in the era of Newton.

Equivalence Principle: Universality of Free Fall

Galileo



Newton



Pendulum Swing

◆ pendulums by Galileo & Newton: $< 10^{-3}$

Modern Tests of EPs: Torsion Balances

◆ Torsion balances by **Eötvös**: $< 10^{-8}$

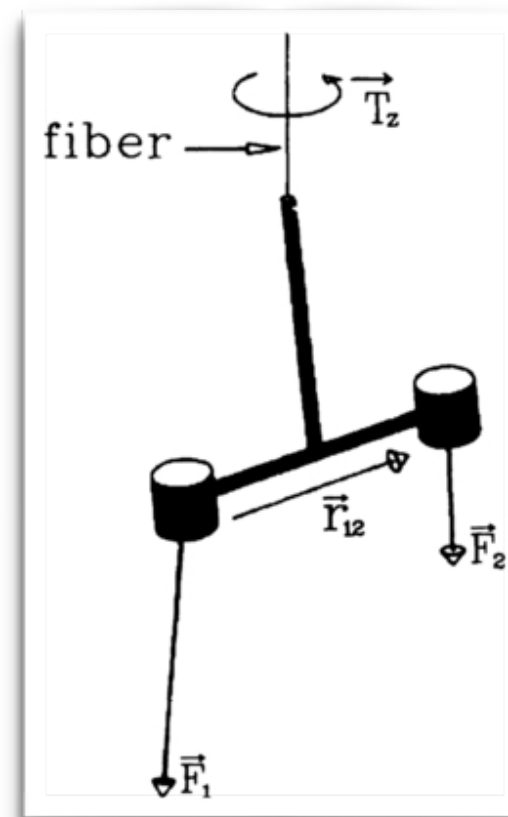
◆ *Rotating* torsion balances

◆ **Dicke**: $< 10^{-11}$

◆ **Braginsky**: $< 10^{-12}$



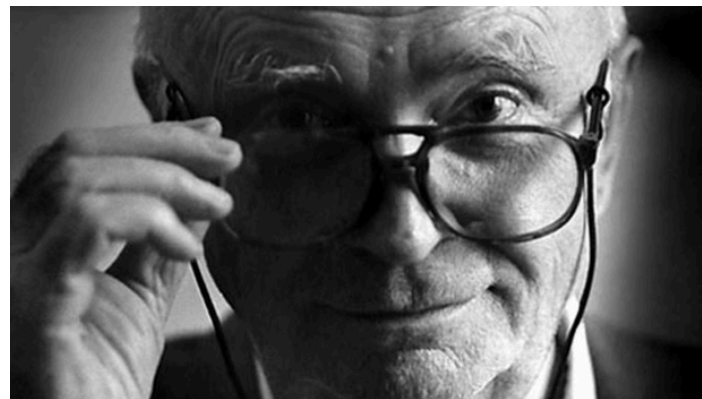
Eötvös



Adelberger



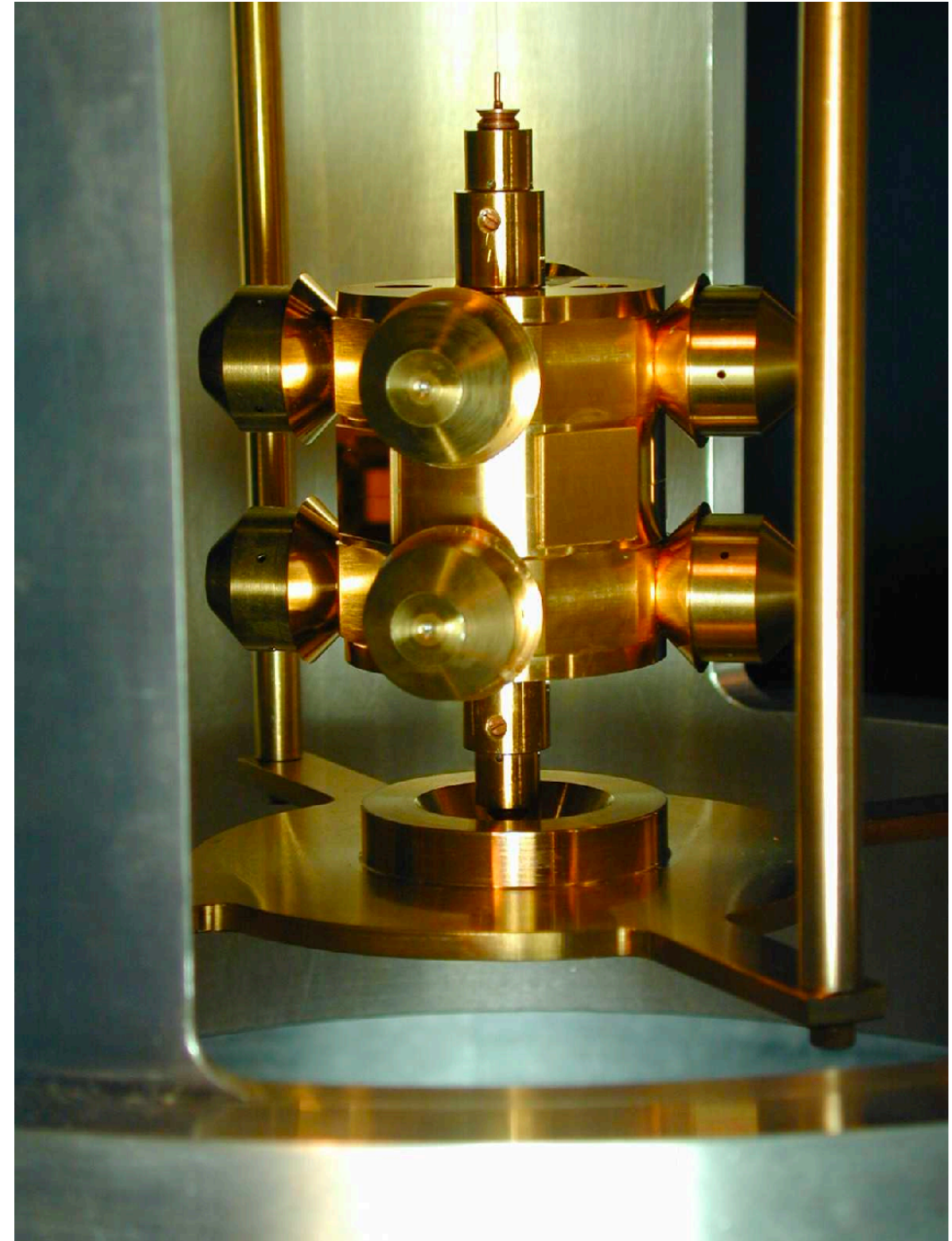
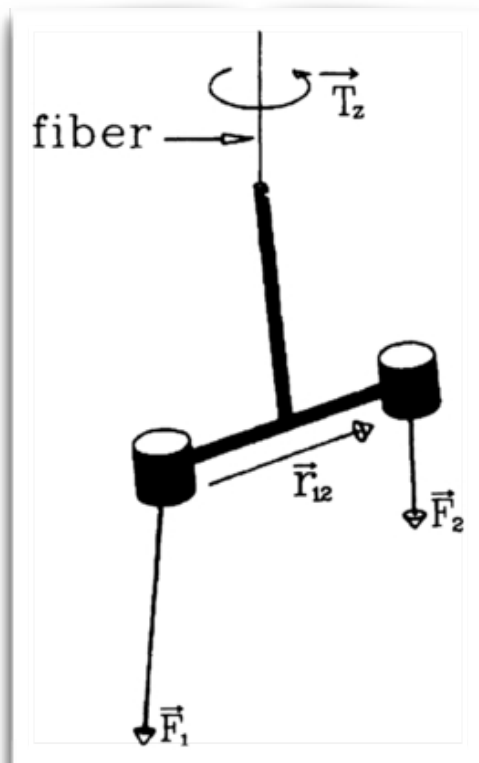
Dicke



Braginsky

◆ **Eöt-Wash group**: $\eta < 10^{-13}$

Rotating Torsion at the Eöt-Wash Group



First Results from the MICROSCOPE Satellite

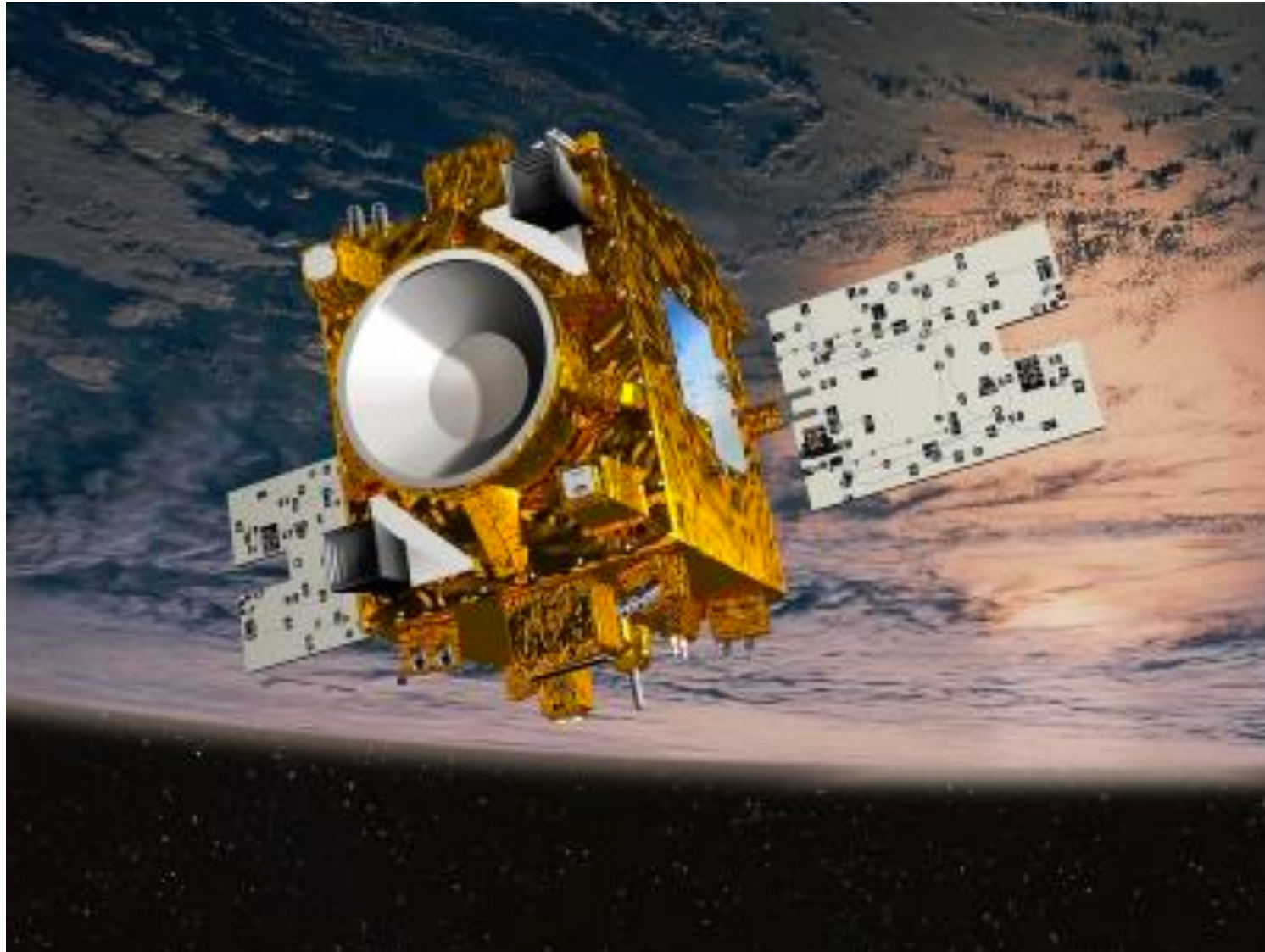
PRL **119**, 231101 (2017)

PHYSICAL REVIEW LETTERS

week ending
8 DECEMBER 2017

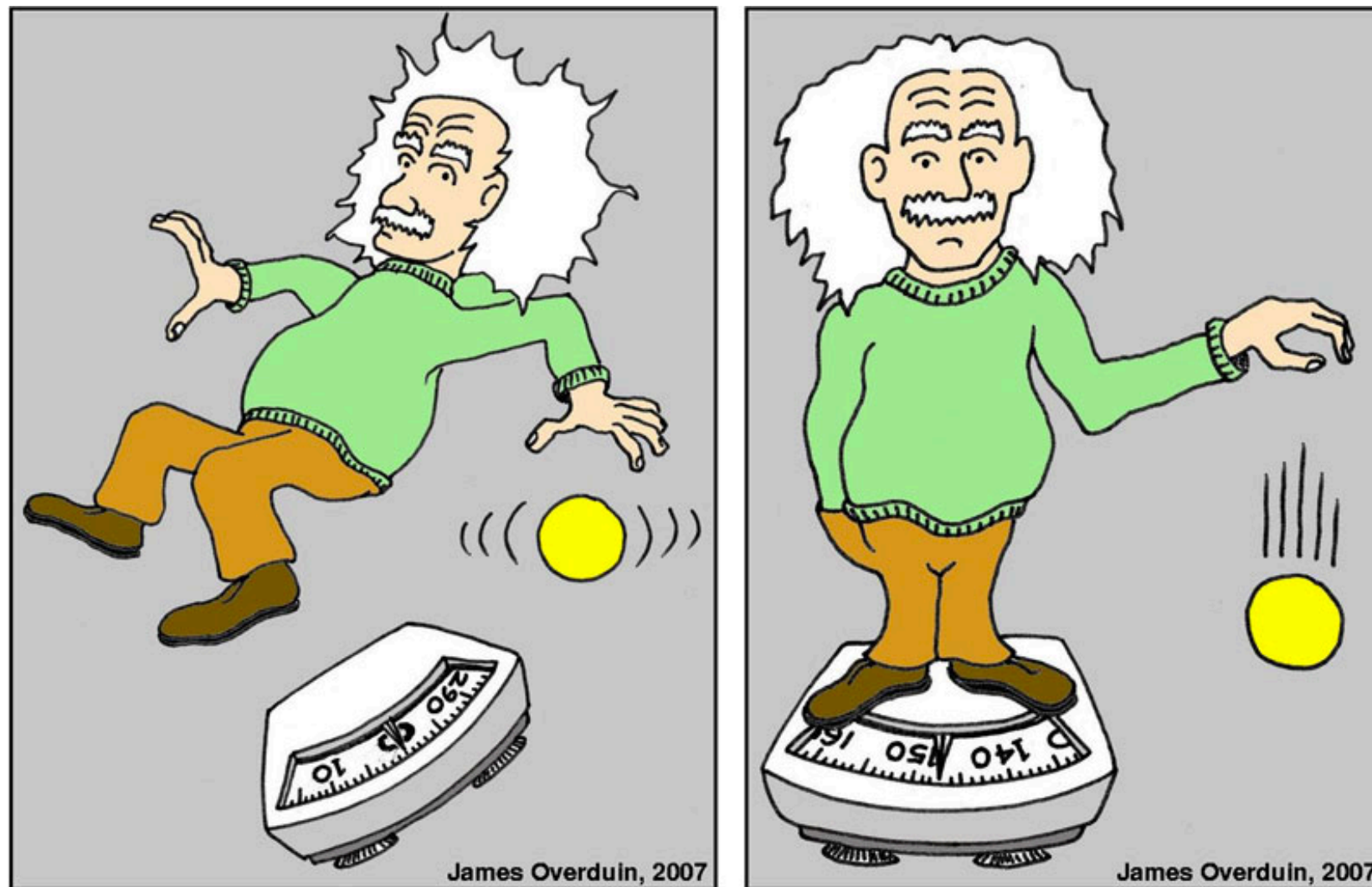


MICROSCOPE Mission: First Results of a Space Test of the Equivalence Principle



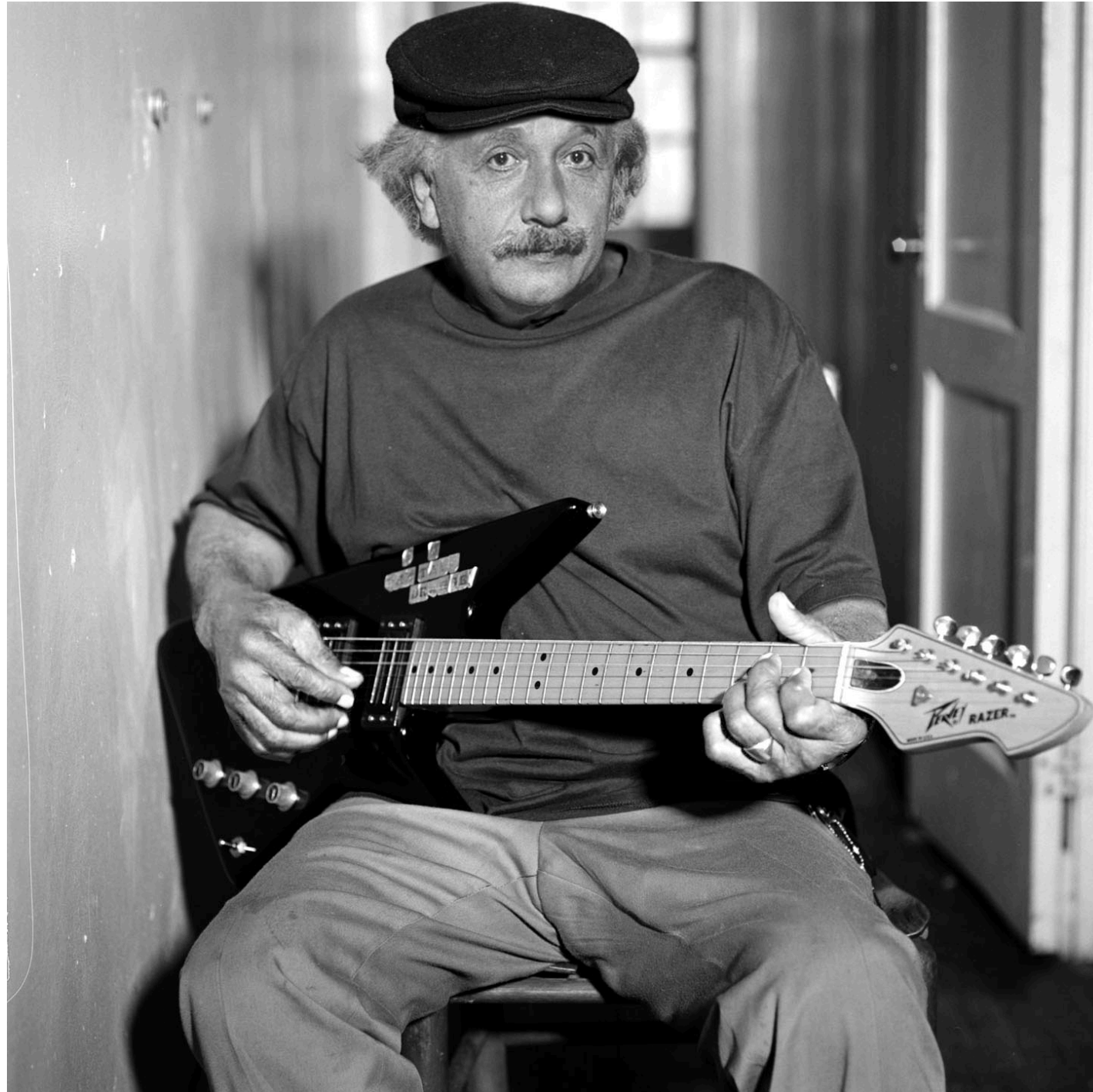
- ◆ *MICROSCOPE*: first result: $< 10^{-14}$
- ◆ Expected for the full mission: $\sim 10^{-15}$

Equivalence Principle in General Relativity



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.

“The Happiest Thought of Life”



Tower of Equivalence Principles (EPs)



$$\eta = \frac{m_G}{m_I} - 1$$

Weak equivalence principle



Einstein equivalence principle



Strong equivalence principle

Will, Theory and Experiment in Gravitational Physics (1993)

Will, Living Rev. Relativity 17 (2014) 4

see also, Casola et al., AJP 83 (2015) 39

Behind EPs... Gravity is geometry!



Behind EPs... Gravity is geometry!

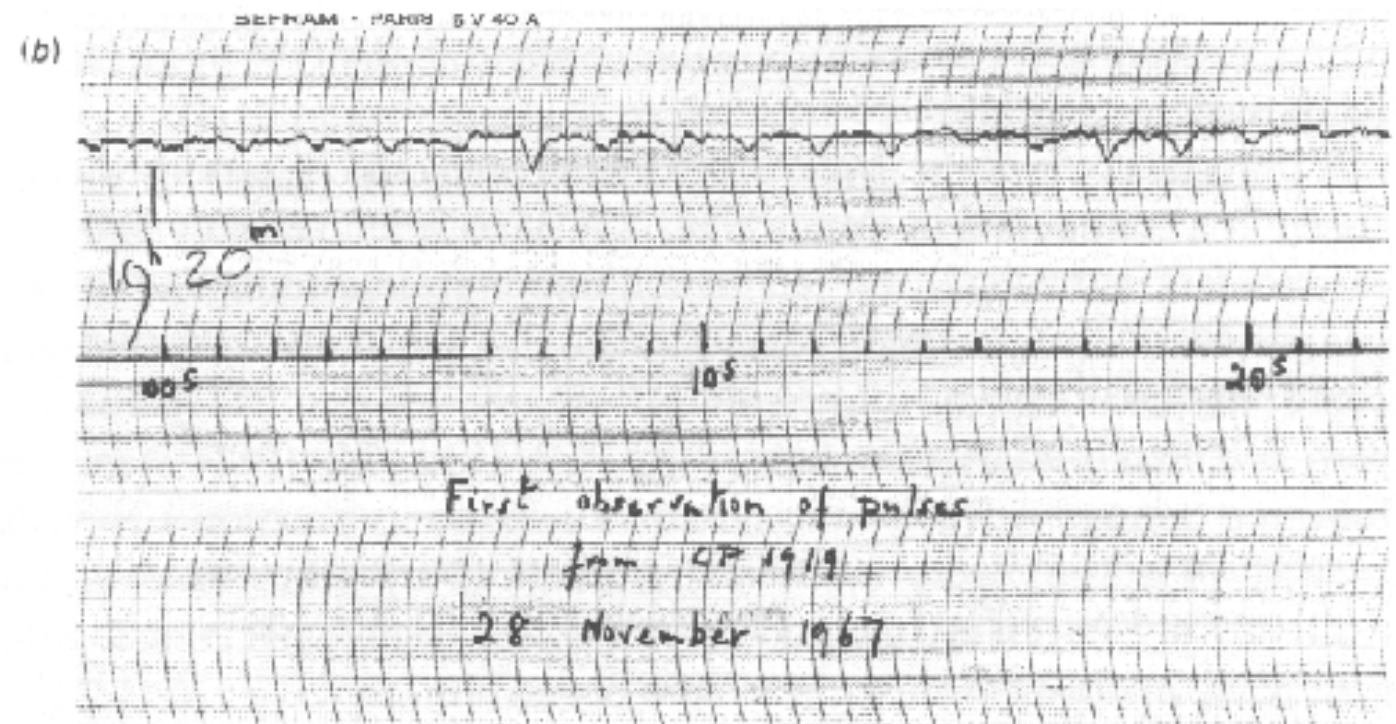
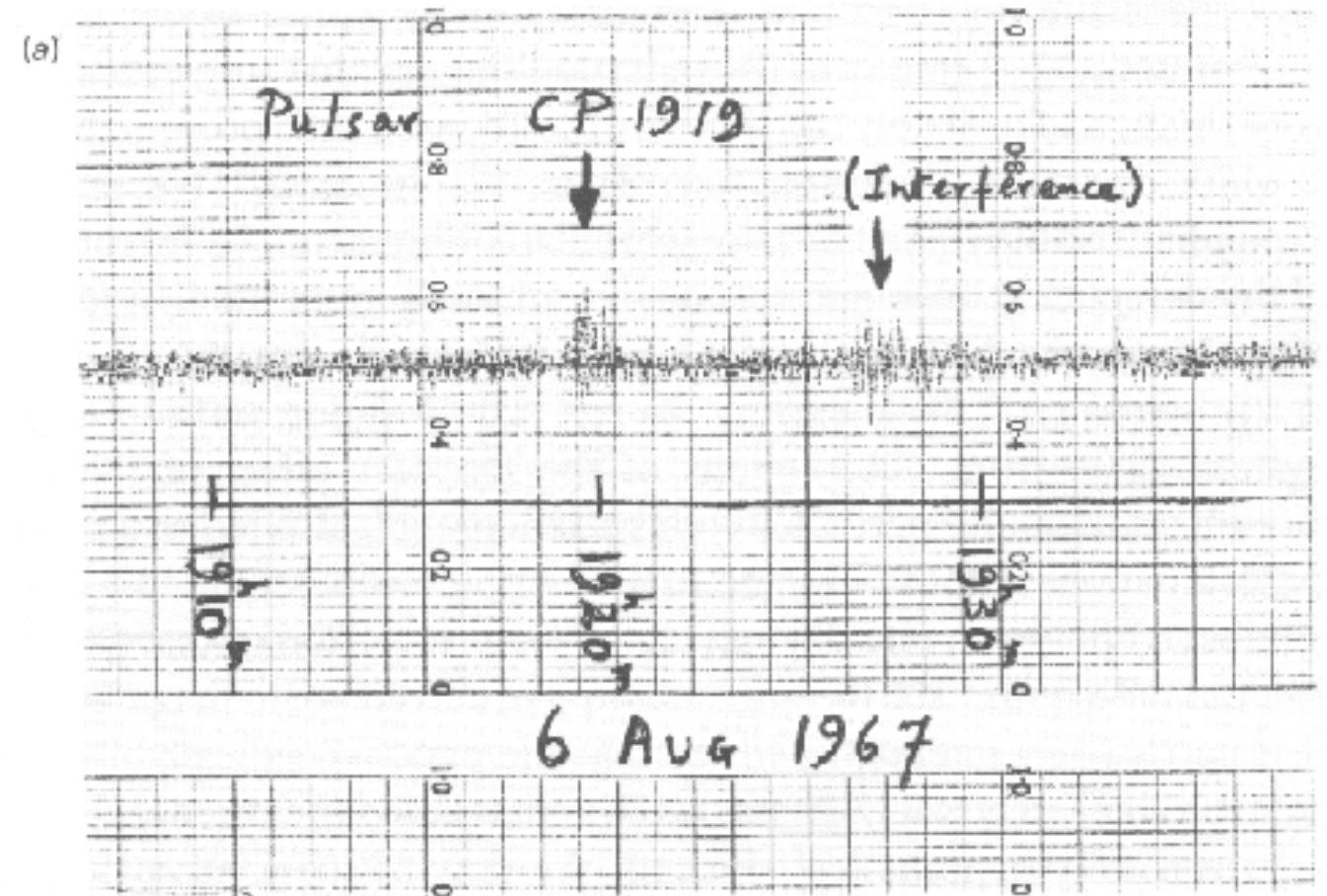
Pulsar Timing

Pulsar Discovery



Jocelyn Bell

about 50 years ago...



Observation of a Rapidly Pulsating Radio Source

by

A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
P. F. SCOTT
R. A. COLLINS

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

Hewish, Bell, et al., Nature 217 (1968) 709

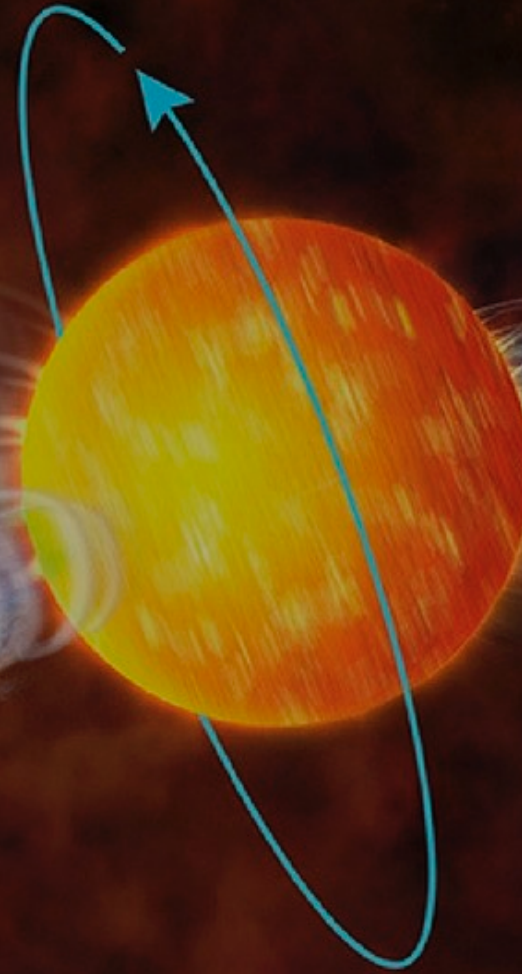


Physics 1974

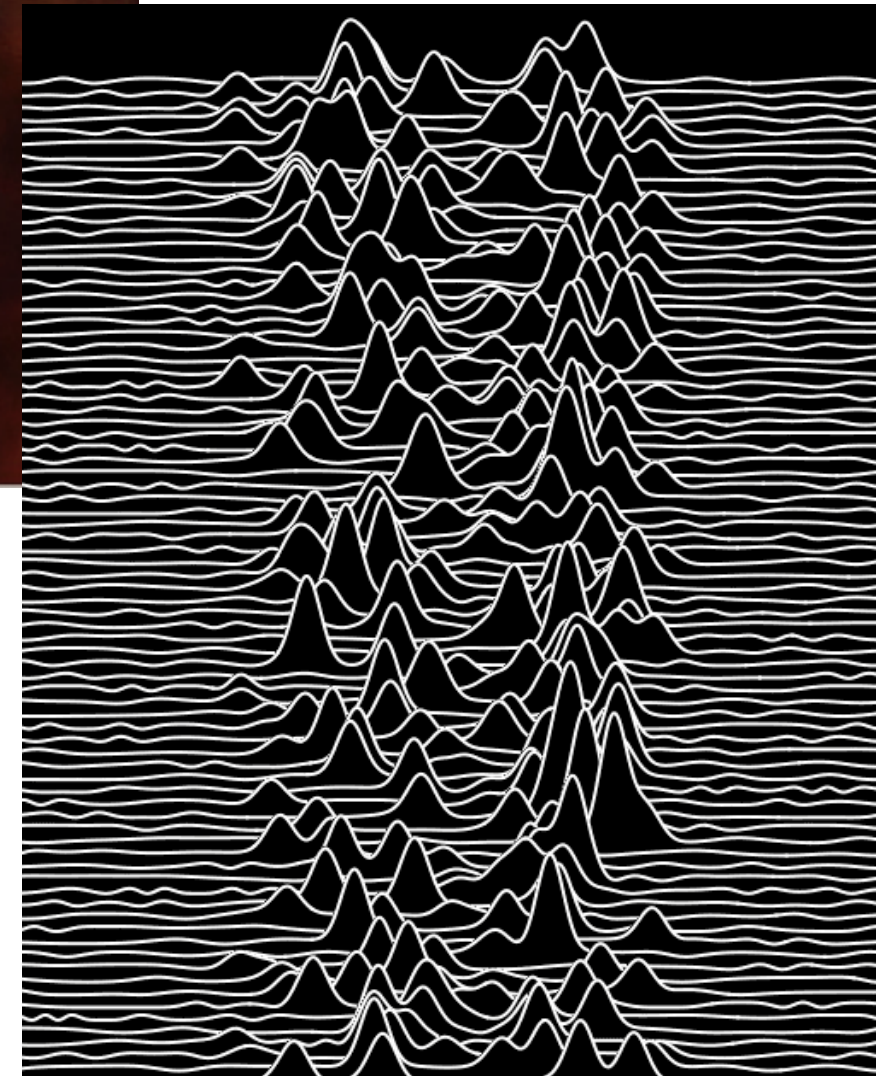
Special Breakthrough Prize 2018

Pulsar: /noun

A star whose core has collapsed into a dense, fast-spinning object, which appears to “pulse” with light.



©S. Sijher





Pulsar Timing

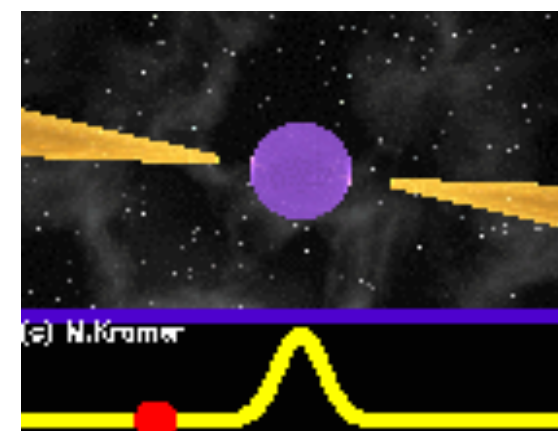
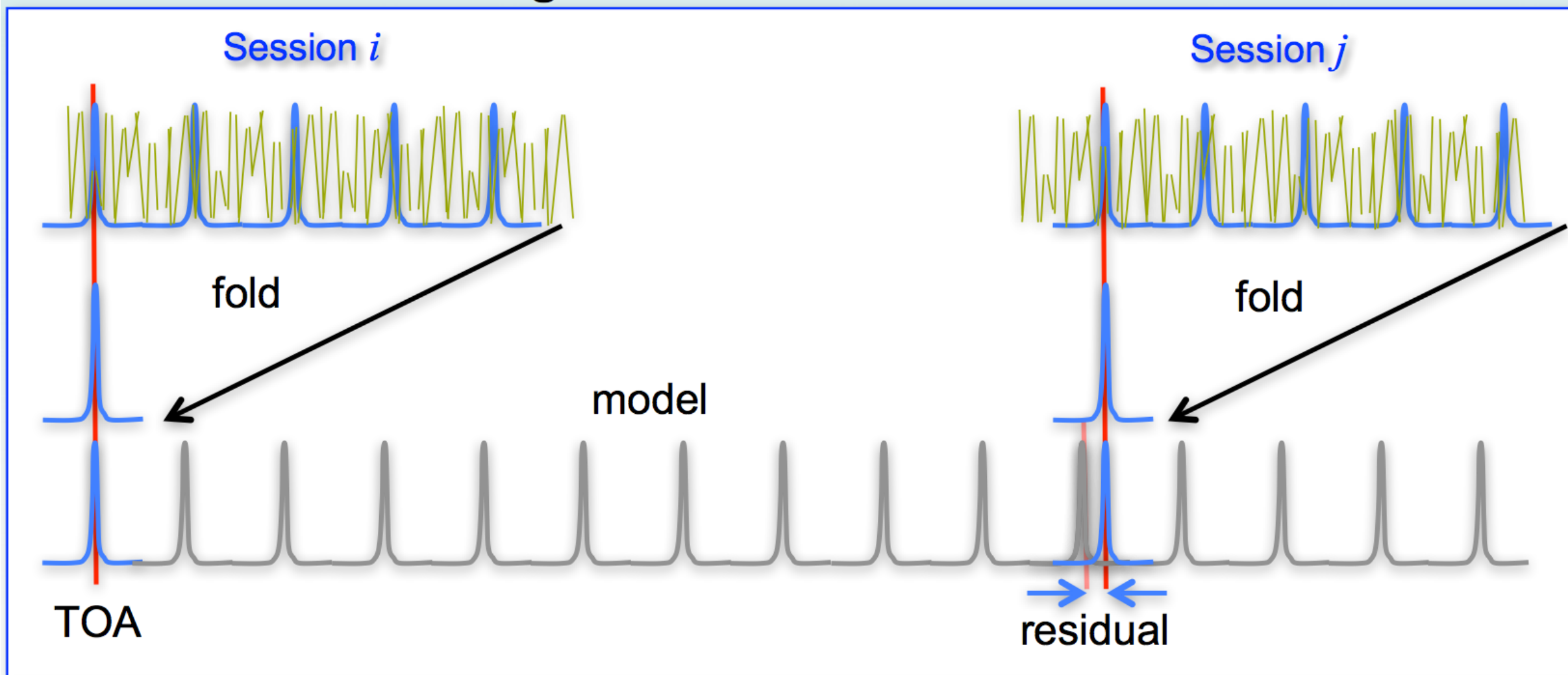


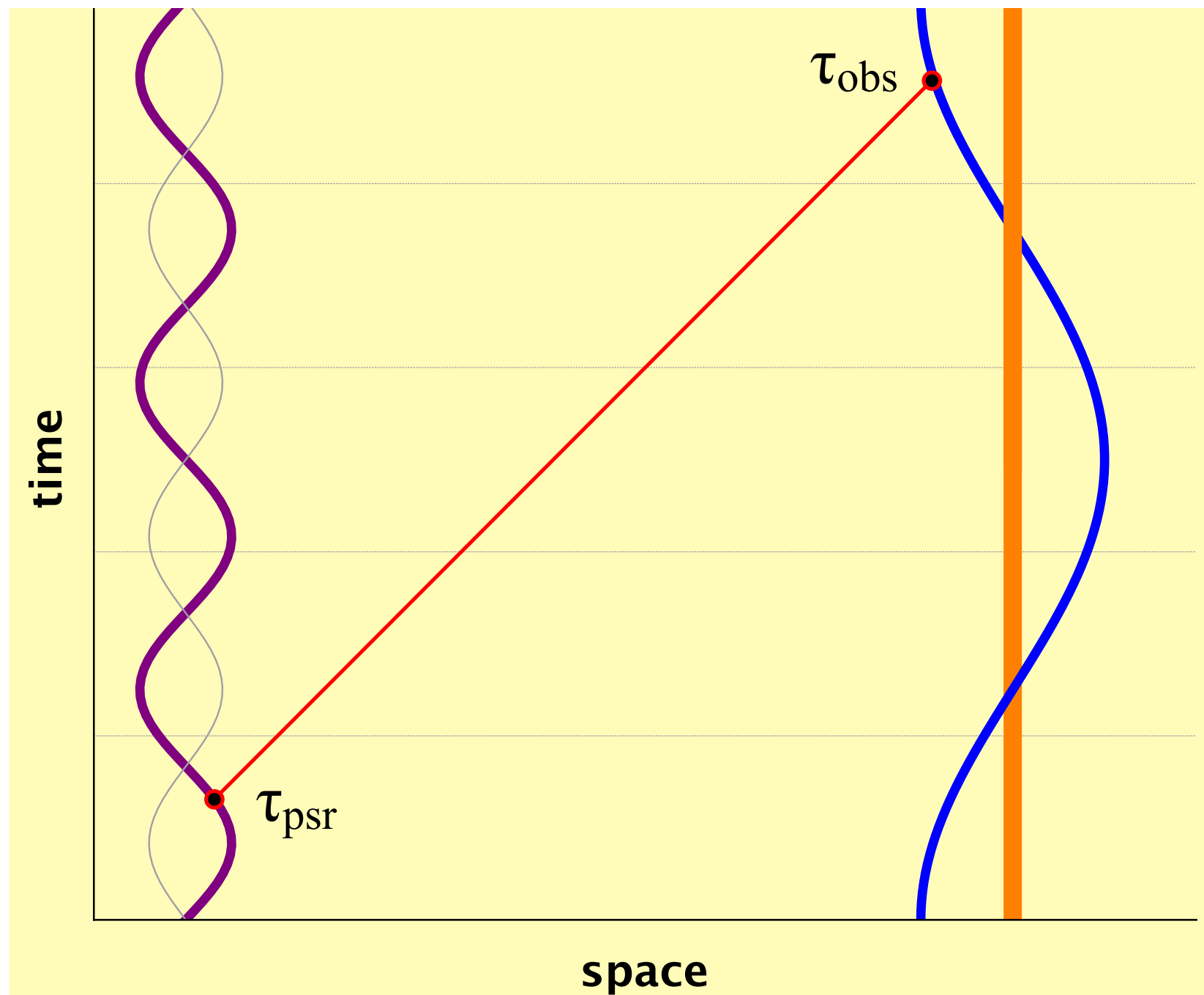
Figure Credit: M. Kramer

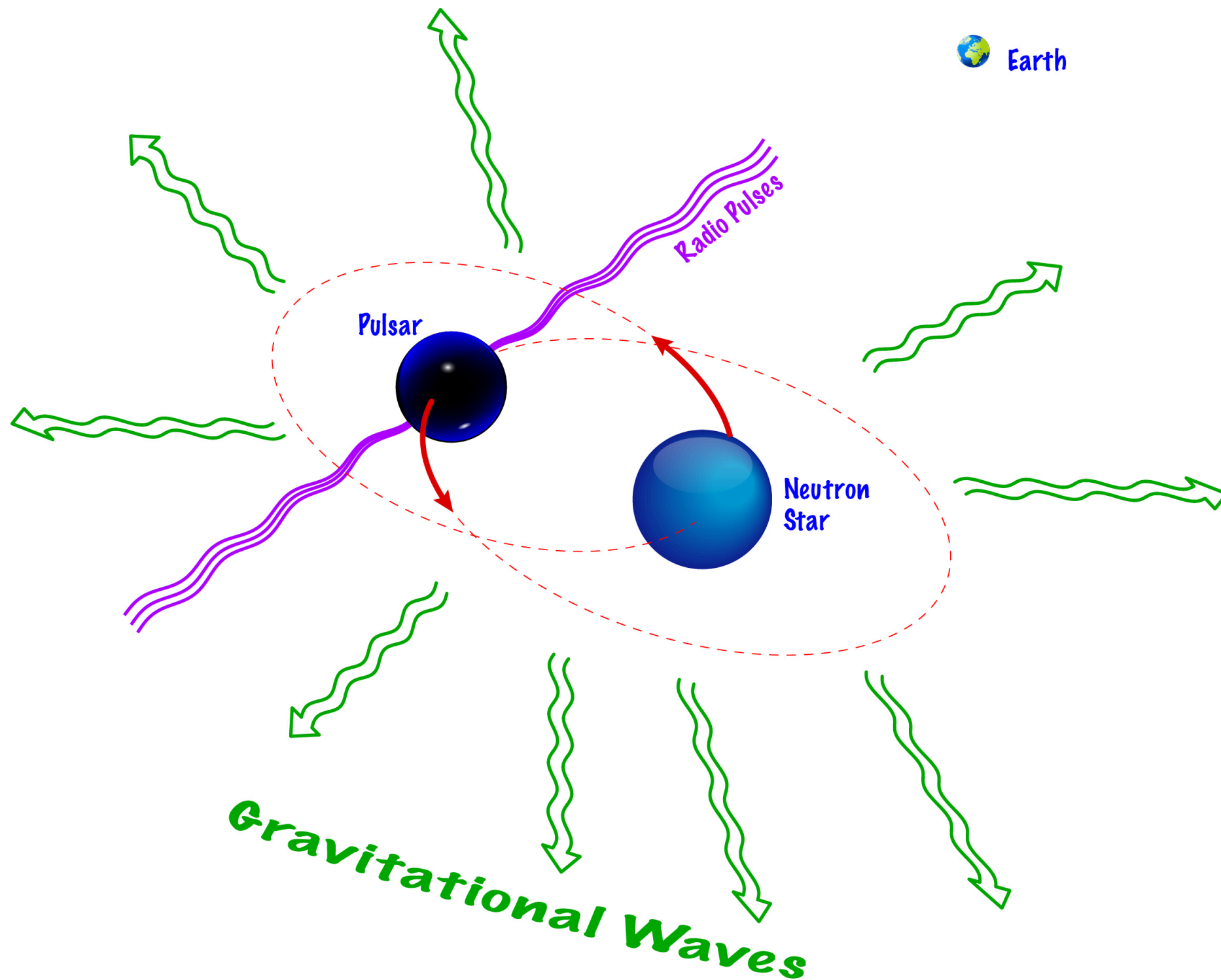
Phase-connected timing solution:

Figure Credit: N. Wex



Pulsar Timing *Modeling*





Russell A. Hulse & Joseph H. Taylor, Jr

“... for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation.”

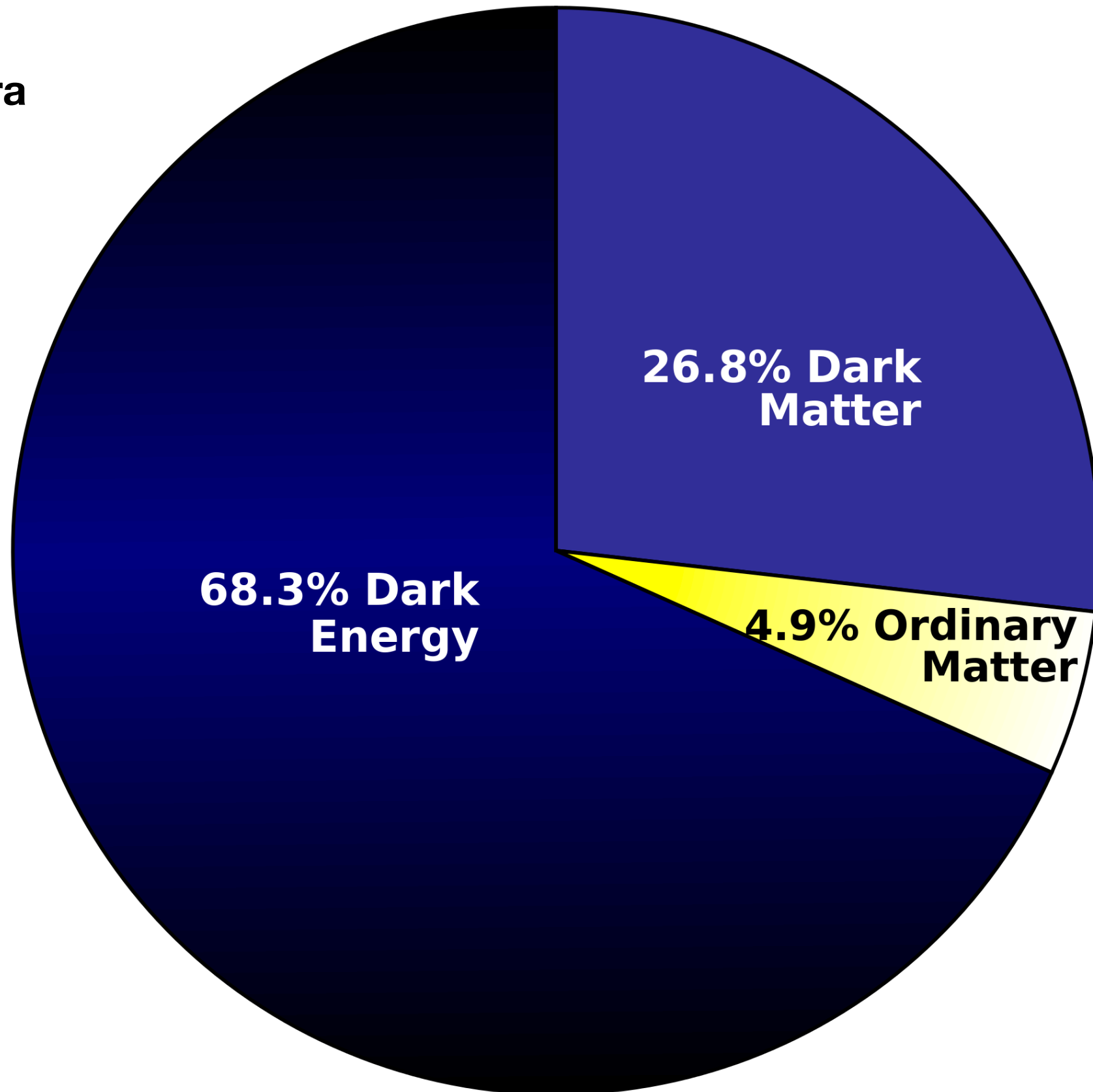


Physics 1993

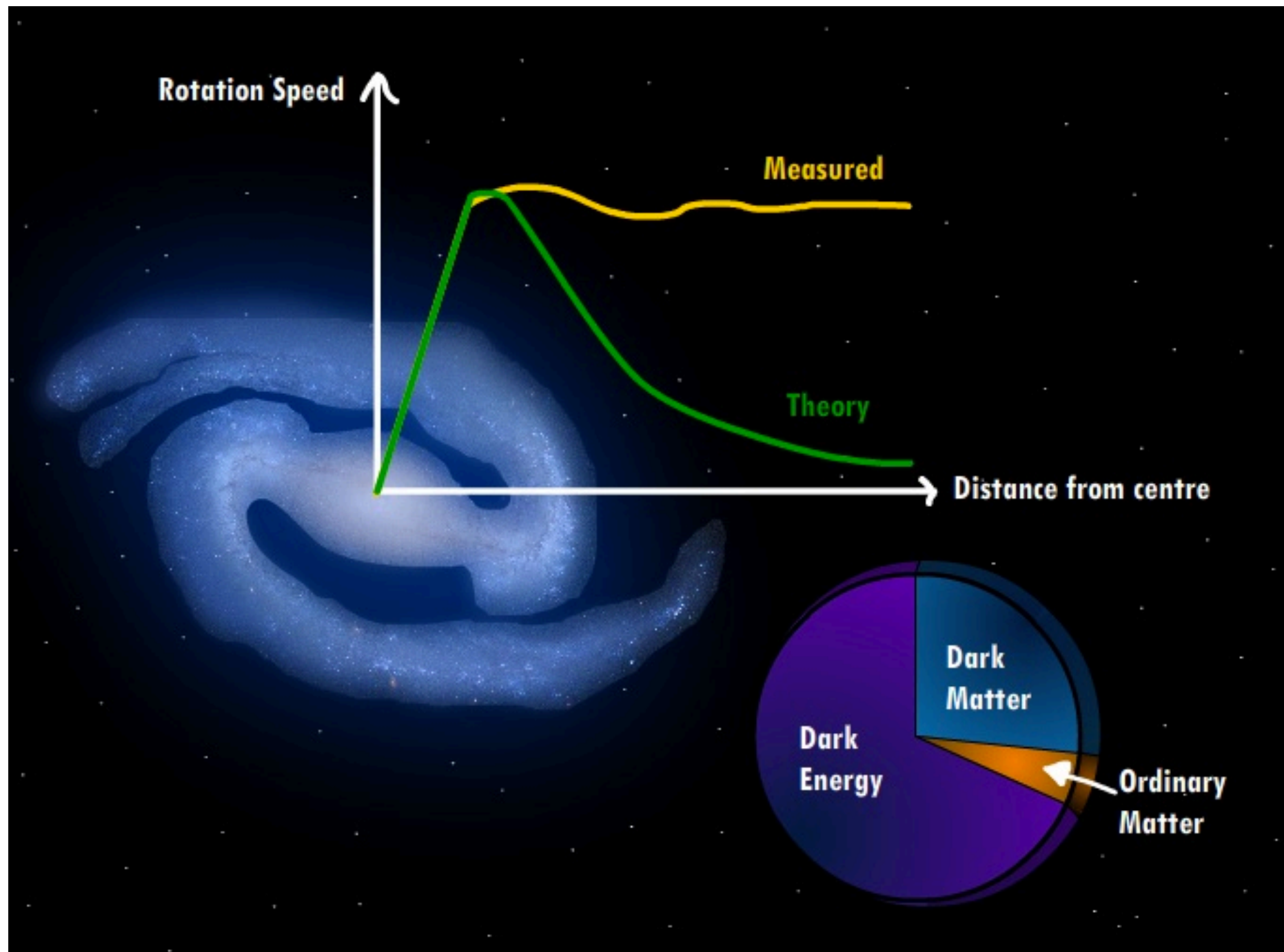
“Dark Matters”

Our Universe

Planck era

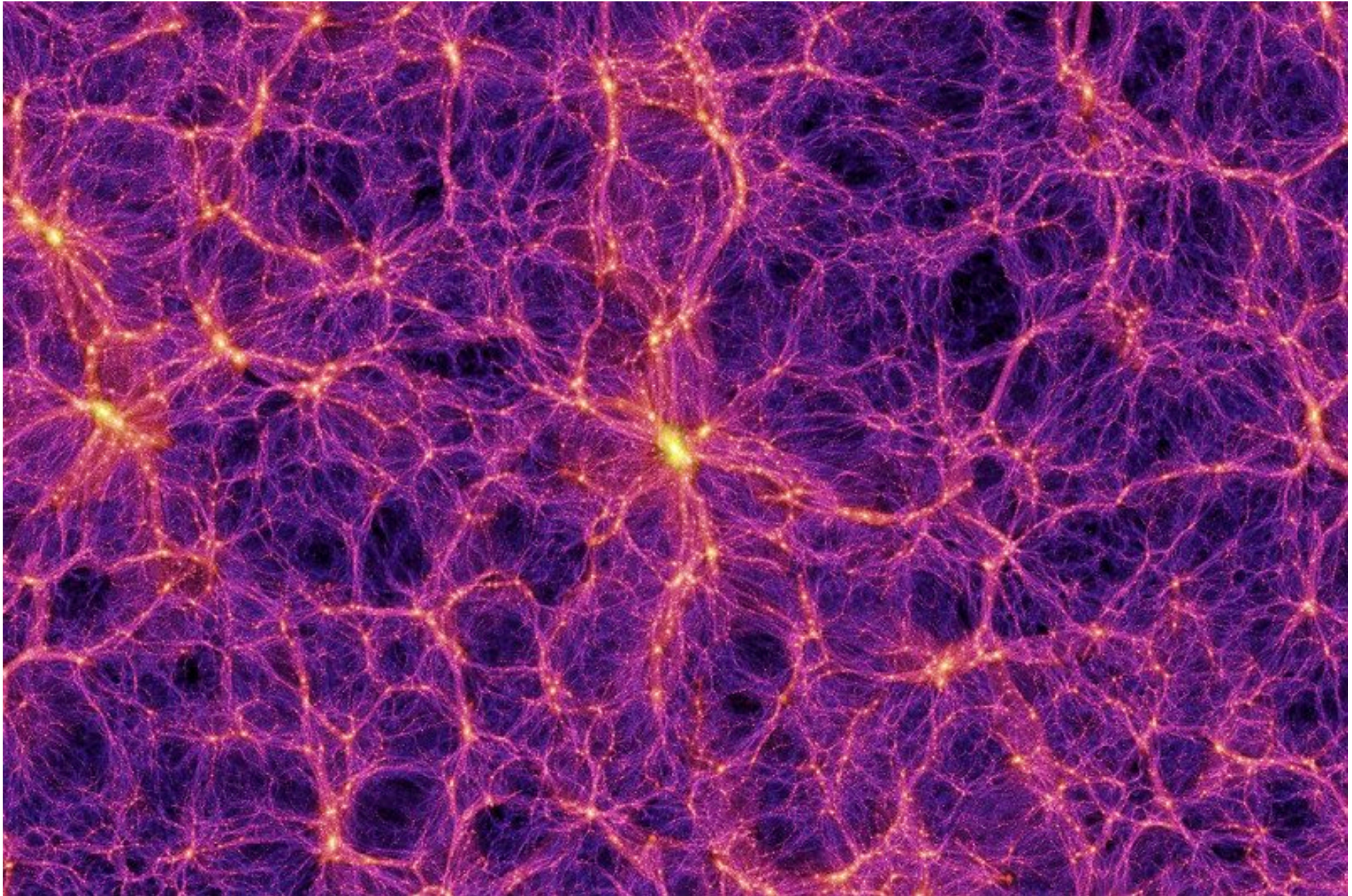


Dark Matters and Rotation Curves



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

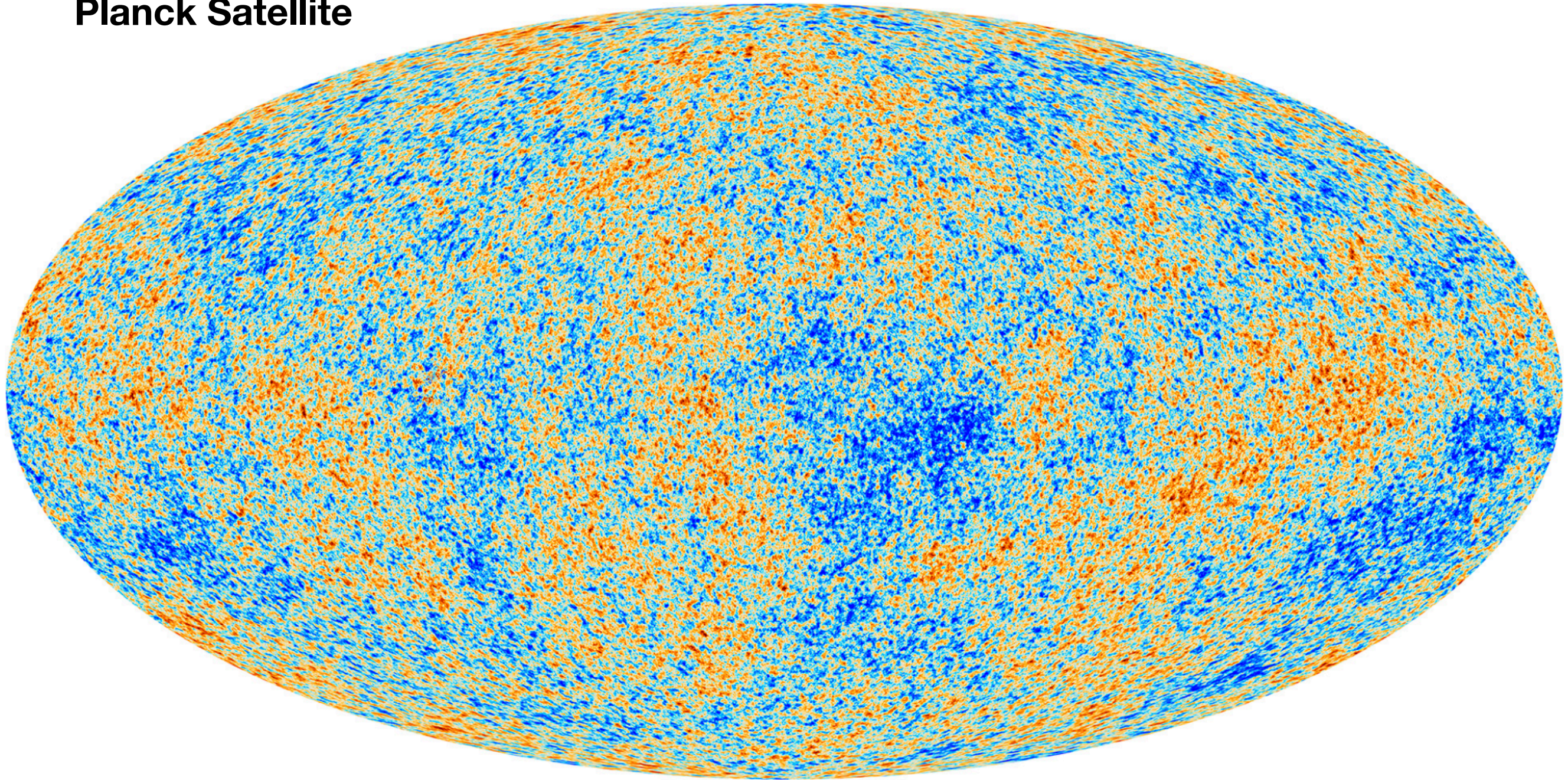
Dark Matters and the Structure of our Universe



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

Dark Matters and the Cosmic Microwave Bkg

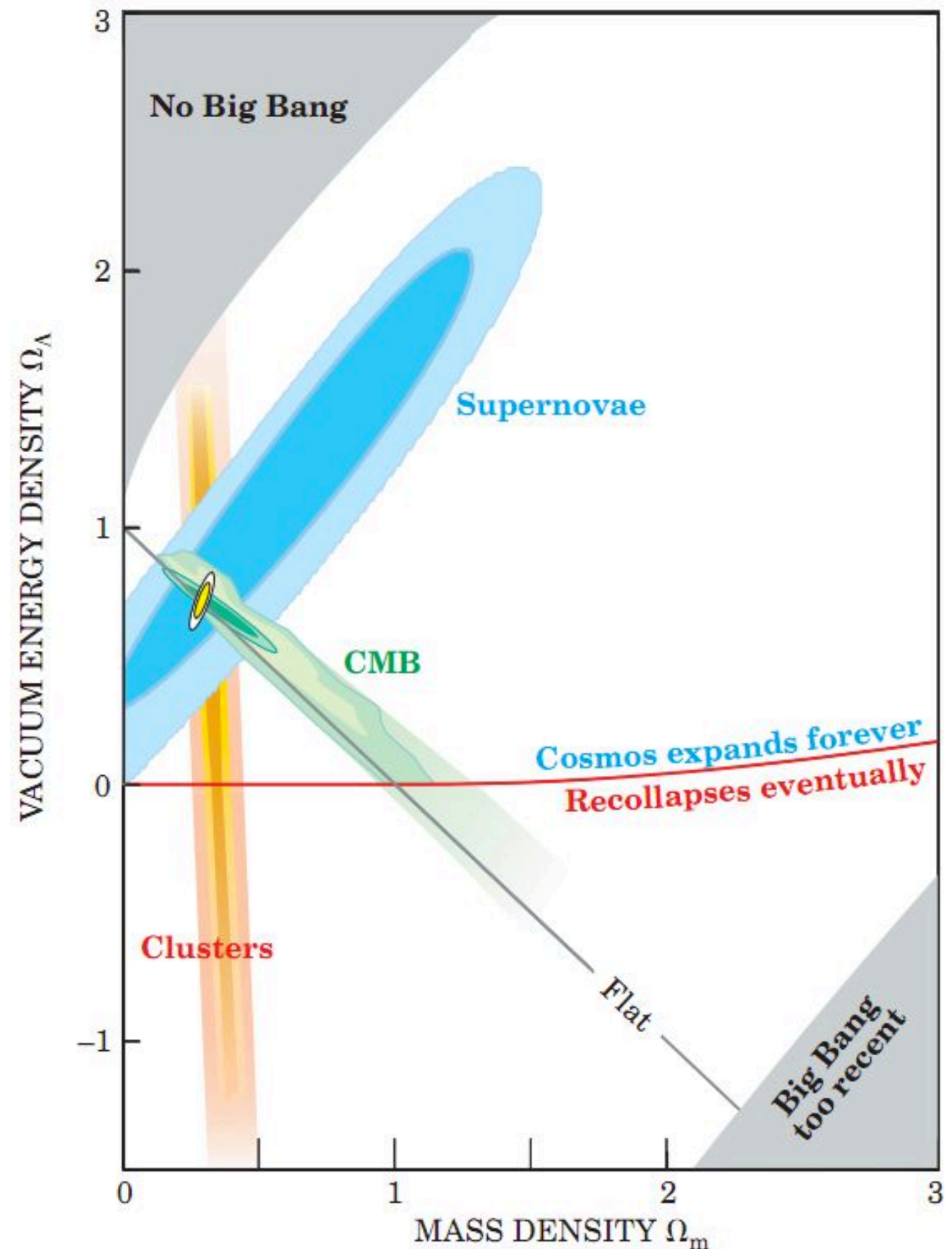
Planck Satellite



Dark matters also leave imprints on the cosmic microwave background.

Λ CDM Cosmology

- ◆ The Λ CDM is a parametrization of the Big Bang cosmological model, in which the universe contains a cosmological constant (denoted by Λ , associated with dark energy), and cold dark matter (abbreviated CDM).
- ◆ It is frequently referred to as the standard model of Big Bang cosmology



But for Searches of “Dark Matters”...

✦ Found nothing yet!

What are “Dark Matters”?

- ◆ What is dark-matter “particles”?
- ◆ Are there non-gravitational forces between dark matters and ordinary matters?

Testing the Universality of Free Fall towards Dark Matter with Pulsars

Driving Forces

test bodies

measurement precision

attractor

driving force

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

The diagram illustrates the components of the equation for $\eta_{\oplus}^{(A,B)}$. The numerator, $a_A - a_B$, is enclosed in a blue box and labeled 'measurement precision' with a blue arrow. The denominator, $\frac{1}{2}(a_A + a_B)$, is enclosed in a red box and labeled 'driving force' with a red arrow. The entire expression is labeled 'attractor' with a purple arrow. The term 'test bodies' is associated with the variable $\eta_{\oplus}^{(A,B)}$ via an orange arrow.

Rotating Torsion Balances in Space

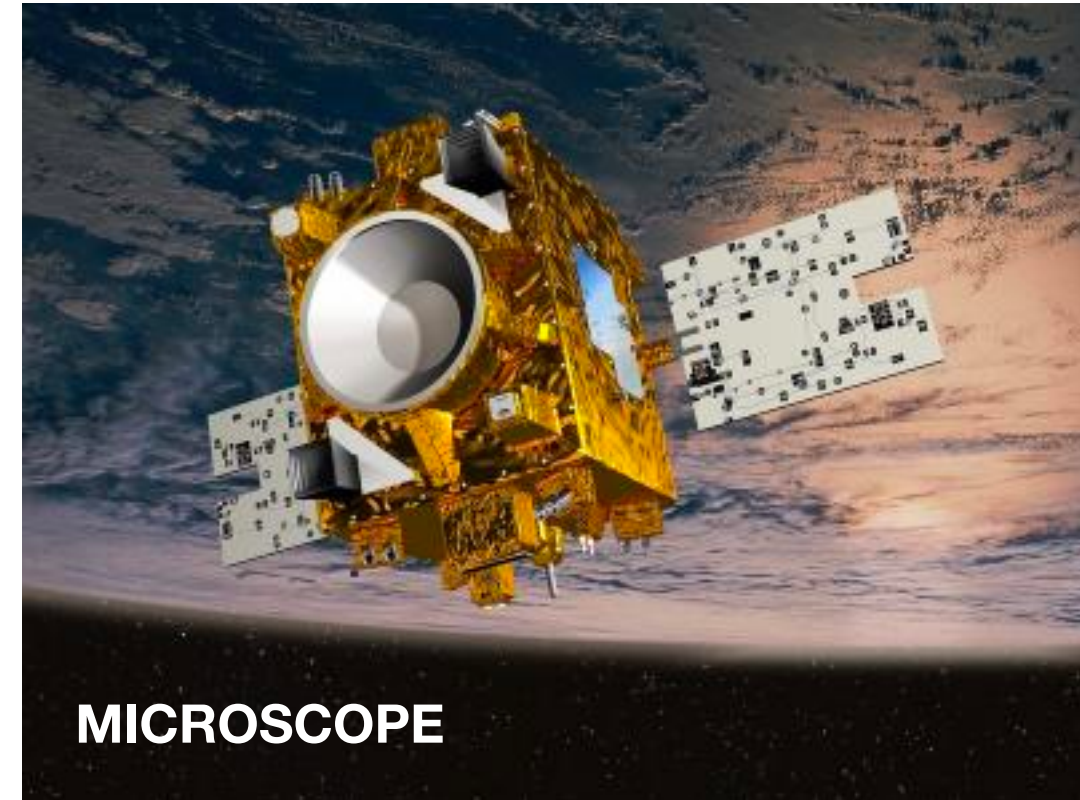
◆ “Every mission going to space needs a strong reason”

◆ reduce noises

◆ *enlarge the driving force by ~500*

◆ MICROSCOPE: first result ($\eta < 10^{-14}$);
expected for the full mission ($\sim 10^{-15}$)

Touboul et al. 2017



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

When Dark Matter is the Attractor...

test bodies

measurement precision

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

attractor

driving force

$\sim 10^{-2} \text{ m s}^{-2}$

The diagram illustrates the definition of the parameter $\eta_{\oplus}^{(A,B)}$. The numerator $a_A - a_B$ is enclosed in a blue box, with a blue arrow pointing to the label 'measurement precision'. The denominator $\frac{1}{2} (a_A + a_B)$ is enclosed in a red box, with a red arrow pointing to the label 'driving force'. A purple arrow points from the symbol $\eta_{\oplus}^{(A,B)}$ to the label 'attractor'. An orange arrow points from the text 'test bodies' towards the symbol.

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

When Dark Matter is the Attractor...

test bodies

measurement precision

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

attractor

driving force

$\sim 10^{-10} \text{ m s}^{-2}$

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

Pulsars and Strong Equivalence Principle

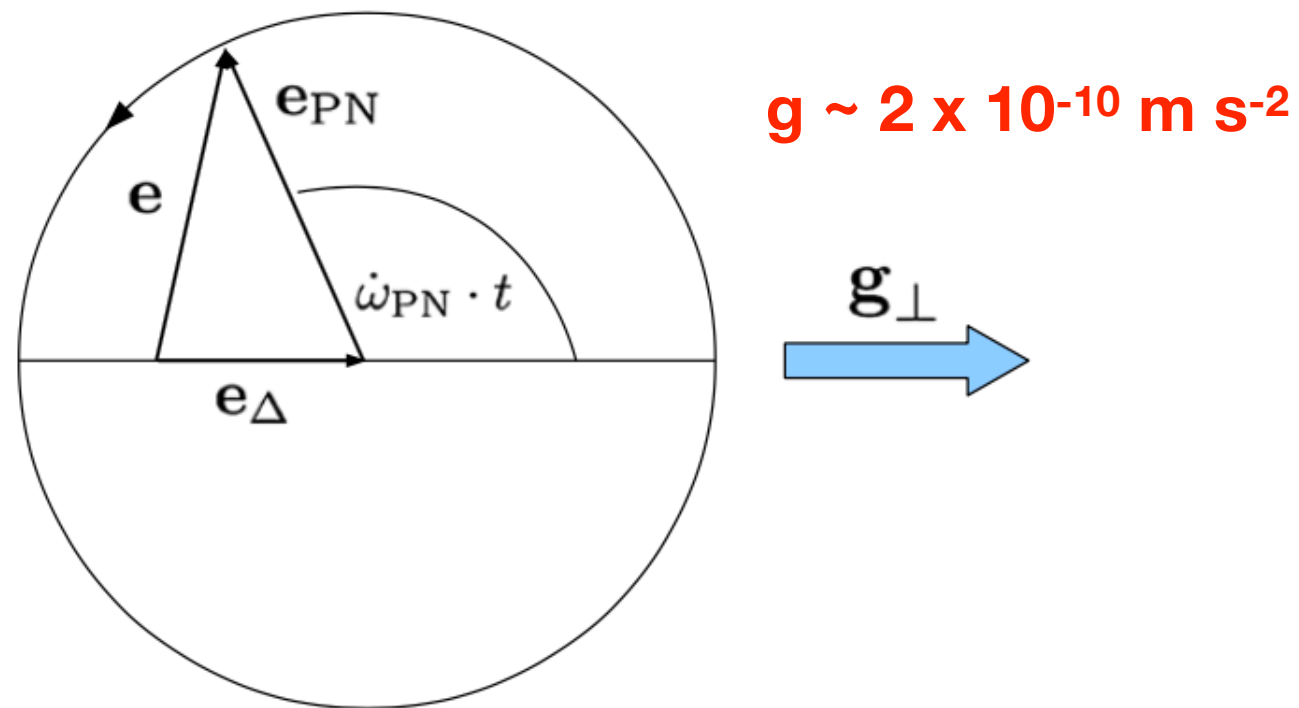
EP violation “polarises” a binary orbit

Nordtvedt 1968

Damour & Schaefer 1991

Zhu et al. 2018

$$\eta < 10^{-3}$$



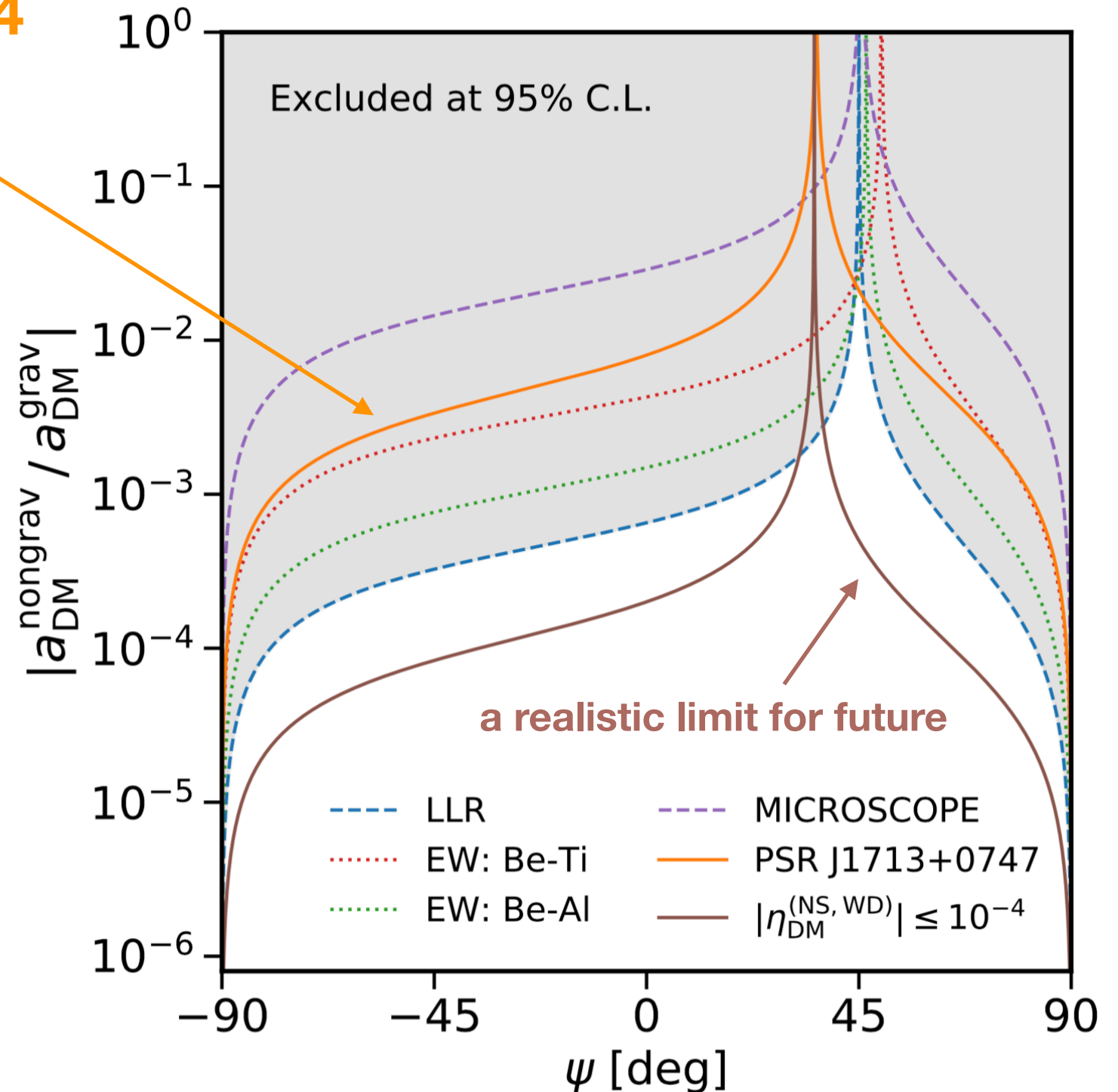
see Freire, Kramer, Wex 2012 for details

Nongrav. Forces from Dark Matter

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

Zhu et al. 2018

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



Shao et al. 2018

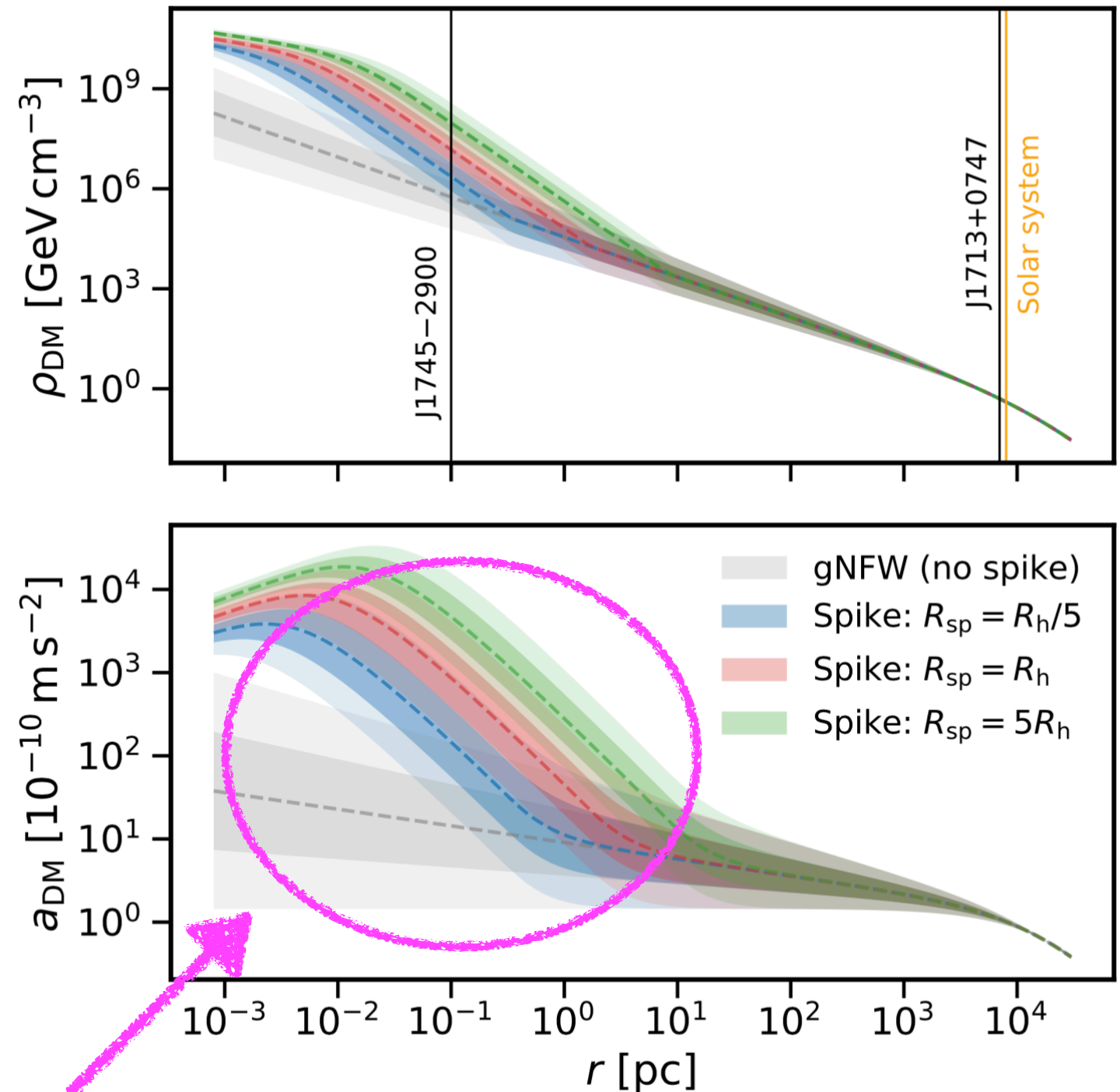
Pulsar Surveys towards Galactic Centre

- ◆ 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

Neutron star: $1.44 M_{\odot}$

Inner white dwarf: $0.20 M_{\odot}$

Outer white dwarf: $0.41 M_{\odot}$



A diagram illustrating a triple pulsar system. In the foreground, a neutron star (represented by a small white sphere) is surrounded by a complex, tangled magnetic field structure (blue lines). Two white dwarf stars (represented by larger blue spheres) are in orbit around the neutron star. The background shows a large, detailed image of the Earth's moon and a starry space background. A red laser beam points from a small red dot in the distance towards the system. A red text label indicates the acceleration $g \sim 2 \times 10^{-1} \text{ cm s}^{-2}$.

$$g \sim 2 \times 10^{-1} \text{ cm s}^{-2}$$

© Bill Saxton

Tests of UFF with a *triple pulsar*

$$\eta < 10^{-6}$$

Archibald et al. 2018

The non-gravitational force between “dark matters” and ordinary matters is less than 1% of the gravitational force.

Thank you!

