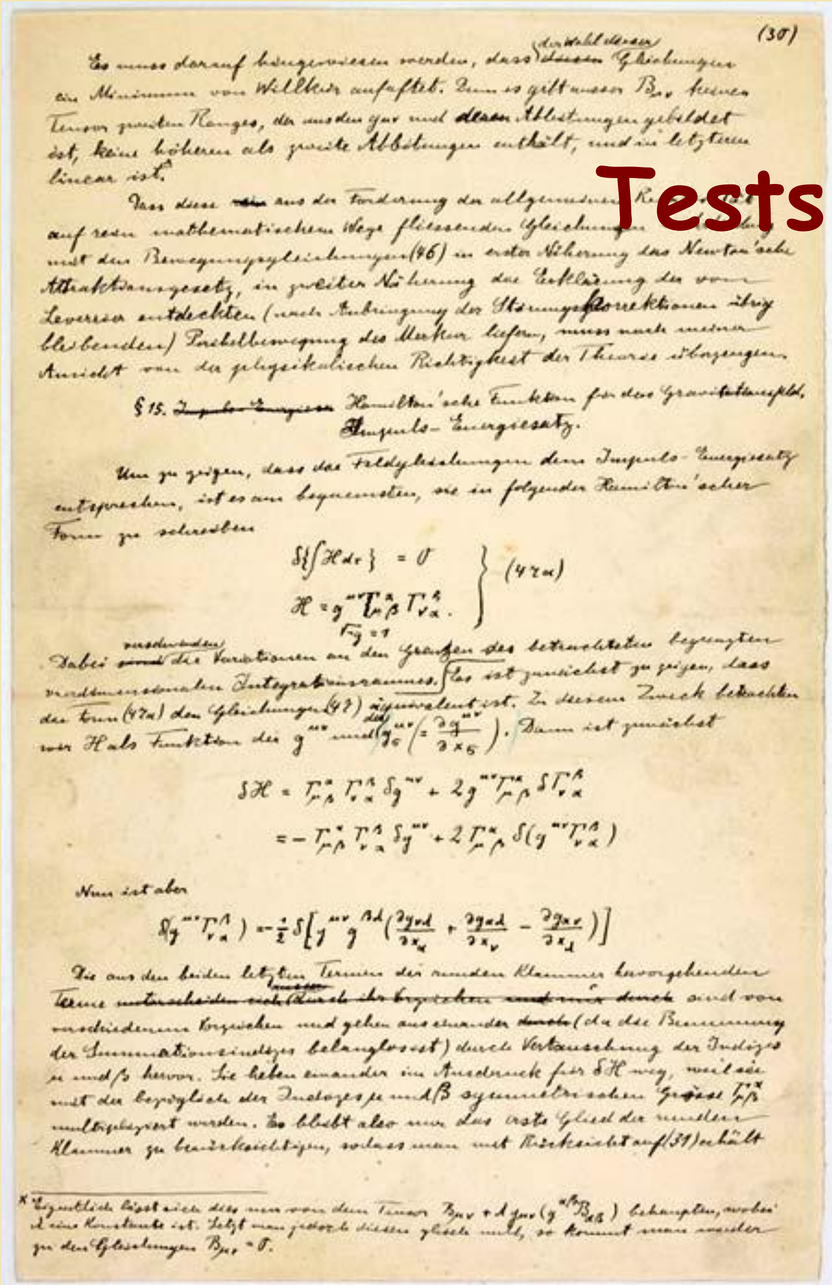
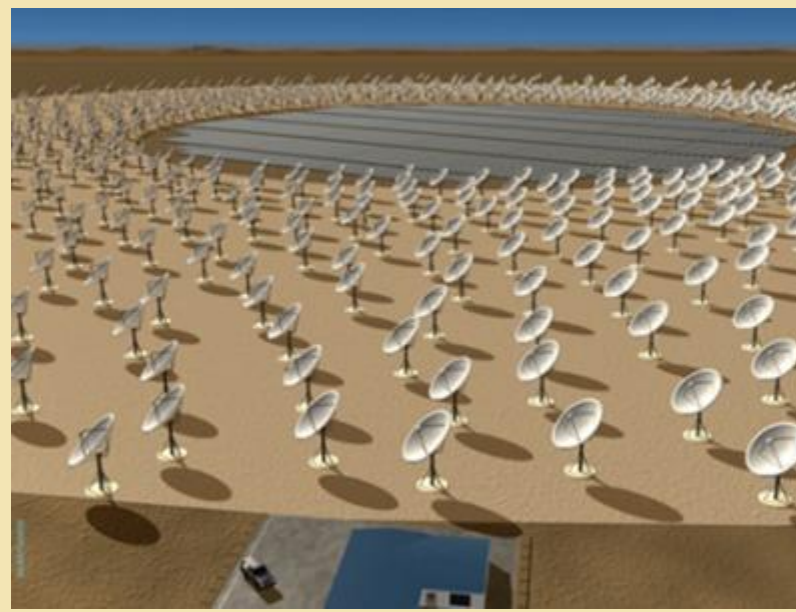
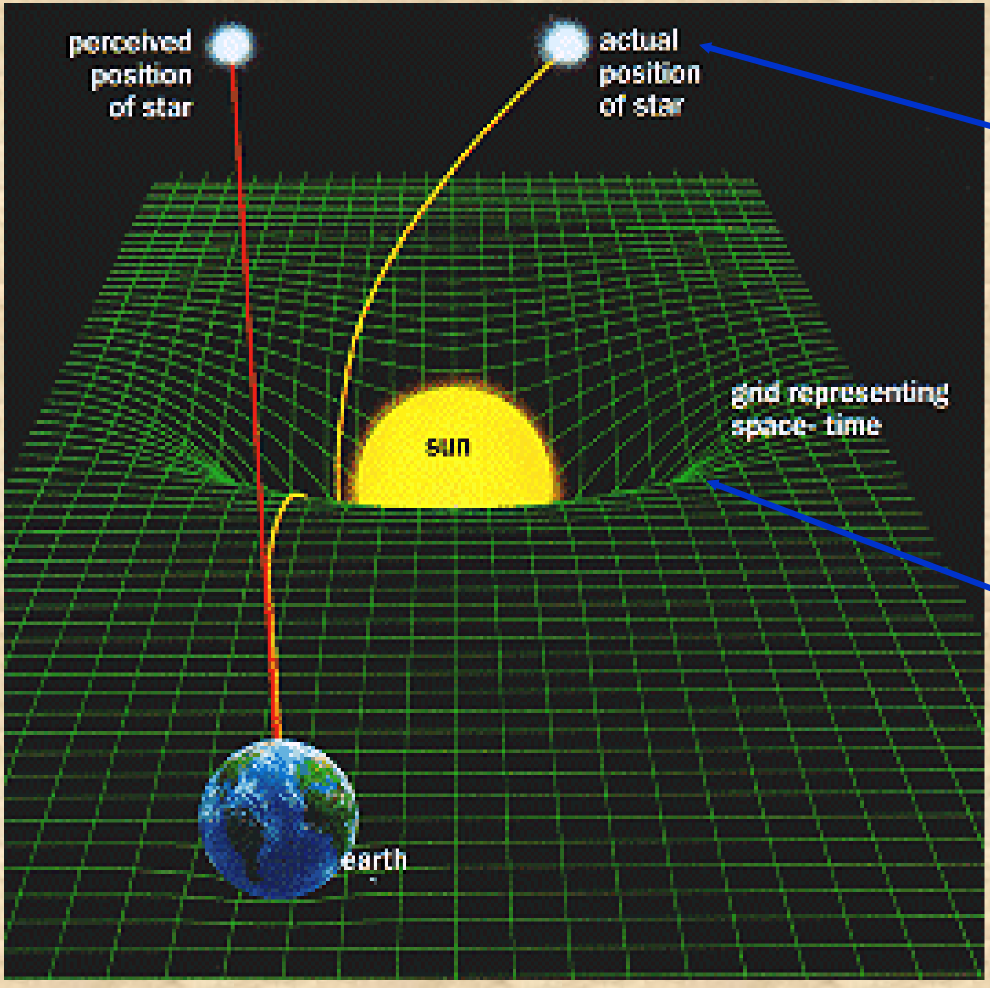


Tests of General Relativity with the SKA

DIMITRIOS PSALTIS
University of Arizona



GENERAL RELATIVITY HAS TWO INGREDIENTS



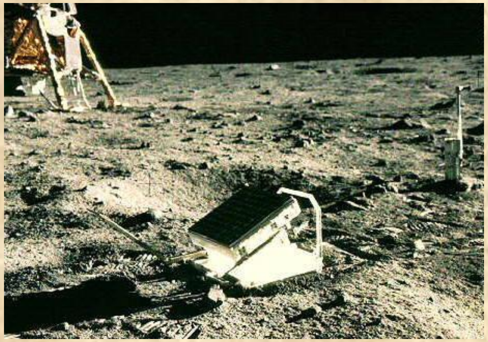
The Equivalence Principle

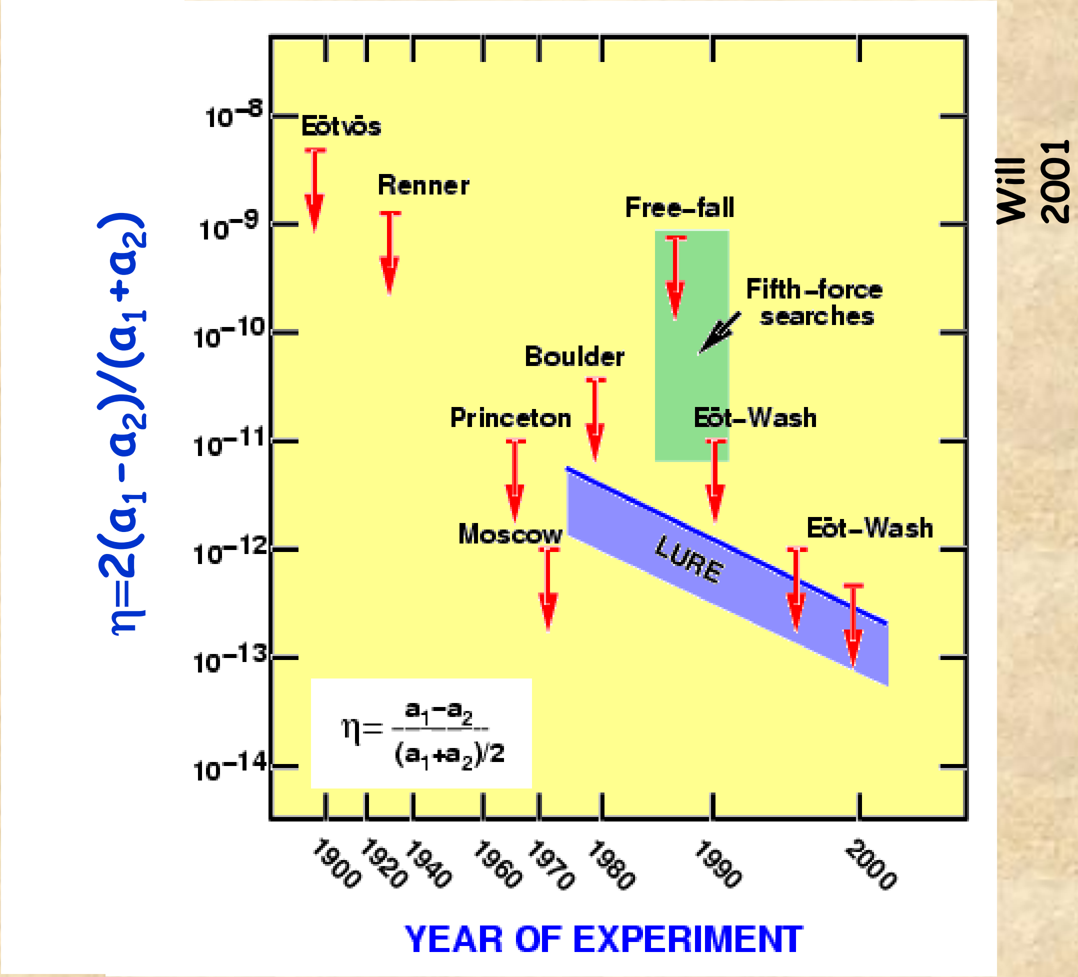
The Einstein Field Equation

The Equivalence Principle encompasses Einstein's two revolutions in our understanding of gravity:

- Gravity is geometry (particles and photons follow geodesics)
- Gravity is relativistic (obeys the Lorentz symmetry)

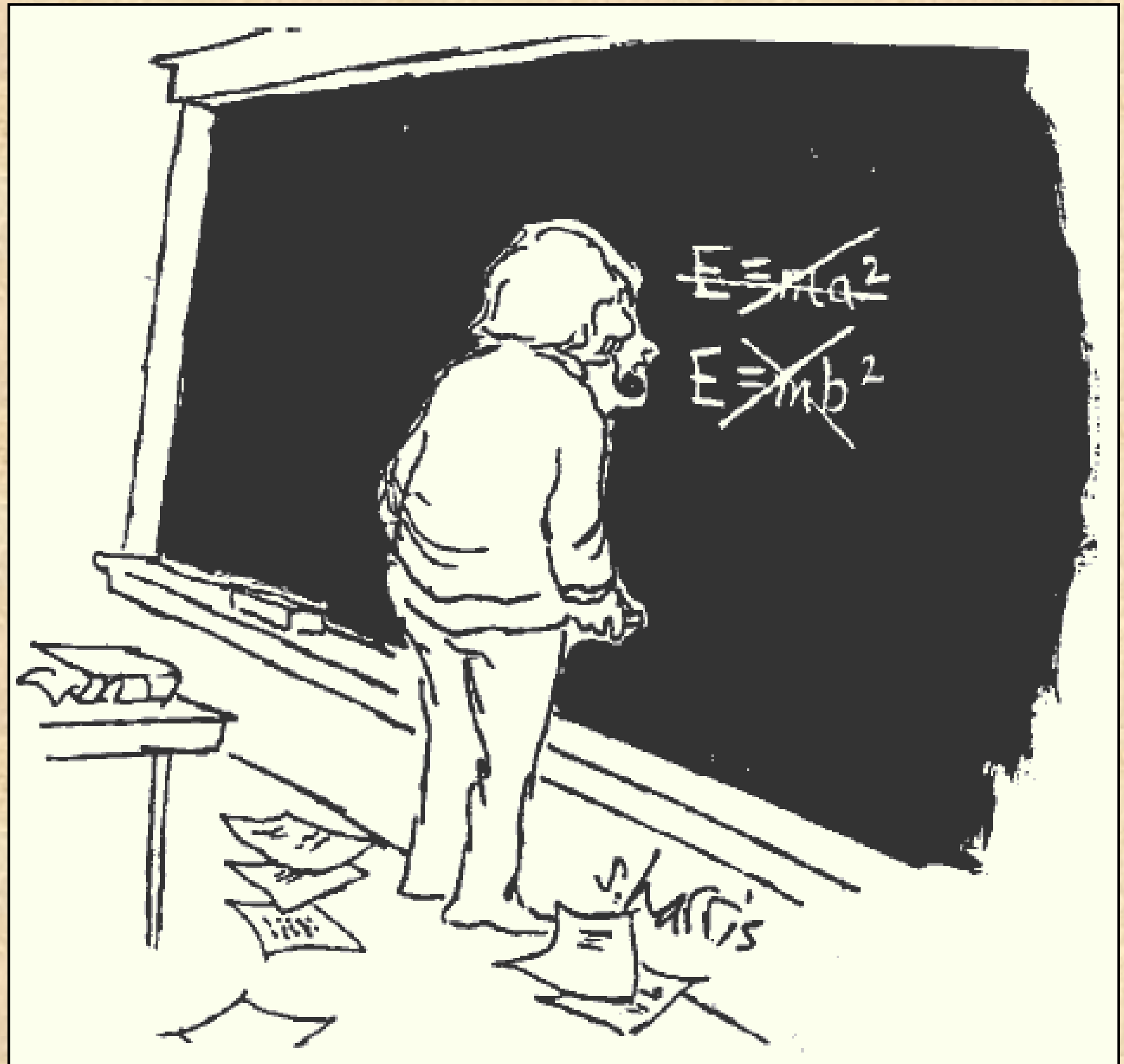
➢ The Equivalence Principle Has Been Tested to a Very High Degree





Double Neutron Star observations with the SKA will improve limits on potential violation of the Strong Equivalence Principle

The Field Equation for Gravity is no revolution…



The Field Equation for Gravity follows general Newtonian ideas

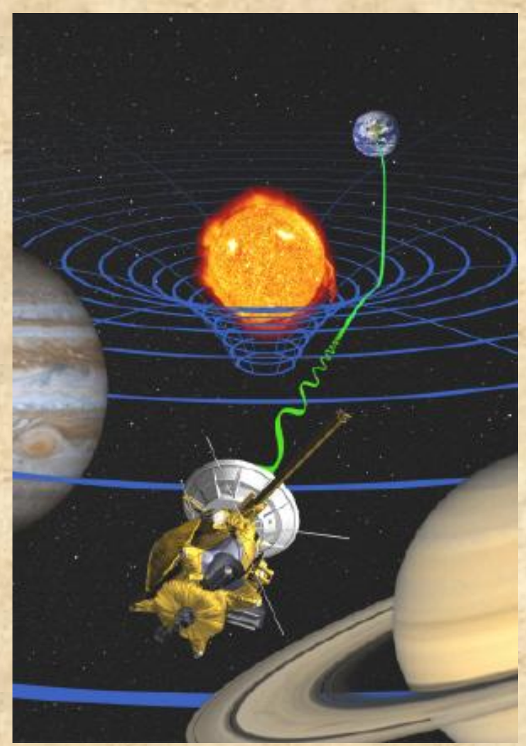
Ricci curvature

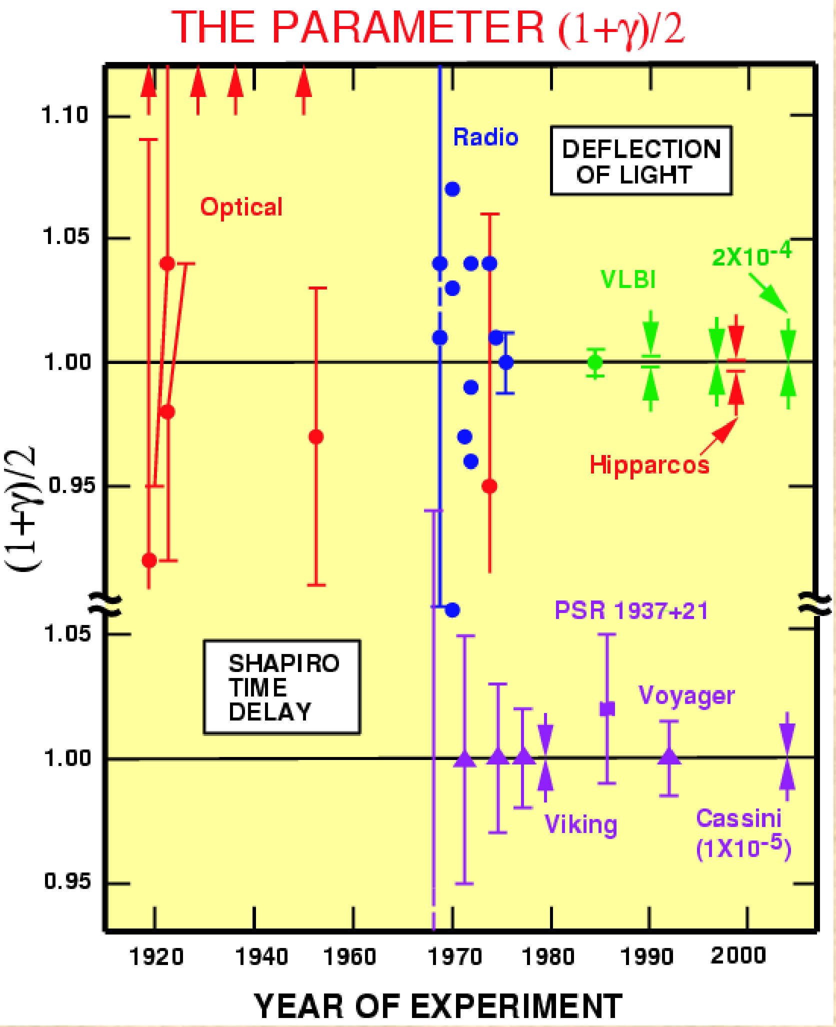
Matter+Radiation

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}R + S_m$$

- 3+1 Dimensions of Spacetime
- Two gravitational degrees of freedom
- Only matter and radiation source the gravitational field
- No parity violating terms
- …

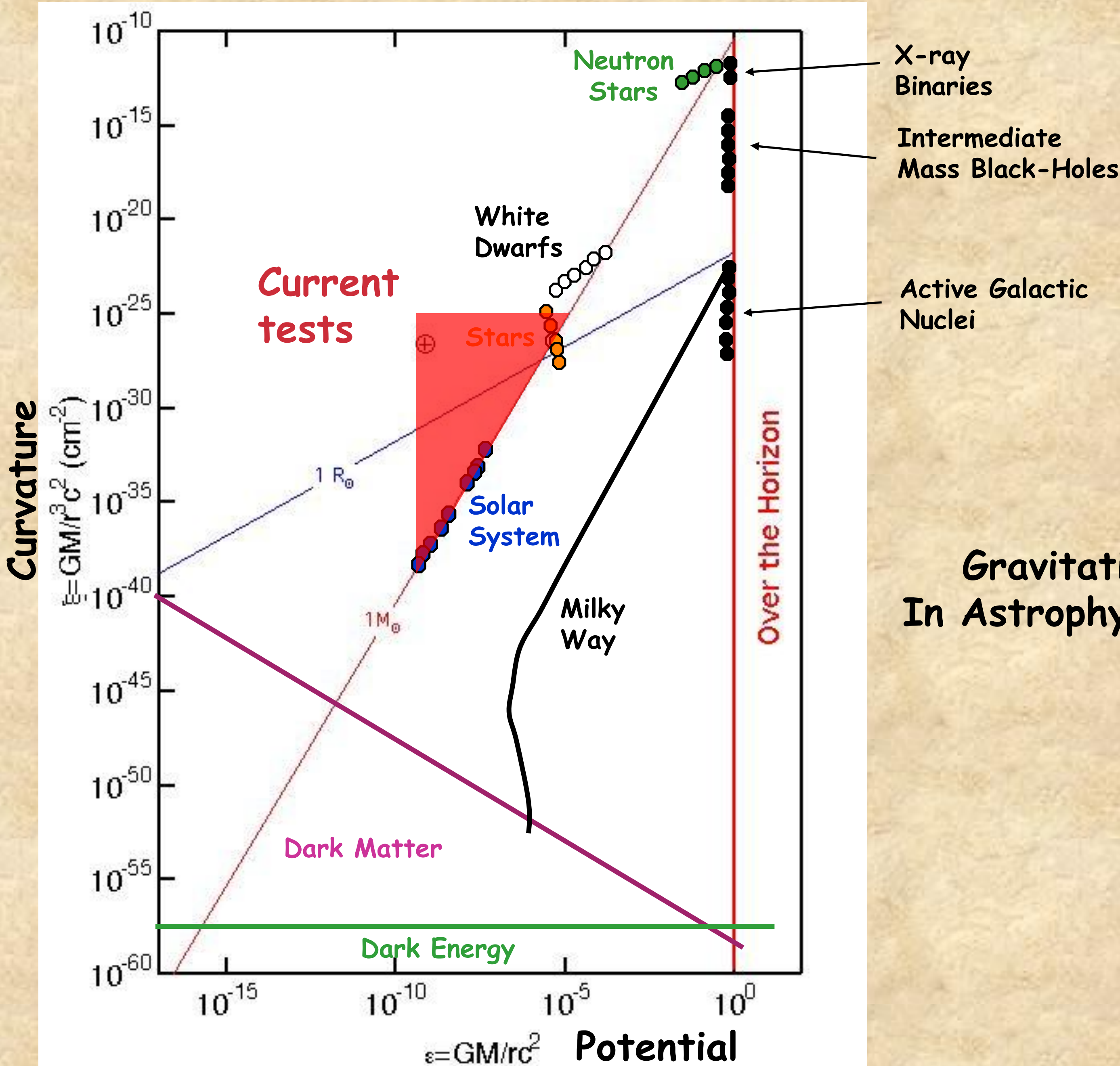
- **The Einstein Field Equations have been tested to ~10^{-5}**





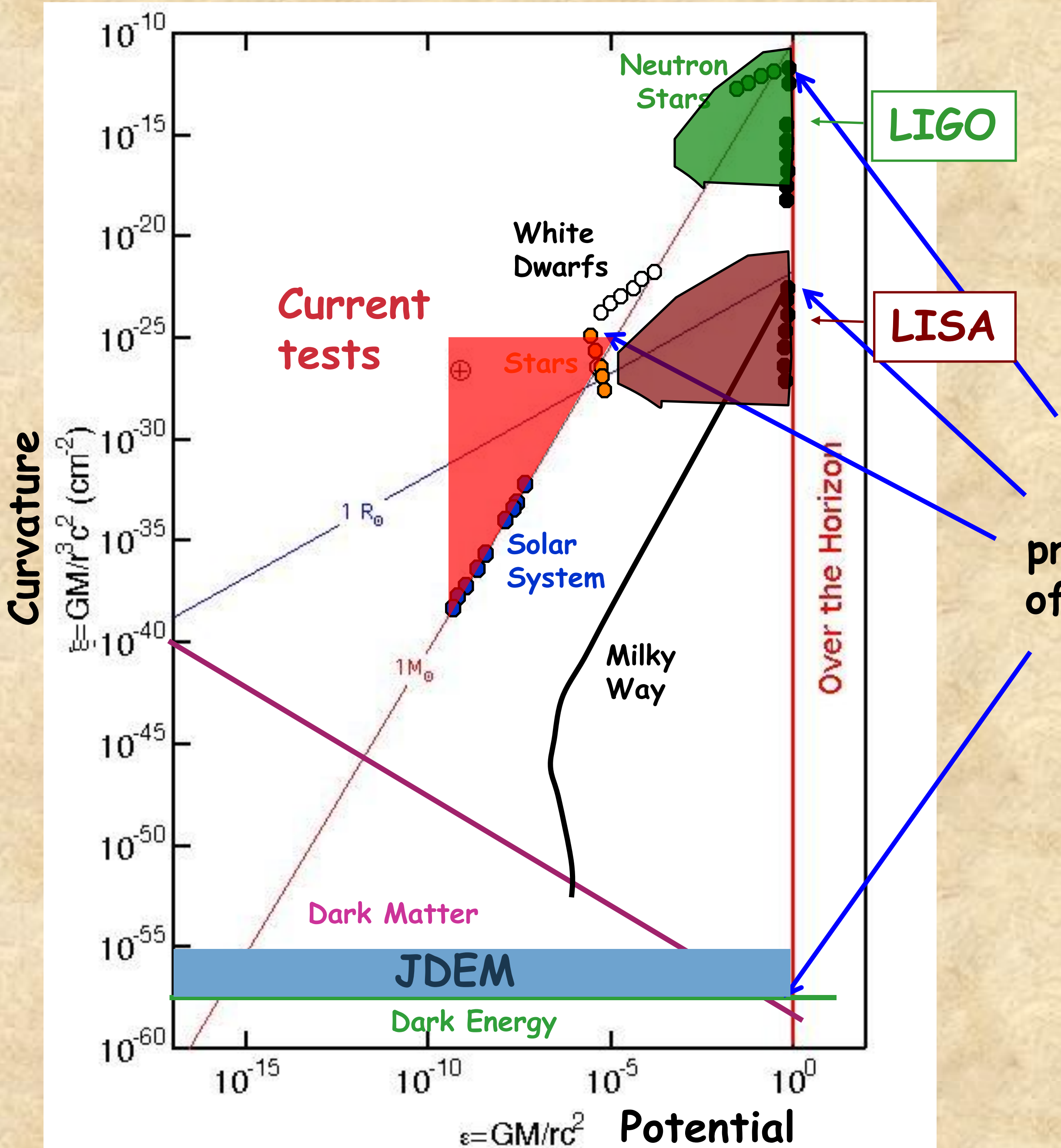
Will 2006

PPN Metric: $$ds^2 = -\left(1 - 2\frac{GM}{rc^2}\right)dt^2 + \left(1 + \gamma\frac{2GM}{rc^2}\right)dr^2 + r^2 d\Omega$$



Gravitational Fields In Astrophysical Systems

Psaltis 2008

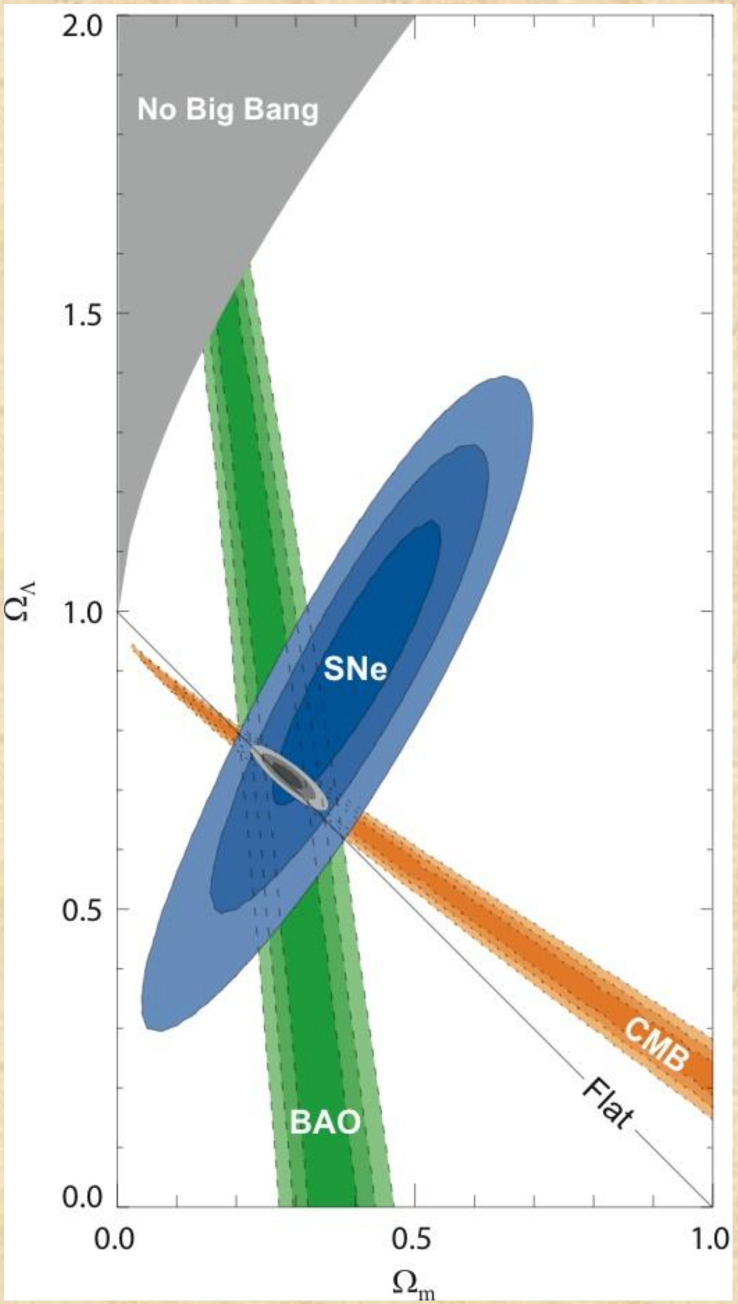


The SKA is unique in probing the entire range of spacetime curvatures!

Are Matter and Radiation the Only Sources of Gravity?

(i) Dark Energy

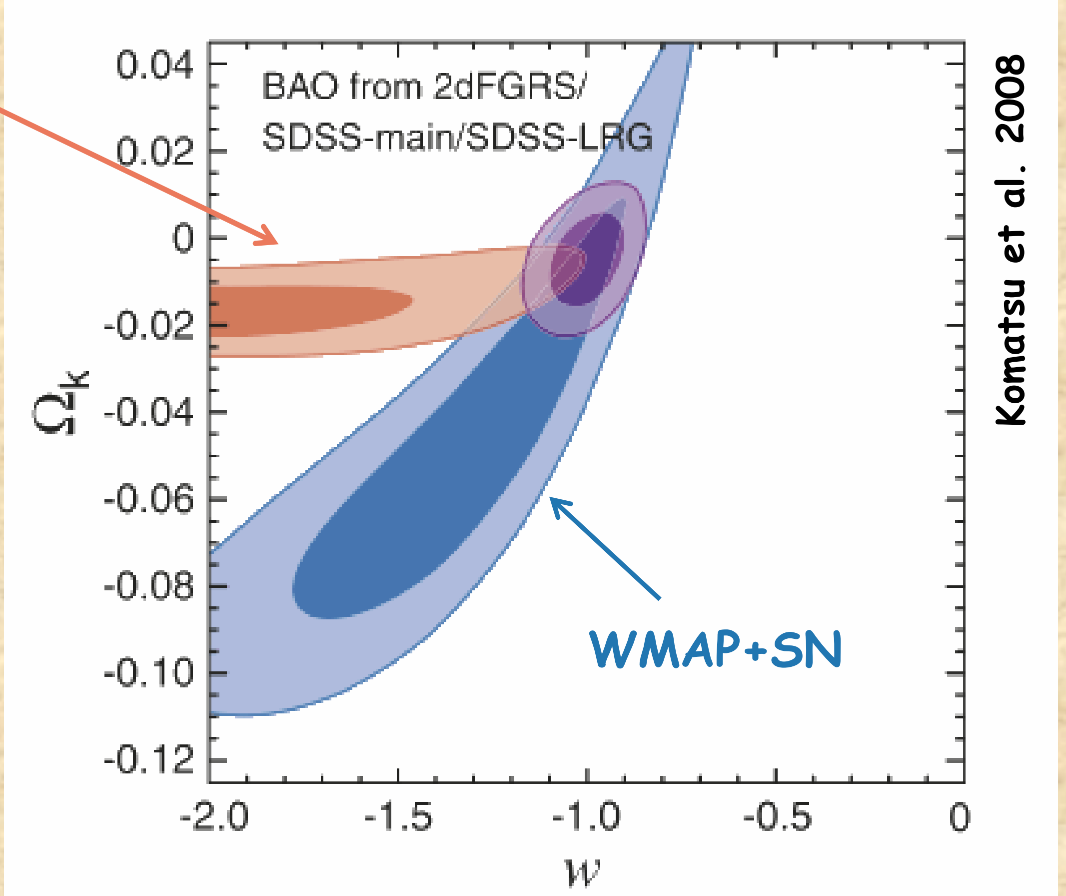
Is it a cosmological constant, or a new gravitating field?



Are Matter and Radiation the Only Sources of Gravity?

(i) Dark Energy?

WMAP+BAO



Dark Energy Equation of State

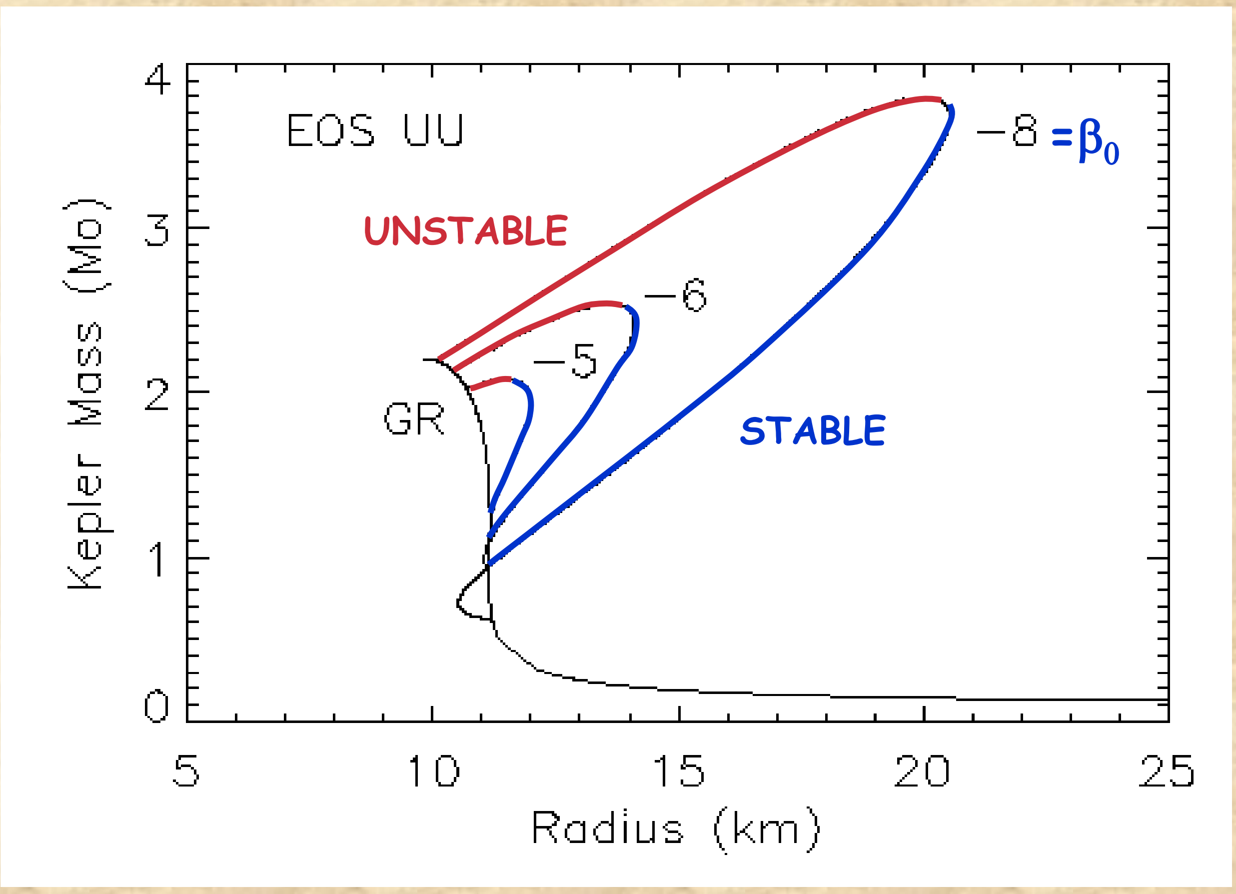
$P = w\rho$

A 21cm Baryon-Acoustic-Oscillation survey with SKA will significantly improve these limits

Are Matter and Radiation the Only Sources of Gravity?

(ii) A scalar field that couples to gravity

$$A(\phi) = 1 + a\phi + \frac{1}{2}\beta\phi^2 + \ldots$$



Damour & Esposito-Farese 1993; DeDeo & Psaltis 2003

Are Matter and Radiation the Only Sources of Gravity?

(ii) A scalar field that couples to gravity

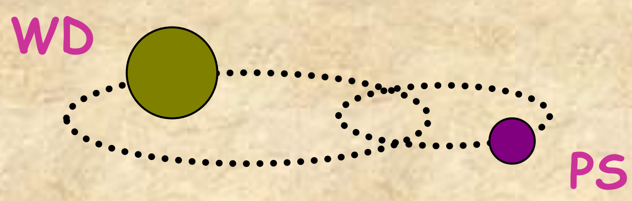
The presence of a scalar field leads to dipole gravitational radiation!

Eardley 1975

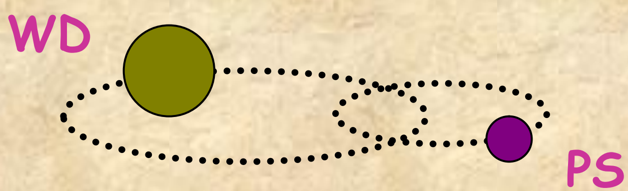
$$\dot{P}_{dipole} = -\frac{4\pi G M_{\odot}}{c^3 P} \frac{M_{NS}}{M_{NS} + M_C} \left[\kappa_D \cdot s^2\right]_{\alpha,\beta}$$

Are Matter and Radiation the Only Sources of Gravity?

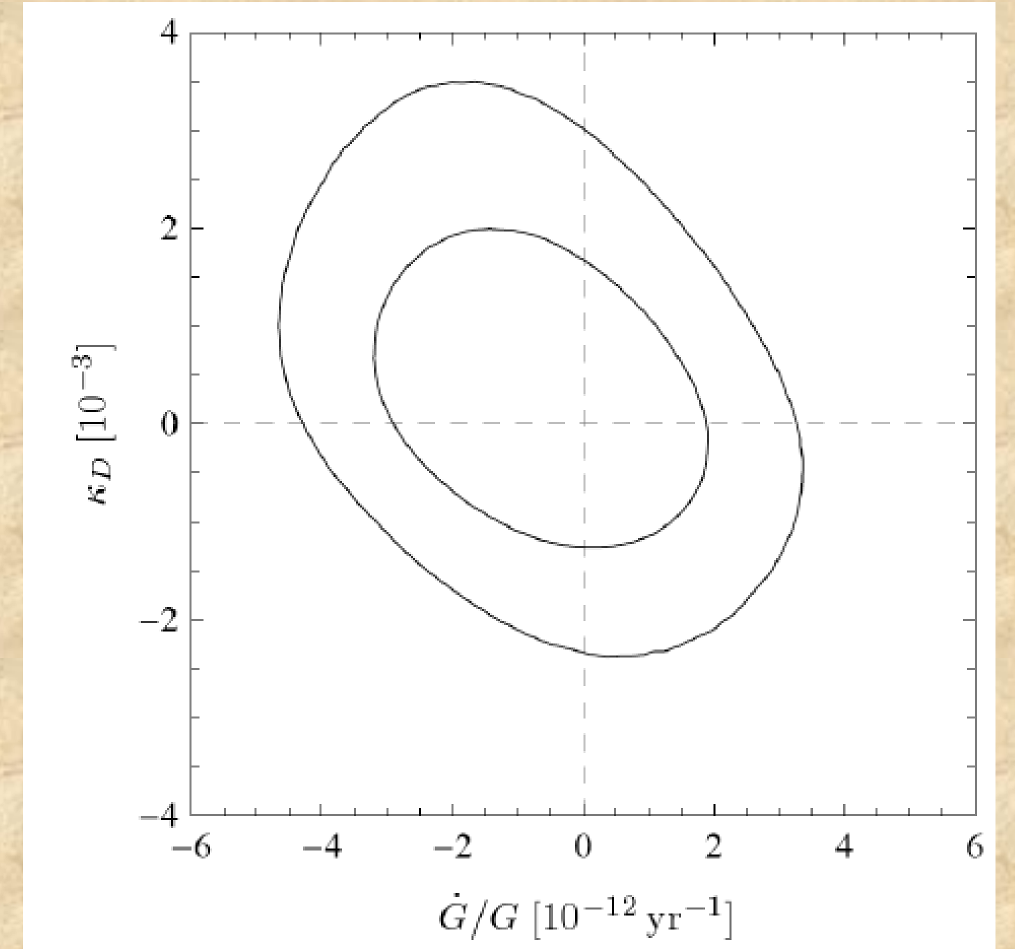
(iii) A scalar field that couples to gravity



J0437-4715: P_b =5.74dR



J1012+5307: P_b =14.4h R



Lazaridis et al. 2009

How many Degrees of Freedom are there in the Gravitational Field?

Newtonian gravity

$$\nabla^2\Phi = 4\pi G\rho \Rightarrow \Phi = -\frac{GM}{r} + \Phi_0$$

and General Relativity

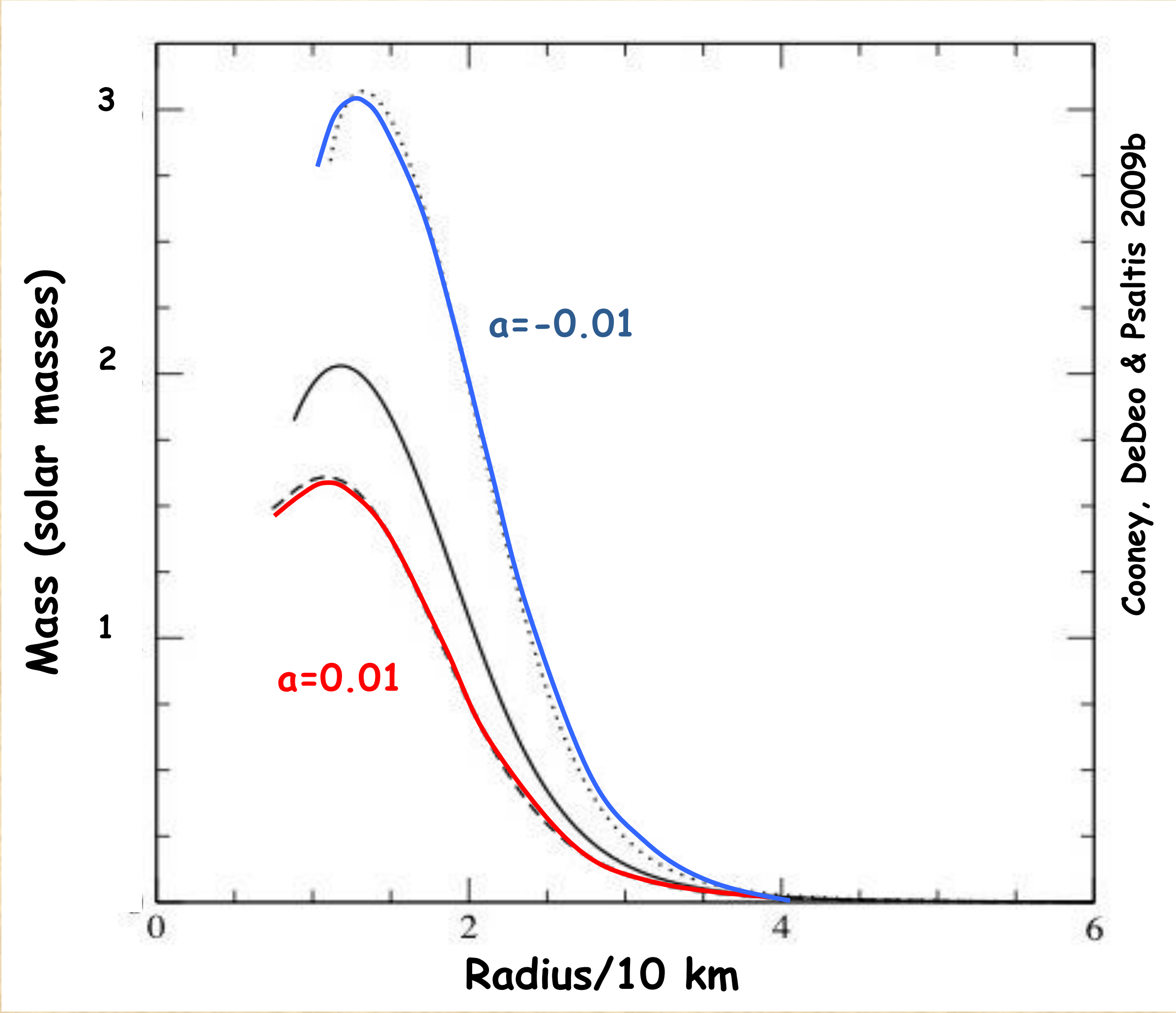
$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}R$$

have only two, but what if, e.g.,

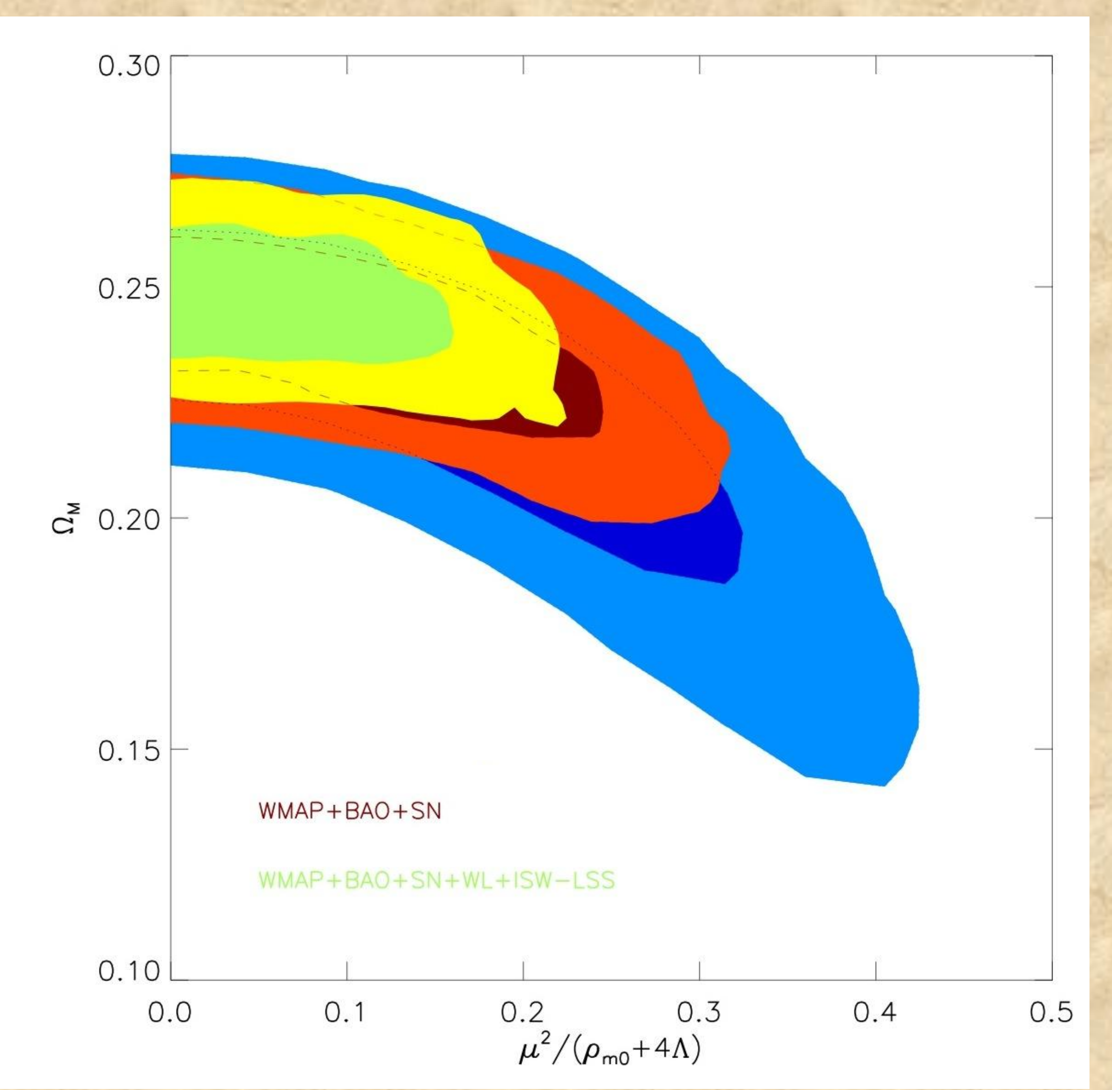
$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left[\mathrm{L}\quad \alpha R^2 + R - \Lambda + \frac{\mu^4}{R} + \frac{\eta^6}{R^2}\mathrm{L}\quad\right]$$

How many Degrees of Freedom are there in the Gravitational Field?

Neutron stars in $f(R) = aR^2 + R$



Cosmology with $f(R) = R - 2\Lambda + \frac{\mu^4}{R}$



Bean, Cooney, DeDeo & Psaltis 2010

Parity violation in Gravity?

The moment of inertia of a slowly spinning neutron star is

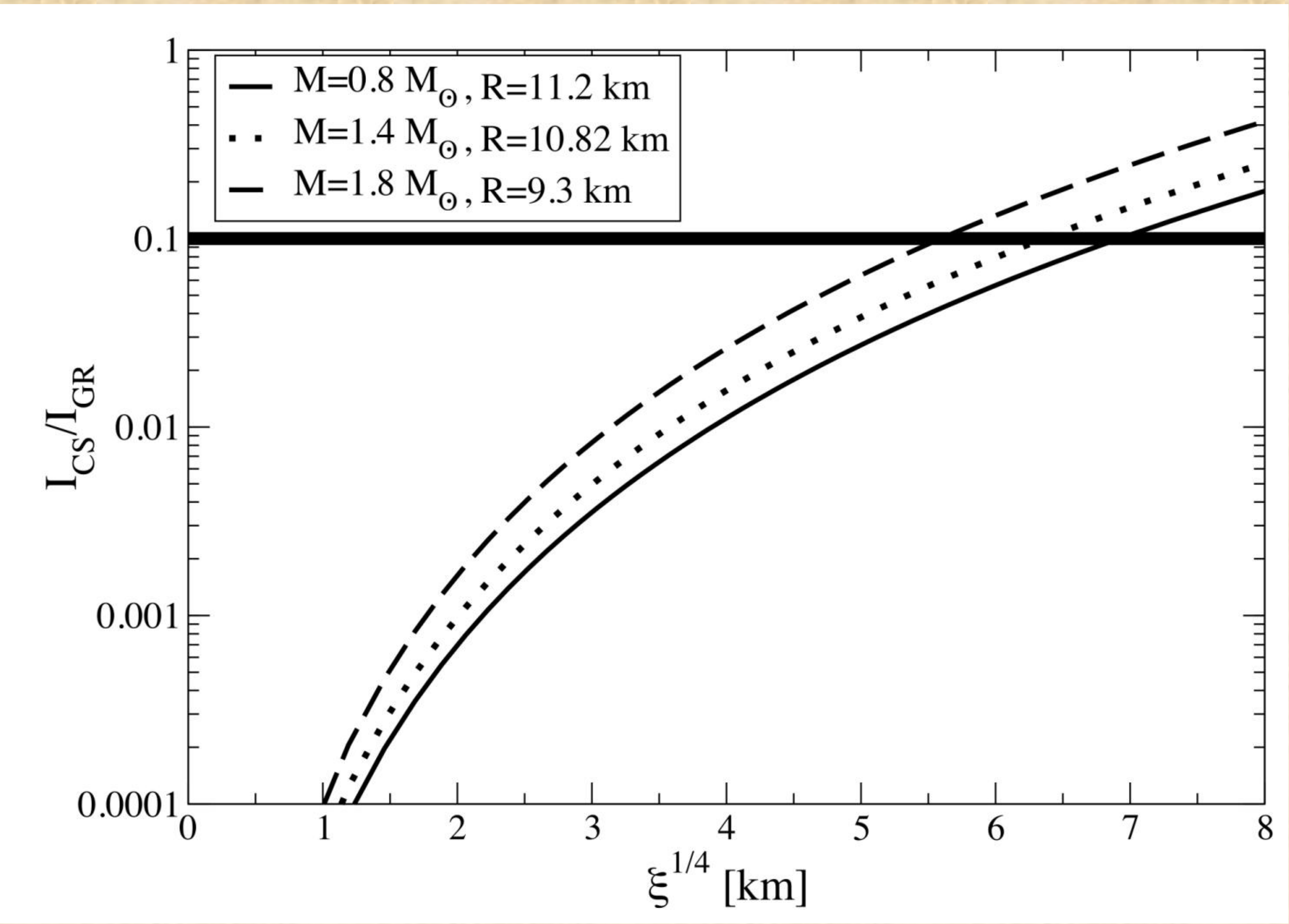
$$I = \frac{8\pi}{3} \int r^4 (\rho + P) \sqrt{\frac{g_{rr}}{g_{tt}}} \left(1 - \frac{g_{t\phi}}{\Omega} \right) dr$$

and depends on the parity violating potential of the gravitational theory

Parity violation in Gravity?

Test case: Neutron Stars in Chern-Simons gravity

Yunes, Psaltis, Ozel, & Loeb, 2010, PRD



Testing the General Relativistic No-Hair Theorem

- expand Kerr metric in multipoles
- use observations to measure at least 3 multipole coefficients
- investigate whether

$$q = -a^2$$

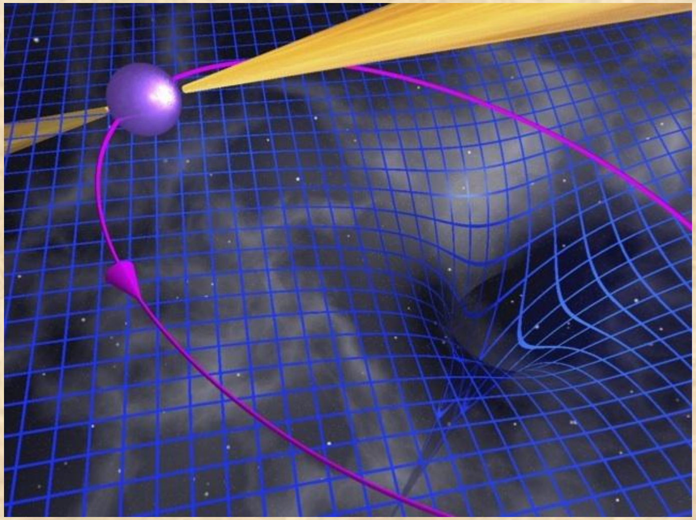
by writing a general spacetime that satisfies $R_{\mu\nu}=0$
but with

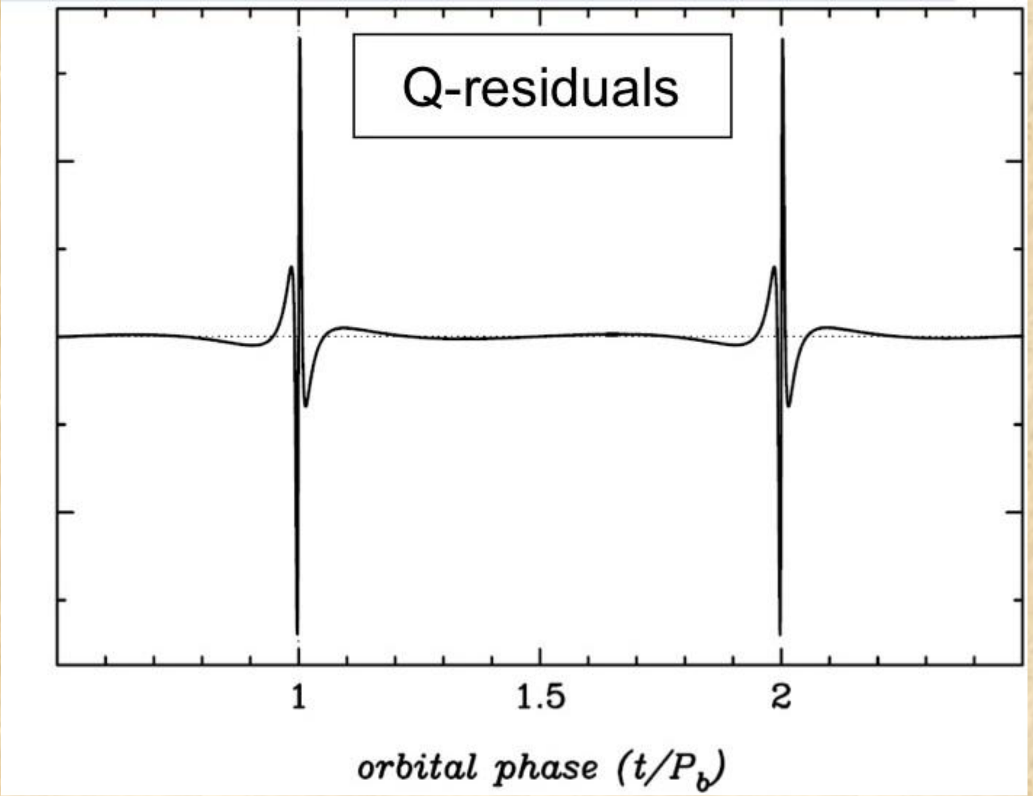
$$q = -(a^2 + \varepsilon)$$

and measuring the deviation parameter ‘ε’

Ryan 1995; Wex & Kopeikin 1999; Collins & Hughes 2004; Glampedakis & Babak 2006
Will 2008; Vigeland & Hughes 2009; Johannsen & Psaltis 2009, 2010

A BH-PSR binary



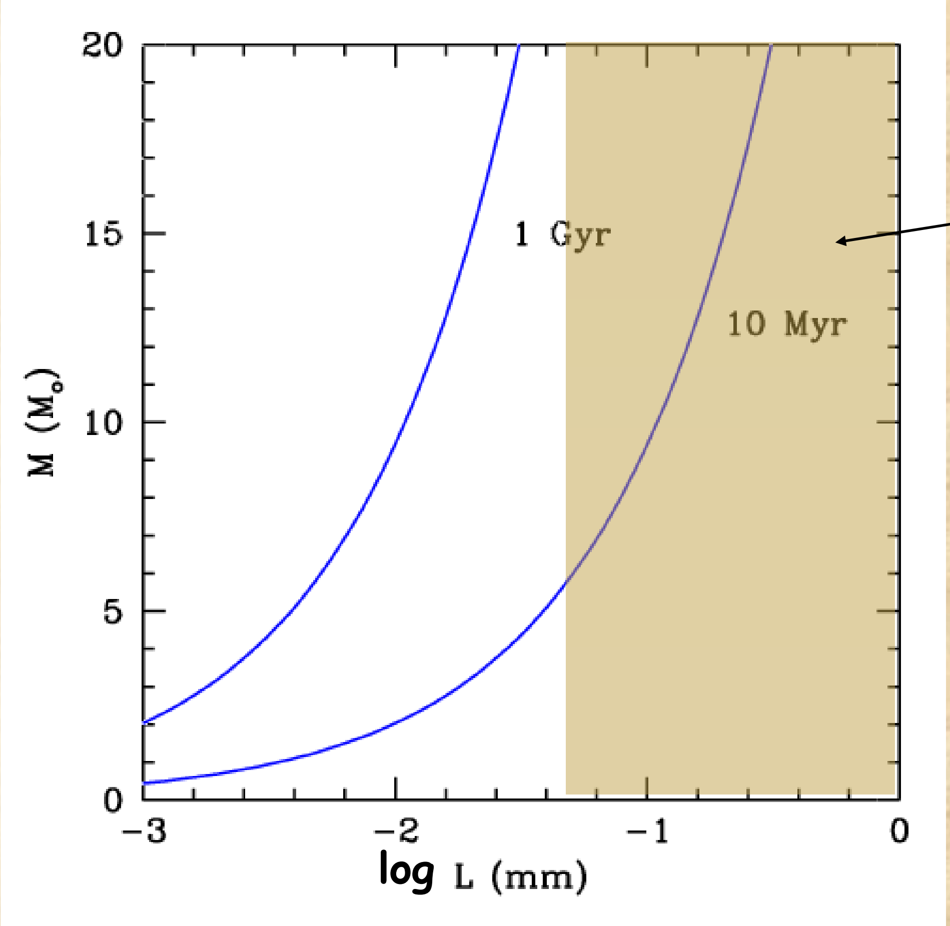


Wex & Kopeikin 1999

How many are the dimensions of the spacetime?

In a universe with large `RS' extra dimensions, black holes evaporate FAST due to emission of gravitons in the bulk

EMPARAN et al. 2002



Tabletop experiments:

$$L < 0.05mm$$

Large Extra Dimensions?

In a BH-PSR binary, the rate of change of the orbital period due to the evaporation of the black hole may dominate that due to the emission of gravitational waves.

Psaltis & Johannsen 2010

If we find no evidence for black-hole evaporation, then the size of the extra dimensions has to be

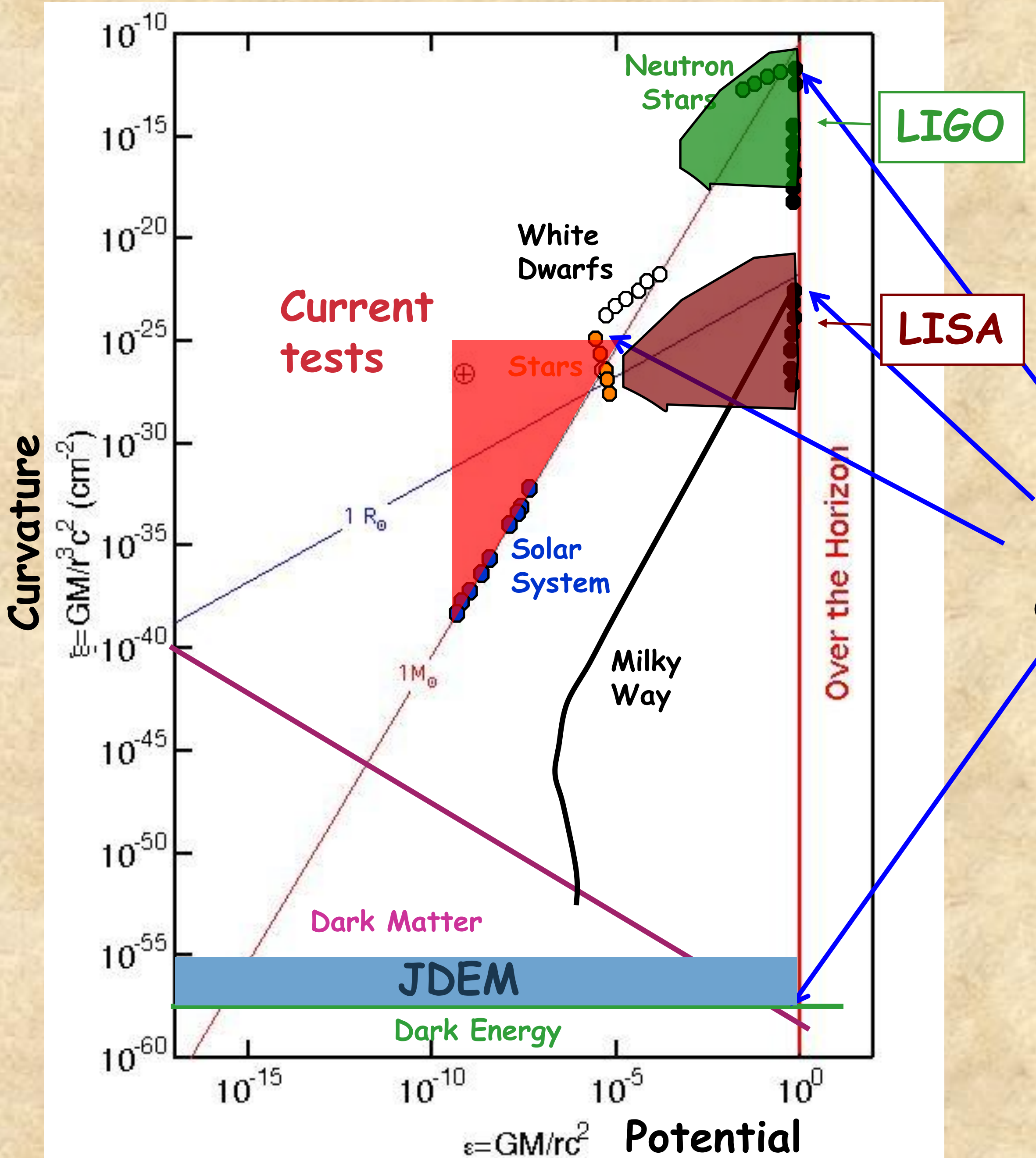
$$L \leq 0.1 \left(\frac{P}{2\mathrm{hr}} \right)^{4/3} \left(\frac{M_{BH}}{10 M_o} \right) \mu m$$

Conclusions

- ✧ General Relativity has been very accurately tested only in the weak-limit regime

- ✧ Many possibilities open regarding the fundamental properties of the gravitational field, e.g., sources, degrees of freedom, dimensionality, parity.

- ✧ The SKA is unique in probing a wide range of scales and a large number of phenomena that will help testing our understanding of gravity

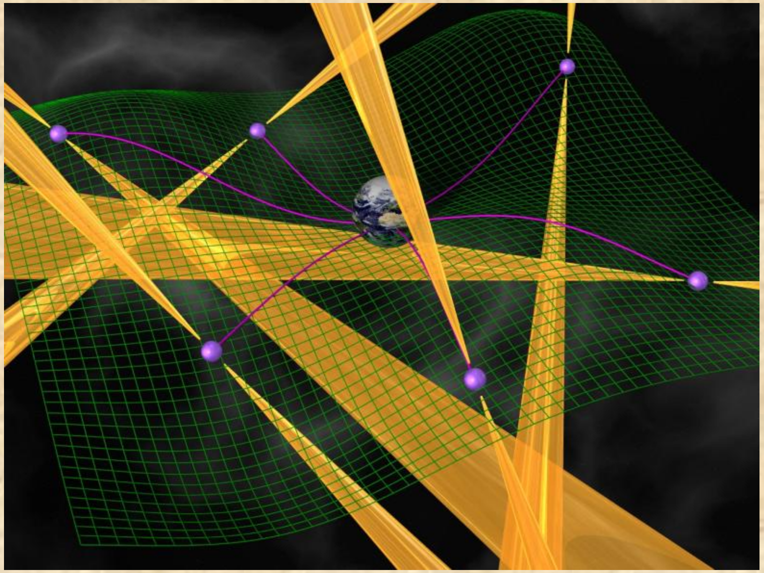


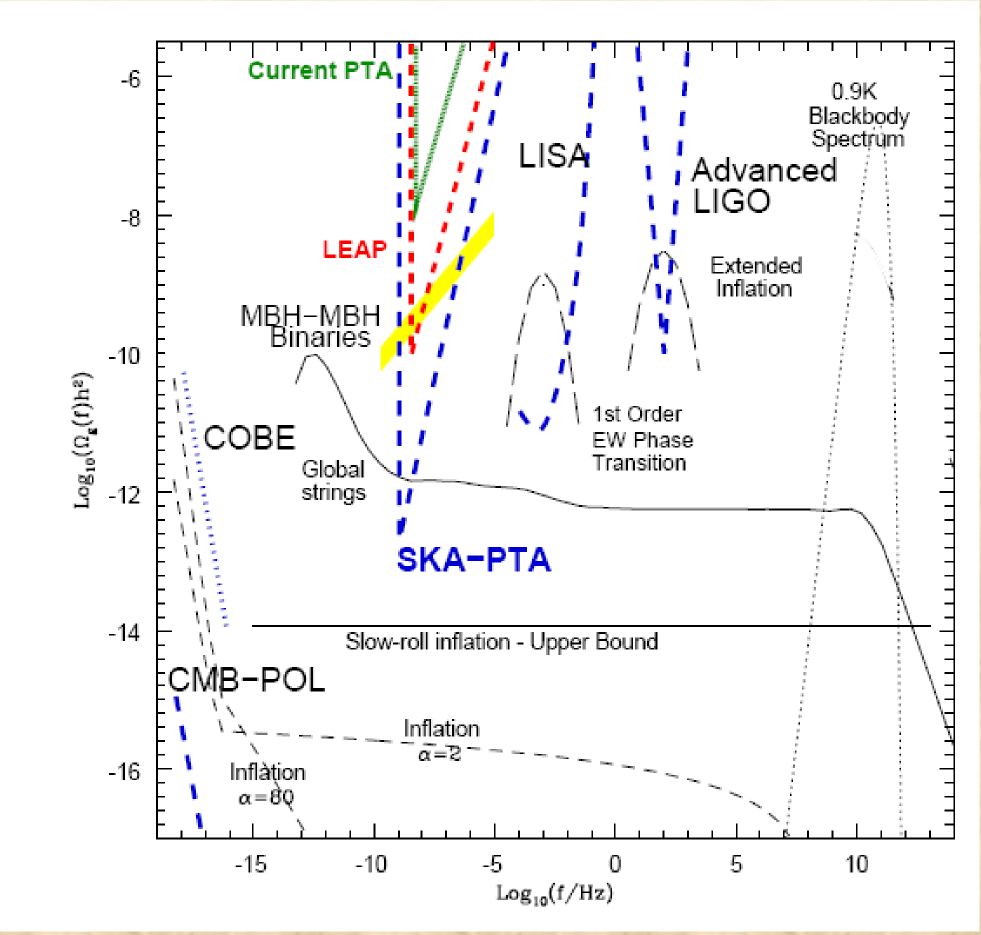
The SKA is unique in probing the entire range of spacetime curvatures!

Are Matter and Radiation the Only Sources of Gravity?

(i) The scalar field responsible for inflation (the inflaton)

A Pulsar Timing Array





Kramer et al. 2004