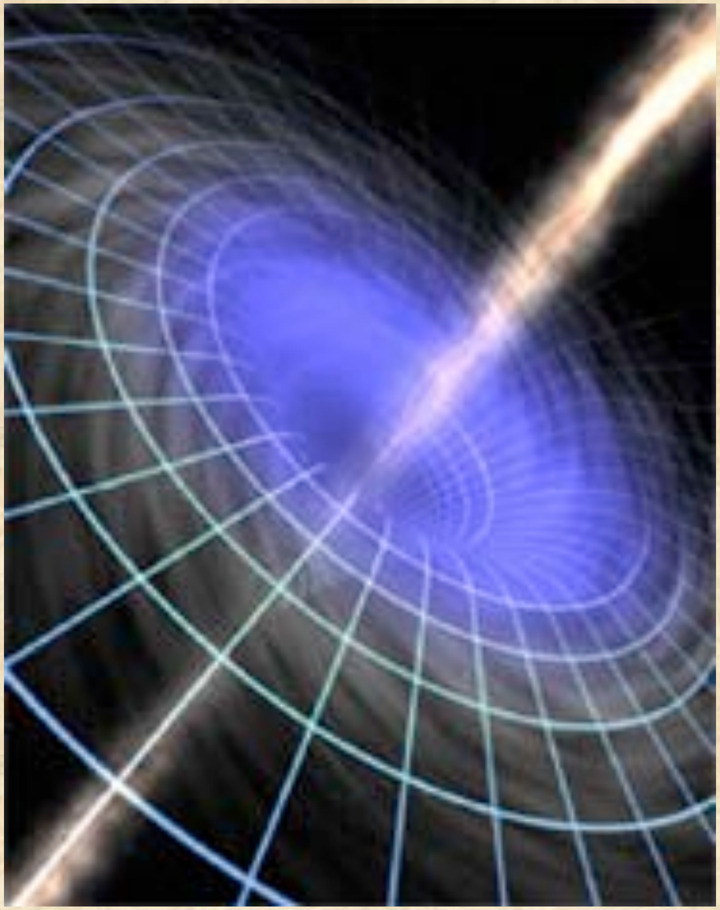


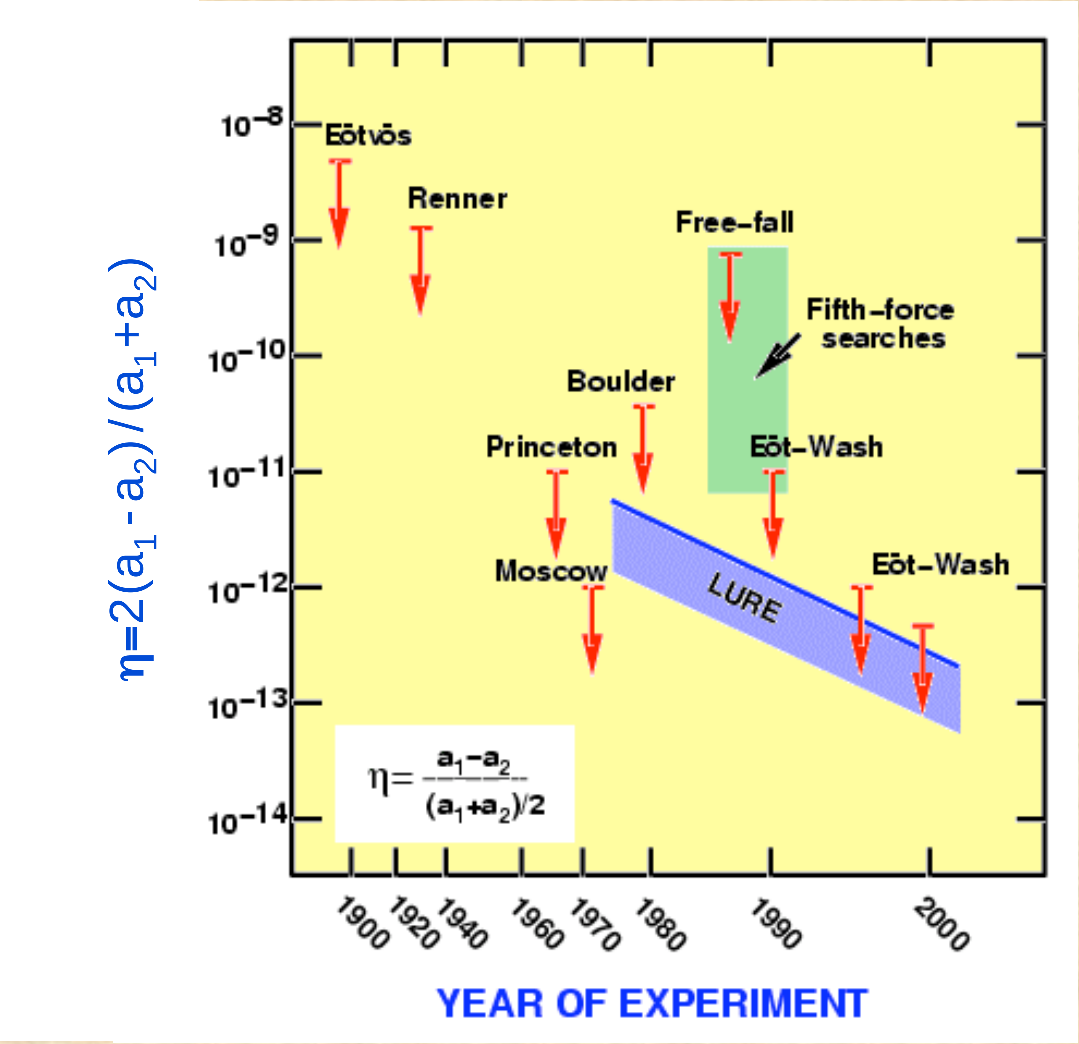
NEW TESTS OF STRONG-FIELD GRAVITY WITH NEUTRON STARS AND BLACK HOLES

DIMITRIOS PSALTIS
University of Arizona

with Simon DeDeo and Tim Johannsen

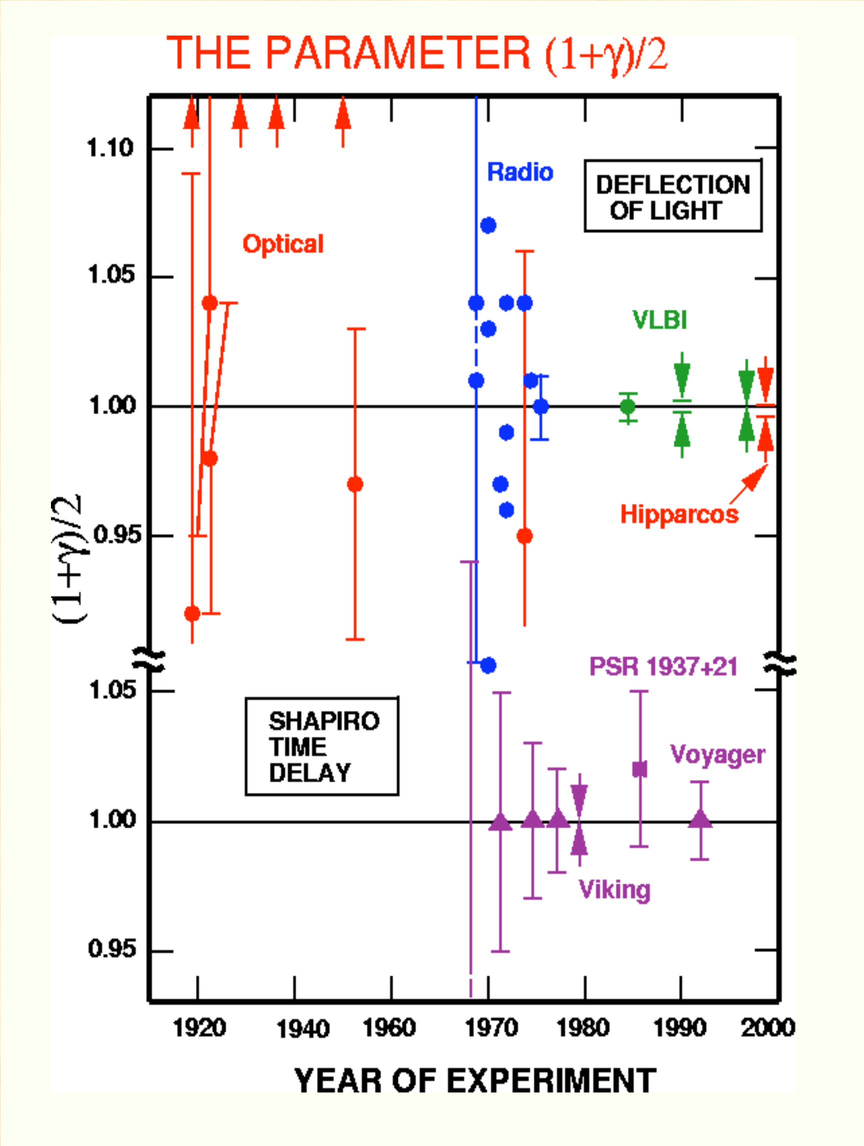
GENERAL RELATIVITY HAS TWO INGREDIENTS

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



Will 2001

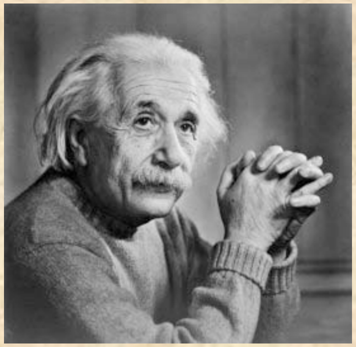
- The Einstein Field Equations has been tested to ~10^{-4}



Will 2001

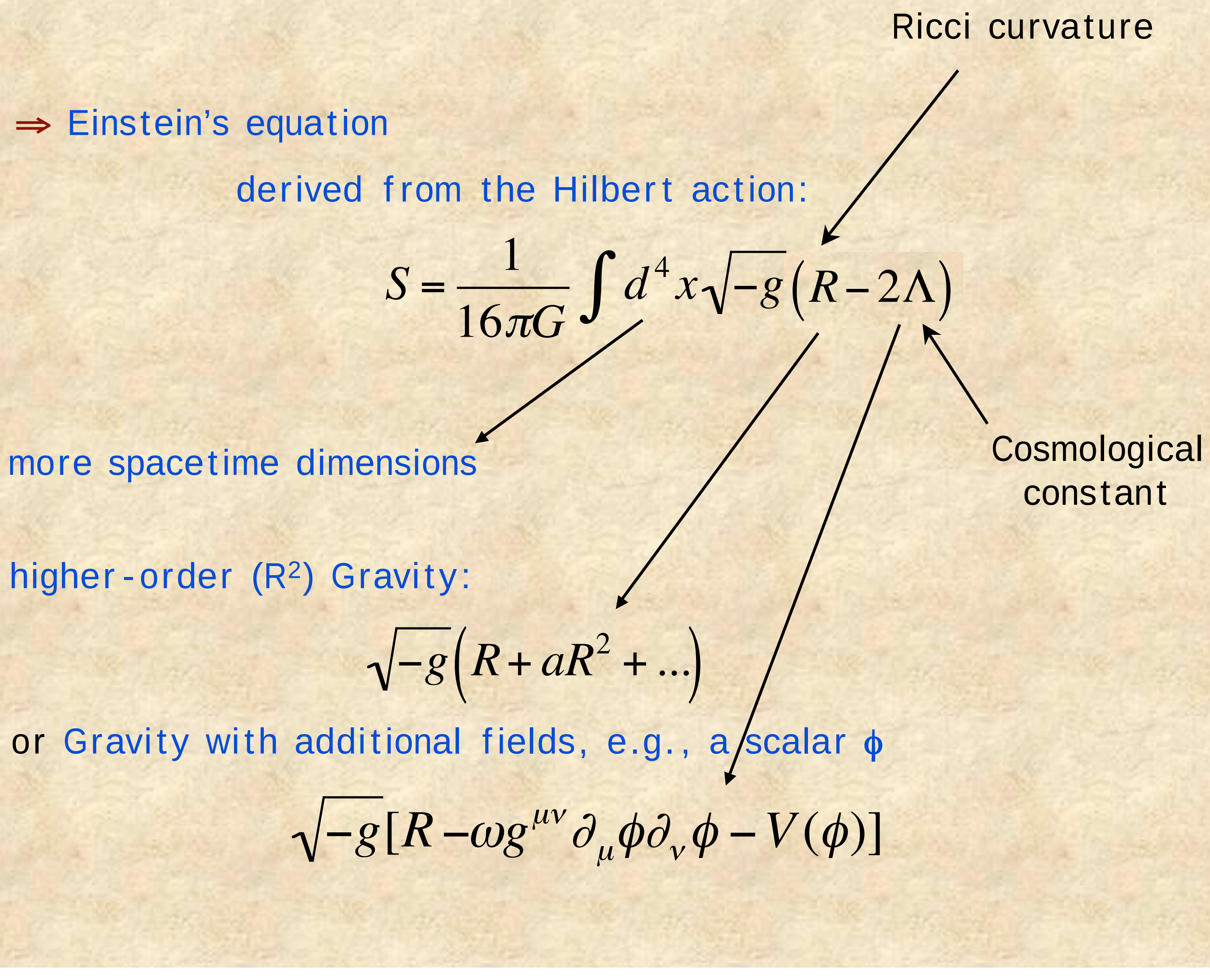
What measures the strength of the gravitational field?

No scale in the theory! No field is either weak or strong!



		Weak Field	Strong Field
Gravity	Potential $\varepsilon \sim \frac{GM}{Rc^2}$	$<<1$	$\cong 1$
Matter	Velocity, u/c	$<<1$	$\cong 1$

Extending Einstein's Equation



Ricci curvature

⇒ Einstein's equation

derived from the Hilbert action:

$$S = \frac{1}{16\pi G}\int d^4 x\sqrt{-g}\left(R-2\Lambda\right)$$

more spacetime dimensions

Cosmological constant

higher-order (R^2) Gravity:

$$\sqrt{-g}\left(R+aR^2+\ldots\right)$$

or Gravity with additional fields, e.g., a scalar ϕ

$$\sqrt{-g}[R-\omega g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi-V(\phi)]$$

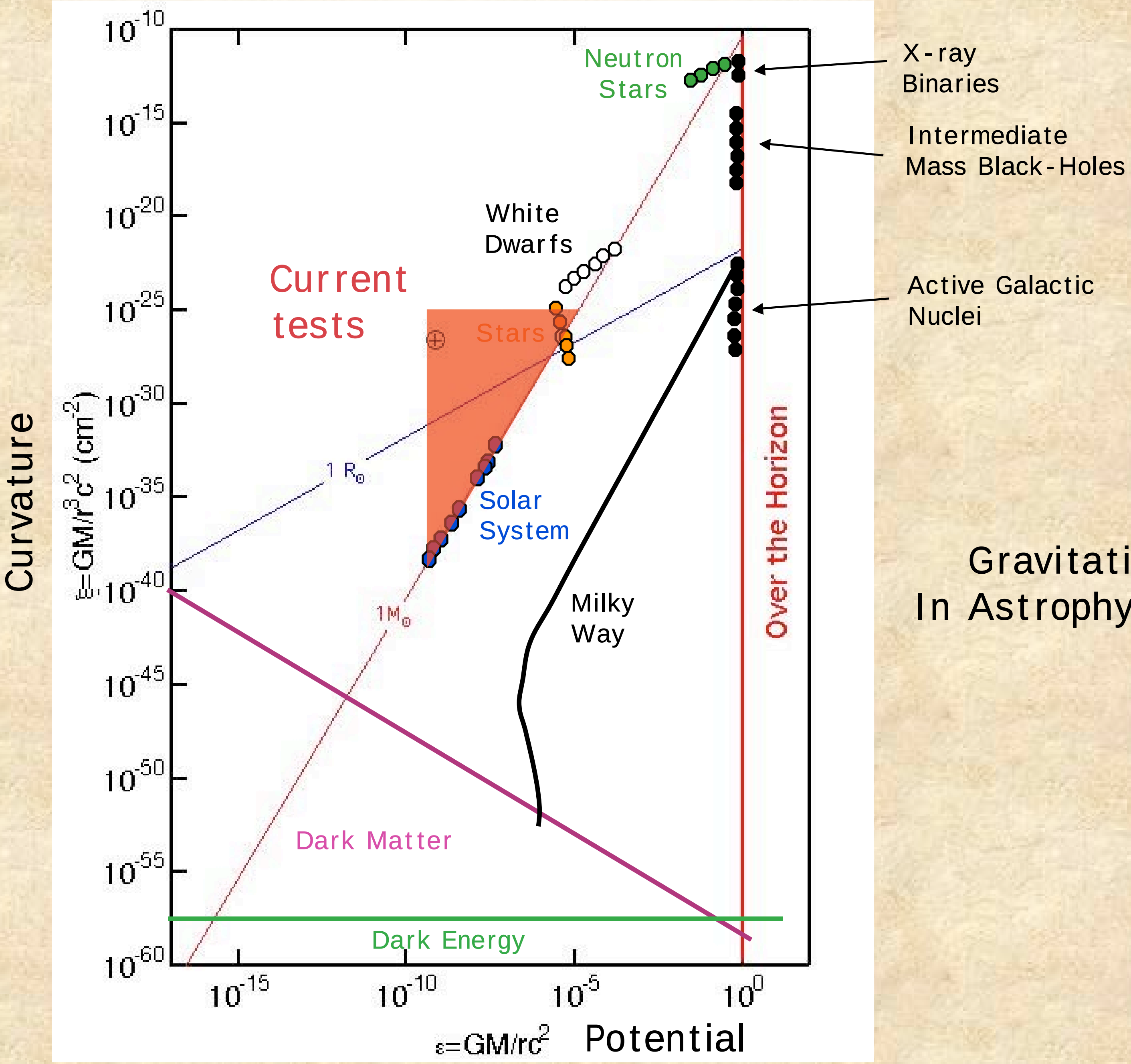
What measures the strength of the gravitational field?

In GR, the strength of the gravitational field is measured by
The gravitational potential

$$\varepsilon \equiv \frac{GM}{rc^2}$$

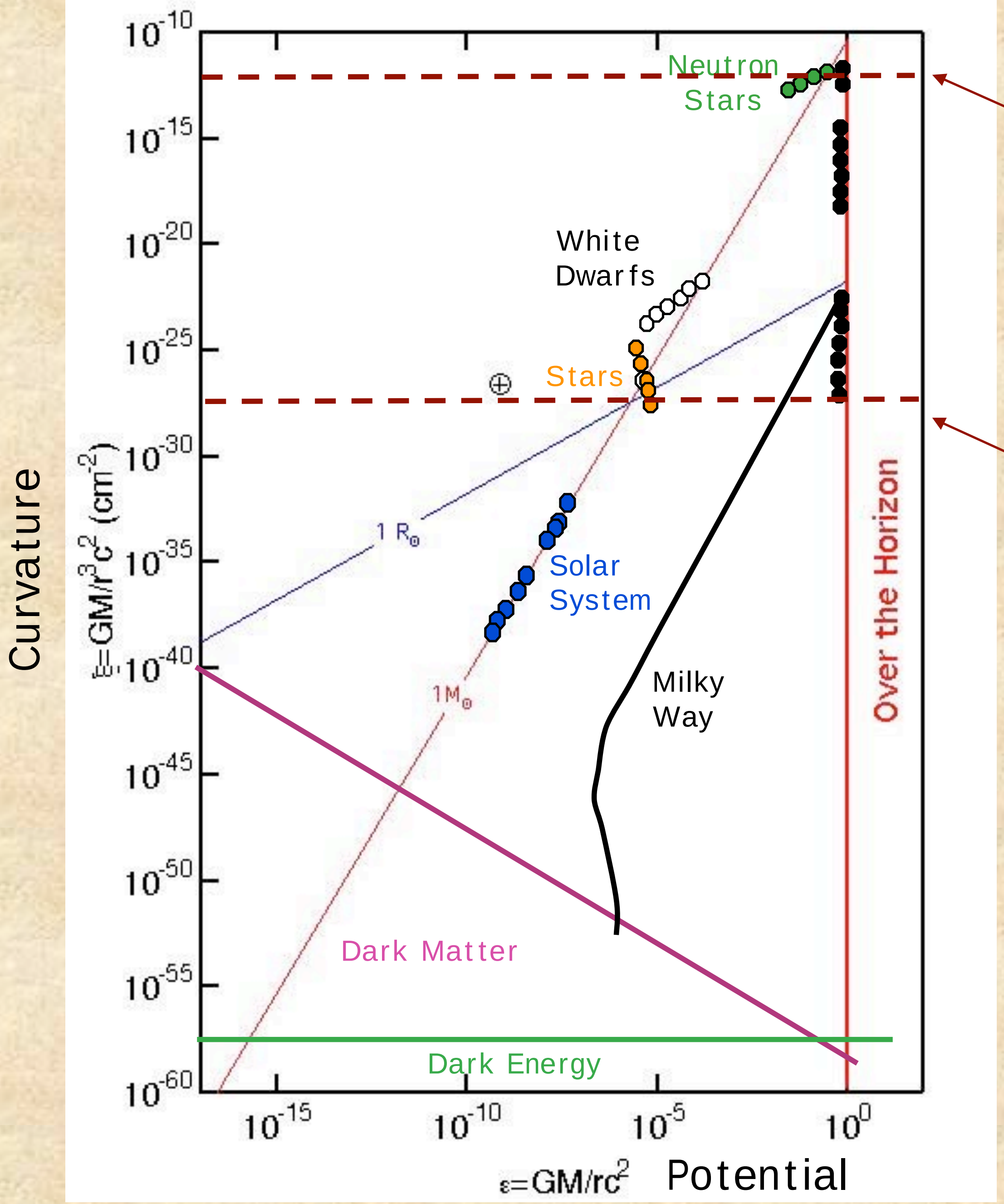
In a general Lagrangian theory with an additional scale,
the strength of the field will be measured by the curvature

$$\xi \equiv \frac{GM}{r^3c^2}$$



Gravitational Fields In Astrophysical Systems

Psaltis 2008

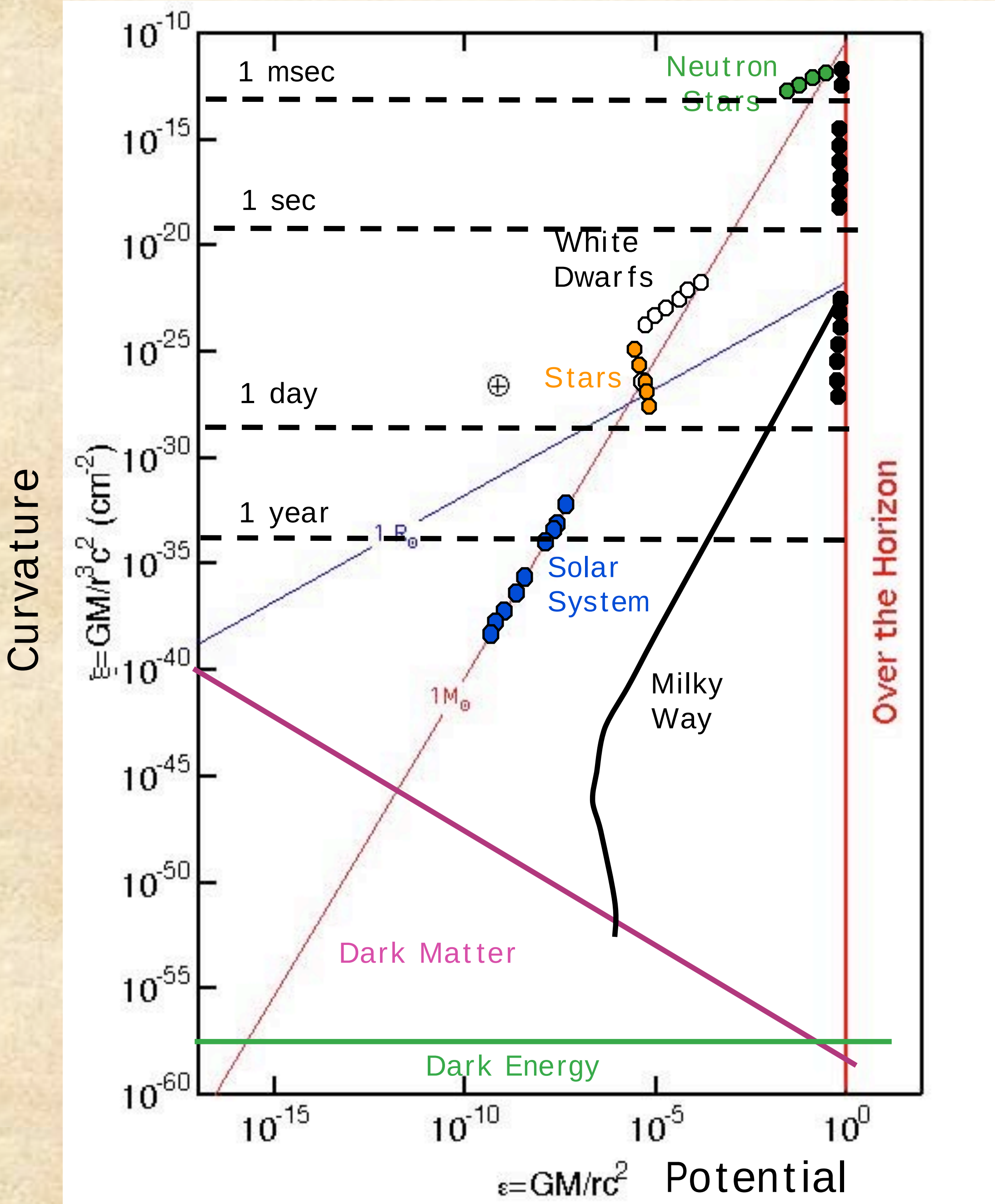


EW Baryogenesis

Nucleosynthesis

Gravitational Fields
In Cosmology

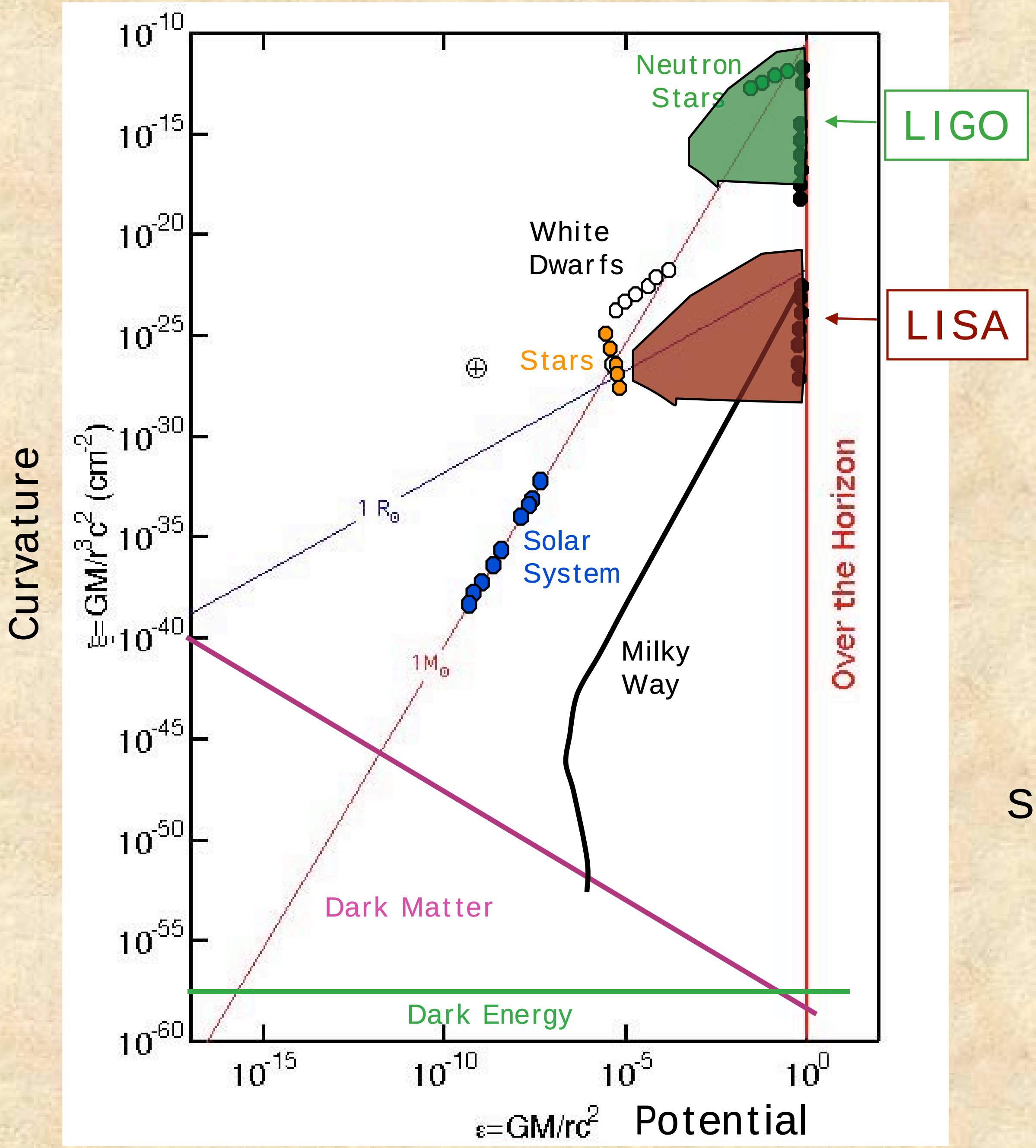
Psaltis 2008



Fast X-ray timing!
(AXTAR & XEUS)

How to Probe the
Strong Gravitational Fields

Psaltis 2008



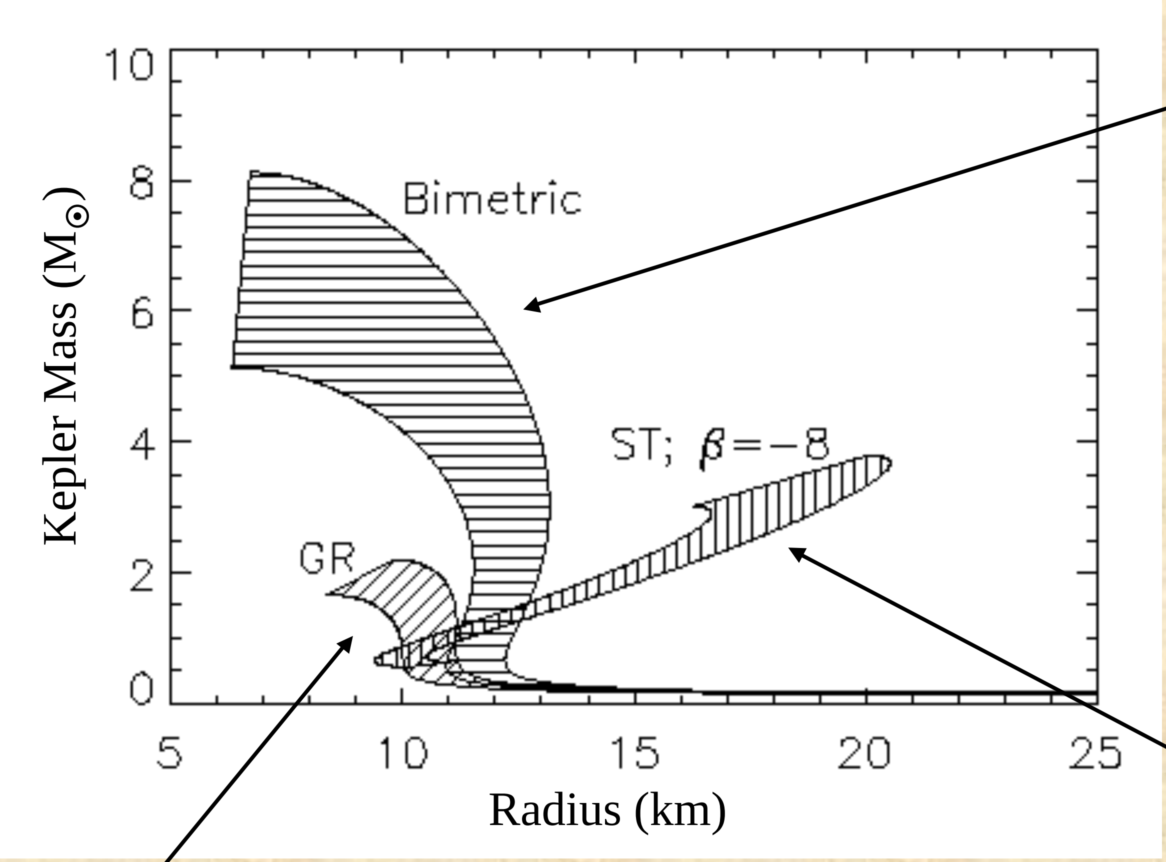
Fast X-ray timing!
(AXTAR & XEUS)

High-Frequency
Gravity Waves
(e.g.,LIGO, GEO600)

How to Probe the Strong Gravitational Fields

Psaltis 2008

NEUTRON STARS IN ALTERNATIVE GRAVITY THEORIES



DeDeo & Psaltis 2003

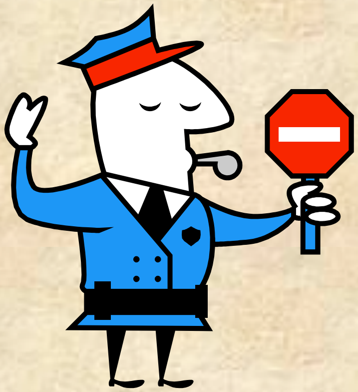
Rosen's Theory

(prior geometry)

Scalar - Tensor
(dynamical)

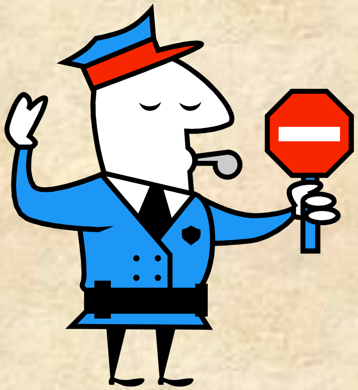
General Relativity

- ➢ All theories consistent with solar system tests!
- ➢ Uncertainty due to gravity larger than EOS!



We have to be very careful when playing with Einstein’s equation…

(*aka* a lesson learned from Cosmology)



Cosmic acceleration can be produced by

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left(R - \frac{\mu^2}{R}\right)$$

Carroll et al. 2004

But:

Universe unstable to small perturbations!

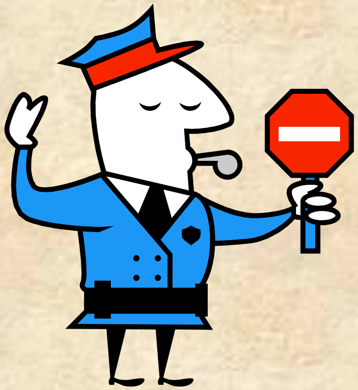
Dolgov & Kawasaki 2003; Sawicki & Hu 2007

Post-Newtonian corrections do not depend on μ!! $(\gamma = 1/2)$

Chiba 2003; Erickek et al 2006

Stars are unstable to small perturbations!!!

Seifert & Wald 2007; Seifert 2007



Cosmic acceleration can be produced by

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left(R - \frac{\mu^2}{R}\right)$$

Carroll et al. 2004

Solution to these problems requires

- fine tuning
- a chameleon field
- perturbative localization

DeDeo & Psaltis 2008, PRL, submitted

Scalar-Tensor Gravity and Neutron Stars

(Damour & Esposito-Farese 1993; DeDeo & Psaltis 2003, 2006)

$$S = \frac{1}{16\pi G_*}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} - 2\tilde{g}_{\mu\nu}\partial_\mu\phi\partial_\nu\phi\right] + S_m\left[\psi, A^2(\phi)\tilde{g}_{\mu\nu}\right]$$

and parametrize the coupling function:

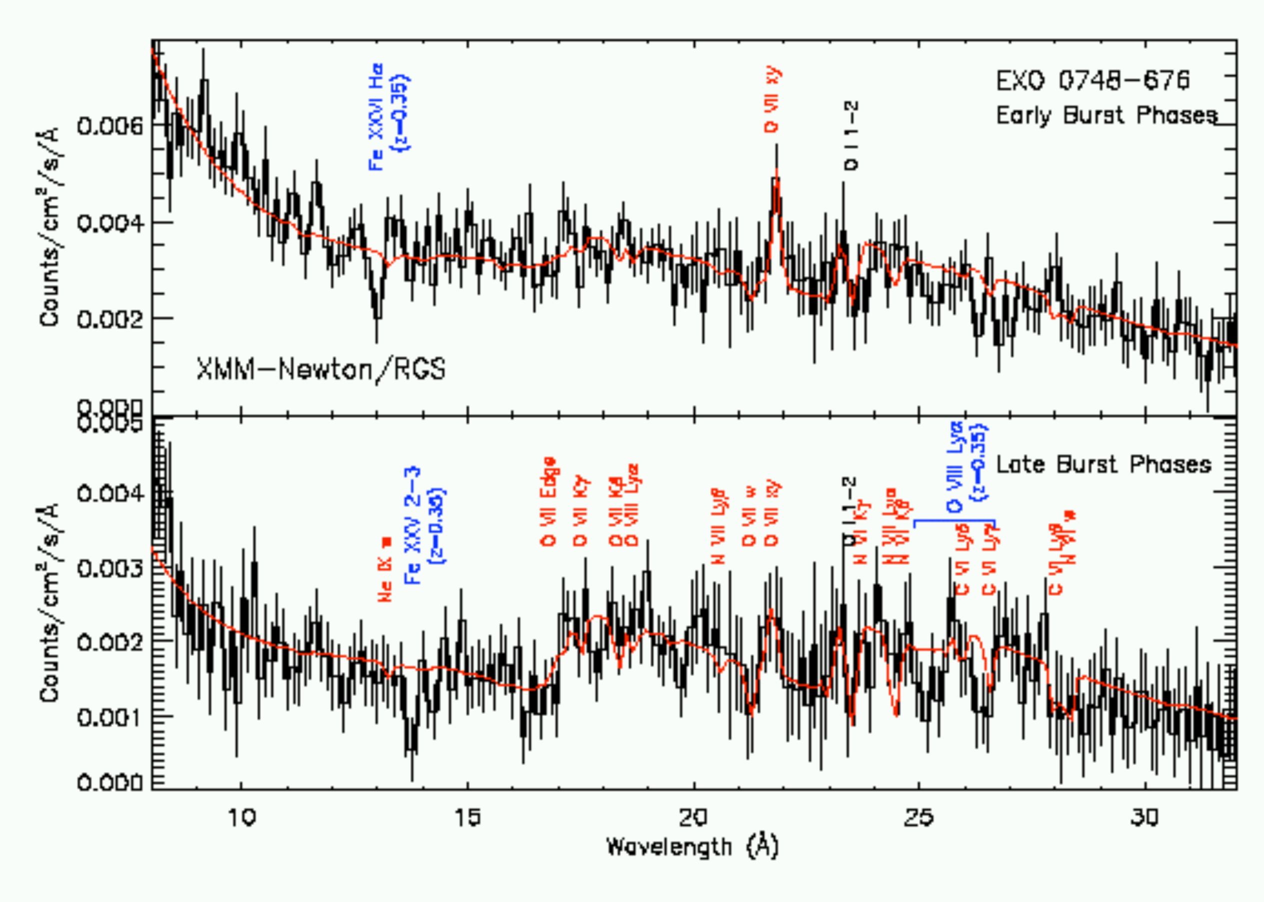
$$A(\phi) = \alpha_0(\phi - \phi_0) + \frac{1}{2}\beta_0(\phi - \phi_0)^2 + \ldots$$

weak-field tests constrain α_0 (Cassini set $a_0<10^{-4}$)

you need strong-field tests to constrain β_0

GRAVITATIONALLY REDSHIFTED LINES

Redshift for EXO 0748-676: $\delta\lambda/\lambda=0.35$

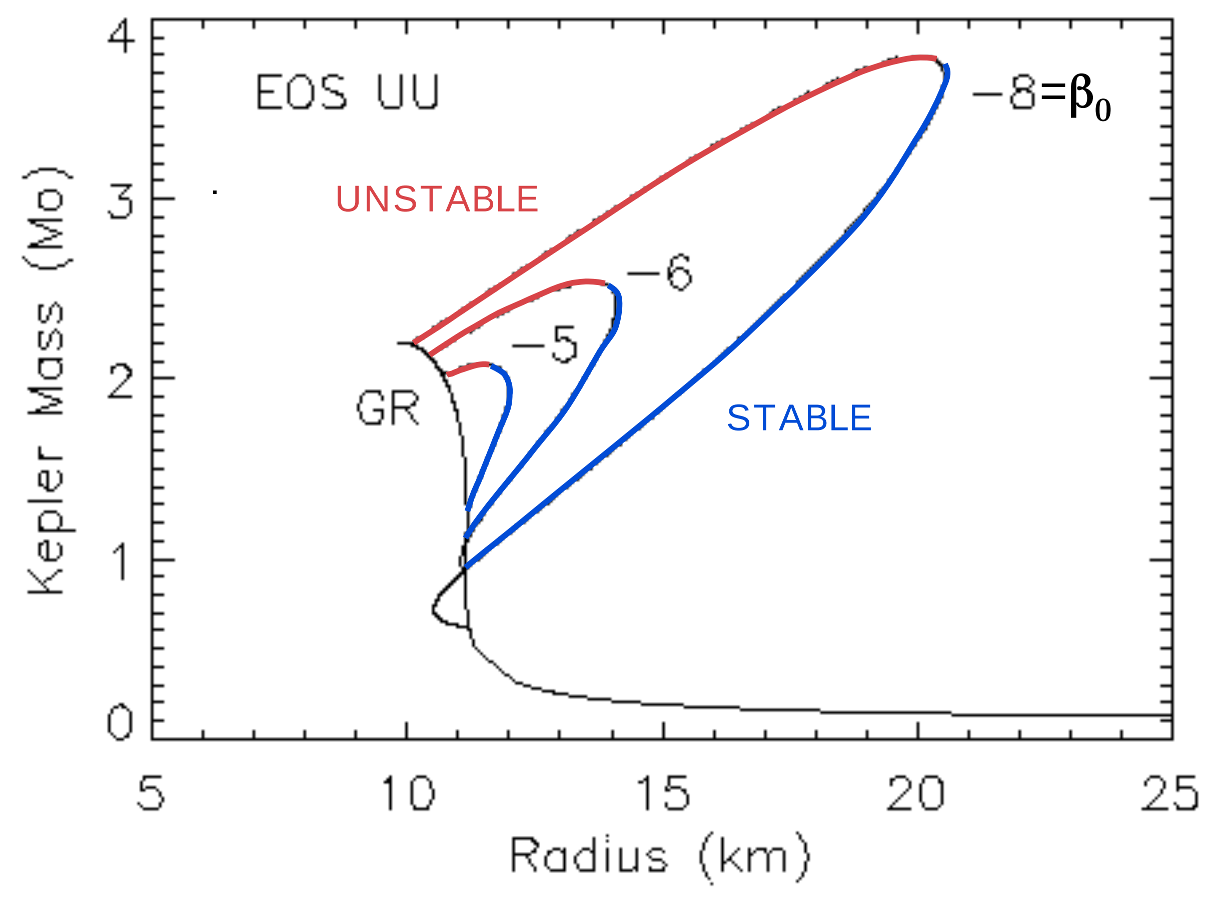


Cottam et al. 2002

Bonus: Neutron Stars are Spherically Symmetric

(when slowly rotating)

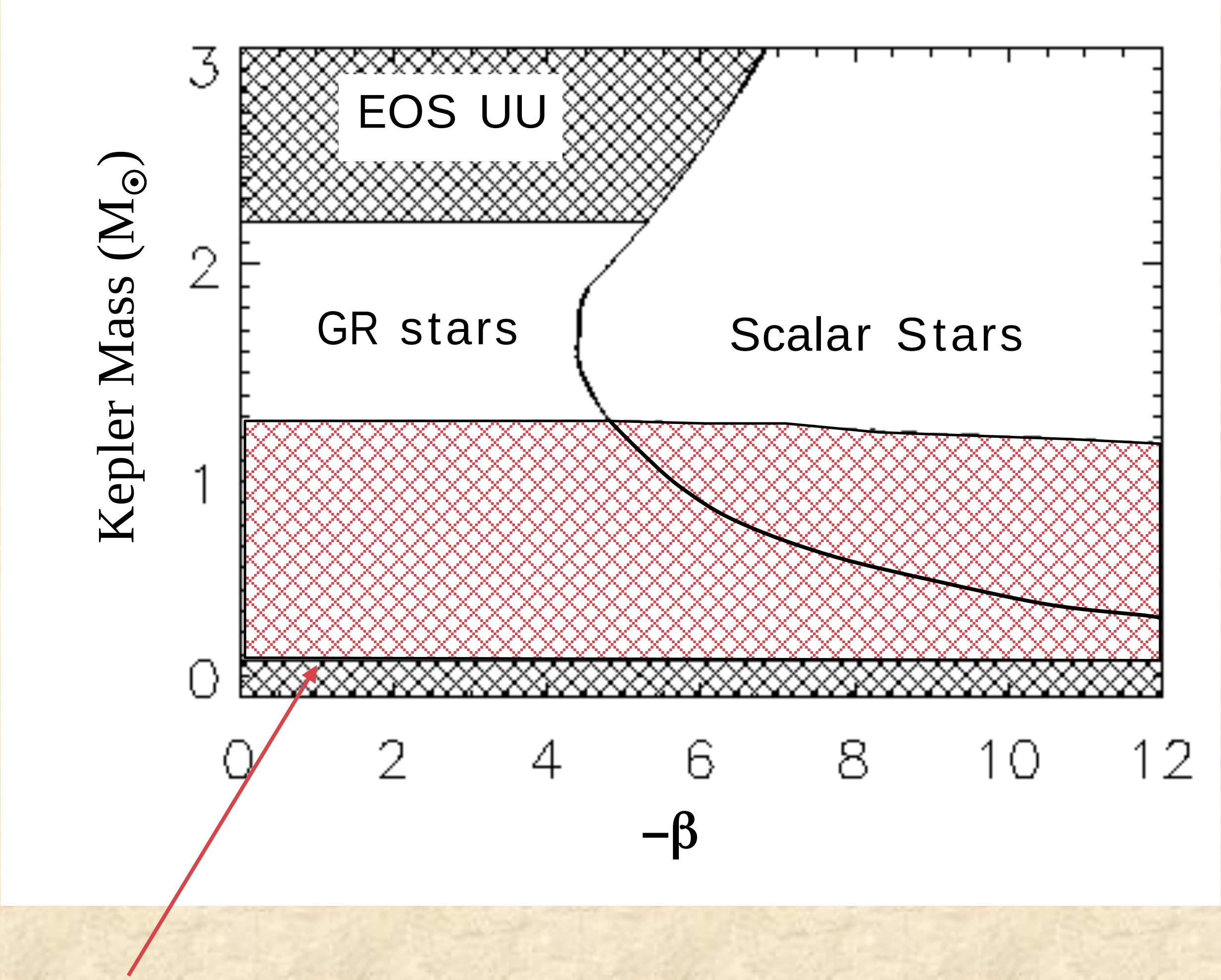
NEUTRON STARS IN SCALAR-TENSOR GRAVITY



DeDeo & Psaltis 2003

Scalar Stars can become Large and Massive

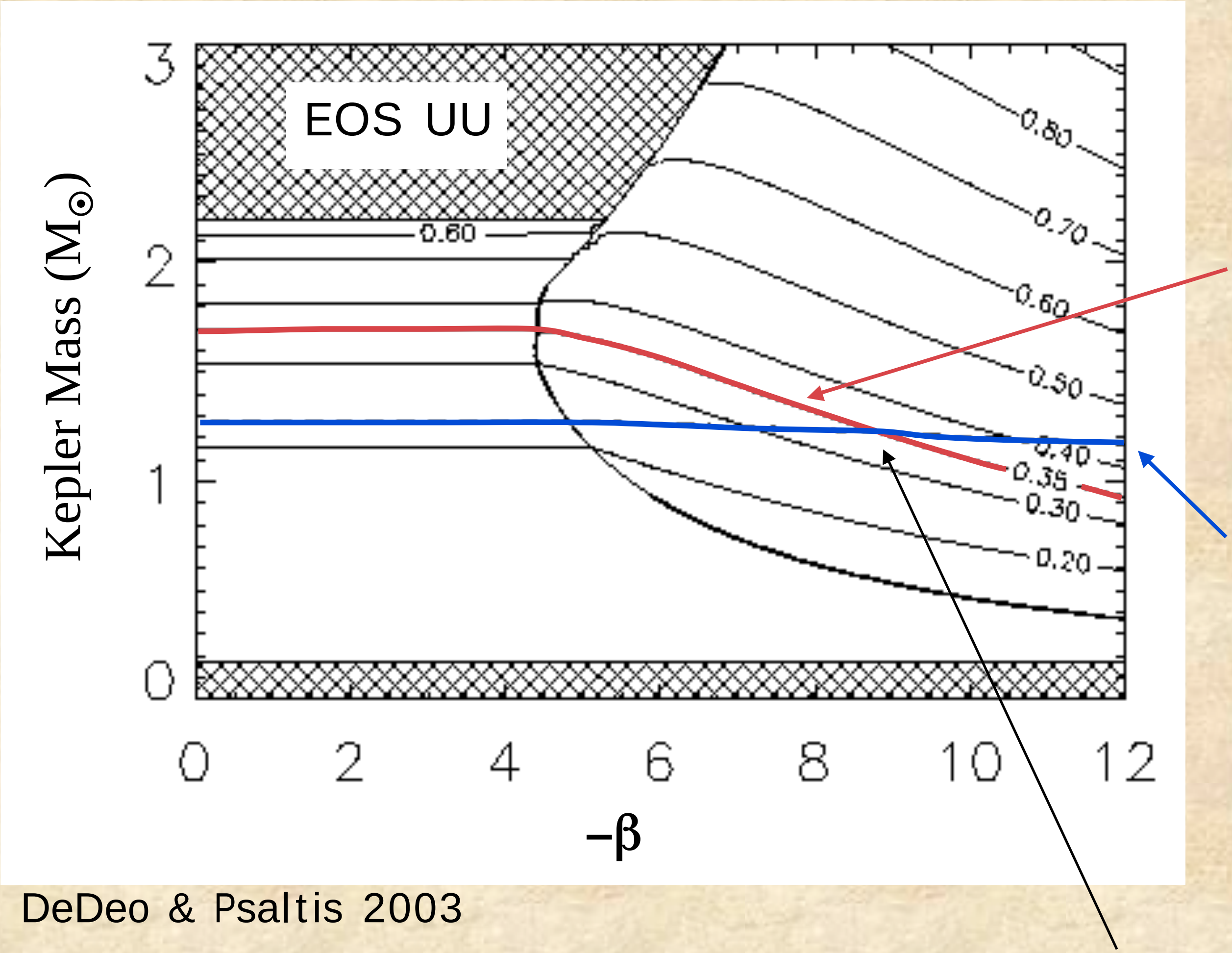
NEUTRON STARS IN SCALAR-TENSOR GRAVITY II



DeDeo & Psaltis 2003

Baryonic Mass < $1.4M_\odot$

LIMITS FROM GRAVITATIONAL REDSHIFTS



z=0.35

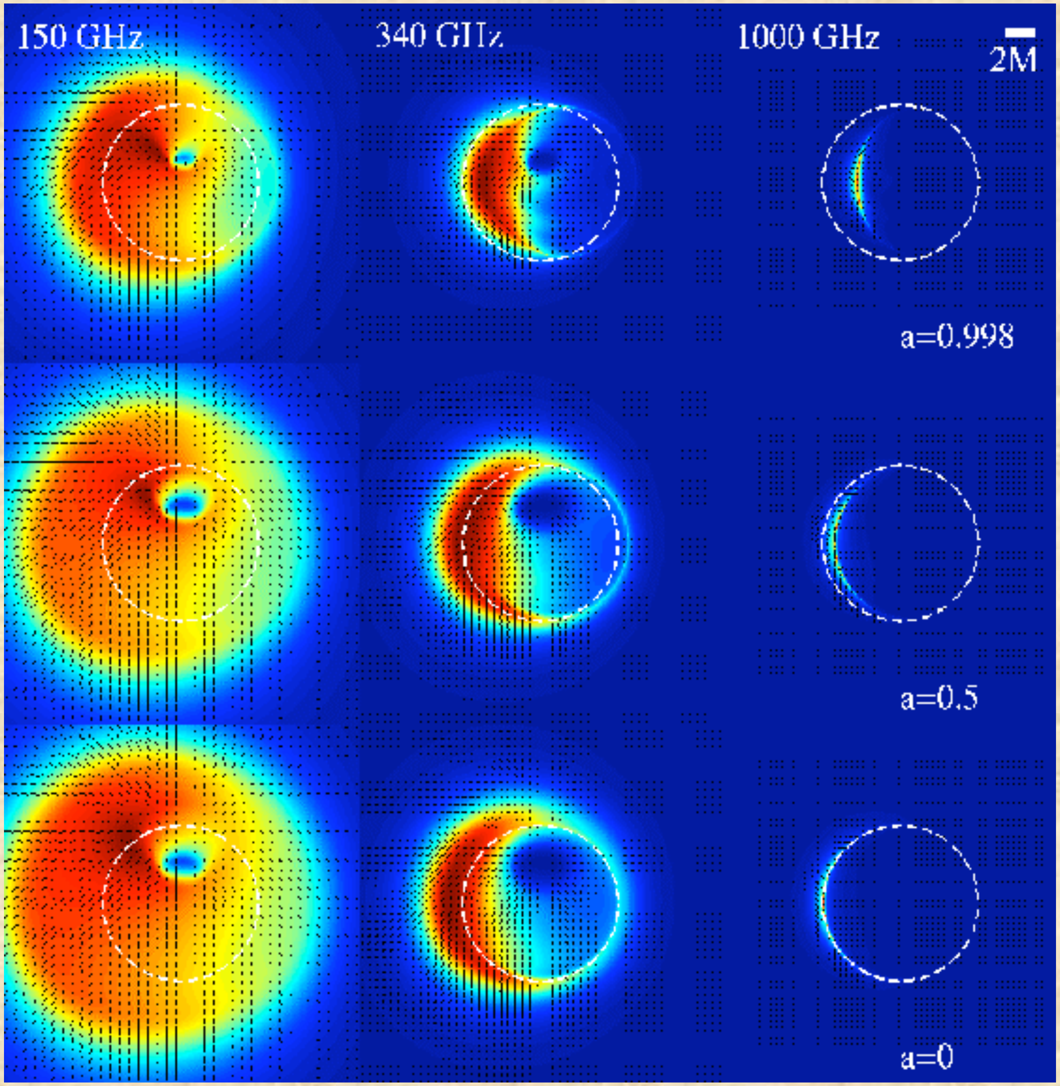
$M_{baryon} > 1.4 M_\odot$

Limit: $-\beta < 9$

DeDeo & Psaltis 2003

If the mass of EXO 0748-676 is measured, limits will become tighter

What can we learn about strong-field GR with Black Holes?



Broderick & Loeb 2006

Scalar-Tensor black holes are identical to GR ones!

Thorne & Dykla 1971; Hawking 1974; Bekenstein 1974; Sheel et al. 1995

Let’s add:

Psaltis, Perrodin, Dienes, & Mocioiu 2008, PRL, 100, 091101

a dynamical vector field

all R^2 terms

any function of R

… in the Palatini formalism

Always get Kerr Black Holes!!!

The Good News

We have a parameter-free solution to an astrophysical problem!

If experiments do not confirm it:

- Strong Violation of Equivalence Principle!
- Large extra dimensions!!

  Emparan et al. 2002
- Massive Gravitons!!!

  Berti, Buonanno, Will 2005
- Non-local physics!!!!

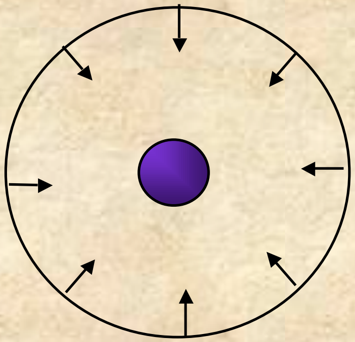
  e.g., Simon 1990, Adams et al. 2006

Large extra dimensions?

Gauss' law tells us that we live in a 4D world!

$$g \sim \frac{GM}{r^2}$$

The exponent "2" is mostly geometric

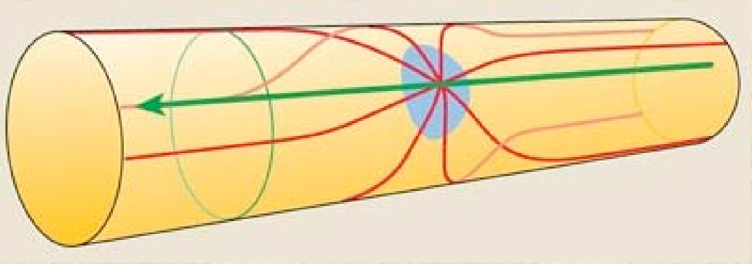


$$\int \vec{g} \cdot d\vec{S} = 4\pi r^2 g = 4\pi GM$$

and is equal to the (number of space dimensions) - 1!

How do we get around Gauss' law?

(I) Compactify extra dimensions (ADD)

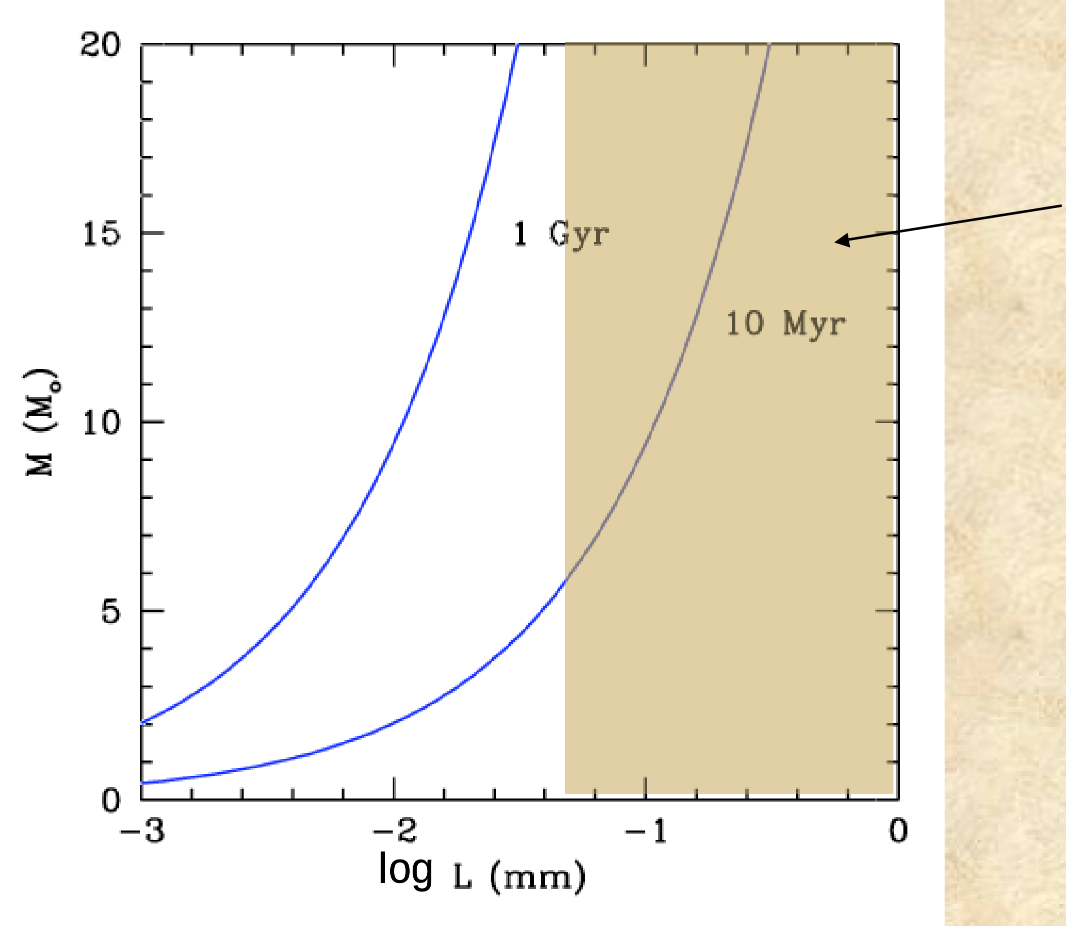


(II) "Fill" bulk with a "cosmological constant" (RS2)

Large Extra Dimensions?

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

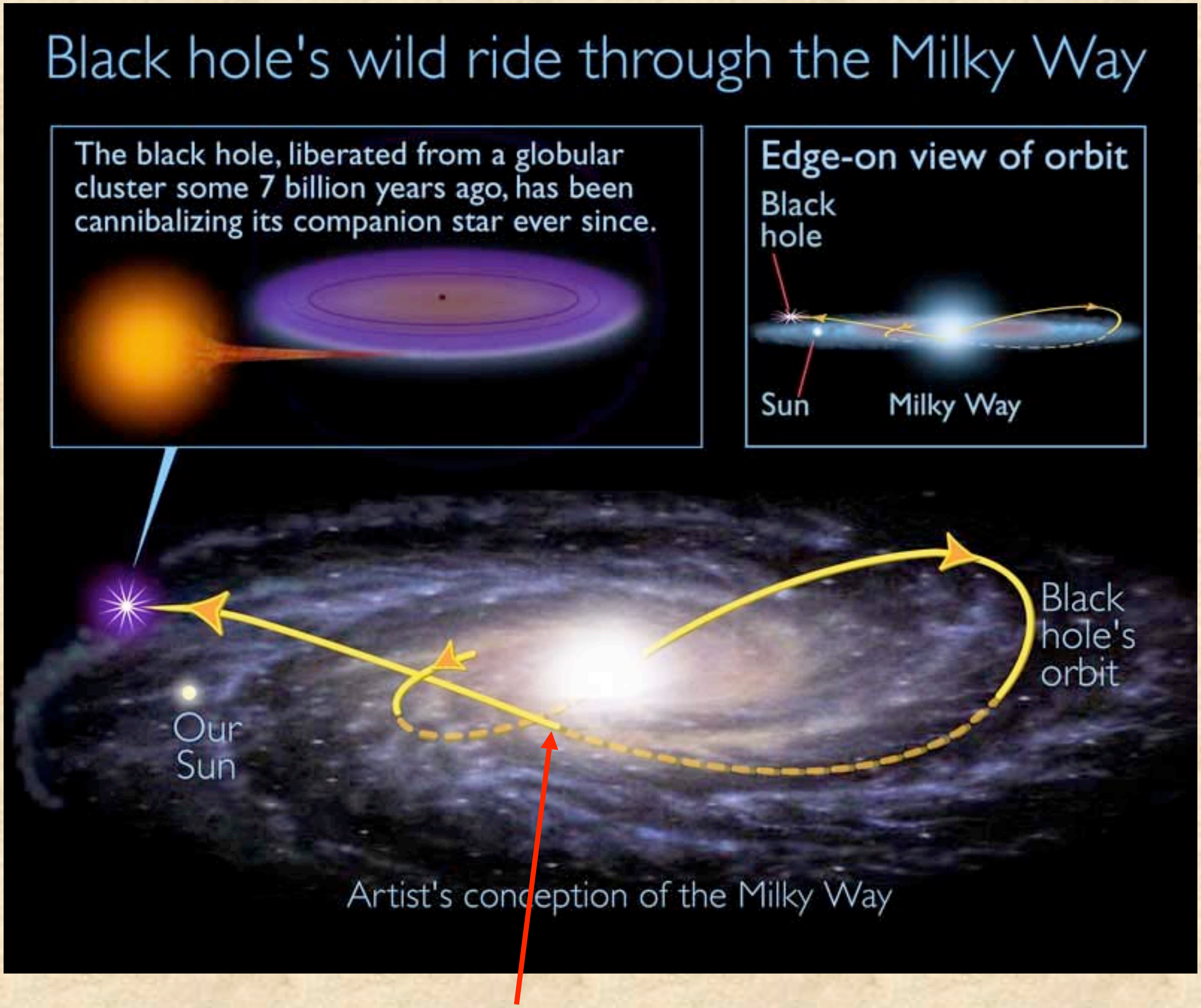
EMPARAN et al. 2002



Tabletop experiments:

$$L < 0.05mm$$

The wild ride of XTE J1118+480 through the galaxy



Black hole's wild ride through the Milky Way

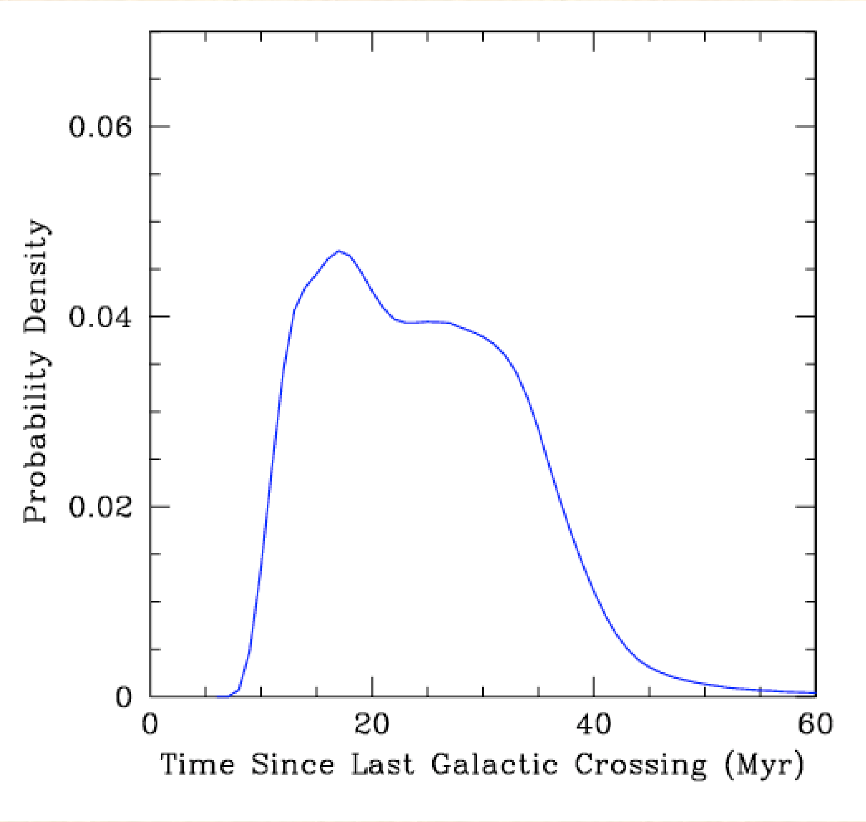
The black hole, liberated from a globular cluster some 7 billion years ago, has been cannibalizing its companion star ever since.

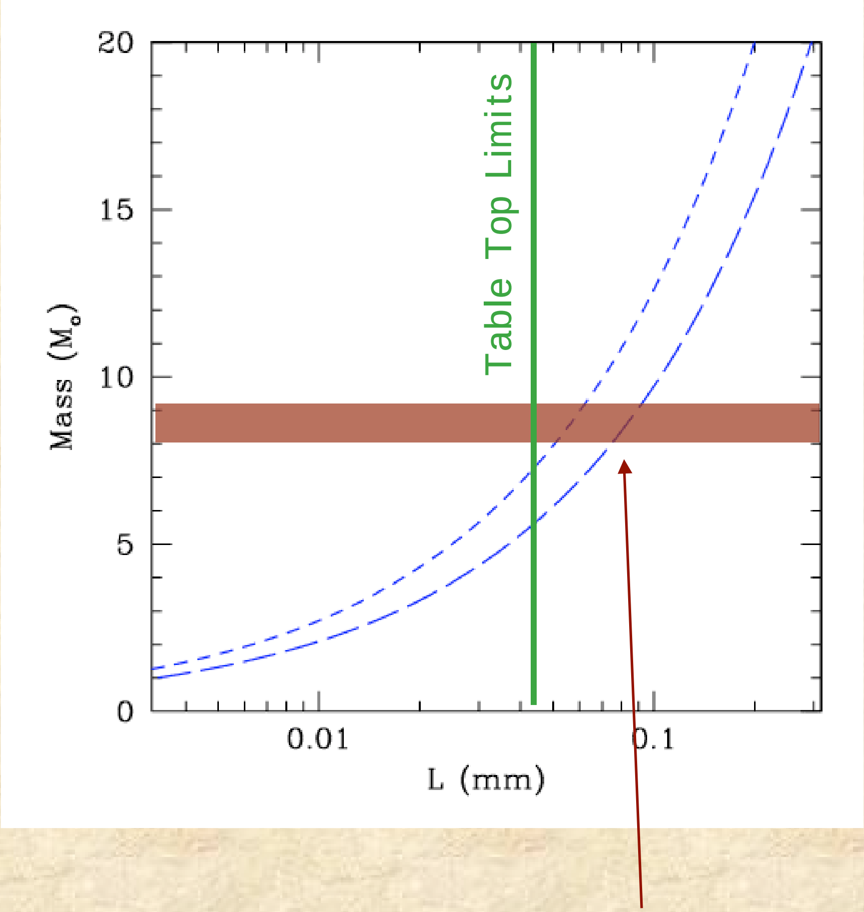
Mirabel et al. 2001

When did this happen?

Constraining the AdS Curvature of Extra Dimensions I

Psaltis 2007, PRL, 98, 1101





Astrophysical Limit: L<0.08mm

Orbital Evolution of Black-Hole Binaries

Johannsen, Psaltis, McClintock 2008

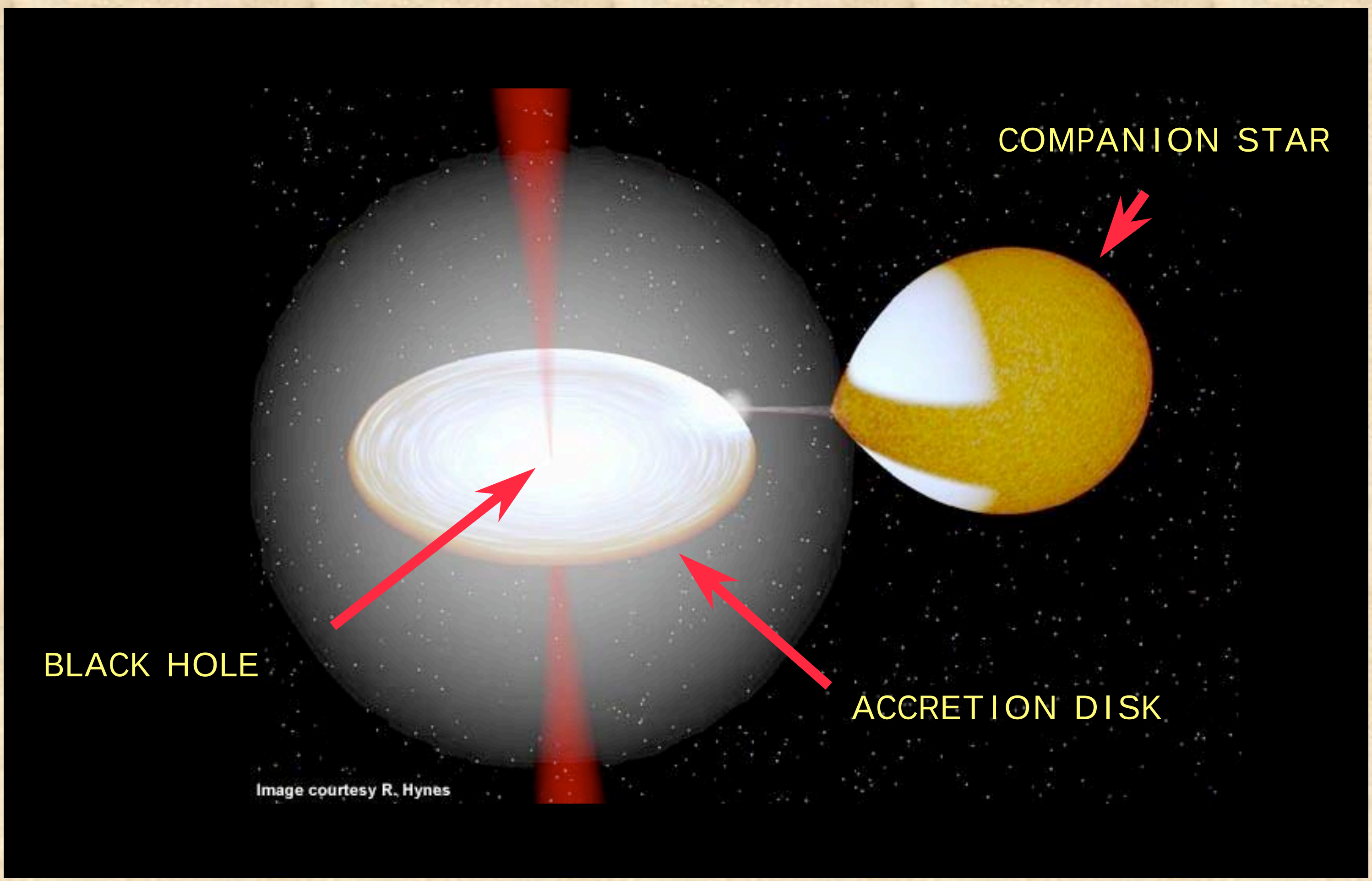
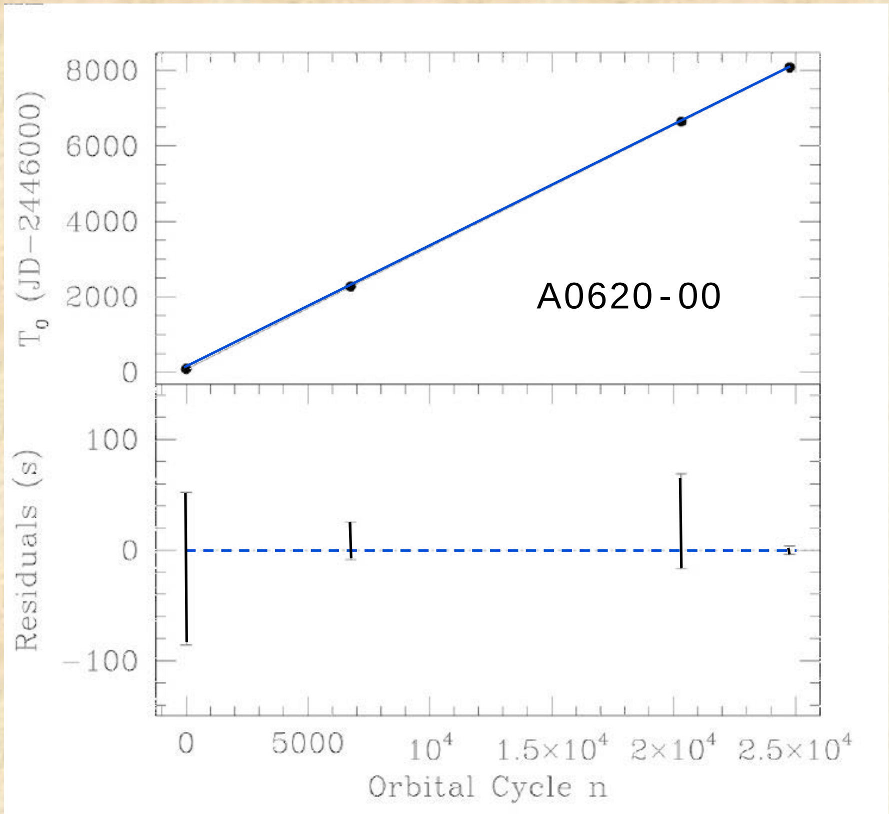
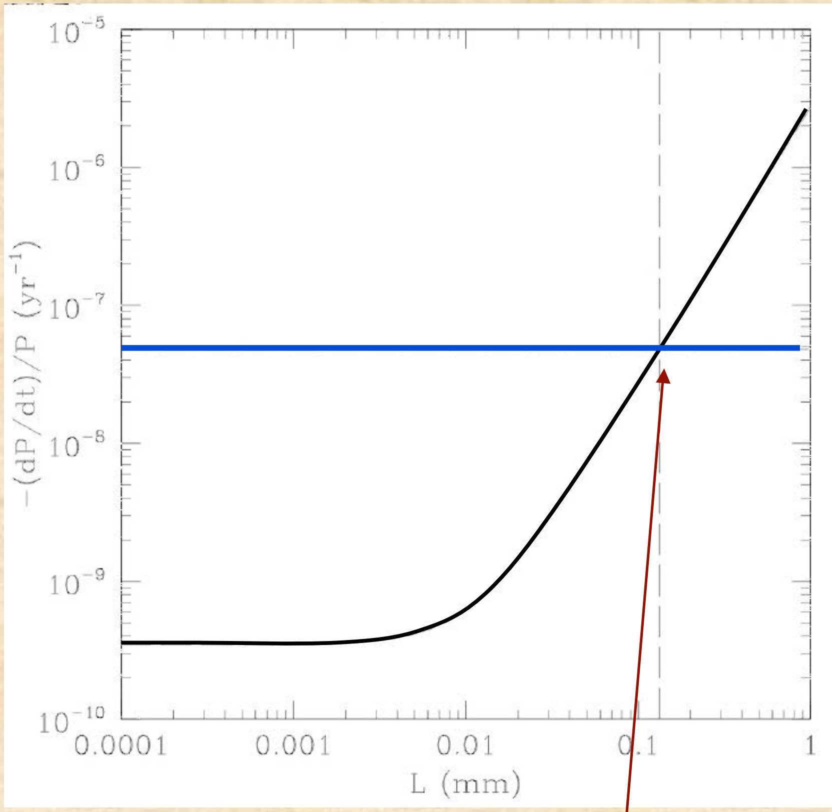


Image courtesy R. Hynes

Constraining the AdS Curvature of Extra Dimensions II

Johannsen, Psaltis, McClintock 2008





Astrophysical Limit: L<0.15mm

CONCLUSIONS

(I) Gravity in the Strong-Field Regime has not been tested

(II) Different characteristics of Neutron Stars and Black Holes are significantly affected by gravity

⇒ a great laboratory to perform gravitational tests

(III) We are in need of a framework for gravity tests beyond the post-Newtonian limit!

(IV) Current observations provide stringent constraints on

⇒ scalar-tensor gravities

⇒ braneworld gravity theories