Open questions in gravitational physics

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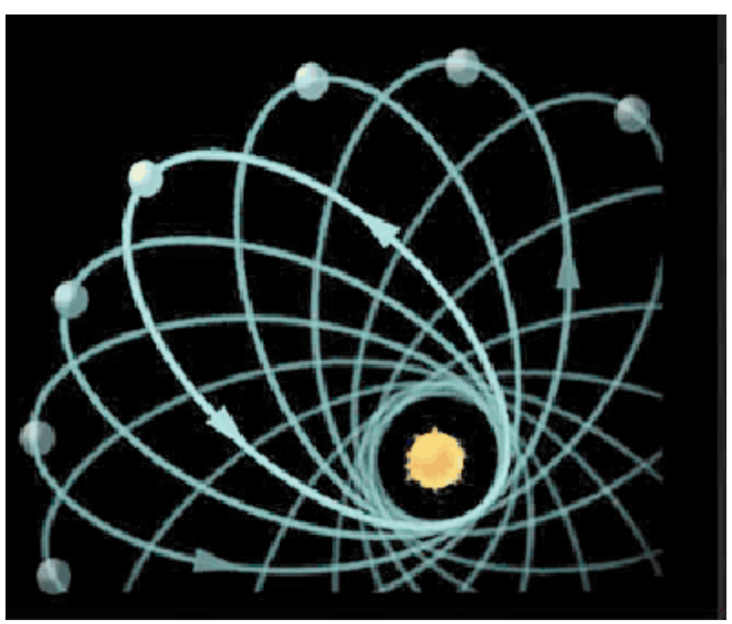
What do we know of gravitational physics?

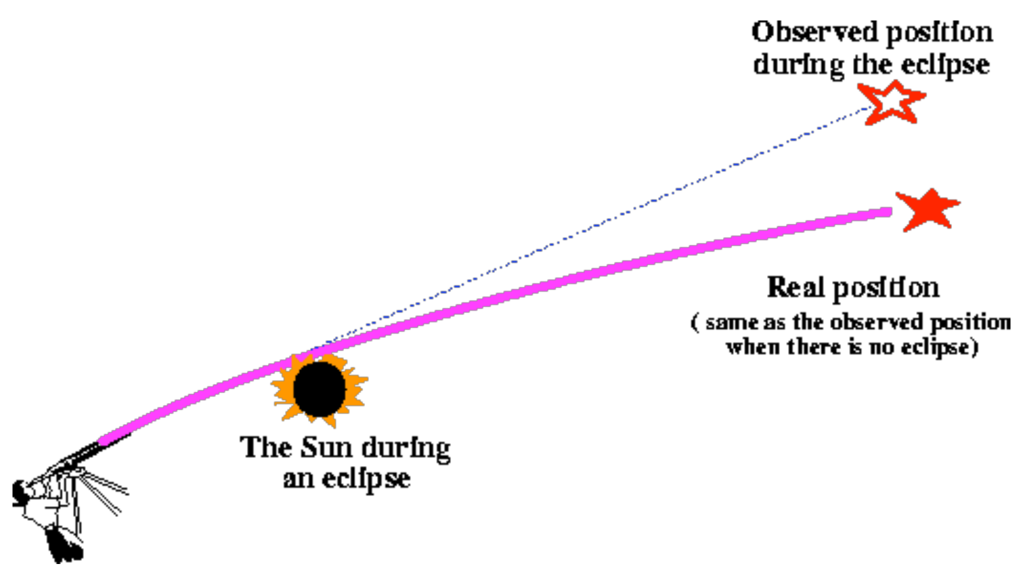
As far as we know, gravity - the weakest among fundamental interactions - is described by one of the most beautiful and elegant theories ever conceived: General Relativity

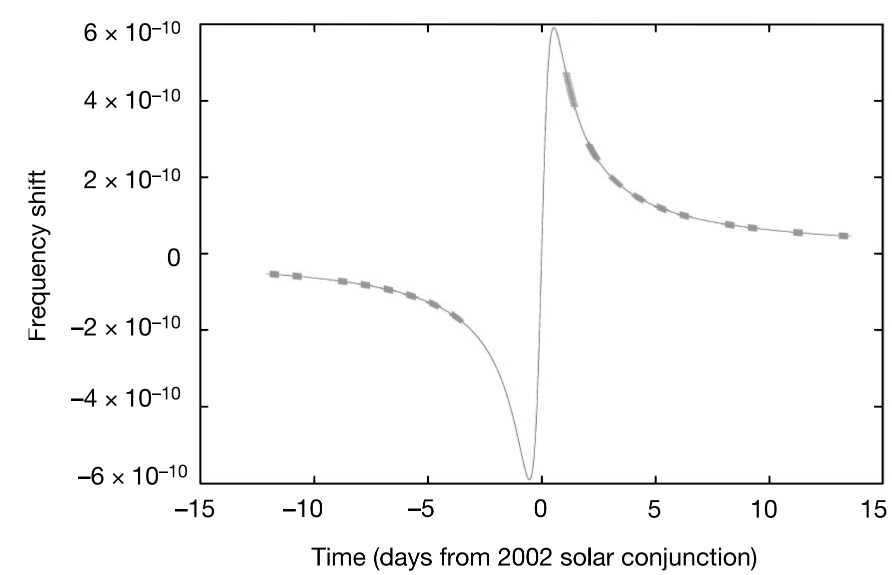
GR passed several observational tests with flying colours:

- **Solar system tests**

Started when GR was first formulated, one century ago (perihelion precession, light deflection, gravitational redshift), solar system tests became more and more accurate, up to the measurent of Shapiro delay from Cassini spacecraft in 2002



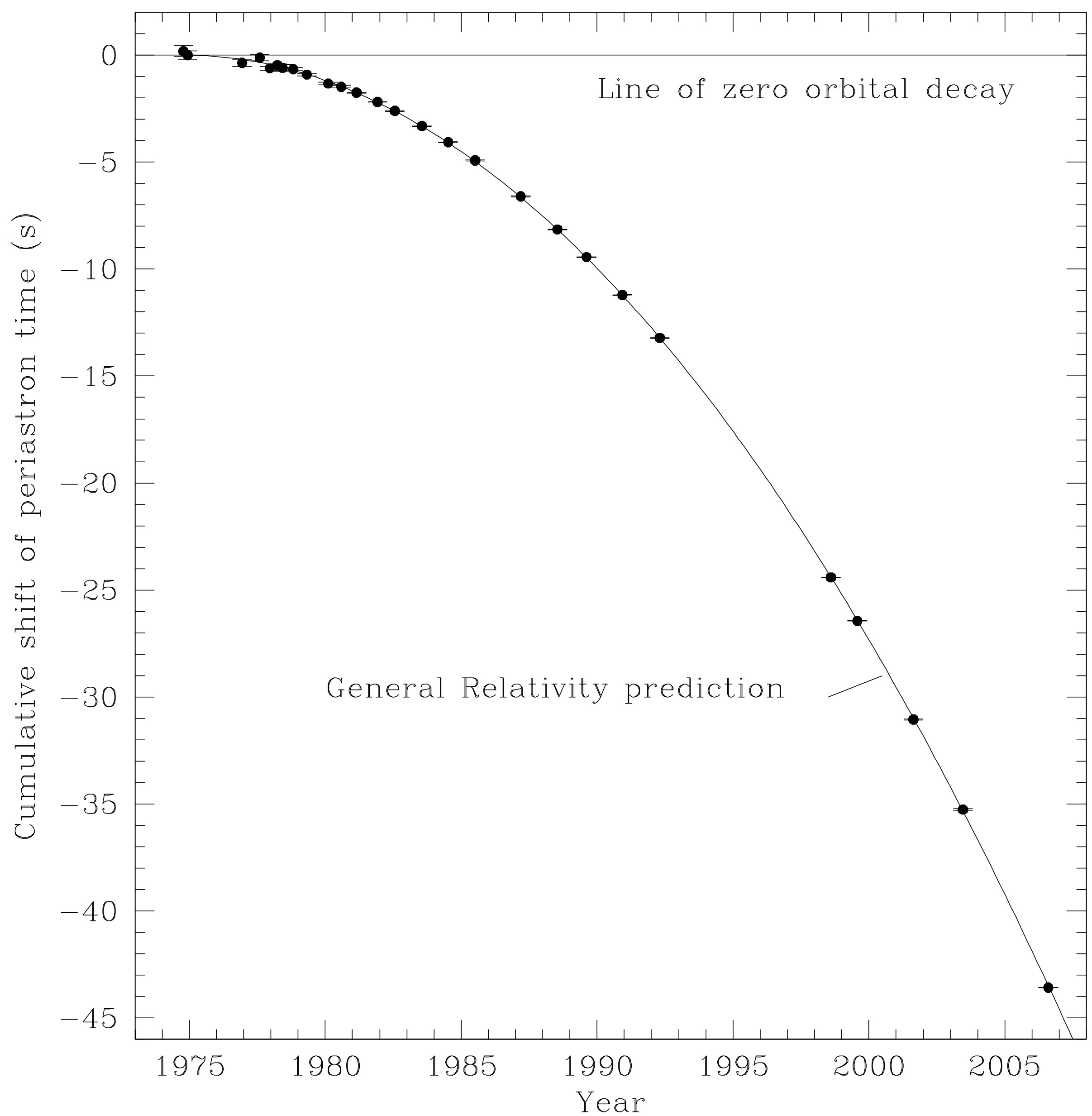




Bertotti et al., Nature ’03

Binary pulsar tests

Binary pulsar PSR 1913+16: inspiral, and increase of orbital period, due to energy loss through gravitational wave emission



Weisberg *et al.*, 2010

Indirect proof of the existence of GWs!

Binary pulsar tests

Double binary pulsar J0737-3039: the most relativistic binary system we know

Post-Keplerian parameters

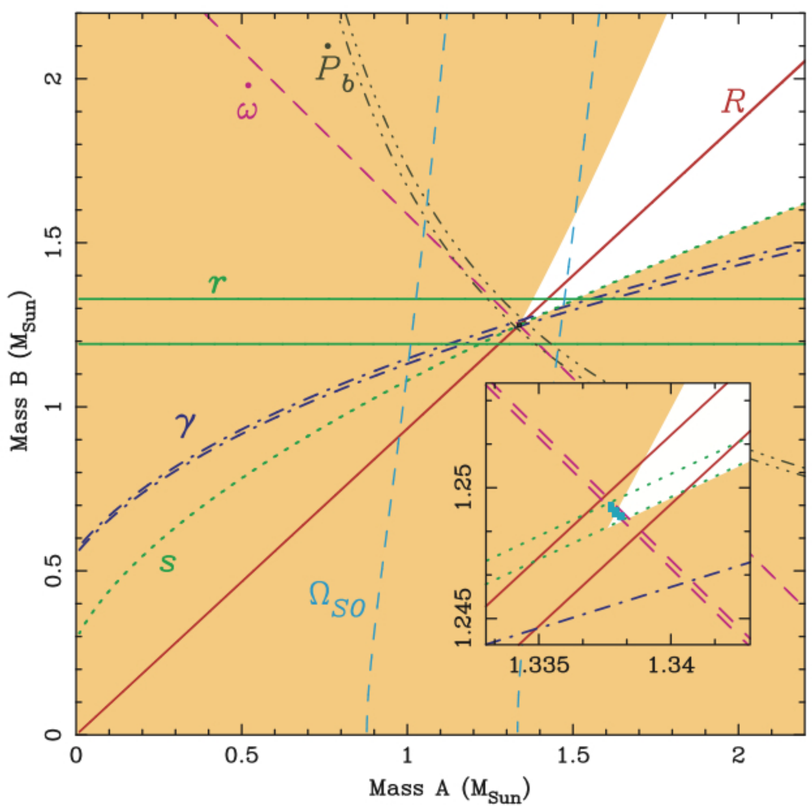
$$\dot\omega = 3T_\odot^{2/3}\left(\frac{T}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}(m_p+m_c)^{2/3}$$

$$\gamma = T_\odot^{2/3}\left(\frac{T}{2\pi}\right)^{1/3} e\frac{m_c(m_p+2m_c)}{(m_p+m_c)^{4/3}}$$

$$r = T_\odot m_c$$

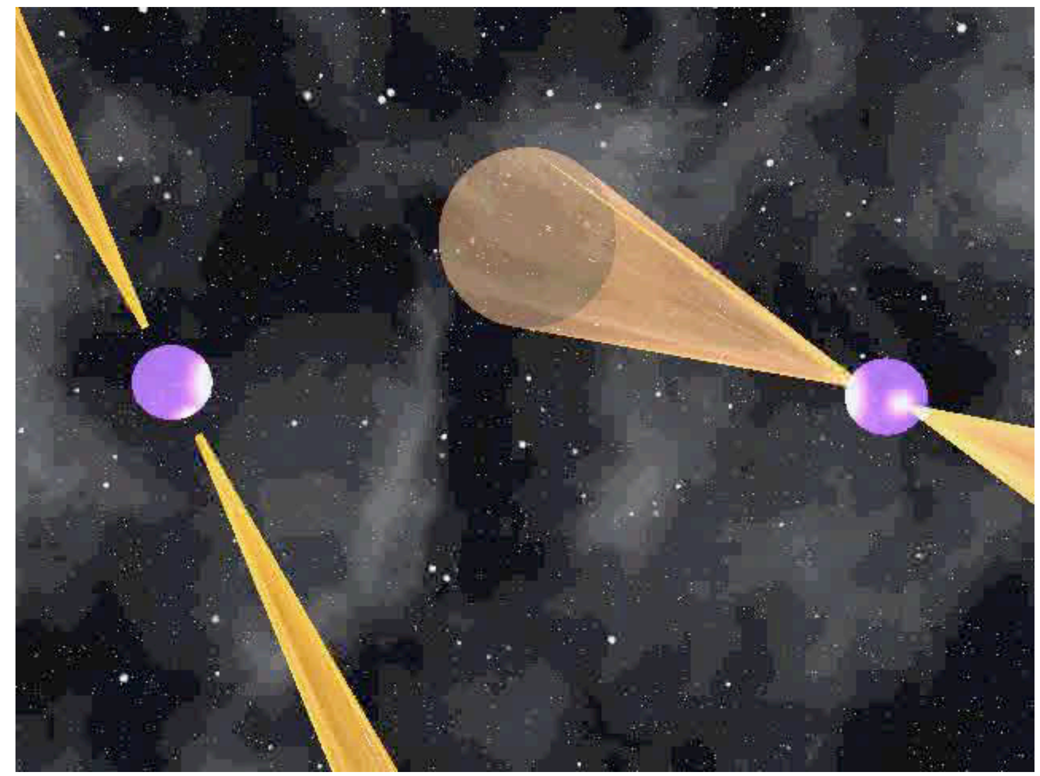
$$s = \sin i = T_\odot^{-1/3}\left(\frac{T}{2\pi}\right)^{-2/3} x_p\frac{(m_p+m_c)^{2/3}}{m_c}$$

$$\dot T = -\frac{192\pi}{5}T_\odot^{5/3}\left(\frac{T}{2\pi}\right)^{-5/3}\cdot\frac{m_p m_c}{(m_p+m_c)^{1/3}}f(e)$$



Kramer & Wex, '09

(Periastron precession of 17°/year!)



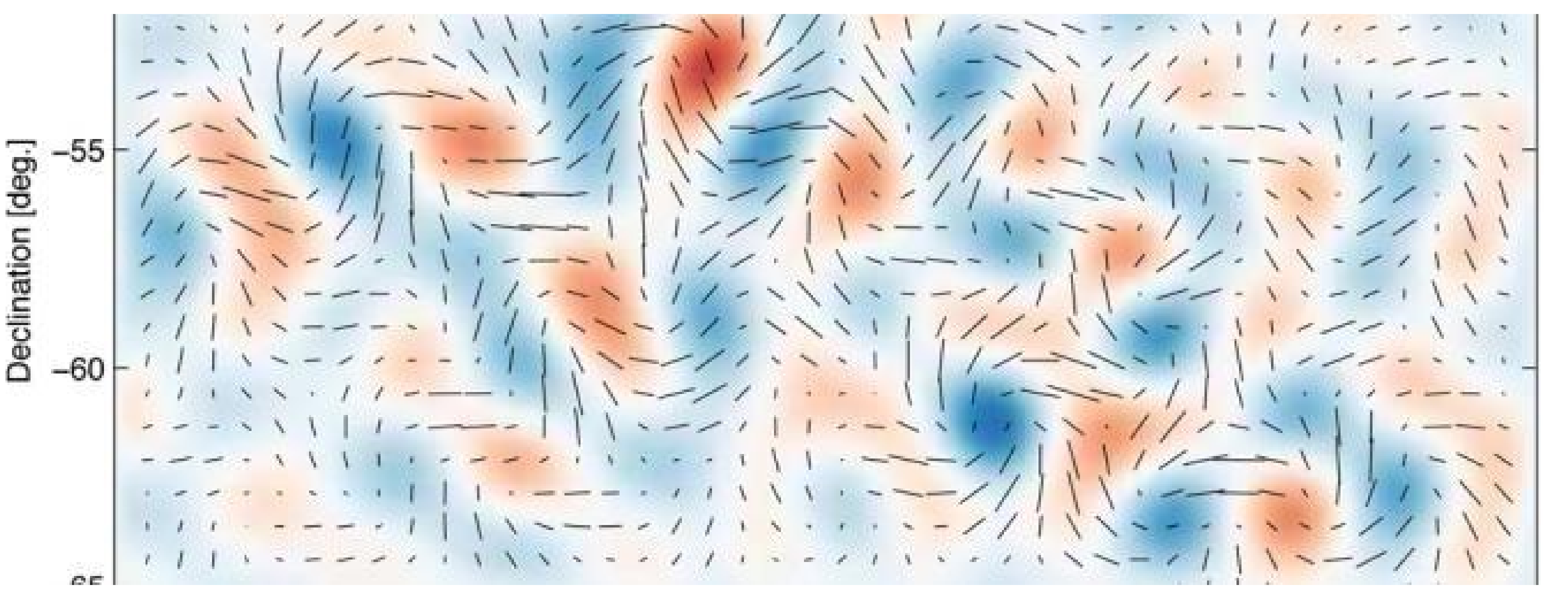
Animation: John Rowe

GR prediction of orbital period derivative satisfied within few parts in a thousand

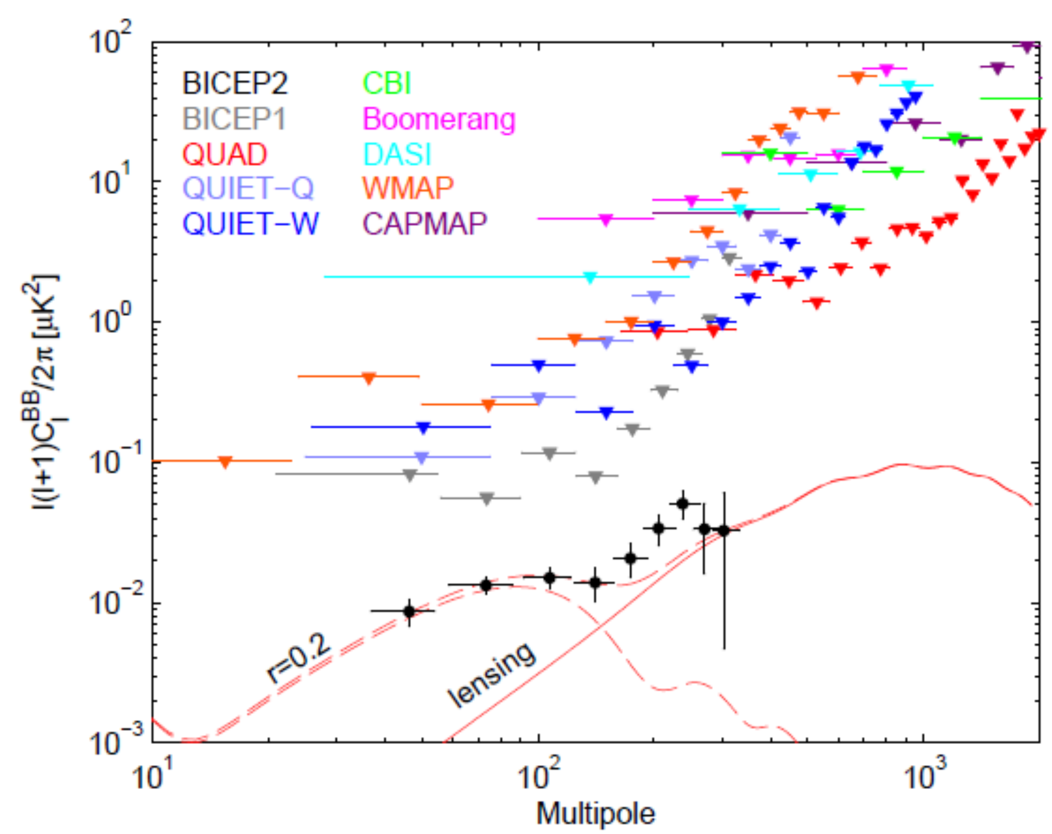
Observational data from the early universe

In recent years, several breakthroughs in cosmology!
Different kinds of observations (supernovae, cosmic microwave background)
allowed us to better understand the early stages of our Universe...
... and to understand the behaviour of gravity at those times and conditions!

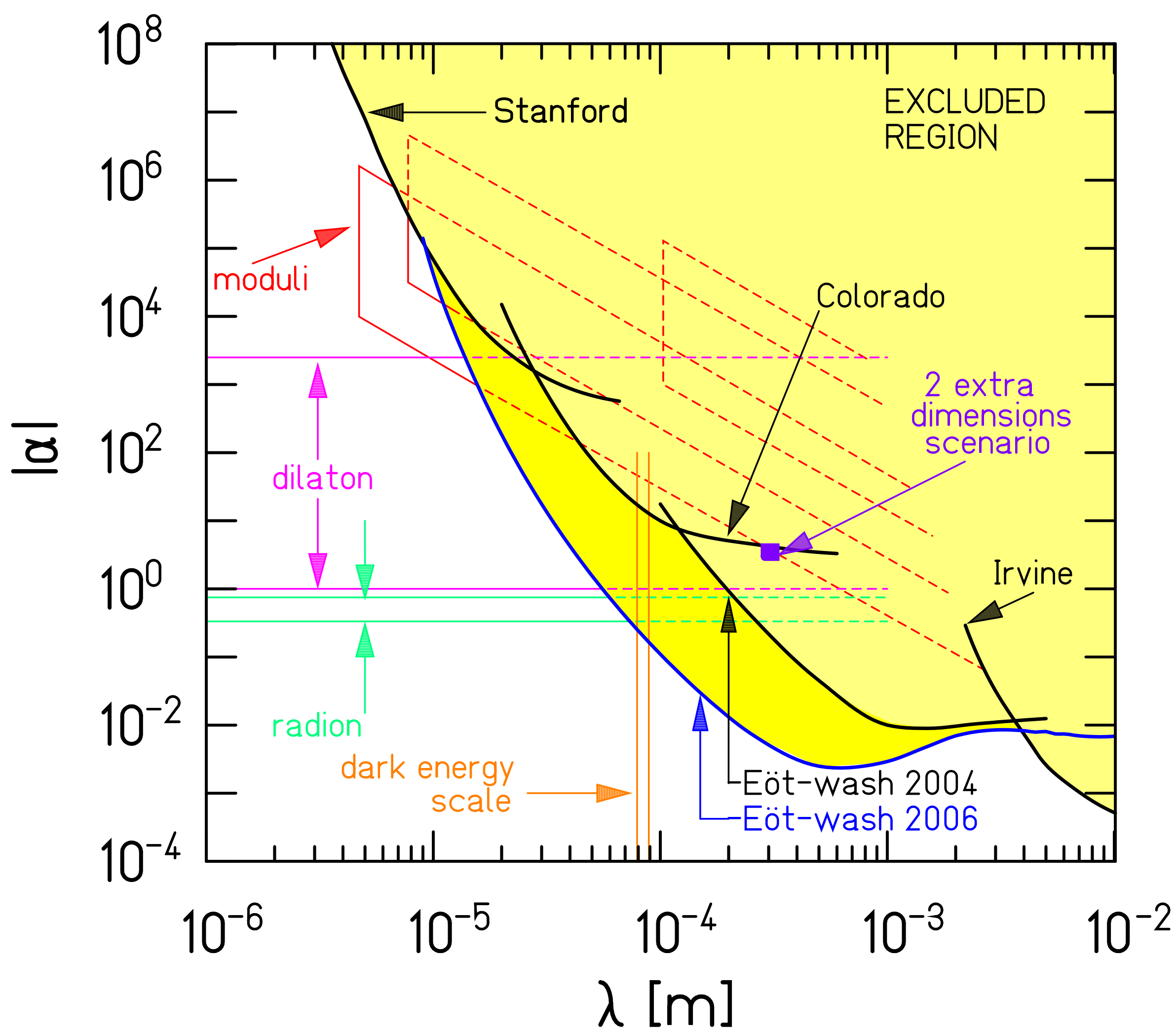
Few weeks ago, a study of the polarization in the CMB confirmed
one of the predictions of the inflationary model of the early universe.
In addition, this result has shown the primordial GW background:
another indirect proof of the existence of GWs,
in a regime completely different from that of compact binaries!



The BICEP2 Collaboration, 2014

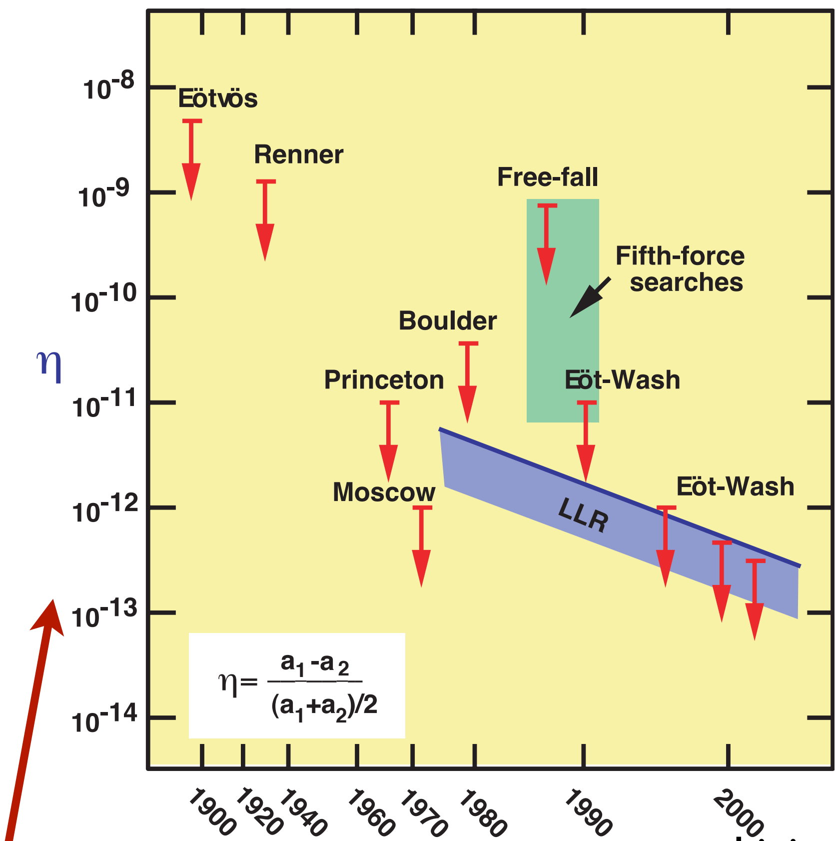


Test of the inverse-square law at short range



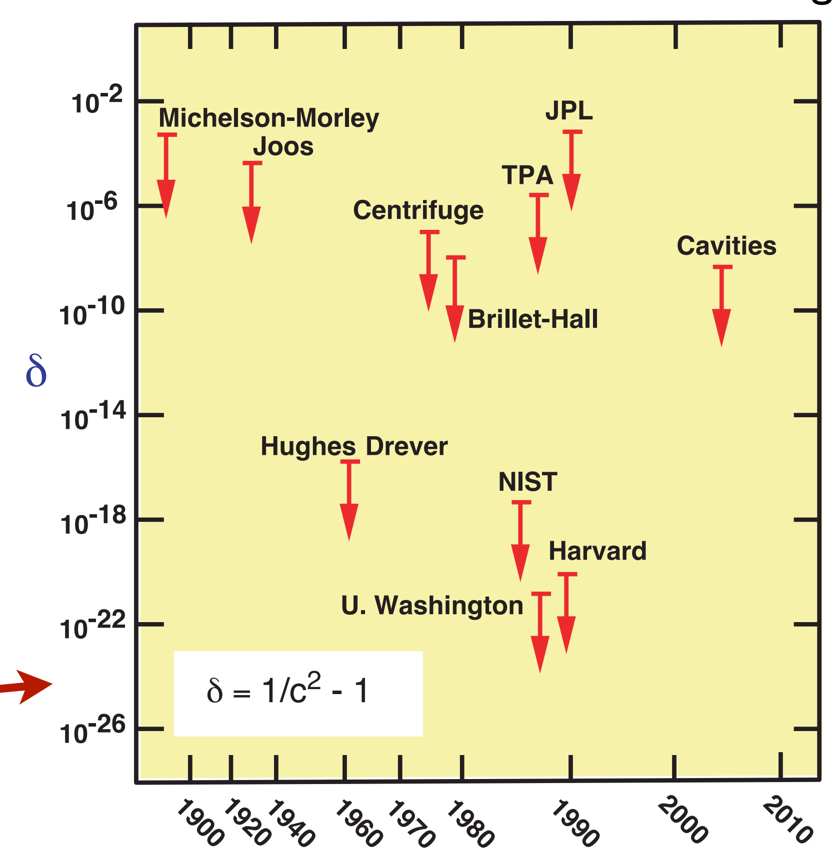
E. Adelberger, Univ. Washington

$$F(r) = \frac{G m_1 m_2}{r^2}\left[1 + \alpha\left(1 + \frac{r}{\lambda}\right)e^{-r/\lambda}\right]$$



C. Will,
Living Review of Relativity

Test of the weak equivalence principle



Test of Lorentz's invariance

... etc. etc. etc. ...

However, we need to probe the strong-field regime of gravity

Why?

1) There is no *fundamental* reason to believe in GR

Weak Equivalence Principle (WEP) has been tested up to $\sim 10^{-12}$, let's assume it.

WEP does not require that gravity dynamics is given by Einstein-Hilbert's action

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

- If we require (together with WEP) that the gravitational theory reproduces Newtonian gravity in an appropriate limit, and that the action only depends on the metric and on the curvature scalar, many other actions are possible, such as those of the so-called f(R) theories

$$S = \frac{c^4}{16\pi G}\int d^4x\sqrt{-g}f(R)$$

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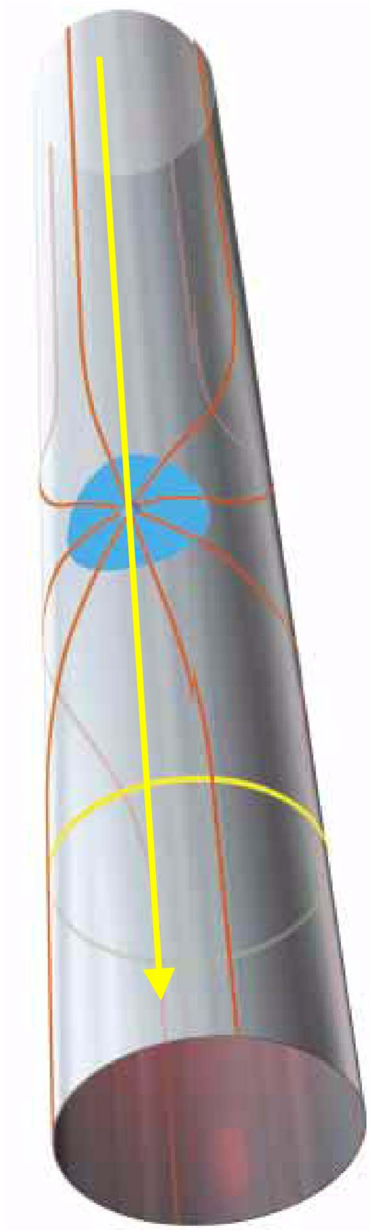


- Other fields may be included in the gravitational action (as suggested by String/M theory).

This is the case, for instance, of scalar-tensor theories:

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left[F(\phi)R - 8\pi G Z(\phi)g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - U(\phi)\right]$$

- We could live in more than four spacetime dimensions (again, as predicted by SMT), some of which could be much larger than the Planck length (*large extra dimensions*)

$$\mathcal{S} \propto \frac{1}{G_D}\int d^Dx\sqrt{{}^Dg}\;{}^DR = \frac{V_{D-4}}{G_D}\int d^4x\sqrt{{}^4g}\;{}^4R$$

2) GR can not be the ultimate theory of gravitational interaction

- All attempts to unify GR with the quantum world have failed.
  At the Planck scale ($E \sim 10^{19}$ GeV, or $l \sim 10^{-35}$ m) neither GR nor Quantum Field Theory can tell us what's going on!

- General Relativity contains its own pathologies:
  it necessarily predicts the presence of singularities, as the outcome of gravitational collapse, which can be reached by an observer in a *finite* amount of proper time.

It has been conjectured that singularities have to be hidden behind horizons (*cosmic censorship*) but it is only a conjecture and would not really solve the problem

Near singularities, weird phenomena can occur (causality violations, etc.).

Note that all of these problems occur in the (very) strong field regime!

3) Last but not least: even if GR is the correct theory of gravity, the phenomenology of its strong field regime is far from being understood

GR is a strongly non-linear theory

$$\left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R - \lambda g_{\mu\nu}\right) = \frac{8\pi G}{c^4}T_{\mu\nu}. \qquad R_{\mu\nu} = g^{\kappa\alpha}R_{\kappa\mu\alpha\nu}$$

$$R^{\lambda}{}_{\mu\nu\kappa} = -\left[\frac{\partial}{\partial x^{\kappa}}\Gamma^{\lambda}{}_{\mu\nu} - \frac{\partial}{\partial x^{\nu}}\Gamma^{\lambda}{}_{\mu\kappa} + \Gamma^{\lambda}{}_{\kappa\eta}\Gamma^{\eta}{}_{\mu\nu} - \Gamma^{\lambda}{}_{\nu\eta}\Gamma^{\eta}{}_{\mu\kappa}\right] \qquad \Gamma^{\gamma}_{\beta\mu} = \frac{1}{2}g^{\alpha\gamma}(g_{\alpha\beta,\mu} + g_{\alpha\mu,\beta} - g_{\beta\mu,\alpha})$$

but we only have tested its linear regime, where gravity is weak

$$\left\{\Box_F h_{\mu\nu} - \left[\frac{\partial^2}{\partial x^{\lambda}\partial x^{\mu}}h^{\lambda}_{\nu} + \frac{\partial^2}{\partial x^{\lambda}\partial x^{\nu}}h^{\lambda}_{\mu} - \frac{\partial^2}{\partial x^{\mu}\partial x^{\nu}}h^{\lambda}_{\lambda}\right]\right\} = -\frac{16\pi G}{c^4}\left(T^{pert}_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}T^{pert\ \lambda}_{\lambda}\right).$$

Quoting S. Chandrasekhar, fundamental science does not only *"seek to analyze the ultimate constitution of matter and the basic concepts of space and time"*, it is also *"concerned with the rational ordering of the multifarious aspects of natural phenomena in terms of the basic concepts"*.

How do behave strongly gravitating objects such as black holes and neutron stars? How do supernovae explode? Which is the power of gamma-ray bursts? What happens when the nonlinearities of gravity set in?

Up to now, we have tested only the weak regime of gravity

The strongest gravitational field probed in the solar system is that at the surface of sun (light deflection), for which gravitational redshift and spacetime curvature are

$$\frac{GM_\odot}{R_\odot c^2} \sim 10^{-6} \qquad \frac{GM_\odot}{R_\odot^3 c^2} \sim 10^{-28}\, cm^{-2}$$

The most accurate test in solar system is probably that of the post-Newtonian parameter γ from Cassini spacecraft, with an accuracy of $\sim 10^{-5}$.

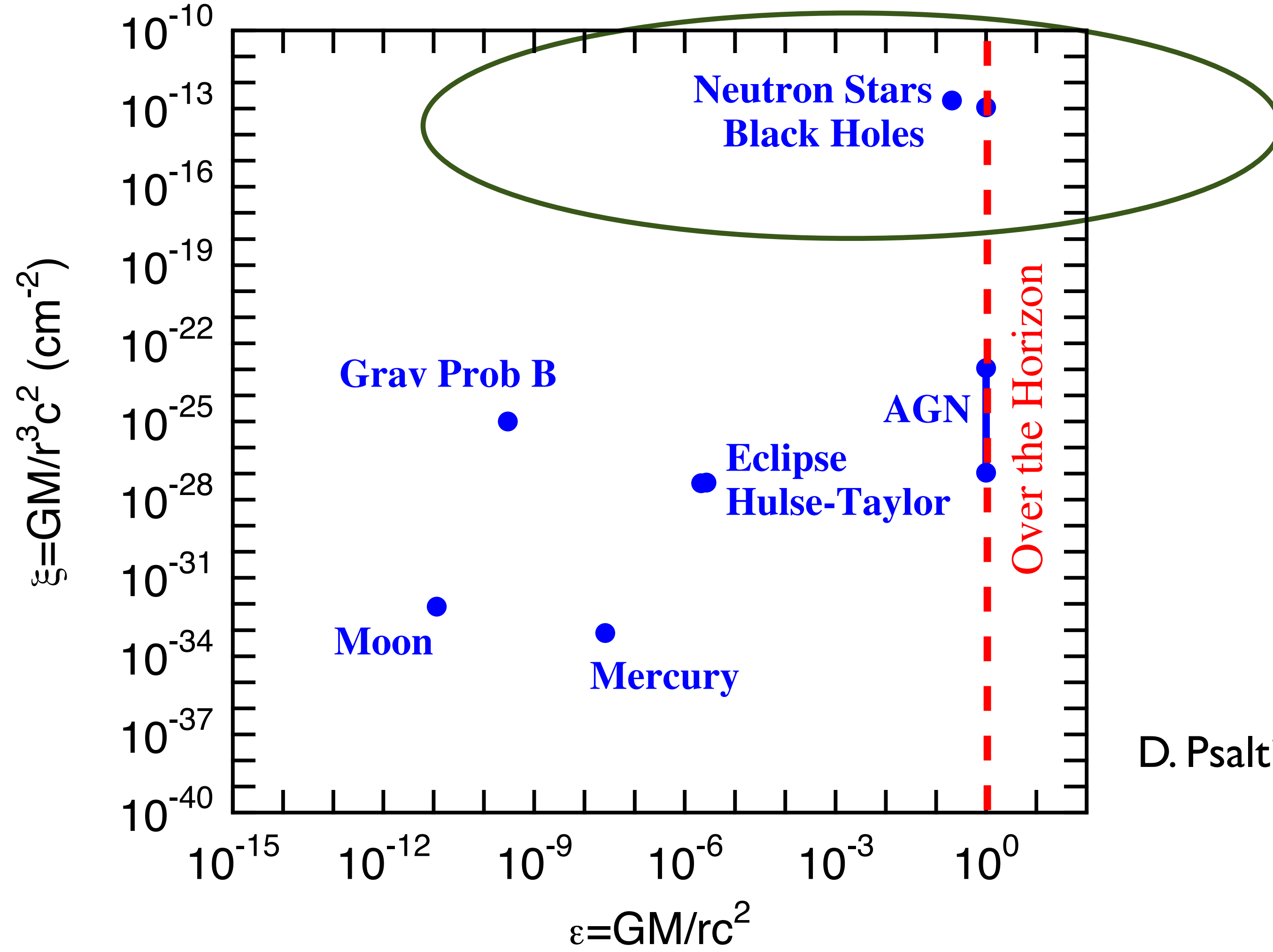
Binary pulsar tests involve masses $M_{NS} \sim M_\odot$ and distances similar to $R_\odot$ therefore they generally test the same regime as solar system test (with the exception of some particular strong field phenomena predicted by specific theories, which can show up in the motion of binary pulsars)

- How do gravity behave when the gravitational redshift and the curvature are much larger, such as near the surface of neutron stars, near the horizon of black holes?
- Do completely unexpected phenomena occur in this still untested regime?
- Is General Relativity the correct theory of gravity?

These are - in my opinion - the main open questions in gravitational theory

Up to now, we have tested only the weak regime of gravity

Parameter space for GR deviations



GW detectors!

D. Psaltis, Living Review of Relativity

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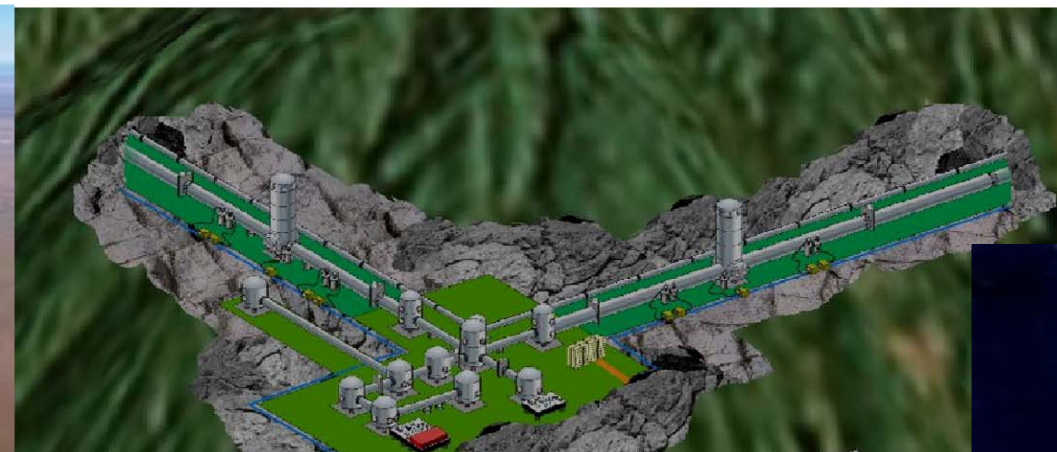
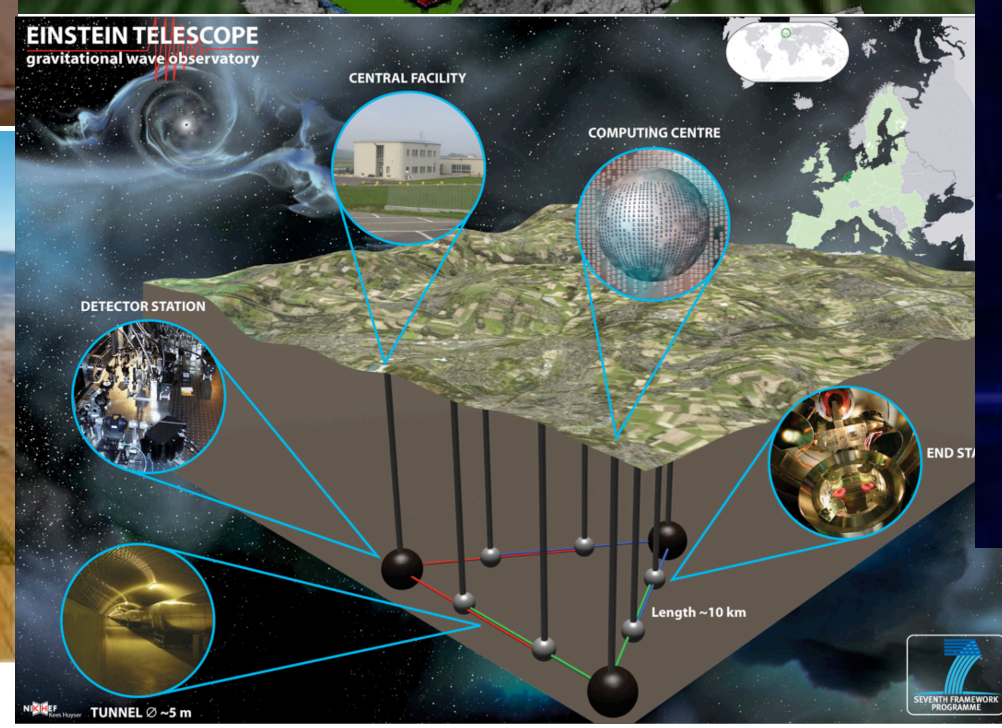
Luckily, after many decades of weak field gravity observations, we are finally close to start looking at the strong field regime of the gravitational interaction!

It is impossible to overestimate the importance of the upcoming gravitational wave detectors! (See previous talks...)





We are going to open a new window on one of the fundamental interactions!

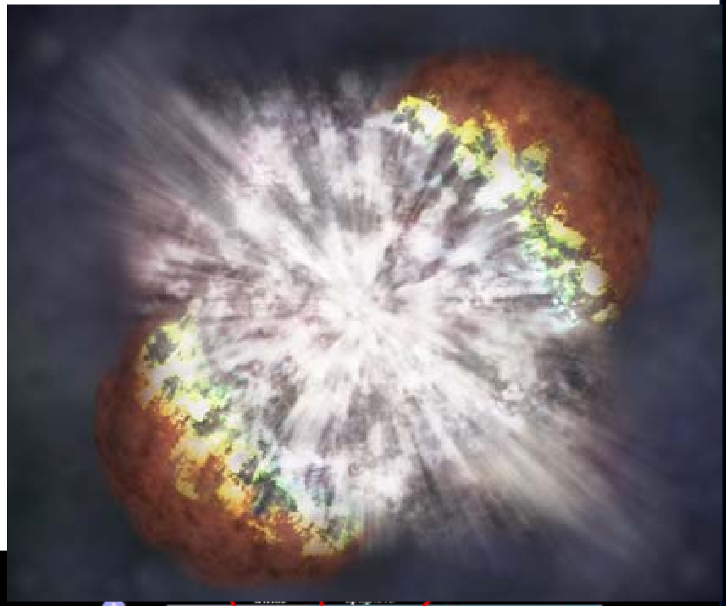
Understanding the *phenomenology* of the gravitational interaction in the strong field regime

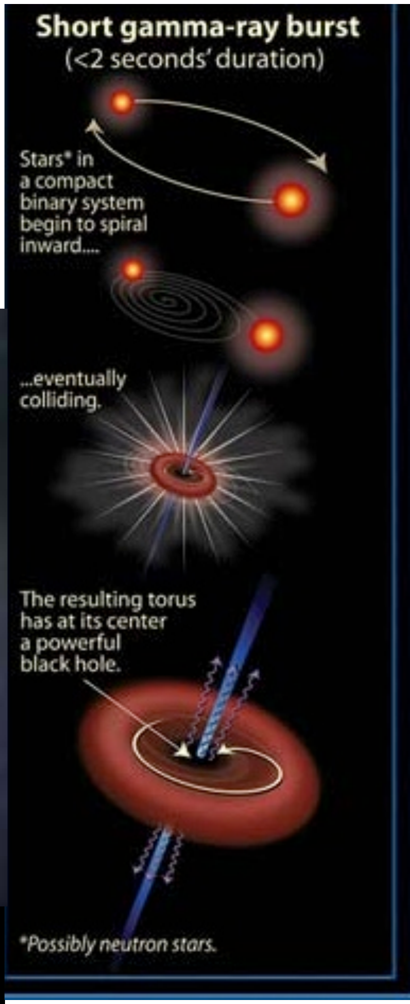
would shed light into other branches of physics as well:

Astrophysics

- Which is the engine of gamma-ray bursts?
- Why do supernovae explode?
- etc. etc...

Nasa

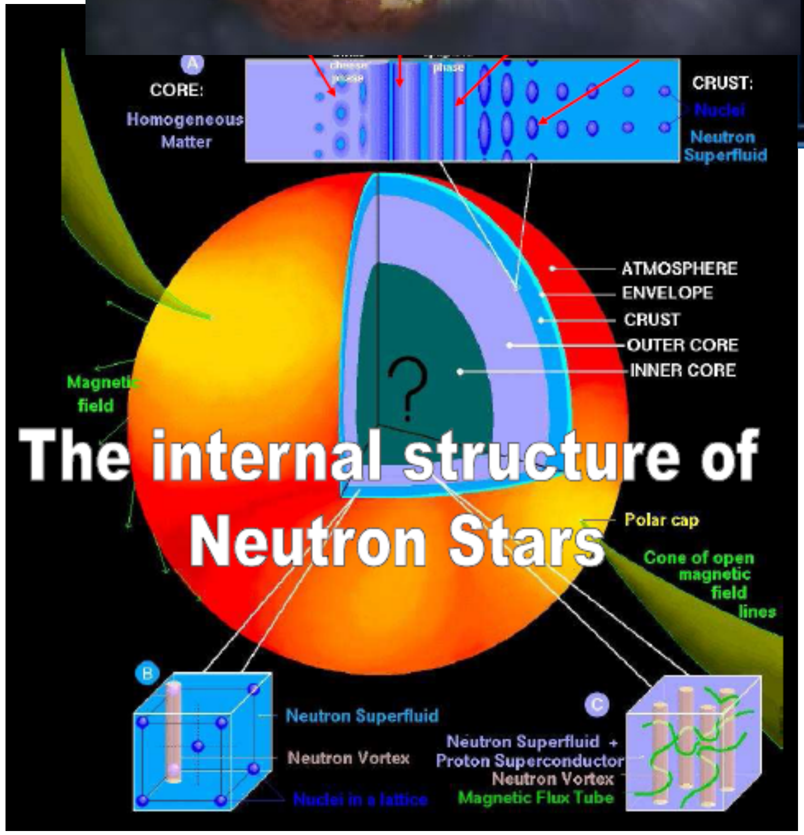




Nuclear physics

Which is the behaviour of matter at supranuclear densities, typical of the inner core of neutron stars? Are there hyperons? Deconfined quarks?

Our poor understanding of the neutron star equation of state reflects our ignorance of non-perturbative QCD



D. Page

Understanding the *nature* of the gravitational interaction

Deviations of GR can be studied either top-down or bottom-up:

- In a top-down approach, one starts from a particular theory, possibly with some motivation/inspiration from some more fundamental theories of framework (such as String/M theory), and looks for phenomenological consequencies of these theories to be compared with present and future observations/experiments.

Some of the theories currently studied:

- Scalar-tensor theories

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{-g} \left[F(\phi) R - 8\pi G Z(\phi) g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - U(\phi) \right]$$

- Modified quadratic gravity (Dynamical Chern-Simons, Einstein-Dilaton-Gauss-Bonnet)

$$S \equiv \int d^4x \sqrt{-g} \Big\{ \kappa R + \alpha_1 f_1(\vartheta) R^2 + \alpha_2 f_2(\vartheta) R_{\mu\nu} R^{\mu\nu} + \alpha_3 f_3(\vartheta) R_{\mu\nu\delta\sigma} R^{\mu\nu\delta\sigma} + \alpha_4 f_4(\vartheta) R_{\mu\nu\delta\sigma}{}^{*} R^{\mu\nu\delta\sigma} - \frac{\beta}{2} \left[\nabla_\mu \vartheta \nabla^\mu \vartheta + 2V(\vartheta) \right] + \mathcal{L}_{\rm mat} \Big\}$$

- Massive graviton theories (Galileons, bigravity) $\lambda_g \equiv h/(m_g c) < \infty$

  What if the graviton has a mass? Huge work to face theoretical issues (ghosts, GR as a limit)

- Theories with large extra dimensions

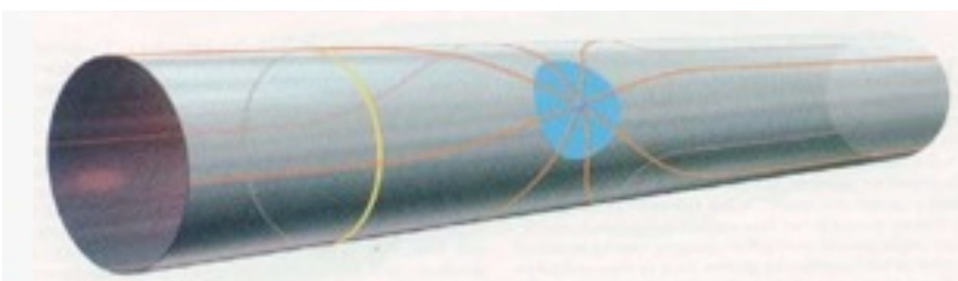
  Inspired by SMT.

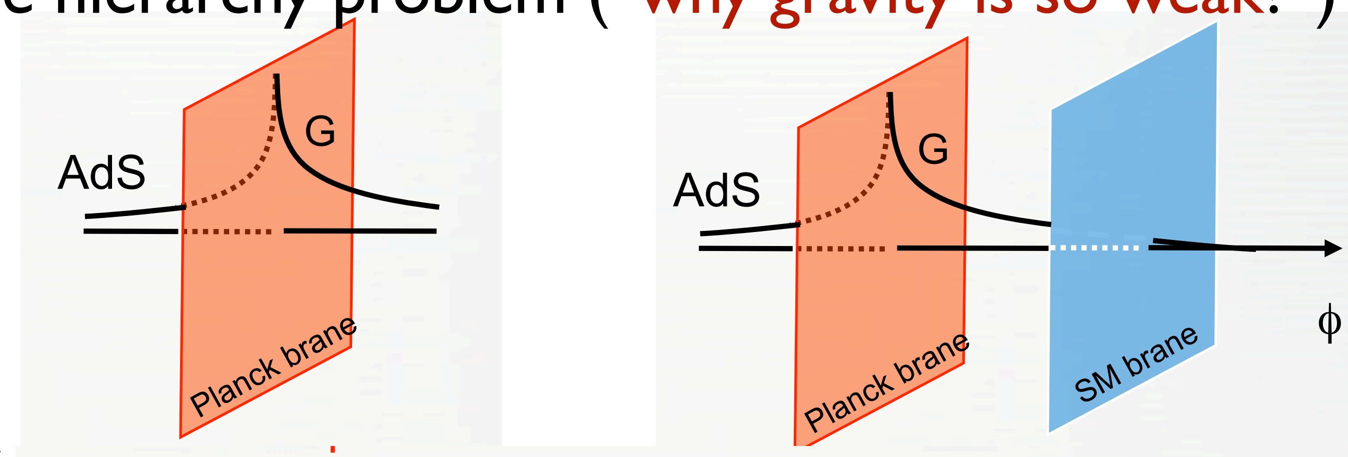
  We live in a four-dimensional subspace (*brane*) of a higher-dimensional space (*bulk*).

  Standard model fields live on the brane, but gravity propagates in the bulk.

  Since gravity tested up to fractions of millimiter, extra dimensions can be "large".

  Some of these models help in explaining the hierarchy problem ("why gravity is so weak?")





Predictions on LHC, but no hint up to now...

$$ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2$$

- Lorentz violating gravity (Einstein-Aether theory, bigravity, Horava gravity, MOND)
- Non-commutative geometry
- f(R) theories
- time dependent G
- etc. etc....

Understanding the *nature* of the gravitational interaction

In a bottom-up approach, one starts from some observables, looking to violations of fundamental symmetries of properties of GR. Once a deviation is detected, one tries to understand its origin.

For instance, violations of:

- the “*no-hair theorem*” of black holes, stating that stationary BHs only depend on mass, angular momentum (and possibly electric charge)
- inverse-square law at short distances
- inverse-square law at large distances
- parity symmetry in the gravitational field
- polarization of the gravitational waves (transverse traceless)
- weak equivalence principle
- Lorentz symmetry

<= speed of GWs, dispersion relation

- masslessness of the graviton

Understanding the *nature* of the gravitational interaction

GR deviations in a bottom-up approach can also be studied introducing appropriate parametrizations, depending on the phenomenology under consideration

- Parametrized post-Newtonian (PPN) approach:
  deviations of post-Newtonian (e.g., expanded in v/c around Newtonian gravity) spacetime metric of n-bodies are expressed in terms of a set of parameters.
  Suitable to describe and perform solar-systems tests of GR.
- Parametrized post-Einsteinian (PPE) approach:
  deviation of the gravitational waveform emitted by the coalescence of a compact binary system is expressed in terms of a set of parameters.
  Suitable for GR tests with ground-based gravitational wave detectors.
- Quadrupole expansion of black hole metric:
  deviation from the Kerr solution describing rotating black holes, and affecting the gravitational waveform from extreme mass-ratio inspirals, is expressed through a multipolar expansion.
  Suitable for GR tests with space-based gravitational wave detectors.

Conclusions

- All experiments and observations of gravity confirm that this interaction is well described by General Relativity, maybe the most beautiful and elegant theory ever conceived - which will celebrate its centenaty in 2015

- However, gravity has only been probed in the weak field regime, in which GR behaves as a linear theory.

- Most of the main open questions in gravitational physics, in my opinon, involve the strong field regime of gravity:
  - Which is the phenomenology of gravity in this regime?
  - Do completely unexpected phenomena occur?
  - Which is the nature of gravity in this regime? Is it well described by GR?

- Gravitational wave detectors will soon allow us to probe - for the first time - the strong field regime of gravity, opening a new window on the Universe and on the gravitational interaction.

The Gravitational Wave Spectrum