Title: Local gravity and the cosmos: using local tests of modified gravity to probe cosmological physics

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Abstract: We have two strong reasons to argue that Einstein\'s theory of general relativity may be incomplete. First, given that it cannot be expressed within a consistent quantum field theory there is reason to expect higher energy corrections. Second, the observation that we are undergoing a current epoch of accelerated expansion might indicate that our understanding of gravity breaks down at the largest scales.

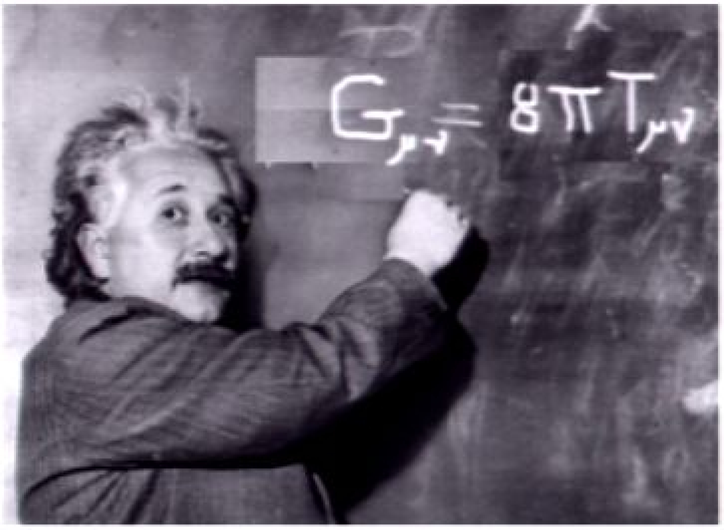
A generic result of modified gravity is the creation of a new degree of freedom within the gravitational sector. This new degree of freedom then generically connects local physics to cosmological dynamics.

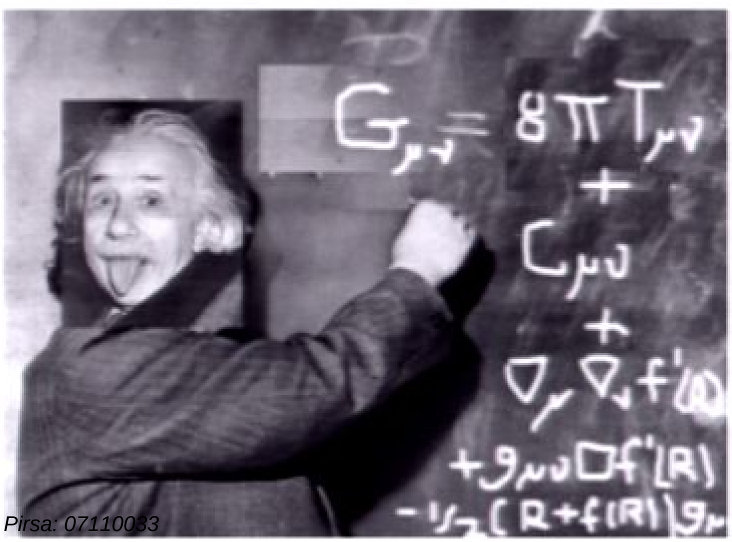
I will present the results of studying two modified theories of gravity emphasizing how they bridge the gap between local and cosmological physics.

First I will discuss work I have done on f(R) modified gravity theories, delineating under what conditions these theories deviate strongly from general relativity. Using these results I will talk about some recent work on attempting to detect a characteristic signature of these theories from gravitational lensing. Second I will discuss recent results on ways we may test Chern-Simons gravity (a result of the low energy effective string action) in the Solar System. Chern-Simons gravity has been identified as a candidate for leptogenesis as well as a source for circularly polarized gravitational-waves from inflation.

As I will discuss, constraints to Chern-Simons gravity may improve in the near future with further observations of double pulsar systems.

ntroduction





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  * Current epoch of accelerated expansion

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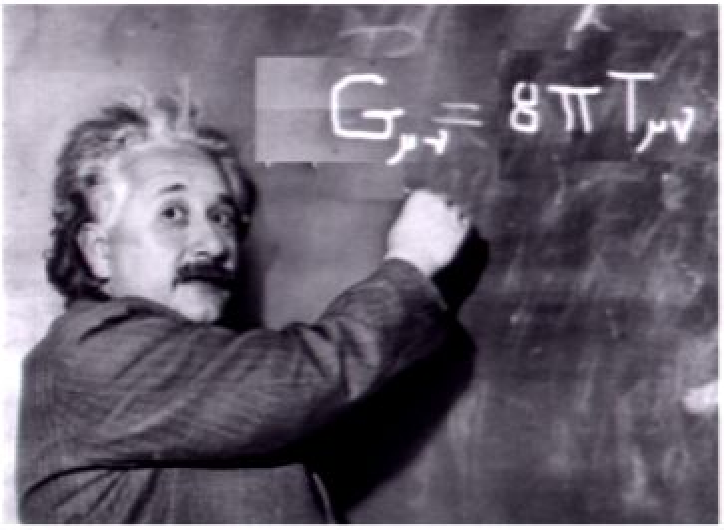

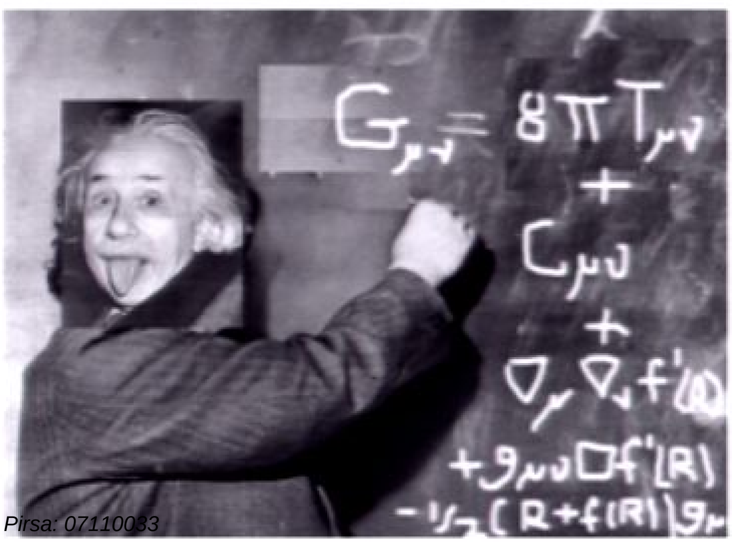

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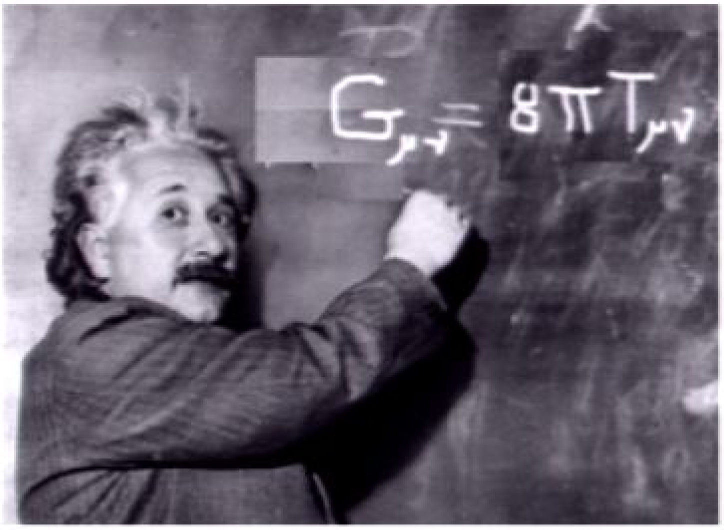

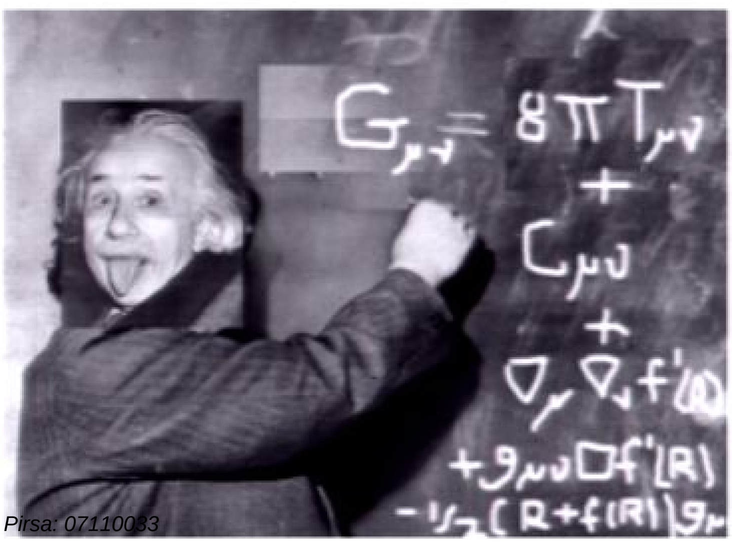

- Reasons we may want to modify Einstein's general relativity:
  - Current epoch of accelerated expansion
  - We know that Einstein's GR isn't the full story because it cannot be quantized

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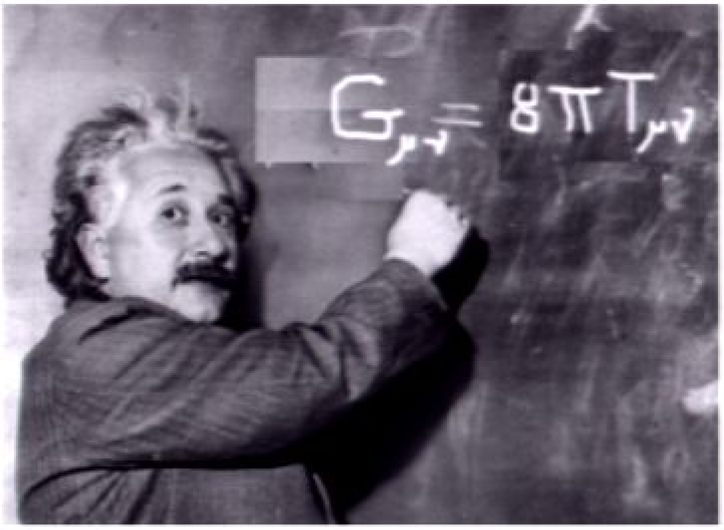
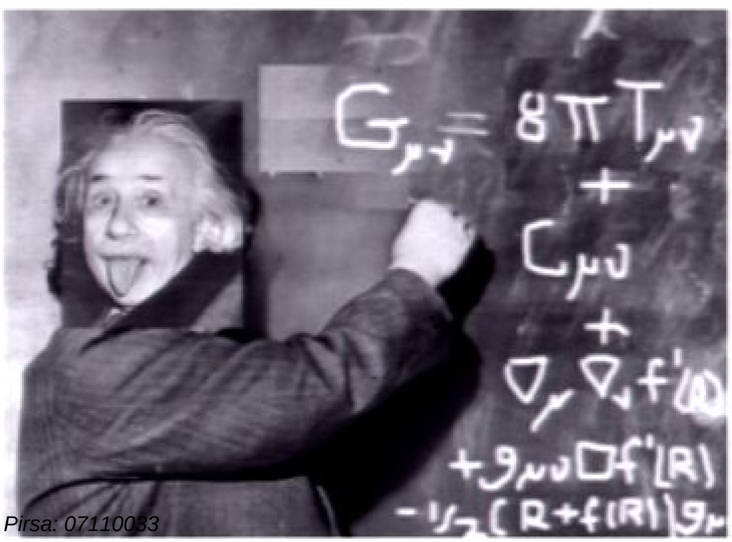
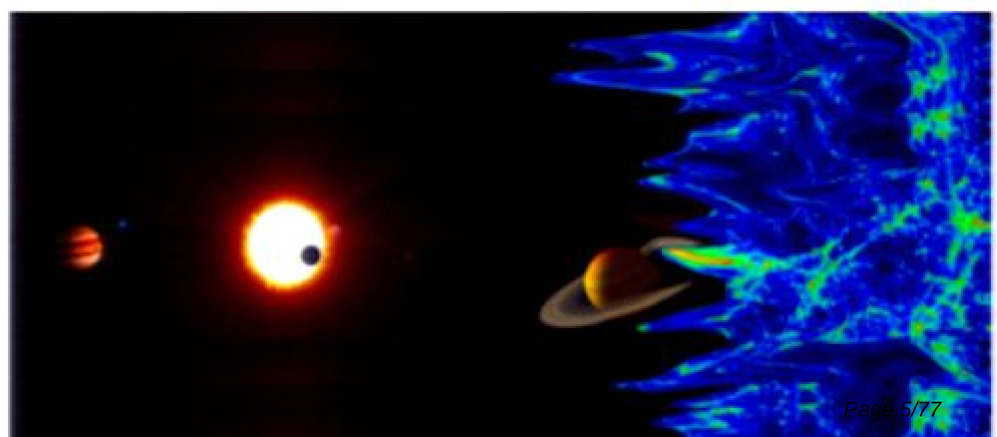
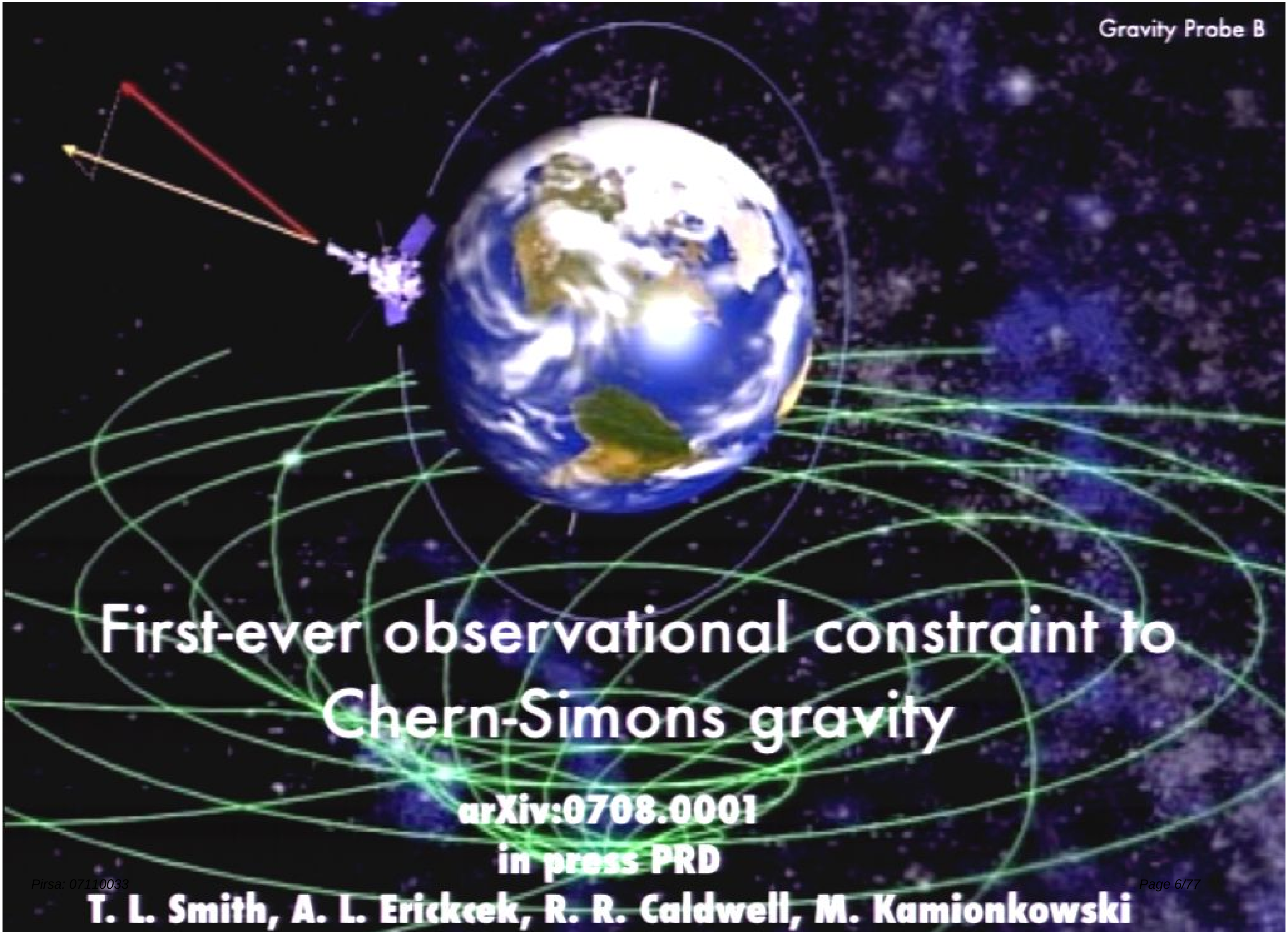




- Generic result of modifying General Relativity:
  - Create a new degree of freedom
  - May connect local dynamics to cosmology!




Gravity Probe B
First-ever observational constraint to Chern-Simons gravity
arXiv:0708.0001
in press PRD
T. L. Smith, A. L. Erickcek, R. R. Caldwell, M. Kamionkowski

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* It is a 'natural' consequence of the effective 4D string action

  Green and Schwartz (1985)
  Campbell et al. (1991)

Chern-Simons (CS) gravity

- Chern-Simons gravity is defined by the action

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[-\frac{1}{2\kappa} R + \frac{\ell}{12} \theta \mathbf{R}\tilde{\mathbf{R}} - \frac{1}{2} (\partial\theta)^2 - V(\theta) + \mathcal{L}_{\mathrm{mat}} \right]$$

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- $-\frac{1}{2\kappa}R$: usual GR term
- $\frac{\ell}{12}\theta \mathbf{R}\tilde{\mathbf{R}}$: Chern-Simons term
- $\frac{1}{2}(\partial\theta)^2 - V(\theta)$: usual scalar kinetic and potential
- $\mathcal{L}_{\rm mat}$: Matter Lagrangian

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* Coupling with scalar can arise due to an approximate 'shift' symmetry: $\nabla_\mu K^\mu = \frac{1}{2}\mathbf{R}\tilde{\mathbf{R}}$ $\qquad \theta \to \theta + \theta_0$

$$S \to \int \mathrm{d}^4x\sqrt{-g}\frac{\ell}{12}\theta_0\mathbf{R}\tilde{\mathbf{R}} = \int \mathrm{d}^4x\sqrt{-g}\frac{\ell}{6}\theta_0\nabla_\mu K^\mu = 0$$

Looking for CS gravity....

* The full field equations in CS gravity take the form

Scalar field: $$\Box\theta = \frac{\mathrm{d}V}{\mathrm{d}\theta} - \frac{1}{12}\ell\mathbf{R}\tilde{\mathbf{R}}$$

Gravitational field: $$G_{\mu\nu} - \frac{\ell\kappa}{3}\underbrace{\nabla_\sigma\left([\nabla_\tau\theta]\,\epsilon^{\tau\lambda\alpha(\mu}R^{\nu)\sigma}{}_{\alpha\lambda}\right)}_{C_{\mu\nu}} = -\kappa T_{\mu\nu}$$

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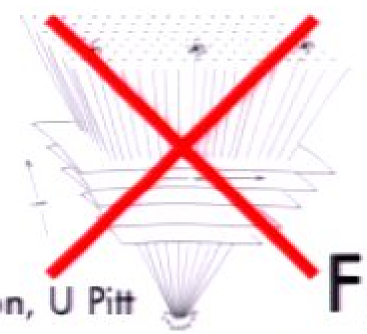

FRW

Linearization of CS gravity

- Linearizing the equations about a flat metric:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$|h_{\mu\nu}| \ll 1$$

- Define the trace-reversed metric perturbation

$$\bar{h}_{\mu\nu} \equiv h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} h$$

- Specialize to a gauge (harmonic) where

$$\partial^{\mu}\bar{h}_{\mu\nu} = 0$$

- Consider the case where $\theta(t)$ and we neglect $\ddot{\theta}(t)$

Gravito-magnetism

* We can write the gravitational field equations in analogy to electromagnetism:

Vector potential: $A_\mu \equiv -\frac{1}{4}\bar{h}_{\mu 0}$

Four-current: $J_\mu \equiv -T_{\mu 0}$

Gravito-electric field: $E^i \equiv \partial_i A_0 - \partial_0 A_i$

Gravito-magnetic field: $B^i \equiv \epsilon^{0ijk}\partial_j A_k$

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$$m_{\rm cs} \equiv -3/(\ell\kappa\dot{\theta})$$

Lorentz force law

- Besides having analogous field equations

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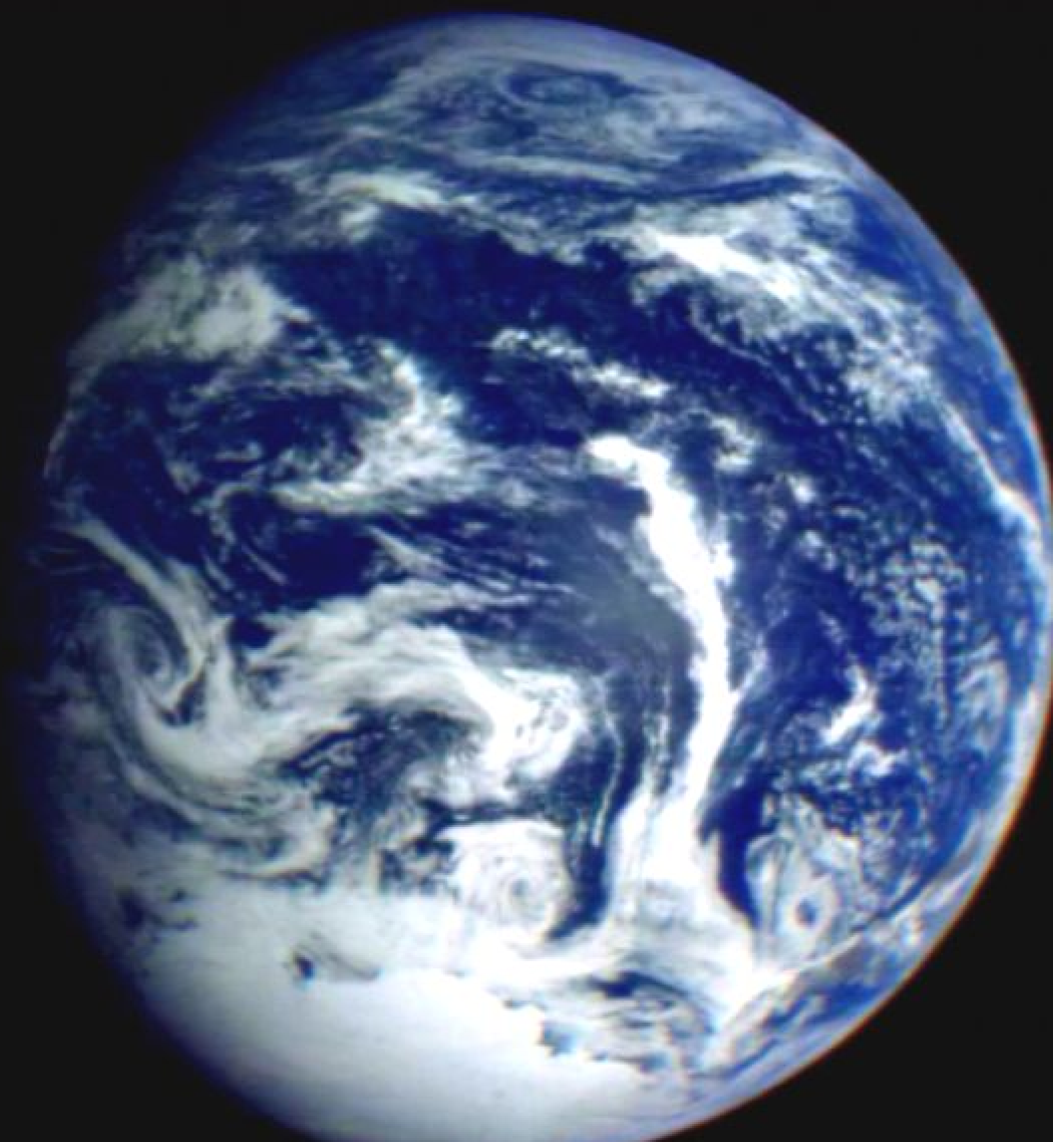
- Only Ampere's law is altered
- To look for an effect of CS gravity we need to produce a gravito-magnetic field (i.e. break spherical symmetry!)
- Where are we going to find a mass current to generate a gravito-magnetic field?

The rotating earth



Credit: NASA, JPL, Doug Ellison

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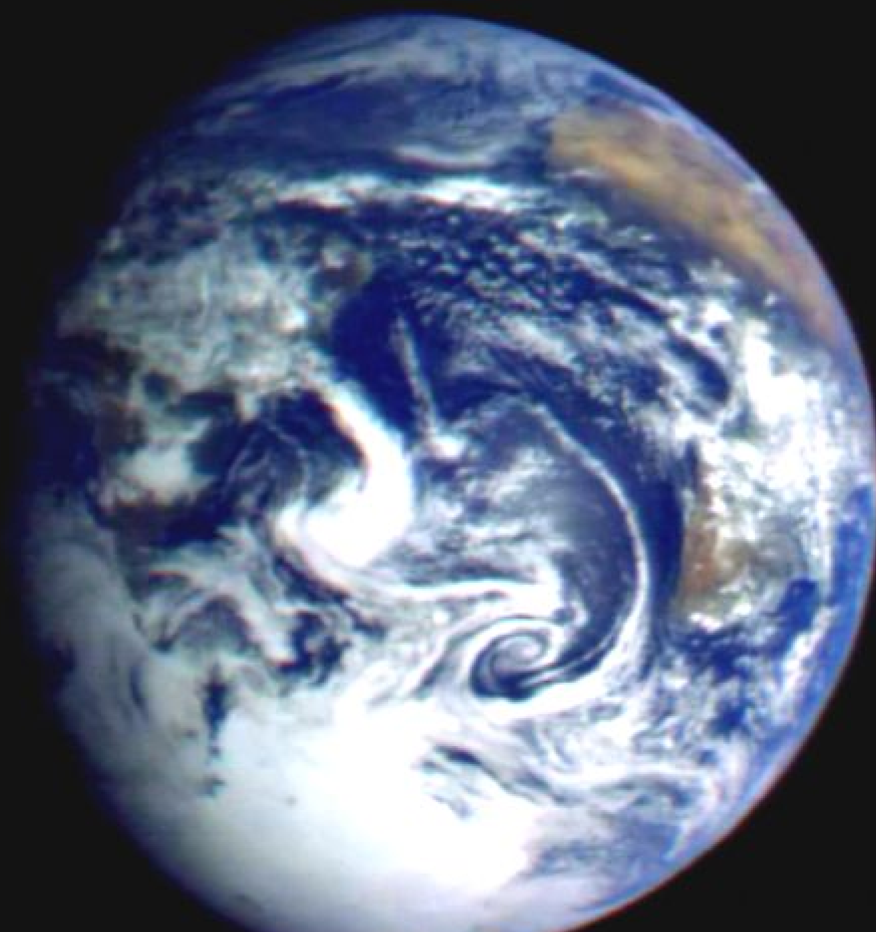

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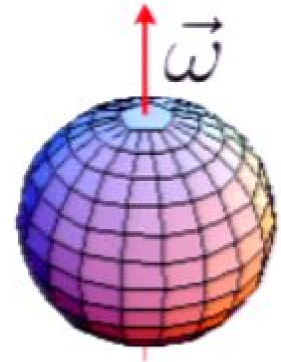
The rotating earth and CS gravity

* The rotation of the earth generates the mass current

$$\vec{J} = \rho r \omega \Theta(R_\oplus - r)\hat{\phi}$$



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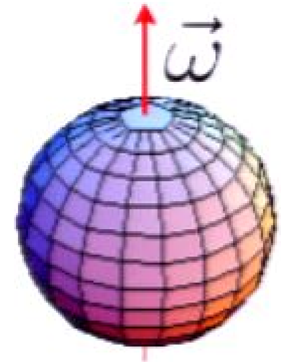

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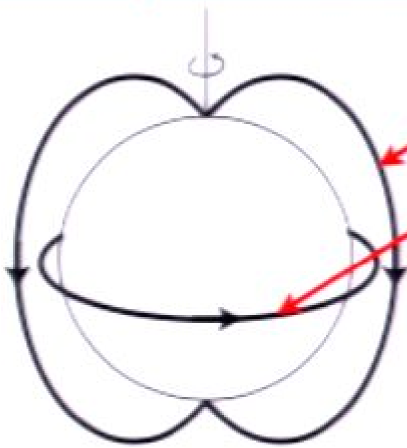
* CS term breaks parity: $\vec{B} \rightarrow -\vec{B}$ (pseudovector)

$$\vec{\nabla} \times \vec{B} + \frac{1}{m_{\rm cs}} \nabla^2 \vec{B} = 4\pi G \vec{J}$$

Parity violation:



Poloidal

Toroidal $\propto \vec{J}$

Massive particle experiences force:

$$\vec{F} \sim \vec{v} \times \vec{B}$$

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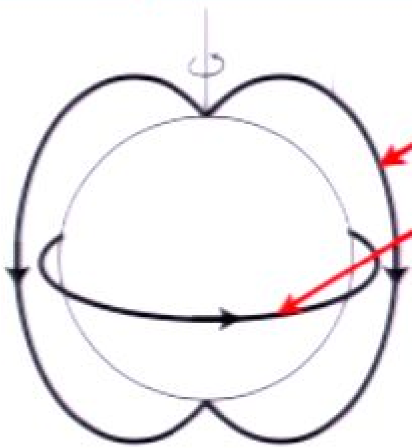

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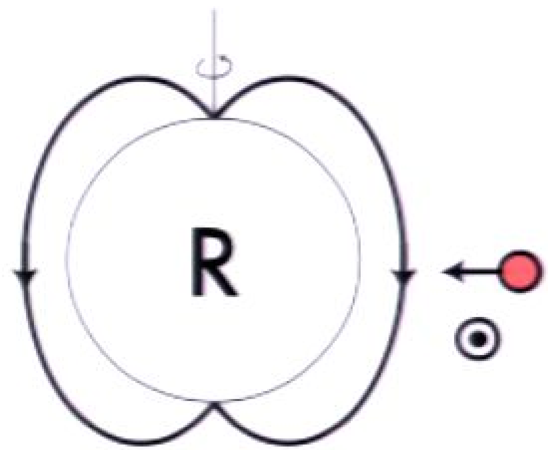

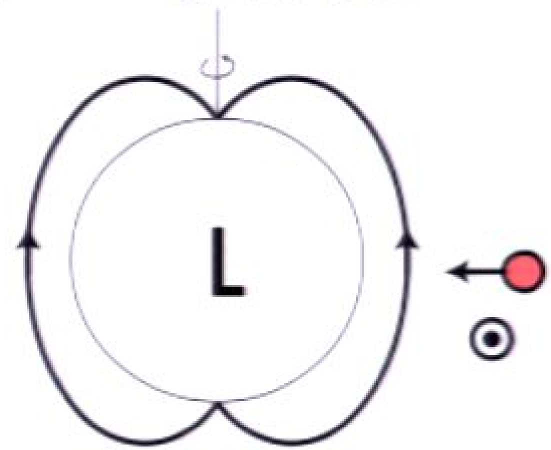

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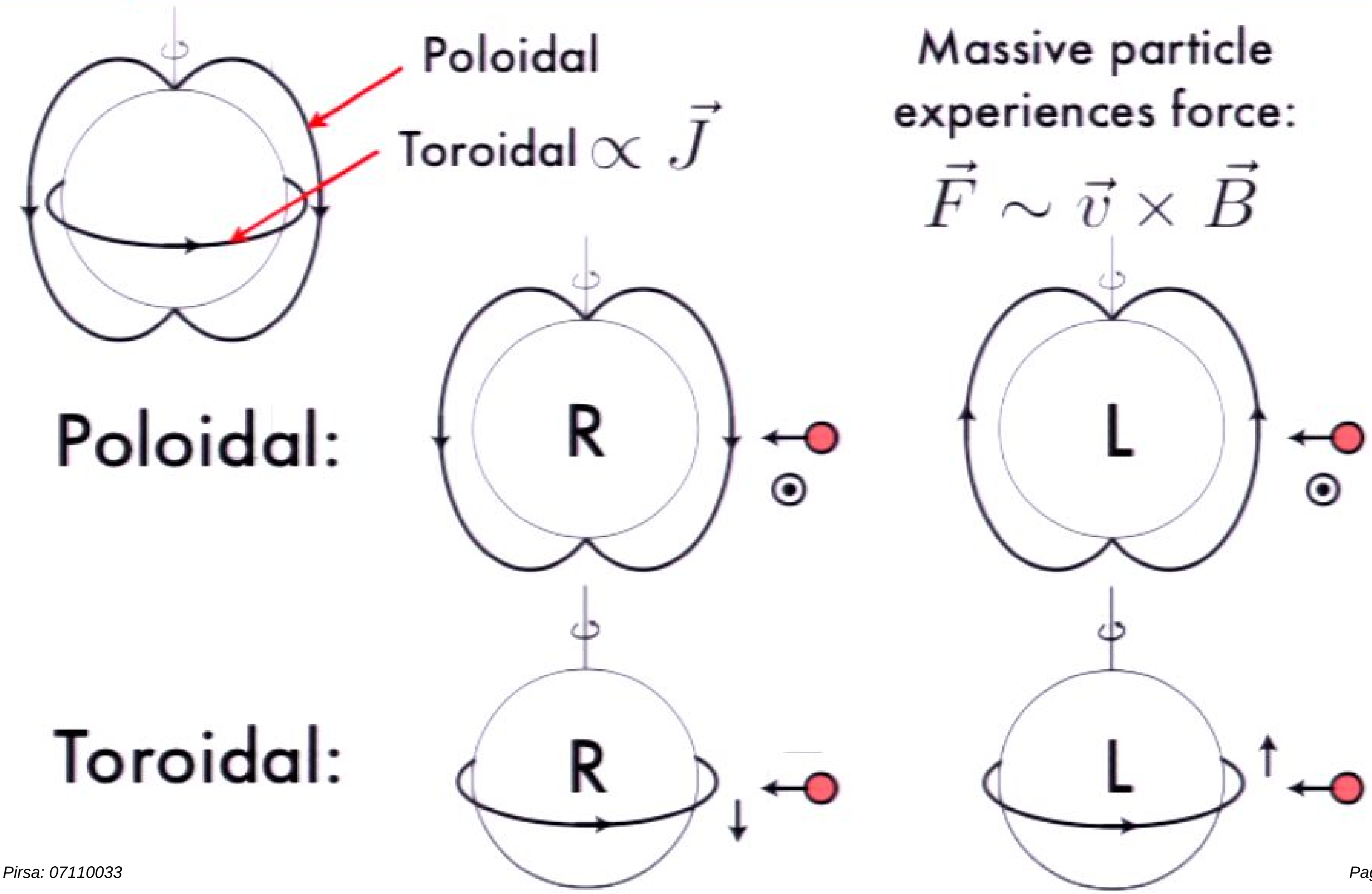
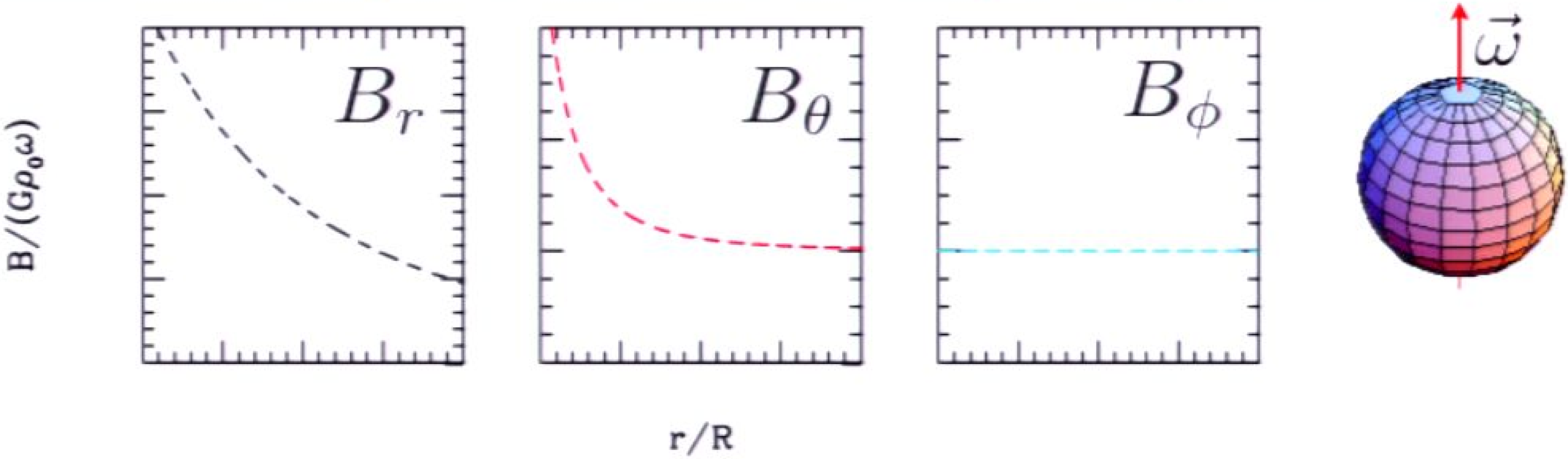


The rotating earth and CS gravity



$$B_r = 8\pi G\frac{R^2}{r^2}\rho_0\Omega\cos(\theta)\left(\frac{R^3}{r}\qquad\qquad\right),$$

$$B_\theta = 4\pi G\frac{R^2}{r}\rho_0\Omega\sin(\theta)\left(\frac{R^3}{r^2}\qquad\qquad\right),$$

$$B_\phi =$$

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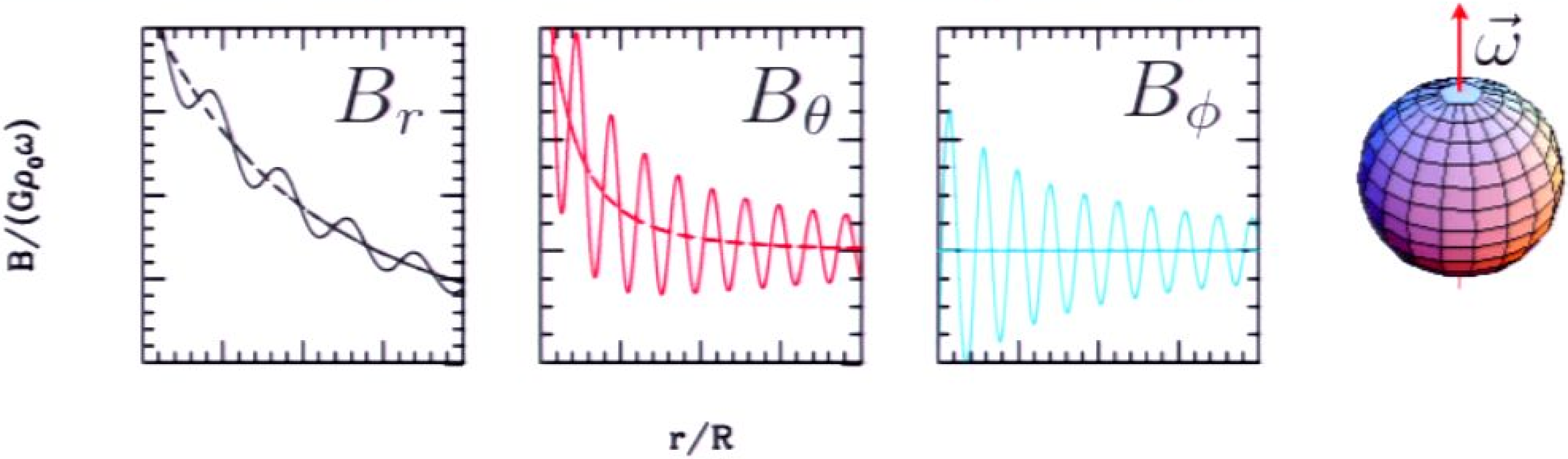

$$B_r = 8\pi G \frac{R^2}{r^2}\rho_0\Omega\cos(\theta)\left(\frac{R^3}{r} + \frac{\sin(mr)\sin(mR)}{m^2}\right),$$

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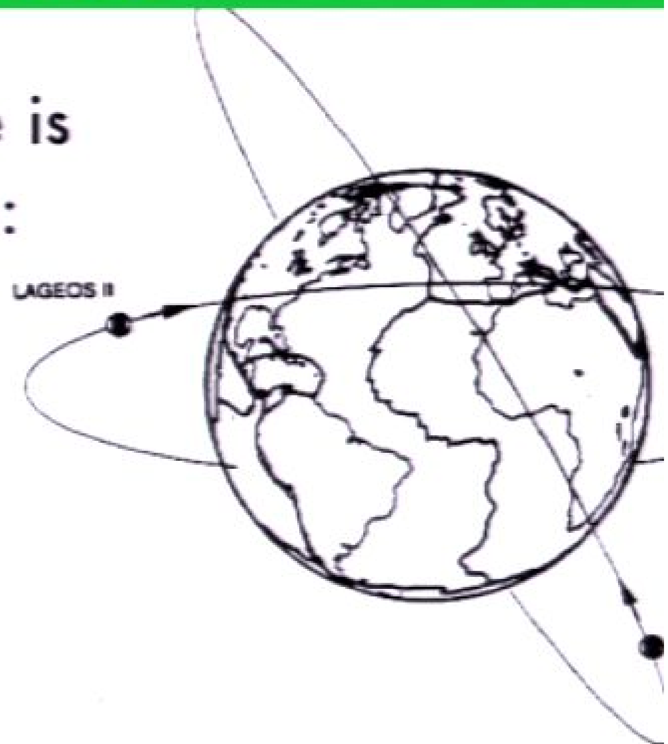
$$B_\phi = -\frac{4\pi G\rho_0\Omega R^2}{mr}\sin(mr)\sin(mR)\sin(\theta).$$

Seeing the gravito-magentic field

* In gravito-magnetism motion of a satellite is dominated by the usual Newtonian force:

$$\vec{a} = -\vec{E} - 4\vec{v} \times \vec{B}$$



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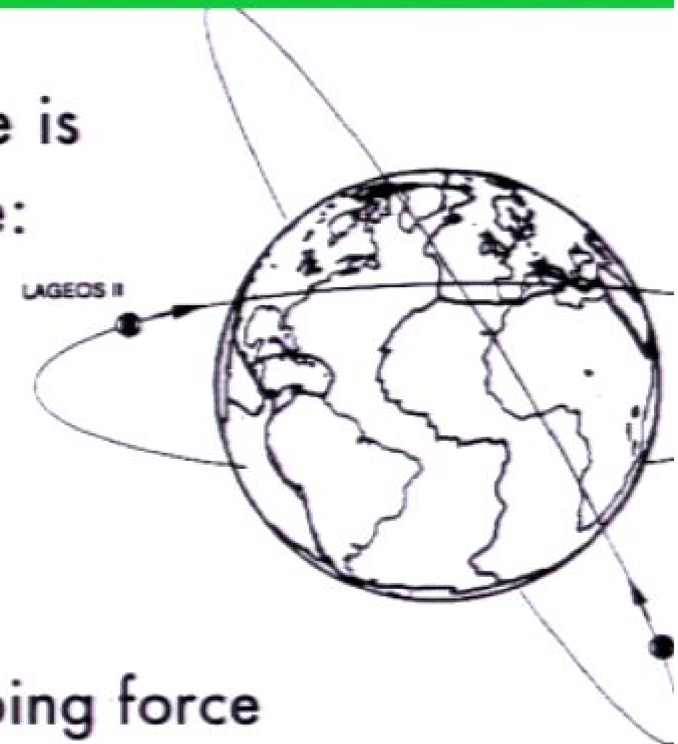

$$\vec{a} = -\vec{E} - 4\vec{v} \times \vec{B}$$

$$\vec{a} = -\vec{\nabla}\Phi + \delta\vec{f}$$

small perturbing force

* Perturb about a Keplerian orbit

* Look at perturbed motion that builds up in time (secular motion)

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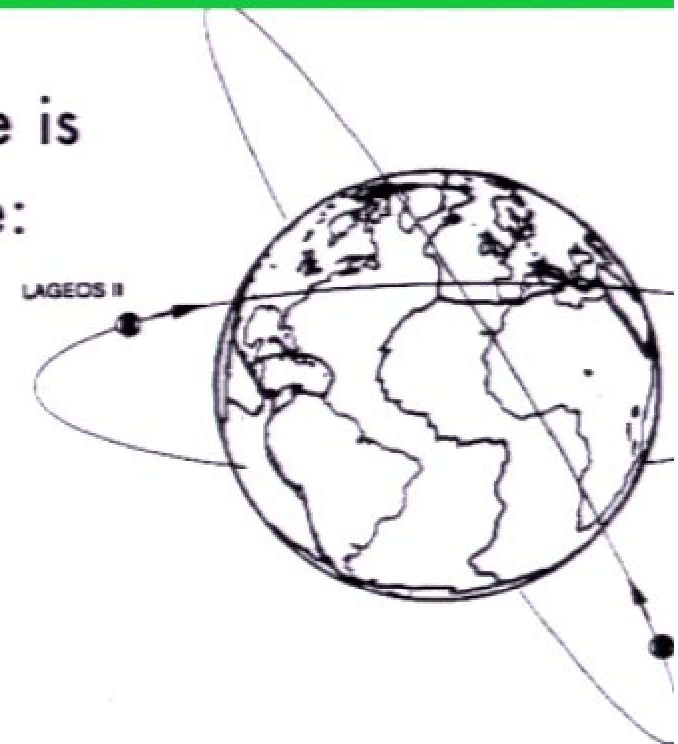

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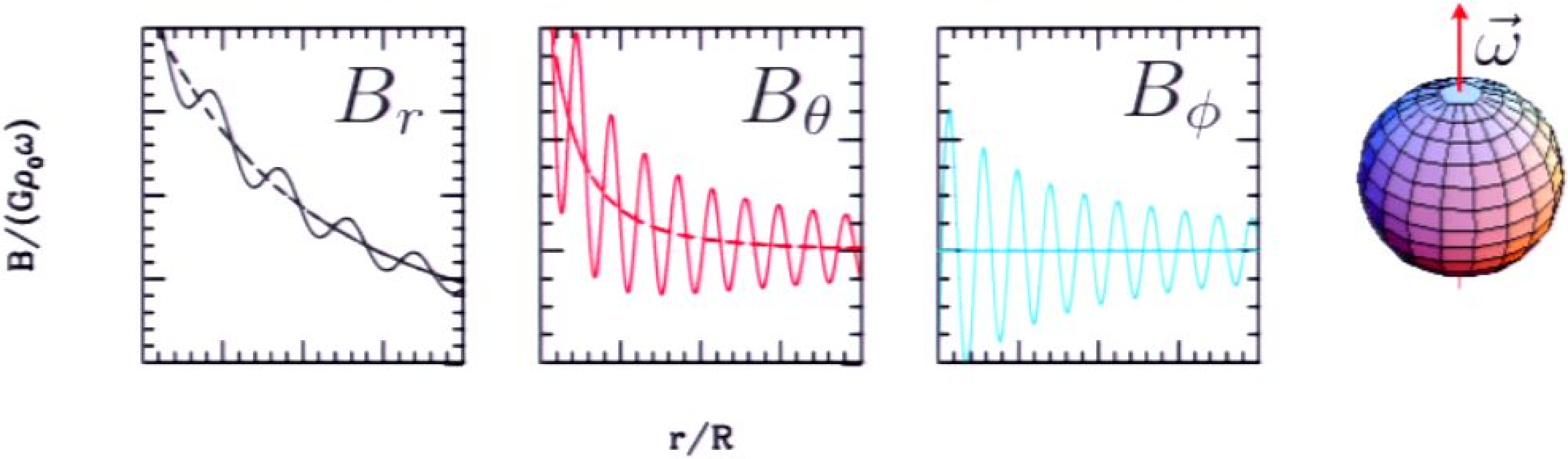


$$
\begin{aligned}
B_r &= 8\pi G \frac{R^2}{r^2}\rho_0 \Omega \cos(\theta)\left(\frac{R^3}{r} + \frac{\sin(mr)\sin(mR)}{m^2}\right), \\
B_\theta &= 4\pi G \frac{R^2}{r}\rho_0 \Omega \sin(\theta)\left(\frac{R^3}{r^2} - \frac{\cos(mr)\sin(mR)}{m}\right), \\
B_\phi &= -\frac{4\pi G \rho_0 \Omega R^2}{mr}\sin(mr)\sin(mR)\sin(\theta).
\end{aligned}
$$

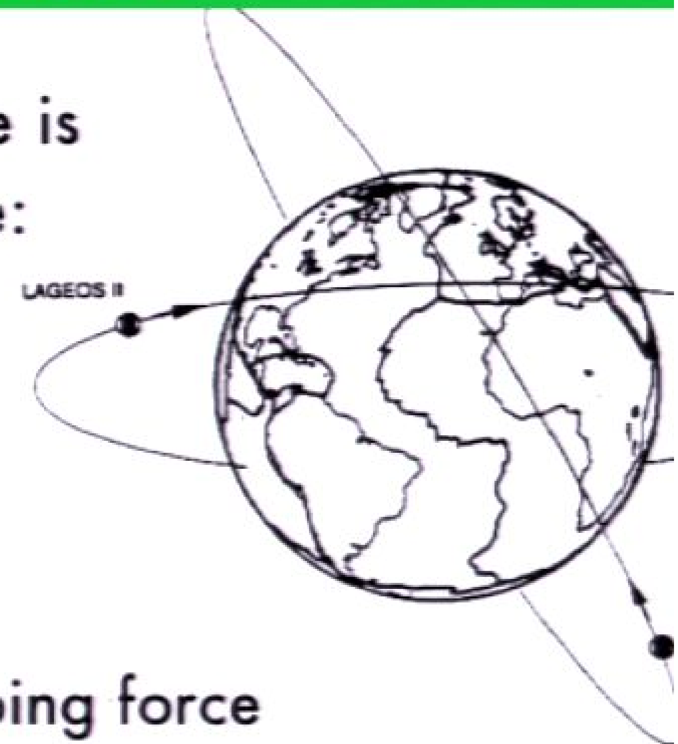
Seeing the gravito-magentic field

* In gravito-magnetism motion of a satellite is dominated by the usual Newtonian force:

$$\vec{a} = -\vec{E} - 4\vec{v} \times \vec{B}$$

$$\vec{a} = -\vec{\nabla}\Phi + \delta\vec{f}$$

small perturbing force



* Perturb about a Keplerian orbit

* Look at perturbed motion that builds up in time (secular motion)

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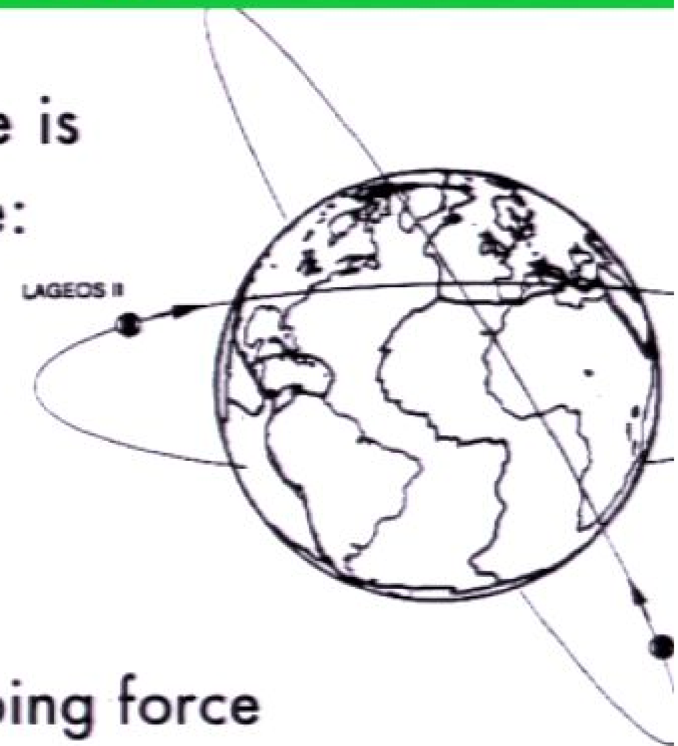


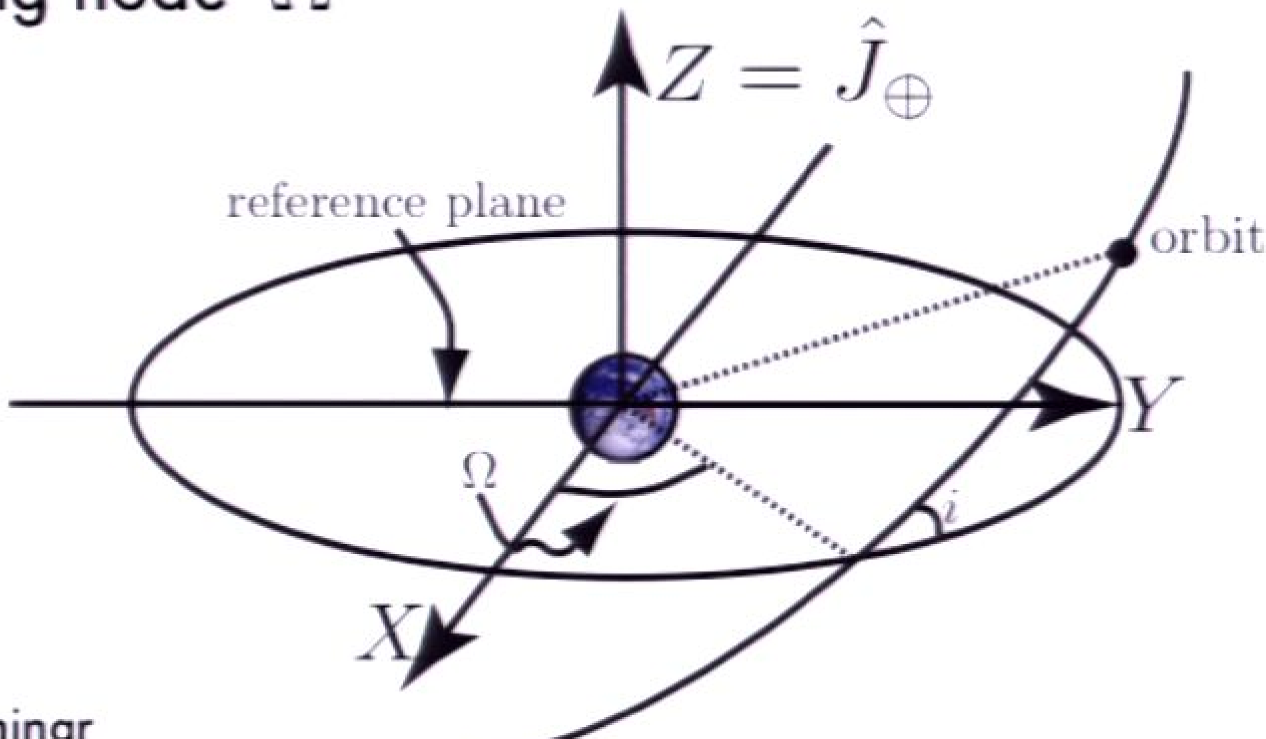
* Perturb about a Keplerian orbit

* Look at perturbed motion that builds up in time (secular motion)

Seeing the gravito-magentic field

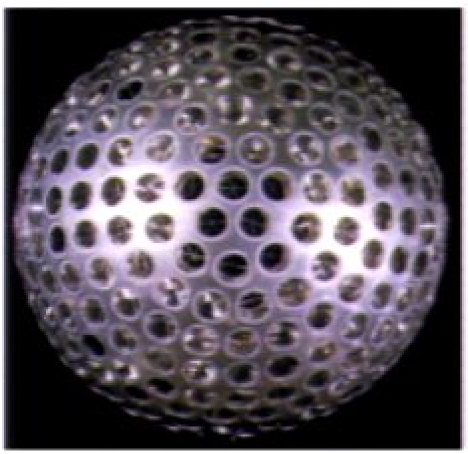
* Motion of a satellite can be described by Keplerian elements

* Measure evolution of the longitude of the ascending node Ω

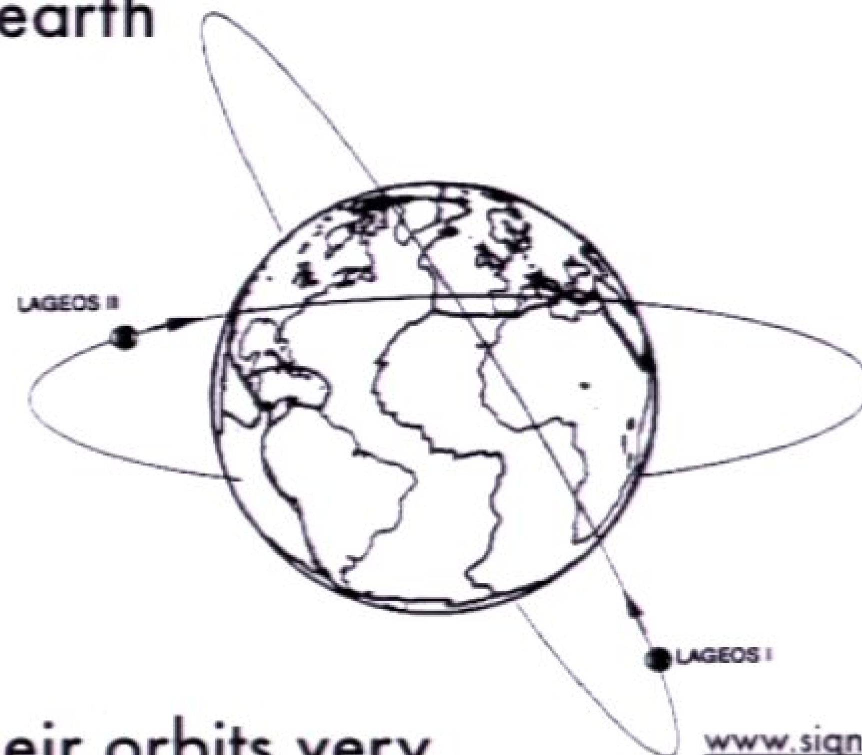


LAGEOS I & II

* LAGEOS I & II are two satellites with several retroreflectors orbiting the earth



Launched 1974 and 1992



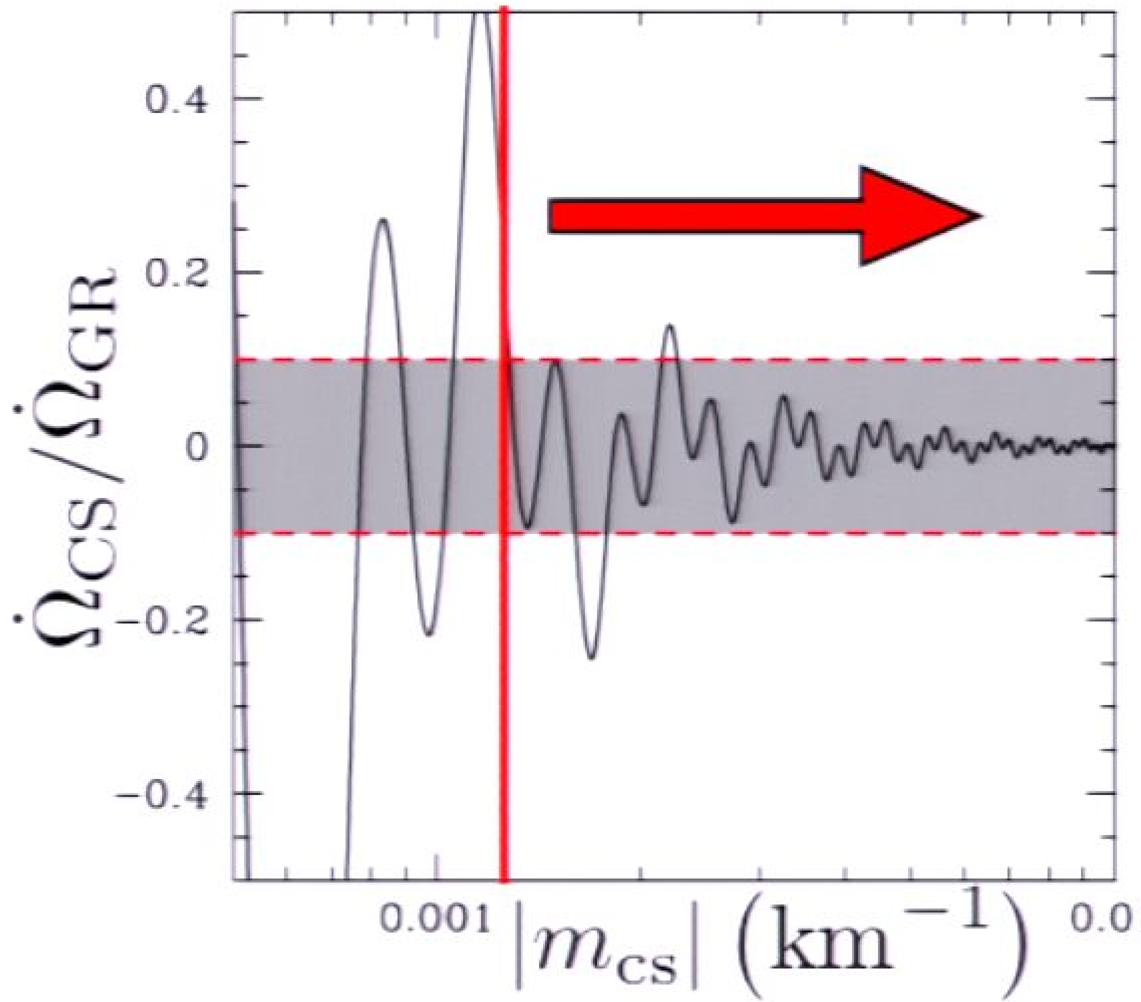
www.signale.de/lageos

* Laser ranging measures their orbits very accurately

LAGEOS I & II

- LAGEOS measurements have confirmed the GR result to with 10%
  Ciufolini and Pavlis (2004)

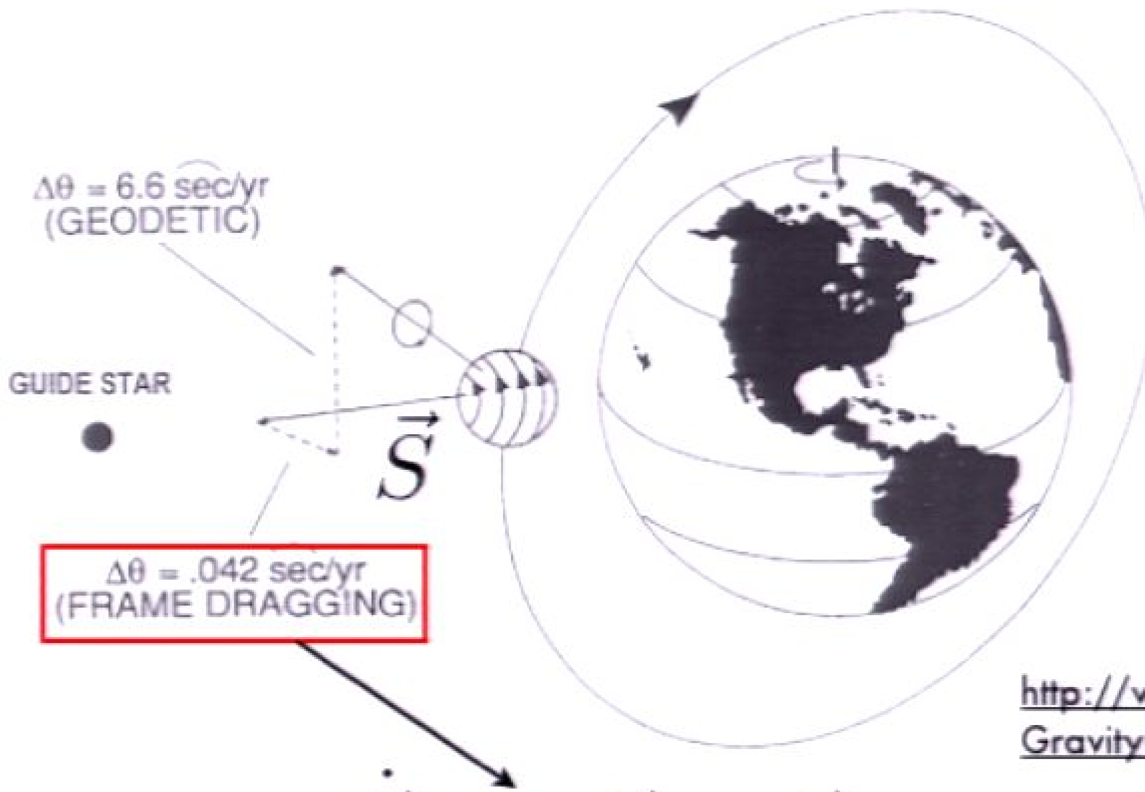
$$\frac{\dot{\Omega}_{\rm CS}}{\dot{\Omega}_{\rm GR}} \sim \frac{a}{m_{\rm cs}^4 R_\oplus^5}$$



$$m_{cs} \gtrsim 0.001\ {\rm km}^{-1} = 10^{-22}\ {\rm GeV}$$

Gravity Probe-B

* Gravity Probe-B (GPB) measures precession of gyroscopes due to the gravito-magnetic field



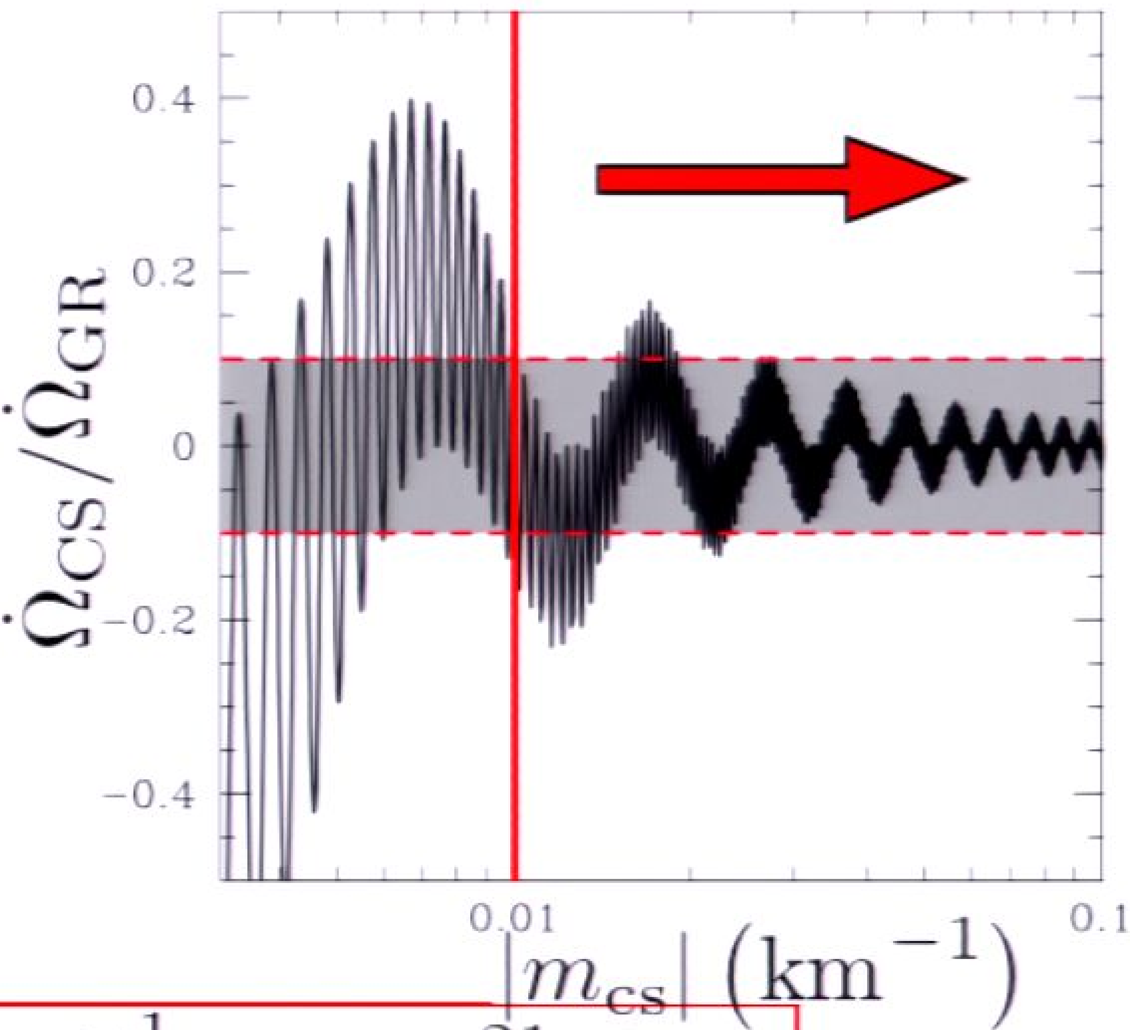
$$\dot{\vec{S}} = 2\vec{B} \times \vec{S}$$

http://www.nap.edu/html/ssb_html/GravityProbeB/gpbch3.shtml

Gravity Probe-B

* If GPB is able to confirm the GR result to 10%

$$\frac{\dot{\Phi}_{CS}}{\dot{\Phi}_{GR}} \sim \frac{a^2}{m_{cs}^2 R_\oplus^4}$$



$$m_{cs} \gtrsim 0.01\ \mathrm{km}^{-1} = 10^{-21}\ \mathrm{GeV}$$

Final limits to m_{cs}

- Current observations place the limit

$$m_{cs} \geq 0.001 \text{ km}^{-1} = 10^{-22} \text{ GeV}$$

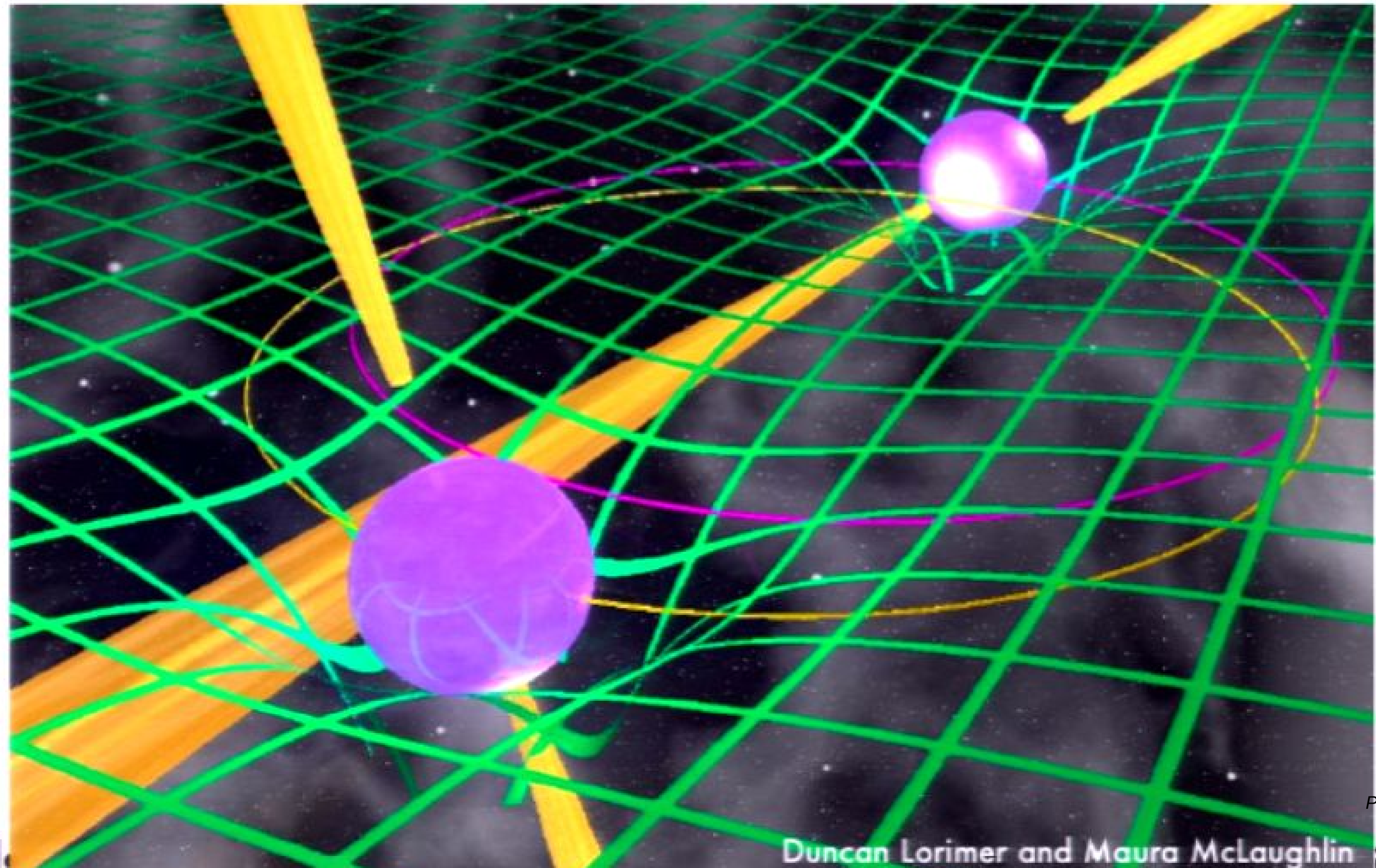
- Future observations may improve this (GPB) by an order of magnitude

$$m_{cs} \geq 0.01 \text{ km}^{-1} = 10^{-21} \text{ GeV}$$

- In order to translate these into constraints to fundamental parameter ℓ need model for $\theta(t)$; left for future work ($m_{\rm cs} \equiv -3/(\ell\kappa\dot{\theta})$)

Double Pulsars!

* Another place to look for gravito-magnetic effects is in double pulsars



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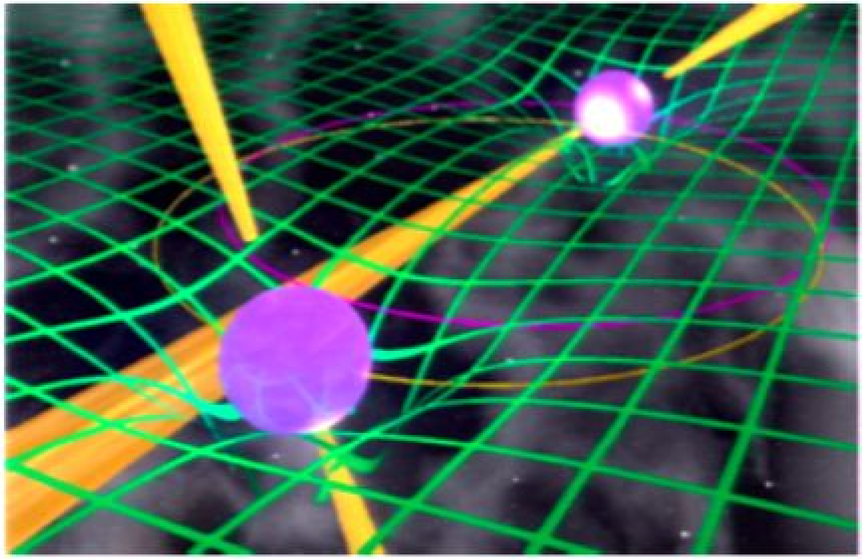


Duncan Lorimer and Maura McLaughlin

- More complicated; two sources of mass current: rotation and orbital motion
- Gravito-magnetic field larger by an order of magnitude
- Orbital motion may improve constraints considerably (causes oscillation in orbital separation)

CS gravity conclusions

* *First ever* observable constraints on the theory

* Violation of parity results in the production of a gravito-magnetic field $\vec{B} \propto \vec{J}$

* Coupling of scalar field (new degree of freedom) necessitates model building; preferred frame effects?

* Future work to articulate new tests of gravity by looking at the gravito-magnetic fields implied by observations of double pulsar systems

Testing the universality of

γ_{PPN}

Using measurements of galaxy lens surveys to test alternative theories of gravity

Credit: The Virgo Consortium

Defining γ through observations

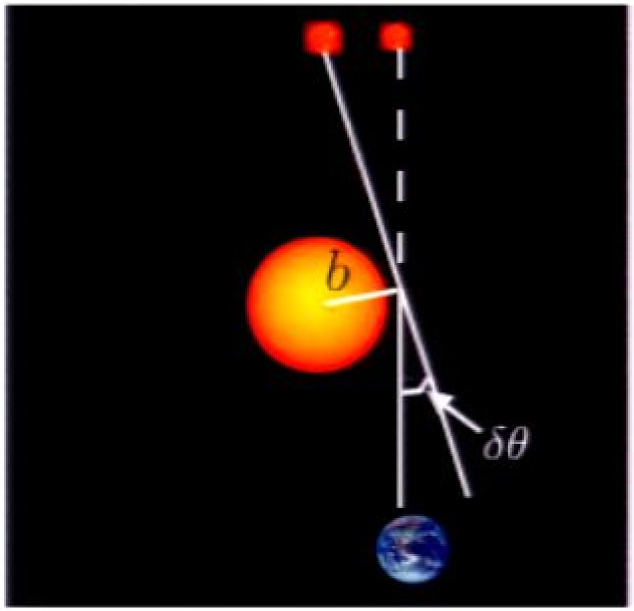
* We parameterize deviations from general relativity when measuring the lensing of light through γ

$$\delta\theta = 2(1+\gamma)\frac{GM}{c^2 b}$$

* In the Solar System we have the constraint

Bertotti, Iess, and Tortora (2003)

$$|1-\gamma_{\odot}| \lesssim 10^{-5}$$



* It is usually assumed that γ is universal... but it may not be

Outline

* Discuss the possible *non-universality* of γ with the example of f(R) gravity

* Describe that for f(R) gravity γ depends on the Newtonian potential of the lensing mass

* Discuss how we may probe a non-universal γ with a sample of elliptical lensing galaxies

* Present preliminary results using the SLACS survey

(R)-gravity and γ

* The theory is defined by the action

$$S = \frac{1}{2\kappa}\int d^4x\sqrt{-g}[R + f(R)] + S_m$$

general relativity → R; f(R) → $f(R)$

Capozziello et al. (2003)
Carroll et al. (2004)

* In f(R) gravity one can show that γ is given by:

$$\gamma = \frac{2 + R/(\kappa\rho)}{4 - R/(\kappa\rho)}$$

(R)-gravity and γ

* In GR we have $R = \kappa\rho$

(R)-gravity and γ

- In GR we have $R = \kappa\rho$
- In f(R) gravity this is replaced with a *differential* relationship:

$$\nabla^2 f'(R) = \frac{1}{3}[R - \kappa\rho]$$

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$\Phi_N < \Phi_0$

$R \ll \kappa\rho$

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Linear		Non-linear
$\Phi_N < \Phi_0$		$\Phi_N \gtrsim \Phi_0$
$R \ll \kappa\rho$	$\gamma = \frac{2 + R/(\kappa\rho)}{4 - R/(\kappa\rho)}$	$R = \kappa\rho$
$\gamma = 1/2$		$\gamma = 1$

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Linear		Non-linear
$\Phi_N < \Phi_0$		$\Phi_N \gtrsim \Phi_0$
$R \ll \kappa\rho$	$\gamma = \frac{2 + R/(\kappa\rho)}{4 - R/(\kappa\rho)}$	$R = \kappa\rho$
$\gamma = 1/2$	A non-universal γ !!	$\gamma = 1$

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- Measure the redshift

$$\gamma = \frac{\quad}{\sigma^2_{\rm obs}} \frac{D_{\rm S}}{D_{\rm LS}} - 1$$

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* Measure the redshift and Einstein radius

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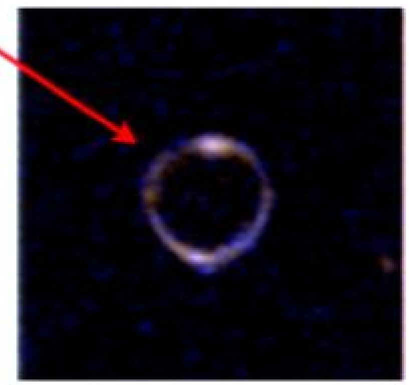

$$\gamma = \frac{\theta_E}{\sigma_{\rm obs}^2}\frac{D_{\rm S}}{D_{\rm LS}} - 1$$

* Actual analysis takes into account: power-law behavior of luminous and total mass density and anisotropy in stellar velocity dispersion

Measurement of γ : preliminary analysis

* Data from SDSS and HST for 15 elliptical lensing galaxies (SLACS survey, Bolton et al.)

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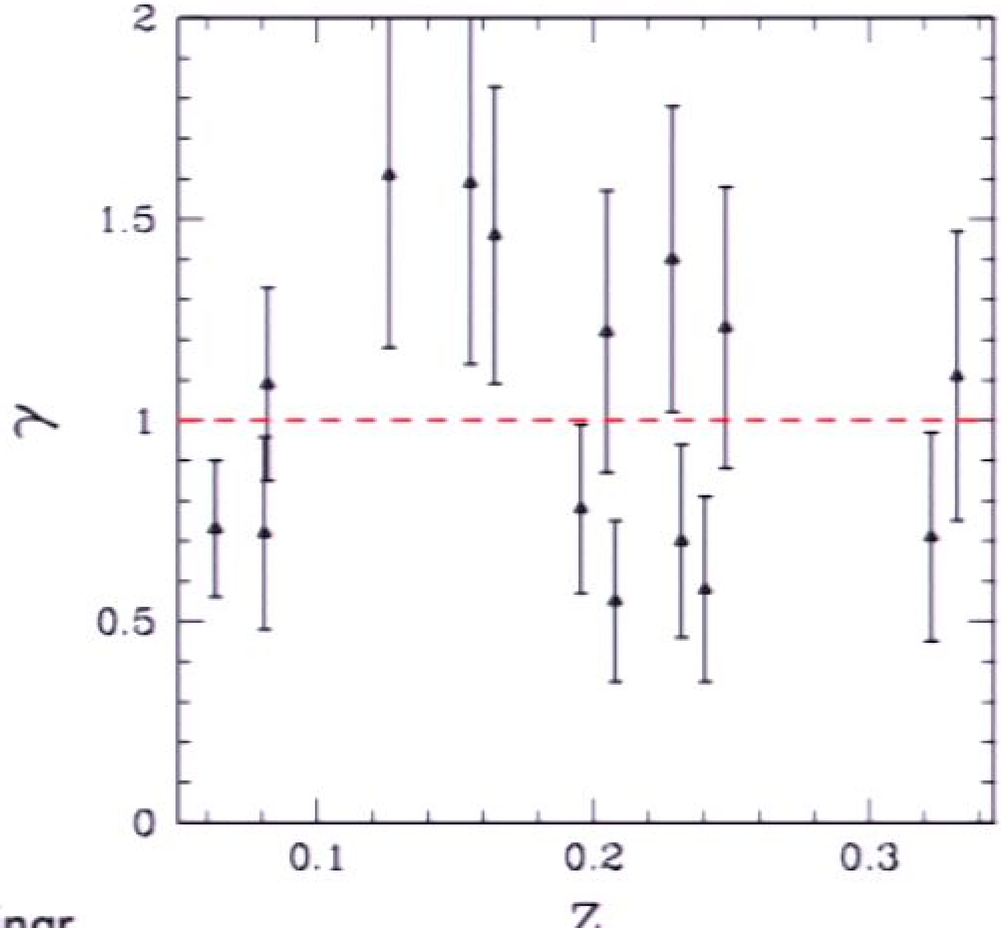

Treu et al.
Bolton et al.

Measurement of γ : preliminary analysis

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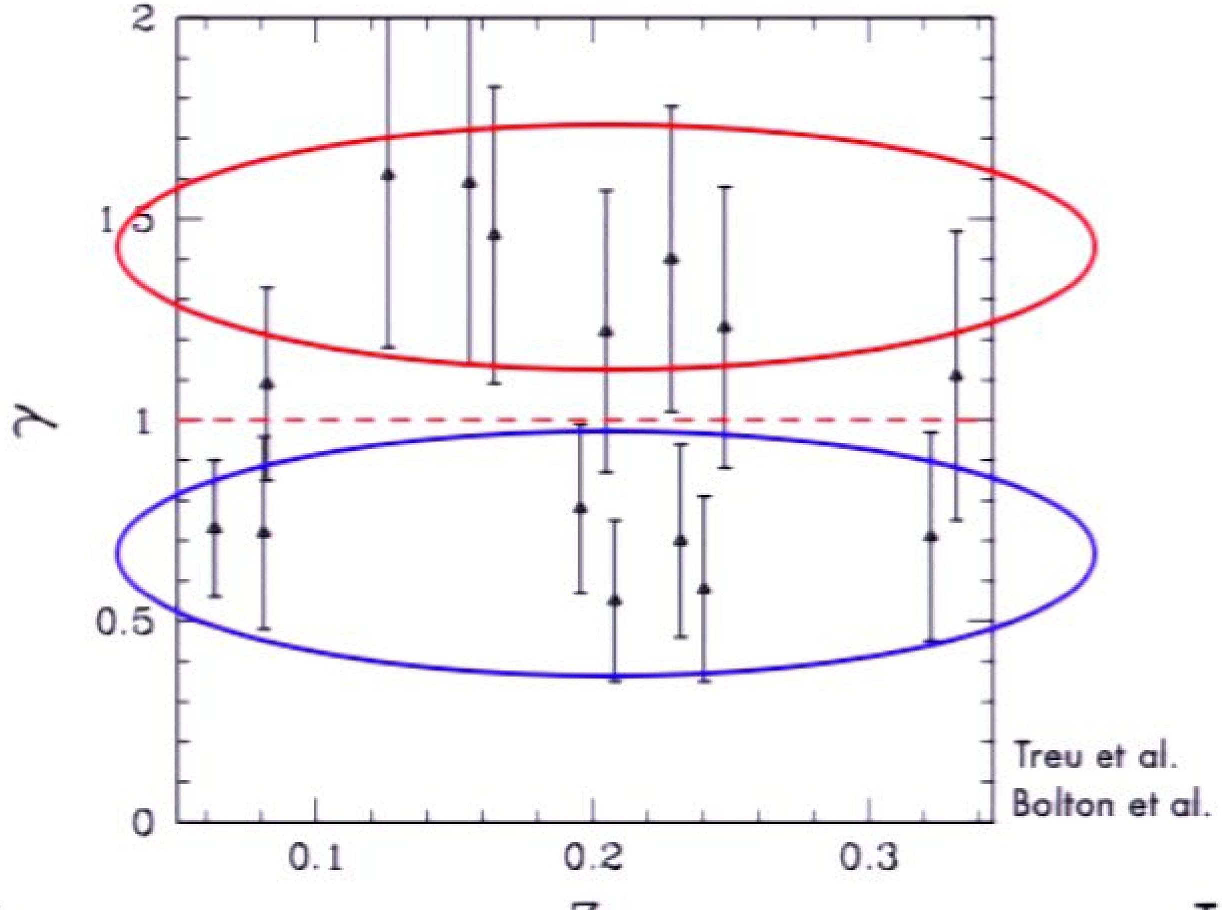


Measurement of γ : preliminary analysis

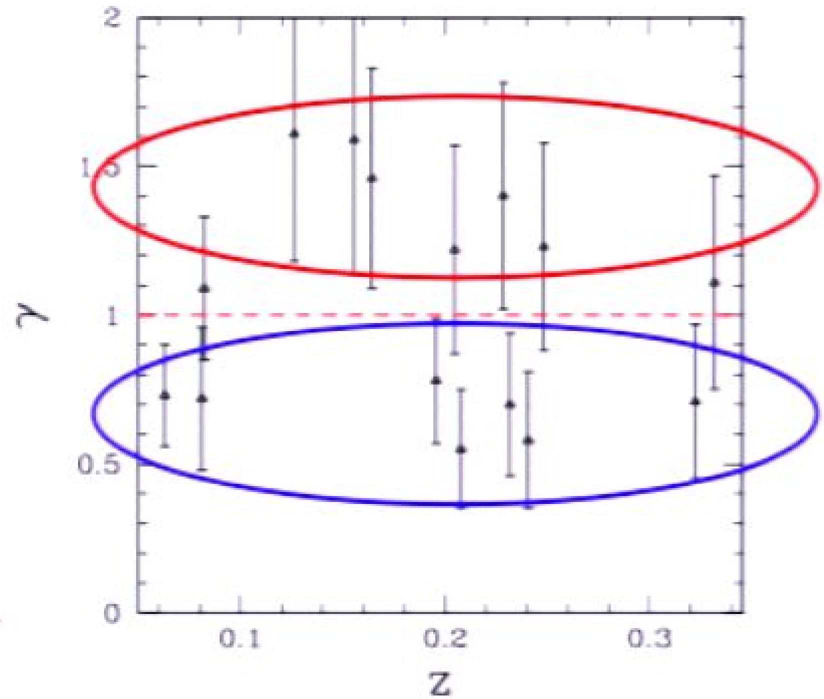
* Data from SDSS and HST for 15 elliptical lensing galaxies (SLACS survey, Bolton et al.)

* 1σ *rejection* of the hypothesis that all points come from single distribution

* By the end of the year 70 more galaxies

  → If bimodality persists with 70, statistically significant

* Correlate γ with local environment: # nearest neighbors, richness of cluster...



Conclusions

* Modifications of general relativity force us to revisit 'standard' calculations

* The modifications present us with novel ways to probe the fundamental nature of gravity

* Exciting because of various new probes of gravity (lensing surveys, double pulsars, direct detection of gravitational-waves, table-top experiments...)