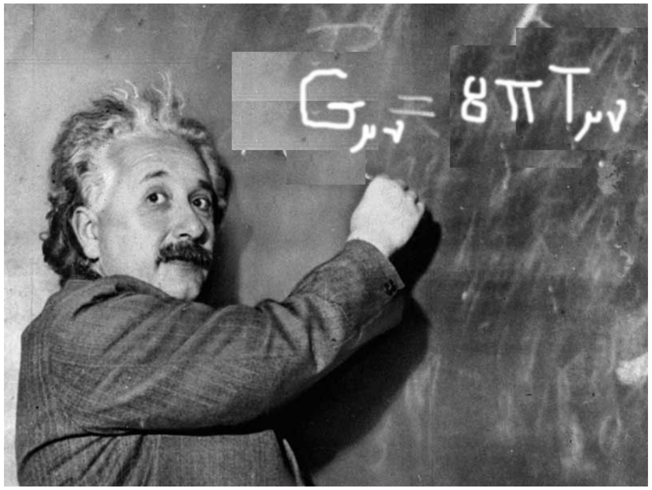
Local gravity and the Cosmos

Using local tests of modified gravity to probe cosmological physics

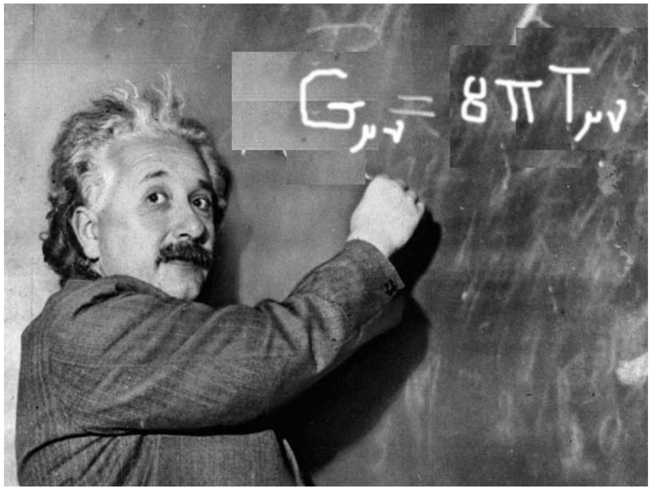
Tristan L. Smith
Caltech

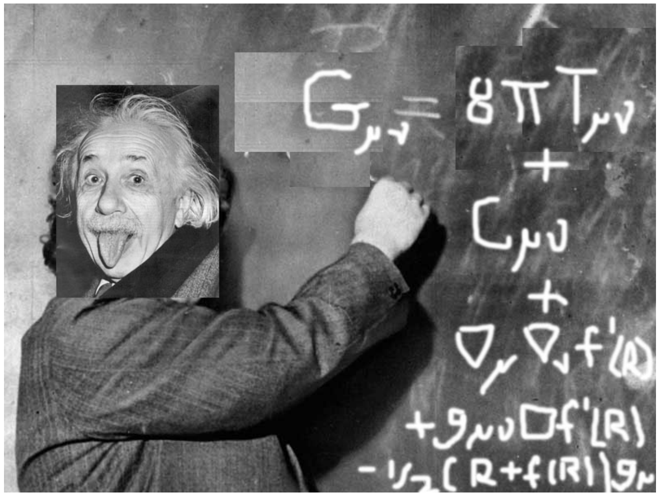
Introduction



- Reasons we may want to modify Einstein's general relativity:

Introduction





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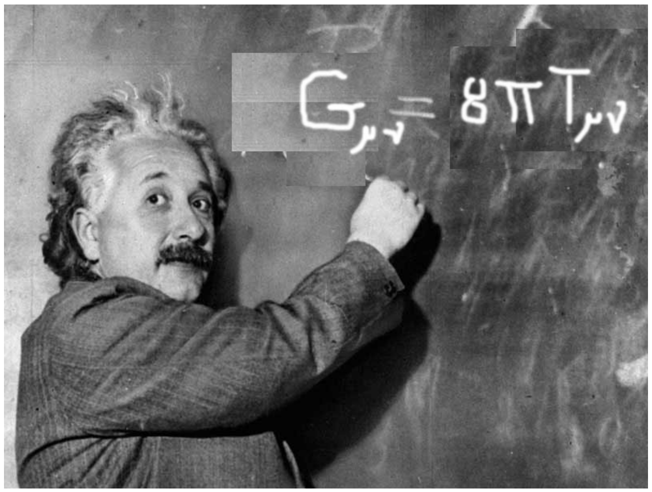

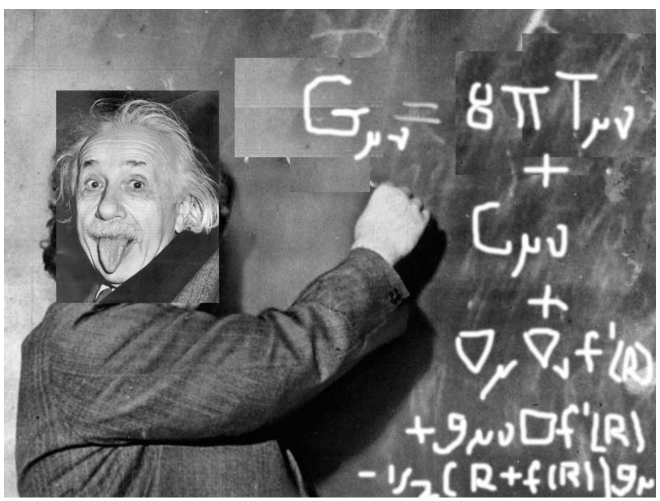

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  - Current epoch of accelerated expansion

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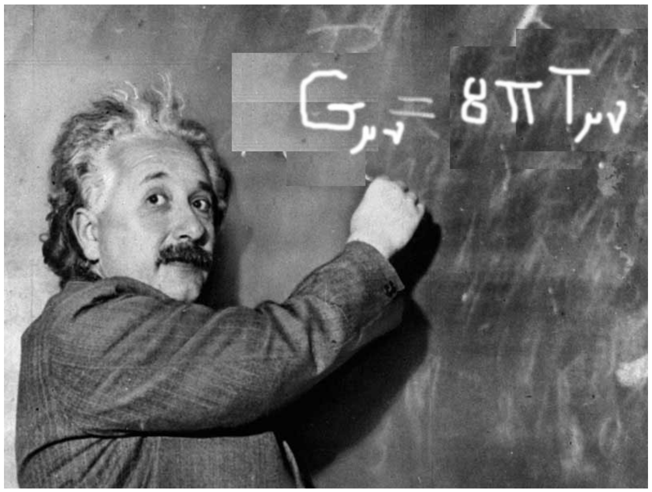
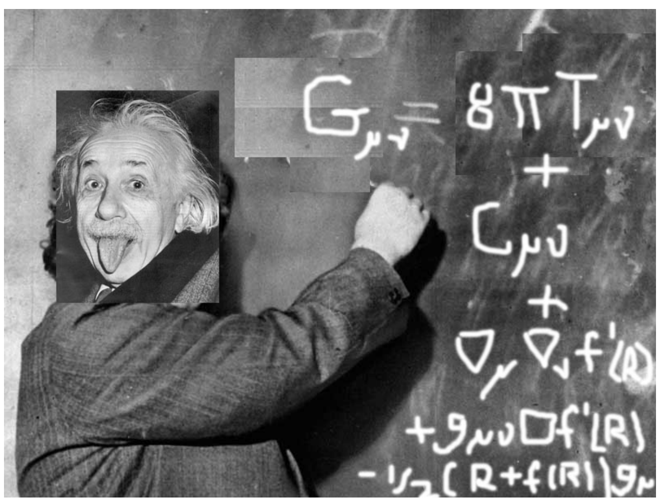
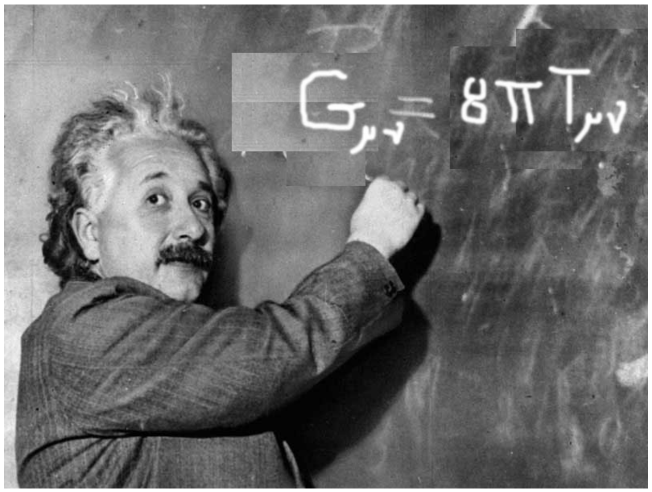
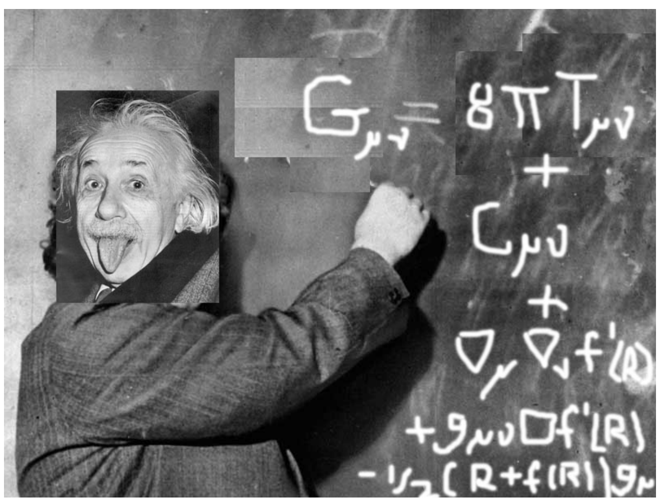




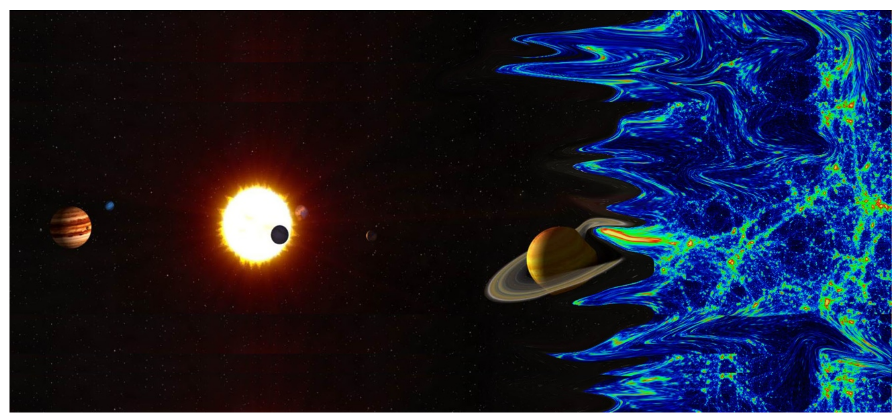
- Reasons we may want to modify Einstein's general relativity:
  - Current epoch of accelerated expansion
  - We know that Einstein's GR isn't the full story because it cannot be quantized

Introduction





* Generic result of modifying gravity:
    * Create a new degree of freedom
    * May connect local dynamics to cosmology!



An introduction to f(R) gravity

* Start with the standard Einstein-Hilbert action

$$S = \frac{1}{2\kappa}\int \mathrm{d}^4x\sqrt{-g}R + S_m$$

An introduction to f(R) gravity

- Start with the standard Einstein-Hilbert action

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

- Modify by adding an extra term

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

general relativity

f(R)

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

An introduction to f(R) gravity

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

- Vary the action to obtain the field equation

$$[1 + f'(R)]G_{\mu\nu} = \kappa T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}[Rf'(R) - f + \Box f'(R)] + \nabla_\mu \nabla_\nu f'(R)$$

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$$\Box f'(R) = \frac{1}{3}\left[\kappa T + R[1 - f'(R)] + 2f(R)\right]$$

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GR terms imply
algebraic relation between
T and R

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$$\Box f'(R) = \frac{1}{3}\Big[\kappa T + R[1 - f'(R)] + 2f(R)\Big]$$

f(R) implies a *non-linear differential* relation between R and T

New scalar propagating degree of freedom!

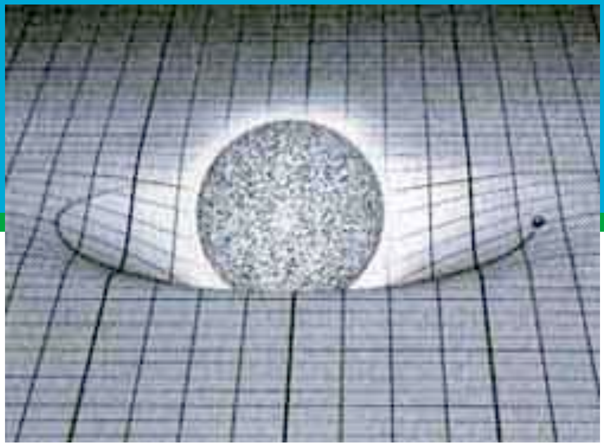
A preview: weak-field f(R)

- A lot of the literature on weak-field f(R) is confusing
- Reinterpret weak-field f(R) as taking a pressureless source ($w = 0$) and giving it $w_{\rm eff} \neq 0$
- The exact value of $w_{\rm eff}$ depends on the solution to the trace of the field equation
- Present the condition that allows us to determine the solution to the trace equation
- As discussed in Hu and Sawicki, viable cosmology and Solar System tests restricts us to f(R) theories where

$$|f(R_{\rm cos})| \lesssim \kappa\rho_{\rm crit} \ll \kappa\rho$$

$$f'(R_{\rm cos}) \ll 1$$

The weak field analysis



- Consider small deviations away from a flat metric

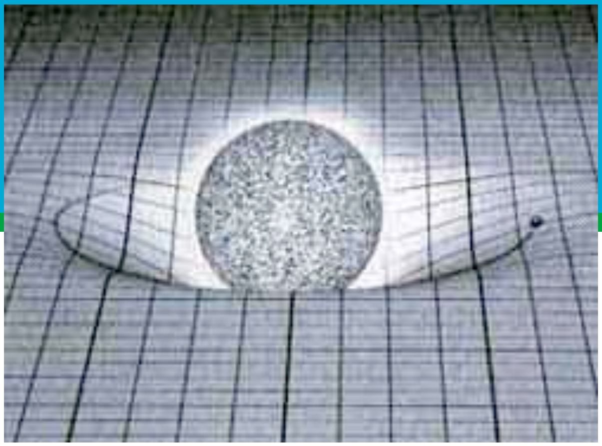
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

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

- Linearize the field equations sourced by a perfect fluid at rest

$$T_{\mu\nu} = (\rho + P)\delta_{\alpha 0}\delta_{\beta 0} + P\eta_{\mu\nu}$$

The weak field analysis



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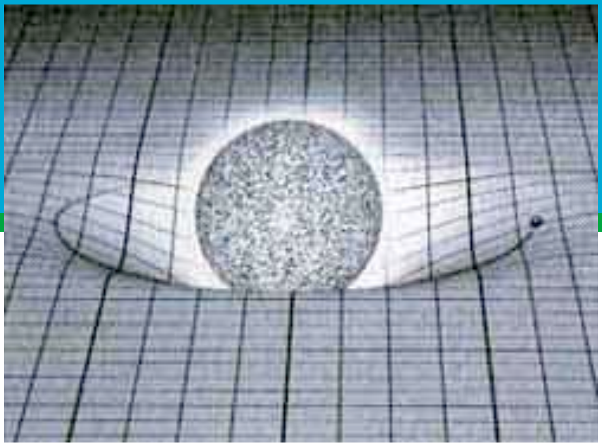
General relativity

$$P \neq 0$$

f(R) gravity

$$P = 0$$

The weak field analysis



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$$\downarrow$$

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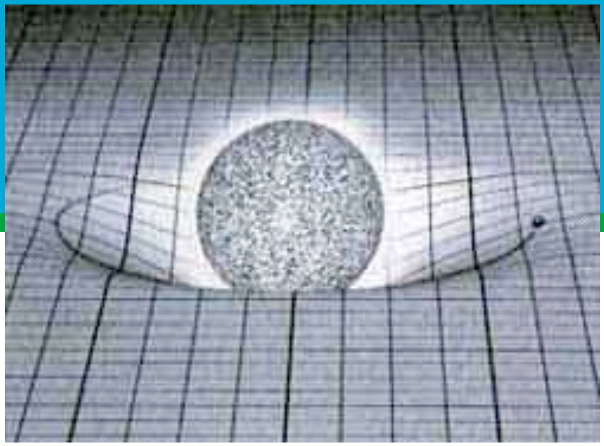

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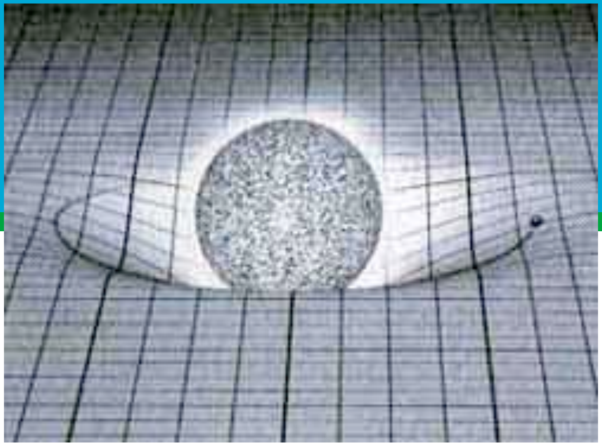
f(R) gravity $P = 0$

$$-\frac{1}{2}\Box h_{\alpha\beta} = \kappa \Big[\quad \rho\delta_{\alpha 0}\delta_{\beta 0} \quad +$$

The weak field analysis



- Linearized field equations are given by:

General relativity $P \neq 0$

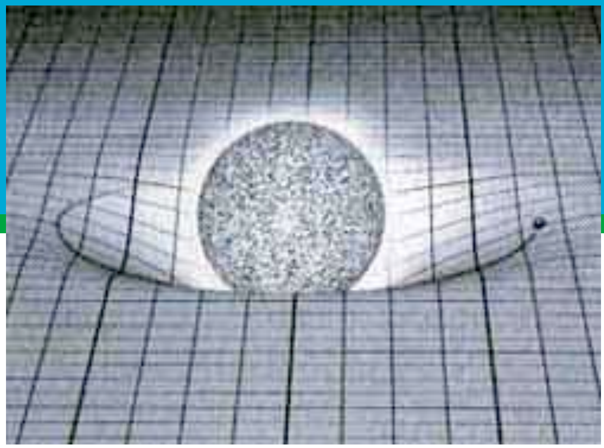
$$-\frac{1}{2}\Box h_{\alpha\beta} = \kappa\left[(\rho + P)\delta_{\alpha 0}\delta_{\beta 0} + \frac{1}{2}(\rho - P)\eta_{\alpha\beta}\right]$$

f(R) gravity $P = 0$

$$-\frac{1}{2}\Box h_{\alpha\beta} = \kappa\left[\rho\delta_{\alpha 0}\delta_{\beta 0} + \frac{1}{2}(\rho - \Gamma)\eta_{\alpha\beta}\right]$$

$$\Gamma \equiv -\frac{1}{3}\left[T + \frac{R}{\kappa}\right]$$

The weak field analysis



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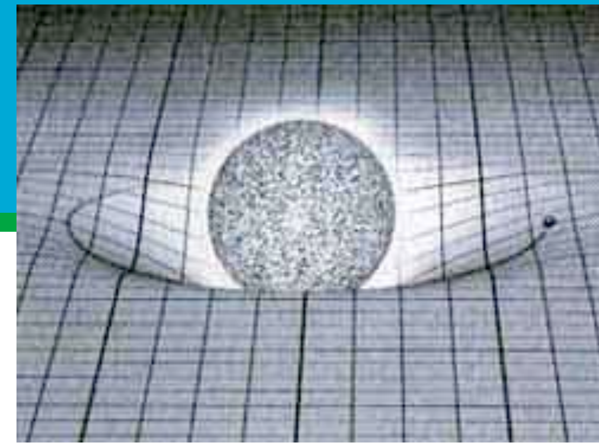
f(R) gravity
$P = 0$

$$-\frac{1}{2}\Box h_{\alpha\beta} = \kappa\left[\rho\delta_{\alpha 0}\delta_{\beta 0} + \frac{1}{2}(\rho - \Gamma)\eta_{\alpha\beta}\right]$$

- Interpreted in terms of GR, f(R) gravity produces an effective pressure: $\tilde{P} = \frac{1}{2}\Gamma \qquad \tilde{\rho} \equiv \rho - \frac{1}{2}\Gamma$

The weak field analysis



- In f(R) gravity we started with a pressureless source
- f(R) gravity produces an effective pressure $\tilde{P} = \frac{1}{2}\Gamma$
- Note: $\tilde{P}$ *does not* affect hydrostatic equilibrium
  → $\tilde{P}$ *only* seen through motion of test bodies

Henttunen, Multamaki, and Vilja

- We can re-express this as an effective equation of state

$$w_{\rm eff} = \frac{\tilde{P}}{\tilde{\rho}} = \frac{1}{2\rho/\Gamma - 1} \qquad \Gamma = -\frac{1}{3}\left[T + \frac{R}{\kappa}\right]$$

Determining w_{eff}

- w_{eff} is determined by the trace of the field equation:

$$\nabla^2 f'(R) = \frac{1}{3}[\kappa T + R] = \frac{\partial V_{\text{eff}}}{\partial f'(R)}$$

Determining $w_{\rm eff}$

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$$R = -\kappa T$$

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- GR extremum is stable if curvature is positive

$$\frac{\partial^2 V_{\rm eff}}{\partial [f'(R)]^2} = \frac{1}{3} f''(R)^{-1} > 0$$

Determining $w_{\rm eff}$

- *If* the system reaches the stable GR minimum:

$$R = -\kappa T$$

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$$\Rightarrow w_{\rm eff} = \frac{1}{2\rho/\Gamma - 1} = 0$$

- ... and we regain GR

Determining $w_{\rm eff}$

- We have established a stable GR minimum, but the theory *does not necessarily* attain this limit
- Two different behaviors of the trace of the field equation: $\nabla^2 f' = \frac{1}{3}[\kappa T + R]$

Linear $\qquad R = R_0 + \delta R \qquad$ Non-linear

Determining $w_{\rm eff}$

- We have established a stable GR minimum, but the theory *<u>does not necessarily</u>* attain this limit

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<u>Linear</u> $\quad R = R_0 + \delta R \quad$ <u>Non-linear</u>

$$\left|\frac{\delta R}{R_0}\right| \ll 1$$

$$|R| = \left|R_0\left(1 + \frac{\delta R}{R_0}\right)\right| \ll |\kappa T|$$

Chiba, Smith, and Erickcek (2007)

Determining $w_{\rm eff}$

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Non-linear

$$\left|\frac{\delta R}{R_0}\right| \gtrsim 1$$

$$R = -\kappa T$$

Hu and Sawicki (2007)

Determining $w_{\rm eff}$

- We have established a stable GR minimum, but the theory *does not necessarily* attain this limit

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<u>Linear</u> $R = R_0 + \delta R$ <u>Non-linear</u>

$$|R| \ll |\kappa T| \qquad\qquad R = -\kappa T$$

$$w_{\rm eff} = \frac{1}{2\rho/\Gamma - 1} = \frac{1}{5} \qquad\qquad w_{\rm eff} = \frac{1}{2\rho/\Gamma - 1} = 0$$

Determining $w_{\rm eff}$

- f(R) theories take a source with zero pressure and generate an effective equation of state

$$w_{\rm eff} = 1/5$$

or

$$w_{\rm eff} = 0$$

- The ability to linearize the trace equation determines $w_{\rm eff}$

- The ability to linearize the trace equation depends on the size of

$$\left|\frac{\delta R}{R_0}\right|$$

Determining $w_{\rm eff}$

- One can show that the linearization of a localized source is determined by the ratio

$$\left|\frac{\delta R}{R_0}\right| = \frac{2}{3}\left|\Phi_N \frac{1}{R_0 f''(R_0)}\right|$$

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- To connect to measurements, we can write w_{eff} in terms of the PPN parameter γ

$$\left|\frac{\delta R}{R_0}\right| = \frac{2}{3}\left|\Phi_N \frac{1}{R_0 f''(R_0)}\right| \begin{cases} \ll 1 \Rightarrow & \gamma = 1/2 \\ \gtrsim 1 \Rightarrow & \gamma = 1 \end{cases}$$

Chiba, Smith, and Erickcek (2007)

Hu and Sawicki (2007)

γ and the environemnt

- For a given localized source (star/galaxy) the value of γ depends on two quantites:

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- The local Newtonian potential

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- The local Newtonian potential

- Background curvature R_0 and functional form $f(R)$

- The background curvature, in turn, may depend on redshift

γ and the environemnt

- For a given localized source (star/galaxy) the value of γ depends on two quantites:

$$\left|\frac{\delta R}{R_0}\right| = \frac{2}{3}\left|\Phi_N \frac{1}{R_0 f''(R_0)}\right|$$

- This theory implies that it may be interesting to measure γ in various environments and at various redshifts...

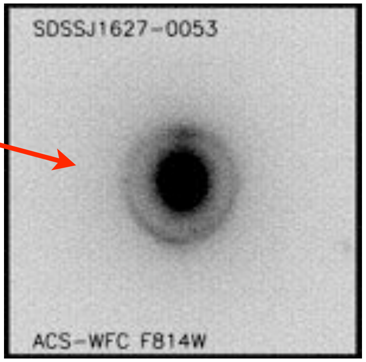
Measurement of γ

- We can measure γ from observations of galaxies
- Directly measure the velocity dispersion (spectra)

$$\sigma_{\rm obs}$$

- Measure the redshift and Einstein radius

$$\theta_E = (1+\gamma) 2\pi\sigma^2_{\rm obs}[D_{\rm LS}(z)/D_{\rm S}(z)]$$



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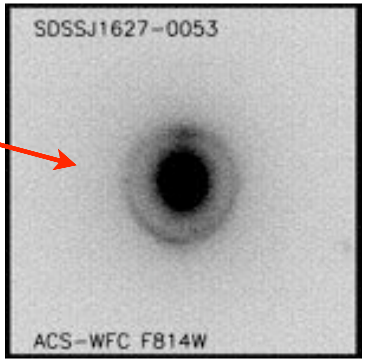


Measurement of γ

- f(R) gravity would predict:

- Two populations of γ

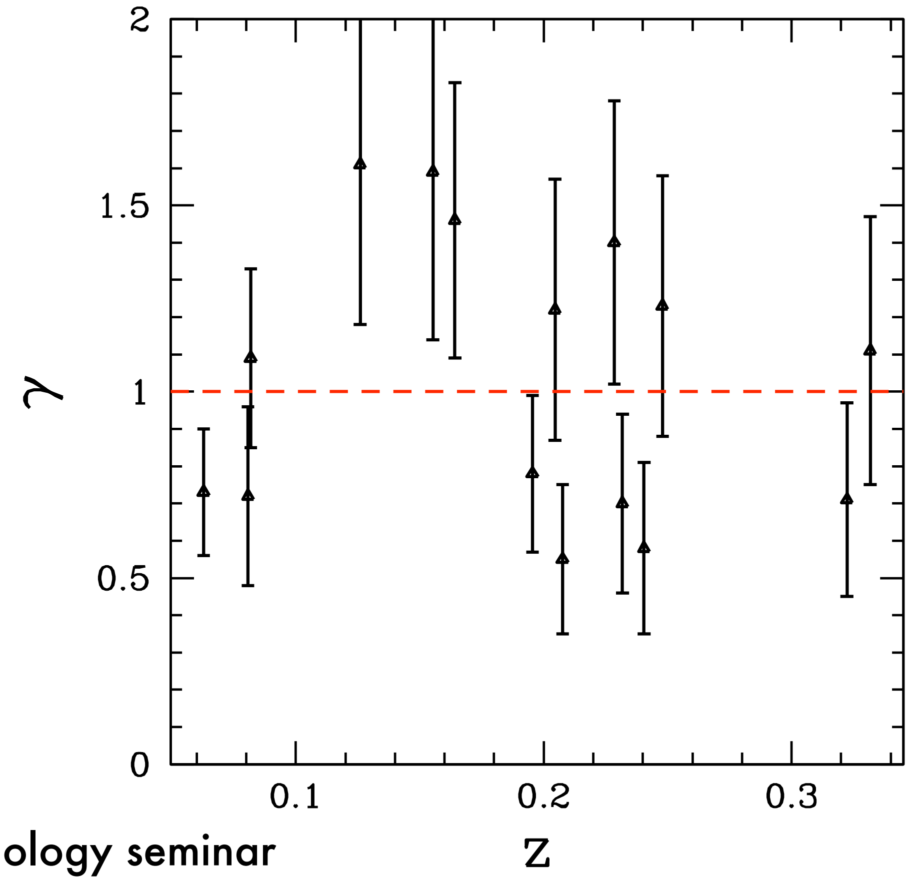
some systems will have $\gamma = 1/2$

others will have $\gamma = 1$

correlated with local environment and possibly redshift...

Measurement of γ : preliminary analysis

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



Treu et al.
Bolton et al.

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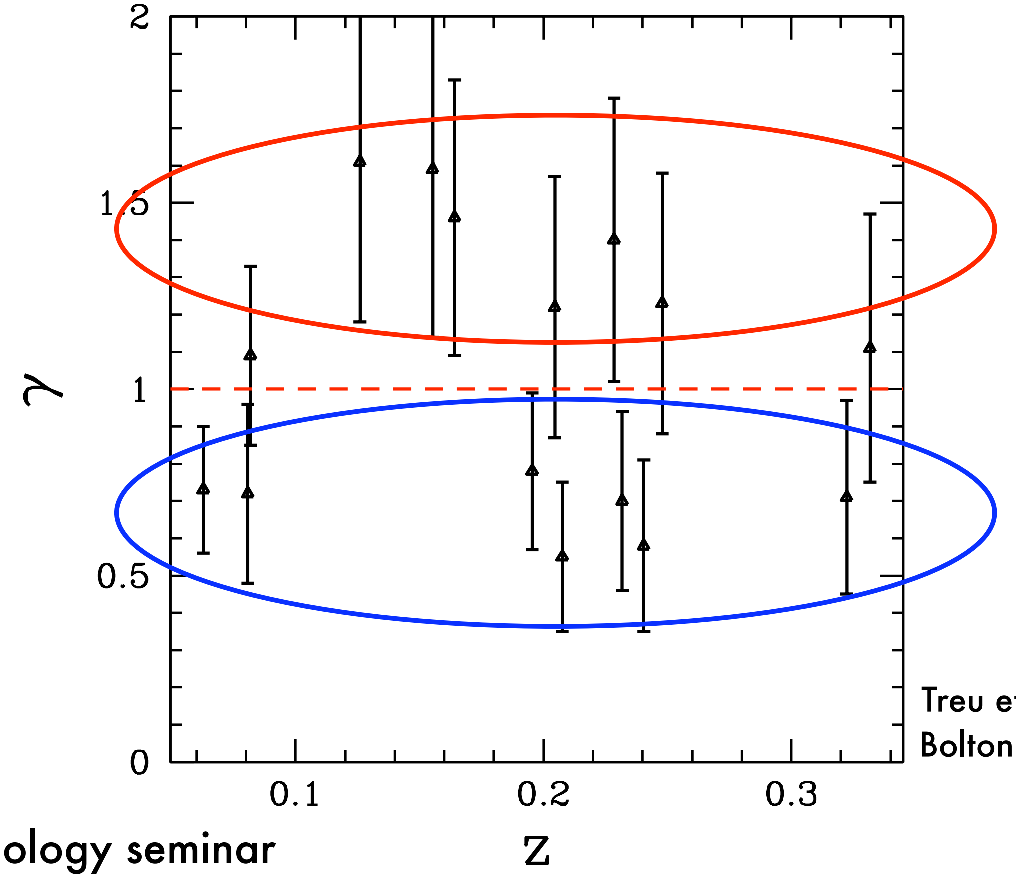


Treu et al.
Bolton et al.

Measurement of γ : preliminary analysis

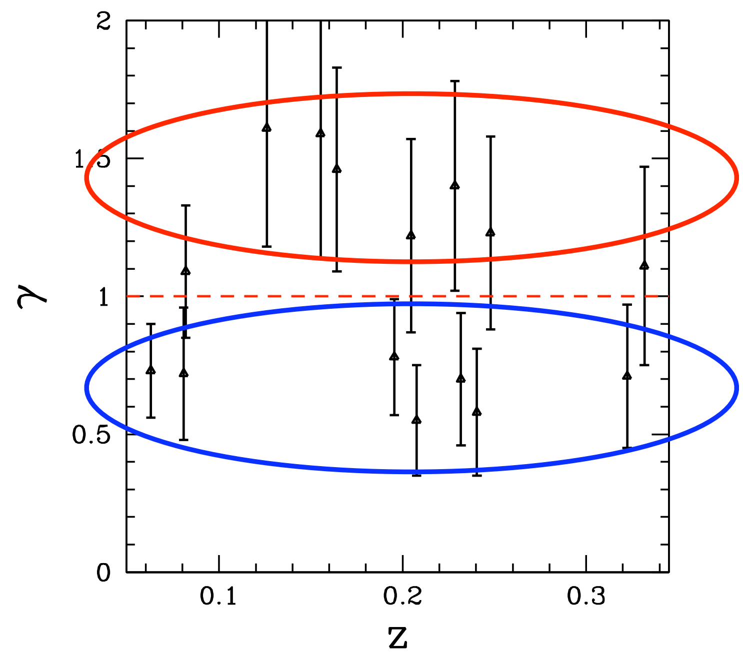
- Data from SDSS and HST for 15 elliptical lensing galaxies (SLACS survey, Bolton et al.)

- 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: peculiar velocity, nearest neighbors...



f(R) conclusions

- f(R) gravity is a theory constructed in order to explain the current epoch of accelerated expansion
- Discussed the weak-field limit of f(R) gravity:
    - Showed that a pressureless ($w = 0$) source, f(R) gravity can generate a $w_{\rm eff} \neq 0$
    - Leads to an environmentally dependent γ (= 1/2 or 1)
    - May probe this using current and future galaxy lens surveys

Chern-Simons gravity

The first observational constraint to

Chern

Simons

Gravity

arXiv:0708.0001

TLS, A. Erickcek, R. R. Caldwell, M. Kamionkowski

Chern-Simons (CS) gravity

* Chern-Simons gravity is defined by the action

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

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usual GR term

Chern-Simons (CS) gravity

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

$$\mathbf{R}\tilde{\mathbf{R}} \equiv \frac{1}{2}\epsilon_{\sigma\tau\gamma\delta}R^{\beta}{}_{\alpha}{}^{\gamma\delta}R^{\alpha}{}_{\beta}{}^{\sigma\tau}$$

Chern-Simons (CS) gravity

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usual GR term

Chern-Simons term

usual scalar kinetic and potential

$$\mathbf{R}\tilde{\mathbf{R}} \equiv \frac{1}{2}\epsilon_{\sigma\tau\gamma\delta}R^{\beta}{}_{\alpha}{}^{\gamma\delta}R^{\alpha}{}_{\beta}{}^{\sigma\tau}$$

Chern-Simons (CS) gravity: motavations

- Higher energy (curvature) correction to EH Lagrangian
- May produce interesting effects (parity violation) in the CMB/ gravitational-wave detection

  Lue, Wang, and Kamionkowski (1999)
  Jackiw and Pi (2003)
  Seto (2006)
- Produces lepton number current anomaly which may lead to matter-antimatter asymmetry

  Alexander, Peskin, and Sheikh-Jabbari (2006)
- It is a 'natural' consequence of the effective 4D string action

  Green and Schwartz (1985)
  Campbell et al. (1991)
- As we did before, we ask whether local tests of gravity can detect effects of CS gravity

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 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 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: $B^i \equiv \epsilon^{0ijk}\partial_j A_k$

Gravito-magnetism

- We can write the field equations in analogy to electromagnetism:

Gauss' Law: $$\vec{\nabla} \cdot \vec{E} = 4\pi G \rho$$

Faraday's Law: $$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

No gravito-magnetic monopoles: $$\vec{\nabla} \cdot \vec{B} = 0$$

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

Ampere's Law: $$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} - \frac{1}{m_{\rm cs}} \Box \vec{B} = 4\pi G \vec{J}$$

Lorentz force law

- Besides have analogous field equations

Gauss' Law: $\vec{\nabla}\cdot\vec{E} = 4\pi G\rho$

Faraday's Law: $\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$

No gravito-magnetic monopoles: $\vec{\nabla}\cdot\vec{B} = 0$

Ampere's Law: $\vec{\nabla}\times\vec{B} - \frac{\partial\vec{E}}{\partial t} - \frac{1}{m_{\rm cs}}\Box\vec{B} = 4\pi G\vec{J}$

- The geodesic equation can be written as a Lorentz force law:

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

Only Ampere's law is changed

Gauss' Law: $\vec{\nabla} \cdot \vec{E} = 4\pi G\rho$

Faraday's Law: $\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$

No gravito-magnetic monopoles: $\vec{\nabla} \cdot \vec{B} = 0$

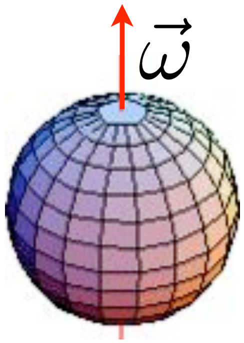
Ampere's Law: $\boxed{\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} - \frac{1}{m_{\rm cs}} \Box \vec{B} = 4\pi G \vec{J}}$

- *Only* Ampere's law is altered
- To look for an effect of CS gravity we need to produce a gravito-magnetic field
- Where are we going to find a mass current to generate a gravito-magnetic field?

The rotating earth

Credit: NASA, JPL, Doug Ellison

The rotating earth and CS gravity



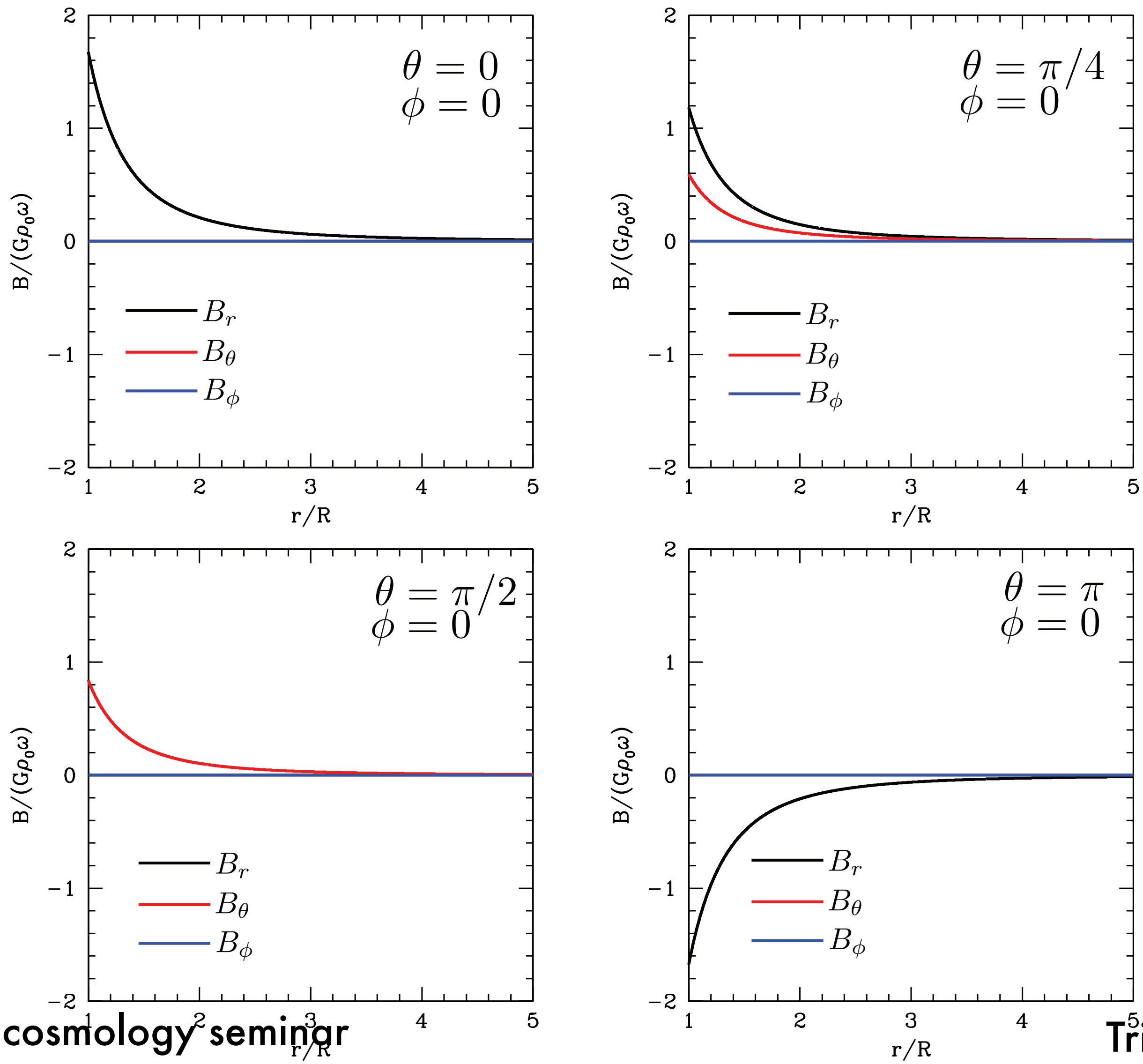
- The rotation of the earth generates the mass current

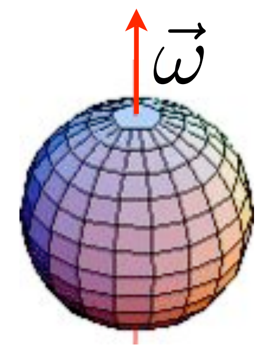
$$\vec{J} = \rho\vec{\omega} \times \vec{r}\Theta(R_\oplus - r)$$
$$= \rho r\omega\Theta(R_\oplus - r)\hat{\phi}$$

- We then solved the static CS Ampere's law:

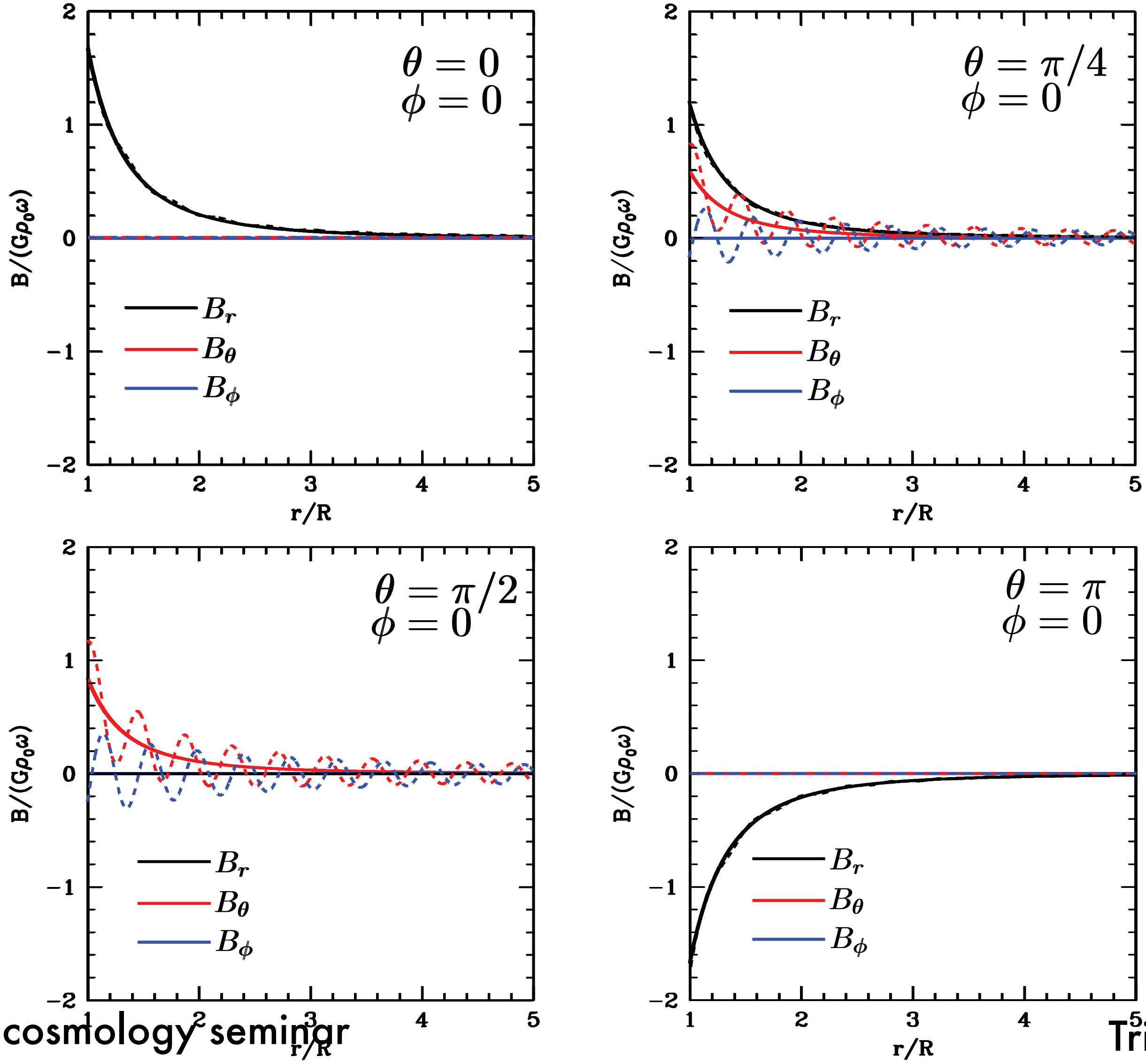
$$\vec{\nabla} \times \vec{B} - \frac{1}{m_{\rm cs}}\nabla^2\vec{B} = 4\pi G\vec{J}$$

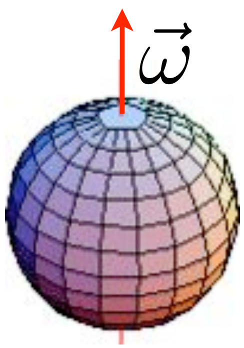
The rotating earth and CS gravity





The rotating earth and CS gravity





Smith, Erickcek, Caldwell, and Kamionkowski (2007)

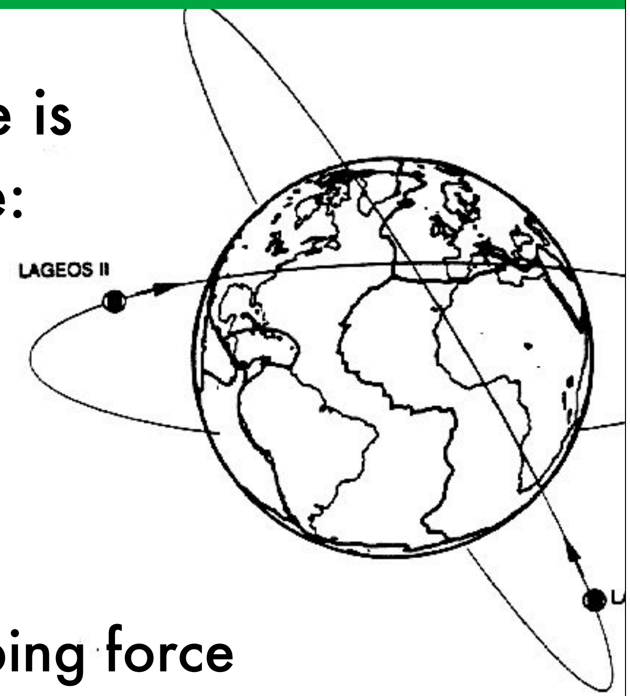
Seeing the gravito-magentic field

* 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

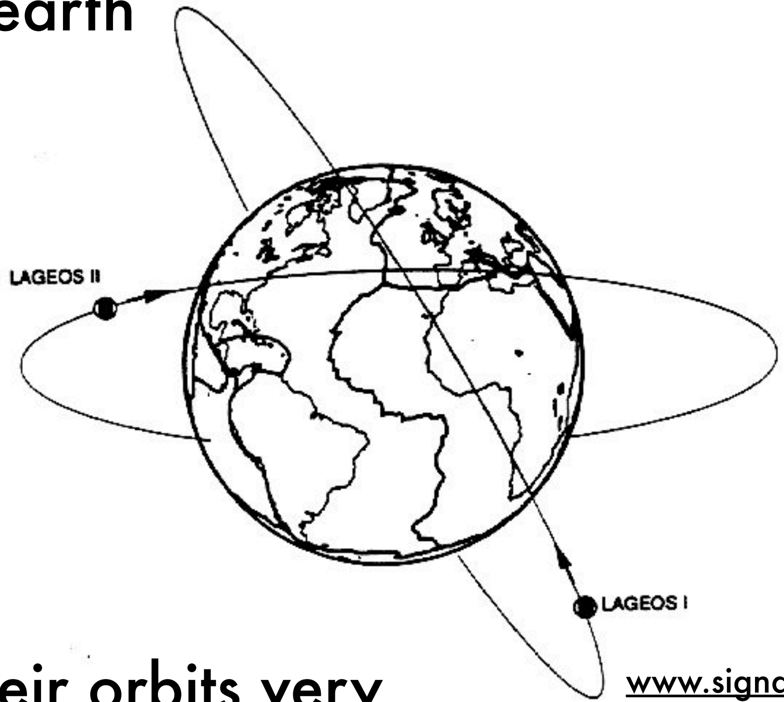


* Perturb about a Keplerian orbit
* Look at perturbed motion that builds up in time (secular motion)

LAGEOS I & II

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

Launched 1974 and 1992



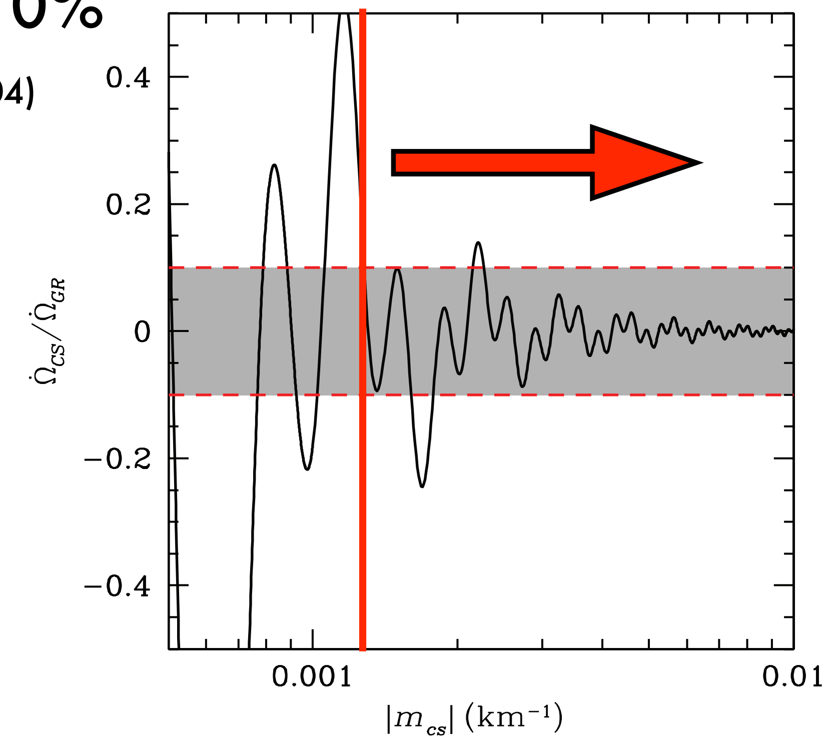
www.signale.de/lageos

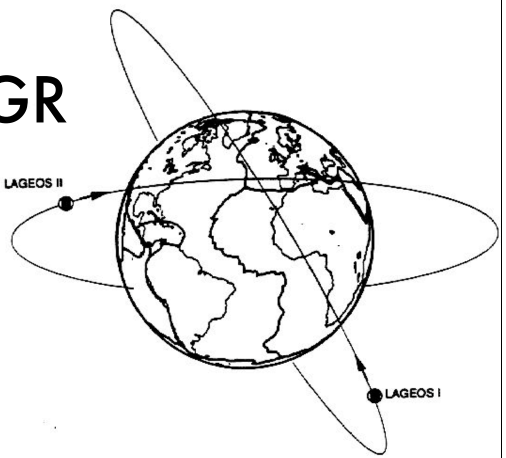
- Laser ranging measures their orbits very accurately

LAGEOS I & II

- LAGEOS measurements have confirmed the GR result to with 10%

  Ciufolini and Pavlis (2004)

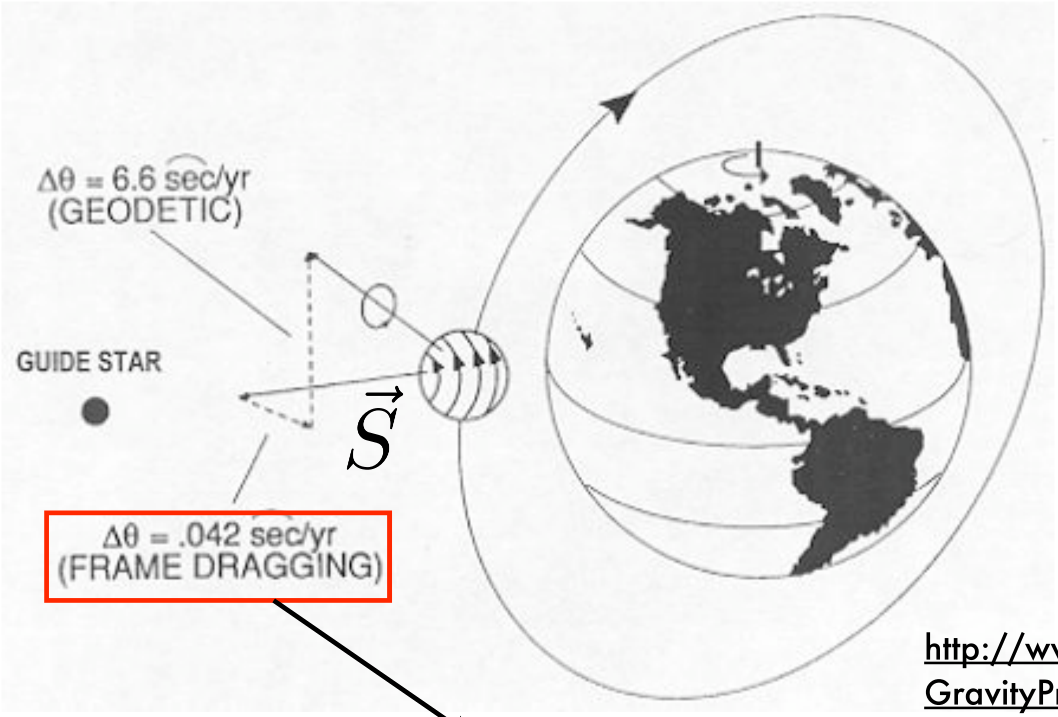




$$m_{cs} \gtrsim 0.001\ \text{km}^{-1} = 10^{-22}\ \text{GeV}$$

Gravity Probe-B

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

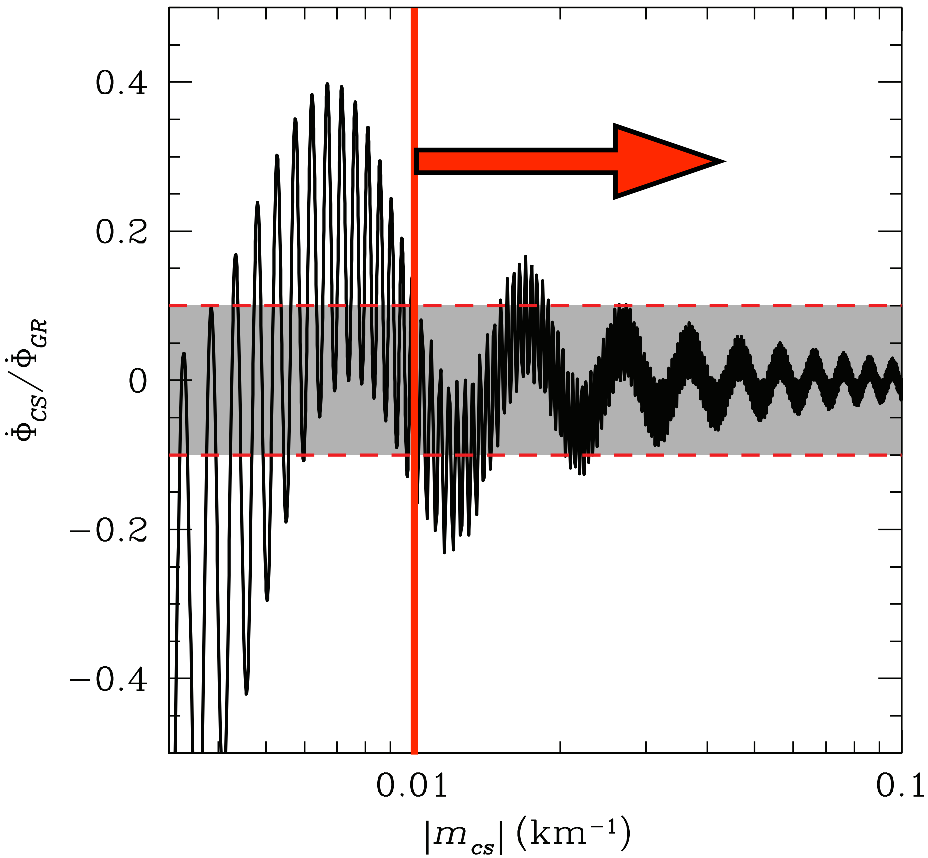


http://www.nap.edu/html/ssb_html/GravityProbeB/gpbch3.shtml

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

Gravity Probe-B

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



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

Final limits to m_{cs}

- Current observations place the limit

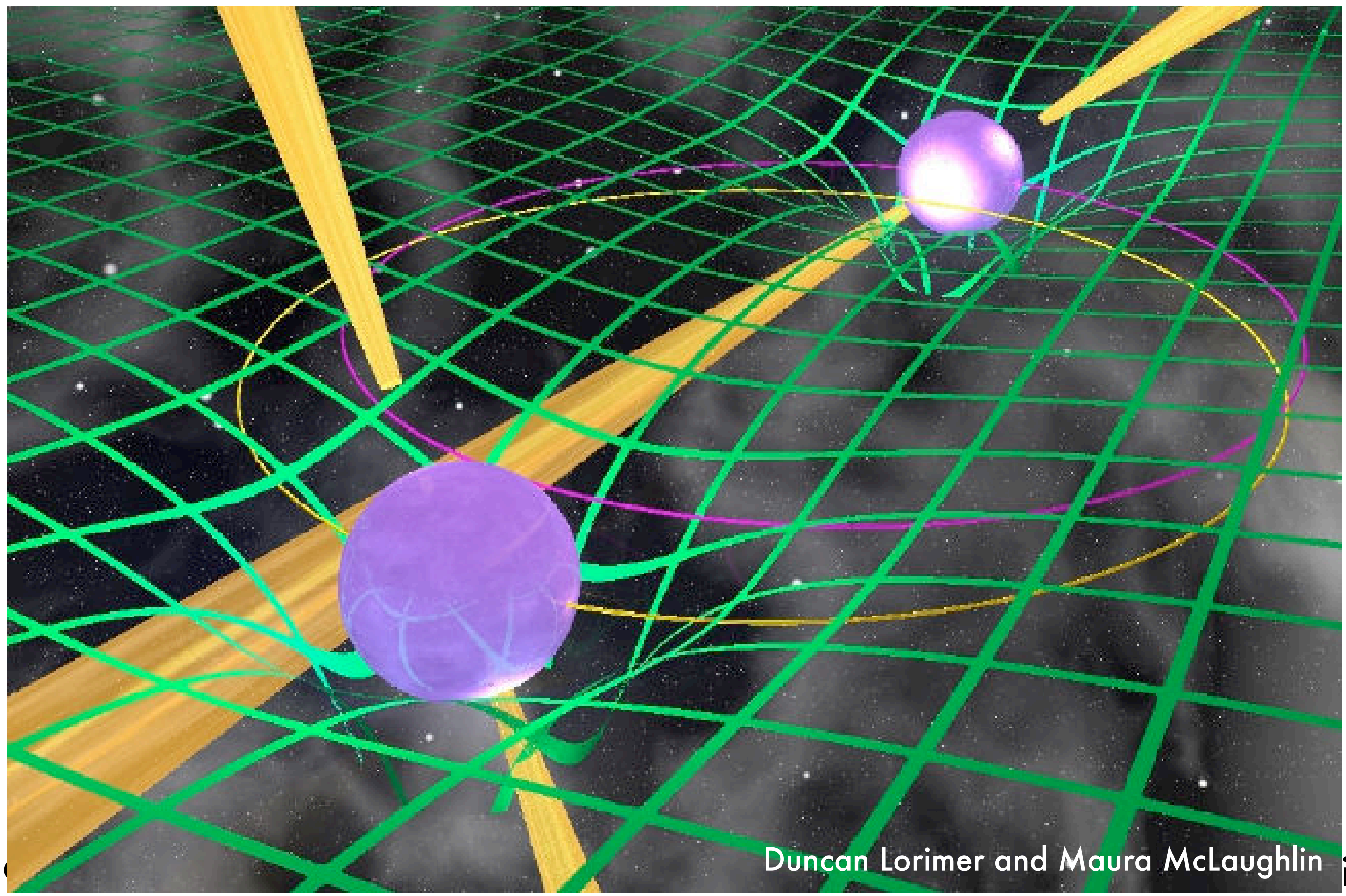
$$m_{cs} \geq 0.001 \text{ km}^{-1} = 10^{-22} \text{ GeV}$$

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

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

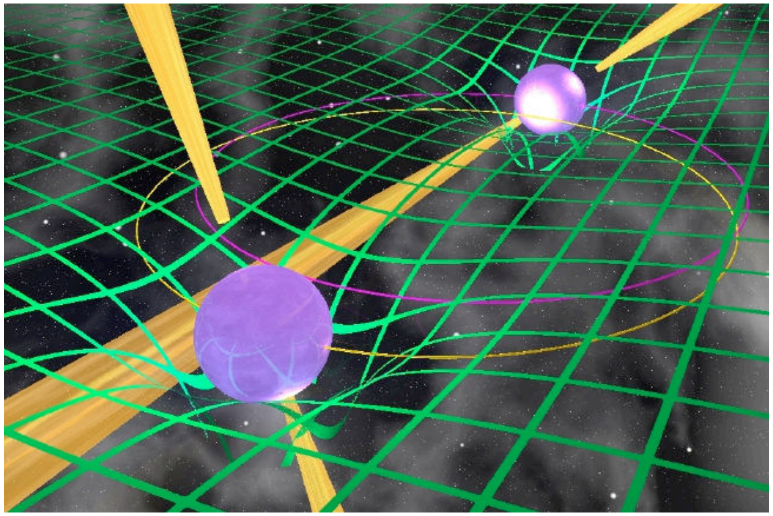
Double Pulsars!

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



Double Pulsars!

- Another place to look for gravito-magnetic effects is in double pulsars
- 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 semi-major axis)



Duncan Lorimer and Maura McLaughlin

Conclusions

* First ever observable constraints on the theory
* Violation of parity may be observable in the CMB/ direct detection of gravitational-waves
* May participate in the matter anti-matter asymmetry
* CS gravity is a higher energy modification of GR
* Future work to improve constraints through observations of double pulsars

Dark energy and modifications of gravity