Experimental Tests and Alternative Theories of Gravity

Gonzalo J. Olmo Alba

gonzalo.olmo@uv.es

University of Valencia (Spain) & UW-Milwaukee

Motivation

- High-precision cosmological tests have improved our view of the Universe.
- The Universe is homogeneous, isotropic, spatially flat and is undergoing a period of accelerated expansion.
- The description given only *ten years ago* by General Relativity is not compatible with the observed accelerated expansion.

Motivation

- High-precision cosmological tests have improved our view of the Universe.
- The Universe is homogeneous, isotropic, spatially flat and is undergoing a period of accelerated expansion.
- The description given only *ten years ago* by General Relativity is not compatible with the observed accelerated expansion.
- Something has to be done to justify the acceleration.

New Ingredients in the cosmic pie?

To justify the current acceleration we could . . .

- Introduce a new source of energy in $T_{\mu\nu}$

New Ingredients in the cosmic pie?

To justify the current acceleration we could ...

- Introduce a new source of energy in $T_{\mu\nu}$
  - Cosmological constant, long-range fields, ...
  - It has been done before and tends to work (dark matter in galaxies, neutrino in β decay,...).

New Ingredients or New Physics?

To justify the current acceleration we could . . .

- Introduce a new source of energy in $T_{\mu\nu}$
- Modify Einstein's equations.

New Ingredients or New Physics?

To justify the current acceleration we could . . .

- Introduce a new source of energy in $T_{\mu\nu}$
- Modify Einstein's equations.
  - Because of quantum effects in curved space, string theory, higher dimensional theories,. . .
  - GR could be the leading order of some effective gravity theory: $R \longrightarrow f(R) \approx R+$corrections .

New Ingredients or New Physics?

To justify the current acceleration we could . . .

- Introduce a new source of energy in $T_{\mu\nu}$
- Modify Einstein's equations.

Today's choice . . .

New Physics

$\rightarrow f(R)$ gravities

What are $f(R)$ gravities?

- $f(R)$ gravities can be seen as a generalization of GR

$$S_{GR} = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g} R + S_m[g_{\mu\nu}, \psi_m]$$

What are $f(R)$ gravities?

- $f(R)$ gravities can be seen as a generalization of GR

$$S_{GR} = \frac{1}{2\kappa^2}\int \underbrace{d^4x\sqrt{-g}}R + S_m[g_{\mu\nu}, \psi_m]$$

- 4D-Volume element
- Gravity Lagrangian
- Matter action
- Matter fields

What are $f(R)$ gravities?

- $f(R)$ gravities can be seen as a generalization of GR

$$S_{GR} = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}R + S_m[g_{\mu\nu}, \psi_m]$$

$$S_f = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}f(R) + S_m[g_{\mu\nu}, \psi_m]$$

What are $f(R)$ gravities?

- $f(R)$ gravities can be seen as a generalization of GR

$$S_f = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}f(R) + S_m[g_{\mu\nu},\psi_m]$$

- Two examples : $f(R) = R - \frac{\mu^4}{R}$, $f(R) = R + \frac{R^2}{M^2}$

What are $f(R)$ gravities?

- $f(R)$ gravities can be seen as a generalization of GR

$$S_f = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}f(R) + S_m[g_{\mu\nu},\psi_m]$$

- Two examples : $f(R) = R - \frac{\mu^4}{R}$, $f(R) = R + \frac{R^2}{M^2}$
- $f(R)$ can be classified as Metric Theories of Gravity.

What are $f(R)$ gravities?

- $f(R)$ gravities can be seen as a generalization of GR

$$S_f = \frac{1}{2\kappa^2}\int d^4x\sqrt{-g}f(R) + S_m[g_{\mu\nu},\psi_m]$$

- Two examples : $f(R) = R - \frac{\mu^4}{R}$, $f(R) = R + \frac{R^2}{M^2}$
- $f(R)$ can be classified as Metric Theories of Gravity.
- MTG are the only theories of gravity that can embody the **Einstein Equivalence Principle**.

So far . . .

We have seen that

- The accelerated expansion of the Universe is currently an unsolved problem.
- New theories have been proposed to justify the acceleration.

So far . . .

We have seen that

- The accelerated expansion of the Universe is currently an unsolved problem.
- New theories have been proposed to justify the acceleration.

How do these theories work?

- How do they change the gravitational physics?

So far . . .

We have seen that

- The accelerated expansion of the Universe is currently an unsolved problem.
- New theories have been proposed to justify the acceleration.

How do these theories work?

- How do they change the gravitational physics?
- Do they modify elementary-particle physics?

The Einstein Equivalence Principle

The **EEP** states that

- Inertial and gravitational masses coincide, i.e., all bodies fall with the same acceleration $\longrightarrow$ WEP.
- The outcome of any local non-gravitational experiment is independent of the velocity of the freely-falling reference frame in which it is performed $\longrightarrow$ Local Lorentz Invariance.
- The outcome of any local non-gravitational experiment is independent of where and when it is performed $\longrightarrow$ Local Position Invariance.

Gravity as a curved-space effect

If **EEP** is valid

- The non-gravitational laws of physics can be formulated by writing the laws of special relativity using the language of differential geometry:

$$\eta_{\mu\nu} \longrightarrow g_{\mu\nu}(x)$$

Gravity as a curved-space effect

If **EEP** is valid

- The non-gravitational laws of physics can be formulated by writing the laws of special relativity using the language of differential geometry:

$$\eta_{\mu\nu} \rightarrow g_{\mu\nu}(x)$$

- Gravitation would be described by an MTG

$$S_{MTG} = S_G[g_{\mu\nu}, \phi, A_\mu, B_{\mu\nu}, \Gamma^{\alpha}_{\mu\nu}, \ldots] + S_m[g_{\mu\nu}, \psi_m]$$

Gravity as a curved-space effect

If **EEP** is valid

- The non-gravitational laws of physics can be formulated by writing the laws of special relativity using the language of differential geometry:

$$\eta_{\mu\nu} \rightarrow g_{\mu\nu}(x)$$

- Gravitation would be described by an MTG

$$S_{MTG} = S_G[g_{\mu\nu}, \phi, A_\mu, B_{\mu\nu}, \Gamma^\alpha_{\mu\nu}, \ldots] + S_m[g_{\mu\nu}, \psi_m]$$

However …

Is the **EEP** really valid ?

Weak Equivalence Principle

- Can be tested comparing the acceleration of two bodies in an external field: $m_I a = m_p g$
- m_I and m_p are made up of rest energy, e.m. energy, weak-interaction energy,...
- If m_I and m_p have different contributions

$$m_p = m_I + \sum_i \eta^i \frac{E^i}{c^2}$$

  - $E^i \equiv$ Internal Energy generated by the i-th interaction
  - $\eta^i \equiv$ strength of the violation

Weak Equivalence Principle

- Can be tested comparing the acceleration of two bodies in an external field: $m_I a = m_p g$
- m_I and m_p are made up of rest energy, e.m. energy, weak-interaction energy,...
- If m_I and m_p have different contributions

$$\eta \equiv \frac{2|a_1 - a_2|}{|a_1 + a_2|} = \sum_i \eta^i \left[\frac{E_1^i}{m_1 c^2} - \frac{E_2^i}{m_2 c^2} \right]$$

  - $E^i \equiv$ Internal Energy generated by the i-th interaction
  - $\eta^i \equiv$ strength of the violation

Weak Equivalence Principle

- Can be tested comparing the acceleration of two bodies in an external field: $m_I a = m_p g$
- m_I and m_p are made up of rest energy, e.m. energy, weak-interaction energy,...
- If m_I and m_p have different contributions

$$\eta \equiv \frac{2|a_1 - a_2|}{|a_1 + a_2|} = \sum_i \eta^i \left[\frac{E_1^i}{m_1 c^2} - \frac{E_2^i}{m_2 c^2} \right]$$

  - $E^i \equiv$ Internal Energy generated by the i-th interaction
  - $\eta^i \equiv$ strength of the violation
- The current bound is $\eta = 4 \cdot 10^{-13}$

Local Lorentz Invariance

- Are elementary-particle experiments tests of LLI?

Local Lorentz Invariance

- Are elementary-particle experiments tests of LLI?
  They are consistent, though not “clean” tests

Local Lorentz Invariance

- Are elementary-particle experiments tests of LLI? They are consistent, though not “clean” tests
- LLI would be violated if c would vary from one inertial reference frame to another.
- This violation would lead to shifts in the energy levels of atoms and nuclei depending on the direction of the quantization axis.

Local Lorentz Invariance

- Are elementary-particle experiments tests of LLI? They are consistent, though not “clean” tests
- LLI would be violated if c would vary from one inertial reference frame to another.
- This violation would lead to shifts in the energy levels of atoms and nuclei depending on the direction of the quantization axis.
- The current bound is $\delta = |c^{-2} - 1| < 10^{-22}$

Local Position Invariance

- Can be tested by measuring the gravitational redshift of light.
- The comparison of the frequencies of two clocks at different locations boils down to the comparison of the velocities of two local Lorentz frames at rest at those positions.

$$\frac{\Delta\nu}{\nu} = (1+\alpha)\frac{\Delta U}{c^2}$$

Local Position Invariance

- Can be tested by measuring the gravitational redshift of light.
- The comparison of the frequencies of two clocks at different locations boils down to the comparison of the velocities of two local Lorentz frames at rest at those positions.

$$\frac{\Delta\nu}{\nu} = (1+\alpha)\frac{\Delta U}{c^2}$$

- The current bound is $|\alpha| < 10^{-5}$.

Local Position Invariance

- Can be tested by measuring the gravitational redshift of light.
- The comparison of the frequencies of two clocks at different locations boils down to the comparison of the velocities of two local Lorentz frames at rest at those positions.

$$\frac{\Delta\nu}{\nu} = (1+\alpha)\frac{\Delta U}{c^2}$$

- The current bound is $|\alpha| < 10^{-5}$.
- It can also be tested by measuring the constancy of the non-gravitational constants.

So far . . .

We have seen that

- $f(R)$ gravities, like **GR** and any other MTG, respect locally the physics of special relativity
  - They do not modify elementary-particle physics

So far . . .

We have seen that

- $f(R)$ gravities, like **GR** and any other MTG, respect locally the physics of special relativity
  - They do not modify elementary-particle physics
- The new interactions and phenomena predicted by string theory, higher dimensional theories, . . . are likely to violate the **EEP**
  - Testing the **EEP** we could place bounds on the strength of those interactions

So far . . .

We have seen that

- $f(R)$ gravities, like **GR** and any other MTG, respect locally the physics of special relativity
  - They do not modify elementary-particle physics
- The new interactions and phenomena predicted by string theory, higher dimensional theories, . . . are likely to violate the **EEP**
  - Testing the **EEP** we could place bounds on the strength of those interactions

We will study now the gravitational tests of MTG

Gravitational Tests

- Post-Newtonian gravity
- Stellar systems
- Cosmology
- Gravitational waves

Gravitational Tests

- Post-Newtonian gravity
  - Deflection of light
  - Time delay of light
  - Perihelion Shift of Mercury
  - Tests of SEP
  - Conservation laws
  - Geodesic precession (gyroscope)
  - Gravitomagnetism

Gravitational Tests

- Post-Newtonian gravity
- Stellar systems
    - Gravitational wave damping of orbital period
    - Internal structure dependence
    - Strong gravity effects

Gravitational Tests

- Post-Newtonian gravity
- Stellar systems
- Cosmology
  - Distribution of anisotropies
  - Hubble diagram of SNIa
  - Age of the Universe

Gravitational Tests

- Post-Newtonian gravity
- Stellar systems
- Cosmology
- Gravitational waves
  - Polarization
  - Speed of grav.waves

Gravitational Tests

- Post-Newtonian gravity
- Stellar systems
- Cosmology
- Gravitational waves

Parametrized P-N Formalism

- In the weak-field, slow-motion limit, the metric of nearly every MTG has the same structure

Parametrized P-N Formalism

- In the weak-field, slow-motion limit, the metric of nearly every MTG has the same structure

$$
\begin{aligned}
g_{00} &= -1 + 2U - 2\beta U^2 - 2\xi \Phi_W + (2\gamma + 2 + \alpha_3 + \zeta_1 - 2\xi)\Phi_1 \\
&\quad +2(3\gamma - 2\beta + 1 + \zeta_2 + \xi)\Phi_2 + 2(1 + \zeta_3)\Phi_3 + 2(3\gamma + 3\zeta_4 - 2\xi)\Phi_4 \\
&\quad -(\zeta_1 - 2\xi)\mathcal{A} - (\alpha_1 - \alpha_2 - \alpha_3)w^2 U - \alpha_2 w^i w^j U_{ij} + (2\alpha_3 - \alpha_1)w^i V_i \\
&\quad +O(\epsilon^3) \\
g_{0i} &= -\frac{1}{2}(4\gamma + 3 + \alpha_1 - \alpha_2 + \zeta_1 - 2\xi)V_i - \frac{1}{2}(1 + \alpha_2 - \zeta_1 + 2\xi)W_i \\
&\quad -\frac{1}{2}(\alpha_1 - 2\alpha_2)w^i U - \alpha_2 w^j U_{ij} + O(\epsilon^{5/2}) \\
g_{ij} &= (1 + 2\gamma U + O(\epsilon^2))\delta_{ij}
\end{aligned}
$$

PPN parameters $\gamma\,,\ \beta\,,\ \xi\,,\ \alpha_1\,,\ \alpha_2\,,\ \alpha_3\,,\ \zeta_1\,,\ \zeta_2\,,\ \zeta_3\,,\ \zeta_4\,.$

Parametrized P-N Formalism

- In the weak-field, slow-motion limit, the metric of nearly every MTG has the same structure
- With the potentials given by

$$
\begin{aligned}
U &= \int \frac{\rho'}{|\mathbf{x}-\mathbf{x}'|} d^3x' \,, \qquad U_{ij} = \int \frac{\rho'(x-x')_i(x-x')_j}{|\mathbf{x}-\mathbf{x}'|^3} d^3x' \\
\Phi_W &= \int \frac{\rho'\rho''(\mathbf{x}-\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|^3} \cdot \left(\frac{\mathbf{x}'-\mathbf{x}''}{|\mathbf{x}-\mathbf{x}''|} - \frac{\mathbf{x}-\mathbf{x}''}{|\mathbf{x}'-\mathbf{x}''|} \right) d^3x' d^3x'' \\
\mathcal{A} &= \int \frac{\rho'[\mathbf{v}'\cdot(\mathbf{x}-\mathbf{x}')]^2}{|\mathbf{x}-\mathbf{x}'|^3} d^3x' \,, \qquad \Phi_1 = \int \frac{\rho' v'^2}{|\mathbf{x}-\mathbf{x}'|} d^3x' \\
\Phi_2 &= \int \frac{\rho' U'}{|\mathbf{x}-\mathbf{x}'|} d^3x' \,, \quad \Phi_3 = \int \frac{\rho'\Pi'}{|\mathbf{x}-\mathbf{x}'|} d^3x' \,, \quad \Phi_4 = \int \frac{p'}{|\mathbf{x}-\mathbf{x}'|} d^3x' \\
V_i &= \int \frac{\rho' v_i'}{|\mathbf{x}-\mathbf{x}'|} d^3x' \,, \qquad W_i = \int \frac{\rho'[\mathbf{v}'\cdot(\mathbf{x}-\mathbf{x}')](x-x')_i}{|\mathbf{x}-\mathbf{x}'|^3} d^3x'
\end{aligned}
$$

Parametrized P-N Formalism

- In the weak-fiel, slow-motion limit, the metric of nearly every MTG has the same structure
- It is characterized by a set of parameters: $\gamma\,,\,\beta\,,\,\xi\,,\,\alpha_1\,,\,\alpha_2\,,\,\alpha_3\,,\,\zeta_1\,,\,\zeta_2\,,\,\zeta_3\,,\,\zeta_4\,.$
- The predictions of a particular theory depend on these parameters

Parametrized P-N Formalism

- In the weak-fiel, slow-motion limit, the metric of nearly every MTG has the same structure
- It is characterized by a set of parameters: $\gamma\,,\,\beta\,,\,\xi\,,\,\alpha_1\,,\,\alpha_2\,,\,\alpha_3\,,\,\zeta_1\,,\,\zeta_2\,,\,\zeta_3\,,\,\zeta_4\,.$
- The predictions of a particular theory depend on these parameters
- We will need to obtain the PPN parameters of $f(R)$ gravities.

P-N limit of $f(R)$ gravities

- The Newtonian limit of these theories was recently discussed in *R.Dick*, **Gen.Rel.Grav.** $36\ (2004)$
- The correct limit could be obtained if $|f(R_0)f''(R_0)| \ll 1.$

P-N limit of $f(R)$ gravities

- The Newtonian limit of these theories was recently discussed in *R.Dick*, **Gen.Rel.Grav.**36 (2004)
- The correct limit could be obtained if $|f(R_0)f''(R_0)| \ll 1$.
- However, these theories are much more involved due to the cosmological evolution of the boundary conditions

P-N limit of $f(R)$ gravities

- The Newtonian limit of these theories was recently discussed in *R.Dick*, **Gen.Rel.Grav.**$36\ (2004)$
- The correct limit could be obtained if $|f(R_0)f''(R_0)| \ll 1$.
- However, these theories are much more involved due to the cosmological evolution of the boundary conditions
- I have the Newtonian limit and the parameter γ

P-N limit of $f(R)$ gravities

- The Newtonian limit of these theories was recently discussed in *R.Dick*, **Gen.Rel.Grav.**$36\ (2004)$
- The correct limit could be obtained if $|f(R_0)f''(R_0)| \ll 1.$
- However, these theories are much more involved due to the cosmological evolution of the boundary conditions
- I have the Newtonian limit and the parameter γ
- ... I hope to have the remaining parameters next week or so

Details of $f(R)$ gravities

- Defining a scalar field $\phi = \frac{df}{dR}$
- And a potential $V(\phi) = Rf'(R) - f(R)$
- The first corrections of the P-N limit are

$$
\begin{aligned}
g_{00} &\approx -1 + \frac{\kappa^2}{4\pi\phi_0}\frac{M}{r}\left(1 + \frac{e^{-m_\phi r}}{3}\right) + \frac{V_0}{6\phi_0}r^2 \\
g_{ij} &\approx \left[1 + \frac{\kappa^2}{4\pi\phi_0}\frac{M}{r}\left(1 - \frac{e^{-m_\phi r}}{3}\right) - \frac{V_0}{6\phi_0}r^2\right]\delta_{ij}
\end{aligned}
$$

Where

$$m_\phi^2 = \frac{\phi_0 V''(\phi_0) - V'(\phi_0)}{3}$$

Compare

Details of $f(R)$ gravities

- Defining a scalar field $\phi = \frac{df}{dR}$
- And a potential $V(\phi) = Rf'(R) - f(R)$
- The relevant parameters are

$$G_N = \frac{1}{\phi_0}\left(1 + \frac{e^{-m_\phi r}}{3}\right)$$

$$\gamma = \frac{3 - e^{-m_\phi r}}{3 + e^{-m_\phi r}}$$

Where

$$m_\phi^2 = \frac{\phi_0 V''(\phi_0) - V'(\phi_0)}{3}$$

Compare

Examples

- The Carroll et al. model $f(R) = R - \frac{\mu^4}{R}$

Examples

- The Carroll et al. model $f(R) = R - \frac{\mu^4}{R}$
  - is characterized by

$$m_\phi^2 = -\frac{R_0}{6\mu^4}(R_0^2 + 3\mu^4)$$

Examples

- The Carroll et al. model $f(R) = R - \frac{\mu^4}{R}$
  - is characterized by

$$m_\phi^2 = \frac{R_0}{6\mu^4}(R_0^2 - 3\mu^4),\ R_0 \propto \frac{1}{t^2}$$

  - Not valid in its original form
  - If $\mu^4 \to -\mu^4$, it is valid at early times only.

Examples

- The Carroll et al. model $f(R) = R - \frac{\mu^4}{R}$
  - is characterized by

$$m_\phi^2 = \frac{R_0}{6\mu^4}(R_0^2 - 3\mu^4), \; R_0 \propto \frac{1}{t^2}$$

  - In general, $f(R) = R + \frac{\mu^{2n+2}}{R^n}$ are not viable models

Examples

- The Carroll et al. model $f(R) = R - \frac{\mu^4}{R}$
  - is characterized by

$$m_\phi^2 = \frac{R_0}{6\mu^4}(R_0^2 - 3\mu^4), \;\; R_0 \propto \frac{1}{t^2}$$

  - In general, $f(R) = R + \frac{\mu^{2n+2}}{R^n}$ are not viable models
- The Starobinsky model $f(R) = R + \frac{R^2}{M^2}$
  - It is characterized by

$$m_\phi^2 = \frac{M^2}{6}$$

Examples

- The Carroll et al. model $f(R) = R - \frac{\mu^4}{R}$
  - is characterized by

$$m_\phi^2 = \frac{R_0}{6\mu^4}(R_0^2 - 3\mu^4), \;\; R_0 \propto \frac{1}{t^2}$$

  - In general, $f(R) = R + \frac{\mu^{2n+2}}{R^n}$ are not viable models
- The Starobinsky model $f(R) = R + \frac{R^2}{M^2}$
  - In general, $f(R) = R + \frac{R^n}{M^{2n+2}}$ are always viable models

$$m_\phi^2 = \frac{M^2}{6}$$

Summary and Conclusions

- $f(R)$ gravities have been proposed to justify the cosmic speed-up

Summary and Conclusions

- $f(R)$ gravities have been proposed to justify the cosmic speed-up
- They are MTG and, therefore, do not modify the physics of special relativity

Summary and Conclusions

- $f(R)$ gravities have been proposed to justify the cosmic speed-up
- They are MTG and, therefore, do not modify the physics of special relativity
- Every experimental test of the **EEP** is potentially a deadly test for gravity as a curved spacetime phenomenon

Summary and Conclusions

- $f(R)$ gravities have been proposed to justify the cosmic speed-up
- They are MTG and, therefore, do not modify the physics of special relativity
- Every experimental test of the **EEP** is potentially a deadly test for gravity as a curved spacetime phenomenon
- The post-Newtonian regime is a good arena to test gravity theories

Summary and Conclusions

- $f(R)$ gravities have been proposed to justify the cosmic speed-up
- They are MTG and, therefore, do not modify the physics of special relativity
- Every experimental test of the **EEP** is potentially a deadly test for gravity as a curved spacetime phenomenon
- The post-Newtonian regime is a good arena to test gravity theories
- The post-Newtonian limit of $f(R)$ gravities is constrained by the cosmic evolution

?

There is nothing in this slide that can be of any interest to you

Parametrized P-N Formalism

- In the weak-fiel, slow-motion limit, the metric of nearly every MTG has the same structure

$$
\begin{aligned}
g_{00} &= -1 + 2U - 2\beta U^2 - 2\xi\Phi_W + (2\gamma + 2 + \alpha_3 + \zeta_1 - 2\xi)\Phi_1 \\
&\quad +2(3\gamma - 2\beta + 1 + \zeta_2 + \xi)\Phi_2 + 2(1 + \zeta_3)\Phi_3 + 2(3\gamma + 3\zeta_4 - 2\xi)\Phi_4 \\
&\quad -(\zeta_1 - 2\xi)\mathcal{A} - (\alpha_1 - \alpha_2 - \alpha_3)w^2 U - \alpha_2 w^i w^j U_{ij} + (2\alpha_3 - \alpha_1)w^i V_i \\
&\quad +O(\epsilon^3) \\
g_{0i} &= -\frac{1}{2}(4\gamma + 3 + \alpha_1 - \alpha_2 + \zeta_1 - 2\xi)V_i - \frac{1}{2}(1 + \alpha_2 - \zeta_1 + 2\xi)W_i \\
&\quad -\frac{1}{2}(\alpha_1 - 2\alpha_2)w^i U - \alpha_2 w^j U_{ij} + O(\epsilon^{5/2}) \\
g_{ij} &= (1 + 2\gamma U + O(\epsilon^2))\delta_{ij}
\end{aligned}
$$

PPN parameters γ , β , ξ , α_1 , α_2 , α_3 , ζ_1 , ζ_2 , ζ_3 , ζ_4 .

Back

Significance of the PPN parameters

Parameter	What it measures relative to GR	Value in GR
γ	How much space-curvature produced by unit rest mass?	1
β	How much “nonlinearity” in the superposition law for gravity?	1
ξ	Preferred-location effects?	0
α_i	Preferred-frame effects?	0
α_3 ζ_j	Violation of conservation of total momentum?	0 0

Back

Tests of the parameter γ

- The deflection of light

$$\delta\theta = \frac{1}{2}(1+\gamma)\left[-\frac{4m_\odot}{d}\cos\chi + \frac{4m_\odot}{d_r}\left(\frac{1+\cos\Phi_r}{2}\right)\right],$$

where d and d_r are the distances of closest approach of the source and reference rays respectively, Φ_r is the angular separation between the Sun and the reference source, and χ is the angle between the Sun-source and the Sun-reference directions, projected on the plane of the sky.

Back

Tests of the parameter γ

- The Time Delay of Light

  A radar signal sent across the solar system past the Sun to a planet or satellite and returned to the Earth suffers an additional non-Newtonian delay in its round-trip travel time, given by

$$\delta t = 2(1+\gamma)m_\odot \ln[(r_\oplus + \mathbf{x}_\oplus \cdot \mathbf{n})(r_e - \mathbf{x}_e \cdot \mathbf{n})/d^2]$$

Back

Tests of the parameter γ

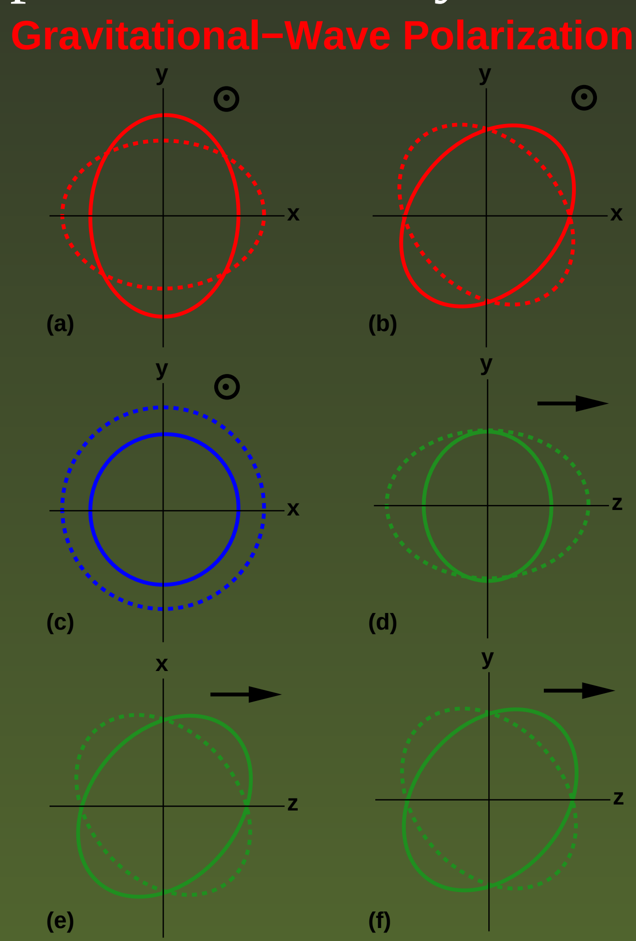
- The perihelion shift of Mercury

$$\dot{\omega} \approx 42.''98 \left[\frac{1}{3}(2 + 2\gamma - \beta) + 3 \cdot 10^{-4} (J_2 / 10^{-7}) \right]$$

Back

Gravitational waves polarization

- Six polarization modes permited in any MTG

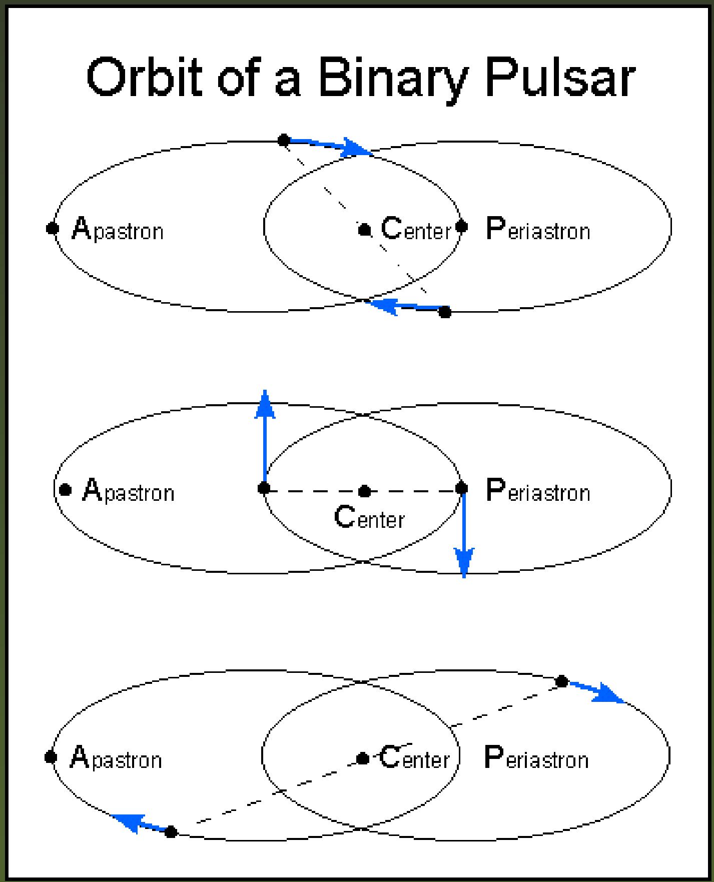


- Shown displacement of each mode induced on a ring of test particles
- Propagation in $+z$ direction
- No displacement out of the plane indicated
- In GR only (a) and (b)
- In scalar-tensor gravity, (c) is also possible

Back

The binary pulsar PSR1913+16

- Magnetized NS rotating with $T = 59$ ms

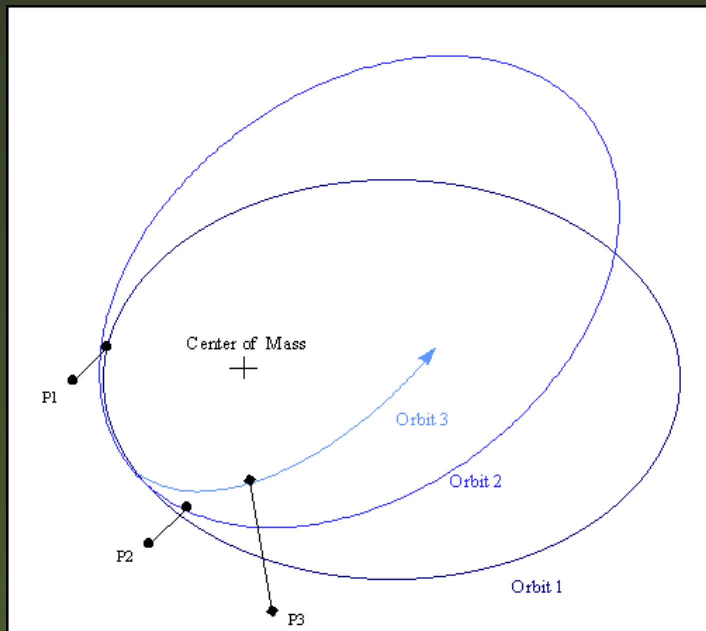


- Orbital period $7^h 45^{min}$

Back

The binary pulsar PSR1913+16

- Magnetized NS rotating with $T = 59$ ms

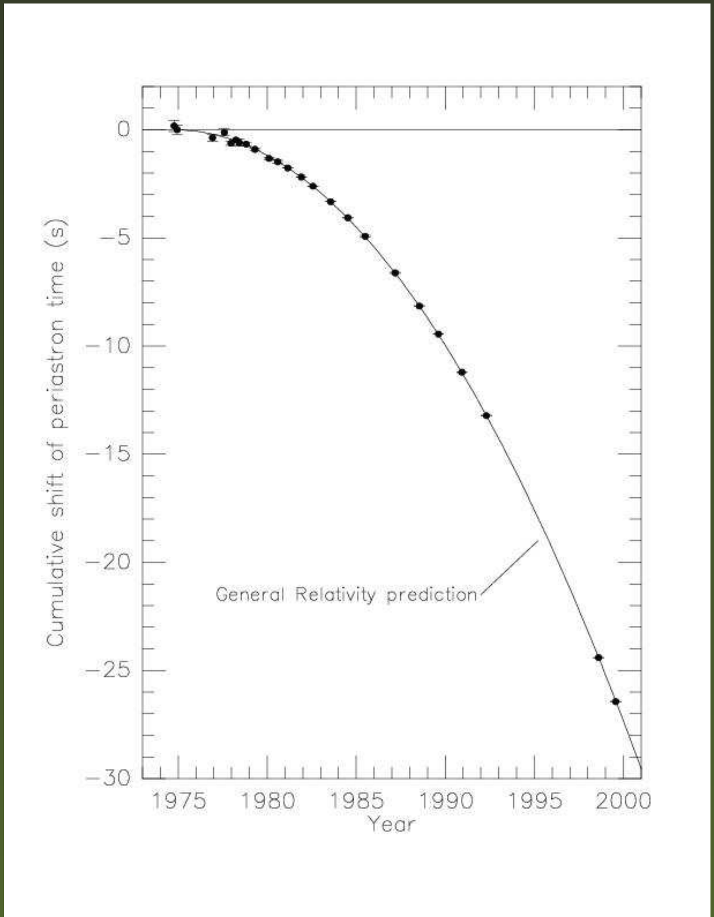


- Orbital period $7^h 45^{min}$
- Perihelion advance in 1 day the same as Mercury in 1 century

Back

The binary pulsar PSR1913+16

- Magnetized NS rotating with $T = 59$ ms



- Orbital period $7^h 45^{min}$
- Perihelion advance in 1 day the same as Mercury in 1 century
- The orbit is shrinking due to grav.wave radiation.

Back

Ten years ago...

Ten years ago, the standard cosmology was described by

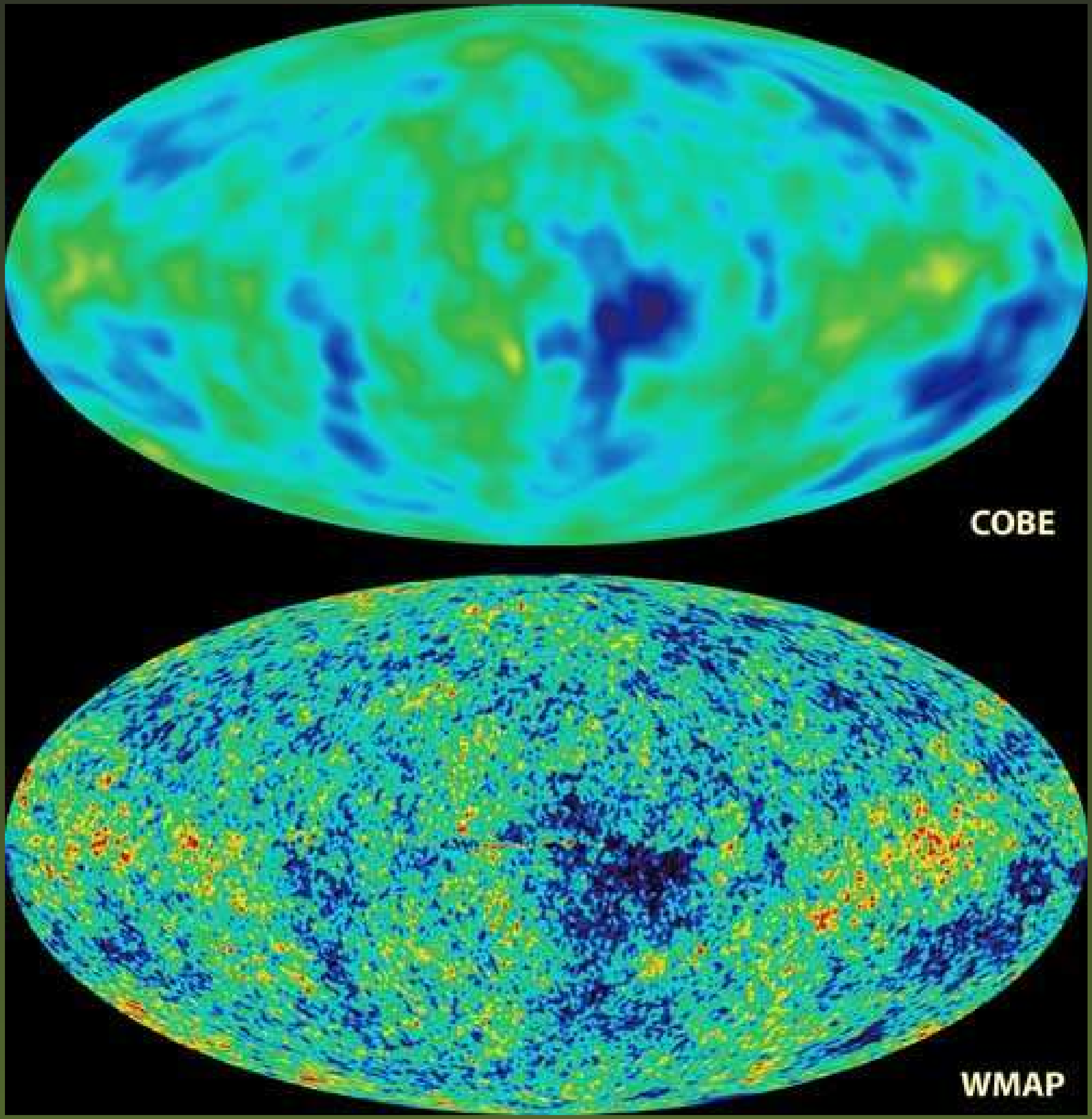
$$\underbrace{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R}_{} = \kappa^2 T_{\mu\nu}$$

Einstein equations

Visible Matter
Dark Matter
Radiation

Back

Cosmic Microwave Brackground



Back