True Tests of the Weak Equivalence Principle for Antiparticles

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Plan:

1) WEP and Anti-particles - folklore

2) Testing WEP without free-fall - Shapiro delay

3) WEP and anti-neutrinos: claims and results

4) Inefficacy of the Shapiro delay tests for relativistic particles

5) Getting to the core of WEP and a new, surprising result

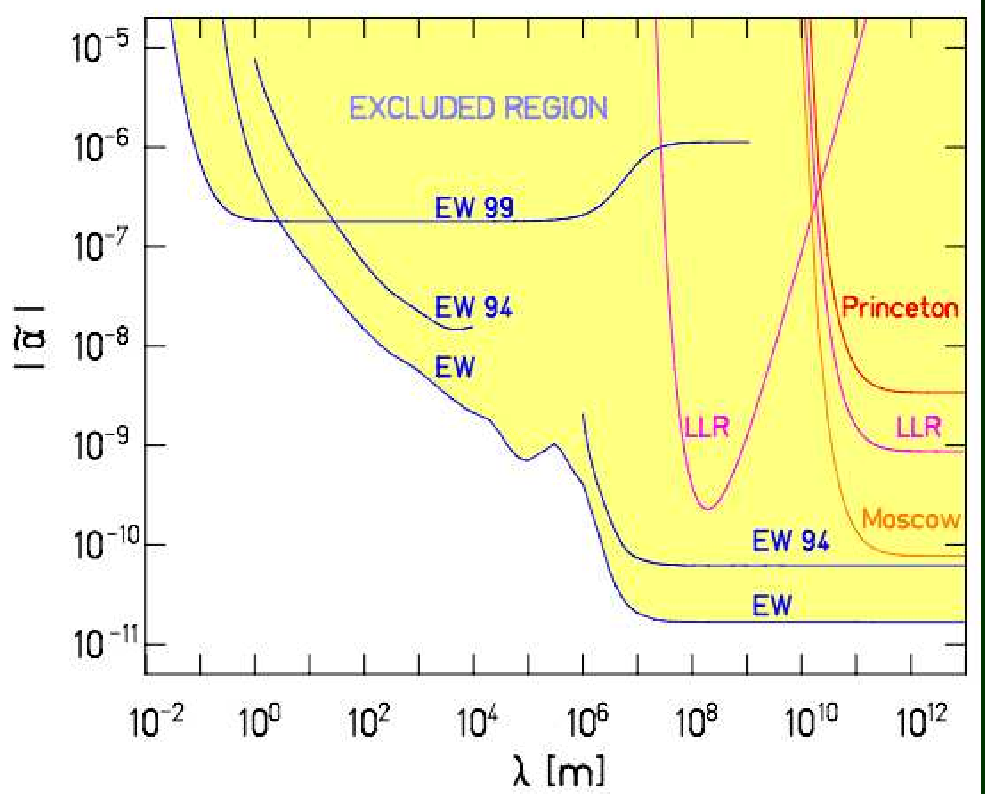
6) The need for new experiments

1) WEP and Anti-particles - the folklore

a) Field theoretic arguments with virtual particles gives a constraint, $\Delta a / a < 10^{-6}$ (Schiff)

b) Force that couples differently to particles and antiparticles must be a vector interaction, and the constraints are already very tight (Adelberger)

Class. Quantum Grav. **29** (2012) 184002



1) WEP and Anti-particles - the folklore

c) Time dilation with antimatter clocks (cyclotron) - will comment on later

d) Indirect arguments involving neutral particles like photons for which particle and anti-particle are the same entity.

e) Indirect arguments involving energy conservation of cyclic processes in a gravitation field.

Unnikrishnan and Gillies, Equivalence principle exotica, Front, Phys. **3,** 444 (2008)

A comment on tests of WEP for 'quantum systems'

Result: The tests of WEP with macroscopic 'classical' bodies (with torsion balances etc.) are valid to the same precision for quantum systems (atoms, BEC, fundamental particles etc.). Nothing special is achieved by a test of lower precision with a 'quantum system'.

A comment on tests of WEP for ‘quantum systems’

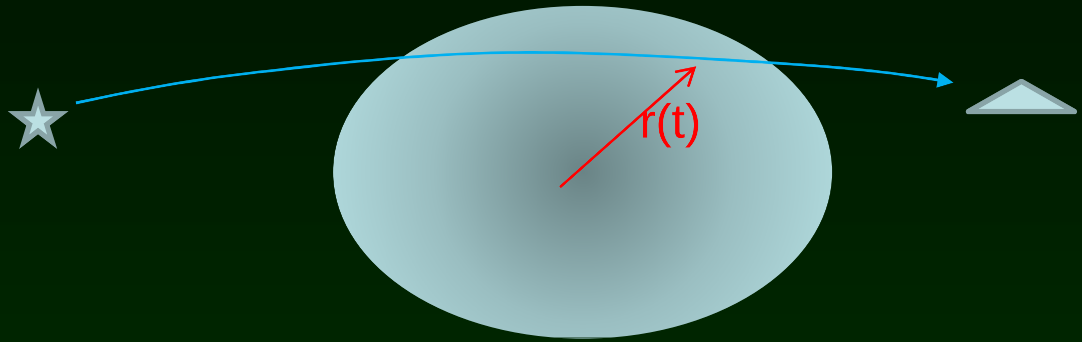
Result: The tests of WEP with macroscopic ‘classical’ bodies (with torsion balances etc.) are valid to the same precision for quantum systems (atoms, BEC, fundamental particles etc.). Nothing special is achieved by a test of lower precision with a ‘quantum system’.

Proof: The action that determines dynamics and phases in the evolution of an arbitrary quantum state in a gravitational field as well as in an accelerating frame is at most second order in dynamical variables (position, velocity) and the quantum propagator is determined by the classical action!

Unnikrishnan, Mod. Phys. Lett. A **17**, 1081 (2002).
Unnikrishnan and Gillies, Equivalence principle exotica, Front, Phys. **3,** 444 (2008)

2) Testing WEP without free-fall

Shapiro delay: $$\Delta t_S = \frac{2}{c^3}\int \phi_N(s)ds \approx \frac{2}{c^2}\int \phi_N(r(t))dt$$



$$\Delta t_S \approx \left(\frac{m_g}{m_i}\right)\frac{2}{c^2}\int \phi_N(r(t))dt$$

With average galactic potential $\phi_{Ng} / c^2 \approx 10^{-6}$

and duration of propagation $30 \text{ kpc} \approx 3\times 10^{12} \text{ s}$

$$\Delta t_S \approx 3\times 10^{6} \text{ s} \approx 1 \text{ month}$$

3) WEP and anti-neutrinos: claims on direct experimental evidence

VOLUME 60, NUMBER 3 PHYSICAL REVIEW LETTERS 18 JANUARY 1988

Test of the Weak Equivalence Principle for Neutrinos and Photons

Lawrence M. Krauss[a]
Center for Theoretical Physics and Department of Astronomy, Yale University, New Haven, Connecticut 06520

and

Scott Tremaine
Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto M5S 1A1, Canada
(Received 29 October 1987)

The observation of a neutrino burst within 3 h of the associated optical burst from supernova 1987A in the Large Magellanic Cloud provides a new test of the weak equivalence principle, by demonstrating that neutrinos and photons follow the same trajectories in the gravitational field of the galaxy. The accuracy of the test depends on the poorly known mass distribution in the outer parts of the galaxy, but is at least 0.5% and probably much better. This result provides direct evidence that the Shapiro geodesic time delay is identical, to this accuracy, for different elementary particles, independent of spin and internal quantum numbers.

$$\bar{\nu} + p = n + e^{+}$$

Thus the coincidence in timing of the neutrino and photon bursts from SN1987A verifies the WEP for neutrinos and photons to better than 0.5% accuracy. This

Test of equivalence principle for neutrinos and antineutrinos

Sandip Pakvasa, Walter A. Simmons, and Thomas J. Weiler*
Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822
(Received 27 May 1988)

Based on data from the supernova SN 1987A it is shown that the Einstein equivalence principle is confirmed for electron neutrinos and their antiparticles to one part per million provided at least one of the events is due to $\nu_e e$ scattering. Bounds on the strengths of new galactic-range forces coupling to neutrinos (of nonzero mass) and to matter are also deduced.

Direct experimental evidence from the near equality of Shapiro delay for neutrinos, anti-neutrinos, and photons (Supernova 87A).

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I will now show that these are not evidence for WEP for anti-particles.

$$\Delta t_S \approx -\left(\frac{m_g}{m_i}\right)\frac{2}{c^2}\int \phi_N(r(t))dt$$

$$m_g = E/c^2 \simeq \frac{p}{c}\left(1 + m_{g0}^2c^2/2p^2\right) = \frac{p}{c}\left(1 + \frac{1}{2\gamma_r^2}\right) \simeq \frac{p}{c}$$

Essentially the entire gravitational mass of the relativistic particle is its kinetic energy and the rest gravitational mass and rest inertial mass are insignificant. So, one is testing only whether kinetic energy obeys WEP. Good limits exist for this.

Unnikrishnan and Gillies, IJMPD (2012), Class. Quantum Grav. v29 (2012).

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With additional long range potentials coupling to 'charge' $Q = \alpha m_g$

$$\Delta t_g = -\frac{m_g}{m_i}\frac{1+\gamma}{c^2}\int \phi_N(r(t))\,\mathrm{d}t - \frac{Q_t}{m_i c^2}\int V_a(\bar{r}(t), q, \alpha)\,\mathrm{d}t$$

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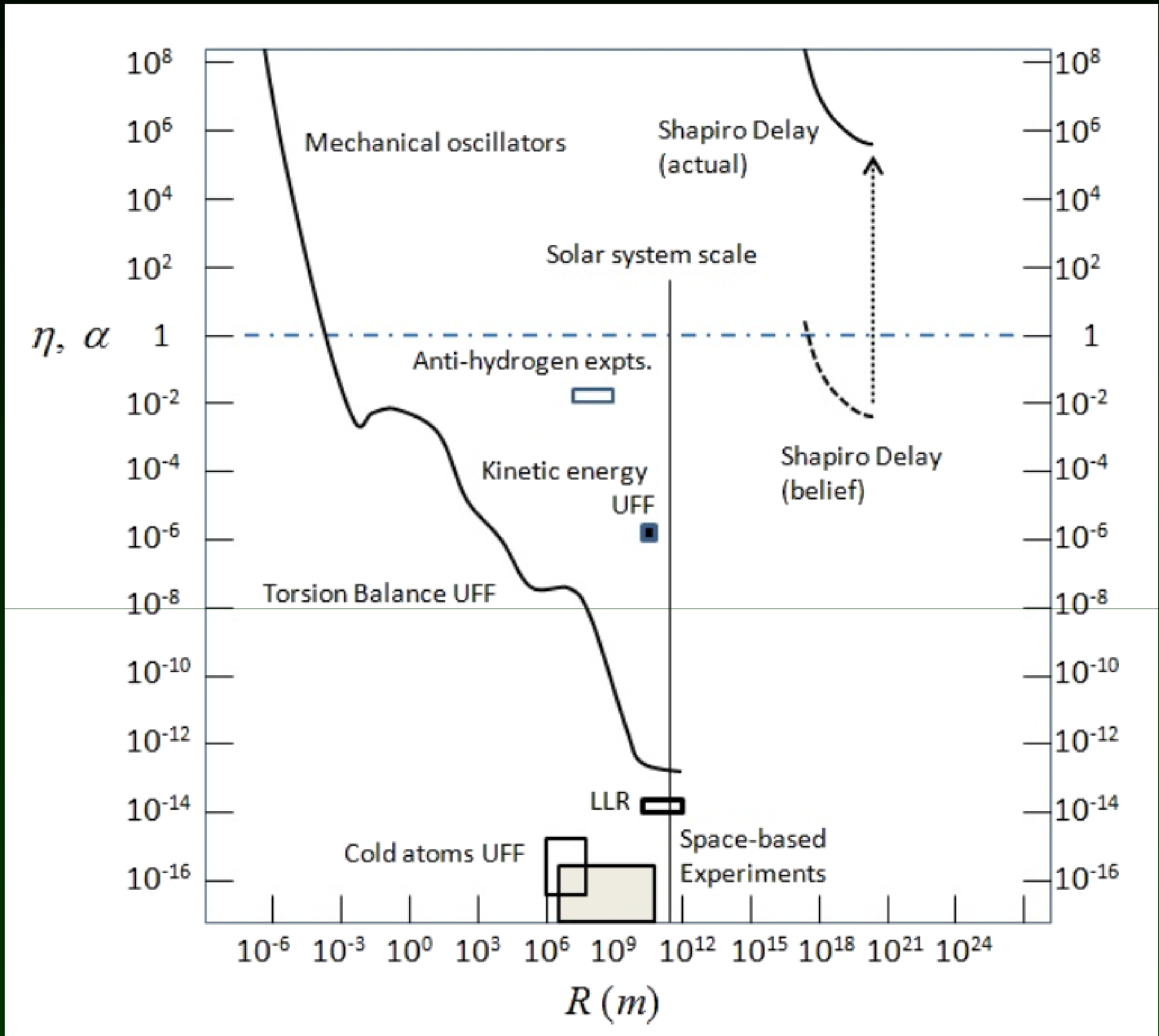
For relativistic particles, Q/m is suppressed by the large Lorentz factor relative to the first term, and the possibility of a meaningful test for the anomalous coupling is lost.

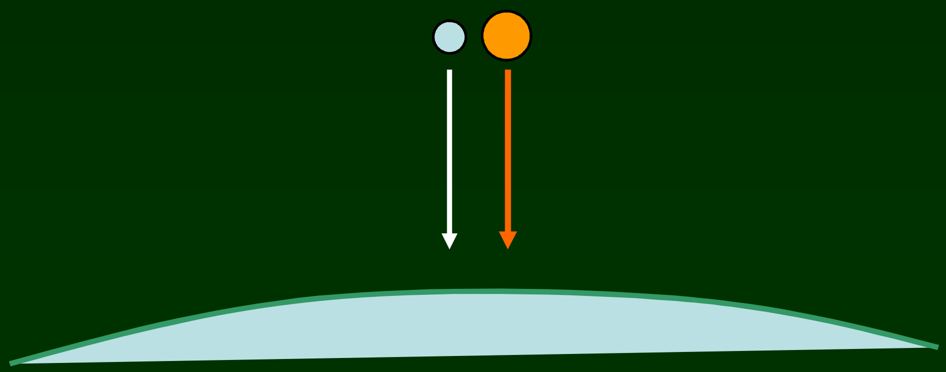
So, the Shapiro delay test is null and void, except as a test of WEP for motional energy

Unnikrishnan and Gillies, IJMPD (2012), CQG, v29 (2012).



Mechanical oscillators
Shapiro Delay
(actual)
Solar system scale
Anti-hydrogen expts.
Kinetic energy
UFF
Shapiro Delay
(belief)
Torsion Balance UFF
LLR
Cold atoms UFF
Space-based
Experiments
η, α
$R\ (m)$

Getting to the core of WEP



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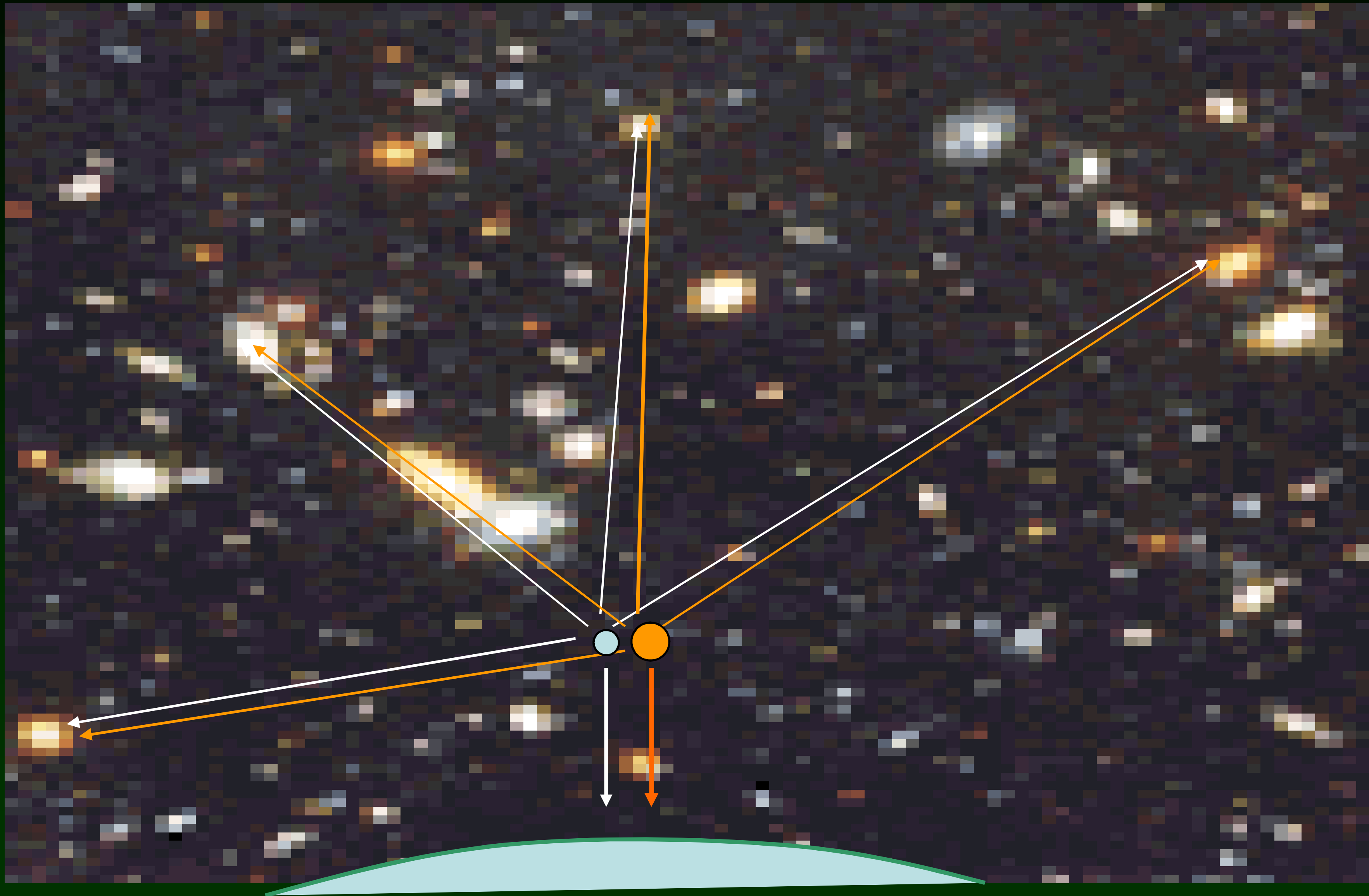
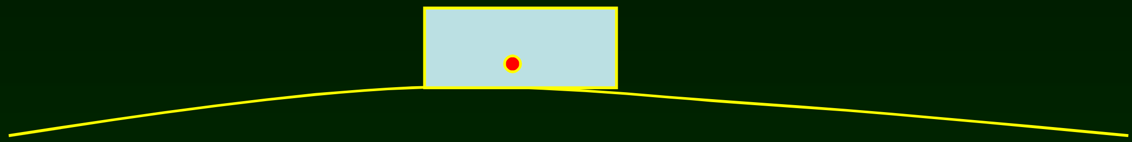


Gravitational potential “here”



Earth: $\frac{GM_E}{c^2 R_E} \sim 10^{-9}$

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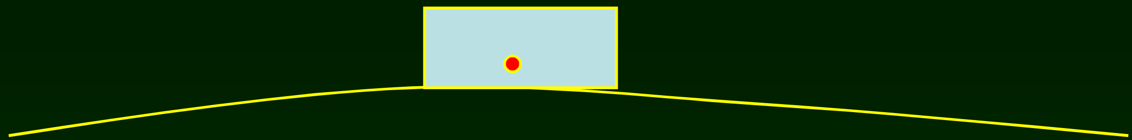


Earth: $\dfrac{GM_E}{c^2 R_E} \sim 10^{-9}$

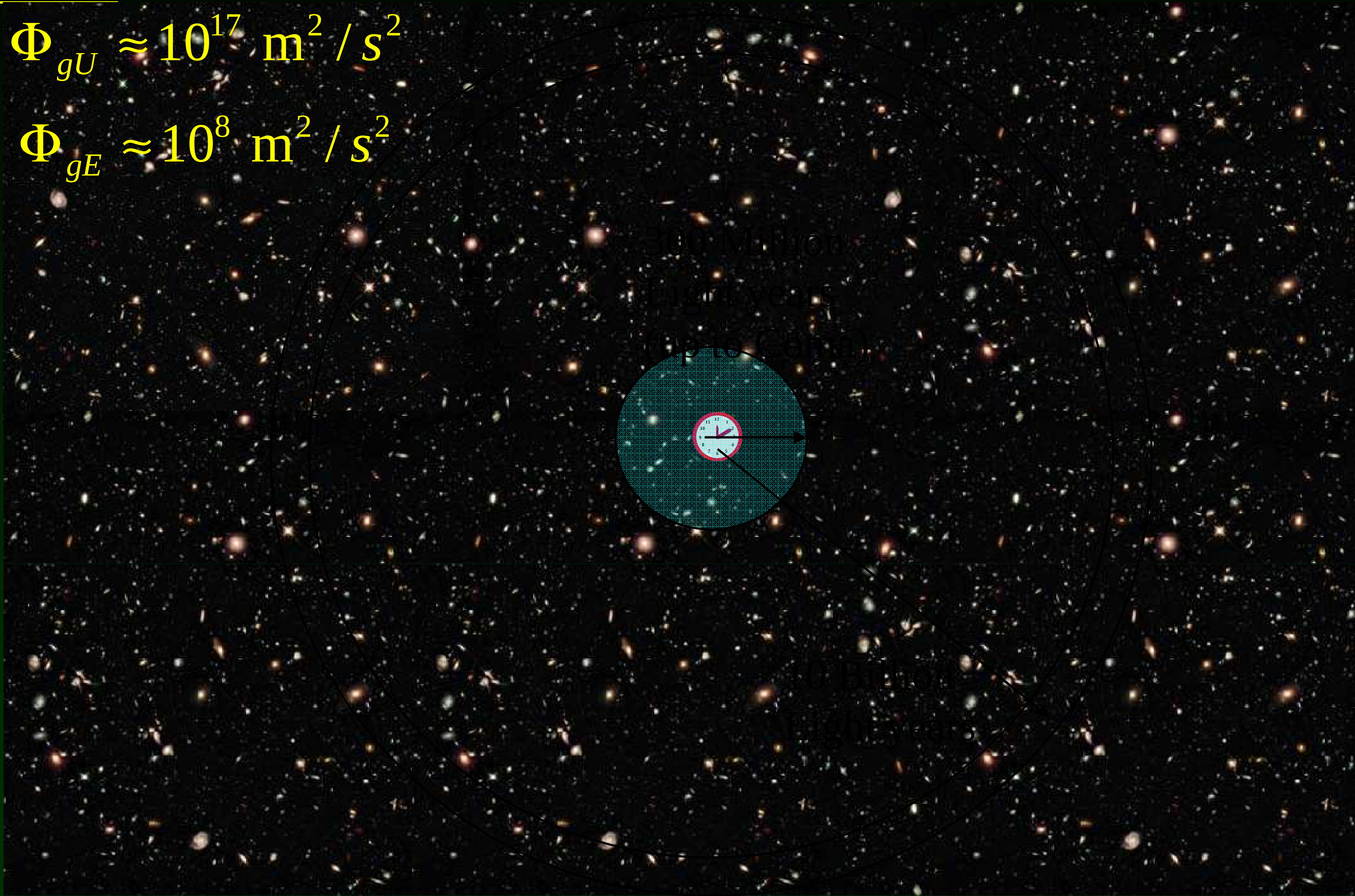
Sun: $\dfrac{GM_S}{c^2 R_S} \sim 10^{-8}$

Galaxy: 10^{-6}

Distant masses dominate!

$$\Phi_{gU} \approx 10^{17}\ \mathrm{m}^2 / s^2$$

$$\Phi_{gE} \approx 10^{8}\ \mathrm{m}^2 / s^2$$



$$\Phi_U \approx \int_{All\,Galaxies} G \cdot (4\pi\rho R^2 dR) / R \approx 2\pi G \rho R^2{}_H$$

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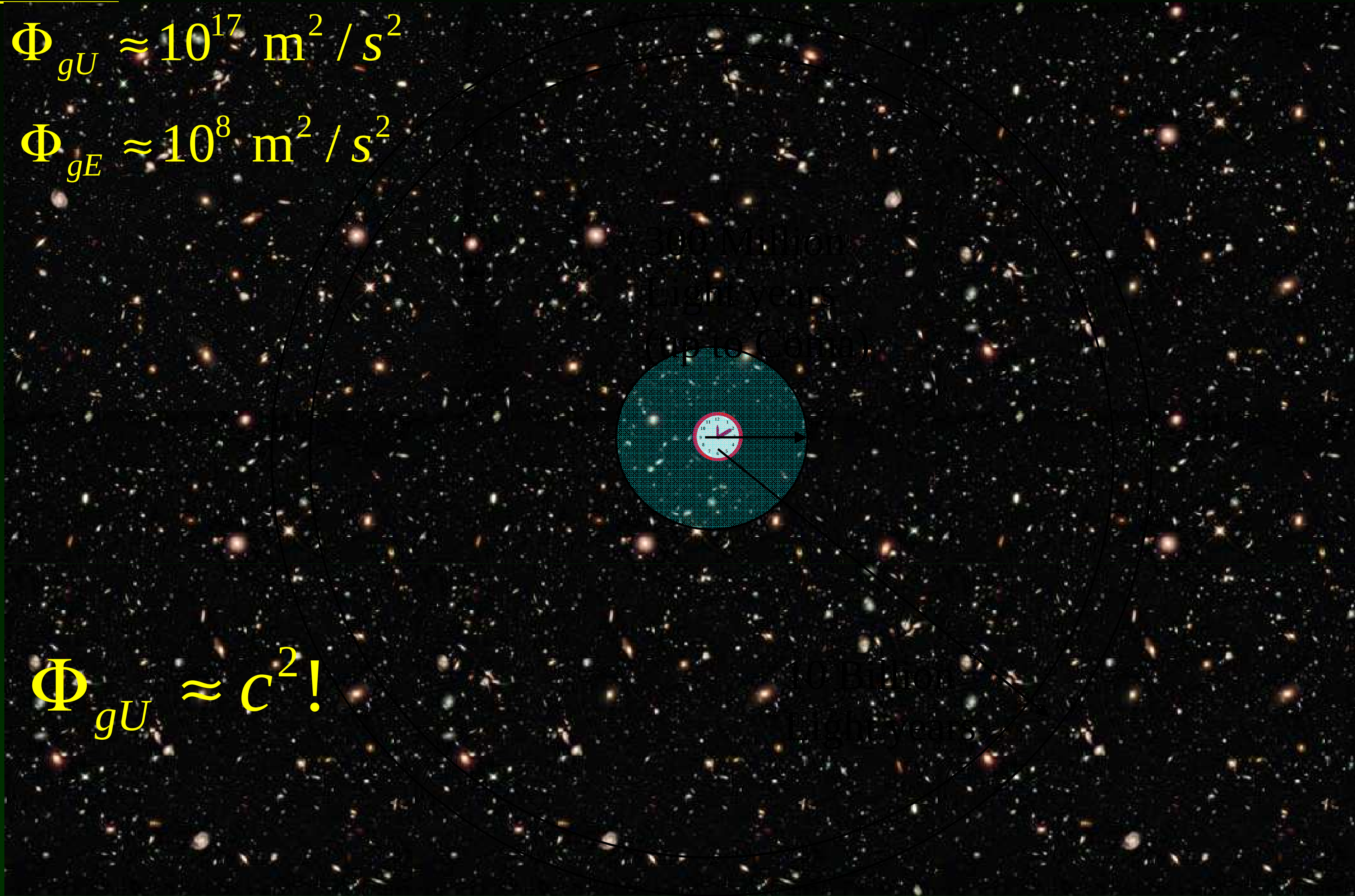

$$\Phi_{gU} \approx c^2!$$

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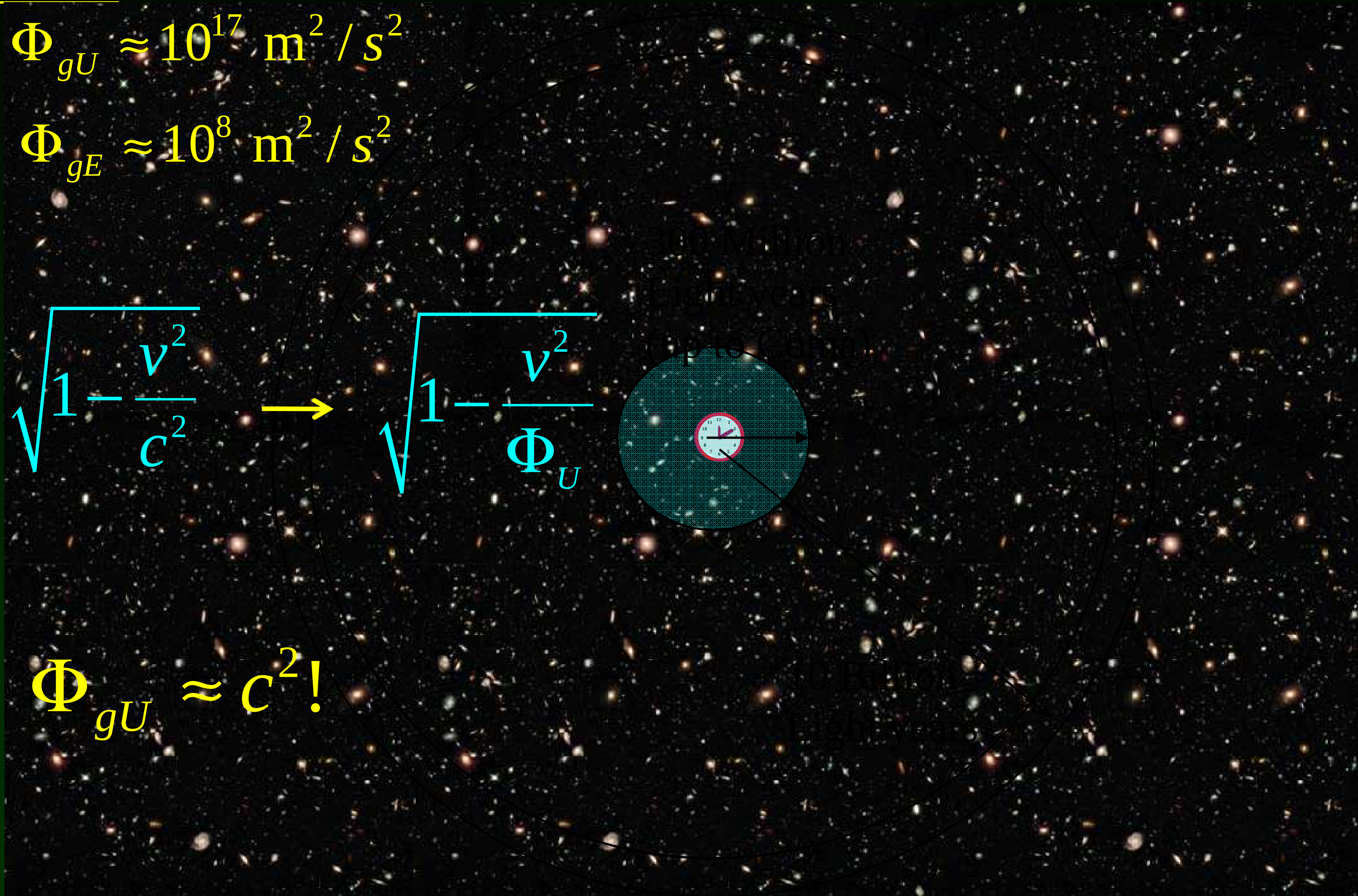

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$$\sqrt{1-\frac{v^2}{c^2}} \rightarrow \sqrt{1-\frac{v^2}{\Phi_U}}$$

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Getting to the core of WEP

Cosmic Relativity:

Gravitational potentials due to all the matter in the universe determine ALL relativistic phenomena, including time dilation, length contraction, limit of the speed of propagation etc.

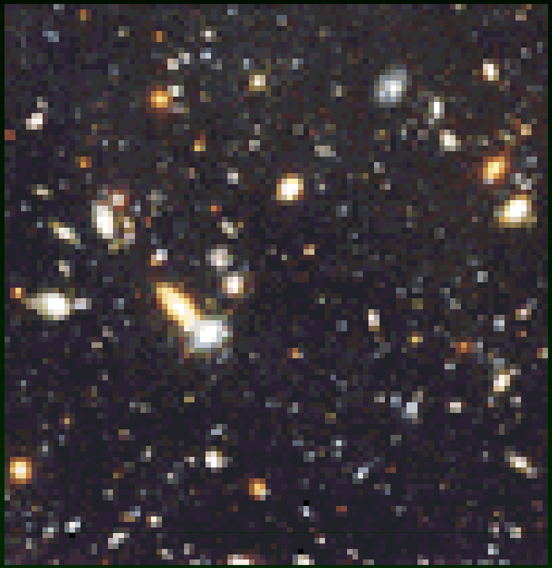
These potentials depend on whether one is moving or not, and there is a (large, v/c) vector (gravitomagnetic) potential apart from the familiar gravitation ('electric') potential.

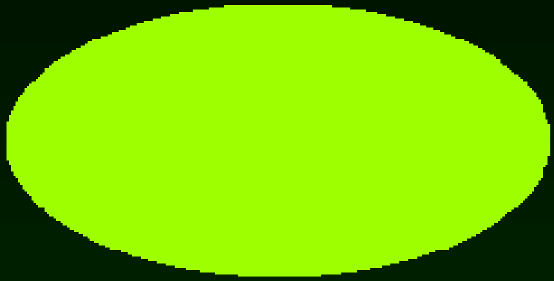
Cosmic gravity determines the law of motion, and the Principle of Equivalence is its direct consequence.

Unnikrishnan, in Advances in Theoretical Physics (World Scientific, 2008)

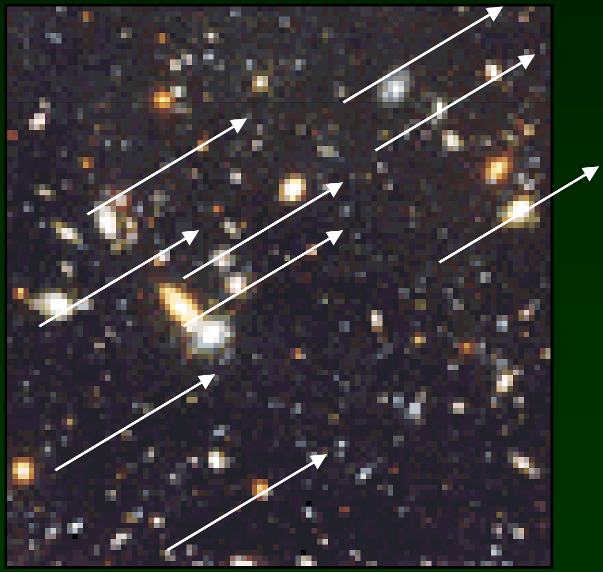
Massive Universe as a preferred frame

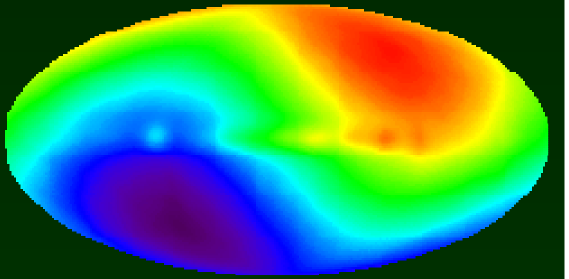
There is ONE special frame in which V=0





In all other frames,





SPACE is anisotropic in the frame of a moving observer.
There is a large current of matter (the charge of gravity)

$$ds^2 = -dt^2 + a^2(t)\{dx^2 + dy^2 + dz^2\}$$

In a frame moving through this matter filled universe, there is a large matter-current and space is ANISOTROPIC

$$x' = x - Vt, \quad t' = t \rightarrow$$

$$\begin{bmatrix} g'_{00} = -(1 - v^2/c^2) & g'_{01} = v/c & 0 & 0 \\ g'_{10} = v/c & g'_{11} = 1 & 0 & 0 \\ 0 & g'_{21} = 0 & g'_{22} = 1 & 0 \\ 0 & 0 & 0 & g'_{33} = 1 \end{bmatrix}$$

Galilean boost gives the physically consistent metric – flat and anisotropic

What are the observable LOCAL influences of the cosmic gravitational potentials?

$$\vec{A}_G = \frac{\vec{v}}{c} \Phi_U$$

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Faraday-Lenz

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Faraday-Lenz

$$F = m_g \frac{\Phi_U}{c^2}\vec{a} = m_i \vec{a}\,!$$

NEWTON'S LAW FROM COSMIC GRAVITY

It is relativistic and 'gravito-magnetic'

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NEWTON'S LAW FROM COSMIC GRAVITY
It is relativistic and 'gravito-magnetic'

$$m_i / m_g = -\Phi_U / c^2$$

EQUIVALENCE PRINCIPLE FROM COSMIC GRAVITY

At that point, there came to me ***the happiest thought of my life****, in the following form:*

Just as is the case with the electric field produced by electromagnetic induction, the gravitational field has similarly only a relative existence. *For if one considers an observer in free fall, e.g. from the roof of a house, there exists for him during his fall no gravitational field – at least in his immediate vicinity."*

Einstein 1919

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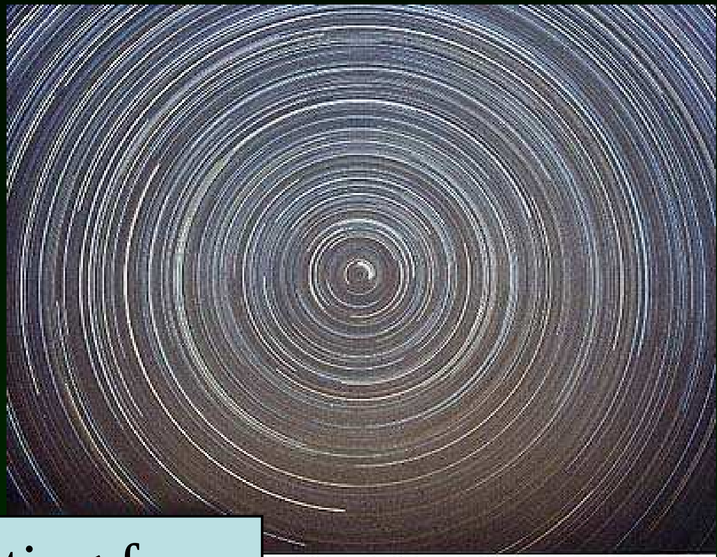
Einstein 1919

The result that Newton's law of motion and the WEP have exactly the same cosmic gravitational origin and physical content implies that all test systems that follow Newton's law in any experiment also obeys the WEP!

Clearly, the dynamical behaviour of anti-particles in storage rings etc. are direct experimental evidence that they obey WEP of long range gravity.

What are the observable influences of the massive Universe?



Universe in rotating frame

Currents of mass generates a vector potential

And its ‘curl’ is a magnetic gravitational force

$$\nabla \times \vec{A}_g = \frac{\Phi_U}{c^2} \nabla \times \vec{V} = 2\Omega$$

Gravitational Lorenz Force $\vec{v} \times \vec{B}_g = 2\vec{v} \times \vec{\Omega}$

Coriolis (and centrifugal) forces are clearly of cosmic gravitational origin

Mach, Sciama…)

Main Results and Conclusions

1) Tests of WEP with relativistic particles merely tests WEP for motional energy and their sensitivity to anomalous charges is suppressed by the Lorentz factor – Since WEP for kinetic energy is already tested well, all such tests (neutrinos/antineutrinos etc.) are incapable of testing gravitational behaviour of anti-particles and will return null results.

2) In matter-filled universe at near critical density, as observationally verified, it is shown that inertia to force is a gravitomagnetic reaction and both Newton's law and the equivalence principle follow. Hence, motion according to Newton's law is proof of universal gravitational behaviour – anti-particles pass this test and obey WEP.

3) Direct experiments with slow anti-matter is still worthwhile and important to look for short or intermediate range anomalous interactions.