A High Energy Glimpse into Gravity

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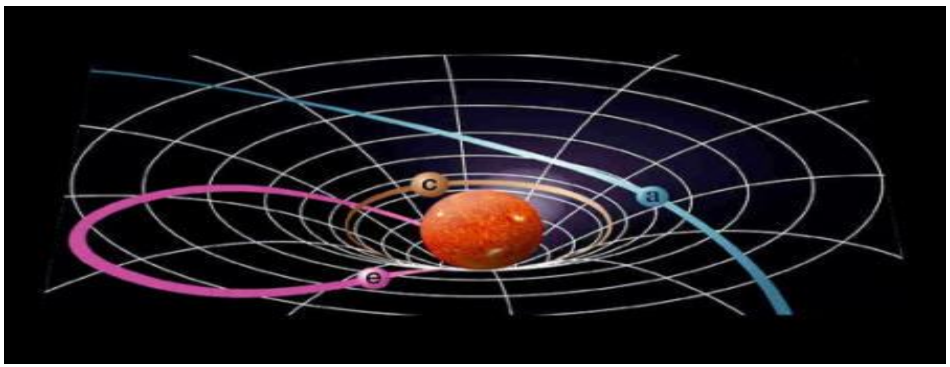
- High Energy Gravity (HEG): theory and measurement.
- General Relativity - Gravitational field as an Optical medium.
- Experimental tool for HEG: Compton scattering
- Testing light deflection by Earth.
- Experimental results: break down of General Relativity.
- Finer experimental details: negative gravity.
- Experiment at PETRA: search for negative gravitation and Quantum Gravity induced birefringence
- Summary.

High Energy Gravity (HEG) theory and measurement

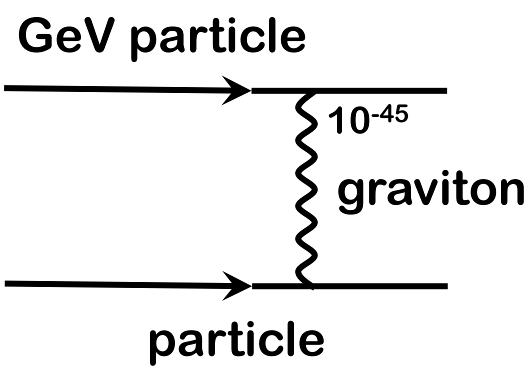
General relativity is the standard theory of gravitation with curved space-time concept.



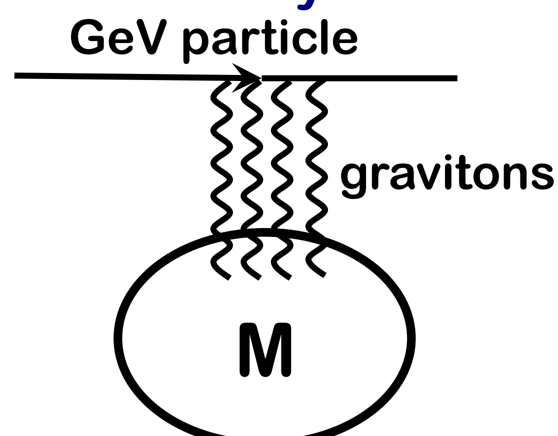
Photon motion is energy independent

Quantum theory

Gravitation

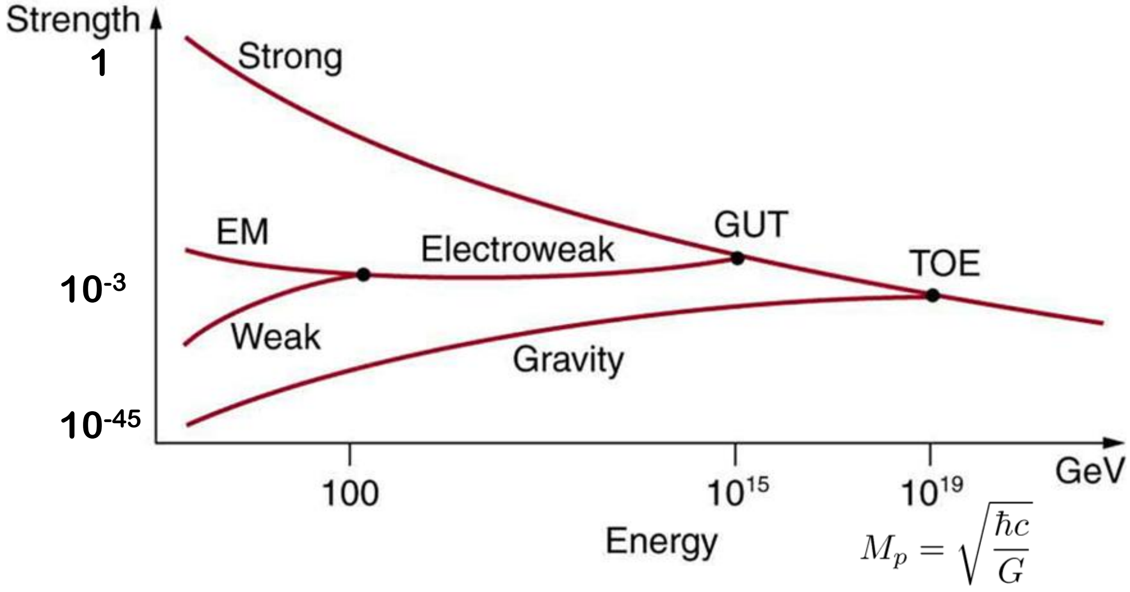


Gravity



High Energy Gravity (HEG) theory and measurement

Coupling constants



If the gravity changes within eV-TeV then it should be a tiny rise toward higher energies.

High Energy Gravity (HEG) theory and measurement

Cosmic rays

Time / Energy

Highest energy

Gravitational redshift

$$\frac{\Delta E}{E} = \frac{GM_\oplus}{c^2 R_\oplus^2} H \approx 10^{-13}/km$$

is measured for keV Mossbauer energies.

Accelerators

Space / Momentum

Gravitational deflection

$$\frac{2GM_\oplus}{c^2 R_\oplus} \frac{L}{\sqrt{L^2 + R_\oplus^2}} = 0.2 \text{ pm / km}$$

High Energy Gravity (HEG) theory and measurement

Conclusion #1:
General relativity, predicts the same deflection for different energy photons; any laboratory measurement of the cumulative deflection (0.2 pm/km) is technically infeasible.

General Relativity $G_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab}$

Gravitational field as an Optical medium

Spherically symmetric gravitational space-time metrics

$$ds^2 = -\left(1-\frac{m}{2r}\right)^2 \left(1+\frac{m}{2r}\right)^{-2} (dx^0)^2 + \left(1+\frac{m}{2r}\right)^4 \delta_{\alpha\beta}\, dx^\alpha\, dx^\beta$$

Electromagnetic field propagating through such space-time

$$\epsilon^{\alpha\beta\gamma}\hat{\nabla}_\beta \mathscr{H}_\gamma - \partial_0(\sqrt{\Delta_h} E^\alpha) = 0$$

$$\epsilon^{\alpha\beta\gamma}\nabla_\beta \mathscr{E}_\gamma + \partial_0(\sqrt{\Delta_h} H^\alpha) = 0$$

After applying the operator $\epsilon^{\alpha\beta\gamma}\hat{\nabla}_\beta$

$$\epsilon^{\alpha\beta\gamma}\hat{\nabla}_\beta(\epsilon_{\gamma\mu\nu}\hat{\nabla}^\mu \mathscr{H}^\nu) + \epsilon_{\sigma\mu\nu}{}^{\alpha l \sigma}(\hat{\nabla}^\mu \mathscr{H}^\nu)\partial_l \ln \sqrt{-g_{00}} + \frac{\epsilon^{\alpha\beta}}{\sqrt{-g_{00}}}\partial_0{}^2 \mathscr{H}_\beta = 0$$

The first two terms become:

$$\begin{aligned} h^{\alpha\beta}h^{\rho\sigma}[&-\partial_\rho\partial_\sigma \mathscr{H}_\beta + \hat{\Gamma}_{\sigma\rho}{}^\mu \partial_\mu \mathscr{H}_\beta + 2\hat{\Gamma}_{\beta\sigma}{}^\tau \partial_\rho \mathscr{H}_\tau - 2\mathscr{H}_\tau \hat{\Gamma}_{\mu\rho}{}^\tau \hat{\Gamma}_{\sigma\beta}{}^\mu + \\ &+ \mathscr{H}_\tau \partial_\beta \hat{\Gamma}_{\sigma\rho}{}^\tau + (\partial_\rho \ln \sqrt{-g_{00}})\partial_\beta \mathscr{H}_\sigma + 2(\partial_\rho \ln \sqrt{-g_{00}})\hat{\nabla}_{[\beta}\mathscr{H}_{\sigma]} \\ &+ \mathscr{H}_\sigma \partial_\beta(\partial_\rho \ln \sqrt{-g_{00}})] + h^{\alpha\beta}(\partial_\rho \ln \sqrt{-g_{00}})\mathscr{H}_\sigma \partial_\beta h^{\rho\sigma}. \end{aligned}$$

Ref: F. de Felice, Gen. Rel. Grav. 2, 347 (1971)

General Relativity
Gravitational field as an Optical medium

Finally this reduces to the wave equation

$$\partial_\rho \partial_\rho \mathscr{H}_\alpha - n^2 \partial_0{}^2 \mathscr{H}_\alpha + 2(\partial_\rho \ln n)\mathscr{H}_{[\rho,\ \alpha]} + \partial_\alpha(\mathscr{H}_\rho \partial_\rho \ln n) = 0$$

with a refractive index

$$n^2 = \left(1 + \frac{m}{2r}\right)^6 \left(1 - \frac{m}{2r}\right)^{-2}$$

For the Earth's weak field

$$n(r) = 1 + \frac{2GM_\oplus}{c^2 r}$$

At the Earth surface

$$n_\oplus = 1 + \frac{2GM_\oplus}{c^2 R_\oplus} = 1 + 1.39 \times 10^{-9}$$

General Relativity
Gravitational field as an Optical medium

Conclusion #1:

General relativity, predicts the same deflection for different energy photons; any laboratory measurement of the cumulative deflection (0.2 pm/km) is technically infeasible.

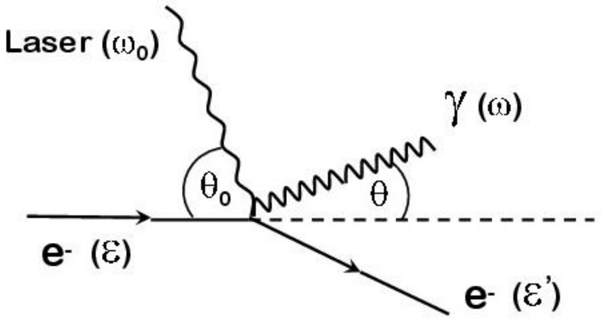
Conclusion #2:

Curved space-time for the photons in general relativity could be reduced to a flat, refractive space-time.

At the Earth's surface: $n_{\oplus} = 1 + \frac{2GM_{\oplus}}{c^2 R_{\oplus}} = 1 + 1.39 \times 10^{-9}$

Experimental tool for high energy gravity: Compton scattering

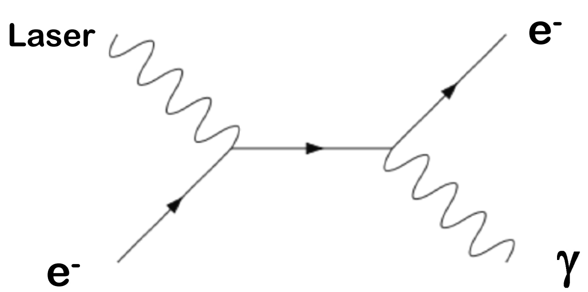
Compton kinematics

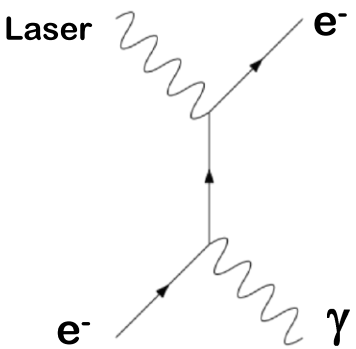


Kinematic parameter is a combination of initial conditions

$$x = 4\gamma\omega_0 \sin^2(\theta_0/2)/m$$

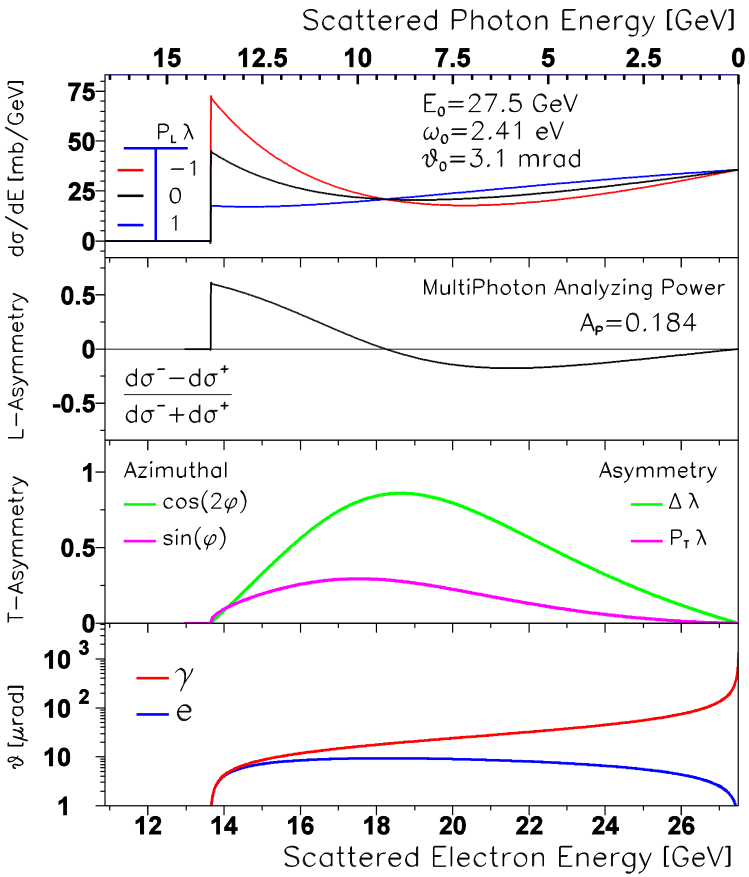
Quantum description





Experimental tool for high energy gravity: Compton scattering

An example of Compton spectrum, energies and angles

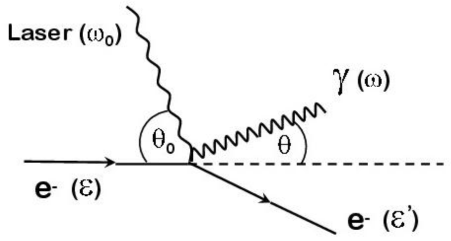


HERA Beam 27.5 GeV e-
Laser 514nm = 2.41eV
Crossing angle p-3.1mrad

Kinematic parameter x = 1.02

Kinematic edge or Compton edge
at
w_{max} = 13.9 GeV
Compton photons max energy

Experimental tool for high energy gravity: Compton scattering



$$x = 4\gamma\omega_0 \sin^2(\theta_0/2)/m$$

In a space with refraction n the photon momentum becomes ωn.

Energy-momentum conservation

$$\mathcal{E}x - \omega(1 + x + \gamma^2\theta^2) + 2\omega\left(1 - \frac{\omega}{\mathcal{E}}\right)\gamma^2(n-1) = 0$$

Ignoring small terms $\mathcal{O}((n-1)^2), \mathcal{O}(\theta^3), \mathcal{O}(\gamma^{-3})$

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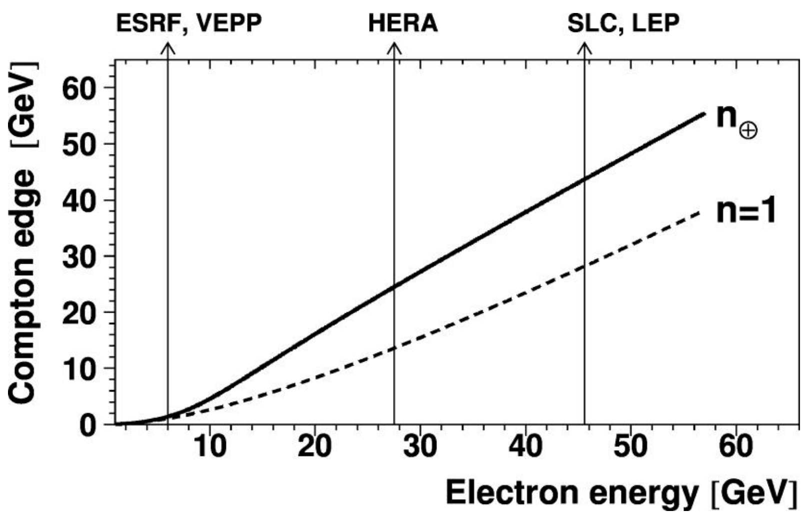
Photons maximal energy in the Earth's gravitational field

$$\omega_{max} = \frac{\mathcal{E}}{2}\left(1 - \frac{1+x}{2\gamma^2(n_\oplus - 1)} + \sqrt{\left(1 - \frac{1+x}{2\gamma^2(n_\oplus - 1)}\right)^2 + \frac{2x}{\gamma^2(n_\oplus - 1)}}\right)$$

$$n_\oplus = 1 + \frac{2GM_\oplus}{c^2 R_\oplus} = 1 + 1.39 \times 10^{-9}$$

Experimental tool for high energy gravity: Compton scattering

Sensitivity of 532nm green laser head-on Compton scattering for different accelerators



Accelerator	Electron energy GeV	Kinematic factor x	ω_{max} $n=1$ GeV	ω_{max} $n=n_\oplus$ GeV	Shift by gravity GeV
ESRF, VEPP	6.0	0.21	1.05	1.39	0.34
HERA	26.5	0.98	13.1	23.4	10.3
SLC, LEP	45.6	1.62	28.2	43.7	15.5

$$\omega_{max} = \frac{\mathcal{E}}{2}\left(1 - \frac{1+x}{2\gamma^2(n_\oplus - 1)} + \sqrt{\left(1 - \frac{1+x}{2\gamma^2(n_\oplus - 1)}\right)^2 + \frac{2x}{\gamma^2(n_\oplus - 1)}}\right)$$

Experimental tool for high energy gravity: Compton scattering

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General relativity, predicts the same deflection for different energy photons; any laboratory measurement of the cumulative deflection (0.2 pm/km) is technically infeasible.

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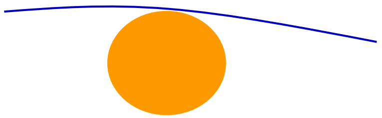
At the Earth's surface: $n_{\oplus} = 1 + \frac{2GM_{\oplus}}{c^2 R_{\oplus}} = 1 + 1.39 \times 10^{-9}$

Conclusion #3:

Compton scattering is highly sensitive to the space refractivity. Tiny changes of this property will alter Compton kinematic edge energy.

Testing light deflection by Earth
Experimental results



Light's gravitational integral deflection is observed from the Sun (8μrad) and Jupiter (76nrad).

Total integral deflection for the Earth is 2.8nrad
Cumulative deflection is 0.2 pm / km.

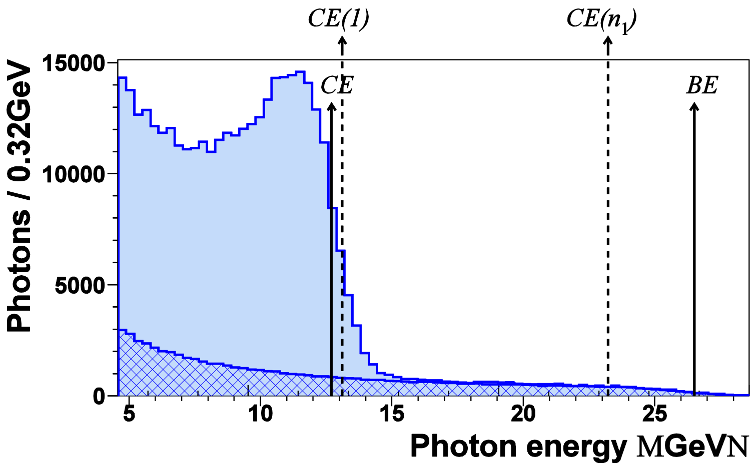
$$\phi(L) = \frac{2GM_\oplus}{c^2 R_\oplus} \frac{L}{\sqrt{L^2 + R_\oplus^2}}$$

Compton scattering measures differential deflection.

$$n - 1 = R_\oplus \frac{d\phi}{dL}$$

Testing light deflection by Earth Experimental results

Compton spectrum on top of bremsstrahlung background measured by HERA polarimeter



SLC polarimeter's spectrometer: scattered electrons energy to position calibration

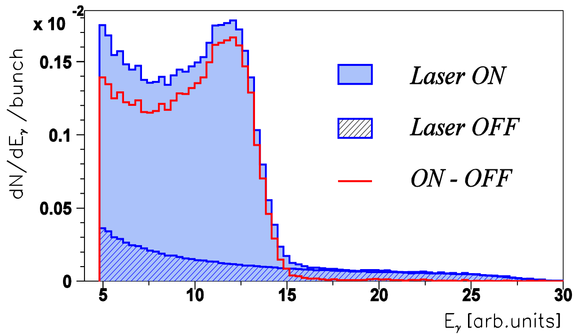
$$S_x = \frac{296.45\ GeV \cdot cm}{\mathcal{E}'} - 9.61\ cm$$

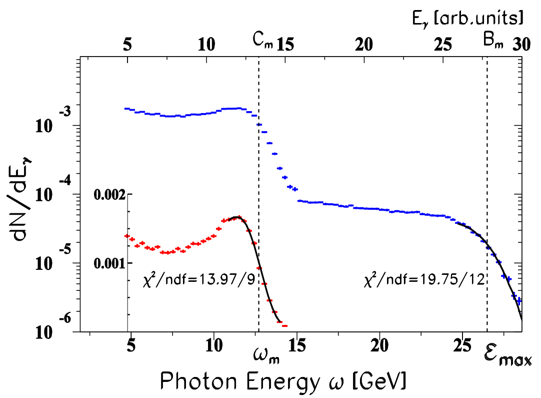
Compton edge position
predicted: 146.4 cm
measured: 17.4 cm

Tested 13-28GeV light deflection contradicting GR prediction dramatically – no need for finer error analysis.
General relativity breaks down at high energies.

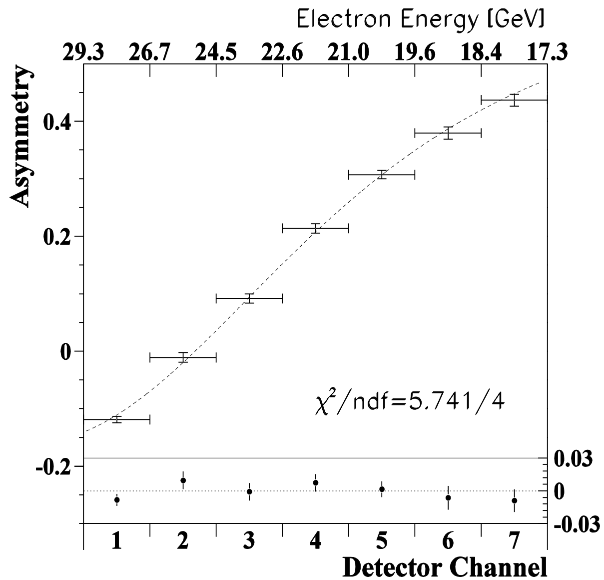
Finer experimental details: negative gravity

HERA polarimeter





SLC polarimeter



Multi-photon mode => large theoretical & systematic errors

$n-1 = -(1.69 \pm 0.47) \times 10^{-11}$

$n-1 = -(4.07 \pm 0.05) \times 10^{-13}$

GR attractive gravity prediction $n-1 = 1.39\times 10^{-9}$

Error analysis: *Phys.Lett.B 611: p.231 (2005)*

Testing light deflection by Earth
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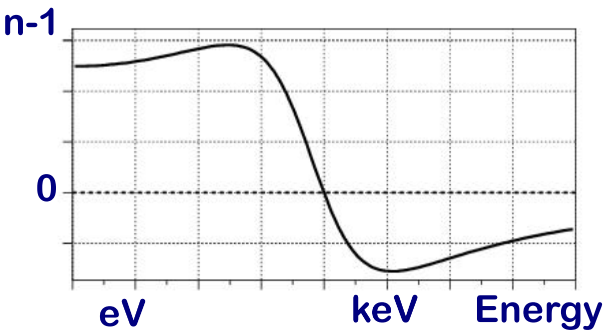
Conclusion #3:
Compton scattering is highly sensitive to the space refractivity.
Tiny changes of this property will alter Compton kinematic edge energy.

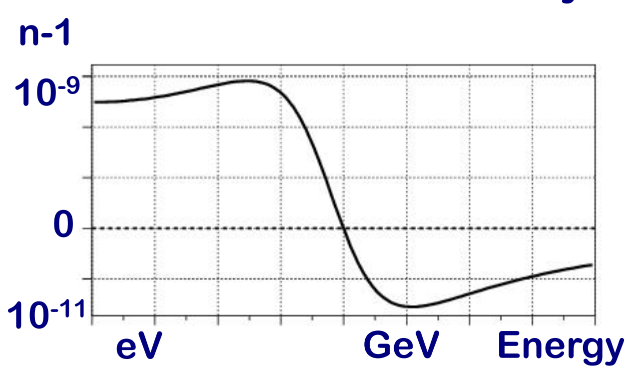
Conclusion #4:
SLC and HERA polarimeters data contradict General relativity.
There are experimental hints for a repulsive gravitation at high energies.

New experiments physics motivation

Matter refractivity



Gravitational refractivity



Photon scattering off graviton:
n-1 ~ f(0) forward scattering amplitude
optical theorem $\sigma_{tot} = 4\pi \,\mathrm{Im}\, f(0) / k$

Search for negative gravitation at GeV energies.

Quantum Gravity phenomenology at Planck scale $M_p = \sqrt{\frac{\hbar c}{G}}$

$$\mathcal{E}^2 = m^2 + P^2 \pm \xi \frac{P^3}{M_P}$$

Does not work in plain vacuum (astrophysical bounds)
May work in gravitational field.

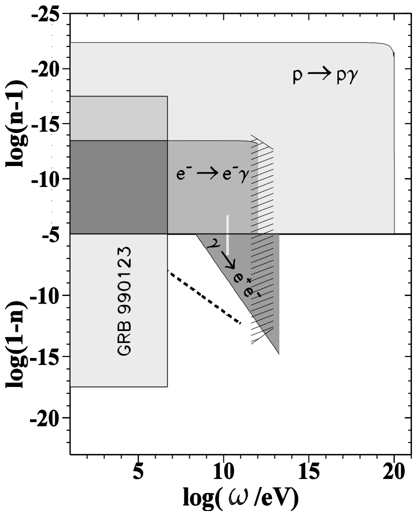
Test the extra term.

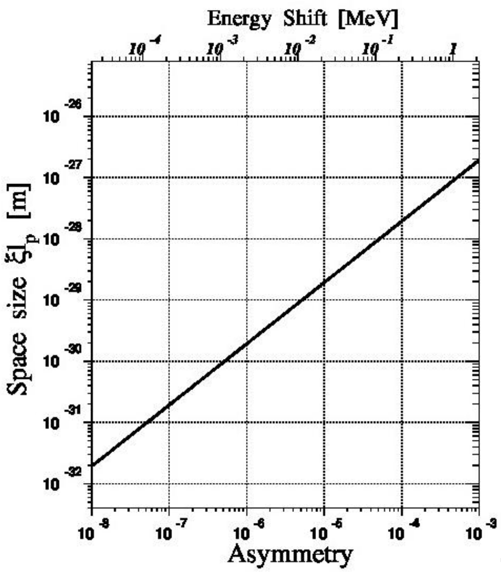
Existing Astrophysical and laboratory constraints

Astrophysical - photon interaction with loop gravitons.
Nothing is detected. Birefringence constraints are based on keV-MeV GRB photons linear polarisation measurements.

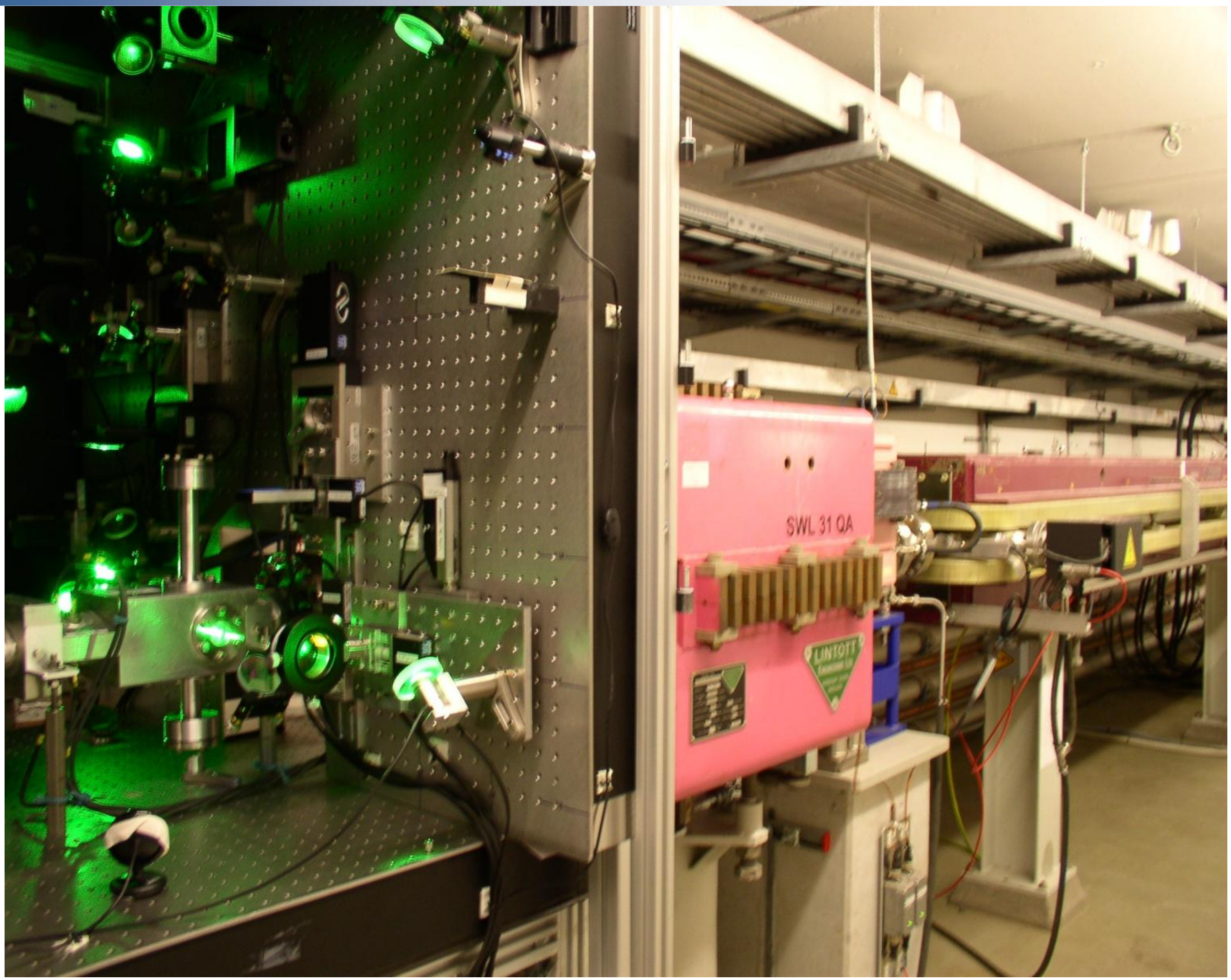
Laboratory – photon interaction with Earth's virtual gravitons.
Low energy
space isotropy - Michelson-Morley type or Pendulum tests.
Null experiments: all measured backgrounds so far are isotropic.

Laser Compton method is superior – sensitivity 10^{-11} and below is demonstrated for 10-20 GeV energy photons (HERA and SLAC).





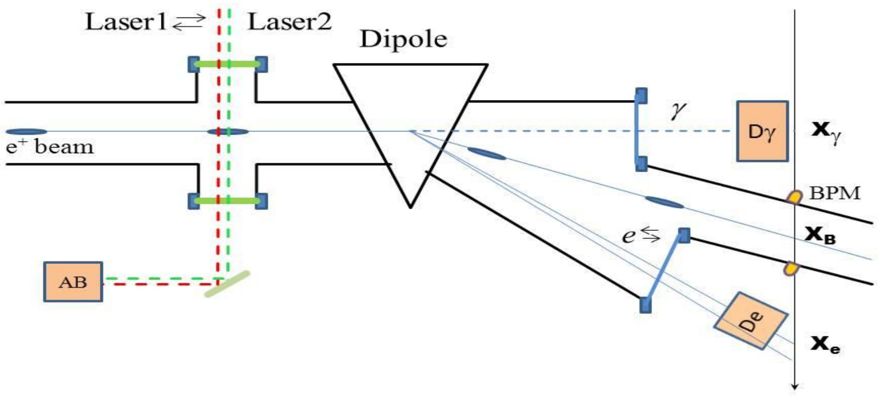
APproaching Planck LEngth ApPLe at PETRA

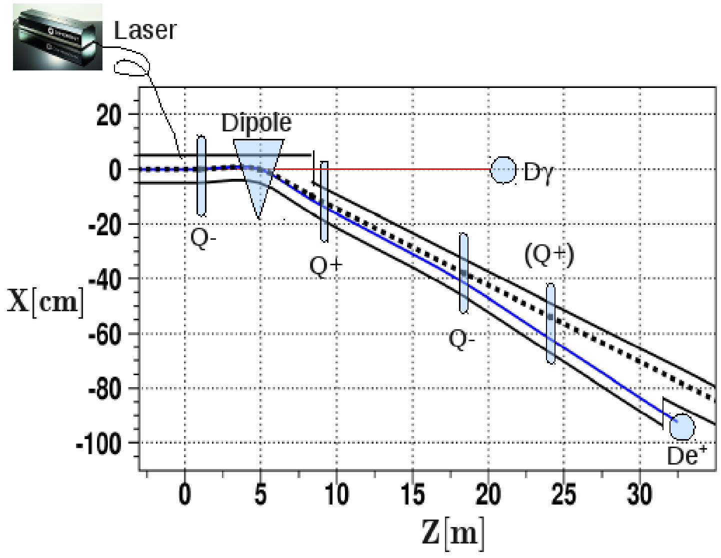


PETRA Laser-Wire setup

Proposed Experimental Setup

Layout





Beamline

Negative gravitation and Quantum Gravity induced extra term

Photons dispersion near Planck scale

$$\omega^2 = k^2 \pm \xi \frac{k^3}{M_P}$$

Negative gravitation: refractivity

n-1

Extra term: birefringence

$$\Delta n = n_L - n_R = 10^{-19} \xi \omega \, [GeV]$$

Laser Compton measures refractivity and birefringence

$$n - 1 = \frac{\mathcal{E}}{2\gamma^2(\mathcal{E} - \omega)} \left(1 + x + \theta^2\gamma^2 - x\frac{\mathcal{E}}{\omega} \right) + \mathcal{O}((n-1)^2)$$

Experimental reach

down to 4×10^{-13}

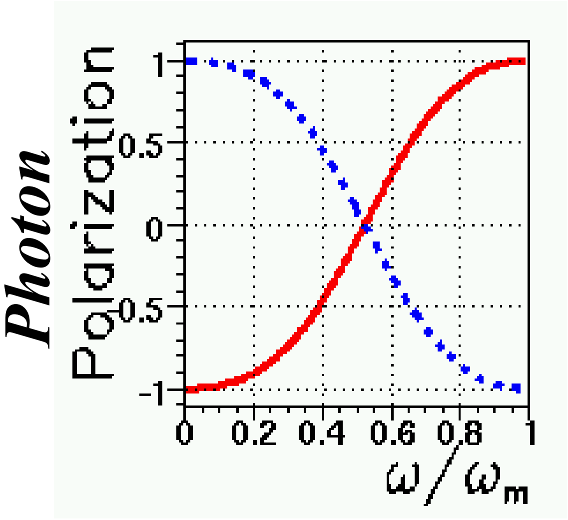
down to 5×10^{-16}

Birefringence measurement

Birefringence will cause the Compton edge shift

$$\Delta n = \frac{\mathcal{E}x}{2\gamma^2\omega_m^+\omega_m^-}\Delta\omega_m \approx \frac{1+x^2}{2x\gamma^2}\frac{\Delta\omega_m}{\mathcal{E}}$$

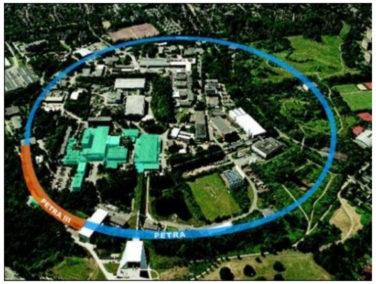
for +/- helicities of the scattered photon which in turn depend on the laser light helicities



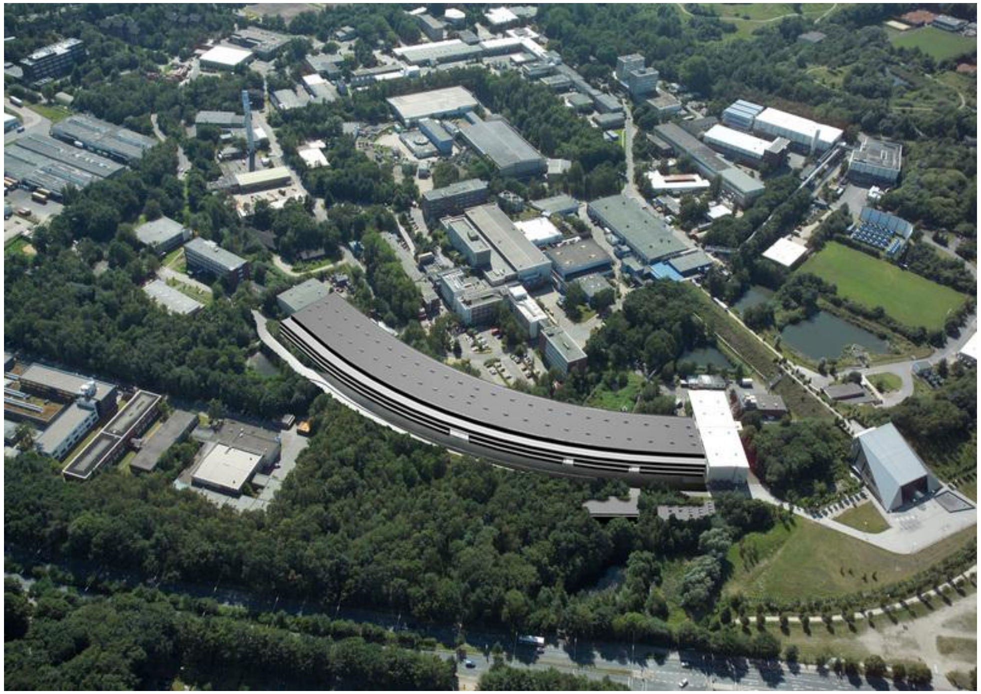
Light helicity

- **–**
- **+**

Petra III



2.3km third generation storage ring
runs 6 GeV positrons, grouped into 100mA 40-960 bunches, evenly distributed over the ring, with 192-8ns spacing.

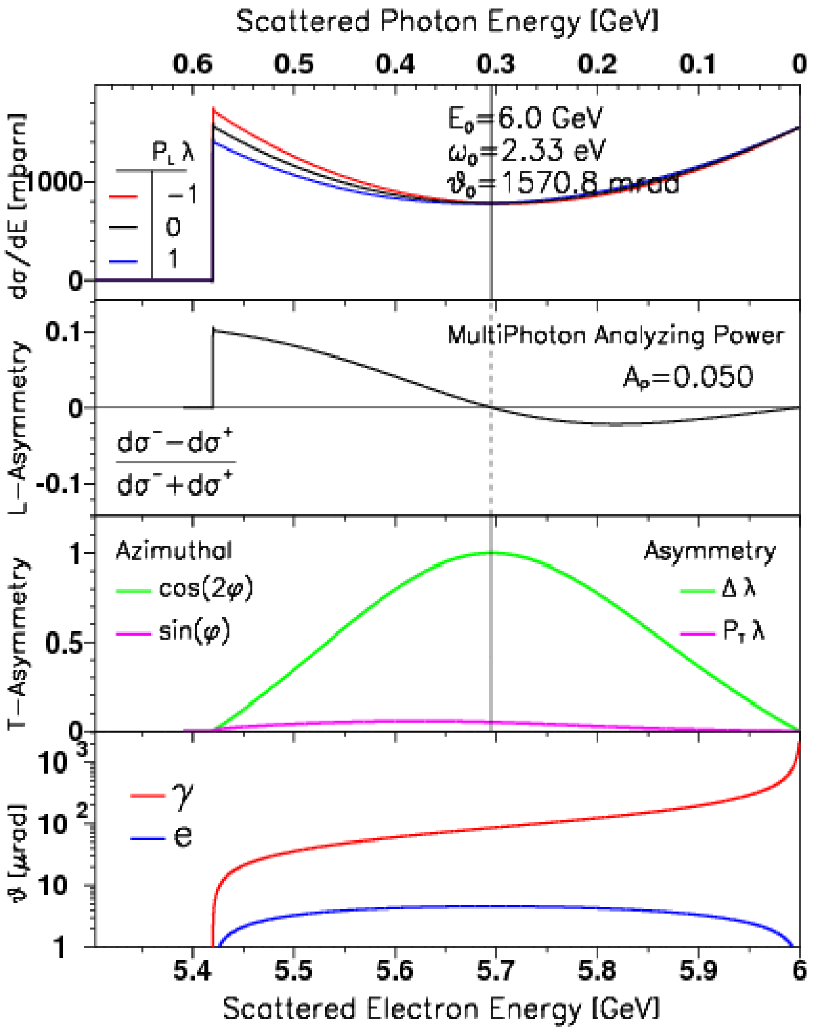


Low emittance (1nm rad)
beam sizes

x	y	z
100um	20um	40ps

top-up injection, high brilliance synchrotron source.

Compton Spectrum, Energies and Angles



Petra III Beam 6 GeV e^-

Lasers 2.33eV and 3.66eV

Crossing Angle 0-90 deg

==========================

Kinematic Parameter x=0.11-0.28

Compton Edge 0.58-1.3GeV

YerPhI 01 Jun 2009

Simulations and estimations

Petra III time resolving mode operation will provide about 50kHz Compton rate.

Gravitational Birefringence

5×10^{-16} sensitivity for 141 days of data taking, using single UV laser.

Gravitational Refractivity

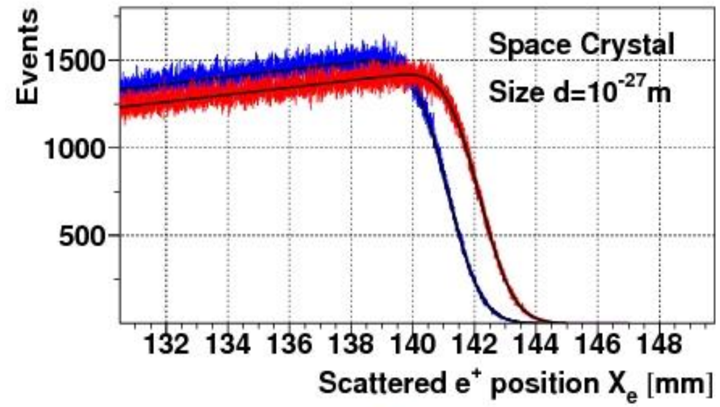
4×10^{-13} sensitivity for sub-minute data sample, needs 2 lasers, UV and green.

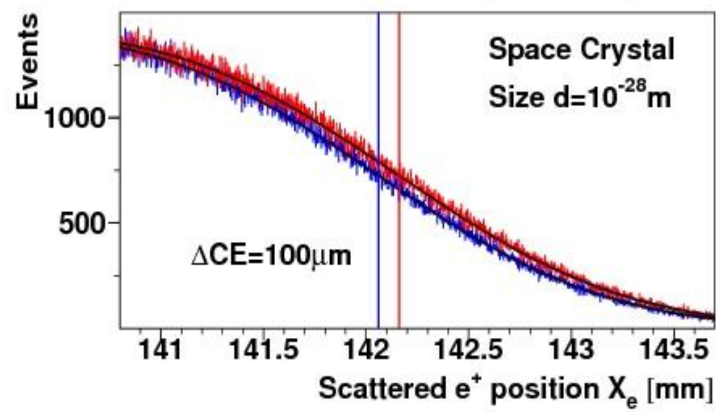
Space Anisotropy

Petra beam pipe declination of 22.58 deg
at the laser IP will allow to scan right ascension for space anisotropy

$$\Delta n_{measured} = \Delta n(0.92 \cos \delta_0 \cos(\alpha - \alpha_0) + 0.38 \sin \delta_0)$$

Simulated spatial spectra.





Systematics

Source of systematics for birefringence	Solution
IP position drifts and helicity correlated jumps.	Excluded by fiber transport of laser light to IP & 90deg crossing angle.
Polarized Laser-electron QED.	Measured & monitored or 0 asymmetry at Compton edge.
Mimicking Effects.	At high energies any EM field or matter induced refractivity or birefringence is disappearing
Conditions change & drift (Temp., Energy, Pressure, etc).	Light helicity kHz flips & combining sub-minute data for asymmetry.

Source of systematics for refractivity	Contribution	Solution
Electron beam energy spread.	$4x10^{-13}$	Increase Machine
Laser 1 and 2 Compton edge electrons' path difference in magnetic field.	$2x10^{-13}$	Energy

Summary

A new method for high energy experimental gravitation is demonstrated.

First results reveal violation of general relativity and a hint for repulsive gravitation.

A proposed experiment at 6GeV PETRA can search for negative gravity down to $4x10^{-13}$ refractivity with 0.58-1.3GeV photons.
A quantum gravitational birefringent term in the energy-momentum relation can be probed down to 10^{-31} m distances.