Astroparticles and Extra Dimensions

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Newton (17th century)

unification of terrestrial gravity and celestial mechanics into Universal Gravitation

The race to unification in Physics

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Einstein(1905-1916)

unification of gravity and space-time geometry into General Relativity

Heisenberg,Schrödinger (1920s)

unification of particle and wave behavior of matter through the advent of Quantum Mechanics

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unification of electromagnetism and weak interactions to electroweak interactions

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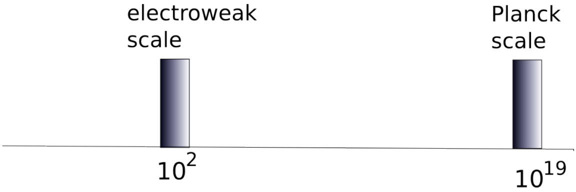
NEXT STEP??

Can we unify all forces?
(Standard Model forces + gravity)

Stumbling block

Two disparate scales coexist

$M_w \sim 10^2 GeV \qquad M_{Pl} \sim 10^{19} GeV$



Quantum corrections tend to mix the scale
Hierarchy problem

A recent proposal

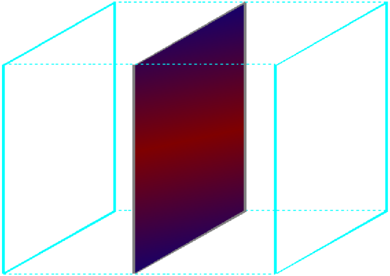
M_{Pl} is an apparent scale

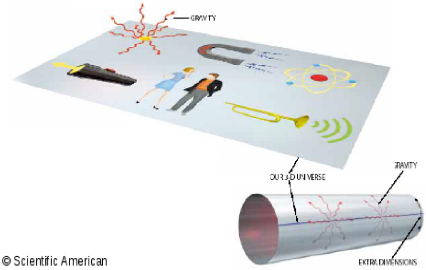
Gravity lives in a higher dimensional space $(4+\delta)$

The true scale of gravity

$M_f \simeq fewTeV$

The picture





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The Brane World

Gravity propagates in a higher dimensional space $D = 4 + \delta$, while the SM fields live on a 4-dim brane

Extra dimensions are compact

$$y \to y + R$$

The Brane World

$$F_4(r) = G_{N(4)} \frac{m_1 m_2}{r^2} \qquad r >> R$$

$$G_{N(4)} = \frac{1}{M_{Pl}^2}$$

$$F_{4+\delta}(r) = G_{N(4+\delta)} \frac{m_1 m_2}{r^{\delta+2}} \qquad r << R$$

$$G_{N(4+\delta)} = \frac{1}{M_f^{2+\delta}}$$

At $r \simeq R$

$$M_{Pl}^2 = R^\delta M_f^{2+\delta}$$

with a large volume of extra space, M_f can become as low as M_w

At $r \simeq R$

$$M_{Pl}^2 = R^\delta M_f^{2+\delta}$$

Black Hole Formation in HE Collisions

A TeV gravity will induce the formation of a black hole in particle collisions whenever $\sqrt{s} \simeq M_f$ and the impact parameter b is smaller than R_s, the Schwarzschild radius

We need Quantum Gravity to study this process since it is not available, we opt for a classical approach, where a particle is scattered in the effective curved background produced by the other

We consider a SM particle moving under the influence of a $(4+\delta)$-dim black hole

The effective metric

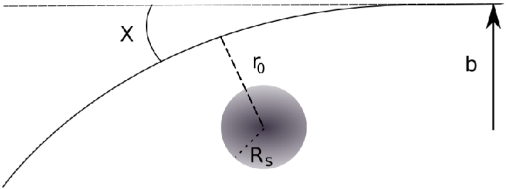
$$ds^2 = f(r)dt^2 - \frac{1}{f(r)}dr^2 - r^2(d\theta^2 + \sin^2\theta d\varphi^2)$$

$$f(r) = 1 - \left(\frac{R_s}{r}\right)^{1+\delta}$$

$$R_s = \frac{1}{\sqrt{\pi}M_f}\left[\frac{M}{M_f}\frac{8\Gamma\left(\frac{\delta+3}{2}\right)}{\delta+2}\right]^{\frac{1}{(\delta+1)}}$$

For particle collisions $M = \sqrt{s}$

A particle at impact parameter b, approaches the BH at the closest distance r_0 and escapes into infinity, deflected by an angle X



The critical parameter is

$$\varrho = \left(\frac{R_s}{r_o}\right)^{1+\delta}$$

- $\varrho << 1$ weak gravity
- $\varrho \simeq 1$ strong gravity

$b - r_0$ relationship

$$b^2 = \frac{r_0^2}{1-\varrho}$$

Deflection angle X

$$X = 2\Phi_0 - \pi$$

$$\Phi_0 = \int_0^1 \frac{d\omega}{\left[1-\omega^2-\varrho\left(1-\omega^{3+\delta}\right)\right]^{1/2}}$$

Small ϱ (Taylor expand)

$$X = I(\delta)\varrho$$

Agreement with available result of perturbative gravity

$$\delta = 0 \qquad\qquad X = \frac{2R_s}{b}$$

Deflection angle X

$$X = 2\Phi_0 - \pi$$

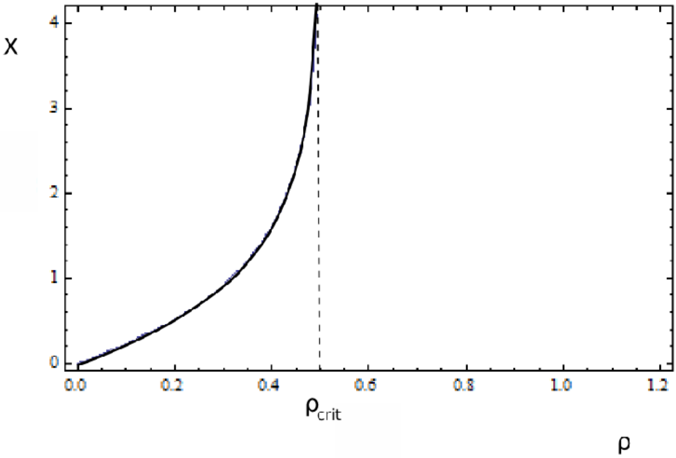
$$\Phi_0 = \int_0^1 \frac{d\omega}{\left[1-\omega^2-\varrho\left(1-\omega^{3+\delta}\right)\right]^{1/2}}$$

Large ϱ

With increasing ϱ, X increases and there is a critical ϱ_{crit} where X diverges logarithmically

$$X = a ln \left[\frac{1}{1-\frac{\varrho}{\varrho_{crit}}}\right]$$

$$a = \varrho_{crit} I(\delta) \qquad \varrho_{crit} = \frac{2}{3+\delta}$$


X
4
3
2
1
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
ρcrit
ρ

What is the physical meaning of ϱ_{crit} ? (Notice for $\delta = 0$ $\quad r_0 = \frac{3}{2} R_s$)

ϱ_{crit} corresponds to the unstable circular orbit around the BH

As $\varrho \to \varrho_{crit}$ we witness the orbiting phenomenon

For $\varrho = \varrho_{crit}$ the particle stays in circular orbit ($X = \infty$)

For $\varrho < \varrho_{crit}$ the particle is fully absorbed by the BH

Transform into cross-section

$$\frac{d\sigma_0(X)}{d\Omega} = C R_s^2 \frac{1}{\sin X} \frac{exp\left(-\frac{X}{a}\right)}{\left[1 - exp\left(-\frac{X}{a}\right)\right]^{\frac{3+\delta}{1-\delta}}}$$

Different b contribute to the same X

Sum over all $X_n = 2n\pi + X$

$$\frac{d\sigma(X)}{d\Omega} = \sum_{n=0}^{\infty} \frac{d\sigma_0(X_n)}{d\Omega}$$

Small X

Cross section diverges like $\left(\frac{1}{X}\right)^{\gamma}$

$\gamma = \frac{4+2\delta}{1+\delta} \qquad (\delta = 0,\ \gamma = 4)$

Large X

Cross section diverges like

$$\frac{1}{X - \pi} \qquad \text{for any } \delta$$

The backward divergence peculiar to the BH existence (compact object with an horizon)

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SIGNAL FOR BH FORMATION

- Striking signatures in cosmic rays
- in neutrino telescopes

Theoretical Issue - DUALITY

Gravity at large distances	$\Leftrightarrow$	QCD at short distances
Gravity at short distances	$\Leftrightarrow$	QCD at large distances

What else can live in Extra Dimensions ?

A sterile neutrino, singlet under SM

$$N = \left(\begin{array}{c} N_R \\ N_L \end{array} \right)$$

Assume for simplicity 1 extra dimension y. Each $N_{R,L}$ a KK tower

$$N(x,y) = \frac{1}{\sqrt{2\pi R}} N_0(x) + \sum_{n=1} \frac{1}{\sqrt{\pi R}} N_n(x) cos\left(\frac{ny}{R}\right)$$

Coupling left - handed lepton (doublet) Higgs scalar - bulk neutrino

$$\frac{h}{\sqrt{M_f}}\bar{L}HN_R\delta(y)$$

$\Rightarrow$ mass term $m\bar{\nu}_L\left(N_{R_0}+\sqrt{2}\sum_{n=1}N_{R_n}\right)$

$$m \sim \frac{h\upsilon M_f}{M_{Pl}} \sim 10^{-4}eV$$

Form

$$\Psi_R = \begin{pmatrix} N_{R_0} \\ N_{R_i} \end{pmatrix} \quad \Psi_L = \begin{pmatrix} \nu_L \\ N_{L_i} \end{pmatrix} \qquad (i = 1, 2, ...)$$

(N_{L_0} decouples)

Mass term $\overline{\Psi}_L M \Psi_R$

$$\mathbf{M} = \begin{pmatrix} m & \sqrt{2}m & \sqrt{2}m & \dots \\ 0 & \frac{1}{R} & 0 & \dots \\ 0 & 0 & \frac{1}{R} & \dots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$H = \frac{1}{2E_\nu} M M^T$$

Inside matter $H_{11} \to H_{11} + \mu$

$$\mu = \sqrt{2} E_\nu R^2 G_F N_n \simeq G_f R^2 \varrho \frac{E_\nu}{\sqrt{2} M_N}$$

With $\xi = mR$ the rescaled eigenvalues λ_n^2 of H satisfy

$$\left[\mu - \lambda^2 + (\lambda\pi)cot(\lambda\pi)\xi^2\right] \prod_{n=1}^{\infty}(n^2 - \lambda^2) = 0$$

The corresponding eigenvectors are B_n $(e_{n_0}, e_{n_1}, e_{n_2}, ...)$

$$e_{n_k} = \frac{k\sqrt{2}\xi}{(k^2 - \lambda_n^2)} e_{n_0}, \qquad (k = 1, 2, ..)$$

$$e_{n_0}^2 \left[\frac{1}{2} + \frac{\pi^2\xi^2}{2} + \frac{\mu}{2\lambda_n^2} + \frac{\left(\lambda_n - \frac{\mu}{\lambda_n}\right)^2}{2\xi^2}\right] = 1$$

Study

ξ variation

$\xi = 0$ (no mixing) $\qquad \lambda_0 = \sqrt{\mu}, \quad \lambda_n = n$

Small ξ $\qquad \lambda_n \simeq n + \frac{\xi^2}{n\pi}$

Large ξ $\qquad \lambda_n \simeq (n + \frac{1}{2}) \left(1 - \frac{1}{\xi^2 \pi^2}\right)$

$\nu - B_n$ admixture determined by $|e_{n_0}|^2$

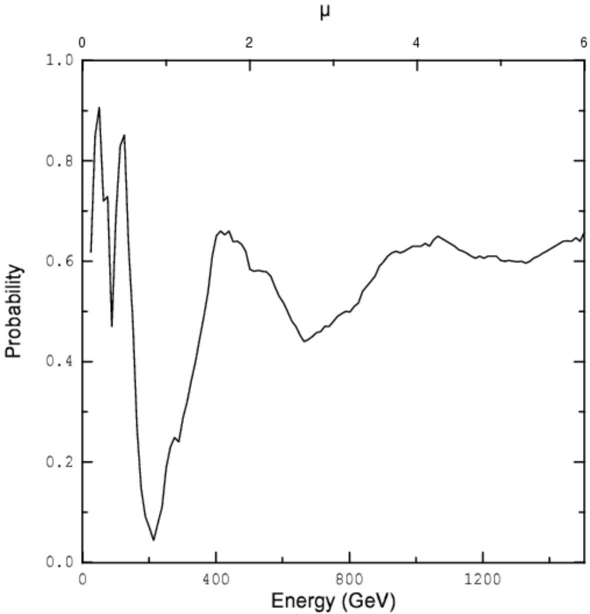
It becomes maximal when

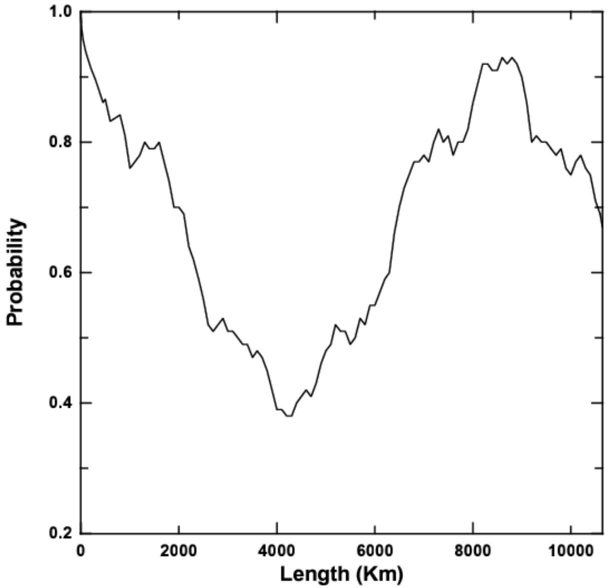
$$\mu = \lambda_n^2 \qquad \text{(resonance condition)}$$

For $\mu \simeq 1$ (first resonance)

$$\left(\frac{\varrho}{10\frac{gr}{cm^3}}\right)\left(\frac{E_\nu}{100\,GeV}\right)\left(\frac{R}{1\mu m}\right)^2 \simeq 1$$

Read off the radius R of the extra dimension


μ
0
2
4
6
1.0
0.8
0.6
0.4
0.2
0.0
Probability
0
400
800
1200
Energy (GeV)


1.0
0.8
0.6
0.4
0.2
Probability
0
2000
4000
6000
8000
10000
Length (Km)

What else can live in Extra Dimensions

The axion

The Peccei - Quinn (PQ) solution to the strong CP problem $\Rightarrow$ predicts a neutral, spin-zero pseudoscalar particle, the axion

Axion - photon oscillation

$$\mathcal{L}_{int} = \frac{1}{f_{PQ}} a F_{\mu\nu} \tilde{F}_{\mu\nu} = \frac{4}{f_{PQ}} a \vec{E} \cdot \vec{B}$$

Introduce one extra compact dimension y

The axion field $a(x^\mu, y)$, projected into the brane, looks like a collection of KK modes $a_n(x^\mu)$, with $m_n = \frac{n}{R}$

The coupling photon - KK axions

$$\mathcal{L}_{int} = \frac{1}{f_{PQ}} \sum_n a_n F_{\mu\nu} \tilde{F}_{\mu\nu} = \frac{4}{f_{PQ}} \sum_n a_n \vec{E} \cdot \vec{B}$$

In the presence of an external magnetic field B, the photon state $A_{||}$ parallel to the magnetic field B, the standard PQ axion a_0 and the KK axions a_n mix up

$$
\mathbf{M} = \begin{pmatrix} \Delta_\gamma & \Delta_B & \Delta_B & \dots & \Delta_B \\ \Delta_B & \Delta_0 & 0 & \dots & 0 \\ \Delta_B & 0 & \Delta_1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \Delta_B & 0 & 0 & & \Delta_N \end{pmatrix}
$$

where

$$
\Delta_\gamma = \frac{\omega_{pl}^2}{2E}, \quad \Delta_0 = \frac{m_{PQ}^2}{2E}, \quad \Delta_n = \frac{n^2}{2ER^2}, \quad \Delta_B = \frac{4B}{f_{PQ}}
$$

Eigenvalues and eigenstates of the mixing matrix M

A resonance occurs $\gamma \to a_n \to \gamma$ whenever

$$\frac{n^2}{2ER^2} = \Delta_B$$

For $n = 1$ the resonance is narrow

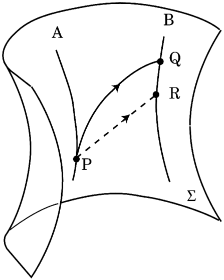
$$\left(\frac{E}{500\,GeV}\right)\left(\frac{R}{10^{-6}\,cm}\right)^2\left(\frac{B}{10^{12}\,G}\right) = 1.0$$

(with $f_{PQ} = 10^{11}$ GeV)

Photons with the resonance energy, are transformed into KK axion, travel freely in the bulk space, before returning back into the brane and observed again as photon (transparency)

Axionic shortcuts

The brane is curved because of self-gravity



Then geodesics in the bulk propagate signals faster compared to the geodesics in the brane

Axionic shortcuts

Toy model

$$ds^2 = dt^2 - dx_1^2 - dx_2^2$$

The curved brane is

$$x_2 = A sin k x_1$$

Bulk shortcut

$$x_2 = 0$$

$$\frac{t_\gamma - t_\alpha}{t_\gamma} \simeq \left(\frac{Ak}{2}\right)^2$$

MAGIC photons

Photons in the $0.25 - 0.6$ TeV range arrive earlier compared to the $1.2 - 10$ TeV photons

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Our working hypothesis:

The first photons satisfy the resonance condition and shortcut through the bulk space

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- Candidates for dark matter, dark energy