Model for gravity at large distances

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Outline

Life, the Universe and Everything (we know)

- Particle Physics
- Cosmology

Puzzles

- Energy budget of the Universe
- Dark matter

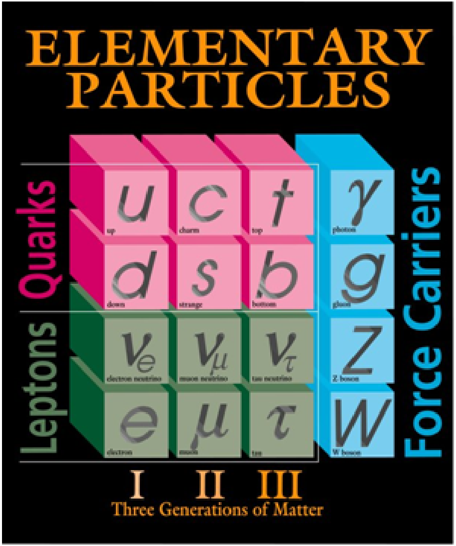
Model for Gravity at Large Distances

- As simple as possible, but not simpler
- Rindler force
- Observations

Outline

Periodic Table of Elementary Particles

Particles we know and have observed:



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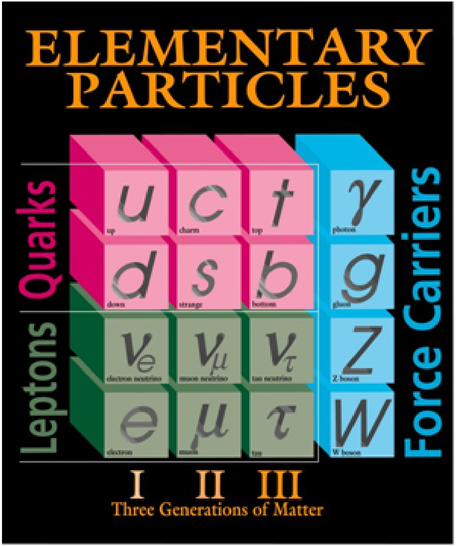

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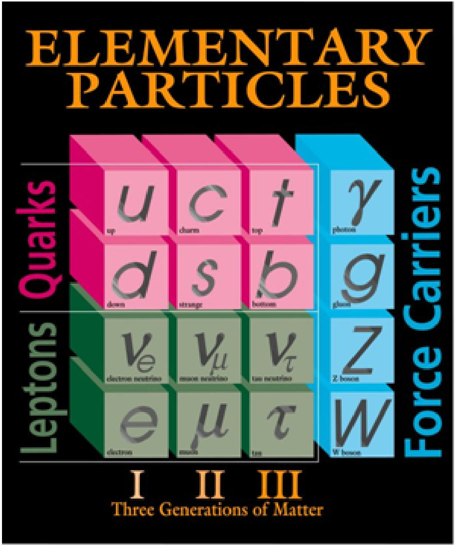

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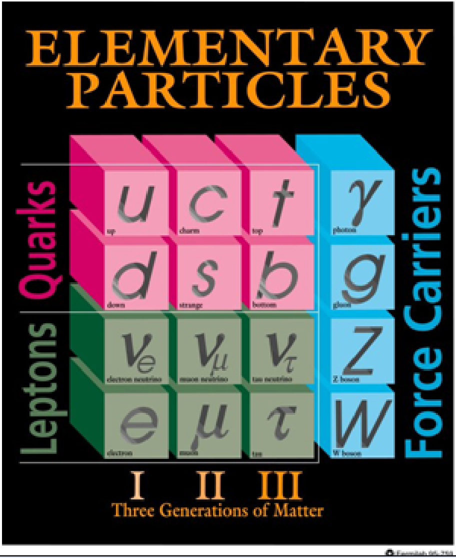

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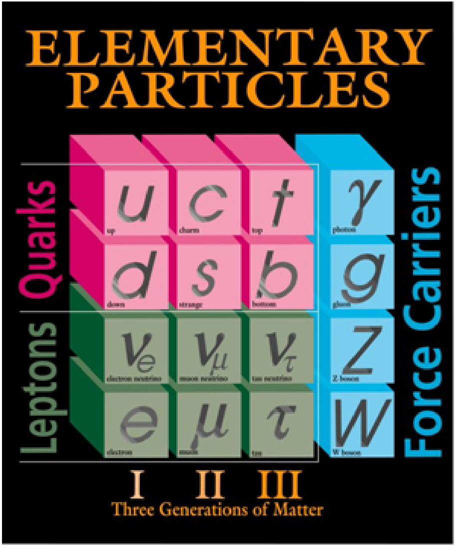

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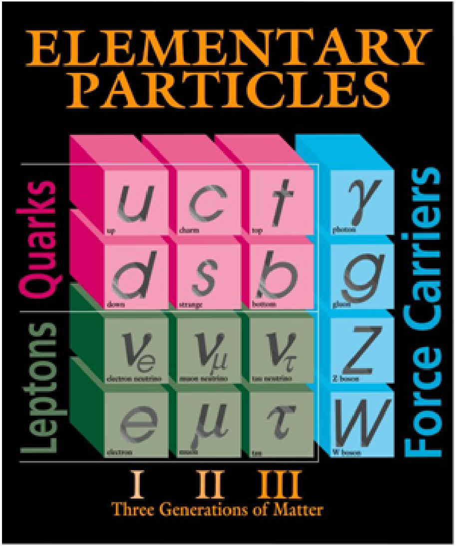

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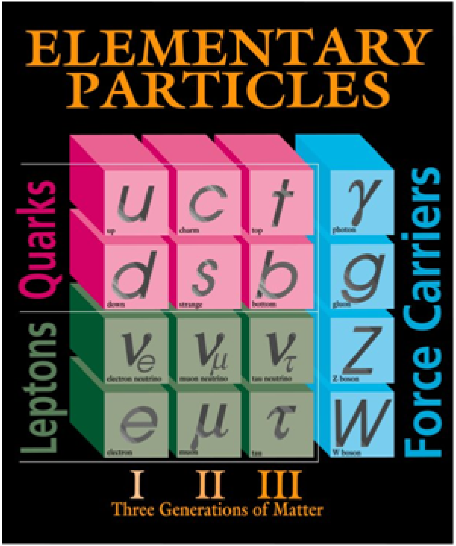

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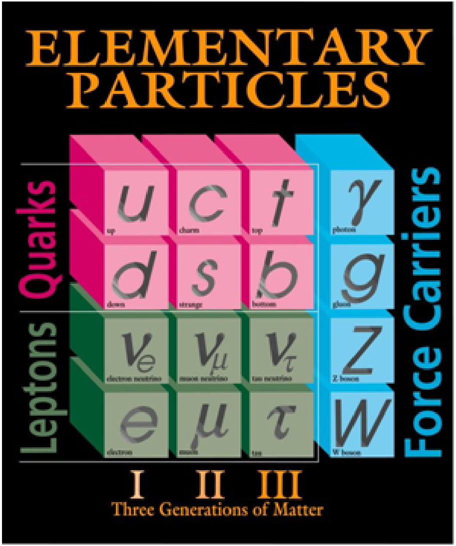

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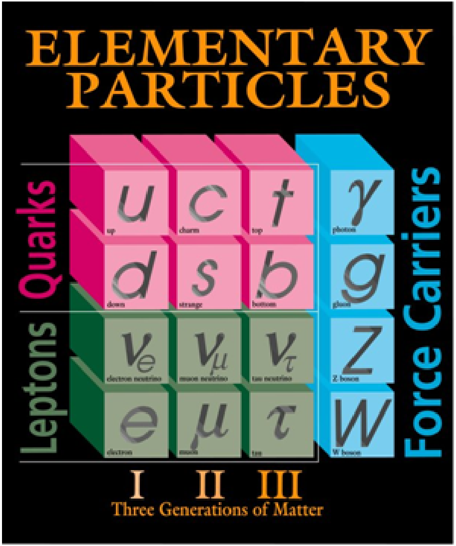

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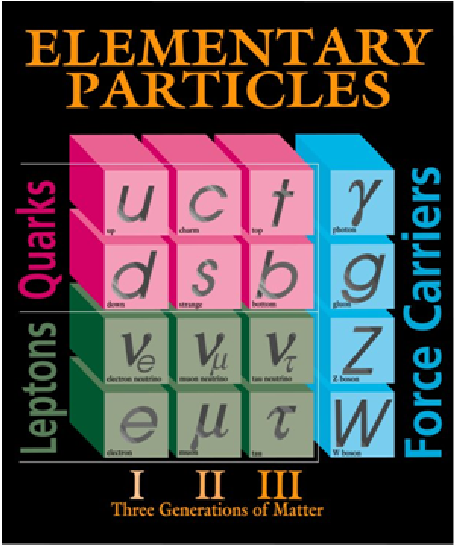

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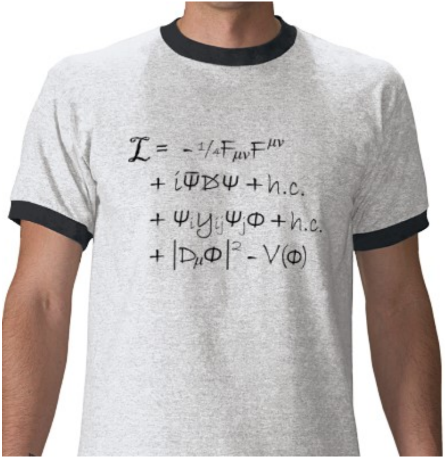
- That's it! (well, almost...)

Standard Model of Particle Physics

A theory of (almost) everything:



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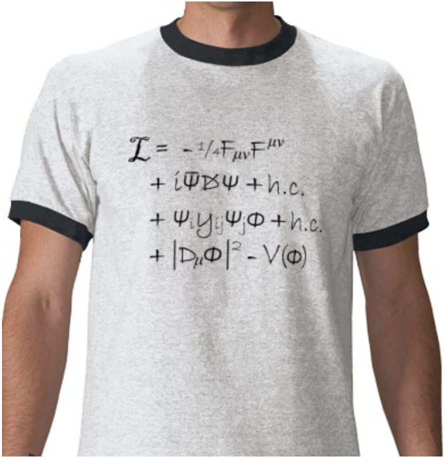

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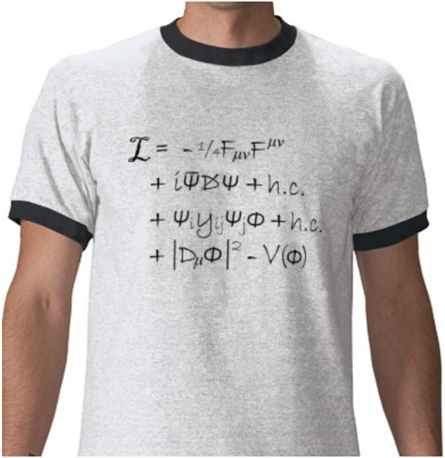

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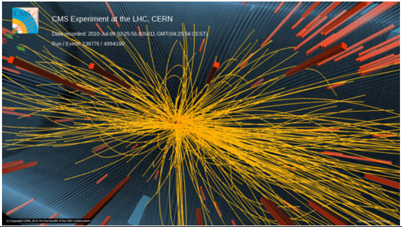
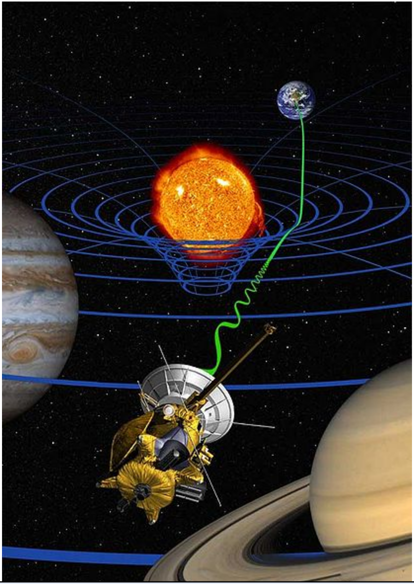
- Currently SM improved at LHC



Gravity

Gravity = Geometry



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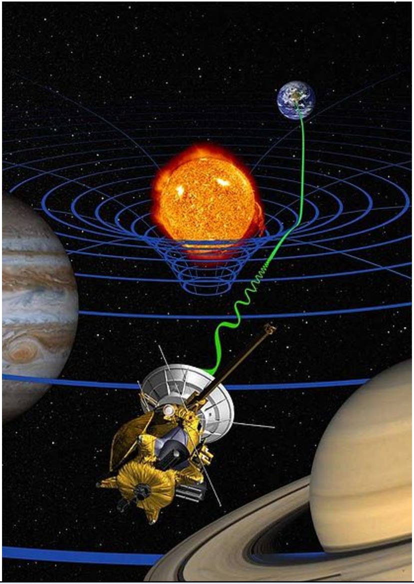

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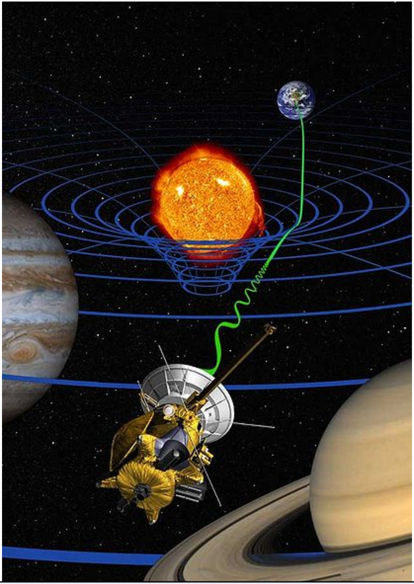

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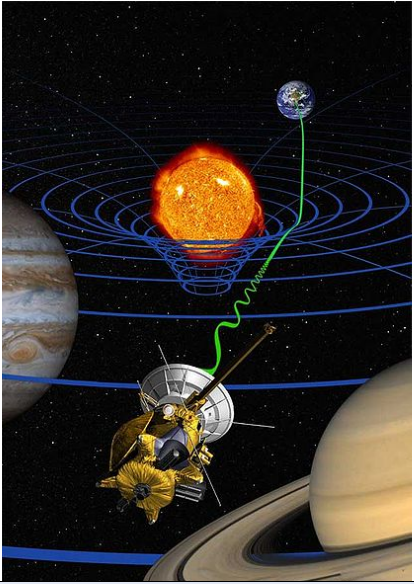

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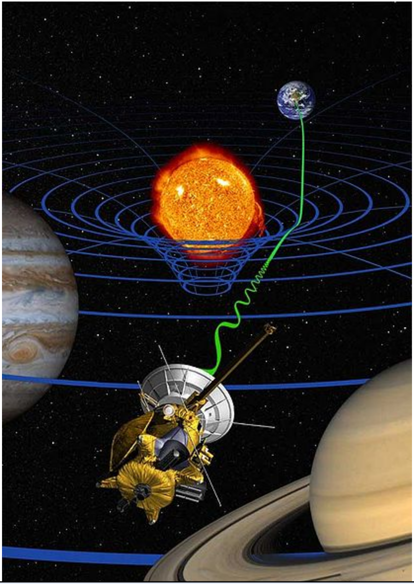

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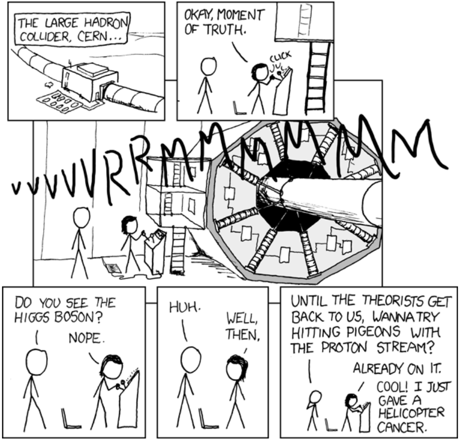
  left: geometry, right: matter
- Tested to high accuracy:
  Perihelion shifts ($\beta - 1 < 2 \cdot 10^{-4}$)
  Radar echo delay ($\gamma - 1 < 2 \cdot 10^{-5}$)
  Binary pulsars ($\alpha_3 < 4 \cdot 10^{-20}$)

Missing Entries in the Periodic Table

Particle in the SM not found yet:



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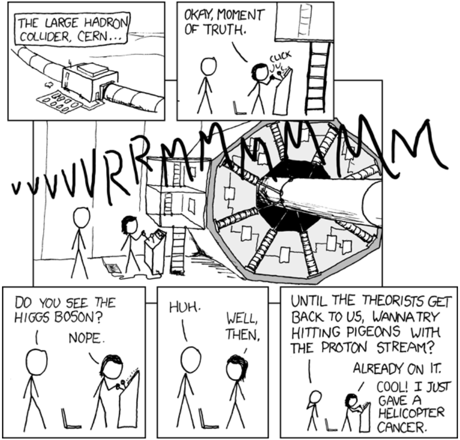

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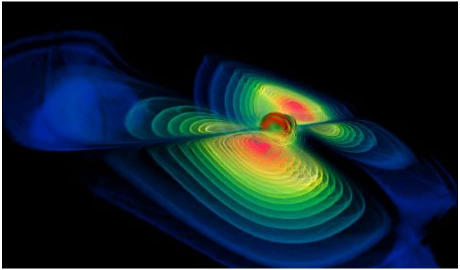

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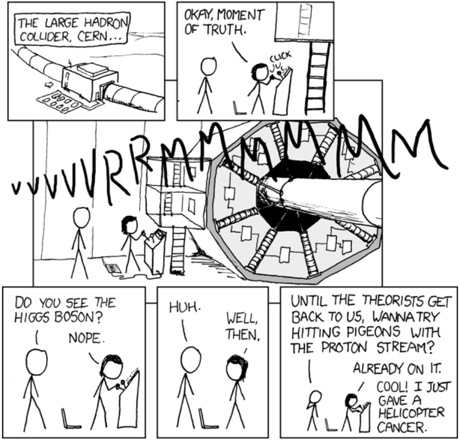

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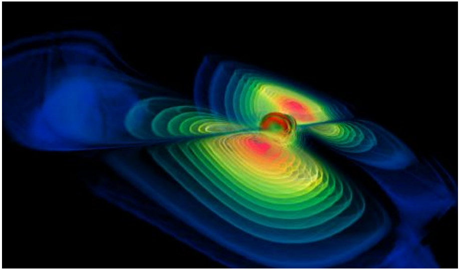

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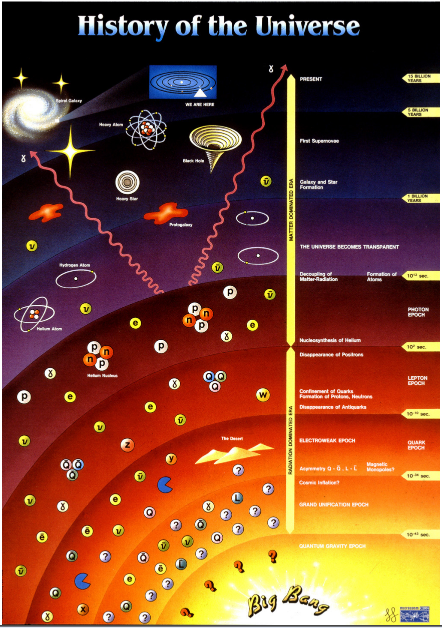
Further particles beyond SM? Inflaton?, SUSY?, Axions?, Dark Spinors?, Kaluza–Kleins?, ...
LHC and Astro/Astroparticle--physics may find clues!

Brief History of the Universe



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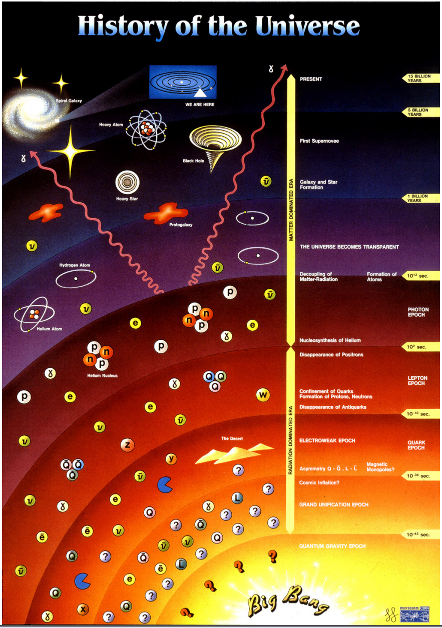

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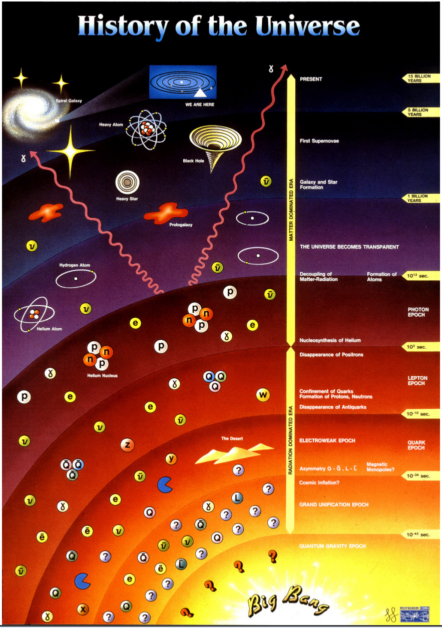

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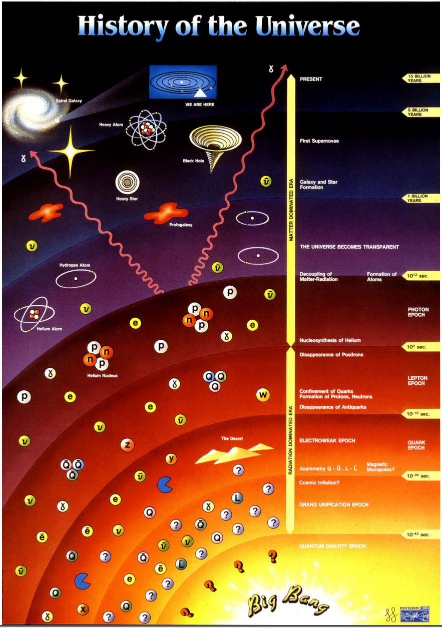

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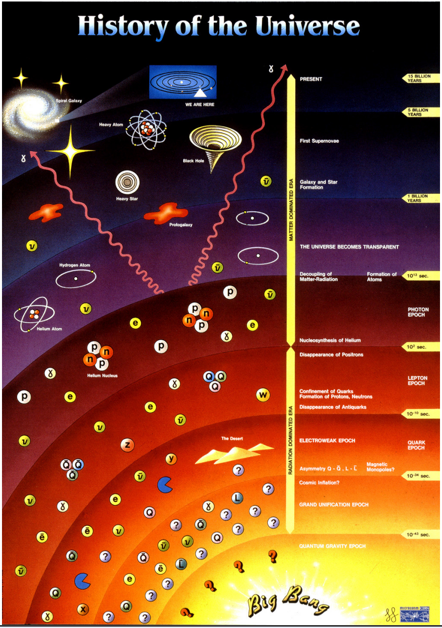

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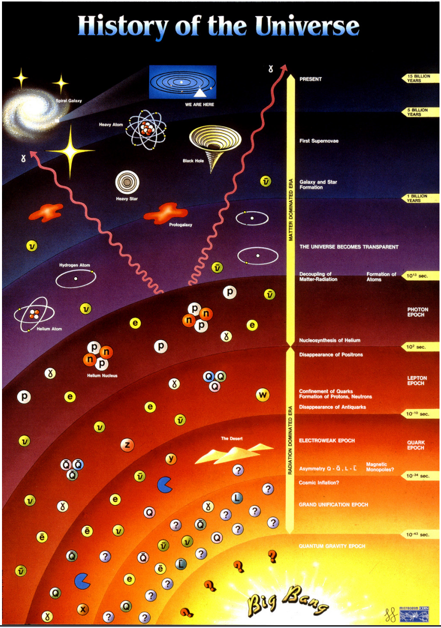

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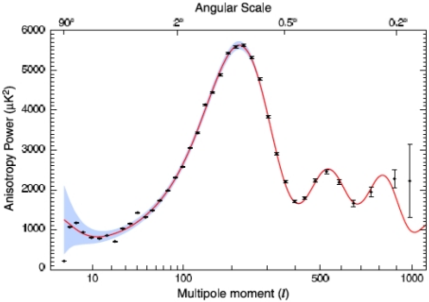
- COBE (1989-1993), WMAP (since 2001), Planck (since 2009)



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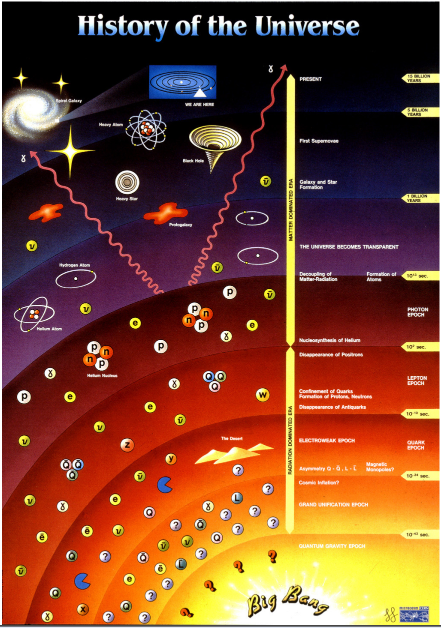

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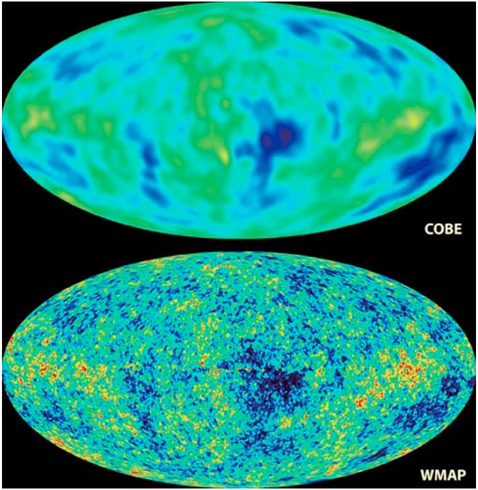
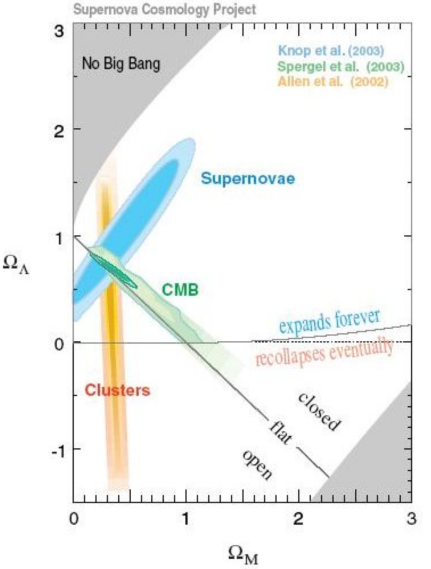


Above: COBE satellite (900km)
Below: WMAP satellite at Lagrange point L2 ($1.5 * 10^6$km)

Standard Model of Cosmology

A theory of (almost) everything:



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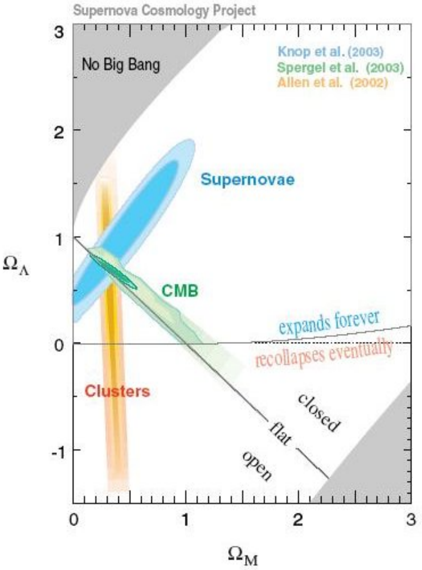

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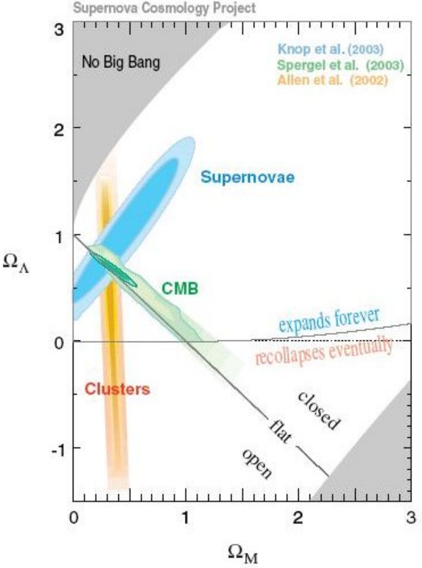

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- Currently many experiments!

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Is anything else missing?

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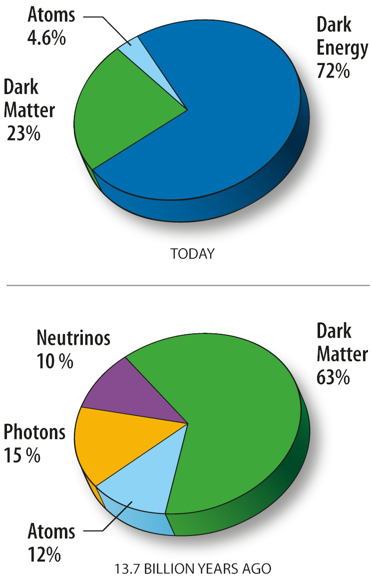

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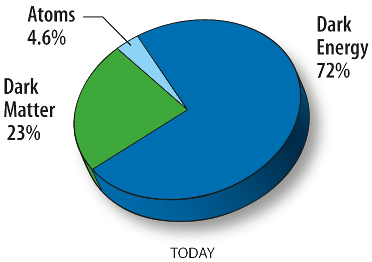

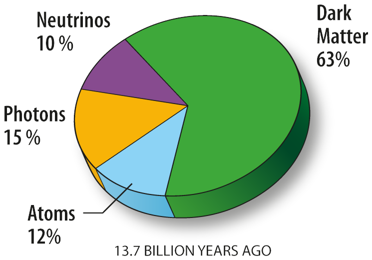

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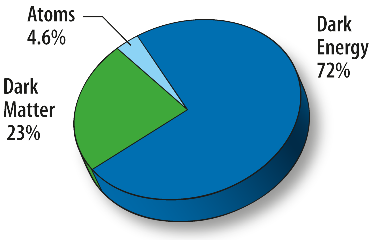
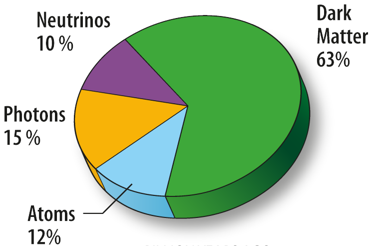


TODAY



13.7 BILLION YEARS AGO

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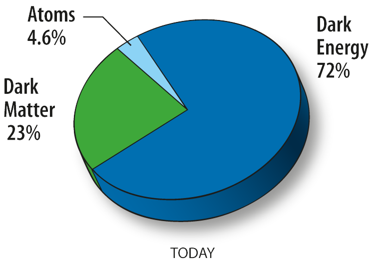

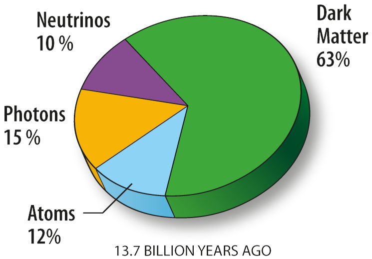

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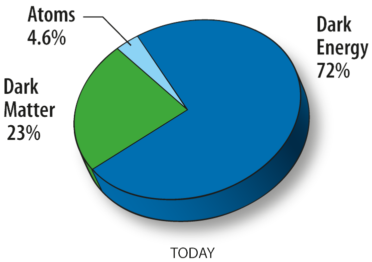

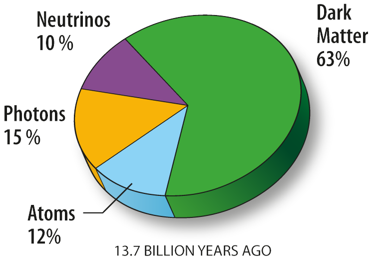

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- Less plausible, but logically possible: dark matter is gravitational effect

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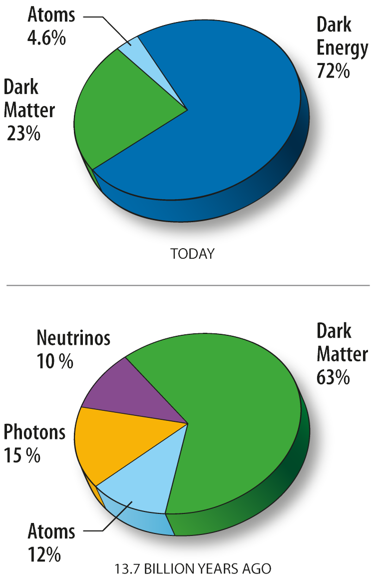

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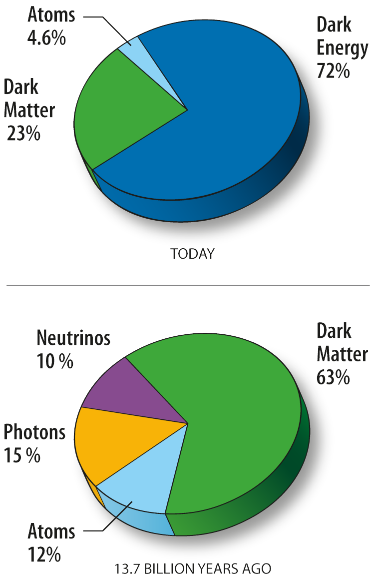

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- Simplest correct explanation: cosmological constant

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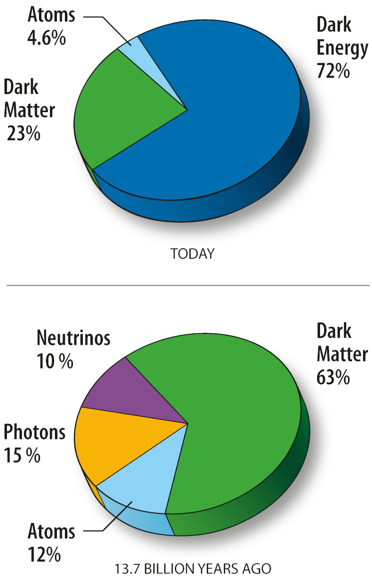

Collect all the available data:

- Progress of last two decades: we understand less than 5% of the Universe, and we know it!
- More than 70% “Dark Energy”
- Simplest correct explanation: cosmological constant
- BUT: why so small??? 10^{-123}

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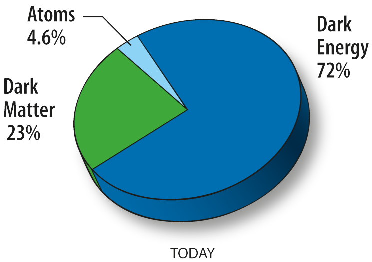

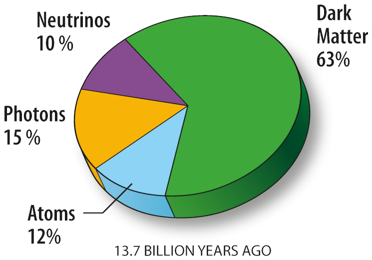

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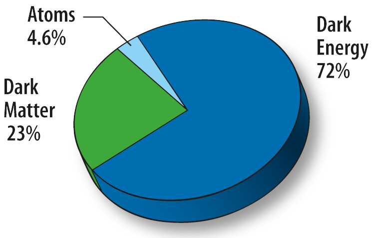
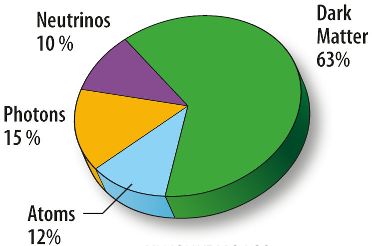


TODAY



13.7 BILLION YEARS AGO

Collect all the available data:

- Progress of last two decades: we understand less than 5% of the Universe, and we know it!
- Dark Matter: many indications, many candidates
- Logically possible: dark matter is gravitational effect
- More than 70% "Dark Energy"
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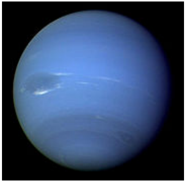
To address these issues we need to understand
GRAVITY AT LARGE DISTANCES!

Dark Matter hypothesis: Early success...

Neptune:



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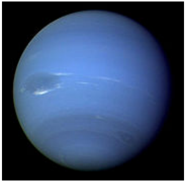

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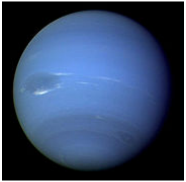

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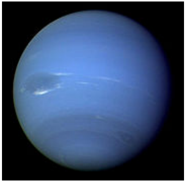

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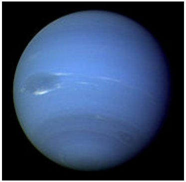

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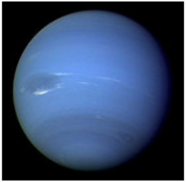

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Discovery of Neptune was first success of the Dark Matter concept!

Dark Matter hypothesis: ...and early failure

Vulcan:

(picture based on

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Dark Matter hypothesis: ...and early failure

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- 1915: Einstein explains perihelion shift of Mercury with General Relativity

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Non-discovery of Vulcan was first failure of the Dark Matter concept!

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Prominent examples:

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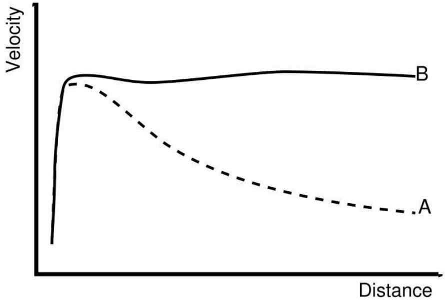
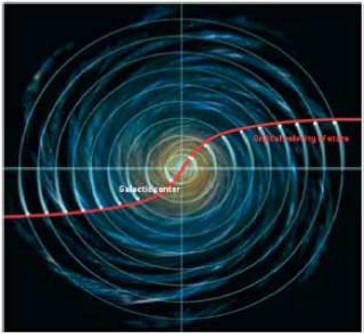
- Galactic rotation curves (pictures by Wikipedia)

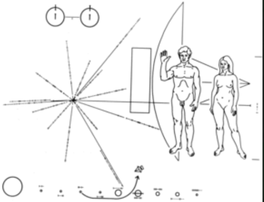
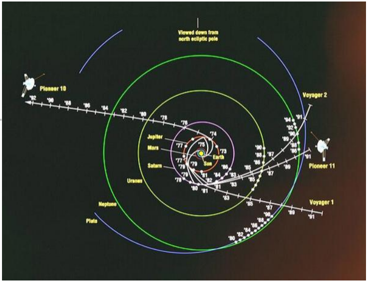




A = Theory, B = Observation

Anomalies = differences between theory and observations
Prominent examples:

- Galactic rotation curves
- Pioneer anomaly? (pictures by NASA)

Anomalous acceleration towards the Sun?

Some crucial facts about the Dark Side of life:

- Fact 1: Vulcan scenario seems unlikely for Dark Matter, but cannot be excluded

MOND, TeVeS, modified theories of gravity, ...

Are we in a Neptune or a Vulcan scenario?
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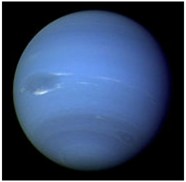

LSP, axion, WIMP, MACHO, ELKO, ...

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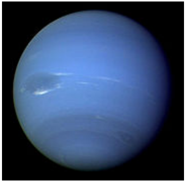
vs.



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- Show that Vulcan scenario is correct
- Show that Neptune scenario is correct

Both strategies are currently out of reach!

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My strategy: remain agnostic and rephrase the question

Outline

Life, the Universe and Everything (we know)

- Particle Physics
- Cosmology

Puzzles

- Energy budget of the Universe
- Dark matter

Model for Gravity at Large Distances

- As simple as possible, but not simpler
- Rindler force
- Observations

Gravity at large distances

Key question:

> What is the most general effective theory of gravity at large distances that can possibly exist?

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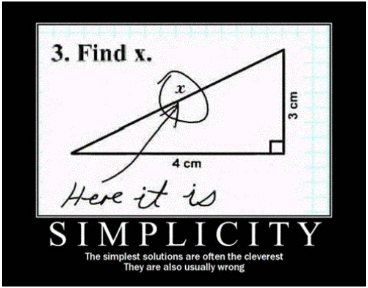

Key question:

What is the most general effective theory of gravity at large distances that can possibly exist?

Input:

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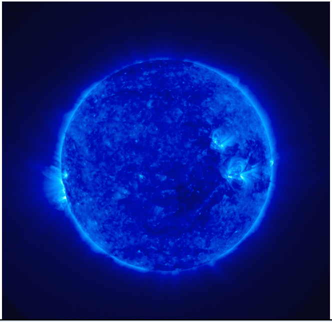
- Assume spherical symmetry at large distances



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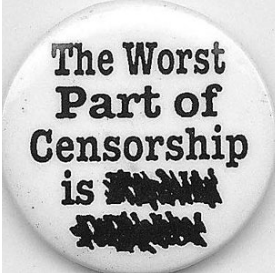

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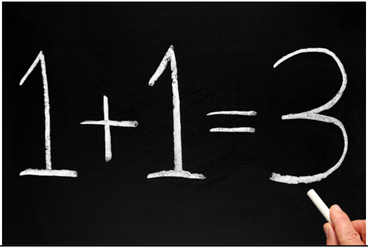

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Output:

Force = Newton + Centrifugal

$$F/m = -M/r^2 + \ell^2/r^3$$

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Force = Newton + Centrifugal + Einstein

$$F/m = -M/r^2 + \ell^2/r^3 - 3M\ell^2/r^4$$

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Output:

Force = Newton + Centrifugal + Einstein + Cosmological + Rindler

$$F/m = -M/r^2 + \ell^2/r^3 - 3M\ell^2/r^4 + \Lambda r - a\,(1 - \ell^2/r^2)$$

New force arises in this model!

The technical slide

Write down most general line-element compatible with spherical symmetry

$$\mathrm{d}s^2 = g_{\alpha\beta}\ \mathrm{d}x^\alpha\,\mathrm{d}x^\beta + \Phi^2\ \mathrm{d}\Omega^2_{S^2}$$

Described by 2d metric g and scalar field Φ.
Use 2d theory to describe these fields!

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Require absence of curvature singularities for large Φ.

$$V = \Lambda\Phi^2 + a\Phi + 1 + \mathcal{O}(1/\Phi)$$

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Solve equations of motion

The technical slide

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$$V = \Lambda\Phi^2 + a\Phi + 1 + \mathcal{O}(1/\Phi)$$

Solve equations of motion and get as most general solution $\Phi = r$,

$$g_{\alpha\beta}\,\mathrm{d}x^\alpha\,\mathrm{d}x^\beta = -K^2\,\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{K^2} \qquad K^2 = 1 - \frac{2M}{r} - \Lambda r^2 + 2ar$$

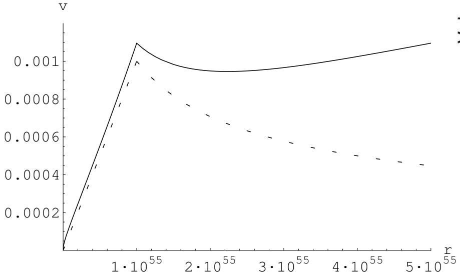
New force at large distances

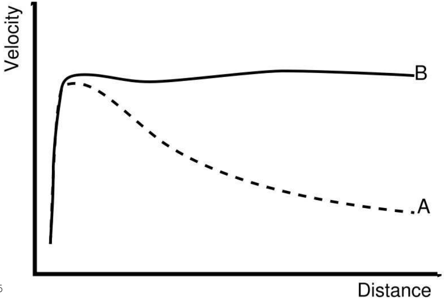
Test this for galaxies

Choose some value for Rindler force a:

$$F/m = -M/r^2 - a$$

Result for velocity profile:





Note: a is positive!

New force at large distances
Test this for Pioneer anomaly

Choose some value for Rindler force a:

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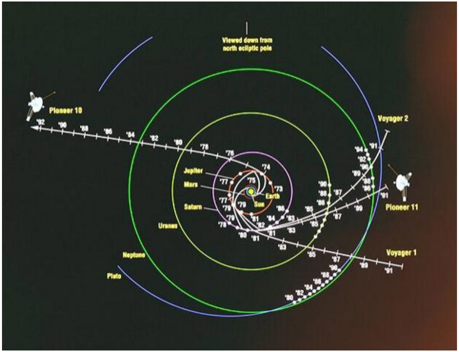
Matches the Pioneer trajectory!



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Solar system tests and bounds on Rindler acceleration

In collaboration between ESA (Carloni) and VUT (DG, Preis)

Scrutinize solar system data to get bounds on Rindler acceleration

- Bound from Pioneer data:

$$|a| < 9 \cdot 10^{-10} m/s^2$$

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- Bounds from perihelion shifts:

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Last bound comes with caveats, however!

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- Obtained recently first (solar system) constraints on this Rindler force

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- Microscopic model predicting Rindler term?
  Where does it come from?

Thank you for your attention! ... questions?