

MASSIVE GRAVITY

(SPECULATIONS IN COSMOLOGY II)

MARK WYMAN

74TH COMPTON LECTURE SERIES

SOME BUSINESS

- No lecture next week! Happy Thanksgiving
- No lectures: Nov. 26th or Dec. 3rd
- Physics with a Bang! Dec. 3rd, 11am - 4pm
- Last lecture - with luncheon, Dec. 10th
- PS: I will discuss the superluminal neutrino news at the end

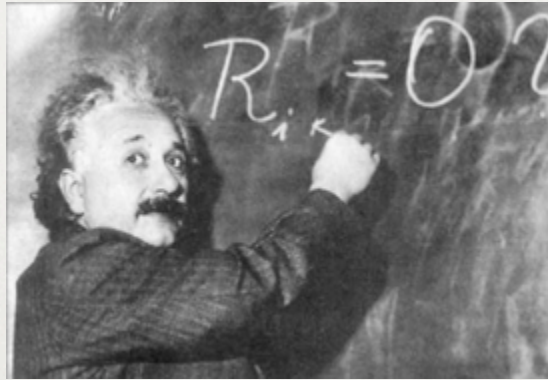


$$m_g \neq 0?$$

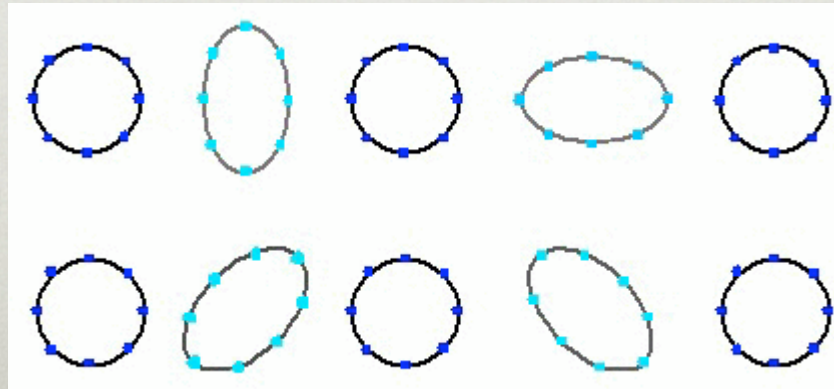
$$m_g^2 (h_{\mu\nu} h^{\mu\nu} - h^2)$$

1939

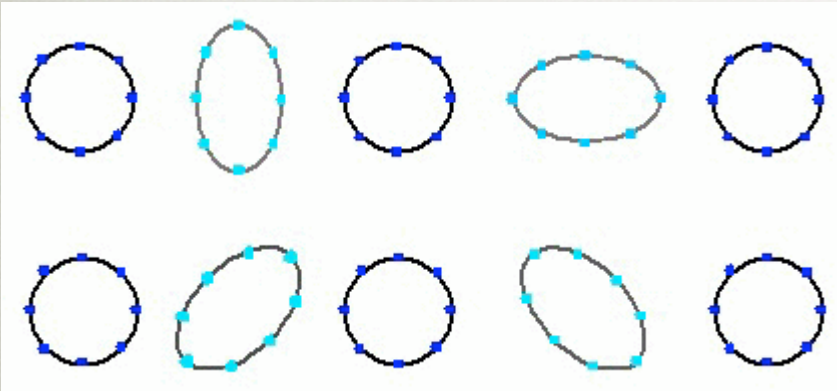
GENERAL RELATIVITY



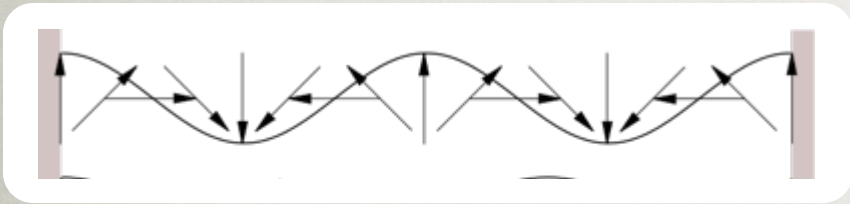
2 “tensor” fields



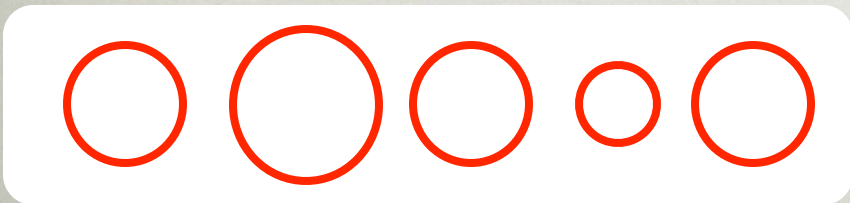
MASSIVE GRAVITY



2 “tensor” fields



2 “vector” fields



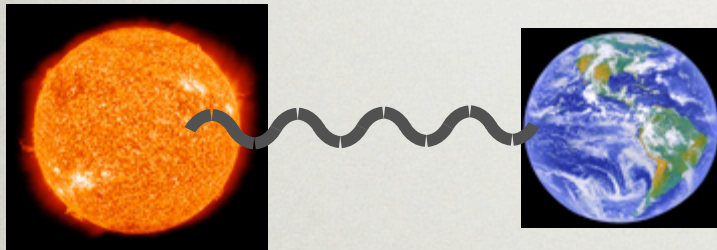
1 scalar field



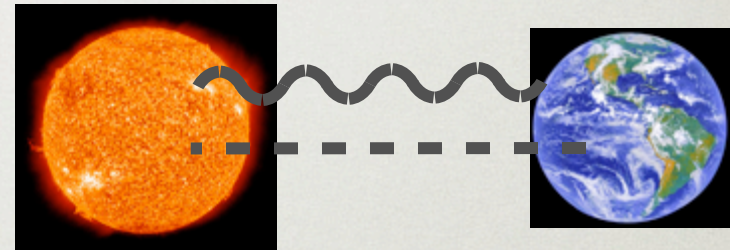
VAN DAM, VELTMAN, ZAKHAROV DISCONTINUITY

1970

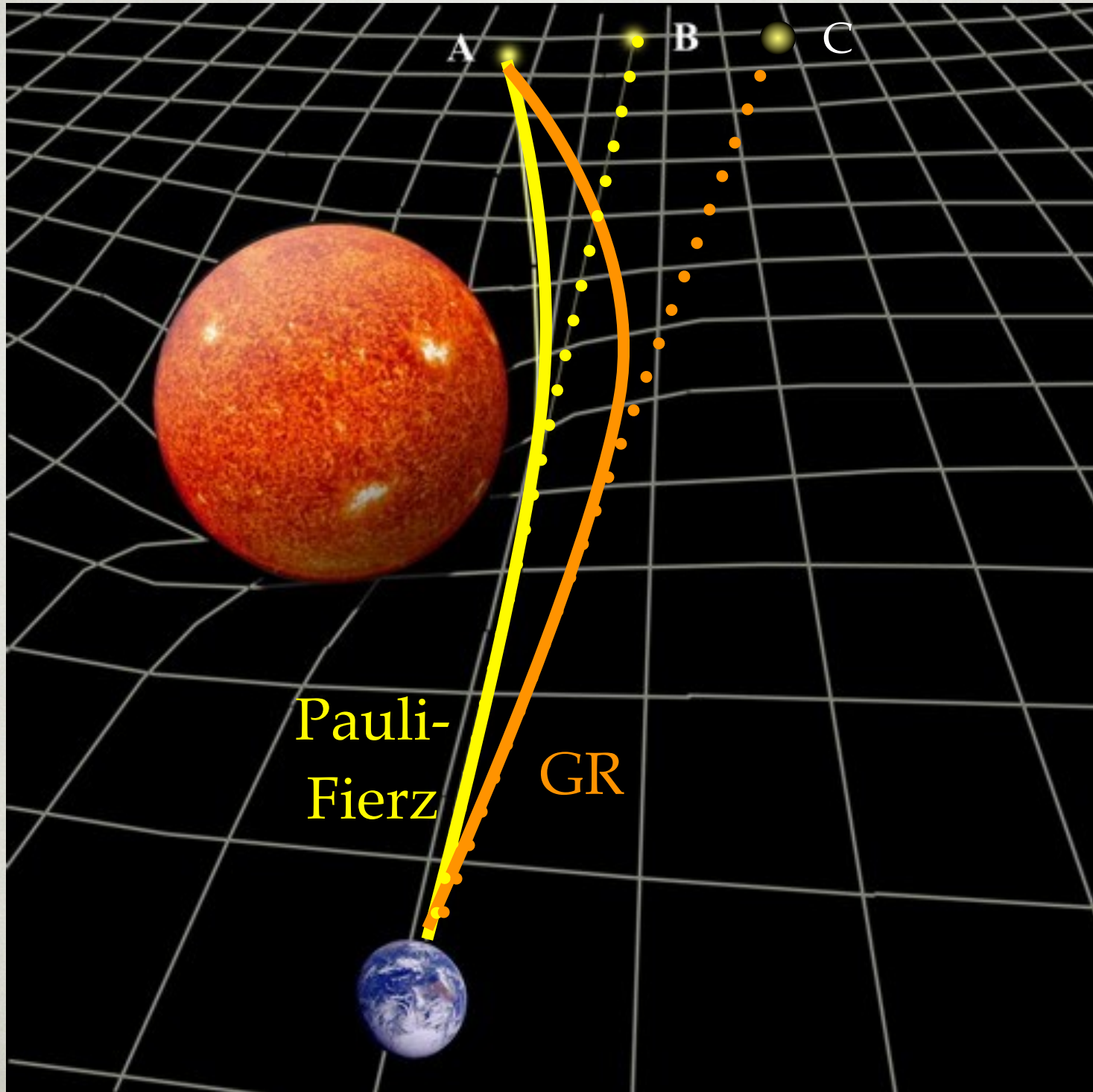
$$G \rightarrow \frac{4}{3}G$$



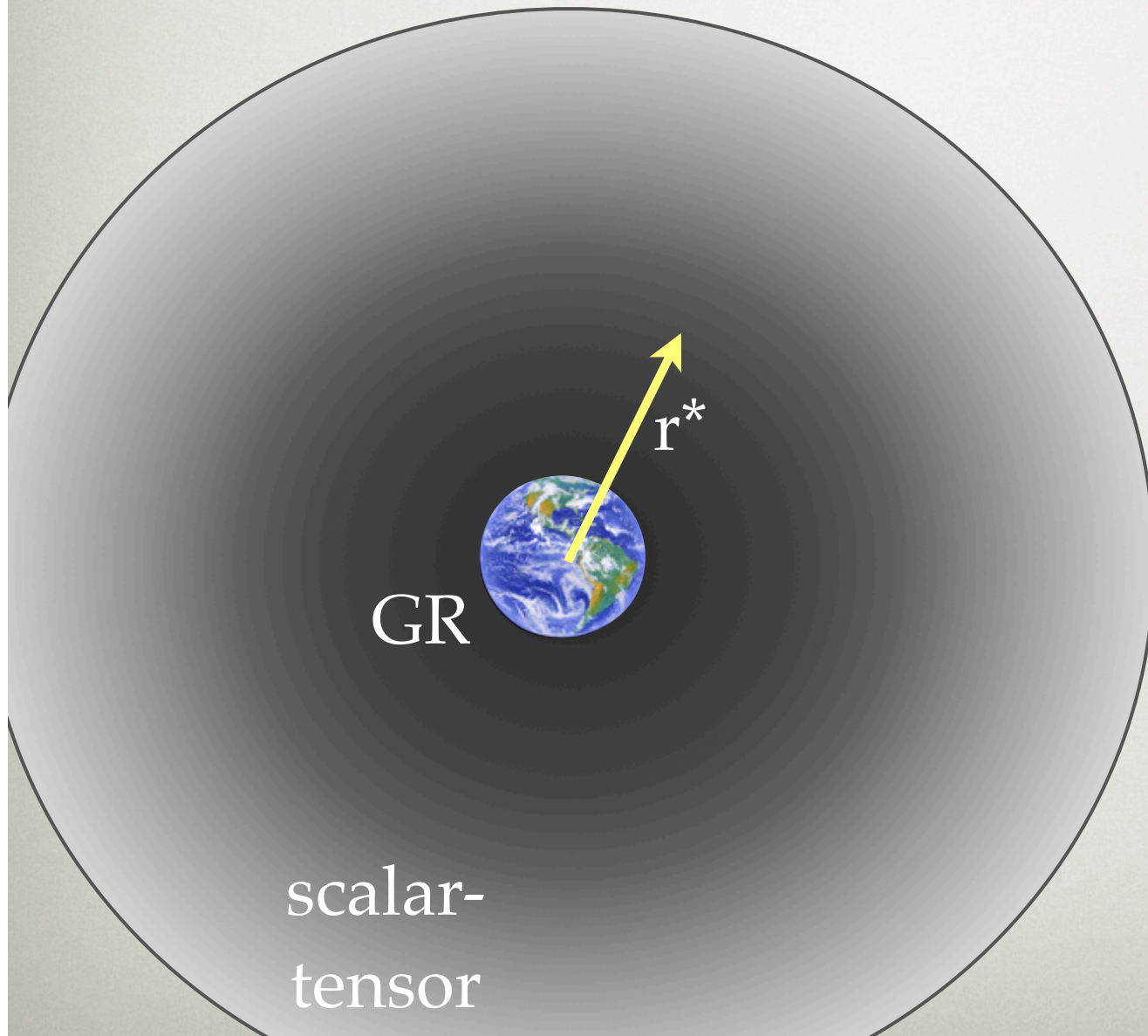
tensor graviton



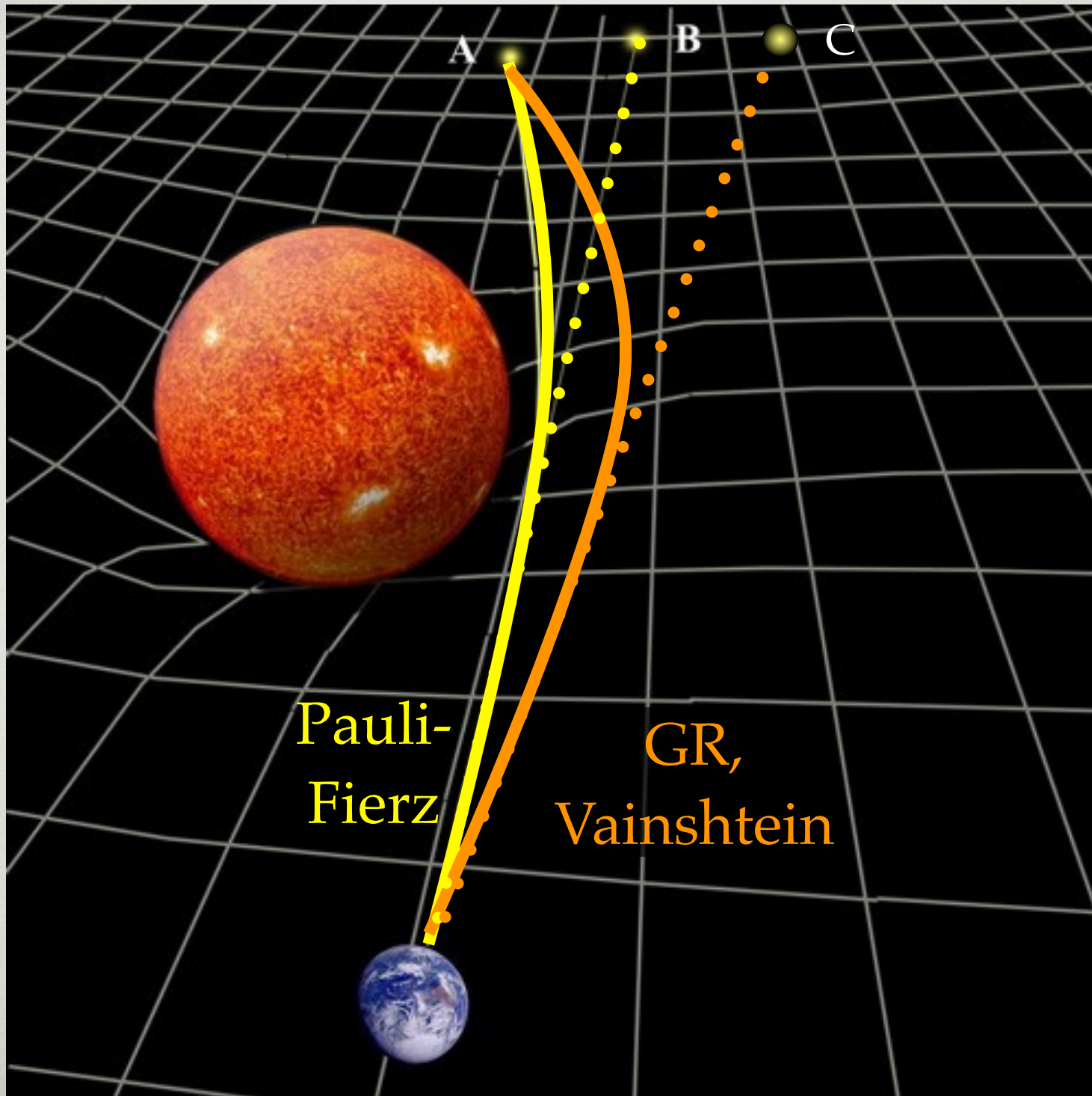
tensor graviton
+
“scalar” graviton



VAINSHTEIN EFFECT



1972

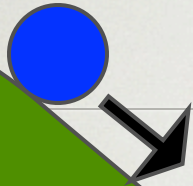


BOULWARE-DESER GHOST

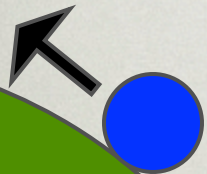


1972

WHAT'S A GHOST?



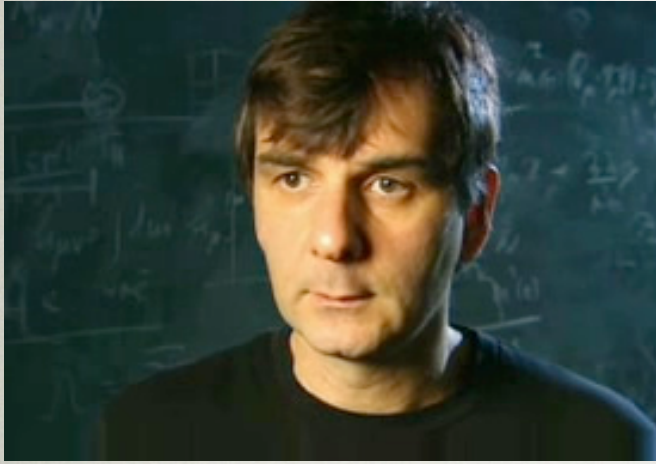
$$E = V + \frac{1}{2}mv^2$$



$$E = V - \frac{1}{2}mv^2$$



THE REVIVAL



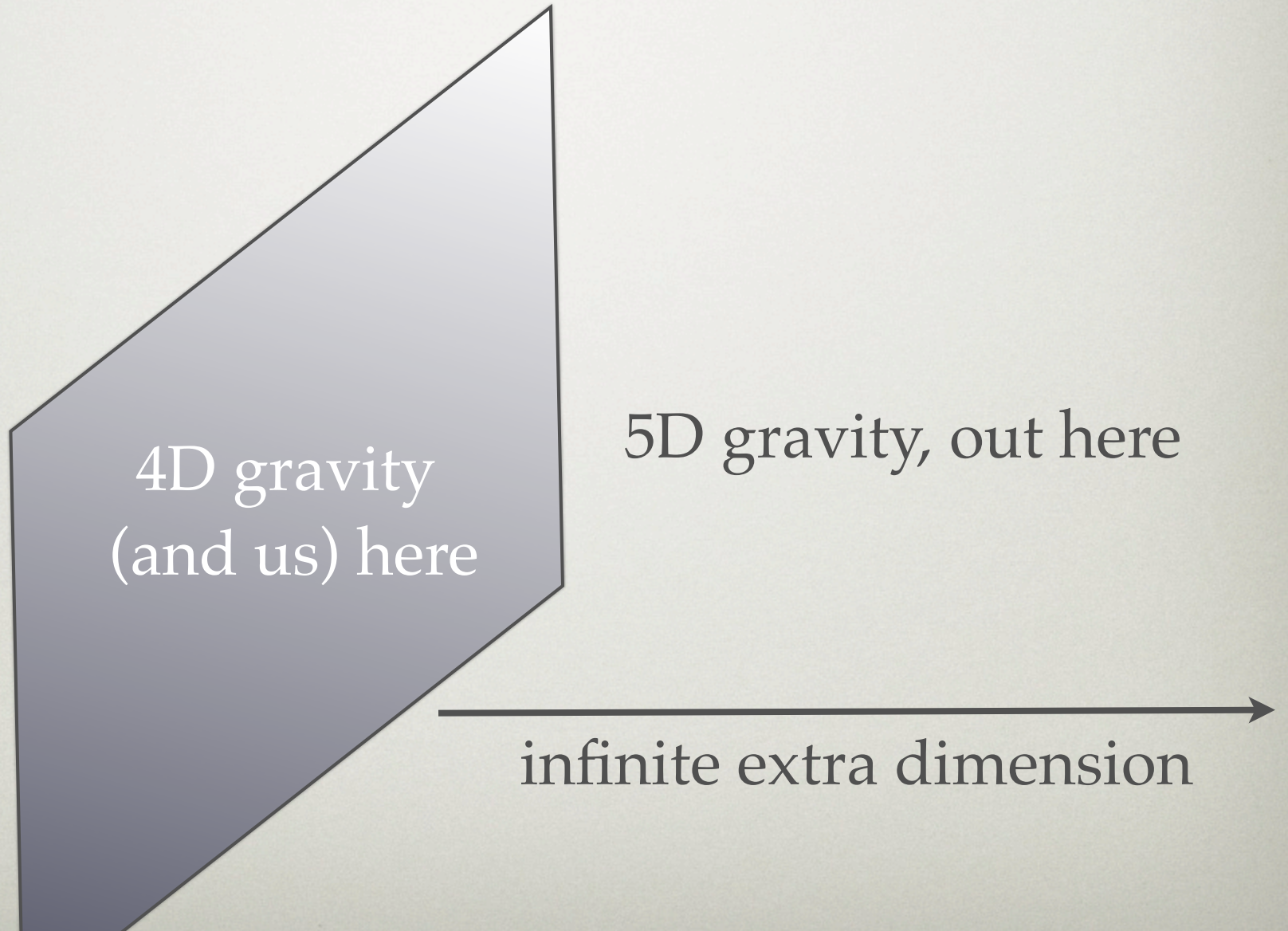
D

G

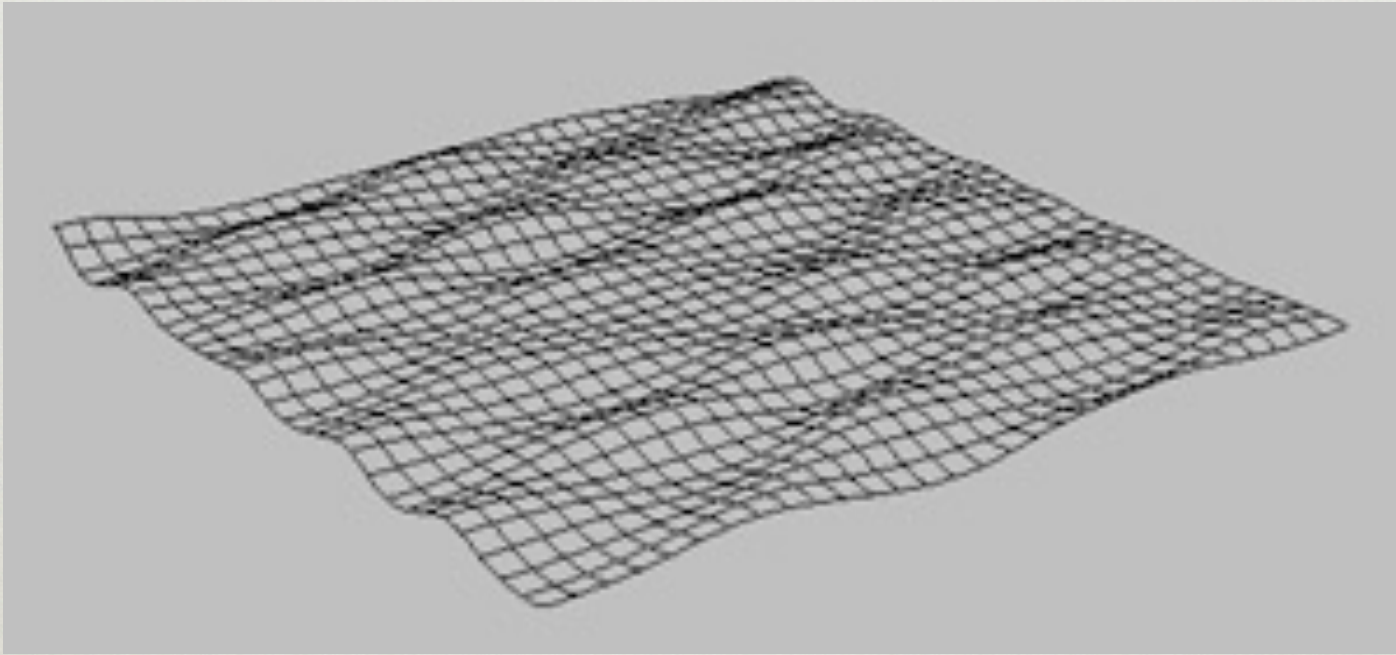
P

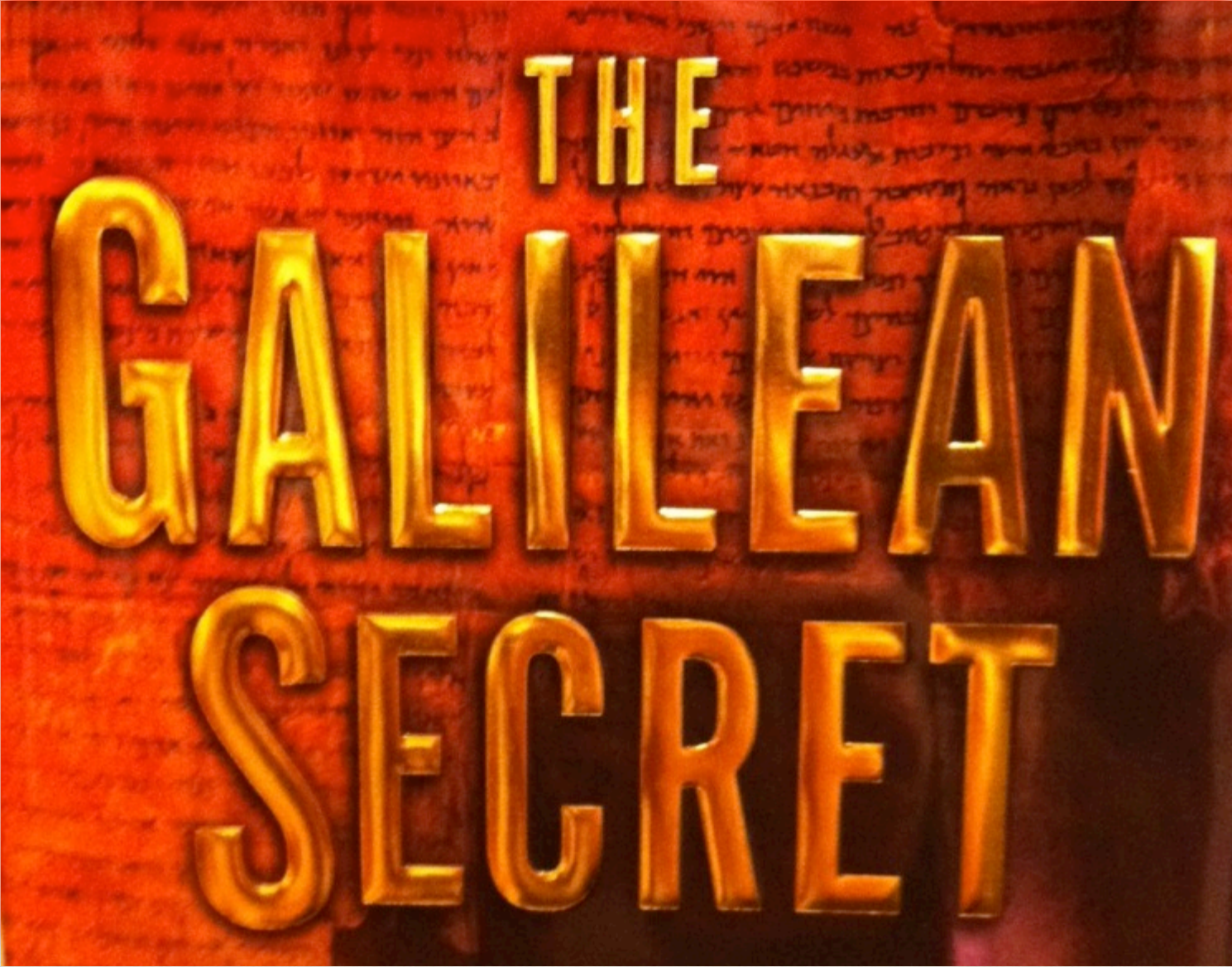
2001

THE DGP IDEA:



“BRANE BENDING”





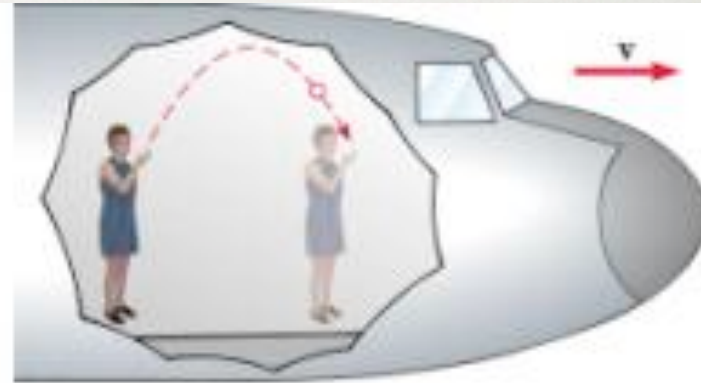
THE
GALILEAN
SECRET

The image shows a title card with the text "THE GALILEAN SECRET" in large, golden, 3D block letters. The background is a textured red surface with faint, illegible Hebrew script. The text is arranged in three lines: "THE" on the top line, "GALILEAN" on the middle line, and "SECRET" on the bottom line. The letters have a metallic sheen and are set against a dark red, textured background that appears to be a book cover or a wall with ancient script. The overall lighting is dramatic, with a strong red glow at the top and bottom edges of the frame.

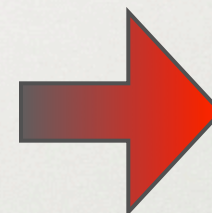
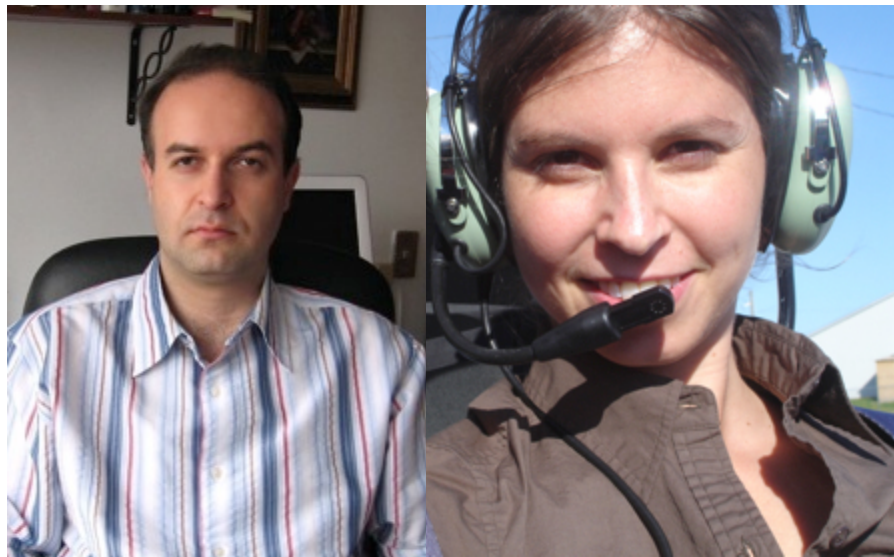
GALILEAN SYMMETRY



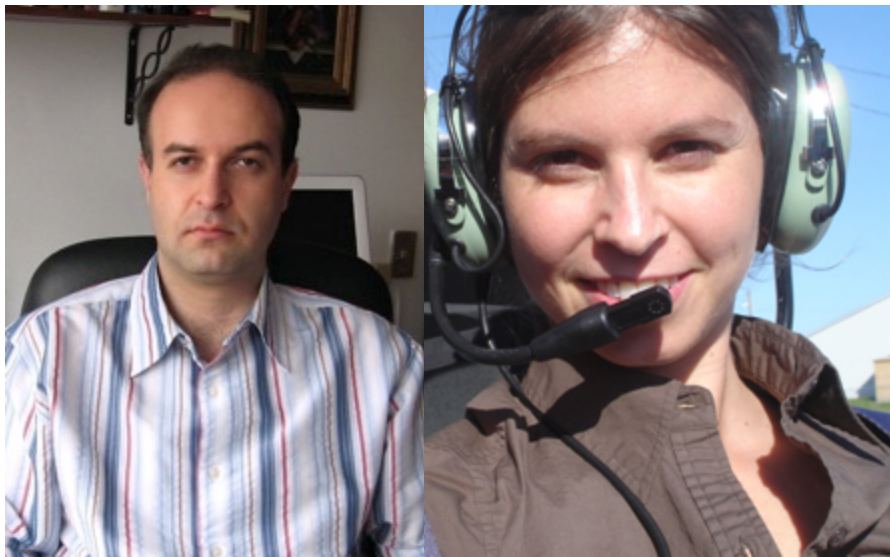
(a)



(b)



graviton
with mass!



purely 4D theory

Formalism: Define the tensor $H_{\mu\nu}$ as the covariantization of the metric perturbation, $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} = H_{\mu\nu} + \eta_{ab}\partial_\mu\phi^a\partial_\nu\phi^b$, where the four Stückelberg fields ϕ^a transform as scalars, and $\eta_{ab} = (-1, 1, 1, 1)$, [3]. The helicity-0 mode π of the graviton can be extracted by expressing $\phi^a = (x^a - \eta^{a\mu}\partial_\mu\pi)$, such that

$$H_{\mu\nu} = h_{\mu\nu} + 2\Pi_{\mu\nu} - \eta^{\alpha\beta}\Pi_{\mu\alpha}\Pi_{\beta\nu}, \quad \Pi_{\mu\nu} \equiv \partial_\mu\partial_\nu\pi. \quad (1)$$

We may therefore define the following quantity

$$\mathcal{K}_\nu^\mu(g, H) = \delta_\nu^\mu - \sqrt{\delta_\nu^\mu - H_\nu^\mu} = - \sum_{n=1}^{\infty} d_n (H^n)_\nu^\mu, \quad (2)$$

$$\text{with } d_n = \frac{(2n)!}{(1-2n)(n!)^2 4^n}. \quad (3)$$

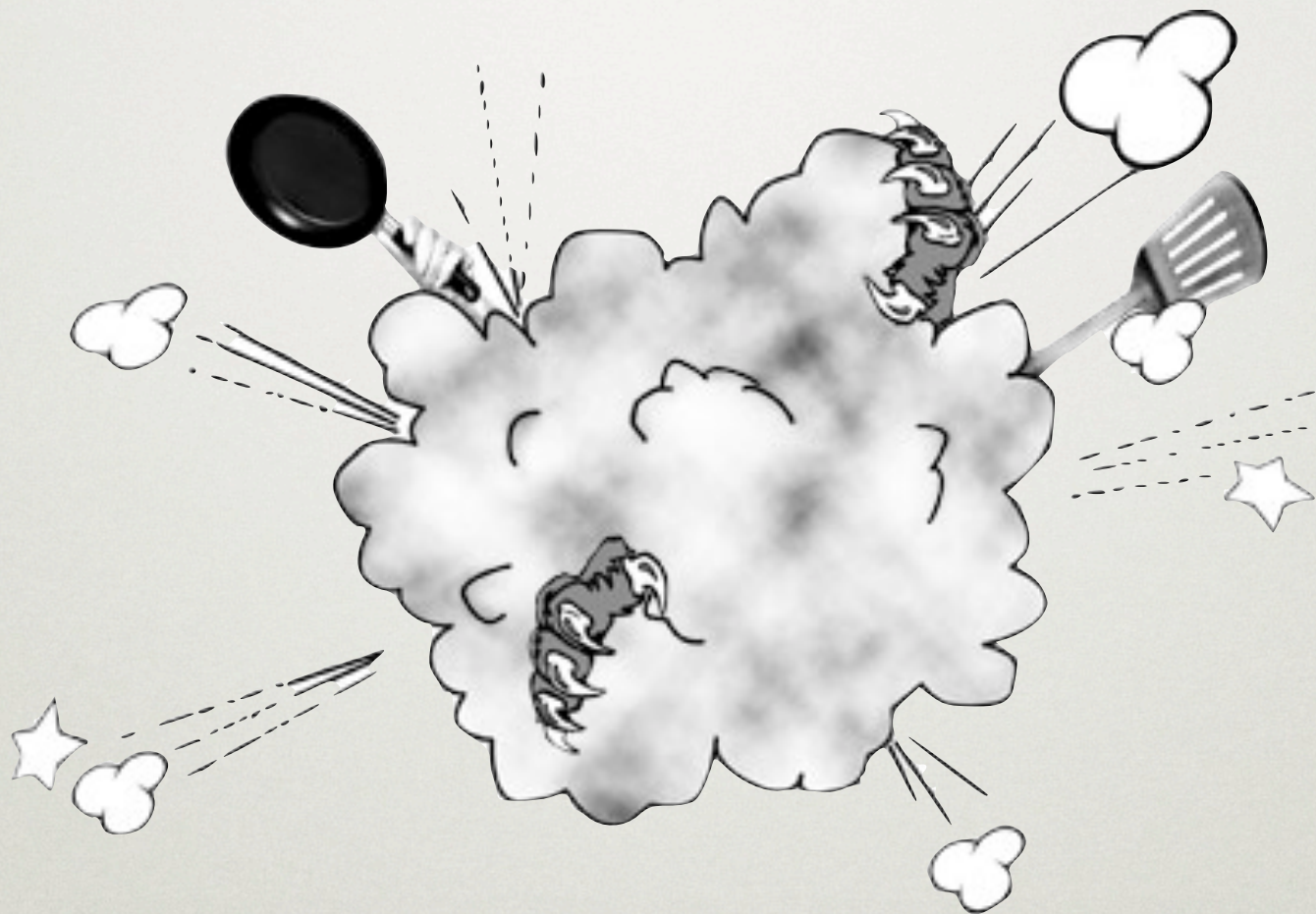
Here $H_\nu^\mu = g^{\mu\alpha}H_{\alpha\nu}$, and $(H^n)_\nu^\mu = H_{\alpha_1}^\mu H_{\alpha_2}^{\alpha_1} \dots H_{\alpha_{n-1}}^{\alpha_{n-2}} H_{\alpha_{n-1}}^\nu$ denotes the product of n tensors H_β^α . Below, unless stated otherwise, all the contractions are made using the metric $g_{\mu\nu}$. The tensor $\mathcal{K}_{\mu\nu} = g_{\mu\alpha}\mathcal{K}_\nu^\alpha$ is defined such a way that

$$\mathcal{K}_{\mu\nu}(g, H) \Big|_{H=0} = \eta_{\mu\nu}. \quad (4)$$

no ghosts!

mid-2010

CONTROVERSY ERUPTS!



late-2010

REALLY, NO GHOSTS!



$$S = -M_p^2 \int d^4x \sqrt{-g} \left[R - 2m^2 \sum_{n=0}^3 \beta_n e_n(\sqrt{g^{-1}}f) \right], \quad (4)$$

where the β_n are given in terms of the α_n of (3) as,

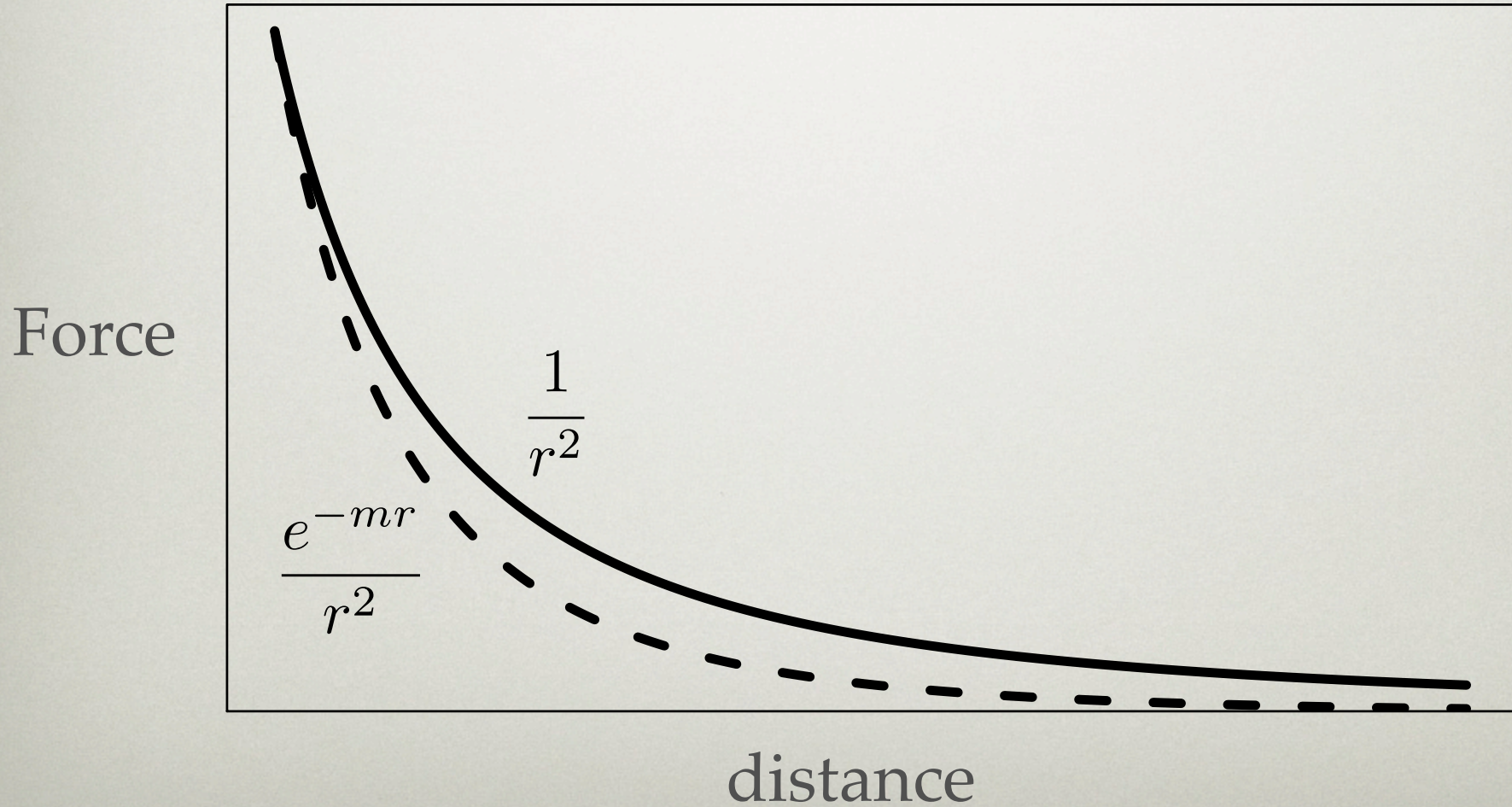
$$\begin{aligned} \beta_0 &= 6 - 4\alpha_3 + \alpha_4, & \beta_1 &= -3 + 3\alpha_3 - \alpha_4, \\ \beta_2 &= 1 - 2\alpha_3 + \alpha_4, & \beta_3 &= \alpha_3 - \alpha_4. \end{aligned} \quad (5)$$

The $e_k(\mathcal{X})$ are elementary symmetric polynomials of the eigenvalues of \mathcal{X} . For a generic 4×4 matrix they are given by,

$$\begin{aligned} e_0(\mathcal{X}) &= 1, \\ e_1(\mathcal{X}) &= [\mathcal{X}], \\ e_2(\mathcal{X}) &= \frac{1}{2}([\mathcal{X}]^2 - [\mathcal{X}^2]), \\ e_3(\mathcal{X}) &= \frac{1}{6}([\mathcal{X}]^3 - 3[\mathcal{X}][\mathcal{X}^2] + 2[\mathcal{X}^3]), \\ e_4(\mathcal{X}) &= \frac{1}{24}([\mathcal{X}]^4 - 6[\mathcal{X}]^2[\mathcal{X}^2] + 3[\mathcal{X}^2]^2 + 8[\mathcal{X}][\mathcal{X}^3] - 6[\mathcal{X}^4]), \\ e_k(\mathcal{X}) &= 0 \text{ for } k > 4, \end{aligned} \quad (6)$$

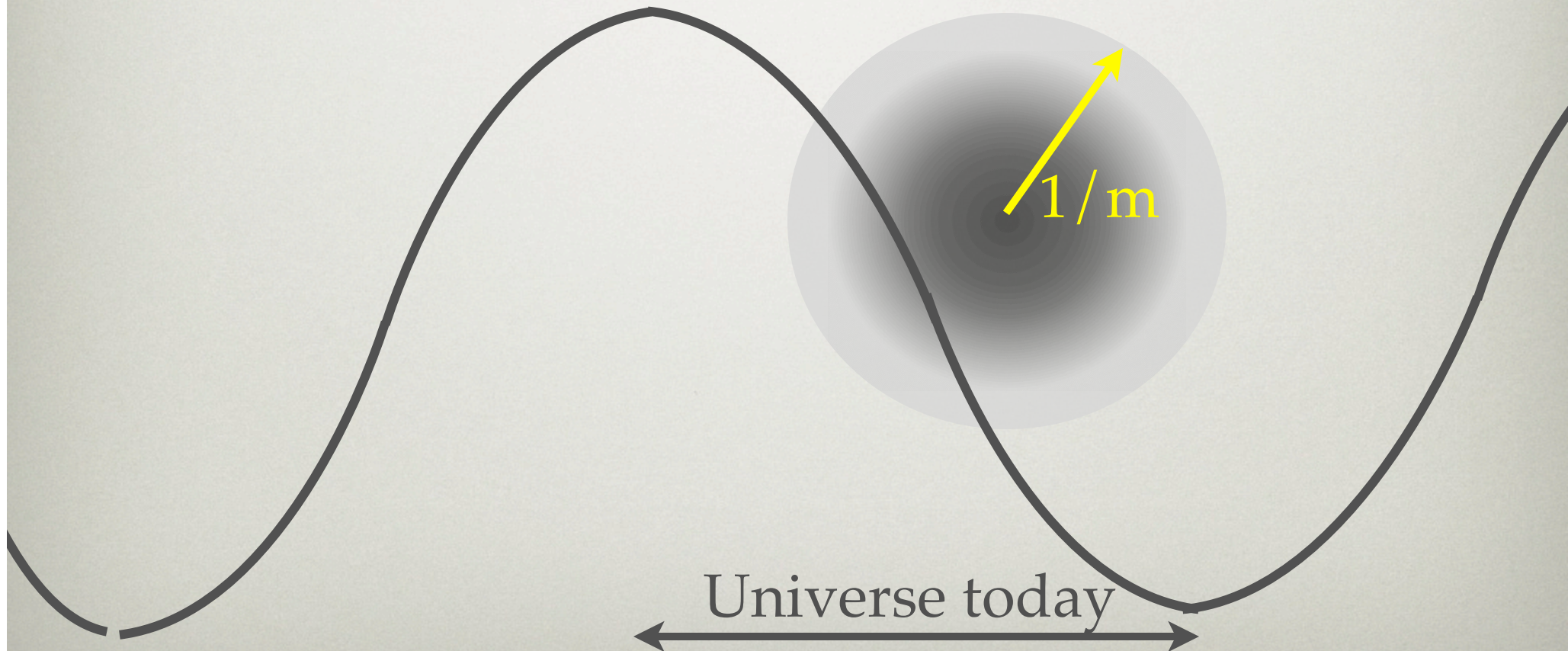
PHYSICAL CONSEQUENCES

YUKAWA FORCE

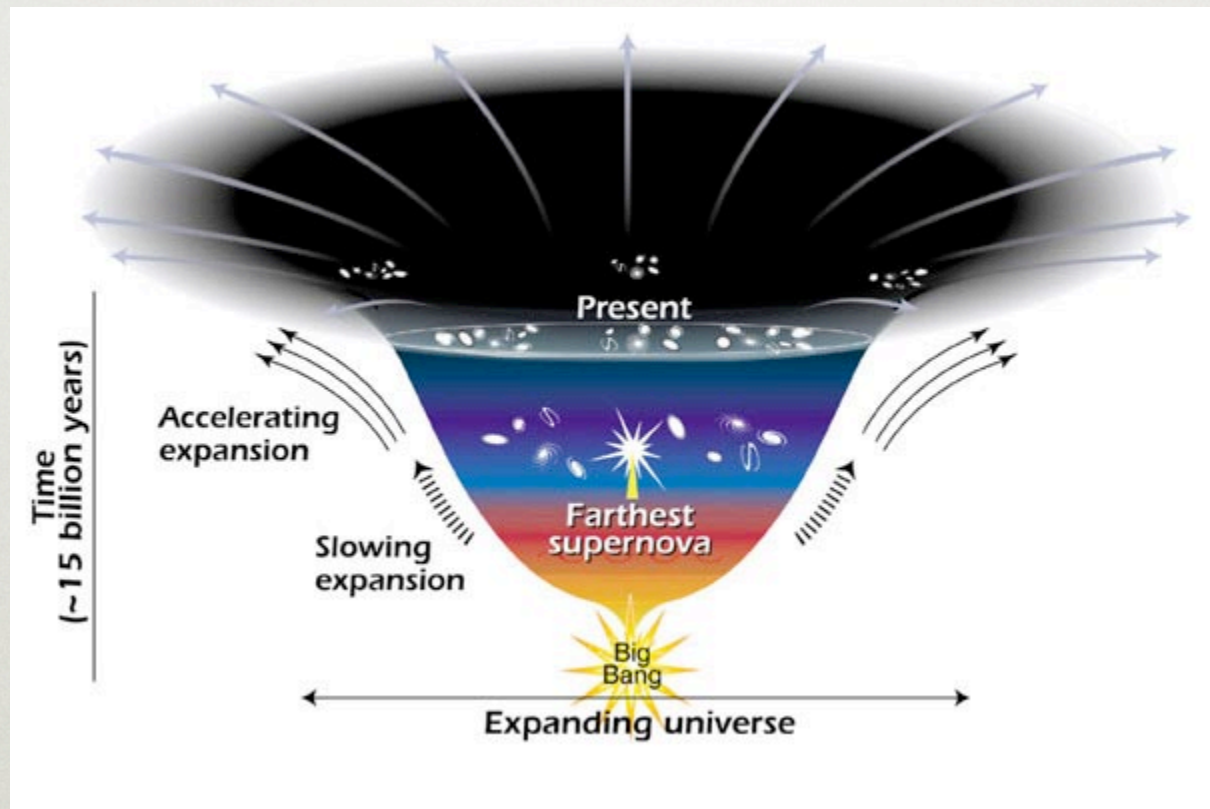


“DEGRAVITATION” OF COSMOLOGICAL CONSTANT?

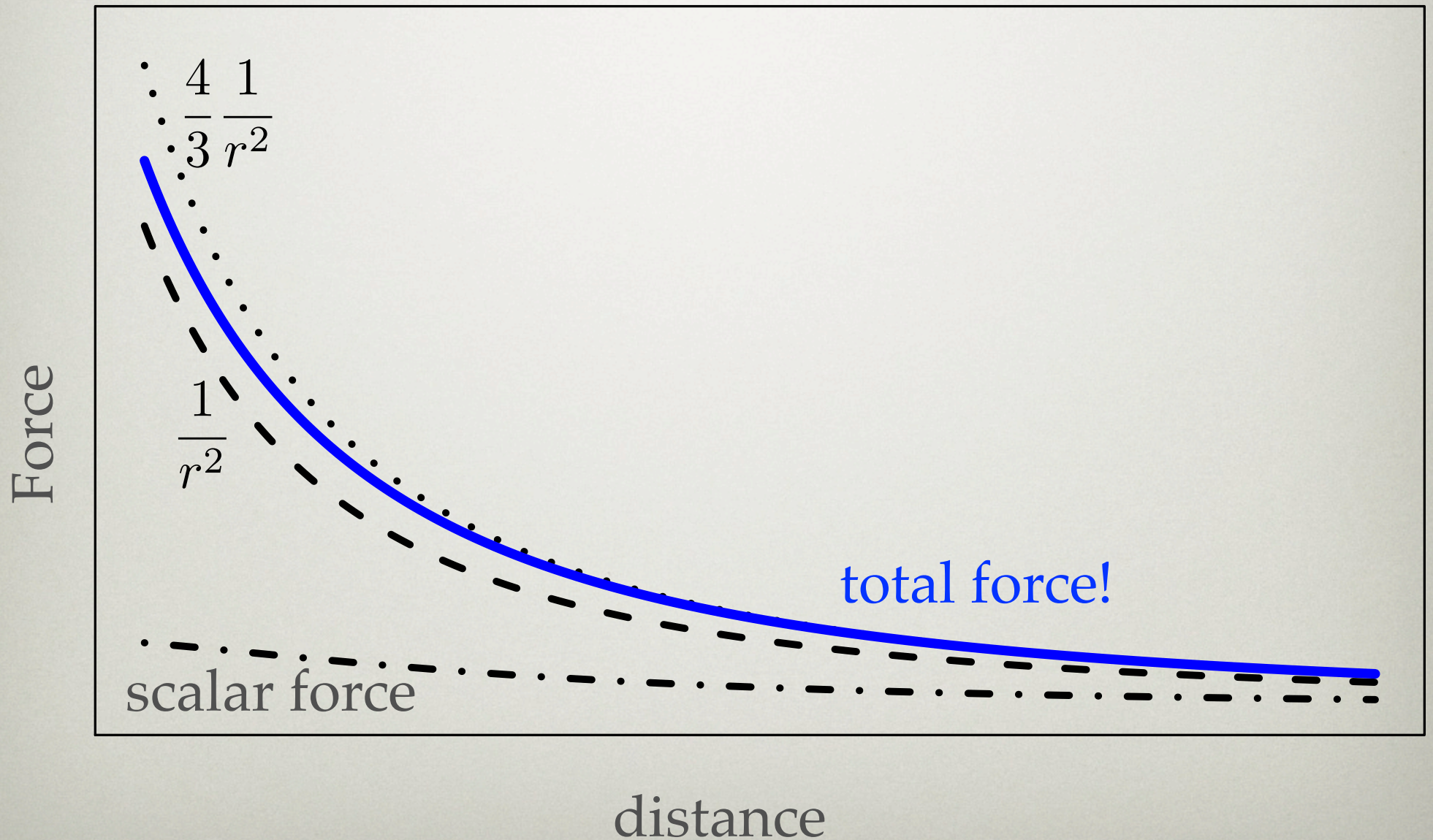
Yukawa = finite range force!



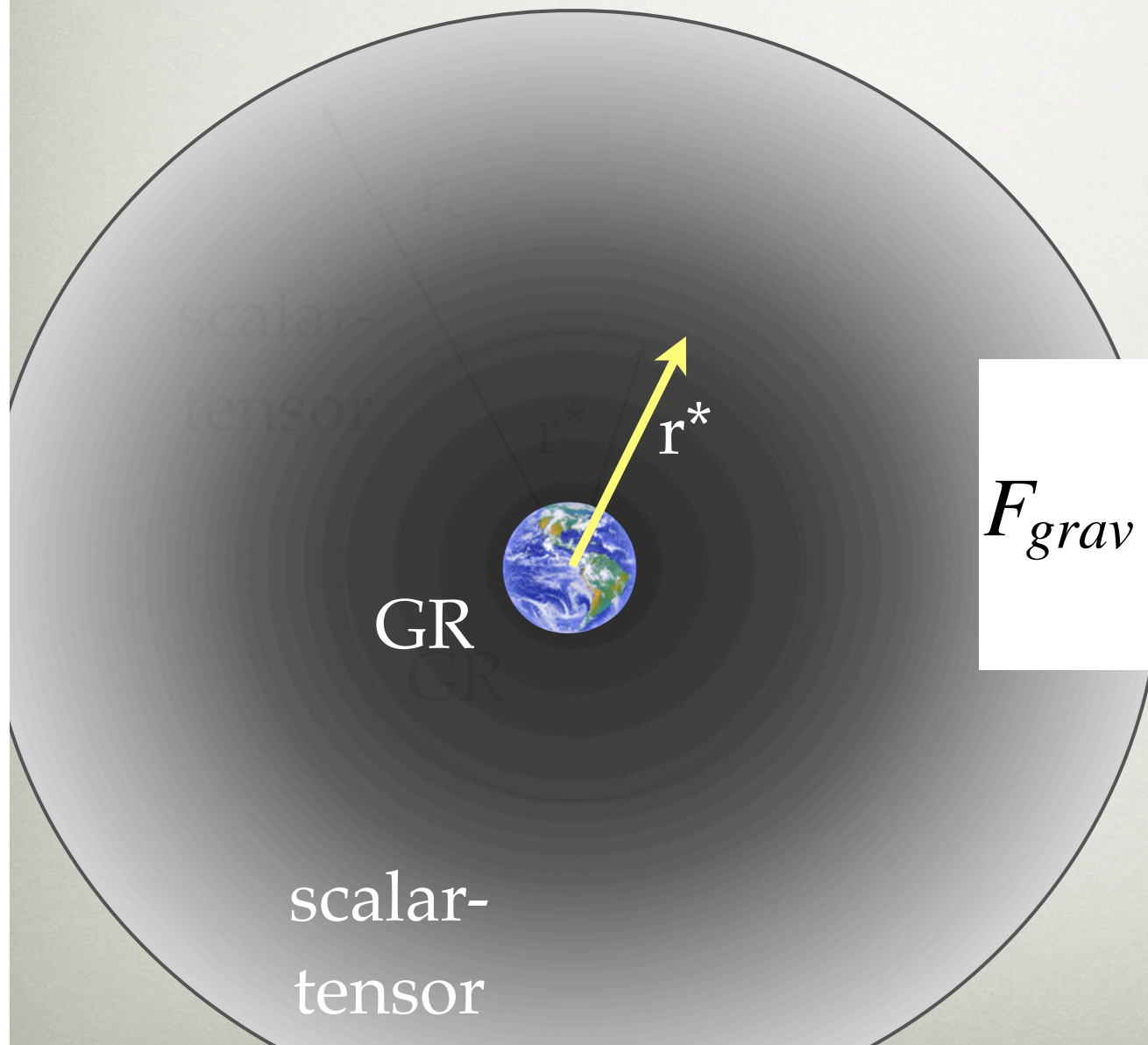
OR: SELF ACCELERATION?



EXTRA SCALAR FORCE

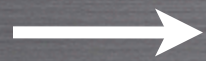


r^* / Vainshtein effect

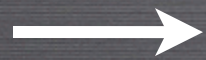


$$F_{grav} = \begin{cases} \frac{GM}{R^2} & R < r^* \\ \frac{4GM}{3R^2} & R > r^* \end{cases}$$

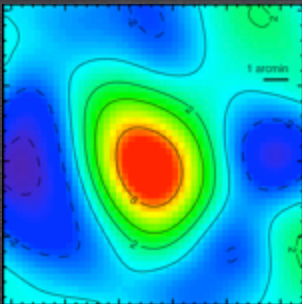
$$r^* = (r_{Sch} r_c^2)^{1/3}$$



~KPC = 10^6 AU



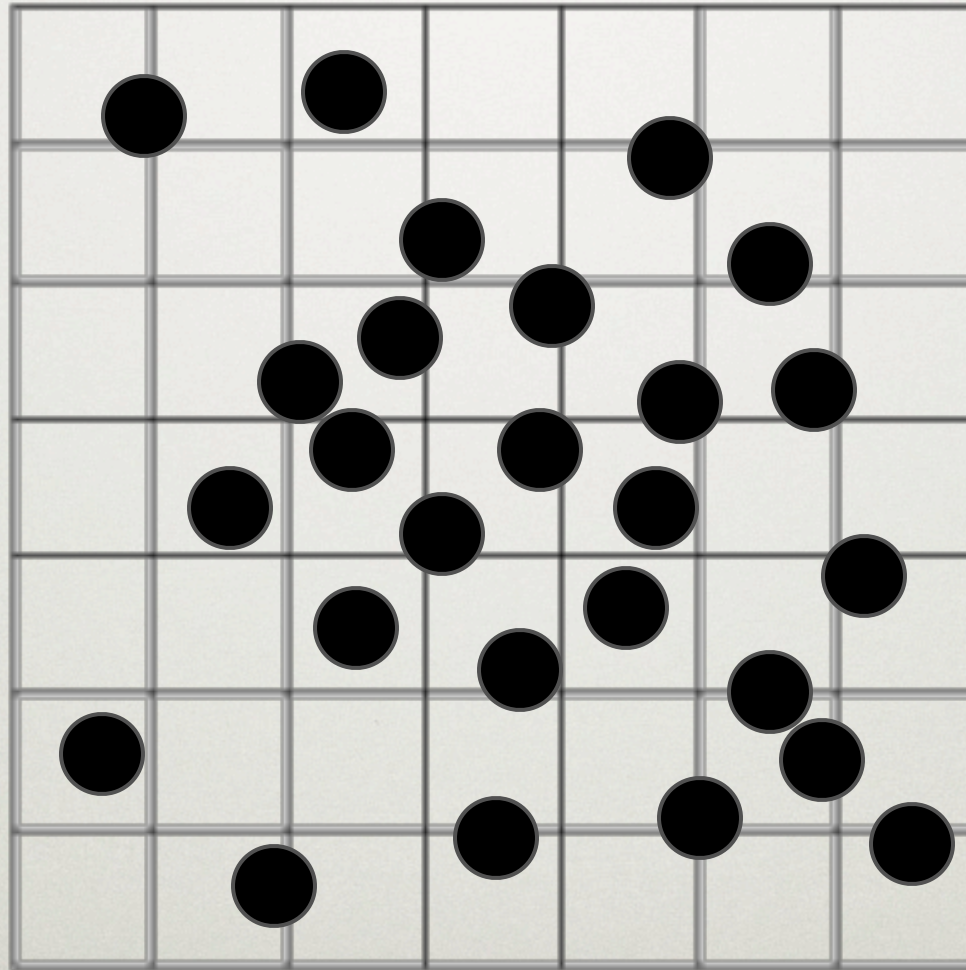
~MPC = 30 GALACTIC
RADII



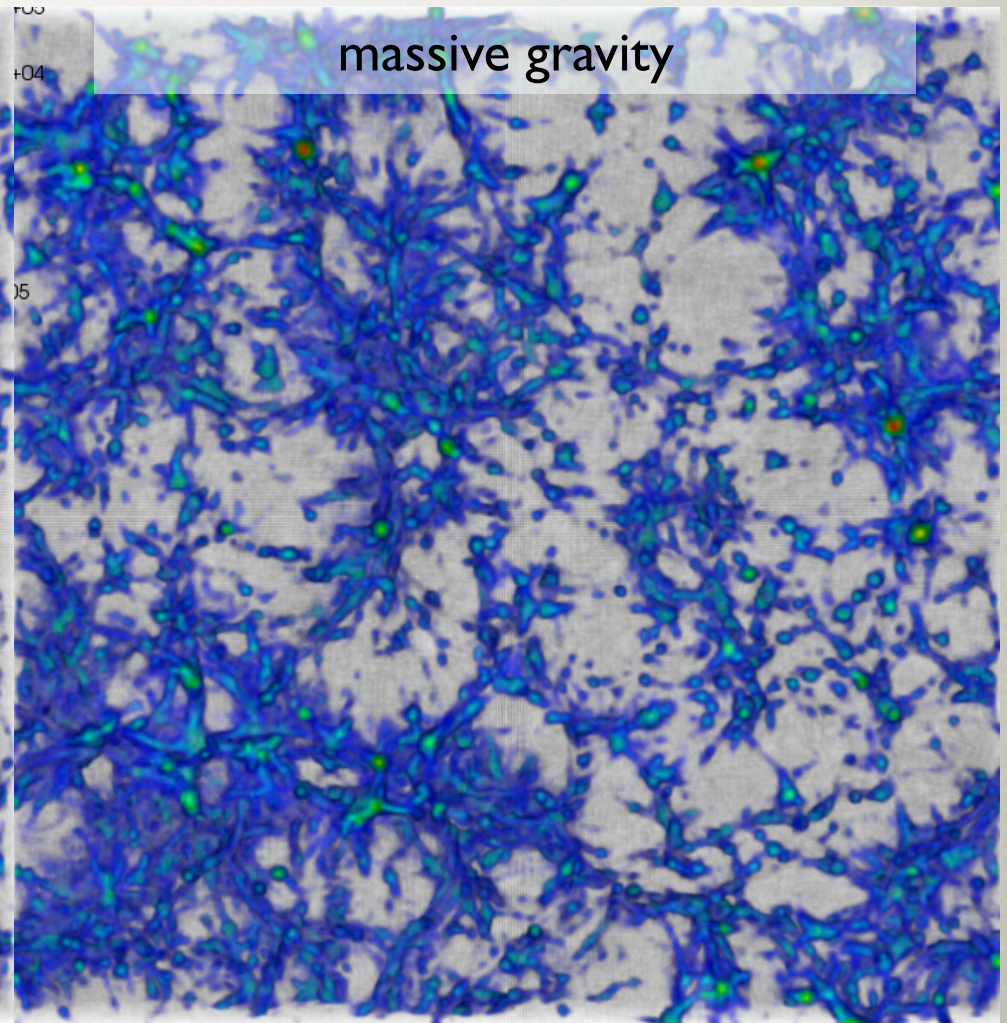
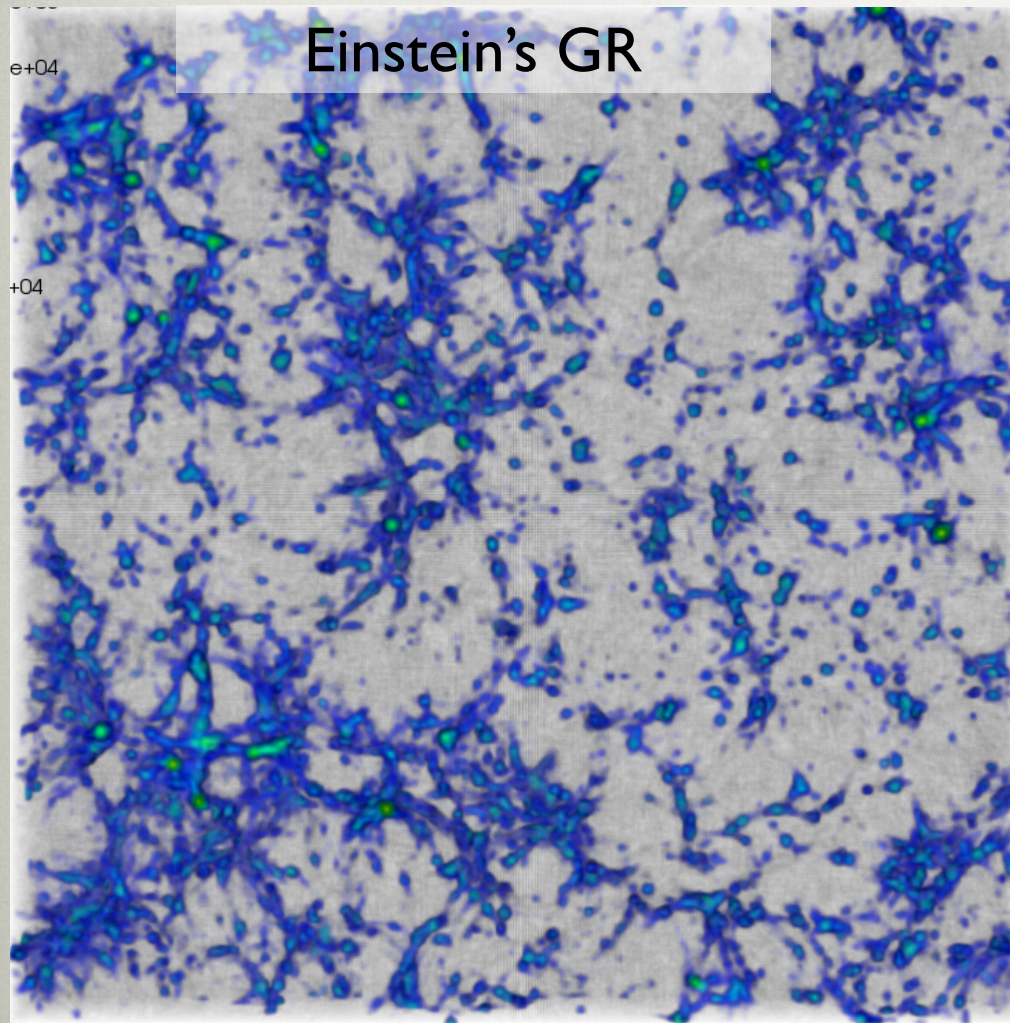
~10 MPC = 10 VIRIAL RADII

OBSERVATIONAL TESTS

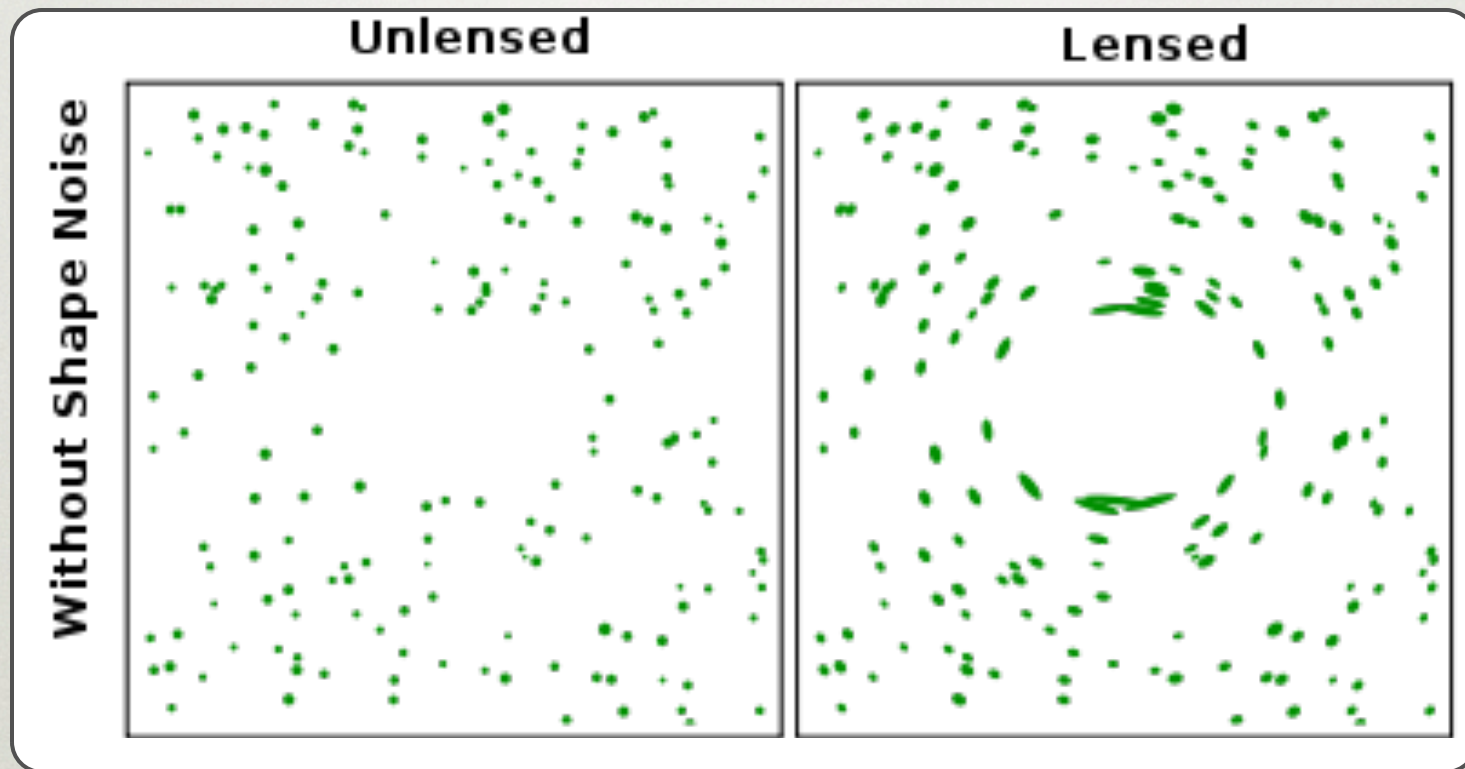
N-BODY CODES



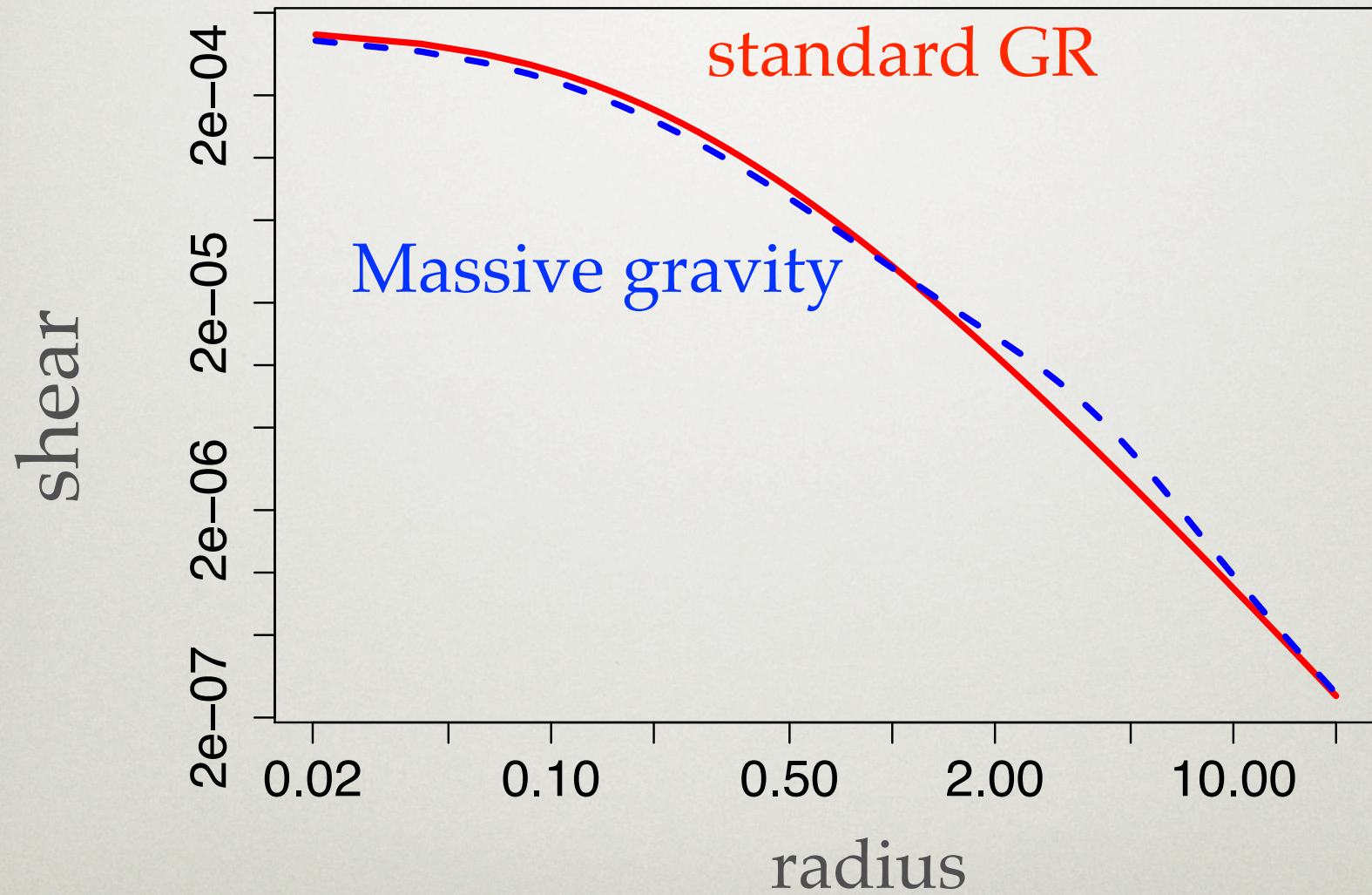
SIMULATIONS OF THIS MODELS



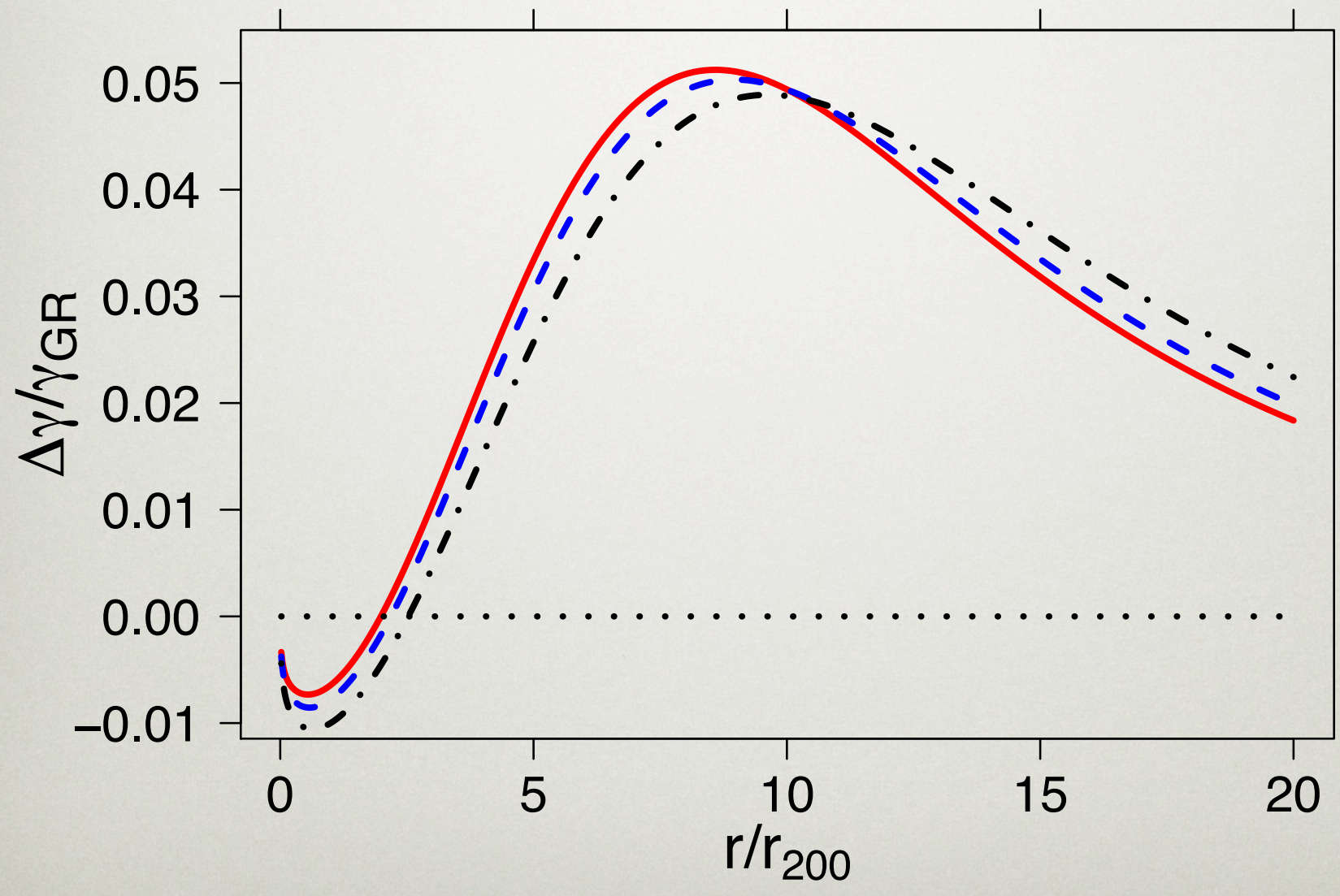
WEAK LENSING



PREDICTIONS



Modification to NFW tangential shear



NEUTRINO UPDATE

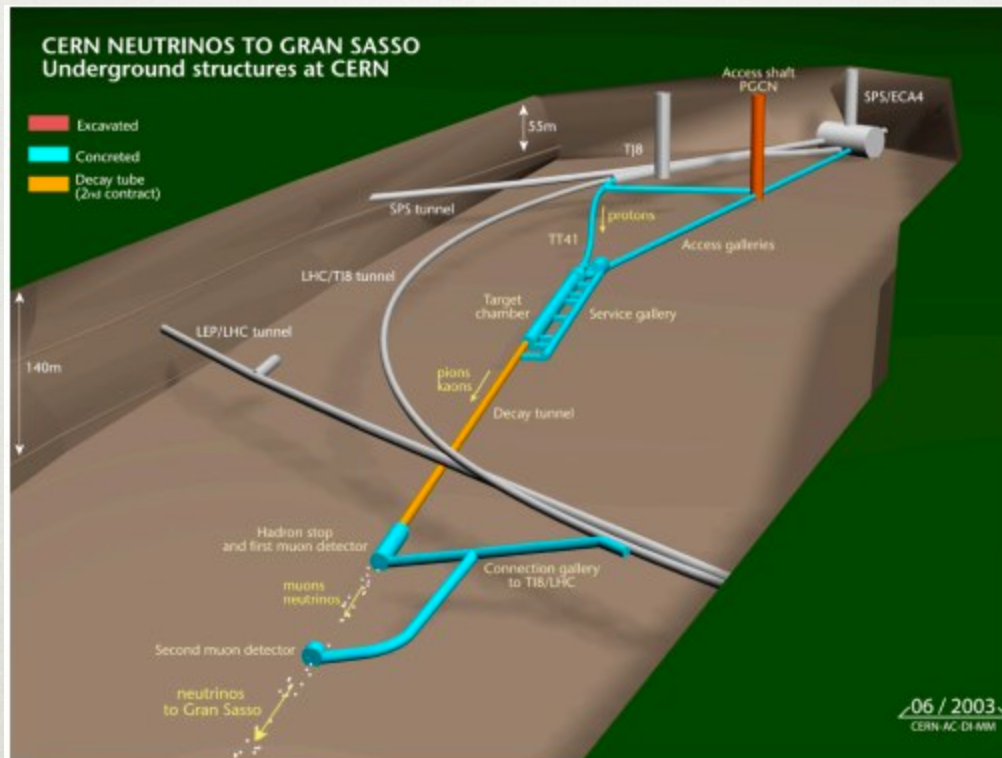
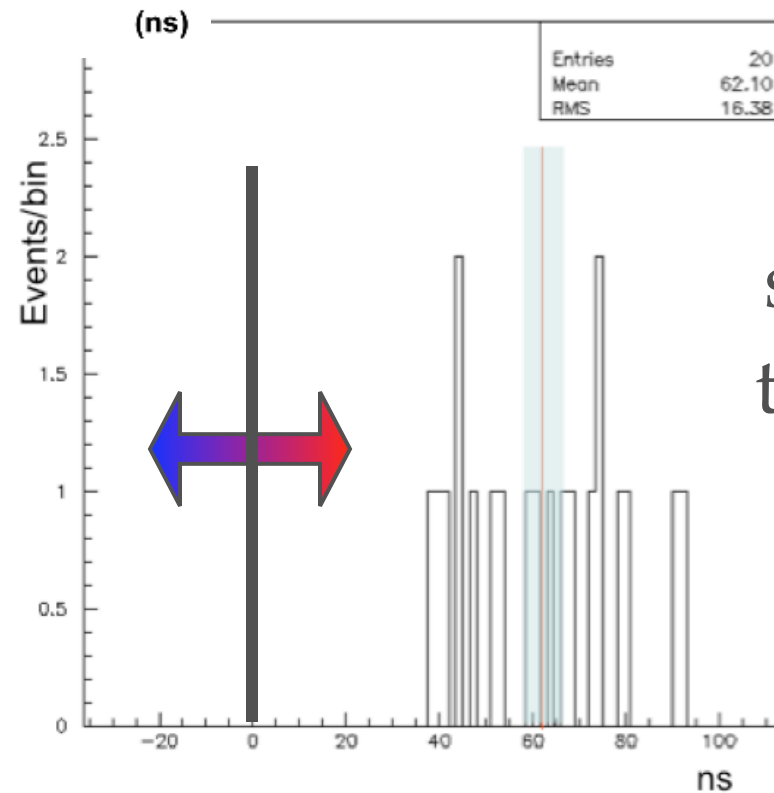
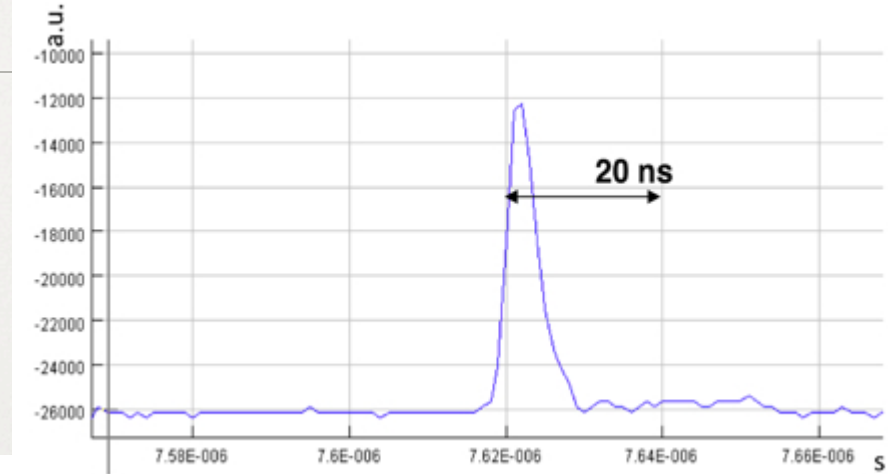
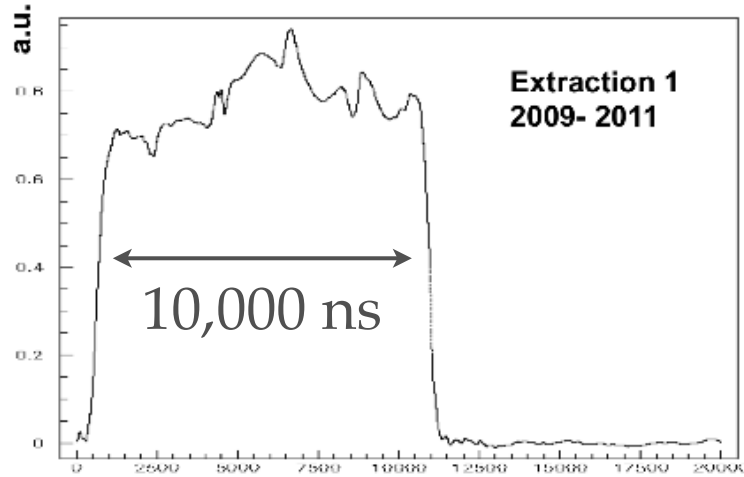


Fig. 1: Artistic view of the SPS/CNGS layout.

NEUTRINO UPDATE



still faster
than light!