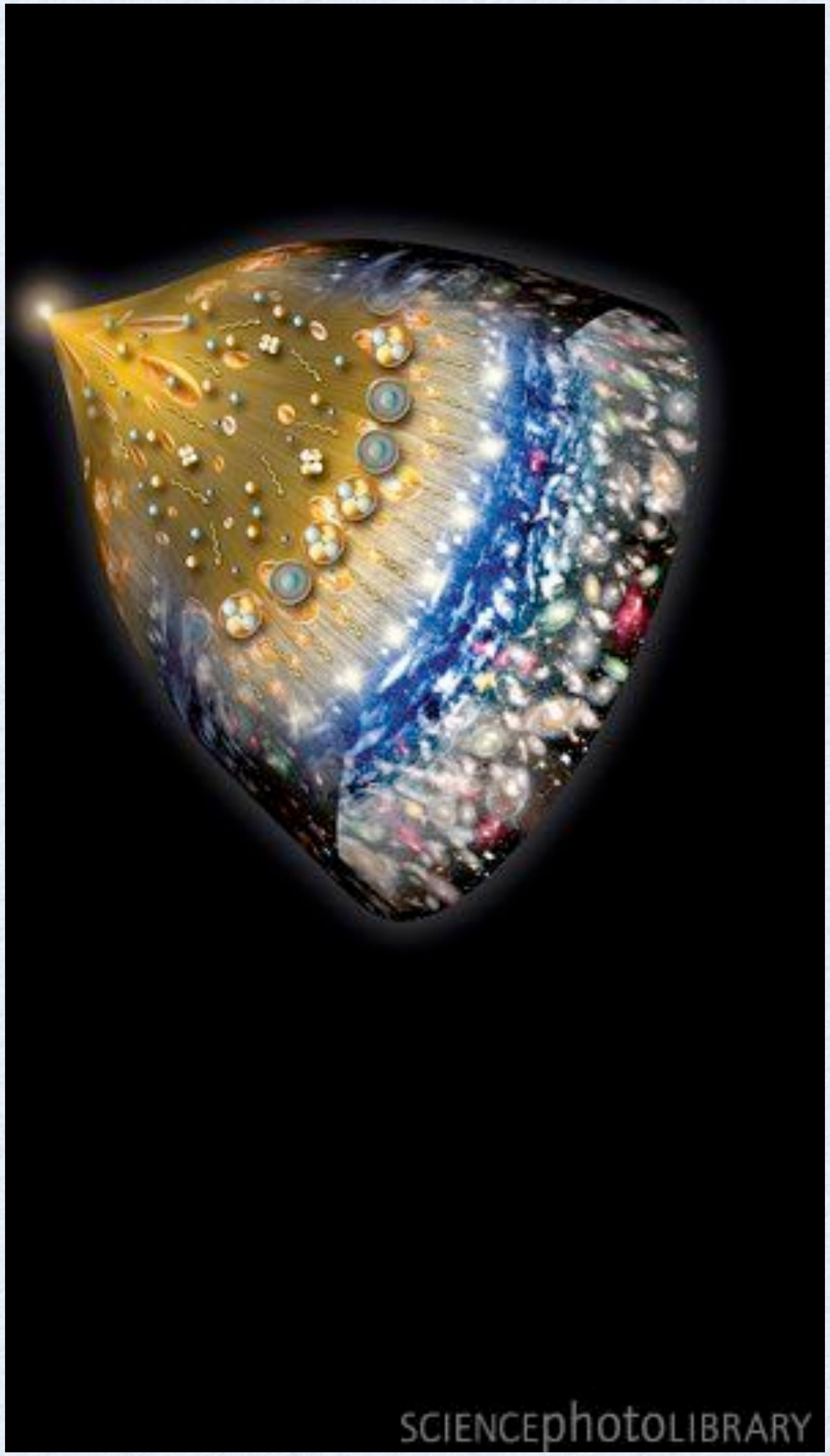
PIERCING THE VAINSHTEIN SCREEN

JOSE BELTRÁN JIMÉNEZ

OUTLINE

- Standard model and cosmic acceleration.
- Horndeski theories.
- Screening mechanisms: Chameleon and Vainshtein.
- The meaning of screening.
- Piercing the screen: constraints from LLR and GW's speed.

STANDARD MODEL OF COSMOLOGY

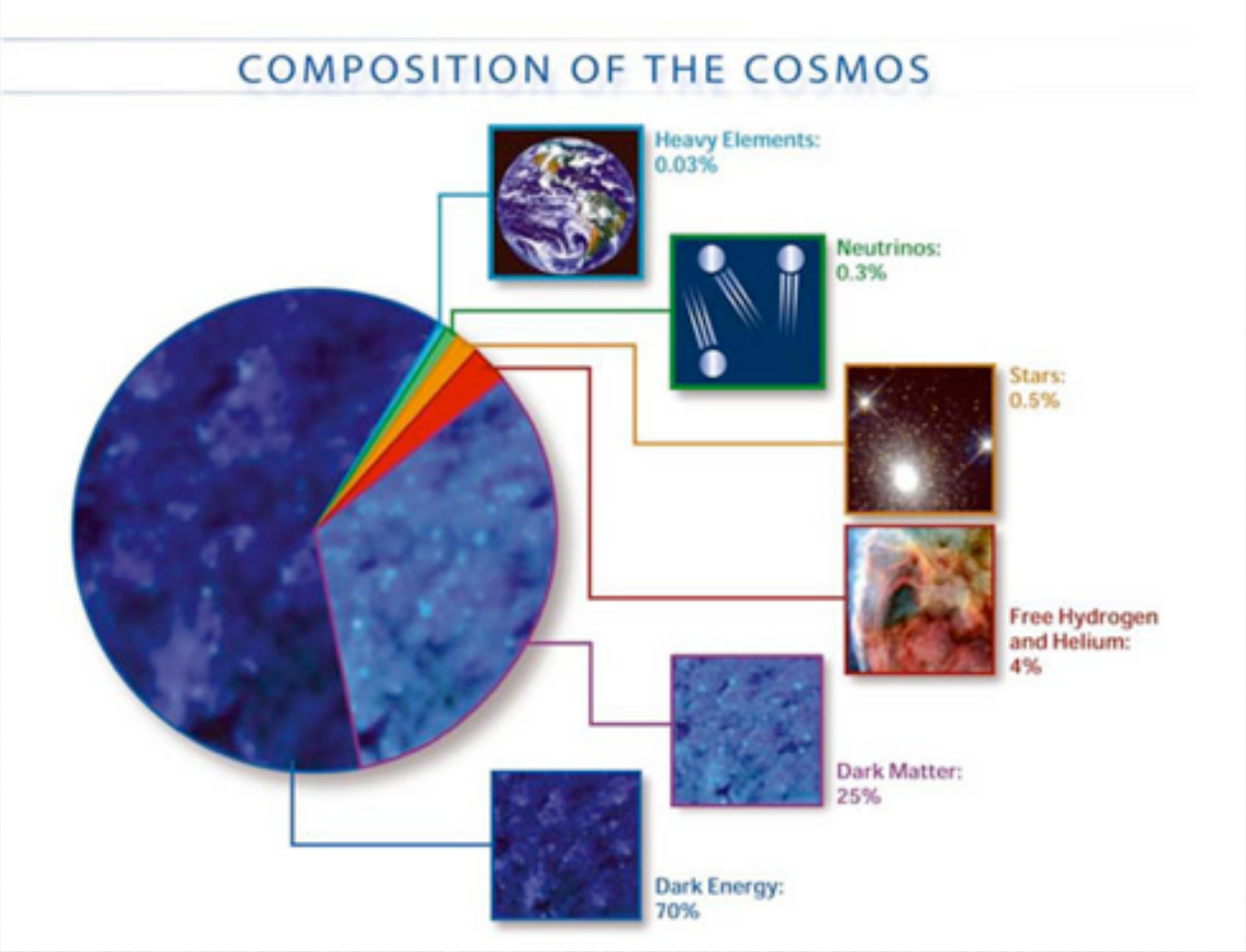


$$ds^2 = dt^2 - a^2(t)d\vec{x}^2$$

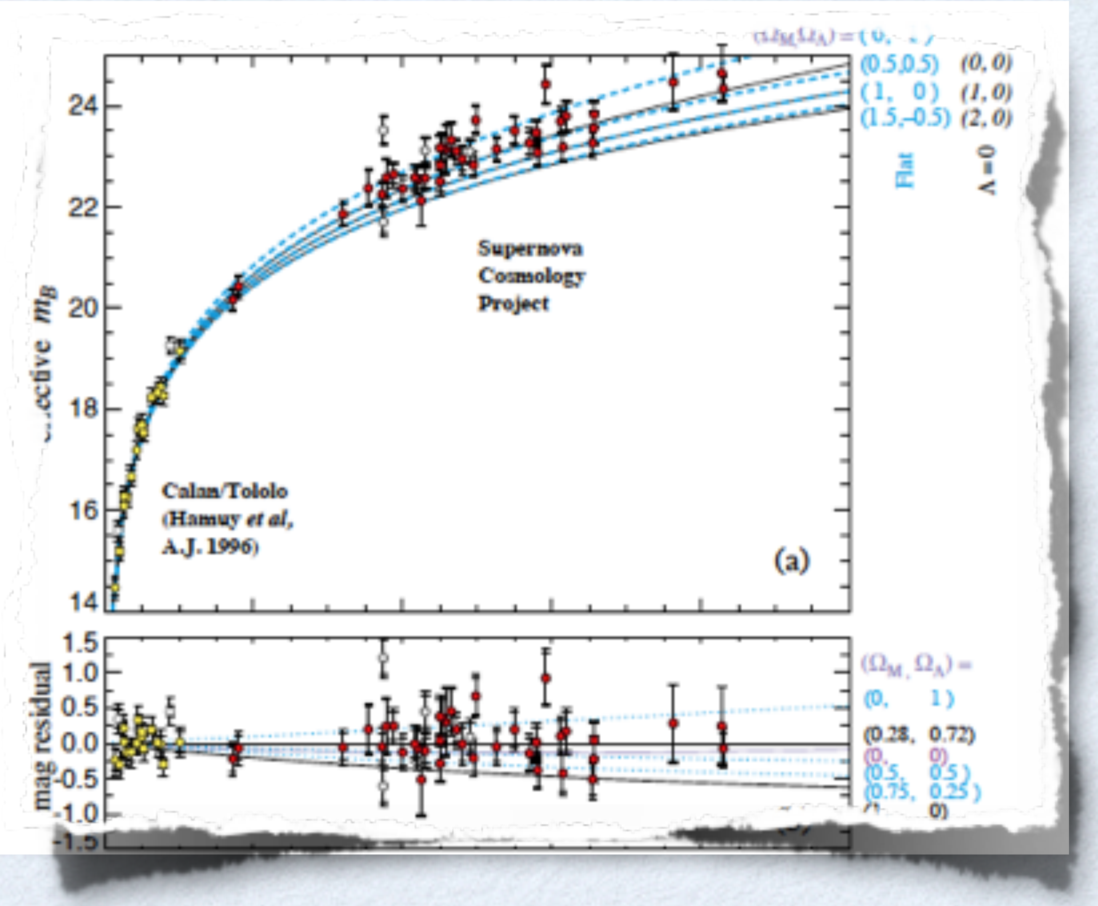
Cosmological Principle

$$H^2 = \frac{8\pi G}{3}\sum_i \rho_i \qquad H = \frac{\dot{a}}{a}$$

General Relativity



COSMIC ACCELERATION



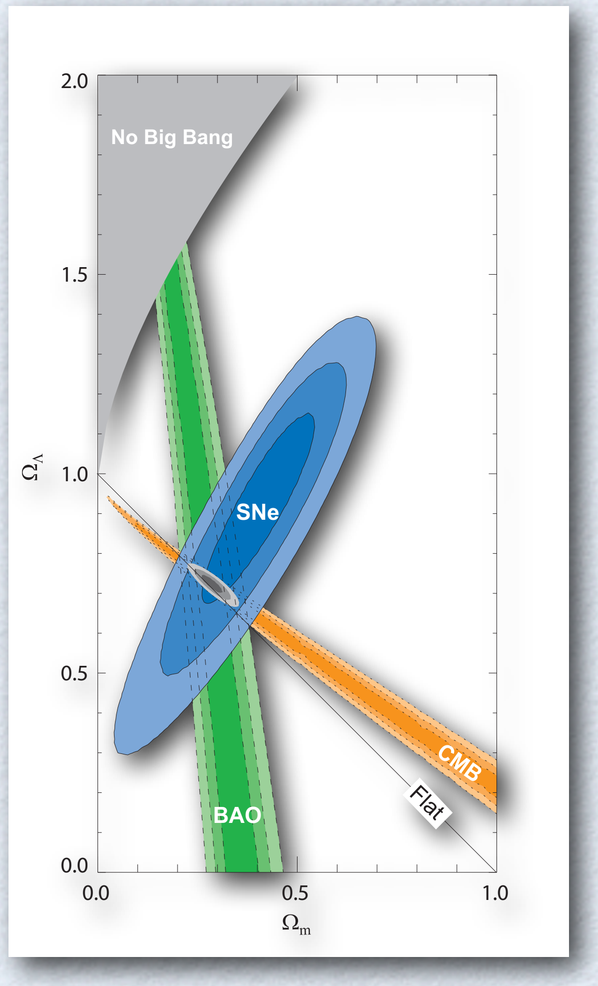
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

Nobel Prize in Physics 2011

Saul
Perlmutter

Brian P.
Schmidt

Adam Riess



COSMIC ACCELERATION

Cosmological constant

$$S = \int d^4x\sqrt{-g}\left(-\frac{1}{16\pi G}R - 2\Lambda\right)$$

$$\downarrow \quad 10^{19}GeV$$

$$\downarrow \quad 10^{-3}eV$$

Unstable against quantum corrections. Not technically natural.
Some MG aim to alleviating and/or solving this problem
(degravitation, unimodular gravity...)

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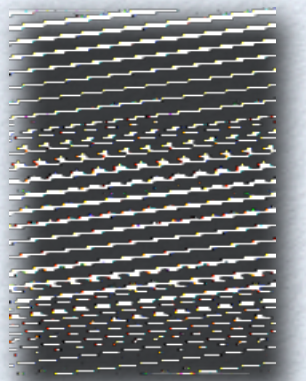
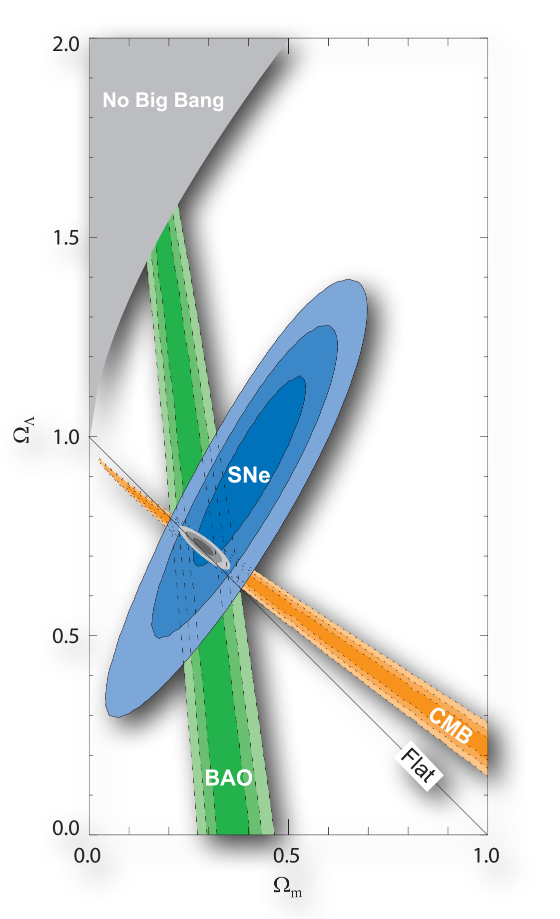


Adam Riess



COSMIC ACCELERATION

Missing photons

Grey dust

Mixing with axion-like particles

Nobel Prize in Physics 2011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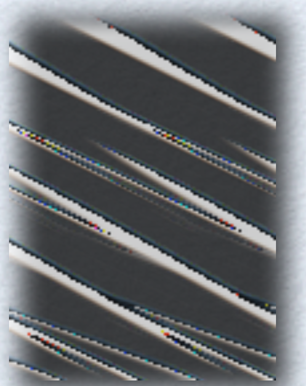
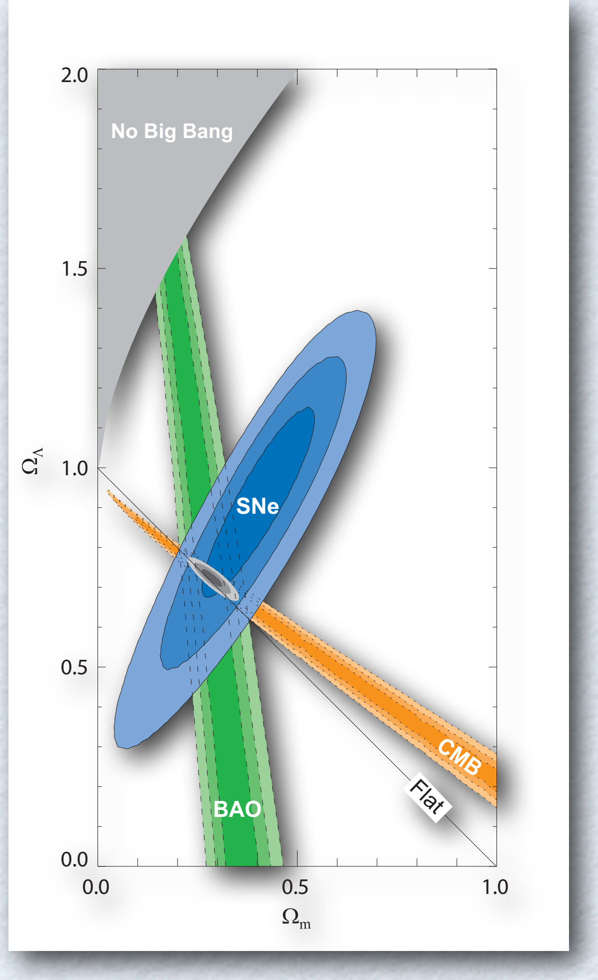
Brian P. Schimdt

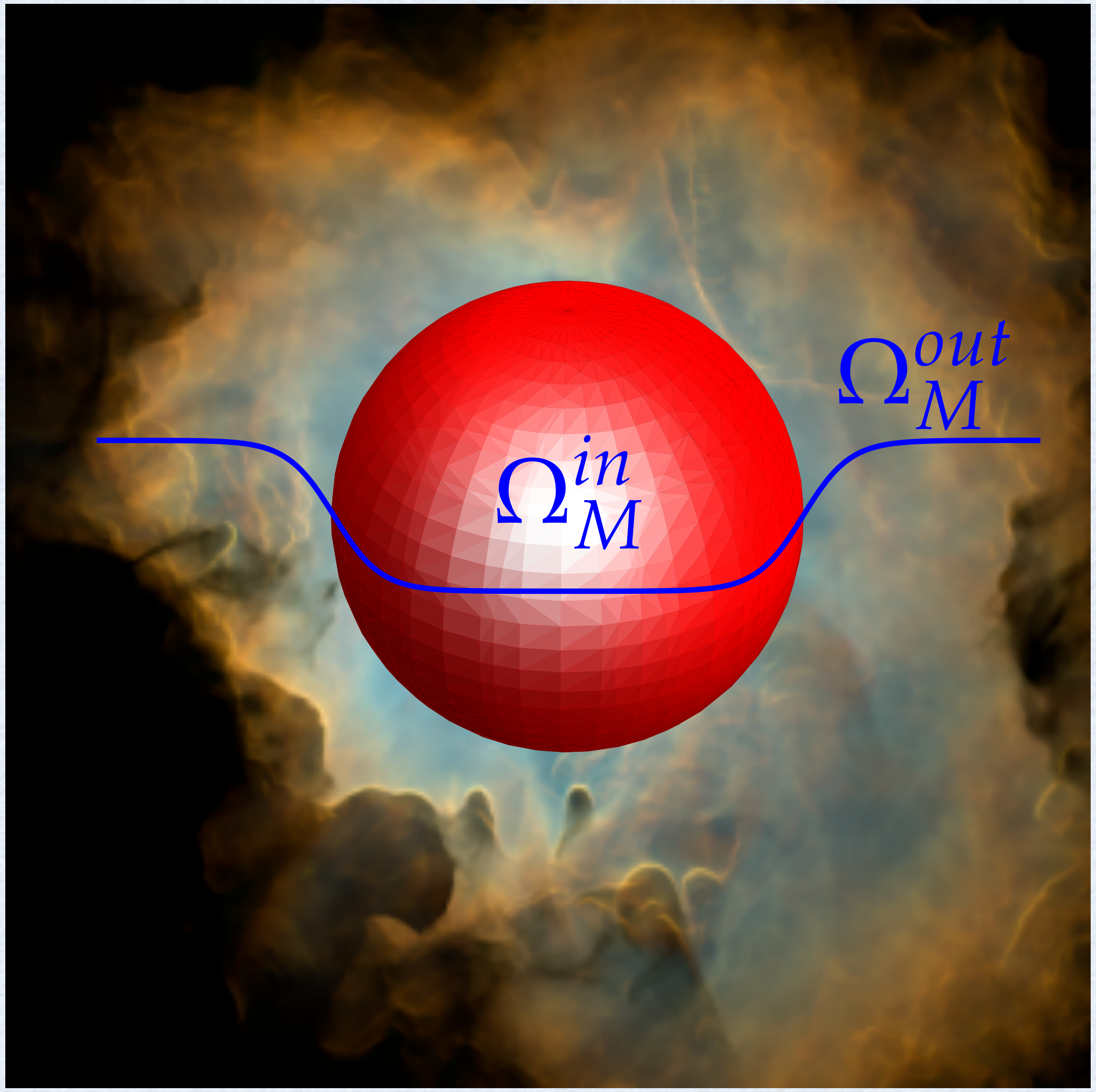

Adam Riess

$$d_L = (1+z)^2 d_A$$



COSMIC ACCELERATION

Inhomogeneous universe (LTB)



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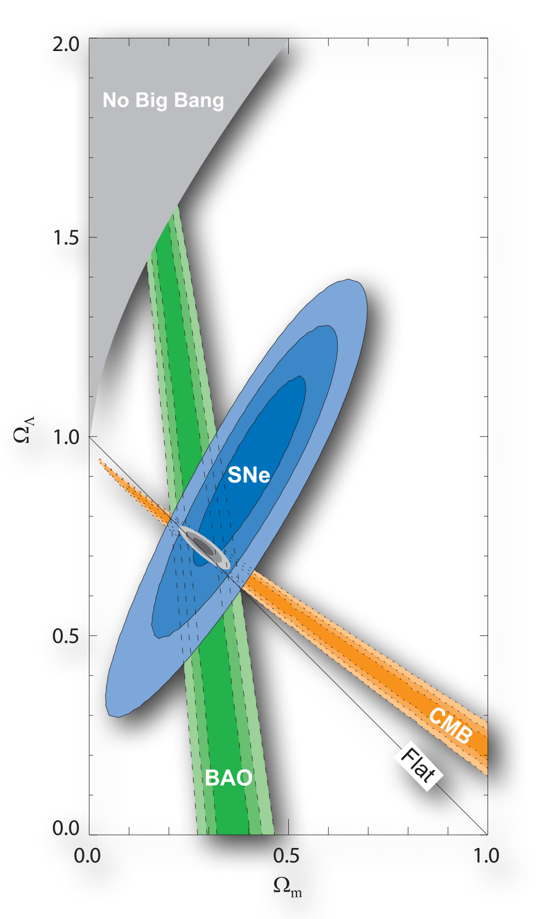

COSMIC ACCELERATION

Inhomogeneous universe (Backreaction)

$$G_{\mu\nu}(\langle g_{\mu\nu}\rangle) \neq \langle G_{\mu\nu}(g_{\mu\nu})\rangle$$

Perturbative backreaction

⇩

Small effect in LCDM

Non-Perturbative backreaction

⇩

?

Things may change in modified cosmologies

JBJ, A. de la Cruz-Dombriz,P.K. Dunsby and D. Saez-Gomez, JCAP (2014)

Nobel Prize in Physics 2011

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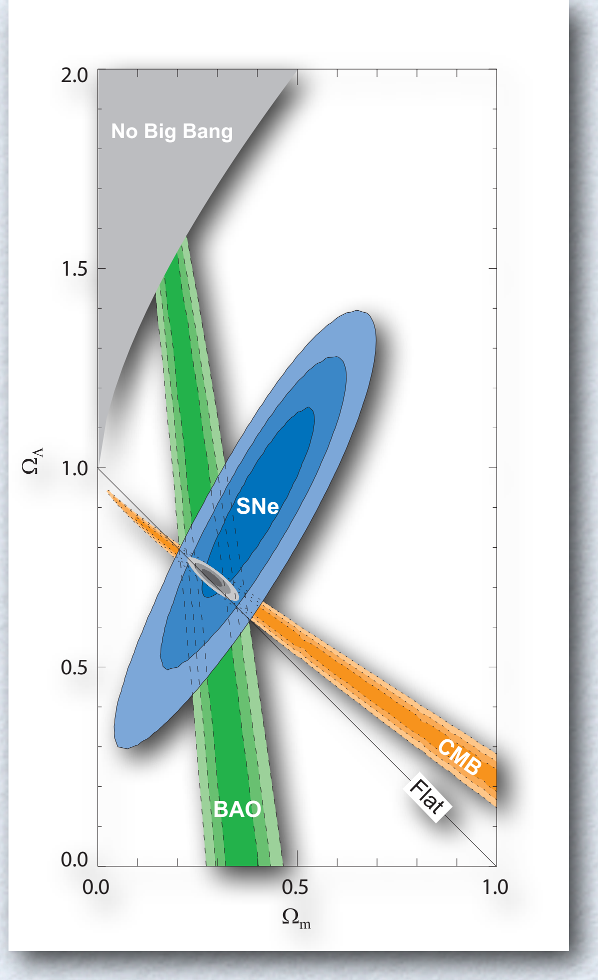

DARK ENERGY VS SELF-ACCELERATION

At the level of the background evolution we typically obtain an effective Friedman equation in modified gravity:

$$H^2 = \frac{8\pi G}{3}\sum_i \rho_i$$

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Dark Energy

Self-acceleration

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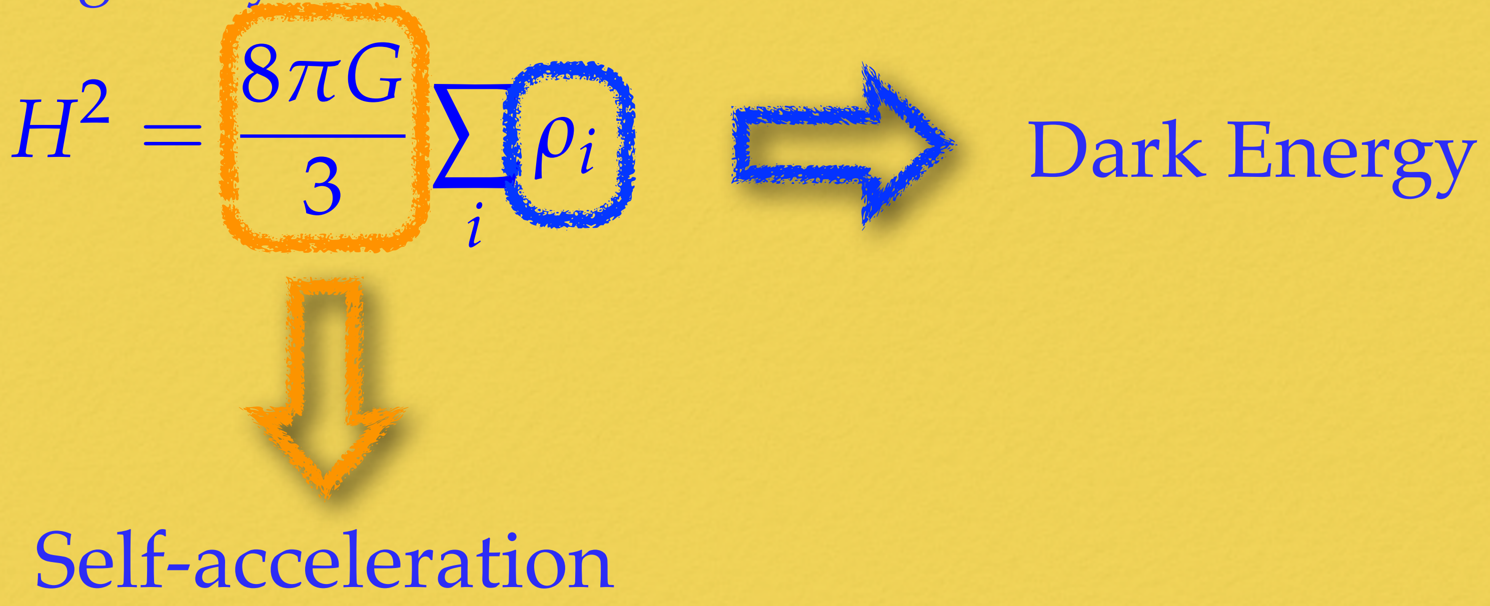


$$H^2 = \boxed{\frac{8\pi G}{3}} \sum_i \boxed{\rho_i} \Rightarrow \text{Dark Energy}$$

$$\Downarrow$$

Self-acceleration

f(R) theories

$$S = \frac{1}{2} M_p^2 \int d^4x \sqrt{-g} f(R)$$

$$\Downarrow \quad g_{\mu\nu} = e^{2\beta\phi/M_p} g^E_{\mu\nu}$$

$$S = \int d^4x \sqrt{-g^E} \left[\frac{1}{2} M_p^2 R_E - \frac{1}{2} (\partial\phi)^2 - V(\phi) \right] + S_m[\psi, e^{2\beta\phi/M_p} g^E_{\mu\nu}]$$

SELF-ACCELERATION IN DGP

$$S = -\frac{1}{2}M_P^2\int d^4x\sqrt{-h}R_{(4)} - \frac{1}{2}M_5^2\int d^5x\sqrt{-g}R_{(5)} + S_{GH}$$

$$r_c = m^{-1} = \frac{M_P^2}{2M_5^3}$$

Modified Friedmann equation

$$H^2 - \epsilon m H = \frac{1}{3M_p^2}\rho$$

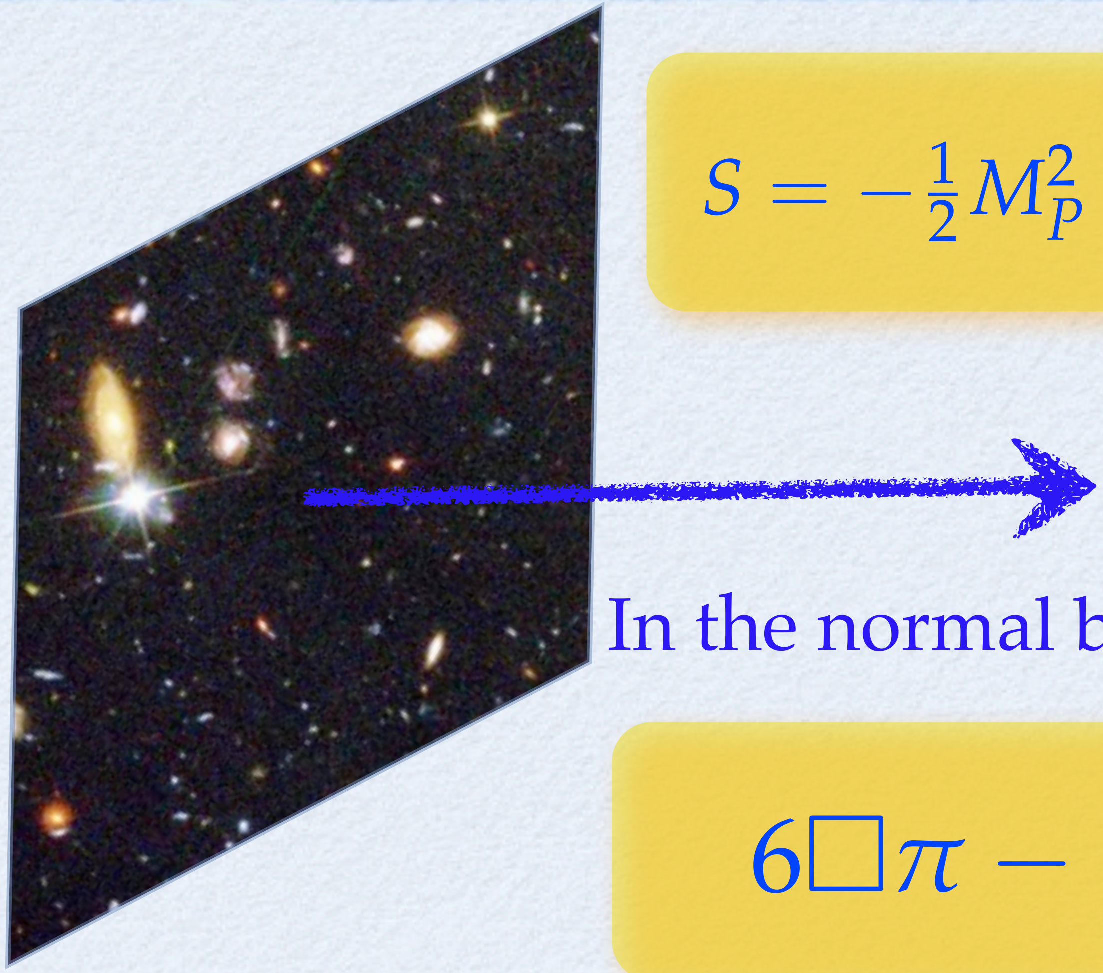
$$H(1 + mH) = 0$$

Normal branch

$$H(1 - mH) = 0$$

Self-accelerated branch (ghost)

SELF-ACCELERATION IN DGP



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$$r_c = m^{-1} = \frac{M_P^2}{2M_5^3}$$

In the normal branch, the bending mode satisfies the equation

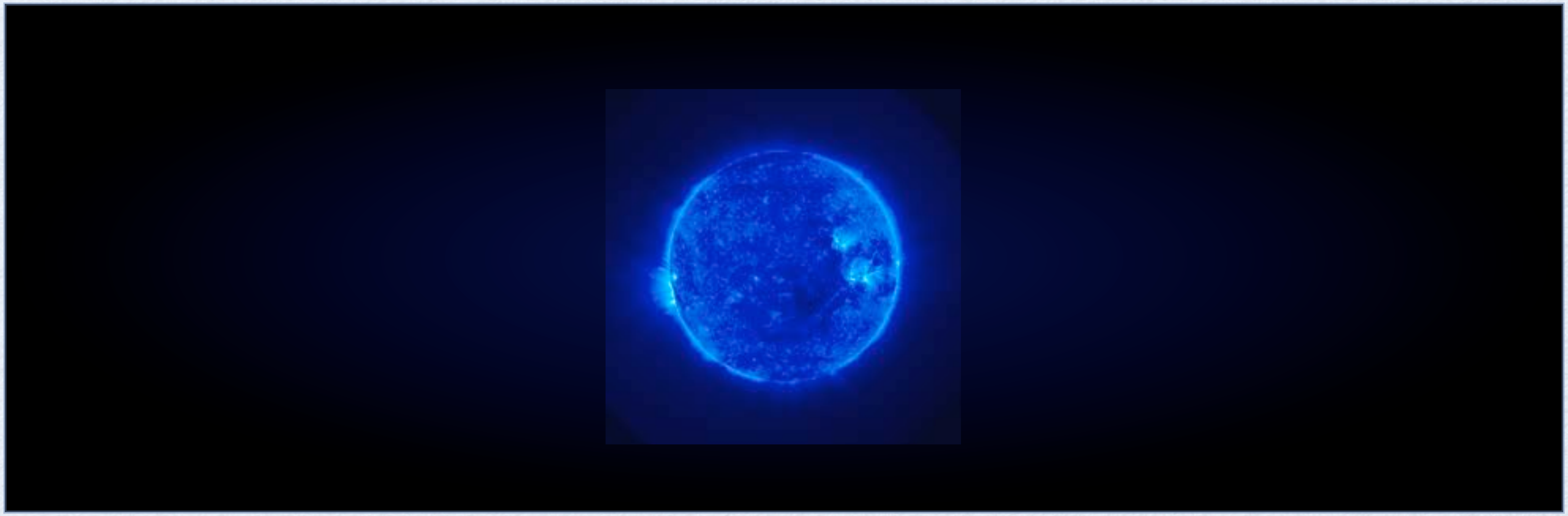
$$6\Box\pi - \frac{4}{m}(\partial_\mu\partial_\nu\pi)^2 + \frac{4}{m}(\Box\pi)^2 = -T$$

This is the cubic Galileon. The most general lagrangian sharing the properties of this bending mode leads to the family of Galileon theories and their covariantization give rise to Horndeski theories.

LOCAL GRAVITY/5TH FORCES

IR modifications of gravity add new dof's which give rise to 5th forces that have never been detected.

$$\mathcal{L}_{\phi-\mathrm{matter}} = A(\phi)T \quad \Longrightarrow \quad \Phi_{\mathrm{eff}} = -\frac{GM}{r}\left(1+\beta e^{-mr}\right)$$



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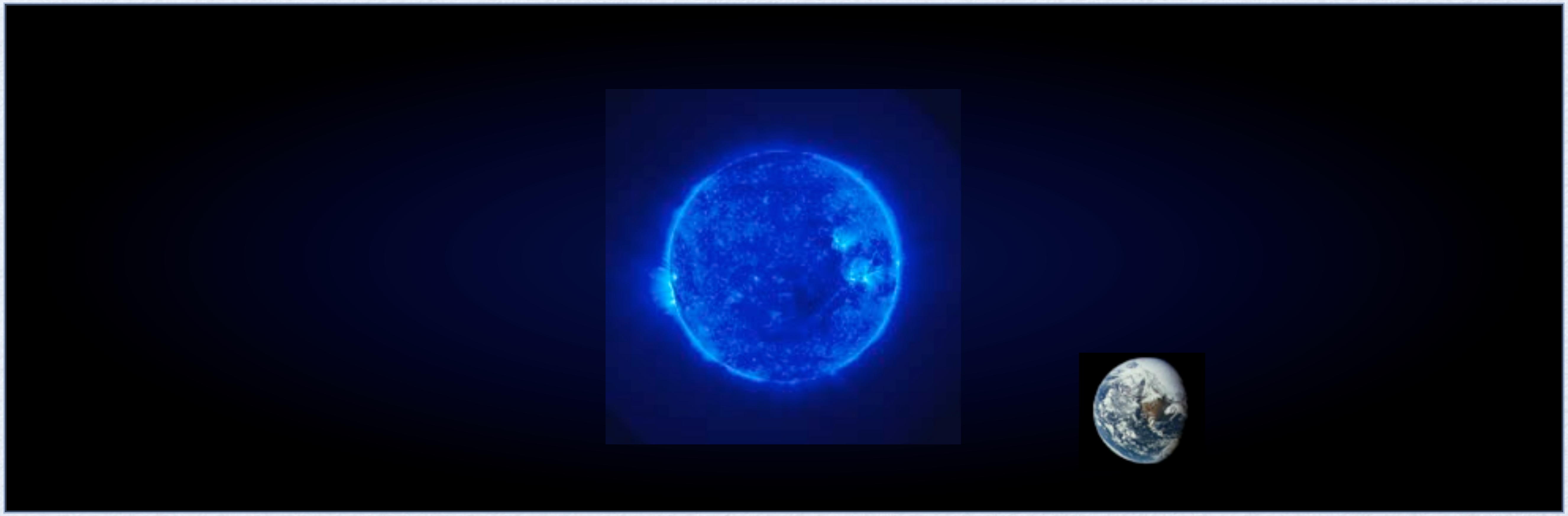

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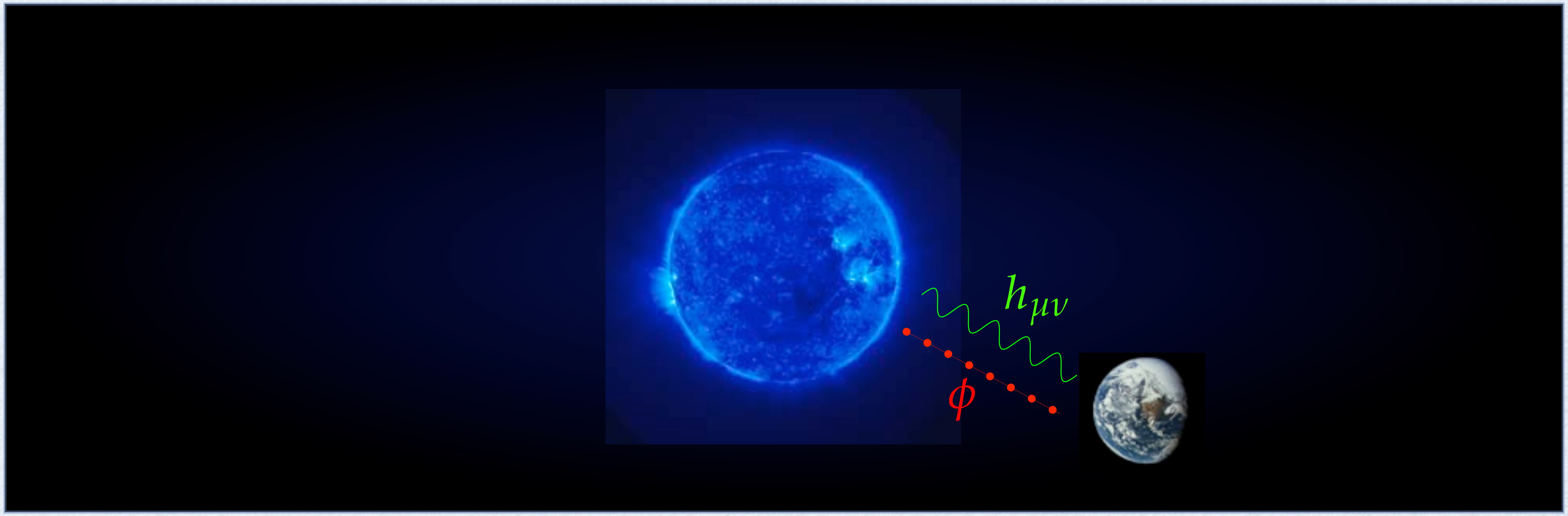

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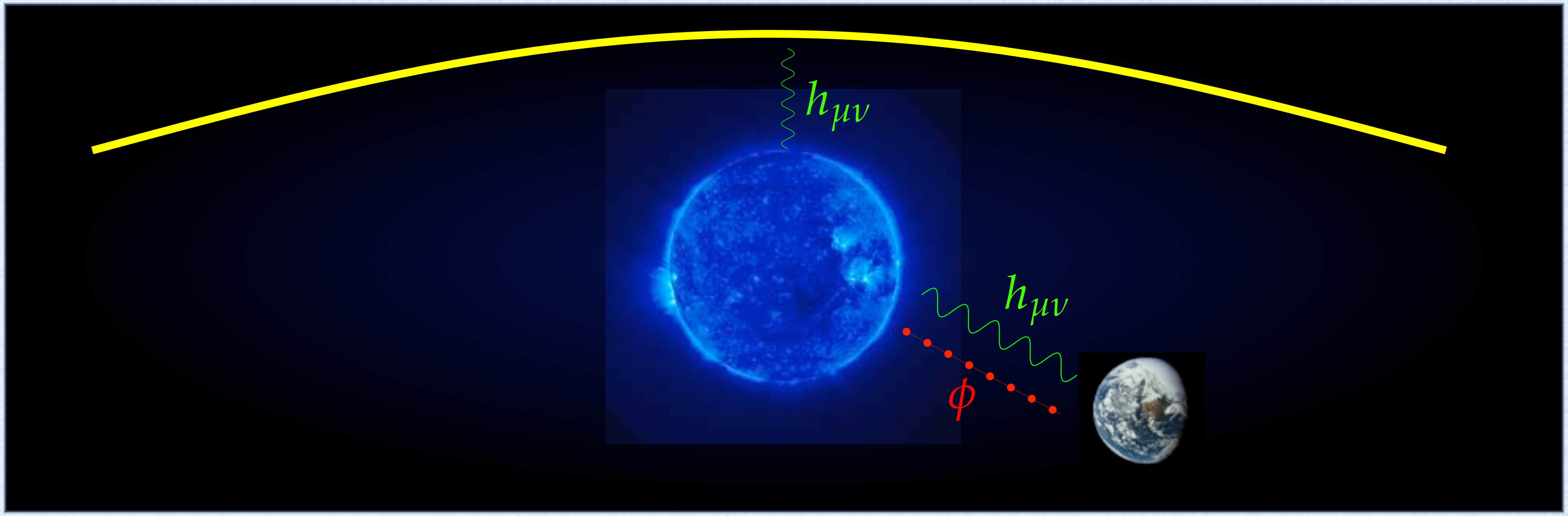

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We need to reconcile the absence of 5th forces on Solar system scales while having non-trivial effects on cosmological scales.

$$\Downarrow$$

Screening mechanisms provided by non-linearities*

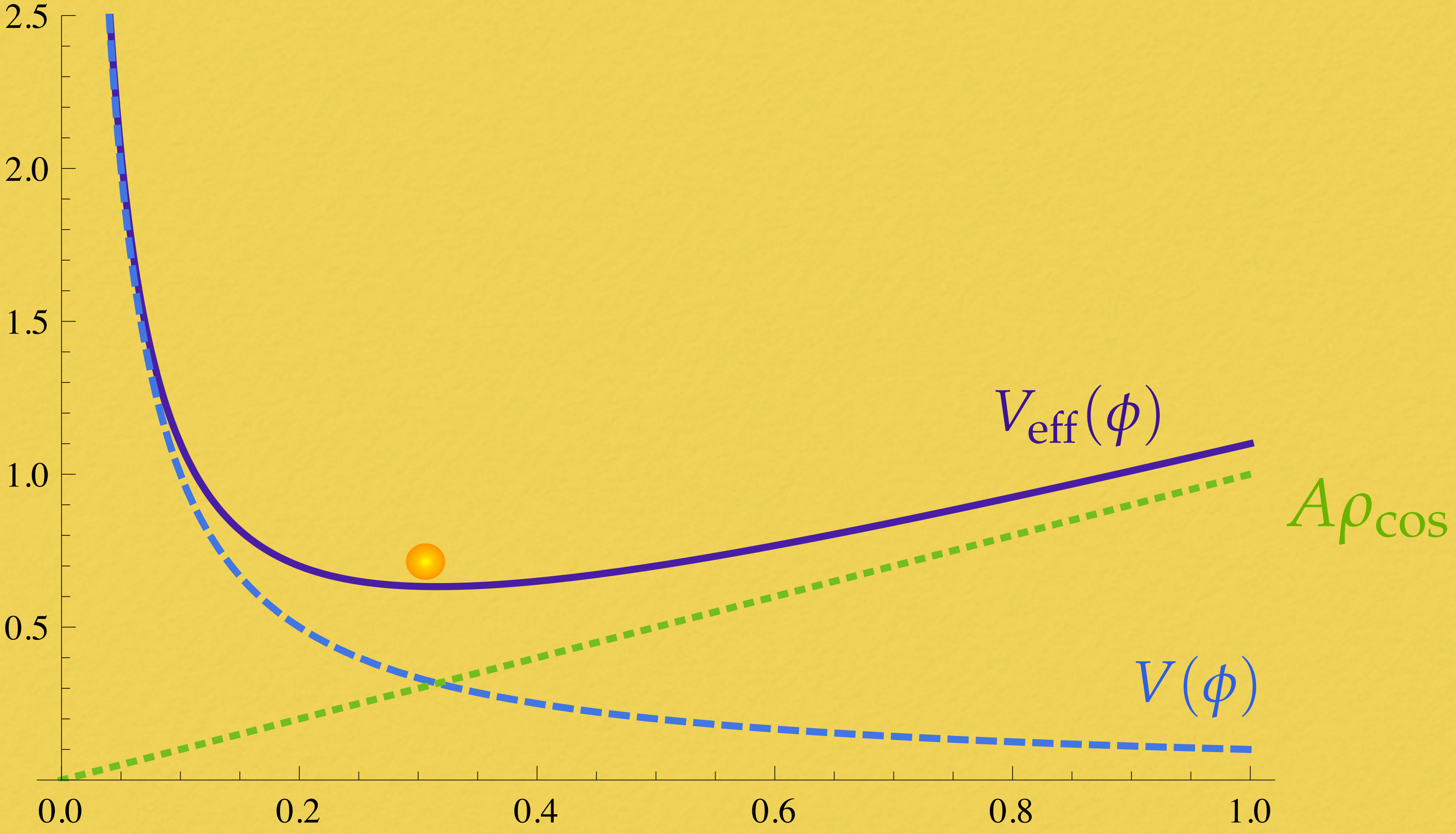
$$\boxed{\mathcal{L} = \frac{1}{2}\underset{\uparrow}{\mathcal{Z}}(\phi_b)\partial_\mu\delta\phi\partial^\mu\delta\phi - \frac{1}{2}\underset{\uparrow}{m^2}(\phi_b)\delta\phi^2 + \underset{\uparrow}{g}(\phi_b)\delta\phi T}$$

Vainshtein/Kinetic/K-mouflage Chameleon Symmetron/Dilaton

* NB: We have the obvious “screening” of canceling the coupling constant at all scales.

CHAMELEON SCREENING

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi) - A(\phi)T \quad \Rightarrow \quad V_{\rm eff} = V(\phi) + A(\phi)T$$



J. Khoury and A. Weltman,
PRL 93 (2004)

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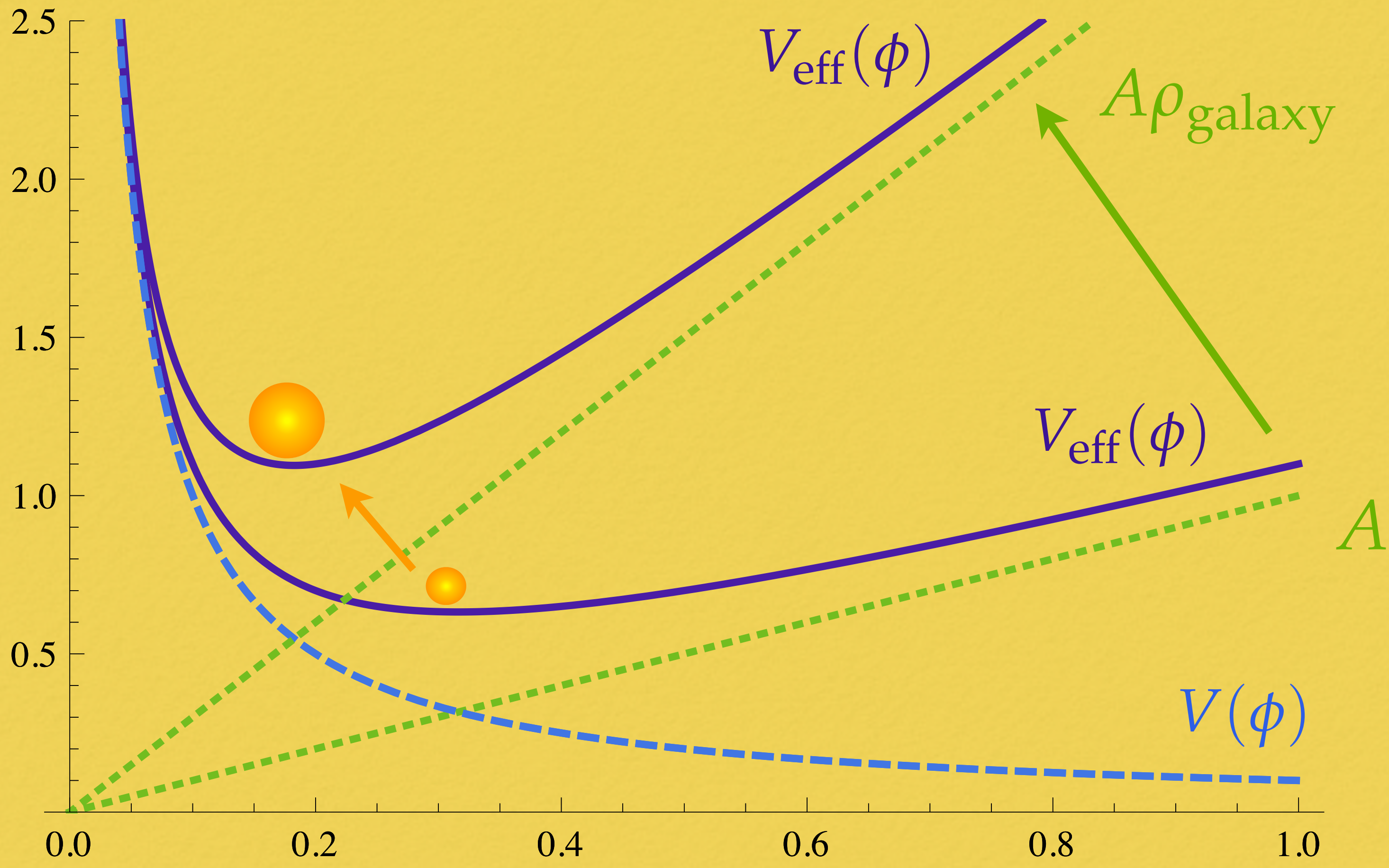

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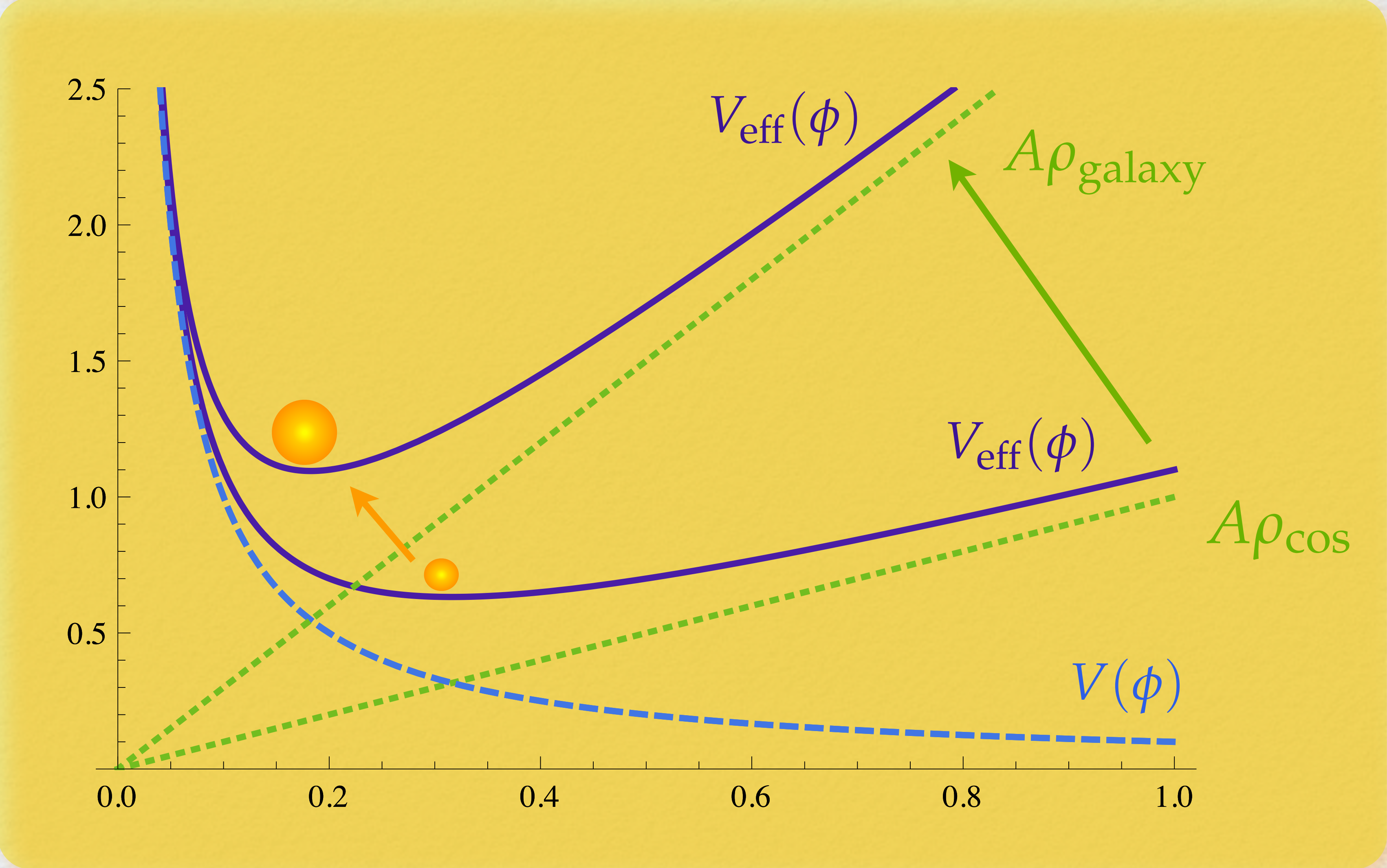

$m^{-1}(\rho_{\mathrm{lab}}) \lesssim 40\mu\mathrm{m}$ ✓Ok

J. Khoury and A. Weltman,
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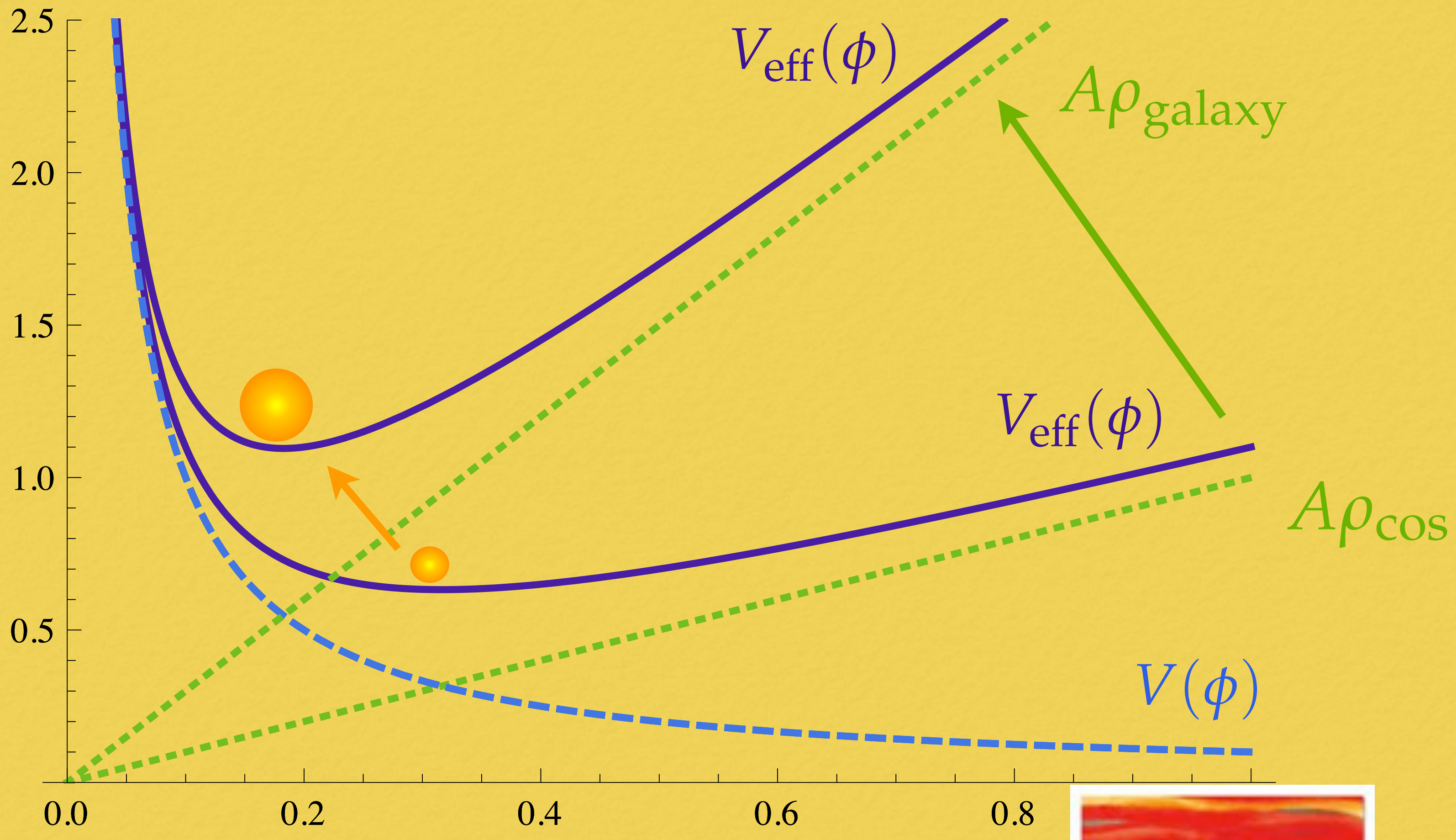


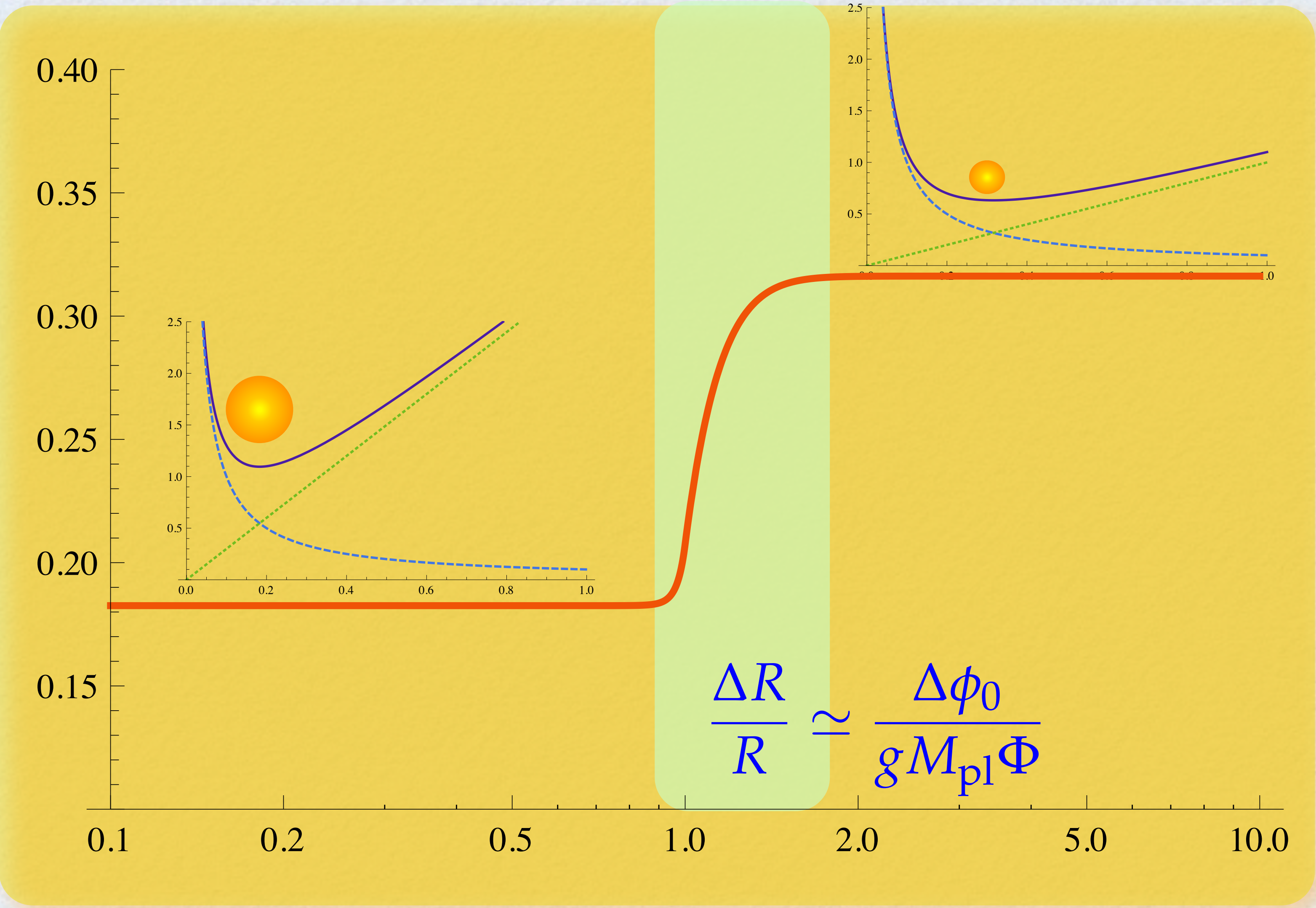
$m^{-1}(\rho_{\text{lab}}) \lesssim 40\mu\text{m}$ ✓Ok

$m^{-1}(\rho_{\text{solar system}}) \lesssim 10^6\text{AU}!$

How do we avoid Solar System constraints?!

J. Khoury and A. Weltman, PRL 93 (2004)

CHAMELEON SCREENING



$$\frac{\Delta R}{R} \simeq \frac{\Delta\phi_0}{g M_{\rm pl}\Phi}$$

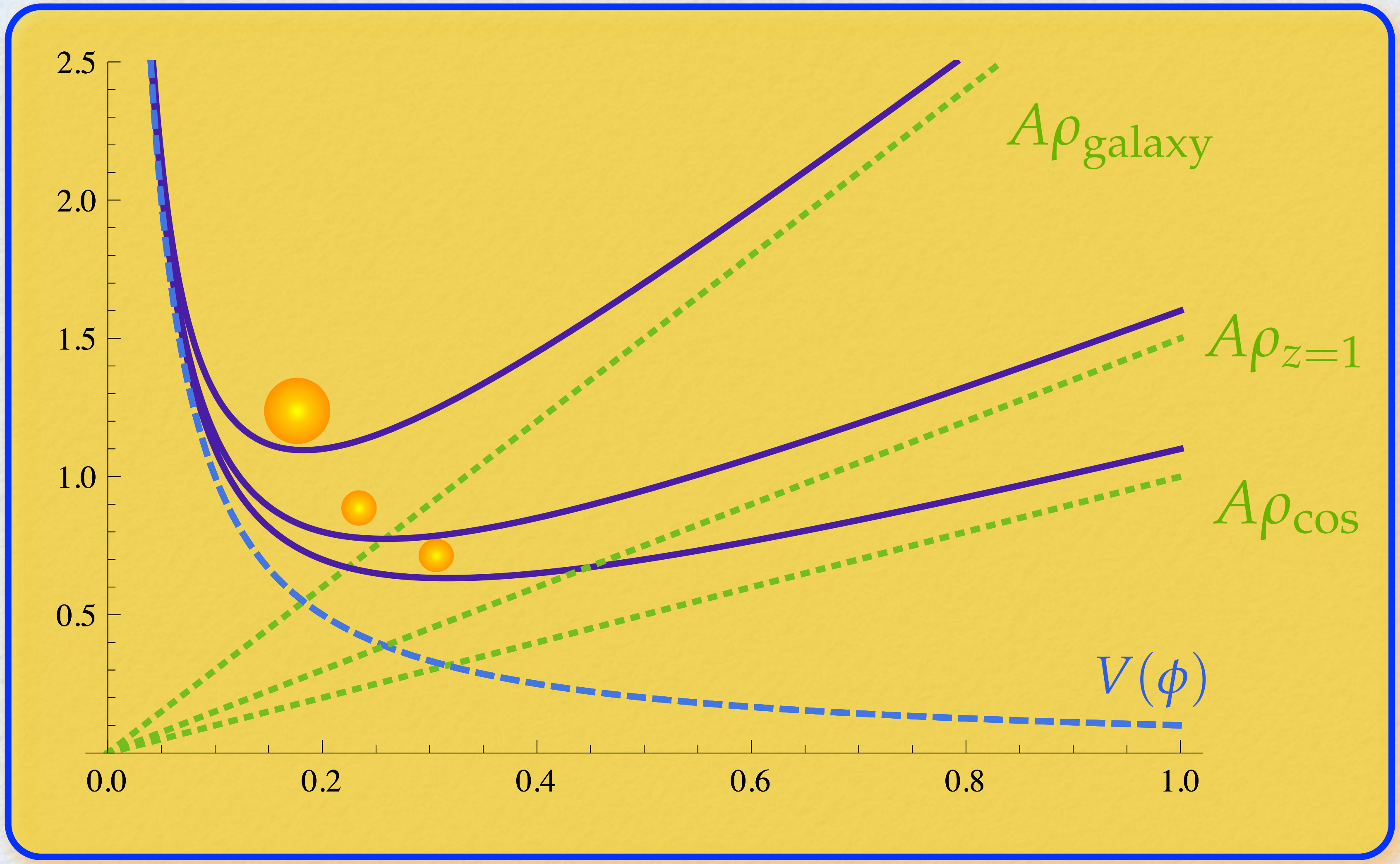
$$\phi(r > R) \simeq -\frac{g}{M_{\rm Pl}}\boxed{\frac{\Delta R}{R}}\frac{M}{r}e^{-m_{\rm out}r} + \phi_{\rm out}$$

Thin-shell effect: the mediated force is strongly suppressed if

$$\frac{\Delta R}{R} \ll 1$$

The screening is determined by the surface potential of the object and depends on the environment.

NO-GO THEOREM



To avoid local gravity conflicts we need

$$\left.\frac{\Delta A}{A}\right|_{\rm MW\to cos} \lesssim 10^{-6}$$

Since $\rho_{\rm MW} \geq \rho_{z\simeq 1}$

we have

$$\left.\frac{\Delta A}{A}\right|_{z\simeq 1\to z\simeq 0} \leq \left.\frac{\Delta A}{A}\right|_{\rm MW\to cos}$$

so no self-acceleration is possible.

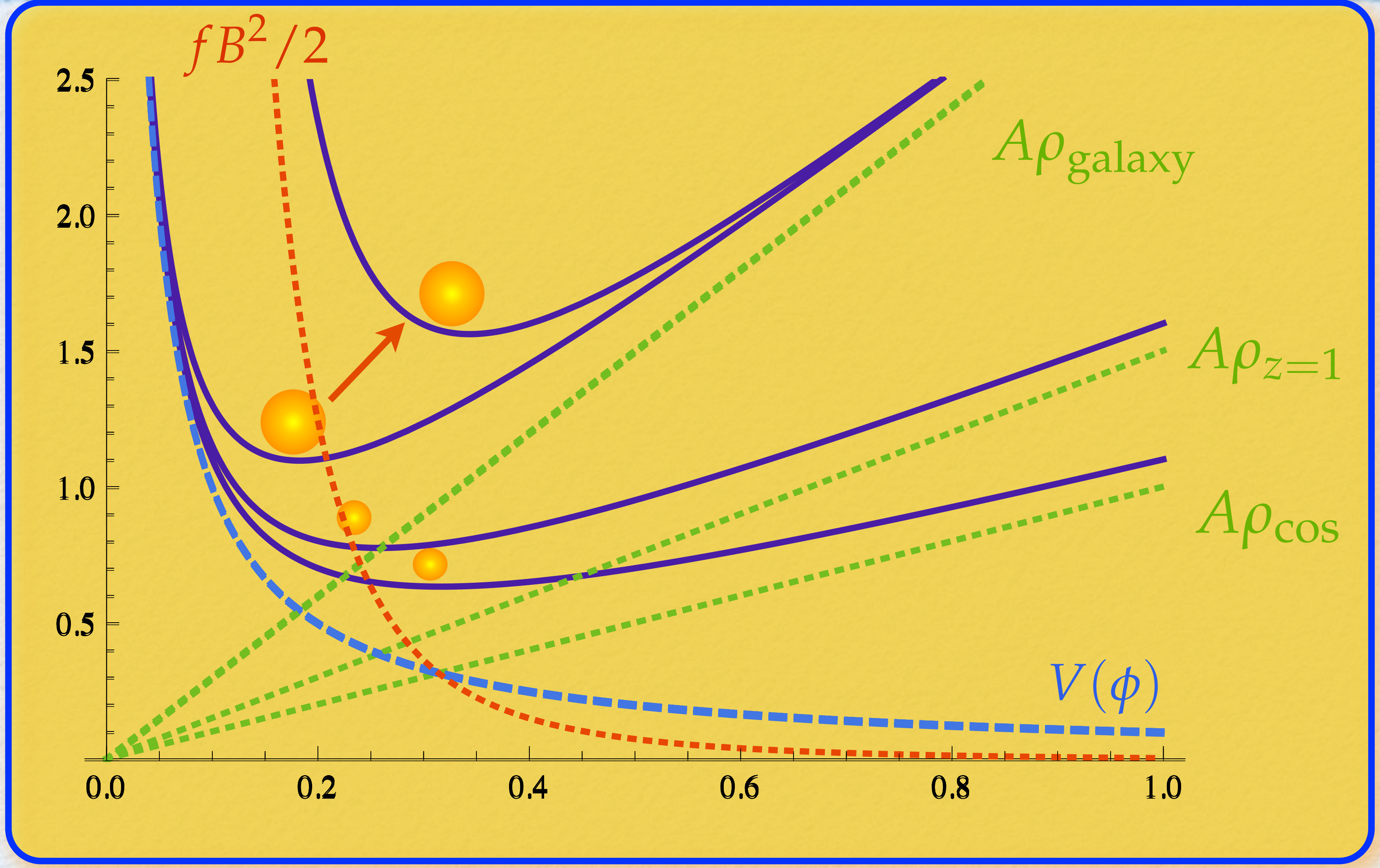
On the other hand, the effective mass can be shown to be given by

$$m^2 \sim \left(\frac{\Delta A}{A}\right)^{-1} H_0^2 \gtrsim ({\rm Mpc})^{-2}$$

Effects only on non-linear scales.

J. Wang, L. Hui and J. Khoury, PRL 109 (2012)

MAGNETIC SCREENING



Work in progress
with F. Piazza

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi) - A(\phi)T - \frac{1}{4}f(\phi)F_{\mu\nu}F^{\mu\nu}$$

$$\Downarrow$$

$$V_{\rm eff}(\phi) = V(\phi) + A(\phi)\rho + \frac{1}{2}f(\phi)B^2.$$

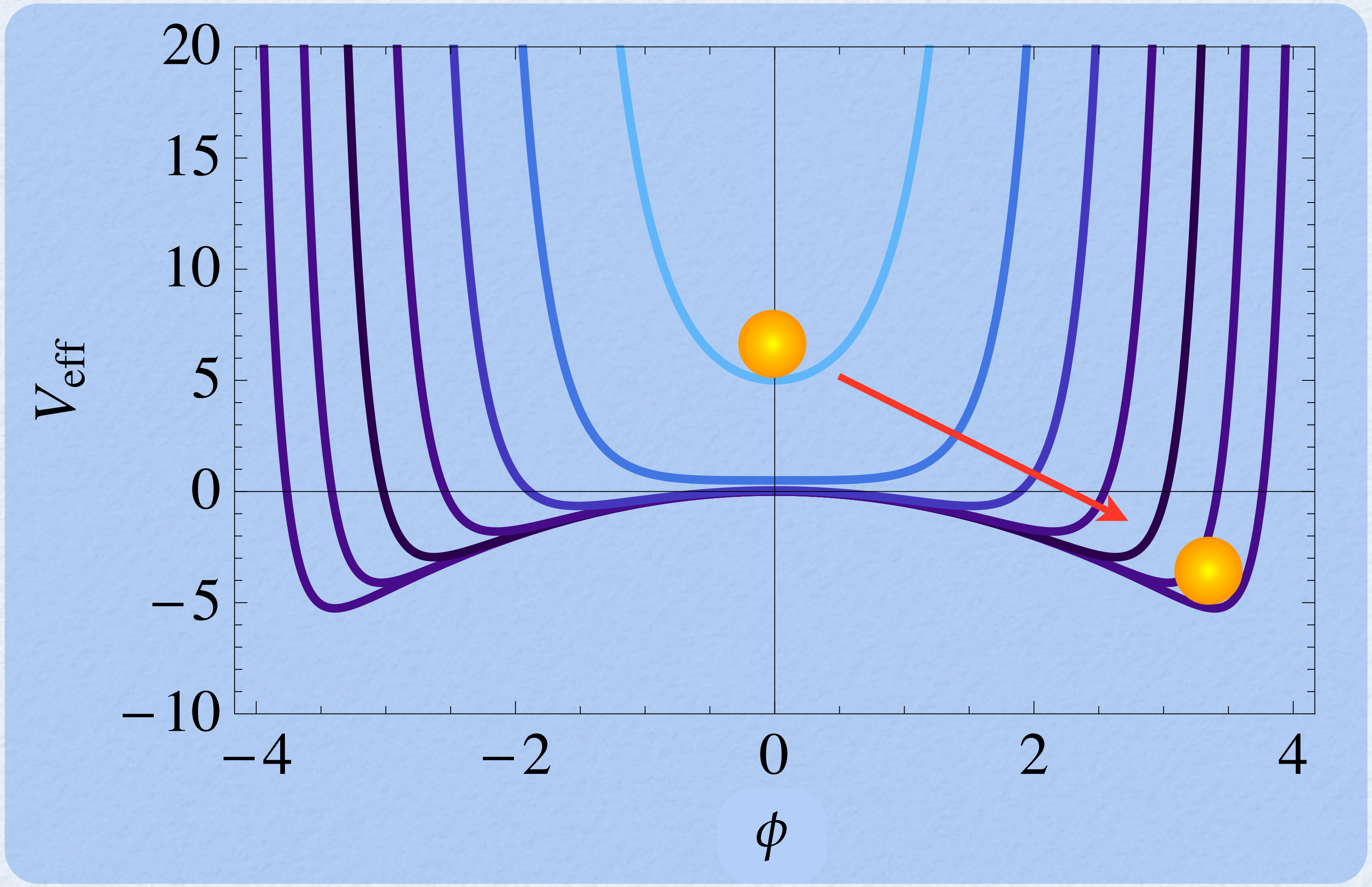
Now the cosmological variation of the conformal coupling is not constrained by local gravity.

There is a hierarchy between the galaxy and the Solar system.

SYMMETRON MECHANISM

$$\boxed{V_{eff}(\phi) = \frac{1}{2}\left(\frac{\rho}{M^2} - m^2\right)\phi^2 + \lambda\phi^4}$$

$$\tilde{g}_{\mu\nu} = \left(1 + \frac{\phi^2}{2M^2}\right) g_{\mu\nu}$$



$$V(\phi) = -\frac{1}{2}m^2\phi^2 + \lambda\phi^4$$

$$\mathcal{L}_{\rm int} = \frac{\phi_0}{M^2}\delta\phi T$$

Fluctuations decouple in dense environments.

K. Hinterbichler & J. Khoury, PRL 104 (2010)

Applicable to screen vector fields

JBJ, A. Froes and D.F. Mota, PLB (2013)

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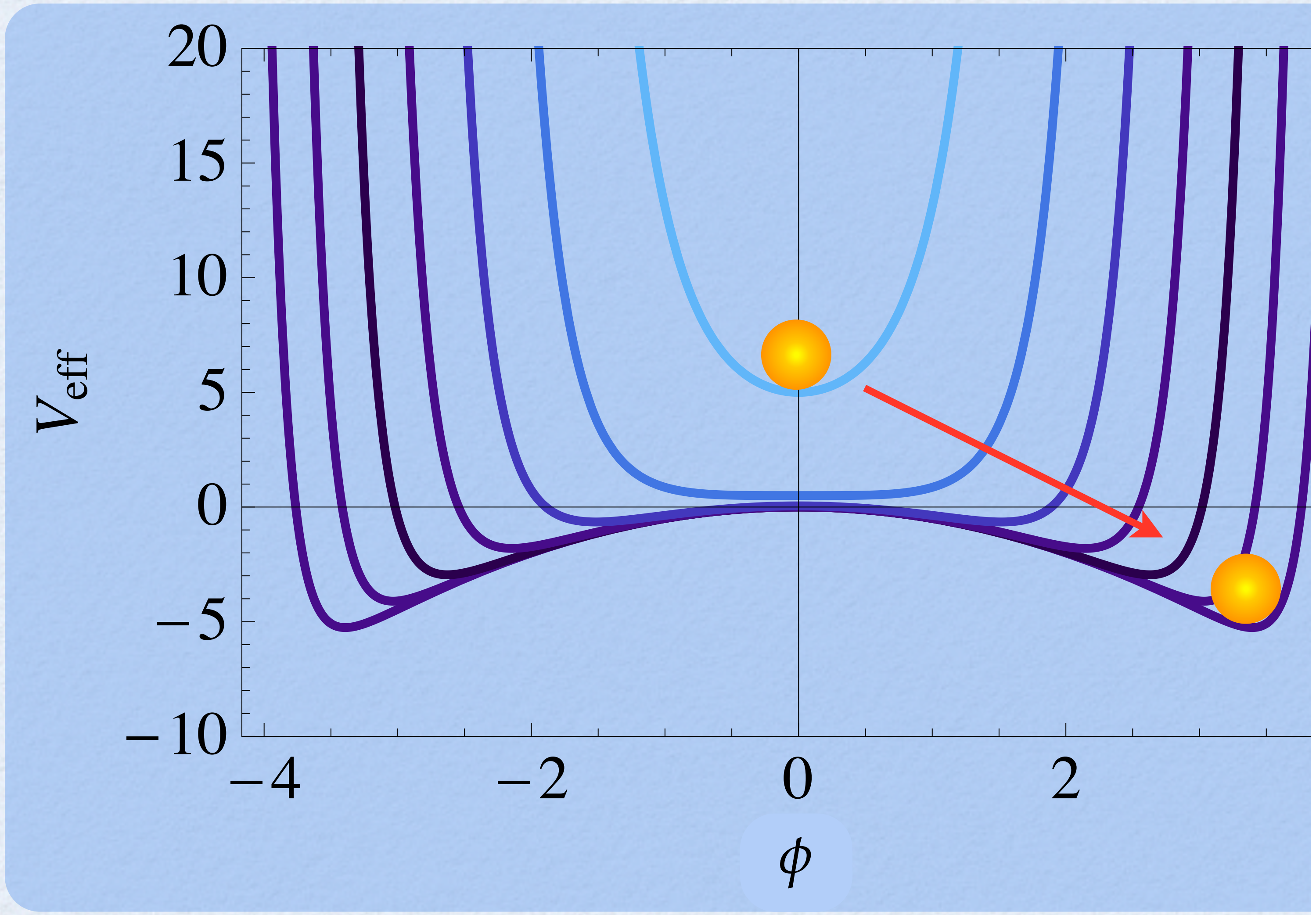

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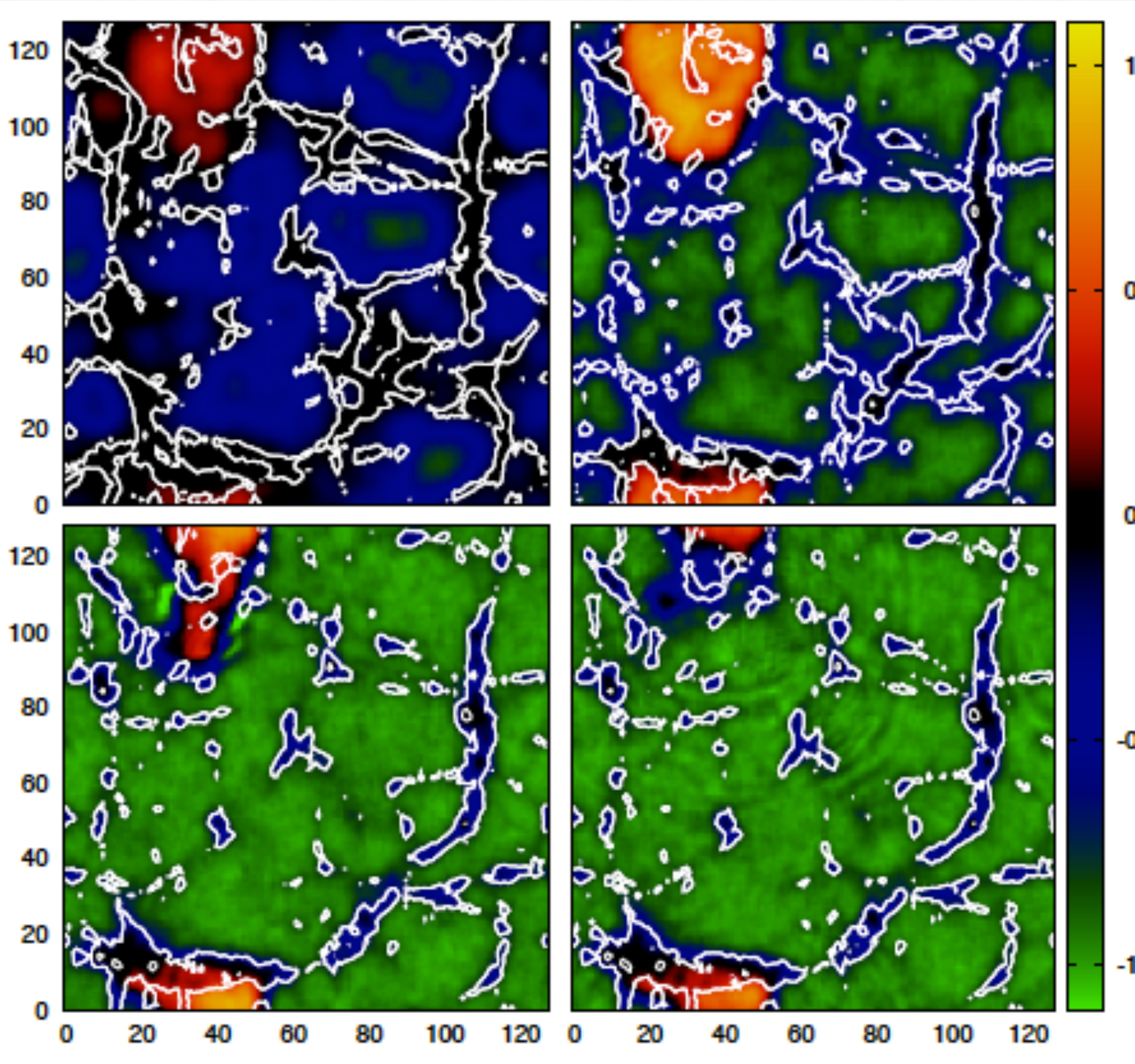

C. Llinares and D.F. Mota, PRL 110 (2013)

The scalar waves can spoil the screening.

R. Hagala, C. Llinares & D.F. Mota, arXiv:1607.02600

VAINSHTEIN SCREENING

The cubic Galileon is the simplest example

A. Vainshtein,
Phys.Lett. B39, 393 (1972)

$$\mathcal{L} = -3(\partial\phi)^2 - \frac{1}{\Lambda^3}(\partial\phi)^2\Box\phi + \frac{g}{M_{\rm Pl}}\phi T$$

First discovered in massive gravity

Around a spherical object:

$$6\phi' + \frac{4}{\Lambda^3}\frac{\phi'^2}{r} = \frac{gM}{4\pi r^2 M_{\rm Pl}}$$

2 branches

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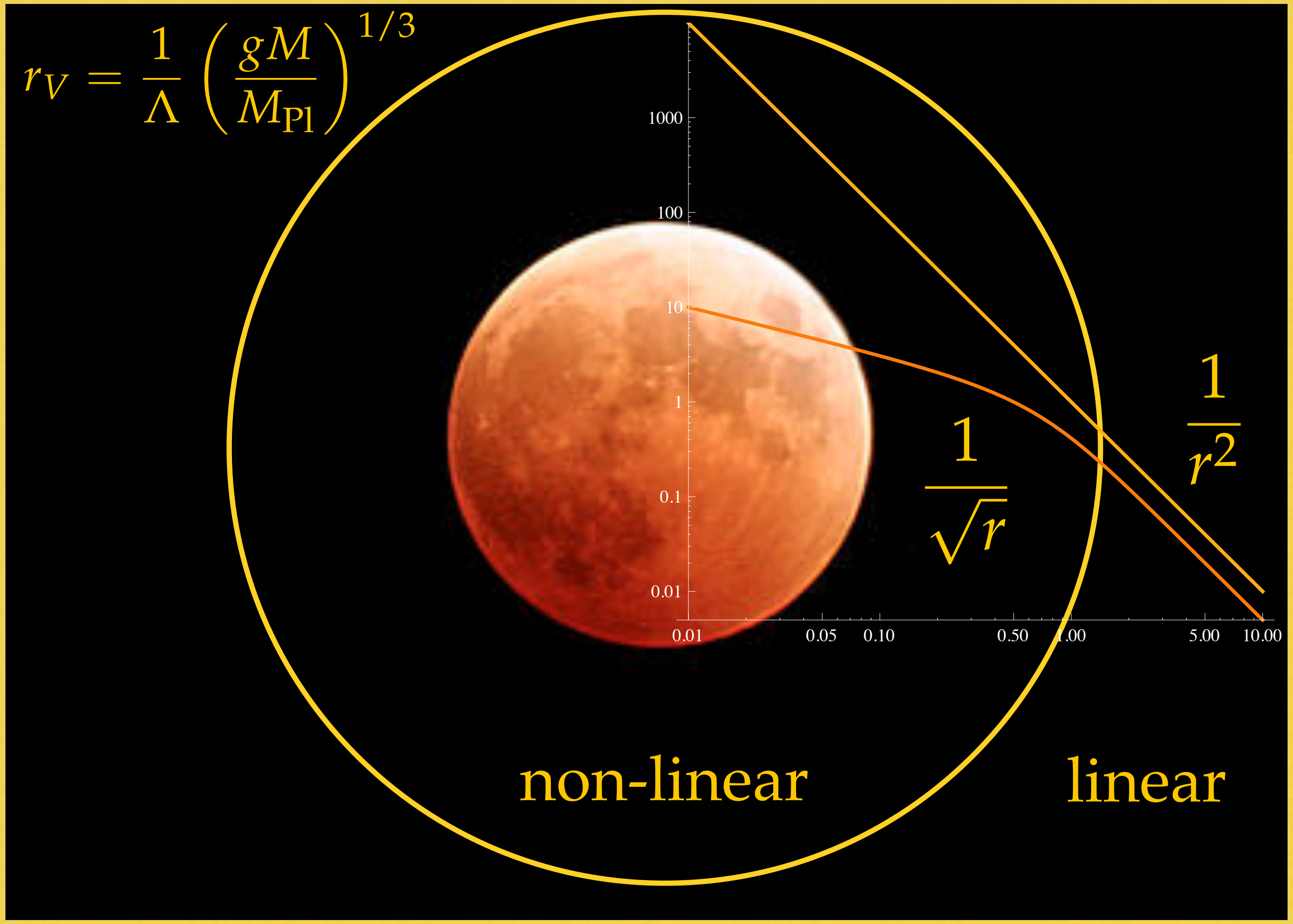


The screening is determined by the total mass of the object.

The Vainshtein radius of the Sun comprises the whole galaxy.

Essentially all objects in our universe are screened.

There is also a cosmological screening.

There seems to be problems in deep voids.

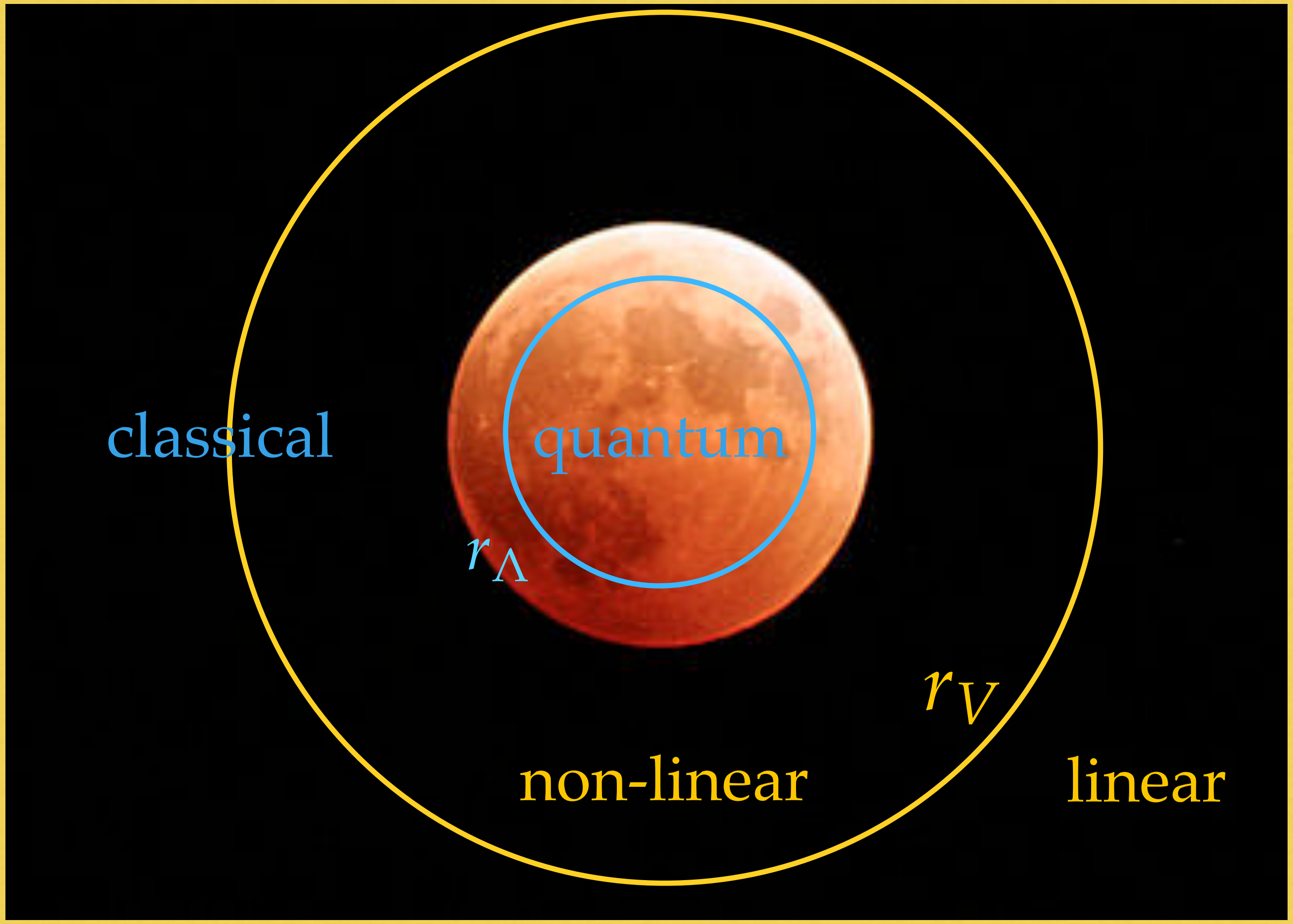
Superluminalities.

VAINSHTEIN SCREENING

Galileons

$$\mathcal{L} = -3(\partial\phi)^2 - \frac{1}{\Lambda^3}(\partial\phi)^2\Box\phi \qquad \alpha_{\rm cl} \sim \left(\frac{r_V}{r}\right)^{3/2}$$

$$\Delta\mathcal{L} = \sum_{n,\ell} \frac{c_{n,\ell}}{\Lambda^{3n+2\ell-4}}\partial^{2\ell}(\partial^2\phi)^n \qquad \alpha_{\rm q} \sim \frac{1}{(r\Lambda)^2}$$



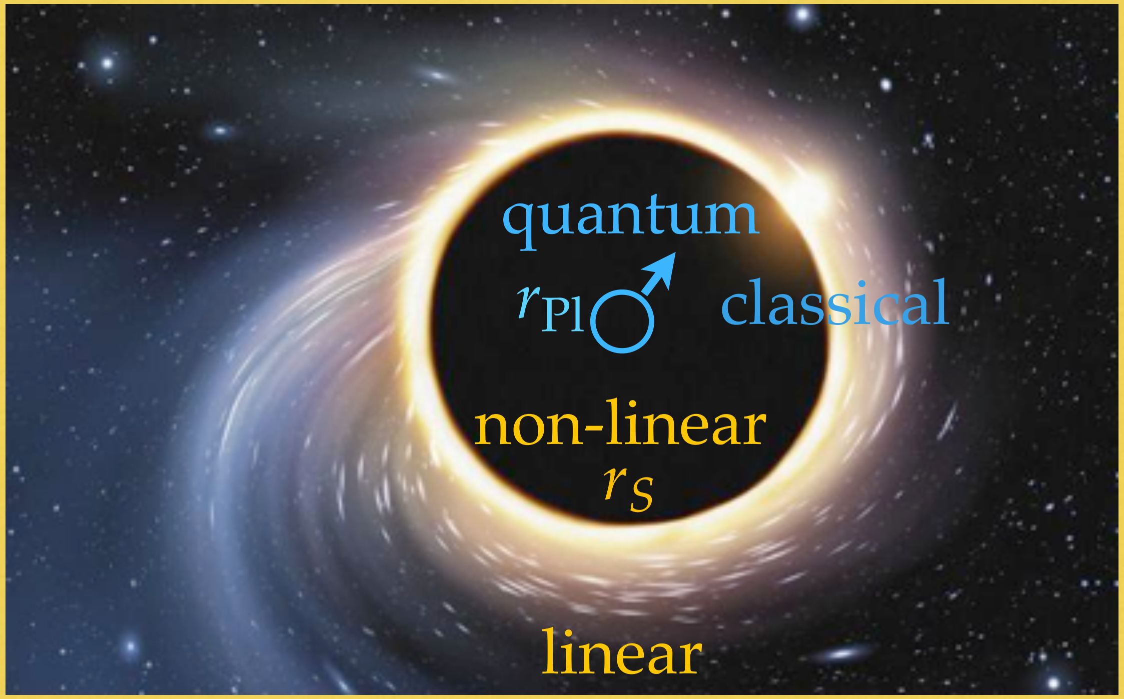
General Relativity

$$\mathcal{L} = M_{\rm pl}^2\sqrt{-g}R = h\partial^2 h + \sum_n \frac{h^n\partial^2 h}{M_{\rm Pl}}$$

$$\alpha_{\rm cl} \sim \left(\frac{r_S}{r}\right)$$

$$\Delta\mathcal{L} = \sqrt{-g}R^2_{\mu\nu\rho\sigma} = \sum_{n,m}\frac{\partial^m h^n}{M_{\rm Pl}^{m+n-4}}$$

$$\alpha_{\rm q} \sim \frac{1}{(rM_{\rm Pl})^2}$$



WHAT SCREENING REALLY MEANS

Most general scalar-tensor theory with second order equations of motion.

H.G Horndeski, Int.J.Theor.Phys 10 (1974)
Deffayet, Deser & Esposito-Farese, PRD80 (2009)
Deffayet, Gao, Steer, Zahariade PRD84 (2011)

$$X \equiv -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi$$

$$\mathcal{L}_2 = K(\phi, X)$$

$$\mathcal{L}_3 = G_3(\phi, X)\Box\phi$$

$$\mathcal{L}_4 = G_4(\phi, X)R - G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]$$

$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi + \frac{1}{6}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right]$$

Quintessence/K-essence

Galileons/
DBI

Higher dimensional
theories/
Generalized Weyl
geometry

Proxy for massive gravity/
EFT of DE

Brans-Dicke theories

Kinetic Gravity Braiding

Stable violation of NEC/
Bouncing solutions

Disformal
transformations

The fab four/
self-tuning

G-Inflation/
Galilean Genesis

Beyond Horndeski

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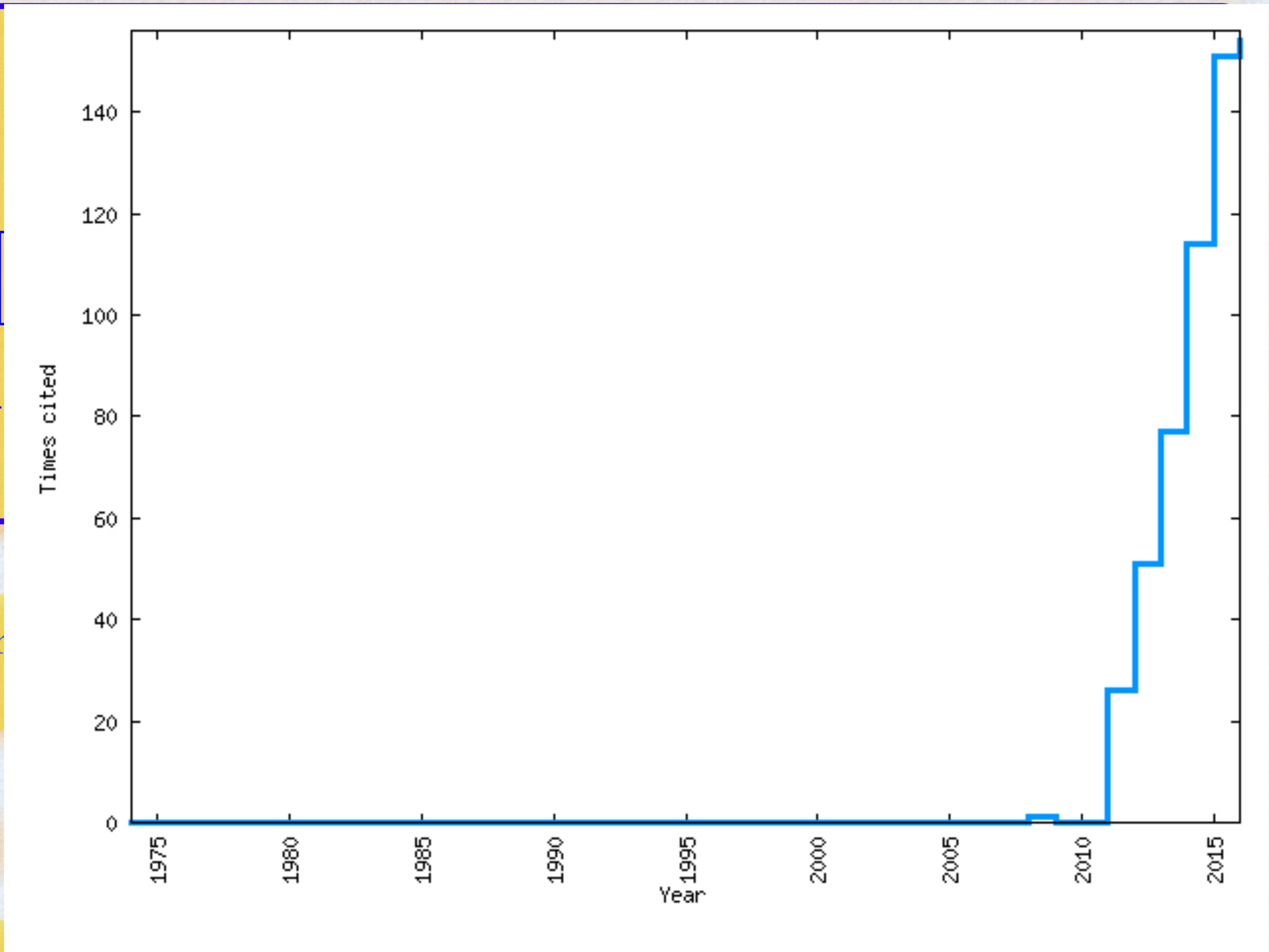
$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi + \frac{1}{6}$$



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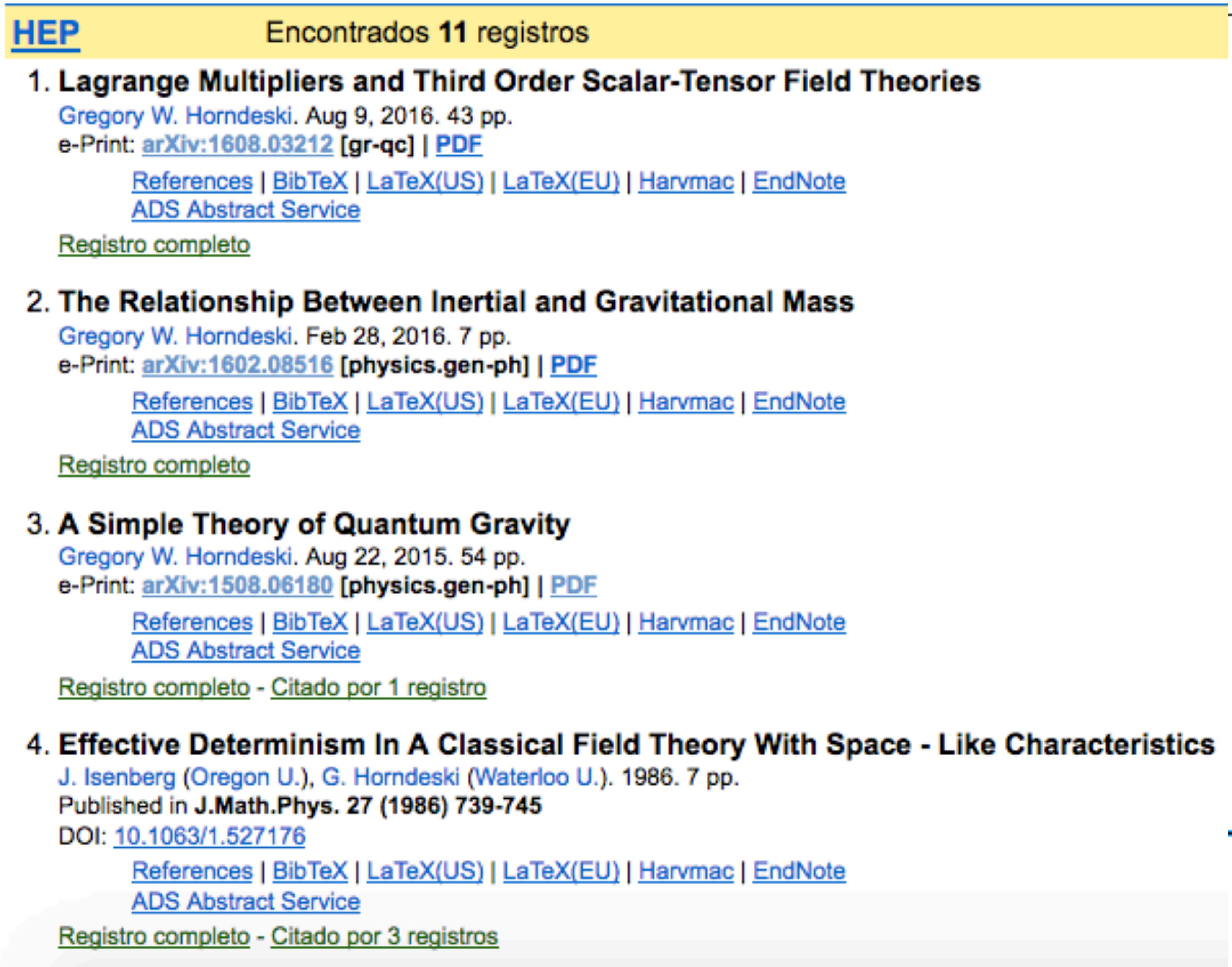

HEP Encontrados **11** registros

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   e-Print: arXiv:1608.03212 **[gr-qc] | PDF**
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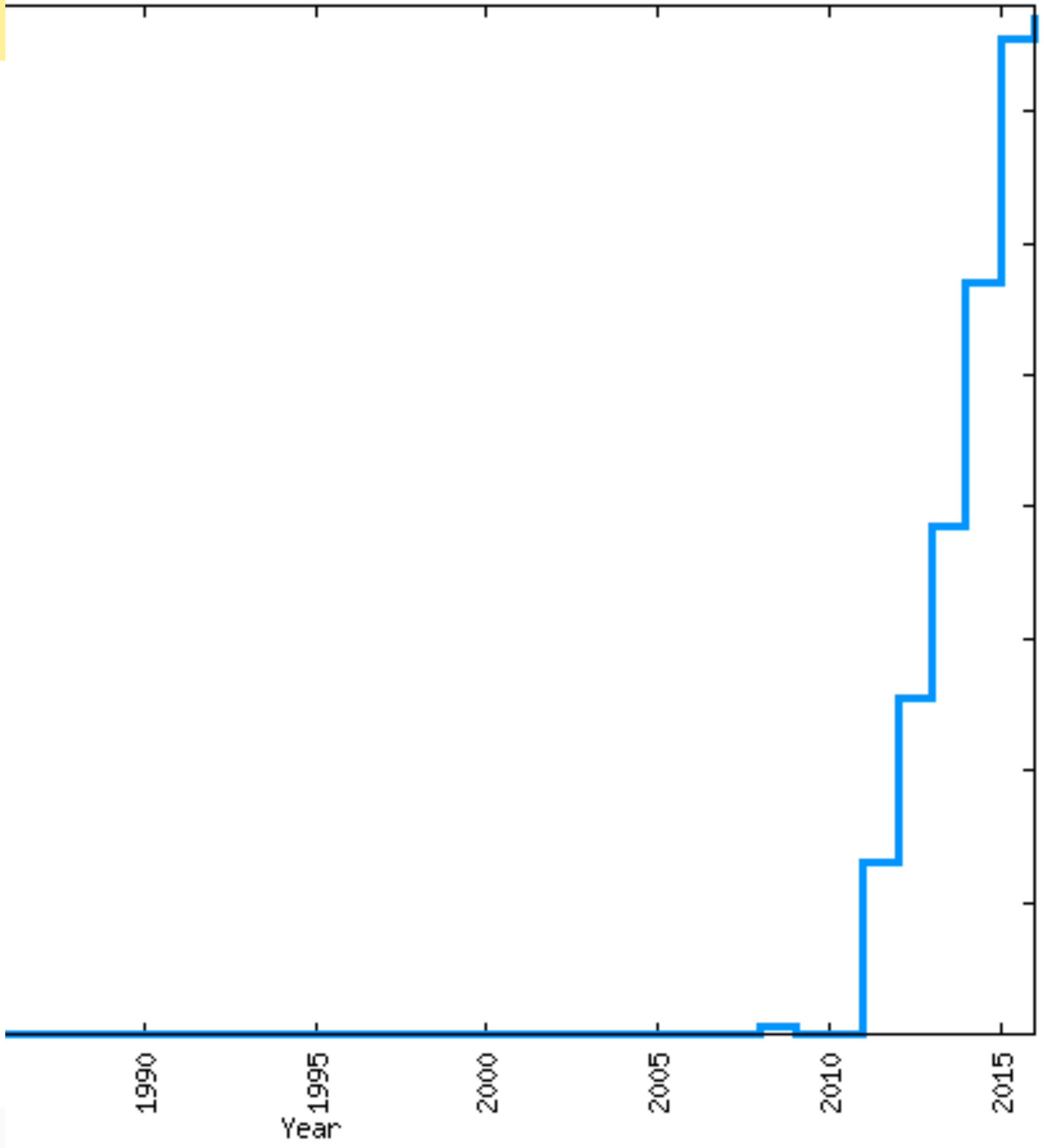

The fab four /
self-tuning

G-Inflation /
Galilean Genesis

Beyond Horndeski

WHAT SCREENING REALLY MEANS

Most general scalar-tensor theory with second order equations of motion.

H.G Horndeski, Int.J.Theor.Phys 10 (1974)
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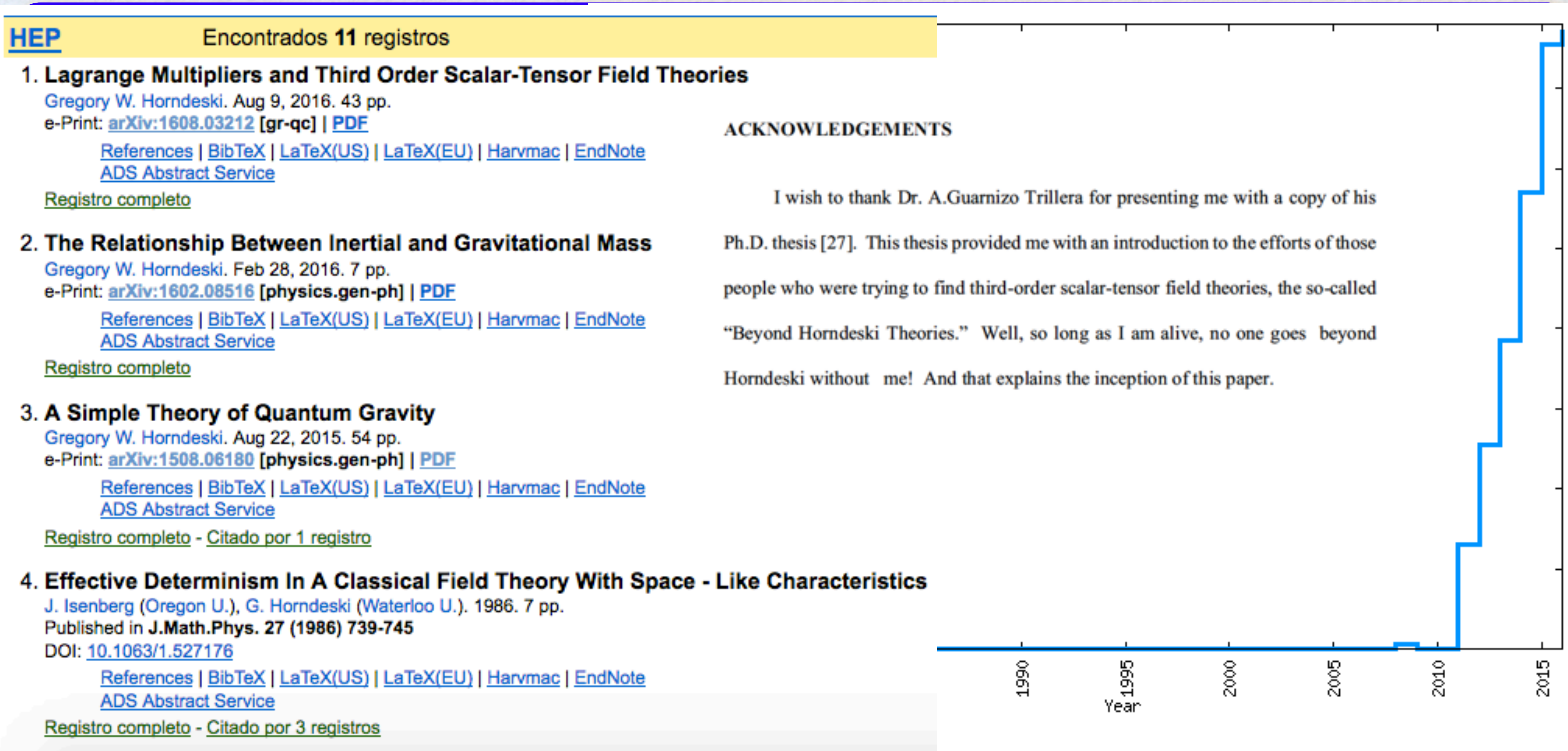

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ACKNOWLEDGEMENTS

I wish to thank Dr. A.Guarnizo Trillera for presenting me with a copy of his Ph.D. thesis [27]. This thesis provided me with an introduction to the efforts of those people who were trying to find third-order scalar-tensor field theories, the so-called "Beyond Horndeski Theories." Well, so long as I am alive, no one goes beyond Horndeski without me! And that explains the inception of this paper.

The fab four /
self-tuning

G-Inflation /
Galilean Genesis

Beyond Horndeski

What screening really means

$$\mathcal{L}_2 = K(\phi, X)$$

$$\mathcal{L}_3 = G_3(\phi, X)\Box\phi$$

$$\mathcal{L}_4 = G_4(\phi, X)R - G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]$$

$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi + \frac{1}{6}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right]$$

$$X \equiv -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi$$

⇩ Expanding around a scalar field background configuration

$$\mathcal{L} = -\frac{1}{4}h_{\mu\nu}\mathcal{E}^{\mu\nu\alpha\beta}(\phi)h_{\alpha\beta} + \frac{1}{2}(\partial\phi)^2 + \mathcal{L}_\phi^{NL} - \frac{1}{M_{\rm Pl}}h_{\mu\nu}T^{\mu\nu} - \frac{g}{M_{\rm Pl}}\phi T$$

WHAT SCREENING REALLY MEANS

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Non-linearities suppress the coupling to matter

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Non-linearities suppress the coupling to matter

⇩

Non-trivial effects on the gravitons persist

Propagating gravitons $D^{ij,kl}h_{kl} = -16\pi G_{\rm gw}\Pi^{ij}$ modified graviton propagator

Potential gravitons

$\nabla^2\Phi = 4\pi G_N\rho$ modified Poisson equation

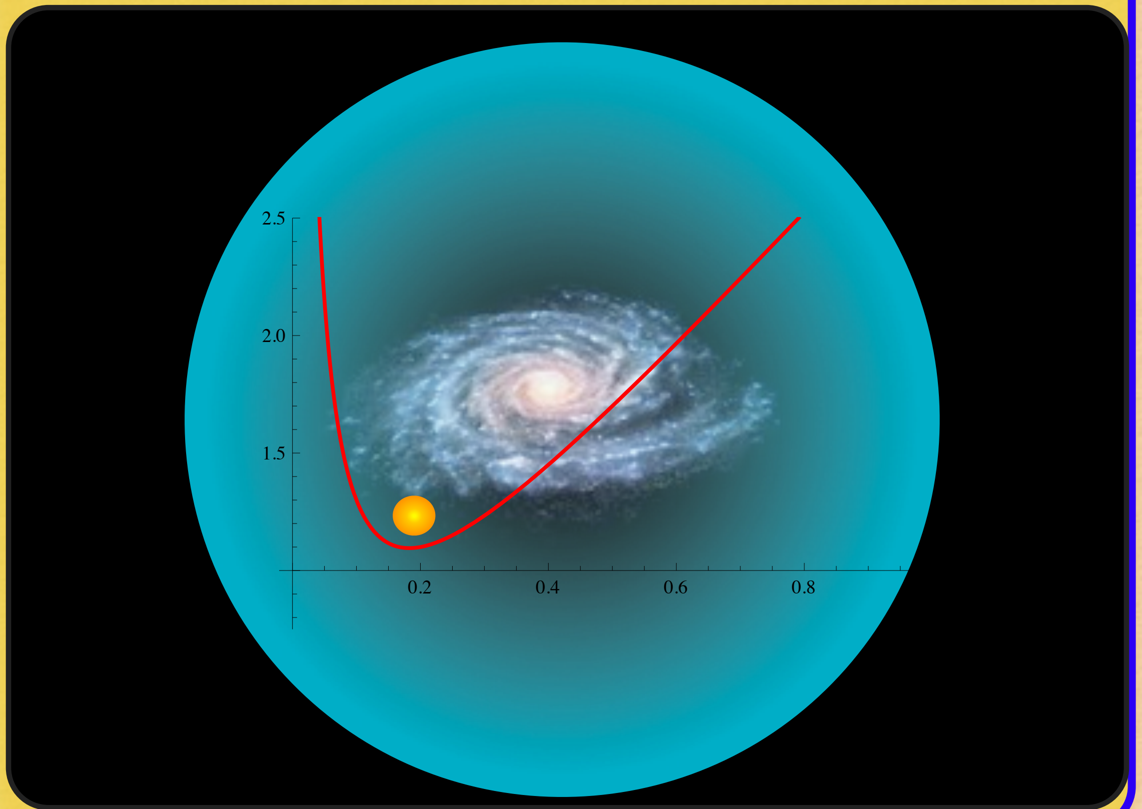
$\gamma_{\rm PPN} = \dfrac{\Psi}{\Phi}$ anomalous slip parameter

COSMOLOGY PIERCES THE SCREEN

No shift-symmetry

The field sits at the bottom of the effective potential, which is determined by the local matter distribution.

The scalar field effectively decouples from the cosmological evolution.



$\dot{\phi}_{\cos}$

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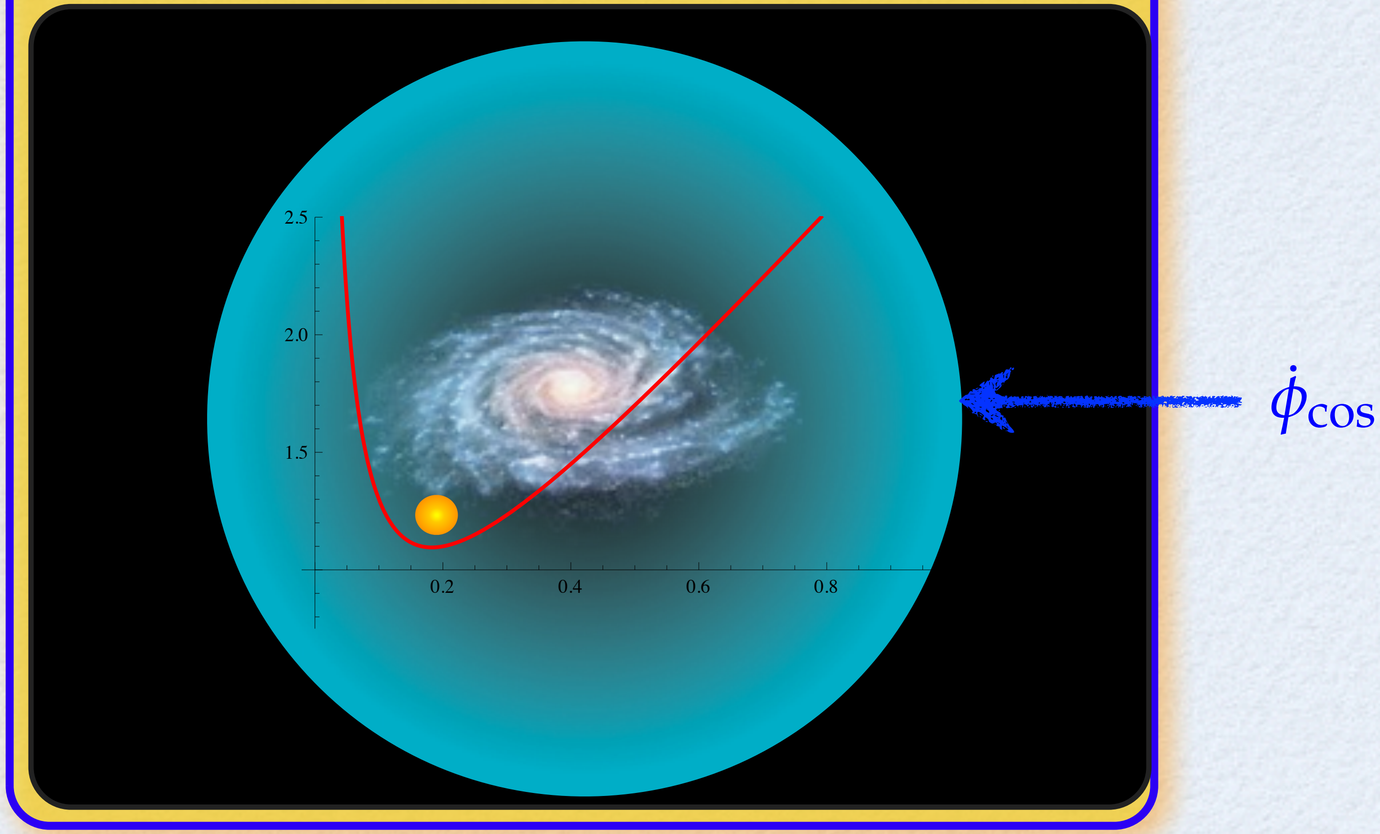

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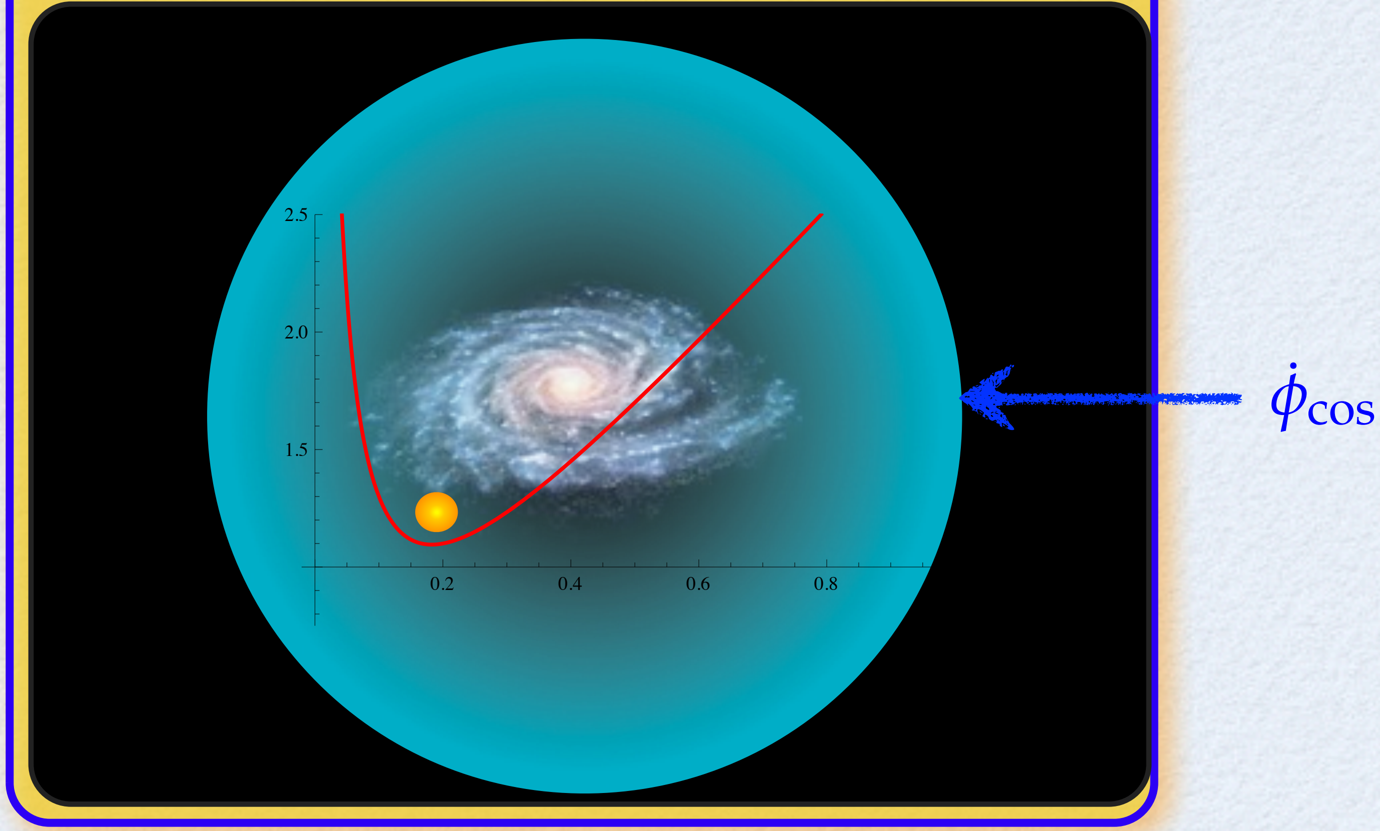
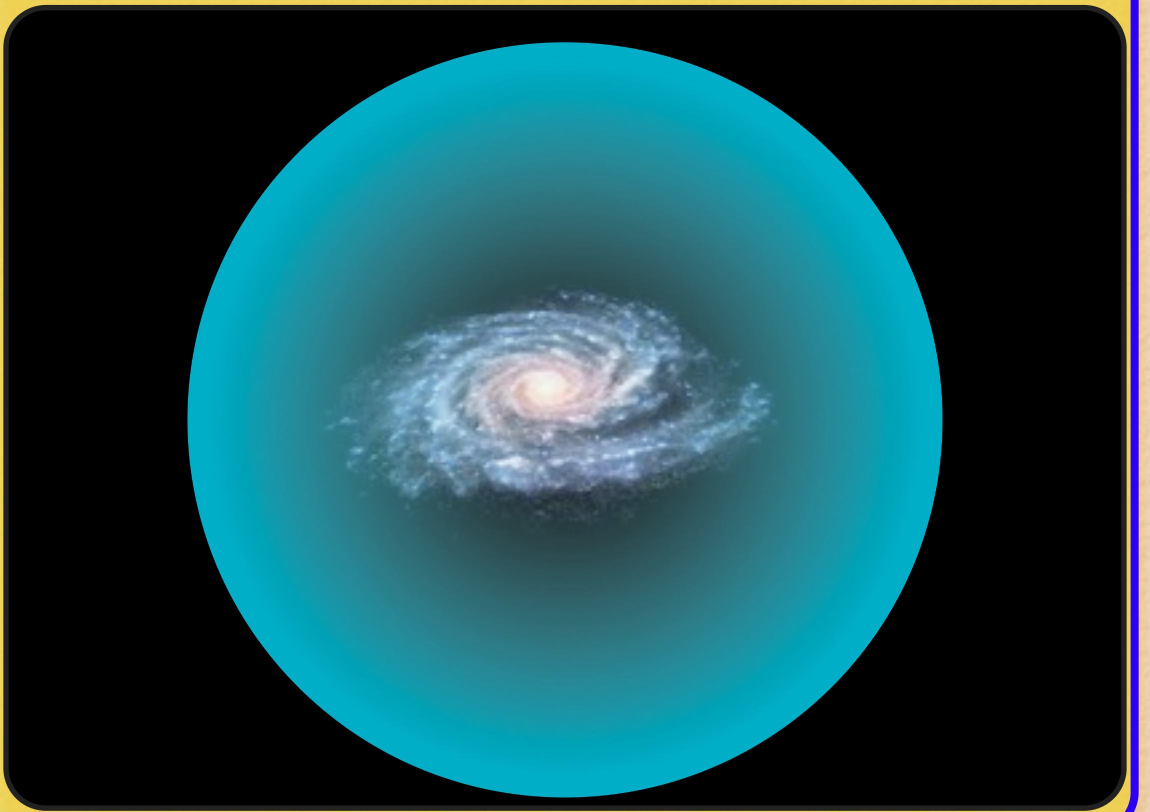


Shift-symmetry

Nothing prevents the field from rolling. The local matter distribution determines the spatial gradient, while the temporal gradient is determined by the cosmological evolution.



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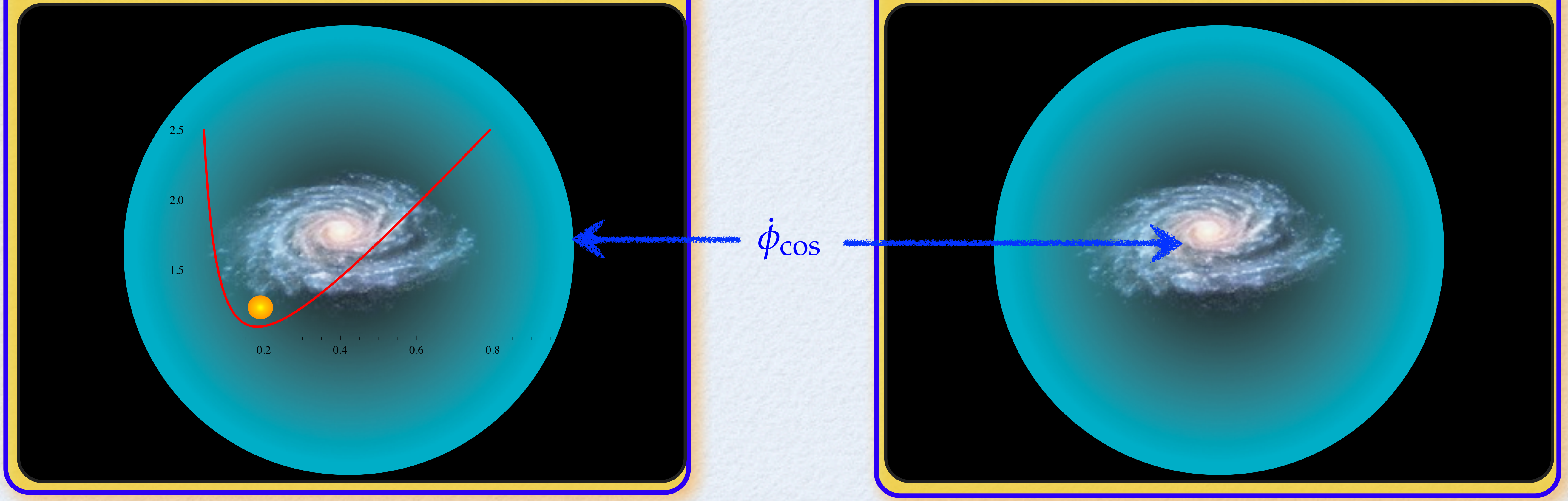

VARIATION OF G

Lunar Laser Ranging experiment

$$\left|\frac{\dot{G}}{G}\right| < 0.02H_0$$

E. Babichev, C. Deffayet, G. Esposito-Farese, PRL 107 (2011)

For a conformal coupling, the variation of Newton's constant is given by

$$\frac{\dot{G}}{G} \sim \frac{\dot{A}}{A} = \frac{A'}{A}\dot{\phi} \simeq \alpha\dot{\phi}_{\text{cos}}$$

The cosmological evolution gives

$\dot{\phi}_{\text{cos}} \sim \alpha H$ matter domination

$\dot{\phi}_{\text{cos}} \sim H$ scalar field domination

Order 1 couplings to matter are ruled out from LLR constraints

ANOMALOUS GW SPEED

$$\mathcal{L} = \frac{1}{64\pi G_{\mathrm{gw}}} \sum_{\alpha=+,\times} \left[\frac{1}{c_T^2}\dot{\gamma}_\alpha^2 - |\vec{\nabla}\gamma_\alpha|^2 \right] \xRightarrow{\tau \equiv c_T t} \frac{\mathrm{d}E}{\mathrm{d}t} = \frac{r^2}{32\pi c_T G_{\mathrm{gw}}} \int \mathrm{d}\Omega \, \langle \partial_t \gamma_{ij} \partial_t \gamma_{ij} \rangle$$

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The solution to the wave equation is the usual one:

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$$\Downarrow$$

The emitted power results in a decreasing of the orbital period of the system. This has 2 contributions: radiating gravitons (energy loss) and potential gravitons (Keplerian orbits)

$$\boxed{\begin{aligned} \dot{P}_b = & -\frac{G_{\rm gw}}{c_T G_N} \frac{192\pi G_N^{5/3}}{5} \left(\frac{P_b}{2\pi}\right)^{-\frac{5}{3}} (1-e^2)^{-\frac{7}{2}} \\ & \times \left(1 + \frac{73e^2}{24} + \frac{37e^4}{96}\right) m_p m_c (m_p + m_c)^{-1/3} \end{aligned}}$$

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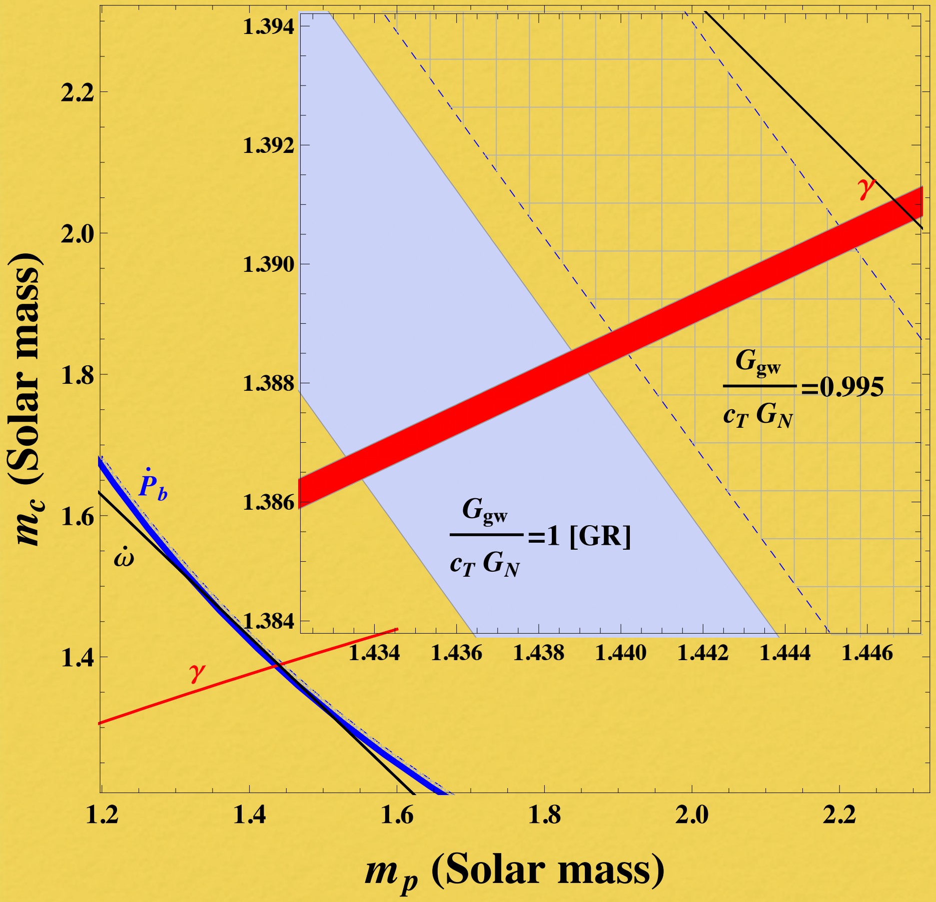
There is also monopolar emission due to the scalar mode. However, the Vainshtein screening is expected to strongly suppress the emitted power in the scalar mode.

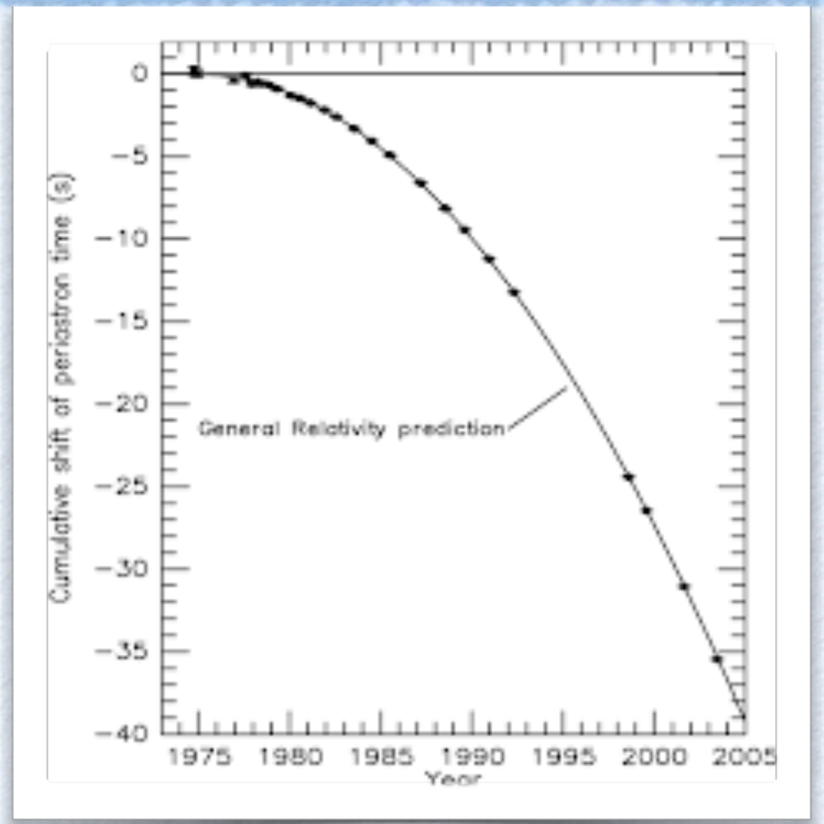
$$\mathcal{L} = \frac{1}{2} \mathcal{Z}(\phi_b) \partial_\mu \delta\phi \partial^\mu \delta\phi - \frac{1}{2} m^2(\phi_b) \delta\phi^2 + g(\phi_b) \delta\phi T$$

HULSE-TAYLOR BINARY PULSAR

$$\dot{P}_b = -\frac{G_{\rm gw}}{c_T G_{\rm N}}\frac{192\pi G_{\rm N}^{5/3}}{5}\left(\frac{P_b}{2\pi}\right)^{-\frac{5}{3}}(1-e^2)^{-\frac{7}{2}} \times\left(1+\frac{73e^2}{24}+\frac{37e^4}{96}\right) m_p m_c (m_p+m_c)^{-1/3}$$



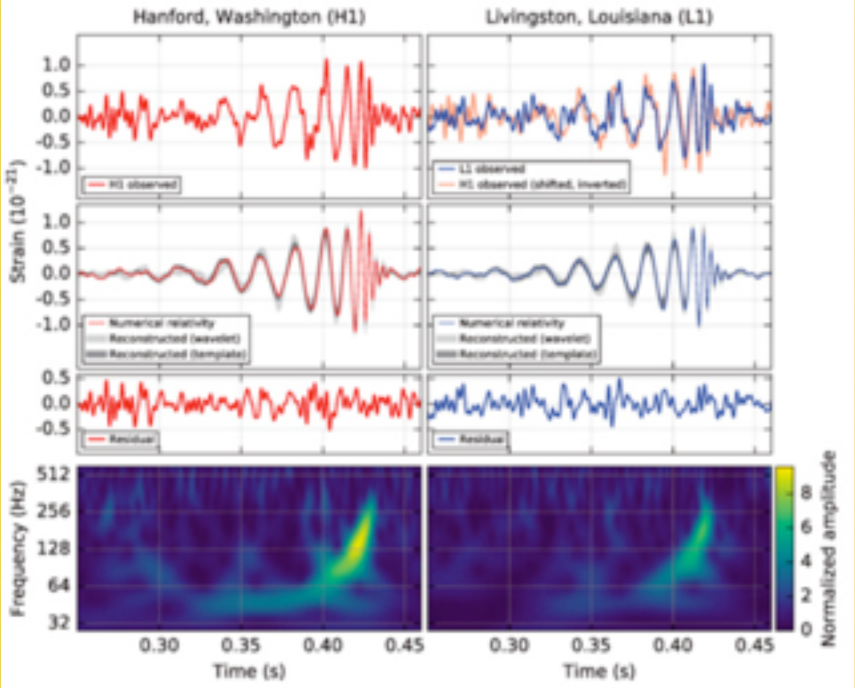
The binary pulsar data simultaneously determine the masses of the system.



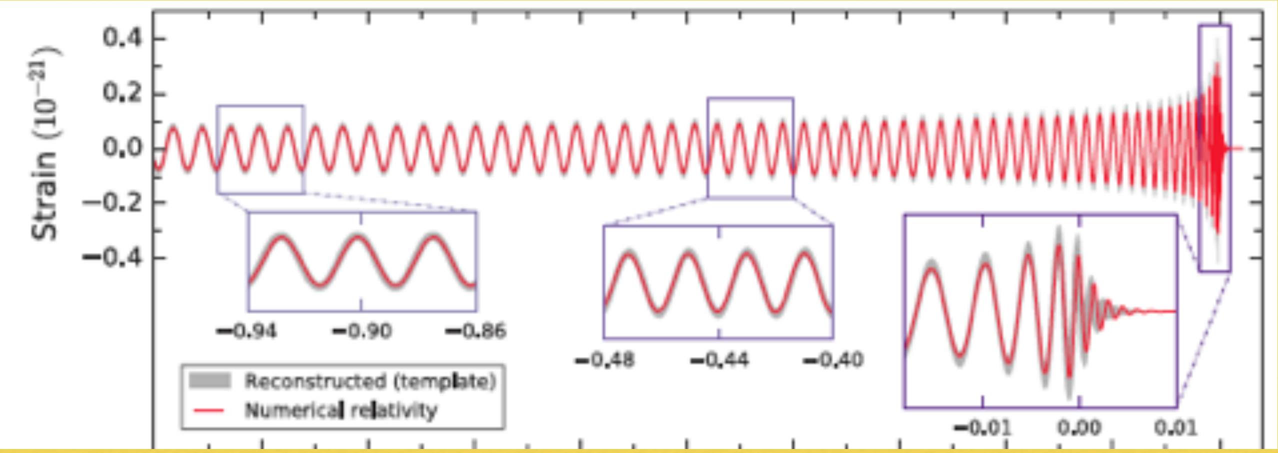
$$\boxed{0.995 \lesssim \frac{G_{\rm gw}}{c_T G_{\rm N}} \lesssim 1.00}$$

J.B.J., F. Piazza & H. Velten (PRL 2016)

CONSTRAINTS FROM GW'S ASTRONOMY



Future LIGO detections will impose stringent constraints on the GWs propagation speed.



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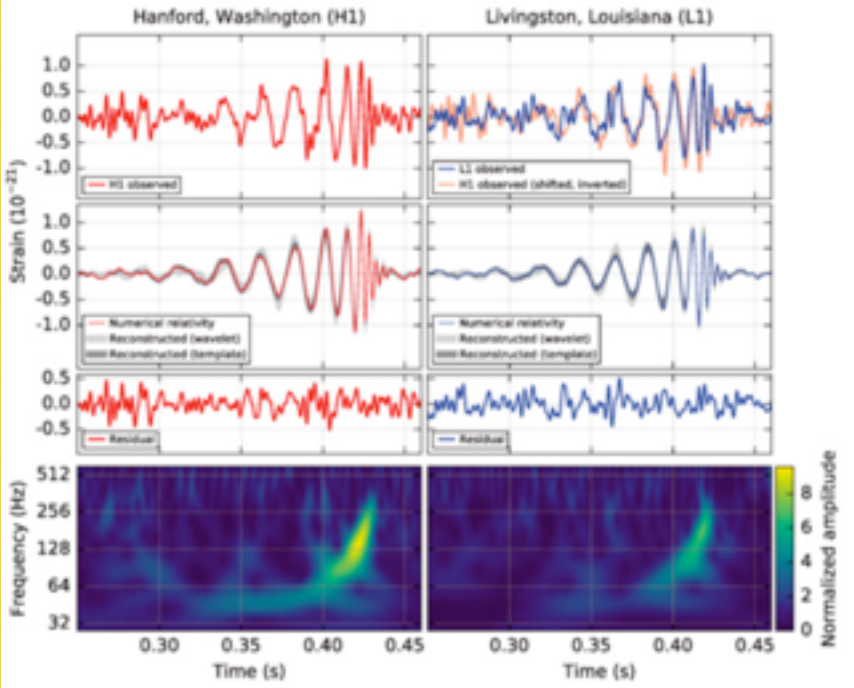

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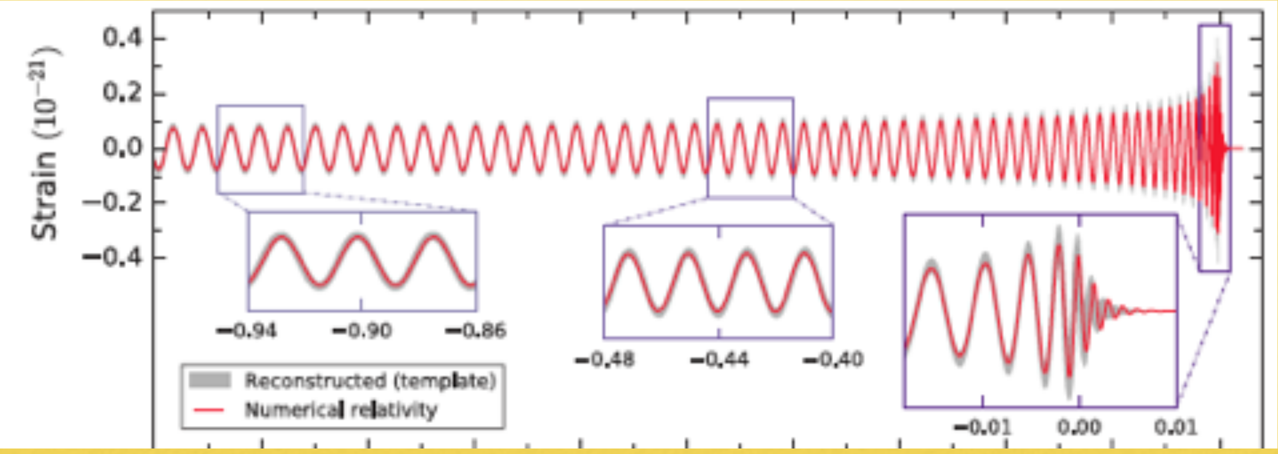

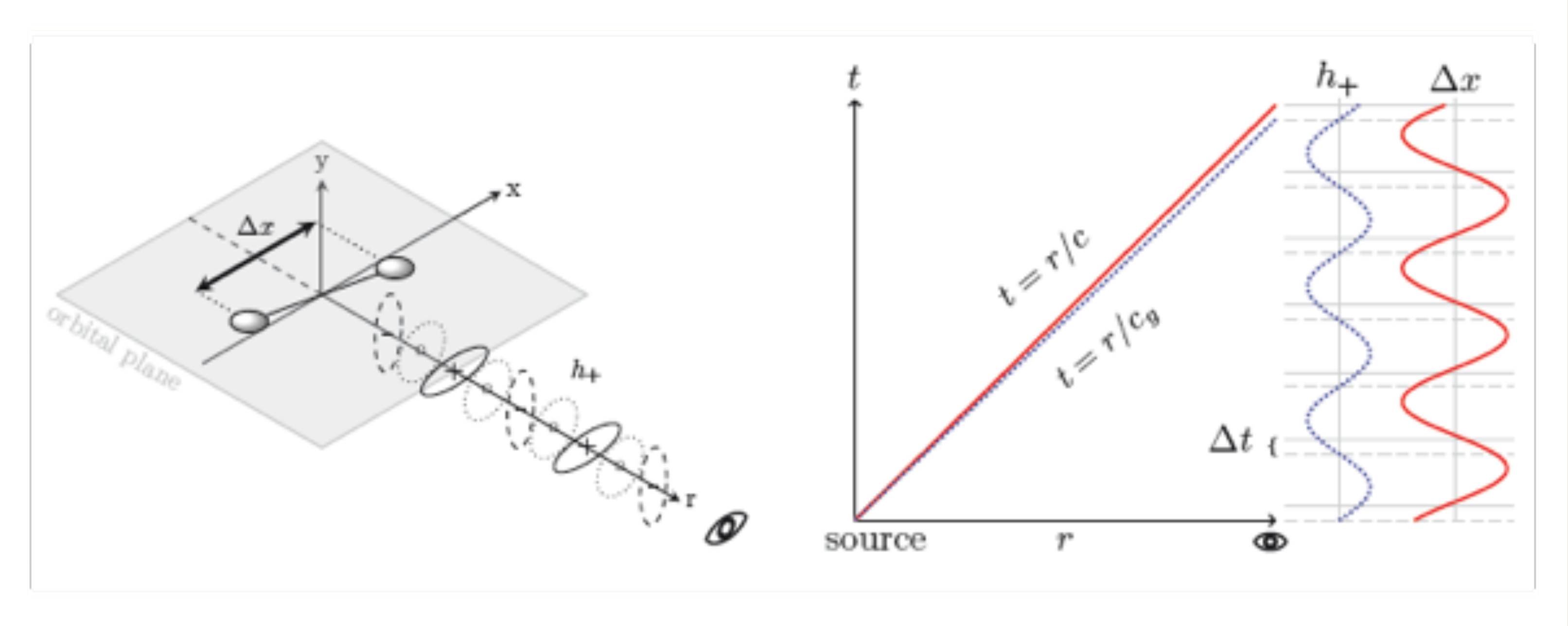

A different speed for GW's and photons can be seen as a phase lag due to the different retarded times that can be measured by simultaneously monitoring the GW's and EM signals.

D. Bettoni, J.M. Ezquiaga, K. Hinterbichler & M. Zumalacárregui, arXiv:1608.01982

CONCLUSIONS

- Scalar fields arise in many scenarios of HEP and MG. Horndeski theories (and beyond) comprise most of them.
- Screening mechanisms potentially allow for cosmological effects while being compatible with the absence of 5th forces.
- No-go result for the simplest chameleon/symmetron.
- For a class of theories, the cosmological evolution of the scalar can pierce the screen.
- LLR and binary pulsar tightly constrain order 1 couplings to matter and quartic and quintic Horndeski theories.