Constraining a scalar fifth force in the Solar system and the cosmos

Jean-Philippe UZAN

The situation

Standard Cosmological model relies on

Theory: Grav=RG + SM + **DM + Λ**

Solutions: Copernican principle

Data drive us to include in an effective way two extra-components:

- Dark matter appears as a *low acceleration* problem
- Dark energy Λ appears as a *low curvature/acceleration* problem

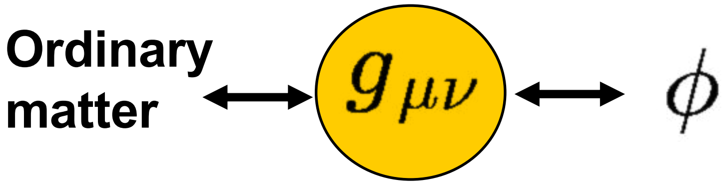
The model calls for the **introduction of new degrees of freedom**:

- geometrical or physical

They are many tensions appearing (S_8, H_0, ...)

Precision vs exactness

Universality classes of extensions *(slide from 2004)*

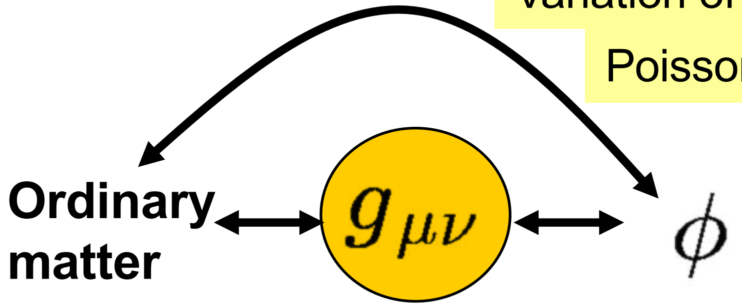


Ex : quintessence, ...

$S_{\rm de}[{\rm de}; g_{\mu\nu}]$

Variation of constants

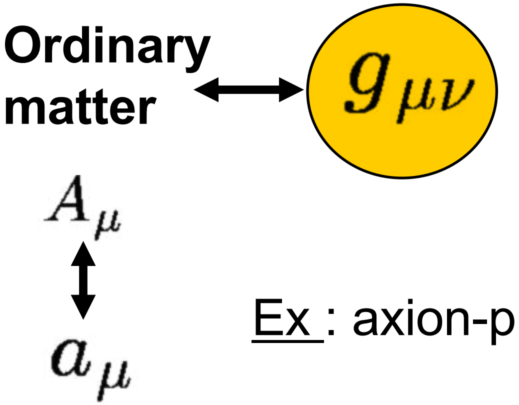
Poisson equation



Ex : scalar-tensor, f(R),TeVeS .... $S_\varphi[\varphi; g_{\mu\nu}]$

$S_m[{\rm mat}; g_{\mu\nu}] \to S_m[{\rm mat}_i; A_i^2(\varphi) g_{\mu\nu}].$

$S_{\rm em}[A_\mu; g_{\mu\nu}] \to S_{\rm em}[A_\mu, a_\mu; g_{\mu\nu}].$

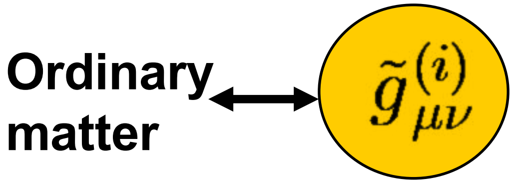


Ex : axion-photon mixing

Distance duality

Variation of constants

Poisson equation



Ex : brane induced gravity
multigravity,...

Always need NEW fields

[JPU, JDEM meeting, 03/2004,
JPU, Aghanim, Mellier, 2005]
[JPU, GRG 2007]

Gravitation

Definition: Long range interaction that is not screened
Description: General relativity

- Einstein equivalence principle (weak and strong)
- dof = massless spin 2

Einstein theory relies heavily on the **universality of free fall**, and its generalisation under the form of **Einstein Equivalence principle**:

- Universality of free fall
- Local Lorentz invariance
- Local position invariance

$$S_{\mathrm{matter}}(\psi, g_{\mu\nu})$$

Not a basic principle of physics but an empirical fact.
Allows to define a local freely falling laboratory.
It implies that we need to define only 1 kilogram!

For today

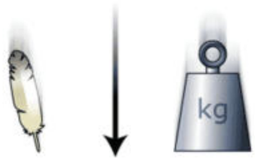
1. **Local scales**
   1. *Testing the WEP (generalities)*
   2. *MICROSCOPE experiments and its implications*
   3. *The limitation of the environment*
   4. *What about the chameleon in space?*
2. **Cosmological scales**
   1. *Has H_0 any link with a fifth force?*
   2. *An old thought…*

Weak equivalence principle in the Solar system

With Joel Bergé (ONERA), Philippe Brax (IPhT)
Martin Pernot-Borràs, Hugo Levy (IAP+ONERA)

Universality of free fall (*à la Newton*)

In Newton physics, the universality of free fall is encoded in the equality between *inertial* and *gravitational* mass



Second law: $F = m_I a$

Definition of weight: $F = m_G g$

$$\left.\begin{array}{l} F = m_I a \\ F = m_G g \end{array}\right\} \quad a = (m_G/m_I)g.$$

The deviation from the UFF is characterized by

$$\eta \equiv 2\frac{|a_1 - a_2|}{|a_1 + a_2|} \qquad \text{so that} \qquad \eta = 2\frac{|m_G^1/m_I^1 - m_G^2/m_I^2|}{m_G^1/m_I^1 + m_G^2/m_I^2}$$

Consider a pendulum of length L in a gravitational field g,

$$\ddot{\theta} + \omega^2\theta = 0 \quad \text{où} \quad \omega \equiv \omega_0\sqrt{\frac{m_G}{m_I}} \qquad \eta \approx 2\frac{|\omega_B - \omega_A|}{\omega_0}$$

$$\frac{|m_G - m_I|}{m_G + m_I} < 10^{-3}$$

Newton (1686)

Beyond universal coupling

$$S_{\mathrm{matter}}[\psi, A_i^2(\phi)]$$

- Violation of the universality of free fall (UFF)

- Variation of the fundamental constants (LPI)

See e.g. JPU 1009.5514 (update on arXiv soon)

Assume for simplicity that A_i=A (universal scalar-tensor theory), the action for a point particle

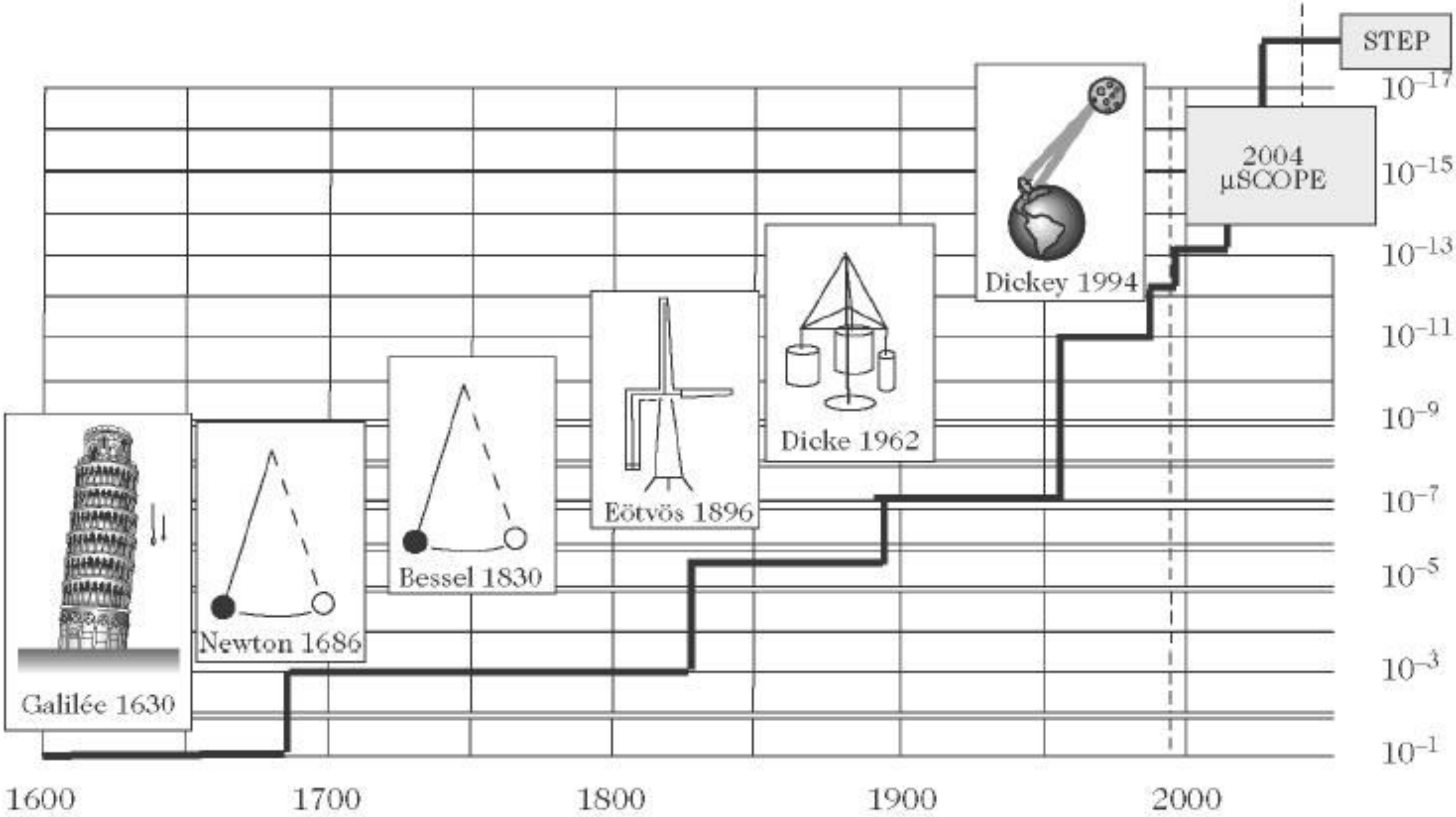
$$S_{\mathrm{p.p.}} = -\int m\sqrt{A^2(\phi) g_{\mu\nu} u^\mu u^\nu}\,\mathrm{d}\tau$$

leads to the equation of motion

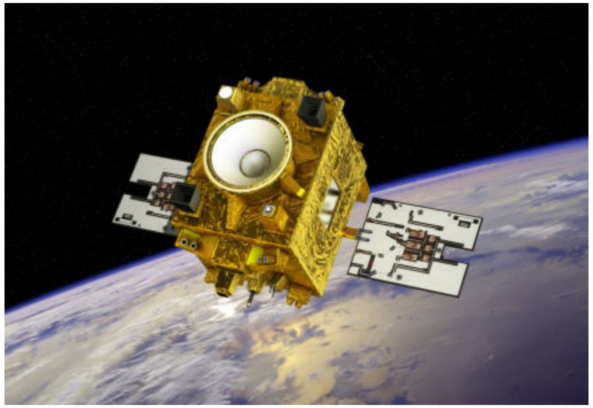
$$u^\mu \nabla_\mu u^\nu = -\alpha(\phi)\left(g^{\mu\nu} + u^\mu u^\nu\right)\partial_\mu \phi \equiv f^\mu$$

- geodesic equation if A=*1* (General Relativity)
- Fifth force is spatial ($f_\mu u^\mu = 0$) and composition dependent in general.

Testing the universality of free fall



MICROSOPE experiment (CNES/ONERA)



First precision WEP test in a laboratory in space

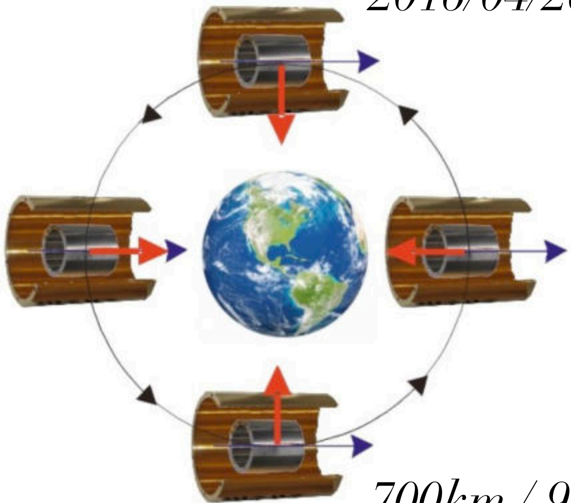
2 differential accelerometers :

• SUREF - reference, test masses of the same material (Pt/Rh)

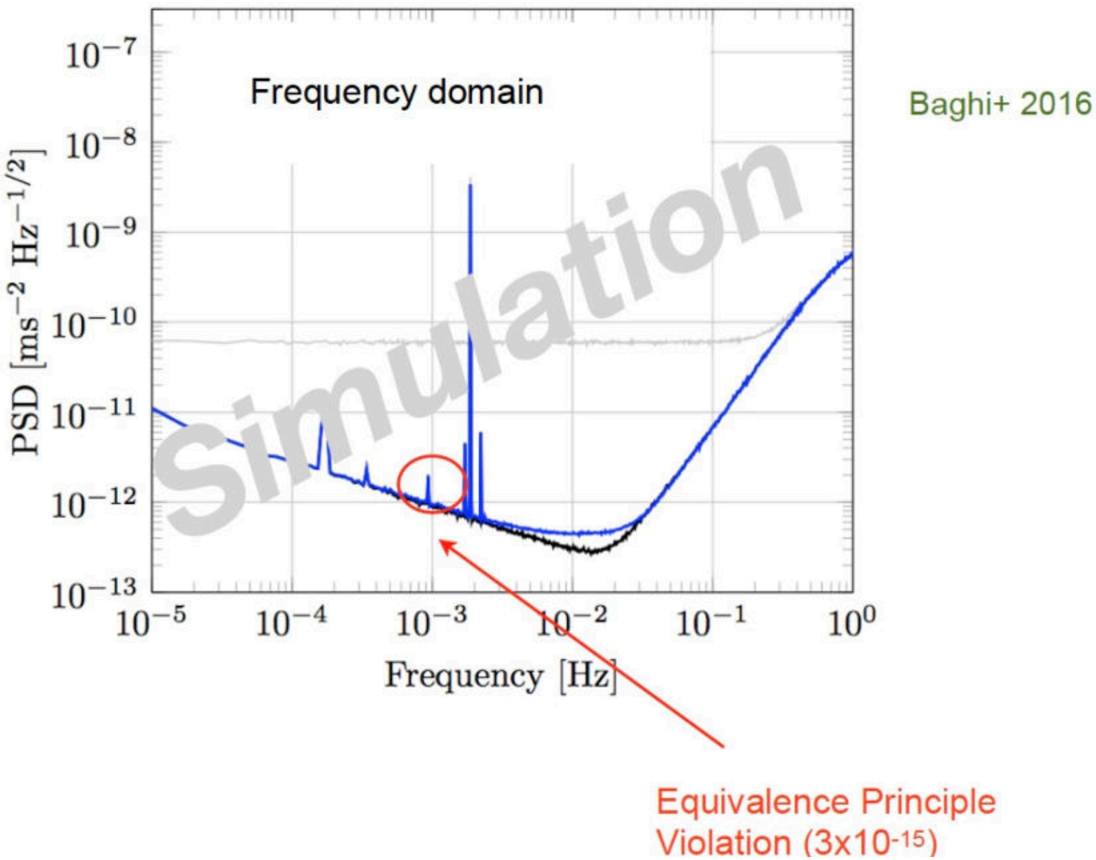
• SUEP - used for WEP test, test masses of different materials (Pt/Rh, Ti)

2016/04/26

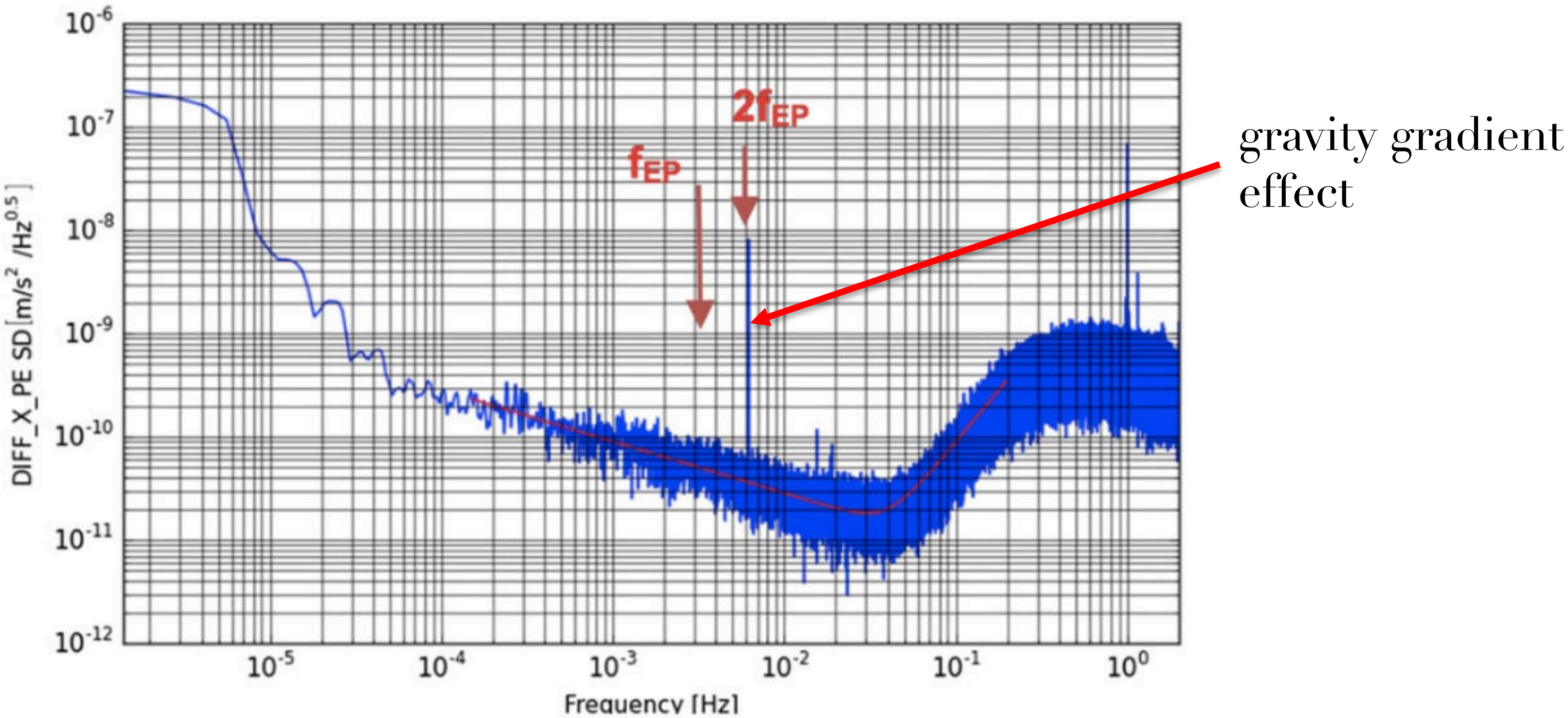
2016/04/26



700km / 90mn



MICROSCOPE results



$$\eta(\mathrm{Ti},\mathrm{Pt}) = [-1.0 \pm 9.0(\mathrm{stat.}) \pm 9.0(\mathrm{syst.})] \times 10^{-15}$$

Touboul et al, PRL 119 231101 (2017)

$$\eta(\mathrm{Ti},\mathrm{Pt}) = [-1.5 \pm 2.3(\mathrm{stat.}) \pm 1.5(\mathrm{syst.})] \times 10^{-15}$$

Touboul et al, PRL 129 121102 (2022)

« Model independent » constraints

Consider a general scalar-tensor interaction in the Newtonian regime,

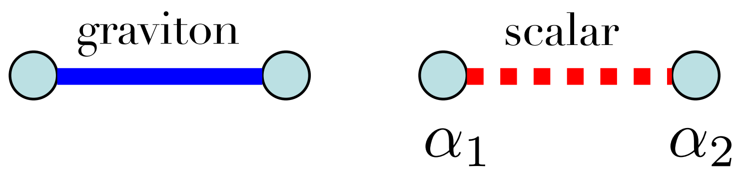
$$\Delta\Phi_N = 4\pi G\rho \quad \xrightarrow{\text{point particle source}} \quad \Phi_N = \frac{GM_1}{r}$$

$$(\Delta - m_\phi^2)\phi = 4\pi G\alpha\rho \qquad\qquad \phi = \frac{GM_1}{r}\alpha_1 \mathrm{e}^{-m_\phi r}$$

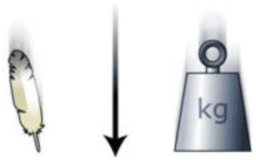
$$\mathbf{F}_{12} = -m_2(\nabla\Phi_N + \alpha_2\nabla\phi) = -\nabla V_{12}$$

$$V_{12} = -\frac{Gm_1m_2}{r}\left[1 + \left(\frac{q}{\mu}\right)_1\left(\frac{q}{\mu}\right)_2 \mathrm{e}^{-r/\lambda}\right]$$

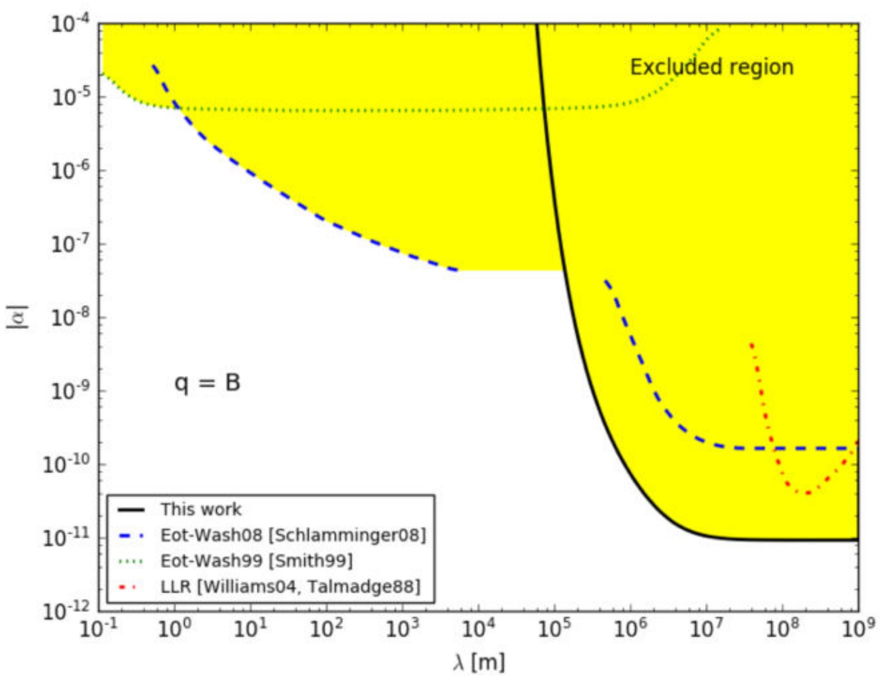
$$\lambda = \frac{\hbar}{m_\phi c}$$

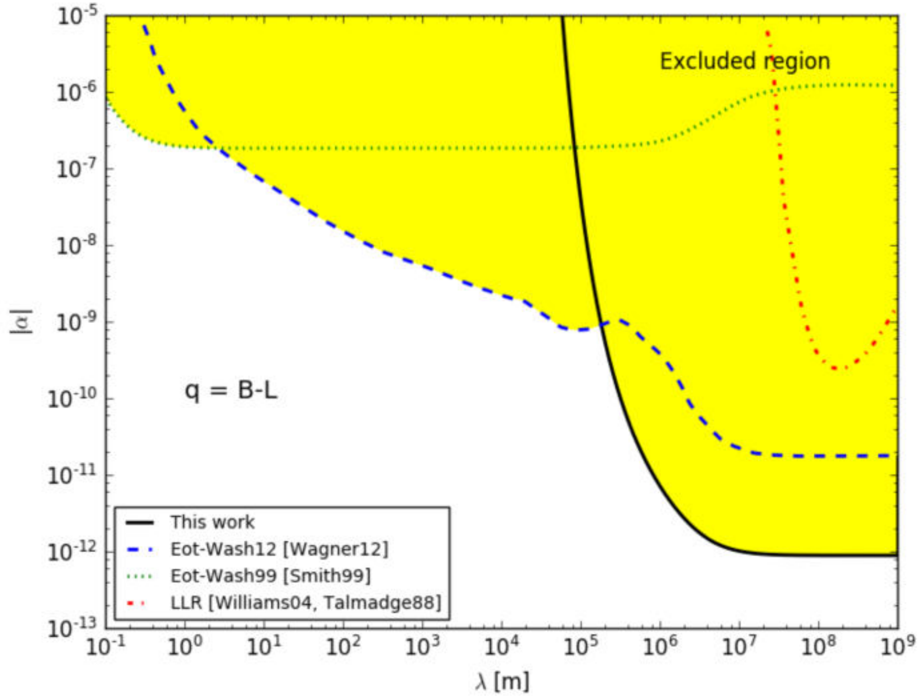


Generic deviations from Newton laws



$$\eta = \alpha \left[\left(\frac{q}{\mu}\right)_{\rm Pt} - \left(\frac{q}{\mu}\right)_{\rm Ti} \right] \left(\frac{q}{\mu}\right)_{\rm Earth} \left(1 + \frac{r}{\lambda}\right) {\rm e}^{-r/\lambda} F\left(\frac{R_{\rm Earth}}{\lambda}\right)$$





[Bergé, Brax, Métris, Pernot-Borràs, Touboul, JPU, 1712.00483]

Light and massive dilaton models

We consider the Damour-Donoghue (2010) in which ϕ couples to F^2, quarks, electrons and gluons

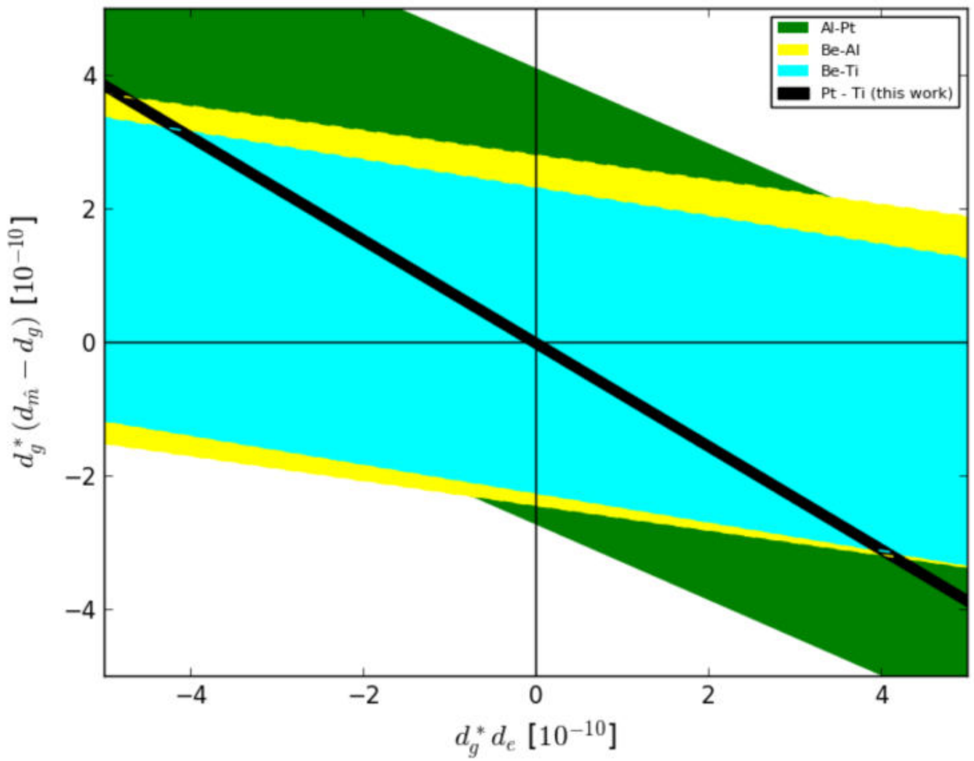
$$\mathcal{L}_{\text{int}} = \phi \left[\frac{d_e}{4e^2} F^2 - \frac{d_g \beta_3}{2 g_3} F_A^2 - \sum_{i=e,u,d} (d_{m_i} + \gamma_i d_g) m_i \bar{\psi}_i \psi_i \right]$$

from which the charges are

$$\alpha_i \approx d_g^* + \left[(d_{\tilde{m}} - d_g) Q'_{\tilde{m}} + d_e Q'_e \right]_i$$

with

$$\begin{cases} Q'_e = -1.4 \times 10^{-4} + 7.7 \times 10^{-4} \dfrac{Z(Z-1)}{A^{4/3}} \\ Q'_{\tilde{m}} = 0.093 - \dfrac{0.036}{A^{1/3}} - 1.4 \times 10^{-4} \dfrac{Z(Z-1)}{A^{4/3}} \end{cases}$$



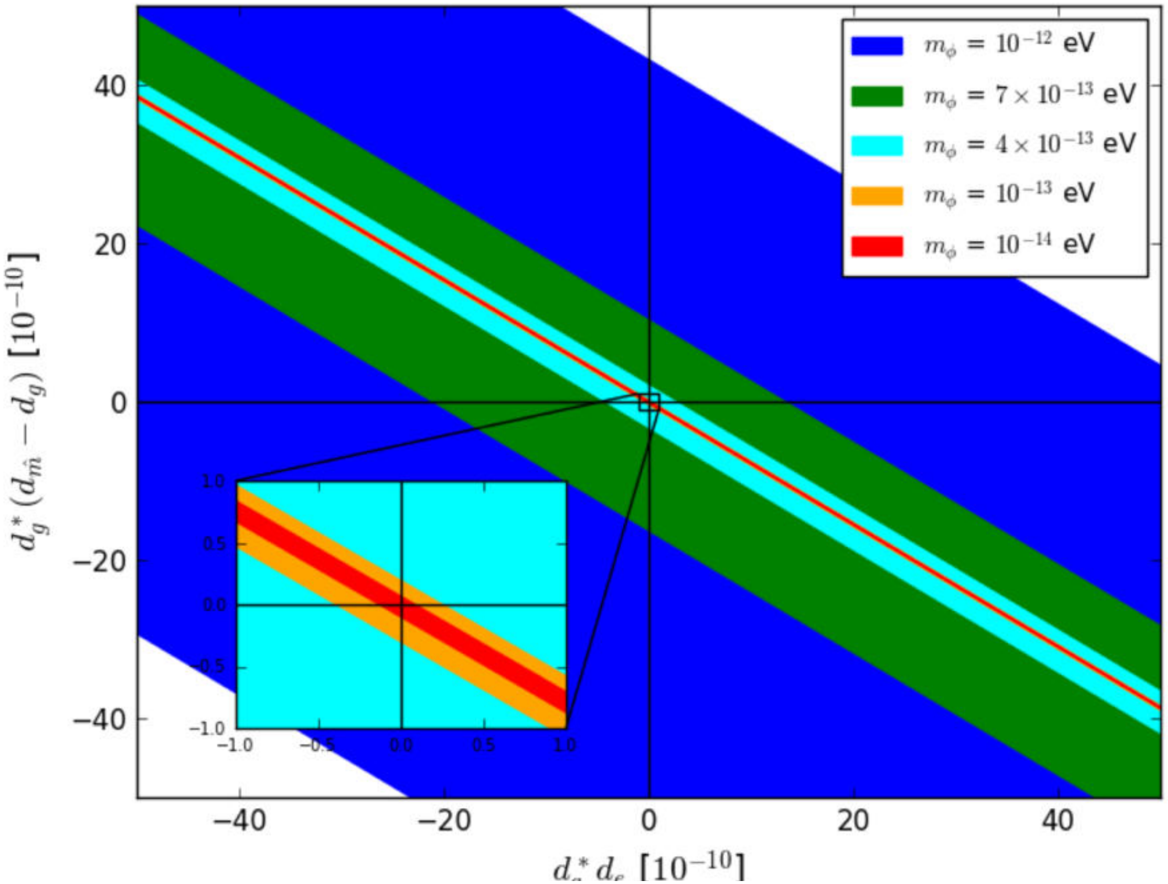
[Bergé, Brax, Métris, Pernot-Borràs, Touboul, JPU, 1712.00483]

Light and massive dilaton models

Same analysis with a massive dilaton

MICROSCOPE is mainly sensitive to masses in the range *10^{-14}–10^{-12}* eV:

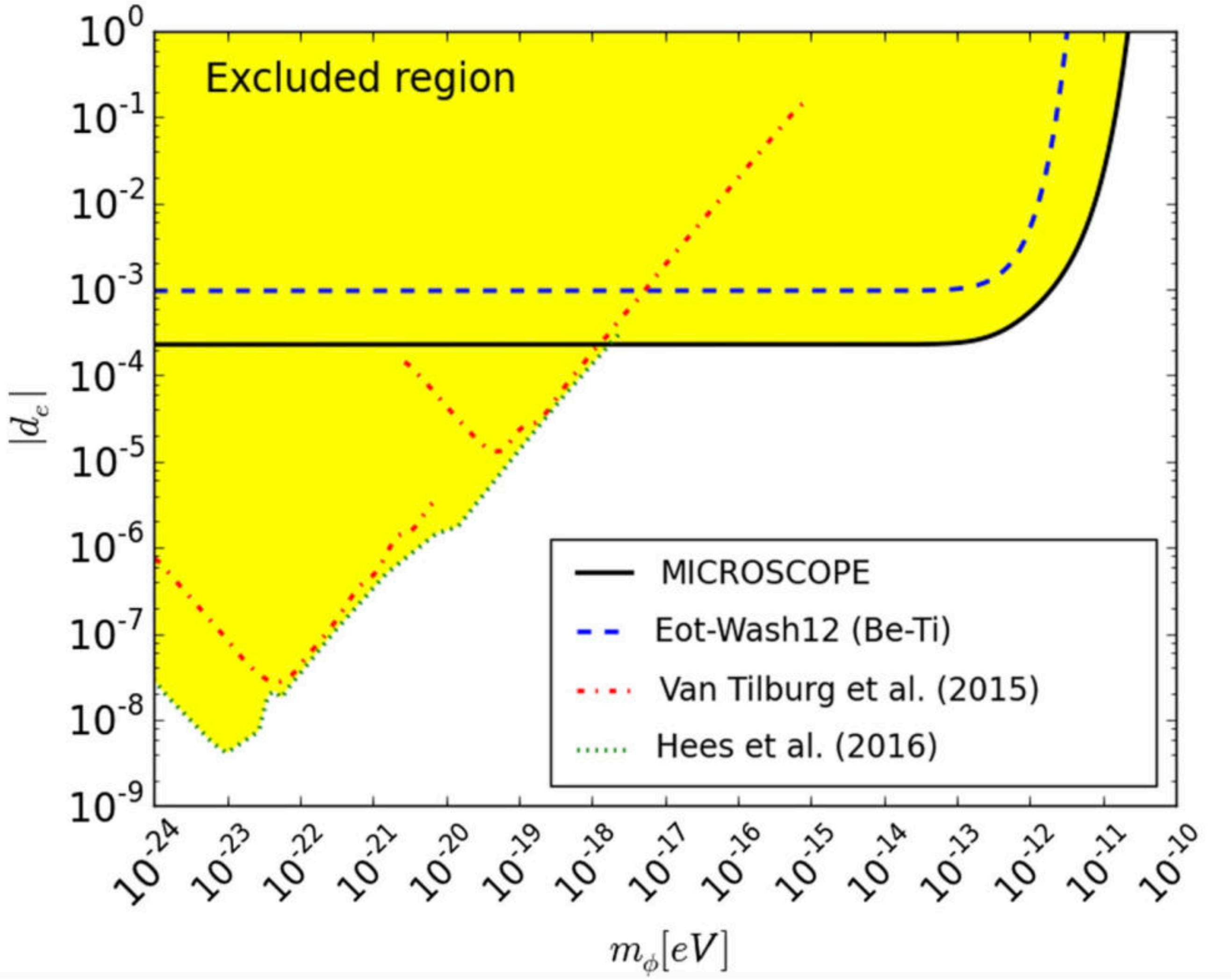
- lower masses similar to massless
- higher correspond to ranges MICROSCOPE cannot probe



[Bergé, Brax, Métris, Pernot-Borràs, Touboul, JPU, 1712.00483]

Varying fine structure constant model

Assuming the dilaton field couples only to the electromagnetic field



[Bergé, Brax, Métris, Pernot-Borràs, Touboul, JPU, 1712.00483]

Why local constraints do matter *even* in cosmology

Consider a theory with varying a

$$S = \int \{ \frac{1}{16\pi G} R - 2(\partial_\mu \phi)^2 - V(\phi) - \frac{1}{4} B(\phi) F_{\mu\nu}^2 \} \sqrt{-g}\, d^4 x$$

The mass of any atom becomes spacetime dependent

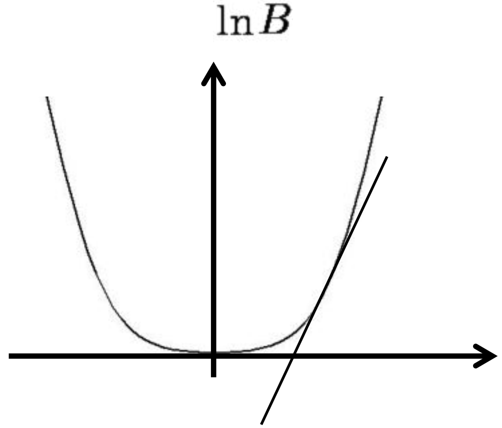
$$m_A(\phi) \supset 98.25 \alpha \frac{Z(Z-1)}{A^{1/3}} \mathrm{MeV} \longrightarrow f_i = \partial_\phi \ln m_i \sim 10^{-2} \frac{Z(Z-1)}{A^{4/3}} \alpha'(\phi)$$

Then the Eötvös parameter

$$\eta_{12} = 2 \frac{|\vec{a}_1 - \vec{a}_2|}{|\vec{a}_1 + \vec{a}_2|} = \frac{f_{\rm ext} |f_1 - f_2|}{1 + f_{\rm ext}(f_1 + f_2)/2}$$

It is of the order of

$$\eta_{12} \sim 10^{-9} \underbrace{\mathrm{X}_{1,2,\mathrm{ext}}(A, Z)}_{\mathcal{O}(0.1-10)} \times (\partial_\phi \ln B)_0^2$$



Requires to be close to the minimum

[JPU 1009.5514]

How well can we test GR in the local environment?

With Joel Bergé (ONERA), Philippe Brax (IPhT)
Martin Pernot-Borràs, Hugo Levy (IAP+ONERA)

** Shall actually be called « second » force*

Geodesy

Geodesy experiments (orbitography) allows one to reconstruct the shape of the Earth if *one assumes GR*.

Geodesic experiments have been used to constrain deviation from GR *assuming a simple description of the Earth* (homogeneous, spherical or J_2).

What is the impact of these assumptions?

Gravity and earth shape

Assume a gravity theory

$$U_{pp} = -\frac{GM}{r}\left(1 + \alpha \mathrm{e}^{-r/\lambda}\right)$$

$$U(\mathbf{r}) = \int U_{pp}(\mathbf{r} - \mathbf{s})\mathrm{d}^3\mathbf{s}$$

Assume a shape of the Earth

$$\rho(\mathbf{s}) = \sum \rho_{\ell m} Y_{\ell m}(\hat{\mathbf{s}})$$

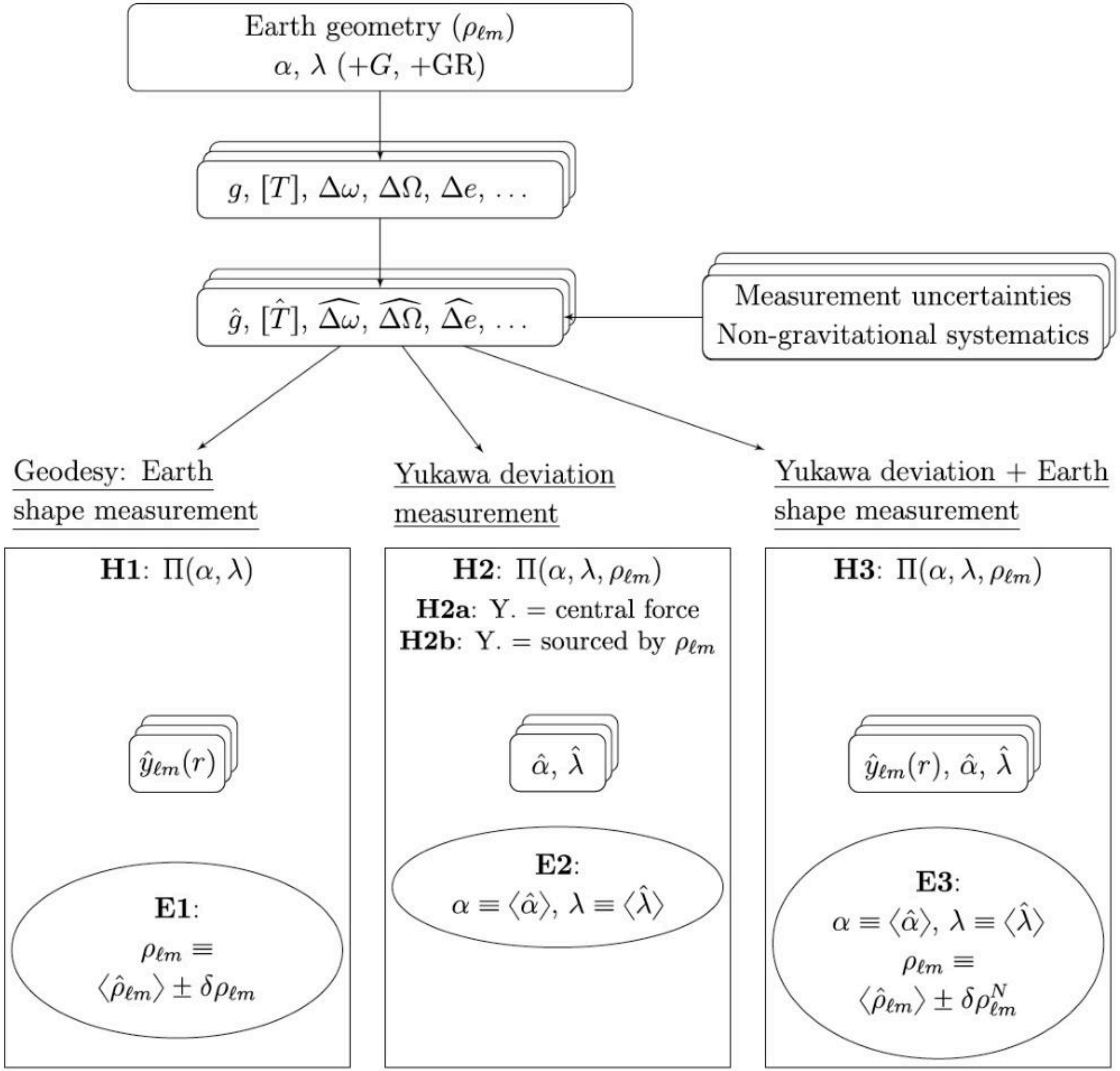
Play with spherical harmonics

$$U = -\frac{GM}{r}\sum_{\ell m}\left(\frac{R}{r}\right)^{\ell} y_{\ell m}(r) Y_{\ell m}$$

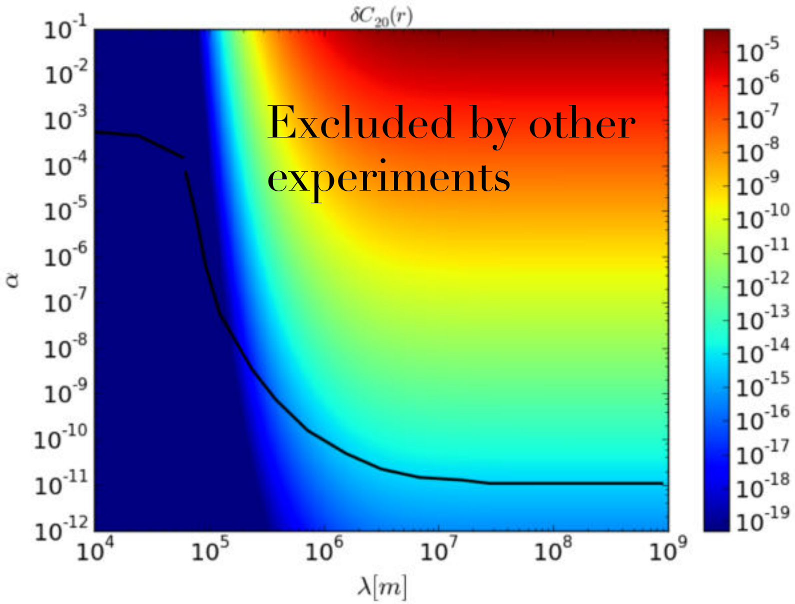
$$y_{\ell m} = \frac{1}{(2\ell+1)M}\int s^2 \left(\frac{s}{R}\right)^{\ell} \rho_{\ell m}(s)\left[1 + \alpha \mathcal{A}\left(\frac{s}{\lambda}\right)\mathcal{B}_{\ell}\left(\frac{r}{\lambda}\right)\right]\mathrm{d}s$$

$$= y^{N}_{\ell m} + \alpha y^{Y}_{\ell m}(r/\lambda)$$

Measured ← Inferred assuming a theory



[Bergé, Brax, Pernot-Borràs, JPU, 1080.00340]

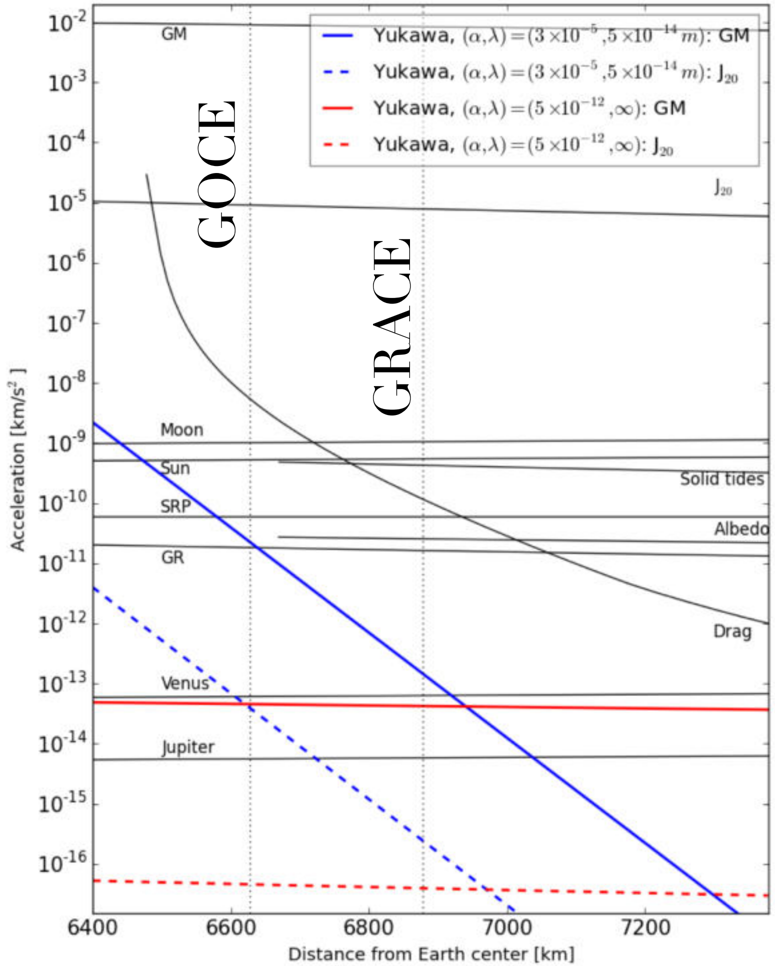


Biais on y_{20}

$$(\alpha, \lambda) = (2 \times 10^{-8}, 1.2 \times 10^5 \mathrm{m})$$

	Yukawa bias (rms increase—E($\hat{\alpha}$) = 0)	Tabulated value	Tabulated uncertainty
GOCE			
y_{20}	7.4×10^{-14}	$-4.841\,653\,042\,45 \times 10^{-4}$	5.423×10^{-12}
y_{40}	1.3×10^{-15}	$5.399\,505\,09 \times 10^{-7}$	2.758×10^{-12}
y_{60}	2.5×10^{-15}	$-1.499\,796\,81 \times 10^{-7}$	3.556×10^{-12}
y_{80}	4.1×10^{-15}	$4.944\,8989 \times 10^{-8}$	3.972×10^{-12}
GRACE			
y_{20}	1.0×10^{-14}	$-4.841\,692\,836\,73 \times 10^{-4}$	1.577×10^{-12}
y_{40}	1.8×10^{-16}	$5.399\,933\,70 \times 10^{-7}$	3.35×10^{-13}
y_{60}	3.8×10^{-16}	$-1.499\,746\,14 \times 10^{-7}$	1.88×10^{-13}
y_{80}	6.7×10^{-16}	$4.947\,7947 \times 10^{-8}$	1.35×10^{-13}

Current space geodesy missions are immune to a Yukawa interaction (as currently constrained by other experiments) [see Prof. Murata's talk]



$$(\alpha, \lambda) = (2 \times 10^{-8}, 1.2 \times 10^5 \mathrm{m})$$

40% bias on the estimation of a due to our knowledge of the Earth.

[Bergé, Brax, Pernot-Borràs, JPU, 1080.00340]

A word on chameleon and MICROSCOPE

With Joel Bergé (ONERA), Philippe Brax (IPhT)
Martin Pernot-Borràs (IAP+ONERA)

1907.10546, 2102.00022,
2102.00023, 2004.08403

One cannot not check this!

VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

Chameleon Fields: Awaiting Surprises for Tests of Gravity in Space

Justin Khoury and Amanda Weltman
ISCAP, Columbia University, New York, New York 10027, USA
(Received 10 September 2003; published 22 October 2004)

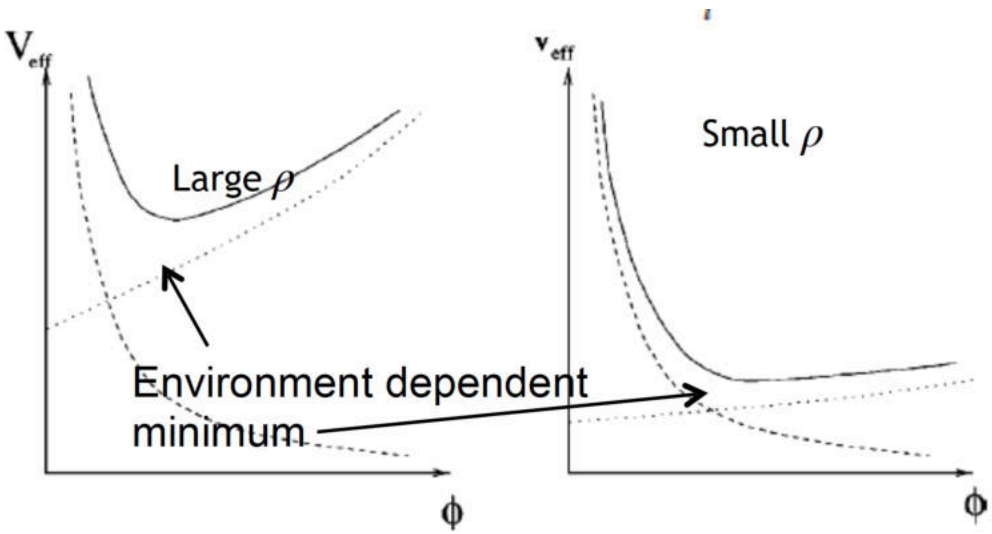
We present a novel scenario where a scalar field acquires a mass which depends on the local matter density: the field is massive on Earth, where the density is high, but is essentially free in the solar system, where the density is low. All existing tests of gravity are satisfied. We predict that near-future satellite experiments could measure an effective Newton's constant in space different from that on Earth, as well as violations of the equivalence principle stronger than currently allowed by laboratory experiments.

DOI: 10.1103/PhysRevLett.93.171104 PACS numbers: 04.50.+h, 04.80.Cc, 98.80.–k

Consider a scalar-tensor theory with

$$A(\varphi) = \exp\frac{1}{2}\phi^2$$

$$V(\varphi) = \Lambda^4\left(1 + \frac{\Lambda^n}{\phi^n}\right)$$



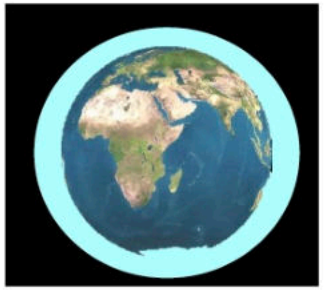
$$\Box\phi = V'_{\rm eff} + \frac{\beta}{M_p}\rho\phi$$

Larger densities correspond to
- smaller ϕ_{min}
- larger mass

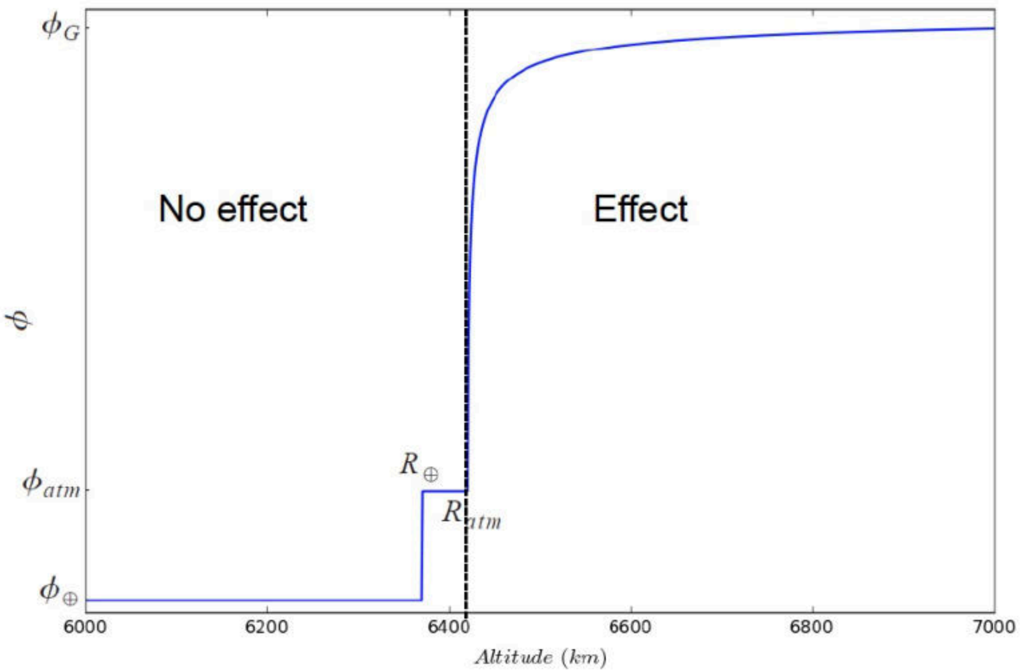
The field can be massive enough on Earth to evade constraints but light enough in space to affect the gravitational dynamics.

Why were there hope?

[Khoury & Weltman (2024)]



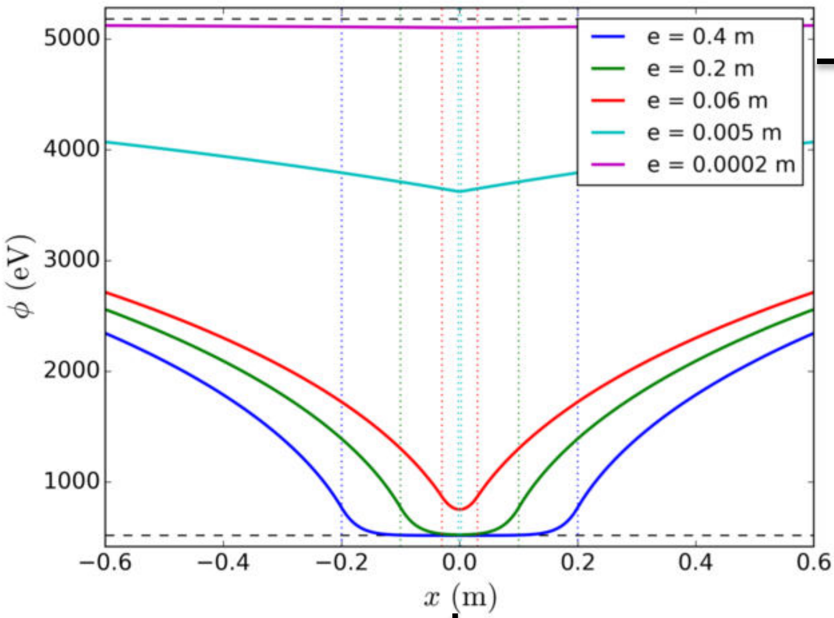
$$\phi(r) \approx \begin{cases} \phi_{\oplus} & \text{for} \quad 0 < r \lesssim R_{\oplus}, \\ \phi_{atm} & \text{for} \quad R_{\oplus} \lesssim r \lesssim R_{atm}, \\ -\left(\frac{\beta}{4\pi M_{Pl}}\right)\left(\frac{3\Delta R_{\oplus}}{R_{\oplus}}\right)\frac{M_{\oplus} e^{-m_G(r-R_{atm})}}{r} + \phi_G & \text{for} \quad r \gtrsim R_{atm}, \end{cases}$$



Chameleon models are screened on Earth but may not be in space.

So MICROSCOPE is the ideal laboratory to test this…

Important feature / screening



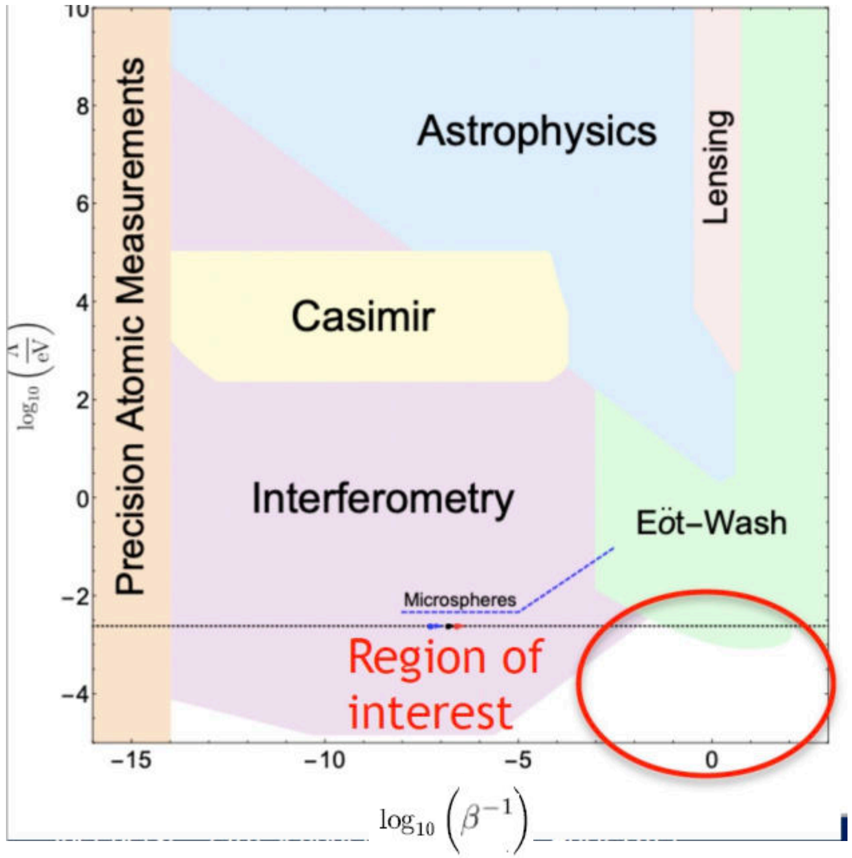
Screening: independence between inner and outer field

Unscreen in low density regions

While point particles satisfy the UFF, macroscopic objects do not!

Is MICROSCOPE screened? Where?

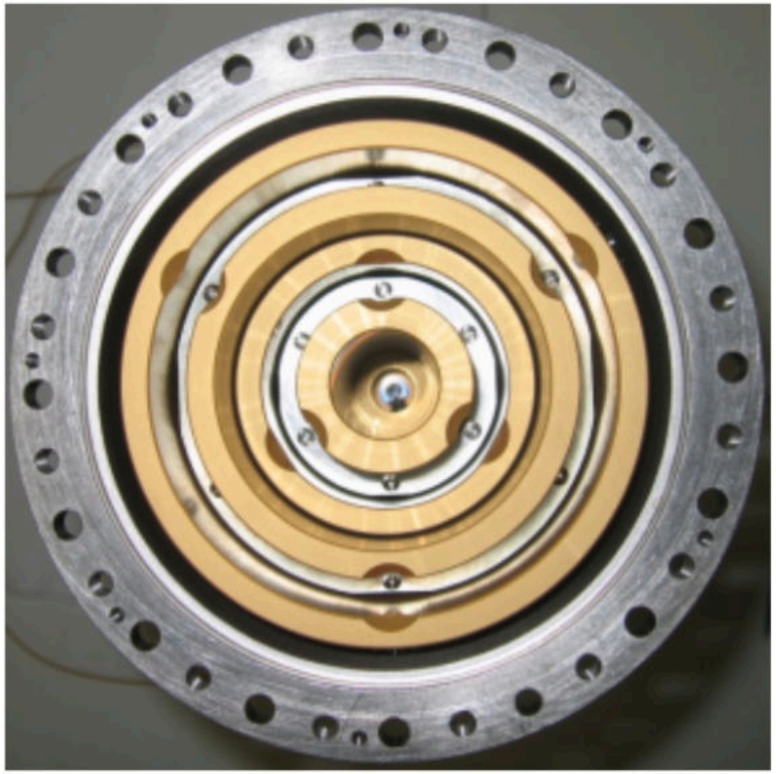
[Burrage & Sakstein, Liv. Rev. Relat. (2018)]

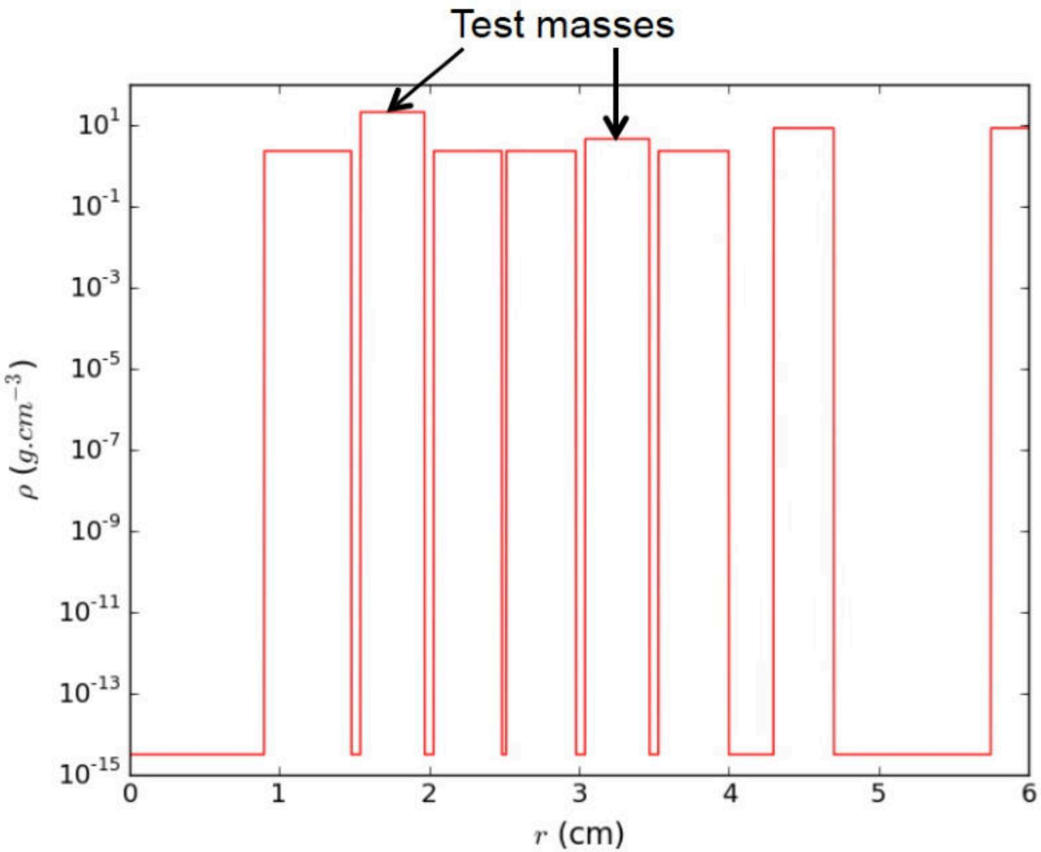


Pernot-Borràs, Bergé, Brax, JPU, 1907.10546]

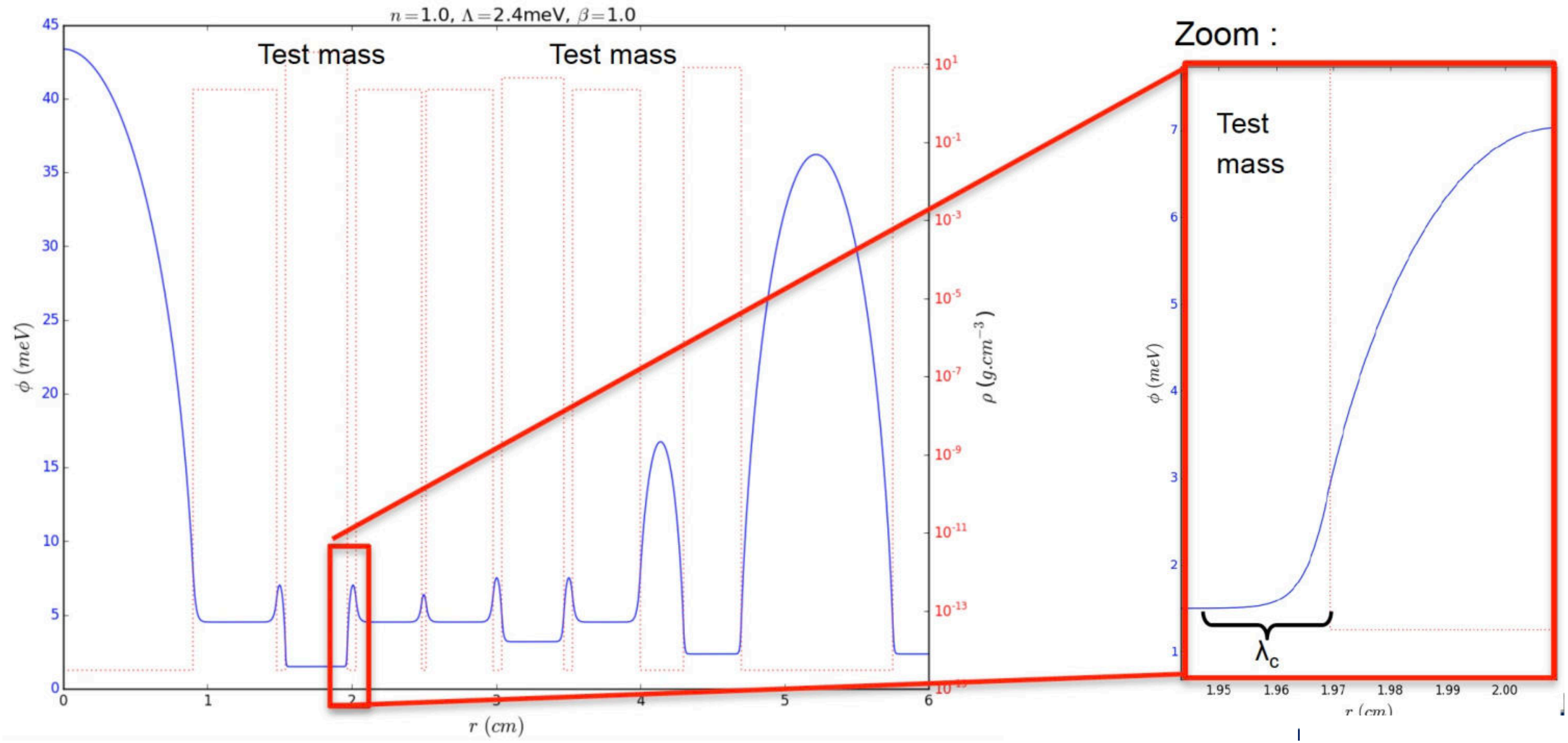
BUT, real world is tougher than theory!

(1) Still some atmosphere at 700km
(2) Test-masses are not in vacuum… but surrounded by a satellite and an experimental apparatus
(3) Need to know how the chameleon field propagates through the cylinders





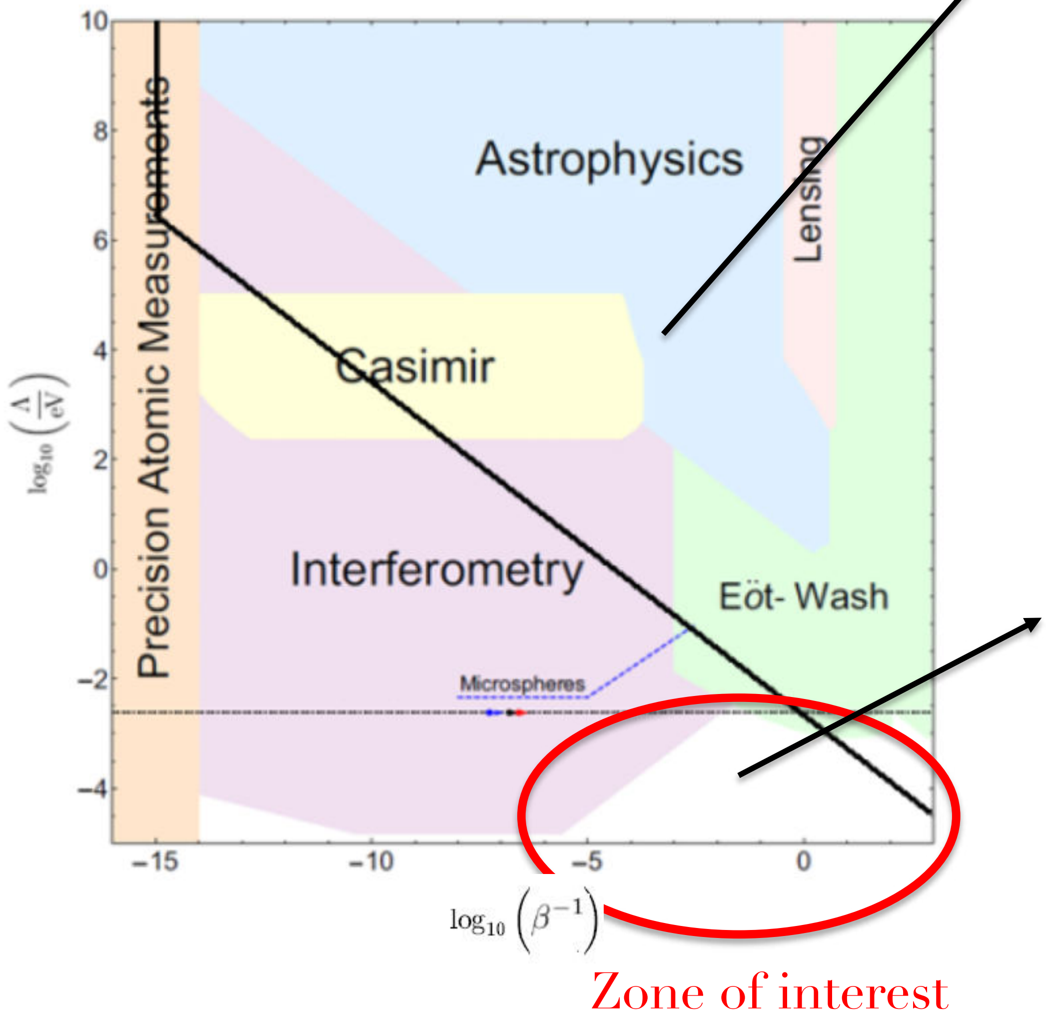
BUT, real world is tougher than theory!



Simulation example : radial profile of chameleon field within nested cylinders

[Pernot-Borràs, Bergé, Brax JPU, 2004.08403]

MICROSCOPE does not constrain chameleon



MICROSCOPE is not screened

- *possible effect of different screening of masses*
- *possible effect of composition dependent chameleon*

MICROSCOPE is completely screened

- *the field inside the satellite is **independent** of the field outside*
- *no effect caused by Earth*

[Pernot-Borràs, Bergé, Brax JPU, 2004.08403]

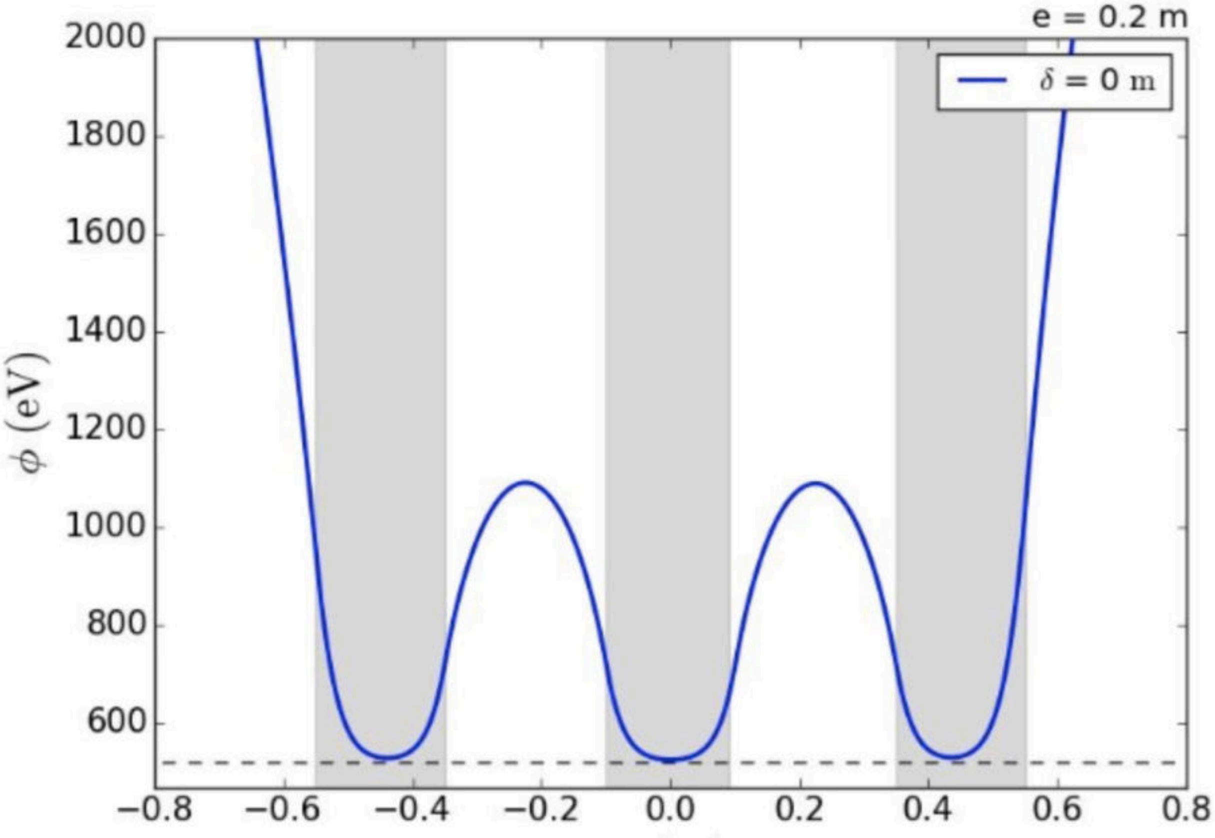
Still… let us have a closer look

The cylinders do not remains co-axial due to disturbing forces.

Consider a moving wall, then the field on each side will have a different profile if the configuration is not symmetric.

As an example, consider a *1D* configuration.

Let’s make a movie!



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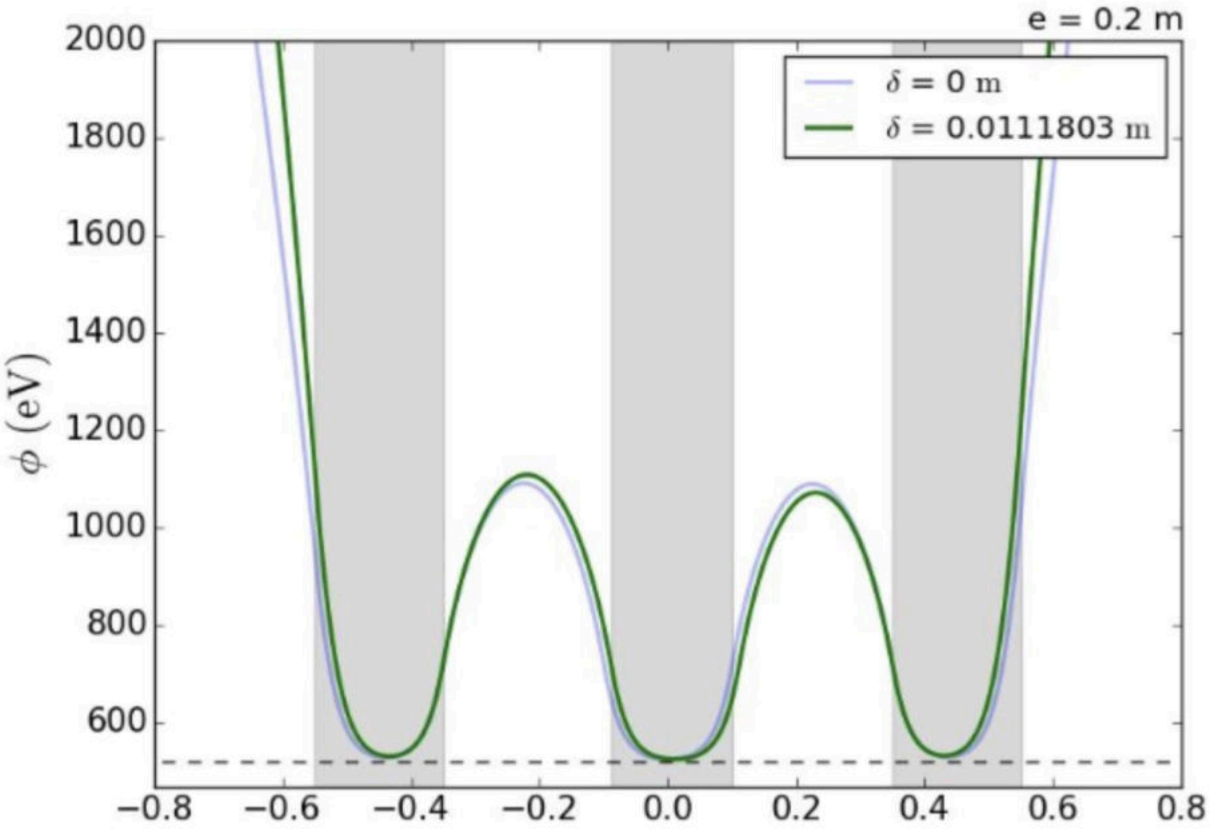

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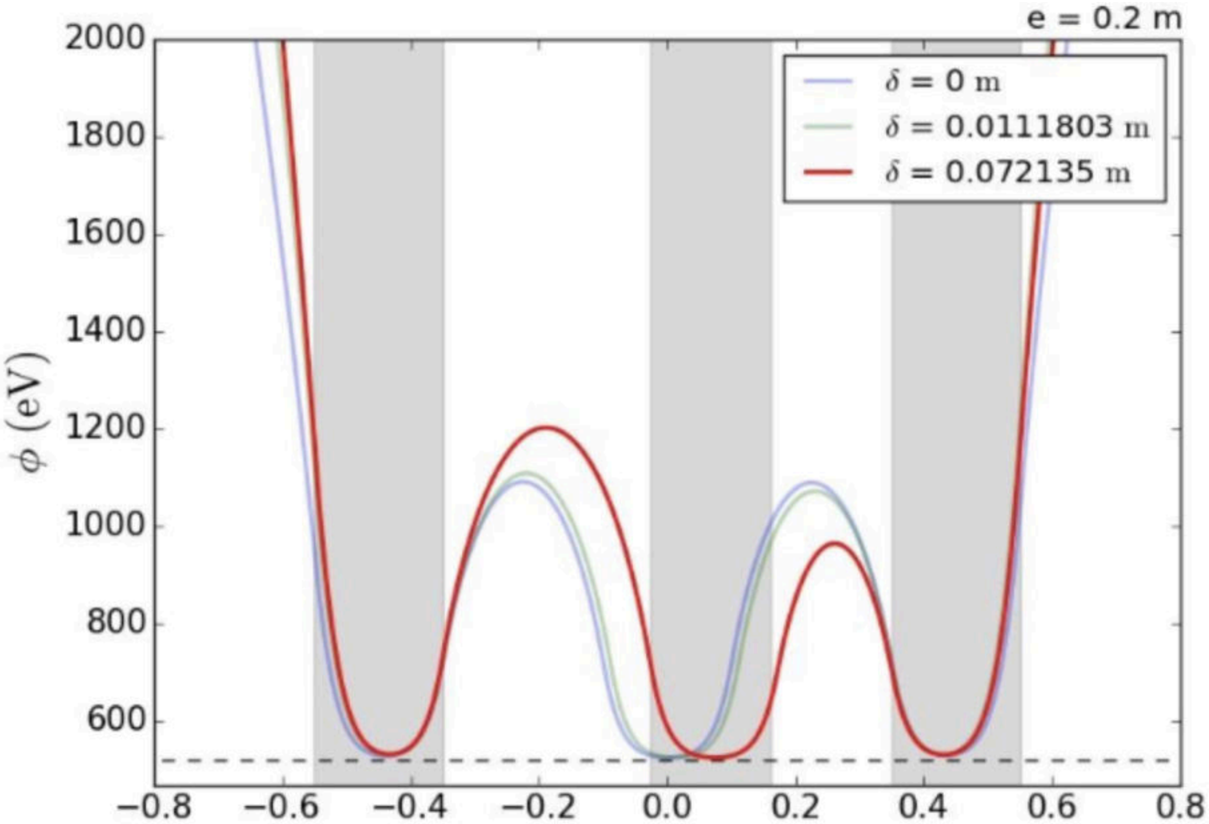
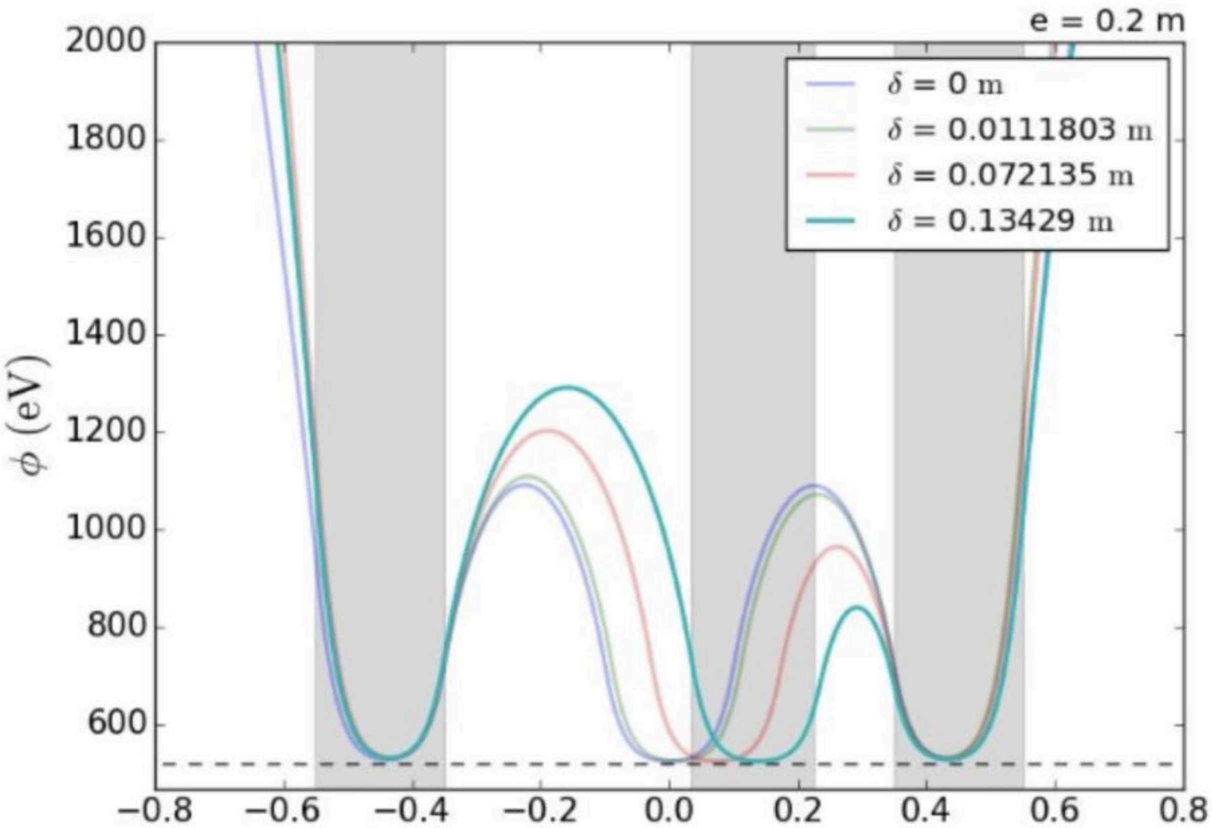
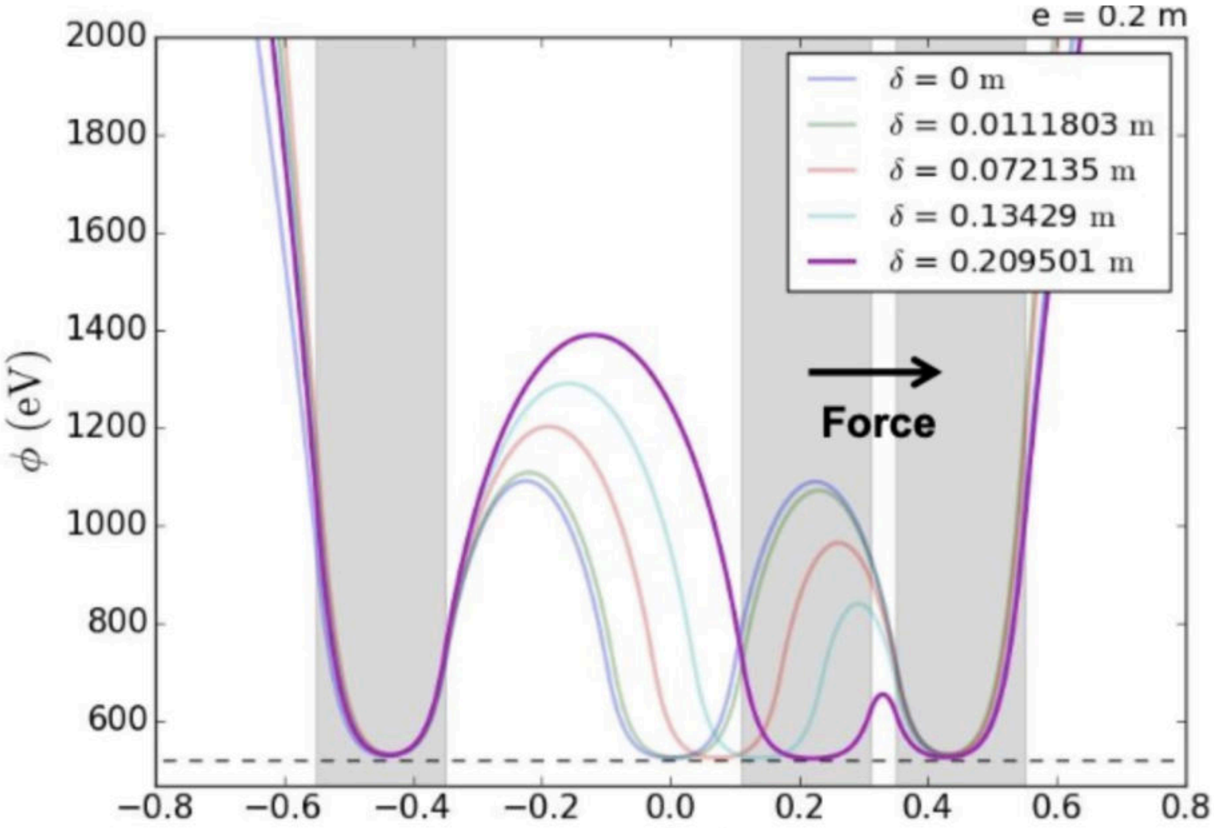


Let’s make a movie!

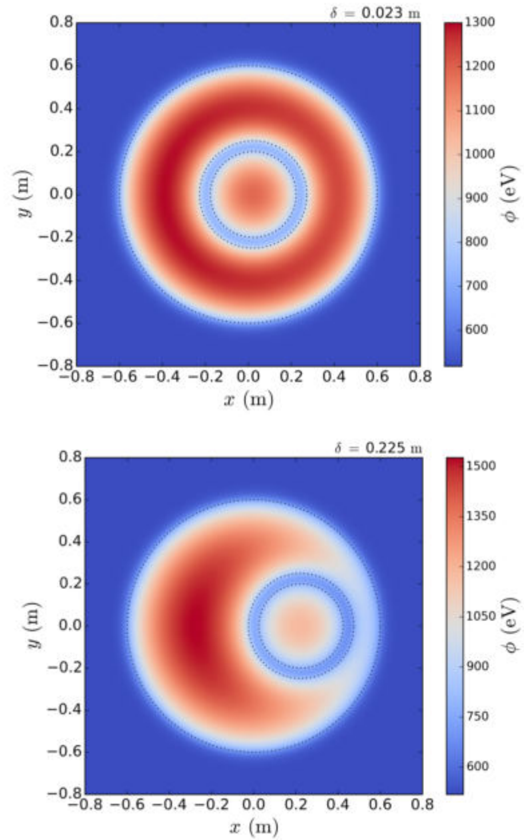


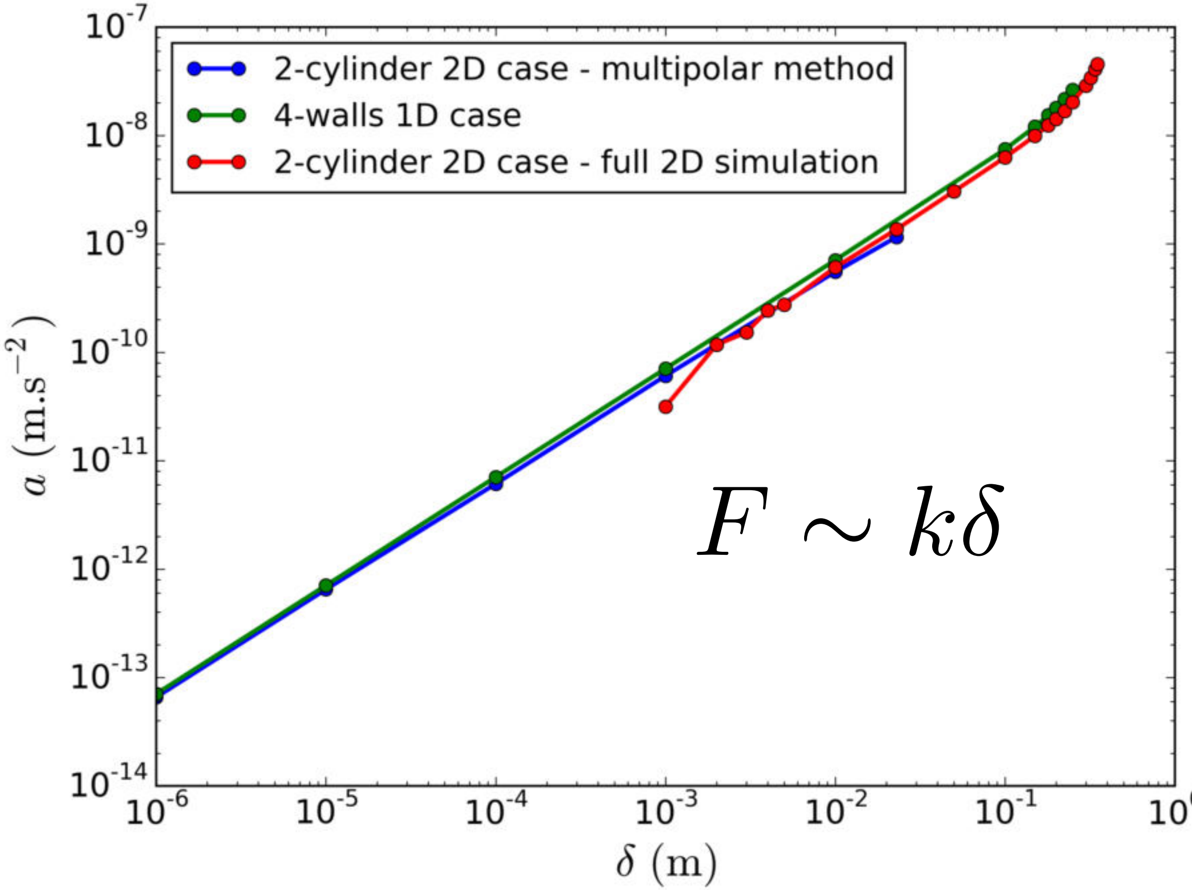
Let's make a movie!



Unexpected stiffness

The chameleon inside the instrument acts as an extra stiffness, that destabilizes the system.

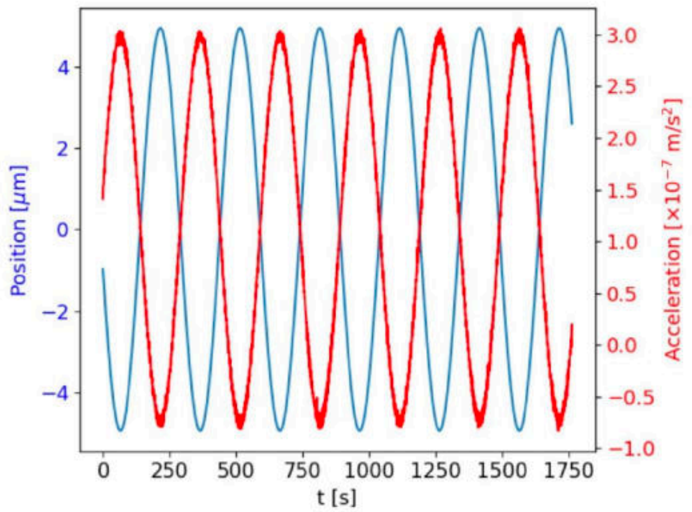




[Pernot-Borràs, Bergé, Brax JPU, Métris, 2102.00023]

This can be constrained

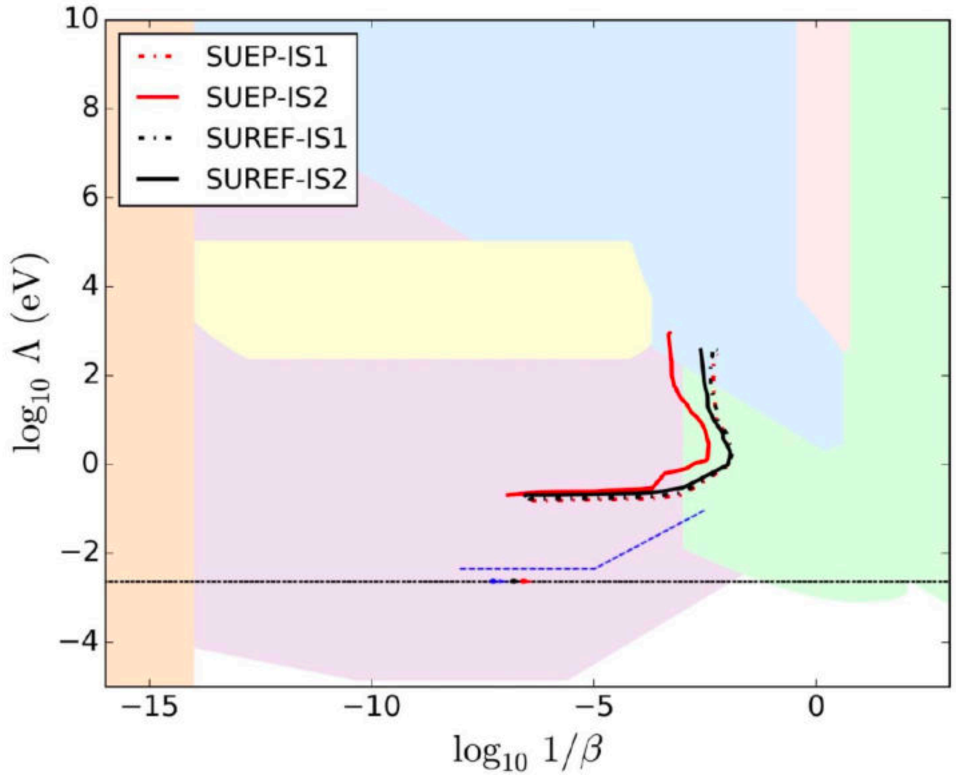
Measurement by a imposing a periodic motion to a test mass:



Model of the siffness (electrostatic, Newtonian, gold wire….)

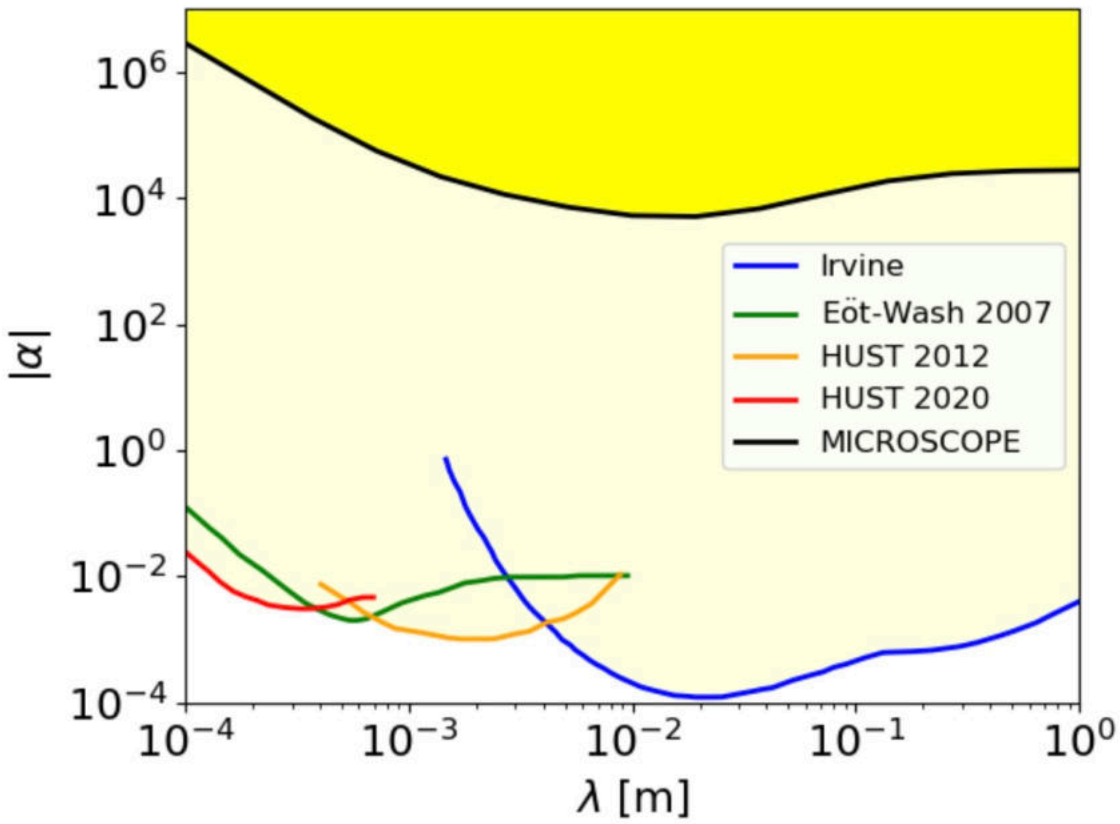
Residual unexplained stiffness

$$\langle \Delta k \rangle = (7.1 \pm 6.0) \times 10^{-4} \text{ N/m}$$



[Pernot-Borràs, Bergé, Brax JPU,Métris, 2102.00022-2102.00023]

You can do the same analysis for Yukawa



Indeed, this is not competitive (*the instrument was not designed for that*)
But analytical and instructive computation.

[Pernot-Borràs, Bergé, Brax JPU,Métris, 2102.00022]

H_0 tension as a sign of a dark fifth* force

With Cyril Pitrou
arXiv:2312.
arXiv:2312.

* *Shall actually be called « second » force*

Guideline

In brief, the H_0 problem is often phrased in terms of high-*z* low-*z* discrepency

$$r_s = \frac{1}{H_0}\int_{z_*}^{\infty}\frac{c_s \mathrm{d}z}{H(z)/H_0} \qquad R_{\mathrm{ang}}(z) = \frac{1}{H_0} f_K\left[\int_0^z \frac{\mathrm{d}z}{H(z)/H_0}\right]$$

Huge number of models….

[Schöneberg et al. 2107.10291; di Valentino, et al. 2103.01183; Abdalla et al., 2203.06142]

Both scale as $1/\sqrt{GH_0^2}$ leading to the idea that a variation of *G* can be the source

But it will not fit with CMB!

Then one realizes that CMB angular spectra remains invariant under

$$H \to \lambda H,\ G\rho \to \lambda^2 G\rho,\ \sigma_T n_e \to \lambda\sigma_T n_e,\ A_s \to A_s \lambda^{1-n_s}$$

[Rich, 1503.06012; Ge et al., 2210.16335]

Varying *G* & m_e models….. [Hart&Schluba, 2107.12465]

But variation of m_e/m_p or α are strongly constrained from BBN and Solar system experiments

[Coc, Nunes, Olive, JPU, Vangioni, astro-ph/0610733; JPU 1009.5514]

Guideline

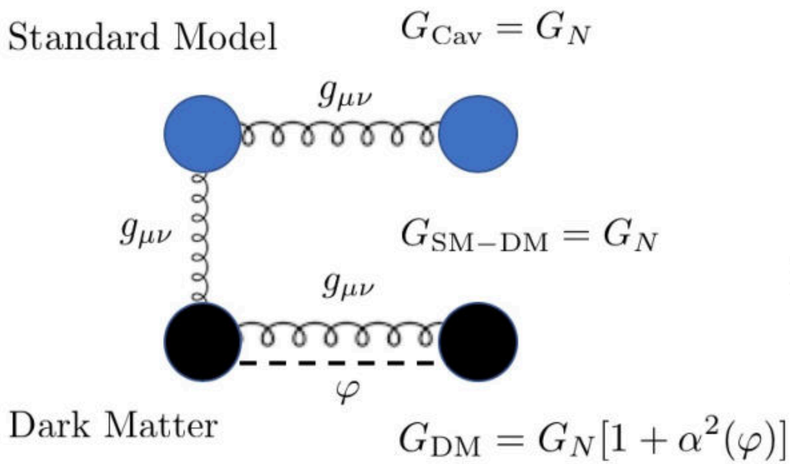
To be conservative, we would like:

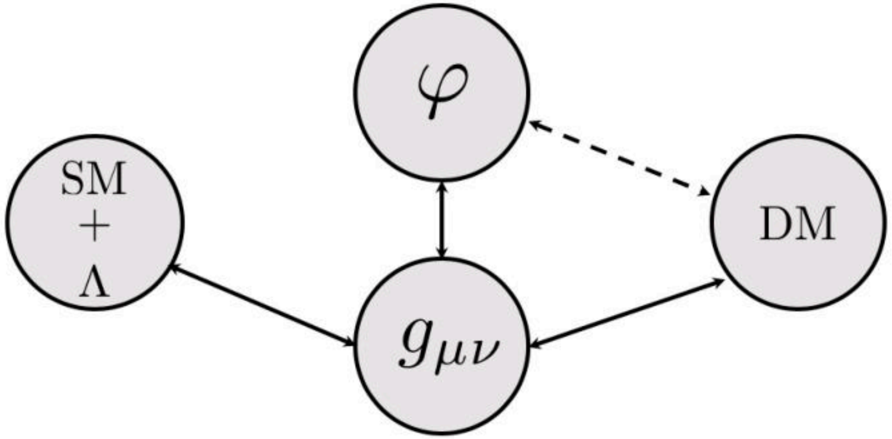
- no effect in any tests of GR in the local;
- no effect on BBN abundance;
- no dominant new dark component in the expansion history.

Given that (almost) all tests of GR are performed with standard model fields and that DM is subdominant during BBN, a natural guess is

dark matter gravitational sector.

The minimal model





$$G_{\mu\nu} = \Lambda_0 g_{\mu\nu} + \kappa T_{\mu\nu} + \kappa T^{(\varphi)}_{\mu\nu} + \kappa T^{(\rm DM)}_{\mu\nu}$$

$$\nabla_\mu T^{\mu\nu} = 0$$

$$\nabla_\mu T^{\mu\nu}_{(\rm DM)} = \alpha(\varphi) T^{(\rm DM)}_{\sigma\rho} g^{\sigma\rho} \partial^\nu \varphi$$

$$\Box\varphi = \frac{{\rm d}V}{{\rm d}\varphi} - \frac{\kappa}{2}\alpha(\varphi) T^{(\rm DM)}_{\mu\nu} g^{\mu\nu}$$

$$\alpha(\varphi) = \frac{{\rm d}\ln A}{{\rm d}\varphi};$$

For the numerical examples: $V = 0,$ $\quad A = 1 + \frac{1}{2}\beta\varphi^2$

Cosmological dynamics

Dark matter evolution

$$\dot{\rho}_{\rm D} + 3H\rho_{\rm D} = \alpha(\varphi)\rho_{\rm D}\dot{\varphi}. \qquad \rho_{\rm D} \propto a^{-3}A$$

$$G\rho_D = G\rho_{D0}\frac{A}{A_0}a^{-3} \equiv G_{\rm eff}(\varphi)\rho_{D0}a^{-3}$$

$$1 + w_{\rm eff} \equiv -\frac{1}{3H}\frac{\dot{\rho}_{\rm DM}}{\rho_{\rm D}}$$

Cosmological dynamics

Dark matter evolution

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$$1+w_{\rm eff}\equiv -\frac{1}{3H}\frac{\dot{\rho}_{\rm DM}}{\rho_{\rm D}}$$

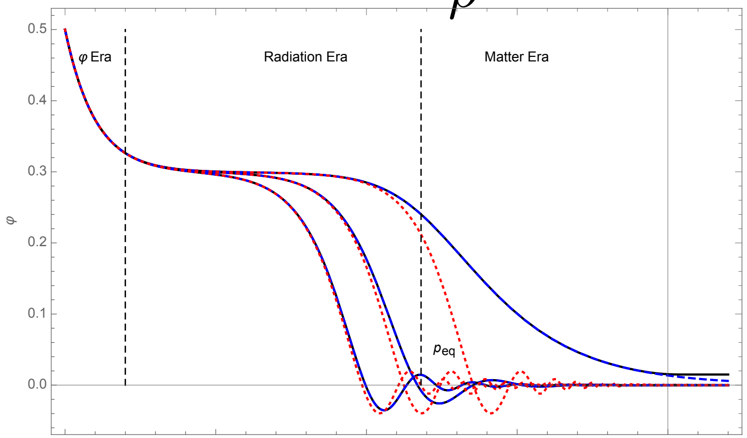
Scalar field

$$\ddot{\varphi}+3H\dot{\varphi}=-\frac{{\rm d}V}{{\rm d}\varphi}-\frac{\kappa}{2}\alpha\rho_{\rm D}$$

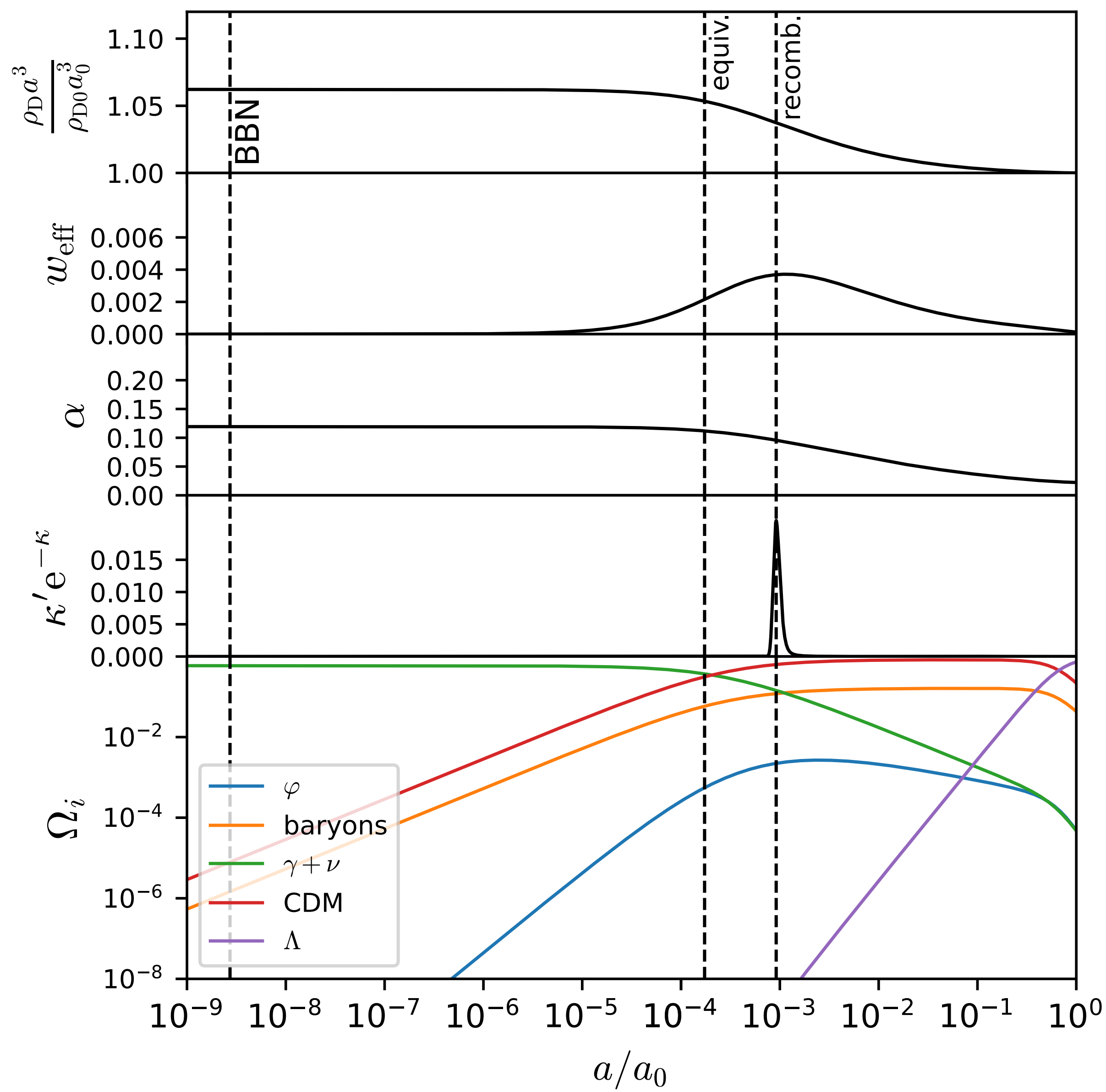
Take $p = ln\, a$ as time variable

$$\frac{\varphi''}{3-\varphi'^2}+(1-w)\varphi'=-\frac{\rho_{\rm D}}{\rho}\alpha(\varphi)$$

$$\frac{\varphi''}{3-\varphi'^2}+\frac{2}{3}\varphi'=-\beta e^{p-p_{\rm eq}}\varphi$$



Cosmological dynamics @background level

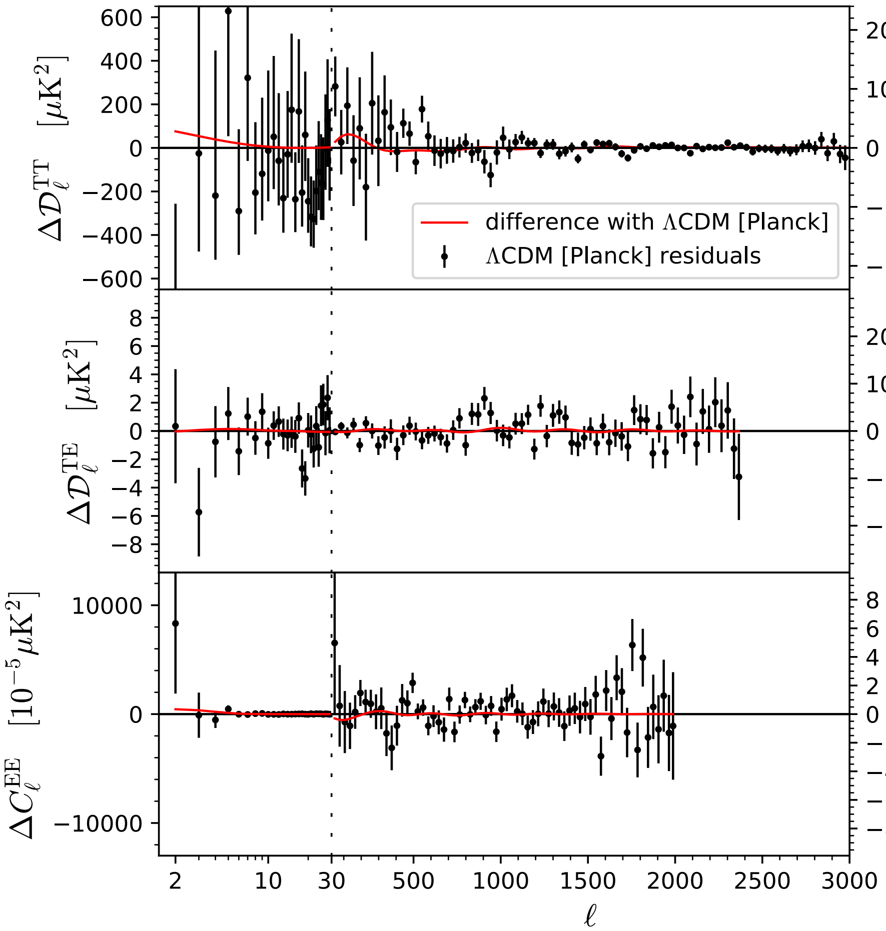


$\rho_{\rm D} \propto a^{-3} A$

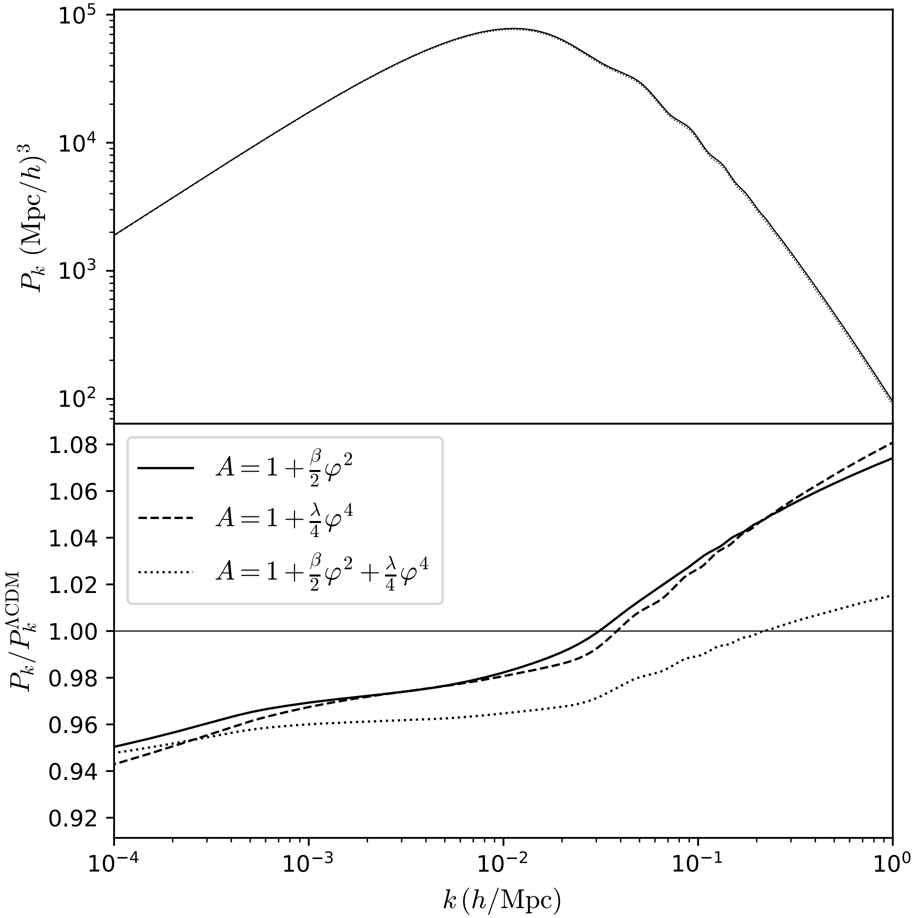
Change happens naturally round equivalence

φ always negligible

Effect on the cosmological observables

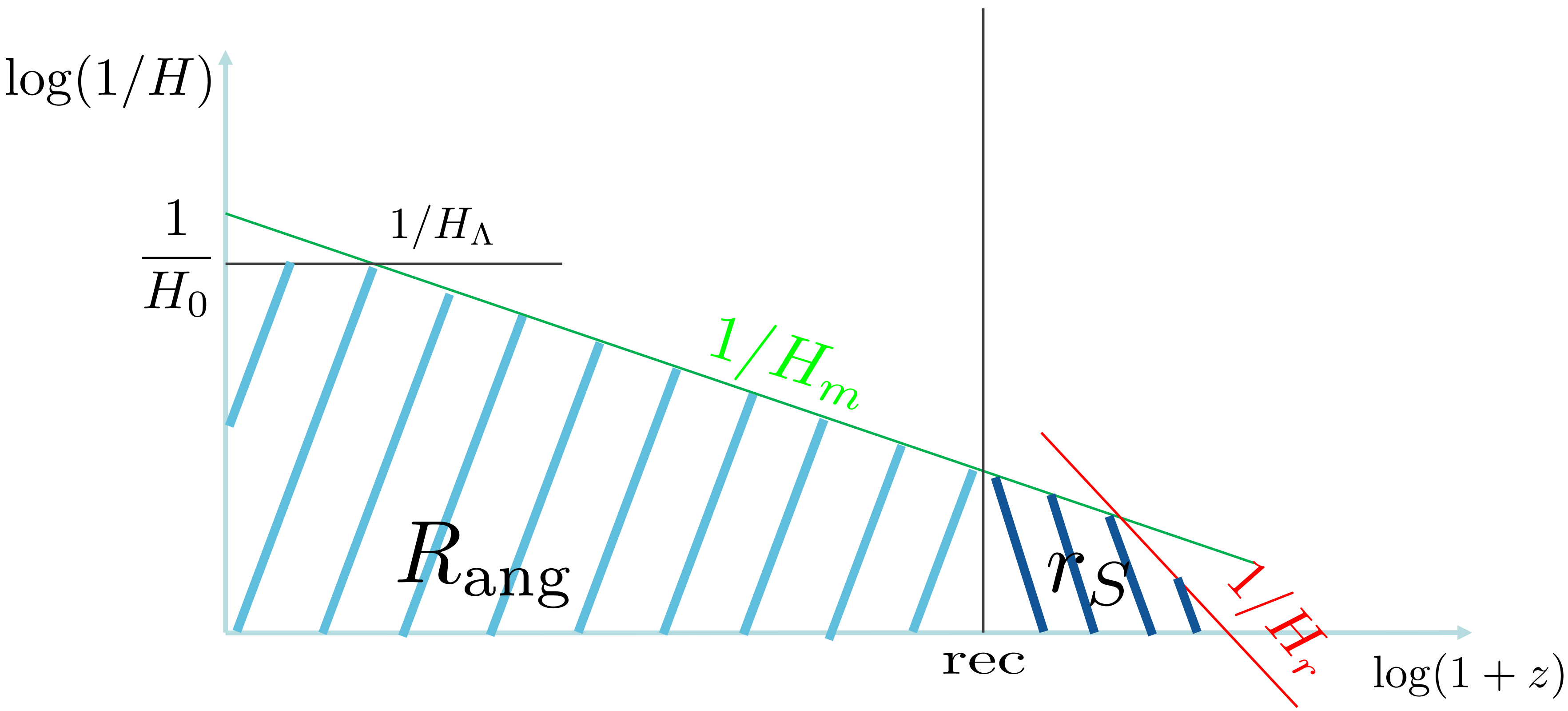


Comparison of ΛβCDM-ΛCDM to the residuals of Planck/ΛCDM

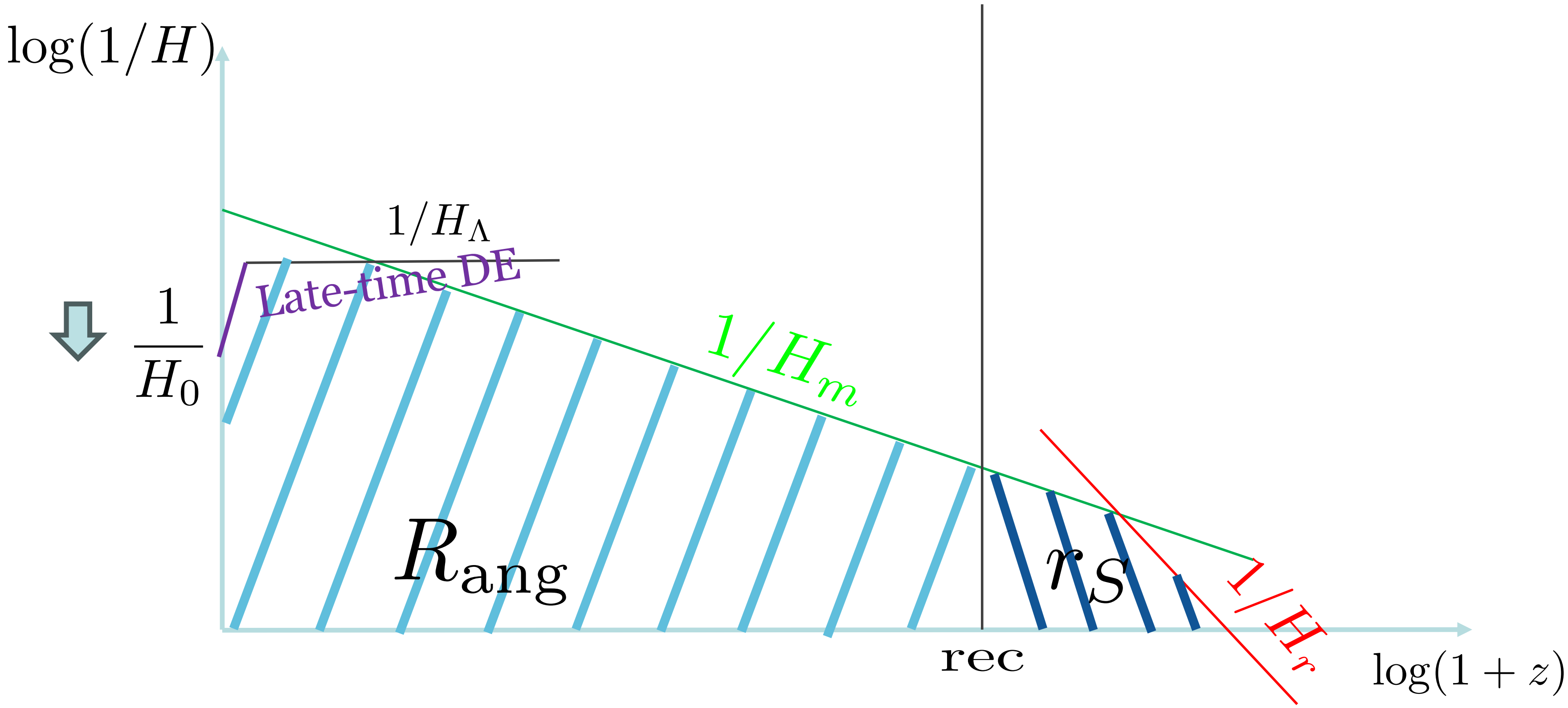


Boosted on smaller scales beyond the peak by less that 10%. Hence S_8 will almost be unaffected.

Mechanisms comparison

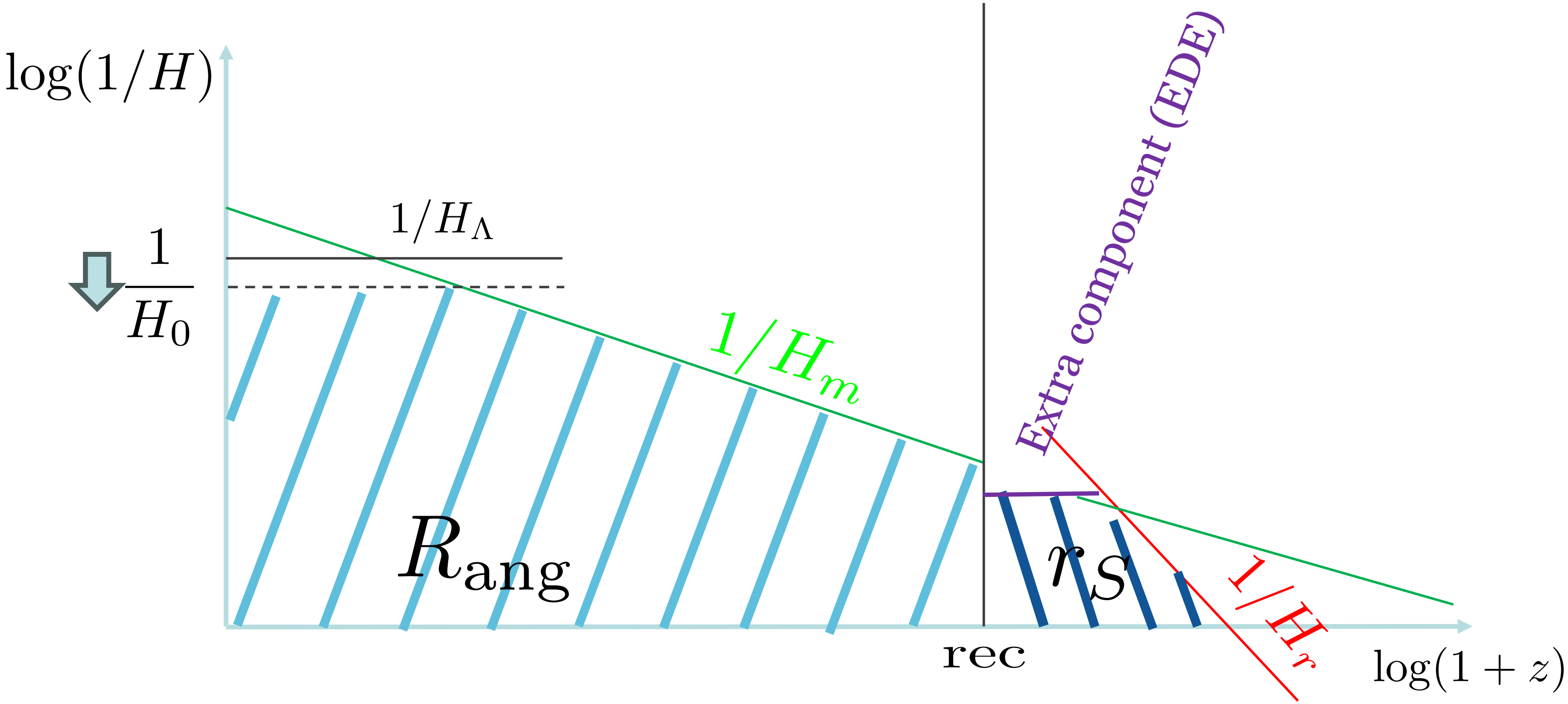


Mechanisms comparison



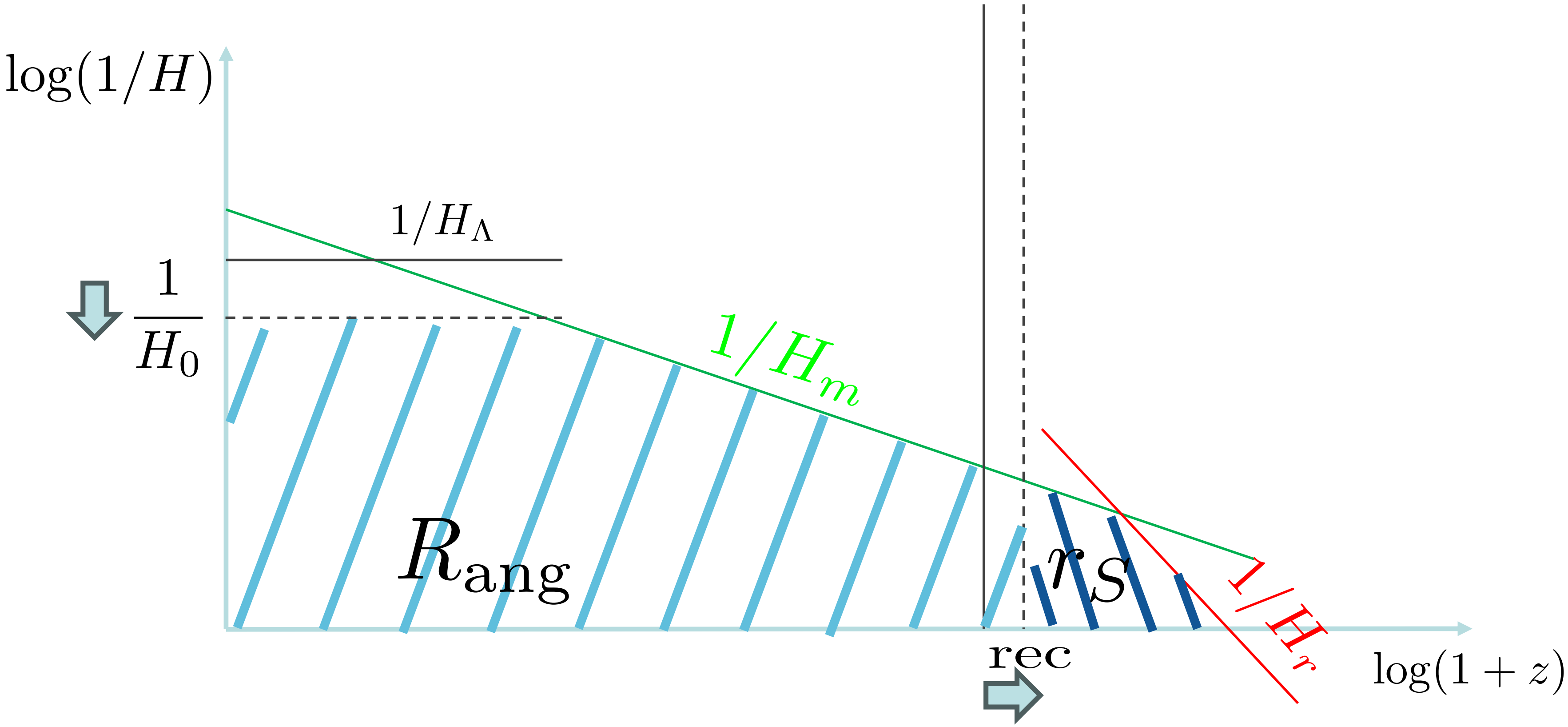
Late time solutions

Mechanisms comparison



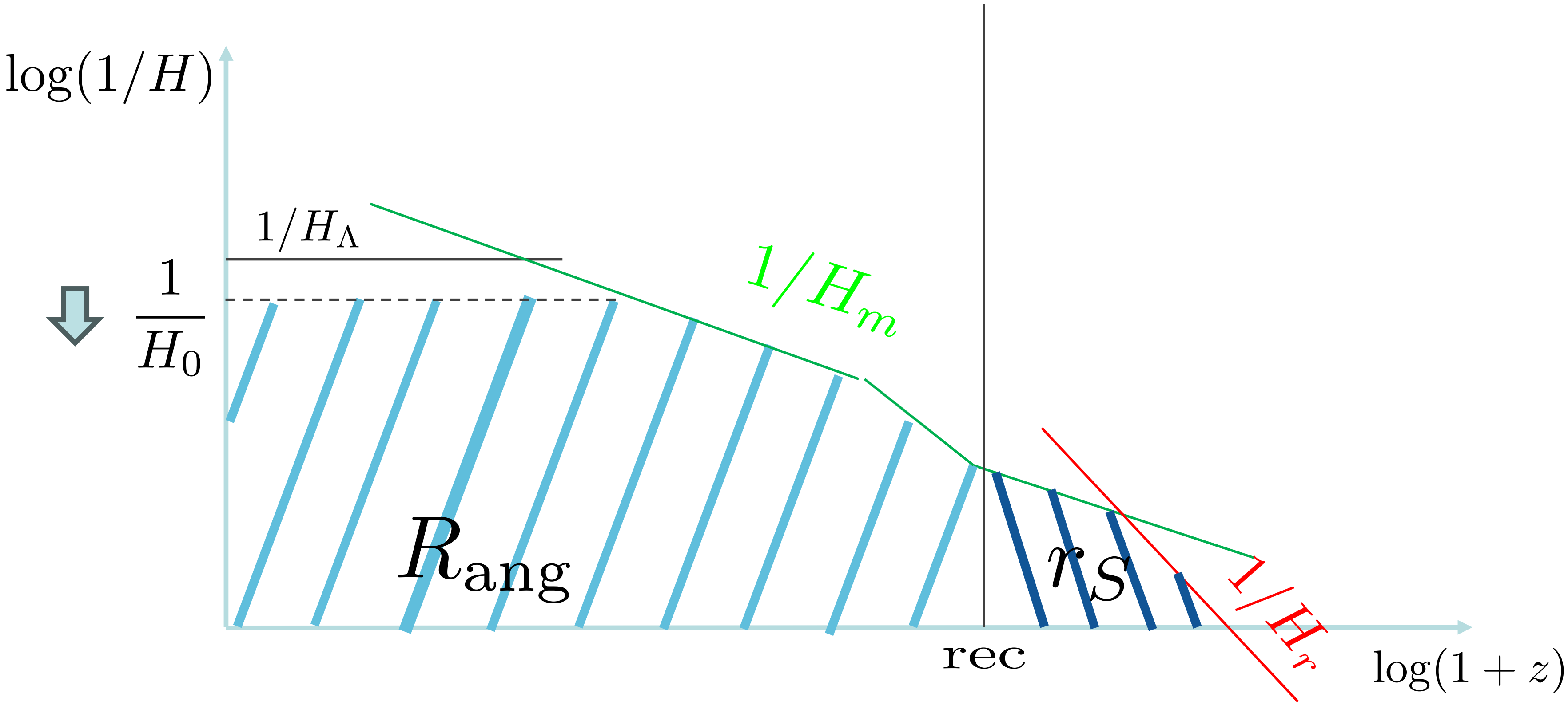
Sound horizon solutions

Mechanisms comparison



Recombination solution [see e.g. Jedamzik, Pogosian 2023]
(e.g. with magnetic field -> clumping -> faster recombination)

Mechanisms comparison



By triggering the disappearance of DM, the ΛβCDM model selects another region of this degeneracy line with a lower Ω_m hence allowing for a larger Hubble constant.

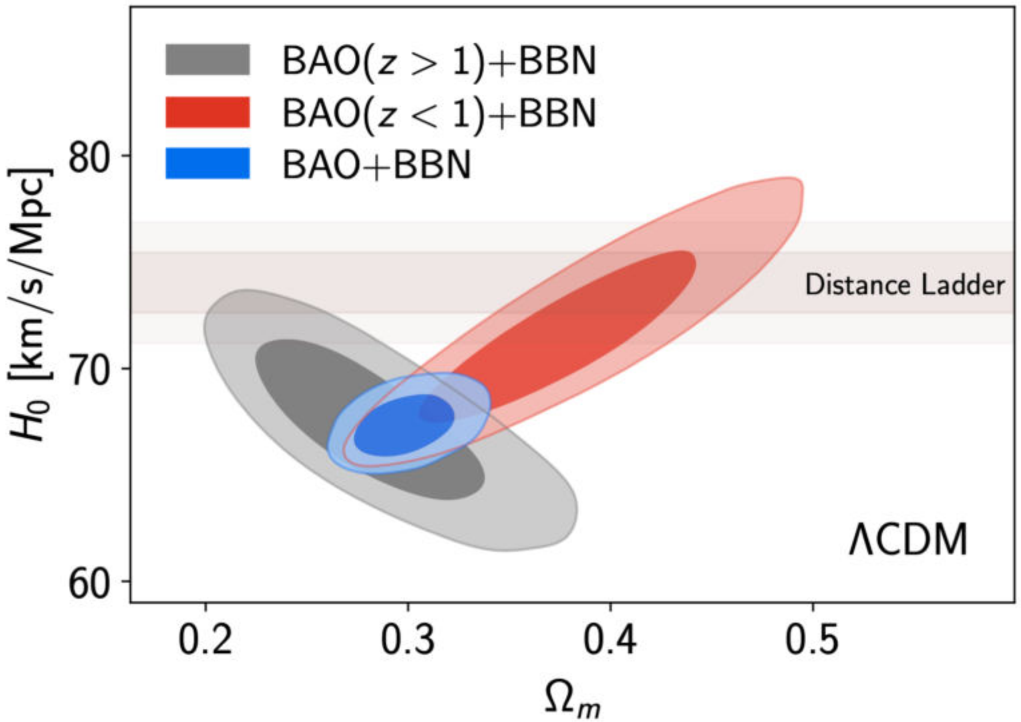
Comparison to data

CMB data: Planck low and high l temperature and polarization, with CMB lensing;
DES Y1 : weak lensing and galaxy correlations;
SN data: Pantheon sample

BAO (high-z): SDSS DR16 (ELG + QSO + Lyα)

BAO (low-z): 6dF + SDSS DR7 (MGS) + SDSS DR12 + SDSS DR16 (LRG)

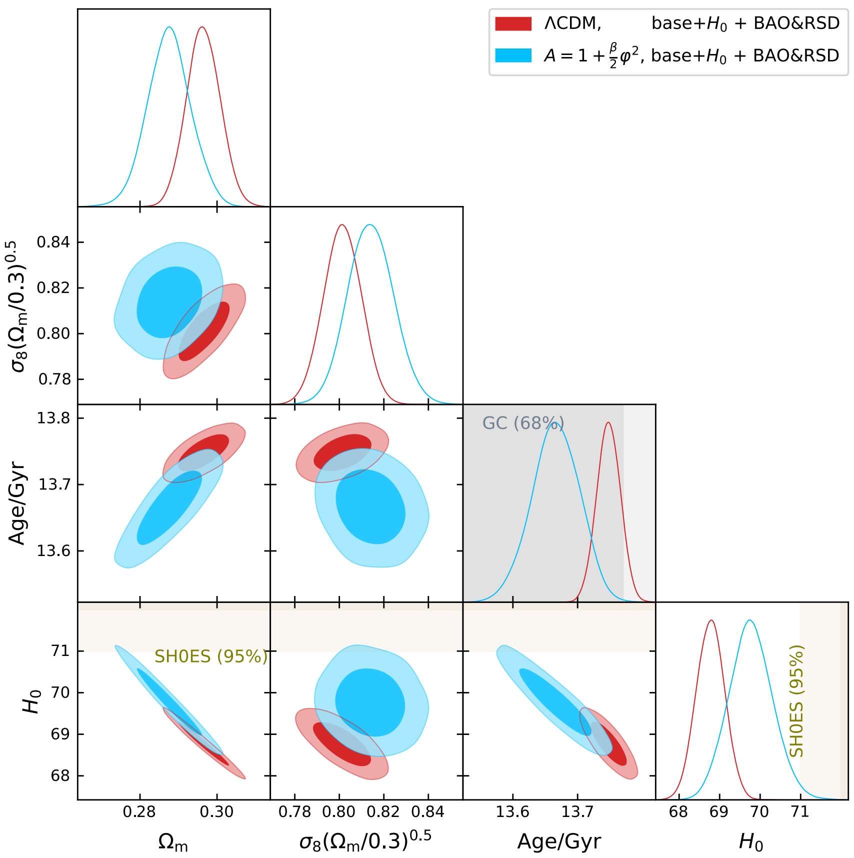
H_0: SHOES



[See Eleonora's talk]

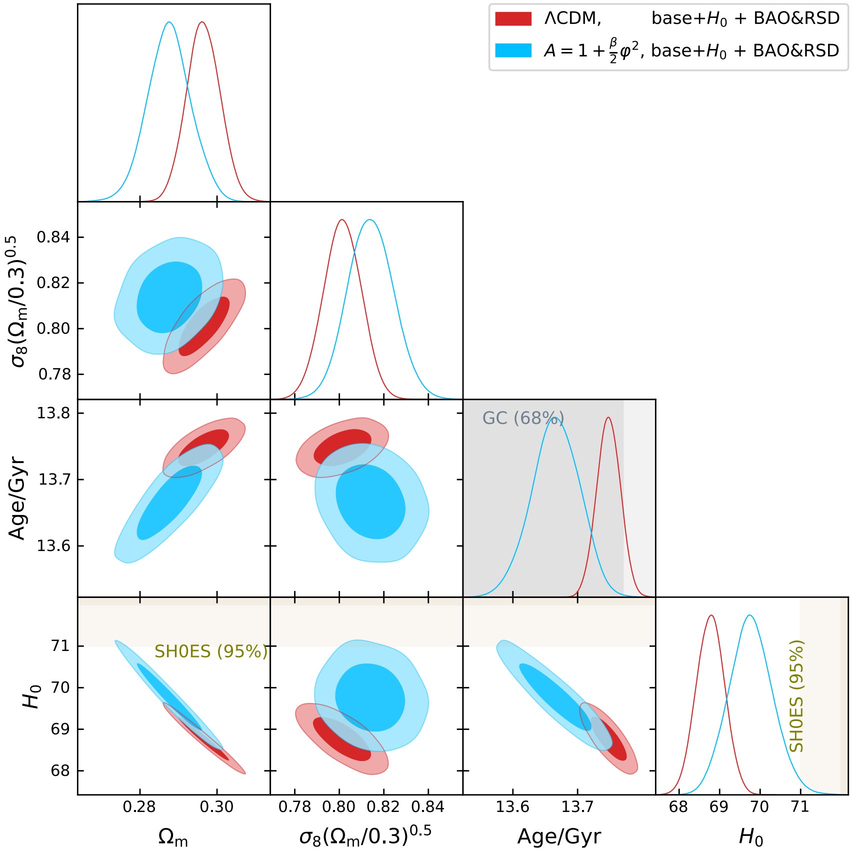
BAO @$z = 0.38, 0.5, 0.7$
+ MGS @ $z = 0.15$

Comparison to data

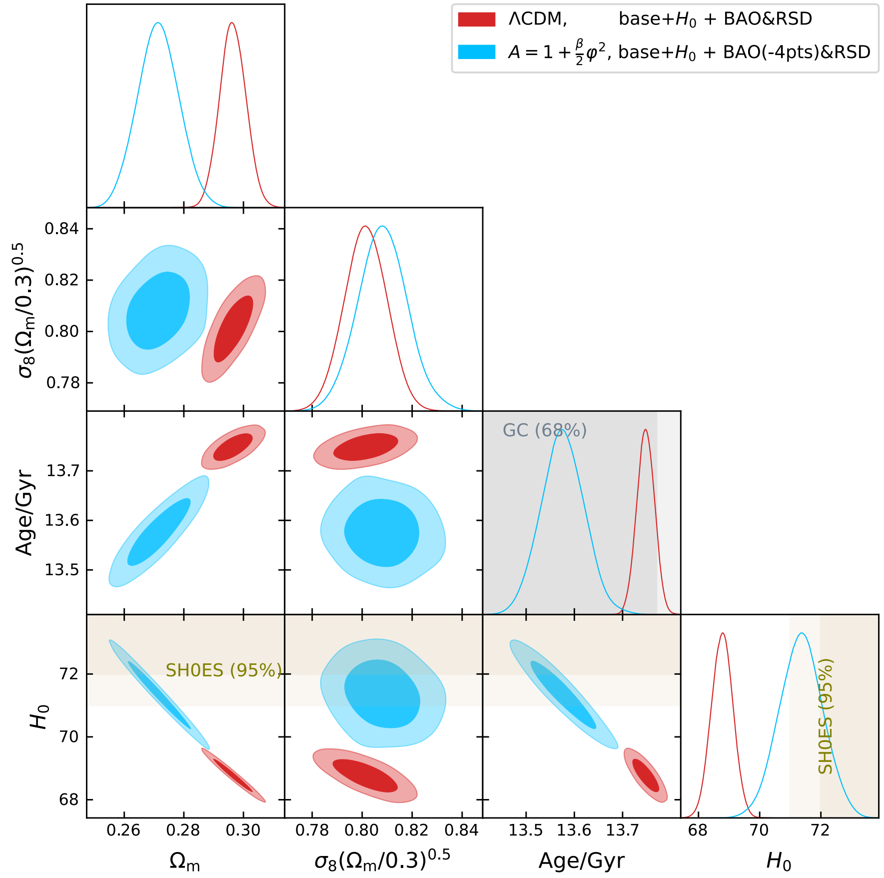


As poor as other models!

Comparison to data



As poor as other models!

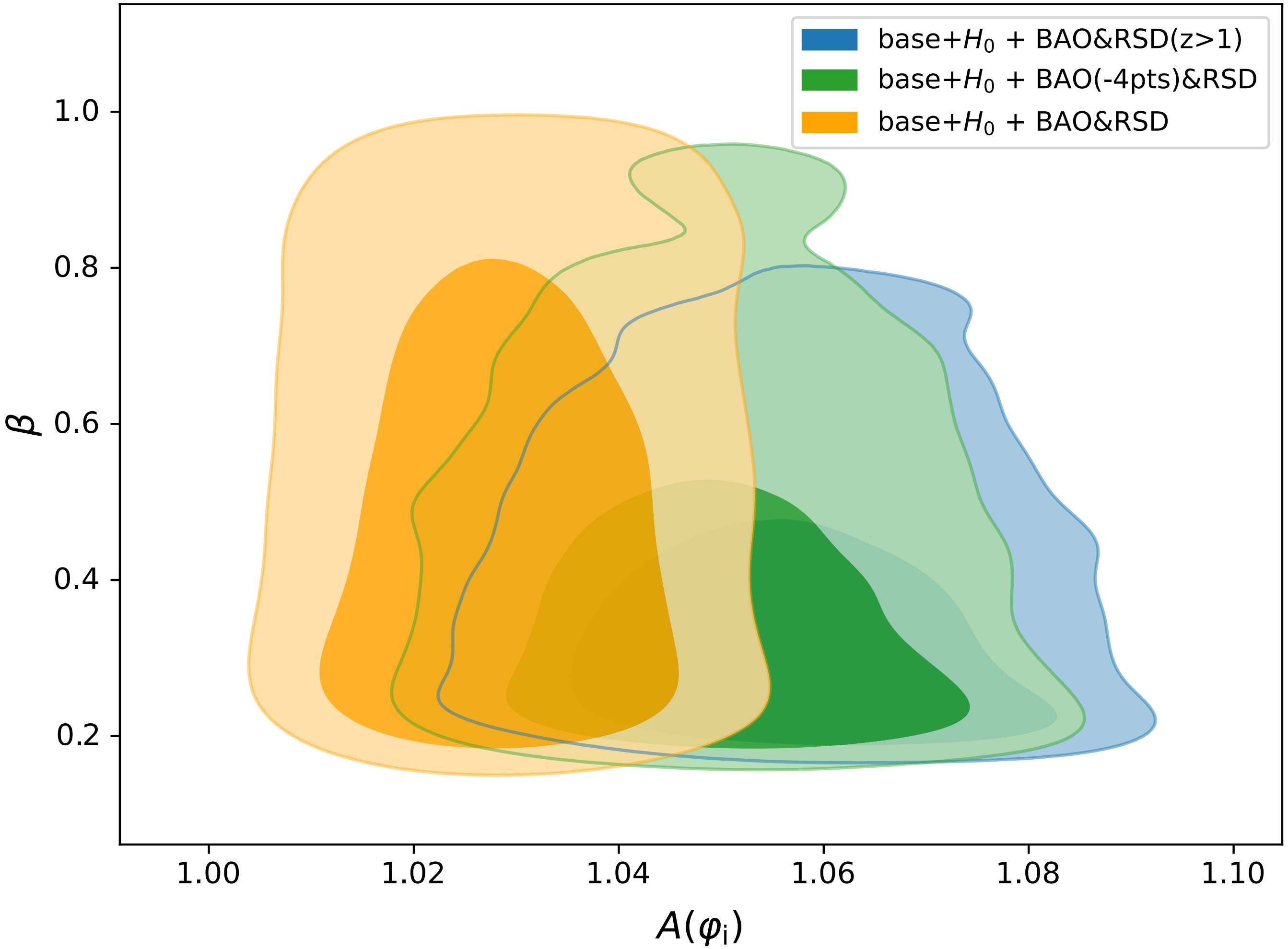


Better!

BAO @$z = 0.38, 0.5, 0.7$
+ MGS @ $z = 0.15$

[See Eleonora's talk]

Sensitivity to initial conditions



No fine tuning on the initial conditions

Best fit & conclusions

Model	base+H_0+	Ω_m	$\Omega_{b0}h^2$	h	S_8	Age (Gyr)	H_0 tension	Q_{DMAP}	ΔAIC
ΛCDM	BAO	0.2965 ± 0.0044	0.02263 ± 0.00013	0.6877 ± 0.0035	0.801 ± 0.009	13.75 ± 0.02	4.4σ	4.8	0
ΛCDM	BAO($z > 1$)	0.2912 ± 0.0052	0.02270 ± 0.00014	0.6919 ± 0.0042	0.794 ± 0.010	13.73 ± 0.02	4.1σ	4.4	0
$\Lambda\beta$CDM	BAO	0.2875 ± 0.0056	0.02249 ± 0.00014	0.6977 ± 0.0054	0.814 ± 0.010	13.67 ± 0.04	3.8σ	3.6	-2.6
$\Lambda\beta$CDM	BAO($z > 1$)	0.2666 ± 0.0073	0.02246 ± 0.00015	0.7187 ± 0.0076	0.807 ± 0.010	13.55 ± 0.05	1.8σ	2.0	-14.5

$$\Delta\mathrm{AIC} = \chi^2_{\mathrm{model,data}} - \chi^2_{\mathrm{LCDM,data}} + 2N$$

- Best fit model preserves the sound horizon and the physical content before the matter/radiation equality;

- Residuals with the CMB data are as good as for the ΛCDM best fit;

- Smaller Ω_m allowing for a larger H_0.

-There is a limit imposed by the current structure of the data that no model can beat (BAO high/low *z*).

- I am more and more convinced that one needs **both** experimental and theory shifts to resolve the H_0 tension

(1) consistent and well-defined field theory so that it is fully predictive in all physical situations, not only in cosmology.

(2) all existing tests on deviations from GR and of tWEP are safe by construction

(3) ϕ is always be subdominant in the matter budget so that its energy density does not change the expansion history:

- it is not a dark energy component
- no direct effect on the dynamics of the universe at low redshift,
- no signature on all astrophysical tests of GR
- no effect on BBN abundances predictions

(4) Deep radiation era, ϕ is frozen and its evolution is triggered by the DM to radiation ratio so that its dynamics naturally occurs around the last scattering surface + No fine-tuninf on initial conditions

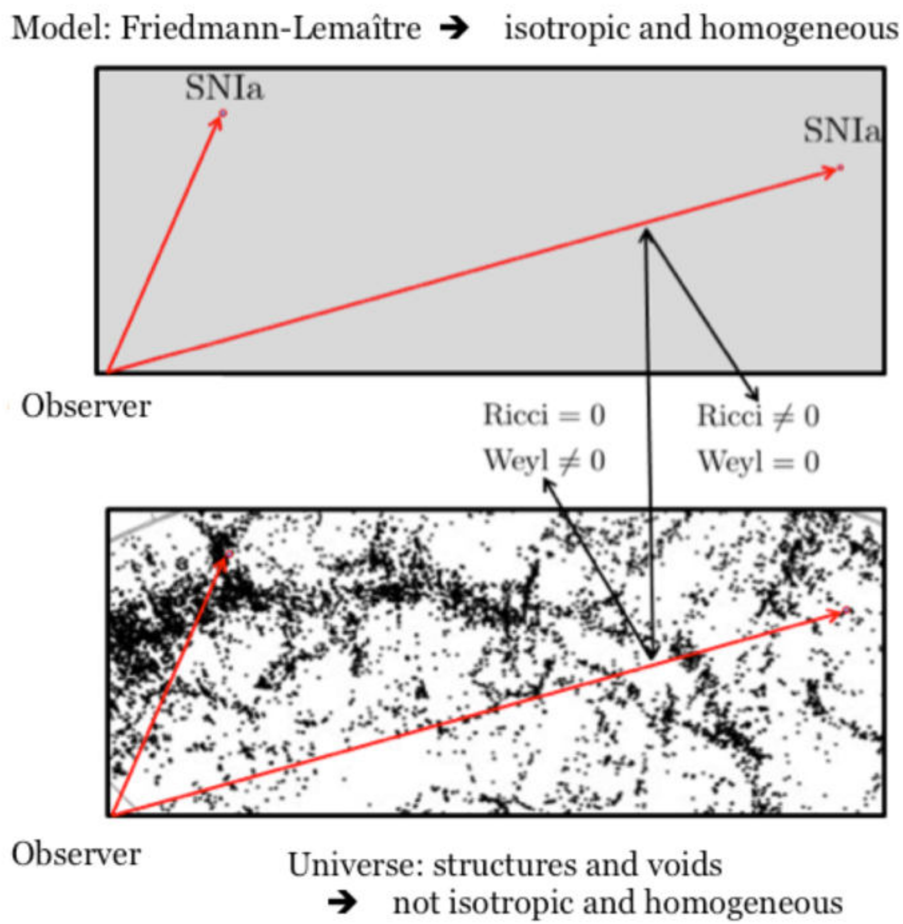
(5) In an effective way, the scalar interaction modifies the evolution of the DM energy density; interpreted either as a variation of the G_{DM} or by the fact that a fraction of DM disappears between equivalence and recombination.

(6) It alleviates the *H0* tension to 3.8σ and resolves it to less than 1.9σ if we discard low-z BAO data.

Fluid approximation (and the Ricci-Weyl problem)

On cosmological scales, the matter is described by a (perfect) fluid.
There is an implicit averaging scales, not specified [**RG is non-linear**]

Effect on the propagation of light [**Ricci-Weyl problem**]

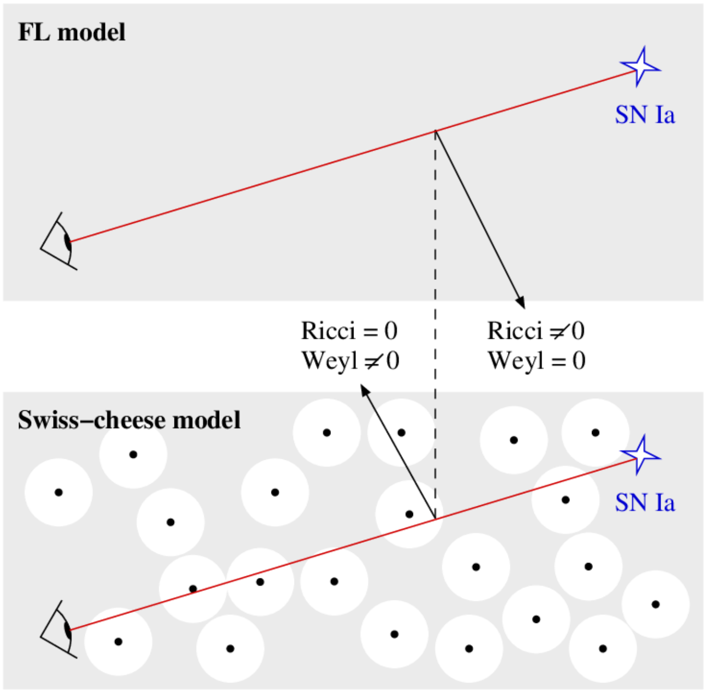


[Clarkson, Ellis, Maartens, Umeh,, JPU, 1109.2484]

The resolution of the **Ricci-Weyl problem** was provided in

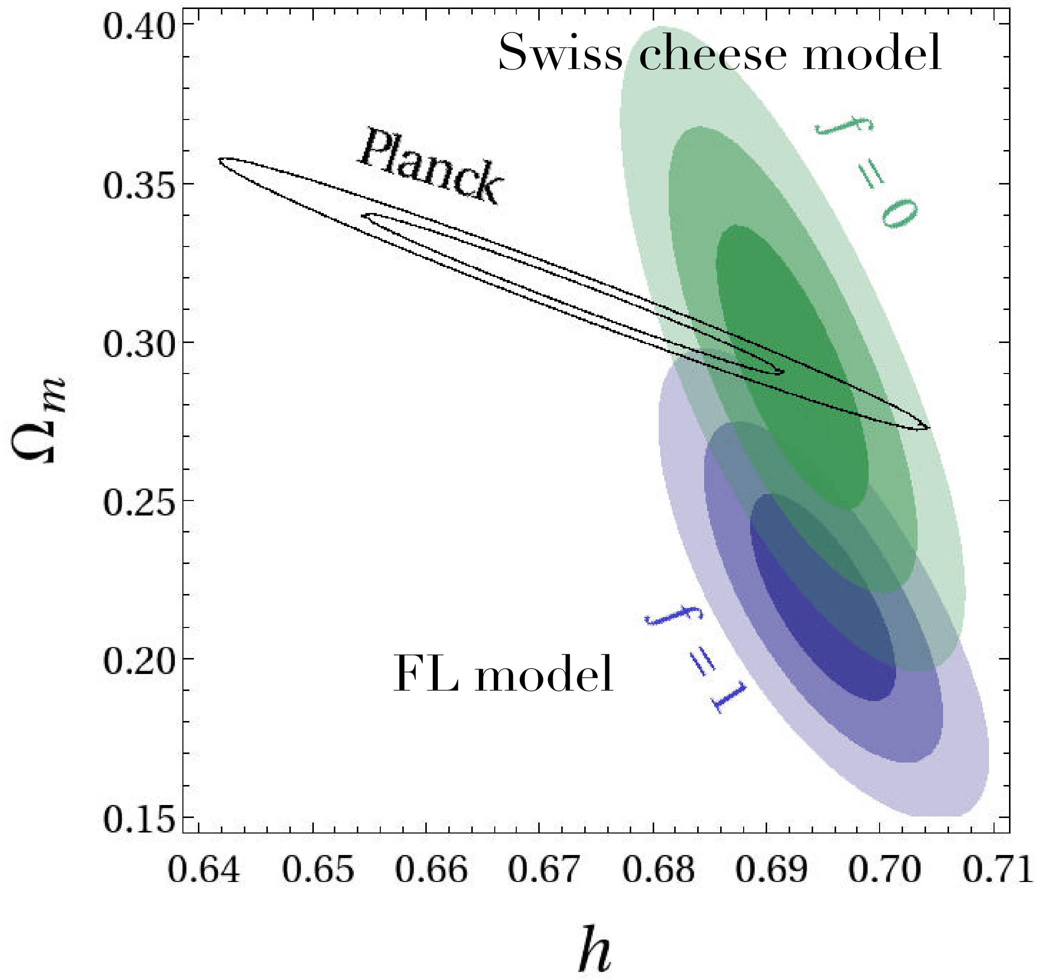
[Fleury, Larena, JPU, 1508.1809, 1706.09383, 1809.03924]

A toy model **example**: Swiss-Cheese



(proxy for the real univers)

$$f \equiv \lim_{V \to \infty} \frac{V_{\rm FL}}{V}$$



Are we sure we can use the same FL metric to interpret large beam and thin beam observation?

if one interprets the Hubble diagram of a Swiss-cheese universe by wrongly assuming that it is strictly homogeneous, then one underestimates the value of Ω_m.

[Fleury, Dupuy, JPU, 1302.5308, 1304.7791]

Summary

1. Local constraints on deviations from GR are *important/required* to take into account together with cosmological data.

2. WEP sets strong constraints on deviation from GR thanks to the results from the MICROSCOPE satellite, in particular on dilaton models.

3. Limitations of orbitography to constraint deviationss from GR have been quantified

4. Chameleon cannot be detected by MICROSCOPE contrary to the initial expectation.

5. But chameleon sources a destabilising stiffness that can allow to set constrains from the electromagnetic stiffness measurement session data.

6. H_0 tension may open a window on gravity in the dark sector. But… questions about accuracy of our interpretation schemes [precision vs exactness]