Three Themes on Dark Energy

Federico Piazza

Nobel Prize in Physics 2011


Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory
Saul Perlmutter


Photo: Belinda Pratten, Australian National University
Brian P. Schmidt

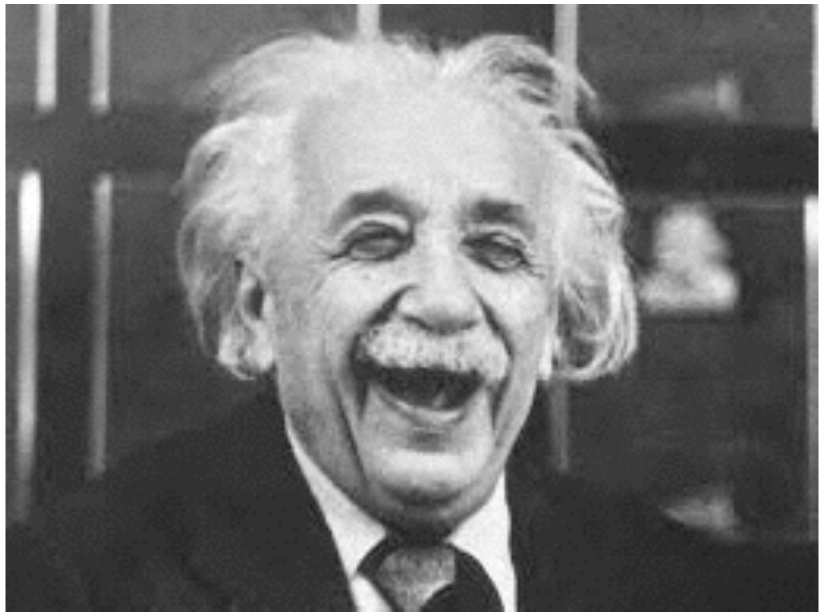

Photo: Homewood Photography
Adam G. Riess

The Universe is accelerating!

Why?!

The three themes:

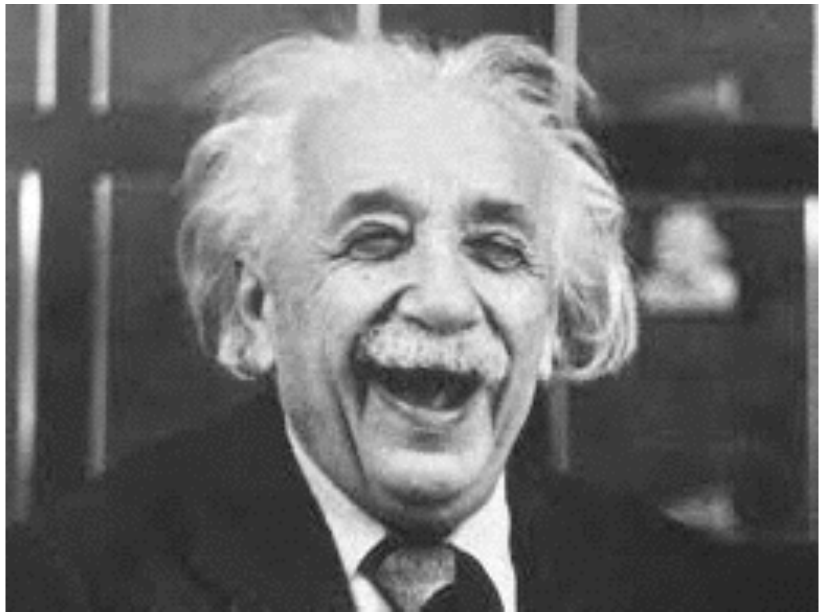
- Dark energy and modified gravity: a more systematic approach…?
- The EFT of dark energy (at work!)
- Modified gravity effects that pierce the screen



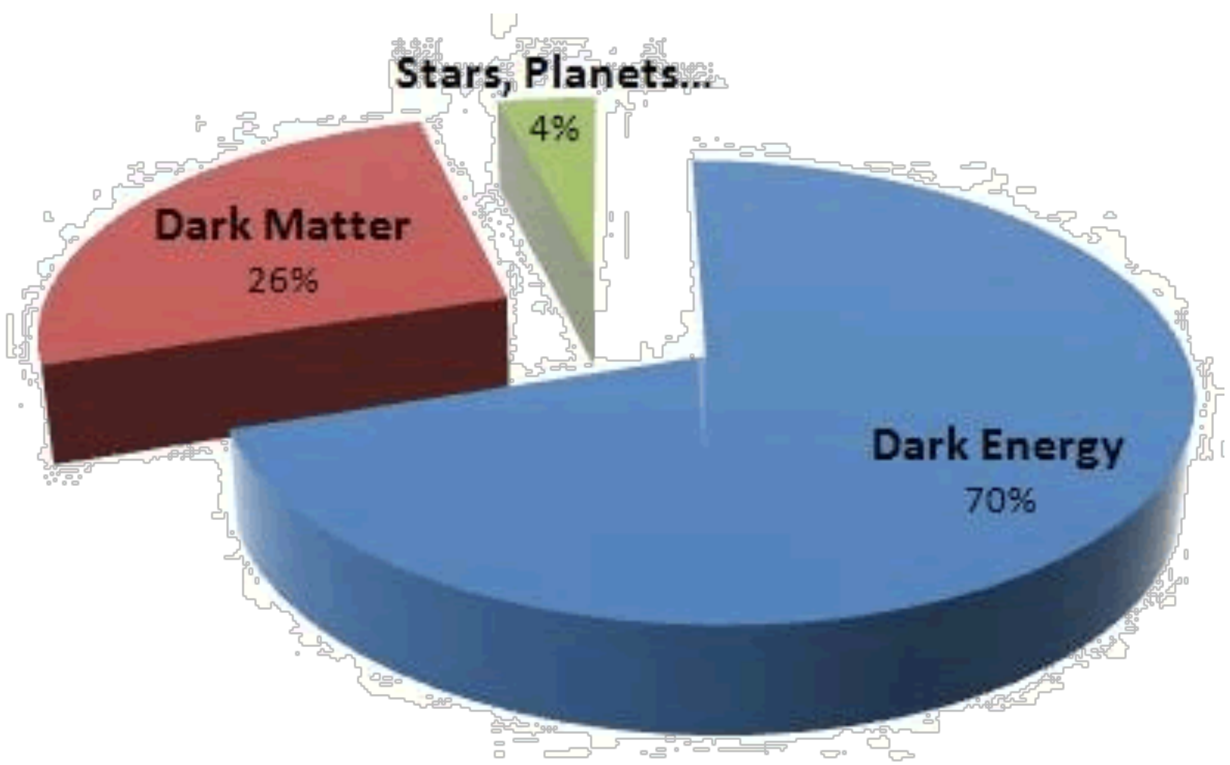
ΛCDM

$g_{\mu\nu}$ + STUFF

Other fundamental ingredients?

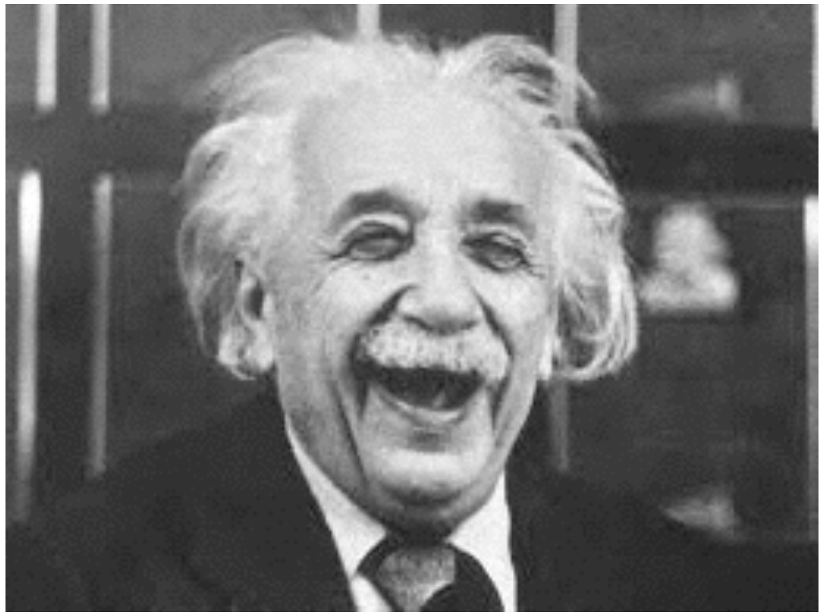


ΛCDM



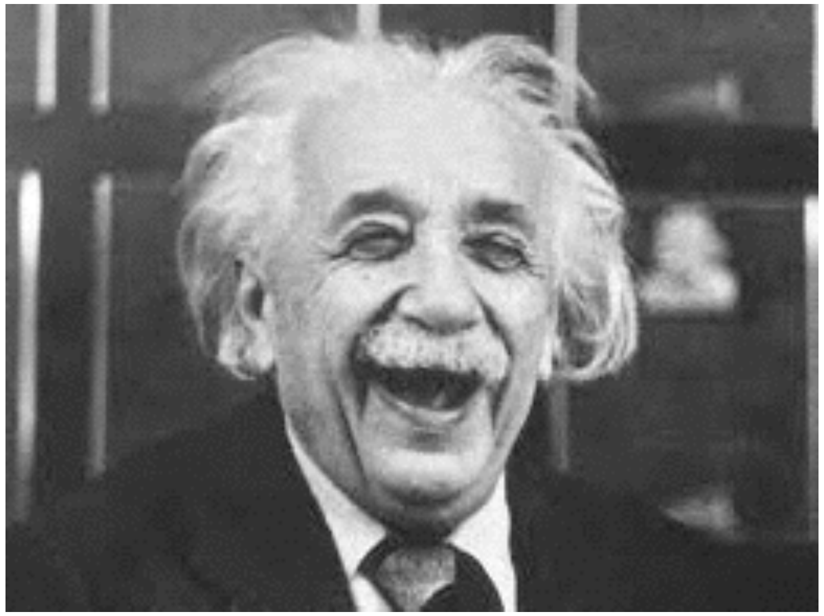
$$\Lambda \sim (10^{-3} eV)^4$$

ΛCDM cosmology



ΛCDM

The only consistent
low energy theory for
a massless spin-two field $g_{\mu\nu}$.

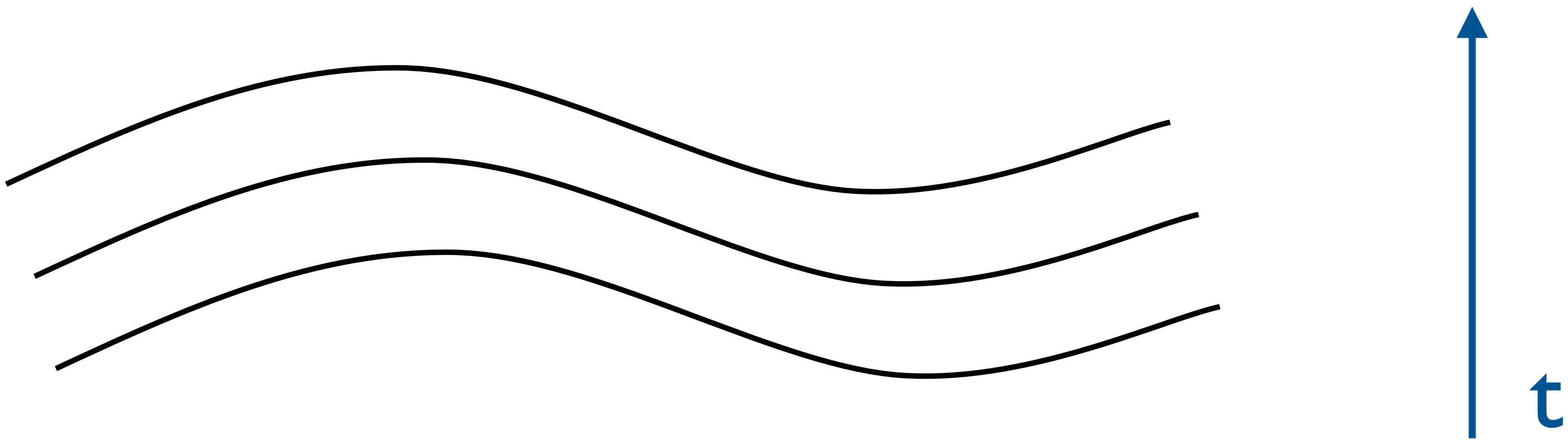


$\Lambda\mathrm{CDM}$

The only consistent
low energy theory for
a massless spin-two field $g_{\mu\nu}$.

$g_{\mu\nu} + \mathrm{STUFF}$

The skeleton of MG

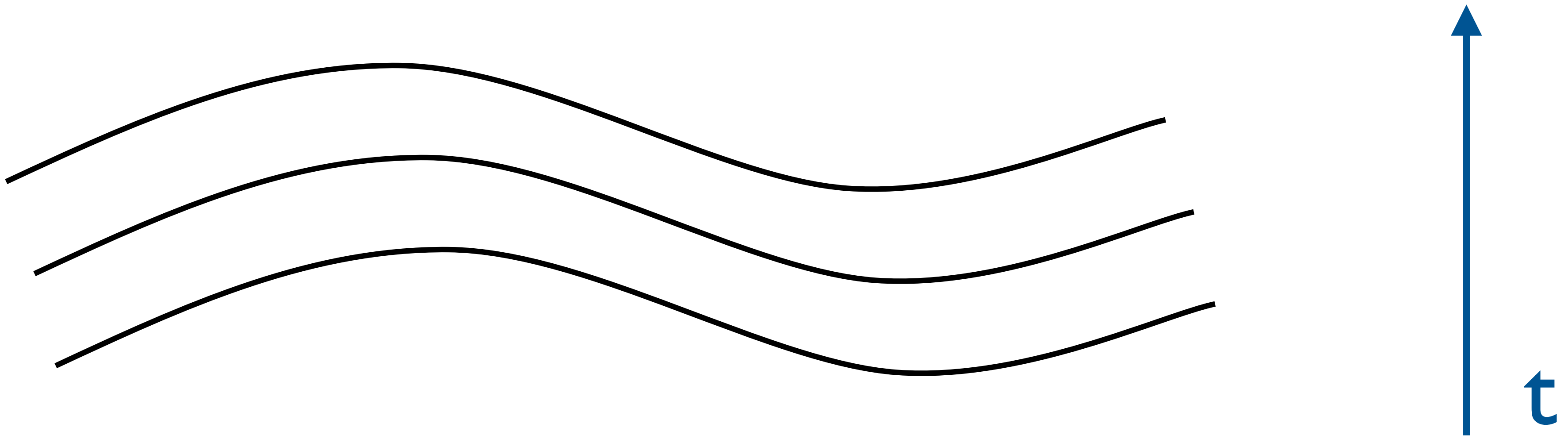


A scalar field, ok, but more importantly (and more deeply?)…
Minkowski:

Internal Charge

$\phi(t)$ K_i H Q

The skeleton of MG

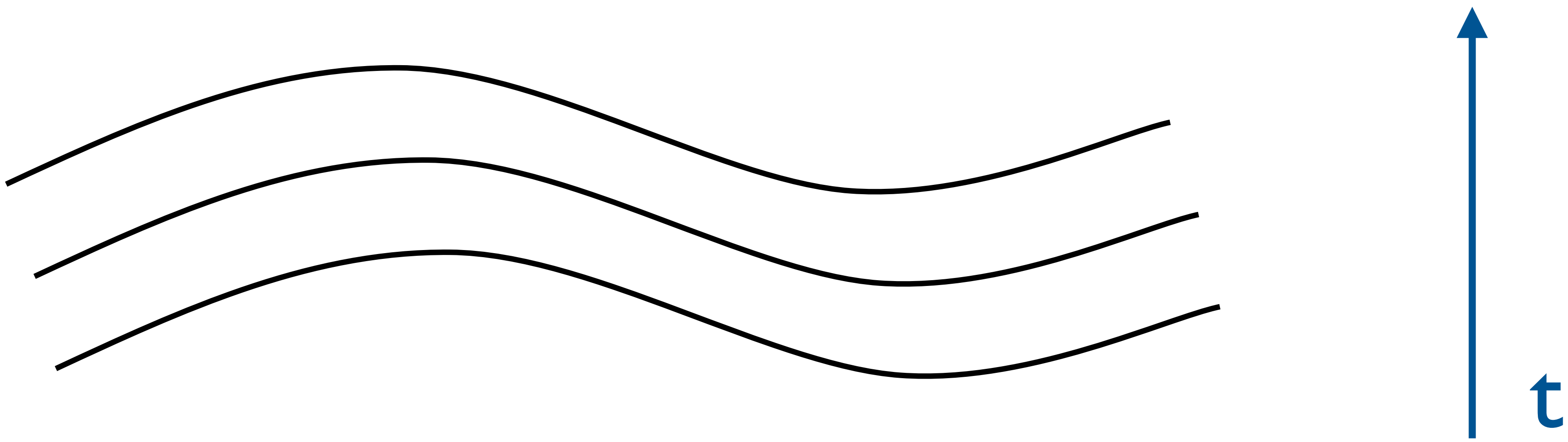


A scalar field, ok, but more importantly (and more deeply?)…
Minkowski:

Internal Charge

$\phi(t)$ ~~K_i~~ H Q

The skeleton of MG



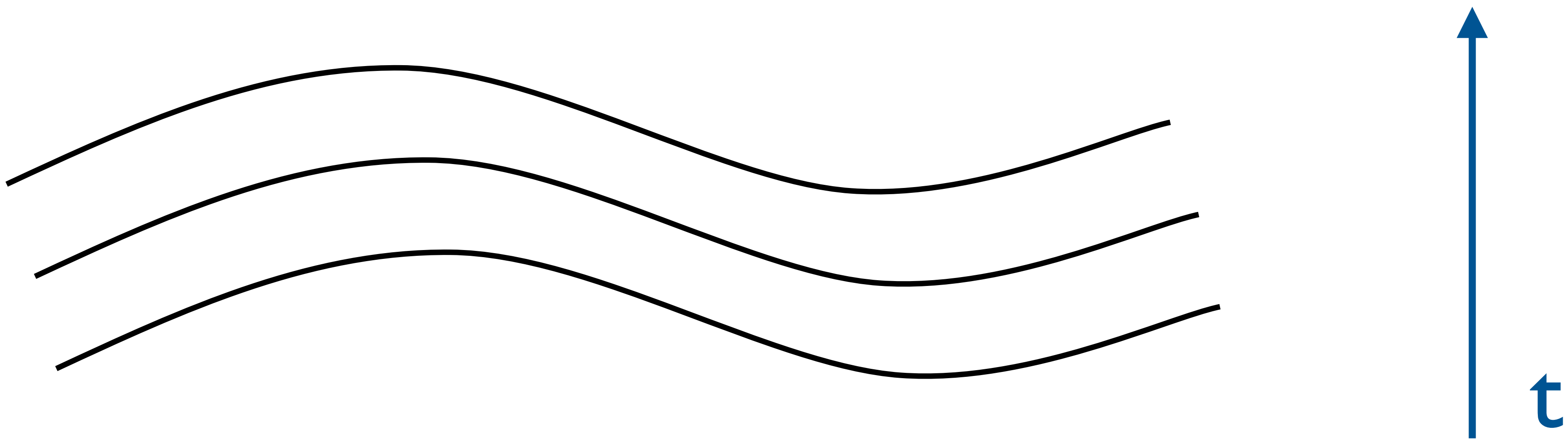
A scalar field, ok, but more importantly (and more deeply?)…
Minkowski:

Internal Charge

$\phi(t)$ ~~K_i~~ ~~H~~ Q

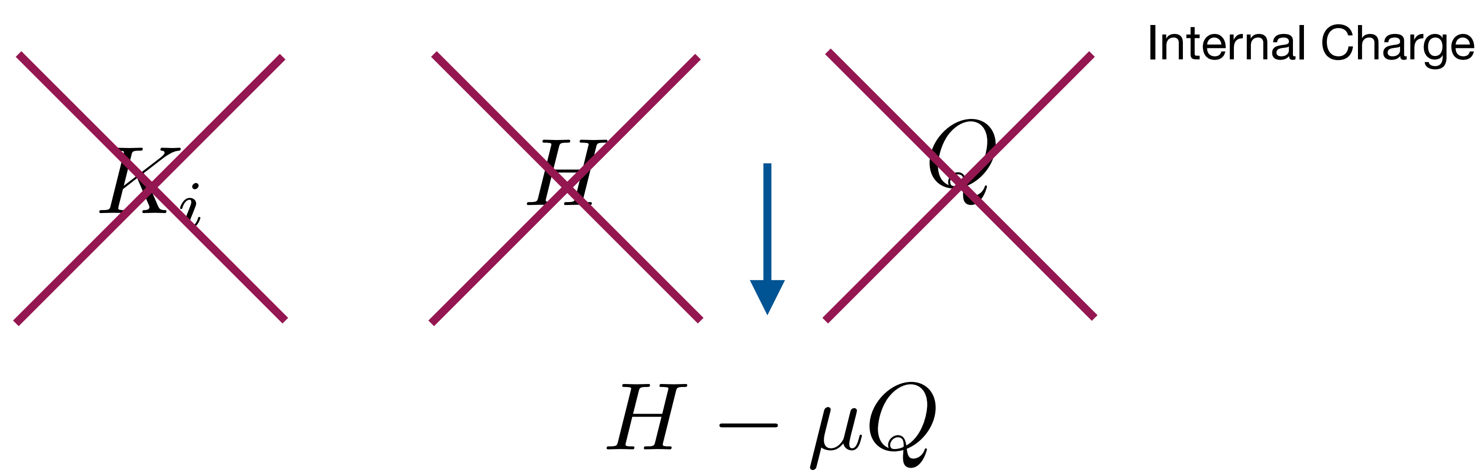
Nicolis, F.P., 2011

The skeleton of MG



A scalar field, ok, but more importantly (and more deeply?)…
Minkowski:

$\phi(t)$



The skeleton of MG: Minkowski theory

- Poincaré invariant theory
- Fields in some representation of Lorentz group
- Boosts spontaneously broken
- Unbroken translations and rotations

The skeleton of MG: Minkowski theory

- Poincaré invariant theory
- Fields in some representation of Lorentz group
- Boosts spontaneously broken
- Unbroken translations and rotations

$$\begin{cases} \bar{P}^{\mu} & \text{translations} \\ \bar{J}^{i} & \text{rotations} \end{cases}$$

$$[\bar{J}_i, \bar{P}_j] = i\epsilon_{ijk}\,\bar{P}_k$$
$$[\bar{J}_i, \bar{J}_j] = i\epsilon_{ijk}\,\bar{J}_k$$

Nicolis, Penco, F.P., Rattazzi, 2015

Classifying Condensed Matter

Full Symmetry group: Poincaré

$$\begin{cases} P^\mu & \text{translations} \\ J^i & \text{rotations} \\ K^i & \text{boosts} \end{cases}$$

+ internal `Q' symmetries

$$\begin{cases} \bar{P}^\mu & \text{translations} \\ \bar{J}^i & \text{rotations} \end{cases}$$

$$[\bar{J}_i, \bar{P}_j] = i\epsilon_{ijk}\, \bar{P}_k$$
$$[\bar{J}_i, \bar{J}_j] = i\epsilon_{ijk}\, \bar{J}_k$$

Nicolis, Penco, F.P., Rattazzi, 2015

Classifying Condensed Matter

Ex:

$$\begin{cases} \bar{H} &= H - \mu Q \\ \bar{P}^i &= P^i \\ \bar{J}^i &= J^i \end{cases}$$

internal symmetry: U(1)

Superfluid

1 Goldstone

$$\langle \phi(x) \rangle = \mu t$$

Nicolis, Penco, F.P., Rattazzi, 2015

Classifying Condensed Matter

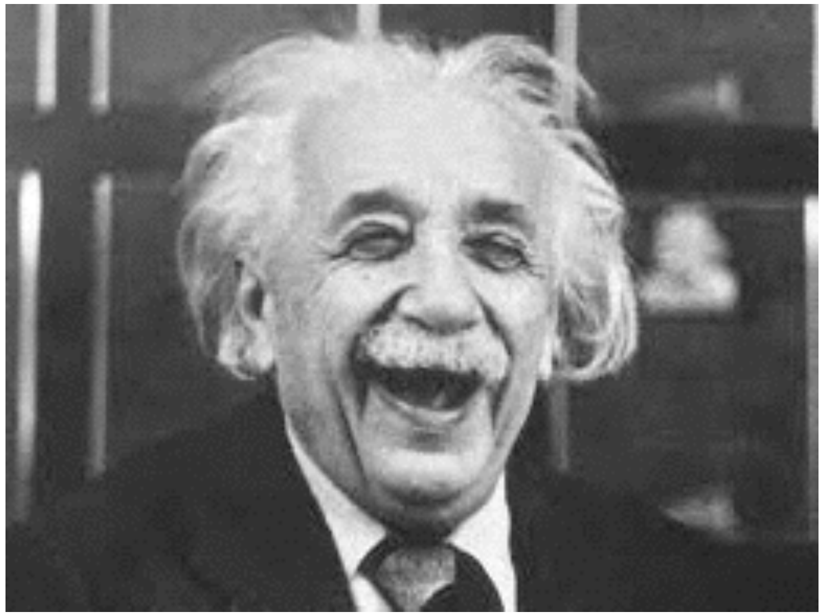
System	Modified generators			# G.B.	Internal symmetries	Extra spacetime symmetries
	P_t	P_i	J_i			
1. type-I framid				3		
2. type-I superfluid	✓			1	$U(1)$	
3. type-I galileid		✓		1		Gal (3+1,1) [4]
4. type-II framid			✓	6	$SO(3)$	
5. type-II galileid	✓	✓		1		Gal (3+1,1) [4]
6. type-II superfluid	✓		✓	4	$SO(3) \times U(1)$	
7. solid		✓	✓	3	$ISO(3)$	
8. supersolid	✓	✓	✓	4	$ISO(3) \times U(1)$	

Condensed matter

superfluids
solids
framids

Cosmology/modified gravity

shift-symmetric scalar
solid inflation
Einstein aether



ΛCDM

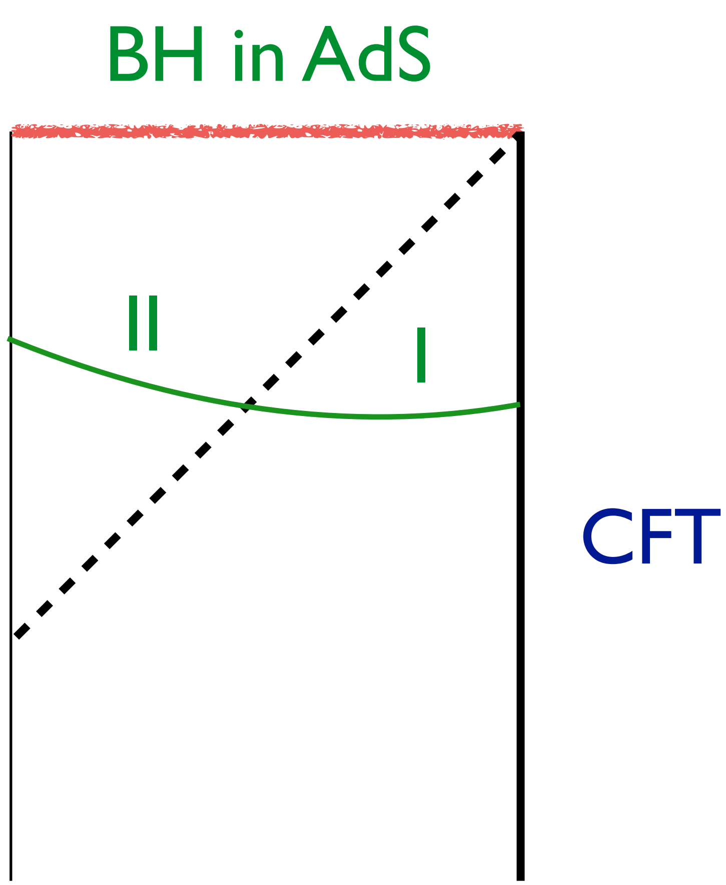
The only consistent low energy theory for a massless spin-two field $g_{\mu\nu}$.


$g_{\mu\nu}$ + STUFF

Other fundamental ingredients?

Where could the EFT 'mantra' be wrong?

Quantum gravity: not necessarily confined to the UV



~~$\mathcal{H} = \mathcal{H}_I \otimes \mathcal{H}_{II}$~~

Inside dof: duplicate of those outside

Papadodimas, Raju, 2012-2016

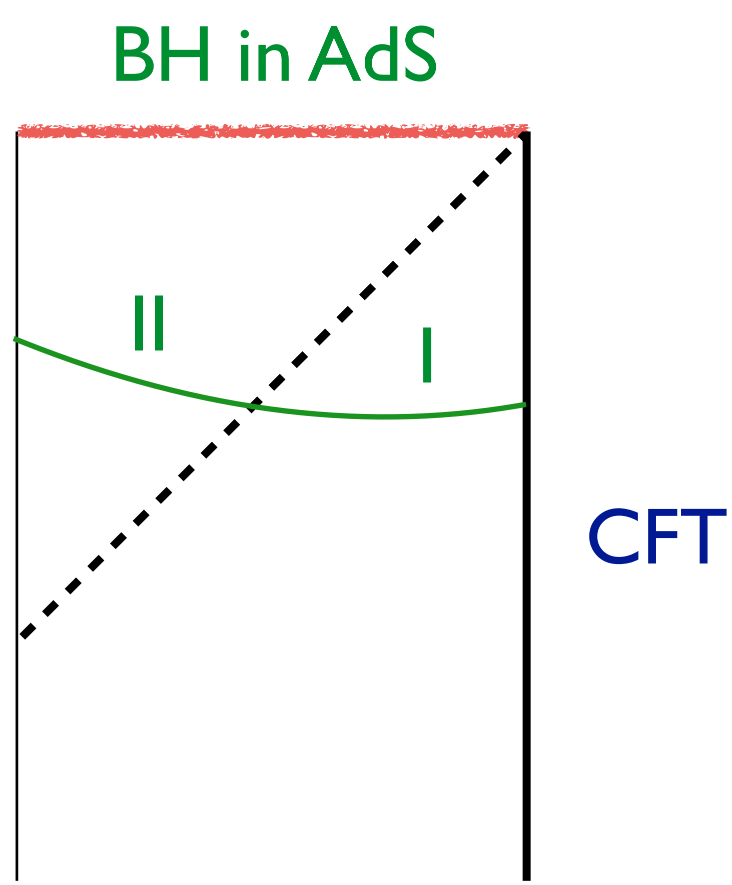
'ER=EPR'

Entanglement defines (and generalizes) spacetime

Susskind, Maldacena, 2013

Where could the EFT ‘mantra’ be wrong?

Quantum gravity: not necessarily confined to the UV



~~$\mathcal{H} = \mathcal{H}_I \otimes \mathcal{H}_{II}$~~

Inside dof: duplicate of those outside

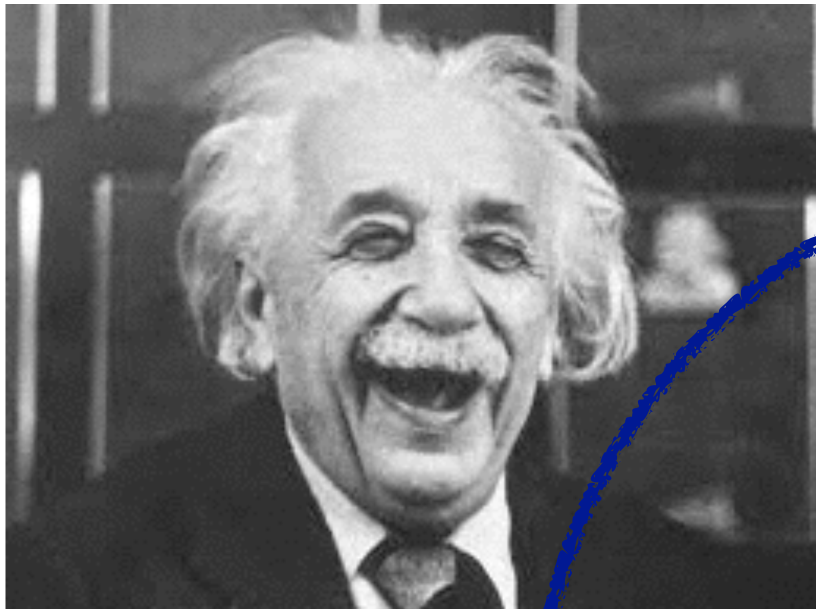
Papadodimas, Raju, 2012-2016

‘ER=EPR’

Entanglement defines (and generalizes) spacetime

Susskind, Maldacena, 2013

In cosmology these effects are expected to be small



ΛCDM

EFT of DE

$+$ a scalar field ϕ

$g_{\mu\nu}$ + ~~STUFF~~

Other fundamental ingredients?

Gubitosi, FP, Vernizzi `12
Gleyzes, Langlois, F.P., Vernizzi `13
F. P., Marinoni, Steigerwald `13

The effective field theory (EFT) of dark energy

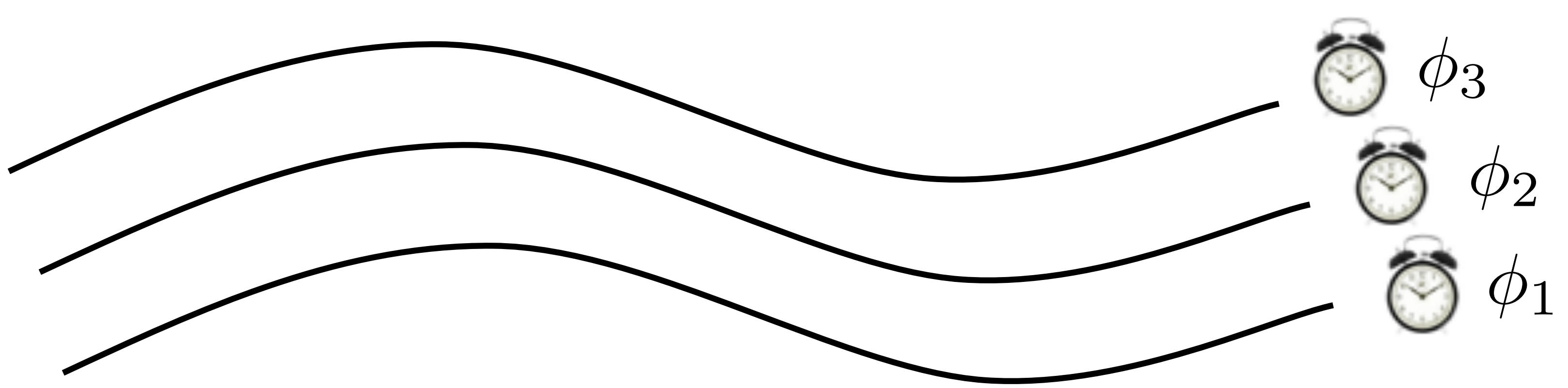
- Most general description of 1 scalar degree of freedom added to GR
- Matter universally coupled (Weak equivalence principle)
- Cosmological perturbations as the relevant objects of the theory
- Background (0th order) and perturbation (linear and +) sectors
- Good parameter space to constrain with data (see Planck 2015)

Unitary gauge in Cosmology (technical detour)

The Effective Field Theory of Inflation (Creminelli et al. `06, Cheung et al. `07)

Main idea: scalar degrees of freedom are `eaten' by the metric. Ex:

$$\phi(t,\vec{x}) \to \phi_0(t) \quad (\delta\phi = 0) \qquad -\frac{1}{2}\partial\phi^2 \to -\frac{1}{2}\dot{\phi}_0^2(t)\ g^{00}$$



Gleyzes, Langlois, F.P., Vernizzi `13

The Action

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2}\, \Big[R \,-\, 2\lambda(t) \,-\, 2\mathcal{C}(t) g^{00}$$

$$+\, \mu_2^2(t)(\delta g^{00})^2 \,-\, \mu_3(t)\, \delta K \delta g^{00} + \,\epsilon_4(t) \left(\delta K^\mu{}_\nu\, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2}\right) \,+ \ldots \Big]$$

Gleyzes, Langlois, F.P., Vernizzi `13

The Action

Background (expansion history)

$$S = \int d^4x \sqrt{-g} \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$

$$\left. + \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\, \delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^{\mu}{}_{\nu}\, \delta K^{\nu}{}_{\mu} - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \dots \right]$$

Gleyzes, Langlois, F.P., Vernizzi `13

The Action

Background (expansion history)

$$S = \int d^4x \sqrt{-g} \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$

$$\left. + \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\,\delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu\, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \dots \right]$$

only affect perturbations

F. P., Steigerwald, Marinoni, `13

Complete background separation

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$

$$\left. + \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\, \delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu\, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \dots \right]$$

$$\lambda(t),\ \mathcal{C}(t),\ \mu(t) \equiv \frac{d \ln M^2(t)}{dt}$$

$\bar{w}(t)$ — Expansion History

$\mu(t)$, $\mu_3(t)$, $\epsilon_4(t)$ — Growth rate, lensing etc.

$\mu_2^2(t)$ — Unconstrained

F. P., Steigerwald, Marinoni, `13

Complete background separation

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \, \Big[R \, - \, 2\lambda(t) \, - \, 2\mathcal{C}(t) g^{00}$$

$$+ \, \mu_2^2(t)(\delta g^{00})^2 \, - \, \mu_3(t)\, \delta K \delta g^{00} + \, \epsilon_4(t) \left(\delta K^\mu{}_\nu \, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)} \, \delta g^{00}}{2} \right) \, + \dots \Big]$$

$$\lambda(t), \; \mathcal{C}(t), \; \mu(t) \equiv \frac{d \ln M^2(t)}{dt}$$

$\bar{w}(t)$ — Expansion History

$\mu(t)$, $\mu_3(t)$, $\epsilon_4(t)$ — Growth rate, lensing etc.

$\mu_2^2(t)$ — Unconstrained

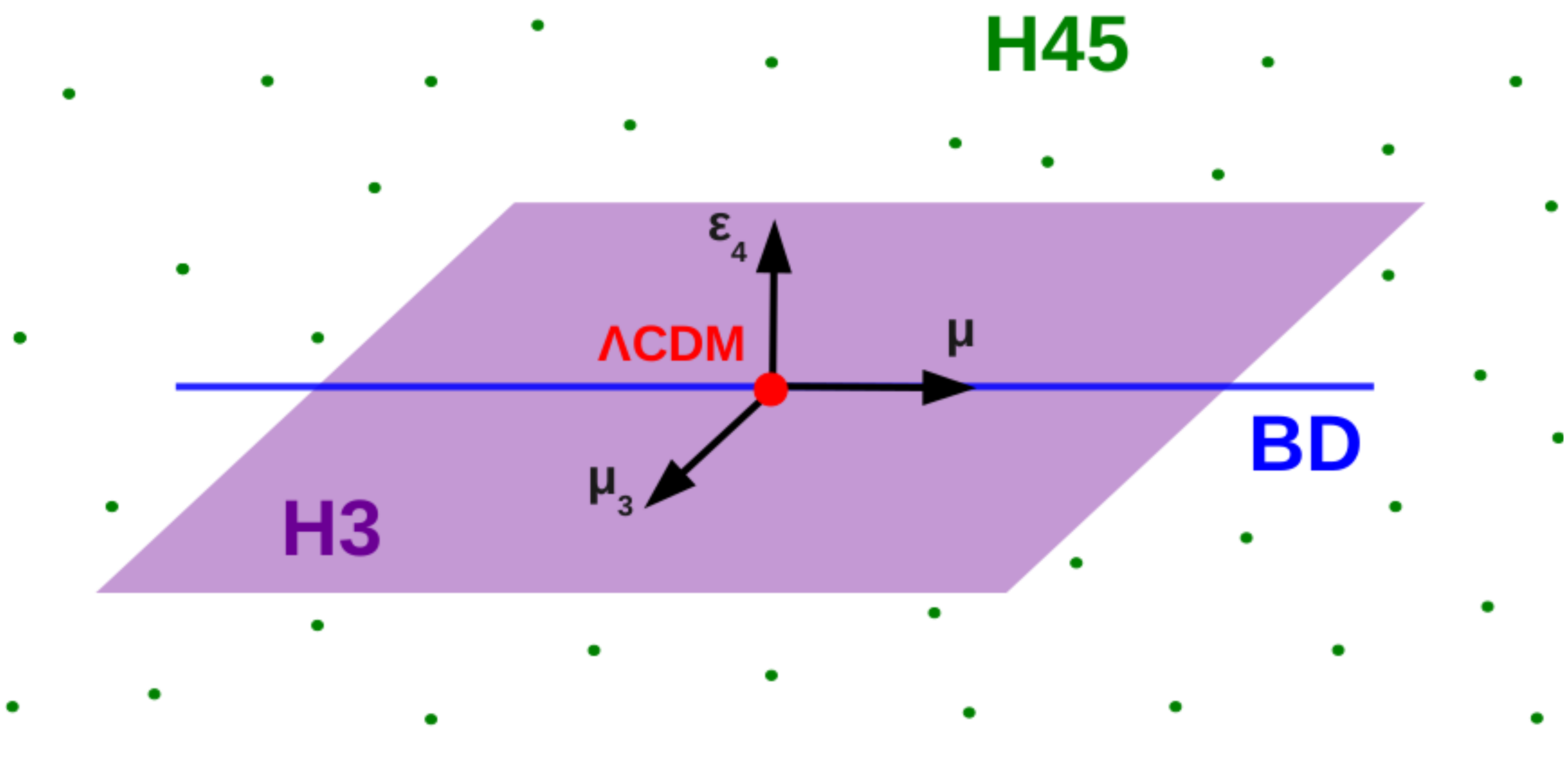
Alternatively

$$\alpha_K(t), \alpha_M(t), \alpha_B(t), \alpha_T(t)$$

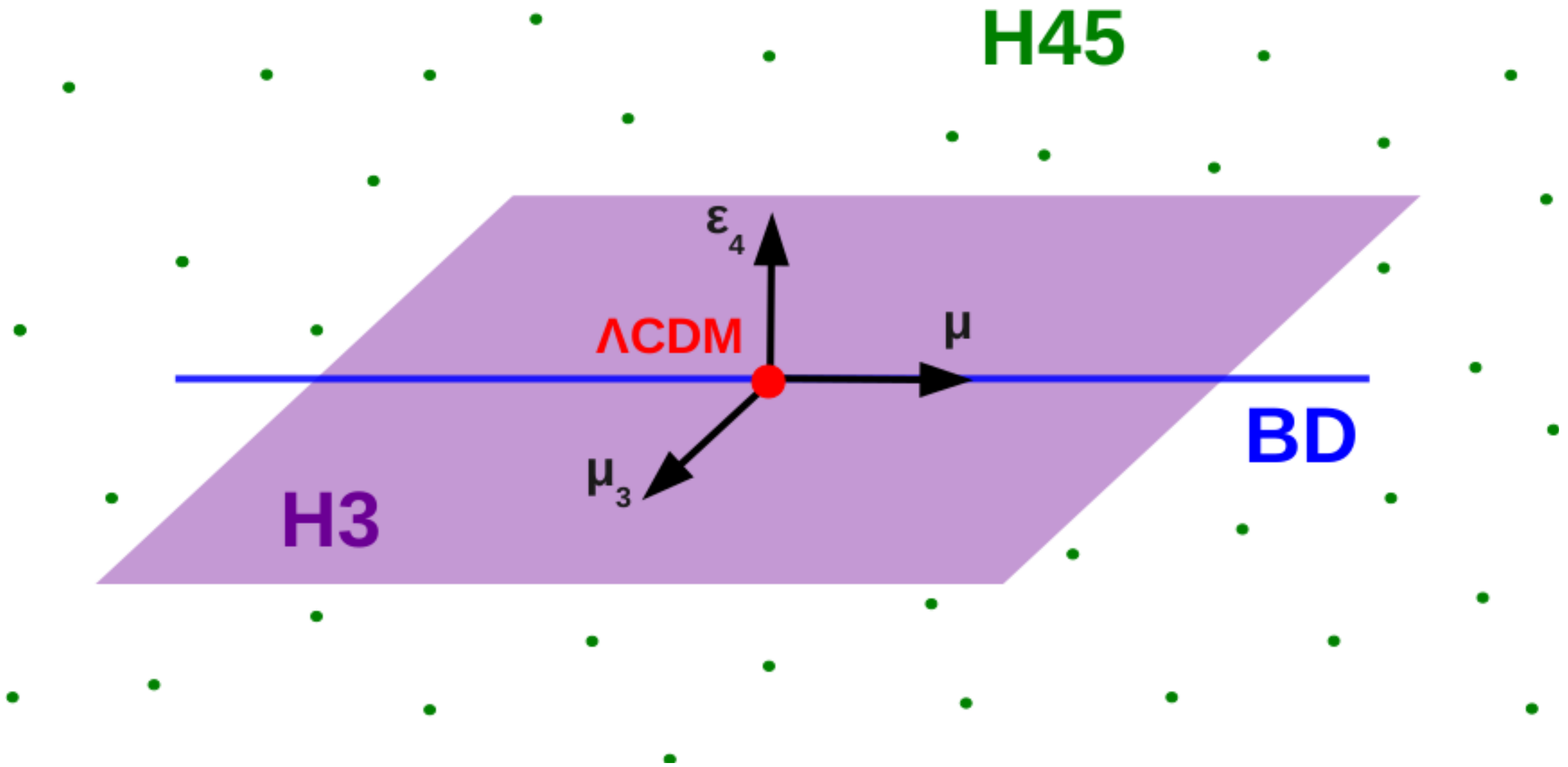
Bellini, Sawicki ’14
Gleyzes, Langlois, F.P., Vernizzi `14
Gleyzes, Langlois, Vernizzi `14

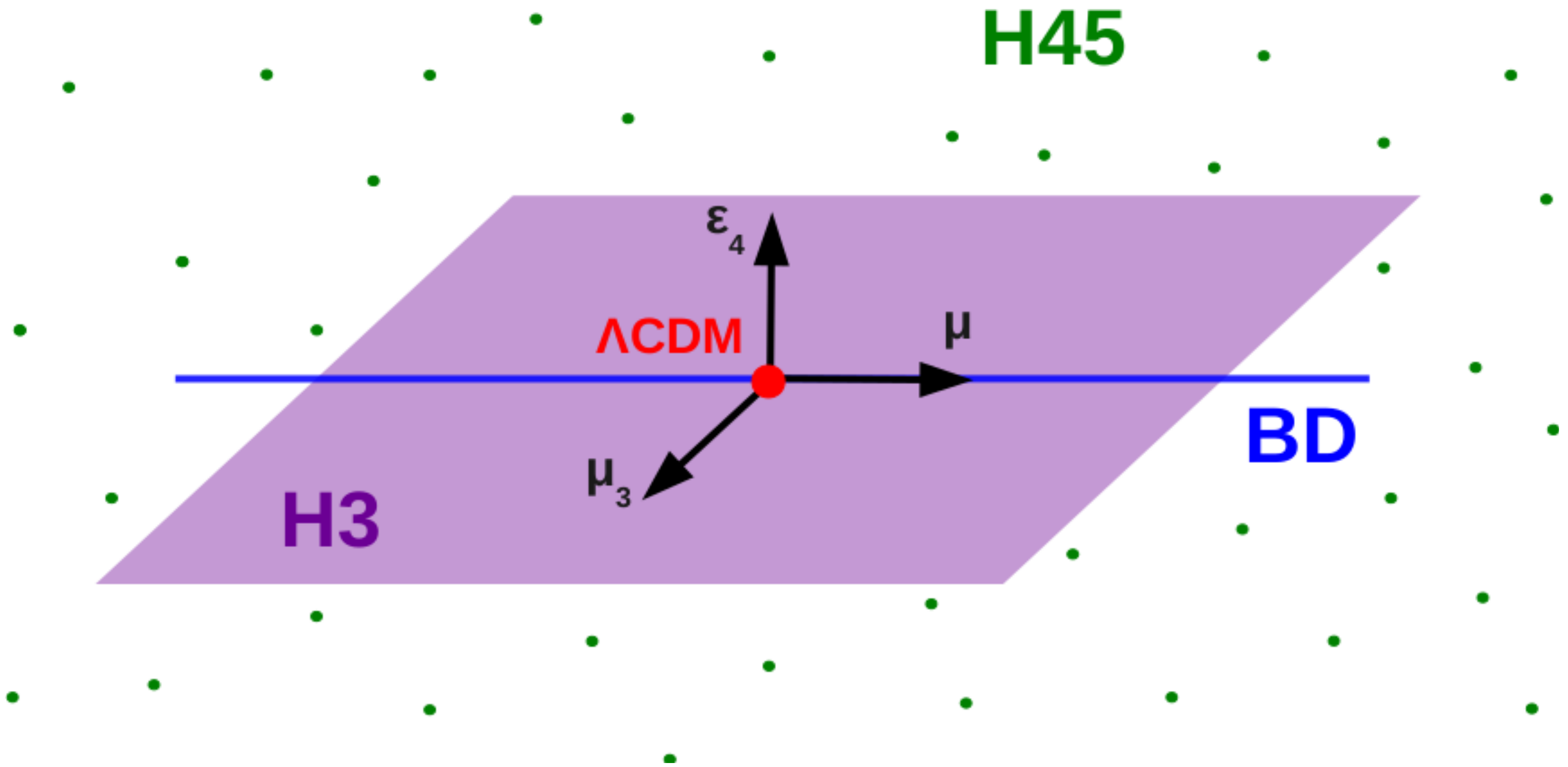
The space of modified gravity

$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$
$$\left. + \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\, \delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu \, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \dots \right]$$



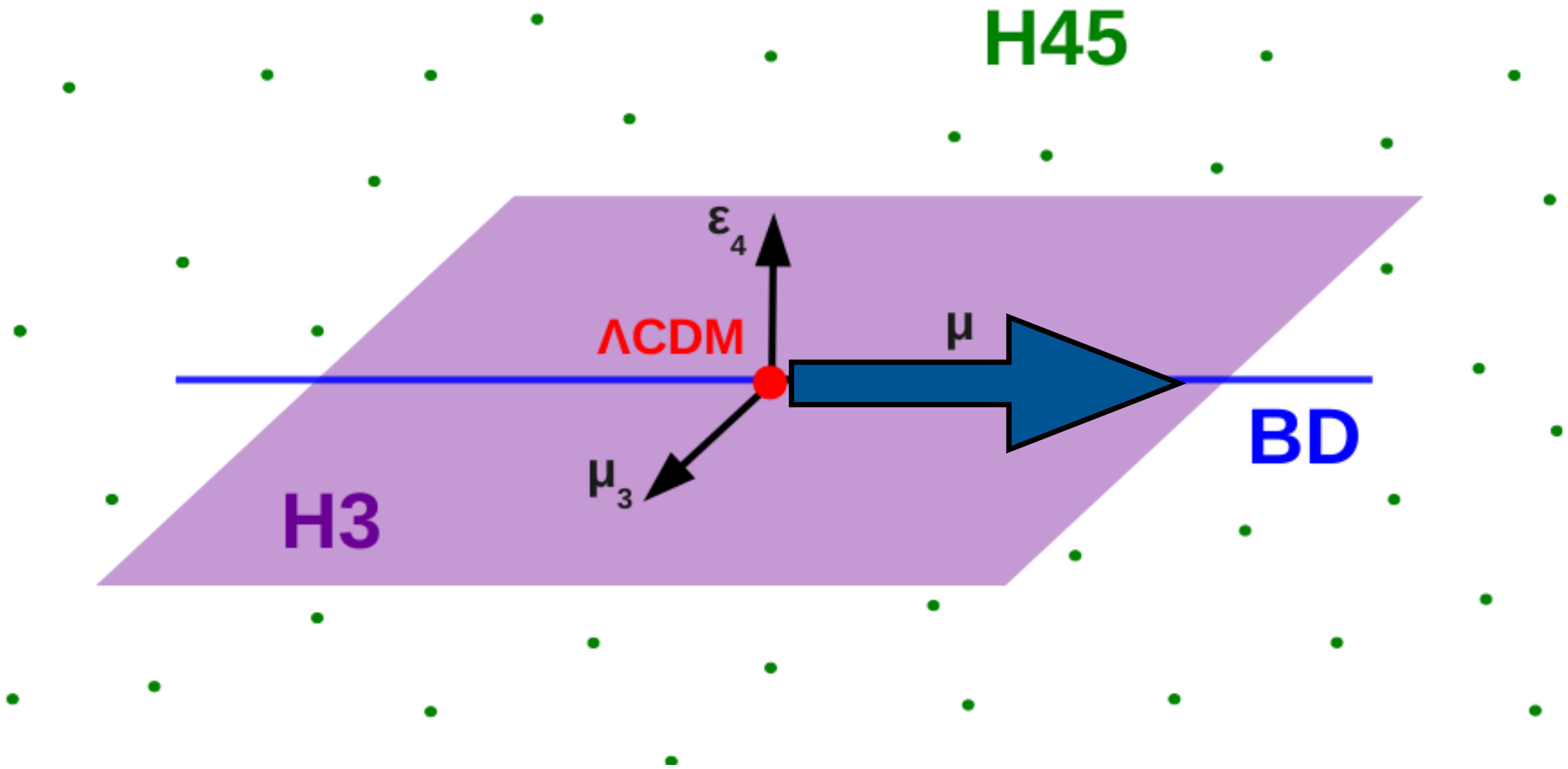
Perenon, F.P., Marinoni, Hui, '15


H45
ε4
ΛCDM
μ
BD
μ3
H3



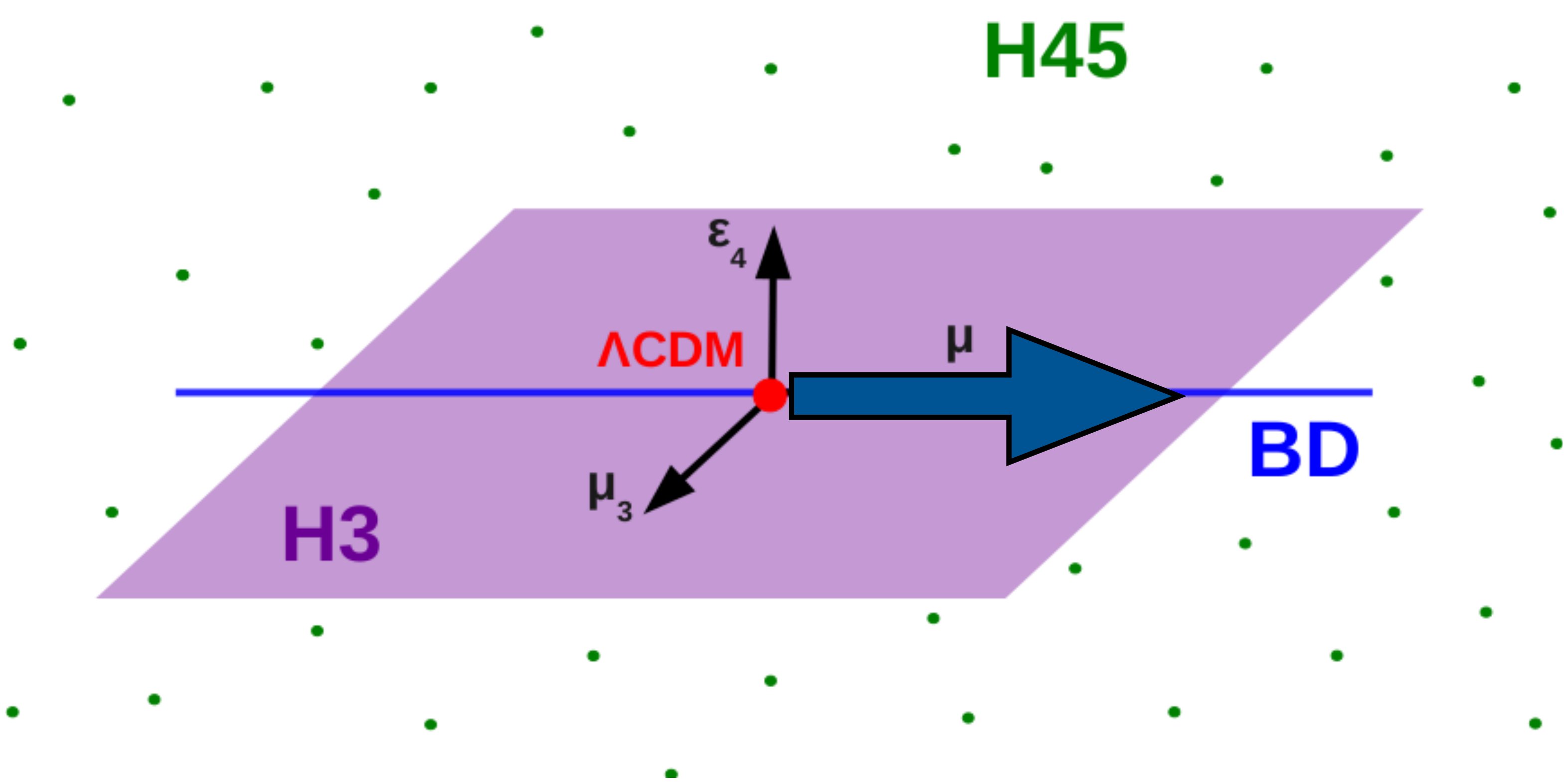
Quintessence
k- essence
etc.

Minimally coupled $(w \neq -1)$



The μ direction (Brans-Dicke, F(R) theories etc.)

$$\mu \equiv \frac{d \log M^2}{dt}$$



The μ direction (Brans-Dicke, F(R) theories etc.)

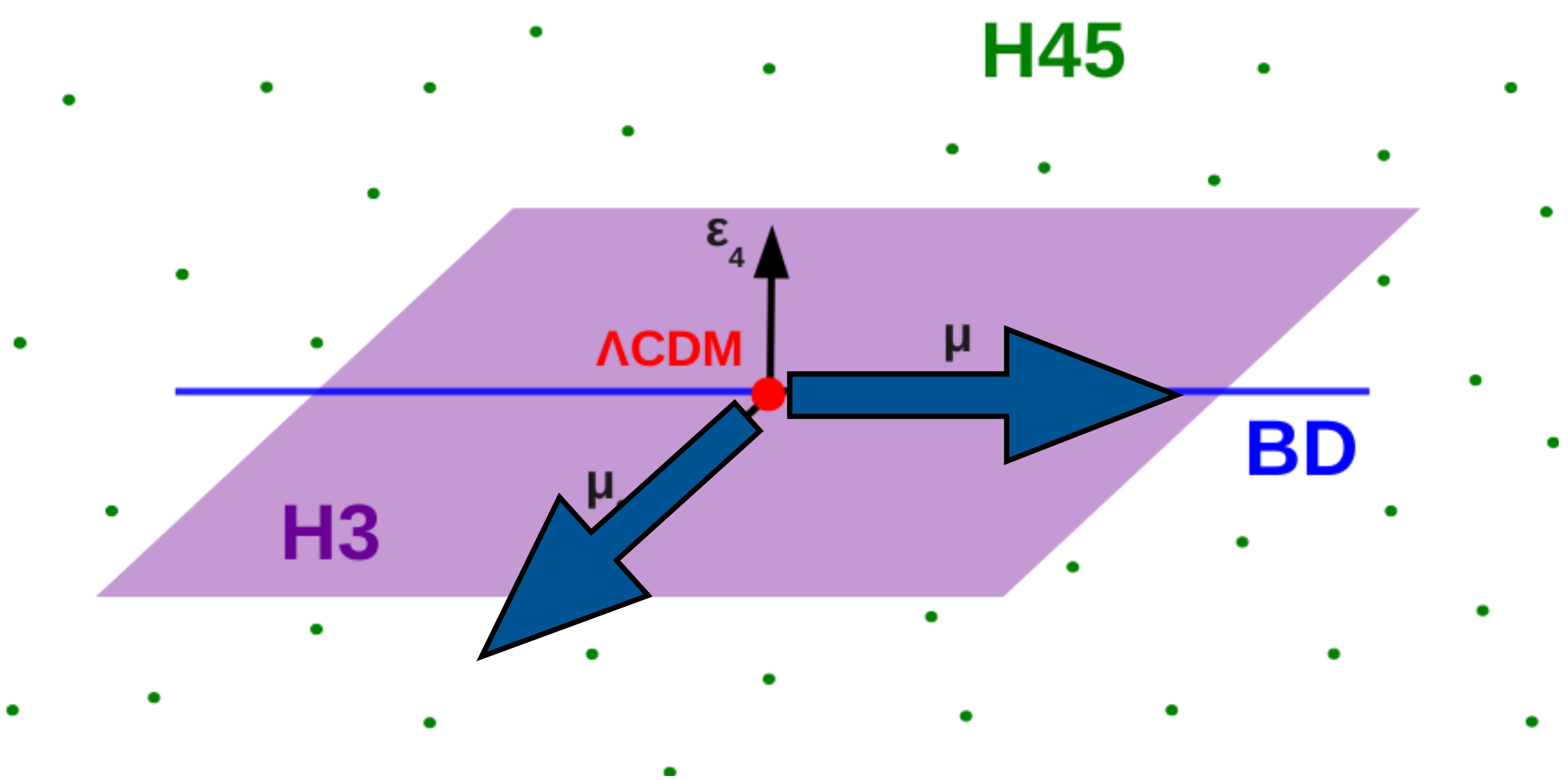
$$\mu \equiv \frac{d \log M^2}{dt}$$

self-acceleration

$$H^2 = \frac{1}{3M^2(t)} \left[\rho_m(t) + \rho_{DE}(t)\right]$$

'normal' negative pressure

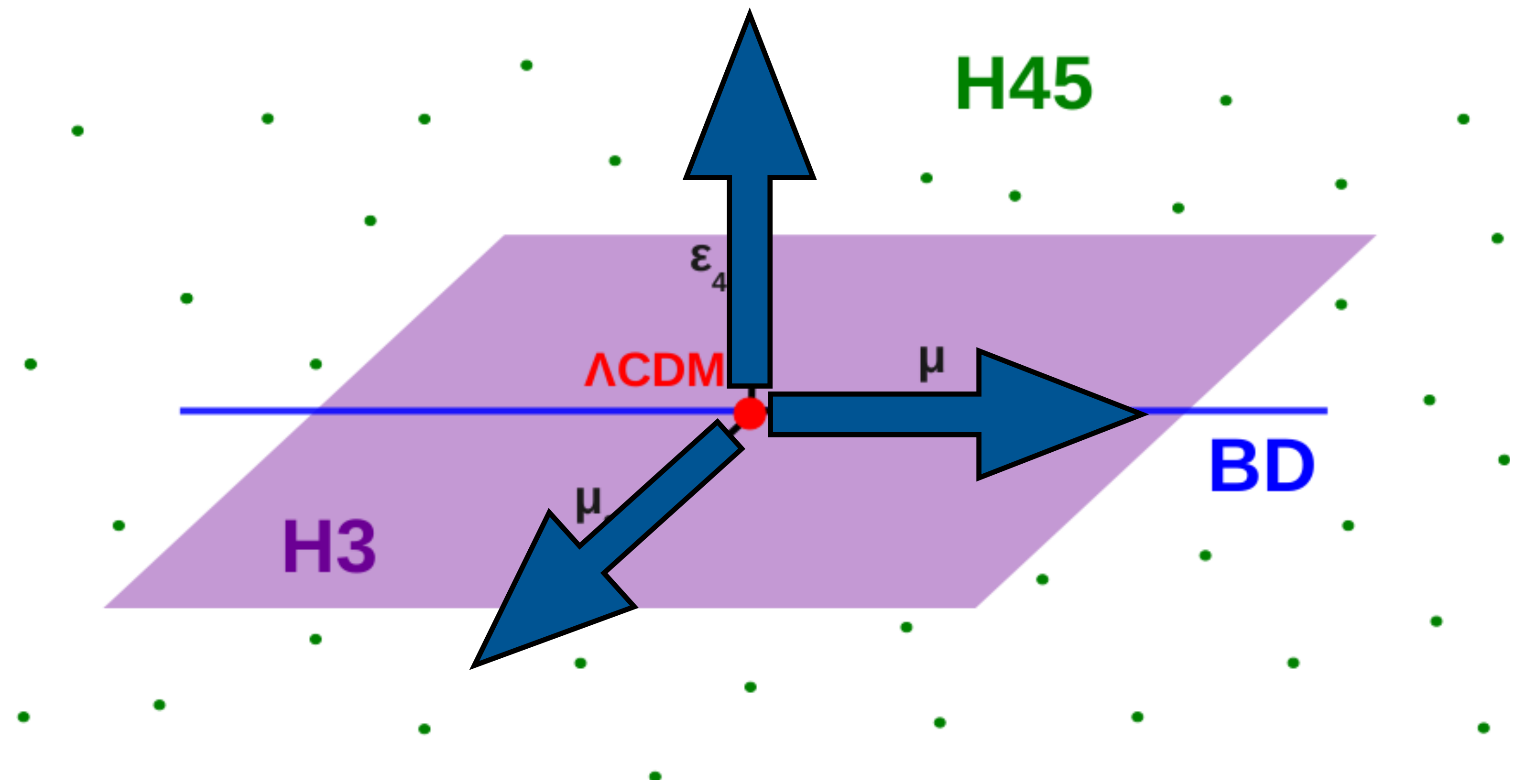
Perenon, F.P., Marinoni, Hui, to appear



The μ3 direction

“Galilean Cosmology” (Chow and Khoury, 2009)

Galileon 3/ Horndeski 3



“Generalized Galileons” (≡ Horndeski)

(Deffayet et al., 2011)

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

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

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

$$\mathcal{L}_5 = D(\phi, X)G^{\mu\nu}\nabla_\mu\nabla_\nu\phi + \frac{1}{3}D_{,X}(\phi, X)\left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right] \ ,$$

Gleyzes, Langlois, F.P., Vernizzi, 1304.4840

The space of modified gravity

$$S = \int d^4x \sqrt{-g} \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$

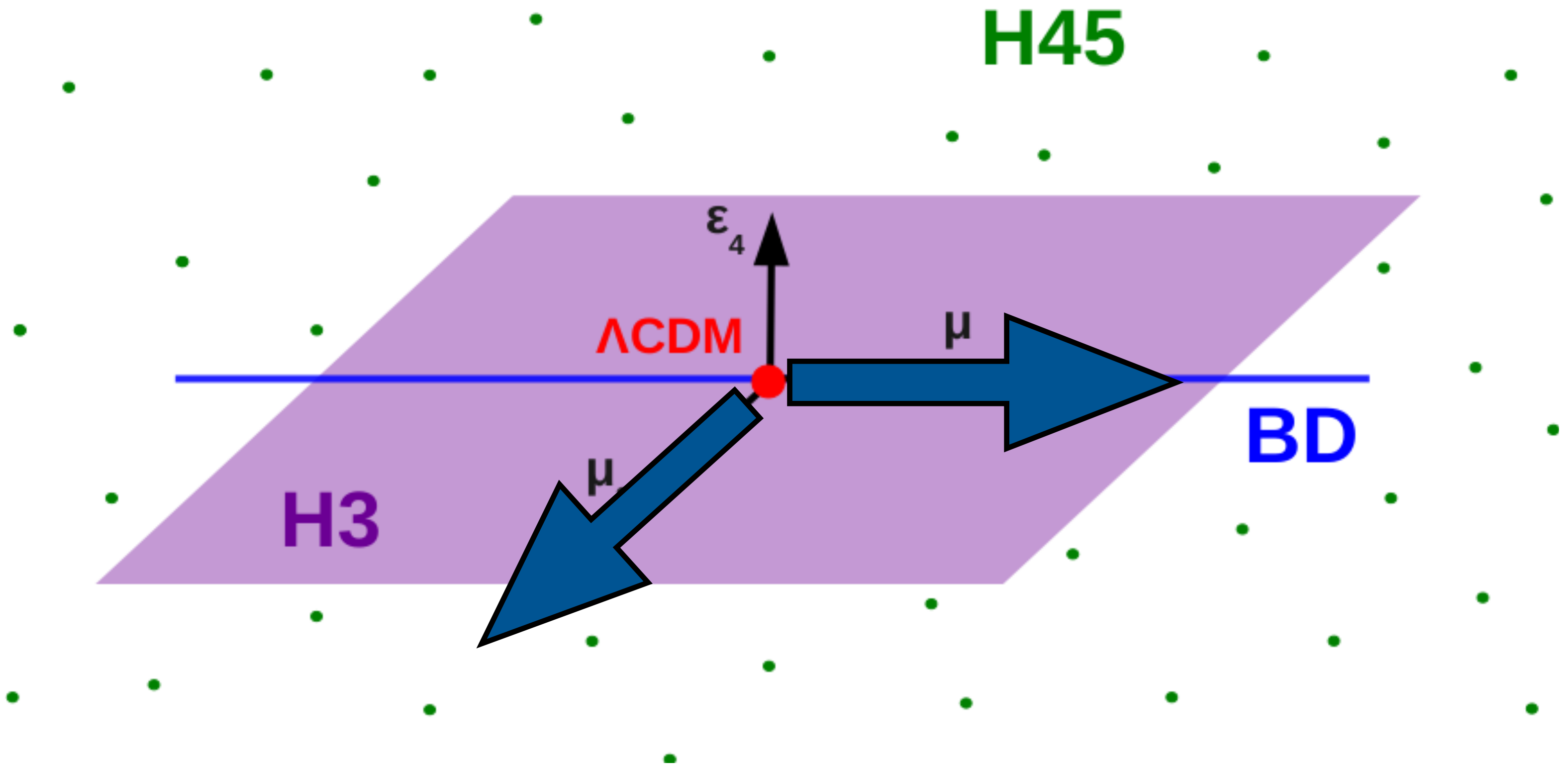
$$\left. + \mu_2^2(t)(\delta g^{00})^2 - \mu_3(t)\, \delta K \delta g^{00} + \epsilon_4(t) \left(\delta K^\mu{}_\nu \, \delta K^\nu{}_\mu - \delta K^2 + \frac{R^{(3)}\, \delta g^{00}}{2} \right) + \dots \right]$$

$\epsilon_4(t)$ $\tilde{\epsilon}_4(t)$

Beyond Horndeski

The most general (linear) theory without higher derivatives on the propagating degree of freedom

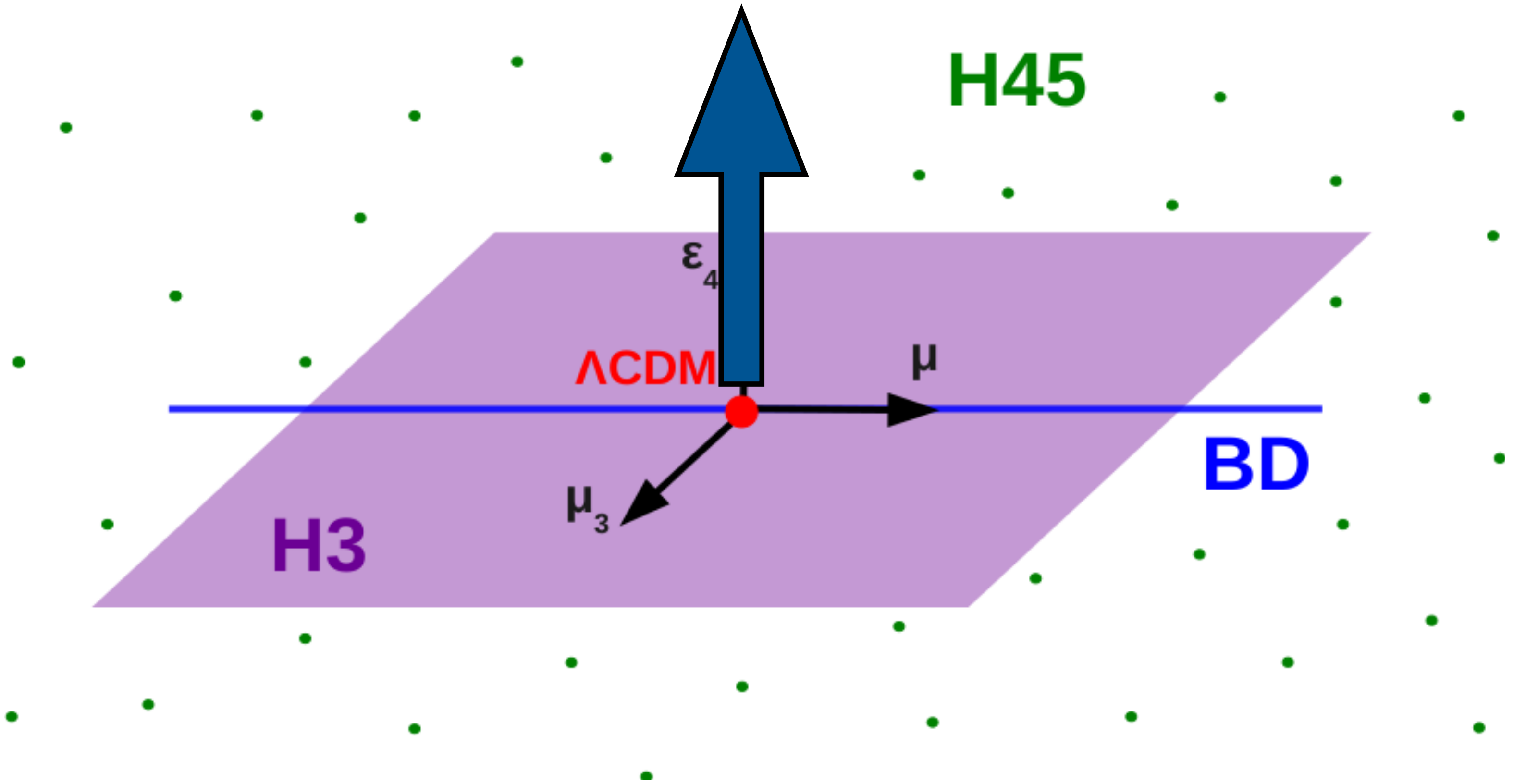
Newtonian gauge: scalar d.o.f.: $\Phi, \Psi, \; \pi$



$$\mathcal{L} \;=\; (\mu - \mu_3)\,\vec{\nabla}\Phi\vec{\nabla}\pi + \ldots$$

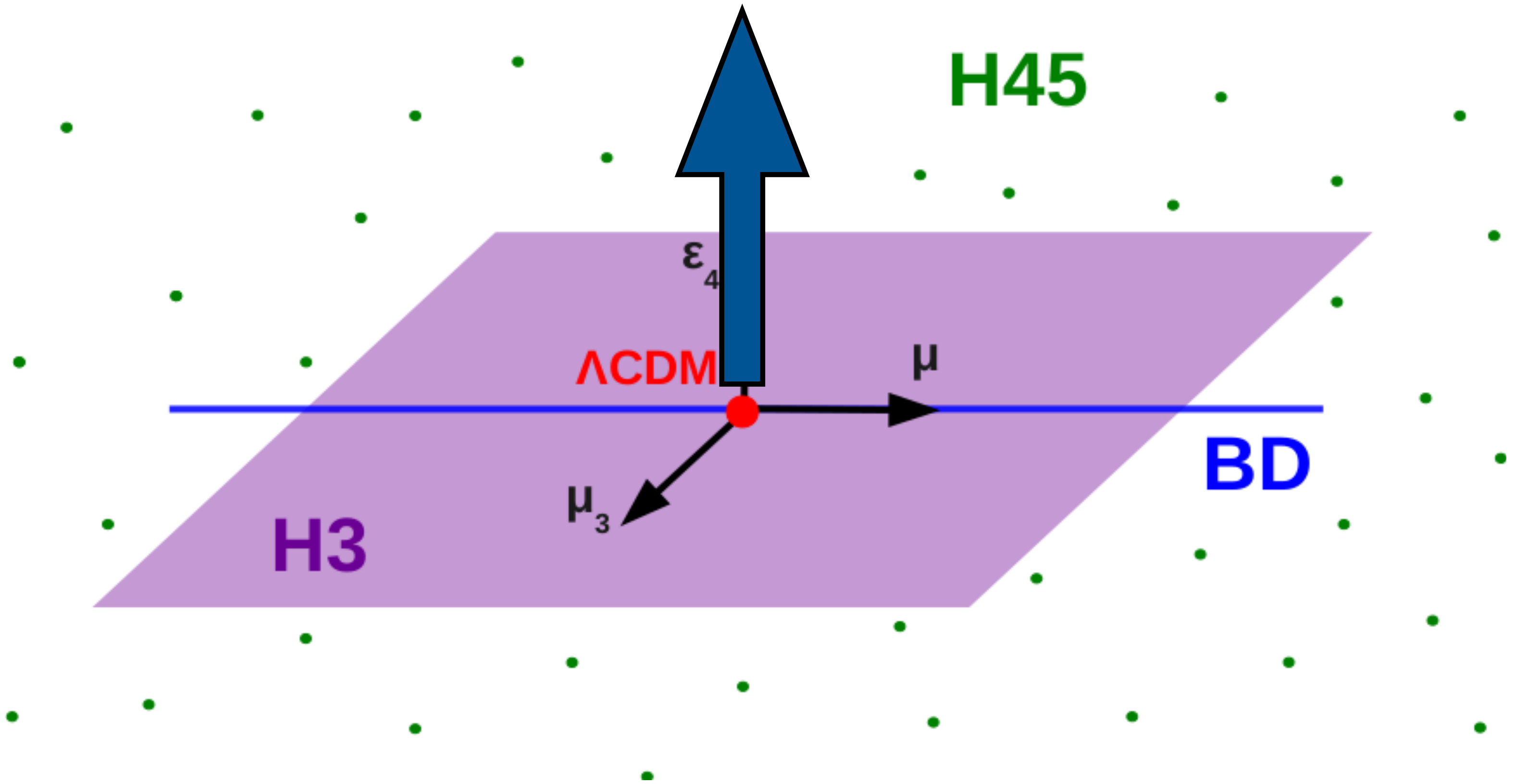
kinetic couplings metric-scalar

Newtonian gauge: scalar d.o.f.: $\Phi, \Psi, \ \pi$



$$\mathcal{L} = (\dot{\epsilon}_4 + H\epsilon_4)\vec{\nabla}\Psi\vec{\nabla}\pi$$

Newtonian gauge: scalar d.o.f.: $\Phi, \Psi, \ \pi$

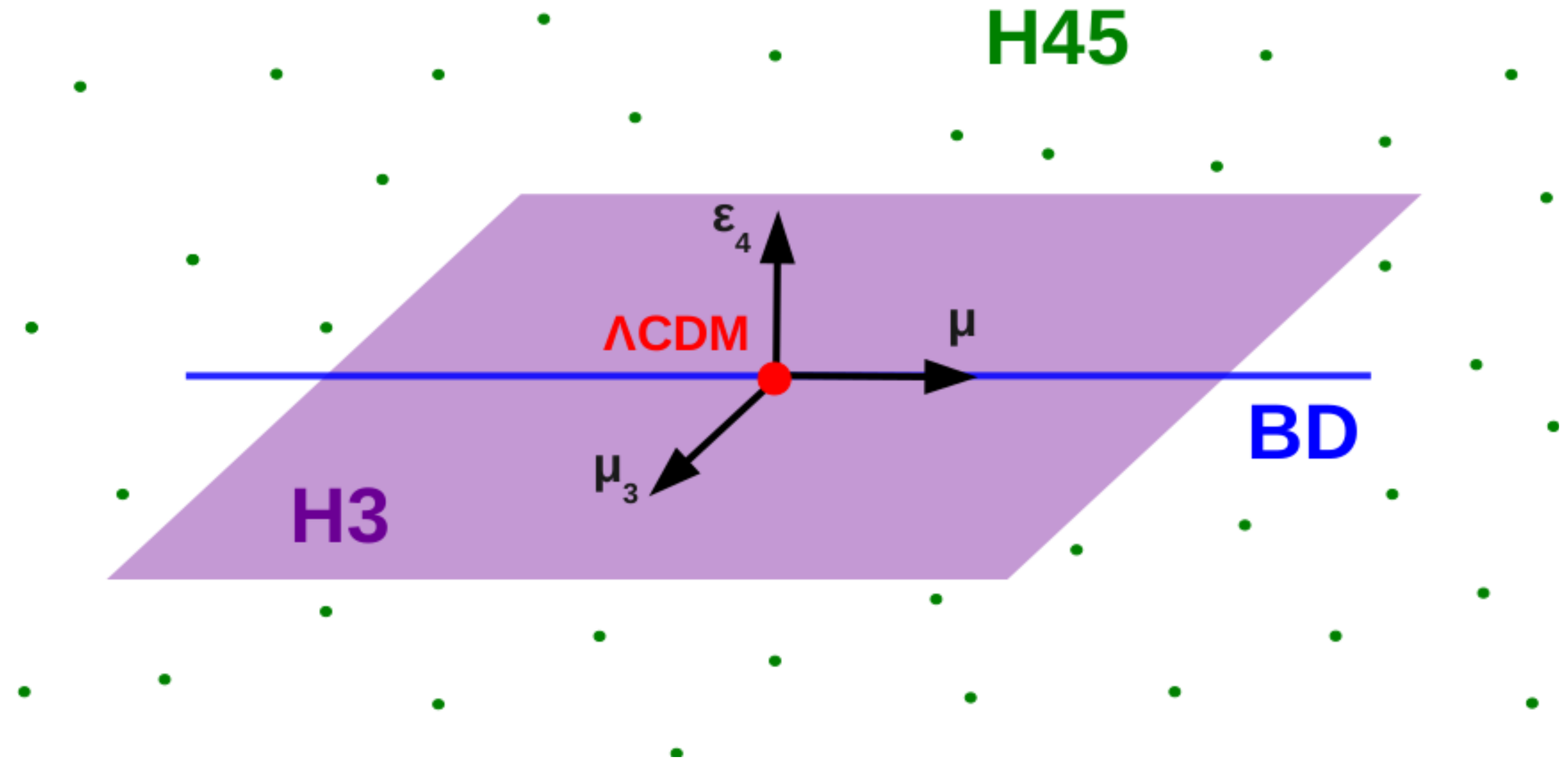


$$\mathcal{L} = (\dot{\epsilon}_4 + H\epsilon_4)\vec{\nabla}\Psi\vec{\nabla}\pi$$

$$c_T^2 = \frac{1}{1+\epsilon_4}$$

but also: speed of gravitational waves!

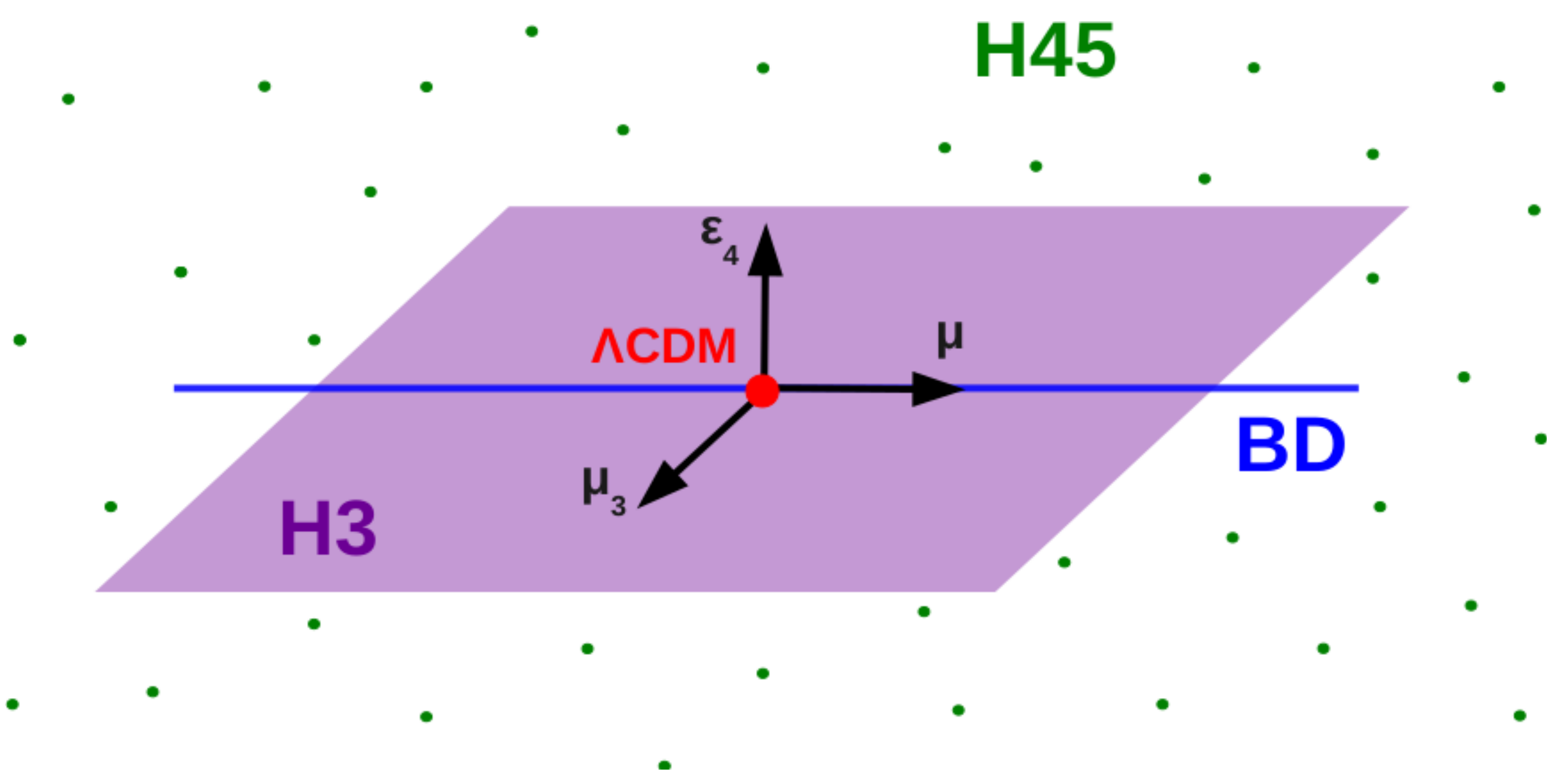
Newtonian gauge: scalar d.o.f.: $\Phi, \Psi, \ \pi$



`Observables' in the perturbation sector:
effective Newton constant and gravitational slip parameter

$$-\frac{k^2}{a^2}\Phi = 4\pi G_{\rm eff}[\mu, \mu_3, \epsilon_4](t) \ \rho_m \delta_m$$

$$\frac{\Psi}{\Phi} = \gamma[\mu, \mu_3, \epsilon_4](t)$$



The space of theories: not so smooth…

F. P., Steigerwald, Marinoni, `13

Stability conditions

$$S_\pi = \int a^3(t) M^2(t) \left[A\left(\mu, \mu_2^2, \mu_3, \epsilon_4\right) \dot{\pi}^2 + B\left(\mu, \mu_3, \epsilon_4\right) \frac{(\vec{\nabla}\pi)^2}{a^2} \right] + \text{lower order in derivatives.}$$

No ghost: A>0

No gradient instabilities: B<0

F. P., Steigerwald, Marinoni, `13

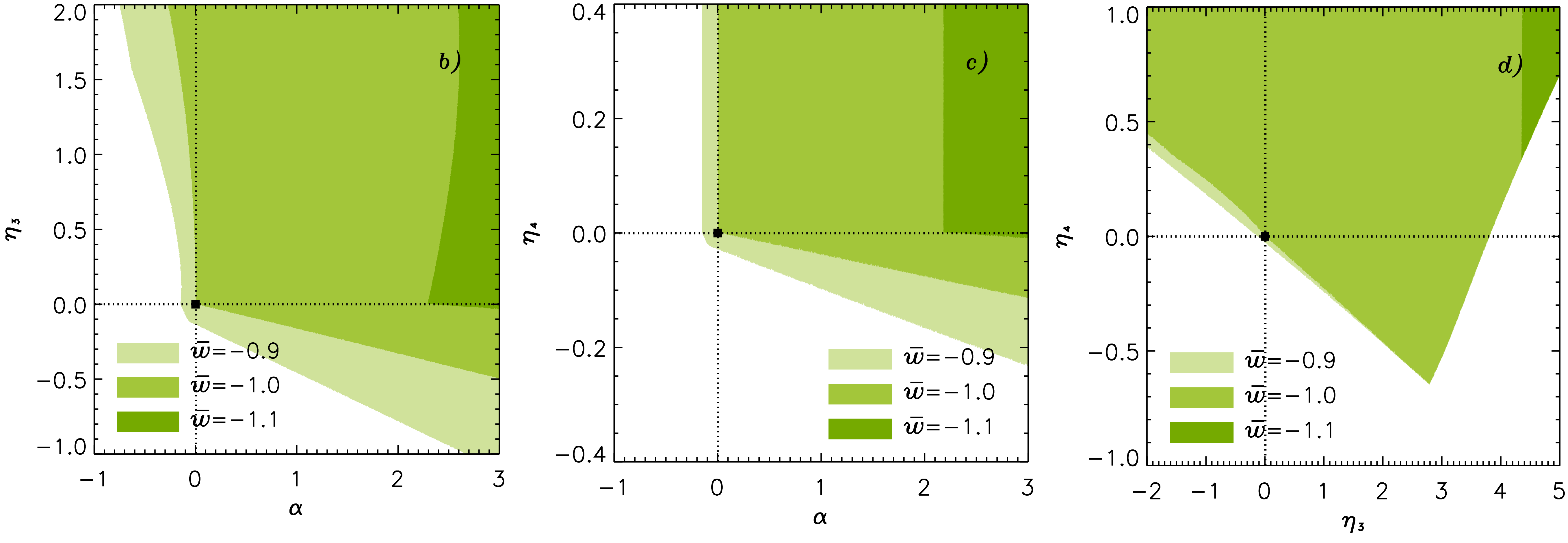
Stability conditions

$$S_\pi = \int a^3(t) M^2(t) \left[A\left(\mu, \mu_2^2, \mu_3, \epsilon_4\right) \dot{\pi}^2 + B\left(\mu, \mu_3, \epsilon_4\right) \frac{(\vec{\nabla}\pi)^2}{a^2} \right] + \text{lower order in derivatives.}$$

No ghost: A>0

No gradient instabilities: B<0

$\mu_2^2 = 0$



Perenon, F.P., Marinoni, Hui ’15
Salvatelli, F.P., Marinoni, ‘16

Stability conditions

$$S_\pi = \int a^3(t) M^2(t) \left[A\left(\mu, \mu_2^2, \mu_3, \epsilon_4\right) \dot{\pi}^2 + B\left(\mu, \mu_3, \epsilon_4\right) \frac{(\vec{\nabla}\pi)^2}{a^2} \right] + \text{lower order in derivatives.}$$

No ghost: A>0

No gradient instabilities: B<0

Basic requirement

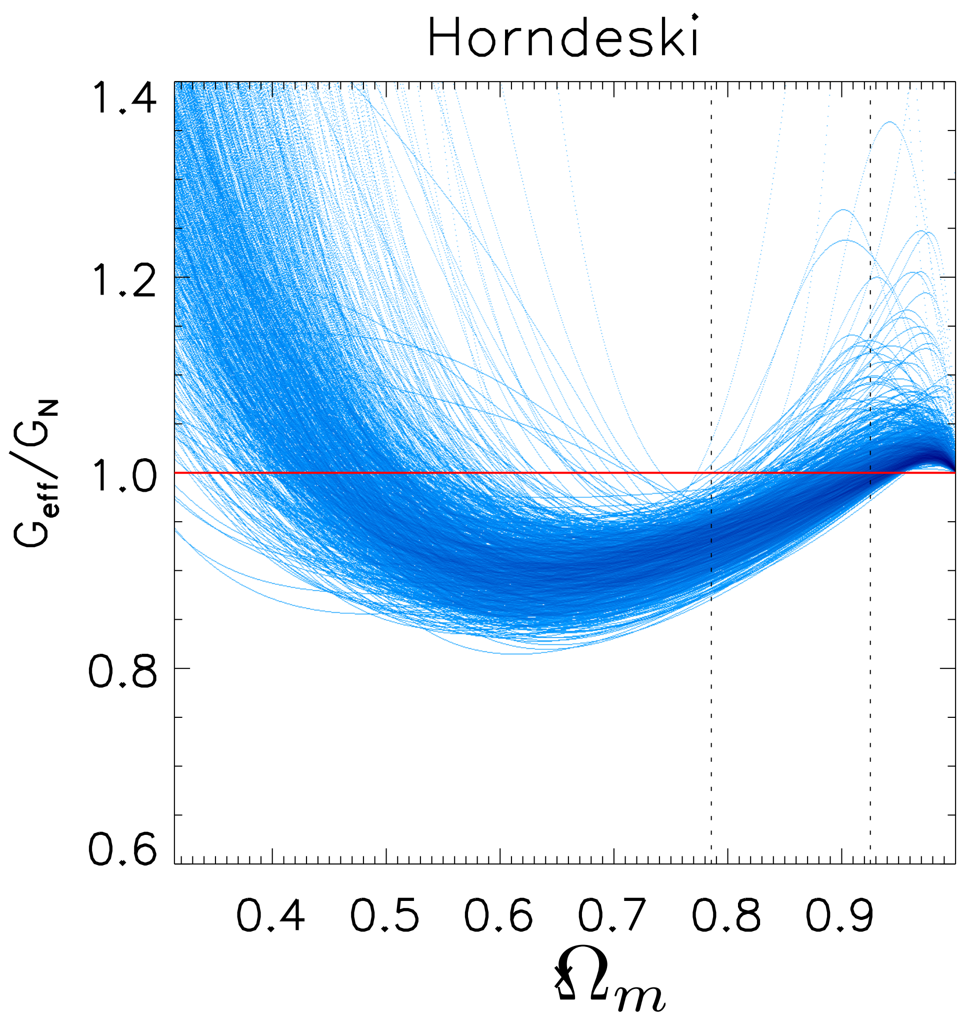
Option 1: $\&\ \ c_s^2 < 1$

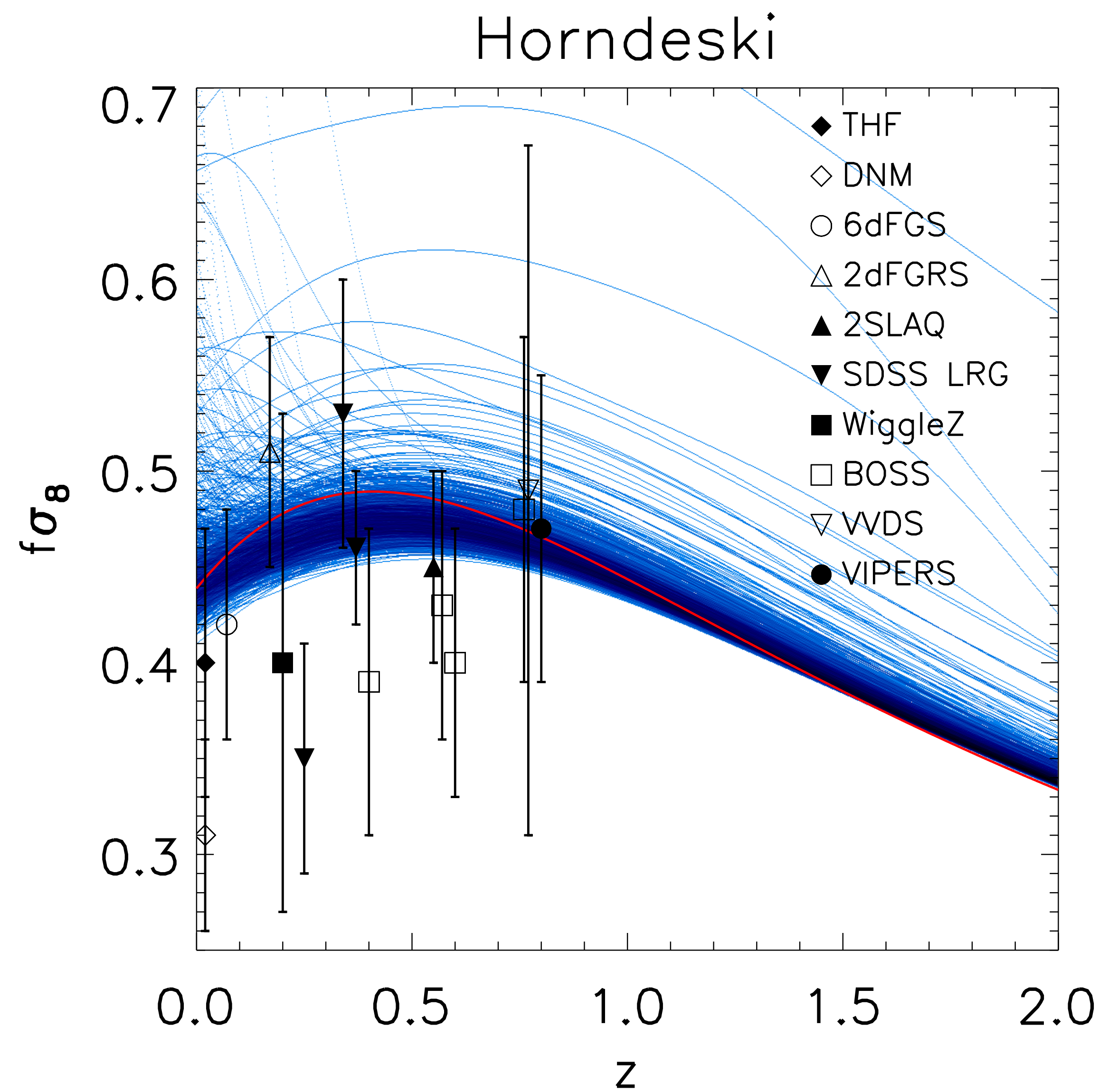
Option 2: $\&\ \ c_T^2 < 1$

Stability requirements make a strong selection

L. Perenon, F.P., C. Marinoni, L. Hui, '15

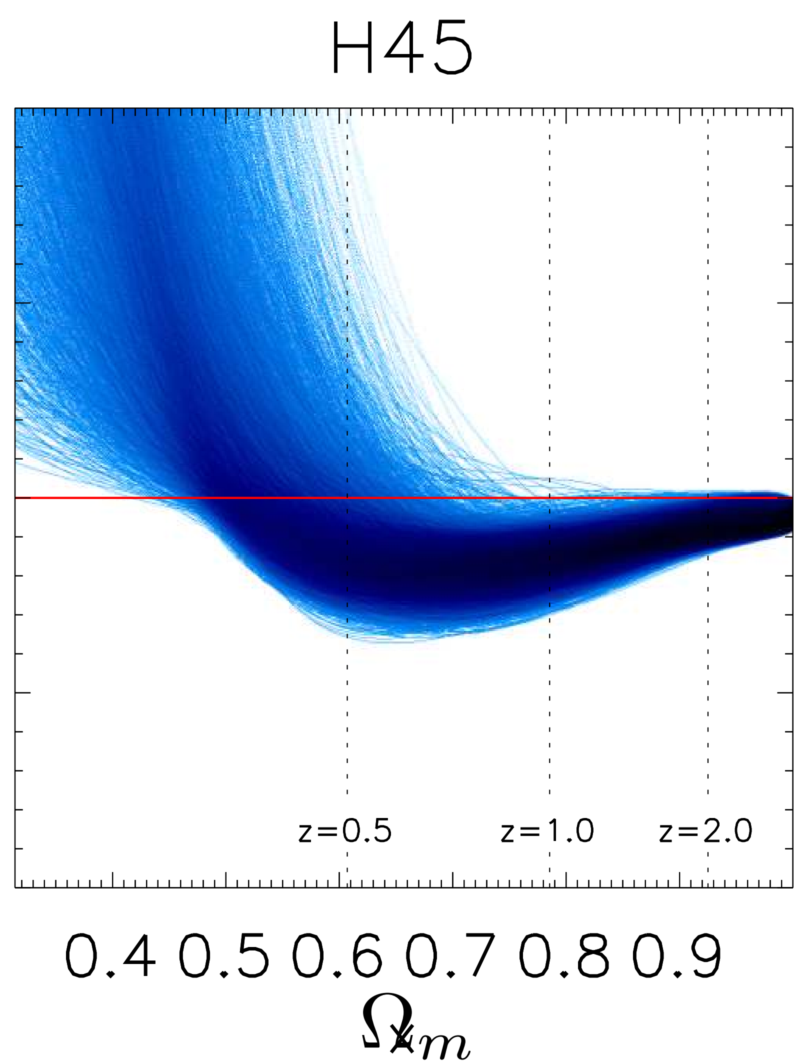
Growth rate

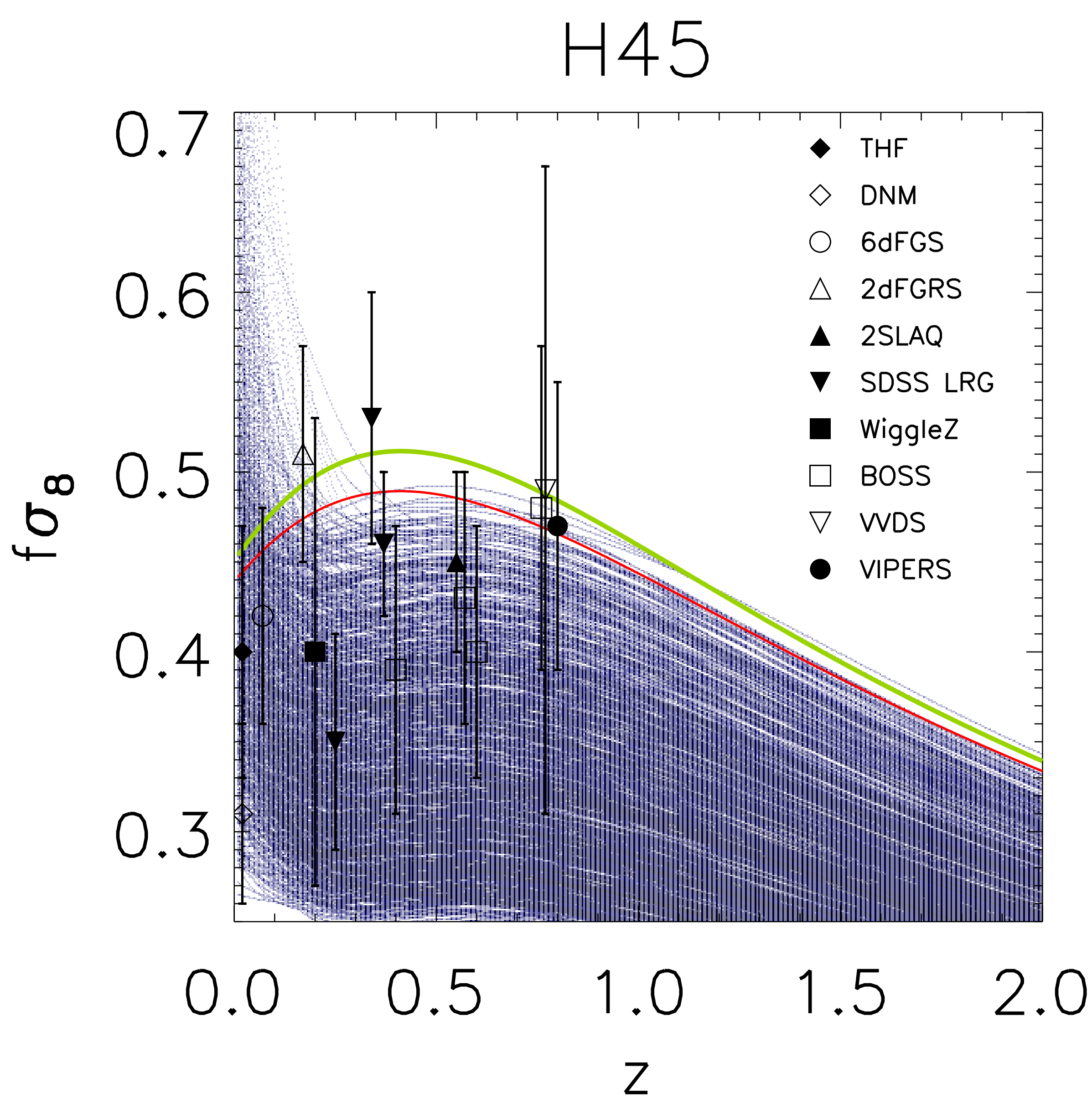




L. Perenon, F.P., C. Marinoni, L. Hui, to appear

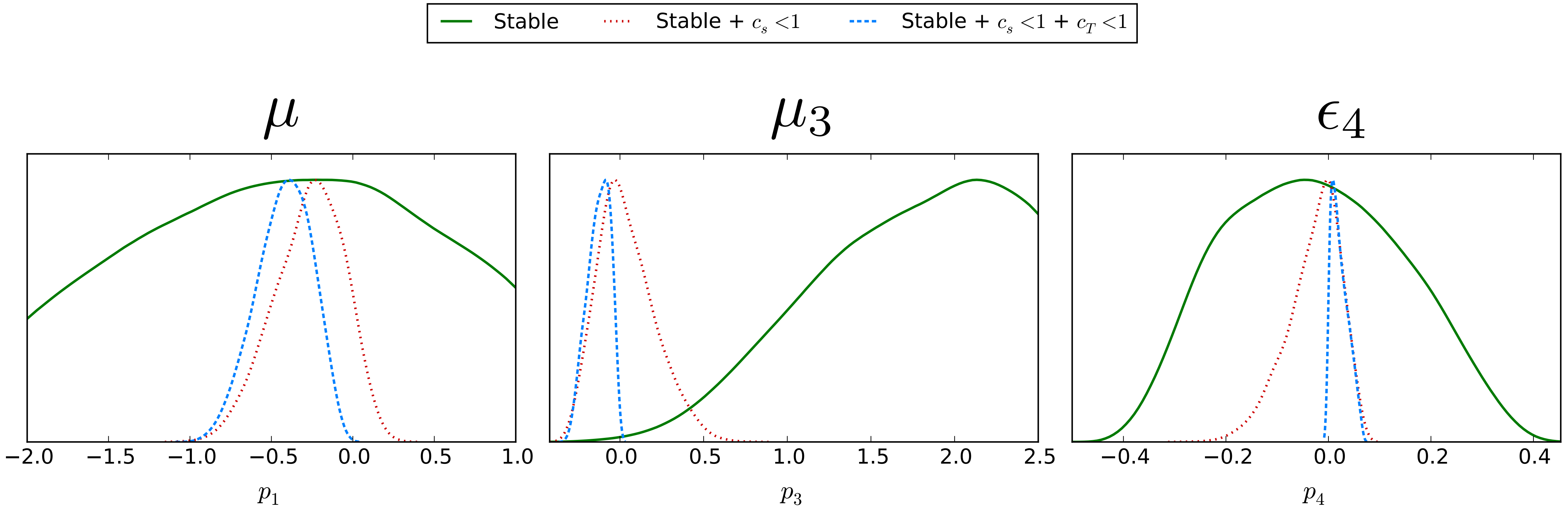
Growth rate (early DE)





V. Salvatelli, F.P., C. Marinoni, 2016

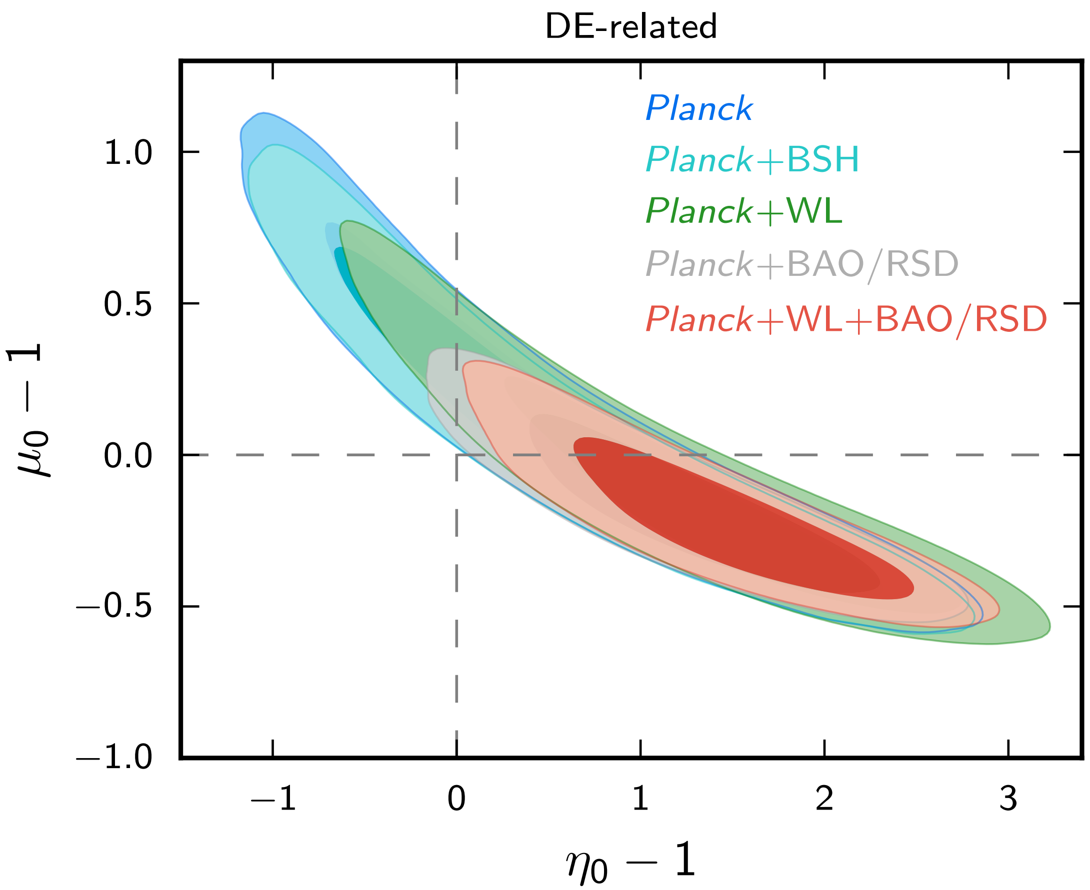
Fitting Planck 2015 CMB data



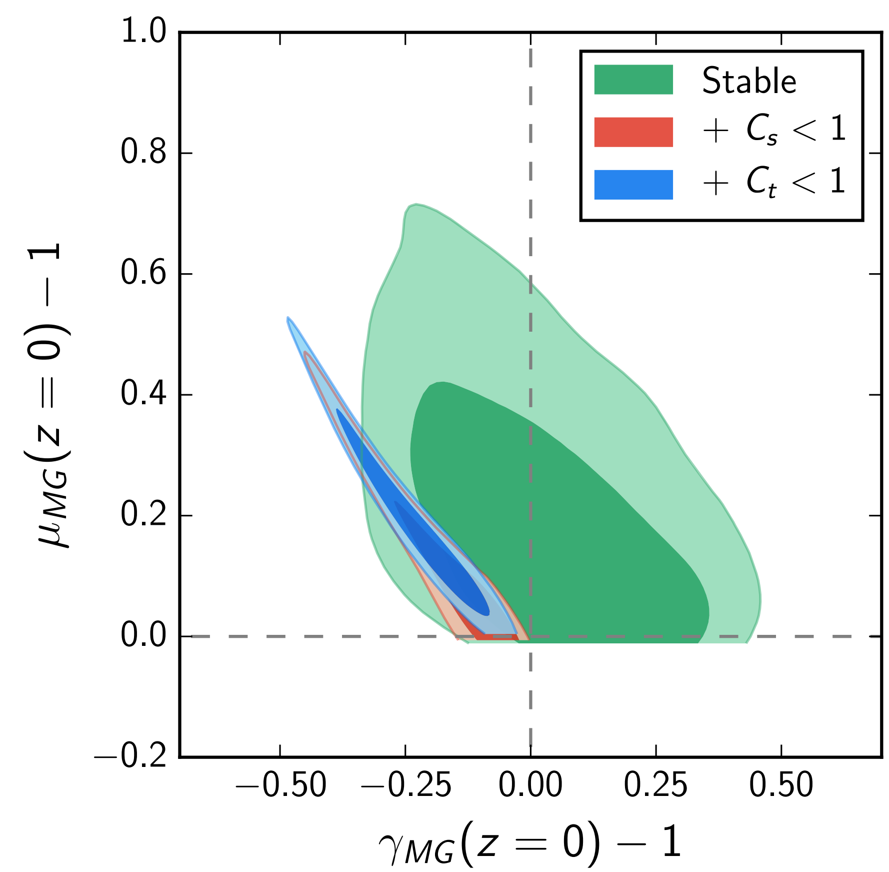
Viability conditions play an important role in determining the posteriors

V. Salvatelli, F.P., C. Marinoni, 2016

Fitting Planck 2015 CMB data



Planck 2015

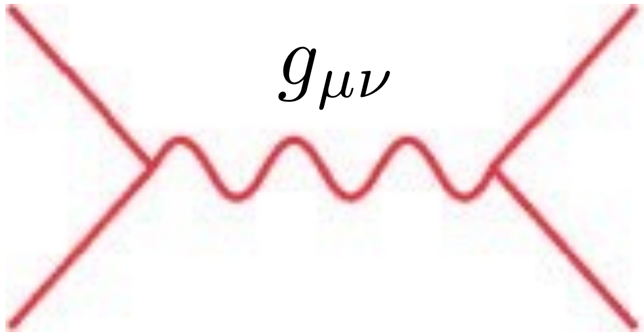


Ad-hoc parameterizations of $G_{\rm eff}$ do not correspond to actual stable theories…

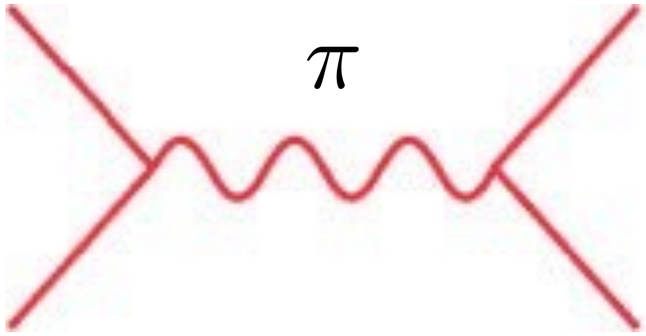
CMB data alone do not show any preference for modified gravity

Protecting solar system gravity with screening

$$\mathcal{L} \; = \; -\frac{M_*^2}{2}\, h_{\mu\nu}\, \mathcal{E}^{\mu\nu}{}_{\alpha\beta}[\phi_0]\, h^{\alpha\beta} - \mathcal{A}^{\mu\nu}[\phi_0]\, \partial_\mu\pi\partial_\nu\pi - \pi T + \frac{1}{2} h^{\mu\nu} T_{\mu\nu}$$



+

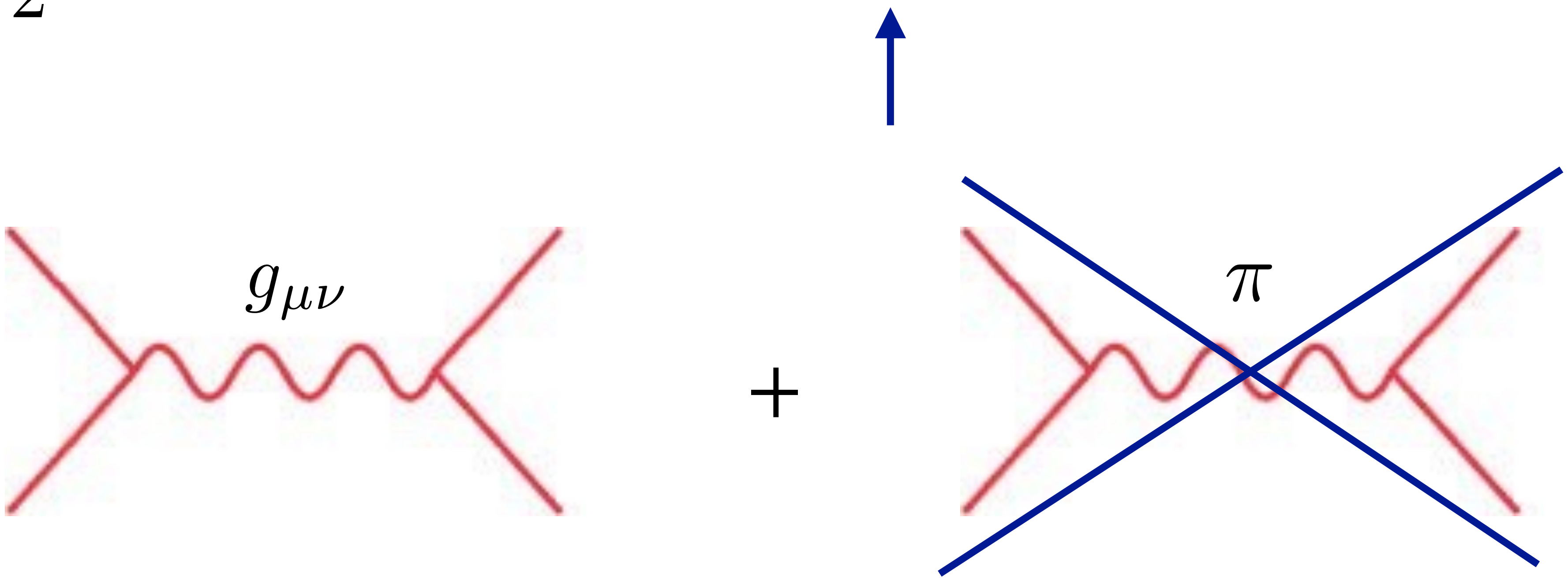


On cosmic scale the scalar contributes O(1)

We need screening!

Vainshtein screening

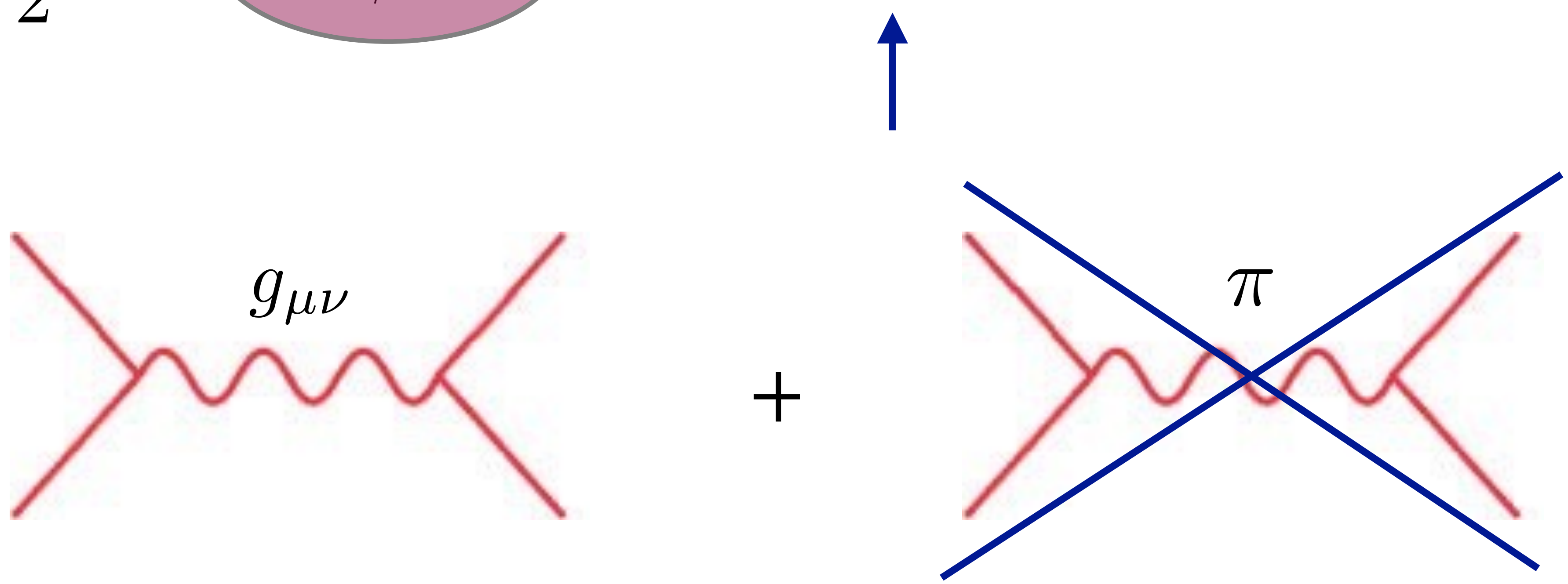
$$\mathcal{L} \;=\; -\frac{M_*^2}{2}\, h_{\mu\nu}\, \mathcal{E}^{\mu\nu}{}_{\alpha\beta}[\phi_0]\, h^{\alpha\beta} - \mathcal{A}^{\mu\nu}[\phi_0]\, \partial_\mu \pi \partial_\nu \pi - \pi T + \frac{1}{2} h^{\mu\nu} T_{\mu\nu}$$



Vainshtein: non-linear effects suppress the scalar contribution

Vainshtein screening

$$\mathcal{L} = -\frac{M_*^2}{2} h_{\mu\nu} \mathcal{E}^{\mu\nu}{}_{\alpha\beta}[\phi_0] h^{\alpha\beta} - \mathcal{A}^{\mu\nu}[\phi_0] \partial_\mu \pi \partial_\nu \pi - \pi T + \frac{1}{2} h^{\mu\nu} T_{\mu\nu}$$



Vainshtein: non-linear effects suppress the scalar contribution

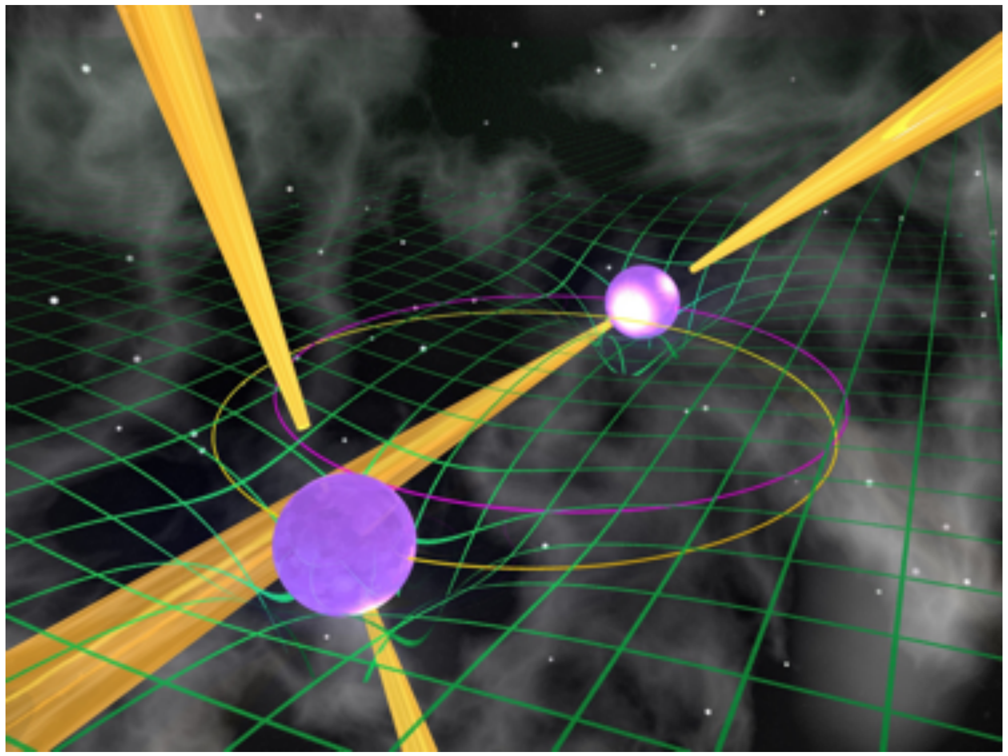
However: there can be modifications in the pure-graviton sector.
This are, generally, unscreanable!

Babichev, Deffayet, Esposito-Farese 2012

Beltran, F.P., Velten, 2015

Gravitational wave speed (as in heaven as on hearth)

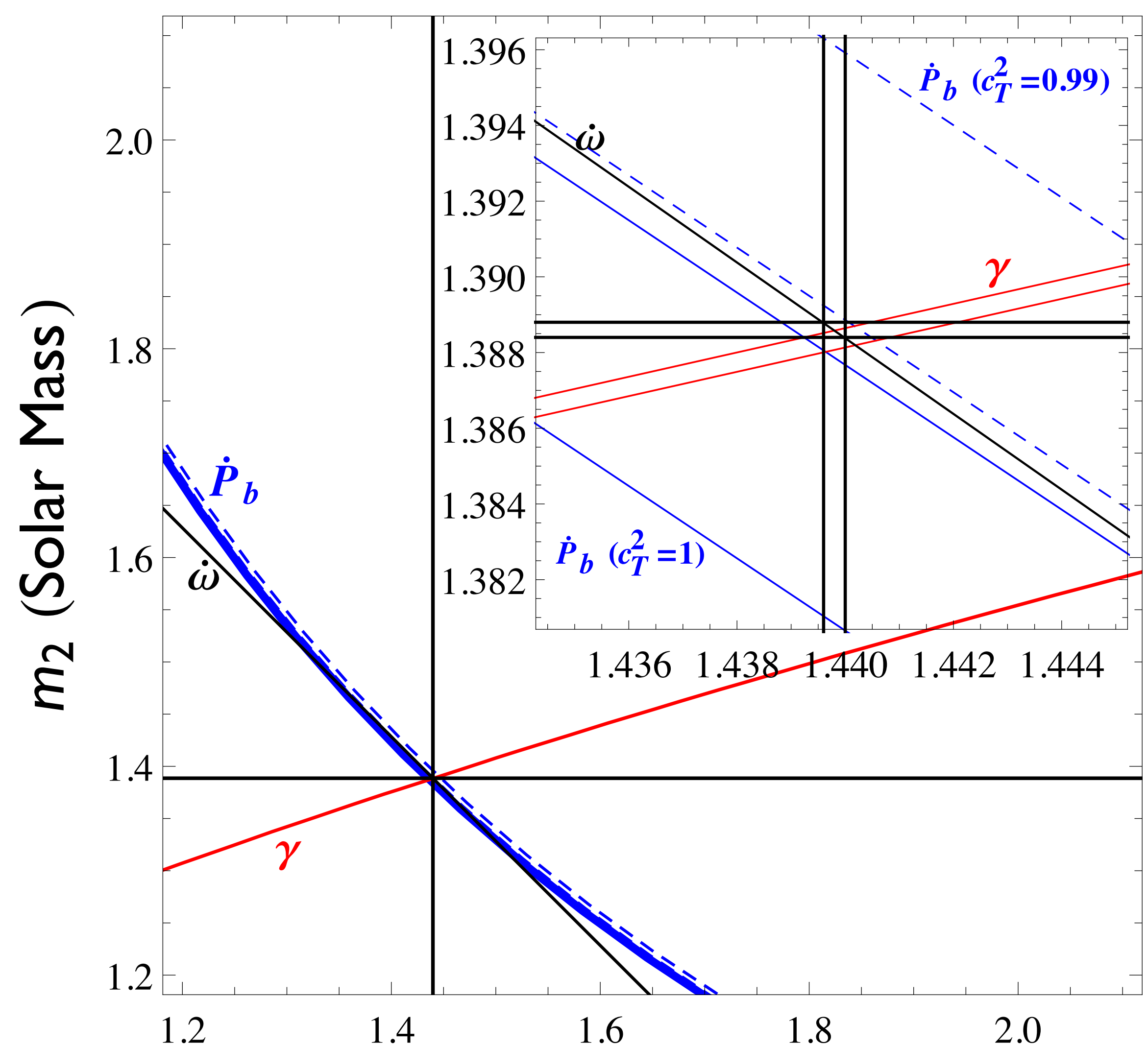
J. Beltran, F.P., H. Velten, 2015



Hulse-Taylor binary pulsars

$$c_T^2 = \frac{1}{1+\epsilon_4}$$

$$\epsilon_4 \lesssim 10^{-2}$$



See also Blas, Sanctuary 2011

A question of timing…

Gravitational wave speed (as in heaven as on earth)

J. Beltran, F.P., H. Velten, 2015

LES

Statistical and Quantum
tum Information, etc.

strophysics

les and Fields

r, and Optical Physics

ics, Fluid Dynamics,
etc.

n Physics

er: Structure, etc.

er: Electronic Properties,

tter, Biological, and
Physics

Show Abstract

Gravitation and Astrophysics

–

Evading the Vainshtein Mechanism with Anomalous Gravitational Wave Speed: Constraints on Modified Gravity from Binary Pulsars

PDF HTML

Jose Beltrán Jiménez, Federico Piazza, and Hermano Velten

Phys. Rev. Lett. **116**, 061101 (2016) – Published 9 February 2016

Show Abstract

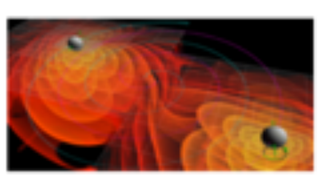
Featured in Physics | Editors' Suggestion

PDF HTML

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)

Phys. Rev. Lett. **116**, 061102 (2016) – Published 11 February 2016



Gravitational waves emitted by the merger of two black holes have been detected, setting the course for a new era of observational astrophysics.

Show Abstract

1.2 1.4 1.6 1.8 2.0

The condition MG's condition is in…

$$G_N \sim \frac{1}{8\pi M^2(t_0)[1+\epsilon_4(t_0)]^2}$$

$$\frac{\dot{G}_N}{G_N} < 0.02 H_0$$ (Lunar Laser Ranging)

self-acceleration

$$H^2 = \frac{1}{3M^2(t)}\left[\rho_m(t) + \rho_{DE}(t)\right]$$

Final remarks

- EFT of DE powerful unifying framework
- Loads of new data from future Galaxy surveys
- Lot of data-fitting work ahead of us

Either

Tension persisting and eased by MG

or...