Dark Energy

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Centre de Physique Théorique

Nobel Prize in Physics 2011

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

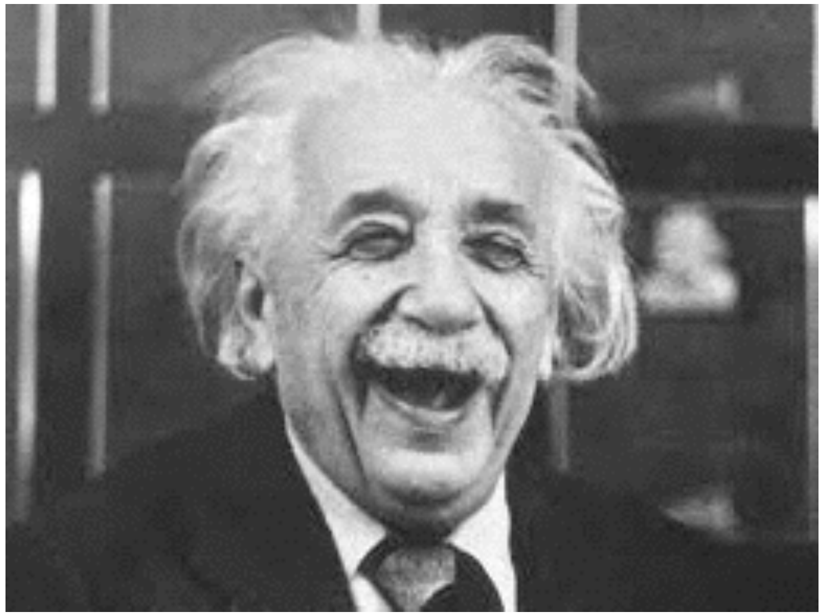
Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess

The Universe is accelerating!

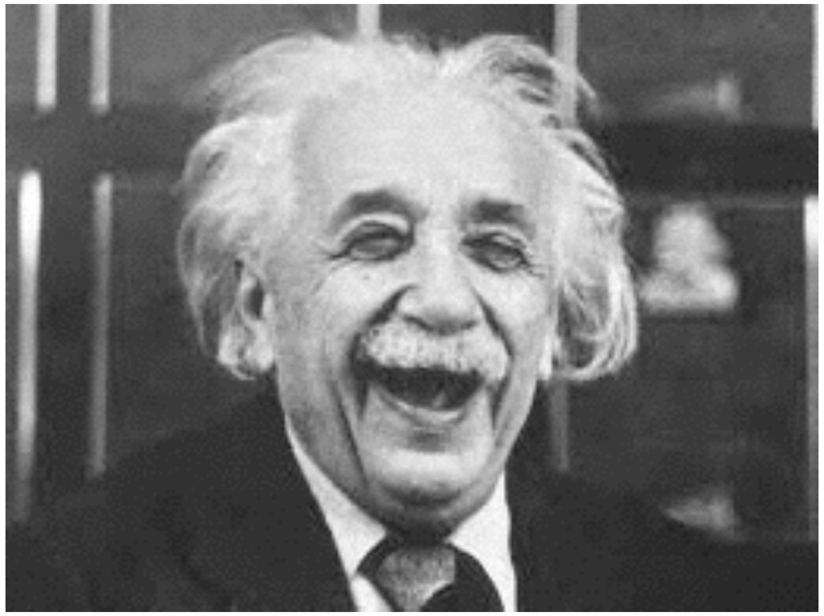
Why?!



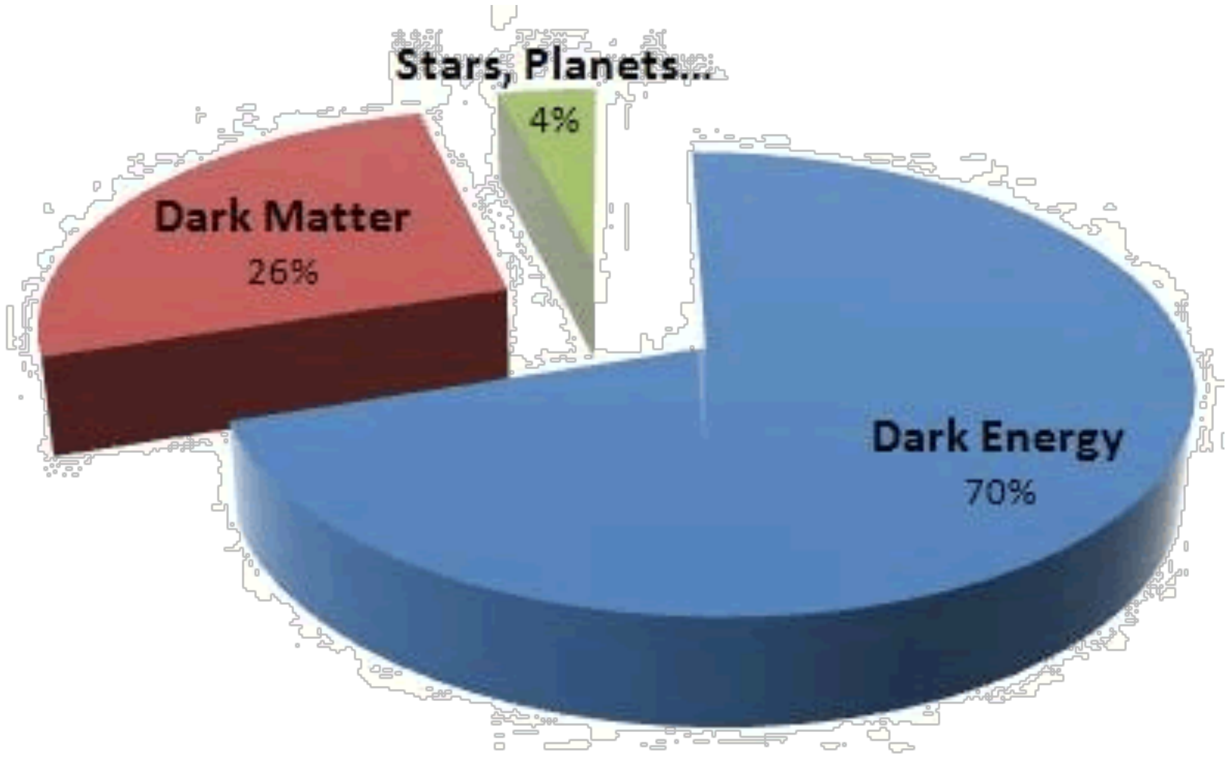
ΛCDM

$g_{\mu\nu}$ + STUFF

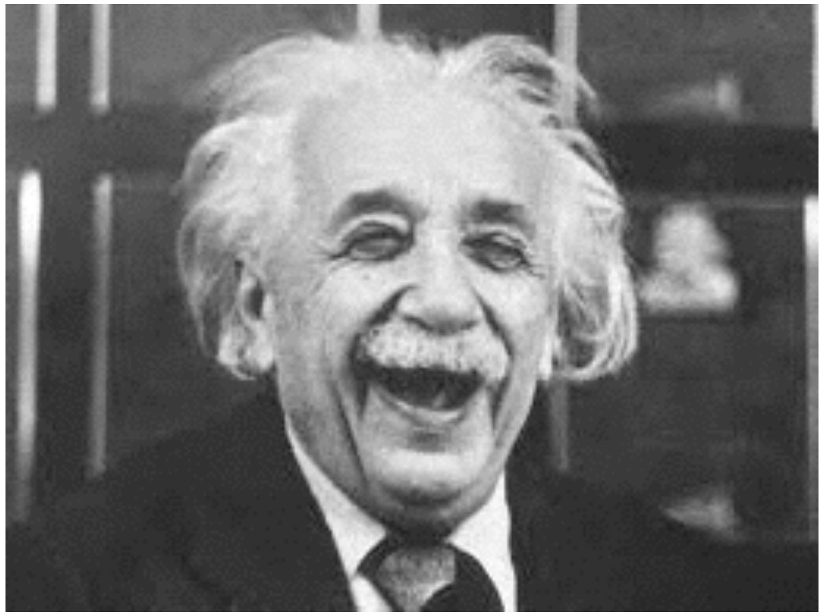
Other fundamental ingredients?



ΛCDM



ΛCDM cosmology



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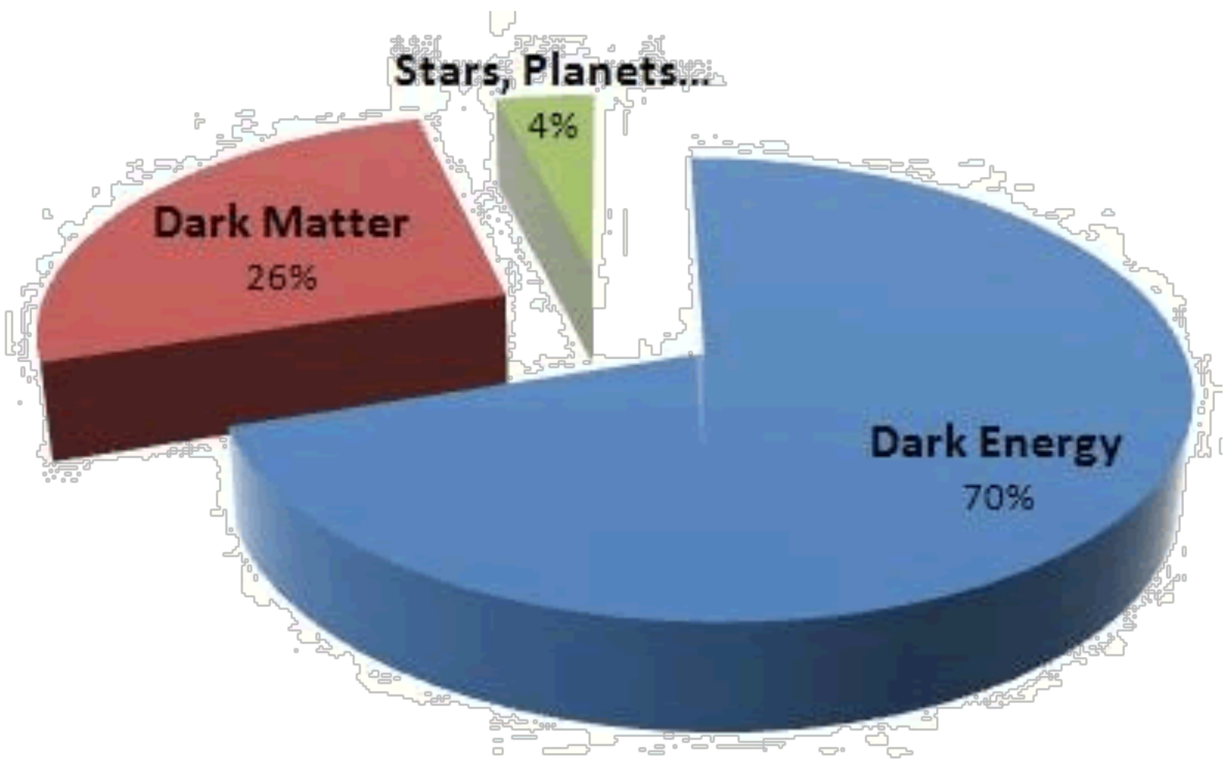
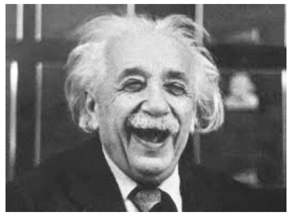


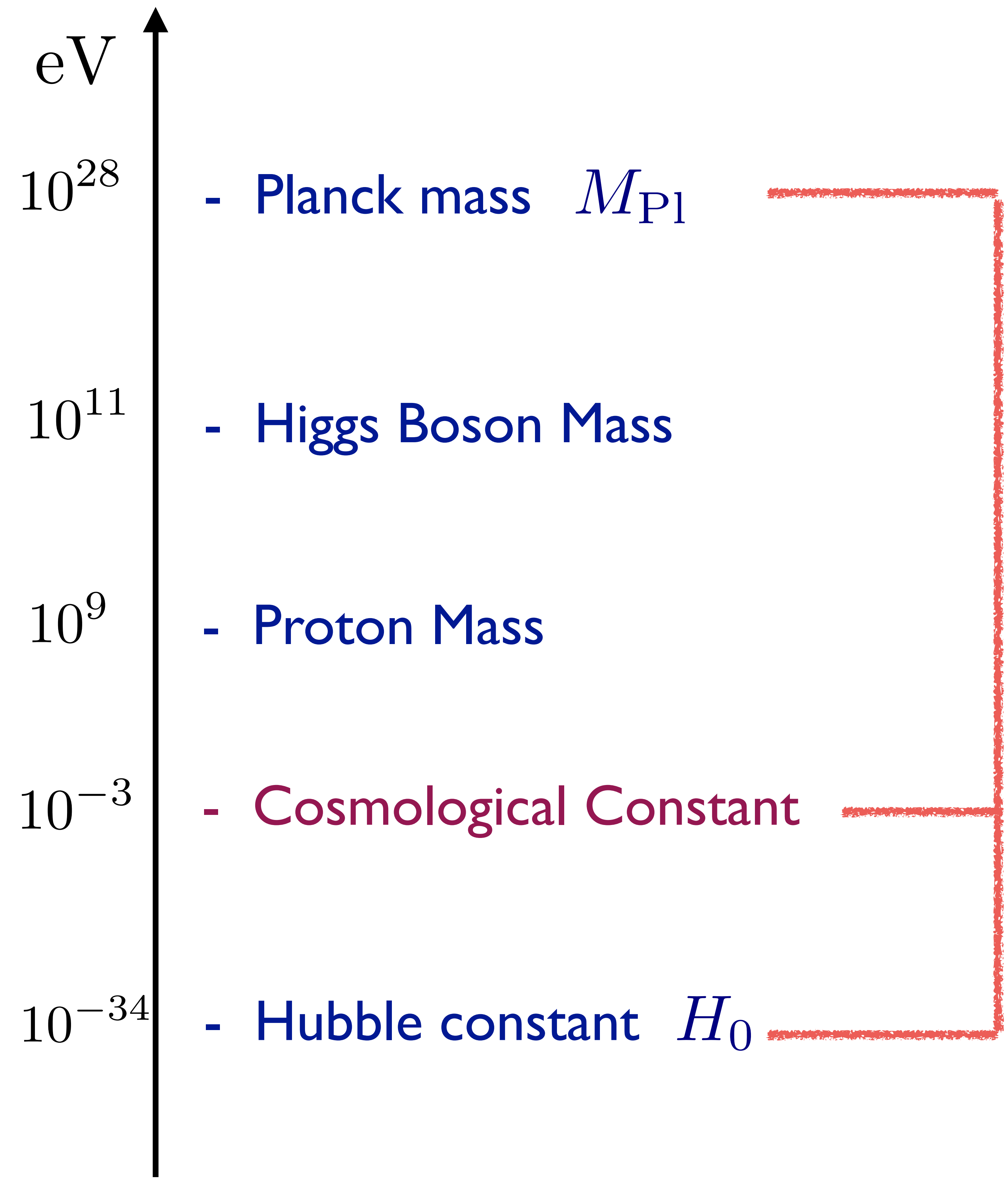
$$\Lambda \sim (10^{-3} eV)^4$$

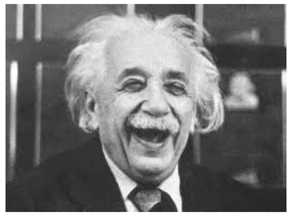
ΛCDM cosmology



$(c = 1,\ \hbar = 1)$

The size of the Cosmological Constant





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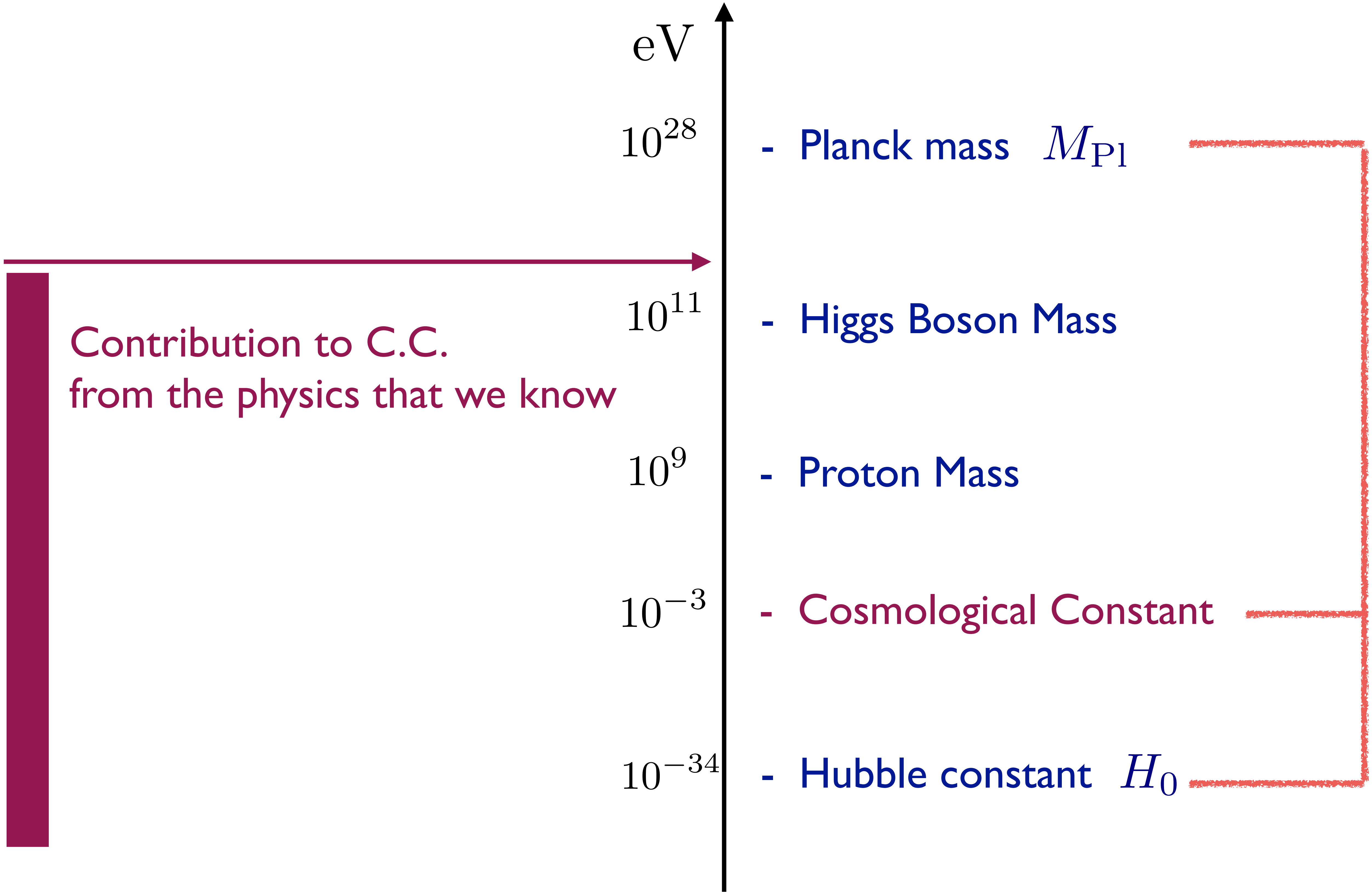
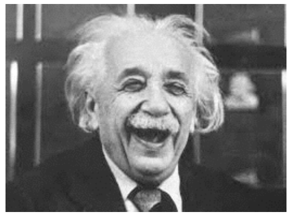
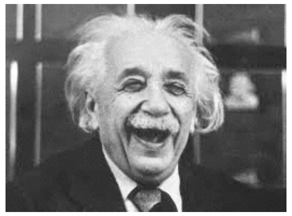




Renounce to naturalness?

Usually, it works! (Ex: pion mass split, neutral kaons)



Renounce to naturalness?

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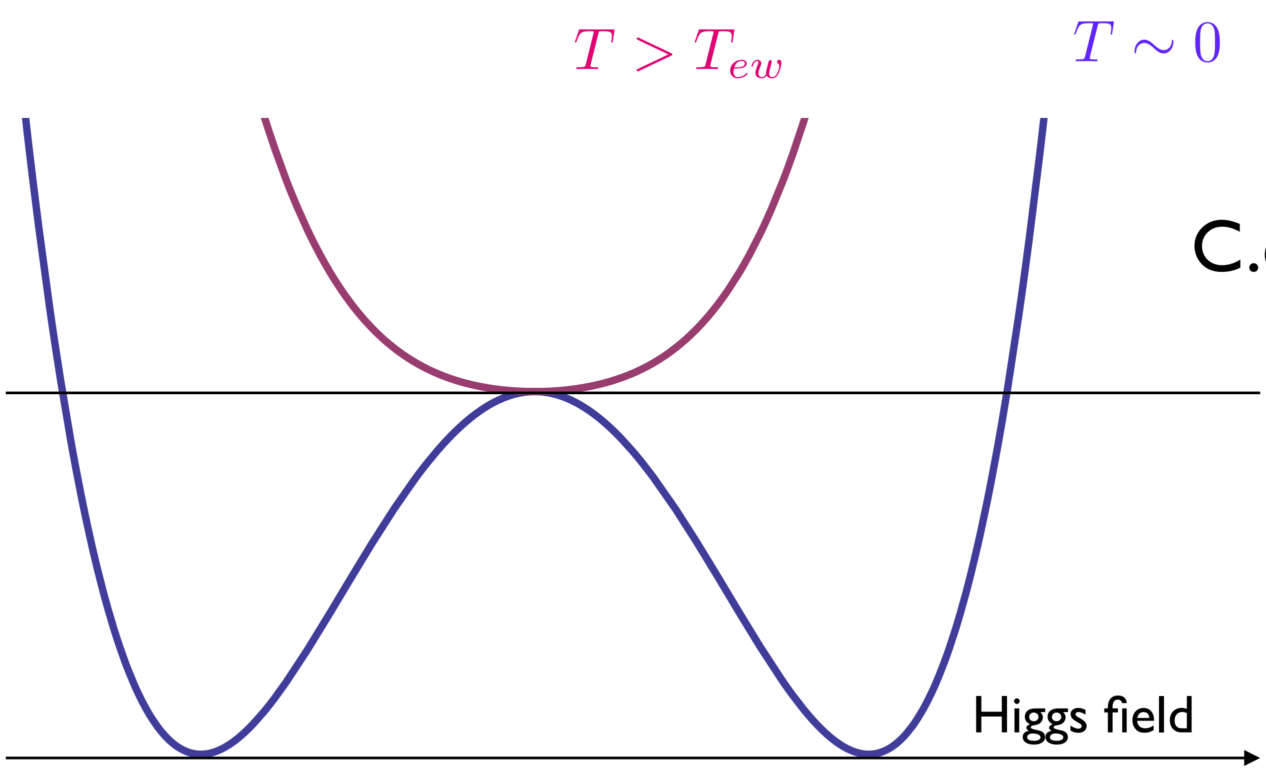
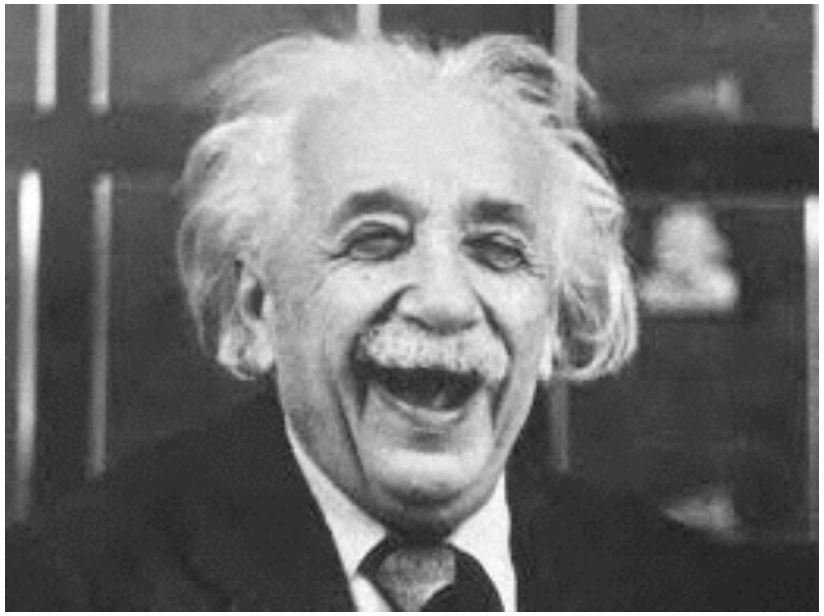
A puzzling value anyway…

EW phase transition

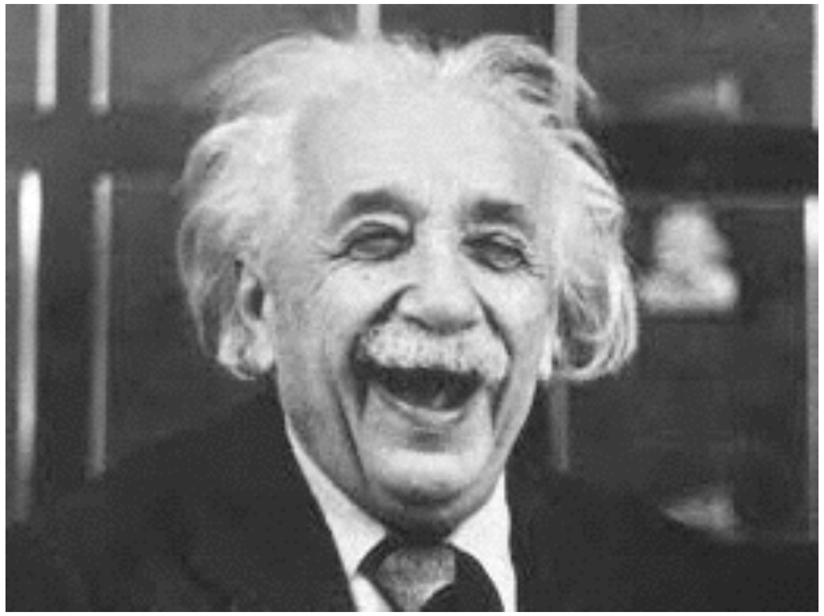


C.c. at early times: $10^{11}\text{eV} + 10^{-3}\text{eV}$!!

$$\Delta\Lambda \sim (100\ \text{GeV})^4$$

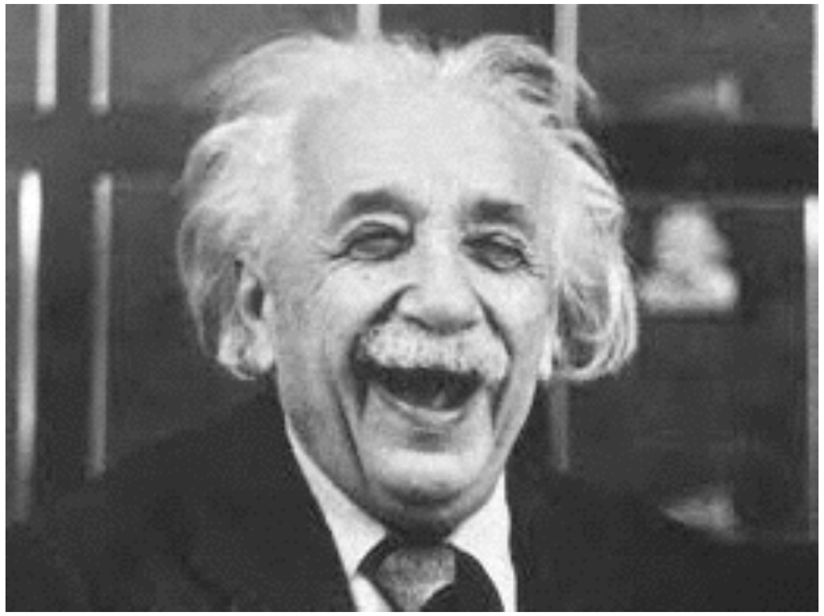


ΛCDM



ΛCDM

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



$\Lambda\mathrm{CDM}$

The only consistent
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$g_{\mu\nu} + \mathrm{STUFF}$

The skeleton of MG: Minkowski theory

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

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$$\left\{ \begin{array}{ll} \bar{P}^\mu & \text{translations} \\ \bar{J}^i & \text{rotations} \end{array} \right.$$

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

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

$\Downarrow$

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

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

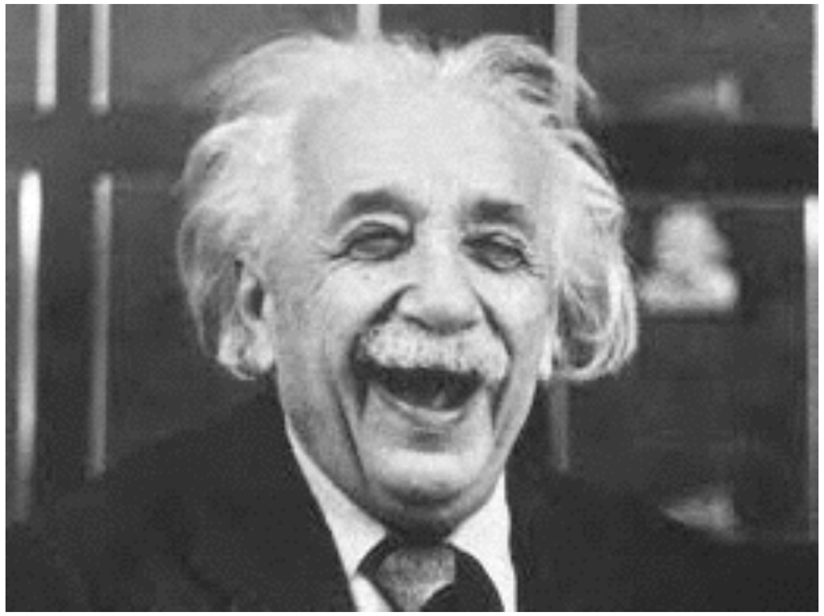
Classifying Condensed Matter

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 ⟷ Cosmology/modified gravity

superfluids
solids
framids

shift-symmetric scalar
solid inflation
Einstein aether



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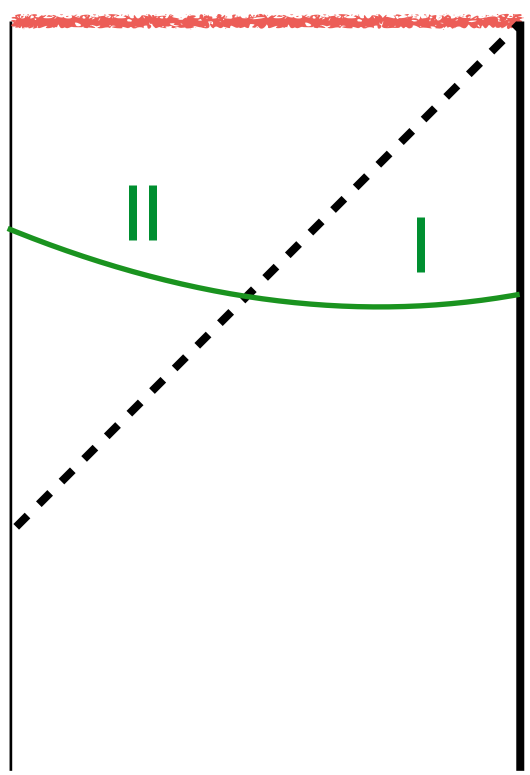
Other fundamental ingredients?

Where could the EFT ‘mantra’ be wrong?

Quantum gravity: not necessarily confined to the UV

BH in AdS



CFT

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

Inside dof: duplicate of those outside

Papadodimas, Raju, 2012-2016

‘ER=EPR’

Entanglement defines (and generalizes) spacetime

Susskind, Maldacena, 2013

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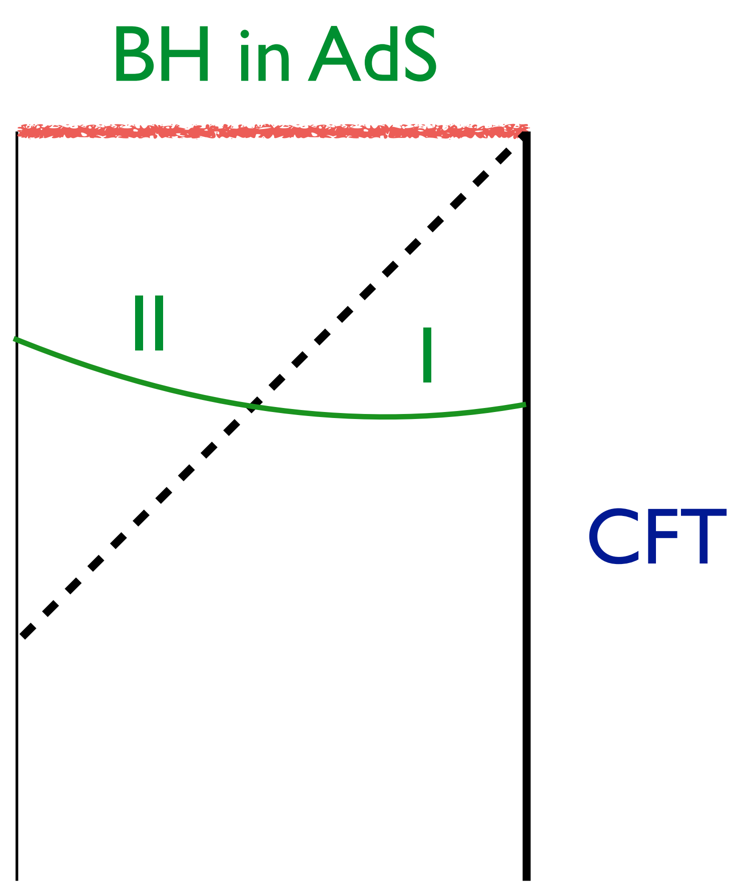

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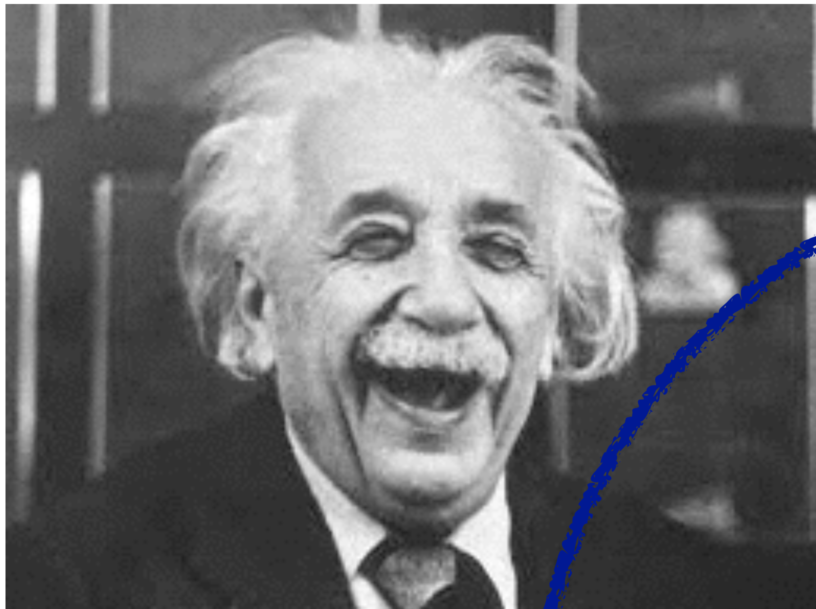
In cosmology these effects are expected to be small



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

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

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

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only affect perturbations

F. P., Steigerwald, Marinoni, `13

Complete background separation

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

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

$\bar{w}(t)$ — Expansion History

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

$\mu_2^2(t)$ — Unconstrained

F. P., Steigerwald, Marinoni, `13

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Alternatively

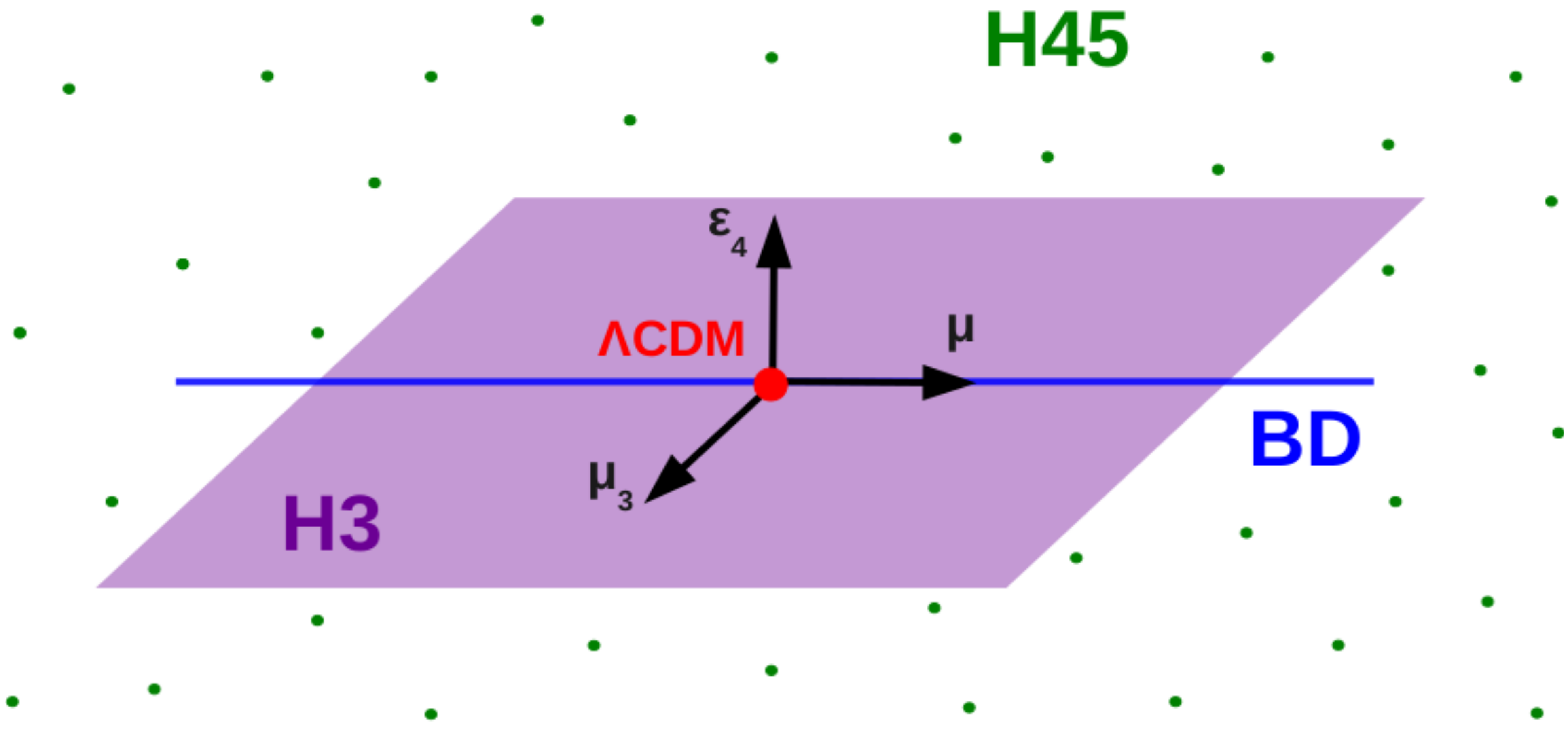
$$\alpha_K(t), \alpha_M(t), \alpha_B(t), \alpha_T(t)$$

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

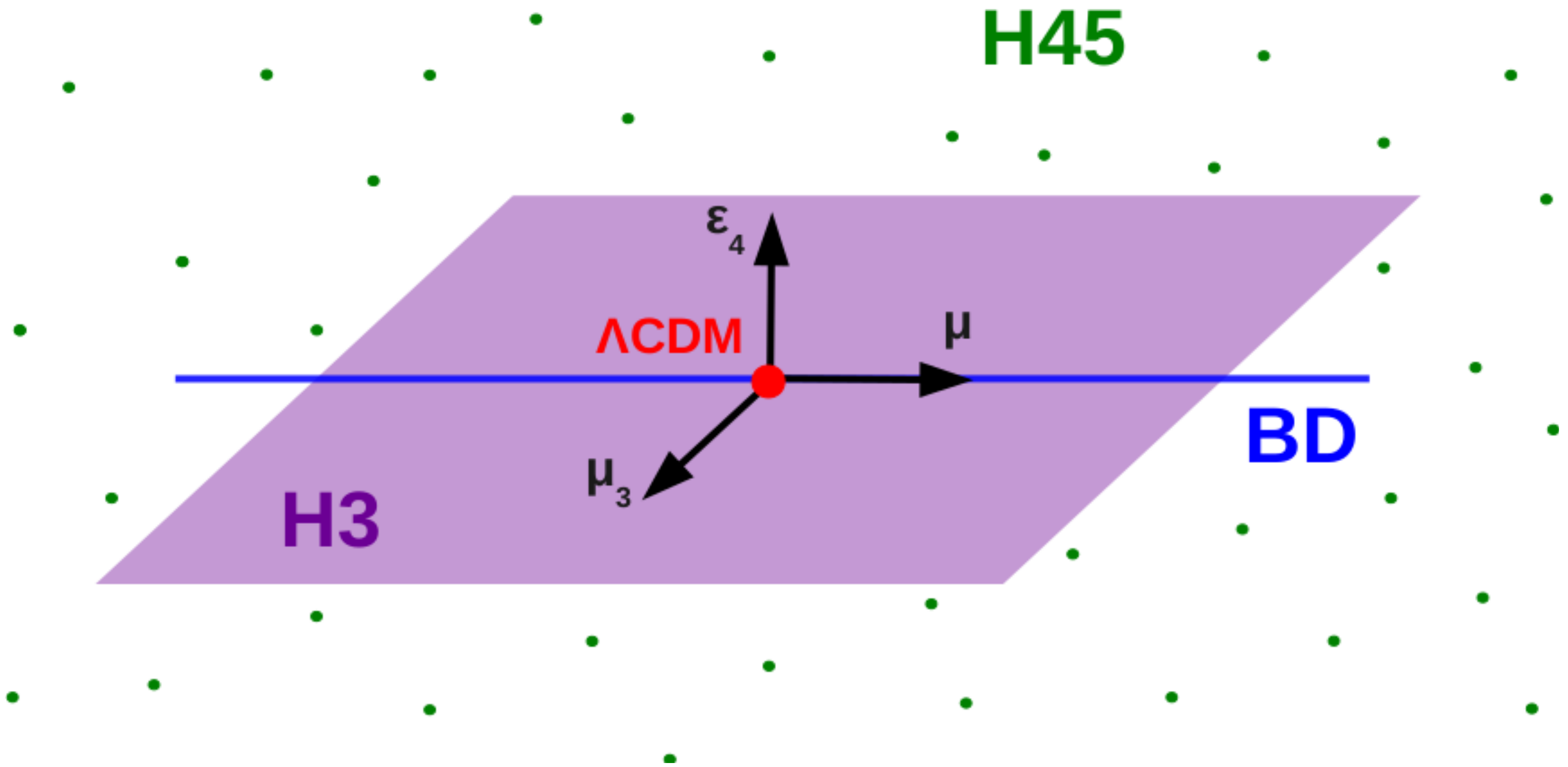
The space of modified gravity

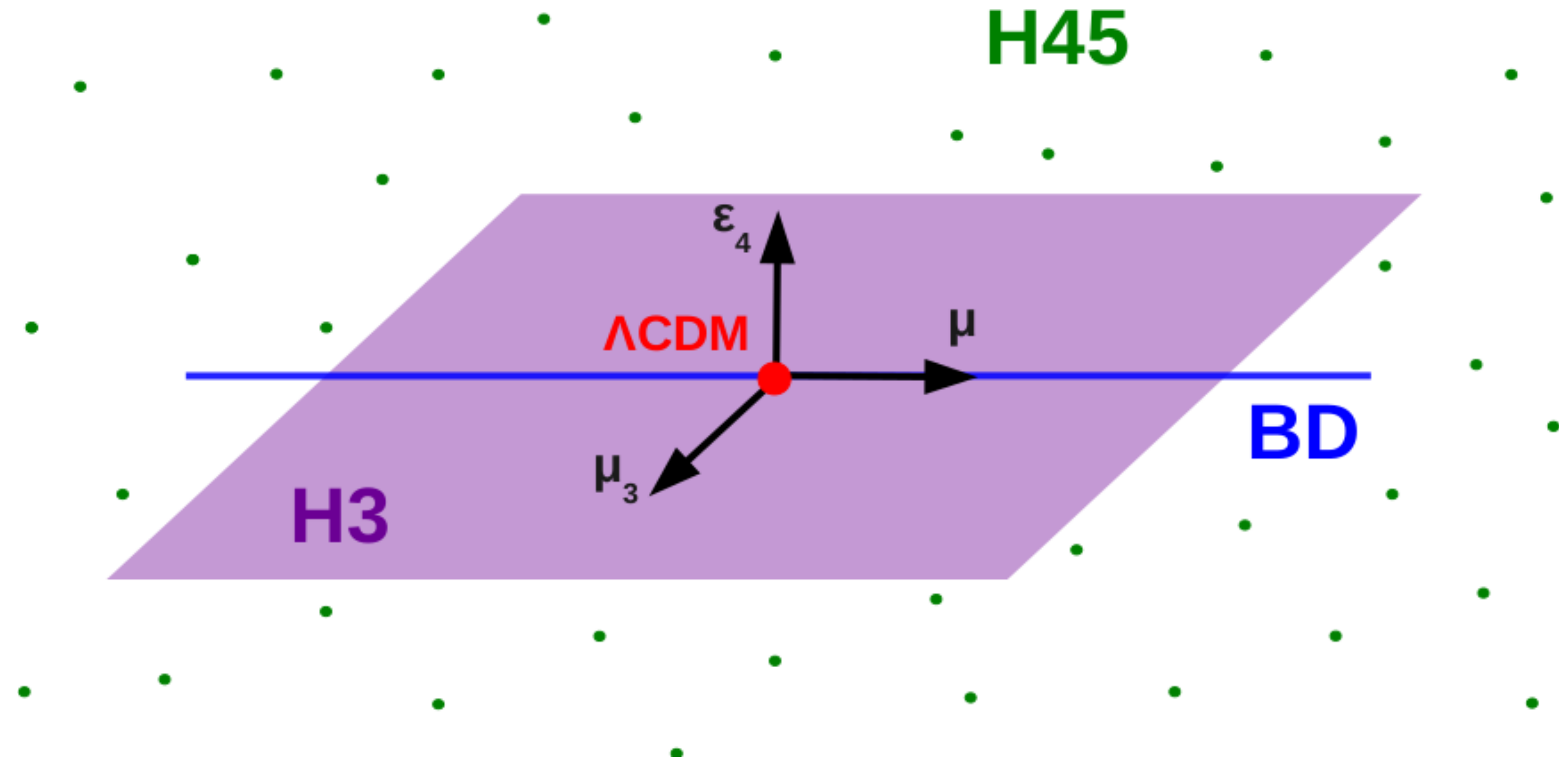
$$S = \int d^4x \sqrt{-g}\, \frac{M^2(t)}{2} \left[R - 2\lambda(t) - 2\mathcal{C}(t) g^{00} \right.$$

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



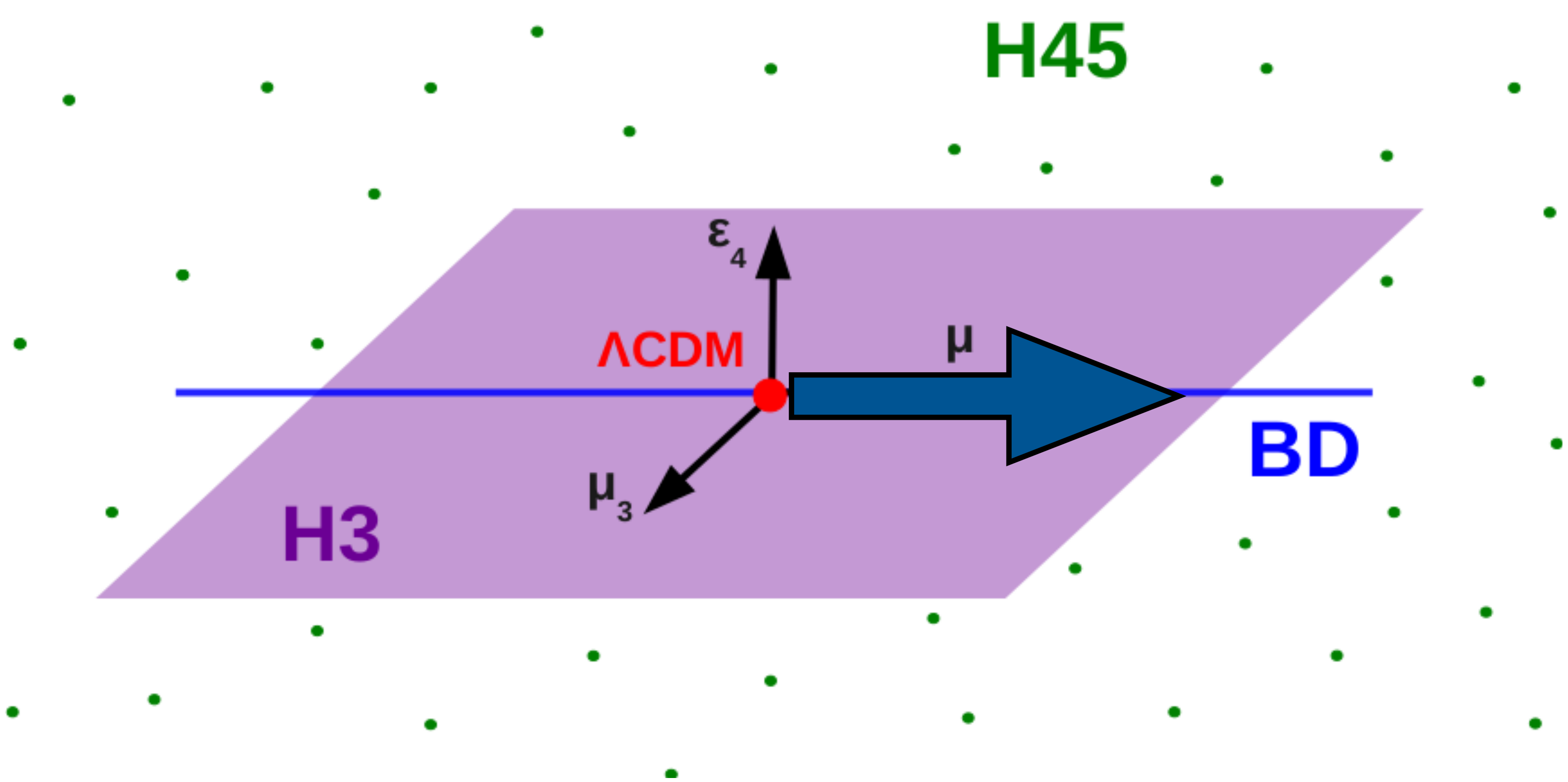
Perenon, F.P., Marinoni, Hui, ‘15


H45
ε4
ΛCDM
μ
BD
μ3
H3



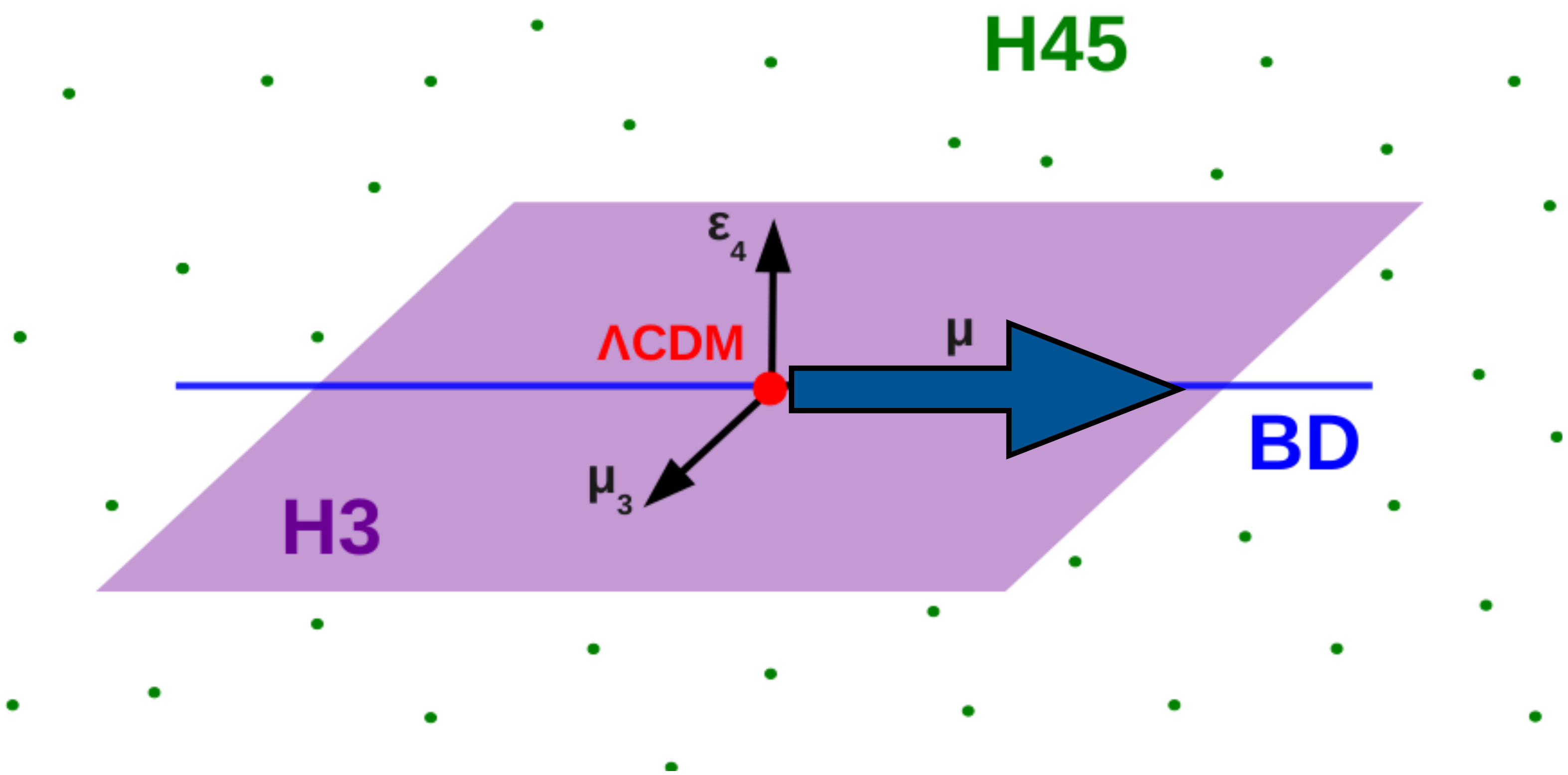
Quintessence
k- essence
etc.

Minimally coupled $(w \neq -1)$



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

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



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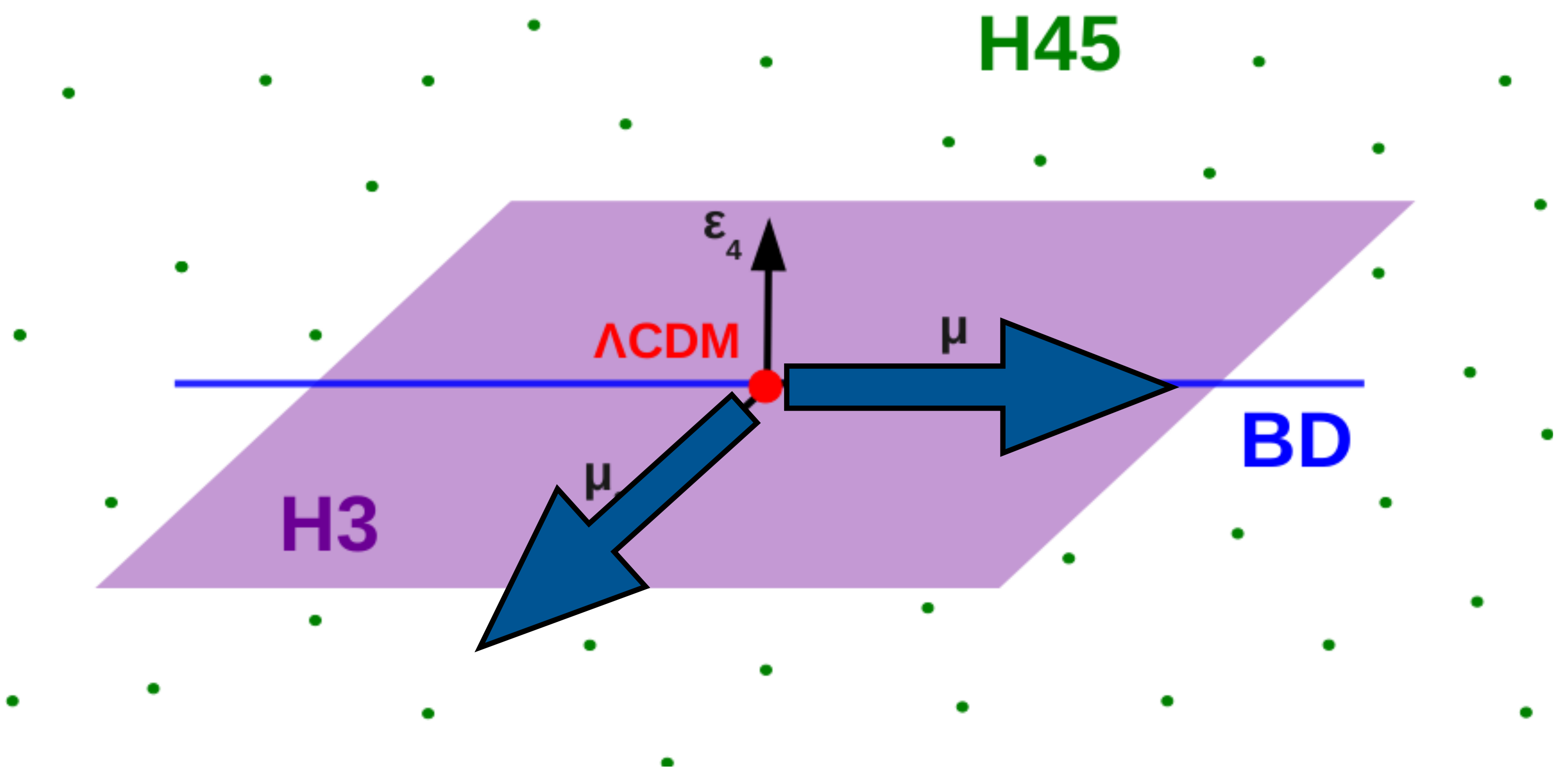
$$\mu \equiv \frac{d \log M^2}{dt}$$

self-acceleration

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

'normal' negative pressure

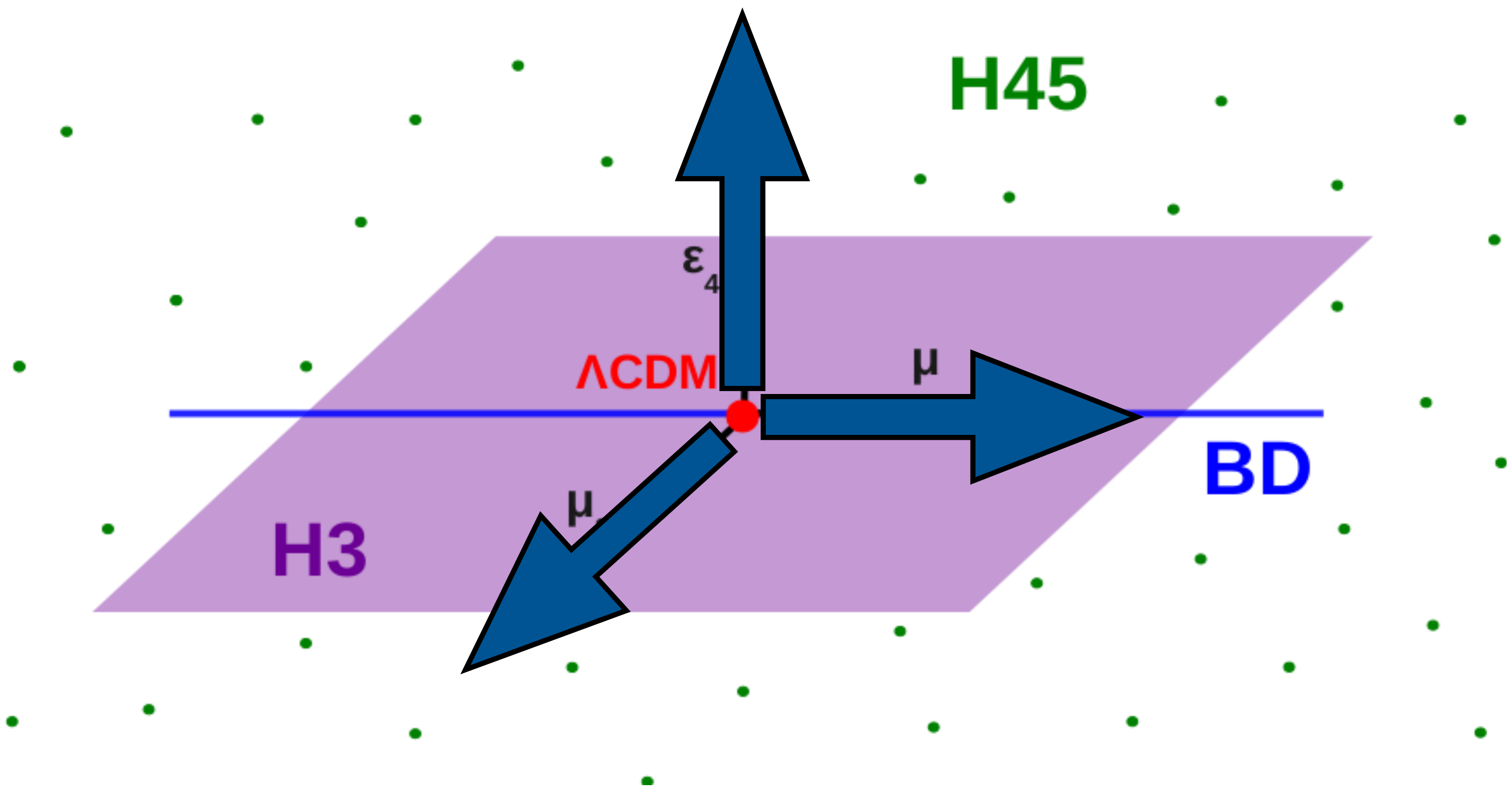
Perenon, F.P., Marinoni, Hui, to appear



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

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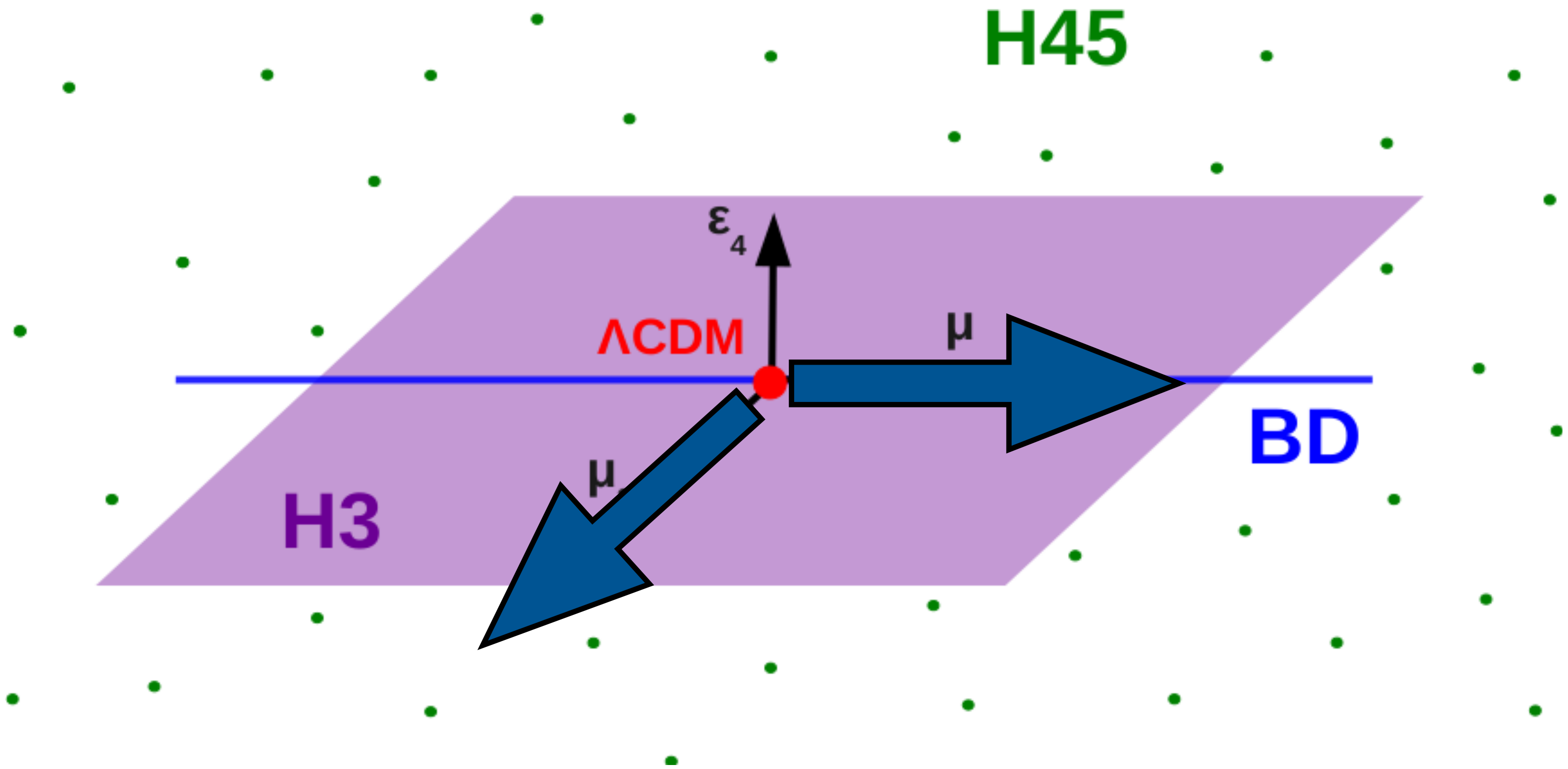
$\epsilon_4(t)$ $\tilde{\epsilon}_4(t)$

Beyond Horndeski

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

see Masahide talk on Friday

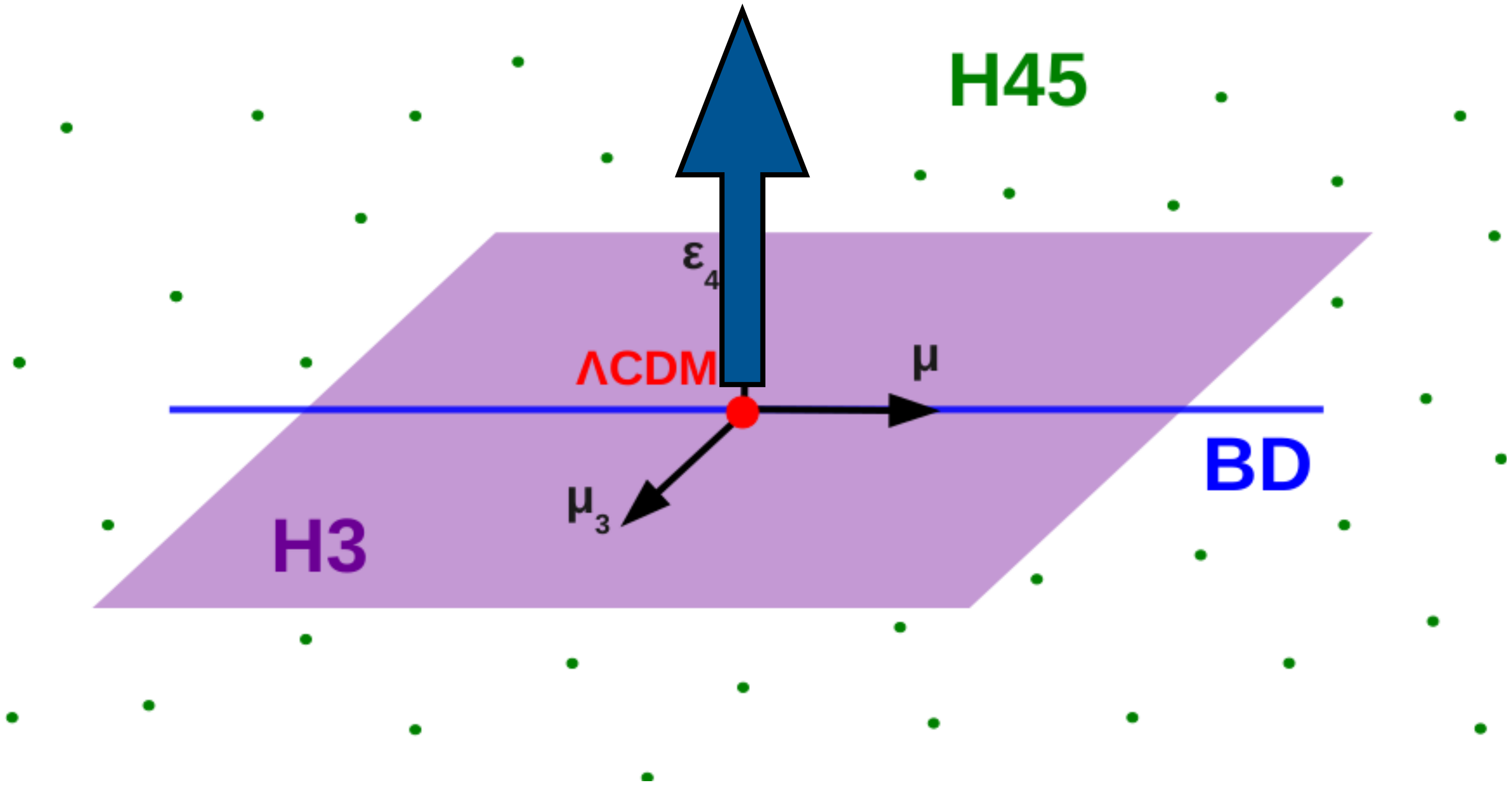
Newtonian gauge: scalar d.o.f.: $\Phi, \Psi, \ \pi$



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

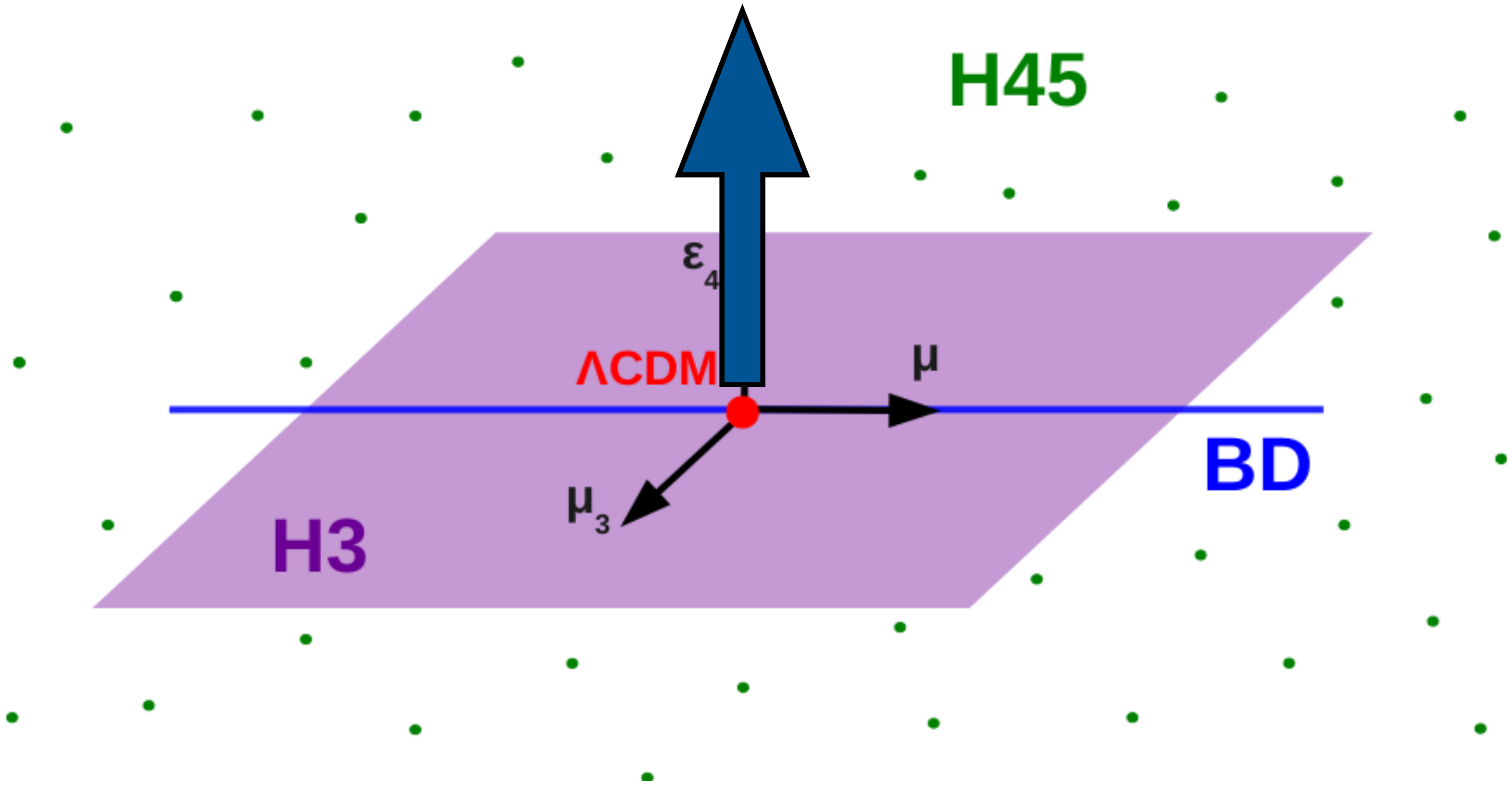
kinetic couplings metric-scalar

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.: Φ, Ψ, π

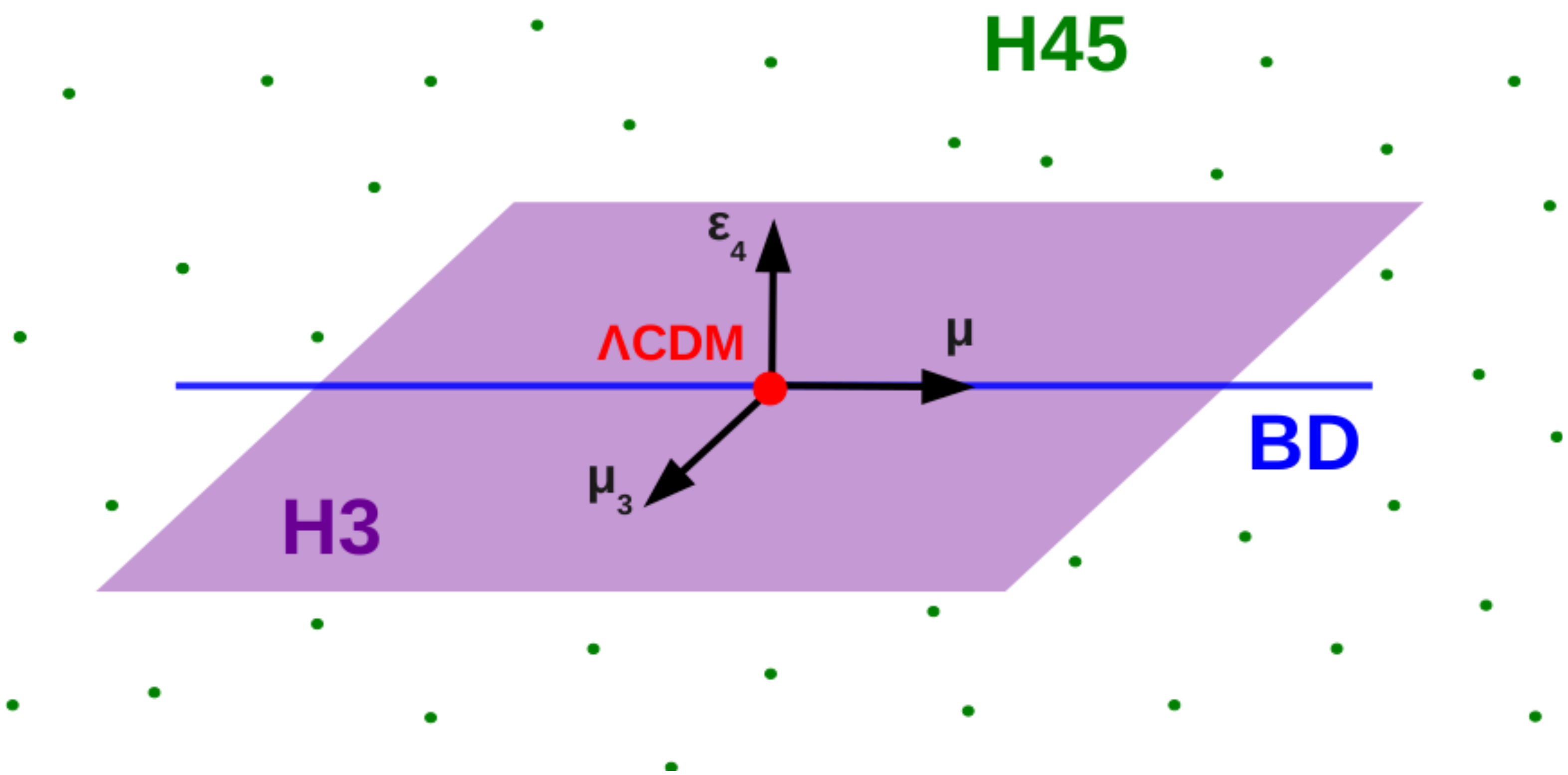


$$\mathcal{L} = (\dot{\epsilon}_4 + H\epsilon_4)\vec{\nabla}\Psi\vec{\nabla}\pi$$

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

but also: speed of gravitational waves!

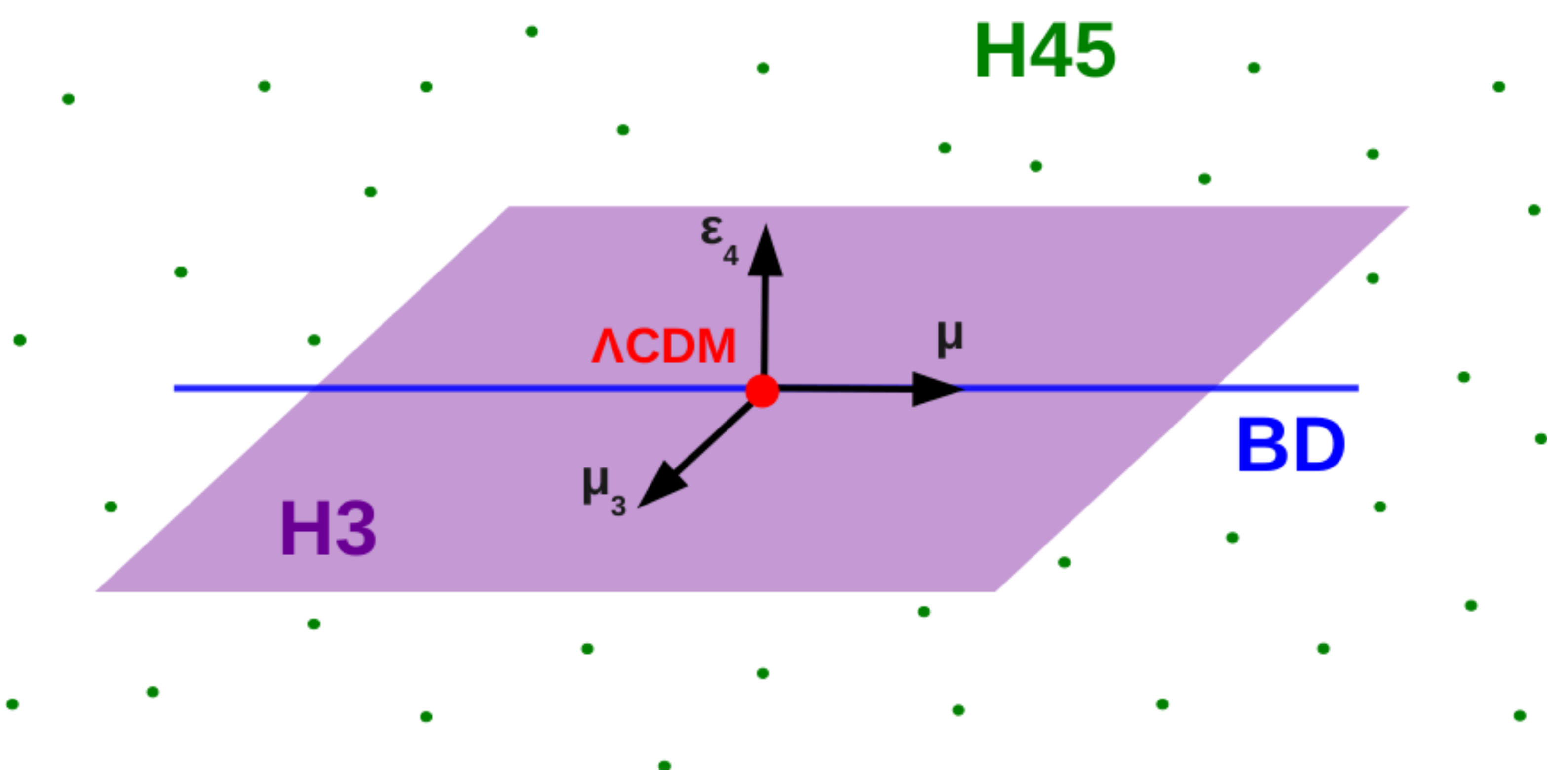
Newtonian gauge: scalar d.o.f.: Φ, Ψ, π



`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…

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

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Basic requirement

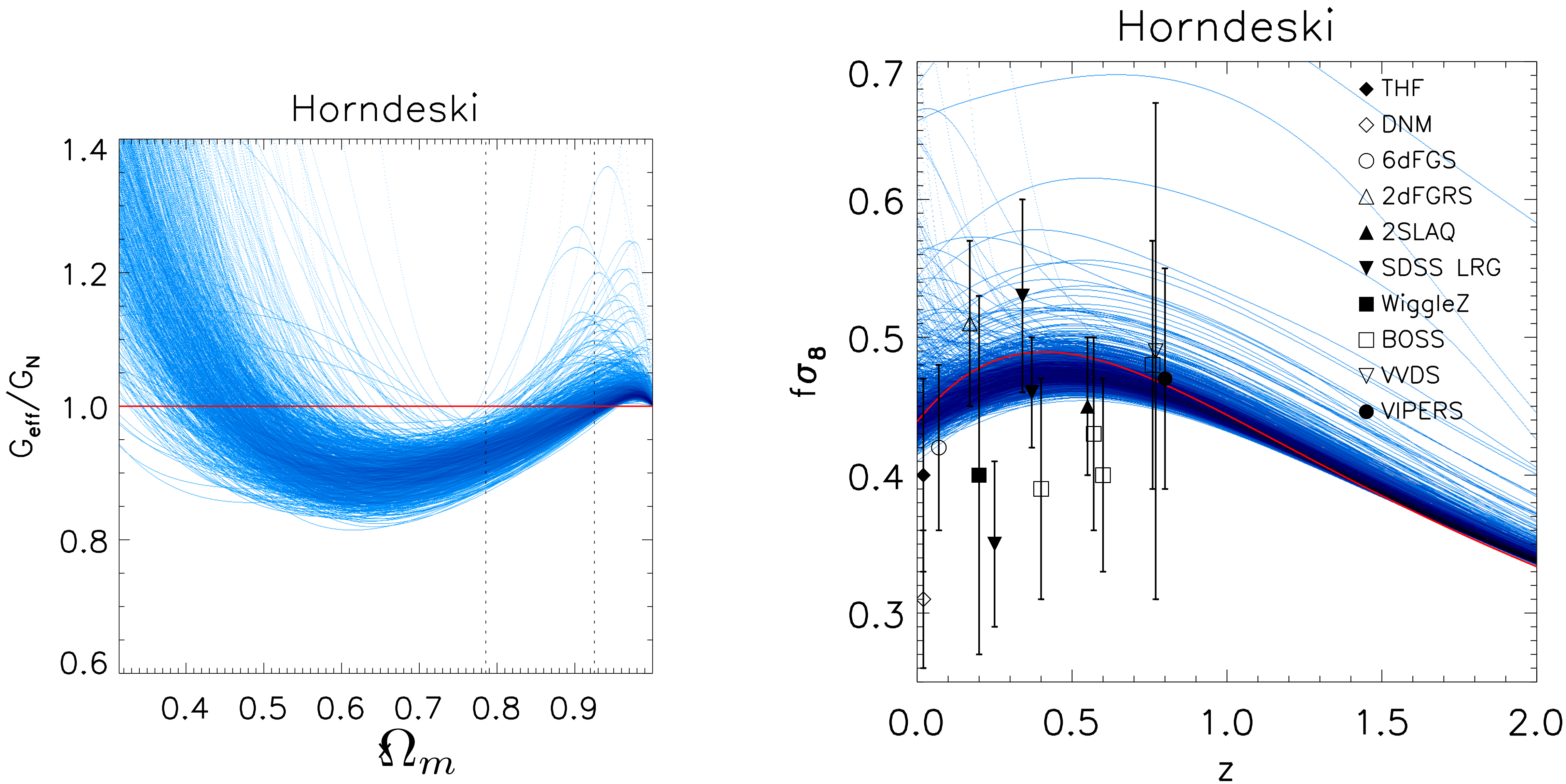
Option 1: $\& \quad c_s^2 < 1$

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

Stability requirements make a strong selection

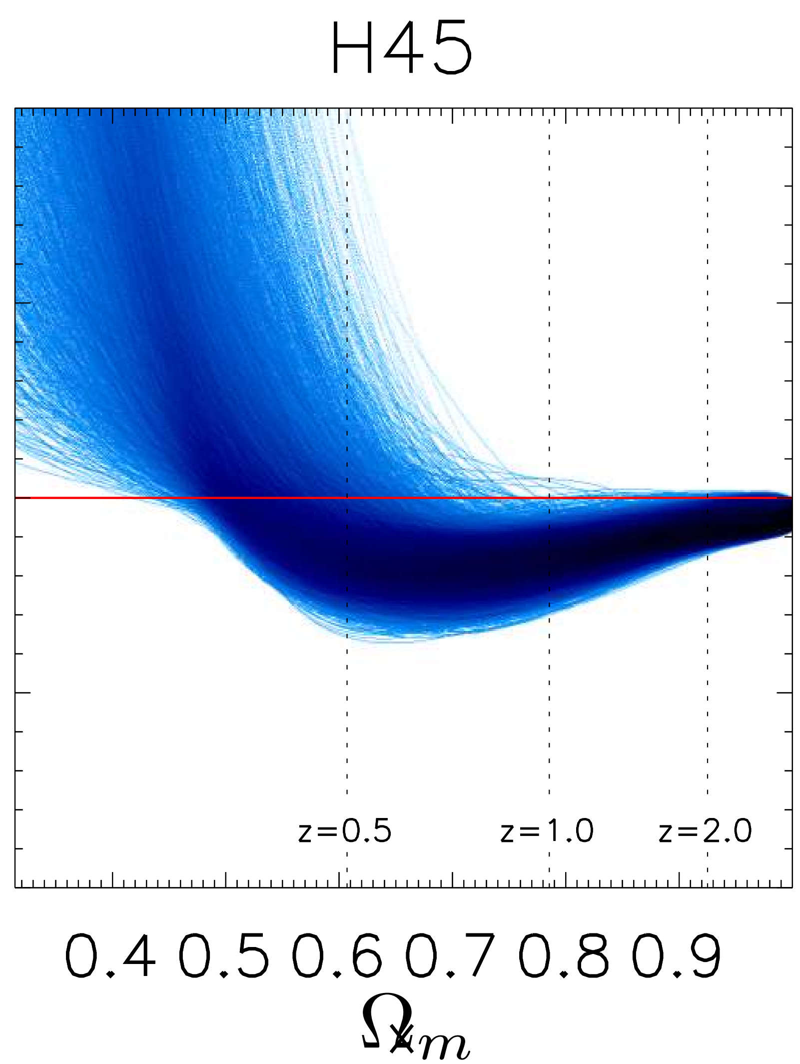
L. Perenon, F.P., C. Marinoni, L. Hui, '15

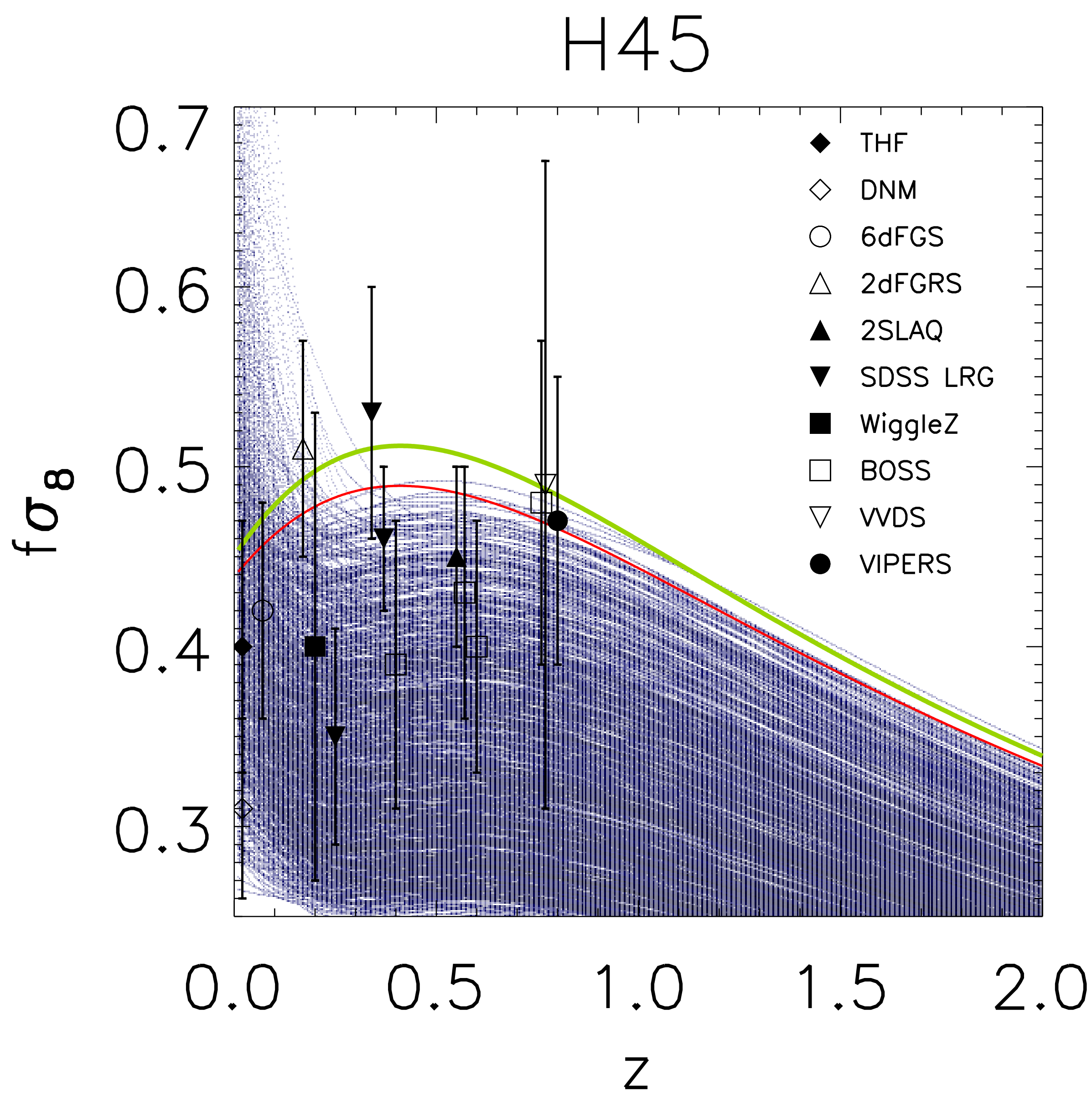
Growth rate



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

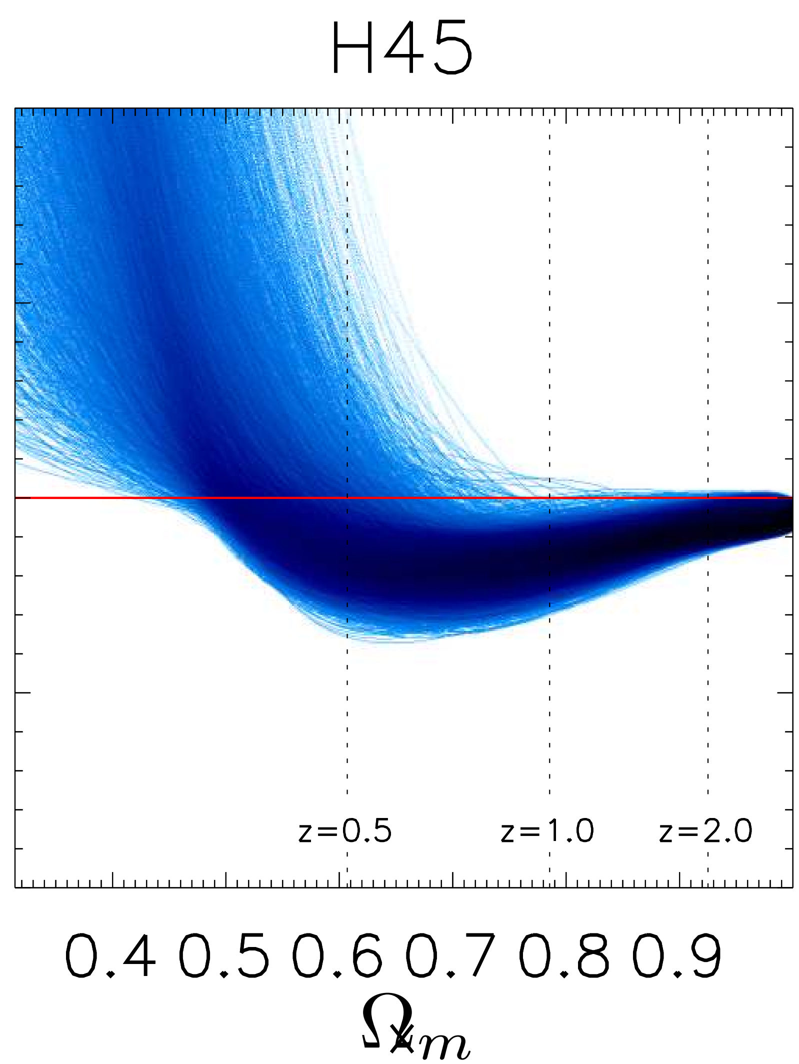
Growth rate (early DE)

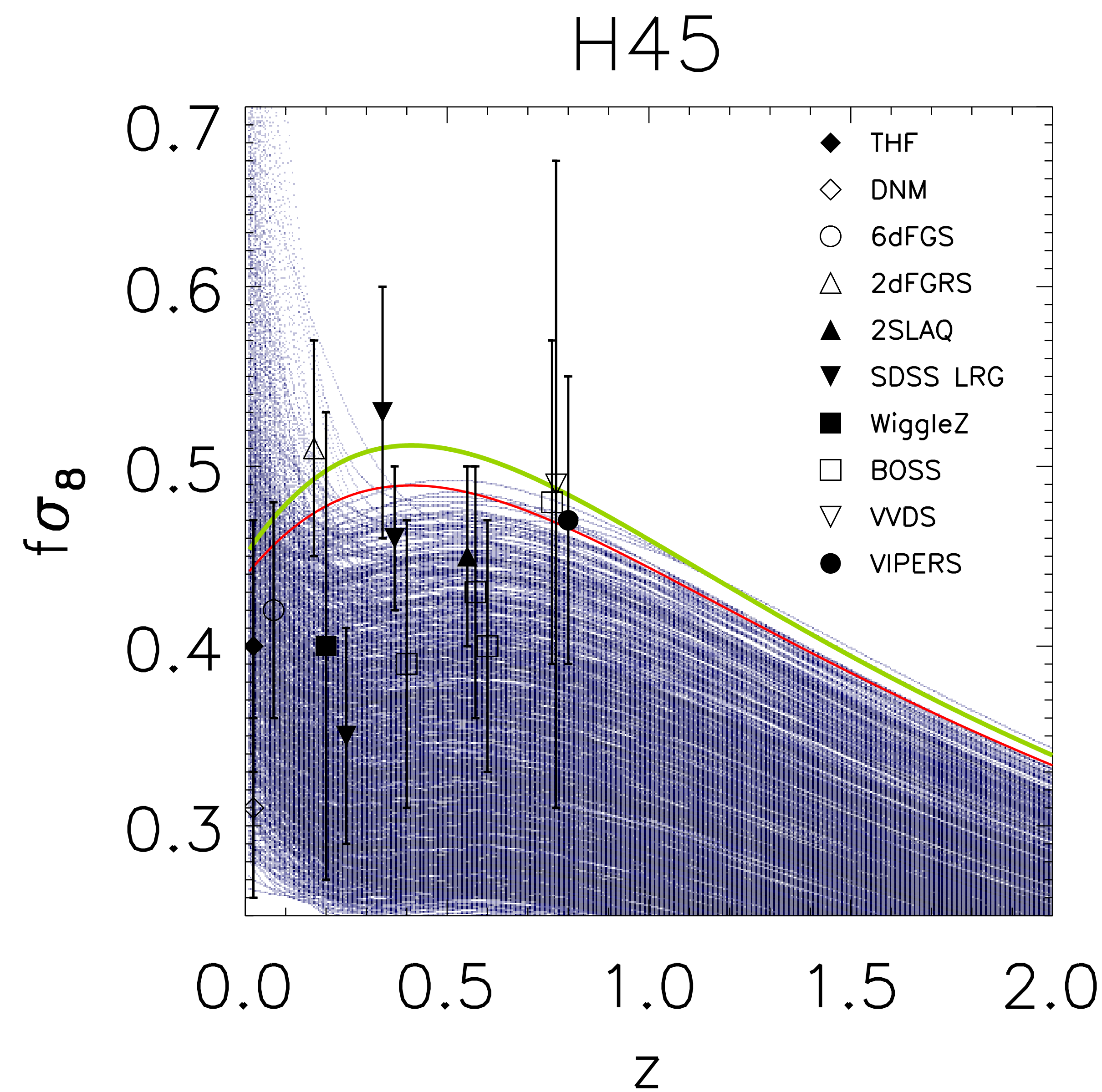




L. Perenon, F.P., C. Marinoni, L. Hui, to appear

Growth rate (early DE)



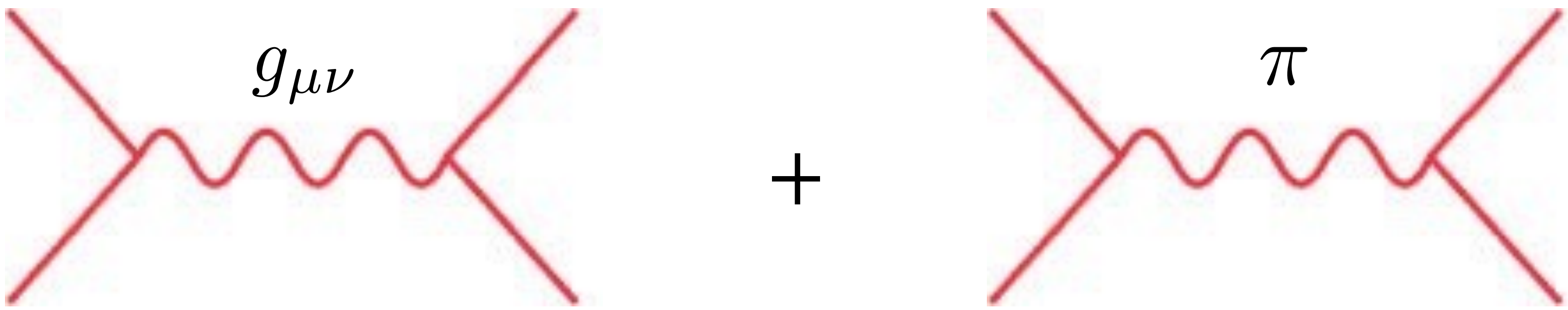


Strong implications on CMB data fitting (Valentina's talk)

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

Protecting solar system gravity with screening

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

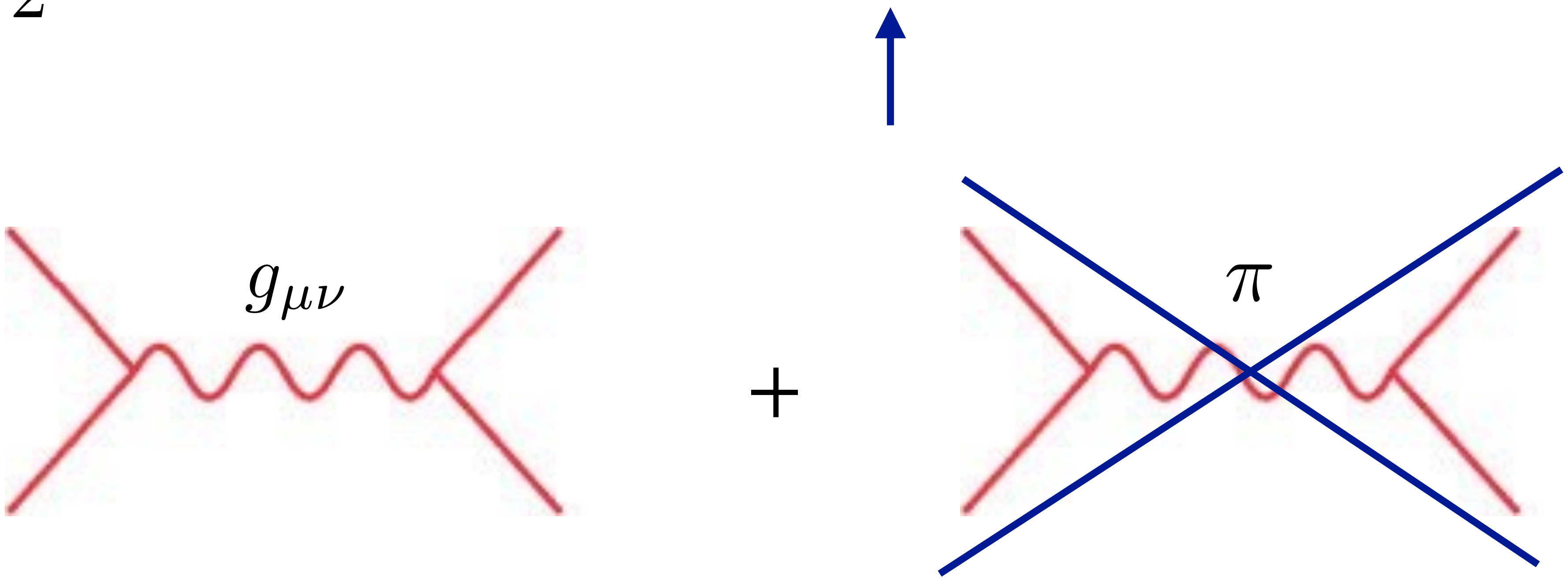


On cosmic scale the scalar contributes O(1)

We need screening!

Vainshtein screening

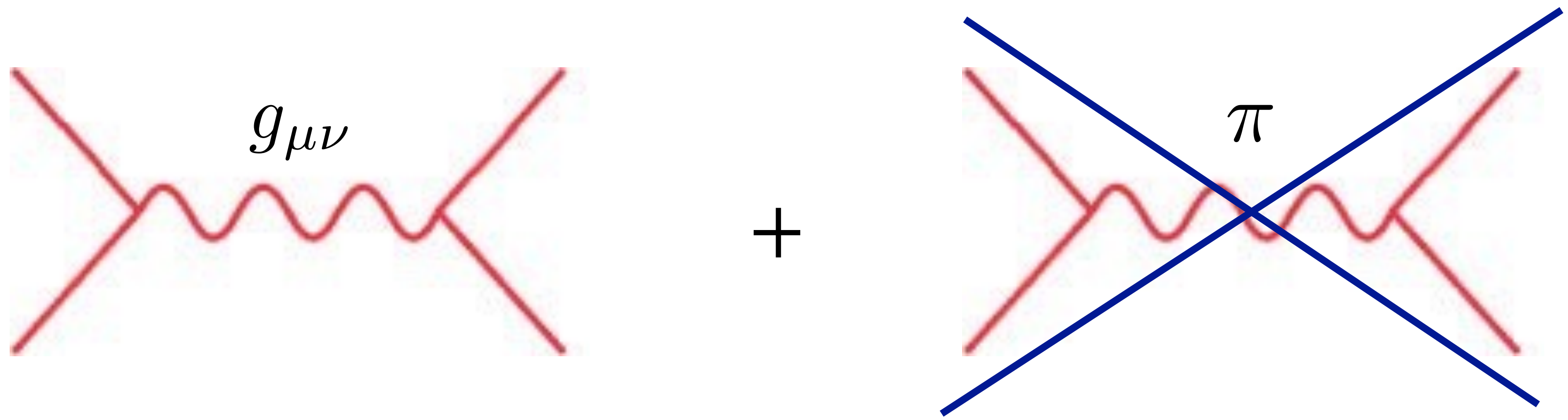
$$\mathcal{L} \; = \; -\frac{M_*^2}{2}\, h_{\mu\nu}\, \mathcal{E}^{\mu\nu}{}_{\alpha\beta}[\phi_0]\, h^{\alpha\beta} - \mathcal{A}^{\mu\nu}[\phi_0]\, \partial_\mu\pi\partial_\nu\pi - \pi T + \frac{1}{2}h^{\mu\nu}T_{\mu\nu}$$



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

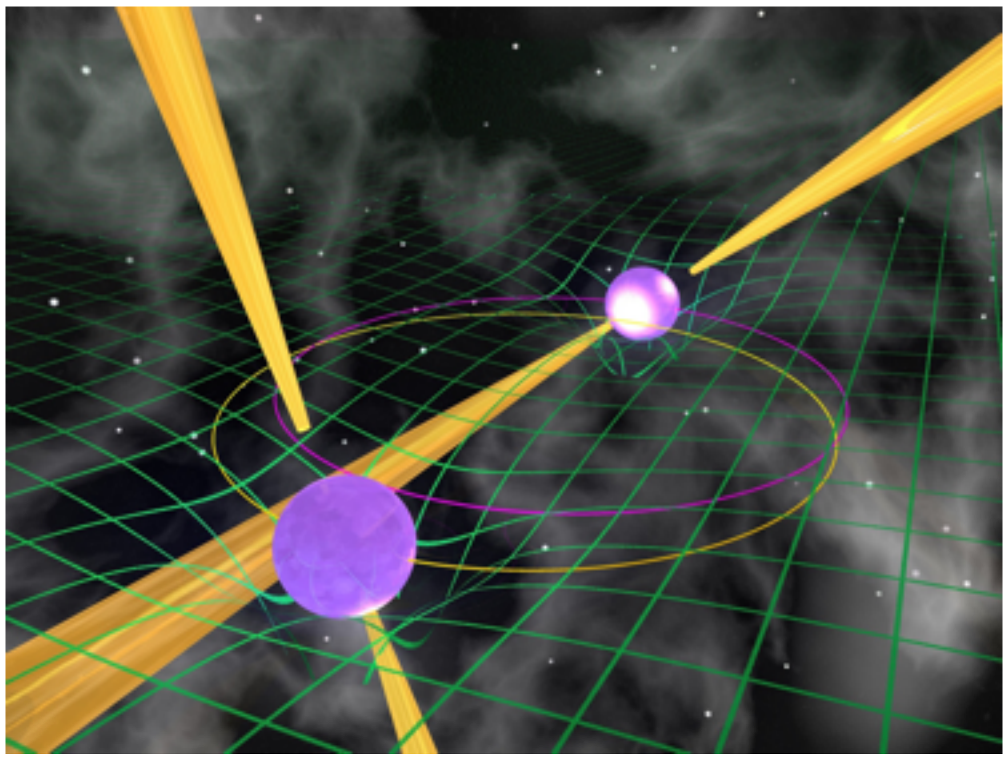
However: there can be modifications in the pure-graviton sector.
This are, generally, unscreanable!

Babichev, Deffayet, Esposito-Farese 2012

Beltran, F.P., Velten, 2015

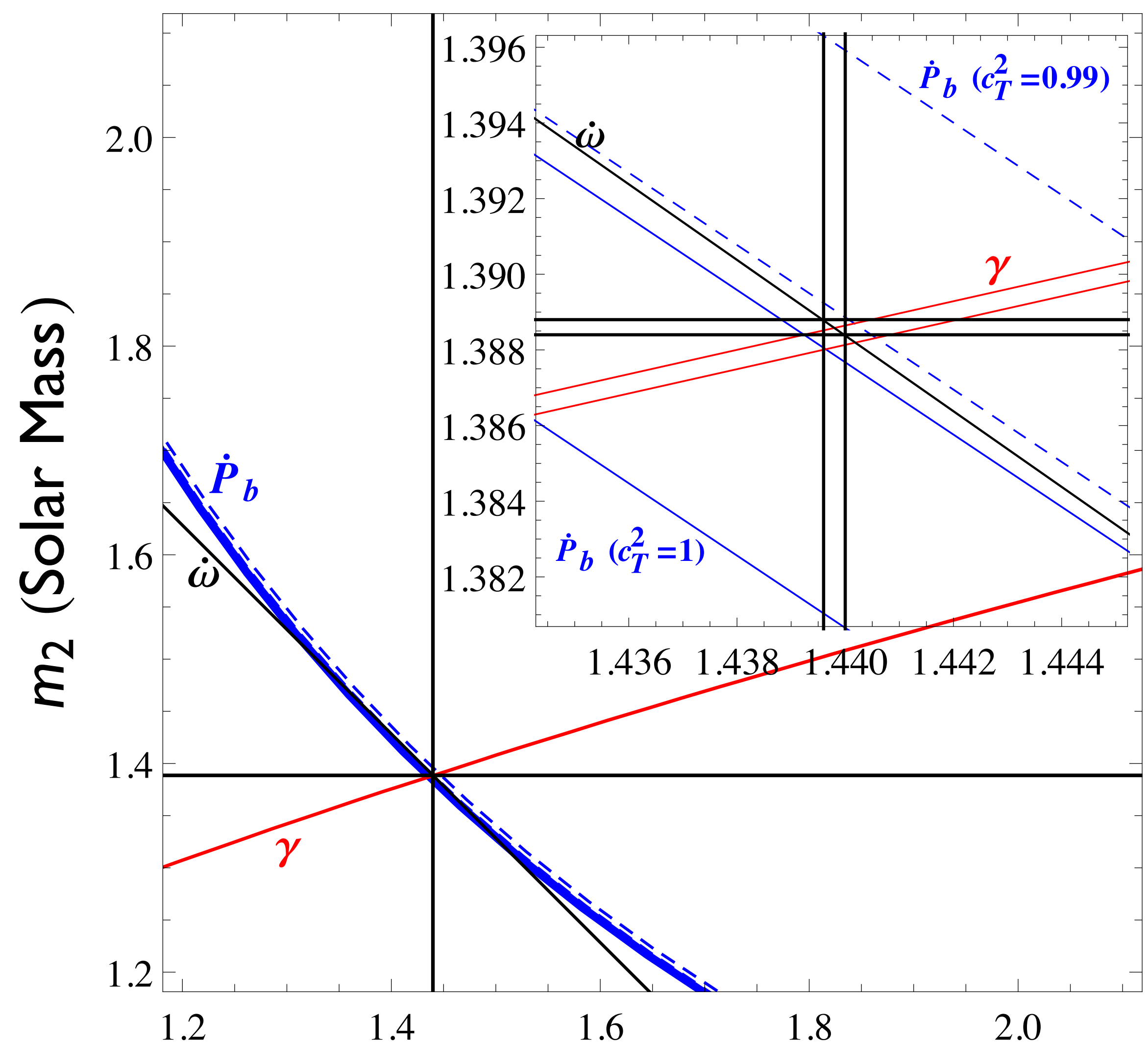
Gravitational wave speed (as in heaven as on hearth)

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

Gravitational wave speed (as in heaven as on earth)

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

A question of timing…

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Gravitation and Astrophysics

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

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Jose Beltrán Jiménez, Federico Piazza, and Hermano Velten

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

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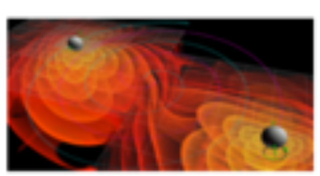
Observation of Gravitational Waves from a Binary Black Hole Merger

PDF HTML

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

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

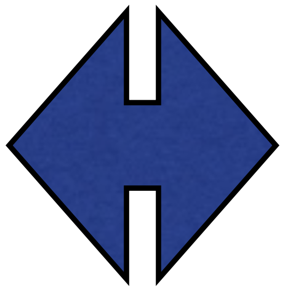
Final remarks

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

Either

or…

Tension persisting and eased by MG



Bruxelles 22/03/2016