Effective field theories of cosmic accelerations

Federico Piazza

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Gravity is attractive for normal matter

Curvature

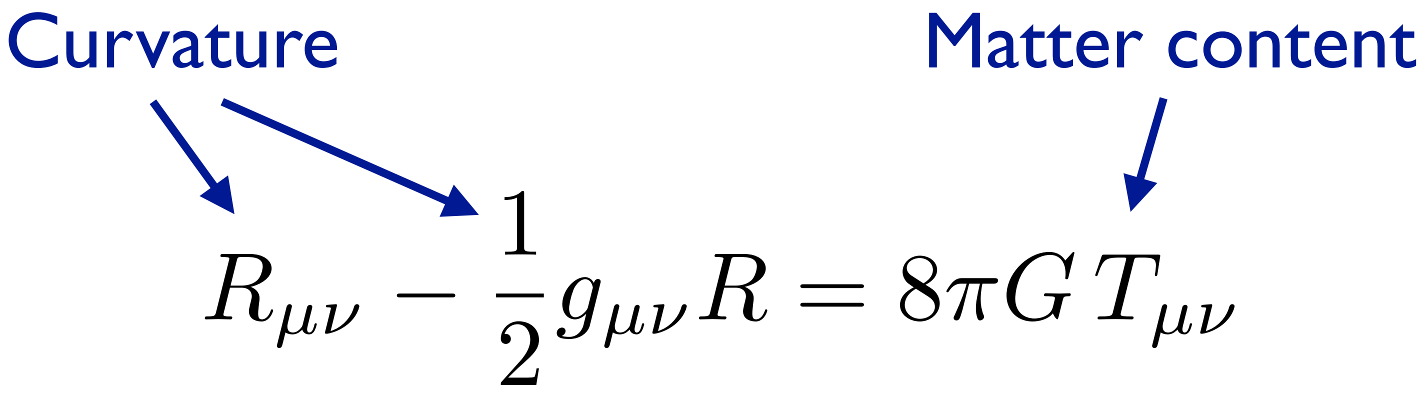
Matter content

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \, T_{\mu\nu}$$

$$w = \frac{\text{pressure}}{\text{energy density}}$$

Acceleration: $w < -\frac{1}{3}$

Gravity is attractive for normal matter



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

$$w = \frac{\text{pressure}}{\text{energy density}}$$

Acceleration: $w < -\frac{1}{3}$

GR: the only consistent low energy theory for a massless spin 2 field

Possibilities:

- General Relativity ($\Lambda\mathrm{CDM}$)
- General Relativity + stuff
- Understanding (quantum) gravity better?

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… and there is more than one Acceleration!

- Inflation (indirect evidence: homogeneity, isotropy, primordial fluctuations)

$$\rho \ \sim \ (10^{16}\mathrm{GeV})^4$$

$$[\rho \ > \ (TeV)^4]$$

- Dark Energy (supernovae, CMB, BAO etc.)

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

Ingredients for cosmic acceleration

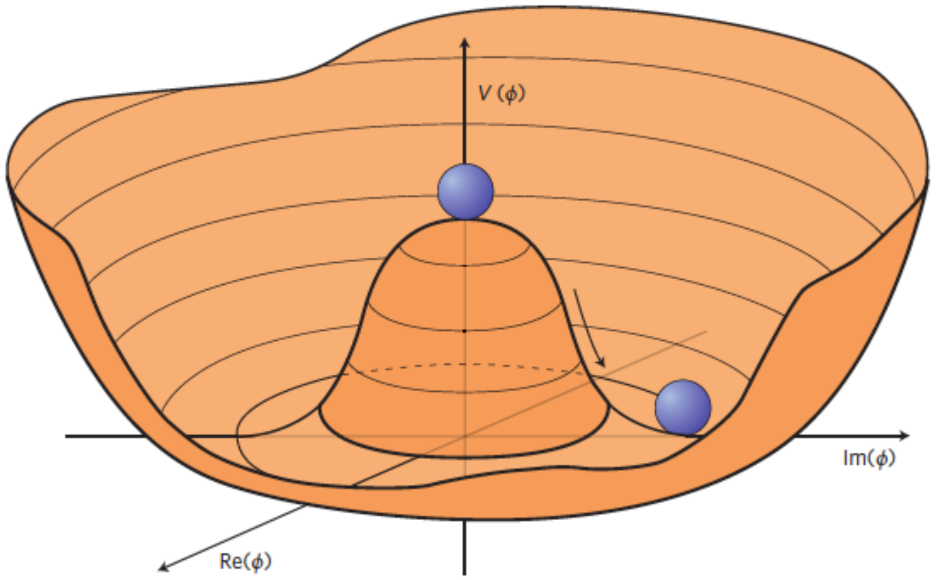
- Λ or a set of fields
- Coherence (~ classical field configuration)
- Symmetries: those of FRW
- Poincaré invariant theories with spontaneously broken boosts

Spontaneous Symmetry Breaking

Symmetry of the theory (of the Lagrangian)
but not of the (ground) state

Spontaneous Symmetry Breaking

- G -> H: one light field (Goldstone) for every broken generator
- Broken symmetries: non linearly realized on Goldstones



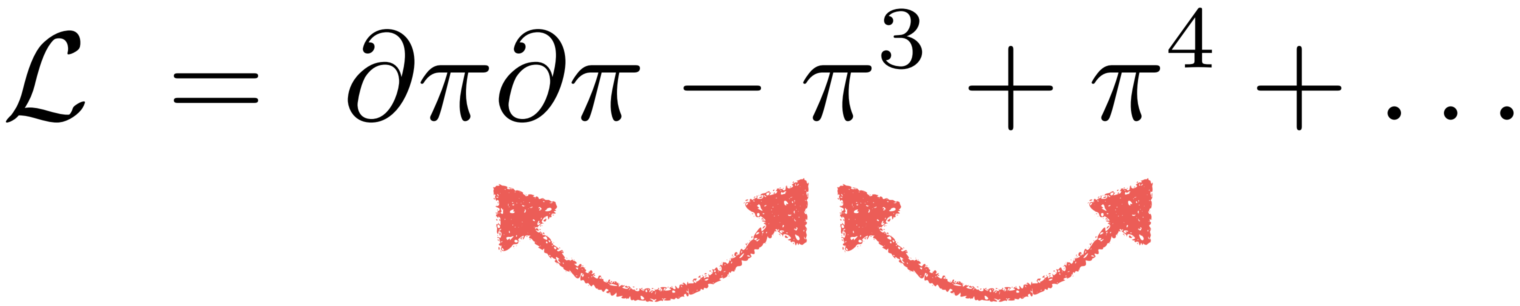
$$\delta \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} -\phi_2 \\ \phi_1 \end{pmatrix}$$

$$R \to R$$

$$\pi \to \pi + c$$

- Low energy dynamics strongly constrained
- Formally: coset construction by Callan, Coleman, Wess and Zumino (CCWZ)

Non linearly realized symmetries relate terms in the Lagrangian with a different number of fields



$$\mathcal{L} \ = \ \partial\pi\partial\pi - \pi^3 + \pi^4 + \ldots$$

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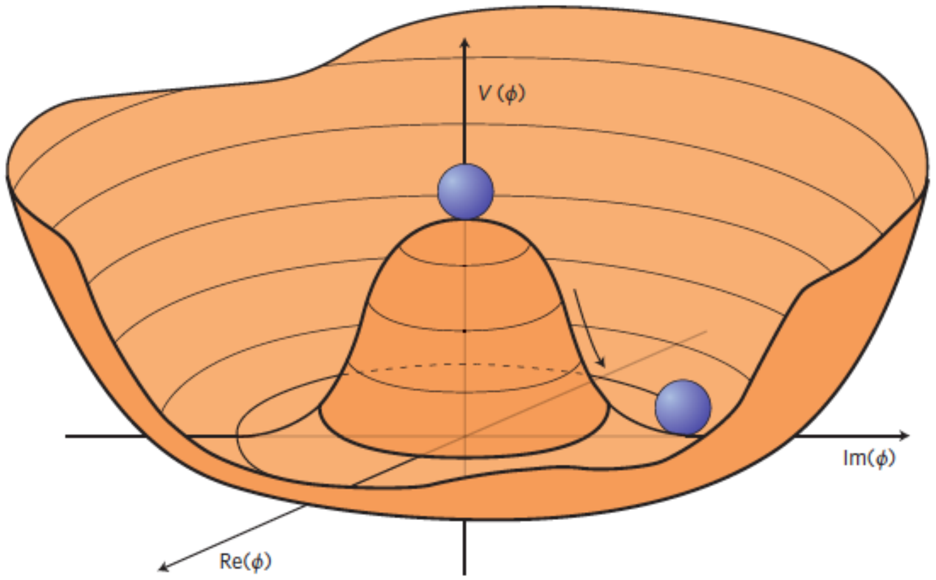

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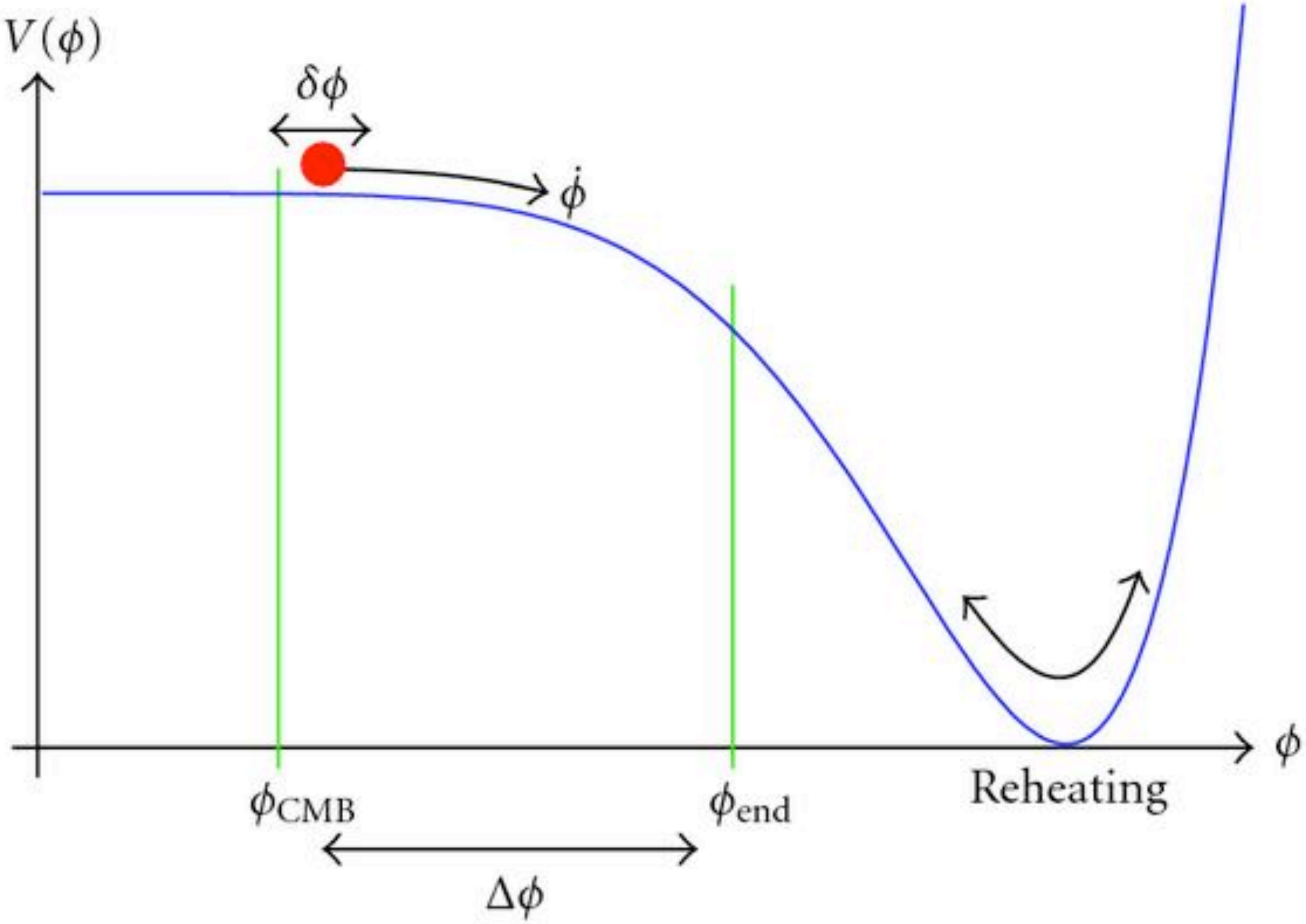
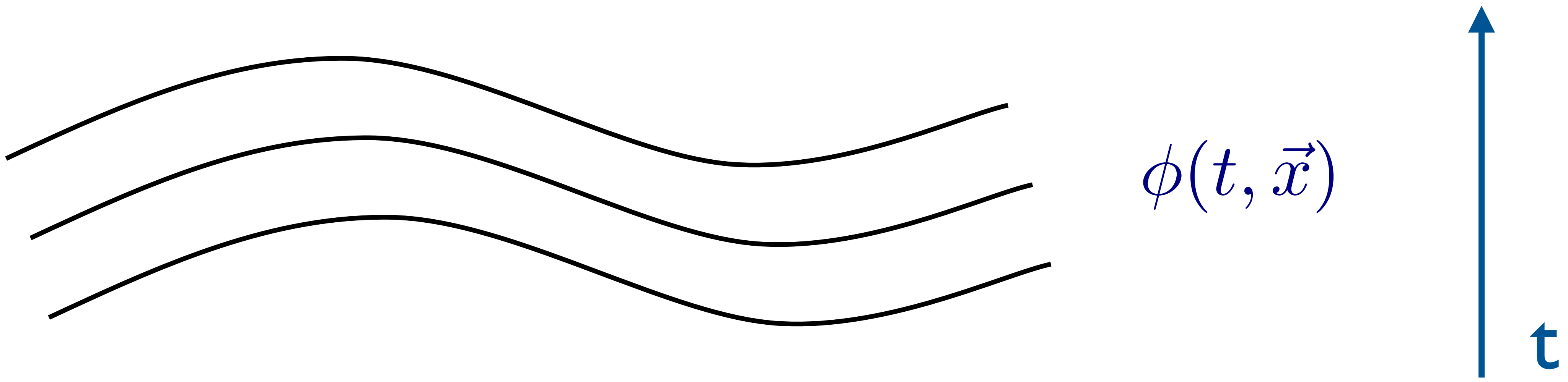
Inflation

- Phase of quasi-exponential expansion = very “flat” potential

$$\frac{V'}{V} \ll 1, \; \frac{V''}{V} \ll 1$$



SSB at work: a cosmological scalar field



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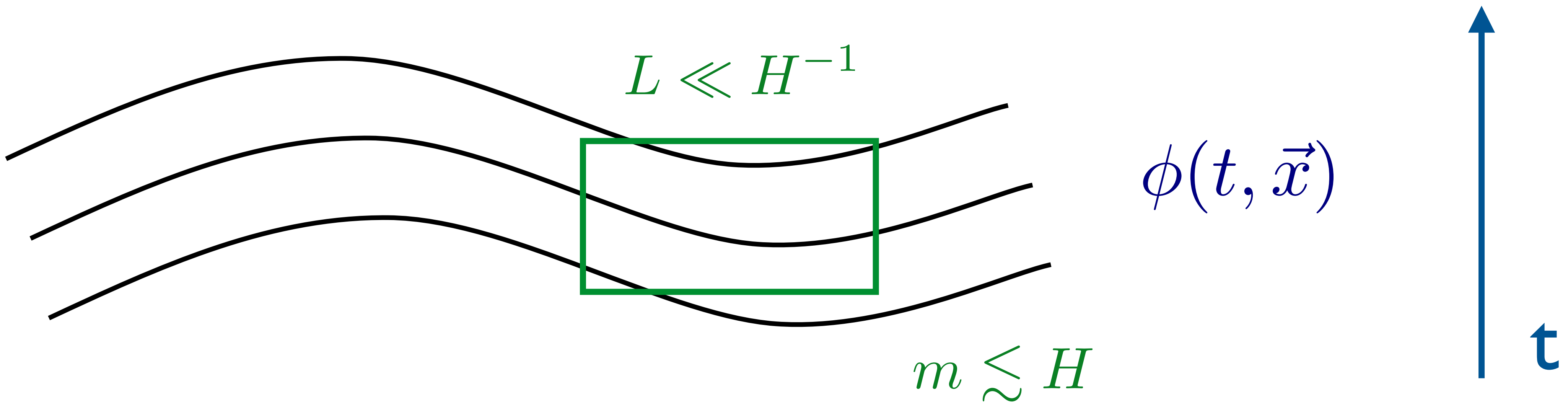


Quintessential rolling scalar: P(X)

$$\mathcal{L} = P(\partial_\mu\phi\partial^\mu\phi)$$

$$\phi = t + \pi(x)$$

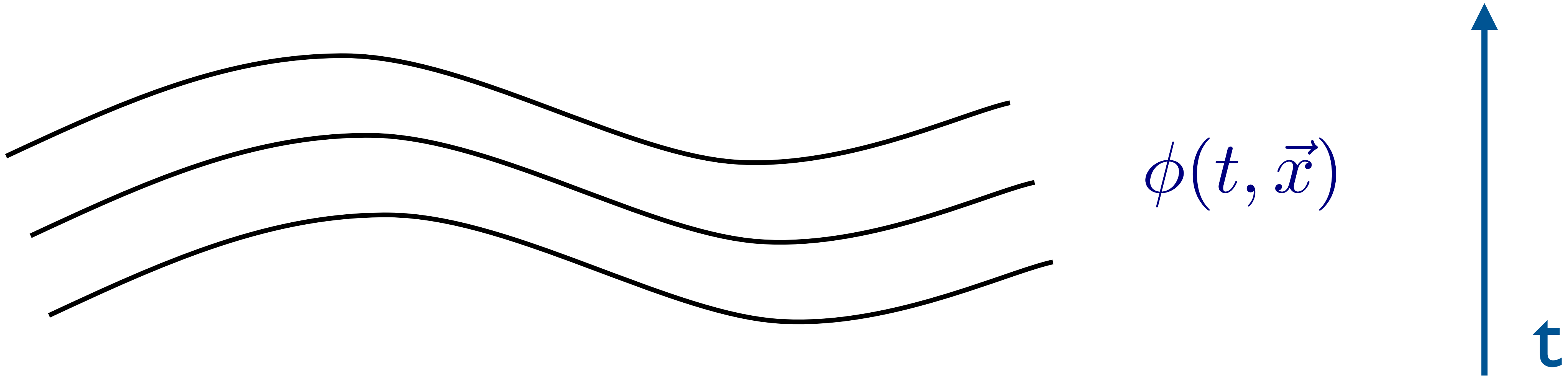
$$X = -1 - 2\dot{\pi} - \dot{\pi}^2 + (\partial_i\pi)^2$$

$$P(X) = P'\left[-\dot{\pi}^2 + (\partial_i\pi)^2\right] + 2P''\left[\dot{\pi}^2 + \dot{\pi}^3 - \dot{\pi}(\partial_i\pi)^2\right] + \ldots$$

$\uparrow$ $\uparrow$

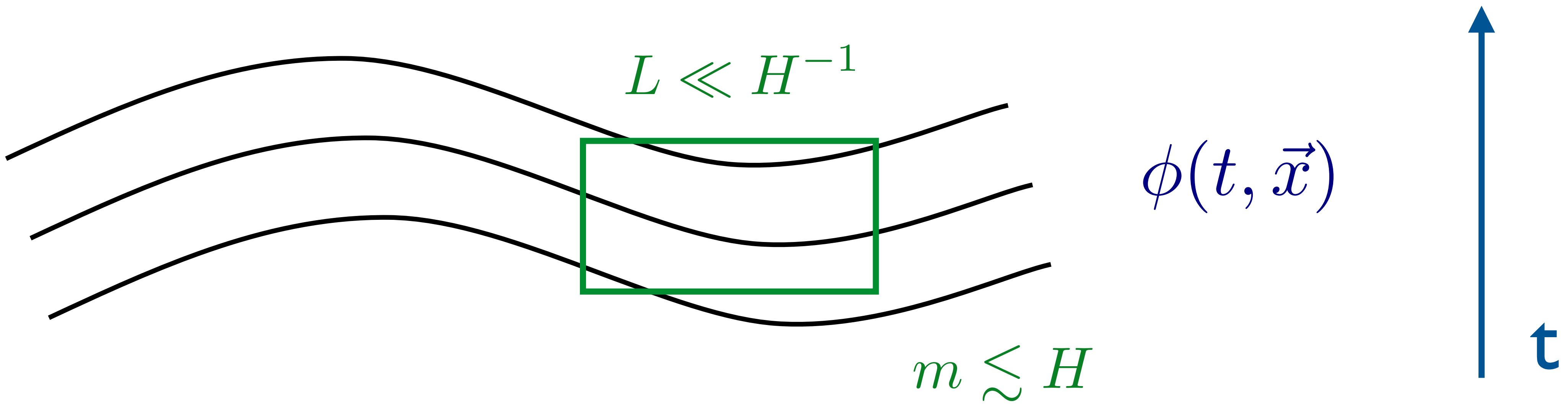
relation between speed of sound and cubic term
boosts non-linearly realized

(More or less) robust features of scalar inflation



- ξ and γ_{ij} conserved on large scales $k \ll H$
- $f_{NL} \propto c_s^{-2}$
- $\Delta_\gamma \sim \frac{H^2}{M_P^2}$
- $\Delta_s \sim \frac{H^2}{\epsilon c_s M_P^2}$

What is a cosmological scalar field?



An order parameter for a specific symmetry breaking pattern!

Quintessential rolling scalar: P(X) $\mathcal{L} = P(\partial_\mu \phi \partial^\mu \phi)$

Minkowski space analysis: $\phi = c\,t$

Poincare' generators: P_i P_0 J_i K_i

Internal symmetry: Q

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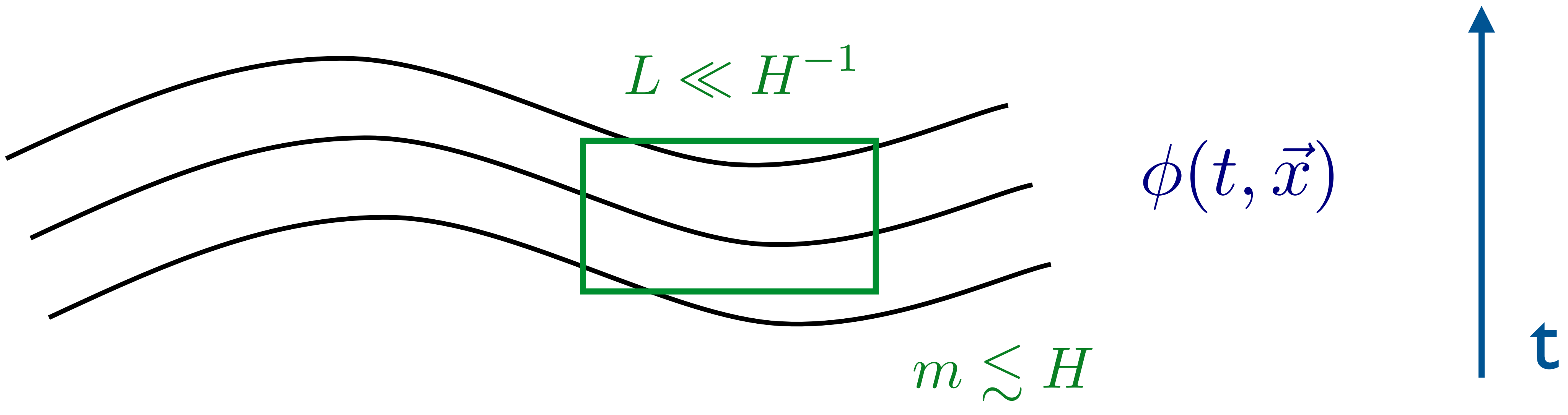

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Internal symmetry: $\cancel{Q}$

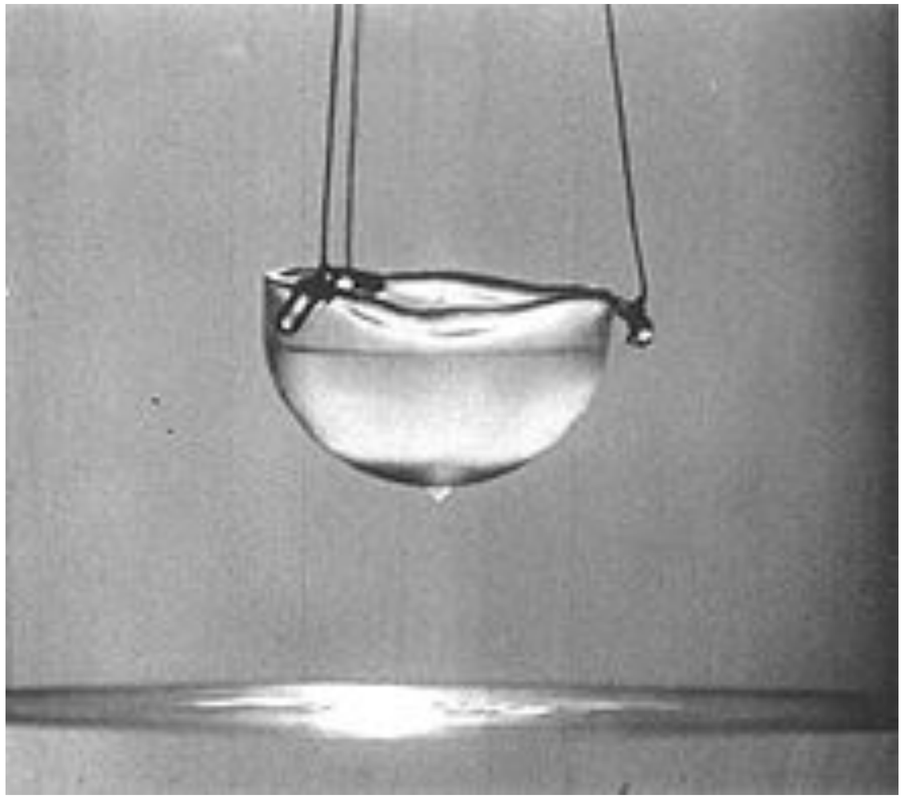
$$\bar{H} = H - \mu Q$$

Unbroken combination

Condensed matter equivalent: ^{4}He superfluid

U(1) broken spontaneously and set at finite charge Q

Existence and dynamics of the phonons (almost) completely determined by the symmetry breaking pattern



$$\bar{H} = H - \mu Q$$

$$(H - \mu Q)|\psi\rangle = 0$$

Ground state

Cosmology = C.M. at play with gravity!

- Boosts spontaneously broken

$$\cancel{K_i}$$

- Unbroken types of translations and rotations

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

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

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Minkowski picture OK

Coupling with gravity important

Cosmology = C.M. at play with gravity!

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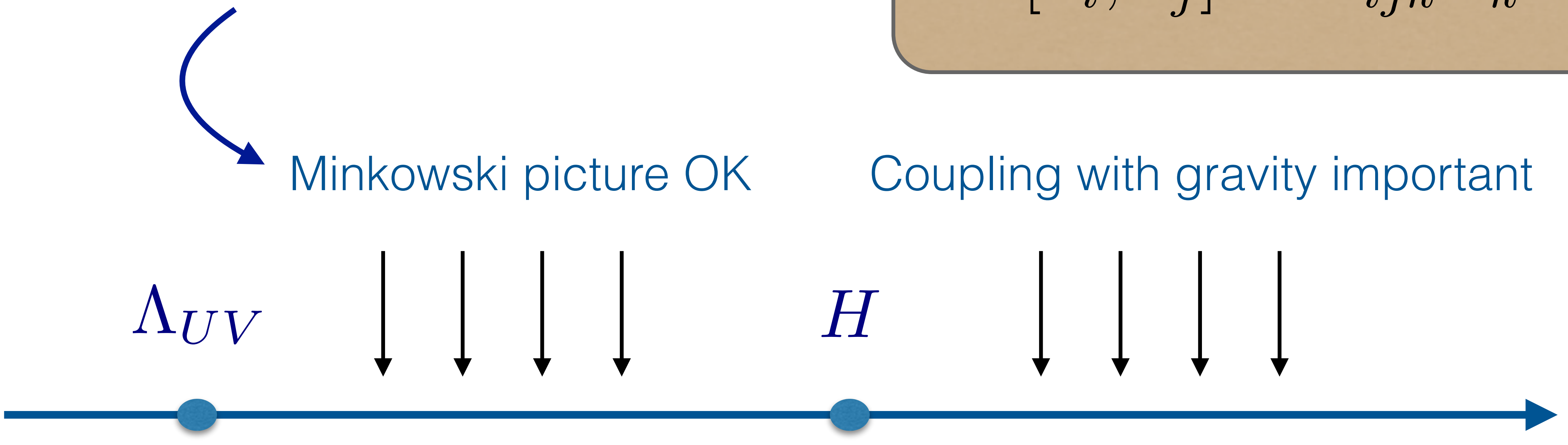


Minkowski picture OK

Coupling with gravity important

Λ_{UV}

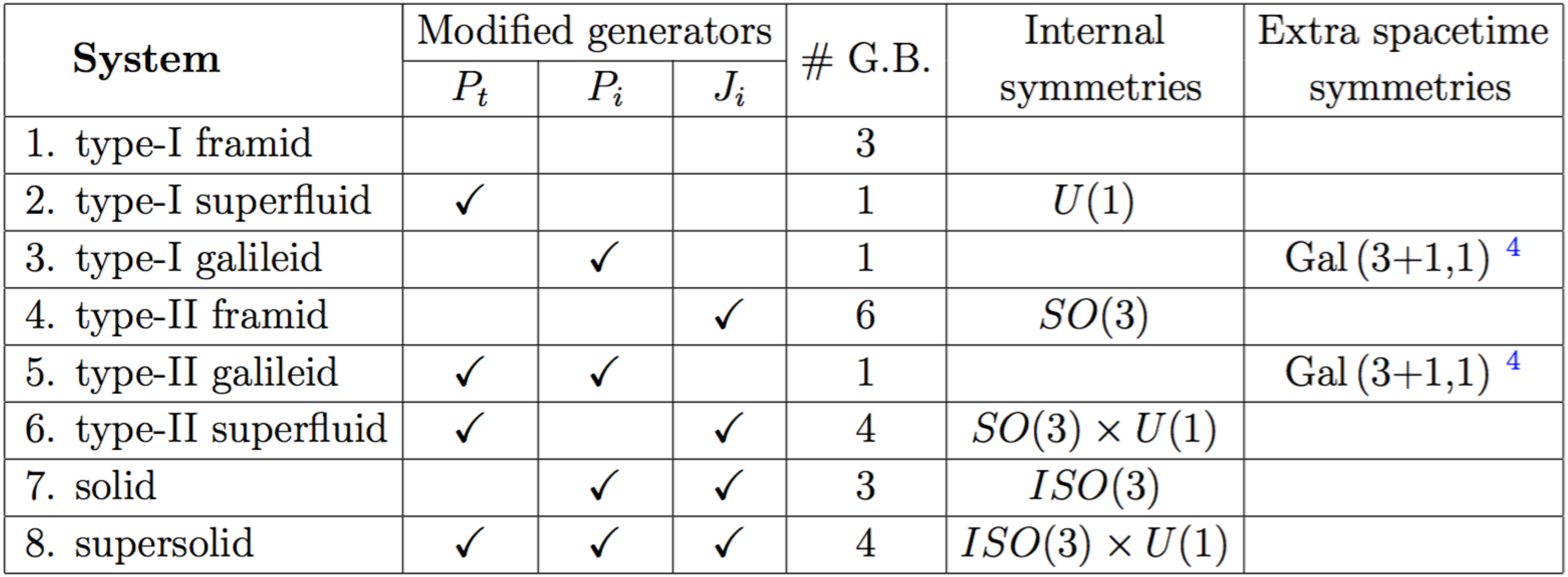
H

Ex: spatially flat gauge

Unitary gauge

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

Solids

Lorentz generators: P_i P_0 J_i K_i

Solids

Lorentz generators: P_i P_0 J_i $\xcancel{K_i}$

Solids

Lorentz generators: $\xcancel{P_i}$ P_0 J_i $\xcancel{K_i}$

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Internal symmetry: Q_i $\tilde{Q}_i$

$\uparrow$ Internal translations

$\uparrow$ Internal rotations

Solids

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Internal translations

Internal rotations

Unbroken combinations $\bar{P}_i = P_i + Q_i$ $\bar{J}_i = J_i + \tilde{Q}_i$

Solids

Lorentz generators: $\cancel{P_i}$ P_0 $\cancel{J_i}$ $\cancel{K_i}$

Internal symmetry: Q_i $\tilde{Q}_i$

Internal translations ↑ Q_i

Internal rotations ↑ $\tilde{Q}_i$

Unbroken combinations $\bar{P}_i = P_i + Q_i$ $\bar{J}_i = J_i + \tilde{Q}_i$

Order parameter: 3 scalar fields $\phi_i \;\to\; R_{ij}\phi_j + c_i$

Solids

Lorentz generators: $\cancel{P_i}$ P_0 $\cancel{J_i}$ $\cancel{K_i}$

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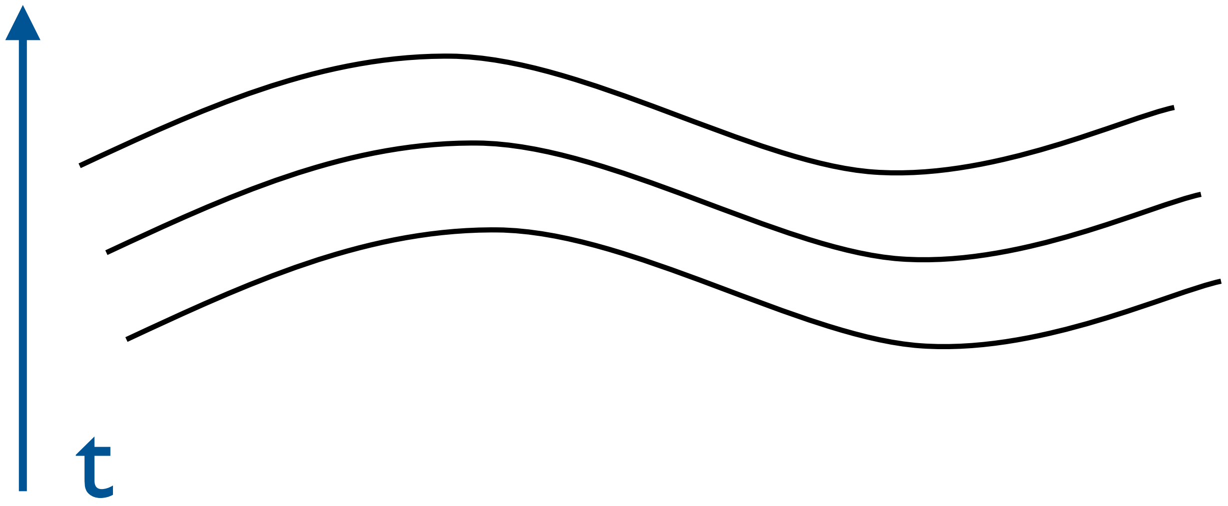
Order parameter: 3 scalar fields $\phi_i \;\rightarrow\; R_{ij}\phi_j + c_i$

Lagrangian (vs Eulerian) description of a solid: $\phi_i(t, \vec{x})$ are the coordinates of that volume element that is at $\vec{x}$ on the ground state $\langle \phi^i \rangle = x^i$

(slow-) roll v.s. Solid Inflation



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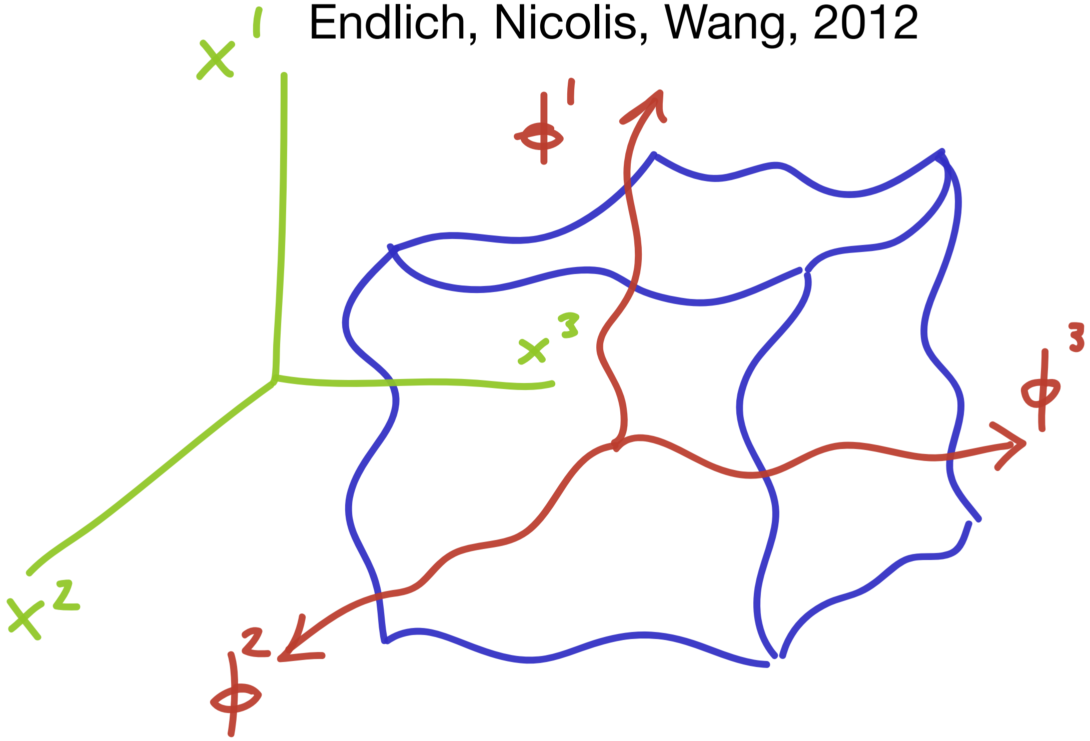
Endlich, Nicolis, Wang, 2012



- NO!
- $f_{NL} \propto \epsilon^{-1} c_s^{-2}$
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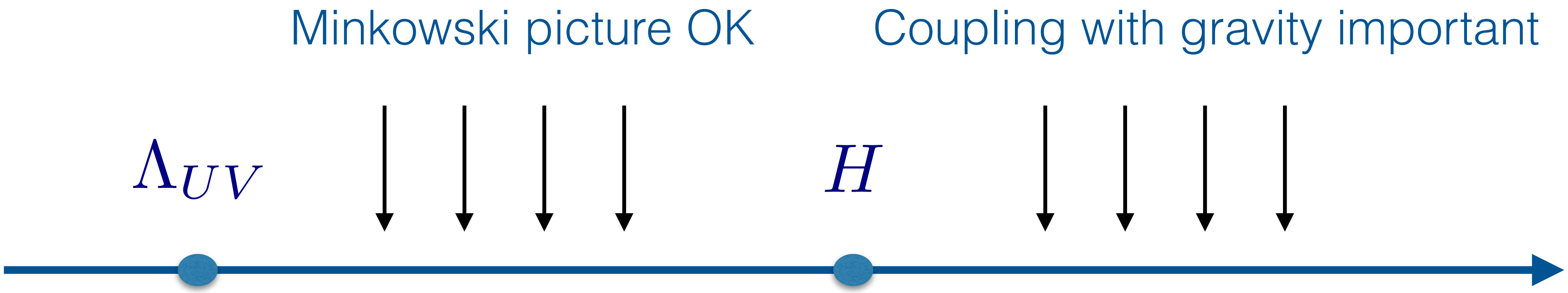
Large scales: couplings with gravity

Minkowski picture OK

Coupling with gravity important

Large scales: couplings with gravity


Minkowski picture OK

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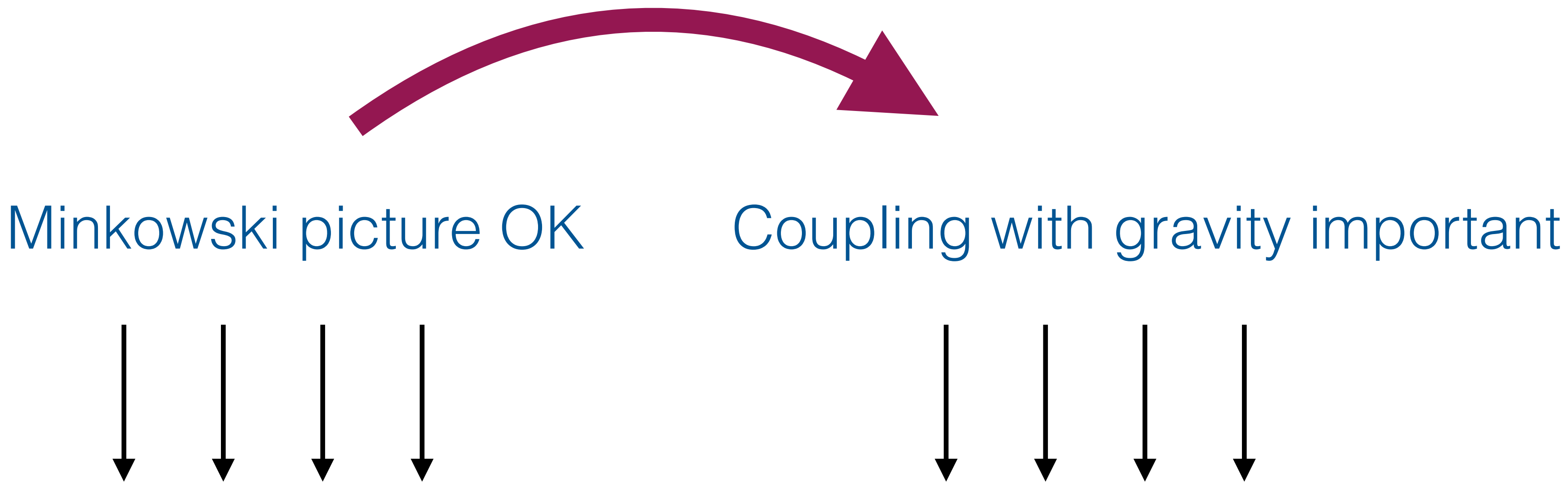
Coupling with gravity important

Ex: spatially flat gauge

Unitary gauge

Large scales: couplings with gravity

Use gauge invariance to transfer as many d.o.f. into $g_{\mu\nu}$



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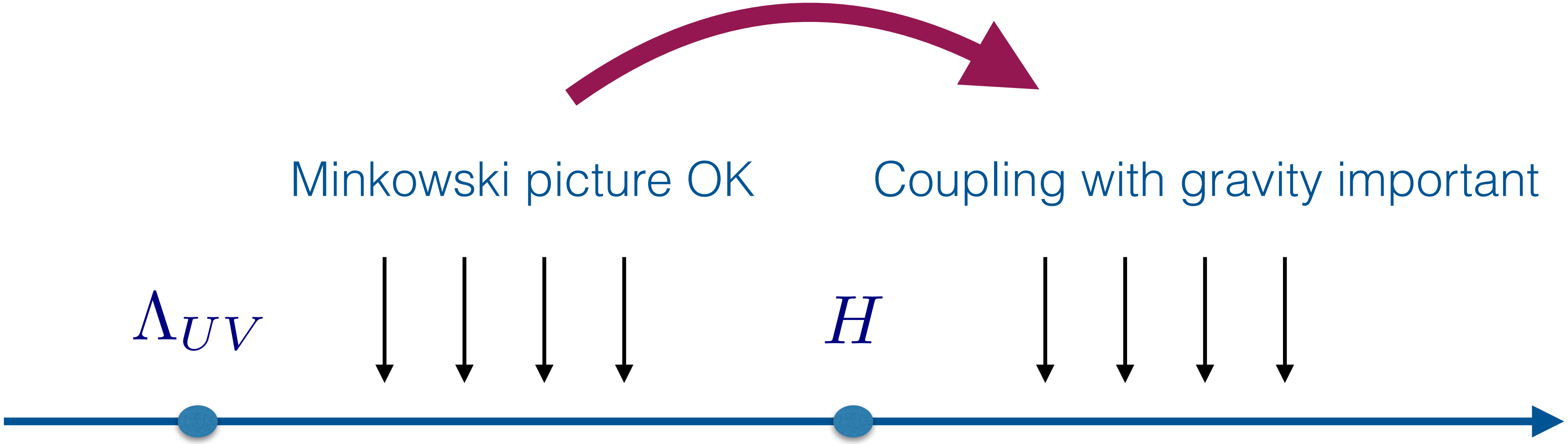

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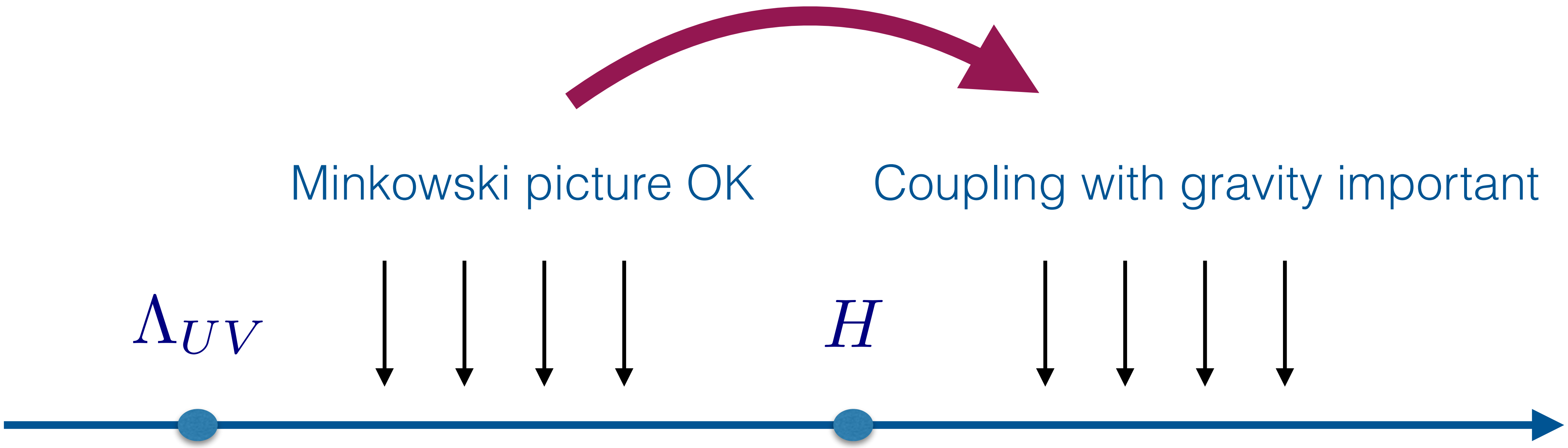

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Unitary gauge for superfluid-type models

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:

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

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

The effective field theory (EFT) of dark energy

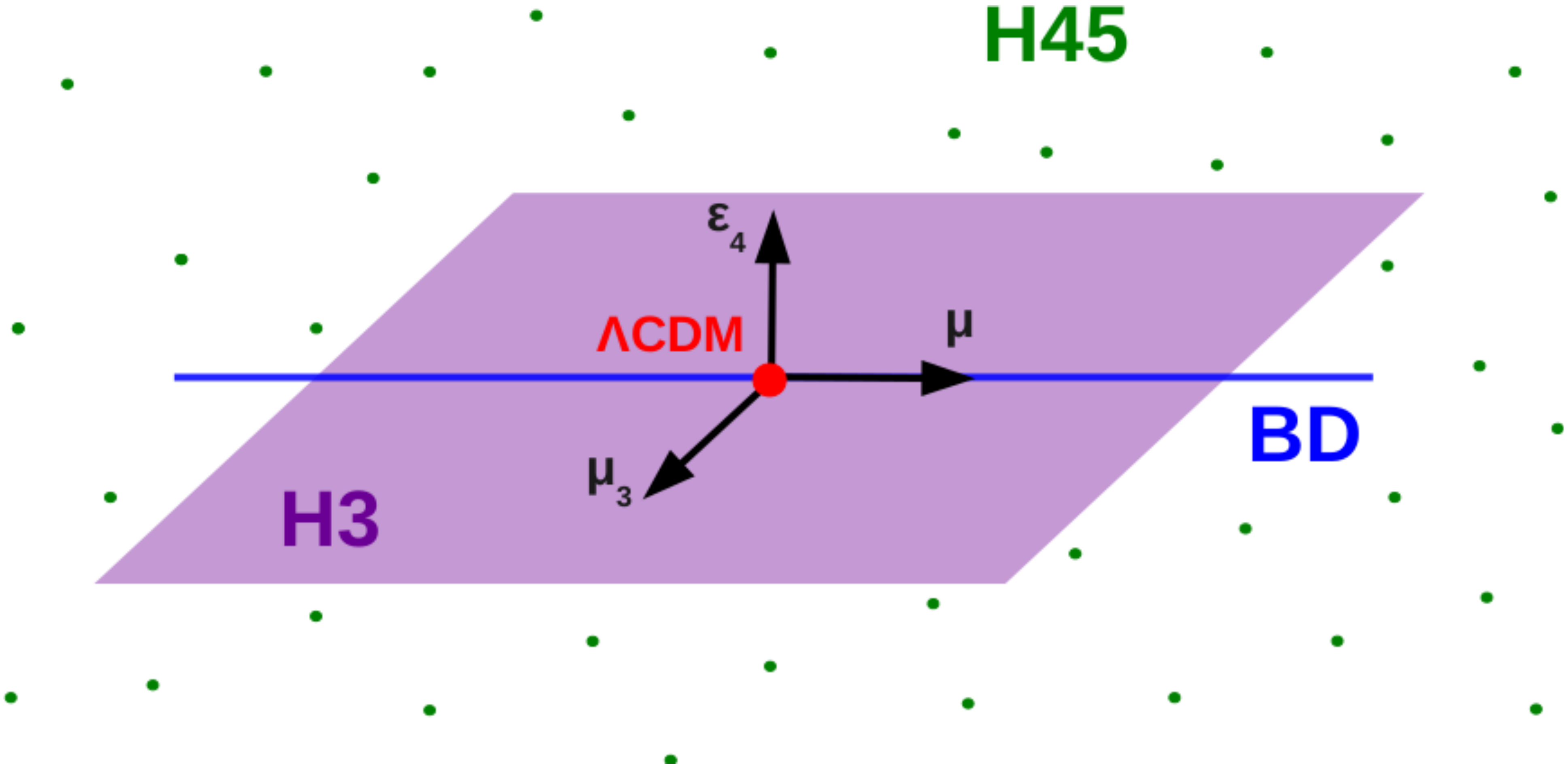
- Most general description of 1 scalar degree of freedom added to GR
- Cosmological perturbations as the relevant objects of the theory
- Background (0th order) and perturbation (linear and +) sectors
- Good parameter space to constrain with data

The space of modified gravity

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

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

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



Perenon, F.P., Marinoni, Hui, ‘15

Potentially well-behaved scalar tensor theories

Horndeski → “GLPV” → DHOST theories

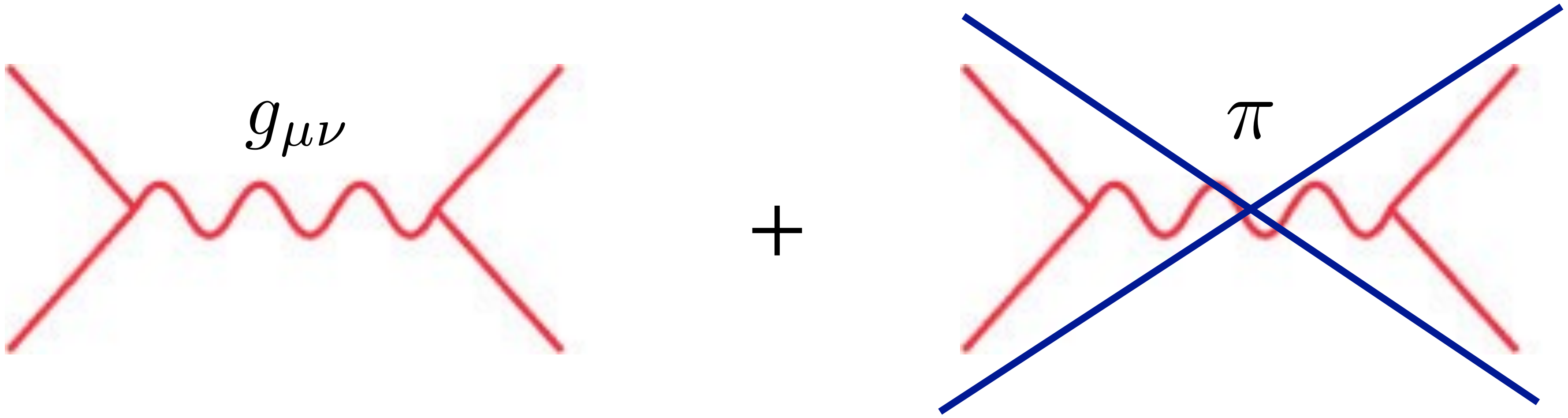
Gleyzes, Langlois, F.P., Vernizzi `14

Langlois, Noui `15

Hard times for scalar tensor theories!

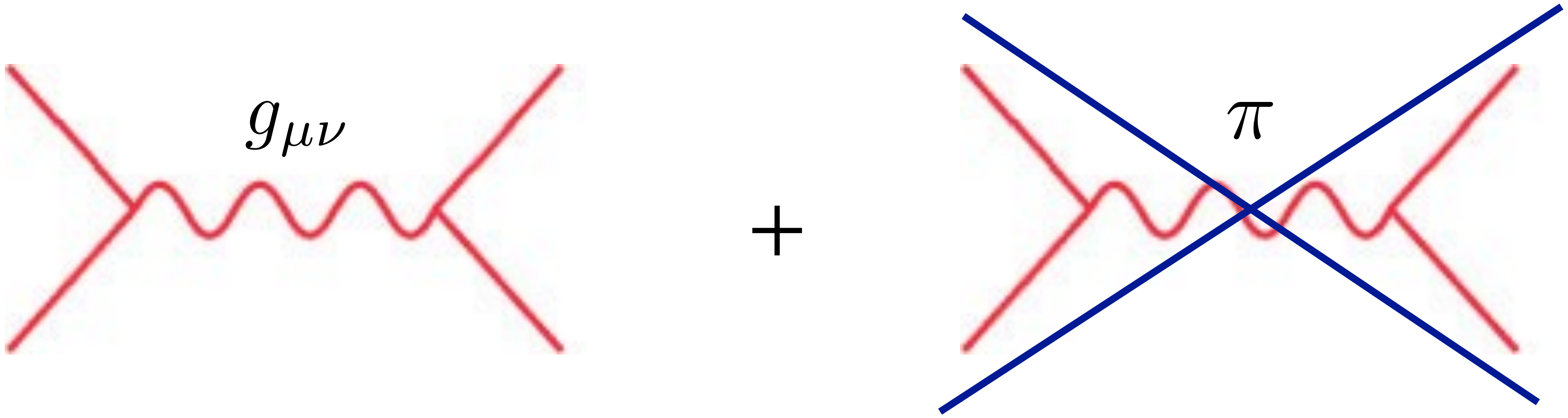
- Vainshtein screen ``pierced” (Beltran, F.P., Velten, 2015)
- Speed of gravity = speed of light (Creminelli, Vernizzi 2017)
- Coupling matter-gravitational waves = G

Vainshtein screening



Vainshtein: non-linear effects suppress the scalar contribution

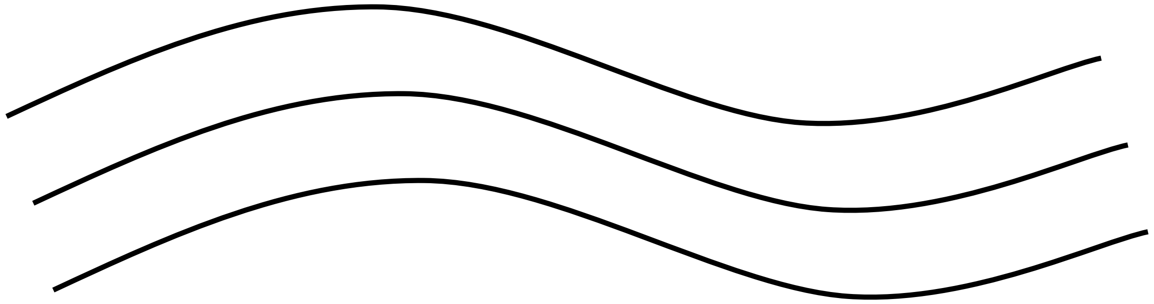
Vainshtein screening: pierced



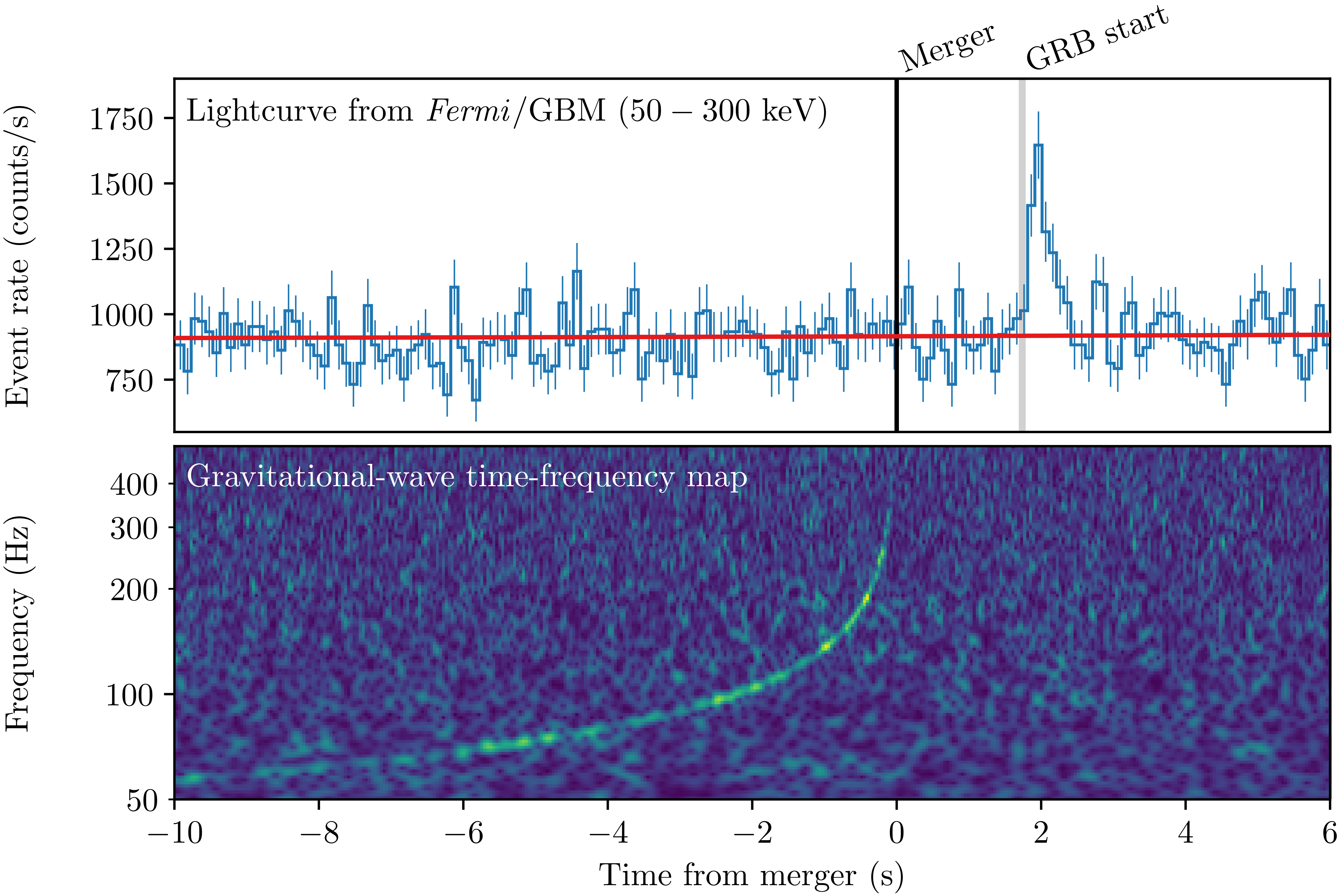
Vainshtein: non-linear effects suppress the scalar contribution

However: a timelike scalar gradient persists inside structures

- (Beltran, F.P., Velten, 2015)



GW170817 = GRB170817



Virgo, LIGO Scient. coll. 17; Virgo, Fermi-GBM, INTEGRAL, LIGO Scient. coll. 17 (courtesy of F. Vernizzi)

$$\boxed{|c_T - c| \lesssim 10^{-15}}$$

Consequence on Horndeski

$$\mathcal{L}_{\mathrm{H}}^{(2)} = G_2(\phi, X)$$

$$\mathcal{L}_{\mathrm{H}}^{(3)} = G_3(\phi, X)\Box\phi$$

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

$$\cancel{\mathcal{L}_{\mathrm{H}}^{(5)} = G_5(\phi, X)G^{\mu\nu}\nabla_\mu\nabla_\nu\phi + \frac{1}{3}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3\Box\phi(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right]}$$

$$X = \nabla_\mu\phi\nabla^\mu\phi$$

$$\Box \equiv g^{\mu\nu}\nabla_\mu\nabla_\nu$$

e.g. Creminelli and Vernizzi, 2017

The fate of self-acceleration

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

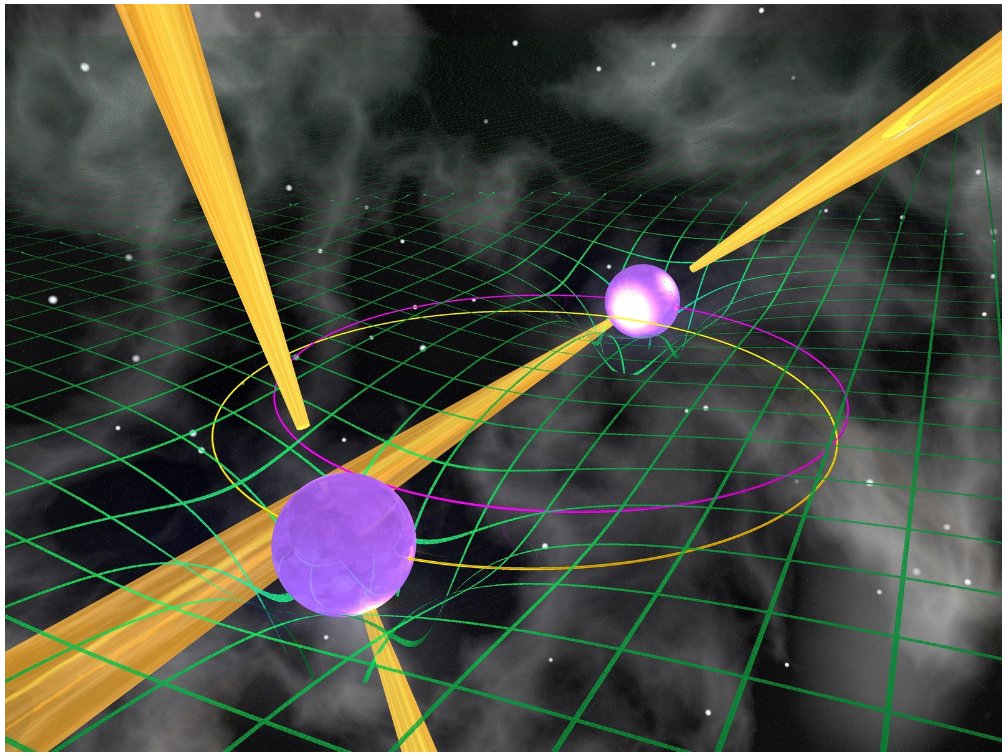
self-acceleration

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

$$\frac{\dot{G}_N}{G_N} < 0.02 H_0$$

(Lunar Laser Ranging)

Universal gravitational coupling



Hulse-Taylor
binary pulsars

$$\left| \frac{G_{gw}}{G_N} - 1 \right| \lesssim 10^{-2}$$

Conclusions

- Pragmatic attitude towards cosmic accelerations
- Cosmological perturbations <-> “Goldstones”
- Scalar field difficulties + recent tensions = Maybe there is more out there!

Main messages:

- New degrees of freedom (if it’s not Λ)
- Universality classes through symmetry breaking patterns
- Cosmological perturbations $\supset$ Nambu-Goldstone modes

Minkowski picture OK

Coupling with gravity important

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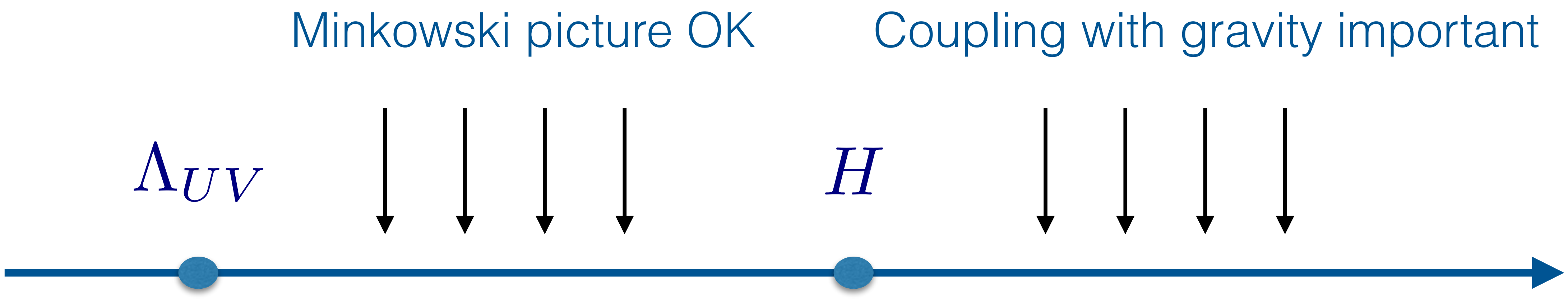


Minkowski picture OK

Coupling with gravity important

Λ_{UV}

H

Summary:

- Universality classes through symmetry breaking patterns
- Cosmological perturbations = Nambu-Goldstone modes
- Pondering the recent tensions

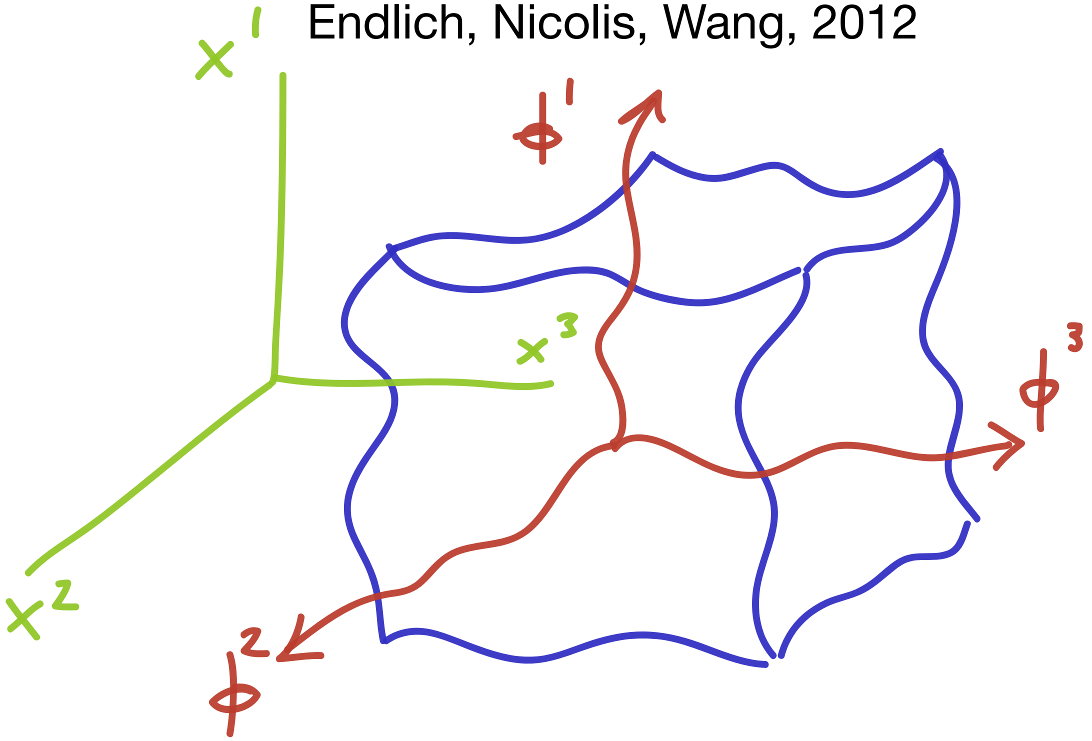
Gaugid inflation v.s. Solid Inflation

F.P.,Pirtskhalava, Rattazzi, Simon, 2017

Endlich, Nicolis, Wang, 2012

Same Universality class
but with gauged internal translations

Order parameter: 3 gauge fields A_μ^I



- ξ and γ_{ij} NOT CONSERVED
- $f_{NL} = ?$
- $\Delta_\gamma \sim \dfrac{H^2}{\epsilon_E c_E^5 M_P^2}$
- $\Delta_s \sim \dfrac{H^2}{\epsilon c_s M_P^2}$

- NO!
- $f_{NL} \propto \epsilon^{-1} c_s^{-2}$
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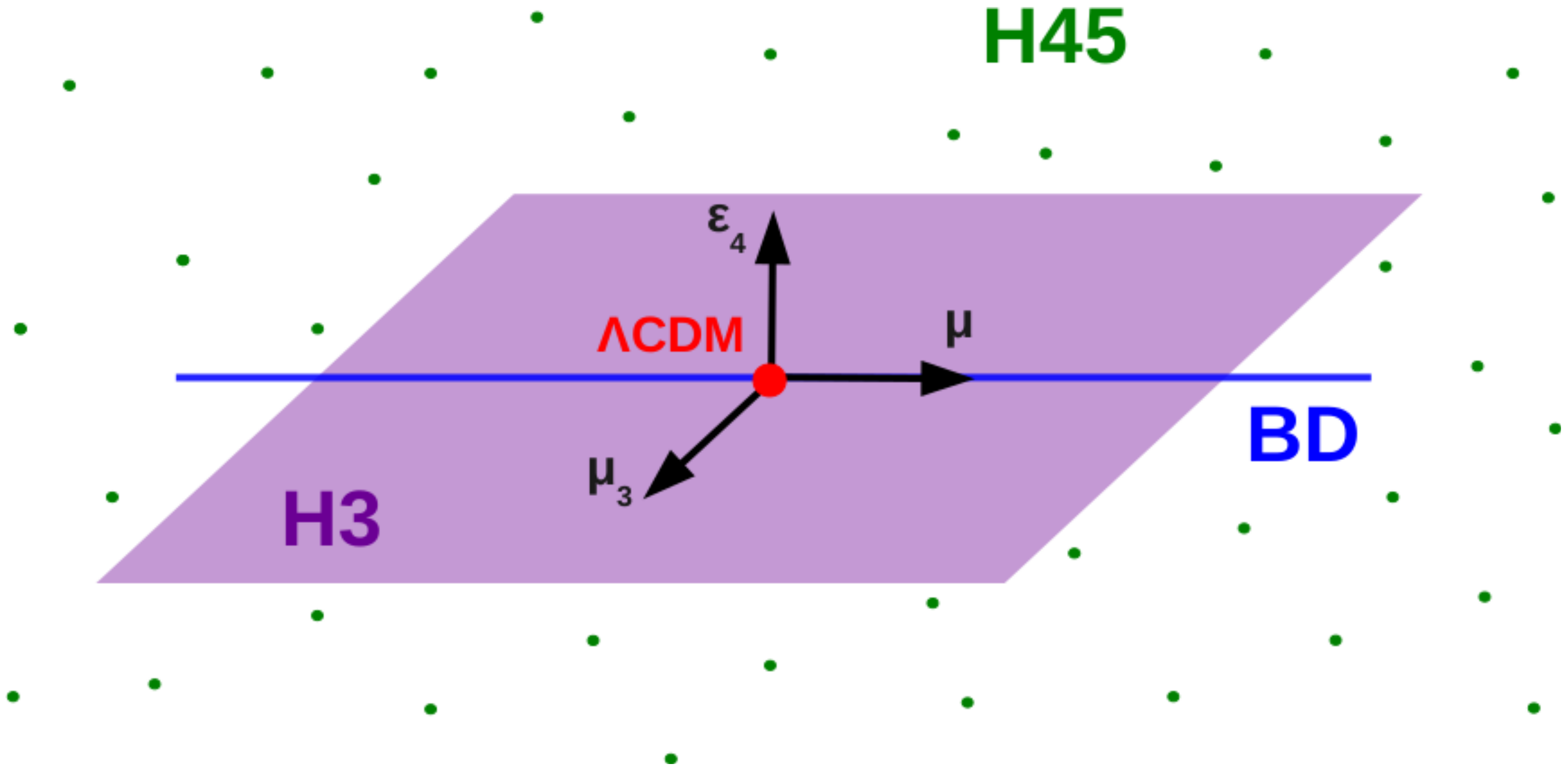
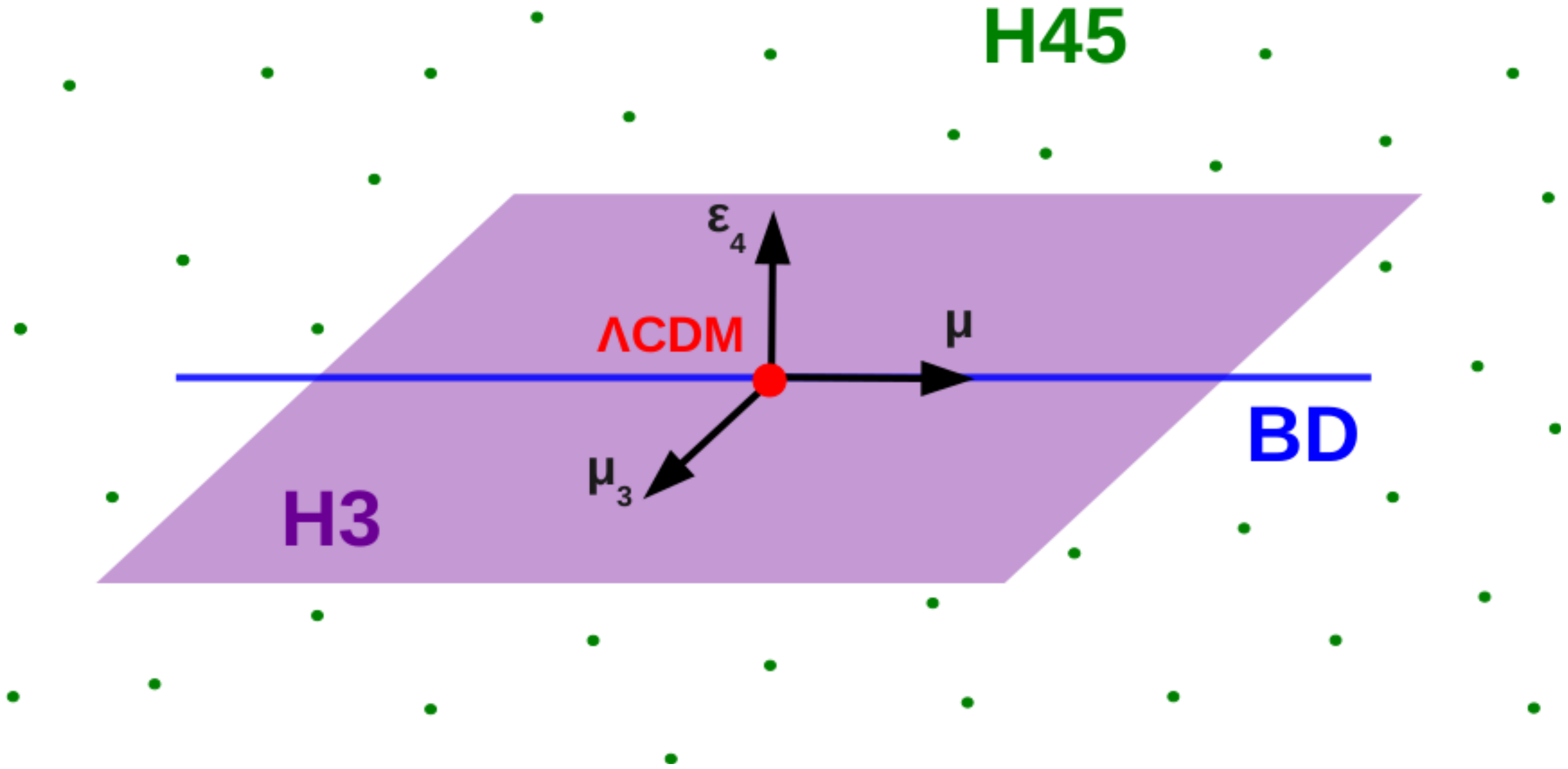
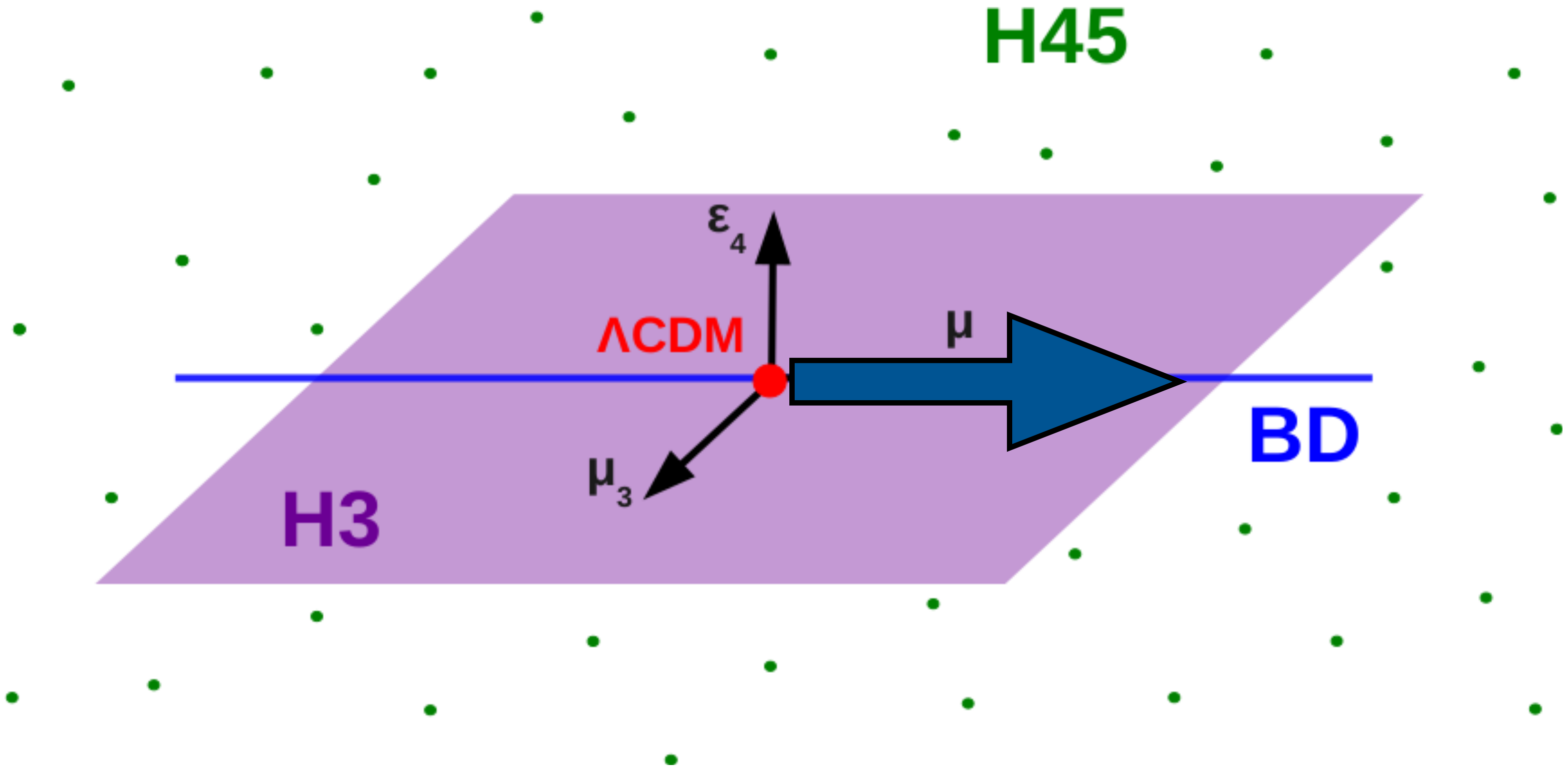

H45
ε4
μ
ΛCDM
BD
μ3
H3



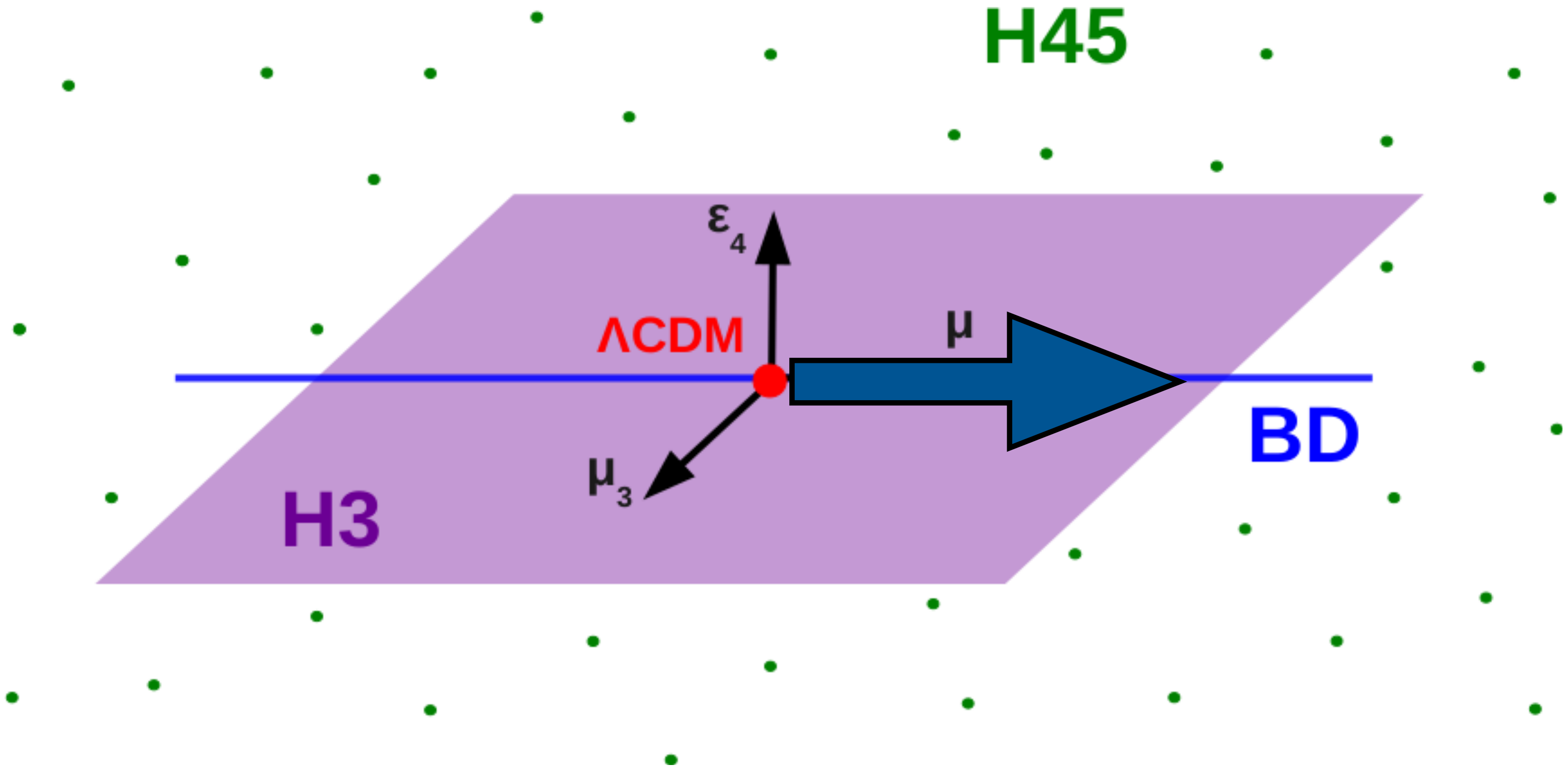
Quintessence
k- essence
etc.

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.)

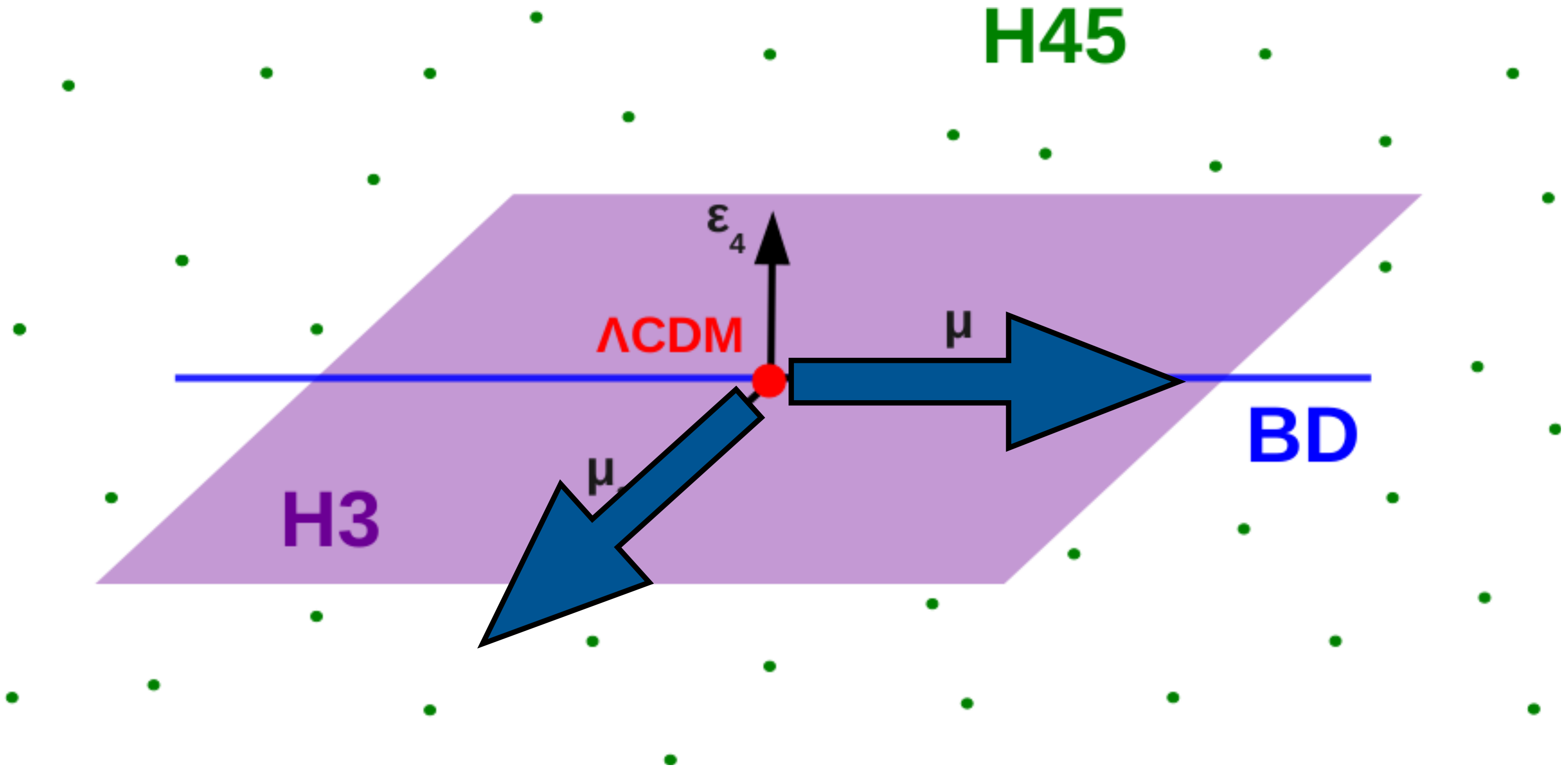
$$\mu \equiv \frac{d \log M^2}{dt}$$

self-acceleration

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

‘normal’ negative pressure

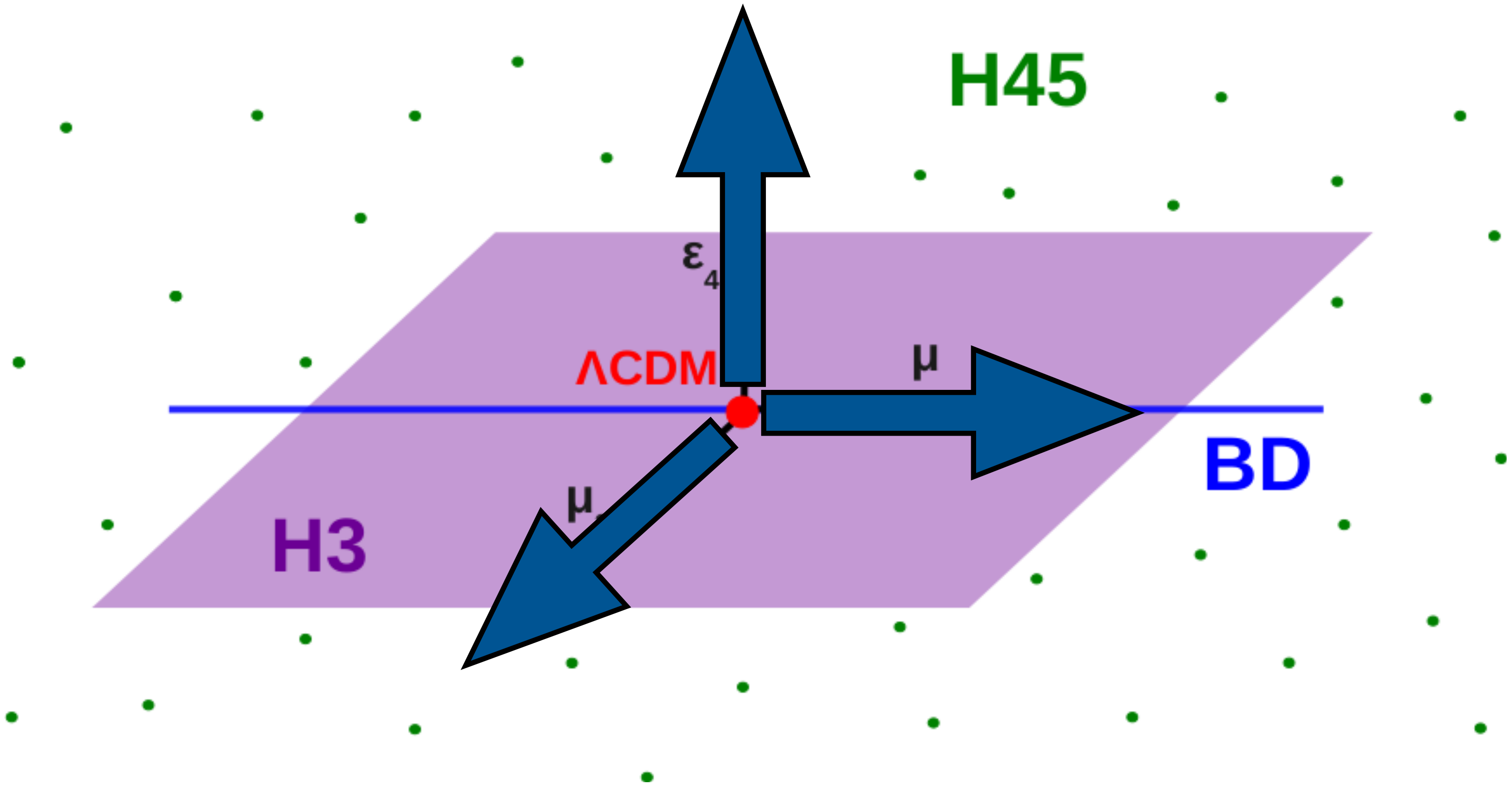
Perenon, F.P., Marinoni, Hui, to appear



The μ3 direction

“Galilean Cosmology” (Chow and Khoury, 2009)

Galileon 3/ Horndeski 3



“Generalized Galileons” (≡ Horndeski)

(Deffayet et al., 2011)

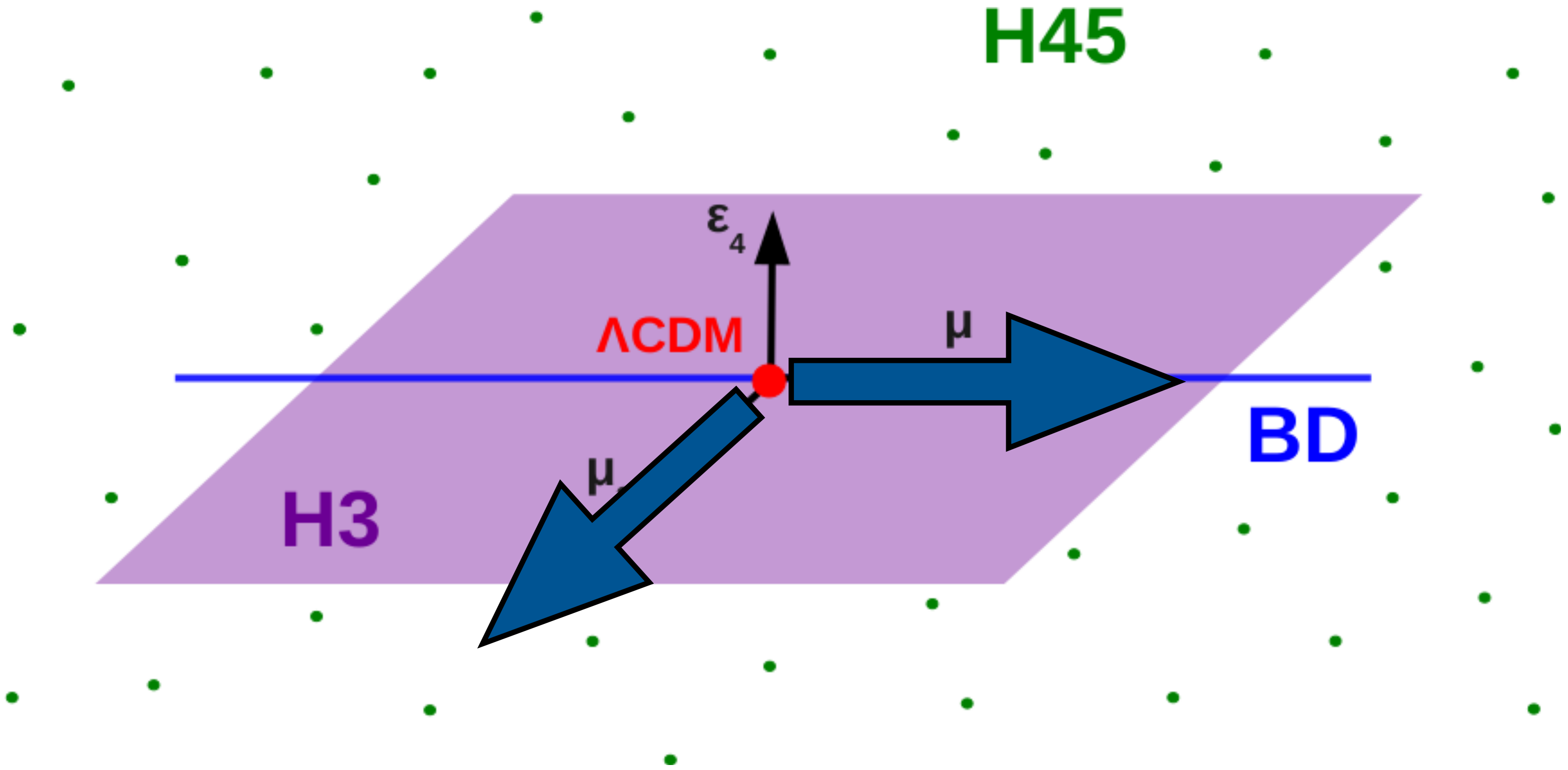
$$\mathcal{L}_2 = A(\phi, X) \ ,$$

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

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

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

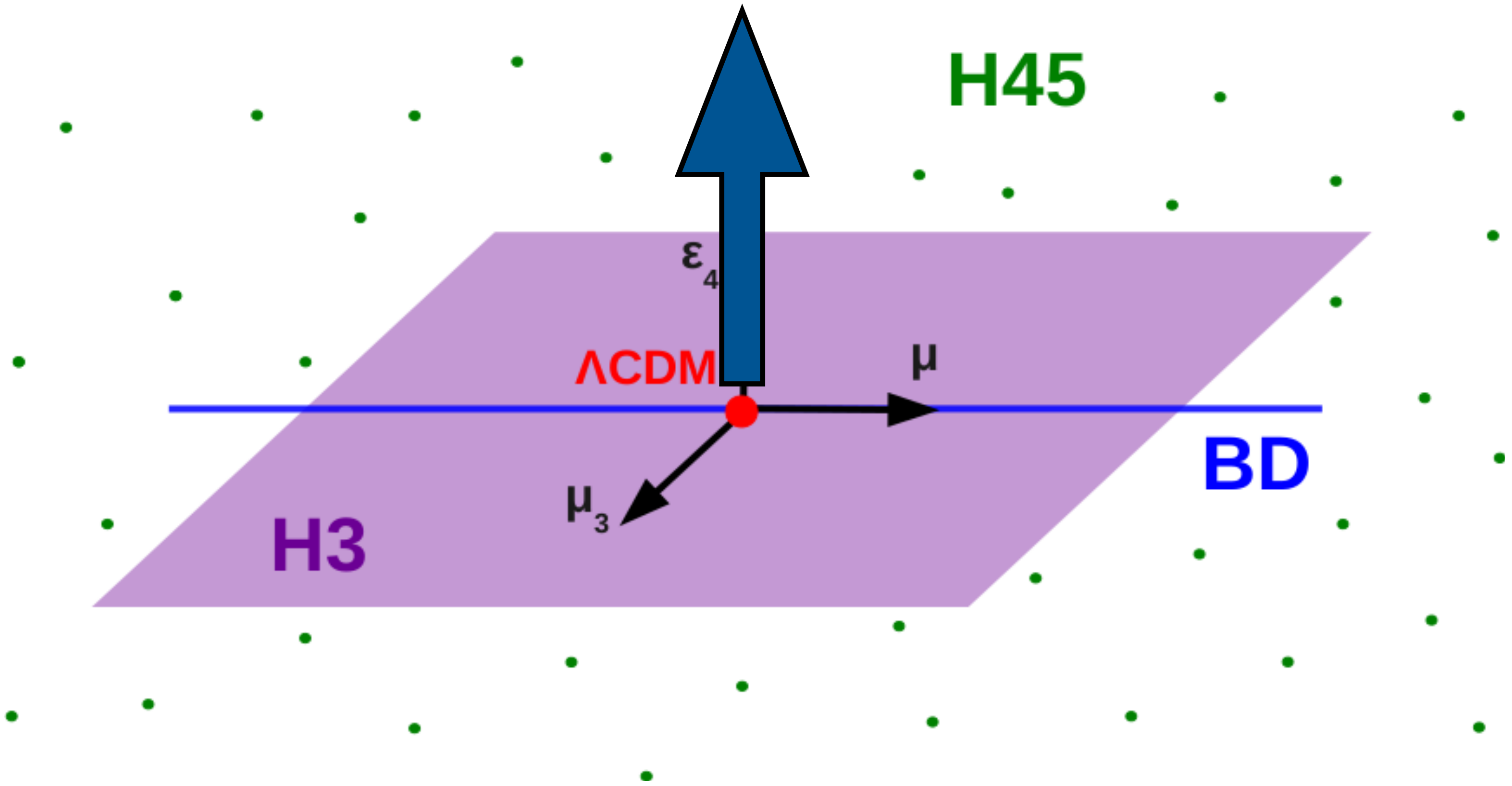
Newtonian gauge: scalar d.o.f.: $\Phi, \Psi, \;\pi$



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

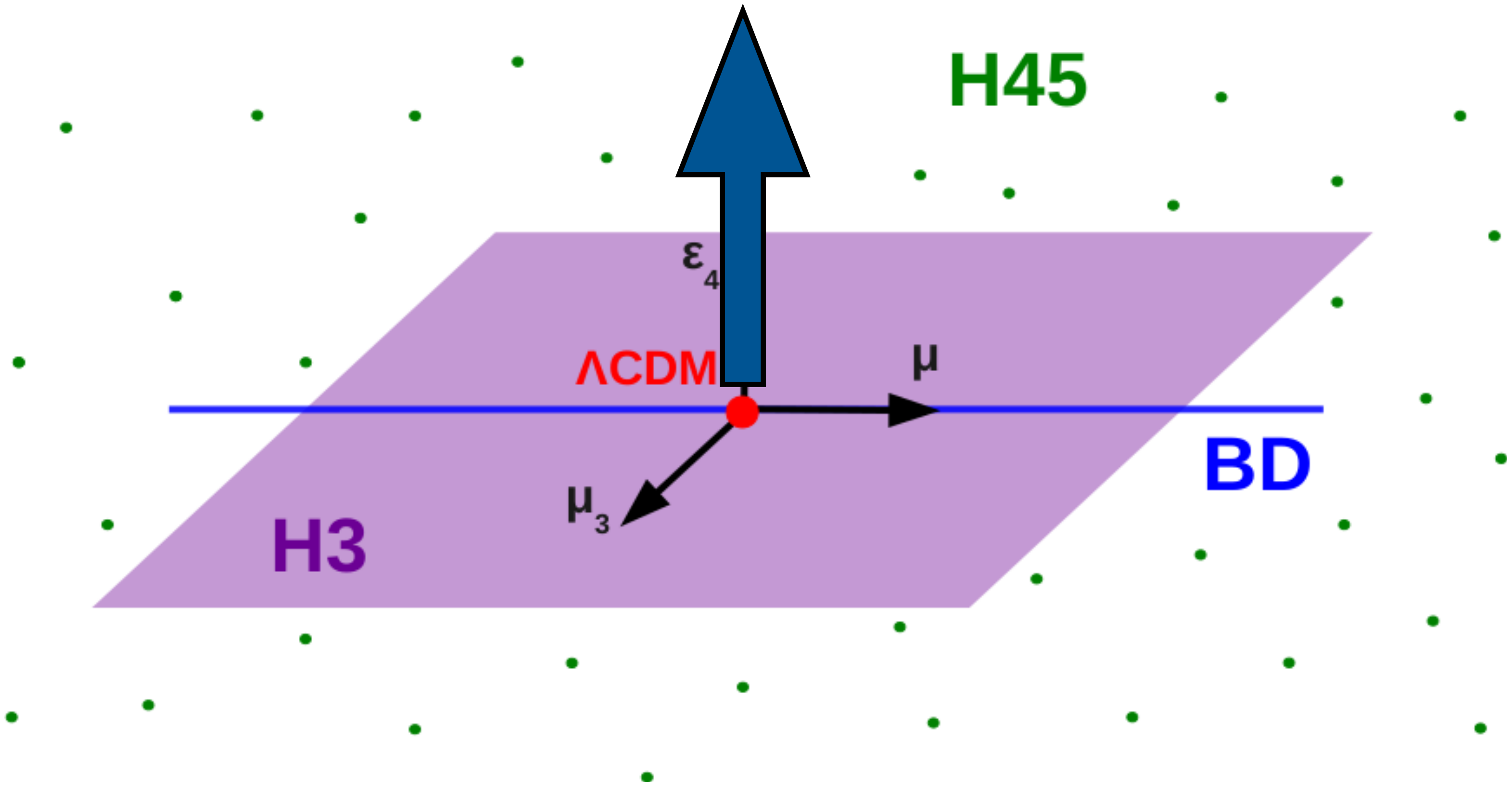
kinetic couplings metric-scalar

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



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

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

but also: speed of gravitational waves!

How to kill a large bunch of theories

Conclusions

- Pragmatic attitude towards cosmic accelerations
- Cosmological perturbations <-> “Goldstones”
- Universality classes of cosmology/condensed matter models according to Lorentz breaking pattern

Main messages:

- New degrees of freedom (if it's not Λ)
- Universality classes through symmetry breaking patterns
- Cosmological perturbations $\supset$ Nambu-Goldstone modes

Minkowski picture OK

Coupling with gravity important

Main messages:

- New degrees of freedom (if it's not Λ)
- Universality classes through symmetry breaking patterns
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