Universality classes of inflation/dark energy as phases of condensed matter: slow-roll, solids, gaugids etc.

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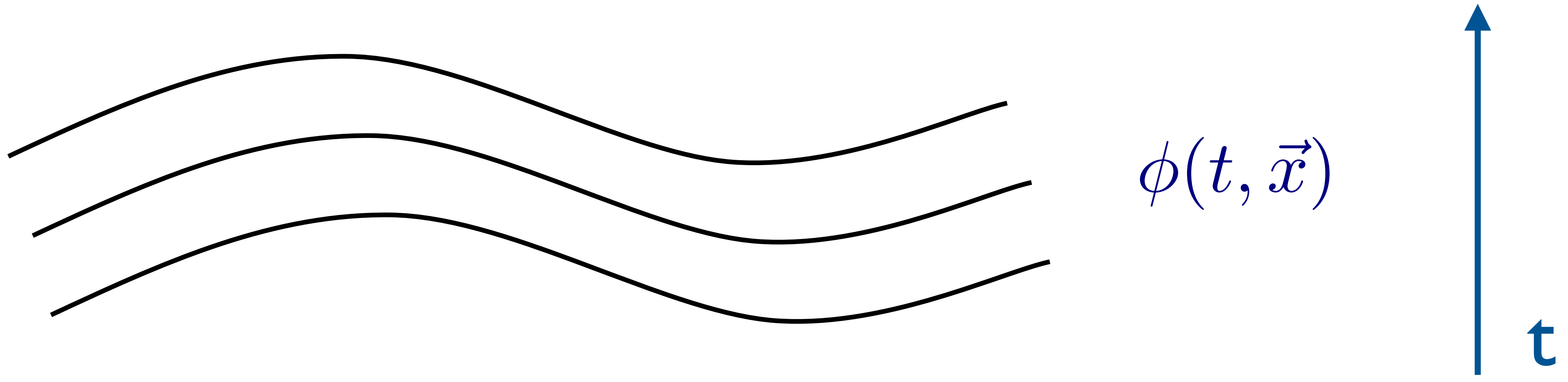
What is a cosmological scalar field?



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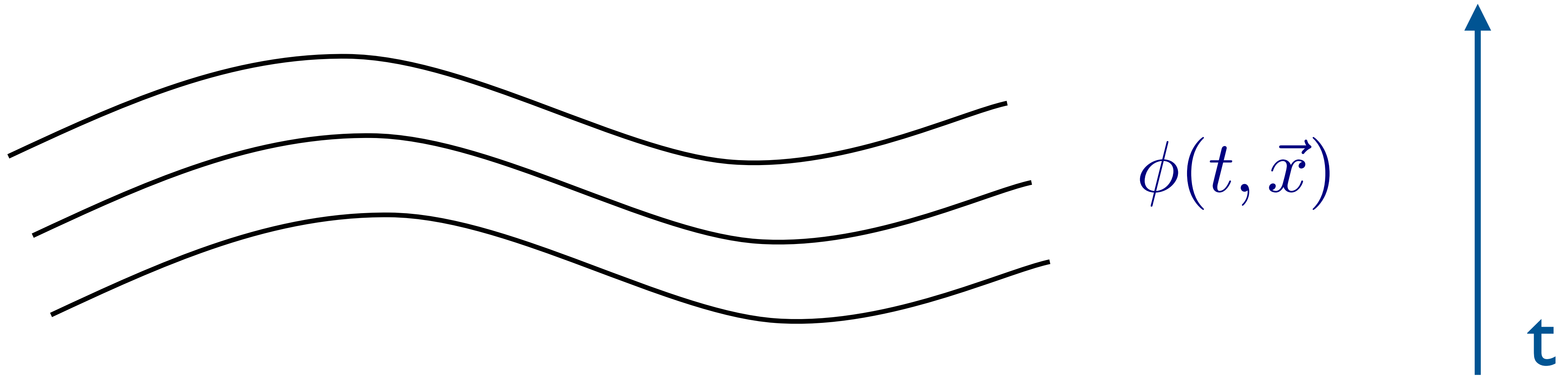

An order parameter for a specific symmetry breaking pattern!

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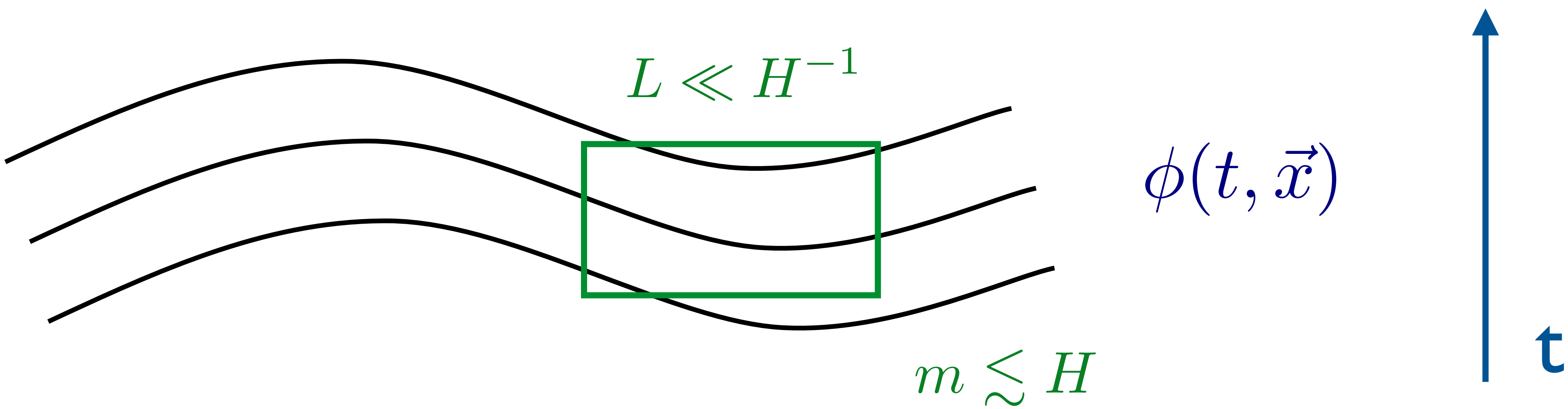

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Quintessential rolling scalar: P(X) $\quad \mathcal{L} = P(\partial_\mu \phi \partial^\mu \phi)$

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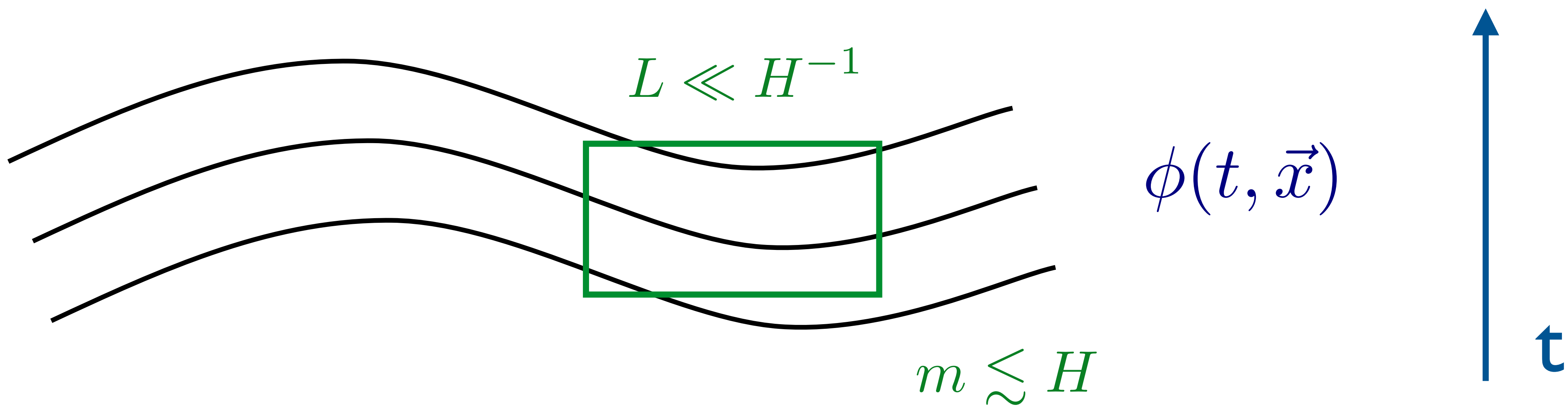

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Minkowski space analysis: $\qquad \phi = c\,t$

Lorentz generators: $\qquad P_i \qquad P_0 \qquad J_i \qquad K_i$

Internal symmetry: $\qquad Q$

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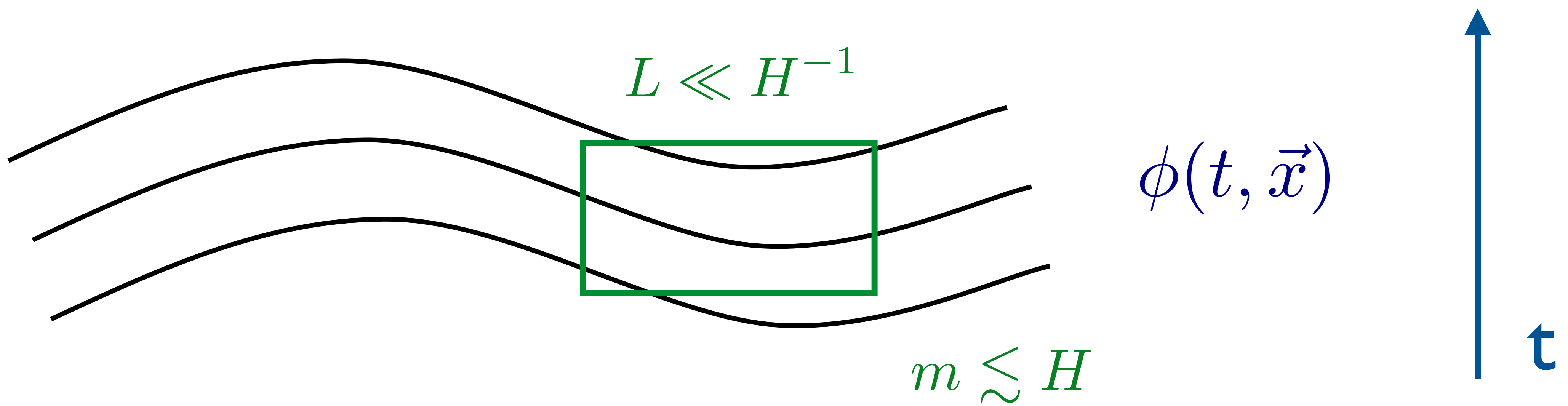

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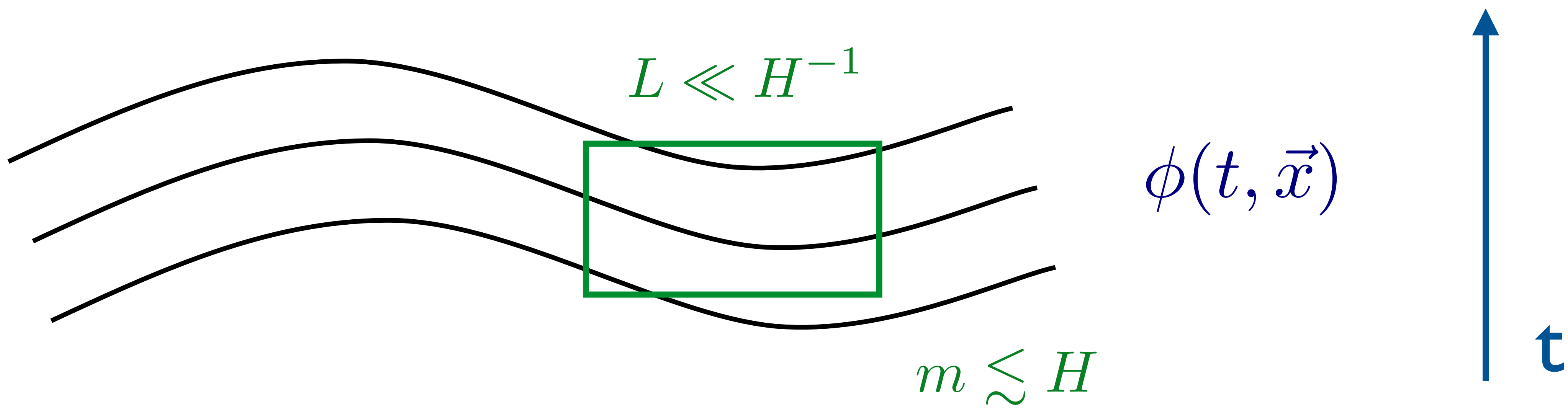

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$$\bar{P}_0 = P_0 - \mu Q$$

Condensed matter equivalent: ^{4}He superfluid

U(1) broken spontaneously and set at finite charge

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

$$\phi = t + \pi(x)$$
$$X = -1 - 2\dot{\pi} - \dot{\pi}^2 + (\partial_i \pi)^2$$
$$P(X) = P' \left[-\dot{\pi}^2 + (\partial_i \pi)^2 \right] + 2P'' \left[\dot{\pi}^2 + \dot{\pi}^3 - \dot{\pi}(\partial_i \pi)^2 \right] + \ldots$$

relation between speed of sound and cubic term

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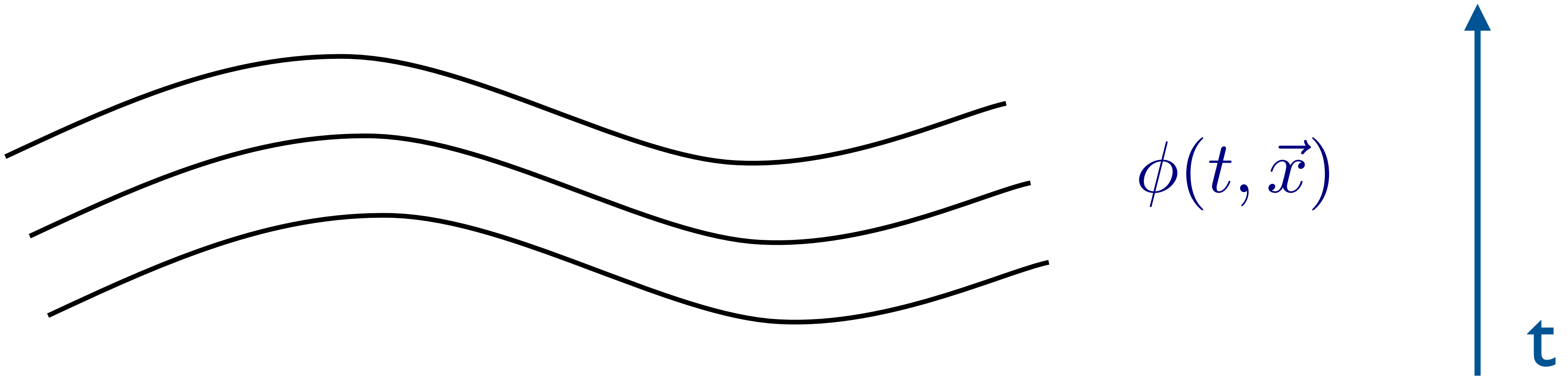
relation between speed of sound and cubic term

This is a relativistic Lagrangian where boosts are non-linearly realised!

(More or less) robust features of rolling scalar



- ξ and γ_{ij} conserved on large scales $k \ll H$
- $f_{NL} \propto c_s^{-2}$
- $\Delta_\gamma \sim \dfrac{H^2}{M_P^2}$
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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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Coupling with gravity important

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

superfluids
solids
framids

Cosmology/modified gravity

shift-symmetric scalar
solid inflation
Einstein aether

Solids: a closer look

Lorentz generators: P_i P_0 J_i K_i

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

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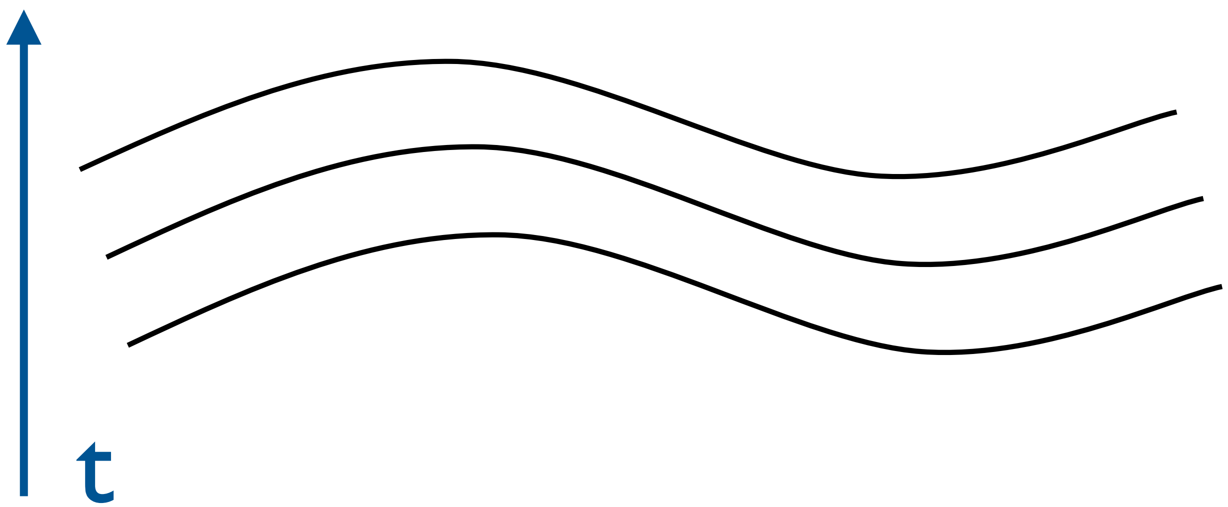
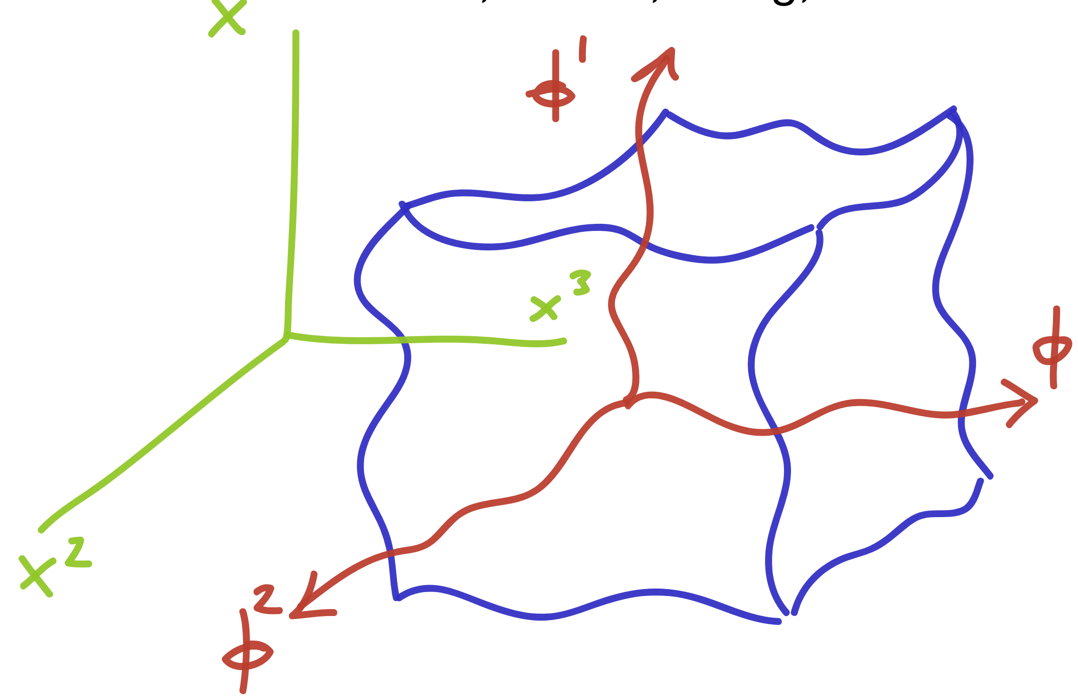
Lagrangian (vs Eulerian) description of a solid: $\phi_i(t, \vec{x})$ are the coordinates of that volume element that is at $\vec{x}$ on the ground state $\langle \phi^i \rangle = x^i$

(slow-) roll v.s. Solid Inflation

Endlich, Nicolis, Wang, 2012





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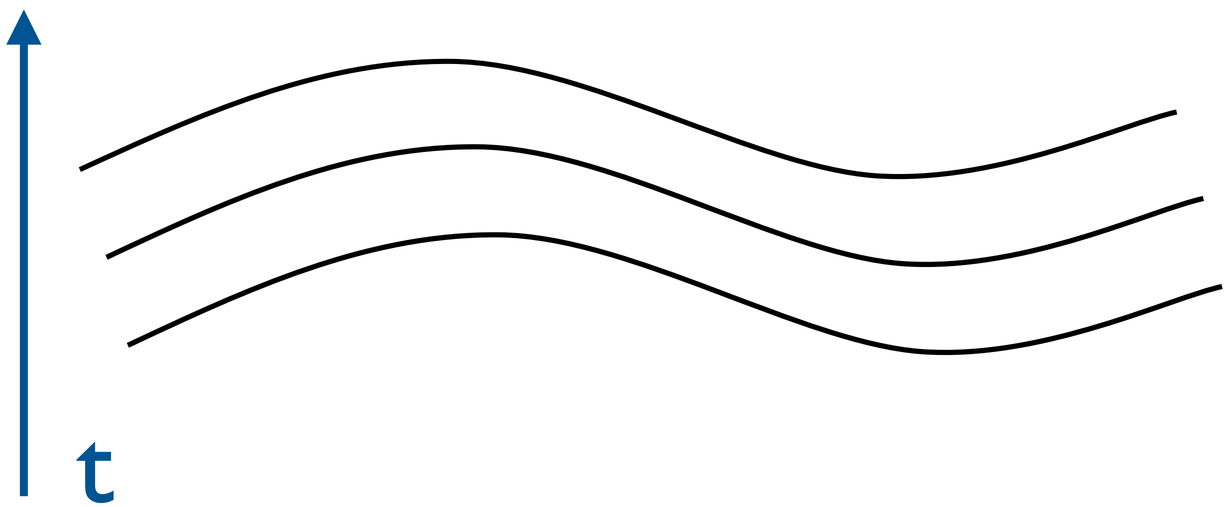

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Gaugid inflation v.s. Solid Inflation

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

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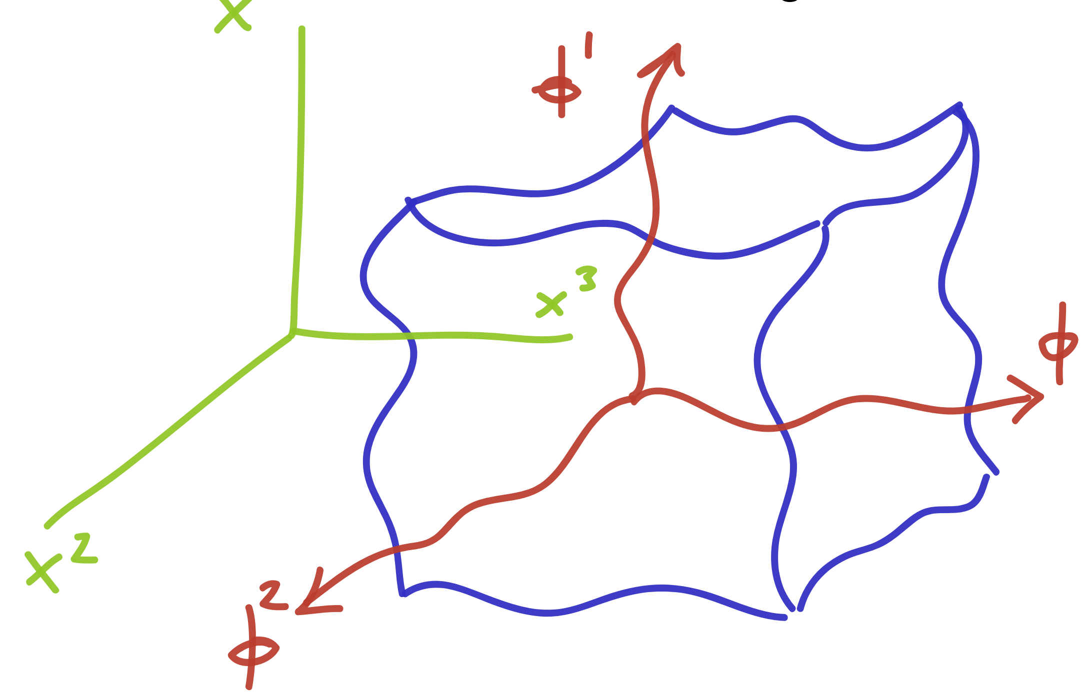

Gaugid inflation

Same Universality class
but with gauged internal translations

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Where have boosts Goldstones gone?

"Inverse Higgs"

Unbroken momentum

IF

$$Q' \subset [\bar{P}, Q]$$

Broken generators

Then: you can write the Goldsones of Q
in terms of derivatives of those of Q'

$$\eta_i \sim \partial_i \pi$$

The would-be Goldstones of the boosts