Enrico Trincherini
(SISSA, Trieste)

Galilean Genesis: an alternative to inflation

Nicolis, Creminelli, ET, *to appear*

Rattazzi, Nicolis, ET, *Energy's and amplitudes'* positivity, JHEP (2010)
Rattazzi, Nicolis, ET, *The Galileon as a local modification of gravity*, PRD (2009)

Outline of the talk

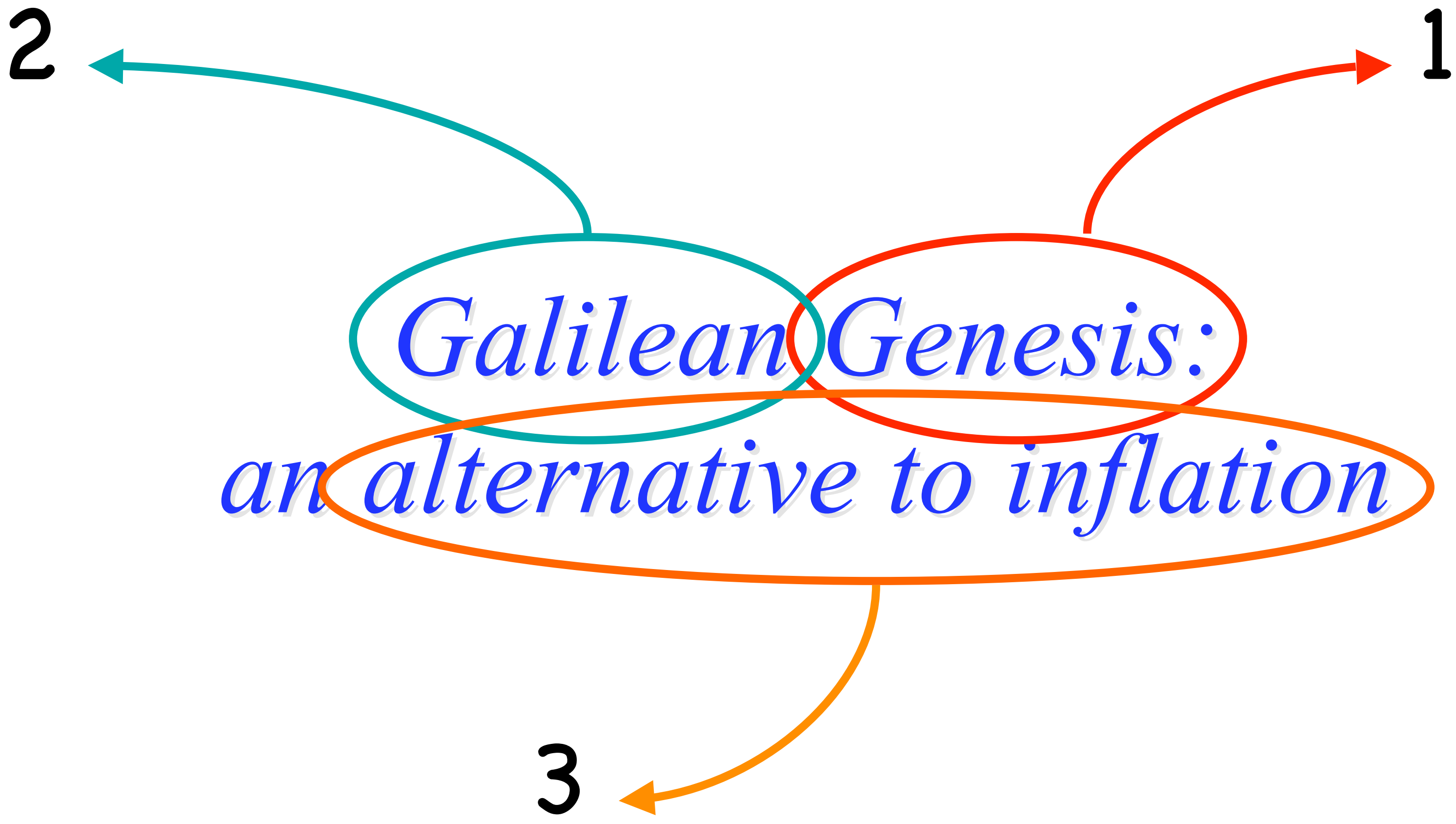
Galilean Genesis:
an alternative to inflation

Outline of the talk

1

Galilean Genesis:
an alternative to inflation

Outline of the talk



The standard picture

FRW universe

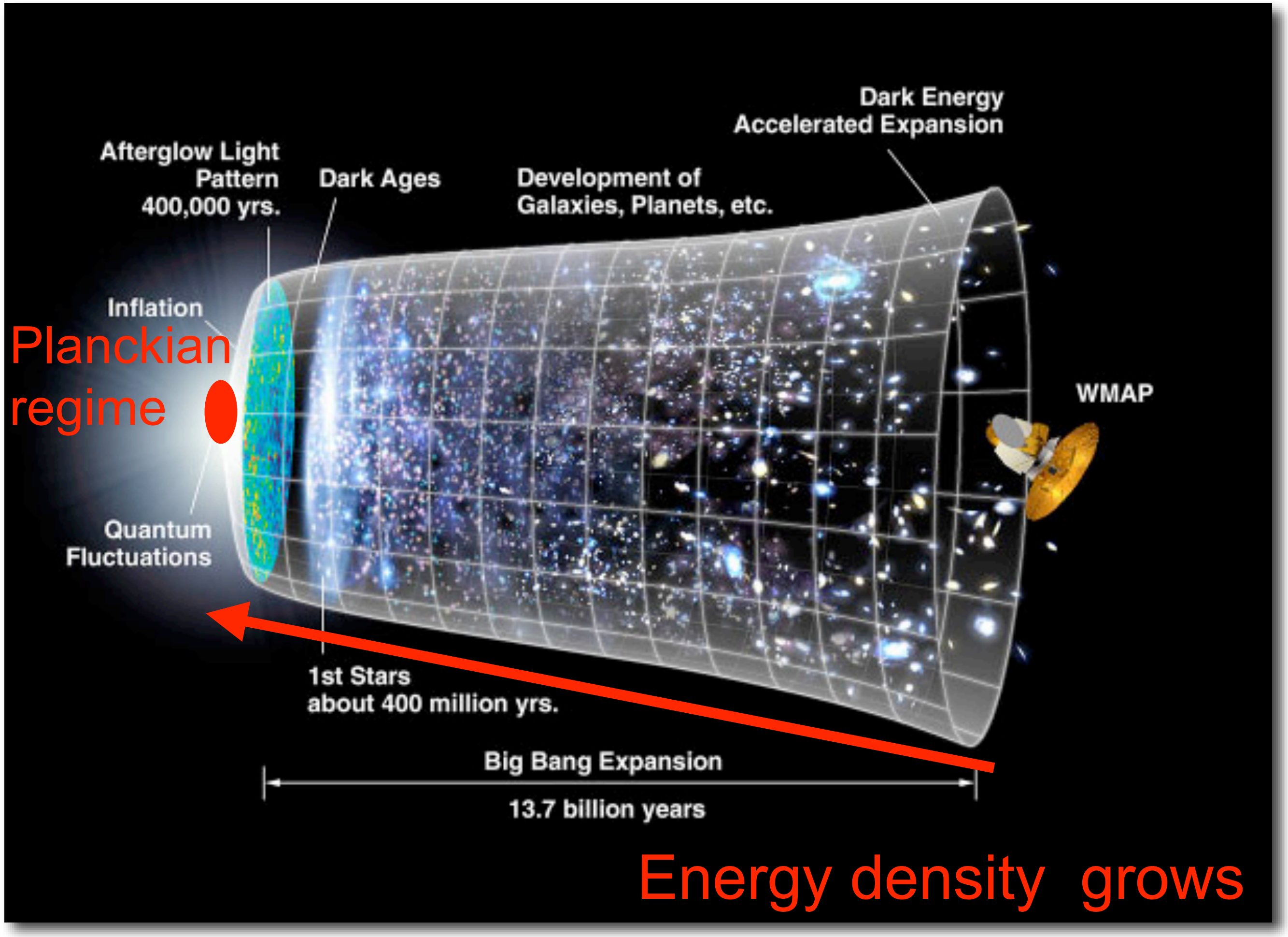
expanding

$\dot{a} > 0$

Going back in time

$E \sim M_{\rm Pl}$

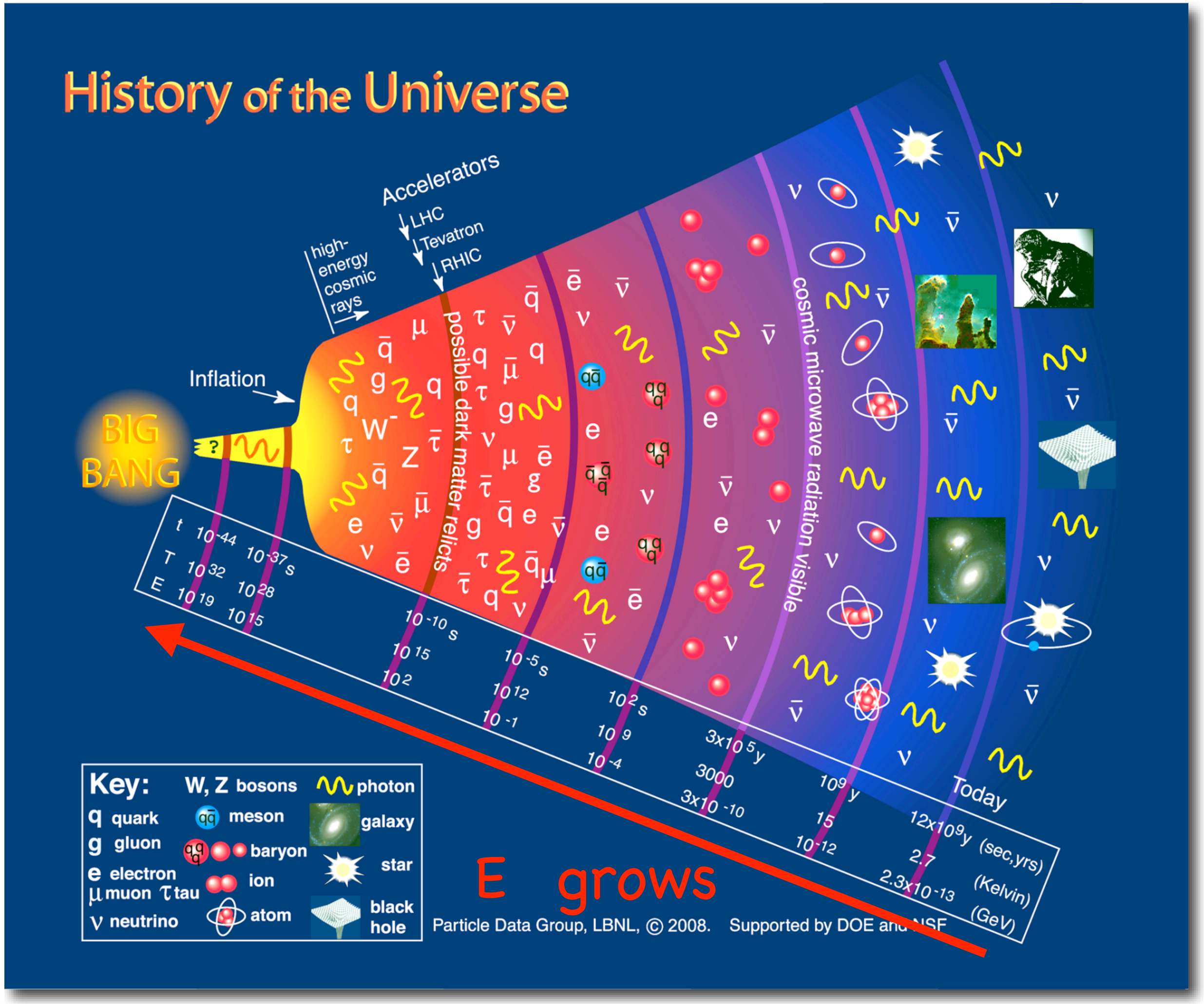
Big Bang



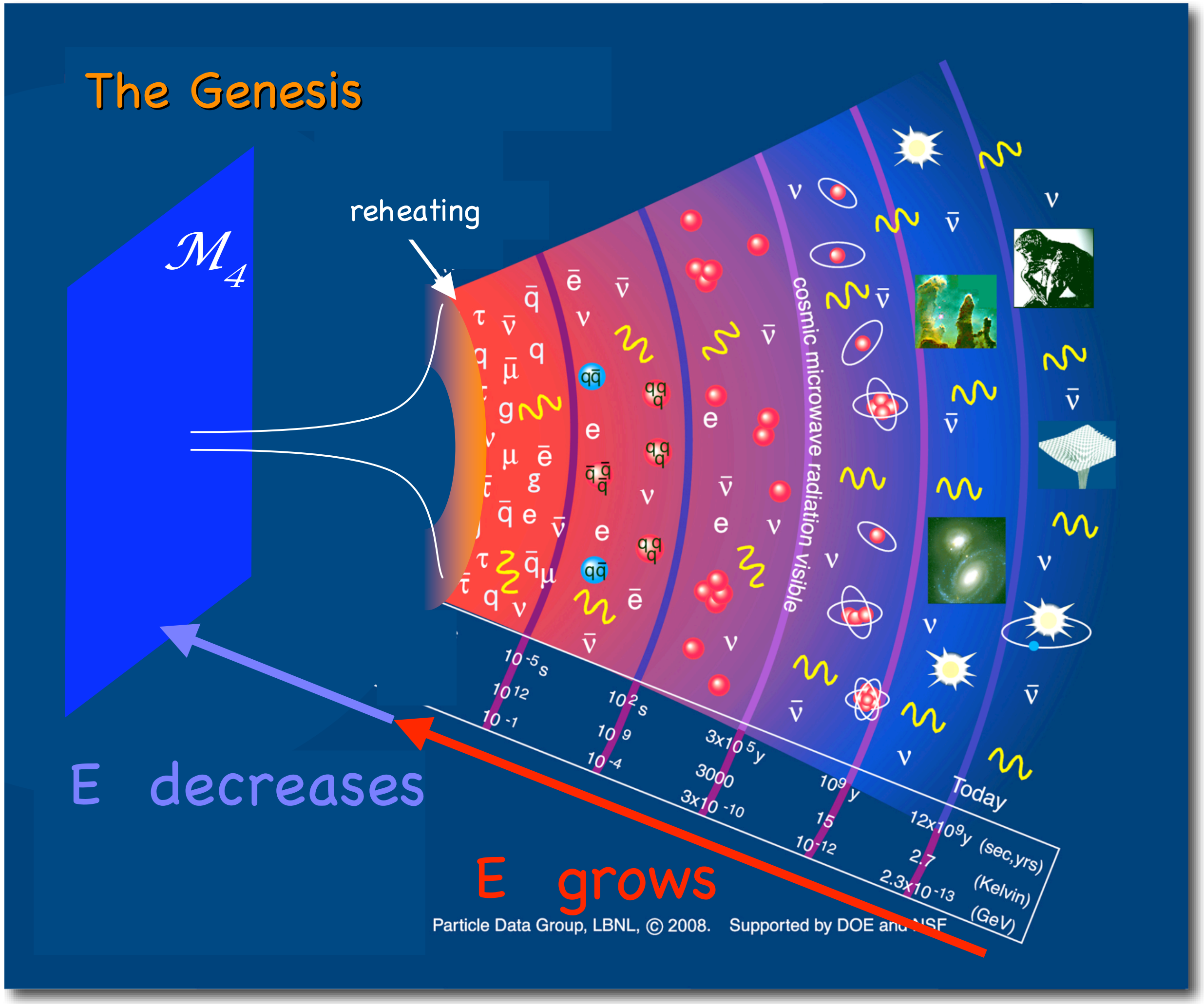
Quantum gravity effects become important. GR as an EFT breaks down

the origin of the expansion is inseparable from the UV completion of gravity

The standard picture



A different history: the Genesis



How can it be possible?

The Big Bang paradigm assumes (at least) the null energy condition (NEC)

$T_{\mu\nu} n^\mu n^\nu \geq 0$ in FRW spacetime reduces to $\boxed{\rho + p \geq 0}$

$$\dot{H} = -4\pi G(\rho + p)$$
$$\dot{\rho} = -3H(\rho + p)$$

$$\boxed{\text{NEC} \implies \dot{H},\ \dot{\rho} \leq 0}$$

NEC satisfied by matter, radiation

NEC saturated by a cosmological constant

Is there a form of matter that violates it?

Can we violate the NEC?

Usually ~~NEC~~ are unstable:

signature $(-+++)$

$$\mathcal{L} = \pm\frac{1}{2}(\partial\phi)^2 - V(\phi)$$

$$\phi = \phi(t) \implies (\rho + p) = \mp\dot{\phi}^2$$

Can we violate the NEC?

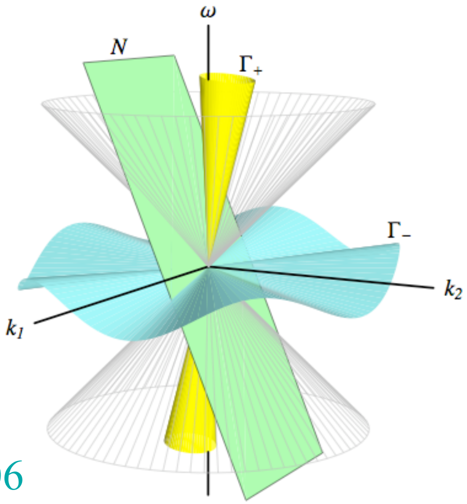
Usually ~~NEC~~ are unstable:

signature $(-+++)$

$$\mathcal{L} = \pm\frac{1}{2}(\partial\phi)^2 - V(\phi) \qquad \phi = \phi(t) \implies (\rho + p) = \mp\dot{\phi}^2$$

No-go theorem

$$\mathcal{L} = F(\phi_I, \partial\phi_I, \partial^2\phi_I, \ldots) \qquad I = 1, \ldots, N$$



There are no stable NEC-violating EFT
if we can neglect HD terms

Dubovsky, Gregoire, Nicolis, Rattazzi 06

- They are irrelevant at low energies. When they are important ~~EFT~~
- They describe new pathological ghost-like degrees of freedom

$$-(\partial\phi)^2 + \frac{1}{M^2}(\Box\phi)^2 \to -(\partial\phi)^2 + (\partial\chi)^2 + M^2\chi^2$$

But there are exceptions...

The ghost condensate

First exception: the ghost condensate Arkani-Hamed, Cheng, Luty, Mukohyama 03

Small deformation marginally violates the NEC $0 < \dot{H} \lesssim H^2$

Creminelli, Luty, Nicolis, Senatore 06

The galileon

Nicolis, Rattazzi, ET 08

Is there a HD lagrangian that gives 2 derivatives EOM?

$$\frac{\delta \mathcal{L}_\pi}{\delta \pi} = F(\partial_\mu \partial_\nu \pi)$$ Avoids new ghost-like DOF

$$\boxed{\pi(x) \rightarrow \pi(x) + c + b_\mu x^\mu}$$

Galilean invariance

$$\Big(x(t) \rightarrow x(t) + x_0 + v_0 t\Big)$$

$$\mathcal{L}^{(n)} \sim \partial^{2n-2} \pi^n$$

The galileon

Nicolis, Rattazzi, ET 08

Is there a HD lagrangian that gives 2 derivatives EOM?

$$\frac{\delta \mathcal{L}_\pi}{\delta \pi} = F(\partial_\mu \partial_\nu \pi)$$ Avoids new ghost-like DOF

$$\boxed{\pi(x) \to \pi(x) + c + b_\mu x^\mu}$$

Galilean invariance

$$\left(x(t) \to x(t) + x_0 + v_0 t\right)$$

$$\mathcal{L}^{(n)} \sim \partial^{2n-2} \pi^n$$

There are D+1 operators in D dimensions

$$\mathcal{L}^{(1)} = \pi$$
$$\mathcal{L}^{(2)} = (\partial \pi)^2$$
$$\mathcal{L}^{(3)} = (\partial \pi)^2 \Box \pi$$
$$\mathcal{L}^{(4)}, \ \mathcal{L}^{(5)}$$

- HD lagrangian with healthy 2-deriv EOM
- Classical non-linear solutions inside EFT

The conformal galileon

Nicolis, Rattazzi, ET 08

Promote galilean transformation + Poincaré to the conformal group SO(4,2)

$$\pi(x) \quad \rightarrow \quad \pi(x) + c$$
$$\pi(x) \quad \rightarrow \quad \pi(x) + b_\mu x^\mu$$

The conformal galileon

Nicolis, Rattazzi, ET 08

Promote galilean transformation + Poincaré to the conformal group SO(4,2)

$$
\begin{aligned}
\pi(x) &\rightarrow \pi(\lambda x) + \log \lambda \\
\pi(x) &\rightarrow \pi\big(x + (c\,x^2 - 2(c\cdot x)x)\big) - 2c_\mu x^\mu
\end{aligned}
$$

π plays the role of the dilaton $\qquad g_{\mu\nu} = e^{2\pi}\eta_{\mu\nu}$

$$\mathcal{L}^{(2)} \rightarrow e^{2\pi}(\partial\pi)^2$$

$$\mathcal{L}^{(3)} \rightarrow (\partial\pi)^2\Box\pi + \frac{1}{2}(\partial\pi)^4$$

The conformal galileon

Promote galilean transformation + Poincaré to the conformal group SO(4,2)

$$\pi(x) \quad \to \quad \pi(\lambda x) + \log \lambda$$
$$\pi(x) \quad \to \quad \pi\big(x + (c\,x^2 - 2(c \cdot x)x)\big) - 2c_\mu x^\mu$$

π plays the role of the dilaton $\qquad g_{\mu\nu} = e^{2\pi}\eta_{\mu\nu}$

$$\mathcal{L}_\pi = f^2 e^{2\pi}(\partial\pi)^2 + \frac{f^3}{\Lambda^3}\Box\pi(\partial\pi)^2 + \frac{f^3}{2\Lambda^3}(\partial\pi)^4$$

$$\boxed{e^{\pi_{\rm dS}} = -\frac{1}{H_0 t}} \qquad -\infty < t < 0 \qquad H_0^2 = \frac{2\Lambda^3}{3f}$$

Riccardo's talk

Pattern of SO(4,2) breaking controlled by V_0 Fubini '76

$V_0 = 0$	$\langle\chi\rangle = f_D = \text{const}$	ISO(3,1) Poincaré-4
$V_0 > 0$	$\langle\chi\rangle \propto \frac{1}{z}$	SO(3,2) AdS4
$V_0 < 0$	$\langle\chi\rangle \propto \frac{1}{t}$	SO(4,1) dS4

generically (without SUSY) spontaneous SO(4,2) ➓ ISO(3,1) not realized

Spontaneously breaks SO(4,2) → SO(4,1) de Sitter group

Conservation+ scale invariance $\quad \boxed{\left\{ \begin{array}{l} \rho = 0 \\ p \propto -\frac{1}{t^4} \end{array} \right.}$ ~~NEC~~

$$\pi(x) = \pi_{\rm dS}(t) + \phi(x)$$

Stable luminal fluctuations

Nicolis, Rattazzi, ET 09

Galilean Genesis

Creminelli, Nicolis, ET, *to appear*

$$\int d^4x \sqrt{-g}\left[f^2 e^{2\pi}(\partial\pi)^2 + \frac{f^3}{\Lambda^3}\Box\pi(\partial\pi)^2 + \frac{f^3}{2\Lambda^3}(\partial\pi)^4\right] + \mathcal{S}_{\rm EH}$$

Conformal galileon minimally coupled to gravity

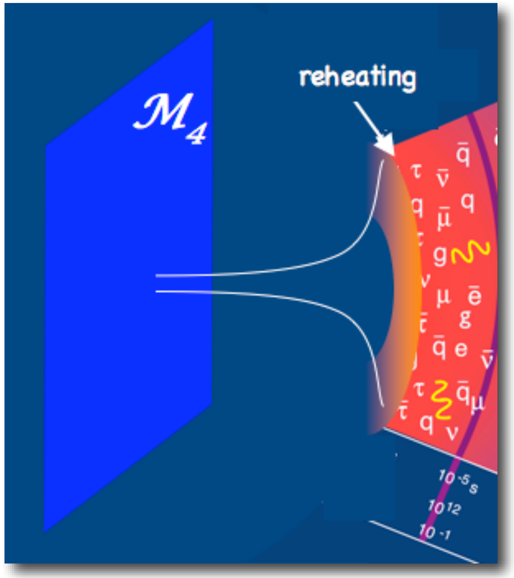
$$ds^2 = -dt^2 + a^2(t)d\vec{x}^2 \qquad \pi = \pi(t)$$

Galilean Genesis

Creminelli, Nicolis, ET, *to appear*

$$\int d^4x\,\sqrt{-g}\left[f^2 e^{2\pi}(\partial\pi)^2 + \frac{f^3}{\Lambda^3}\Box\pi(\partial\pi)^2 + \frac{f^3}{2\Lambda^3}(\partial\pi)^4\right] + \mathcal{S}_{\rm EH}$$

Conformal galileon minimally coupled to gravity



$$ds^2 = -dt^2 + a^2(t)d\vec{x}^2 \qquad \pi = \pi(t)$$

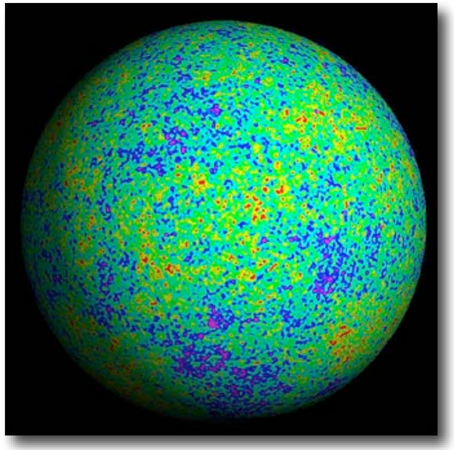
Solve Friedmann's equations for H perturbatively

$$\dot{H} = -\frac{1}{2M_{\rm Pl}^2}(\rho + p) \sim \frac{f^2}{M_{\rm Pl}^2}\frac{1}{H_0^2 t^4}$$

$$\boxed{H \simeq -\frac{1}{3}\frac{f^2}{M_{\rm Pl}^2}\frac{1}{H_0^2 t^3} + c} \qquad a(t) \sim e^{\frac{f^2}{6M_{\rm Pl}^2}\frac{1}{H_0^2 t^2}}$$

$$\pi \simeq \pi_{\rm dS} - \frac{1}{2}\frac{f^2}{M_{\rm Pl}^2}\cdot\frac{1}{H_0^2 t^2}$$

Scalar perturbations



Homogeneus attractor $t \to t + c$

π perturbations are not scale invariant

$$\langle\zeta(t,\vec{k})\zeta(t,\vec{k}')\rangle = (2\pi)^3\delta(\vec{k}+\vec{k}')\frac{1}{18}\frac{f^2}{M_{\rm Pl}^4 H_0^2}\frac{1}{2k}\frac{1}{t^2}$$

ζ action: $S_\zeta = \frac{9M_{\rm Pl}^4}{f^2}\int d^4x\,(H_0 t)^2\left[\dot{\zeta}^2 - (\vec{\nabla}\zeta)^2\right] \qquad \zeta \sim \text{const}, \quad \frac{1}{t}$

During the genesis, flow towards the "other" adiabatic mode

$$t \to t + \epsilon(t) \qquad x^i \to x^i(1-\lambda) \qquad \Psi \to \Psi + H\epsilon - \lambda \qquad \Phi \to \Phi - \dot{\epsilon}$$

$$\epsilon(t) = \frac{\lambda}{a(t)}\int_0^t a(t')dt' + \frac{c}{a(t)}$$

Scalar perturbations of π are always irrelevant at cosmological scales

Scale invariant perturbations

Any coupling to π has to go through the fictitious metric

$$g_{\mu\nu}^{(\pi)} = e^{2\pi(x)}\eta_{\mu\nu}$$

A spectator massless scalar field σ behave as in de Sitter

Its spectrum is scale invariant because of the dS symmetry

Exp. small corrections from the evolution of the real metric for modes of cosmological interest

Scale invariant perturbations

Any coupling to π has to go through the fictitious metric

$$g_{\mu\nu}^{(\pi)} = e^{2\pi(x)}\eta_{\mu\nu}$$

A spectator massless scalar field σ behave as in de Sitter

Its spectrum is scale invariant because of the dS symmetry

Exp. small corrections from the evolution of the real metric for modes of cosmological interest

Conversion of σ fluctuations

Analogous to "second field" mechanism in inflation

Typical signatures

Large local non-Gaussianities

Low GWs: perturbations produced at low energy

Blue GWs: contraction or ~~NEC~~

$$\frac{d}{dt}H^2 = 2H\dot{H} > 0$$

Superluminality

Perturbations are luminal about the fake de Sitter background

Any deformation will have superluminal perturbations

1) The cutoff is lower, it forbids superluminal propagation but also NEC-violating solution is outside the EFT

2) Both the solution and superluminal propagation are inside EFT

Not necessary an inconsistency

Ex: No closed time-like curves

Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi 06

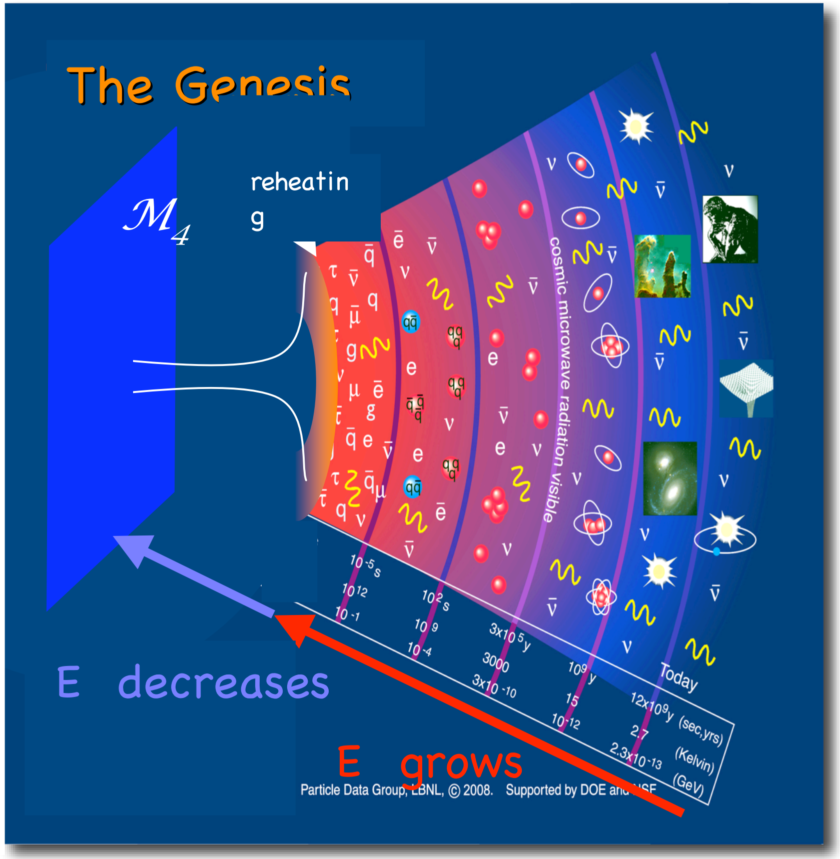
But the UV completion cannot be a Lorentz-invariant local QFT

Summary

If ~~NEC~~ the history of the universe can be drastically modified

Galilean Genesis is a stable EFT

Scale invariant spectrum forced by The symmetries



~~NEC~~ $\Rightarrow$ superluminality?

Swampland?

Amplitudes

If ~~EFT~~ is the low energy limit of a theory that obeys properties of S-matrix (unitarity, analiticity, Froissart bound) then

$2 \to 2$ forward scattering amplitude cannot go to zero faster than cs^2 with $c>0$

In some examples $c>0 \Rightarrow$ subluminality

In our case even the non forward relations for $2 \to 2$ are obeyed by a theory with superluminal excitations

Maybe the request of subluminality is encoded in $n \to n$ amplitudes. How?