Title: Galilean Genesis: an alternative to inflation

Date: Apr 29, 2010 02:45 PM

URL: http://pirsa.org/10040109

Abstract: I will discuss an alternative to inflation based on a Galileon field. The model starts in a (contracting or expanding) quasi Minkowski phase and all the energy of the Universe in generated suddenly in a sort of Genesis associated with a strong violation of the Null Energy Condition. The symmetries of the model force any additional scalar field to acquire a scale invariant spectrum of perturbations.

Paolo Creminelli, ICTP Trieste

Galilean Genesis: an alternative to inflation

with A. Nicolis and E. Trincherini, to appear

Energy conditions in GR

Covariant ways to say: " E > 0 "

Strong Energy Condition: $(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T)\xi^\mu \xi^\nu \geq 0$

Null Energy Condition: $T_{\mu\nu} k^\mu k^\nu \geq 0$

In cosmology: $$T_{\mu\nu} = \begin{pmatrix} \rho & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix}$$

SEC is violated!

SEC: $\rho + 3p \geq 0$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) \quad \Rightarrow \quad \ddot{a} \leq 0$$

SEC forbids acceleration

The two revolutions in cosmology in the last 25 years,
inflation + present acceleration,
are based on the violation of the SEC

What about NEC?

$T_{\mu\nu}k^\mu k^\nu \geq 0$ is insensitive to c.c. $T_{\mu\nu} = -\Lambda g_{\mu\nu}$

NEC is the only sensible energy condition,
the others can be fixed by a suitable c.c.

$$T_{\mu\nu}k^\mu k^\nu \geq 0 \quad \Rightarrow \quad \rho + p \geq 0 \qquad\qquad w \equiv \frac{p}{\rho} \qquad w \geq -1$$

$$\nabla_\mu T^{\mu 0} = 0 \quad \Rightarrow \quad \dot{\rho} = -3H(\rho + p)$$

In a spatially flat Universe: $\boxed{\text{NEC} \quad \Rightarrow \quad \dot{H} \leq 0}$

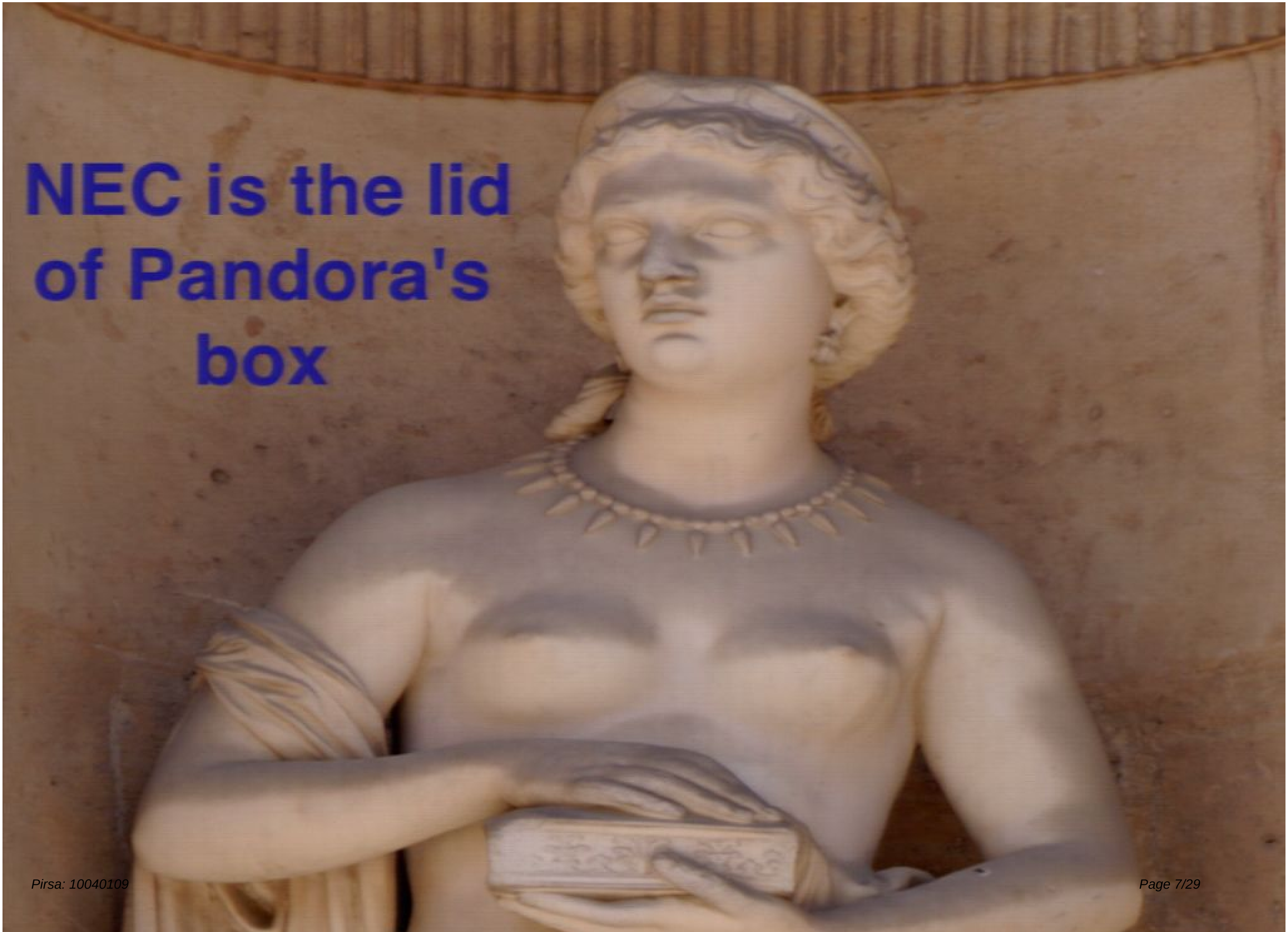
Cosmological consequences

NEC says energy density (and thus H) decreases as Universe expands

If ~~NEC~~ :

- No need for a Big Bang
- One can even have $H \to 0$ in the far past: start the Universe !
- Bouncing cosmologies. H must flip from negative to positive: $\dot{H} > 0$
- Observation of w < -1 in the present acceleration

NEC is the lid of Pandora's box



What is wrong with NEC?

Typically a ~~NEC~~ theory suffers from instabilities

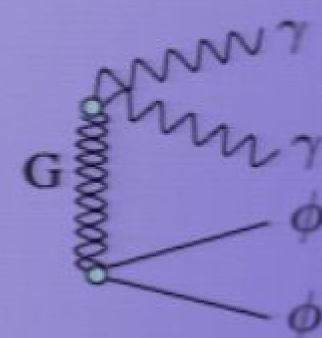
E.g. States with negative energy (ghosts) will violate it

$$\mathcal{L} = -\left[-\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2\right]$$

Classical instability:

Quantum mechanical disaster:

Vacuum decay



A no-go theorem

Dubovsky, Gregoire, Nicolis, Rattazzi, C

Forget about gravity

Can we construct a sensible QFT with ~~NEC~~?

$$\mathcal{L} = \Lambda^4 F\left(\epsilon\frac{\phi_I}{\Lambda}, \frac{\partial^\mu\phi_I\partial_\mu\phi_J}{\Lambda^4}, \frac{\partial^2\phi_I\partial^2\phi_J}{\Lambda^6}\right)$$

No, if hd terms are irrelevant

- They are irrelevant at low energy
- They describe new (pathological) degrees of freedom

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

- When they are important ~~EFT~~

1^{st} case: Ghost Condensate

Arkani-Hamed, Cheng, Luty, Mukhoyama,

HD operators are not always irrelevant at low energy

Degenerate dispersion relation: $\dot{\pi}^2 + 0 \times (\nabla\pi)^2$

Higher dimension operators: $(\Box\phi)^2 \rightarrow \underbrace{\ddot{\pi}^2 + (\nabla\dot{\pi})^2}_{\text{Higher dim.}} + (\nabla^2\pi)^2$

Non relativistic scaling: consistent derivative expansion

1st counterexample

Small deformation of the GC theory leads to consistent ~~NEC~~

PC, Luty, Nicolis, Senatore, 06

The Pandora's box is open!

(not wide open: $\dot{H} \lesssim H^2$)

Bouncing cosmologies: new ekpyrosis

Lehners, McFadden, Turok, Steinhardt 0
PC, Senatore, 07
Buckbinder, Khoury, Ovrut, 07

- Bounce from a GC-like field
- Perturbations from isocurvature scalar along a negative exponential

2^{nd} case: Galileon

Nicolis, Rattazzi, Trincherini,

HD terms do not always lead to new (pathological) dof

EOM with 2 derivatives and not more: $\frac{\delta \mathcal{L}_\pi}{\delta \pi} = F(\partial_\mu \partial_\nu \pi)$

Galilean symmetry: $\pi(x) \rightarrow \pi(x) + c + b_\mu x^\mu$

The lowest dim Galilean operators are ok: $\mathcal{L}^{(n)} \sim \partial^{2n-2} \pi^n$

$$\mathcal{L}^{(2)} = -\frac{1}{2}(\partial\pi)^2 \qquad \mathcal{L}^{(3)} = -\frac{1}{2}(\partial\pi)^2 \Box\pi$$

There are only 5 in total (in 4d)!

From the Galileon to the dilaton

Technically it is easier to extend Galilean symmetry + Poincare'
to the conformal group SO(4,2)

$$D: \qquad \pi(x) \to \pi'(x) \equiv \pi(\lambda x) + \log\lambda$$

$$K_\mu: \qquad \pi(x) \to \pi'(x) \equiv \pi\big(x + (c\,x^2 - 2(c\cdot x)x)\big) - 2c_\mu x^\mu$$

$$g^{(\pi)}_{\mu\nu} \equiv e^{2\pi(x)}\eta_{\mu\nu}$$

$$\begin{aligned} \mathcal{L}_2 &\to -\tfrac{1}{2}\,e^{2\pi}(\partial\pi)^2 \\ \mathcal{L}_3 &\to -\tfrac{1}{2}(\partial\pi)^2\Box\pi - \tfrac{1}{4}(\partial\pi)^4 \end{aligned}$$

Let us study solutions: SO(4,2) → SO(4,1)

2^{nd} case: Galileon

Nicolis, Rattazzi, Trincherini,

HD terms do not always lead to new (pathological) dof

EOM with 2 derivatives and not more: $\frac{\delta \mathcal{L}_\pi}{\delta \pi} = F(\partial_\mu \partial_\nu \pi)$

Galilean symmetry: $\pi(x) \to \pi(x) + c + b_\mu x^\mu$

The lowest dim Galilean operators are ok: $\mathcal{L}^{(n)} \sim \partial^{2n-2} \pi^n$

$$\mathcal{L}^{(2)} = -\frac{1}{2}(\partial \pi)^2 \qquad \mathcal{L}^{(3)} = -\frac{1}{2}(\partial \pi)^2 \Box \pi$$

There are only 5 in total (in 4d)!

From the Galileon to the dilaton

Technically it is easier to extend Galilean symmetry + Poincare' to the conformal group SO(4,2)

$$D: \qquad \pi(x) \to \pi'(x) \equiv \pi(\lambda x) + \log \lambda$$

$$K_\mu: \qquad \pi(x) \to \pi'(x) \equiv \pi\big(x + (c\,x^2 - 2(c\cdot x)x)\big) - 2c_\mu x^\mu$$

$$g^{(\pi)}_{\mu\nu} \equiv e^{2\pi(x)}\eta_{\mu\nu}$$

$$\begin{aligned} \mathcal{L}_2 &\to -\tfrac{1}{2}e^{2\pi}(\partial\pi)^2 \\ \mathcal{L}_3 &\to -\tfrac{1}{2}(\partial\pi)^2\Box\pi - \tfrac{1}{4}(\partial\pi)^4 \end{aligned}$$

Let us study solutions: SO(4,2) → SO(4,1)

2nd case: Galileon

Nicolis, Rattazzi, Trincherini,

HD terms do not always lead to new (pathological) dof

EOM with 2 derivatives and not more: $\frac{\delta \mathcal{L}_\pi}{\delta \pi} = F(\partial_\mu \partial_\nu \pi)$

Galilean symmetry: $\pi(x) \to \pi(x) + c + b_\mu x^\mu$

The lowest dim Galilean operators are ok: $\mathcal{L}^{(n)} \sim \partial^{2n-2} \pi^n$

$$\mathcal{L}^{(2)} = -\frac{1}{2}(\partial\pi)^2 \qquad \mathcal{L}^{(3)} = -\frac{1}{2}(\partial\pi)^2 \Box\pi$$

There are only 5 in total (in 4d)!

From the Galileon to the dilaton

Technically it is easier to extend Galilean symmetry + Poincare' to the conformal group SO(4,2)

$$D: \qquad \pi(x) \to \pi'(x) \equiv \pi(\lambda x) + \log\lambda$$

$$K_\mu: \qquad \pi(x) \to \pi'(x) \equiv \pi\big(x + (c\,x^2 - 2(c\cdot x)x)\big) - 2c_\mu x^\mu$$

$$g^{(\pi)}_{\mu\nu} \equiv e^{2\pi(x)}\eta_{\mu\nu}$$

$$\mathcal{L}_2 \;\to\; -\tfrac{1}{2}e^{2\pi}(\partial\pi)^2$$

$$\mathcal{L}_3 \;\to\; -\tfrac{1}{2}(\partial\pi)^2\Box\pi - \tfrac{1}{4}(\partial\pi)^4$$

Let us study solutions: SO(4,2) → SO(4,1)

Genesis

Nicolis, Rattazzi, Trincherini, 09
PC, Nicolis, Trincherini, to appe

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

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

Scale invariance: $T^{\mu\nu} = \tau^{\mu\nu}\frac{1}{t^4} \longrightarrow \rho = 0 \quad p \propto -\frac{1}{t^4}$

Brutal violation of NEC: $\dot{H} = -\frac{1}{2M_P^2}(\rho + p) \propto \frac{1}{t^4}$

$$H = -\frac{1}{3}\frac{f^2}{M_P^2}\frac{1}{H_0^2 t^3} + c \qquad a \propto \exp\left(\frac{1}{t^2}\right)$$

Can start in contraction or expansion

Genesis at t ~ 0 exit EFT description

(Subtle) perturbations

- Homogeneous attractor: t → t + c
- π perturbations live in (fake) dS: scale invariance? No $\quad \frac{1}{H_0^4 t^4}\left[-\frac{1}{2}H_0^2 t^2(\partial\varphi)^2 - \frac{1}{2}(-4H_0^2)\varphi^2\right]$
- ζ action: $\quad \frac{9M_{\rm Pl}^4}{f^2}\int d^4x\,(H_0 t)^2\left[\dot\zeta^2 - (\vec\nabla\zeta)^2\right] \qquad \zeta \sim \text{const}\,.\,\frac{1}{t}$
- During genesis, squeezing towards the "other" adiabatic mode

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

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

Weinberg 03

Scale invariance from the fake de Sitter

In inflation, scale invariance comes from symmetries of dS

Here $g^{(\pi)}_{\mu\nu} \equiv e^{2\pi(x)}\eta_{\mu\nu}$ is dS

A spectator massless scalar will behave as in dS !

Signatures:

- Local non-Gaussianities
- Unobservable, strongly blue GWs
- Possible isocurvature

"Predictions" of alternatives to inflation

1. Low GWs: perturbations are produced at low energy
2. Blue GWs: contraction or ~~NEC~~

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

3. Local NGs: smoking gun of a "second field" mechanism

PC, Zaldarriaga 04

$$f_{\rm NL}^{\rm loc} \gtrsim {\rm few}$$

4. No tilt (?): deviation from scale invariance ~% is not as automatic as in inflation

(Subtle) perturbations

- Homogeneous attractor: t → t + c
- π perturbations live in (fake) dS:
  scale invariance? No

$$\frac{1}{H_0^4 t^4}\left[-\tfrac{1}{2}H_0^2 t^2 (\partial\varphi)^2 - \tfrac{1}{2}(-4H_0^2)\varphi^2\right]$$

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

- During genesis, squeezing towards the "other" adiabatic mode

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

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

Weinberg 03

Genesis

Nicolis, Rattazzi, Trincherini, 09
PC, Nicolis, Trincherini, to appe

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

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

Scale invariance: $T^{\mu\nu} = \tau^{\mu\nu}\frac{1}{t^4} \longrightarrow \rho = 0 \quad p \propto -\frac{1}{t^4}$

Brutal violation of NEC: $\dot{H} = -\frac{1}{2M_P^2}(\rho + p) \propto \frac{1}{t^4}$

$$H = -\frac{1}{3}\frac{f^2}{M_P^2}\frac{1}{H_0^2 t^3} + c \qquad a \propto \exp\left(\frac{1}{t^2}\right)$$

Can start in contraction
or expansion

Genesis at t ~ 0
exit EFT description

(Subtle) perturbations

- Homogeneous attractor: t → t + c
- π perturbations live in (fake) dS: scale invariance? No $\frac{1}{H_0^4 t^4}\left[-\frac{1}{2}H_0^2 t^2(\partial\varphi)^2 - \frac{1}{2}(-4H_0^2)\varphi^2\right]$
- ζ action: $\frac{9M_{\rm Pl}^4}{f^2}\int d^4x\,(H_0 t)^2\left[\dot{\zeta}^2 - (\vec{\nabla}\zeta)^2\right]$ $\quad\zeta \sim \text{const} \,.\, \frac{1}{t}$
- During genesis, squeezing towards the "other" adiabatic mode

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

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

Weinberg 03

Genesis

Nicolis, Rattazzi, Trincherini, 09
PC, Nicolis, Trincherini, to appe

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

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

Scale invariance: $T^{\mu\nu} = \tau^{\mu\nu} \frac{1}{t^4} \longrightarrow \rho = 0 \quad p \propto -\frac{1}{t^4}$

Brutal violation of NEC: $\dot{H} = -\frac{1}{2M_P^2}(\rho + p) \propto \frac{1}{t^4}$

$$H = -\frac{1}{3} \frac{f^2}{M_P^2} \frac{1}{H_0^2 t^3} + c \qquad a \propto \exp\left(\frac{1}{t^2}\right)$$

Can start in contraction
or expansion

Genesis at t ~ 0
exit EFT description

"Predictions" of alternatives to inflation

1. Low GWs: perturbations are produced at low energy

2. Blue GWs: contraction or NEC

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

3. Local NGs: smoking gun of a "second field" mechanism

PC, Zaldarriaga 04

$$f_{\rm NL}^{\rm loc} \gtrsim \text{few}$$

4. No tilt (?): deviation from scale invariance ~% is not as automatic as in inflation

"Predictions" of alternatives to inflation

1. Low GWs: perturbations are produced at low energy

2. Blue GWs: contraction or ~~NEC~~

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

3. Local NGs: smoking gun of a "second field" mechanism

PC, Zaldarriaga 04

$$f_{\rm NL}^{\rm loc} \gtrsim \text{few}$$

4. No tilt (?): deviation from scale invariance ~% is not as automatic as in inflation

5. A paper by Linde will come out to criticize yours !!

Superluminality

- Perturbations are luminal around the fake dS solution
  as the only background is the metric
- **Perturbations around a deformed solution will be superluminal**
- No CTC, because the field itself defines a preferred slicing
- No standard Lorentz invariant UV completion

  Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi
- Is it a general feature?

Conclusions

1. NEC is a crucial constraint on cosmology
2. Generically associated with instabilities
3. There are counterexamples: Ghost Condensate, Galileon
4. Galilean Genesis
   - No instability
   - Initial contraction or expansion are ok
   - Scale invariance forced by symmetries of action
5. Superluminality. Swampland?