Title: Galilean Genesis

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Abstract: We propose a novel cosmological scenario, in which standard inflation is replaced by an expanding phase with a drastic violation of the Null Energy Condition (NEC): \dot H >> H^2. The model is based on the recently introduced Galileon theories, which allow NEC violating solutions without instabilities. The unperturbed solution describes a Universe that is asymptotically Minkowski in the past, expands with increasing energy density until it exits the regime of validity of the effective field theory and reheats. This solution is a dynamical attractor and the Universe is driven to it, even if it is initially contracting. Adiabatic perturbations turn out to be cosmologically irrelevant. The model, however, suggests a new way to produce a scale invariant spectrum of isocurvature perturbations, which can be later

converted to adiabatic: the Galileon is forced by symmetry to couple to the other fields as a dilaton; the effective metric it yields on the NEC violating solution is that of de Sitter space, so that all light scalars will automatically acquire a nearly scale-invariant spectrum of perturbations.

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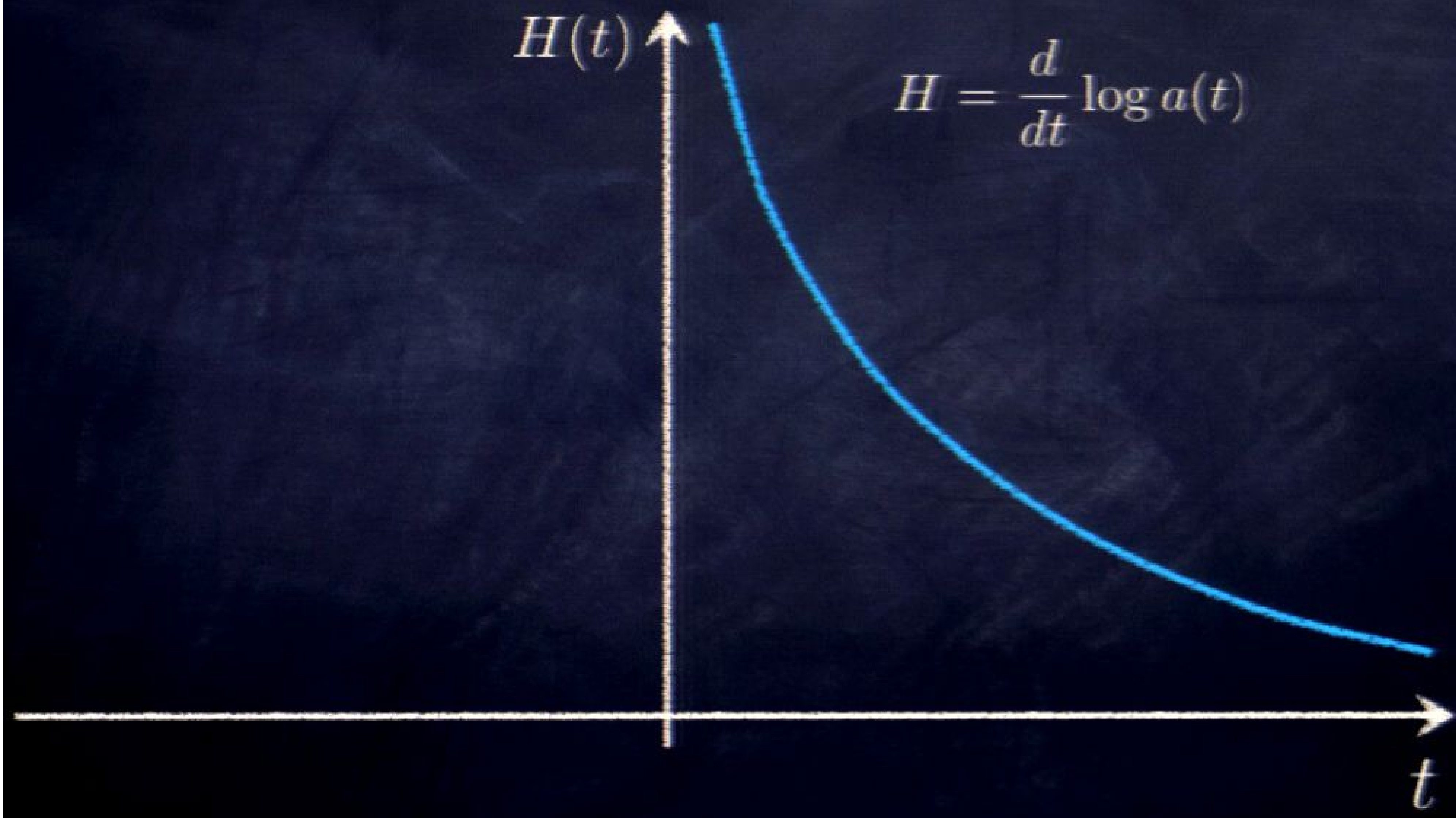
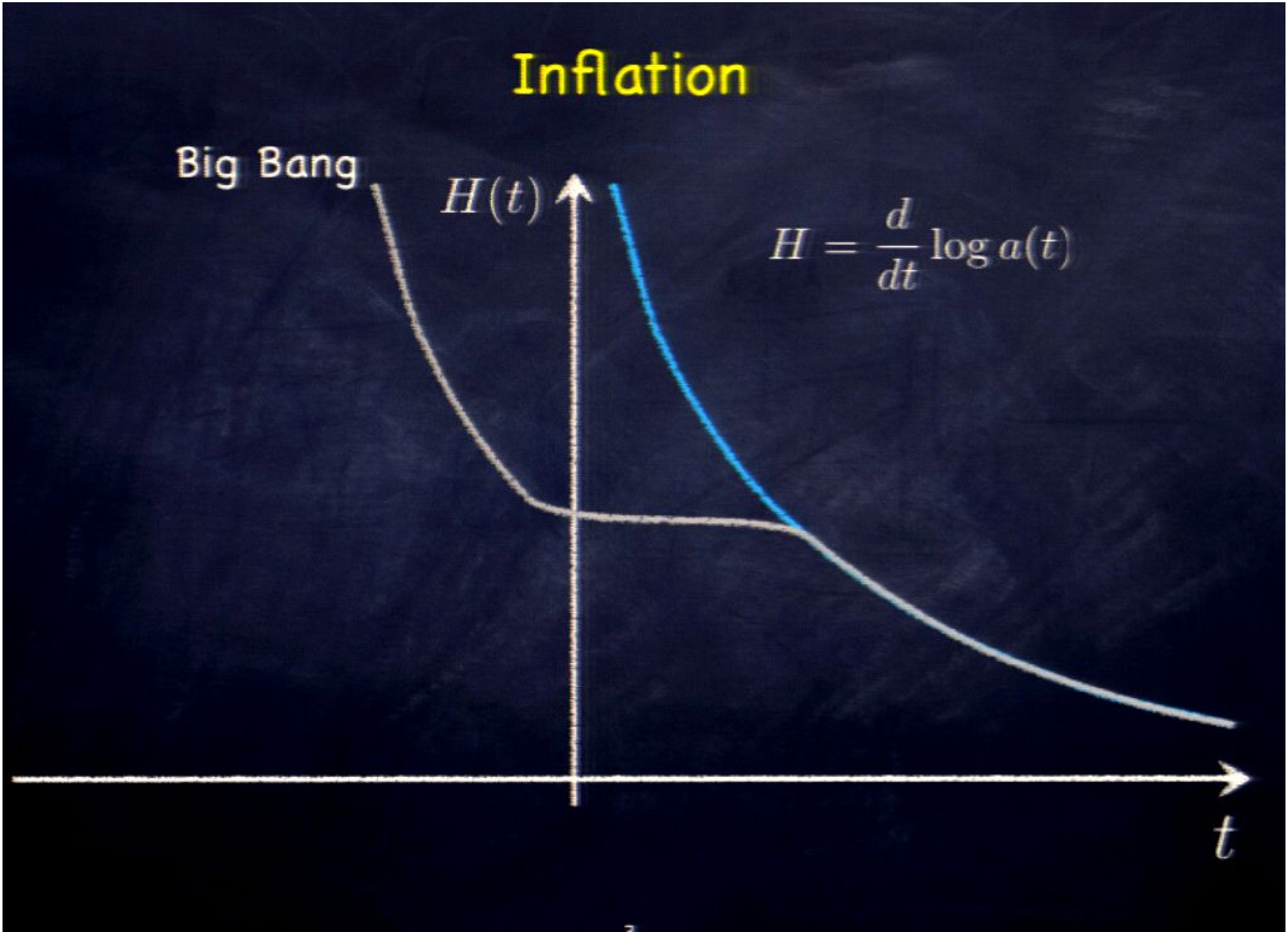
Galilean Genesis

w/ Creminelli and Trincherini, 2010

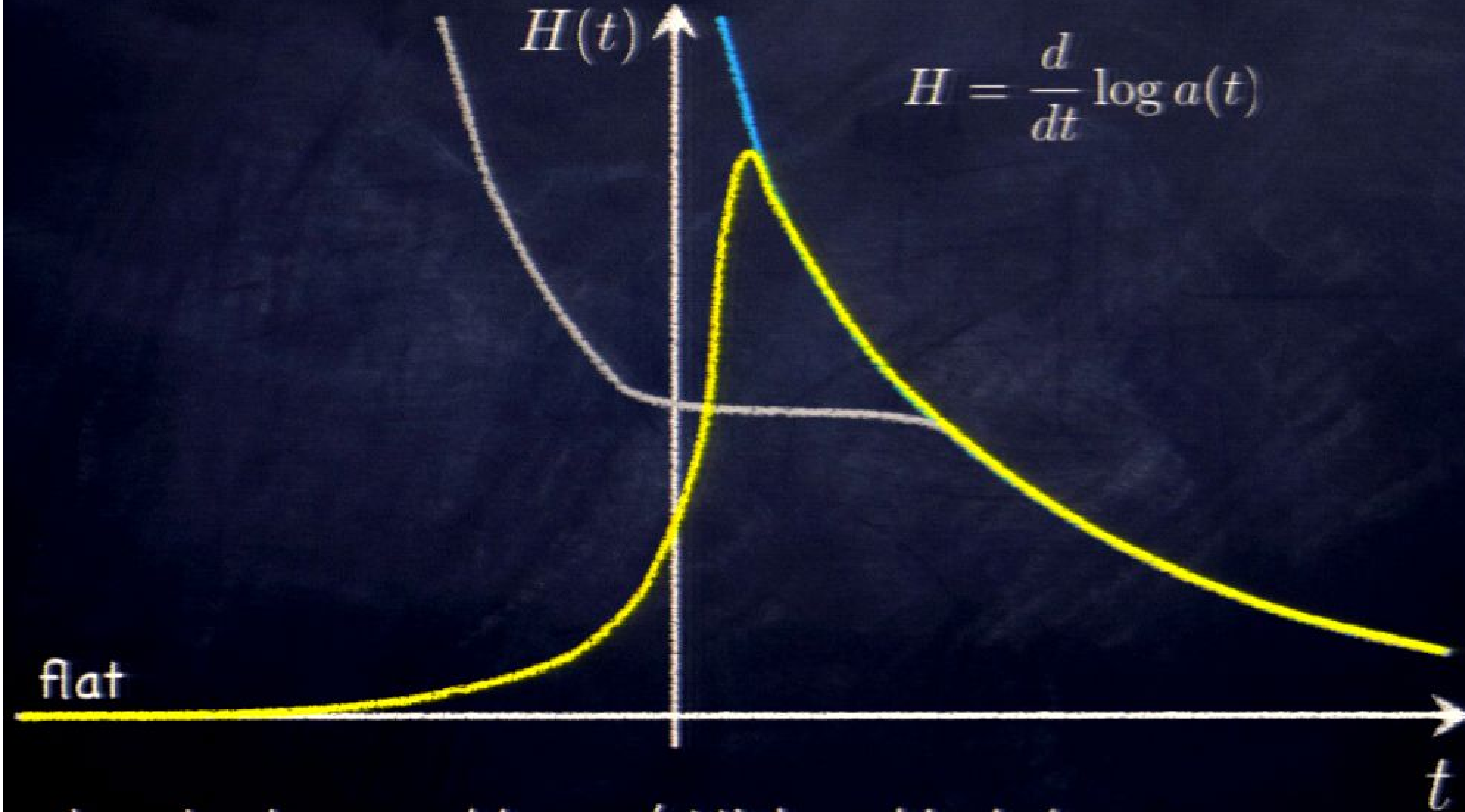
(also: w/ Creminelli, Dubovsky, Gregoire, Luty, Rattazzi, Senatore, Trincherini 2005-2010)

Big Bang cosmology




Inflation
Big Bang
$H(t)$
$H = \frac{d}{dt} \log a(t)$
t

Our story



solves horizon problem w/ Minkowski at $t = -\infty$

Will try to be super-kosher from the QFT standpoint:

- no ghosts
- no superluminal modes about reasonable solutions
- Lorentz invariant vacuum
- S-matrix positivity
- radiatively stable structure
- (too reactionary?)

Want to get rid of the Big Bang

Why so difficult?

Because of null energy condition

Energy conditions in GR

- " E > 0 "
- several ways to make it covariant: weak, strong, dominant, null (...?)
- different contractions of $T_{\mu\nu}$

- The "null" one (NEC) stands out as the most robust

- $T_{\mu\nu} n^\mu n^\nu \geq 0$ for all null n^μ's

- saturated by a c.c. $T_{\mu\nu} \propto g_{\mu\nu}$

- all the others violated or fixed by a suitable c.c.

  $\Longrightarrow$ ambiguous

- For cosmology: NEC $\Rightarrow$ $(\rho + p) \geq 0$
- Friedmann eqs. $\dot{H} \propto -(\rho + p)$
- NEC $\Rightarrow$ Expansion?
  Big Bang
  Need UV-completion

Can one construct a sensible NEC-violating QFT?

- Difficult! Usually:

stability $\Longrightarrow$ NEC

- Simplest example

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

$$\phi = \phi(t) \quad \Longrightarrow \quad (\rho + p) = \pm\dot{\phi}^2$$

- Let's qualify the "usually"

- Neglect gravity for the moment
- Well defined QFT question
- Whatever we get, will translate into an "Einstein frame" statement

Fact

- ~~NEC~~ needs spontaneous Lorentz breaking

$$T_{\mu\nu} \neq \eta_{\mu\nu}$$

- There are light Golstones!
- Their dynamics largely model-independent
- Those are the guys to worry about

Consider a system of scalars

$$\mathcal{L} = F(\phi^I, \partial\phi^I, \partial\partial\phi^I, \ldots)$$

$$I, J, \cdots = 1, \ldots, N$$

- Includes any mixture of fluids and solids

(Dubovsky, Gregoire, Nicolis, Rattazzi 2005)

- At low energies stop at the $\partial\phi^I$ level

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$$\mathcal{L} \to F(\phi^I, \partial\phi^I) \to F(\phi^I, B^{IJ})$$

$$B^{IJ} \equiv \partial_\mu \phi^I \partial^\mu \phi^J$$

- Lorentz breaking solution: $\partial_\mu \phi^I \neq 0$
- Stress tensor: $T_{\mu\nu} \sim F_{IJ}\, \partial_\mu \phi^I \partial_\nu \phi^J$
- Kinetic action for fluctuations $\phi^I \to \phi^I + \pi^I$

$$\mathcal{L} \sim \left[F_{IJ}\eta_{\mu\nu} + 2F_{IK,JL}\, \partial_\mu \phi^K \partial_\nu \phi^L\right] \partial^\mu \pi^I \partial^\nu \pi^J$$

Thorough (=boring) analysis...

(Dubovsky, Gregoire, Nicolis, Rattazzi 2005)

Theorem:

Thorough (=boring) analysis...

(Dubovsky, Gregoire, Nicolis, Rattazzi 2005)

Theorem:

isotropy

Stability and

Thorough (=boring) analysis...

(Dubovsky, Gregoire, Nicolis, Rattazzi 2005)

Theorem:

Stability and { isotropy or subluminality }

⇓

NEC !

Rewind...

Rewind... Consider a system of scalars

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- Includes any mixture of fluids and solids
- At low energies stop at the $\partial\phi^I$ level

Why stop at the $\partial\phi^I$ level?

- Most relevant at low energies

- Higher derivatives problematic (when important):

- classically...

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

- ... and quantum-mechanically: ~~EFT~~

1st Caveat: the ghost-condensate

(Arkani-Hamed, Cheng, Luty, Mukohyama 2003)

- Suppose the system is degenerate at lowest order in spatial derivatives

$$\mathcal{L} \sim \dot{\pi}^2 - 0 \cdot (\vec{\nabla}\pi)^2$$

- Higher derivative terms

$$(\Box\phi)^2 \rightarrow \quad \ddot{\pi}^2, \;\; (\vec{\nabla}\dot{\pi})^2, \;\; (\nabla^2\pi)^2$$

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- Higher derivative terms

$$(\Box\phi)^2 \rightarrow \quad \ddot{\pi}^2, \;\; (\vec{\nabla}\dot{\pi})^2, \;\; \underbrace{(\nabla^2\pi)^2}_{\text{leading gradient energy}}$$

2nd Caveat: the Galileon

(Nicolis, Rattazzi, Trincherini 2008)

- No-go theorem assumes no higher-derivatives in L
- The (classical) problem is having higher-derivative EOM
- Galileon has higher-derivative L with two-derivative EOM

- For simplicity assume purely two-derivative eom

$$\frac{\delta \mathcal{L}}{\delta \pi} = f(\partial_\mu \partial_\nu \pi)$$

- Invariant under

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

"Galilean invariance"

- Analogous to $x(t) \to x(t) + x_0 + v_0 t$

Galilean Invariants

$$\mathcal{L}_1 = \pi \tag{34}$$

$$\mathcal{L}_2 = -\tfrac{1}{2}\,\partial\pi\cdot\partial\pi \tag{35}$$

$$\mathcal{L}_3 = -\tfrac{1}{2}\,[\Pi]\,\partial\pi\cdot\partial\pi \tag{36}$$

$$\mathcal{L}_4 = -\tfrac{1}{4}\left([\Pi]^2\,\partial\pi\cdot\partial\pi - 2\,[\Pi]\,\partial\pi\cdot\Pi\cdot\partial\pi - [\Pi^2]\,\partial\pi\cdot\partial\pi + 2\,\partial\pi\cdot\Pi^2\cdot\partial\pi\right) \tag{37}$$

$$\begin{aligned}\mathcal{L}_5 = -\tfrac{1}{5}\Big(&[\Pi]^3\,\partial\pi\cdot\partial\pi - 3[\Pi]^2\,\partial\pi\cdot\Pi\cdot\partial\pi - 3[\Pi][\Pi^2]\,\partial\pi\cdot\partial\pi + 6[\Pi]\,\partial\pi\cdot\Pi^2\cdot\partial\pi \\ &+2[\Pi^3]\,\partial\pi\cdot\partial\pi + 3[\Pi^2]\,\partial\pi\cdot\Pi\cdot\partial\pi - 6\,\partial\pi\cdot\Pi^3\cdot\partial\pi\Big)\end{aligned} \tag{38}$$

$$\Pi^{\mu}{}_{\nu} \equiv \partial^{\mu}\partial_{\nu}\pi \qquad\qquad [\cdots] \equiv \mathrm{Tr}\{\cdots\}$$

$$\mathcal{L}_\pi = \sum_{i=1}^{5} c_i \mathcal{L}_i$$

Quantum mechanically

- Galilean invariance protects the structure of the Lagrangian
- large classical non-linearities possible within EFT (cf. GR)
- i.e., small radiative corrections and fluctuations perturbative

(Nicolis, Rattazzi 2004)

Can the galileon violate the NEC without instabilities?

(Nicolis, Rattazzi, Trincherini 2009)

- Promote galilean transformation + Poincare' to conformal group

$$\begin{cases} \pi \to \pi + c \\ \pi \to \pi + b_\mu x^\mu \end{cases}$$

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- Promote galilean transformation + Poincare' to conformal group

$$\begin{cases} \pi(x) \to \pi(\lambda x) + \log\lambda \\ \pi(x) \to \pi(x + bx^2 - (b\cdot x)x) - 2b_\mu x^\mu \end{cases}$$

- i.e., promote the galileon to a dilaton

$$g_{\mu\nu}^{\text{fake}} = e^{2\pi}\eta_{\mu\nu}$$

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$$g_{\mu\nu}^{\text{fake}} = e^{2\pi}\eta_{\mu\nu}$$

- same good features as the galileon

- Just by symmetry, "de Sitter" solution

$$e^{\pi(x)} = -\frac{1}{H_0 t} \qquad -\infty < t < 0$$

- Spontaneous breaking

$$SO(4,2) \to SO(4,1)$$

- scale invariance + conservation:

$$\begin{cases} \rho = 0 \\ p = \# \frac{1}{t^4} \end{cases}$$

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- Spontaneous breaking

$$SO(4,2) \to SO(4,1)$$

- scale invariance + conservation:

$$\begin{cases} \rho = 0 \\ p = \underset{\substack{\uparrow \\ \text{negative?}}}{\#} \frac{1}{t^4} \end{cases}$$

- YES: We can choose Lagrangian coefficients to violate NEC with no instabilities

- Fluctuations live in a fictitious deSitter space

⇒ exactly luminal

⇒ scale invariant !?! tricky. later...

Turn on gravity: genesis

(Creminelli, Nicolis, Trincherini 2010)

$$\dot{H} \propto -(\rho + p) \sim 1/t^4$$

$$t \to -\infty$$

$$H \sim 1/|t|^3$$

Gravitational couplings break conformal symmetry

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Gravitational couplings break conformal symmetry

$\Downarrow$

Solution modified at late times ($t \lesssim -t_0$)

$$e^{\pi} \sim 1/t^2$$

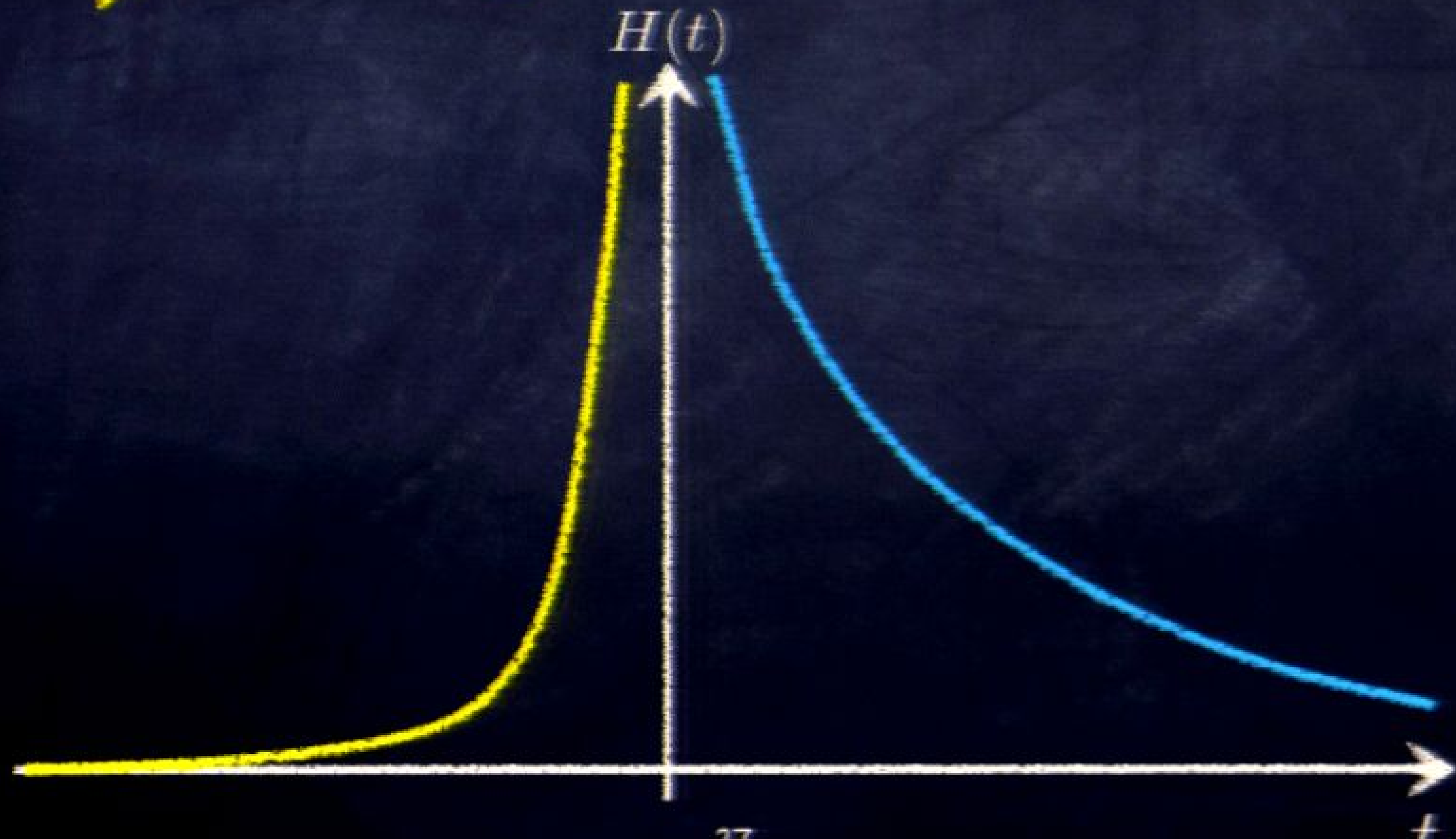
$$1/M_{\rm Pl} \ll t_0 \ll 1/H_0$$

$$H \sim 1/|t|^3$$

For $t \to 0^-$:

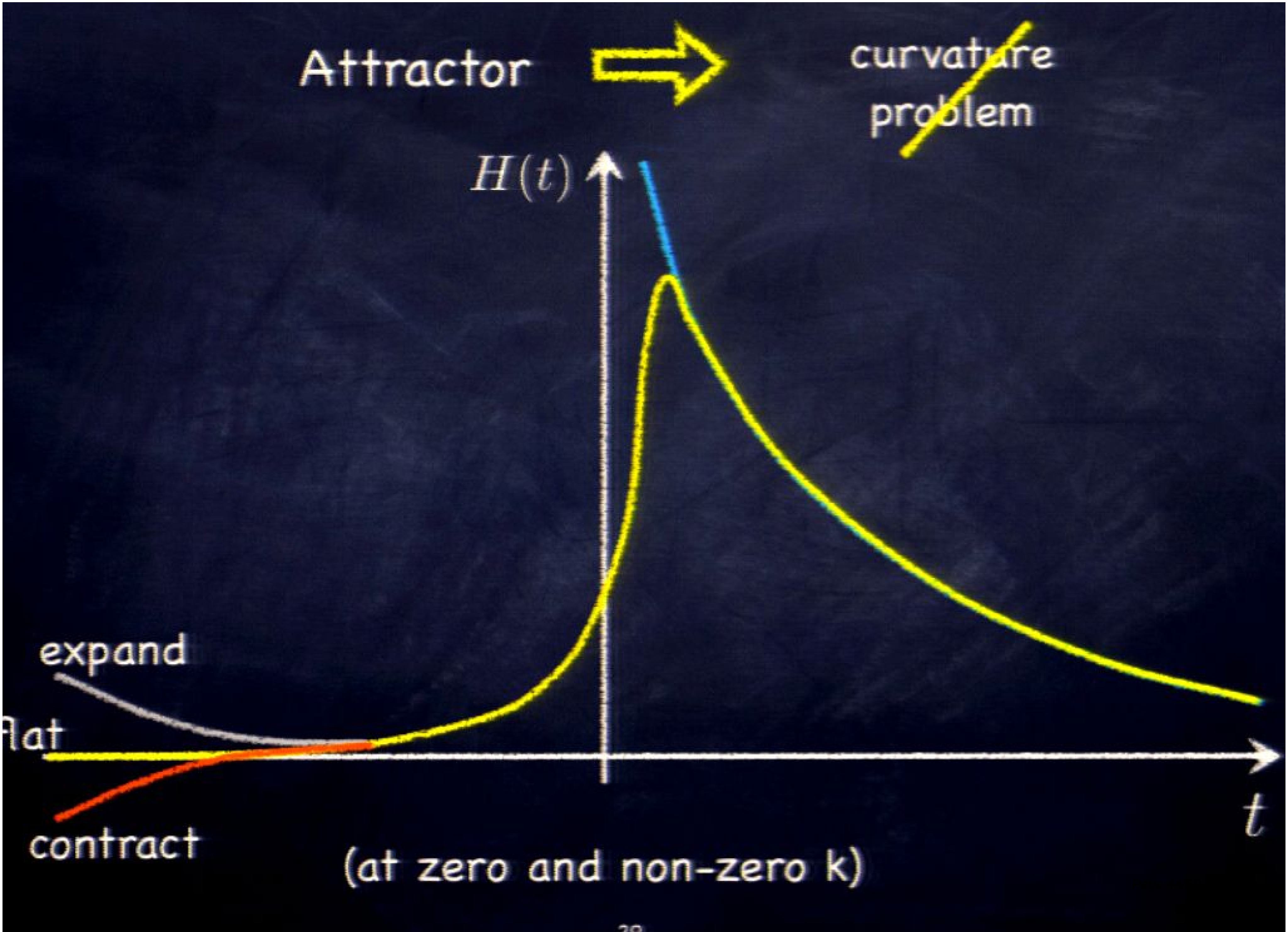
$H, \partial\pi, \partial^2\pi$ exceed strong coupling scale

⇨ Reheating



- No control over reheating phase (No UV completion)
- Strong coupling scale parameterically smaller than Planck's
- GR still valid

(Weakly coupled model: Perreault-Levasseur, Brandeberger, Davis 2011)


Attractor
curvature
problem
H(t)
expand
flat
contract
t
(at zero and non-zero k)

Scalar perturbations

- In the early phase, scalar sees deSitter, gravity sees Minkowski
- Adiabatic perturbations behave very differently than in inflation

$$S_\zeta \sim M_{\rm Pl}^2 \int d^4x\, (t/t_0)^2 (\partial\zeta)^2$$

$$\zeta_{k\to 0} \sim {\rm const}, 1/t$$

- compare with

$$\zeta_{k\to 0} \sim {\rm const}, e^{-Ht}$$

Spectrum

From symmetries of S_ζ:

$$\langle\zeta\zeta\rangle \sim \frac{t_0^2}{M_{\rm Pl}^2} k^2 F(kt)$$

Match low-k time dependence above:

$$\langle\zeta\zeta\rangle \sim \frac{1}{M_{\rm Pl}^2}\frac{t_0^2}{t^2}\frac{1}{k}$$

Very blue -- irrelevant on observable scales

Isocurvature perturbations naturally scale invariant

- couple other scalars respecting conformal sym.:

$$\sqrt{g_{\rm fake}}\, g^{\mu\nu}_{\rm fake}\, \partial_\mu\sigma\partial_\nu\sigma, \ldots$$

- fake dS phase: all tensors proportional to fake dS metric; gravity negligible

- light scalars acquire scale-invariant spectra:

$$\langle\sigma\sigma\rangle \sim H_0^2/k^3$$

- convert later to adiabatic (curvaton, inhomogeneous reheating, ...)

Like for multi-field inflation:

- Amplitude model dependent
- sizable local non-gaussianities

Like for bouncing models:

- negligible, blue tensor modes

The problem: superluminality

- Our cosmology: sub-luminal perturbations
- Other (very accessible) backgrounds: superluminal perturbations
- Unavoidable, in the present version

More precisely:

- forward dispersion relations for $\pi\pi$ scattering

$$\Downarrow$$

superluminality within EFT **or** ~~NE~~C solution outside EFT

(Nicolis, Rattazzi, Trincherini 2009)

No Lorentz-invariant UV completion

Possible way-outs:

- Include more galileon-like fields (Padilla, Saffin, Zhou 2010)
- Promote galilean sym + Poincare' to something other than SO(4,2) (deRham, Tolley 2010)
- Demote SO(4,2) to scale invariance... (usual theorem/conjecture does not apply)

Our problem:

S-matrix positivity

$\Downarrow$

positive $(\partial\pi)^4$

$\Downarrow$

non-zero $(\partial\pi)^2\Box\pi$

special c.t.

$\Downarrow$

superluminality

Our problem:

S-matrix positivity

positive $(\partial\pi)^4$

non-zero $(\partial\pi)^2\Box\pi$

special c.t.

superluminality

The solution:

S-matrix positivity

$\Downarrow$

positive $(\partial\pi)^4$

$\not\Downarrow$ ~~special~~ c.t.

non-zero $(\partial\pi)^2\Box\pi$

$\Downarrow$

superluminality

Ideally: choose coefficients s.t.:

dS solution

- Exists
- violates NEC
- stable
- stricly sub-luminal perturbations

$\pi = 0$ solution

- stable
- positive amplitudes $(\partial\pi)^4 > 0$
- no superluminality about "reasonable" sols.:

$$\Box\pi(\partial\pi)^2 \to 0$$

Dominated by $\mathcal{L}_4$

So far:

dS solution

- Exists
- violates NEC
- stable
- stricly sub-luminal perturbations

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$$\Box\pi(\partial\pi)^2 \to 0$$

Dominated by $\mathcal{L}_4$

Summary

- N~~E~~C model. Starts from Minkowski -- no B.B.
- Consistent EFT
- Dynamics constrained and protected by sym.
- Attractor. Solves horizon and flatness pr.'s
- Negligible adiabatic. Negligible tensors
- Scale-invariant isocurvature
- large local non-gaussianities
- No superluminality
- No consistent Lorentz-invariant state

Recurrent connection: ~~NEC~~ and superluminality

- GR: DEC ($\sim$NEC) = no superluminal flow
- GR: NEC for matter implies ~~CTC~~'s
- our no-go theorem: ~~NEC~~ (+ stability) implies superluminality for matter
- Conformal Galileon: certain solutions violate NEC, others are superluminal
- Scale invariant Galileon and ghost condensate: no Lorentz invariant vacuum