Title: The null energy condition and its violators

Date: Jul 18, 2009 11:30 AM

URL: http://pirsa.org/09070033

Abstract: TBA

Alberto Nicolis
Columbia University

The null energy condition and its violators

w/ Rattazzi and Trincherini, to appear

also: w/ Dubovsky, Gregoire, Rattazzi, '05
w/ Creminelli, Luty, Senatore, '06

Energy conditions in GR

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

Assumed to prove good things...

Assumed to prove good things...

- ~~CTC's~~
- positive energy theorem

Assumed to prove good things...

- ~~CTC's~~
- positive energy theorem
- 2nd law of black-hole thermodynamics

Assumed to prove good things...

- ~~CTC's~~
- positive energy theorem
- 2nd law of black-hole thermodynamics

... and bad ones:

Assumed to prove good things...

- ~~CTC's~~
- positive energy theorem
- 2nd law of black-hole thermodynamics

... and bad ones:

- singularity theorems

Are they obeyed by all
well-behaved physical systems?

Are they obeyed by all well-behaved physical systems?

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

Are they obeyed by all well-behaved physical systems?

- 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

Are they obeyed by all well-behaved physical systems?

- 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. $T_{\mu\nu} \propto g_{\mu\nu}$

Are they obeyed by all well-behaved physical systems?

- 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.

Are they obeyed by all well-behaved physical systems?

- 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. ⇨ ambiguous somewhat

- NEC closely related to the "dominant" one (DEC)

$$\text{DEC} = \text{NEC} + \rho \geq 0$$

- NEC closely related to the "dominant" one (DEC)

$$\text{DEC} = \text{NEC} + \rho \geq 0$$

- more covariantly

$T_{\mu\nu}\, u^{\nu}$ time-like, future-directed

for all time-like, future-directed u^{μ}'s

- NEC closely related to the "dominant" one (DEC)

$$\text{DEC} = \text{NEC} + \rho \geq 0$$

- more covariantly

$T_{\mu\nu}\, u^{\nu}$ time-like, future-directed

for all time-like, future-directed u^{μ}'s

- $\sim$ no superluminal flow of energy-momentum for any observer.

- For cosmology: NEC $\Rightarrow$ $(\rho + p) \geq 0$

- For cosmology: NEC $\Rightarrow$ $(\rho + p) \geq 0$
- Friedmann eqs. $\dot{H} \propto -(\rho + p)$

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

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

- For cosmology: NEC $\Rightarrow$ $(\rho + p) \geq 0$
- Friedmann eqs. $\dot{H} \propto -(\rho + p)$
- NEC $\Rightarrow$ Expansion?
  Big Bang
  Need UV-completion
- For black holes: NEC/DEC $\Rightarrow$ 2nd law

- For cosmology: NEC $\Rightarrow$ $(\rho + p) \geq 0$
- Friedmann eqs. $\dot{H} \propto -(\rho + p)$
- NEC $\Rightarrow$ Expansion?
  Big Bang
  Need UV-completion
- For black holes: NEC/DEC $\Rightarrow$ 2nd law
- crucial for thermodynamic/holographic interpretation

holographic cosmology

Can one construct a sensible NEC-violating QFT?

Can one construct a sensible NEC-violating QFT?

- Difficult! Usually:

stability $\Longrightarrow$ NEC

Can one construct a sensible NEC-violating QFT?

- Difficult! Usually:

stability $\Longrightarrow$ NEC

- Simplest example

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

Can one construct a sensible NEC-violating QFT?

- Difficult! Usually:

stability $\Longrightarrow$ NEC

- Simplest example

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

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

Can one construct a sensible NEC-violating QFT?

- Difficult! Usually:

stability $\Longrightarrow$ NEC

- Simplest example

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

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

- I want to qualify the "usually"

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

Fact

Fact

- ~~NEC~~ needs spontaneous Lorentz breaking

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

Fact

- ~~NEC~~ needs spontaneous Lorentz breaking

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

- There are light Golstones!
- Their dynamics largely model-independent

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

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

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

Consider a system of scalars

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

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

- Includes any mixture of fluids and solids

Consider a system of scalars

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

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

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

Consider a system of scalars

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

$$I, J, \dots = 1, \dots, N$$

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

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

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

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

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

- Lorentz breaking solution: $\partial_\mu \phi^I \neq 0$

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

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

- Lorentz breaking solution: $\partial_\mu \phi^I \neq 0$
- Stress tensor: $T_{\mu\nu} \sim F_{IJ}\, \partial_\mu \phi^I \partial_\nu \phi^J$

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

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

- 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 $\phi^I \to \phi^I + \pi^I$

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

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

- 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:

Stability and

Thorough (=boring) analysis...

(Dubovsky, Gregoire, Nicolis, Rattazzi 2005)

Theorem:

Stability and $\left\{ \text{isotropy} \right.$

Thorough (=boring) analysis...

(Dubovsky, Gregoire, Nicolis, Rattazzi 2005)

Theorem:

Stability and $\left\{ \begin{array}{c} \text{isotropy} \\ \text{or} \\ \text{subluminality} \end{array} \right.$

Thorough (=boring) analysis...

(Dubovsky, Gregoire, Nicolis, Rattazzi 2005)

Theorem:

Stability and $\left\{ \begin{array}{c} \text{isotropy} \\ \text{or} \\ \text{subluminality} \end{array} \right.$

$\Downarrow$

NEC !

- Conversely, there are stable systems with anistropic and superluminal NEC-violating solutions

- Conversely, there are stable systems with anistropic and superluminal NEC-violating solutions

- useless for cosmology

- Conversely, there are stable systems with anistropic and superluminal NEC-violating solutions
- useless for cosmology
- to evade the theorem, try to evade the assumptions

Rewind...

Rewind... Consider a system of scalars

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

$$I, J, \dots = 1, \dots, N$$

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

Rewind... Consider a system of scalars

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

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

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

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

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

- Most relevant at low energies

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

- Most relevant at low energies
- Higher derivatives problematic (when important):

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

- Most relevant at low energies
- Higher derivatives problematic (when important):
- classically...

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

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)

1st Caveat: the ghost-condensate

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

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

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

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

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

$$(\Box\phi)^2 \rightarrow \quad \underbrace{\ddot{\pi}^2, \quad (\vec{\nabla}\dot{\pi})^2}_{\text{negligible at low energies}}, \quad (\nabla^2\pi)^2$$

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

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

- Consistent derivative expansion (w/ non-relativistic scaling $\omega \sim \vec{k}^2$)

- Consistent derivative expansion (w/ non-relativistic scaling $\omega \sim \vec{k}^2$)

- no ghost-like new d.o.f.

- Consistent derivative expansion (w/ non-relativistic scaling $\omega \sim \vec{k}^2$)
- no ghost-like new d.o.f.
- allows consistent NEC-violating cosmological scenarios: bounce, "starting the universe", w<-1 now

(Creminelli, Luty, Nicolis, Senatore 2006,
Creminelli, Senatore 2007,
Creminelli's talk, yesterday)

2nd Caveat: the Galileon

(Nicolis, Rattazzi, Trincherini 2008)

2nd Caveat: the Galileon

(Nicolis, Rattazzi, Trincherini 2008)

- The (classical) problem is having higher-derivative eom

2nd Caveat: the Galileon

(Nicolis, Rattazzi, Trincherini 2008)

- The (classical) problem is having higher-derivative eom
- Is there a higher-derivative Lagrangian that yields two-derivative eom?

- For simplicity assume purely two-derivative eom

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

- 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"

- 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-invariant terms

Galilean-invariant terms

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

- Simplest:

Galilean-invariant terms

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

- Simplest: $\mathcal{L}^{(1)} = \pi$
- Next to simplest:

Galilean-invariant terms

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

- Simplest: $\mathcal{L}^{(1)} = \pi$
- Next to simplest: $\mathcal{L}^{(2)} = (\partial\pi)^2$
- Less trivial (DGP):

Galilean-invariant terms

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

- Simplest: $\mathcal{L}^{(1)} = \pi$
- Next to simplest: $\mathcal{L}^{(2)} = (\partial\pi)^2$
- Less trivial (DGP): $\mathcal{L}^{(3)} = (\partial\pi)^2\,\Box\pi$
- Invariance:

In general:

Exactly one invariant at each order in π

In general:

Exactly one invariant at each order in π

Galilean invariant Lagragian term	$\longleftrightarrow$	Cayley-invariant of matrix $\partial_\mu \partial_\nu \pi$

In general:

Exactly one invariant at each order in π

Galilean invariant Lagragian term $\longleftrightarrow$ Cayley-invariant of matrix $\partial_\mu \partial_\nu \pi$

Rank($\partial_\mu \partial_\nu \pi$) = D $\Longrightarrow$ D invariants (+tadpole)

In general:

Exactly one invariant at each order in π

Galilean invariant Lagragian term $\longleftrightarrow$ Cayley-invariant of matrix $\partial_\mu \partial_\nu \pi$

Rank($\partial_\mu \partial_\nu \pi$) = D $\Longrightarrow$ D invariants (+tadpole)

D=1 (mechanics): $x,\ \dot{x}^2$

In general:

Exactly one invariant at each order in π

Galilean invariant Lagragian term $\longleftrightarrow$ Cayley-invariant of matrix $\partial_\mu \partial_\nu \pi$

Rank($\partial_\mu \partial_\nu \pi$) = D $\Longrightarrow$ D invariants (+tadpole)

D=1 (mechanics): $x,\ \dot{x}^2$

D=4 (us): $\pi,\ (\partial\pi)^2,\ \ldots\ \partial\pi\,\partial\pi(\partial^2\pi)^3$

Galilean Invariants

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

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

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

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

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

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

(Nicolis, Rattazzi, Trincherini 2008)

Quantum mechanically

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

(Nicolis, Rattazzi 2004)

Can the galileon violate the NEC without instabilities?

(Nicolis, Rattazzi, Trincherini, in preparation)

Can the galileon violate the NEC without instabilities?

(Nicolis, Rattazzi, Trincherini, in preparation)

- higher-derivative Lagrangian with healthy two-derivative eom

Can the galileon violate the NEC without instabilities?

(Nicolis, Rattazzi, Trincherini, in preparation)

- higher-derivative Lagrangian with healthy two-derivative eom
- classical non-linear solutions inside the EFT ($\sim$ GR)

Can the galileon violate the NEC without instabilities?

(Nicolis, Rattazzi, Trincherini, in preparation)

- higher-derivative Lagrangian with healthy two-derivative eom
- classical non-linear solutions inside the EFT ($\sim$ GR)
- possible exception to the no go theorem

Interesting NEC-violating cosmological solution

Interesting NEC-violating cosmological solution

- Convenient to promote galilean transformation + Poincare' to conformal group

Interesting NEC-violating cosmological solution

- Convenient to promote galilean transformation + Poincare' to conformal group

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

Interesting NEC-violating cosmological solution

- Convenient to promote galilean transformation + Poincare' to conformal group

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

Interesting NEC-violating cosmological solution

- Convenient to 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

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

Interesting NEC-violating cosmological solution

- Convenient to 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

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

- galiean invariant terms become conformally invariant terms (upon straightforward modifications) -- same good features

- Just by symmetry, "de Sitter" solution

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

- Just by symmetry, "de Sitter" solution

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

- Spontaneous breaking

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

- Just by symmetry, "de Sitter" solution

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

- Spontaneous breaking

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

- scale invariance + conservation:

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

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

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

- Fluctuations live in a fictitious deSitter space

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

- Fluctuations live in a fictitious deSitter space

$\Rightarrow$ exactly luminal

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

- Fluctuations live in a fictitious deSitter space

⇨ exactly luminal

⇨ scale invariant !?!

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

- Fluctuations live in a fictitious deSitter space

  ⇒ exactly luminal

  ⇒ scale invariant !?!

- No. They are massive $m \sim H_0$ (implied by broken time translation)

With gravity: starting the universe 2

With gravity: starting the universe 2

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

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

Solution modified at late times

With gravity: starting the universe 2

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

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

Solution modified at late times

Derivatives grow... strong coupling

With gravity: starting the universe 2

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

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

Solution modified at late times

Derivatives grow... strong coupling

Reheating?

Final Thoughts

Final Thoughts

- Two consistent NEC-violating EFTs

Final Thoughts

- Two consistent NEC-violating EFTs
- Effective Lagrangian for cosmological adiabatic perturbations

Final Thoughts

- Two consistent NEC-violating EFTs

- Effective Lagrangian for cosmological adiabatic perturbations

⇒ only two possibilities
(in cosmology, w/ one dof)

(Creminelli, Luty, Nicolis, Senatore 2006)

Final Thoughts

- Two consistent NEC-violating EFTs

- Effective Lagrangian for cosmological adiabatic perturbations

⇒ only two possibilities
(in cosmology, w/ one dof)

(Creminelli, Luty, Nicolis, Senatore 2006)

- No superluminality, still...

- Ghost condensate: no Lorentz-invariant phase

- Ghost condensate: no Lorentz-invariant phase

$\Rightarrow$ Lorentz-invariant UV completion?

- Ghost condensate: no Lorentz-invariant phase

⇒ Lorentz-invariant UV completion?

- Galileon: superluminality for other solutions (w/ localized sources)

- Ghost condensate: no Lorentz-invariant phase

$\Rightarrow$ Lorentz-invariant UV completion?

- Galileon: superluminality for other solutions (w/ localized sources)

- also certain scattering amplitude too soft

- Ghost condensate: no Lorentz-invariant phase

⇨ Lorentz-invariant UV completion?

- Galileon: superluminality for other solutions (w/ localized sources)

- also certain scattering amplitude too soft

⇨ probably no standard Lorentz invariant UV completion

Recurrent connection: ~~NEC~~ and superluminality

Recurrent connection: ~~NEC~~ and superluminality

- GR: DEC ($\sim$NEC) = no superluminal flow

Recurrent connection: ~~NEC~~ and superluminality

- GR: DEC ($\sim$NEC) = no superluminal flow
- GR: NEC for matter implies ~~CTC~~'s

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

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
- Galileon: certain solutions violate NEC, others are superluminal

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
- Galileon: certain solutions violate NEC, others are superluminal

Deep? Accidental?