

Title: The null energy condition and its violators

Date: Jul 18, 2009 11:30 AM

URL: <http://pirsa.org/09070033>

Abstract: TBA

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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...

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- ~~CTC's~~

- positive energy theorem

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... and **bad** ones:

- singularity theorems

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c.c.  ambiguous somewhat

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

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Big Bang
Need UV-completion

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• For black holes: NEC/DEC \Rightarrow 2nd law

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• crucial for thermodynamic/holographic interpretation

holographic cosmology

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- 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

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

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

Consider a system of scalars

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

Thorough (=boring) analysis...

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

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- to evade the theorem, try to evade the assumptions

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

1st Caveat: the ghost-condensate

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

- Higher derivative terms

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

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leading gradient energy

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- 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, Trinchnerini 2008)



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- 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

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"Galilean invariance"

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"Galilean invariance"

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

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

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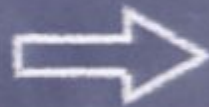
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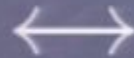
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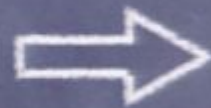
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D=1 (mechanics): x, \dot{x}^2

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

Galilean Invariants

$$\mathcal{L}_1 = \pi \quad (34)$$

$$\mathcal{L}_2 = -\frac{1}{2} \partial\pi \cdot \partial\pi \quad (35)$$

$$\mathcal{L}_3 = -\frac{1}{2} [\Pi] \partial\pi \cdot \partial\pi \quad (36)$$

$$\mathcal{L}_4 = -\frac{1}{4} ([\Pi]^2 \partial\pi \cdot \partial\pi - 2 [\Pi] \partial\pi \cdot \Pi \cdot \partial\pi - [\Pi^2] \partial\pi \cdot \partial\pi + 2 \partial\pi \cdot \Pi^2 \cdot \partial\pi) \quad (37)$$

$$\mathcal{L}_5 = -\frac{1}{5} ([\Pi]^3 \partial\pi \cdot \partial\pi - 3 [\Pi]^2 \partial\pi \cdot \Pi \cdot \partial\pi - 3 [\Pi] [\Pi^2] \partial\pi \cdot \partial\pi + 6 [\Pi] \partial\pi \cdot \Pi^2 \cdot \partial\pi + 2 [\Pi^3] \partial\pi \cdot \partial\pi + 3 [\Pi^2] \partial\pi \cdot \Pi \cdot \partial\pi - 6 \partial\pi \cdot \Pi^3 \cdot \partial\pi) \quad (38)$$

$$\Pi^\mu{}_\nu \equiv \partial^\mu \partial_\nu \pi$$

$$[\dots] \equiv \text{Tr}\{\dots\}$$

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

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

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$$\left\{ \begin{array}{l} \pi \rightarrow \pi + c \\ \pi \rightarrow \pi + b_{\mu} x^{\mu} \end{array} \right.$$

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

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

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- scale invariance + conservation:

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

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

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Reheating?

Final Thoughts

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- No superluminality, still...

- Ghost condensate: no Lorentz-invariant phase

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probably **no** standard Lorentz
invariant UV completion

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Deep? Accidental?