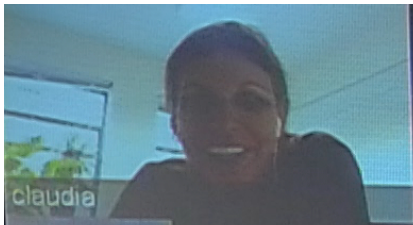


Title: Unitary Cosmological Bounces

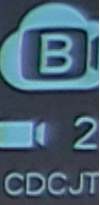
Date: Jun 27, 2017 10:00 AM

URL: <http://pirsa.org/17060099>

Abstract: A non-singular cosmological bounce in the Einstein frame can only take place if the Null Energy Condition (NEC) is violated. I will explore the constraints imposed by demanding tree level unitarity on a cosmological background in single scalar field theories before focusing on the explicit constraints that arise in $P(X)$ theories. In that context, perturbative unitarity makes it impossible for the NEC violation to occur within the region of validity of the effective field theory but I will show explicitly how unitarity may be restored by involving irrelevant operators that arise at a higher scale.

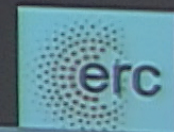


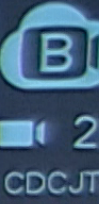
Bounce Scenarios in Cosmology
Perimeter Institute for Theoretical Physics
June 2017



Unitary Cosmological Bounces

Imperial College
London Claudia de Rham

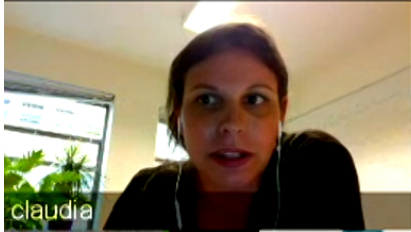




Thanks to Organizers
& Collaborator Scott Melville (PhD @ imperial)



1703.00025 (PRD)



A century of success *With open questions...*

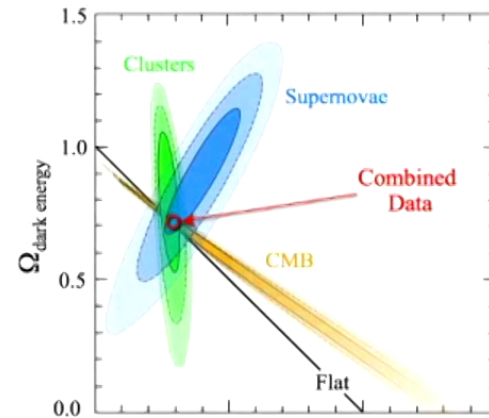
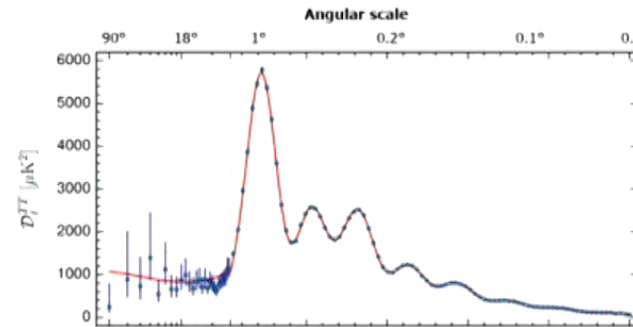
Nature of Inflaton

Pre Big Bang ? Alternatives to Inflation?

Nature of Dark Energy

Cosmological
Constant
Problem

Nature of Dark Matter



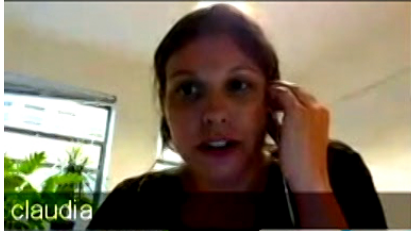


2
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Setting different EFTs apart

- There has recently been an **explosion of models** that can play important roles for **cosmology**

(eg. DBI, K-inflation, G-inflation, gauge inflation, ghost inflation, Axion Monodromy, Chromo-Natural Inflation, $f(R)$, Chameleon, Symmetron, ghost condensate, Galileon, generalized galileon, Horndeski, beyond Horndeski, beyond beyond Horndeski, Fab4, beyond Fab4, EST, DHOST, K-essence, DGP, cascading gravity, massive gravity, minimal massive gravity, bi-gravity, multi-gravity, mass-varying massive gravity, $f(R)$ massive gravity, mass-varying massive gravity, quasi-dilaton, extended quasi-dilaton, superfuid dark matter, Proca dark energy, generalized Proca, beyond generalized Proca, gauge field dark energy, Galileon genesis, extended Galileon genesis, SLED, mimetic gravity, unimodular gravity, dipolar dark matter, ..., ..., ...)



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Setting different EFTs apart

- We could simply wait for observations to tell them apart (but they evolve with observations...)
- As low EFTs they often have very peculiar features that can make us question their whole validity

Do these models:

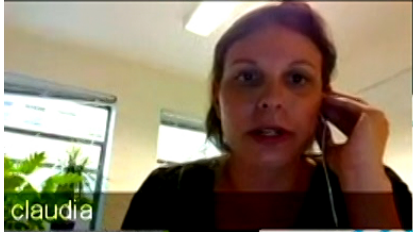
1. make sense in the “traditional” strong coupling regime?
2. preserve perturbative unitarity ?
3. have any chance of ever admitting a standard Wilsonian UV completion ?
4. ... 5. ...



Decoupling limit

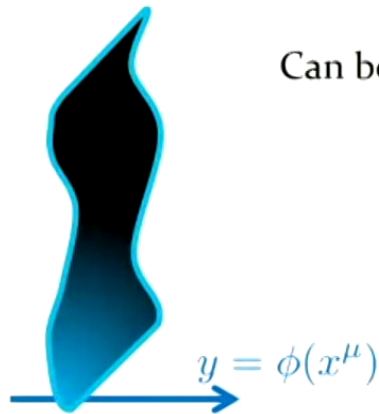
- Most of these theories have been developed with a cosmological motivation in mind and are therefore fundamentally gravitational theories
- However a huge insight on the consistency of the theory can be gained by focusing on the scalar (or other) degree of freedom on a particular cosmological background
- This is justified by taking an appropriate decoupling limit where the gravitational degrees of freedom decouple (eg. $M_{\text{Pl}} \rightarrow \infty$ While keeping the scale at which the other fields interact fixed).
- This approximation can then be checked a posteriori

$$\mathcal{L}[g_{\mu\nu}, \Phi] \xrightarrow{g_{\mu\nu} = \bar{g}_{\mu\nu}(t), \Phi = \bar{\phi}(t) + \varphi} \mathcal{L}[\varphi, t]$$



Zoo of scalar EFT's for Cosmology

- Eg. DBI: $\mathcal{L}_{\text{DBI}} \sim -\sqrt{1 - X} \sim \gamma^{-1}$
 $X = -(\partial\phi)^2$ + higher derivative operators



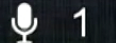
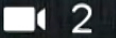
Can be thought as coming from probe brane in extra dimension

Poincare invariance in 5d implies global symmetry for DBI in 4d:

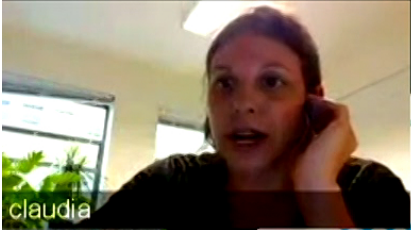
$$\phi \rightarrow \phi + c + v_\mu (x^\mu + \phi \partial^\mu \phi)$$

Applications for inflation, dark energy, dark matter, ...

Silverstein, Tong, PRD70, 2004
Alishahiba, Silverstein, Tong, PRD70, 2004

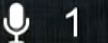
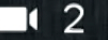


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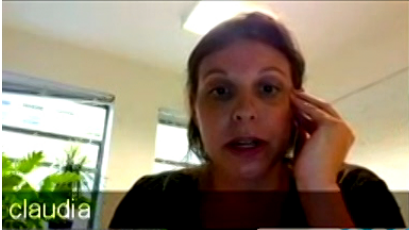


Riding on irrelevant Operators

- Eg. of DBI $\mathcal{L}_{\text{DBI}} \sim -\sqrt{1-X} \sim -\frac{1}{2}(\partial\phi)^2 + \frac{1}{\Lambda^4}(\partial\phi)^4 + \dots$
+ higher derivative operators
- The interesting phenomenology requires the irrelevant operators to be important $\left| \frac{(\partial\phi)^2}{\Lambda^4} \right| \sim 1$
- In this type of theories, the breakdown of the EFT is not measured by “ $\partial\phi$ ” but rather by “ ∂ ” itself.
- So we can trust a regime where $\partial\phi \sim \Lambda^2$
- So long as $\partial\partial\phi \ll \Lambda^3$



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Riding on irrelevant Operators

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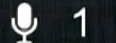
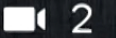
$$\frac{\delta^2 \mathcal{L}}{\delta\phi^2} = Z^{\mu\nu}[\phi] \partial_\nu \partial_\nu \quad \mathcal{L}_{\text{DBI}}[\bar{\phi} + \delta\varphi] \sim Z^{\mu\nu}(\bar{\phi}) \partial_\mu \delta\varphi \partial_\nu \delta\varphi$$

- We expect loop corrections of the form

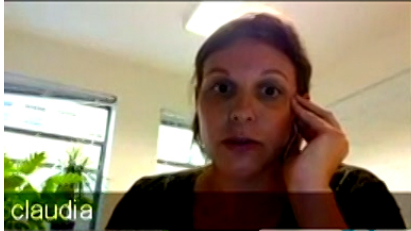
$$\Gamma_{1\text{-loop}} \sim \left(\frac{\partial Z}{Z}\right)^2 + \frac{\partial^2 Z}{Z}$$

Which can be under control even if $\partial\phi \sim \Lambda^2$ so long as the gradients are under control...

Caveats: sound speed can typically be very small (hierarchy of eigenvalues in $Z^{\mu\nu}$)



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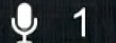
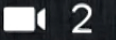


Natural theoretical questions (concerns...)

Do these models:

1. make sense in the “traditional” strong coupling regime?
2. preserve perturbative unitarity ?⁴
3. have any chance of ever admitting a standard Wilsonian UV completion ?

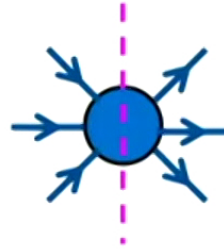
4 5



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Optical theorem:



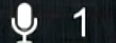
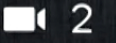
Scattering amplitude $\mathcal{A} = \langle \text{final} | \hat{T} | \text{initial} \rangle$

$$2 \operatorname{Im} \left[\text{Diagram: Blue circle with four outgoing arrows} \right] = \sum_X \left| \text{Diagram: Blue circle with two outgoing arrows and a pink shaded region} \right|^2 \geq \left| \text{Diagram: Blue circle with two outgoing arrows} \right|^2$$

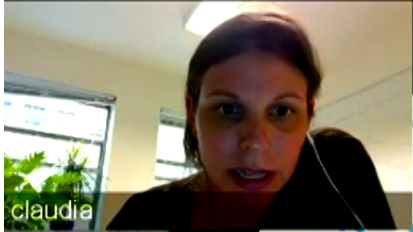
$$\mathcal{A}(s, t) = 16\pi \sqrt{\frac{s}{s - 4m^2}} \sum_{\ell=0}^{\infty} (2\ell + 1) P_{\ell}(\cos \theta) a_{\ell}(s) \quad \rightarrow \quad \operatorname{Im} a_{\ell}(s) = |a_{\ell}(s)|^2 + \dots$$

$$|\mathcal{A}| < \mathcal{O}(1)$$

$$0 \leq |a_{\ell}(s)|^2 \leq \operatorname{Im} a_{\ell}(s) \leq 1$$



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2. Perturbative Unitarity (with small sound speed)

- Many new models of inflation (with non-trivial kinetic terms) with very low sound speed have emerged

eg. could lead to *enhanced non-gaussianities* $f_{\text{NL}} \approx c_s^{-2}$

- In itself this *may* be the first hint of *perturbative unitarity breaking*...

$$\mathcal{L} = \dot{\phi}^2 - c_s^2 (\partial_i \phi)^2 + \text{interactions}$$

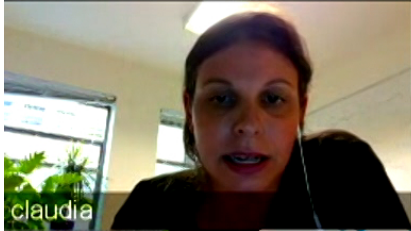
From Optical theorem: $|A_{2 \rightarrow 2}| \lesssim c_s^3$



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2. Perturbative Unitarity (with small sound speed)

- Sound speed effect on perturbative unitarity breaking...

$$S = \int dt d^3x \left(\dot{\phi}^2 - c_s^2 (\partial_i \phi)^2 + \frac{(\partial_i \phi)^{2\ell}}{\Lambda^{4(\ell-1)}} + \dots \right)$$

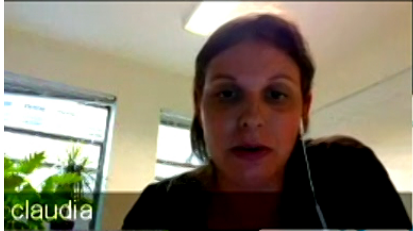


$$x^i = c_s \hat{x}^i$$

$$\phi = c_s^{-3/2} \hat{\phi}$$

$$S = \int dt d^3\hat{x} \left(\dot{\hat{\phi}}^2 - (\hat{\partial}_i \hat{\phi})^2 + \frac{(\hat{\partial}_i \hat{\phi})^{2\ell}}{c_s^{5\ell-3} \Lambda^{4(\ell-1)}} + \dots \right)$$

Strong coupling energy scale $\longrightarrow 0$ as $c_s \rightarrow 0$



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2. Perturbative Unitarity (with small sound speed)

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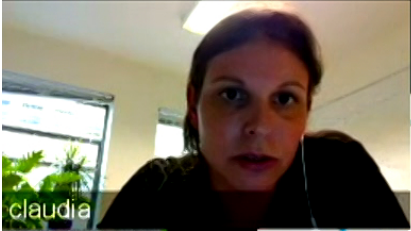


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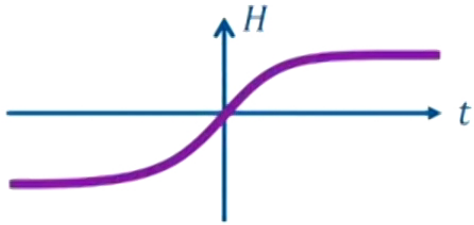
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Strong coupling energy scale $\longrightarrow 0$ as $c_s \rightarrow 0$



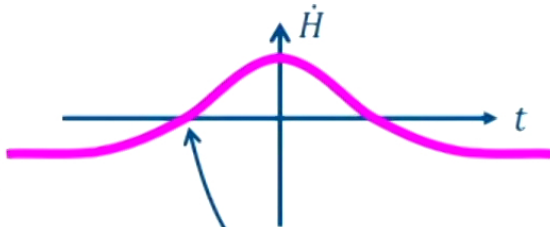
Eg. of $P(\phi, X)$ bounces

- Cosmological bounces are known to be "possible" in $P(\phi, X)$, $X = -(\partial\phi)^2 = \dot{\phi}^2$



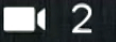
$$M_{\text{Pl}}^2 \dot{H} = -\frac{1}{2}(\rho + p) = -XP'(X)$$

~~NEC~~ for $(\rho + p) < 0$ i.e. $P'(X) < 0$

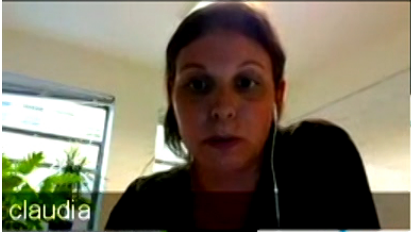


$$c_s^2 = \frac{P'(X)}{2XP''(X) + P'(X)}$$

$c_s^2 = 0$

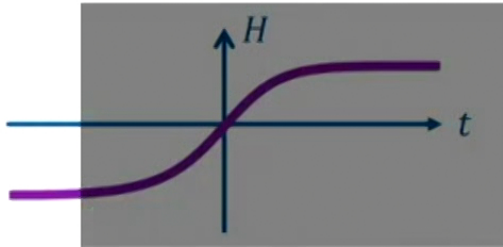


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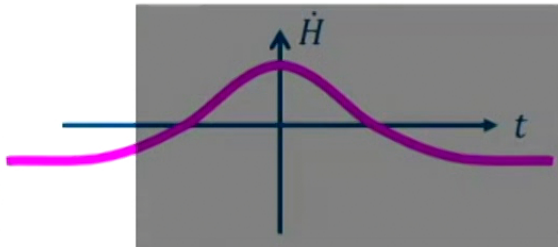
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$$\rightarrow M_{\text{Pl}}^2 \dot{H} = -\frac{1}{2}(\rho + p) = -XP'(X)$$

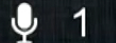
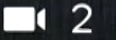
~~NEC~~ for $(\rho + p) < 0$ i.e. $P'(X) < 0$



$$c_s^2 = \frac{P'(X)}{2XP''(X) + P'(X)}$$

Unitarity requires $|\mathcal{A}_{2 \rightarrow 2}| \lesssim c_s^3$

unitarity necessarily breaks down **before** the onset of ~~NEC~~



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High energy operators

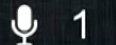
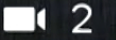
- In practice any EFT will have to involve some irrelevant operators that enter at high energy

$$\mathcal{L} \supset -\frac{1}{2}(\partial\chi)^2 - \frac{1}{2}\mathcal{M}^2\chi^2 + \frac{1}{2}\chi\Box\phi \quad \text{No ghost}$$

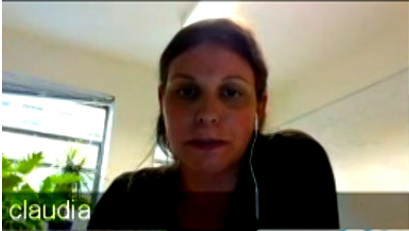
$$\int \mathcal{D}\chi$$

$$\mathcal{L} \supset \frac{1}{\Box + \mathcal{M}^2} (\Box\phi)^2 = \frac{1}{\mathcal{M}^2} (\Box\phi)^2 + \dots$$

No Ostrogradski ghost,
as reach scale \mathcal{M} all other operators are to be included



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High energy operators

- In practice any EFT will have to involve some irrelevant operators that enter at high energy

$$\mathcal{L} = \Lambda^4 P(X/\Lambda^4) + \frac{(\square\phi)^2}{\mathcal{M}^2} + \dots \quad X = -(\partial\phi)^2$$

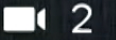
Λ : Traditional strong coupling scale

Scale at which *background is strongly coupled*
EFT for perturbations on top of that background
can see a different strong coupling scale,
(need to remain weakly coupled to trust that background)

$$\Lambda \ll \mathcal{M}$$

\mathcal{M} : Cutoff of the low energy EFT

background has to remain below cutoff to trust low energy EFT
perturbations have to remain below redressed cutoff



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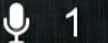
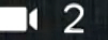
High energy operators

- In practice any EFT will have to involve some irrelevant operators that enter at high energy

$$\mathcal{L} = \Lambda^4 P(X/\Lambda^4) + \frac{(\square\phi)^2}{\mathcal{M}^2} + \dots \quad X = -(\partial\phi)^2$$

Effective Speed of sound: $c_{\text{eff}}^2 = \underbrace{\frac{P'}{P' + XP''}}_{c_s^2} + \frac{k^2}{\mathcal{M}^2} + \mathcal{O}\left(\frac{k^4}{\mathcal{M}^4}\right)$

$$k \ll \mathcal{M}$$



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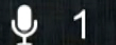
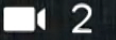
High energy operators

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Subtle trade-off between having the high energy operators
"save" unitarity without spoiling the low-energy EFT



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The low-energy EFT

$$\mathcal{L} = \frac{A}{2} \dot{\varphi}^2 - \frac{B}{2a^2} (\partial_i \varphi)^2 - \frac{m^2}{2} \varphi^2 + \frac{1}{\mathcal{M}^2} \left(\ddot{\varphi} - \frac{1}{a^2} (\partial_i^2 \varphi) \right)^2 + \dots$$

Modified
Dispersion relation:
(mass can be ignored)

$$F = A\omega^2 - B\tilde{k}^2 - \frac{1}{\mathcal{M}^2} (\omega^2 - \tilde{k}^2)^2 = 0$$

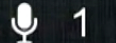
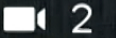
$$\tilde{k} = k/a$$

$$\omega^2(k) = c_{\text{eff}}^2(k) \tilde{k}^2 = c_s^2 \tilde{k}^2 + \frac{\tilde{k}^4}{A\mathcal{M}^2} + \dots$$

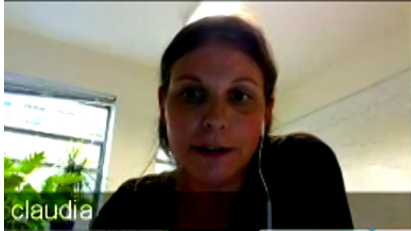
assuming
 $B \ll A$

μ_c : scale at which transition between
relativistic and non-relativistic form

$$\mu_c = \frac{B}{\sqrt{A}} \mathcal{M}$$



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The low-energy EFT

$$\mathcal{L} = \frac{A}{2} \dot{\varphi}^2 - \frac{B}{2a^2} (\partial_i \varphi)^2 - \frac{m^2}{2} \varphi^2 + \frac{1}{\mathcal{M}^2} \left(\ddot{\varphi} - \frac{1}{a^2} (\partial_i^2 \varphi) \right)^2 + \dots$$

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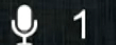
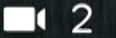
$$\omega^2(k) = c_{\text{eff}}^2(k) \tilde{k}^2 = c_s^2 \tilde{k}^2 + \frac{\tilde{k}^4}{A\mathcal{M}^2} + \dots$$

$$\omega_{\text{new mode}}^2(k) = A\mathcal{M}^2$$

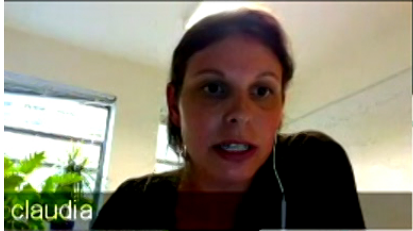
Energy Cutoff (upper bound):

$$\Lambda_{\text{cutoff}} \leq \sqrt{A}\mathcal{M}$$

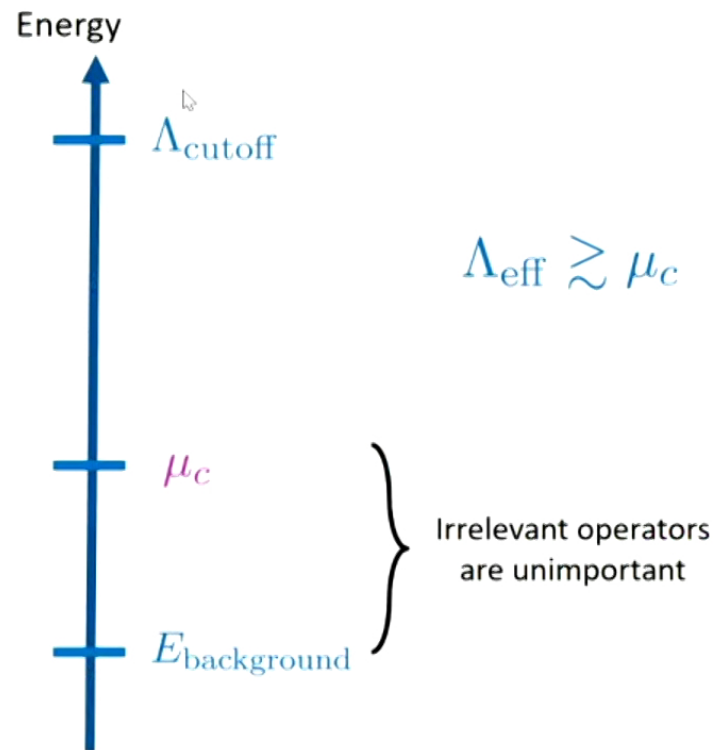
μ_c : scale at which transition between
relativistic and non-relativistic form



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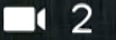


Low vs high energy modes

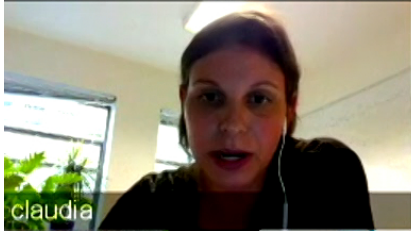


μ_c : scale at which transition between relativistic and non-relativistic form

The effective strong coupling scale derived in that regime should be larger than μ_c otherwise we are in the same situation as earlier



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The low-energy EFT

$$\mathcal{L} = \frac{A}{2} \dot{\varphi}^2 - \frac{B}{2a^2} (\partial_i \varphi)^2 - \frac{m^2}{2} \varphi^2 + \frac{1}{\mathcal{M}^2} \left(\ddot{\varphi} - \frac{1}{a^2} (\partial_i^2 \varphi) \right)^2 + \dots$$

Modified
Dispersion relation:
(mass can be ignored)

$$F = A\omega^2 - B\tilde{k}^2 - \frac{1}{\mathcal{M}^2} (\omega^2 - \tilde{k}^2)^2 = 0$$

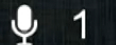
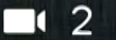
$$\tilde{k} = k/a$$

$$\omega^2(k) = c_{\text{eff}}^2(k) \tilde{k}^2 = c_s^2 \tilde{k}^2 + \frac{\tilde{k}^4}{A\mathcal{M}^2} + \dots$$

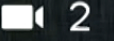
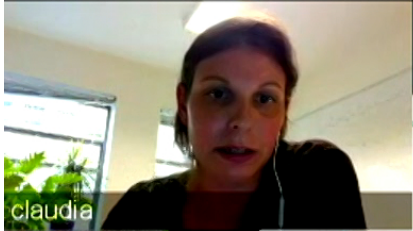
assuming
 $B \ll A$

μ_c : scale at which transition between
relativistic and non-relativistic form

$$\mu_c = \frac{B}{\sqrt{A}} \mathcal{M}$$



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Low vs high energy modes

Energy



Λ_{cutoff}



$$\Lambda_{\text{eff}} \gtrsim \mu_c$$

μ_c : scale at which transition between relativistic and non-relativistic form

μ_c



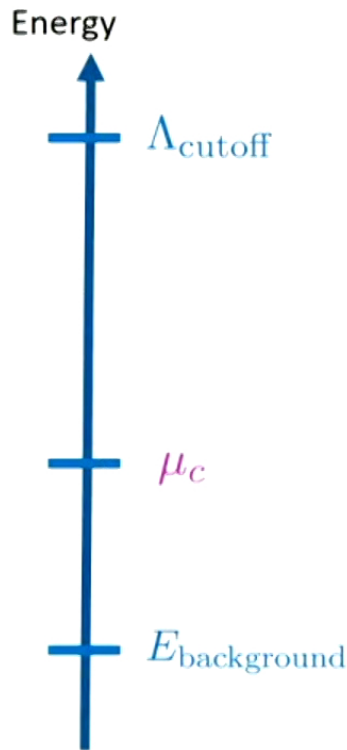
Irrelevant operators are unimportant

The effective strong coupling scale derived in that regime should be larger than μ_c otherwise we are in the same situation as earlier

$E_{\text{background}}$



Low vs high energy modes



For a $P(X)$ theory,

$$|\mathcal{A}_{2 \rightarrow 2}| \lesssim c_s^3$$



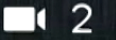
$$(P''(X))^{-1} \gtrsim c_s \mathcal{M}^4$$

one of the most important operators turns out to be

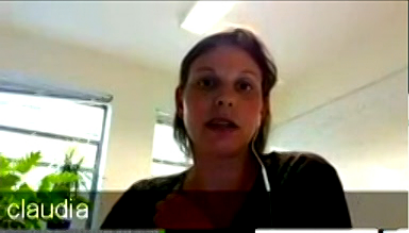
$$P''(X)(\partial_i \varphi)^4$$

This bound is always violated in any ghost condensate type of cosmological bounce

$$\mathcal{L} = -pX + \frac{q}{\Lambda^4} X^2$$



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claudia

For a $P(\phi, X)$ theory, $\mathcal{L} = \Lambda^4 \sum_{\ell, n} \frac{c_{n, \ell}}{\Lambda^{n+4\ell}} \Phi X^\ell$

The EFT for the fluctuations then looks like

$$\mathcal{L}[\varphi] = A\dot{\varphi}^2 - \frac{B}{a^2}(\partial_i\varphi)^2 - \frac{1}{2}m^2\varphi^2 + \sum \frac{\tilde{c}}{\Lambda^{n+4\ell+2m-4}}\varphi^n\dot{\varphi}^m(\partial_i\varphi)^{2\ell}$$

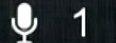
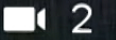
$$c_{n, \ell} \sim \mathcal{O}(1) \Rightarrow A, \tilde{c}_{n, m, \ell} \sim \mathcal{O}(1)$$

$$\mathcal{L}_{\text{int}} \supset \frac{\varphi^5}{\Lambda}$$

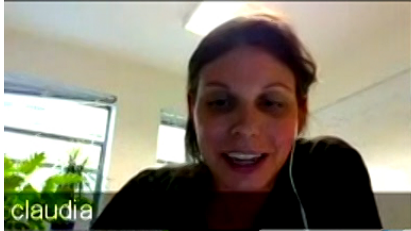
For modes with $\omega \lesssim \mu_c$, the effective strong coupling scale associated with that operator is

$$\Lambda_* \sim A^{1/4}B^{9/4}\Lambda \gtrsim \mu_c \sim \frac{B}{A^{1/2}}\mathcal{M}$$

$$A > B^{-5/3}(\mathcal{M}/\Lambda)^{4/3} \gg 1$$



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Explicit (tuned) $P(\phi, X)$ model

$$\mathcal{L} = \frac{M_{\text{Pl}}^2}{2} R + P(\Phi, X) + \frac{1}{2\Lambda_c^2} (\square\Phi)^2$$

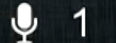
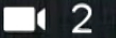
$$P(\Phi, X) = -\Lambda^4 V(\Phi) + p(\Phi)X + \frac{q(\Phi)}{\Lambda^4} X^2$$

with

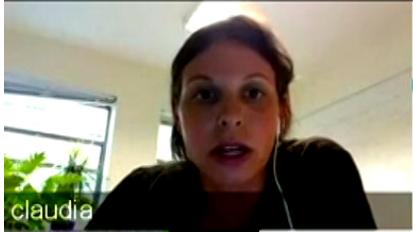
$$V(\Phi) = -\frac{1}{4}q(\Phi)\frac{\Phi^4}{\Lambda^4} + \left(3\frac{\Lambda^2}{M_{\text{Pl}}^2}h^2(\Phi) + \Phi h'(\Phi)\right) - \frac{\Phi^2}{2\mathcal{M}^2} \left(1 + 3\frac{\Lambda^2}{M_{\text{Pl}}^2}h(\Phi)\right)^2$$
$$p(\Phi) = -q(\Phi)\frac{\Phi^2}{\Lambda^2} - 2\frac{\Lambda^2}{\Phi}h'(\Phi) + \frac{2\Lambda^2}{\mathcal{M}^2} \left[1 + 3\frac{\Lambda^2}{M_{\text{Pl}}^2}h(\Phi) + 3\frac{\Lambda^2}{M_{\text{Pl}}^2}\Phi h'(\Phi)\right]$$

So that the background profile be simply

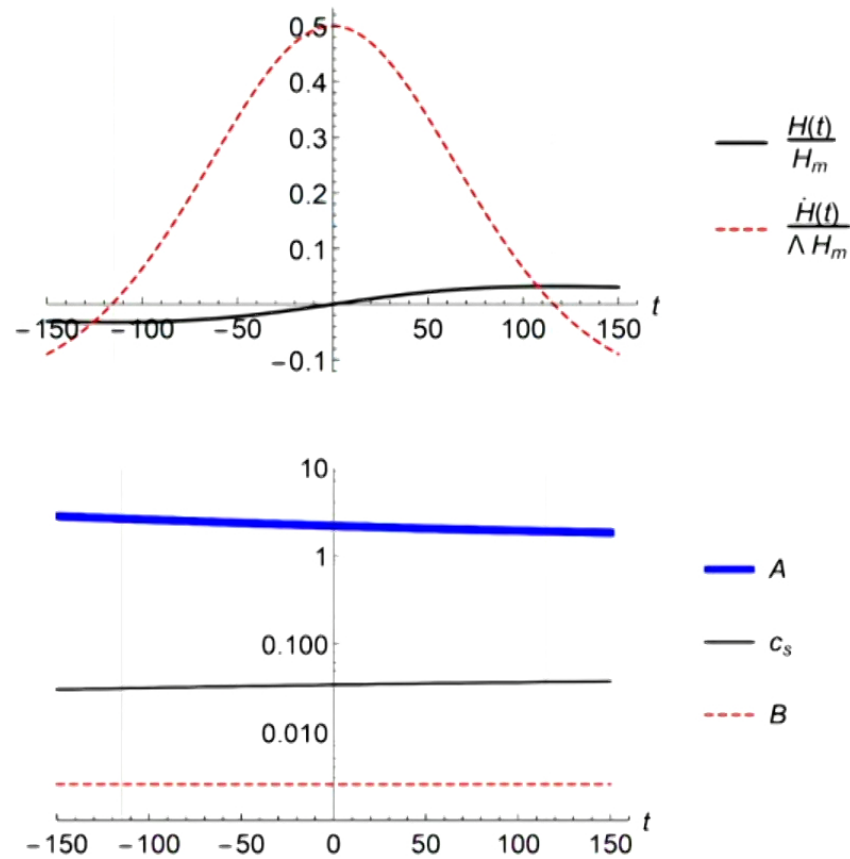
$$\dot{\phi} = \Lambda\phi, \quad H = \frac{\Lambda^3}{M_{\text{Pl}}^2} h(\phi)$$



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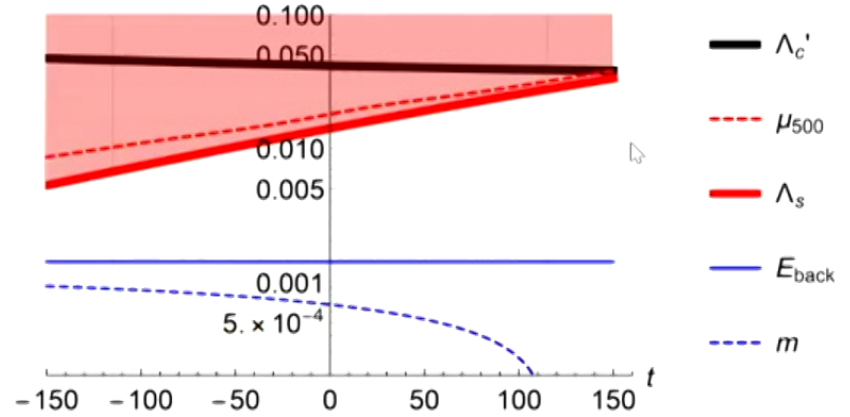
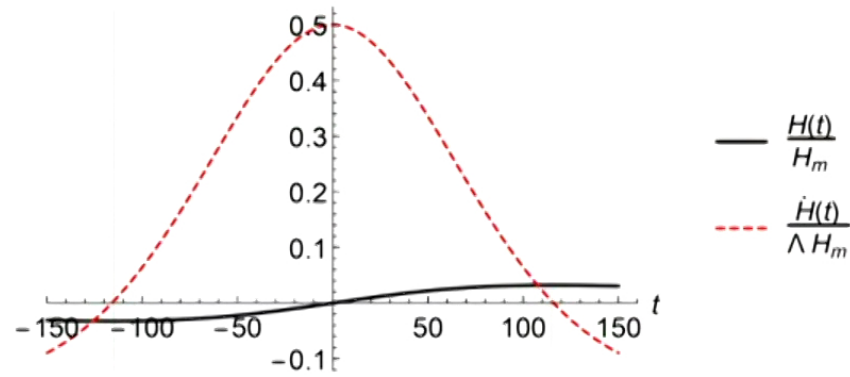


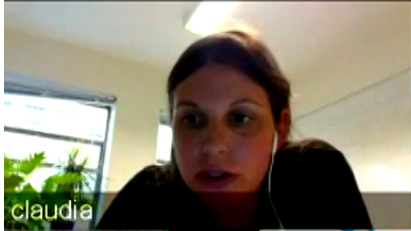
(t, X) bounce with high energy irrelevant operators





$(, X)$ bounce with high energy irrelevant operators



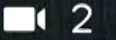


Natural theoretical questions (concerns...)

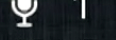
Do these models:

1. make sense in the “traditional” strong coupling regime?
2. preserve perturbative unitarity ?
3. have any chance of ever admitting a standard Wilsonian UV completion ?

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2

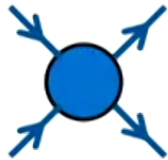


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2 → 2 Scattering Amplitude

For a low energy EFT described by a massive Lorentz invariant scalar field



Mandelstam variables:
 s : center of mass energy²
 t : momentum transfer
 $u = 4m^2 - s - t$

$$|\text{initial state}\rangle \longrightarrow |\text{final state}\rangle = \hat{S} |\text{initial state}\rangle$$

$$\hat{S} = 1 + i\hat{T}$$

$$\text{Scattering amplitude } \mathcal{A} = \langle \text{final} | \hat{T} | \text{initial} \rangle$$



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Optical theorem:

$$\mathcal{A} = \langle \text{final} | \hat{T} | \text{initial} \rangle$$

$$\sigma(s) = \frac{\text{Im}\mathcal{A}(s, 0)}{\sqrt{s(s - 4m^2)}} \geq 0$$

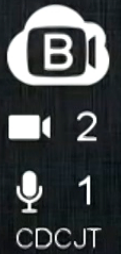
Physical scattering for $s \geq 4m^2$
 In the forward scattering limit, ie. $t = 0$

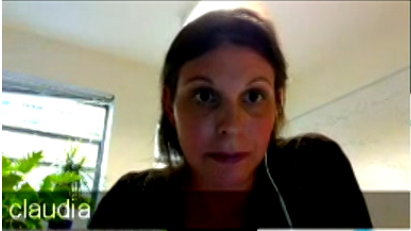
$$2 \text{Im} \left[\text{Diagram: a blue circle with four lines extending outwards} \right] = \sum_X \left| \text{Diagram: a blue circle with a pink shaded region and an 'X' label} \right|^2 \geq \left| \text{Diagram: a blue circle with two lines crossing} \right|^2$$

Analyticity (implied by causality) & locality imply:

$$B''(s) \sim \int_{4m^2}^{\infty} d\mu \frac{\text{Im}A(\mu)}{(\mu - s)^3}$$

$$B''(s)|_{s=0} > 0$$





Positivity bounds for $P(X)$

eg. $P(X)$ model $\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 + \frac{c}{\Lambda^4}(\partial\phi)^4 + \dots$

$$\mathcal{A}_{2\rightarrow 2}^{\text{tree}} = \frac{c}{\Lambda^4} (s^2 + t^2 + u^2 - 4m^2)$$



Positivity bounds requires: $c > 0$

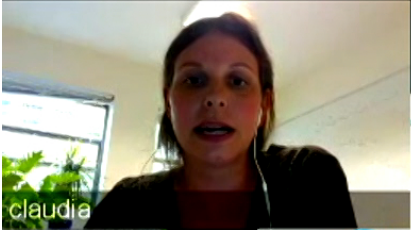
No $P(X)$ model with $c \leq 0$ can ever have an analytic Wilsonian UV completion



2

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Positivity bounds for $P(X)$

eg. $P(X)$ model $\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 + \frac{c}{\Lambda^4}(\partial\phi)^4 + \dots$

$$\mathcal{A}_{2\rightarrow 2}^{\text{tree}} = \frac{c}{\Lambda^4} (s^2 + t^2 + u^2 - 4m^2) \quad \times$$

Positivity bounds requires: $c > 0$

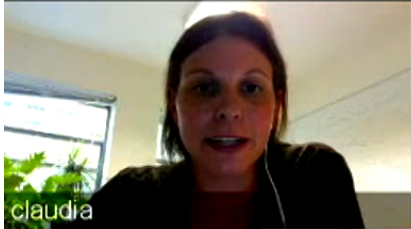
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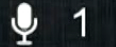
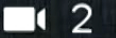
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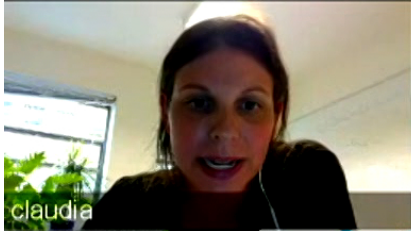
Setting different EFTs apart

- There has recently been an explosion of models that can play important roles for cosmology

(eg. DBI, K-inflation, G-inflation, gauge inflation, ~~ghost inflation~~, Axion Monodromy, Chromo-Natural Inflation, $f(R)$, Chameleon, Symmetron, ~~ghost condensate~~, Galileon, generalized galileon, Horndeski, beyond Horndeski, beyond beyond Horndeski, Fab4, beyond Fab4, EST, DHOST, ~~K-essence~~, DGP, cascading gravity, massive gravity, minimal massive gravity, bi-gravity, multi-gravity, mass-varying massive gravity, $f(R)$ massive gravity, mass-varying massive gravity, quasi-dilaton, extended quasi-dilaton, ~~superfluid dark matter~~, Proca dark energy, generalized Proca, beyond generalized Proca, gauge field dark energy, Galileon genesis, extended Galileon genesis, SLED, mimetic gravity, unimodular gravity, dipolar dark matter, ...)



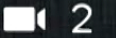
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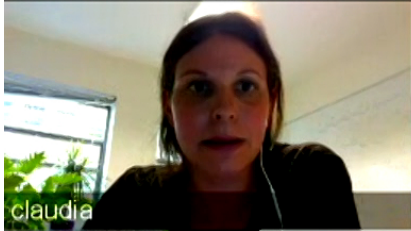
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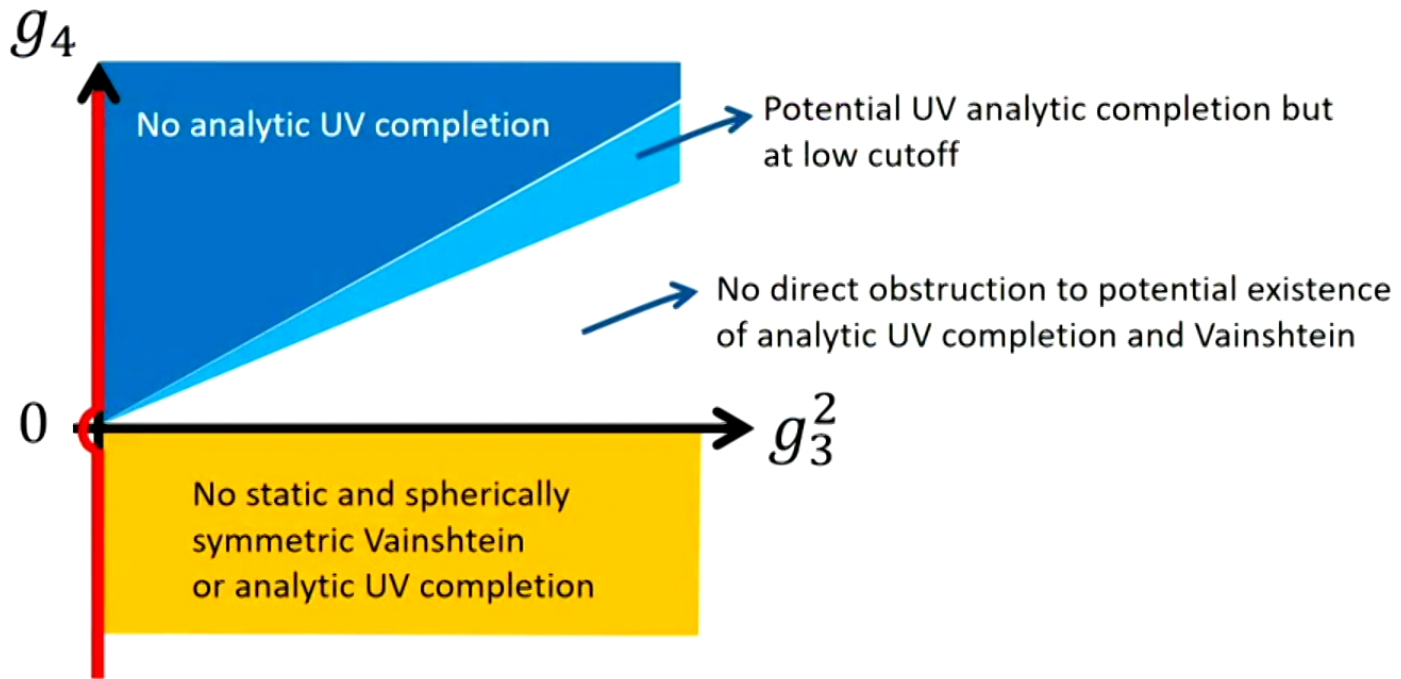
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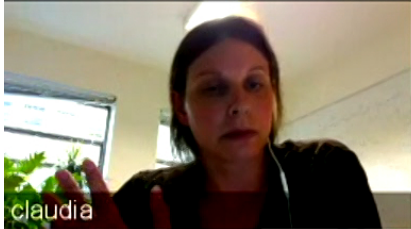
Sensitivity bounds for massive Galileon



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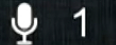
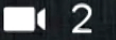
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Summary

- (perturbative) unitarity can place strong constraints on different classes of cosmological models
- In the context of $P(\phi, X)$ cosmological bounces, unitarity is always violated unless some high order operators that enter at or above the cutoff are considered
- Even considering these irrelevant operators, perturbative unitarity is violated in many models (including ghost condensate)
- But a window of opportunities remains open ...



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