Infra-red modifications of gravity

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Motivation

3 problems in late-time cosmology

Motivation

1) Accelerated Expansion of the Universe

'Simplest' explanation: "dead CC". Fne-tuning 1 in 10^{120}

Options:

A) justify the fine-tuning (Landscape of vacua + anthropics)

B) Modify IR
- B-1) Modify Matter (Weinberg no-go thm)
- B-1.5) something in between
- B-2) Modify Gravity (degravitation & mass)

C) (other)

Motivation

2) The phantom menace

$$w = -0.91^{+0.16}_{-0.20}(\mathrm{stat})^{+0.07}_{-0.14}(\mathrm{sys})$$ Conley et al 2011

$$w = -1.016^{+0.077}_{-0.079}$$ Sullivan et al 2011

'Phantom' region $w < -1$ observationally not excluded

can we consistently model phantom behaviour?

--> stable violation of Null Energy Condition (NEC)

Motivation

3) Possible Anomalies in Structure Formation

(Afshordi Geshnizjani Khoury '09)

- ISW Galaxy surveys-CMB cross-correlation higher than ΛCDM by 2σ
- Large bulk flows on large scales (>50 Mpc)
- Excess of power in Lyman-α forest
- (CBI excess, lack of large-angle correlation in CMB)

Is ΛCDM enough??

Does LSS suggest that gravity is stronger at large scales??

Plan

- Massive gravity
- The Galileon
- High-Derivative interactions & Imperfect DE

Massive Gravity

What can we expect from Massive Gravity? (*assuming it exists*)

$$\Box\phi + m^2\phi = J$$

1) Screening of the CC (*Degravitation*)

$J = const;$ $\phi = J/m^2$

2) Source-free `condensates' (*Self-Acceleration*)

$J = 0;$ $\phi = \cos(mt)$

=> Scale of condensate = mass (~ H_0) is *Radiatively Stable*

3) Additional degrees of freedom:

helicity 0 --> *additional attraction at large scales* (*Vainshtein mechanism*)

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Massive Gravity

Linearized Massive gravity: 2 tensor + 2 vector + 1 scalar

only allowed mass term $m^2 h^{\mu\nu}(h_{\mu\nu} - h\eta_{\mu\nu})$ **Pauli-Fierz** '39

$$h_{\mu\nu} = \partial_\mu \partial_\nu \phi \longrightarrow -m^2 \phi\, \partial^\nu \partial^\mu \left(\partial_\mu \partial_\nu - \Box \eta_{\mu\nu}\right)\phi$$

(Stückelberg trick)

higher-derivative terms cancel

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How about Non-Linear completions of Massive Gravity?

"Boulware-Deser ghost" ('72) $(h_{\mu\nu})^N \Rightarrow (\partial_\mu \partial_\nu \phi)^N$

Massive Gravity

Recently, a ghost free nonlinear completion was explicitly constructed. (3 parameters.) Gabadadze, de Rham and Tolley 09

The mplications of the model are currently under scrutiny.

Cosmology: subtle 

Degravitation: No 

Self-accleleration: Yes 

Galileon

Galileon

Insight: nonlinear completion of massive gravity relates to scalar High-Derivative self-interactions

Nicolis Rattazzi Trincherini '08

-> can one have interactions involving $\partial_\mu \partial_\nu \phi$?

-> can one have interactions involving only $\partial_\mu \partial_\nu \phi$??

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YES! *DGP:* $\Box\phi + (\Box\phi)^2 - (\partial\partial\phi)^2 = 0$

Finite number of 2-derivative terms with Galilean symmetry $\partial_\mu \phi \to \partial_\mu \phi + c_\mu$

5 Galilean-invariant terms, $(\partial^{2N-2}\phi^N,\ N = 1, 2, \ldots, D+1)$

ϕ $(\partial\phi)^2$ $\Box\phi(\partial\phi)^2$ $\partial^6\phi^4$ $\partial^8\phi^5$

Galileon

Virtues of the Galileon

- non-renormalization theorem Luty Porrati Rattazzi ‘03

(they are Wess-Zumino terms of broken spacetime symmetries) Goon Hinterbichler Joyce Trodden ‘11

- Vainshtein effect under control

- no ghosts

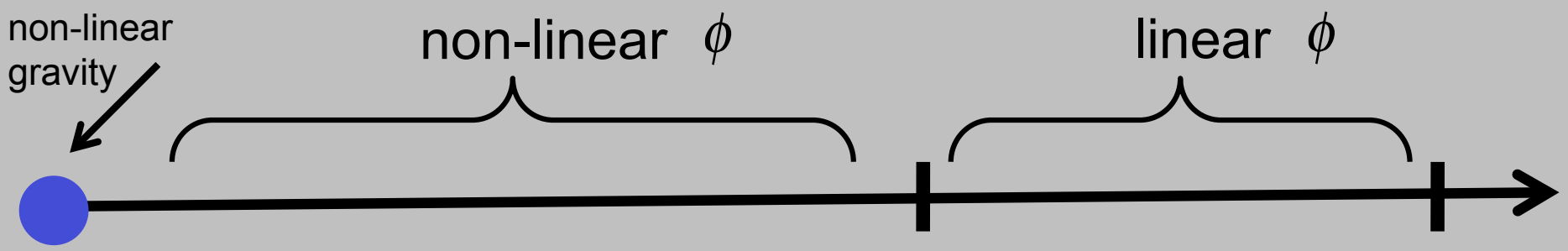
- stable violation of NEC

Galileon

Galileon as an IR modification of gravity $L = (\partial\phi)^2 + \frac{\Box\phi(\partial\phi)^2}{\Lambda^3}$

$\Lambda \simeq (1000\,Km)^{-1} \ll M_P$

- Decoupling regime



$\frac{\Box\phi}{\Lambda^3} \gg 1$

=> coupling to matter suppressed (Vainshtein mechanism)

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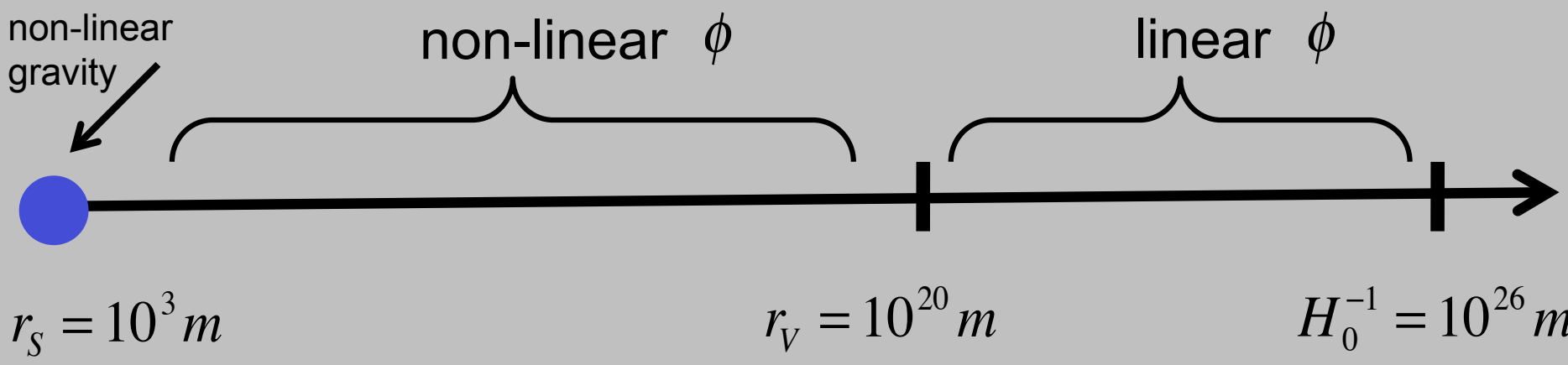

- Self-acceleration: $\phi = x^\mu x_\mu$ mimics a de Sitter metric $h_{\mu\nu} + \phi\,\eta_{\mu\nu}$

General HD couplings

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General HD couplings

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Most general theory propagating a single scalar is parametrized by 4 functions

Horndesky '74,

Deffayet Gao Steer Zahariade '11

$$L = K(\phi, X) + G(\phi, X)\Box\phi + \ldots$$

$$X \equiv \partial_\mu \phi \, \partial^\mu \phi$$

- Relax Galilean invariance
- Still, no ghosts
- Include gravity => DE-type model (or something in between)

General HD couplings

Simplest HD model *Kinetic Gravity Baiding*

Deffayet, O.P. Sawicki Vikman '10

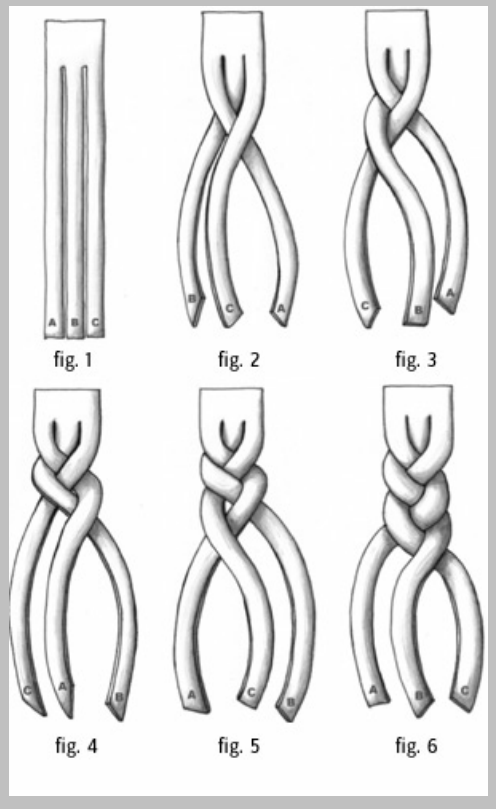
$$L = K(\phi, X) + G(\phi, X)\Box\phi$$

Generic features

--> Braiding $G(\phi, X)\left[\partial\partial\,\phi + \partial g\,\partial\phi\right]$

Essential nonlinear mixing
Modification of gravity?

--> Imperfect fluid => imperfect DE
generalization of `k-essence'



Kinetic Gravity Braiding

Concentrate on shift-symmetric case: $K(X)$, $G(X)$

is a Goldstone boson

Chance not to worsen fine-tuning problems!

Kinetic Gravity Braiding

Concentrate on shift-symmetric case: $K(X),\ G(X)$

is a Goldstone boson

$$A^{\mu\nu}\,\nabla_\mu\nabla_\nu\phi + (g^{\alpha\beta}H^{\mu\nu} - g^{\alpha\mu}H^{\beta\nu})\,\nabla_\alpha\nabla_\beta\phi\ \ \nabla_\mu\nabla_\nu\phi - G'\,\nabla_\mu\phi\,\nabla_\nu\phi R^{\mu\nu} = 0$$

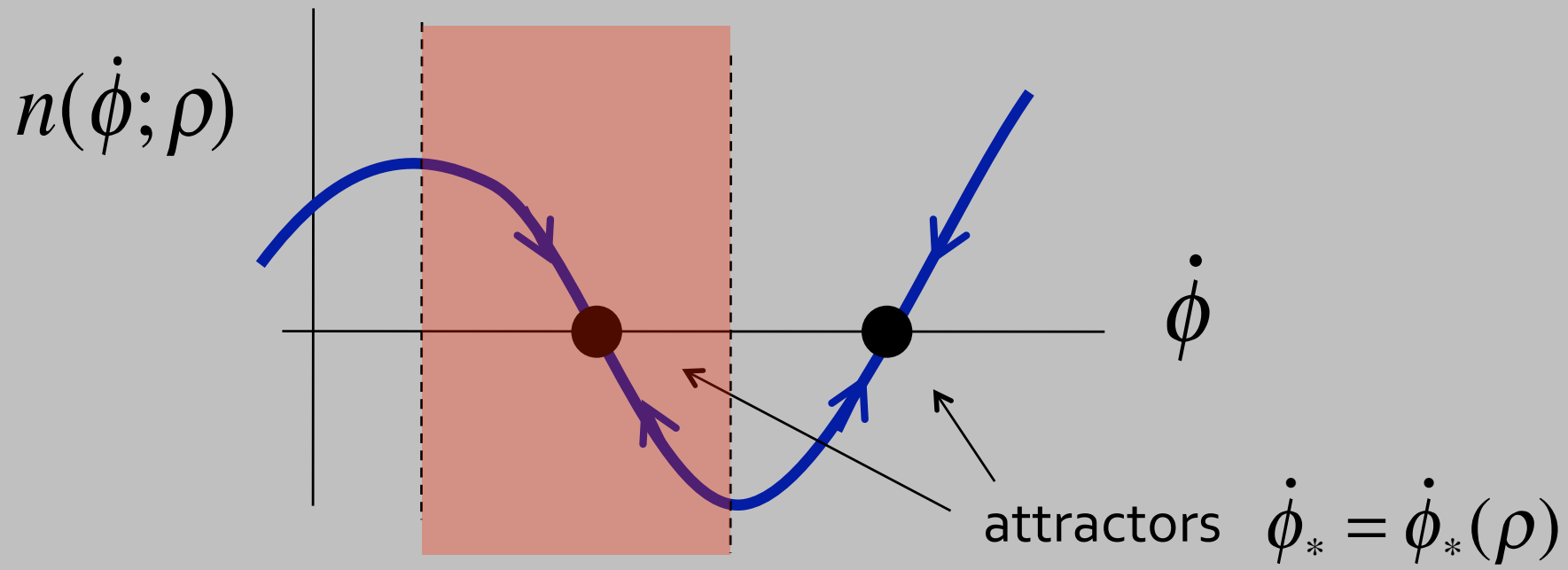
"Kinetic Braiding" $\quad \nabla\phi\,[\nabla,\nabla]\,\nabla\phi$

=> sourced by matter even if no microscopic coupling in the Lagrangian

Imperfect Dark Energy

Background cosmology (flat, homogeneous, FRW)

- Scalar Eom: $\left\{ \begin{array}{l} \nabla^\mu J_\mu = 0 \\ J_\mu = n\, u_\mu \end{array} \right\} \Longrightarrow\; n \equiv \dot\phi \left(K' + 3H\, \dot\phi\, G' \right) = \dfrac{n_0}{a^3(t)}$



Imperfect Dark Energy

one can split $\varepsilon = \varepsilon_* + \varepsilon_n$

Attractor:

Tracks matter

$\dot{\phi}_* = \dot{\phi}_*(\rho(t))$

Off-attractor:

normal (dilutes)

$w_n(w_{Matter}) > 0$

phantom behaviour $w_* < -1$
(in the stable case)

asymptotes de Sitter

($w_* \to -1$ from below)

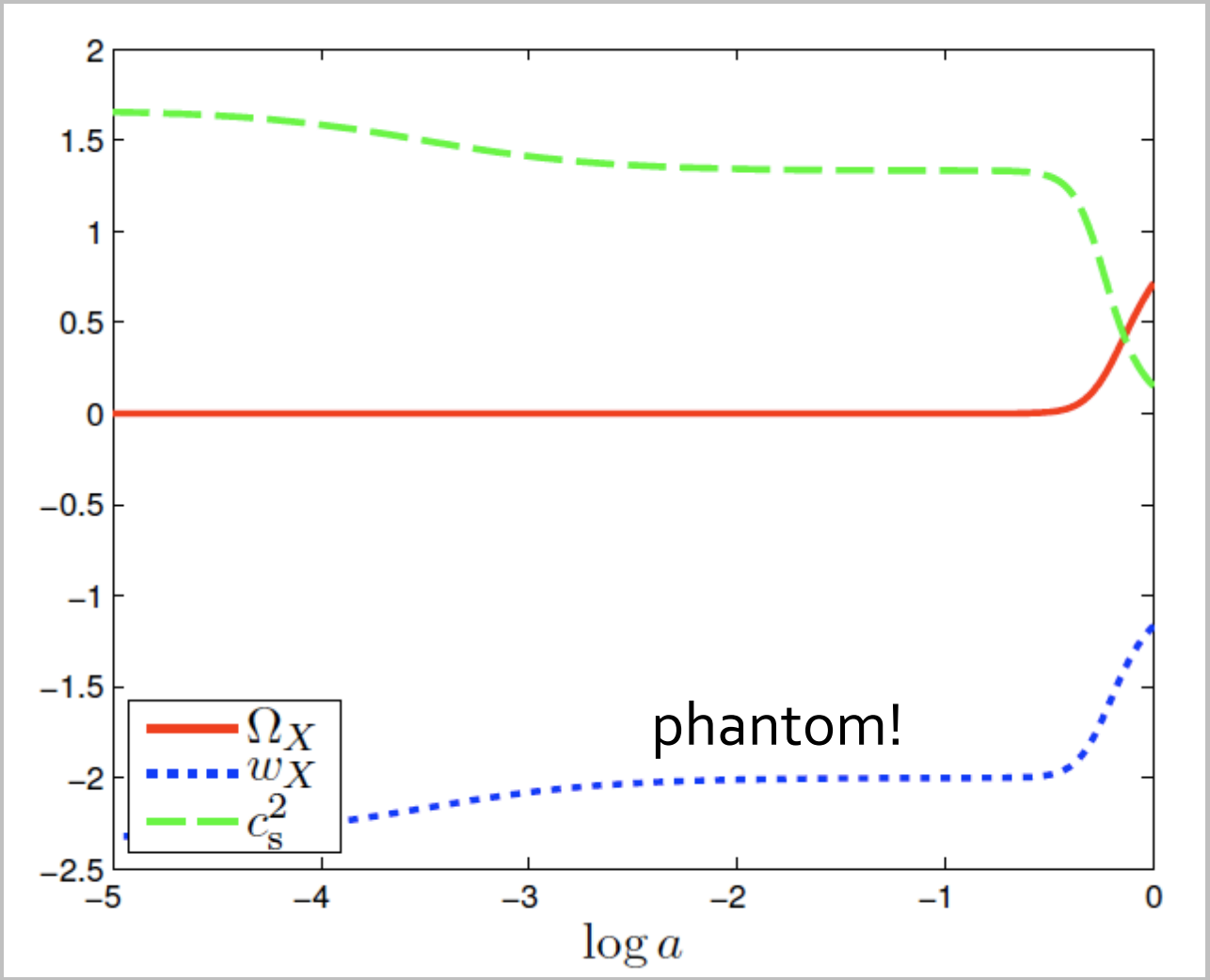
Imperfect Dark Energy

On the attractor

$$K(X) = -X$$

$$G(X) = \frac{X}{\Lambda^3}$$

$$\Lambda \sim (1000\,Km)^{-1}$$



Imperfect Dark Energy

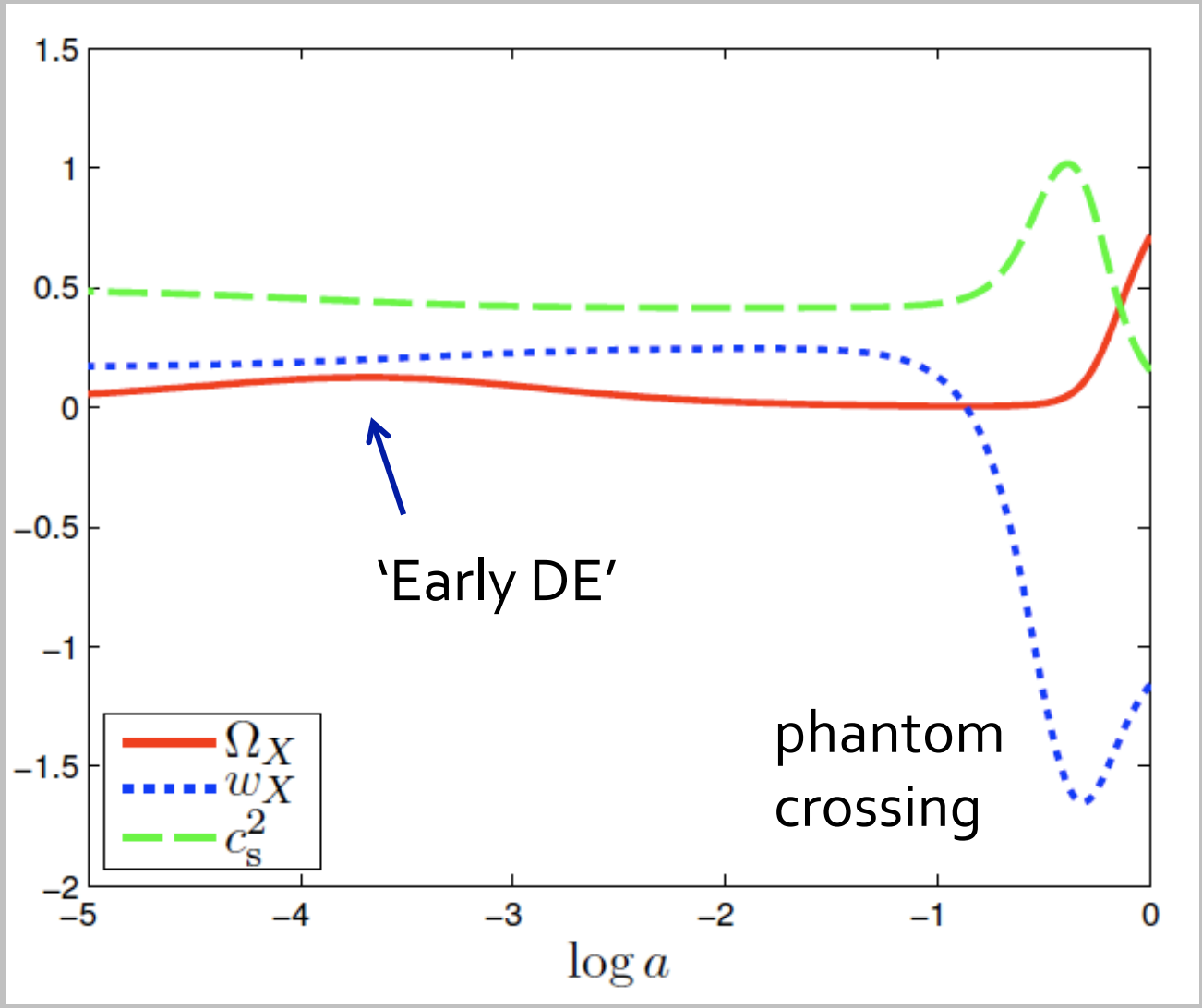
Off-attractor

Early Dark Energy

at most ~10%

@ equality

=> *n* not too large



Conclusions

- Large class of new models has been 'discovered'

- Working model of massive gravity => ??

- Working model of phantom DE

-> Generically, Early Dark Energy also

- Models with additional d.o.f. (active at large scales)
Generically, stronger Structure formation.

Main open issues:

- Can we degravitate away the CC?

- Typically low strong coupling scale, radiative stability,
UV completions, Lorentz Violation, BHs with violation of NEC, ...

Thank you!