Ginzburg Conference on Physics

May 28 - June 2, 2012
Lebedev Institute

Alexander Vikman

CERN

31.05.2012

Ginzburg Conference on Physics

May 28 - June 2, 2012
Lebedev Institute

G-Bounce

Alexander Vikman

CERN

31.05.2012

THIS TALK IS BASED ON

- ***Imperfect Dark Energy from Kinetic Gravity Braiding*** [1]
  arXiv:1008.0048, JCAP 1010:026, 2010

- ***The Imperfect Fluid behind Kinetic Gravity Braiding*** [2]
  arXiv:1103.5360, JHEP 1111 (2011) 156

- ***G-Bounce,*** [3] **arXiv:1109.1047,** JCAP 1111:021, 2011

IN COLLABORATION WITH

Cédric Deffayet,[1] Damien Easson,[3]
Oriol Pujolàs,[1,2] Ignacy Sawicki[1,2,3]

PLAN

- Motivation
- General class of models - “perfect” imperfect fluids
- G - Bounce
- Open problems

ORIGIN OF THE UNIVERSE?

- Was there a beginning of time i.e. of the quasiclassical universe? Was there a strong quantum gravity époque in our past?
- If there was a beginning, was the universe collapsing or expanding immediately afterwards?
- If the universe experienced an early period of inflation, which *all* observations currently ***perfectly*** confirm, what happened ***before inflation***? Indeed, *inflation* is not past-complete - Borde, Guth, Vilenkin (2001), *Vilenkin's talk today*

CAN ONE CONSTRUCT

A **STABLE**

(WITH REAL SOUND SPEED AND WITHOUT GHOSTS)

CLASSICAL MODEL

WHERE A

SPATIALLY FLAT

FRIEDMANN UNIVERSE

BOUNCES:

GOES FROM COLLAPSE TO EXPANSION **???**

OBSTACLE:

TO BOUNCE ONE HAS TO VIOLATE

NULL ENERGY CONDITION (NEC),

$$T_{\mu\nu} n^\mu n^\nu \geq 0$$

BUT NORMAL FIELDS AND PERFECT FLUIDS CANNOT DO IT!

go to imperfect fluids i.e. to even less canonical fields!

GO *G*!

G STANDS FOR GALILEON

Nicolis, Rattazzi , Trincherini, (2008)

In current literature: ***Galileons* =** scalar-tensor theories with

***higher derivatives* in the action**

but with **equations of motion** which are ***all*** of the

second order - NO *Ostrogradsky's* ***ghosts***

the most general theory of this type was derived

by *Horndeski (1974), and rederived by Deffayet, Gao, Steer, Zahariade (2011)*

International Journal of Theoretical Physics, Vol. 10, No. 6 (1974), pp. 363–384

Second-Order Scalar-Tensor Field Equations in a Four-Dimensional Space

GREGORY WALTER HORNDESKI

Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, Canada

Received: 10 *July* 1973

International Journal of Theoretical Physics, Vol. 10, No. 6 (1974), pp. 363–384

Second-Order Scalar-Tensor Field Equations in a Four-Dimensional Space

GREGORY WALTER HORNDESKI

Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, Canada

Received: 10 *July* 1973

$$\mathcal{L} = K + \mathcal{G}\phi^{;\mu}_{;\mu} +$$
$$+\,\mathcal{G}_2 R + \mathcal{G}_2' \left[\left(\phi^{;\mu}_{;\mu}\right)^2 - \phi^{;\nu}_{;\mu}\phi^{;\mu}_{;\nu} \right] +$$
$$+\,\mathcal{G}_3 G^{\mu}_{\nu}\phi^{;\nu}_{;\mu} - \frac{1}{6}\mathcal{G}_3' \left[\left(\phi^{;\mu}_{;\mu}\right)^3 - 3\phi^{;\lambda}_{;\lambda}\phi^{;\nu}_{;\mu}\phi^{;\mu}_{;\nu} + 2\phi^{;\mu}_{;\alpha}\phi^{;\alpha}_{;\beta}\phi^{;\beta}_{;\mu} \right]$$

Kobayashi, Yamaguchi, Yokoyama (2011)

where we have 4 free functions!

$K(\phi, X)$ and $\mathcal{G}_i(\phi, X)$

$$\mathcal{G}_i' = \frac{\partial \mathcal{G}_i}{\partial X}$$

$$X \equiv \tfrac{1}{2} g^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi$$

Thursday, May 31, 2012

WHY IS THIS *G* INTERESTING?

One can **stably violate** the most basic of the classical energy conditions-Null Energy Condition (NEC): $T_{\mu\nu}n^{\mu}n^{\nu} \geq 0$ which in cosmology reduces to: $p + \varepsilon \geq 0$ or $\dot{H} \leq 0$

Pandora's box

WHY IS THIS *G* INTERESTING?

One can **stably violate** the most basic of the classical energy conditions-Null Energy Condition (NEC): $T_{\mu\nu} n^{\mu} n^{\nu} \geq 0$ which in cosmology reduces to: $p + \varepsilon \geq 0$ or $\dot{H} \leq 0$

Pandora's box

WHY IS THIS *G* INTERESTING?

One can **stably violate** the most basic of the classical energy conditions-Null Energy Condition (NEC): $T_{\mu\nu}n^{\mu}n^{\nu} \geq 0$ which in cosmology reduces to: $p + \varepsilon \geq 0$ or $\dot{H} \leq 0$

Pandora's box

- *Healthy* and *testable* Phantom Dark Energy,

  Deffayet, Pujolas, Sawicki, AV, 2010

- *Bouncing* Cosmology for a *spatially flat* Friedmann universe

  Creminelli, Nicolis, Trincherini 2010; Easson, Sawicki, AV; Taotao Qiu, Evslin, Cai, Li, Zhang 2011

- *Super*inflation with *blue* spectra of gravity waves

  Kobayashi, Yamaguchi, Yokoyama 2010

SIMPLEST INTERESTING SUBSECTOR OF GALILEONS /HORNDESKI'S THEORIES -

Kinetic Gravity Braiding

kinetic mixing / braiding

$$S_\phi = \int \mathrm{d}^4x \sqrt{-g}\,\left[K(\phi, X) + \overset{\partial\phi}{G}(\phi, X)\,\overset{\partial g}{\Box\phi}\right]$$

***Armendariz-Picon, Damour, Mukhanov, Steinhardt* 1999/2000**

Pujolàs, *Deffayet, Sawicki, AV*, 2010

where $X \equiv \frac{1}{2} g^{\mu\nu} \nabla_\mu \phi \nabla_\nu \phi$

Minimal coupling to gravity $S_{\mathrm{tot}} = S_\phi + S_{\mathrm{EH}}$

However, derivatives of the metric are coupled to the derivatives of the scalar, provided $G_X \neq 0$

No "Galilean symmetry"! $\cancel{\partial_\mu\phi \to \partial_\mu\phi + c_\mu}$

Thursday, May 31, 2012

EQUATION OF MOTION I

$$L^{\mu\nu}\nabla_\mu\nabla_\nu\phi + (\nabla_\alpha\nabla_\beta\phi)\, Q^{\alpha\beta\mu\nu}\,(\nabla_\mu\nabla_\nu\phi) +$$
$$+Z - G_X R^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi = 0$$

Braiding

EOM is of the second order: $L_{\mu\nu}\,, Q^{\alpha\beta\mu\nu},\ Z$

constructed from field and it's first derivatives

$Q^{\alpha\beta\mu\nu}$ **is such that EOM is a 4D Lorentzian generalization of the Monge-Ampère Equation, always *linear* in** $\ddot{\phi}$

SHOULD ϕ BE FUNDAMENTAL?
NO NOT AT ALL
ϕ CAN MODEL SOME HYDRODYNAMICS !

$K(X)$ for equation of state, $G(X)$: transport coefficient

EQUATION OF MOTION II

- **Shift-Charge Noether Current: - interpret as "particle" current** J_μ

- **New Equivalent Lagrangian:** $\mathcal{P}$ **pressure!**

- **Equation of motion is a "conservation law":**

EQUATION OF MOTION II

- **Shift-Charge Noether Current: - interpret as "particle" current** J_μ

- **New Equivalent Lagrangian:** $\mathcal{P}$ **pressure!**

- **Equation of motion is a "conservation law":**

$$\boxed{\nabla_\mu J^\mu = \mathcal{P}_\phi}$$

EQUATION OF MOTION II

- **Shift-Charge Noether Current: - interpret as "particle" current** J_μ

$$J_\mu = (\mathcal{L}_X - 2G_\phi)\,\nabla_\mu\phi - G_X\nabla_\mu X$$

- **New Equivalent Lagrangian:** $\mathcal{P}$ **pressure!**

- **Equation of motion is a "conservation law":**

$$\boxed{\nabla_\mu J^\mu = \mathcal{P}_\phi}$$

EQUATION OF MOTION II

- **Shift-Charge Noether Current: - interpret as "particle" current** J_μ

$$J_\mu = (\mathcal{L}_X - 2G_\phi)\,\nabla_\mu\phi - G_X\nabla_\mu X$$

- **New Equivalent Lagrangian:** $\mathcal{P}$ **pressure!**

$$\mathcal{P} = K - 2XG_\phi - G_X\nabla^\lambda\phi\nabla_\lambda X$$

- **Equation of motion is a "conservation law":**

$$\boxed{\nabla_\mu J^\mu = \mathcal{P}_\phi}$$

IMPERFECT FLUID FOR TIMELIKE GRADIENTS

- **Four velocity** : $u_\mu \equiv \frac{\nabla_\mu \phi}{\sqrt{2X}}$ ➡ ϕ is an ***internal clock***

  Shift-symmetry
  $\phi \longrightarrow \phi + c$
  violates
  $\phi \longrightarrow -\phi$
  and introduces
  arrow of time

- **projector:** $\perp_{\mu\nu} = g_{\mu\nu} - u_\mu u_\nu$

- **Time derivative:** $(\dot{\ }) \equiv \frac{\mathrm{d}}{\mathrm{d}\tau} \equiv u^\lambda \nabla_\lambda$

- **Expansion :** $\theta \equiv \perp^\lambda_\mu \nabla_\lambda u^\mu = \dot{V}/V$

  comoving volume

EFFECTIVE MASS & CHEMICAL POTENTIAL

$$\kappa \equiv 2XG_X$$

- charge density: $n \equiv J^\mu u_\mu = n_0 + \kappa\theta$

"Braiding"

- energy density: $\mathcal{E} \equiv T^{\mu\nu} u_\mu u_\nu = \mathcal{E}_0 + \theta\dot{\phi}\kappa$
- effective mass per shift-charge / chemical potential:

$$m \equiv \left(\frac{\partial \mathcal{E}}{\partial n}\right)_{V,\phi} = \sqrt{2X} = \dot{\phi}$$

c.f. Schutz 1970

SHIFT-CURRENT AND "DIFFUSION"

"Diffusion"

$$J_\mu = n u_\mu - \frac{\kappa}{m} \perp_\mu^\lambda \nabla_\lambda m$$

§ 59, L&L, vol. 6

$$\kappa \equiv 2 X G_X$$

Is a "diffusivity"/ transport coefficient

Particle / charge current is not parallel to energy flow!

DIFFUSION OF CHARGE?

For incompressible motion $\theta \equiv 0$

equation of motion is:

$$\dot{n} = -\overline{\boldsymbol{\nabla}}_\mu \left(\mathfrak{D} \overline{\boldsymbol{\nabla}}^\mu n \right) + \mathfrak{D} a^\mu \overline{\boldsymbol{\nabla}}_\mu n$$

where the diffusion constant: $\mathfrak{D} \equiv -\dfrac{\kappa}{n_m m}$

c.f. § *59, L&L, vol. 6, p 232*

4-acceleration: $a^\mu \equiv \dot{u}^\mu$

spatial gradient: $\overline{\boldsymbol{\nabla}}_\mu \equiv \perp_\mu^\nu \nabla_\nu$

IMPERFECT FLUID ENERGY-MOMENTUM TENSOR

- **Pressure** $$\mathcal{P} = P_0 - \kappa \dot{m}$$

- **Energy Flow**

No Heat Flux!

$$q_\mu = -\kappa \perp_\mu^\lambda \nabla_\lambda m = m \perp_\mu^\lambda J_\lambda$$

- **Energy Momentum Tensor**

$$T_{\mu\nu} = \mathcal{E} u_\mu u_\nu - \perp_{\mu\nu} \mathcal{P} + 2u_{(\mu} q_{\nu)}$$

Solving for $\dot{m}$ *for small gradients or small* κ *one obtains "bulk viscosity" but change of frame results in a prefect fluid with vorticity up to* $\mathcal{O}\left(\kappa^2\right)$

ENERGY CONSERVATION IN COMOVING VOLUME

Energy conservation: $u_\nu \nabla_\mu T^{\mu\nu} = 0$

$$\mathrm{d}E = -\mathcal{P}\mathrm{d}V + m\mathrm{d}\mathcal{N}_{\mathrm{dif}}$$

Euler relation: $\mathcal{E} = mn - P_0$

Momentum conservation:

$$\perp_{\mu\nu} \nabla_\lambda T^{\lambda\nu} = 0$$

COSMOLOGY

$$q_\mu = 0 \quad \textbf{and} \quad \theta = 3H$$

Friedmann Equation:

$$H^2 = \kappa m H + \frac{1}{3}\left(\mathcal{E}_0 + \rho_{\text{ext}}\right)$$

$r_{\rm c}^{-1} = \kappa m$ **"crossover" scale in DGP**

EQUATION OF MOTION IN COSMOLOGY
(CHARGE CONSERVATION)

$$\dot{n} + 3Hn = \mathcal{P}_\phi$$

If there is shift-symmetry then

$$\mathcal{P}_\phi = 0$$

$$n \propto a^{-3}$$

ACTION FOR THE COSMOLOGICAL PERTURBATIONS

$$S_2 = \int \mathrm{d}^3x \, \mathrm{d}t \, A \left[\dot{\zeta}^2 - \frac{c_{\mathrm{s}}^2}{a^2} \left(\partial_i \zeta \right)^2 \right]$$

where $$A = \frac{X a^3}{(H - m\kappa/2)^2} D$$

$$D = \frac{\mathcal{E}_m - 3H\kappa}{m} + \frac{3}{2}\kappa^2$$

Controls “ghosts” $D > 0$ No ghosts!

SOUND SPEED

$$c_{\rm s}^2 = \frac{\mathcal{P}_m + 2\dot{\kappa} + \kappa\left(4H - \kappa m/2\right)}{\mathcal{E}_m - 3\kappa\left(H - \kappa m/2\right)} \neq \frac{\dot{\mathcal{P}}}{\dot{\mathcal{E}}}$$

The relation between the equation of state, the sound speed and the presence of ghosts is very different from the k-*essence* & perfect fluid.

A manifestly stable *Phantom* ($w_X < -1$) is possible even with a *single* degree of freedom and *minimal* coupling to gravity

G BOUNCE IDEA I

- **Consider matter with constant equation of state - radiation, dust, spatial curvature etc...** $p_{\rm ext} = w\rho_{\rm ext}$ **with** $w = {\rm const}$
- **Shift-symmetric Lagrangian for the scalar field** $K\left(\cancel{\phi}, X\right)$ **and** $G\left(\cancel{\phi}, X\right)$
- **Phase space is two dimensional** $\left(m, \rho_{\rm ext}\right)$
- **Go to new coordinates** $\left(m, H\right)$ **by solving the Friedmann equation**
- **Integral of motion i.e. 1st integral**

$$I\left(m, H\right) = \frac{n^{1+w}}{\rho_{\rm ext}}$$

G BOUNCE IDEA II

- In new coordinates (m, H) at $H = 0$ pose conditions

$$\rho_{\rm ext} > 0,\ D > 0,\ \dot{H} > 0,\ c_{\rm s}^2 > 0$$

- These conditions are on the range of chemical potential Δm and on the equation of state $K(m)$ along with the transport coefficient $\kappa(m)$ or on $K(X)$ and $G(X)$

"Healthy" Bounce!

IS IT POSSIBLE TO SATISFY ALL THESE CONDITIONS ?


YES WE CAN


We Can Do It!
WAR PRODUCTION CO-ORDINATING COMMITTEE

SIMPLE HIERARCHY

if $K(m)$ and $\kappa(m)$ satisfy the hierarchy:

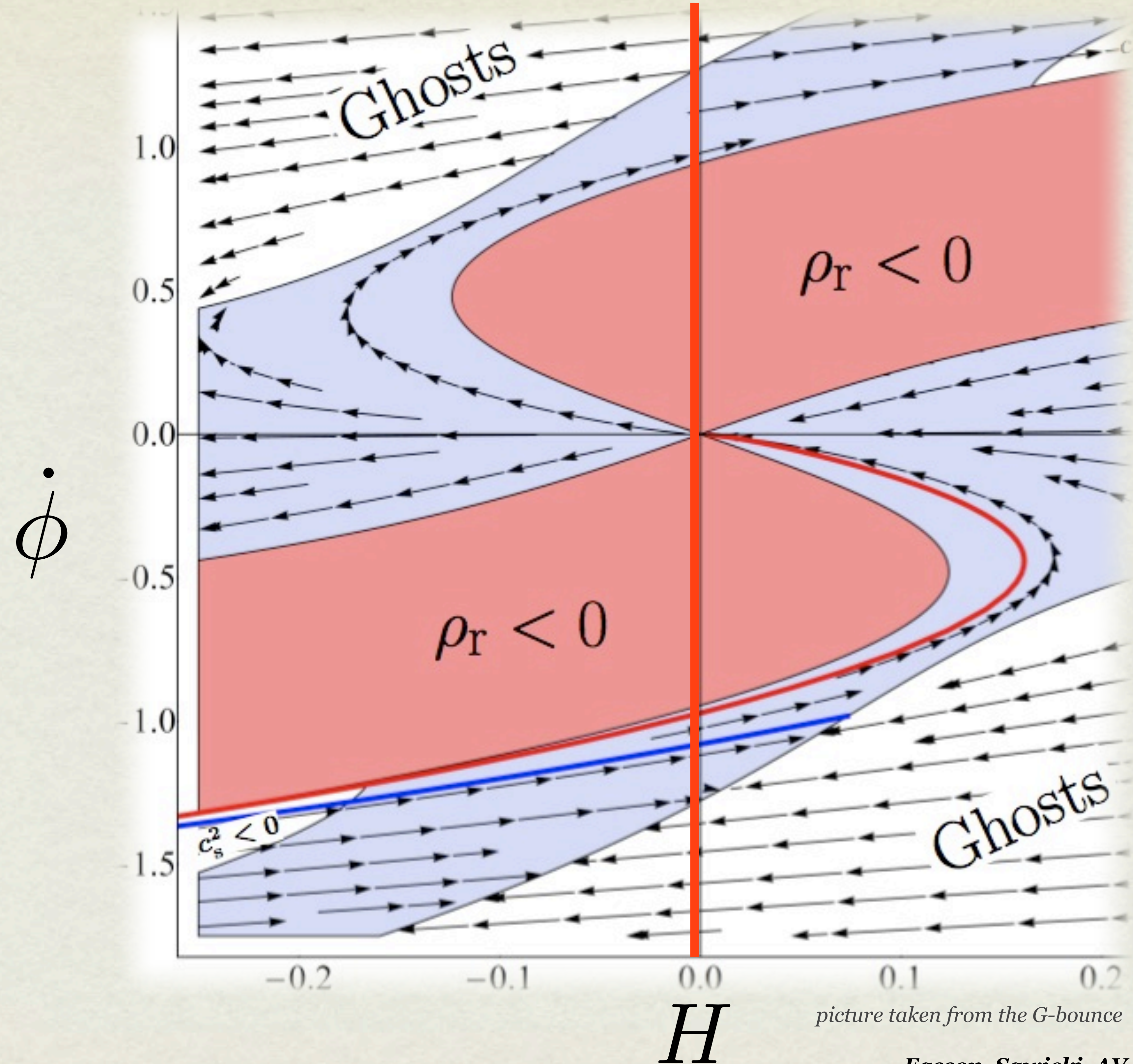
$$K > mK_m > \frac{1}{2}(m\kappa)^2 > 0 > \frac{1}{2}m^2 K_{mm} > -\frac{3}{4}(m\kappa)^2$$

does not depend on external equation of state w !

then at $H = 0$:

$$\rho_{\mathrm{ext}} > 0,\ D > 0,\ \dot{H} > 0,\ c_{\mathrm{s}}^2 > 0$$

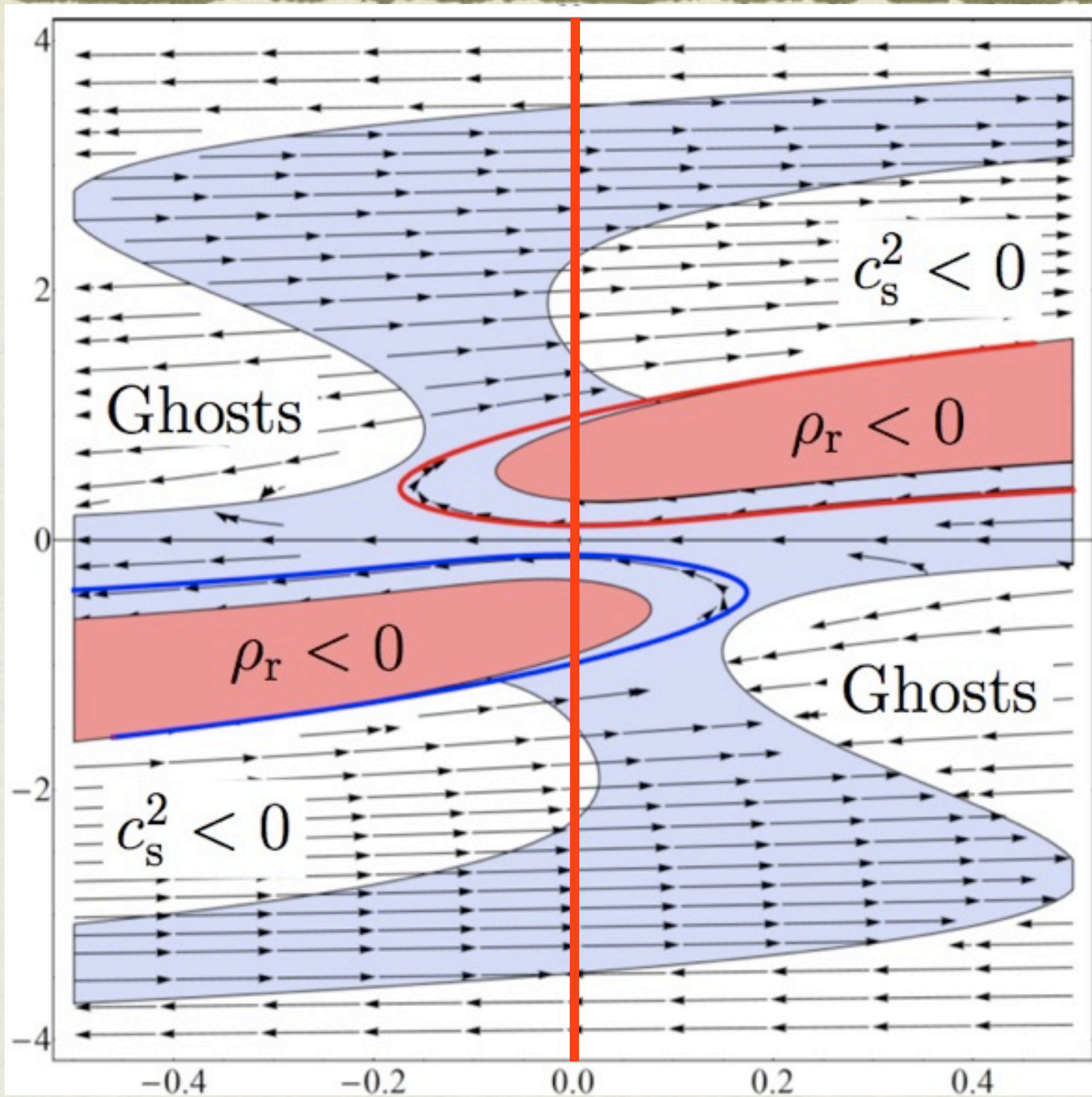
"Healthy" Bounce!



picture taken from the G-bounce

Easson, Sawicki, AV (2011)

G-Bounce: $\mathcal{L} = X - \alpha X^3 + \varkappa X \Box \phi$ **+ Radiation** $\rho_{\rm r}$



$\dot{\phi}$

H

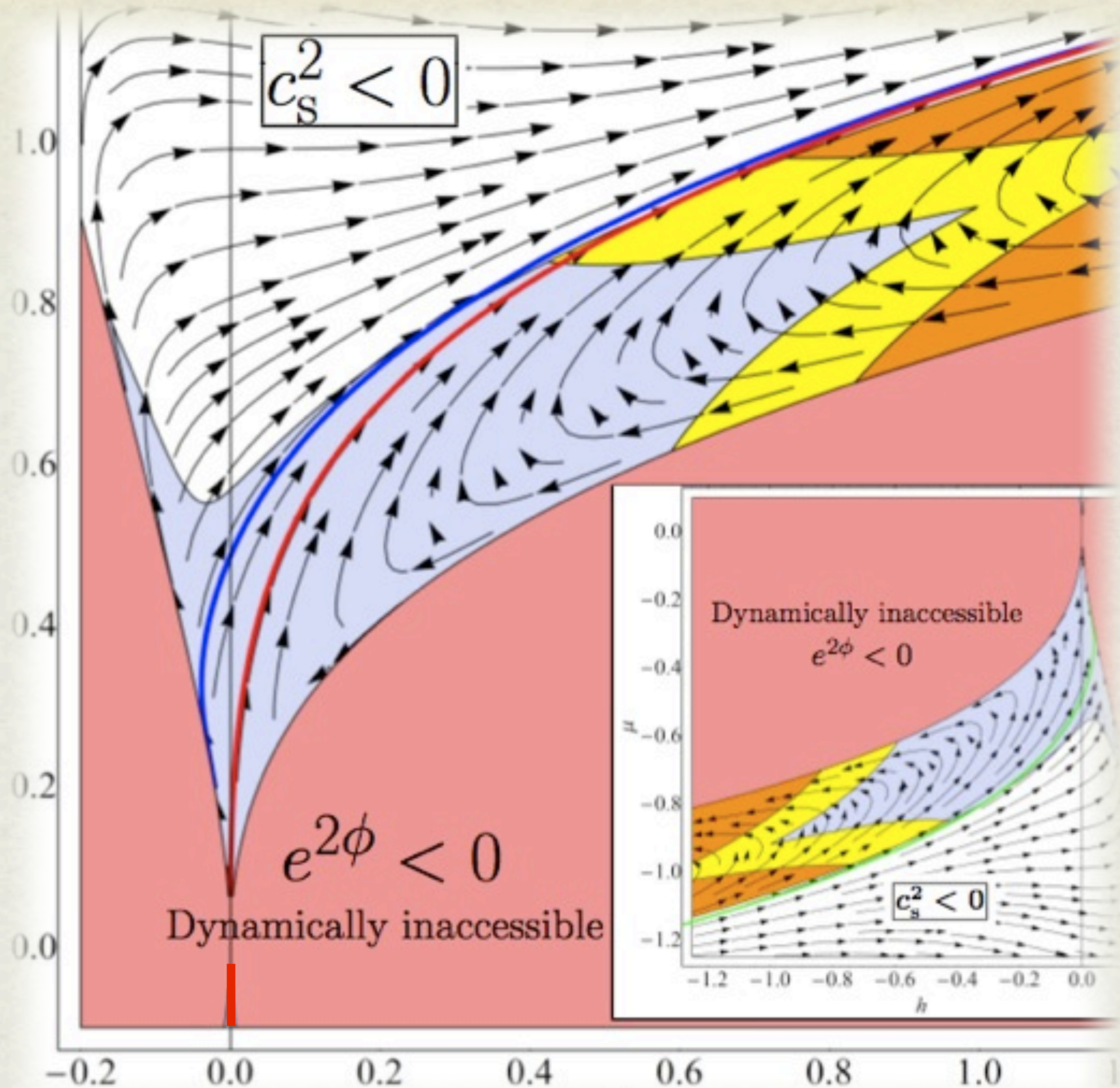
picture taken from the G-bounce

Easson, Sawicki, AV (2011)

$\kappa = 2\beta X + \gamma X^2 \quad K = -\Lambda + X - X^3$ **+ Radiation** ρ_r

CAN ONE GENERALIZE THIS APPROACH FOR SYSTEMS WITHOUT SHIFT-SYMMETRY ?

$\dot{\phi}$



H

picture taken from the G-bounce

***Galilean Genesis:** Creminelli, Nicolis, Trincherini (2010)*

wrong “ghosty” sign

“Conformal Galileon”:

$$\mathcal{L} = -2f^2 e^{2\phi} X + \frac{2f^3}{\Lambda^3} X^2 + \frac{2f^3}{\Lambda^3} X \Box \phi$$

where: $X \equiv \frac{1}{2} g^{\mu\nu} \nabla_\mu \phi \nabla_\nu \phi$ and Λ, f are constants

OPEN QUESTIONS

- Strong coupling?
- Possible anisotropy? Too strong tachyonic / Jeans instabilities?
- Can one arrange a cyclic i.e. oscillating evolution?
- Can one avoid all singularities and troubles for the past?
- Perturbations?
- Any *realistic* scenarios? Smooth transition to standard cosmology and inflation?

THANKS A LOT FOR YOUR ATTENTION!