Modified Gravity, Vector Fields, and Galileons

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Based on works with:

Matthew Hull, Marco Crisostomi; Kazuya Koyama, Gustavo Niz, Ivonne Zavala

Dark energy Dark energy

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- Why (scalar masses receive large corrections) ions at solar system scales?

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 - Why don't we see them with observations at **solar system scales**?

3?

- For scalars: What's keeping their mass **small**?
- (scalar masses receive large corrections)
- Why (scalar masses e effern with observations at solar system scales?



• We need set all the mass the acceleration symmetry: $\pi \to \pi + c + b_{\mu}x^{\mu}$

• Why don't we see them with observations at **solar system scales**?

<u>**Embedding Galileo**</u> <u>Given these considerations, is it possib</u> Dark energy Given these considerations, is it ▷ Consistency conditions (abser strai Consistency conditions Ster Scenarios: Possible realizations straints on the structure urrent acceleration is compatible with positive co or Centracceleration is no supatible i wet wiplo sitiste ve source inne. > Implessive fine tipe is required > Implessive for an eworld scenar What on o test lat o tea uses neve fields besides i dieste in streivity tovitrive activity dataes never die las besides bister averagie versatiere activity and, _t (\$\alpha] Colorith appropriate interactions © Goldstone bosons of broken s First exampleGod (Godfferstrive), d.o.f.'s control the cosmolor (Solutions) as Goldsones of broken symmetries (see e.g. [Goon et al]) sonamics (every reave to tional d.o.f.'s control the Cosmo (See e.g. [Goon et al]) sonamics (every reave to tional d.o.f.'s control the Cosmo (See e.g. [Goon et al]) sonamics (every reave to to the Cosmo (See e.g. [Goon et al]) sonamics • In a suitable decoupling limit, the m: Why differ we neveral these new d.o.f.'s at solar systems scales called bagates self-interaction oblems: em: Wyhylidudtnye weveeltelesenese dewf.d.a.f.selar system scales? scales? em: Why didn't we reveal these new d.o.f.'s at solaresystem scalaself-in • We need pervicing the fields detains and symmetries fare important Challengingecomes (isin • Why don't we see them with observations at **solar system scales**? res Vectors breakin

What's the role of vector fields for modified gravity ?

Can they have anything to do with cosmic acceleration and screening mechanisms?

- Vectors play role in different scenarios
 - Original Kaluza-Klein idea: get electromagnetism from 5d Einstein gravity



- Brane-world models: DBI action contains world-volume vector fields
- Other well-known models: TeVeS, Einstein Ether etc
- Vectors and dark energy: [Koivisto, Mota; Uzan et al,..]

What's the role of vector fields for modified gravity ?

Can they have anything to do with cosmic acceleration and screening mechanisms?

- ► Vectors **less explored** in dark energy models exploiting derivative self-interactions
 - Sake of simplicity (scalar-tensor theories are already complicated enough)
 - They don't couple to sources
 - They appear at least quadratically in the action
- But they can have cosmological consequences in modified gravity Strongly coupled around self-accelerating solutions in massive gravity
- ► Vector Horndeski is simple:

Most general theory with gauge symmetry, coupling vector to gravity, with second order eqs of motion

$$\Delta \mathcal{L} = \sqrt{-g} \,\epsilon^{\mu_1 \mu_2 \mu_3 \mu_4} \epsilon_{\nu_1 \nu_2 \nu_3 \nu_4} F_{\mu_1 \mu_2} F^{\nu_1 \nu_2} R_{\mu_3 \mu_4}^{\nu_3 \nu_4}$$

Screening mechanisms Galileons from broken gauge invariance $\mathbf{O}\mathbf{V}$ • Chamaleon, Vainshtein mechanism Galileons Trenk eresting for

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- Scalars with appropriate derivative self-interactions rive acceleration Anceleration of the lice weekeeness the appreciate of derivative self-in Galileons Nicolis et all

 - Stigns [Nicolis et al] Stigns coupling effects income acceleration: $\pi \propto t^2$ Self-interactions drive cosmic acceleration: $\pi \propto t^2$ Simplest realization of Vainspropriate interactions At small scales (within r_V) non-linear calculations drive cosmic annear and interaction: Scalar Titch force gets of the scales (within r_V) non-linear self-i New gravitational d.o.f. s control the cosmological dyna at large scales

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- Vectors are able to mediate long • Vectors are abl**Second(singleg)** remaindered: think to electric break symmetry through interactions including derivatives
- Longitudinal polarization of vector mediates dark energy Task: build vector theory that is ghost-free and interest • Vectors have been important in the history of modifications of GR, since the (GT, Heisanburgays (Kaluza-Klein, Einstein-Aether, TeVeS)
- Vectors are able to mediate long range forces: think to electromagnetism!
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 Vectors are able to mediate long range forces: think to electromagnetism?
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 A small mass m_A or small vector couplings can be technically natural.
 Task: build vector theory that is ghost-free and interesting [GT, Heisenberg]
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 Break gauge symmetry: the longitudinal vector polarization gets dynamical
- and acquires Galileon interactions in a decoupling limit.
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vectors opeakings abenan symmetry • A small myserie practice of the light synchronically natural. Longitudinal polarization of vector mediates dark energy Longitudinal polarization of vector mediates dark energy Task: buildet one chare been important instighting of an incertain of the state of etism! $\mathcal{L}_{(0)} = \nabla ectors are able to mediate long range forces: think to electromagnetism!$ netism! Vectors are able to mediate long range forces: think to electromagnetism! łamical • A small mass m_A or small vector couplings can be **technically natural**. cal. $\underline{A} = \underline{small}_{2} \underline{A}_{\mu}^{\alpha} \underline{A}_{\mu}^{\alpha} \underline{A}_{\rho}^{\alpha} \underline{A}_{\nu}^{\alpha} \underline{A}_{\nu}^$ Task: m_{build} vector theory that is ghost-free and interesting **Break gayge, Strakerysets and get and acquires Galileon** interactions in a decoupling limit. Nice feature: Metti figura Preakter introduce ghosts: the time-component A_0 remains non-dynamical and acquires Galileon transformed the component A_0 remains non-dynamical of experience prosesses the time-component A_0 remains non-dynamical Metti figura introduce ghosts: the time-component A_0 remains non-dynamical Netti figura introduce ghosts introduce the time-component A_0 remains non-dynamical Netti figura introduce ghosts introduce the time-component A_0 remains non-dynamical Netti figura introduce ghosts introduce the time-component A_0 remains non-dynamical Netti figura introduce figure introduce the time-component A_0 remains non-dynamical Netti figure introduce figure introduce the time-component A_0 remains non-dynamical Netti figure introduce figure introduce the time-component A_0 remains non-dynamical Netti figure introduce figure introduce the time-component A_0 remains non-dynamical Netti figure introduce figure introduce the time-component A_0 remains non-dynamical Netti figure introduce figure introduce the time-component A_0 remains non-dynamical Netti figure introduce figure introduce the time-component A_0 remains non-dynamical Netti figure introduce figure introduce the time-component A_0 remains non-dynamical Netti figure introduce figure introduce the time-component A_0 remains non-dynamical introduce figure introduce fig • **Nice feature**: The full theory **Scripting variable vertex beyond decoupling limit**! The full theory is relatively easy to study – also **beyond decoupling limit**! Pbgsibily theory is relatively easy to study – also beyond decoupling limit! The vector longitudinal polarization π is dynamical Nice for the vector longitudinal potentization π is the sectors. The full the vector longitudinal potential control of the vectors vectors. The full the vector of the provided of the provided of the vectors of the Possibly allout to istrong for the synthese of Possibly, deie Check, what happens coupling to other fields

Vector Galileons

Motivations

- ▶ Relation with Galileons: possibly share some of the nice features mentioned above
- ► Galileons from broken symmetries : **analogy with massive gravity**.
 - Opportunity to understand (some of) its features in a simpler set-up

► Moreover

- Easier to study **dynamics of perturbations around cosmological space-times**, outside decoupling limit
- **Higgs mechanism**: spontaneous symmetry breaking leads to vector galileons

Solution of the second of the

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(quad) where $\mathcal{L}_{E(\mu uad)}^{(quad)}$ is the expansion of the Einstein-Hilbert action at quadratic order, and the effective Planck scale is given by present of the Einstein-Hilbert action at quadratic order, and the effective Planck scale is given by present of the Einstein-Hilbert action at quadratic order, and the effective Planck scale is given by present of the Einstein-Hilbert action at quadratic order, and the effective Linearszed t Inearized fluctuations around de Sitter (2 Inearized • Tensor Fluctuations

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• Vector Fluctuation

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again, similar problems as in other models

Generalizations: going beyond time-like vector background

... but then one has to be careful of not inducing spatial anisotropies, so we need to keep the theory simple ...

Couple gauge potential A_{μ} to curvature $R_{\mu\nu}$

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{Pl}^2}{2} R - \frac{1}{4} F^2 - \frac{1}{2} \left(m^2 + \xi R \right) A_{\mu} A^{\mu} \right]$$

Break the conformal invariance of Maxwell eqs to get interesting cosmology:

Magnetogenesis [Turner, Widrow]

Magnetic field magnitude: $|ec{B}|^2~\propto~a^{-5+\sqrt{1-48\,\xi}}$

Couple gauge potential A_{μ} to curvature $R_{\mu\nu}$

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{Pl}^2}{2} R - \frac{1}{4} F^2 - \frac{1}{2} \left(m^2 + \xi R \right) A_{\mu} A^{\mu} \right]$$

► Vector inflation [Golovnev, Mukhanov, Vanchurin; Armendariz-Picon,], FRW cosmology from triplet of vectors each pointing in different spatial direction $A_{\mu}^{(1)} = (0, a(t) \mathcal{B}(t), 0, 0) ; A_{\mu}^{(2)} = (0, 0, a(t) \mathcal{B}(t), 0) ; A_{\mu}^{(3)} = (0, 0, 0, a(t) \mathcal{B}(t))$

... or large number of vectors with random directions...

Couple gauge potential A_{μ} to curvature $R_{\mu\nu}$

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{Pl}^2}{2} R - \frac{1}{4} F^2 - \frac{1}{2} \left(m^2 + \xi R \right) A_{\mu} A^{\mu} \right]$$

▶ <u>Vector inflation</u>

 $A_{\mu}^{(1)} = (0, a(t) \mathcal{B}(t), 0, 0) \quad ; \quad A_{\mu}^{(2)} = (0, 0, a(t) \mathcal{B}(t), 0) \quad ; \quad A_{\mu}^{(3)} = (0, 0, 0, a(t) \mathcal{B}(t))$

Choose
$$\xi = -1/6$$
.
Equations of motion:
 $H^2 = \frac{1}{2M_{Pl}^2} \left[\dot{\mathcal{B}}^2 + m^2 \, \mathcal{B}^2 \right]$
 $\ddot{\mathcal{B}} + 3 H \, \dot{\mathcal{B}} + m^2 \, \mathcal{B} = 0$

Very similar to chaotic inflation

Couple gauge potential A_{μ} to curvature $R_{\mu\nu}$

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{Pl}^2}{2} R - \frac{1}{4} F^2 - \frac{1}{2} \left(m^2 + \xi R \right) A_{\mu} A^{\mu} \right]$$

Vector inflation

$$A^{(1)}_{\mu} = (0, a(t) \mathcal{B}(t), 0, 0) \quad ; \quad A^{(2)}_{\mu} = (0, 0, a(t) \mathcal{B}(t), 0) \quad ; \quad A^{(3)}_{\mu} = (0, 0, 0, a(t) \mathcal{B}(t))$$

Interesting:

- Simple alternative to scalar-field inflation!
- Small violation of isotropy can be easily generated, by coupling N vectors
- Cosmological perturbations have specific features: coupling between modes at linearized level, anisotropic stress etc etc
- Can be used for dark energy as well

Couple gauge potential A_{μ} to curvature $R_{\mu\nu}$

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{Pl}^2}{2} R - \frac{1}{4} F^2 - \frac{1}{2} \left(m^2 + \xi R \right) A_{\mu} A^{\mu} \right]$$

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But:

This scenario has ghost instabilities [Himmetoglu, Contaldi, Peloso]

maybe not surprising, since the EOMs are higher order

Way out to resurrect the model

Use vector galileons

Add derivative ''counterterms'' that make the EOMs second order

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{Pl}^2}{2} R - \frac{1}{4} F^2 - \frac{1}{2} \left(m^2 + \xi R \right) A_\mu A^\mu + \xi \left[(\nabla_\mu A^\mu)^2 - \nabla_\mu A_\nu \nabla^\mu A^\nu \right] \right]$$

Such counterterms are total derivatives in flat space

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{Pl}^2}{2} R - \frac{1}{4} F^2 - \frac{1}{2} \left(m^2 + \xi R \right) A_\mu A^\mu + \xi \left[(\nabla_\mu A^\mu)^2 - \nabla_\mu A_\nu \nabla^\mu A^\nu \right] \right]$$

The theory is still quadratic in the fields vector inflation can be studied as Mukhanov's scenario

The background equations are:

$$H^{2} = \frac{1}{2M_{Pl}^{2}} \left[\dot{\mathcal{B}}^{2} + \left(m^{2} + (1 + 6\xi)H^{2} \right) \, \mathcal{B}^{2} + 2(1 + 4\xi) \, \dot{\mathcal{B}} \, \mathcal{B} \, H \right]$$
$$\ddot{\mathcal{B}} + 3 \, H \, \dot{\mathcal{B}} + \left[m^{2} + H^{2}(2 + \xi(6 - 4\epsilon) - \epsilon)) \right] \, \mathcal{B} = 0$$

Cosmological perturbations don't have previously found ghosts. Still checking the details...

Conclusions

- ▶ Vector Galileons allow to get galileons as Goldstone bosons of U(1) gauge symmetry breaking operators.
- ► They represent a **concrete**, **simple setting** for studying field theory and cosmology set-ups enjoying galileon symmetries in appropriate limits
- ► They share some of the **features** (and problems) with systems like massive gravity. Accelerating solutions driven by time-like vectors have strong coupling problems.
- Given the simplicity of the set-up, cosmology can be studied relatively easily, including possibilities so far unexplored:
 - anisotropic field configurations, that leads to (quasi)isotropic FRW metric
 - stability of configurations with vectors non-minimally coupled with curvature