Dynamics of Self-Gravitating Media and Dark Energy

Luigi Pilo

University of L'Aquila (Italy)
&
Laboratori Nazionali del Gran Sasso (INFN)

based on:
JCAP 1709 (2017) 09 036 arXiv:1704.0322
PRD D98 (2018) 6 064016 arXiv: 1711.10424
JCAP 1901 (2019) 01 057 arXiv: 1712.04827

in collaboration with M. Celoria and D. Comelli

What if Dark Energy is not a cosmological constant ?

Lots of proposal for dark energy/MG

Limited number of observables will be available

What if Dark Energy is not a cosmological constant ?

Lots of proposal for dark energy/MG

Limited number of observables will be available

- no sign of strong coupling for the new DoF

What if Dark Energy is not a cosmological constant ?

Lots of proposal for dark energy/MG

Limited number of observables will be available

- no sign of strong coupling for the new DoF
- speed of gravity close to c

What if Dark Energy is not a cosmological constant ?

Lots of proposal for dark energy/MG

Limited number of observables will be available

- no sign of strong coupling for the new DoF
- speed of gravity close to c

Goal

Build a sufficient general effective description of DE

based on symmetries

Starting point: symmetries and fields

Basic assumption: action principle and diff invariance

Starting point: symmetries and fields

Basic assumption: action principle and diff invariance

If the metric is the only field $\Rightarrow$ GR and 2 DoF

Starting point: symmetries and fields

Basic assumption: action principle and diff invariance

If the metric is the only field $\Rightarrow$ GR and 2 DoF

adding fields $\Rightarrow$ more DoF

Starting point: symmetries and fields

Basic assumption: action principle and diff invariance

If the metric is the only field $\Rightarrow$ GR and 2 DoF

adding fields $\Rightarrow$ more DoF

Simplest option: scalar fields minimally coupled to gravity

Starting point: symmetries and fields

Basic assumption: action principle and diff invariance

If the metric is the only field $\Rightarrow$ GR and 2 DoF

adding fields $\Rightarrow$ more DoF

Simplest option: scalar fields minimally coupled to gravity

Internal symmetries

Starting point: symmetries and fields

Basic assumption: action principle and diff invariance

If the metric is the only field $\Rightarrow$ GR and 2 DoF

adding fields $\Rightarrow$ more DoF

Simplest option: scalar fields minimally coupled to gravity

Internal symmetries

Four scalars with shift symmetry $\varphi^A \quad \rightarrow \quad \varphi^A + c^A \qquad A = 0, 1, 2, 3$

Starting point: symmetries and fields

Basic assumption: action principle and diff invariance

If the metric is the only field $\Rightarrow$ GR and 2 DoF

adding fields $\Rightarrow$ more DoF

Simplest option: scalar fields minimally coupled to gravity

Internal symmetries

Four scalars with shift symmetry $\varphi^A \quad \rightarrow \quad \varphi^A + c^A \qquad A = 0, 1, 2, 3$

With four scalars their eqs of motion $\Leftrightarrow$ $\nabla^\nu T_{\mu\nu} = 0$

Starting point: symmetries and fields

Basic assumption: action principle and diff invariance

If the metric is the only field $\Rightarrow$ GR and 2 DoF

adding fields $\Rightarrow$ more DoF

Simplest option: scalar fields minimally coupled to gravity

Internal symmetries

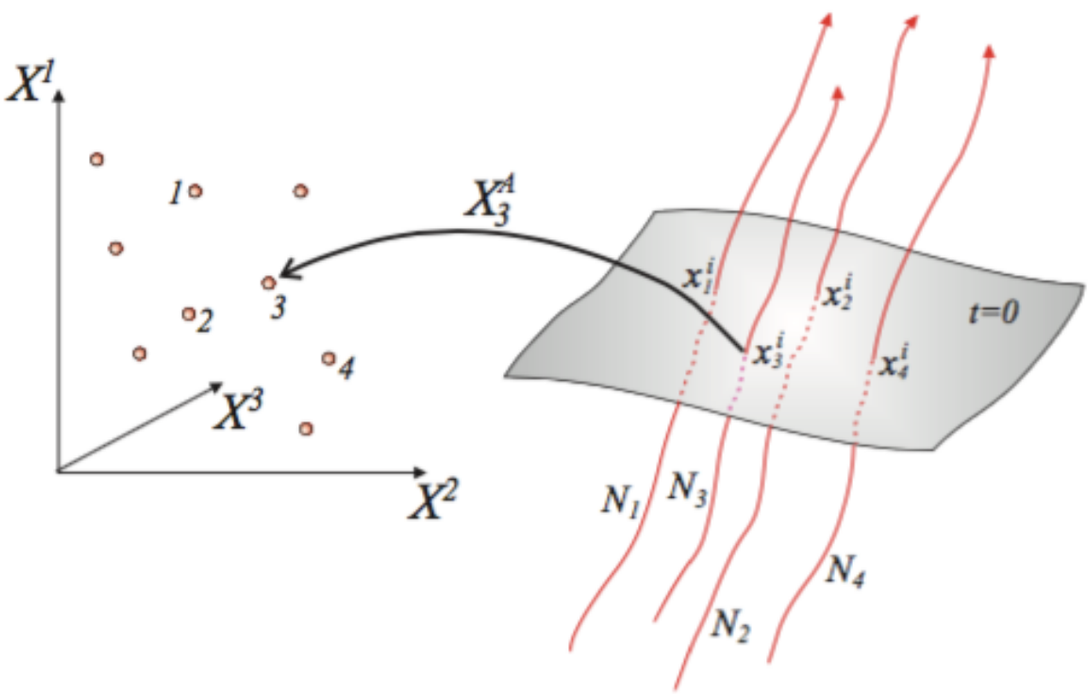
Four scalars with shift symmetry $\varphi^A \quad \rightarrow \quad \varphi^A + c^A \qquad A = 0, 1, 2, 3$

With four scalars their eqs of motion $\Leftrightarrow$ $\nabla^\nu T_{\mu\nu} = 0$

rotational invariance $\varphi_a \quad \rightarrow \quad \mathcal{R}^a_b \varphi_b \qquad a = 1, 2, 3$

Effective description of the low energy dynamics of a self-gravitating medium minimally coupled with gravity

Basic variables: four scalar fields

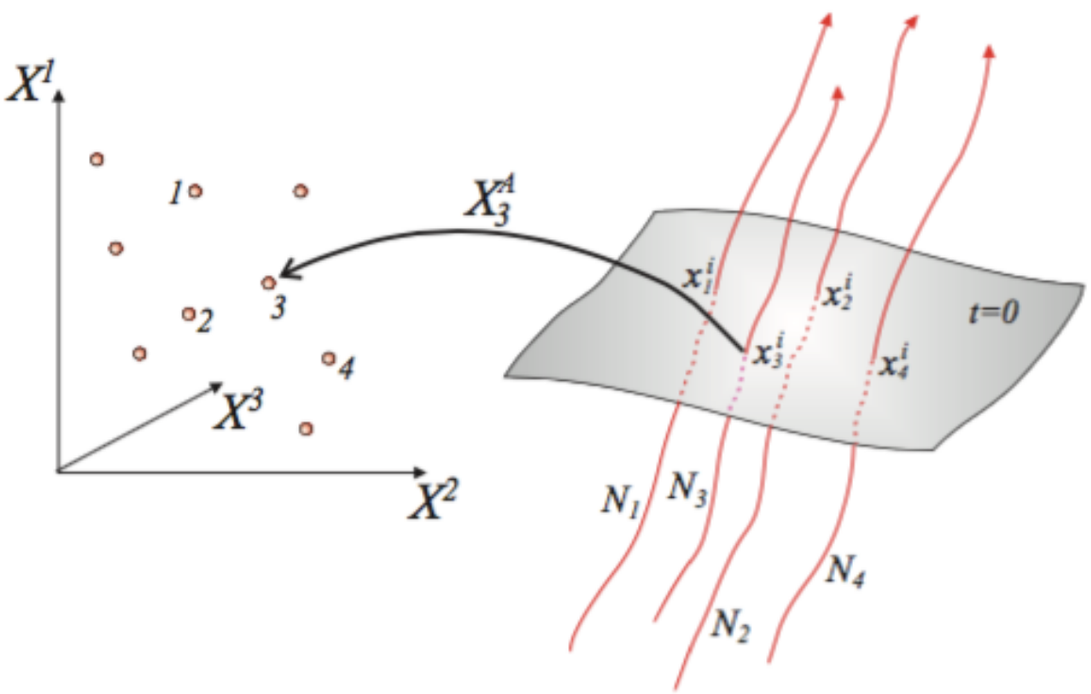


$\varphi^a = X^a \qquad a = 1, 2, 3$ spatial coordinates

φ^0 medium's clock

Effective description of the low energy dynamics of a self-gravitating medium minimally coupled with gravity

Basic variables: four scalar fields



$\varphi^a = X^a$ $\quad a = 1, 2, 3$ spatial coordinates

φ^0 medium's clock

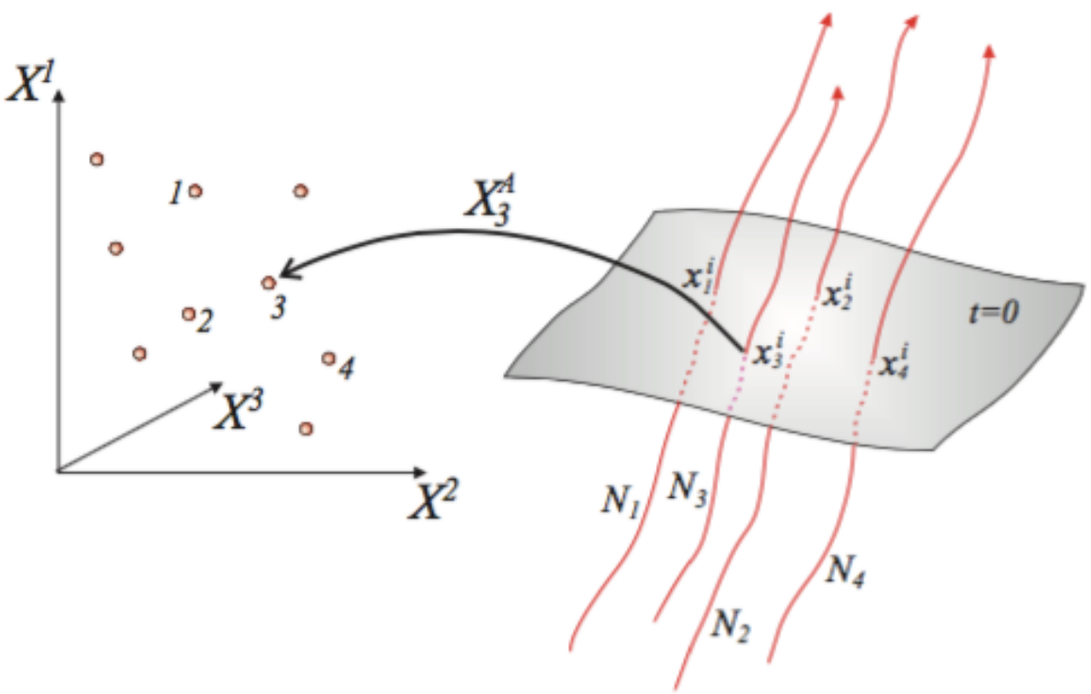
The presence of the medium breaks spontaneously Lorentz: scalars fluctuate around non-trivial configurations

$$\varphi^a = x^a + \pi^a$$

$$\varphi^0 = \phi(t) + \pi^0$$

Effective description of the low energy dynamics of a self-gravitating medium minimally coupled with gravity

Basic variables: four scalar fields



$\varphi^a = X^a$ $\quad a = 1, 2, 3$ spatial coordinates

φ^0 medium's clock

The presence of the medium breaks spontaneously Lorentz: scalars fluctuate around non-trivial configurations

$$\varphi^a = x^a + \pi^a$$

$$\varphi^0 = \phi(t) + \pi^0$$

fluctuations are the Goldstone bosons (phonons) of broken translations

$$S = M_{Pl}^2 \int d^4x \, \sqrt{-g} \, R + \int d^4x \sqrt{-g} \, U(\partial\varphi)$$

$$S = M_{Pl}^2 \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U(\partial\varphi)$$

Perfect fluids

$U(X)$ $\quad X = g^{\mu\nu}\partial_\mu\varphi^0\partial_\nu\varphi^0$ $\quad \mathcal{V}^\mu = -\frac{\partial^\mu\varphi^0}{\sqrt{-X}}$ **shift symmetric k-essence**

$U(b,Y)$ $\quad Y = u^\mu\partial_\nu\varphi^0$ $\quad b = \det\left(g^{\mu\nu}\partial_\mu\varphi^a\partial_\nu\varphi^b\right)^{1/2}$ $\quad u^\mu = -\frac{\epsilon^{\mu\nu\alpha\beta}}{6\,b\sqrt{-g}}\epsilon_{abc}\,\partial_\nu\varphi^a\,\partial_\alpha\varphi^b\,\partial_\beta\varphi^c$

$$T_{\mu\nu} = p g_{\mu\nu} + (\rho + p) u_\mu u_\nu$$

$$\rho = -U + Y\, U_Y$$

$$p = U - b\, U_b$$

$$S = M_{Pl}^2 \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U(\partial\varphi)$$

Perfect fluids

$U(X)$ $\quad X = g^{\mu\nu}\partial_\mu\varphi^0\partial_\nu\varphi^0$ $\quad \mathcal{V}^\mu = -\frac{\partial^\mu\varphi^0}{\sqrt{-X}}$ **shift symmetric k-essence**

$U(b,Y)$ $\quad Y = u^\mu\partial_\nu\varphi^0$ $\quad b = \det\left(g^{\mu\nu}\partial_\mu\varphi^a\partial_\nu\varphi^b\right)^{1/2}$ $\quad u^\mu = -\frac{\epsilon^{\mu\nu\alpha\beta}}{6\,b\sqrt{-g}}\epsilon_{abc}\,\partial_\nu\varphi^a\,\partial_\alpha\varphi^b\,\partial_\beta\varphi^c$

$$T_{\mu\nu} = p g_{\mu\nu} + (\rho + p) u_\mu u_\nu$$

$$\rho = -U + Y\, U_Y$$

$$p = U - b\, U_b$$

Fluid-Superfluid

$U(b,Y,X)$ $\quad T_{\mu\nu} = (U - bU_b)g_{\mu\nu} + (YU_Y - bU_b)u_\mu u_\nu + 2XU_X\mathcal{V}_\mu\mathcal{V}_\nu$

$$S = M_{Pl}^2 \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U(\partial\varphi)$$

Perfect fluids

$U(X)$ $\quad X = g^{\mu\nu}\partial_\mu\varphi^0\partial_\nu\varphi^0$ $\quad \mathcal{V}^\mu = -\frac{\partial^\mu\varphi^0}{\sqrt{-X}}$ **shift symmetric k-essence**

$U(b,Y)$ $\quad Y = u^\mu\partial_\nu\varphi^0$ $\quad b = \det\left(g^{\mu\nu}\partial_\mu\varphi^a\partial_\nu\varphi^b\right)^{1/2}$ $\quad u^\mu = -\frac{\epsilon^{\mu\nu\alpha\beta}}{6\,b\sqrt{-g}}\epsilon_{abc}\,\partial_\nu\varphi^a\,\partial_\alpha\varphi^b\,\partial_\beta\varphi^c$

$$T_{\mu\nu} = p g_{\mu\nu} + (\rho + p) u_\mu u_\nu$$

$$\rho = -U + Y\, U_Y$$

$$p = U - b\, U_b$$

Fluid-Superfluid

$U(b,Y,X)$ $\quad T_{\mu\nu} = (U - bU_b)g_{\mu\nu} + (YU_Y - bU_b)u_\mu u_\nu + 2XU_X\mathcal{V}_\mu\mathcal{V}_\nu$

Solid

$U(\tau_1,\tau_2,\tau_3)$ $\quad \tau_n = \mathrm{Tr}(\boldsymbol{B}^n)$ $\quad B^{ab} = g^{\mu\nu}\partial_\mu\varphi^a\partial_\nu\varphi^b$

$$T_{\mu\nu} = p g_{\mu\nu} + (\rho + p) u_\mu u_\nu + \pi_{\mu\nu}$$

$$\rho = -U \qquad p = U - \frac{2}{3}\sum_{n=1}^{3} n\tau_n U_{\tau_n}$$

Unitary gauge

$$ds^2 = \left(\eta_{\mu\nu} + h^{(U)}_{\mu\nu}\right) dx^\mu dx^\nu \qquad \varphi^A_{(U)} = \bar{\varphi}^A$$

Unitary gauge

$$ds^2 = \left(\eta_{\mu\nu} + h^{(U)}_{\mu\nu}\right) dx^\mu dx^\nu \qquad \varphi^A_{(U)} = \bar{\varphi}^A$$

scalar field fluctuations are gauged away, all dynamics is in the metric

Unitary gauge

$$ds^2 = \left(\eta_{\mu\nu} + h^{(U)}_{\mu\nu}\right) dx^\mu dx^\nu \qquad \varphi^A_{(U)} = \bar{\varphi}^A$$

scalar field fluctuations are gauged away, all dynamics is in the metric

at the quadratic level in the UG the scalar theory looks like mgr

$$\mathcal{L}^{(U)}_m = \sqrt{-g}\, U\Big|_{\mathcal{O}(2)} = \frac{M^2_{\rm Pl}}{4}\left[\lambda_0^2\, h^{(U)\,2}_{00} + 2\,\lambda_1^2\, h^{(U)\,2}_{0i} - 2\,\lambda_4^2\, h^{(U)}_{00}\, h^{(U)}_{ii} + \lambda_3^2\, h^{(U)\,2}_{ii} - \lambda_2^2\, h^{(U)\,2}_{ij}\right]$$

Unitary gauge

$$ds^2 = \left(\eta_{\mu\nu} + h^{(U)}_{\mu\nu}\right) dx^\mu dx^\nu \qquad \varphi^A_{(U)} = \bar{\varphi}^A$$

scalar field fluctuations are gauged away, all dynamics is in the metric

at the quadratic level in the UG the scalar theory looks like mgr

$$\mathcal{L}^{(U)}_m = \sqrt{-g}\, U\Big|_{\mathcal{O}(2)} = \frac{M^2_{\rm Pl}}{4}\left[\lambda_0^2\, h^{(U)\,2}_{00} + 2\,\lambda_1^2\, h^{(U)\,2}_{0i} - 2\,\lambda_4^2\, h^{(U)}_{00}\, h^{(U)}_{ii} + \lambda_3^2\, h^{(U)\,2}_{ii} - \lambda_2^2\, h^{(U)\,2}_{ij}\right]$$

typically λ_0^2 = 0 is required to vanish to avoid instabilities with 5 DoF

Unitary gauge

$$ds^2 = \left(\eta_{\mu\nu} + h^{(U)}_{\mu\nu}\right) dx^\mu dx^\nu \qquad \varphi^A_{(U)} = \bar{\varphi}^A$$

scalar field fluctuations are gauged away, all dynamics is in the metric

at the quadratic level in the UG the scalar theory looks like mgr

$$\mathcal{L}^{(U)}_m = \sqrt{-g}\, U\Big|_{\mathcal{O}(2)} = \frac{M^2_{\rm Pl}}{4}\left[\lambda_0^2\, h^{(U)\,2}_{00} + 2\,\lambda_1^2\, h^{(U)\,2}_{0i} - 2\,\lambda_4^2\, h^{(U)}_{00}\, h^{(U)}_{ii} + \lambda_3^2\, h^{(U)\,2}_{ii} - \lambda_2^2\, h^{(U)\,2}_{ij}\right]$$

typically λ_0^2 = 0 is required to vanish to avoid instabilities with 5 DoF

however in the medium picture things are different: all mass terms can be non zero with 6 DoF

Unitary gauge

$$ds^2 = \left(\eta_{\mu\nu} + h^{(U)}_{\mu\nu}\right) dx^\mu dx^\nu \qquad \varphi^A_{(U)} = \bar{\varphi}^A$$

scalar field fluctuations are gauged away, all dynamics is in the metric

at the quadratic level in the UG the scalar theory looks like mgr

$$\mathcal{L}^{(U)}_m = \sqrt{-g}\, U\Big|_{\mathcal{O}(2)} = \frac{M^2_{\rm Pl}}{4}\left[\lambda_0^2\, h^{(U)\,2}_{00} + 2\,\lambda_1^2\, h^{(U)\,2}_{0i} - 2\,\lambda_4^2\, h^{(U)}_{00}\, h^{(U)}_{ii} + \lambda_3^2\, h^{(U)\,2}_{ii} - \lambda_2^2\, h^{(U)\,2}_{ij}\right]$$

typically λ_0^2 = 0 is required to vanish to avoid instabilities with 5 DoF

however in the medium picture things are different: all mass terms can be non zero with 6 DoF

Look for general stability conditions in flat space, gravity neglected

(high energy limit)

Linear Stability

$$\varphi^0 = \phi^0(t) + \pi^0 \qquad \varphi^i = x^i + \partial_i \pi_l + V^i$$

background EMT for the medium

$$T^{\mu\nu}_{\rm Mink} = (\rho\ \delta^\mu_0\ \delta^\nu_0\ + p\ \delta^\mu_i\ \delta_{ij}\ \delta^\nu_j) = p\ \eta^{\mu\nu} + (\rho + p)\ u^\mu\ u^\nu$$

Linear Stability

$$\varphi^0 = \phi^0(t) + \pi^0 \qquad \varphi^i = x^i + \partial_i \pi_l + V^i$$

background EMT for the medium

$$T^{\mu\nu}_{\rm Mink} = (\rho\, \delta^\mu_0\, \delta^\nu_0 \; + p\, \delta^\mu_i\, \delta_{ij}\, \delta^\nu_j) = p\, \eta^{\mu\nu} + (\rho + p)\, u^\mu\, u^\nu$$

Scalar Sector

$$L^{(s)}_\pi = \frac{k^2}{2}\left(\hat{M}_1 + p + \rho\right)\pi_l'^2 + \hat{M}_0\, \pi_0'^2 + \frac{k^2}{2}\,\hat{M}_1 \pi_0^2 + k^2\left(\hat{M}_1 - 2\,\hat{M}_4\right)\pi_0'\,\pi_l + k^4\left(\hat{M}_3 - \hat{M}_2\right)\pi_l^2$$

Linear Stability

$$\varphi^0 = \phi^0(t) + \pi^0 \qquad \varphi^i = x^i + \partial_i \pi_l + V^i$$

background EMT for the medium

$$T^{\mu\nu}_{\rm Mink} = (\rho\, \delta^\mu_0\, \delta^\nu_0 \; + p\, \delta^\mu_i\, \delta_{ij}\, \delta^\nu_j) = p\, \eta^{\mu\nu} + (\rho + p)\, u^\mu\, u^\nu$$

Scalar Sector

$$L^{(s)}_\pi = \frac{k^2}{2}\left(\hat{M}_1 + p + \rho\right) \pi_l'^2 + \hat{M}_0\, \pi_0'^2 + \frac{k^2}{2}\, \hat{M}_1 \pi_0^2 + k^2 \left(\hat{M}_1 - 2\, \hat{M}_4\right) \pi_0'\, \pi_l + k^4 \left(\hat{M}_3 - \hat{M}_2\right) \pi_l^2$$

Vector Sector

$$L^{(V)}_\pi = \frac{1}{2}\left(\hat{M}_1 + p + \rho\right)\; \vec{V}'^2 - k^2\; \hat{M}_2\; \vec{V}^2$$

Linear Stability

$$\varphi^0 = \phi^0(t) + \pi^0 \qquad \varphi^i = x^i + \partial_i \pi_l + V^i$$

background EMT for the medium

$$T^{\mu\nu}_{\rm Mink} = (\rho\, \delta^\mu_0\, \delta^\nu_0 \; + p\, \delta^\mu_i\, \delta_{ij}\, \delta^\nu_j) = p\, \eta^{\mu\nu} + (\rho + p)\, u^\mu\, u^\nu$$

Scalar Sector

$$L^{(s)}_\pi = \frac{k^2}{2}\left(\hat{M}_1 + p + \rho\right) \pi_l'^2 + \hat{M}_0\, \pi_0'^2 + \frac{k^2}{2}\, \hat{M}_1 \pi_0^2 + k^2 \left(\hat{M}_1 - 2\, \hat{M}_4\right) \pi_0'\, \pi_l + k^4 \left(\hat{M}_3 - \hat{M}_2\right) \pi_l^2$$

Vector Sector

$$L^{(V)}_\pi = \frac{1}{2}\left(\hat{M}_1 + p + \rho\right)\; \vec{V}'^2 - k^2\; \hat{M}_2\; \vec{V}^2$$

Absence of instabilities

$$M_0 > 0\,, \quad -(p+\rho) < \hat{M}_1 < 0\,, \qquad M_2 > 0\,, \qquad M_2 > M_3$$

$$M_0 = \lambda_0^2 - \frac{\rho}{2\, M_{\rm Pl}^2}, \qquad M_{1,2} = \lambda_{1,2}^2 - \frac{p}{M_{\rm Pl}^2}, \qquad M_{3,4} = \lambda_{3,4}^2 - \frac{p}{2\, M_{\rm Pl}^2}$$

- If the background pressure and density are neglected: the stability window with max number of DoF closes down

- If the background pressure and density are neglected: the stability window with max number of DoF closes down
- in the media picture neglecting them is unnatural, the medium would be absent

- If the background pressure and density are neglected: the stability window with max number of DoF closes down
- in the media picture neglecting them is unnatural, the medium would be absent
- For a fluid-like medium we do expect the possibility of two stable phonon-like modes

- If the background pressure and density are neglected: the stability window with max number of DoF closes down
- in the media picture neglecting them is unnatural, the medium would be absent
- For a fluid-like medium we do expect the possibility of two stable phonon-like modes
- Alternative to the path the leads to de Rham-Gabadadze-Tolley (dRGT) formulation of massive gravity with 5 DoF

DGRT phenomenology is problematic

- If the background pressure and density are neglected: the stability window with max number of DoF closes down
- in the media picture neglecting them is unnatural, the medium would be absent
- For a fluid-like medium we do expect the possibility of two stable phonon-like modes
- Alternative to the path the leads to de Rham-Gabadadze-Tolley (dRGT) formulation of massive gravity with 5 DoF

DGRT phenomenology is problematic

The case $p + \rho = 0$ is special (Lambda media)

What happens when gravity is turned on

What happens when gravity is turned on

cosmological background

$$ds^2 = a^2\,\eta_{\mu\nu}\,dx^\mu dx^\nu + 2\,a^2\left[\Psi(t,\,\vec{x})\,dt^2 + \Phi(t,\,\vec{x})\,d\vec{x}^2\right]$$

$$\varphi^0 = \phi(t) + \pi_0(t,\vec{x}), \qquad \varphi^a = x^a + \partial_a \pi_L(t,\vec{x})$$

What happens when gravity is turned on

cosmological background

$$ds^2 = a^2\,\eta_{\mu\nu}\,dx^\mu dx^\nu + 2\,a^2\left[\Psi(t,\,\vec{x})\,dt^2 + \Phi(t,\,\vec{x})\,d\vec{x}^2\right]$$

$$\varphi^0 = \phi(t) + \pi_0(t,\vec{x}), \qquad \varphi^a = x^a + \partial_a \pi_L(t,\vec{x})$$

large k limit: same condition as in flat space for absence of instabilities

What happens when gravity is turned on

cosmological background

$$ds^2 = a^2\,\eta_{\mu\nu}\,dx^\mu dx^\nu + 2\,a^2\left[\Psi(t,\,\vec{x})\,dt^2 + \Phi(t,\,\vec{x})\,d\vec{x}^2\right]$$

$$\varphi^0 = \phi(t) + \pi_0(t,\vec{x}), \qquad \varphi^a = x^a + \partial_a \pi_L(t,\vec{x})$$

large k limit: same condition as in flat space for absence of instabilities

all k

together with

$$M_0 > 0 \qquad \text{and} \qquad \hat{M}_1 + (p+\rho) > 0$$

when $\hat{M}_0 < \rho$ kinetic energy is positive

What happens when gravity is turned on

cosmological background

$$ds^2 = a^2\,\eta_{\mu\nu}\,dx^\mu dx^\nu + 2\,a^2\left[\Psi(t,\,\vec{x})\,dt^2 + \Phi(t,\,\vec{x})\,d\vec{x}^2\right]$$

$$\varphi^0 = \phi(t) + \pi_0(t,\vec{x}), \qquad \varphi^a = x^a + \partial_a \pi_L(t,\vec{x})$$

large k limit: same condition as in flat space for absence of instabilities

together with

all k

$$M_0 > 0 \qquad \text{and} \qquad \hat{M}_1 + (p+\rho) > 0$$

when $\hat{M}_0 < \rho$ kinetic energy is positive

flat space analysis confirmed

Symmetries determine:

- thermodynamics properties of the medium
- dynamics of linear cosmological perturbation

Symmetries determine:

- thermodynamics properties of the medium
- dynamics of linear cosmological perturbation

$$\delta g_{00} = 2a^2\Psi$$
$$\delta g_{ij} = 2\delta_{ij}a^2\Phi$$

Supersolids

- two independent scalar perturbations: $\Phi,\ \delta\sigma$
- entropy per particle perturbation $\delta\sigma$
- anisotropic stress $\Psi \neq \Phi$
- massive dispersion relation for gravitons

Symmetries determine:

- thermodynamics properties of the medium
- dynamics of linear cosmological perturbation

$$\delta g_{00} = 2a^2\Psi$$
$$\delta g_{ij} = 2\delta_{ij}a^2\Phi$$

Supersolids

- two independent scalar perturbations: $\Phi,\ \delta\sigma$
- entropy per particle perturbation $\delta\sigma$
- anisotropic stress $\Psi \neq \Phi$
- massive dispersion relation for gravitons

Fluids and Superfluids

- one independent scalar perturbations (fluids):
- $\delta\sigma$ constant in time but still sources Φ
- $\delta\sigma$ dynamical for superfluids
- anisotropic stress is zero

Symmetries

Four-dimensional media		
Symmetries of the action	**LO scalar operators**	**Type of medium**
$SO(3)_s \quad \& \quad \varphi^A \to \varphi^A + f^A\,, \quad \partial_\mu f^A = 0$	$X,\, Y,\, \tau_n,\, y_n$	supersolids
$\varphi^a \to \varphi^a + f^a(\varphi^0)$	$X,\, w_n$	
$\varphi^0 \to \varphi^0 + f(\varphi^0)$	$\tau_n,\, w_n,\, \mathcal{O}_{\alpha\beta n}$	
$\varphi^a \to \varphi^a + f^a(\varphi^0)\ \&\ \varphi^0 \to \varphi^0 + f(\varphi^0)$	w_n	
$\varphi^0 \to \varphi^0 + f(\varphi^a)$	$Y,\, \tau_n$	solids
V_sDiff: $\varphi^a \to \Psi^a(\varphi^b)\,, \quad \det\lvert\partial\Psi^a/\partial\varphi^b\rvert = 1$	$b,\, Y,\, X$	superfluids
$\varphi^0 \to \varphi^0 + f(\varphi^0) \quad \&\ V_s$Diff	$b,\, \mathcal{O}_\alpha$	
$\varphi^0 \to \varphi^0 + f(\varphi^a) \quad \&\ V_s$Diff	$b,\, Y$	perfect fluid
$\varphi^A \to \Psi^A(\varphi^B)\,, \quad \det\lvert\partial\Psi^A/\partial\varphi^B\rvert = 1$	$b\,Y$	perfect fluid with $\rho + p = 0$

Conclusions

Conclusions

- Medium picture indicates that a stable massive gravity theory with two scalar modes exists

Conclusions

- Medium picture indicates that a stable massive gravity theory with two scalar modes exists
- Stability conditions are mild and can be realised for fluids, superfluids and solids

Conclusions

- Medium picture indicates that a stable massive gravity theory with two scalar modes exists
- Stability conditions are mild and can be realised for fluids, superfluids and solids
- Symmetry driven framework for dark energy

Conclusions

- Medium picture indicates that a stable massive gravity theory with two scalar modes exists
- Stability conditions are mild and can be realised for fluids, superfluids and solids
- Symmetry driven framework for dark energy
- DE model with 2 scalar + 2 vectors + 2 tensor modes

Conclusions

- Medium picture indicates that a stable massive gravity theory with two scalar modes exists
- Stability conditions are mild and can be realised for fluids, superfluids and solids
- Symmetry driven framework for dark energy
- DE model with 2 scalar + 2 vectors + 2 tensor modes
- anisotropic stress and massive dispersion relation for tensors

Conclusions

- Medium picture indicates that a stable massive gravity theory with two scalar modes exists
- Stability conditions are mild and can be realised for fluids, superfluids and solids
- Symmetry driven framework for dark energy
- DE model with 2 scalar + 2 vectors + 2 tensor modes
- anisotropic stress and massive dispersion relation for tensors
- The case of exact w=-1 is special: Lambda media and deserves special analysis

Conclusions

- Medium picture indicates that a stable massive gravity theory with two scalar modes exists
- Stability conditions are mild and can be realised for fluids, superfluids and solids
- Symmetry driven framework for dark energy
- DE model with 2 scalar + 2 vectors + 2 tensor modes
- anisotropic stress and massive dispersion relation for tensors
- The case of exact w=-1 is special: Lambda media and deserves special analysis

Conclusions

- Medium picture indicates that a stable massive gravity theory with two scalar modes exists
- Stability conditions are mild and can be realised for fluids, superfluids and solids
- Symmetry driven framework for dark energy
- DE model with 2 scalar + 2 vectors + 2 tensor modes
- anisotropic stress and massive dispersion relation for tensors
- The case of exact w=-1 is special: Lambda media and deserves special analysis

$$s = -J_0^\alpha u_\alpha = U_Y - 2YU_X \qquad n = -J_\alpha u^\alpha = b \qquad \sigma = \frac{s}{n}$$

$$J_A^\mu = \frac{\partial U}{\partial(\partial_\mu \varphi^A)} = 2U_{AB}\nabla^\mu \varphi^B, \qquad U_{AB} = \frac{\partial U}{\partial C^{AB}}$$

Shift symmetries Currents

Fluids

Fluids with $U(bY)$

protected by

$$\varphi^A \to \psi^A(\varphi^B)\,, \qquad \det\left|\partial\psi^A/\partial\varphi^B\right| = 1$$

Fluids

Fluids with $U(bY)$

protected by

$$\varphi^A \to \psi^A(\varphi^B)\,, \qquad \det\left|\partial\psi^A/\partial\varphi^B\right| = 1$$

ρ is constant, scalar fields non-trivial

impossible to distinguish from a CC

Fluids

Fluids with $U(bY)$

protected by

$$\varphi^A \to \psi^A(\varphi^B)\,, \qquad \det\left|\partial\psi^A/\partial\varphi^B\right| = 1$$

ρ is constant, scalar fields non-trivial

impossible to distinguish from a CC

Solids

Fluids

Fluids with $U(bY)$

protected by

$$\varphi^A \to \psi^A(\varphi^B)\,, \qquad \det\left|\partial\psi^A/\partial\varphi^B\right| = 1$$

ρ is constant, scalar fields non-trivial

impossible to distinguish from a CC

Solids

$$U_S^\Lambda = U\left(Y\tau_1^{3/2}, \frac{\tau_2}{\tau_1^2}, \frac{\tau_3}{\tau_1^3}\right)$$

$$\varphi^0 \to \varphi^0 + f(\varphi^j)$$

$$\begin{cases} \varphi^0 \to & \lambda^{-3}\,\varphi^0 \\ \varphi^j \to & \lambda\,\varphi^j \end{cases}$$

Fluids

Fluids with $U(bY)$

protected by

$$\varphi^A \to \psi^A(\varphi^B)\,, \qquad \det\left|\partial\psi^A/\partial\varphi^B\right| = 1$$

ρ is constant, scalar fields non-trivial

impossible to distinguish from a CC

Solids

$$U_S^\Lambda = U\left(Y\tau_1^{3/2}, \frac{\tau_2}{\tau_1^2}, \frac{\tau_3}{\tau_1^3}\right)$$

$$\varphi^0 \to \varphi^0 + f(\varphi^j)$$

$$\begin{cases} \varphi^0 \to & \lambda^{-3}\,\varphi^0 \\ \varphi^j \to & \lambda\,\varphi^j \end{cases}$$

Special Super Solids

Fluids

Fluids with $U(bY)$

protected by

$$\varphi^A \to \psi^A(\varphi^B)\,, \qquad \det\left|\partial\psi^A/\partial\varphi^B\right| = 1$$

ρ is constant, scalar fields non-trivial

impossible to distinguish from a CC

Solids

$$U_S^\Lambda = U\left(Y\tau_1^{3/2}, \frac{\tau_2}{\tau_1^2}, \frac{\tau_3}{\tau_1^3}\right)$$

$$\varphi^0 \to \varphi^0 + f(\varphi^j)$$

$$\begin{cases} \varphi^0 \to \lambda^{-3}\,\varphi^0 \\ \varphi^j \to \lambda\,\varphi^j \end{cases}$$

Special Super Solids

$$U_{SS}^\Lambda = U\left(X w_1^3, \frac{w_2}{w_1^2}, \frac{w_3}{w_1^3}\right)$$

$$\varphi^j \to \varphi^j + f^j(\varphi^0)$$

$$\begin{cases} \varphi^0 \to \lambda^{-3}\,\varphi^0 \\ \varphi^j \to \lambda\,\varphi^j \end{cases}$$

Fluids

Fluids with $U(bY)$

protected by

$$\varphi^A \to \psi^A(\varphi^B)\,, \qquad \det\left|\partial\psi^A/\partial\varphi^B\right| = 1$$

ρ is constant, scalar fields non-trivial

impossible to distinguish from a CC

Solids

$$U_S^\Lambda = U\left(Y\tau_1^{3/2}, \frac{\tau_2}{\tau_1^2}, \frac{\tau_3}{\tau_1^3}\right)$$

$$\varphi^0 \to \varphi^0 + f(\varphi^j)$$

$$\begin{cases} \varphi^0 \to & \lambda^{-3}\,\varphi^0 \\ \varphi^j \to & \lambda\,\varphi^j \end{cases}$$

Special Super Solids

$$U_{SS}^\Lambda = U\left(X w_1^3, \frac{w_2}{w_1^2}, \frac{w_3}{w_1^3}\right)$$

$$\varphi^j \to \varphi^j + f^j(\varphi^0)$$

$$\begin{cases} \varphi^0 \to & \lambda^{-3}\,\varphi^0 \\ \varphi^j \to & \lambda\,\varphi^j \end{cases}$$

entropy per particle σ also constant

CC: ρ and p constant, no perturbation

matter perturbation also absent during CC perturbation

CC: ρ and p constant, no perturbation

matter perturbation also absent during CC perturbation

Lambda Media:

CC: ρ and p constant, no perturbation

matter perturbation also absent during CC perturbation

ρ = - p but non constant

Lambda Media:

CC: ρ and p constant, no perturbation

matter perturbation also absent during CC perturbation

ρ = - p but non constant

non-trivial perturbations in the dark sector

$$\delta p = -\delta\rho \sim \delta\sigma$$

Lambda Media:

CC:

ρ and p constant, no perturbation

matter perturbation also absent during CC perturbation

Lambda Media:

ρ = - p but non constant

non-trivial perturbations in the dark sector

$$\delta p = -\delta\rho \sim \delta\sigma$$

anisotropic stress is present: massive tensor

CC:

ρ and p constant, no perturbation

matter perturbation also absent during CC perturbation

Lambda Media:

ρ = - p but non constant

non-trivial perturbations in the dark sector

$$\delta p = -\delta\rho \sim \delta\sigma$$

anisotropic stress is present: massive tensor

matter perturbations grow during Lambda-medium domination

$$\delta_{\rm DM} \sim a^2\,\delta\sigma$$

CC:

ρ and p constant, no perturbation

matter perturbation also absent during CC perturbation

Lambda Media:

ρ = - p but non constant

non-trivial perturbations in the dark sector

$$\delta p = -\delta\rho \sim \delta\sigma$$

anisotropic stress is present: massive tensor

matter perturbations grow during Lambda-medium domination

$$\delta_{\rm DM} \sim a^2\,\delta\sigma$$

Clear prediction for lensing

$$\Phi - \Psi = \frac{3}{4}\,a^2\,\delta\sigma_{ph}$$

Examples

Fluids $U(b, Y)$ $$T_{\mu\nu} = (U - b\,U_b)g_{\mu\nu} + (Y\,U_Y - b\,U_b)u_\mu\,u_\nu$$

$$p = w\,\rho$$

$$U(b) = b^{1+w}\,;$$
$$U(Y) = Y^{\frac{1+w}{w}}\,;$$
$$U(X) = X^{\frac{1+w}{2\,w}}\,;$$
$$U(b, Y) = b^{1+w}\,\mathcal{U}(Y\,b^{-w}) \quad \text{or} \quad b^{1+w} + \lambda\,Y^{\frac{1+w}{w}}$$

Super Fluids $U(b, Y, X)$

$$T_{\mu\nu} = (U - b\,U_b)\;g_{\mu\nu} + (Y\,U_Y - b\,U_b)\;u_\mu\,u_\nu + 2X\,U_X\,\mathcal{V}_\mu\,\mathcal{V}_\nu$$

Mass Parameters

$$M_0 = \frac{\phi'^2}{2\,M_{pl}^2}\left[a^2\left(U_{Y^2} - 2\,U_X\right) - 4\,a\,\phi'\,U_{XY} + 4\,U_{X^2}\,\phi'^2\right]$$

$$M_1 = \frac{2\,\phi'^2}{M_{pl}^2}\left(\sum_{n=0}^{3} a^{-2\,n}\,U_{y_n} + a^2\,U_X\right)$$

$$M_2 = -\frac{2}{M_{pl}^2}\sum_{n=1}^{3} n^2\,a^{2(2-n)}\,U_{\tau_n}$$

$$M_3 = \frac{1}{M_{pl}^2}\left(2\sum_{m,n=1}^{3} m\,n\,a^{-2m-2n+4}\,U_{\tau_m\tau_n} + 2\sum_{n} n\,a^{1-2n}\,U_{b\tau_n} - \sum_{n,m=1}^{3} a^{4-2n}\,U_{\tau_n} + \frac{1}{2\,a^2}\,U_{b^2}\right)$$

$$M_4 = \frac{1}{M_{pl}^2}\left[\frac{\phi'}{2}\left(2\sum_{m,n=1}^{3} a^{3-2n}\,U_{Y\tau_n} - a^3\,U_Y + U_{bY}\right) + \phi'^2\left(-2\sum_{n=1}^{3} a^{2-2n}\,U_{X\tau_n} + a^2\,U_X - \frac{1}{a}\,U_{bX}\right)\right]$$

Early References

Matarrese 1985

H. Leutwyler 1994, 1996;

R. Jackiw, V.P. Nair, S.Y Pi, A.P. Polychronakos 2004;

D.T. Son 2005;

S. Dubovsky, T. Gregoire, A. Nicolis, and R. Rattazzi 2006;

S. Dubovsky, L. Hui, A. Nicolis, and D.T. Son 2012

G. Ballesteros, B. Bellazzini, 2013

G. Ballesteros 2015

Unitary Gauge

Unitary Gauge

$$S = M_{pl} \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U(X, Y, \tau_n, y_n)$$

$$\Rightarrow \quad S = M_{pl}^2 \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U\left(N, \xi^i, \gamma^{ij}\right)$$

Unitary Gauge

$$S = M_{pl} \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U(X, Y, \tau_n, y_n)$$

$$\Rightarrow \quad S = M_{pl}^2 \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U\left(N, \xi^i, \gamma^{ij}\right)$$

in the unitary gauge the medium action (fluids, solids ..) is interpreted as modification of gravity

Unitary Gauge

$$S = M_{pl} \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U(X, Y, \tau_n, y_n)$$

$$\Rightarrow \quad S = M_{pl}^2 \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U\left(N, \xi^i, \gamma^{ij}\right)$$

in the unitary gauge the medium action (fluids, solids ..) is interpreted as modification of gravity

in the unitary gauge diffs appear to be broken

Unitary Gauge

$$S = M_{pl} \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U(X, Y, \tau_n, y_n)$$

$$\Rightarrow \quad S = M_{pl}^2 \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U\left(N, \xi^i, \gamma^{ij}\right)$$

in the unitary gauge the medium action (fluids, solids ..) is interpreted as modification of gravity

in the unitary gauge diffs appear to be broken

in a generic gauge diffs are "restored" by the Stuckelberg fields Φ^A

Unitary Gauge

$$S = M_{pl} \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U(X, Y, \tau_n, y_n)$$

$$\Rightarrow \quad S = M_{pl}^2 \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U\left(N, \xi^i, \gamma^{ij}\right)$$

in the unitary gauge the medium action (fluids, solids ..) is interpreted as modification of gravity

in the unitary gauge diffs appear to be broken

in a generic gauge diffs are "restored" by the Stuckelberg fields Φ^A

what really matters is the number of DoF and underlying symmetries

Unitary Gauge

$$S = M_{pl} \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U(X, Y, \tau_n, y_n)$$

$$\Rightarrow \quad S = M_{pl}^2 \int d^4x \sqrt{-g}\, R + \int d^4x \sqrt{-g}\, U\left(N, \xi^i, \gamma^{ij}\right)$$

in the unitary gauge the medium action (fluids, solids ..) is interpreted as modification of gravity

in the unitary gauge diffs appear to be broken

in a generic gauge diffs are "restored" by the Stuckelberg fields Φ^A

what really matters is the number of DoF and underlying symmetries

GR has 2 DoF realized in a minimal way: just by the metric
other theories will typically have more DoF and more fields