Late stage Universe: cosmological models with interacting and non-interacting perfect fluids and scalar fields

Alvina Burgazli
Odesa National University, Ukraine

New Trends in HEP, Odesa, 2019

Outline

1. Late stage Universe.
   Much more later then the recombination stage.

Outline

1. Late stage Universe.
   Much more later then the recombination stage.
2. Small scales (<190 Mpc).

Outline

1. Late stage Universe.
   Much more later then the recombination stage.
2. Small scales (<190 Mpc).
3. The Universe filled with dust-like matter in the form of discretely distributed galaxies, a minimally coupled scalar field and radiation as matter sources.

Outline

1. Late stage Universe.
   Much more later then the recombination stage.
2. Small scales (<190 Mpc).
3. The Universe filled with dust-like matter in the form of discretely distributed galaxies, a minimally coupled scalar field and radiation as matter sources.
4. Mechanical approach.
   This means that the peculiar velocities of the inhomogeneities (in the form of galaxies) as well as fluctuations of other perfect fluids are non-relativistic. Such fluids are designated as coupled because they are concentrated around inhomogeneities.

Outline

1. Late stage Universe.
   Much more later then the recombination stage.
2. Small scales (<190 Mpc).
3. The Universe filled with dust-like matter in the form of discretely distributed galaxies, a minimally coupled scalar field and radiation as matter sources.
4. Mechanical approach.
   This means that the peculiar velocities of the inhomogeneities (in the form of galaxies) as well as fluctuations of other perfect fluids are non-relativistic. Such fluids are designated as coupled because they are concentrated around inhomogeneities.

The scalar field coupled to inhomogeneities may exist and can provide the late cosmic acceleration.

Outline

We investigate the conditions under which a scalar field can become coupled, and show that, at the background level, such coupled scalar field behaves as a two component perfect fluid: a network of frustrated cosmic strings with EoS parameter $w=-1/3$ and a cosmological constant.

Outline

We investigate the conditions under which a scalar field can become coupled, and show that, at the background level, such coupled scalar field behaves as a two component perfect fluid: a network of frustrated cosmic strings with EoS parameter $w=-1/3$ and a cosmological constant.

The potential of this scalar field is very flat at the present time. Hence, the coupled scalar field can provide the late cosmic acceleration.

Outline

We investigate the conditions under which a scalar field can become coupled, and show that, at the background level, such coupled scalar field behaves as a two component perfect fluid: a network of frustrated cosmic strings with EoS parameter $w = -1/3$ and a cosmological constant.

The potential of this scalar field is very flat at the present time. Hence, the coupled scalar field can provide the late cosmic acceleration.

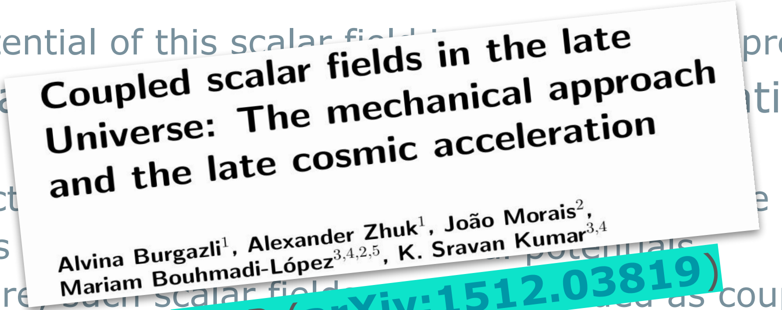
The fluctuations of the energy density and pressure of this field are concentrated around the galaxies screening their gravitational potentials.
Therefore, such scalar fields can be regarded as coupled to the inhomogeneities.

Outline

We investigate the conditions under which a scalar field can become coupled, and show that, at the background level, such coupled scalar field behaves as a two component perfect fluid: a network of frustrated cosmic strings with EoS parameter w=−1/3 and a cosmological constant.

The potential of this scalar fiel… present time. Hence, the coupled scalar field ca… ation.

The fluct… e of this field are concentrated around the galaxies … potentials. Therefore, such scalar field… ed as coupled to the inhomogeneities.


Coupled scalar fields in the late Universe: The mechanical approach and the late cosmic acceleration

Alvina Burgazli[1], Alexander Zhuk[1], João Morais[2], Mariam Bouhmadi-López[3,4,2,5], K. Sravan Kumar[3,4]

JCAP (arXiv:1512.03819)

Outline

We investigat… at the backgrou… network of frustrated cosmic string… cosmological constant.

Rigorous theoretical constraint on constant negative EoS parameter ω and its effect for the late Universe

Alvina Burgazli[a,1], Maxim Eingorn[b,2,3,4], Alexander Zhuk[c,2]

The European Physical Journal C (arXiv:1301.0418)

The potential of this scalar field … present time. Hence, the coupled scalar field ca… …tion.

Coupled scalar fields in the late Universe: The mechanical approach and the late cosmic acceleration

Alvina Burgazli[1], Alexander Zhuk[1], João Morais[2], Mariam Bouhmadi-López[3,4,2,5], K. Sravan Kumar[3,4]

JCAP (arXiv:1512.03819)

The fluct… …e of this field are concentrated around the galaxies … potentials. Therefore, such scalar field… …ed as coupled to the inhomogeneities.

The great challenge for modern cosmology

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

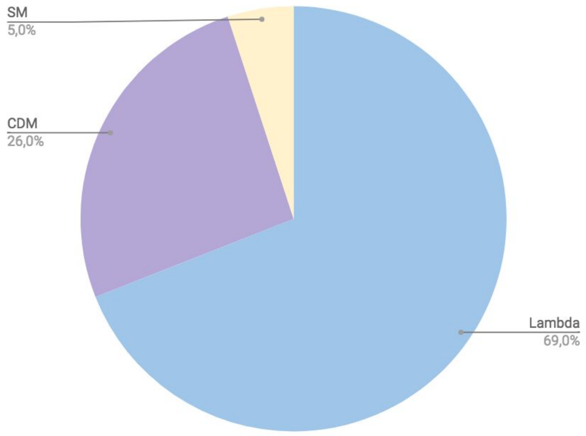
Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess

Concordance cosmology

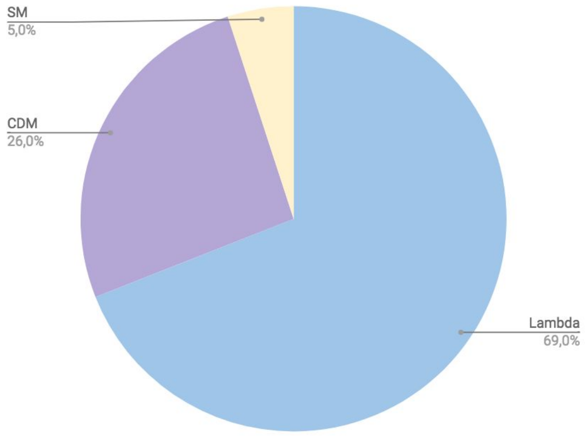


Planck 2015 Results.
XIII. Cosmological parameters.

Concordance cosmology

The nature of the cosmological constant is, however, still unclear.

- There are, in fact, about 120 orders of magnitude between its observed value and the theoretically expected one, which is related to the vacuum energy density.

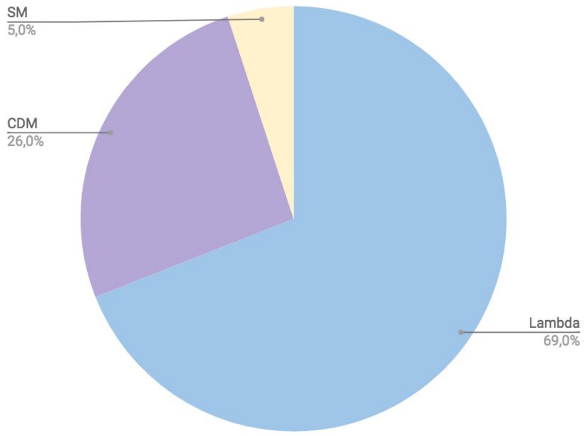


Planck 2015 Results.
XIII. Cosmological parameters.

Concordance cosmology

The nature of the cosmological constant is, however, still unclear.

- There are, in fact, about 120 orders of magnitude between its observed value and the theoretically expected one, which is related to the vacuum energy density.
- The cancellation mechanism between the various energy densities that would reduce this large theoretical value of the cosmological constant is still a mystery.

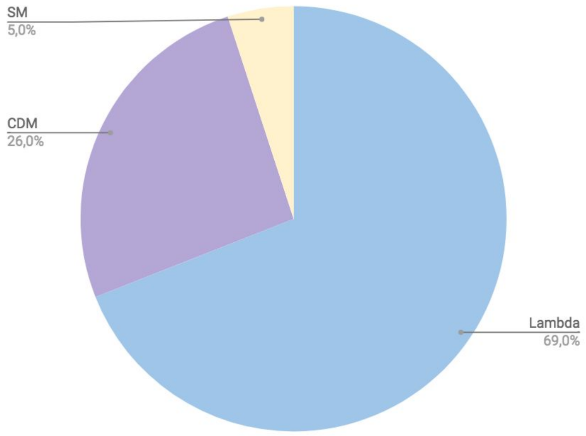


Planck 2015 Results.
XIII. Cosmological parameters.

Concordance cosmology

The nature of the cosmological constant is, however, still unclear.

- There are, in fact, about 120 orders of magnitude between its observed value and the theoretically expected one, which is related to the vacuum energy density.
- The cancellation mechanism between the various energy densities that would reduce this large theoretical value of the cosmological constant is still a mystery.
- In addition, the ΛCDM model (as well as a lot of other dark energy models) faces the coincidence problem, that is the question, why is the cosmological constant at present of the same order of magnitude as the energy density of dark matter?



Planck 2015 Results.
XIII. Cosmological parameters.

Concordance cosmology

The nature of the cosmological constant is, however, still unclear.

- There are, in fact, about 120 orders of magnitude between its observed value and the theoretically expected one, which is related to the vacuum energy density.
- The cancellation mechanism between the various energy densities that would reduce this large theoretical value of the cosmological constant is still a mystery.
- In addition, the ΛCDM model (as well as a lot of other dark energy models) faces the coincidence problem, that is the question, why is the cosmological constant at present of the same order of magnitude as the energy density of dark matter?

Alternative models using scalar fields to explain the DE:

- quintessence ($-1 < \omega < 0$)
- phantom ($\omega < -1$)
- quintom ($\omega = -1$ crossing)

ω = const?

The mechanical approach

Works perfectly:

- for the ΛCDM model where the peculiar velocities of the inhomogeneities (e.g. galaxies) can be considered as negligibly small (as compared with the speed of light);

The mechanical approach

Works perfectly:

- for the ΛCDM model where the peculiar velocities of the inhomogeneities (e.g. galaxies) can be considered as negligibly small (as compared with the speed of light);
- deep inside of the cell of uniformity.

Then, we may drop the peculiar velocities at the first order approximation.

The mechanical approach

Works perfectly:

- for the ΛCDM model where the peculiar velocities of the inhomogeneities (e.g. galaxies) can be considered as negligibly small (as compared with the speed of light);
- deep inside of the cell of uniformity.

Then, we may drop the peculiar velocities at the first order approximation.

MA was generalised to the case of cosmological models with different perfect fluids which can play the role of dark energy and dark matter. Fluctuations of these additional perfect fluids also form their own inhomogeneities. In the mechanical approach, it is supposed that the velocities of displacement of such inhomogeneities is of the order of the peculiar velocities of inhomogeneities of dust-like matter, i.e. they are non-relativistic.

The mechanical approach

Works perfectly:

- for the ΛCDM model where th… …ular velocities of the inhomogeneities (e.g. galaxies) can be considered as … (as compared with the speed of light);
- deep in… … …iformity.
- The coupled scalar field behaves (at the background level) as a two-component perfect fluid;

Then we may drop the peculiar velocities at the first order approximation.

MA was generalised to the case of cosmological models with different perfect fluids which can play the role of dark energy and dark matter. Fluctuations of these additional perfect fluids also form their own inhomogeneities. In the mechanical approach, it is supposed that the velocities of displacement of such inhomogeneities is of the order of the peculiar velocities of inhomogeneities of dust-like matter, i.e. they are non-relativistic.

The mechanical approach

Works perfectly:

- for the ΛCDM model where th[illegible] [illegible]ular velocities of the inhomogeneities (e.g. galaxies) can be considered as [illegible] (as com[illegible] with the speed of light);
- deep in[illegible]

The[illegible] we [illegible] the peculiar velocities at the first order approximation.

- The coupled scalar field behaves (at the background level) as a two-component perfect fluid;
- the potential of such scalar field is very flat;

MA was generalised to the case of cosmological models with different perfect fluids which can play the role of dark energy and dark matter. Fluctuations of these additional perfect fluids also form their own inhomogeneities. In the mechanical approach, it is supposed that the velocities of displacement of such inhomogeneities is of the order of the peculiar velocities of inhomogeneities of dust-like matter, i.e. they are non-relativistic.

The mechanical approach

Works perfectly:

- for the ΛCDM model where th... ...ular velocities of the inhomo... ...ies) can be considered as ... (as com... ...ith th...
- deep in... ...the ... ...uniform...

The... we ... ...at the first order approximation.

- The coupled scalar field behaves (at the background level) as a two-component perfect fluid;
- the potential of such scalar field is very flat;
- the scalar field fluctuations are absent, its energy density and pressure fluctuate due to the interaction of the gravitational potential and with the scalar field background.

MA was ge... ...case of cosmological models with different perfect fluids which can play th... ...of dark energy and dark matter. Fluctuations of these additional perfect fluids also form their own inhomogeneities. In the mechanical approach, it is supposed that the velocities of displacement of such inhomogeneities is of the order of the peculiar velocities of inhomogeneities of dust-like matter, i.e. they are non-relativistic.

The mechanical approach

Works perfectly:

- for ... velocities of the inhomo... ...ies) can be ...
- deep in ...

The... at the first order approximation.

- The coupled ... behaves (at the background level) as a two-component perfect ...
- the potential of such scalar field ... density and pressure
- the scalar field fluctuations are absent ...
- the scalar ... fluctuate due to the interaction of the gravitational potential... with the scalar field background.

- The fluctuations of the energy density of the scalar field are concentrated around the galaxies, screening their gravitational potentials.

MA was g... case of cosmological models with different perfect fluids which can play th... of dark energy and dark matter. Fluctuations of these additional perfect fluids also form their own inhomogeneities. In the mechanical approach, it is supposed that the velocities of displacement of such inhomogeneities is of the order of the peculiar velocities of inhomogeneities of dust-like matter, i.e. they are non-relativistic.

The mechanical approach

Works perfectly:

- for ... velocities of the inhomo... ies) can be ...
- de...

The... at the first order approximation.

... behaves (at the background level) as a ... density and pressure ... with the ... gravitational potentials ...

- the two ...
- the potential ...
- the scalar field fluctuations ... of the ... fluctuate due to the interaction ... scalar field background.

- The fluctuations of the energy density of the scalar field are concentrated around the galaxies, screening their gravitational potentials.
- Such a distribution of the energy density of the scalar field fluctuations justifies the coupling condition.

MA was g... case of cosmological models with different perfect fluids which can play th... of dark energy and dark matter. Fluctuations of these additional perfect fluids also form their own inhomogeneities. In the mechanical approach, it is supposed that the velocities of displacement of such inhomogeneities is of the order of the peculiar velocities of inhomogeneities of dust-like matter, i.e. they are non-relativistic.

The mechanical approach

Works perfectly:

- The fluctuations of the energy density of the scalar field are concentrated around the galaxies, screening their gravitational potentials.
- Such a distribution of the energy density of the scalar field fluctuations justifies the coupling condition.
- We obtain the expressions for the gravitational potential for flat, open and closed topologies of the Universe.

behaves (at the background level) as a

density and pressure

with the

... the first order approximation.

fluctuate

scalar field background

MA was g... case of cosmological models with different perfect fluids which can play th... of dark energy and dark matter. Fluctuations of these additional perfect fluids also form their own inhomogeneities. In the mechanical approach, it is supposed that the velocities of displacement of such inhomogeneities is of the order of the peculiar velocities of inhomogeneities of dust-like matter, i.e. they are non-relativistic.

The mechanical approach

Works perfectly:

- The fluctuations of the energy density of the scalar field are concentrated around the galaxies, screening their gravitational potentials.
- Such a distribution of the energy density of the scalar field fluctuations justifies the coupling condition.
- We obtain the expressions for the gravitational potential for flat, open and closed topologies of the Universe.
- An important property of this potential is that its averaged (over the volume of the Universe) value is equal to zero, as it should be.

... at the first order approximation.

... models with different perfect fluids which ... fluids also form their own inhomogeneities. In the mechanical approach, it is supposed that the velocities of displacement of such inhomogeneities is of the order of the peculiar velocities of inhomogeneities of dust-like matter, i.e. they are non-relativistic.

Background equations

Friedman-Lemaître-Robertson-Walker background metric:

$$ds^2 = a^2\left(d\eta^2 - \delta_{\alpha\beta}dx^\alpha dx^\beta\right)$$

scale factor $a(\eta)$

conformal time

comoving spatial coordinate

physical distance: $R = ar$

Background equations

Friedman-Lemaître-Robertson-Walker background metric:

$$ds^2 = a^2\left(d\eta^2 - \delta_{\alpha\beta}dx^\alpha dx^\beta\right)$$

scale factor $a(\eta)$ conformal time comoving spatial coordinate

physical distance: $R = ar$

The Universe is filled with a scalar field minimally coupled to gravity. Its action and energy-momentum tensor:

$$S_\phi = \int d^4x\sqrt{-g}\left(\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right), \quad T^\mu_\nu(\phi) = g^{\mu\lambda}\partial_\nu\phi\partial_\lambda\phi - \delta^\mu_\nu\left(\frac{1}{2}g^{\lambda\rho}\partial_\lambda\phi\partial_\rho\phi - V(\phi)\right)$$

Background equations

Friedman-Lemaître-Robertson-Walker background metric:

$$ds^2 = a^2\left(d\eta^2 - \delta_{\alpha\beta}dx^\alpha dx^\beta\right)$$

scale factor $a(\eta)$ conformal time comoving spatial coordinate

physical distance: $R = ar$

The Universe is filled with a scalar field minimally coupled to gravity. Its action and energy-momentum tensor:

$$S_\phi = \int d^4x\sqrt{-g}\left(\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right), \quad T^\mu_\nu(\phi) = g^{\mu\lambda}\partial_\nu\phi\partial_\lambda\phi - \delta^\mu_\nu\left(\frac{1}{2}g^{\lambda\rho}\partial_\lambda\phi\partial_\rho\phi - V(\phi)\right)$$

The equation of motion reads:

$$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\partial_\nu\phi\right) + \frac{dV}{d\phi}(\phi) = 0$$

Background equations

Friedman-Lemaître-Robertson-Walker background metric:

$$ds^2 = a^2\left(d\eta^2 - \delta_{\alpha\beta}dx^\alpha dx^\beta\right)$$

scale factor $a(\eta)$ conformal time comoving spatial coordinate

physical distance: $R = ar$

The Universe is filled with a scalar field minimally coupled to gravity. Its action and energy-momentum tensor:

$$S_\phi = \int d^4x\sqrt{-g}\left(\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right), \quad T^\mu_\nu(\phi) = g^{\mu\lambda}\partial_\nu\phi\partial_\lambda\phi - \delta^\mu_\nu\left(\frac{1}{2}g^{\lambda\rho}\partial_\lambda\phi\partial_\rho\phi - V(\phi)\right)$$

The equation of motion reads: $$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\partial_\nu\phi\right) + \frac{dV}{d\phi}(\phi) = 0$$

For the background energy density and pressure we get:

$$\bar{T}^0_0 \equiv \bar{\varepsilon}_\varphi = \frac{1}{2a^2}(\phi'_c)^2 + V(\phi_c)$$

$$-\bar{T}^i_i \equiv \bar{p}_\varphi = \frac{1}{2a^2}(\phi'_c)^2 - V(\phi_c)$$

where the prime denotes the derivative with respect to conformal time η.

Background equations

Friedman-Lemaître-Robertson-Walker background metric:

$$ds^2 = a^2\left(d\eta^2 - \delta_{\alpha\beta}dx^\alpha dx^\beta\right)$$

scale factor $a(\eta)$ conformal time comoving spatial coordinate

physical distance: $R = ar$

The Universe is filled with a scalar field minimally coupled to gravity. Its action and energy-momentum tensor:

$$S_\phi = \int d^4x\sqrt{-g}\left(\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right), \quad T^\mu_\nu(\phi) = g^{\mu\lambda}\partial_\nu\phi\partial_\lambda\phi - \delta^\mu_\nu\left(\frac{1}{2}g^{\lambda\rho}\partial_\lambda\phi\partial_\rho\phi - V(\phi)\right)$$

The equation of motion reads: $$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\partial_\nu\phi\right) + \frac{dV}{d\phi}(\phi) = 0$$

For the background energy density and pressure we get:

$$\bar{T}^0_0 \equiv \bar{\varepsilon}_\varphi = \frac{1}{2a^2}(\phi_c')^2 + V(\phi_c)$$

$$-\bar{T}^i_i \equiv \bar{p}_\varphi = \frac{1}{2a^2}(\phi_c')^2 - V(\phi_c)$$

where the prime denotes the derivative with respect to conformal time η.

The background equation of motion is: $$\phi_c'' + 2\mathcal{H}\phi_c' + a^2\frac{dV}{d\phi}(\phi_c) = 0.$$

Background equations

Friedman-Lemaître-Robertson-Walker background metric: $$ds^2 = a^2\left(d\eta^2 - \delta_{\alpha\beta}dx^\alpha dx^\beta\right)$$

scale factor $a(\eta)$ conformal time comoving spatial coordinate

physical distance: $R = ar$

The Universe is filled with a scalar field minimally coupled to gravity. Its action and energy-momentum tensor:

$$S_\phi = \int d^4x\sqrt{-g}\left(\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right), \quad T^\mu_\nu(\phi) = g^{\mu\lambda}\partial_\nu\phi\partial_\lambda\phi - \delta^\mu_\nu\left(\frac{1}{2}g^{\lambda\rho}\partial_\lambda\phi\partial_\rho\phi - V(\phi)\right)$$

The equation of motion reads: $$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\partial_\nu\phi\right) + \frac{dV}{d\phi}(\phi) = 0$$

For the background energy density and pressure we get:

$$\bar{T}^0_0 \equiv \bar{\varepsilon}_\varphi = \frac{1}{2a^2}(\phi_c')^2 + V(\phi_c)$$
$$-\bar{T}^i_i \equiv \bar{p}_\varphi = \frac{1}{2a^2}(\phi_c')^2 - V(\phi_c)$$

where the prime denotes the derivative with respect to conformal time η.

The background equation of motion is: $$\phi_c'' + 2\mathcal{H}\phi_c' + a^2\frac{dV}{d\phi}(\phi_c) = 0.$$

The Friedmann and Raychaudhuri equations for our cosmological model:

$$\mathcal{H}^2 = \frac{1}{3}a^2\kappa\left[\bar{\varepsilon}_{\rm dust} + \bar{\varepsilon}_{\rm rad} + \frac{1}{2}(\phi_c')^2/a^2 + V(\phi_c)\right] - \mathcal{K} \quad , \mathcal{H}' = \frac{1}{3}a^2\kappa\left[-\bar{\varepsilon}_{\rm rad} - \frac{1}{2}\bar{\varepsilon}_{\rm dust} - (\phi_c')^2/a^2 + V(\phi_c)\right]$$

Scalar perturbations and Einstein equations

The metrics: $ds^2 = a^2(\eta)\left[(1+2\Phi)\,d\eta^2 - (1-2\Psi)\,\gamma_{\alpha\beta}dx^\alpha dx^\beta\right]$

Scalar perturbations and Einstein equations

The metrics: $ds^2 = a^2(\eta)\left[(1+2\Phi)\,d\eta^2 - (1-2\Psi)\,\gamma_{\alpha\beta}dx^\alpha dx^\beta\right]$

The perturbations of the scalar field energy-momentum tensor:

$$\delta T^0_0 \equiv \delta\varepsilon_\varphi = -\frac{1}{a^2}\left(\phi_c'\right)^2\Phi + \frac{1}{a^2}\phi_c'\varphi' + \frac{dV}{d\phi}(\phi_c)\varphi\,,$$

$$\delta T^0_i = \frac{1}{a^2}\phi_c'\partial_i\varphi\,,$$

$$\delta T^i_j \equiv -\delta^i_j\delta p_\varphi\,,$$

$$\delta p_\varphi = -\frac{1}{a^2}\left(\phi_c'\right)^2\Phi + \frac{1}{a^2}\phi_c'\varphi' - \frac{dV}{d\phi}(\phi_c)\varphi\,.$$

Scalar perturbations and Einstein equations

The metrics: $ds^2 = a^2(\eta)\left[(1+2\Phi)\,d\eta^2 - (1-2\Psi)\,\gamma_{\alpha\beta}dx^\alpha dx^\beta\right]$

The perturbations of the scalar field energy-momentum tensor:

$$\delta T_0^0 \equiv \delta\varepsilon_\varphi = -\frac{1}{a^2}\left(\phi_c'\right)^2\Phi + \frac{1}{a^2}\phi_c'\varphi' + \frac{dV}{d\phi}(\phi_c)\varphi\,,$$

$$\delta T_i^0 = \frac{1}{a^2}\phi_c'\partial_i\varphi\,,$$

$$\delta T_j^i \equiv -\delta_j^i\delta p_\varphi\,,$$

$$\delta p_\varphi = -\frac{1}{a^2}\left(\phi_c'\right)^2\Phi + \frac{1}{a^2}\phi_c'\varphi' - \frac{dV}{d\phi}(\phi_c)\varphi\,.$$

Where we split the sc.f. into the background part $\phi_c(\eta)$ and its fluctuation part $\varphi(\eta,\mathbf{r})$: $\phi = \phi_c + \varphi$

Scalar perturbations and Einstein equations

The metrics: $ds^2 = a^2(\eta)\left[(1+2\Phi)\,d\eta^2 - (1-2\Psi)\,\gamma_{\alpha\beta}dx^\alpha dx^\beta\right]$

The perturbations of the scalar field energy-momentum tensor:

$$\delta T_0^0 \equiv \delta\varepsilon_\varphi = -\frac{1}{a^2}\left(\phi_c'\right)^2\Phi + \frac{1}{a^2}\phi_c'\varphi' + \frac{dV}{d\phi}(\phi_c)\varphi\,,$$

$$\delta T_i^0 = \frac{1}{a^2}\phi_c'\partial_i\varphi\,,$$

$$\delta T_j^i \equiv -\delta_j^i\delta p_\varphi\,,$$

$$\delta p_\varphi = -\frac{1}{a^2}\left(\phi_c'\right)^2\Phi + \frac{1}{a^2}\phi_c'\varphi' - \frac{dV}{d\phi}(\phi_c)\varphi\,.$$

Where we split the sc.f. into the background part $\phi_c(\eta)$ and its fluctuation part $\varphi(\eta,\mathbf{r})$: $\phi = \phi_c + \varphi$

For the considered model, Einstein equations are reduced (after linearising the system of 3 equations) to:

$$\Delta\Phi - 3\mathcal{H}(\Phi' + \mathcal{H}\Phi) + 3\mathcal{K}\Phi = \frac{\kappa}{2}a^2\left(\delta\varepsilon_{\mathrm{dust}} + \delta\varepsilon_{\mathrm{rad}}\right) - \frac{\kappa}{2}\left[(\phi_c')^2\Phi - \phi_c'\varphi' - a^2\frac{dV}{d\phi}(\phi_c)\varphi\right],$$

$$\partial_i\Phi' + \mathcal{H}\partial_i\Phi = \frac{\kappa}{2}\phi_c'\partial_i\varphi\,,$$

$$\frac{2}{a^2}\left[\Phi'' + 3\mathcal{H}\Phi' + \Phi\left(2\frac{a''}{a} - \mathcal{H}^2 - \mathcal{K}\right)\right] = \kappa\left(\delta p_{\mathrm{rad}} - \frac{1}{a^2}\left(\phi_c'\right)^2\Phi + \frac{1}{a^2}\phi_c'\varphi' - \frac{dV}{d\phi}(\phi_c)\varphi\right)$$

Spatial distributions of $\delta\varepsilon_{\mathrm{rad}}$ is defined by Φ

After substitution of the second Einstein equation, usage of some well-known relations and help of the background Friedmann and Raychaudhuri equations and the equation of motion, the third Einstein equation takes the form:

$$\Phi\left[-\frac{2}{3}a^2\kappa\bar{\varepsilon}_{\mathrm{rad}}-\frac{1}{2}a^2\kappa\bar{\varepsilon}_{\mathrm{dust}}\right]=\kappa\frac{a^2}{2}\delta p_{\mathrm{rad}}$$

Spatial distributions of $\delta\varepsilon_{\mathrm{rad}}$ is defined by Φ

After substitution of the second Einstein equation, usage of some well-known relations and help of the background Friedmann and Raychaudhuri equations and the equation of motion, the third Einstein equation takes the form:

$$\Phi\left[-\frac{2}{3}a^2\kappa\bar{\varepsilon}_{\mathrm{rad}}-\frac{1}{2}a^2\kappa\bar{\varepsilon}_{\mathrm{dust}}\right]=\kappa\frac{a^2}{2}\delta p_{\mathrm{rad}}$$

Because, $\bar{\varepsilon}_{\mathrm{rad}}\sim 1/a^4$ and $\bar{\varepsilon}_{\mathrm{dust}}\sim 1/a^3$, we can drop the first term in the brackets in the left-hand-side of this equation and obtain:

$$\delta p_{\mathrm{rad}}=-\Phi\bar{\varepsilon}_{\mathrm{dust}}=-\Phi\frac{\bar{\rho}c^2}{a^3}=\frac{1}{3}\delta\varepsilon_{\mathrm{rad}}$$

Spatial distributions of $\delta\varepsilon_{\rm rad}$ is defined by Φ

After substitution of the second Einstein equation, usage of some well-known relations and help of the background Friedmann and Raychaudhuri equations and the equation of motion, the third Einstein equation takes the form:

$$\Phi\left[-\frac{2}{3}a^2\kappa\bar{\varepsilon}_{\rm rad}-\frac{1}{2}a^2\kappa\bar{\varepsilon}_{\rm dust}\right]=\kappa\frac{a^2}{2}\delta p_{\rm rad}$$

Because, $\bar{\varepsilon}_{\rm rad}\sim 1/a^4$ and $\bar{\varepsilon}_{\rm dust}\sim 1/a^3$, we can drop the first term in the brackets in the left-hand-side of this equation and obtain:

$$\delta p_{\rm rad}=-\Phi\bar{\varepsilon}_{\rm dust}=-\Phi\frac{\bar{\rho}c^2}{a^3}=\frac{1}{3}\delta\varepsilon_{\rm rad}$$

Since the definition for $\delta\varepsilon_{\rm rad}$, taking into account the resulted second and third Einstein equations, some algebra and after substitution $\Phi=\Omega/a$, where Ω is a function of a and the spatial coordinates, the first Einstein equation reads:

$$\frac{\Delta\Omega}{a}-\frac{\kappa}{2}\frac{\delta\rho c^2}{a}=\frac{\Omega}{a}\left[-3\mathcal{K}-\frac{\kappa}{2}(\phi_c')^2\right]+\frac{d\Omega}{da}\left[3\mathcal{H}^2+\mathcal{H}'-\mathcal{H}\frac{\phi_c''}{\phi_c'}+a^2\frac{dV}{d\phi}(\phi_c)\frac{1}{\phi_c'}\mathcal{H}\right]+\frac{d^2\Omega}{da^2}a\mathcal{H}^2$$

Then, we are looking for the solutions of this equation which have a Newtonian limit near gravitating masses.

The coupled scalar field can provide the late cosmic acceleration

In the flat *K=0* topology, if the dust-like matter is described by the discrete distributed gravitating sources (galaxies) with masses m_i and the rest-mass density $\rho = \sum_i m_i \delta(\mathbf{r} - \mathbf{r}_i)$, the grav. potential is:

$$\Phi = -\frac{G_N}{c^2}\frac{1}{a}\sum_i \frac{m_i}{|\mathbf{r} - \mathbf{r}_i|} = -\frac{G_N}{c^2}\sum_i \frac{m_i}{|\mathbf{R} - \mathbf{R}_i|}$$

It also demonstrates that $\Phi \sim 1/a$. After $\phi_c' = \beta = const$, we get that $\phi_c = \beta\eta + \gamma, \quad \gamma = \mathrm{const}$

Then the eq. of motion: $2\frac{a'}{a}\beta + a^2\frac{dV}{d\phi}(\phi_c) = 2\frac{a'}{a}\beta + a^2\frac{V'}{\beta} = 0\,,$

$$\Rightarrow \quad V = \frac{\beta^2}{a^2} + V_\infty, \quad V_\infty = \mathrm{const}$$

The coupled scalar field can provide the late cosmic acceleration

In the flat *K=0* topology, if the dust-like matter is described by the discrete distributed gravi...ing sources (galaxies) with masses m_i and the rest-mass density $\rho = \sum_i m_i \delta(\mathbf{r} - \mathbf{r}_i)$, the grav...

$$\Phi = -\frac{G_N}{c^2}\frac{1}{a}\sum_i \frac{m_i}{|\mathbf{r}-\mathbf{r}_i|} = -\frac{G_N}{c^2}\sum_i \ldots$$

It also demonstrates that $\Phi \sim 1/$... $=$*const*, we get that $\phi_c = \beta\eta + \gamma, \quad \gamma = \mathrm{const}$

Then the eq... $2\frac{a'}{a}\beta + a^2\frac{dV}{d\phi}(\phi_c) = 2\frac{a'}{a}\beta + a^2\frac{V'}{\beta} = 0\,,$

$$\Rightarrow \quad V = \frac{\beta^2}{a^2} + V_\infty\,, \quad V_\infty = \mathrm{const}$$

The scalar field behaves as a two-component perfect fluid

The coupled scalar field can provide the late cosmic acceleration

In the flat *K=0* topology, if the dust-like matter is described by the discrete distributed gravit ing sources (galaxies) with masses m_i and the rest-mass density $\rho = \sum_i m_i \delta(\mathbf{r} - \mathbf{r}_i)$, the grav

$$\Phi = -\frac{G_N}{c^2}\frac{1}{a}\sum_i \frac{m_i}{|\mathbf{r}-\mathbf{r}_i|} = -\frac{G_N}{c^2}\sum_i \frac{m_i}{|\mathbf{r}}$$

The scalar field behaves as a two-component perfect fluid

It also demonstrates that $\Phi \sim 1/$ $=$*const*, we get that $\phi_c = \beta\eta + \gamma, \quad \gamma = \mathrm{const}$

Then the eq tion: $2\frac{a'}{a}\beta + a^2\frac{dV}{d\phi}(\phi_c) = 2\frac{a'}{a}\beta + a^2\frac{V'}{\beta} = 0\,,$

$$\Rightarrow \quad V = \frac{\beta^2}{a^2} + V_\infty\,, \quad V_\infty = \mathrm{const}$$

For the background energy density and pressure: $\bar{\varepsilon}_\varphi = \frac{3}{2}\frac{\beta^2}{a^2} + V_\infty\,, \quad \bar{p}_\varphi = -\frac{1}{2}\frac{\beta^2}{a^2} - V_\infty$

We derived a specific form for the time dependence of the background scalar field and for its potential so that the scalar field is consistent with such a coupling to the inhomogeneities.

The fluctuations of the scalar field are absent but the fluctuations of the energy density and pressure are non-zero. These fluctuations are concentrated around galaxies, in full agreement with the coupling condition.

The coupled scalar field can provide the late cosmic acceleration

In the flat *K=0* topology, if the dust-like matter is described by the discrete distributed gravi…ing sources (galaxies) with masses m_i and the rest-mass density $\rho = \sum_i m_i \delta(\mathbf{r}-\mathbf{r}_i)$, the grav…

$$\Phi = -\frac{G_N}{c^2}\frac{1}{a}\sum_i \frac{m_i}{|\mathbf{r}-\mathbf{r}_i|} = -\frac{G_N}{c^2}\sum_i \frac{m_i}{\ldots}$$

The scalar field behaves as a two-component perfect fluid

It also demonstrates that $\Phi \sim 1/\ldots$ … $=$*const*, we get that $\phi_c = \beta\eta + \gamma, \quad \gamma = \text{const}$

Then the eq…tion: $2\frac{a'}{a}\beta + a^2\frac{dV}{d\phi}(\phi_c) = 2\frac{a'}{a}\beta + a^2\frac{V'}{\beta} = 0\,,$

$$\Rightarrow \quad V = \frac{\beta^2}{a^2} + V_\infty, \quad V_\infty = \text{const}$$

For the background energy den… $\frac{3}{2}\frac{\beta^2}{\ldots} + V_\infty, \quad \bar{p}_\varphi = -\frac{1}{2}\frac{\beta^2}{a^2} - V_\infty$

$$V \simeq V_\infty + \frac{\beta^2}{a_0^2}\left(\frac{\phi_c}{A}\right)^2 = V_\infty\left[1 + \frac{2\Omega_\beta}{3\Omega_\lambda}\left(\frac{\phi_c}{A}\right)^2\right]$$

We derived a specific form for … s potential so that the scalar field is consistent wi…

The fluctuations of the scalar field are absent but the fluctuations of the energy density and pressure are non-zero. These fluctuations are concentrated around galaxies, in full agreement with the coupling condition.

The coupled scalar field ca… …ic acceleration

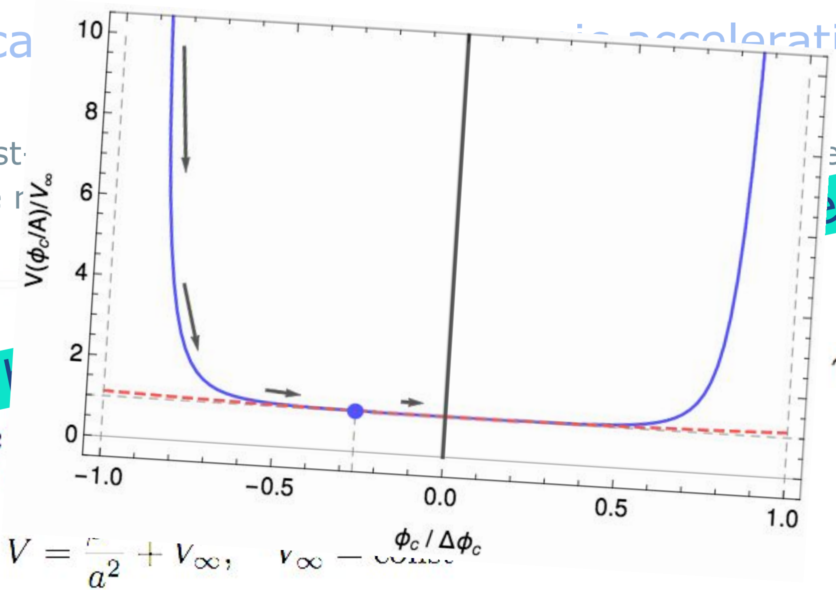
In the flat $K=0$ topology, if the dust… …ed gravitating sources (galaxies) with masses m_i and the r…

ect fluid

It also demonstrates that $\Phi \sim 1/\dots$

The scalar field …

Then the eq…ation: $2\frac{\dots}{a}\beta + a^2$



$\gamma = \mathrm{const}$

$$\Rightarrow \quad V = \frac{\dots}{a^2} + V_\infty ; \quad V_\infty = \mathrm{const}$$

For the background energy den… $\dots \frac{3}{\dots}\frac{\beta^2}{\dots} + V_\infty ; \quad \bar{p}_\varphi = -\frac{1}{2}\frac{\beta^2}{a^2} - V_\infty$

$$V \simeq V_\infty + \frac{\beta^2}{a_0^2}\left(\frac{\phi_c}{A}\right)^2 = V_\infty\left[1 + \frac{2\Omega_\beta}{3\Omega_\lambda}\left(\frac{\phi_c}{A}\right)^2\right]$$

We derived a specific form for… …s potential so that the scalar field is consistent wit…

The fluctuations of the scalar field are absent but the fluctuations of the energy density and pressure are non-zero. These fluctuations are concentrated around galaxies, in full agreement with the coupling condition.

Conclusions

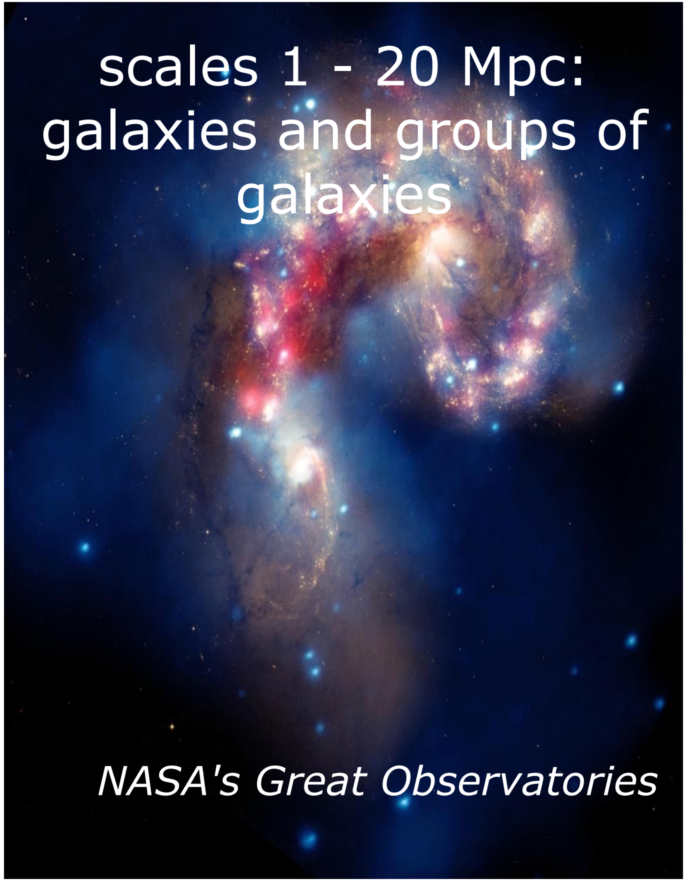
- Considered scalar field behaves as a two component perfect fluid.
- Its potential should be very at at the present time.
- The fluctuations of this field are absent but the fluctuations of the energy density and pressure are non-zero. These fluctuations are concentrated around galaxies, in full agreement with the coupling condition.

The coupled scalar fields may exist under the conditions mentioned above and can provide the late cosmic acceleration.

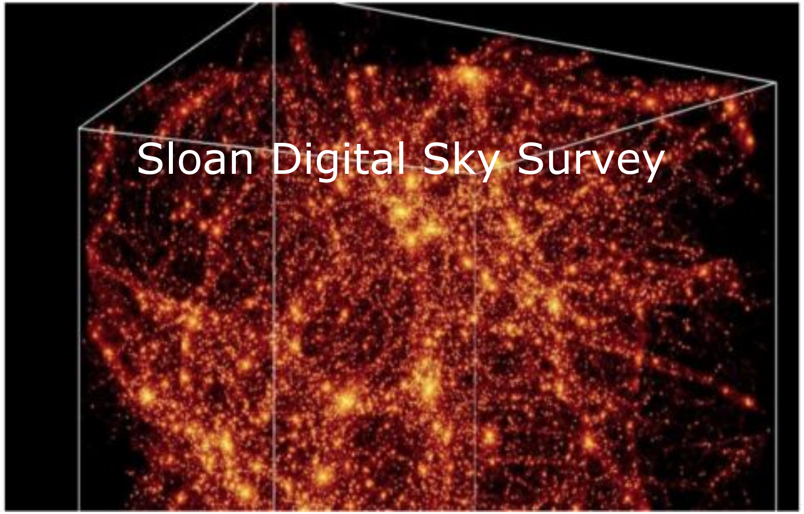
Thank you for your attention!

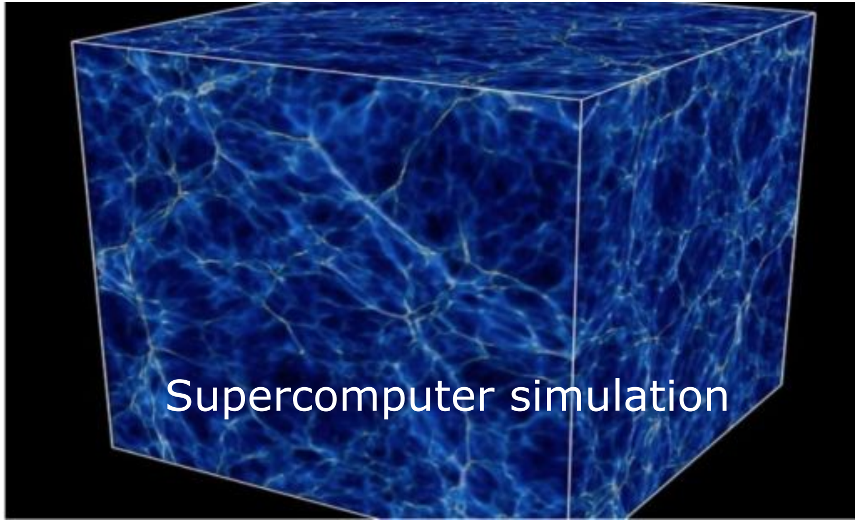
Alvina Burgazli
aburgazli@gmail.com

Inhomogeneous Universe



Scales 50-200 Mpc: filaments and voids





Newtonian potential $\Phi \sim 1/R$ is used to simulate the structure formation.

Up to which scales can we use the Newtonian potential?

Cosmological Principle (CP)

→ Physical background for the CP:

CP is the notion that the spatial distribution of matter in the Universe is homogeneous and isotropic when viewed on large enough scales

However, recent observations (XXI Century):

There are cosmic structures with $l \gg 300\,\mathrm{Mpc}$.

The largest cosmic structures

$$l \approx 423\,\mathrm{Mpc}$$

Giant filament consisting of a number of superclusters

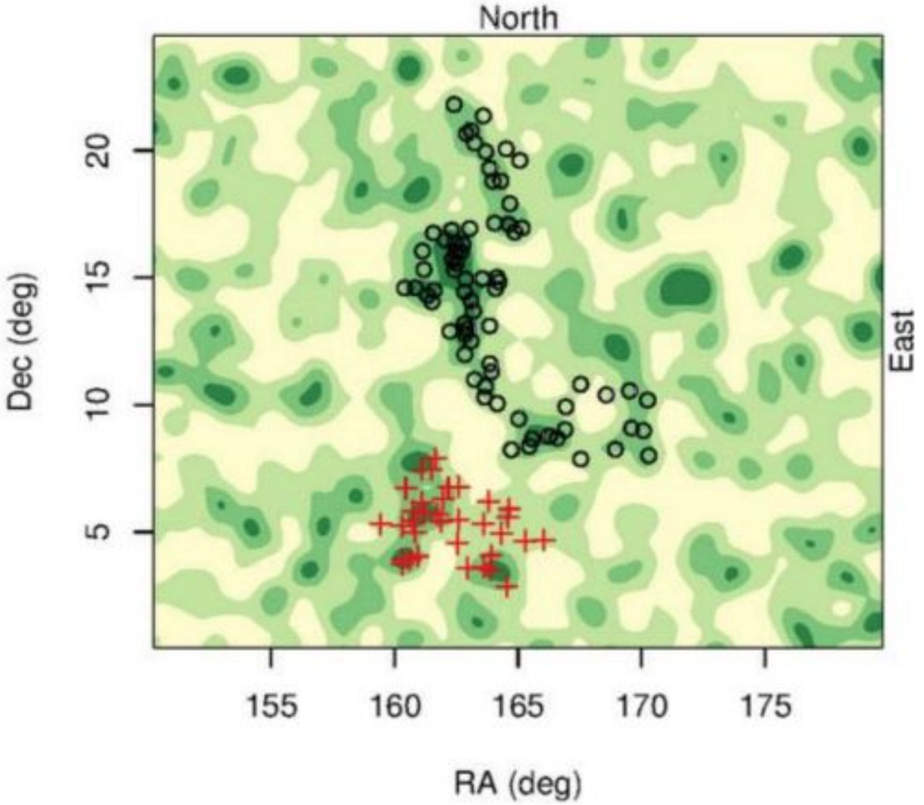
Large Quasar Groups

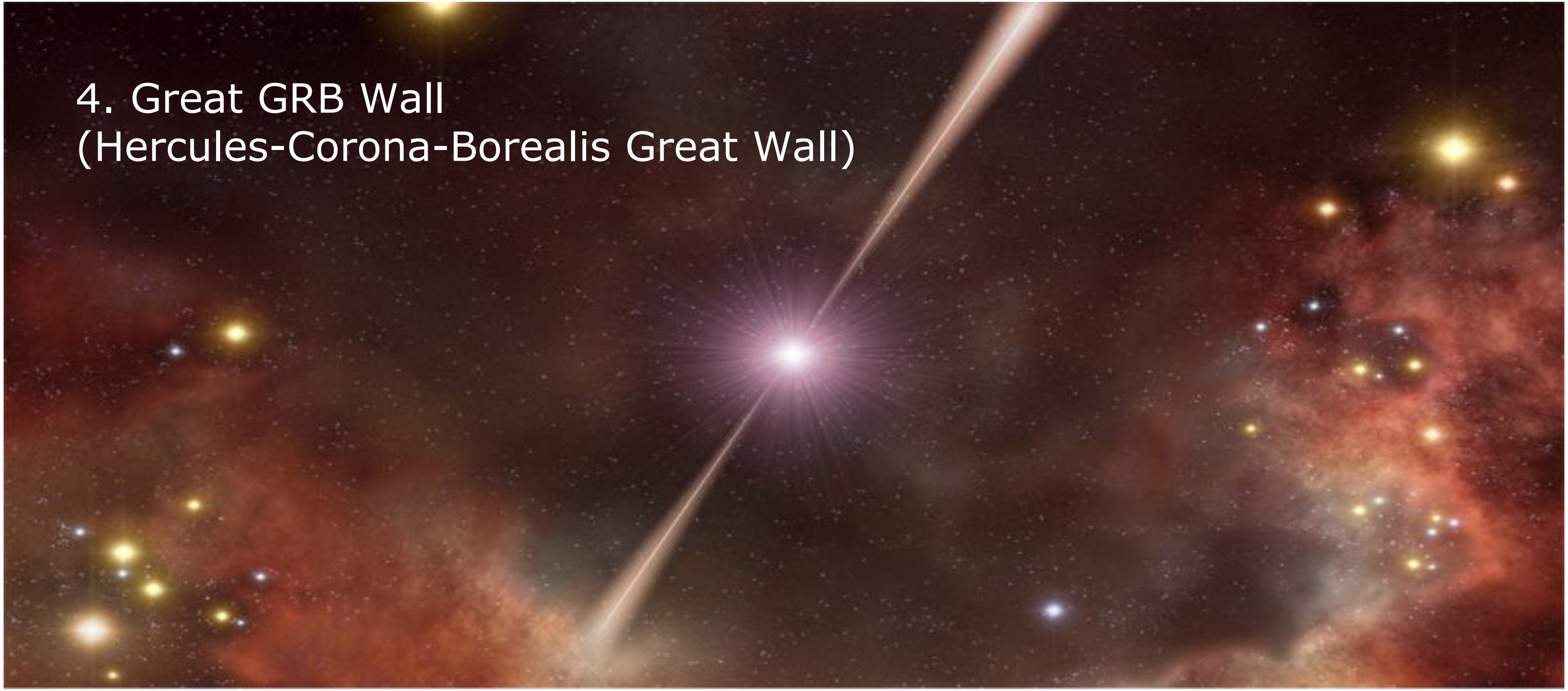
2. Clowes-Campusano LQG:
34 quasars (red crosses)

$$l \approx 613\,\mathrm{Mpc}$$

3. Huge LQG:
73 quasars (black rings)

$$l \approx 1226\,\mathrm{Mpc}$$





A region of the sky seen in the data set mapping of gamma-ray bursts (GRBs) that has been found to have an unusually higher concentration of similarly distanced GRBs than the expected average distribution.

These huge structures are the great challenge!

- Can we explain such big structures?
- Do larger structures exists?
- From which scales does the cosmological principle start to work?
- Can we use the Newtonian potential for the structure formation simulation on any cosmological scale?

?

Two main distinct approaches to structure growth investigation

relativistic perturbation theory	N-body simulations generally based on Newtonian cosmological approximation
Keywords	
early Universe; linearity; large scales	late Universe; nonlinearity; small scales
fails in describing nonlinear dynamics at small distances	do not take into account relativistic effects becoming non-negligible at large distances

Origin of cosmic structures

Cosmic structures are formed (grow up) due to the gravitational interaction → **Gravitational potential** $\Phi, \nabla\Phi \neq 0$

Newtonian mechanics

Poisson eq. $\Delta\Phi = \frac{4\pi G}{c^2}\rho \equiv \frac{\kappa}{2}\rho c^2, \quad \rho -$ **rest-mass density**

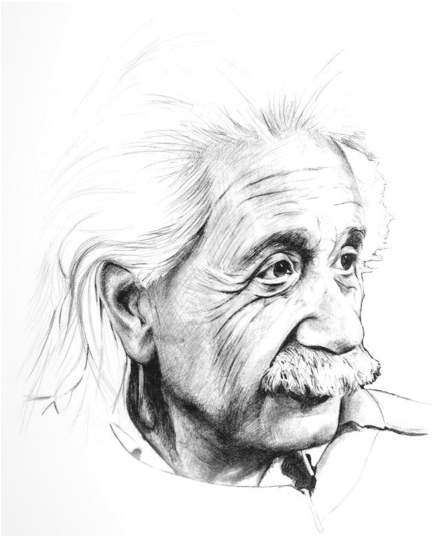
$$\rho = \sum_n m_n \delta\left(\vec{R} - \vec{R}_n\right)$$

$$\Phi(R) \sim \sum_n \frac{m_n}{\left|\vec{R} - \vec{R}_n\right|}$$

This sum is divergent in the case of infinite number of sources → Neumann-Seeliger paradox

The Neumann-Seeliger paradox

should be resolved within the framework of General Relativity (taking into account relativistic effects)



Einstein equations

Background equations

Background FLRW metric (homogeneous and isotropic):

$$ds^2 = a^2\left(d\eta^2 - \delta_{\alpha\beta}dx^\alpha dx^\beta\right)$$

scale factor $a(\eta)$ conformal time comoving spatial coordinate

physical distance: $R = ar$

Background matter (CDM: $\bar{p} = 0$):

energy density $\bar{\varepsilon} = \bar{\rho}c^2 = \dfrac{\bar{\rho}_c c^2}{a^3}$, $\bar{\rho}_c = \text{const} \longleftarrow$ comoving rest mass density

Friedmann equations

in the framework of the pure ΛCMD model (with a negligible radiation contribution):

$$\frac{3\tilde{H}^2}{a^2} = \kappa\overline{\varepsilon} + \Lambda \qquad \frac{2\tilde{H}' + \tilde{H}^2}{a^2} = \Lambda$$

energy density of nonrelativistic pressureless matter

cosmological constant

$$\tilde{H} \equiv \frac{a'}{a} \qquad \kappa \equiv 8\pi G_N / c^4$$

Newtonian gravitational constant

overline: **average value ;**
prime: **derivative with respect to η**

Newtonian approximation in cosmology

without relativistic effects (see e.g. Peebles, Gorbunov & Rubakov)

$$\Delta_c\Phi = \frac{4\pi G}{c^2}a^2\delta\rho = \frac{4\pi G}{c^2}\frac{\delta\rho_c}{a}, \qquad \delta\rho_c = \rho_c - \bar{\rho}_c, \quad \Delta_c = a^2\Delta$$

$$\rho_c = \sum_n m_n \delta(\vec{r} - \vec{r}_n)$$

Solution:

$$\Phi \sim \int d\vec{r}' \frac{\rho_c|_{\vec{r}=\vec{r}'} - \bar{\rho}_c}{|\vec{r} - \vec{r}'|}, \quad -\nabla\Phi \sim \int d\vec{r}' \frac{\rho_c|_{\vec{r}=\vec{r}'}}{|\vec{r} - \vec{r}'|^3}(\vec{r} - \vec{r}') \sim \sum_n \frac{m_n}{|\vec{r} - \vec{r}_n|^3}(\vec{r} - \vec{r}_n)$$

are not well-defined!

Can we resolve both of these problems:
- to define an upper limit on the size of cosmic structures;
- to obtain well-defined form of the gravitational potential?

Solution: **relativistic effects!**

Gravitational potential in general relativity

Theory of scalar perturbations

gravitational potential

Perturbed FLRW metric: $$ds^2 = a^2\left[\left(1+2\Phi\right)d\eta^2 - \left(1-2\Phi\right)\delta_{\alpha\beta}dx^\alpha dx^\beta\right]$$

Linearized Einstein equations $(\Phi \ll 1)$:

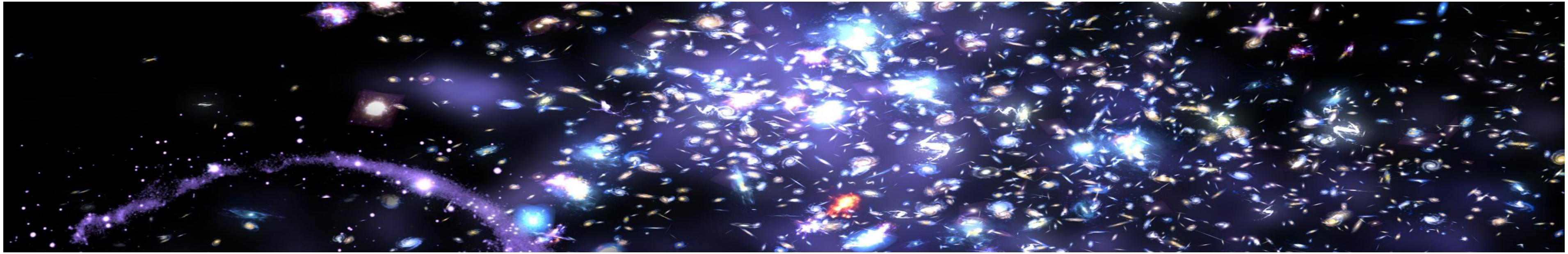
$$G_0^0 = \kappa T_0^0 + \Lambda \quad \Rightarrow \quad \Delta_c\Phi - 3\tilde{H}(\Phi' + \tilde{H}\Phi) = \frac{1}{2}\kappa a^2 \delta T^0_{0(\mathrm{CDM})}$$

$$G_\alpha^0 = \kappa T_\alpha^0 + \Lambda \quad \Rightarrow \quad \frac{\partial}{\partial x^\alpha}(\Phi' + \tilde{H}\Phi) = \frac{1}{2}\kappa a^2 \delta T^0_{\alpha(\mathrm{CDM})}$$

$$G_\beta^\alpha = \kappa T_\beta^\alpha + \Lambda \quad \Rightarrow \quad \Phi'' + 3\tilde{H}\Phi' + \left(2\tilde{H}' + \tilde{H}^2\right)\Phi = 0$$

$${}' \equiv \frac{d}{d\eta}, \qquad \tilde{H} = \frac{da}{d\eta}\frac{1}{a}$$

We consider CDM as a set of point-like inhomogeneities (e.g. galaxies, groups and clusters of galaxies).



Energy-momentum tensor (EMT) of inhomogeneities (e.g. Landau&Lifshitz):

$$T^{ik} = \sum_n \frac{m_n c^2}{(-g)^{1/2}[\eta]} \frac{dx_n^i}{d\eta} \frac{dx_n^k}{d\eta} \frac{1}{ds_n / d\eta} \delta(\mathbf{r} - \mathbf{r}_n)$$

$$\tilde{v}_n^\alpha \equiv \frac{dx_n^\alpha}{d\eta} = \frac{a}{c}\frac{dx_n^\alpha}{dt} = \frac{a v_n^\alpha}{c} = \frac{v_{phn}^\alpha}{c}, \quad \alpha = 1,2,3$$ ← comoving peculiar velocity

$$\rho_c = \sum_n m_n \delta(\mathbf{r} - \mathbf{r}_n) \equiv \sum_n \rho_{cn}$$ ← comoving rest-mass density

Due to explicit dependence T_0^0 on g_{ik} and ρ

EMT perturbations:

effects of nonlinearity:

$$\delta T^0_{0(\mathrm{CDM})} \approx \frac{\delta\rho_c c^2}{a^3} + \boxed{\frac{3\bar{\rho}_c c^2}{a^3}\Phi},$$

$\delta\rho_c = \rho_c - \bar{\rho}_c$ – can be $\gg \bar{\rho}_c$

$$\delta T^0_\alpha = -\frac{c^2}{a^3}\sum_n m_n \delta(\vec{r}-\vec{r}_n)\tilde{v}^\alpha_n = -\frac{c^2}{a^3}\sum_n \rho_{cn}\tilde{v}^\alpha_n, \quad \delta T^\alpha_\beta = 0$$

effective velocity potential: $\sum_n \rho_{cn}\vec{\tilde{v}}_n \equiv \nabla\Xi + \cancel{\mathrm{curl}}$

$$\frac{\partial}{\partial x^\beta}(\Phi' + \tilde{\mathrm{H}}\Phi) = \frac{1}{2}\kappa a^2 \delta T^0_{\beta(\mathrm{CDM})} \longrightarrow \Phi' + \tilde{H}\Phi = -\frac{\kappa c^2}{2a}\Xi$$

$$\Delta_c\Phi - 3\tilde{\mathrm{H}}(\Phi' + \tilde{\mathrm{H}}\Phi) = \frac{1}{2}\kappa a^2 \delta T^0_{0(\mathrm{CDM})}$$

Helmholtz (not Poisson!) equation

$$\boxed{\Delta_c\Phi - \frac{a^2}{\lambda^2}\Phi = \frac{\kappa c^2}{2a}\delta\rho_c - \frac{3\kappa c^2\tilde{H}}{2a}\Xi}$$

$$\Xi = \frac{1}{4\pi}\sum_n m_n \frac{(\vec{r}-\vec{r}_n)\tilde{\vec{v}}_n}{|\vec{r}-\vec{r}_n|^3}$$

$$\lambda = \left[\frac{3\kappa}{2}\bar{\varepsilon}\right]^{-1/2} = \sqrt{\frac{2a^3}{3\kappa\bar{\rho}_c c^2}} = \sqrt{\frac{2c^2}{9H_0^2\Omega_M}\left(\frac{a}{a_0}\right)^3}, \quad \Omega_M \equiv \frac{\kappa\bar{\rho}_c c^4}{3H_0^2 a_0^3}$$

λ defines the range of the Yukawa interaction!

At present time $\lambda_0 \approx 3700$ Mpc

Cosmological screening (i.e. finite λ) is the effect of the background: $\bar{\varepsilon} \neq 0$

$\frac{1}{3}$ for CDM — Newton potential — Yukawa potential

$$\Phi = \boxed{\frac{\kappa\bar{\rho}_c c^2}{2a}\frac{\lambda^2}{a^2}} - \boxed{\frac{\kappa c^2}{8\pi a}\sum_n \frac{m_n}{\left|\vec{r}-\vec{r}_n\right|}\exp\left(-q_n\right)}$$

$$+\frac{3\kappa c^2}{8\pi a}\tilde{H}\sum_n \frac{m_n\left[\tilde{\vec{v}}_n\left(\vec{r}-\vec{r}_n\right)\right]}{\left|\vec{r}-\vec{r}_n\right|}\frac{1-\left(1+q_n\right)\exp\left(-q_n\right)}{q_n^2}$$

$$\vec{q}_n \equiv \frac{a}{\lambda}\left(\vec{r}-\vec{r}_n\right) = \frac{1}{\lambda}\left(\vec{R}-\vec{R}_n\right)$$

1. Newtonian approximation: $\left|\vec{R}-\vec{R}_n\right| \ll \lambda$ (and ignore velocities as a source of the grav. field)
2. Exponential suppression: $\left|\vec{R}-\vec{R}_n\right| \gg \lambda$

→ the largest structures $\le \lambda$ $\left(\lambda_0 \approx 3700\ \mathrm{Mpc} > 3066\ \mathrm{Mpc}\right)$; (Great GRBs Wall)
the absence of the Neumann-Seeliger paradox.

The Yukawa interaction range and the horizons

$$\lambda = \left[\frac{3\kappa}{2}\bar{\varepsilon}\right]^{-1/2} = \sqrt{\frac{2a^3}{3\kappa\bar{\rho}_c c^2}} = \frac{1}{\sqrt{3(1+q)}}\frac{c}{H} \sim a^{3/2}$$

At the present time: $\lambda_0 \approx 3.7\times 10^3\ \mathrm{Mpc}$

Hubble horizon (radius): (this horizon is not really a physical size)

$$c/H_0 \approx 4.1\times 10^3\,\mathrm{Mpc} > \lambda_0$$

$$\underset{\substack{\uparrow \\ a=1.16\,a_0}}{c/H} = \lambda \quad \text{at the deceleration parameter} \quad q = -\ddot{a}/(aH^2) = -2/3$$

Particle horizon: (this is the farthest distance that any photon can freely stream from the Big Bang – the size of the observable Universe)

$$l_p(t_0) = a(t_0)\int_0^{t_0}\frac{cd\tilde{t}}{a(\tilde{t})} \approx 14.26\times 10^3\ \mathrm{Mpc}$$ - radius of the observable Universe

Universality of the Yukawa suppression

Additionally two sets of continuous perfect fluids:

$$\underbrace{\text{Linear EoS } p_I = \omega_I \varepsilon_I, \quad \omega_I = \text{const} \text{ . Non linear EoS } p_J = f_J(\varepsilon_J)}_{\text{Dark energy: } (p \approx -\varepsilon), \quad \text{radiation: } (p = \varepsilon/3) \quad \text{etc}}$$

Total Φ can be split into individual contributions from inhomogeneities of each matter source:

$$\Phi = \Phi_{\text{CDM}} + \underbrace{\sum_I \Phi_I + \sum_J \Phi_J}_{\text{continuous perfect fluids}}$$

discrete CDM

Each of components Φ satisfies the Helmholtz eq. with the **same** λ

$$\begin{cases} \Delta_c \Phi_{CDM} - \dfrac{a^2}{\lambda^2}\Phi_{CDM} = \dfrac{\kappa c^2}{2a}\delta\rho_c - \dfrac{3\kappa c^2 \tilde{H}}{2a}\Xi \\ \Delta_c \Phi_I - \dfrac{a^2}{\lambda^2}\Phi_I = \dfrac{\kappa}{2}\dfrac{\delta A_I}{a^{1+3\omega_I}} - \dfrac{3\kappa\tilde{H}}{2}\dfrac{1+\omega_I}{a^{1+3\omega_I}}\xi_I \\ \Delta_c \Phi_J - \dfrac{a^2}{\lambda^2}\Phi_J = \dfrac{\kappa a^2}{2}\bar{\varepsilon}_J \delta_J - \dfrac{3\kappa a^2 \tilde{H}}{2}\left(\bar{\varepsilon}_J + \bar{p}_J\right)\nu_J \end{cases}$$

$$\frac{1}{\lambda^2} = \frac{3\kappa}{2}\left[\bar{\varepsilon}_{\mathrm{CDM}} + \underbrace{\sum_I \left(\bar{\varepsilon}_I + \bar{p}_I\right) + \sum_J \left(\bar{\varepsilon}_J + \bar{p}_J\right)}_{\bar{p} \approx -\bar{\varepsilon} \;\Rightarrow\; \approx 0}\right] = \frac{3}{c^2}H^2(1+q)$$

$\longrightarrow$ $\lambda \approx \lambda_0 \approx 3700\ \mathrm{Mpc}$ at present time

Conclusions

1. Our approach works **at all cosmological scales** (i.e. sub-horizon and super-horizon) and incorporates **linear and nonlinear effects** with respect to the energy density fluctuations ($\delta\varepsilon / \bar{\varepsilon}$ can be $\gg$1).

2. The gravitational potential can be split into individual contributions from inhomogeneities of each matter source (i.e. discrete CDM and continuous DE). Each of these contributions satisfies its own Helmholtz-type equation.

3. The gravitational potentials are characterized by a finite time-dependent Yukawa interaction range being the **same** for each individual contributions. At the present time

$$\lambda \approx \lambda_0 \approx 3700 \text{ Mpc}$$

The value λ_0 is bigger than **the largest known structure** in the Universe (**Great GRBs Wall**):

$$\lambda_0 \approx 3700 \text{ Mpc} > 3066 \text{ Mpc}$$

4. At distances $\left|\vec{R}-\vec{R}_n\right| > \lambda$ the gravitational potential of the n-th fluctuation is exponentially suppressed. This suppression is called the cosmological screening. The cosmological background is responsible for this effect (greetings to Ernst Mach!).

$\left|\vec{R}-\vec{R}_n\right| << \lambda \longrightarrow$ Newton

$$\Phi(R) \sim \sum_n \frac{m_n}{\left|\vec{R}-\vec{R}_n\right|}$$

$\left|\vec{R}-\vec{R}_n\right| >> \lambda \longrightarrow$ Yukawa

$$\Phi \sim \sum_n \frac{m_n}{\left|\vec{R}-\vec{R}_n\right|} \exp(-q_n)$$

Newton is wrong at the cosmological distances $\left|\vec{R}-\vec{R}_n\right| > \lambda$

arXiv:1509.03835
arXiv:1607.03394