Diffusive DE and DM

Eduardo Guendelman With my student David Benisty, expanding on previous talk by Emil Nissimov

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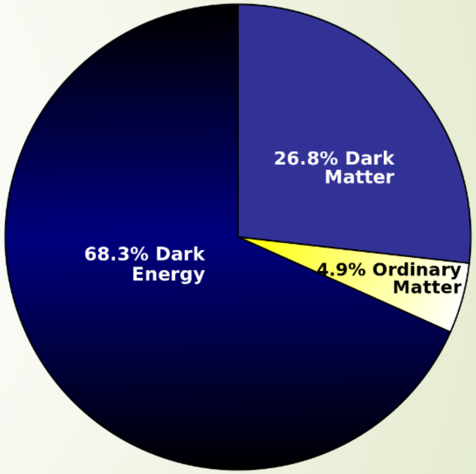
Problems in late cosmology

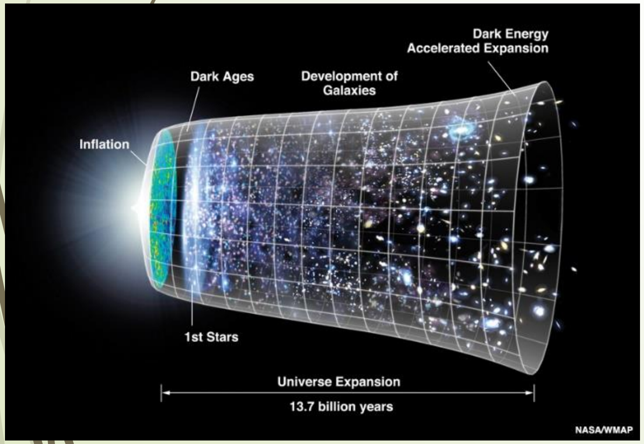
The vacuum energy behaves as the Λ term in Einstein's field equation

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \Lambda g_{\mu\nu} + T_{\mu\nu}$$

called the cosmological constant.

- Why is the observed value so many orders of magnitude smaller than that expected in QFT?





- Why is it of the same order of magnitude as the matter density of the universe at the present time?

Two Measure Theory

- In addition to the regular measure $\sqrt{-g}$, as we have seen in the previous lecture introduce other measures which is also a density and a total derivative. For example constructing this measure out of a 4 index field strength as done in the previous lecture, recall also the talk by Padilla, who is basically describing a particular case of our modified measure theories. We can also proceed by using 4 scalar fields $\phi^{(a)}$, where a = 1, 2, 3, 4:

$$\Phi = \frac{1}{4!}\varepsilon^{\mu\nu\rho\sigma}\varepsilon_{abcd}\partial_\mu\phi^{(a)}\partial_\nu\phi^{(b)}\partial_\rho\phi^{(c)}\partial_\sigma\phi^{(d)} = \det\left\|\phi^{(i)}_{,j}\right\|$$

with the total action:

$$S = \int \sqrt{-g}\mathcal{L}_1 + \Phi\mathcal{L}_2$$

- The variation from the scalar fields $\phi^{(a)}$ we get $\mathcal{L}_2 = \mathrm{M} = \mathrm{const.}$

Unified scalar DE-DM, like in talk before, for a very simple case

- For a scalar field theory with a new measure:

$$S = \int \sqrt{-g}R + (\sqrt{-g} + \Phi)\Lambda \, \mathrm{d}^4\mathrm{x}$$

where $\Lambda = g^{\alpha\beta}\varphi_{,\alpha}\varphi_{,\beta}$. The Equations of Motion:

$$\Lambda = M = const$$

$$j^\mu = \left(1 + \frac{\Phi}{\sqrt{-g}}\right)\partial^\mu\varphi$$

$$T^{\mu\nu} = g^{\mu\nu}\Lambda + \left(1 + \frac{\Phi}{\sqrt{-g}}\right)\partial^\mu\varphi\partial^\nu\varphi = g^{\mu\nu}\Lambda + j^\mu\partial^\nu\varphi$$

- Dark Energy and Dark Matter From Hidden Symmetry of Gravity Model with a Non-Riemannian Volume Form European Physical Journal C75 (2015) 472-479 arXiv:1508.02008
- A two measure model of dark energy and dark matter Eduardo Guendelman, Douglas Singleton, Nattapong Yongram, arXiv:1205.1056 [gr-qc]

- Which gives constant scalar filed $\dot{\varphi} = \sqrt{C_1}$ and.

- A conserved current: $\nabla_\mu j^\mu = \frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}j^\mu\right) = \frac{1}{a^3}\frac{\partial}{\partial t}(a^3 j^0) = 0$

or $j^0 = \frac{C_3}{a^3}$. The complete set of the densities:

$$\rho_\Lambda = \dot{\varphi}^2 = C_1 \qquad p_\Lambda = -\rho_\Lambda$$

$$\rho_{\mathrm{d}} = \frac{C_3}{a^3}\dot{\varphi} = \frac{\sqrt{C_1}C_3}{a^3} \qquad p_{\mathrm{d}} = 0$$

- The precise solution for Friedman equation $\rho \sim \left(\frac{\dot{a}}{a}\right)^2$ in this case is:

$$a_{\Lambda-d} = \left(\frac{C_3}{\sqrt{C_1}}\right)^{1/3} \sinh^{2/3}\left(\frac{3}{2}\sqrt{C_1}t\right)$$

- Which helps us to reconstruct the original physical values:

$$\Omega_\Lambda = \frac{C_1}{H_0} \qquad \Omega_\Lambda = \frac{C_3\sqrt{C_1}}{H_0}$$

There have been some other Unified Models of DE/DM, worth mentioning , for example the **Chaplygin gas, see, eg.,**

Unification of dark matter and dark energy: The Inhomogeneous Chaplygin gas
Neven Bilic, Gary B. Tupper, Raoul D. Viollier (Cape Town U.). Nov 2001. 10 pp.
Published in **Phys.Lett. B535 (2002) 17-21**

In that case there is also some communication between DE and DM

- WE ARE GOING TO CONSIDER A GENERALIZALION OF OUR unified DE/DM THAT ALSO INVOLVES DE/DM EXCHANGE, THAT IS THOSE TWO COMPONENTS ARE NOT GOING TO BE SEPARATELLY CONSERVED. AND THE WAY THEY WILL EXCHANGE ENERGY WILL BE IN A DIFFUSIVE WAY. SO WE NOW REVIEW A FEW NOTIONS ,

Velocity diffusion notion
In General Relativity

Diffusion may also play a fundamental role in the large scale dynamics of the matter in the universe.

- J. Franchi, Y. Le Jan. Relativistic Diffusions and Schwarzschild Geometry. Comm. Pure Appl. Math., 60 : 187251, 2007;
- Z. Haba. Relativistic diffusion with friction on a pseudoriemannian manifold. Class. Quant. Grav., 27 : 095021,;2010
- J. Hermann. Diffusion in the general theory of relativity. Phys. Rev. D, 82: 024026, 2010;
- S. Calogero. A kinetic theory of diffusion in general relativity with cosmological scalar field. J. Cosmo. Astro. Particle Phys. 11 .016 ,2011

Kinetic diffusion on curved s.t

- Kinetic diffusion equation(Fokker Planck):

$$\partial_t f + v\,\partial_x f = \sigma\,\partial_w^2 f \qquad \Longrightarrow \qquad p^\mu \partial_\mu f - \Gamma^i_{\mu\nu} p^\mu p^\nu \partial_{p^i} f = D_p f$$

f – distribution function, v – velocity, σ – diffusion coefficient.

- The current density and the energy momentum tensor $T^{\mu\nu}$ are defined as:

$$j^\mu = -\sqrt{-g}\int f \frac{p^\mu}{p_0} dp^1 \wedge dp^2 \wedge dp^3$$

$$T^{\mu\nu} = -\sqrt{-g}\int f \frac{p^\mu p^\nu}{p_0} dp^1 \wedge dp^2 \wedge dp^3$$

j^μ is a time-like vector field and $T^{\mu\nu}$ verifies the dominant and strong energy conditions.

$$\nabla_\mu T^{\mu\nu} = 3\sigma j^\nu \qquad \nabla_\mu j^\nu = 0$$

- The number of particles is conserved, but not the energy momentum tensor.

Connection to Cosmology

- Calogero's , Haba's, idea: ϕ CDM. The cosmological constant is replaced by a scalar filed, which would the source of the Cold Dark Matter stress energy tensor:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = T_{\mu\nu} + \varphi g_{\mu\nu}$$

$$\nabla_\mu T^{\mu\nu} = 3\sigma j^\nu$$
$$\nabla^\nu \varphi = -3\sigma j^\nu$$

The value 3σ measures the energy transferred from the scalar field to the matter

per unit of time due to diffusion.

This modification applied "by hand", and not from action principle.

- Alternative approach, through a - **Diffusive Energy Action**. A generalization of the non Riemannian volume form is required

1^{st} step, from metric independent Volume form to Dynamical time

- The basic result of can be expressed as a covariant conservation of a stress energy tensor:

$$\Phi = \frac{1}{4!}\varepsilon^{\mu\nu\rho\sigma}\varepsilon_{abcd}\partial_\mu\phi^{(a)}\partial_\nu\phi^{(b)}\partial_\rho\phi^{(c)}\partial_\sigma\phi^{(d)}$$

$$S = \int \Phi \mathcal{L}_1 \quad \Longrightarrow \quad S(\chi) = \int \sqrt{-g}\,\chi_{\mu;\nu} T^{\mu\nu}_{(\chi)}\, d^4x$$

- χ^λ - dynamical space-time vector field , $\chi_{\mu;\nu} = \partial_\nu \chi_\mu - \Gamma^\lambda_{\mu\nu}\chi_\lambda$ in second order formalism $\Gamma^\lambda_{\mu\nu}$ is Christoffel Symbol.
- $T^{\mu\nu}_{(\chi)}$ - stress energy tensor. The variation according to χ gives a **conserved** energy momentum tensor: $\nabla_\mu T^{\mu\nu}_{(\chi)} = 0$, in addition to $T^{\mu\nu}_{(G)} = \frac{\delta S(\chi)}{\delta g^{\mu\nu}}$.
- Dynamical time is as T.M.T for $T^{\mu\nu}_{(\chi)} = g^{\mu\nu}\Lambda$.

2nd step, the Diffusive energy action principle

- We replace the dynamical space time vector χ_μ by a gradient of a scalar filed $\chi_{,\mu}$:

$$S(\chi) = \int \sqrt{-g}\, \chi_{,\mu;\nu} T^{\mu\nu}_{(\chi)}\, d^4x$$

χ - scalar filed , $\chi_{,\mu;\nu} = \partial_\nu \partial_\mu \chi - \Gamma^{\lambda}_{\mu\nu} \partial_\lambda \chi$, $T^{\mu\nu}_{(\chi)}$ - stress energy tensor.

- The variation according to χ gives a **non-conserved** diffusive energy momentum tensor:

$$\nabla_\mu T^{\mu\nu}_{(\chi)} = f^\nu \;\; ; \;\; \nabla_\nu f^\nu = 0$$

- The variation according to the metric gives a **conserved** stress energy tensor, (which is familiar from Einstein eq. $T^{\mu\nu}_{(G)} = R^{\mu\nu} - \frac{1}{2} g^{\mu\nu} R$) :

$$T^{\mu\nu}_{(G)} = \frac{-2}{\sqrt{-g}} \frac{\delta\left(\sqrt{-g}\mathcal{L}_m\right)}{\delta g^{\mu\nu}}$$

Alternative formulation without higher derivative with mass like term

- An action **with no high derivatives**, is obtained by adding another term involving χ_μ:

$$S(\chi) = \int \sqrt{-g}\, \chi_{\mu;\nu} T^{\mu\nu}_{(\chi)}\, d^4x + \frac{\sigma}{2}\int \sqrt{-g}\left(\chi_\mu + \partial_\mu A\right)^2 d^4x$$

- **$\delta\chi^\lambda$:** $\nabla_\mu T^{\mu\nu}_{(\chi)} = \sigma\,(\chi^\nu + \partial^\nu A\,)$
- **δA:** $\sigma\, \nabla_\nu(\chi^\nu + \partial^\nu A\,) = 0$

- One difference between those theories:

Here - σ appears as a parameter

- in the higher derivative theory σ appears as an integration constant.

Symmetries

- If the matter is coupled through its energy momentum tensor as:

$$T^{\mu\nu}_{(\chi)} \rightarrow T^{\mu\nu}_{(\chi)} + \lambda g^{\mu\nu}$$

the process will not affect the equations of motion. In Quantum Field Theory this is "normal ordering".

$$\chi \rightarrow \chi + \lambda$$

A toy model

- We start with a simple action of one dimensional particle in a potential $V(x)$.

$$S = \int \ddot{B}\left[\frac{1}{2}m\dot{x}^2 + V(x)\right]dt$$

- δB gives the total energy of a particle with constant power P:

$$\frac{1}{2}m\dot{x}^2 + V(x) = E(t) = E_0 + Pt$$

- δx gives the condition for B:

$$m\ddot{x}\ddot{B} + m\dot{x}\dddot{B} = V'(x)\ddot{B} \qquad \text{or} \qquad \frac{\dddot{B}}{\ddot{B}} = \frac{2V'(x)}{\sqrt{2m\big(E(t)-V(x)\big)}} - \frac{P}{2\big(E(t)-V(x)\big)}$$

A conserved Hamiltonian

- Momentums for this toy model:

$$\pi_x = \frac{\partial \mathcal{L}}{\partial \dot{x}} = m\dot{x}\ddot{B}$$

$$\pi_B = \frac{\partial \mathcal{L}}{\partial \dot{B}} - \frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \ddot{B}} = -\frac{d}{dt}E(t)$$

$$\Pi_B = \frac{\partial \mathcal{L}}{\partial \ddot{B}} = E(t)$$

- The Hamiltonian (with second order derivative):

$$\mathcal{H} = \dot{x}\pi_x + \dot{B}\pi_B + \ddot{B}\Pi_B - \mathcal{L} = m\dot{x}\ddot{B} - \dot{B}\dot{E} = \pi_x\sqrt{\frac{2}{m}\left(\Pi_B - V(x)\right)} + \dot{B}\pi_B$$

- The action isn't dependent on time explicitly, so the Hamiltonian is conserved.

Interacting Diffusive DE – DM

(with high derivatives)

- The diffusive stress energy tensor in this theory:

$$T^{\mu\nu}_{(\chi)} = \Lambda g^{\mu\nu}$$

with the kinetic “k-essence” term $\Lambda = g^{\alpha\beta}\varphi_{,\alpha}\varphi_{,\beta}$,

where φ – a scalar filed.

- The full theory:

$$S = \int \frac{1}{2}\sqrt{-g}R + \sqrt{-g}(\sqcup\, \chi + 1)\Lambda\, d^4x$$

when $8\pi G = c = 1$.

Equation of motions

- $\delta\chi$ - non trivial evolving dark energy:

$$\sqcup\,\Lambda = 0$$

- $\delta\varphi$ - a conserved current:

$$j_\beta = 2(\sqcup\,\chi + 1)\varphi_{,\beta}$$

- $\delta g^{\mu\nu}$ - a conserved stress energy tensor:

$$T^{\mu\nu}_{(G)} = g^{\mu\nu}\left(-\Lambda + \chi^{,\sigma}\Lambda_{,\sigma}\right) + j^{\mu}\varphi^{,\nu} - \chi^{,\mu}\Lambda^{,\nu} - \chi^{,\nu}\Lambda^{,\mu}$$

Dark Energy **Dark Matter**

F.L.R.W solution

- $\sqcup\Lambda = 0$:

$$2\dot{\varphi}\ddot{\varphi} = \frac{C_2}{a^3} \qquad \Leftrightarrow \qquad \dot{\varphi}^2 = C_1 + C_2 \int \frac{dt}{a^3}$$

- $j_\beta = 2(\sqcup\chi + 1)\varphi_{,\beta}$:

$$\dot{\chi} = \frac{C_4}{a^3} + \frac{1}{a^3}\int a^3\, dt - \frac{C_3}{2a^3}\int \frac{dt}{\dot{\varphi}}$$

- $T^{\mu\nu}_{(G)}$ - a conserved stress energy tensor:

$$\rho_\Lambda = \dot{\varphi}^2 + \frac{C_2}{a^3}\dot{\chi} \qquad p_\Lambda = -\rho_\Lambda$$

$$\rho_\mathrm{d} = \frac{C_3}{a^3}\dot{\varphi} - 2\frac{C_2}{a^3}\dot{\chi} \qquad p_\mathrm{d} = 0$$

Asymptotic solution

- The field $\dot{\chi}$ asymptotically goes to the value as De Sitter space $a \sim e^{H_0 t}$:

$$\lim_{t\to\infty} \dot{\chi} = \frac{1}{a^3}\int a^3\, dt = \frac{1}{3H_0}$$

- The asymptotic values of the densities are:

$$\rho_\Lambda = C_1 + C_2 \int \frac{dt}{a^3} + \frac{C_2}{a^3}\dot{\chi} = C_1 + O\left(\frac{1}{a^6}\right)$$

$$\rho_{\mathrm{CDM}} = \left(C_3\sqrt{C_1} - \frac{2C_2}{3H_0}\right)\frac{1}{a^3} + O\left(\frac{1}{a^6}\right)$$

- The observable values:

$$\frac{C_1}{H_0} = \Omega_\Lambda \qquad C_3\sqrt{C_1} - \frac{2C_2}{3H_0} = H_0\Omega_{\mathrm{d}}$$

Stability of the solutions

- More close asymptotically with ΛCDM: the dark energy become constant, and the amount of dark matter slightly change $\rho_{\mathrm{CDM}} \sim \frac{1}{a^3}$.

- $C_3\sqrt{C_1} > \frac{2C_2}{3H_0}$ for positive dust density. For $C_2 < 0$ cause higher dust density asymptotically, and there will be a positive flow of energy in the inertial frame to the dust component, but the result of this flow of energy in the local inertial frame will be just that the dust energy density will decrease a bit slower that the conventional dust (but still decreases).

- Explaining the particle production, "Taking vacuum energy and converting it into particles" as expected from the inflation reheating epoch. May be this combined with a mechanism that creates standard model particles.

Late universe solution

- The familiar solution of non-interacting DE-DM solution is for $\boldsymbol{C_2 = 0}$.
- Which gives constant scalar filed $\dot{\varphi} = \sqrt{C_1}$ and $\ddot{\varphi} = 0$.

$$\rho_\Lambda = \dot{\varphi}^2 = C_1 \qquad p_\Lambda = -\rho_\Lambda$$

$$\rho_\mathrm{d} = \frac{C_3}{a^3}\dot{\varphi} = \frac{\sqrt{C_1}C_3}{a^3} \qquad p_\mathrm{d} = 0$$

- The precise solution for Friedman equation $\rho \sim \left(\frac{\dot{a}}{a}\right)^2$ in this case is:

$$a_{\Lambda-d} = \left(\frac{C_3}{\sqrt{C_1}}\right)^{1/3} \sinh^{2/3}\left(\frac{3}{2}\sqrt{C_1}t\right)$$

- Which helps us to reconstruct the original physical values:

$$\Omega_\Lambda = \frac{C_1}{H_0} \qquad \Omega_\mathrm{d} = \frac{C_3\sqrt{C_1}}{H_0}$$

Perturbative solution

- The scalar field has perturbative properties $\lambda_{1,2} \ll 1$:

$$\lambda_1(t, t_0) = \frac{C_2}{C_1} \int \frac{dt}{a^3}$$

$$\lambda_2(t, t_0) = \frac{C_2}{\sqrt{C_1} C_3} \dot{\chi}$$

- For a first order solution in perturbation theory:

$$\rho_\Lambda = C_1 \left(1 + \lambda_1 + \frac{C_3}{\sqrt{C_1}} \lambda_2 \right) + O_2(\lambda_1, \lambda_2)$$

$$\rho_{CDM} = \frac{\sqrt{C_1} C_3}{a^3} \left(1 + \frac{1}{2} (\lambda_1 + \lambda_2) \right) + O_2(\lambda_1, \lambda_2)$$

- For rising dark energy, dark matter amount goes lower ($C_2 < 0, C_{1,3,4} > 0$). For decreasing dark energy, the amount of dark matter goes up(all components are positive).

Diffusive energy without higher derivatives

- The full theory:

$$\mathcal{L} = \frac{1}{2}\sqrt{-g}R + \sqrt{-g}\chi_{\mu;\nu}T^{\mu\nu}_{(\chi)} + \frac{\sigma}{2}\sqrt{-g}\left(\chi_\mu + \partial_\mu A\right)^2 + \sqrt{-g}\Lambda$$

Where $\Lambda = g^{\alpha\beta}\varphi_{,\alpha}\varphi_{,\beta}$, and $T^{\mu\nu}_{(\chi)} = \Lambda g^{\mu\nu}$.

- All the E.o.M are the same, except:

$$T^{\mu\nu}_{(G)} = g^{\mu\nu}\left(-\Lambda + \chi^{,\lambda}\Lambda_{,\lambda} + \frac{\mathbf{1}}{\mathbf{2}\boldsymbol{\sigma}}\boldsymbol{\Lambda}^{,\boldsymbol{\lambda}}\boldsymbol{\Lambda}_{,\boldsymbol{\lambda}}\right) + j^\mu\varphi^{,\nu} - \chi^{,\mu}\Lambda^{,\nu} - \chi^{,\nu}\Lambda^{,\mu} + \frac{\mathbf{1}}{\boldsymbol{\sigma}}\boldsymbol{\Lambda}^{,\boldsymbol{\mu}}\boldsymbol{\Lambda}^{,\boldsymbol{\nu}}$$

- For the late universe both theories are equivalent, $\Lambda^{,\mu}\Lambda^{,\nu} \sim \frac{1}{a^6}$.

- For $\sigma \to \infty$, the term $\frac{\sigma}{2}\sqrt{-g}\left(\chi_\mu + \partial_\mu A\right)^2$ forces $\chi_\mu = -\partial_\mu A$, and D.T becomes Diffusive energy with high energy.

Comparison with Calogero's and Haba's model φCMD

- Calogero put two stress energy tensor of DE-DM. Each stress energy tensor in non-conserved:

$$\nabla_\mu T^{\mu\nu}_{(\Lambda)} = -\nabla_\mu T^{\mu\nu}_{(\mathrm{Dust})} = 3\sigma j^\nu, j^\nu_{;\nu} = 0$$

- For FRWM, this calculation leads to the solution:

$$\rho_\Lambda = C_1 + C_2 \int \frac{dt}{a^3}$$

$$\rho_{\mathrm{Dust}} = \frac{C_3}{a^3} - \frac{C_2 t}{a^3}$$

The two model became approximate for $\mathrm{C}_2\dot{\chi} \ll 1$. Our asymptotic solution becomes with constant densities, because $\mathrm{C}_2\dot{\chi} \to \frac{C_2}{3H_0}$, which makes the DE decay lower from φCMD, and DM evolution as ΛCMD.

Preliminary ideas on Quantization

- Taking Dynamical space time theory (with source), and by integration by parts:

$$S = \int \sqrt{-g}R + \int \sqrt{-g}\,\Lambda - \int \sqrt{-g}\,\chi_\mu T^{\mu\nu}_{(\chi);\nu}\, d^4x + \frac{\sigma}{2}\int \sqrt{-g}\,(\chi_\mu + \partial_\mu A)^2 d^4x$$

- $\boldsymbol{\delta\chi_\mu}$: $\nabla_\nu T^{\mu\nu}_{(\chi)} = f^\nu = \sigma(\chi^\nu + \partial^\nu A)$ and put back into the action:

$$S = \int \sqrt{-g}R + \int \sqrt{-g}\,\mathrm{g}^{\alpha\beta}\phi_\alpha\phi_\beta - \frac{1}{2\sigma}\int \sqrt{-g}\, f_\nu f^\nu d^4x + \int \sqrt{-g}\,\partial_\mu A f^\nu d^4x$$

- The partition function considering Euclidean metrics (exclude the gravity terms):

$$\mathrm{Z} = \int D\phi\, \delta\left(f^\mu_{;\mu}\right) \exp\left[\frac{1}{2\sigma}\int \sqrt{g}\, f_\nu f^\nu d^4x - \int \sqrt{g}\,\mathrm{g}^{\alpha\beta}\phi_\alpha\phi_\beta\right]$$

- We see that for $\sigma < 0$, there will a convergent functional integration, so this is a good sign for the quantum behavior of the theory.

Preliminary numerical results

- Show early universe dominated by stiff eq. of state, w equals to 1 that suffers then a transition to DM/DE, playing with initial conditions the w equals to 1

Final Remarks

- T.M.T - Unified Dark Matter Dark Energy. The cosmological constant appears as an integration constant.
- The Dynamical space time Theories – both energy momentum tensor are conserved.
- Diffusive Unified DE and DM – the vector field is taken to be the gradient of a scalar, the energy momentum tensor $T^{\mu\nu}_{(x)}$ has a source current, unlike the $T^{\mu\nu}_{(G)}$ which is conserved. The non conservation of $T^{\mu\nu}_{(x)}$ is of the diffusive form. There is an integration constant, C_2 that controls how much model deviates from the Lambda CDM, i.e. how the Lambda CDM is deformed. This constant C_2 measures how much we DEFORM our model from ΛCDM in the sense Steinheimer talked about deforming theories.
- Asymptotically stable solution ΛCDM is a fixed point.
- For rising dark energy, dark matter amount goes lower. For decreasing dark energy, the amount of dark matter goes up.
- The partition function is convergent for $\sigma < 0$, and therefor the theory is a good property before quantizing the theory.

Future research

- Numerical solution for $C_2 \neq 0$, and using these to impose limits on C_2 from data, David Benisty is working on this
- A Stellar model, spherically symmetric solutions, David Benisty is working on this
- Quantum solutions – Wheeler de Witt equation
- A solution for coincidence problem
- Tracing the full history of the Universe, generalizing the darkon field of the previous lecture to have difussive interactions with DE and incorporation of inflaton , standard model fields, scale invariance and gauge symmetry breaking without fifth force problem as a consequence of scale invariance.
- The vector formulation with a mass like term suggests a gauge field mediated force between DE and DM, goes along well with the philosophy that interactions should be be generated through gauge fields. A point that could be explored further.

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references

Interacting Diffusive Unified Dark Energy and Dark Matter from Scalar Fields
David Benisty, E.I. Guendelman (Ben Gurion U. of Negev). Jan 30, 2017. 10 pp.
Published in **Eur.Phys.J. C77 (2017) no.6, 396**
DOI: 10.1140/epjc/s10052-017-4939-x
e-Print: **arXiv:1701.08667** **[gr-qc]** | **PDF**

And this is only the beginning…