Non-perturbative screening: Anderson localization for Dark Energy and Inflation

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Outlines

1. Motivation
2. Equation of state of exotic substances: an example from nuclear physics
3. Screening of the long range forces: non-perturbative screening from the Anderson localization
4. Cosmology: Dark Energy & Inflation

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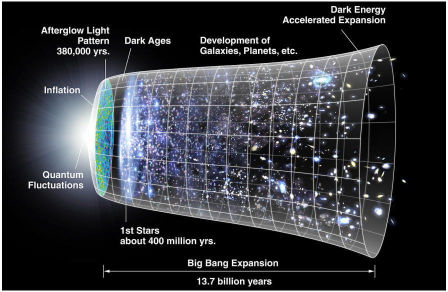
Motivation

Motivation



- Accelerated expansion of the Universe:
  Inflation & Dark Energy
- Dynamic description: Quintessence
- Quintessence-matter interaction: constraints on fifth forth
- Solutions: Chameleon, Symmetron, Vainshtein Mechanism (arXiv:1306.432)

Thought experiment

Back to the roots

Is it possible to compose a simple artificial matter-like substance having the equation of state of DE?

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Yes, it is possible...

Thought experiment

Back to the roots

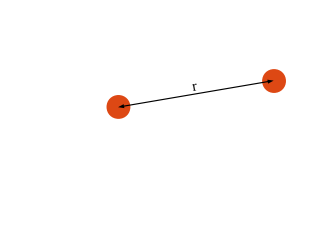
Is it possible to compose a simple exotic matter-like substance having the equation of state of DE?

Yes, it is possible... **and it turns out to be no exotic at all – the non-perturbative screening** *aka* **Anderson localization**

(2)

Exotic matters. . .

A classical particle and scalar field system

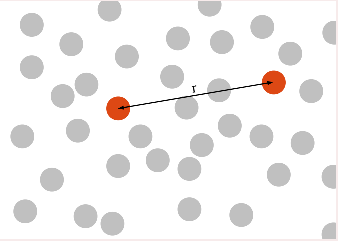


Vacuum

$$\mathcal{L} \supset \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 + \bar{\psi}\not{\partial}\psi - M\bar{\psi}\psi + g\,\phi\bar{\psi}\psi$$

$$\rho = \frac{1}{V}\sum_{i\neq j}^{N} U(r_{ij}), \qquad U(r) = -\frac{g}{4\pi\, r}e^{-m\,r}$$

A classical particle and scalar field system



From vacuum to gas-like substance

$$G(x-y) \longrightarrow \overline{G(x-y;T,n,\dots)}$$

$$U(r) = -\frac{g}{4\pi\, r} e^{-m\, r} \longrightarrow U(r) = -\frac{g}{4\pi\, r} e^{-m(m_0,n,T,\dots)\, r}$$

$$m \longrightarrow m(m_0,n,T,\dots)$$

Cold and dilute limit

Let us assume

$$\left.\begin{array}{l}\text{Cold and dilute} \\ m_{\rm vac} \ll m(n)\end{array}\right\} \Rightarrow m = m(n)$$

Known in nuclear physics for continous environment [arXiv:0902.1825]

$$\left.\begin{array}{l}\rho = \left(g\frac{n}{m(n)}\right)^2 \\ p = \left(g\frac{n}{m(n)}\right)^2\left(1 - \frac{2n}{m(n)}\frac{\partial m(n)}{\partial n}\right)\end{array}\right\} \Rightarrow \omega = 1 - \frac{2n}{m(n)}\frac{\partial m(n)}{\partial n}$$

Cold and dilute limit

For example, if

$$m(n) = \sigma n$$

$$\rho = \left(g \frac{n}{m(n)}\right)^2$$

$$p = \left(g \frac{n}{m(n)}\right)^2 \left(1 - \frac{2n}{m(n)} \frac{\partial m(n)}{\partial n}\right)$$

$$\Downarrow$$

$$p = -\rho = -\left(\frac{g}{\sigma}\right)^2 \quad \longleftarrow \textbf{Dark Energy!}$$

$$\omega = -1$$

Semiconclusions

If $m(n) = \sigma n$ then $p = -\rho = -(g/\sigma)^2$ and $\omega = -1$

...and we have DE!

An annoying minor question

...is there anything like $m(n) \propto n$ in the real world?

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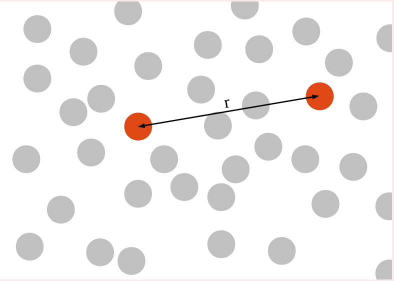
Non-perturbative screening: excursion to the localization

Propagator of ϕ in a cold and dilute environment



$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \bar{\psi}\partial\!\!\!/\psi - M\bar{\psi}\psi + g\,\phi\bar{\psi}\psi$$

Randomly distributed ψ particles $\Rightarrow \mathcal{L} \supset \frac{1}{2}(\partial\phi)^2 - V(x)\phi^2$

where $V(x)$ is a "quenched" noise

Propagator of ϕ in a cold and dilute environment

Quenched noise

$$\mathcal{L} \supset \frac{1}{2}(\partial\phi)^2 - V(x)\phi^2$$

$$V(x) \sim \text{ Gaussian white noise}$$

Averaging over noise

$$\overline{G(x-y)} = \int DV\, e^{-\int dx^4 \frac{V^2}{2\sigma^2}}\, G(x-y)$$

A really painful procedure! Tons of literature on the topic, see weak and Anderson localization, quantum transport etc.

Localization & electron transport

Nobel Prize in Physics (1977)
P. W. Anderson, N. F. Mott &
J. H. van Vleck "for their fundamental theoretical investigations of the electronic structure of magnetic and disordered systems"

- **Anderson, P. W.** (1958). "Absence of Diffusion in Certain Random Lattices". Phys. Rev. 109 (5) 1492

Propagator of ϕ in a cold and dilute environment

Averaging over noise

$$\overline{G(x-y)} = \int DV\, e^{-\int dx^4 \frac{V^2}{2\sigma^2}}\, G(x-y)$$

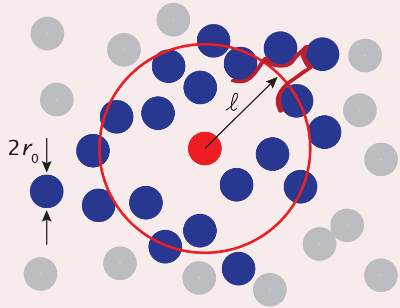
Localization

- Localized/nonlocalized, the Ioffe-Regel condition

$$\lambda < \ell, \quad \text{non-localized}$$
$$\lambda > \ell, \quad \text{localized}$$

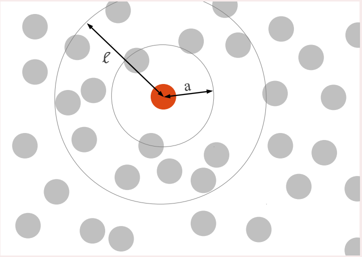
  where $\ell \equiv (\sigma n)^{-1}$ is the mean free path
- Localization is intrinsically a nonperturpative effect

Mean free path ℓ



$$\ell = \frac{1}{\sigma n}, \quad \sigma = \pi r_0^2$$

Propagator of ϕ in a cold and dilute environment



Three different regime of the propagator of ϕ

Vacuum: $r \lesssim a$, where $a \equiv n^{-1/3}$ – no screening
Nonlocalized: $a < r \lesssim \ell$ – perturbative screening, $\propto \sqrt{n}$
Localized: $r > \ell$ – non-perturbative screening, $\propto n$

Propagator of ϕ in a cold and dilute environment

In conclusion, the density corrections to the Yukawa mass term

$$m(n,r) = \begin{cases} \sim 0 & r \lesssim a \quad \text{vacuum, } \textbf{no screening} \\ \propto \sqrt{n} & a < r \lesssim \ell \quad \text{nonlocalized, } \textbf{pert. screening} \\ \propto n & r > \ell \quad \text{localized, } \textbf{non-pert. screening} \end{cases}$$

What about cosmology?

The density corrections to the mass of ϕ

$$m(n,r) = \begin{cases} \sim 0 & r \lesssim a & \text{vacuum} \\ \propto \sqrt{n} & a < r \lesssim \ell & \text{nonlocalized} \\ \propto n & r > \ell & \text{localized} \end{cases}$$

Contribution to cosmology

$$\rho = \begin{cases} \propto a^{-4} & \text{vacuum} \\ \propto a^{-3} & \text{nonlocalized} \\ \propto \text{const} & \text{localized} \end{cases}$$

Only the latter term is relevant for cosmology!

(4)

Dark Energy

Scale of DE

$$\rho = (g/\sigma)^2 \Rightarrow \quad \Lambda_{\rm DE} = \rho^{1/4} = \sqrt{\frac{g}{\sigma}}$$

What is σ

$$m(n) = \sigma n \quad \overset{?}{\longleftrightarrow} \quad \ell^{-1} = \sigma n = \sigma_{\phi\psi\to\phi\psi} n$$

Relation between ℓ and $m(n)$

$$m(n)_{\rm non-pert} = \mathcal{O}(1)\,\ell^{-1} \quad \longleftarrow \text{ non-perturbative!}$$

$$\sigma_{\phi\psi\to\phi\psi} = \frac{g^4}{8\pi M^2}$$

$$m(n) \simeq \sigma_{\phi\psi\to\phi\psi} n = \frac{g^4}{8\pi M^2}\, n$$

Relation between observed DE and our particle physical model

The relation

$$\Lambda_{\mathrm{DE}} = \sqrt{\frac{g}{\sigma}} = \sqrt{g\,\frac{8\pi\, M^2}{g^4}} = M\sqrt{\frac{8\pi}{g^3}}$$

Scales

$$M\, g^{-\frac{3}{2}} \simeq \Lambda_{\mathrm{DE}} \approx 10^{-3}\ \mathrm{eV} \quad (g \lesssim 1)$$

"Thermal" coincidence?

- $T_{\mathrm{CMB}} \simeq 10^{-4}$ eV $\approx \Lambda_{\mathrm{DE}}$? But...
  $g_{\mathrm{eff}} = g_{\mathrm{eff}}^{\mathrm{SM}} + (1 + 0.6)$
  $g_{\mathrm{eff}} \approx 3 \ldots 3.5$ at the recombination ($T_{\mathrm{rec}} \approx 0.3$ eV)
  $g_{\mathrm{eff}} \approx 3$ at BBN ($T_{\mathrm{BBN}} \approx 1$ MeV)

Candidates in particle physics

Neutrino?

- $M \approx \Lambda_{\rm DE}$ $(g \simeq 1) \longleftrightarrow m_\nu \approx \Lambda_{\rm DE}$. But...
  $g \lesssim 10^{-7}$ [1311.3873] $\Rightarrow m_\nu \approx 10^{-13}$

Sterile neutrino

- Again: $M \approx \Lambda_{\rm DE}$ $(g \simeq 1) \longleftrightarrow m_\nu^{\rm ster} \approx \Lambda_{\rm DE}$
- Non-thermal history?
- If the same species form Dark Matter the coupling g is constrained

Conclusions, Problems & Questions

- A matter like substance can behave like DE
- The model is rather restrictive (which can be considered as a positive selling point)
- Is it possible to get rid of the restrictive relation?

$$\sigma = \frac{g^4}{8\pi M^2}$$

- Question: microscopic stability of the substance
- The preprint will appear in this week
- Many thanks to G. Dvali & G. Hutsi for helpful discussions

Thank you!