WHERE THE WILD ULTRALIGHT THINGS ARE

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Who cares?

- Universe is mostly dark > 95%
- LCDM - DM (billiard balls) + DE (one number)
- …
- C'mon, really???
- …
- Well, maybe really… But not sure yet.

hep-th/1903:11676, NK
hep-th/1809:05109, G. D'Amico, A. Lawrence, NK
hep-ph/1804:01542, G. D'Amico, T. Hamill, NK
hep-th/1605:00996, G. D'Amico, T. Hamill, NK
hep-th/0803:3809, L. Sorbo, NK

Can the dark sector be more interesting?

- ONE starting assumption: QFT works (maybe this is wrong but so far QFT has done well)
- But... maybe you can mess with EFT (sic!)...
- Suppose DE is not just a single number
- So DM and DE are fluids of some QFT stuff
- Do they "mix" with each other? Do they "mix" with SM?
- Lots of literature on this! (search Inspire or just google)
- But most of it is just playing with gravitating hydrodynamics - (almost) no QFT exploration
- Our question: are there interacting QFTs of DE with unusual signatures?

Leitmotif

Wheeler:

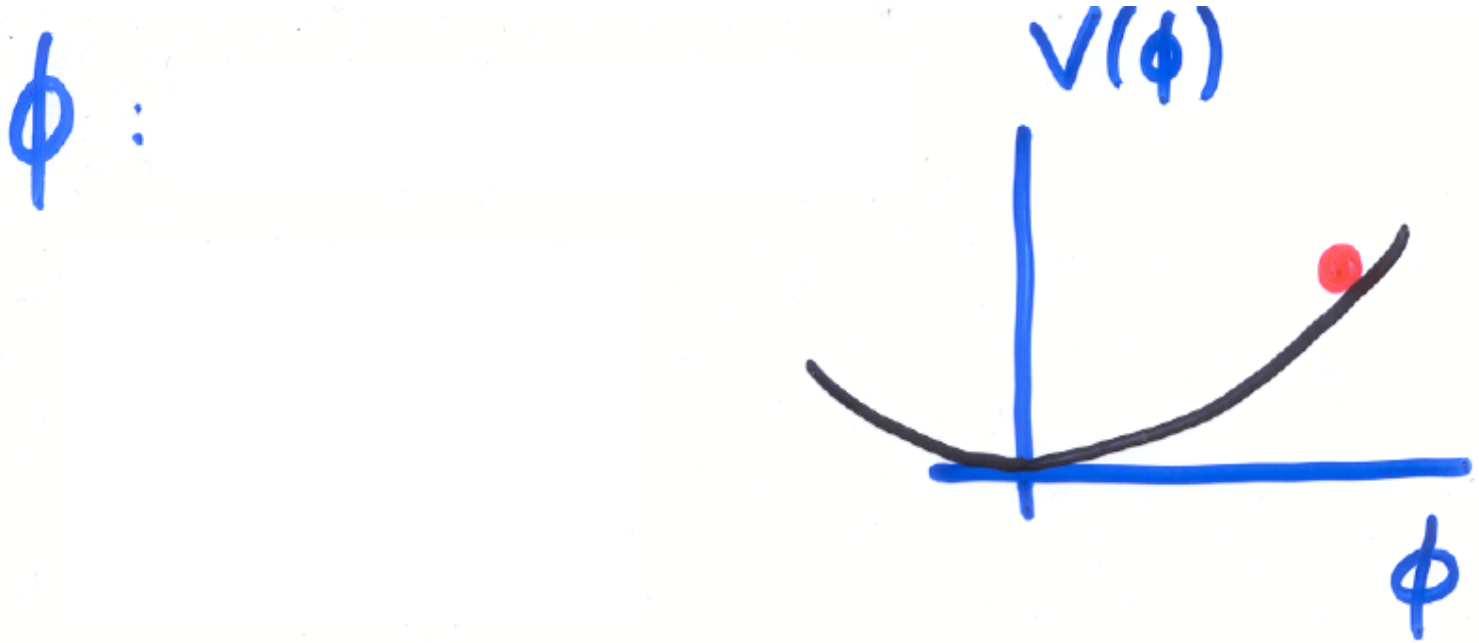
the principle of "radical conservatism": adhere to well-established physical principles while pushing them into extreme situations (attributed to Bohr).

So... Let's follow Wheeler's and Bohr's nose...

(could do a lot worse...)

Modelling DM/DE interactions

- Assume DE is a light "quintessence" in slow roll
- Its mass is tiny now, < Hubble
- $V \sim (10^{-3}\ eV)^4$
- $\partial^2 V \sim 10^{-66}\ eV^2$



Modelling DE interactions with heavies

- Suppose we allow a heavy particle ("billiard balls") - eg `wimp' to couple to DE
- To code interactions imagine

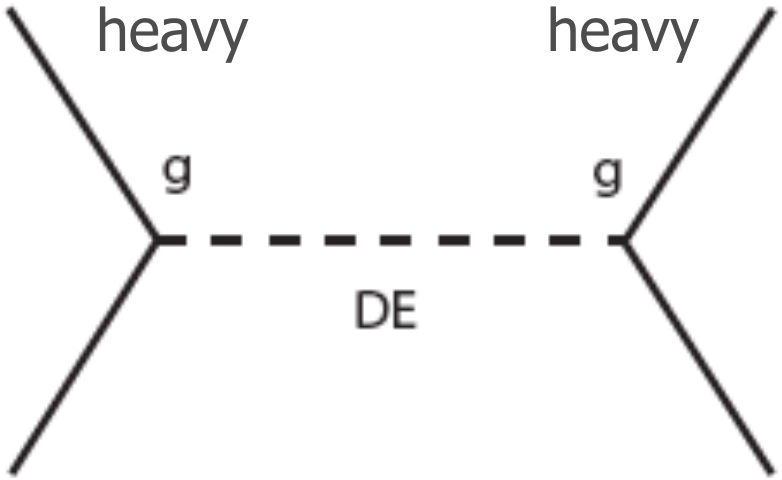
$$m_\psi(\phi) = m^0_\psi(1 + c\,\phi/M_{\rm Pl} + \ldots) = m^0_\psi + g\,\phi + \ldots$$

- If Yukawa is absent the interactions are tiny and generically less interesting - best bet for strong interactions is Yukawa

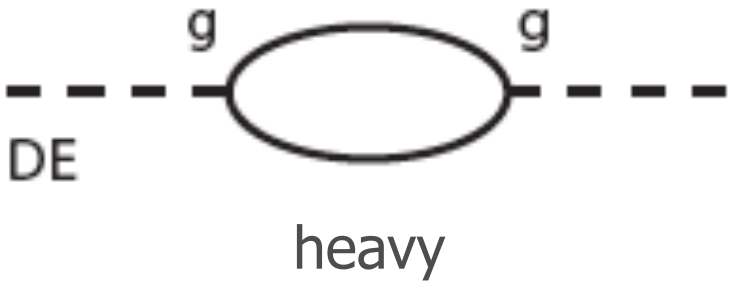
$$\mathcal{L} = g\phi\bar{\psi}\psi = c\frac{m^0_\psi}{M_{\rm Pl}}\phi\bar{\psi}\psi$$

hep-th/1605:00996, G. D'Amico, T. Hamill, NK

But...



extra long range force
mediated by ultralight DE



DE selfenergy generated
by a virtual heavy

These yield bounds!

- long range forces:

$$V_{\text{heavy}} \simeq -\frac{g^2}{r} e^{-m_{DE} r} \simeq -c^2 G_N \frac{m^0_{\psi 1}\, m^0_{\psi 2}}{r} e^{-m_{DE} r}$$

- DE mass corrections

$$\Delta m^2_{DE} \simeq g^2 \int d^4p \frac{1}{p^2 - (m^0_\psi)^2} \simeq g^2 (m^0_\psi)^2 \ln\left(\frac{m^0_\psi}{\mathcal{M}}\right) \simeq c^2 G_N (m^0_\psi)^4 \ln\left(\frac{m^0_\psi}{\mathcal{M}}\right)$$

- The extra "heavy" long range forces cannot differ from baryonic ones by more than 10% of gravity (`local tests" of EP and cosmological bounds from LSS)

$$\frac{V_{\text{heavy}}}{V_N} \simeq c^2 \quad \Rightarrow \quad |c| \lesssim 1/3$$

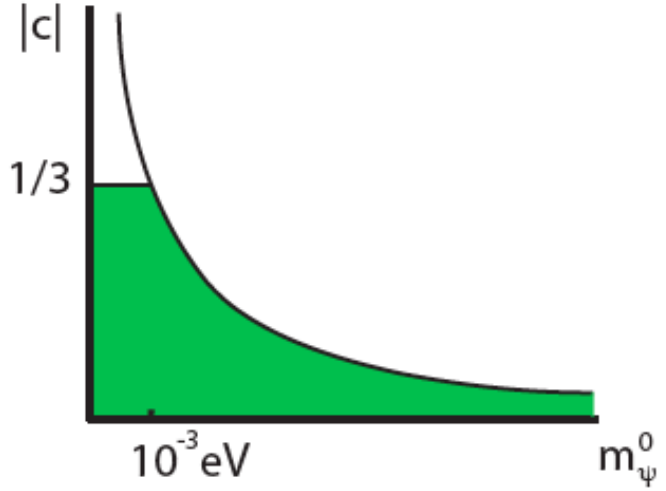
- Interestingly the bounds are not better! Having improved by only an order of magnitude or so in the past 20 years...

See also later work by Choi et al

Ultraligt DE must stay ultralight

$$\Delta m_{DE} \lesssim m_{DE} \qquad |c| \lesssim \frac{M_{\rm Pl}\, m_{DE}}{(m^0_\psi)^2} \lesssim \frac{M_{\rm Pl}\, H_0}{(m^0_\psi)^2} \simeq \left(\frac{10^{-3}\,{\rm eV}}{m^0_\psi}\right)^2$$

- Note: this is NOT a "hierarchy" problem - it's the REAL hierarchy problem! It involves the masses of presumed real particles! Like the Top dressing the Higgs...
- Interactions very strongly constrained! THIS IS JUST DECOUPLING!



- Quintessence can only interact with heavies with masses in the milli-eV range: but that can be at most a tiny amount of DM, or it can be MASSIVE NEUTRINO

Game over?

- Neutrinos in normal QFT do not like to help quintessence (recall the MAVANS fiasco)
- Actually quintessence may help neutrinos in turn: they can have cosmologically variable mass which helps with problems with having too many sterile neutrinos - so Neff problems can be averted - see hep-ph/1804:01542
- But is the analysis of DM/DE interactions which imprint on LSS and cosmological background merely a numerological exercise which has no foundation in QFT?
- ...
- Axion monodromies to the rescue! hep-th/0803:3809, hep-th/1605:00996, hep-th/1809:05109

A simple way around

(>) 3

A theory with (at least) 3 axions: for example...

- One is light and is DE ($m < H_0$)
- Another has mass $m \gtrsim H_0$ and is part of DM today (cannot be more than $\sim 5\%$ of DM)
- A third which the main component of DM ($m \gg H_0$)

We couple the DE axion to the intermediate-mass axion via a monodromy potential

$$V = \mu_1^4 \left[1 - \cos\left(\frac{\phi_1}{f_1}\right)\right] + \mu_2^4 \left[1 - \cos\left(\frac{\phi_2}{f_2}\right)\right] + \mu_3^4 \left[1 - \cos\left(\frac{\phi_1}{f_1} - n\frac{\phi_2}{f_2}\right)\right]$$

hep-th/1605:00996, G. D'Amico, T. Hamill, NK

Why (>) 3?

- $m < H_0 \Rightarrow \phi > M_{\rm Pl}$ (for a single axion)
- This would require $f > M_{pl}$

To avoid $f > M_{\rm Pl}$, couple the DE axion to a second axion using a monodromy. This allows you to have enough accelerated expansion without $f > M_{pl}$.

This is how monodromy fixes the problem - the point is the "Goldilocks" axion will have a mass comparable to the ultralight one - and there are cosmological bounds on ultralight DM - so it cannot be all of DM (Barbieri & Amendola…) But it was a contribution to DE at an earlier stage.

for DM phenomenology application, see Jackel et al

When interactions are turned on, the higher order corrections actually tend to HELP! They assist slow roll rather than spoil it!

hep-th/1709.07014; hep-th/1809:05109, G. D'Amico, A. Lawrence, NK
see also Silverstein, Westphal et al ("… exercises…")

4π in the sky

- An ultralight pseudo scalar is dual to a massive 4-form; this is just a canonical transformation like in CM; start with

$$\mathcal{L}^{(\text{full})} = -\frac{1}{48}F^2_{\mu\nu\lambda\sigma} - \frac{m^2}{12}(A_{\mu\nu\lambda} - h_{\mu\nu\lambda})^2 - \sum_{n>2}\frac{a'_n}{M^{2n-4}}\tilde{F}^n$$
$$- \sum_{n>1}\frac{a''_n}{M^{4n-4}}m^{2n}(A_{\mu\nu\lambda} - h_{\mu\nu\lambda})^{2n} - \sum_{k\geq 1,\, l\geq 1}\frac{a'''_{k,l}}{M^{4k+2l-4}}m^{2k}(A_{\mu\nu\lambda} - h_{\mu\nu\lambda})^{2k}\tilde{F}^l$$

- Dualize by $F \sim \epsilon(m\phi + Q) \quad mA \sim \epsilon\partial\phi$

$$\mathcal{L} = K\Big(\varphi, X\Big) - V_{eff}(\varphi) = \frac{M^4}{16\pi^2}\mathcal{K}\Big(\frac{4\pi m\varphi}{M^2}, \frac{16\pi^2 X}{M^4}\Big) - \frac{M^4}{16\pi^2}\mathcal{V}_{eff}\Big(\frac{4\pi m\varphi}{M^2}\Big)$$

- effectively this is just k-essence
- IMPORTANT: normalization $\sim \frac{4\pi m}{M}$ counts separation between strong coupling scale and cutoff
- All numerical coefficients are either ~ 1 or $= 0$ (symmetry!)
- The underlying assumption is naturalness - this is NDA

hep-th/1809:05109

Flattened potentials!

$$\mathcal{L} = k\left(\frac{m\varphi}{M_s^2}\right)(\partial\varphi)^2 - M_s^4\mathcal{V}_{eff}\left(\frac{m\varphi}{M_s^2}\right)$$

- Classical wave function renormalization makes the couplings smaller

$$\mathcal{L} = (\partial\chi)^2 - M_s^4\overline{\mathcal{V}}_{eff}\left(\frac{m\chi}{M_s^2}\right)$$

- Easy to get slow roll with (near) subplanckian variations of the field
- Need to have

$$m \gtrsim H_0 \simeq 10^{-33}\,\mathrm{eV} \qquad M \simeq \sqrt{4\pi}V_{eff}^{1/4} \simeq 3\times 10^{-3}\,\mathrm{eV}$$

- Extra stuff heavier than M, as much as $\mathcal{N} \simeq \left(\frac{m_{\rm Pl}}{\mathcal{M}}\right)^2$

WGC in the Sky?

- So many dofs - observable?
- Not so easy: recall RS2 (aka warped compactifications):

$$N \sim (m_{Pl} L)^2, \quad L \lesssim mm \rightarrow N \lesssim 10^{60}$$ Hebecker, March-Russell

- If only gravitationally coupled, very difficult to produce...
- Nonperturbative effects can enhance production rates... But why???
- Problems in LCDM: disagreement between local and cosmological measurement of H_0 is rising: 74 vs 67, 3.4 sigma now and growing
- A possible resolution: early dark energy, which decays at z~5000 into dark radiation (see eg Riess et al; Kaminokowski et al): delays onset of matter domination, raises the Planck value of H_0
- Very mysterious: maybe a consequence of Weak Gravity Conjecture: masses of extra states depend on field vevs and if those range by Planck scale, many fields get light - ie relativistic

hep-th/1903:11676, NK

Dark Preheating

- Trouble with EDE: if it is quintessence under control - ia axion in slow roll, when it starts to roll it behaves as DM
- This must not be since it runs afoul of BAO
- How could it decay into radiation FAST? First you need radiation - ie relativistic species
- Perturbative production too slow:

$$\Gamma \sim m^3/\mathcal{M}^2 \ll m$$

- Preheating faster:

$$\mu(\chi)\bar{\psi}\psi \sim 4\pi\frac{m}{M}\chi\bar{\psi}\psi \sim 4\pi\sqrt{\frac{H_c}{m_{\rm Pl}}}\chi\bar{\psi}\psi \qquad \Gamma_{\bar{\psi}\psi} \sim 2\pi\frac{H_c^2}{m_{\rm Pl}}$$

$$\Gamma_{\rm total} \sim \sum_{\rm flavor}\Gamma_{\rm flavor} \sim 2\pi\frac{H_c^2}{m_{\rm Pl}}\mathcal{N}$$

- WGC: lots of light species pop up once field changes by Planck:
-

$$\mathcal{N} \lesssim \mathcal{N}_{total} \lesssim \left(\frac{m_{Pl}}{M}\right)^2$$

Party time!!

$$\Gamma_{\rm total} \sim 2\pi \frac{H_c^2\, m_{\rm Pl}}{M^2} \sim 2\pi H_c$$

- NOW EDE can decay FAST and convert into relativistic stress energy

$$m \sim H_c \sim H_0 \times (5000)^{3/2} \sim 10^{-27}{\rm eV} \sim {\rm MPc}^{-1}, \qquad M \sim {\rm eV}$$

- Tabletop sub-mm gravity prediction:

$$V_N \simeq -G_N \frac{m_1 m_2}{r}\left(1+\frac{\mathcal{N}}{m_{\rm Pl}^2 r^2}\right) \simeq -G_N \frac{m_1 m_2}{r}\left(1+\frac{\mathcal{O}(1)}{M^2 r^2}\right)$$

- LHC? Naively...

$$\sigma_{p\bar{p}\to missing\ energy} \sim \mathcal{N}\frac{f(\sqrt{s_{cm}})}{m_{Pl}^2}$$

- But the EFT is cut off at $M \ll \sqrt{s_{cm}}$ and the form factor could suppress this process dramatically
- There might be other options as well-stay tuned

Summary

- DE interactions with other stuff is not a complete misconception
- MANY SPECIES OF ULTRALIGHT WILD THINGS MIGHT CIRCUMVENT DECOUPLING - while EFT still reigns just fine
- Today's ultralight DM cannot be more that 5% of the cosmic content - but it is more abundant than eg neutrinos... The two can mix, neutrino mass might have evolved as a result
- Today's ultralight DM might have been yesterday's EDE - if EDE is really needed to fix the tension with H0 this can have dramatic implications
- To dissipate fast, if EDE is a QFT ultralight field, and ranges by a Planck scale, there might be many ultralights enforcing the WGC - may be probed by sky surveys!!!
- Quantum Gravity in the sky!

IS THERE MORE TO DARKNESS THAN ANTHROPICS?