FUZZY DARK MATTER

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March 2000 – Internship at LAPTH with Pierre

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Subject: Tasting Quintessence

The Dark Energy Problem

$\sim$ 70% of the Universe energy has a negative pressure!

- **Cosmological Constant**
  A new physics constant...
- **Vacuum Energy**
  Applying Quantum Field Theory to Dark Energy?
  Not very Successful yet...
- **Quintessence**
  Dark energy as a real scalar field?
- **...**

Quintessence

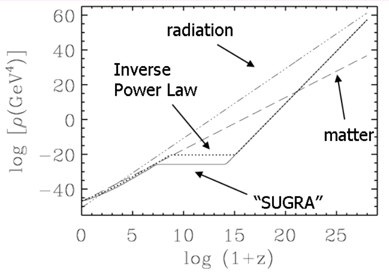
Quintessence = real homogeneous scalar field

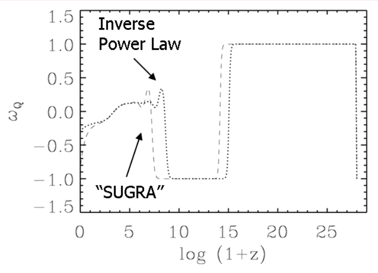
- Lagrangian density: $\mathcal{L} = g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)$
- Density and pressure: $\begin{cases} \rho_\varphi = \frac{1}{2}\dot{\varphi}^2 + V(\varphi) \\ P_\varphi = \frac{1}{2}\dot{\varphi}^2 - V(\varphi) \end{cases}$
- Friedmann equations: $\begin{cases} \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\sum\rho - \frac{k}{a^2} \\ \frac{\ddot{a}}{a} = -\frac{3\pi G}{3}(\sum\rho + 3\sum P) \end{cases}$
- Klein-Gordon equation: $\ddot{\varphi} + 3H\dot{\varphi} + \frac{\partial V}{\partial\varphi} = 0$
- Usual potentials: $V(\varphi) = \alpha\varphi^{-\beta}$
  $V(\varphi) = \alpha\exp(-\beta\varphi)$
  $V(\varphi) = \alpha\left[\cosh(\beta\varphi) - 1\right]^n$

Quintessence

Theoretical constraints

- No fine tuning in the potential
- No fine tuning in the initial conditions
- Today, $\omega_\varphi \equiv \frac{P_\varphi}{\rho_\varphi} \approx -1$





October 2000 – PhD at LAPTH with Pierre

October 2000 – PhD at LAPTH with Pierre

A new Quest...

Not an easy task...

Not an easy task...

What I learnt from Pierre...

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What I learnt from Pierre...

Dark Matter? Or Dark Energy? Or both?

What if Dark Matter and Dark Energy are in interaction?

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What if they are different aspects of a same dark component?

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Can we model Dark Matter with a quintessential scalar field?

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What if Dark Matter and Dark Energy are in interaction?

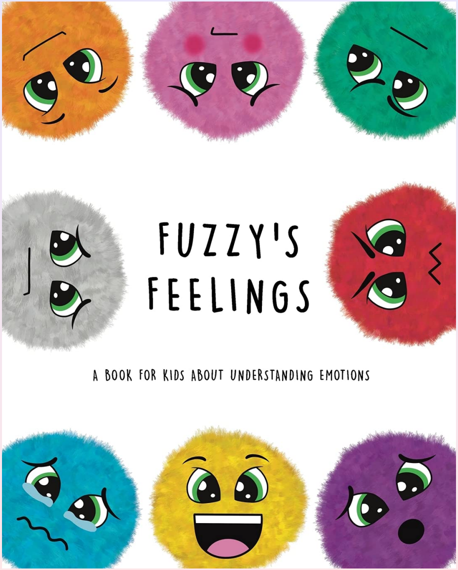
What if they are different aspects of a same dark component?

Can we model Dark Matter with a quintessential scalar field?

$\rightarrow$ Fuzzy Dark Matter

W. Hu, R. Barkana, A. Gruzinov, Phys. Rev. Lett. 85 (2000) 1158

Understanding Fuzzy Dark Matter...



Dark Matter scalar field

Massive and complex Scalar Field

- $\mathcal{L} = g^{\mu\nu}\partial_\mu\phi^*\partial_\nu\phi - V(\phi)$
- $V(\phi) = m^2|\phi|^2$

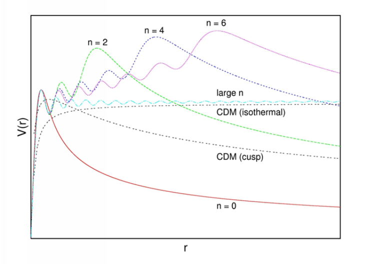
A. Arbey, J. Lesgourgues & P. Salati, Phys. Rev. D 64, 123528 - Phys. Rev. D 65, 083514 - Phys. Rev. D 68, 023511

Addition of a $U(1)$ internal symmetry in comparison to the original fuzzy dark matter model

Galaxy Rotation Curves (1)

- **Internal rotation**: $\phi(\vec{x},t) = \dfrac{\sigma(r)}{\sqrt{2}} e^{i\omega t}$
- **Static and isotropic metric**:
  $d\tau^2 = e^{2u} dt^2 - e^{2v}\left\{dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2\right\}$
- **Klein-Gordon equation**:
  $$e^{-2v}\left\{\sigma'' + \left(u' + v' + \frac{2}{r}\right)\right\} + \omega^2 e^{-2u}\sigma - m^2\sigma = 0$$
- **Einstein equations**:
  $$2v'' + v'^2 + \frac{4v'}{r} = -8\pi G e^{2v}\left\{e^{-2u}\frac{\omega^2\sigma^2}{2} + e^{-2v}\frac{\sigma''}{2} + \frac{m^2\sigma^2}{2}\right\}$$
  $$u'' + v'' + u'^2 + \frac{1}{r}(u' + v') =$$
  $$8\pi G\left\{e^{2v}\left[e^{-2u}\frac{\omega^2\sigma^2}{2} - e^{-2v}\frac{\sigma''}{2} - \frac{m^2\sigma^2}{2}\right] + \rho_{baryon}\right\}$$

Resolution $\rightarrow$ discrete number of solutions, *i.e.* fundamental and excited states of a Bose-Einstein condensate

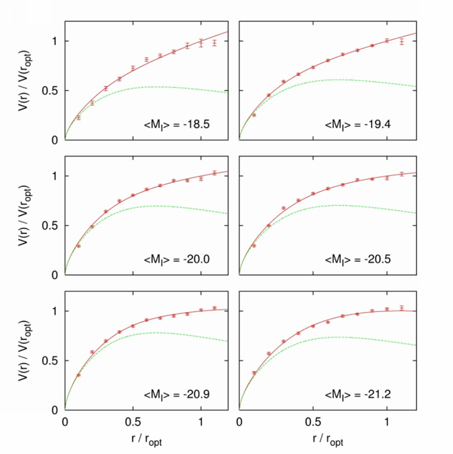


To ensure stability, we consider only the fundamental and less-energetic state, n=0

Newtonian limit: $\omega^2 \approx m^2 \rightarrow P \approx (\omega^2 - m^2)\sigma^2 \approx 0$

Rotation curves obtained with: $v^2(r) = r\frac{\partial}{\partial r}\Phi_{grav}(r) = rc^2u'(r)$

Galaxy Rotation Curves (3)



Universal Rotation Curves
(Persic, Salucci & Stel)

The favoured mass is around
10^{-23} **eV**!

→ No cuspy halos, smooth profiles → *Fuzzy* !!

Cosmological Behaviour

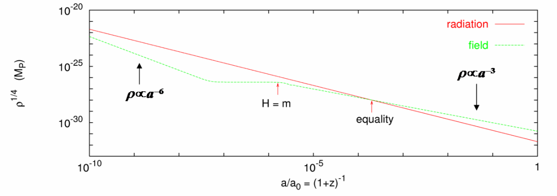
Friedmann-Lemaître Universe with radiation and scalar field

Internal rotation: $\phi(t) = \frac{\sigma(t)}{\sqrt{2}} e^{i\theta(t)}$

Friedmann equation: $3H^2 = 8\pi G(\rho_\gamma + \rho_\phi)$

with $\rho_\phi = \frac{1}{2}\left\{\left(\frac{d\sigma}{dt}\right)^2 + \left(\frac{d\theta}{dt}\right)^2 \sigma^2 + m^2\sigma^2\right\}$

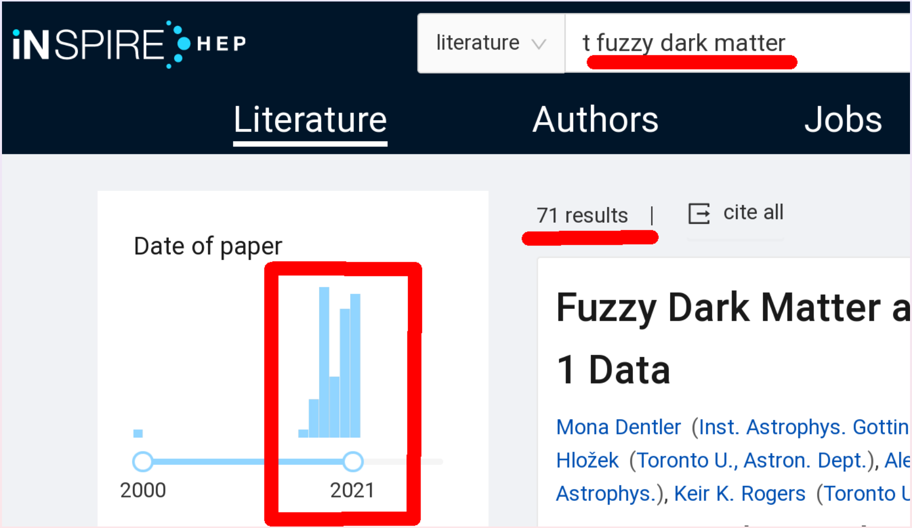
Klein-Gordon equation: $\begin{cases} \frac{d^2\sigma}{dt^2} + \frac{3}{a}\frac{da}{dt}\frac{d\sigma}{dt} + m^2\sigma - \left(\frac{d\theta}{dt}\right)^2 \sigma = 0 \\ \frac{d^2\theta}{dt^2}\sigma + \frac{3}{a}\frac{da}{dt}\frac{d\theta}{dt}\sigma + 2\frac{d\theta}{dt}\frac{d\sigma}{dt} = 0 \end{cases}$



The field has an adequate matter behaviour since recombination!

About 20 years later...

Fuzzy Dark Matter has become a hot topic!



Fuzzy dark matter simulations

S. May, V. Springel, arXiv:2101.01828

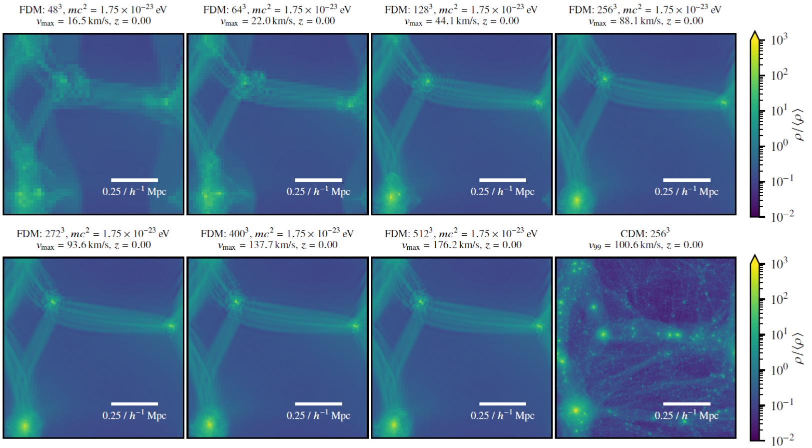


Figure 1. Projected dark matter density at $z = 0$ in $L = 1\ h^{-1}$ Mpc cosmological box simulations of FDM with $mc^2 = 1.75 \times 10^{-23}$ eV and CDM ICs for different resolutions. A high-resolution CDM simulation is shown for comparison. The 99th-percentile velocity of the particles in the CDM simulation is given as v_{99}.

Fuzzy dark matter simulations

S. May, V. Springel, arXiv:2101.01828

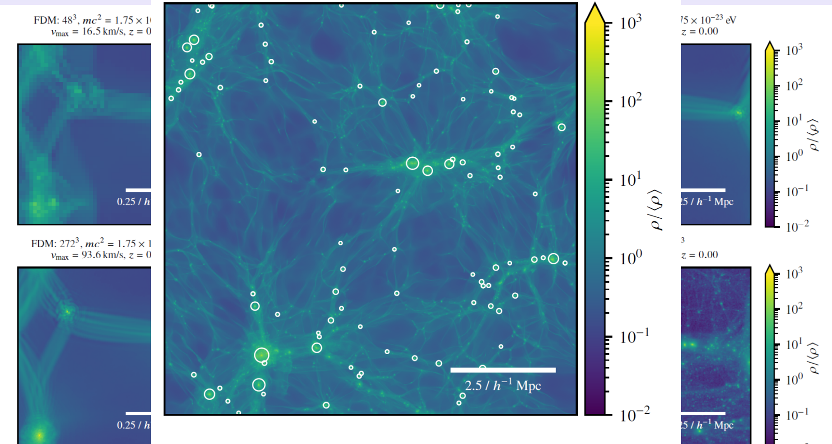


Figure 11. Projected dark matter density at $z = 3$ of a $3\,h^{-1}$ Mpc (comoving) slab in a high-resolution cosmological box simulation of FDM with box size $L = 10\,h^{-1}$ Mpc, FDM mass $mc^2 = 7 \times 10^{-23}$ eV, mesh size $N^3 = 8640^3$, and CDM ICs. The largest haloes identified with the halo finder are marked with circles whose radii indicate the haloes' virial radii R_{200}.

Figure 1. Projected dark m… resolutions. A high-resolut… V and CDM ICs for different … simulation is given as v_{99}.

On my side: Unifying scalar fields, my favourite hobby!

PHYSICAL REVIEW D **74,** 043516 (2006)

Dark fluid: A complex scalar field to unify dark energy and dark matter

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In this article, we examine a model which proposes a common explanation for the presence of additional attractive gravitational effects—generally considered to be due to dark matter—in galaxies and in clusters, and for the presence of a repulsive effect at cosmological scales—generally taken as an indication of the presence of dark energy. We therefore consider the behavior of a so-called dark fluid based on a complex scalar field with a conserved $U(1)$-charge and associated to a specific potential, and show that it can at the same time account for dark matter in galaxies and in clusters, and agree with the cosmological observations and constraints on dark energy and dark matter.

DOI: 10.1103/PhysRevD.74.043516 PACS numbers: 98.80.Cq, 04.50.+h, 95.35.+d, 95.36.+x

On my side: Unifying scalar fields, my favourite hobby!

Unifying dark matter, dark energy and inflation with a fuzzy dark fluid

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Abstract. Scalar fields appear in many cosmological models, in particular in order to provide explanations for dark energy and inflation, but also to emulate dark matter. In this paper, we show that it is possible for a scalar field to replace simultaneously dark matter, dark energy and inflation by assuming the existence of a non-minimal coupling to gravity, a Mexican hat potential, and a spontaneous symmetry breaking before inflation. After inflation, the scalar field behaves like a dark fluid, mimicking dark energy and dark matter, and has a dark matter behaviour similar to fuzzy dark matter.

Keywords: dark energy theory, dark matter theory, inflation

ArXiv ePrint: 2007.05376

Thank you very much, Pierre !

Bonne retraite et bonne chasse
(à la matière noire) !