Ultra-light scalar fields: a story of three potentials

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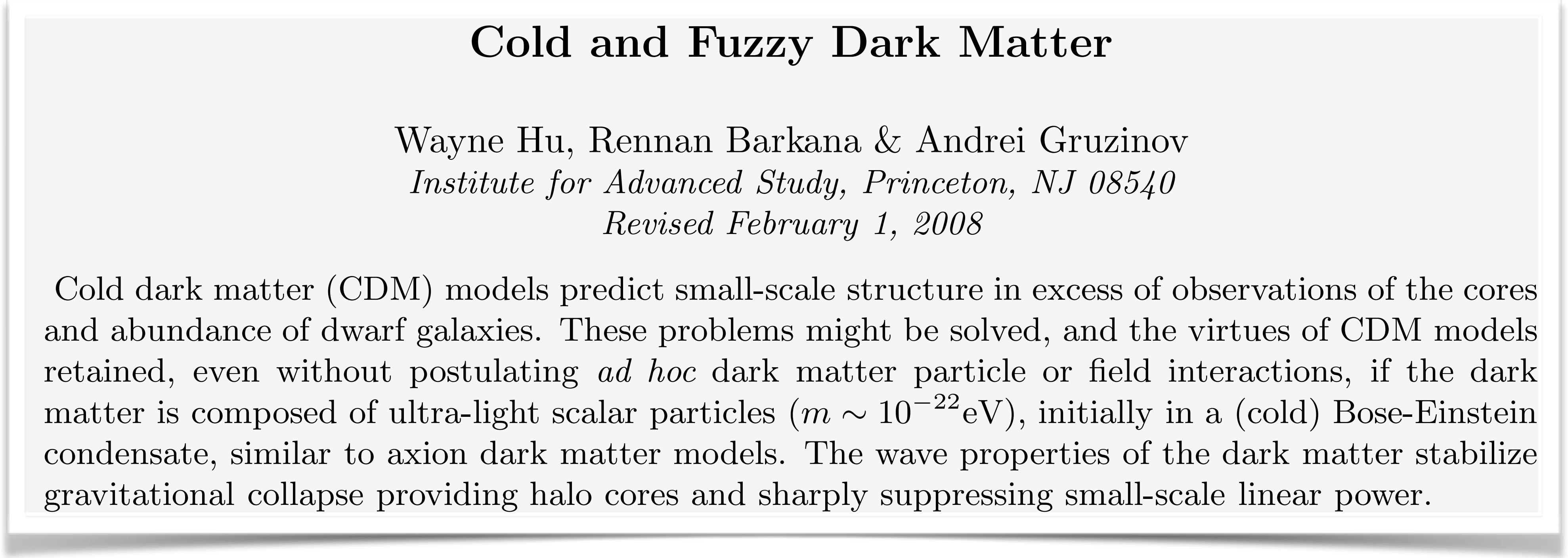
Cosmology from Home 2020

Nostalgia

Non-relativistic!



Cold and Fuzzy Dark Matter

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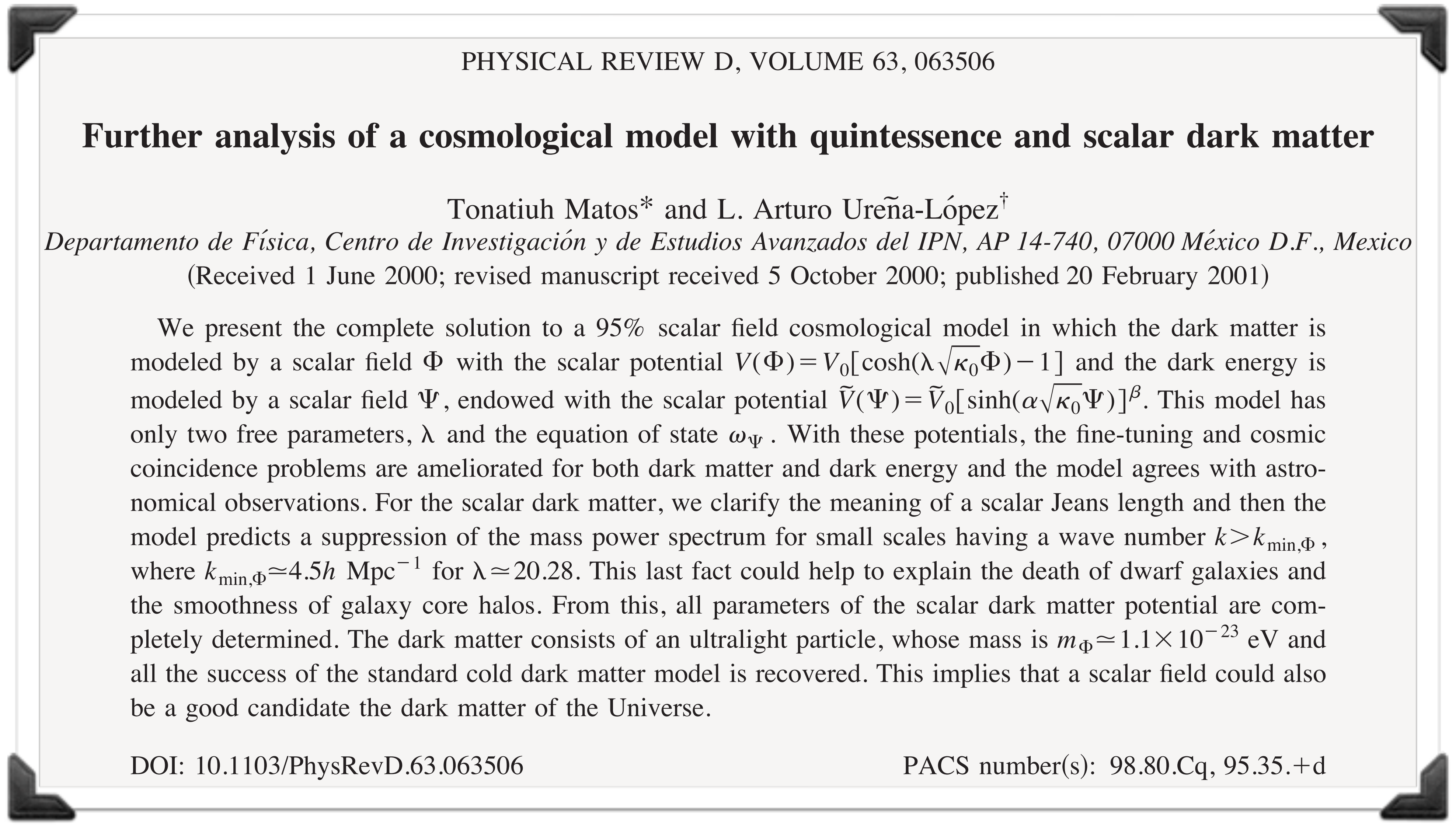
Institute for Advanced Study, Princeton, NJ 08540
Revised February 1, 2008

Cold dark matter (CDM) models predict small-scale structure in excess of observations of the cores and abundance of dwarf galaxies. These problems might be solved, and the virtues of CDM models retained, even without postulating *ad hoc* dark matter particle or field interactions, if the dark matter is composed of ultra-light scalar particles ($m \sim 10^{-22}$eV), initially in a (cold) Bose-Einstein condensate, similar to axion dark matter models. The wave properties of the dark matter stabilize gravitational collapse providing halo cores and sharply suppressing small-scale linear power.

astro-ph/0003365



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Further analysis of a cosmological model with quintessence and scalar dark matter

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We present the complete solution to a 95% scalar field cosmological model in which the dark matter is modeled by a scalar field Φ with the scalar potential $V(\Phi)=V_0[\cosh(\lambda\sqrt{\kappa_0}\Phi)-1]$ and the dark energy is modeled by a scalar field Ψ, endowed with the scalar potential $\tilde{V}(\Psi)=\tilde{V}_0[\sinh(\alpha\sqrt{\kappa_0}\Psi)]^{\beta}$. This model has only two free parameters, λ and the equation of state ω_Ψ. With these potentials, the fine-tuning and cosmic coincidence problems are ameliorated for both dark matter and dark energy and the model agrees with astronomical observations. For the scalar dark matter, we clarify the meaning of a scalar Jeans length and then the model predicts a suppression of the mass power spectrum for small scales having a wave number $k>k_{\min,\Phi}$, where $k_{\min,\Phi}\simeq 4.5h$ Mpc^{-1} for $\lambda\simeq 20.28$. This last fact could help to explain the death of dwarf galaxies and the smoothness of galaxy core halos. From this, all parameters of the scalar dark matter potential are completely determined. The dark matter consists of an ultralight particle, whose mass is $m_\Phi\simeq 1.1\times 10^{-23}$ eV and all the success of the standard cold dark matter model is recovered. This implies that a scalar field could also be a good candidate the dark matter of the Universe.

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astro-ph/0006024

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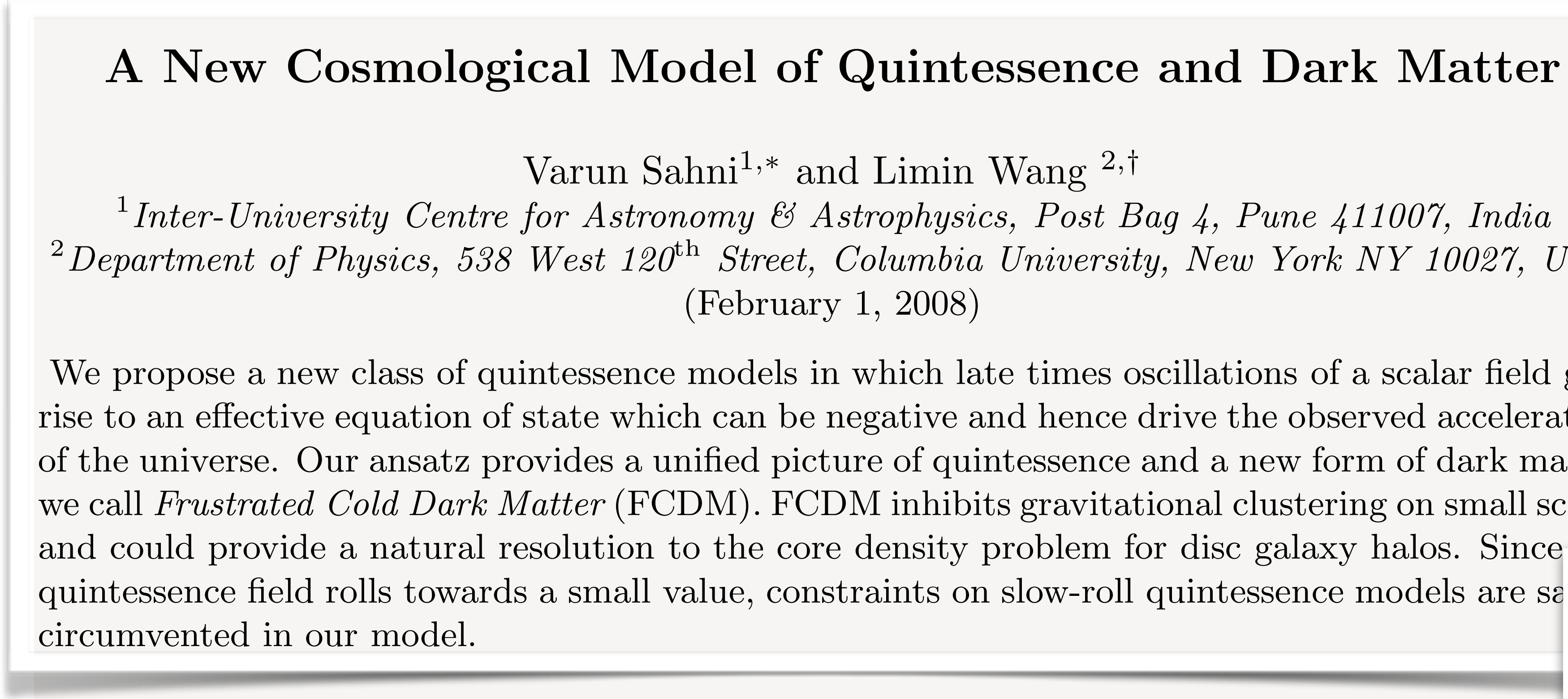

A New Cosmological Model of Quintessence and Dark Matter

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(February 1, 2008)

We propose a new class of quintessence models in which late times oscillations of a scalar field give rise to an effective equation of state which can be negative and hence drive the observed acceleration of the universe. Our ansatz provides a unified picture of quintessence and a new form of dark matter we call *Frustrated Cold Dark Matter* (FCDM). FCDM inhibits gravitational clustering on small scales and could provide a natural resolution to the core density problem for disc galaxy halos. Since the quintessence field rolls towards a small value, constraints on slow-roll quintessence models are sa circumvented in our model.

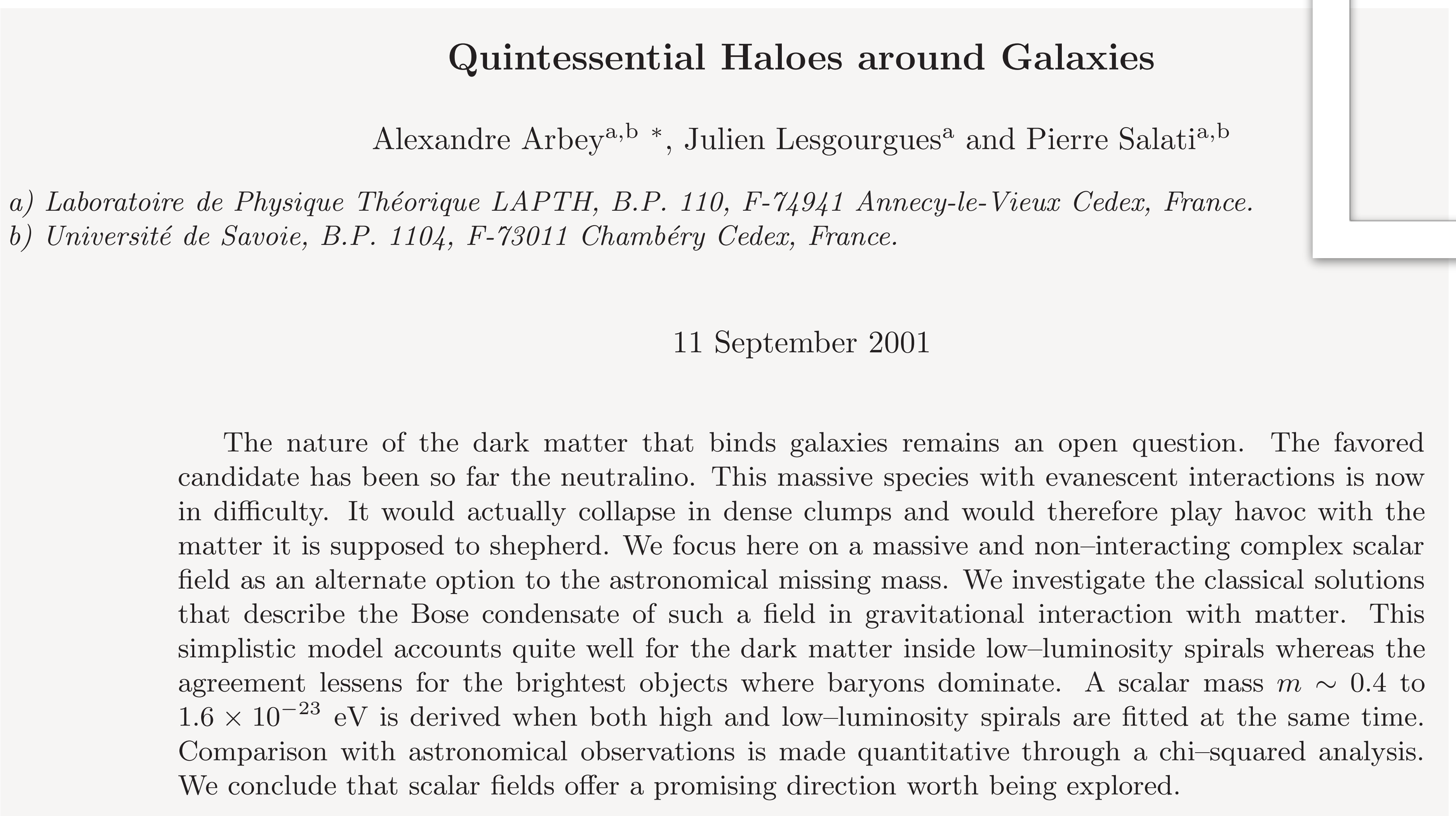
Klein-Gordon equation

$$\frac{1}{\sqrt{-g}}\partial_\mu(\sqrt{-g}\,g^{\mu\nu}\partial_\nu\phi) = \frac{\partial V}{\partial\phi}$$

$$V(\phi) = \frac{1}{2}m_a^2\phi^2$$

(Fuzzy Dark Matter)

astro-ph/0105564



Quintessential Haloes around Galaxies

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11 September 2001

The nature of the dark matter that binds galaxies remains an open question. The favored candidate has been so far the neutralino. This massive species with evanescent interactions is now in difficulty. It would actually collapse in dense clumps and would therefore play havoc with the matter it is supposed to shepherd. We focus here on a massive and non–interacting complex scalar field as an alternate option to the astronomical missing mass. We investigate the classical solutions that describe the Bose condensate of such a field in gravitational interaction with matter. This simplistic model accounts quite well for the dark matter inside low–luminosity spirals whereas the agreement lessens for the brightest objects where baryons dominate. A scalar mass $m \sim 0.4$ to 1.6×10^{-23} eV is derived when both high and low–luminosity spirals are fitted at the same time. Comparison with astronomical observations is made quantitative through a chi–squared analysis. We conclude that scalar fields offer a promising direction worth being explored.

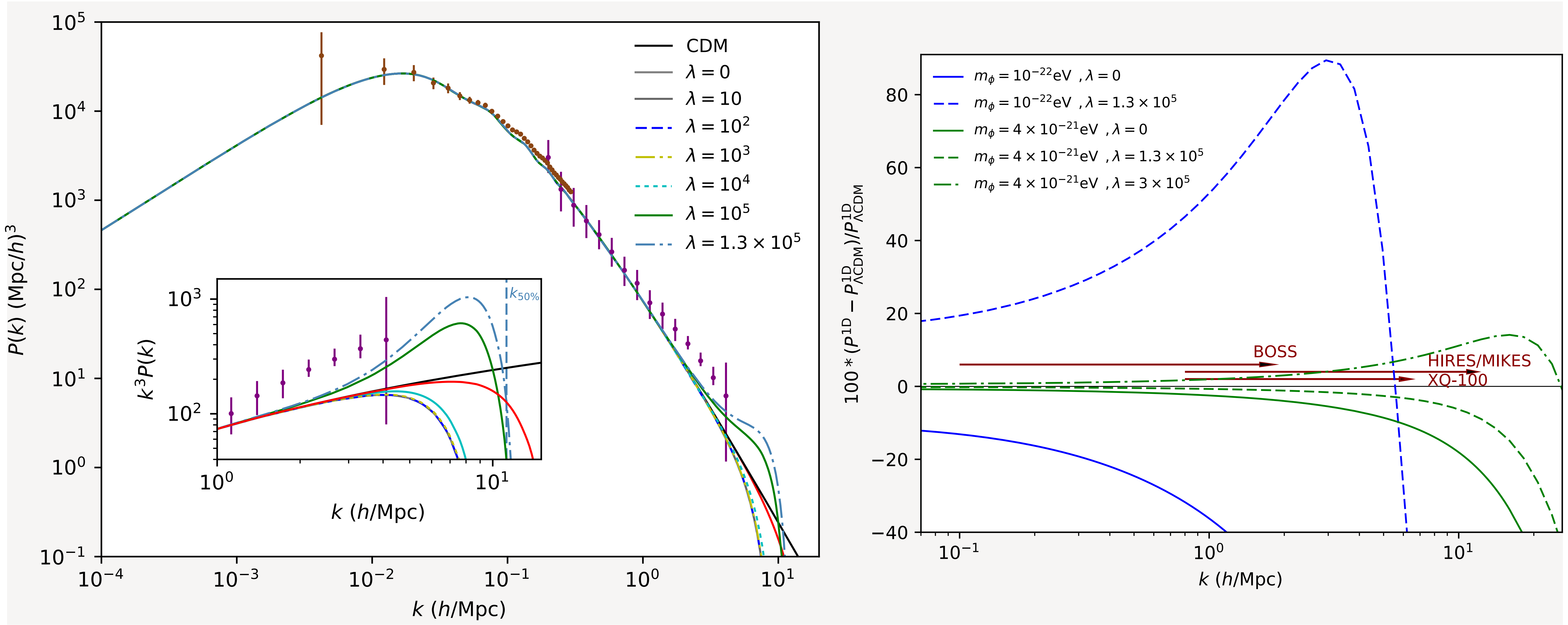
Axion-like potential

$$V(\phi) = m_a^2 f_a^2 [1 - \cos(\phi/f_a)]$$

Linares et al, PRD 96 (2017) 061301(R)
(Francisco Linares' and Stefany Medellín's talks at CfH)

$$\lambda = \frac{3m_{\rm Pl}^2}{8\pi f_a^2} \qquad \mathrm{FDM:}\ \lambda = 0\ (f_a \to \infty)$$

Leong et al, MNRAS 484 (2018) 4273



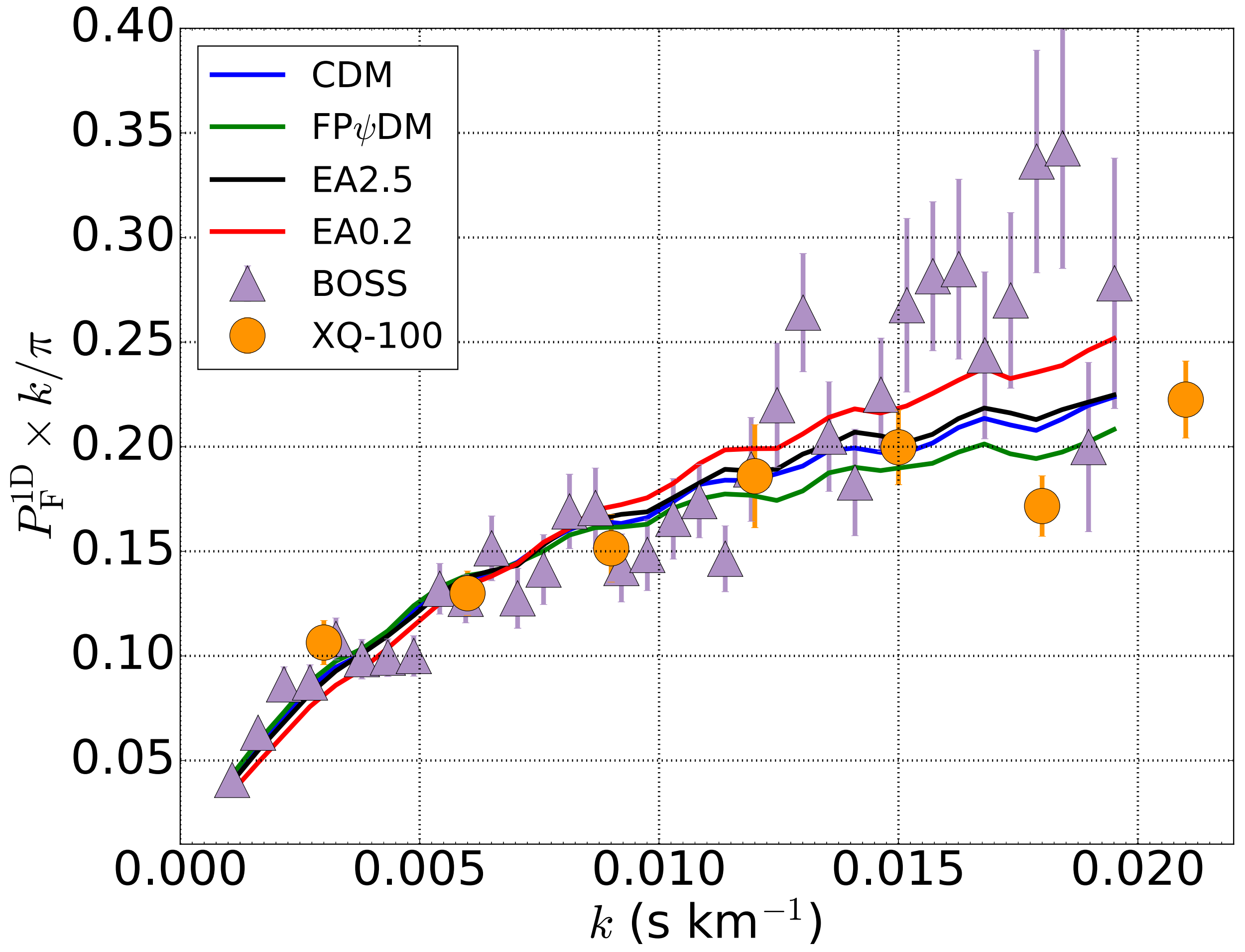


Figure 8. The transmitted flux power spectra of BOSS (Palanque-Delabrouille et al. 2013), XQ-100 (Iršič et al. 2017c) and model predictions at $z = 4.0$. It clearly shows that the power of BOSS is higher than that of XQ-100 around $k > 0.015$ s km^{-1}, while the predictions are closer to the latter than the former.

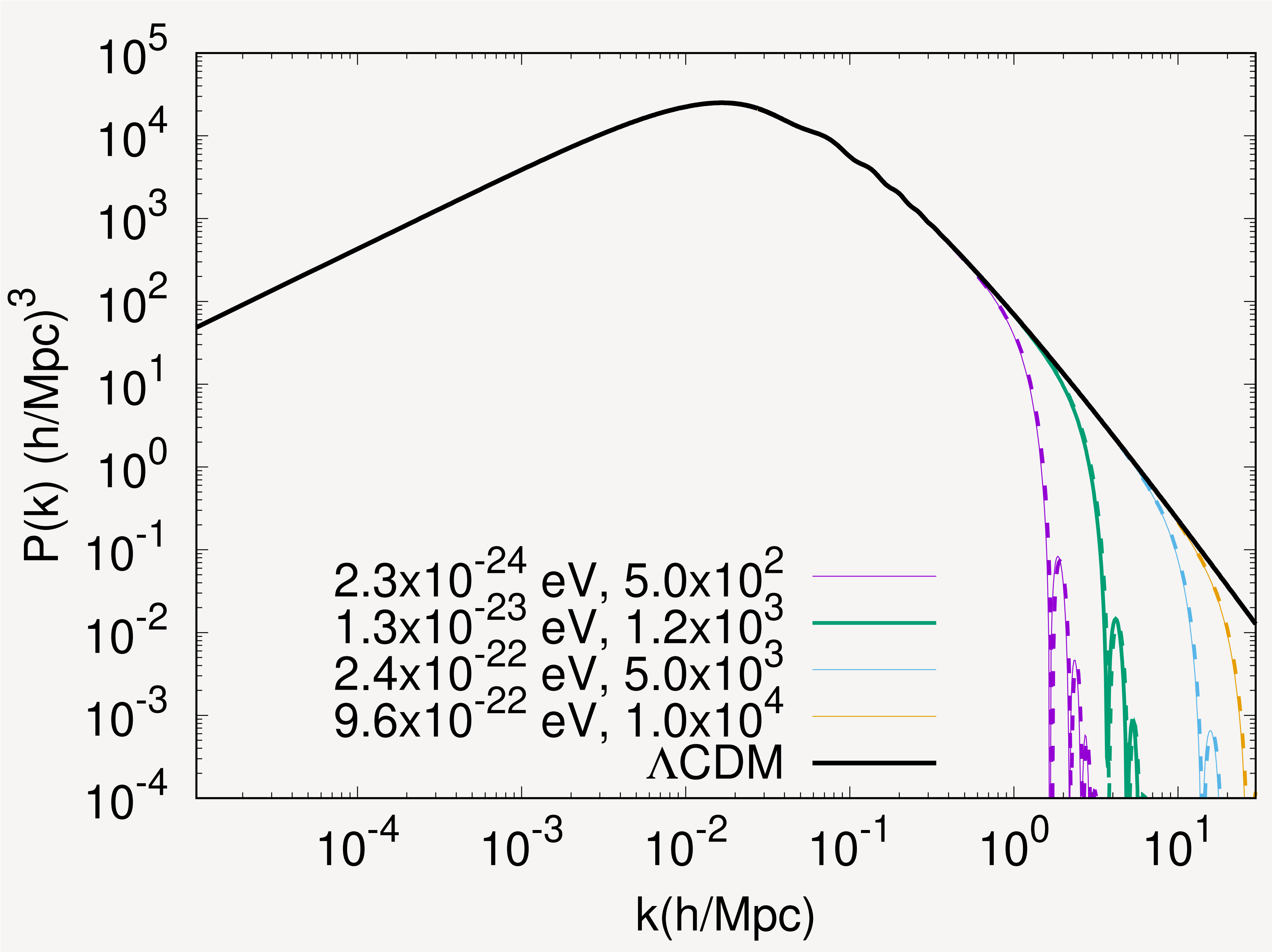
Cosh-like potential

$$V(\phi) = m_a^2 f_a^2 [\cosh(\phi/f_a) - 1]$$

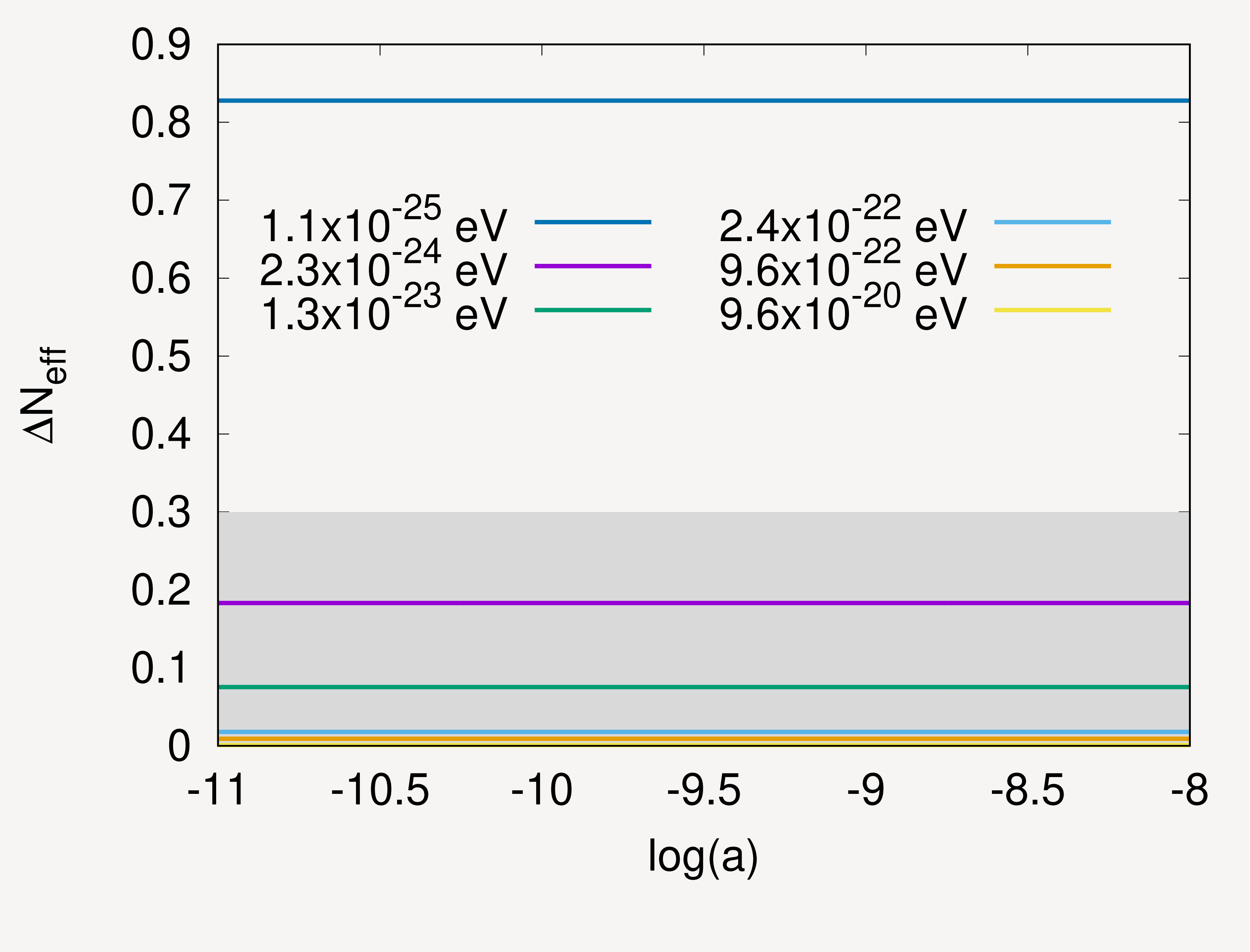
$$\lambda = -\frac{3m_{\rm Pl}^2}{8\pi f_a^2}$$

U-L, JCAP 06 (2019) 009

Matos, U-L, PRD 63 (2001) 063506
astro-ph/0006024 (CMBFAST)



Cosh = FDM



Extra relativistic degrees of freedom

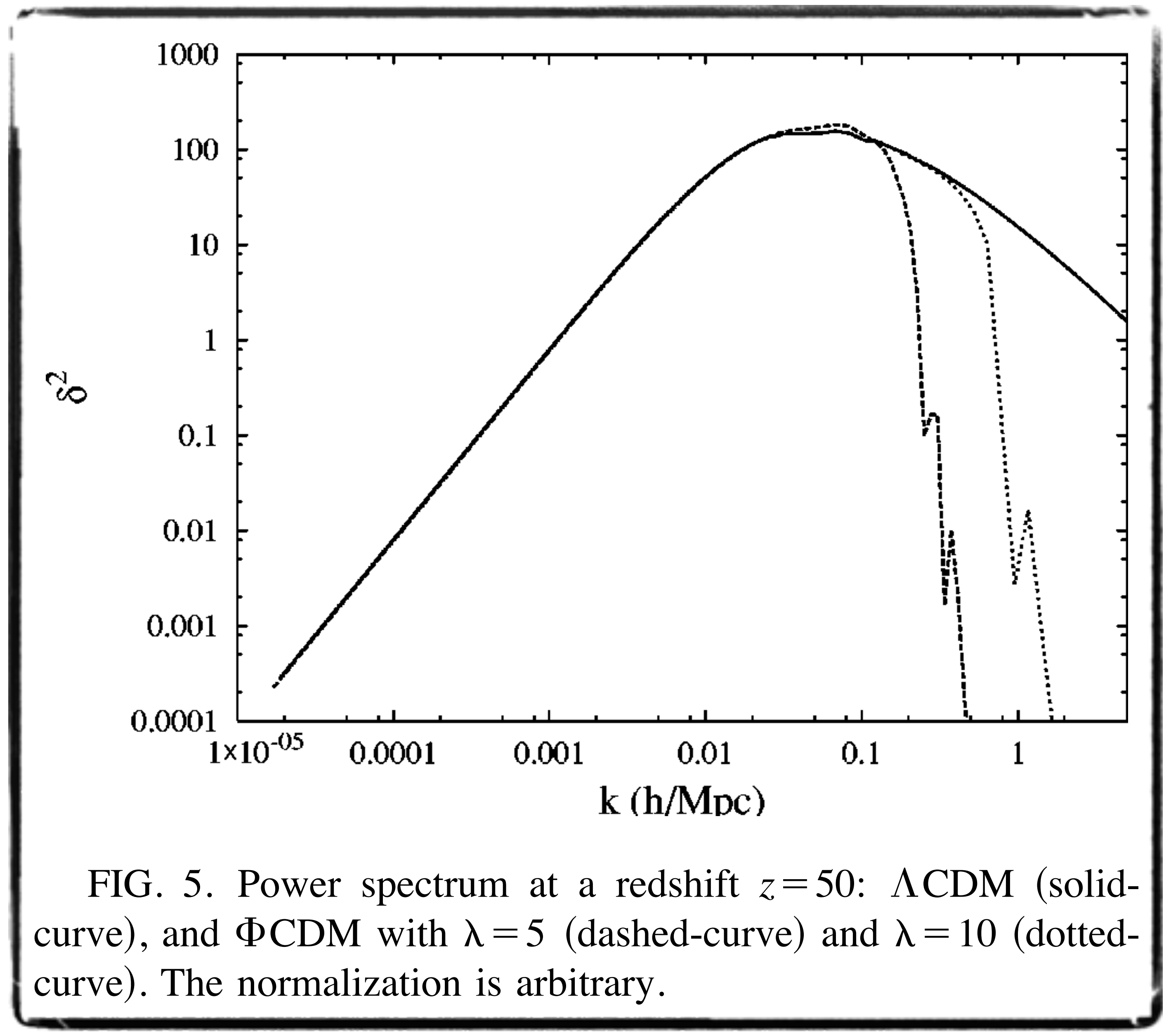


FIG. 5. Power spectrum at a redshift $z=50$: ΛCDM (solid-curve), and ΦCDM with $\lambda=5$ (dashed-curve) and $\lambda=10$ (dotted-curve). The normalization is arbitrary.

Non-relativistic dynamics

$$\phi = \psi e^{-i m_a t} + \mathrm{C.C.}$$

$$i\dot{\psi} = -\frac{1}{2m_a}\nabla^2\psi + \left(\Phi_g + \frac{\lambda}{6m_a^2}|\psi|^2\right) m_a\psi$$

$$\nabla^2\Phi_g = 4\pi G m_a |\psi|^2\left(1 + \frac{\lambda}{6m_a^2}|\psi|^2\right)$$

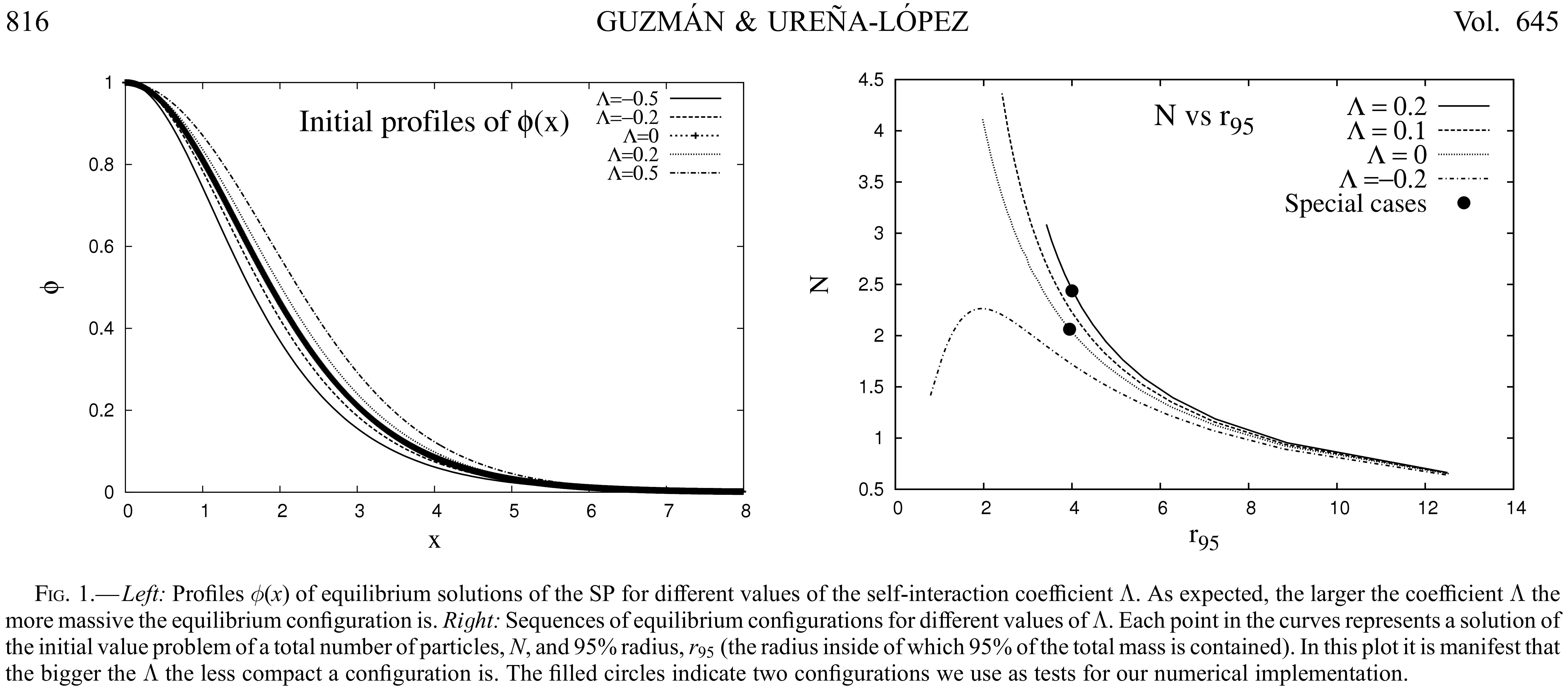


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Fig. 1.—*Left:* Profiles $\phi(x)$ of equilibrium solutions of the SP for different values of the self-interaction coefficient Λ. As expected, the larger the coefficient Λ the more massive the equilibrium configuration is. *Right:* Sequences of equilibrium configurations for different values of Λ. Each point in the curves represents a solution of the initial value problem of a total number of particles, N, and 95% radius, r_{95} (the radius inside of which 95% of the total mass is contained). In this plot it is manifest that the bigger the Λ the less compact a configuration is. The filled circles indicate two configurations we use as tests for our numerical implementation.

Gravitational cooling of self-gravitating Bose condensates; Guzmán, U-L, ApJ 645 (2006) 814

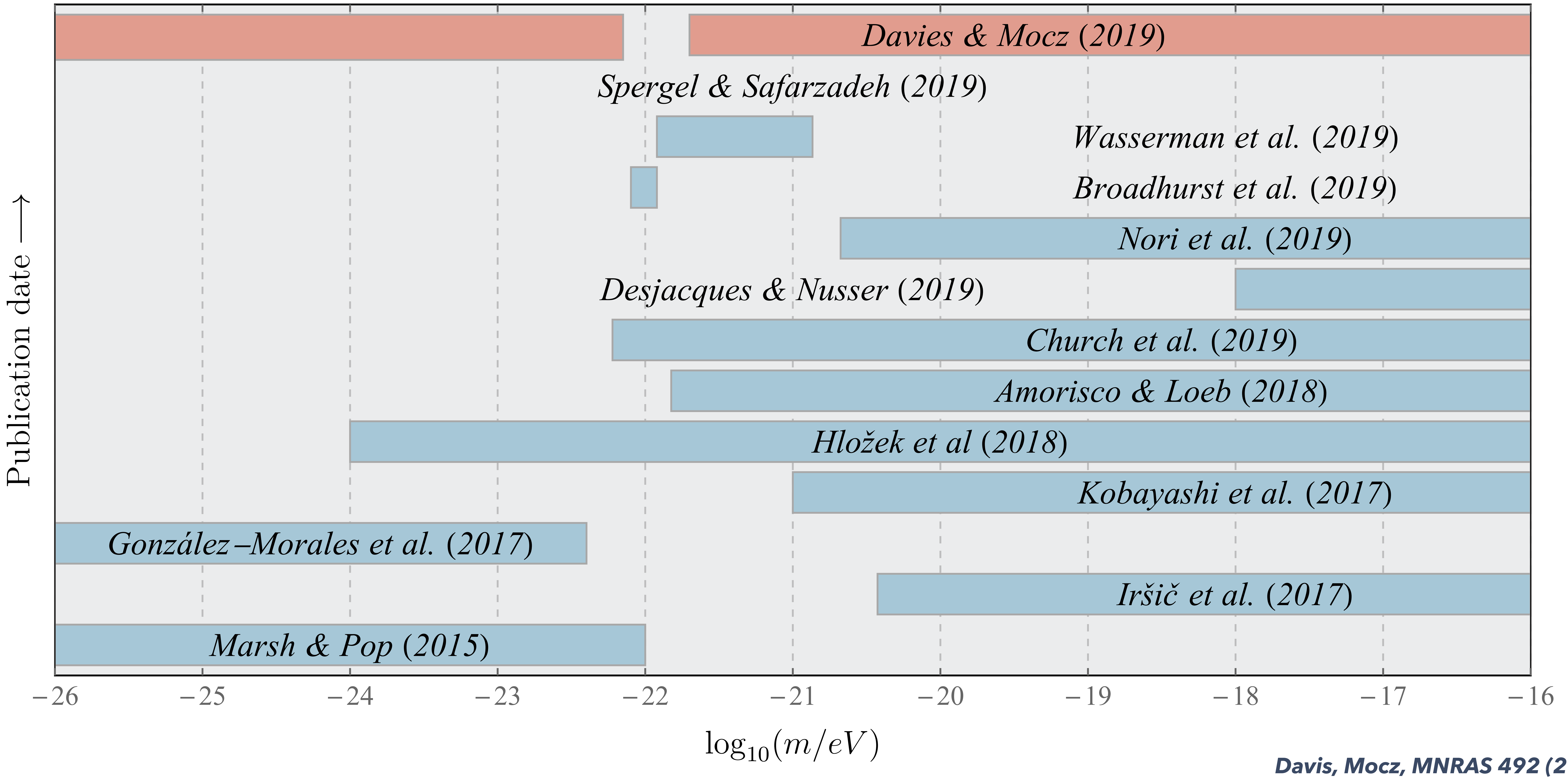
Ultra-light scalar fields

Axion-like:	$\lambda > 0$
FDM:	$\lambda = 0$
Cosh-like:	$\lambda < 0$

Critical mass of gravitational collapse

Axion-like:	$M_c = \lambda^{-1/2}\frac{m_{\mathrm{Pl}}^2}{m_a} < 10^{12}\,M_\odot$
FDM:	$M_c = 0.6\,\frac{m_{\mathrm{Pl}}^2}{m_a} \simeq 10^{12}\,M_\odot \quad (m_a = 10^{-22}\,\mathrm{eV})$
Cosh-like:	$M_c = \lvert\lambda\rvert^{1/2}\frac{m_{\mathrm{Pl}}^2}{m_a} > 10^{12}\,M_\odot$

Current constraints on the mass



λ?

Davis, Mocz, MNRAS 492 (2020) 4, 5721

Thank you!
¡Gracias!