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Ultralight scalar dark matter

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University of Guanajuato, México

- **México is the most populated Spanish-speaking country in the world**
- **Guanajuato is a medium-size state located in central Mexico, 400 km from Mexico City, with around 6M people**
- **State university with a population about 40k students (high-school, undergraduates, graduates)**
  - **Department of Physics (Campus León). City of León (1.2M people, 1,884 m asl)**
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Main building facade of the University of Guanajuato

68 languages; most spoken: Spanish, Nahuatl and Mayan

Mesoamerica was one of the ancient civilization centres in the world

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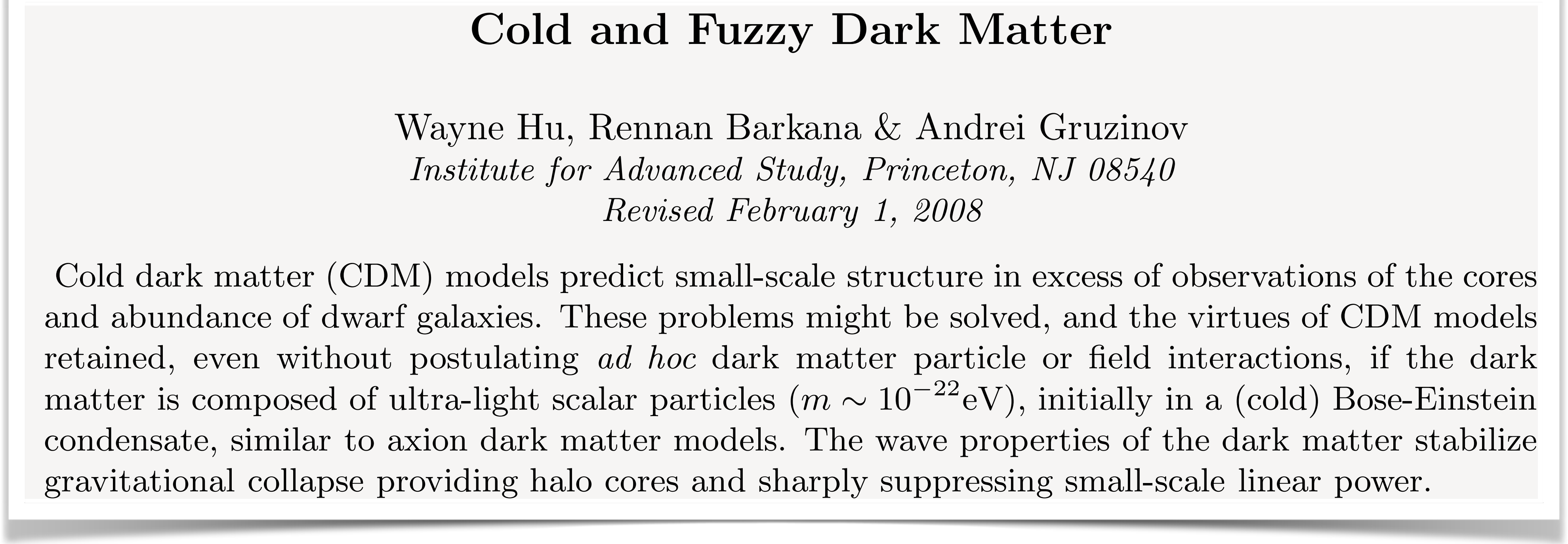
Motivation

Nostalgia: 25 years ago somewhere in CINVESTAV

Non-relativistic!

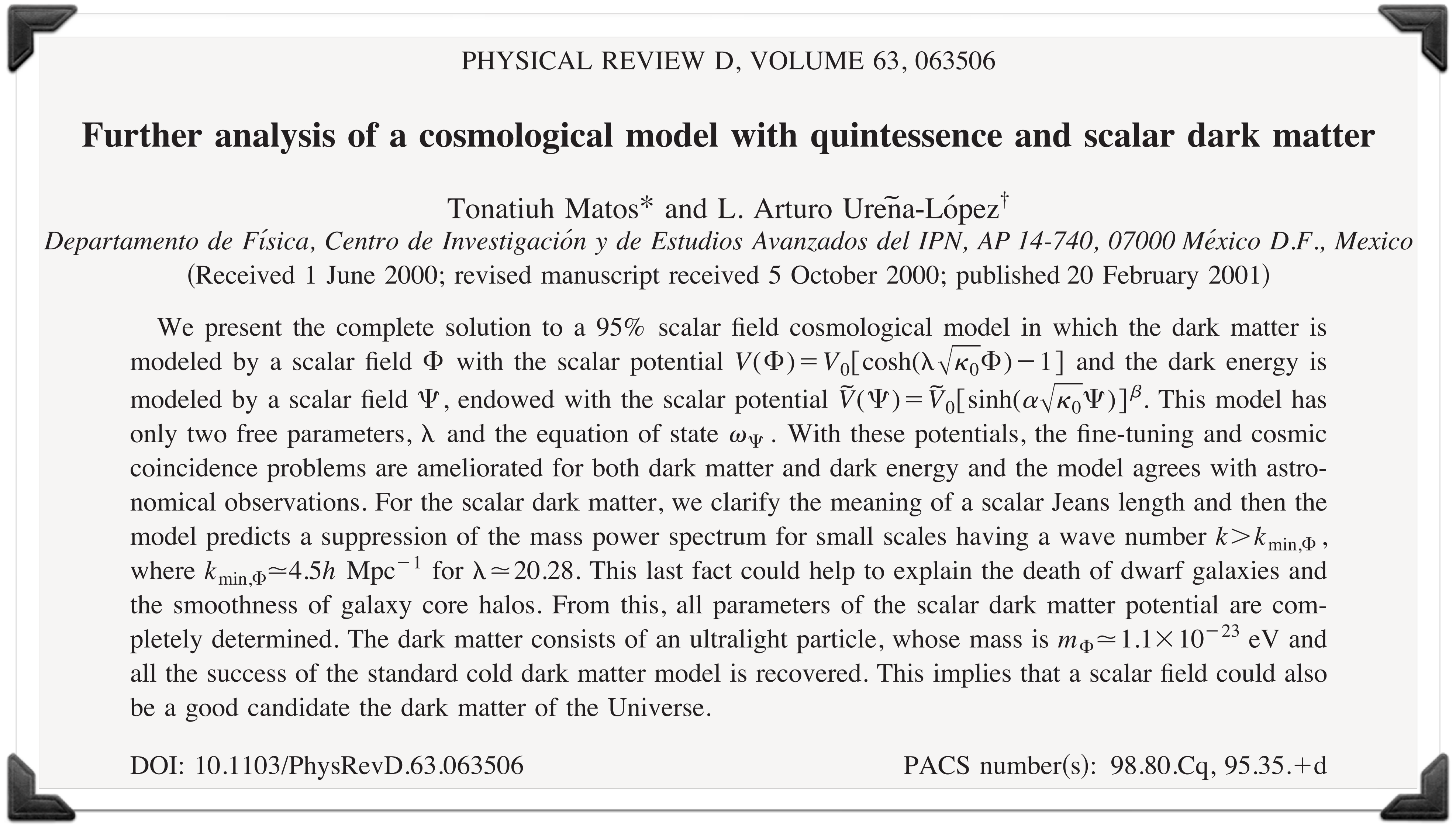


Cold and Fuzzy Dark Matter

Wayne Hu, Rennan Barkana & Andrei Gruzinov
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



PHYSICAL REVIEW D, VOLUME 63, 063506

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

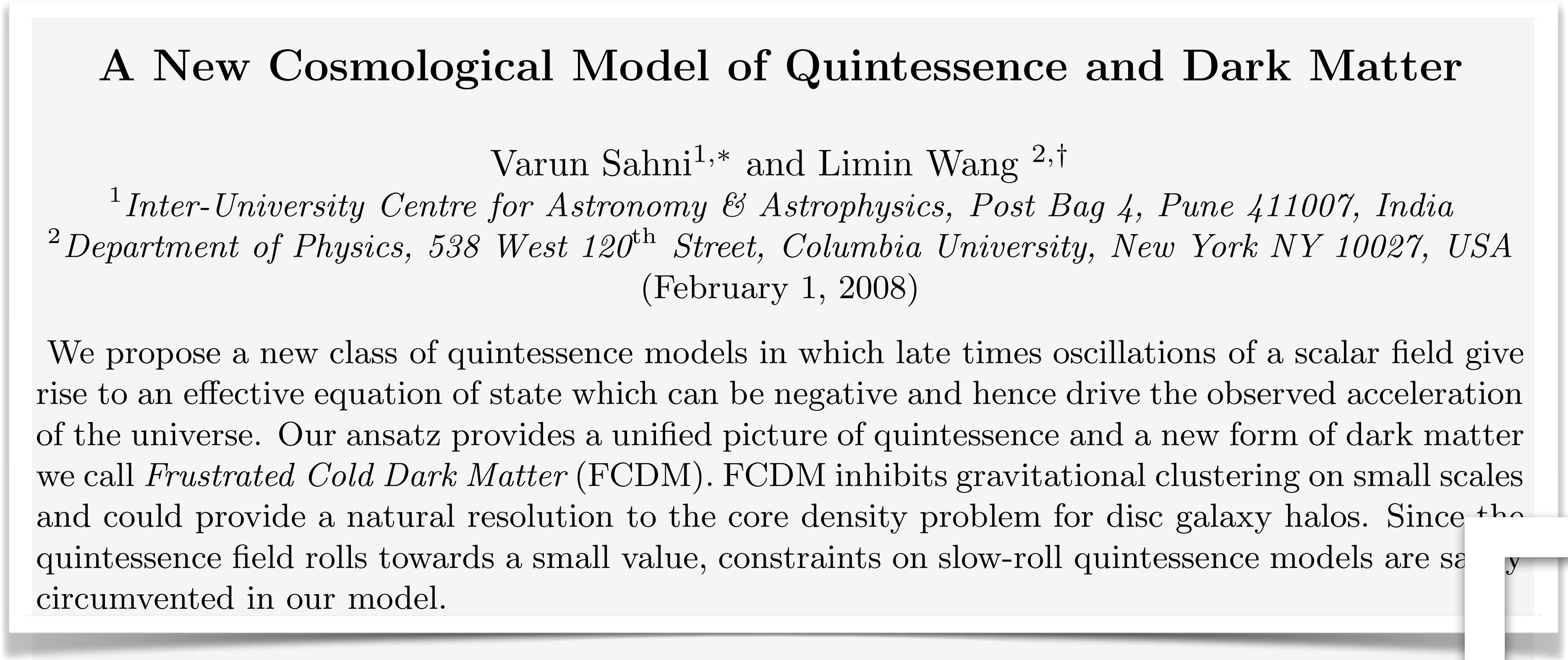
Tonatiuh Matos* and L. Arturo Ureña-López†
Departamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, AP 14-740, 07000 México D.F., Mexico
(Received 1 June 2000; revised manuscript received 5 October 2000; published 20 February 2001)

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.

DOI: 10.1103/PhysRevD.63.063506 PACS number(s): 98.80.Cq, 95.35.+d

astro-ph/0006024

astro-ph/9910097

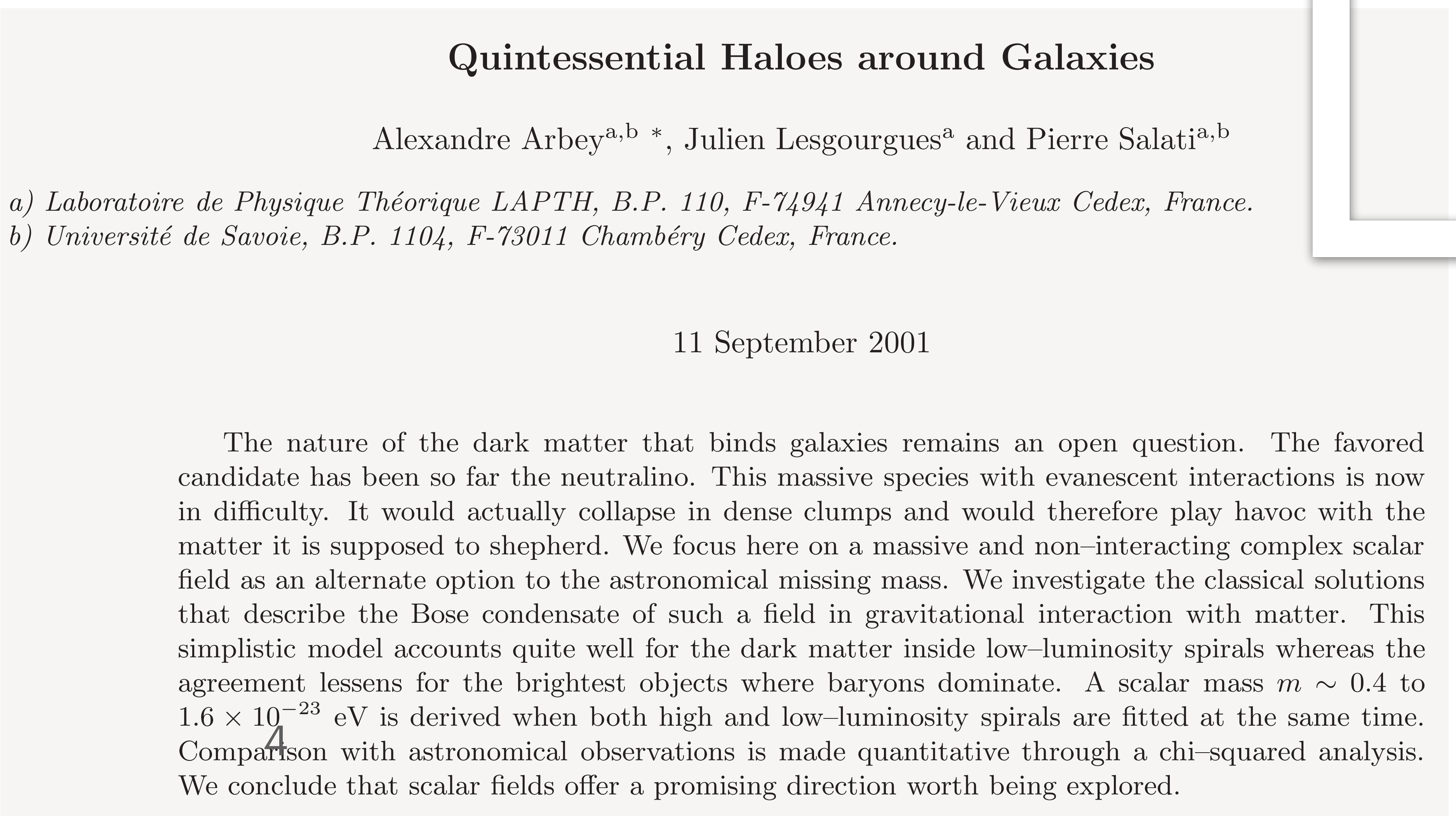


A New Cosmological Model of Quintessence and Dark Matter

Varun Sahni[1,*] and Limin Wang [2,†]
[1] *Inter-University Centre for Astronomy & Astrophysics, Post Bag 4, Pune 411007, India*
[2] *Department of Physics, 538 West 120th Street, Columbia University, New York NY 10027, USA*
(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 y circumvented in our model.

astro-ph/0105564



Quintessential Haloes around Galaxies

Alexandre Arbey[a,b] *, Julien Lesgourgues[a] and Pierre Salati[a,b]

a) Laboratoire de Physique Théorique LAPTH, B.P. 110, F-74941 Annecy-le-Vieux Cedex, France.
b) Université de Savoie, B.P. 1104, F-73011 Chambéry Cedex, France.

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.

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)

Klein-Gordon equation

- Famous equation formulated by **Erwin Schrodinger (1925)**
- Famous equation proposed by **Oscar Klein & Walter Gordon (1926)**
- Equation of motion to describe ***massive*** wave packets in quantum physics, with mass m_a
- It *<u>does not work</u>* with the hydrogen atom
- **Typical length scale**: Compton length $L_C = h/(m_a c)$ $\left[L_C = 1/m_a\right]$
- **Typical time scale**: $T_C = h/(m_a c^2)$ $\left[T_C = 1/m_a\right]$

Klein

Gordon

Schrödinger

$$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}\,g^{\mu\nu}\phi\right) - \partial_\phi V(\phi) = 0$$

$$\begin{aligned} V(\phi) &= m_a^2 f_a^2 F(\phi/f_a) \\ &= \frac{1}{2!}m_a^2\phi^2 + \frac{\lambda_3}{3!}\frac{m_a^2}{f_a}\phi^3 + \frac{\lambda_4}{4!}\frac{m_a^2}{f_a^2}\phi^4 + \cdots \end{aligned}$$

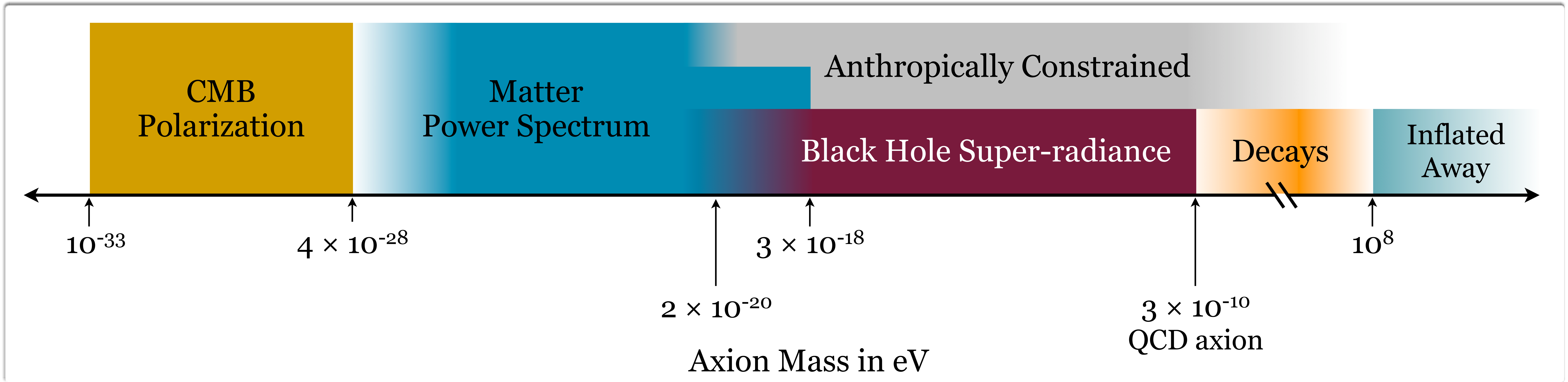
Useful references

- **Short Review of the main achievements of the Scalar Field, Fuzzy, Ultralight, Wave, BEC Dark Matter model,** Matos, Ureña-López, Lee, arXiv:2312.00254.
- **The Search for Ultralight Bosonic Dark Matter**, Jackson and van Bibber eds., Springer (Open Access) 2021.
- **Wave Dark Matter**, Hui, Annual Review of Astronomy and Astrophysics 59, 247 (2021), arXiv:2101.11735.
- **Ultra-Light Dark Matter**, Ferreira, Astron Astrophys Rev 29, 7 (2021), arXiv:2005.03254.
- **Small-scale structure of fuzzy and axion-like dark matter**, Niemeyer, Progress in Particle and Nuclear Physic 113, 103787 (2020), arXiv:1912.07064
- **Brief review on scalar field dark matter models**, Ureña-López, Frontiers in Astronomy and Space Sciences, Volume 6, 47 (2019).
- **Ultralight scalars as cosmological dark matter**, Hui, Ostriker, Tremaine and Witten, Phys. Rev. D 95, 043541 (2017), arXiv:1610.08297.
- **Axion Cosmology**, Marsh, Physics Reports 643, 1-79 (2016), arXiv:1510.07633.
- **Structure formation with scalar field dark matter: the field approach**, Magaña, Matos, Suárez and Sánchez-Salcedo; J. Cosmology Astroparticle Phys. 10, (2012), 003, arXiv:1204.5255.
- **A brief Review of the Scalar Field Dark Matter model**, Magaña, Matos, Robles and Suárez; J. Phys.: Conf. Ser. 378 012012 (2012), arXiv:1201.6107.
- **Scaled-up darkness**. Could a single dark matter particle be light-years wide? Musser; Sci. Am. 291, 26 (2004).
- **Scalar field dark matter**, Wikipedia, https://en.wikipedia.org/wiki/Scalar_field_dark_matter.

Theoretical expectations for ultra-light axions

String compactifications give rise to many 'axion' fields

$$V(\phi) = \Lambda_a[1 - \cos(\phi/f_a)] \simeq \begin{cases} 2\Lambda_a & \phi/f_a \sim \pi \\ (\Lambda_a/f_a^2)\phi^2/2 & \phi/f_a \sim 0 \end{cases}$$



Arvanitaki et al, Phys. Rev. D 83, 044026 (2011)

INFLATION-DARK MATTER-DARK ENERGY

- All in one with *many* single fields: the axiverse

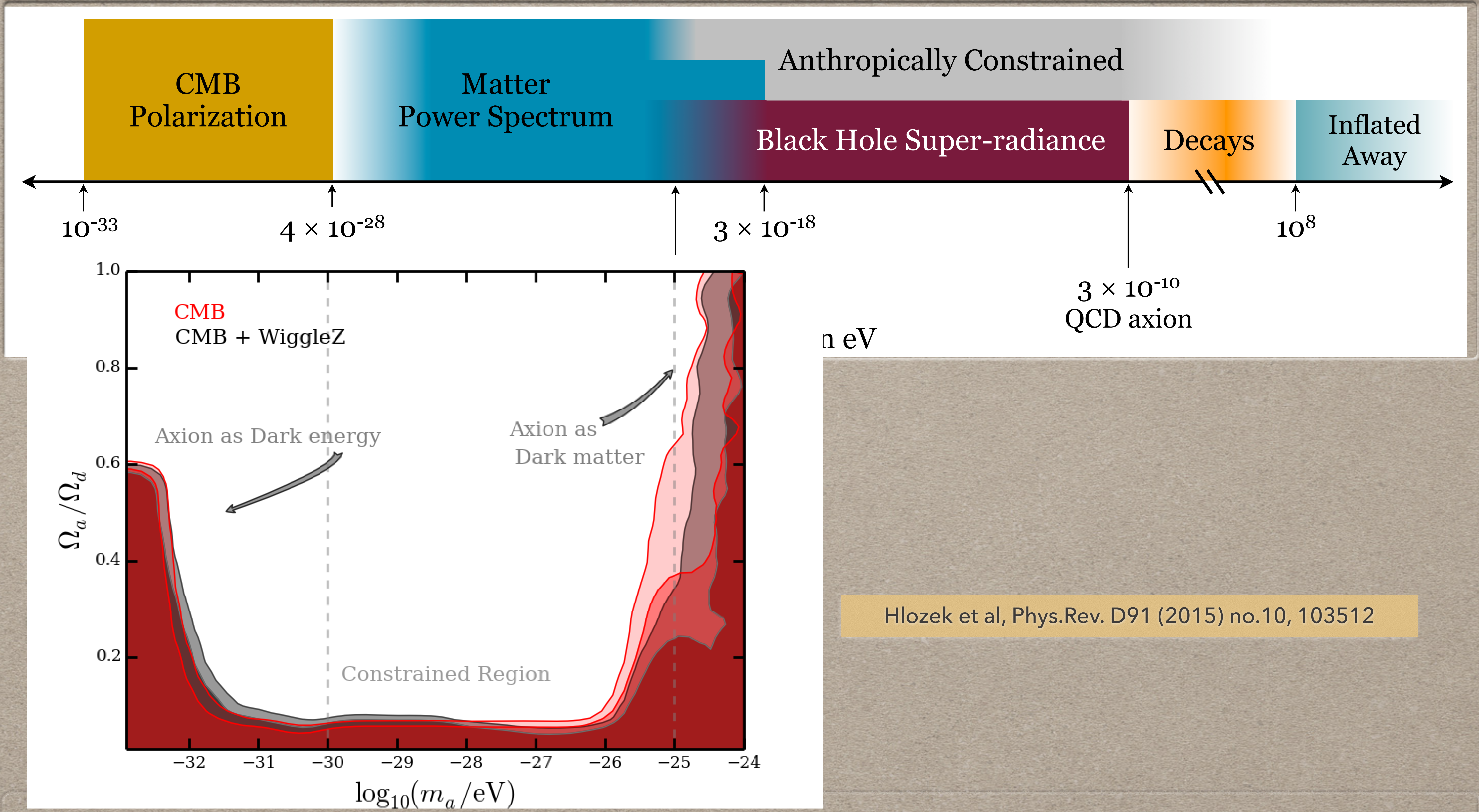
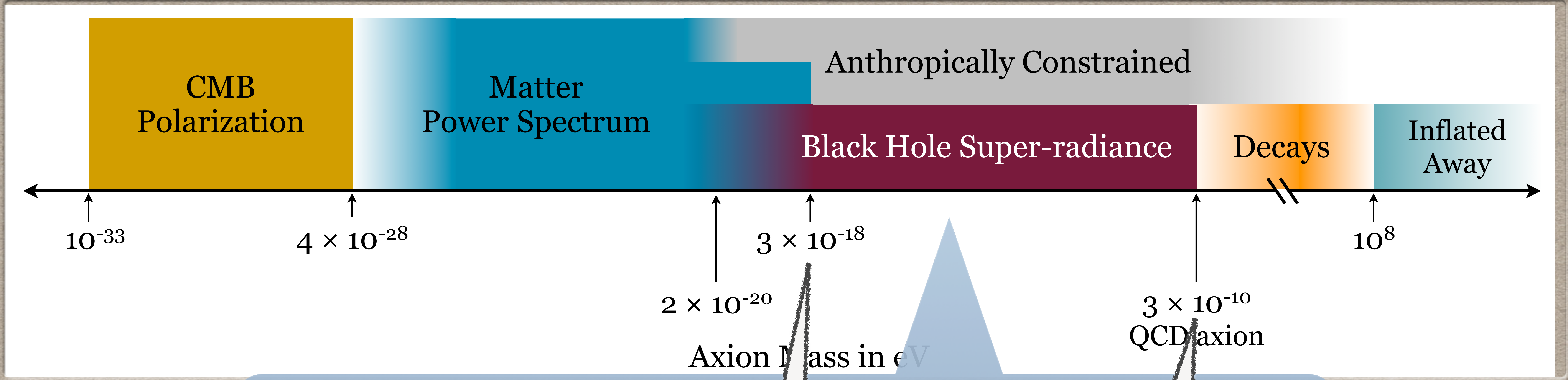


FIG. 1. Marginalized 2 and 3σ contours show limits to the ultra-light axion (ULA) mass fraction Ω_a/Ω_d as a function of ULA mass m_a. The vertical lines denote our 3 sampling regions, discussed below. The mass fraction in the middle region is constrained to be $\Omega_a/\Omega_d \lesssim 0.05$ at 95% confidence. Red regions show CMB-only constraints, while grey regions include large-scale structure data.

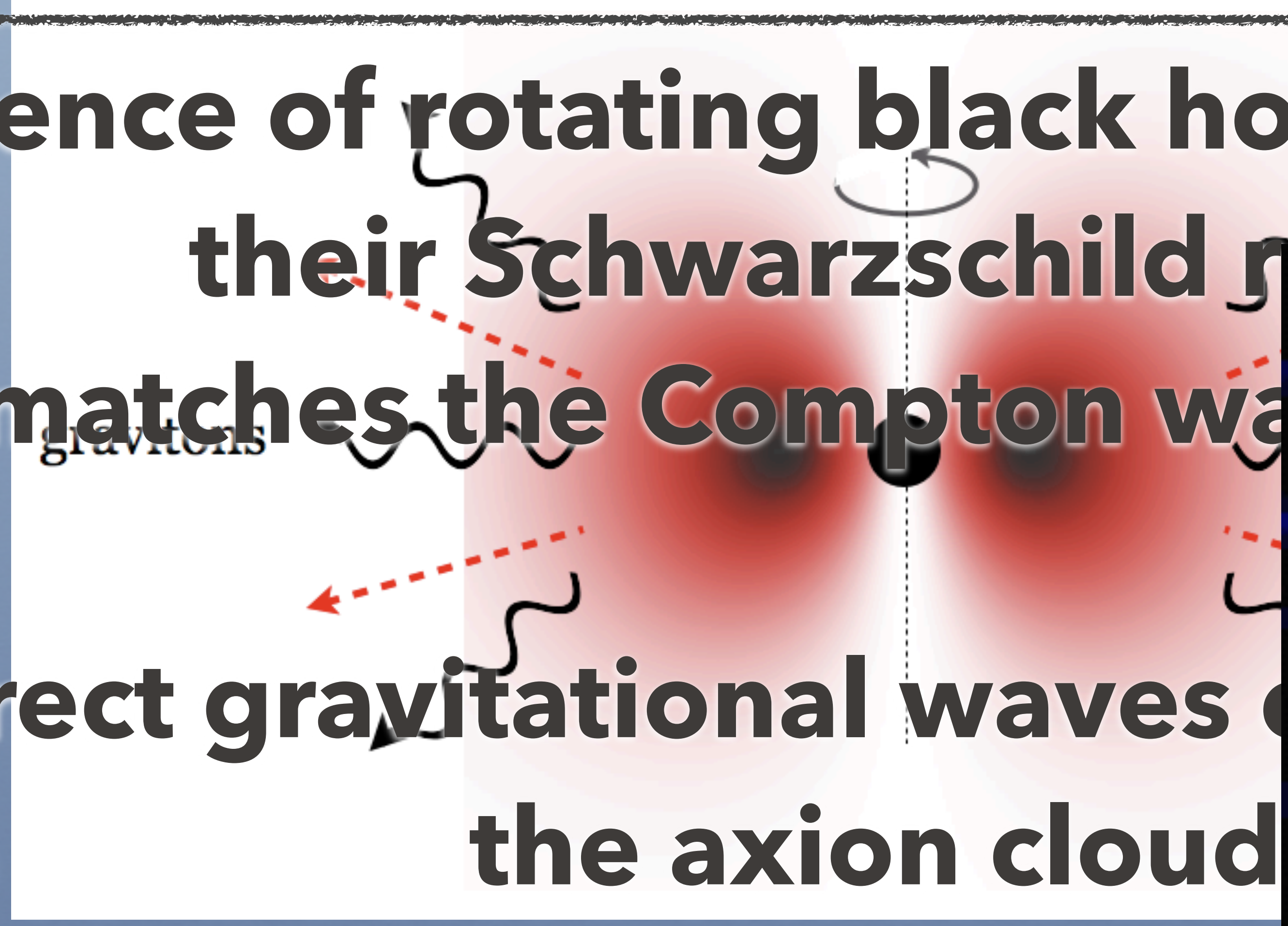
Hlozek et al, Phys.Rev. D91 (2015) no.10, 103512



$10^7 M_\odot$

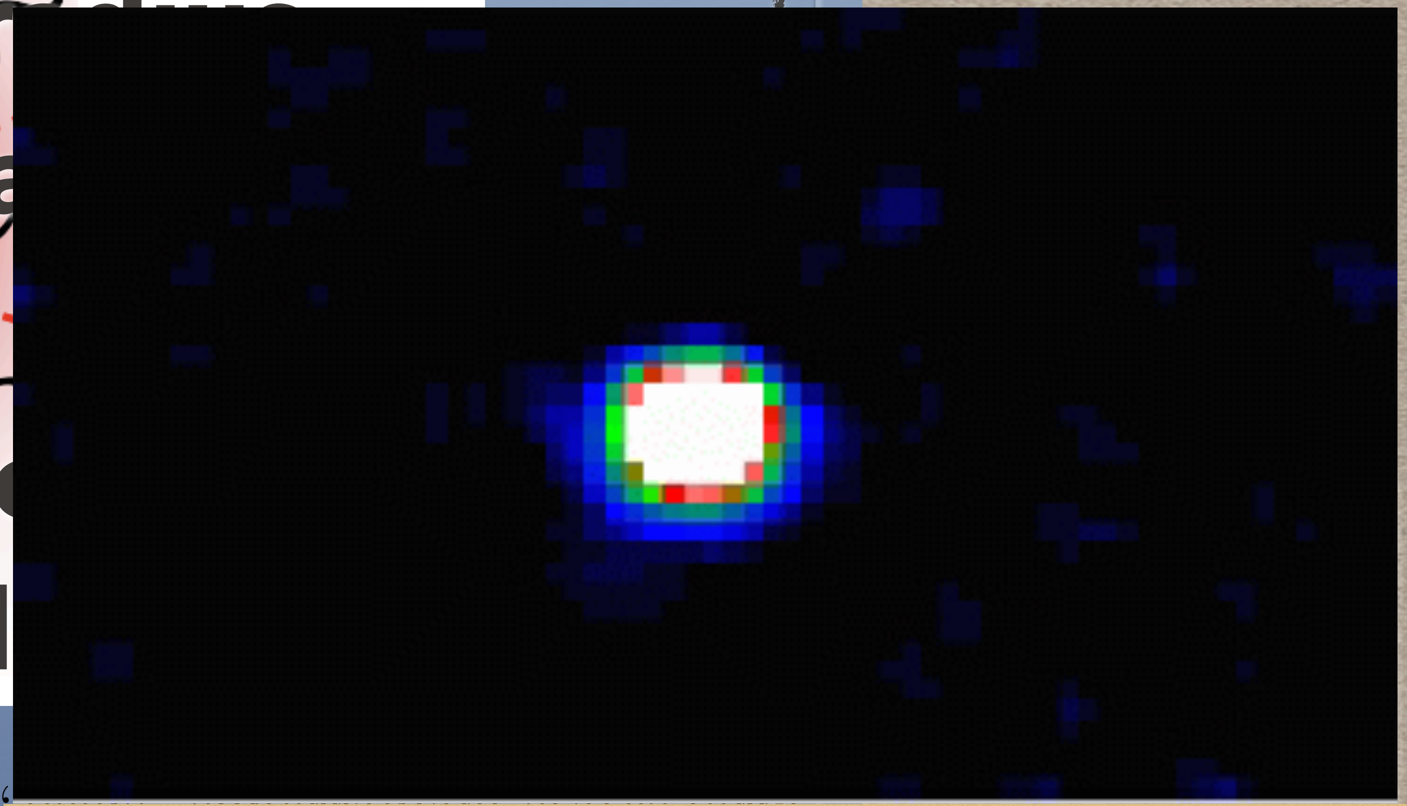
$1 M_\odot$

-Absence of rotating black holes whenever their Schwarzschild radius matches the Compton wa



-Direct gravitational waves

the axion cloud



http://www.nist.gov/public_affairs/releases/bosenova.cfm

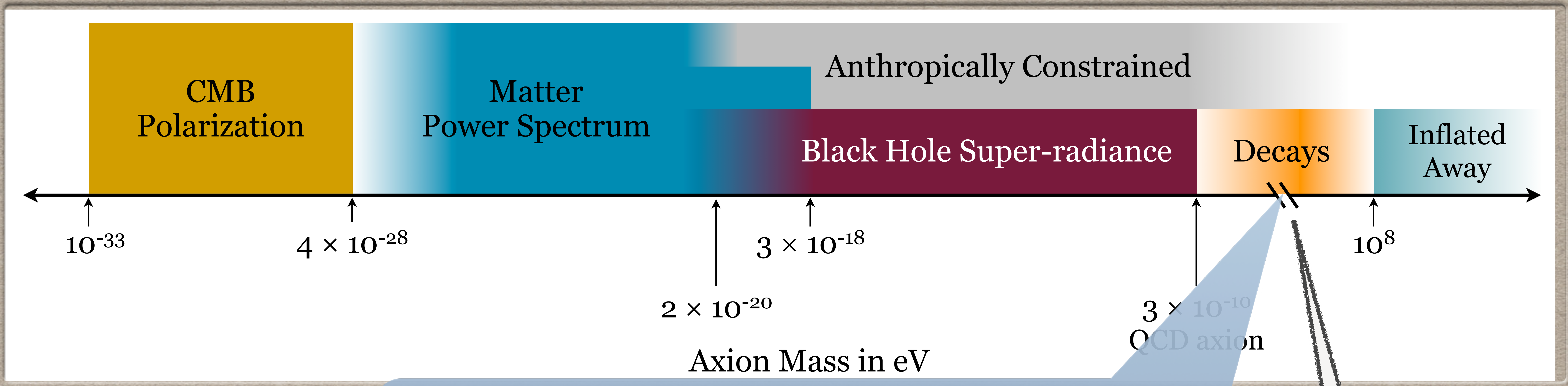
"Bosenova"

Figure 1: **Axionic Black Hole Atom:** The spinning black hole
ing an axion Bose-Einstein condensate. The resulting bosonic a
axion transitions between levels and an emit
interactions in the axion field.

INFLATIO

- All a

Barranco et al, PRD 89 (2014) 083006; PRD 96 (2017) 024049



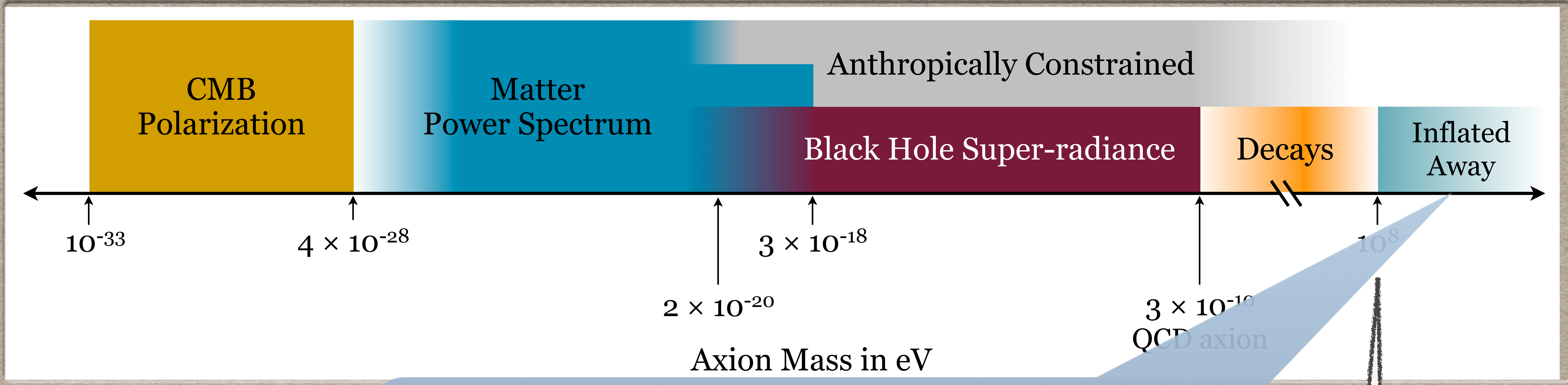
-Axions are massive enough and coupled to SM Particles

-They decay into SM Particles before the onset of nucleosynthesis, and become part of the radiation background

Reheating
Radiation domination
Baryogenesis
Nuclesynthesis

INFLATION-DARK MATTER-DARK ENERGY

- All action with *many* single fields: the axiverse



-Axions are very massive, even during inflation, when they behave as "dust"

-They were but wiped out by the inflationary expansion

$m > H_{\rm inf}$

INFLATION-DARK MATTER-DARK ENERGY

- All action with many single fields: the axiverse

Ultralight axions and SM

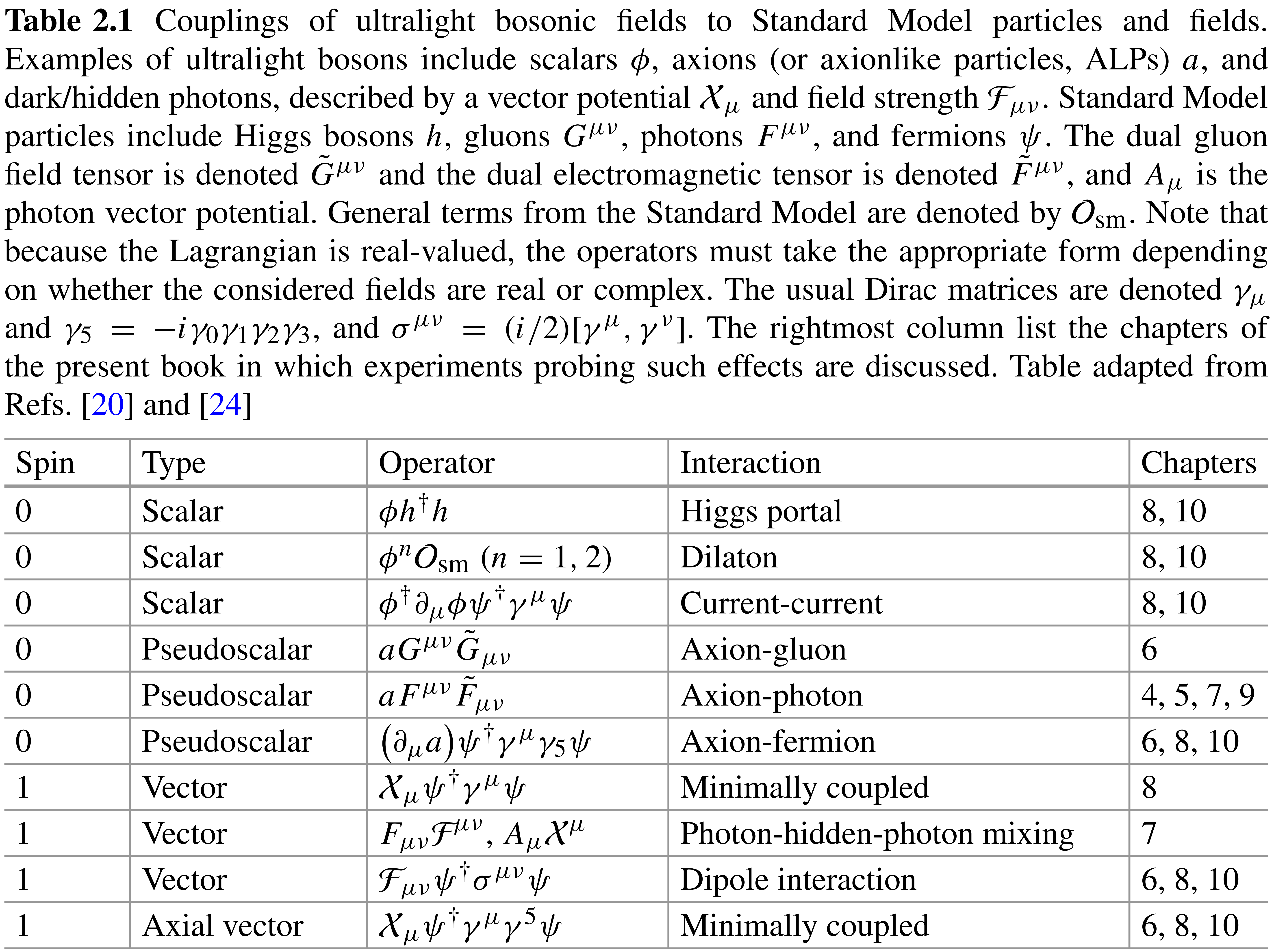


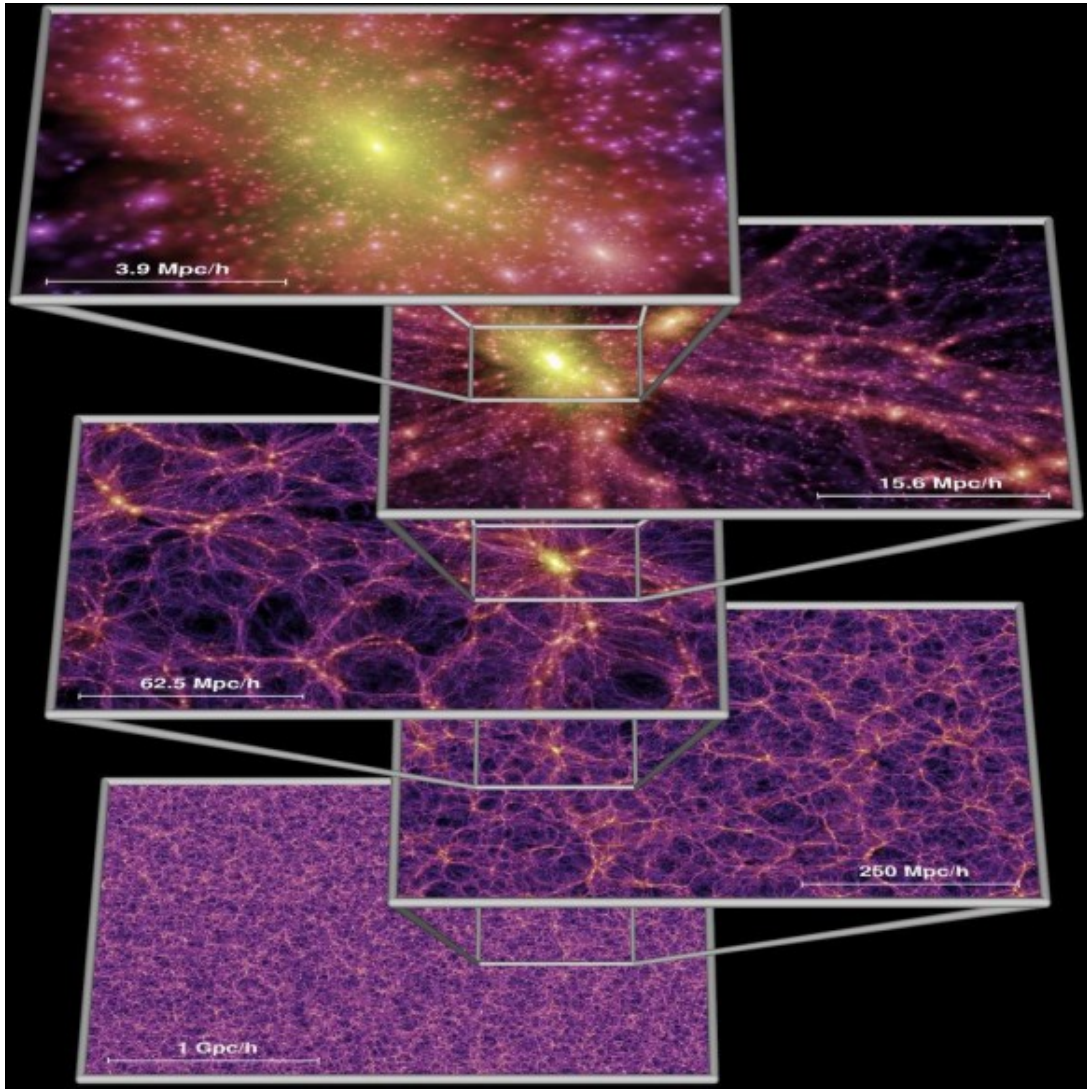
Table 2.1 Couplings of ultralight bosonic fields to Standard Model particles and fields. Examples of ultralight bosons include scalars ϕ, axions (or axionlike particles, ALPs) a, and dark/hidden photons, described by a vector potential $\mathcal{X}_\mu$ and field strength $\mathcal{F}_{\mu\nu}$. Standard Model particles include Higgs bosons h, gluons $G^{\mu\nu}$, photons $F^{\mu\nu}$, and fermions ψ. The dual gluon field tensor is denoted $\tilde{G}^{\mu\nu}$ and the dual electromagnetic tensor is denoted $\tilde{F}^{\mu\nu}$, and A_μ is the photon vector potential. General terms from the Standard Model are denoted by $\mathcal{O}_{\rm sm}$. Note that because the Lagrangian is real-valued, the operators must take the appropriate form depending on whether the considered fields are real or complex. The usual Dirac matrices are denoted γ_μ and $\gamma_5 = -i\gamma_0\gamma_1\gamma_2\gamma_3$, and $\sigma^{\mu\nu} = (i/2)[\gamma^\mu, \gamma^\nu]$. The rightmost column list the chapters of the present book in which experiments probing such effects are discussed. Table adapted from Refs. [20] and [24]

Spin	Type	Operator	Interaction	Chapters
0	Scalar	$\phi h^\dagger h$	Higgs portal	8, 10
0	Scalar	$\phi^n \mathcal{O}_{\rm sm}$ $(n = 1, 2)$	Dilaton	8, 10
0	Scalar	$\phi^\dagger \partial_\mu \phi \psi^\dagger \gamma^\mu \psi$	Current-current	8, 10
0	Pseudoscalar	$a G^{\mu\nu} \tilde{G}_{\mu\nu}$	Axion-gluon	6
0	Pseudoscalar	$a F^{\mu\nu} \tilde{F}_{\mu\nu}$	Axion-photon	4, 5, 7, 9
0	Pseudoscalar	$(\partial_\mu a) \psi^\dagger \gamma^\mu \gamma_5 \psi$	Axion-fermion	6, 8, 10
1	Vector	$\mathcal{X}_\mu \psi^\dagger \gamma^\mu \psi$	Minimally coupled	8
1	Vector	$F_{\mu\nu} \mathcal{F}^{\mu\nu}$, $A_\mu \mathcal{X}^\mu$	Photon-hidden-photon mixing	7
1	Vector	$\mathcal{F}_{\mu\nu} \psi^\dagger \sigma^{\mu\nu} \psi$	Dipole interaction	6, 8, 10
1	Axial vector	$\mathcal{X}_\mu \psi^\dagger \gamma^\mu \gamma^5 \psi$	Minimally coupled	6, 8, 10

The Search for Ultralight Bosonic Dark Matter, Jackson and van Bibber eds., Springer (Open Access) 2021.

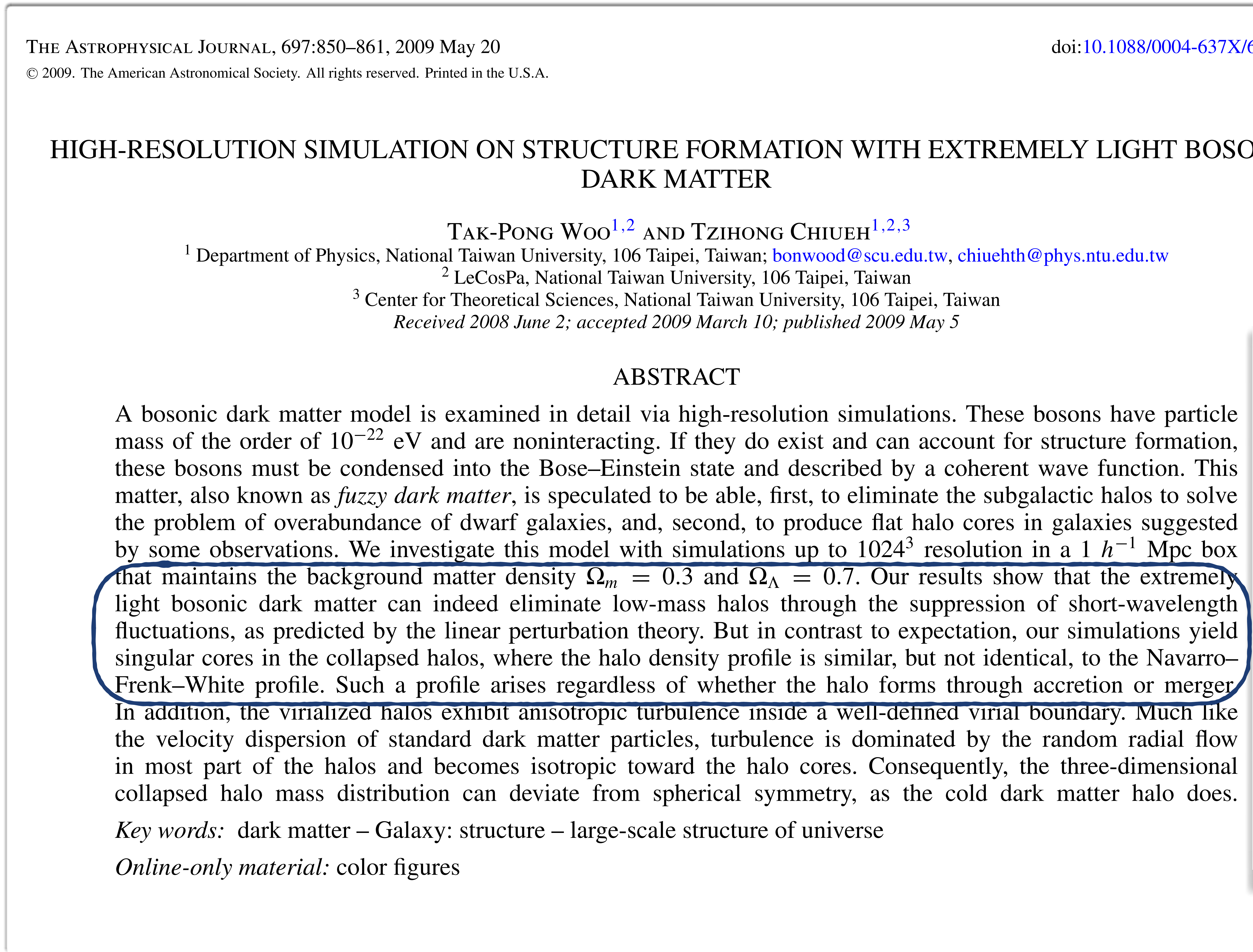
Structure formation: cosmological simulations

Dark matter and cosmological structure



Structure formation

First steps



The Astrophysical Journal, 697:850–861, 2009 May 20 doi:10.1088/0004-637X/697/1/850

HIGH-RESOLUTION SIMULATION ON STRUCTURE FORMATION WITH EXTREMELY LIGHT BOSONIC DARK MATTER

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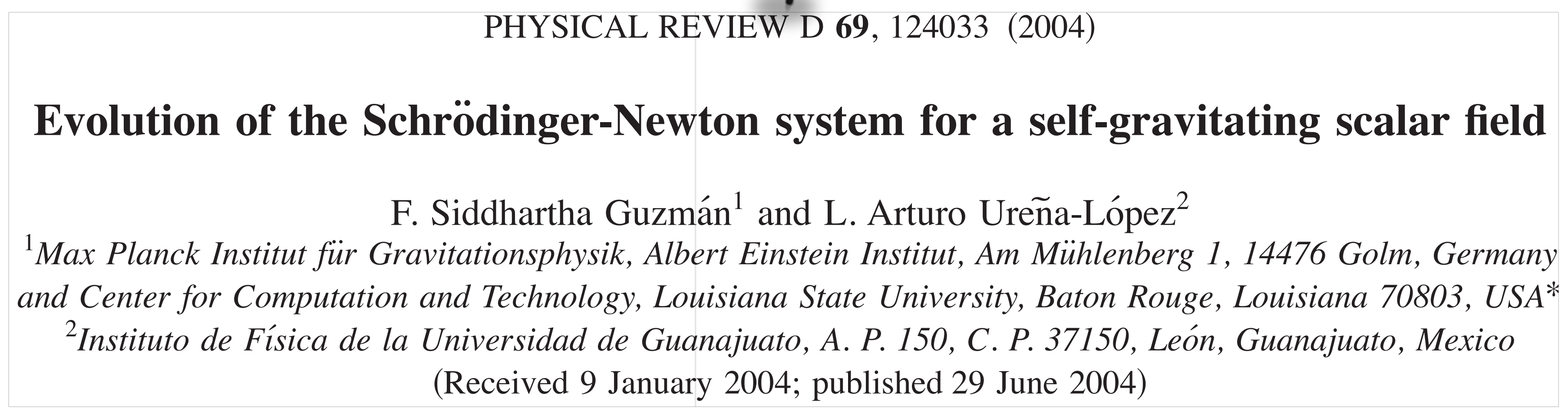
Received 2008 June 2; accepted 2009 March 10; published 2009 May 5

ABSTRACT

A bosonic dark matter model is examined in detail via high-resolution simulations. These bosons have particle mass of the order of 10^{-22} eV and are noninteracting. If they do exist and can account for structure formation, these bosons must be condensed into the Bose–Einstein state and described by a coherent wave function. This matter, also known as *fuzzy dark matter*, is speculated to be able, first, to eliminate the subgalactic halos to solve the problem of overabundance of dwarf galaxies, and, second, to produce flat halo cores in galaxies suggested by some observations. We investigate this model with simulations up to 1024^3 resolution in a 1 h^{-1} Mpc box that maintains the background matter density $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. Our results show that the extremely light bosonic dark matter can indeed eliminate low-mass halos through the suppression of short-wavelength fluctuations, as predicted by the linear perturbation theory. But in contrast to expectation, our simulations yield singular cores in the collapsed halos, where the halo density profile is similar, but not identical, to the Navarro–Frenk–White profile. Such a profile arises regardless of whether the halo forms through accretion or merger. In addition, the virialized halos exhibit anisotropic turbulence inside a well-defined virial boundary. Much like the velocity dispersion of standard dark matter particles, turbulence is dominated by the random radial flow in most part of the halos and becomes isotropic toward the halo cores. Consequently, the three-dimensional collapsed halo mass distribution can deviate from spherical symmetry, as the cold dark matter halo does.

Key words: dark matter – Galaxy: structure – large-scale structure of universe

Online-only material: color figures



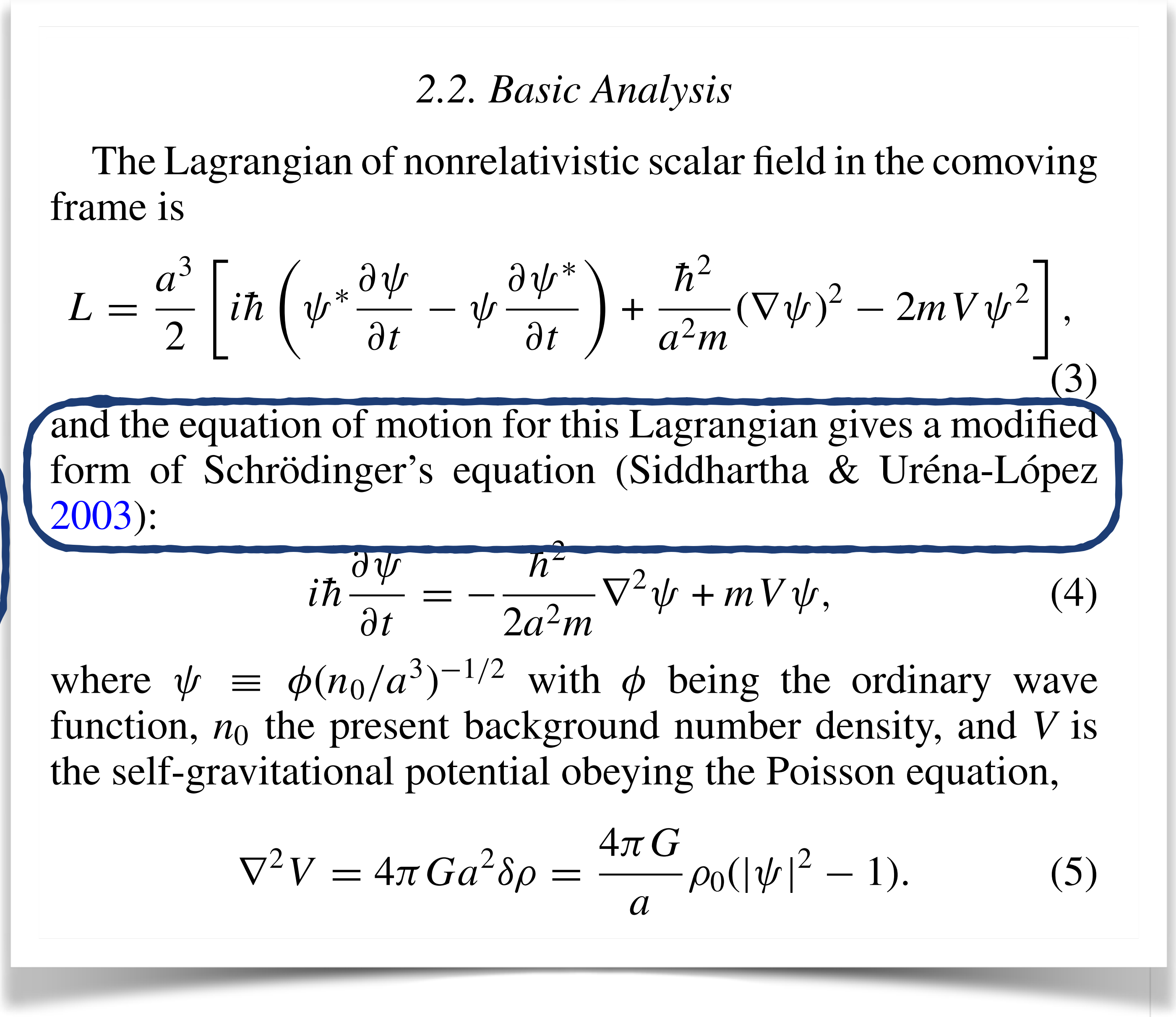
PHYSICAL REVIEW D **69**, 124033 (2004)

Evolution of the Schrödinger-Newton system for a self-gravitating scalar field

F. Siddhartha Guzmán[1] and L. Arturo Ureña-López[2]
[1]*Max Planck Institut für Gravitationsphysik, Albert Einstein Institut, Am Mühlenberg 1, 14476 Golm, Germany and Center for Computation and Technology, Louisiana State University, Baton Rouge, Louisiana 70803, USA**
[2]*Instituto de Física de la Universidad de Guanajuato, A. P. 150, C. P. 37150, León, Guanajuato, Mexico*

(Received 9 January 2004; published 29 June 2004)

Newtonian version



2.2. Basic Analysis

The Lagrangian of nonrelativistic scalar field in the comoving frame is

$$L = \frac{a^3}{2}\left[i\hbar\left(\psi^*\frac{\partial\psi}{\partial t} - \psi\frac{\partial\psi^*}{\partial t}\right) + \frac{\hbar^2}{a^2 m}(\nabla\psi)^2 - 2mV\psi^2\right], \quad (3)$$

and the equation of motion for this Lagrangian gives a modified form of Schrödinger's equation (Siddhartha & Uréna-López 2003):

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2a^2 m}\nabla^2\psi + mV\psi, \quad (4)$$

where $\psi \equiv \phi(n_0/a^3)^{-1/2}$ with ϕ being the ordinary wave function, n_0 the present background number density, and V is the self-gravitational potential obeying the Poisson equation,

$$\nabla^2 V = 4\pi G a^2\delta\rho = \frac{4\pi G}{a}\rho_0(|\psi|^2 - 1). \quad (5)$$

Relativistic scale length

$$L_C = \frac{h}{m_a c}$$

↓

Nonrelativistic scale length

$$L_{dB} = \frac{h}{m_a v} = \frac{c}{v} L_C$$

Structure formation

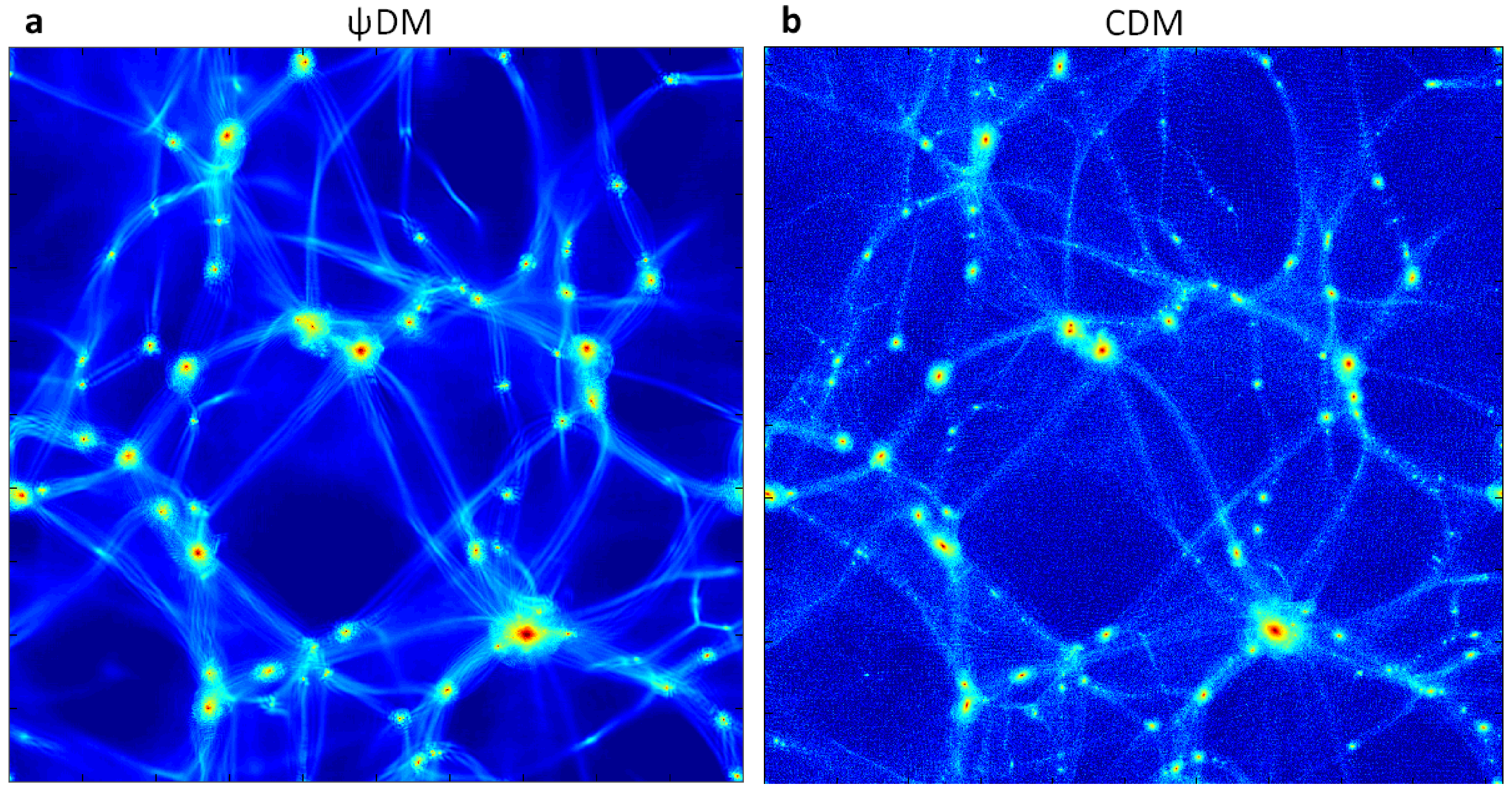


Figure 1: Comparison of cosmological large-scale structures formed by standard CDM and by wave-like dark matter, ψDM. Panel (**a**) shows the structure created by evolving a single coherent wave function for $\Lambda\psi$DM calculated on AMR grids. Panel (**b**) is the structure simulated with a standard ΛCDM N-body code GADGET-2[12] for the same cosmological parameters, with the high-k modes of the linear power spectrum intentionally suppressed in a way similar to the ψDM model to highlight the comparison of large-scale features. This comparison clearly demonstrates that the large scale distribution of filaments and voids is indistinguishable between these two completely different calculations, as desired given the success of ΛCDM in describing the observed large scale structure. ψDM arises from the low momentum state of the condensate so that it is equivalent to collisionless CDM well above the Jeans scale.

$$m = 8 \times 10^{-23}\,\mathrm{eV}$$

Schrödinger-Poisson system

Schive, Chiueh, Broadhurst, Nature Physics 10, 496–499 (2014)
Schive et al, Phys.Rev.Lett. 113 (2014) no.26, 261302

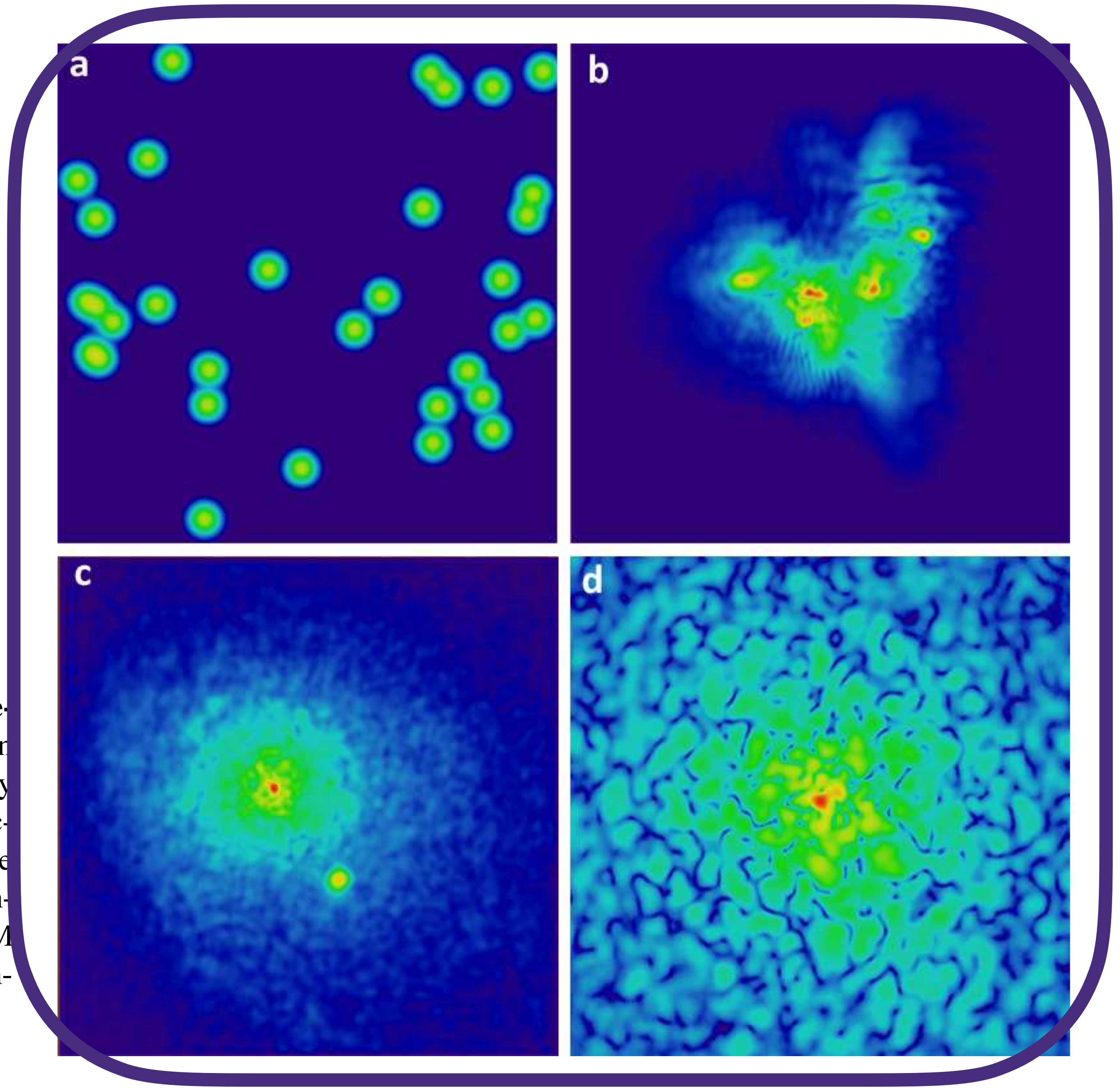


FIG. 3: Snapshots of a soliton collision simulation. Panels (a)-(c) show the projected density distribution at the initial and intermediate stages, and panel (d) shows a close-up of the conspicuous solitonic core at the final stage. Fluctuating density granules resulting from the quantum wave interference appear everywhere and have a size similar to the central soliton.

Schive et al, Phys.Rev.Lett. 113 (2014) no.26, 261302
e-Print: arXiv:1407.7762

SOLITON

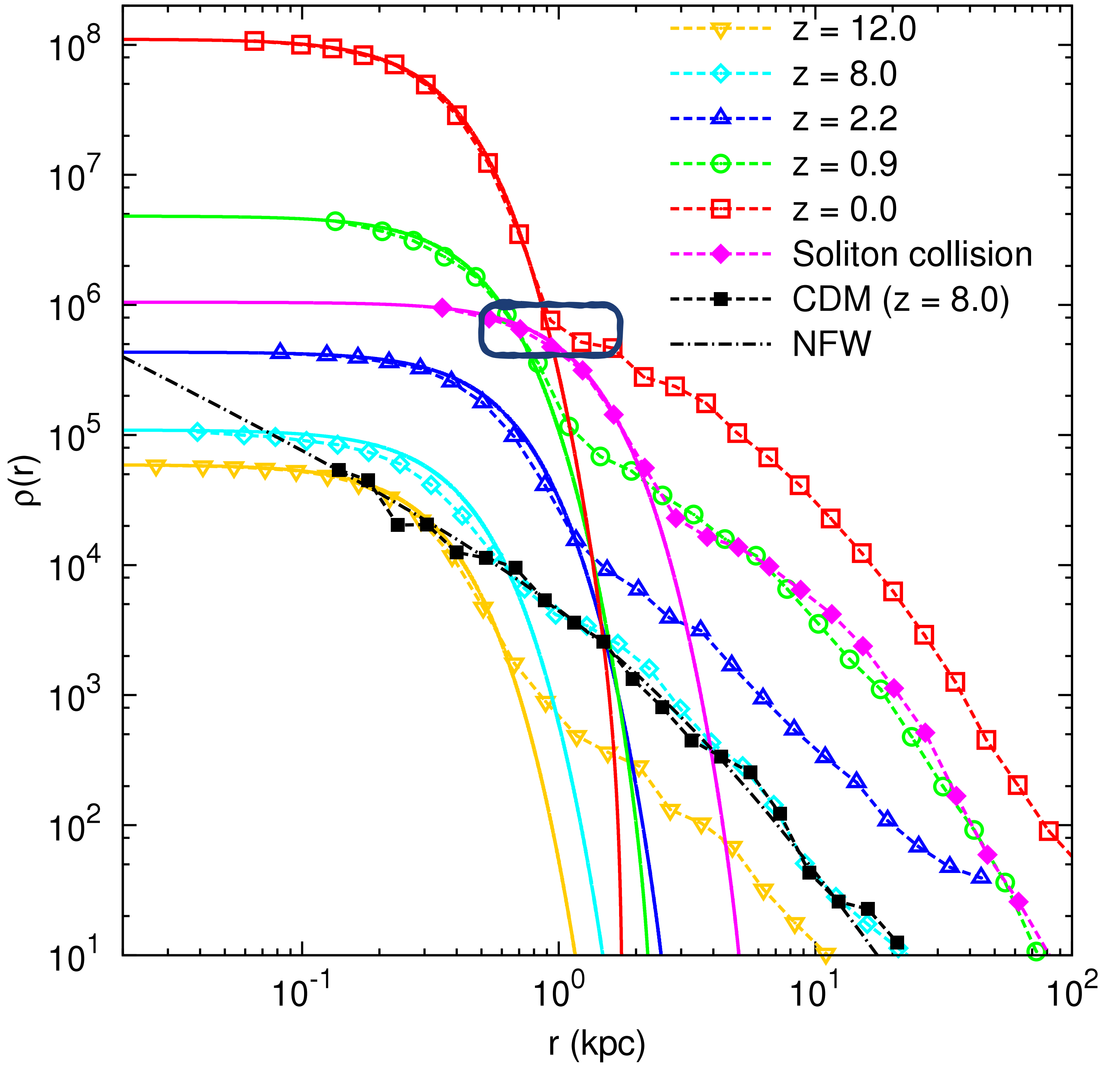
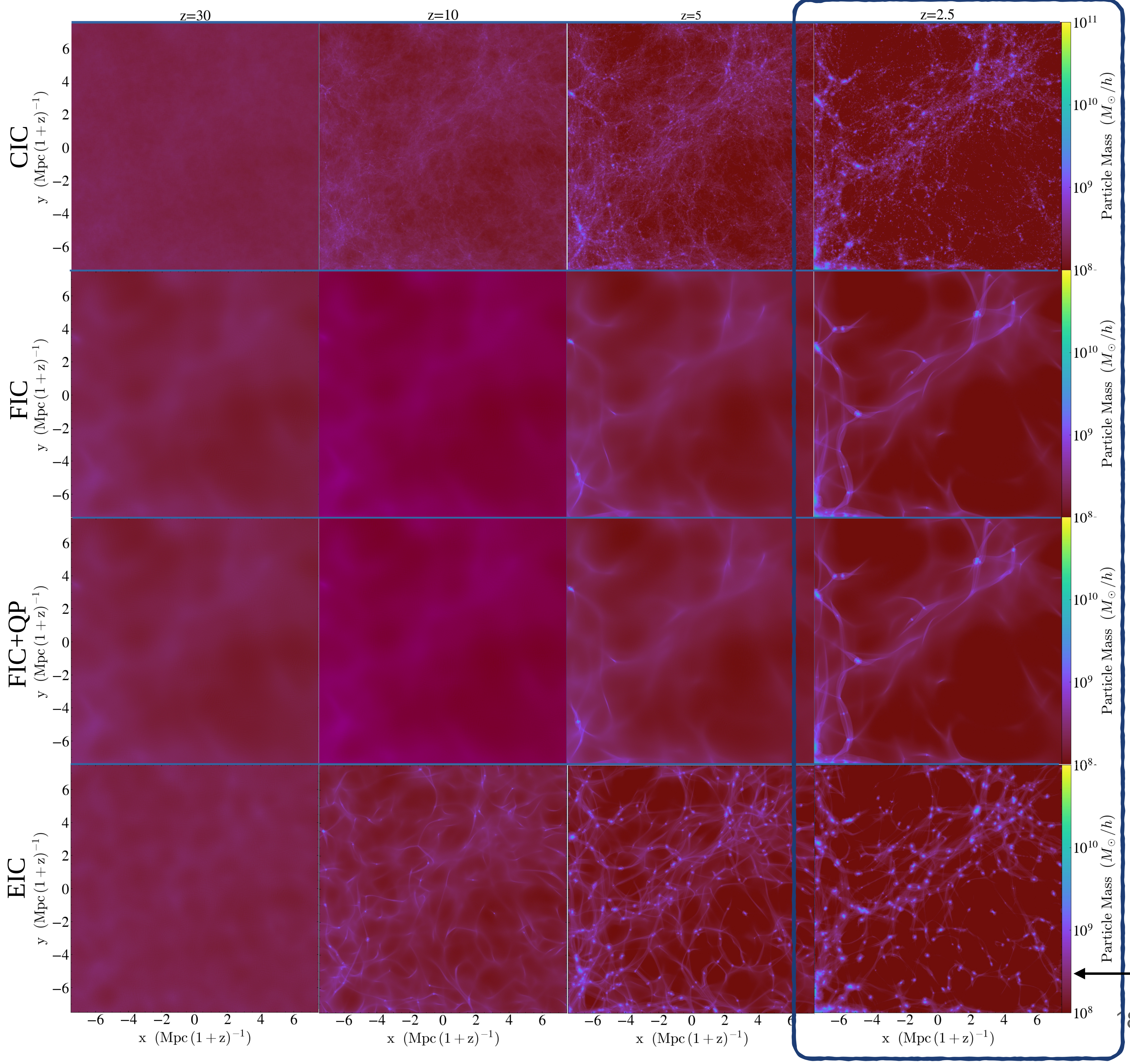


FIG. 1: Density profiles of ψDM halos. Dashed lines with various opened symbols show five examples at different redshifts between $12 \geq z \geq 0$. The DM density is normalized to the cosmic background density. A distinct core forms in every halo as a gravitationally self-bound object, satisfying the redshift-dependent soliton solution (solid lines) upon proper λ scaling. Filled diamonds show an example from the soliton collision simulations renormalized to the comoving coordinates at $z = 0$. The same $z = 8$ halo in a CDM simulation (filled squares) fit by an NFW profile (dot-dashed line) is also shown for comparison.

Axion simulations via modified gravity



$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla(\Phi + Q)$$

$$\nabla^2(\Phi + Q) = 4\pi G\rho - \frac{1}{2m_a^2}\nabla^2\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

Modified matter component + Standard gravity

=

Standard CDM component + Modified gravity

MG-PICOLA
https://github.com/HAWinther/MG-PICOLA-PUBLIC

$f_a = 4.7 \times 10^{15}$ GeV

Medellín-González, González-Morales, U-L, PRD 103, 083509 (2021), arXiv:2010.13998

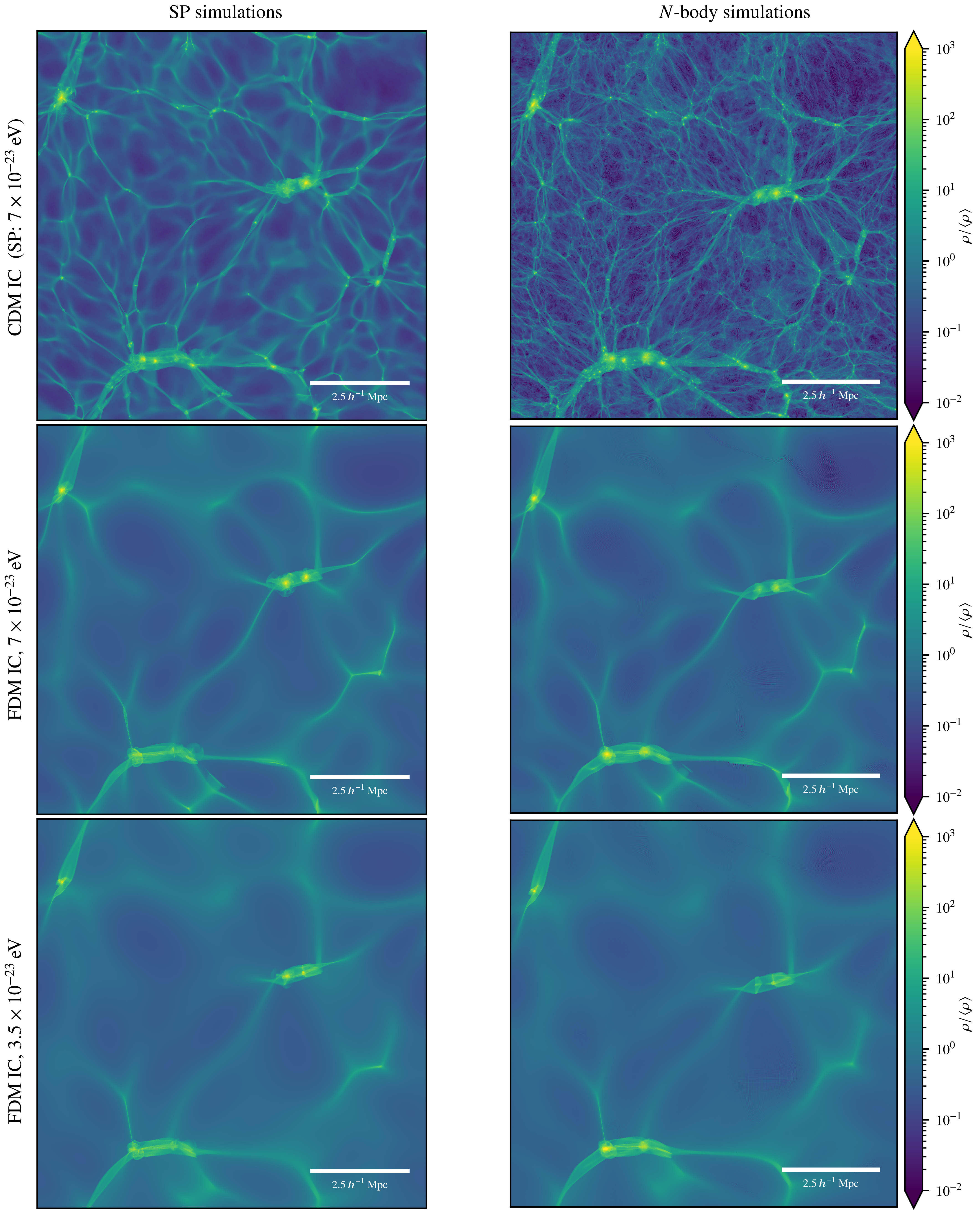
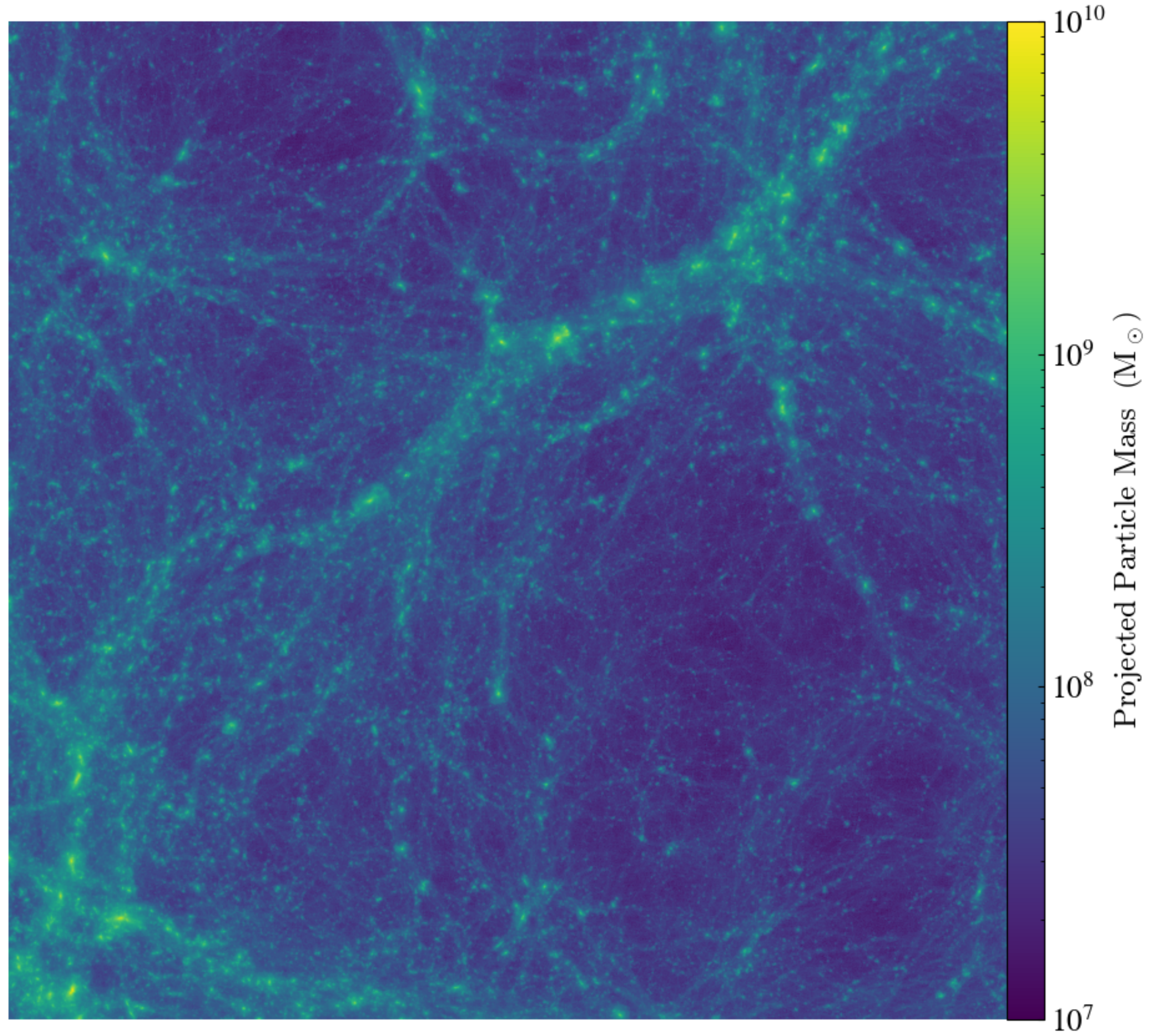
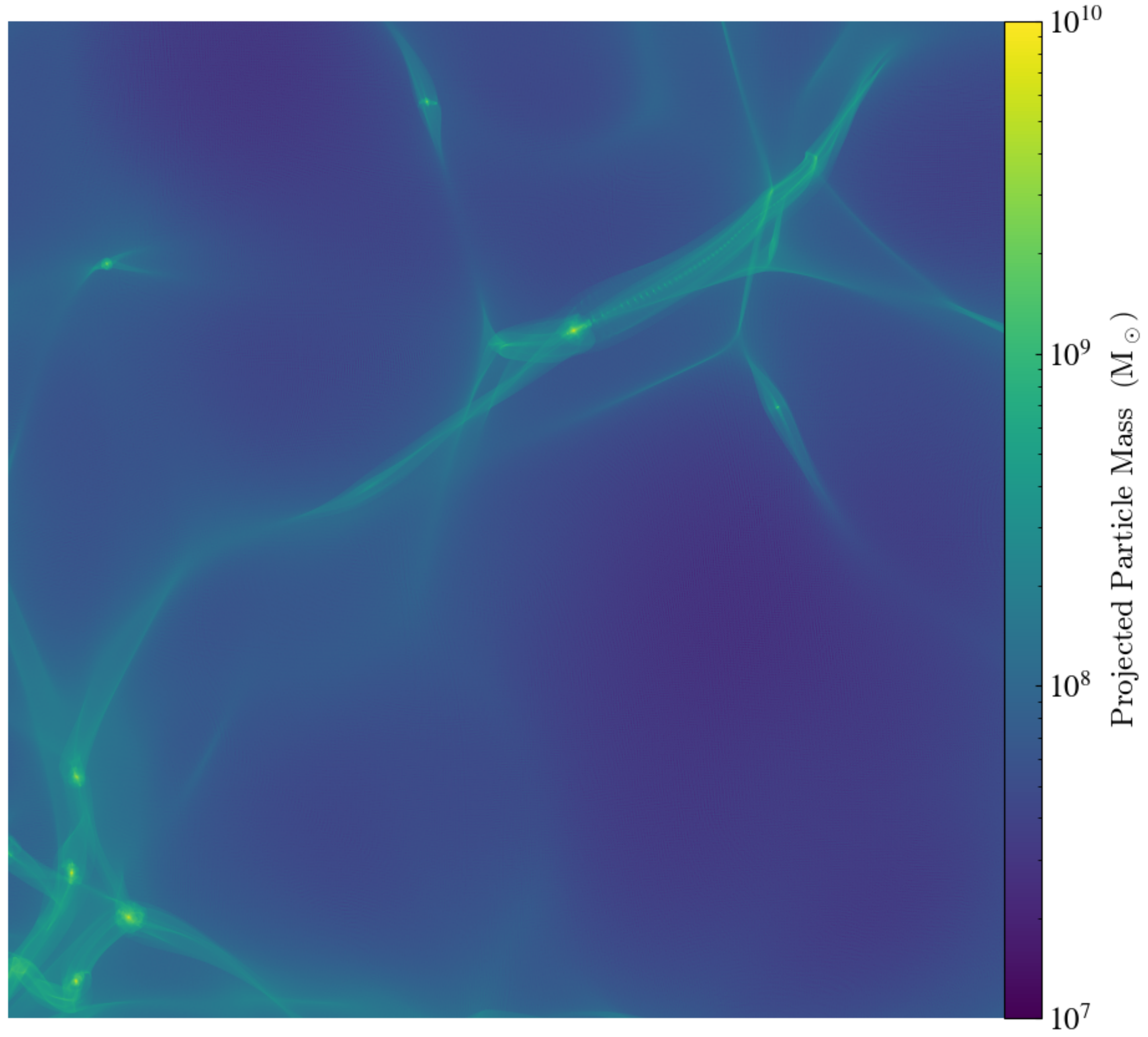


Figure 1. Projected dark matter densities along a thin ($100\,h^{-1}$ kpc) slice in cosmological box simulations for different dynamics (FDM/SP, left column; or CDM/N-body, right column) and ICs (FDM or CDM, rows), for box sizes $L = 10\,h^{-1}$ Mpc at $z = 3$.

May, Springel, arXiv:2209.14886
The halo mass function and filaments in full cosmological simulations with fuzzy dark matter



Medellín-González, González-Morales, U-L, PRD 103, 083509 (2021), arXiv:2010.13998



Axion-like potential

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

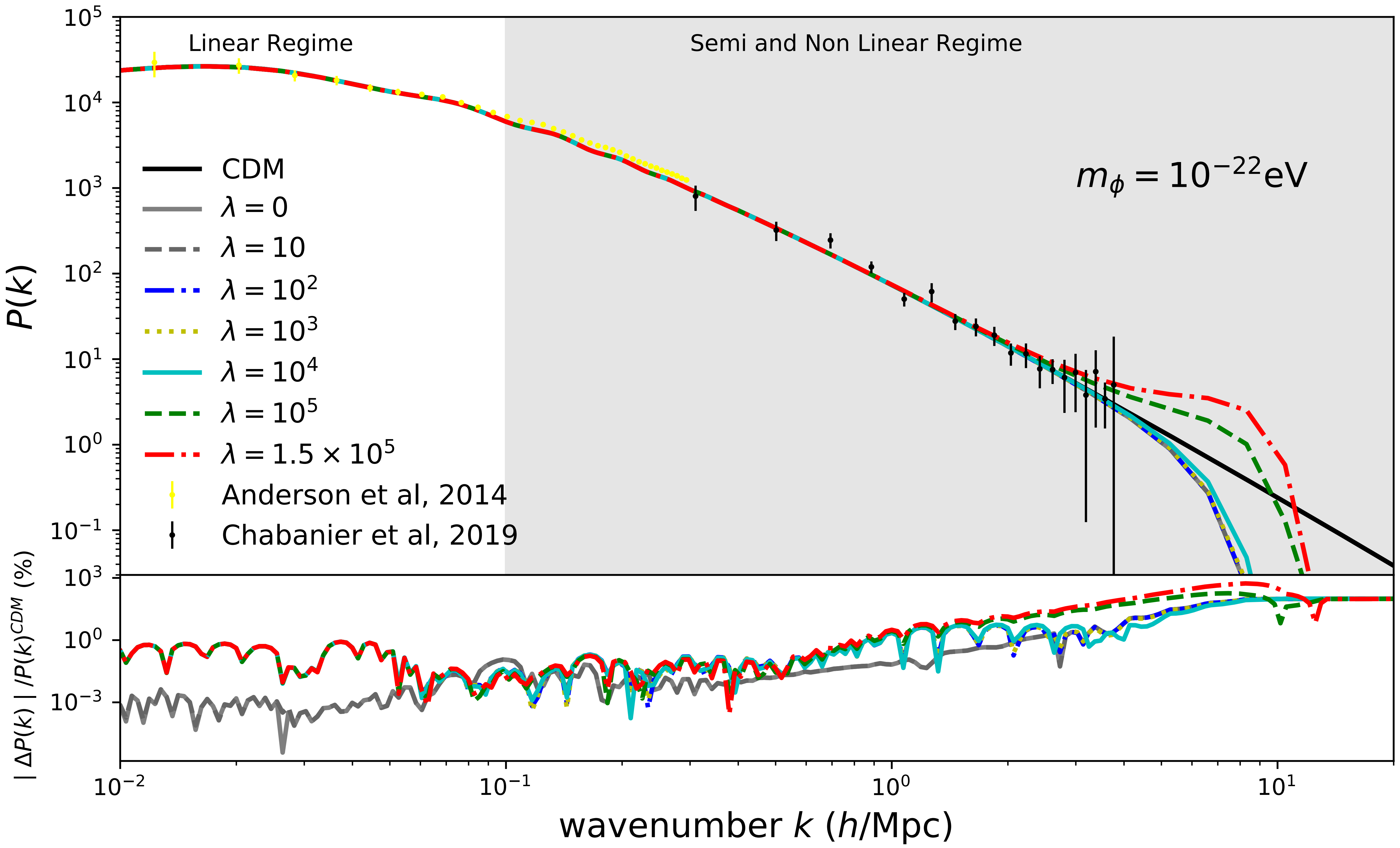
Linares-Cedeño, González-Morales, U-L, JCAP 1, 051 (2021), arXiv:2006.05037

Linares-Cedeño, González-Morales, U-L et al, PRD 96 (2017) 061301(R)

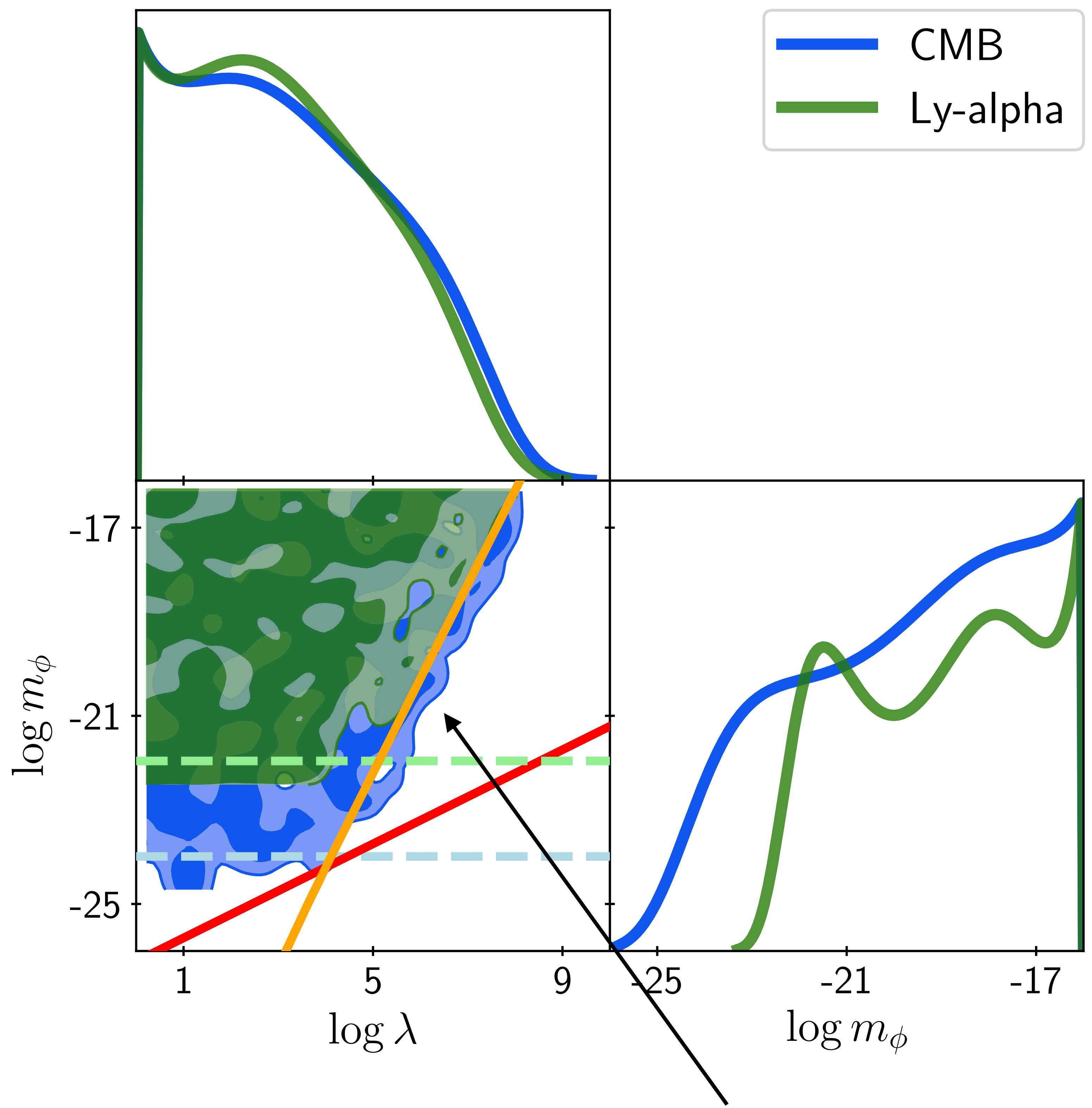
$$\lambda = \frac{3m_{\mathrm{Pl}}^2}{8\pi f_a^2}$$

$$\mathrm{FDM}:\ \lambda = 0\ (f_a \to \infty)$$

$$m_a \gtrsim 10^{-22}\,\mathrm{eV}/c^2\ (95.5\,\%\,\mathrm{CL})$$



Tachyonic instability of **linear** density perturbations

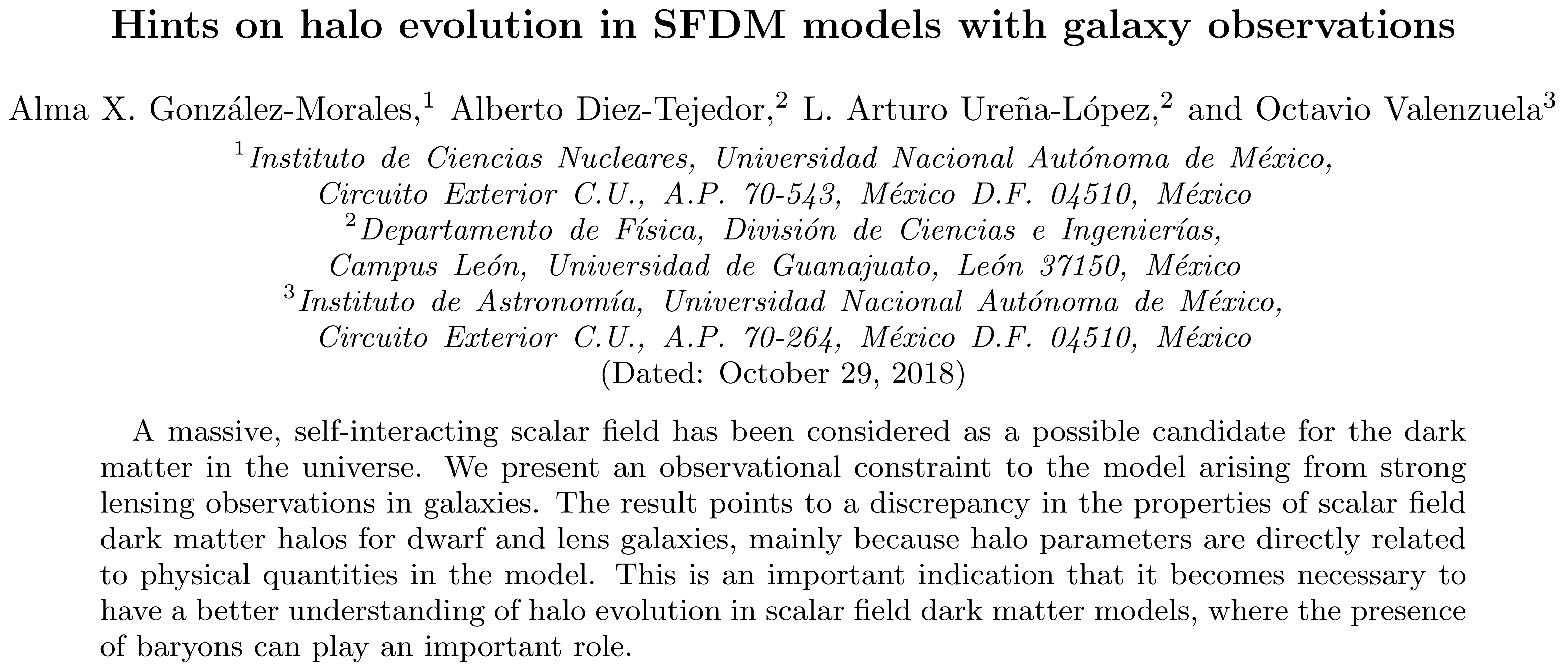


Available prior volume: **no evidence for an extra parameter!**

(Axion DM is the total DM budget)

Strong lensing:
The case of ‘density granules’

Strong lensing and SFDM (early)



Hints on halo evolution in SFDM models with galaxy observations

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(Dated: October 29, 2018)

A massive, self-interacting scalar field has been considered as a possible candidate for the dark matter in the universe. We present an observational constraint to the model arising from strong lensing observations in galaxies. The result points to a discrepancy in the properties of scalar field dark matter halos for dwarf and lens galaxies, mainly because halo parameters are directly related to physical quantities in the model. This is an important indication that it becomes necessary to have a better understanding of halo evolution in scalar field dark matter models, where the presence of baryons can play an important role.

González-Morales et al, PRD D 87, 021301(R) (2013), arXiv:1211.6431

STRONG GRAVITATIONAL LENSING BY WAVE DARK MATTER HALOS

Antonio Herrera-Martín,[1, 2] Martin Hendry,[1] Alma X. Gonzalez-Morales,[3, 4] and
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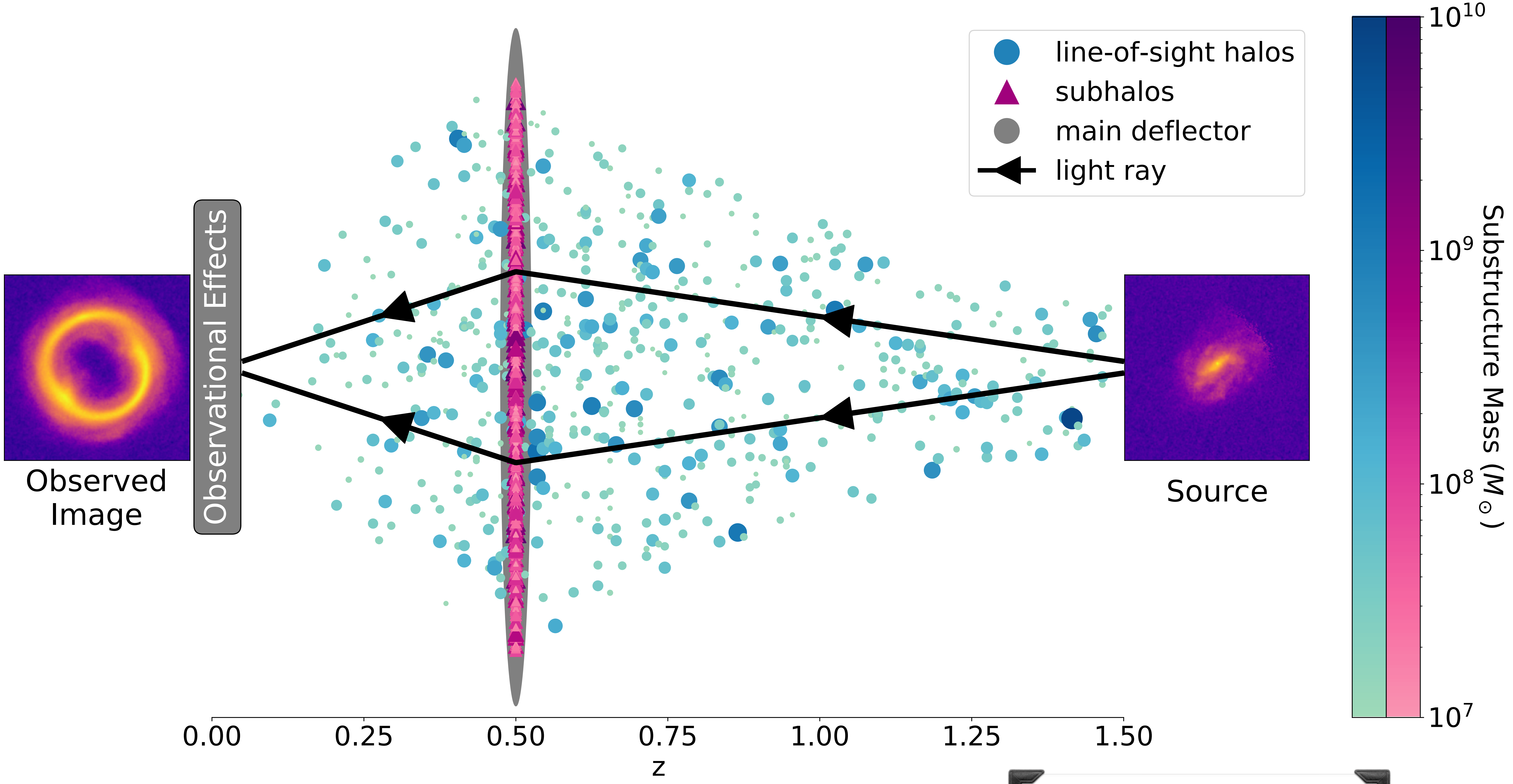
(Dated: February 8, 2019)

ABSTRACT

Wave Dark Matter (WaveDM) has recently gained attention as a viable candidate to account for the dark matter content of the Universe. In this paper we explore the extent to which, and under what conditions, dark matter halos in this model are able to reproduce strong lensing systems. First, we explore analytically the lensing properties of the model, finding that a pure WaveDM density profile, soliton profile, produces a weaker lensing effect than similar cored profiles. Then we analyze models with a soliton embedded within an NFW profile, as has been found in numerical simulations of structure formation. We use a benchmark model with a boson mass of $m_a = 10^{-22}\,\mathrm{eV}$, for which we see that there is a bi-modality in the contribution of the external NFW part of the profile, and some of the free parameters associated with it are not well constrained. We find that for configurations with boson masses $10^{-23} - 10^{-22}\,\mathrm{eV}$, a range of masses preferred by dwarf galaxy kinematics, the soliton profile alone can fit the data but its size is incompatible with the luminous extent of the lens galaxies. Likewise, boson masses of the order of $10^{-21}\,\mathrm{eV}$, which would be consistent with Lyman-α constraints and consist of more compact soliton configurations, necessarily require the NFW part in order to reproduce the observed Einstein radii. We then conclude that lens systems impose a conservative lower bound $m_a > 10^{-24}\,\mathrm{eV}$ and that the NFW envelope around the soliton must be present to satisfy the observational requirements.

Herrera-Martin et al, ApJ 872, 1 (2019), arXiv:1707.09929

Quick recipe for strong lensing

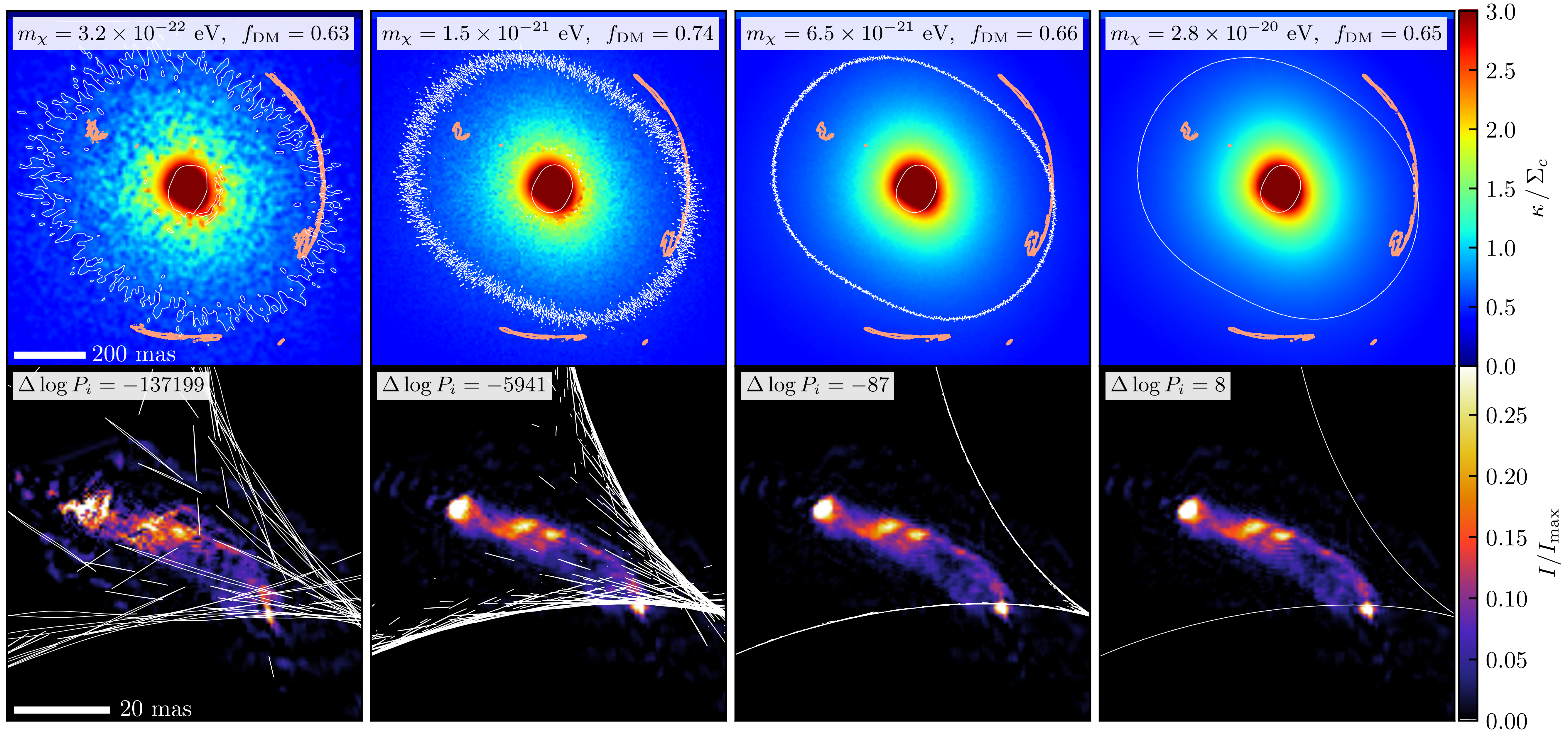


PALTAS
https://github.com/swagnercarena/paltas

Strong lensing and SFDM (recently)

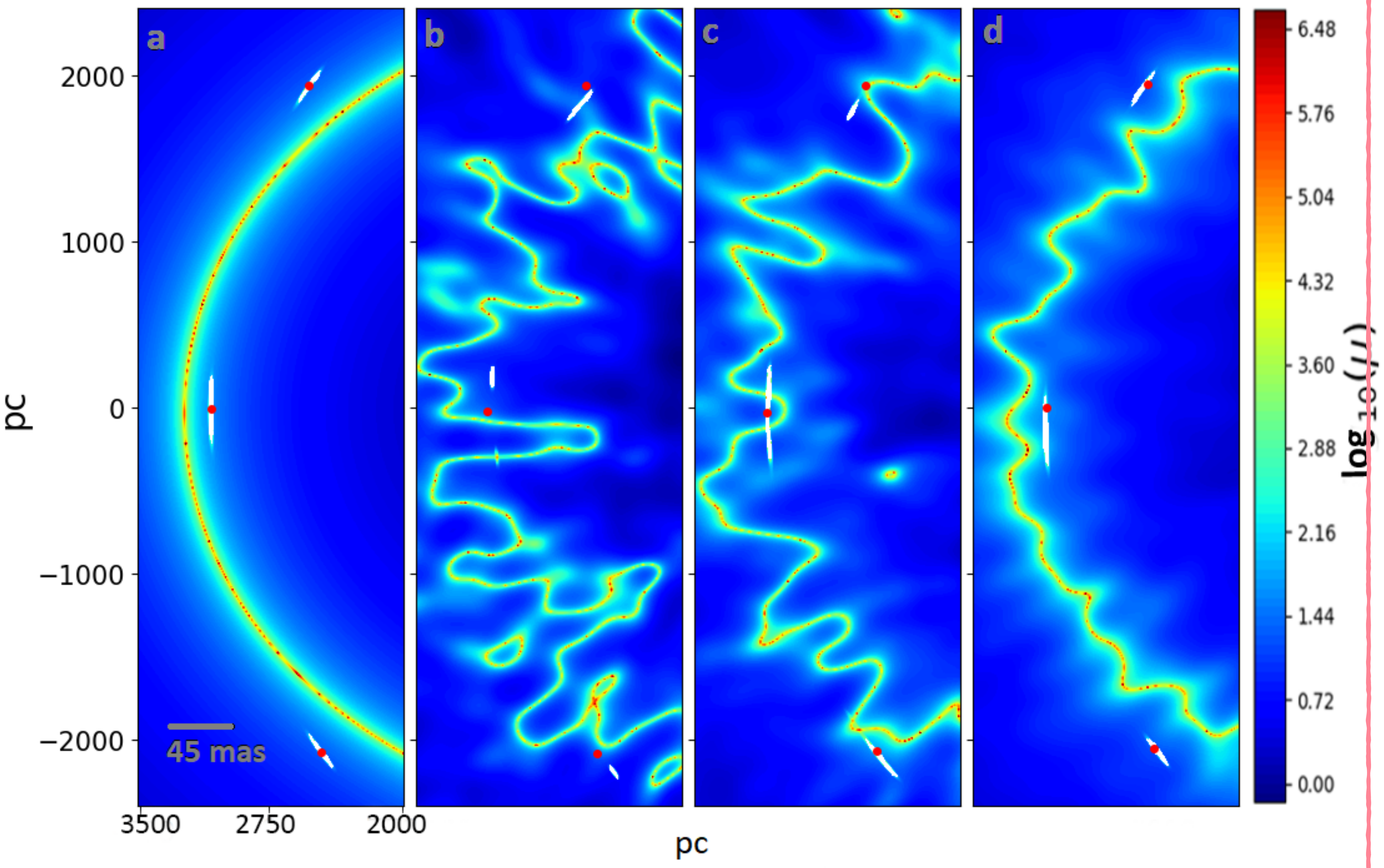
A lensed radio jet at milli-arcsecond resolution II: Constraints on fuzzy dark matter from an extended gravitational arc

Devon M. Powell,[1]★ Simona Vegetti,[1] J. P. McKean,[2,3] Simon D.M. White,[1]
Elisa G. M. Ferreira,[4,5] Simon May[6,7], and Cristiana Spingola[8]



- Start with a 3D mass density: $\rho(\mathbf{x}) + \delta\rho(\mathbf{x})$
- Calculate a surface density and normalize it to obtain the convergence field: $\kappa(\xi) + \delta\kappa(\xi) = \dfrac{\Sigma(\xi) + \delta\Sigma(\xi)}{\Sigma_c}$
- How to calculate the perturbations in the convergence?
- Assume: a collection of eigenfunctions on the same potential well, and use them to model the total matter density.
  - Caveat: the number of eigenfunctions is not well determined by the potential well, and may lead to artificial enhancement of the granule population in the halo. Likewise, artificial enhancement of the perturbations in the convergence of the lens.

Strong lensing and SFDM (recently)



- Start with a 3D mass density: $\rho(\mathbf{x}) + \delta\rho(\mathbf{x})$
- Calculate a surface density and normalize it to obtain the convergence field: $\kappa(\xi) + \delta\kappa(\xi) = \dfrac{\Sigma(\xi) + \delta\Sigma(\xi)}{\Sigma_c}$
- How to calculate the perturbations in the convergence?
- Assume: variance in column density is proportional to variance in the 3D density along the line of sight.
  - Caveat: the exact proportionality in the equations below is not known!

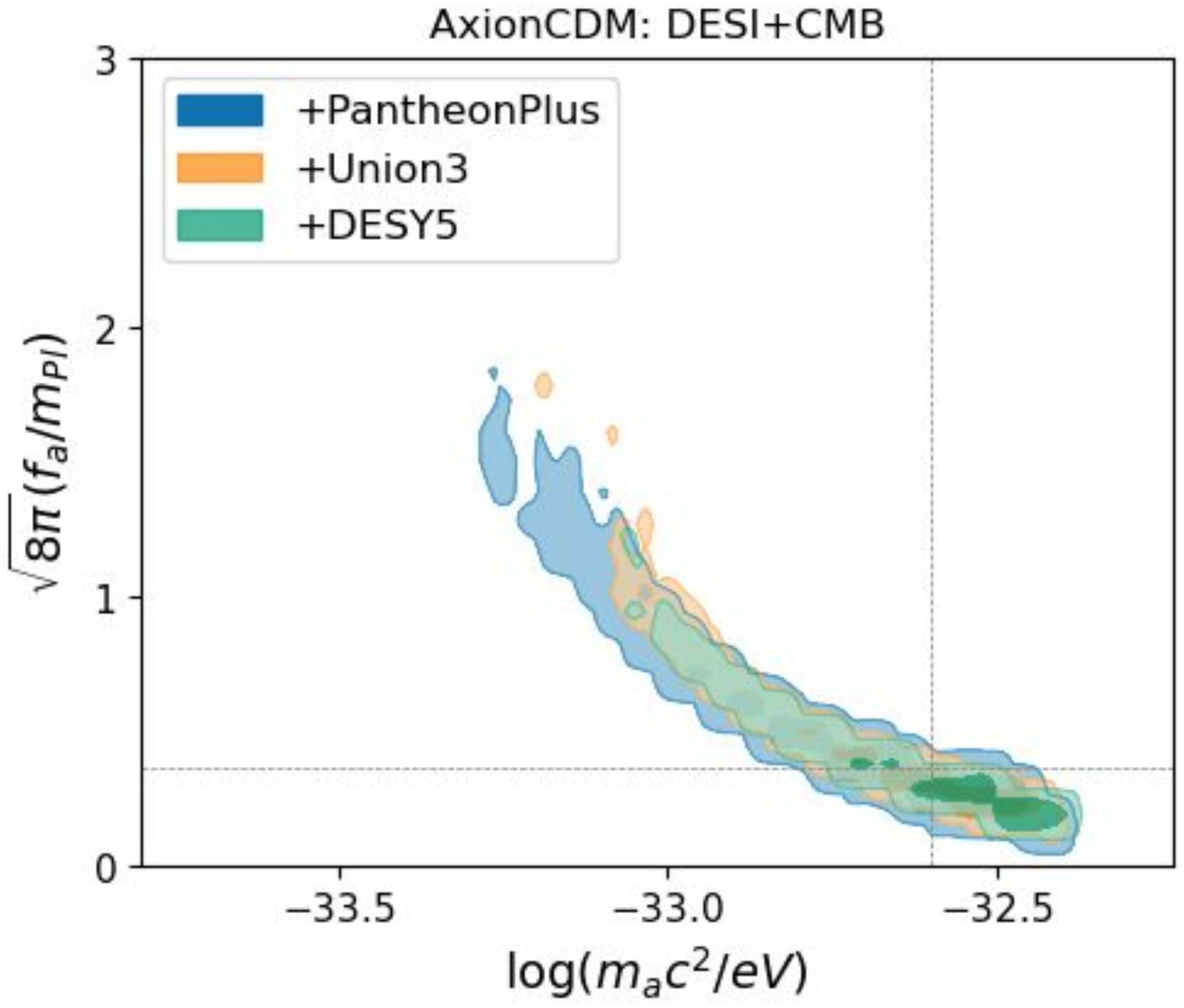
$$\sigma_\Sigma^2(\boldsymbol{\xi}) = \lambda_{\rm dB} \int_{-\infty}^{\infty} \sigma_\rho^2(z, \boldsymbol{\xi}) dz$$

$$\simeq \lambda_{\rm dB} \int_{-\infty}^{\infty} \rho_{\rm smooth}^2(z, \boldsymbol{\xi}) dz$$

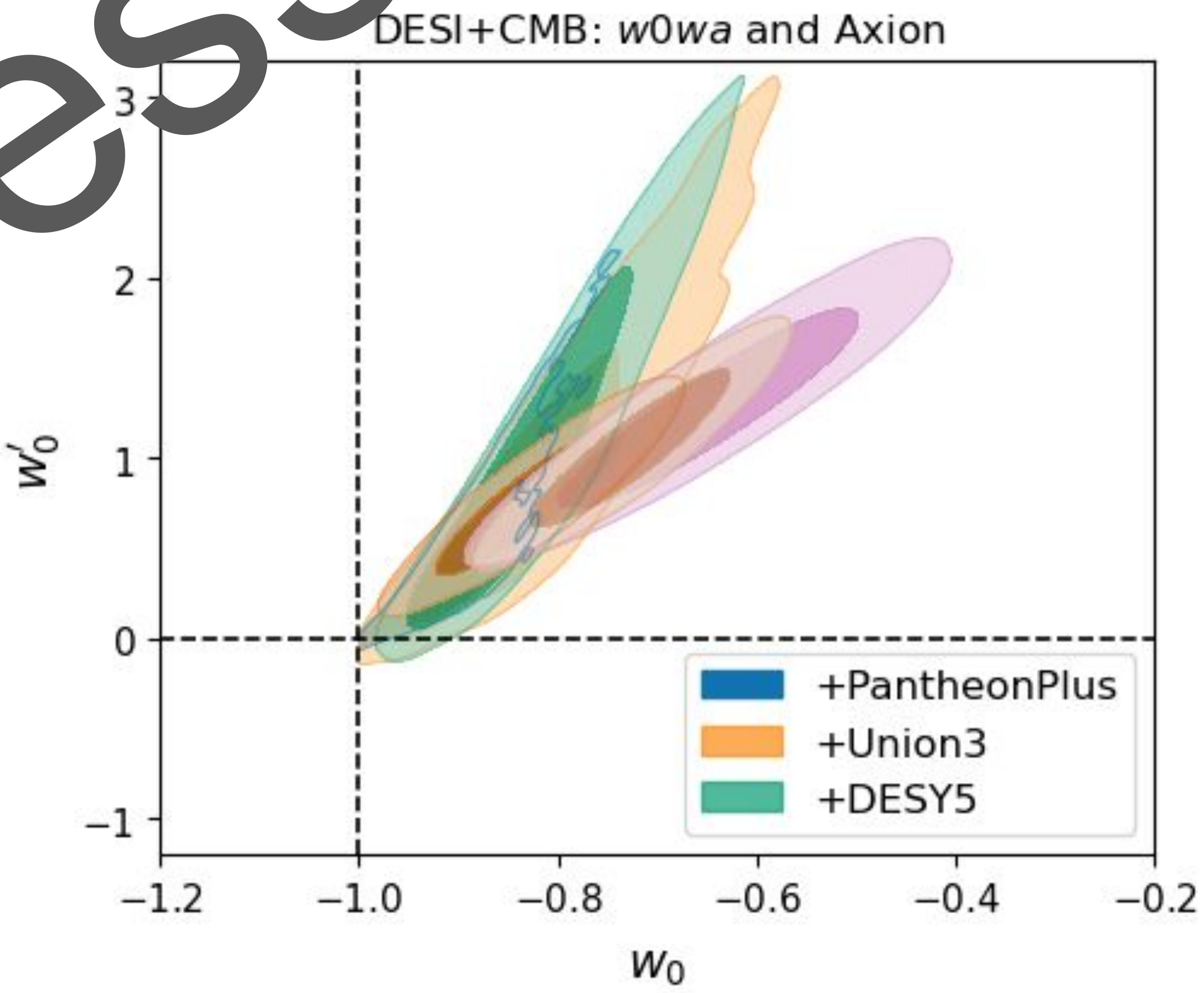
Amruth et al, Nat Astron (2023), arXiv:2304.09895

Extra bonus ...

DESI constraints on AxionDE



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



The axion model of dark energy (aka PNGB model)

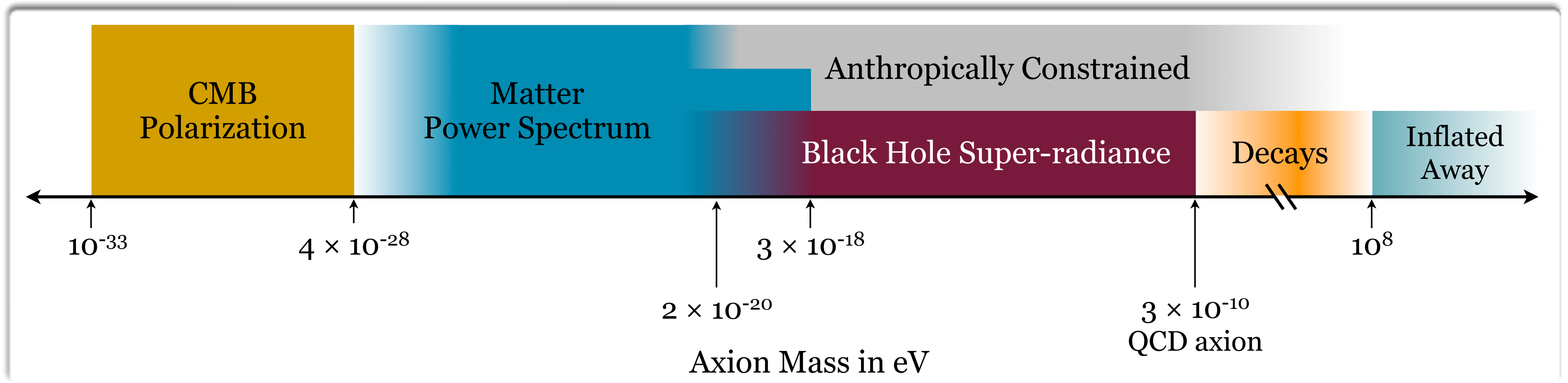
UNIVERSIDAD DE GUANAJUATO

Conclusions

- Work in progress …
- It’s been under scrutiny for more than two decades
- It’s a good scientific model: it can be falsified by different ranges of observations
- If the DM riddle needs an exotic solution, what is more exotic than quantum effects at galactic level?
- **Is there any characteristic scale in the DM field?**

$$L_C = \frac{h}{m_a c} = 0.4\, m_{a22}^{-1}\,\mathrm{pc} \qquad L_{dB} = \frac{h}{m_a v} = 400\, m_{a22}^{-1}\,\mathrm{pc}$$

- Ultimate challenge: cosmological simulations and Lyman-alpha observations, for a joint view of the model from different scales



Fuzzy dark matter confronts rotation curves of nearby dwarf irregular galaxies

Bañares-Hernández et al, ArXiv 2304:05793

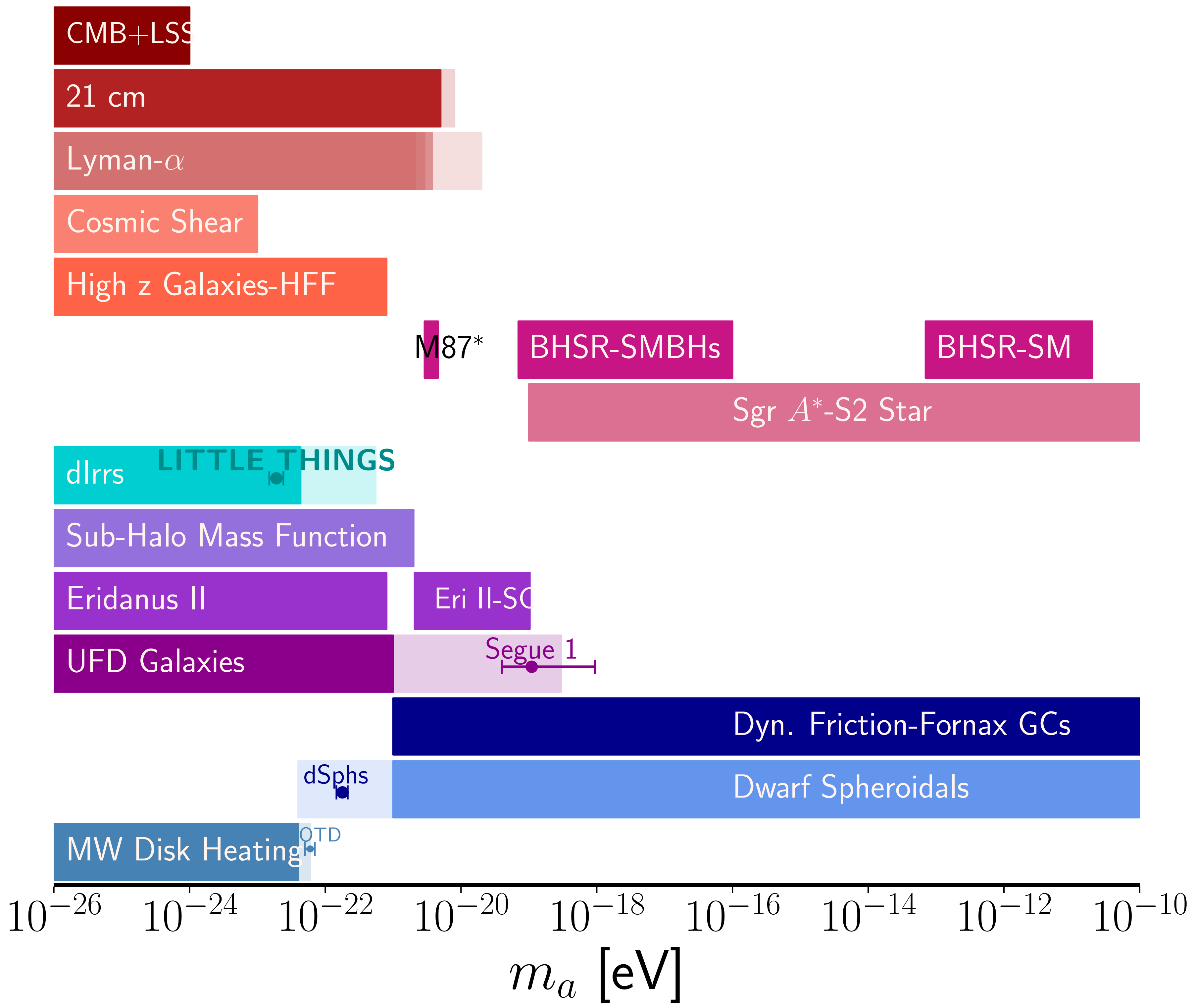


Fig. 9: Bounds from cosmology and astrophysics on the axion mass. The constraint from HMF in the local group with the haloes of nearby dwarf irregulars (dIrrs) from the LTs catalog is displayed with dark turquoise bars. On the dIrrs bar, we also show the optimal mass $m_a = 1.9^{+0.5}_{-0.4} \times 10^{-23}$ eV (uncertainties at 2σ CL). Our constraints are compared to other cosmological and astrophysical limits (see main text for details).