UNIVERSIDAD DE GUANAJUATO

Dark matter with ultralight bosons and its imprint on cosmological structure

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A Rainbow of Dark Sectors, March 22 - April 2

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

PHYSICAL REVIEW D, VOLUME 63, 063506

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

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(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

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[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.

Klein-Gordon equation

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

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

(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.

Scalar field dark matter, ULB's, ALP's, …

- ……
- **Halo Abundance and Assembly History with Extreme-Axion Wave Dark Matter at z ≥ 4,** Hsi-Yu Schive, Tzihong Chiueh. e-Print: arXiv:1706.03723 [astro-ph.CO].
- **Cosmological Perturbations of Extreme Axion in the Radiation Era**. Ui-Han Zhang, Tzihong Chiueh. e-Print: arXiv:1705.01439 [astro-ph.CO]
- **Cosmological signatures of ultra-light dark matter with an axion-like potential**. Francisco X. Linares Cedeño, Alma X. González-Morales, L. Arturo Ureña-López. e-Print: arXiv:1703.10180 [gr-qc]
- **The mass discrepancy-acceleration relation: a universal maximum dark matter acceleration and implications for the ultra-light scalar field dark matter model**, L. Arturo Ureña-López, Victor H. Robles, T. Matos, e-Print: arXiv:1702.05103.
- **Cosmological production of ultralight dark matter axions**, Alberto Diez-Tejedor, David J. E. Marsh, e-Print: arXiv:1702.02116
- **On the hypothesis that cosmological dark matter is composed of ultra-light bosons, Lam Hui, Jeremiah P. Ostriker, Scott Tremaine, Edward Witten. Phys.Rev. D95 (2017) no.4, 043541. e-Print: arXiv:1610.08297.**
- **Simulations of solitonic core mergers in ultra-light axion dark matter cosmologies,** Bodo Schwabe, Jens C. Niemeyer, Jan F. Engels (Gottingen U.). e-Print: arXiv:1606.05151.
- **Contrasting Galaxy Formation from Quantum Wave Dark Matter**. Hsi-Yu Schive, Tzihong Chiueh, Tom Broadhurst, Kuan-Wei Huang. Astrophys.J. 818 (2016) no.1, 89
- **Towards accurate cosmological predictions for rapidly oscillating scalar fields as dark matter,** L. Arturo Ureña-López, Alma X. Gonzalez-Morales. e-Print: arXiv:1511.08195.
- **On wave dark matter in spiral and barred galaxies.** Luis A. Martinez-Medina, Hubert L. Bray, Tonatiuh Matos, JCAP 1512 (2015) no.12, 025. e-Print: arXiv:1505.07154
- **Cosmic Structure as the Quantum Interference of a Coherent Dark Wave**. Hsi-Yu Schive, Tzihong Chiueh, Tom Broadhurst. e-Print: arXiv:1406.6586 [astro-ph.GA]
- ……

FDM potential

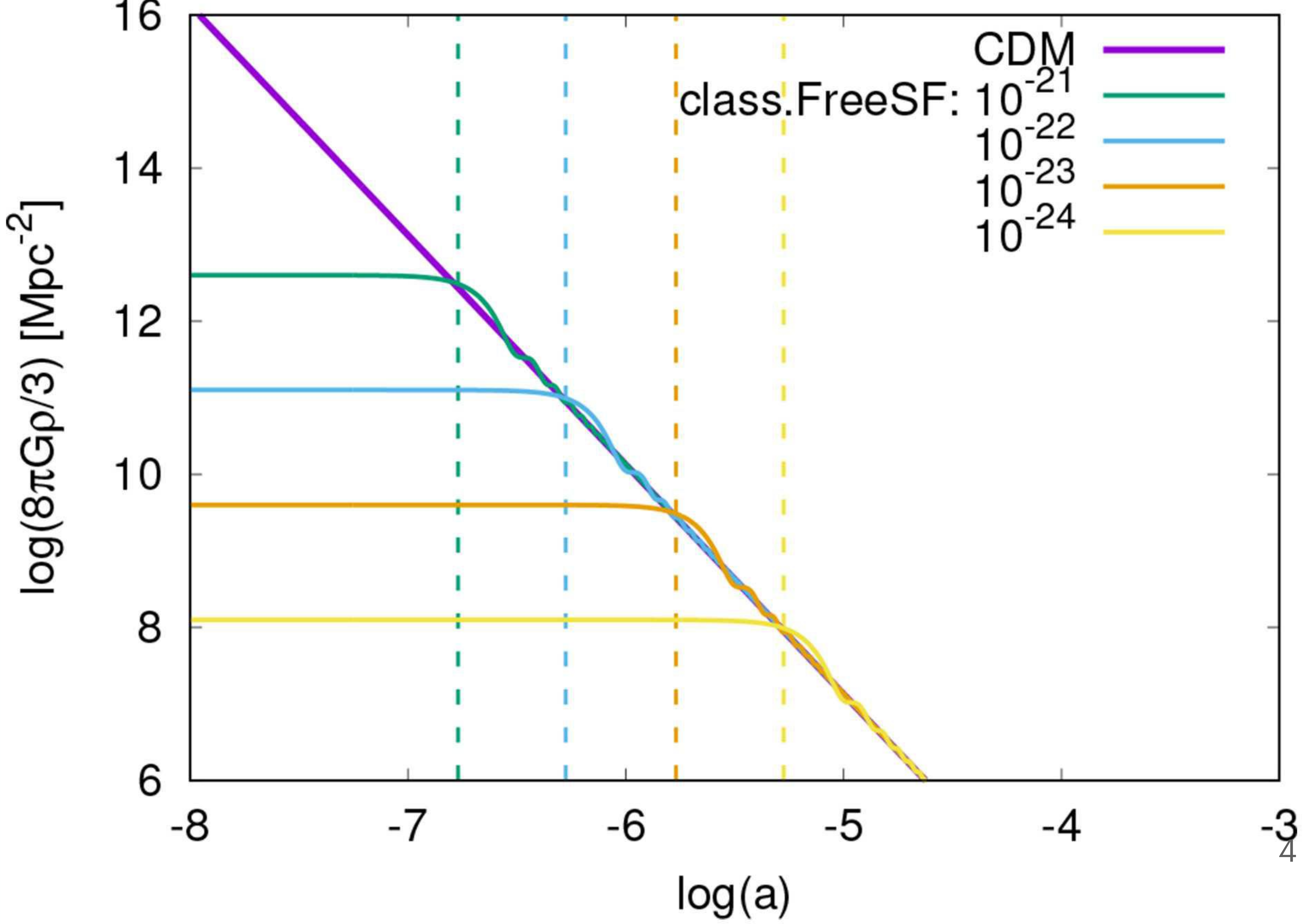
$$V(\phi) = \frac{1}{2} m_a^2 \phi^2$$

U-L, JCAP 06 (2019) 009

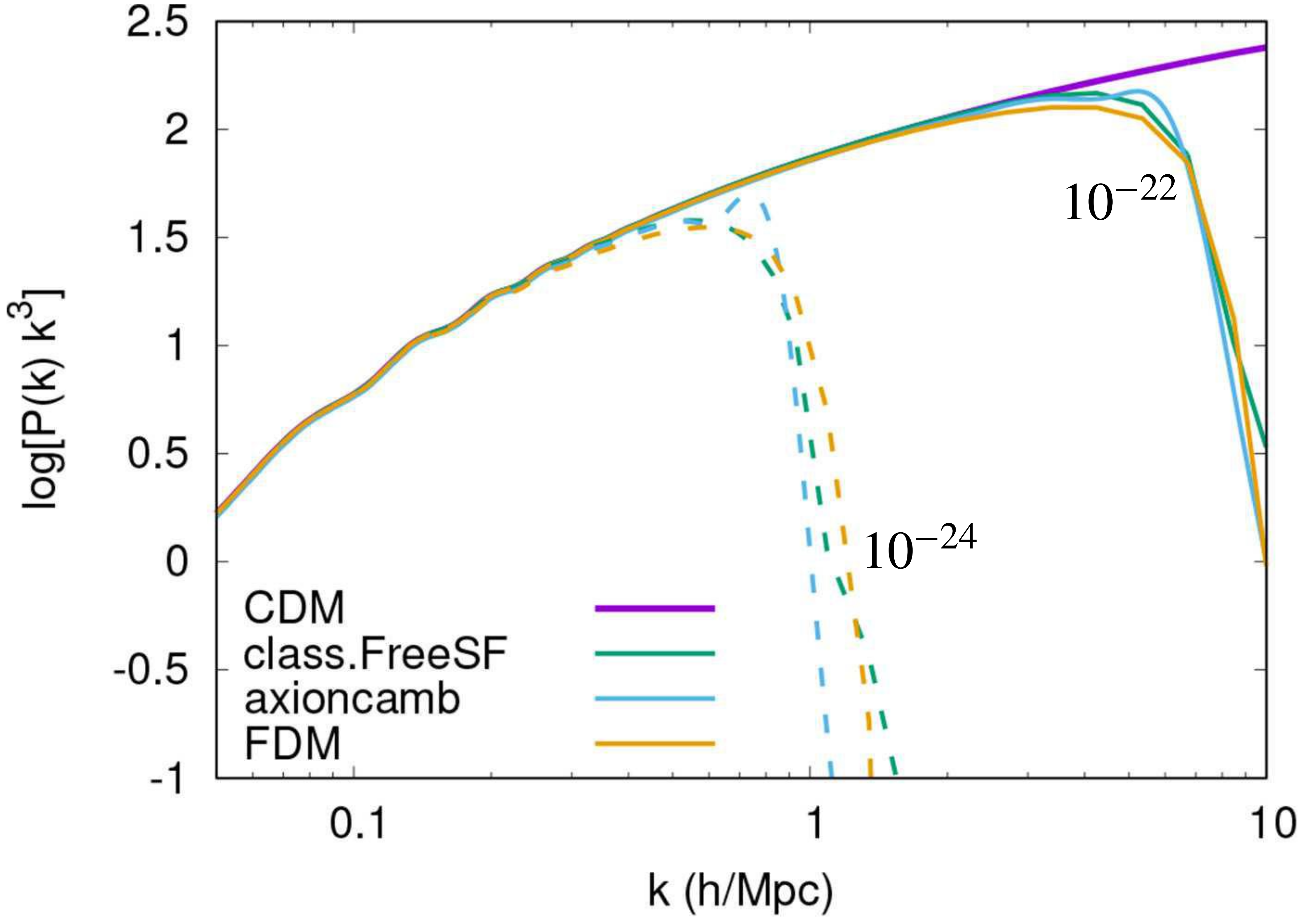
U-L, González-Morales, JCAP 07 (2016) 048
*Cookmeyer et al, PRD 101, 023501 (2020)**

**How sound are our ultra-light axion approximations?*

Mass $m_a c^2 / eV$ is a time scale of reference!

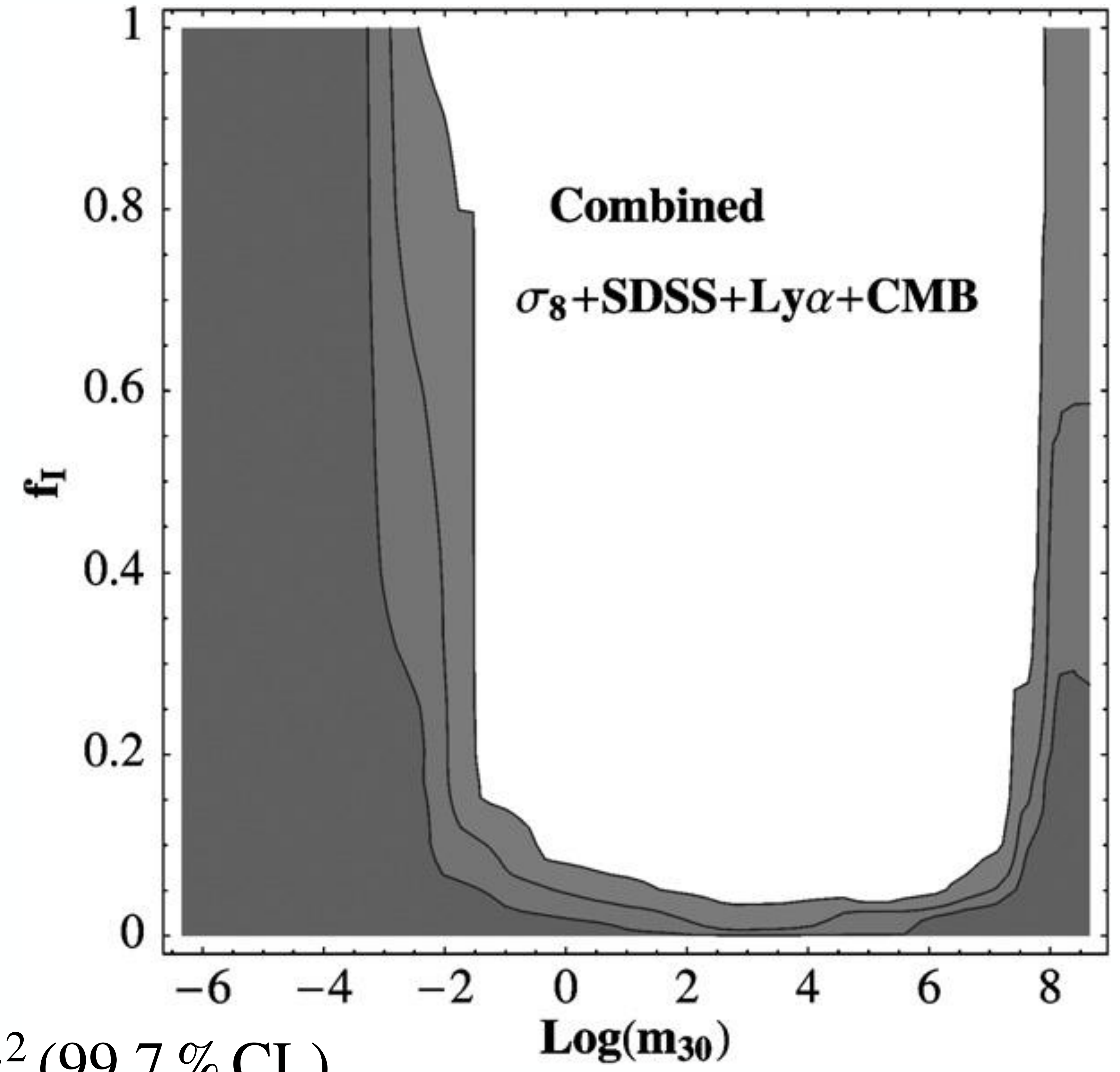


Mass $m_a c^2 / eV$ is a distance scale of reference!



Current constraints on the mass

$m_a \gtrsim 10^{-25.5}\,\mathrm{eV}/c^2$ (95 % CL)



$m_a \gtrsim 10^{-22}\,\mathrm{eV}/c^2$ (99.7 % CL)

Fig. 5. Combined likelihood function at 68.95 and 99.7% c.l. (dark to light gray) for the parameters $m_{30} \equiv m_I/10^{-30}$ eV and f_I obtained marginalizing over τ, $\Omega_m h^2$, n_s and h, and fixing $\Omega_b h^2 = 0.023$.

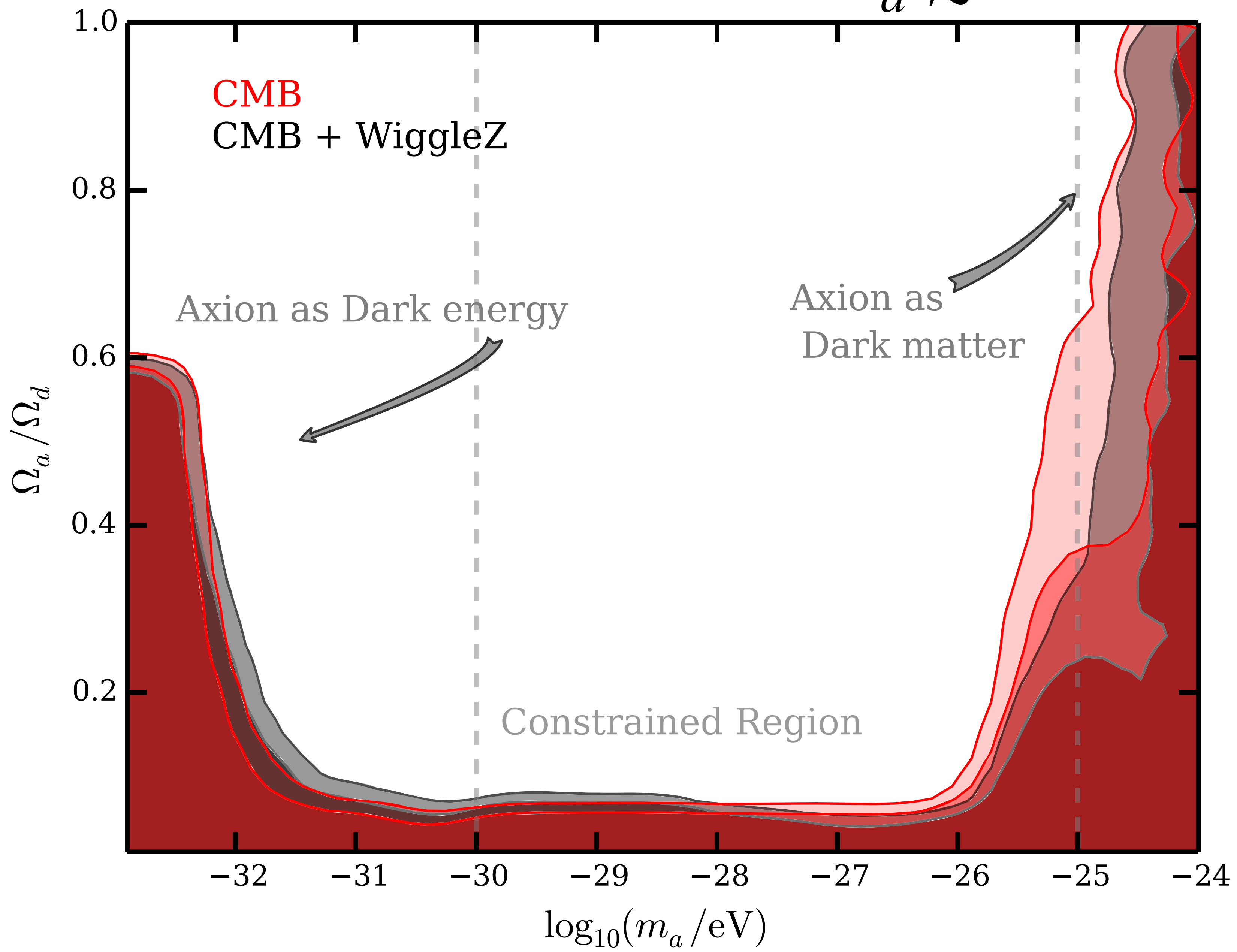
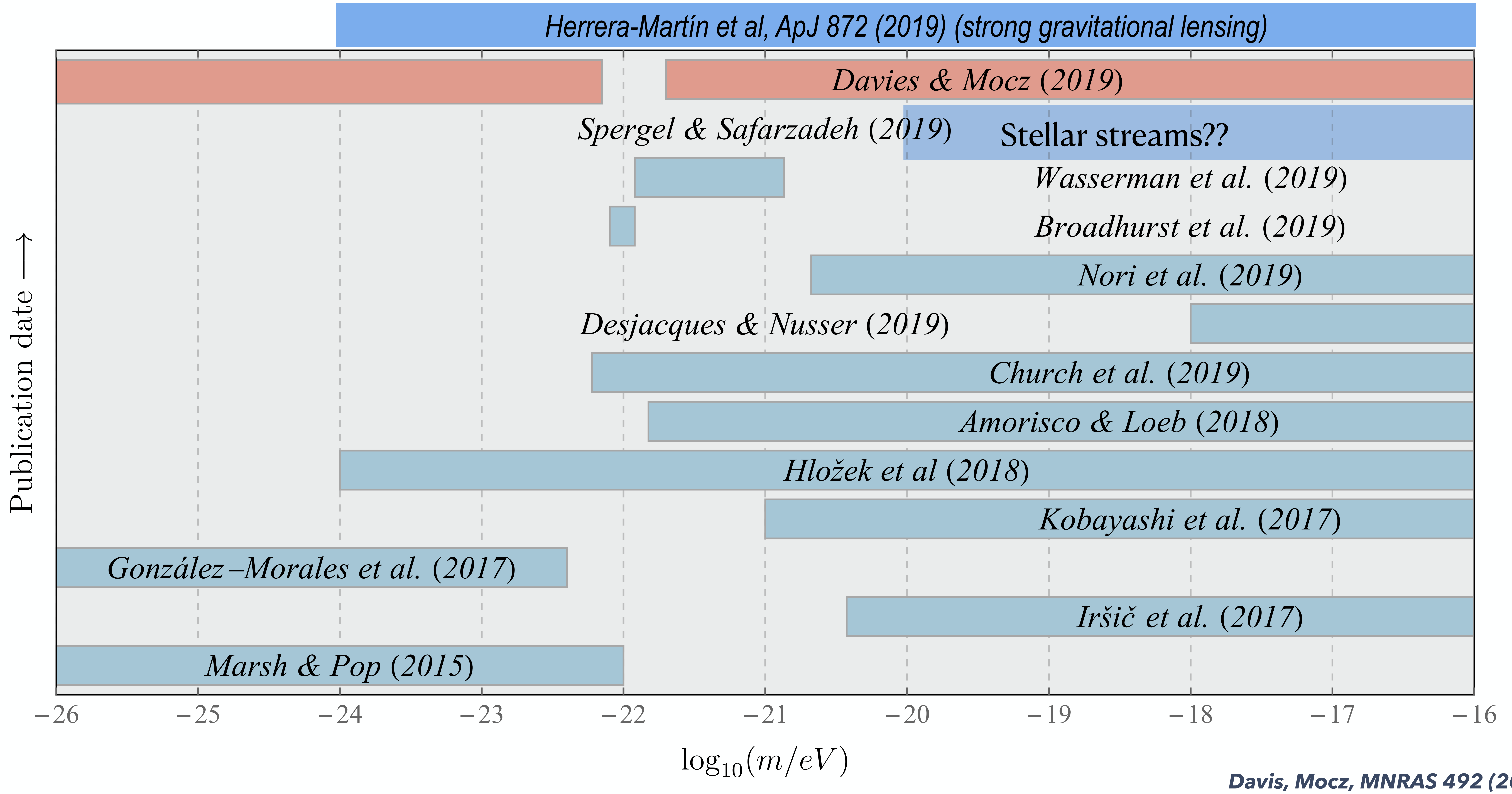


FIG. 1 (color online). Marginalized 2 and 3σ contours show limits to the ultralight axion (ULA) mass fraction Ω_a/Ω_d as a function of ULA mass m_a, where Ω_a is the axion relic-density parameter today and Ω_d is the total dark-matter energy density parameter. The vertical lines denote our three sampling 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.

Amendola, Barbieri, PLB 642 (2006) 192

Hlkozek et al, PRD 91 (2015) 103512

Current constraints on the mass



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

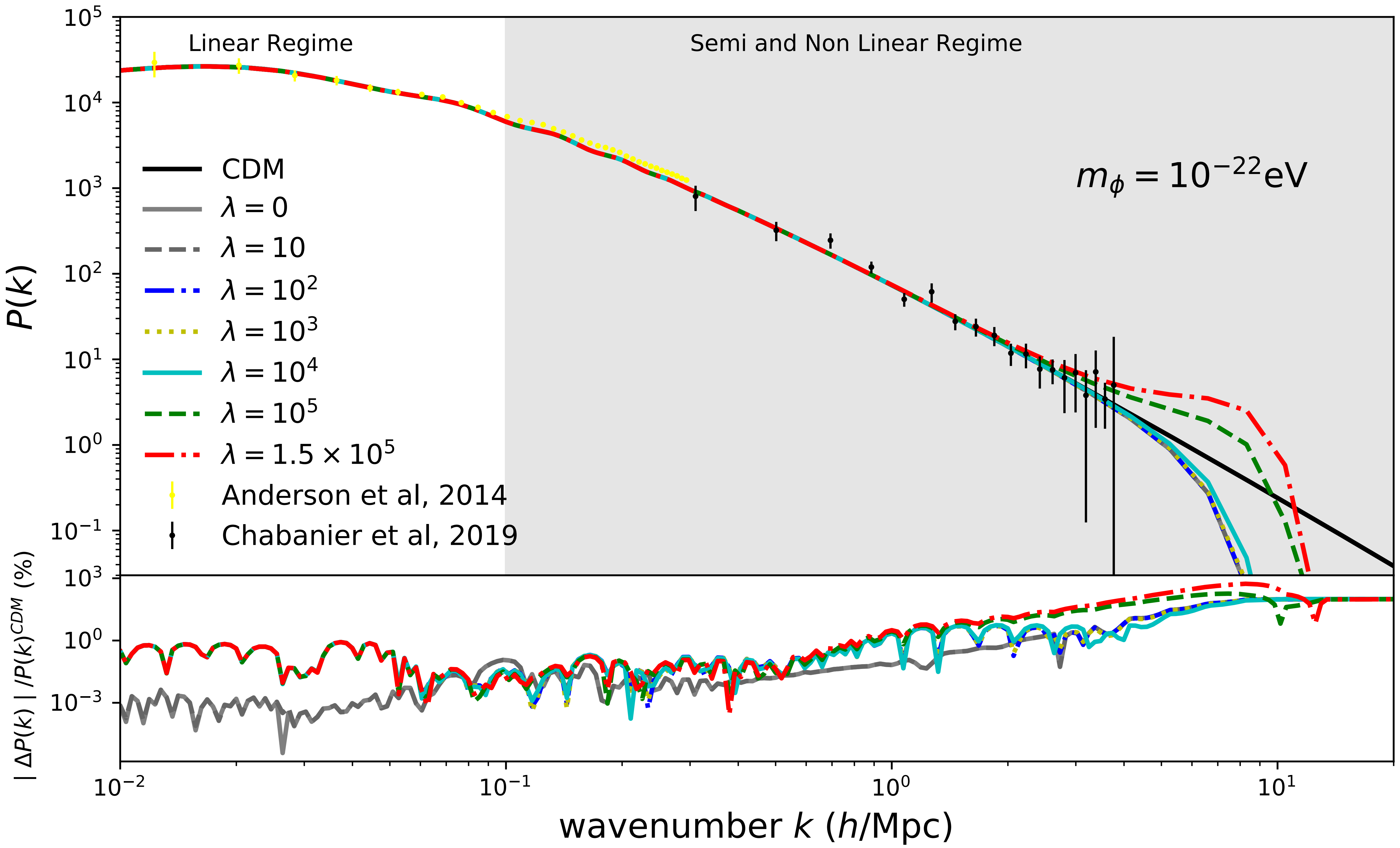
Axion-like potential

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

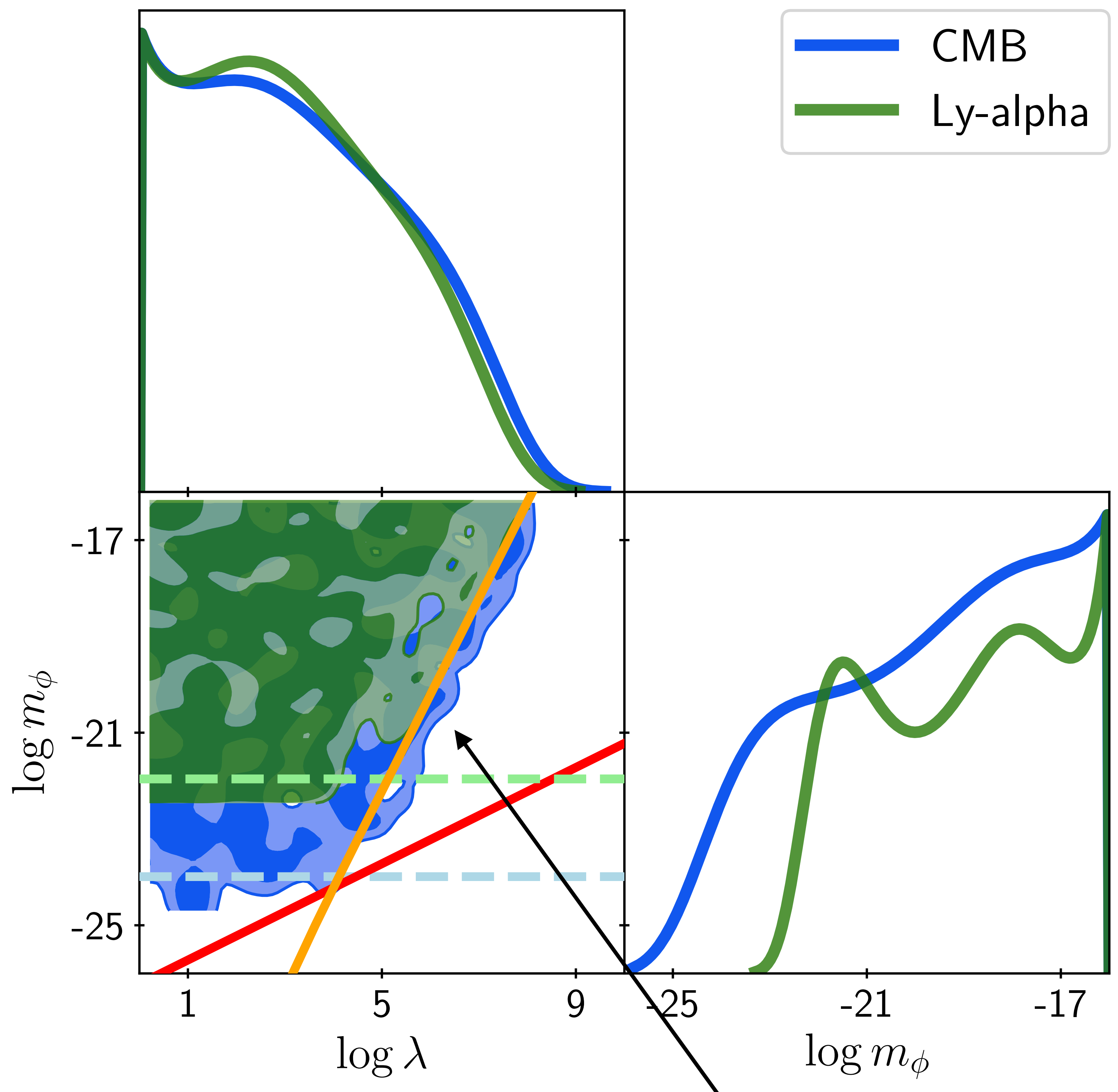
Linares-Cedeño, González-Morales, U-L, JCAP 1, 051 (2021), arXiv:2006.05037

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

$$\lambda = \frac{3m_{\rm Pl}^2}{8\pi f_a^2} \qquad \text{FDM}: \ \lambda = 0 \ (f_a \to \infty) \qquad m_a \gtrsim 10^{-22}\,\text{eV}/c^2 \,(95.5\,\%\,\text{CL})$$



Tachyonic instability of **linear** density perturbations



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

(Axion DM is the total DM budget)

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

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,

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

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

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

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[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)

Relativistic scale length

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

$$\downarrow$$

Nonrelativistic scale length

$$L_{dB} = \frac{h}{m_a v} \simeq 10^3\, L_C$$

Structure formation

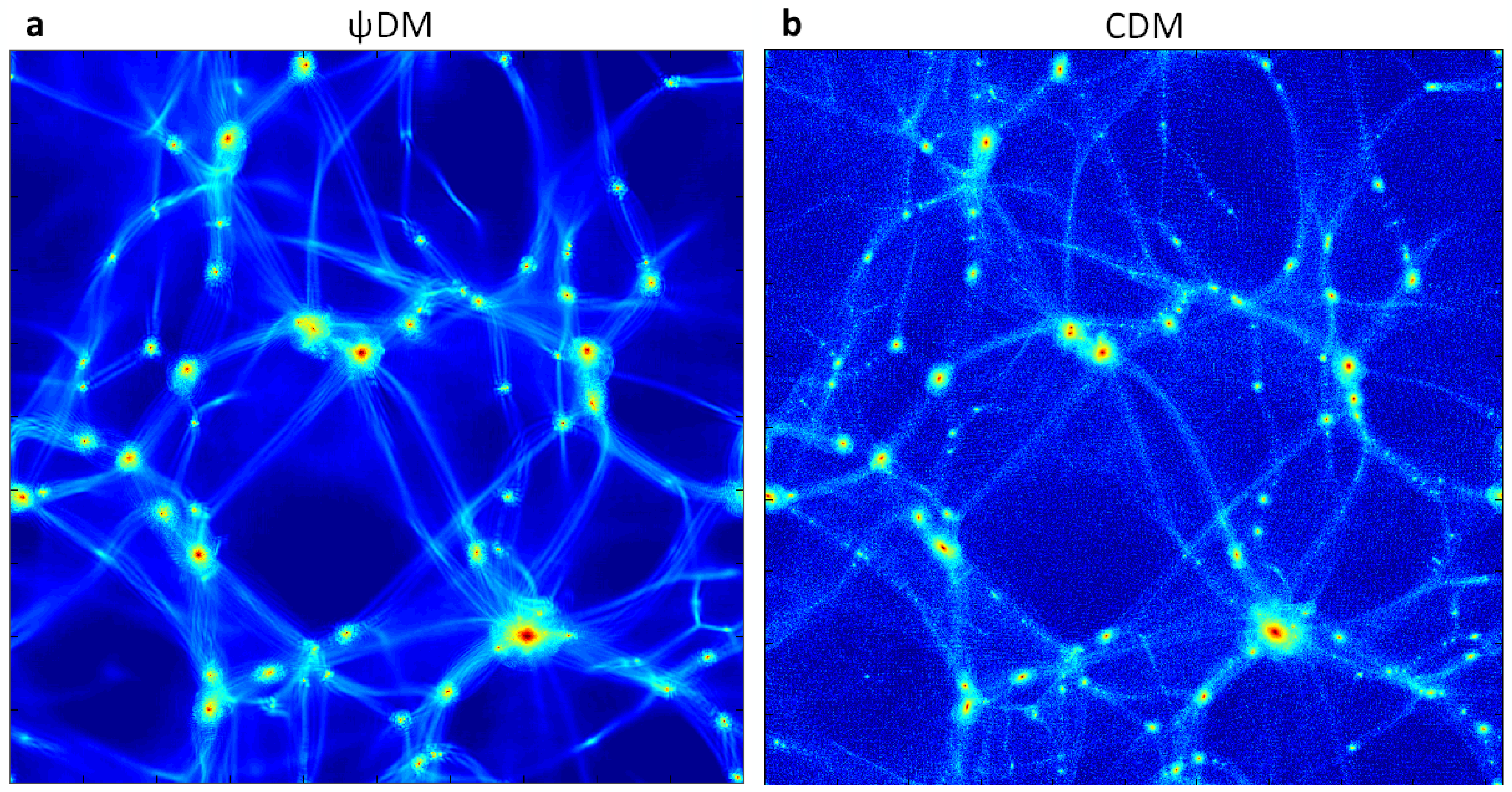


Figure 1: Comparison of cosmological large-scale structures formed by standard CDM and by wave-like dark matter, ψDM. Panel (**a**) shows the structure created by evolving a single coherent wave function for $\Lambda\psi$DM calculated on AMR grids. Panel (**b**) is the structure simulated with a standard 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

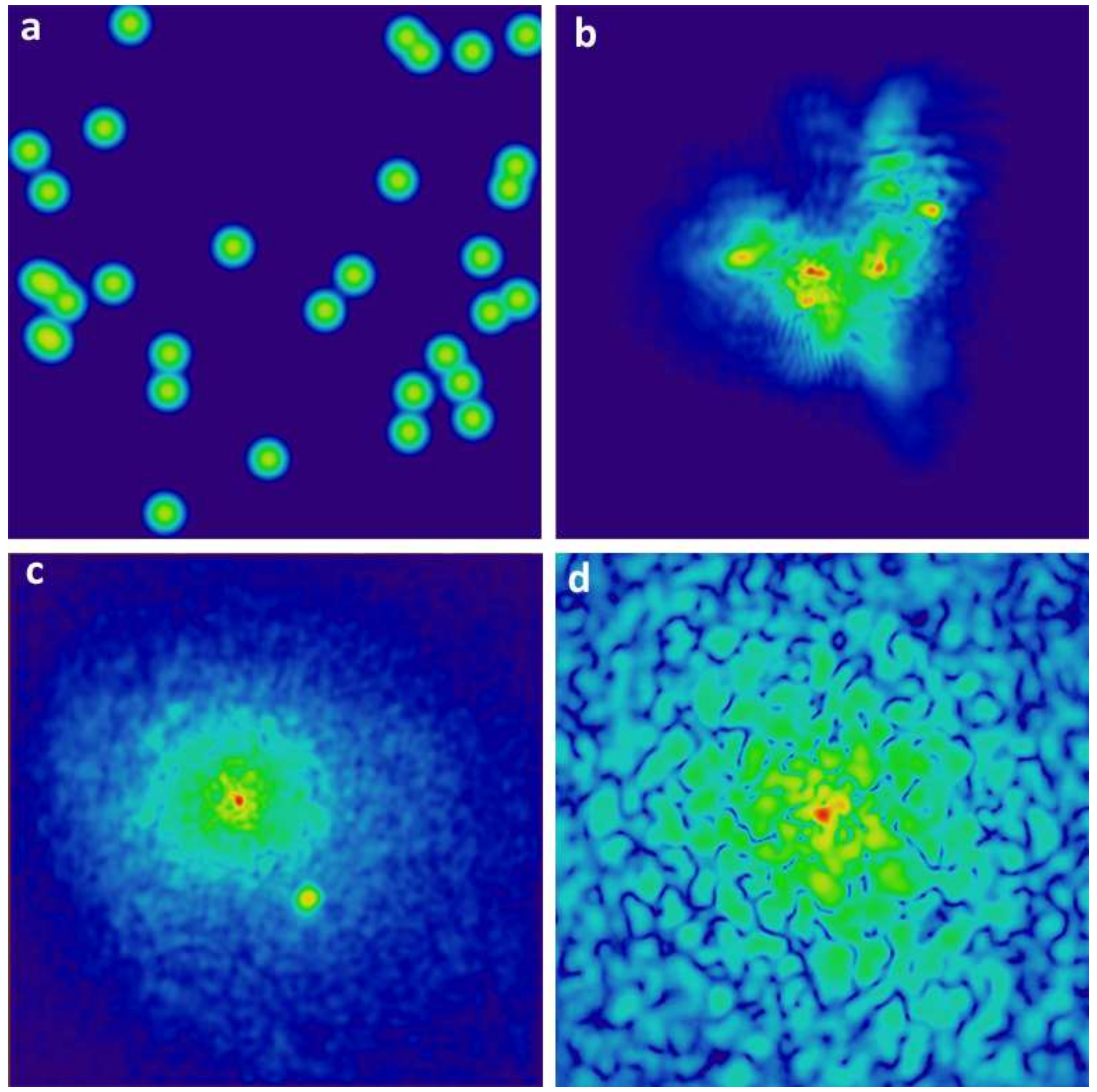


FIG. 3: Snapshots of a soliton collision simulation. Panels (a)-(c) show the projected density distribution at the initial and intermediate stages, and panel (d) shows a close-up of the conspicuous solitonic core at the final stage. Fluctuating density granules resulting from the quantum wave interference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

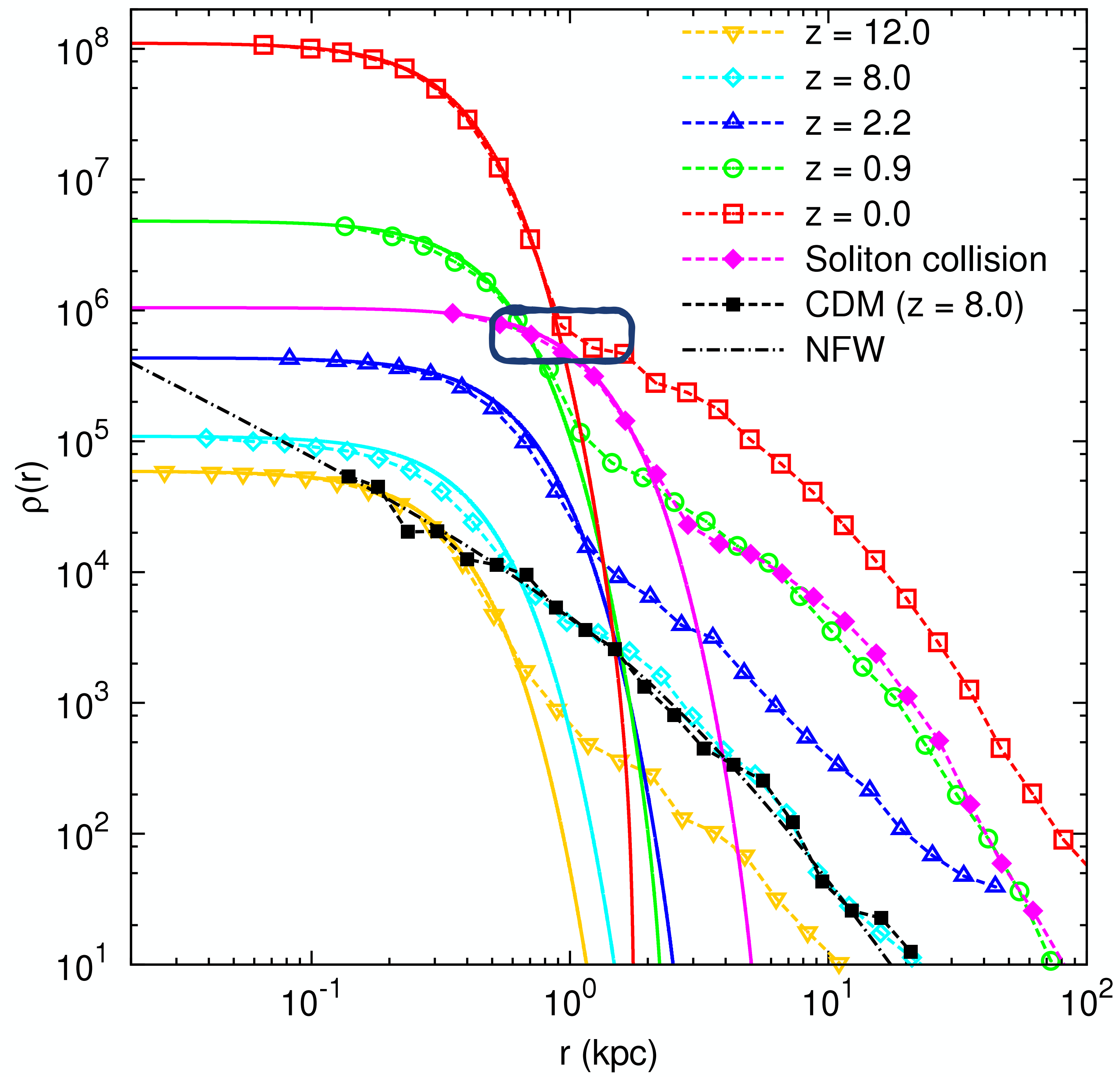
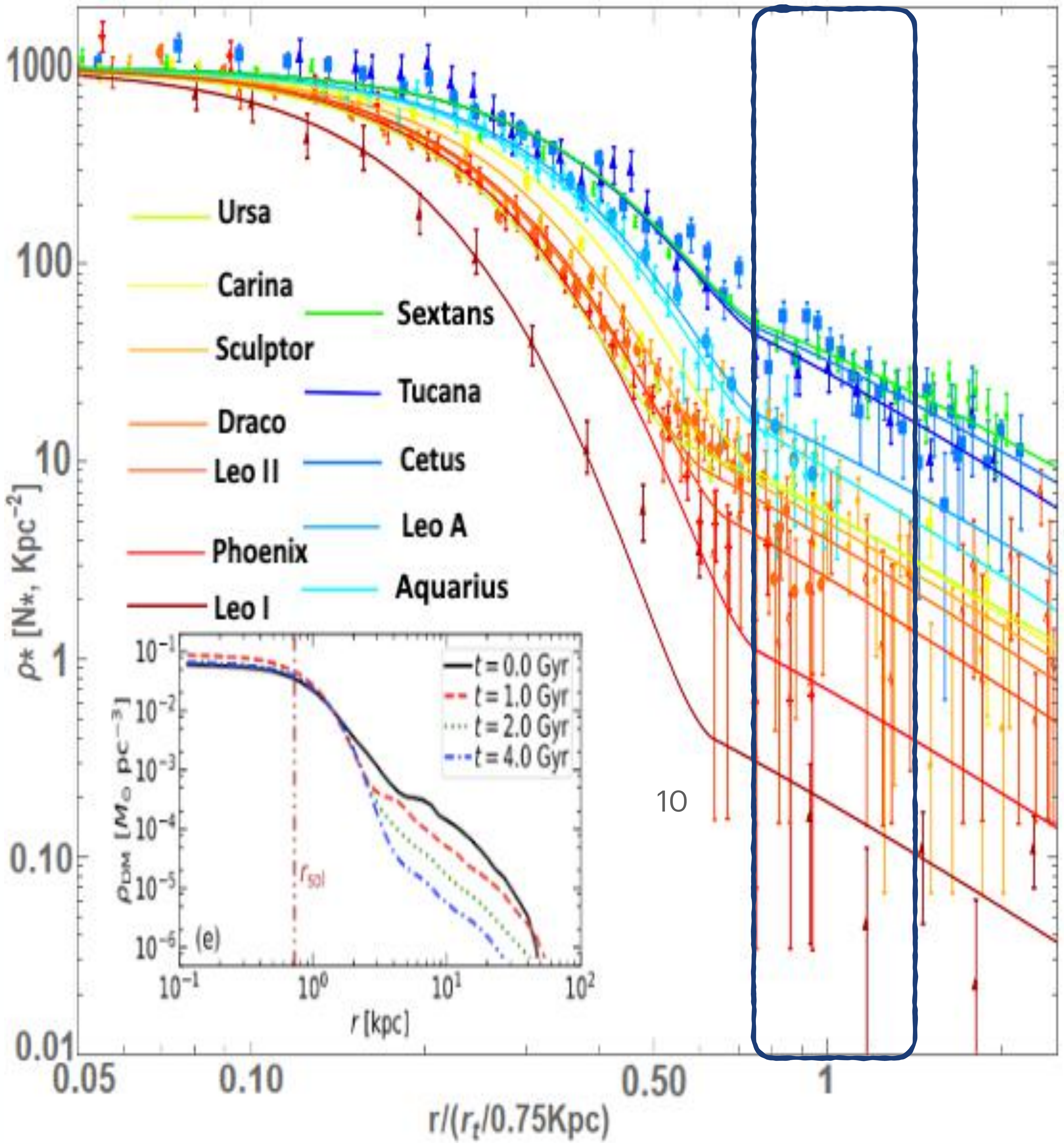


FIG. 1: Density profiles of ψDM halos. Dashed lines with various opened symbols show five examples at different redshifts between $12 \geq z \geq 0$. The DM density is normalized to the cosmic background density. A distinct core forms in every halo as a gravitationally self-bound object, satisfying the 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.

Current constraints on the mass

Pozo et al, ArXiv 2010:10337



Transition radius

Galaxy	m_ψ (10^{-22} eV)	M_h ($10^{10} M_\odot$)	r_t (kpc)	σ (km/s)	χ^2_{red}	Gap(Log) Δ_{C-H}	D Milky Way (kpc)	Pericenter (kpc)
Aquarius	$1.12^{+0.12}_{-0.09}$	$6.89^{+1.99}_{-1.68}$	1.13	7.9	0.85	1.78	1071	-
Cetus	$1.17^{+0.33}_{-0.19}$	$4.79^{+3.11}_{-2.51}$	1.04	8.3	1.13	1.34	775	-
Tucana	$1.63^{+0.24}_{-0.18}$	$6.28^{+2.43}_{-2.13}$	0.68	15	0.96	1.5	887	-
Leo A	$1.12^{+0.13}_{-0.1}$	$3.44^{+1.08}_{-0.94}$	1.43	6.7	1.23	1.76	800	-
Sextans	1.2	2	1.28	6.9	2.05	1.36	90	71^{+11}_{-12}
Phoenix	1.7	4	1.23	7.9	1.41	3.44	415	263^{+126}_{-219}
Leo I	1.7	6	1.20	8.8	1.76	3.43	250	45^{+80}_{-34}
Draco2001	1.5	30	0.58	9.1	0.63	2.32	80	28^{+12}_{-7}
Draco2004	1.7	15	0.56	9.1	1.58	2.32	80	28^{+12}_{-7}
Carina	1.8	7	0.75	6.7	1.17	2.26	101	60^{+21}_{-16}
Sculptor2005	1.9	10	0.63	9.2	3.7	2.23	80	51^{+15}_{-10}
Sculptor2007	1.7	9	0.74	9.2	1.69	2.18	80	51^{+15}_{-10}
Ursa Minor	1.3	8	0.99	9.5	5.56	2.14	66	29^{+8}_{-6}
Leo II	1.8	24	0.54	7.4	1.08	2.45	210	45^{+121}_{-30}

TABLE I. Observations and ψDM profile fits. Column 1: Dwarf galaxy colour coded as in figure 3a, Column 2: Boson mass m_ψ, Column 3: Halo mass M_h, Column 4: Transition point r_t, Column 5: Velocity dispersion σ, Column 6: Reduced Chi-square χ^2_{red}, Column 7: Gap Δ_{C-H}, Column 8: Distances from Milky Way center & Column 9: Pericenter determined from GAIA (Fritz et al. 2018)

SOLITON

Simulations: Madelung transformation

From wave to fluid

$$\boxed{i\hbar\partial_t\psi = -\frac{\hbar}{2m_a}\nabla^2\psi + \Phi\psi\,, \quad \nabla^2\Phi = 4\pi G m_a^2|\psi|^2}$$

$$\psi(t,\mathbf{x}) \;=\; \varphi(t,\mathbf{x})\exp(-iS(t,\mathbf{x})/\hbar).$$

$$\boxed{Q = -\frac{1}{2}\frac{\nabla^2\varphi}{\varphi}}$$

$$\mathbf{v} = -\nabla S \qquad\qquad \rho = m_a^2|\psi|^2 = m_a^2\varphi^2$$

$$\boxed{\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0\,, \quad \frac{\partial\mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla\Phi - \nabla Q\,, \quad \nabla^2\Phi = 4\pi G\rho\,.}$$

Simulations

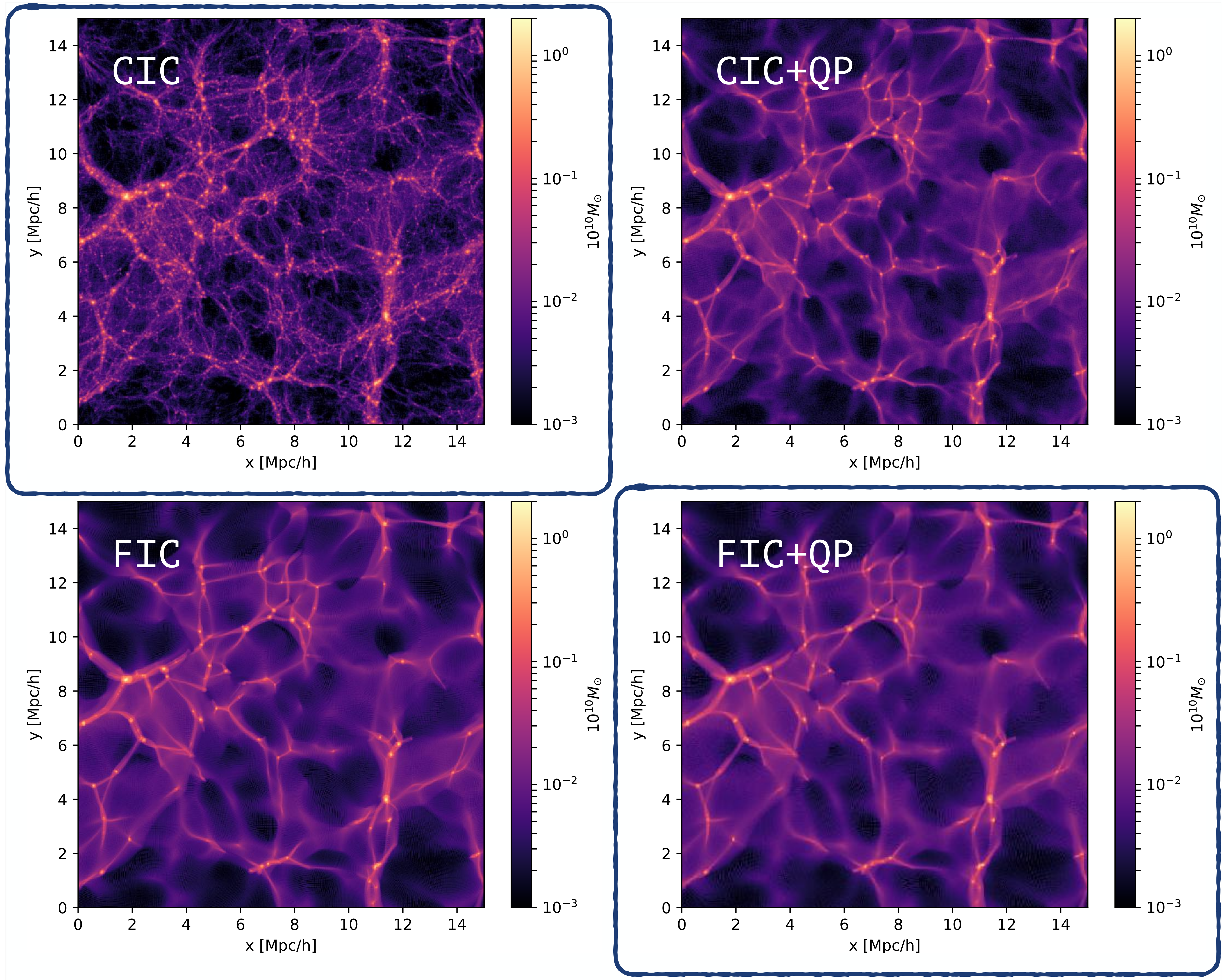


Figure 9. Density distribution of four simulations starting from standard initial conditions (*top*) or suppressed with AxionCAMB (*bottom*) and evolved with (*right*) or without (*left*) Quantum Potential effects.

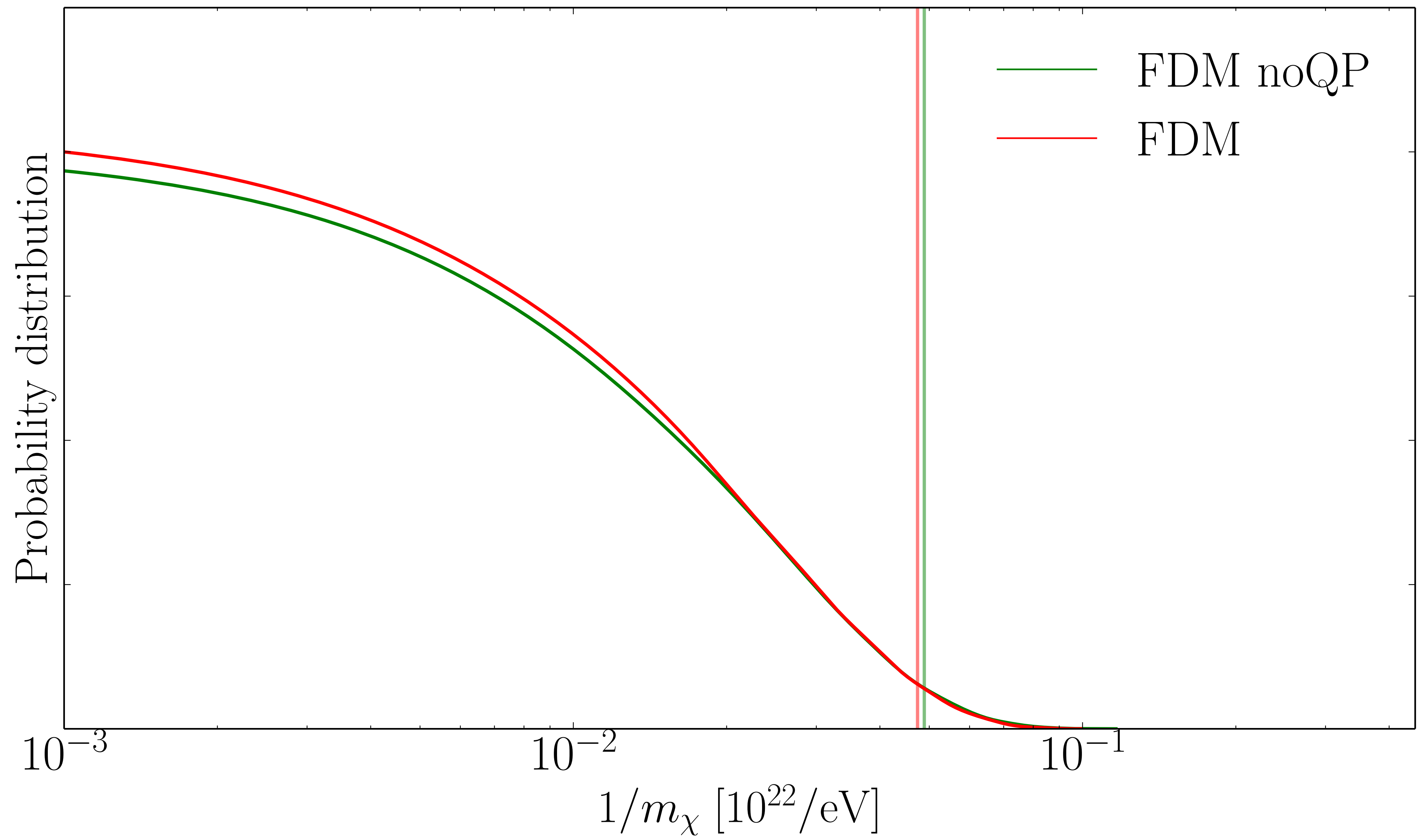
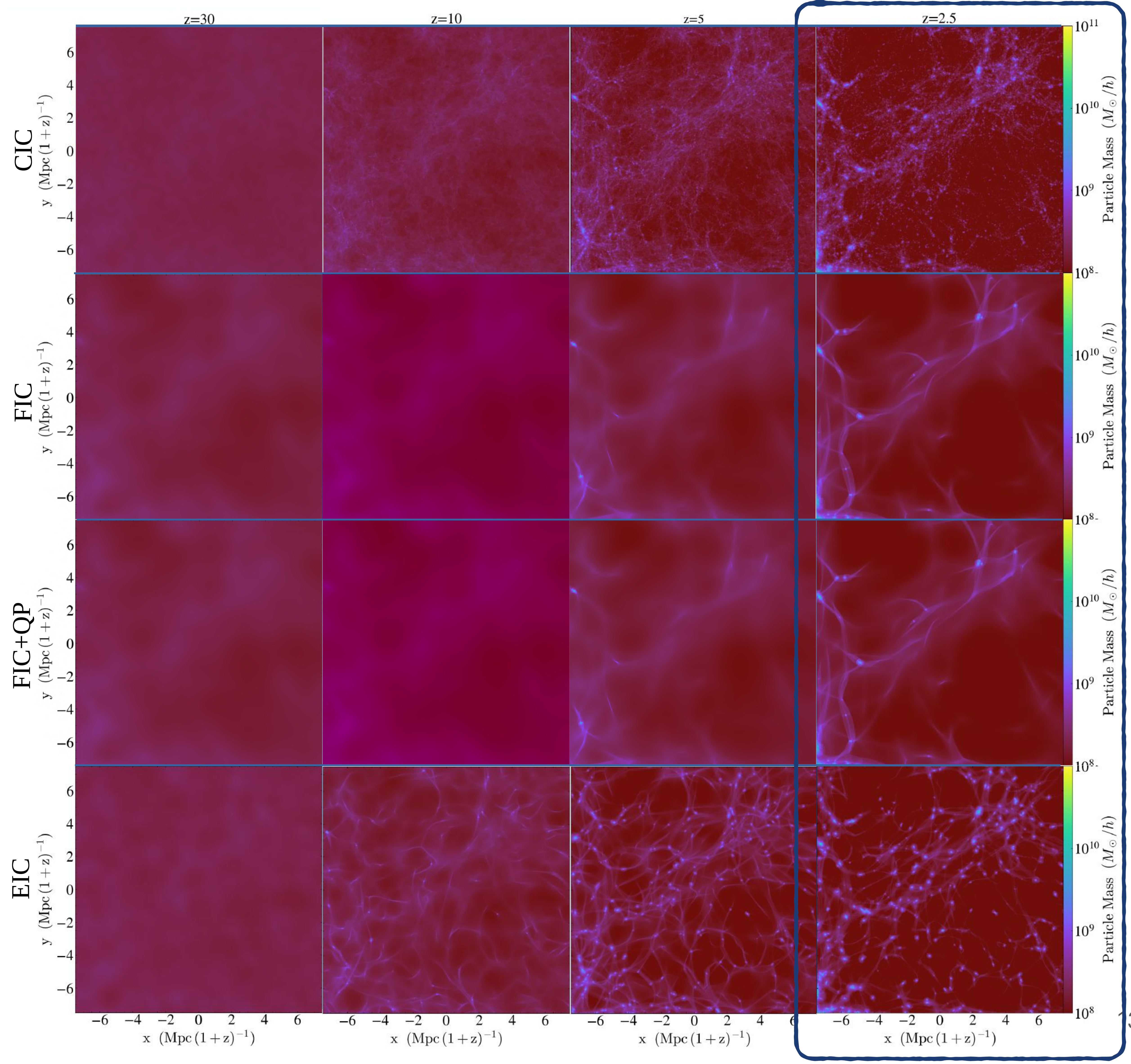


Figure 6. Here we plot the marginalised posterior distribution of $1/m_\chi$ from both the analyses performed by Iršič et al. (2017a) (green lines, without QP) and ours (red lines, with QP). The vertical lines stand for the 2σ C.L. limits.

$$m_a \gtrsim 2 \times 10^{-21}\,\mathrm{eV}/c^2\,(2\sigma\,\mathrm{CL})$$

Nori et al, MNRAS 482 (2019) 3227, arXiv:1809.09619
Nori, Baldi, MNRAS 478 (2018) 3935, arXiv:1801.08144

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

=

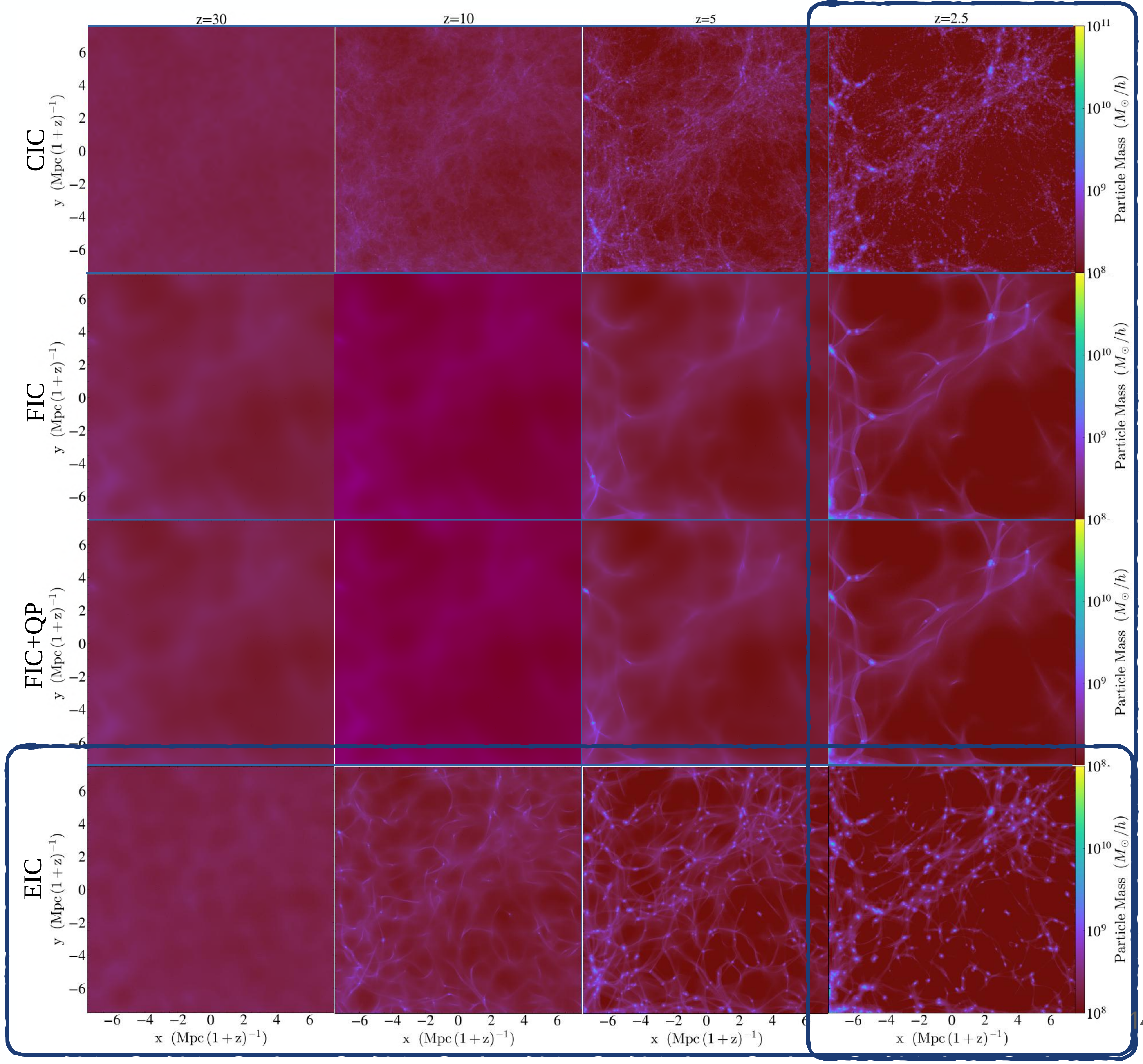
Standard CDM component + Modified gravity

MG-PICOLA

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

Medellín-González, González-Morales, U-L, PRD in press (2021), arXiv:2010.13998

Axion simulations via modified gravity



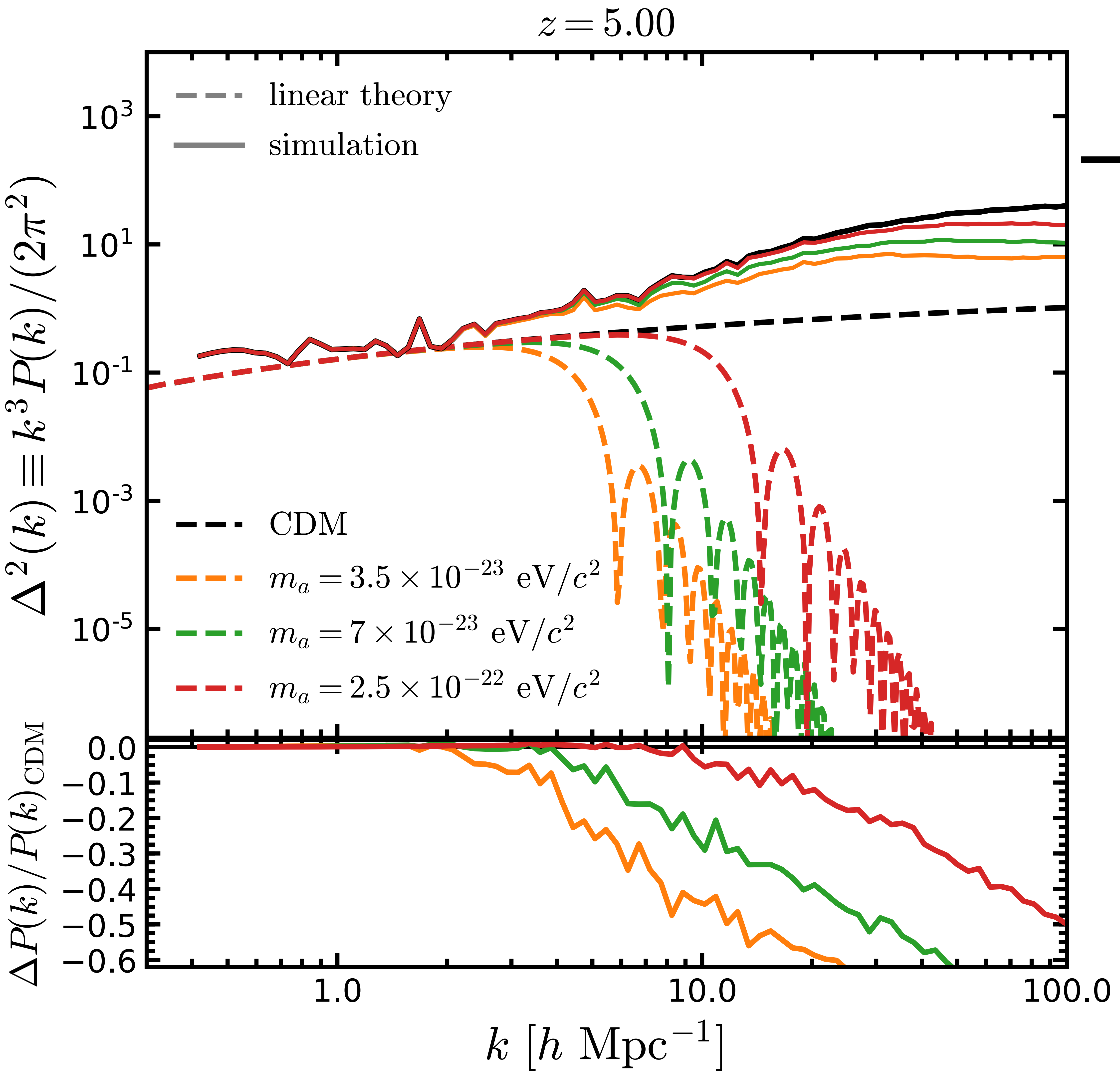
Ref.	m_a (eV/c^2)	Method	Box size (Mpc/h)	$N_{\rm part}$
May & Springel (2021) [28]	$3. \times 10^{-23}$, 7×10^{-23}	SP	10, 5	8640^3, 4320^3, 3072^3, 2048^3
Schwabe et al. (2020) [19]	10^{-22}	SP	$2h$	1024^3
Li et al. (2019) [29]	10^{-22}, 10^{-23}	SP vs SPH	20, 10, 3	1024^3
Mocz et al. (2018) [20]	10^{-22}, 10^{-21}	SP vs SPH	0.250	1024^3
Nori et al. (2018) [21]	10^{-22}	SPH	10, 15	256^3, 512^3
Zhang et al. (2018) [30]	10^{-22}	SPH	0.400	10^6
Woo & Chiueh (2009) [23]	10^{-22}	SP	1	1024^3

Type	Model	Initial conditions	m_a (eV/c^2)	$N_{\rm part}$	Box size (Mpc/h)
CIC	ΛCDM	CDM	$\cdots$	1024^3	15
FIC	ΛCDM	FDM	3×10^{-23}	1024^3	15
FIC + QP	ΛFDM	FDM	3×10^{-23}	1024^3	15
EIC + QP	ΛFDM	EFDM	3×10^{-23}	1024^3	15

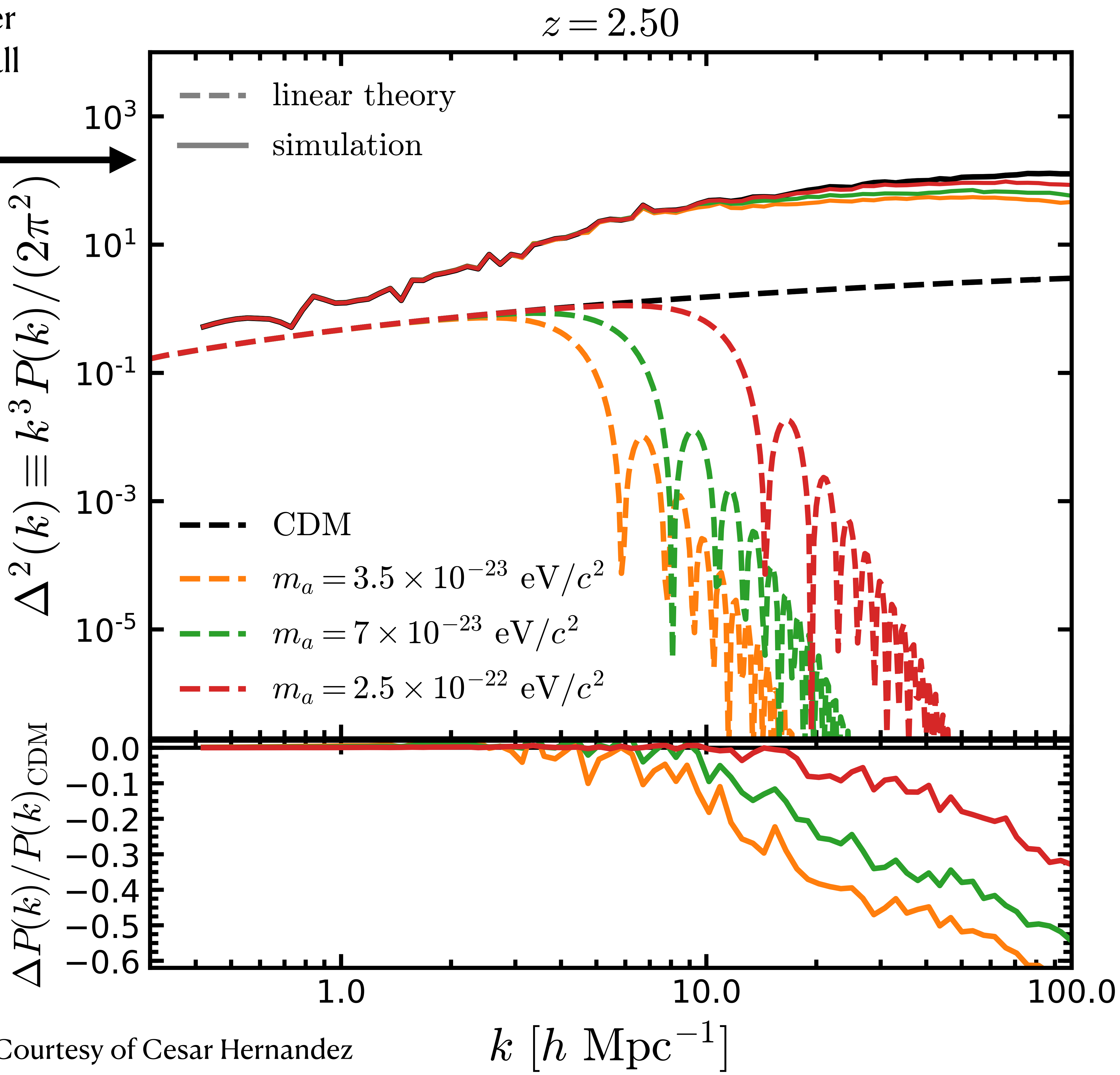
$\longleftarrow$ $f_a = 4.7 \times 10^{15}\,\mathrm{GeV}$

Medellín-González, González-Morales, U-L, PRD in press (2021), arXiv:2010.13998

Axion simulations via modified gravity



Transfer of power from large to small scales



Courtesy of Cesar Hernandez

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)

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

Medellín-González, González-Morales, U-L, PRD in press (2021), arXiv:2010.13998

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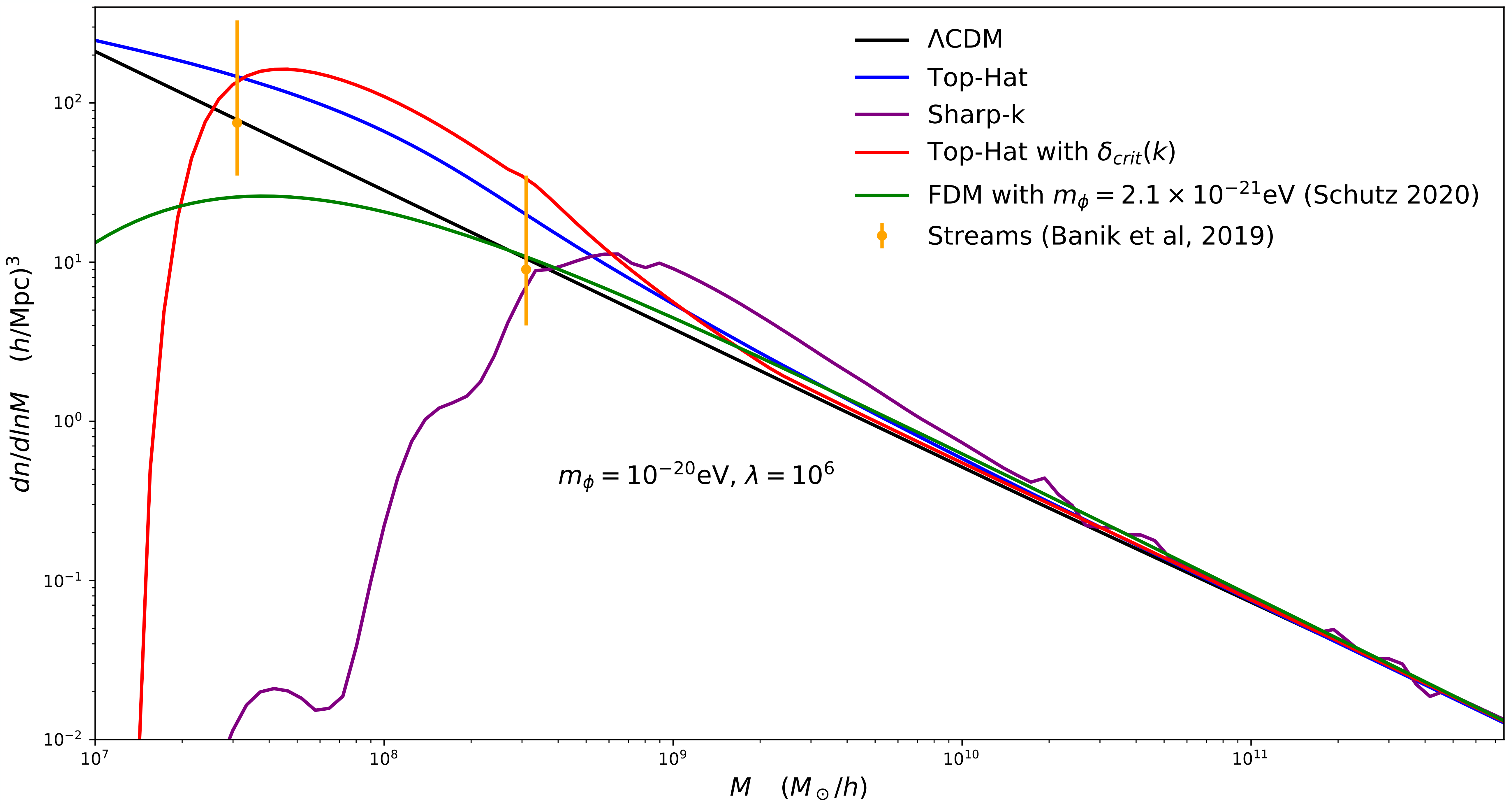
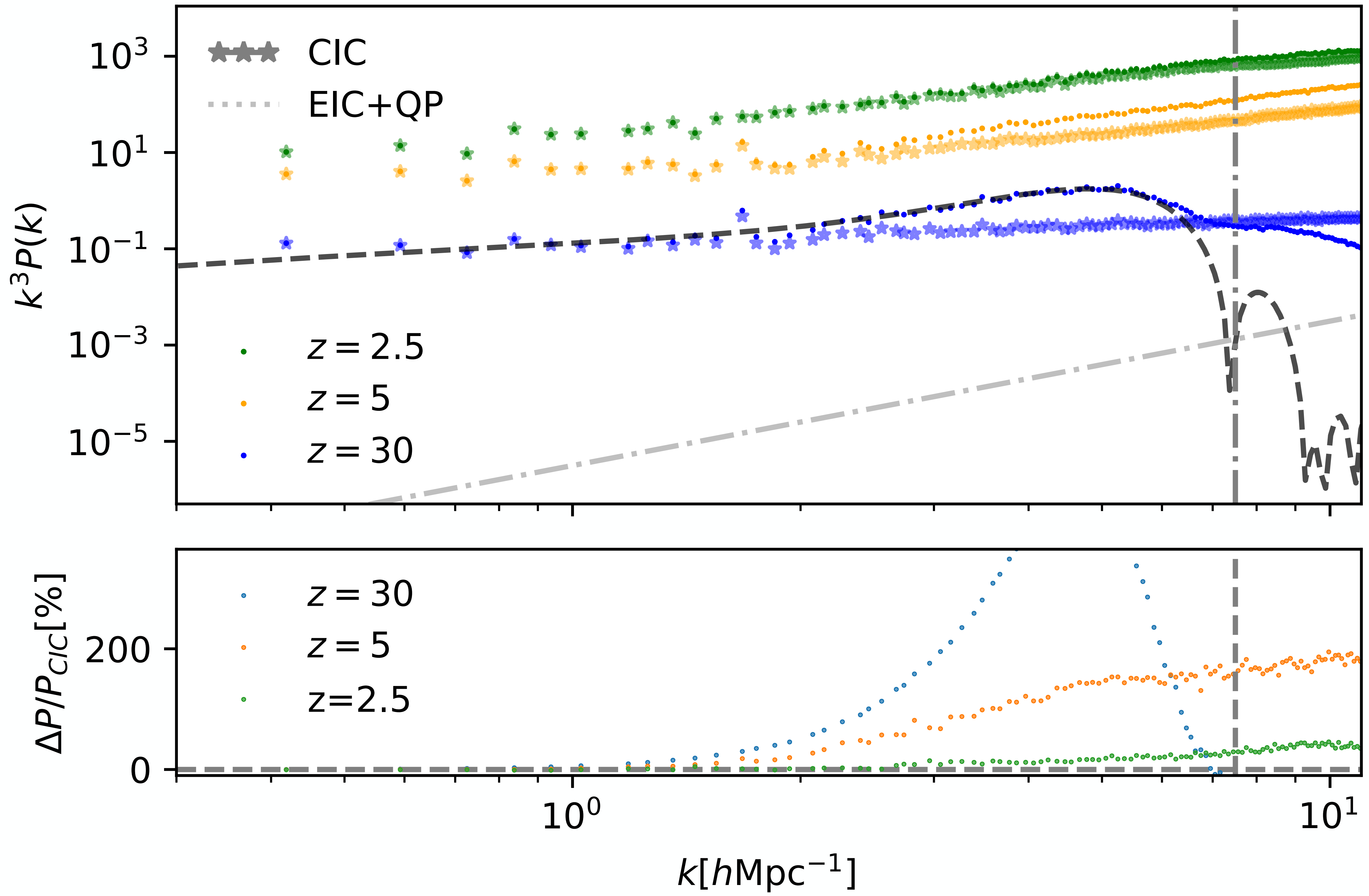




Stellar streams can also be another astrophysical probe

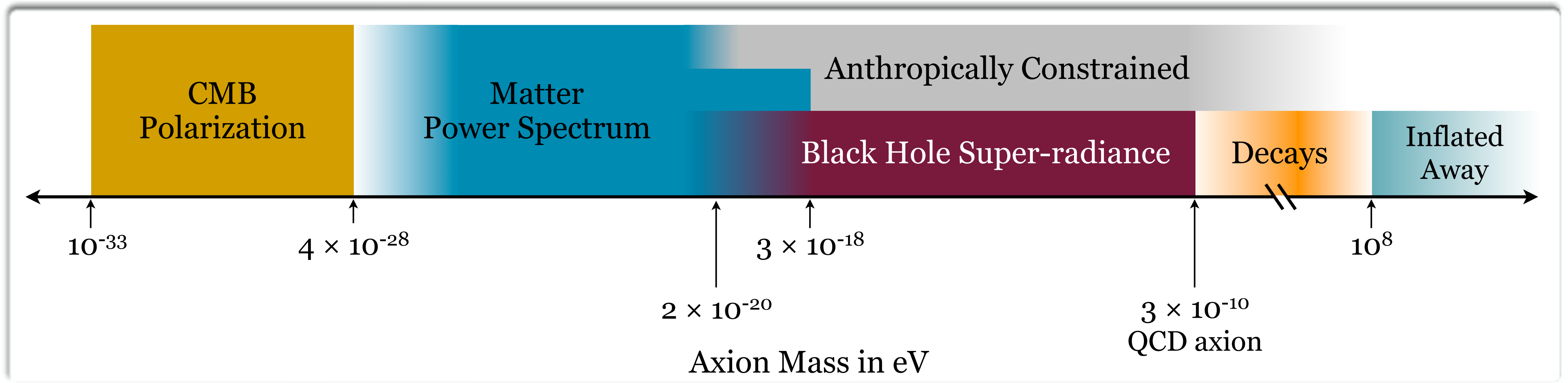
Medellín-González, González-Morales, U-L, PRD in press (2021), arXiv:2010.13998

Conclusions

- Work in progress …
- It's been under scrutiny for almost 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



Astro2020 Science White Paper: Gravitational probes of ultra-light axions
Grin et al, ArXiv 1904:09003

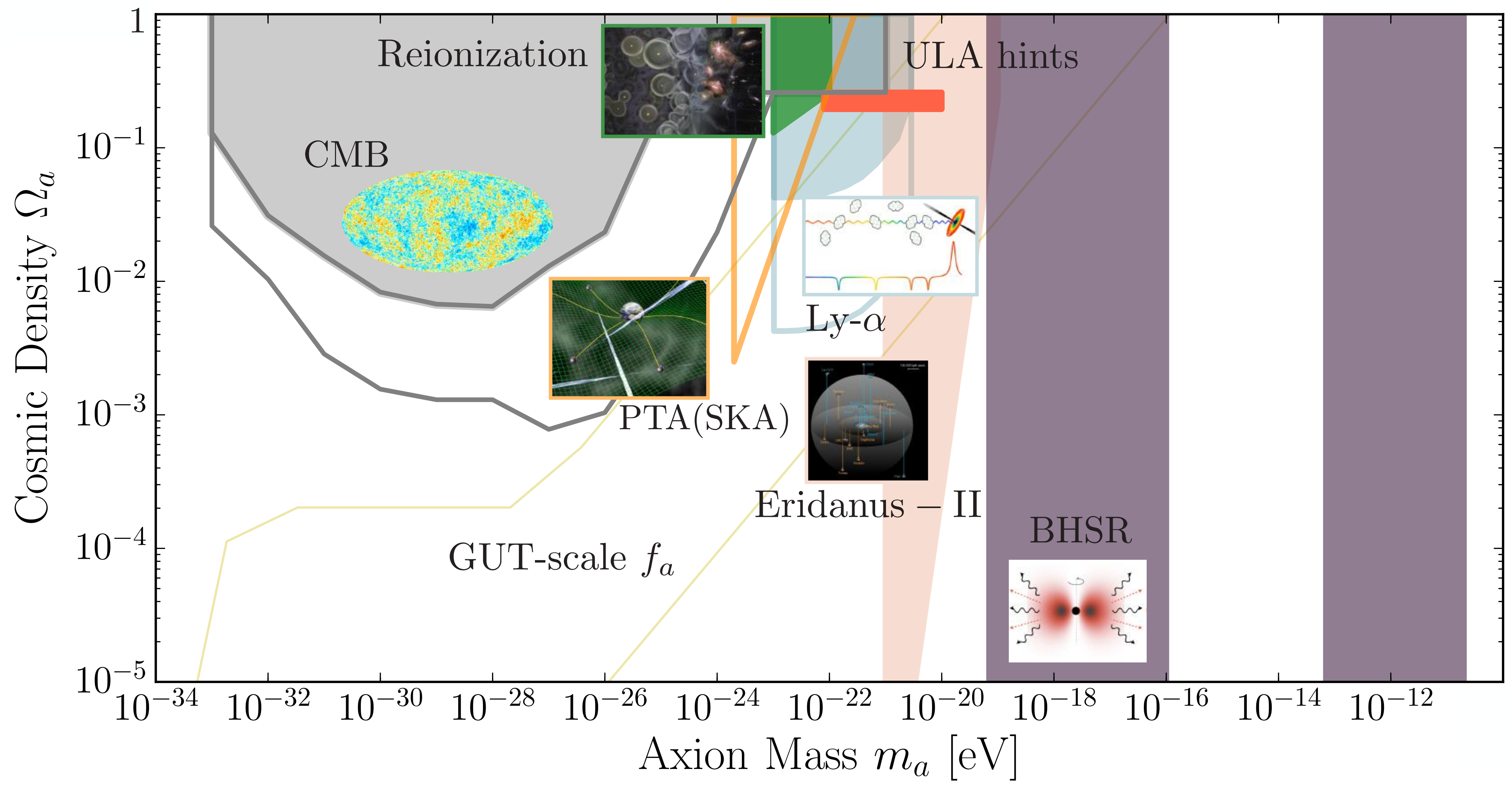


Figure 1. The cosmic window on ultralight axions, showing the reach of various astronomical probes. Shaded regions are currently excluded. Lines below them indicate the sensitivity of future experiments/surveys. ULA hints refers to the ULA mass scale suggested by MW-scale challenges. Local group schematic, *Credit: J. T. A. de Jong, Leiden University.* Planck CMB map, *Credit ESA, http://www.esa.int.* Black-hole super-radiance schematic [85] used with permission from American Physical Society, License RNP/19/MAR/012767. PTA Schematic *Image Credit: David Champion.* Lyman Alpha Schematic, *Image Credit: Ned Wright.* Reionization schematic used with permission from artist, J. F. Podevin, originally used in Ref. [86].

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¡Gracias! Thank you!