# ULTRA-LIGHT SCALAR FIELDS AS DARK MATTER

Ana A. Avilez-Lopez

CINVESTAV

Cinvestav

CONACYT
Consejo Nacional de Ciencia y Tecnología

# OUTLINE

Introduction: About the need of  dark matter

Astrophysical View: Ultra-light Scalar Field as Dark Matter

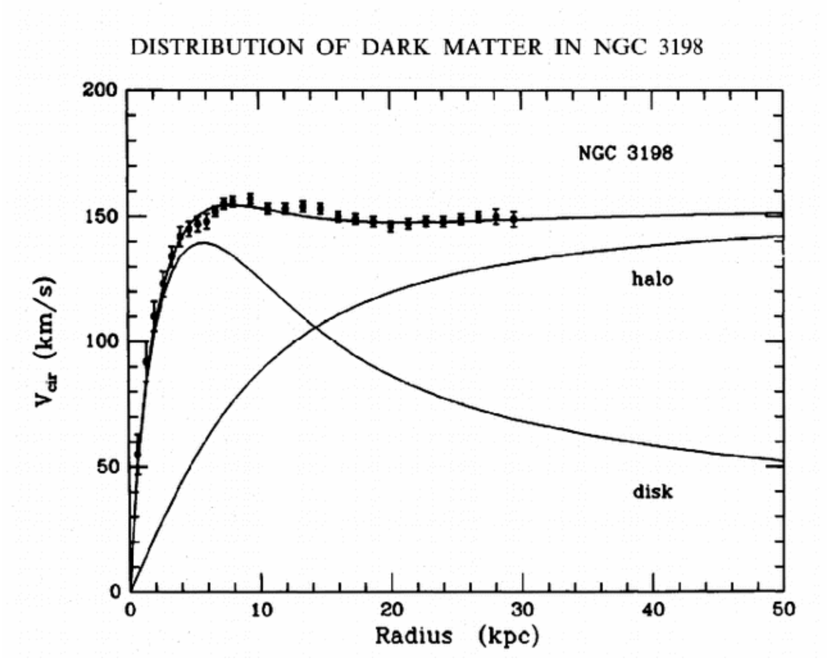
Axion-like fields and some Observational Signatures

Conclusions

# Why Dark Matter?

- At galactic scales…. pc-kpc
- GR + Barions (Standard Matter) fail to explain some phenomena like :

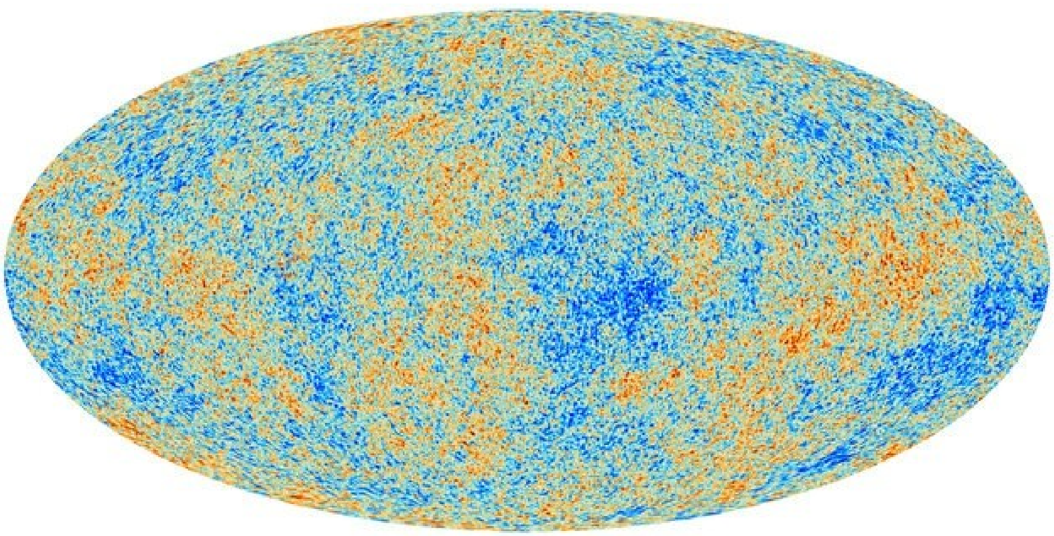
  rotation curves of stars in galaxies and the bullet cluster.

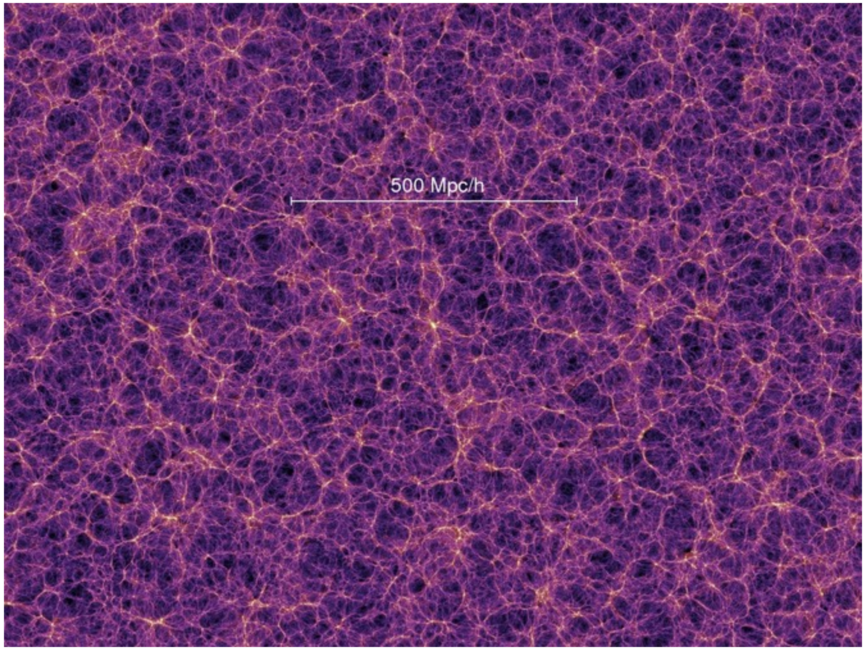


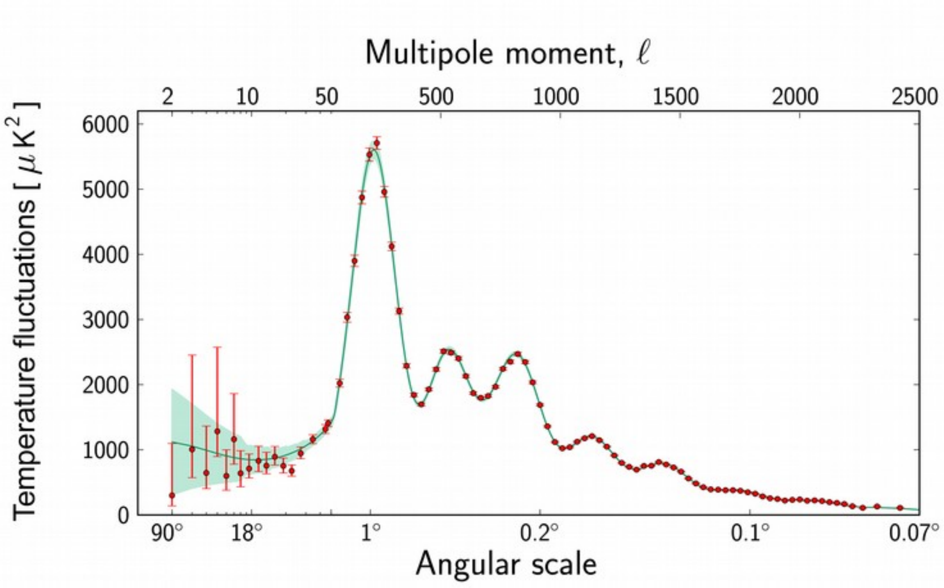

Cold Dark Matter: Weak Interacting Massive Particles

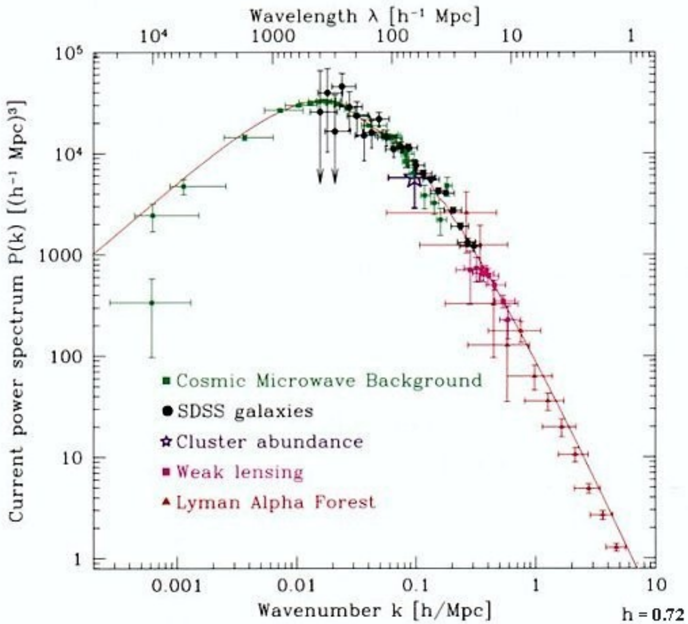
Large structures form by hierarchy.

# DARK MATTER AND THE STRUCTURE DISTRIBUTION





# MINIMAL COSMOLOGICAL MODEL

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

General Relativity + Cosmological Principle

LFRW $\longrightarrow$ $$ds^2 = -dt^2 + a(t)\left\{\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + sin^2\theta d\varphi^2)\right\}$$

Matter: Perfect Fluid $\longrightarrow$ $$T^{\mu}{}_{\nu} = diag\left\{\rho(t), -p(t), -p(t), -p(t)\right\}$$

Friedman equations

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

$$\ddot{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

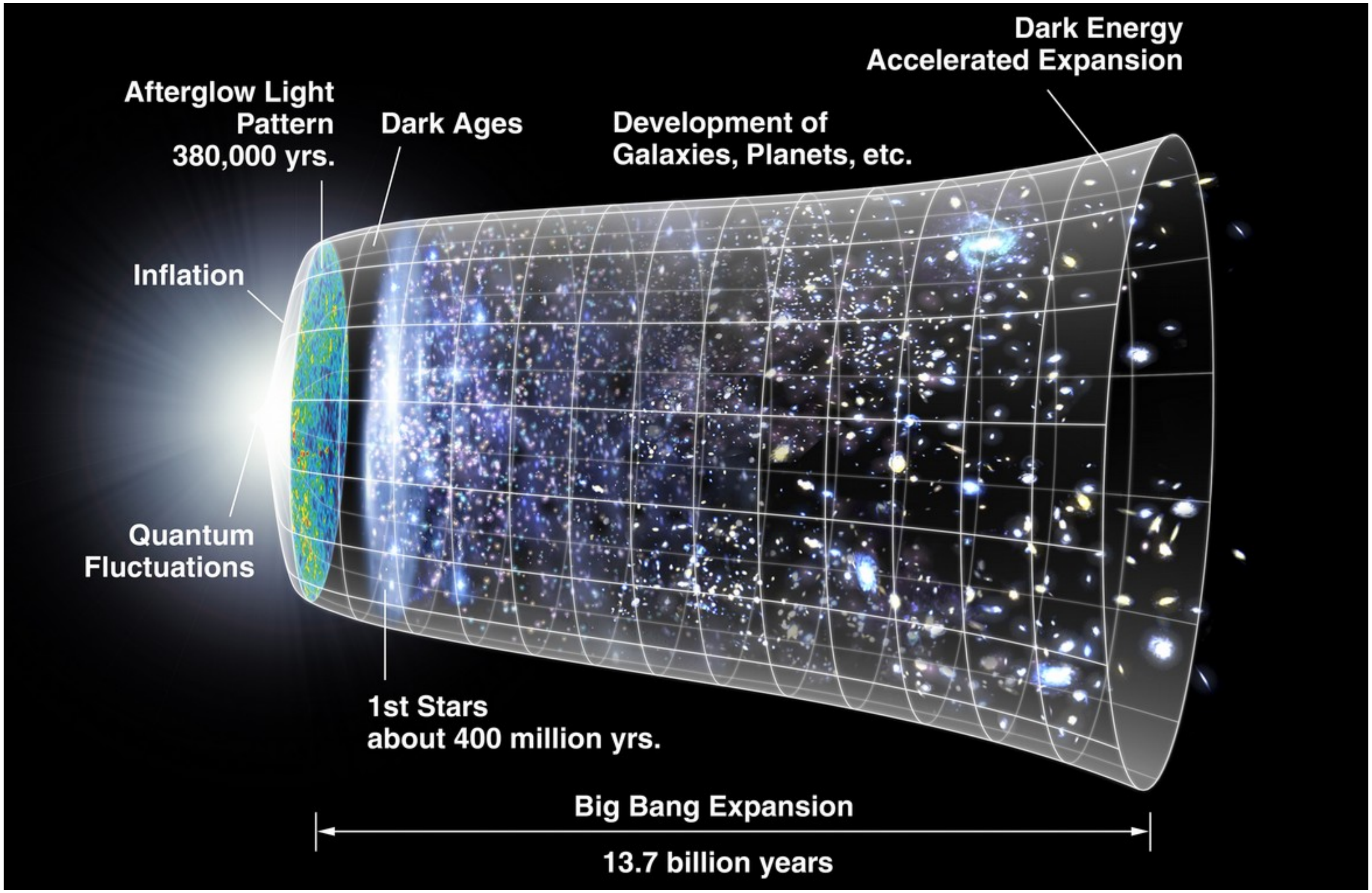
$H \equiv \frac{\dot{a}}{a}$ expansion rate

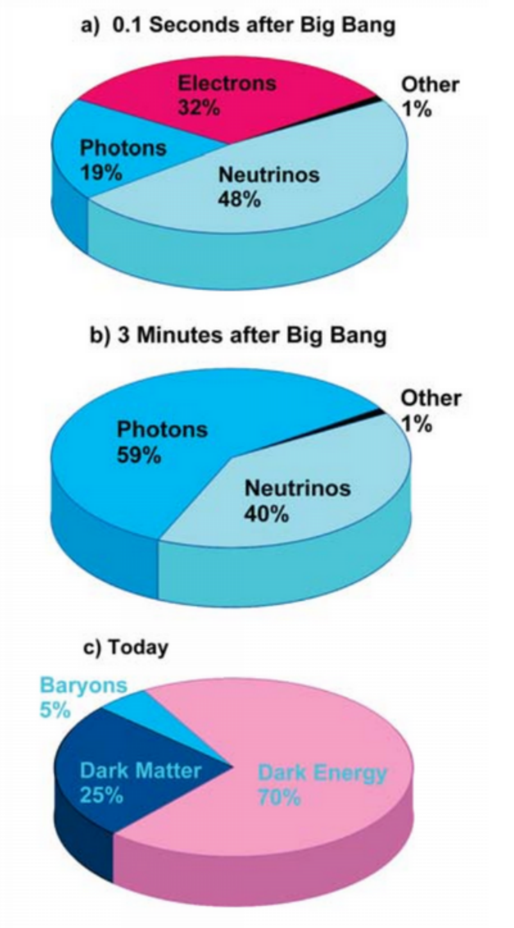
$k$: $> 0$ closed; $= 0$ flat; $< 0$ open

$T^{\mu\nu}{}_{;\nu} = 0$ $\Rightarrow$ $\rho \propto a^{-3(1+w)}$ $\quad w = p/\rho$

Various kinds of the cosmic fluids with different $w$

- radiation $\quad p_R = \rho_R/3 \quad w = 1/3 \quad \rho \propto a^{-4}$
- matter $\quad p_M = 0 \quad w = 0 \quad \rho \propto a^{-3}$
- vacuum $\quad p_\Lambda = -\rho_\Lambda \quad w = -1 \quad \rho \propto a^{0}$




Last observations from Planck:

-baryonic matter: ~ 5%
-dark matter: ~ 27%
-dark energy or Λ: ~ 68%.

# Some open questions about the Standard Cosmological Model

Coincidence

Cosmological Constant Problem

Cuspy central density profiles

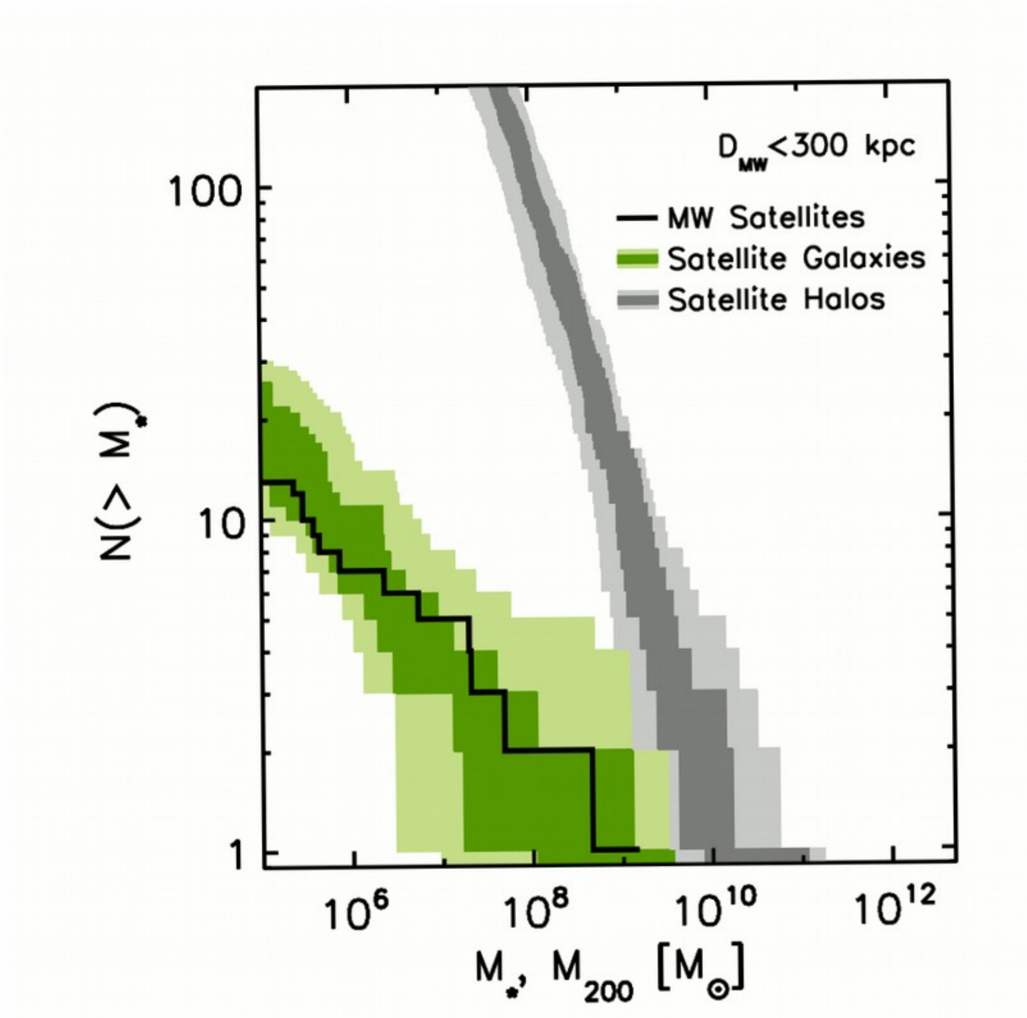
Missing Satellites Problem

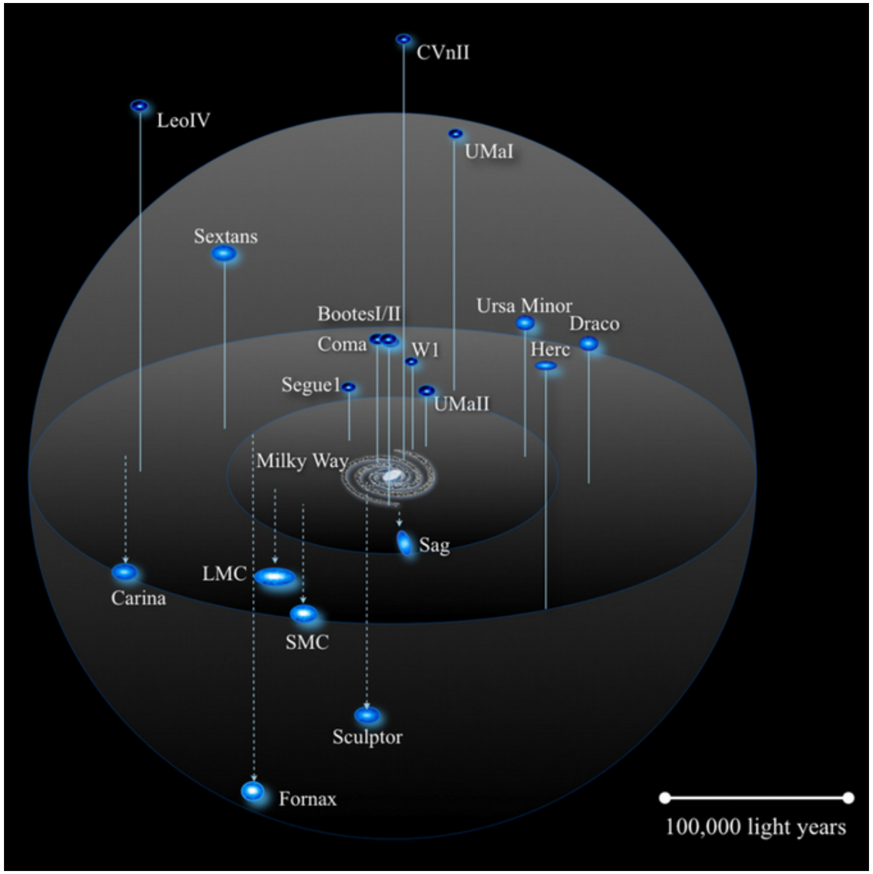
Voids are too empty

No-detection of DM

etc.

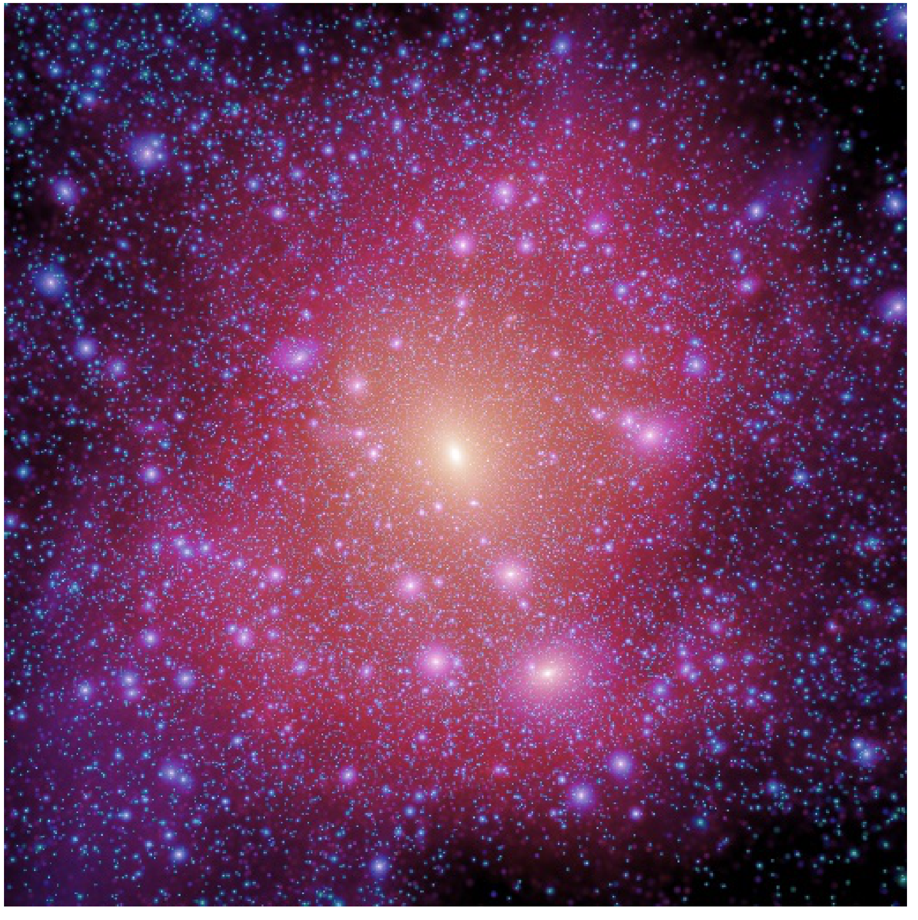
# MISSING SATELLITE PROBLEM

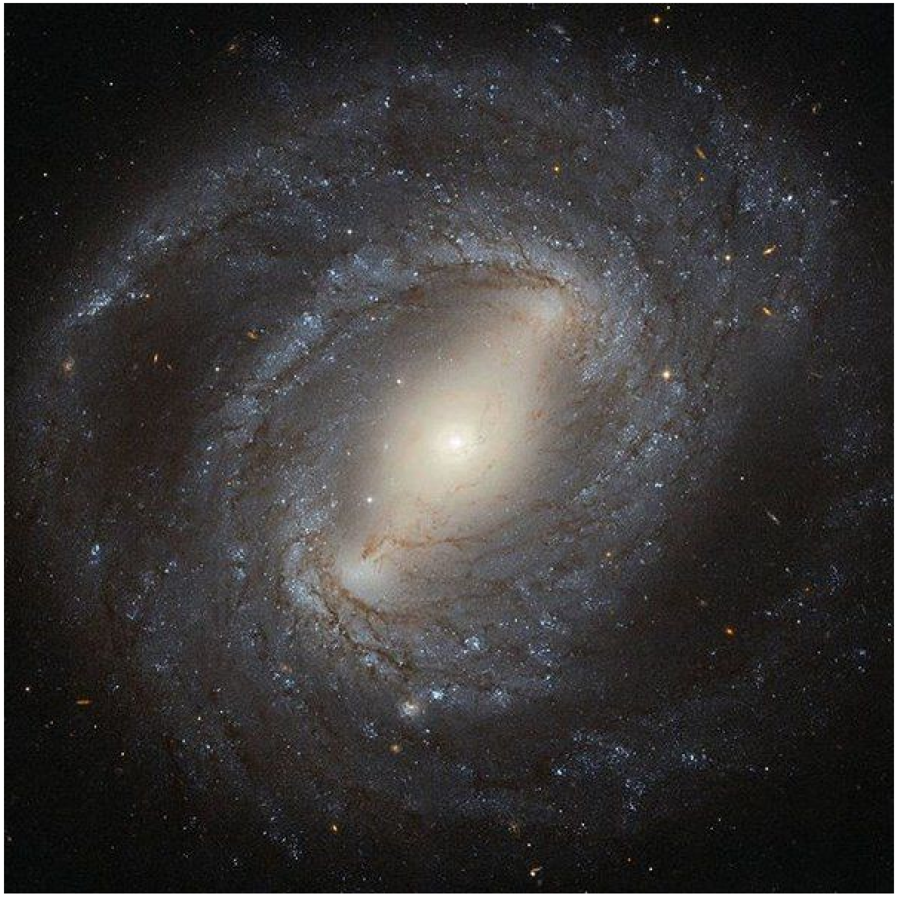



T. Sawala, C. Frenk, J. Navarro, S. Withe, et. al. MNRAS 457(2016)1931 arXiv:1511.01098

# CUSP-CORE PROBLEM

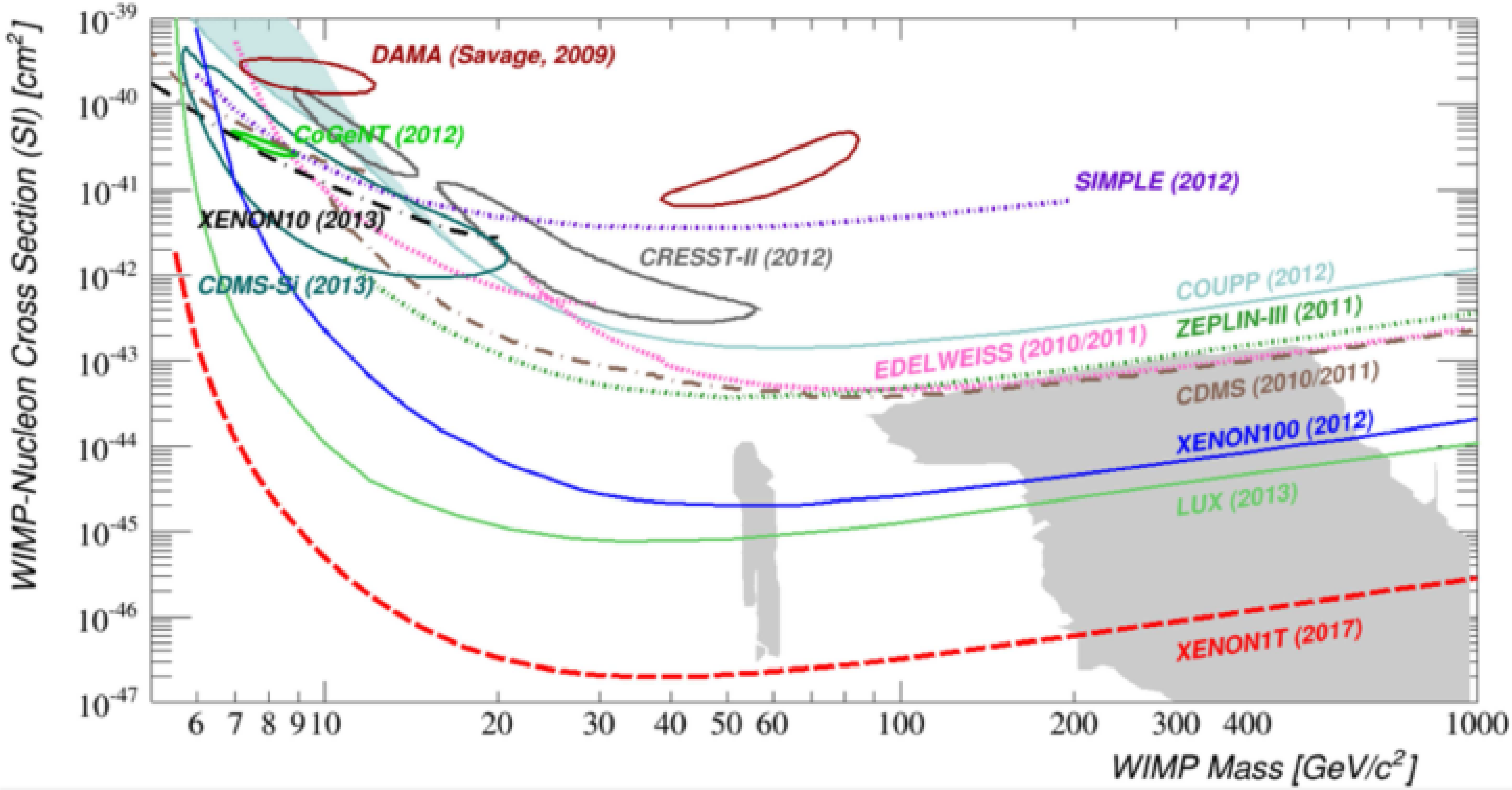




$\rho(r) \propto r^{-1}$

Usually adressed by barionic physics: feedback...however still a mistery how cored galaxies appear at high redshift.

# WIMPS DIRECT DETECTION



# THE MOST FAMOUS SCALAR FIELDS

- Most famous example: Higgs-boson, needed to give mass to particles via a spontaneous symmetry breaking
- QCD axions, helpful in modeling CP violations
- Most extensions of the Standard Model of Particles predict a plethora of scalar fields: axions, moduli, dilaton, …
- In condensed matter systems (such as superconductors, superfluid helium etc) scalar fields are widely observed, associated with any phase transition. People working in that subject normally refer to the scalar fields as `order parameters'.
- Popular in cosmology to model dark energy and dark matter.

*Higgs potential*

$$\lambda^2(\phi^2 - M^2)^2$$

*Chaotic inflation*

$$(1/2)m^2\phi^2$$

*Axion*

$$\Lambda[1 - \cos(\phi/f_a)]$$

*Quintessence*

$$V_0 e^{-\lambda\phi/m_{\rm Pl}}$$

# ULTRA-LIGHT SCALAR-FIELD DARK MATTER (SFDM)

Dark matter haloes: Self-gravitating configurations of ultralight bosons (excitations of an effective scalar field) all laying at the ground state

**suppress small-scale clustering**

$$\nabla_\mu \nabla^\mu \Phi = \frac{dV}{d\Phi}$$

$$G_{\mu\nu} = 4\pi G (T^{\Phi}_{\mu\nu} + T^{m}_{\mu\nu})$$

$$V(\Phi) = \frac{m^2}{2}|\Phi|^2 + \frac{\lambda}{4}(|\Phi|^2)^2$$

m ~ $10^{-22}$ eV

$$i\frac{\partial \Phi}{\partial t} = \left(-\frac{1}{2m}\nabla^2 + m\Psi + \lambda|\Phi|^2\right)\Phi$$

$$\nabla^2\Psi = 4\pi\Phi\Phi^*$$

Non-relativistic limit

Schroedinger-Poisson Classical Solutions

↕

Gross-Pitaevskii Order Parameter:
Number of particles

| | |
|---|---|
| SFDM: | Matos y Guzman (2000), Ureña y Matos (2001) |
| Fuzzy DM: | Hu et al. (2000) |
| Wave DM: | Bray (2010); Schive et al. (2014), |
| Bose-Einstein Condensate DM: | Bohmer and Harko (2007) |
| Ultra-light Axion DM: | Marsh and Ferreira (2010) .... Hui, Ostriker, Tremaine y Witten (2016) |

# THE ULTRA-LIGHT SFDM AS A SUPER-FLUID

At galactic scales, relevant after condensation, all the bosons in the system lay in the ground state and then the macroscopic state of the system is described by the classical solution.

$$\nabla_\mu \nabla^\mu \Phi = \frac{dV}{d\Phi}$$
$$G_{\mu\nu} = 4\pi G (T^{\Phi}_{\mu\nu} + T^{m}_{\mu\nu})$$
$$V(\Phi) = \frac{m^2}{2}|\Phi|^2 + \frac{\lambda}{4}(|\Phi|^2)^2$$

$$\Phi(t,\mathbf{x}) = \Psi(t,\mathbf{x}) e^{-imt},$$

And weak gravity limit!

$$i\frac{\partial \Psi}{\partial t} - \frac{1}{2m}\nabla^2\Psi - \phi_g \Psi - \Lambda |\Psi|^2 \Psi = 0$$
$$\nabla^2 \phi_g = \kappa^2 \Psi \Psi^*$$

Schroedinger-Poisson
Gross-Pitaevskii system

$$\Psi = \sqrt{\hat{\rho}}\, \mathrm{e}^{\mathrm{i}S}. \qquad \boldsymbol{v} \equiv \frac{\hbar}{m}\boldsymbol{\nabla} S$$

$$\dot{\hat{\rho}} + \boldsymbol{\nabla}\cdot(\hat{\rho}\boldsymbol{v}) - \frac{\hbar}{m}(\hat{\rho}\dot{S}) = 0, \tag{9a}$$

$$\dot{\boldsymbol{v}} + (\boldsymbol{v}\cdot\boldsymbol{\nabla})\boldsymbol{v} = -\boldsymbol{\nabla}\phi + \frac{3\lambda}{2m^2}\boldsymbol{\nabla}\hat{\rho} + \frac{\hbar^2}{2m^2}\boldsymbol{\nabla}\left(\frac{\nabla^2\sqrt{\hat{\rho}}}{\sqrt{\hat{\rho}}}\right) + \frac{\hbar}{m}\dot{\boldsymbol{v}}\dot{\boldsymbol{S}} - \frac{\hbar^2}{2m^2}\boldsymbol{\nabla}\left(\frac{\partial_t^2\sqrt{\hat{\rho}}}{\sqrt{\hat{\rho}}}\right) + \frac{\lambda k_B^2}{4m^2} T\boldsymbol{\nabla} T \tag{9b}$$

$$\hat{\rho}\dot{\boldsymbol{v}} + \hat{\rho}(\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = \hat{\rho}\boldsymbol{F}_\phi - \boldsymbol{\nabla}p + \hat{\rho}\boldsymbol{F}_Q + \boldsymbol{\nabla}\cdot\sigma,$$

$$\boldsymbol{F}_\phi = -\boldsymbol{\nabla}\phi \qquad \boldsymbol{F}_Q = -\boldsymbol{\nabla}U_Q$$

$$p = w\hat{\rho}^2, \qquad U_Q = -\frac{\hbar^2}{2m^2}\left(\frac{\nabla^2\sqrt{\hat{\rho}}}{\sqrt{\hat{\rho}}}\right),$$

# BACKGROUND COSMOLOGY

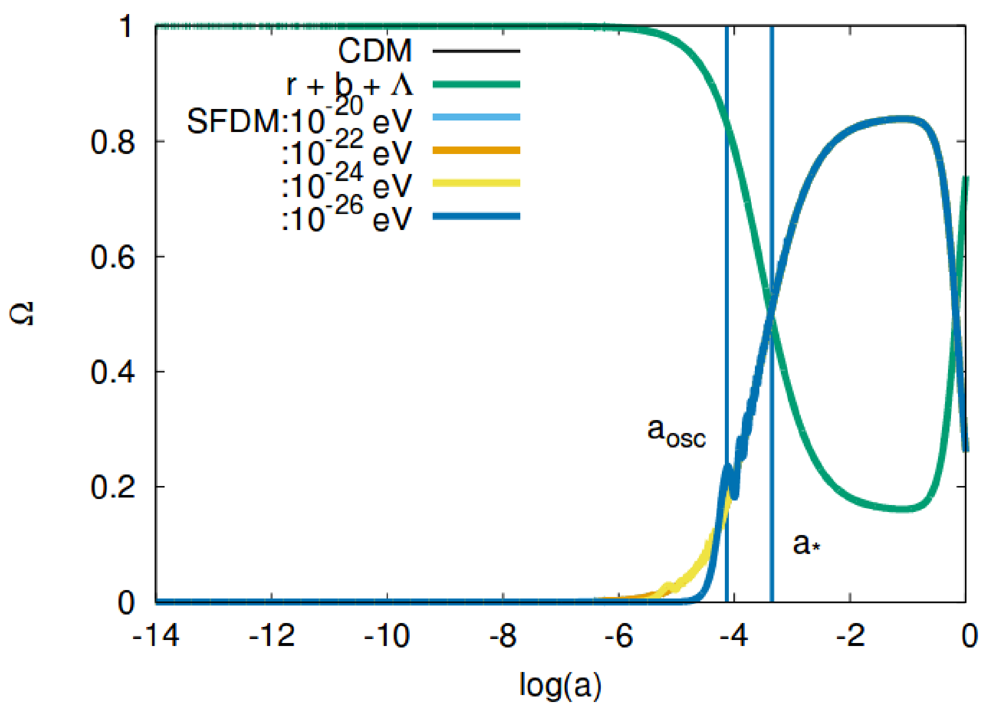
$H \gtrsim m$ — The scalar is almost constant until the Z2 (or U(1)) symmetry is broken.

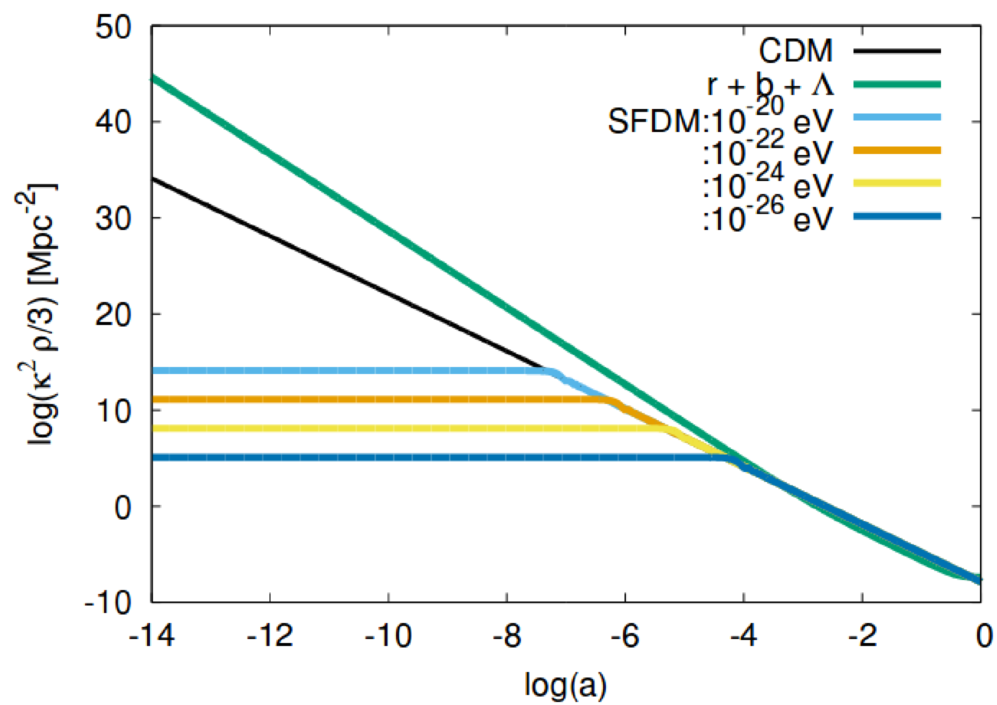
Afterwards...it starts oscillating at

$H \sim m$ — $T_0 \sim (m\,M_{\rm Pl})^{1/2} \sim 500$ eV. redshift $\sim 2 \times 10^6$

after nucleosynthesis

PRD 95, 043541 (2017). arXiv:1610.08297

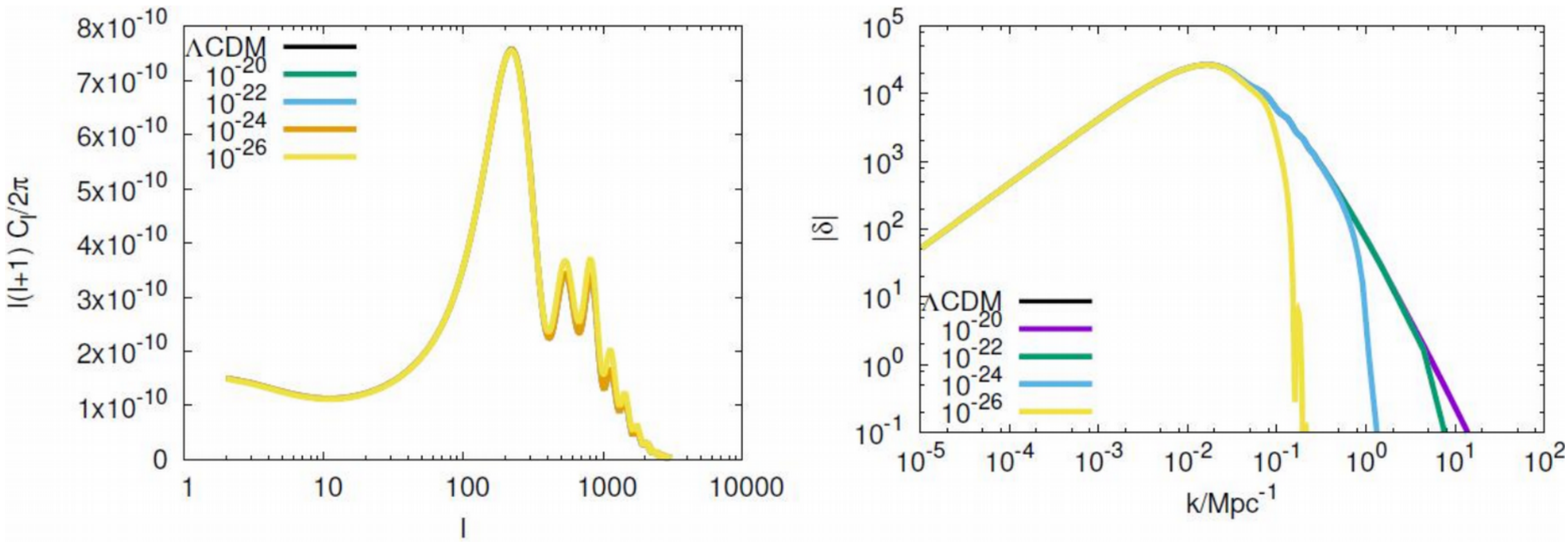



L. Arturo Ureña-López[a] and Alma X. Gonzalez-Morales[a,b] arXiv:1511.08195v2 [astro-ph.CO]

- SFDM density evolution: early times → dark energy, late times → dust

# LINEAR PERTURBATIONS




- For m~ 10^{-22} eV the CMB power spectrum is reproduced
- The matter power spectrum has a natural cut al small scales
- Heavier fields fail to reproduce observations.
- Non-linear regime → requires numerical simulations

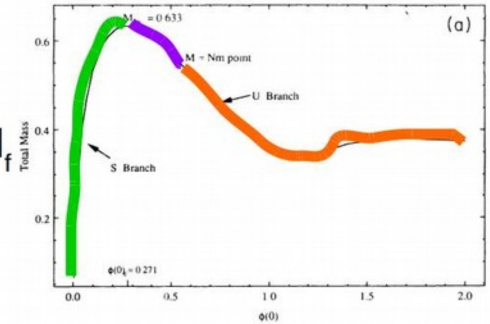
# STABILITY CONDITIONS OF SFDM SOLUTIONS

Numerical Simulations outcomes

Initial $M_i$

BSSN

$M_f$




$$M_{\rm crit} = 0.633\frac{m_{\rm Pl}^2}{m}.$$

$$m \sim 1GeV \quad \rightarrow \quad M_{\rm crit} \sim 10^{-19} M_\odot$$

$$m \sim 10^{-22} eV \quad \rightarrow \quad \sim 10^{12} M_\odot$$

Stable

$E=M_f-Nm$

Disperssive $E<0$

SFDM stable bound configurations up to Mcrit

Larger structure form by hierarchy

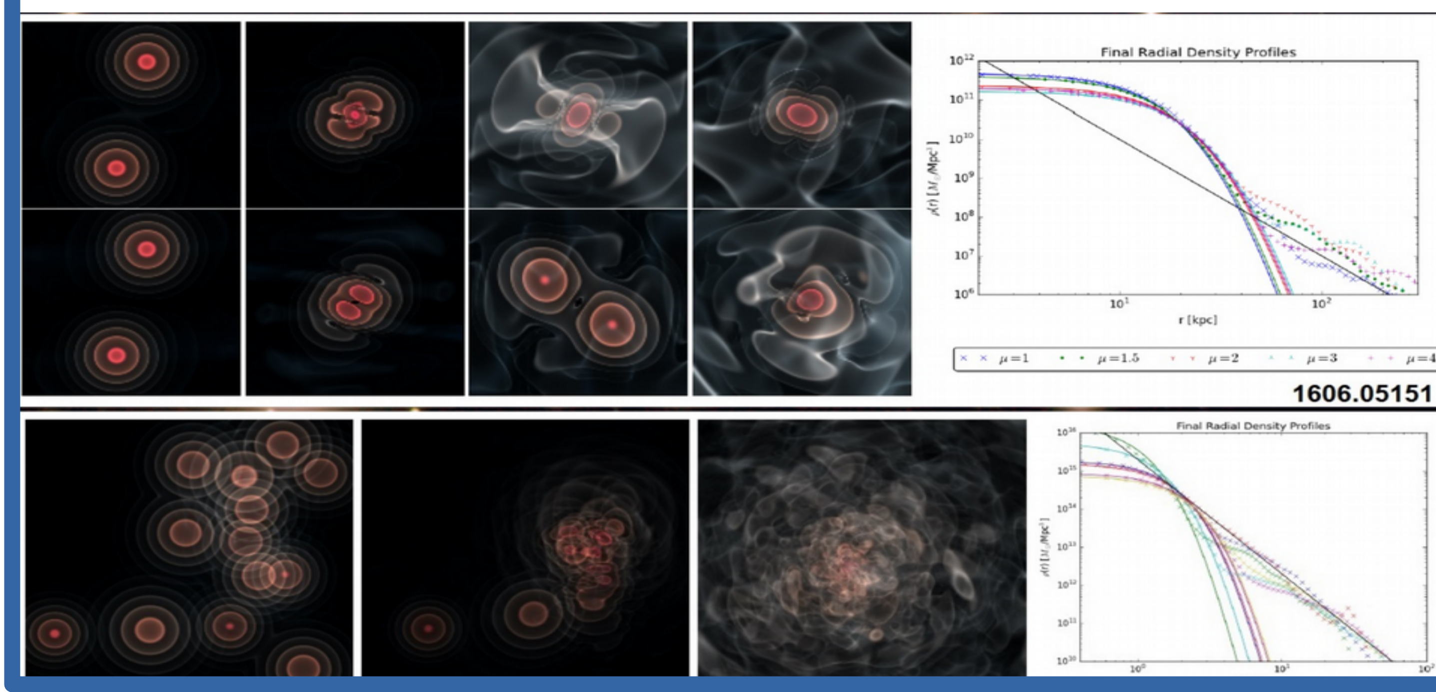
$M_i > M_f$ — Migrating

$M_i < M_f$ — Collapsing

$E>0$

# NON-LINEAL STRUCTURE FORMATION

- Newtonian- Regime Schroedinger-Poisson system
- Numerical Simulations: mergers of initially spheric BECS




1606.05151

$$\rho_{\mathrm{FDM}}(r) = \begin{cases} \rho_{\mathrm{soliton}}(r) = \frac{\rho_c}{[1+0.091(r/r_c)^2} \\ \rho_{\mathrm{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}, \end{cases}$$

NATURAL CORES WITHOUT FEEDBACK!

NFW tail due to interactions

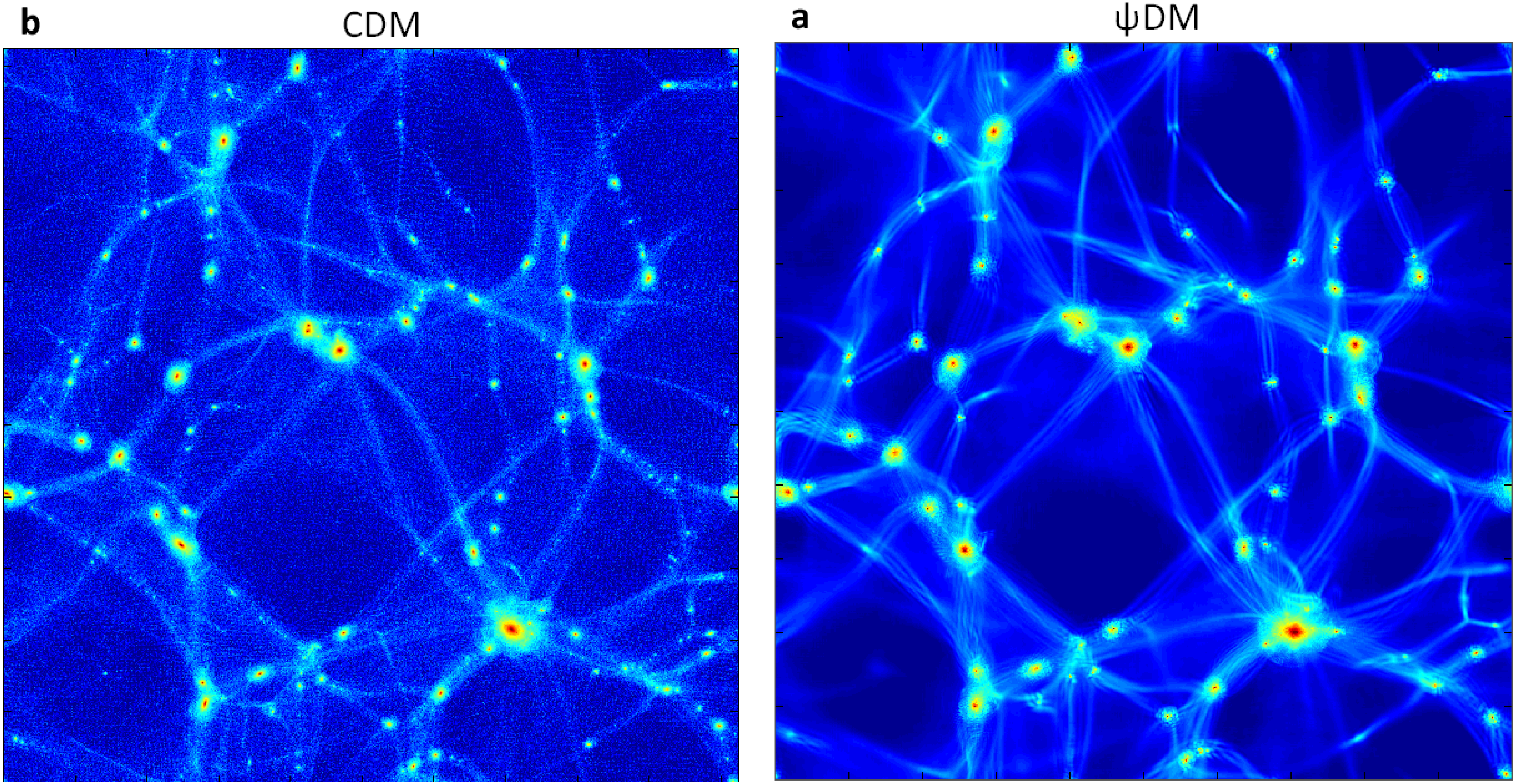
**Simulations of solitonic core mergers in ultra-light axion dark matter cosmologies**


Bodo Schwabe, Jens C. Niemeyer, and Jan F. Engels
*Institut für Astrophysik*
*Universität Göttingen*

(Dated: January 3, 2017)

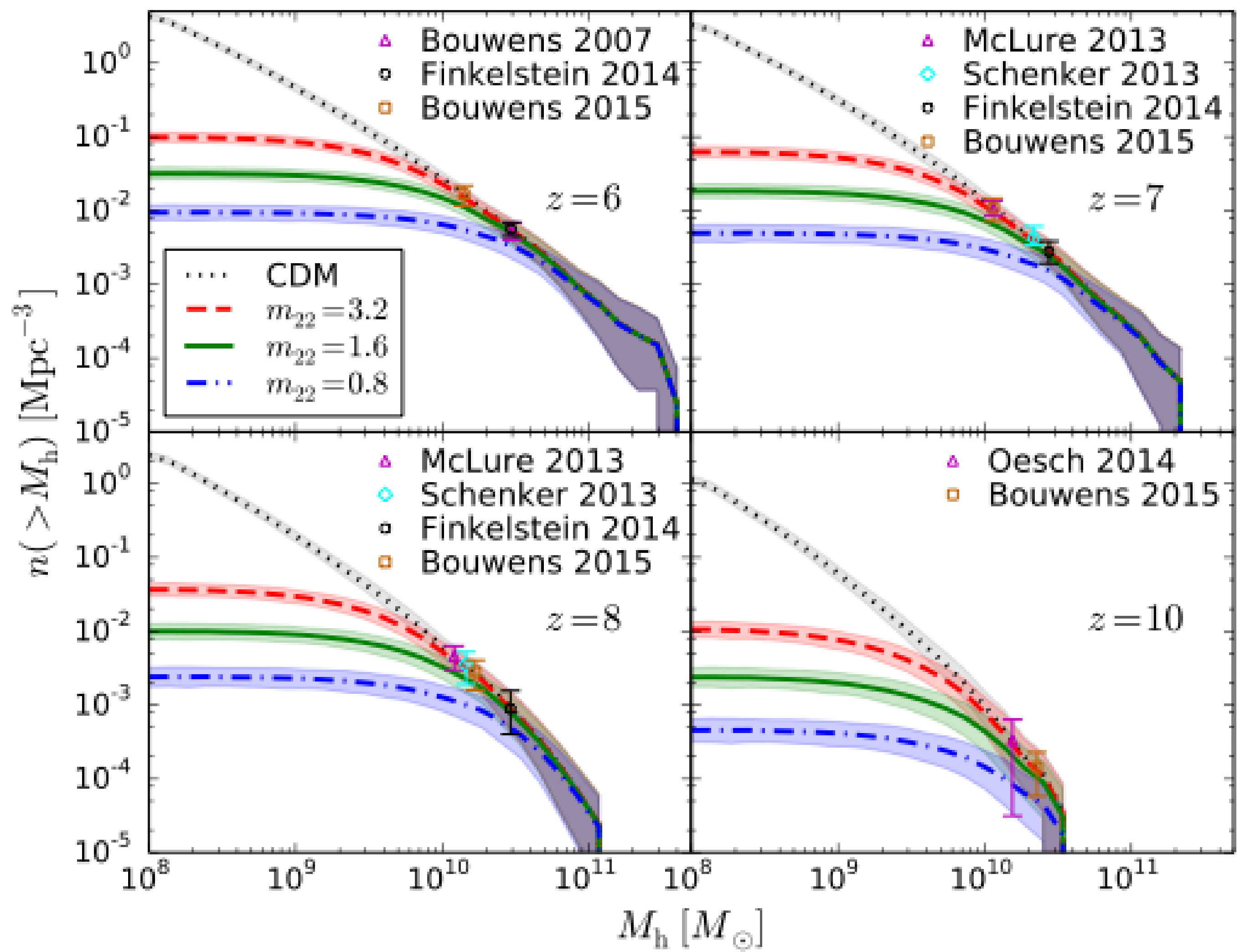
# LARGE SCALE STRUCTURE FORMATION

Hsi-Yu Schive[1], Tzihong Chiueh[1,2]* and Tom Broadhurst[3,4]



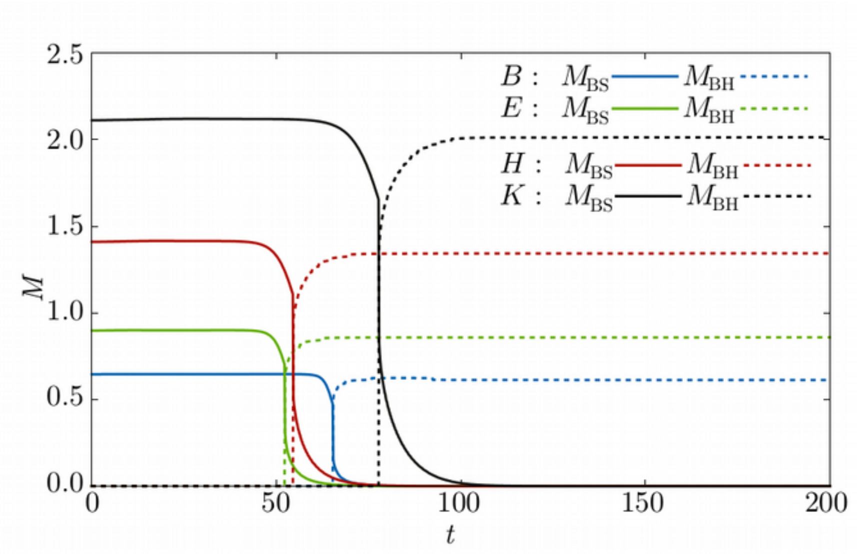
# NOT MISSING SATELLITES

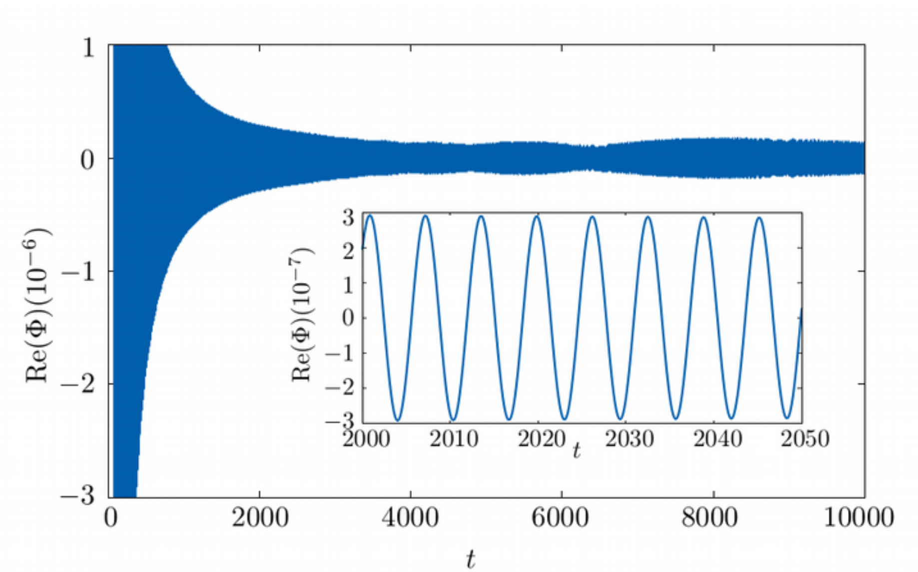
Hsi-Yu Schive, Tzihong Chiueh, Tom Broadhurst, & Kuan-Wei Huang. ApJ 818,(2016),89

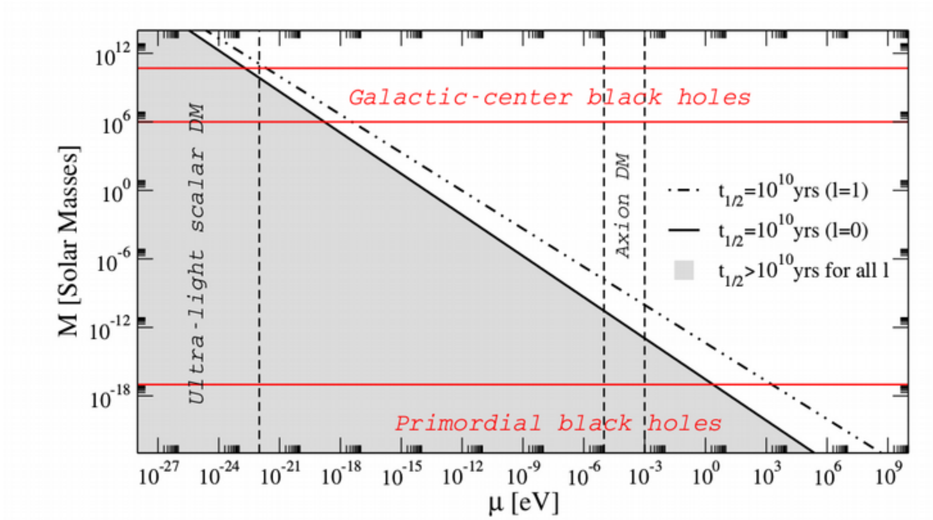


# SFDM CONFIGURATIONS AROUND SUPERMASSIVE BLACK HOLES

- No-Hair Theorems: forbid stable scalar solutions around BH
- Barranco et. al 2012; Herdeiro et al. 2014; Escorihuela 2017.
- Spherically symmetric unstable (quasi-resonant) and longlasting solutions



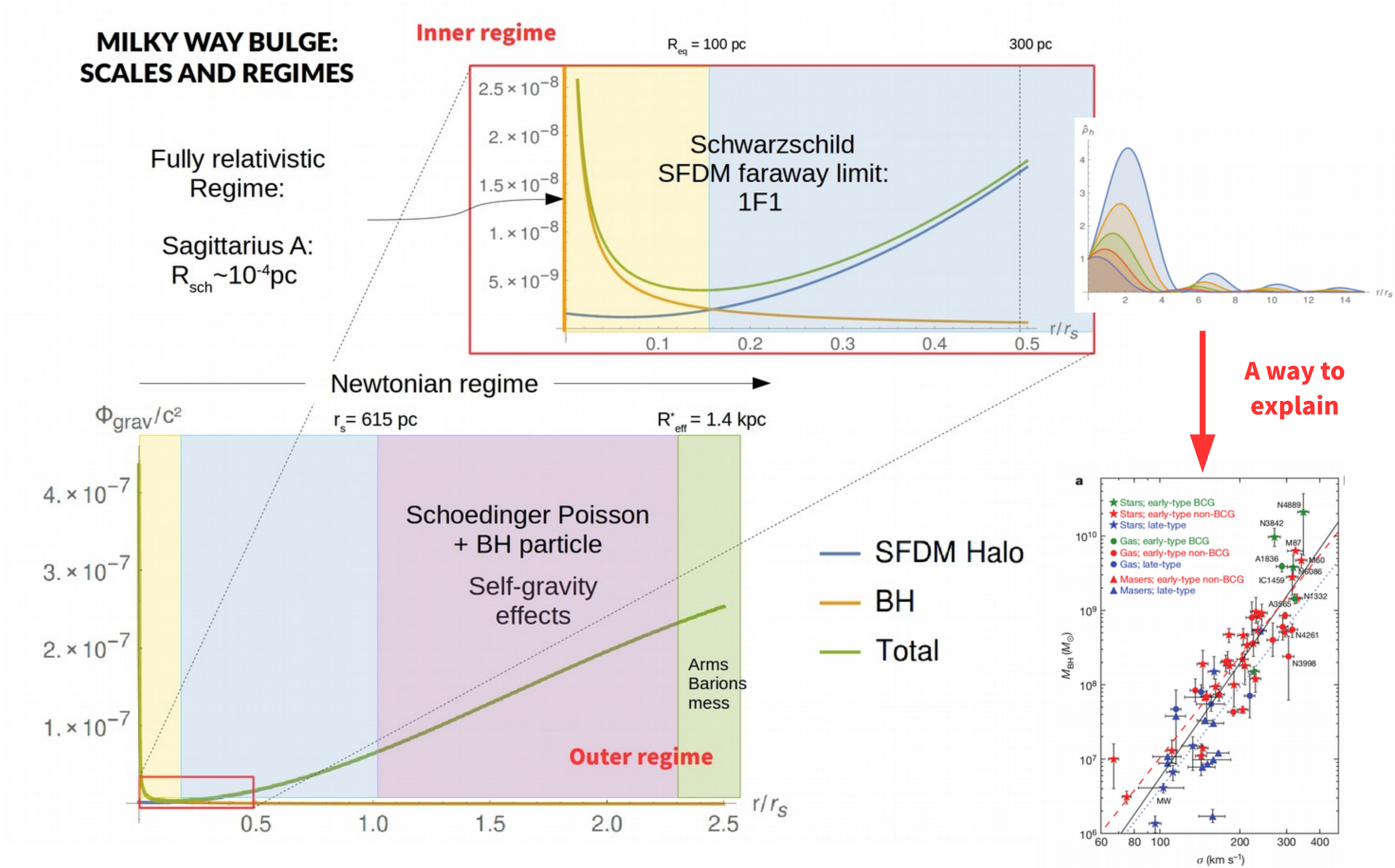




All this is OK
for
Boson Stars.

# On the Possibility that Ultra-Light Boson haloes host and form Super-massive Black Holes

arXiv:1704.07314v1 [gr-qc]

Ana A. Avilez[1],* Luis E. Padilla[1],† Tula Bernal[2]‡ and Tonatiuh Matos[1]§ ¶
1 Departamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, AP 14-740, Ciudad de México 07000, México
2 Instituto Nacional de Investigaciones Nucleares, Departamento de Física , AP 18-1027, Ciudad de México 11801, México



# ULTRA-LIGHT AXION-LIKE PARTICLES

Lam Hui, Jeremiah P. Ostriker, Scott Tremaine and Edward Witten.
On the hypothesis that cosmological dark matter is composed of ultra-light bosons.
PRD 95, 043541 (2017). arXiv:1610.08297

- **QCD-axion**: pseudo-Nambu-Goldstone boson in the Peccei-Quinn mechanism, proposed as a dynamical solution to the strong CP-problem in QCD.
- Pseudoscalar fields with axion-like properties generically arise in **string theory** compactifications as Kaluza–Klein (KK) zero modes of antisymmetric tensor fields
- Axion-like particles: Shift symmetries (with violations only by an exponentially small amount. ) V(a) is a periodic function.

$$I = \int d^4x \sqrt{-g} \left[ \tfrac{1}{2} F^2 g^{\mu\nu} \partial_\mu a \, \partial_\nu a - \mu^4 (1 - \cos a) \right].$$

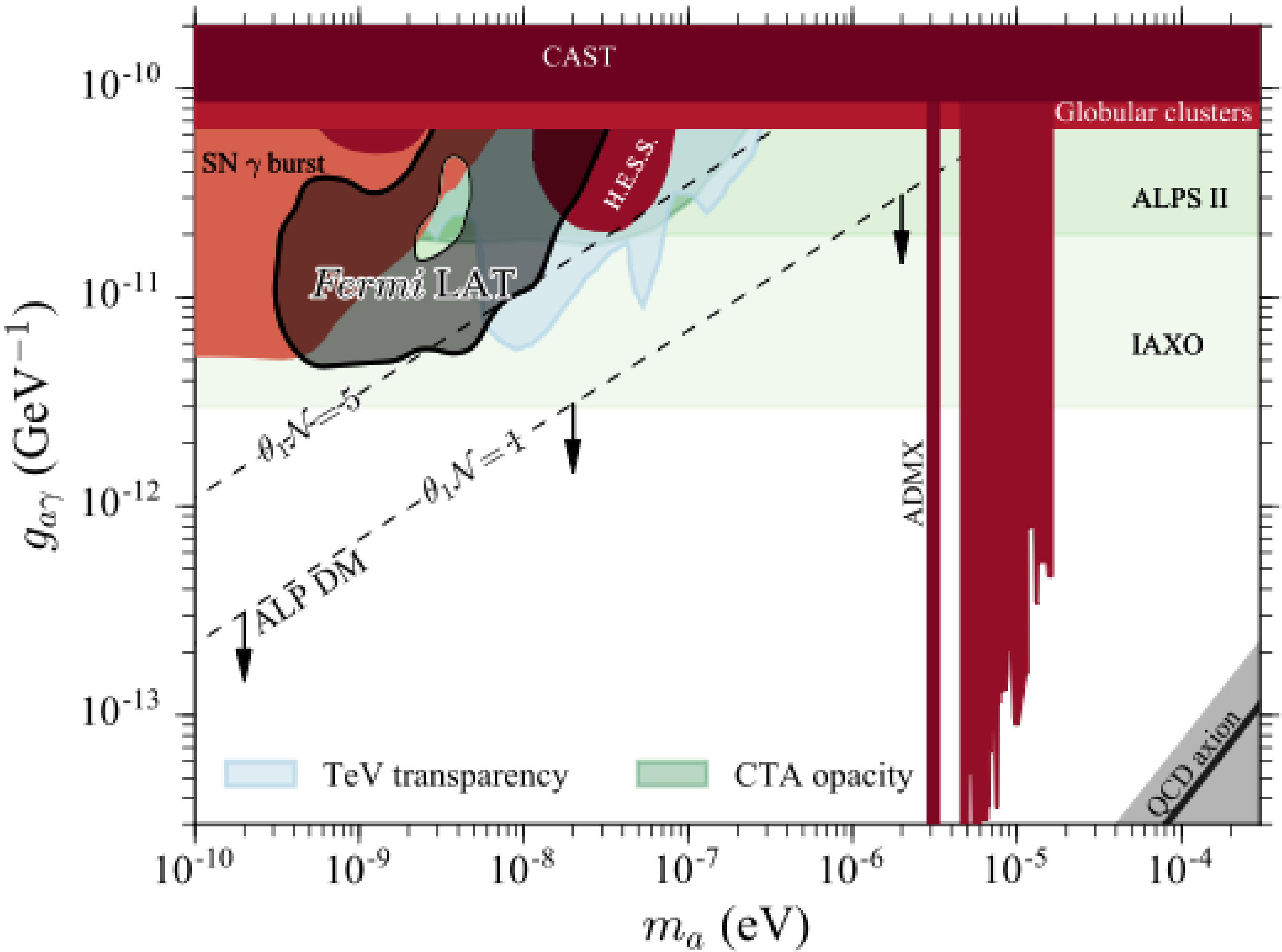
generated by nonperturbative instanton effects

$$m = \frac{\mu^2}{F}, \qquad m \sim 10^{-22}\text{–}10^{-21} \text{ eV}.$$

$$10^{18} \text{ GeV} \gtrsim F \gtrsim 10^{16} \text{ GeV}.$$

"model-independent" axion of the weakly coupled heterotic string

Fermi-LAT Collaboration, PRL 116, 161101 (2016).

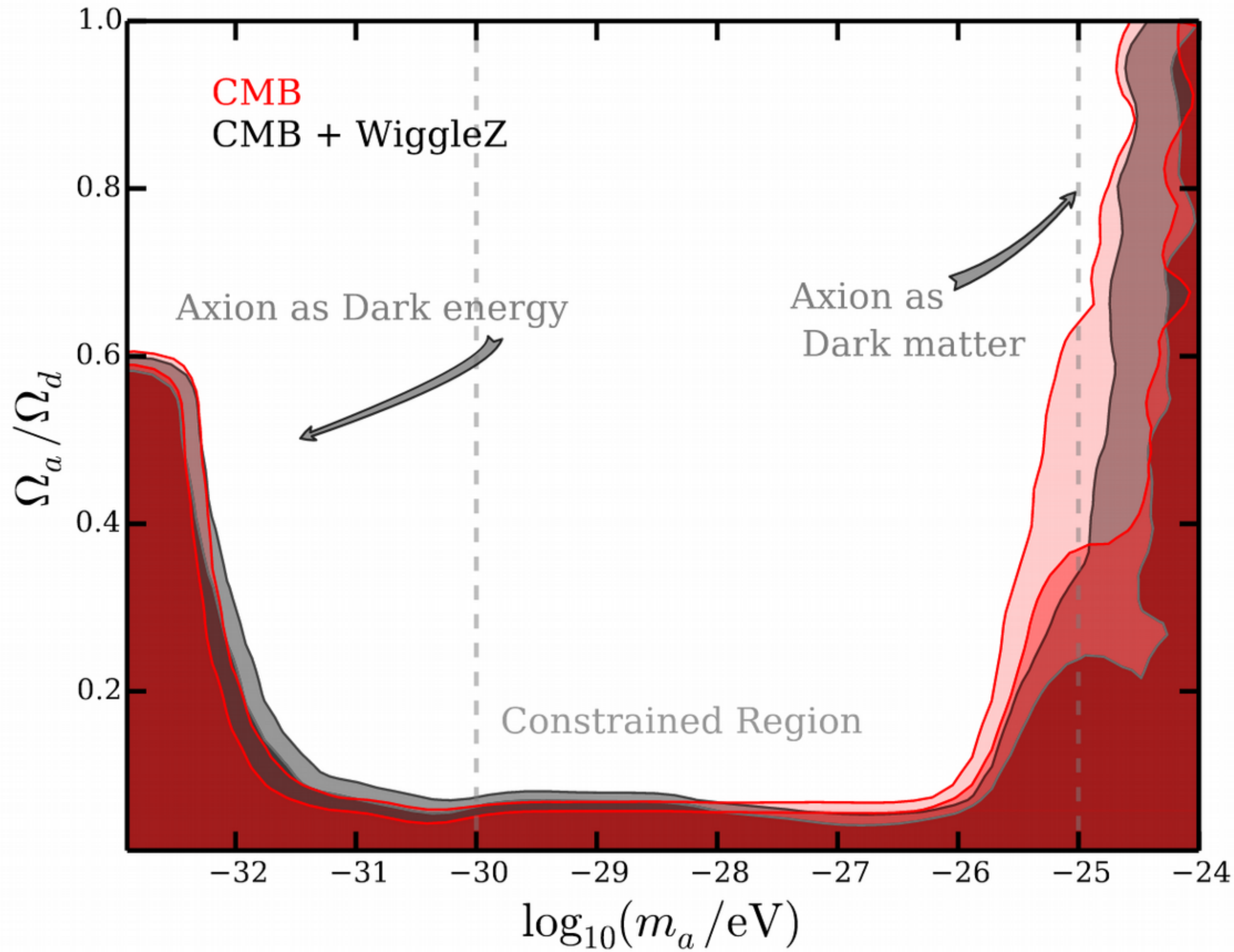


# A search for ultralight axions using precision cosmological data

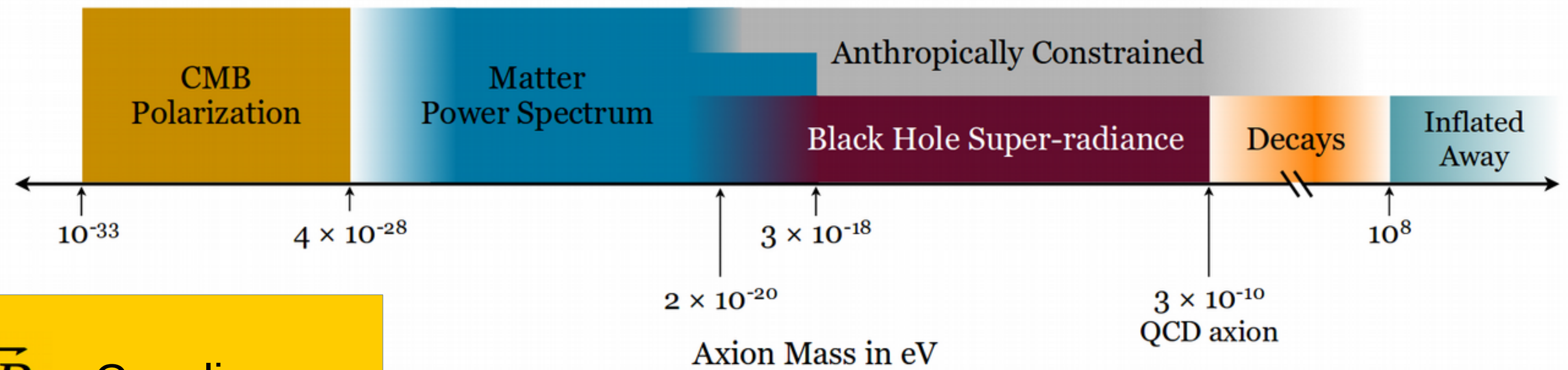
Renée Hlozek,[1] Daniel Grin,[2] David J. E. Marsh,[3,*] and Pedro G. Ferreira[4]

[1] *Department of Astronomy, Princeton University, Princeton, NJ 08544, USA*
[2] *Kavli Institute for Cosmological Physics, Department of Astronomy and Astrophysics, University of Chicago, Chicago, Illinois, 60637, U.S.A.*
[3] *Perimeter Institute, 31 Caroline Street N, Waterloo, ON, N2L 6B9, Canada*
[4] *Astrophysics, University of Oxford, DWB, Keble Road, Oxford, OX1 3RH, UK*

(Dated: May 22, 2015)



# AXIONS OBSERVATIONAL SIGNATURES




$\vec{E} \cdot \vec{B}$ Coupling

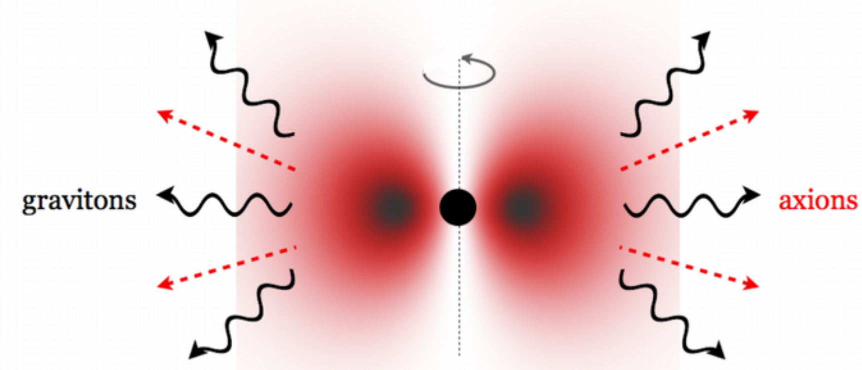
CMB Polarization

Rotates $10^{-3}$

Dark Matter
Axiverse plethora

Steps in the small
Scale perturbation
Height ~ DM fraction

BOSS, 21 cm line




Black-Hole
superradiance

**String Axiverse**

Asimina Arvanitaki[a,b], Savas Dimopoulos[c], Sergei Dubovsky[c,d], Nemanja Kaloper[e], and John March-Russell[f]

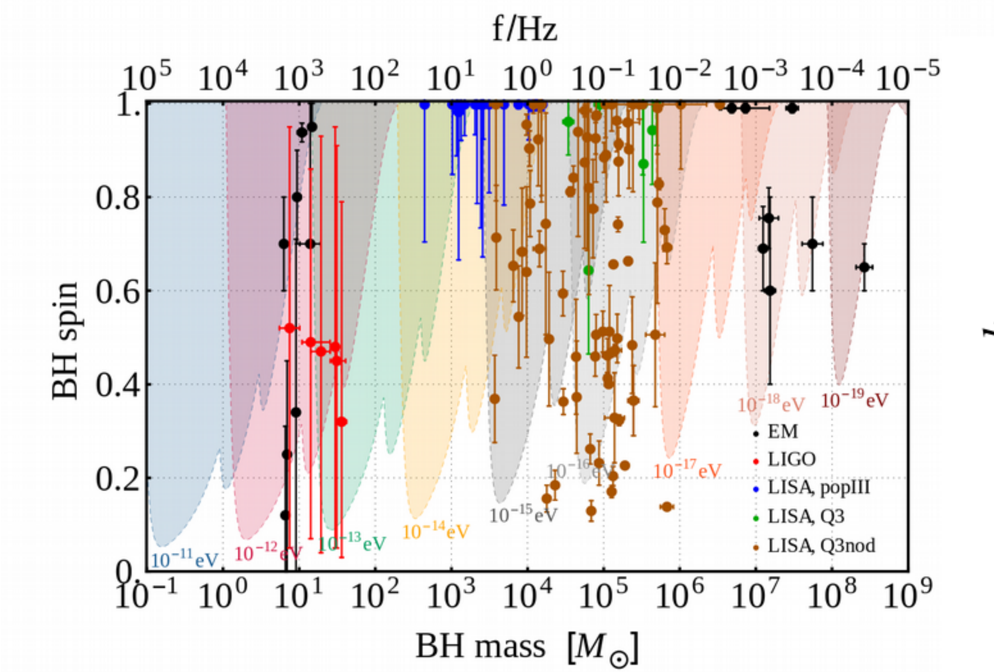
arXiv:0905.4720v2 [hep-th]

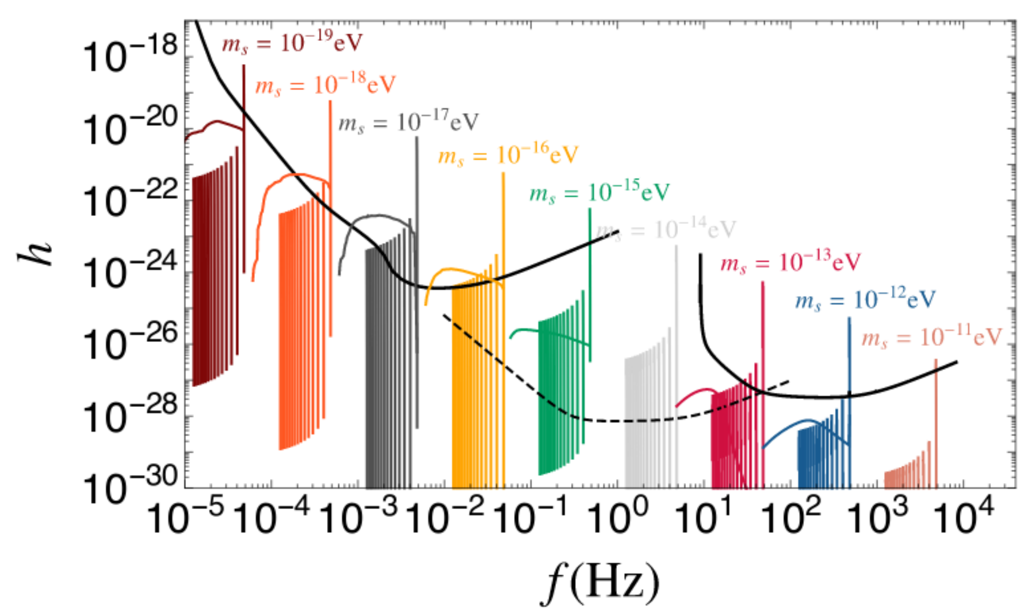
Detection of light-boson condensates around BHs with GW interferometers

Constraints of the mass of the boson from stochastic background produced by the superposition of GW signals from BH-boson condensate systems.

**LISA:** $m_s \in [5 \times 10^{-19}, 5 \times 10^{-16}]\,\mathrm{eV}$

**LIGO:** $m_s \in [2 \times 10^{-13}, 10^{-12}]\,\mathrm{eV}$




Brito et al.
Phys. Rev. D 96, 064050 (2017)

arXiv:1706.06311v2 [gr-qc]

# Gravitational wave searches for ultralight bosons with LIGO and LISA

Richard Brito[1,*], Shrobana Ghosh[2], Enrico Barausse[3], Emanuele Berti[2,4],
Vitor Cardoso[4,5], Irina Dvorkin[3,6], Antoine Klein[3], Paolo Pani[7,4]

[1] Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, Potsdam-Golm, 14476, Germany
[2] Department of Physics and Astronomy, The University of Mississippi, University, MS 38677, USA
[3] Institut d'Astrophysique de Paris, Sorbonne Universités,
UPMC Univ Paris 6 & CNRS, UMR 7095, 98 bis bd Arago, 75014 Paris, France
[4] CENTRA, Departamento de Física, Instituto Superior Técnico,
Universidade de Lisboa, Avenida Rovisco Pais 1, 1049 Lisboa, Portugal
[5] Perimeter Institute for Theoretical Physics, 31 Caroline Street North Waterloo, Ontario N2L 2Y5, Canada
[6] Institut Lagrange de Paris (ILP), Sorbonne Universités, 98 bis bd Arago, 75014 Paris, France and
[7] Dipartimento di Fisica, "Sapienza" Università di Roma & Sezione INFN Roma1, Piazzale Aldo Moro 5, 00185, Roma, Italy[*]

arXiv:1706.06311v2 [gr-qc]

**Bose-Einstein-condensed scalar field dark matter and the gravitational wave background from inflation: new cosmological constraints and its detectability by LIGO**

Bohua Li[*] and Paul R. Shapiro[†]
*Department of Astronomy and Texas Cosmology Center,*
*The University of Texas at Austin, 2515 Speedway C1400, Austin, TX 78712, USA*

Tanja Rindler-Daller[‡]
*Institut für Astrophysik, Universitätssternwarte Wien,*
*University of Vienna, A-1180 Vienna, Austria*
*Department of Physics and Michigan Center for Theoretical Physics,*
*University of Michigan, Ann Arbor, MI 48109, USA*
(Dated: April 26, 2017)

The stochastic gravitational-wave background from inflation is amplified in the presence of a complex SFDM at its stiff-matter era and it becomes detectable by advanced LIGO/Virgo and LISA for a broad range of $T_{reheat}$ .

# CONCLUSIONS

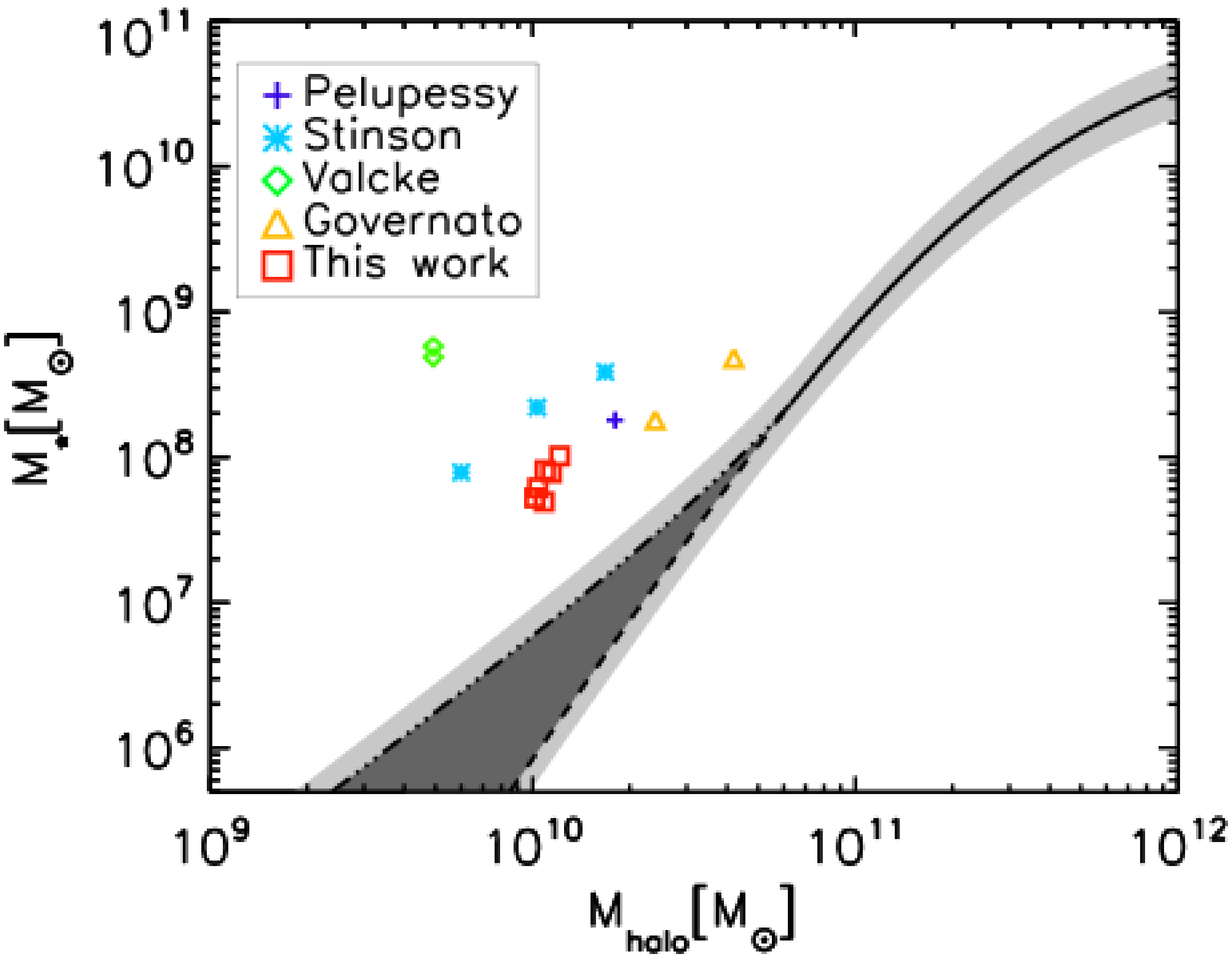
- Ultra-light bosons as dark matter was initially motivated in that it naturally suppresses the small scale clustering solving various potential issues of CDM.
- At very large scales SFDM yields the same predictions than CDM at very large scales.
- Stability conditions of SFDM solutions allow initial perturbations of 10^{12}Msun at most, therefore larger structures form by hierarchy.
- The collapse of SFDM unstable configurations provide an alternative mechanism of formation of SMBH in galaxies. Quasi-resonant remaining solutions may explain some features of galactic haloes hosting SMBH.
- Some extensions of the SM predict the existence of a plethora of ultra-light scalar fields. The lighter ones are candidates of a dominant fraction of dark matter while the heavier ones could only form a subdominant fraction. The last ones could yield observational signatures in the CMB radiation, in SGWB, etc

# Credits

PHI-GROUP


GRACIAS
SGR A*

# TOO-BIG-TO-FAIL PROBLEM



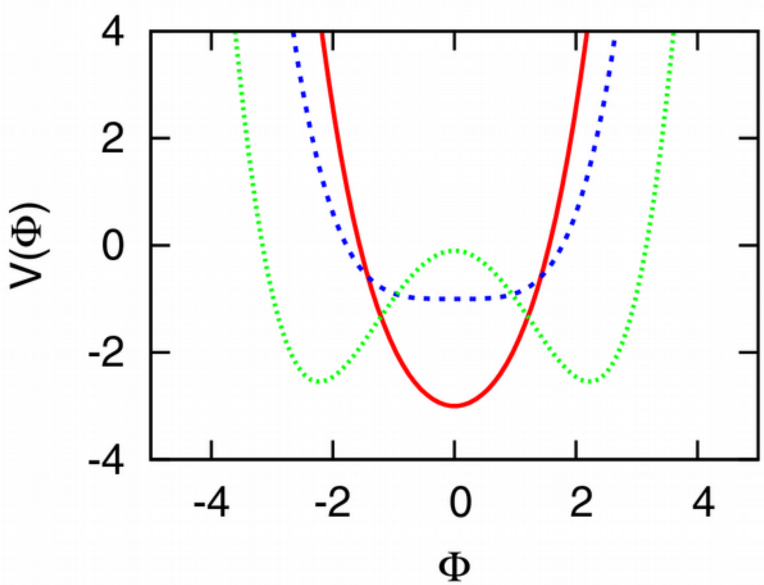

The dwarf galaxies formed in hydrodynamical simulations are almost two orders of magnitude more luminous than expected for haloes of this mass.

Till Sawala, Qi Guo, Cecilia Scannapieco, Adrian Jenkins and Simon White. Mon. Not. Roy. Astron. Soc. 413, (2011), 659

# SFDM HALOES AS BOSE-EINSTEIN CONDENSATES

$$V(\Phi) = -\frac{1}{2}\frac{\hat{m}^2c^2}{\hbar^2}\Phi^2 + \frac{\hat{\lambda}}{4}\Phi^4 + \frac{\hat{\lambda}}{8}k_B^2T^2\Phi^2 - \frac{\pi^2k_B^4T^4}{90\hbar^2c^2},$$

$$k_BT_C = \frac{2\hat{m}c^2}{\sqrt{\lambda}}.$$




Schroedinger-Poisson Classical Solutions

Gross-Pitaevskii Order Parameter: Number of particles

T>Tc The field oscillates around a minimum and grows until the universe reaches:

T~Tc Z2 Symmetry breaking. Condensation, haloes form.

T<Tc The field falls to a new minimum. DM fluctuations start growing

In the SFDM model, the primordial DM haloes form almost at the same time and very rapidly due to the SB.

EXACT SOLUTION TO FINITE TEMPERATURE SFDM: NATURAL CORES WITHOUT FEEDBACK

Victor H. Robles and T. Matos
Departamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, AP 14-740, 0700 D.F., México, Mexico;
vrobles@fis.cinvestav.mx, tmatos@fis.cinvestav.mx
Received 2012 August 6; accepted 2012 November 11; published 2012 December 28

# SUPERRADIANCE

- When the axion Compton wavelength is of order of the black hole size, the axions develop "superradiant" atomic bound states around the black hole "nucleus". Their occupation number grows exponentially by extracting rotational energy and angular momentum from the ergosphere, culminating in a rotating Bose-Einstein axion condensate emitting gravitational waves.