Astrophysical searches of wave dark matter

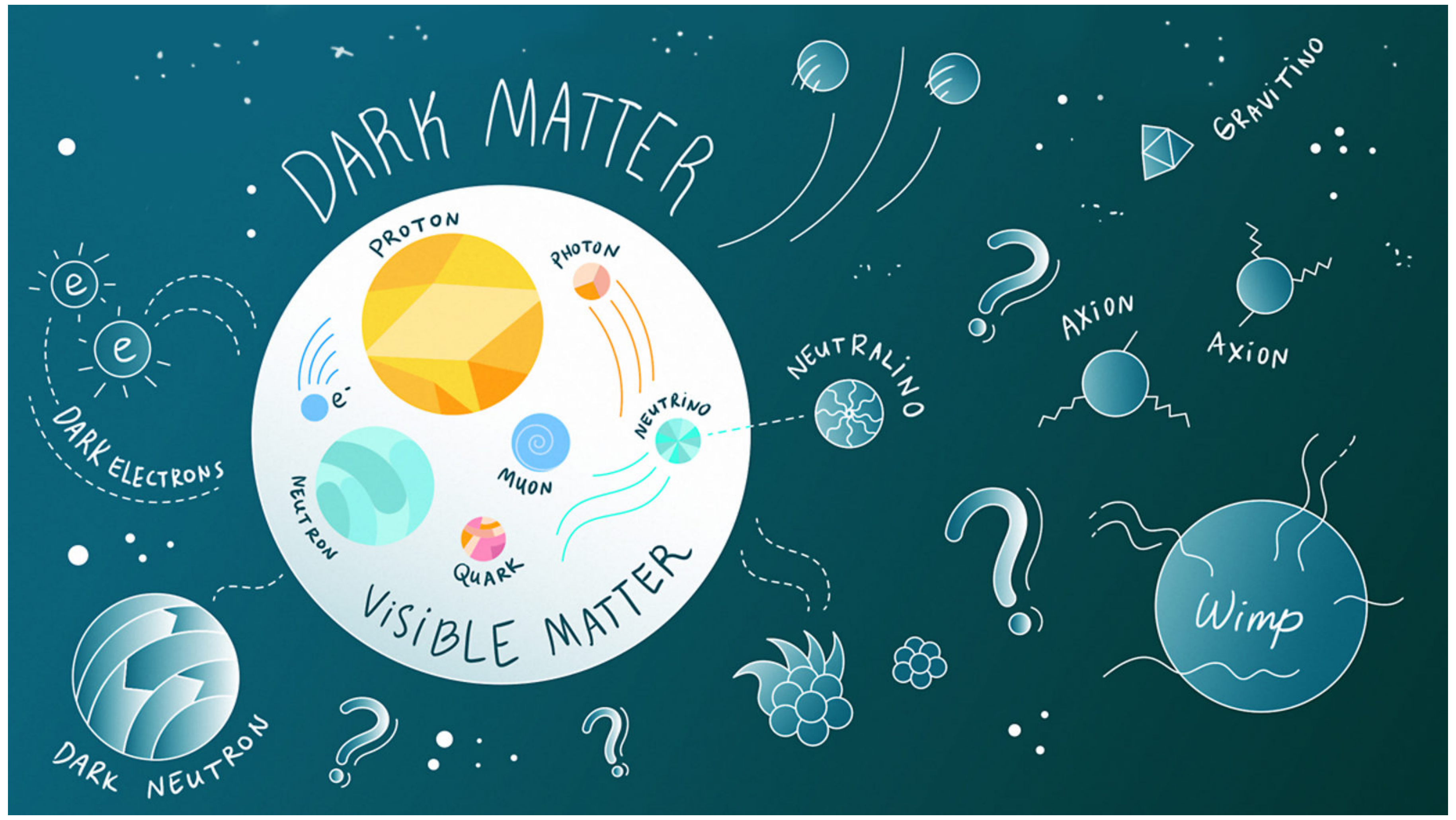
A lightning review to the Astroparticle Theory group

Jorge Martin Camalich

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC ·

Astroparticle Theory

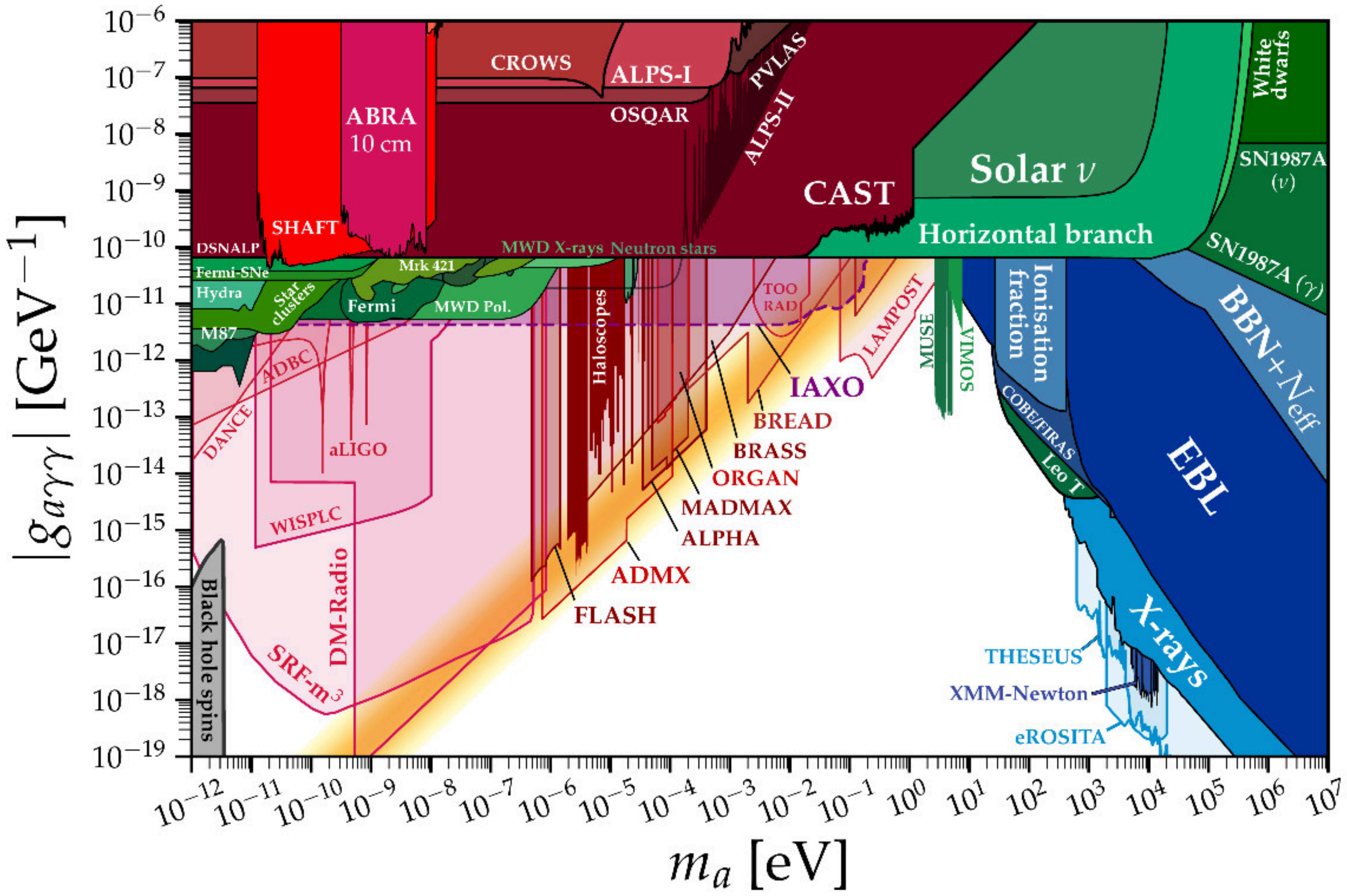
The quest for Dark Matter



- ***Prominent*** **problem in modern physics**
  - Natural in physics beyond the SM (WIMPs, axions, dark photons, …)
  - Very rich diversity of experimental signatures

Axion-like particles (ALPs)

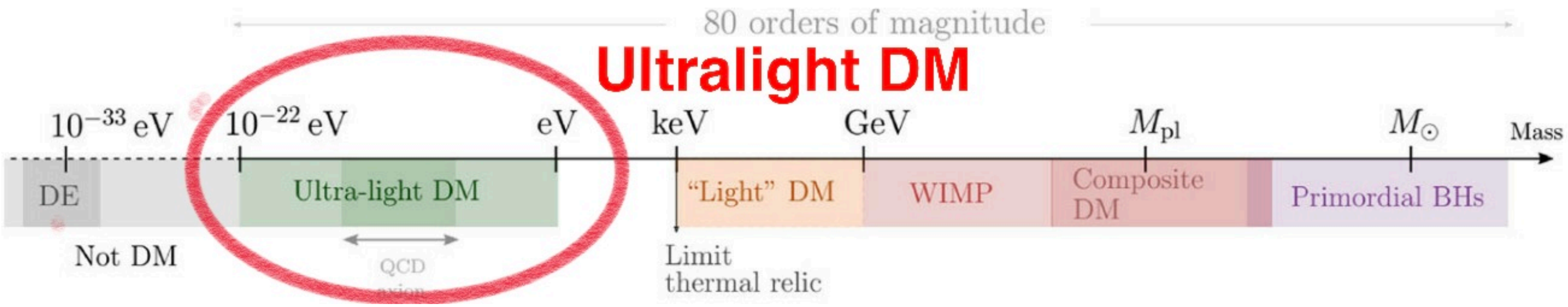
Jaeckel et al. Snowmass 2021



Huge parameter space to be explored

What are ALPs?

- ALPs are *bosonic* (scalar) particles
  - Theoretical Motivation: Strong *CP* problem (**QCD axion**) or String Theory (**Axiverse**)



Ferreira`s Review 2021

- **ALPs are the prototype of (non-thermally produced) ULDM** Marsh´2014

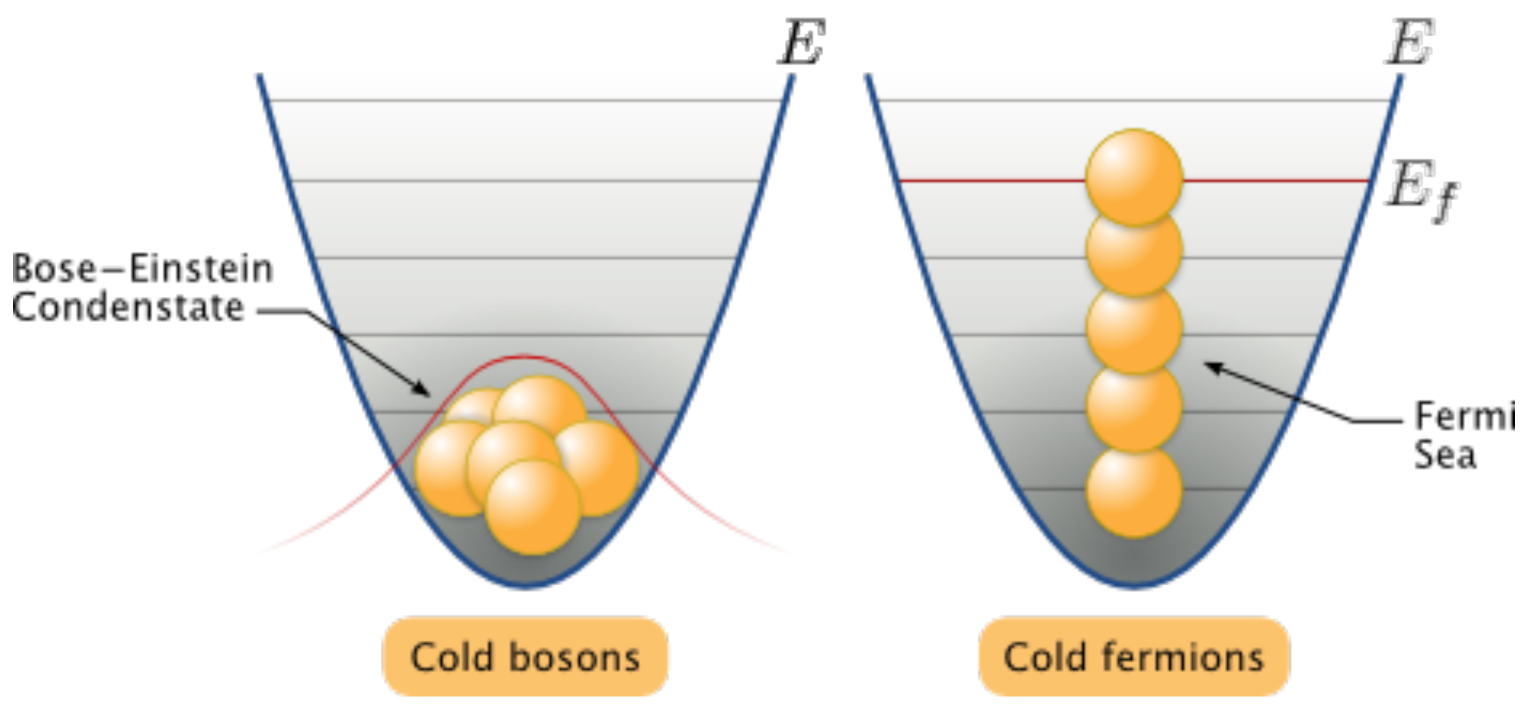
$$\Omega_a h^2 \simeq 0.12 \left(\frac{f_a \theta_0}{6 \times 10^{16} \mathrm{GeV}} \right)^2 \left(\frac{m_a}{2 \times 10^{-21} \mathrm{eV}} \right)^{1/2}$$

- **Relevant parameters**
  - The axion decay constant f_a (high-energy dynamics)
  - Mass of the axion m_a

Wave dark matter

Bose-Einstein Condensate (BEC)

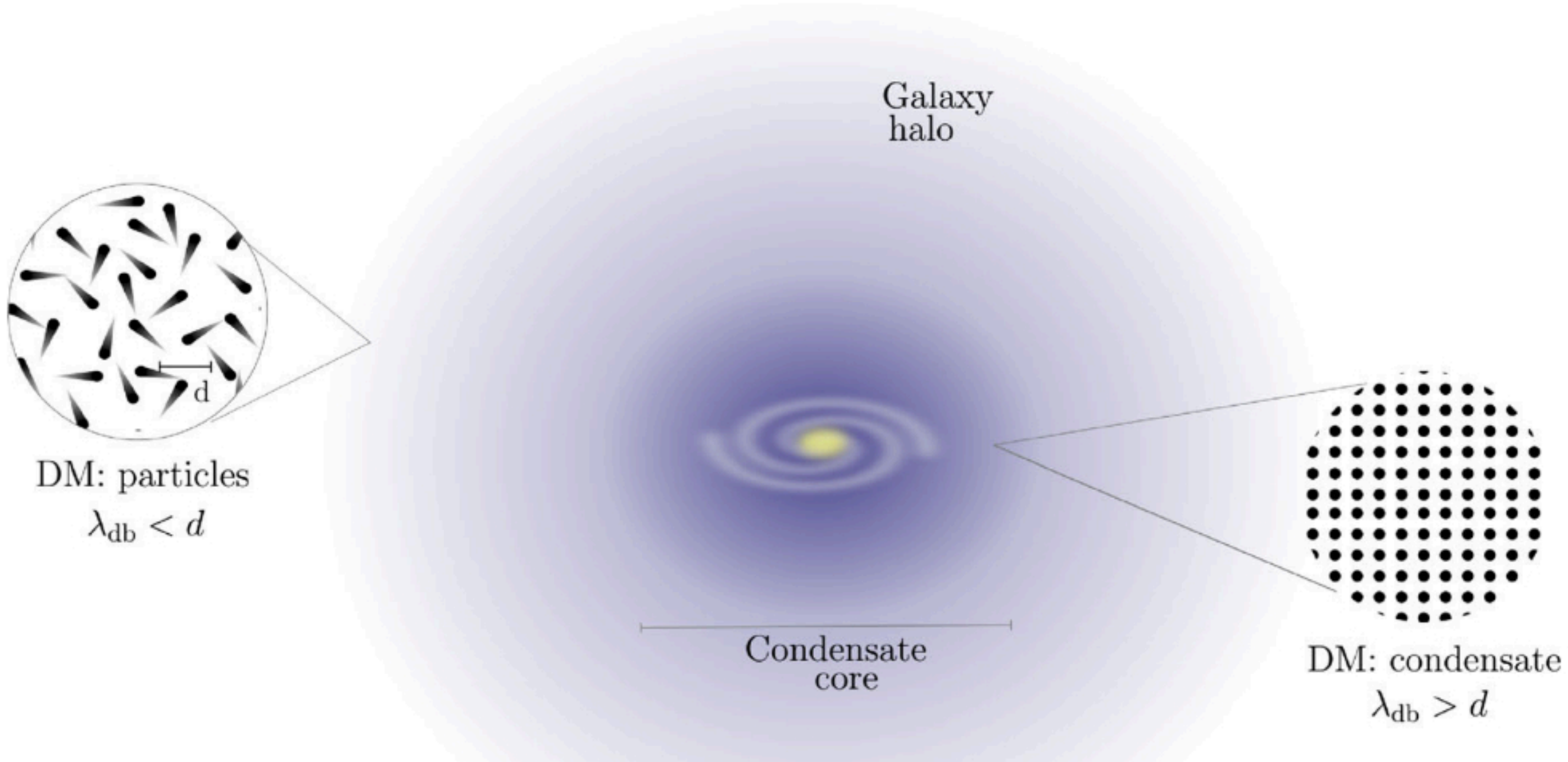
- Distance between particles $\ll \lambda_{\mathrm{dB}}$
- Behaves as a **classical wave** (e.g. Light)



$$\lambda_{\mathrm{dB}} = \frac{2\pi}{mv} = 0.5\,\mathrm{kpc}\left(\frac{10^{-22}\mathrm{eV}}{m_a}\right)\left(\frac{250\,\mathrm{km\,s^{-1}}}{v}\right)$$

- **ULDM ($m_a \sim 10^{-22}\,\mathrm{eV}$):**
  - Forms BEC at galactic scales
  - Behaves as CDM at large scales

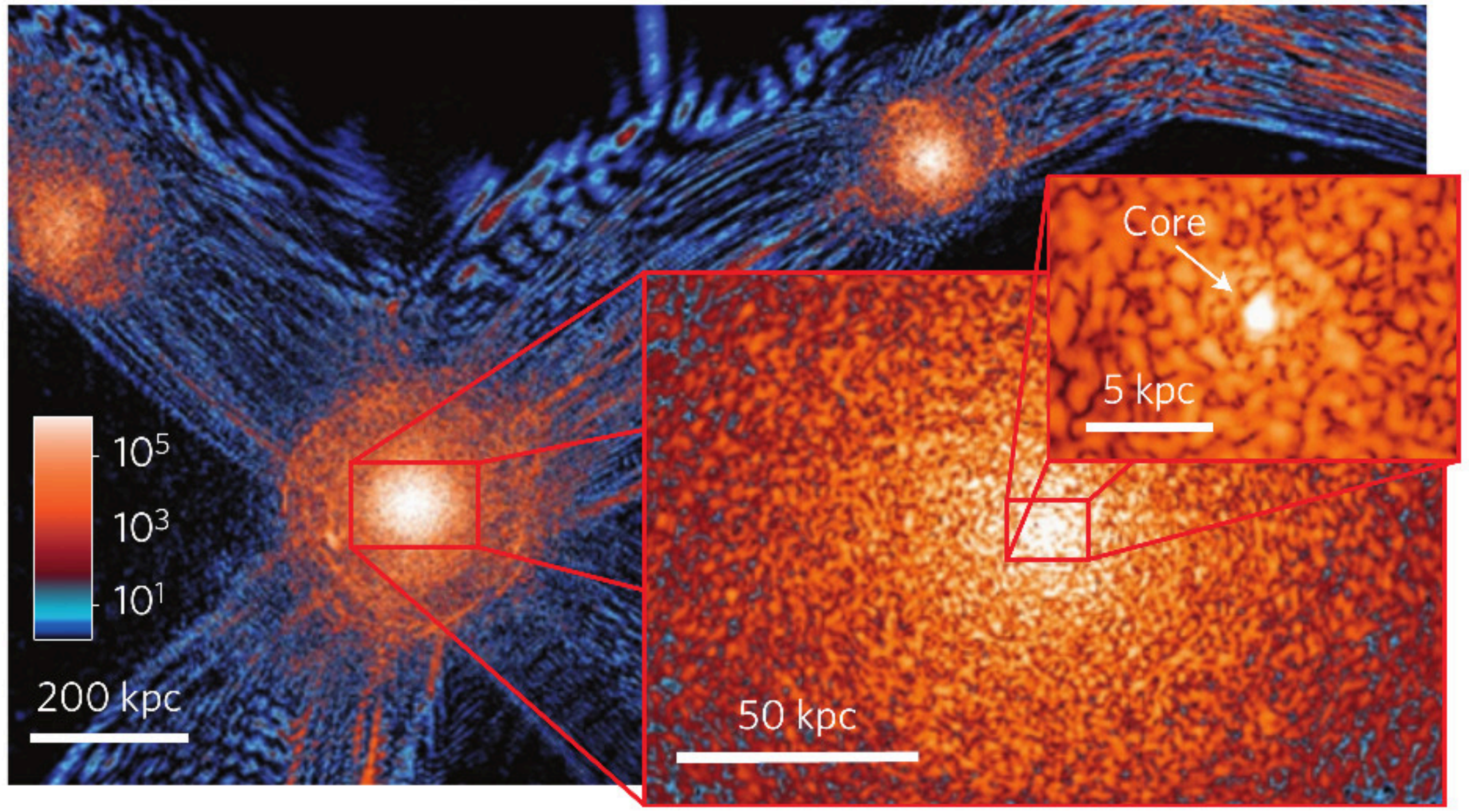
Fuzzy DM, wave DM, …



Ferreira`s Review 2021

Lam Hui`s Review 2021

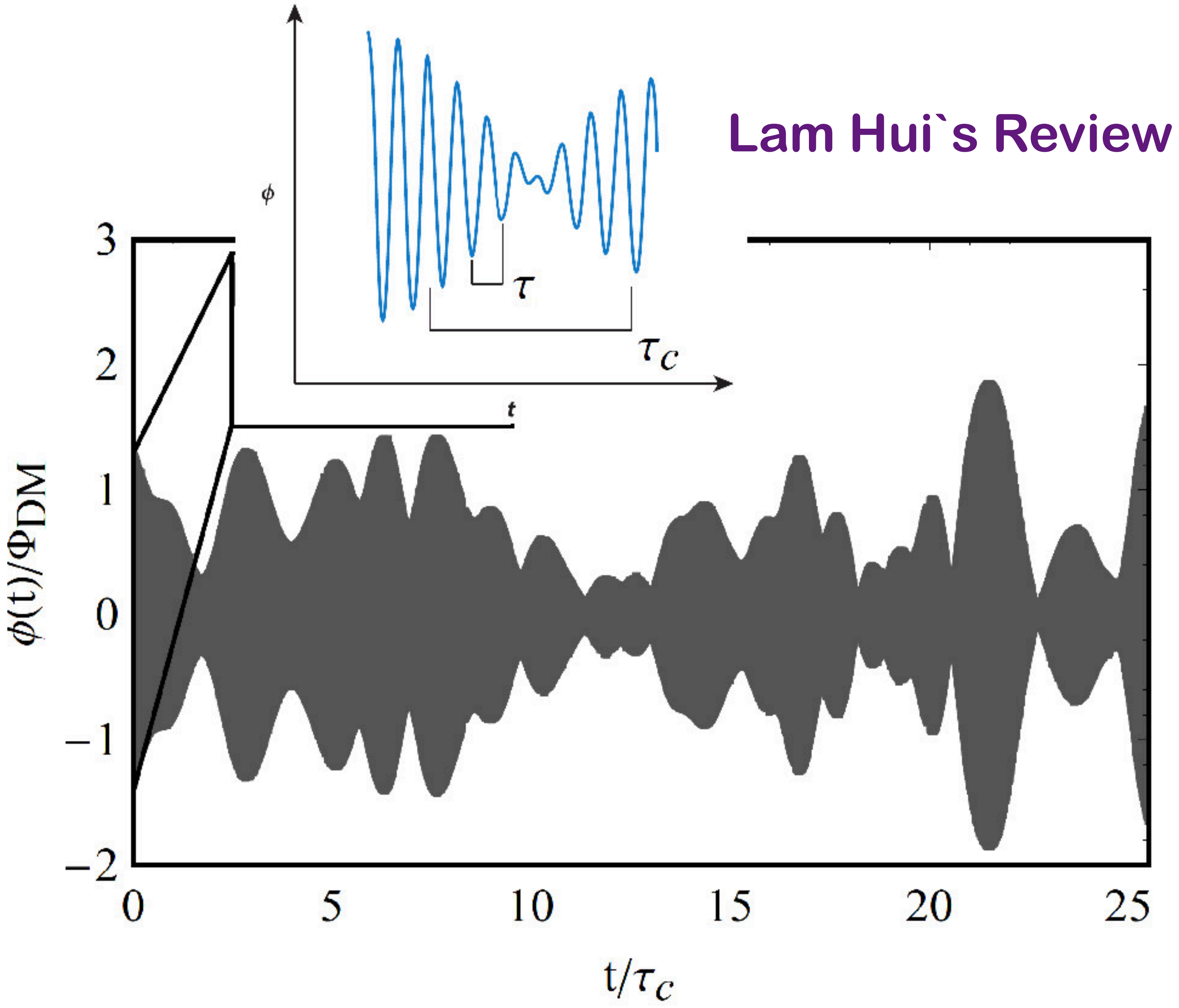
Phenomenology of wave DM



Schive et al 2014

Wave-like behaviour at kpc scales

- Interference patterns/fringes
- Core (*soliton*) at center of galaxies



Lam Hui`s Review 2021

Stochastic amplitude of the ALP field

- **Compton:** $\tau = \frac{2\pi}{m_a} = 1.3\,\mathrm{yr}\left(\frac{10^{-22}\mathrm{eV}}{m_a}\right)$
- **Coherence:** $\tau_c = \frac{2\pi}{m_a v^2} = 2\cdot 10^6\,\mathrm{yr}\left(\frac{10^{-22}\mathrm{eV}}{m_a}\right)\left(\frac{250\,km\,s^{-1}}{v}\right)^2$

Axion-light interactions

$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E}\cdot\mathbf{B}$$

Modified Maxwell Equations

$$\nabla\cdot\mathbf{E} = \rho - g_{a\gamma\gamma}\mathbf{B}\cdot\nabla a\,,$$

$$\nabla\cdot\mathbf{B} = 0\,,$$

$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}\,,$$

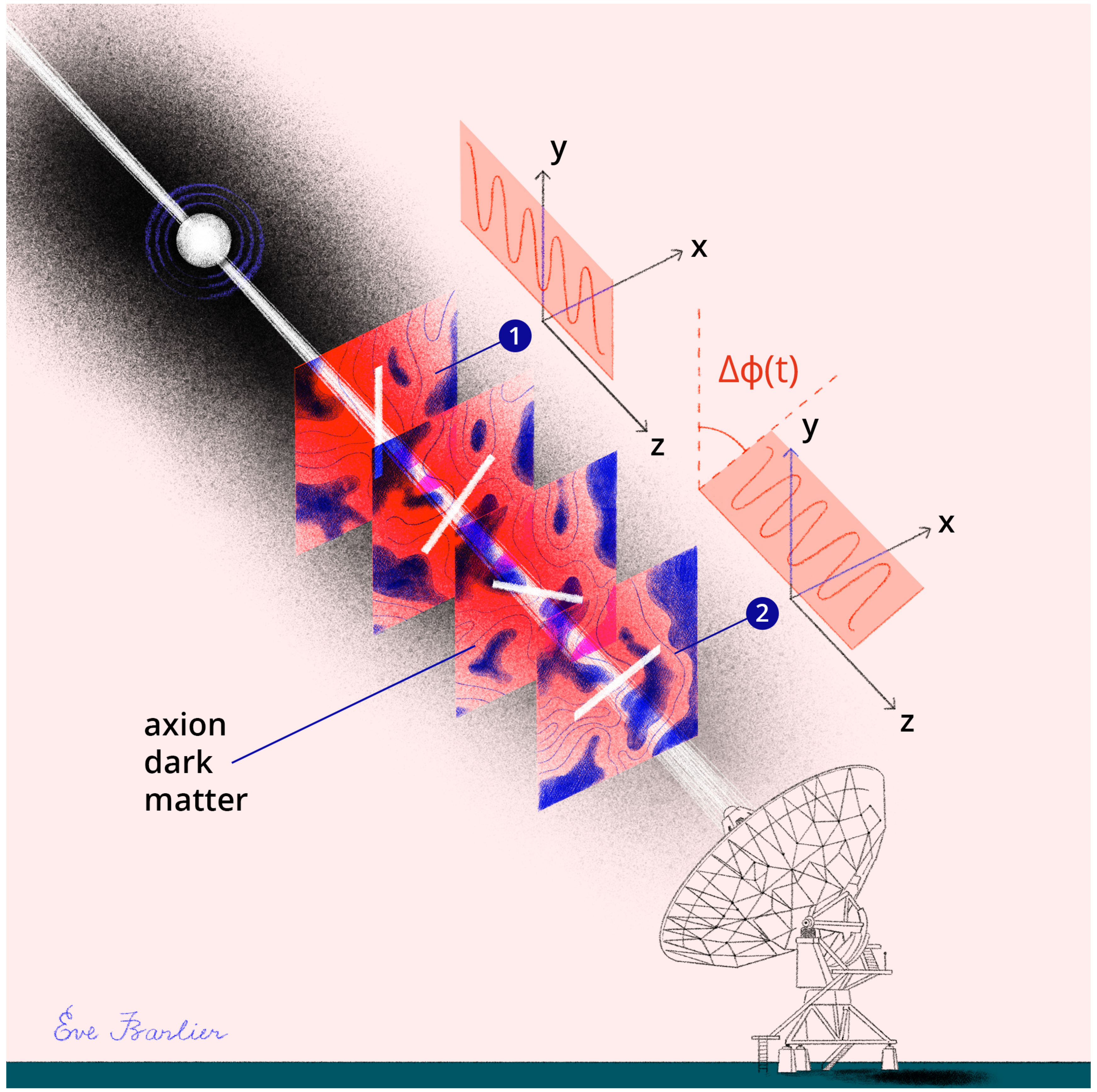
$$\nabla\times\mathbf{B} = \frac{\partial\mathbf{E}}{\partial t} + \mathbf{J} - g_{a\gamma\gamma}\left(\mathbf{E}\times\nabla a - \frac{\partial a}{\partial t}\mathbf{B}\right)$$

Sikivie & Harari 1992

Axion-induced birrefringence effect

- Polarization dependent d.r.

$$\omega_{\pm} \simeq k \pm \frac{1}{2} g_{a\gamma}\left(\partial_t a + \nabla a\cdot\hat{\mathbf{k}}\right)$$

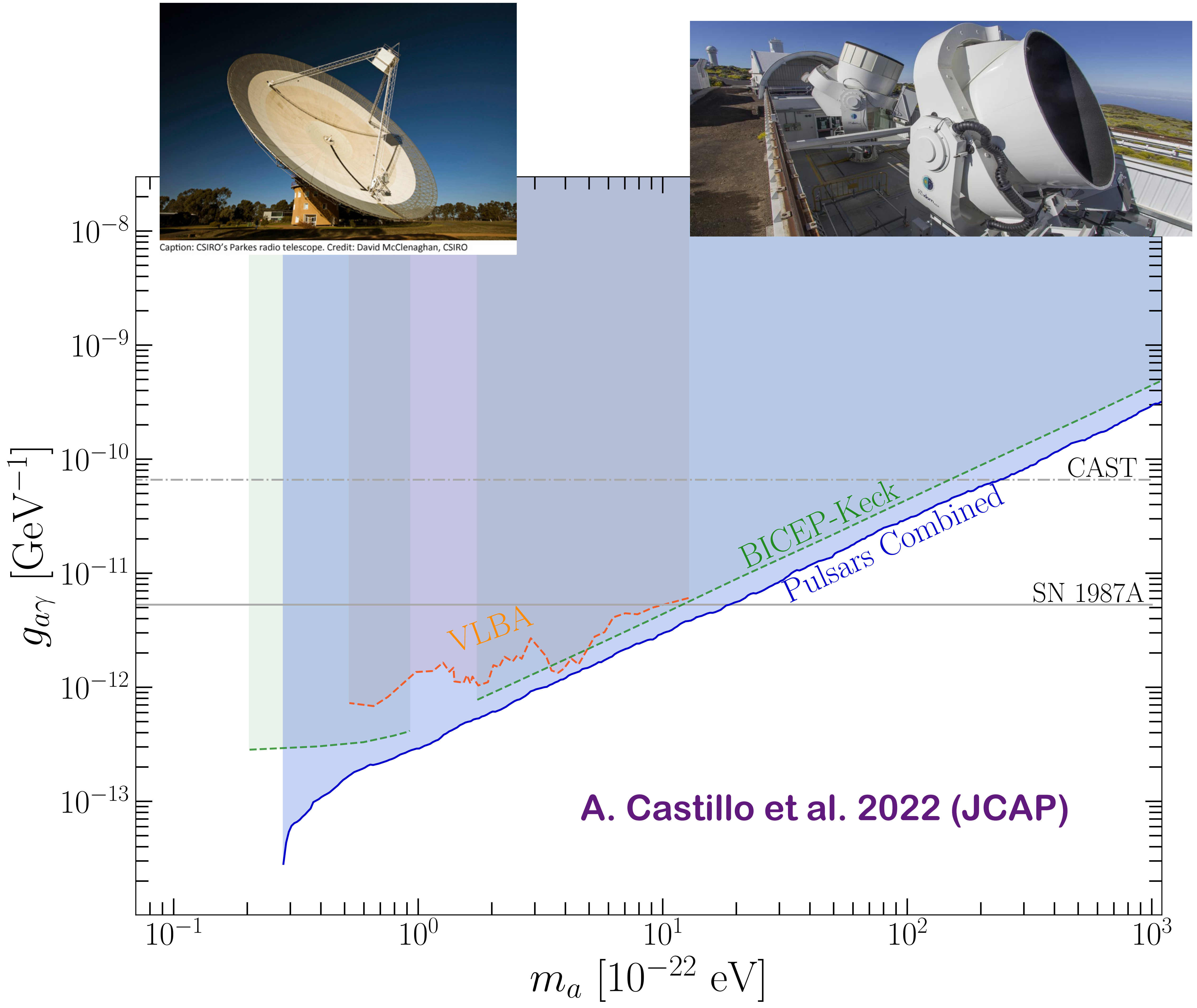


Bounds on ALP-photon coupling from QUIJOTE+PPTA

Strongest limit in $m_a \sim 10^{-22}\,\mathrm{eV}$

$$\phi_a \propto 1.12^\circ \left(\frac{g_{a\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right)\left(\frac{m_a}{10^{-22}\ \mathrm{eV}}\right)^{-1}\left(\frac{\rho_{DM}}{1\ \mathrm{GeV\ cm}^{-3}}\right)^{1/2}$$

- **Robust frequentist analysis**
  - Periodograms and MC
  - Combined limit of 21 *pulsars*
  - Incorporates stochasticity



Bounds on ALP-photon coupling: What´s next?

Collaboration with EPTA

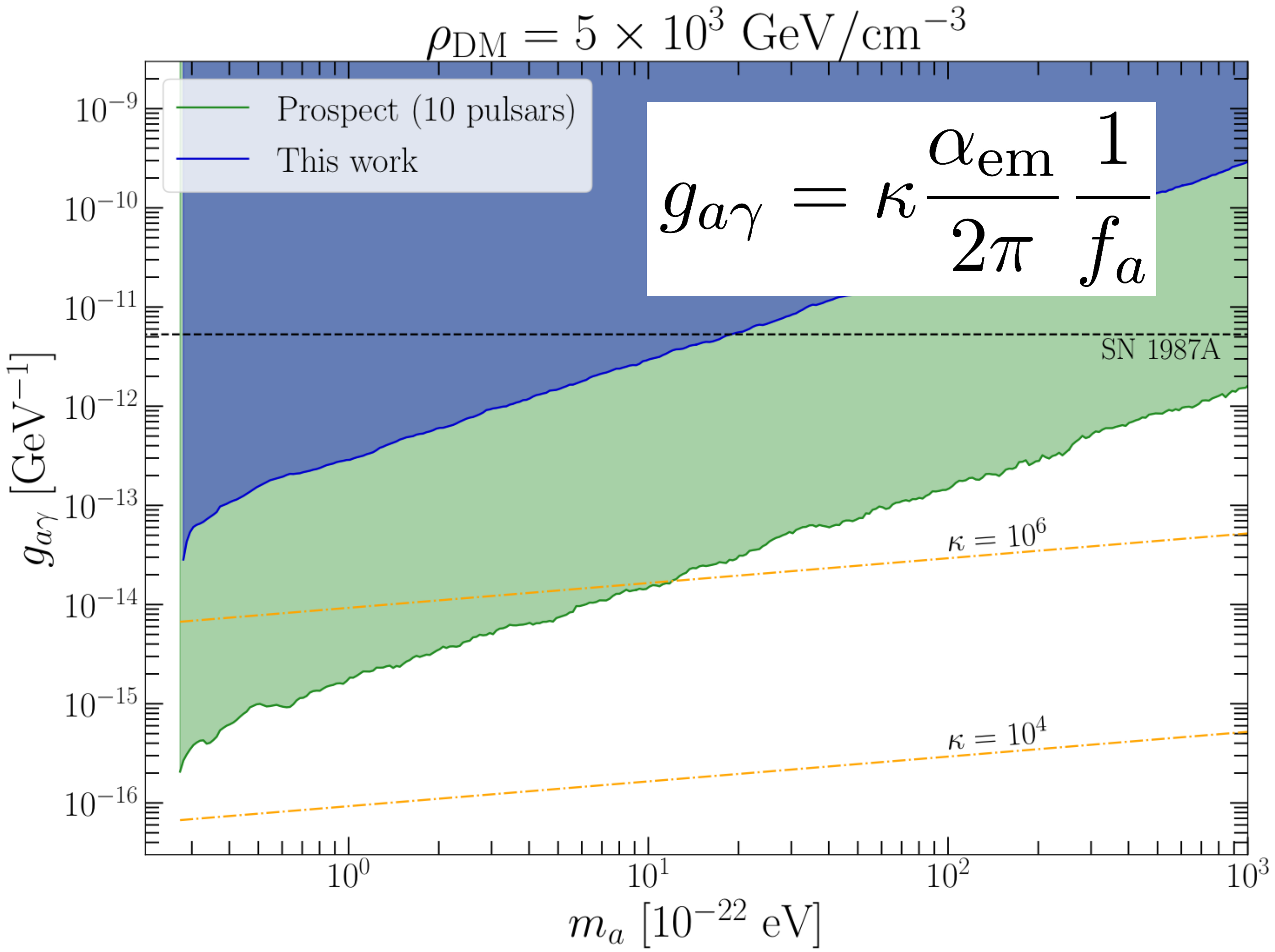
Polarisation measured for 24 yr

- **Ideal targets:**

Pulsars close to Galactic Center $\phi \propto \rho_{\rm DM}^{1/2}$

Prototype: GC Magnetar (SGR J1745-2900)

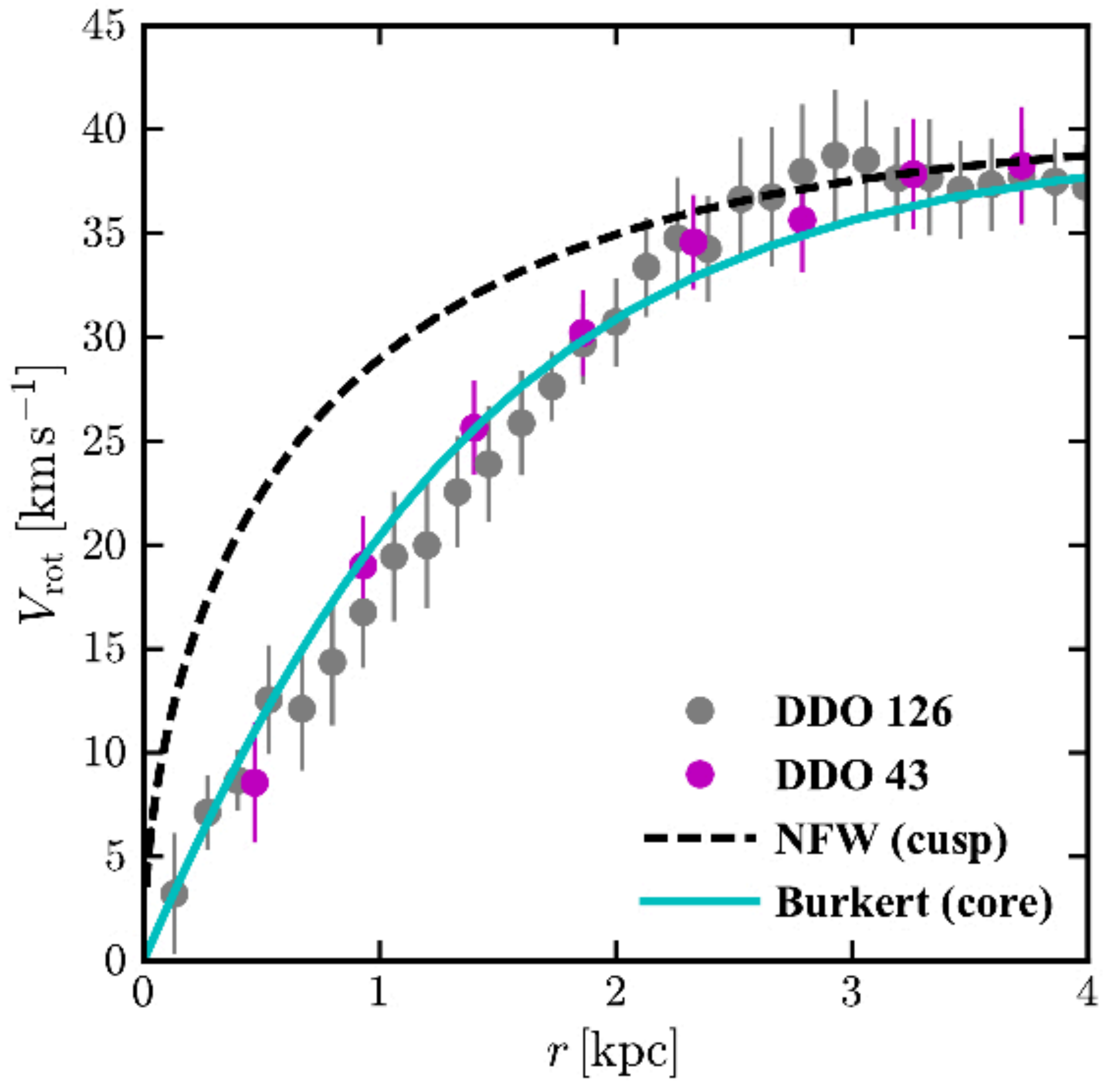
- **Far from vanilla ALP-DM. However:**
  1. Enhancements can appear in models
  2. Charting **unexplored** territory



ULDM and galaxies

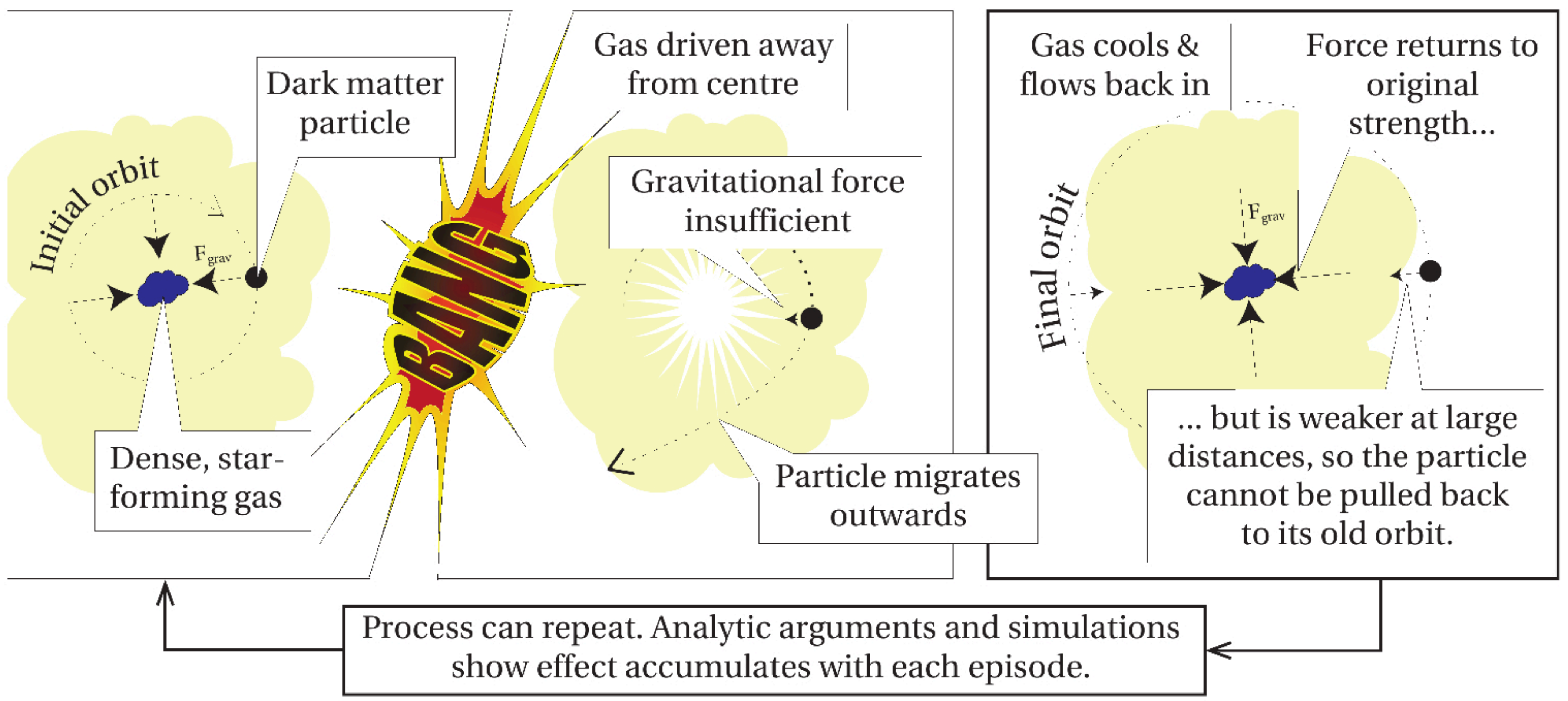
Small-scale problems

- Missing satellite problem
- Cusp-core problem



Bullock & Boylan-Kolchin Review 2021

- **Complicated baryonic feedback?**



Effects minimised for $M_* \lesssim 10^7 M_\odot$

DiCintio et al. 2014

- **Non CDM behaviour at small scales?**
  - Self-interacting DM
  - Degenerate fermionic DM
  - ULDM - fuzzy DM

ULDM and galaxies

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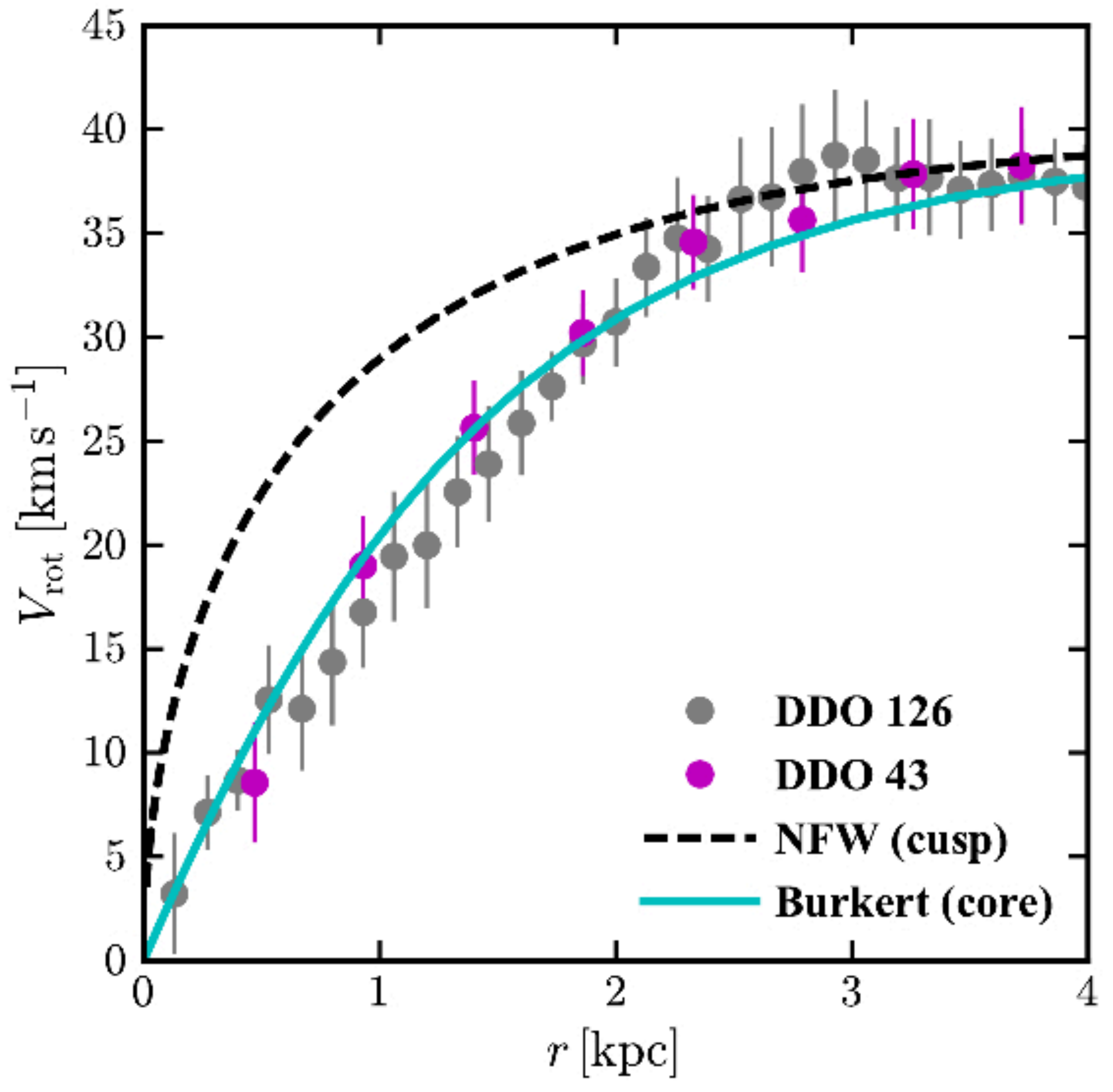

Bullock & Boylan-Kolchin Review 2021

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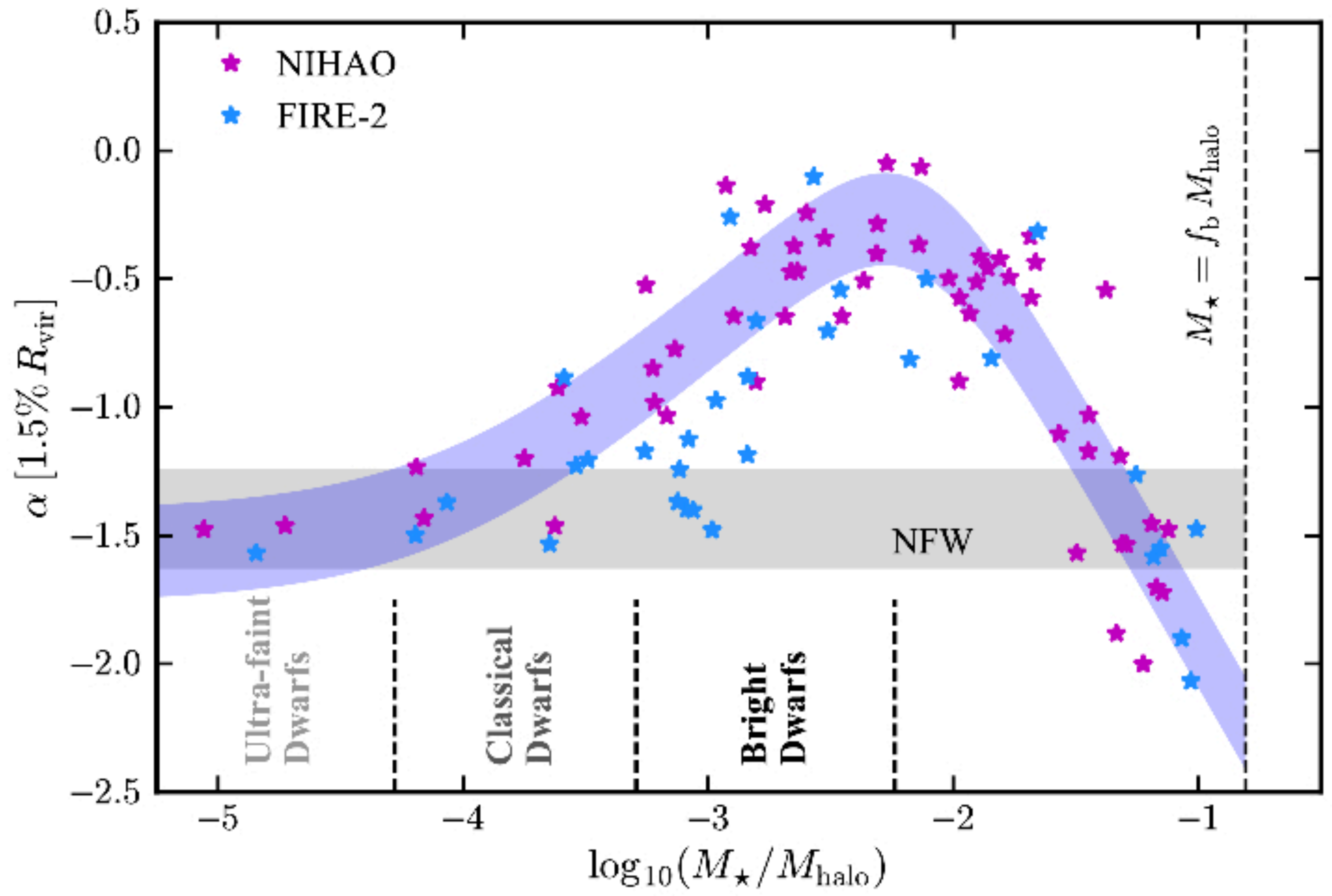

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The soliton in ULDM

Review in Lam Hui, Ostriker, Tremaine, Witten 2017

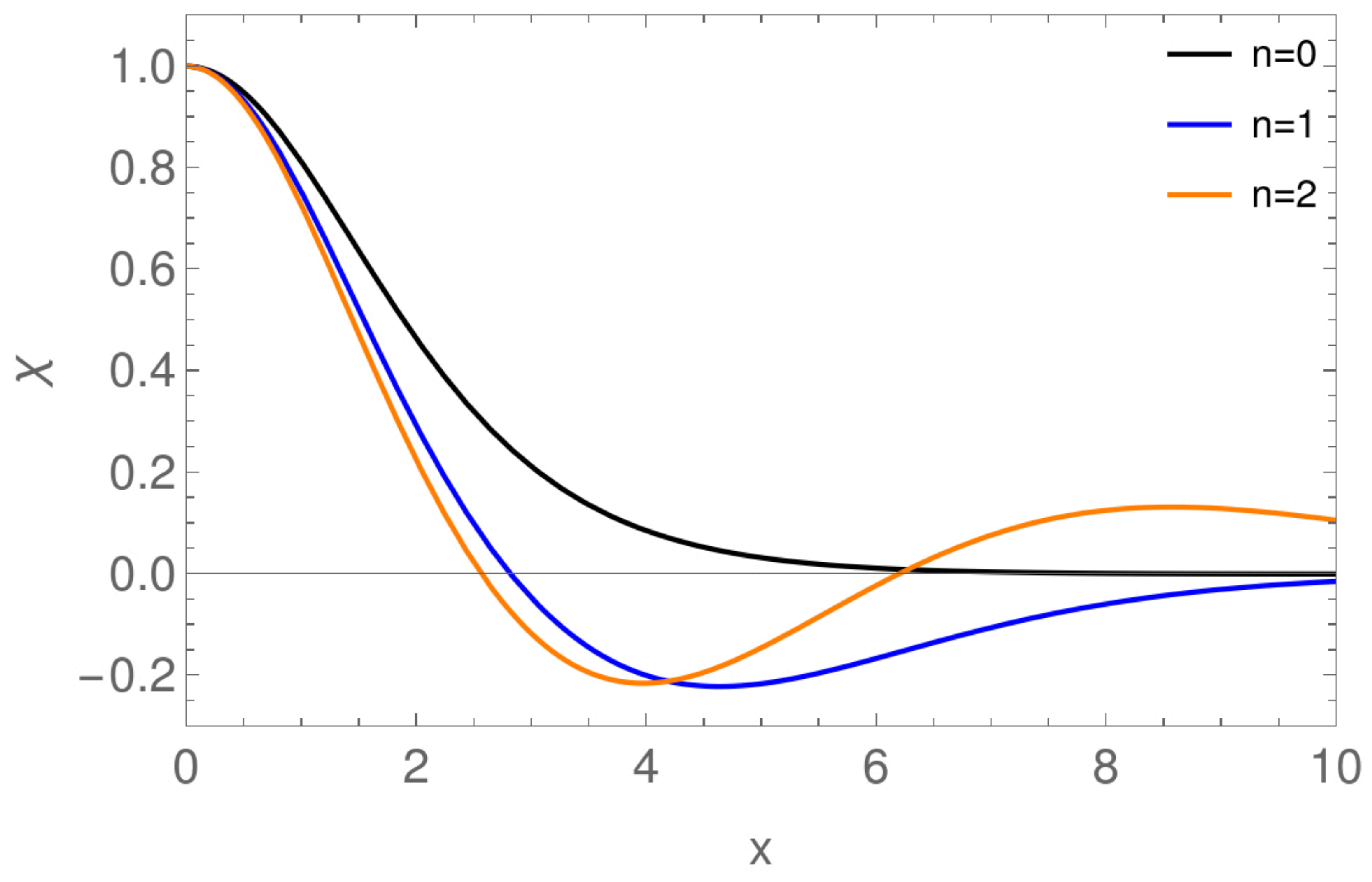
The Schrödinger-Poisson Equations

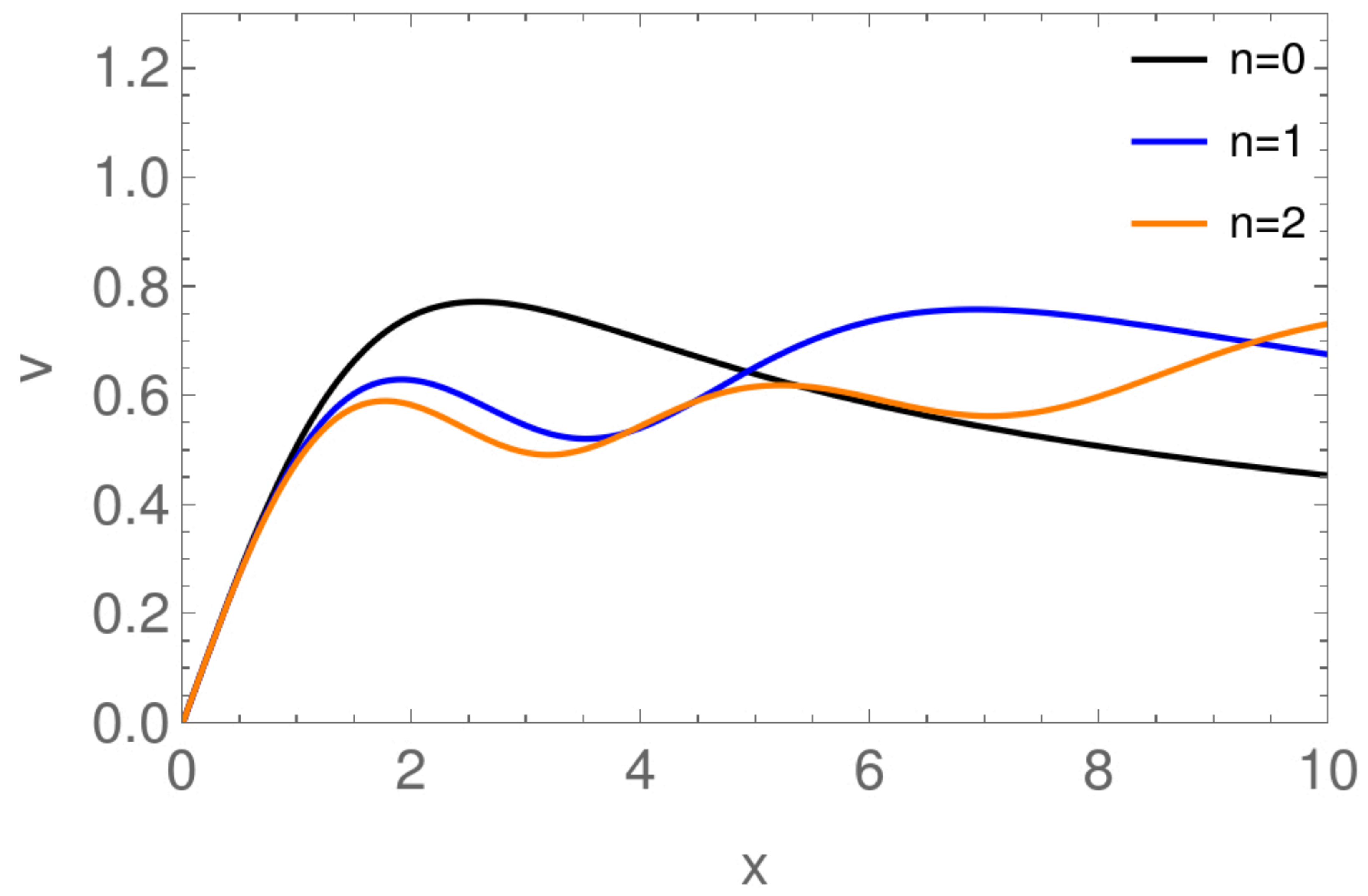
$$i\partial_t \psi = -\frac{1}{2m}\nabla^2\psi + m\Phi\psi$$

$$\nabla^2\Phi = 4\pi G|\psi|^2.$$

- **Eigenvalue problem**
  - Depends on m_a and re-scaling parameter λ
  - **Soliton:** Ground-state solution
    - **Mass:** $M_c = 2.8\cdot 10^9 M_\odot \left(\frac{\lambda}{10^{-3}}\right)\left(\frac{10^{-22}\,\text{eV}}{m_a}\right)$
    - **Radius:** $r_c = 80\text{pc}\left(\frac{10^{-3}}{\lambda}\right)\left(\frac{10^{-22}\,\text{eV}}{m_a}\right)$

Template Solutions $\lambda = 1$

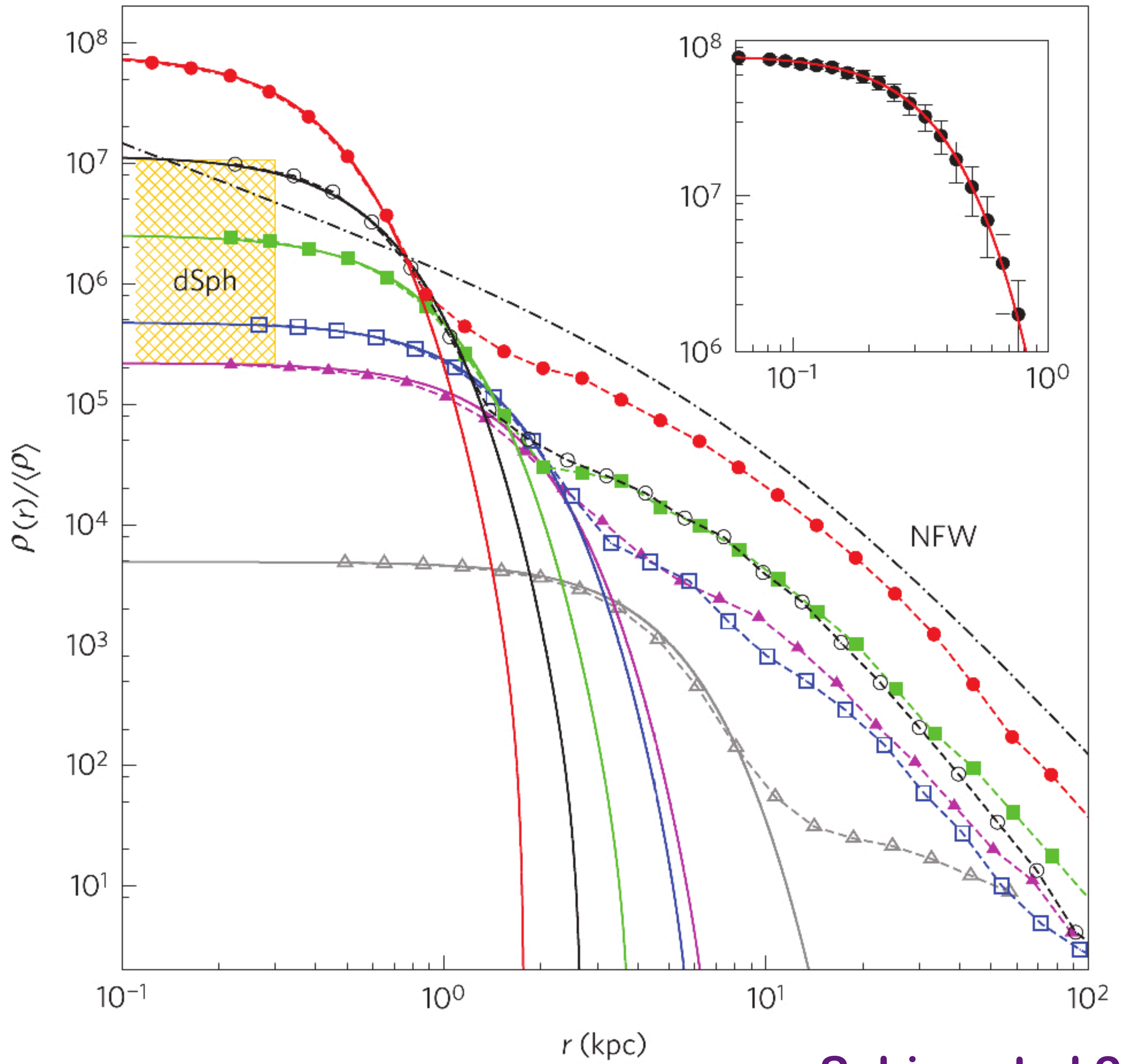




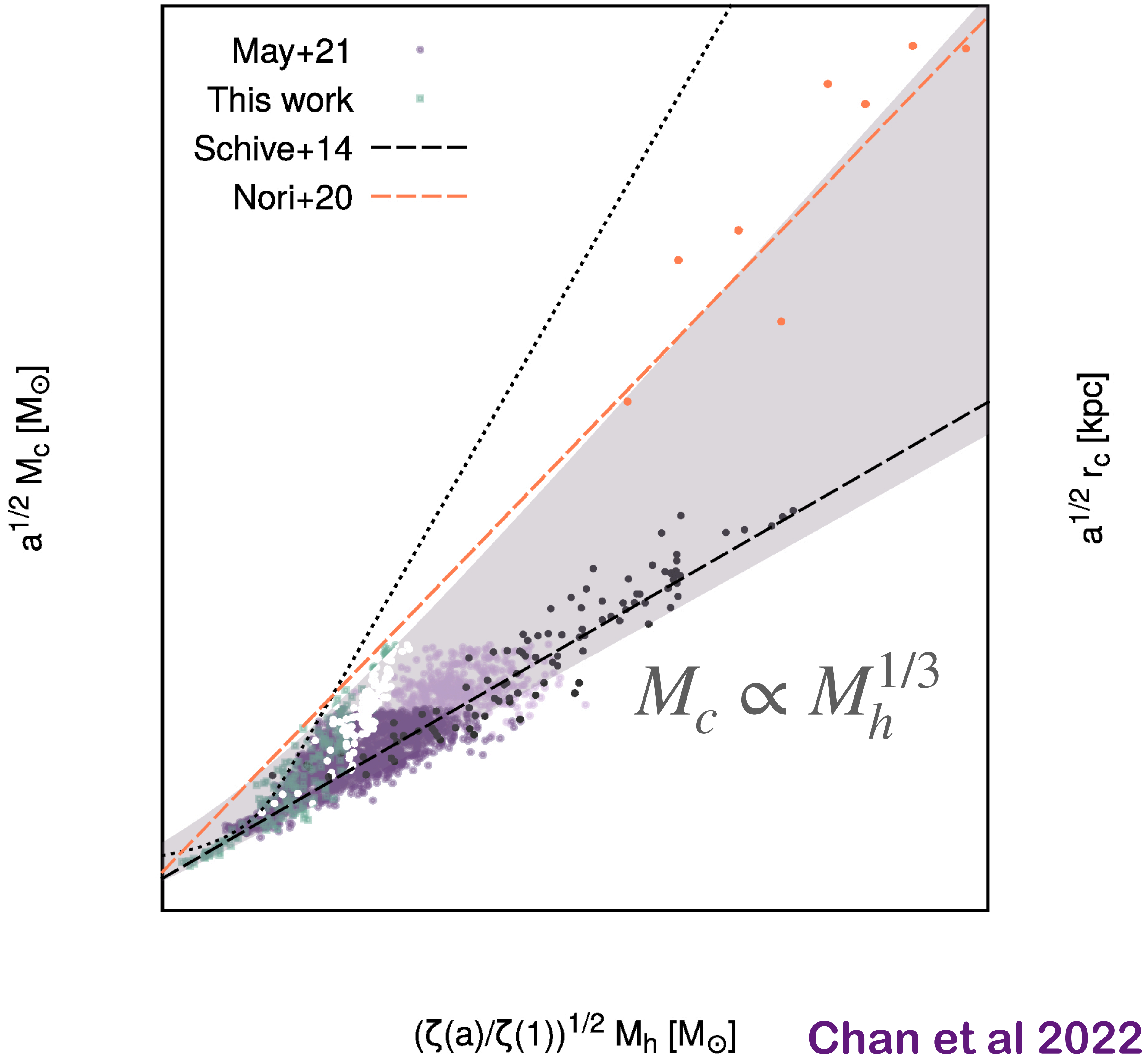
The soliton-halo relation

- **Properties of soliton (λ) determined by M_h**
  - Obtained from simulations

Diversity of Soliton-halo relations



Schive et al 2014

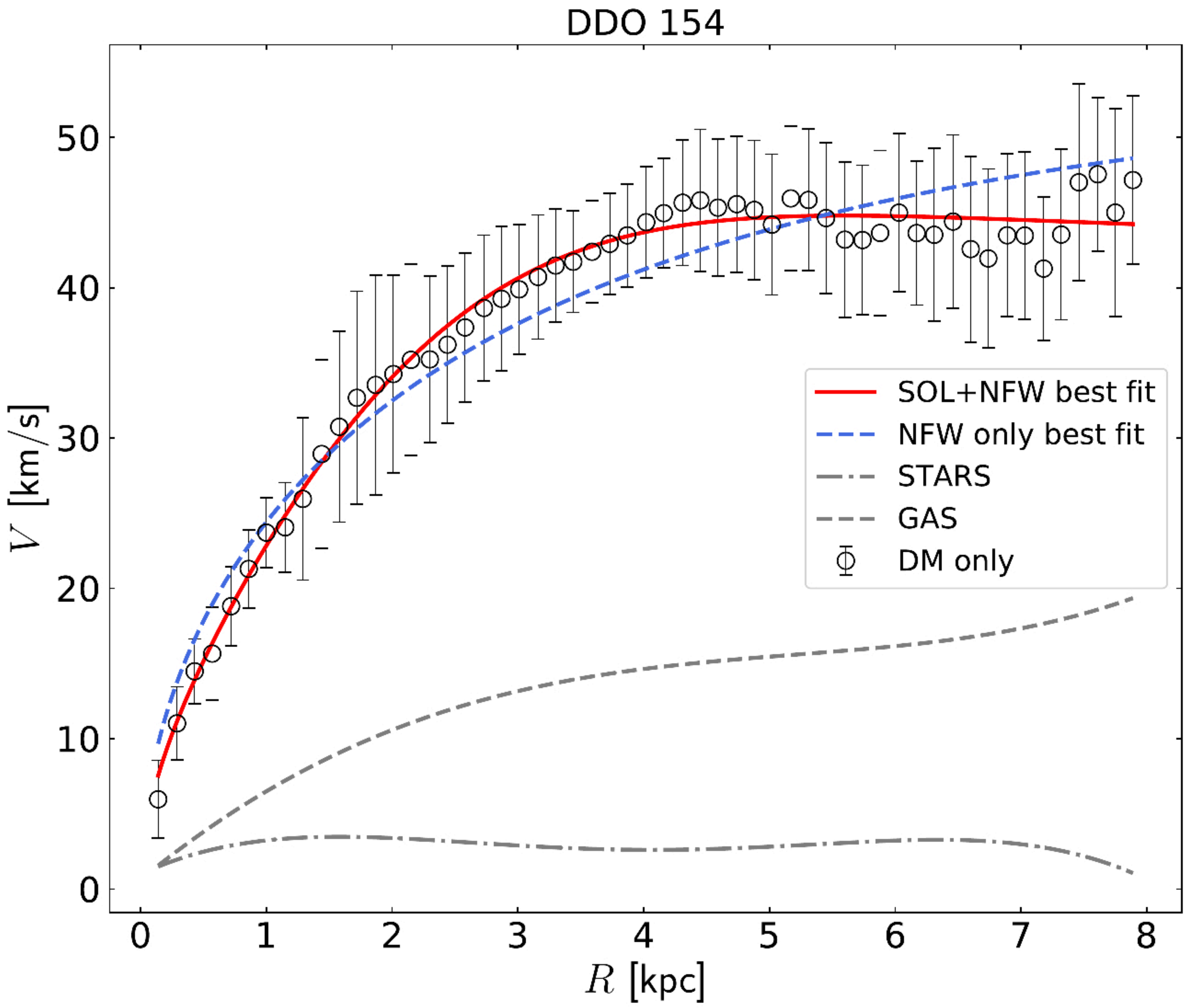


Chan et al 2022

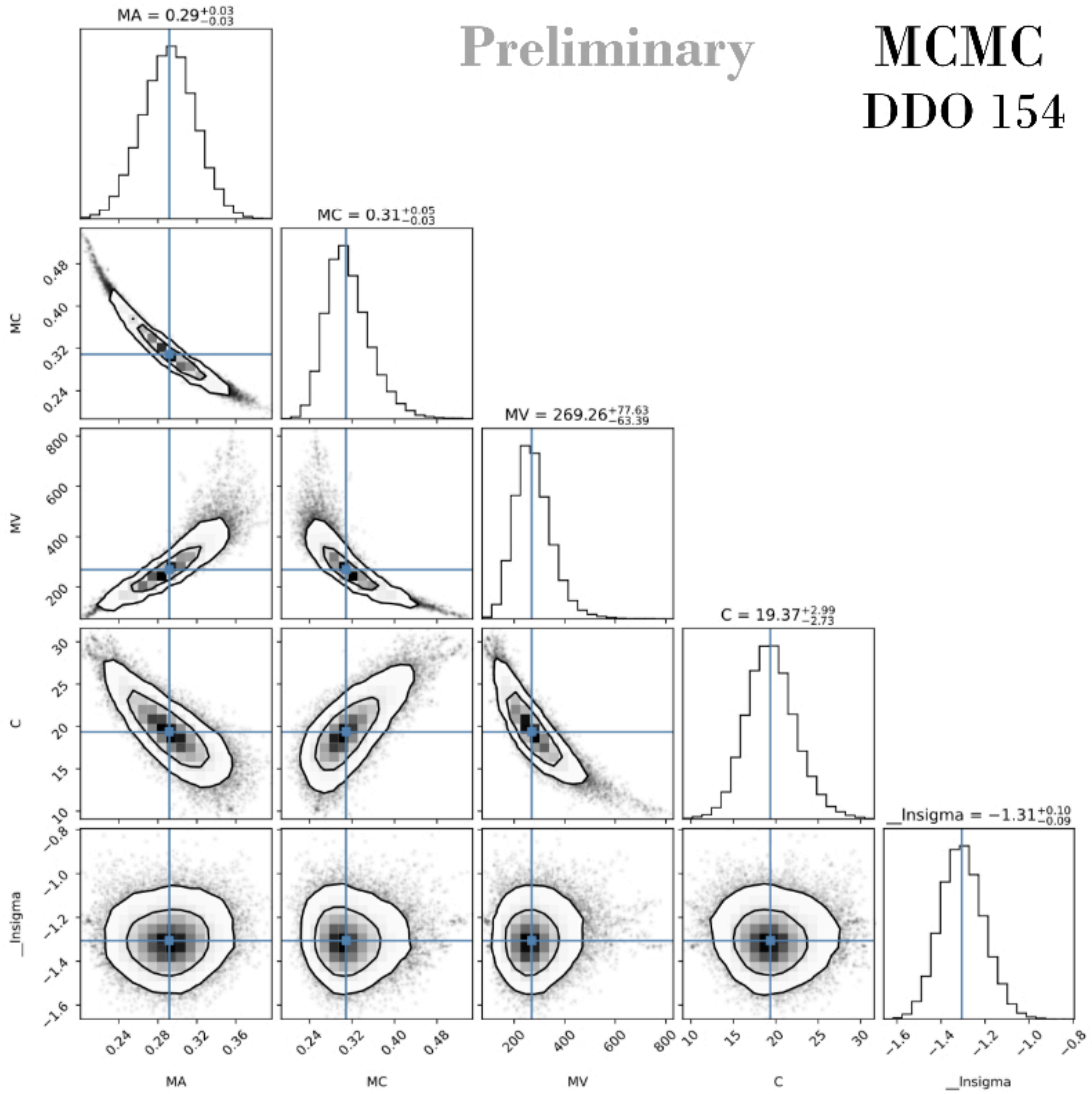
Confronting ULDM to rotation curves

Nearby dwarf irregular galaxies

- $10^6 M_\odot \lesssim M_* \lesssim 10^8 M_\odot$
- LITTLE THINGS catalog ~10 galaxies
- SPARC catalog ~15 galaxies

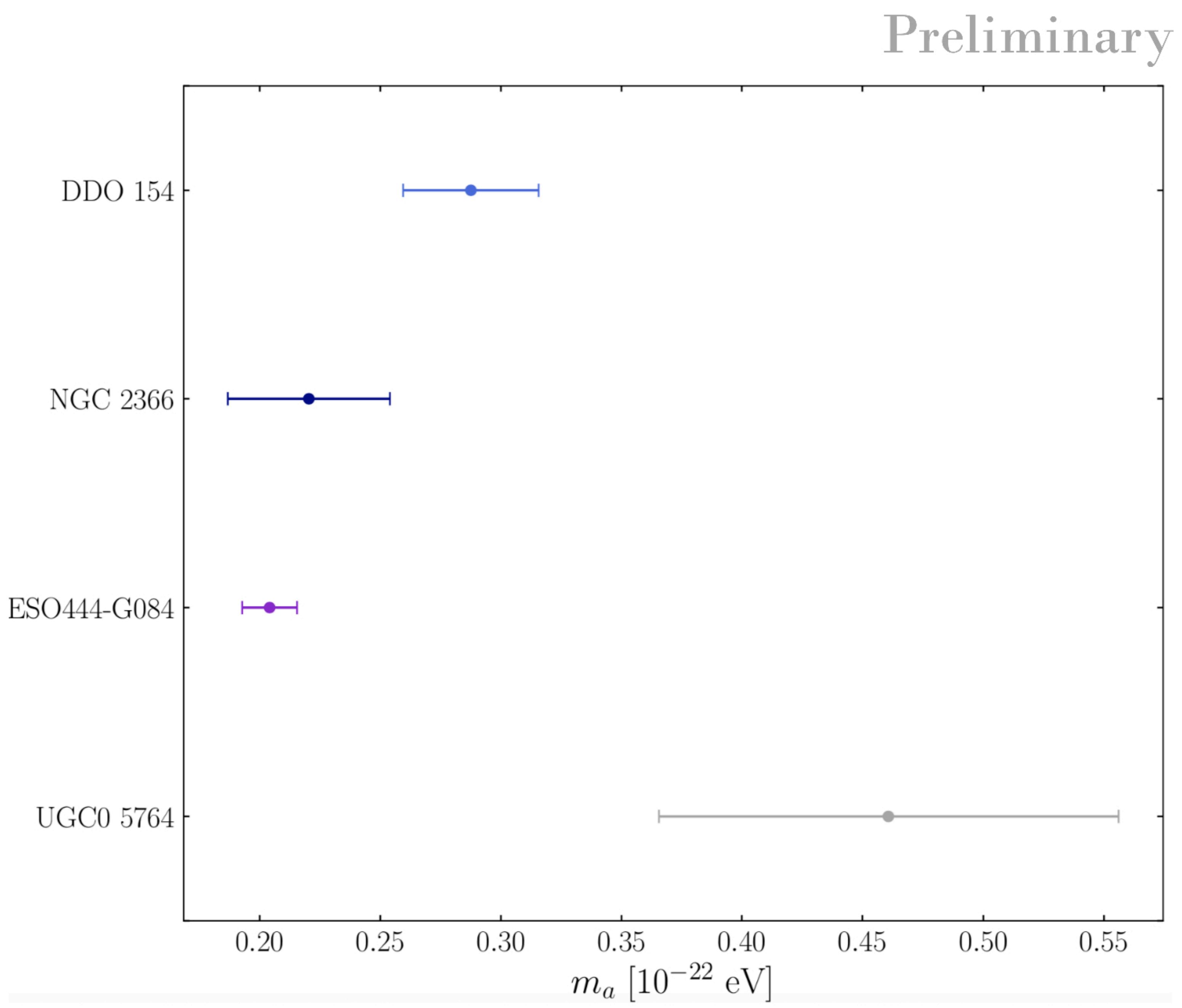


- Markov Chain MCs

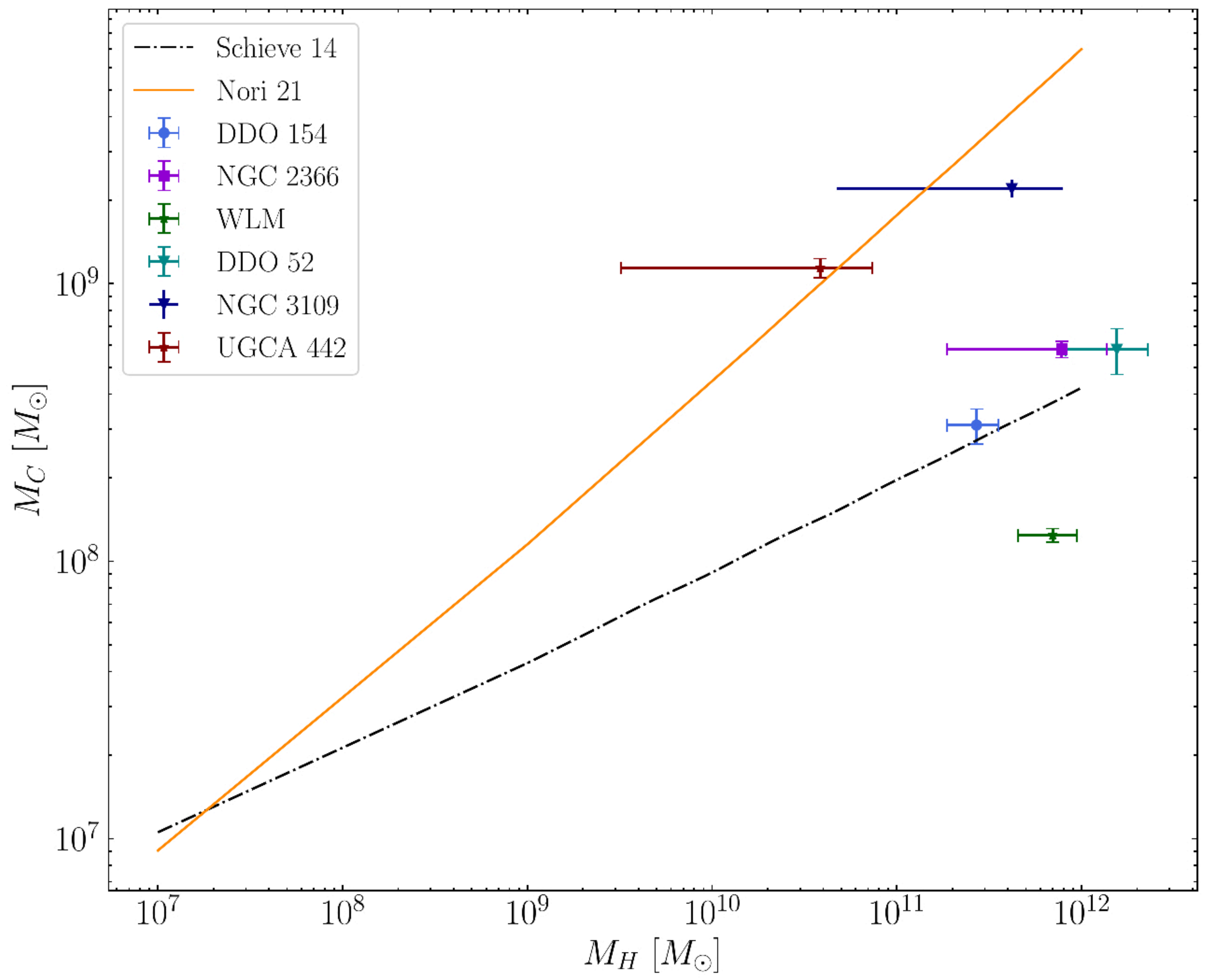


Self-consistency of ULDM

- Mass of the ALP



- Soliton-halo mass ratio



Challenging data

- Find robust/clean systems? Add more data/effects (stellar kinematics)?
- Nature of errors, purging outliers, degeneracy of parameters …
- **Assistance from G. Bataglia, N. Trujillo, J. Sánchez**

Summary activities of AT @ IAC

Members of the group

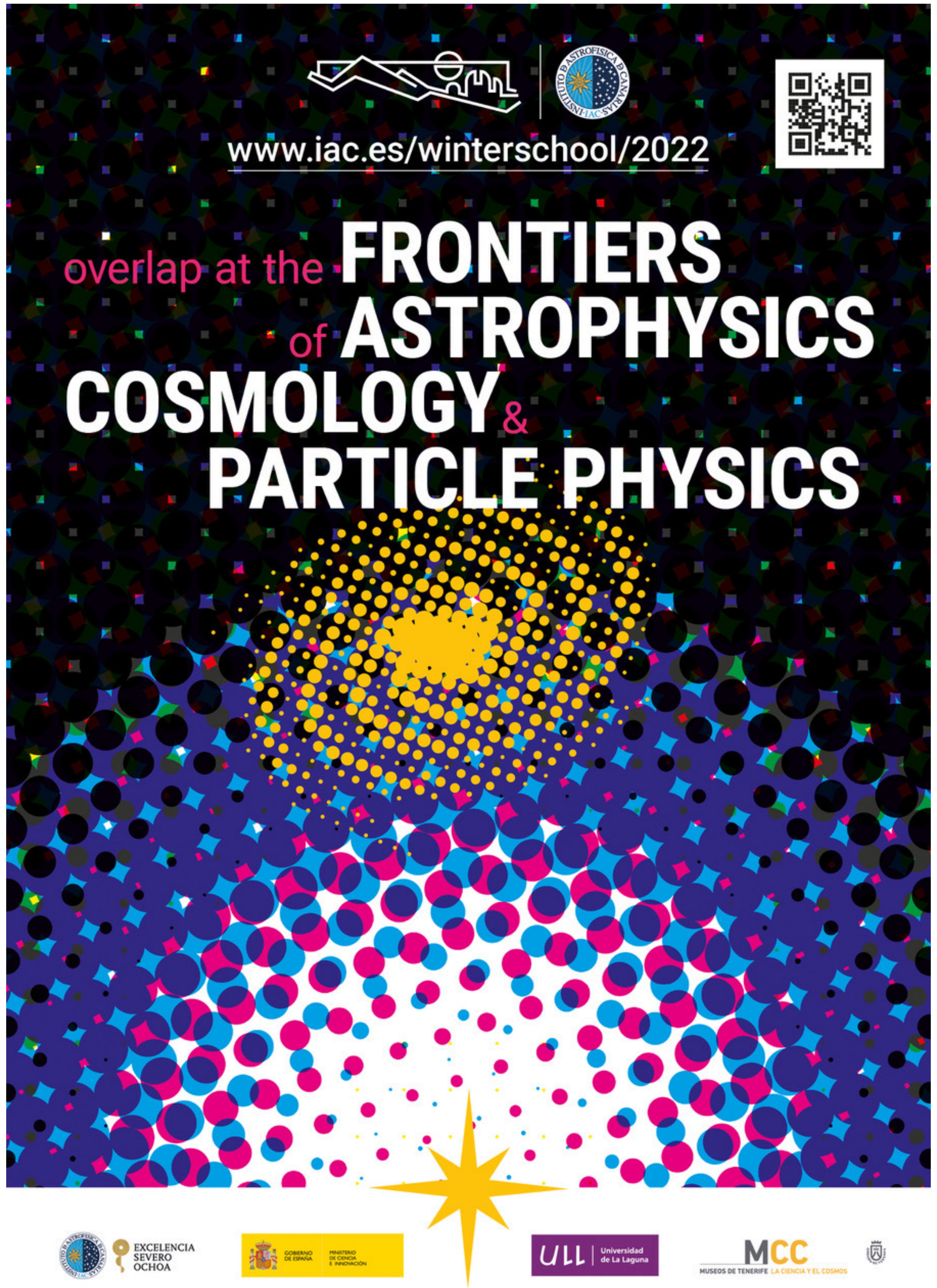
- **IP:** J. Martin Camalich
- **Postdoc:** A. Castillo
- **PhD:** J. Terol-Calvo (2), A. Bañares (1)

Other projects

- **Stellar cooling and ULDM:** Impact of heavy flavours in SN
- **Early Universe particle physics:** Baryogenesis and thermal axions
- **Sensitivity of TMS to axion flux from GC**

XXXIII Winter School of the Canary Islands

Organisers: C. Hernández-Monteagudo & J. Martin Camalich



Overview on connections between Cosmology and Particle Physics
Prof Diego Blas
IFAE - Barcelona
Personal webpage

Fundamental Physics with the Cosmic Microwave Background
Prof Fabio Finelli
INAF - Bologna

Dark Energy - theoretical and observational status
Prof Luca Amendola
University of Heidelberg

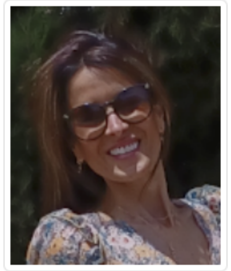
Fundamental Physics with Large Scale Structure
Prof Matteo Viel
SISSA - Trieste

Fundamental Physics with galaxies
Prof Kfir Blum
Weizmann Institute of Science - Rehovot

Early Universe and Inflation
Prof Valerie Domcke
CERN - Geneva

Dark Matter - theoretical and observational status
Prof Tracy Slatyer
MIT - Cambridge

Fundamental Physics with cosmic rays and gamma rays
Prof Francesca Calore
LAPTh - Annecy



Neutrinos in Cosmology and astrophysics
Prof Olga Mena
IFIC - Valencia

Gravitational Waves
Prof Vitor Cardoso
CENTRA/IST - Lisboa & Niels Bohr Institute - Copenhagen

Distinguished Lecturer
Prof Malcolm Longair
Cavendish Laboratory - University of Cambridge