Selected aspects of the particle vs wave nature of dark matter

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msca_axitools

Outline

- Particle vs wave behaviour is a rich topic, potentially deeply philosophical; impossible to cover in 30 mins
- Focus on axions and axion-like particles (ALPs); biased, but class of DM where both behaviours are relevant

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- Topics: some background, ultralight ALPs, DM simulations, observational opportunities
- Also: broader picture, complementary searches for ALPs and connections to other talks in this session, results from recent study of heavy ALPs in cosmology[2205.13549]

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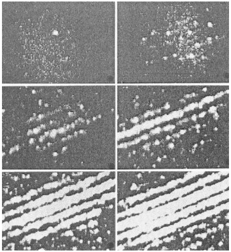

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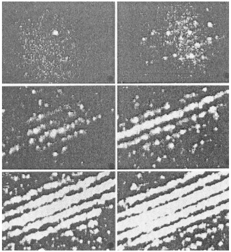

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➽ Key observable for "wavy DM" (ΨDM): *interference effects*

Where and how can we detect these?!

Manifestation of wavelike effects

Fundamental scale for the regime of wavelike behaviour is the *de Broglie wavelength*:

$$\lambda_{\mathrm{dB}} \equiv \frac{2\pi\hbar}{p} \sim 1\,\mathrm{kpc}\left(\frac{10^{-22}\,\mathrm{eV}}{m}\right)\left(\frac{100\,\mathrm{km/s}}{v}\right)$$

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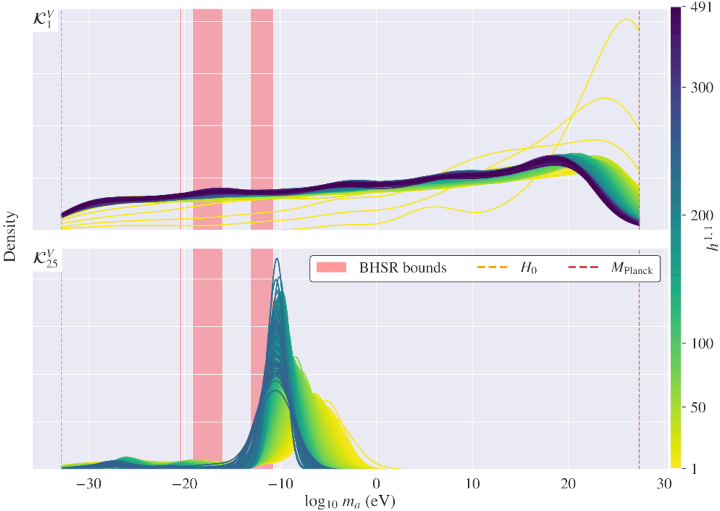
- Depends on mass and speed i.e. the particle model and its context (creation, environment)
- CMB and galaxy surveys tell us a lot about the largest scales, need to look at effects on sub-galaxy scale
- Galaxy sizes $\sim$ 1–100 kpc, so $m \gtrsim 10^{-22}\,\mathrm{eV}$ [astro-ph/0003365, 1610.08297]

Why study (ALPs as) ψDM?

ALPs in string theory



The "string axiverse" contains many ALPs over a wide mass range.[0905.4720] Explicit distributions have been computed for some type IIB compactifications.[2011.08693, 2103.06812] (some caveats?[2110.02964])

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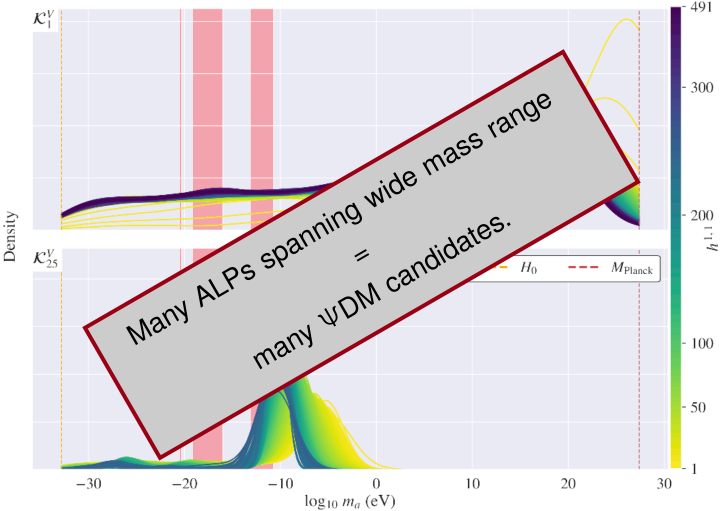

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Several “problems” have been discussed in past[e.g. 1707.04256]

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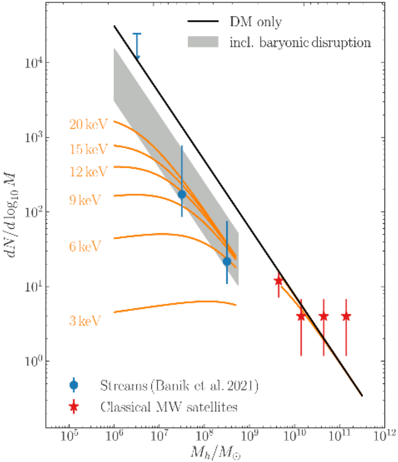
➽ Potentially “non-problems” or explained by galaxy formation history, baryonic physics; still, allow test of ΨDM!

Effects of ΨDM

ΨDM similar to warm DM: suppresses structures with smaller sizes or masses; e.g. halo distribution of subhalo mass function[1911.02663]



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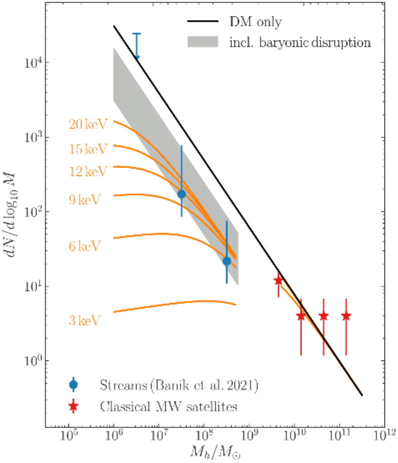
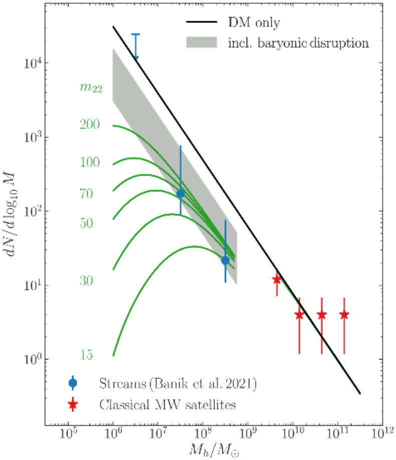
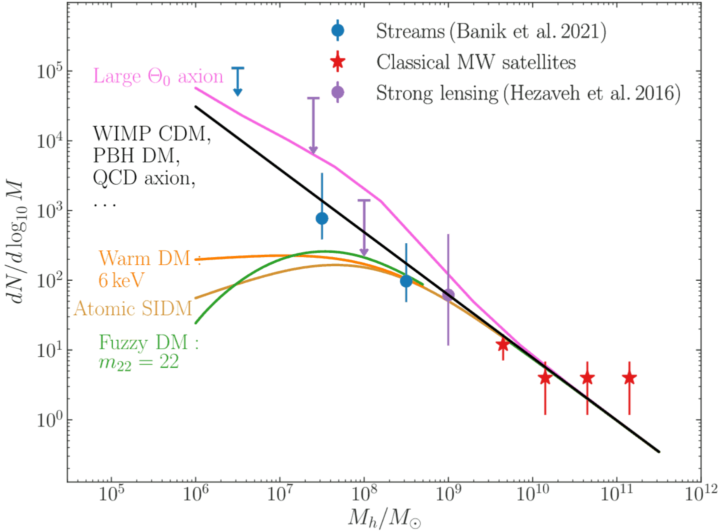


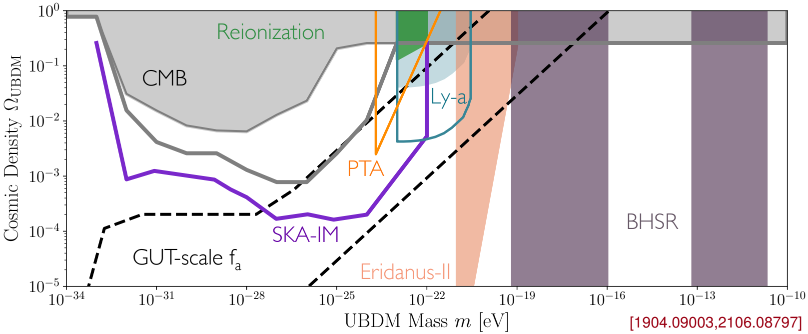


Effects of ΨDM

Shape of SHMF can be probed with different observables[1911.02663]



Outlook on Ψ constraints



[1904.09003,2106.08797]

More details in talks by E. Kendall & B. Bucciotti, later today

- ΨDM solitons: tracer star dispersion, direct detection, axionova, exotic compact object in GWs
- BH(SR), (stimulated) decays, dSphs, Ly-α, PTAs, strong lensing, ...

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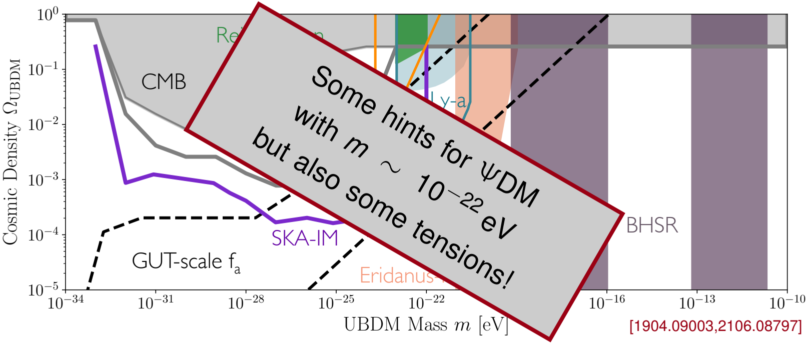

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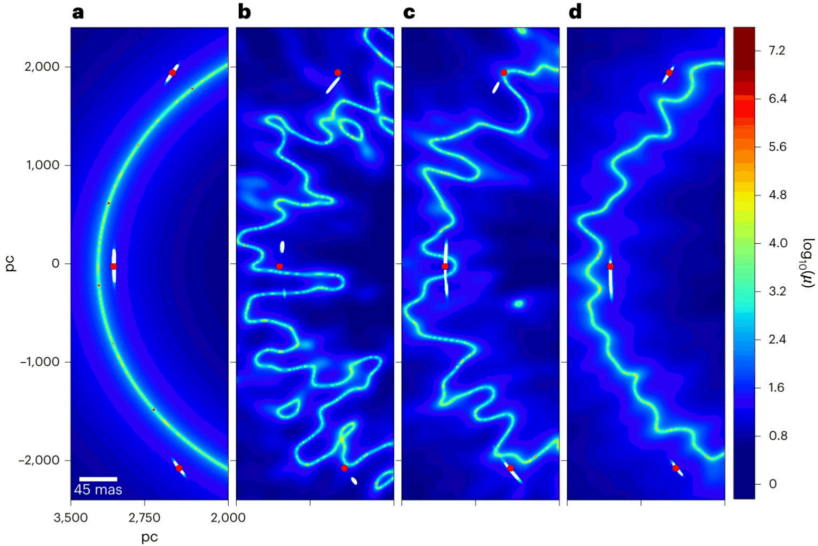
➽ ΨDM predicts more SHs and underdensities due to destructive interference: distinguishable!

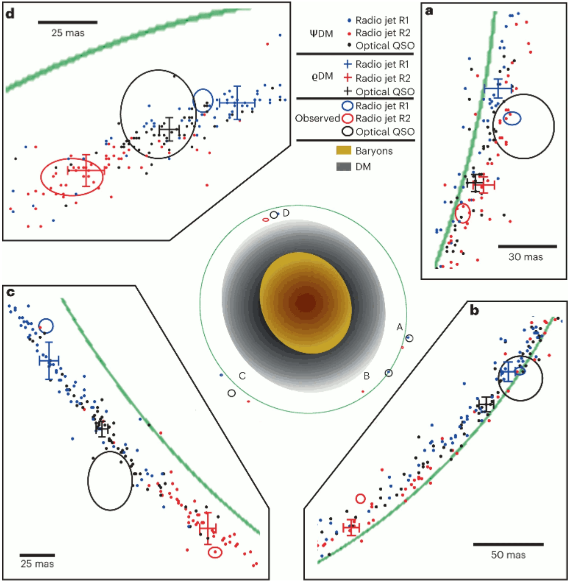
➽ New study[2304.09895] looks at quadruply-lensed quasistellar object + 2 radio jets in HS 0810+2554

Strong gravitational lensing for ΨDM



Lensing magnification for (a) particle DM, (b)–(d) ΨDM with increasing number of baryons[2304.09895]

Strong gravitational lensing for ΨDM



- Claim: ΨDM gives better fit[2304.09895]
- However: how good is the fit really in absolute terms? Modelling with Gaussian random fields realistic?

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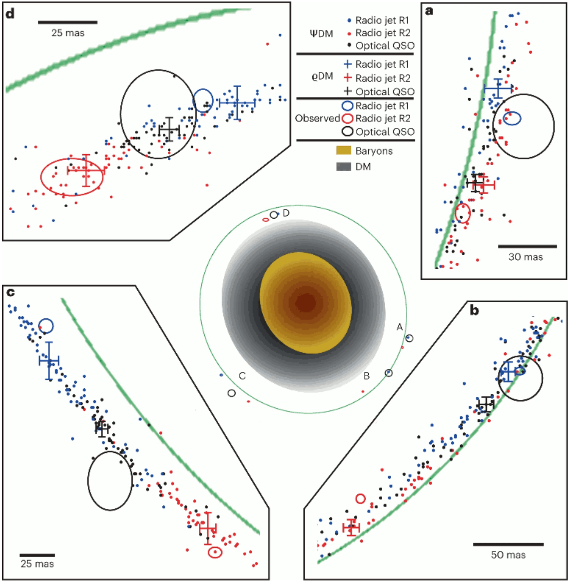

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- However: how good is the fit really in absolute terms? Modelling with Gaussian random fields realistic?

➸ Let's be cautious, but could be getting interesting!

The case for ALPs as (Ψ)DM

- String theory predicts many ALPs with many different masses; could be ΨDM
- Bosons/ALPs with $m \sim 10^{-22}$ eV affect structure formation and are testable in many ways
- Bosons do not suffer from the Pauli exclusion principle; fermions have $m_f \lesssim$ keV[Tremaine & Gunn '79]
- Many other theoretically appealing properties,[1510.07633, 2003.01100] numerous ongoing and planned ALP searches[1602.00039]

Simulations

Numerical description for DM sims

Schrödinger–Poisson (SP) eq. describes ΨDM (with AMR techniques)[talk by E. Kendall]

$$\mathrm{i}\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2ma}\nabla^2\psi + mV\psi\,, \quad \nabla^2 V = \frac{4\pi G_\mathrm{N}}{a}\left(|\psi|^2 - \langle|\psi|^2\rangle\right)$$

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Vlasov–Poisson (VP) eq. describes particle DM using N-body techniques; “(simulation) particle” have masses orders of magnitude larger than the DM particle mass and “softer” gravitational potential V

$$\frac{\partial f}{\partial t} = -\frac{1}{ma^2}\mathbf{p}\cdot\nabla f + \nabla V\cdot\frac{\partial f}{\partial \mathbf{p}}\,, \quad \ldots$$

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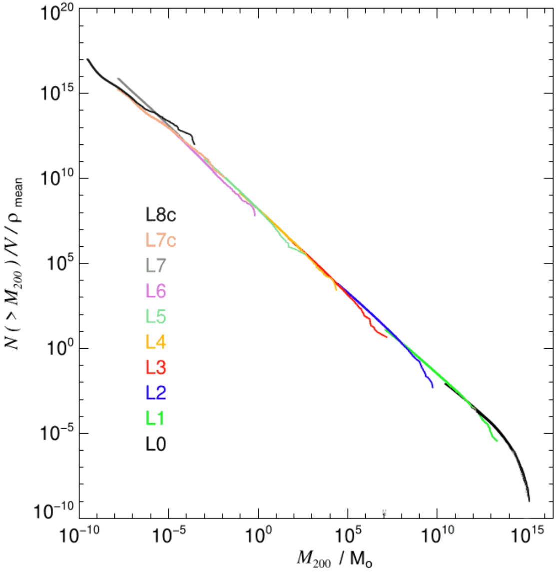
SP-VP correspondence: on larger-than-halo scales, the two approaches are found to be in agreement; deviations $\mathcal{O}(\hbar^2/m^2)$.

See Snowmass community report for current status of sims[2203.07049]

Status of pure CDM N-Body sims

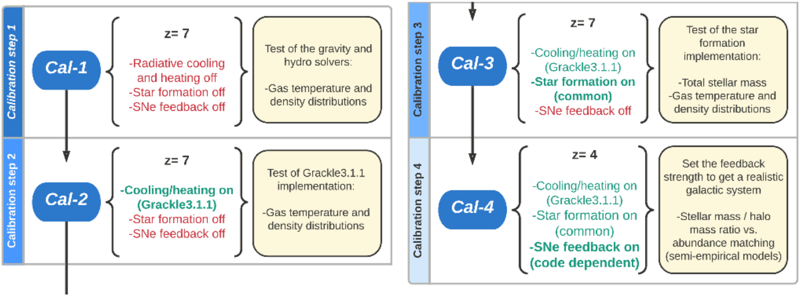


- Pure particle CDM case "solved" now across all masses with zoom-in simulations[1911.09720]
- Currently: refine hydro, baryonic effects, SN feedback, …

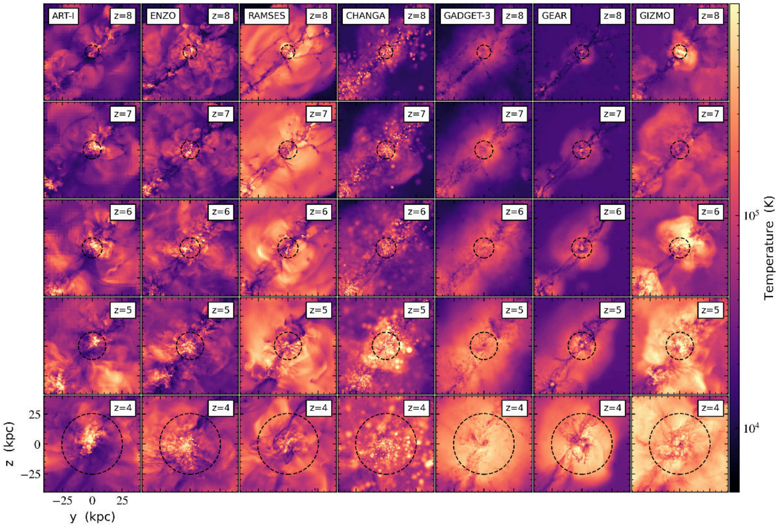
The AGORA project

Can we trust the DM sims? Can baryonic effects successfully explain the observations? Sims are expensive – better make sure that we all agree on the outcome/conclusions.

Goal of the AGORA project. Systematically calibrate software codes and compare results



The AGORA project



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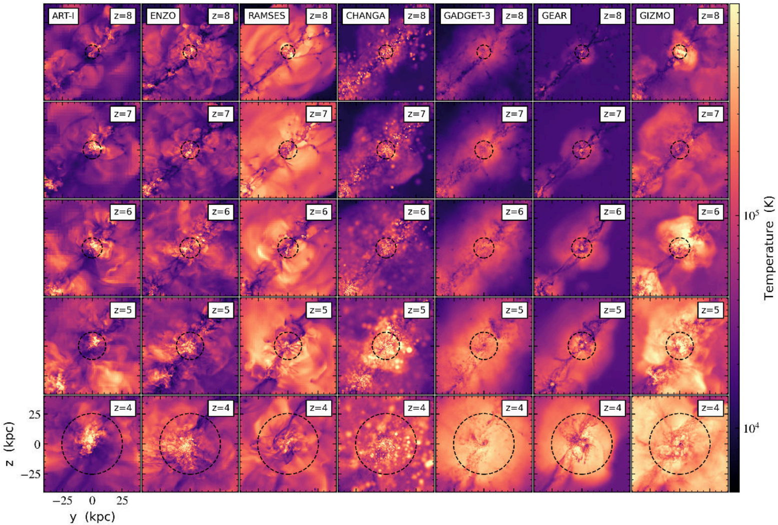
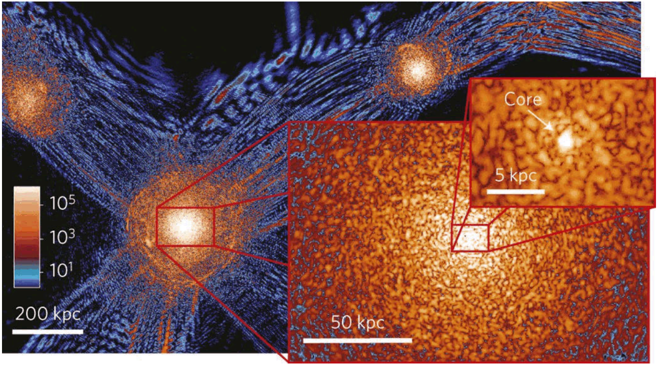


➽ Calibration ensures agreement on "basics" – consolidation of codes; remaining differences due to more complex physics

Simulations of ΨDM

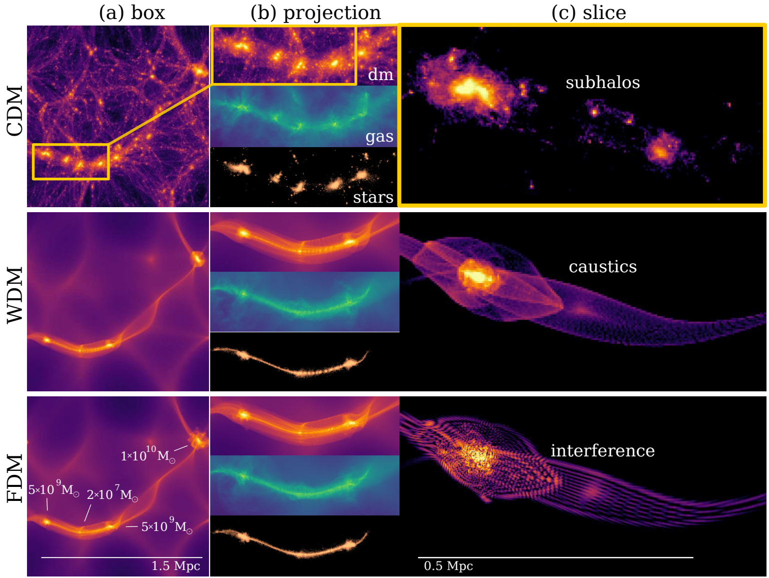
Do we see wavelike effects of ΨDM in simulations?



Yes! Simulations[1406.6586] find interference fringes; halos with NFW in outer region, solitonic cores (standing waves) in inner region:

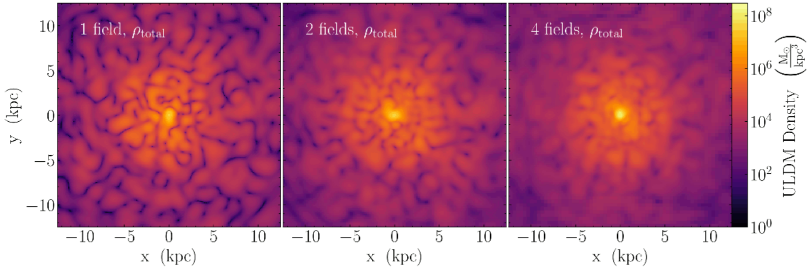
$$\rho_* \propto \left[1 + 0.09\left(\frac{r}{r_*}\right)^2\right]^{-8}, \quad M_* \propto M_{\text{halo}}^{-1/3}$$

Simulations of ΨDM



Large-scale structure for different DM types[1910.01653]

Simulations of multi-field ΨDM



- Recall: string theory predicts many (light) axion fields; what if they interact gravitationally?[2301.07114]
- Interference pattern/granular structure washes out (unless there is an extreme mass hierarchy)
- Observable effects on stellar velocity dispersion:

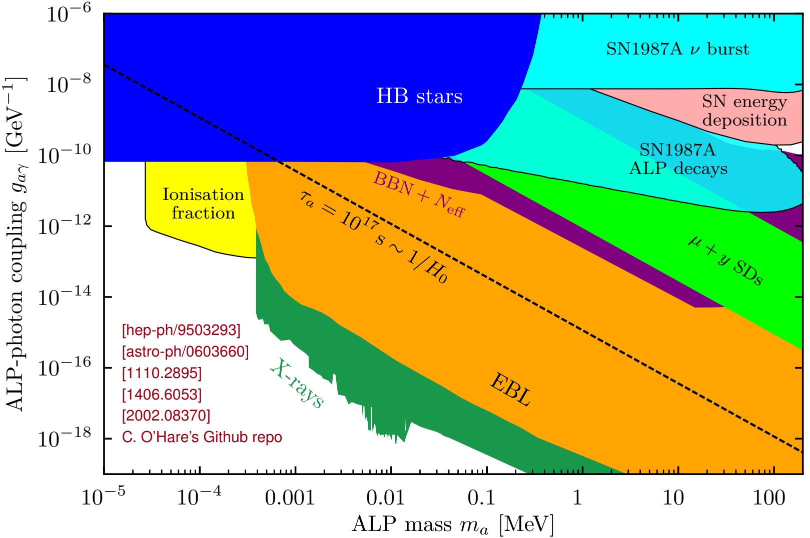
$$\Delta\sigma^2 \propto N^{-2} \sum_i m_i^{-3} \sim N^{-2} \min_i \{m_i\}$$

See also similar simulation studies[2212.14288, 2302.04302]

MeV-scale ALPs in cosmology

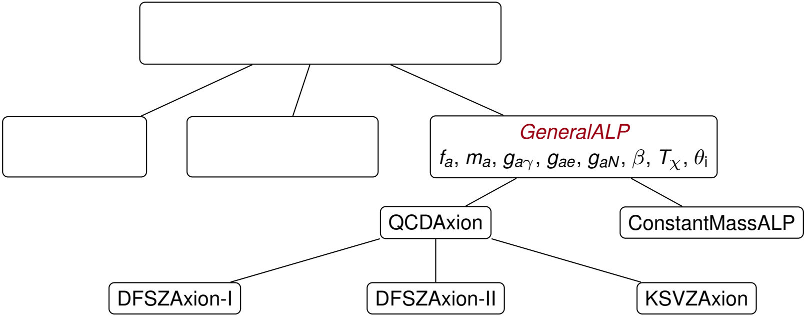
High-mass ALPs – cosmologically excluded?

Now: $m \sim$ MeV; explore connections to cosmo and astro[2205.13549]



ALP models in GAMBIT

Can extend "family tree" of ALP models in GAMBIT[1705.07908] from previous study[1810.07192] and "CosmoBit" extension[2009.03286, 2009.03287]



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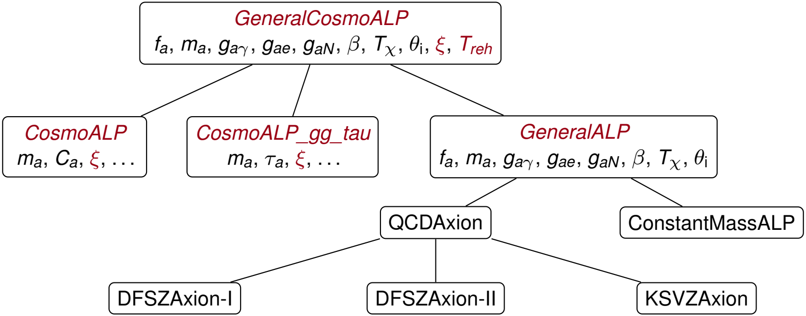

- New params: abundance ξ and reheating temperature T_reh
- Automatic parameter translation: can use pre-existing axion likelihoods out of the box

The ALP model

GeneralCosmoALP
8 model parameters:
f_a, m_a, $g_{a\gamma}$, g_{ae}, g_{aN}, β, T_χ, θ_i, ξ, T_reh

- Only interaction: coupling to photons via $\mathcal{L} \propto g_{a\gamma}\, \vec{E} \cdot \vec{B}$

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- Simple ALP: m_a const.

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GeneralCosmoALP

4 model parameters:

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- Simple ALP: m_a const.
- Thermal and realignment contributions to ξ but we focus on irreducible freeze-in mechanism[0911.1120]

$$\xi_{FI} \sim \left(\frac{m_a}{50\,\mathrm{MeV}}\right)\left(\frac{T_{reh}}{5\,\mathrm{MeV}}\right)\left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^2 \mathrm{e}^{-m_a/T_{reh}}$$

The ALP model

GeneralCosmoALP

3 model parameters:

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- Choose ξ as free parameter (multi-component DM model), fix $T_\mathrm{reh} = 5\,\mathrm{MeV}$ to ignore degeneracies

The ALP model

CosmoALP_gg_tau
3 model parameters:
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➸ Parameters: mass m_a, lifetime $\tau_a \leftrightarrow g_{a\gamma}$, abundance ξ

The cosmological model (target region)

- 6-parameter ΛCDM model: ω_b, ω_c, H_0, z_re, A_s, n_s
- *In total 12 parameters*: 3 ALP, 6 LCDM, 2 experimental parameters, neutron lifetime

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- Can the ^{7}Li problem[1203.3551] be improved by ALPs?[2011.06519]

- ROI: 0.01 MeV $< m_a <$ 200 MeV; 10^4 s $< \tau_a < 10^{13}$ s, i.e. decays between BBN and CMB formation

Constraints & likelihoods in target region

Cosmology

- CMB anisotropies (modification of recombination history)
- CMB spectral distortions (SDs/energy injection from ALPs)
- BBN element abundances (photodisintegration)
- ΔN_{eff}, η_{b} (photon injection/higher T_γ)
- BAO (structure formation)

Astrophysics (see other talks later today!)

- SN1987A missing gamma-ray burst (ALP decays); update of [1702.02964], see also [2212.09764]
- HB vs RGB star counts (stellar evolution, cooling)
- Type-Ia SNe (Pantheon sample)

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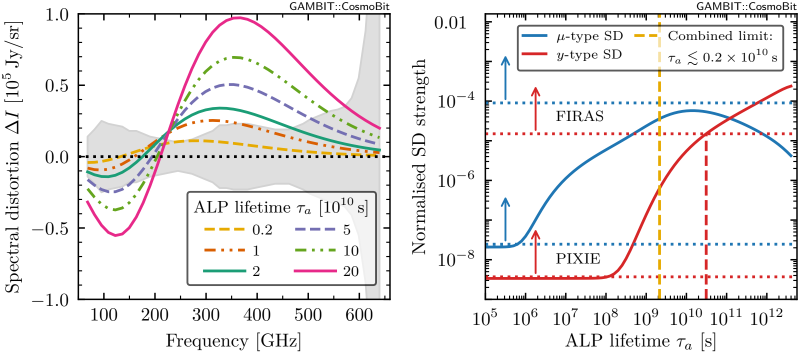
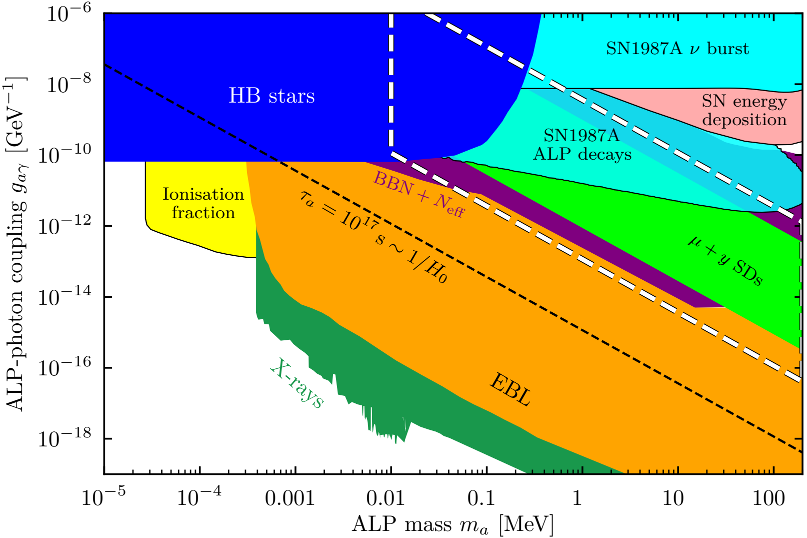
➸ Not all constraints are equally relevant in this study

ALP constraints from spectral distortions (SDs)



- ALPs with $\tau_a \lesssim 10^{10}$ s induce larger-than-observed SDs
- Total SD shape (from CLASS/MontePython) is significantly more constraining than μ or y SDs individually
- Proposed future CMB missions (e.g. PIXIE) could give orders of magnitude stronger constraints

Results – ALP limits



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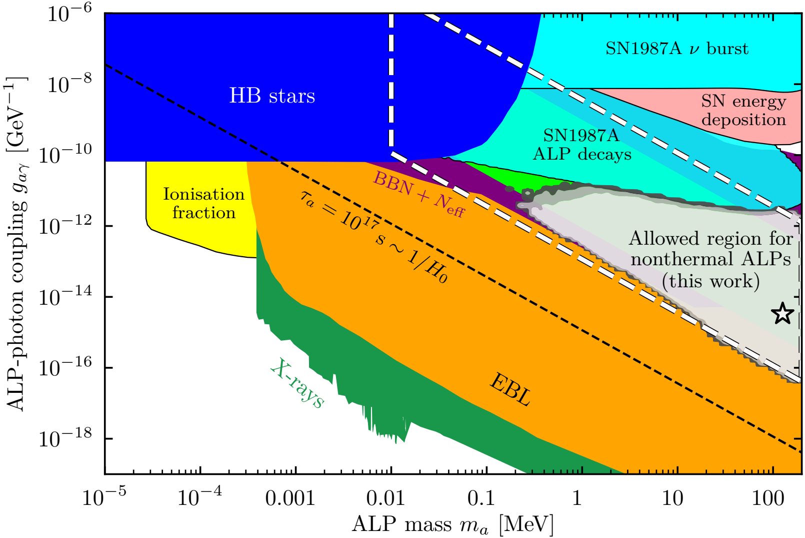
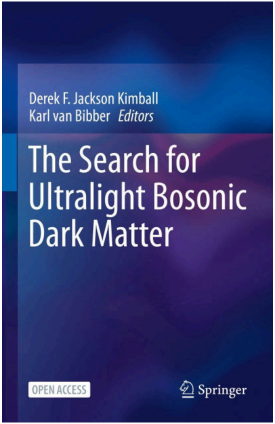


Where to find out more?

Open-access textbook with exercises:



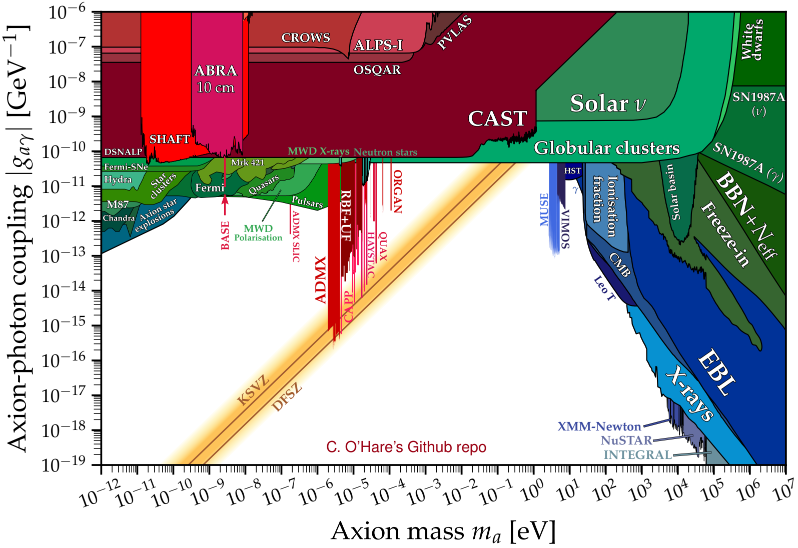
- Slides from FDM Workshop 2020
- Many good reviews on ΨDM: [1912.07064, 2005.032544, 2101.11735, 2203.07049, . . .]
- Talks at this conference on PTAs light particles and stellar or extreme astrophysical environments, UL/ΨDM constraints
- Ask questions now!

Some take-home messages

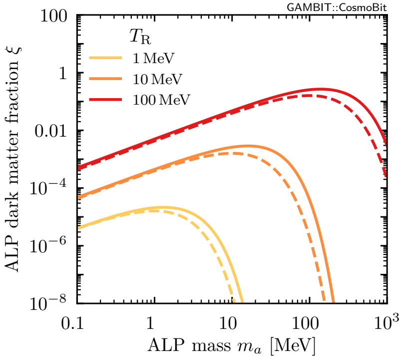
- Wave DM? Particle DM? Depends on m and v!
- ALP models span many orders of magnitude in mass; wavelike effects can occur
- ΨDM suppresses structure formation, solitons form in centre of halos, interference $\rightarrow$ density fluctuations
- Observable/distinguishable with dSphs, (strong) lensing, PTAs, Ly-α, ..., BHSR and other astro constraints
- Heavy ALPs are still viable in cosmology, but cannot solve ^{7}Li problem due to SD constraints

Backup slides

ALP searches

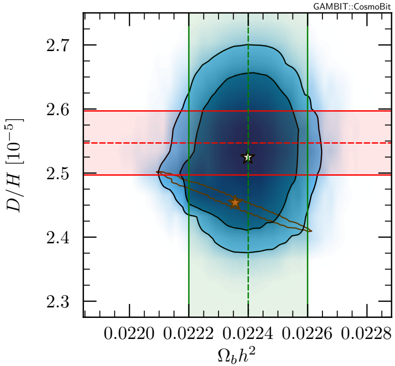


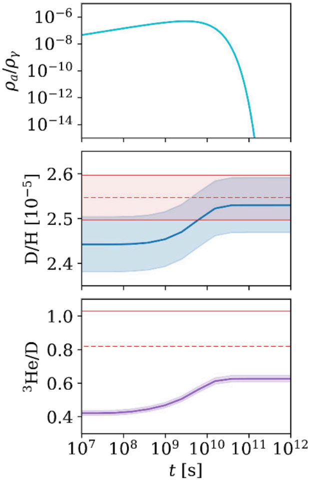
ALP DM from freeze-in



- Precalculate and tabulate freeze-in contribution to nonthermal abundance (ξ_{FI}) with `micrOMEGAs`
- Ensure consitently that $\xi \geq \xi_{FI}$ by invalidating points otherwise

Improvement of the MeV ALP fit





- ALPs slightly ($< 1\sigma$) improve fit
- In ΛCDM: correlation between $\Omega_\mathrm{b} h^2$ & [D/H]; for ΛCDM+ALPs: no corr. due to photodisintegration