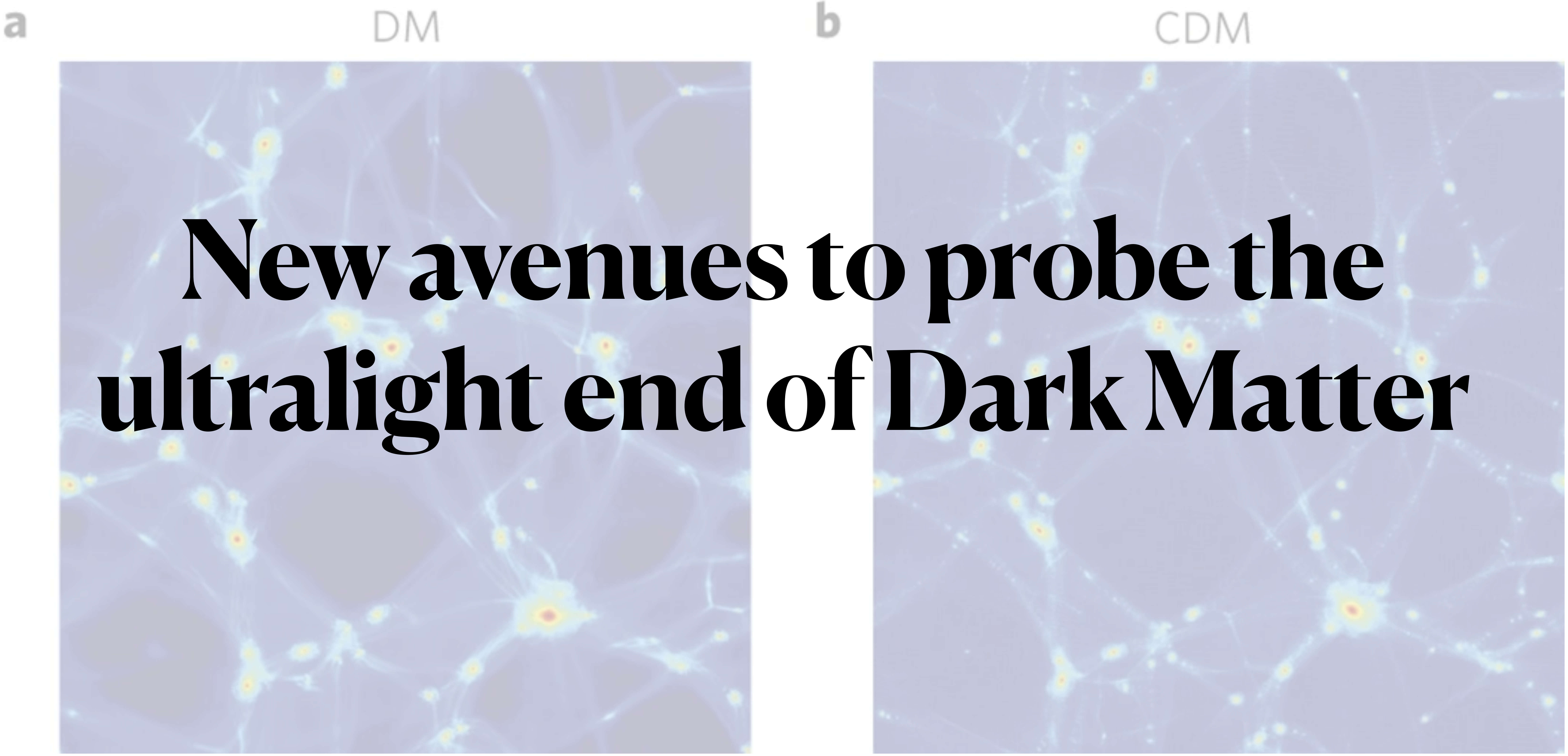
New avenues to probe the ultralight end of Dark Matter



What if Dark Matter is made of ultralight axions? ($m_a \ll$ eV)

- It has (at least) two big phenomenological differences from Cold Dark Matter
  - the formation of cores in the centers of DM halos
  - the suppression of small scale inhomogeneities (light halos, $M_{\rm v} < 10^8\, M_\odot$)

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- **Why? (very fast)**
- **How does it compare to observations? And what new avenues are we studying**

Why the formation of cores?

About the quantum wave nature

- The Compton wavelength $\lambda = \dfrac{h}{m_a}$, defines the scale at which a particle's wave (quantum) nature needs to be taken into account
- For $m_a = \mathcal{O}\left(10^{-22}\,\mathrm{eV}\right) \rightarrow \lambda = \mathcal{O}\left(1\,\mathrm{pc}\right)$, galactic scales are kiloparsec
- Inside the halo that hosts a galaxy, there is a high occupation making the DM wave a classical object

Why the formation of cores?

About the quantum wave nature

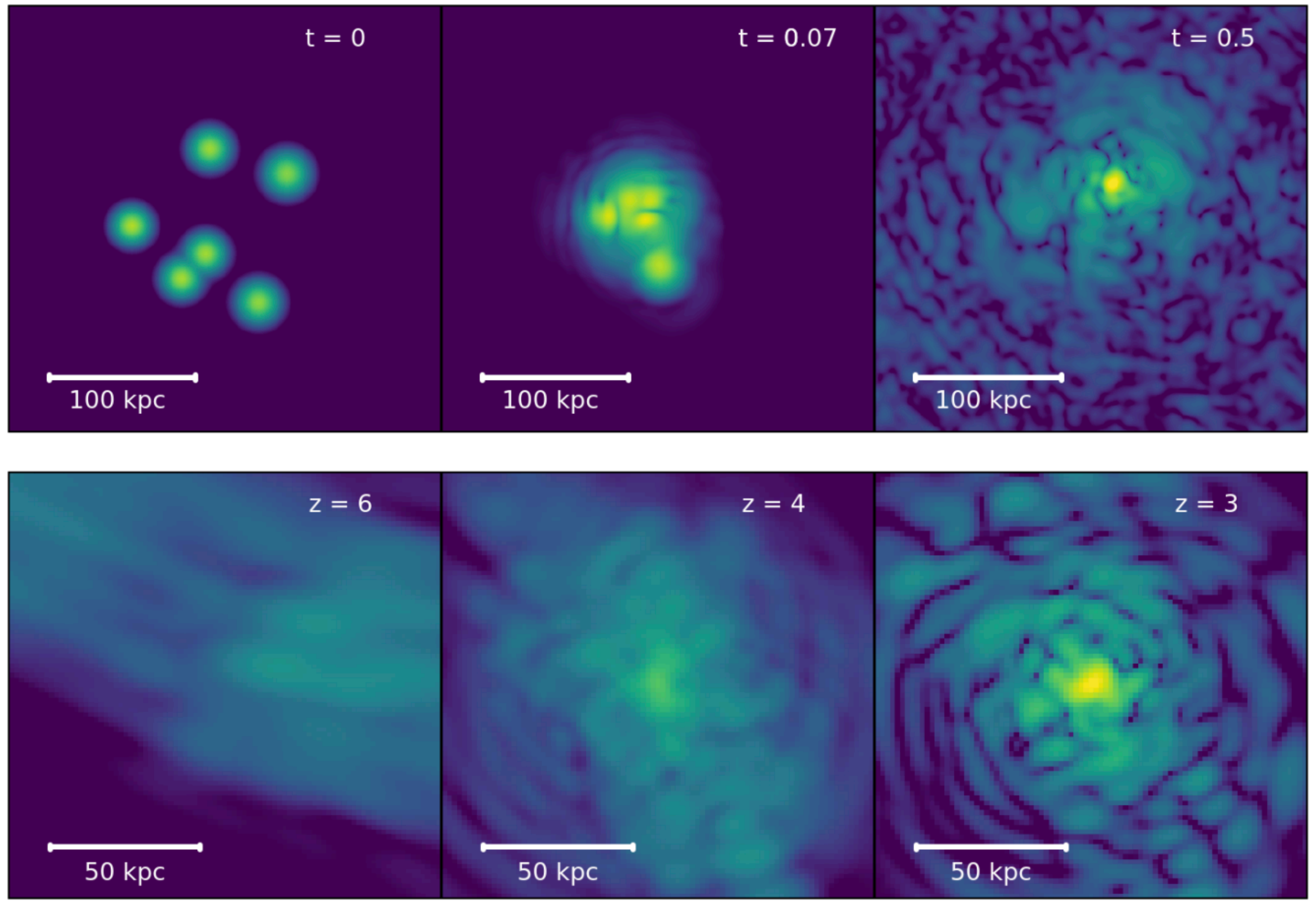
- You need to solve the coupled non-linear Schrödinger like equations where the density of the field has to solve a Poisson equation
- needs to be solved numerically,

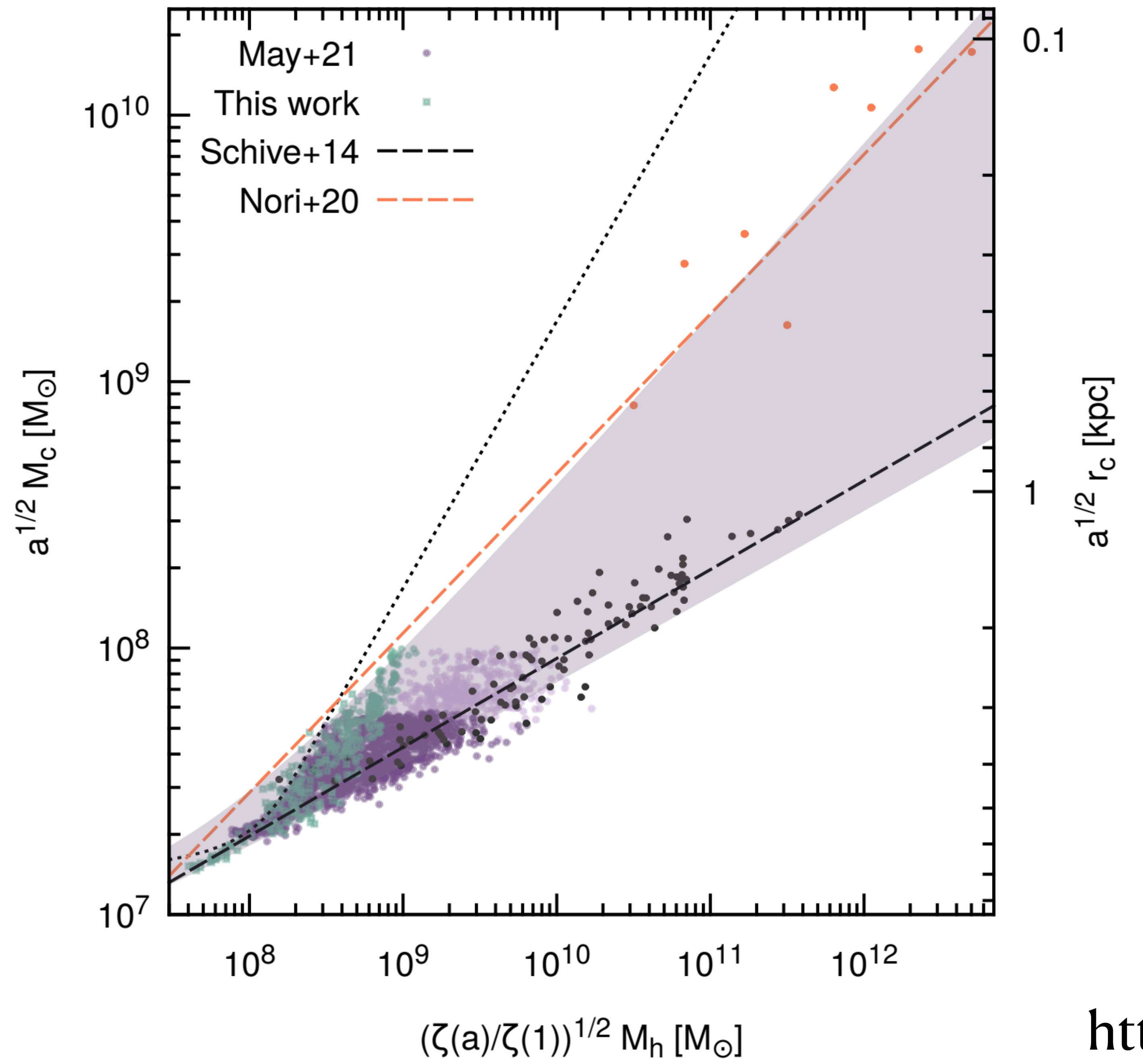
$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi,$$
$$\frac{\nabla^2 V}{4\pi G} = m\left|\psi\right|^2,$$

Why the formation of cores?

About the quantum wave nature

- You can rely on cosmological simulations, which predict big spreads for the relation between the core properties and the halo that hosts them, it reflects the range of merger histories and environments



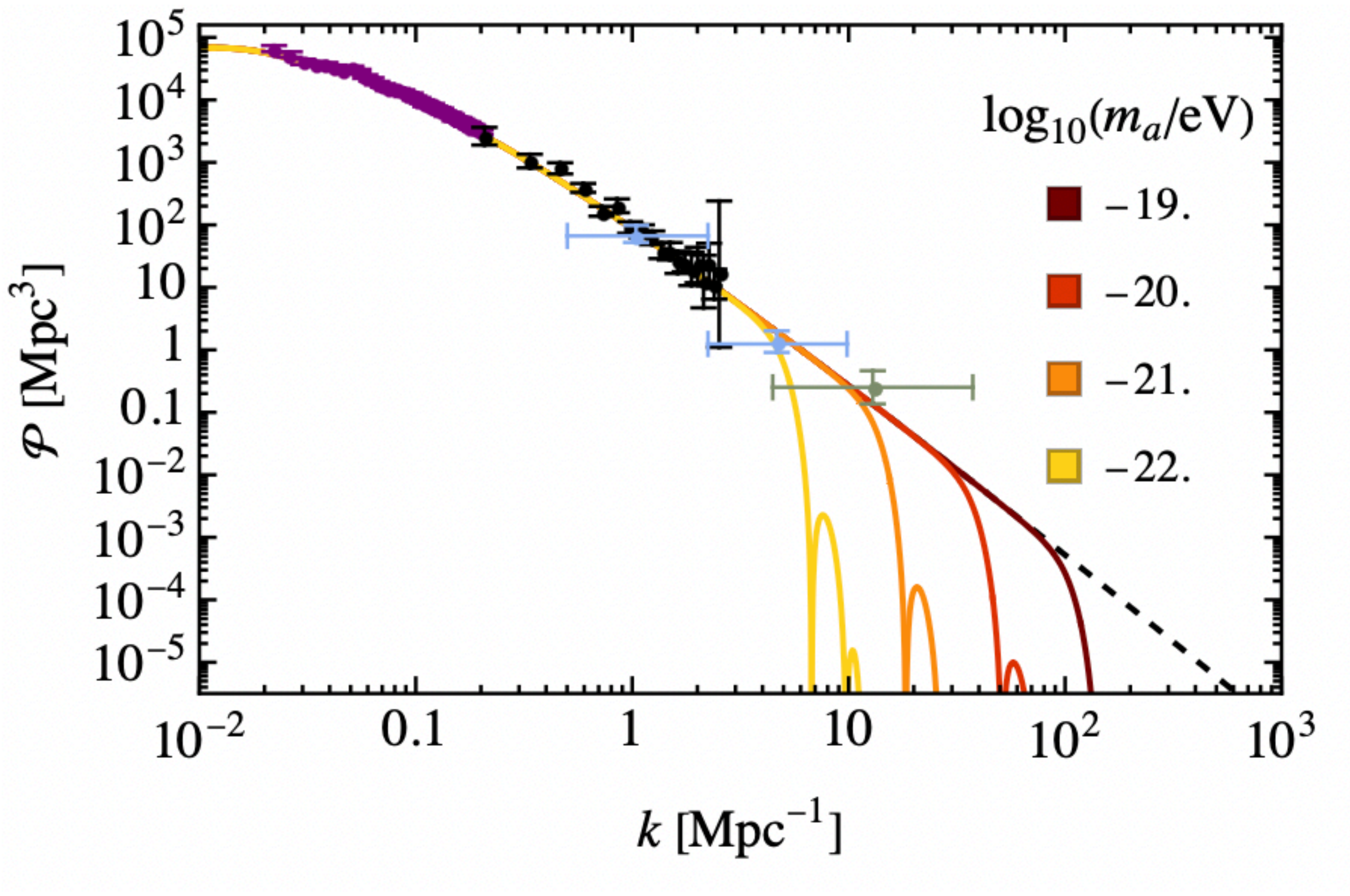


https://arxiv.org/pdf/2110.11882

Why the supresion of small scales?

About Heisenberg's uncertainty principle

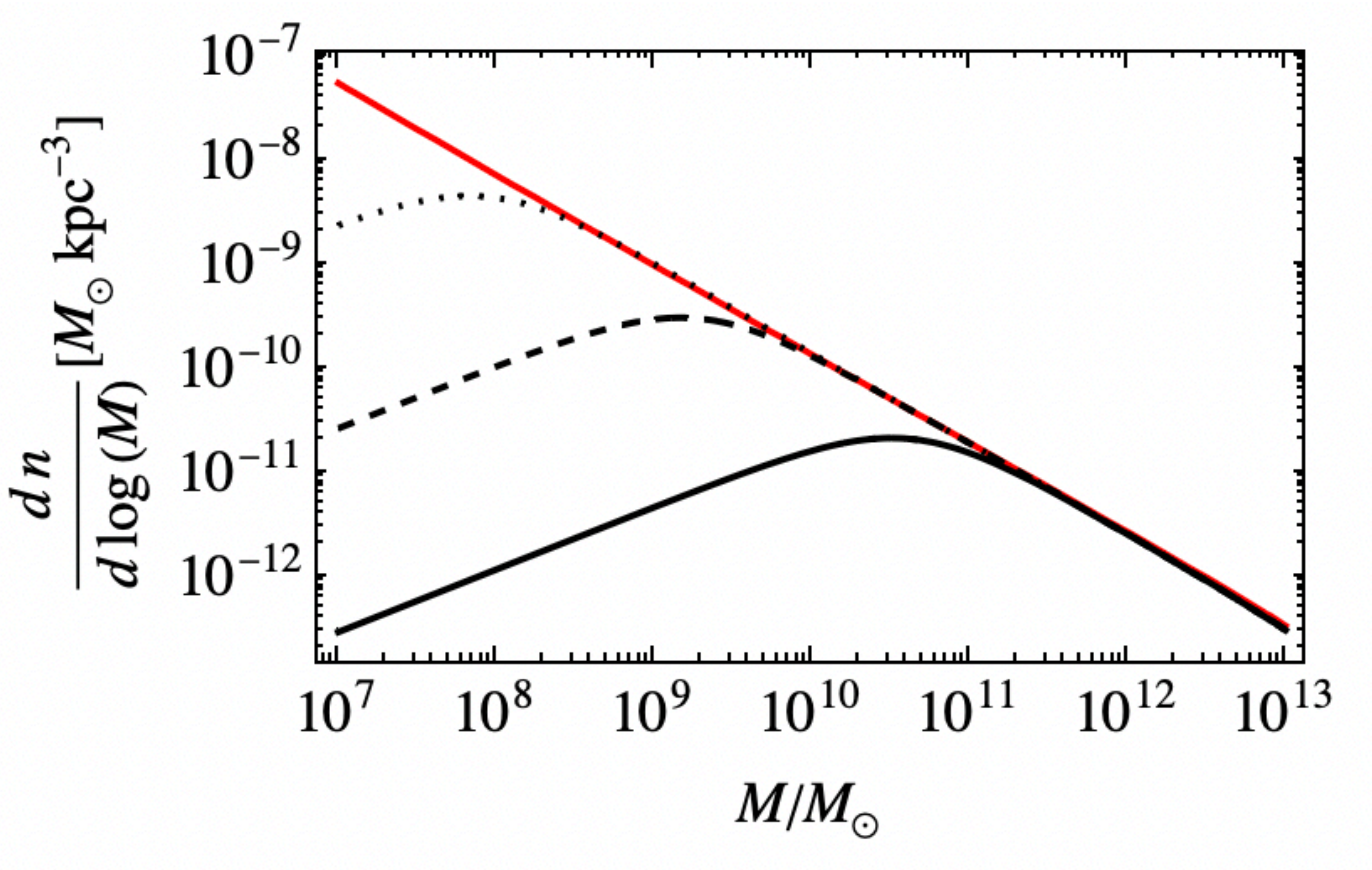
- Matter perturbations are affected by quantum pressure which supresses perturbations between the Jeans scale, $k_J = \frac{9 \times 10^{-3}}{\text{kpc}} \times \left(\frac{m_a}{10^{-22}\text{eV}} \right)^{1/2}$

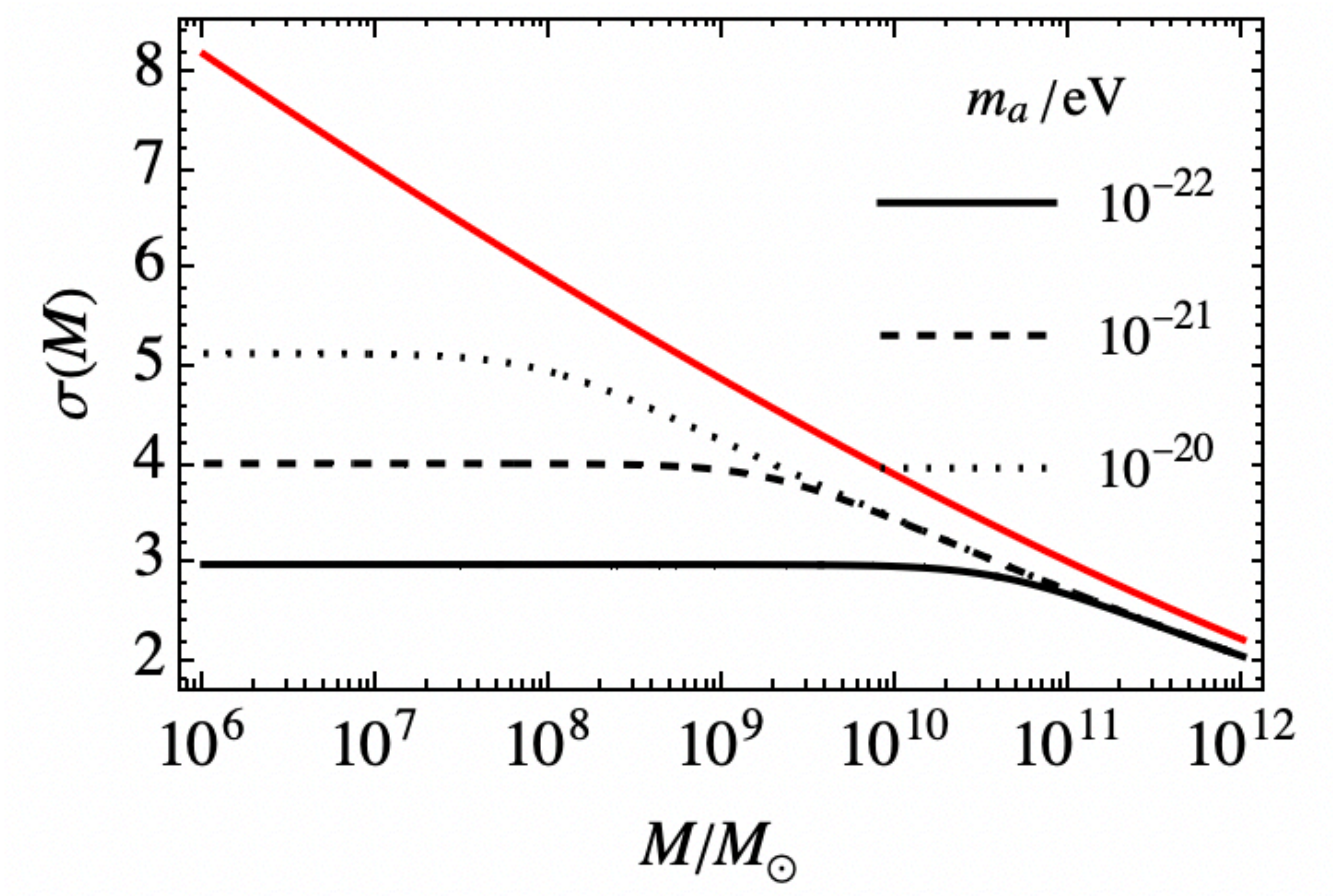


Why the suppression of small scales?

About Heisenberg's uncertainty principle

- These suppression of small scales translates into a very sharp reduction of light mass halos,
- the windowing function+EPS formalism determines the halo mass function





Juan Urrutia-KBFI 2025, PhD student

The problems with Cold Dark Matter (CDM) or why FDM is popular

- Missing satellite problem → **suppression of small scales**
- Cusp vs core problem → **formation of cores**
- Where CDM works so does FDM
- It is a generic prediction of String Theory, (i.e. the axiverse)

Fuzzy dark matter fails to explain the cores in ultra-faint dwarfs

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Soon to appear on the arXiv!

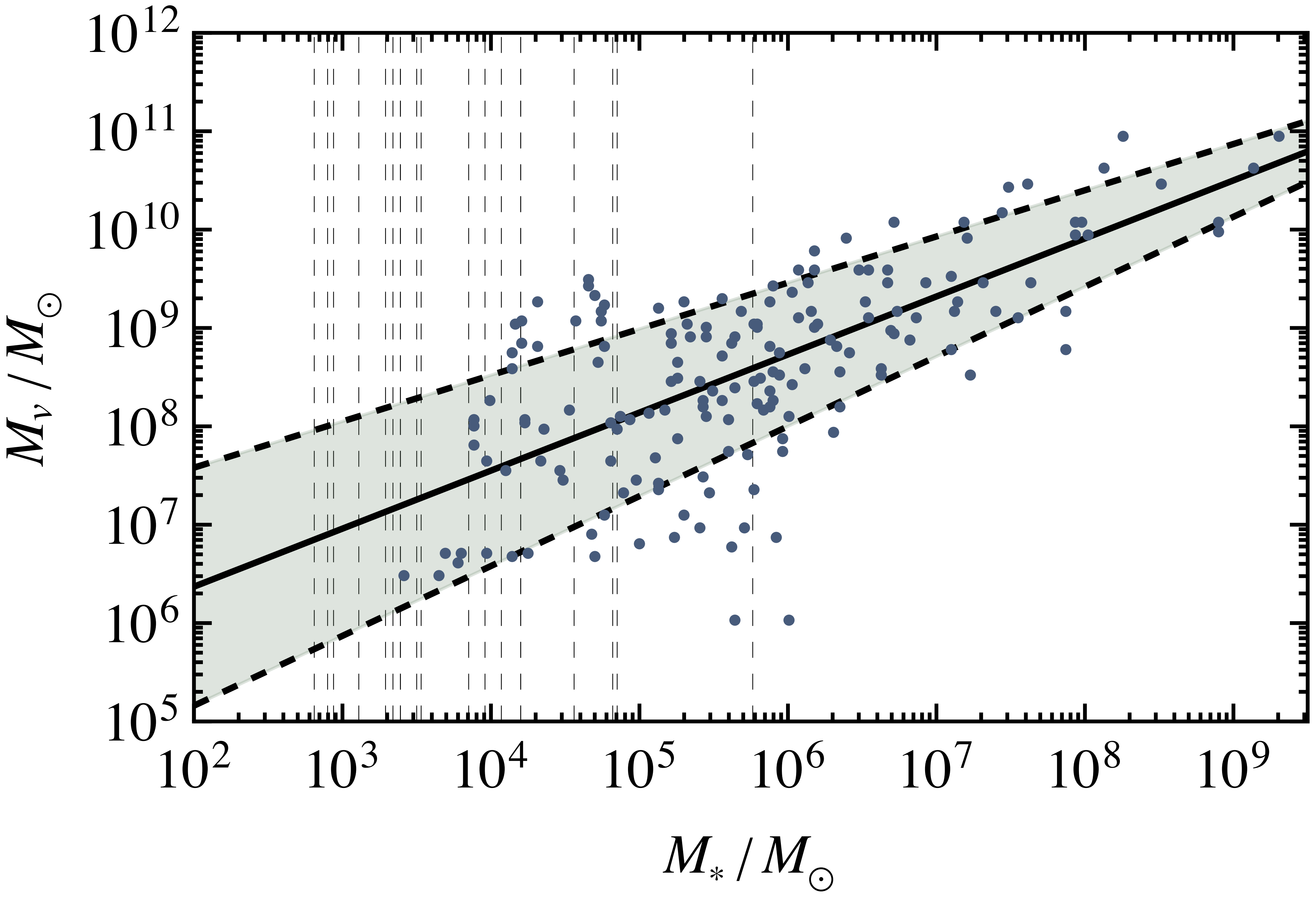
Ultrafaint dwarfs

- We compiled Milky Way and Magellanic cloud satellites, of very light stellar masses $M_* < 10^6\, M_\odot$, because the baryonic feedback is too low to modify the DM profile
- They all seem to have cored DM profiles
- We have tested the FDM hypothesis in light of these observations, some of which are new

	$M_\star / 10^3\, M_\odot$	$r_c^\star /$ pc
Horologium-I	1.96 ± 0.40	24.3 ± 5.0
Horologium-II	2.47 ± 0.50	22.5 ± 4.6
Hydra-II	7.1 ± 1.46	61.0 ± 12.5
Phoenix-II	1.31 ± 0.27	27.9 ± 15.73
Sagittarius-II	2.47 ± 0.50	23.4 ± 4.81
Triangulum-II	0.89 ± 0.18	20.4 ± 4.19
Boötes	67 ± 6	191 ± 5
Canes Venatici-I	580 ± 40	452 ± 13
Canes Venatici-II	16 ± 4	70.7 ± 11.2
Coma Bernices	9.2 ± 1.7	72.1 ± 3.8
Hercules	72 ± 12	216 ± 17
Leo-IV	16 ± 6	114 ± 12
Segue-I	1.3 ± 0.2	24.2 ± 2.8
Ursa Major-I	37 ± 5	234 ± 10
Ursa Major-II	12 ± 1	128 ± 5
Willman-I	3.2 ± 0.6	27.7 ± 2.4
Grus-II	$3.4^{+0.3}_{-0.4}$	93 ± 14
Tucana-III	0.8 ± 0.1	44 ± 6
Tucana-IV	$2.2^{+0.4}_{-0.3}$	127 ± 24

The importance of spreads

- We want to relate the observables (r_c, M_*), into the DM properties of the dwarf, ($M_{\rm v}$, m_a) and eventually integrate out the halo mass to recover the favored axion mass.
- Let's first focus on converting the stellar mass into the halo mass
- Two orders of magnitude scatter



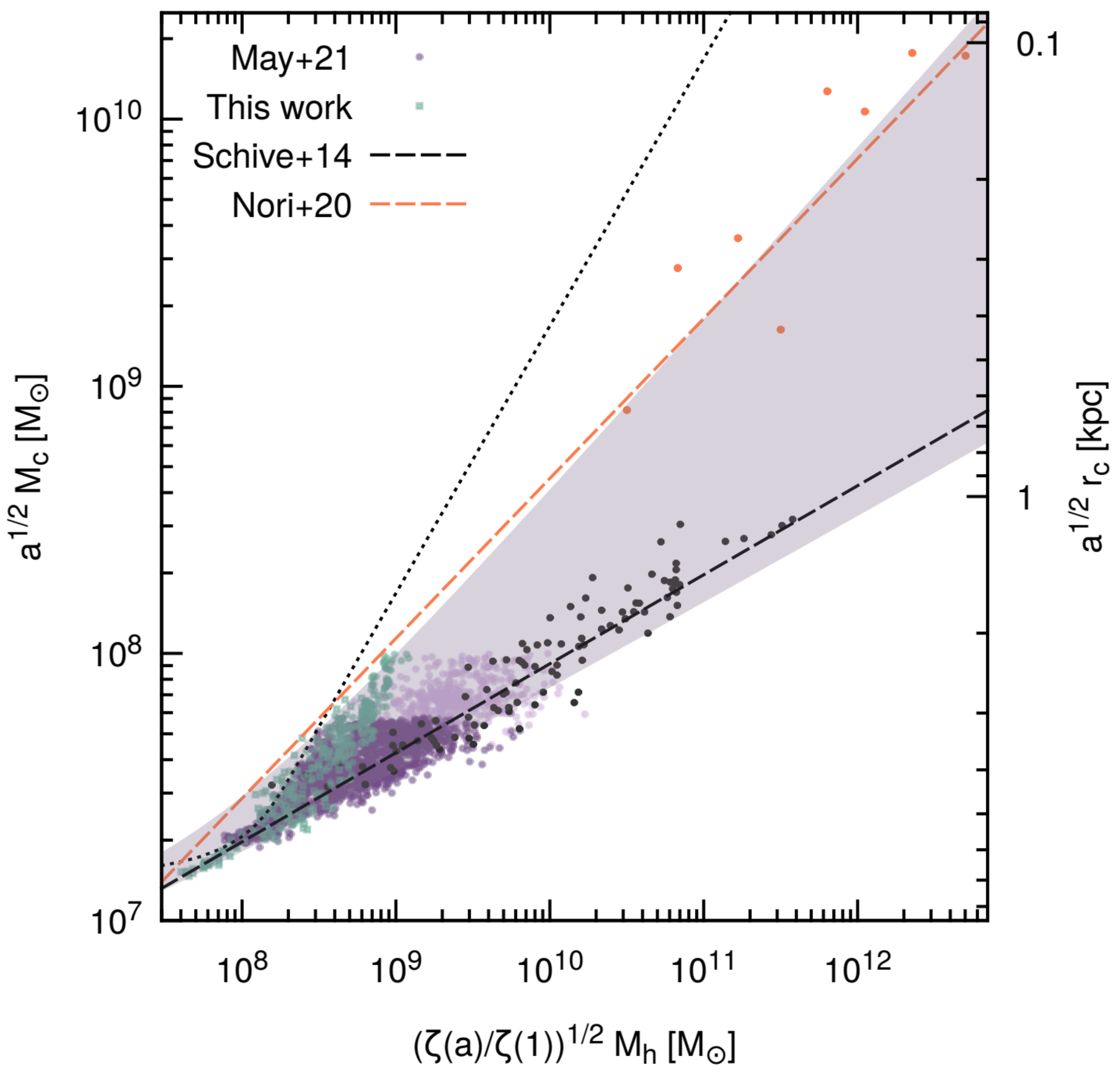
The importance of spreads

- We want to get from a core radius and a halo mass to an axion mass distribution
- We opted to get the results from the simulations and also include the spread in the halo mass to core mass

$$\frac{r_c}{\mathrm{kpc}} = \left[\frac{m_a}{10^{-23}\mathrm{eV}}\right]^{-2} \left[\frac{M_c}{5.5 \times 10^9 M_\odot}\right]^{-1},$$

$$\frac{M_c(\boldsymbol{\theta})}{10^6 M_\odot} = \beta \left[\frac{m_a}{8 \times 10^{-23}\,\mathrm{eV}}\right]^{-\frac{3}{2}} + \left[\frac{M_v}{\gamma M_\odot}\right]^{\alpha} \left[\frac{m_a}{8 \times 10^{-23}\,\mathrm{eV}}\right]^{\frac{3}{2}(\alpha-1)}$$

The importance of spreads



Another order of magnitude spread !

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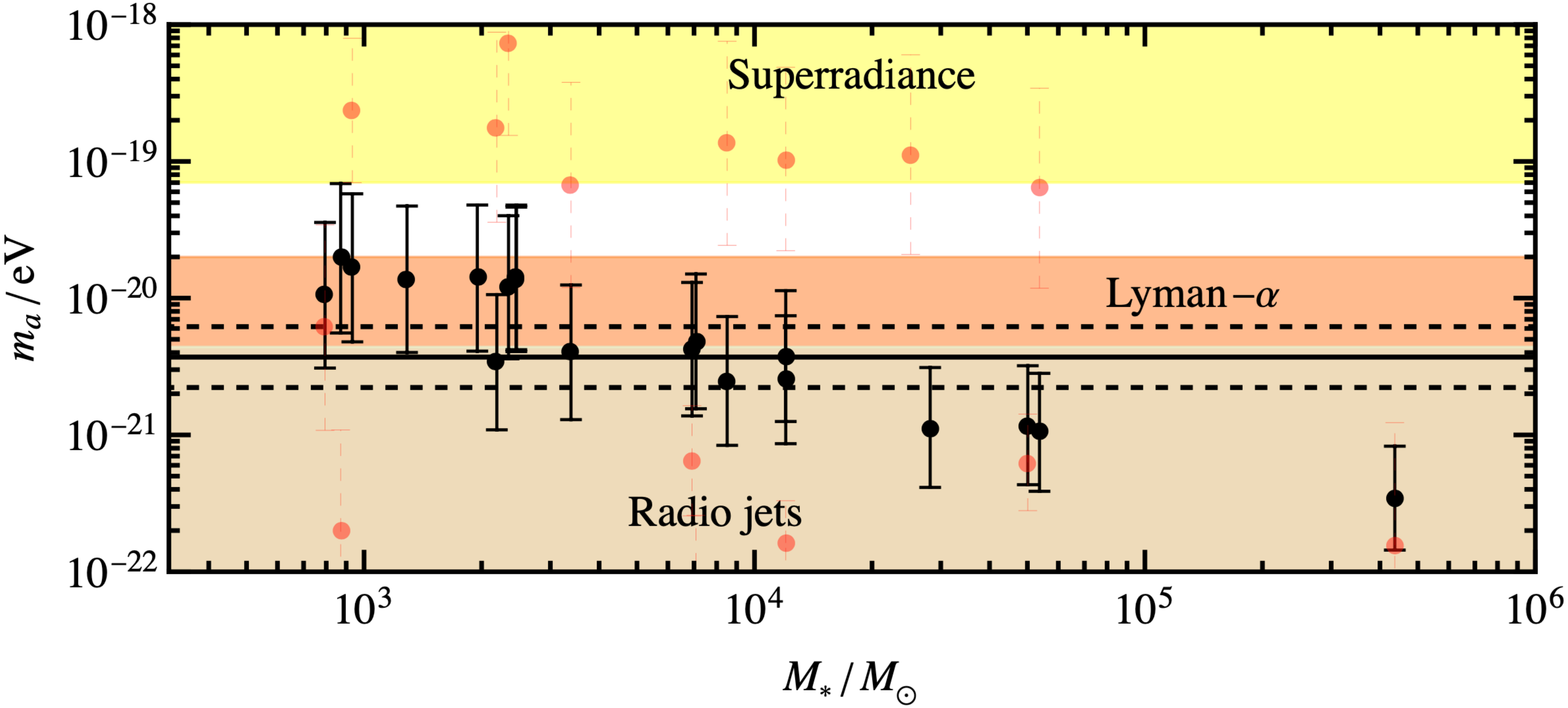
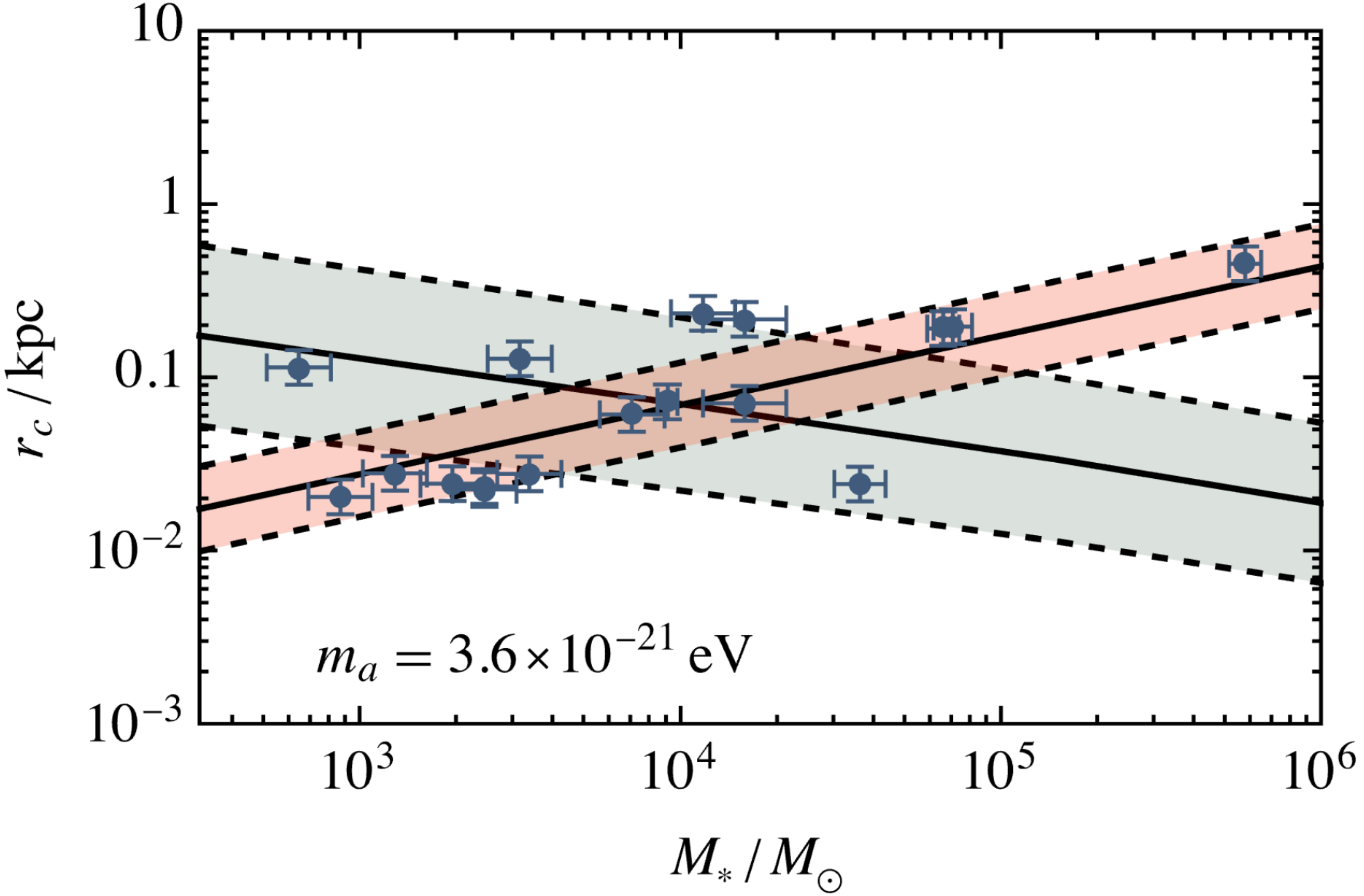
Axion mass posteriors for every galaxy



Axion mass posteriors for every galaxy



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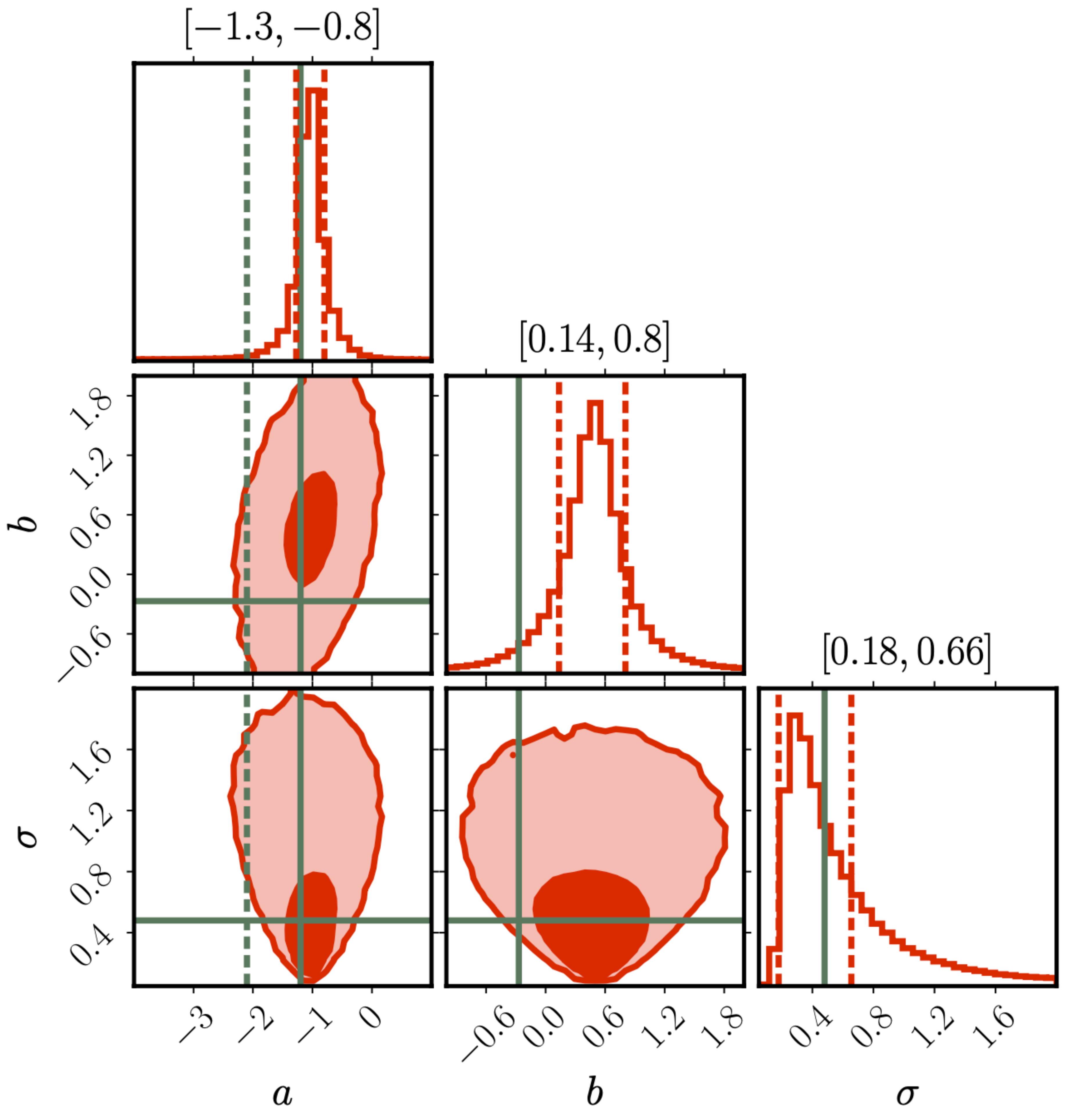

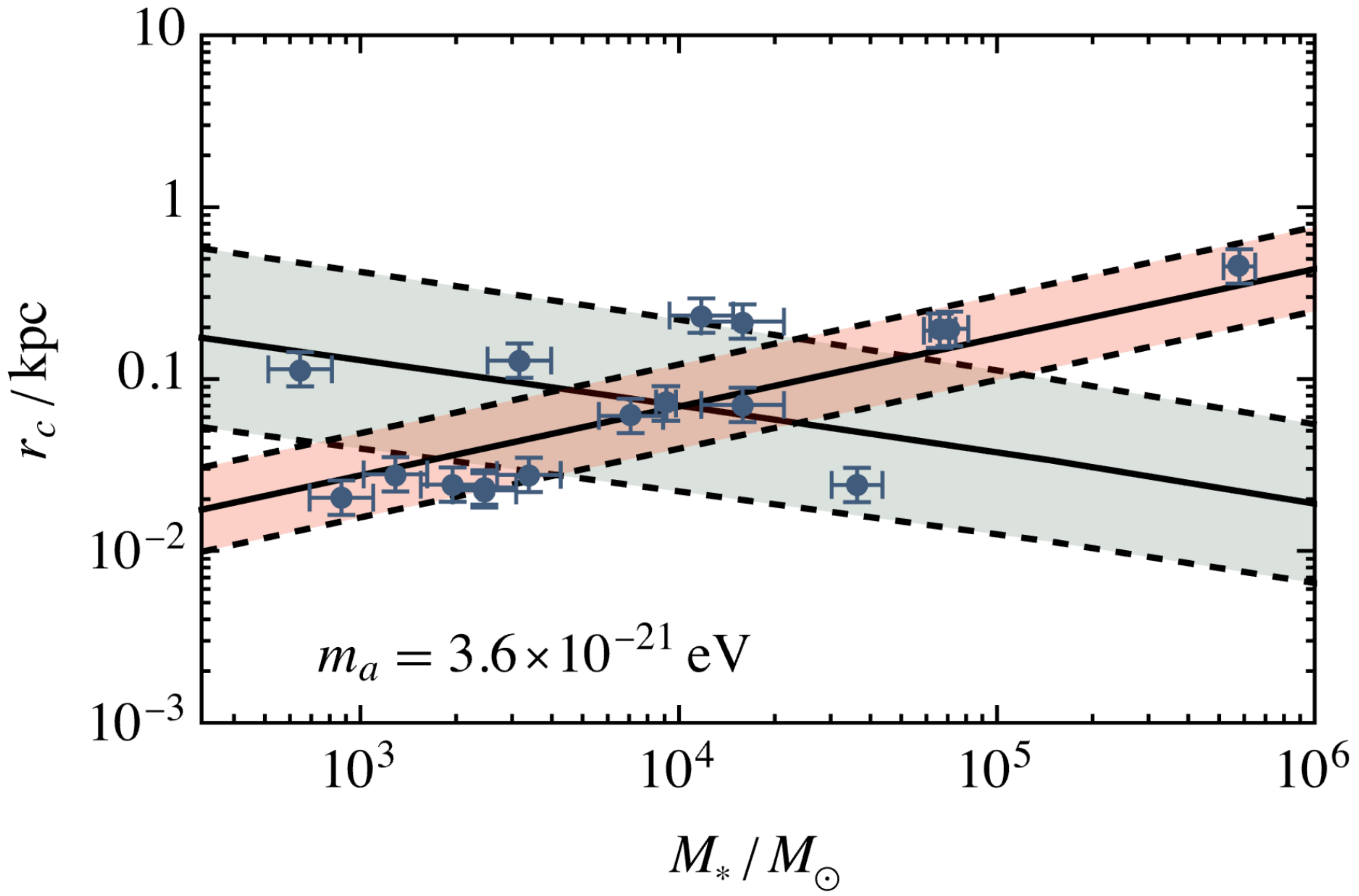

Hypothesis disfavored at more than $3\,\sigma$

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Why FDM fails to explain the DM cores

- The necessary mass is ruled out by cosmological bounds
- FDM predicts the wrong scaling for the core radius with the halo mass
- If it cannot explain the cores in ultrafaint dwarfs, which have "pure" DM profiles and the smallest cores, it cannot explain the bigger cores in bigger galaxies for which the origin might be anyway releated to baryonic effects

The problems with Cold Dark Matter (CDM) or why FDM is popular

- Missing satellite problem → **suppression of small scales**
- Cusp vs core problem → **formation of cores**
- Where CDM works so does FDM
- It is a generic prediction of String Theory, (i.e. the axiverse)

John Ellis,[1,2,*] Malcolm Fairbairn,[1,†] Juan Urrutia,[3,4,‡] and Ville Vaskonen[3,5,6,§]

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Abstract

KCL-PH-TH/2024-55, CERN-TH-2024-184, AION-REPORT/2024-05

Soon to appear on the arXiv!

Super massive black hole detour

- We are entering a new era in BH research, (i.e. GW from LIGO)
- Is the moment also for SMBHs
  - JWST is illuminating the formation and evolution of the seeds of the SMBH
  - PTA arrays have detected evidence for a GW background in the nanoHertz frequency, where SMBH binaries are the main suspect

Article

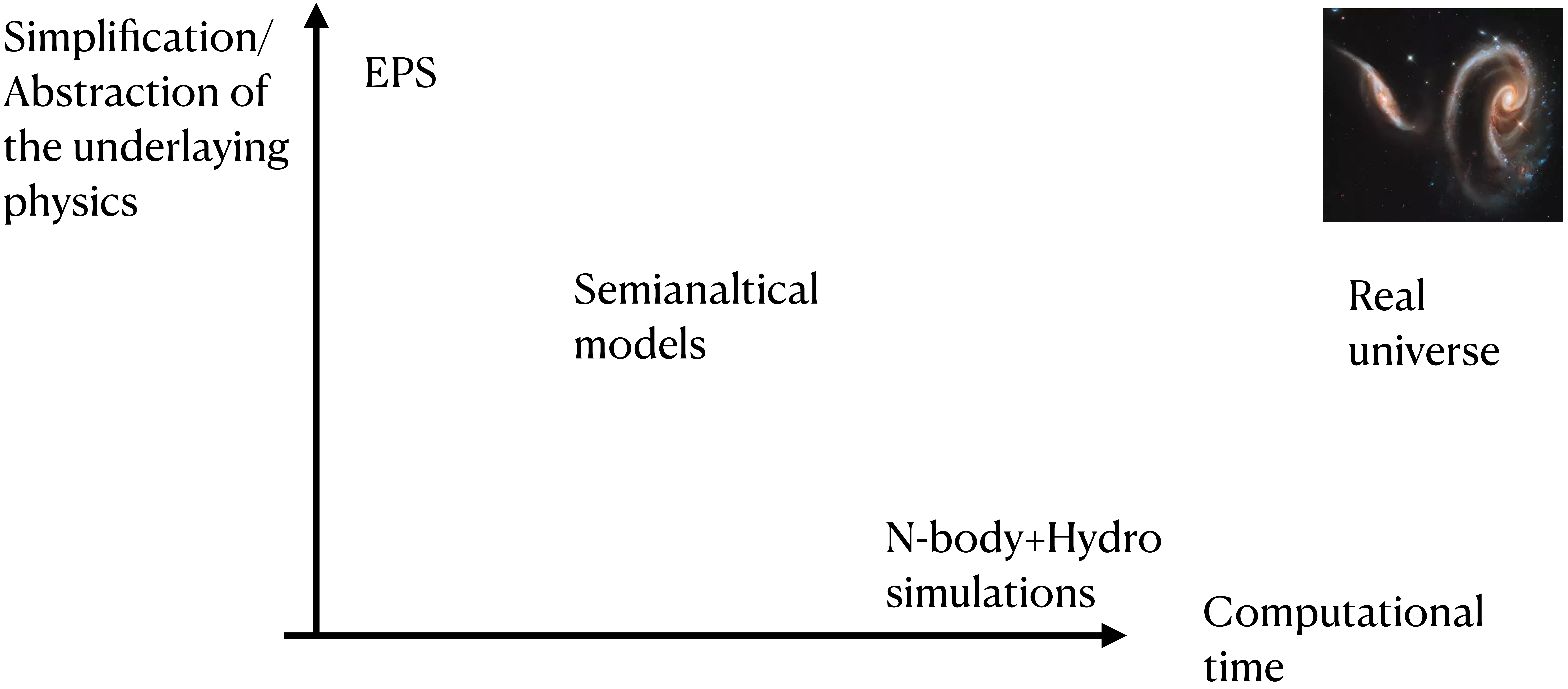
Gravitational Waves:

Echoes of the Biggest Bangs since the Big Bang and/or BSM Physics?

John Ellis [1,*] 0000-0002-7399-0813

https://arxiv.org/pdf/2402.10755

The universe growth at different levels of abstraction

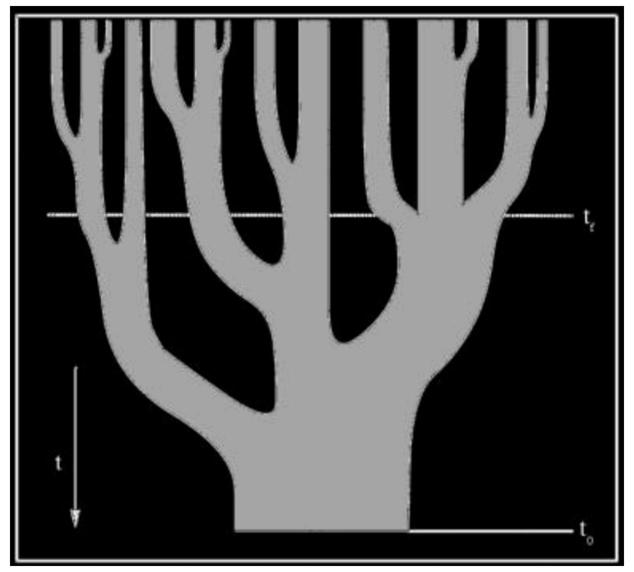


The universe growth at different levels of abstraction

Simplification/ Abstraction of the underlaying physics

EPS

Merger tree



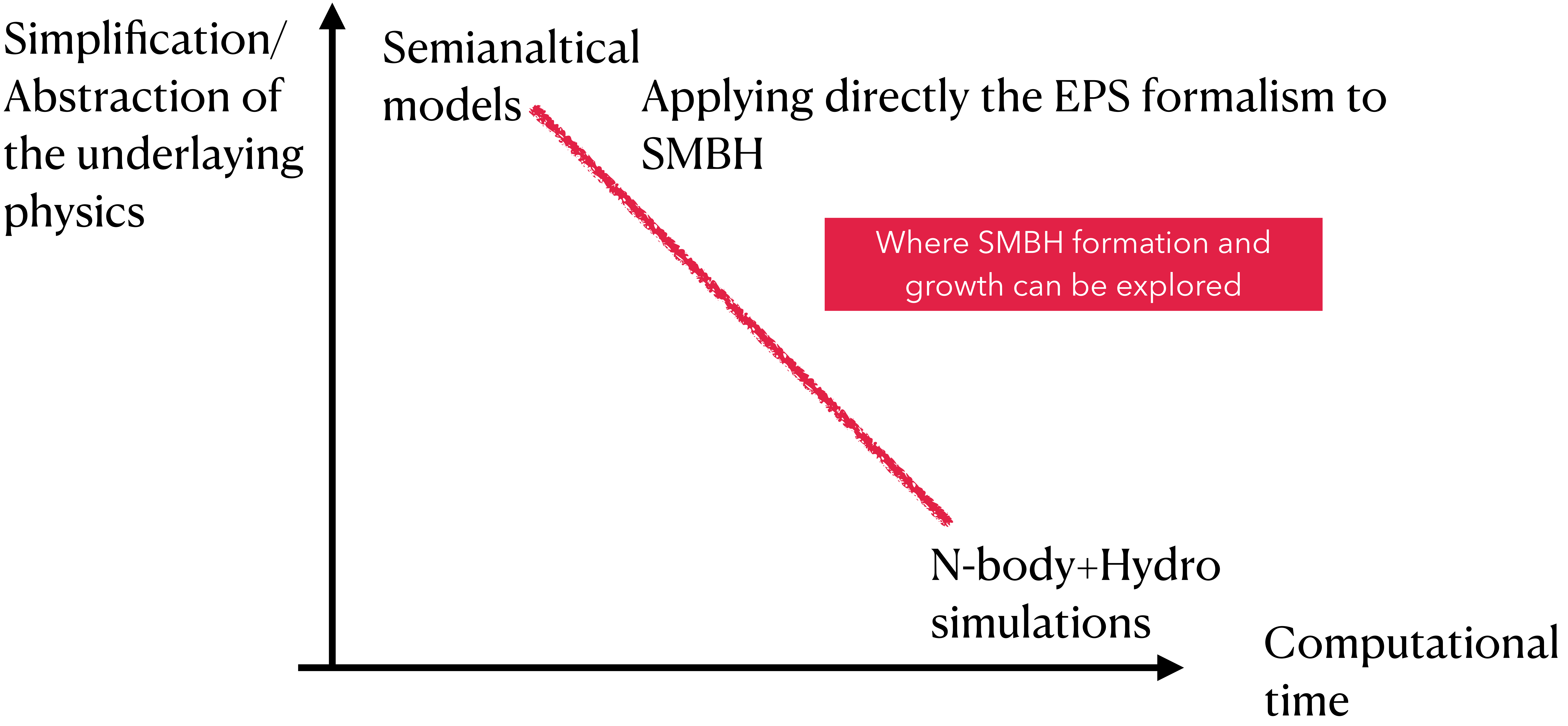
Semianaltical models

Where SMBH formation and growth can be explored

N-body+Hydro simulations

Computational time

The universe growth at different levels of abstraction



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Growth beyond merger trees

- Applying the EPS formalism more directly to SMBH growth, the key insight behind this approach is that *a SMBH inside a halo on average has had the same history as the average mass of the halo.*
- We can track the differential growth by mergers for DM, gas, stars and SMBHs
- But this **is sensitive to the DM model**

$$
\begin{aligned}
M_J(M,z') + \Delta M_J^{\mathrm{merg.}}(M,z,z') &= \left[\frac{\mathrm{d}n(z)}{\mathrm{d}M}\right]^{-1}\int_0^M \mathrm{d}M'\,\frac{\mathrm{d}n(z')}{\mathrm{d}M'}\frac{\mathrm{d}P(M,z|M',z')}{\mathrm{d}M}M_J(M',z') \\
&= \int_0^M \mathrm{d}M'\left|\frac{\mathrm{d}S}{\mathrm{d}M'}\right|\frac{M}{M'}M_J(M',z')\frac{\delta_c(z')-\delta_c(z)}{\sqrt{2\pi[S(M')-S(M)]^3}}e^{-\frac{[\delta_c(z')-\delta_c(z)]^2}{2[S(M')-S(M)]}}
\end{aligned}
$$

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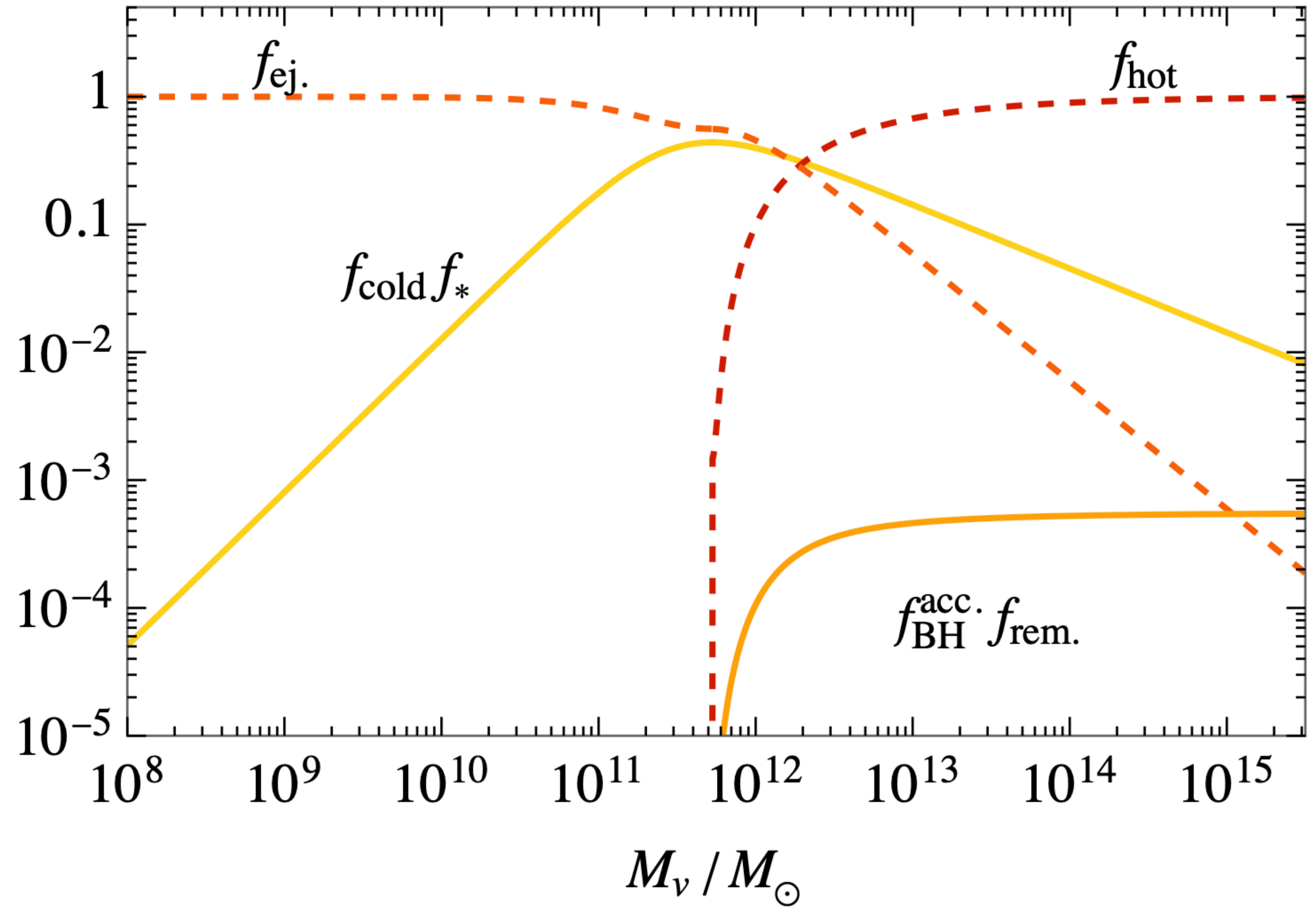
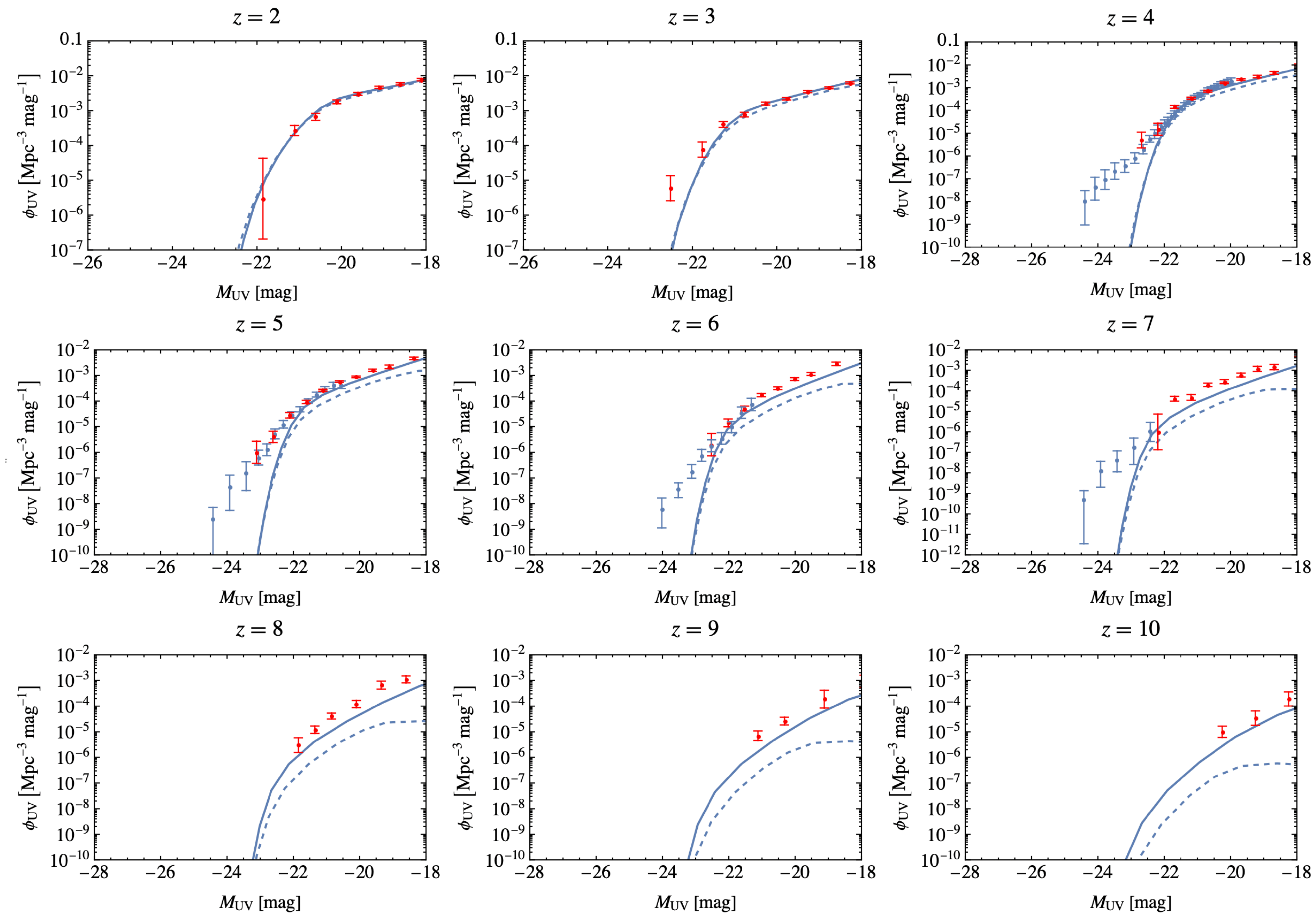
Phenomenological feedbacks

- Ejected gas by SN feedback
- heated gas by AGN activity
- these feedbacks need to match the UV luminosity function, there is an interplay between DM model and the feedbacks



UV-luminosity function



$$\Phi_{\mathrm{UV}} = \frac{\mathrm{d}n}{\mathrm{d}M_{\mathrm{h}}} \times \frac{\mathrm{d}M_{\mathrm{h}}}{\mathrm{d}M_{\mathrm{UV}}}$$

- for each DM model the star formation rate and feedbacks needs to be reajusted

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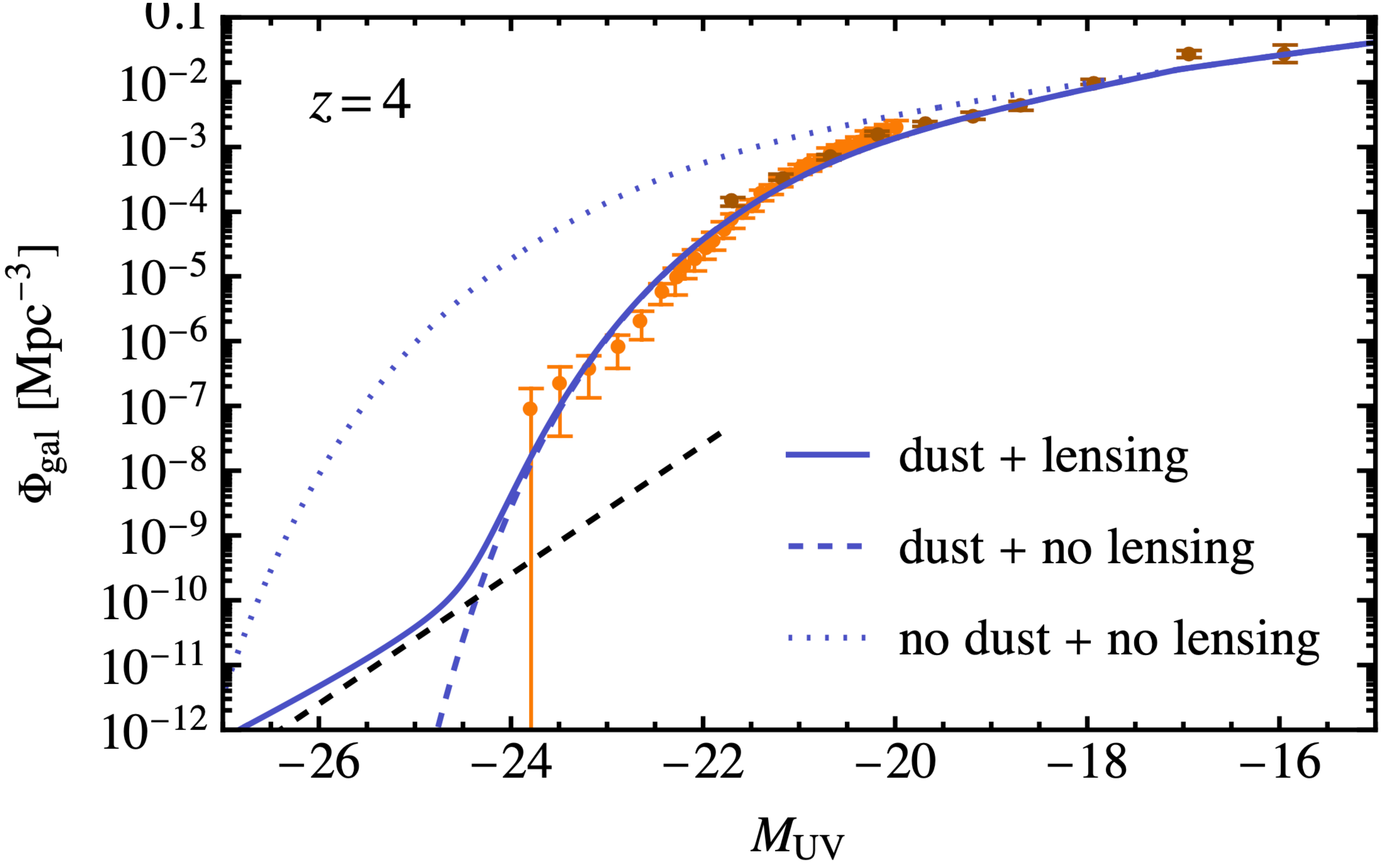
UV-luminosity function



- also for the weak lensing contribution

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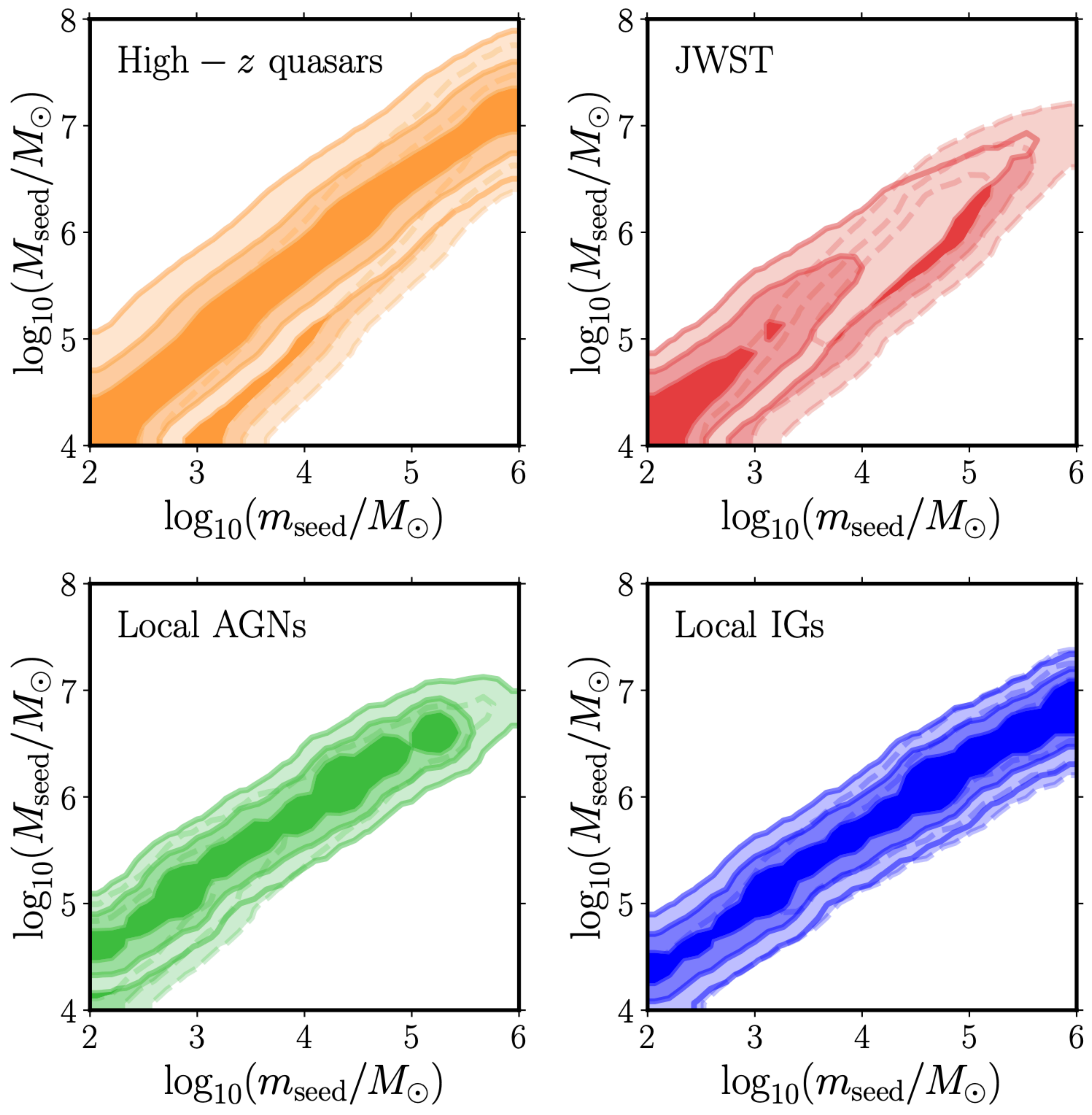
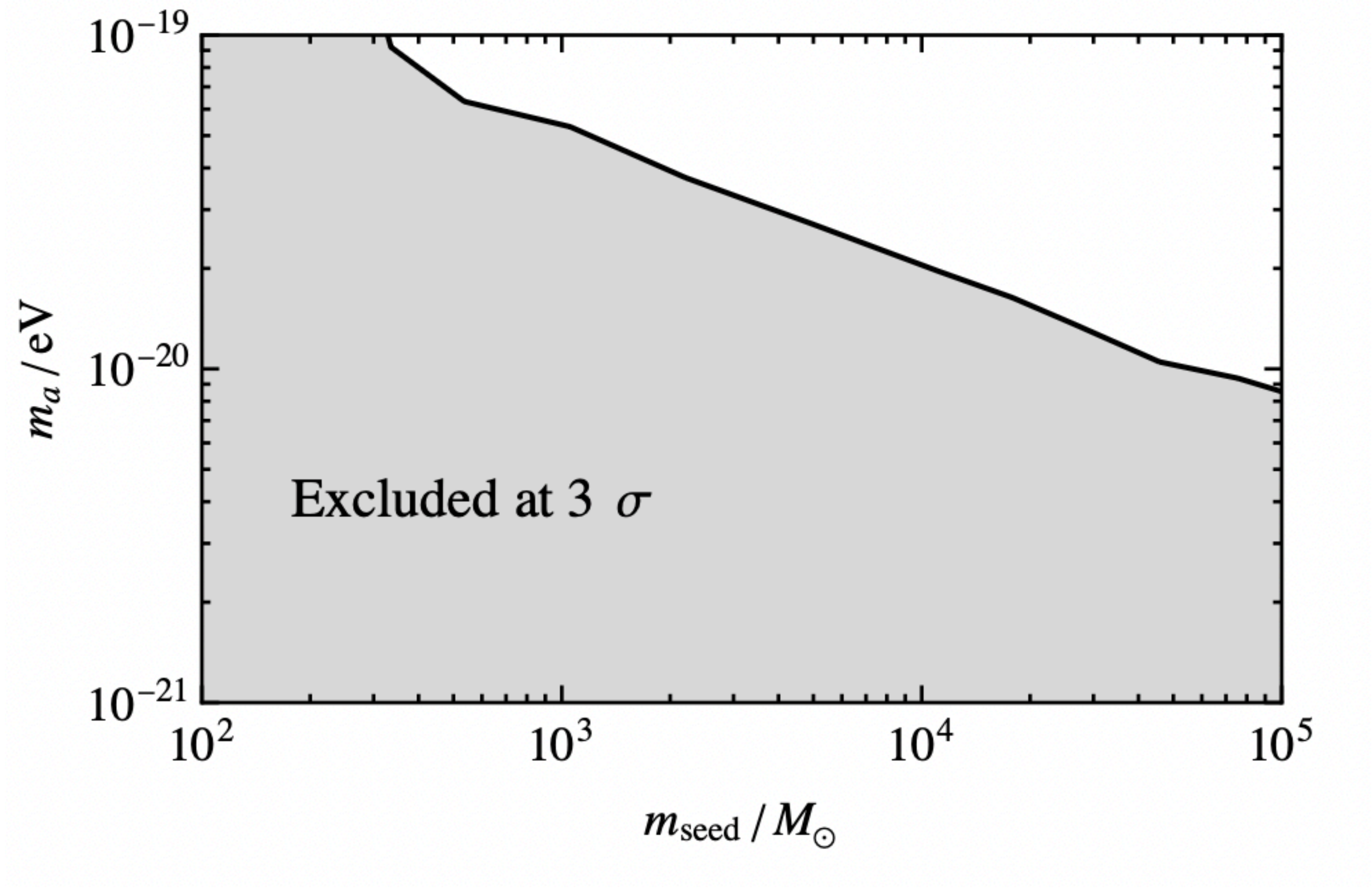
SMBH seeds are very sensitive to DM



- Assuming CDM
- the seeds are very sensitive to the minimal halo mass at which the first seed appear ($M_{\rm seed}$)
- at $z \sim 20$ the abundance of these halos is very sensitive to the DM model

The evolution of SMBH in FDM universe



- There is a correlation between the axion mass and the "seed" mass of the SMBH
- Making two of the biggest mysteries in cosmology linked

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Conclusions

- FDM is an attractive DM candidate because it solves some problems from CDM without spoiling the successes and it is a simple model that is natural in many theories
- When more critically analyzed it seems like **FDM cannot explain the cores** in DM halos successfully
- SMBH are very sensitive to the nature of DM, we are performing the first studies interlinking the growth of both. JWST and future GW observatories are going to illuminate the origin of the SMBH and severely constrain deviations from CDM.