Constraining Fuzzy Dark Matter Mass with Lensed High-z Galaxies

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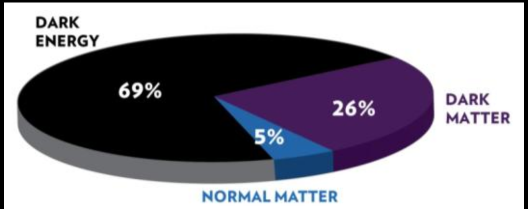
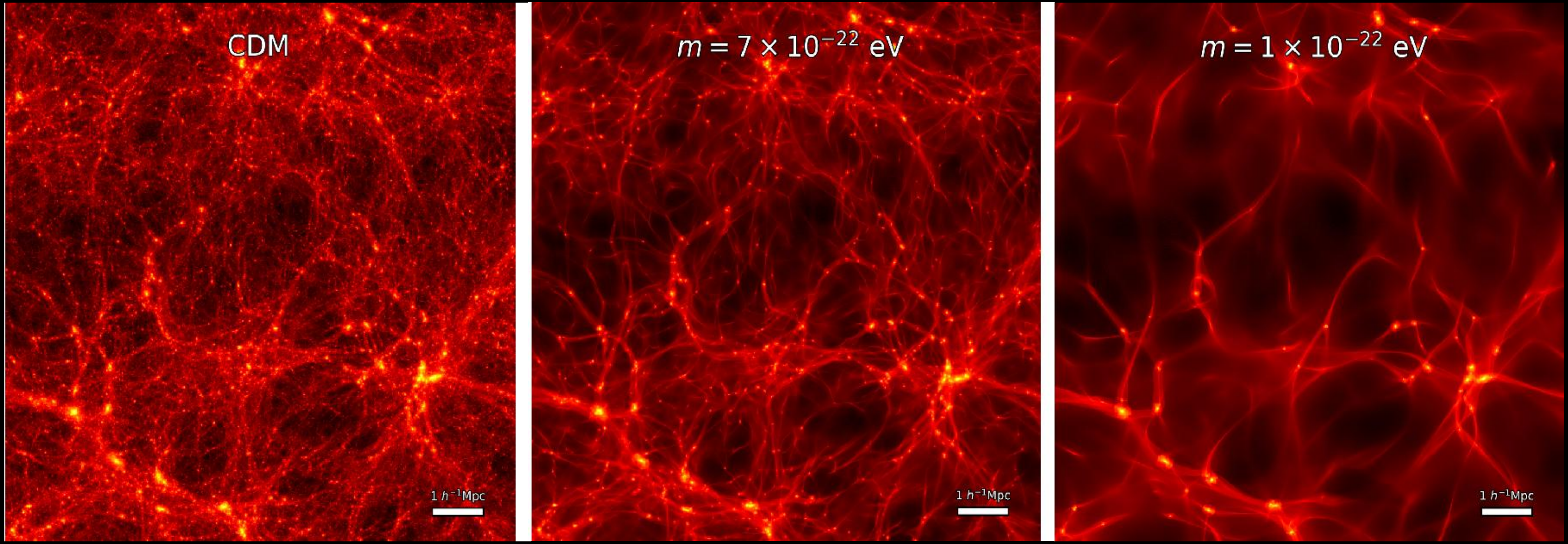
MACS J0416 as imaged by Hubble Frontier Fields

IF dark matter is wavy/fuzzy

- *Lensing makes fainter Universe more accessible*
- *Abundance of fainter galaxies reveals the nature of dark matter*

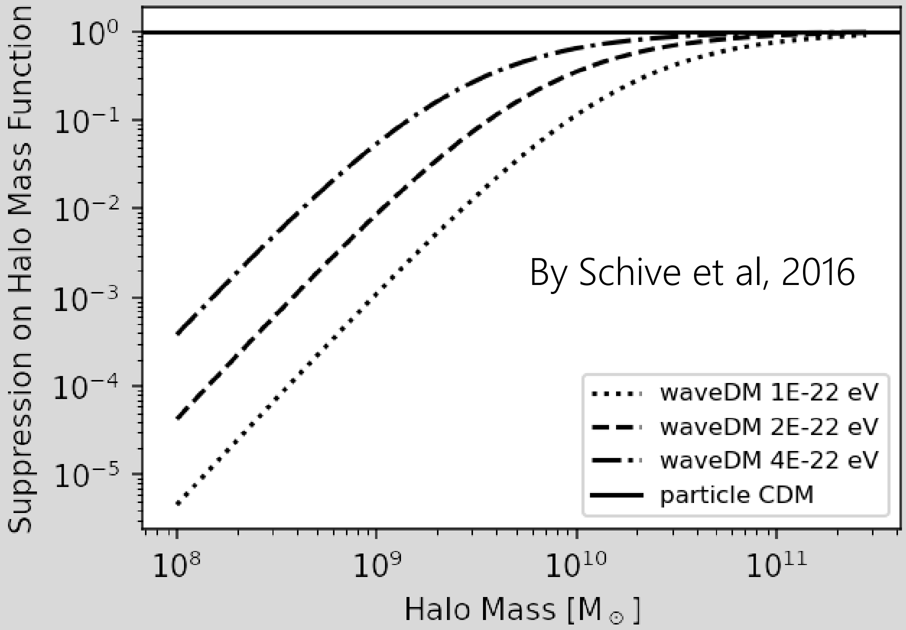


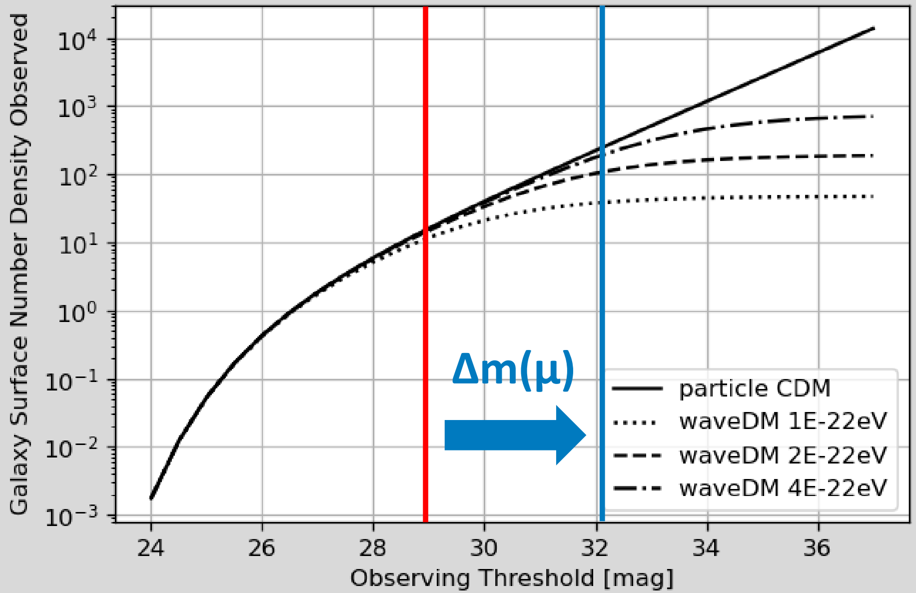


N-body simulation with CDM and waveDM-like initial conditions, z=3.9, Dome et al, 2023

IF dark matter is wavy/fuzzy

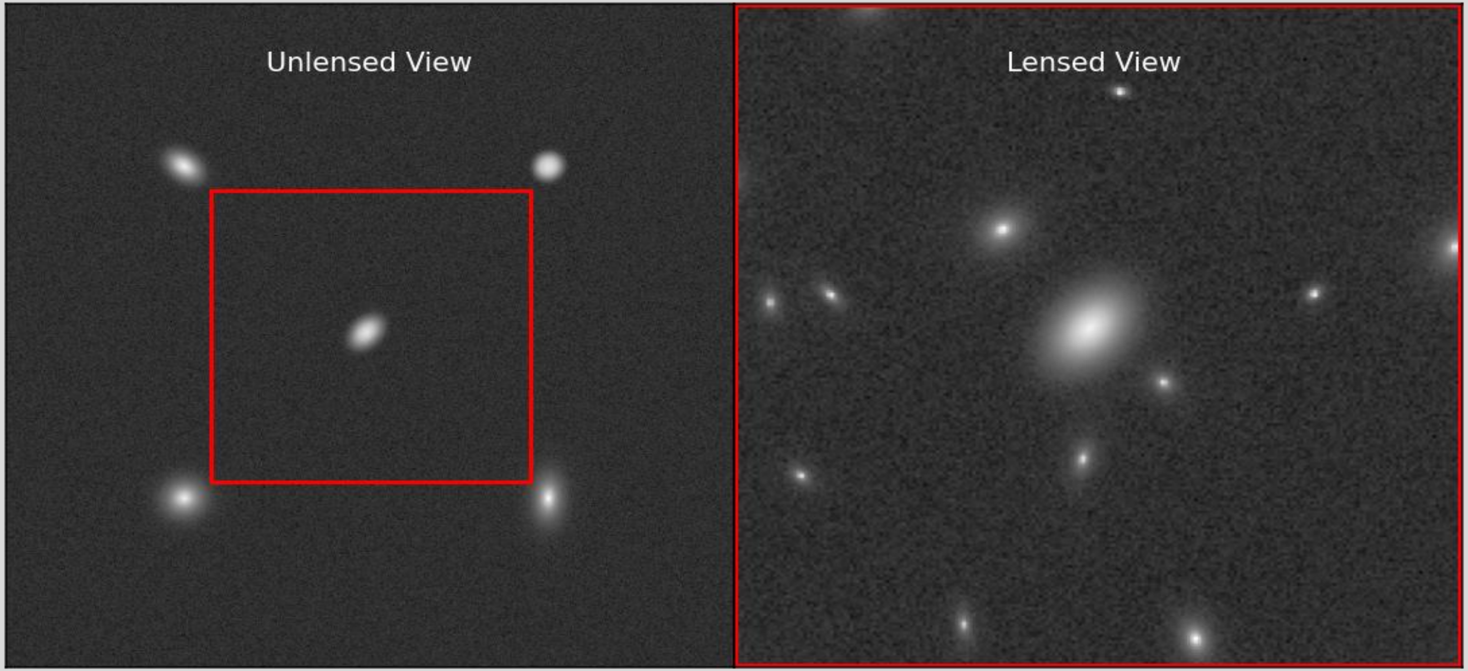
- *Imprint on Halo Mass Function/UV Luminosity Function as faint end turnover*
- *Total galaxy surface number density observed flattens as we probe fainter*





This work

- *We test for faint end turnovers by measuring the densities of lensed fainter galaxies*
- *We rely on magnification bias to relate the integral of LF with observed surface number density*



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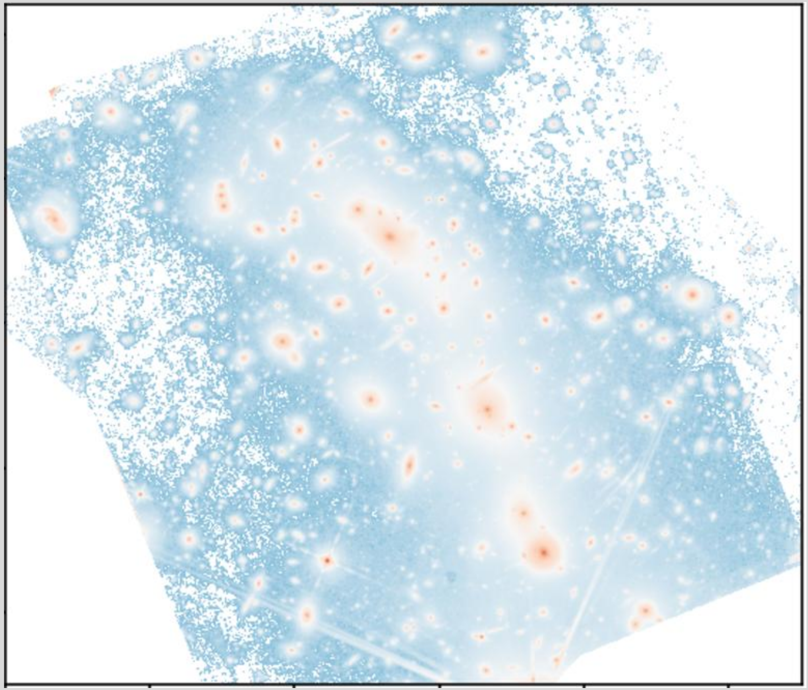
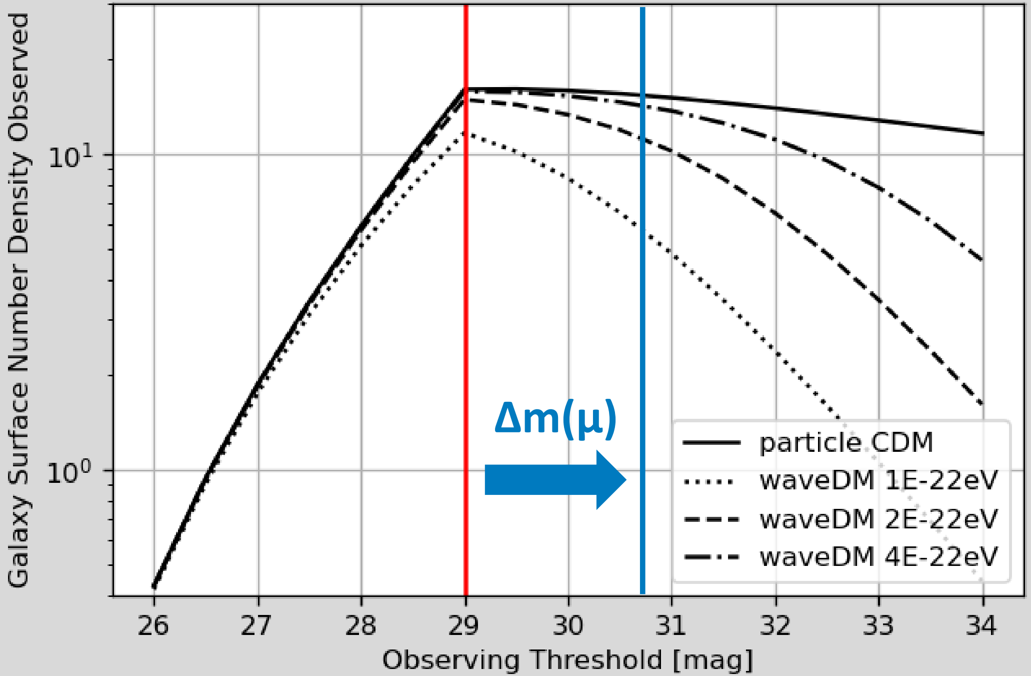
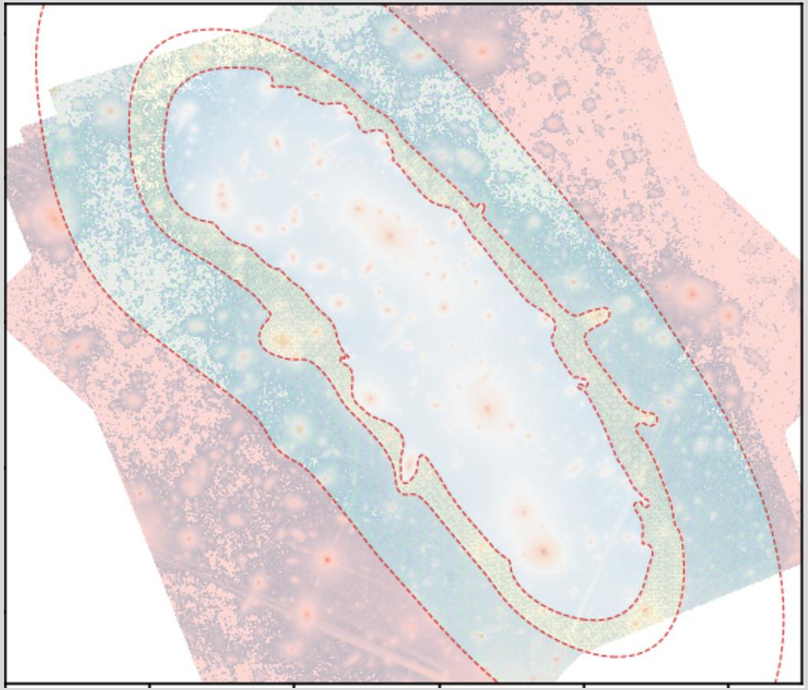
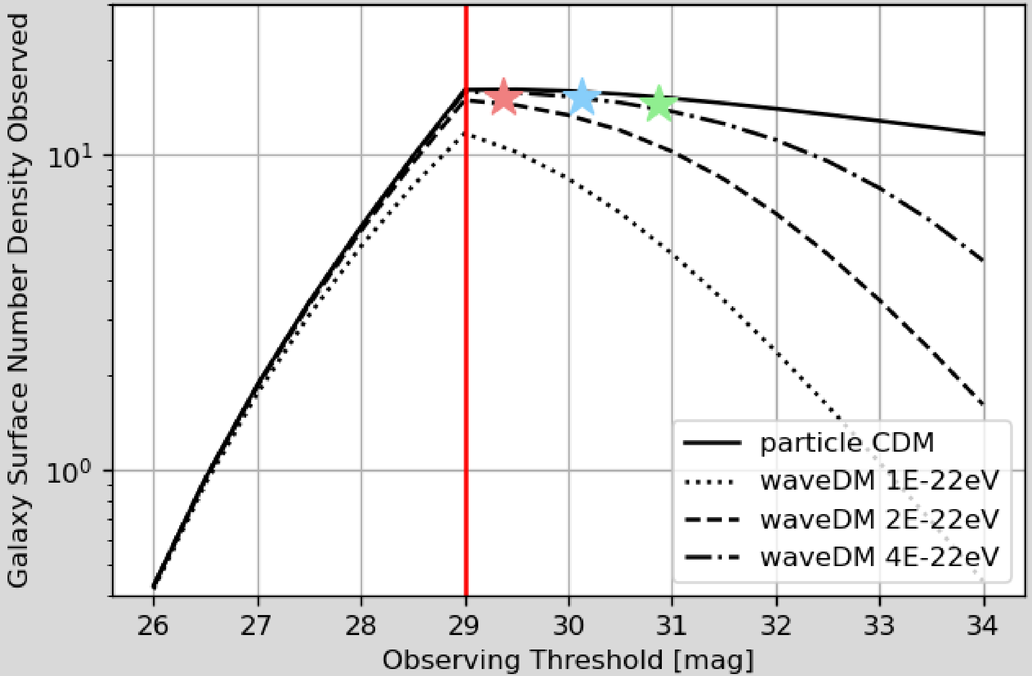




This work

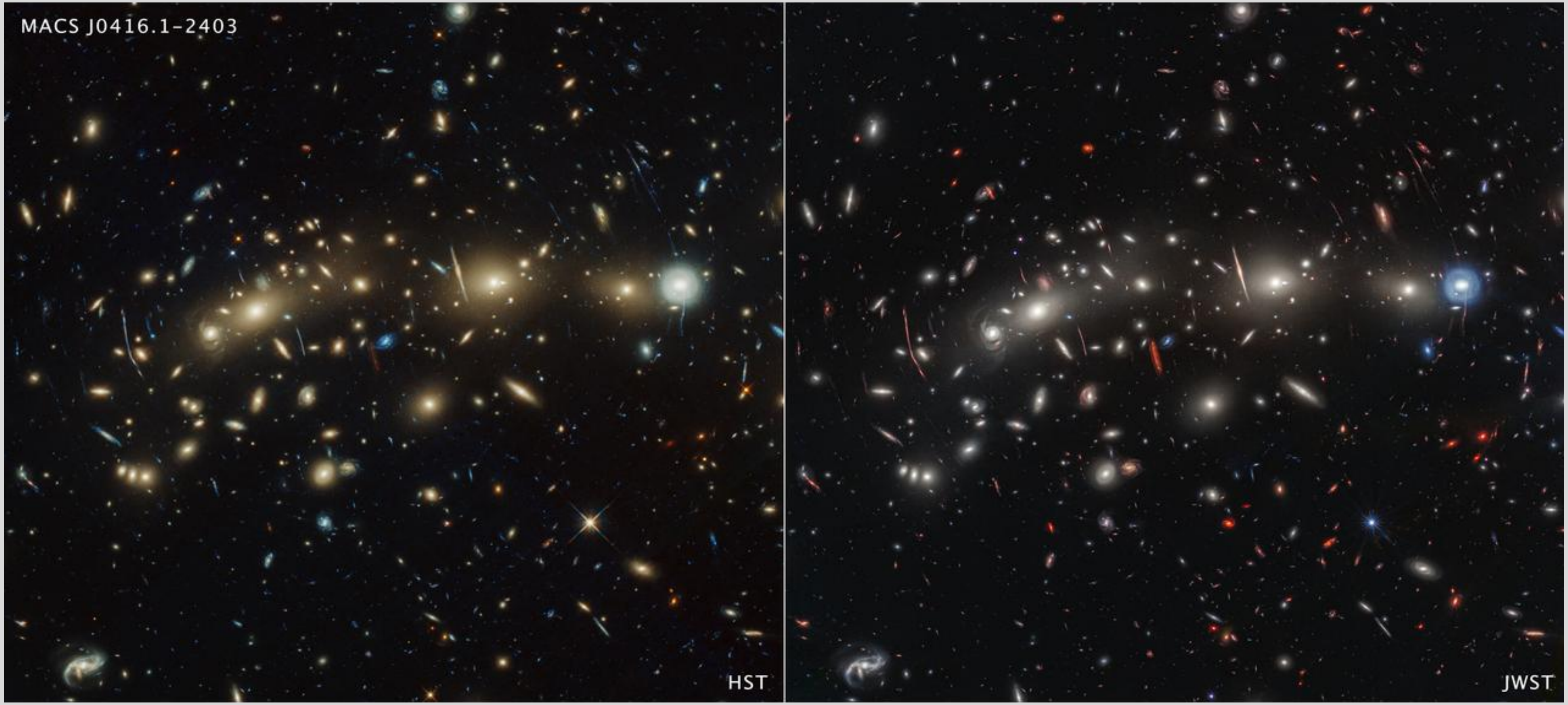
- *We test for faint end turnovers by measuring the densities of lensed fainter galaxies*
- *Strategy : break into magnification bins, measure density of galaxies lensed to different degree*





This work

- *We test for faint end turnovers by measuring the densities of lensed (fainter) galaxies*
- *We construct a more complete catalog by combining deep JWST and HST*

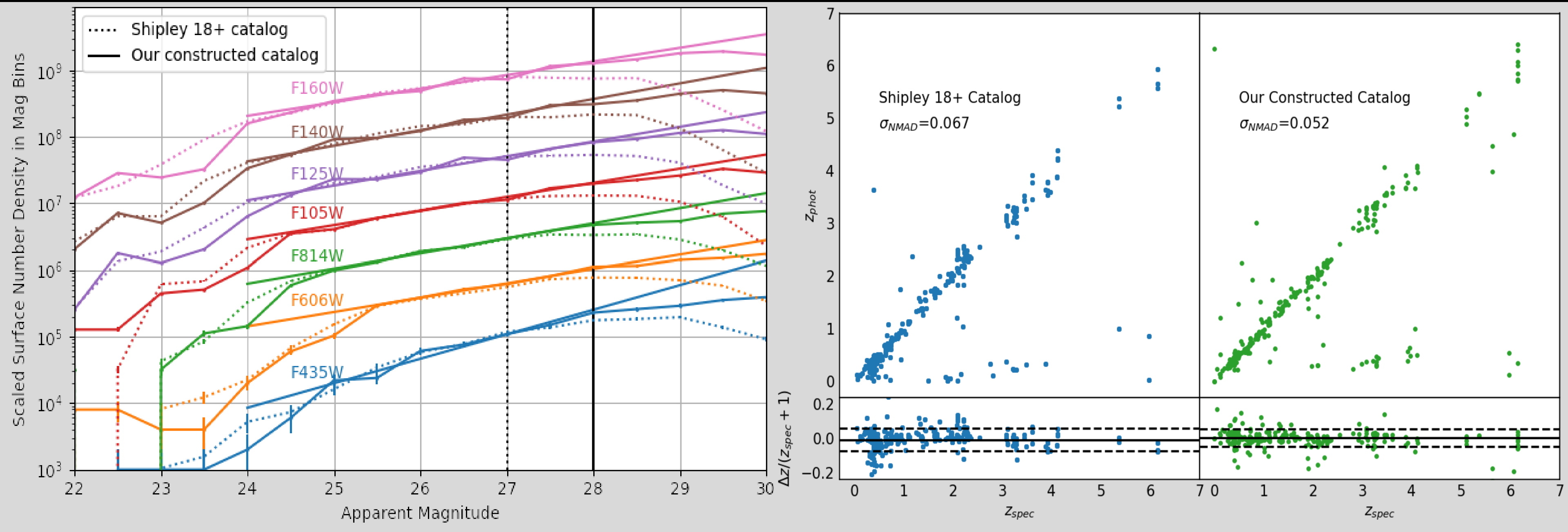


Cataloging with GNU Astronomy Utility

- *Astronomical signals : neighbouring pixels are corrected*

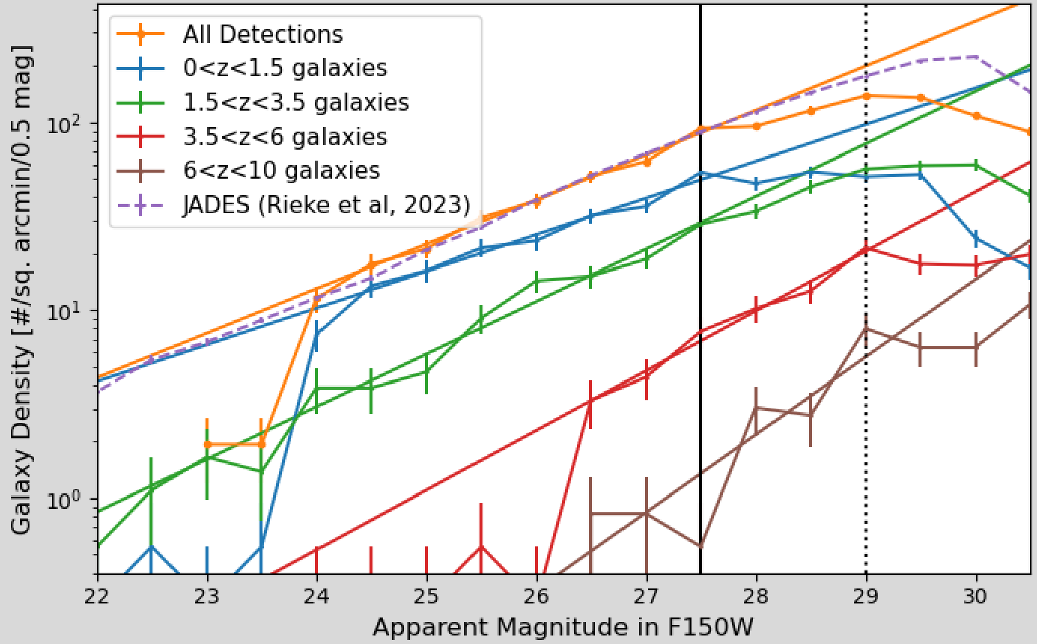
This work

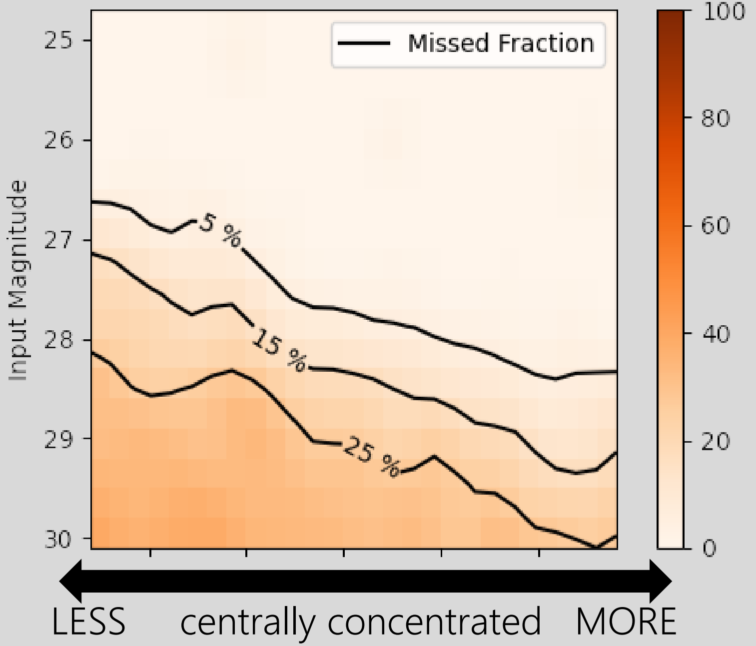
- *A more complete catalog by combining deep JWST + HST, and better photo-z*



This work

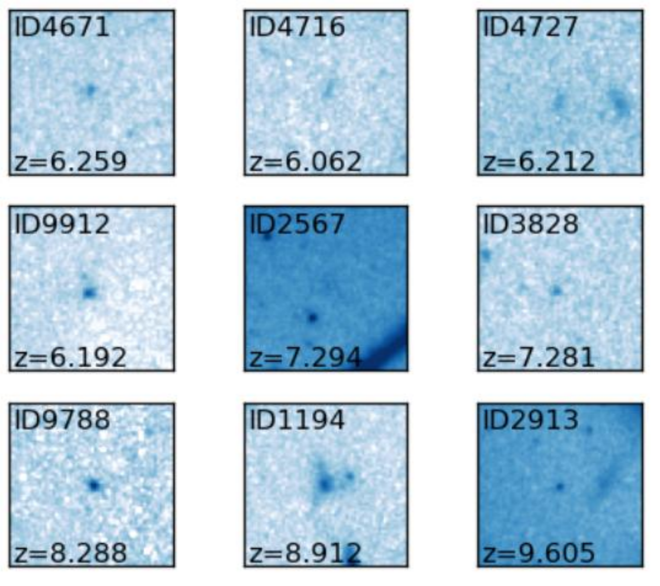
- *Interesting to notice data completeness limit depends on morphology of galaxies*
- *Galaxies at low-z tend to be more diffuse, at high-z tend to be more compact*



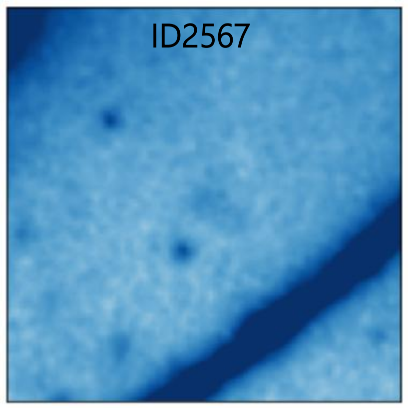


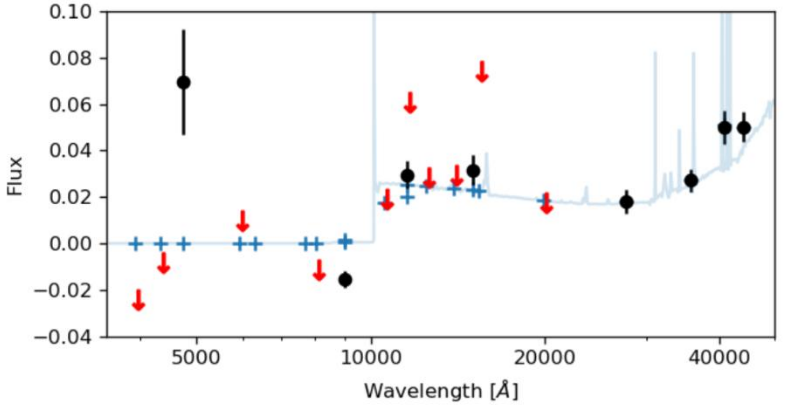
This work

- *A more complete catalog by combining deep JWST + HST, and better photo-z*
- *Focus on 6<z<10 (stronger suppression, JWST captures rest-frame Balmer breaks)*

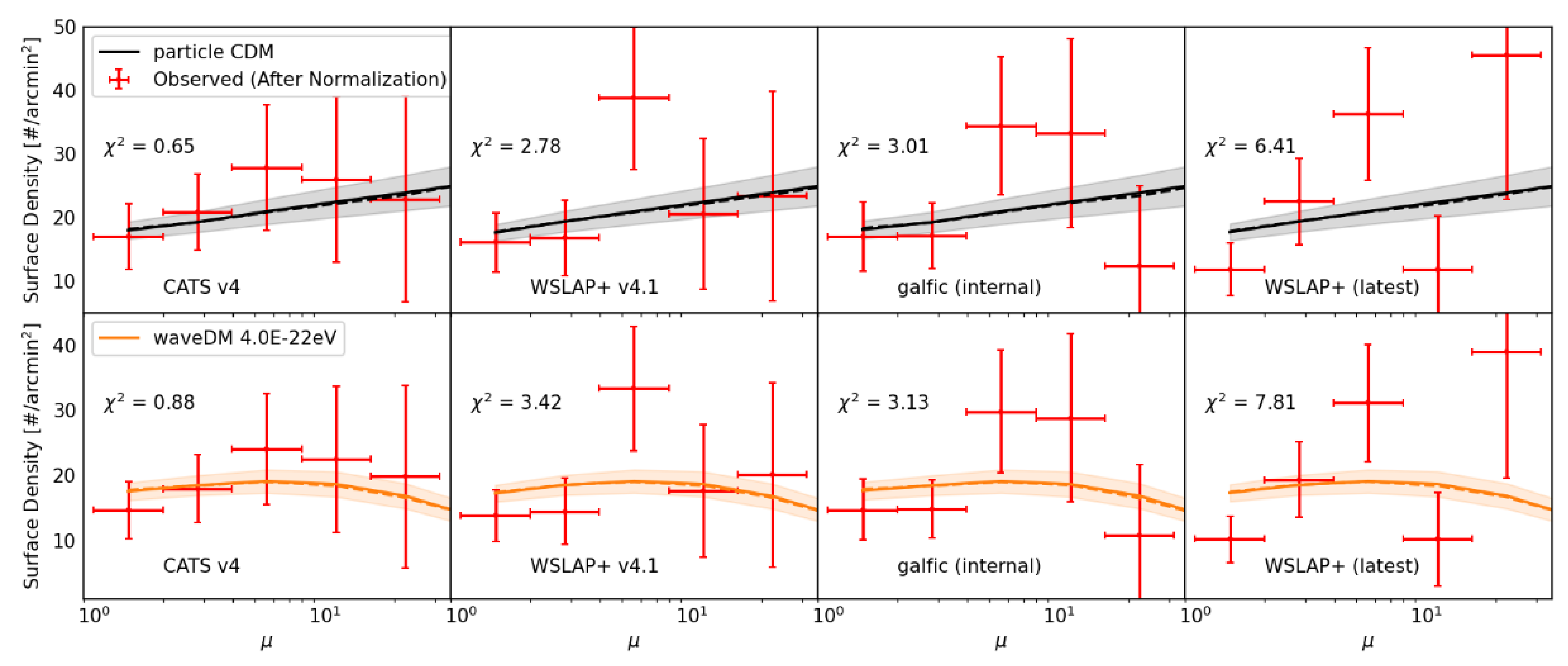


Selected 37 galaxies, each carefully examined to ensure a robust sample



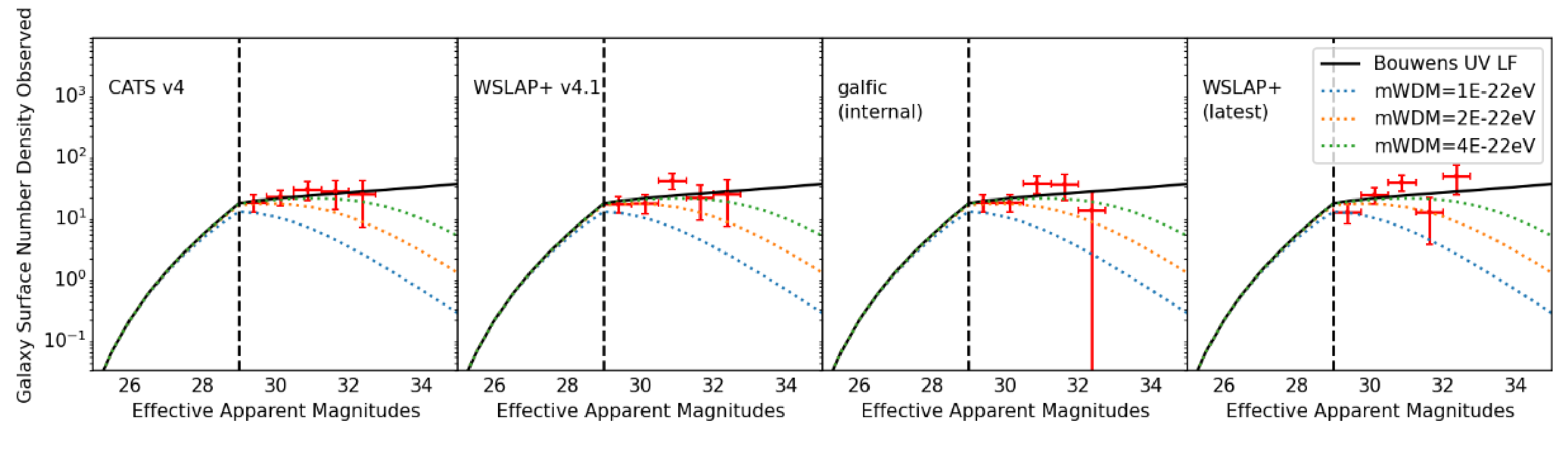


Magnification Bias Results over 6<z<10



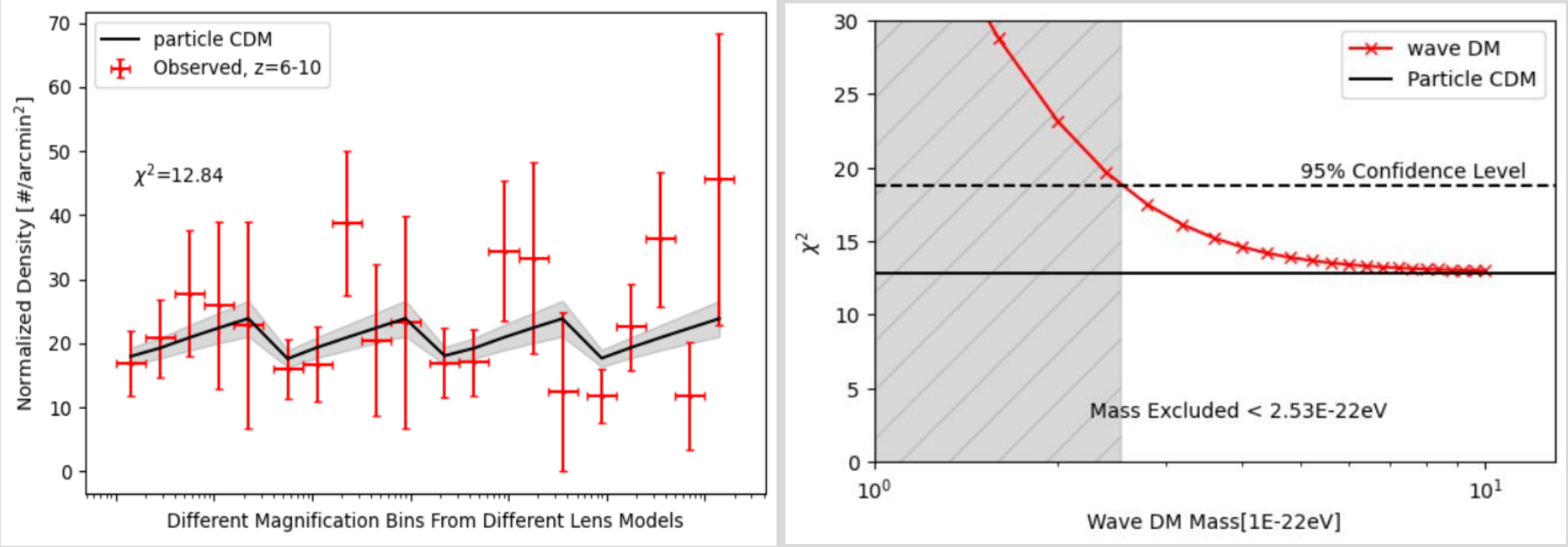
Magnification Bias Results over 6<z<10

- *To interpret the results in magnitudes…*



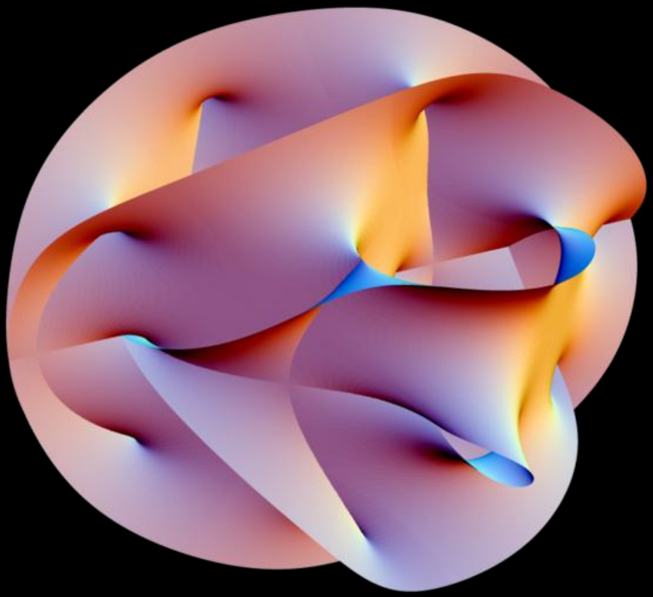
Mass Bounds

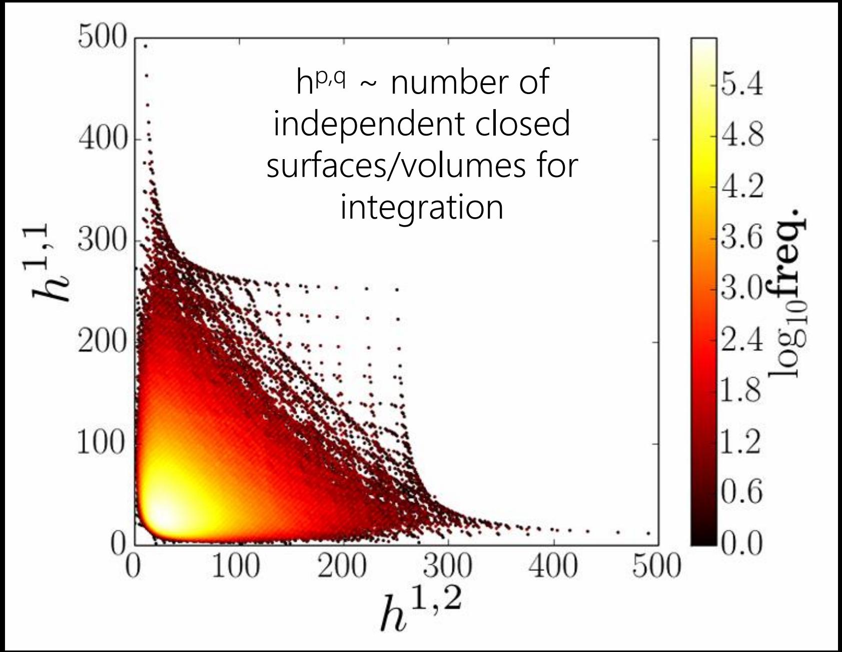
- *Combine all data points to obtain a lens model independent chi-square*
- *Over redshift 6-10, exclude mass <2.53E-22 eV at 95% confidence level*



Extension : What if, FDM is not made of single copy…?

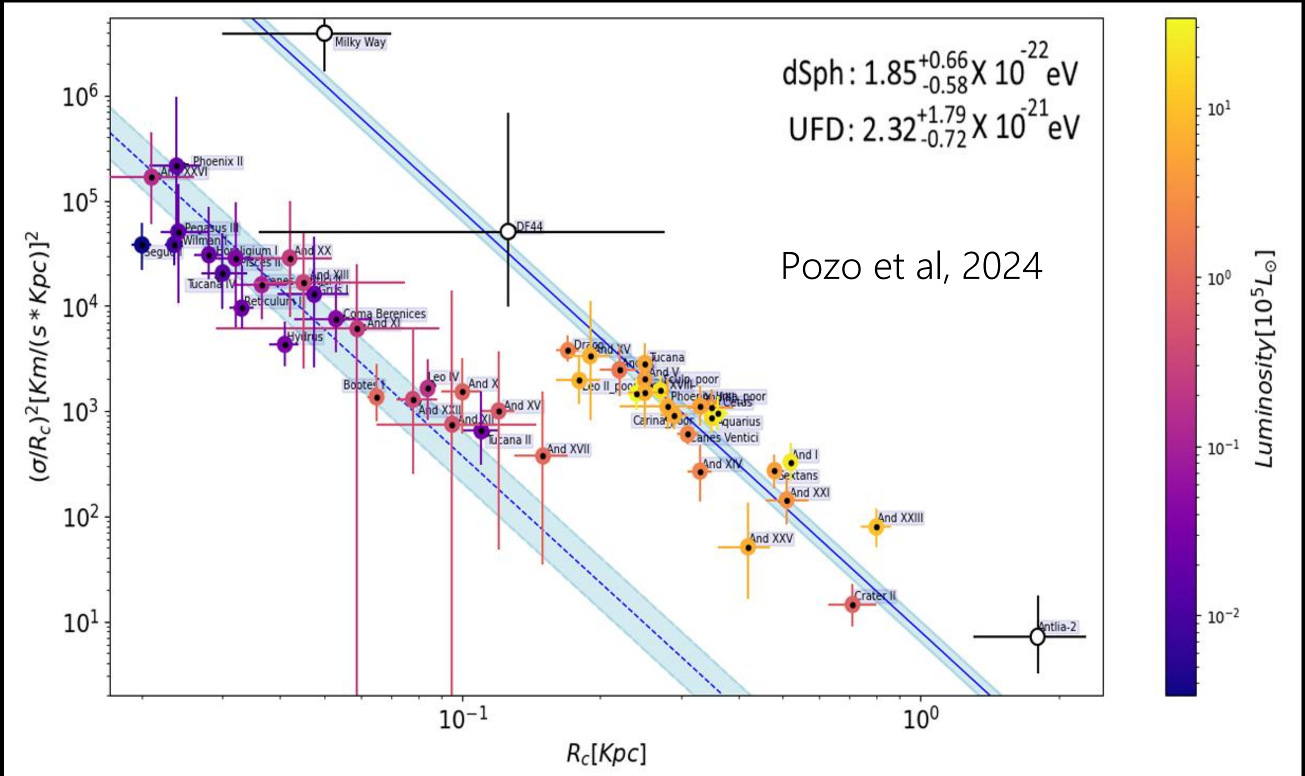
- String Axiverse gives rise many axion-like particles (ALPs) as FDM candidates
- Loosely speaking, these ALPs arise from the integrating the background flux along closed cycles/surfaces of compactified manifold.





Extension : What if, FDM is not made of single copy…?

- There are also observational evidence for multi-copies from dwarf galaxies



Extension : What if, FDM is not made of single copy…?

- Previous mass bound (in particular model UV LF) assumed FDM to be a single copy
- When there are multiple copies of ALPs, how does structure formation proceed?
- Consider the linear density contrasts in such a Universe

$$\boxed{\partial_t^2 \begin{pmatrix} \delta_1 \\ \vdots \\ \delta_J \\ \vdots \\ \delta_N \end{pmatrix}} + \boxed{2\mathcal{H}\partial_t \begin{pmatrix} \delta_1 \\ \vdots \\ \delta_J \\ \vdots \\ \delta_N \end{pmatrix}} - \boxed{\begin{pmatrix} 4\pi G\overline{\rho_1} - \boxed{\frac{k^4}{4m_1^2a^4}} & \cdots & 4\pi G\overline{\rho_J} & \cdots & 4\pi G\overline{\rho_N} \\ 4\pi G\overline{\rho_1} & \cdots & 4\pi G\overline{\rho_J} & \cdots & 4\pi G\overline{\rho_N} \\ 4\pi G\overline{\rho_1} & \cdots & 4\pi G\overline{\rho_J} - \boxed{\frac{k^4}{4m_J^2a^4}} & \cdots & 4\pi G\overline{\rho_N} \\ 4\pi G\overline{\rho_1} & \cdots & 4\pi G\overline{\rho_J} & \cdots & 4\pi G\overline{\rho_N} \\ 4\pi G\overline{\rho_1} & \cdots & 4\pi G\overline{\rho_J} & \cdots & 4\pi G\overline{\rho_N} - \boxed{\frac{k^4}{4m_N^2a^4}} \end{pmatrix} \begin{pmatrix} \delta_1 \\ \vdots \\ \delta_J \\ \vdots \\ \delta_N \end{pmatrix}} = 0$$

"Force" felt by contrasts

Expansion counters their growth

Density contrasts grow under **mutual** gravitational potential

Growth is suppressed on small scales by wavelike nature

Extension : What if, FDM is not made of single copy…?

- Owing to their mutual couplings to gravitational potential, above equations could be re-arranged into a single equation

$$\ddot{\delta}_{tot} + 2\mathcal{H}\dot{\delta}_{tot} - 4\pi G\delta_{tot}\overline{\rho_{tot}} + \frac{k^4}{4m_{eff}^2 a^4}\delta_{tot} = 0 \quad \text{where} \quad \delta_{tot} = \frac{\sum_I \overline{\rho_I}\delta_I}{\overline{\rho_{tot}}} \qquad \frac{1}{m_{eff}^2}\delta_{tot}\overline{\rho_{tot}} \equiv \sum_I \frac{\overline{\rho_I}\delta_I}{m_I^2}$$

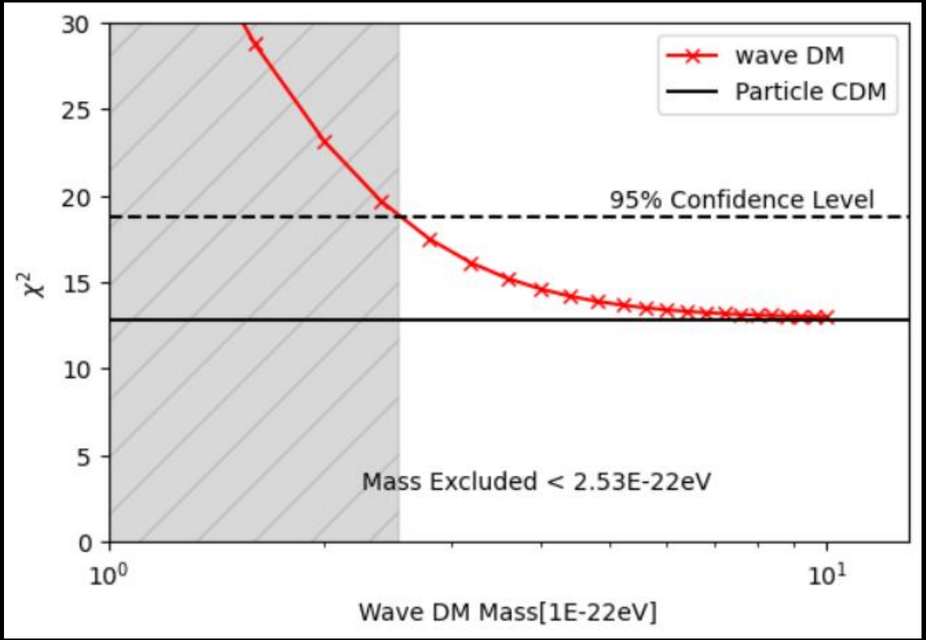
i.e. δ_{tot} is the total density contrast (total density perturbation/total density)

and m_{eff} is an effective mass for the total density contrast

- Compare the original equation : $\ddot{\delta}_I + 2\mathcal{H}\dot{\delta}_I - 4\pi G\overline{\rho_{tot}}\delta_{tot} + \frac{k^4\delta_I}{4a^4 m_I^2} = 0$
- There are then two different limits for each copy of ALPs
  - when suppression by wave nature could be neglected : δ_{tot} and all δ_I equates!
  - when suppression by wave nature dominates: different δ_I decouples

Interpreting the mass constraint

- As all δ_I becomes equivalent to the total density contrast δ_{tot} before suppression effect of FDM becomes apparent,
- anticipate the suppression on structure growth begins at the scale of m_{eff} !



Correspondingly, obtained mass bound is also on m_{eff} , where

$$\frac{1}{m_{eff}^2} = \sum_I \frac{\overline{\rho_I}/\overline{\rho_{tot}}}{m_I^2}$$

Lighter copies can still exist (and dominate low-z galaxies), but cannot dominate the dark matter budget…

Conclusion

- If dark matter is wavy, abundance of faint galaxies would be suppressed
- This could be tested by measuring galaxy surface number density in different magnification regions
- By combining deep JWST and HST images, we constructed a more complete and robust catalog reaching ~1 mag fainter
- We argue that wave dark matter lighter than 2.53E-22eV could be ruled out at 95% confidence interval
- In Universe with multiple copies of ALPs/FDM particles, above mass bound is instead on the effective mass scale given by $\frac{1}{m_{eff}^2} = \sum_I \frac{\overline{\rho_I}/\overline{\rho_{tot}}}{m_I^2}$