

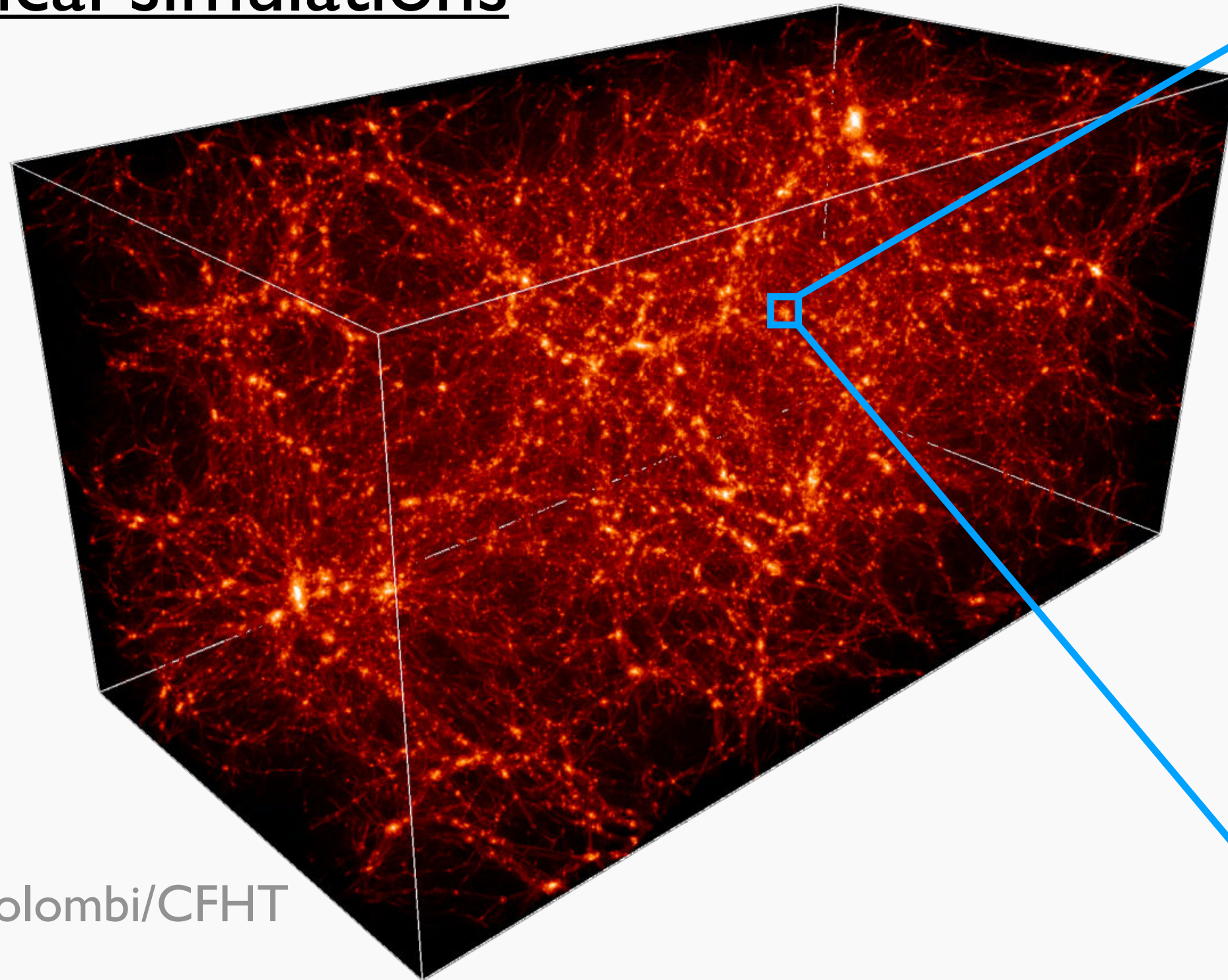
Small-scale structure of dark matter probed by gravitational lensing

Masamune Oguri

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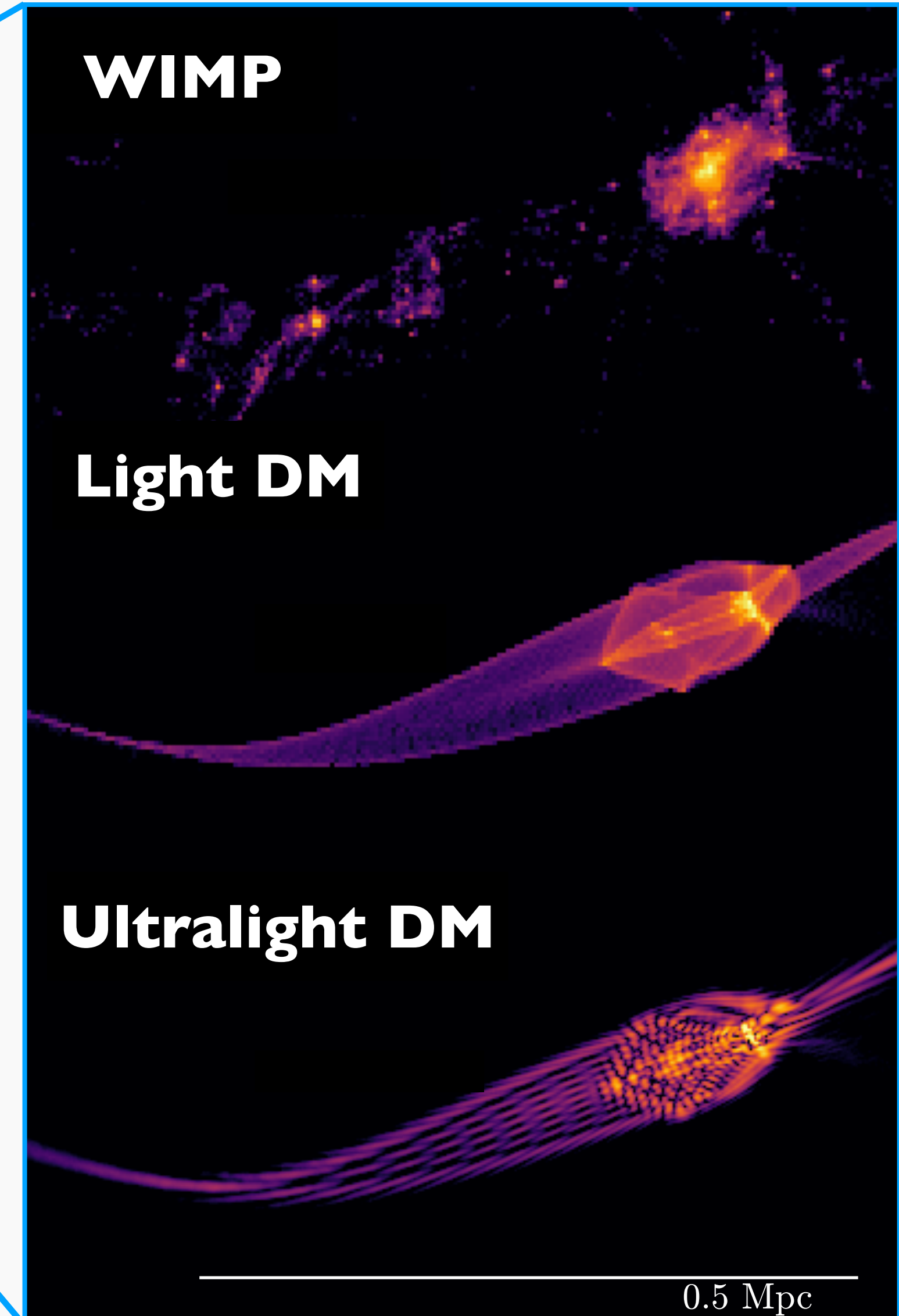
Small-scale structure of dark matter

numerical simulations



S. Colombi/CFHT

small-scale dark matter distribution provides a clue to its nature



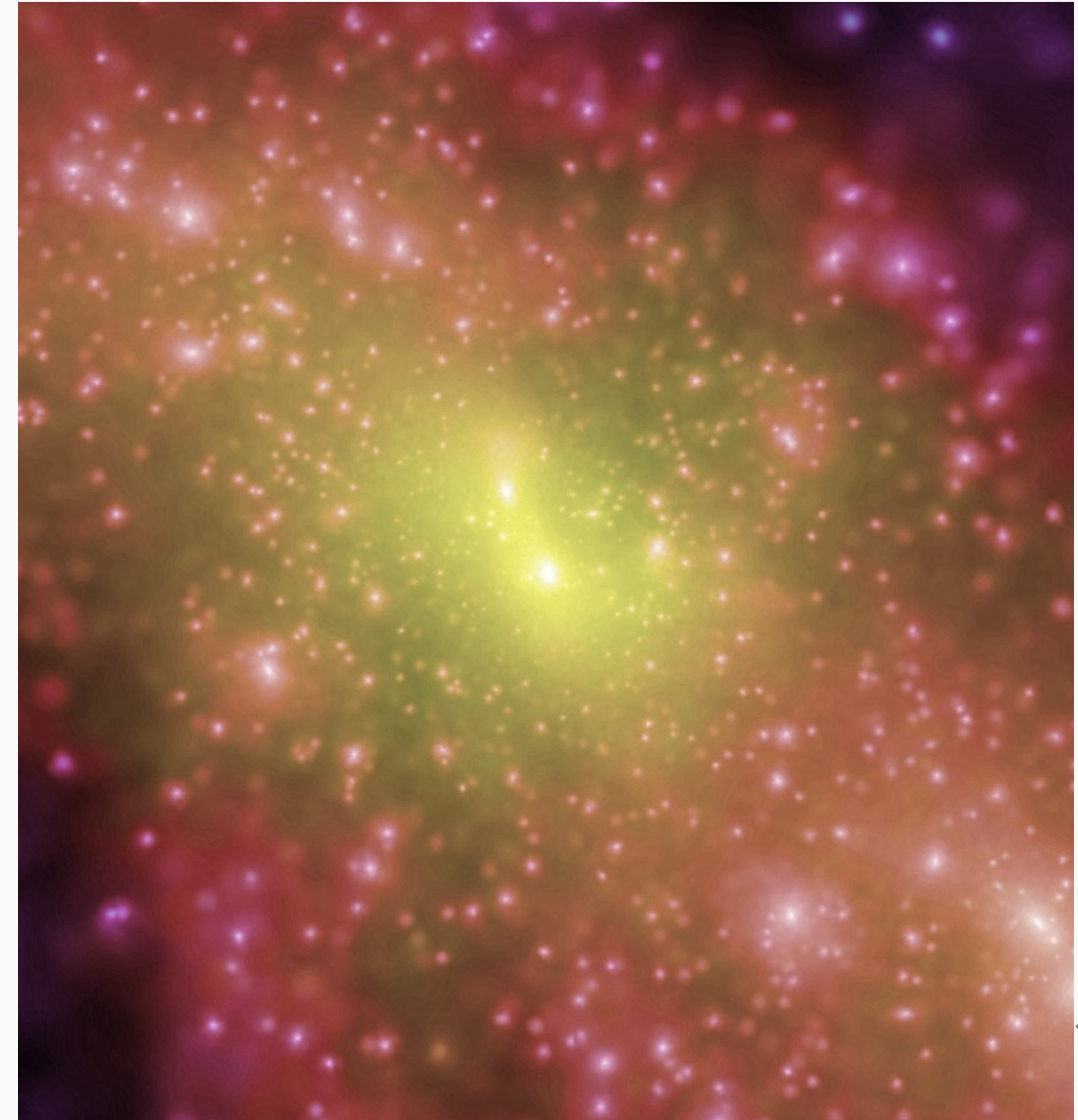
Mocz+ MNRAS 494(2020)2027

Contents

- core-cusp problem
- strong lensing detections of low-mass objects

Small-scale challenges (?) to cold dark matter (CDM)

- cusp-core problem
→ this talk
- missing satellite problem
many faint satellite galaxies discovered in SDSS, HSC, etc., now consistent with CDM
(e.g., Kim+2018; Homma+2024; ...)
- too-big-to-fail problem
naturally resolved by baryon physics
(e.g., Sawala+2016; Wetzel+2016; ...)
- ...



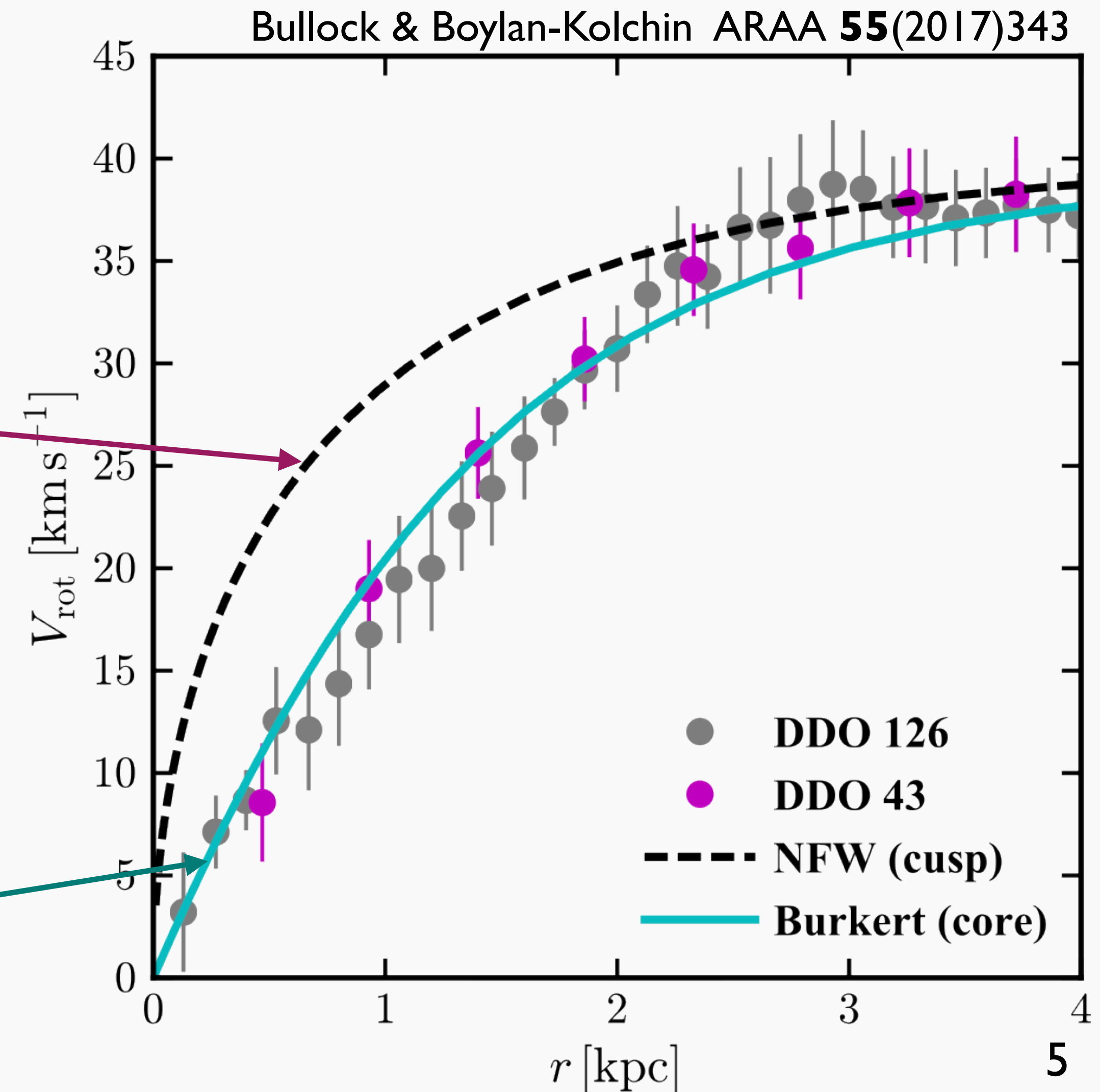
Core-cusp problem

- NFW profile: density profile of dark matter halo predicted by standard CDM

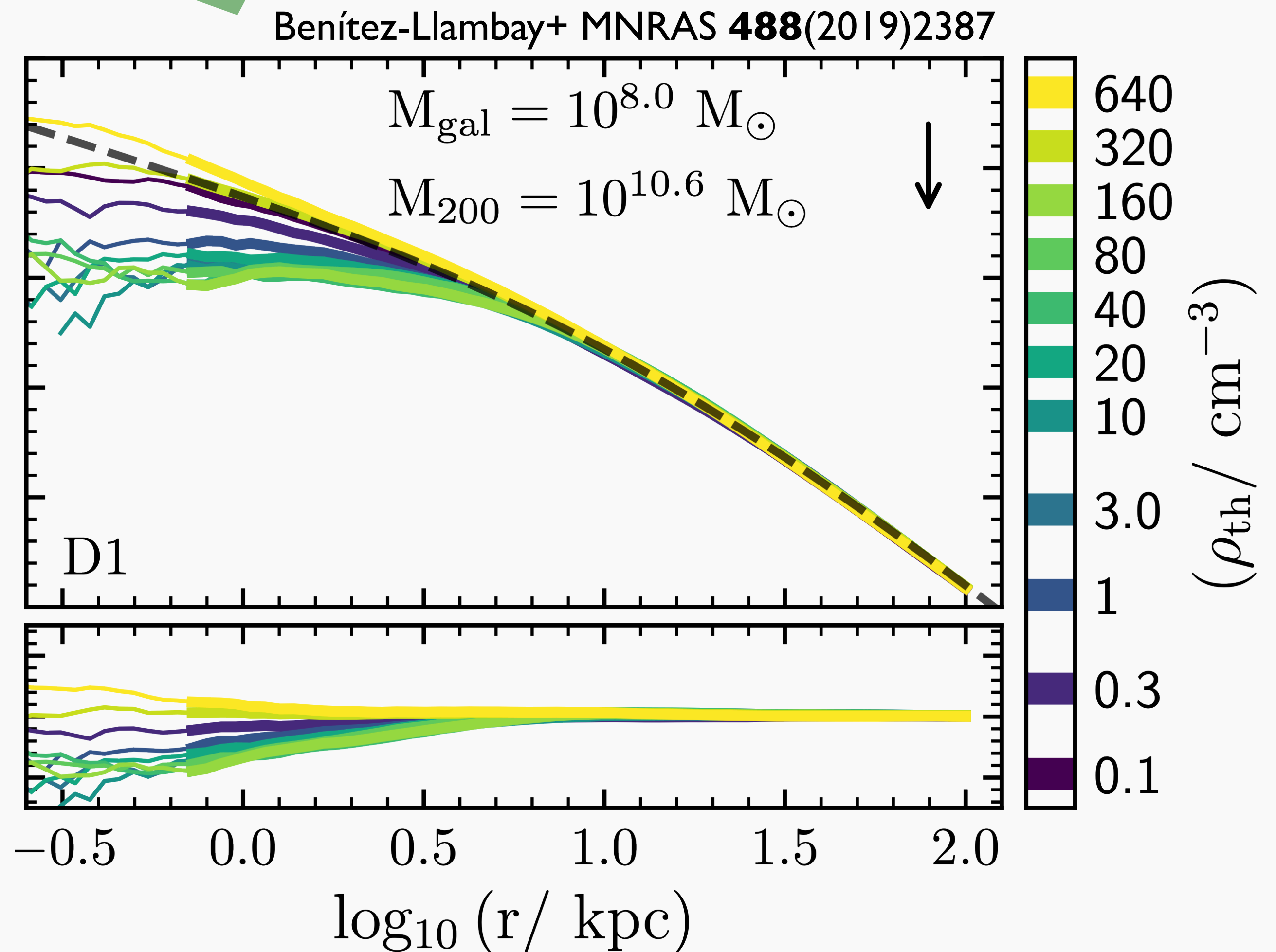
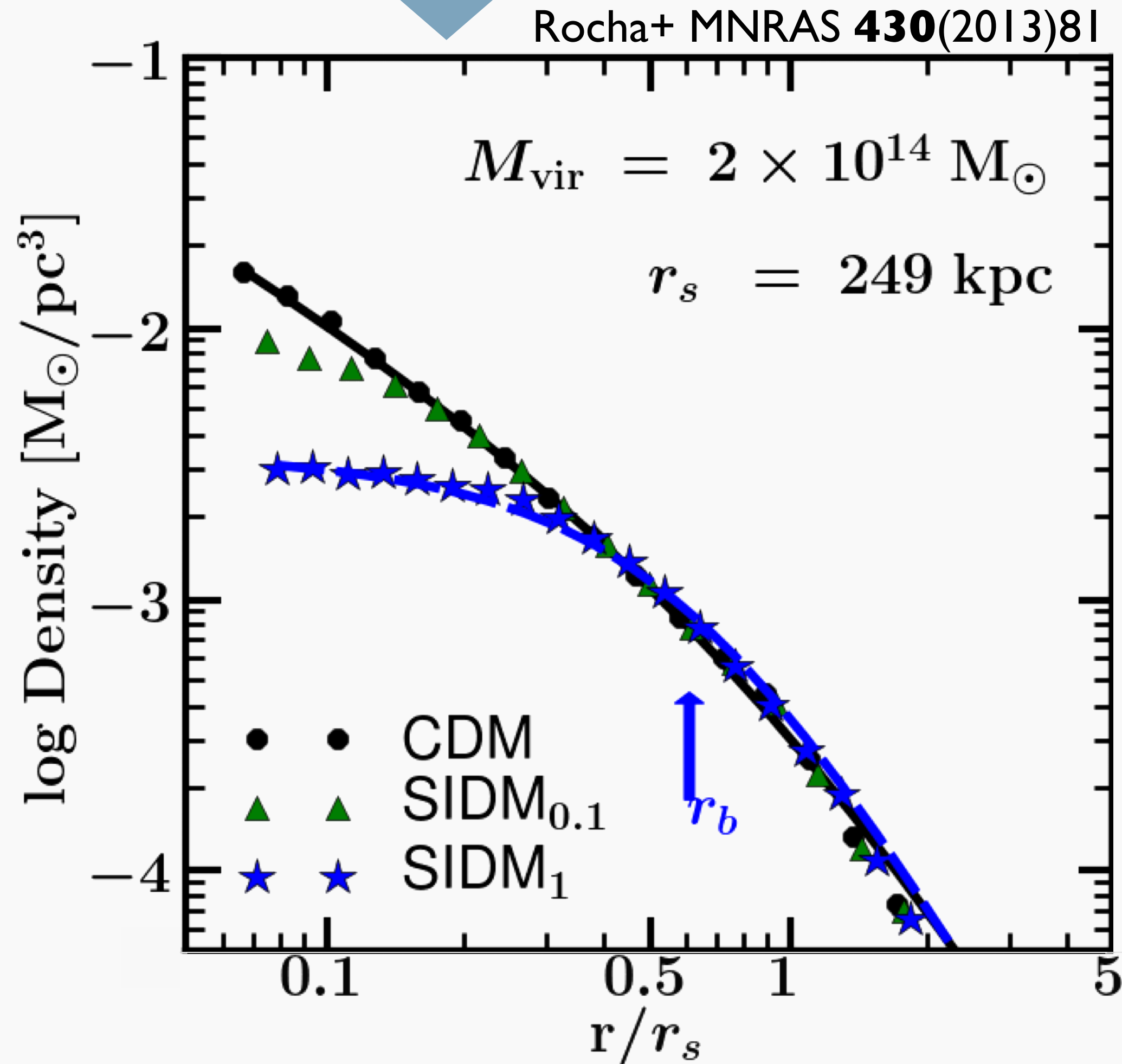
$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

- observations of rotation curves of some galaxies indicate cored profile

$$\rho(r) = \frac{\rho_s}{(1 + r/r_s)(1 + (r/r_s)^2)}$$

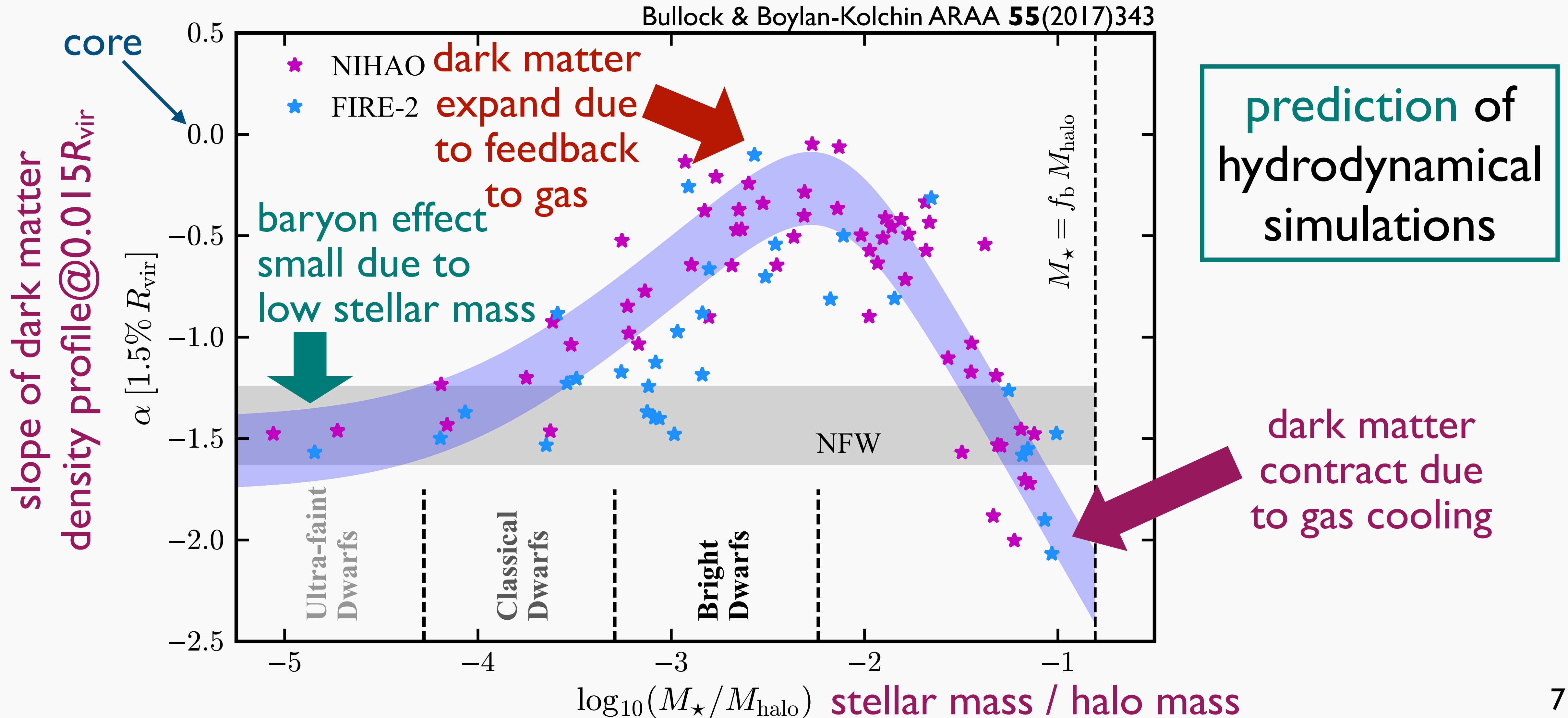


Dark matter or baryon physics?



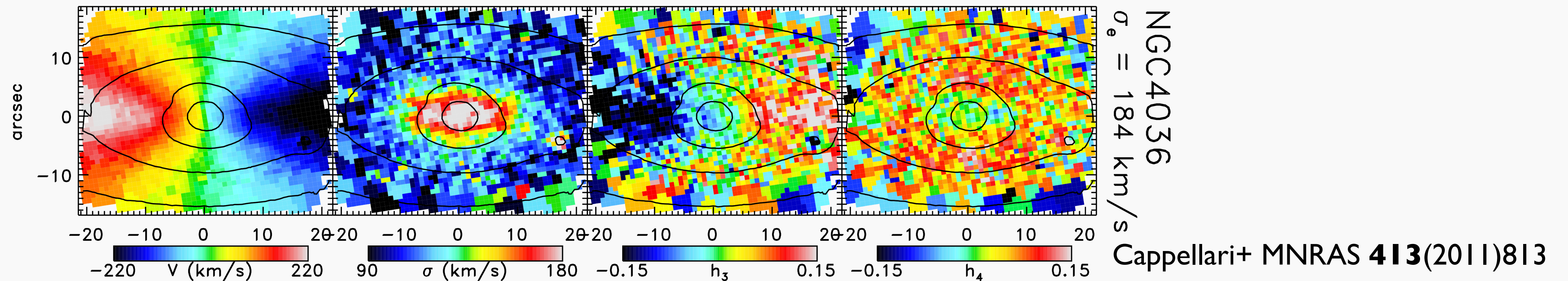
Self-interacting DM, Warm DM, Fuzzy DM, ... baryon cooling and star formation

Stellar mass dependence of baryon effect

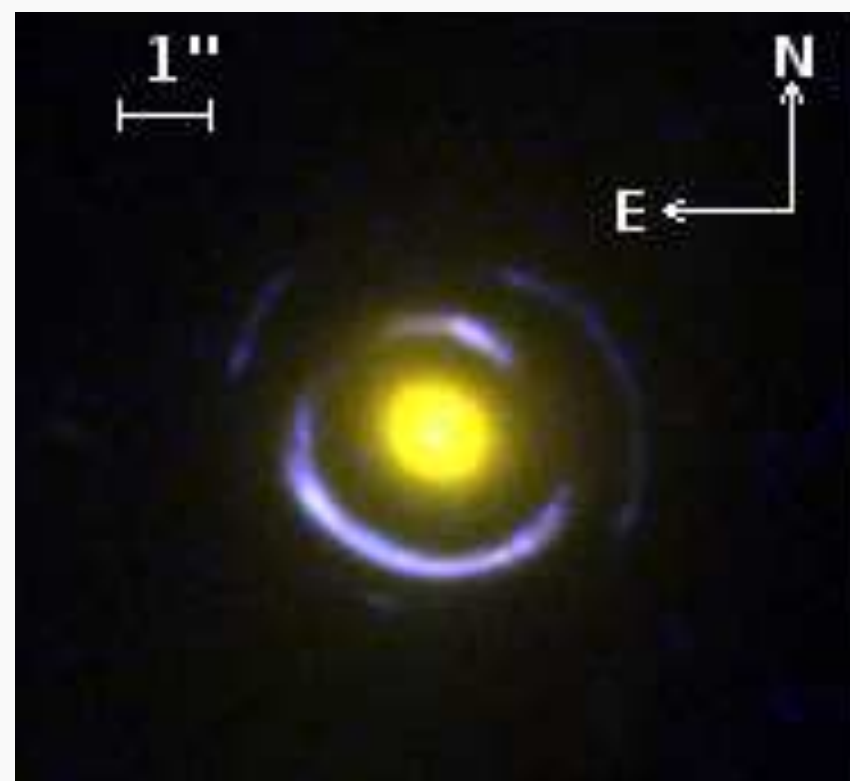


Observations of central DM profiles

- kinematics (velocity dispersion, rotation curve, ...)



- strong gravitational lensing

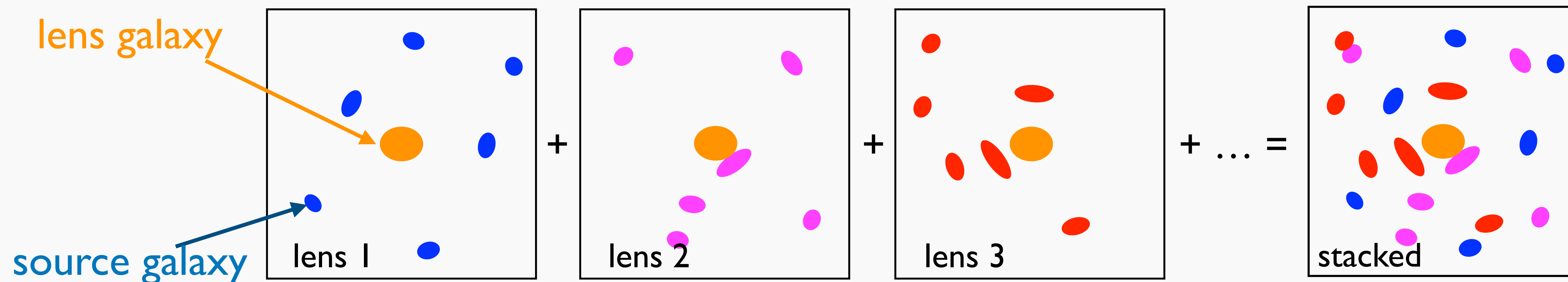


Sonnenfeld+ ApJ **752**(2012)163



New approach: weak gravitational lensing

- first study of central dark matter and stellar mass distributions with **stacked weak gravitational lensing**



lens: Subaru HSC photometric luminous red galaxies Oguri+ PASJ **78**(2026)416

$$N_{\text{LRG}} \simeq 10^6 \quad (0.4 < z < 0.6)$$

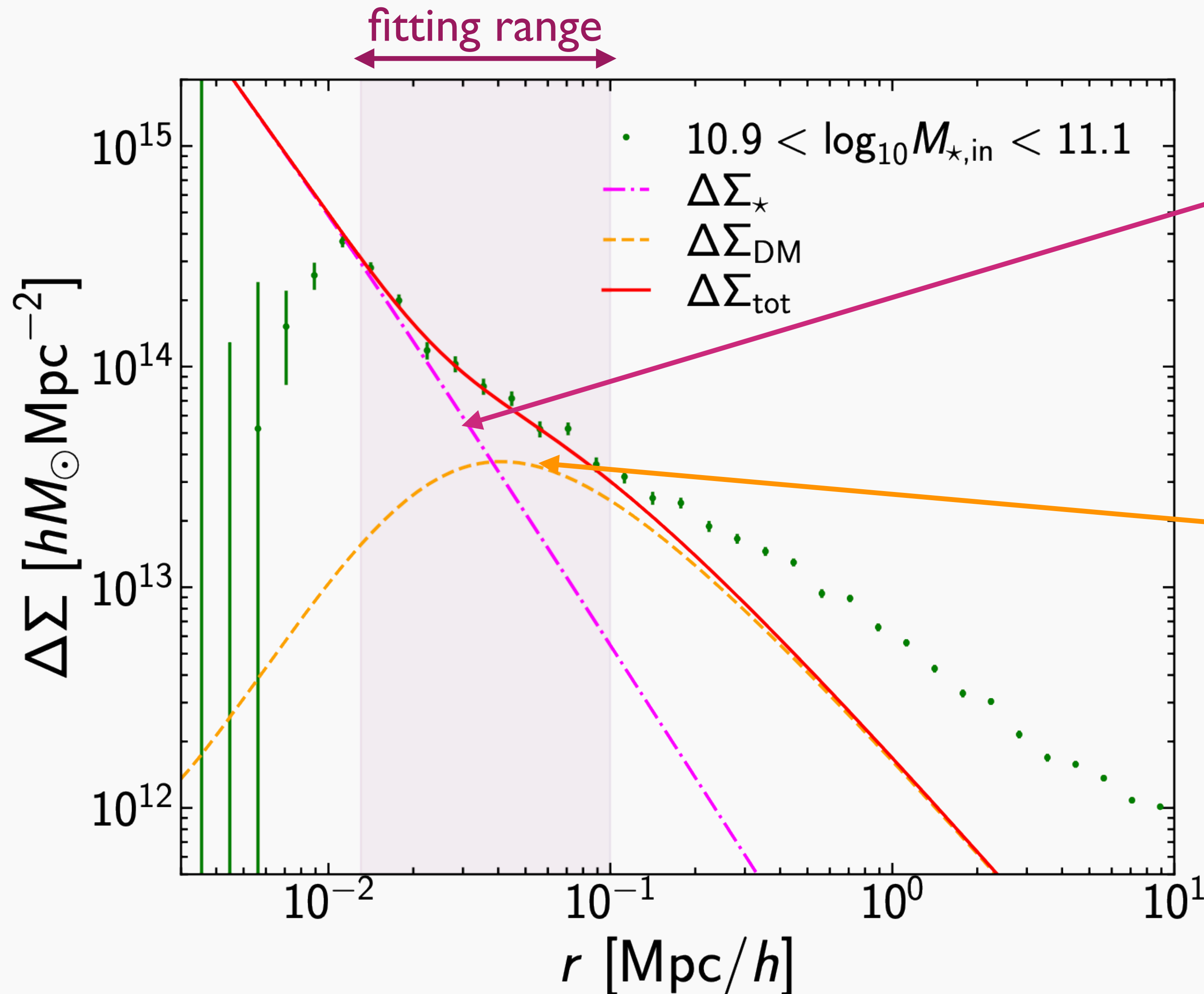
source: Subaru HSC three-year shear catalog Li+ PASJ **74**(2022)421

$$N_{\text{source}} \simeq 3.5 \times 10^7$$



Central lensing profile

differential surface density
(tangential shear)



stellar mass: Hernquist profile

$$\rho_{\star}(r) = \frac{M_{\star} a}{2\pi r (r + a)^3}$$

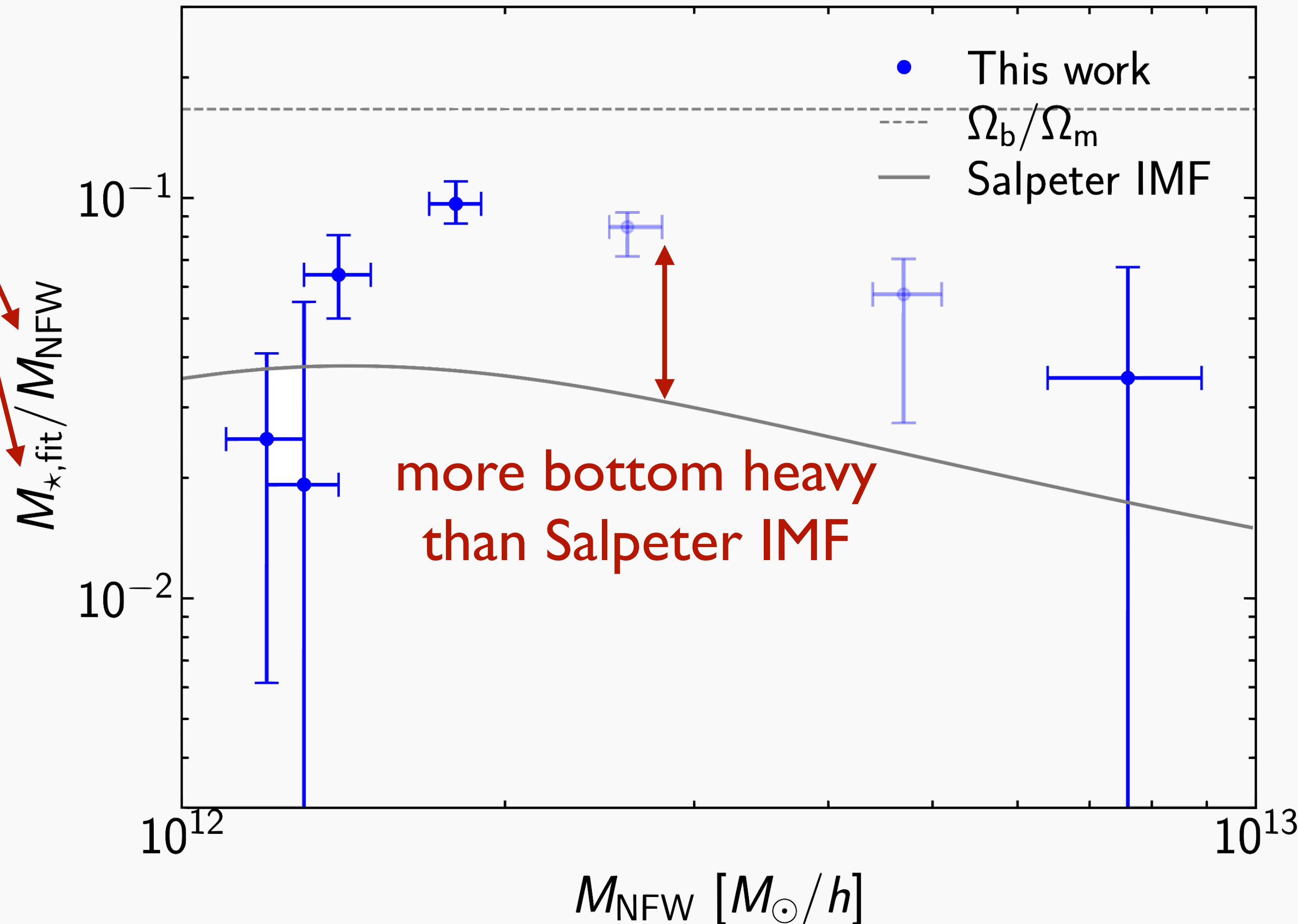
dark matter: cored power-law

$$\rho_{\text{DM}}(r) \propto (r^2 + r_c^2)^{\gamma/2}$$



Byproduct: stellar-to-halo mass relation (SHMR)

both directly
measured by
weak lensing



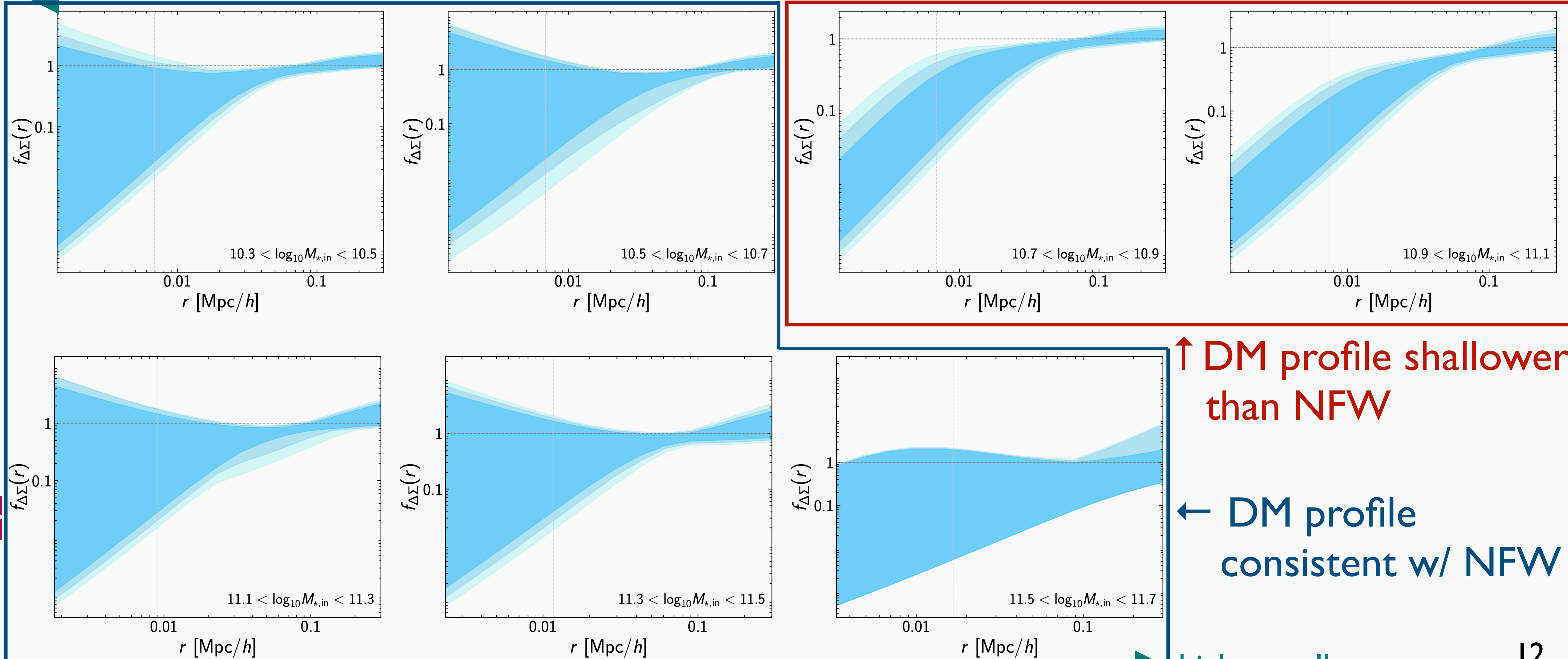
for the first time
SHMR is derived
only by lensing!



Comparison with NFW profile

$$f_{\Delta\Sigma} = \Delta\Sigma(\text{obs}) / \Delta\Sigma(\text{NFW})$$

lower stellar mass



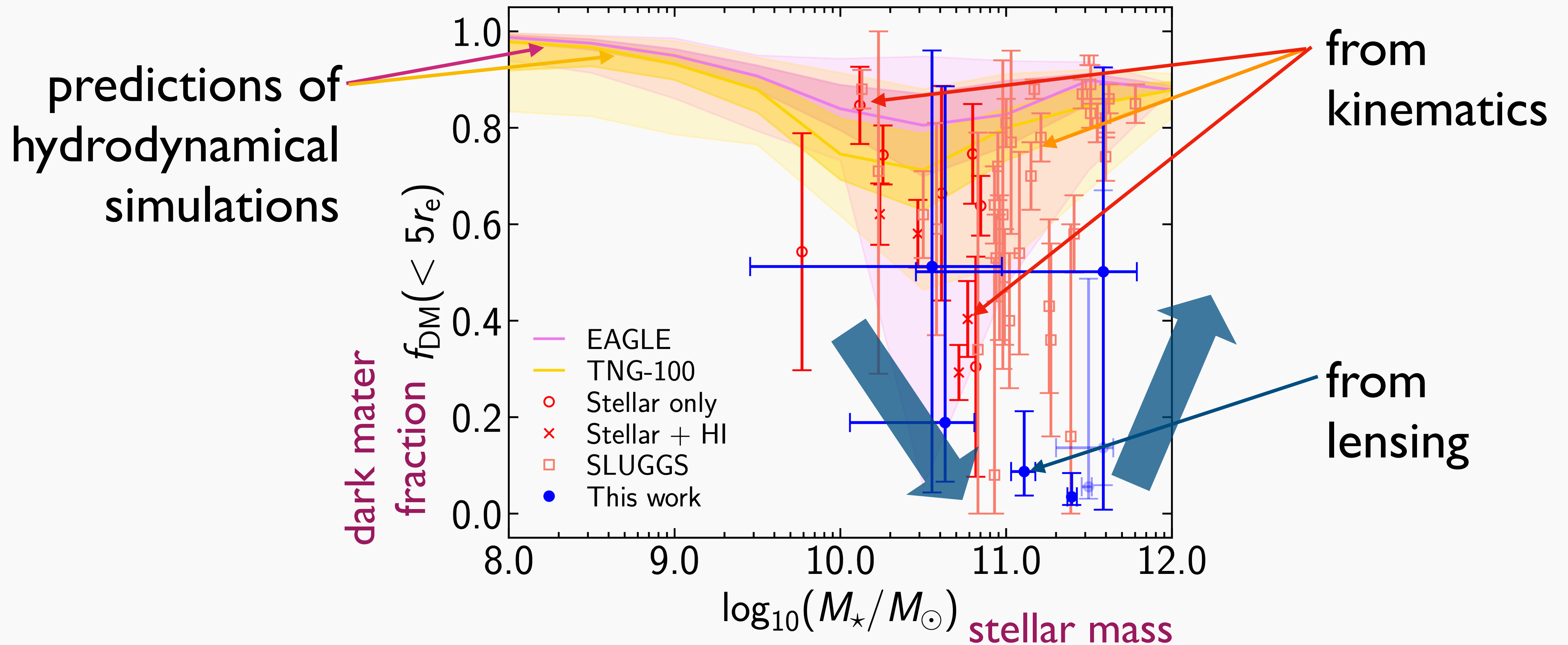
↑ DM profile shallower than NFW

← DM profile consistent w/ NFW

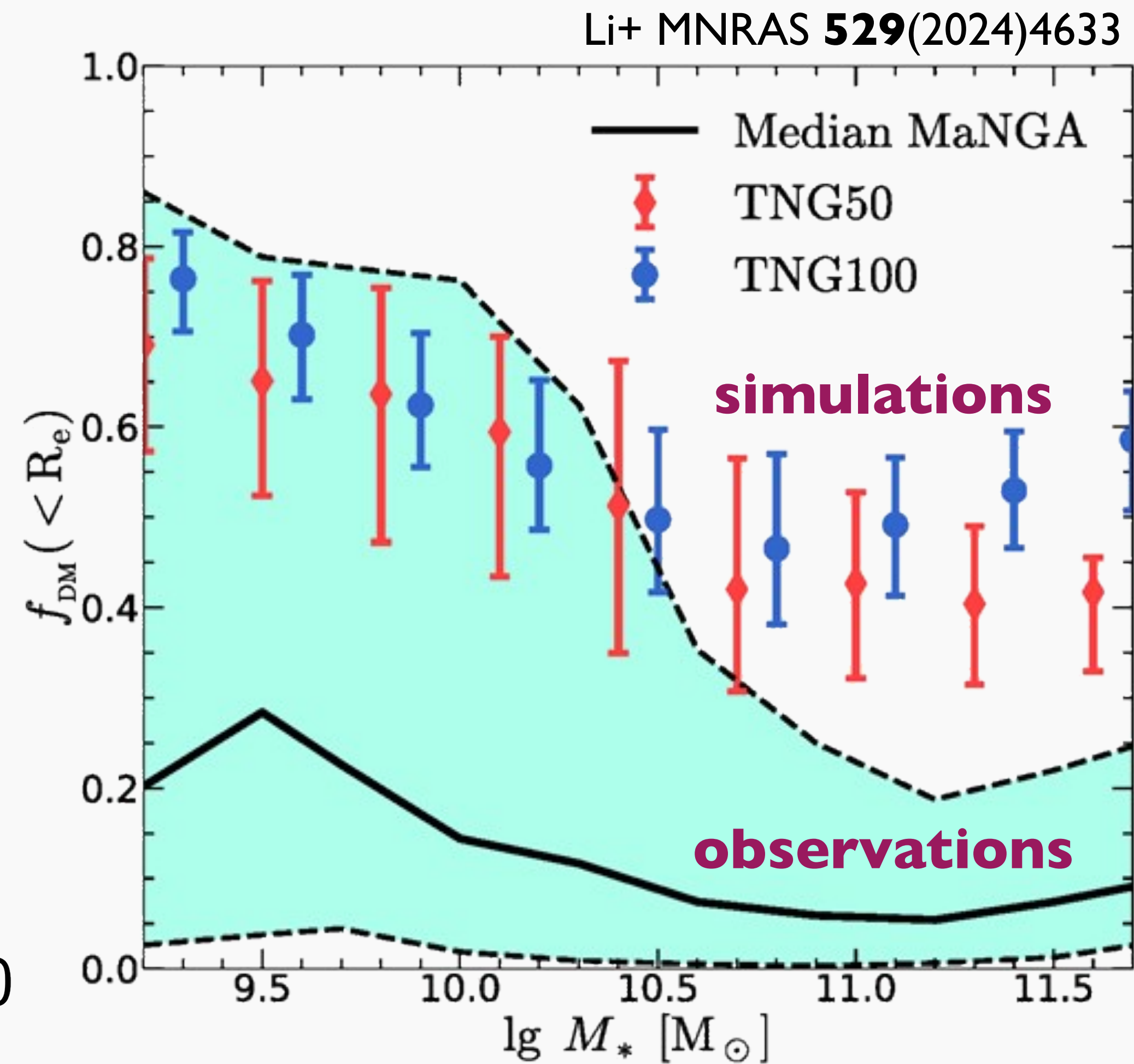
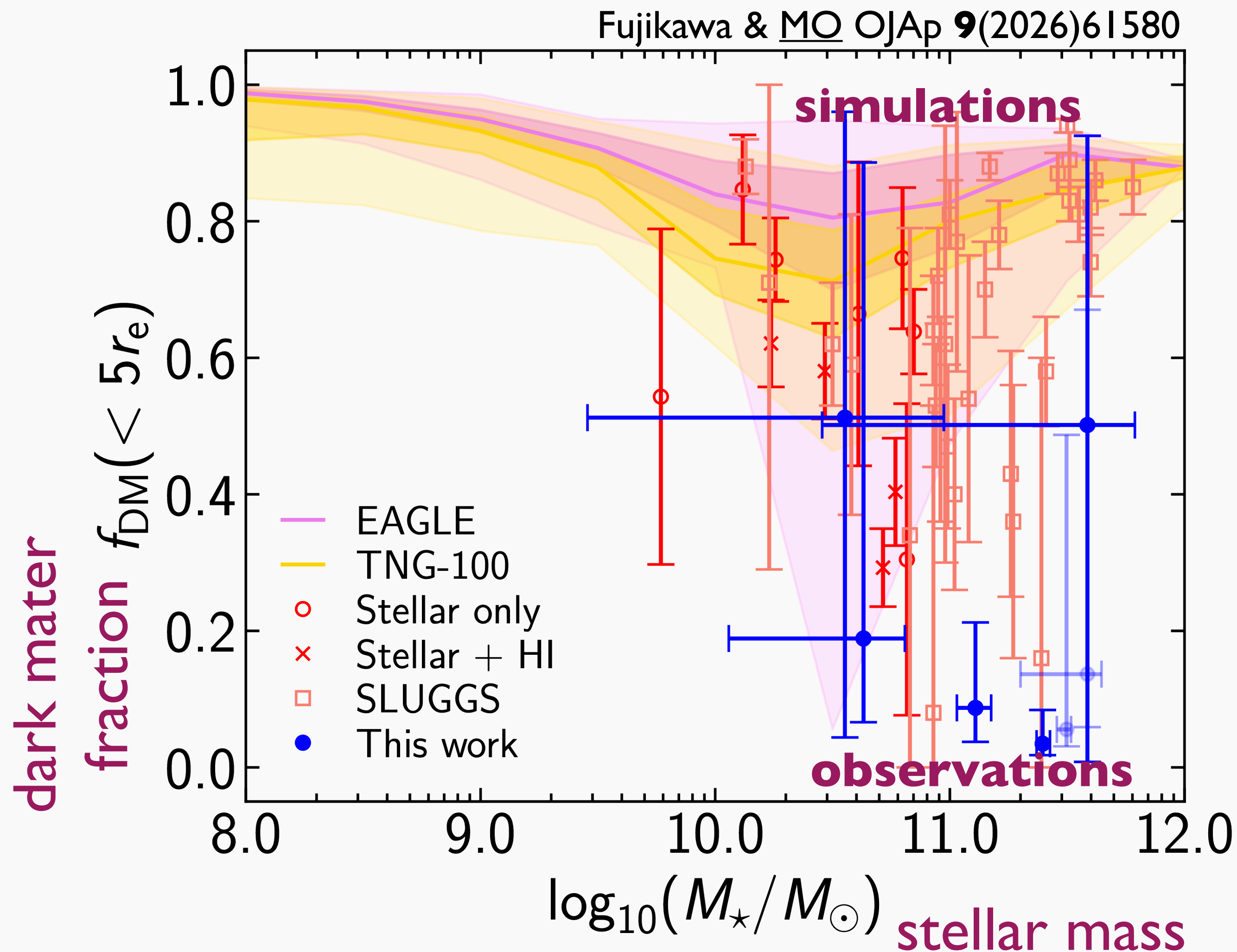
higher stellar mass



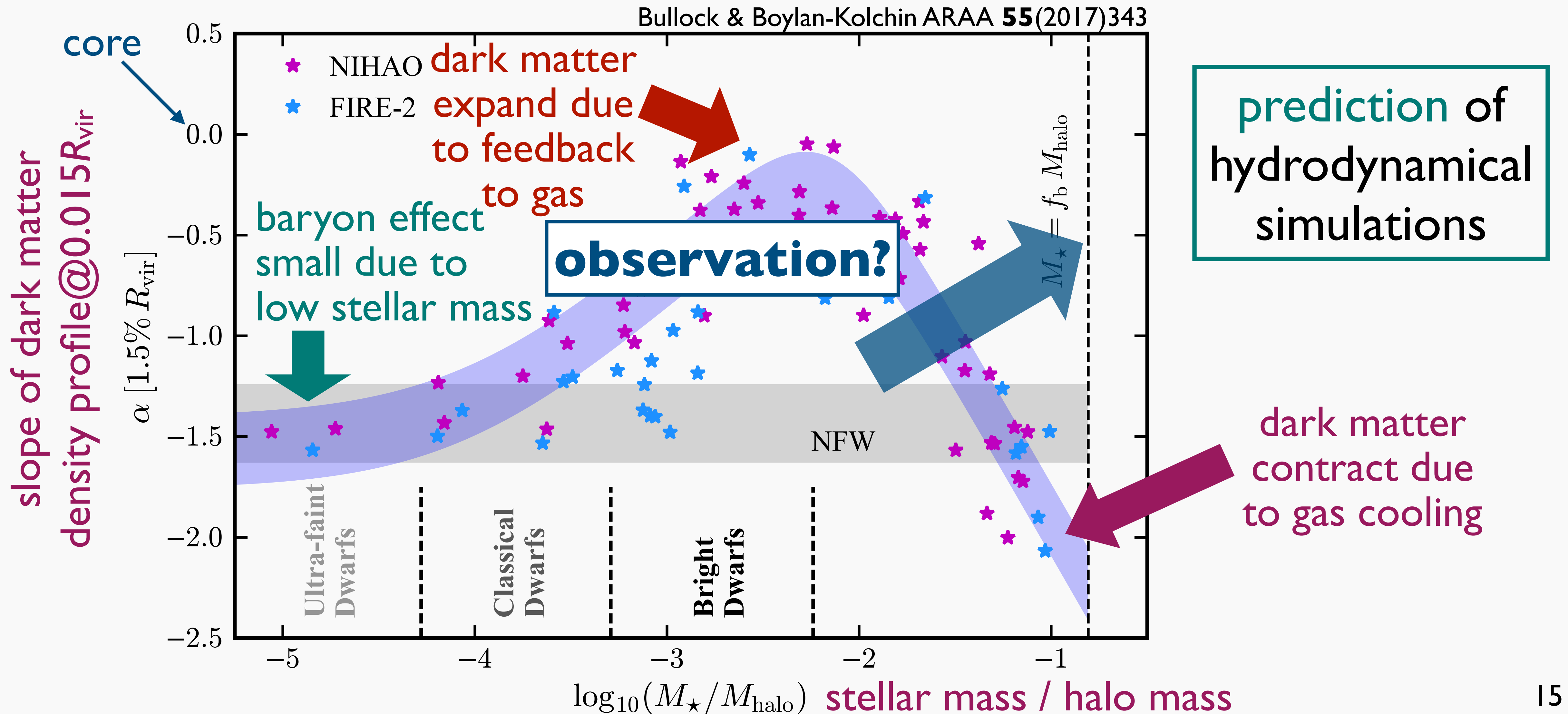
Dark matter fraction



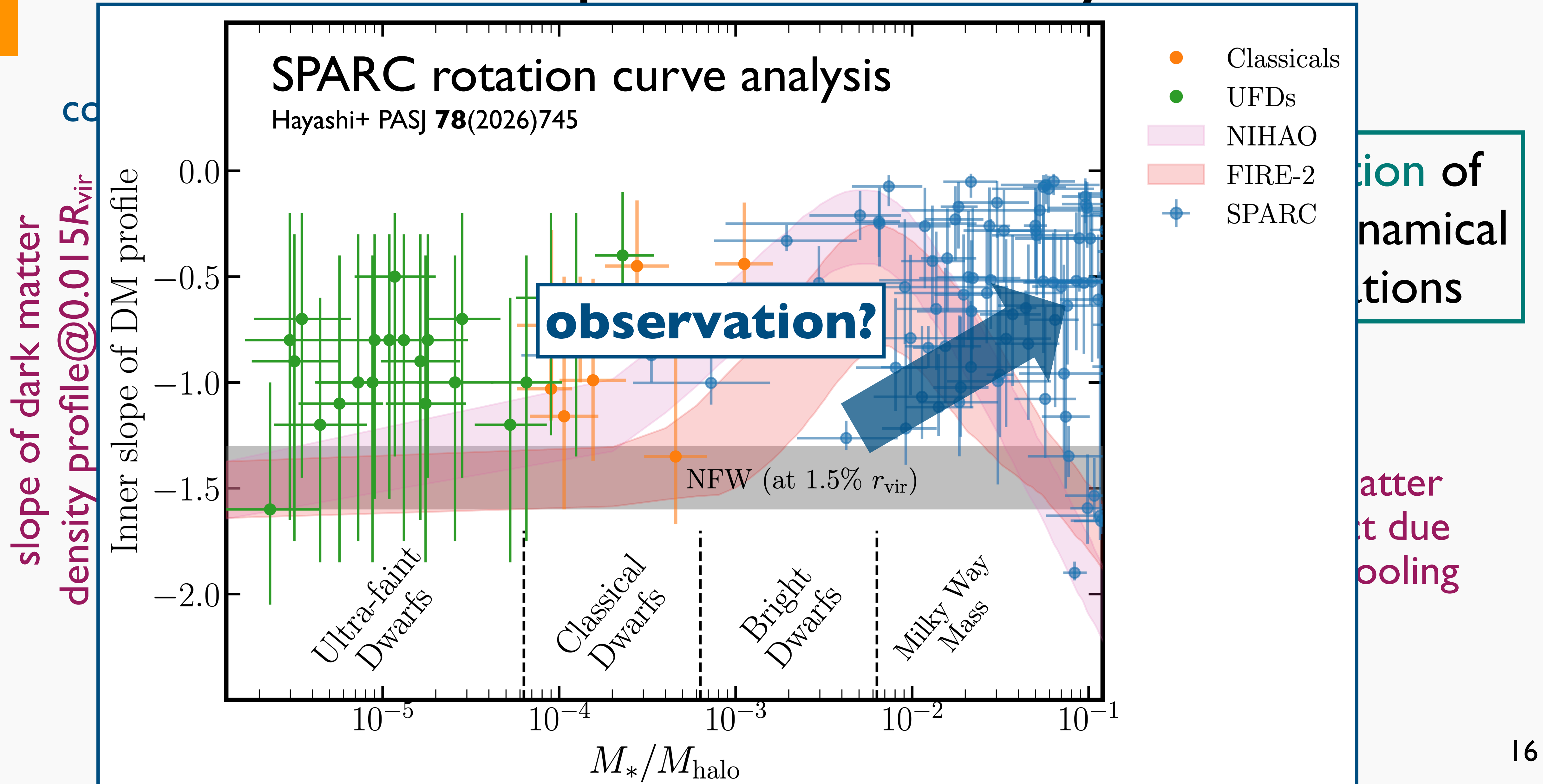
Lower DM fraction than simulations?



Stellar mass dependence of baryon effect



Stellar mass dependence of baryon effect



Summary: core-cusp problem

- **stacked weak lensing** provides a new promising approach to study central density profiles of dark matter and stars
- DM profiles shallower than NFW for galaxies with $M_{\star} \sim 10^{11} M_{\odot}$
- **observed DM fraction lower than hydrodynamical simulations**
 - less efficient adiabatic contraction, stronger feedback
 - or could it be explained by an alternative DM model?
(e.g., resonant self-interacting dark matter?? Chu+ PRL **122**(2019)071103)

Low-mass dark matter halos

- dark matter halos with $M \lesssim 10^6 M_\odot$ contain no star



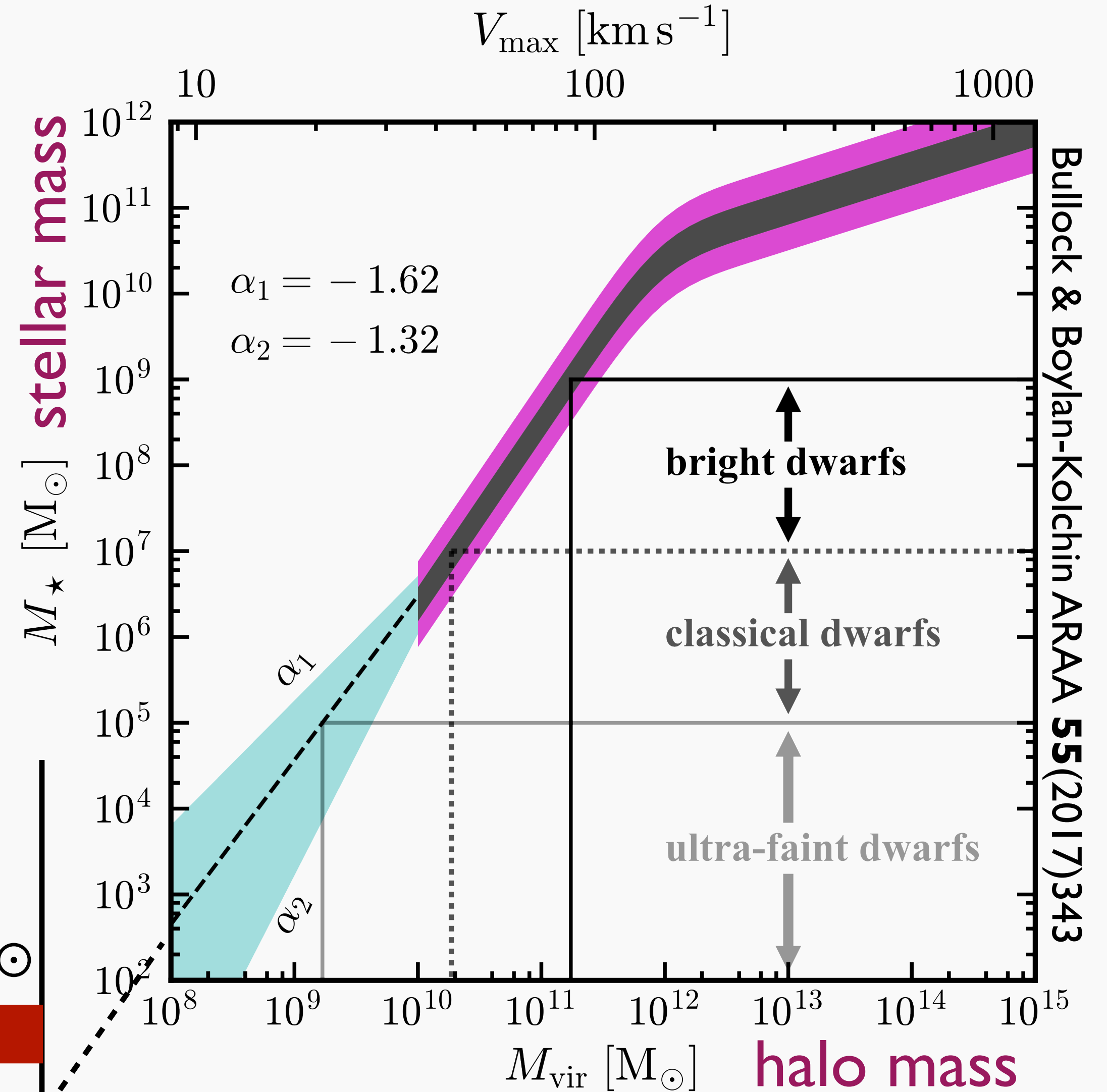
no baryon effect



ideal for testing DM models

holy grail!

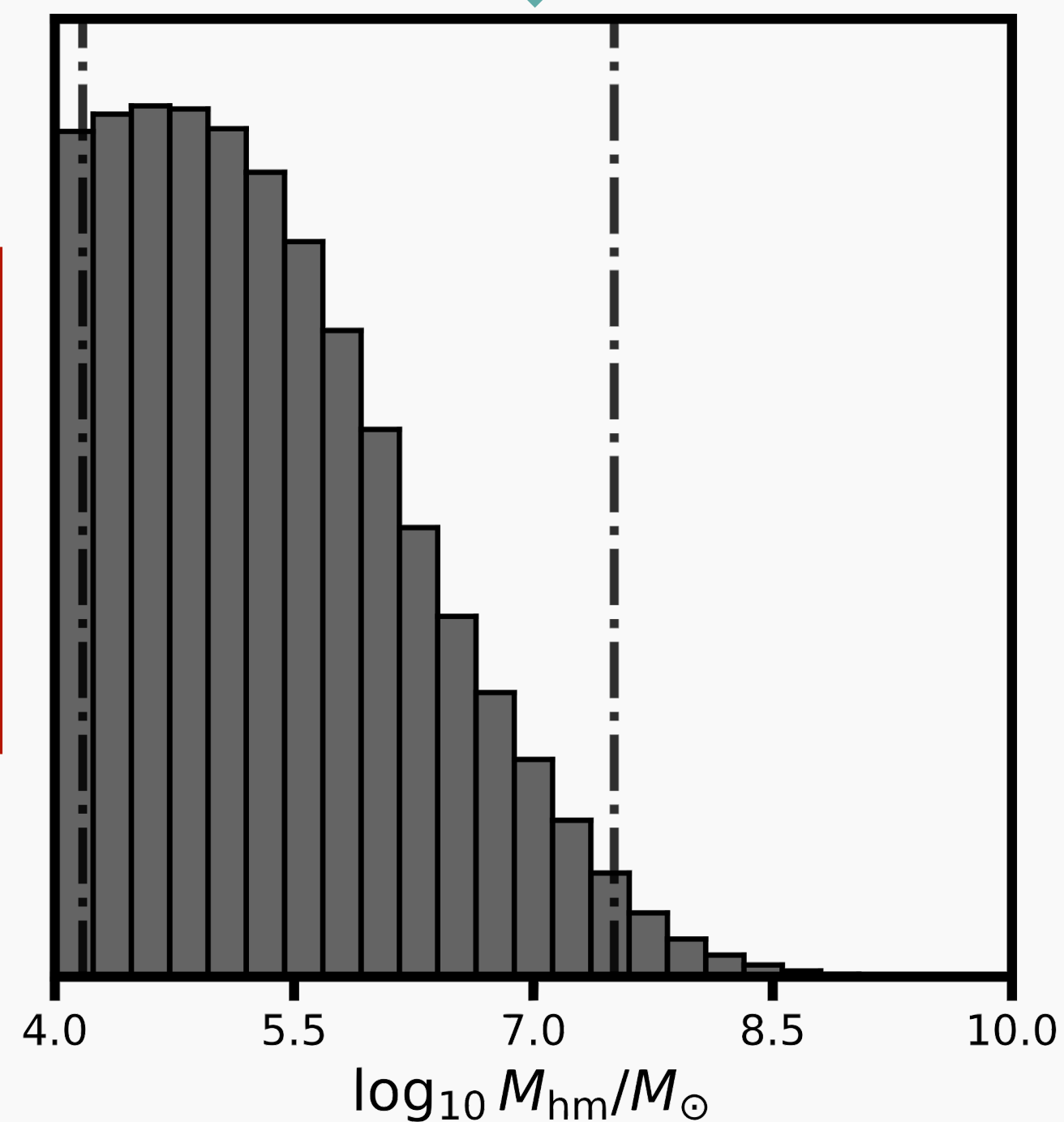
$\lesssim 10^6 M_\odot$



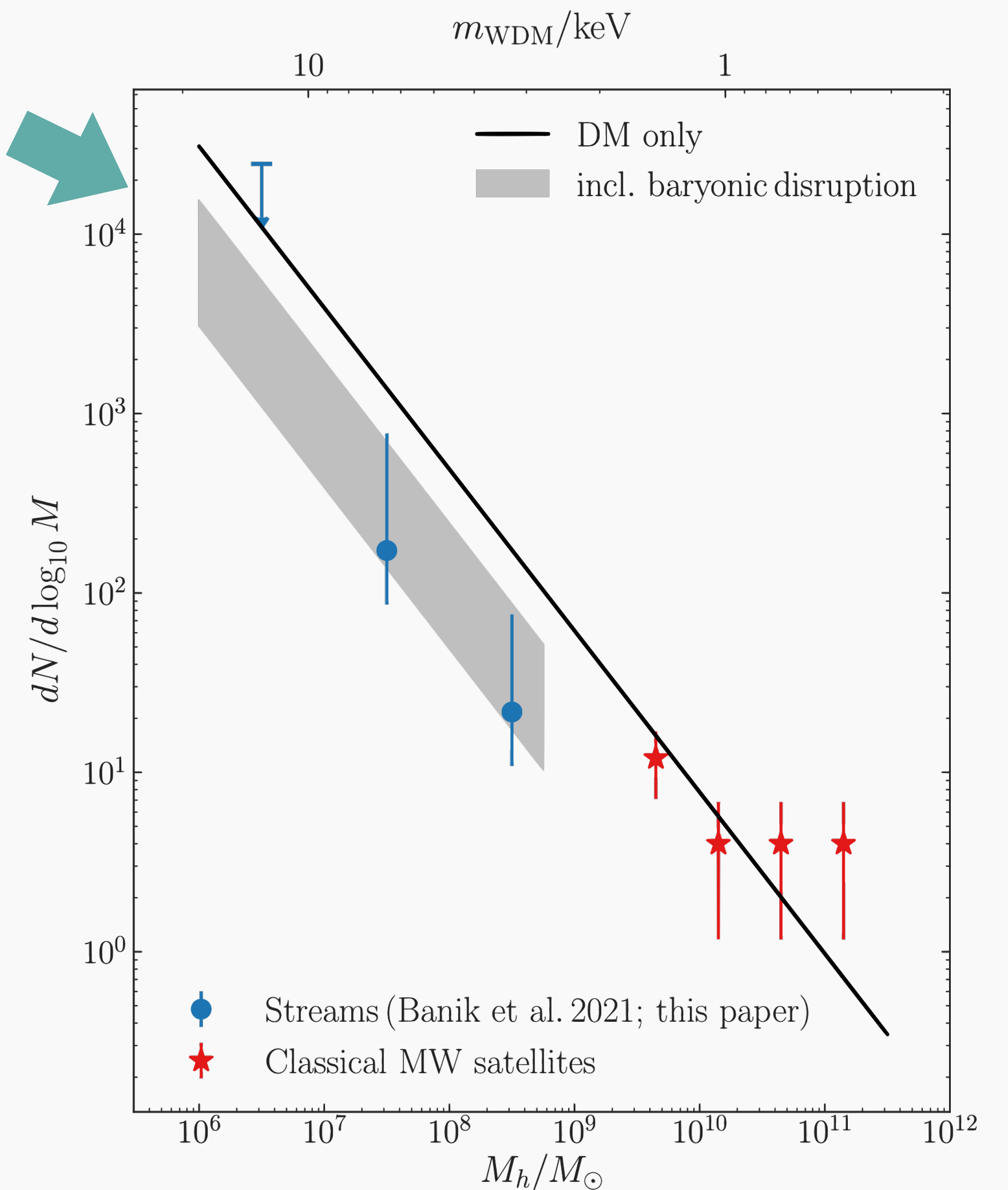
Observing low-mass dark matter halos

- perturbation on Milky Way tidal streams
- perturbation on strong lens systems

abundance consistent w/
standard CDM model
down to $\simeq 10^{7-8} M_{\odot}$



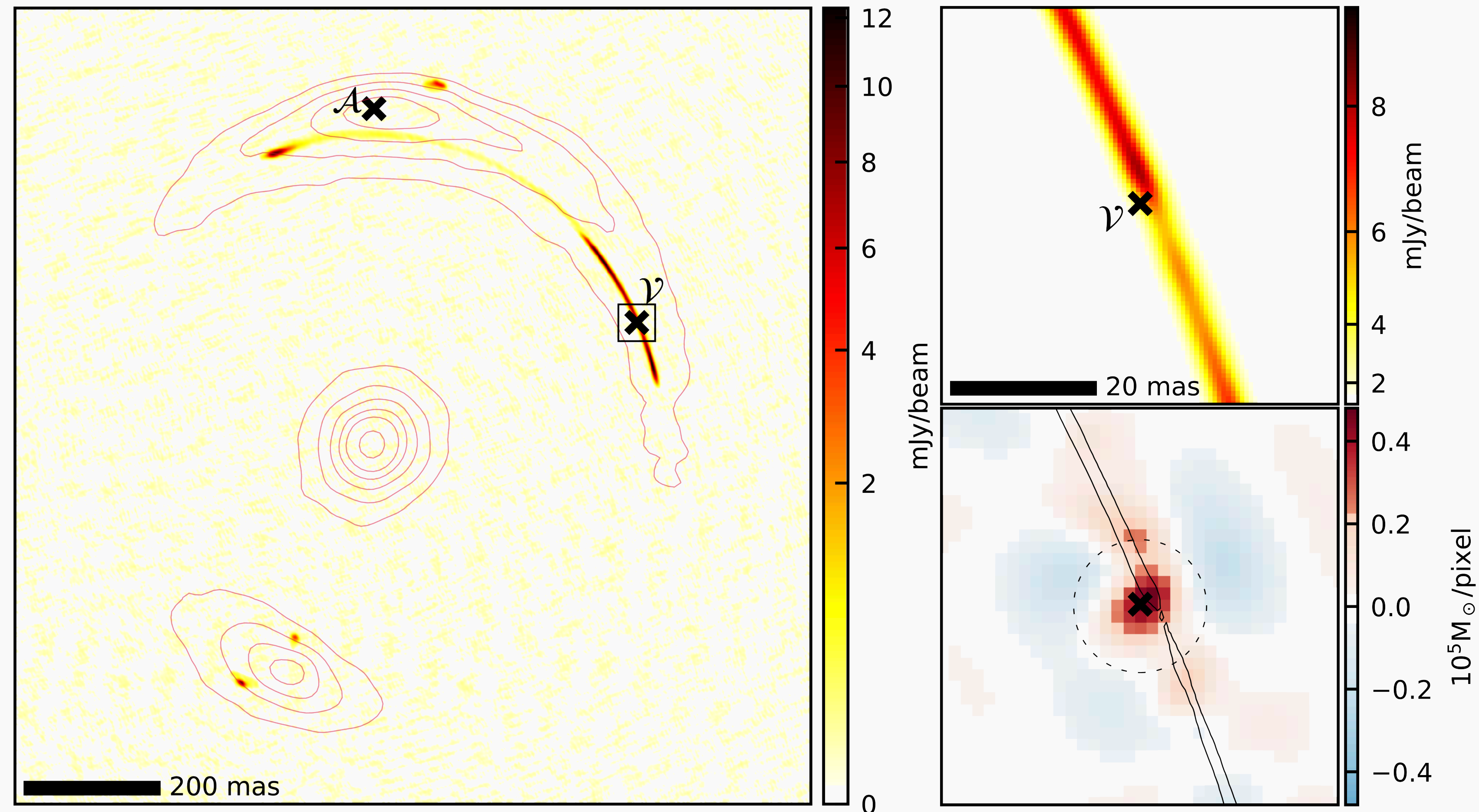
Keeley+ MNRAS **535**(2024)1652



Banik+ MNRAS **502**(2021)2364

Discovery of $\sim 10^6 M_{\odot}$ object

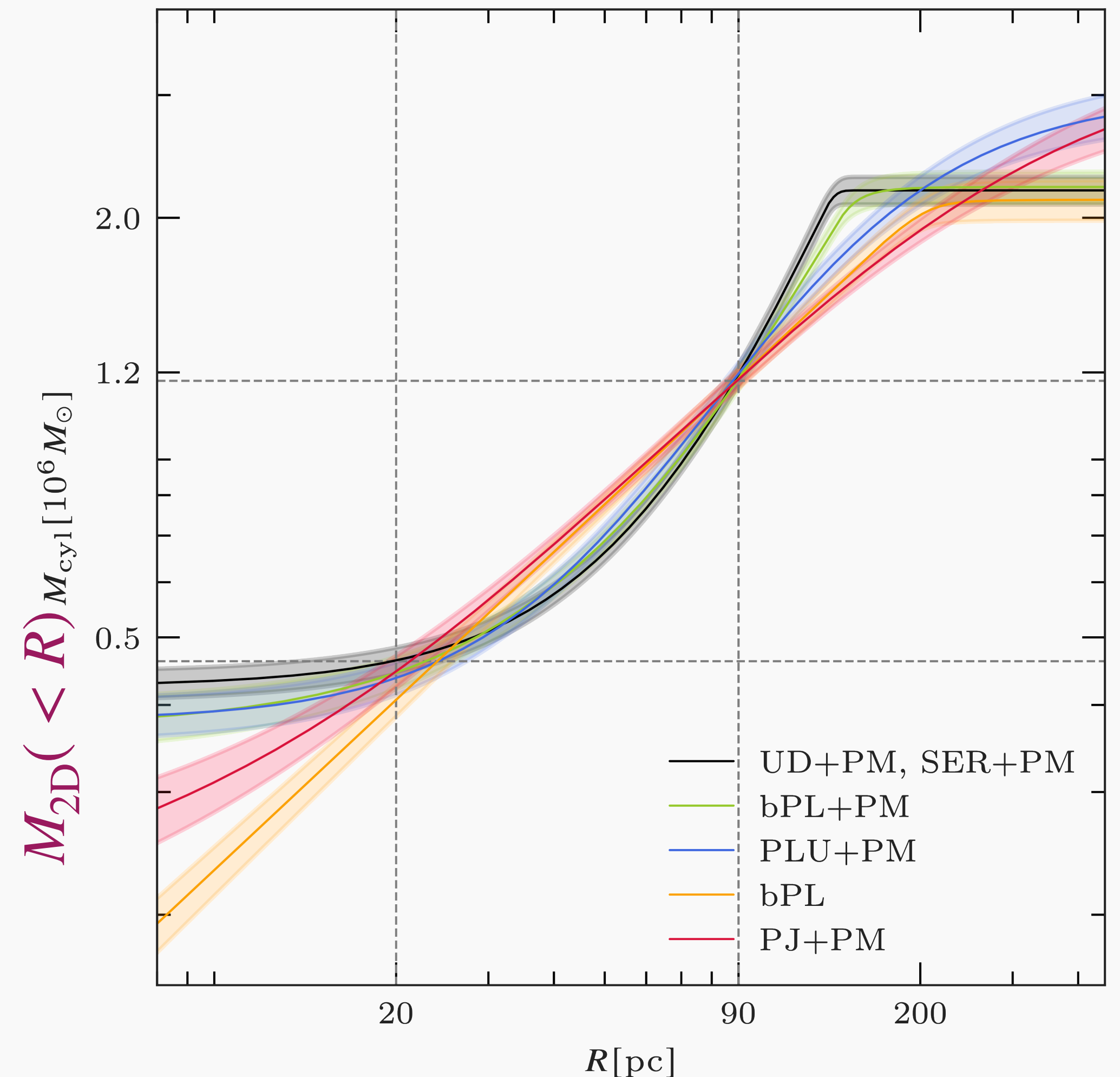
- high-res. imaging of strong lens system B1938+666 with global VLBI
- dark $\sim 10^6 M_{\odot}$ object detected from distortion of arc shape (26σ)
- its abundance consistent w/ CDM



Powell+ Nat.Ast. **9**(2025)1714

Density profile of $\sim 10^6 M_\odot$ object

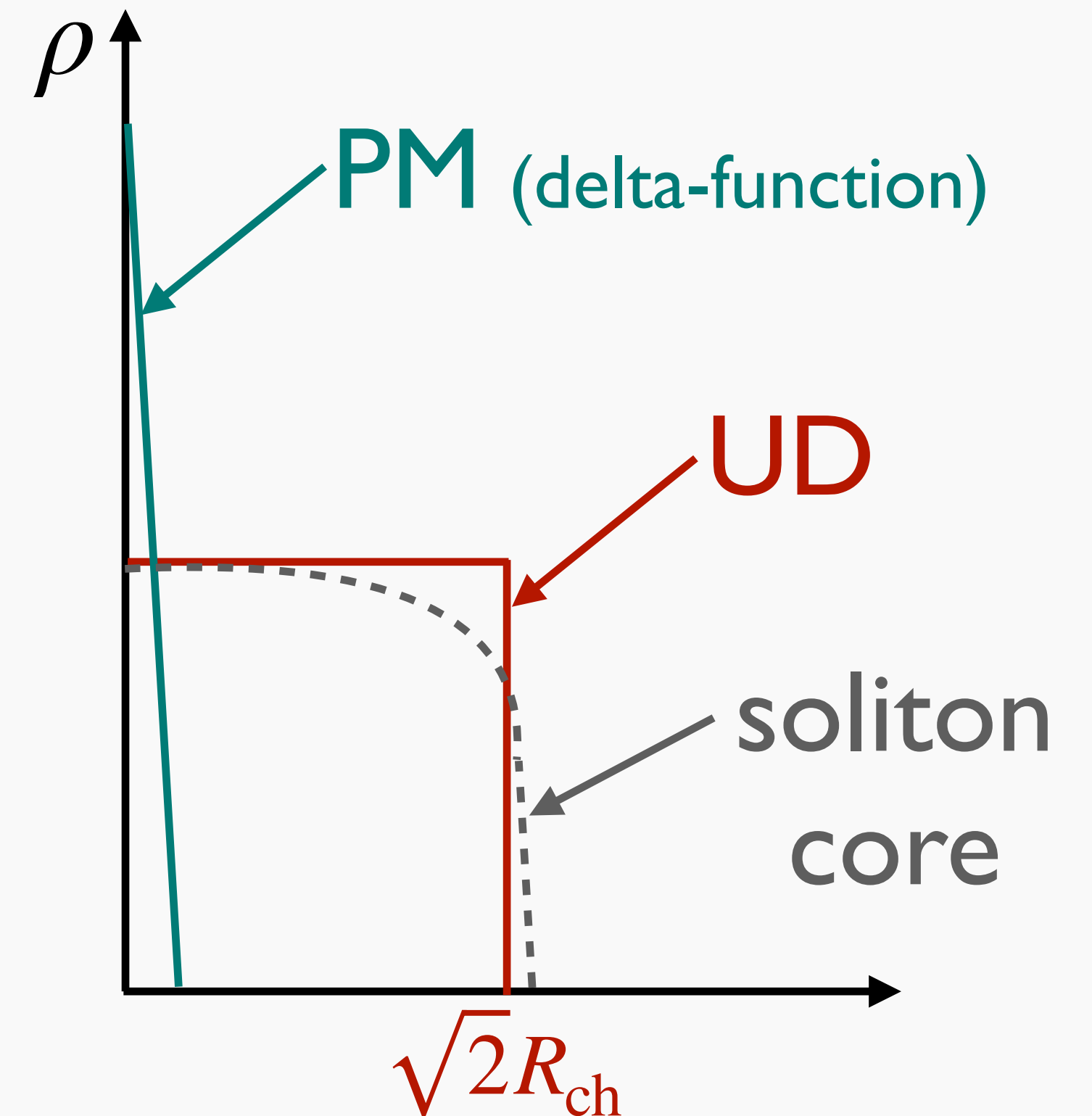
- since it is detected at 26σ , its density profile is tightly constrained
- UD (constant density core plus truncation) + PM (point mass) provide best-fit
- **it does not resemble any known astronomical object**
(self-interacting dark matter with $\sigma \sim 800 \text{ cm}^2 \text{ g}^{-1}$??)





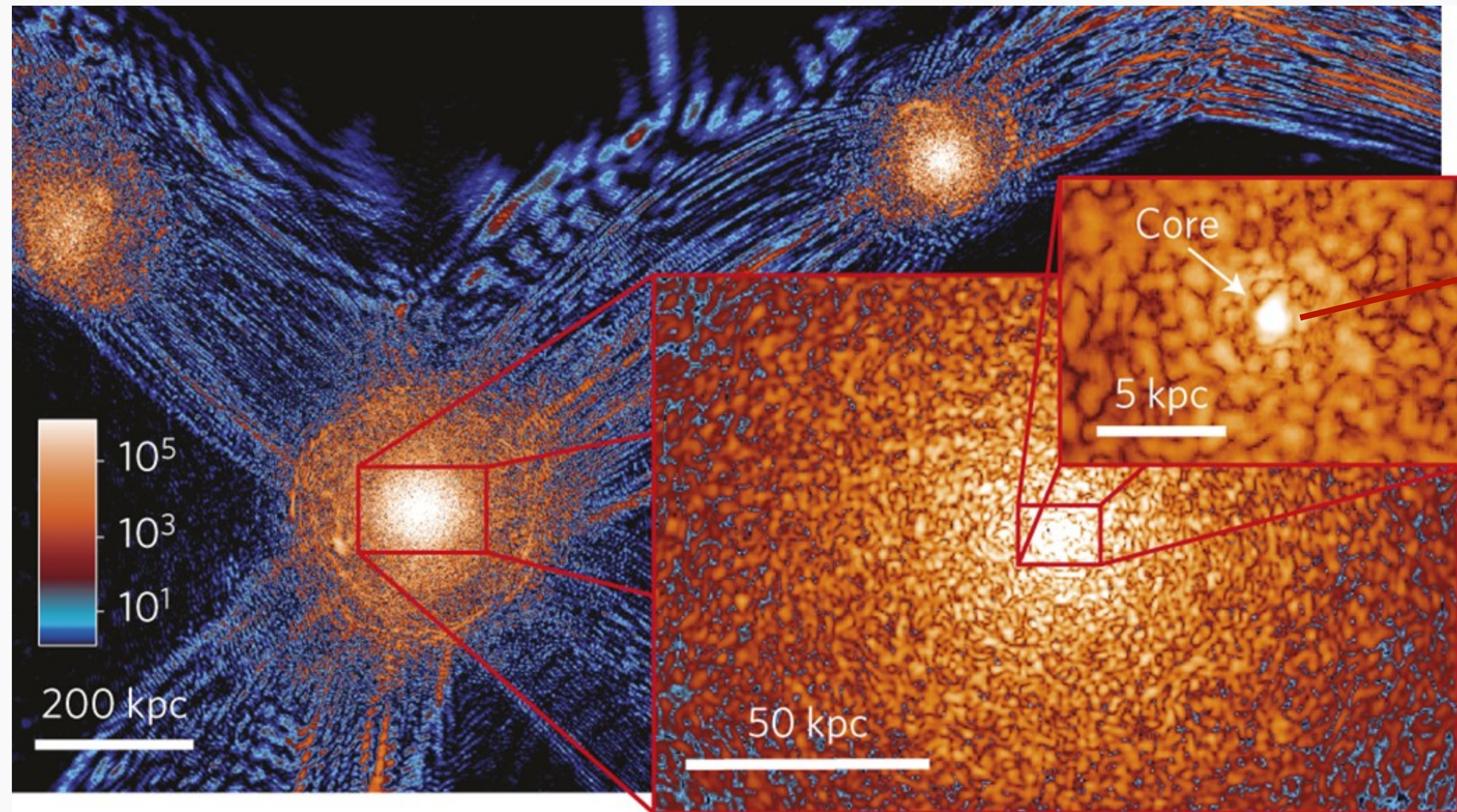
New scenario: FDM soliton core+SMBH

- idea: UD+PM model looks like **soliton core** in fuzzy dark matter (**FDM**) model plus supermassive black hole (**SMBH**)
- since masses of UD and PM are well constrained by observations, we can discuss this scenario quantitatively

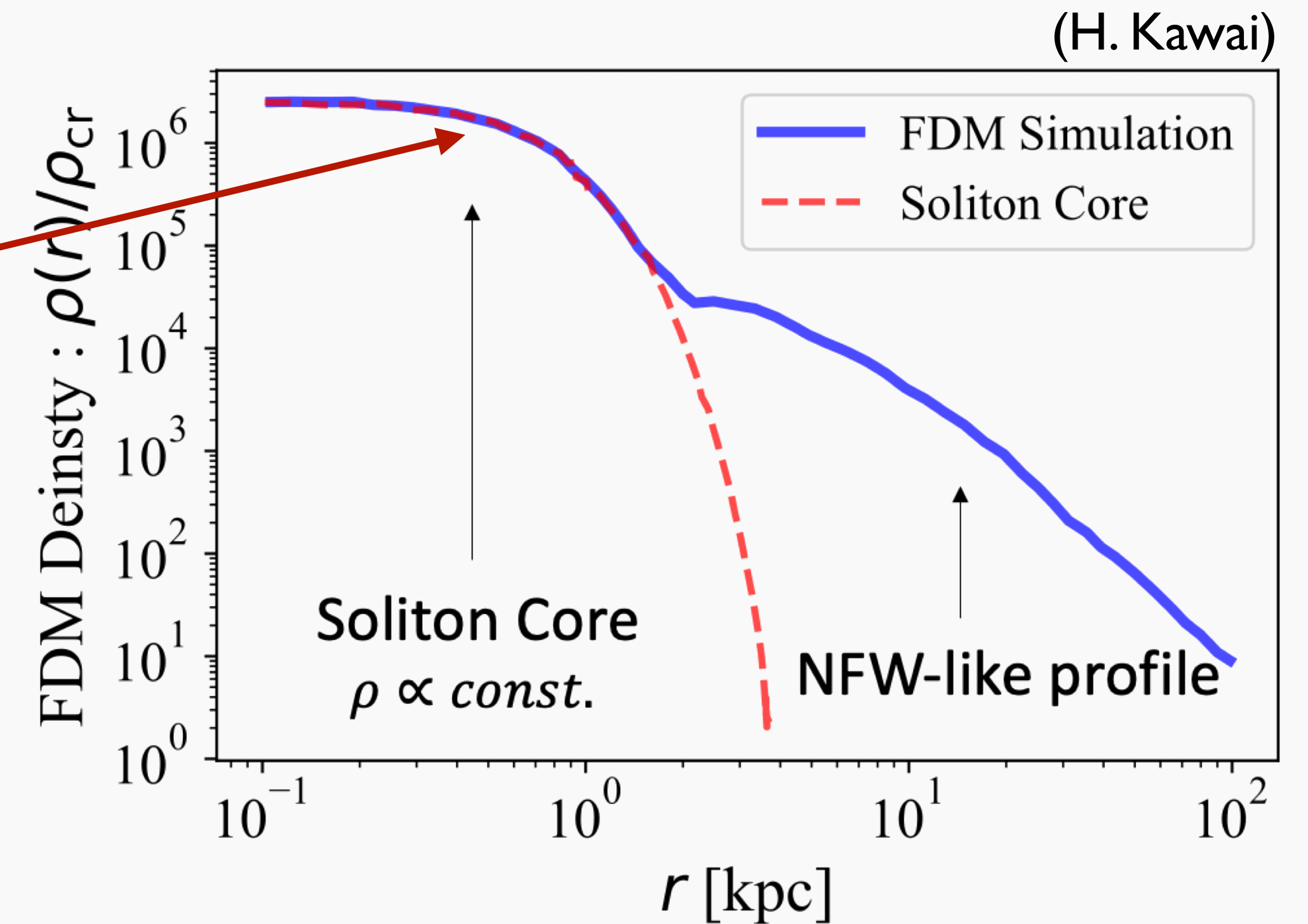


| Model | $\Delta \ln \mathcal{E}$ | M [$10^6 M_\odot$] | M_{PM} [$10^5 M_\odot$] | $M_{\text{cyl},90}$ [$10^6 M_\odot$] | R_{ch} [pc] |
|-------|--------------------------|---------------------------|---------------------------------------|---|-------------------------|
| UD+PM | 0 | 1.76 ± 0.10 | 4.25 ± 0.21 | 1.167 ± 0.039 | 98 ± 3 |

FDM soliton core



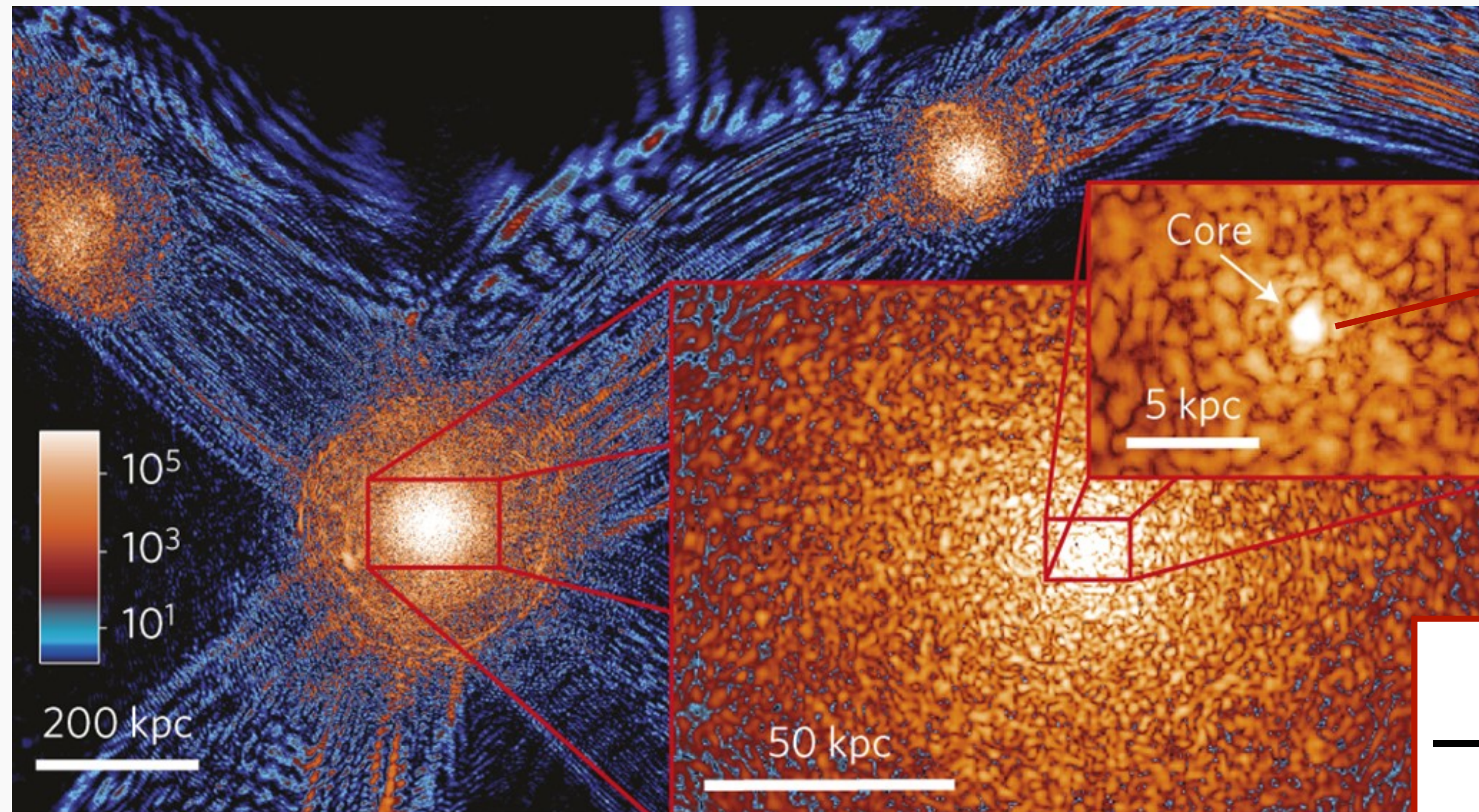
Schive+ Nat. Phys. **10**(2014)496



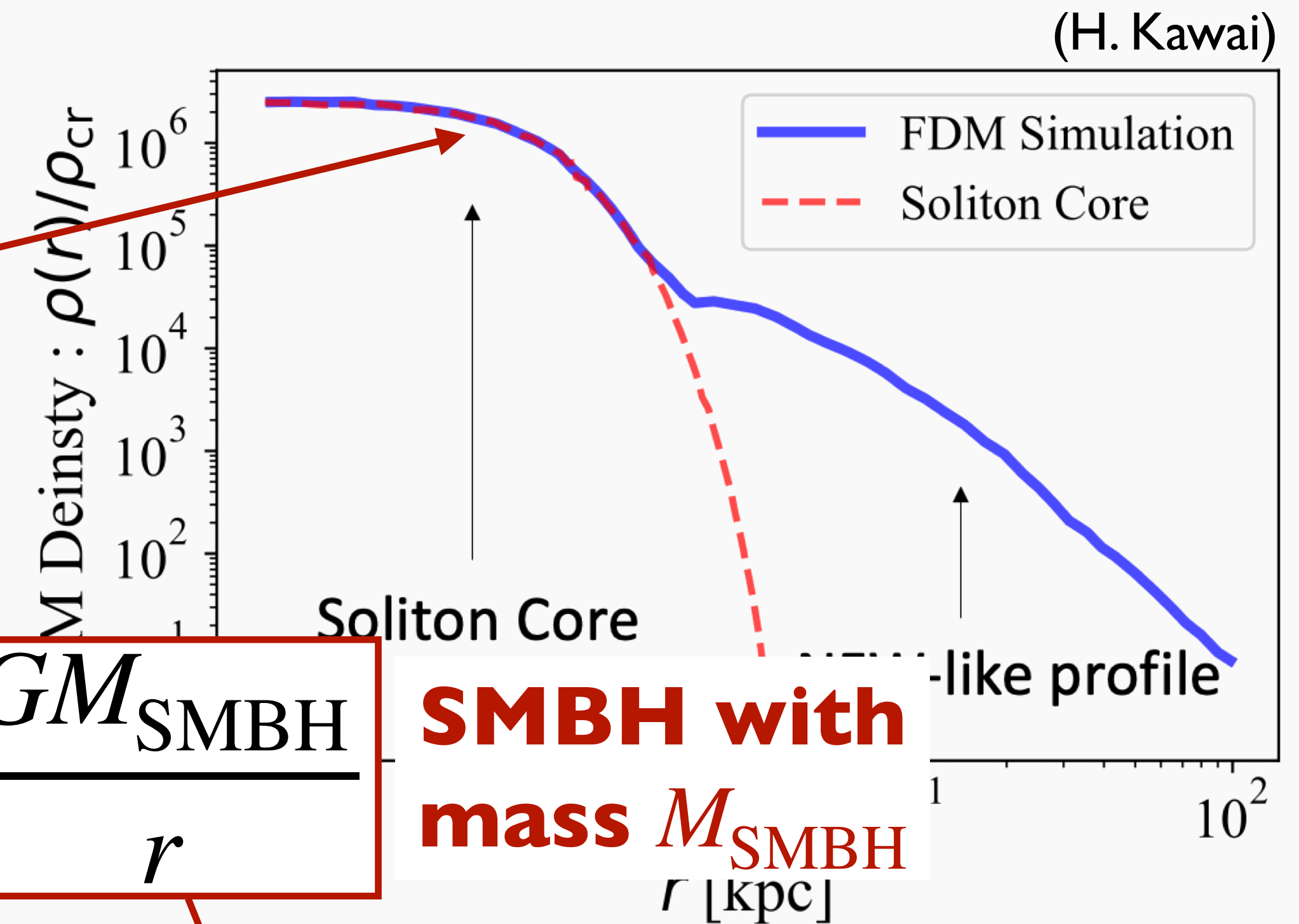
ground state solution of
Schödinger-Poisson eq.

$$i\hbar \frac{\partial \psi}{\partial t} = \left[-\frac{\hbar^2}{2m} \nabla^2 + m\Phi \right] \psi \quad \nabla^2 \Phi = 4\pi G \overline{\rho(r, t)}$$

Effect of SMBH on soliton core



Schive+ Nat. Phys. **10**(2014)496



$$-m \frac{GM_{\text{SMBH}}}{r}$$

SMBH with mass M_{SMBH}

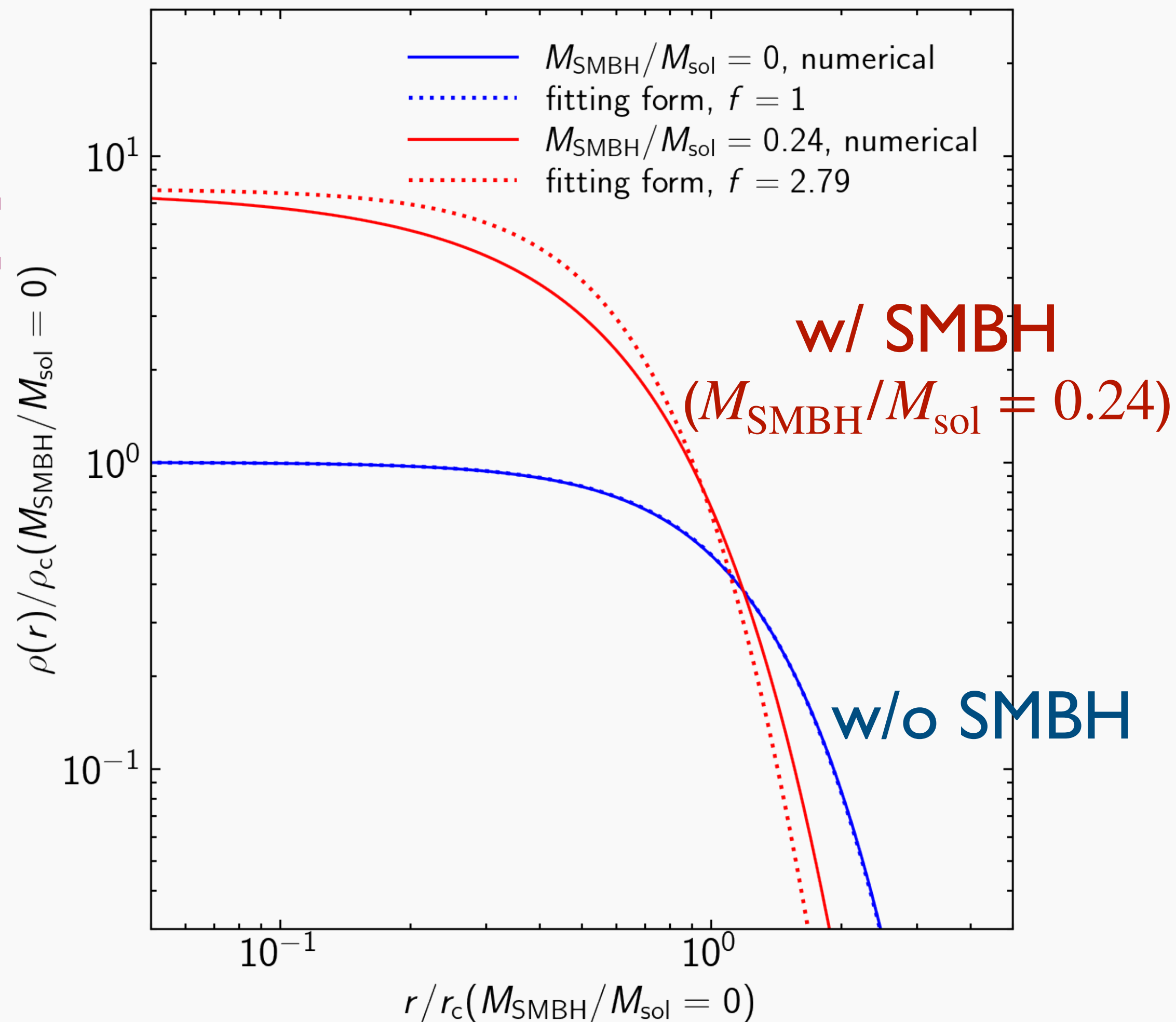
ground state solution of Schödinger-Poisson eq.

$$i\hbar \frac{\partial \psi}{\partial t} = \left[-\frac{\hbar^2}{2m} \nabla^2 + m\Phi \right] \psi \quad \nabla^2 \Phi = 4\pi G \overline{\rho(r, t)}$$



Effect of SMBH on soliton core

soliton core density profile

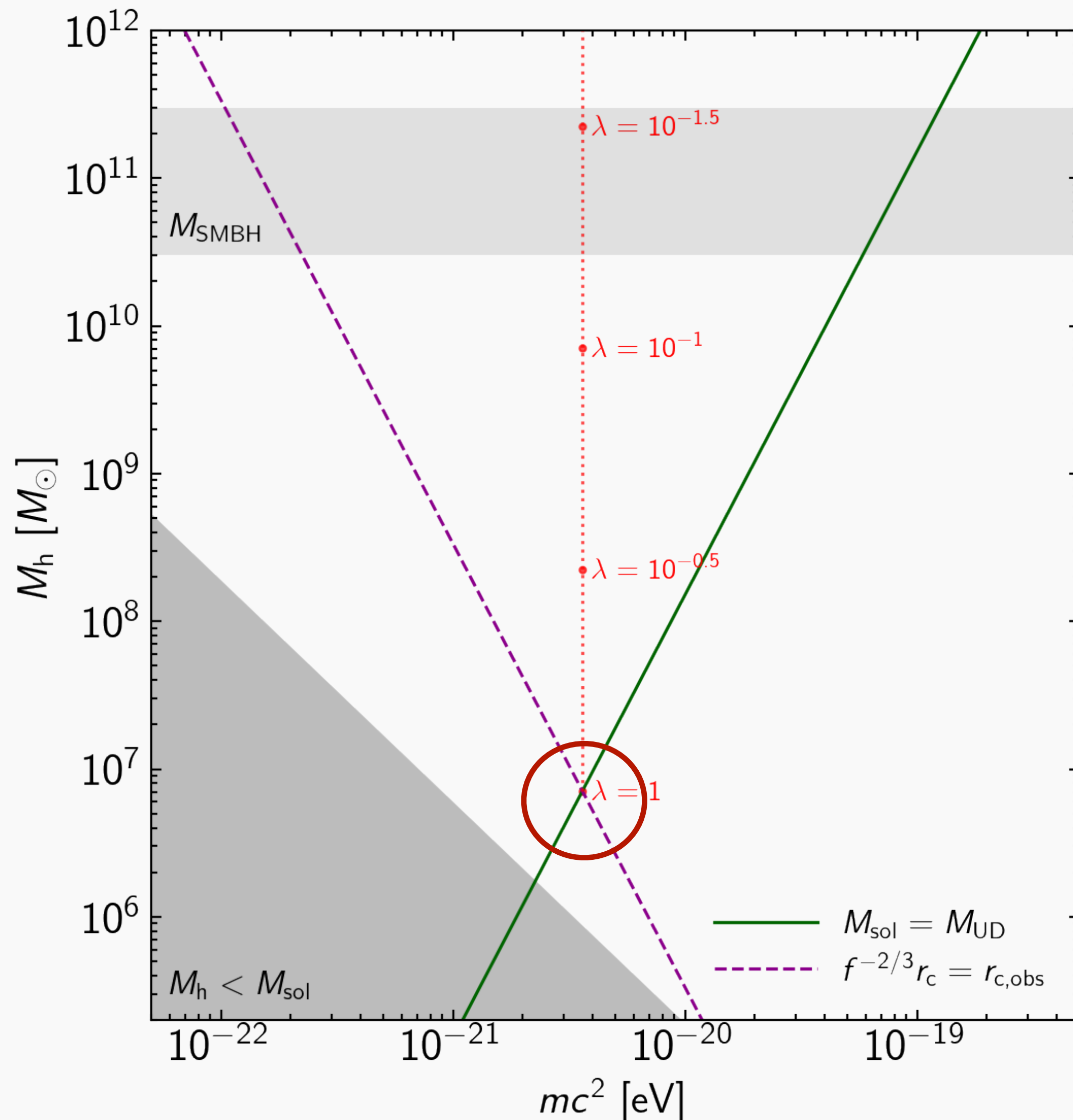


- SMBH can affect density profile of soliton core depending on M_{SMBH} Davies & Mocz MNRAS **492**(2020)5721
- for observed mass ratio, effect of SMBH is significant
- enhancing central density roughly by an order of magnitude!

stronger perturbation on lensing
less tidal mass loss/disruption



Constraint on parameters



- from core mass-halo mass relation in simulation (Schive PRL **113**(2014)261302) parameters are constrained as

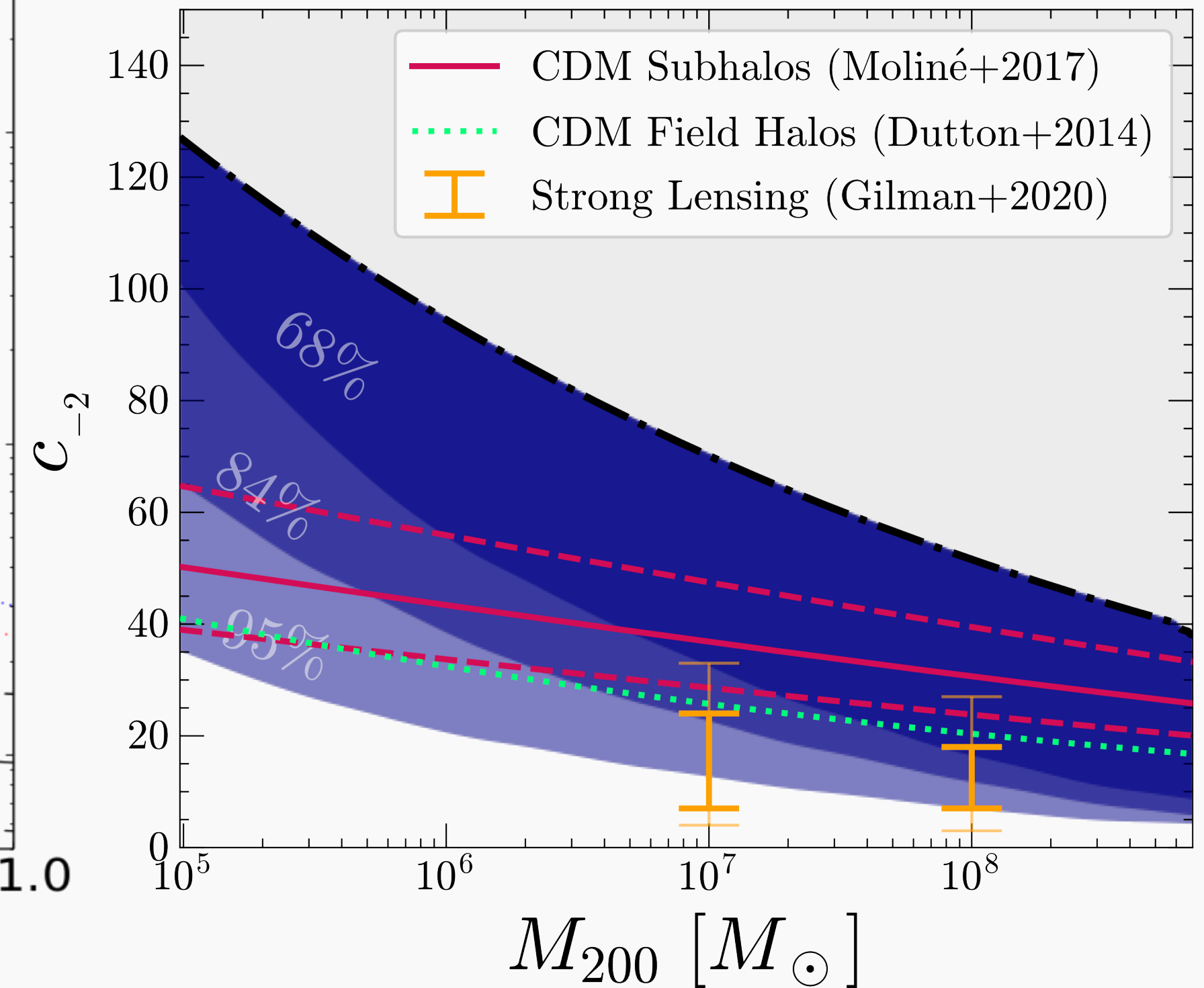
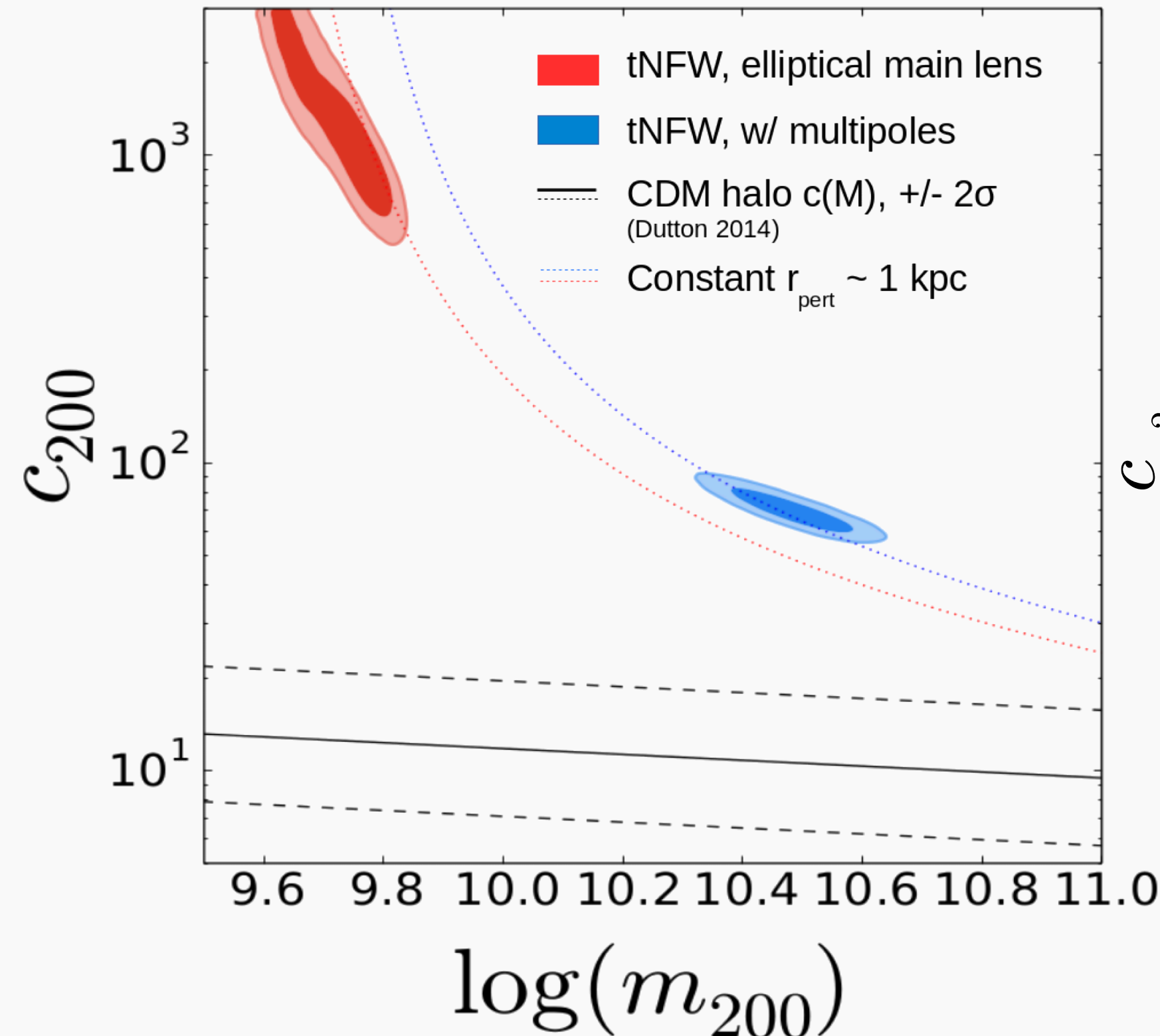
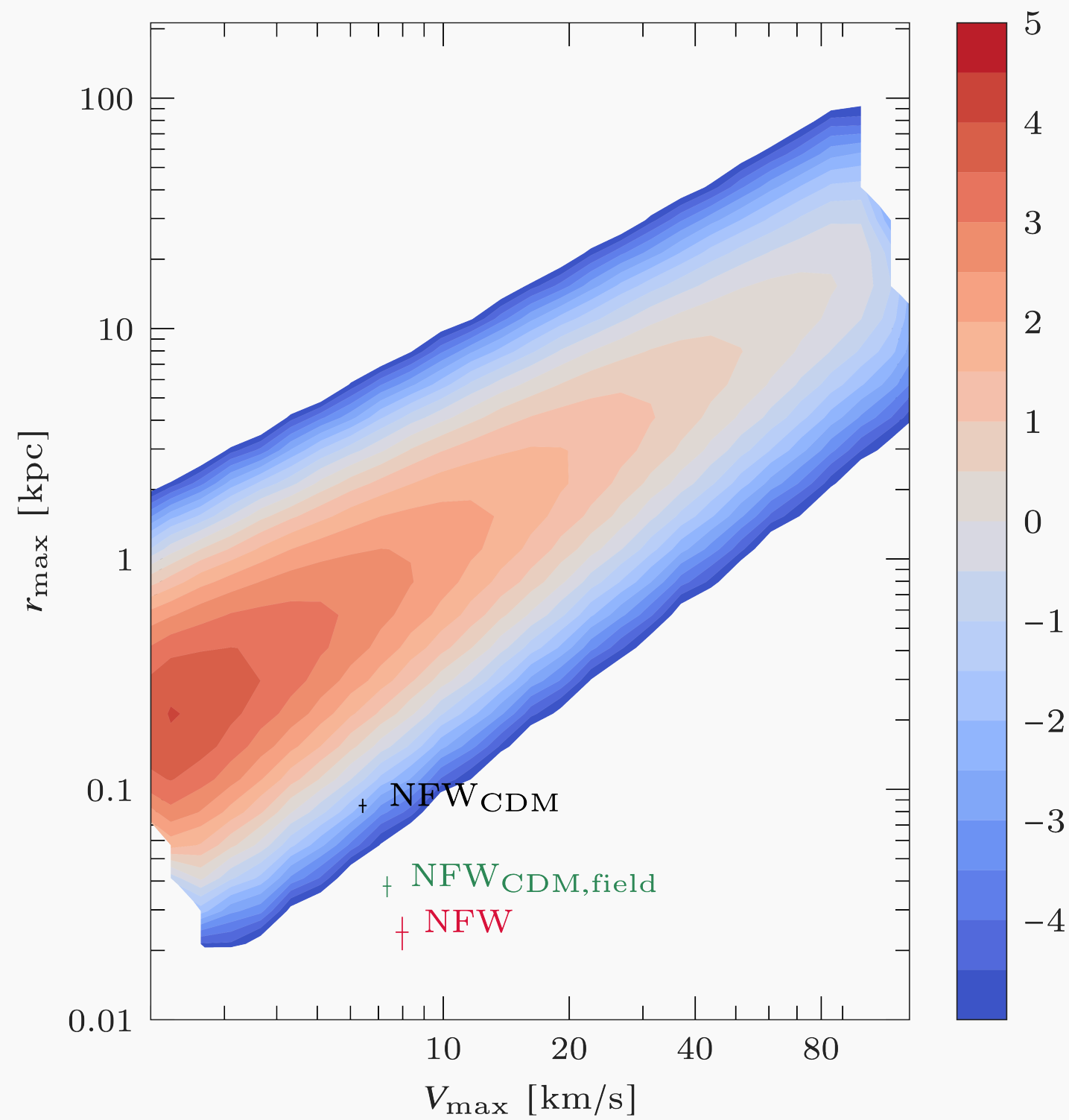
$$mc^2 \simeq 3.6 \times 10^{-21} \text{eV}$$

$$M_h \simeq 7.1 \times 10^6 M_\odot$$
- will require heavy BH scenario to explain high SMBH mass
- challenge: FDM with this mass excluded by observations (?)

e.g., Eberhardt & Ferreira arXiv:2507.00705

self-interaction? multi-field?

Too dense low mass perturbers ubiquitous?



$\sim 10^6 M_\odot$ perturber in
BI 933+666

Vegetti+ Nat.Ast. **10**(2026)440

perturber in strong lens
SDSSJ0946+1006

Minor+ MNRAS **507**(2021)1662

perturber in Milky Way
stellar stream GD-I

Nibauer+ arXiv:2510.02247

Summary: new small-scale challenges??

- shallow central profile, low DM fraction for $M_{\star} \sim 10^{11} M_{\odot}$ galaxies that are inconsistent with hydrodynamical simulations
- low-mass ($\sim 10^6 M_{\odot}$) dark objects that are too dense compared with CDM prediction