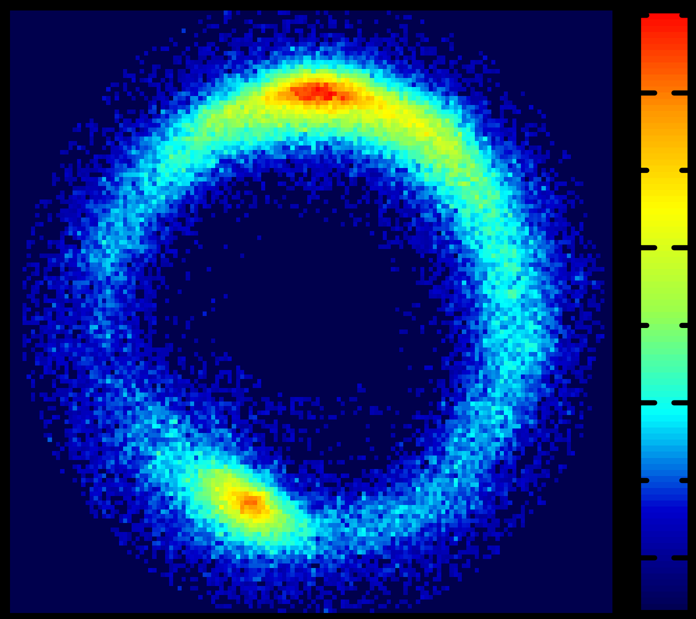
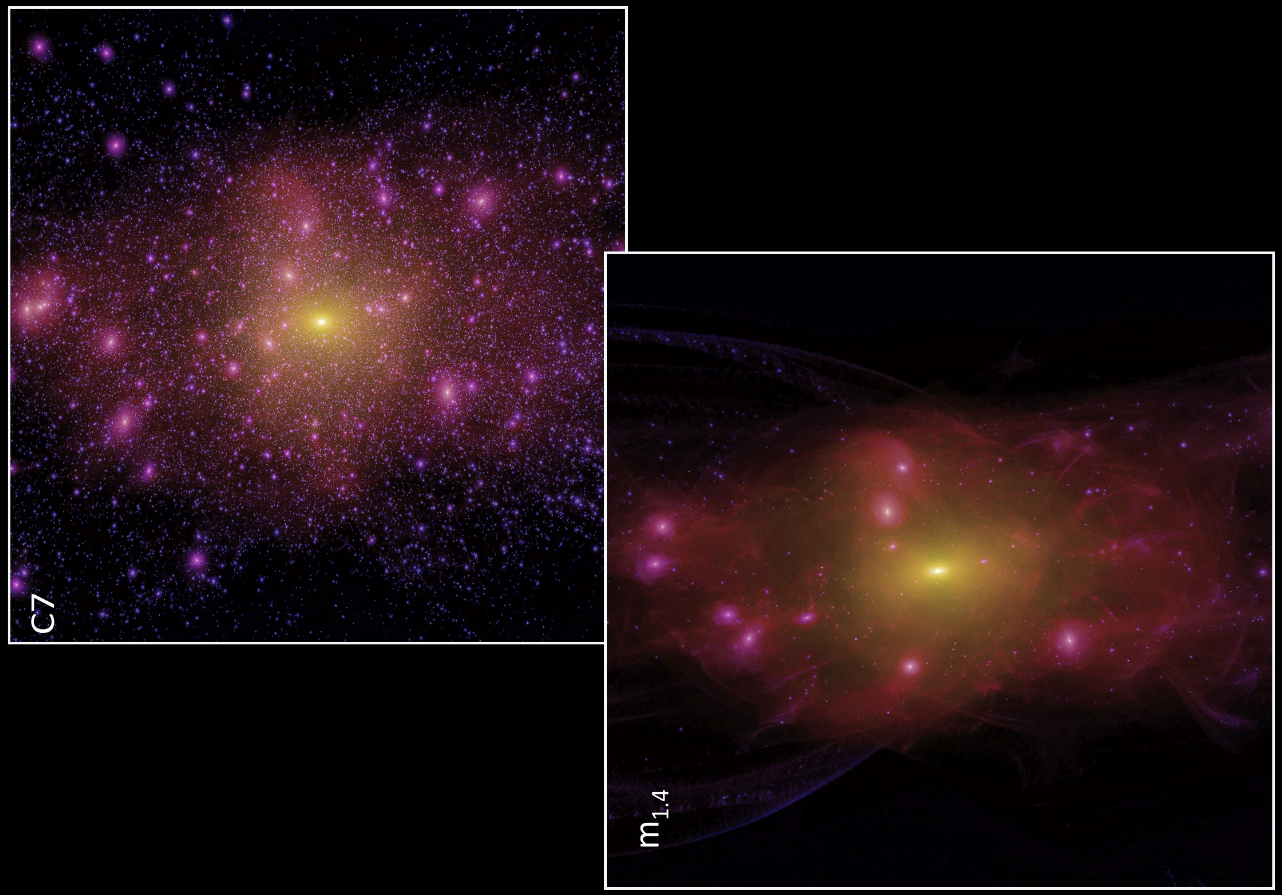
# CONSTRAINING DARK MATTER WITH STRONG GRAVITATIONAL LENSING

Giulia Despali

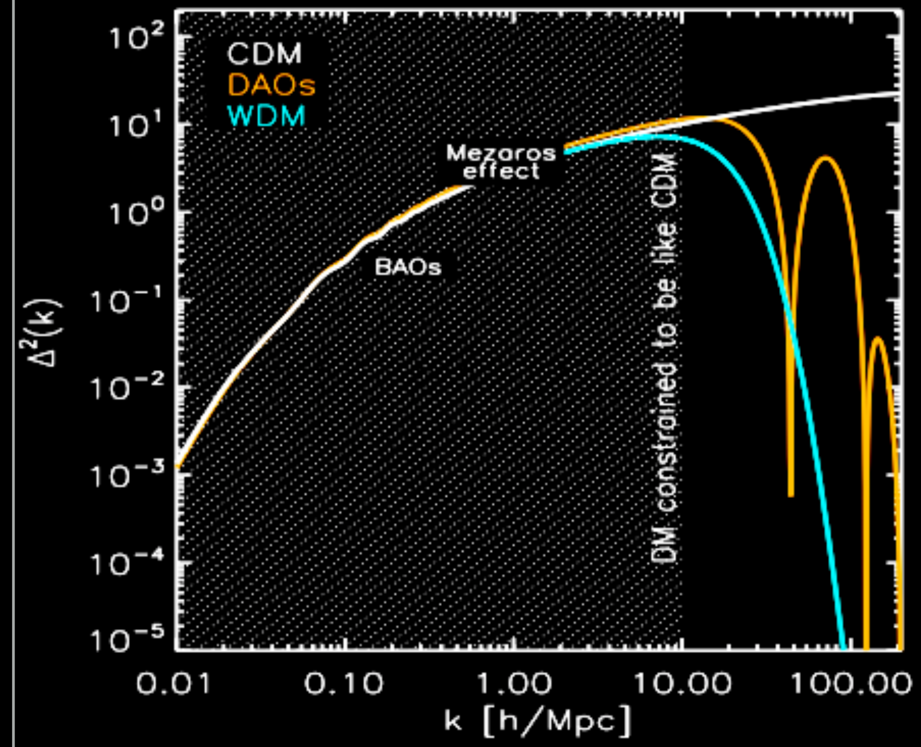
ZAH/ITA - Uni Heidelberg





$$P_{WDM}(k) = T^2 P_{CDM}(k)$$

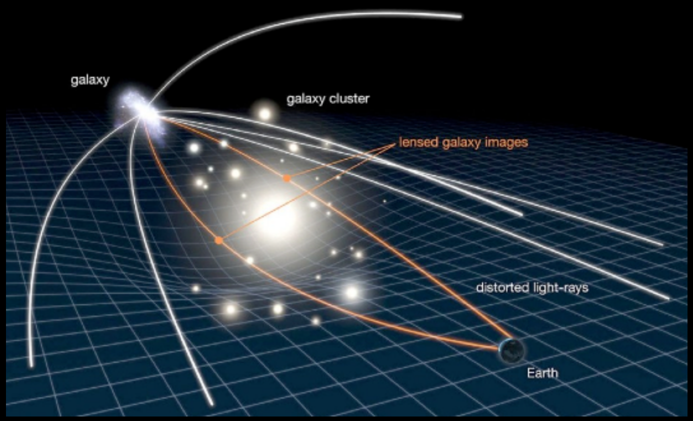
$$\frac{n_{WDM}}{n_{CDM}} = (1 + \gamma M_{hm} M^{-1})^{\beta}$$

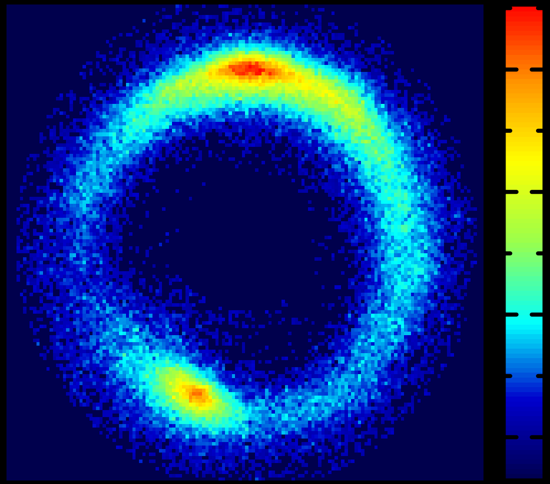


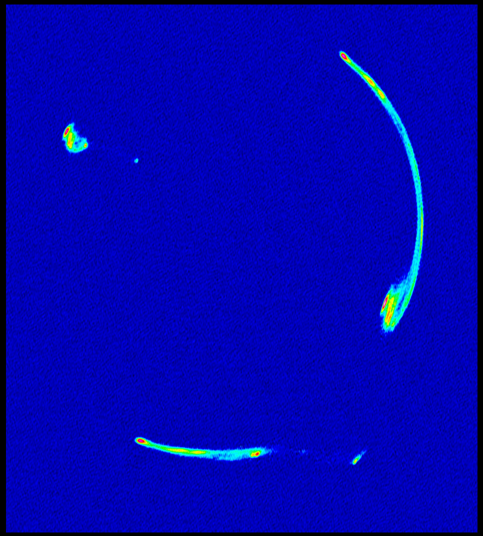

$$dn \equiv N(M)dM =$$

$$= \frac{1}{\sqrt{\pi}} \left(1 + \frac{n}{3}\right) \frac{\bar{\rho}}{M^2} \left(\frac{M}{M^*}\right)^{(3+n)/6}$$

$$\exp\left(-\left(\frac{M}{M^*}\right)^{(3+n)/3}\right) dM$$





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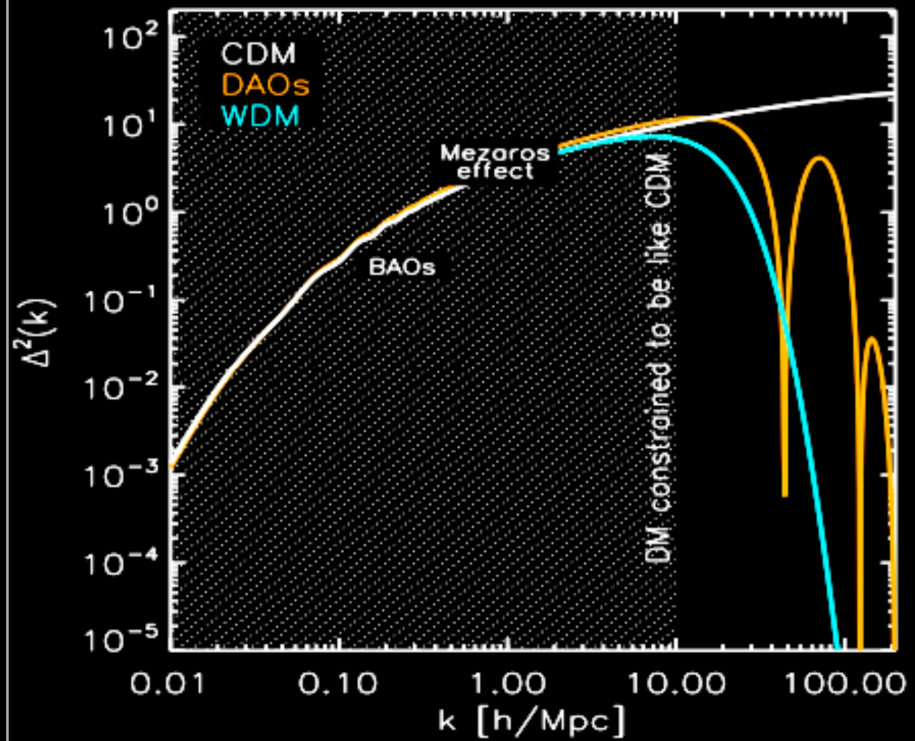


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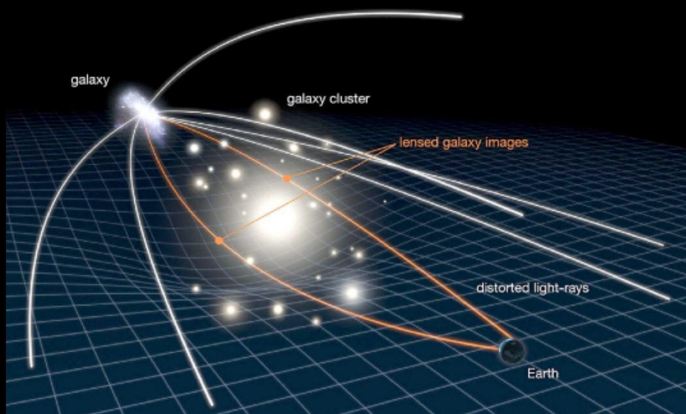


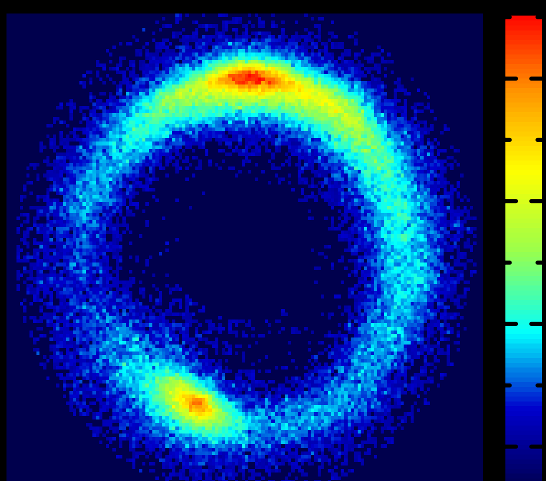

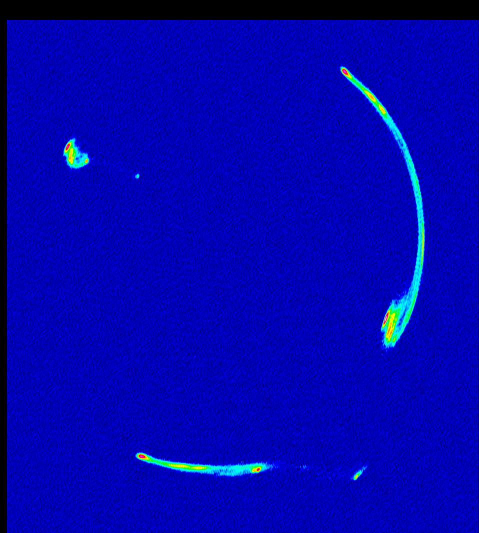

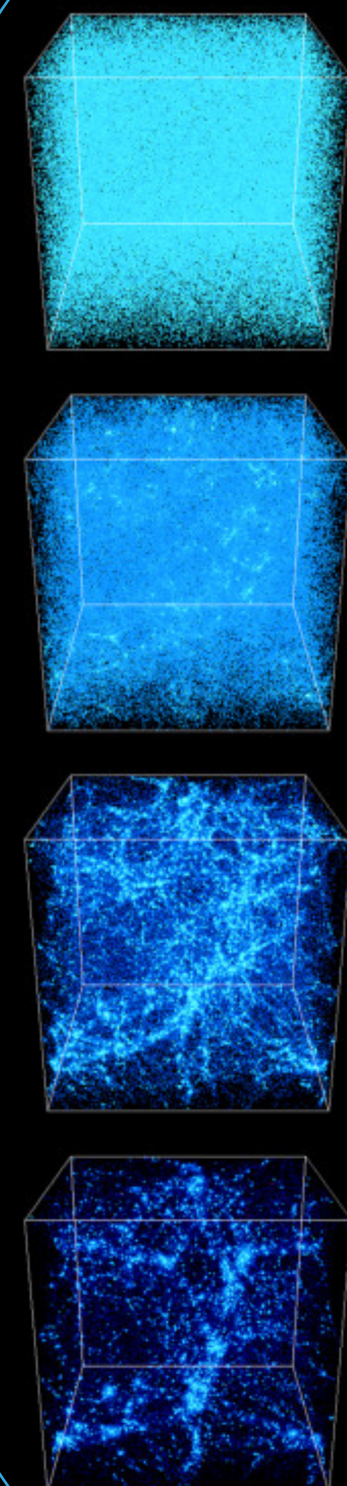

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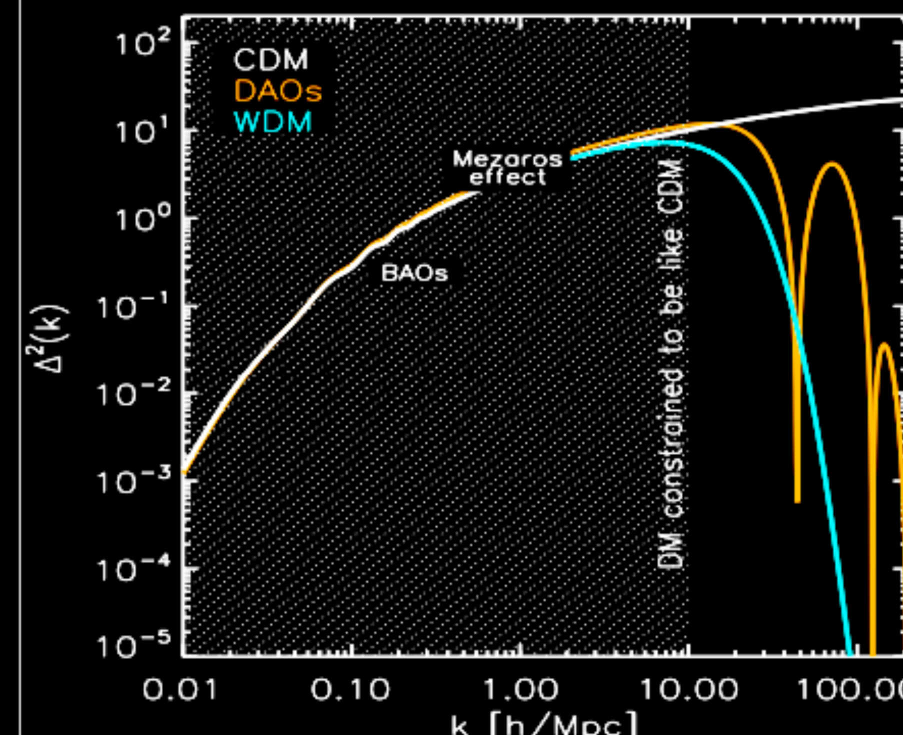


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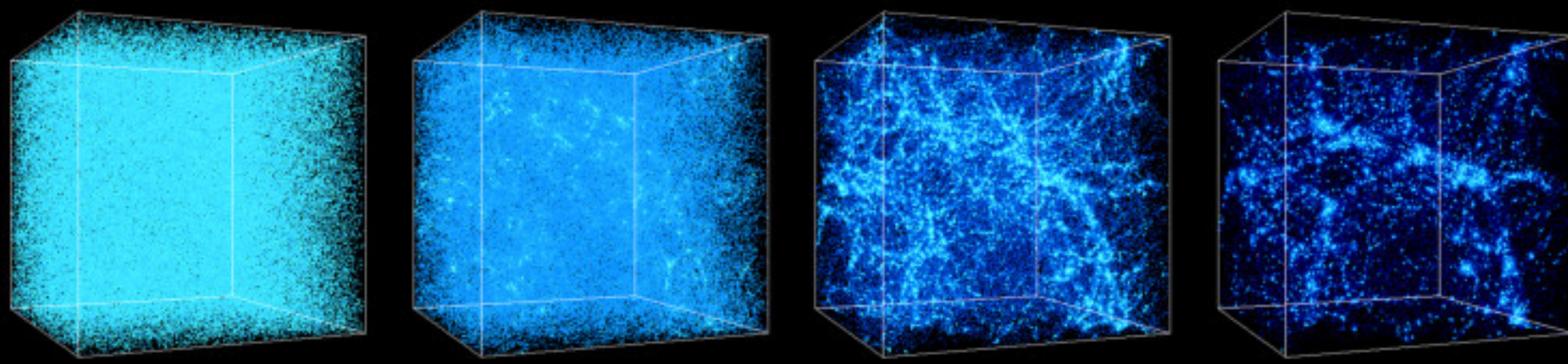
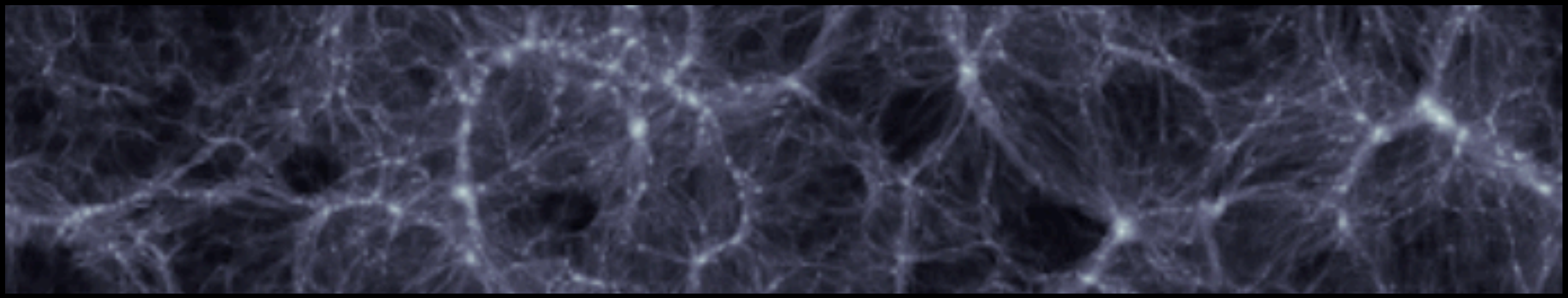
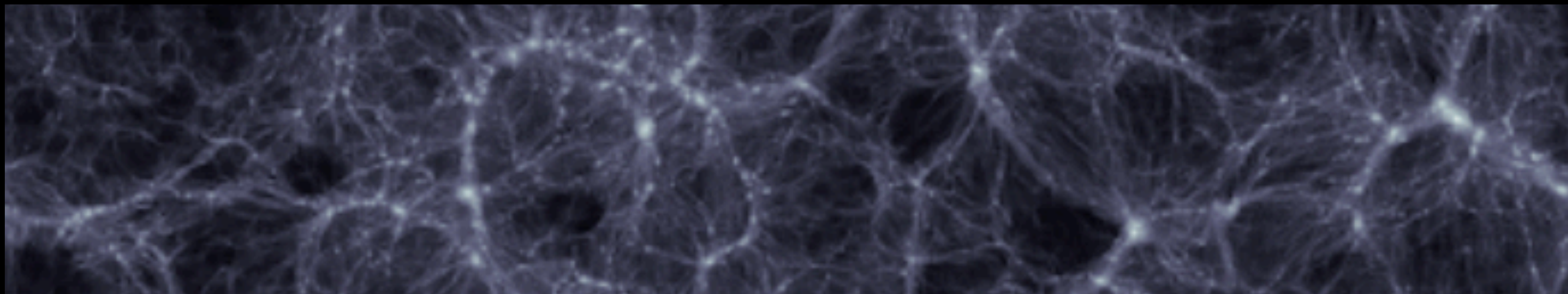
the dark matter model
shapes the formation
of structures in the universe



*(A. Kravtsvov)*



SIMULATIONS
*(Hahn et al. 2014)*



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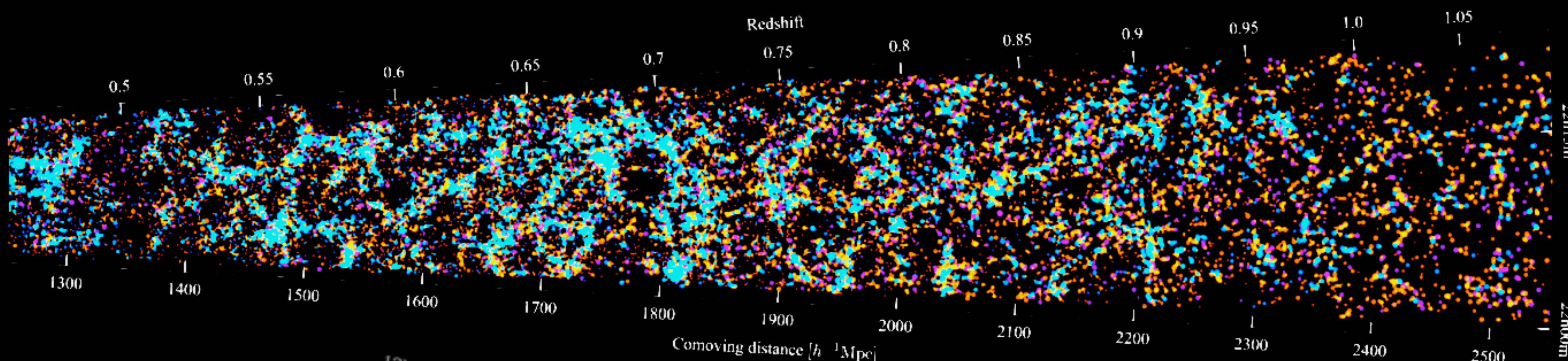
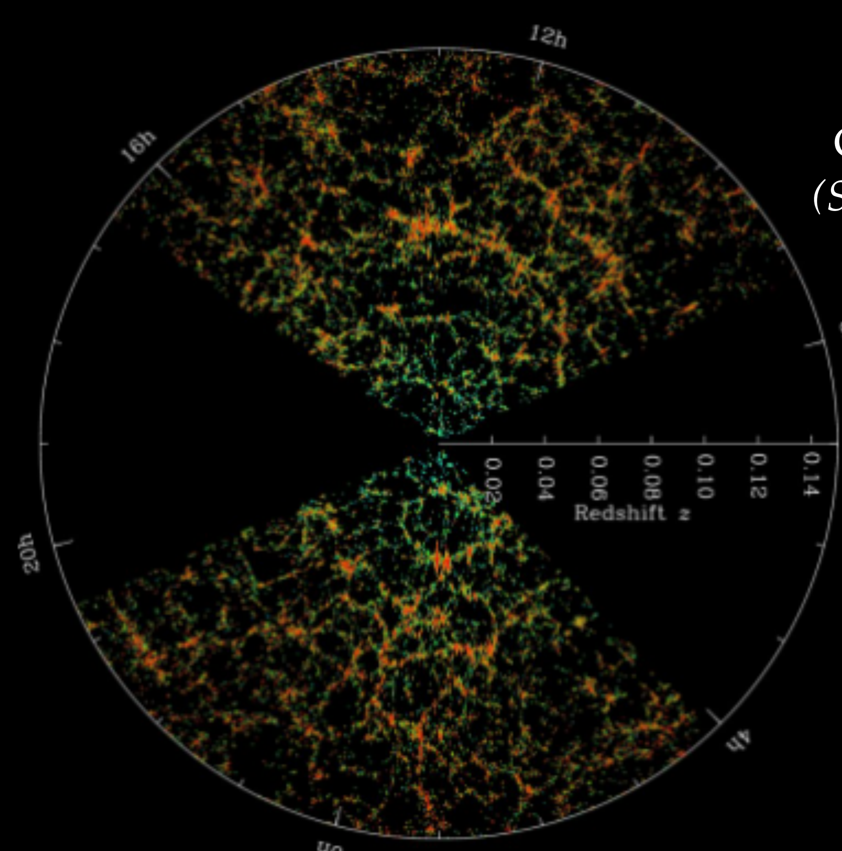
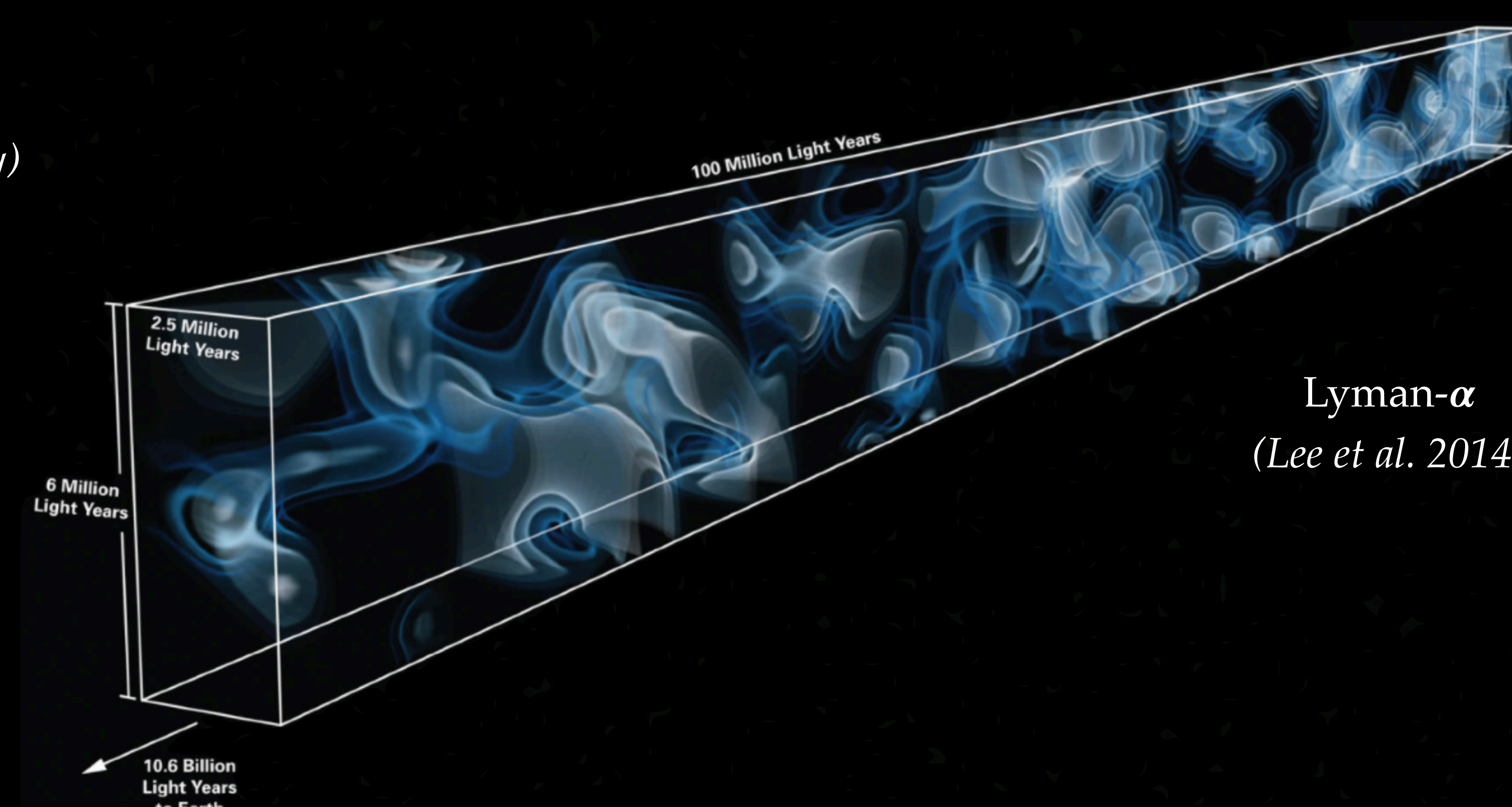



GALAXIES
*(VIPERS coll.)*




GALAXIES
*(SDSS survey)*



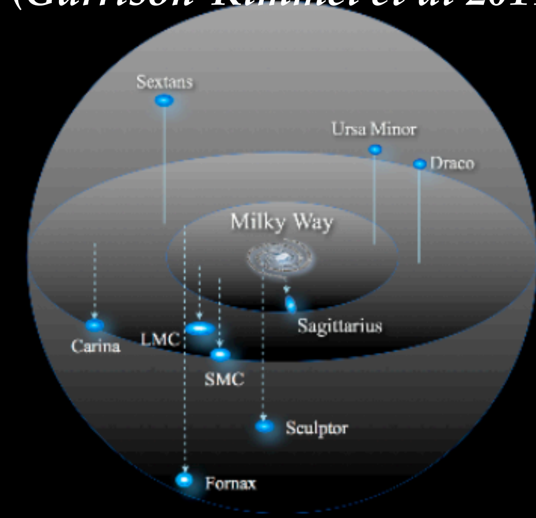

Lyman-$\alpha$
*(Lee et al. 2014)*

- Warm Dark Matter:
  - thermal relics
  - sterile neutrinos
  - m~ keV

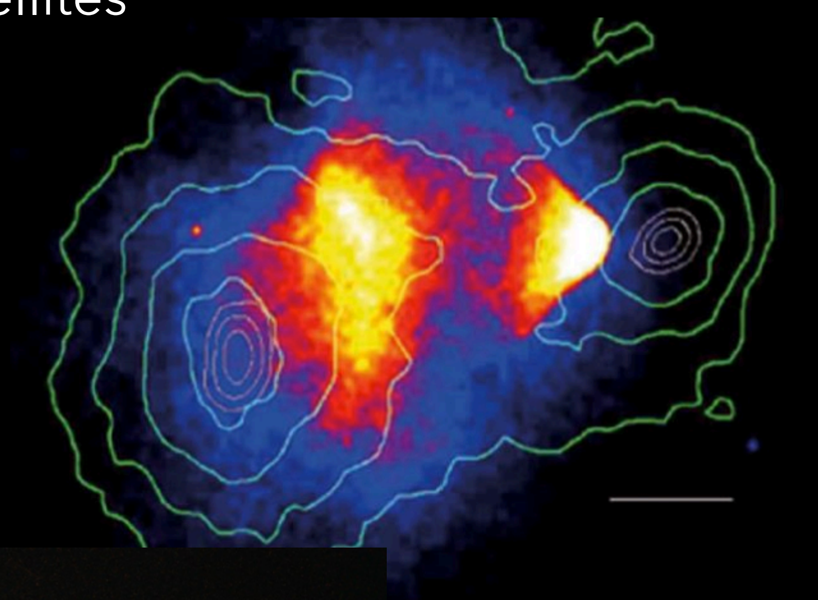
lighter and with higher velocities than CDM

small-scale perturbations are destroyed

(Garrison-Kimmel et al 2014)




"too big to fail"
and
"missing satellites"
problems



explain DM distribution

- Self-interacting dark matter:
  - many different models and cross-sections

DM particles interact with each other and scatter

small object and the shape of density peaks are affected

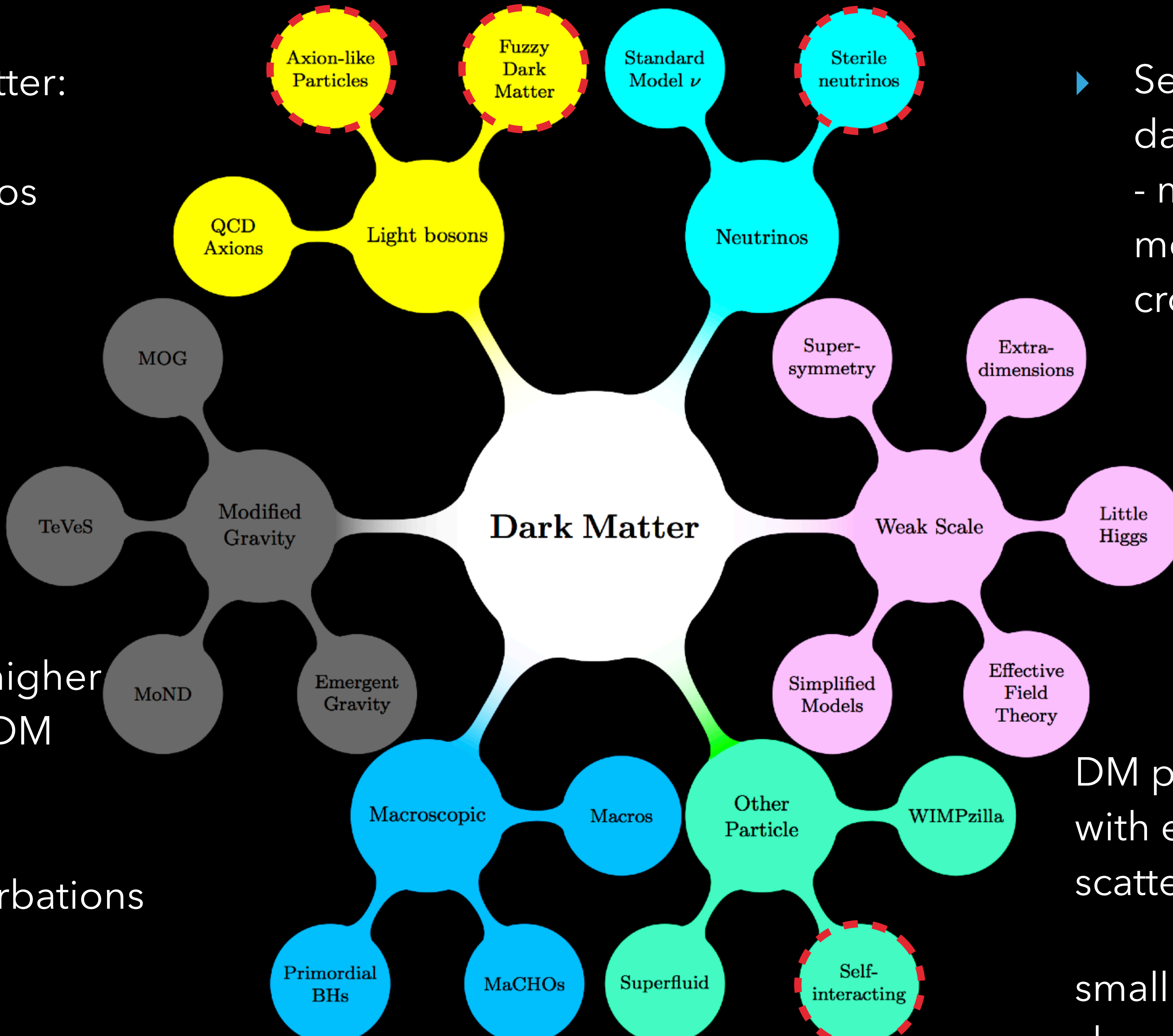
- Warm Dark Matter:
  - thermal relics
  - sterile neutrinos
  - m~ keV

↓

lighter and with higher velocities than CDM

↓

small-scale perturbations are destroyed

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↓

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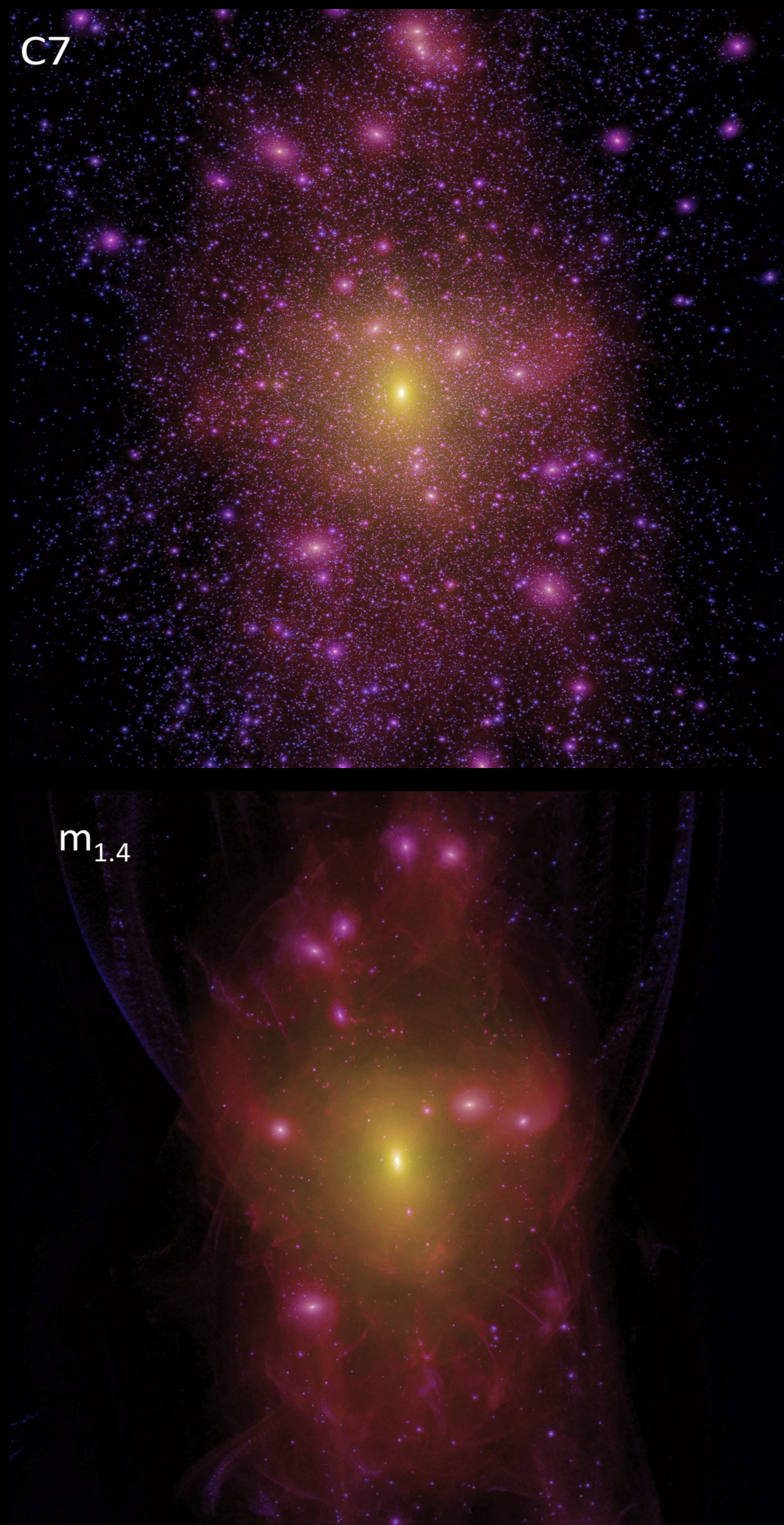
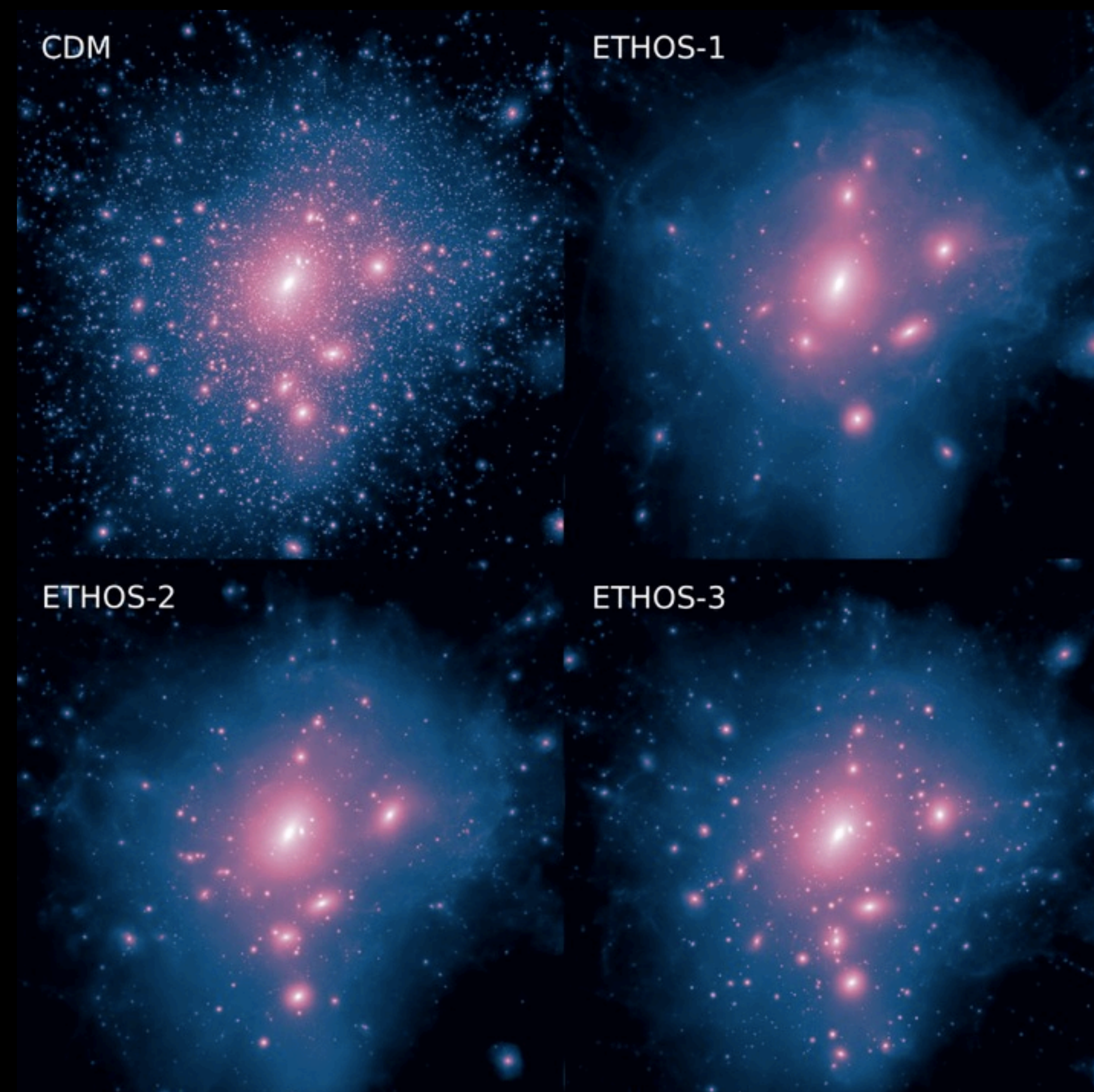
↓

small object and the shape of density peaks are affected

# WDM & SIDM




(Lovell et al. 2012)

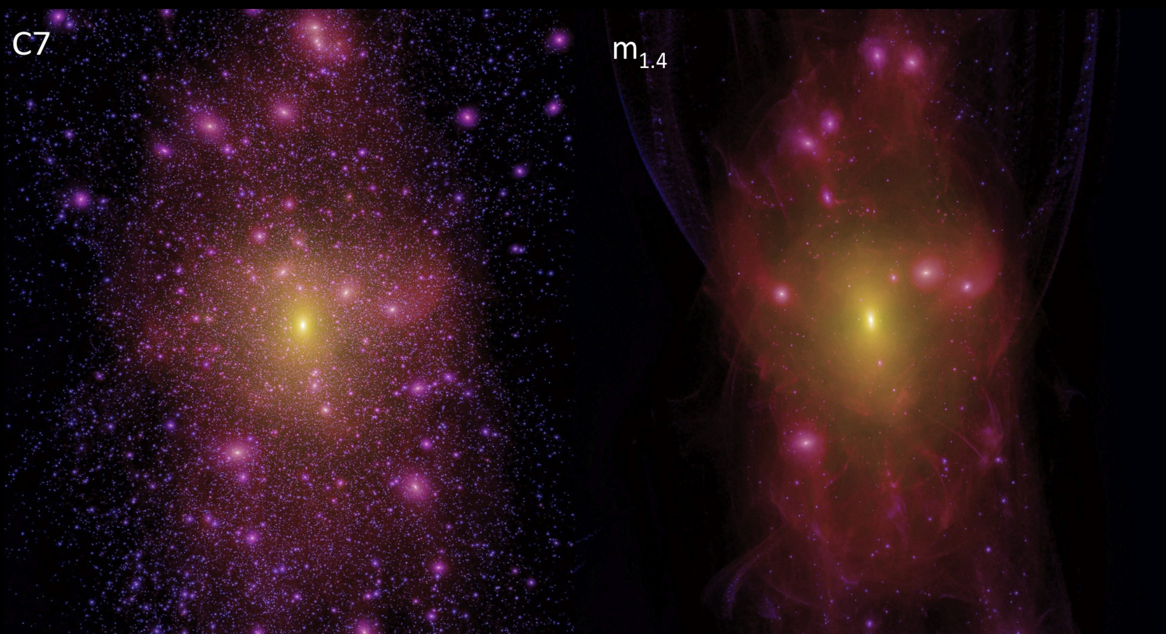



(Vogelsberger et al. 2016)

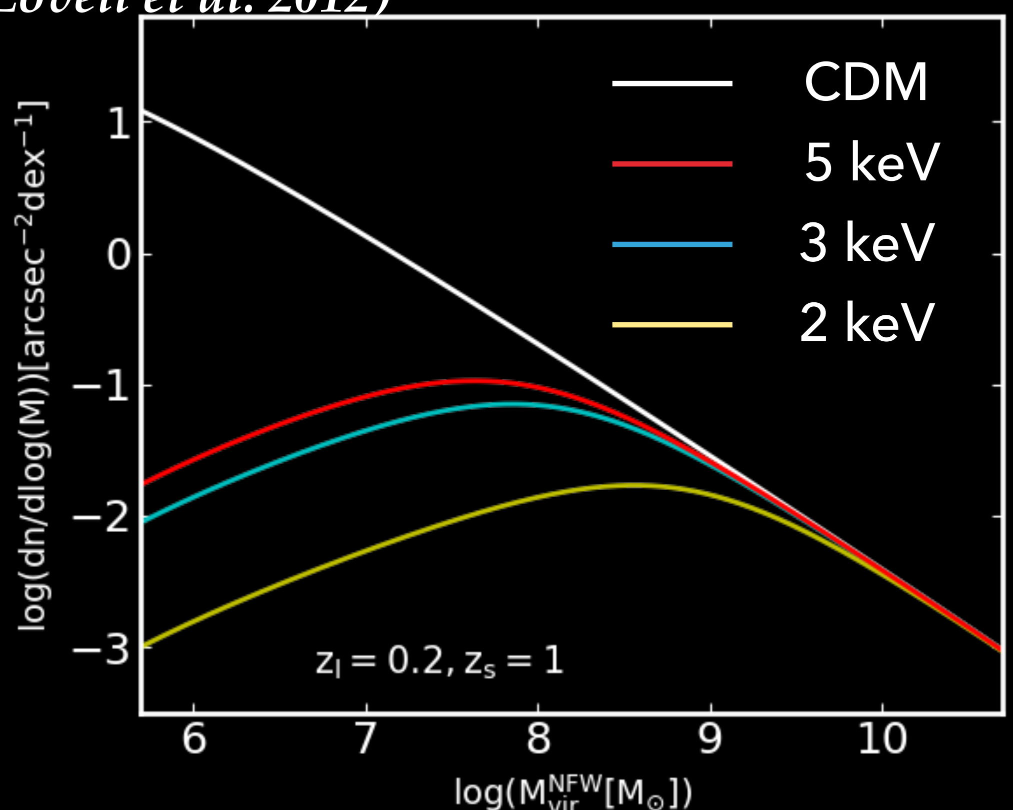
# WDM & SIDM



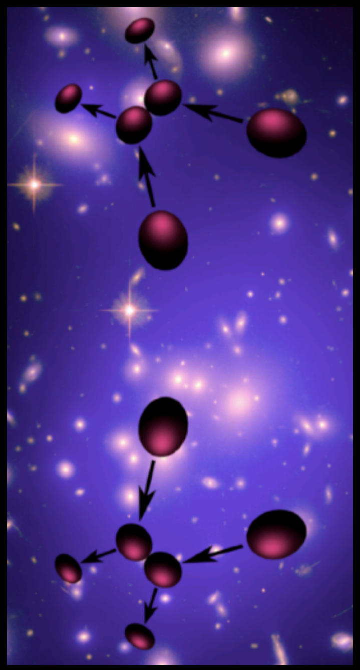
Sterile Neutrino WDM

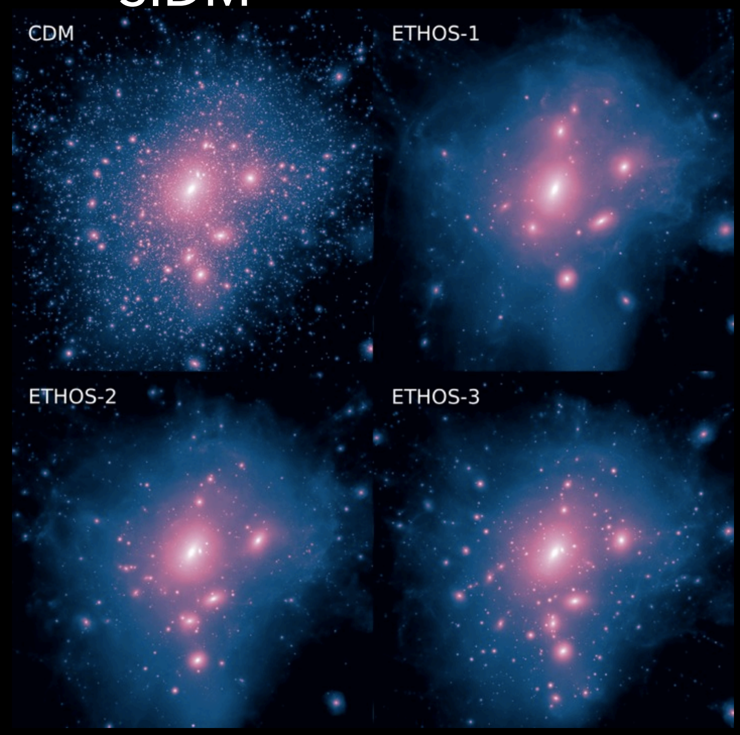



(Lovell et al. 2012)

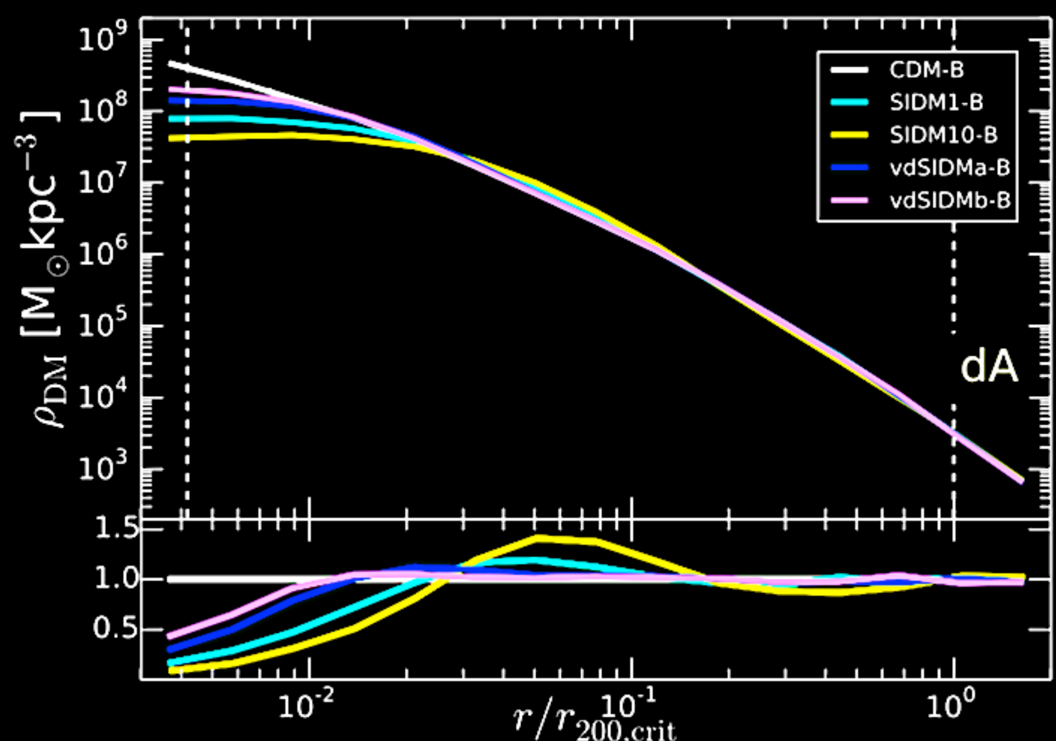



SIDM






(Vogelsberger et al. 2016)

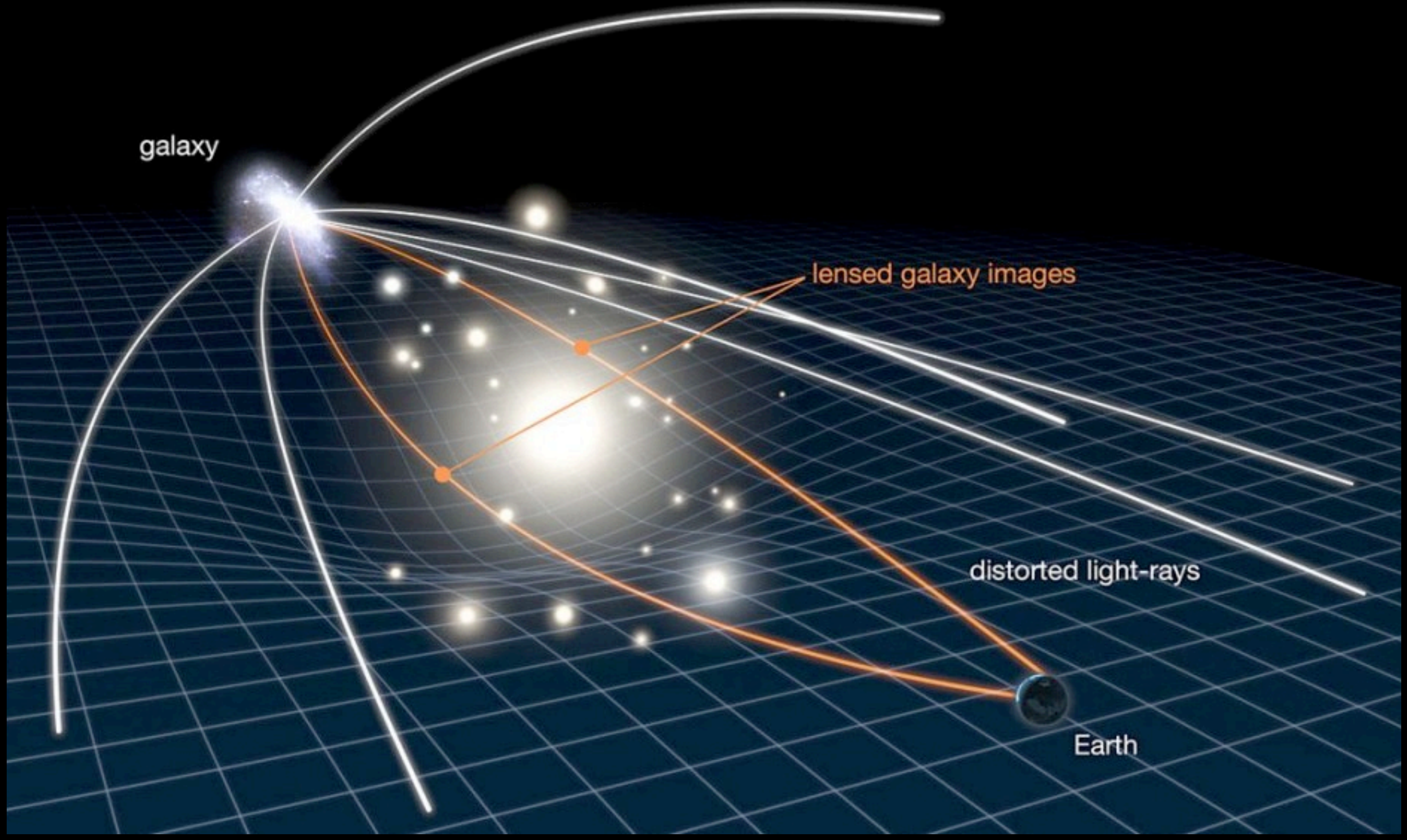


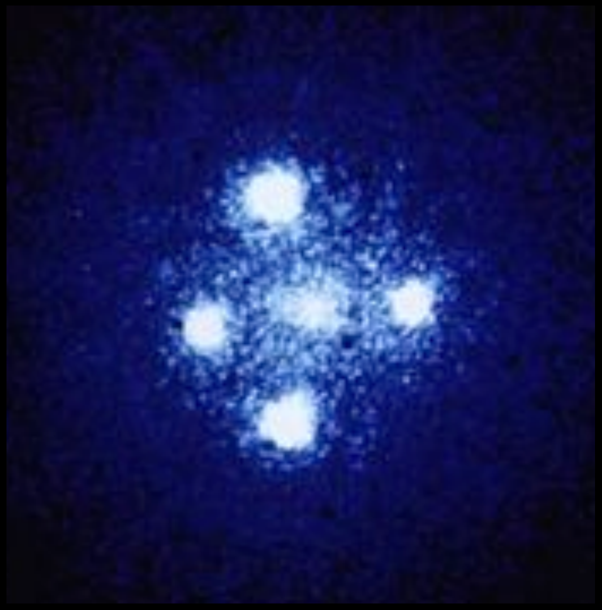

- subhalo counts from sterile neutrino WDM
- subhalo profiles and distribution

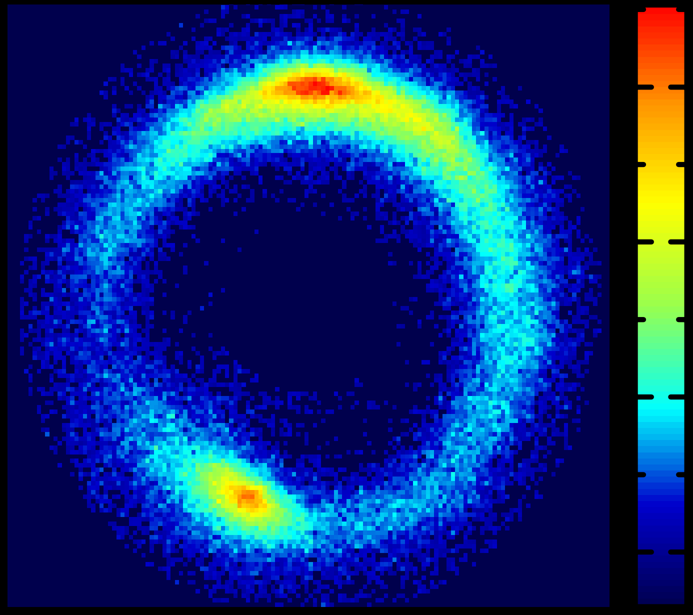
- impact of SIDM on the main halo propertie
- different distribution of Einstein rings?

# STRONG LENSING

- the shape of the image is heavily affected by the lensing
- <u>small</u> angular separation between the source and the lens position, i.e. almost aligned
- occurs in the central regions of galaxies and galaxy clusters where the density is “critical”
- **<u>multiple images</u>** of background sources, such as bright QSO
- extended sources may be heavily distorted in **<u>gravitational arcs</u>**



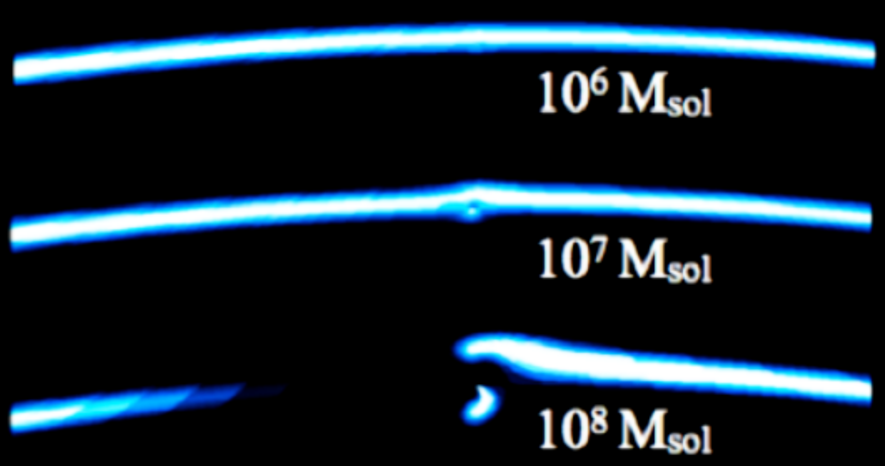



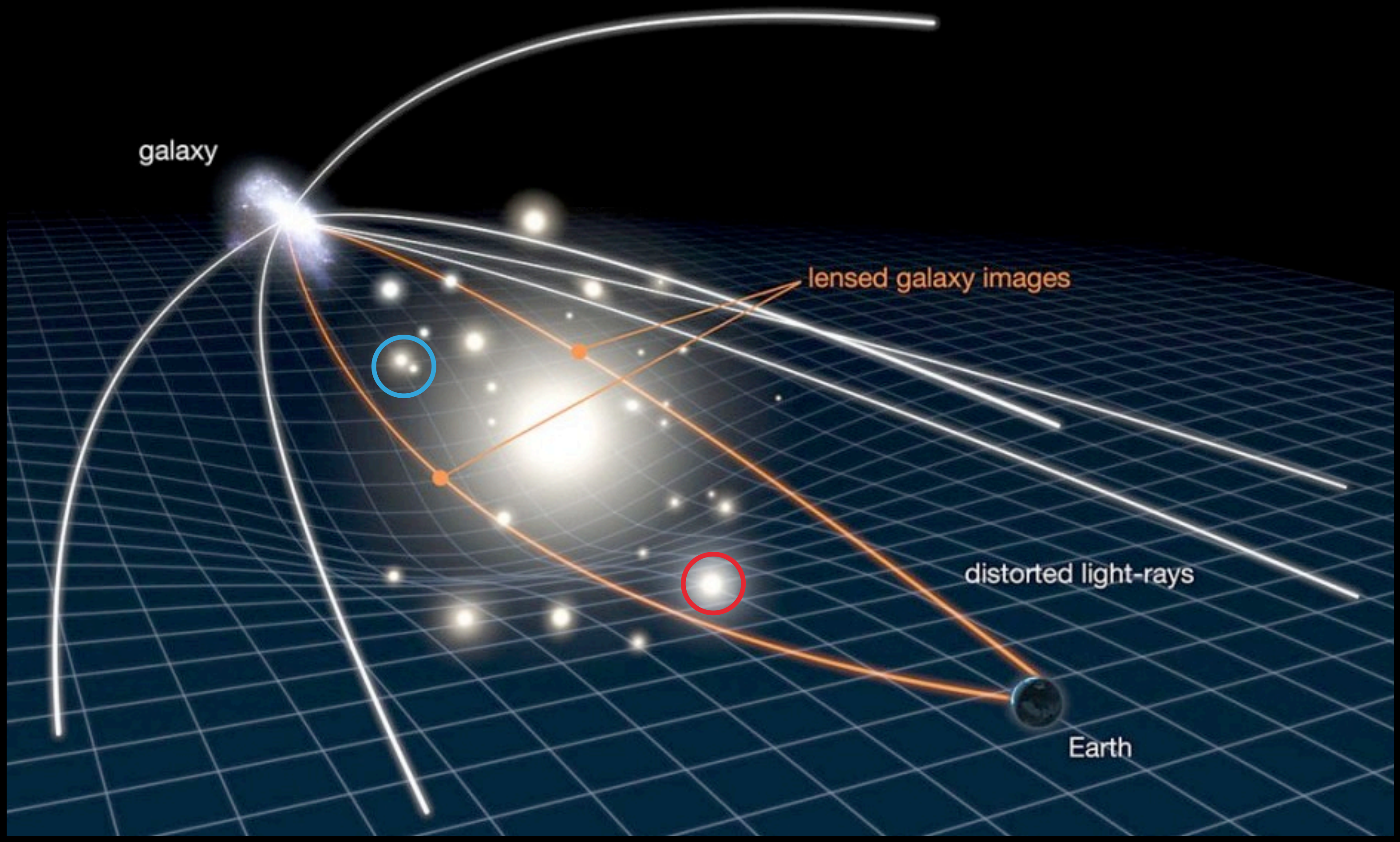


# STRONG LENSING & DM



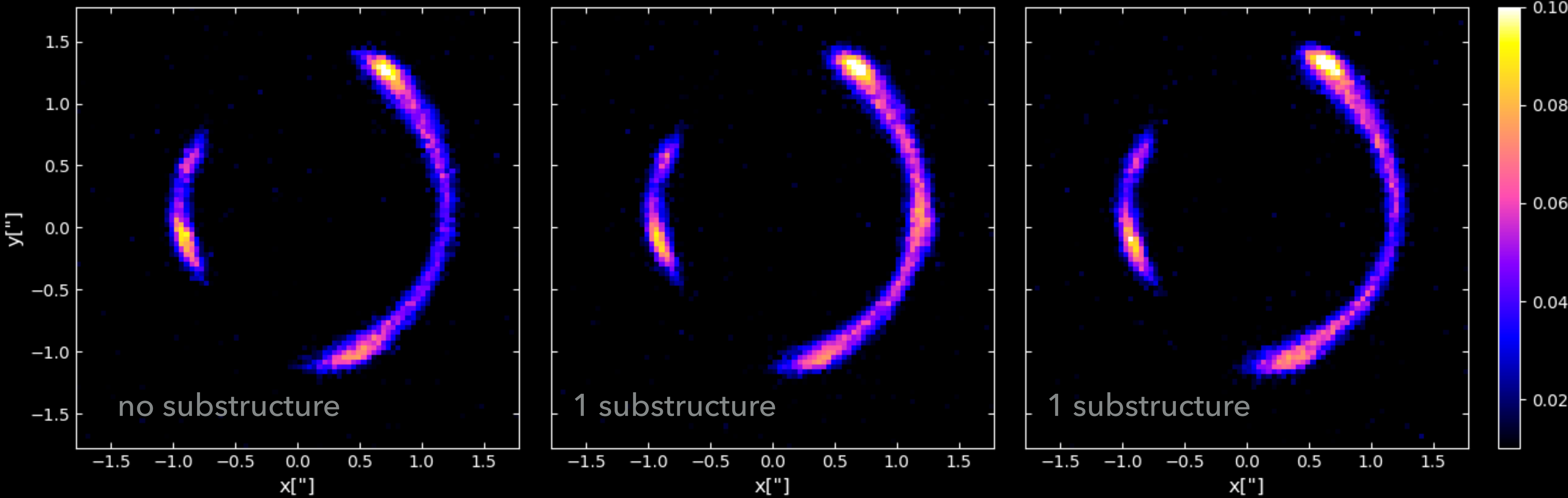
properties of the small
scale structures
in the lens or
**along the line-of-sight**

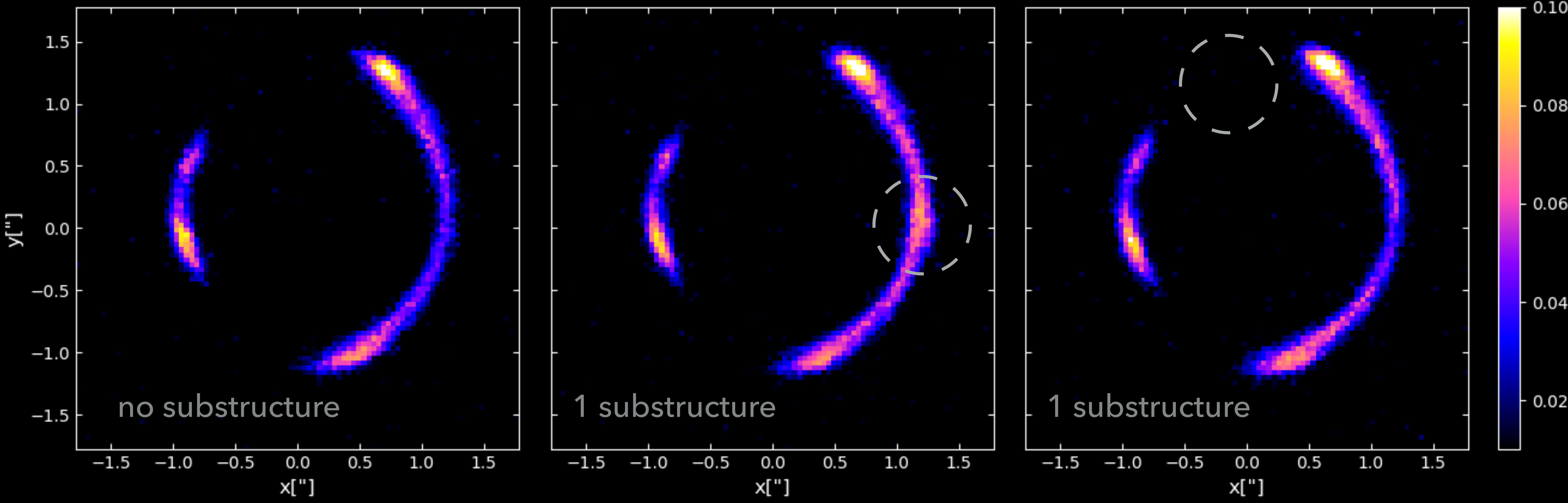


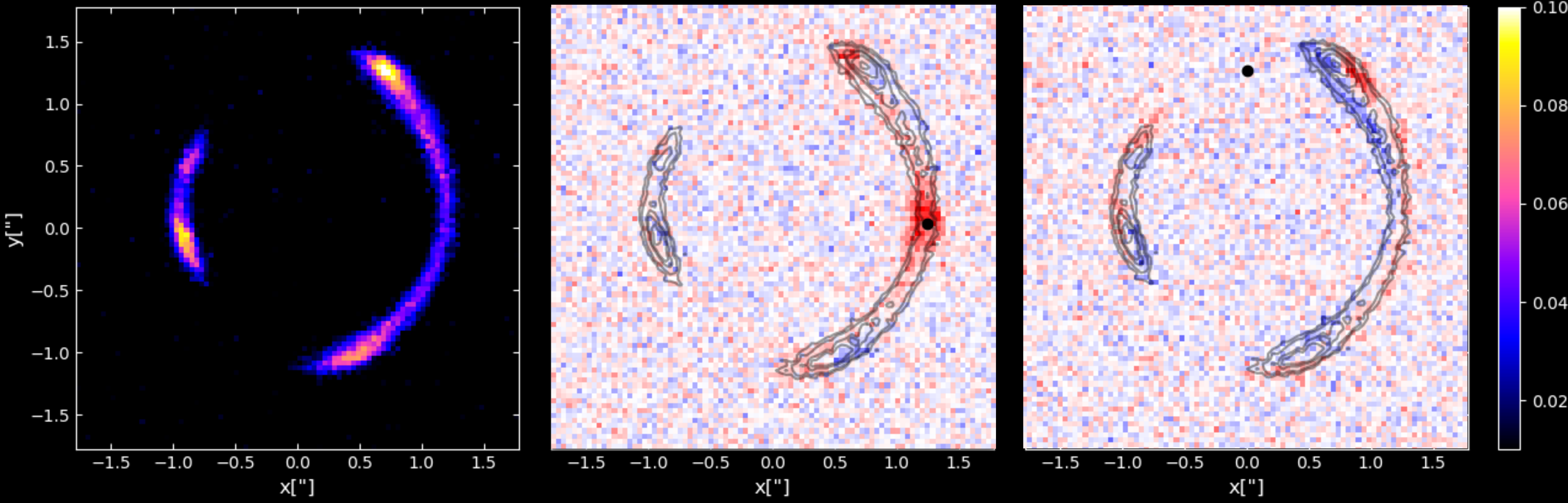




test CDM and
discriminate between
CDM and **WDM** (and SIDM)

# OBSERVATIONAL TECHNIQUE



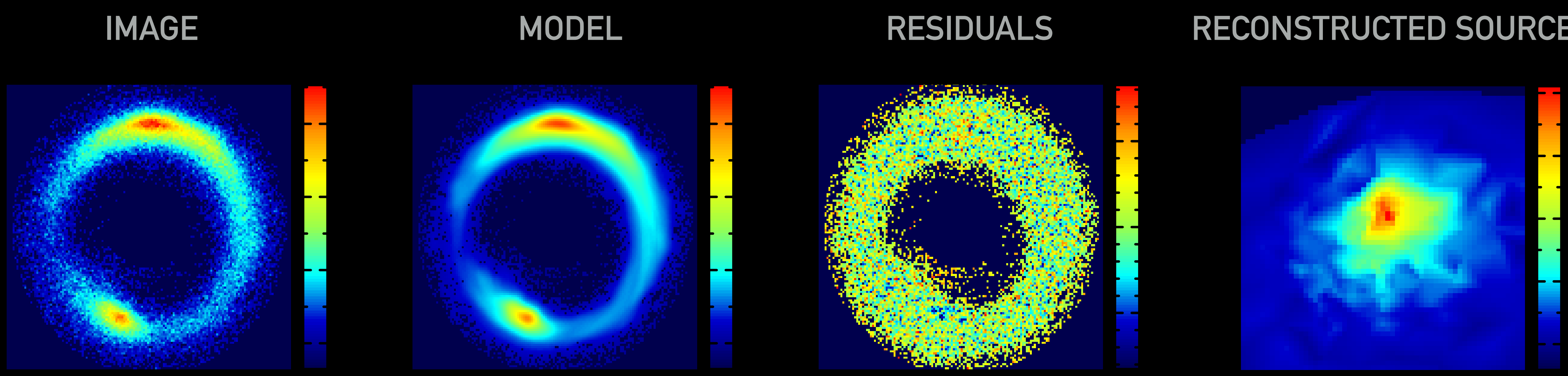

no substructure
1 substructure
1 substructure
x["]
y["]
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
0.10
0.08
0.06
0.04
0.02


y["]
x["]
x["]
x["]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0.10
0.08
0.06
0.04
0.02

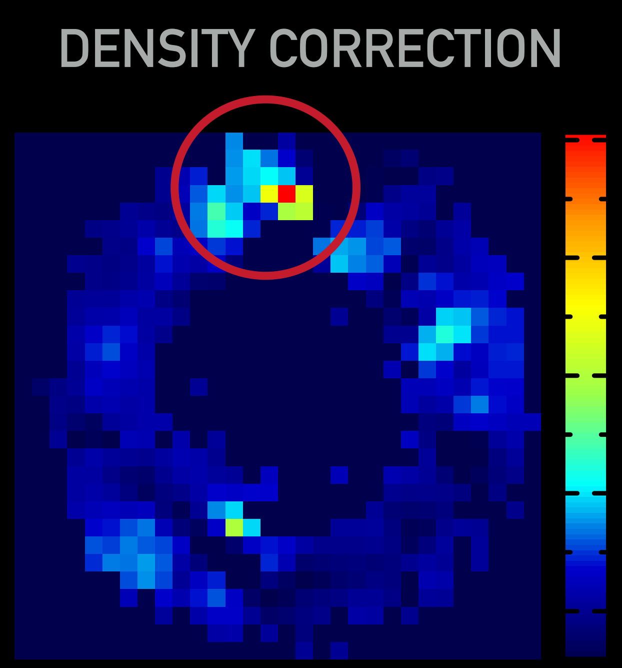
# GRAVITATIONAL IMAGING



*(Vegetti et al. 2012)*

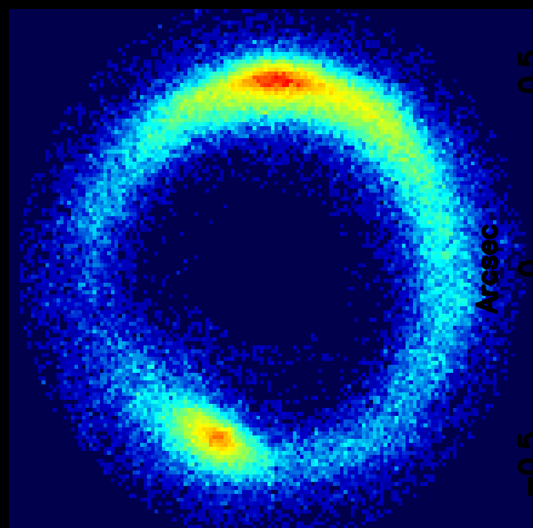



- Small mass clumps are detected as corrections to an overall smooth potential, based on perturbations in the surface brightness distribution
- if present, more than one can be detected and we can quantify its mass
- in order to claim a detection, we require the smooth lens+clump model to fit the data better than the smooth lens alone at the $10\sigma$ level

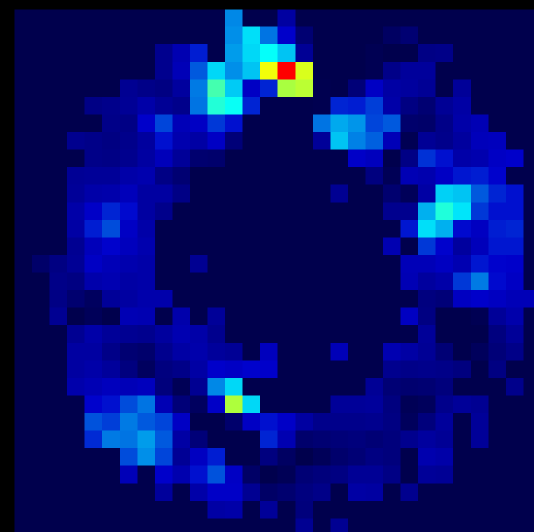


# STRONG LENSING AS A DARK MATTER PROBE

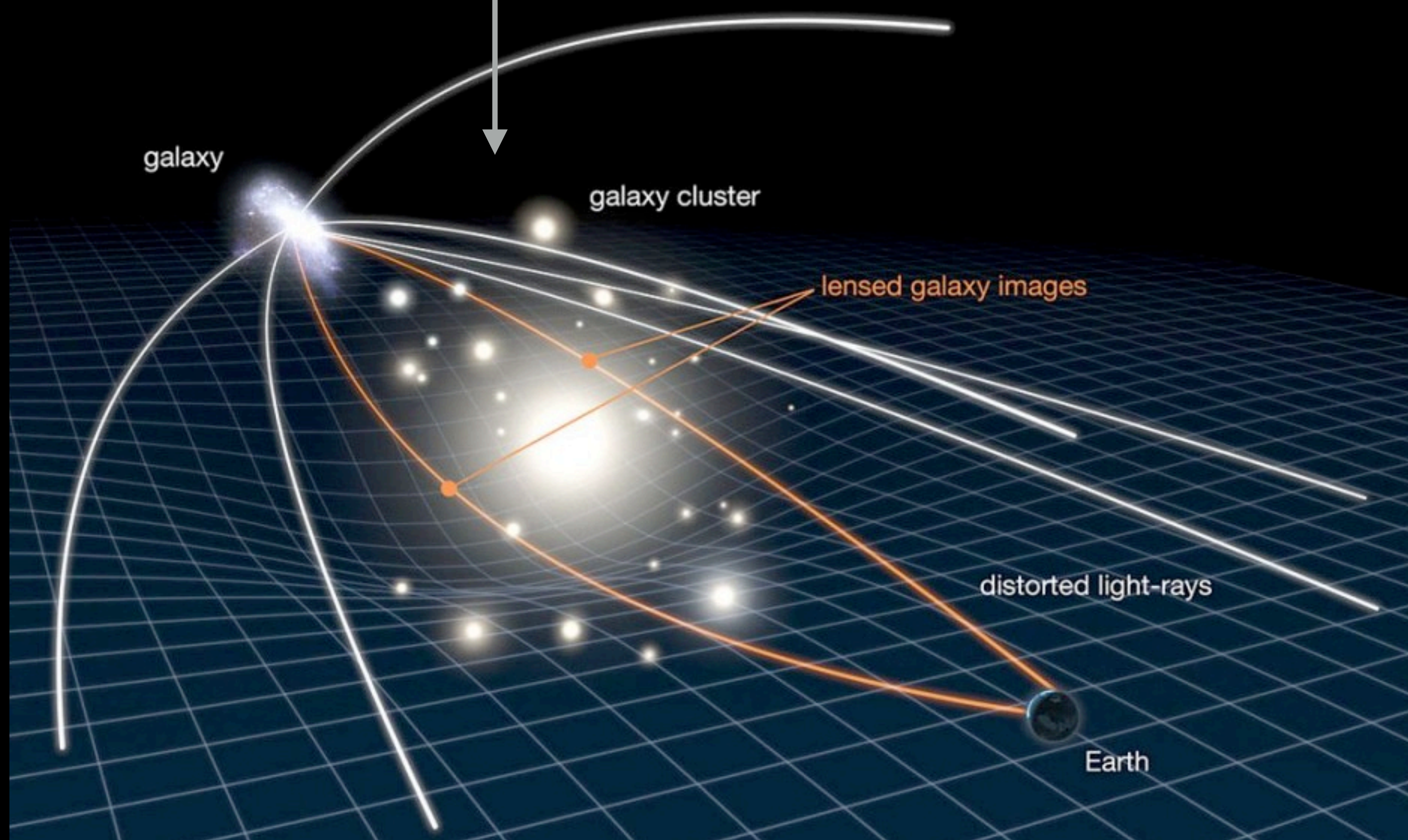
IMAGE

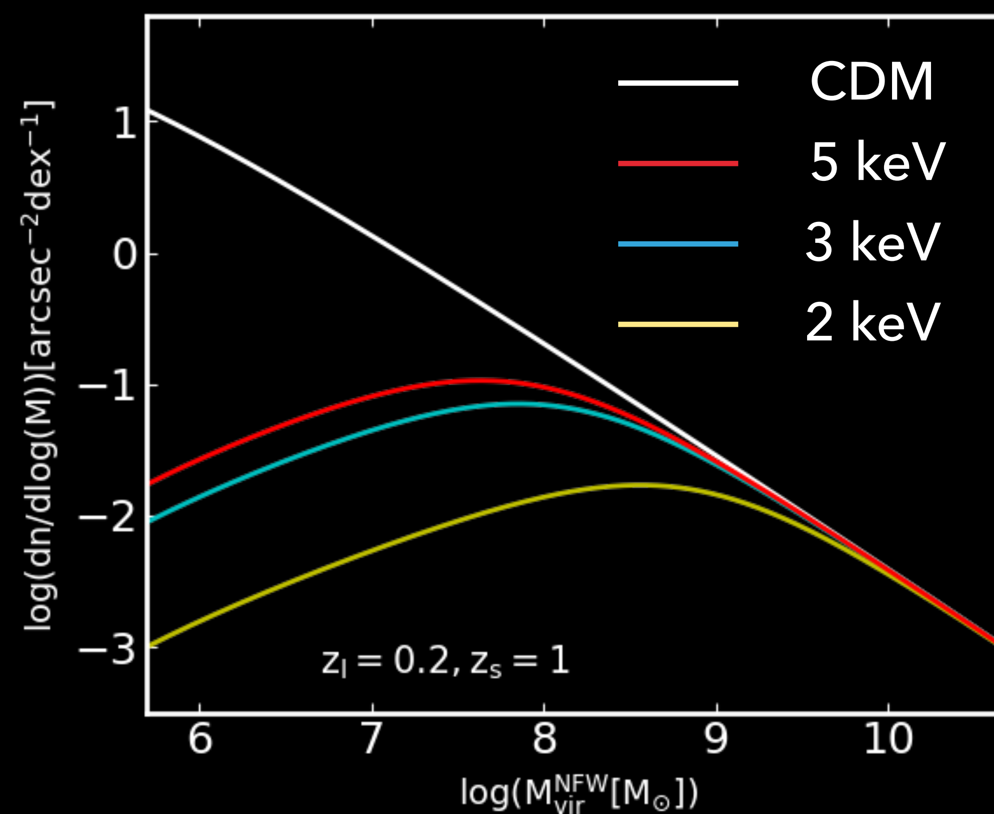


DENSITY CORRECTION

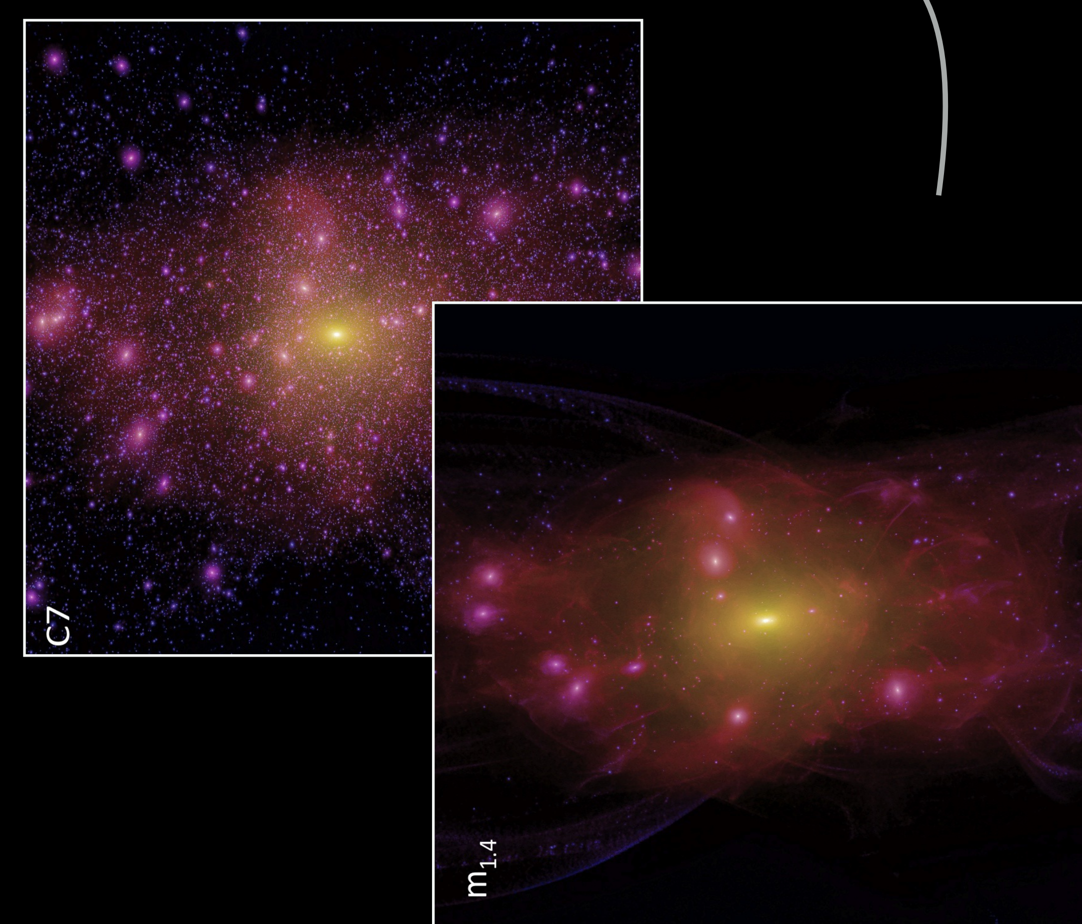


*(Vegetti et al. 2012)*




constrains on dark matter models

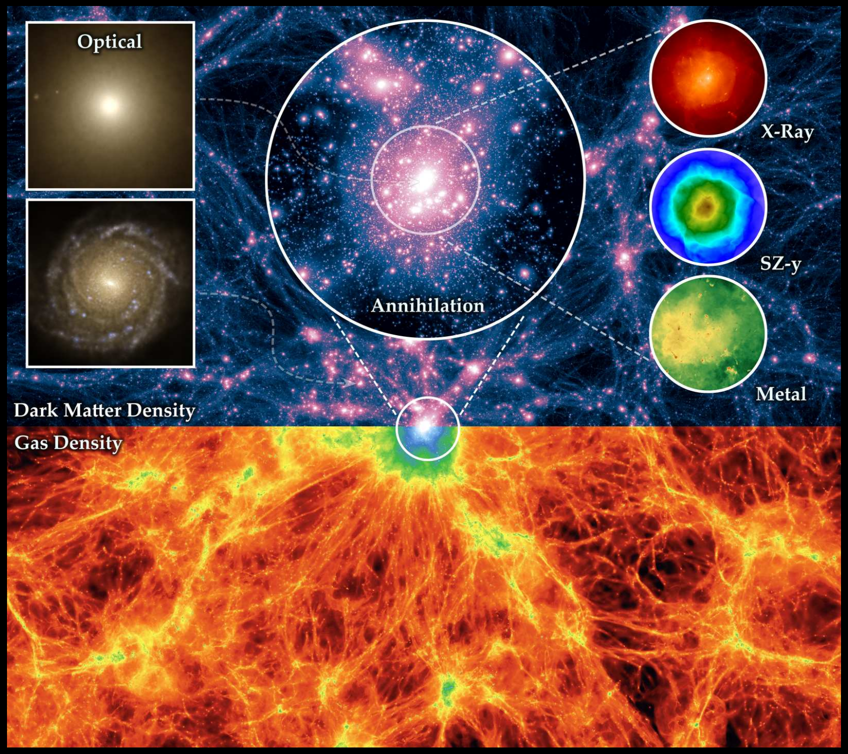


# COSMOLOGICAL BOXES



**ILLUSTRIS**

*(Vogelsberger et al 2014)*

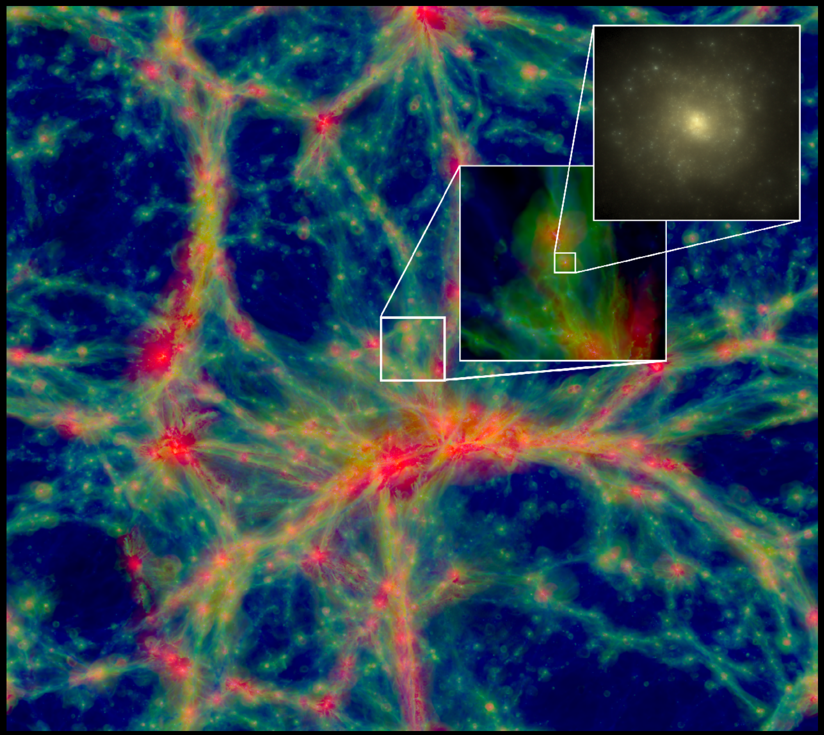



*(Genel et al. 2014, Sijacki et al. 2015, Pillepich et al. 2014, Nelson et al. 2015, Zhu et al. 2016, etc)*

very similar, but with different baryonic physics

**EAGLE**

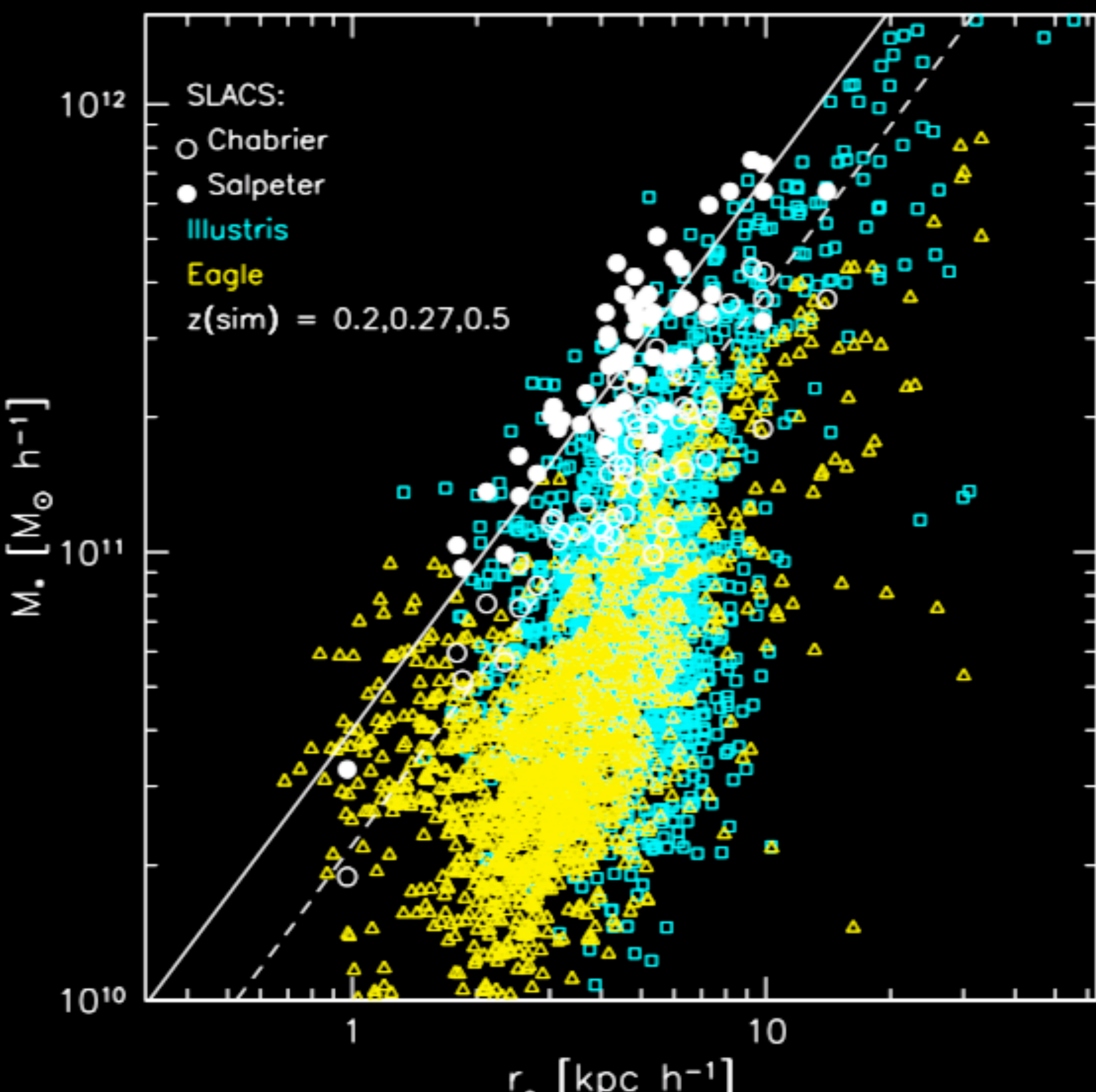
*(Schaye et al 2015)*

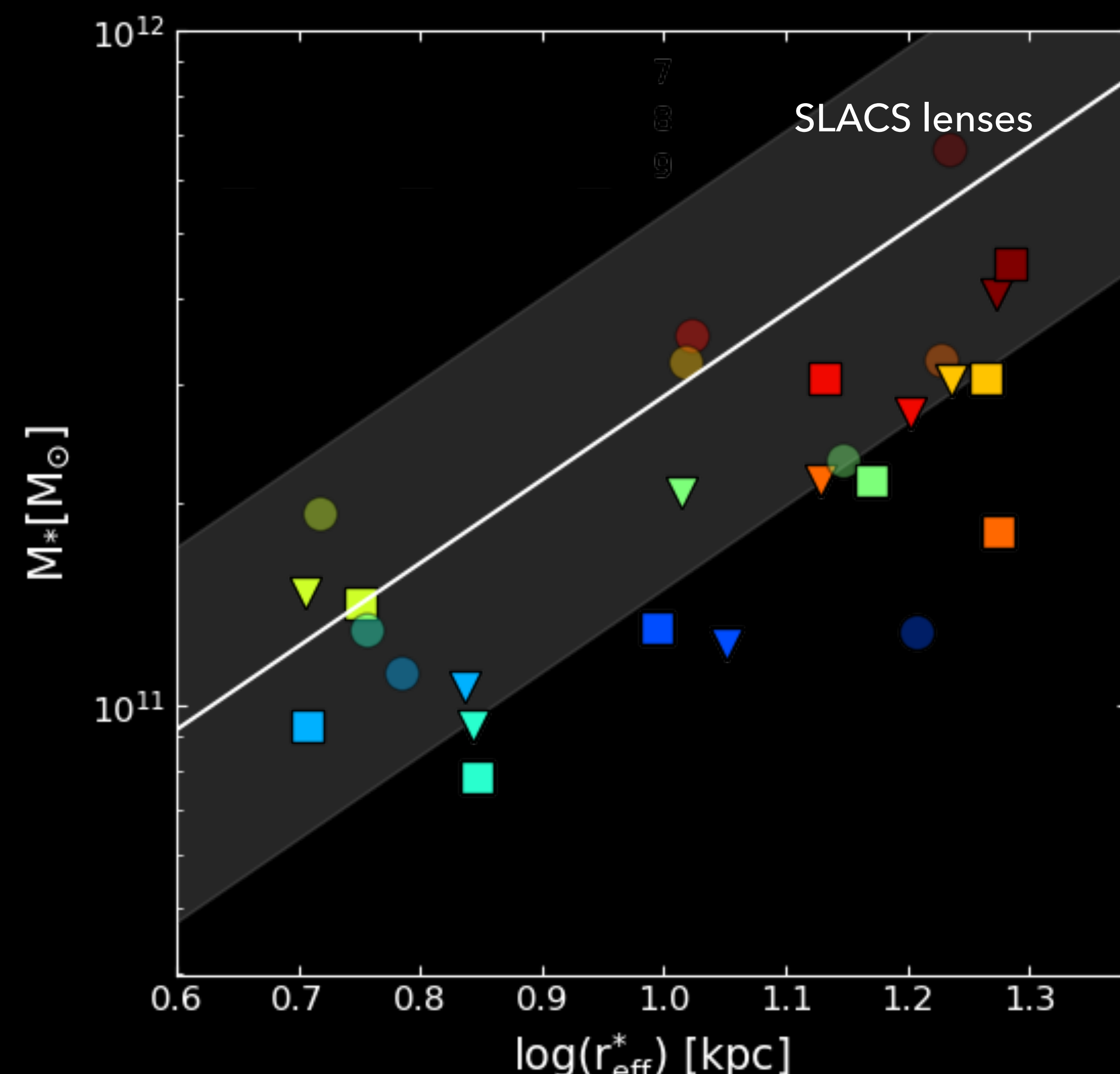


*(Crain et al. 2014, Schaller et al. 2014 - 2015, Trayford et al. 2014 - 2015, Velliscig et al. 2015, etc)*

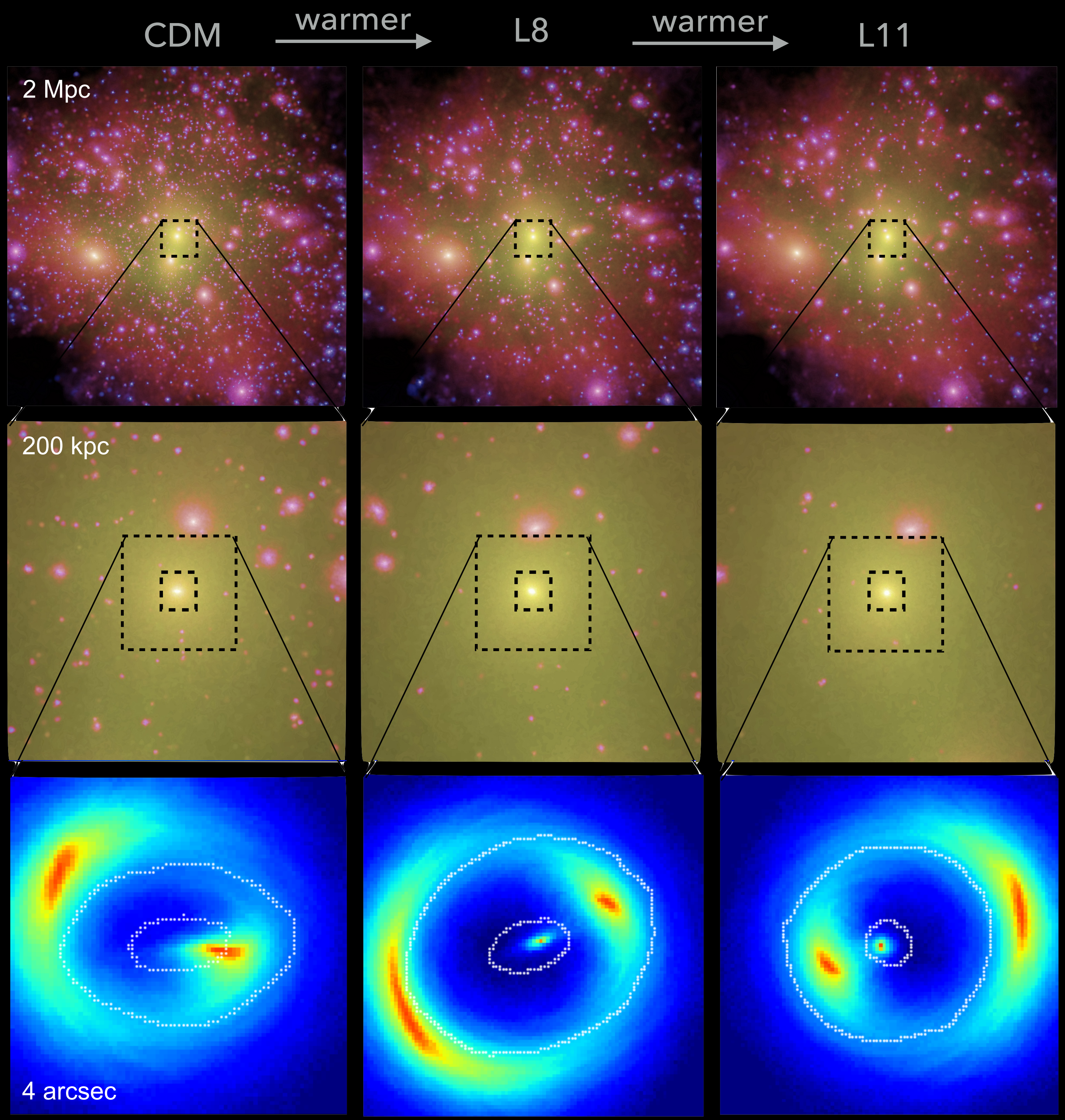
# ZOOM-IN SIMULATIONS





*(Despali, Lovell et al. 2019)*

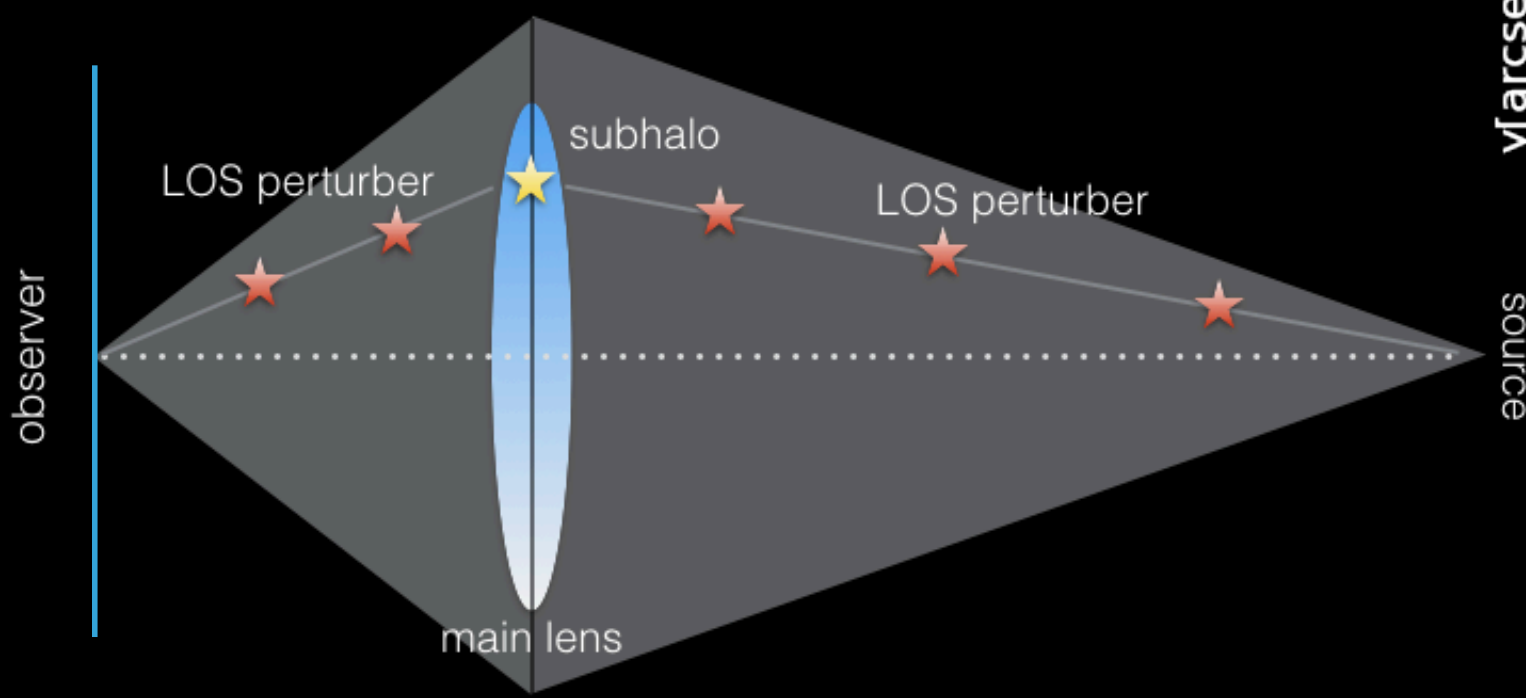


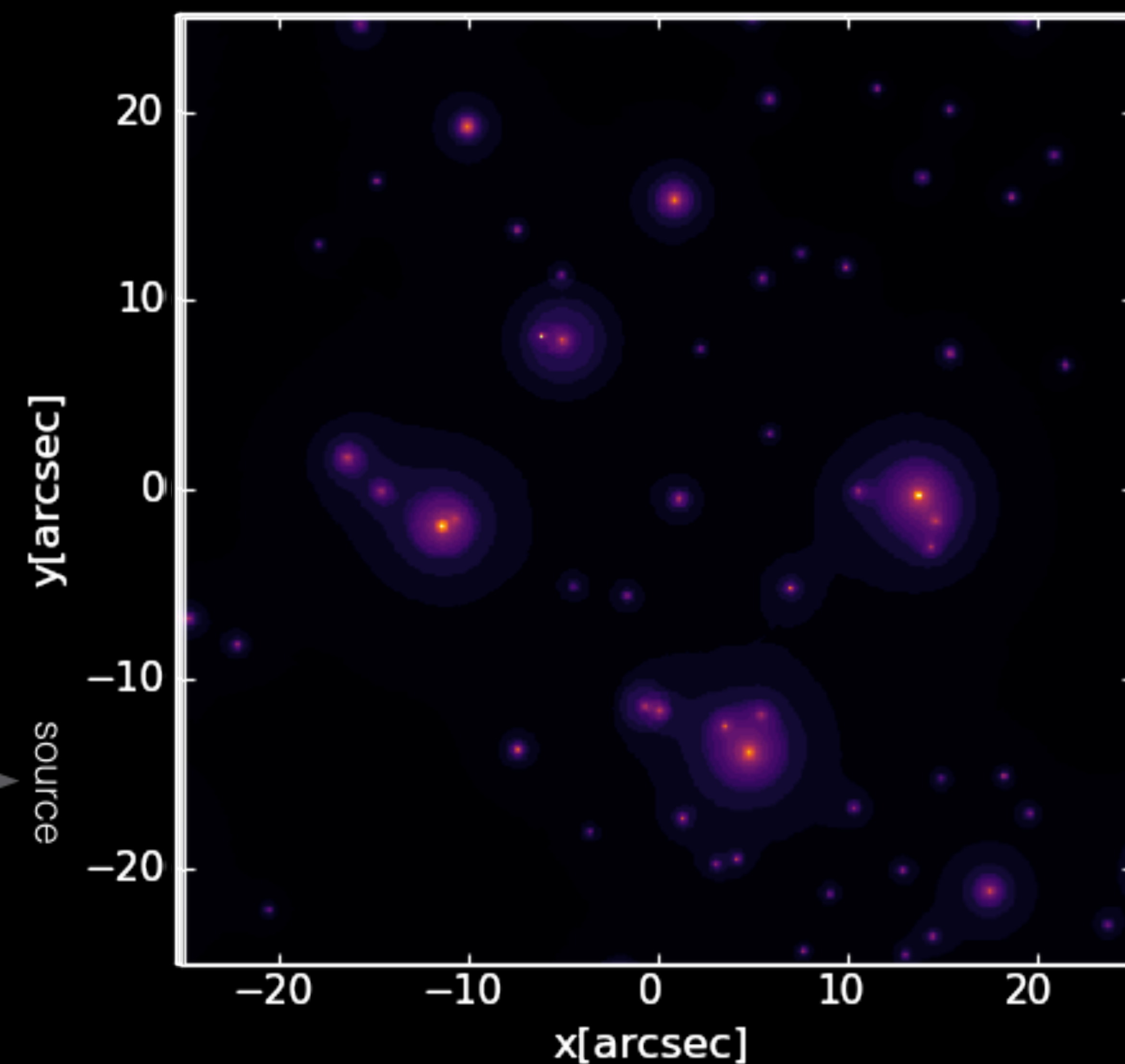
# EXPECTED NUMBER OF PERTURBERS *(Despali et al. 2018, Li et al. 2017)* SIMULATIONS

$$\frac{n_{WDM}}{n_{CDM}} = (1 + \gamma M_{hm} M^{-1})^{\beta}$$

$$N_{LOS} = \int_0^{z_S} \int_{M_{LOW}(z)}^{M_{max}} n(m,z) dm \frac{dV}{dz} dz$$

lensing is sensitive to the whole mass distribution between the observer and the source



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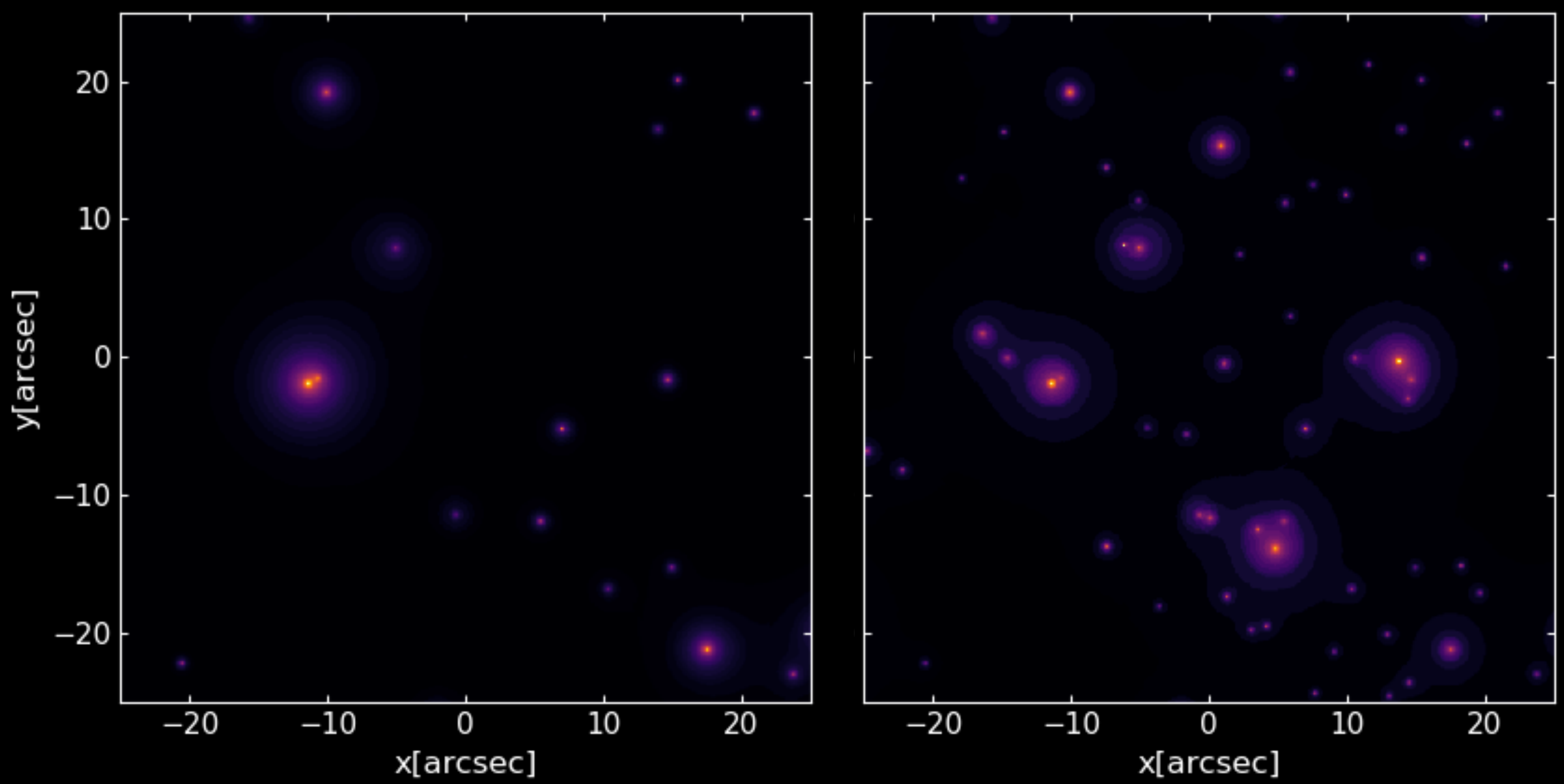


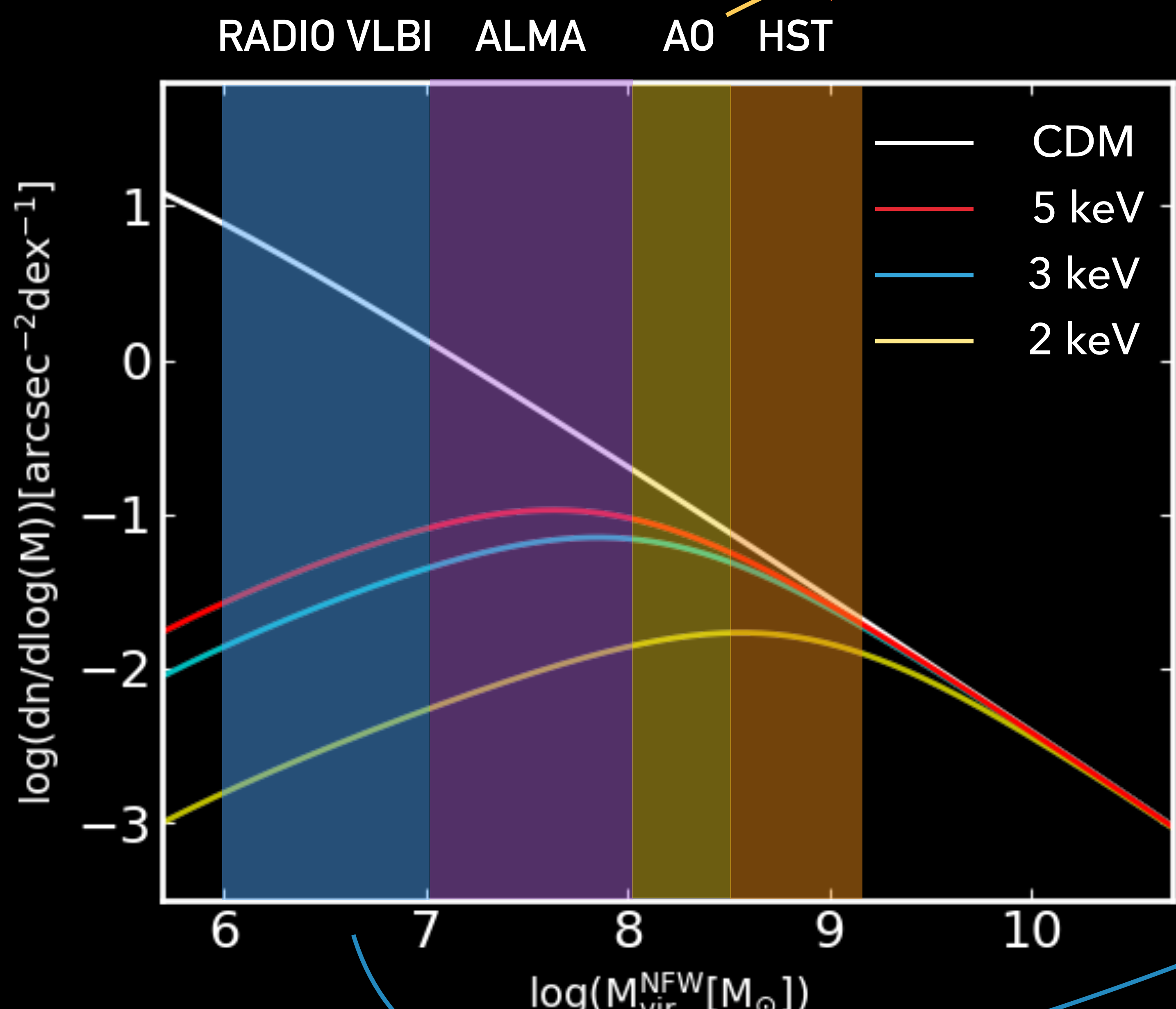
# EXPECTED NUMBER OF PERTURBERS

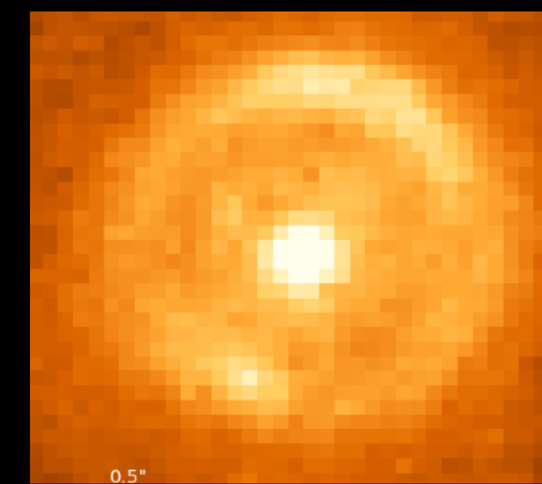
*(Despali et al. 2018)*

SIMULATIONS

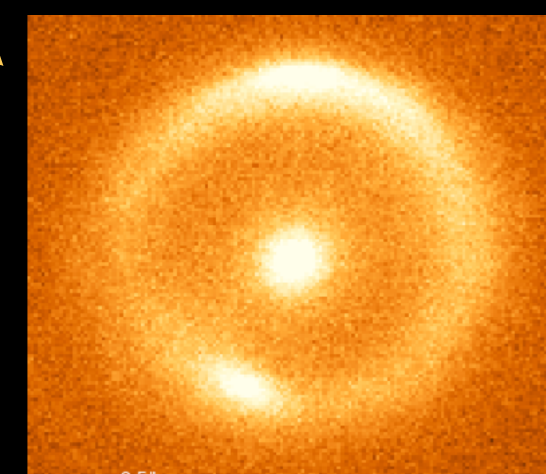
$$\frac{n_{WDM}}{n_{CDM}} = (1 + \gamma M_{hm} M^{-1})^{\beta}$$

"half-mode mass":
related to the cut-off point



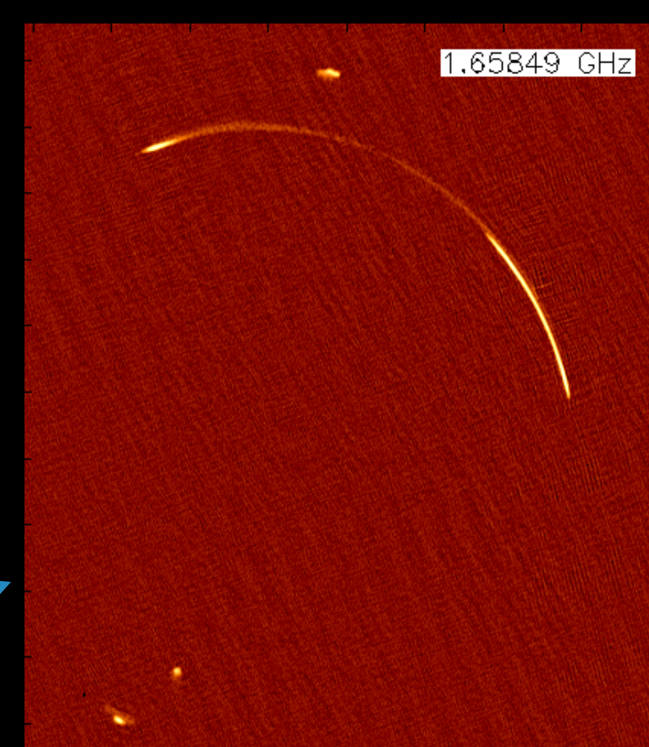
HST



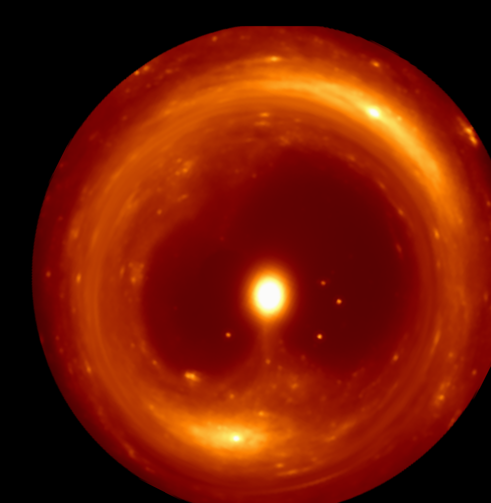
KECK AO

"SHARP LENSES"

RADIO GVLBI



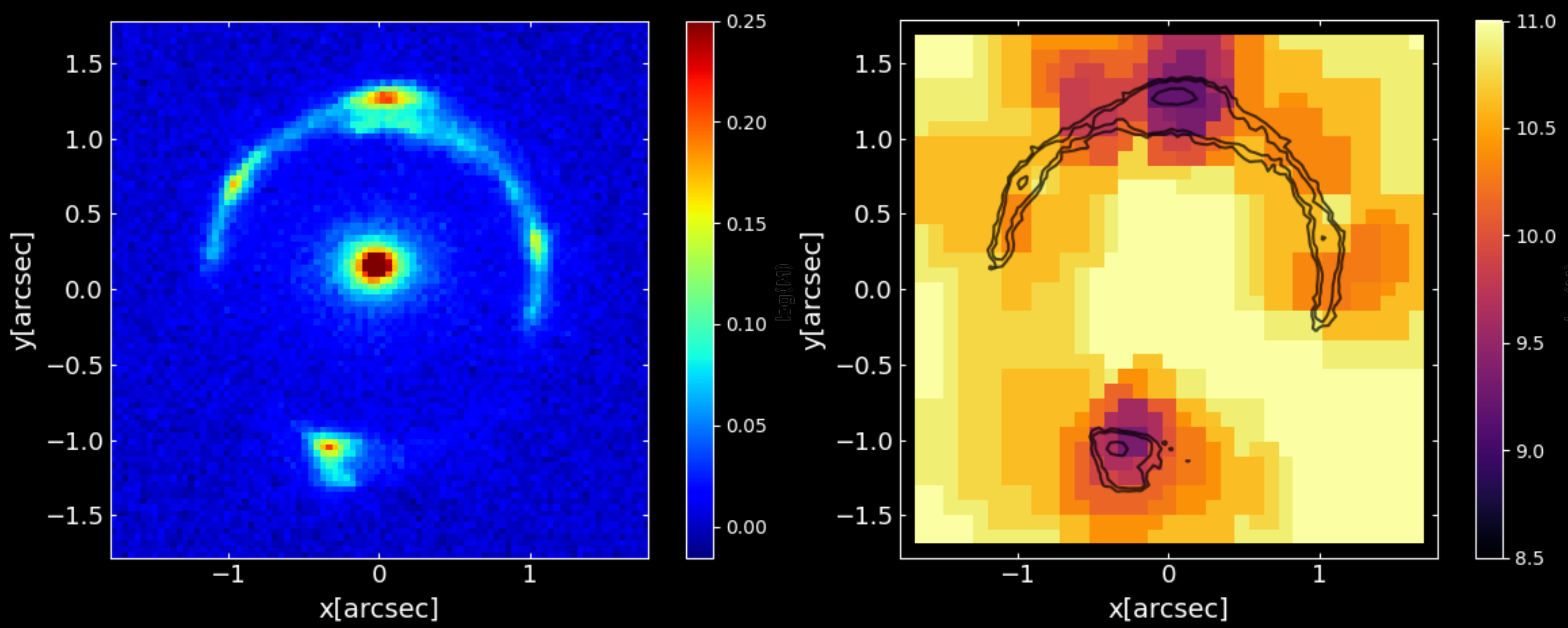

EELT (mock)



# NUMBER OF DETECTABLE HALOES: OBSERVATIONS

IMAGE

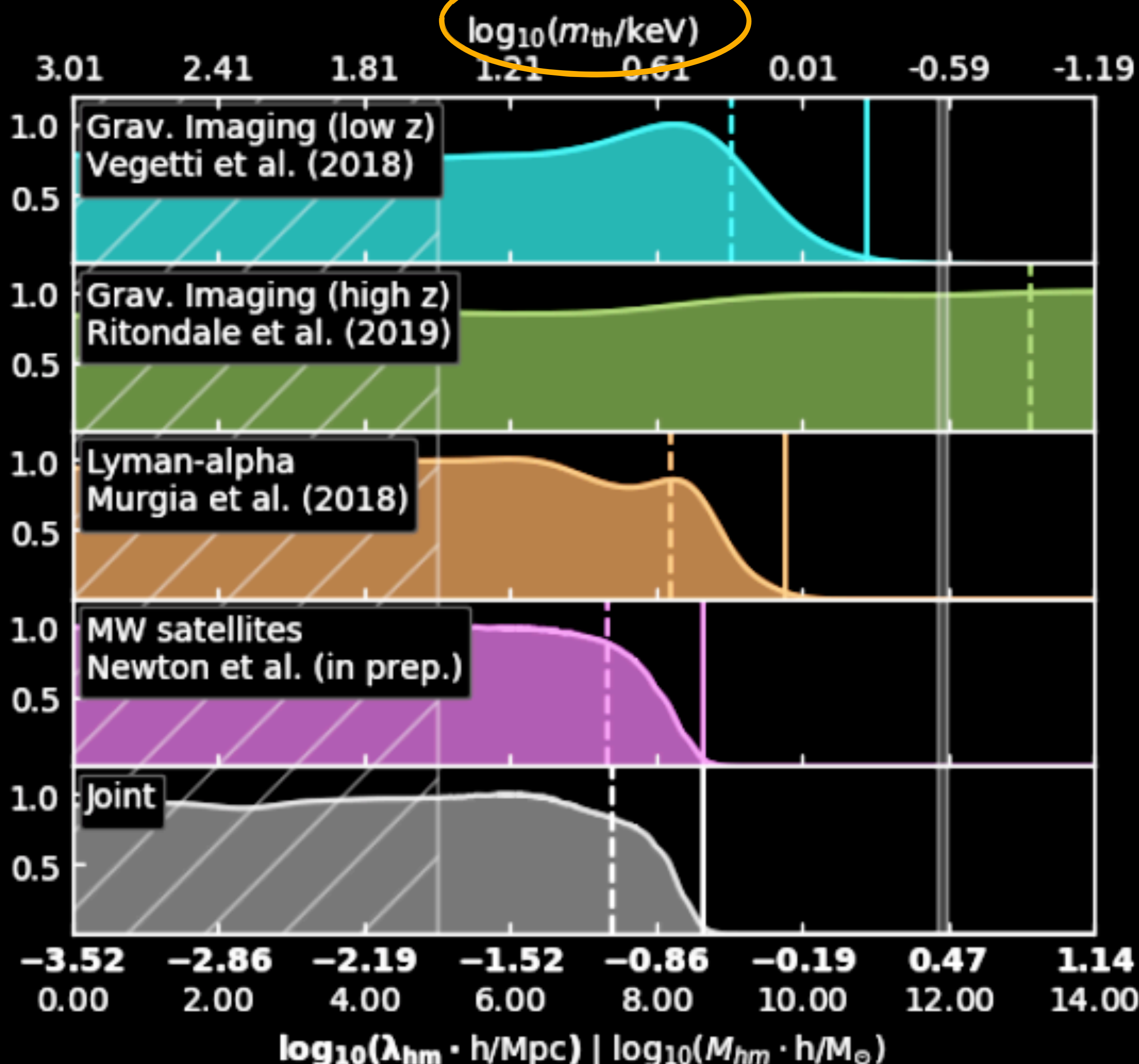
SENSITIVITY MAP



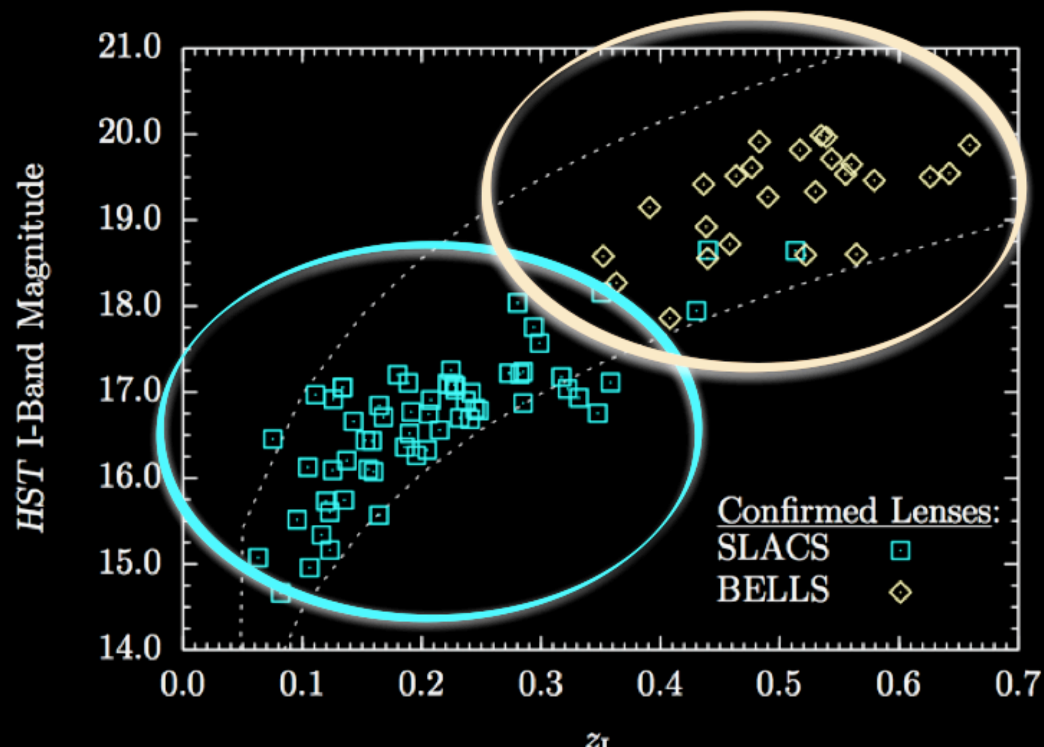

*(Despali et al. 2021)*

# CURRENT CONSTRAINTS ON WDM

*(Enzi et al. 2021)*

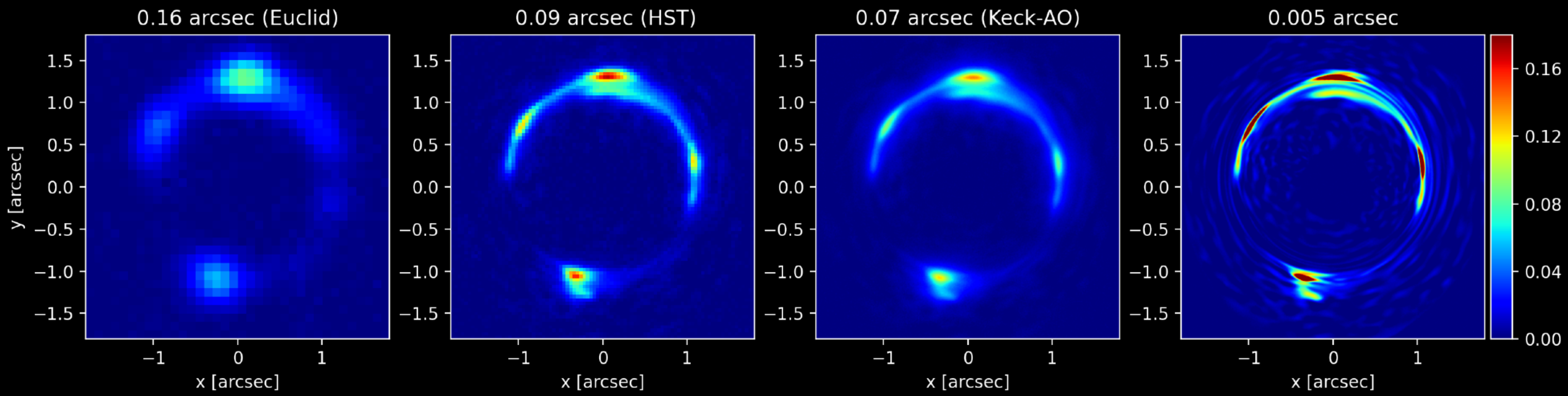



Lensing




*(Ritondale et al. 2019)*

# MOCK DATA FOR ACCURATE PREDICTIONS




- HST images from the BELLS-GALLERY sample *(Ritondale et al. 2019)*
- Keck-AO images from the SHARP sample *(Vegetti et al. 2012)*
- ALMA data from *Stacey et al. 2021* (sub.)
- zl>0.5, zs>2

**QUESTION 1:**

how many lenses do we need to test CDM and/or distinguish it from alternative WDM models?

**QUESTION 2:**

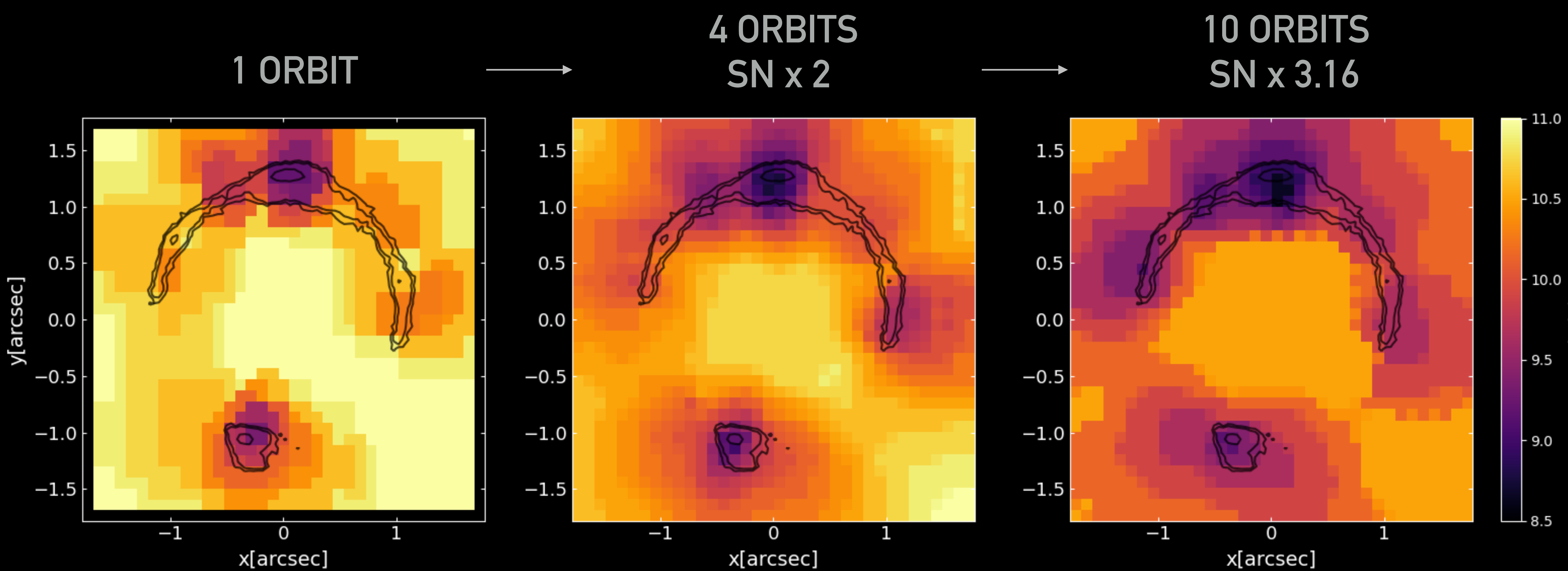
what is the best observational strategy to achieve this goal?

**QUESTION 3:**

what lens/source properties can influence detections?

*(Despali et al. 2021)*

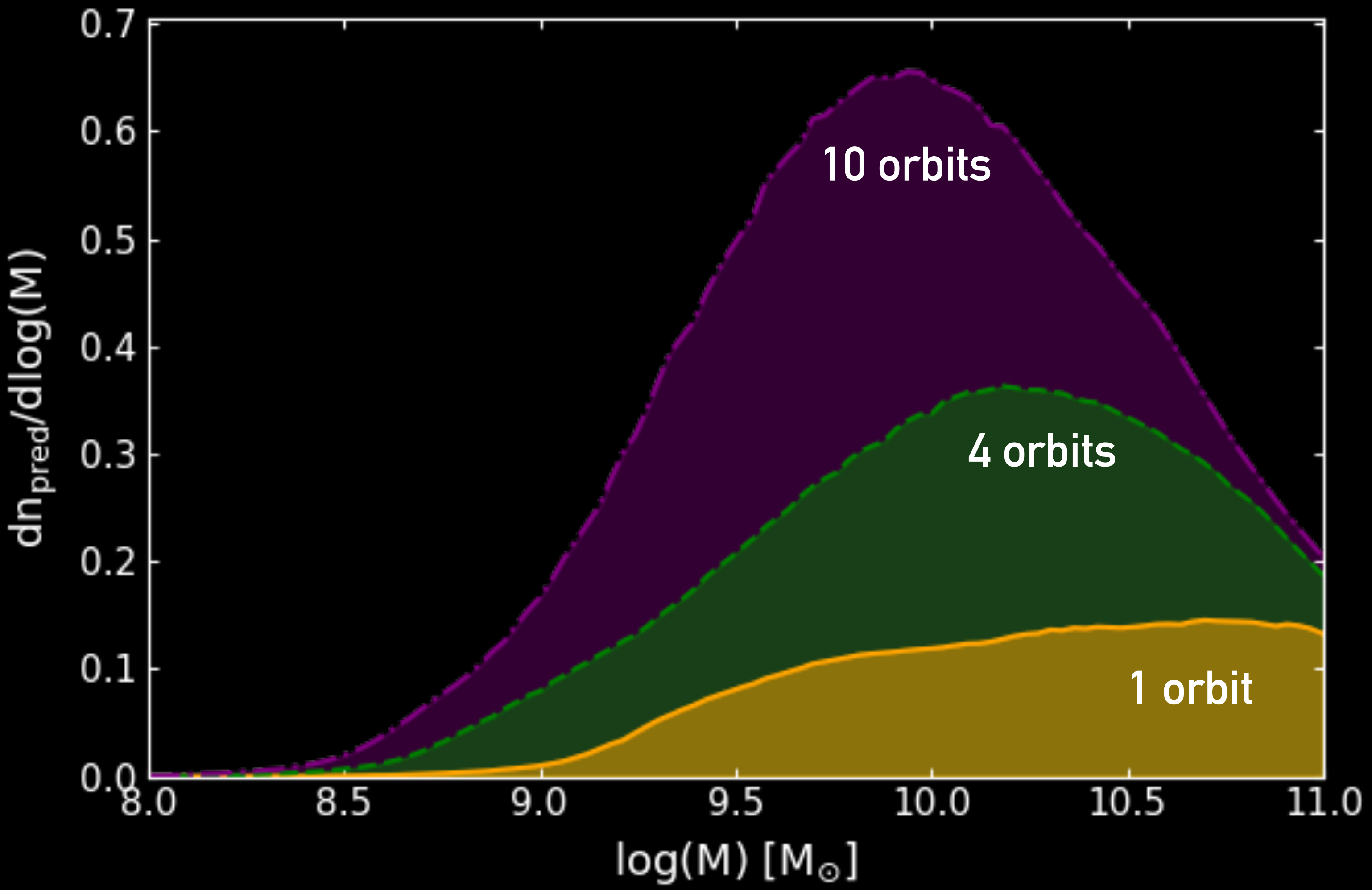
# VARYING SIGNAL-TO-NOISE RATIO



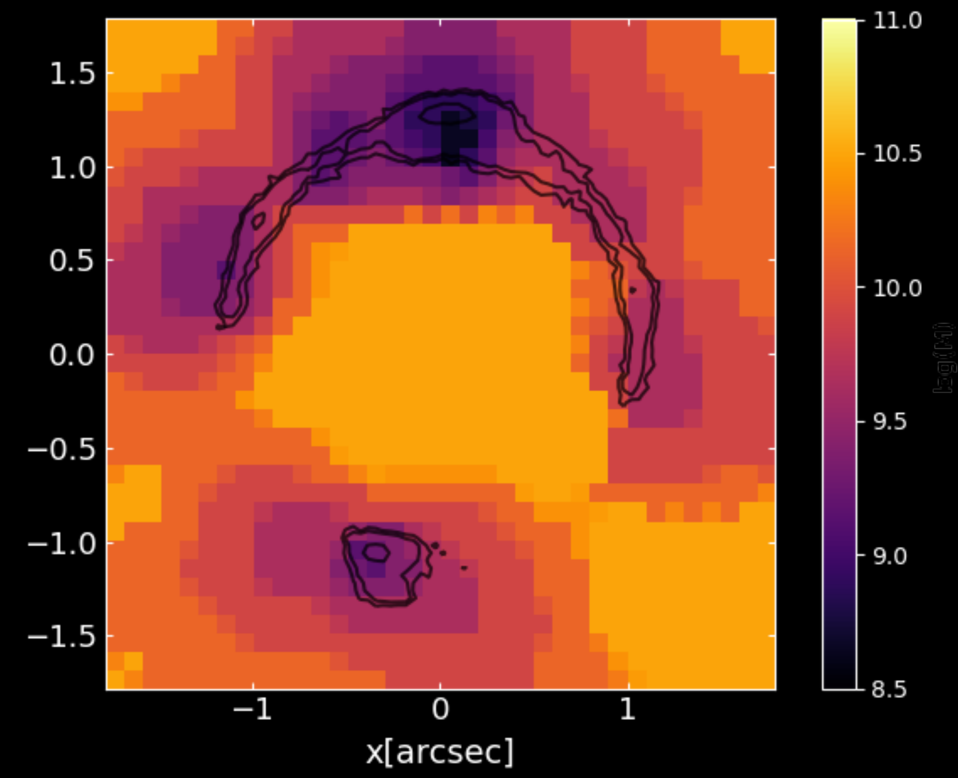

the number of predicted detections linearly increases with SNR

*(Despali et al. 2021)*

# VARYING SIGNAL-TO-NOISE RATIO

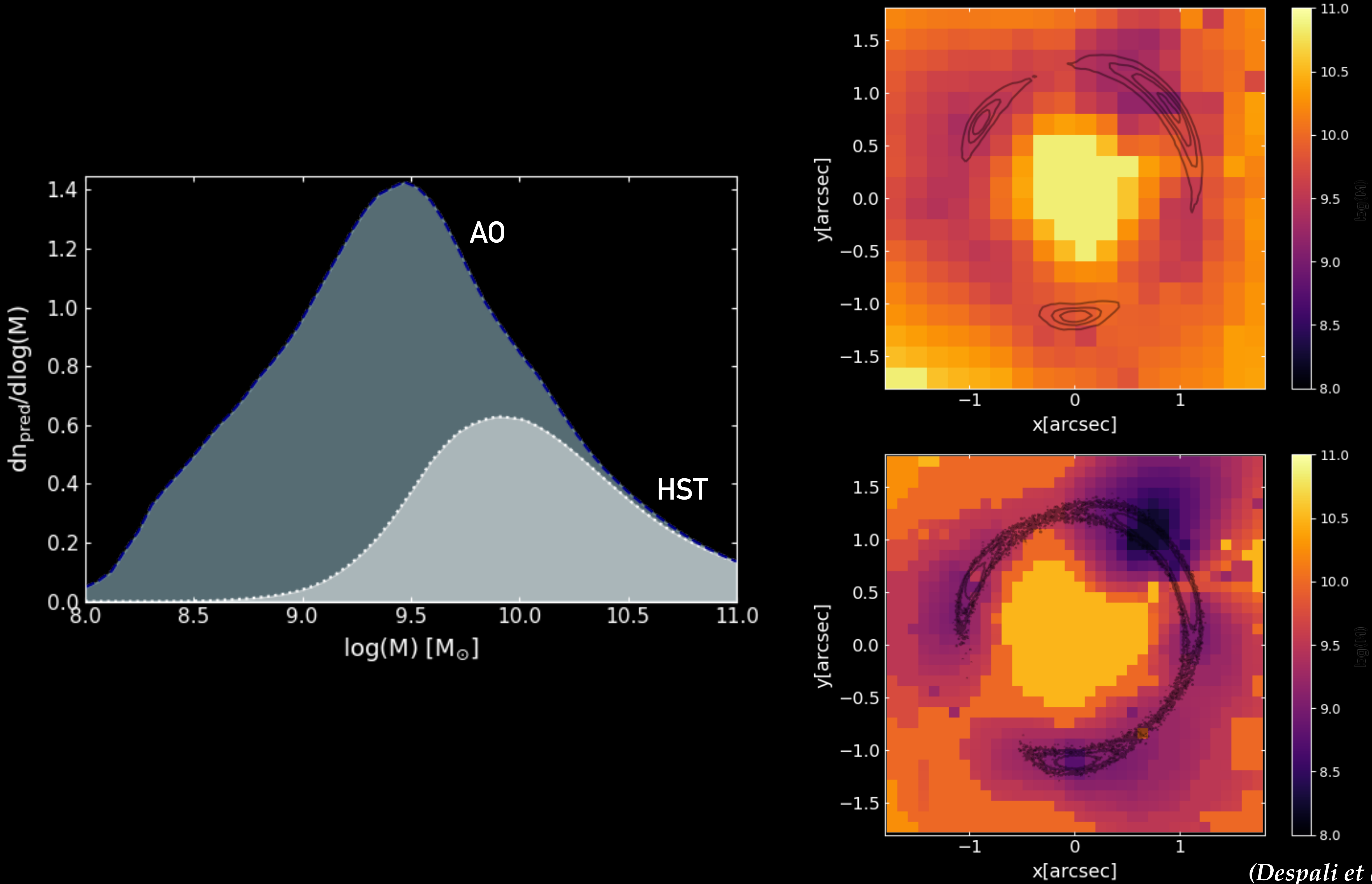



10 ORBITS
SN x 3.16




(*Despali et al. 2021*)

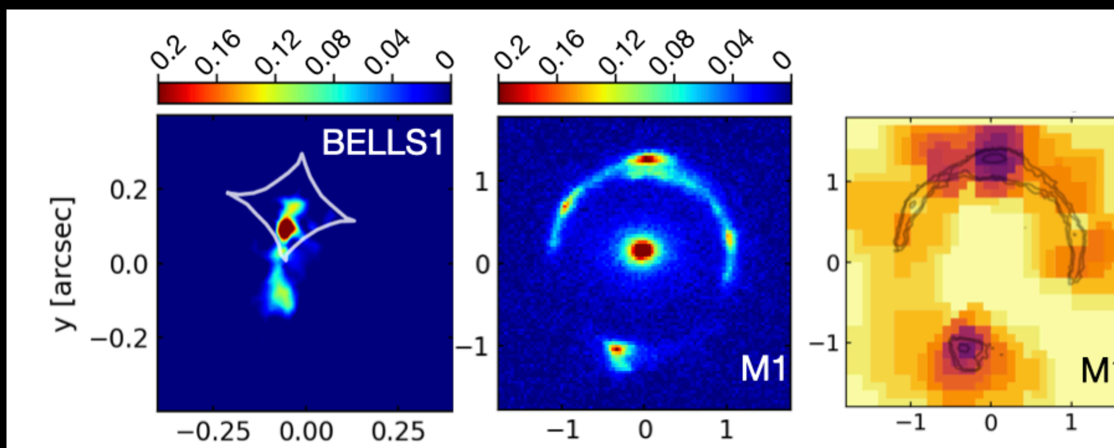
# VARYING ANGULAR RESOLUTION

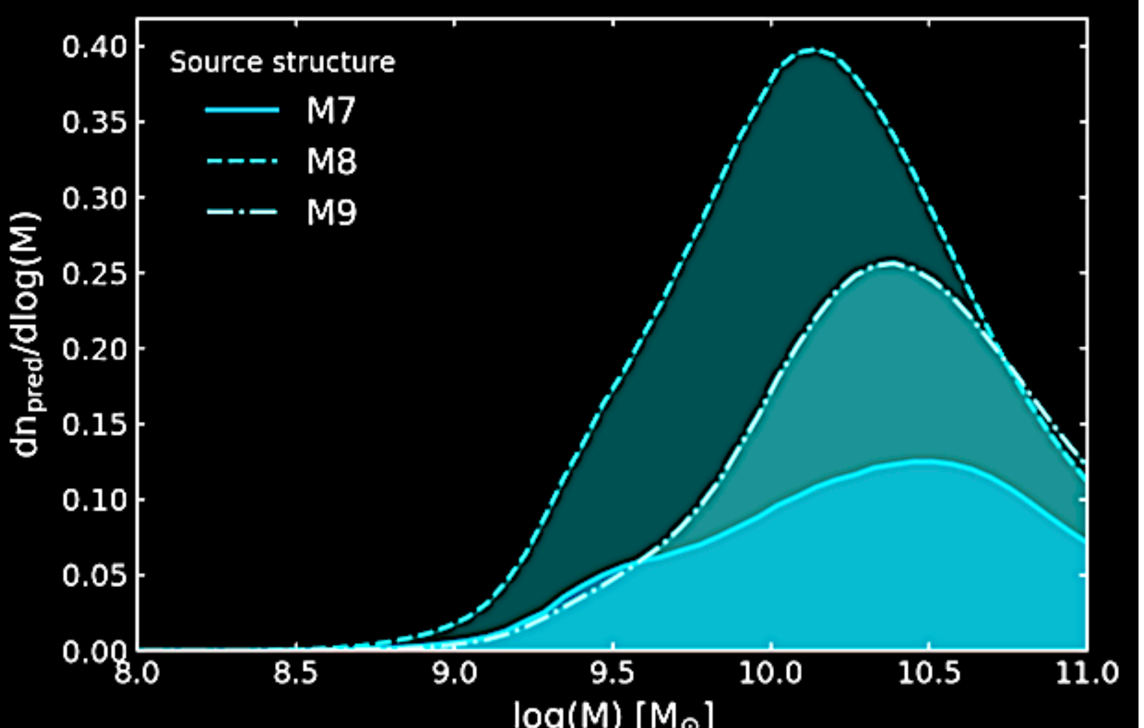


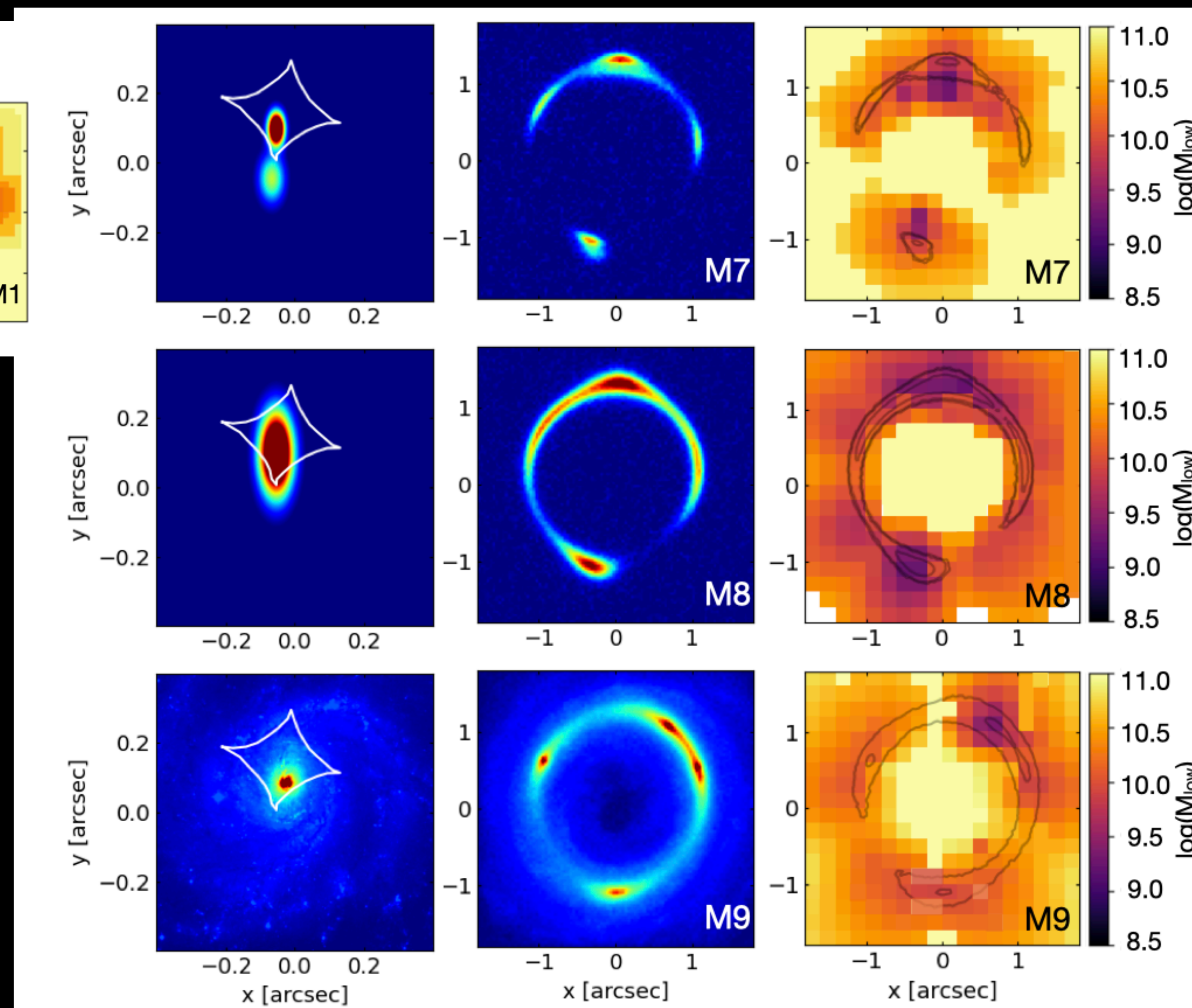

(Despali et al. 2021)

# VARYING SOURCE PROPERTIES

changing the structure of the source

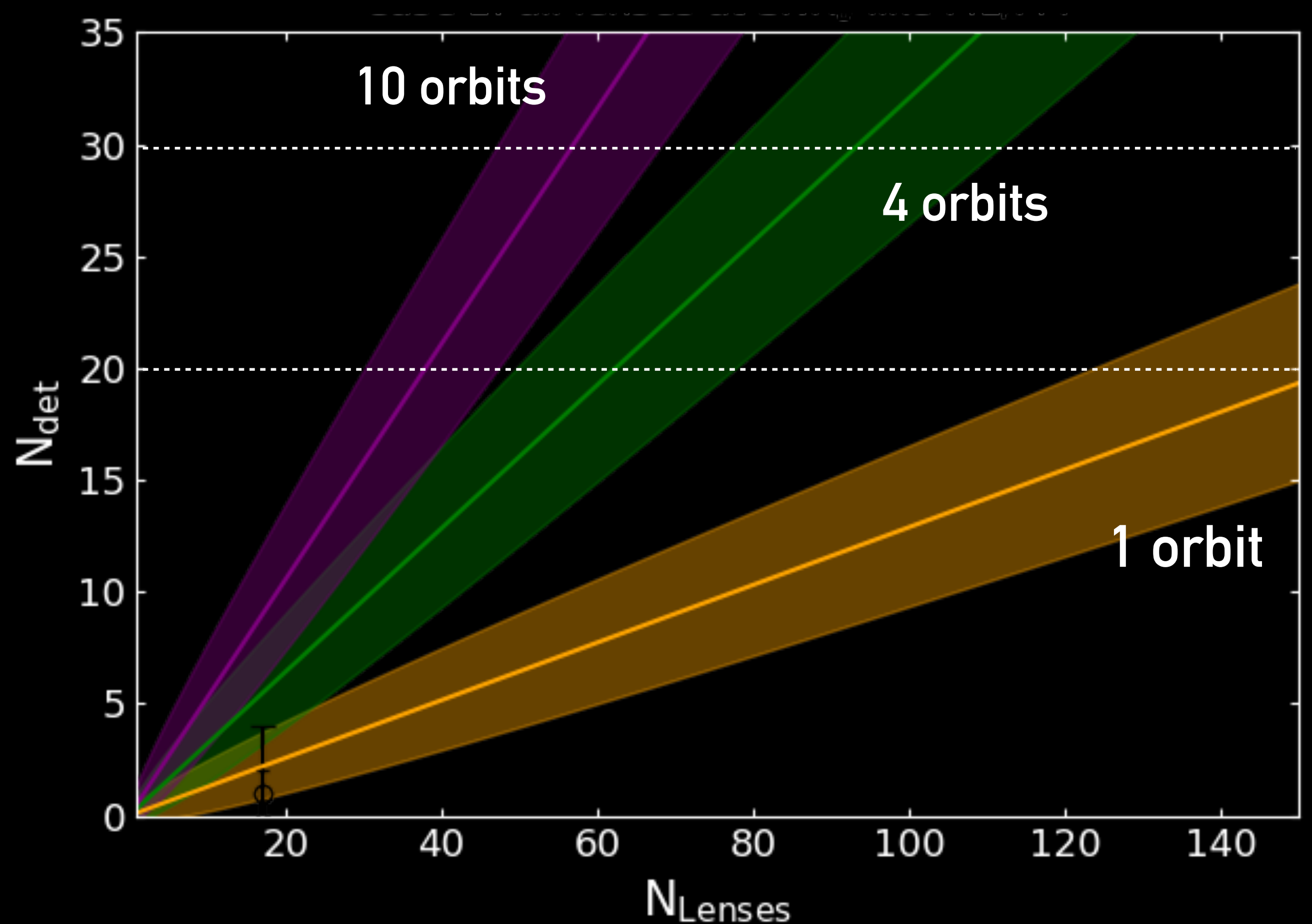


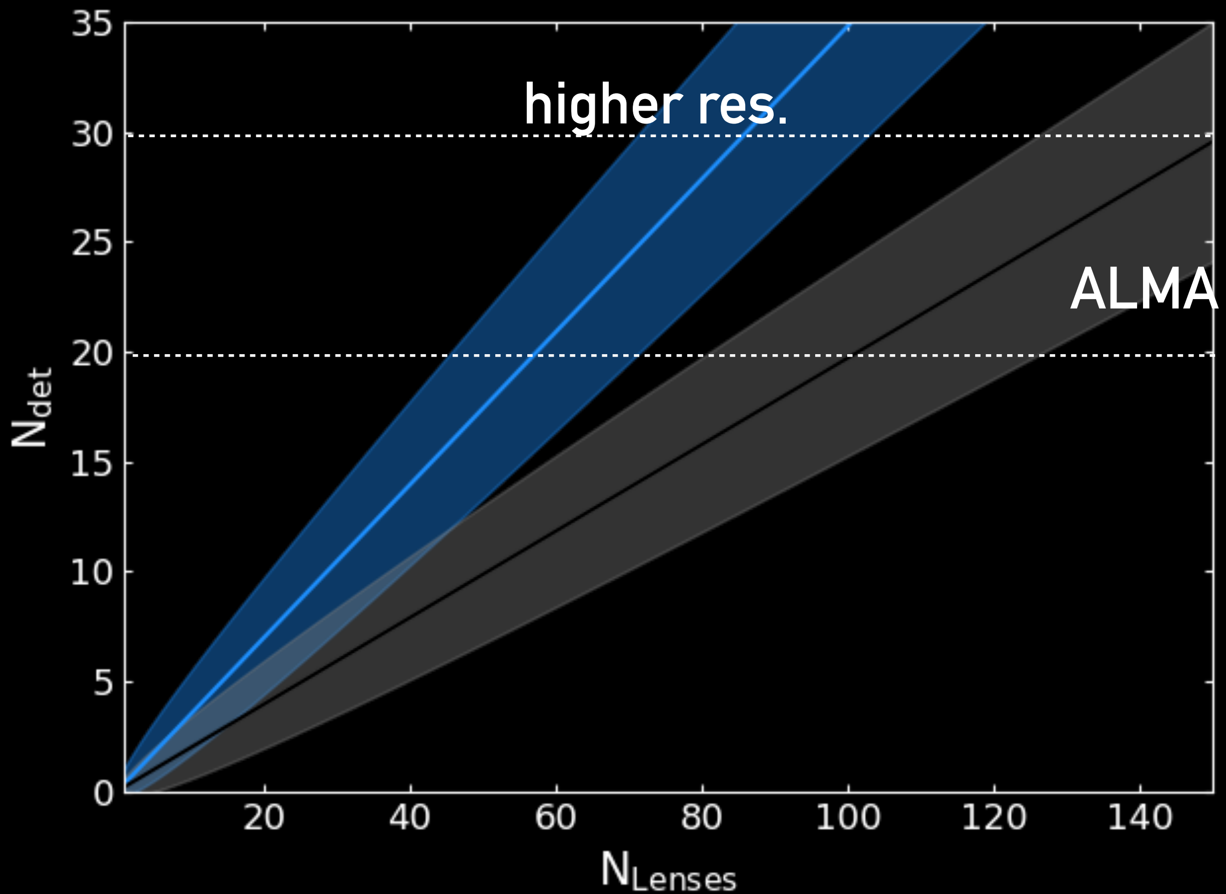




(*Despali et al. 2021*)

# TESTING COLD DARK MATTER



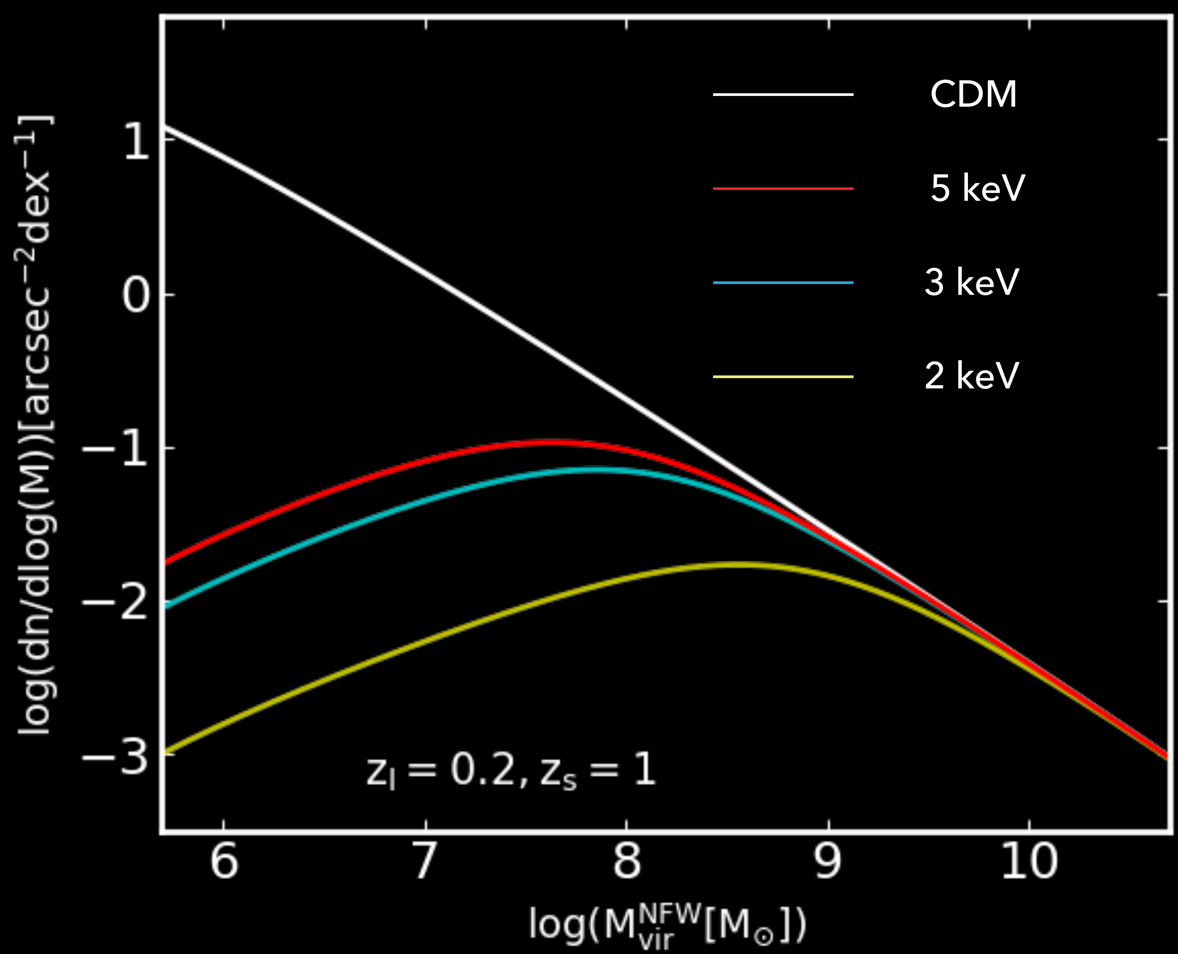



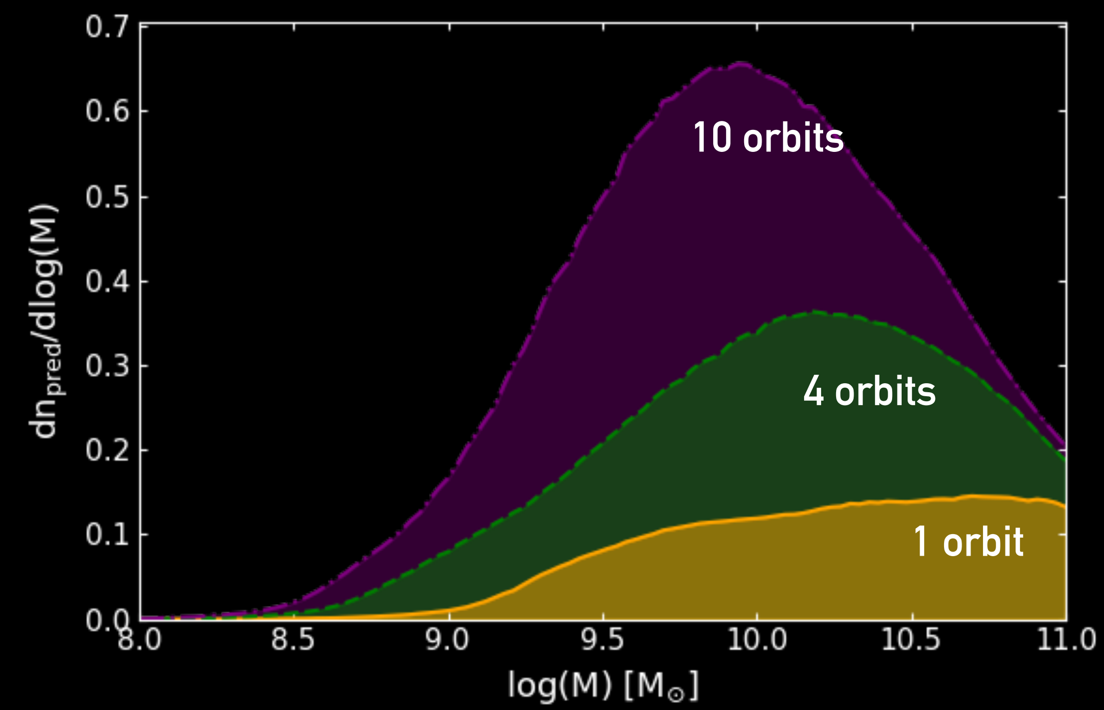

| | P~ $10^{-2}$ | P~ $10^{-4}$ |
|---|---|---|
| HST - 1 orbit | 36 | 72 |
| HST - 4 orbits | 14 | 30 |
| HST - 10 orbits | 8 | 18 |

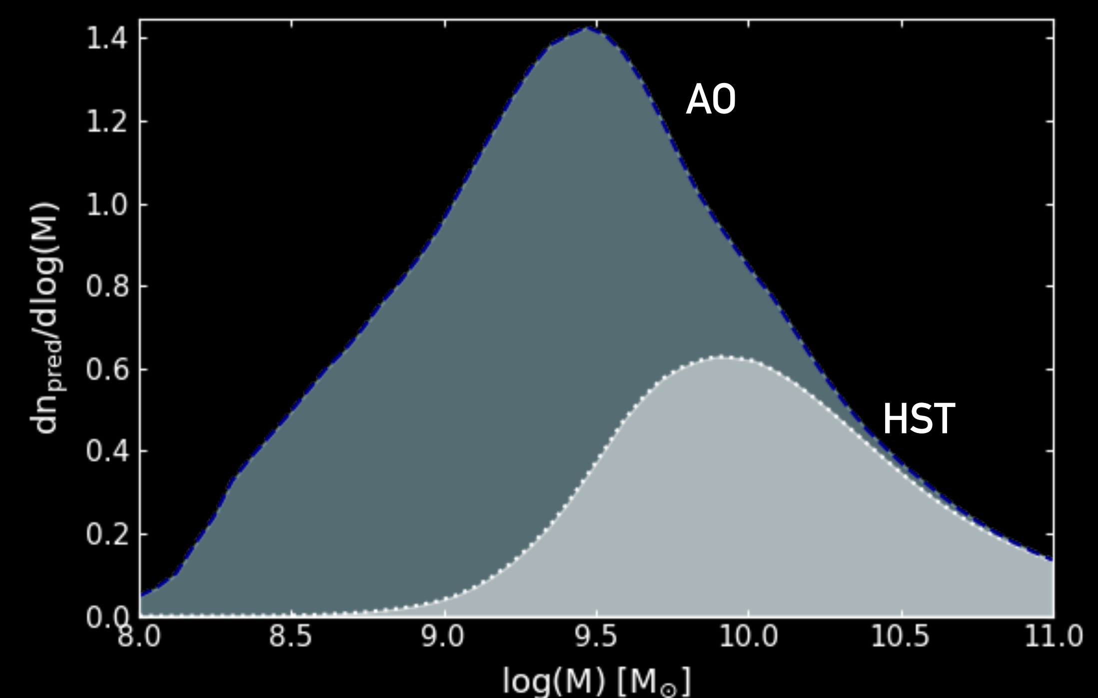
**QUESTION 1:**

how many lenses do we need to test CDM?

# CDM VS ALTERNATIVE MODELS

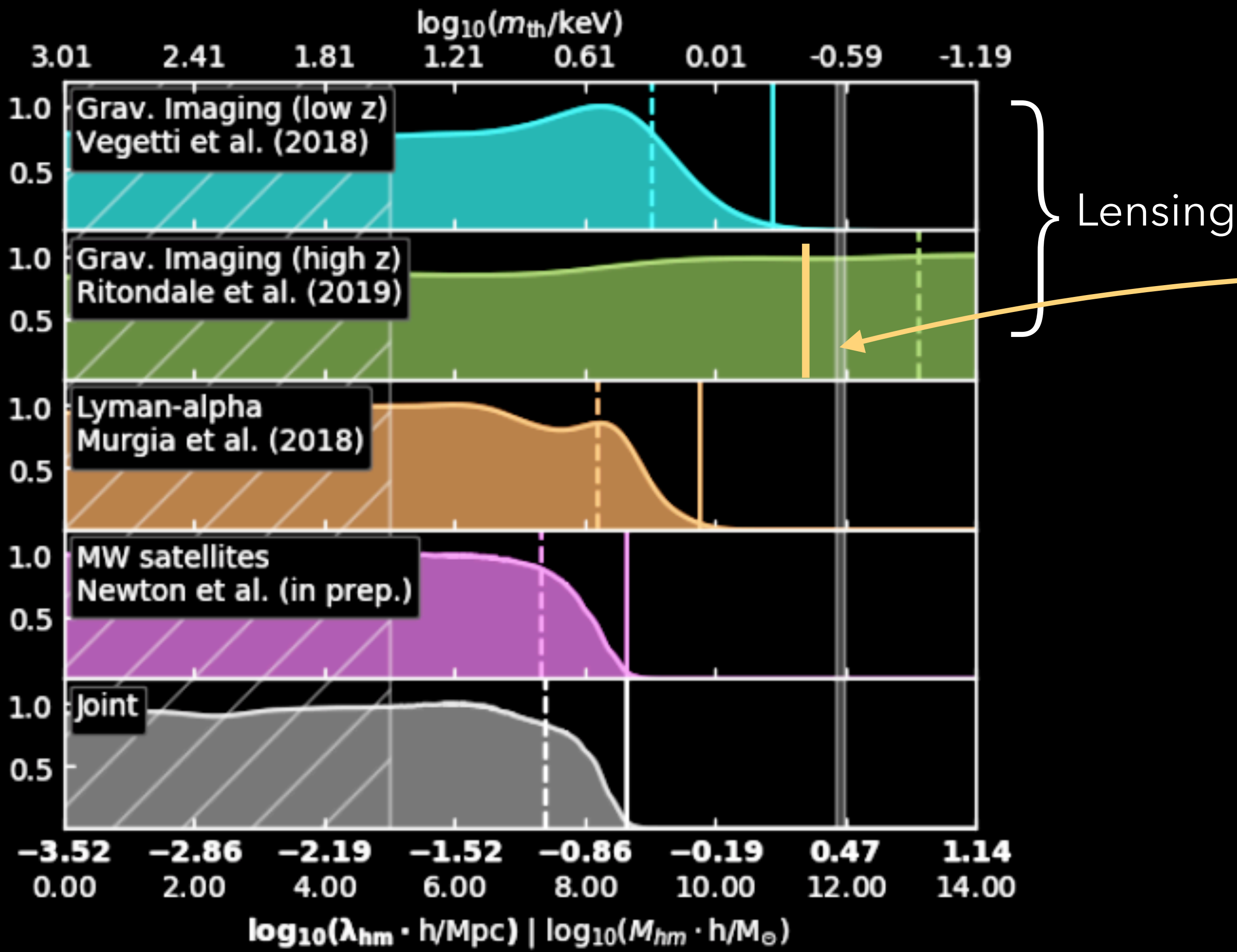


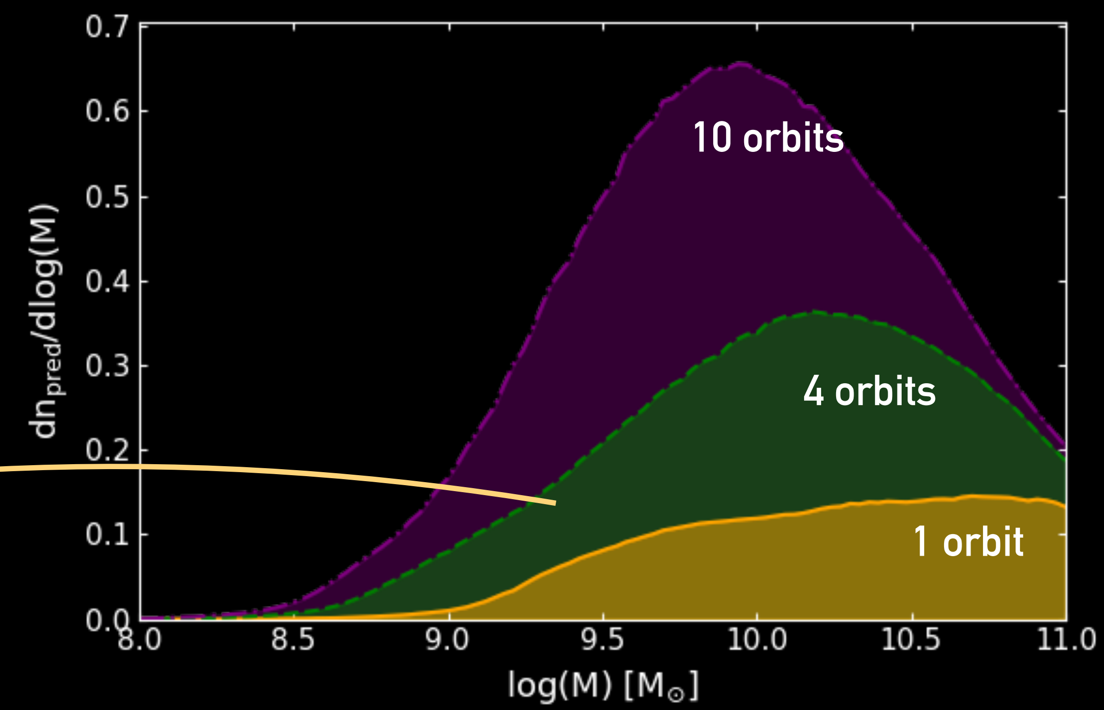



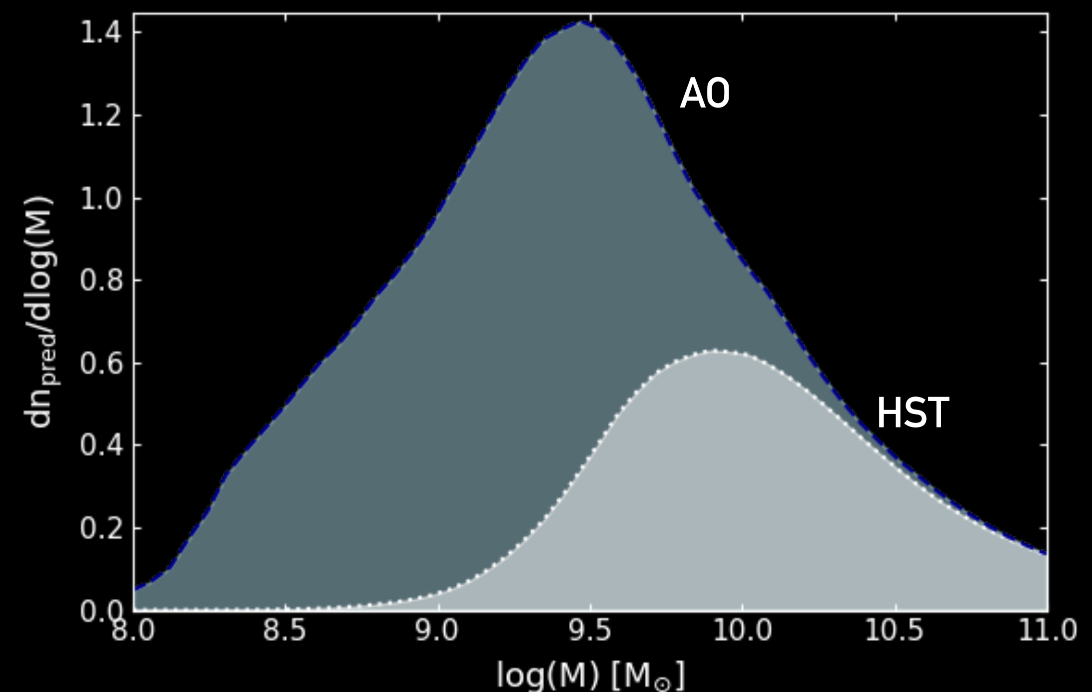



# CDM VS ALTERNATIVE MODELS

*(Enzi et al. 2021)*

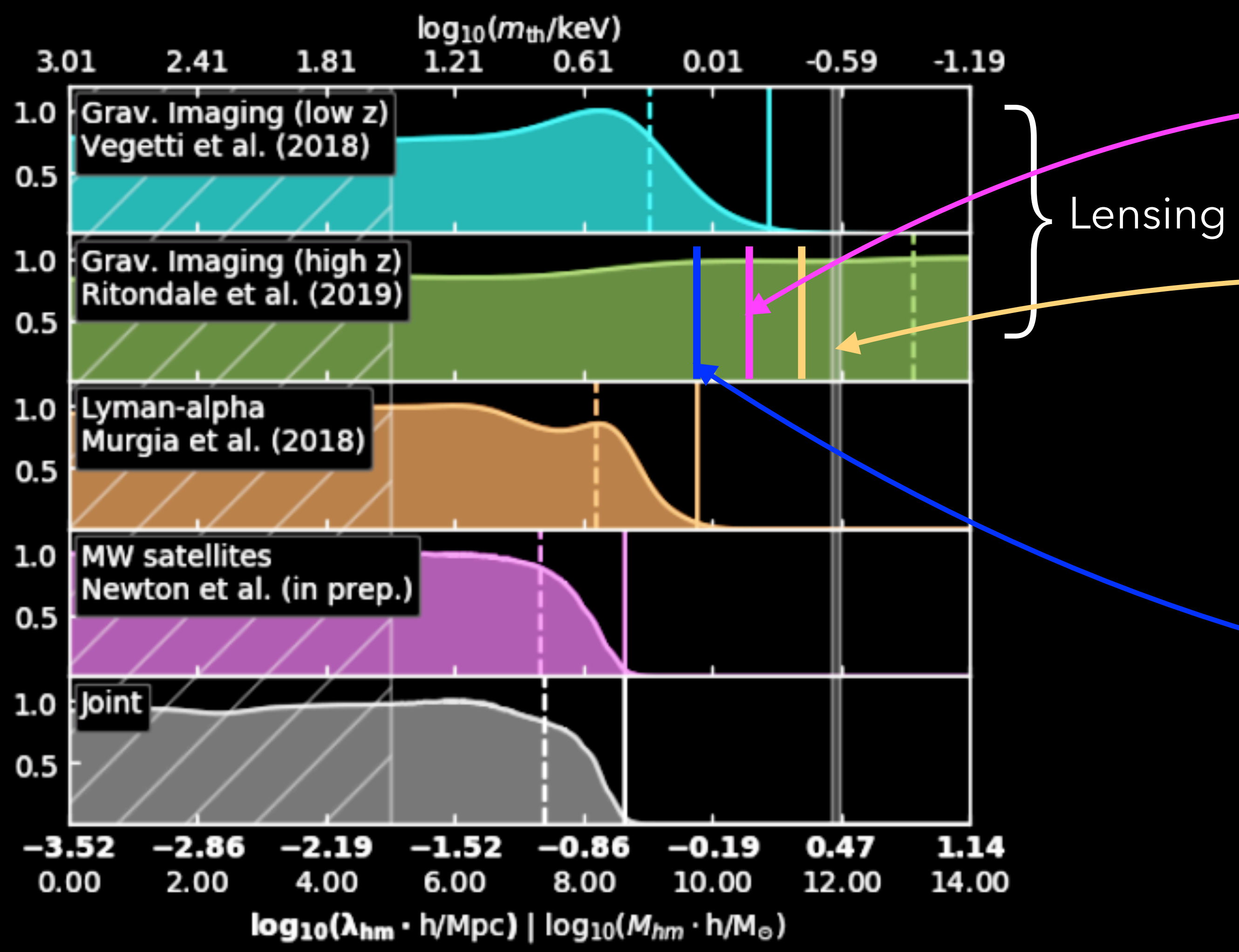


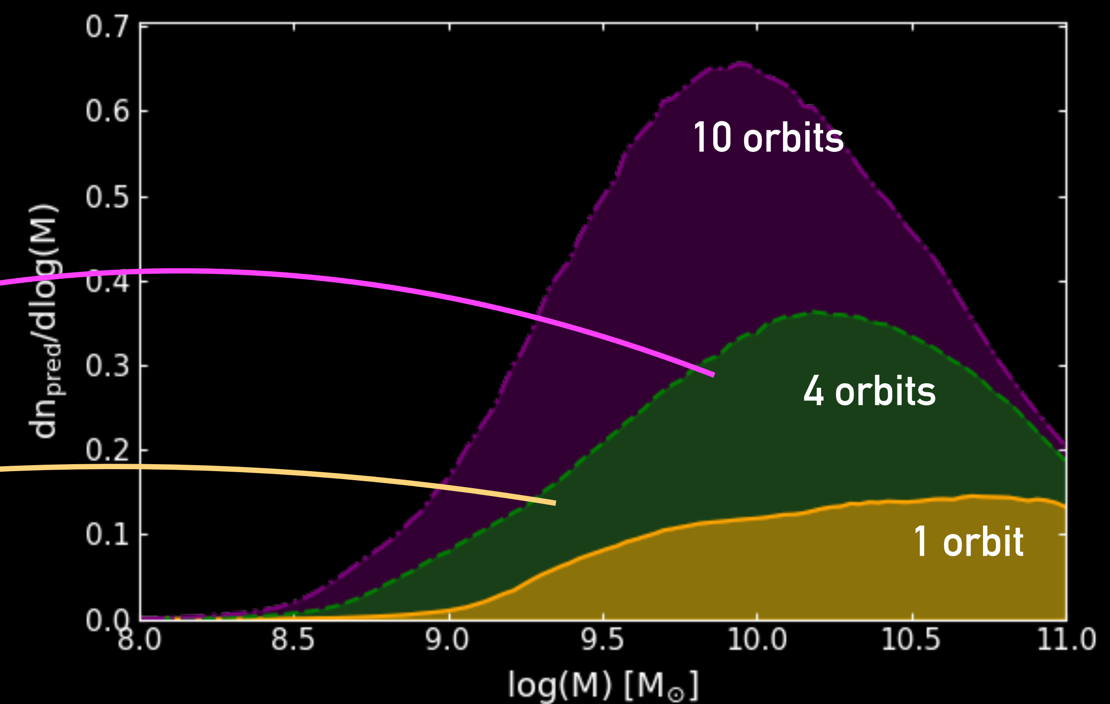



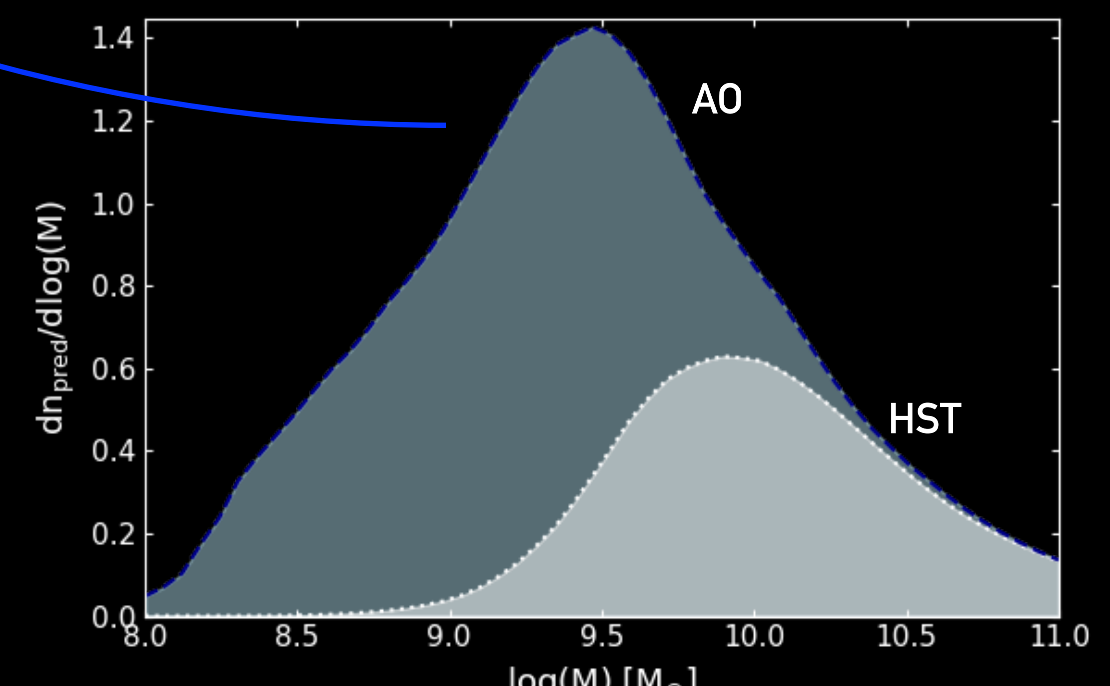



# CDM VS ALTERNATIVE MODELS

*(Enzi et al. 2021)*

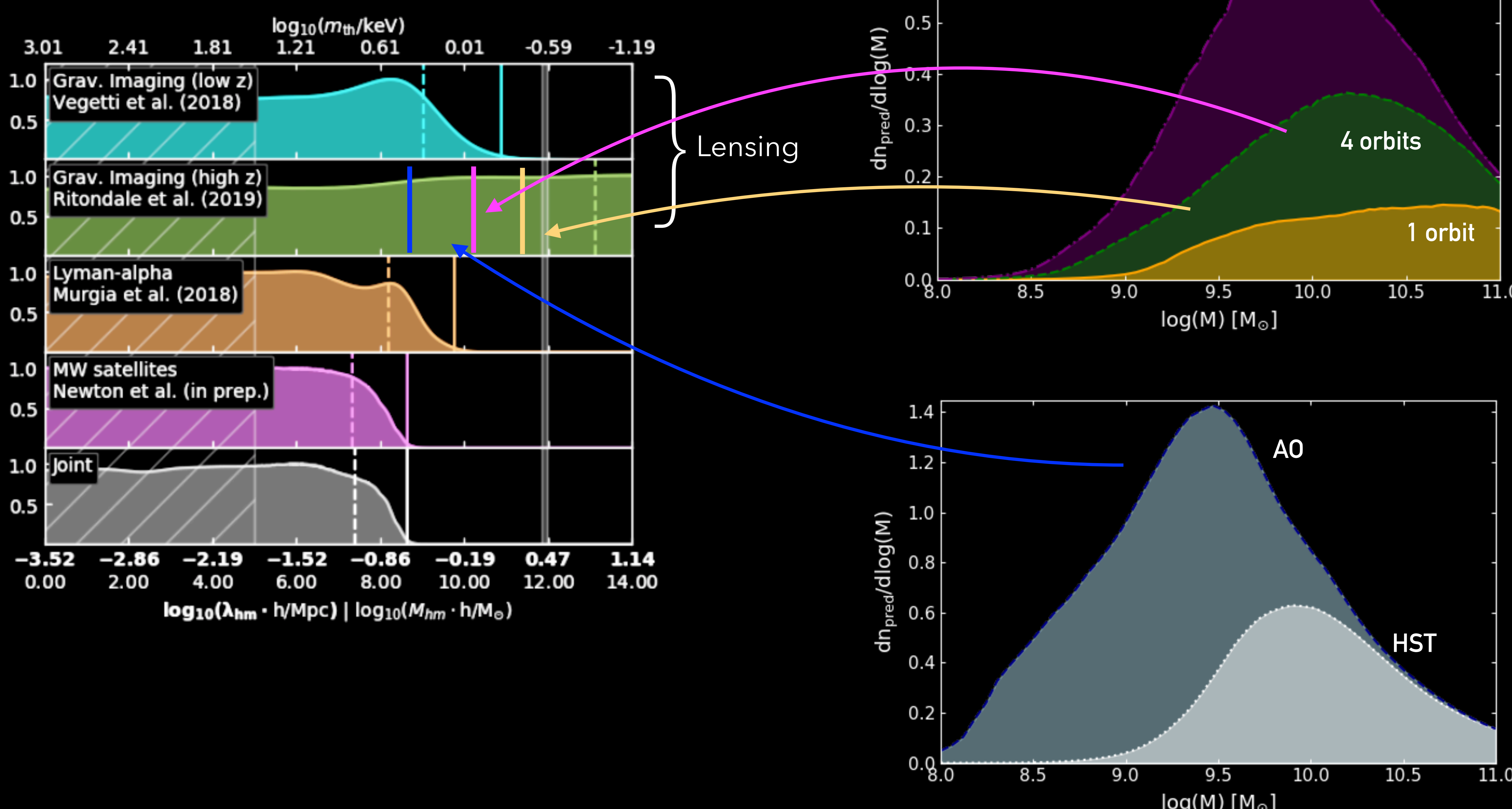


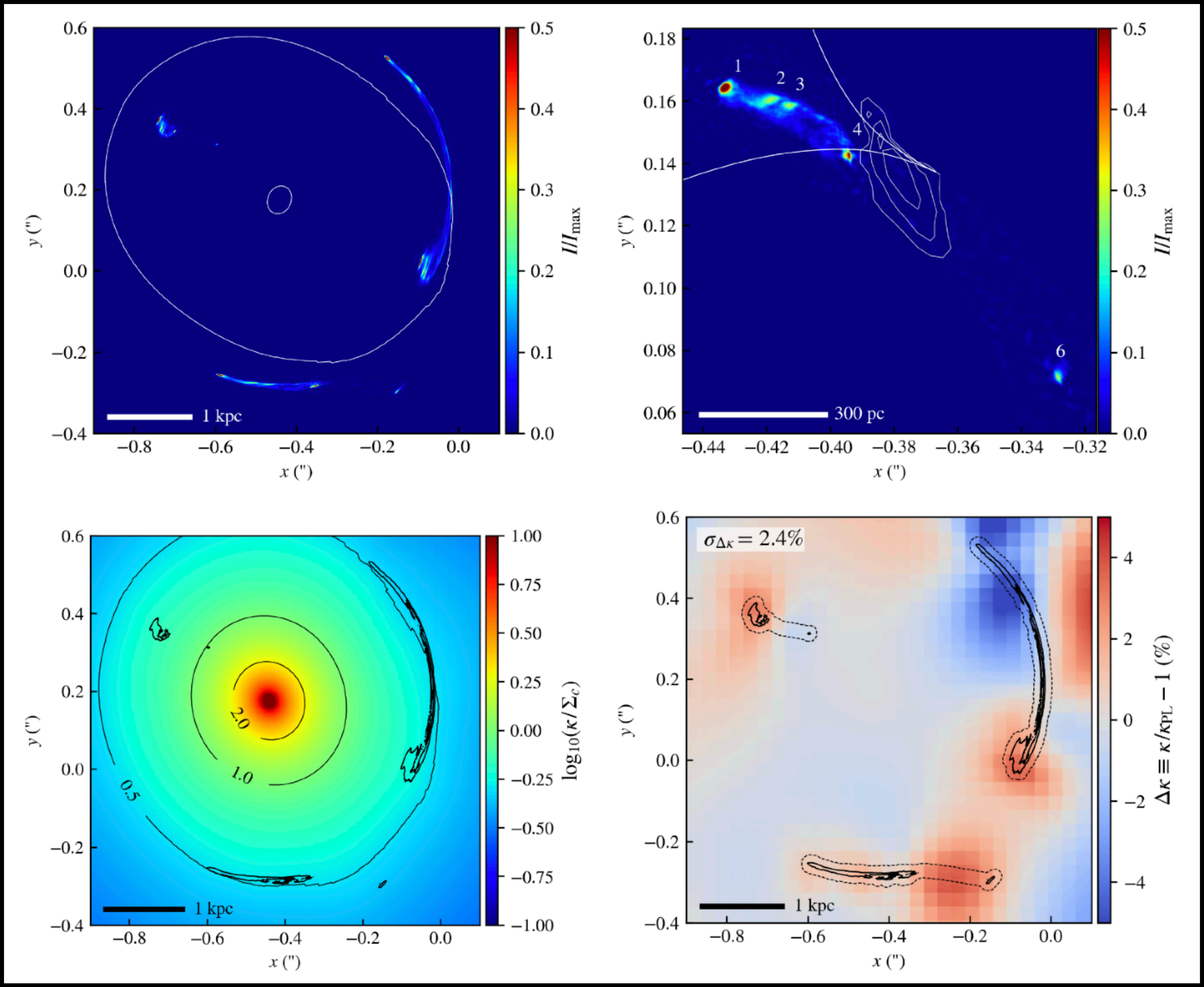
# CDM VS ALTERNATIVE MODELS

*(Enzi et al. 2021)*



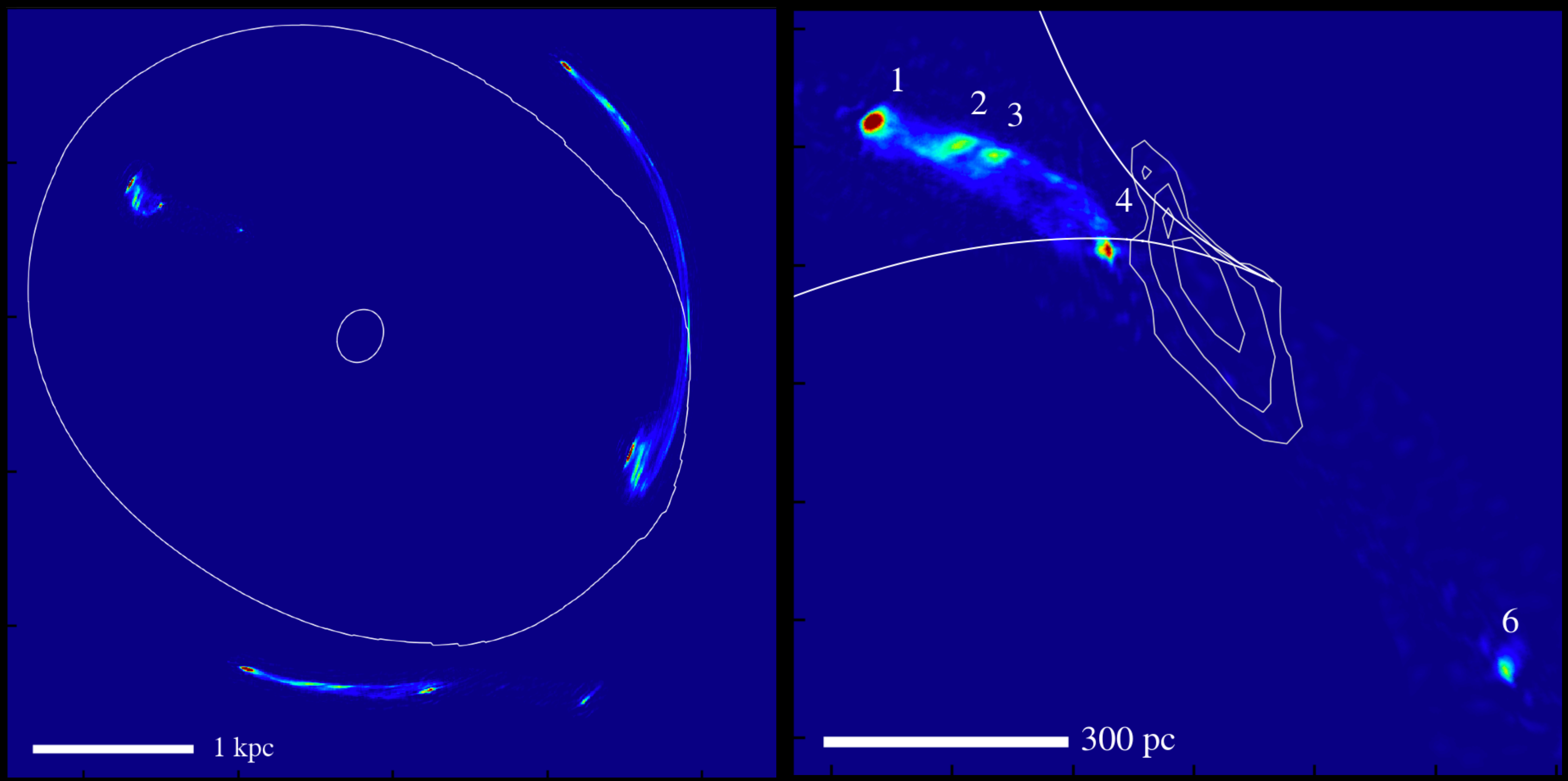
# RADIO INTERFEROMETRY

- highest angular resolution imaging of extended gravitational arcs from a gravitational lens
- we can measure astrometric anomalies of the order of ~ **1mas**
- price to pay: huge data and more complex analysis



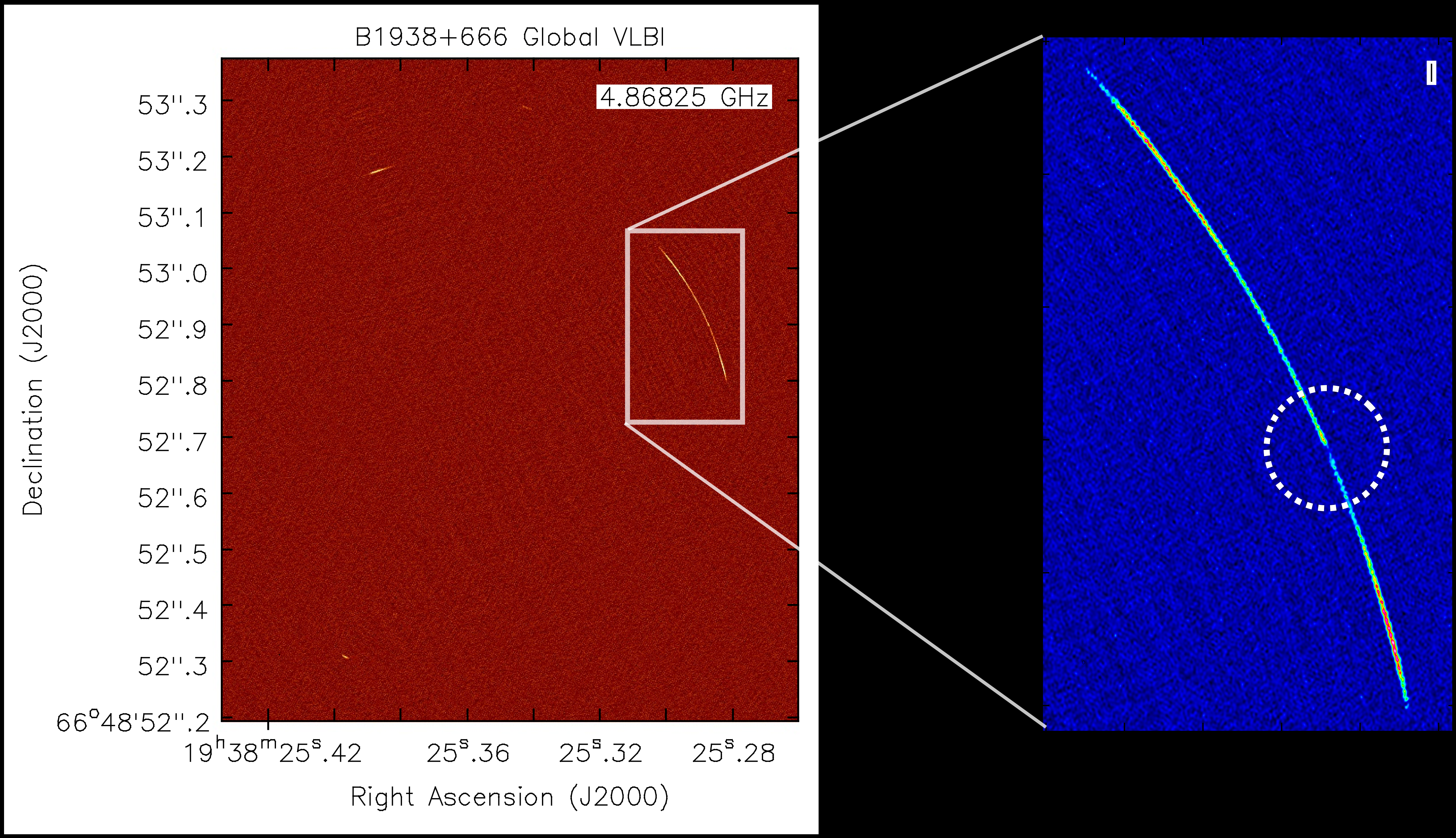

*Powell et al 2022. in prep*

# RADIO INTERFEROMETRY




*Powell et al 2022. in prep*

# RADIO INTERFEROMETRY



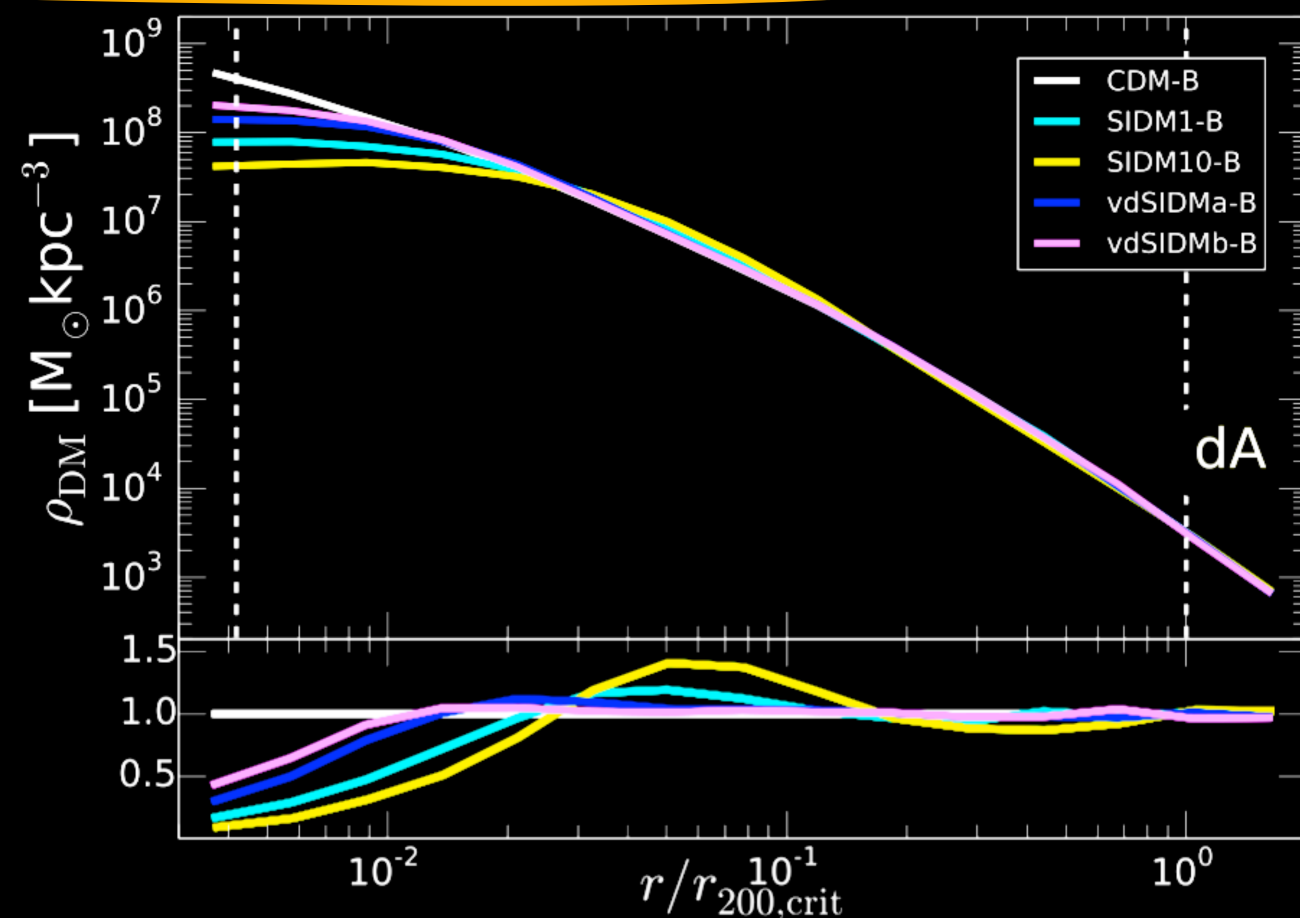

*Vegetti et al. in prep*

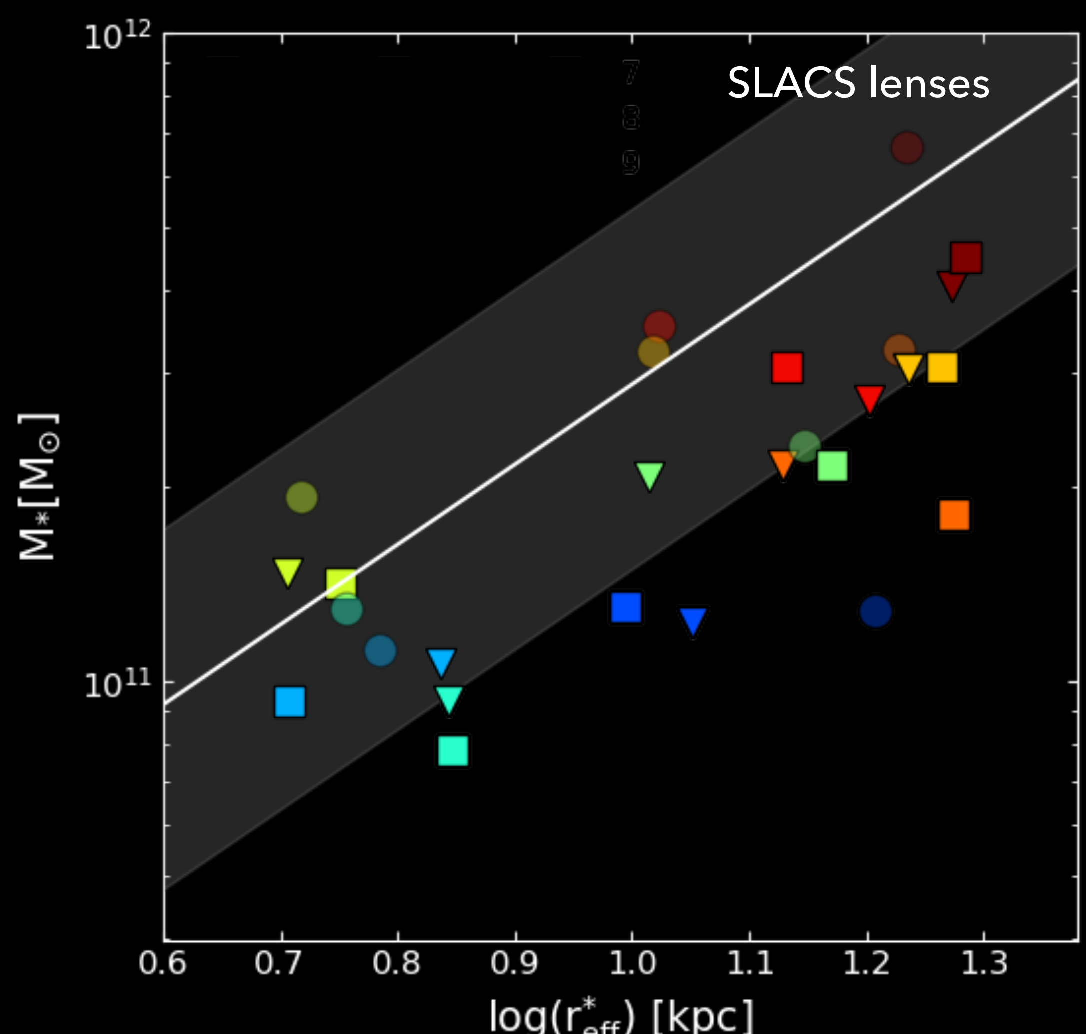
# SELF-INTERACTING DARK MATTER

*(Despali et al. 2019)*

- 10 ETG-analogues selected from the Illustris simulation
- resimulated with SIDM **+ baryons**

depending on the SIDM cross-section, DM particles scatter in high-density regions

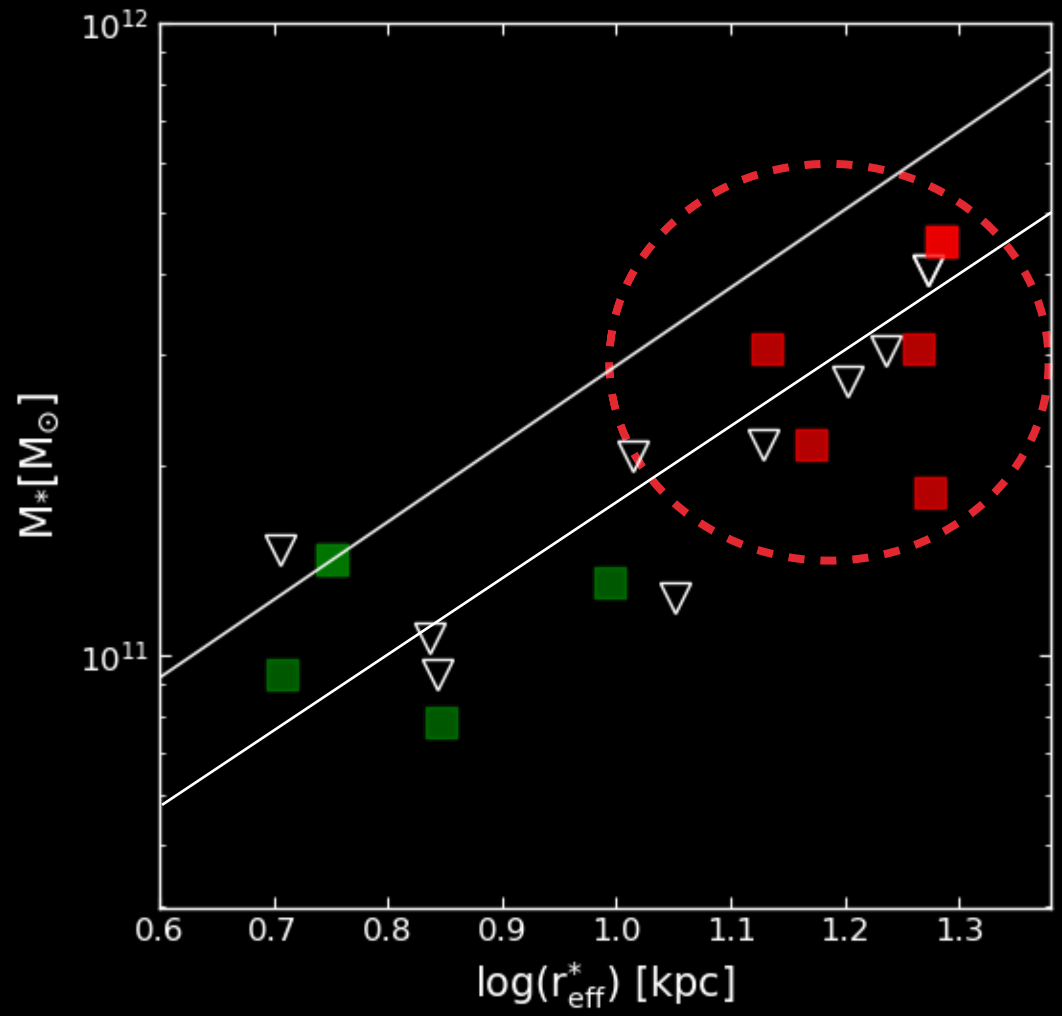


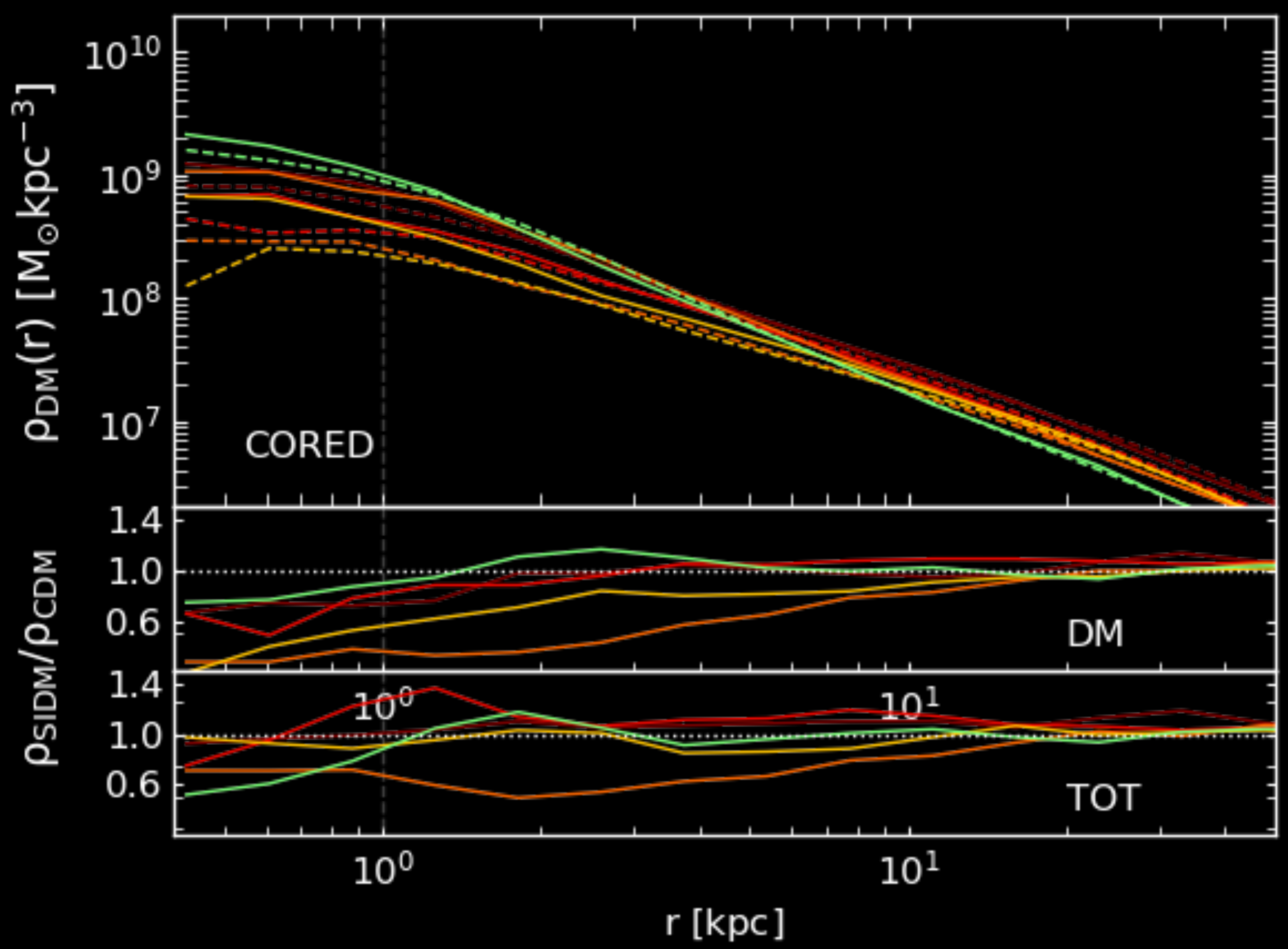




| Name | $\sigma_T^{\max}/m_\chi\,[\mathrm{cm}^2\,\mathrm{g}^{-1}]$ | $v_{\max}\,[\mathrm{km\,s}^{-1}]$ |
|---|---|---|
| CDM | – | – |
| SIDM1 | 1 | – |
| SIDM10 | 10 | – |
| vdSIDMa | 3.5 | 30 |
| vdSIDMb | 35 | 10 |

**Vogelsberger et al. 2014**

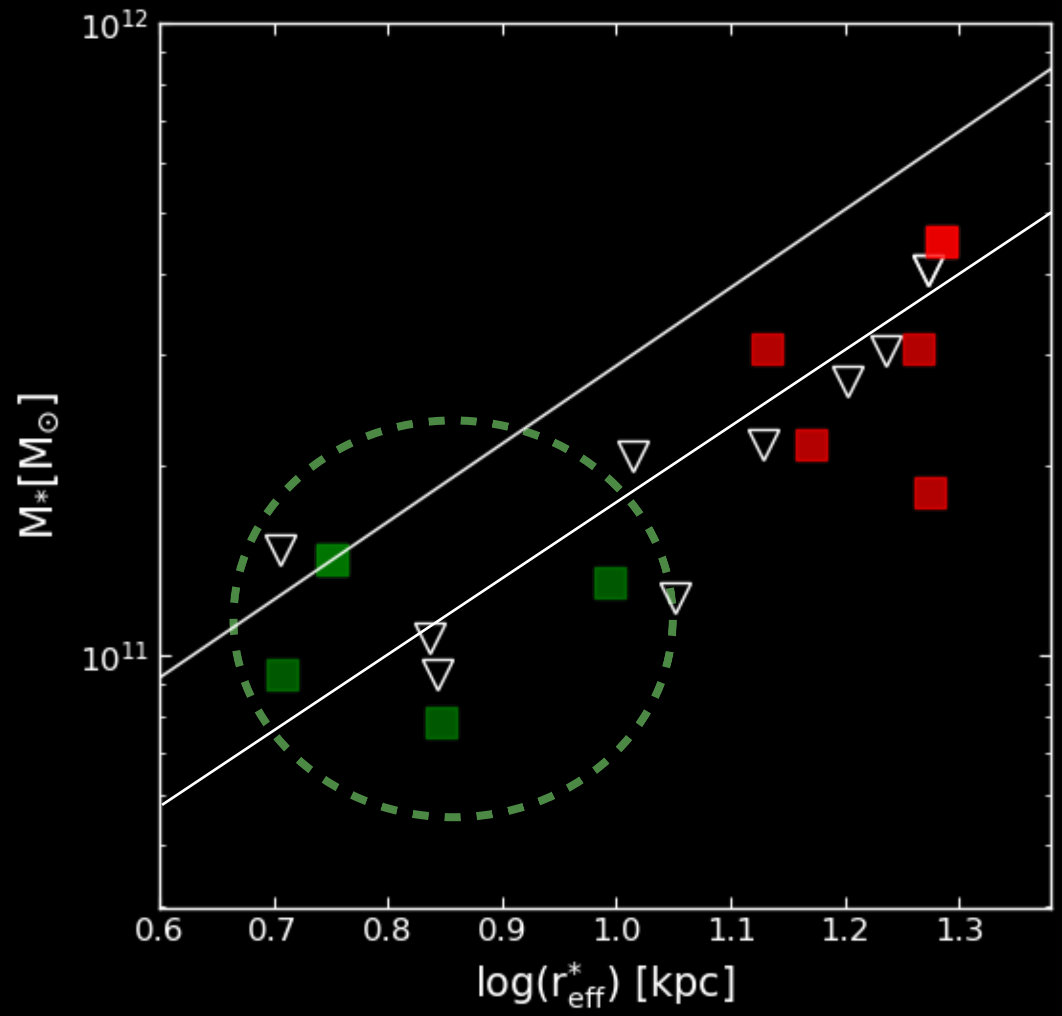
# SELF-INTERACTING DARK MATTER

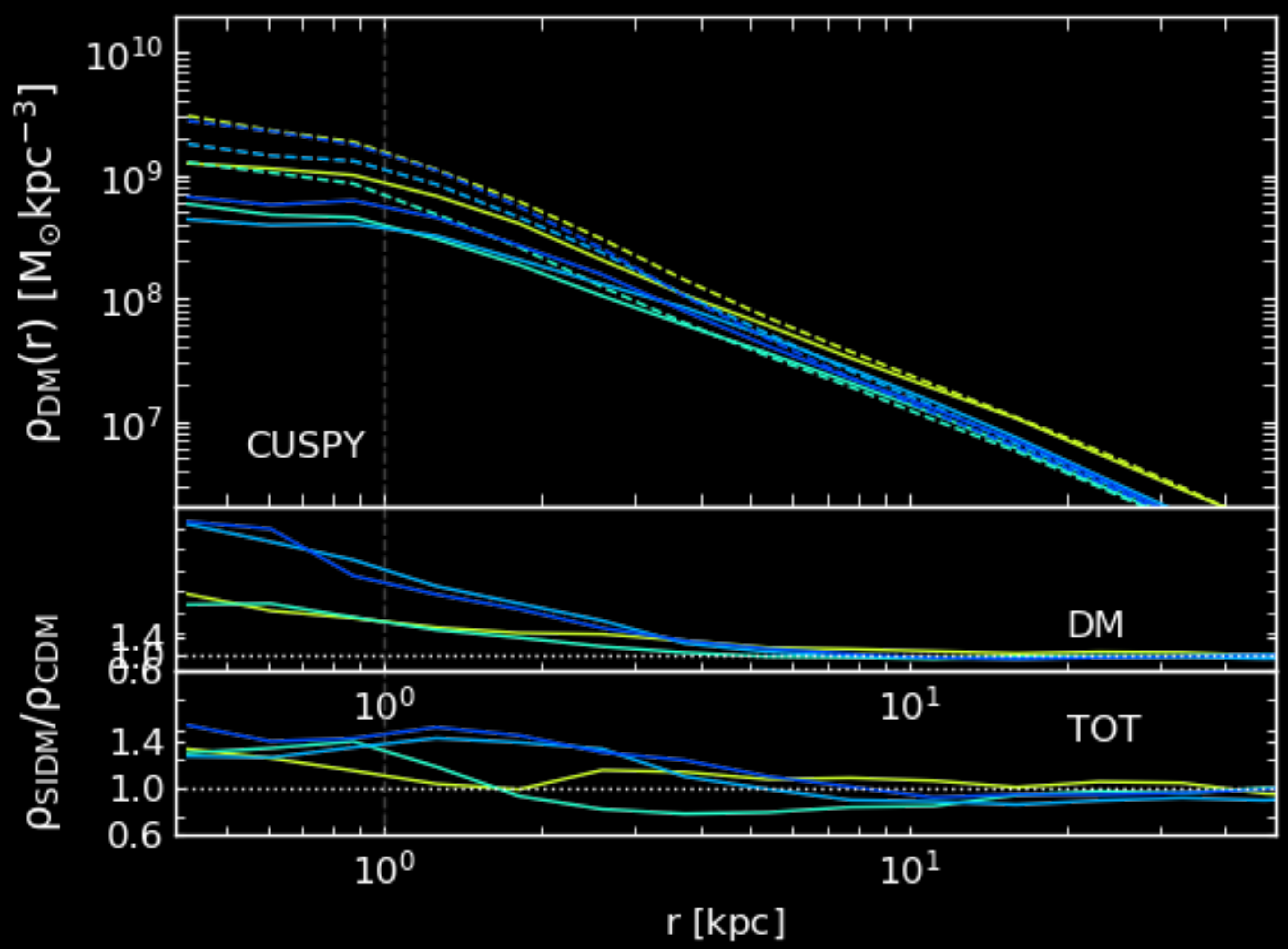



- the self-interaction influences the main halo profile
- **in the presence of baryons things are more complicated** *(Sameie+18, Robertson+18)*

# SELF-INTERACTING DARK MATTER

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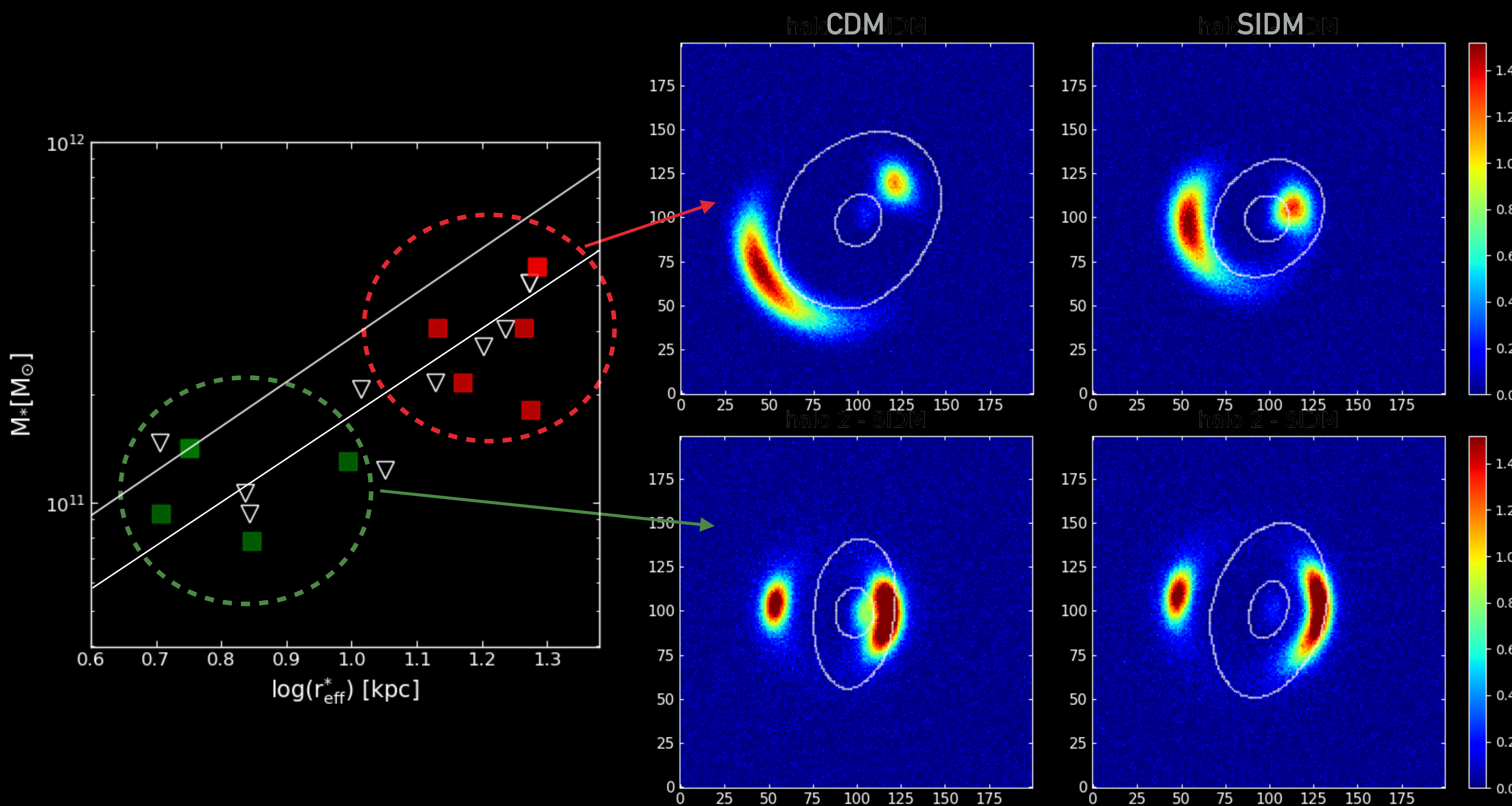
# SELF-INTERACTING DARK MATTER




- the self-interaction influences the main halo profile
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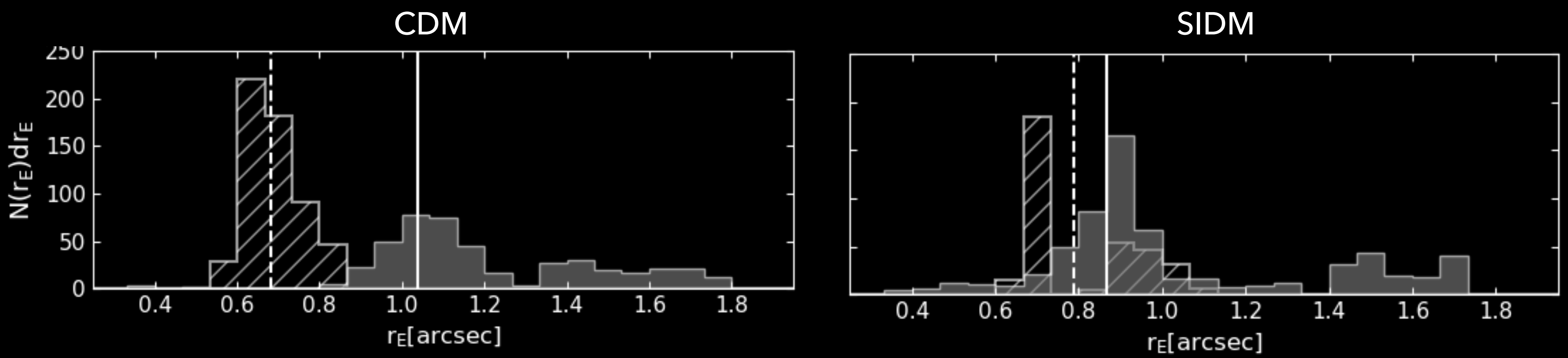
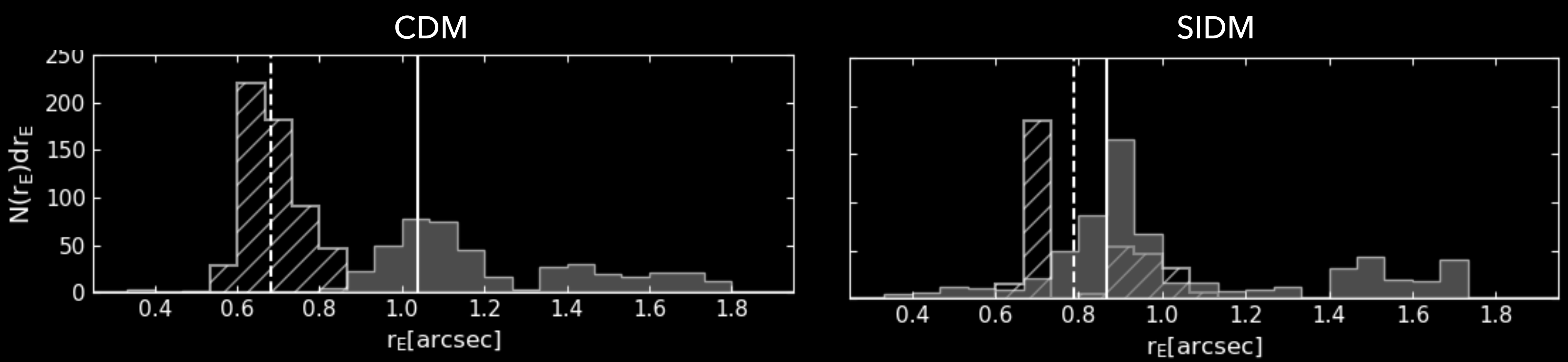
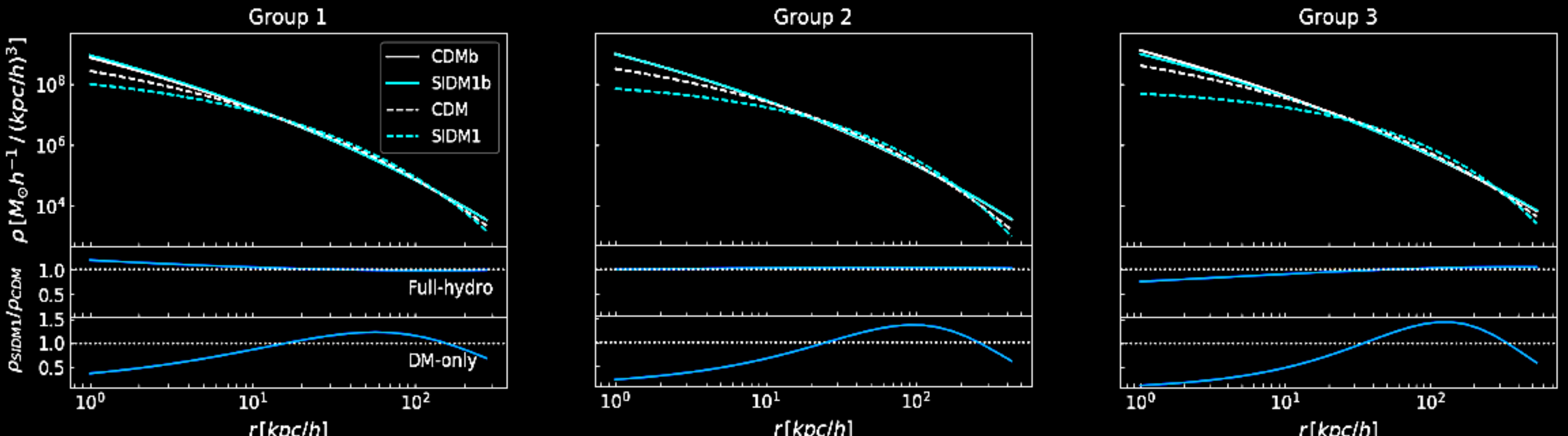
# SELF-INTERACTING DARK MATTER



# SELF-INTERACTING DARK MATTER



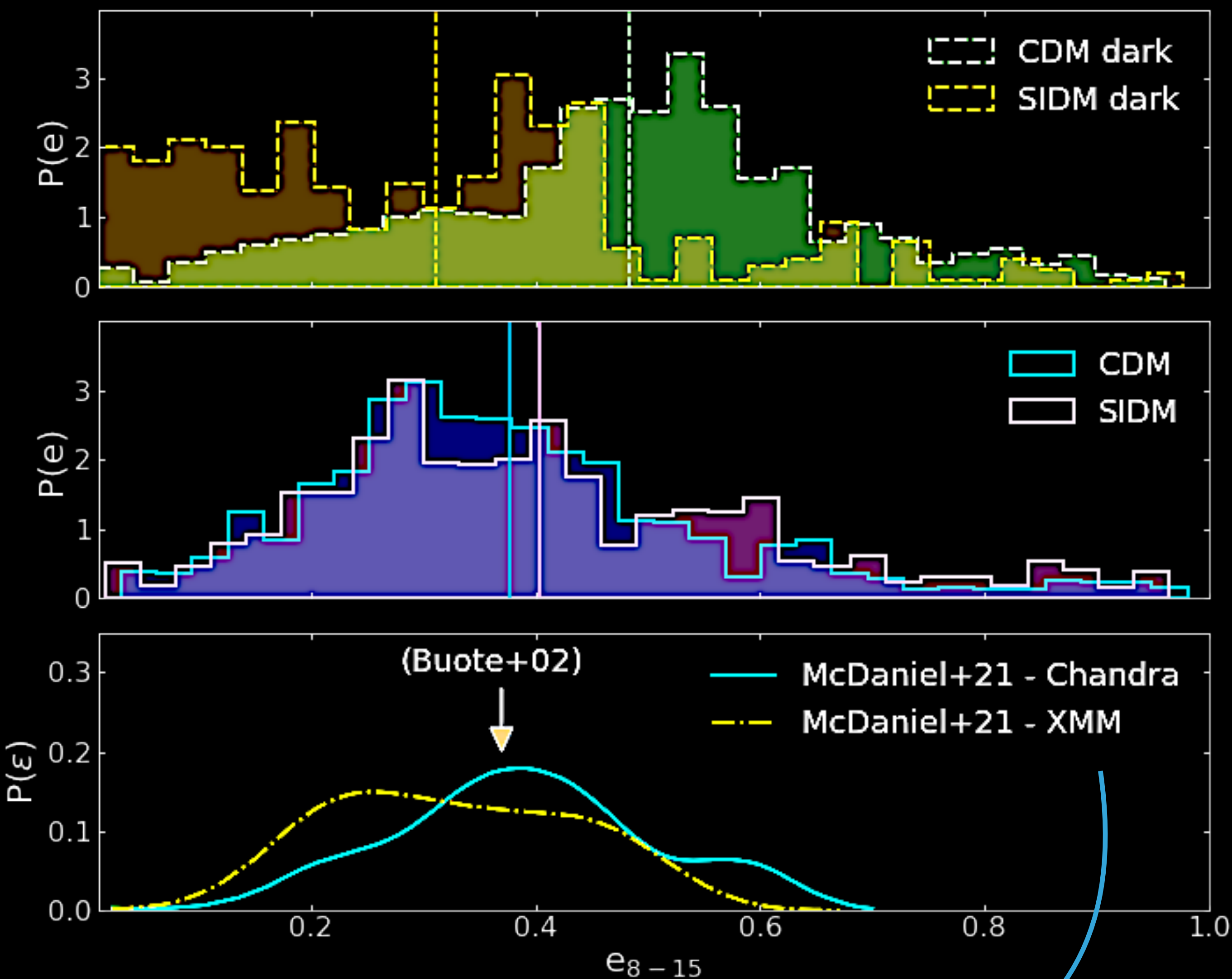

*Mastromarino et al. in prep* -> extension to a bigger box



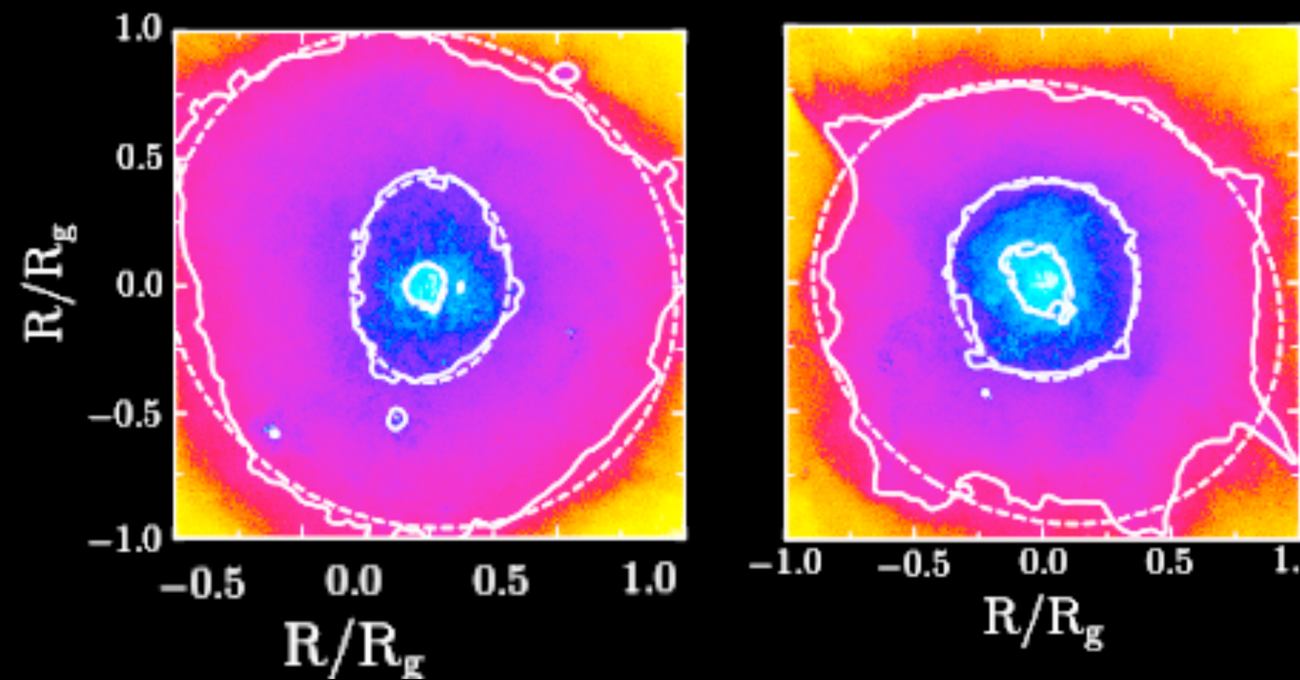
# SELF-INTERACTING DARK MATTER

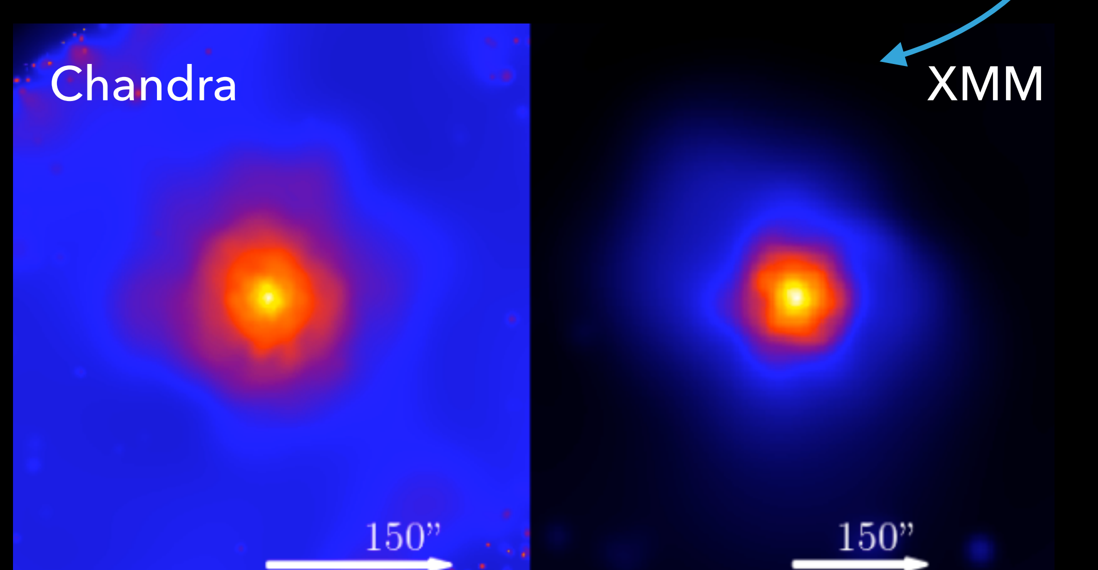
*Despali, Walls et al. in prep*

> SIDM also influences the inner halo shape and then the shape of the X-Ray central isophotes



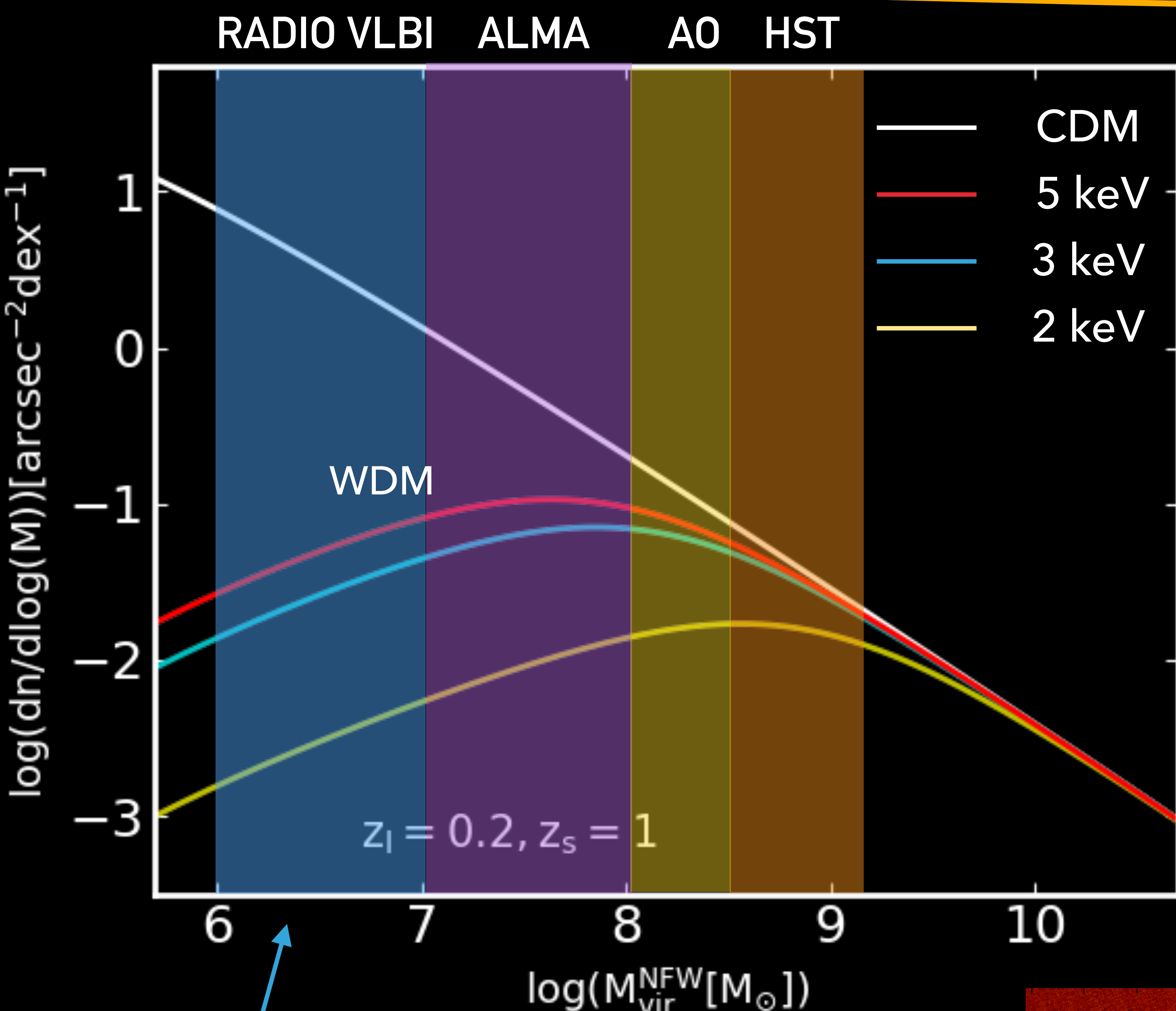

simulations

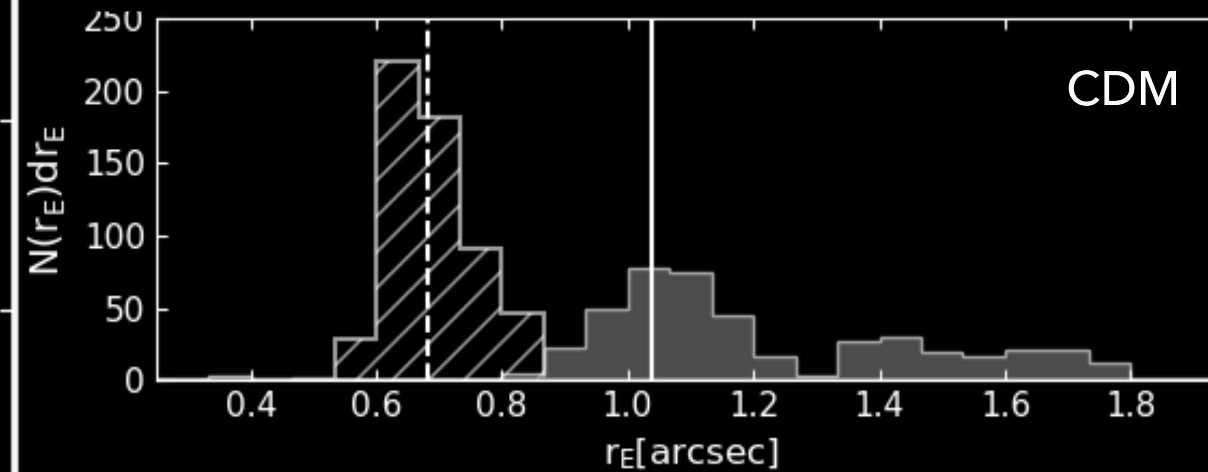


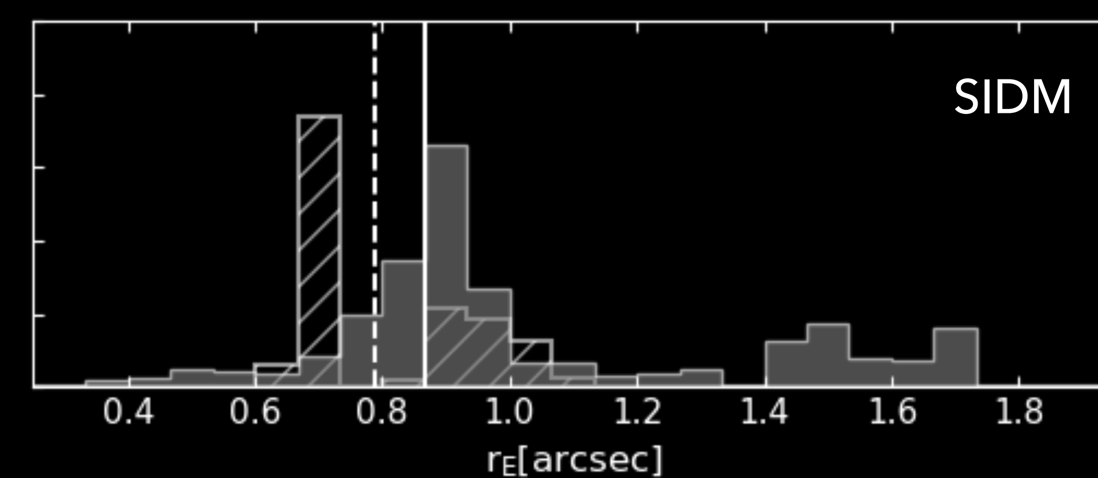



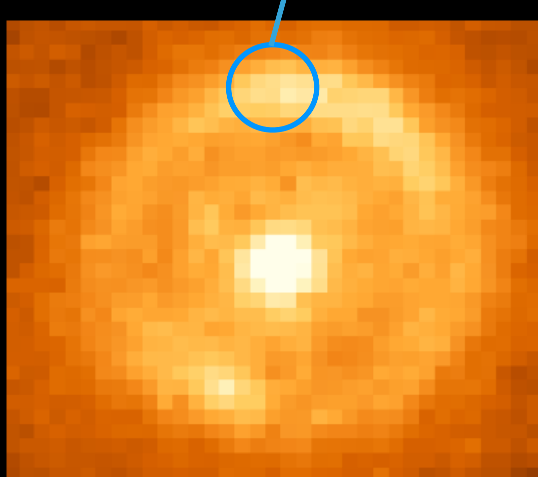

real data

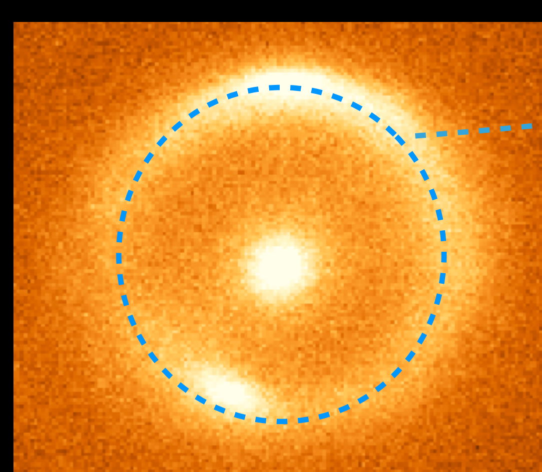
# SUMMARY

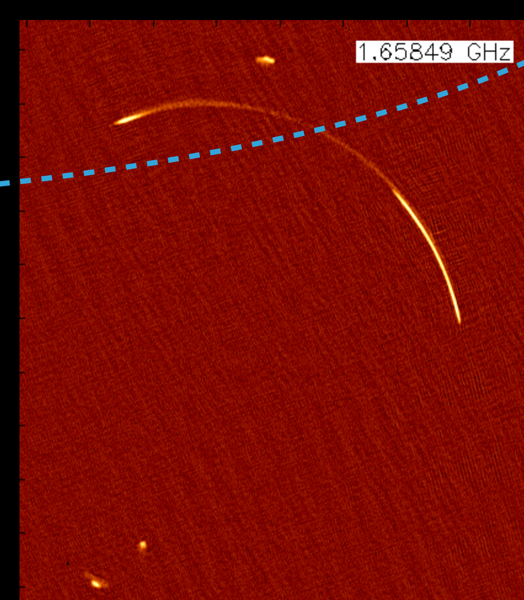

RADIO VLBI
ALMA
AO
HST
CDM
5 keV
3 keV
2 keV
WDM
$z_l = 0.2, z_s = 1$
$\log(dn/d\log(M))[\mathrm{arcsec}^{-2}\mathrm{dex}^{-1}]$
$\log(M_{vir}^{NFW}[M_\odot])$
1
0
−1
−2
−3
6
7
8
9
10


CDM
$N(r_E)dr_E$
250
200
150
100
50
0
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
$r_E$[arcsec]


SIDM
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
$r_E$[arcsec]






1.65849 GHz