Gravitational Lensing in Warm Dark Matter and Evolving Dark Energy Cosmologies

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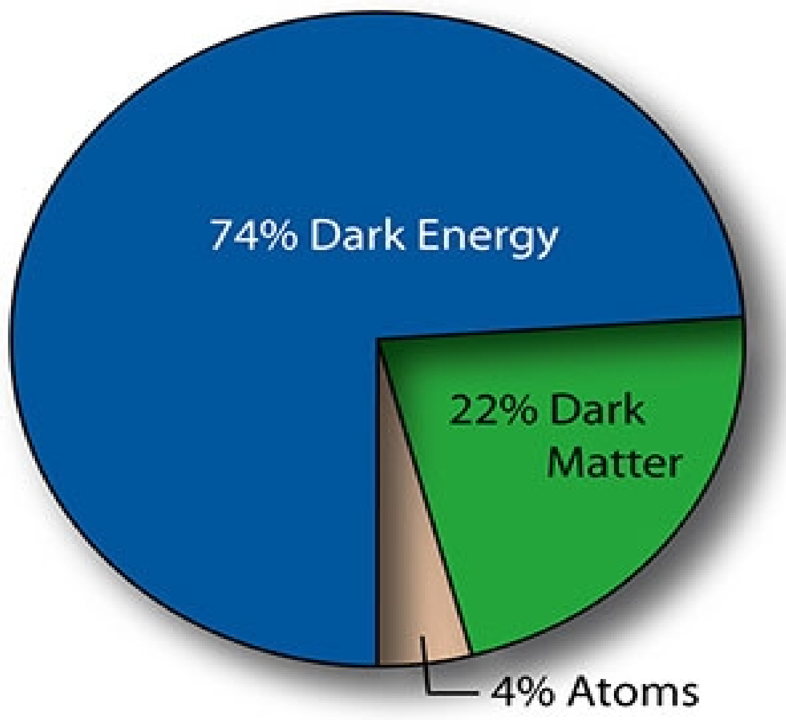
Components of the Universe



DM: does not emit or absorb light; it has only been detected indirectly by its gravity

DE: 'anti-gravity'. responsible for the present-day acceleration of the universal expansion.

ΛCDM cosmological model

DE	+	DM
cosmological constant		Cold dark matter
Λ Simplest candidate of DE		Non-Baryonic
Energy density remains constant		Ex: WIMPs
$\omega_{DE} = -1$		

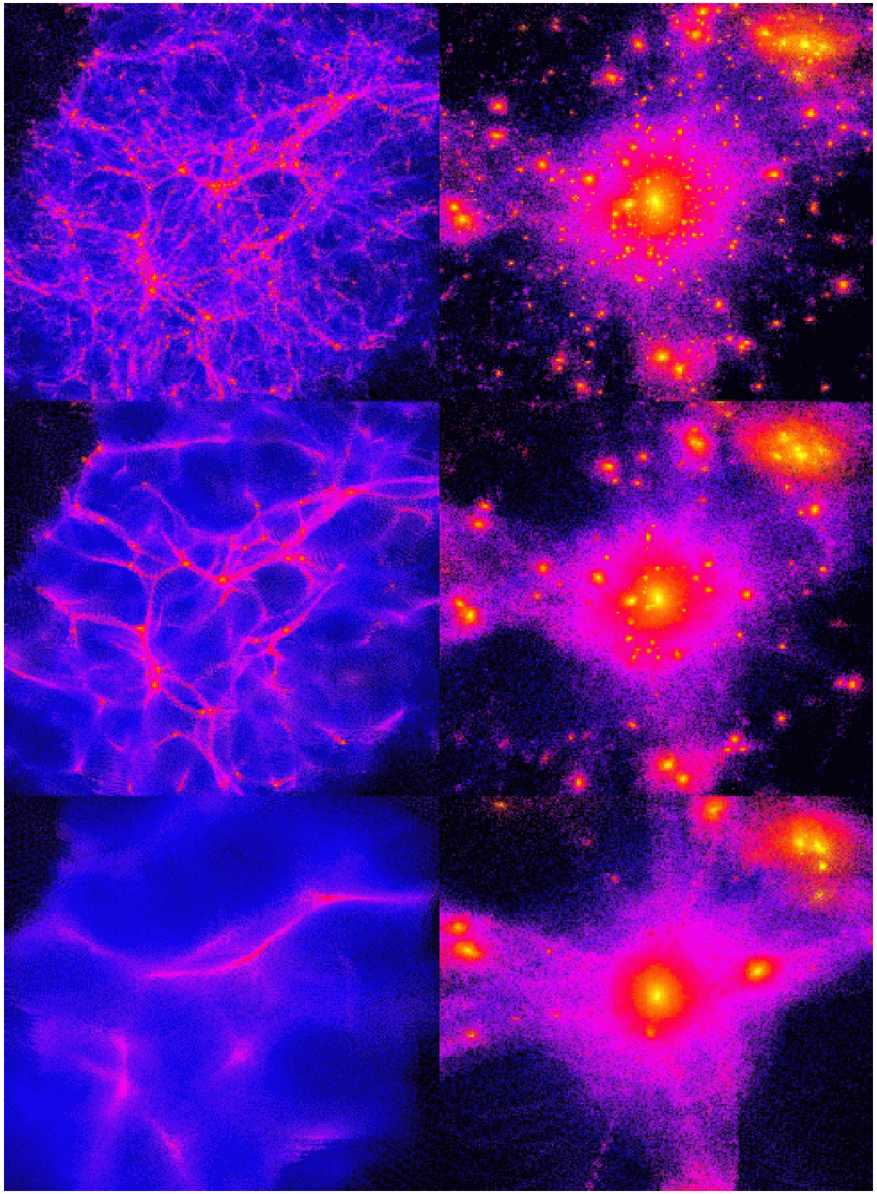
DOES NOT AGREE WITH OBSERVATIONS ON SMALL-SCALE

Is dark matter hot, cold or warm?

ΛCDM

ΛWDM

ΛHDM



agrees better with observations on small scales

free streaming scale is found to be too large and hence galaxies would not form (White et al. 1983)

Dark energy cosmologies

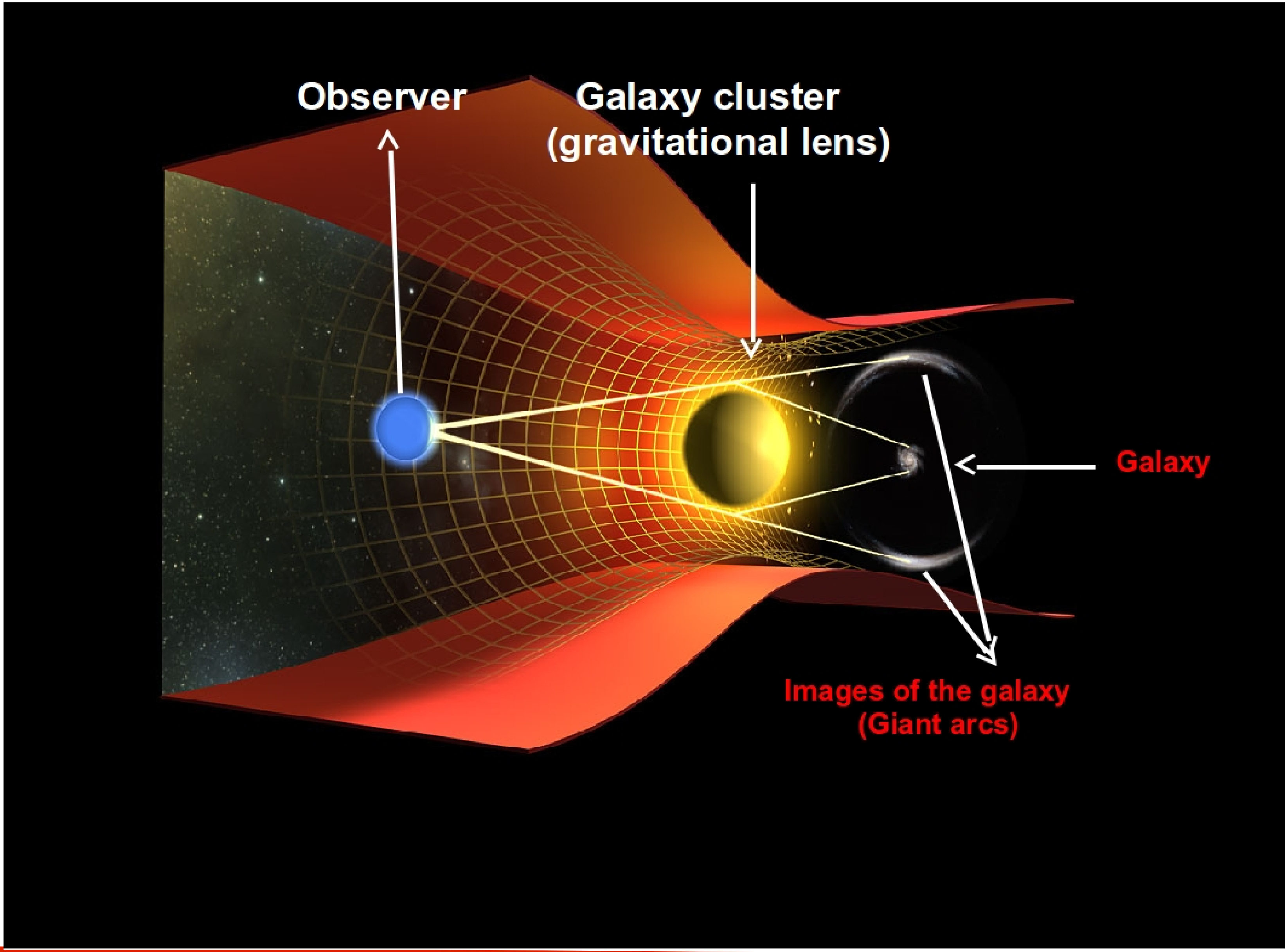
$$G^{\mu}_{\nu} = 8\pi G T^{\mu}_{\nu}$$

Quintessence, K-essence, Perfect fluids

ω_{DE} varies in time

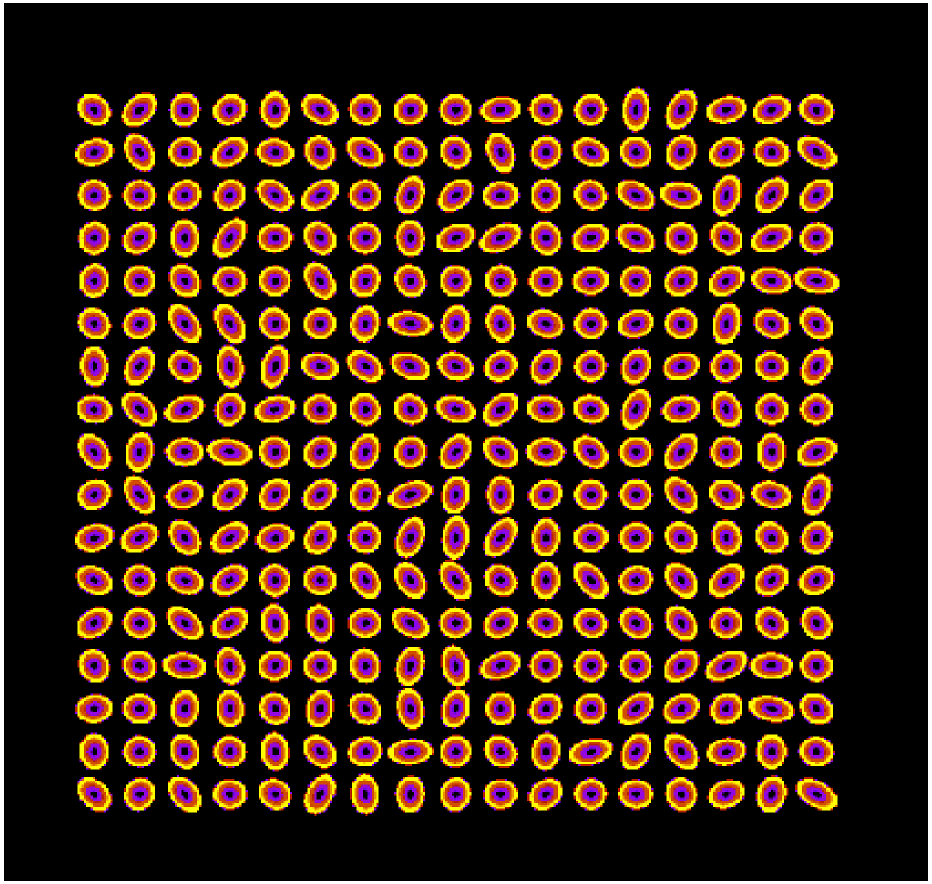
This work: Gravitational lensing signatures in ΛWDM and coupled and uncoupled dark energy cosmologies.

GRAVITATIONAL LENSING

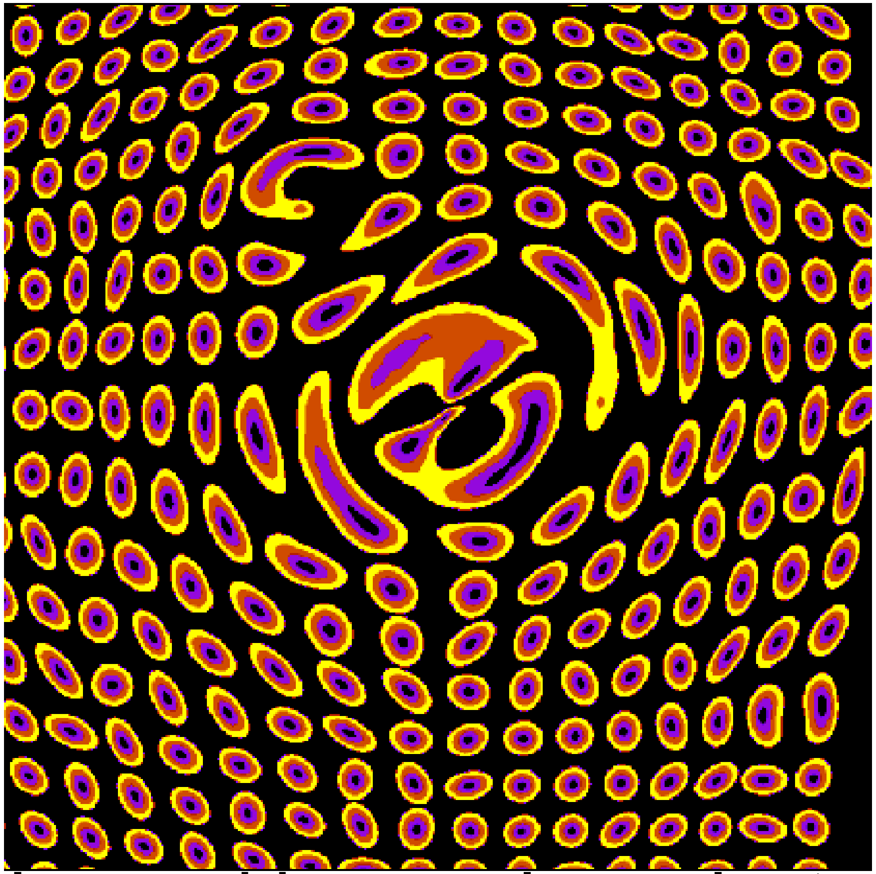


Types of Gravitational lensing

Strong Lensing: strong distortion, magnification, multiple images (giant arcs).
Weak Lensing: slight distortion, magnification. K, γ << 1
Microlensing: Lensing by point masses (stellar objects).



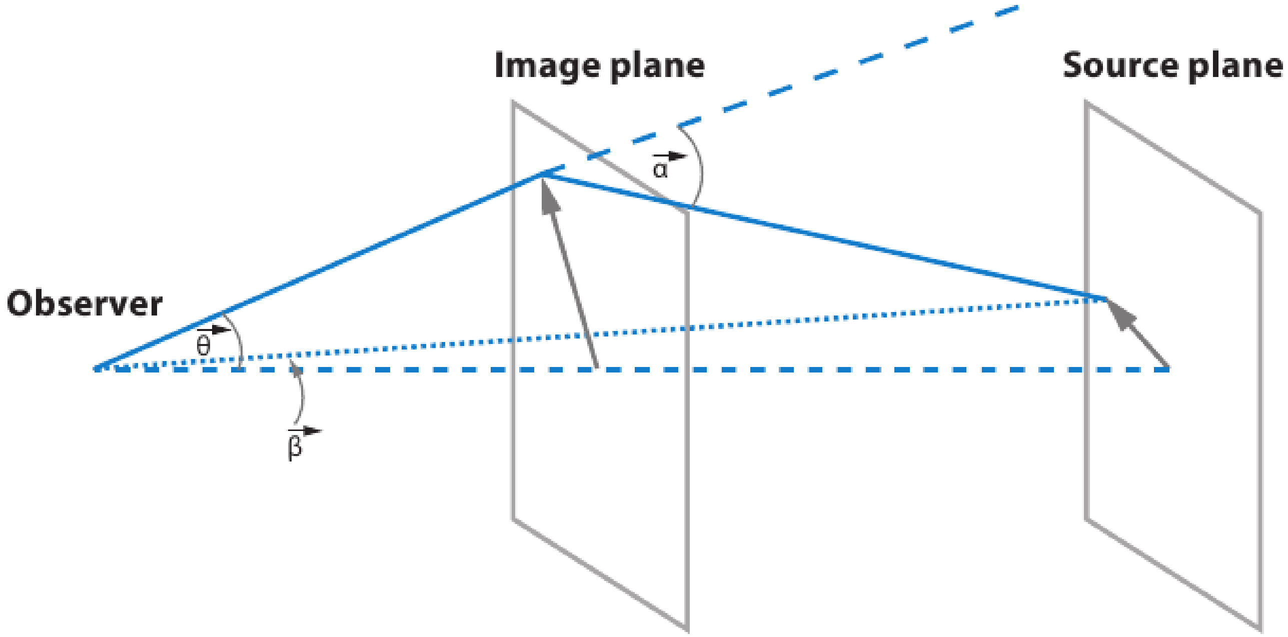
No Lens



Lensed by a galaxy cluster

mov

Geometrical configuration of gravitational lensing



Lens equation

$$\beta = \theta - \alpha(\theta)$$

β = angular position on the source plane

θ = angular position on the lens plane

α = deflection angle

$$\boldsymbol{\alpha}(\boldsymbol{\theta}) = \frac{1}{\pi}\int \kappa(\boldsymbol{\theta}')\frac{\boldsymbol{\theta} - \theta'}{|\boldsymbol{\theta} - \theta'|^2}\,\mathrm{d}^2\theta'$$

$$\kappa = \frac{\Sigma}{\Sigma_{\rm crit}};$$

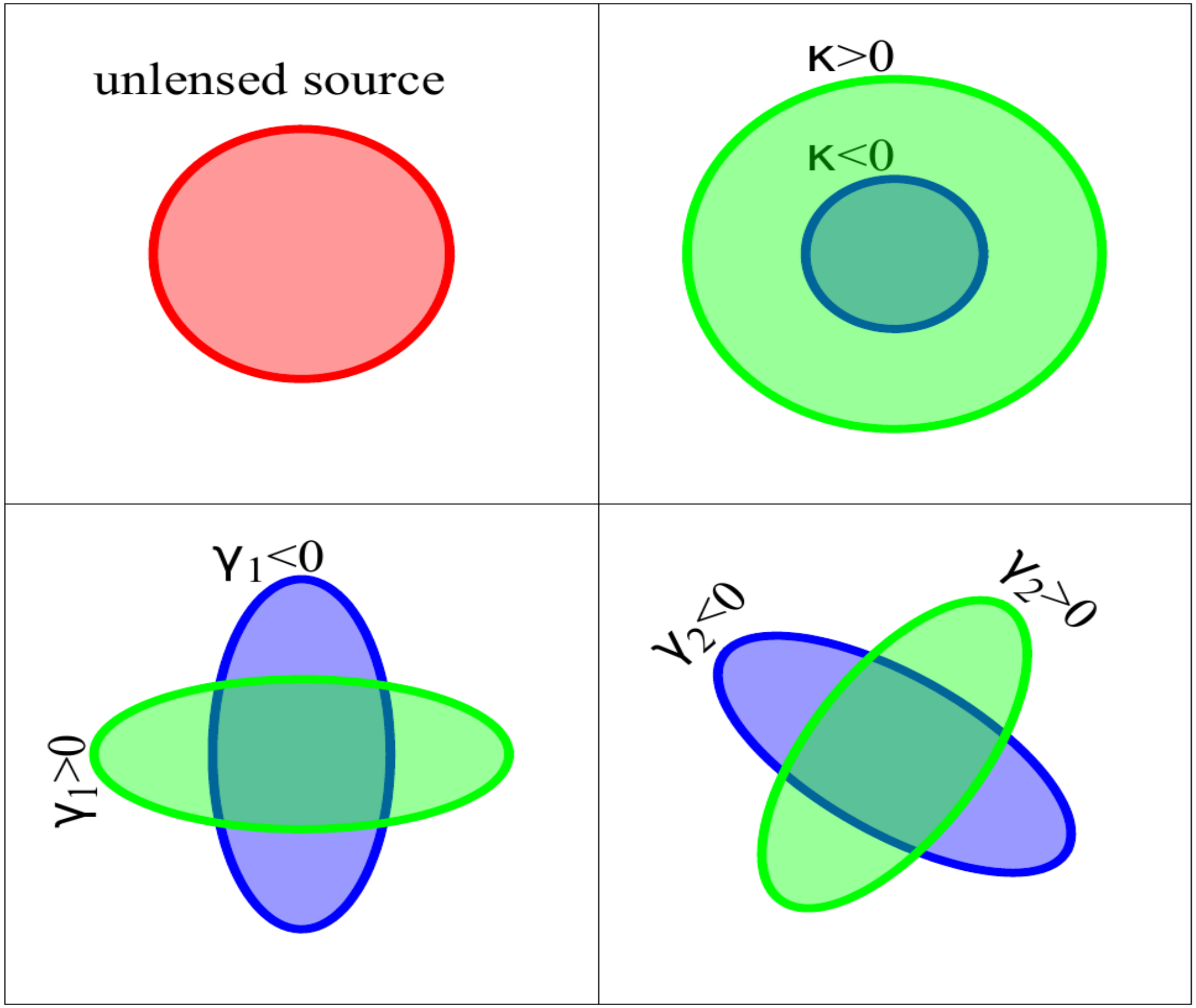
$$\Sigma_{\rm crit} = \frac{c^2}{4\pi G}\frac{D_{\rm S}}{D_{\rm L}D_{\rm LS}}$$

CONVERGENCE AND SHEAR

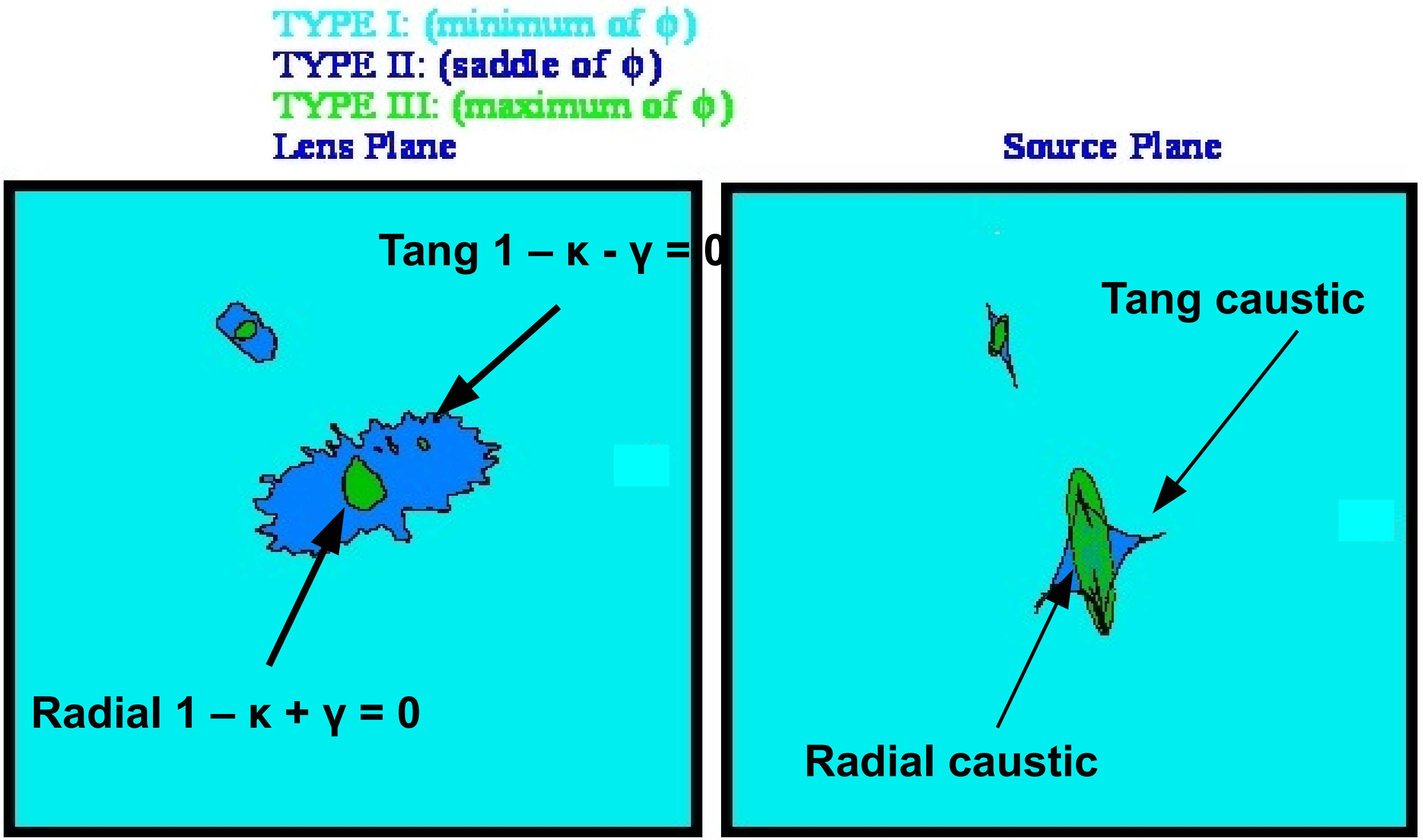
$$\mathbf{A} = \frac{\partial \beta}{\partial \theta} = \delta_{ij} - \frac{\partial^2 \psi}{\partial \theta_i \partial \theta_j} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

Magnification tensor

κ – convergence
γ – shear
ψ – lens potential



CRITICAL LINES AND CAUSTICS



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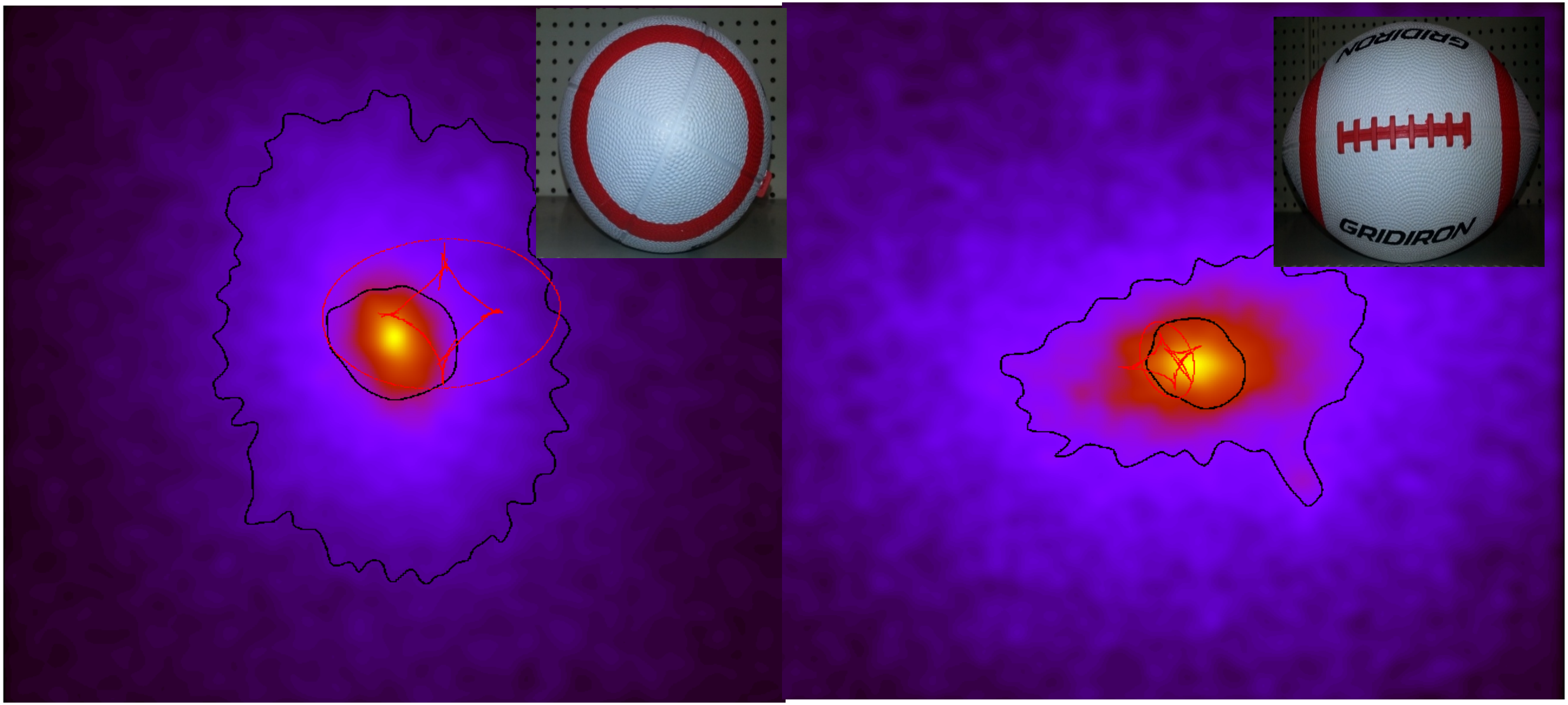
Gravitational Lensing: WDM vs CDM

Triaxial shape
And substructures



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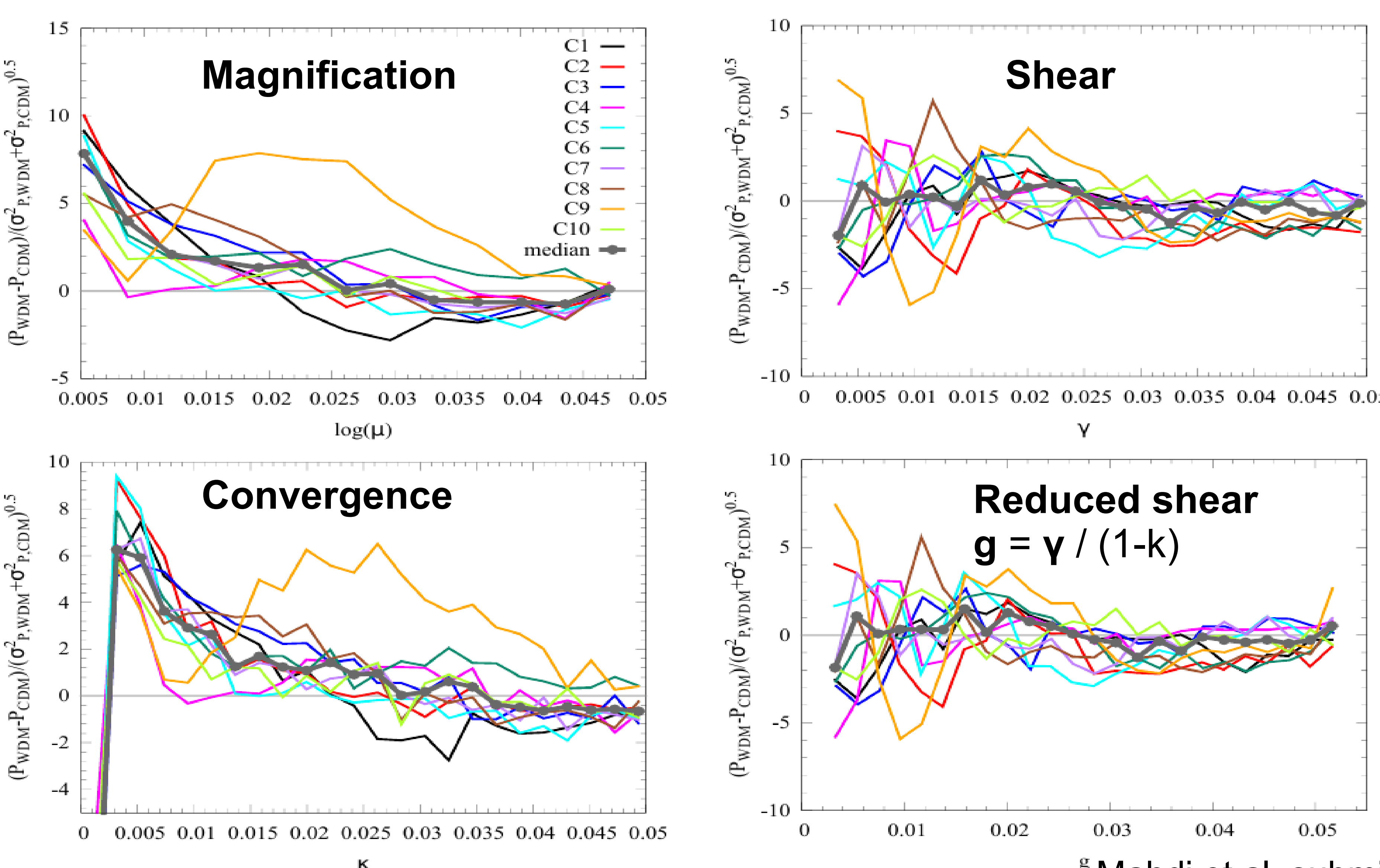
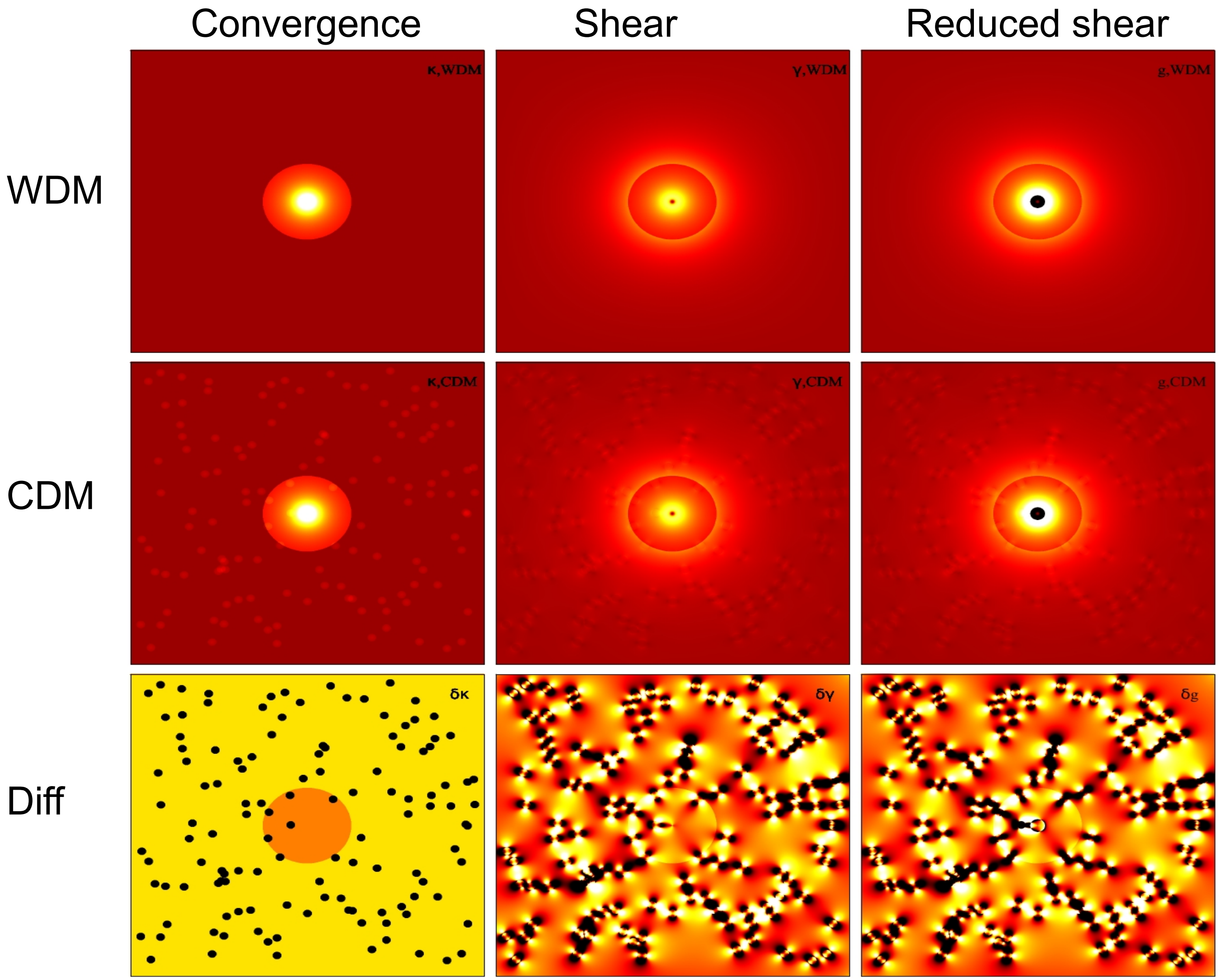
Weak Lensing: WDM vs CDM



Mahdi et al. submitted

mov

Weak Lensing: WDM vs CDM



R_H=0.125 L_{box}
R_{sub} = 0.0125 L_{box}

$$M_{\rm sub,tot} = f_{\rm sub} M_{\rm tot}$$

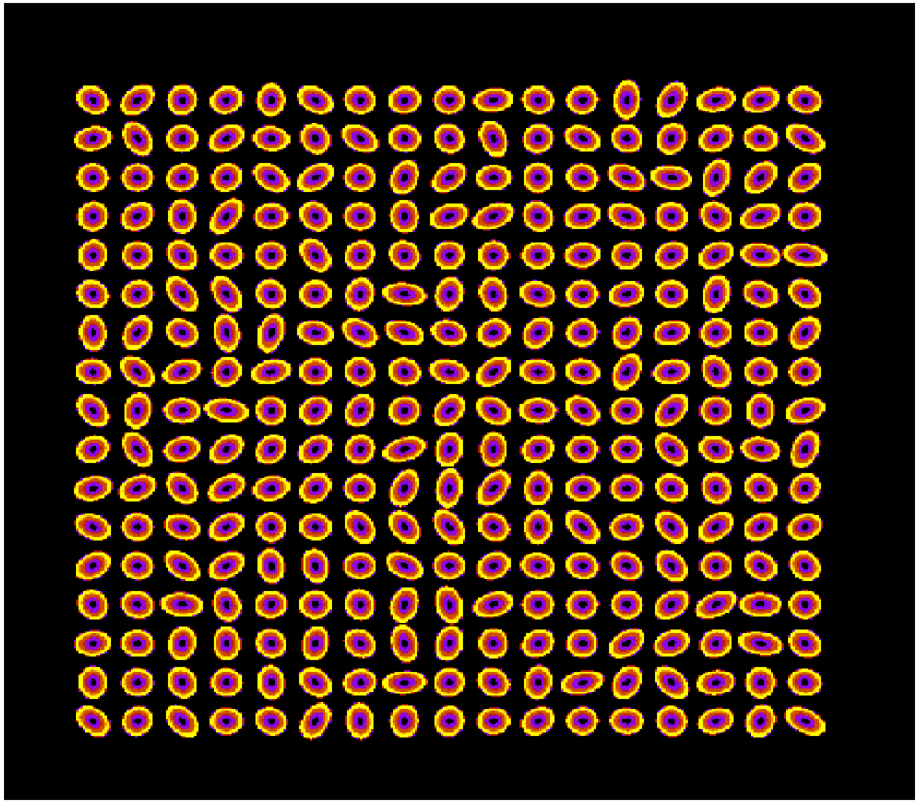
$$\text{yellow} = \delta\kappa, \delta\gamma, \delta g > 0$$
$$\text{orange} = \delta\kappa, \delta\gamma, \delta g = 0$$
$$\text{black} = \delta\kappa, \delta\gamma, \delta g < 0.$$

$\delta\kappa > 0$ (89%) $\delta\kappa < 0$ (6%)
$\delta\gamma > 0$ (40%) $\delta\gamma < 0$ (60%)

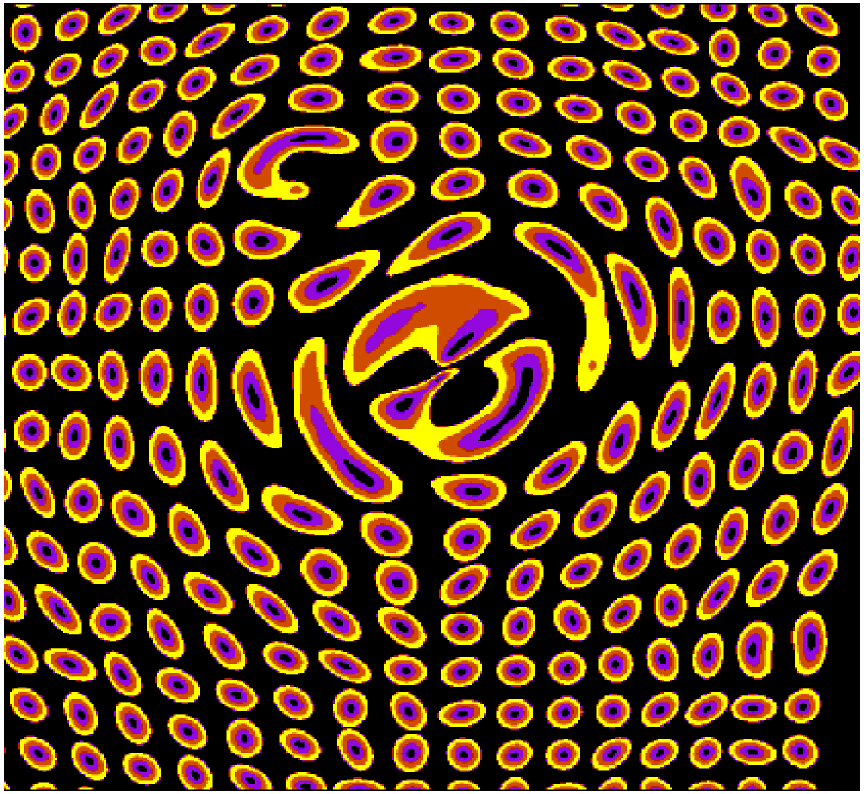
Mahdi et al. submitted

WDM vs CDM: Number density of galaxies

Magnification (Brightening): $S \rightarrow \mu S$
Vs
Dilution: $d\Omega \rightarrow \mu^2 d\Omega$

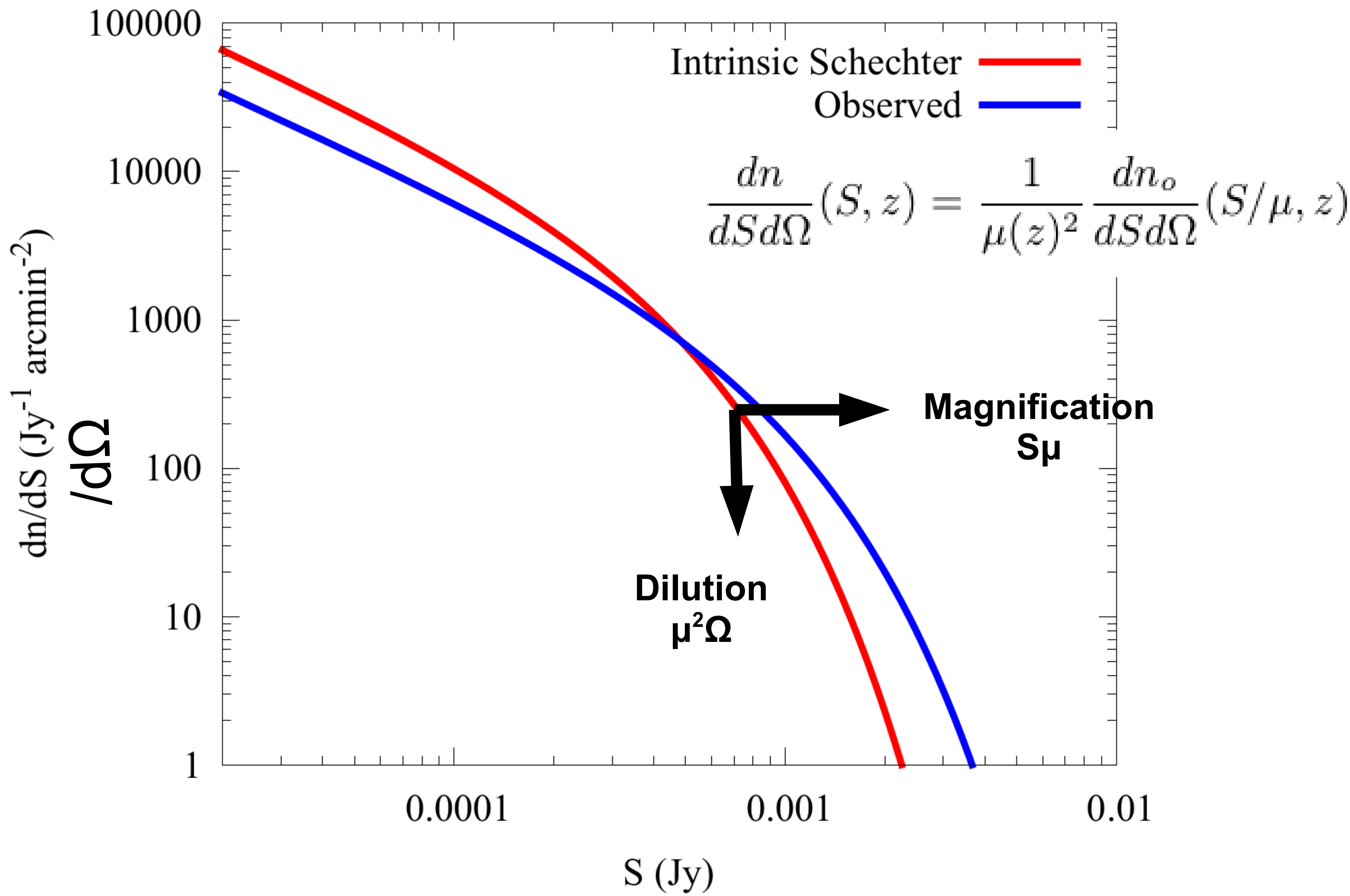


No Lens

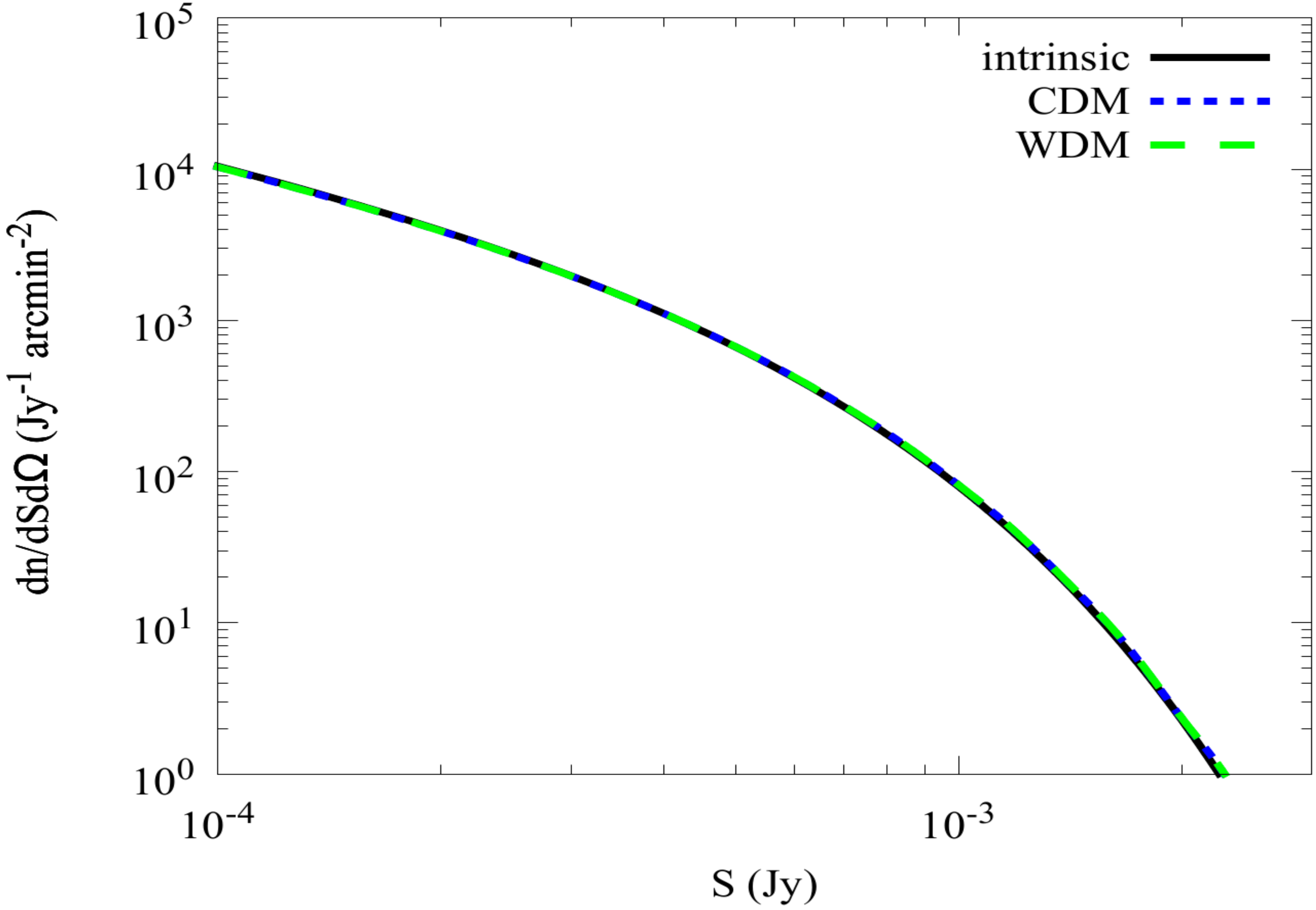


Lensed by a galaxy cluster

WDM vs CDM: Number density of galaxies

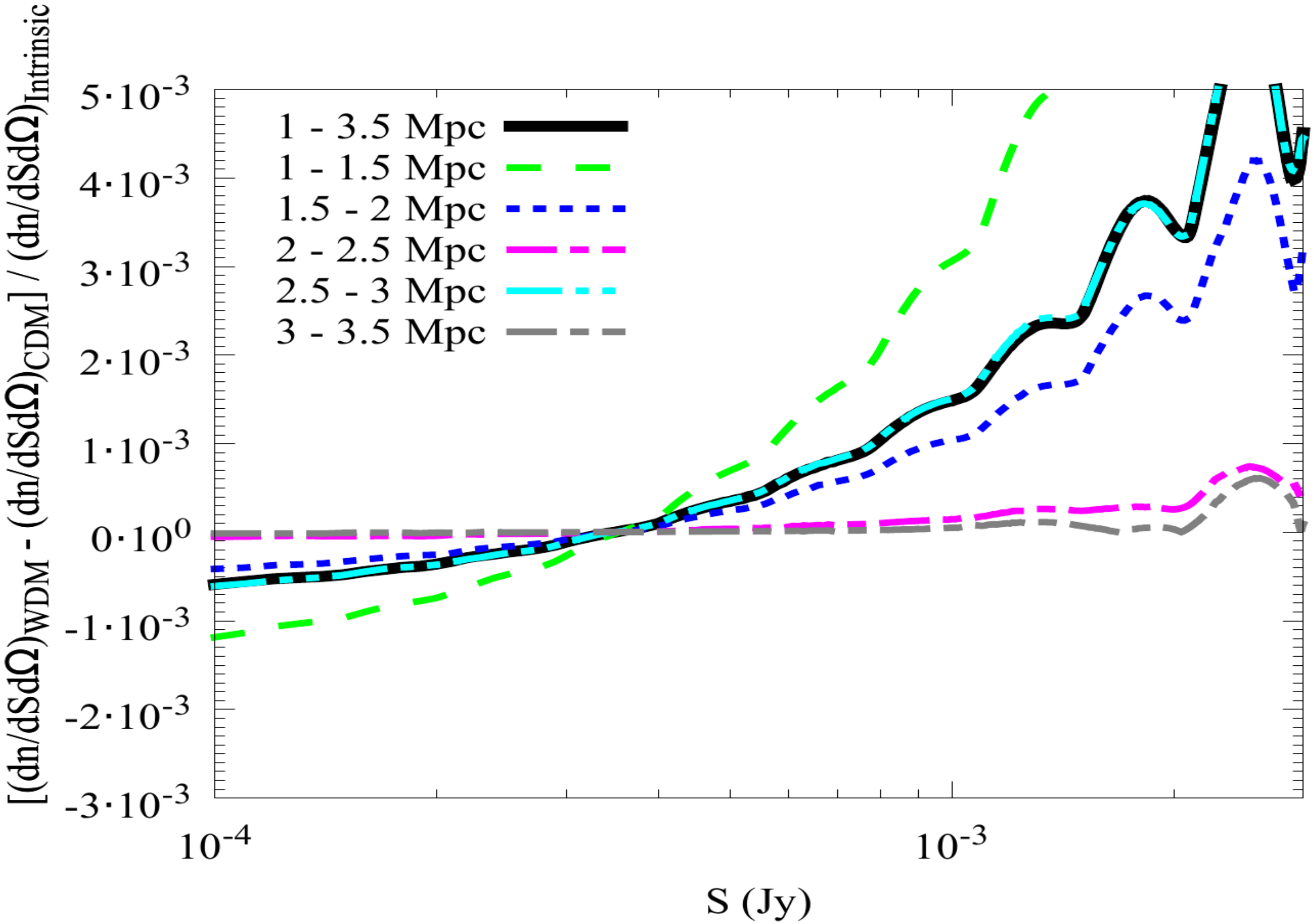


WDM vs CDM: Number density of galaxies



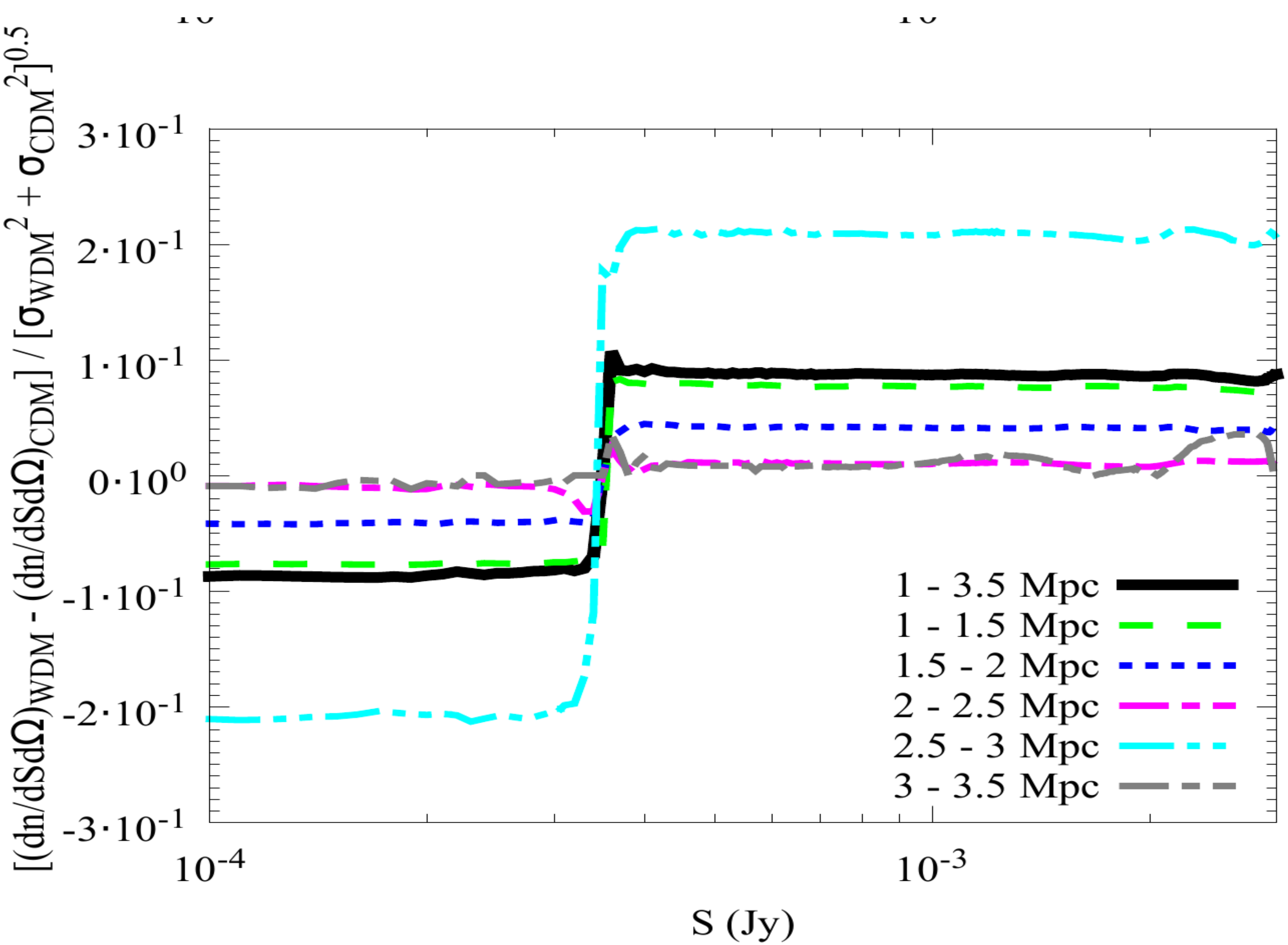
Mahdi et al. submitted

WDM vs CDM: Number density of galaxies



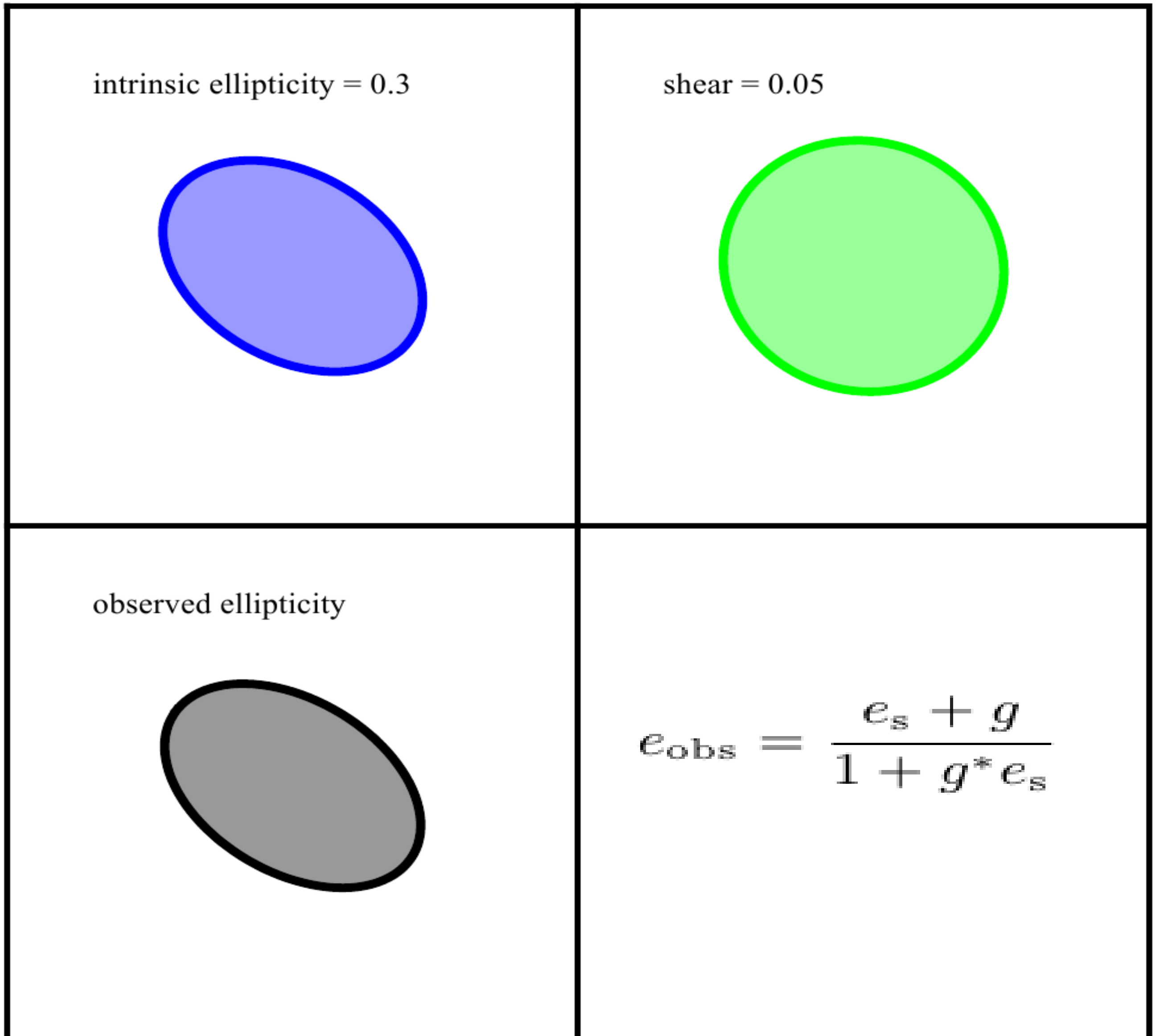
Mahdi et al. submitted

WDM vs CDM: Number density of galaxies



Mahdi et al. submitted

WDM vs CDM: Shape Measurements



WDM vs CDM: Shape Measurements

$\sigma(es) = 0.1$

$$\bar{x}_i = \frac{\sum I(x_1, x_2) x_i}{\sum I(x_1, x_2)}$$

Centroid: first moment

$$Q_{ij} = \frac{\sum I(x_1, x_2)(\bar{x}_i - x_i)(\bar{x}_j - x_j)}{\sum I(x_1, x_2)}$$

Quadruple moment

$$e_i = \frac{Q_{xx} - Q_{yy} + 2iQ_{xy}}{Q_{xx} + Q_{yy} + 2\sqrt{Q_{xx}Q_{yy} - Q_{xy}}}$$

$$\gamma \sim \langle e_i \rangle$$

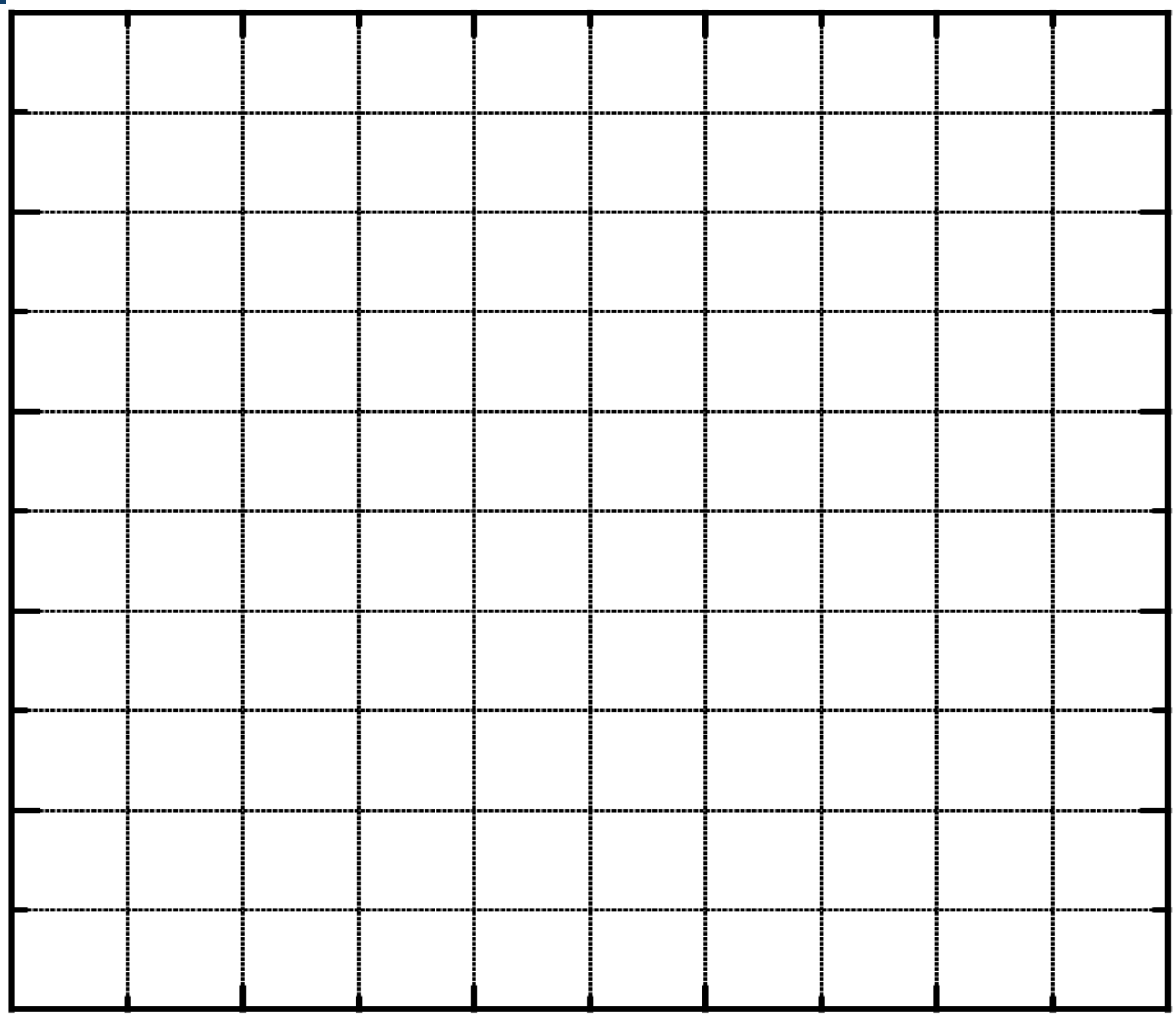
$$(S/N)_\gamma = \sqrt{N}|\gamma|/\sigma(e_s)$$

WDM vs CDM: Shape Measurements

Weak lensing

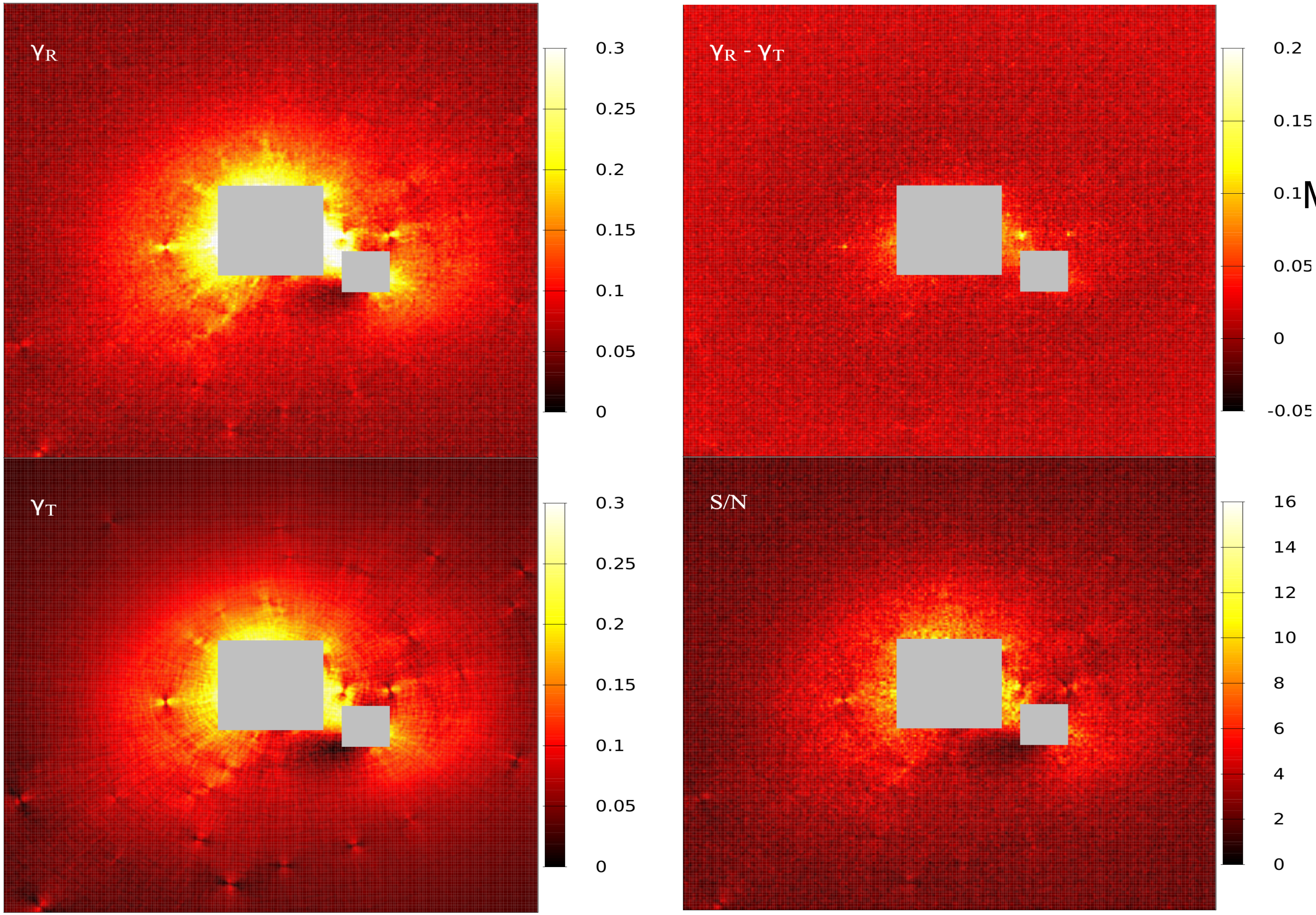
$\gamma \sim g \sim \langle e \rangle$

16 pixels
3.52 "



4 Mpc
4096 pixels
256 cells

WDM vs CDM: Shape Measurements



Med= 0.0148

Med= 2.9

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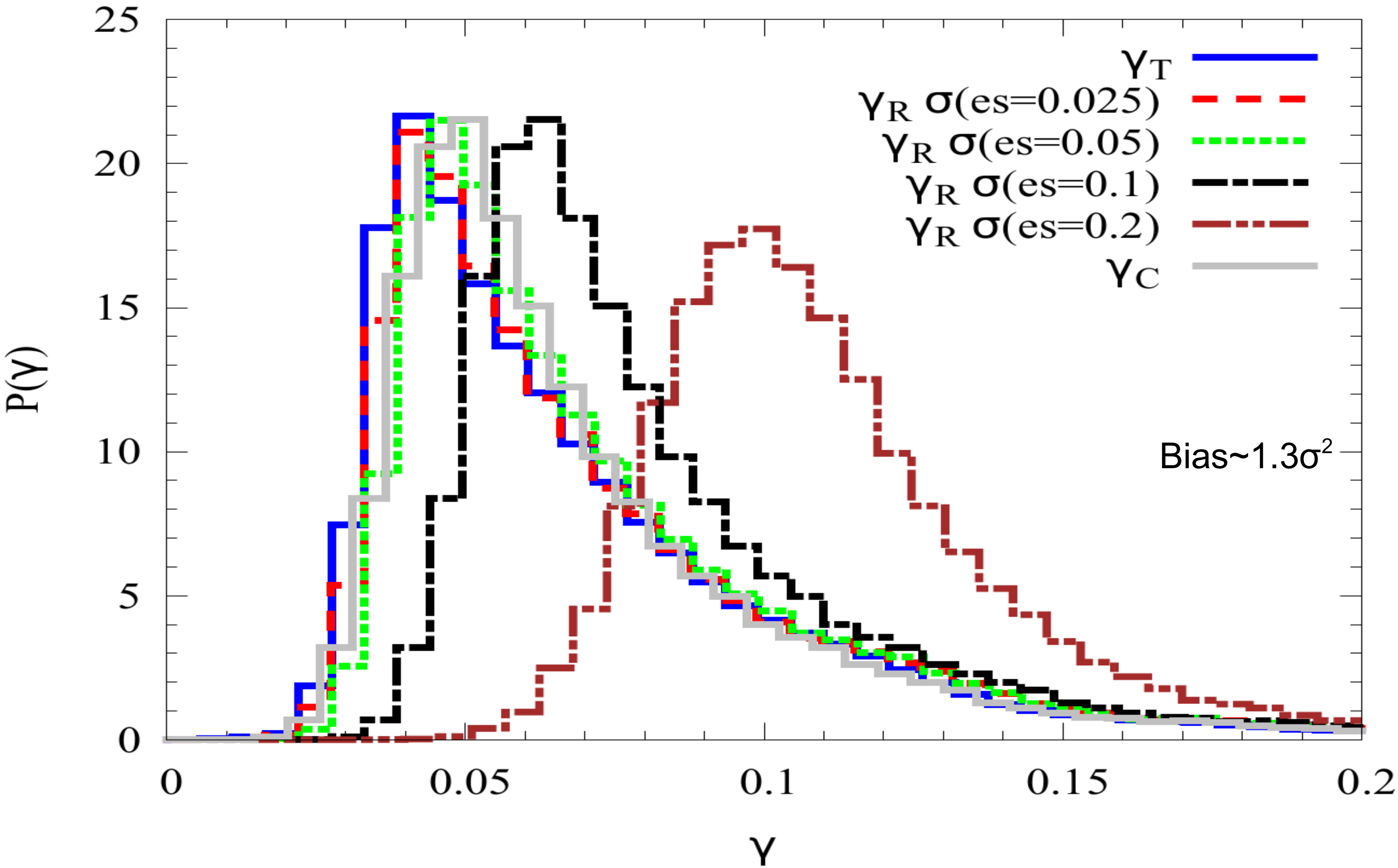
WDM vs CDM: Shape Measurements



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WDM vs CDM: Shape Measurements

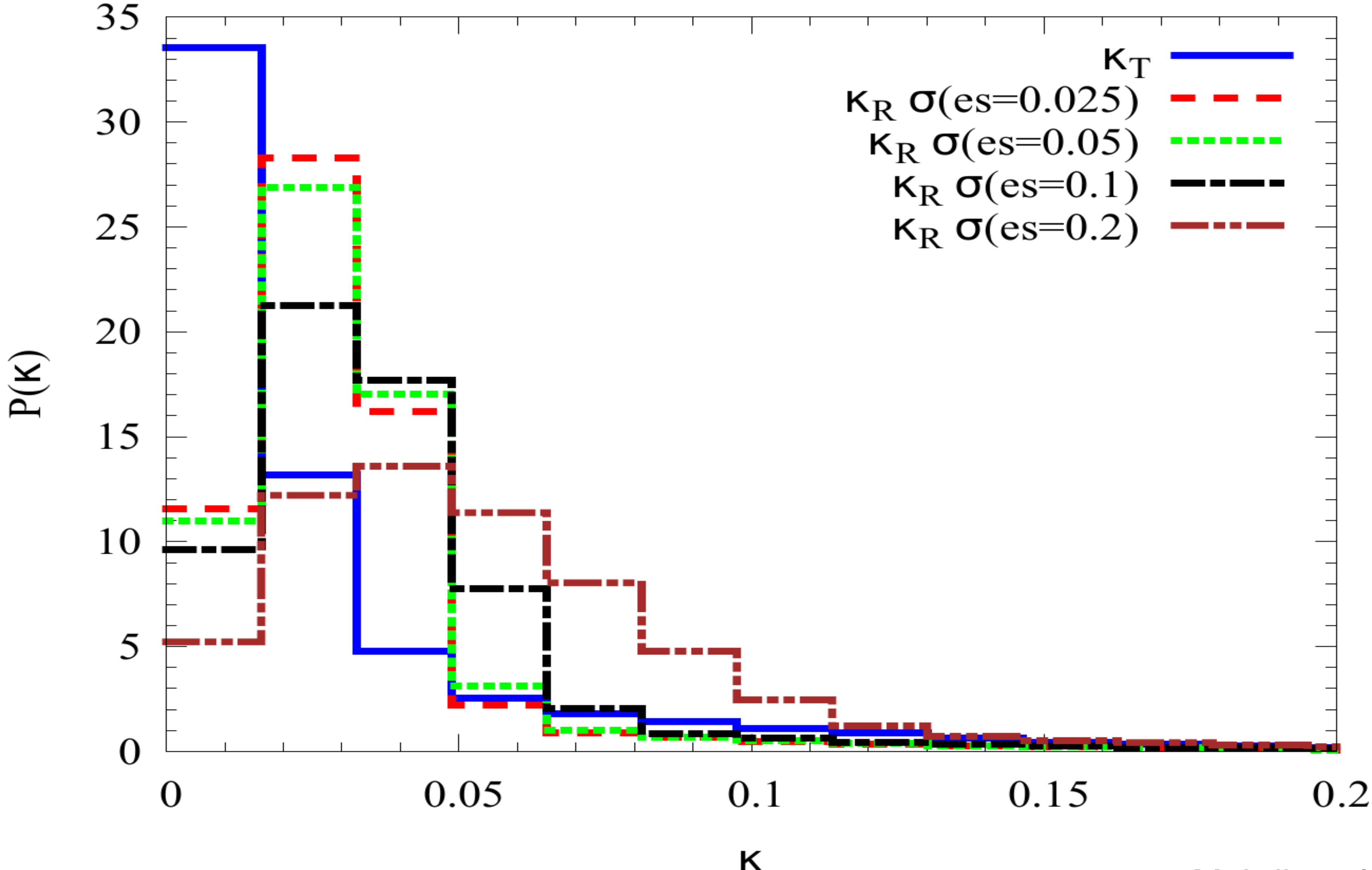
Convergence reconstruction

$$\kappa - \kappa_o = \frac{1}{\pi} \int \left[1 - \kappa_{\rm old}(\boldsymbol{\theta}')\right] \Re\left[\mathfrak{D}^*(\boldsymbol{\theta} - \boldsymbol{\theta}') \langle e \rangle (\boldsymbol{\theta}')\right] d\boldsymbol{\theta}$$

$$\mathfrak{D}(\boldsymbol{\theta}) = \frac{-1}{(\theta_1 - i\theta_2)^2}$$

Kaiser & Squires 1993
Seitz & Schneider 1995
Bartelmann & Schneider 2001

WDM vs CDM: Shape Measurements



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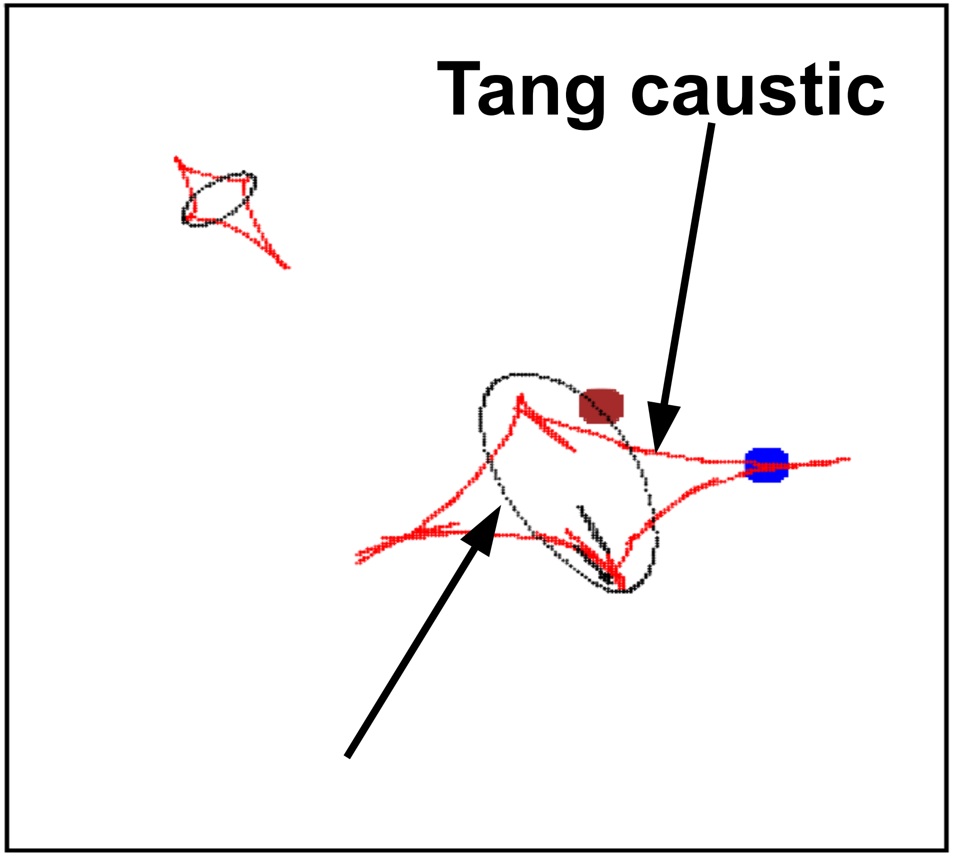
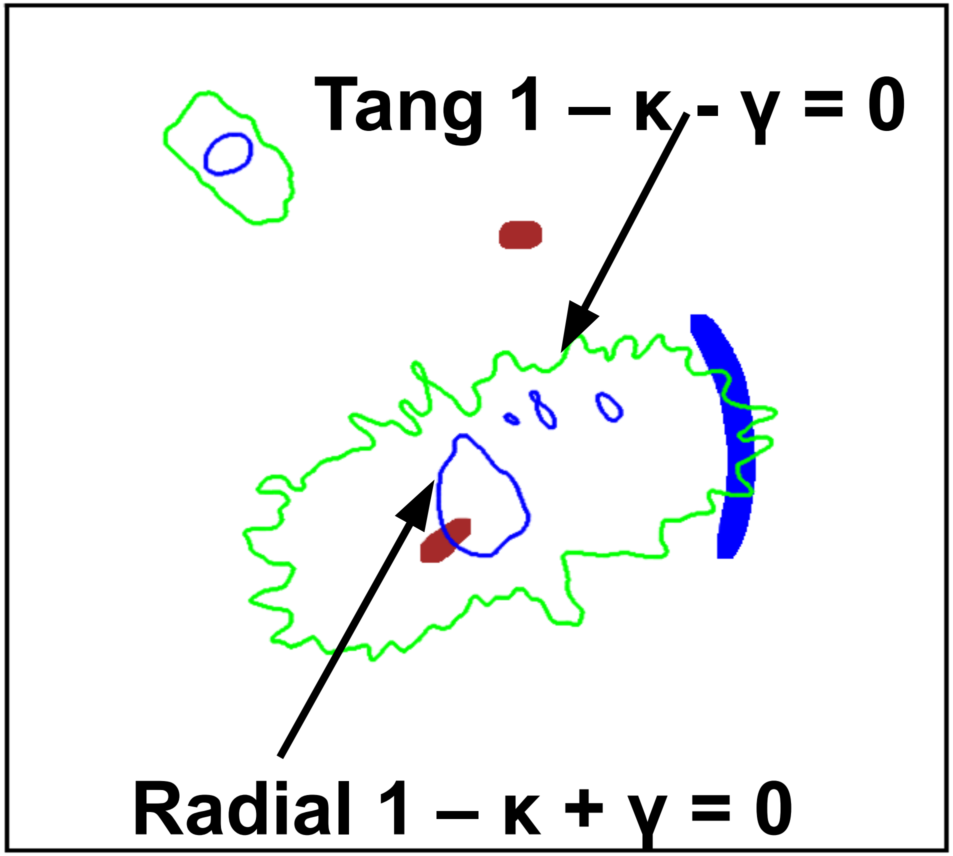
Strong Lensing: WDM vs CDM

Two types of giant arcs (radial and tangential giant arcs)



Caustics
Source Plane

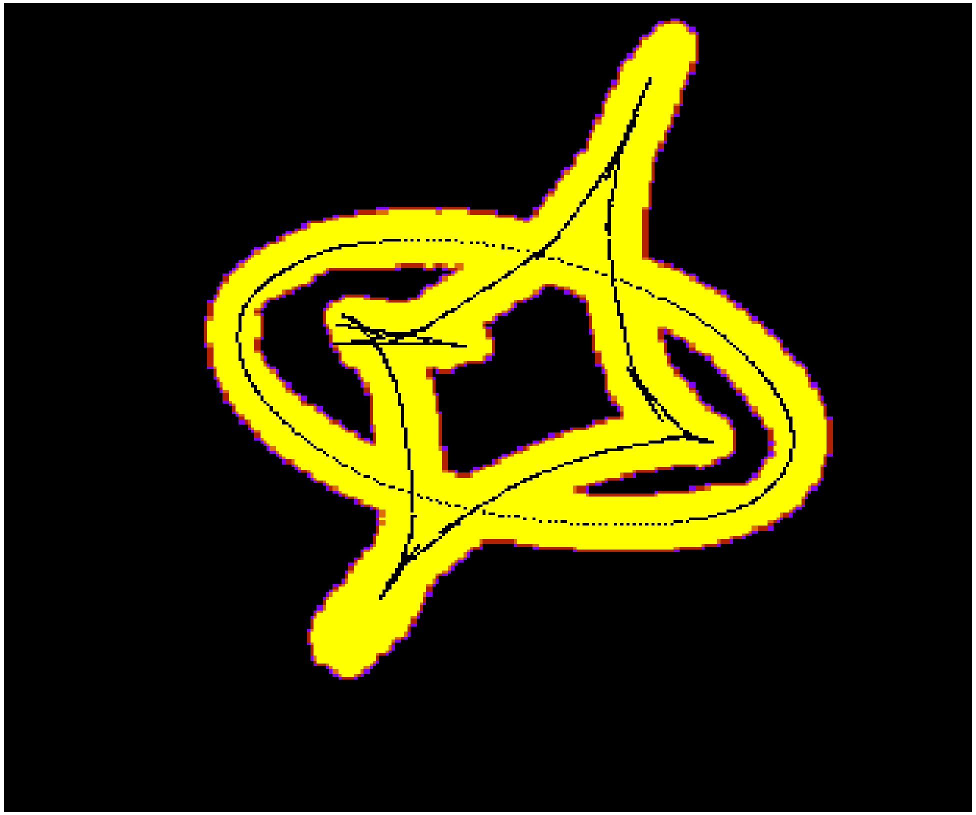


Critical lines
Lens Plane

Strong Lensing: WDM vs CDM

Strong Lensing Efficiency

Cross section for giant arcs: the area on the source plane where a source should be located to be lensed as a giant arc.

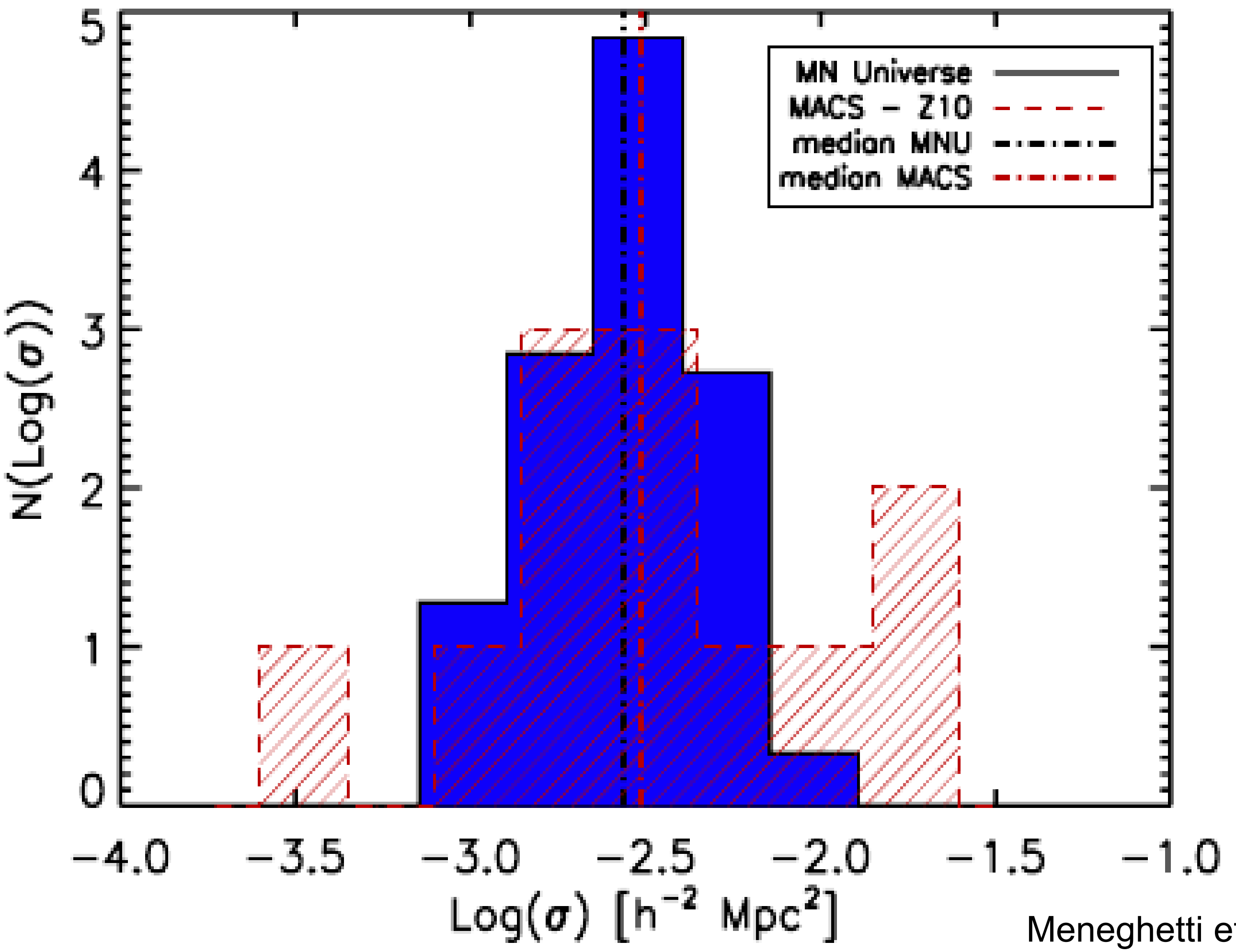


Einstein radius: The size of tangential critical line

Strong Lensing: WDM vs CDM

Arc Statistics Problem

Discrepancy ~ 2



Meneghetti et al. 2011

12 MACS clusters vs MARENOSTRUM simulation

Strong Lensing: WDM vs CDM

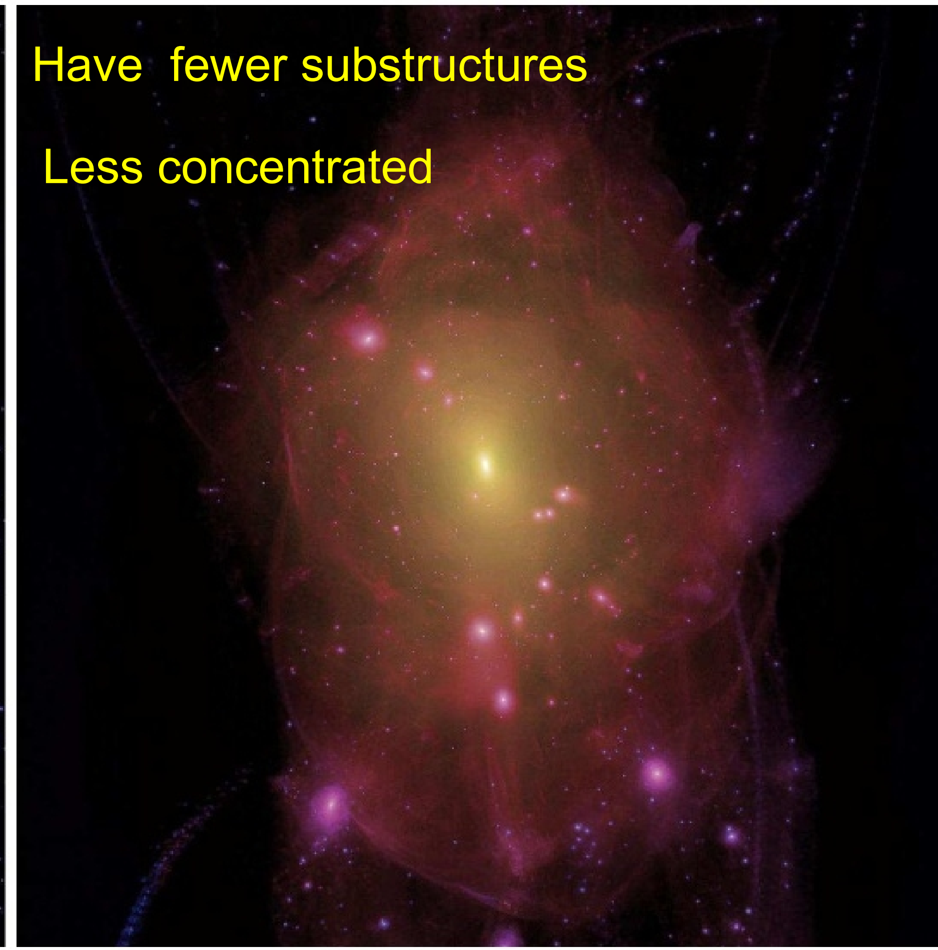
LENSING CROSS SECTION FOR GIANT ARCS

1- Identify critical lines and caustics
2- Distribute sources near caustics
3- compute length-to-width ratio of images
4- Image ($L/W \geq 7.5$) giant arc $\lambda r/\lambda t$ $\lambda t/\lambda r >= 7.5$
Compute area covered by sources that produce giant arcs

mov

Strong Lensing: WDM vs CDM

CDM vs **WDM**



Lovell et al. 2012

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Strong Lensing: WDM vs CDM

WDM (SLIGHTLY) STRONGER LENSES THAN CDM!!!

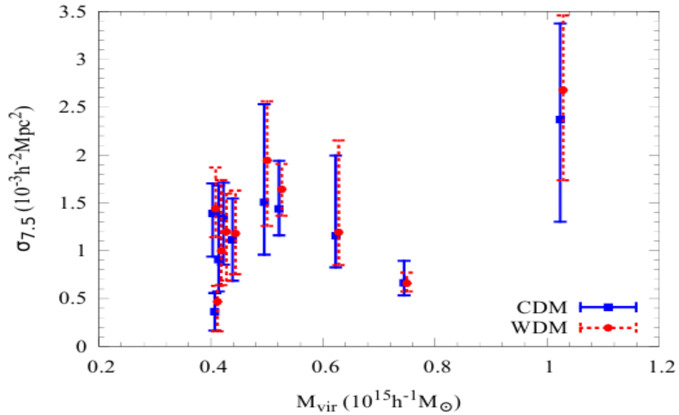
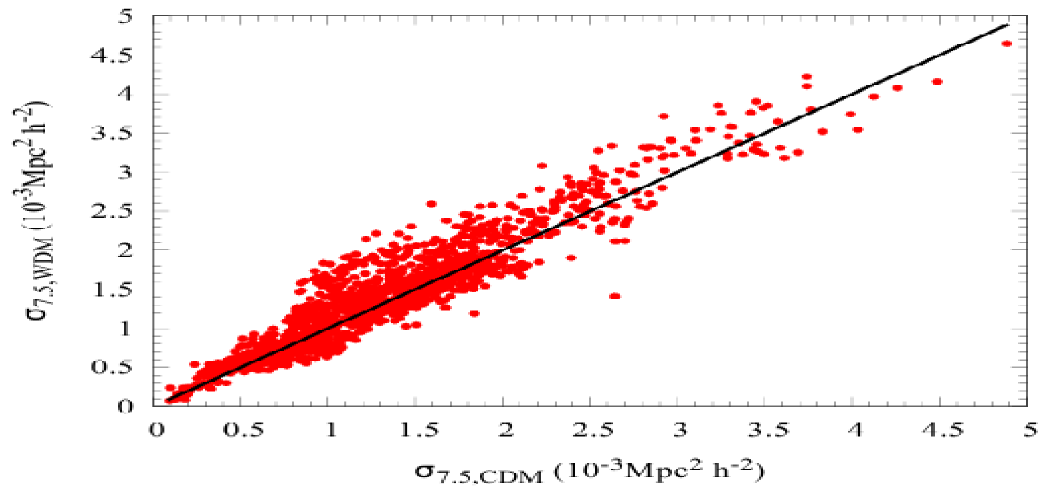


Figure 7. The median cross section for giant arcs along with the 16th and 84th percentile over the 150 los as a function of the virial mass of CDM version of clusters (blue squares) and WDM counterparts (red circles).



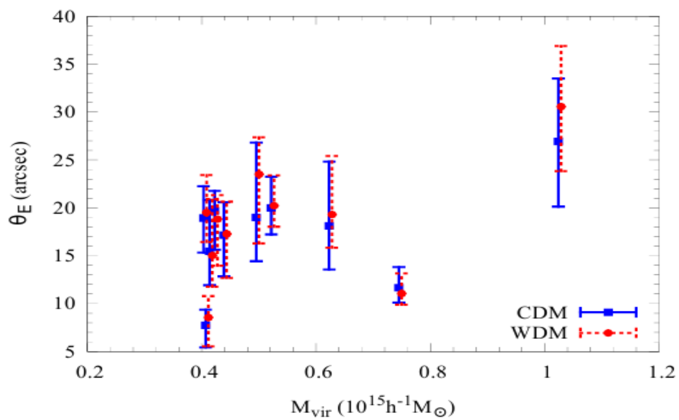
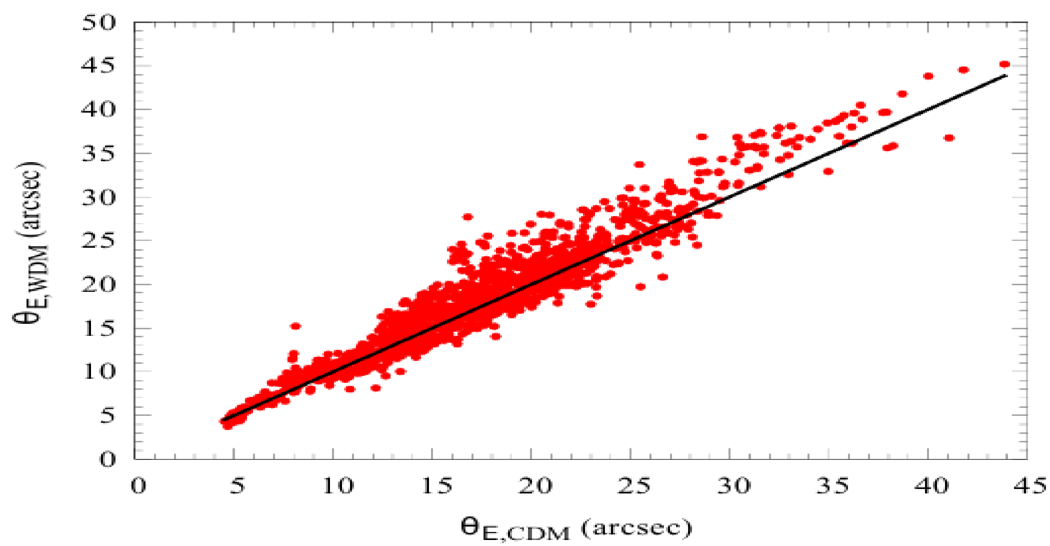
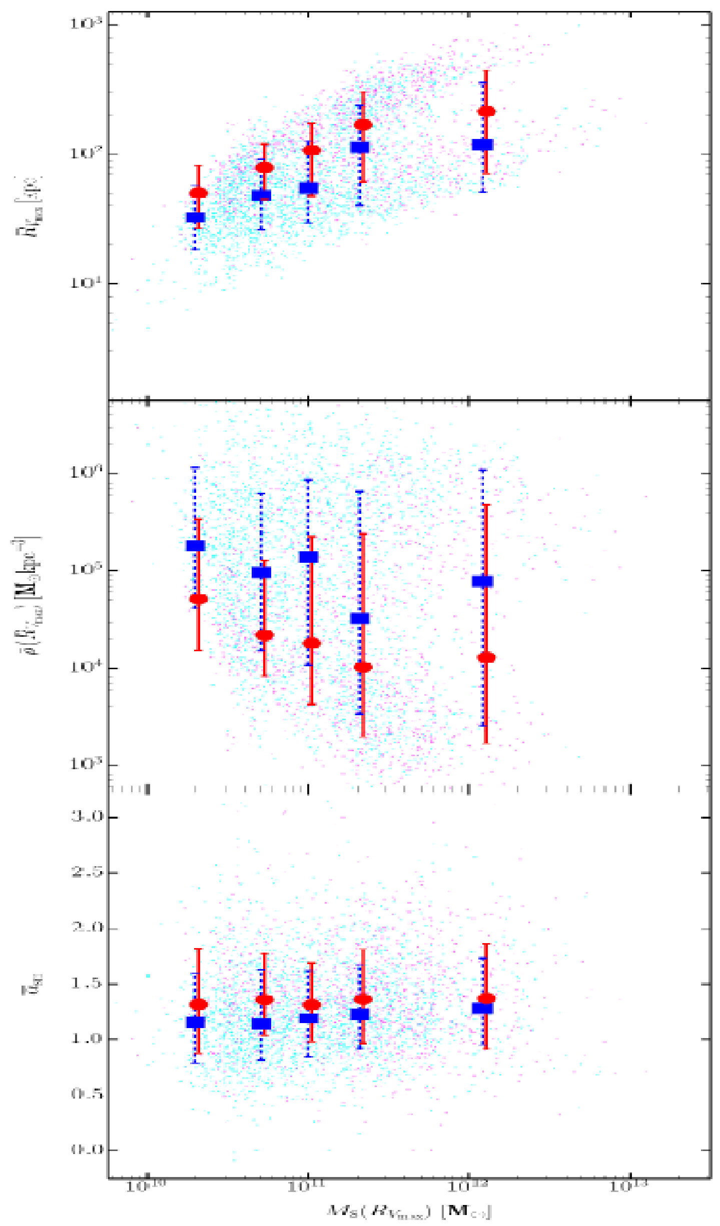


Figure 8. The median Einstein radius for giant arcs along with the 16th and 84th percentile over the 150 los as a function of the virial mass of CDM version of clusters (blue squares) and WDM counterparts (red circles).



Mahdi et al. 2014

Strong Lensing: WDM vs CDM



bigger subhaloes

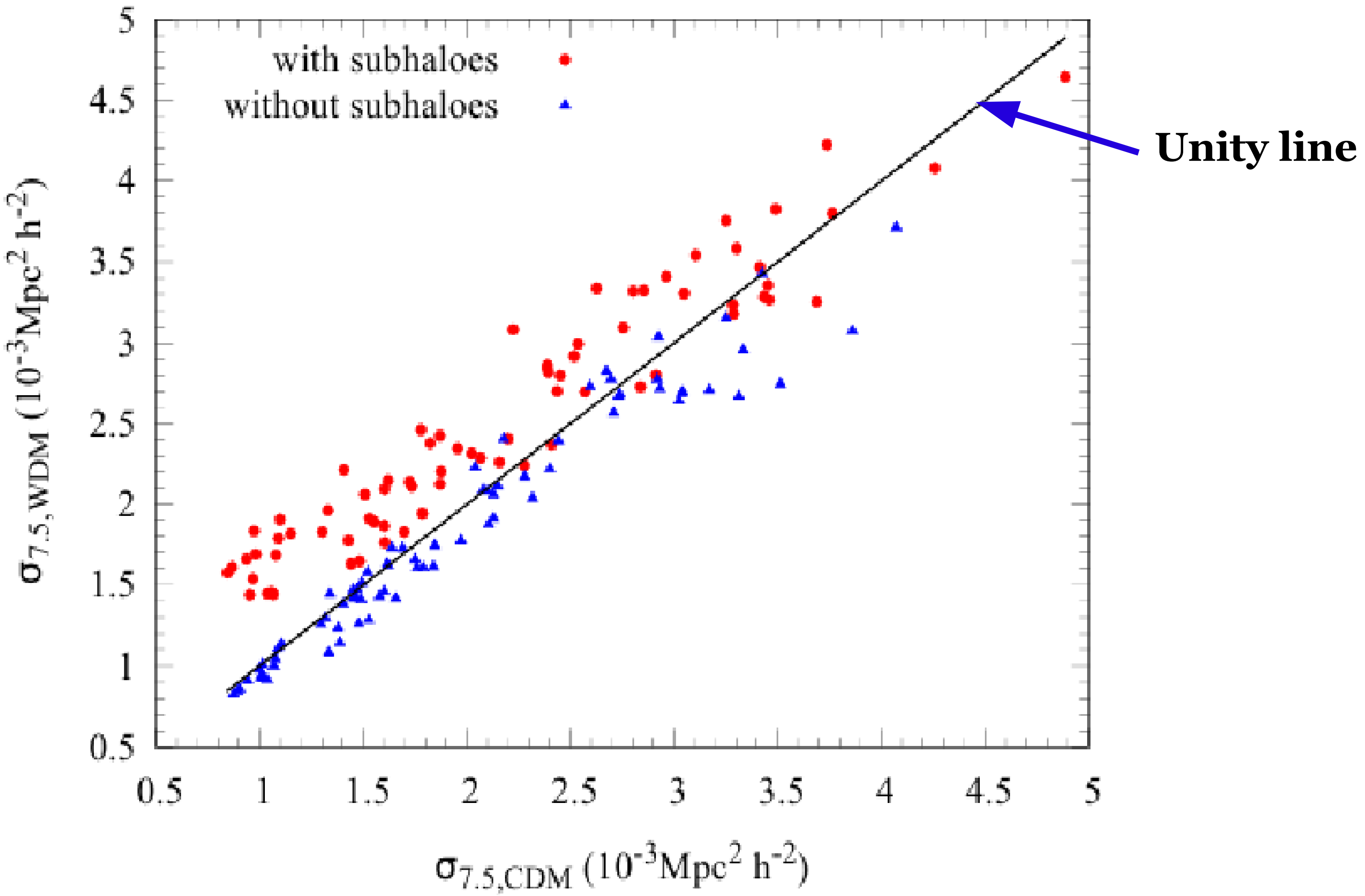
But less dense

Higher mass accretion

Elahi et al. 2014

Strong Lensing: WDM vs CDM

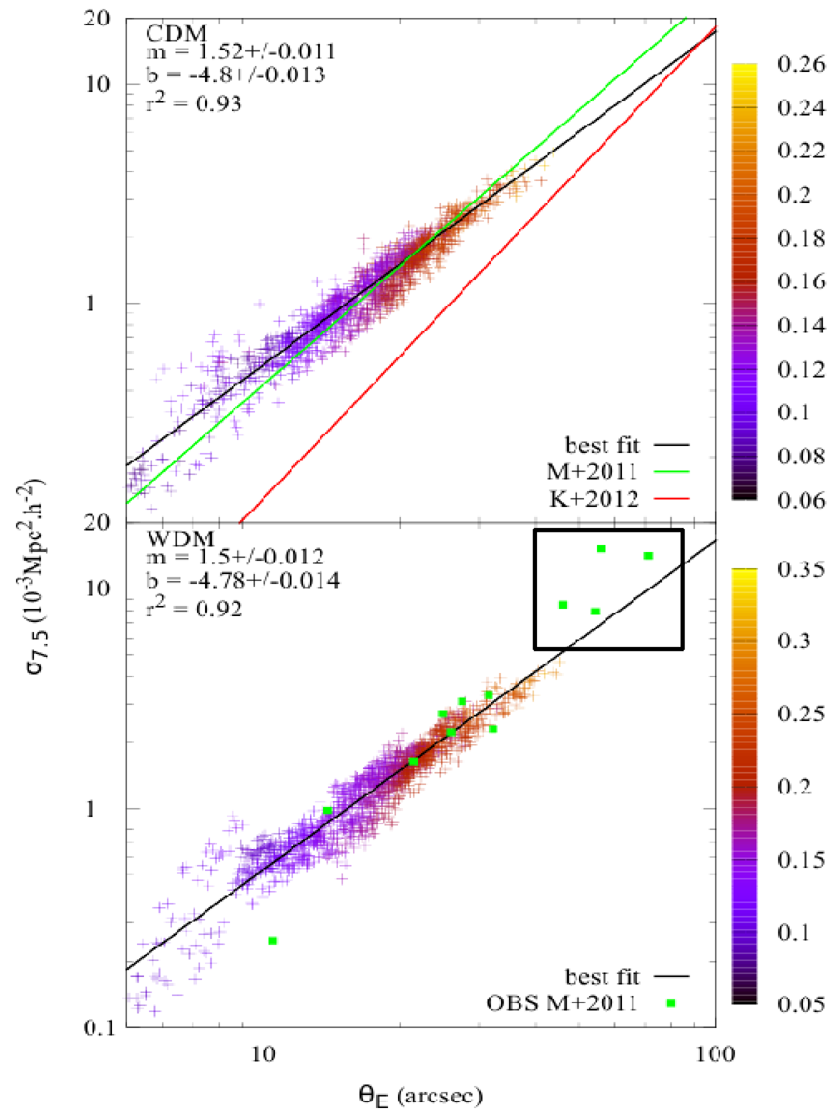
Do the WDM subhaloes really boost the lensing efficiency?



Mahdi et al. 2014

Strong Lensing: WDM vs CDM

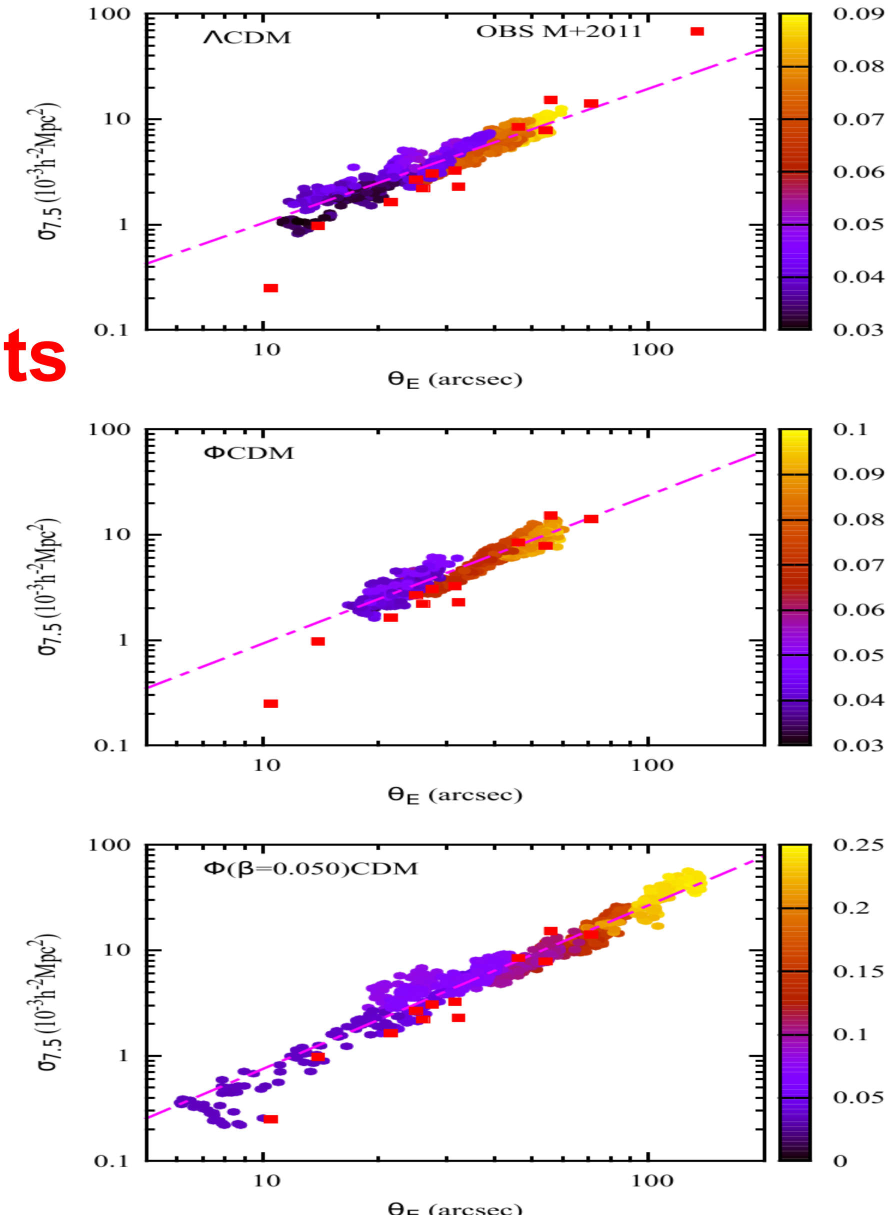
$\text{Log}(\sigma7.5) = m \log(\theta E) + b$



Mahdi et al. 2014

Strong Lensing: Coupled and uncoupled quintessence models

Preliminary Results



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CONCLUSIONS

Weak lensing: WDM vs CDM

- WDM: more homogeneous

- Number density of galaxies S/N ~ 0.1 vs shape measurements method S/N ~ 3

Strong lensing: WDM vs CDM

- WDM subhaloes are more physically extended: Arc statistics problem.

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Thank you