Constraining the cross section of dark matter with giant radial arcs in galaxy clusters

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Summary

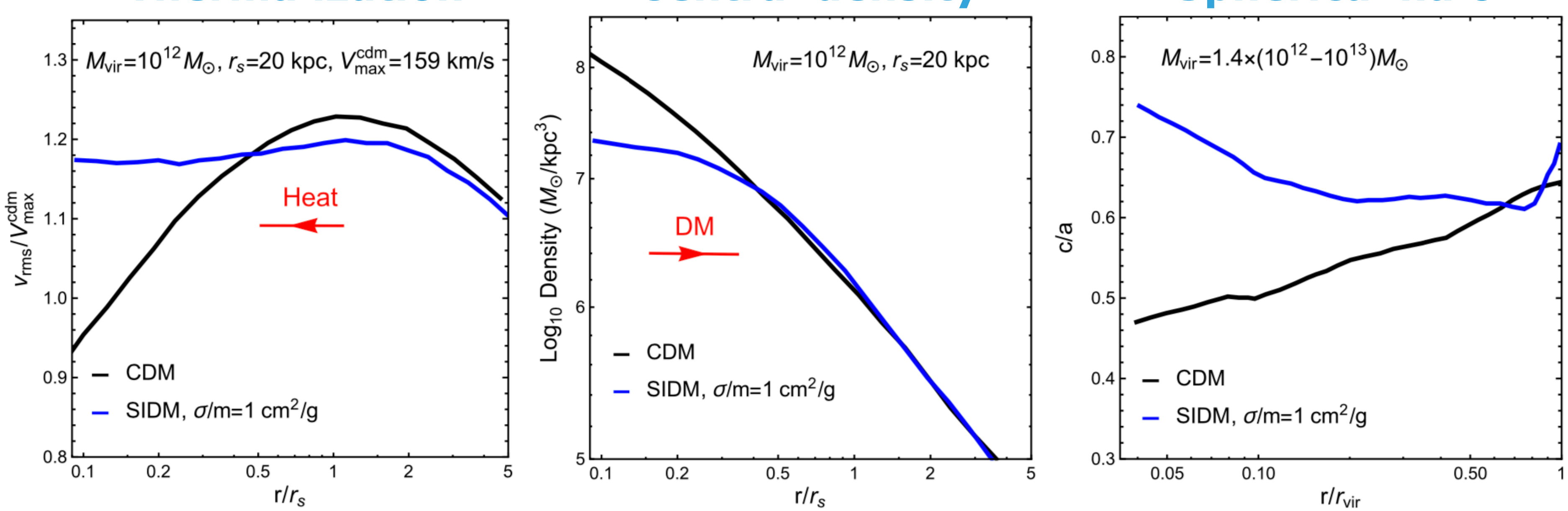
1. Motivation
2. SIDM simulations of cluster-size halos
3. Gravitational lensing by galaxy clusters
4. Radial arcs statistics
5. Conclusions and future prospects

1. Motivation

- Lambda Cold Dark Matter (ΛCDM)
  - **Collision-less cold DM**
  - ✓ Extremely successful for large scale structure
  - Crisis on small scales (core-cusp, diversity, missing satellites, TBTF problems)
  - Cluster scales (**core-cusp problem** / baryon physics (AGN) → cluster cores)

- Self-interacting dark matter (*Spergel & Steinhardt 2000*)
  - Elastic scatter DM (σ/m): $R_{\rm scat} = \sigma v_{\rm rel} \rho_{\rm dm}/m \approx 0.1\ {\rm Gyr}^{-1} \times \left(\frac{\rho_{\rm dm}}{0.1\ {\rm M}_\odot/{\rm pc}^3}\right)\left(\frac{v_{\rm rel}}{50\ {\rm km/s}}\right)\left(\frac{\sigma/m}{1\ {\rm cm}^2/{\rm g}}\right)$
  - Small scales: cusps into cores and TBTF (***σ/m* ~ 0.5-1 cm²/g**)

Thermalization **Central density** **Spherical halo**



Credits: Tulin & Yu 2018

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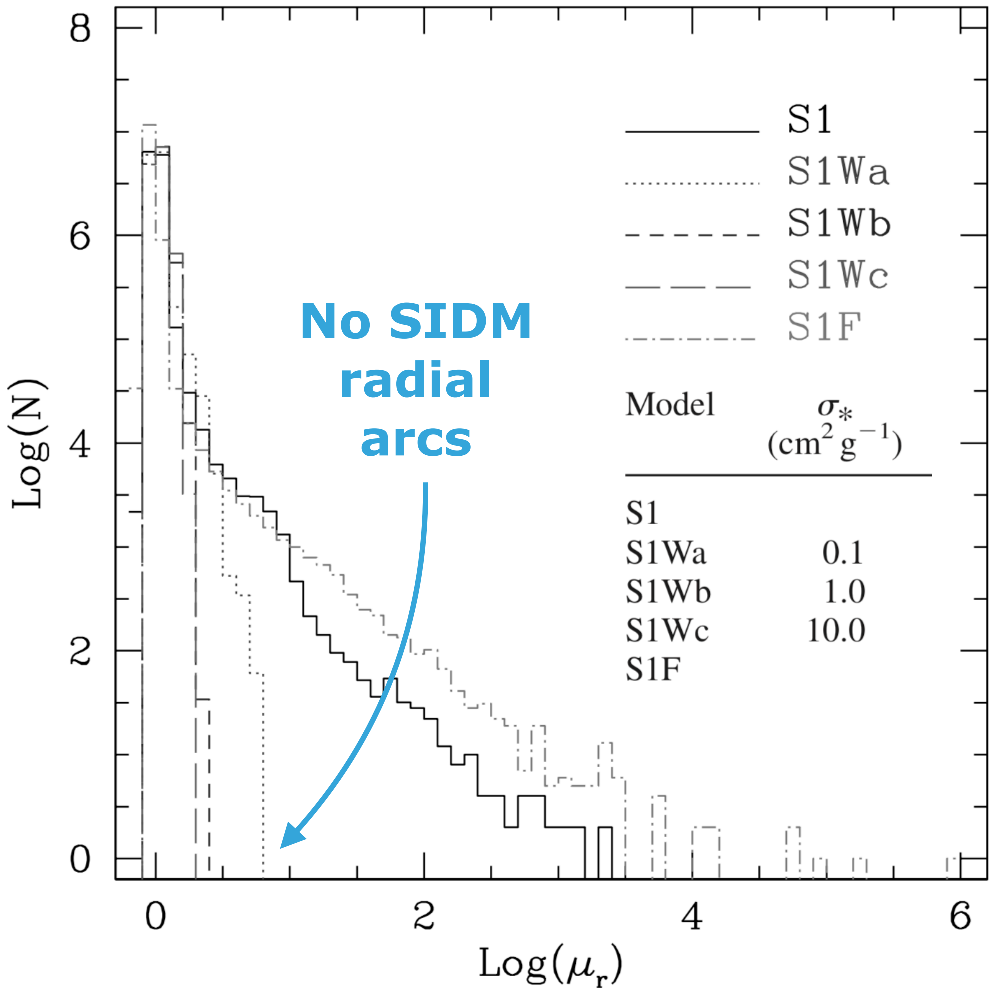
  - Small scales: cusps into cores and TBTF (***σ/m* ~ 0.5-1 cm²/g**)
  - **Cluster scales**
    - Bullet cluster: ***σ/m* ≲ 0.1 cm²/g** (*Randall et al. 2008*)
    - core clusters with ***σ/m* ~ 0.1 cm²/g** (*Yoshida et al. 2000, Rocha et al. 2013*)
    - Diversity central densities with ***σ/m* ~ 1 cm²/g** (*Rocha et al. 2013*)
    - Cluster ellipticity: ***σ/m* ~ 1 cm²/g not excluded** (*Peter et al. 2013*)
    - **Strong lensing: σ/m < 0.1 cm²/g (*Meneghetti et al. 2001*)**

1. Motivation

- *Meneghetti et al. 2001*
  - **Extreme strong lensing arcs** in simulated SIDM cluster-size halo
  - **1 halo with M_{vir} = 7.4 x 10^{14} h^{-1} $M_\odot$ at z= 0.278** (from *Yoshida et al. 2000a,b*)
  - SIDM with σ/m < 0.1, 1, 10 cm^2/g
    - **NO Radial arcs ⇒ σ/m < 0.1 cm^2/g**



2. SIDM simulations of cluster-size halos

- 1 halo **zoom simulations** (**M_{200c} ~ 10^{15} h^{-1} $M_\odot$** at z=0)

  Strongest lens and mayor merger at z ~ (0.250-0.333)

MultiDark (MDR1)
Prada et al. 2012
www.cosmosim.org
2048^3 part. $1h^{-1}$Gpc box

283 most massive halos →
WMAP7+BAO+SNI
Ω_M=0.27, Ω_Λ=0.73, Ω_b=0.0469, h=0.7

MUSIC project
http://music.ft.uam.es/
4096^3 particles
sphere $6h^{-1}$Mpc radius

- 5 halo **zoom simulations** (**M_{200c} > 10^{15} h^{-1} $M_\odot$** at z=0)

  Strongest lenses at z ~ (0.250, 0.333, 0.429, 0.538)

MultiDark (MDPL2)
Klypin et al. 2016
www.cosmosim.org
3840^3 part. $1h^{-1}$Gpc box

324 most massive halos →
PLANCK 2016
Ω_M=0.3, Ω_Λ=0.69, Ω_b=0.048, h=0.678

300th project
http://the300-project.org
3840^3 particles
sphere $15h^{-1}$Mpc radius

Non-radiative runs (adiabatic): DM + GAS

2. SIDM simulations of cluster-size halos

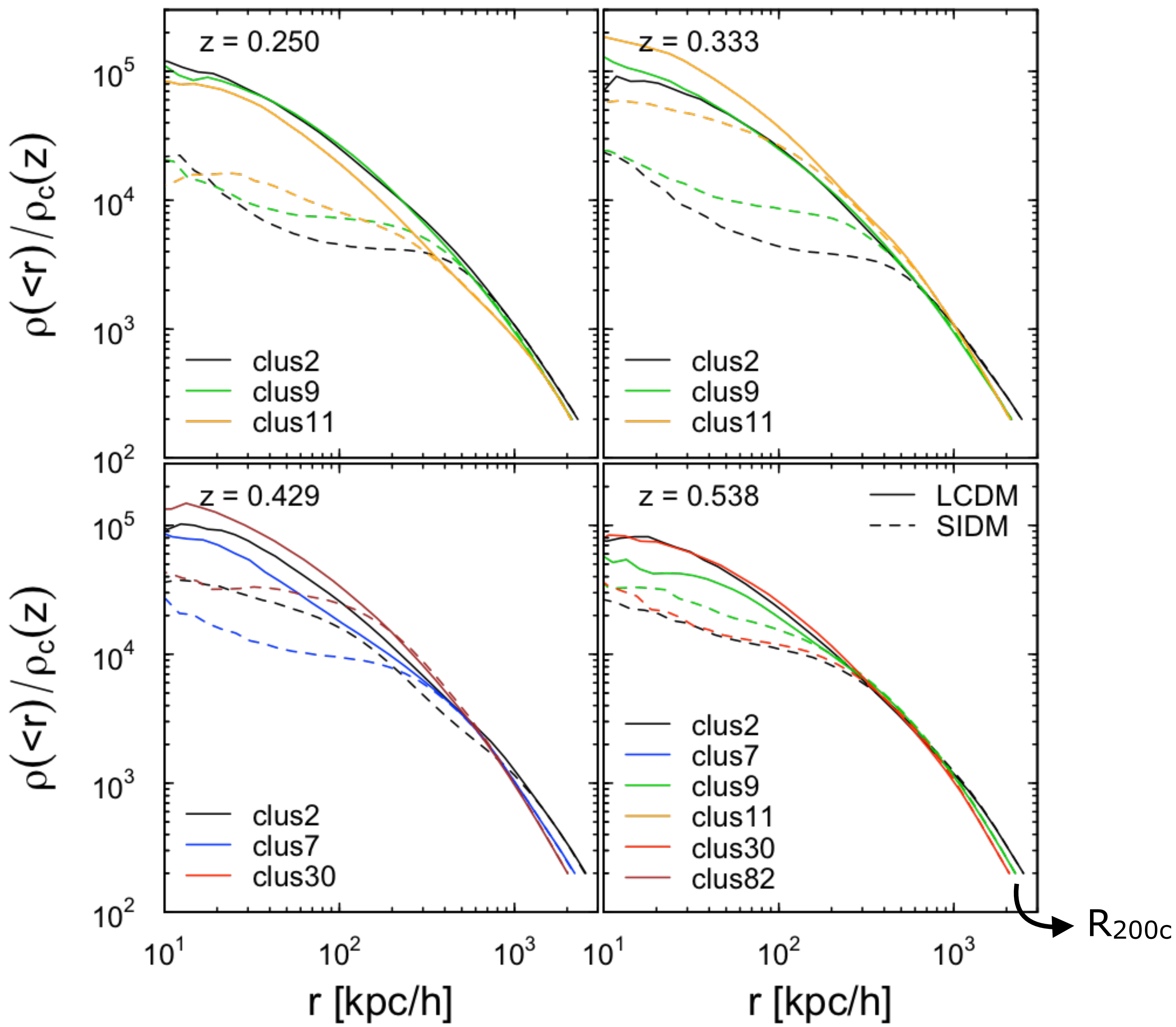
- 6 cluster-size halos with GIZMO (*Hopkings 2015, 2017*)
  - Based on P-GADGET and GADGET-2 (*Springel 2005*)
  - SPH + grid-based/AMR schemes
  - SIDM module (*Rocha et al. 2013*)
  - DM + GAS (non-radiative) particles
  - Same ΛCDM initial conditions
  - **SIDM cross-section** (velocity independent)

$$\boldsymbol{\sigma/m = 1\ \mathrm{cm^2/g}}$$

2. SIDM simulations of cluster-size halos

- 6 cluster-size halos with SIDM

σ/m = 1 cm²/g



cluster	model	z	M_{SO}	M_{EO}	b/c	a/c
clus2	ΛCDM	0.250	1.88	2.15	0.52	0.37
clus2	SIDM	0.250	1.91	2.13	0.54	0.42
clus2	ΛCDM	0.333	2.04	2.21	0.58	0.38
clus2	SIDM	0.333	2.05	2.19	0.58	0.43
clus2	ΛCDM	0.429	2.10	2.18	0.64	0.44
clus2	SIDM	0.429	2.07	2.16	0.65	0.47
clus2	ΛCDM	0.538	1.82	1.92	0.67	0.47
clus2	SIDM	0.538	1.80	1.92	0.66	0.48
clus7	ΛCDM	0.429	1.38	1.49	0.48	0.44
clus7	SIDM	0.429	1.36	1.48	0.49	0.45
clus9	ΛCDM	0.250	1.48	1.54	0.70	0.47
clus9	SIDM	0.250	1.49	1.54	0.75	0.53
clus9	ΛCDM	0.333	1.36	1.44	0.65	0.45
clus9	SIDM	0.333	1.37	1.43	0.73	0.53
clus9	ΛCDM	0.538	1.31	1.34	0.65	0.50
clus9	SIDM	0.538	1.32	1.34	0.70	0.55
clus11	ΛCDM	0.250	1.41	1.40	0.60	0.55
clus11	SIDM	0.250	1.40	1.39	0.63	0.58
clus11	ΛCDM	0.300	1.31	1.32	0.61	0.57
clus11	SIDM	0.300	1.31	1.32	0.68	0.64
clus11	ΛCDM	0.333	1.25	1.28	0.57	0.51
clus11	SIDM	0.333	1.24	1.27	0.58	0.54
clus30	ΛCDM	0.538	1.03	1.10	0.59	0.45
clus30	SIDM	0.538	1.03	1.10	0.62	0.47
clus82	ΛCDM	0.429	1.03	1.07	0.74	0.46
clus82	SIDM	0.429	1.04	1.07	0.74	0.48

M_{200c} [$10^{15}\ h^{-1}\ M_\odot$]

Axis ratios

3. Gravitational lensing by galaxy clusters

- Deflection angle, convergence, shear and magnification

Deflection angle

$$\vec{\alpha}(\vec{\theta}) \equiv \frac{D_{\rm LS}}{D_{\rm S}} \hat{\vec{\alpha}}(\vec{\theta})$$

Lens equation

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$

$$\gamma_1 = \frac{1}{2}\left(\frac{\partial \alpha_x}{\partial x} - \frac{\partial \alpha_y}{\partial y}\right), \quad \gamma_2 = \frac{\partial \alpha_x}{\partial y} = \frac{\partial \alpha_y}{\partial x}$$

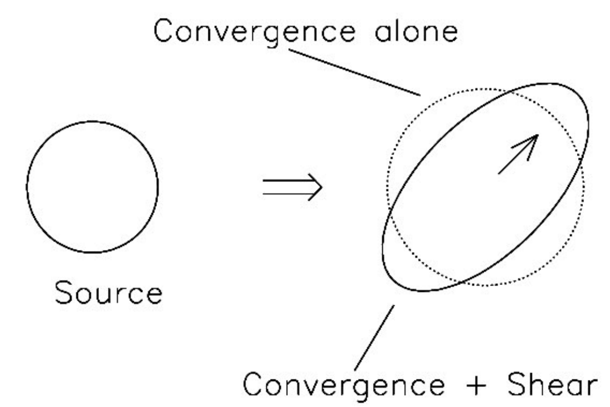
Shear

$$\gamma = \sqrt{\gamma_1^2 + \gamma_2^2}$$

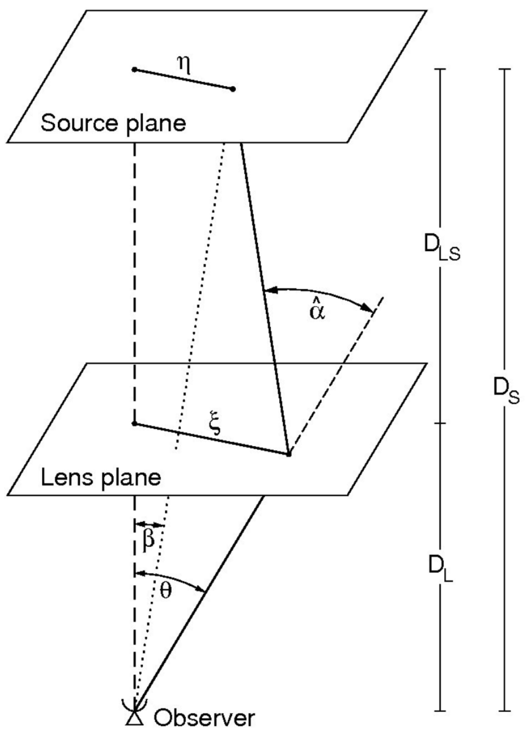
$$\kappa = \frac{1}{2}\left(\frac{\partial \alpha_x}{\partial x} + \frac{\partial \alpha_y}{\partial y}\right)$$

Convergence

$$\kappa(\vec{x}) \equiv \frac{\Sigma(\vec{x})}{\Sigma_{\rm cr}}$$



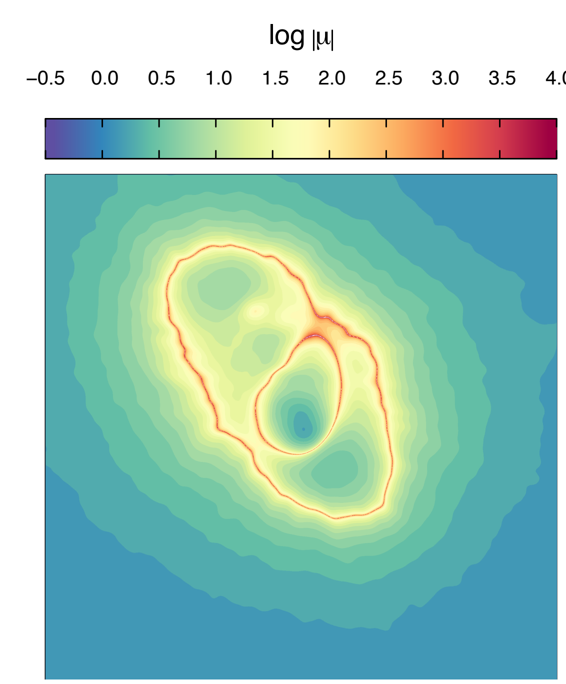
Critical density of the Universe $\Sigma_{\rm cr} = \frac{c^2}{4\pi G}\frac{D_{\rm S}}{D_{\rm L} D_{\rm LS}}$



Magnification

$$\mu = \mu_t \mu_r = \frac{1}{\underbrace{(1-\kappa-\gamma)}_{=0}\underbrace{(1-\kappa+\gamma)}_{=0}}$$

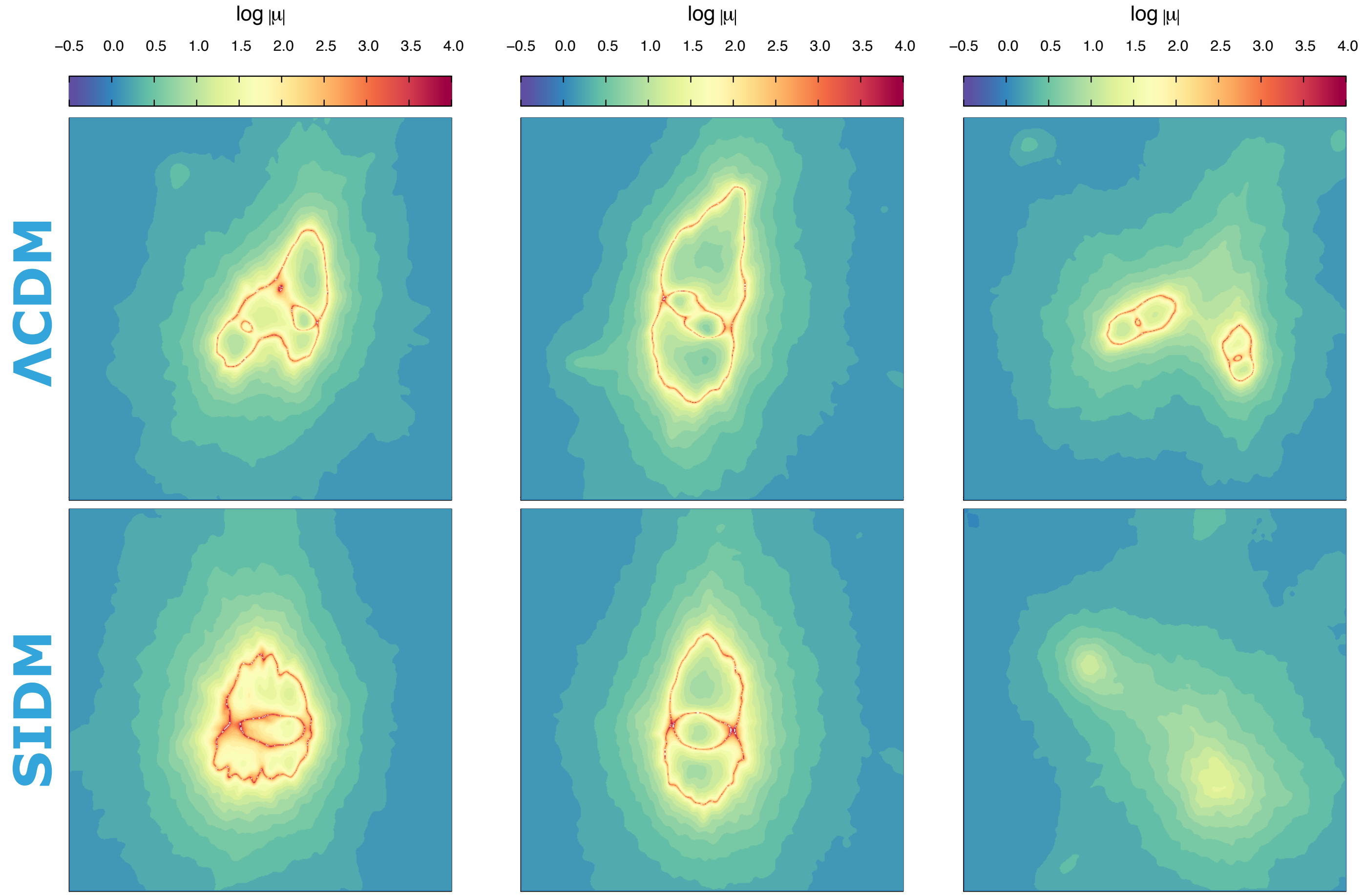
=0 *Tangential CC (total mass)* | **=0** ***Radial CC (slope mass)***



Lens plane z = 0.3 (z_s = 2.0)

3. Gravitational lensing by galaxy clusters

- Ray-shooting (*Meneghetti et al. 2008, 2010*)
  - Project halo particles (DM+GAS) within 4.3h^{-1}Mpc side box
  - Light-rays through a regular grid of 512 × 512 pix (250'' x 250'')
  - **1,000 random projections** on the lens plane
  - Select **super-critical projections** with $\boldsymbol{\mu_r > 1{,}000}$



Clus2
z = 0.429
z_s = 2.0

3. Gravitational lensing by galaxy clusters

- Super-critical projections (μ_r > 1,000)

Cluster	*z*	ΛCDM	SIDM
clus2	0.250	✓	✗
clus9	0.250	✓	✗
clus11	0.250	✓	✗
clus11	0.300	✓	✓
clus2	0.333	✓	✗
clus9	0.333	✓	✓
clus11	0.333	✓	✓
clus2	0.429	✓	✓
clus7	0.429	✓	✓
clus82	0.429	✓	✓
clus2	0.538	✓	✓
clus9	0.538	✓	✓
clus30	0.538	✓	✓

Strong lensing comparison ΛCDM/SIDM
6 halos
4 redshifts

SIDM clusters at low redshift are not supercritical

↑

Cores with
$\Sigma < \Sigma_c$

↑

DM self-interactions in mergers

3. Gravitational lensing by galaxy clusters

- Super-critical projections ($\mu_r > 1{,}000$)

  - Einstein radius slightly larger in ΛCDM than SIDM

$$\theta_E \propto \sqrt{\Sigma(< R_E)}$$

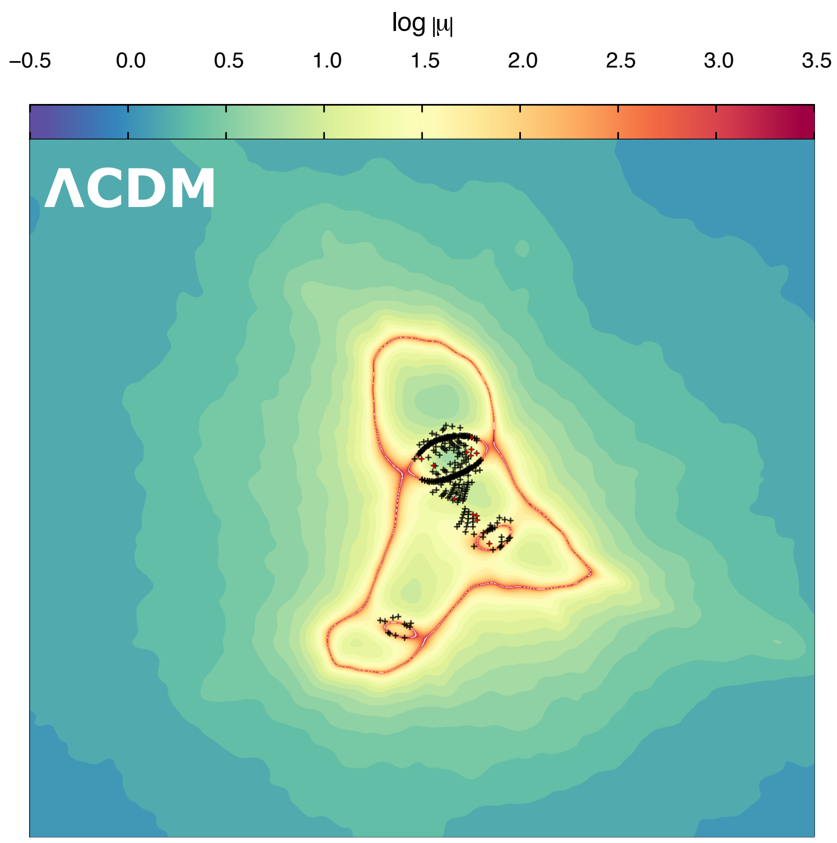
  - Number of projections with tangential CC larger in ΛCDM than SIDM

  - Number of projections with radial CC larger in ΛCDM than SIDM

cluster	model	z	$\theta_E('')$	max(θ_E)	n_t	n_r
clus11	ΛCDM	0.300	$35.9^{+5.9}_{-12.1}$	62.6	1000	238
clus11	SIDM	0.300	$31.5^{+6.9}_{-12.4}$	58.2	1000	163
clus11	ΛCDM	0.333	$35.3^{+3.6}_{-3.4}$	56.0	1000	580
clus11	SIDM	0.333	$20.4^{+13.2}_{-5.5}$	50.7	1000	194
clus9	ΛCDM	0.333	$20.3^{+3.9}_{-3.2}$	41.7	966	213
clus9	SIDM	0.333	$16.8^{+1.1}_{-2.7}$	20.2	60	37
clus2	ΛCDM	0.429	$21.3^{+14.5}_{-5.5}$	52.8	1000	361
clus2	SIDM	0.429	$33.2^{+2.2}_{-3.8}$	49.1	297	77
clus7	ΛCDM	0.429	$19.5^{+7.9}_{-4.9}$	49.4	802	148
clus7	SIDM	0.429	$18.0^{+2.6}_{-5.5}$	41.4	335	40
clus82	ΛCDM	0.429	$33.2^{+4.7}_{-5.5}$	45.0	1000	771
clus82	SIDM	0.429	$30.4^{+4.6}_{-4.7}$	43.6	1000	449
clus2	ΛCDM	0.538	$18.8^{+4.6}_{-2.8}$	32.3	733	411
clus2	SIDM	0.538	$18.4^{+3.6}_{-3.4}$	29.5	160	14
clus9	ΛCDM	0.538	$27.2^{+2.1}_{-4.1}$	40.5	943	497
clus9	SIDM	0.538	$23.0^{+2.1}_{-4.8}$	33.7	869	301
clus30	ΛCDM	0.538	$21.1^{+3.7}_{-3.5}$	37.2	1000	272
clus30	SIDM	0.538	$17.3^{+5.6}_{-4.7}$	33.9	602	427

4. Radial arcs statistics

- High-res maps (2048x2048 pix^2, **0.12x0.12 arcsec^2** resolution)
- Lensing of $\mathcal{O}$**(10^4) random sources** in the source plane (z_s = 2.0)
    - Spatial density of sources increases near the caustics
    - **Elliptical sources** (axis ratios > 0.5), surface = circle 1'' radius
- **Radial arcs** selection: $\boldsymbol{\mu_r > 5}$ and $\boldsymbol{(\mu_r / \mu_t) > 4}$



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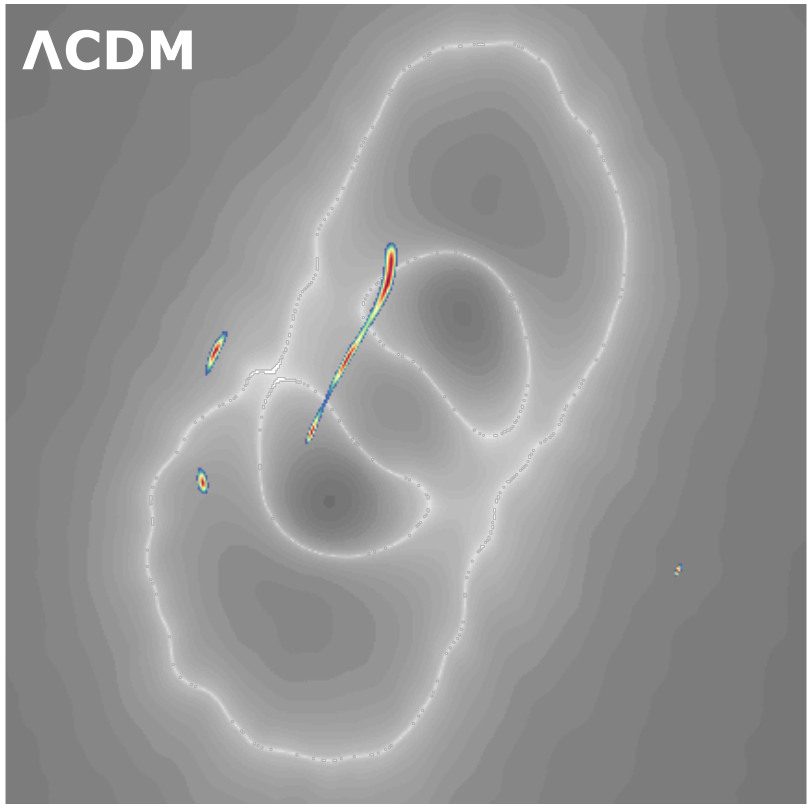

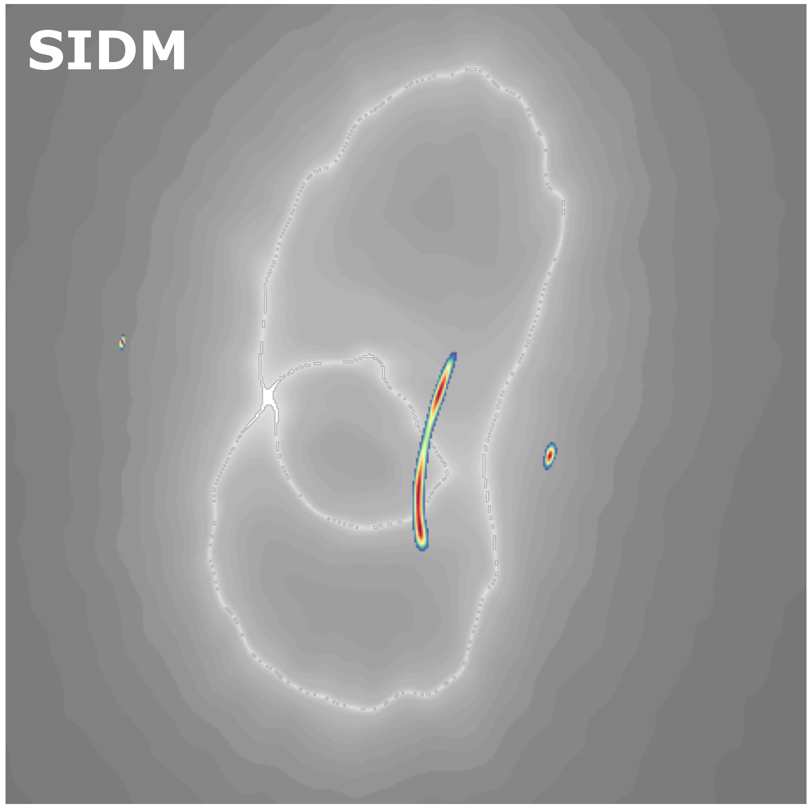

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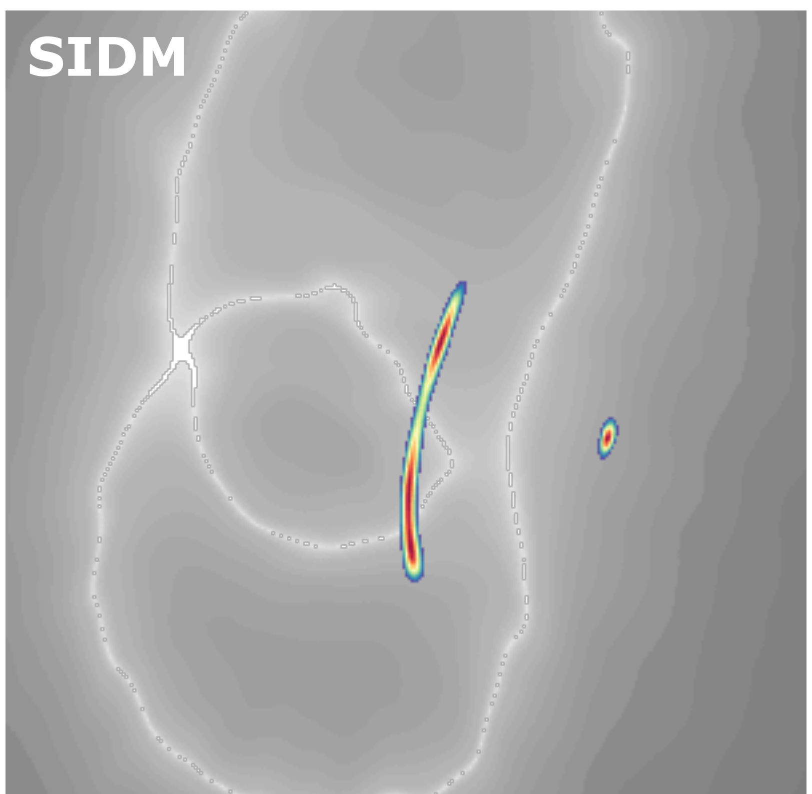
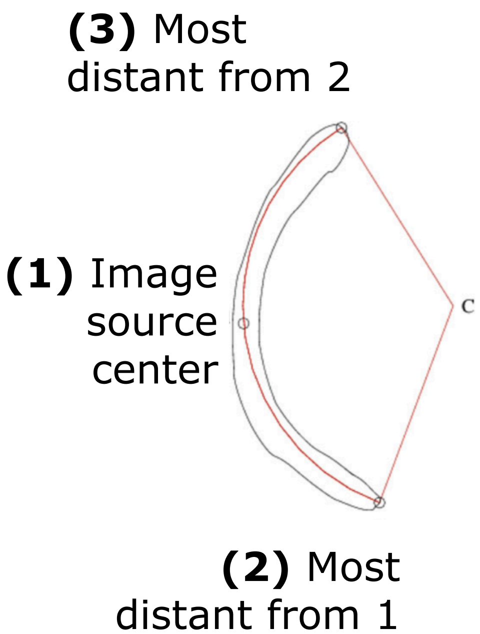


Length (l) and width (w) of radial arcs

(Miralda-Escudé 1993, Bartlemann & Weiss 1994)



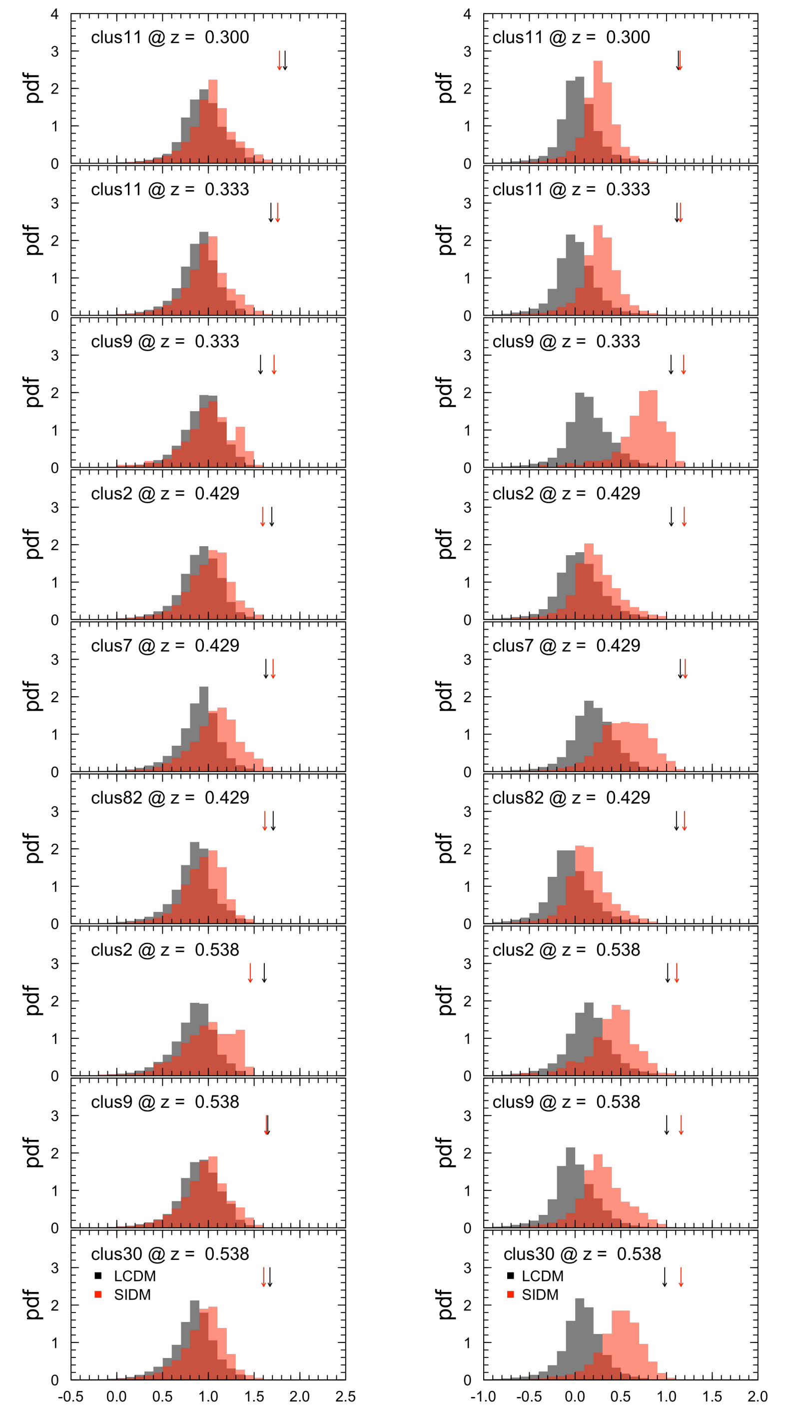
Length (l): segment connecting 1 and 3

Width (l): fitting ellipse, circle, rectangle and ring

4. Radial arcs statistics

cluster	model	z	n_t	n_r	$\log l('')$ (Log *l* (''))	$\max(\log l)$	$\log w('')$ (Log *w* (''))	$\max(\log w)$	n_{arcs} (Number of radial arcs)
clus11	ΛCDM	0.300	1000	238	$0.94^{+0.14}_{-0.14}$	1.84	$0.03^{+0.12}_{-0.11}$	1.13	212219
clus11	SIDM	0.300	1000	163	$1.04^{+0.13}_{-0.13}$	1.78	$0.27^{+0.10}_{-0.10}$	1.15	93961
clus11	ΛCDM	0.333	1000	580	$0.90^{+0.11}_{-0.14}$	1.68	$-0.01^{+0.13}_{-0.12}$	1.11	343837
clus11	SIDM	0.333	1000	194	$1.00^{+0.13}_{-0.14}$	1.76	$0.27^{+0.11}_{-0.11}$	1.15	67274
clus9	ΛCDM	0.333	966	213	$0.96^{+0.13}_{-0.15}$	1.57	$0.13^{+0.16}_{-0.12}$	1.05	62213
clus9	SIDM	0.333	60	37	$1.03^{+0.16}_{-0.17}$	1.72	$0.77^{+0.12}_{-0.15}$	1.19	707
clus2	ΛCDM	0.429	1000	361	$0.92^{+0.13}_{-0.15}$	1.69	$0.04^{+0.16}_{-0.14}$	1.05	135897
clus2	SIDM	0.429	297	77	$1.04^{+0.13}_{-0.17}$	1.59	$0.21^{+0.16}_{-0.12}$	1.19	19173
clus7	ΛCDM	0.429	802	148	$0.91^{+0.11}_{-0.14}$	1.63	$0.19^{+0.15}_{-0.14}$	1.15	37496
clus7	SIDM	0.429	335	40	$1.09^{+0.16}_{-0.17}$	1.71	$0.55^{+0.19}_{-0.19}$	1.20	3291
clus82	ΛCDM	0.429	1000	771	$0.86^{+0.11}_{-0.14}$	1.71	$-0.07^{+0.15}_{-0.13}$	1.11	437454
clus82	SIDM	0.429	1000	449	$0.97^{+0.13}_{-0.16}$	1.62	$0.13^{+0.14}_{-0.12}$	1.20	206500
clus2	ΛCDM	0.538	733	411	$0.86^{+0.13}_{-0.15}$	1.61	$0.14^{+0.14}_{-0.14}$	1.01	69457
clus2	SIDM	0.538	160	14	$1.01^{+0.19}_{-0.21}$	1.46	$0.44^{+0.13}_{-0.17}$	1.11	619
clus9	ΛCDM	0.538	943	497	$0.91^{+0.14}_{-0.15}$	1.65	$-0.02^{+0.15}_{-0.12}$	1.00	166090
clus9	SIDM	0.538	869	301	$0.99^{+0.14}_{-0.16}$	1.63	$0.29^{+0.16}_{-0.13}$	1.16	42223
clus30	ΛCDM	0.538	1000	272	$0.85^{+0.12}_{-0.14}$	1.67	$0.08^{+0.13}_{-0.12}$	0.98	100856
clus30	SIDM	0.538	602	427	$0.98^{+0.13}_{-0.16}$	1.60	$0.50^{+0.14}_{-0.14}$	1.16	19179

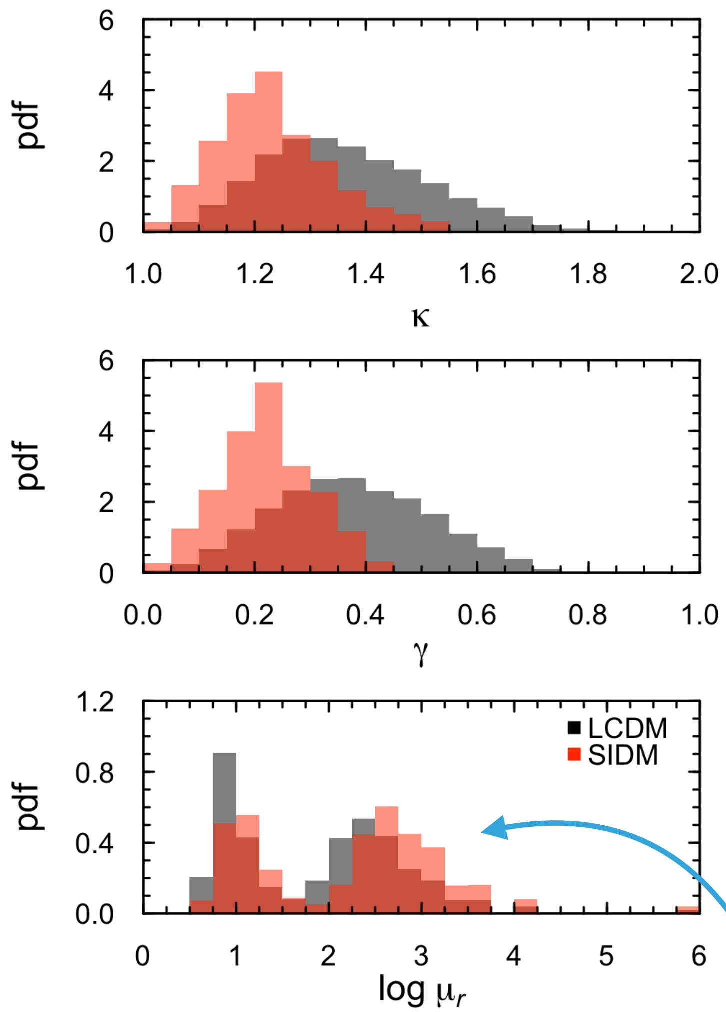
ΛCDM SIDM



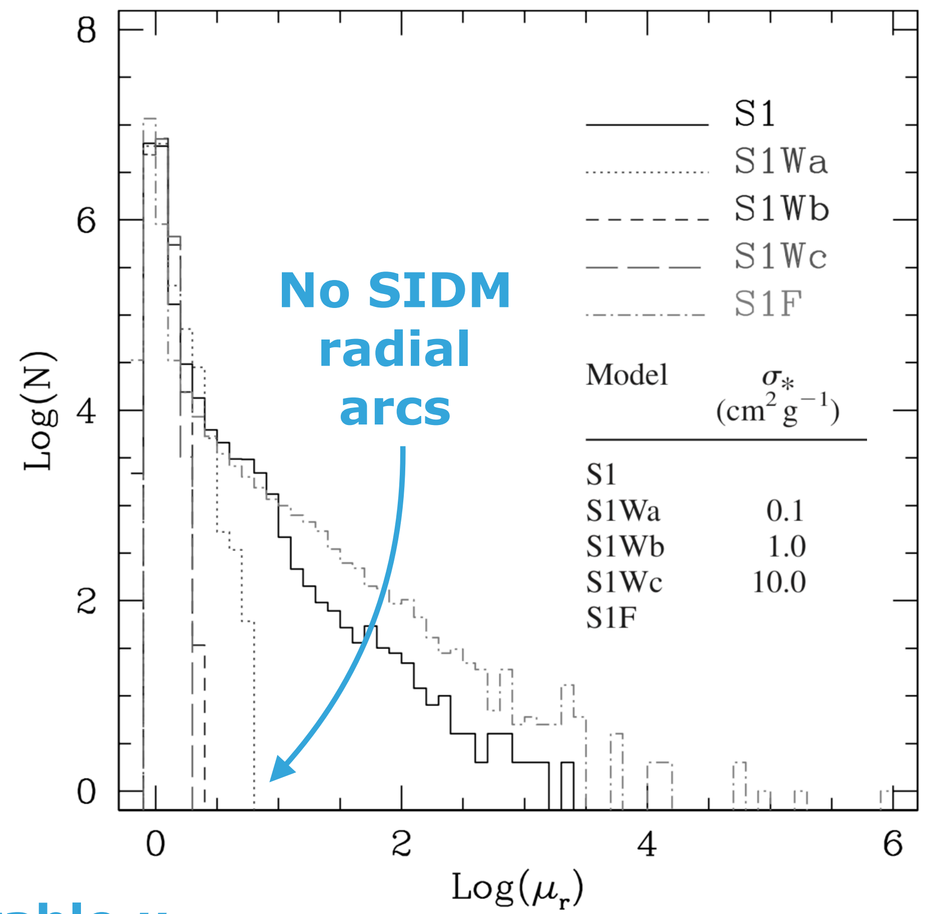
4. Radial arcs statistics

- All radial arcs found

This work



Meneghetti et al. 2001



No SIDM radial arcs

Comparable μ_r

ΛCDM SIDM

5. Conclusions and future prospects

- 6 cluster-size DM halos @ $z \sim (0.250, 0.300, 0.333, 0.429, 0.538)$
- LCDM and SIDM (**σ/m = 1 cm²/g**) cosmological models
- **1,000 different projections** on the lens plane
- **High-resolution** lensing maps (0.12 arcsec/pix)
- **No supercritical SIDM halo for $z < 0.3$**
- Length of radial arcs:
  - **$mean(l_{SIDM}) \gtrsim mean(l_{LCDM})$**
  - **$max(l_{SIDM}) \sim 60''$, $max(l_{LCDM}) \sim 69''$**
- Width of radial arcs: **$mean(w_{SIDM}) > mean(w_{LCDM})$**
- Radial arcs in SIDM in regions with **smaller convergence and shear**
- **Comparable radial magnifications**

5. Conclusions and future prospects

SIDM with σ/m = 1 cm^2/g cannot be ruled out based strong lensing by galaxy clusters

To do list:

- **Lensing probability in ΛCDM/SIDM** (both tangential and radial)
- Increase number of halos (variation in density profiles)
- Velocity-dependence of DM interactions in GIZMO
- **Baryonic effects in SIDM** simulations (*Brinckmann et al. 2018*)

Thank you!