Self-interacting Dark Matter: New Constraints from Galaxy Groups and Clusters

Laura Sagunski

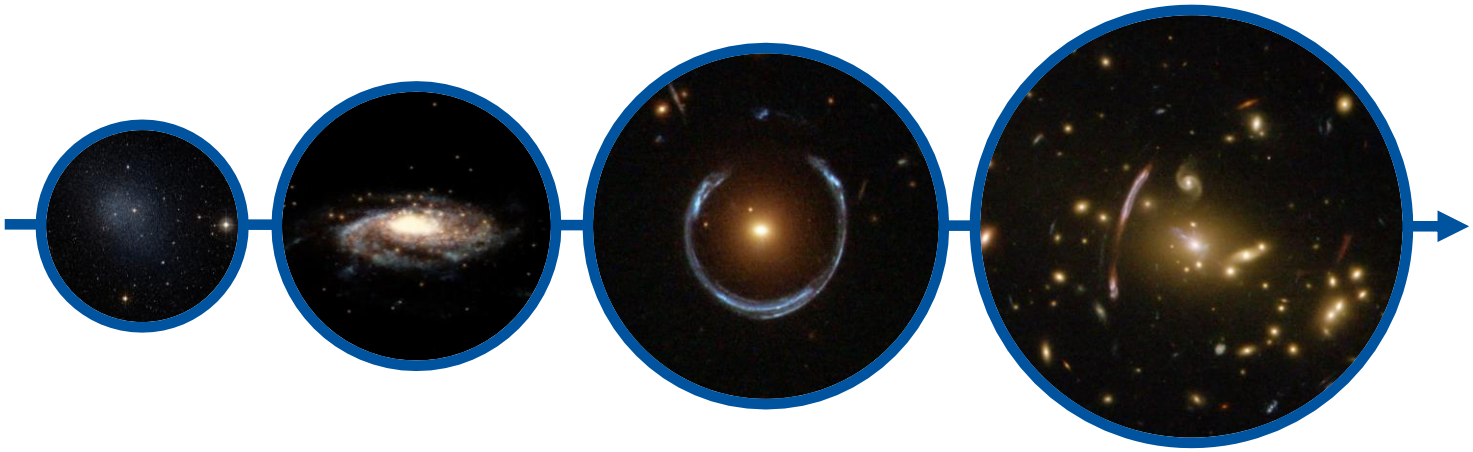
with

Brian Colquhoun, Sophia Nasr, Sean Tulin

YORK UNIVERSITÉ UNIVERSITY

RWTH AACHEN UNIVERSITY

Astrophysical probes of dark matter



Images: [ESO/Digitized Sky Survey 2][Daley; smithsonian.com]
[NASA, ESA; Bolton, SLACS Team][NASA, ESA; Richard, Kneib]

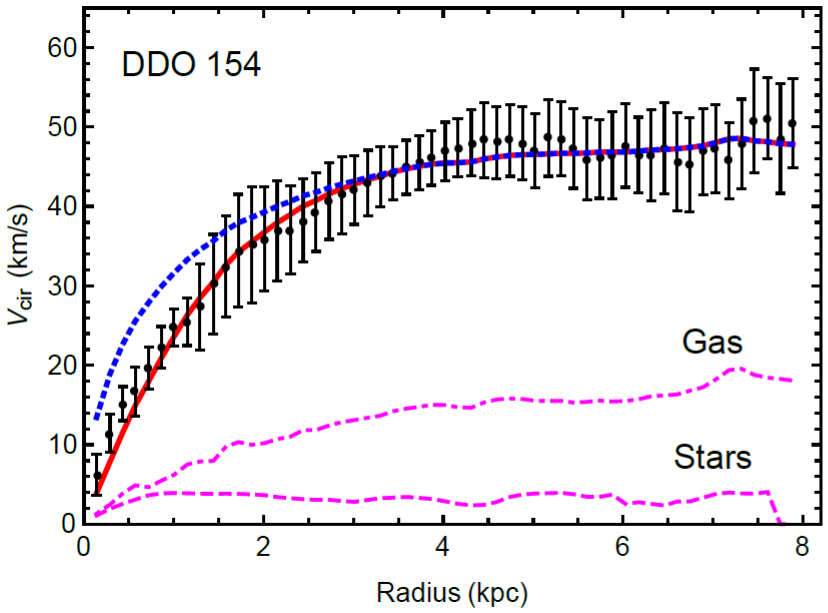
Dwarf galaxies

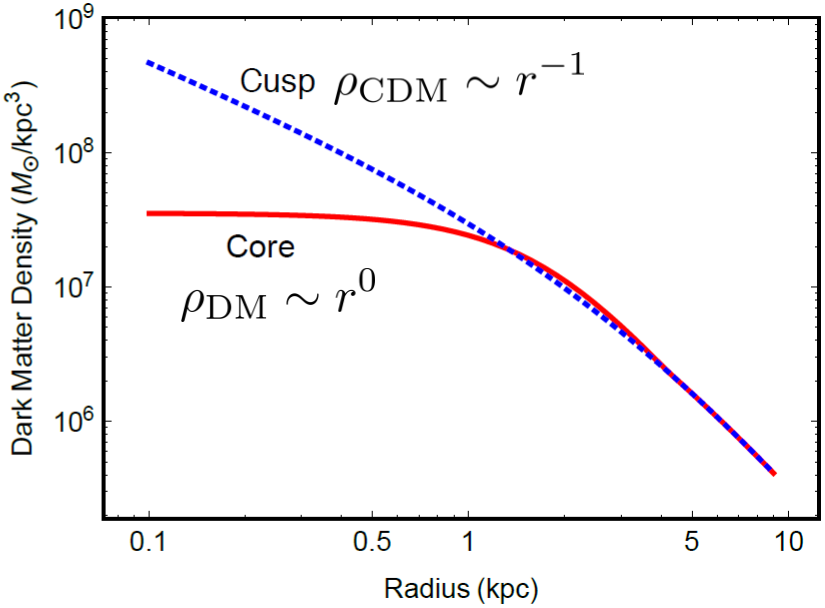
Core-cusp problem:

[Moore, '94][Flores, Primack, '94]

DM density profile: core ↔ cusp (cold, collisionless dark matter)

→ Small-scale crisis





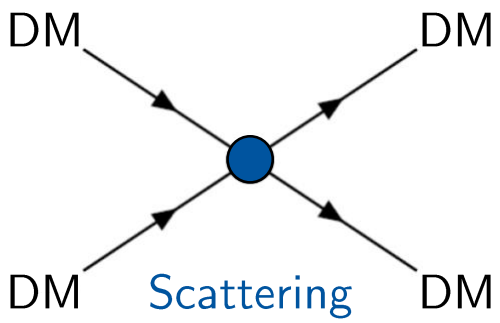
Adapted from: [Tulin, Yu, '17]

Self-interacting dark matter (SIDM)

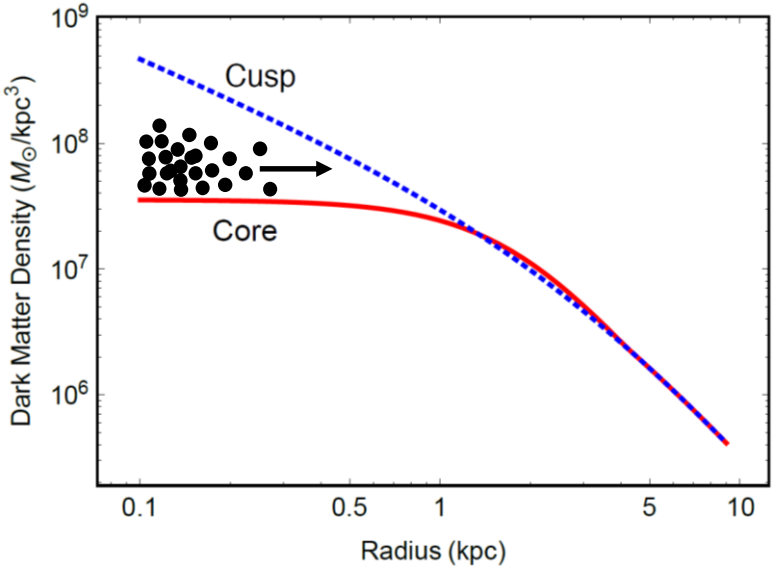
CDM = cold, collisionless dark matter

SIDM = cold, collisional dark matter [Spergel, Steinhardt, '99]

$\longrightarrow$ DM particles self-interact



$$\sigma/m \sim 1\ \mathrm{cm}^2/\mathrm{g} \sim 2\ \mathrm{barns/GeV}$$

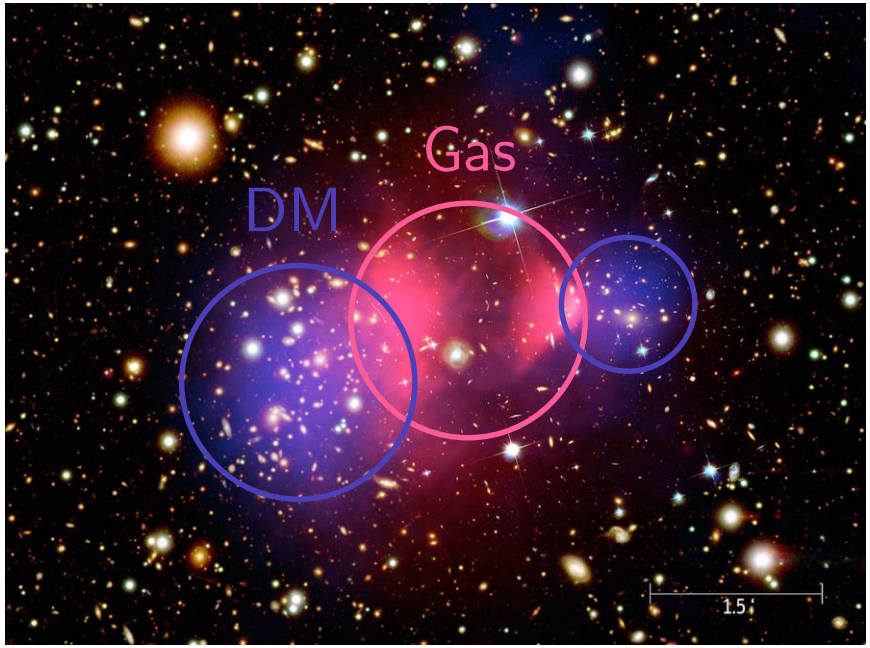


Adapted from: [Tulin, Yu, '17]

Clusters

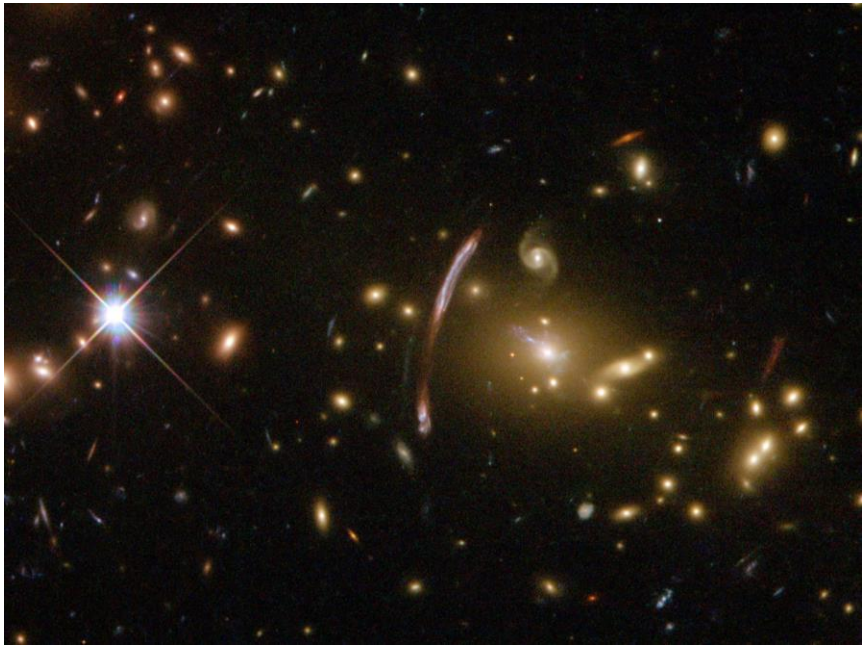
Mergers

[NASA/CXC; Weiss]



Relaxed systems

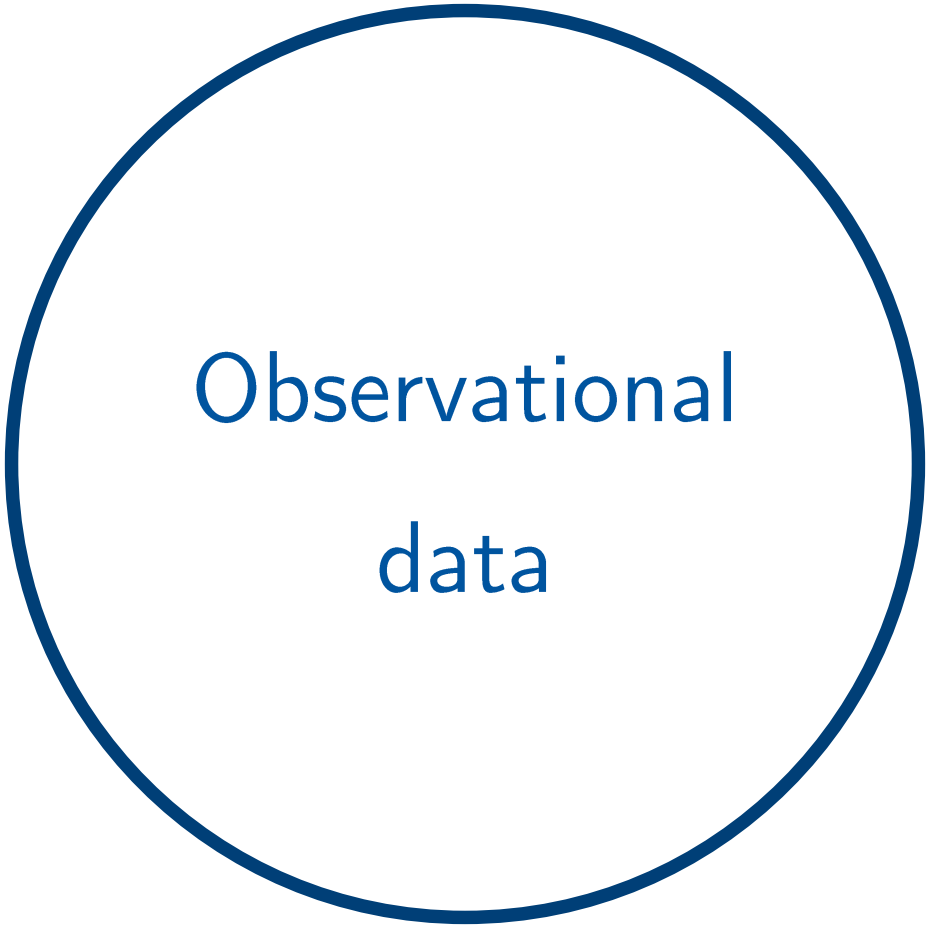
[NASA,ESA; Richard, Kneib]



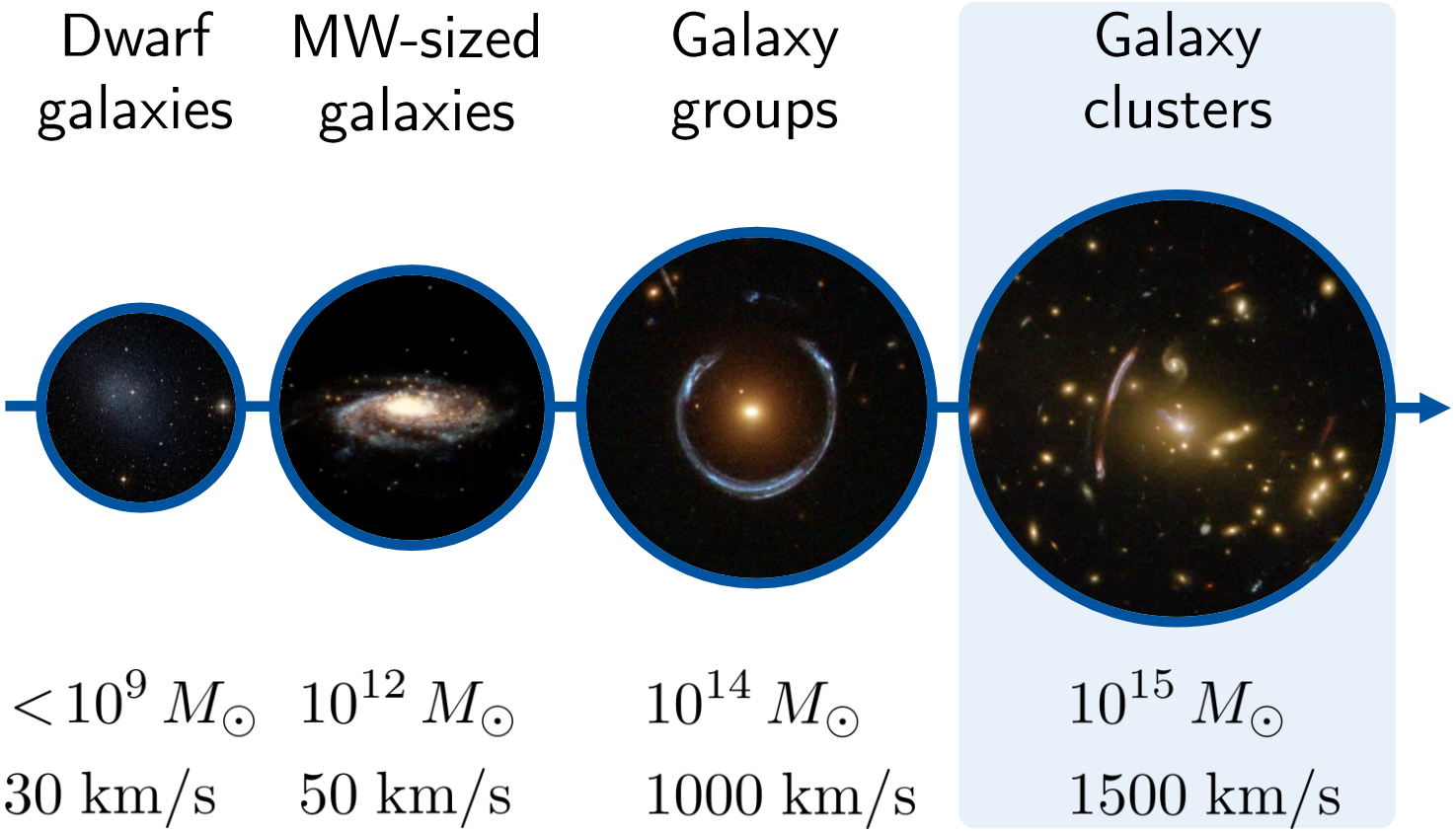
Bullet cluster: [Randall et al., '07]

$$\sigma/m < 1.25\,\mathrm{cm}^2/\mathrm{g}\ (68\%\ \mathrm{CL})$$

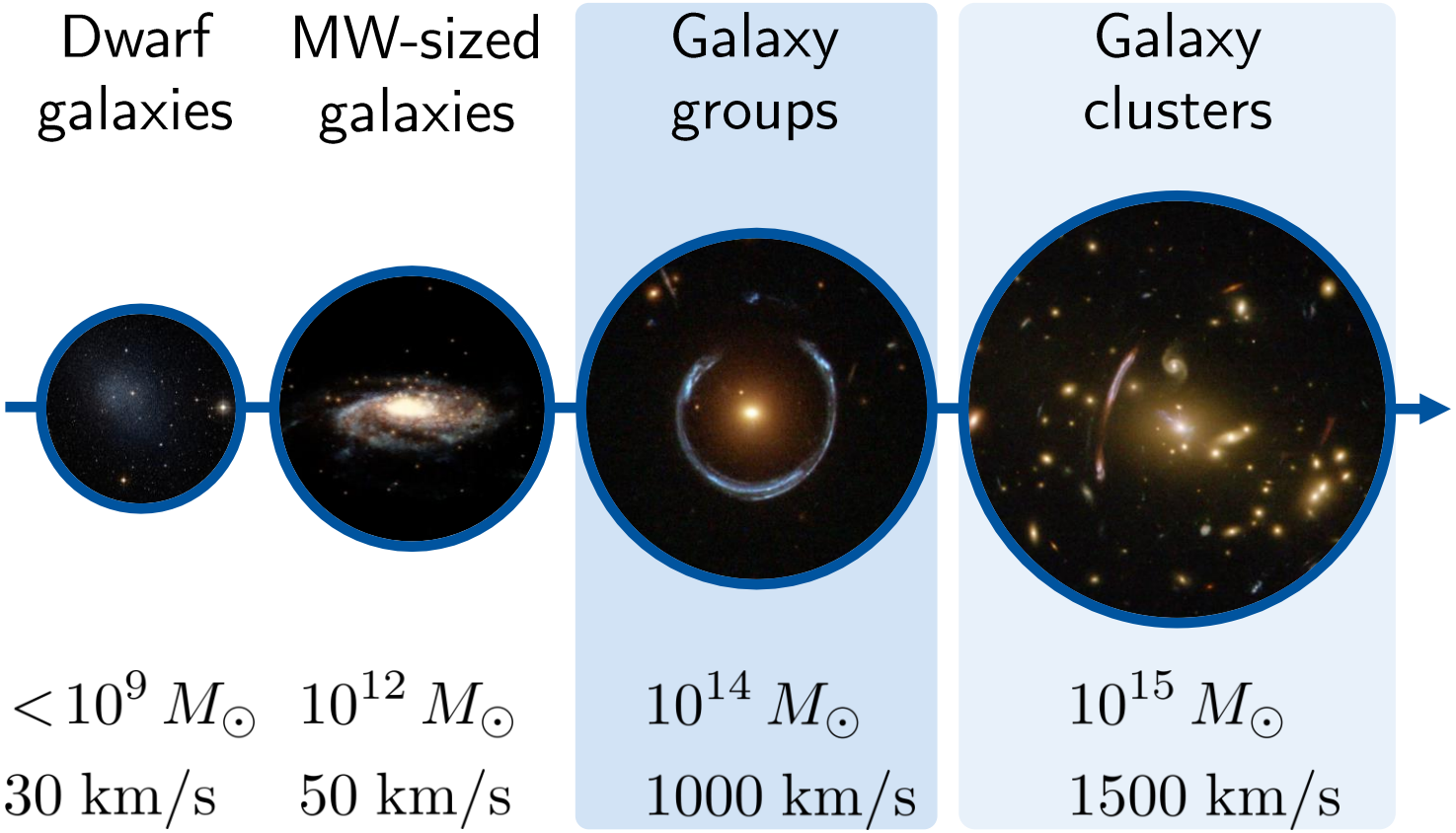
$\longrightarrow$ Much stronger bounds!


Observational
data

DM halos as particle colliders



DM halos as particle colliders



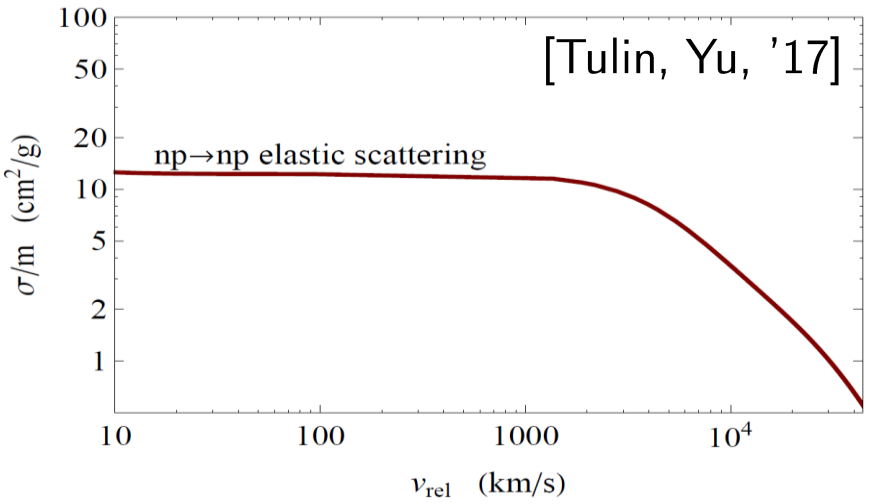
DM halos as particle colliders

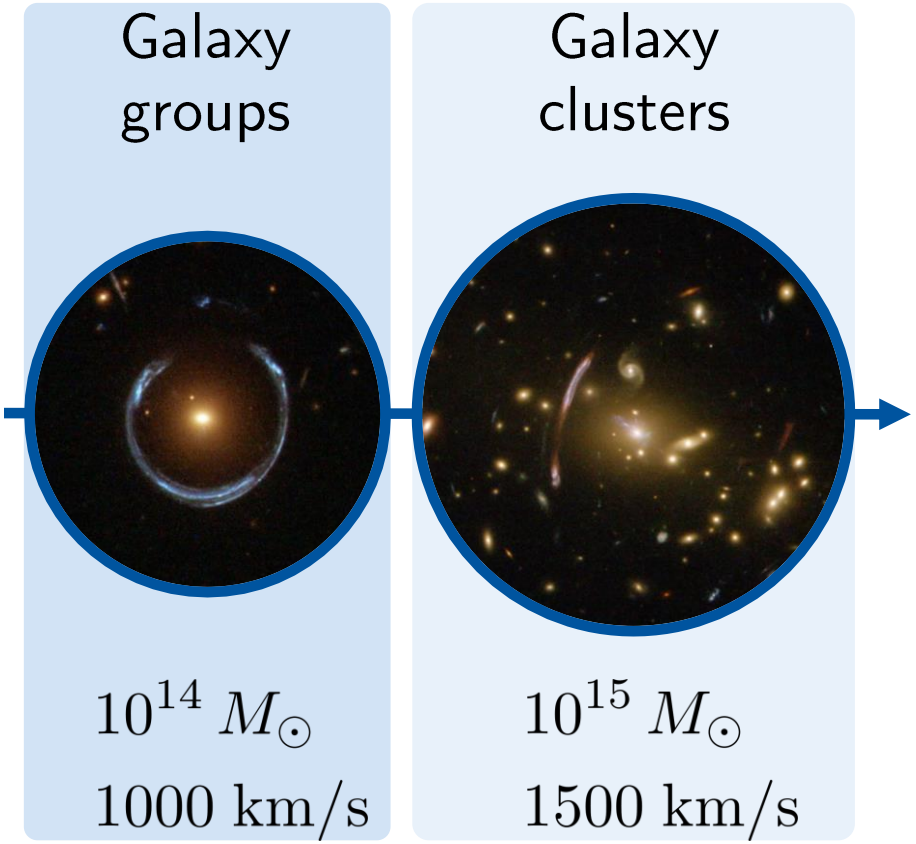
Particle physics:

σ/m is velocity-dependent

→ Example:

"nucleon self-interactions"





Observational data

Data from 15 relaxed systems:

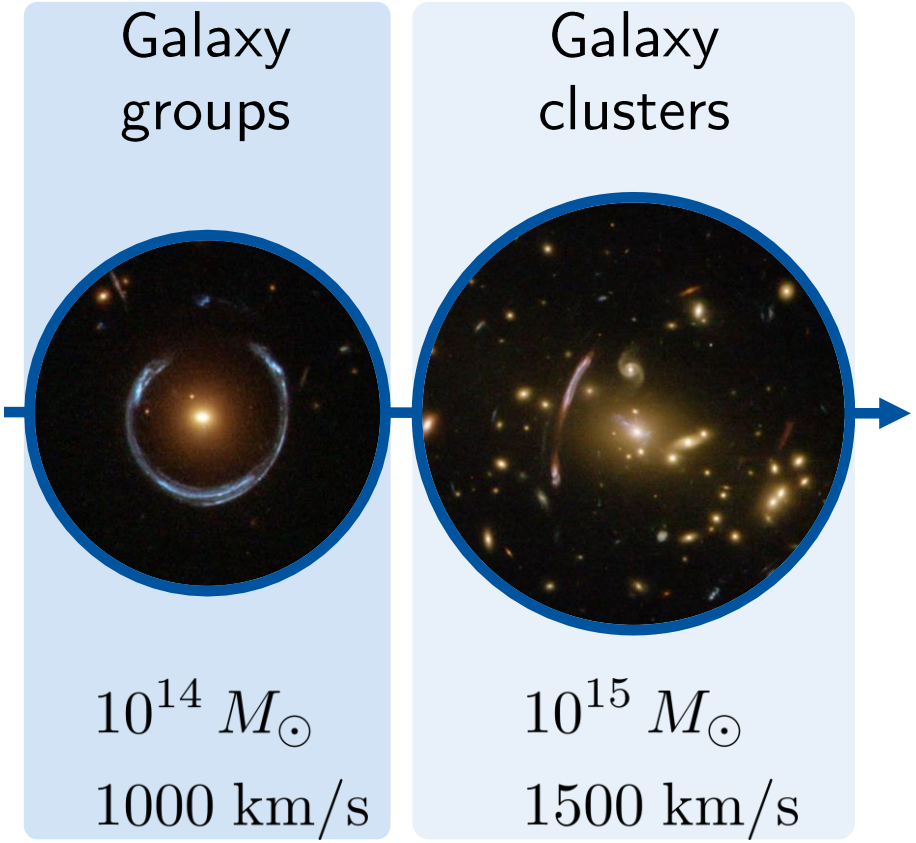
- 8 galaxy groups

  [Newman, Ellis, Treu, '15]

- 7 galaxy clusters

  [Newman et al. '12]
  [Newman, Ellis, Treu, '12]

→ For the first time: probe SIDM at group scales!



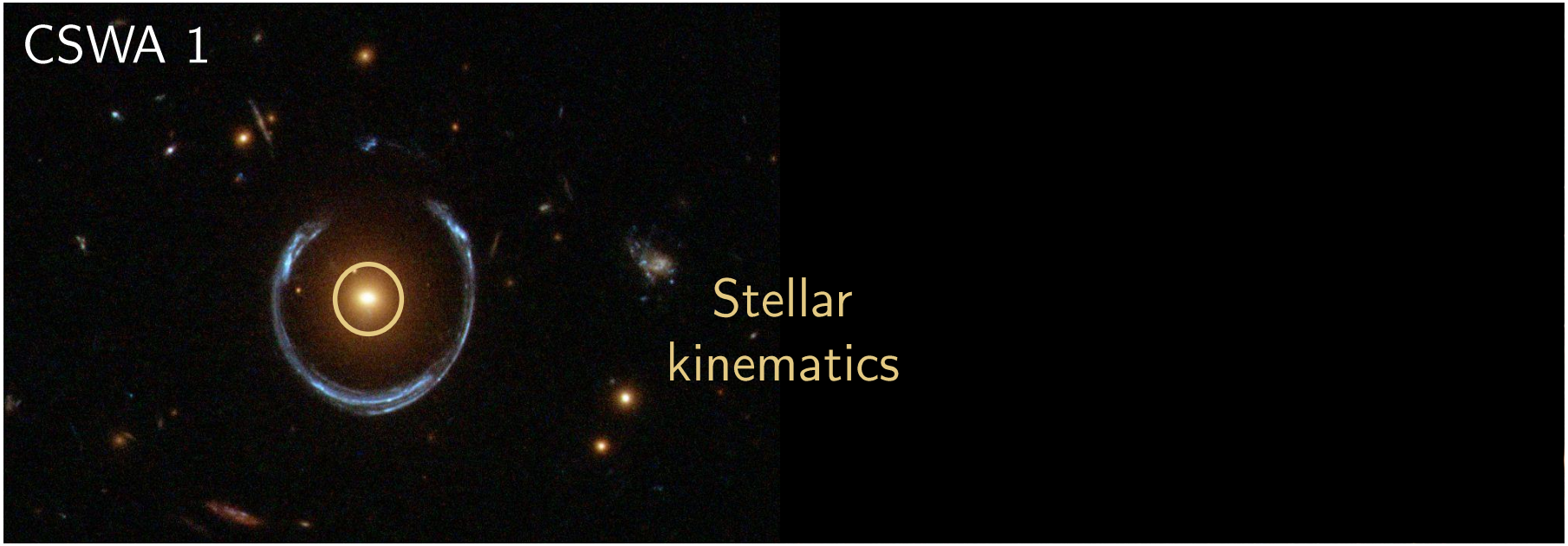
Observational data

8 galaxy groups:

[ESA/Hubble, NASA]

Observational data

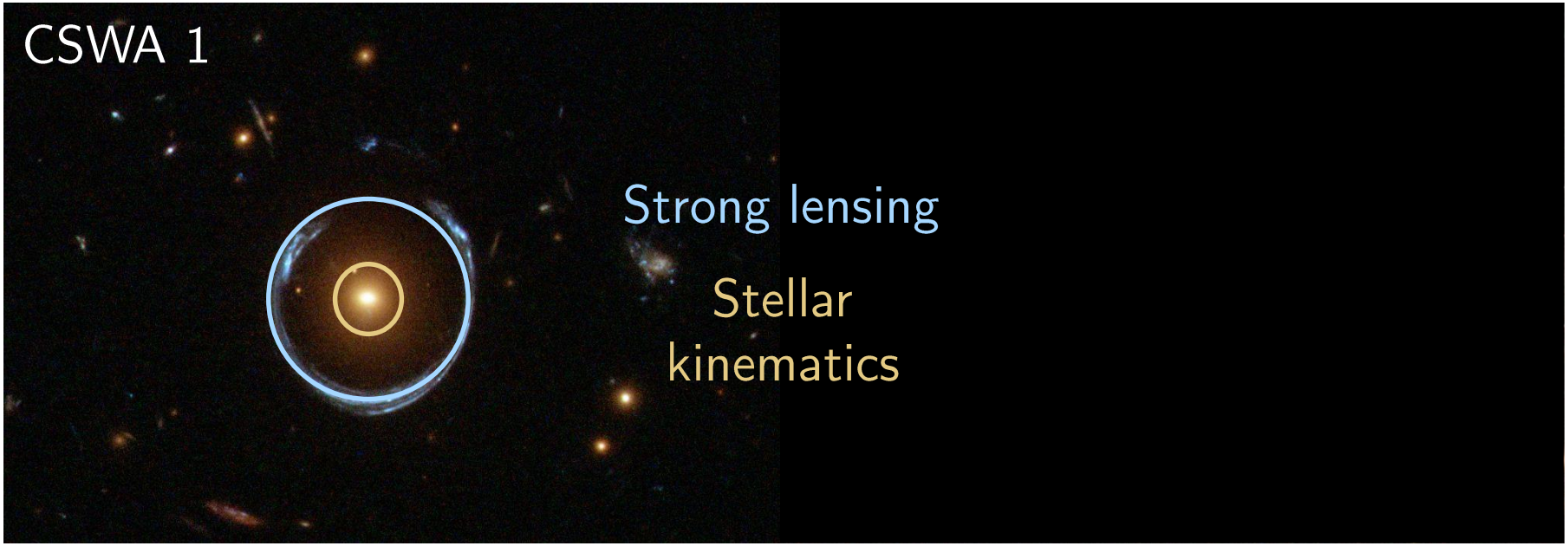
8 galaxy groups:



[ESA/Hubble, NASA]

Observational data

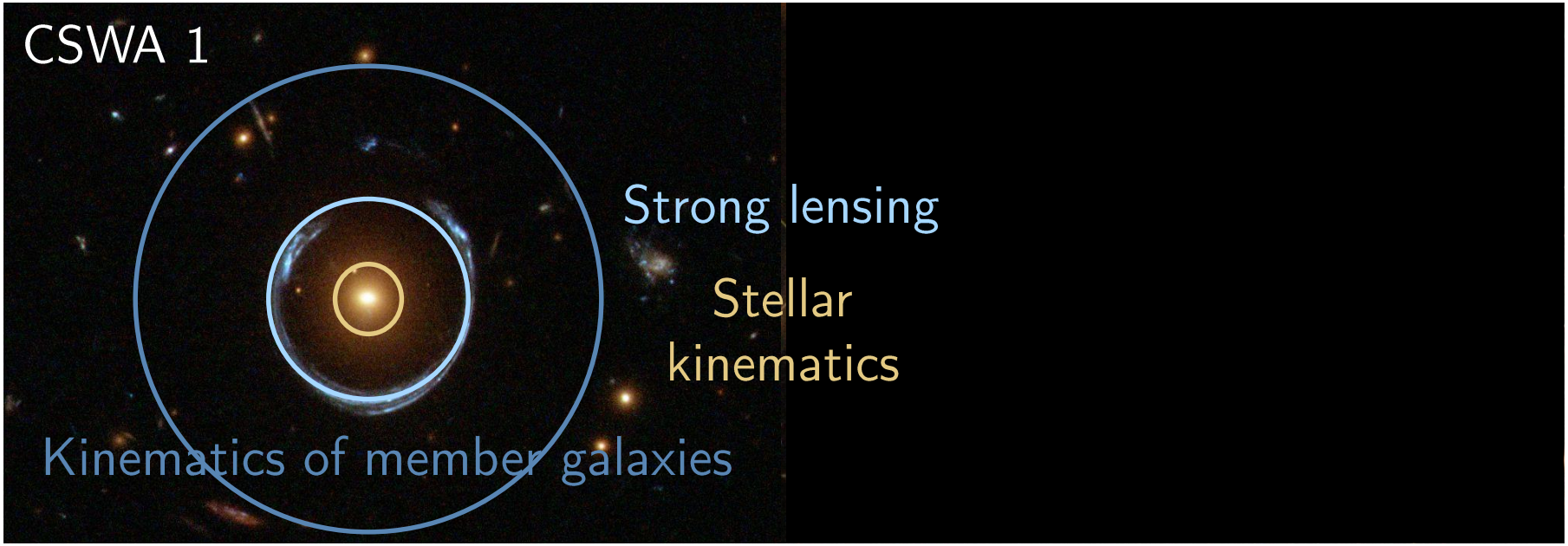
8 galaxy groups:



[ESA/Hubble, NASA]

Observational data

8 galaxy groups:

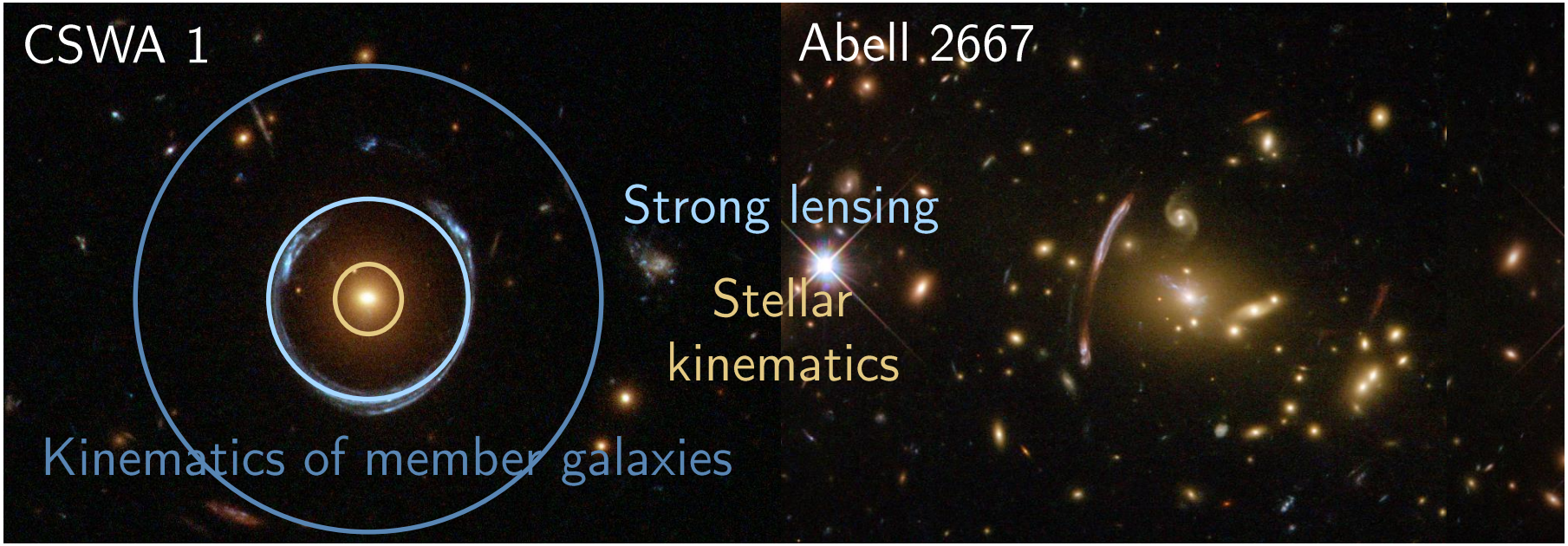


[ESA/Hubble, NASA]

Observational data

8 galaxy groups:

7 galaxy clusters:



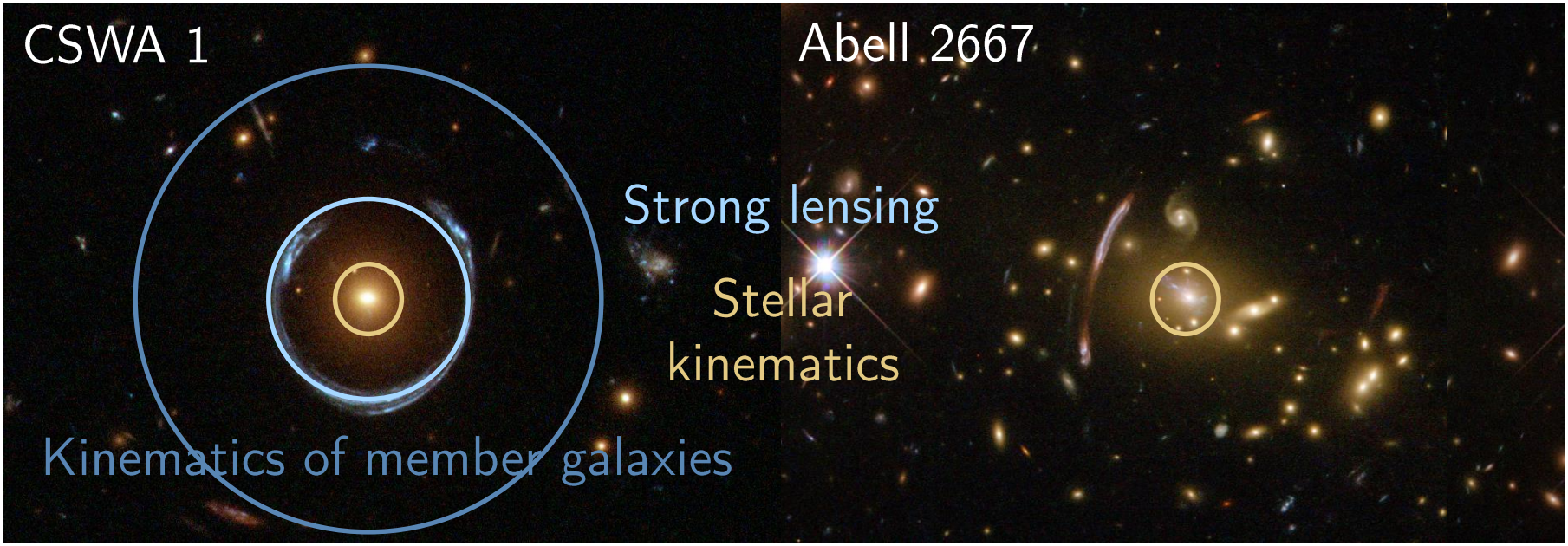
[ESA/Hubble, NASA]

Adapted from: [ESA/Hubble, NASA, J. Kneib]

Observational data

8 galaxy groups:

7 galaxy clusters:



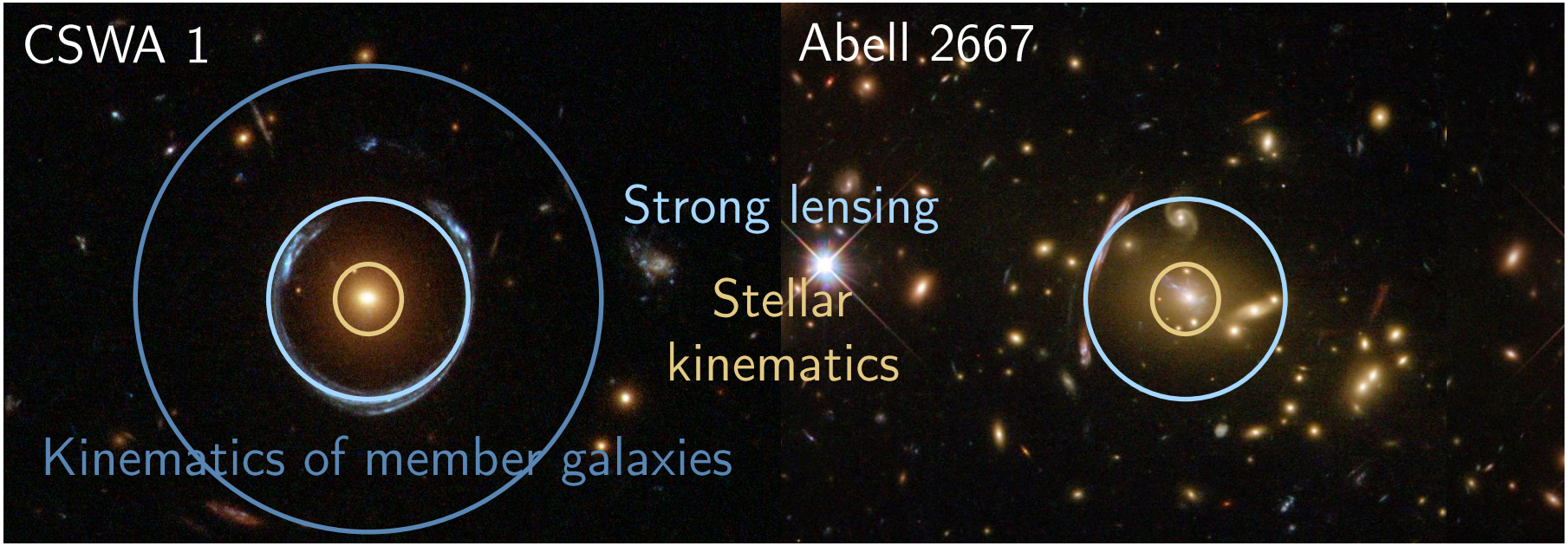
[ESA/Hubble, NASA]

Adapted from: [ESA/Hubble, NASA, J. Kneib]

Observational data

8 galaxy groups:

7 galaxy clusters:



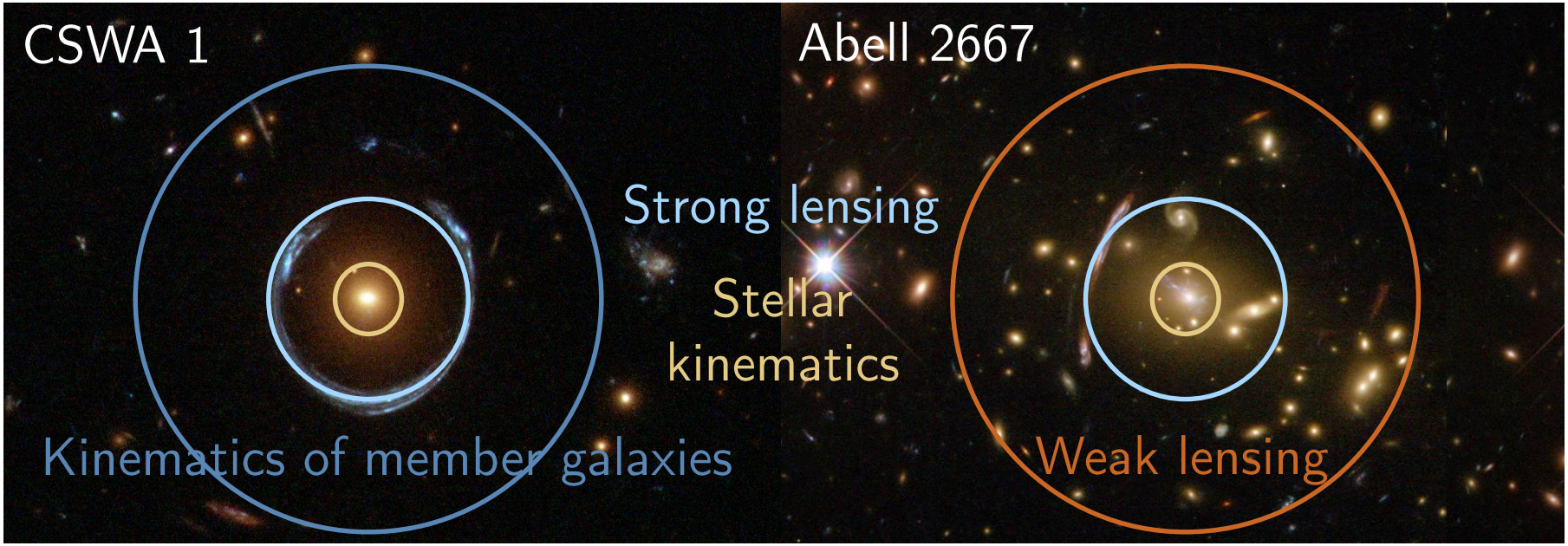
[ESA/Hubble, NASA]

Adapted from: [ESA/Hubble, NASA, J. Kneib]

Observational data

8 galaxy groups:

7 galaxy clusters:



[ESA/Hubble, NASA]

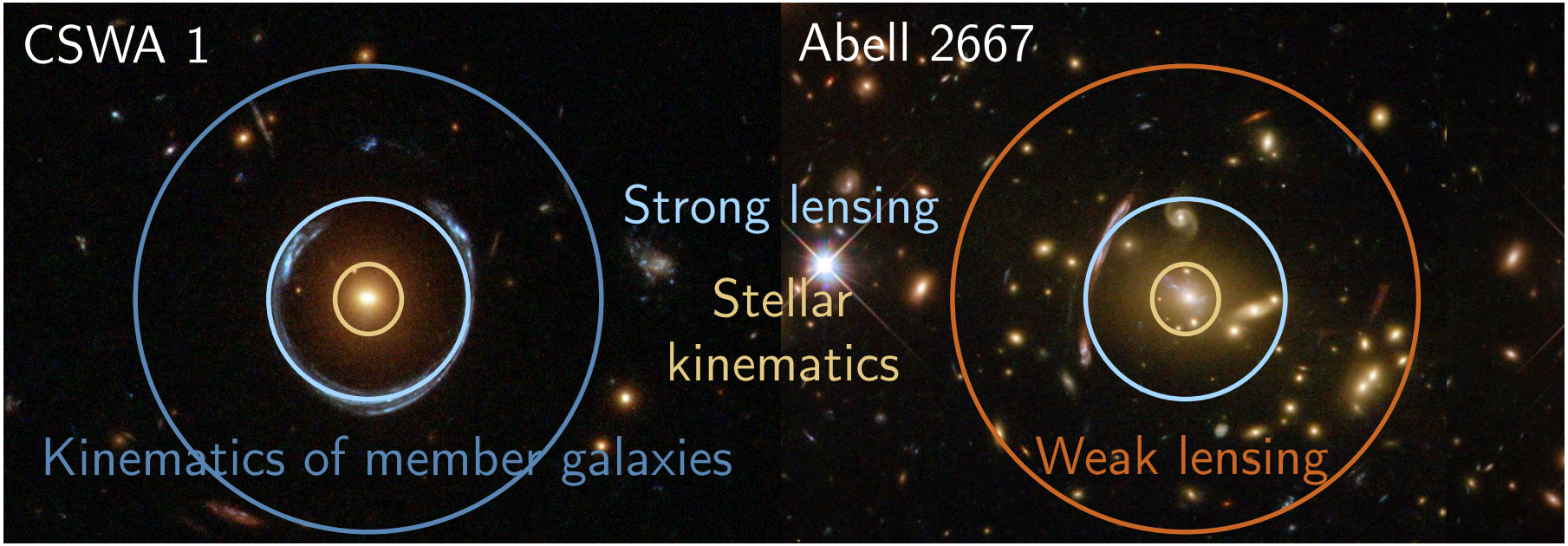
Adapted from: [ESA/Hubble, NASA, J. Kneib]

$\longrightarrow$ Observables at different radii

Observational data

8 galaxy groups:

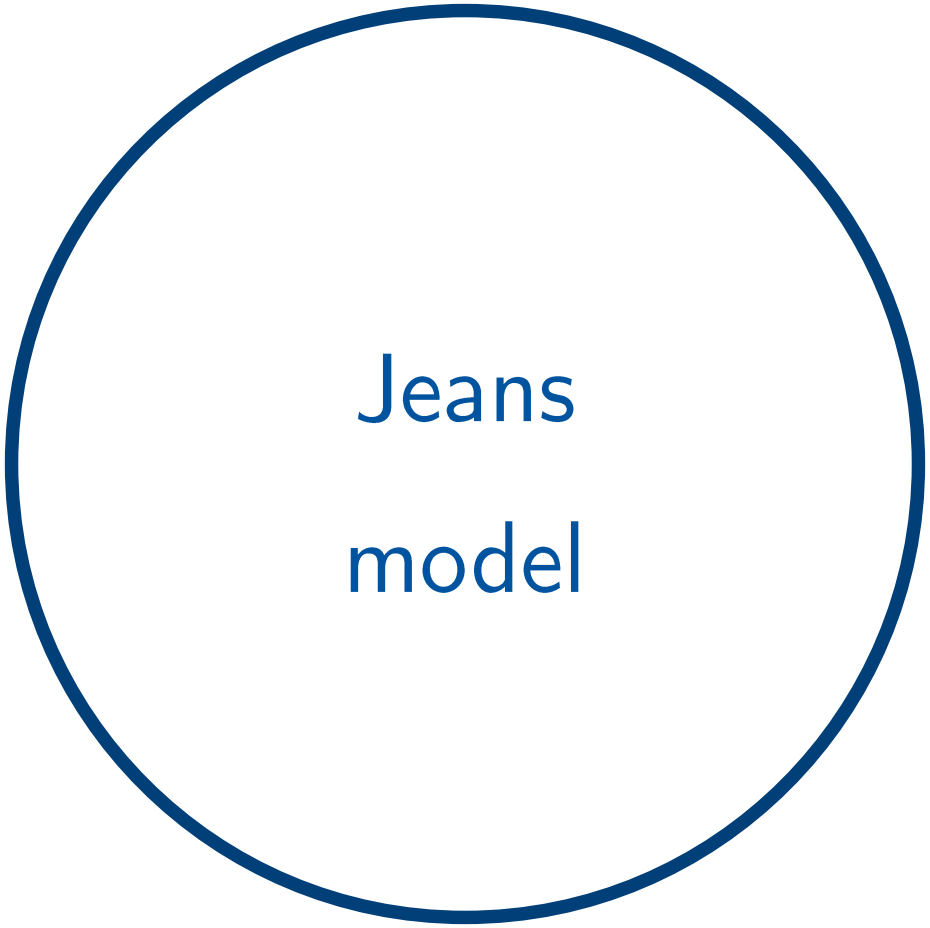
7 galaxy clusters:



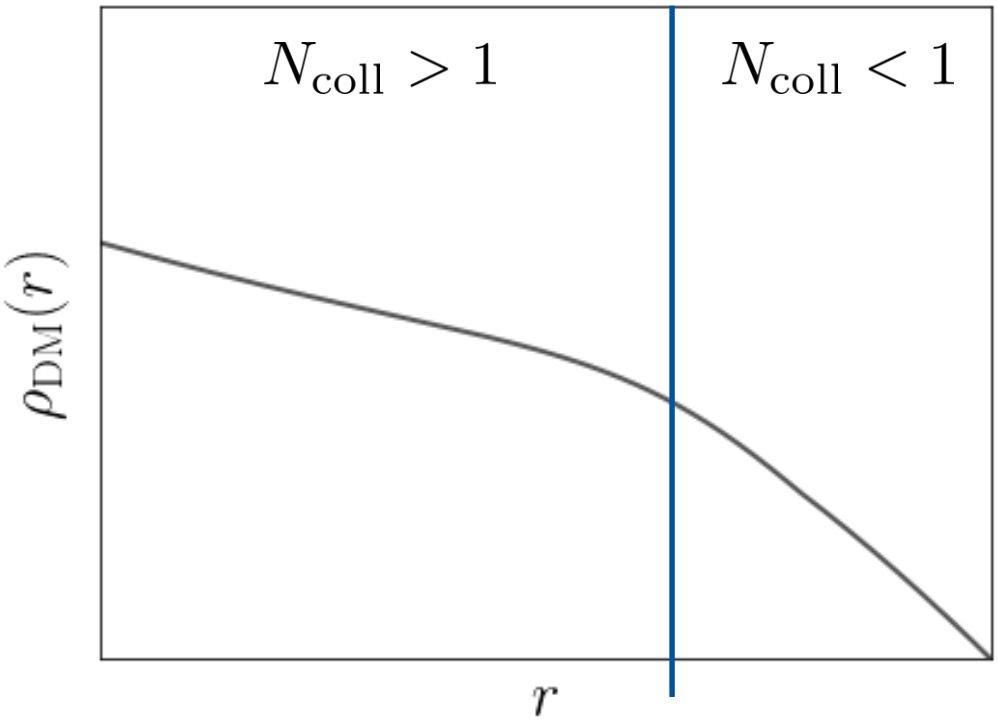
[ESA/Hubble, NASA]

Adapted from: [ESA/Hubble, NASA, J. Kneib]

$\longrightarrow$ Reconstruct full DM halo density profile


Jeans
model

Jeans model



At r_1:

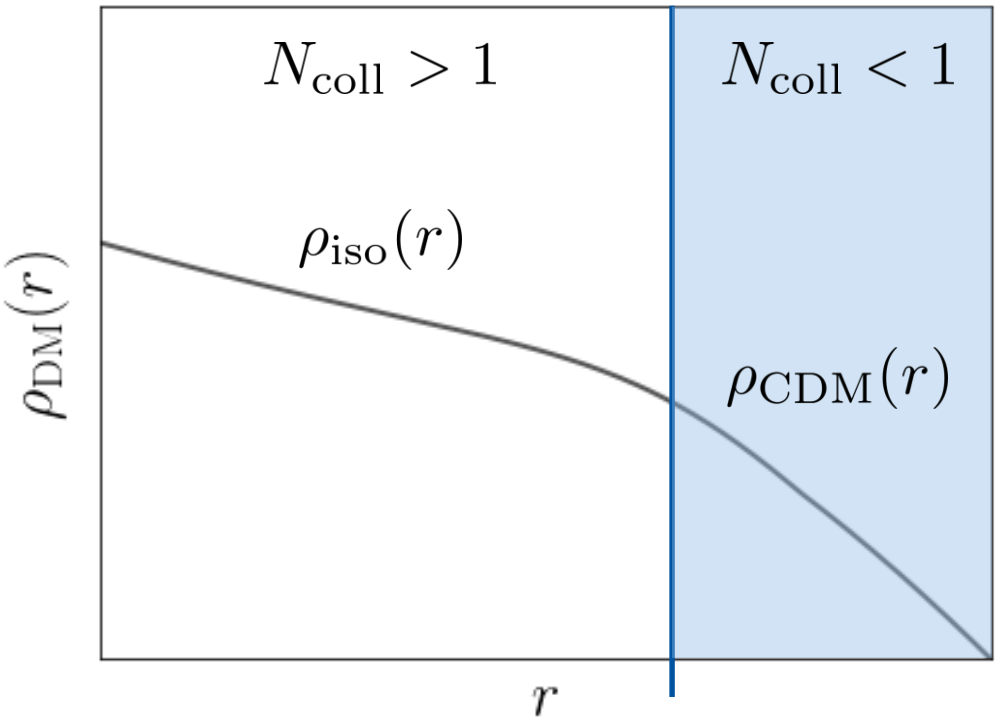
$N_{\rm coll} = 1$

SIDM halo density profile:

$$\rho_{\rm SIDM}(r) = \begin{cases} \rho_{\rm iso}(r), & r < r_1 \\ \rho_{\rm CDM}(r), & r \geq r_1 \end{cases}$$

[Rocha et al., '12][Kaplinghat et al.,'13][Kaplinghat, Tulin, Yu, '15]

Jeans model



At r_1 :

$N_{\rm coll} = 1$

SIDM halo density profile:

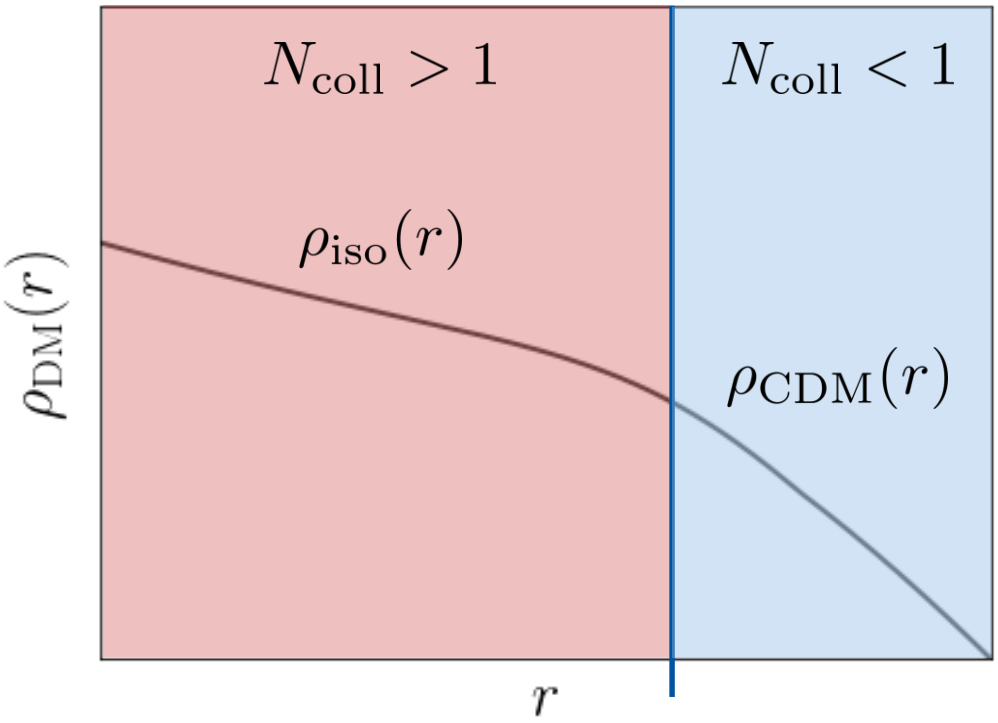
$$\rho_{\rm SIDM}(r) = \begin{cases} \rho_{\rm iso}(r), & r < r_1 \\ \rho_{\rm CDM}(r), & r \geq r_1 \end{cases}$$

NFW profile (CDM)

[Navarro, Frenk, White, '96]

[Rocha et al., '12][Kaplinghat et al.,'13][Kaplinghat, Tulin, Yu, '15]

Jeans model



At r_1 :

$N_{\rm coll} = 1$

SIDM halo density profile:

Isothermal profile from Jeans equation

$$\rho_{\rm SIDM}(r) = \begin{cases} \rho_{\rm iso}(r), & r < r_1 \\ \rho_{\rm CDM}(r), & r \geq r_1 \end{cases}$$

NFW profile (CDM)

[Navarro, Frenk, White, '96]

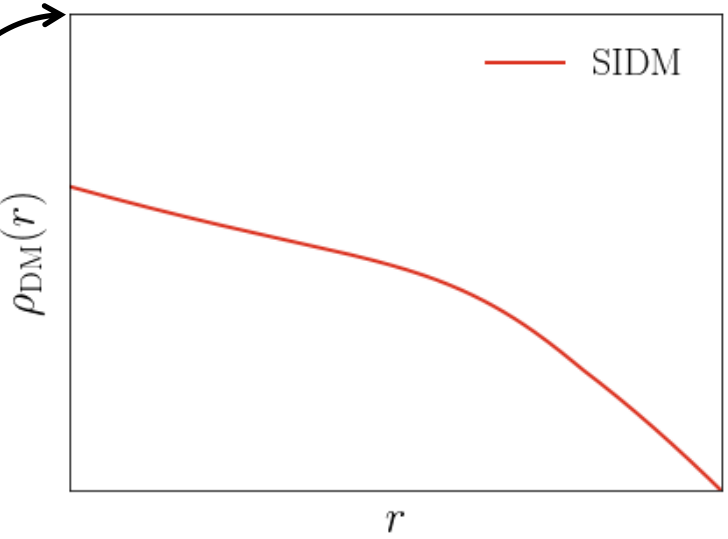
[Rocha et al., '12][Kaplinghat et al.,'13][Kaplinghat, Tulin, Yu, '15]

Fitting procedure

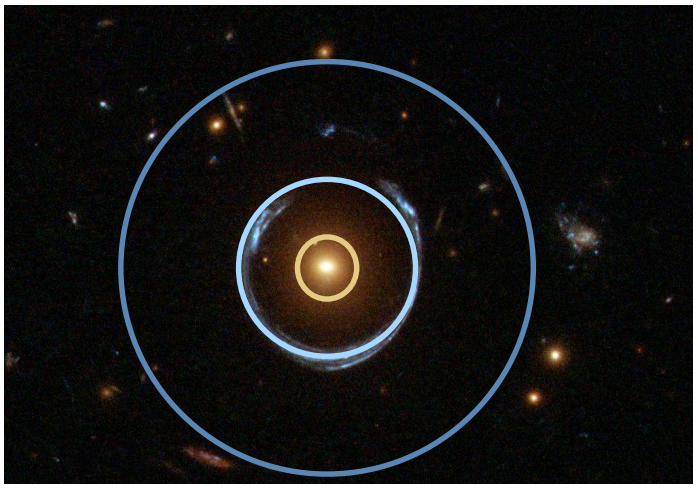
Free parameters SIDM

M_{200}, c_{200}, $\langle\sigma v\rangle/m$, ...

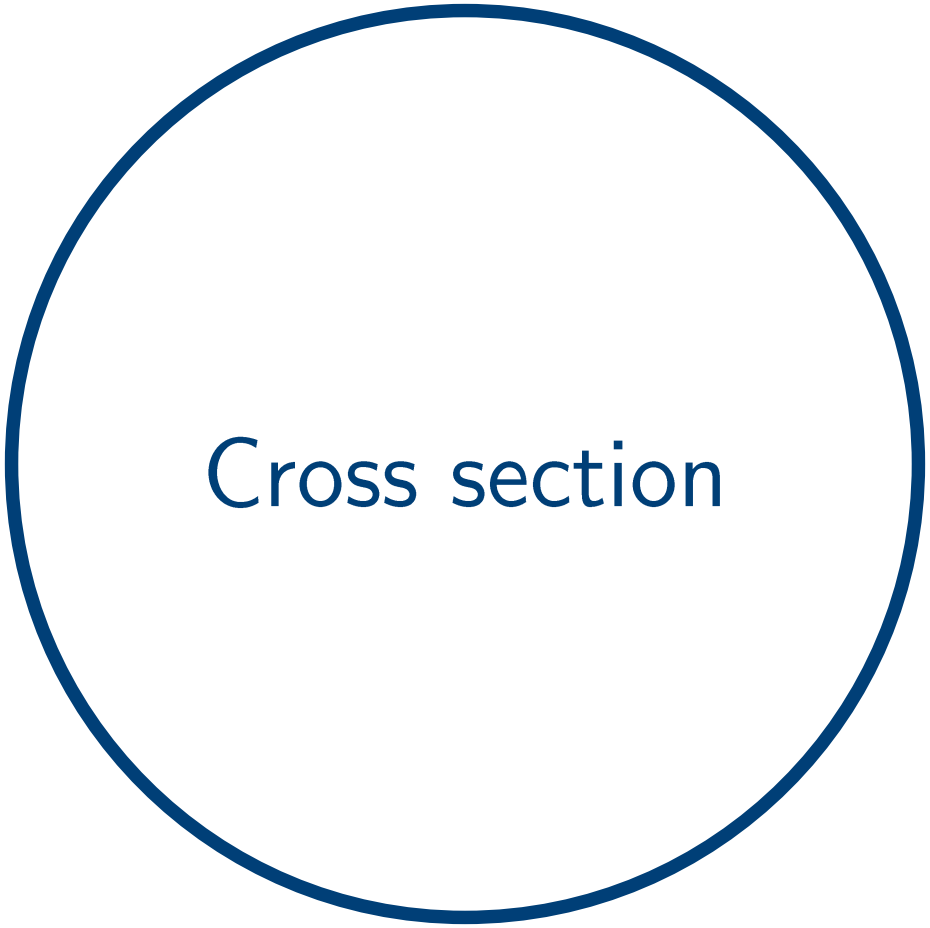
DM density profile with Jeans model



Predictions for observables ↔ data

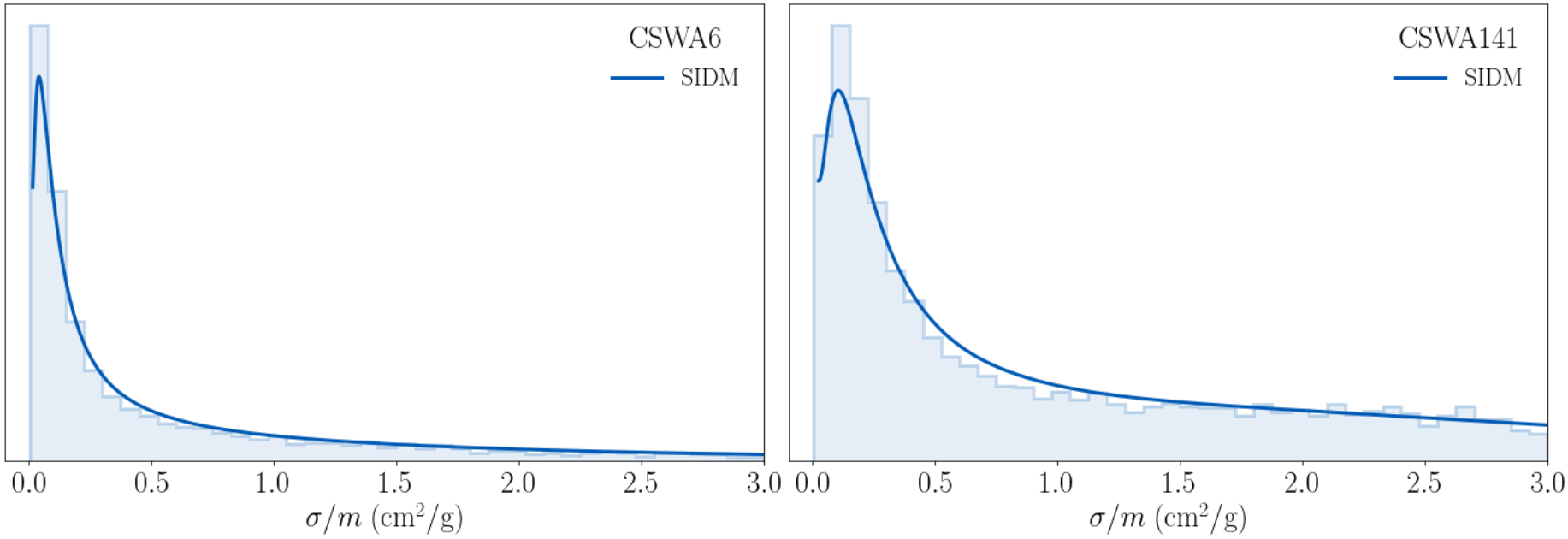


→ Cross section σ/m for every system


Cross section

Cross section σ/m

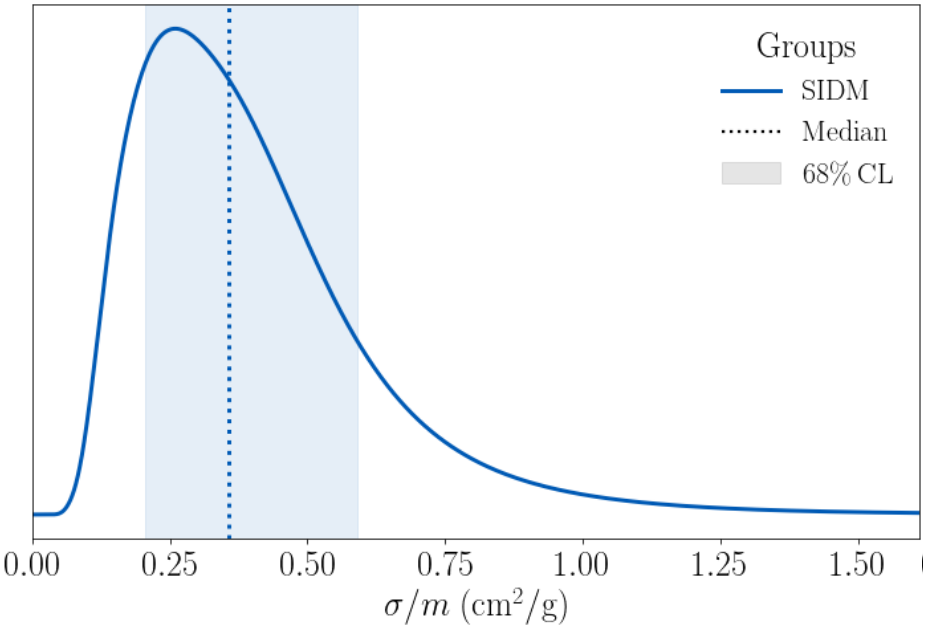
Probability distribution:



$\longrightarrow$ σ/m very small!

Cross section bound

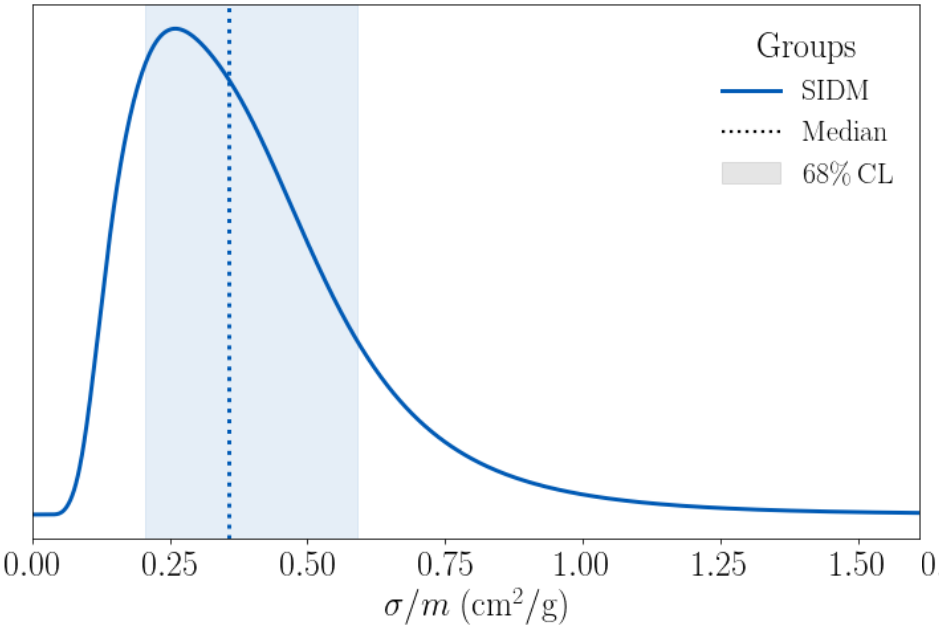
→ Joint probability distribution:

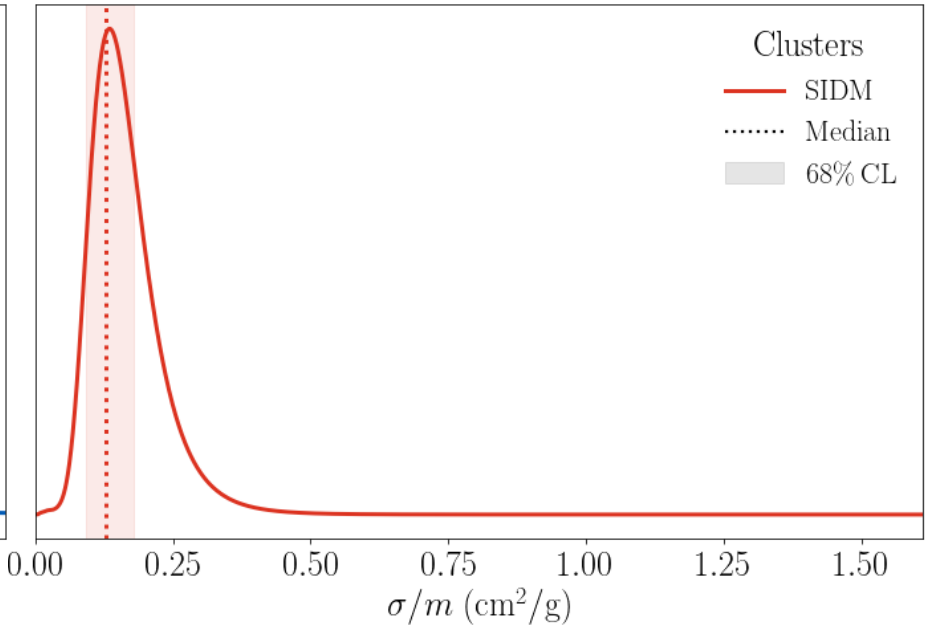


$$\sigma/m = 0.36\,^{+0.23}_{-0.15}\,\mathrm{cm}^2/\mathrm{g}\ (68\%\ \mathrm{CL})$$

Cross section bound

→ Joint probability distribution:



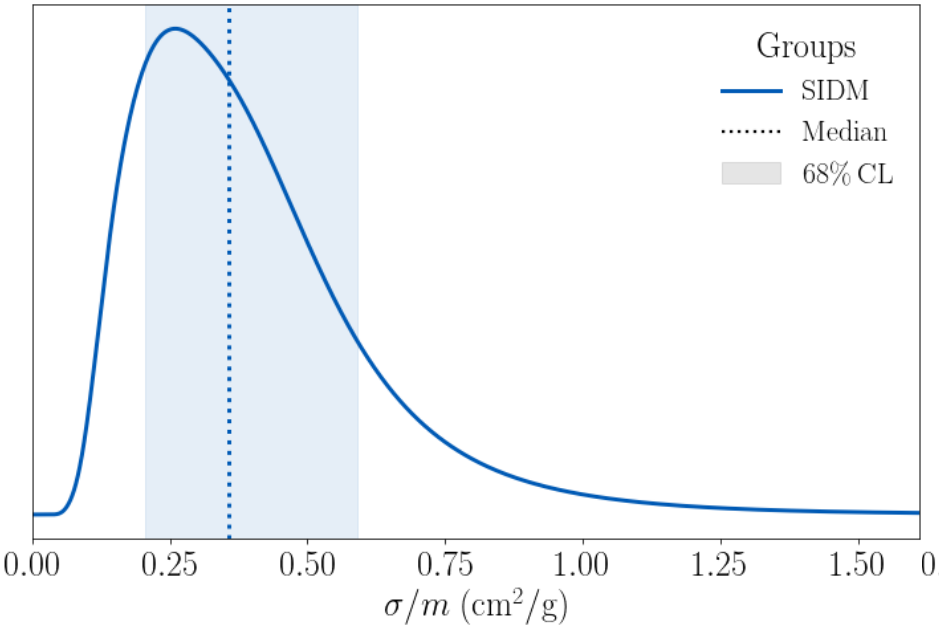


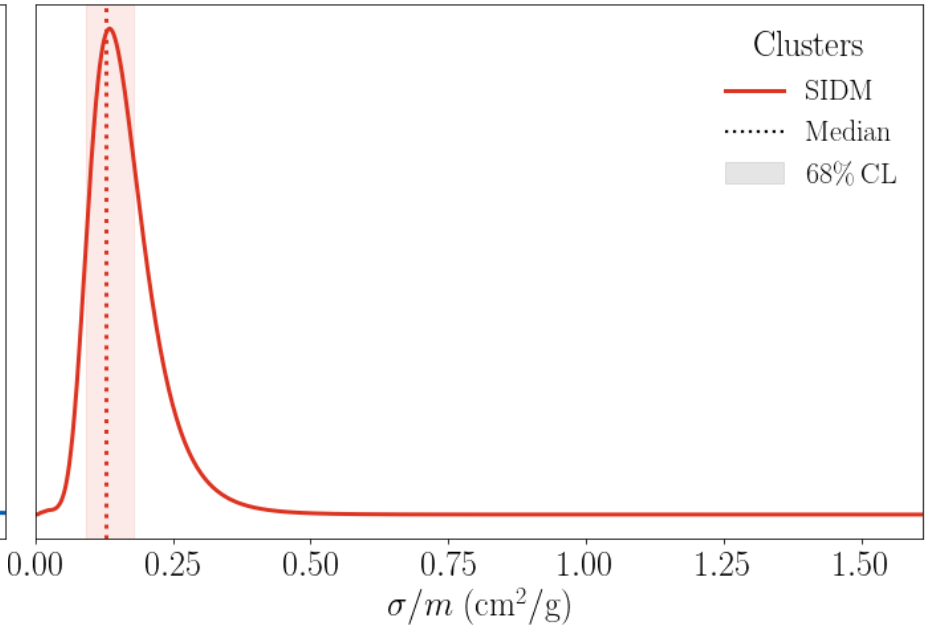
$\sigma/m = 0.36\,^{+0.23}_{-0.15}\,\mathrm{cm}^2/\mathrm{g}$ (68% CL)

$\sigma/m = 0.13\,^{+0.05}_{-0.04}\,\mathrm{cm}^2/\mathrm{g}$ (68% CL)

Cross section bound

→ Joint probability distribution:



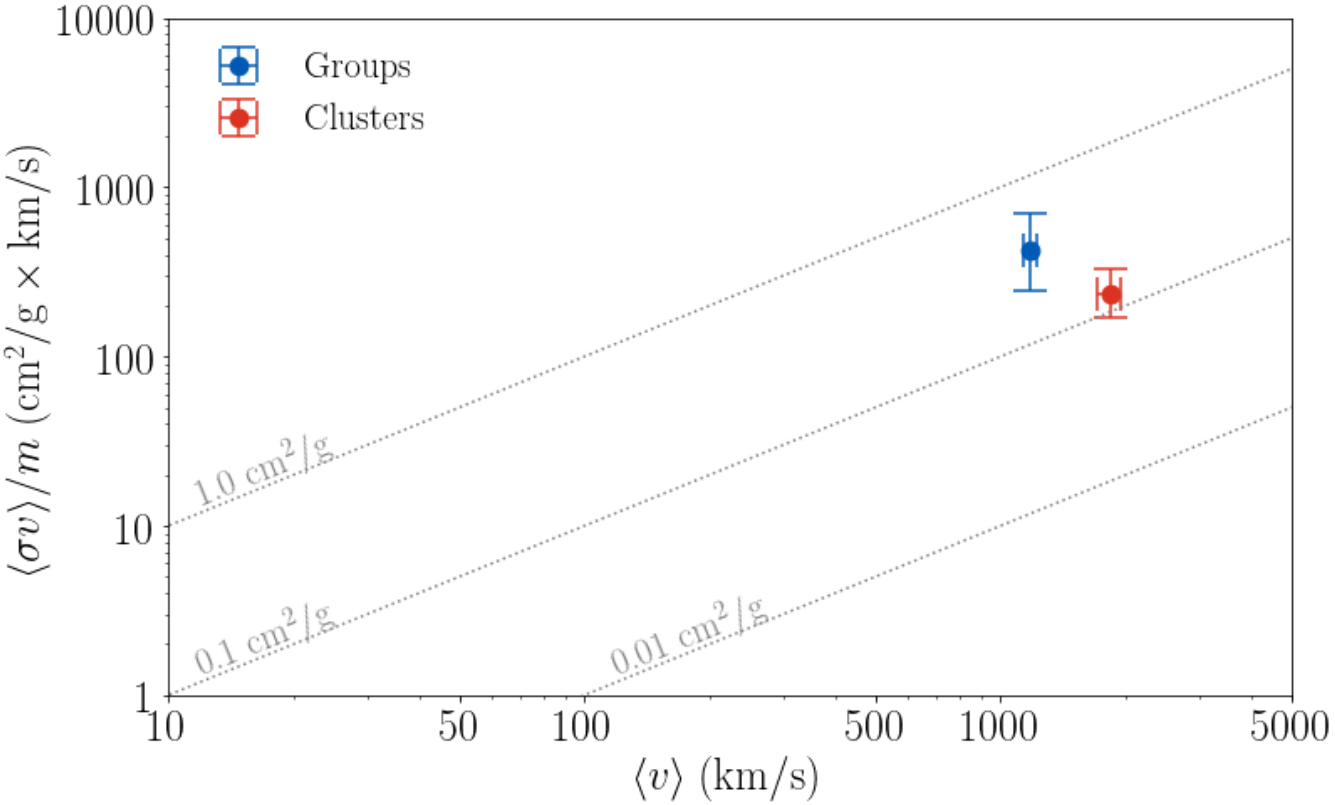


$\sigma/m = 0.36\,^{+0.23}_{-0.15}\,\mathrm{cm}^2/\mathrm{g}$ (68% CL)

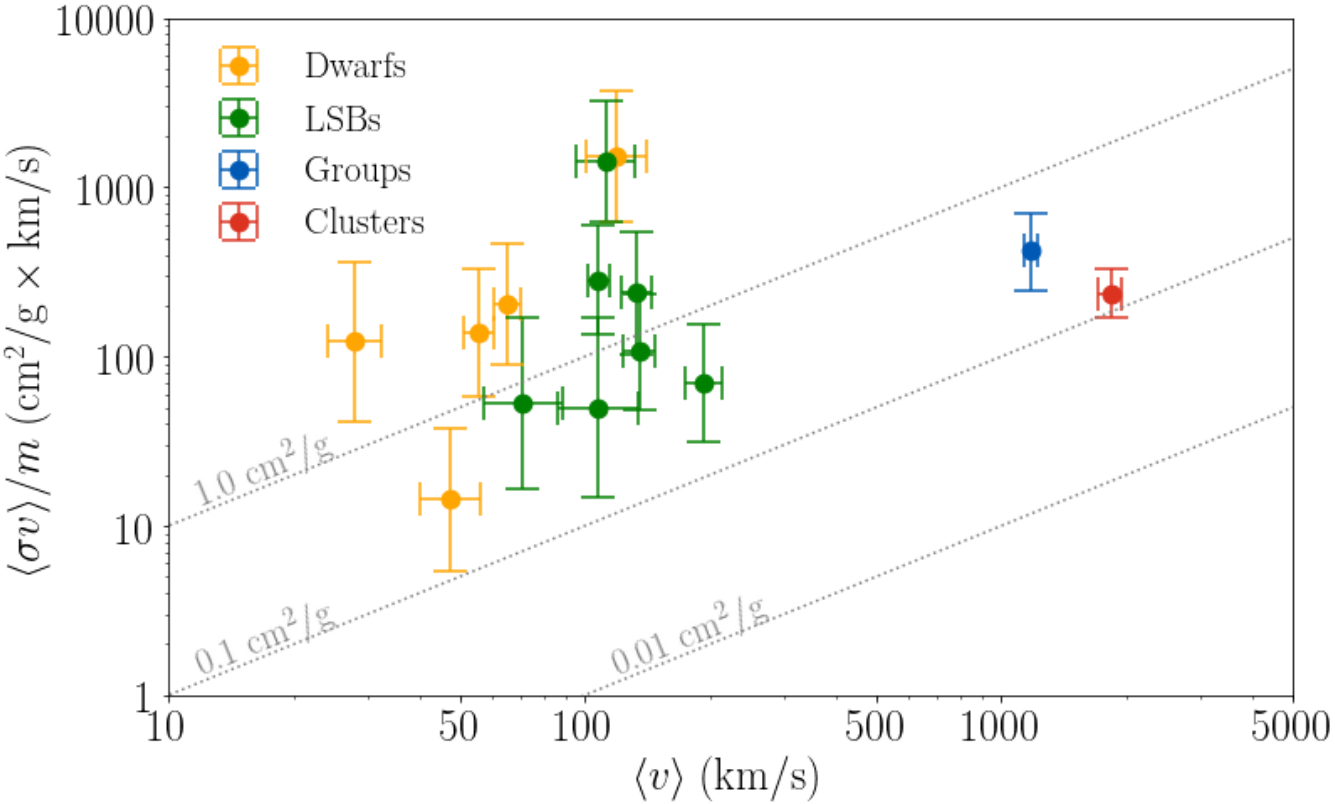
$\sigma/m = 0.13\,^{+0.05}_{-0.04}\,\mathrm{cm}^2/\mathrm{g}$ (68% CL)

→ σ/m is velocity-dependent!

Velocity-dependent cross section

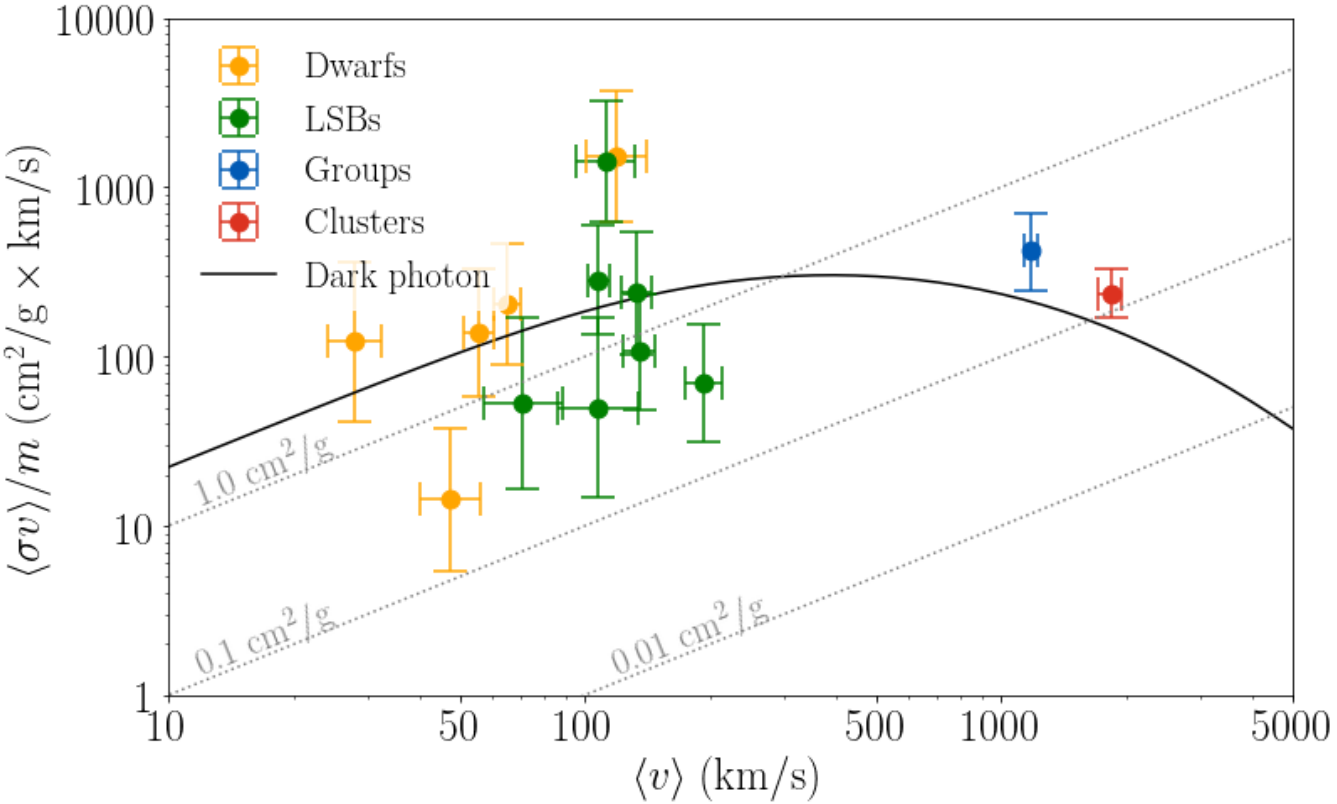


Velocity-dependent cross section



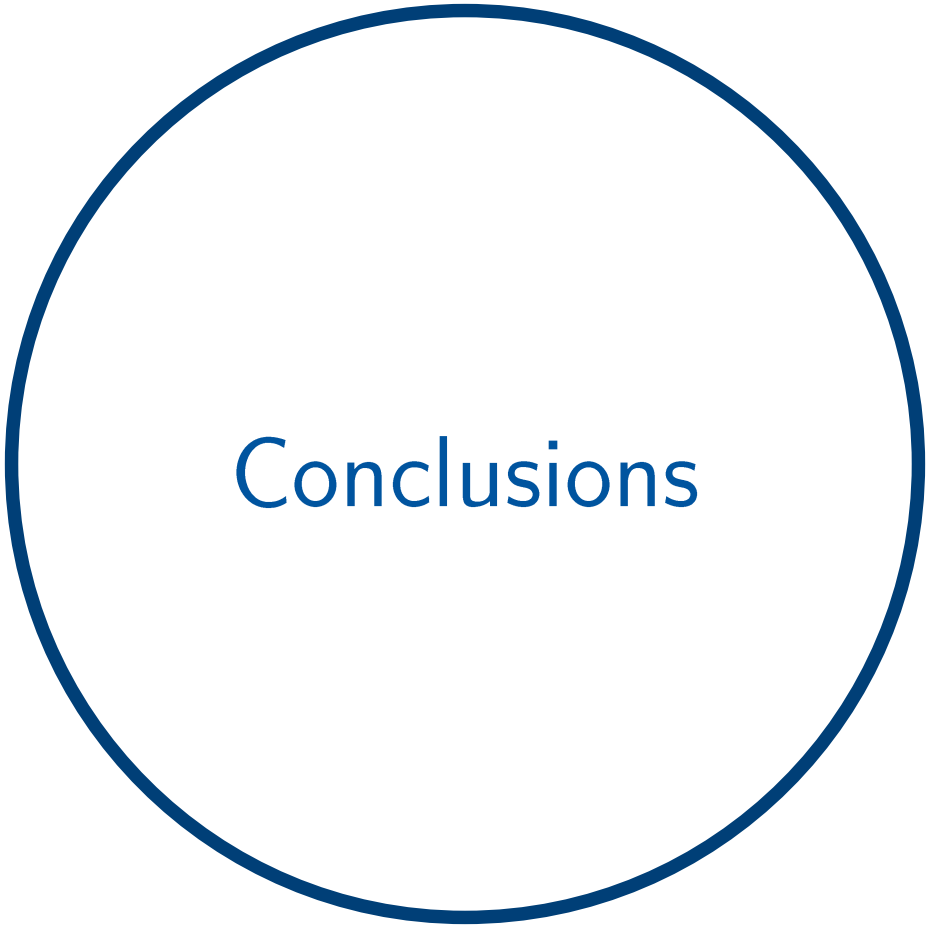
[Kaplinghat, Tulin, Yu, '15]

Implications for particle physics



DM mass: 15 GeV, dark photon mass: 17 MeV

[Kaplinghat, Tulin, Yu, '15]


Conclusions

Conclusions

Motivation:

Astrophysical probes: powerful tool to explore particle physics of DM

$\longrightarrow$ DM halos as particle colliders

$\longrightarrow$ Groups + clusters: new energy window into self-interactions!

Results:

- Strong bounds on self-interaction cross section
- Needs to be velocity dependent

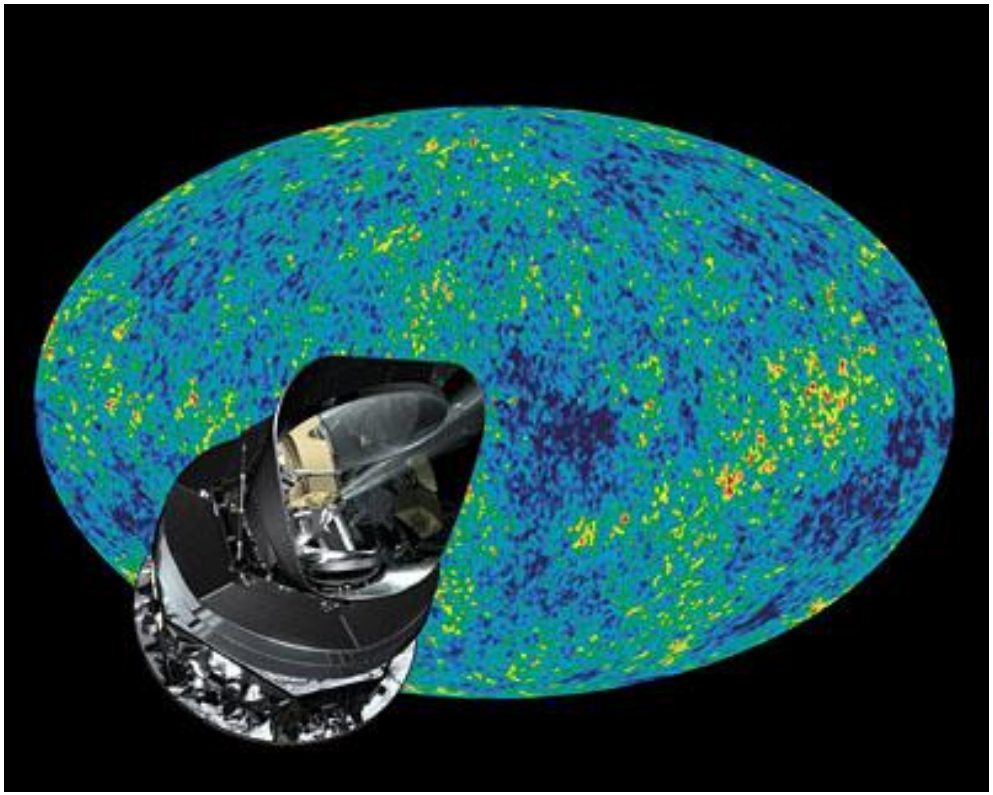
  $\longrightarrow$ Important for DM model building!

Thank you for your attention!

Backup

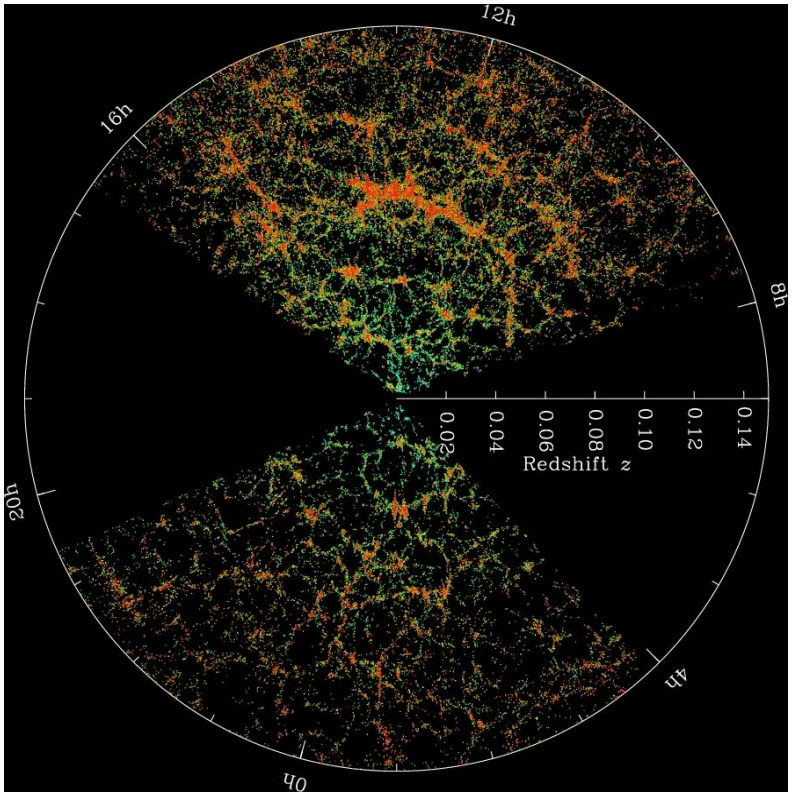
Cold collisionless dark matter (CDM): Success on large scales

Cosmic Microwave Background



[ESA/NASA, Planck/WMAP]

Large-scale structure



[www.sdss.org/science]

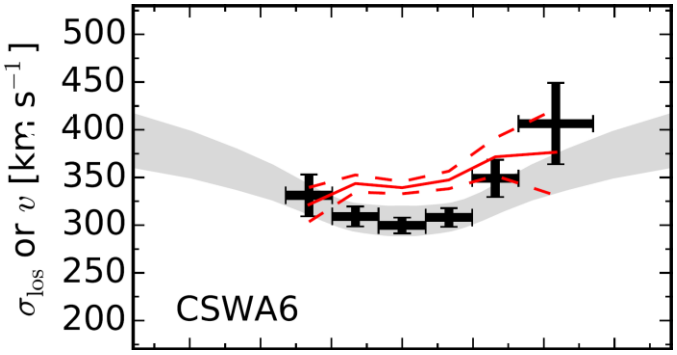
8 galaxy groups

Observables:

[Newman, Ellis, Treu, '15]

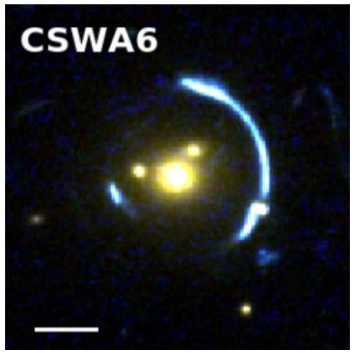
Stellar kinematics:

Line-of-sight velocity dispersion $\sigma_{\rm los}$



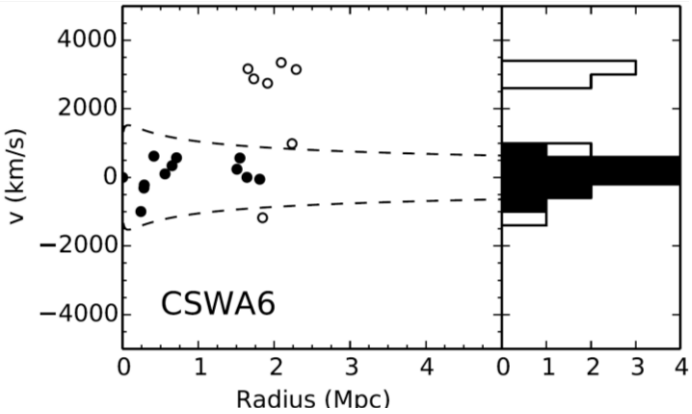
Strong lensing:

Mean convergence $\overline{\kappa}$



Kinematic of member galaxies:

$\sigma \longrightarrow$ virial mass M_{200}



$$\rightarrow \chi^2 = \chi^2_{\sigma_{\rm los}} + \chi^2_{\overline{\kappa}} + \chi^2_{M_{200}} + \chi^2_{\nabla \Upsilon_\star}$$

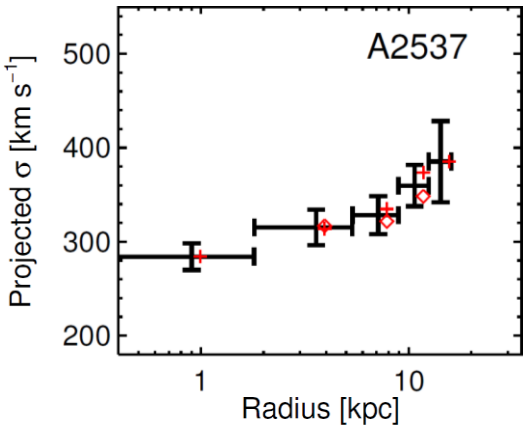
7 galaxy clusters

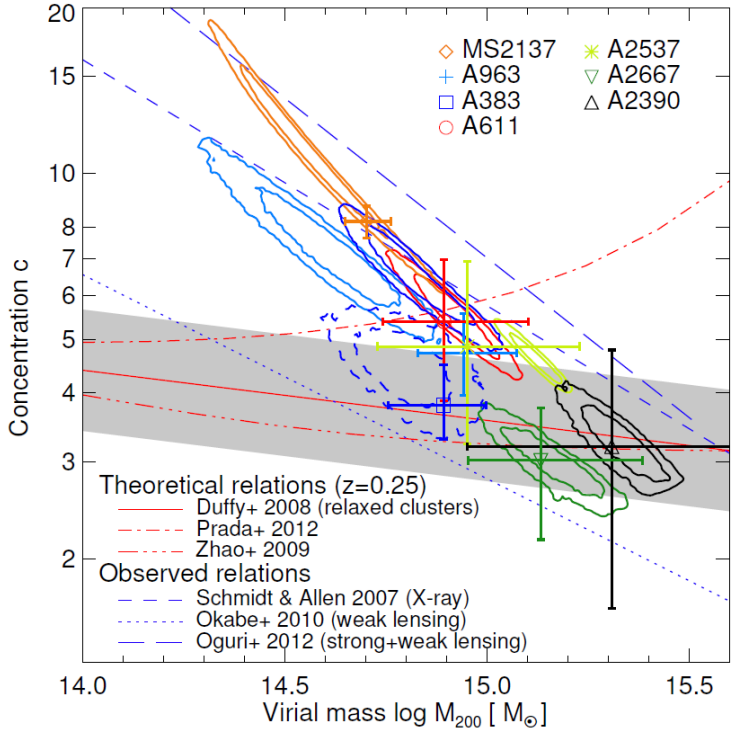
Observables:

[Newman et al. '12][Newman, Ellis, Treu, '12]

Stellar kinematics:

Line-of-sight velocity dispersion $\sigma_{\rm los}$



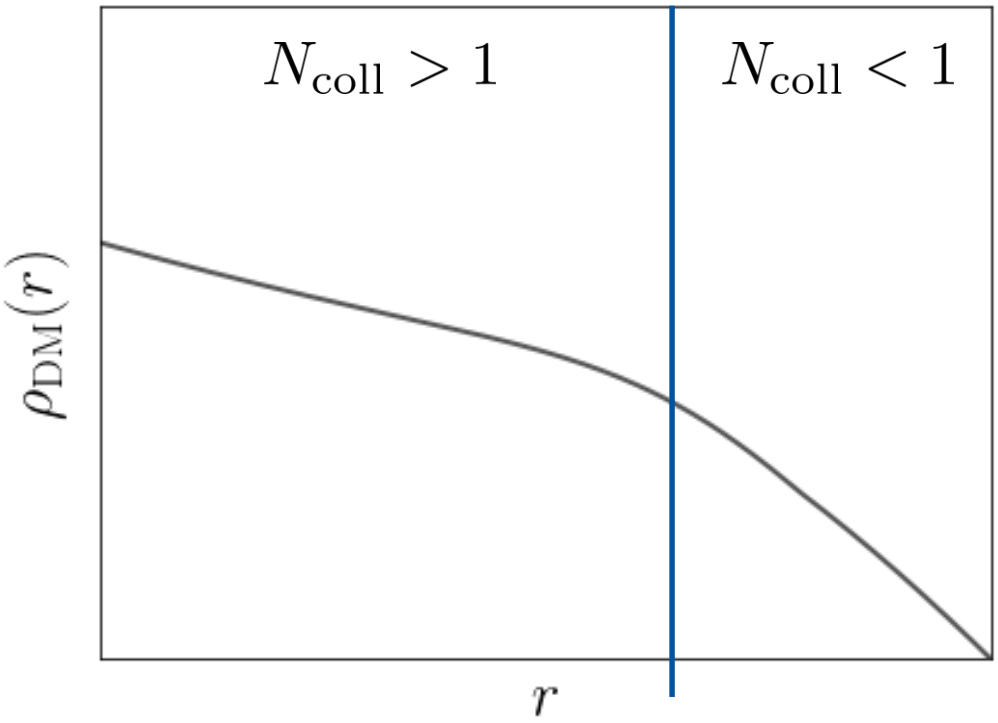


Strong + weak lensing:

Total enclosed mass $M_{\rm tot}\,(100\,{\rm kpc})$, virial mass M_{200}

$$\rightarrow \chi^2 = \chi^2_{\sigma_{\rm los}} + \chi^2_{M_{\rm tot}(100\,{\rm kpc})} + \chi^2_{M_{200}} + \chi^2_{\Upsilon_\star}$$

Jeans model



At r_1 :

$N_{\rm coll} = 1$

Rate equation:

$$\frac{N_{\rm coll}}{t_{\rm age}} \cdot t_{\rm age} = 1$$

$$\rho_{\rm SIDM}(r_1) \frac{\langle \sigma v \rangle}{m} \cdot t_{\rm age} = 1$$

$\longrightarrow$ Solve for r_1

$\longrightarrow$ Depends on σ/m

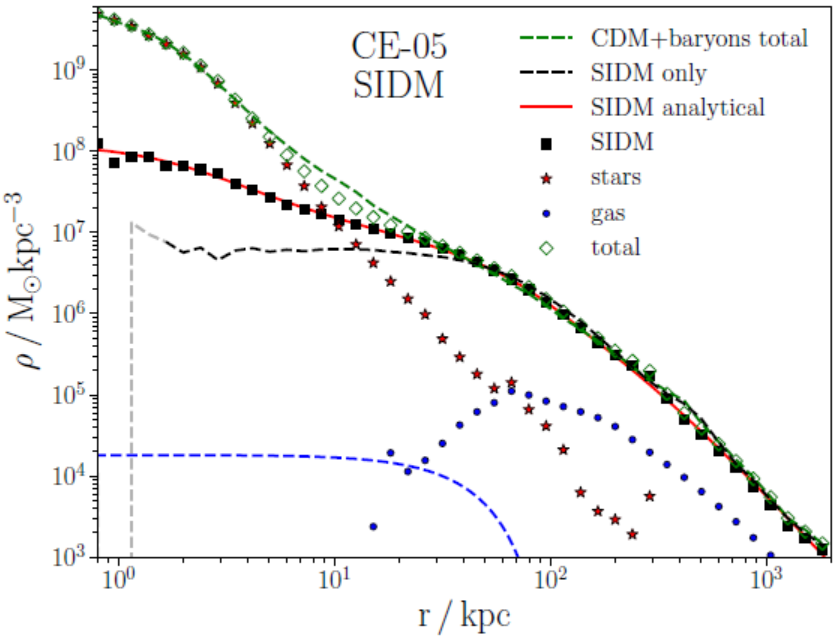
[Rocha et al., '12][Kaplinghat et al.,'13][Kaplinghat, Tulin, Yu, '15]

Jeans model

SIDM-plus-baryons simulation: $\sigma/m = 1\ \mathrm{cm}^2/\mathrm{g}$

[Robertson et al. '18]

→ Jeans model predicts SIDM density profiles remarkably well

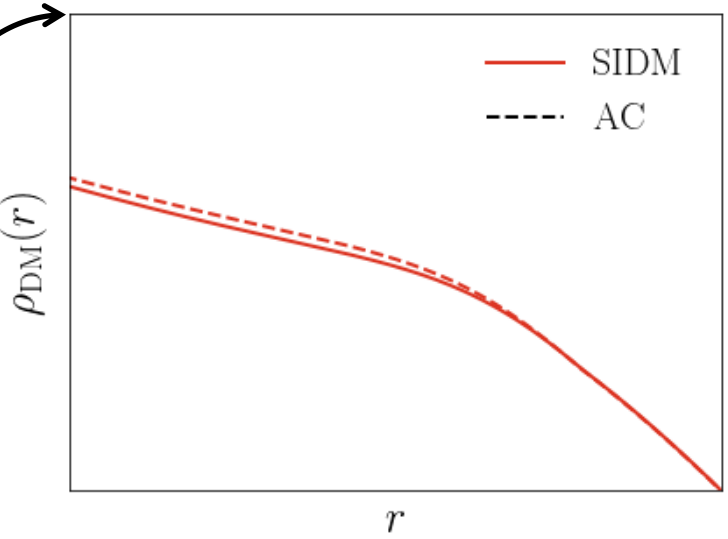


Fitting procedure

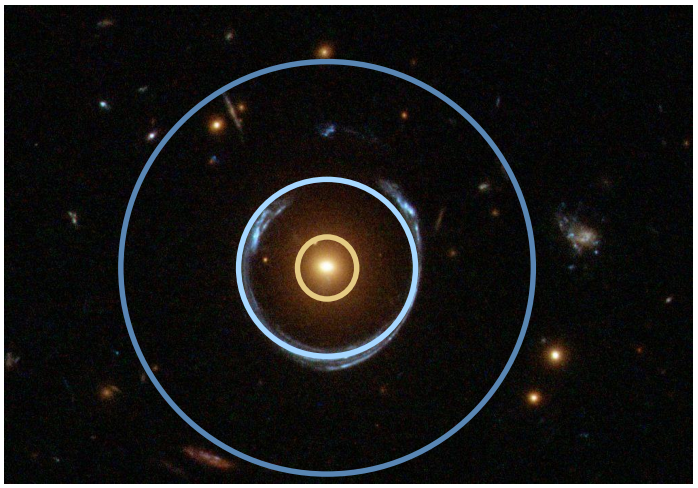
Free parameters SIDM+AC

M_{200}, c_{200}, $\langle\sigma v\rangle/m$, AC, ...

DM density profile with Jeans model



Predictions for observables ↔ data



→ Cross section σ/m for every system

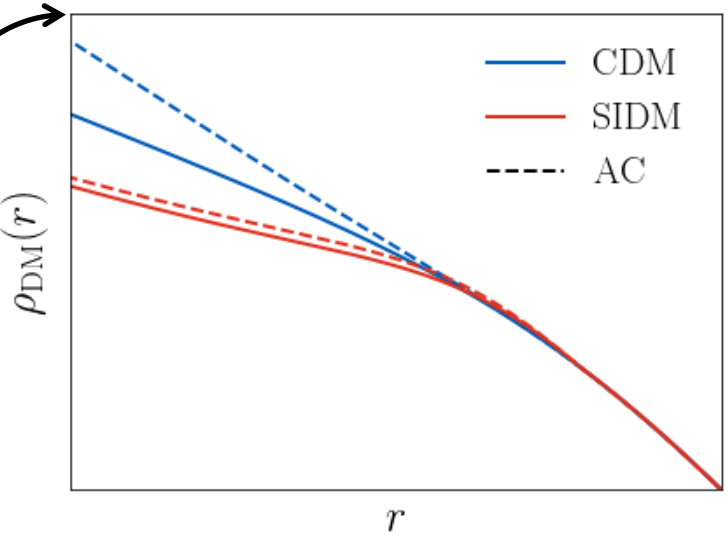
Fitting procedure

Free parameters

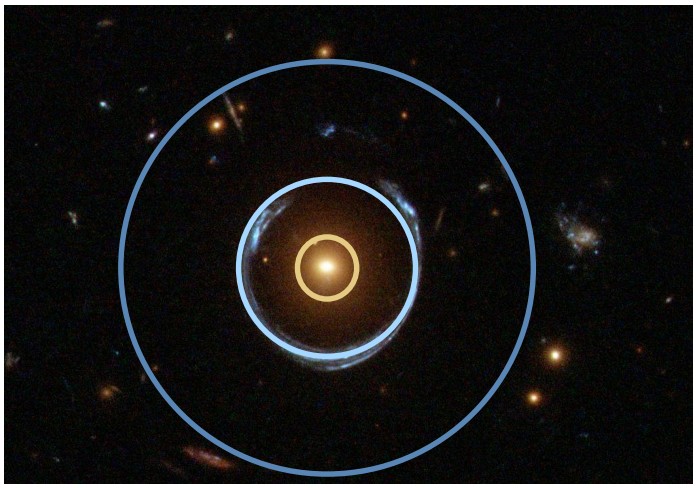
CDM+AC

M_{200}, c_{200}, ~~$\langle\sigma v\rangle/m$~~, AC, ...

DM density profile with ~~Jeans model~~



Predictions for observables ↔ data



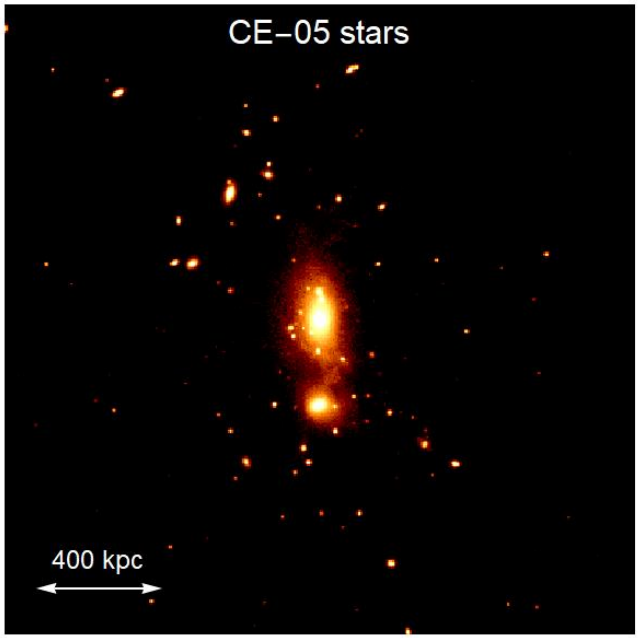
→ Cross section σ/m for every system

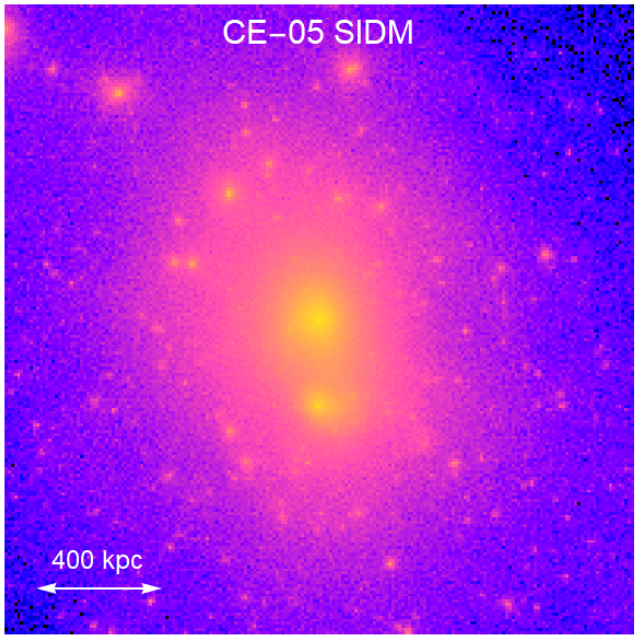
Test fitting procedure

SIDM-plus-baryons simulation: $\sigma/m = 1\ \mathrm{cm}^2/\mathrm{g}$

[Robertson et al. '18]

$\longrightarrow$ Mock observations for different lines-of-sight:



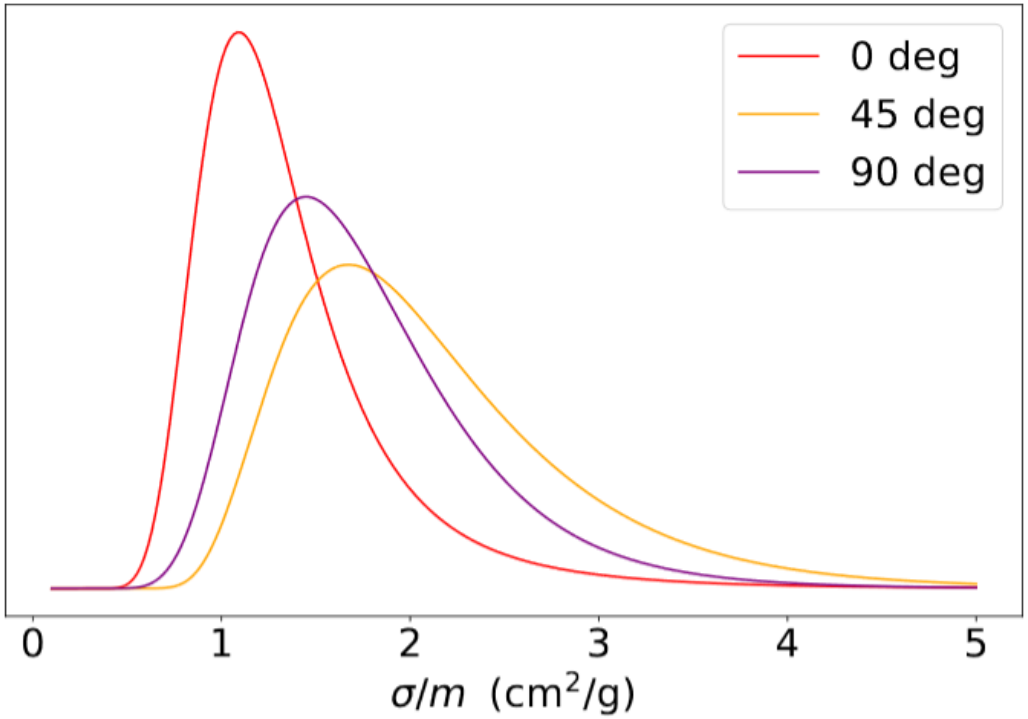


Test fitting procedure

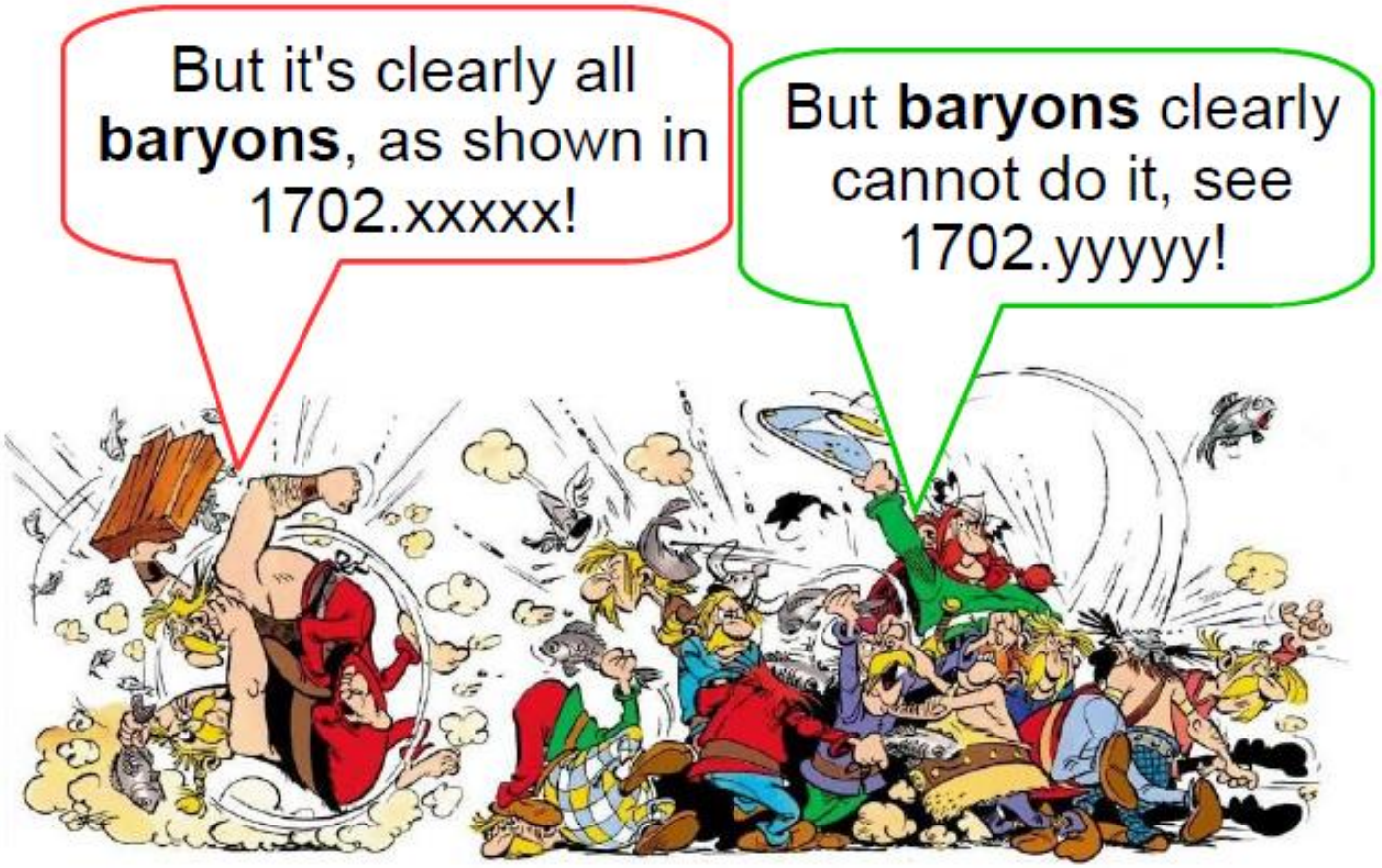
SIDM-plus-baryons simulation: $\sigma/m = 1\ \mathrm{cm}^2/\mathrm{g}$

[Robertson et al. '18]

$\longrightarrow$ Fit results:



Baryonic effects



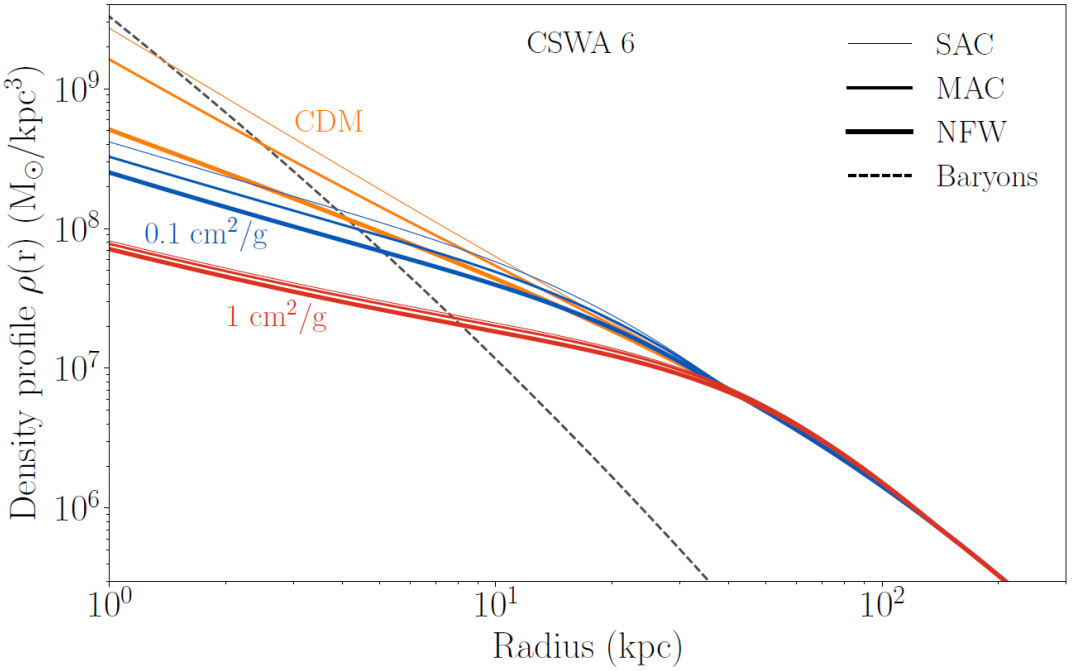
[Credit: Kai Schmidt-Hoberg]

Baryonic effects

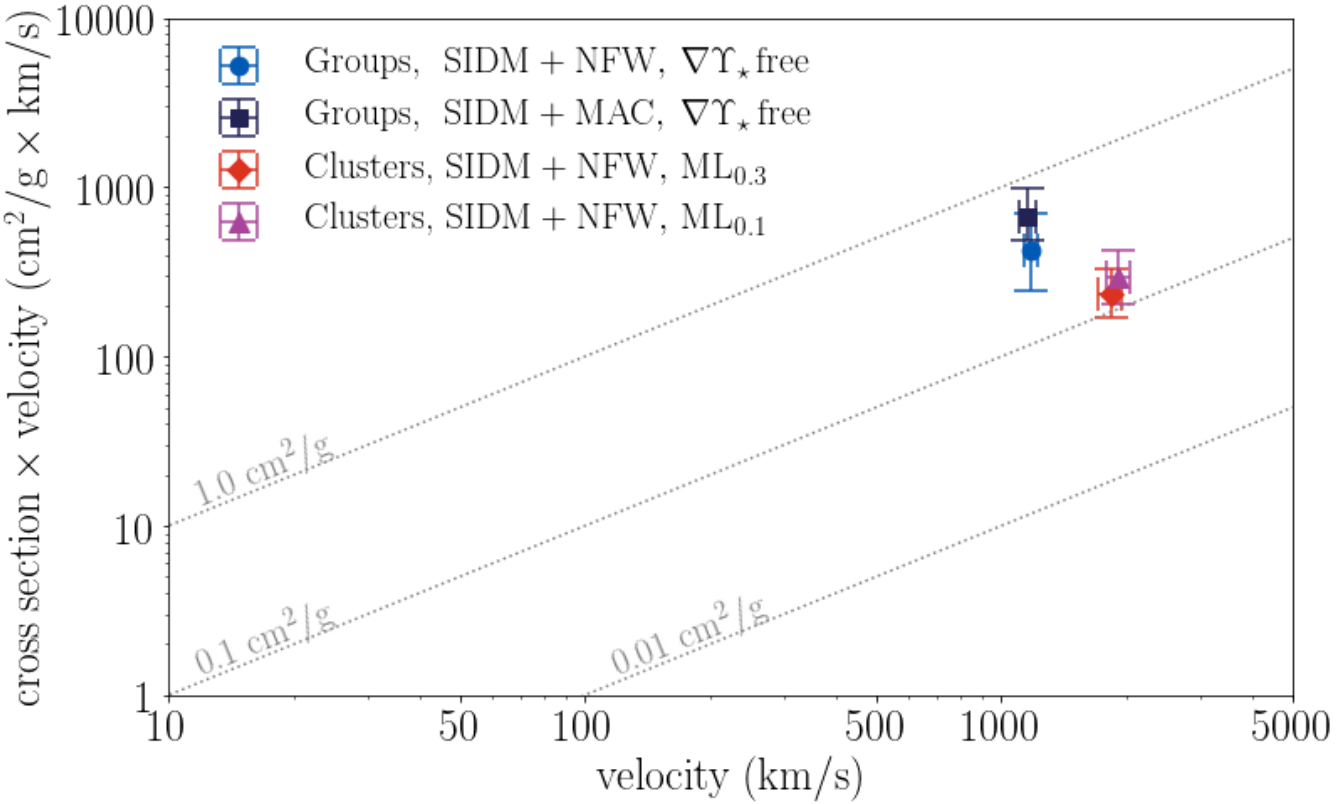
Baryonic infall and cooling [Blumenthal et al., '86][Gnedin et al., '04] [Gnedin et al., '11]

→ Adiabatic contractions of DM halo

→ Steepens profile in inner region



Velocity-dependent cross section



Cross section

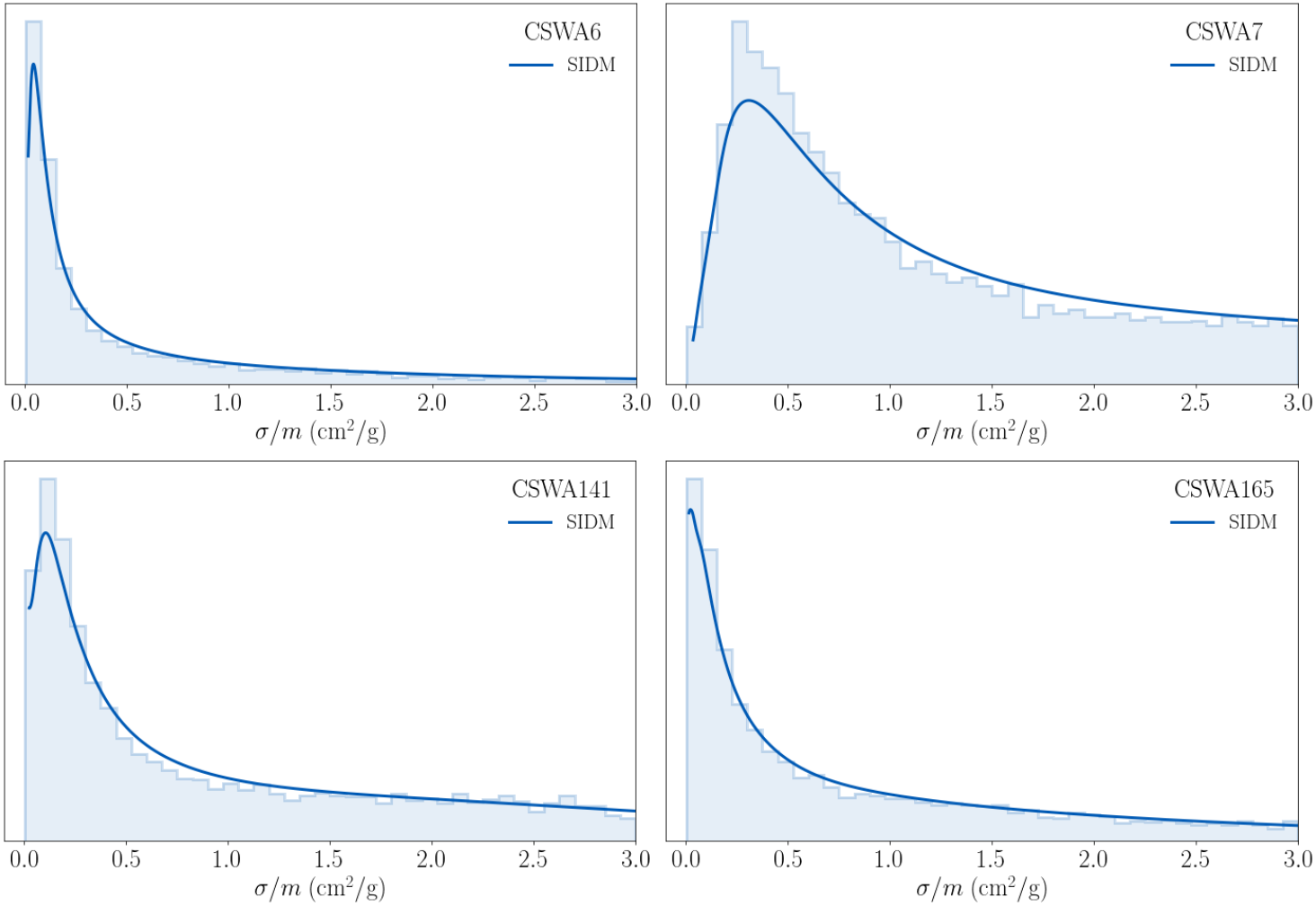
- If cross section is constant in velocity:

$$\frac{\sigma}{m} = \frac{1}{\langle v \rangle} \frac{\langle \sigma v \rangle}{m}$$

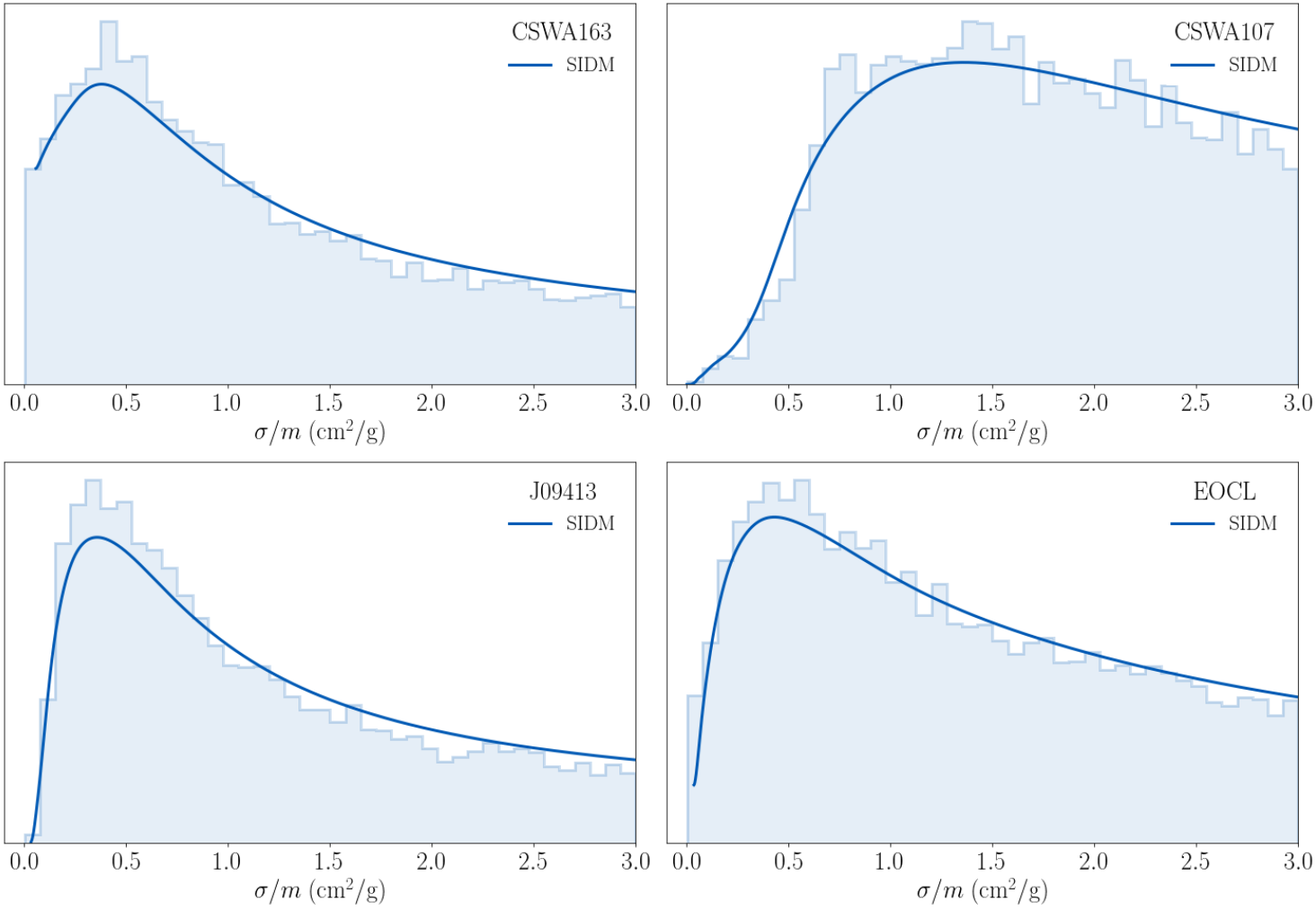
- Mean relative velocity for scattering:

$$\langle v \rangle = 4\sigma_0 / \sqrt{\pi}$$

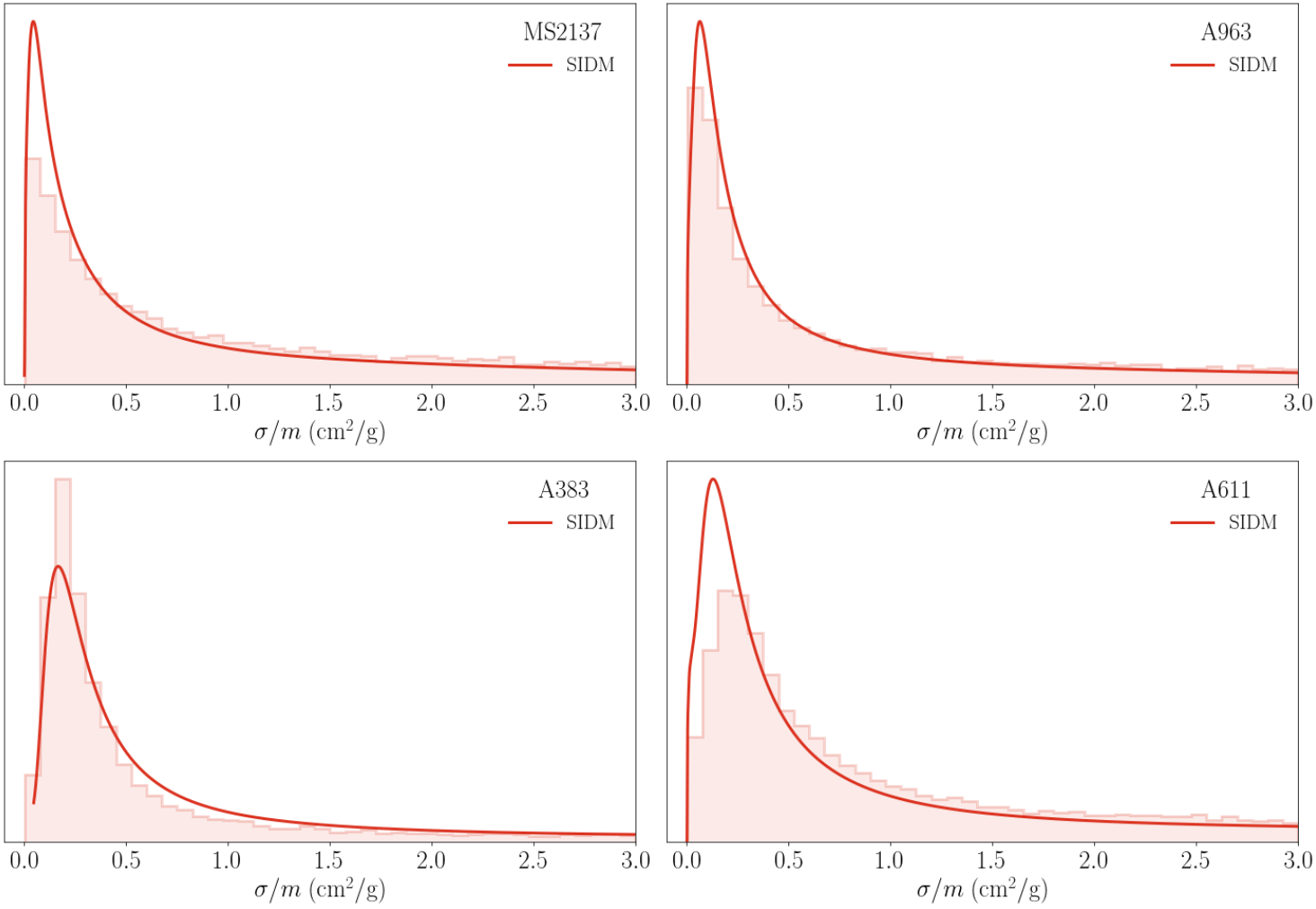
Groups


CSWA6
SIDM
0.0
0.5
1.0
1.5
2.0
2.5
3.0
σ/m (cm^2/g)
CSWA7
SIDM
0.0
0.5
1.0
1.5
2.0
2.5
3.0
σ/m (cm^2/g)
CSWA141
SIDM
0.0
0.5
1.0
1.5
2.0
2.5
3.0
σ/m (cm^2/g)
CSWA165
SIDM
0.0
0.5
1.0
1.5
2.0
2.5
3.0
σ/m (cm^2/g)

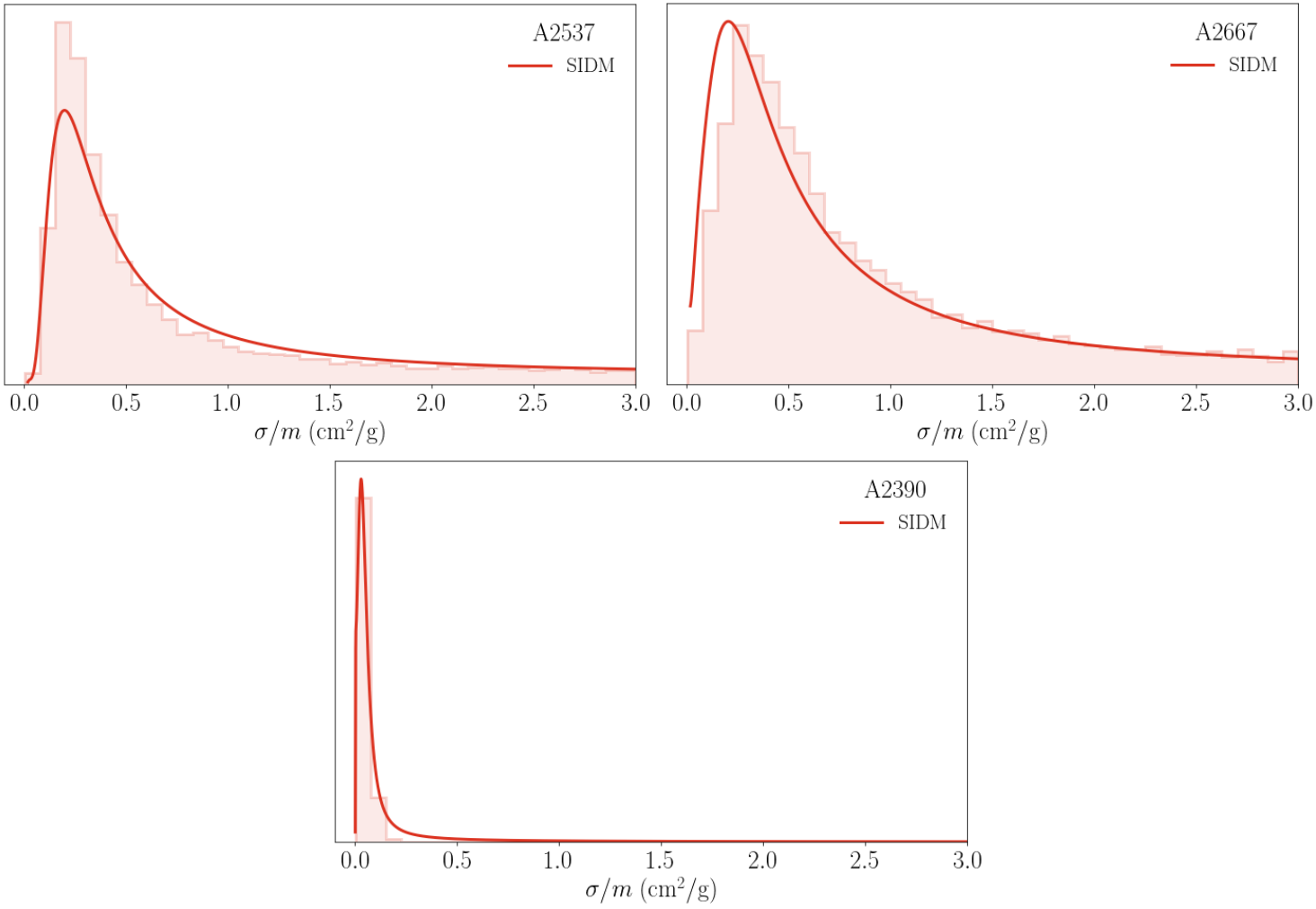
Groups


CSWA163
SIDM
0.0
0.5
1.0
1.5
2.0
2.5
3.0
σ/m (cm^2/g)
CSWA107
SIDM
0.0
0.5
1.0
1.5
2.0
2.5
3.0
σ/m (cm^2/g)
J09413
SIDM
0.0
0.5
1.0
1.5
2.0
2.5
3.0
σ/m (cm^2/g)
EOCL
SIDM
0.0
0.5
1.0
1.5
2.0
2.5
3.0
σ/m (cm^2/g)

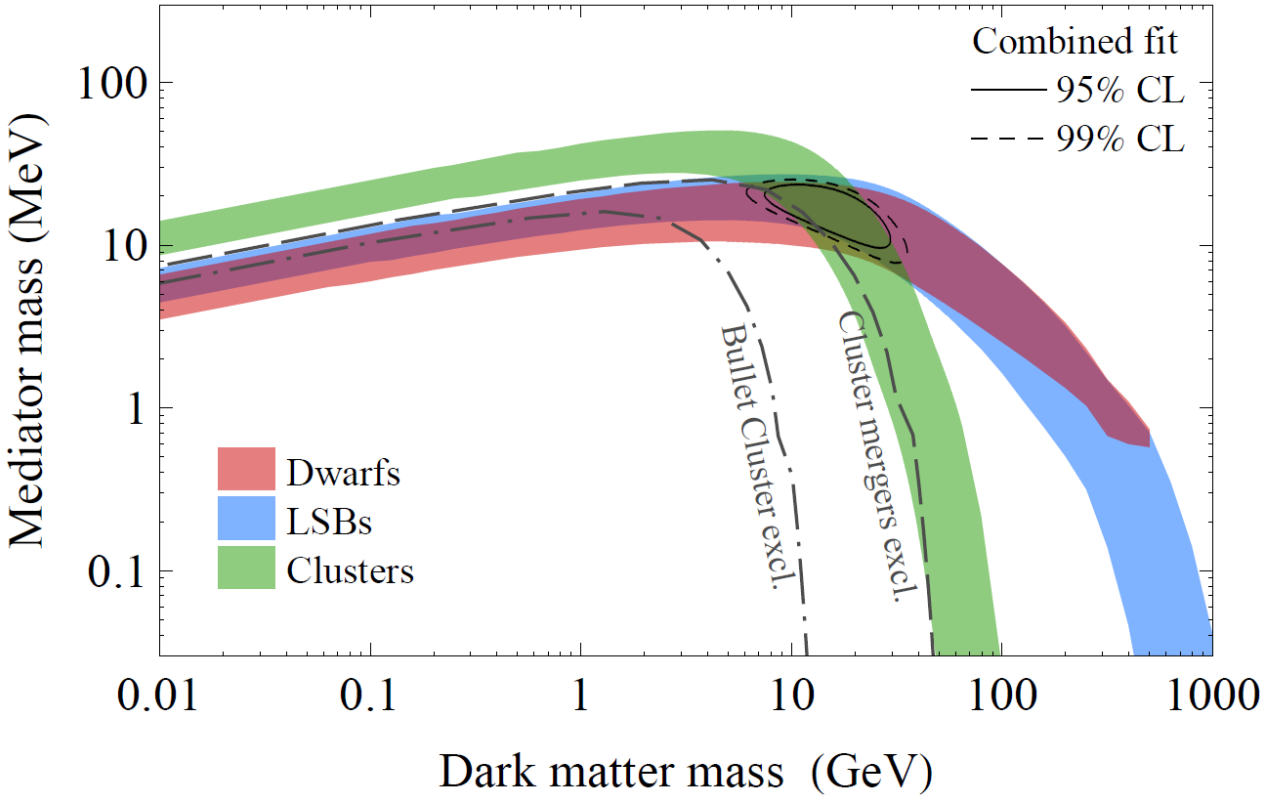
Clusters


MS2137
SIDM
A963
SIDM
A383
SIDM
A611
SIDM
0.0
0.5
1.0
1.5
2.0
2.5
3.0
σ/m (cm^2/g)

Clusters


A2537
SIDM
0.0
0.5
1.0
1.5
2.0
2.5
3.0
σ/m (cm^2/g)
A2667
SIDM
0.0
0.5
1.0
1.5
2.0
2.5
3.0
σ/m (cm^2/g)
A2390
SIDM
0.0
0.5
1.0
1.5
2.0
2.5
3.0
σ/m (cm^2/g)

Dark photon model



DM mass: 15 GeV, dark photon mass: 17 MeV

[Kaplinghat, Tulin, Yu, '15]