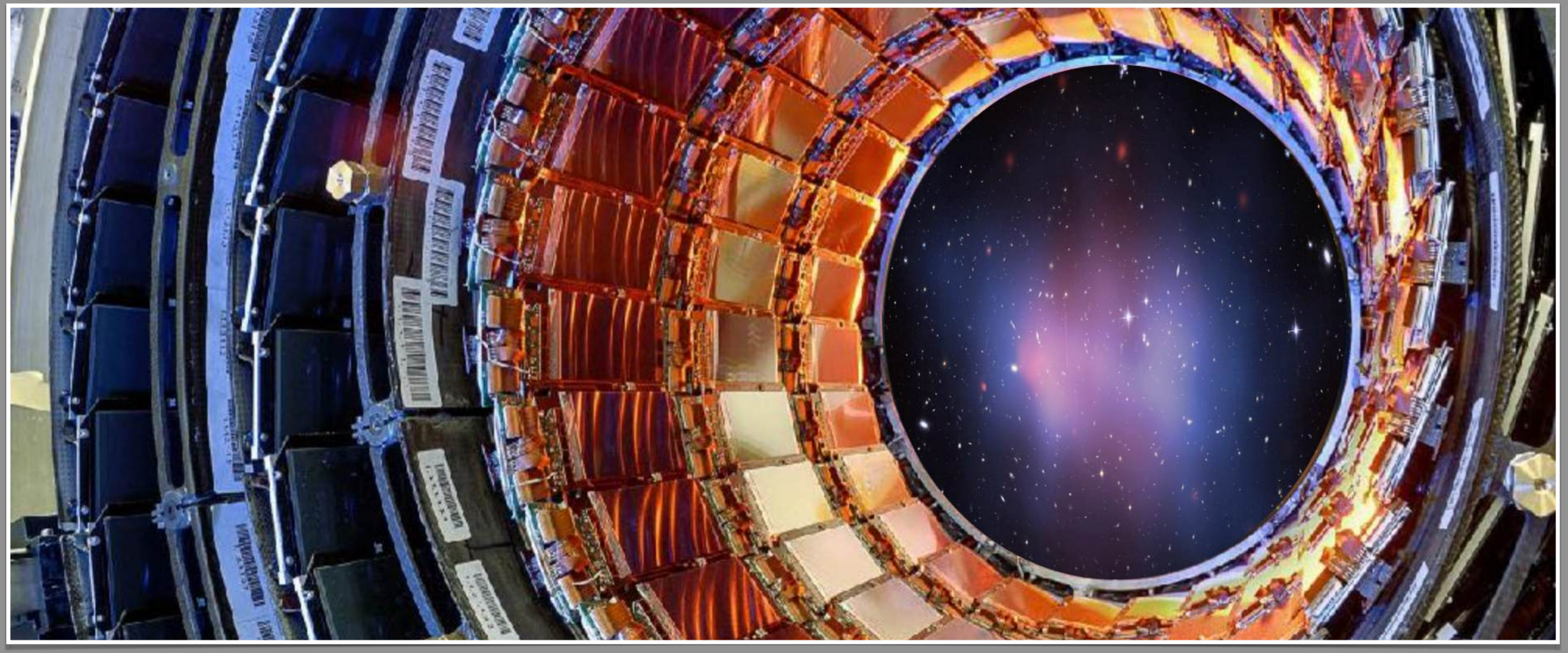
The 11th KIAS Workshop on Cosmology and Structure Formation

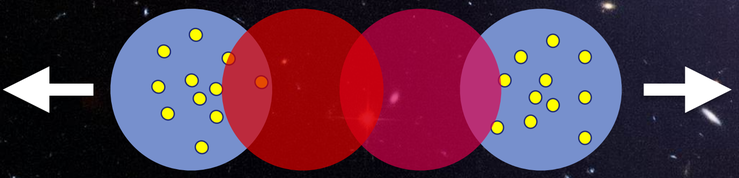


Robust Constraints on Dark Matter Self-interaction Cross-section with Large Halo Colliders

M. James Jee, Dongak Park, Wonki Lee, and YOUNG Department of Astronomy, Yonsei University

Large Halo Colliders

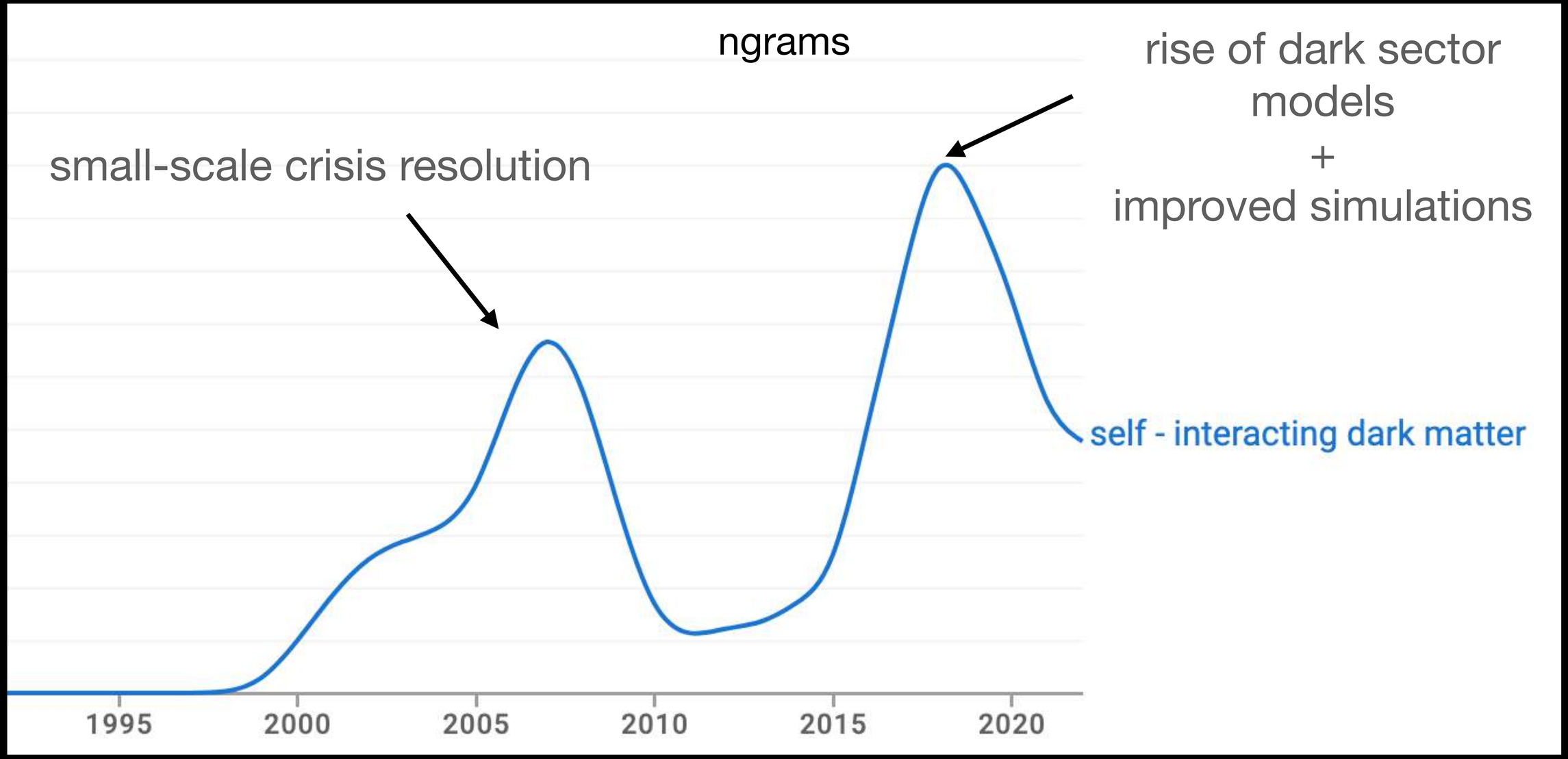
DM plasma



- Energetic: $\gtrsim 10^{64}$ergs
- Maximize DM-DM interaction
- Microscopic properties having macroscopic consequences.

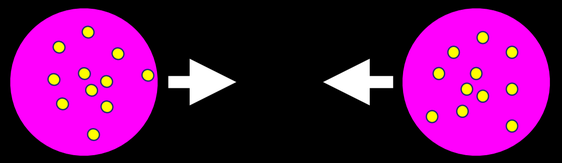
"El Gordo": Jee et al. (2014)

Motivation for Self-Interacting Dark Matter

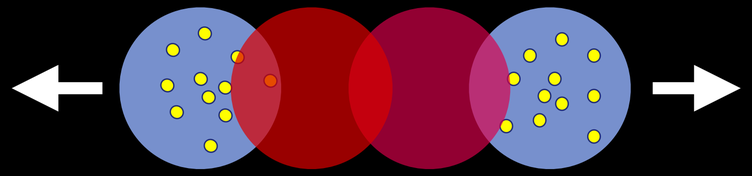


Early Ideas and Why They Do Not Work

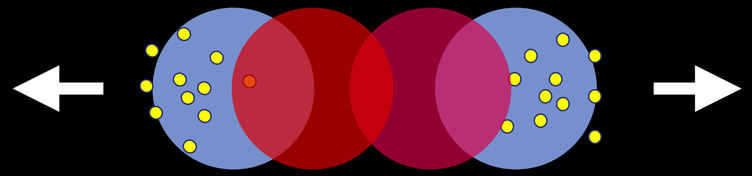
Before:



After:

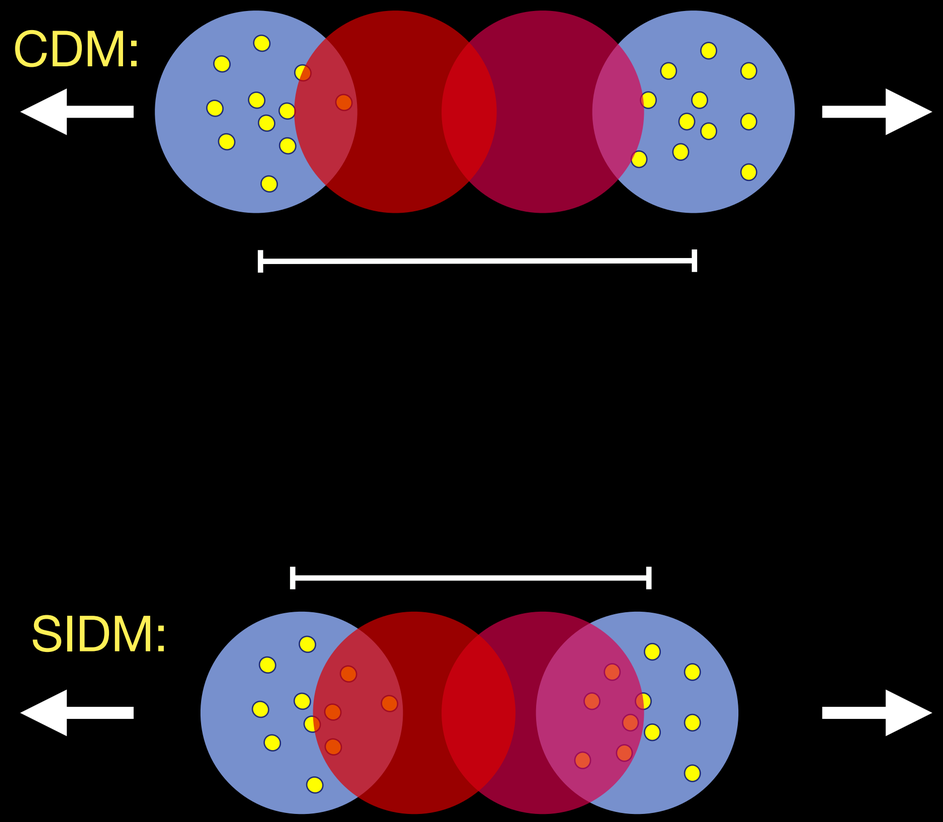


If DM is self-interacting,



- The mass-galaxy offset is extremely small.
- We don’t know the merger phase.

New Window: Self-Interaction Slowing Down Halos



The halo-halo distance is sensitive to interaction strength.

But,

- we don’t know the merger phase
- we don’t know the viewing angle
- we don’t know the collision speed
- we don’t know the impact parameter
- …

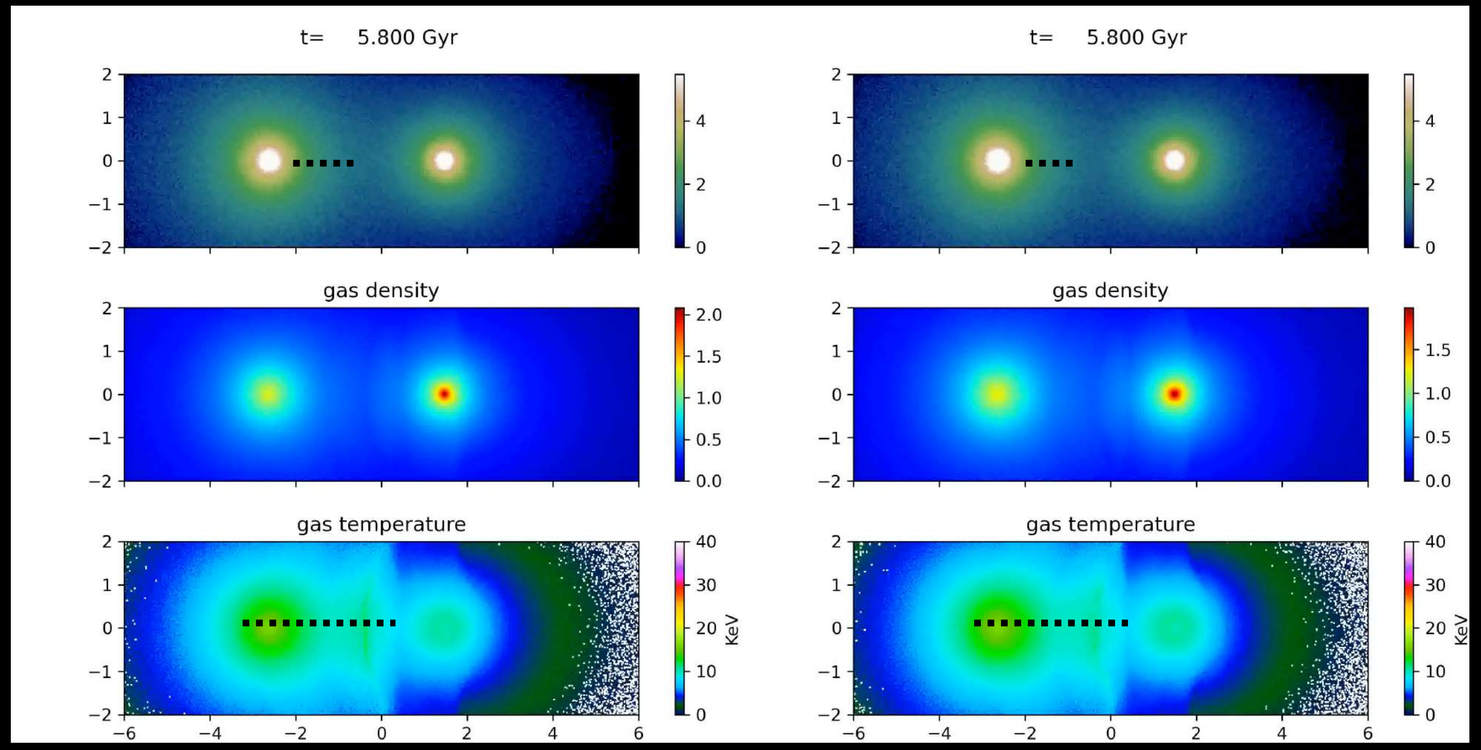
Shock wave: independent clock

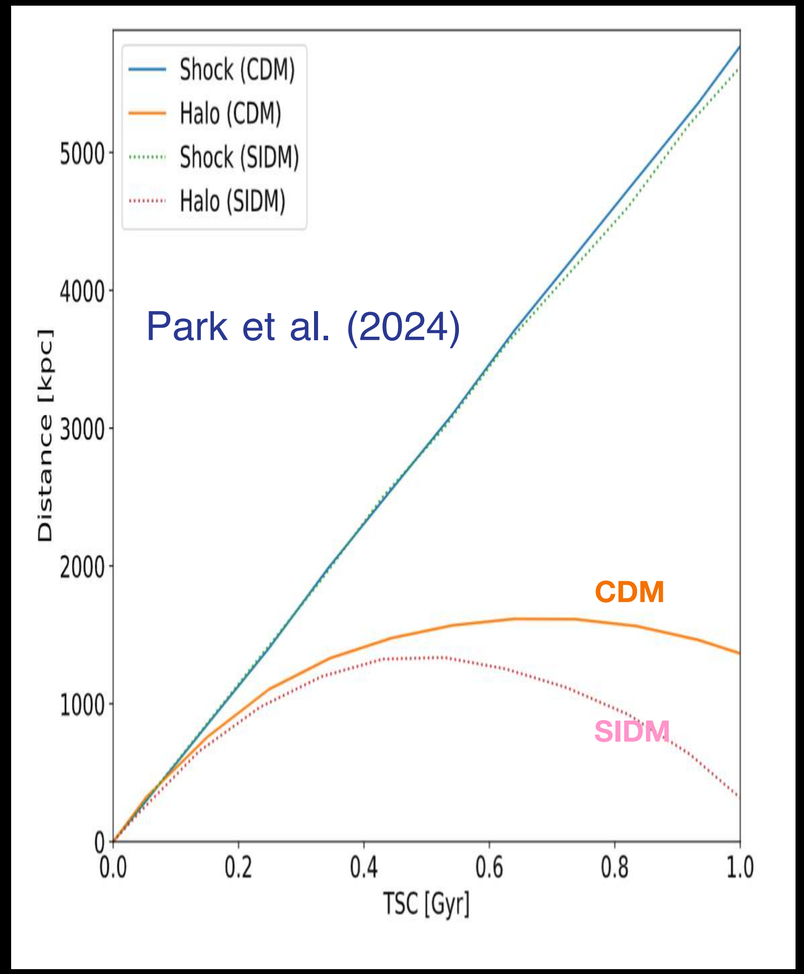
CDM SIDM

DM

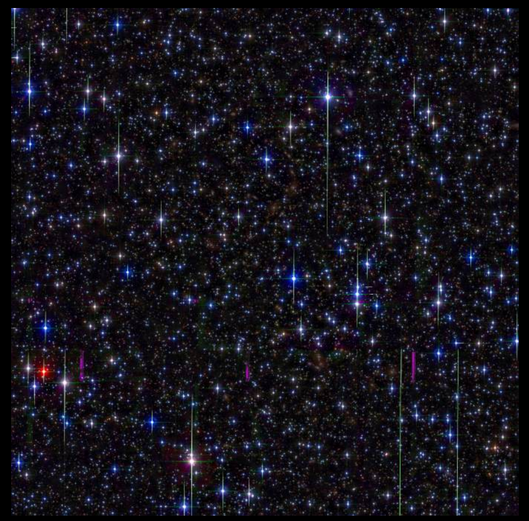
gas ρ

gas T

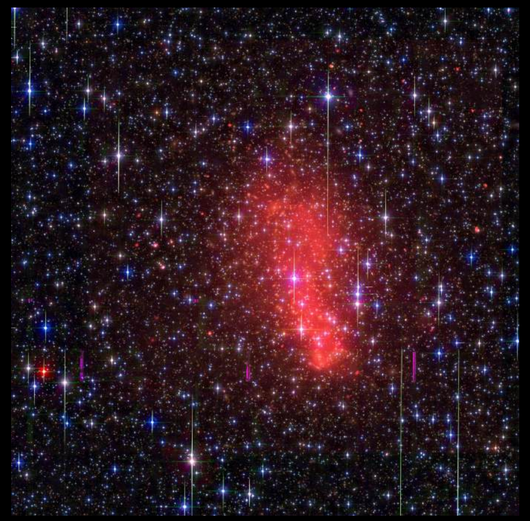




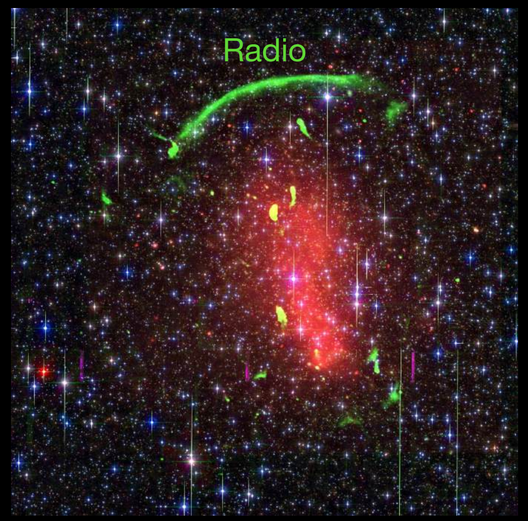
Multiwavelength Observations



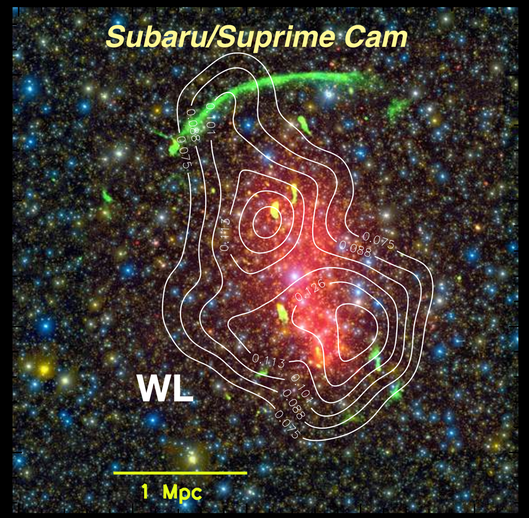
optical



optical+X-ray

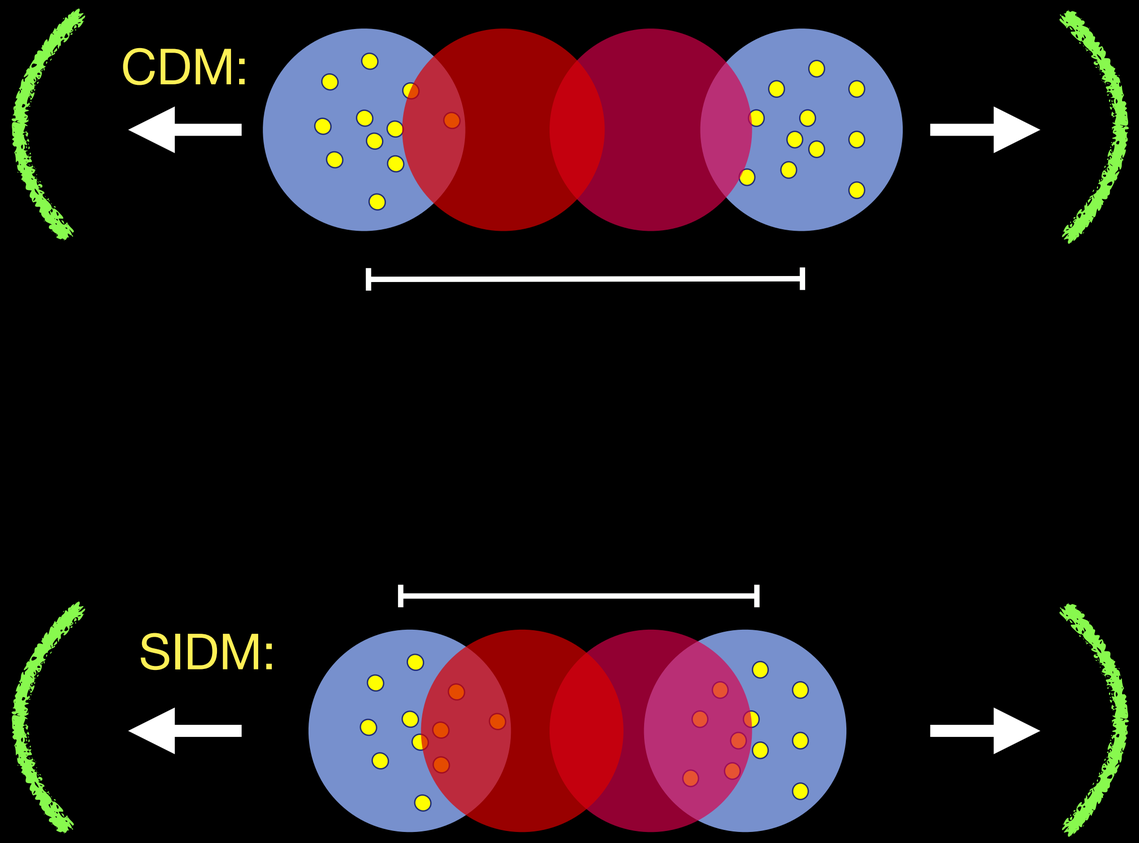


optical+X-ray+radio



WL+X-ray+radio

Shocks are Shockingly Useful!

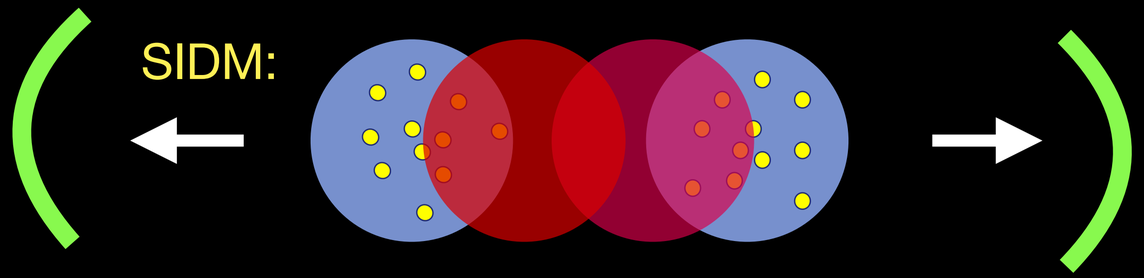


The halo-halo distance is sensitive to interaction strength.

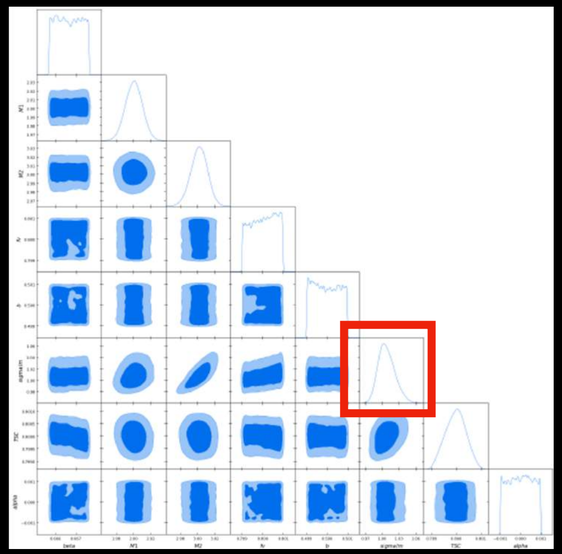
But,

- we don't know the merger phase
- we don't know the viewing angle
- we don't know the collision speed
- we don't know the impact parameter
- …

Test with a Single System

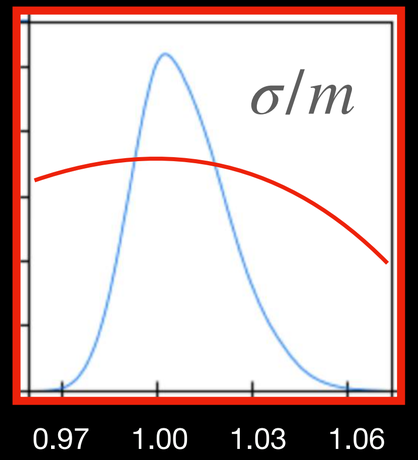


$$\log(\text{likelihood}) = -0.5 \times \sum \frac{\vec{d}^{obs} - \vec{d}^{pred}}{\vec{\sigma}^{obs}}$$



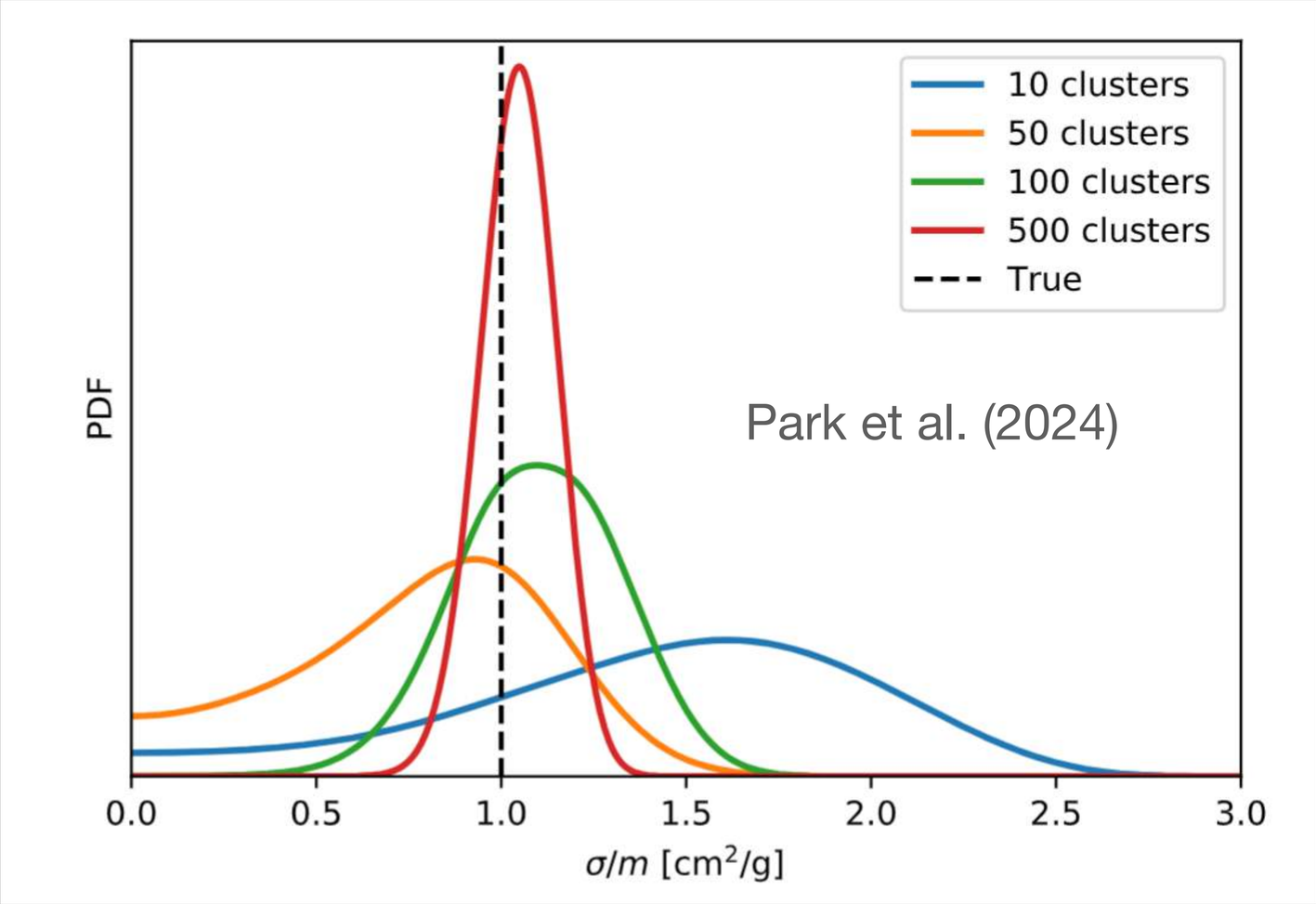
$$\vec{d}^{obs} = (d_h^o, d_s^o)$$

$$\vec{d}^{pred}(\beta, M_1, M_2, v, b, \sigma/m, TSC, \alpha) = (d_h^p, d_s^p)$$



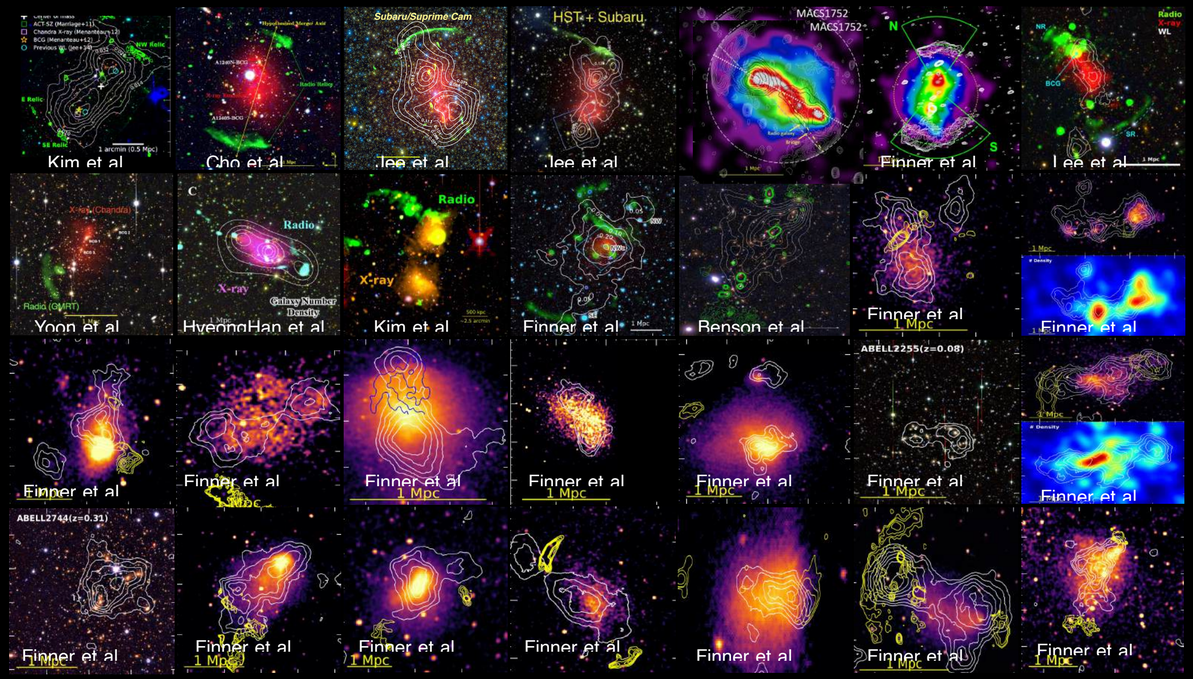
Test with Many Systems

$$p(\sigma/m) = p_1(\sigma/m) \times p_2(\sigma/m) \times \ldots \times p_n(\sigma/m)$$



Observational Data

Kyle Finner at Caltech

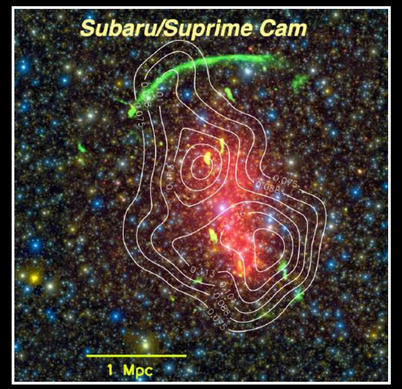


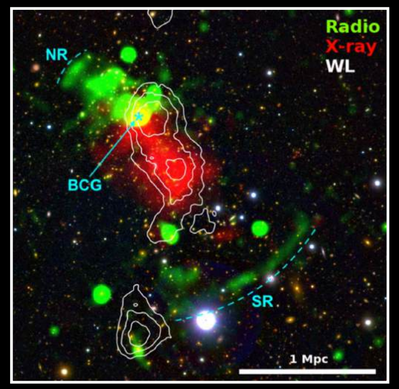
- Bi-modality in mass
- Double-radio relics
- Alignment between halo-halo and shock-shock vectors

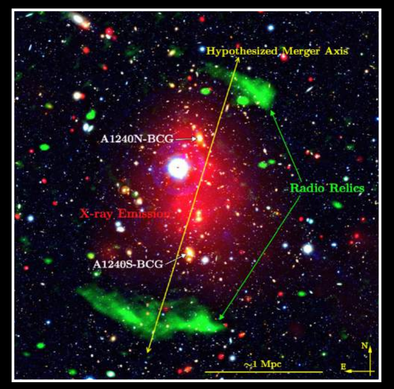
10 Golden Samples

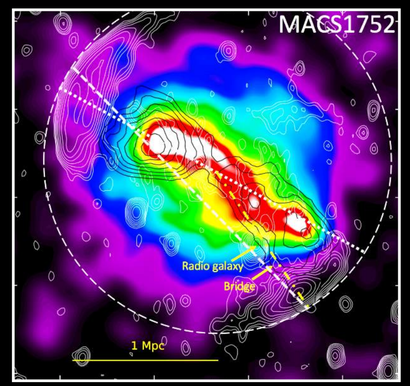
Park et al. (2024)

name	d_{shock} [Mpc]	d_{halo} [Mpc]	M_1 [10^{14} $M_\odot$]	M_2 [10^{14} $M_\odot$]
ACT-CL J0102-4915[a]	1.82 ± 0.02	0.77 ± 0.13	6.5 ± 1.65	9.9 ± 2.15
CIZA J2242.8+5301[b]	2.56 ± 0.03	1.07 ± 0.29	9.8 ± 3.15	11 ± 3.45
MACS J1752.0+4440[c]	2.10 ± 0.02	1.19 ± 0.065	5.6 ± 1.7	5.9 ± 1.77
ZWCL 1856.8+6616[c]	1.92 ± 0.02	0.66 ± 0.093	1.0 ± 0.5	1.2 ± 0.5
Abell 1240[d]	2.23 ± 0.02	1.10 ± 0.16	1.09 ± 0.38	2.61 ± 0.55
ZWCL1447.2+2619[e]	2.01 ± 0.02	0.36 ± 0.15	1.0 ± 0.5	2.7 ± 0.8
RXC J1314.4-2515[f]	1.5 ± 0.01	0.54 ± 0.092	2.5 ± 1.15	3.8 ± 1.8
Zwcl 0008.8+5215[f]	1.61 ± 0.02	1.02 ± 0.10	2.8 ± 1.5	2.8 ± 1.8
Abell 3376[g]	2.08 ± 0.02	1.1 ± 0.11	0.9 ± 0.65	3.0 ± 1.5

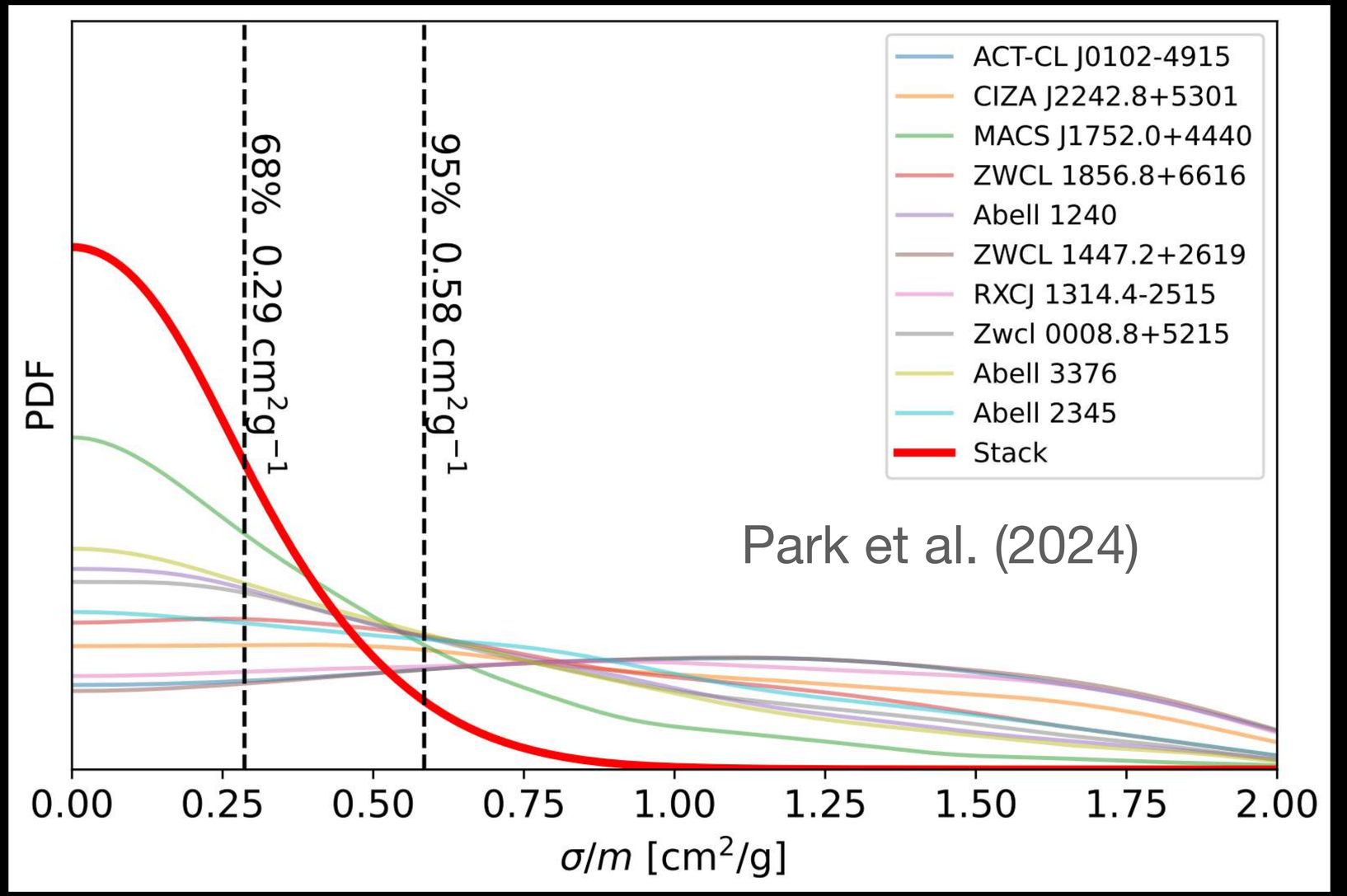








SIDM Constraint from 10 LHCs



Randall et al. (2008):

$\frac{\sigma}{m} \lesssim 1.25\ \mathrm{cm^2\ g^{-1}}$ (68%)

Harvey et al. (2015):

$\lesssim 0.47\ \mathrm{cm^2\ g^{-1}}$ (95%)

Wittman et al. (2018):

$\lesssim 2\ \mathrm{cm^2\ g^{-1}}$ (95%)

Current study:

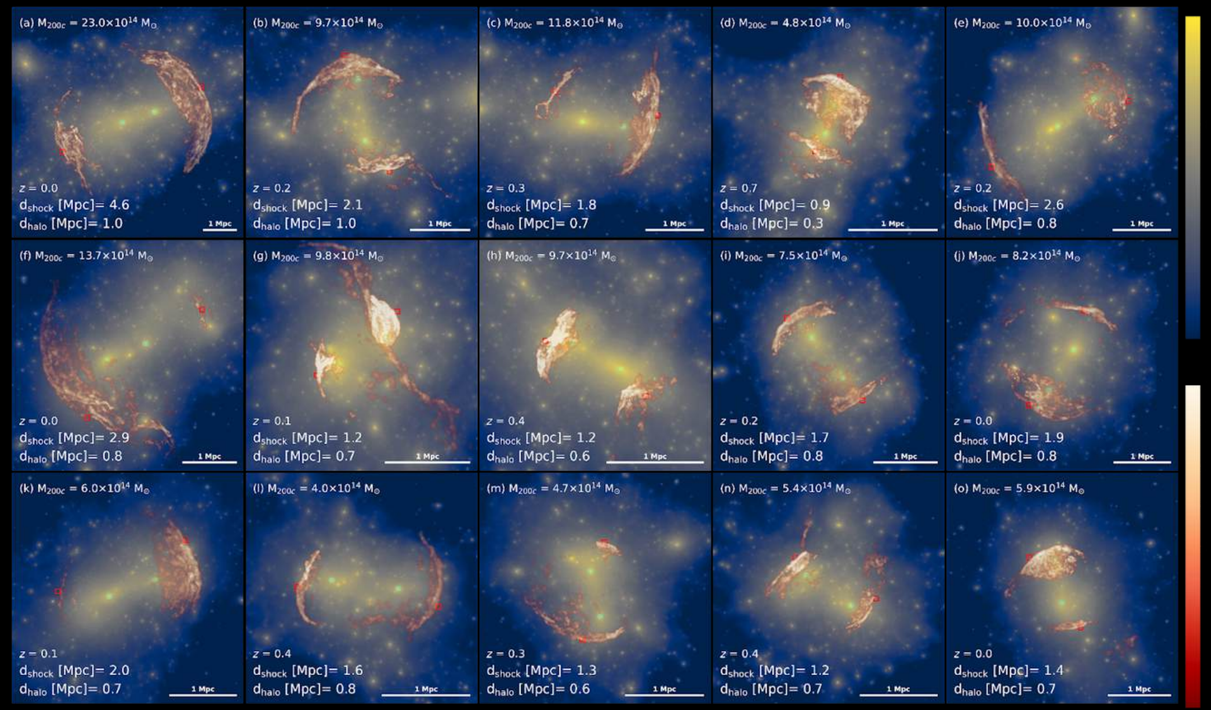
$\frac{\sigma}{m} \lesssim 0.3\ \mathrm{cm^2\ g^{-1}}$ (68%)

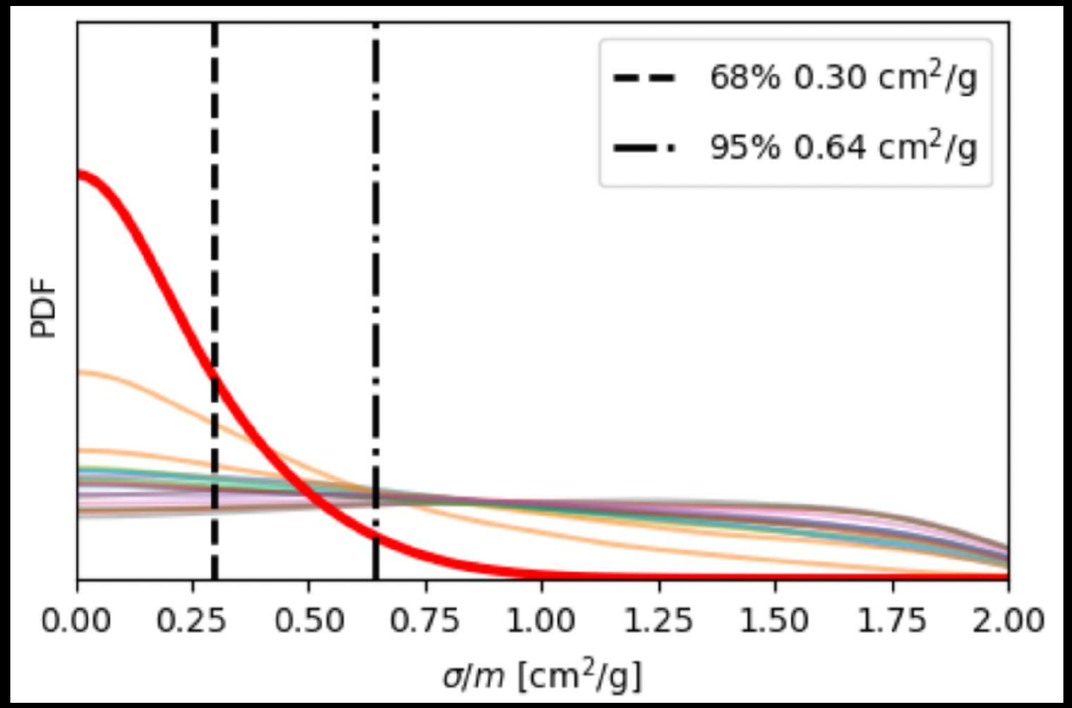
$\lesssim 0.58\ \mathrm{cm^2\ g^{-1}}$ (95%)

The tightest upper limit to date after marginalizing over degeneracies.

Null Test in the Cosmological Context

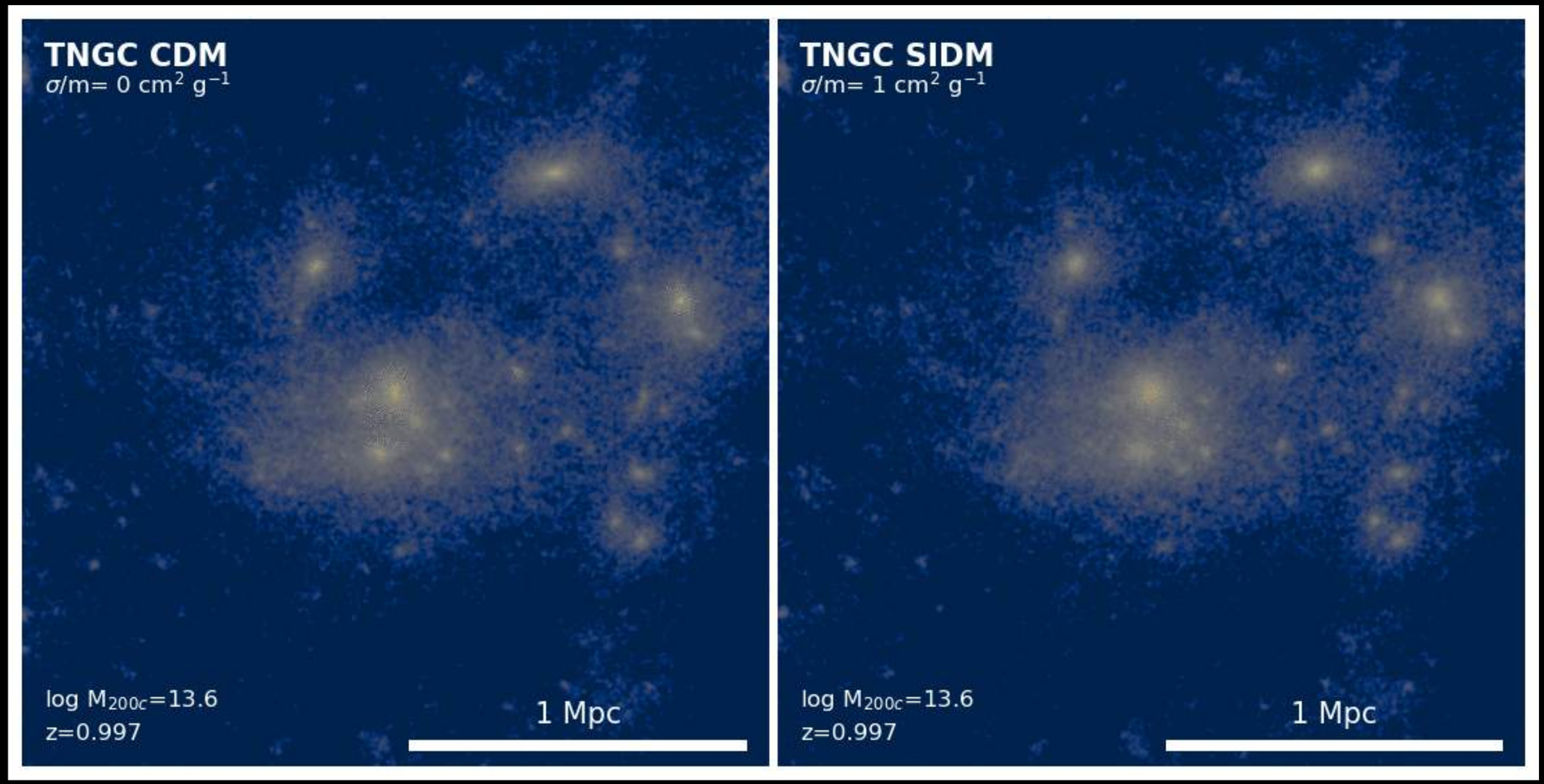
Merging clusters in TNG-Cluster





No significant bias due to the environmental effect.

TNGC-SIDM Project



PI: Wonki Lee

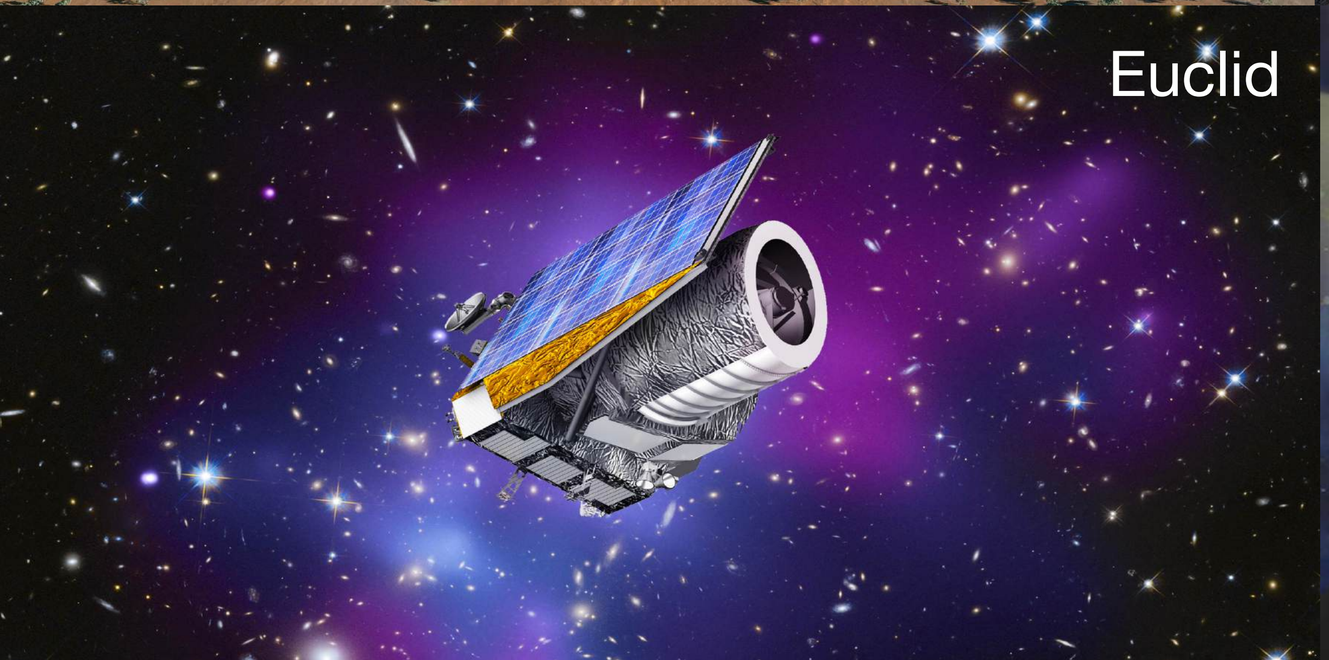
Co-Is:

Volker Springel
Mark Vogelsberger
Dylan Nelson
Annalisa Pillepich
Dongak Park
James Jee

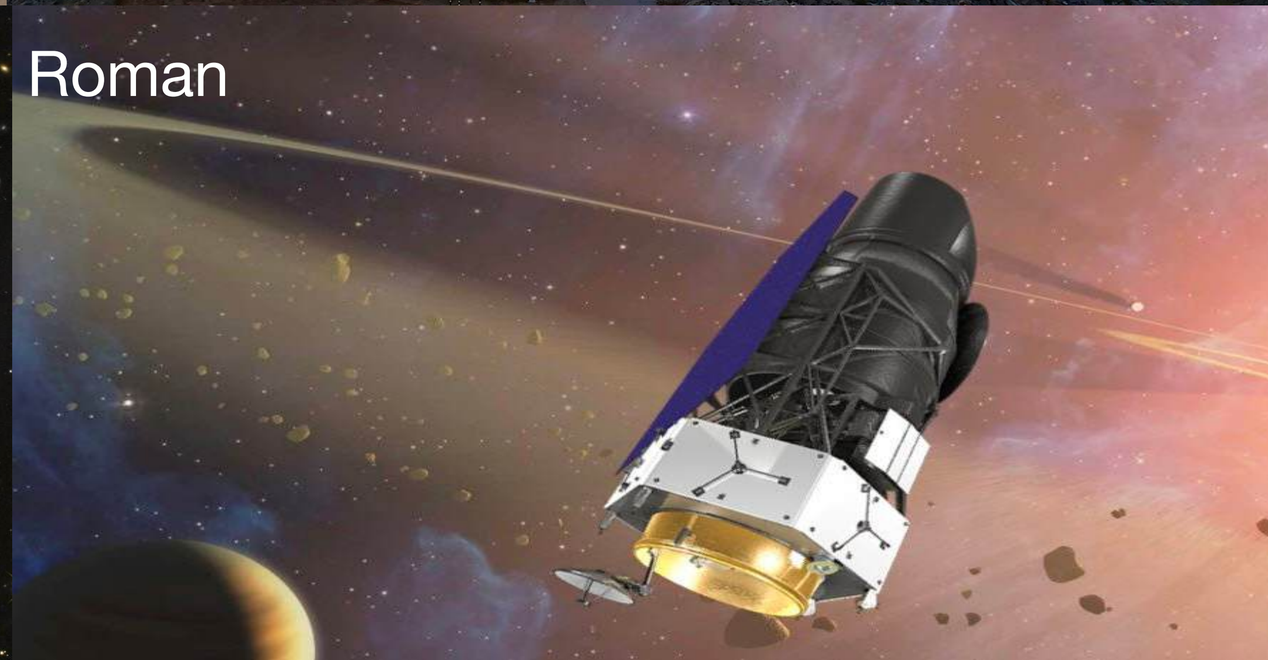
The future is on our side!

SKA

Rubin



Euclid



Roman

Conclusion/Summary

- LHCs (Large Halo Colliders) are powerful probes of dark matter.
- Earlier studies were based on incorrect hypotheses.
- The ratio of h-h distance to r-r distance is sensitive to DM interaction.
- Out of 10 golden samples, we provide the tightest constraints on self-interaction cross-section $\frac{\sigma}{m} \lesssim 0.3\ \mathrm{cm}^2\ \mathrm{g}^{-1}\ (68\%)$.
- Future radio surveys will provide >~2000 radio relics, which will enable precision DM measurement.
- In case we support SIDM, particle physicists will consider dark sector models more seriously.
- In case we rule out SIDM, particle physicists will spend their time in a more meaningful way.

Future improvements

- polarization -> viewing angle
- Mach number -> collision velocity
- X-ray data -> additional constraint
- cosmological simulation -> merger calibration
- rSIDM vs fSIDM -> different species of DM
- intracluster light -> tighter constraint on halo-halo distance

Yonsei Observable UNiverse Group

Thank you!