Interactions about self-interacting dark matter

Felix Kahlhoefer

SubirFest

Oxford, 11 September 2023

Self-interacting dark matter, July 31, 2017 to August 4, 2017 Niels Bohr Institute

Copenhagen Conference, 1930

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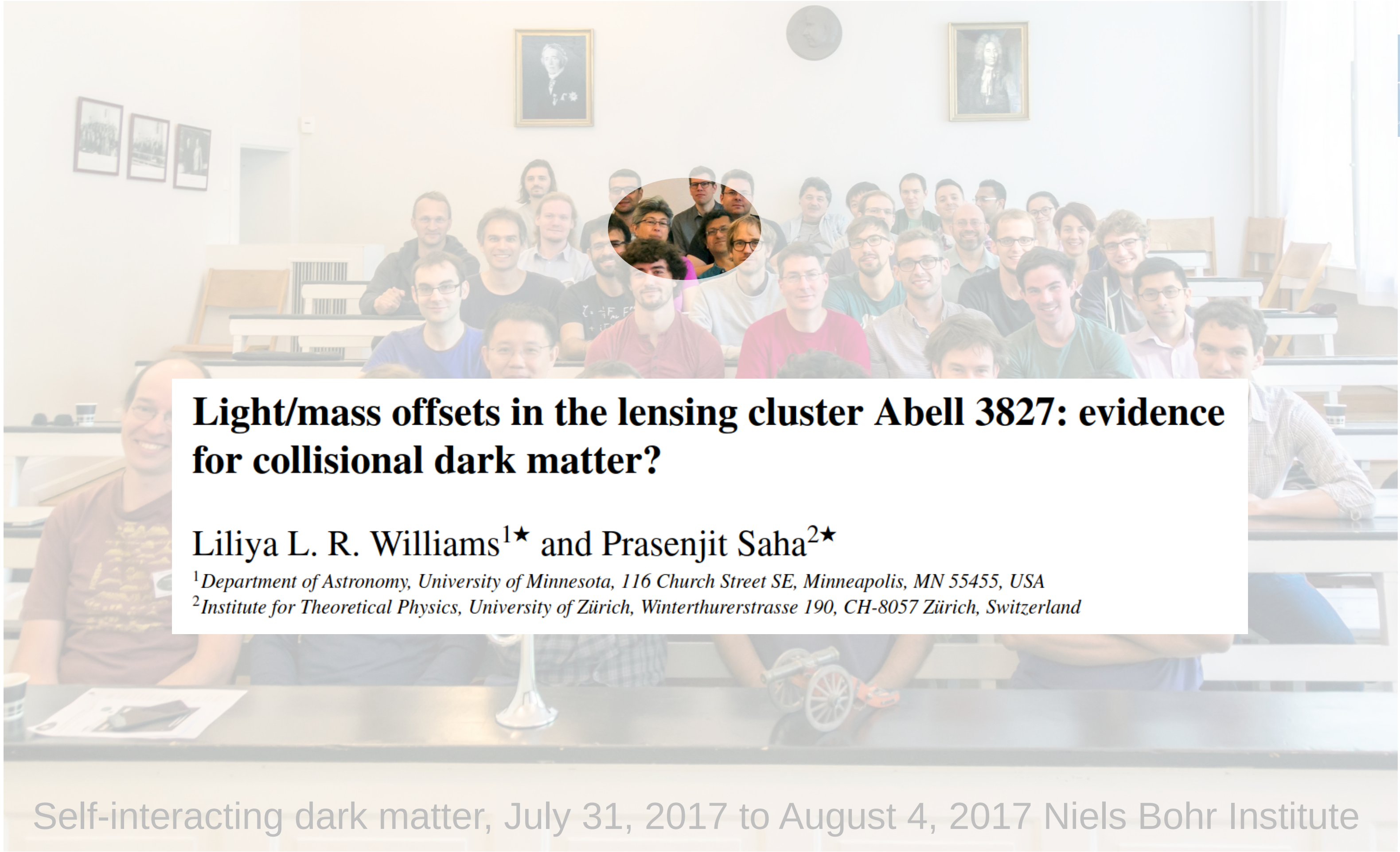

Light/mass offsets in the lensing cluster Abell 3827: evidence for collisional dark matter?

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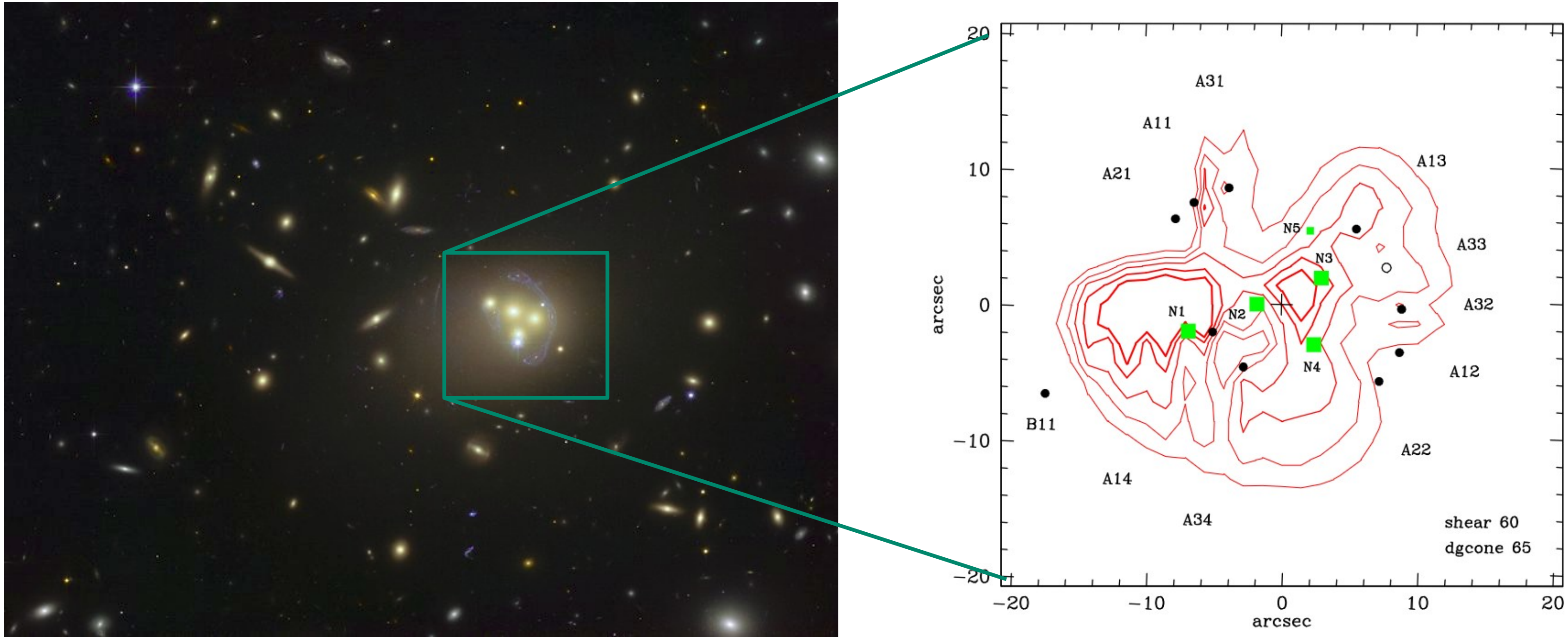
Abell 3827



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Abell 3827

- **Key observation:** Four central galaxies that appear to be separated from the peaks of the dark matter distribution

- **Possible interpretation:** Effective drag force on dark matter haloes, arising from the self-interaction of dark matter particles

A promising opportunity to prove ΛCDM wrong!

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Self-interacting dark matter

- WIMPs are generally not expected to have large self-interactions
- Papers on dark matter particles with new strong interactions (e.g. technibaryons) go back to the 1980s

SELF-INTERACTING DARK MATTER

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Received 1992 March 17; accepted 1992 April 20

Self-interacting dark matter

- WIMPs are generally not expected to have large self-interactions
- Papers on dark matter particles with new strong interactions (e.g. technibaryons) go back to the 1980s
- Idea gained traction in early 2000s when it was proposed as a solution for various discrepancies between N-body simulations and observations

Observational Evidence for Self-Interacting Cold Dark Matter

David N. Spergel and Paul J. Steinhardt

Princeton University, Princeton, New Jersey 08544

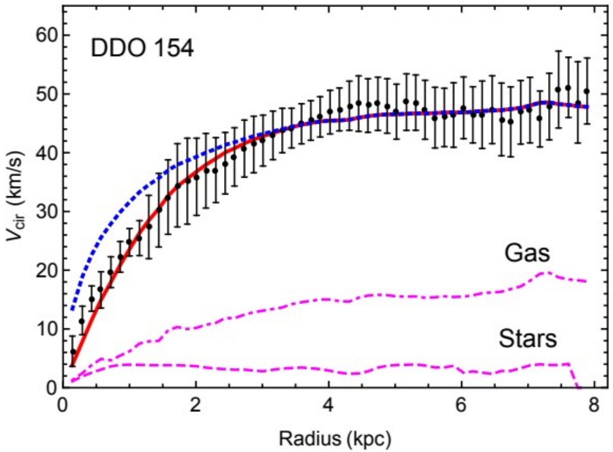
(Received 20 September 1999)

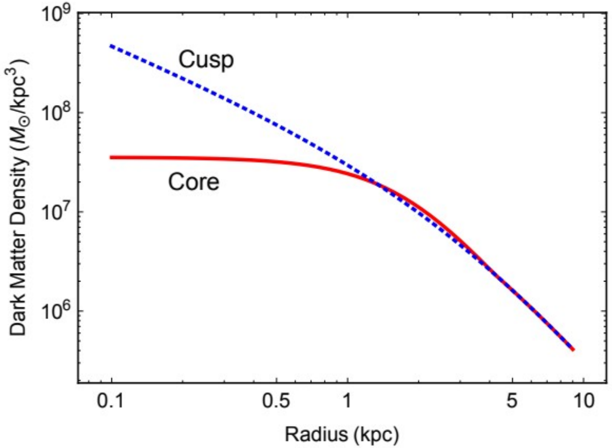
The cusp-core problem

Tulin & Yu, arXiv:1705.02358

- Discrepancy between predicted and observed circular velocities in the central region of DM haloes

- Deficit in mass points to constant-density cores rather than cuspy density profiles





- Problem: Reliable observations → many stars → large baryonic effects

  Small baryonic effects → few stars → unreliable observations

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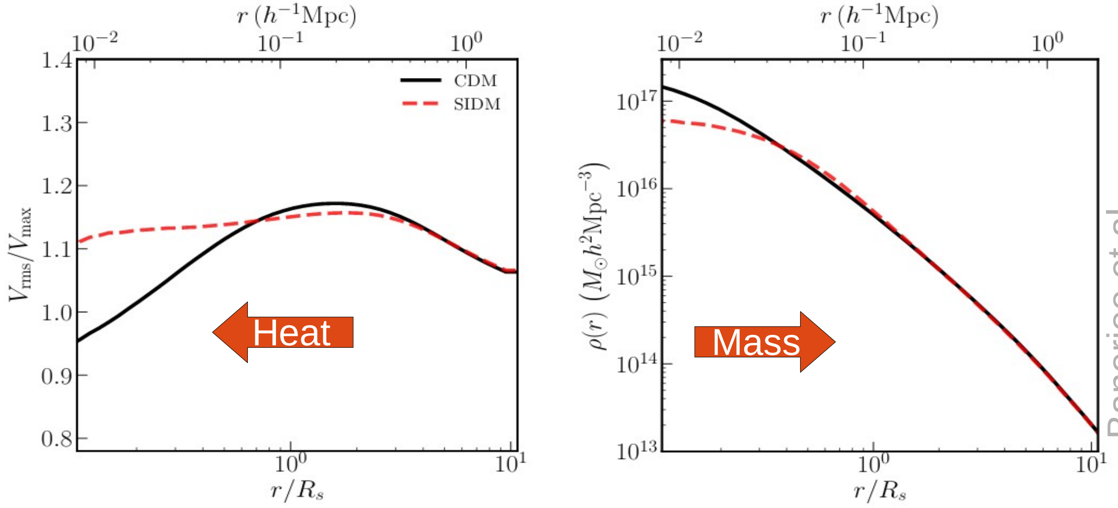
Resolving the small-scale tensions

- Dark matter (DM) self-interactions can transfer energy from hot regions of a DM halo (shallow gravitational potential) to cold regions (deep gravitational potential)
- As a result, they transform halos with cuspy profile into halos with central cores



Banerjee et al., arXiv:1906.12026

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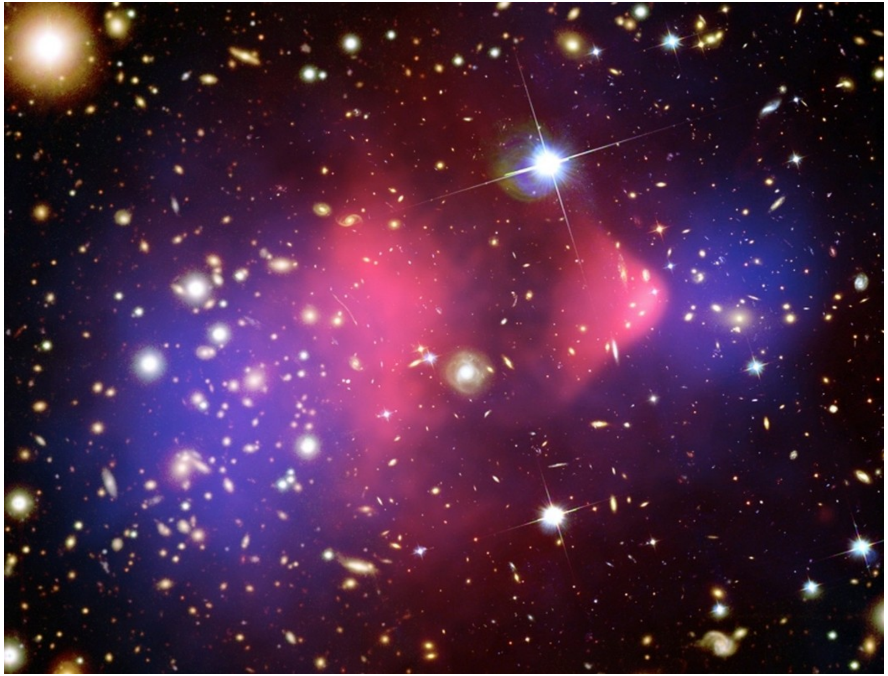
But isn’t dark matter collisionless?



- Most DM particles travel through the Bullet Cluster without scattering
- The Bullet Cluster has a surface DM density of $\Sigma \sim 0.3\ \mathrm{g/cm^2}$
- This implies $\Sigma\ \sigma / m_\chi \lesssim 0.5$, and thus $\sigma / m_\chi \lesssim 1.5\ \mathrm{cm^2/g} = 3\ \mathrm{barn/GeV}$
- Not at all a small cross section – comparable to neutron scattering!

Subhaloes in Self-Interacting Galactic Dark Matter Haloes

Mark Vogelsberger[1]⋆, Jesus Zavala[2,3]†, Abraham Loeb[1]

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[2] *Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*
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Constraining Self-Interacting Dark Matter with the Milky Way's dwarf spheroidals

Jesús Zavala[1,2]⋆, Mark Vogelsberger[3]† and Matthew G. Walker[3]‡,

[1] *Perimeter Institute for Theoretical Physics, 31 Caroline St. N., Waterloo, ON, N2L 2Y5, Canada*
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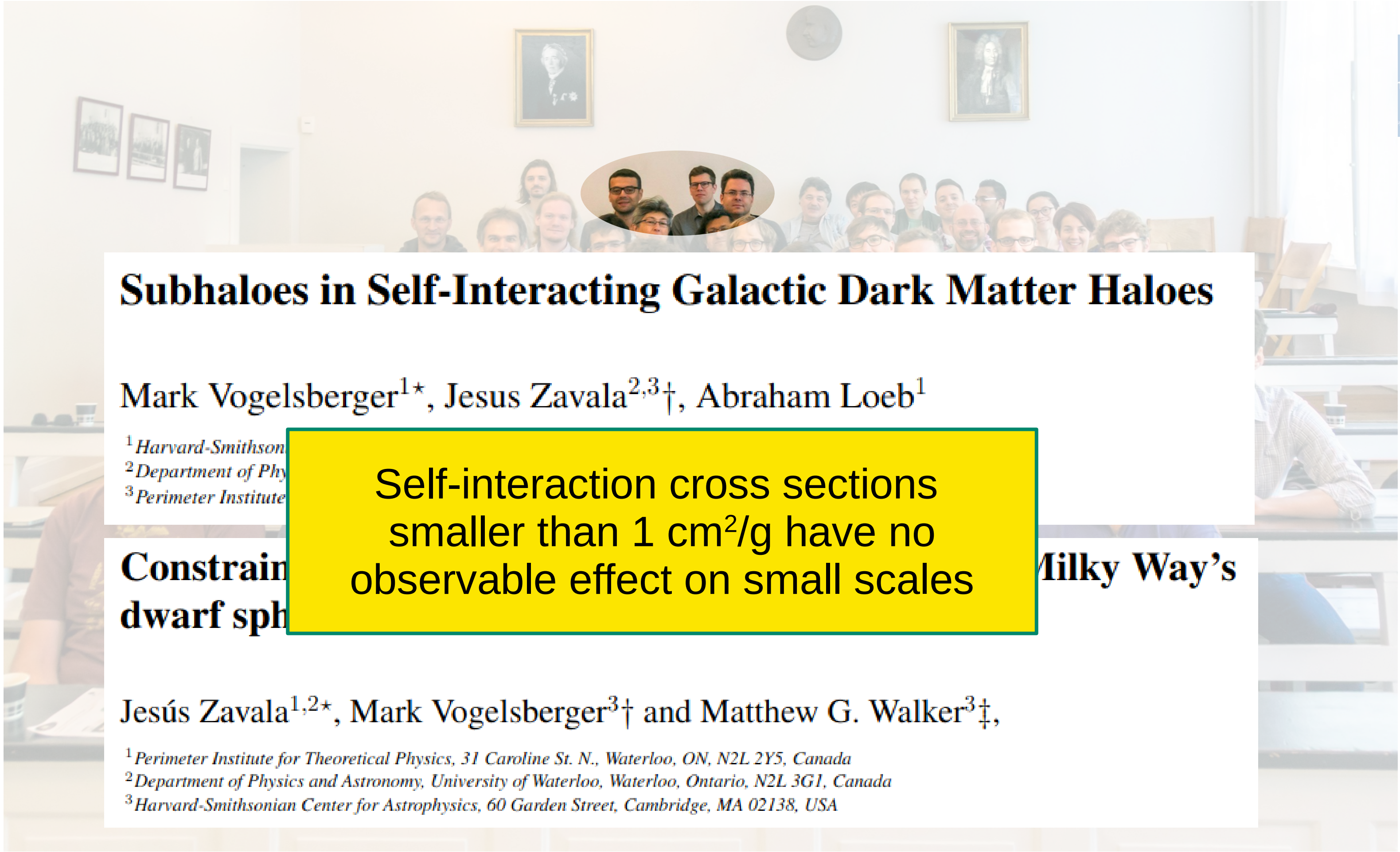

Subhaloes in Self-Interacting Galactic Dark Matter Haloes

Mark Vogelsberger[1⋆], Jesus Zavala[2,3]†, Abraham Loeb[1]

[1] Harvard-Smithson
[2] Department of Phy
[3] Perimeter Institute

Self-interaction cross sections smaller than 1 cm²/g have no observable effect on small scales

Constrain … Milky Way's dwarf sph

Jesús Zavala[1,2⋆], Mark Vogelsberger[3]† and Matthew G. Walker[3]‡,

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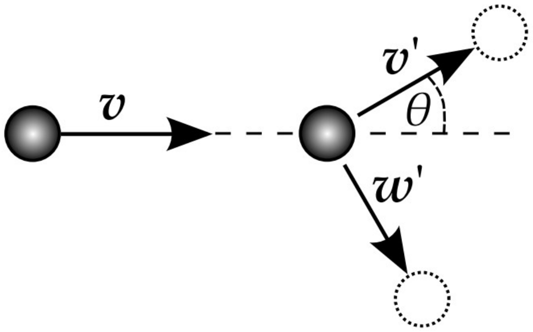
Rare and frequent self-interactions

- Early studies assumed that collisions between dark matter particles are rare and lead to large momentum transfer



- Dark matter particles ejected through individual collisions

  → Mass loss and deformation of dark matter halos

- How does this relate to the effective drag force assumed by Williams & Saha?

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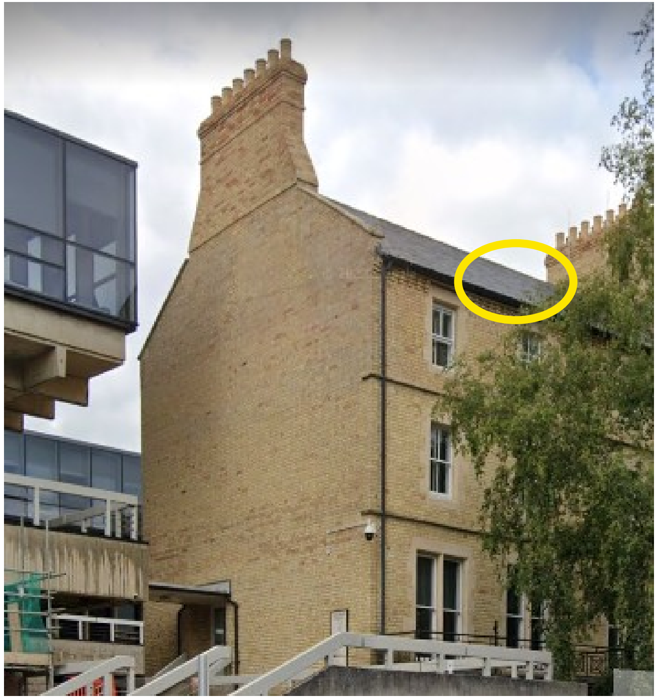
A summer under the roof



Colliding clusters and dark matter self-interactions

Felix Kahlhoefer,[1*] Kai Schmidt-Hoberg,[2] Mads T. Frandsen[3] and Subir Sarkar[1,4]
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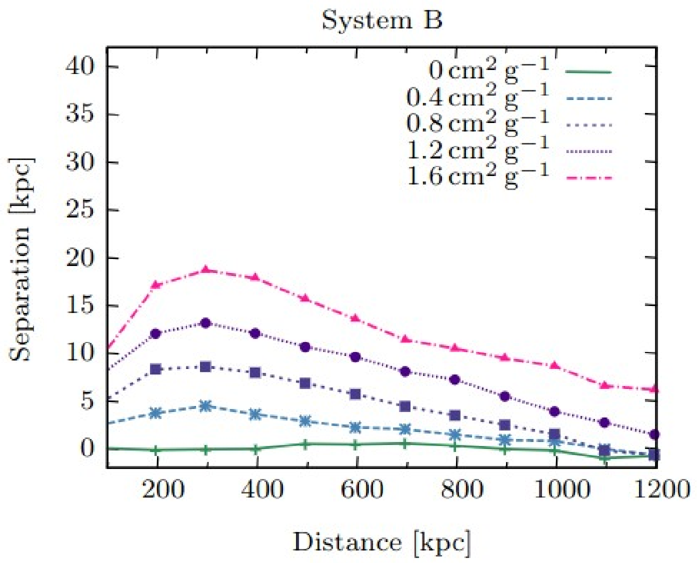
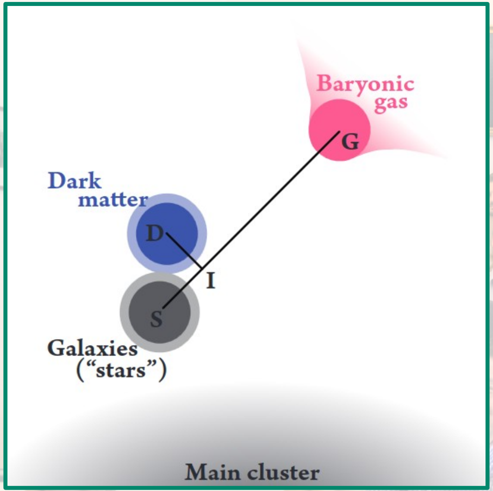
- An effective drag force arises from averaging over a large number of scattering processes with small scattering angle
- Frequent self-interactions give qualitatively different behaviour compared to rare self-interactions
- **Key result:** drag force compensated by gravitational forces → remaining effect is small





On the cross-section of Dark Matter using substructure infall into galaxy clusters

David Harvey[1⋆], Eric Tittley[1], Richard Massey[2], Thomas D. Kitching[3], Andy Taylor[1], Simon R. Pike[4], Scott T. Kay[4], Erwin T. Lau[5,6] and Daisuke Nagai[5,6]

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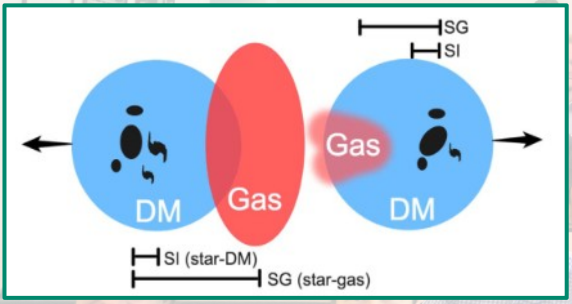
[2] *Institute for Computational Cosmology, Durham University, South Road, Durham DH1 3LE, UK*
[3] *Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK*
[4] *Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Manchester, M13 9PL, UK*
[5] *Department of Physics, Yale University, New Haven, CT 06520, USA*
[6] *Yale Center for Astronomy & Astrophysics, New Haven, CT 06520, USA*



The Mismeasure of Mergers: Revised Limits on Self-interacting Dark Matter in Merging Galaxy Clusters

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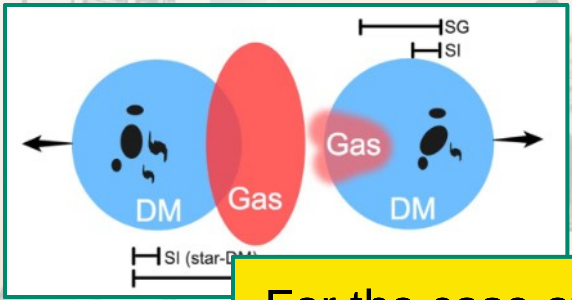
Received 2017 January 17; revised 2018 August 21; accepted 2018 September 12; published 2018 December 17



For the case of frequent self-interactions a statistical combination of several merging clusters gives $\sigma / m_\chi < 2\ \mathrm{cm}^2/\mathrm{g}$ (similar to rare self-interactions)

The Mismeas … Matter in Merging

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What about Abell 3827?

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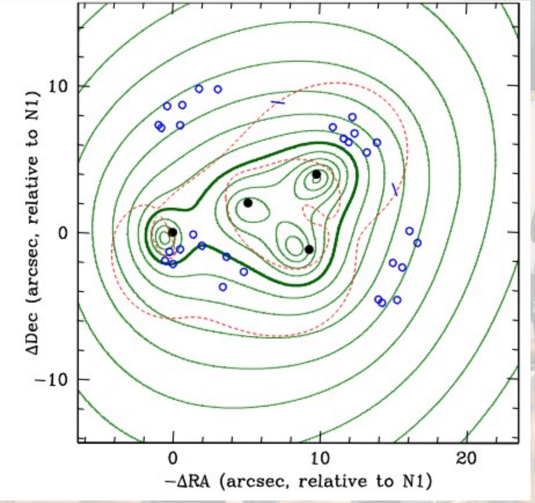
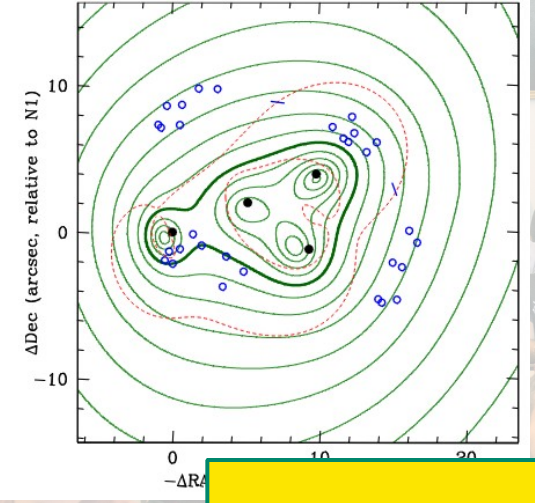


The behaviour of dark matter associated with 4 bright cluster galaxies in the 10 kpc core of Abell 3827

Richard Massey[1,2★], Liliya Williams[3], Renske Smit[2], Mark Swinbank[2], Thomas D. Kitching[4], David Harvey[5], Mathilde Jauzac[1,6], Holger Israel[1], Douglas Clowe[7], Alastair Edge[2], Matt Hilton[6], Eric Jullo[8], Adrienne Leonard[9], Jori Liesenborgs[10], Julian Merten[11,12], Irshad Mohammed[13], Daisuke Nagai[14], Johan Richard[15], Andrew Robertson[2], Prasenjit Saha[13], Rebecca Santana[7], John Stott[2] & Eric Tittley[16]



The beha... bright cluster ga...

Statistically significant offset remains!
Best-fit self-interaction cross section:
$\sigma / m_\chi < (1.7 \pm 0.7)\ \mathrm{cm^2/g}$

Richard Massey[1,2*], Liliya Williams[3], Renske Smit[2], Mark Swinbank[2], Thomas D. Kitching[4], David Harvey[5], Mathilde Jauzac[1,6], Holger Israel[1], Douglas Clowe[7], Alastair Edge[2], Matt Hilton[6], Eric Jullo[8], Adrienne Leonard[9], Jori Liesenborgs[10], Julian Merten[11,12], Irshad Mohammed[13], Daisuke Nagai[14], Johan Richard[15], Andrew Robertson[2], Prasenjit Saha[13], Rebecca Santana[7], John Stott[2] & Eric Tittley[16]

On the interpretation of dark matter self-interactions in Abell 3827

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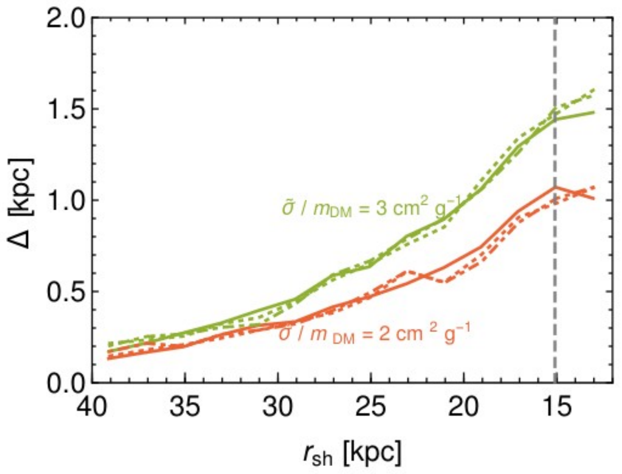
[3] Niels Bohr Institute, Blegdamsvej 17, 2100 København Ø, Denmark

- Improved modeling implies larger self-interaction cross section ($\sigma / m_\chi \sim 3\ \mathrm{cm}^2/\mathrm{g}$)
- Possible tension with upper bounds from major mergers
- Need for improved modeling and better lensing data



Idea to organise a workshop

F: “Hey Subir, how about we apply to [theoretical physics institute] for a topical workshop on self-interacting dark matter?”

S: ”Let’s do the workshop at Niels Bohr International Academy instead. Money is not a problem.”

Highlight 1: Full-day excursion to Lousiana

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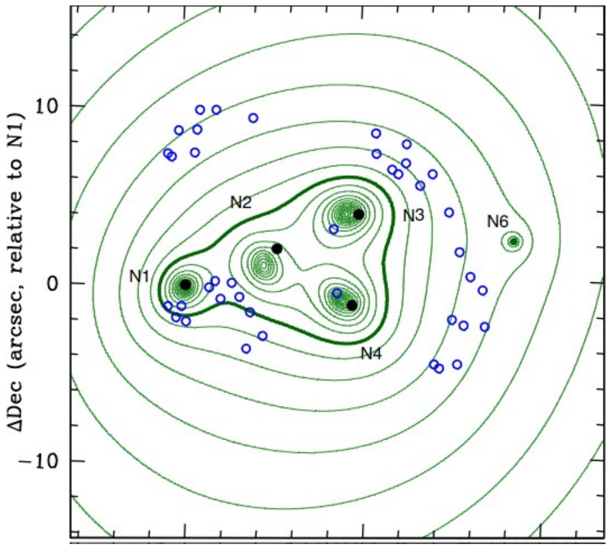
Highlight 2: New data from Abell 3827

Highlight 2: New data from Abell 3827

Dark matter dynamics in Abell 3827:
new data consistent with standard Cold Dark Matter

Richard Massey[1,2*], David Harvey[3], Jori Liesenborgs[4], Johan Richard[5], Stuart Stach[2], Mark Swinbank[2], Peter Taylor[6], Liliya Williams[7], Douglas Clowe[8], Frédéric Courbin[3], Alastair Edge[2], Holger Israel[1,9], Mathilde Jauzac[1,2,10], Rémy Joseph[3], Eric Jullo[11], Thomas D. Kitching[4], Adrienne Leonard[12], Julian Merten[13,14], Daisuke Nagai[15], James Nightingale[2], Andrew Robertson[1], Luis Javier Romualdez[16,17], Prasenjit Saha[18], Renske Smit[19], Sut-Ieng Tam[2] & Eric Tittley[20]



- "The new spectroscopic data enable better subtraction of foreground light, and better identification of multiple background images"
- "Our new analysis shows that there is no statistically significant offset between galaxies and their dark matter in Abell 3827, projected onto the plane of the sky."

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Subject: Bon voyage

Many thanks to all of you for making this a real workshop. Our idea of bringing astronomers and particle phenomenologists together did seem to work ... I do believe we learnt a lot from each other and picked up new ideas to pursue.

Hope you had a great time in Copenhagen and wish you a good trip back home!

Subir

Self-interacting dark matter – 6 years later

- Constraints from merging clusters imply that velocity-dependent self-interaction cross section is required to address small-scale problems

- Obtaining positive evidence for dark matter self-interactions from major mergers appears challenging

- Lots of recent activity on understanding core formation and collapse in dwarf galaxies and Milky Way satellites

Gravothermal collapse

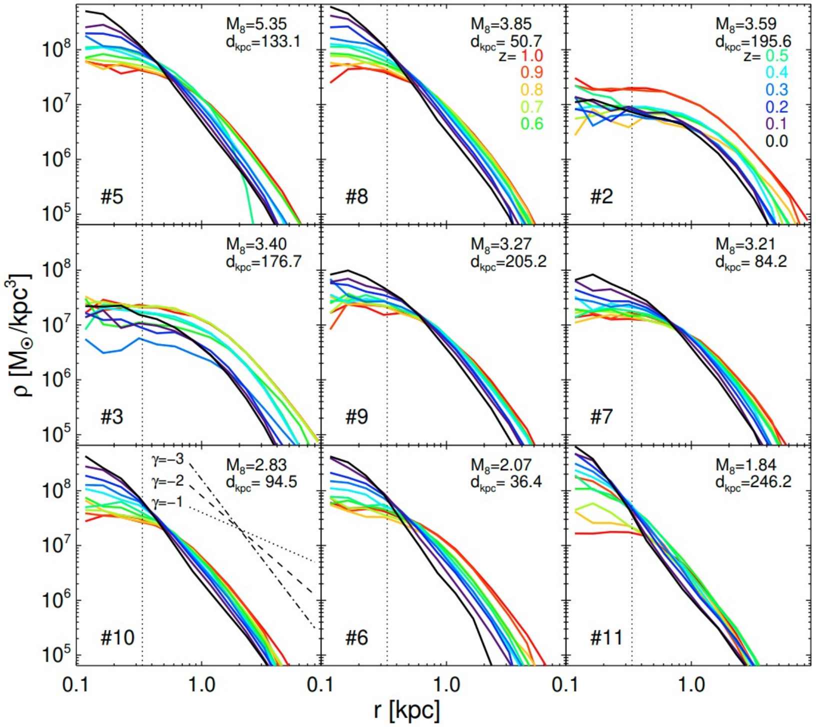
- Cores created by DM self-interactions are not stable

- Once the inner region is fully thermalised, the direction of the heat flow reverses and the central region starts cooling down

- After sufficiently long times (or for very large cross sections) cores experience gravitational collapse and cusps reappear

  → gravothermal catastrophe

Turner et al., arXiv:2010.02924



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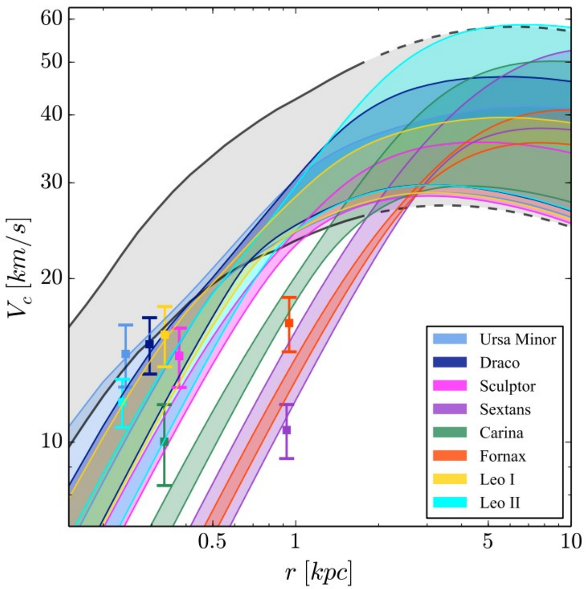
The impact of tidal forces

- If the outer parts of a DM halo are stripped by tidal forces (e.g. from a nearby galaxy), the heat loss increases and core collapse accelerates



- High concentration halos become even denser while low concentration halos are disrupted

Sameie et al., arXiv:1904.07872; FK et al., arXiv: 1904.10539

- Moreover, central density of a Milky Way satellite depends on its precise orbit (i.e. the pericenter distance)

- Possible explanation of the observed diversity of MW satellites

Valli & Yu, arXiv:1711.03502

Two outstanding questions

- How to simulate core formation for frequent DM self-interactions?
- How to match rare and frequent DM self-interactions?

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Simulating frequent self-interactions

- Naive implementation of drag force leads to continuous energy loss and the collapse of dark matter haloes
- Key idea: Re-inject dissipated energy as “heat”

N-body simulations of dark matter with frequent self-interactions

Moritz S. Fischer,[1★] Marcus Brüggen,[1] Kai Schmidt-Hoberg,[2] Klaus Dolag,[3,4] Felix Kahlhoefer,[5] Antonio Ragagnin,[6,7] Andrew Robertson[8]

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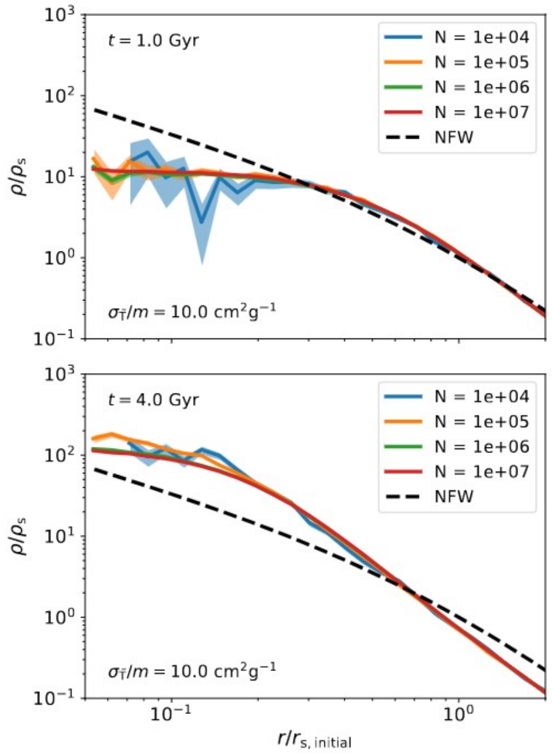

Matching rare & frequent self-interactions

- Landau & Lifshitz Volume 10, Chapter 1, Section 10, Problem 1:

  Heat conductivity is governed by the effective cross section

$$\sigma_\kappa(r) = \frac{2\int v^2 dv\, d\cos\theta \frac{d\sigma}{d\cos\theta} \sin^2\theta v^5 \exp\left[-\frac{v^2}{4\sigma_{1\mathrm{D}}^2(r)}\right]}{\int v^2 dv\, d\cos\theta \sin^2\theta v^5 \exp\left[-\frac{v^2}{4\sigma_{1\mathrm{D}}^2(r)}\right]}$$

- Different microscopic models that have the same effective cross section predict the same rate of core formation and core collapse

Outmezguine et al., arXiv:2204.06568, Yang & Yu, arXiv:2205.03392

Work in preparation with M. Fischer, Sabarish, L. Kasselmann,
M. Brüggen, K. Dolag, A. Ragagnin, A. Robertson, K. Schmidt-Hoberg

“If you're referring to the incident with the Dragon, I was barely involved. All I did was give your uncle a little nudge out of the door.”

Thank you, Subir...

...for giving me a little nudge in an exciting direction!

Your nudge led to ~15 new collaborators, 10 publications, an awesome workshop in Copenhagen and tons of stimulating discussions and ideas

Whether or not dark matter is self-interacting remains to be seen...

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