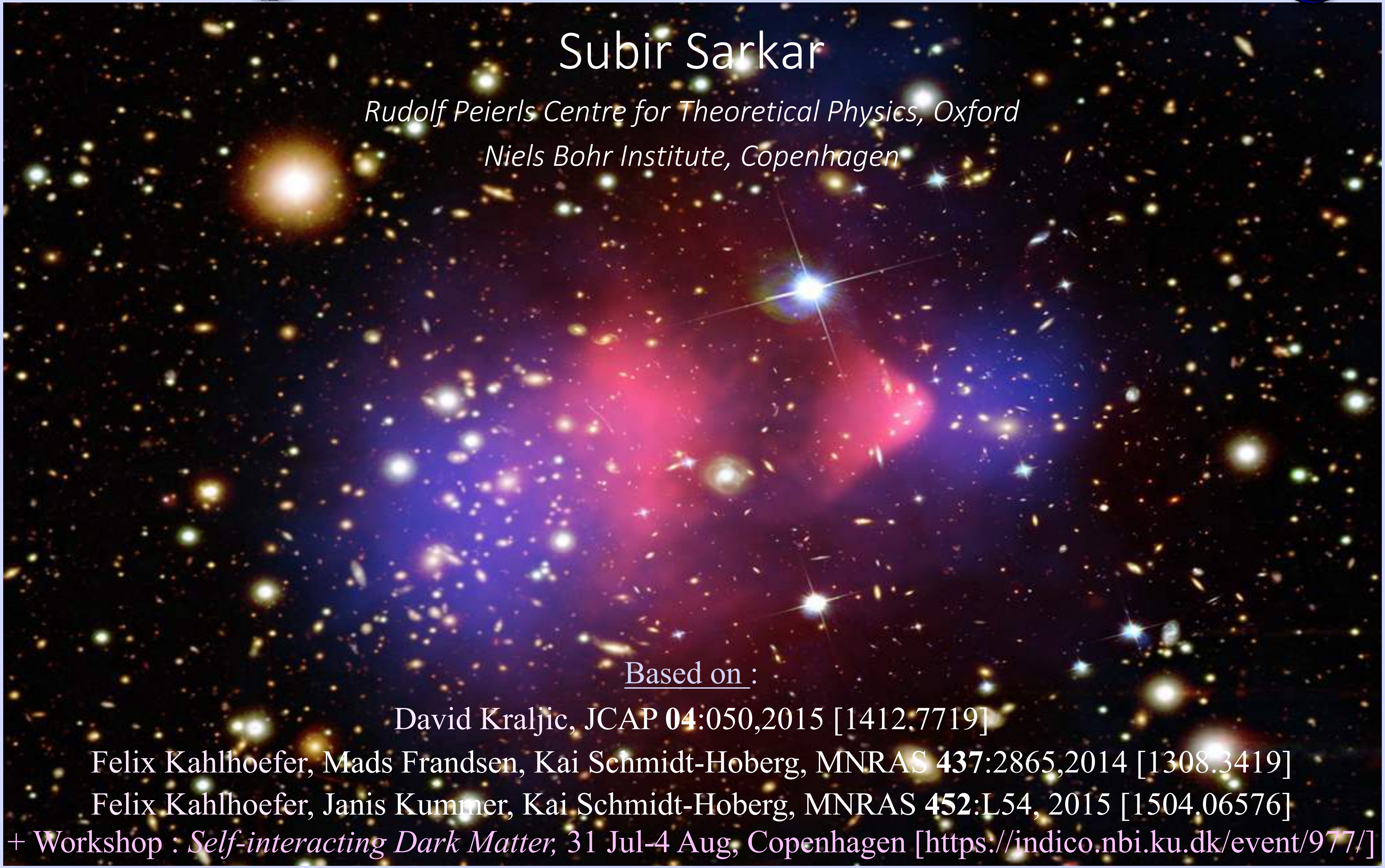
The great collider in the sky



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Based on :

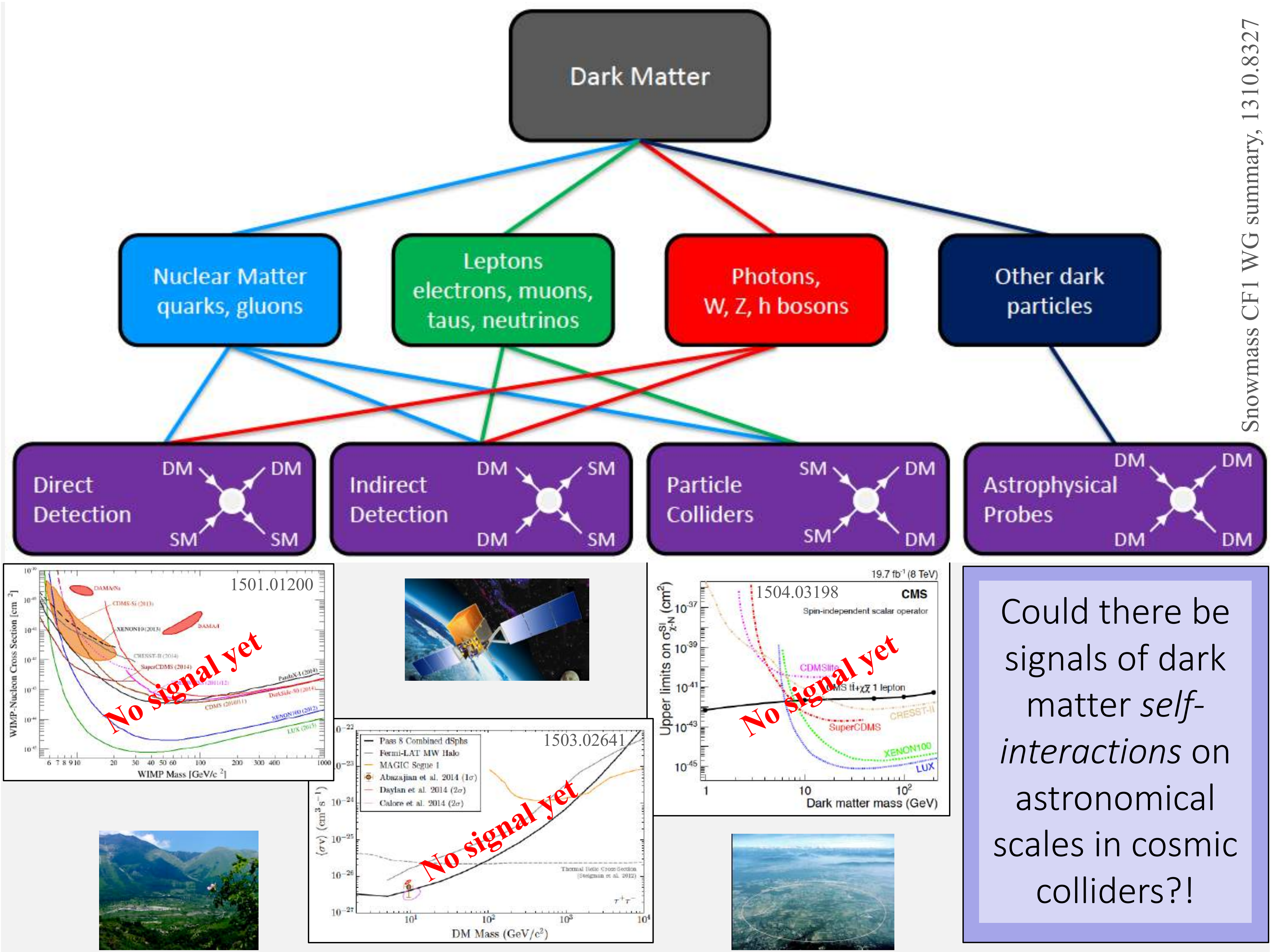
David Kraljic, JCAP **04**:050,2015 [1412.7719]

Felix Kahlhoefer, Mads Frandsen, Kai Schmidt-Hoberg, MNRAS **437**:2865,2014 [1308.3419]

Felix Kahlhoefer, Janis Kummer, Kai Schmidt-Hoberg, MNRAS **452**:L54, 2015 [1504.06576]

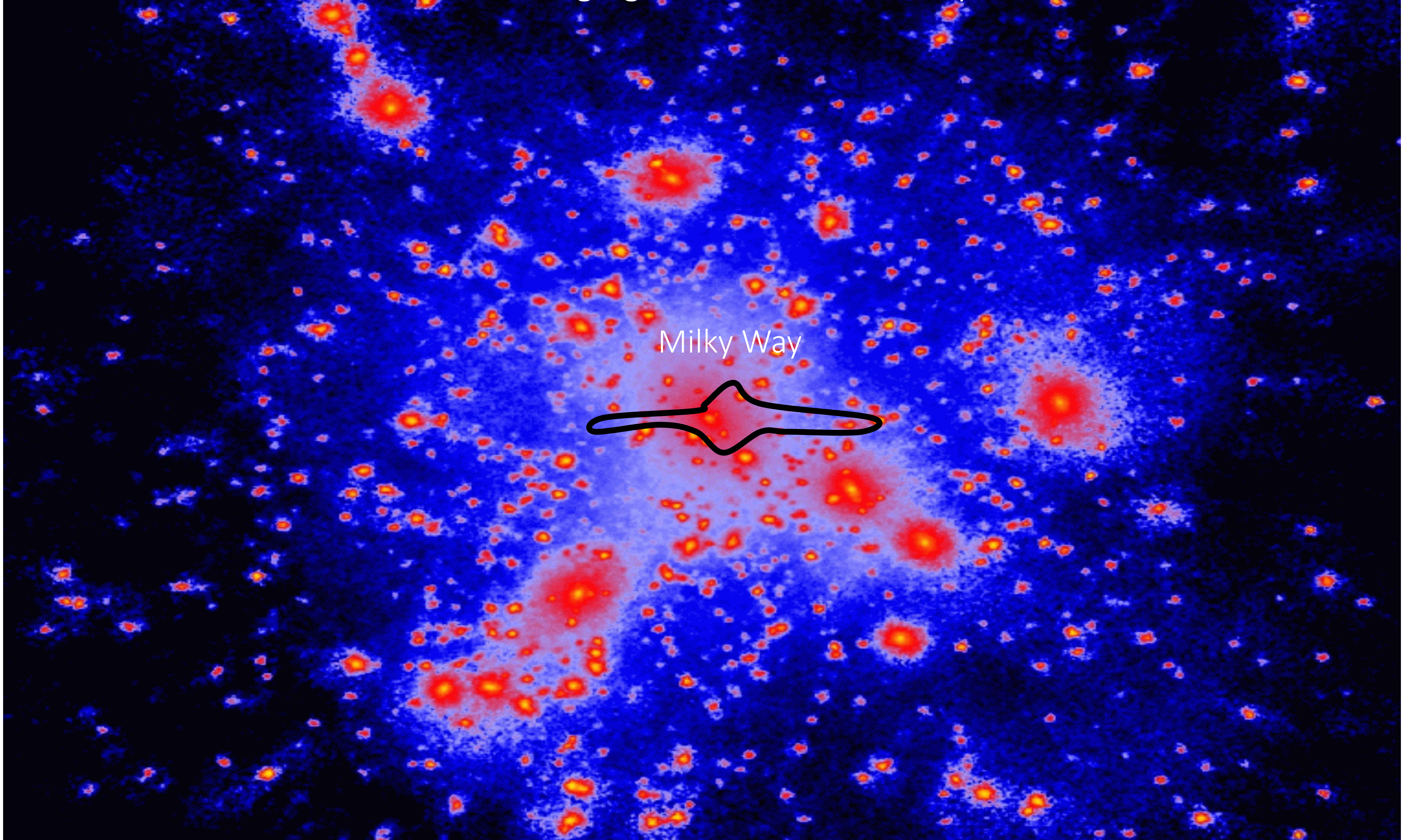
\+ Workshop : *Self-interacting Dark Matter,* 31 Jul-4 Aug, Copenhagen [https://indico.nbi.ku.dk/event/977/]

Collider Physics & the Cosmos, Galileo Institute, Florence, 9-13 October 2017



Dark Matter
Nuclear Matter quarks, gluons
Leptons electrons, muons, taus, neutrinos
Photons, W, Z, h bosons
Other dark particles
Direct Detection
DM DM SM SM
Indirect Detection
DM SM DM SM
Particle Colliders
SM DM SM DM
Astrophysical Probes
DM DM DM DM
Snowmass CF1 WG summary, 1310.8327
1501.01200
No signal yet
WIMP Mass [GeV/c²]
WIMP-Nucleon Cross Section [cm²]
1503.02641
No signal yet
DM Mass (GeV/c²)
Pass 8 Combined dSphs
Fermi-LAT MW Halo
MAGIC Segue 1
Abazajian et al. 2014 (1σ)
Daylan et al. 2014 (2σ)
Calore et al. 2014 (2σ)
1504.03198
No signal yet
CMS
19.7 fb⁻¹ (8 TeV)
Spin-independent scalar operator
Dark matter mass (GeV)
Upper limits on σ^SI_χ-N (cm²)
CDMSlite
SuperCDMS
CRESST-II
XENON100
LUX
Could there be signals of dark matter self-interactions on astronomical scales in cosmic colliders?!

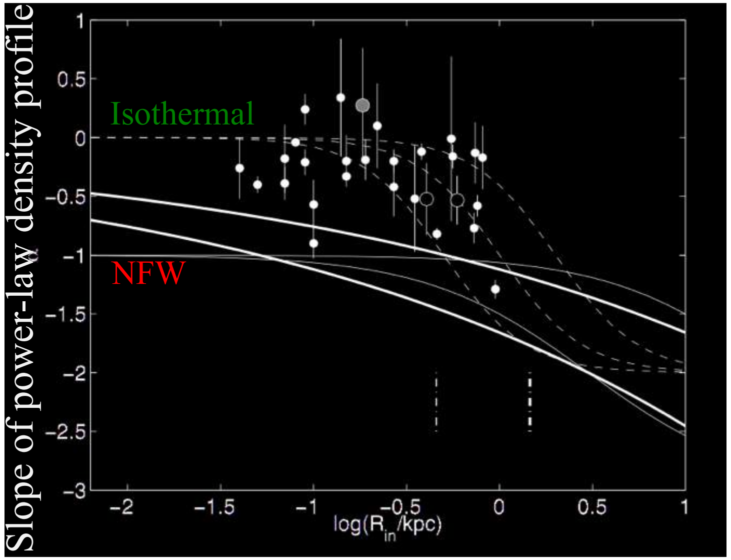
We can get an idea of what the Milky Way halo looks like from numerical simulations of structure formation through gravitational instability in cold dark matter



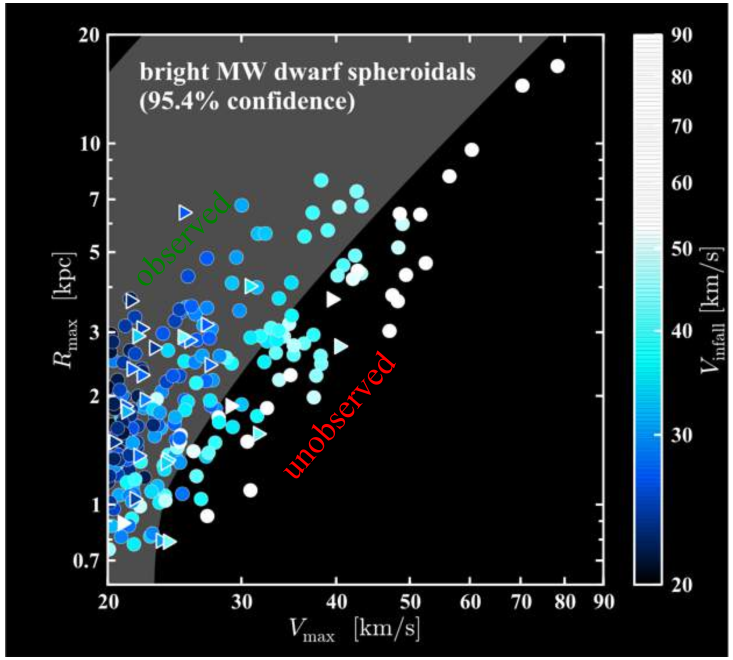
A galaxy such as ours is supposed to have resulted from the merger of many smaller structures, tidal stripping, baryonic infall and disk formation *etc* over billions of years

There appear to be some discrepancies between N-body simulations of *collisionless* cold DM and astrophysical observations on galactic scales:

- Cusp-versus-core problem
- Too-big-to-fail problem
- Missing-satellites problem
- Diversity problem



Zackrisson *et al.*, astro-ph/0603523



Boylan-Kochlin *et al*, 1103.0007

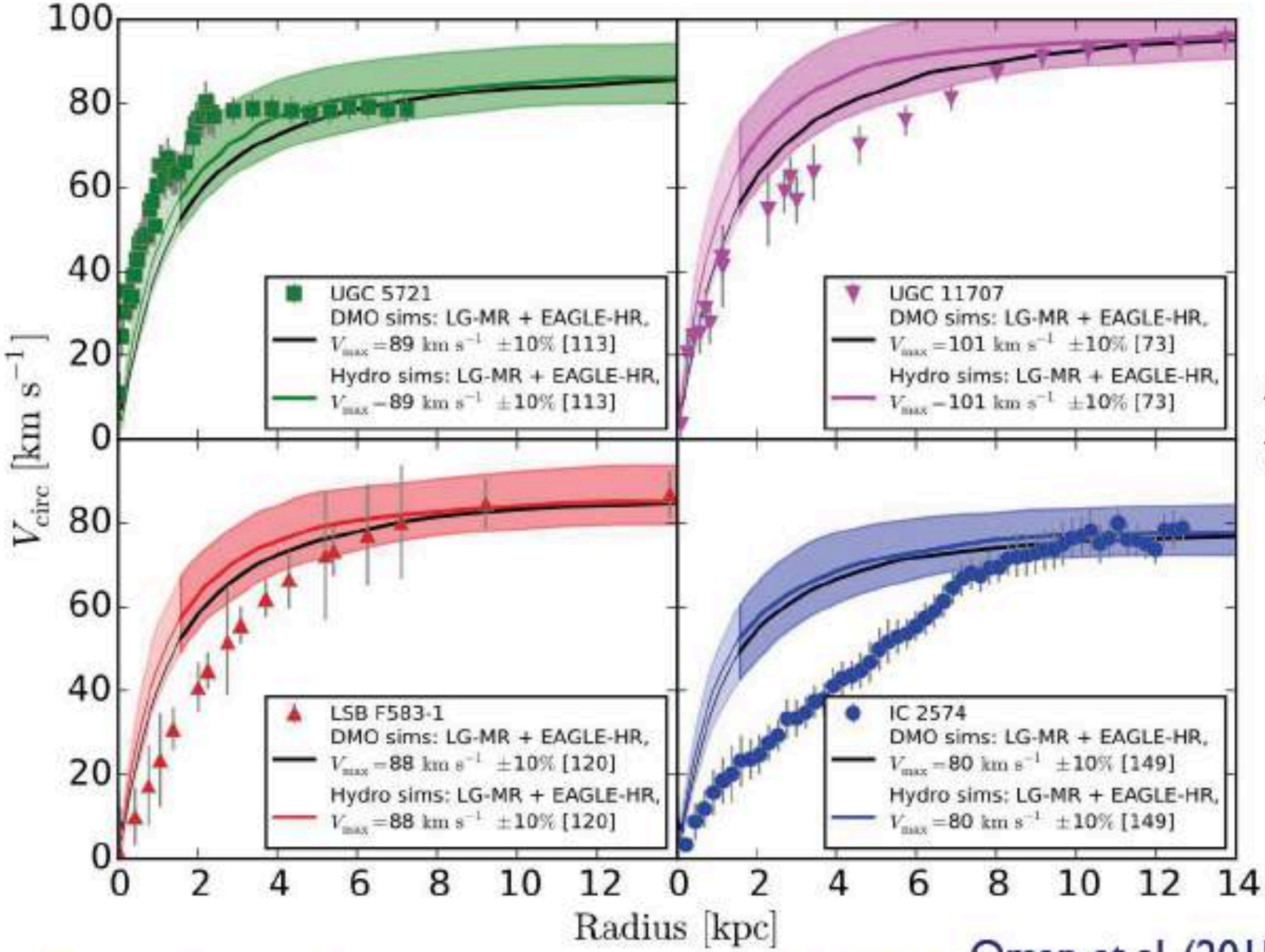
There may well be conventional astrophysical explanations, in particular 'baryonic feedback' … simulations have only just begun to address these complex issues

or … dark matter self-interactions may solve these problems (Spergel & Steinhardt, astro-ph/9909386)

$$\sigma_{XX} = 8.1 \times 10^{-25}\ \mathrm{cm}^2 \left(\frac{m_x}{\mathrm{GeV}}\right)\left(\frac{\lambda}{1\ \mathrm{Mpc}}\right)^{-1}$$ for $\rho_{DM} = 0.4\ \mathrm{GeV/cm}^3$

The Diversity Problem

Courtesey: Haibo Yu



All galaxies have the same Vmax!

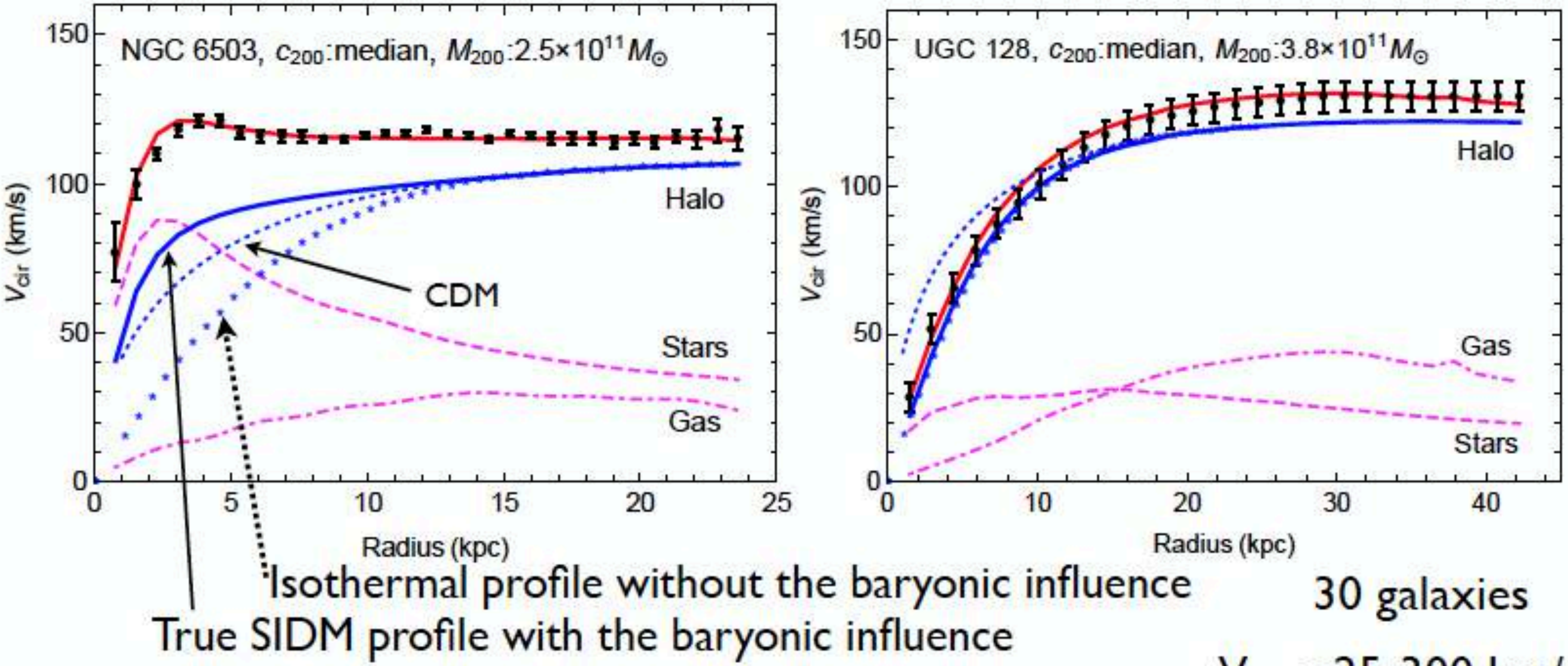
… but different inner rotation curves

Oman et al. (2015)

Colored bands: hydrodynamic simulations of ΛCDM

See also Kuzio de Naray, Martinez, Bullock, Kaplinghat (2009)

Solving the Diversity Problem



Courtesey: Haibo Yu

30 galaxies

V_{max}~25-300 km/s

- DM self-interactions thermalize the inner halo together with baryons

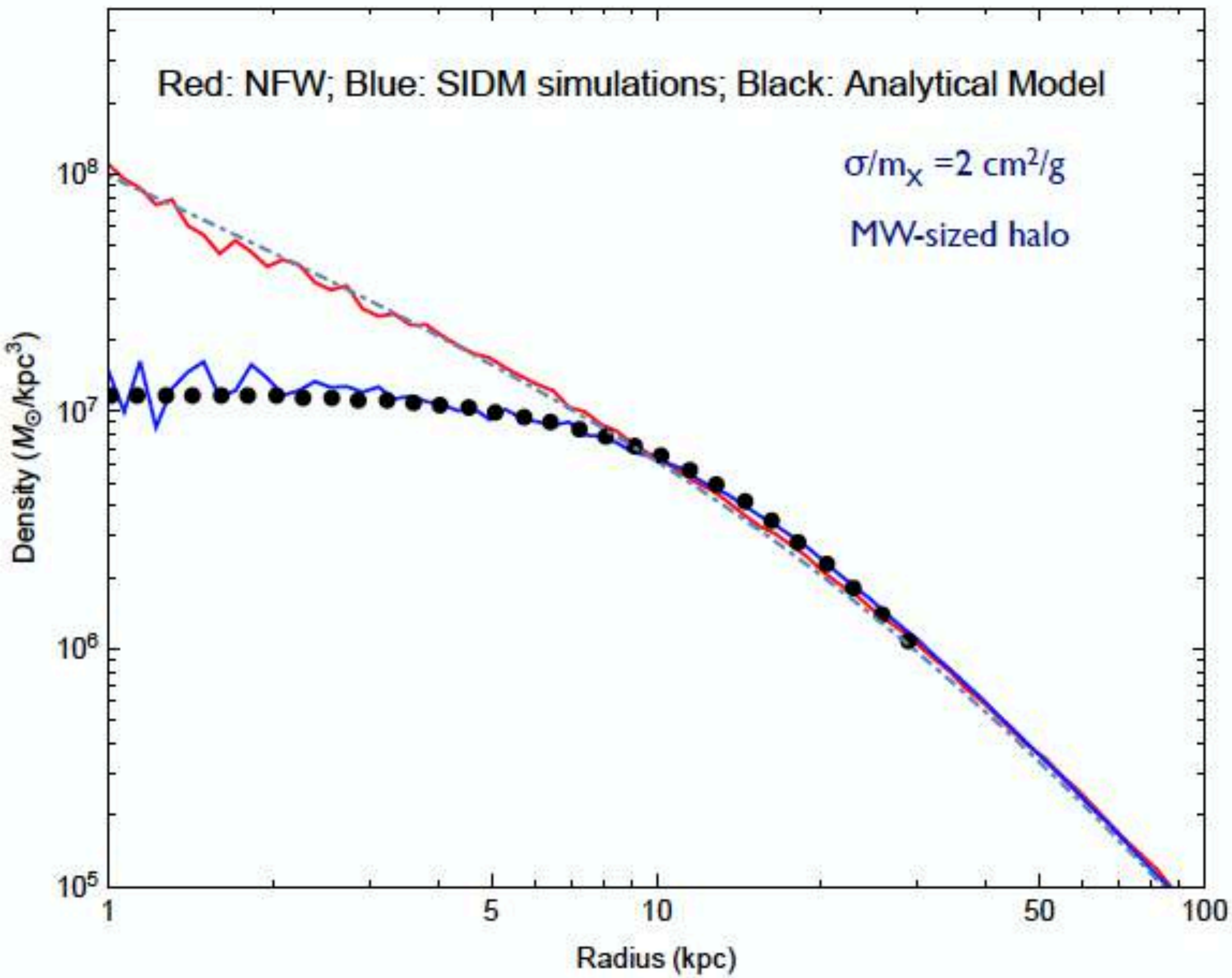
High luminous galaxies (NGC 6503): small and dense core
Low luminous galaxies (UGC 128): large and shallow core

with Kamada, Kaplinghat, Pace (2016)

This can possibly also account for the baryonic Tully-Fisher relationship

Modelling SIDM Halos

- The model works well remarkably



Self-interactions thermalise the inner halo and thus lower the central density

Courtesey: Haibo Yu

Self-interacting DM

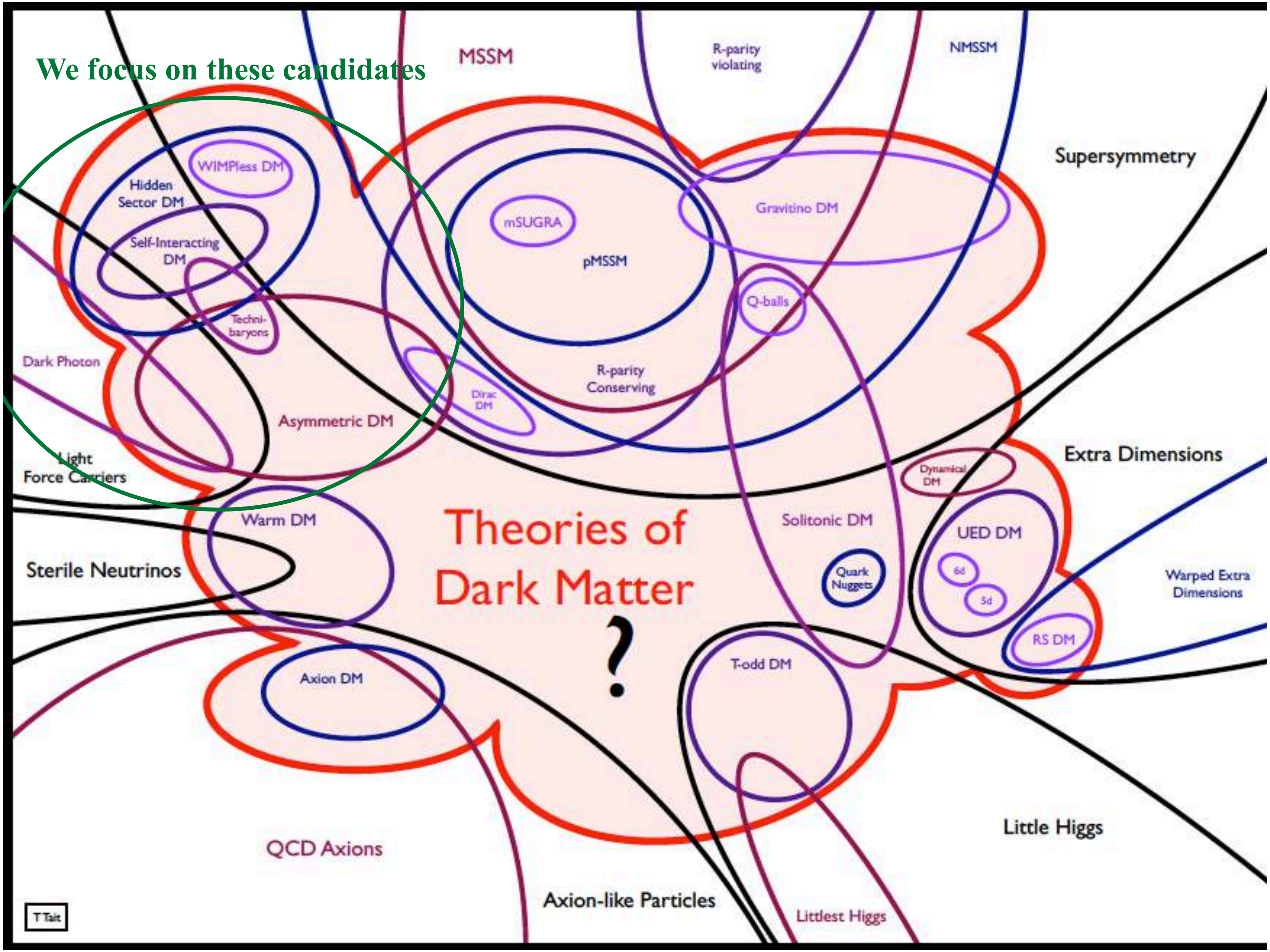
- To have *observable* effects on astrophysical scales, self-interaction #-sections must be *large*, typically: $\sigma/m_\chi \sim 1\ \mathrm{cm^2/g} \sim 2$ barns/GeV

- The typical self-interaction #-section of a WIMP is smaller by $>10^{14}$ … hence astrophysical evidence for DM self-interactions would *rule out* popular particle candidates e.g. axions, neutrinos & neutralinos!

- Such large self-interactions are natural in models such as:

  - Strongly interacting DM — Kusenko & Steinhard: astro-ph/0106008; Frandsen, Sarkar & Schmidt-Hoberg: 1103.4350; …
  - Mirror DM — Berezhiani, Dolgov & Mohapatra: hep-ph/9511221; Mohapatra, Nussinov & Teplitz: hep-ph/0111381; …
  - Atomic DM — Kaplan, Krnjaic, Rehermann & Wells: 0909.0753; Cyr-Racine & Sigurdson:1209.5752; …
  - …

- Using *astrophysical* colliders we can study the 'dark sector' *even* when DM has highly suppressed couplings to the Standard Model

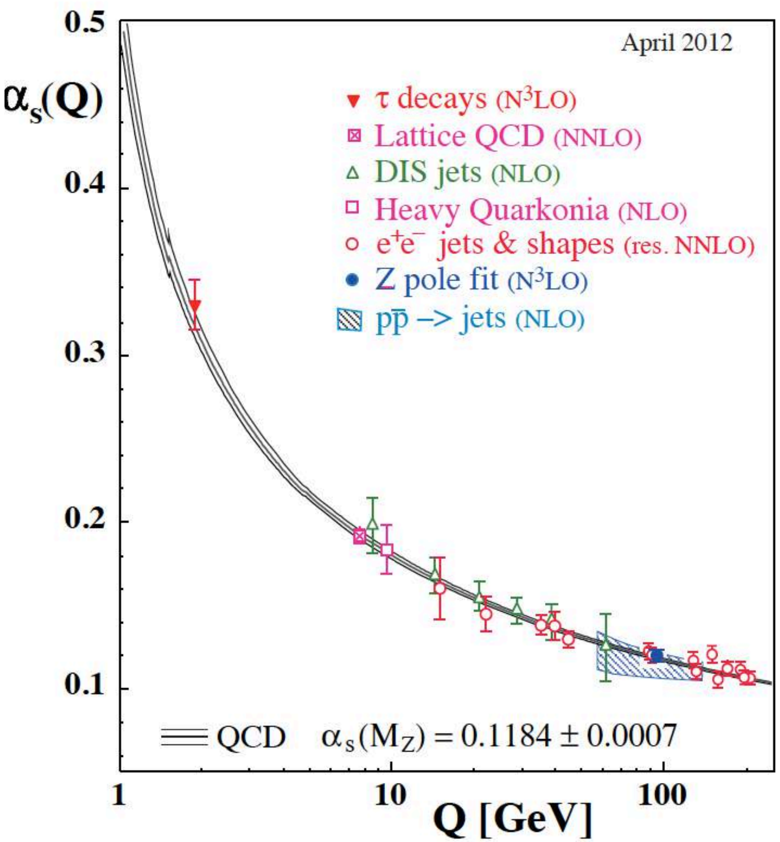


We focus on these candidates
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Warm DM
Sterile Neutrinos
Theories of Dark Matter
?
Solitonic DM
Quark Nuggets
Dynamical DM
Extra Dimensions
UED DM
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

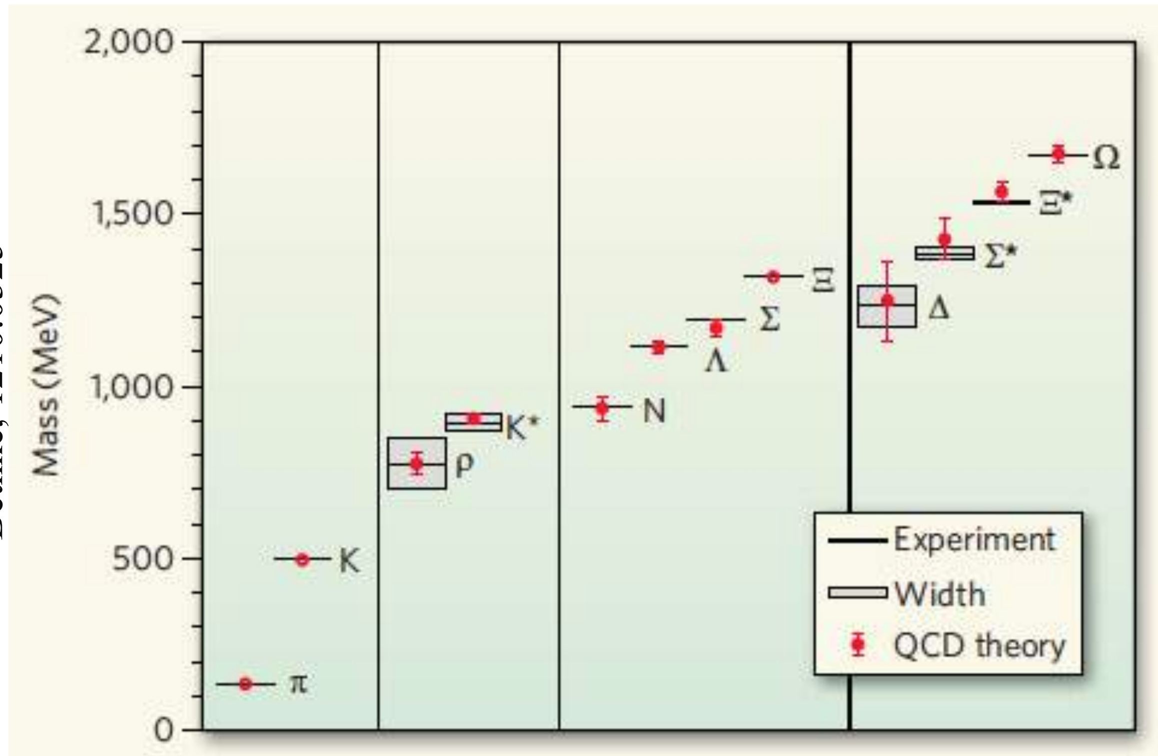
Particle candidates for (dark) matter

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr	'freeze-out' from thermal equilibrium	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$

We have a good theoretical explanation for why baryons are massive and stable



Bethke, 1210.0325



Durr *et al*, *Science* **322**:2224,2008

We understand the dynamics of QCD … and can calculate the mass spectrum

Nevertheless, we get the cosmology of baryons *badly* wrong!

$$\dot{n} + 3Hn = -\langle\sigma v\rangle(n^2 - n_T^2)$$

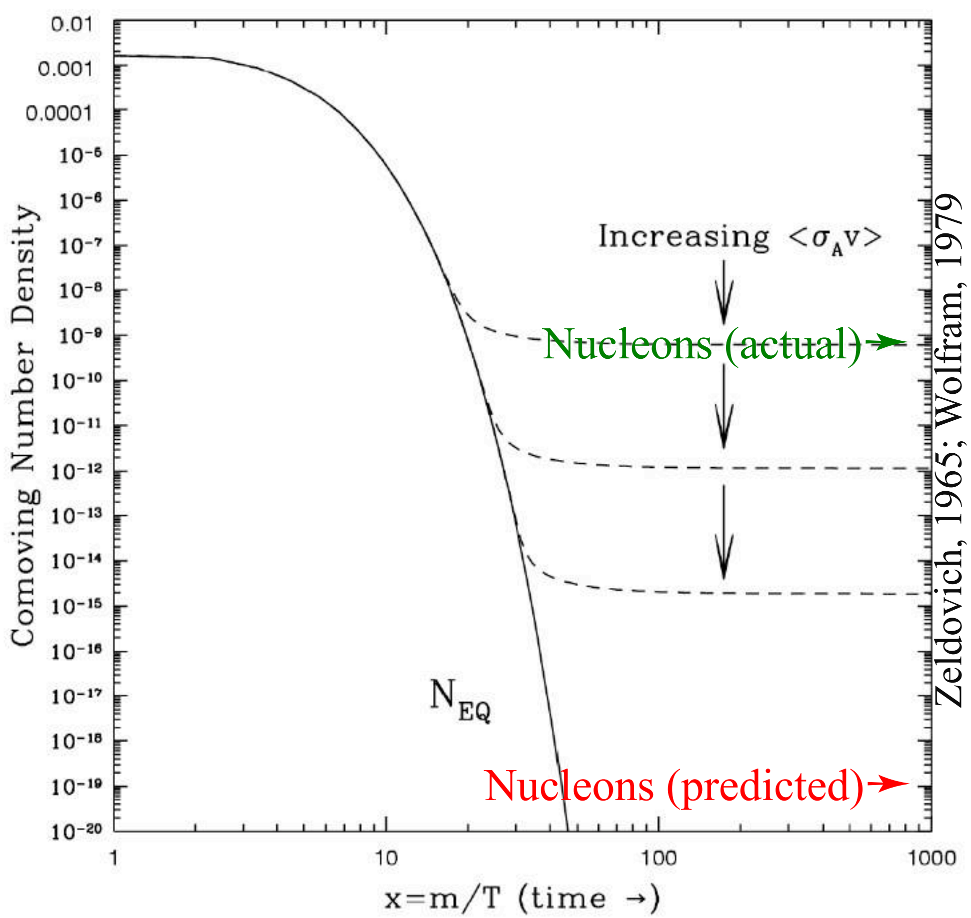
Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate

'Freeze-out' occurs when annihilation rate:

$$\Gamma = n\sigma v \sim m_N^{3/2} T^{3/2} e^{-m_N/T} \frac{1}{m_\pi^2}$$

becomes comparable to the expansion rate

$$H \sim \frac{\sqrt{g}T^2}{M_P}$$ where $g \sim$ # relativistic species

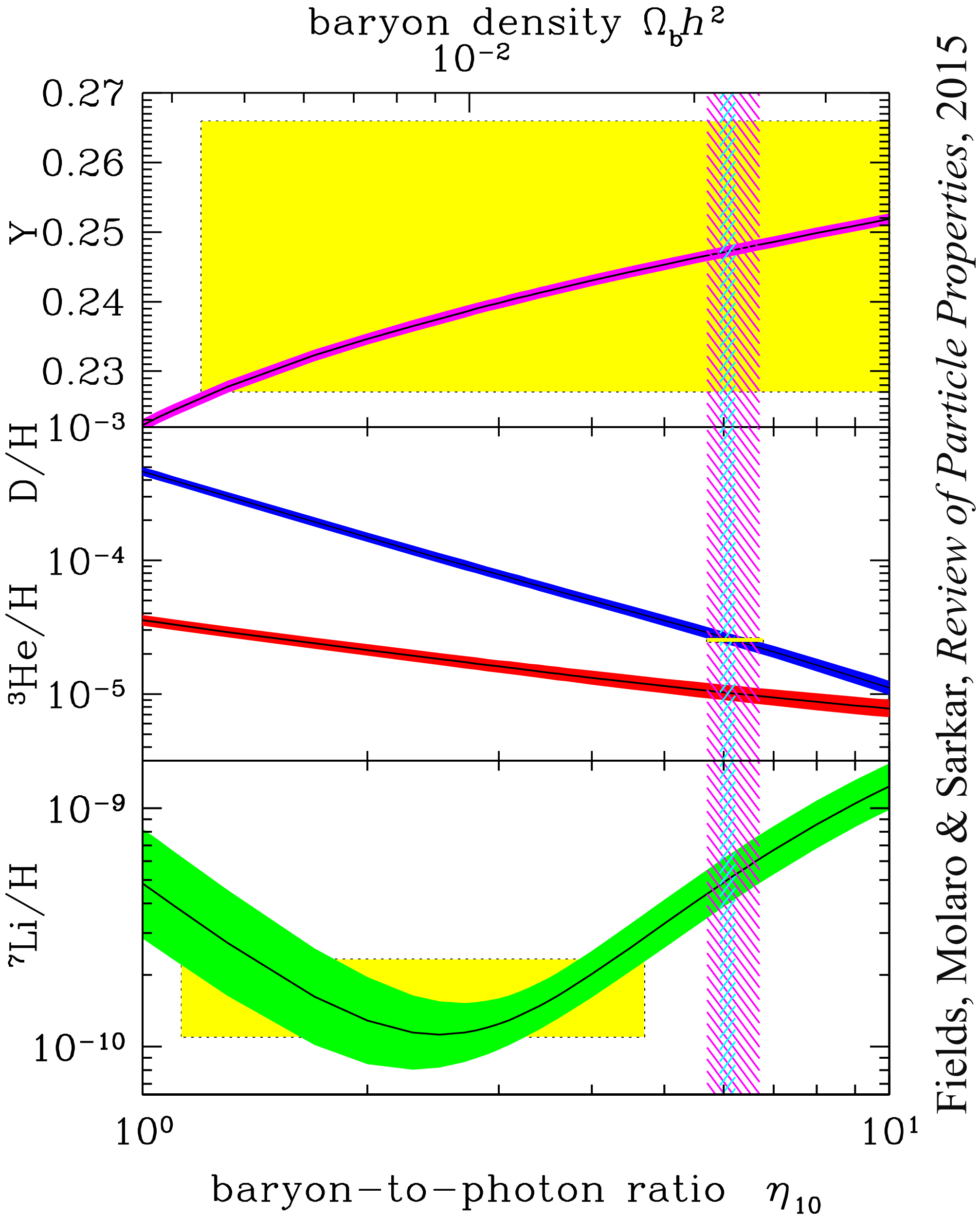


i.e. 'freeze-out' occurs at $T \sim m_N/45$, with: $\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$

However the observed ratio is 10^9 times bigger for baryons, and there seem to be *no* antibaryons, so we must invoke an initial asymmetry: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$

Why not call this the 'Baryon disaster' *cf.* 'WIMP miracle'!

Although vastly overabundant compared to the natural expectation, baryons *cannot* close the universe (BBN ✚ CMB concordance)



… the dark matter must therefore be mainly *non*-baryonic

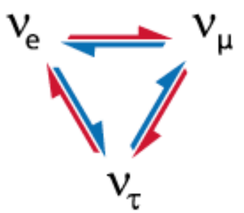
To make the baryon asymmetry requires *new* physics ('Sakharov conditions')

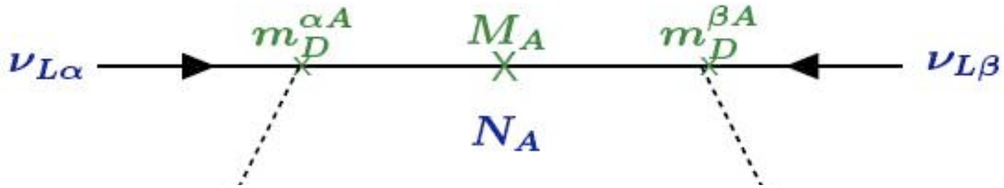
- *B*-number violation
- *CP* violation
- Departure for thermal equilibrium

The SM *allows* *B*-number violation (through non-perturbative – 'sphaleron-mediated' – processes) … but *CP*-violation is too *weak* and $SU(2)_L$ x $U(1)_Y$ breaking is *not* a 1st order phase transition

Hence the generation of the observed matter-antimatter asymmetry requires new BSM physics … can be related to the observed neutrino masses if these arise from lepton number violation → leptogenesis

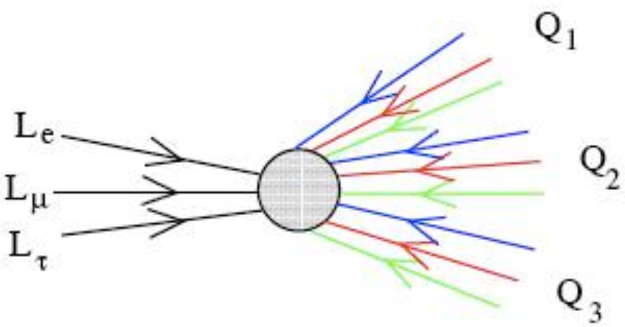
'See-saw': $\mathcal{L} = \mathcal{L}_{SM} + \lambda^*_{\alpha J}\bar{\ell}_\alpha \cdot H N_J - \frac{1}{2}\overline{N_J} M_J N_J^c \qquad \lambda M^{-1}\lambda^{\mathrm{T}}\langle H^0\rangle^2 = [m_\nu]$



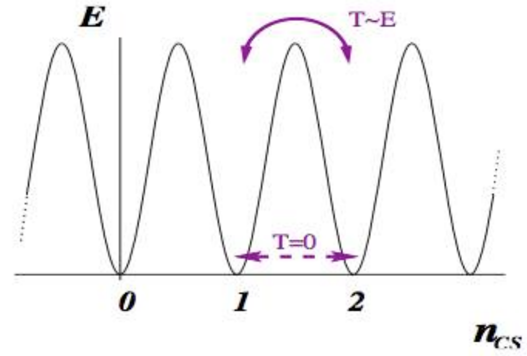


$$\Delta m^2_{atm} = m_3^2 - m_2^2 \simeq 2.6 \times 10^{-3}\mathrm{eV}^2 \qquad \Delta m^2_\odot = m_2^2 - m_1^2 \simeq 7.9 \times 10^{-5}\mathrm{eV}^2$$

Asymmetric baryonic matter



$$\partial_\mu j_i^\mu = \partial_\mu(\bar{\psi}^i \gamma^\mu \psi^i) = \frac{g^2}{8\pi} W^{a\mu\nu} \tilde{W}^a_{\mu\nu}$$



Any primordial lepton asymmetry (e.g. from out-of-equilibrium decays of the right-handed *N*) would be redistributed by *B*+*L* violating processes (which conserve *B*-*L*) amongst *all fermions* which couple to the electroweak anomaly – in particular **baryons**

$$\begin{aligned} Y_{\Delta B} &= \frac{n_N^{eq}(T \gg M_1)}{s} \sum_\alpha \frac{n_{\ell_\alpha} - n_{\bar{\ell}_\alpha}}{n_N} \times \eta_\alpha \times C \\ &\sim 4 \times 10^{-3} \sum_\alpha \epsilon_{\alpha\alpha} \times \eta_\alpha \times \frac{1}{3} \end{aligned}$$

$\sim 10^{-10}$ for reasonable parameter values

A new particle present which also couples to the *SU*(2) anomaly will *naturally* acquire a similar asymmetry (if its symmetric component annihilates away)

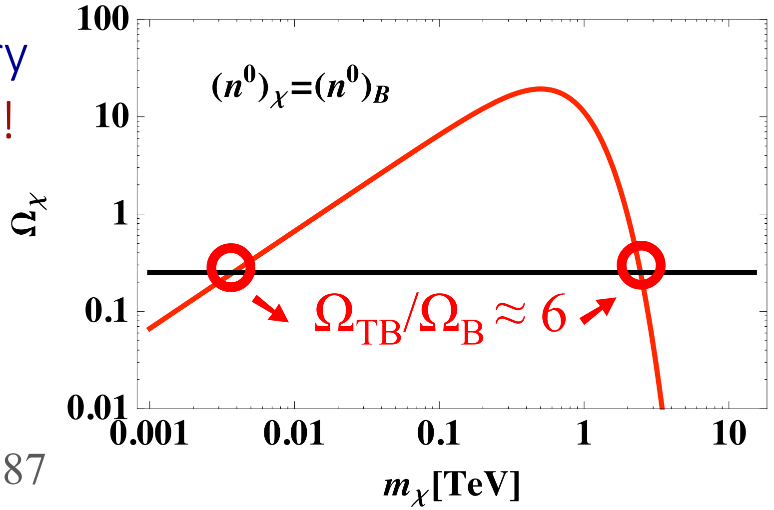
What *should* dark matter be made of ?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	'Freeze-out' from thermal equilibrium Asymmetric baryogenesis (how?)	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{QCD'} \sim 6\Lambda_{QCD}$	Dark baryon?	$U(1)_{DB}$	plausible	Asymmetric (like the *observed* baryons)	$\Omega_{DB} \sim 0.3$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino? Technibaryon?	*R*-parity (walking) Technicolour	violated? $\tau > 10^{18}$ yr	'Freeze-out' from thermal equilibrium Asymmetric (like the *observed* baryons)	$\Omega_{LSP} \sim 0.3$ $\Omega_{TB} \sim 0.3$

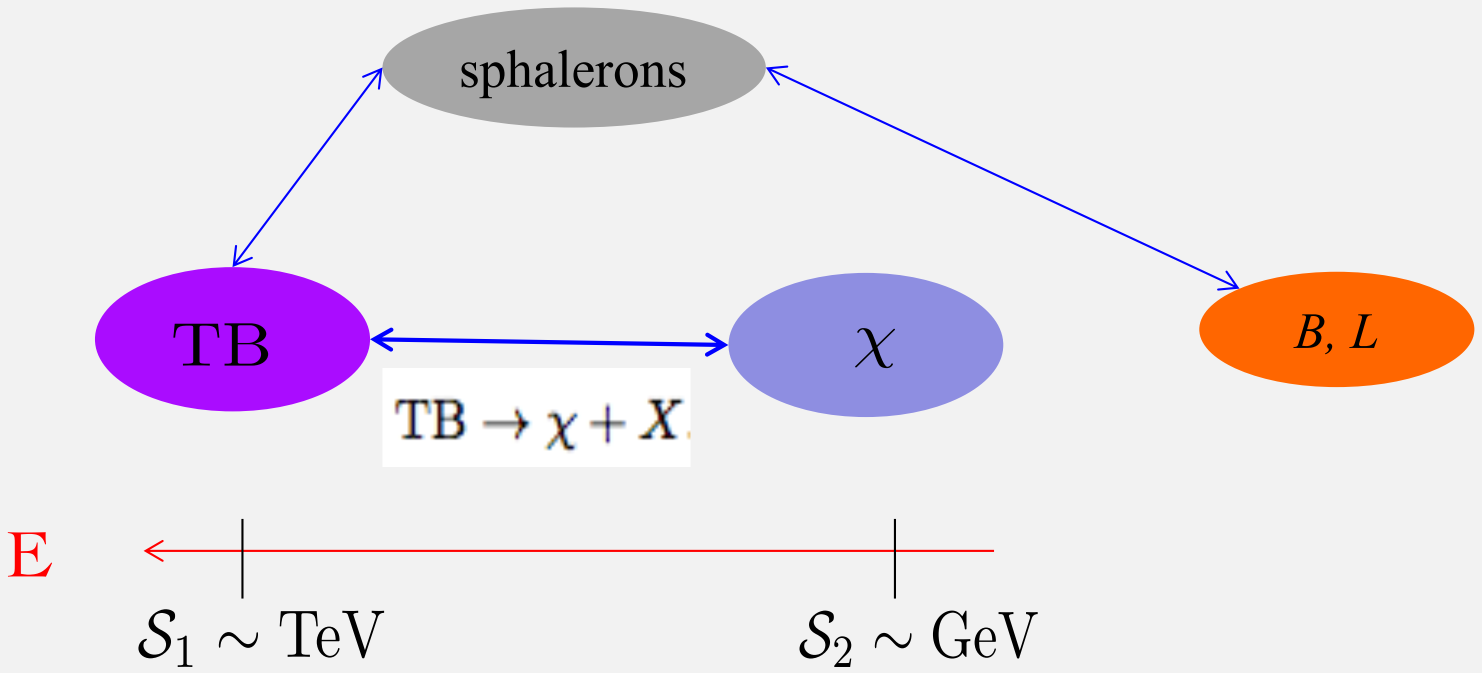
A new particle can naturally share in the *B*/*L* asymmetry if it couples to the *W* … linking dark to baryonic matter!

Then a *O*(TeV) mass technibaryon can be the DM … alternatively a ~5 GeV mass 'dark baryon' in a hidden sector (into which the technibaryon *decays* – transferring to it its own asymmtery): $\Omega_\chi = (m_\chi \mathcal{N}_\chi / m_B \mathcal{N}_B)\Omega_B$

Nussinov, PL 165B:55, 1985; Gelmini, Hall & Lin, NP **B281**:726,1987



Why may we not have seen such particles yet?



Frandsen, Sarkar & Schmidt-Hoberg, 1103.4350

S_1 States (constituents) carry weak charges and are connected to sphalerons so inherit any pre-existing fermion asymmetry (just as baryons do)

S_2 States are SM singlets (in a hidden sector) but directly connected to the S_1 sector (with scale separation – TeV ➛ GeV – because of different β-function)

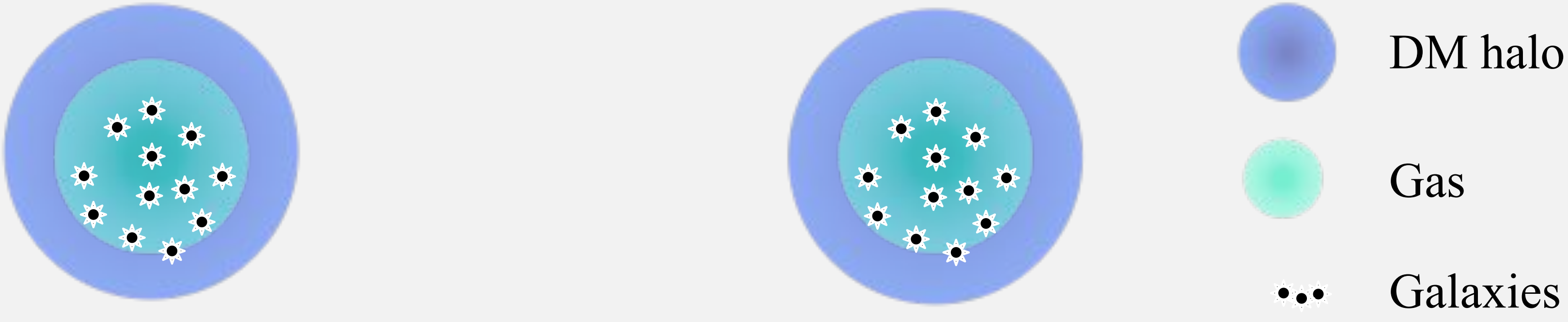
$\mathrm{TB} \to \chi + \mathrm{X}$ is in equilibrium until $T \lesssim T_{\mathrm{sph}}$, then χ decouples and becomes DM

The S_1 states do couple to the SM (so ***ought to show up*** *at LHC Run II*)

There are other such (viable) models … falsifiable through experiment

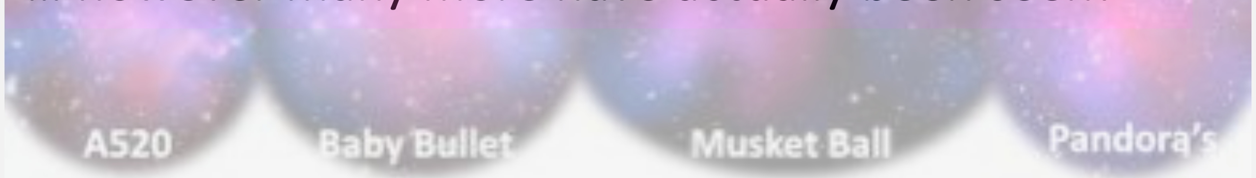
Observational constraints

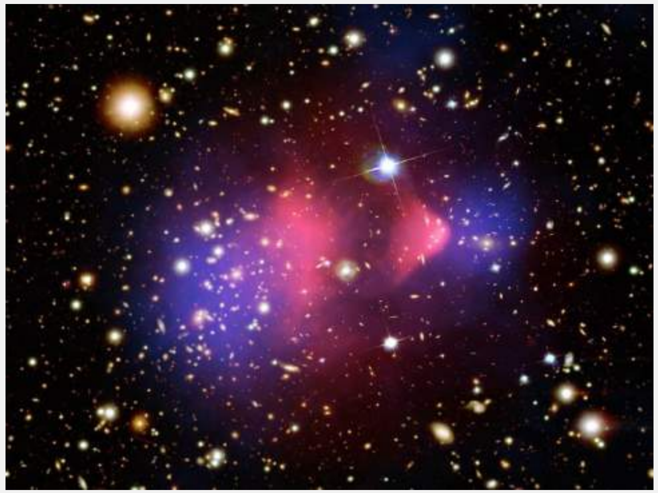
In the *absence* of DM self-interactions, we expect the following:



… in agreement with observations

NB: Such colliding clusters should however be rare – only ~0.1 systems like the Bullet Cluster should be seen up to $z \sim 0.3$ (Kraljic & Sarkar, 1412.7719)
… however many more have actually been seen!





http://www.mergingclustercollaboration.org/

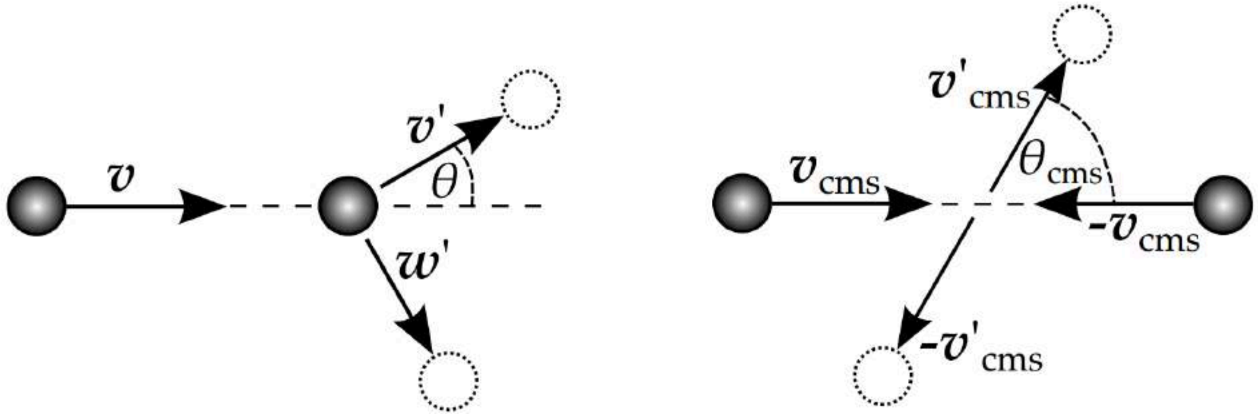
Observations of the **Bullet Cluster** (Clowe *et al,* astro-ph/0608407) constrain the rate of halo *evaporation* and halo *deceleration* due to DM self-interactions:

- $\sigma/m_\chi < 1\ \mathrm{cm}^2/\mathrm{g}$ (analytic)
- $\sigma/m_\chi < 0.7\ \mathrm{cm}^2/\mathrm{g}$ (numerical)

Markevitch *et al*, astro-ph/0309303
Randall *et al*, arXiv:0704.0261

These bounds come from 'evaporation'

Kahlhoefer *et al*, 1308.3419



- The collision of two DM particles leads to the evaporation of a DM particle if $w'^2 = v^2 + w^2 - v'^2 > v_{\rm esc}^2$ and $v'^2 > v_{\rm esc}^2$

- This is the case if $\frac{2\,v_{\rm esc}^2}{v_0^2} - 1 < \cos\theta_{\rm cms} < 1 - \frac{2\,v_{\rm esc}^2}{v_0^2}$

- "imd" denotes *immediate* evaporation i.e. if in a single ("expulsive") collision the momentum transfer is large enough to remove a DM particle from the halo

Evaporation rate

- Defining the fraction of expulsive collisions

$$f = \frac{\int_{2\, v_{\mathrm{esc},1}/v_0^2 - 1}^{1-2\, v_{\mathrm{esc},1}/v_0^2} \mathrm{d}\Omega_{\mathrm{cms}}\ (\mathrm{d}\sigma/\mathrm{d}\Omega_{\mathrm{cms}})}{\int \mathrm{d}\Omega_{\mathrm{cms}}\ (\mathrm{d}\sigma/\mathrm{d}\Omega_{\mathrm{cms}})}$$

the halo fraction lost to evaporation is

$$\frac{\Delta N_{\mathrm{imd}}}{N} = 1 - \exp\left[-\frac{\Sigma_2\, \sigma\, f}{m_{\mathrm{DM}}}\right]$$

$$\Sigma_2 = \int \rho_2(z)\, \mathrm{d}z$$

DM surface density of main cluster

$$\sigma \equiv \int \mathrm{d}\Omega_{\mathrm{cms}}\, \mathrm{d}\sigma/\mathrm{d}\Omega_{\mathrm{cms}}$$

Total self-interaction cross section

- For the Bullet Cluster, we require $\frac{\Delta N_{\mathrm{imd}}}{N} < 30\%$

Kahlhoefer *et al*, 1308.3419

Two solutions

$$\frac{\Delta N_{\rm imd}}{N} = 1 - \exp\left[-\frac{\Sigma_2\,\sigma\,f}{m_{\rm DM}}\right] < \, 30\%$$

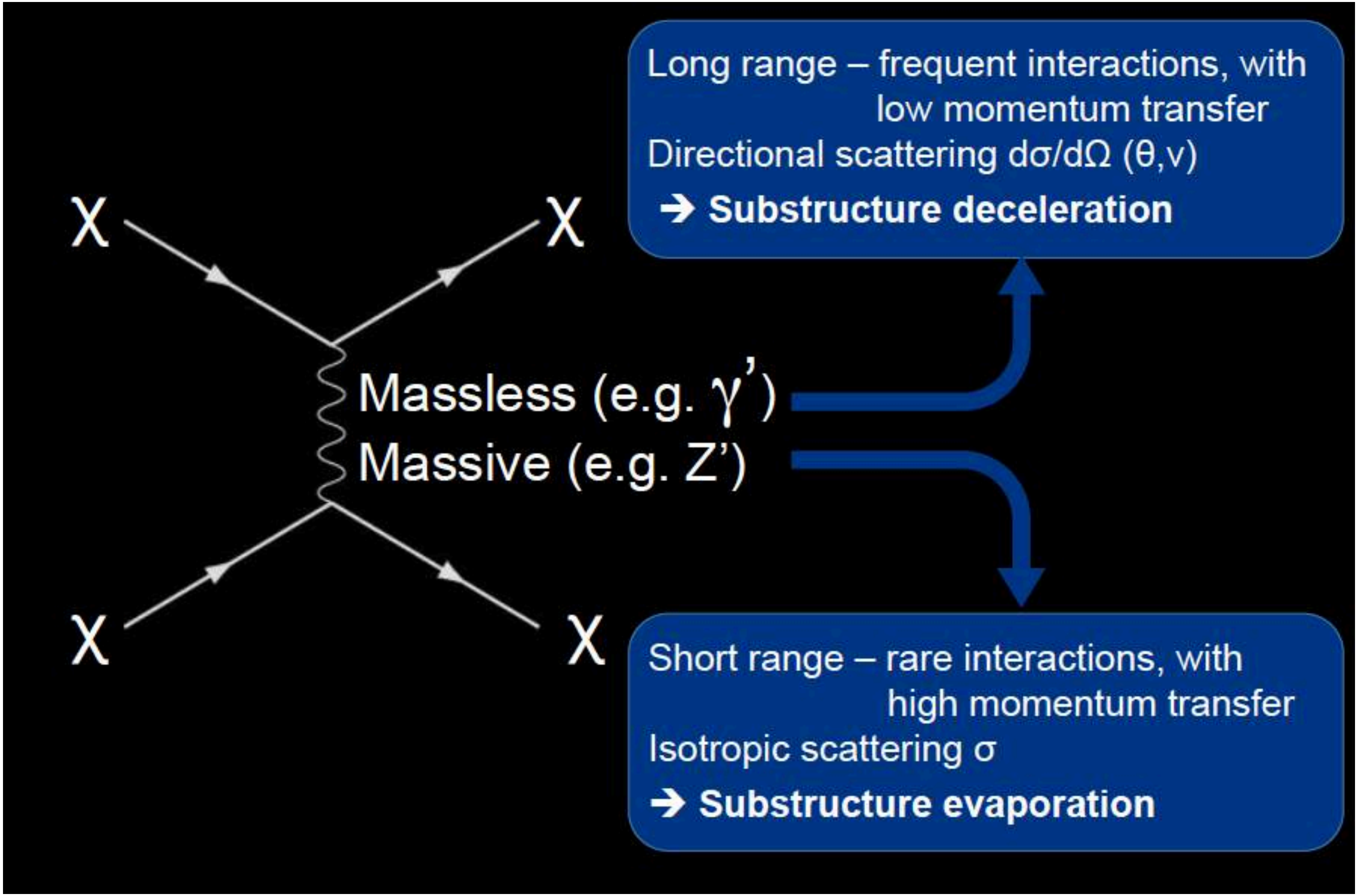
- If the fraction of expulsive collisions is large ($f \approx 1$), scattering must be *rare* in order for the sub-cluster to survive:

$$\Sigma_2\,\sigma/m_\chi < 1$$

- An alternative way to satisfy this constraint is to have *frequent* self-interactions ($\Sigma_2\,\sigma/m_{\rm DM} \gg 1$) but a *small* fraction of expulsive collisions ($f \ll 1$)

Kahlhoefer *et al*, 1308.3419

Observable distinction between short-range and long-range scattering



Frequent interactions: Predictions

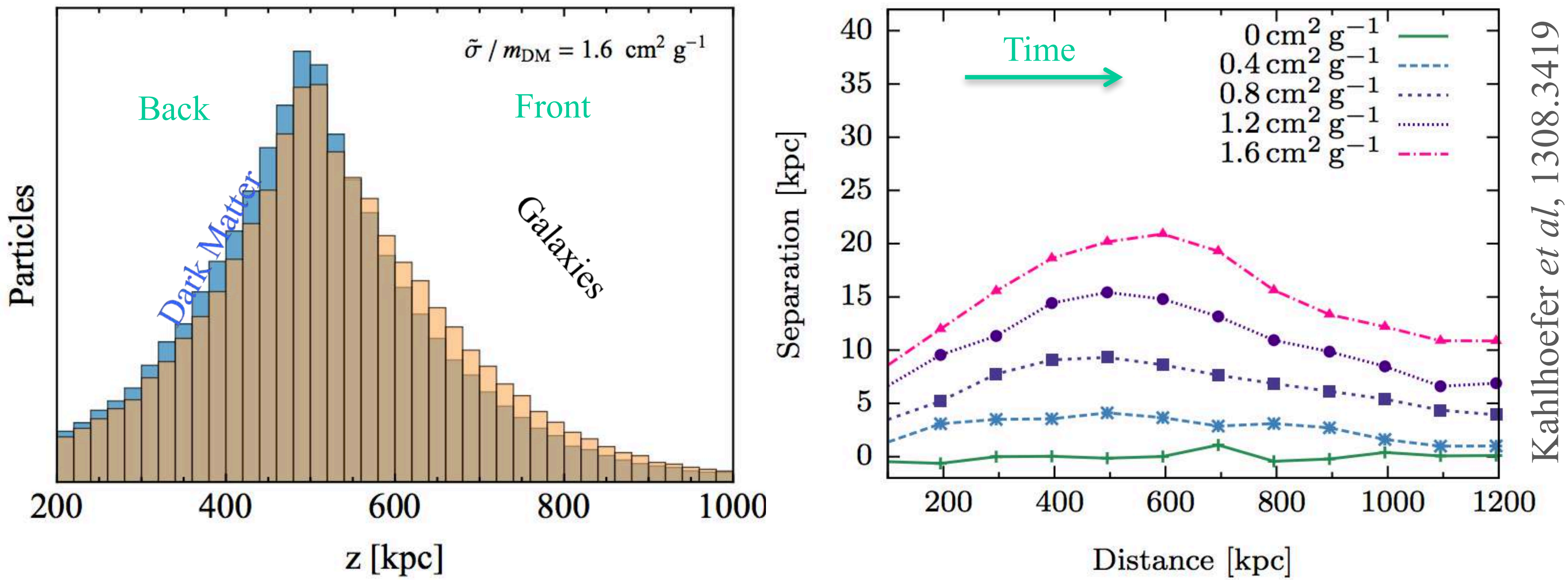
- Frequent DM self-interactions affect all particles equally and therefore lead to a deceleration of DM halos without changing their shape.
- In the frame of the DM halo, galaxies will experience a fictitious accelerating force, shifting the distribution of galaxies relative to the DM halo.
- Moreover, some galaxies can escape and will end up travelling ahead of the DM halo.

Just after the collision

At late times

Numerical simulations

- Simplified numerical simulation: Trace the motion of a set of test particles (DM and galaxies) in a time- dependent gravitational potential



Rare self-interactions

- Rare self-interactions mean that in a cluster collision the probability for multiple scattering is negligible.
- Consequently, a typical DM particle will fall in one of three categories:

  a) The DM particle scatters once with high momentum transfer and escape from the sub-cluster.

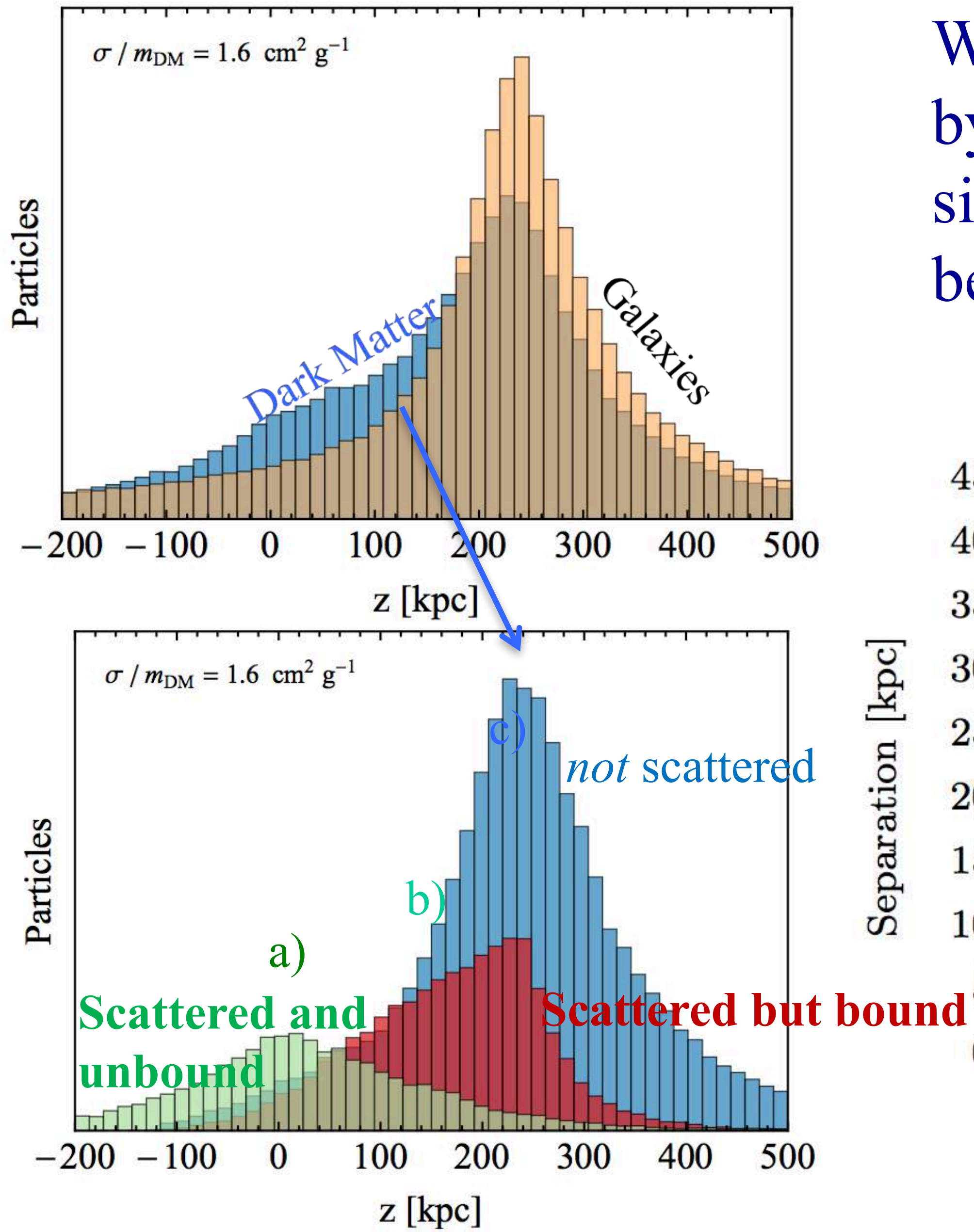
  b) The DM particle scatters once with low momentum transfer and remains bound to the sub-cluster.

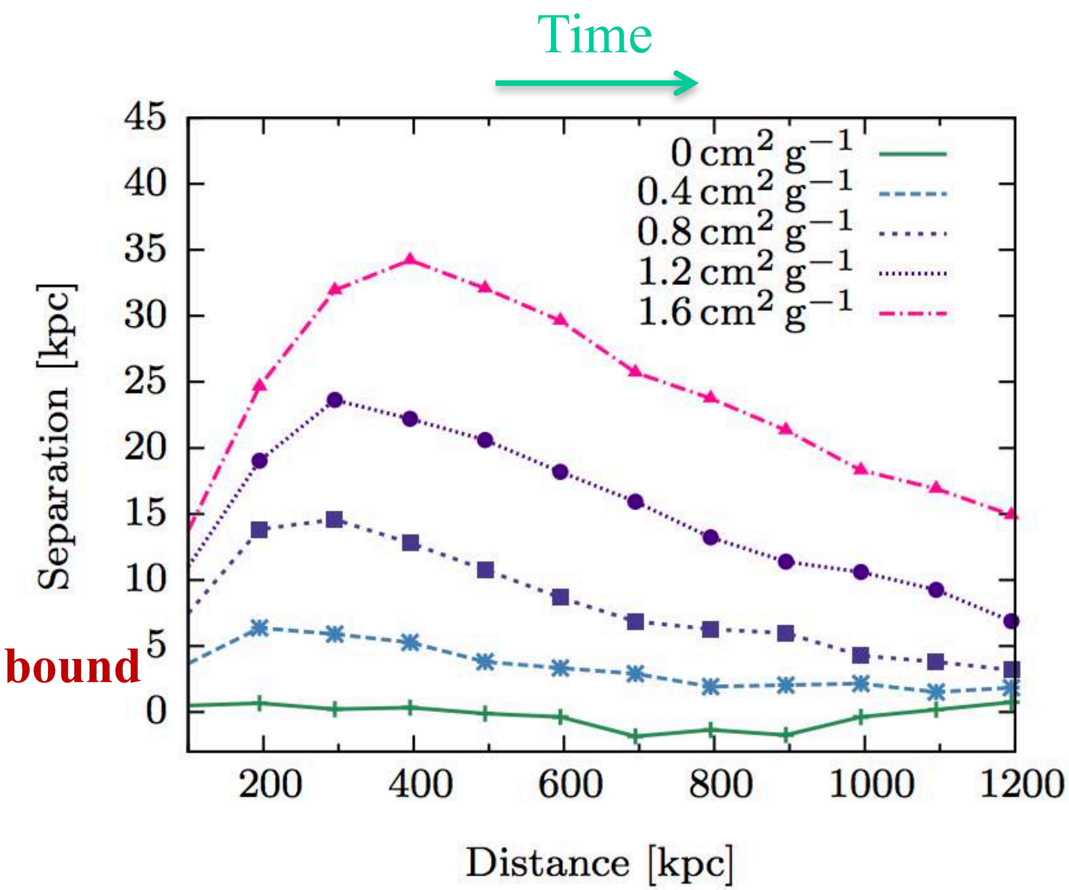
  c) The DM particle does not scatter at all.

Just after the collision   At late times

Numerical simulations

We can confirm our expectations by extending our numerical simulation to include scattering between individual DM particles.





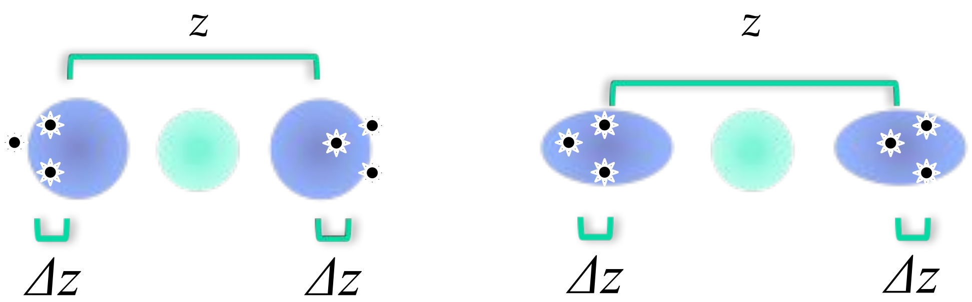
Kahlhoefer *et al*, 1308.3419

Common features

- For both rare and frequent self-interactions, the peak of the DM distribution remains coincident with the peak of the distribution of galaxies.
- The effect of self-interactions is never large enough to *completely* separate DM halo and galaxies.
- Consequently, the expected separation between DM halo and galaxies is largest shortly after the collision.
- Nevertheless, even at the peak the predicted separation is small (10 – 40 kpc).

DM-galaxy separation

- Here we will focus on the potential separation between DM halos and galaxies caused by self-interactions.



- The separation *Δz* is defined as the distance between the respective centroids of the DM halo and the distribution of galaxies.
- Given existing bounds on DM self-interactions, can we expect an observable separation?

Outlook

- Predicted separations are *just below* current bounds for the Bullet Cluster ($\Delta z < 50$ kpc)
- There are promising new strategies:
  - Statistical analysis of a large number of mergers (or infalling sub-halos) Harvey *et al.*: 1310.1731
  - Measurement of the shape of DM halos and the corresponding galaxy distributions
- The second method may be able to distinguish between rare and frequent self-interactions and therefore provide additional information on DM

Infalling subhalos

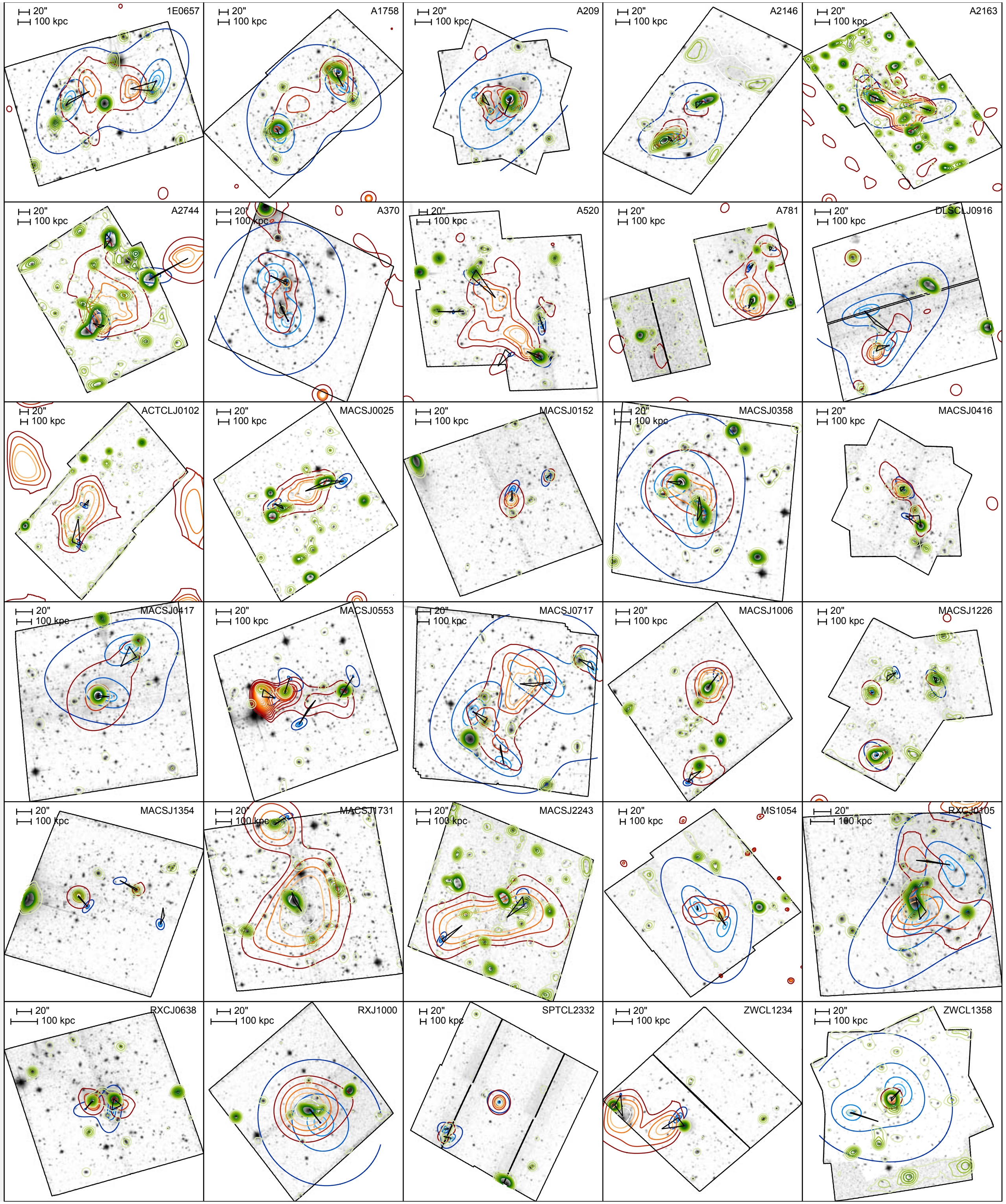
There have been several studies on constraining DM self-interactions via the observation of DM sub-halos falling into galaxy clusters

Through statistical analysis of a large number of gravitationally lensed clusters in the Chandra catalogue, the DM self-interaction is bounded as:

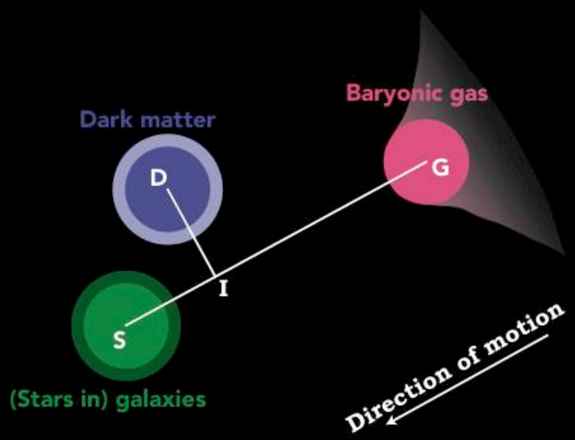
$$\sigma/m_\chi < 0.5 \text{ cm}^2/\text{g}$$

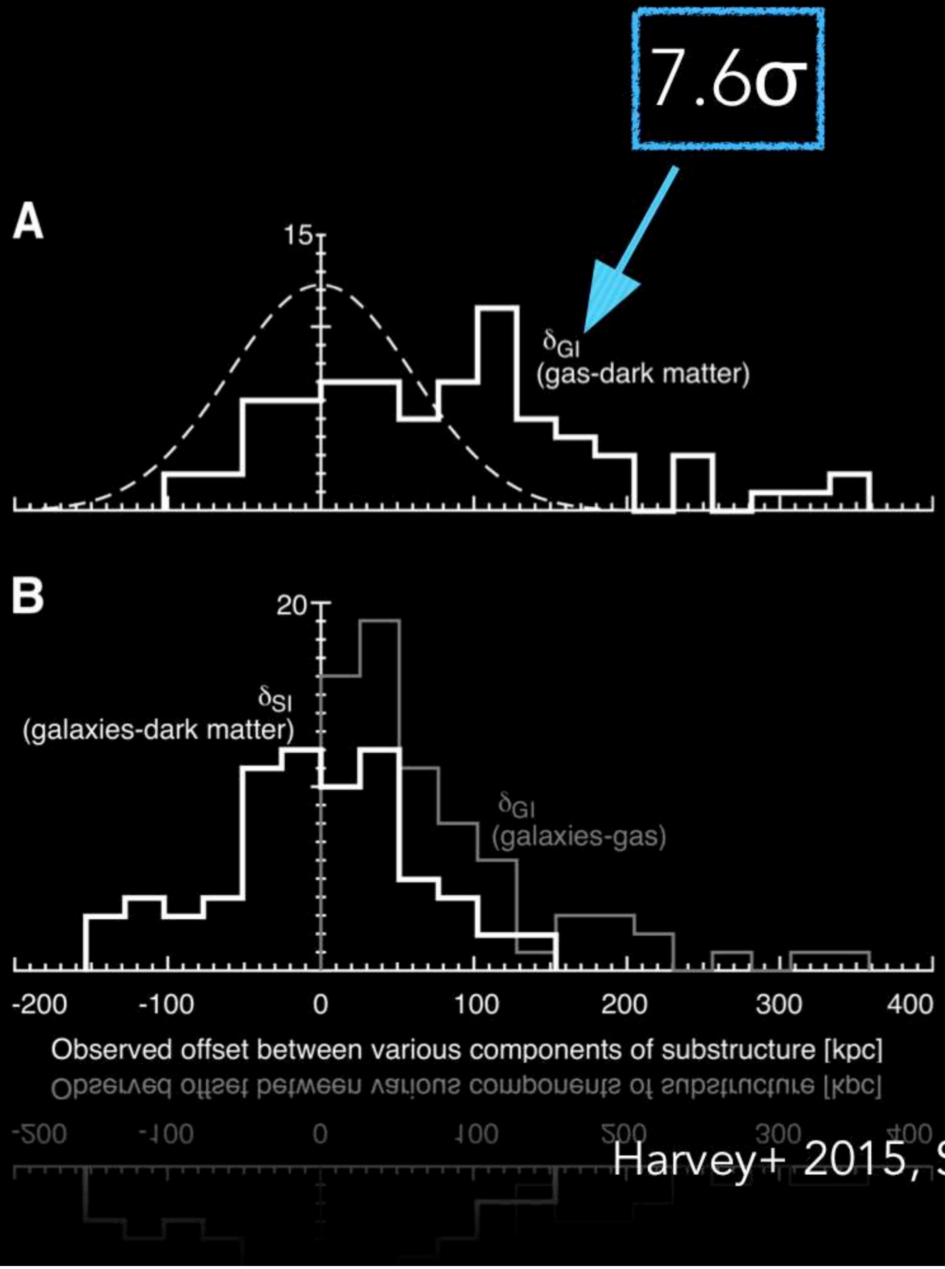
Massey *et al*, 1007.1924; Harvey *et al*, 1305.2117, 1310.1731, 1503.07675

But Wittman *et al* (1701.05877) argue using better data for the *same* clusters that this bound should be relaxed to < 2 cm^2/g



RESULTS FROM 72 MERGING SYSTEMS





5.8 ± 8.2 Kpc

25 ± 29 Kpc
For Bullet Cluster

Harvey+ 2015, Science

Courtesey: David Harvey

- Several astrophysical observations have been argued to constrain the DM self-interaction cross section (several may need *reexamination*):
  - Core density in clusters — Yoshida *et al*, astro-ph/0006134
  - Core density in dwarfs — Dave *et al*, astro-ph/0006218
  - Halo ellipticity — Miralda-Escude, astro-ph/0002050
  - Subhalo evaporation rate — Gnedin & Ostriker, astro-ph/0010436

- *Should* there be any conflict, a simple solution could be velocity-dependent self-interactions, which would be enhanced in low-velocity systems such as dwarf satellites:
  - Long-range interactions via dark photons — Ackerman, Buckley & Carroll, Kamionkowski: 0810.5126
  - Yukawa interactions via light mediators — Feng, Kaplinghat & Yu: 0905.3039; Buckley & Fox: 0911.3898; Loeb & Weiner: 1011.6374

- Nevertheless, velocity-*independent* DM self-interactions with $\sigma/m_\chi \sim 1\ \mathrm{cm^2/g}$ is still viable

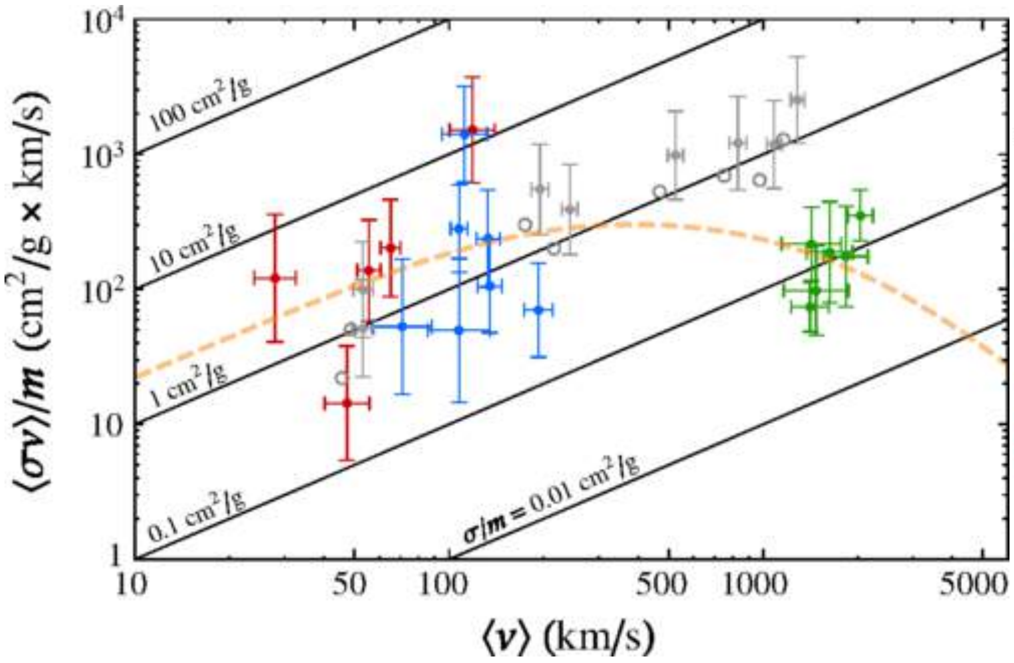
Vogelsberger, Zavalla & Loeb, 1201.5892
Rocha *et al*, 1208.3025
Peter *et al*, 1208.3026
Zavalla, Vogelsberger & Walker, 1211.6426

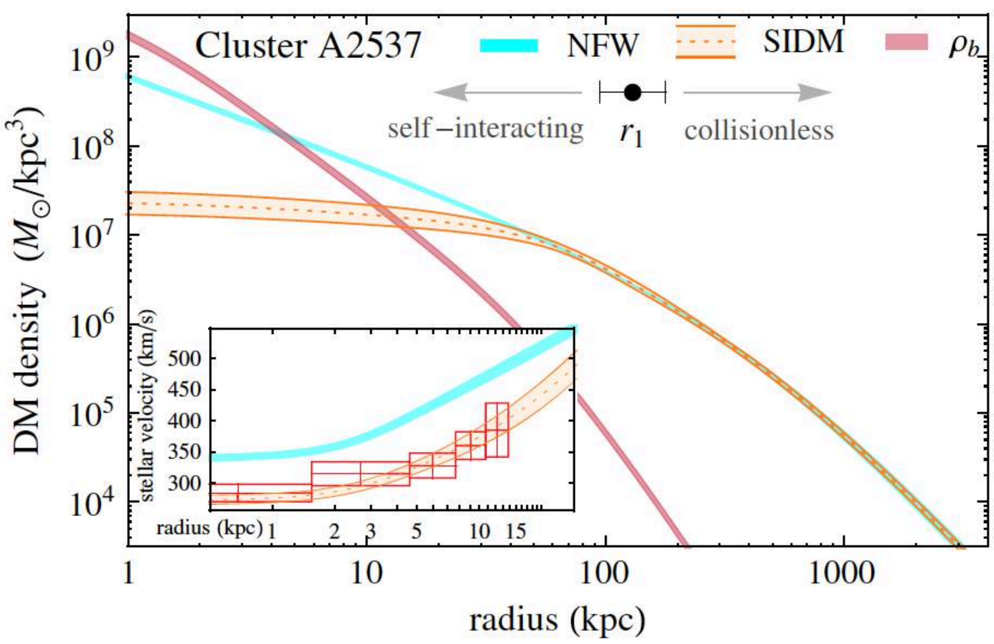
Possible evidence for a velocity-*dependent* self scattering cross-section

Kaplinghat, Tulin & Yu, 1508.033339

5 dwarf galaxies, 7 low-surface-brightness galaxies, 6 galaxy clusters
compared with
8 simulated halos with $\sigma/m_\chi = 1\ \text{cm}^2/\text{g}$

$$\text{rate} \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho(r_1) t_{\text{age}} \approx 1$$





Core size in observed clusters is ~10 Kpc …. if σ/m_χ were to be 1 cm^2/g it would be ~100 kpc!

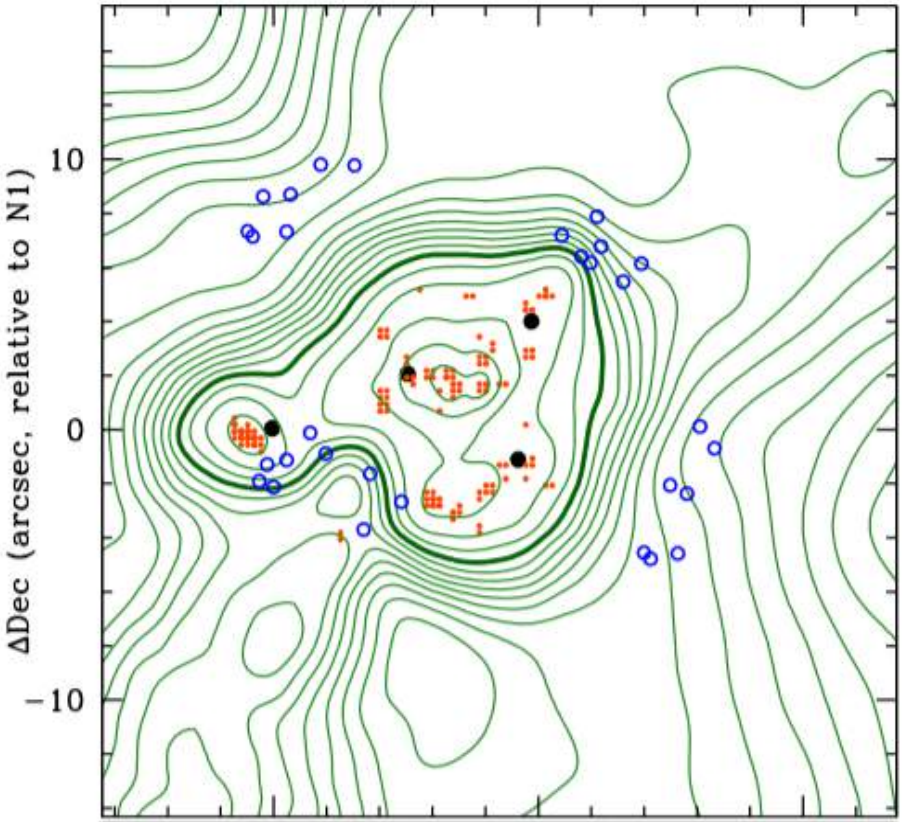
There is debate however about whether there really is any discrepancy with collisionless dark matter (NFW profile) given the observational uncertainties …

But in A3827 an offset is observed between a galaxy and its DM halo!

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

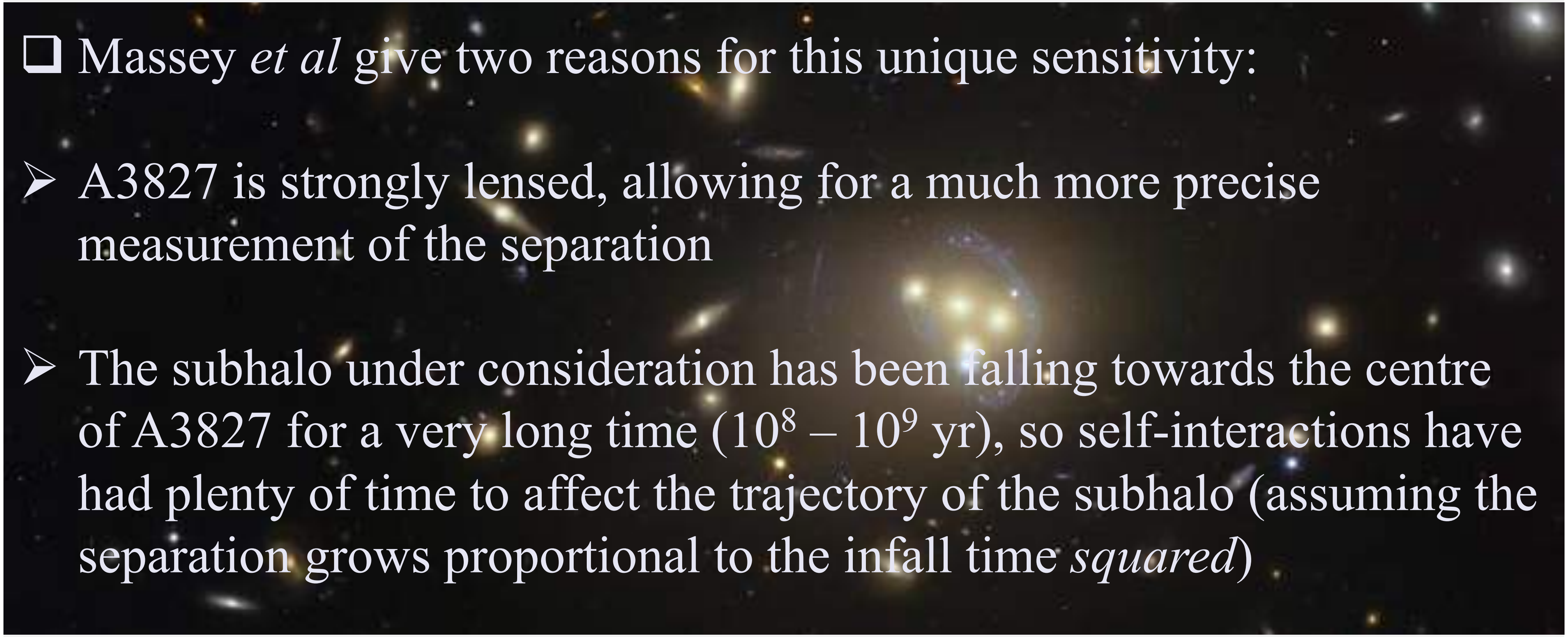
Massey *et al.*, 1504.03388

"The best-constrained offset is 1.62±0.48 kpc, where the 68% confidence limit includes both statistical error and systematic biases in mass modelling. […]
With such a small physical separation, it is difficult to definitively rule out astrophysical effects operating exclusively in dense cluster core environments – but **if interpreted solely as evidence for self-interacting dark matter, this offset implies a cross-section $\sigma/m=(1.7\pm0.7)\times10^{-4}\ cm^2/g\ (t/10^9 yr)^{-2}$ where t is the infall duration.**"



Evidence in A3827?

- The quoted self-interaction cross section is orders of magnitude *smaller* than any existing bound, making it seemingly impossible to confirm or rule out this claim using other astrophysical systems



- Massey *et al* give two reasons for this unique sensitivity:

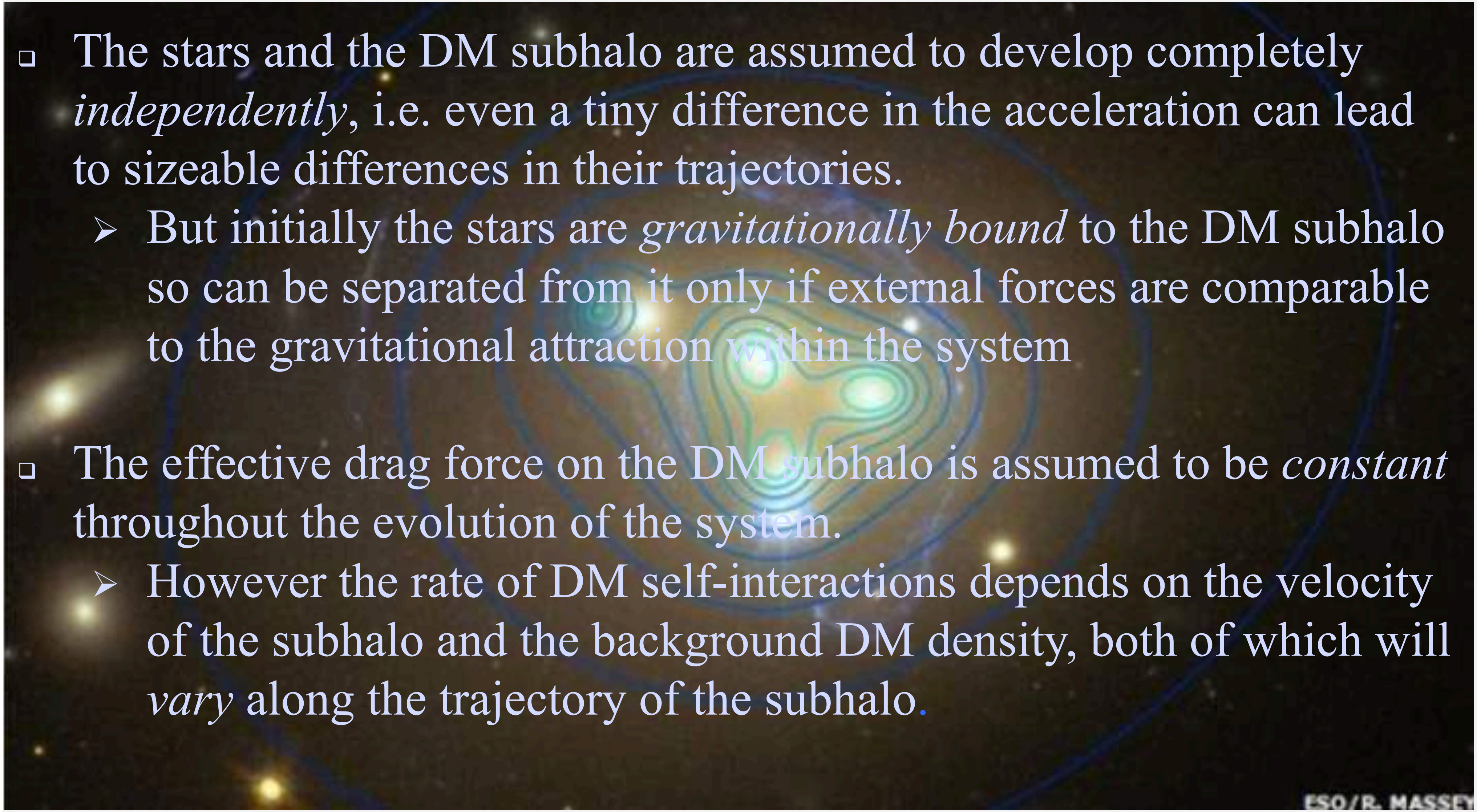
- A3827 is strongly lensed, allowing for a much more precise measurement of the separation

- The subhalo under consideration has been falling towards the centre of A3827 for a very long time (10^8 – 10^9 yr), so self-interactions have had plenty of time to affect the trajectory of the subhalo (assuming the separation grows proportional to the infall time *squared*)

Williams & Saha, arXiv:1102.3943

Evidence in A3827?

This conclusion is based on two *incorrect* assumptions:



- The stars and the DM subhalo are assumed to develop completely *independently*, i.e. even a tiny difference in the acceleration can lead to sizeable differences in their trajectories.
  - But initially the stars are *gravitationally bound* to the DM subhalo so can be separated from it only if external forces are comparable to the gravitational attraction within the system

- The effective drag force on the DM subhalo is assumed to be *constant* throughout the evolution of the system.
  - However the rate of DM self-interactions depends on the velocity of the subhalo and the background DM density, both of which will *vary* along the trajectory of the subhalo.

Kahlhoefer *et al*, 1504.06576

Approximate estimate

$$\frac{F_{\rm sh}}{m_{\rm star}} = \frac{G_{\rm N}\, M_{\rm sh}(\Delta)}{\Delta^2}$$

$$\frac{F_{\rm drag}}{m_{\rm DM}} = \frac{1}{4}\,\frac{\tilde{\sigma}}{m_{\rm DM}}\, v^2\, \rho$$

$$F_{\rm sh}/m_{\rm star} < F_{\rm drag}/m_{\rm DM}$$

$$\frac{\tilde{\sigma}}{m_{\rm DM}} > \frac{4}{v^2\,\rho}\,\frac{G_{\rm N}\, M_{\rm sh}\,\Delta}{a_{\rm sh}^3}$$

$$\rho \sim 4\,{\rm GeV\,cm^{-3}} \quad \text{and} \quad v \sim 1500\,{\rm km\,s^{-1}}$$

$$\Rightarrow \quad \frac{\tilde{\sigma}}{m_{\rm DM}} \gtrsim 2\,{\rm cm^2\,g^{-1}}$$

Kahlhoefer *et al*, 1504.06576

Refining the estimate

- Realistic density profiles for the subhalo and the central cluster
- Realistic trajectory for the infalling subhalo

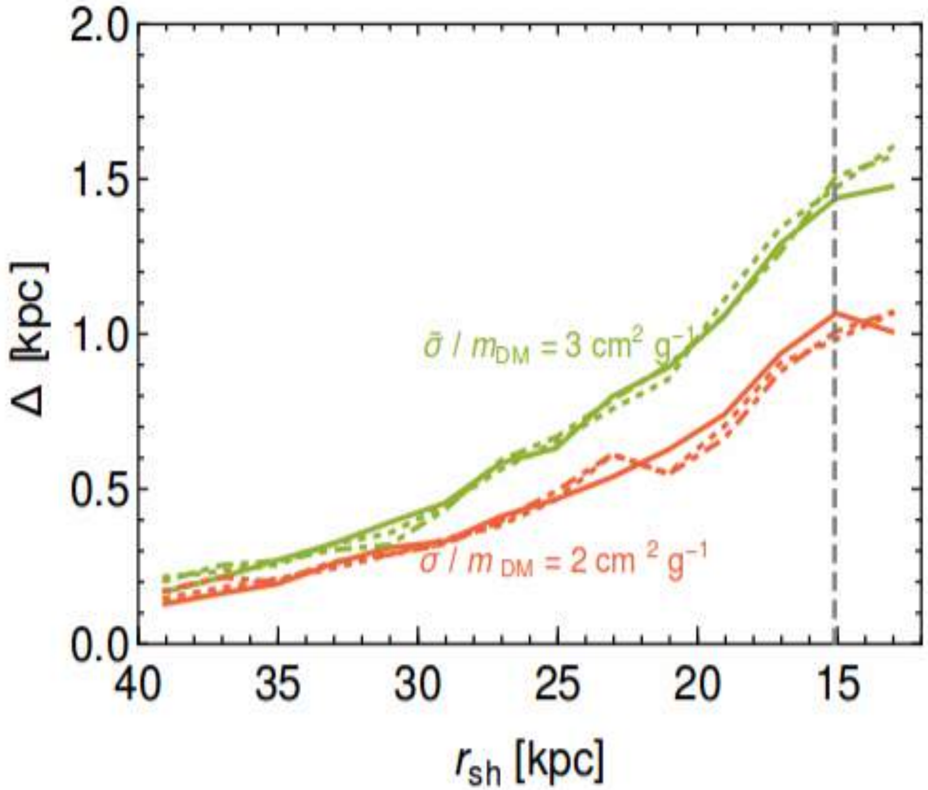
To include these refinements requires a full three-dimensional simulation … which we had developed already to study the Bullet Cluster

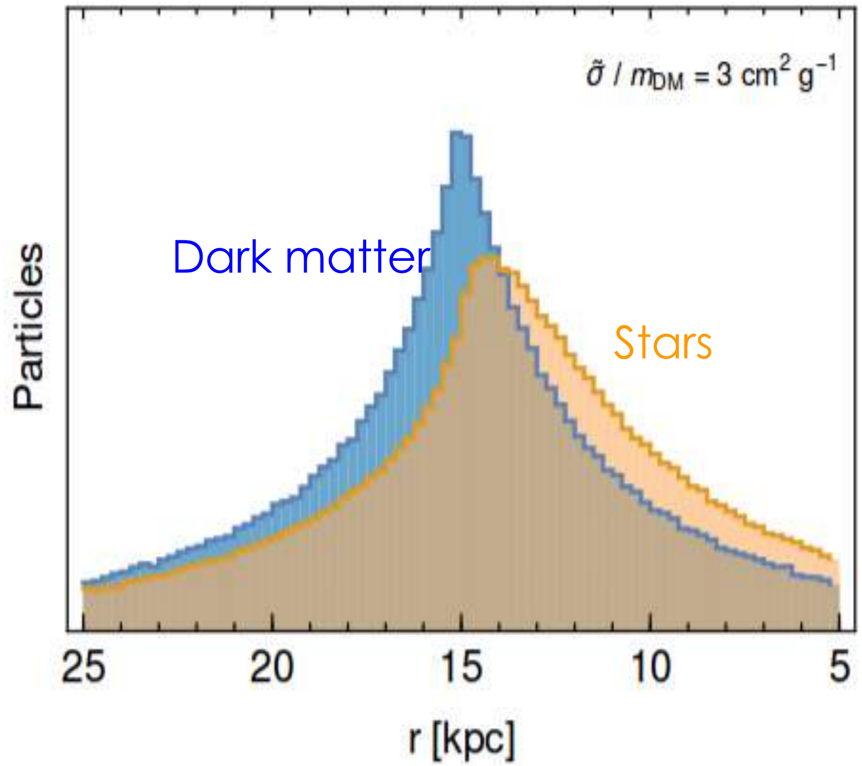
Kahlhoefer *et al*, 1308.3419

- We treat the gravitational potential of the cluster as time-independent, while for the sub-halo the profile is allowed to vary with time and is determined self-consistently from the simulation.
- Assuming an initial density profile, the simulation chooses a representative set of particles and then calculates their motion in the combined gravitational potential of cluster and sub-halo.

Kahlhoefer *et al*, 1504.06576

Frequent self-interactions





Kahlhoefer *et al*, 1504.06576

- As expected, the peaks of the two distributions are slightly shifted
- Furthermore the tail of the distribution of stars is enhanced in the forward direction due to stars that have escaped from the gravitational potential of the sub-halo
- The #-section needed to get a separation of 1.5 kpc is $\sigma/m_\chi \sim 3$ cm^2/g

The particle physics perspective

- In order to obtain an effective drag force, we have assumed that each DM particle participates in a large number of scattering processes

- This is possible only if in each scattering process the momentum transfer is small (i.e. scattering is peaked in the forward direction)

- The easiest way to obtain such an angular dependence is from long-range interactions via 'dark photons' or Yukawa interactions via light mediators (Ackerman *et al*: 0810.5126, Feng *et al* 0905.3039, Buckley & Fox: 0911.3898, Loeb & Weiner: 1011.6374)

- However, long-range interactions also imply that scattering is suppressed for large velocities proportional to $1/v^4$ (Rutherford), so *no* observable effects would then be expected in galaxy clusters

But what if DM self-interactions are not so frequent?

Rare self-interactions

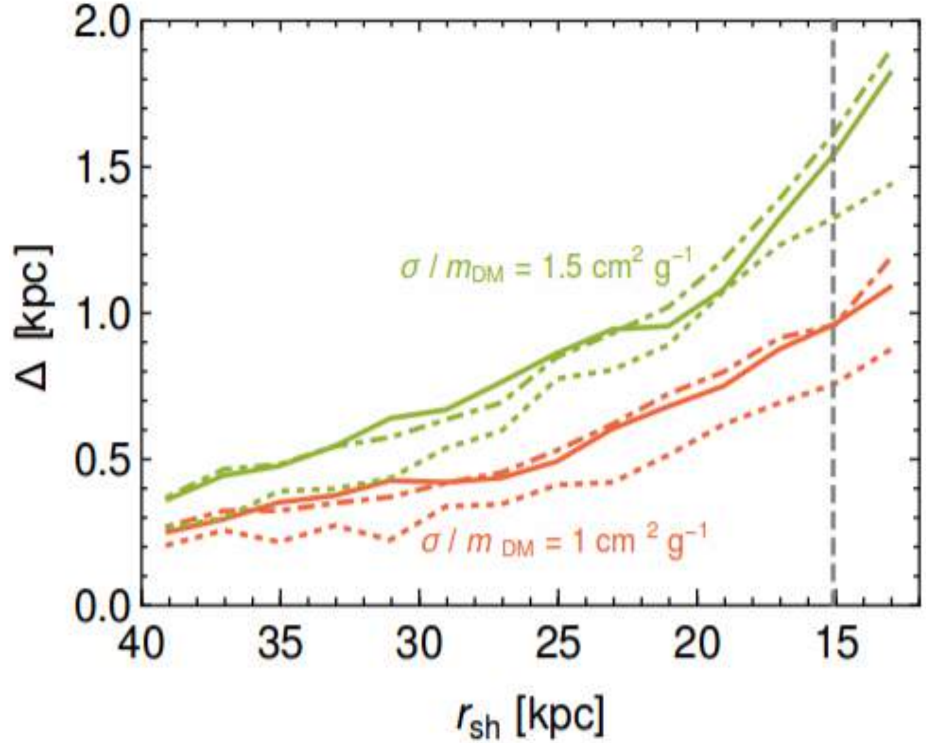
- Rare self-interactions mean that for a typical DM particle the probability for multiple scattering is *negligible*

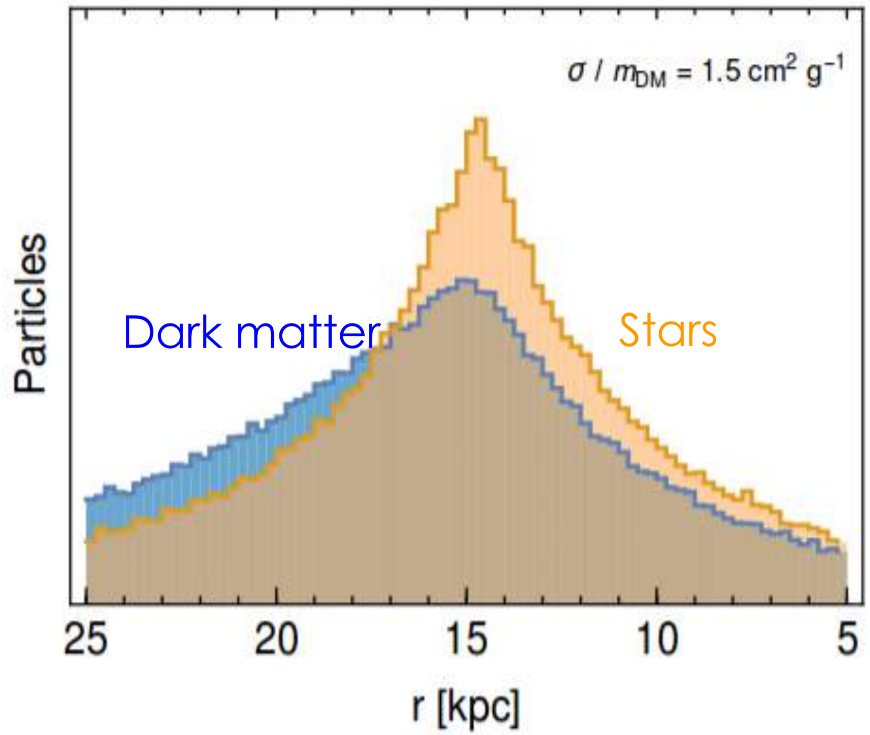
- A significant fraction of DM particles will not experience any scattering and behave just like the (collisionless) stars

- However whenever a DM particle scatters, it will typically receive such a high momentum transfer that it *escapes* from the sub-halo

- A separation between the DM sub-halo and stars can also occur in this case, but the separation is due to DM particles leaving the subhalo in the *backward* direction

Rare self-interactions

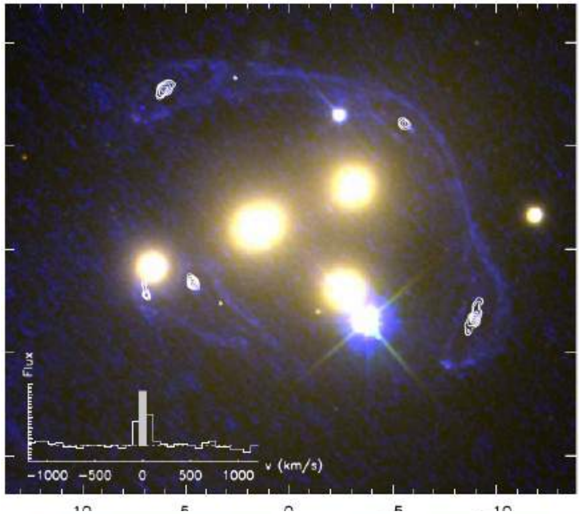




Kahlhoefer *et al*, 1504.06576

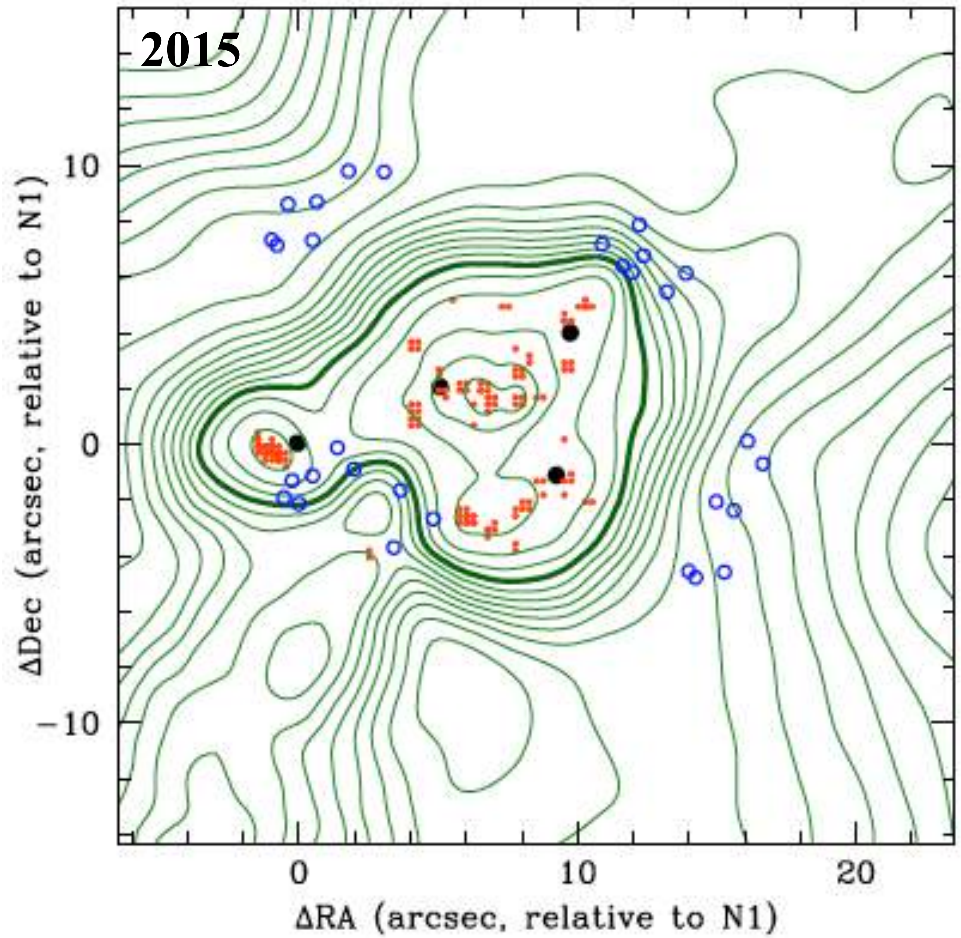
- The cross section required to obtain a separation of 1.5 kpc is now: $\sigma/m_\chi \sim 1.5$ cm^2/g
- NB: the separation is mainly due to differences in the *shapes* of the two respective distributions, while the peaks of the distributions remain *coincident*

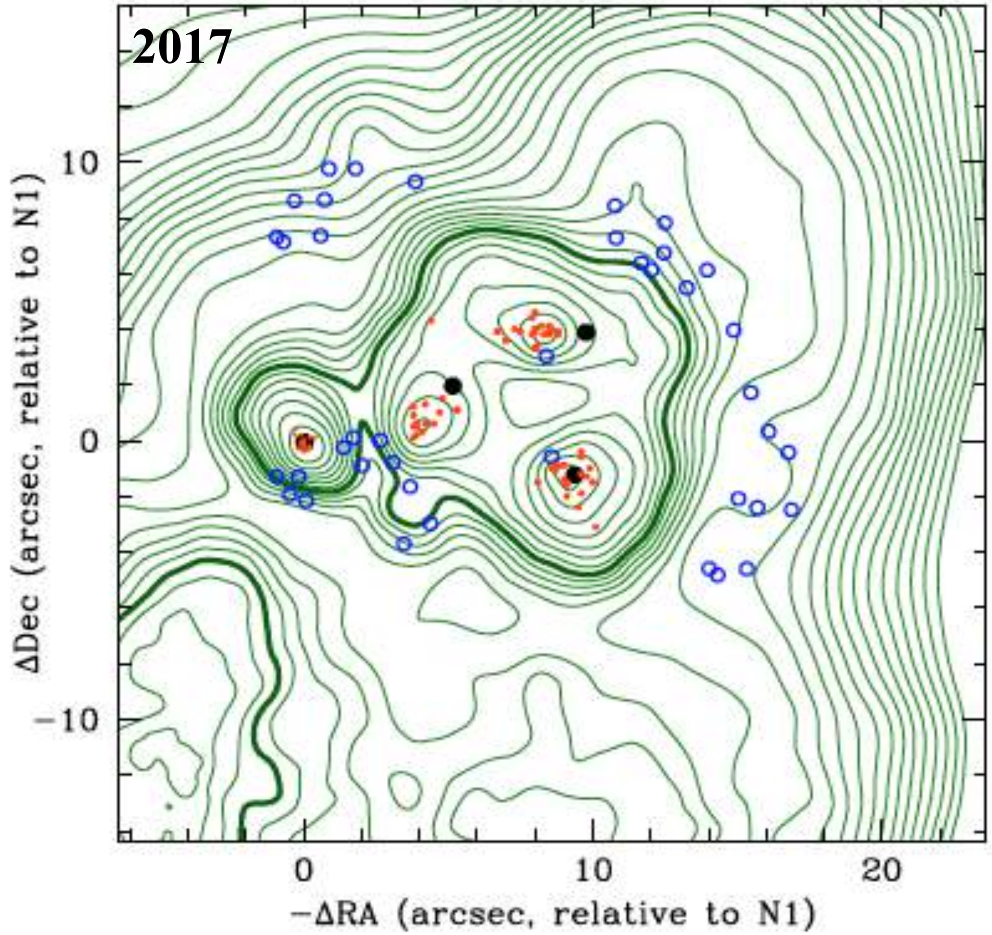
However recent data from ALMA (mm integral field spectroscopy) enables an improved reconstruction of the dark matter distribution (by enabling better matching of the (counter) images of the many multiply-imaged star forming knots - colour/brightness/morphology in HST imaging is complicated by bright foregrounds …)



The offset with the galaxy has now disappeared!

Courtesey: Richard Massey



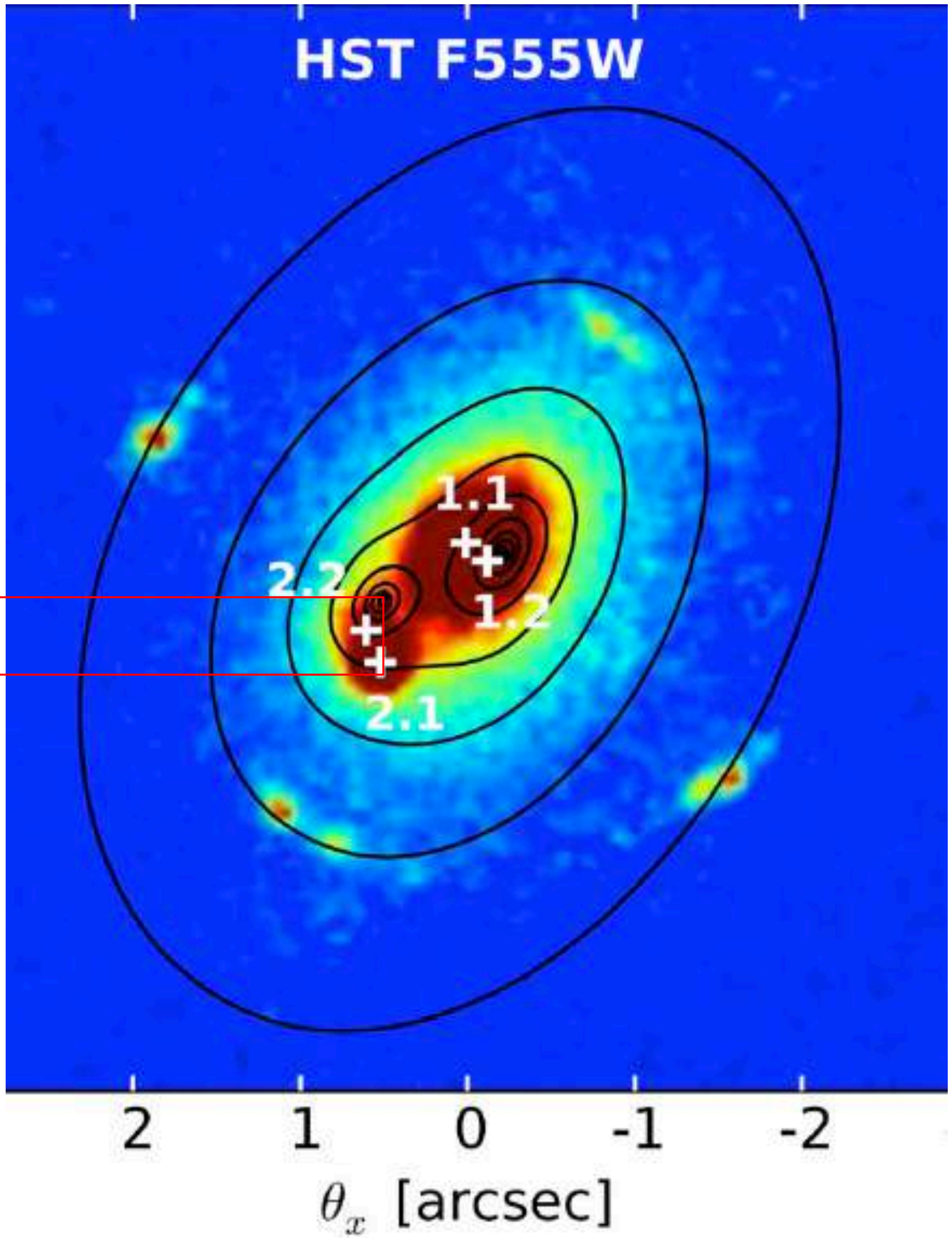


But all is not lost … there are other candidates too!

Kiloparsec Mass/Light Offsets the Galaxy Pair-Lyα Emitter Lens System SDSS J1011+0143

1.1 ± 0.2 Kpc

… The black contours represent the surface mass isodensity levels. White plus signs mark the individual light peaks.



"The detected mass/light offsets can potentially serve as an important test for the self-interacting dark matter model. However, other mechanisms such as dynamical friction on spatially differently distributed dark matter and stars could produce similar offsets. Detailed hydrodynamical simulations of galaxy-galaxy interactions with self-interacting dark matter could accurately quantify the effects of different mechanisms."

Shu *et al*, 1602.02927

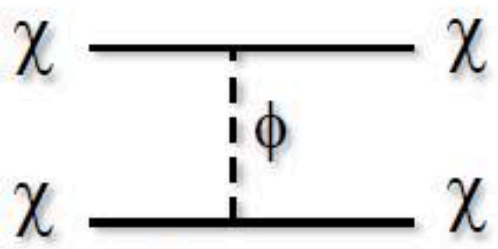
Courtesey: Sean Tullin

Particle physics of self-interactions

Large cross section required $\sigma/m_\chi \sim 1\ \mathrm{cm}^2/\mathrm{g}$

MSIDM (Minimal SIDM) model: DM + light mediator ϕ

Feng, Kaplinghat, Yu (2009); Buckley & Fox (2009); Loeb & Weiner (2011); ST, Yu, Zurek (2012+13)



self-interaction

Cross section: $\sigma \sim \dfrac{g^4 m_\chi^2}{m_\phi^4}$

Mediator mass below than weak scale

$m_\phi \sim 1 - 100\ \mathrm{MeV}$

Velocity-dependence controlled by mediator mass m_ϕ

Hard-sphere scattering	Rutherford-like scattering
Constant cross section	Cross section falls with $1/v_{\rm rel}^4$
$m_\phi \gg m_\chi v_{\rm rel}$	$m_\phi \ll m_\chi v_{\rm rel}$

What type of models are viable?

- **Light mediator models**

- **Strongly-interacting DM**

QCD-like theories

Dark hadrons or dark nuclei

- **Massless mediator models**

Dark atoms

DM with dark radiation

Courtesey: Sean Tullin

Conclusions

- Nature may have been kind enough to provide us a natural collider laboratory for dark matter self-interactions

- The separation observed in A3827 if due to DM self-interactions requires: $\sigma/m_\chi > 1\ \mathrm{cm}^2/\mathrm{g}$ … this interpretation is *testable* using observations of gravitational lensed colliding galaxy clusters (where the DM-star separation is expected to be ~10-50 kpc)

- … *if* proved true, this would be a most significant step forward in understanding the particle nature of dark matter

- Particle phenomenologists can contribute by quantifying observational signatures (skewness, sphericity, radial change in ellipticity ..) of different types of self-interactions, for the benefit of astronomers studying gravitational lensing