The great collider in the sky

Subir Sarkar

Niels Bohr International Academy, Copenhagen

Rudolf Peierls Centre for Theoretical Physics, Oxford

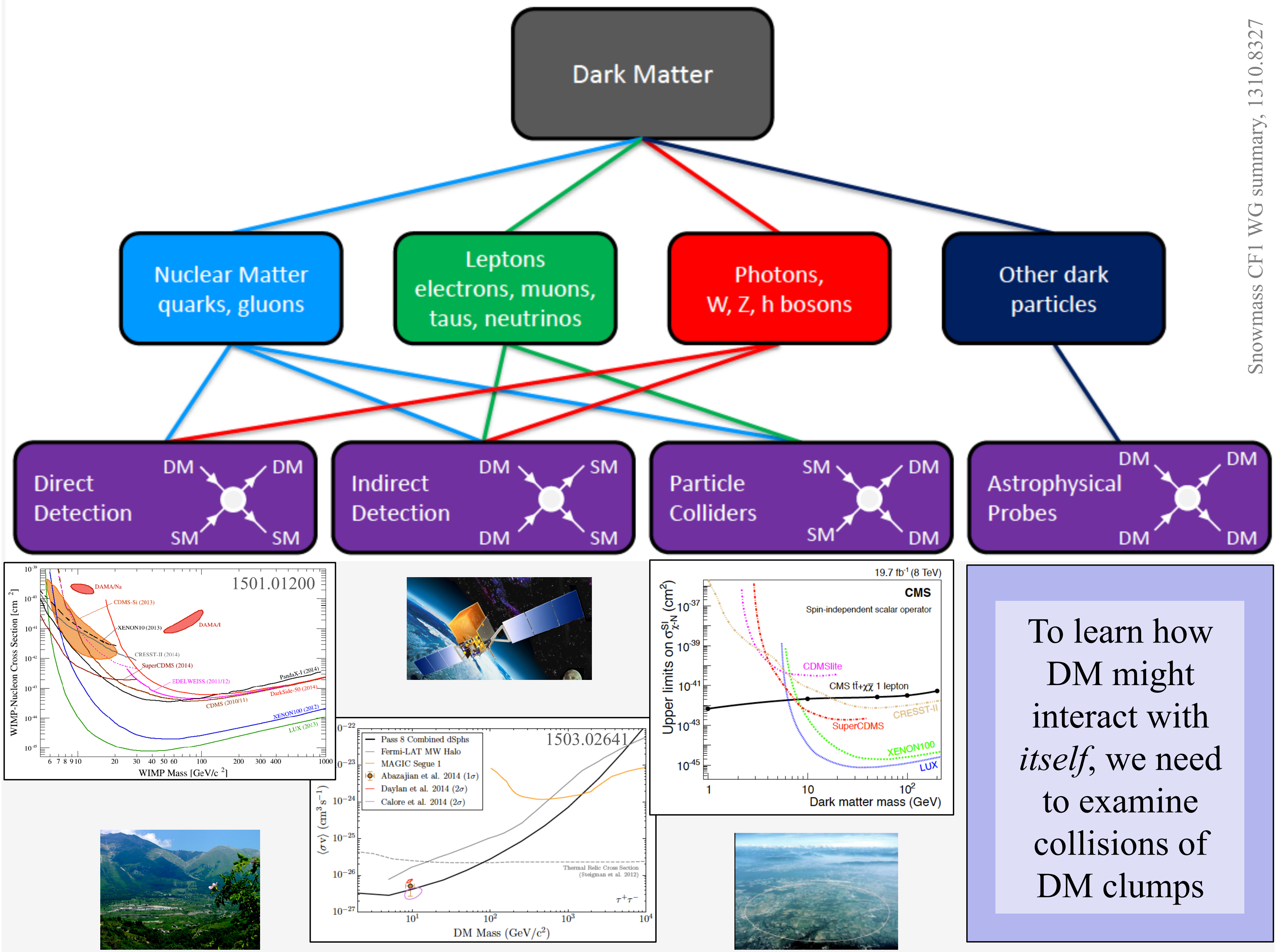
Based on work done with:

David Kraljic, JCAP04:050,2015 [arXiv:1412.7719]

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

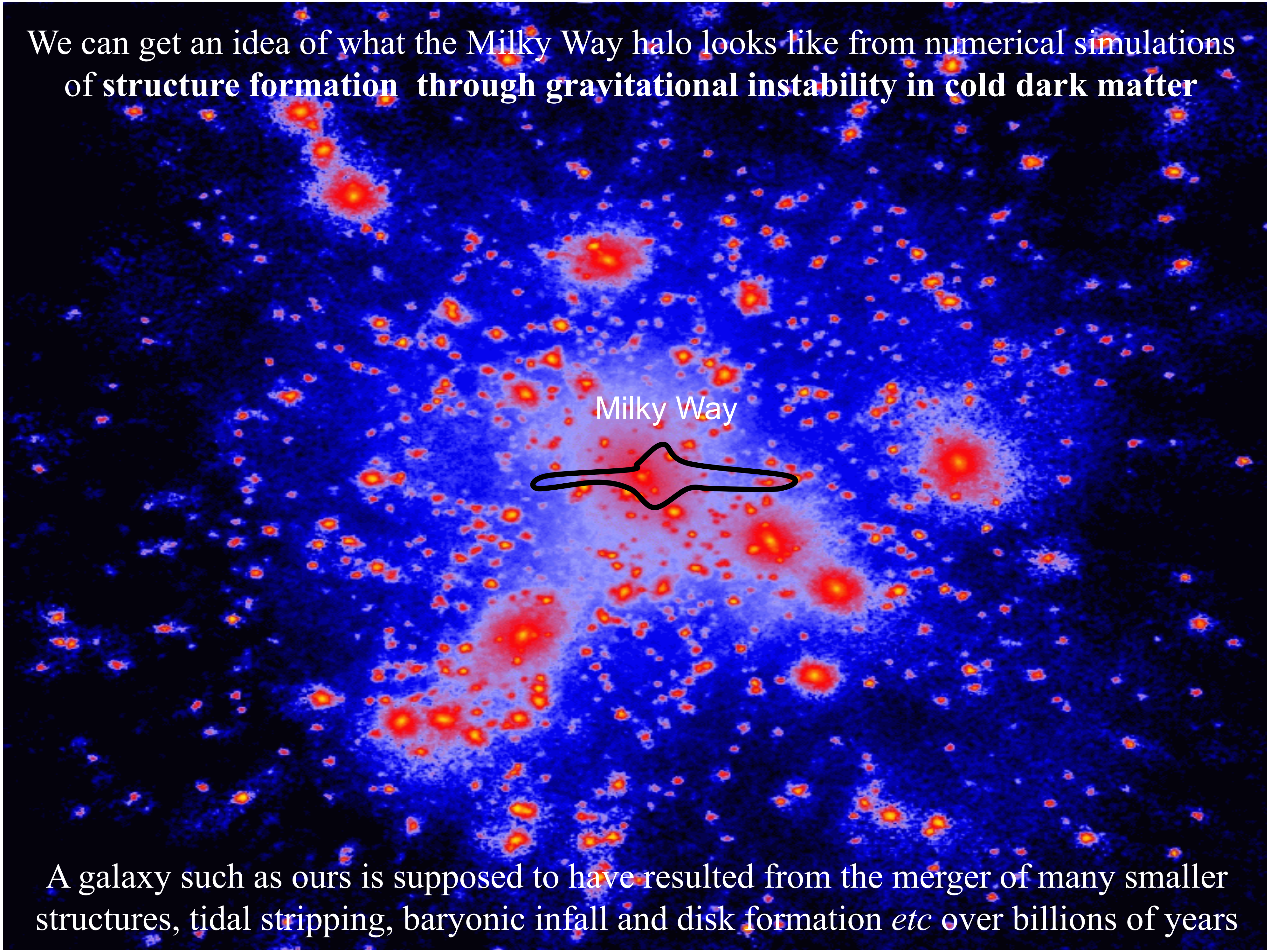
Felix Kahlhoefer, Janis Kummer, Kai Schmidt-Hoberg, MNRAS 452:L54, 2015 [1504.06576]

Current Themes in High Energy Physics & Cosmology, Copenhagen, 17-21 Aug 2015



Snowmass CF1 WG summary, 1310.8327

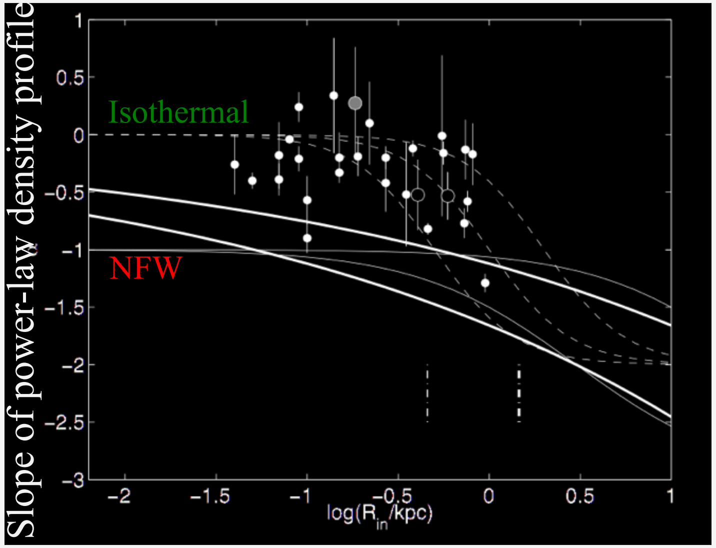
We can get an idea of what the Milky Way halo looks like from numerical simulations of **structure formation through gravitational instability in cold dark matter**



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

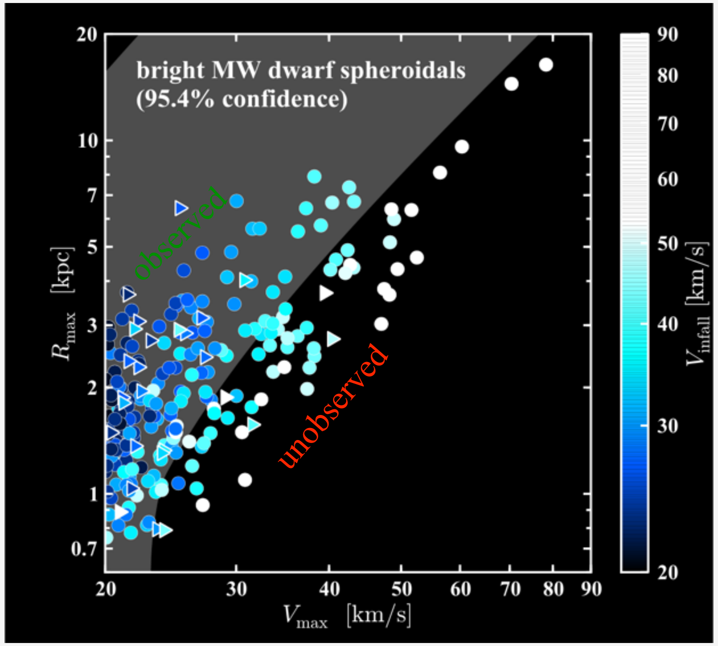
There are well-publicised discrepancies between N-body simulations of *collisionless* cold DM and astrophysical observations on galactic scales:

- Cusp-versus-core problem
- Too-big-to-fail problem
- Missing-satellite problem
- …



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

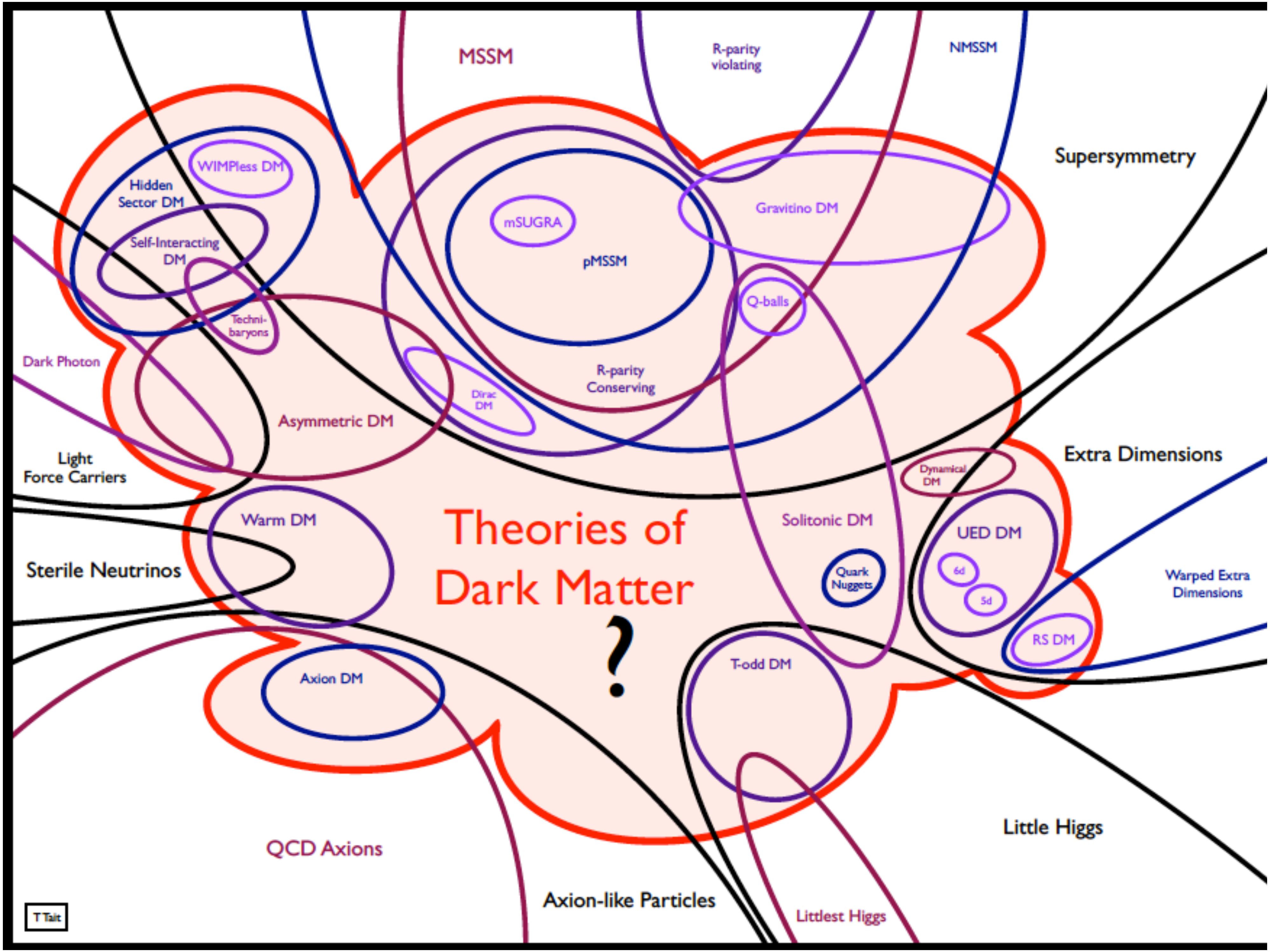
There may be astrophysical explanations (e.g. 'baryonic feedback' for the Cusp-vs-core problem) … simulations are only *now* beginning to be able to address these complex issues



Boylan-Kochlin *et al*, 1103.0007

or …

DM self-interactions may solve these problems (Spergel & Steinhardt, astro-ph/9909386)



Theories of Dark Matter
?
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
Dynamical DM
Extra Dimensions
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Self-interacting DM

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

- The typical self-interaction #-section of a WIMP is smaller by $>10^{15}$ … hence astrophysical evidence for DM self-interactions would *rule out* most popular particle candidates such as axions and neutralinos!

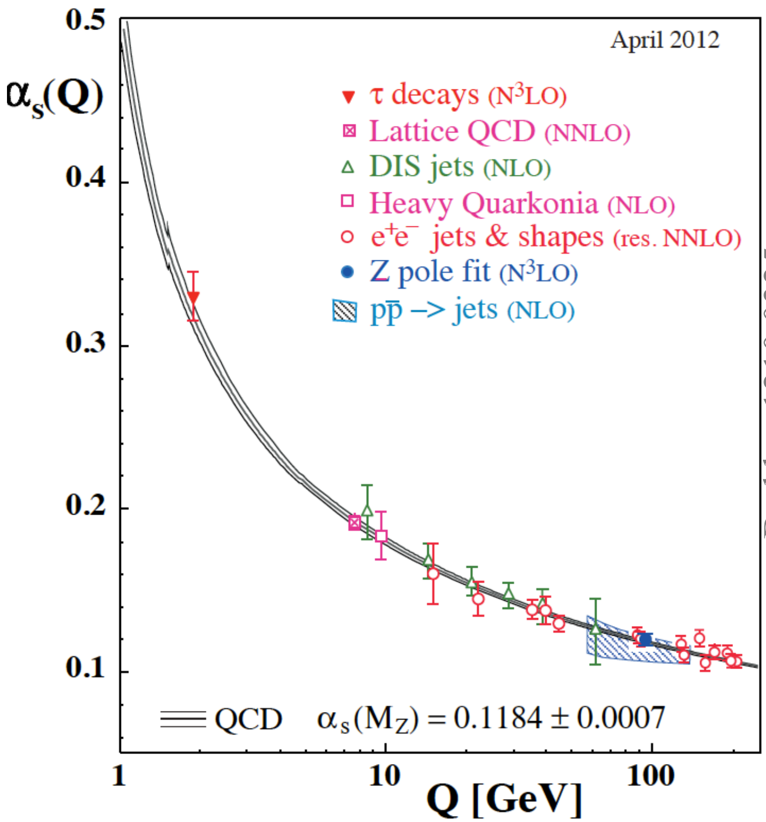
- However large self-interactions are natural in models such as:
  - Strongly interacting DM
    Kusenko & Steinhard: astro-ph/0106008
    Frandsen, Sarkar & Schmidt-Hoberg: 1103.4350
    …
  - Mirror DM
    Berezhiani, Dolgov & Mohapatra: hep-ph/9511221
    Mohapatra, Nussinov & Teplitz: hep-ph/0111381
    …
  - Atomic DM
    Kaplan, Krnjaic, Rehermann & Wells: 0909.0753
    Cyr-Racine & Sigurdson:1209.5752
    …

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

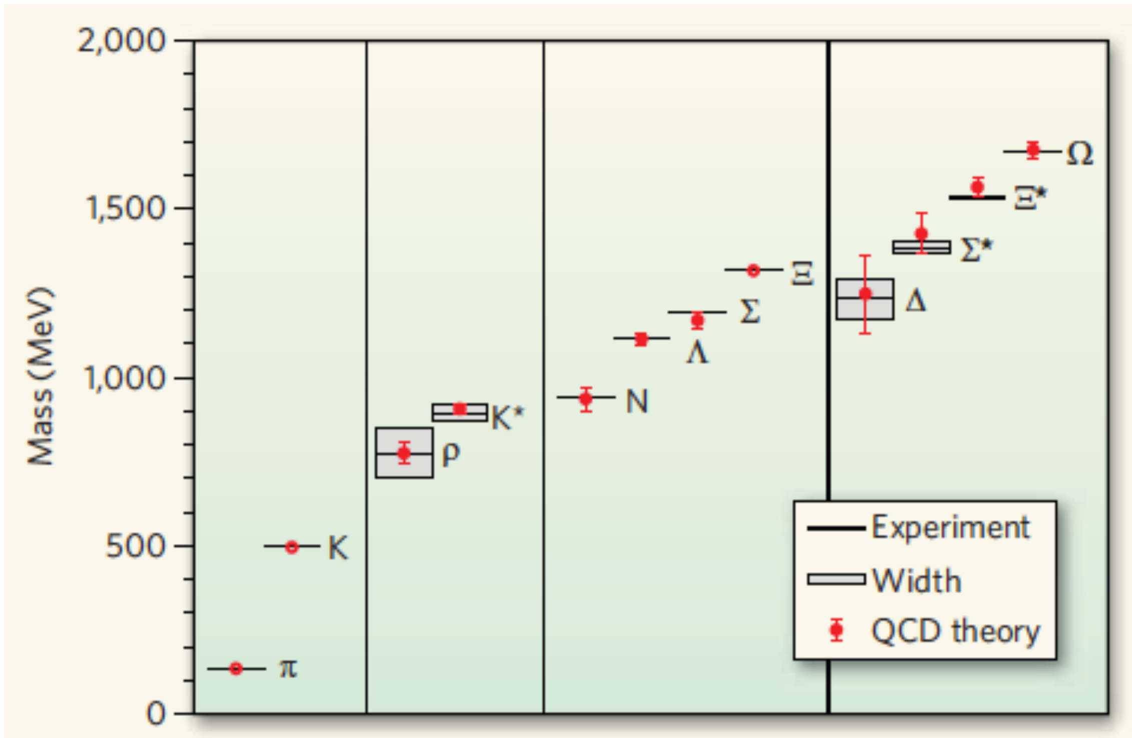
What should the world be made of?

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!

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

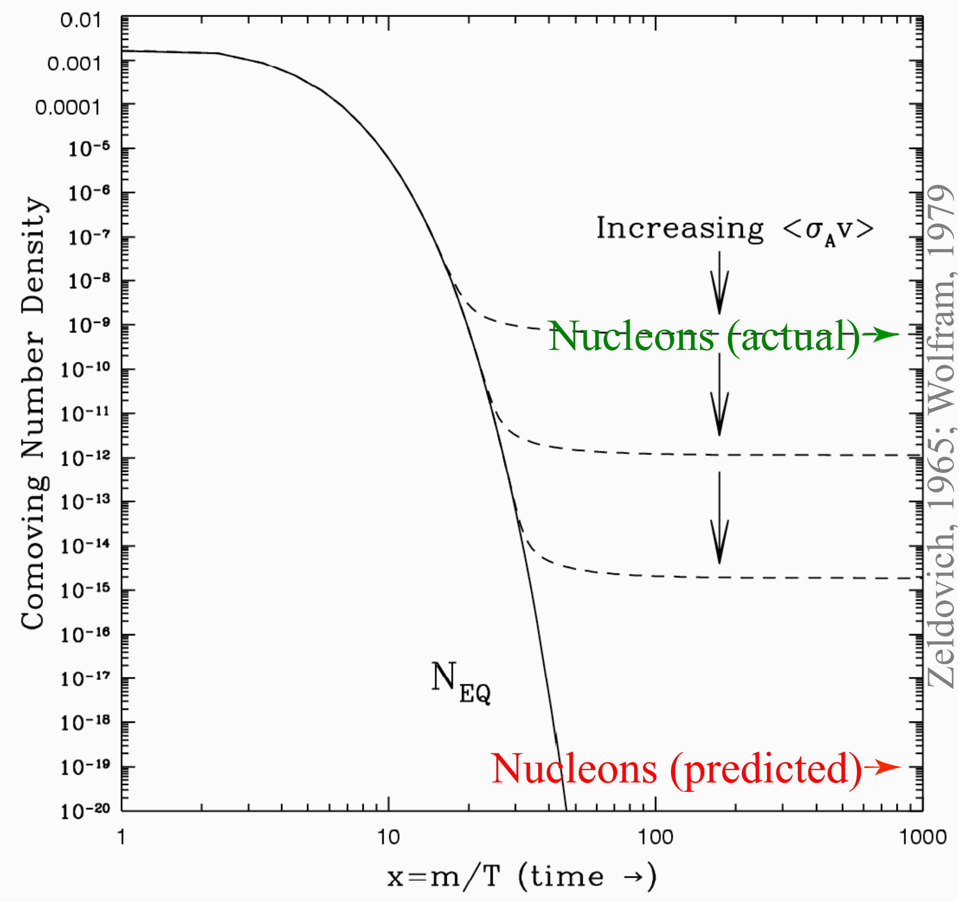
Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate

'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

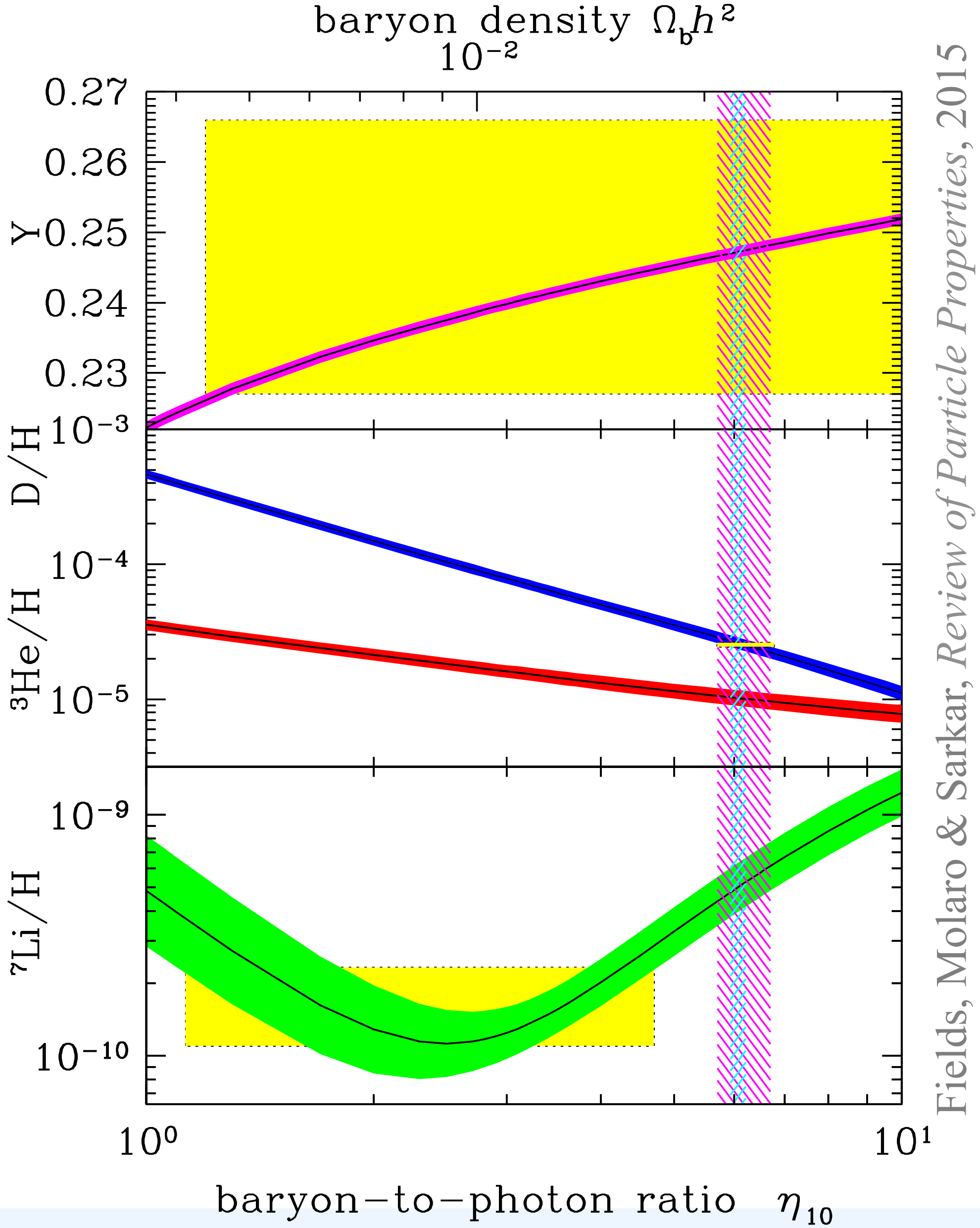
$$H \sim \frac{\sqrt{g}T^2}{M_{\rm P}}$$ where $g \sim$ # relativistic species



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**: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$

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

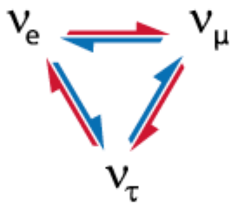
To make the baryon asymmetry requires *new* physics ('Sakharov conditions')

- 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

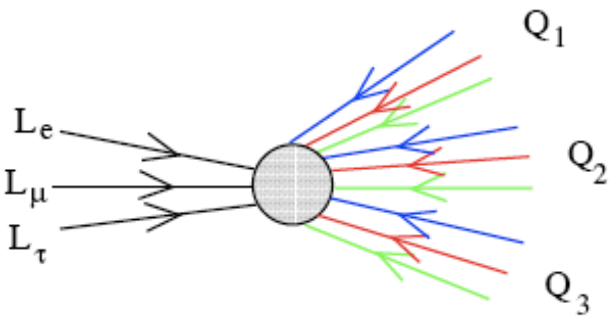
Hence the generation of the observed matter-antimatter asymmetry requires *new* BSM physics … can be related to the observed neutrino masses if these arise from *lepton number* violation → **leptogenesis**

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

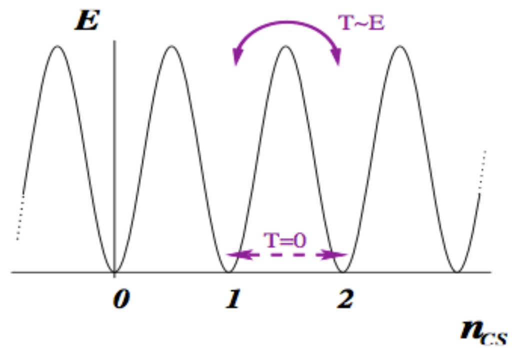


$\Delta m^2_{atm} = m_3^2 - m_2^2 \simeq 2.6 \times 10^{-3}\mathrm{eV}^2 \qquad \Delta m^2_\odot = m_2^2 - m_1^2 \simeq 7.9 \times 10^{-5}\mathrm{eV}^2$

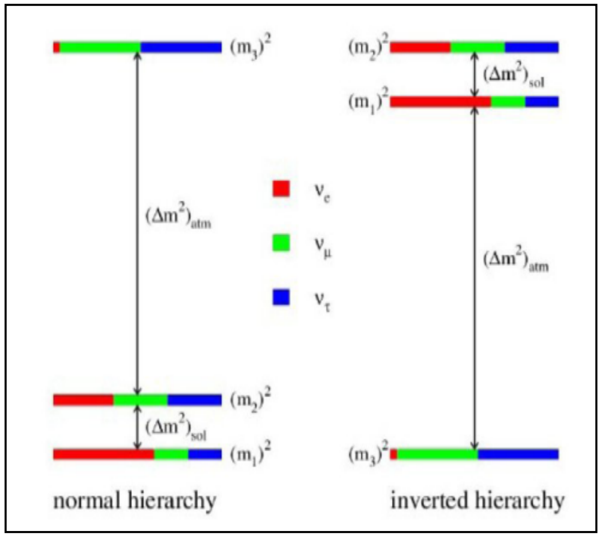
Asymmetric baryonic matter



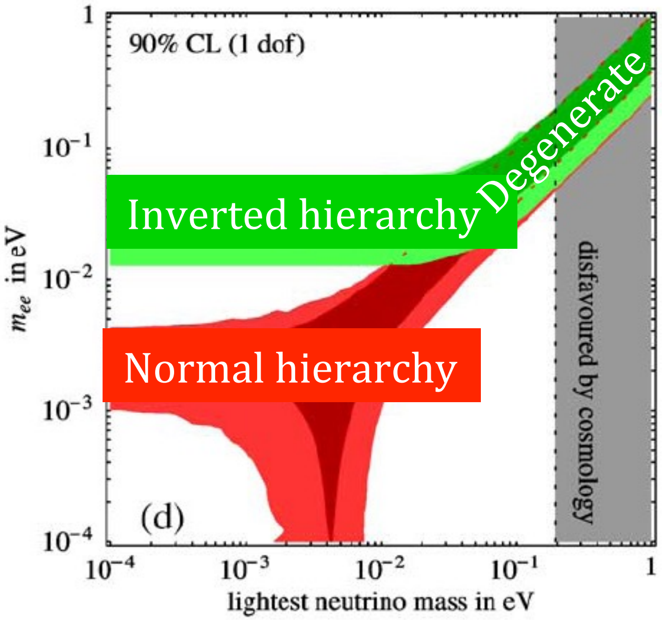
$$\partial_\mu j_i^\mu = \partial_\mu(\bar{\psi}^i \gamma^\mu \psi^i) = \frac{g^2}{8\pi} W^{a\mu\nu} \tilde{W}^a_{\mu\nu}$$



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**

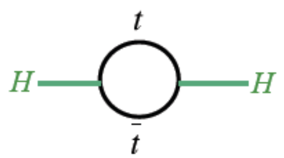


An essential requirement is that neutrino mass must be Majorana … test by detecting neutrino*less* double beta decay (and measuring the absolute neutrino mass scale)

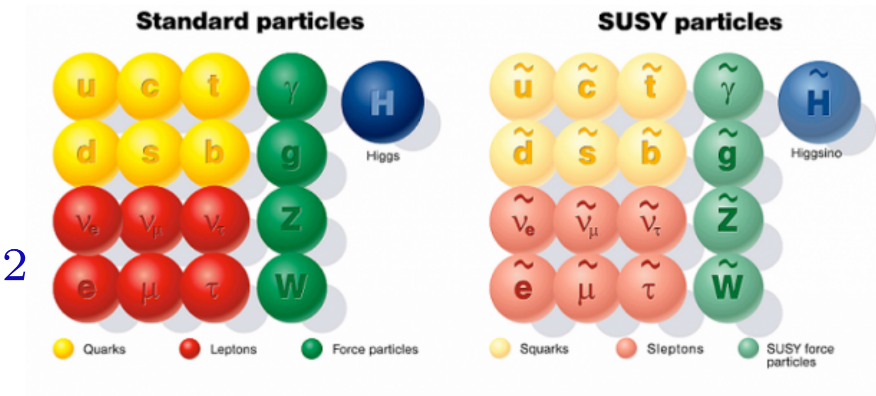


What *should* the world be made of?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr	~~'freeze-out' from thermal equilibrium~~ Asymmetric baryogenesis	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	*R*-parity?	Violated? (matter parity *adequate* to ensure B stability)	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$



$$\mathcal{L}_{\rm eff} \supset M_A A_\mu A^\mu + m_{\rm f} \bar{f}_{\rm L} f_{\rm R} + m_H^2 |H|^2$$



For (softly broken) **supersymmetry** we have the 'WIMP miracle':

$$\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}\mathrm{cm}^{-3}\mathrm{s}^{-1}}{\langle\sigma_{\rm ann} v\rangle_{T=T_{\rm f}}} \simeq 0.1 \quad , \text{ since } \langle\sigma_{\rm ann} v\rangle \sim \frac{g_\chi^4}{16\pi^2 m_\chi^2} \approx 3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$$

But why should a *thermal* relic have an abundance comparable to non thermal relic baryons?

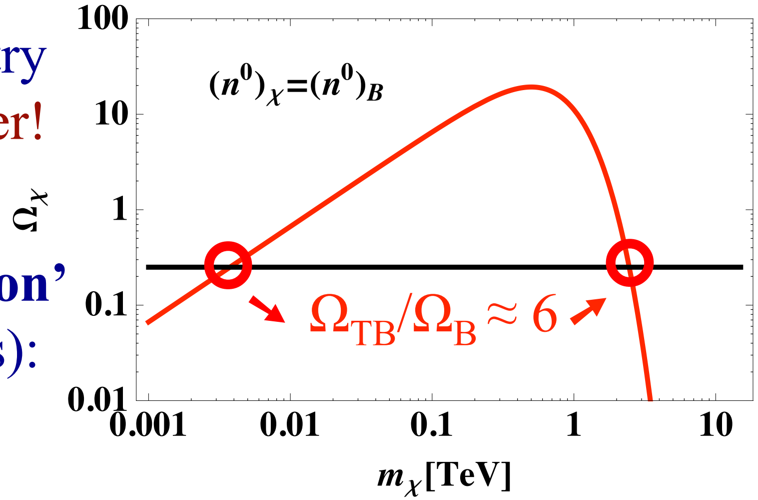
What *should* the world be made of ?

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?	*R*-parity	violated?	'Freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$
	Technibaryon?	(walking) Technicolour	$\tau \sim 10^{18}$ yr e^+ excess?	Asymmetric (like the *observed* baryons)	$\Omega_{TB} \sim 0.3$

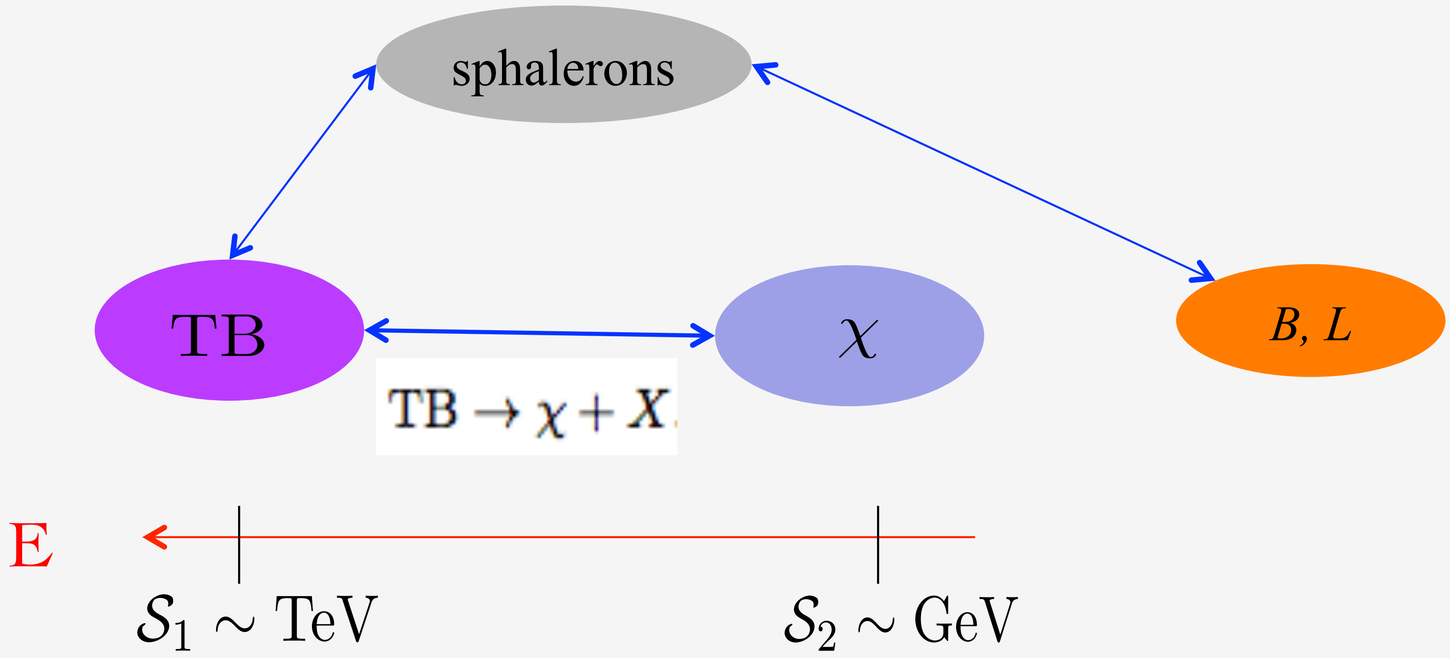
A new particle can naturally *share* in the *B/L* asymmetry if it couples to the *W* … linking dark to baryonic matter!

Then a *O*(TeV) mass **technibaryon** can be the dark matter … alternatively a ~5-10 GeV mass **'dark baryon'** in a *hidden sector* (into which the technibaryon decays):

$$\Omega_\chi = (m_\chi \mathcal{N}_\chi / m_B \mathcal{N}_B)\Omega_B$$



Why may we not have seen these 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 (➛ baryon asymmetry)

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

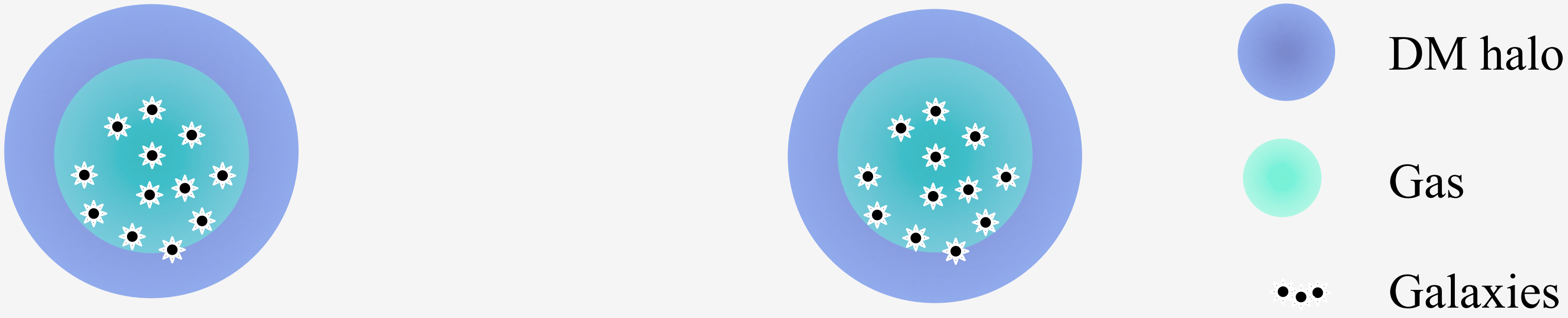
$\mathrm{TB} \to \chi + \mathrm{X}$ is in equilibrium until $T \lesssim T_{\rm sph}$, then χ decouples and becomes DM

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

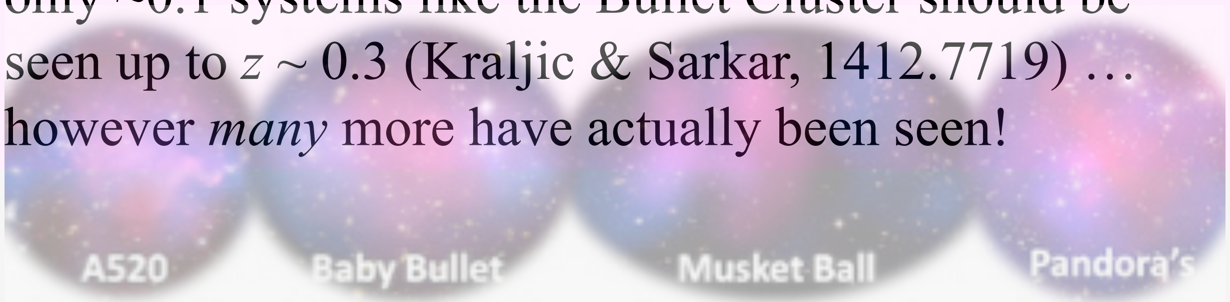
Observational constraints

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!



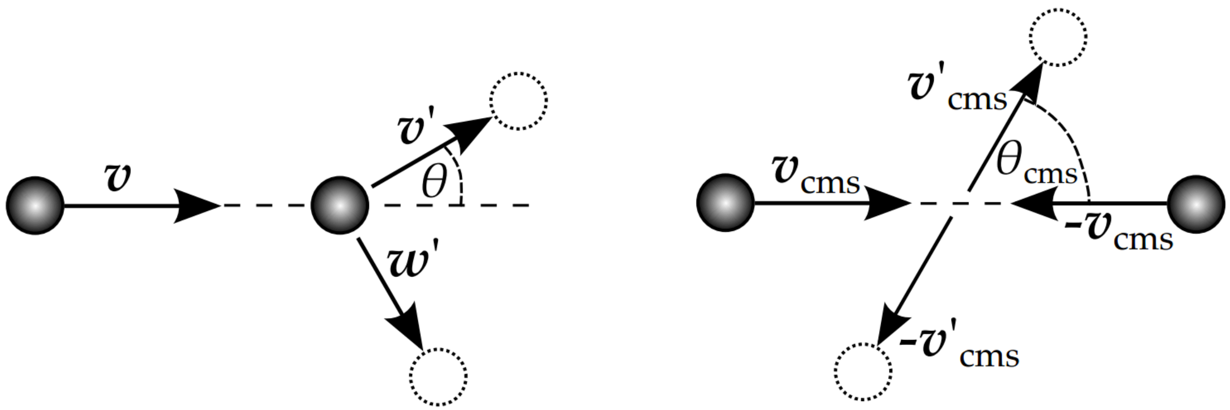
http://www.mergingclustercollaboration.org/

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:

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

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

Evaporation bounds



- 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 $\dfrac{2\,v_{\rm esc}^2}{v_0^2} - 1 < \cos\theta_{\rm cms} < 1 - \dfrac{2\,v_{\rm esc}^2}{v_0^2}$

- Denote by "imd" *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 $\dfrac{\Delta N_{\mathrm{imd}}}{N} < 30\%$

Other observational constraints

- Several astrophysical observations have been argued to constrain the DM self-interaction cross section (some 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

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

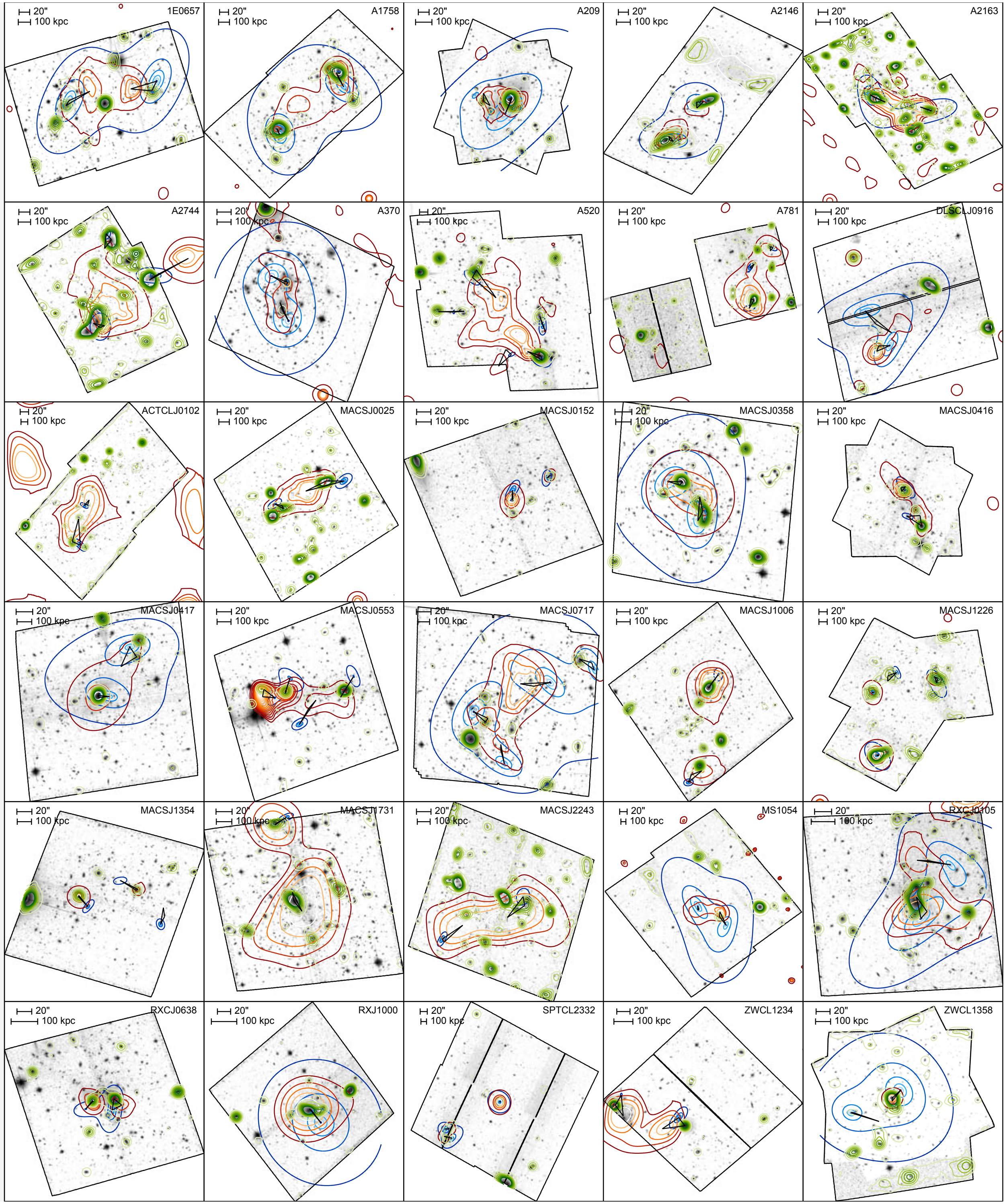
Vogelsberger, Zavalla & Loeb, 1201.5892
Rocha *et al*, 1208.3025
Peter *et al*, 1208.3026
Zavalla, Vogelsberger & Walker, 1211.6426

Infalling subhalos

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

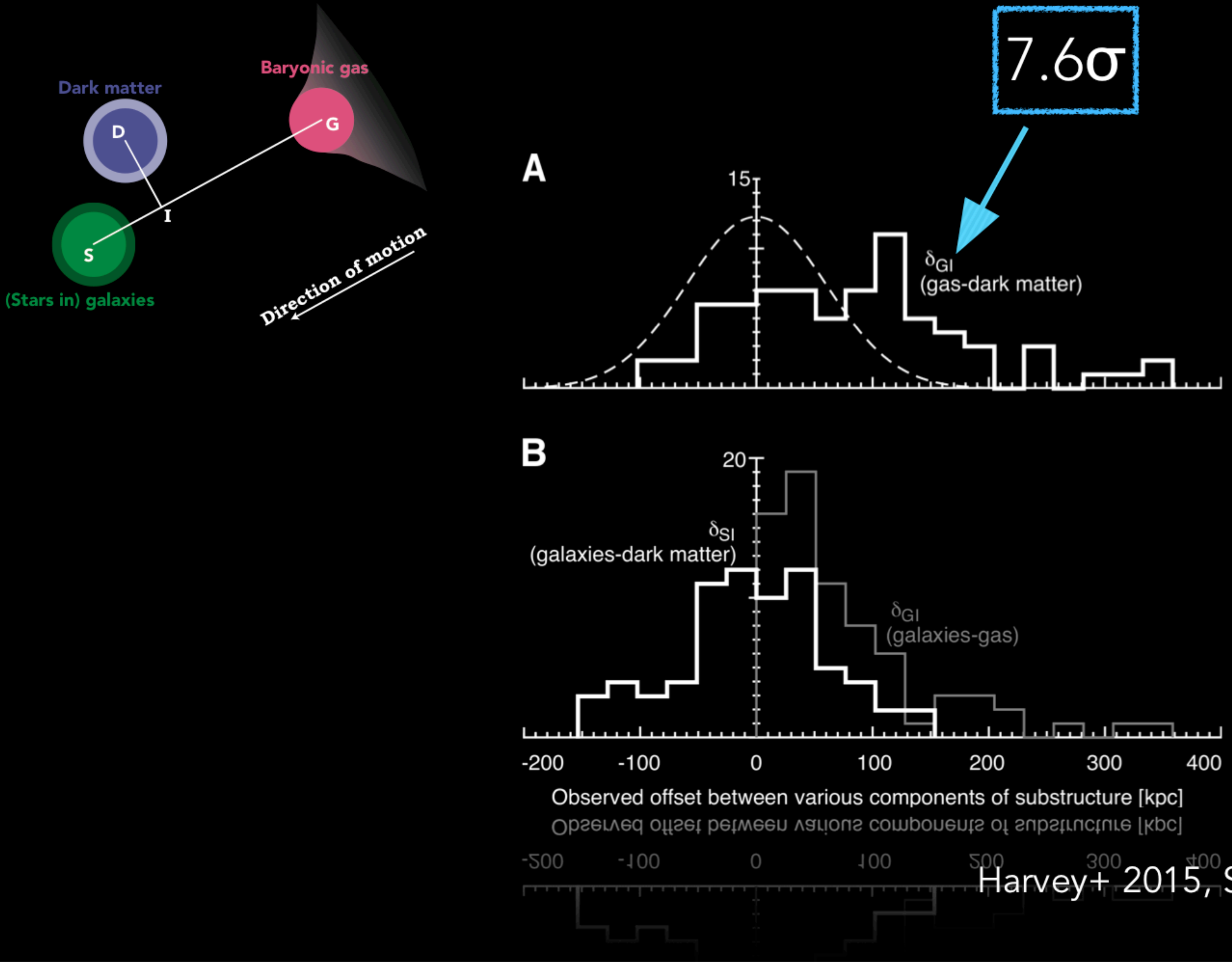
Through statistical analysis of a large number of gravitationally lensed clusters in the Chandra catalogue, the DM self-interaction is bounded as:

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



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

RESULTS FROM 72 MERGING SYSTEMS



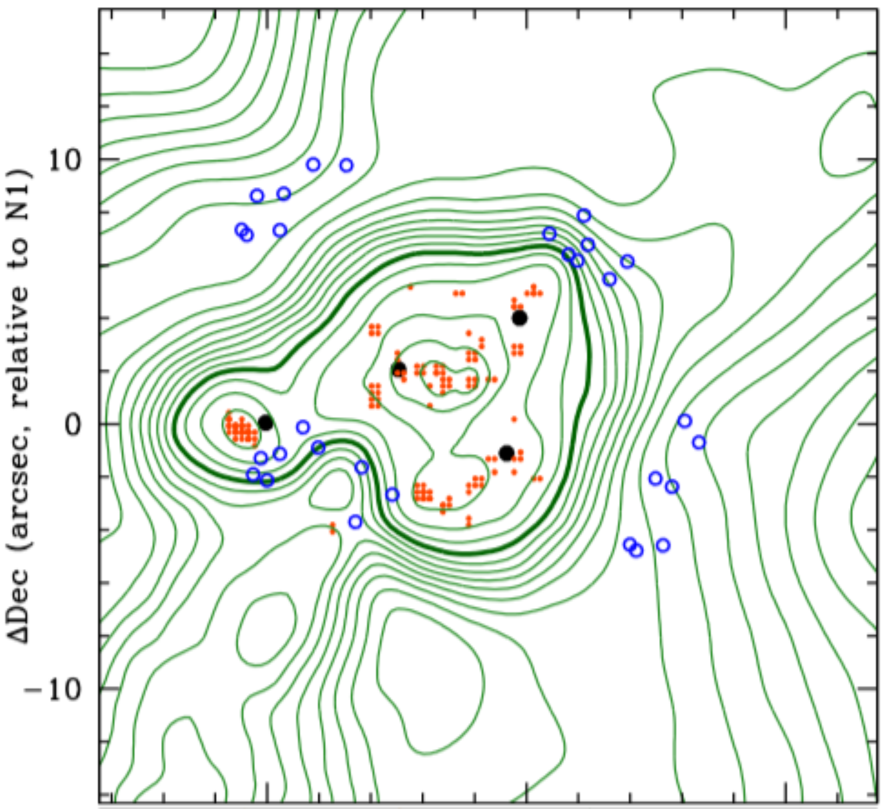
Harvey+ 2015, Science

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

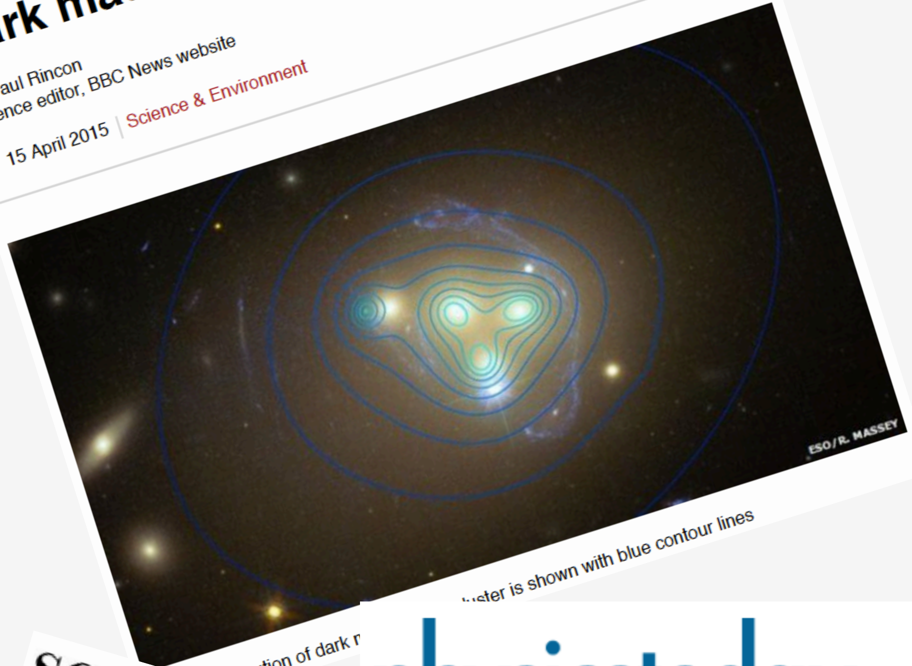
"The best-constrained offset is 1.62±0.48 kpc, where the 68% confidence limit includes both statistical error and systematic biases in mass modelling. […]
With such a small physical separation, it is difficult to definitively rule out astrophysical effects operating exclusively in dense cluster core environments – but **if interpreted solely as evidence for self-interacting dark matter, this offset implies a cross-section σ/m=(1.7±0.7) x10^{-4} cm^2/g ($t/10^9$yr)$^{-2}$ where t is the infall duration**."



Dark matter becomes less 'ghostly'

By Paul Rincon
Science editor, BBC News website

15 April 2015 | Science & Environment



...istribution of dark m... ...uster is shown with blue contour lines

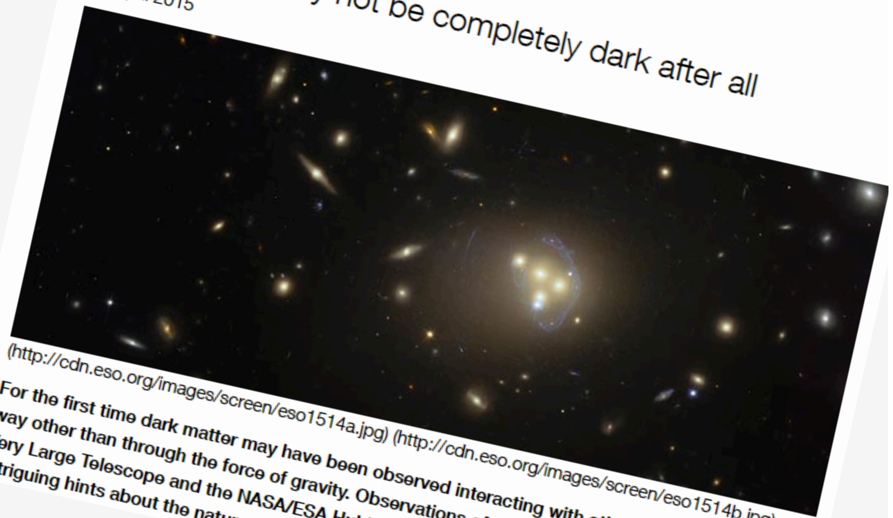
eso1514 — Science Release

First Signs of Self-interacting Dark Matter?

SPACE SCOOP

Dark matter may not be completely dark after all

15 April 2015



(http://cdn.eso.org/images/screen/eso1514a.jpg) (http://cdn.eso.org/images/screen/eso1514b.jpg)

For the first time dark matter may have been observed interacting with other dark matter in a way other than through the force of gravity. Observations of colliding galaxies made with ESO's Very Large Telescope and the NASA/ESA Hubble Space Telescope have picked up the first intriguing hints about the nature of this mysterious component of the Universe.

SCIENTIFIC AMERICAN™

Permanent Address: http://www.scientificamerican.com/article/dark-matter-may-feel-a-dark-force-that-the-rest-of-the-universe-does-not1/

Space » News

Dark Matter May Feel a "Dark Force" That the Rest of the Universe Does Not

Astronomers watching galaxies collide found evidence of nongravitational forces that could suggest dark matter interacts with itself

physicstoday

Remarkable gravitational lensing by the galaxy cluster Abell 3827

By Steven K. Blau
June 2015, page 18

Science AAAS

Gravity from this cluster of four galaxies produces multiple distorted images (blue streams) of a more distant galaxy.

Subtly shifted star could force ...think of dark matter

Dynamics

- Frequent DM self-interactions lead to the deceleration of DM halos moving through a larger system:

$$R_{\mathrm{dec}} \equiv v_0^{-1}\,\mathrm{d}v_{\parallel}/\mathrm{d}t = \frac{\rho_2\, v_0\, \sigma_{\mathrm{T}}}{2\, m_{\mathrm{DM}}}$$

where the momentum transfer cross section is

$$\sigma_{\mathrm{T}} = 4\pi \int_0^1 \mathrm{d}\cos\theta_{\mathrm{cms}}\,(1-\cos\theta_{\mathrm{cms}})\,\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_{\mathrm{cms}}}$$

- This deceleration can be described in terms of an effective drag force

$$\frac{F_{\mathrm{drag}}}{m_{\mathrm{DM}}} = \frac{\tilde{\sigma}}{4\, m_{\mathrm{DM}}}\,\rho\, v_0^{2m} \longleftarrow \begin{cases} m = -1 & \text{for long-range interactions} \\ m = 1 & \text{for velocity-independent interactions} \end{cases}$$

Predictions

- In the presence of such a drag force, a DM sub-halo falling into a galaxy cluster will retain its shape, since the drag force affects all DM particles *equally*

- In the decelerating frame of the DM subhalo, stars will experience a fictitious *accelerating* force

- The resulting tilt in the effective potential will shift the *distribution* of stars relative to the DM halo

- Moreover, some galaxies can escape and will end up travelling *ahead* of the DM halo

- Both of these effects can lead to a *separation* between the peak of the distribution of stars and the centroid of the DM halo

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.

Approximate estimate

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

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

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

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

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

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

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.

Mass modelling

- We use a Hernquist profile for both the cluster and the subhalo.

$$\rho(r) = \frac{M}{2\pi} \frac{a}{r\,(a+r)^3}$$

- Advantages: finite central potential and analytical expression for velocity distribution function

- Very similar results expected for an NFW profile (only differs from Hernquist at large radii)

- We fix *M* and *a* for each system by matching the observed surface density, the observed projected mass in the central region and the observed velocity dispersion

  - Mcluster = 7×10^{13} M_{Sun}, $a_{cluster}$ = 60 kpc
  - Msubhalo = 5×10^{11} M_{Sun}, $a_{subhalo}$ = 7 kpc

Centroid definition

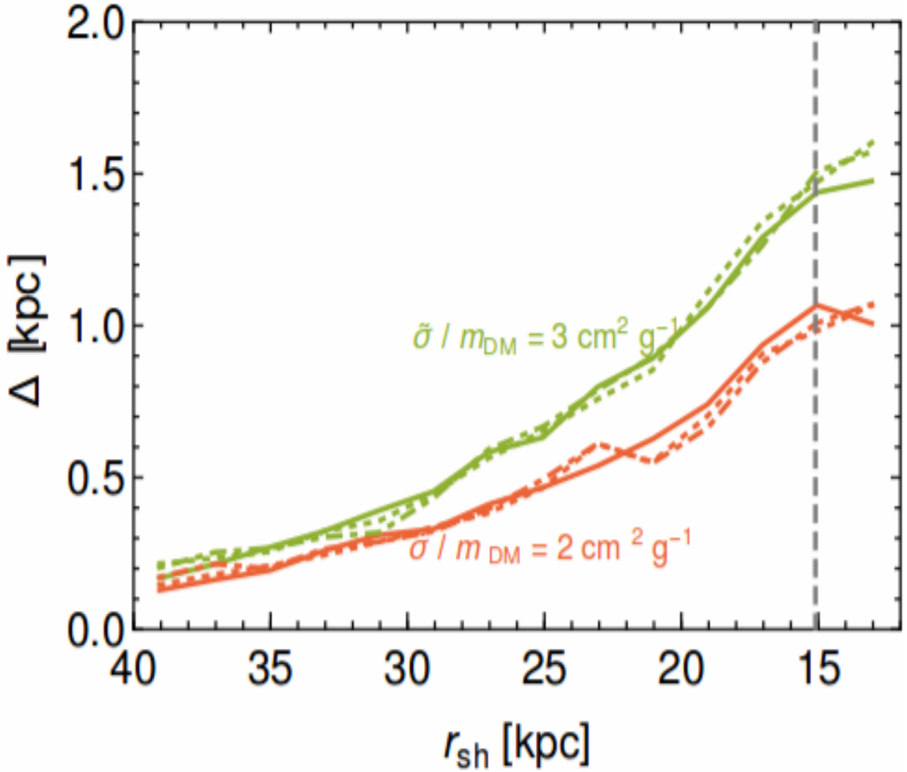
- It is inconsistent to calculate the subhalo position including just all initially bound particles, because particles that have escaped would strongly bias the centroid position

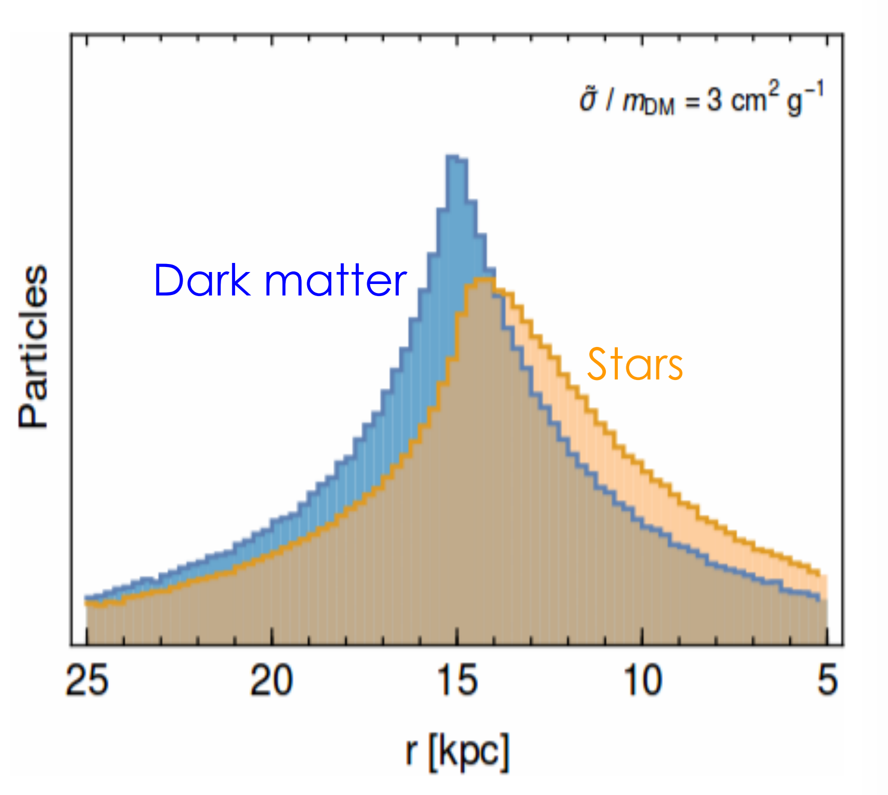
- It is also not sensible to just determine the peak position, which (for the DM distribution) cannot be obtained observationally

- For a realistic estimate we include only particles within the iso-density contour containing 20% of the total mass of the DM subhalo (corresponding roughly to the inner 4 kpc)

- To study how strongly our results depend on this choice, we show the result of including only the inner 5%, as well as when we include the inner 20% for DM and the inner 5% for stars

Results





- 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

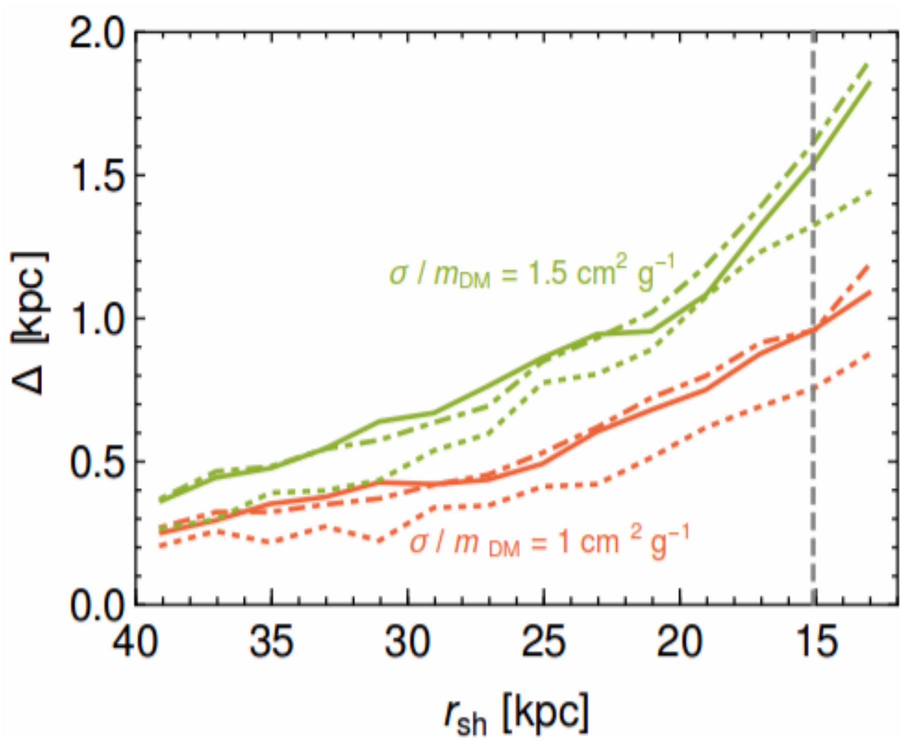
- Rare self-interactions mean that for a typical DM particle the probability for multiple scattering is *negligible*

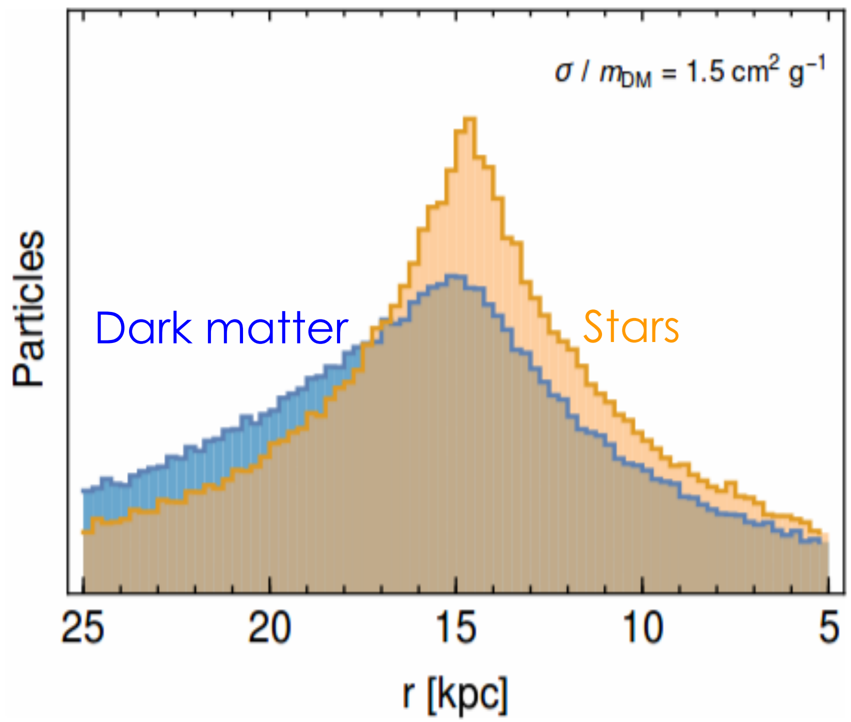
- A significant fraction of DM particles will not experience any scattering and behave just like the (collisionless) stars

- 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





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

Rare self-interactions

- The case of contact interactions can potentially be distinguished from the case of an effective drag force by studying in detail the shape of the DM sub-halo and the relative position of the peaks of the two distributions.

- **Contact interactions:** The DM sub-halo is deformed due to the scattered DM particles leaving the sub-halo in the backward direction, such that the position of the centroid depends sensitively on the definition of the centroid

- **Effective drag force:** The DM sub-halo is expected to retain its shape, while the distribution of stars will be both shifted and deformed

Conclusions

- Sub-halos falling into galaxy clusters are a novel and interesting probe of dark matter self-interactions

- While a separation between the DM sub-halo and the stars can develop from both frequent and rare DM self-interactions, the latter is better motivated from a particle physics viewpoint

- The separation will grow only when the sub-halo is close to the cluster centre and is therefore *insensitive to the total infall time*

- The separation observed in A3827 if due to DM self-interactions requires: $\sigma/m_\chi > 1 \text{ cm}^2/\text{g}$ … 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* true, would be the most significant step forward in understanding the nature of dark matter!