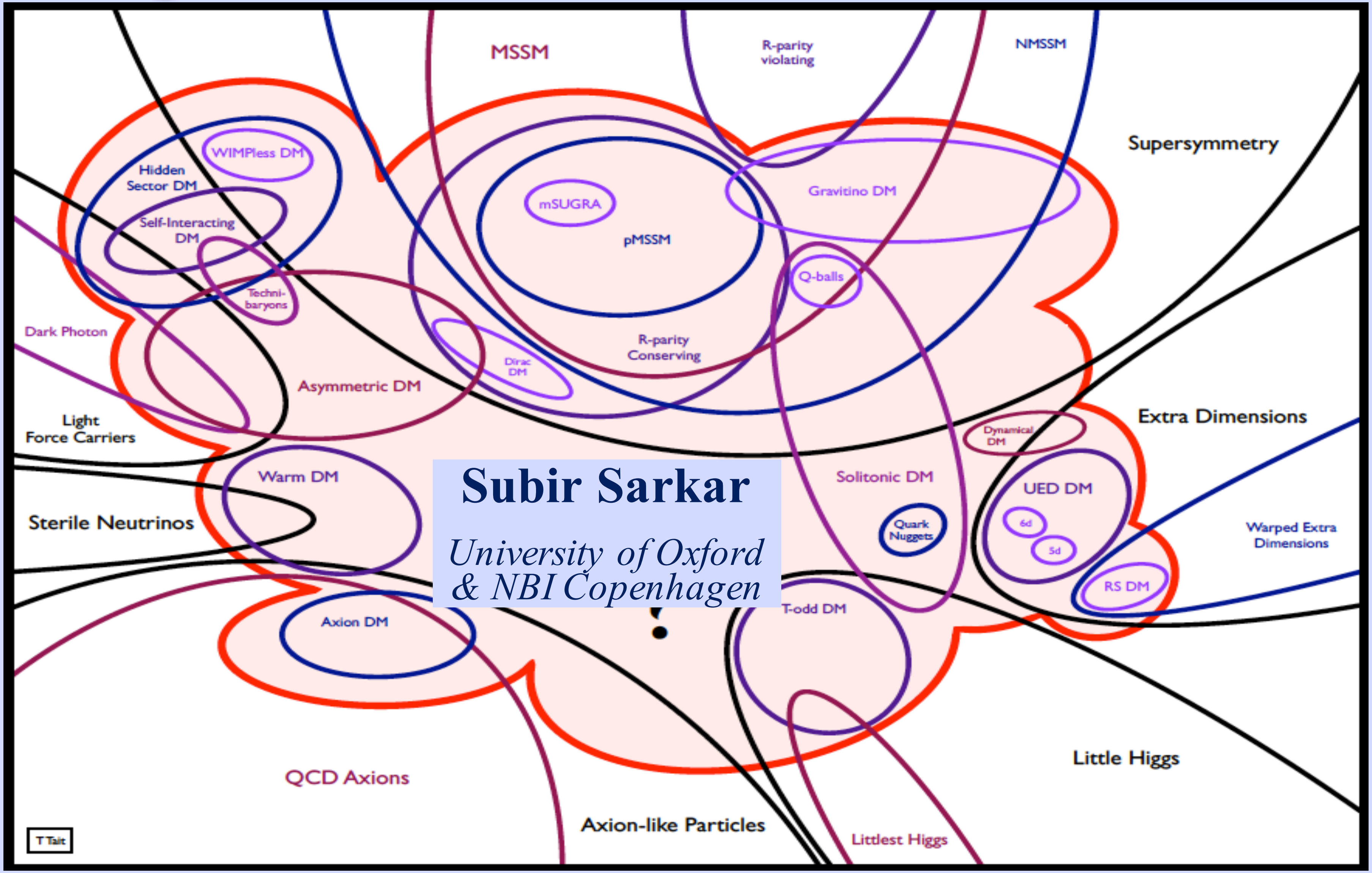
Beyond the 'WIMP miracle'

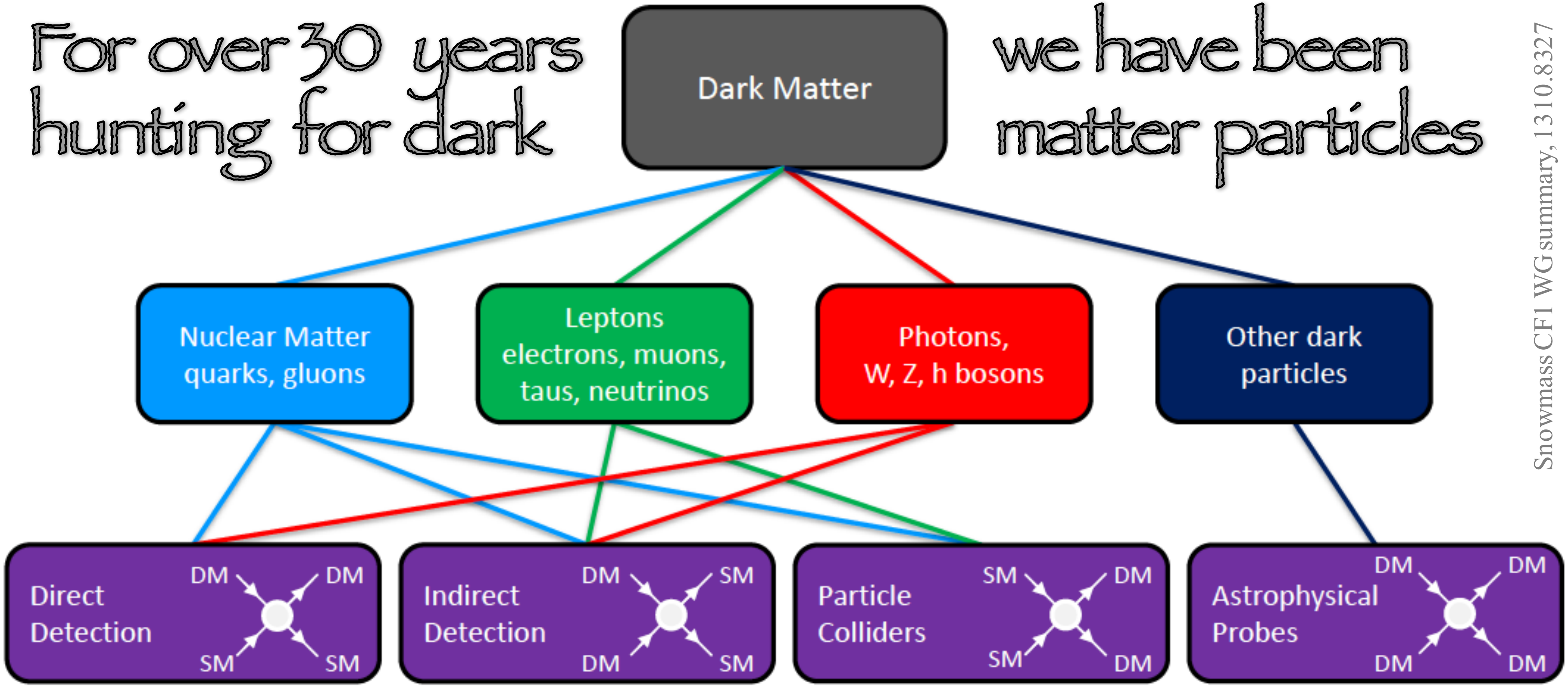


Subir Sarkar

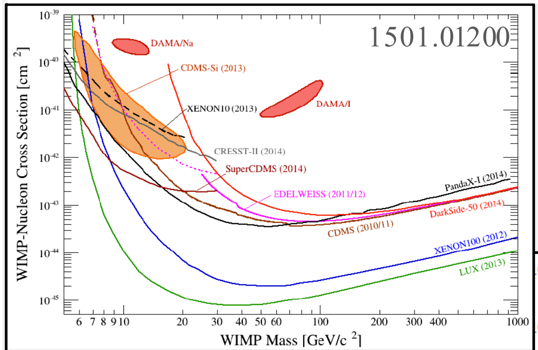
University of Oxford & NBI Copenhagen

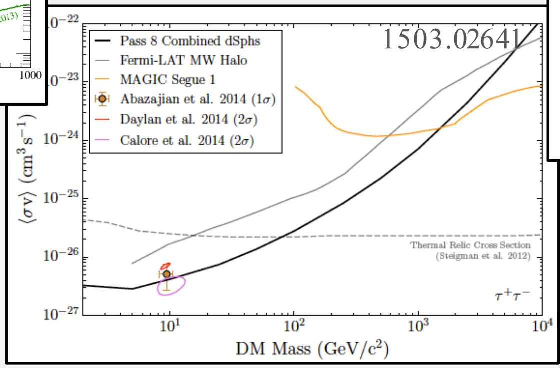
Axion-like particles: Theory and Experiment, Durham, 13-15 April 2016

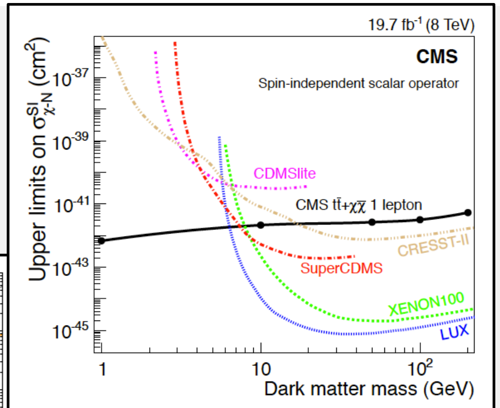
For over 30 years we have been hunting for dark matter particles



Snowmass CF1 WG summary, 1310.8327







From halo evaporation

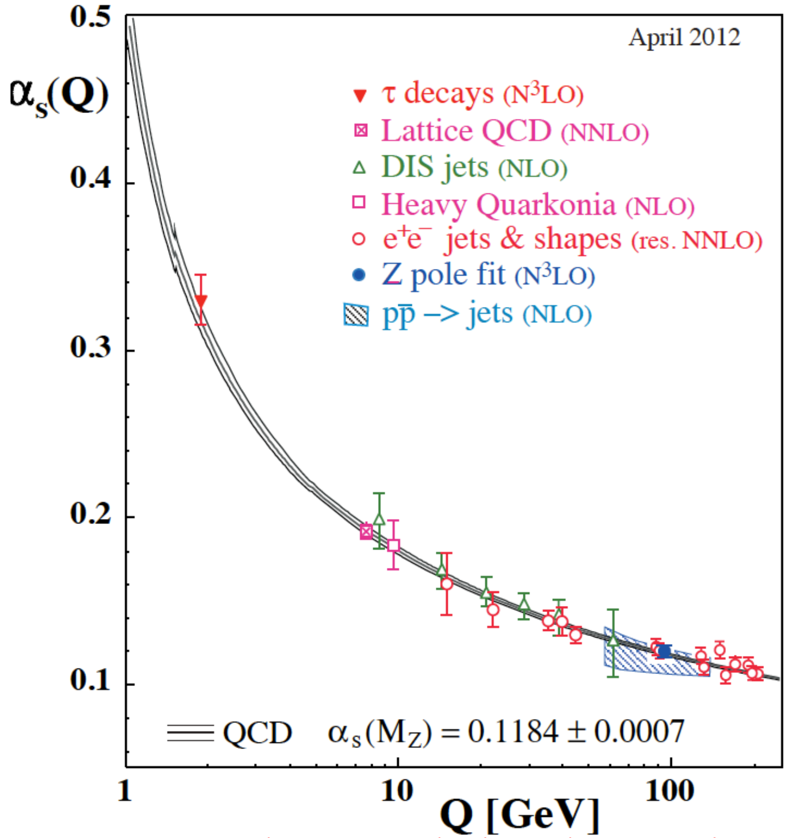
$\sigma/m_\chi < 0.7\ \mathrm{cm}^2/\mathrm{g}$

Randall *et al*, 0704.0261

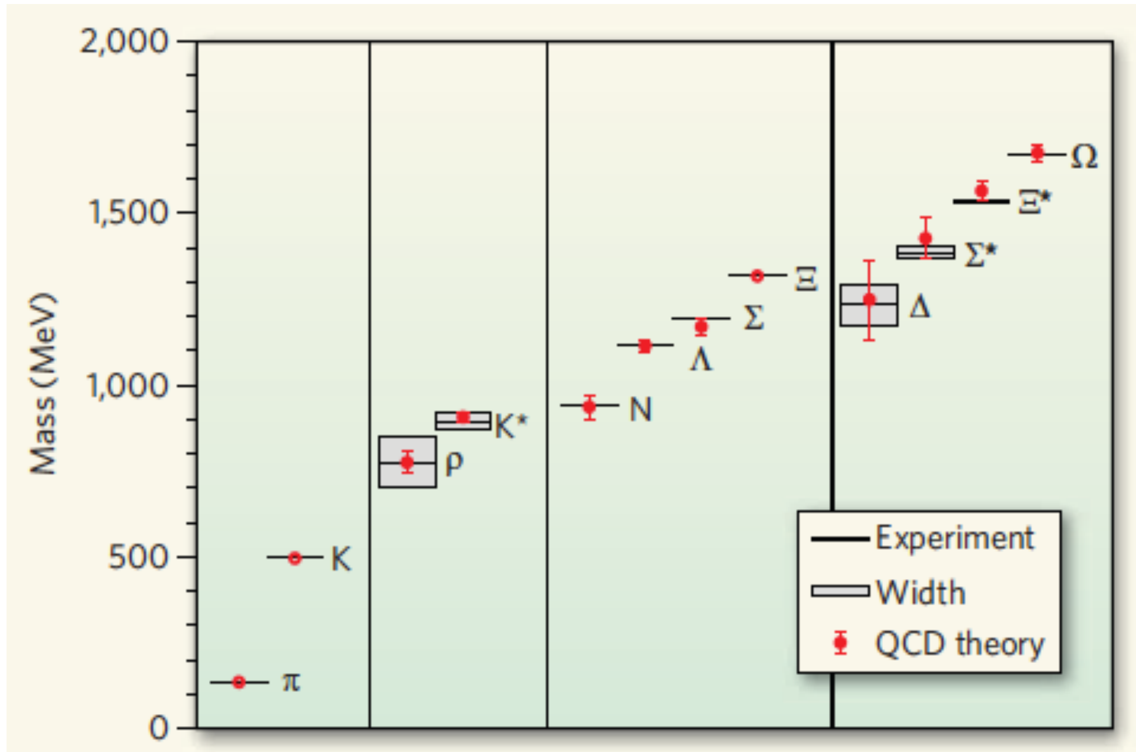
What should the world be made of?

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

But we cannot correctly predict the cosmological abundance of baryons!

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

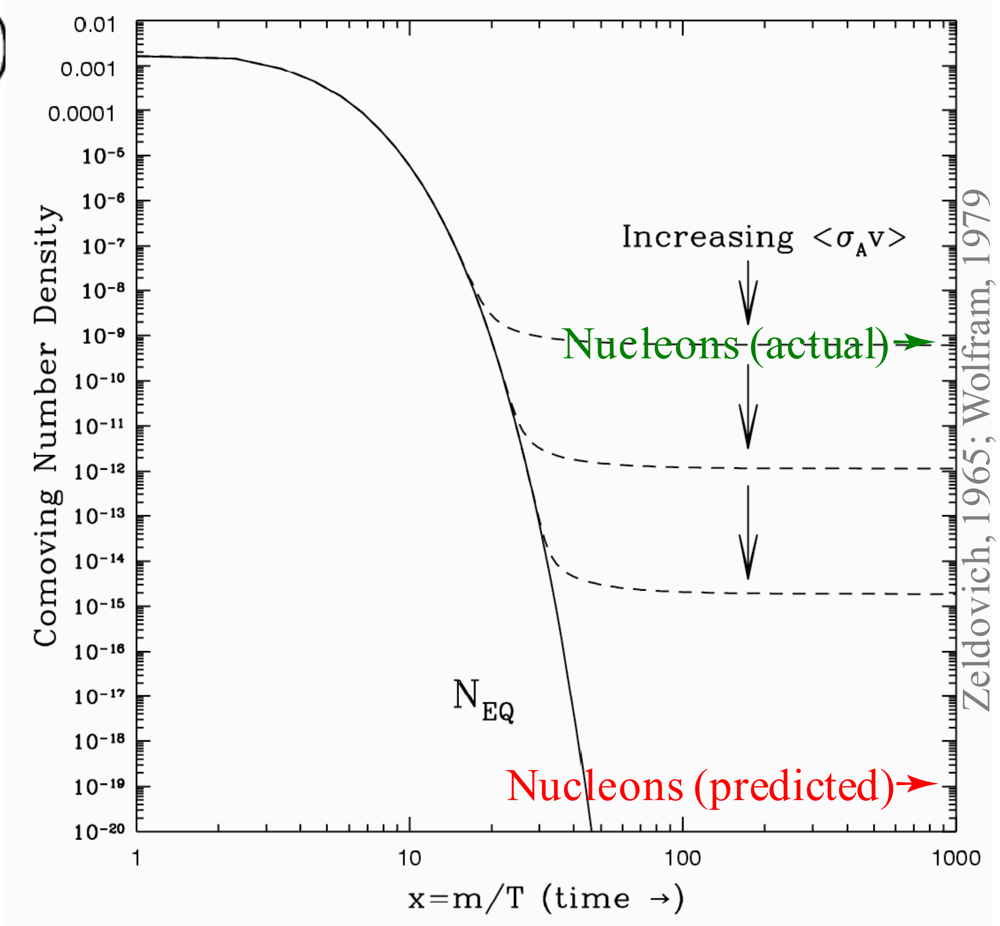
Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate

'Freeze-out' occurs when annihilation rate:

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

becomes comparable to the expansion rate

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



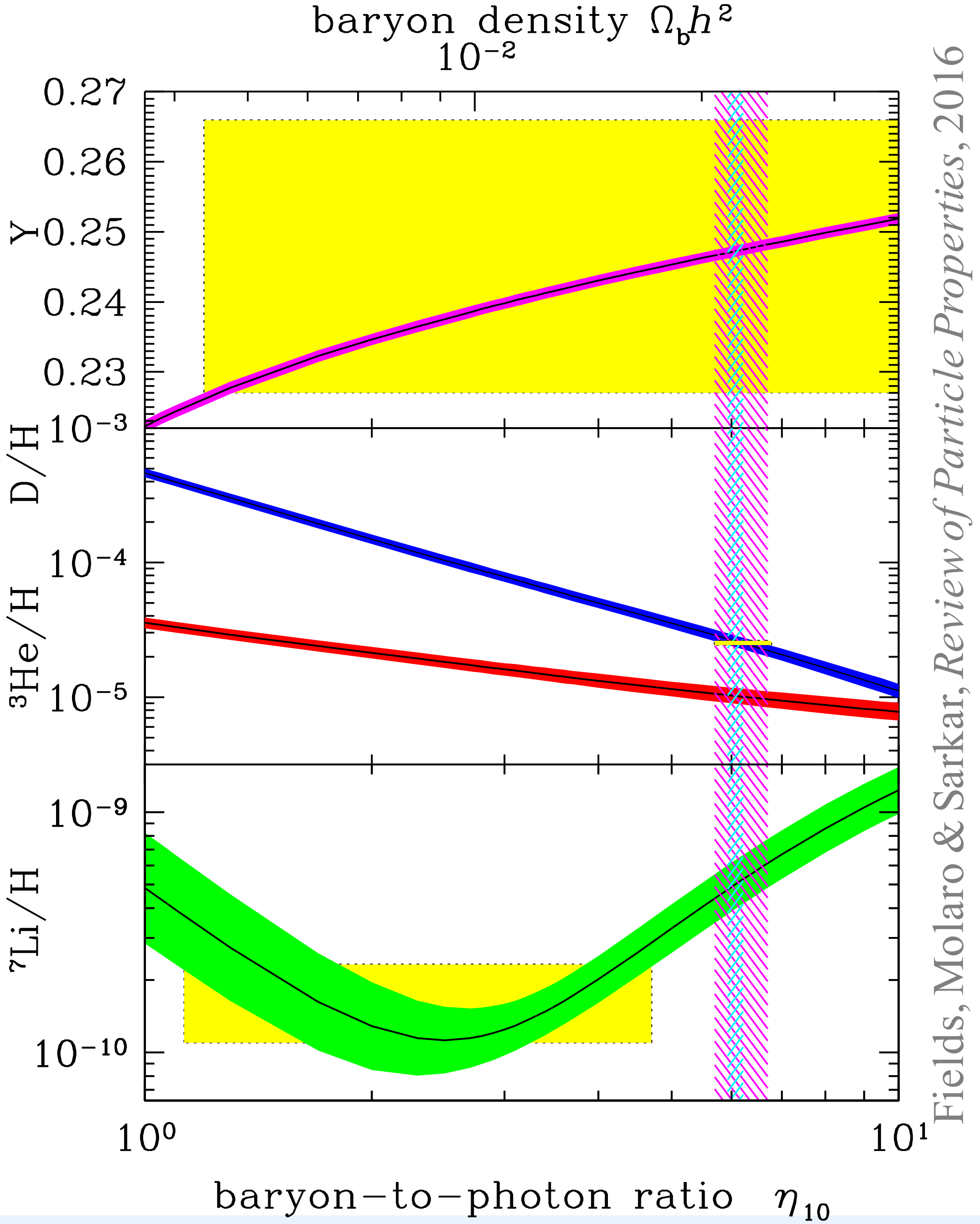
i.e. 'freeze-out' occurs at $T \sim m_N/45$, with: $$\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$$

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 do we 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

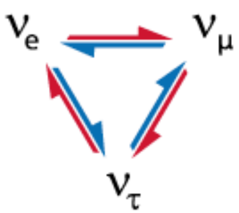
To make the baryon asymmetry requires *new* physics ('Sakharov conditions')

- *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 $SU(2)_L \times U(1)_Y$ breaking is *not* a 1st order phase transition

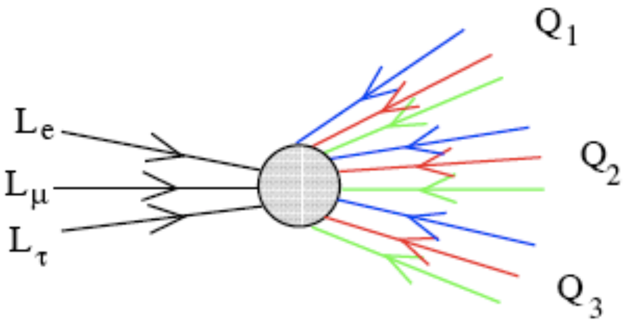
Hence the generation of the observed matter-antimatter asymmetry requires *new* BSM physics … can be related to the observed neutrino masses if these arise from *lepton number* violation → **leptogenesis**

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

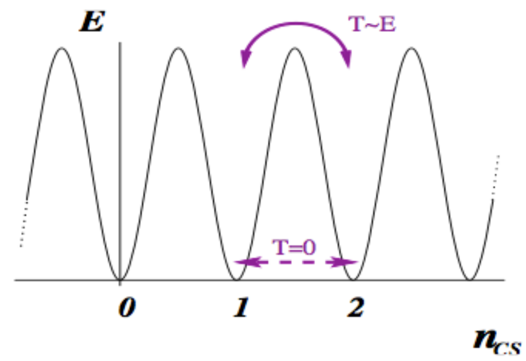


$$\Delta m^2_{atm} = m_3^2 - m_2^2 \simeq 2.6 \times 10^{-3}\mathrm{eV}^2 \qquad \Delta m^2_{\odot} = m_2^2 - m_1^2 \simeq 7.9 \times 10^{-5}\mathrm{eV}^2$$

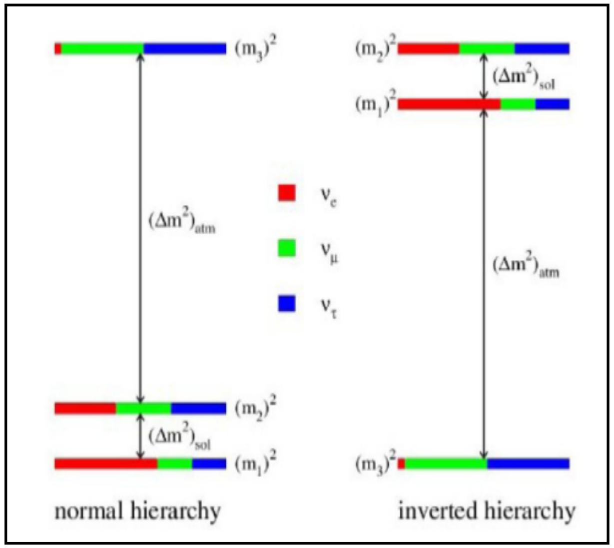
Asymmetric baryonic matter



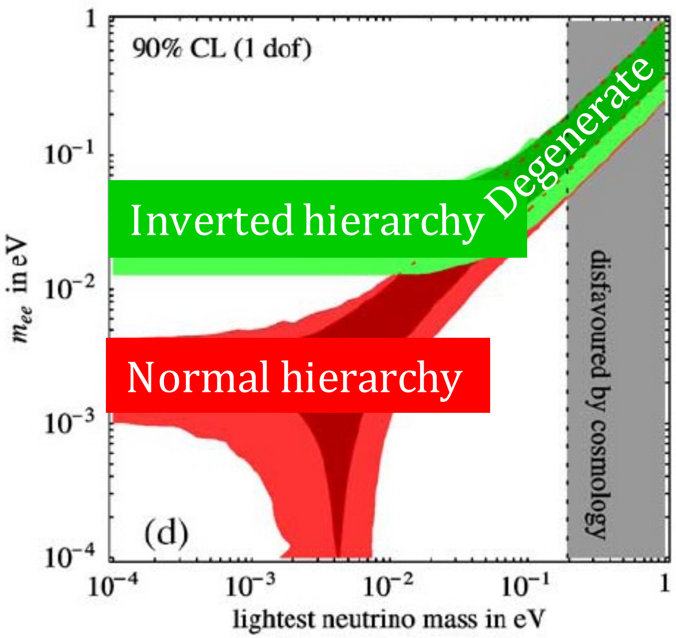
$$\partial_\mu j_i^\mu = \partial_\mu(\bar{\psi}^i \gamma^\mu \psi^i) = \frac{g^2}{8\pi} W^{a\mu\nu} \tilde{W}^a_{\mu\nu}$$



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**

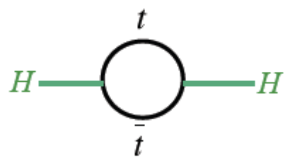


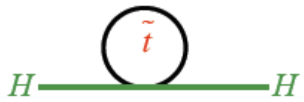
An essential requirement is that neutrino mass must be Majorana … test by detecting neutrino*less* double beta decay (and measuring the absolute neutrino mass scale)



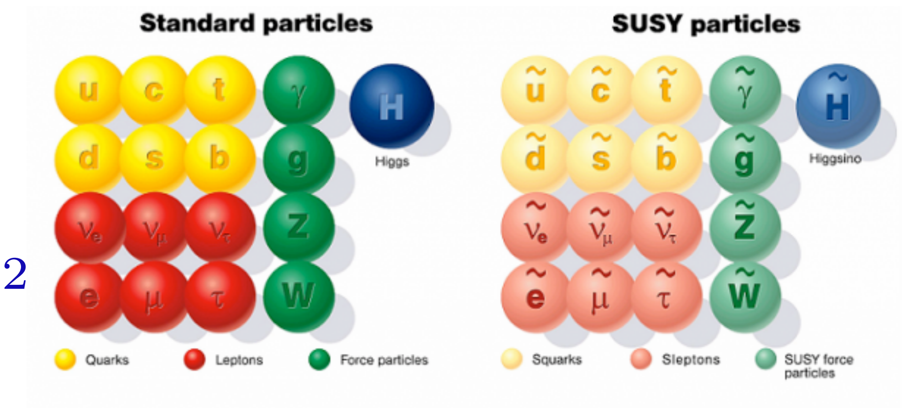
What *should* the world be made of?

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':

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

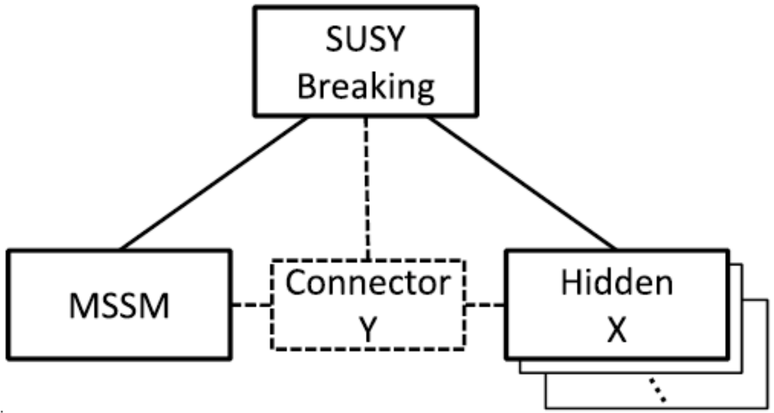
But why should a *thermal* relic have an abundance comparable to non thermal relic baryons?

What *should* the world be made of?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr	~~'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* for *p* stability)	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$

Hidden sector (GMSB) matter also provides the '*WIMPless* miracle' (Feng & Kumar, 0803.4196 see also: Boehm & Fayet, hep-ph/0305261)

… because: $g_h^2/m_h \sim g_\chi^2/m_\chi \sim F/16\pi^2 M$



Such dark matter can have *any* mass: ~0.1 GeV → ~few TeV

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

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

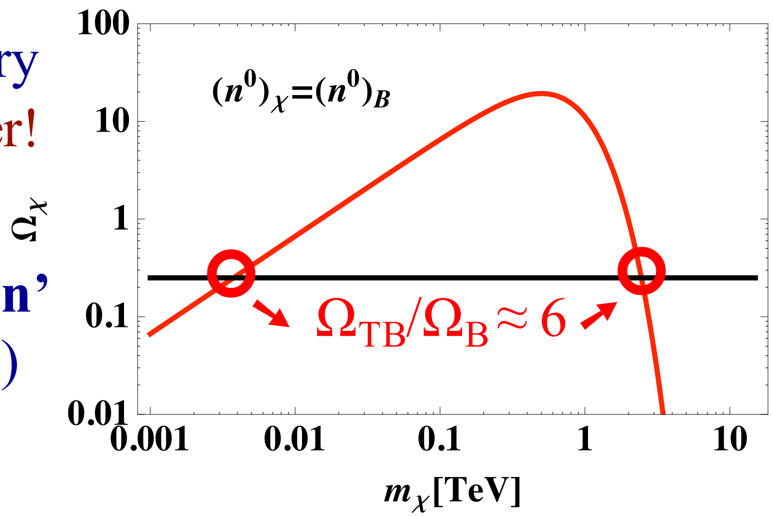
What *should* the world be made of ?

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

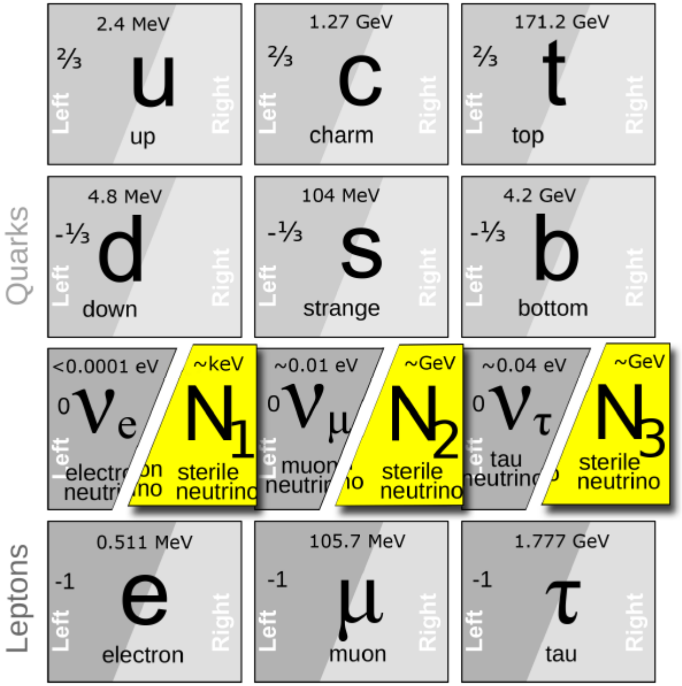
A new particle can naturally *share* in the *B*/*L* asymmetry if it couples to the *W* … linking dark to baryonic matter!

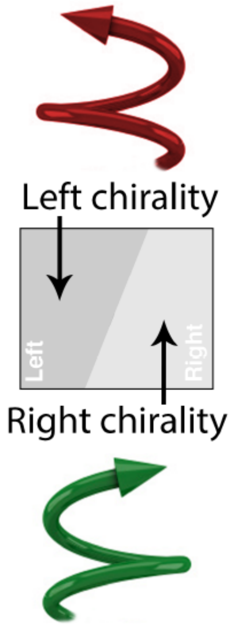
Then a *O*(TeV) mass **technibaryon** can be the dark matter … alternatively a ~few GeV mass **'dark baryon'** in a *hidden sector* (into which the technibaryon decays)

$$\Omega_\chi = (m_\chi/m_B)(n_\chi/n_B)\Omega_B$$



Sterile neutrino dark matter



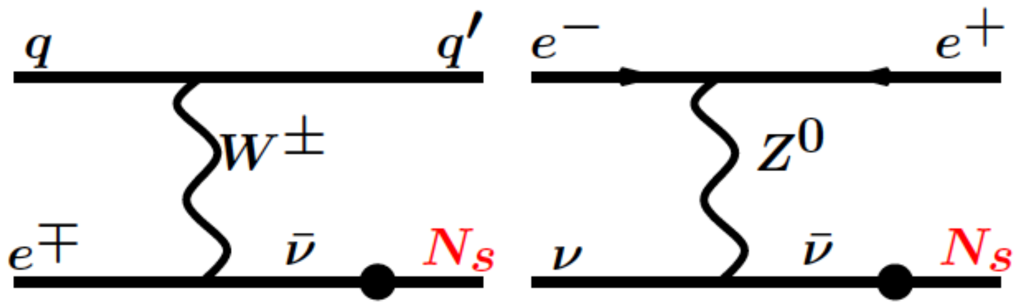


If they mix with the left-handed 'active' neutrinos then would behave as super-weakly interacting particles with an effective coupling: $\theta G_{\mathrm{Fermi}}$

$$\theta^2_{e,\mu,\tau} \equiv \frac{|M_{\mathrm{Dirac}}|^2}{|M_{\mathrm{Majorana}}|^2} = \frac{\mathcal{M}_{\mathrm{active}}}{\mathcal{M}_{\mathrm{sterile}}}$$

$$\approx 5 \times 10^{-5} \left(\frac{\mathcal{M}_{\mathrm{sterile}}}{\mathrm{KeV}}\right)^{-1}$$

So they will be created when active neutrinos scatter, at a rate $\propto \theta^2 \Gamma_{\mathrm{active}}$



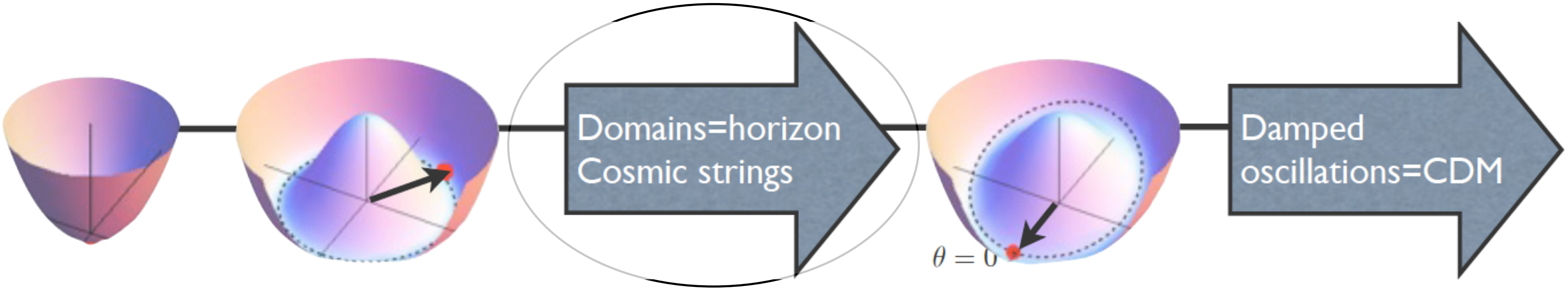
Hence although they may never come into equilibrium, the relic abundance will be of order the dark matter for a mass of order KeV (however there is no *natural* motivation for such a mass scale)

Axion dark matter

$$\mathcal{L}_{\rm eff} = F^2 + \bar{\Psi}\, \not{D}\Psi + \bar{\Psi}\Psi\Phi + (D\Phi)^2 + \Phi^2 \quad \boxed{+\theta_{\rm QCD} F\tilde{F}}$$

The SM admits a term which would lead to *CP* violation in strong interactions, hence an (unobserved) electric dipole moment for neutrons → requires $\theta_{\rm QCD} < 10^{-10}$

To achieve this without fine-tuning, $\theta_{\rm QCD}$ must be made a dynamical parameter, through the introduction of a new $U(1)_{\rm Peccei\text{-}Quinn}$ symmetry which must be broken … the resulting (pseudo) Nambu-Goldstone boson is the QCD **axion** which later acquires a small mass through its mixing with the pion (the pNGB of QCD): $m_a = m_\pi\, (f_\pi/f_{\rm PQ})$



Javier Redondo

When the temperature drops to $\Lambda_{\rm QCD}$ the axion potential turns on and the coherent oscillations of relic axions contain energy density that behaves like cold dark matter with $\Omega_a h^2 \sim 10^{11}\ {\rm GeV}/f_{\rm PQ}$ … however the *natural* P-Q scale is probably $f_{\rm PQ} \sim 10^{18}$ GeV

Hence QCD axion dark matter would need to be *significantly diluted*, i.e. its relic abundance is not predictable (or seek anthropic explanation for why $\theta_{\rm QCD}$ is small?)

What *should* the world be made of?

Mass scale	Lightest stable particle	Symmetry/ Quantum #	Stability ensured?	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr	~~'Freeze-out' from equilibrium~~ Asymmetric baryogenesis	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{QCD'} \sim 6\Lambda_{QCD}$	Dark baryon?	$U(1)_{DB}$	plausible	Asymmetric (like *observed* baryons)	$\Omega_{DB} \sim 0.3$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity	violated?	'freeze-out' from equilibrium	$\Omega_{LSP} \sim 0.3$
	Technibaryon?	(walking) Techni-colour	$\tau \sim 10^{18}$ yr	Asymmetric (like observed baryons)	$\Omega_{TB} \sim 0.3$
$\Lambda_{hidden\ sector} \sim (\Lambda_F M_P)^{1/2}$	Crypton? hidden valley?	Discrete symmetry (very model-dependent)	$\tau \gtrsim 10^{18}$ yr	Varying gravitational field during inflation	$\Omega_X \sim 0.3$?
$\Lambda_{see\text{-}saw} \sim \Lambda_{Fermi}^2/\Lambda_{B\text{-}L}$	**Neutrinos**	Lepton number	Stable	Thermal (abundance ~ CMB photons)	$\Omega_\nu > 0.003$
M_{string}/M_{Planck}	Kaluza-Klein states?	?	?	?	?
	Axions	Peccei-Quinn	Stable	Field oscillations	$\Omega_a \gg 1$!

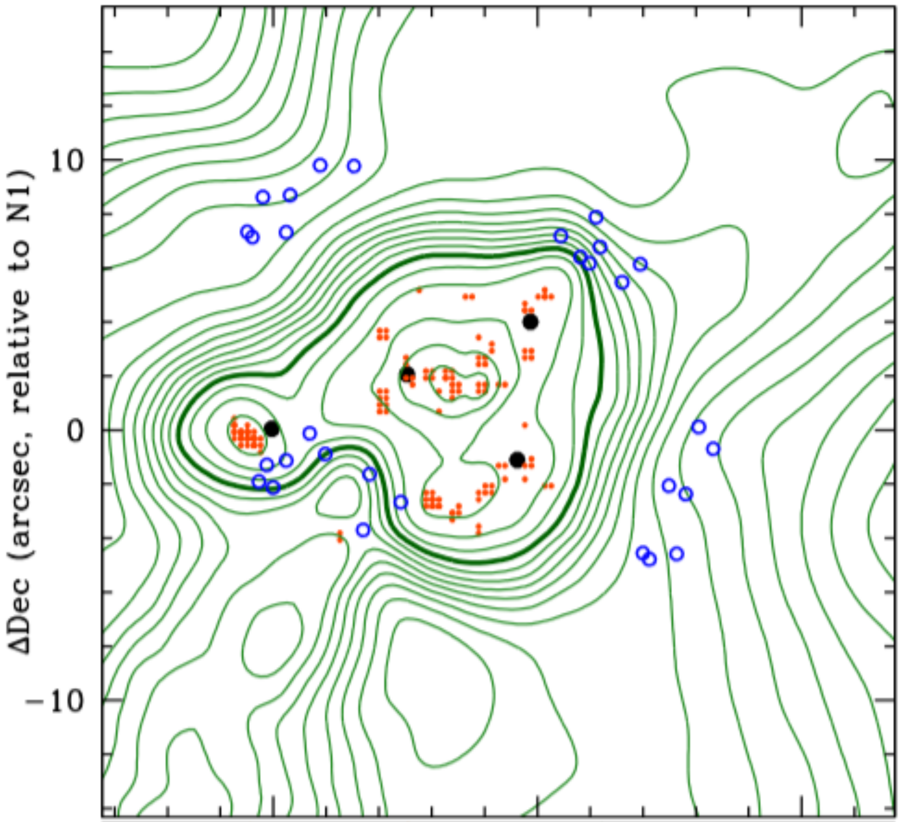
No definite indication from theory
must decide by experiment!

But Nature may hold a surprise – dark matter may be strongly self-interacting!

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 $\sigma/m=(1.7\pm0.7)\times10^{-4}\ \mathrm{cm^2/g}\ (t/10^9\mathrm{yr})^{-2}$ where *t* is the infall duration**."



Evidence for SIDM in A3827?

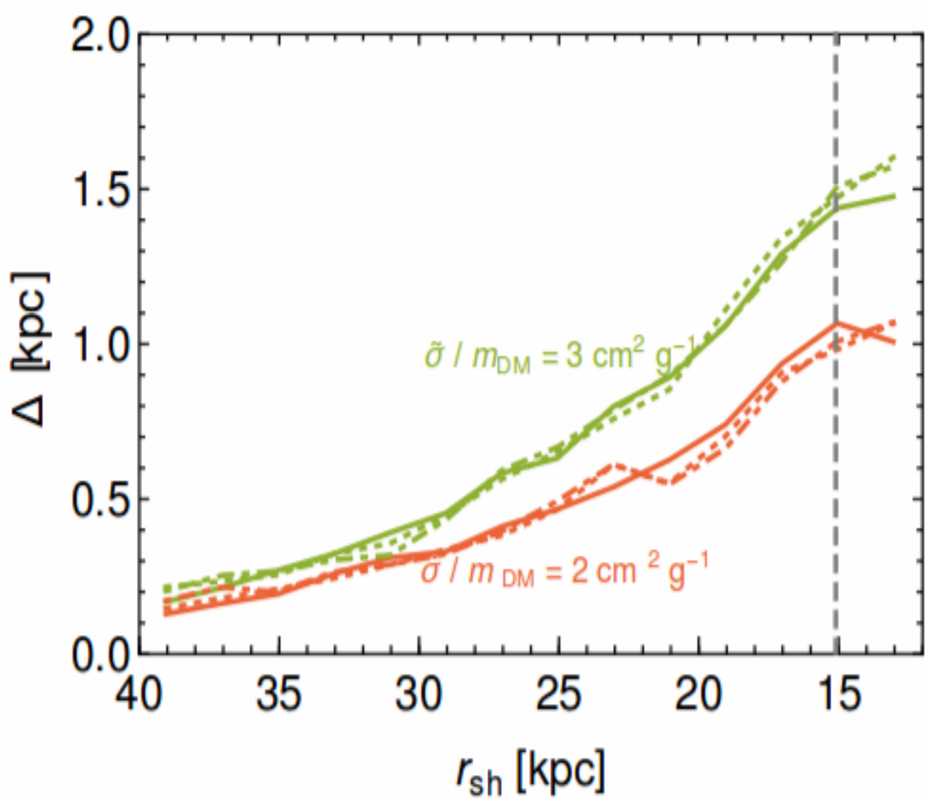
However this numerical value is based on two *incorrect* assumptions:

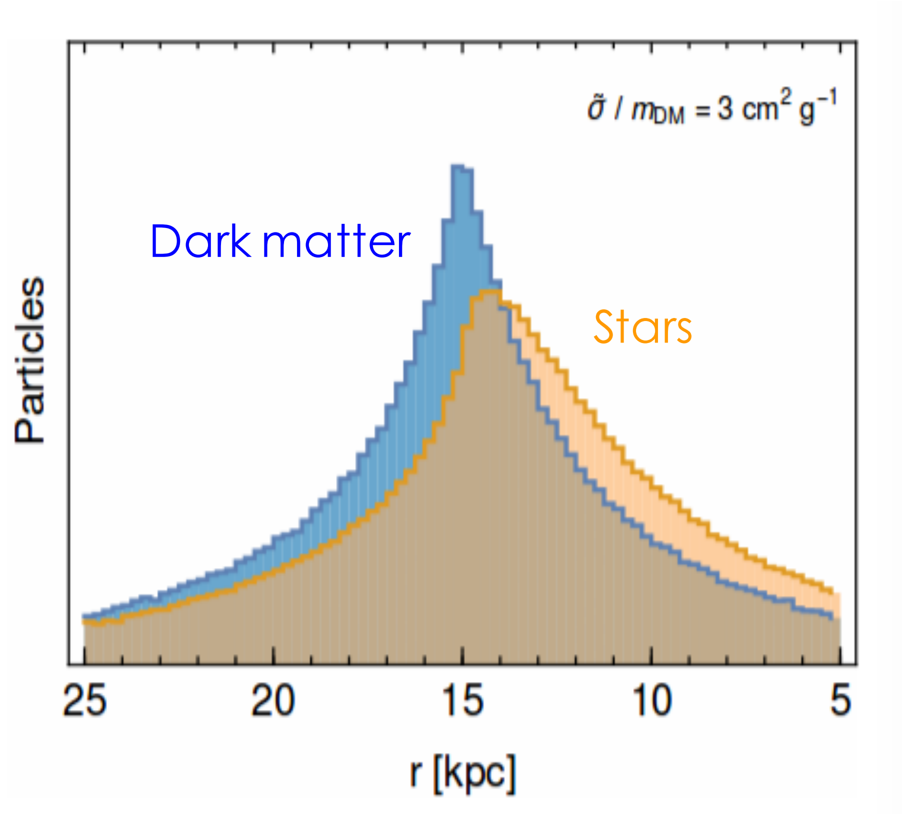
- The stars and the DM subhalo are assumed to develop completely *independently*, i.e. even a tiny difference in the acceleration can lead to sizeable differences in their trajectories.
  - But initially the stars are *gravitationally bound* to the DM subhalo so can be separated from it only if external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

To include these refinements requires a fully 3-D simulation (which we had developed to study the Bullet Cluster: Kahlhoefer *et al*, 1308.3419)

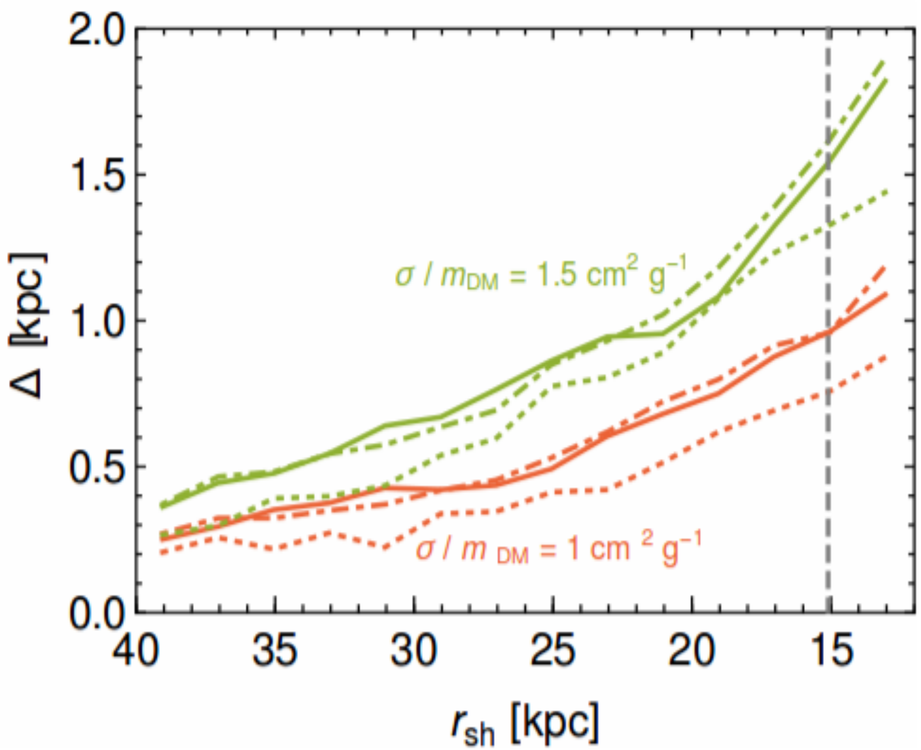
For long-range interactions via 'dark photons' (or Yukawa interactions via light mediators) there are many soft scatterings … peaked forward!

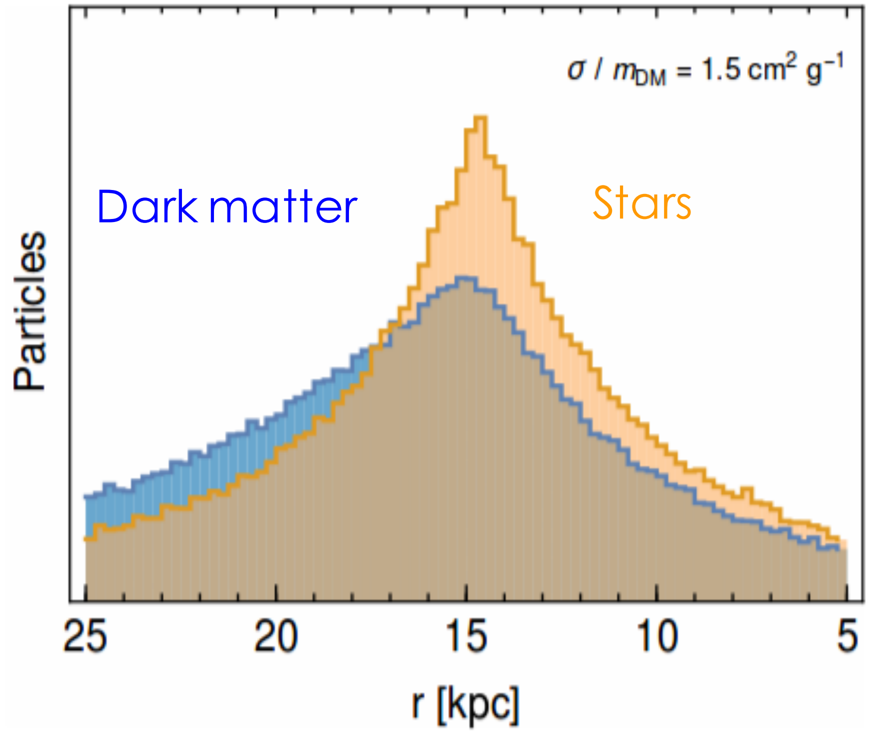




- The peaks of the dark matter and star distributions are slightly shifted
- The tail of the star distribution is enhanced in the forward direction due to stars that have escaped from the grav. potential of the halo
- The #-section needed to get a separation of 1.5 kpc is $\sigma/m_\chi \sim 3$ cm^2/g

But for **contact interactions**, most dark matter particles will *not* scatter so will behave just like (collisionless) stars … however when a scattering does occur the particle is likely to escape from the halo in the *backward* direction – leading to an apparent separation from the stars





- The separation is due to differences in the *shapes* of the dark matter and stellar distributions, while the peaks remain *coincident*

- The cross section required to obtain a separation of 1.5 kpc is now: $\sigma/m_\chi \sim 1.5$ cm^2/g

Conclusions

- For 3 decades searches for dark matter have focussed on WIMPs but dark matter may be neither weakly interacting nor massive (and perhaps not even a particle)!

- While nuclear recoil experiments continue to optimise for weak scale mass particles, collider (monojet) searches are sensitive to much lighter particles which are just as well motivated!

- If dark matter $\Longrightarrow$ coherent oscillations of axions then rather different search strategies are required

- 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* true, would be the most significant step forward in understanding the nature of dark matter!