Discovering dark matter

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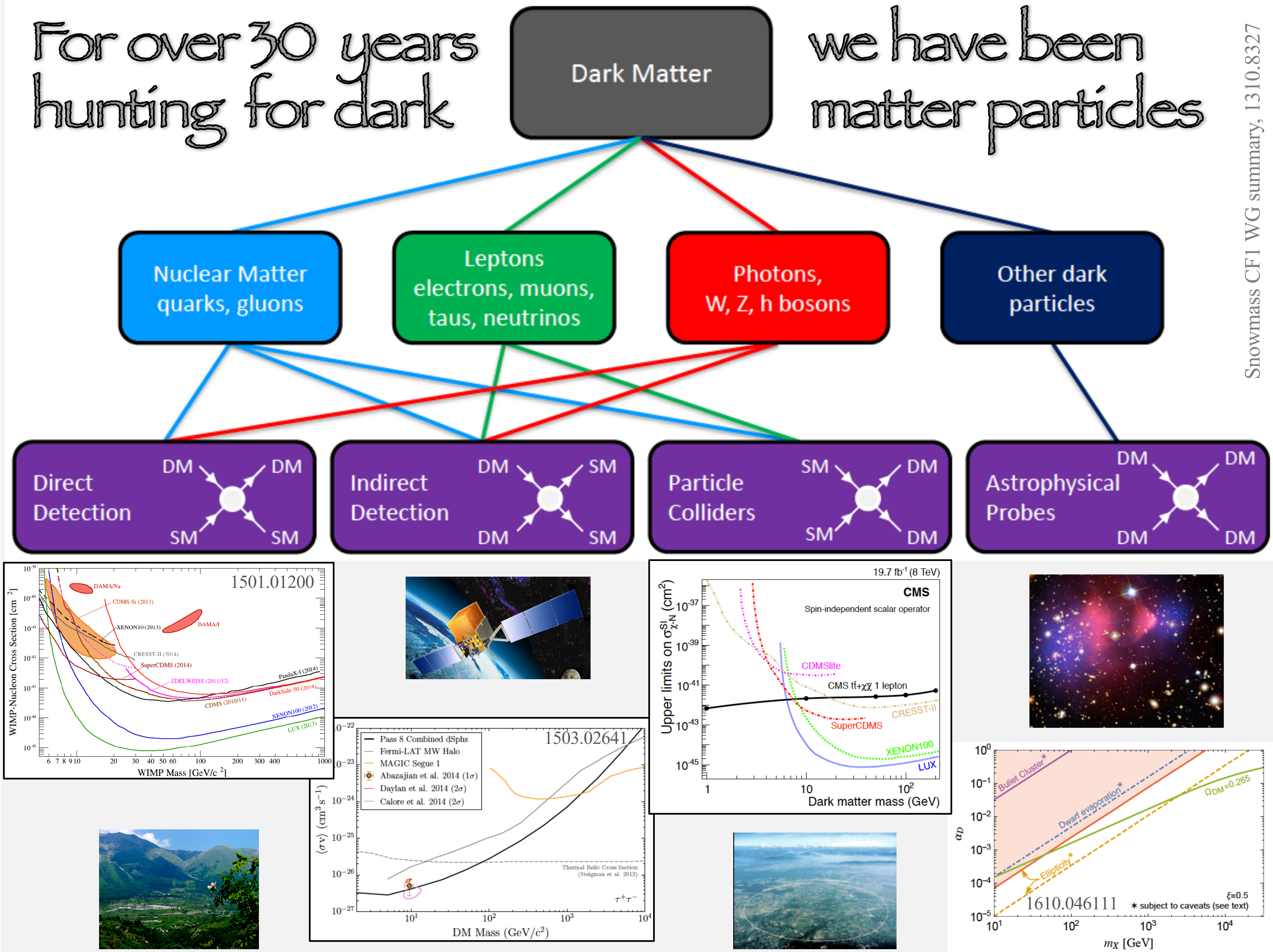
Dark matter from aeV to ZeV: 3rd IBS-Multidark-IPPP workshop, Lumley Castle, 21-25 Nov 2016

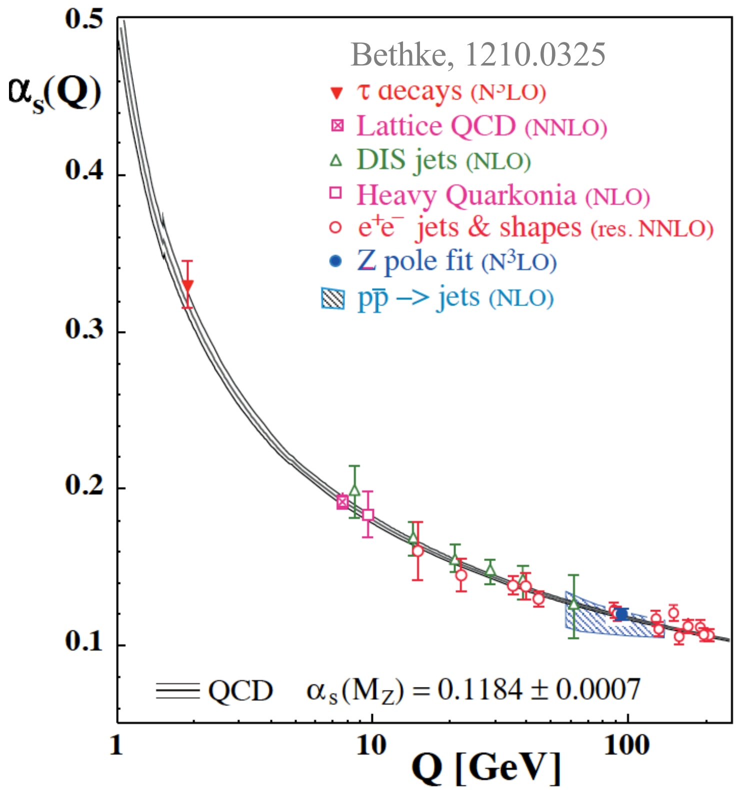


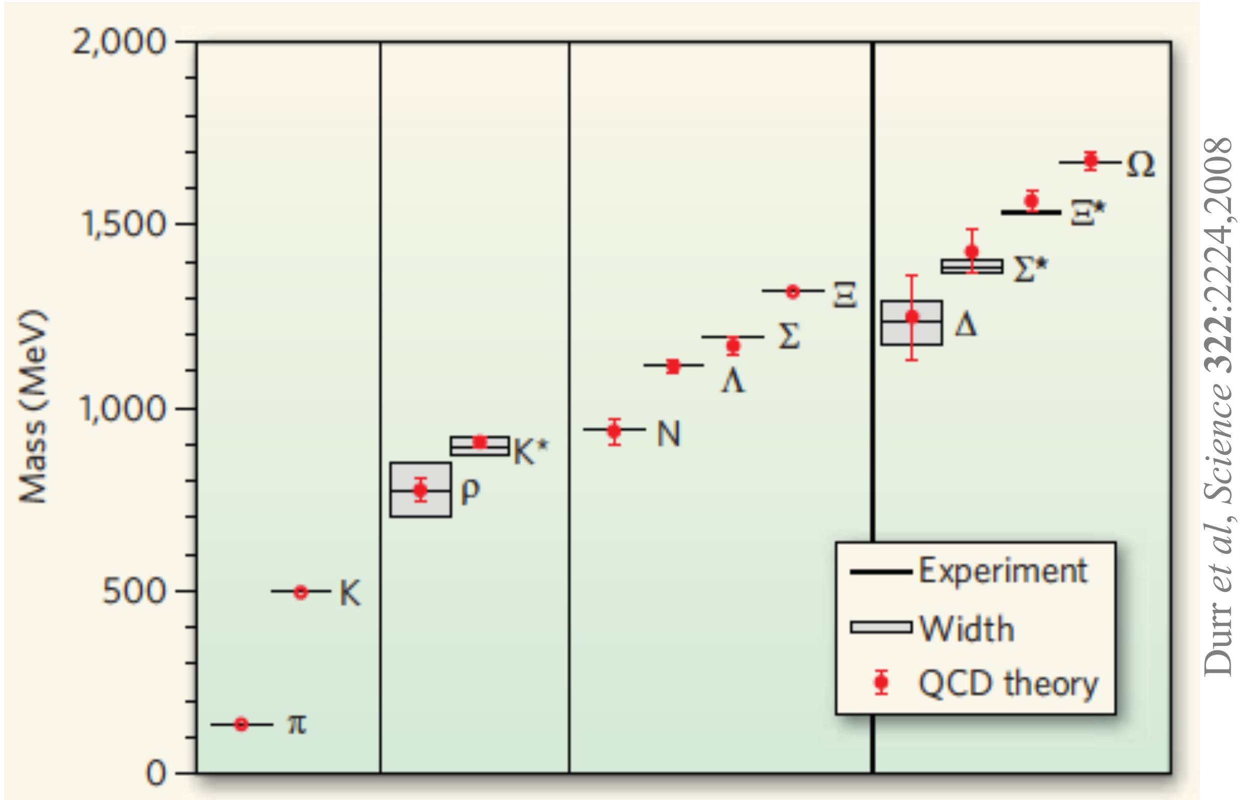
For over 30 years we have been hunting for dark matter particles
Dark Matter
Nuclear Matter quarks, gluons
Leptons electrons, muons, taus, neutrinos
Photons, W, Z, h bosons
Other dark particles
Direct Detection
DM DM SM SM
Indirect Detection
DM SM DM SM
Particle Colliders
SM DM SM DM
Astrophysical Probes
DM DM DM DM
Snowmass CF1 WG summary, 1310.8327
1501.01200
WIMP-Nucleon Cross Section [cm²]
WIMP Mass [GeV/c²]
1503.02641
DM Mass (GeV/c²)
Pass 8 Combined dSphs
Fermi-LAT MW Halo
MAGIC Segue 1
Thermal Relic Cross Section
19.7 fb⁻¹ (8 TeV)
CMS
Spin-independent scalar operator
Dark matter mass (GeV)
CDMSlite
SuperCDMS
CRESST-II
XENON100
LUX
1610.046111
Bullet Cluster
Dwarf evaporation
Ellipticity
* subject to caveats (see text)

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





We understand the dynamics (QCD) … and can even calculate the mass spectrum

Yet we get the predicted relic thermal abundance of baryons badly *wrong*!

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

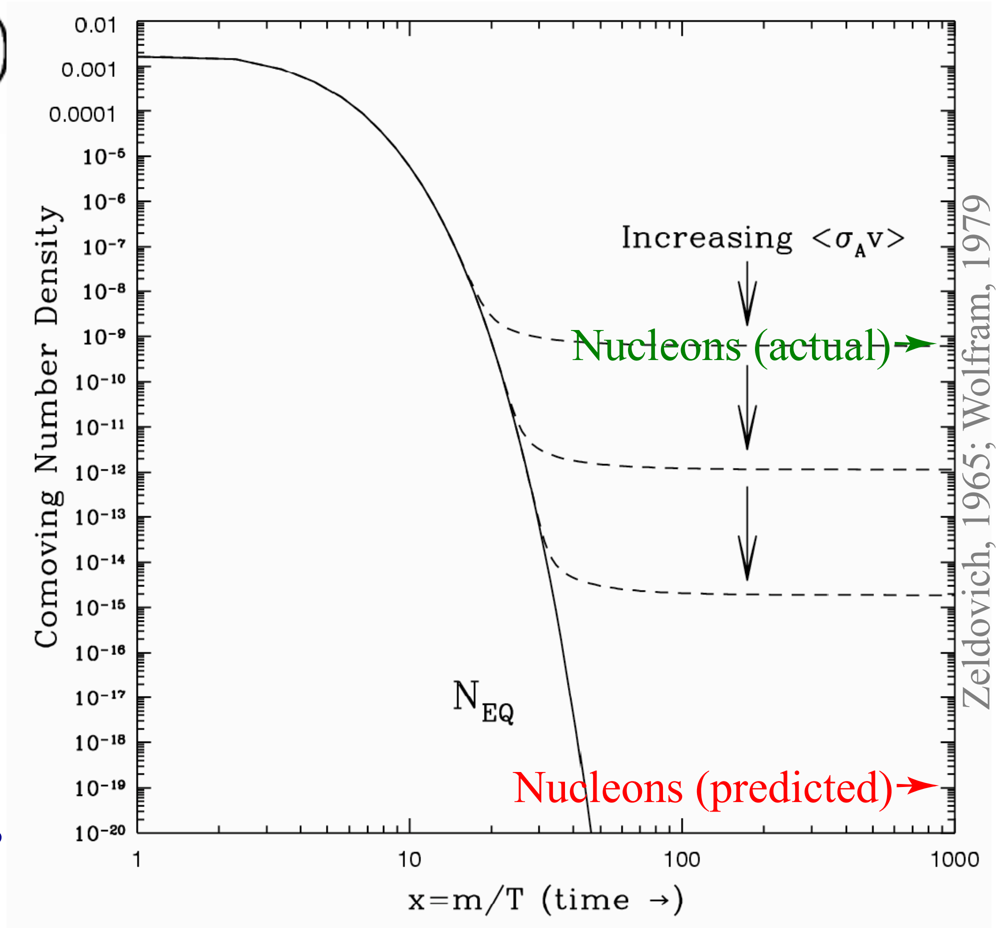
Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate

'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



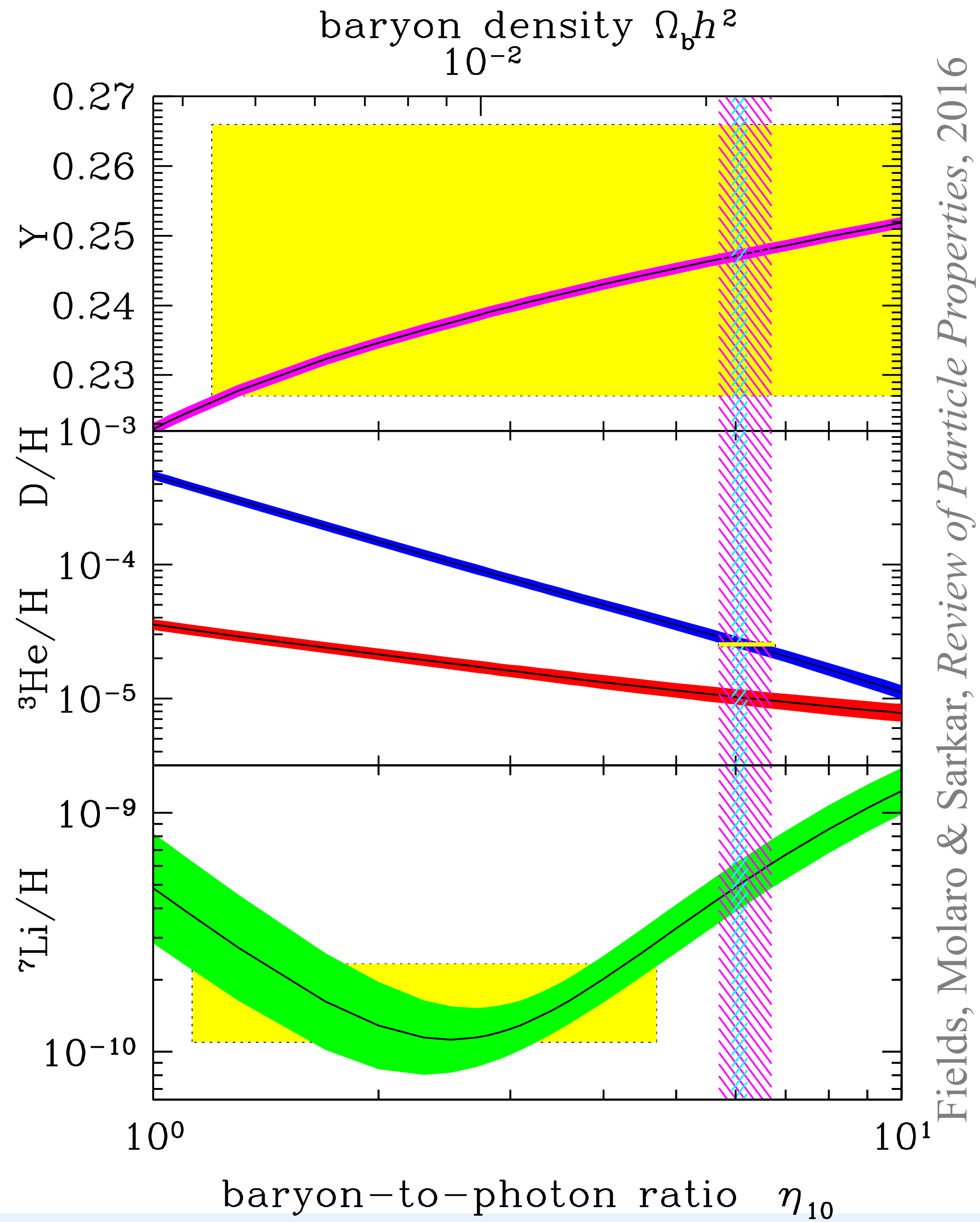
i.e. 'freeze-out' occurs at $T \sim m_N/45$, with: $\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$

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 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

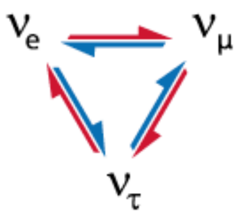
To make the baryon asymmetry requires *new* physics ('Sakharov conditions')

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

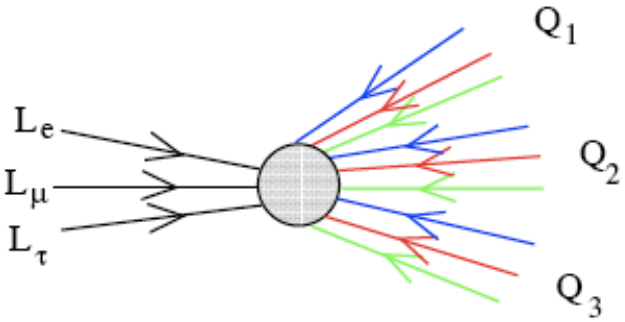
Hence the generation of the observed matter-antimatter asymmetry requires *new* BSM physics … can be related to the observed neutrino masses if these arise from *lepton number* violation → **leptogenesis**

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

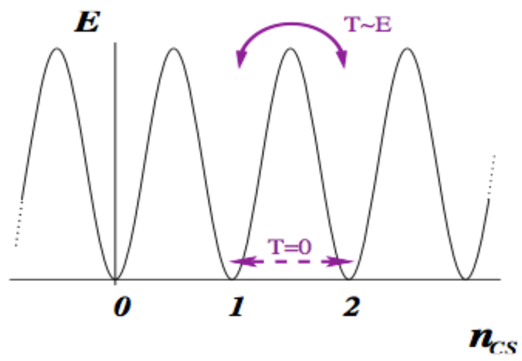


$\Delta m^2_{atm} = m_3^2 - m_2^2 \simeq 2.6 \times 10^{-3}\mathrm{eV}^2$ $\qquad \Delta m^2_\odot = m_2^2 - m_1^2 \simeq 7.9 \times 10^{-5}\mathrm{eV}^2$

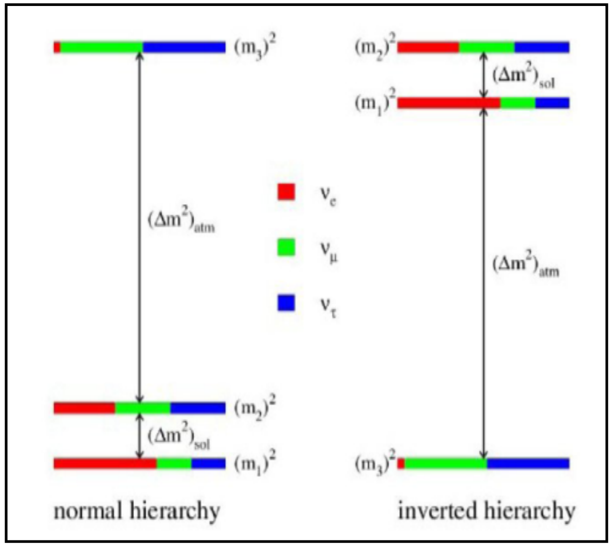
Asymmetric baryonic matter



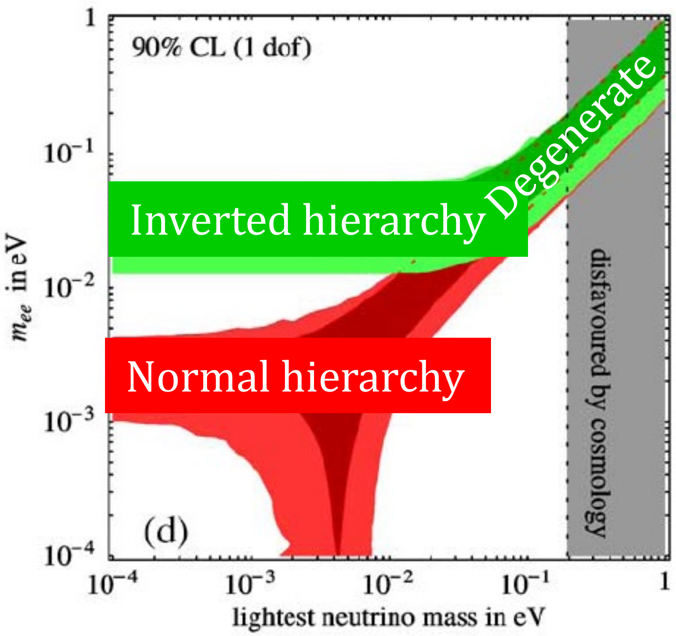
$$\partial_\mu j_i^\mu = \partial_\mu(\bar{\psi}^i \gamma^\mu \psi^i) = \frac{g^2}{8\pi} W^{a\mu\nu} \tilde{W}^a_{\mu\nu}$$



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**

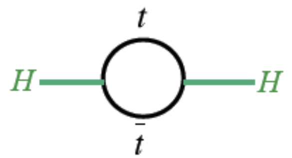


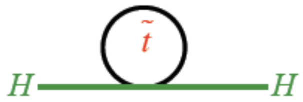
An essential requirement is that neutrino mass must be *Majorana* … test by detecting neutrino*less* double beta decay (and measuring the absolute neutrino mass scale)

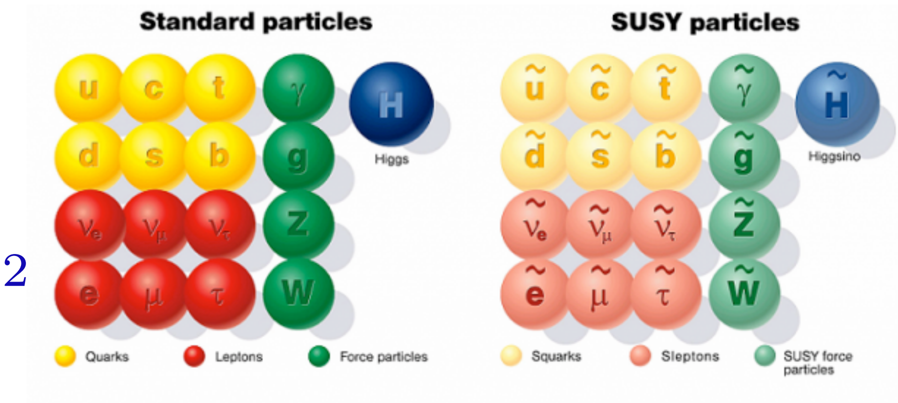


What *should* the world be made of?

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







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

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?

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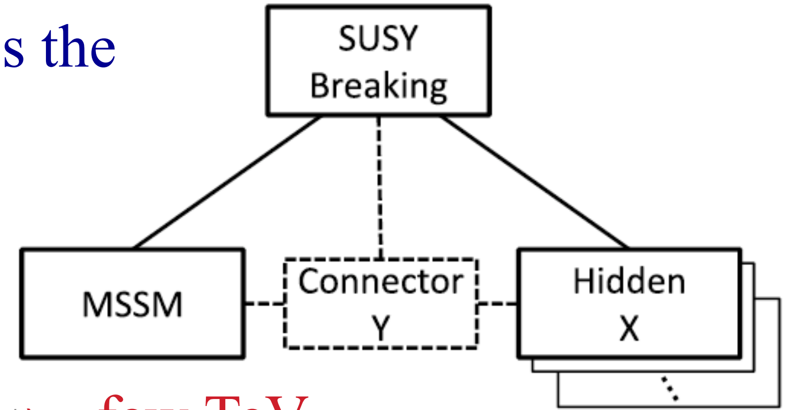
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	*R*-parity?	Violated? (matter parity *adequate* for *p* stability)	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$

Hidden sector (e.g. GMSB) matter also provides the 'WIMP*less* miracle' (Feng & Kumar, 0803.4196)

… 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: sub-GeV → ~few TeV

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

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

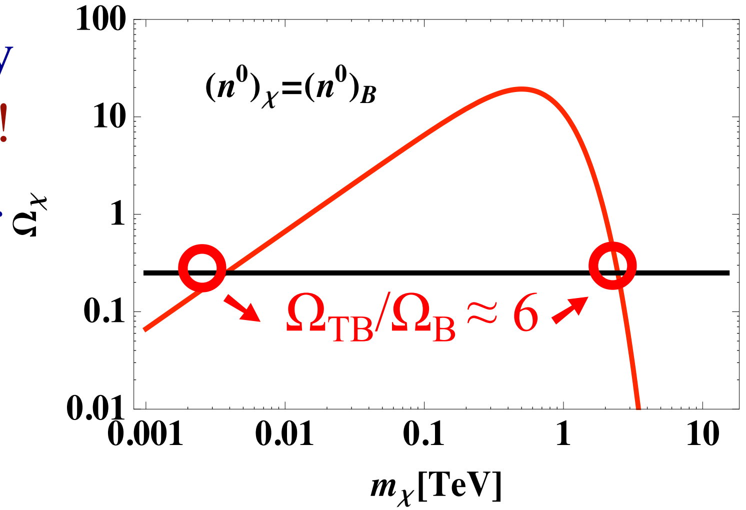
What *should* the world be made of ?

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)	$\Omega_{TB} \sim 0.3$

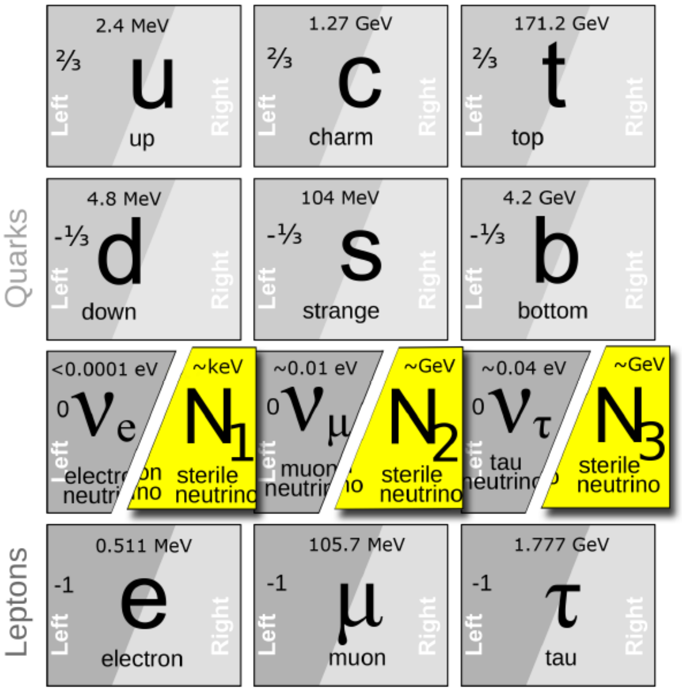
A new particle can naturally *share* in the *B/L* asymmetry if it couples to the *W* … linking dark to baryonic matter!

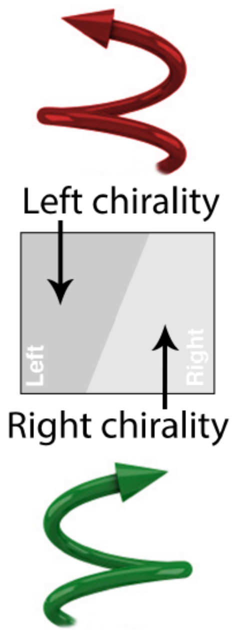
So a *O*(TeV) mass **technibaryon** can be the dark matter … alternatively a ~few GeV mass **'dark baryon'** in a *hidden sector* (e.g. into which the technibaryon decays)

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



Sterile neutrino dark matter

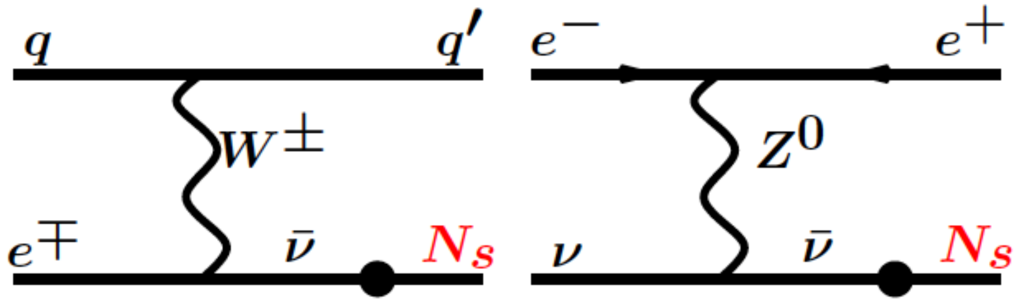




If they mix with the left-handed 'active' neutrinos then would behave as super-weakly interacting particles with an effective coupling: $\theta G_{\mathrm{Fermi}}$

$$\theta^2_{e,\mu,\tau} \equiv \frac{|M_{\mathrm{Dirac}}|^2}{|M_{\mathrm{Majorana}}|^2} = \frac{\mathcal{M}_{\mathrm{active}}}{\mathcal{M}_{\mathrm{sterile}}} \approx 5 \times 10^{-5} \left(\frac{\mathcal{M}_{\mathrm{sterile}}}{\mathrm{KeV}}\right)^{-1}$$

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)

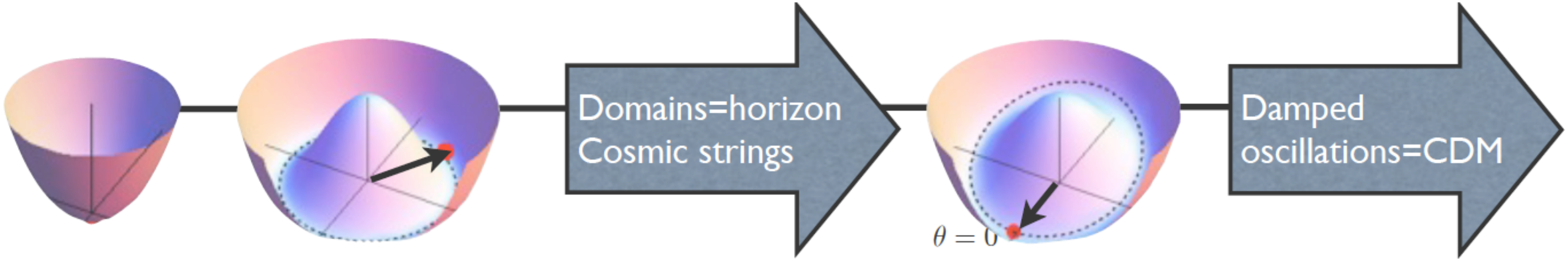
Axion dark matter

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

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

$\theta_{\rm QCD}$ must be made a *dynamical* parameter, by introducing a $U(1)_{\text{Peccei-Quinn}}$ symmetry which must be broken … the resulting (pseudo) Nambu-Goldstone boson is the QCD **axion** which acquires a small mass through its mixing with the pion: $m_a = m_\pi\,(f_\pi/f_{\rm PQ})$

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 $M_{\rm string} \sim 10^{18}$ 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?)

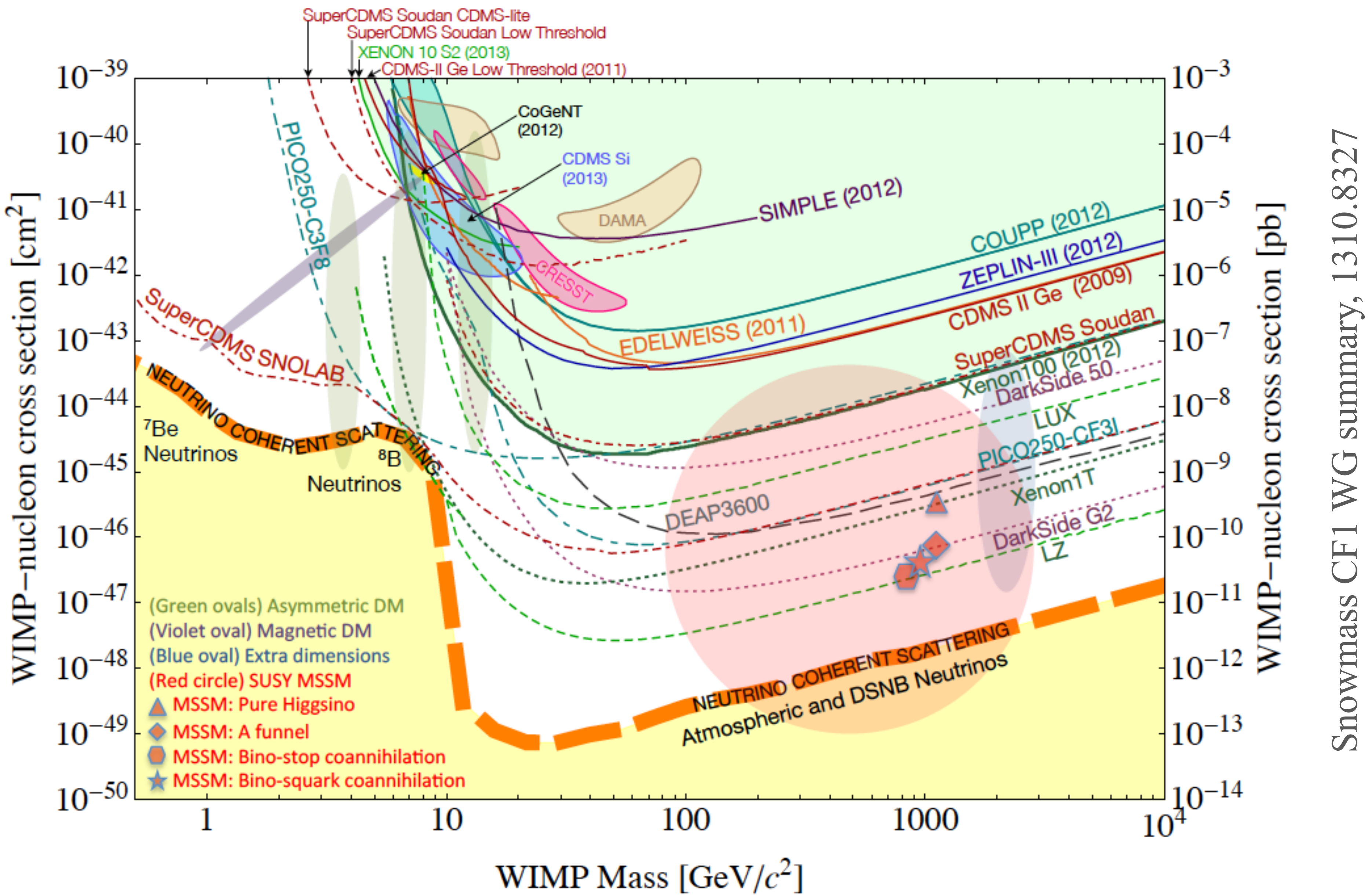
Many other possibilities for 'axion-like particles' … over a very large range of mass scales

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!

Direct detection has focussed on WIMPs, so is most sensitive at ~weak scale



Several claims for putative signals have apparently been ruled out by more sensitive experiments … but are we making a fair comparison?

There are many ambiguities in interpreting the measured recoil rate:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R}(E_R,t) = M_{\mathrm{tar}}\frac{\rho_\chi}{2\,m_\chi\mu^2}\frac{(f_p Z + f_n(A-Z))^2}{f_n^2}\sigma_n F^2(E_R)\int_{v_{\mathrm{min}}}^{\infty}\mathrm{d}^3v\,\frac{f_{\mathrm{local}}(\vec{v},t)}{v}$$

Nuclear physics

Particle physics

astrophysics

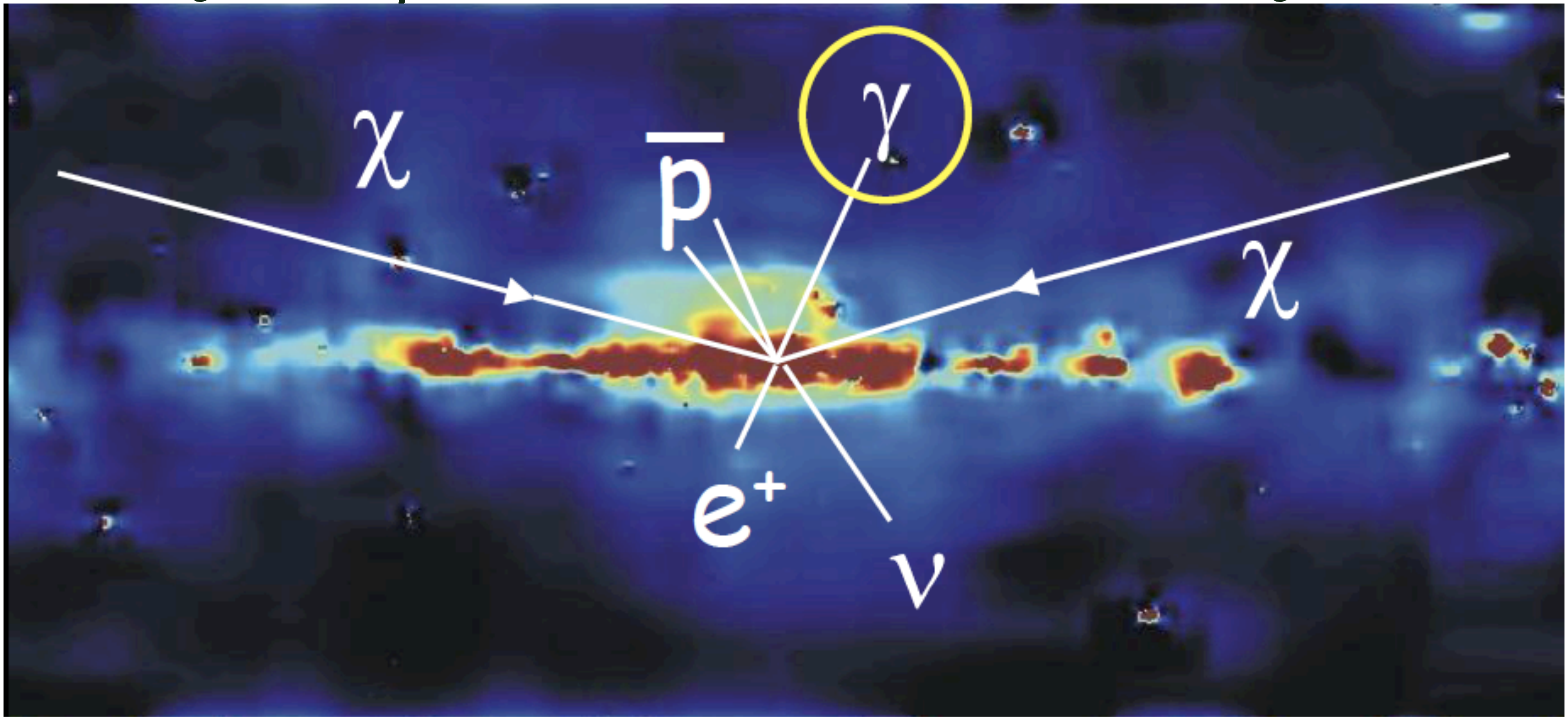
★ Dark matter interacts *differently* with neutrons & protons (Giulani, hep-ph/0504157) if the mediator is a (new) vector boson … so e.g. the events seen by CDMS-Si *can be* consistent with the upper limits set by XENON100 or LUX

★ Moreover different experiments are sensitive to different regions of the (uncertain) dark matter velocity distribution, hence apparently inconsistent results (e.g. CoGeNT and DAMA) can be reconciled by departing from the *assumed* isotropic Maxwellian form (Fox *et al*, 1011.1915, Frandsen *et al,* 1111.0292, Del Nobile *et al*, 1306.5273)

★ Then there are experimental uncertainties (instrumental backgrounds, efficiencies, energy resolution) + uncertainties in translating measured energies into recoil energies (channelling, quenching) + uncertain nuclear form factors …

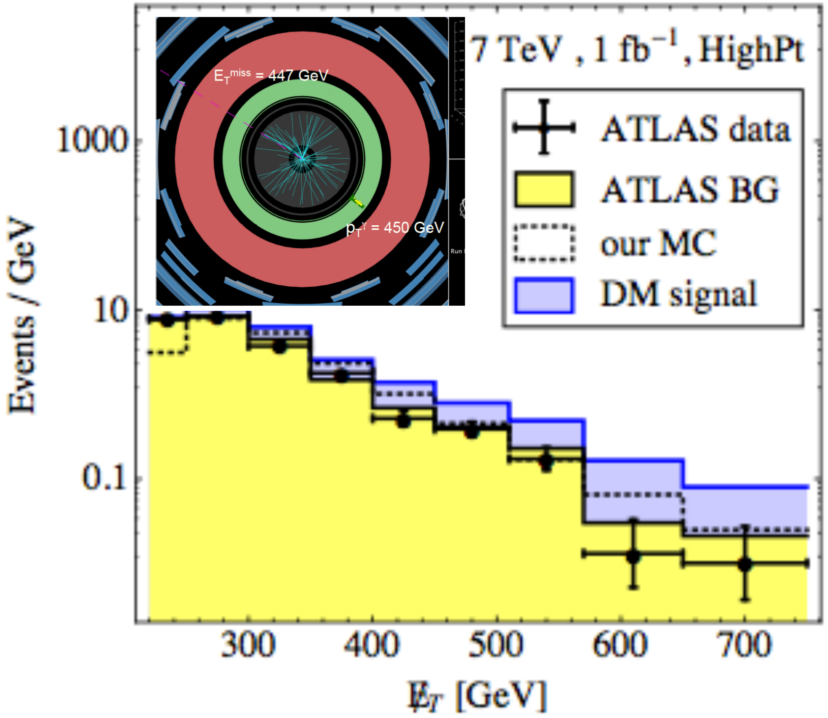
No single experiment can either confirm or rule out dark matter
(and it is *not* a good strategy to look just under the WIMP lamp post!)

Many techniques for indirect detection … and many claims!



The *PAMELA/AMS-02* anomaly (e^+), *WMAP/Planck* 'haze' (radio), *Fermi* 'bubbles' + Galactic Centre 'excess' + 130 GeV line (γ-ray) … have all been ascribed to dark matter

These are probes of dark matter *elsewhere* in the Galaxy so complement direct detection experiments … but we are just beginning to understand the astrophysical foregrounds!



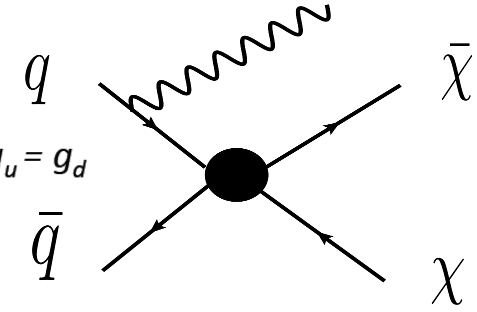
'Monojet' events at colliders directly measure the coupling of dark matter to SM particles in an EFT, e.g.

$$\mathcal{L}_\chi^{\rm eff} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

$$\rightarrow \sigma_p^{\rm SI} = \frac{f^2\mu_{\chi n}^2}{\pi\Lambda^4}, \text{ where } f = 3 \text{ for } g_u = g_d$$

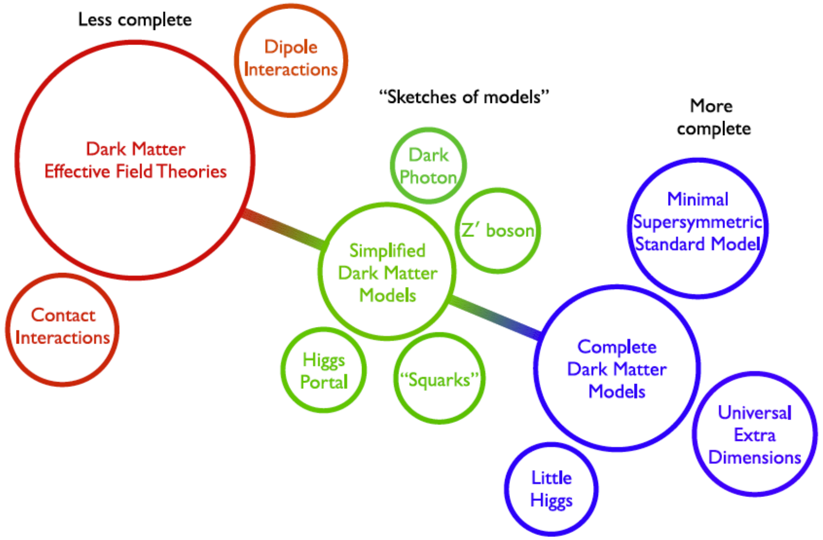
$$\Lambda = m_R/\sqrt{g_q g_\chi}$$

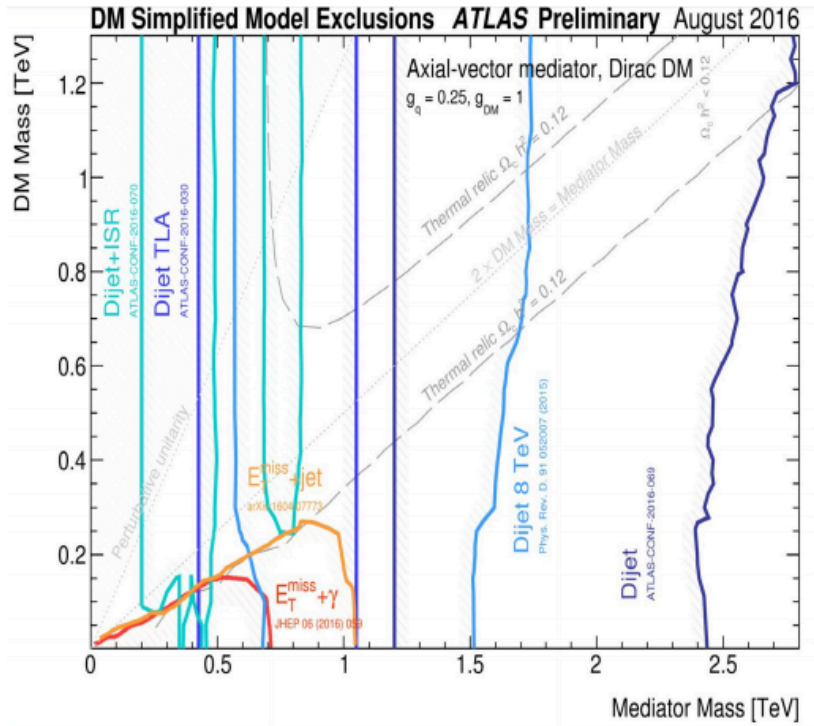
$$\rightarrow \sigma\,(j + \text{MET}) \sim 1/\Lambda^4 \sim \sigma_p$$



These bounds require the scale Λ to exceed ~0.8 TeV, while perturbative unitarity requires $g_q, g_\chi < \sqrt{4\pi}$ i.e. $m_R < 2$ TeV … so *cannot* rely on EFT description for higher energy collisions (Fox *et al*, 1203.1662)

Recent move to 'simplified models' wherein the DM particle and its mediator to SM particles are specified to optimise search strategies (1506.03116, 1607.06680)

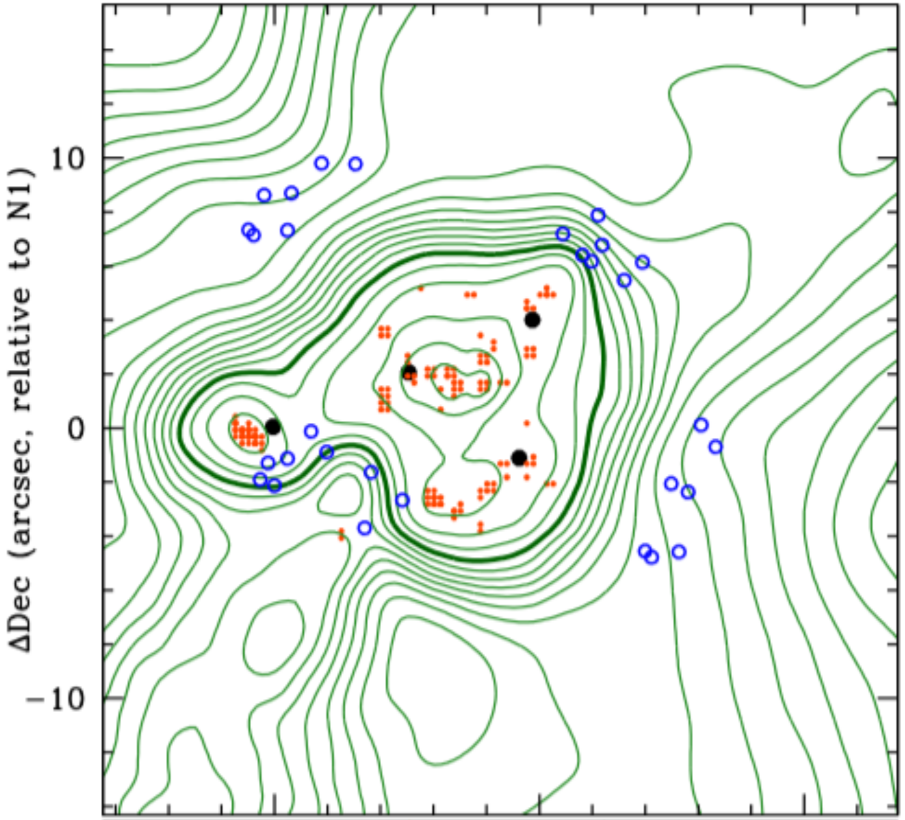




Nature may have a surprise for us … dark matter may be strongly self-interacting!

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



The *corrected* value of the self-interaction cross-section is ~1.5 cm^2/g (Kahlhoefer *et al*, 1308.3419, 1504.06576) … *comparable* to the upper limits derived from colliding galaxy clusters

Conclusions

- Searches for dark matter have focussed mainly on WIMPs so far but dark matter may be neither weakly interacting nor massive (and perhaps not even a particle)!

- Lighter particles, which are just as well motivated, have just begun to be searched for with nuclear recoil experiments … complemented by collider searches for concommitant signals.

- Dark matter may be coherent oscillations of axions necessitating very different search strategies (over a wide axion mass range).

- Colliding galaxy clusters provide an interesting laboratory for strongly self-interacting dark matter (with the DM-stellar pop. separation predicted to be ~10-50 kpc for σ/m ~ barn/GeV)

Interesting times ahead … recall that it took 48 years from the prediction of the Higgs boson to its discovery