Identifying dark matter

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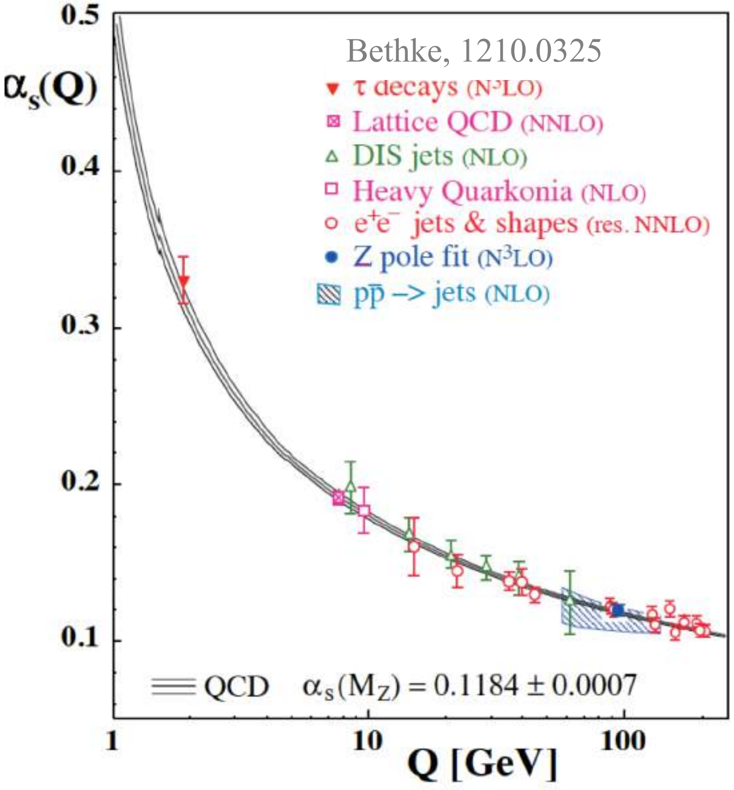
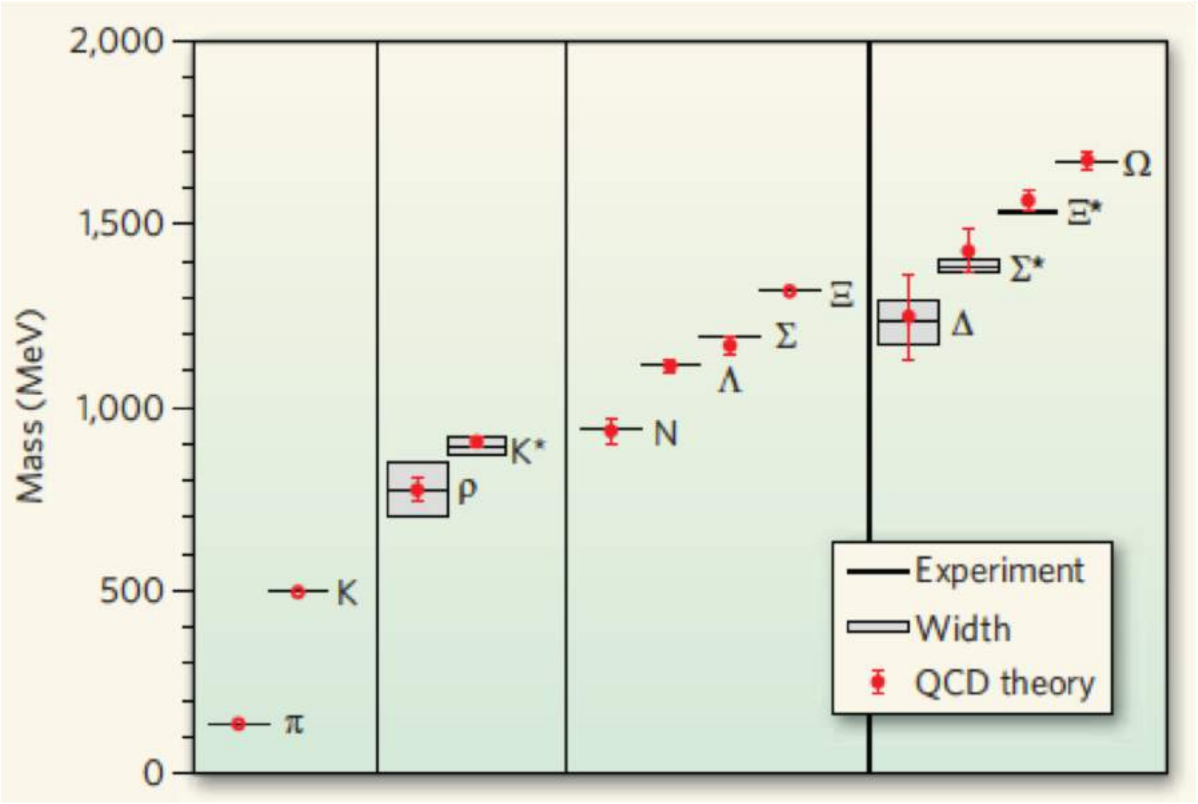
What *should* the world be made of?

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*





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

However, in the standard cosmology *none* should be left-over from the Big Bang!

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

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

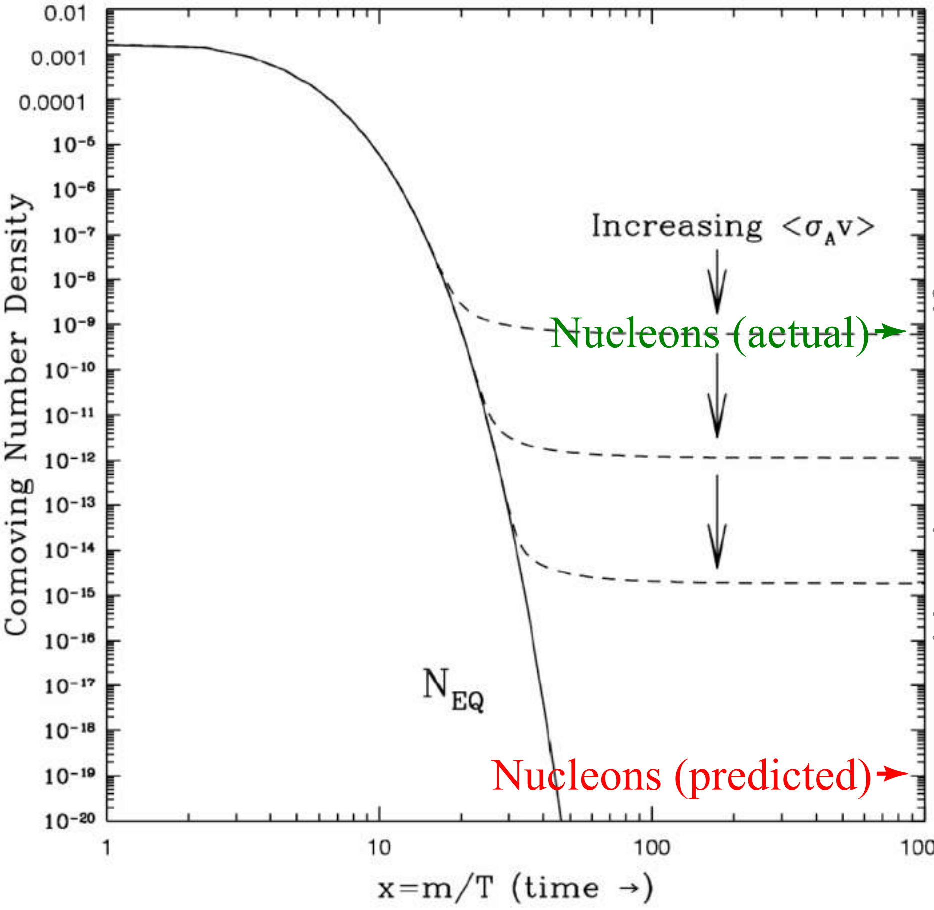
Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate

'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



Zeldovich, 1965; Wolfram, 1979

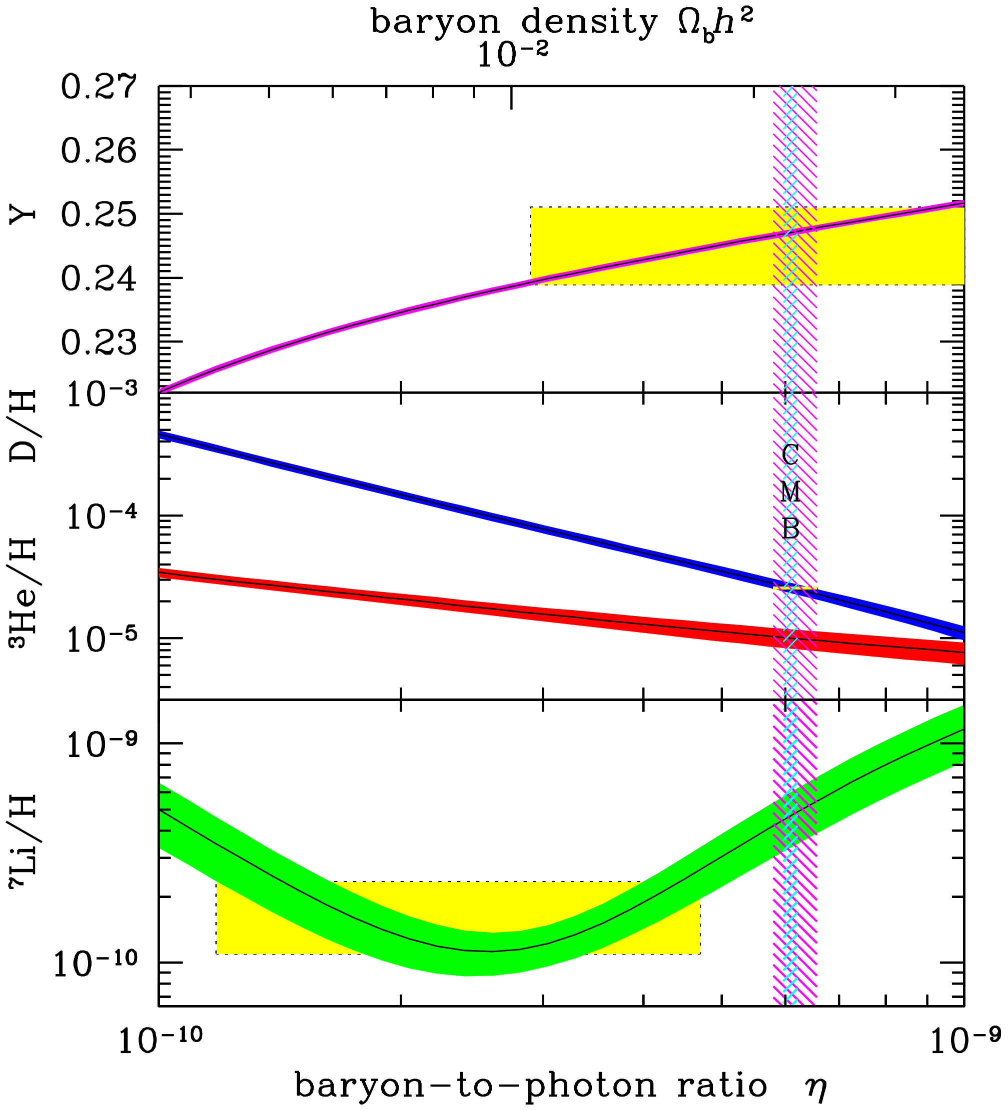
i.e. 'freeze-out' occurs at $T \sim m_N/45$, with: $\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$

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**:

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

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)



Fields, Molaro & Sarkar, *Review of Particle Properties*, 2018

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

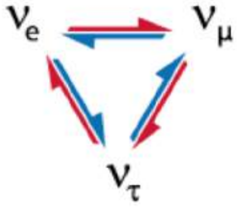
To make the baryon asymmetry requires *new* physics ('Sakharov conditions')

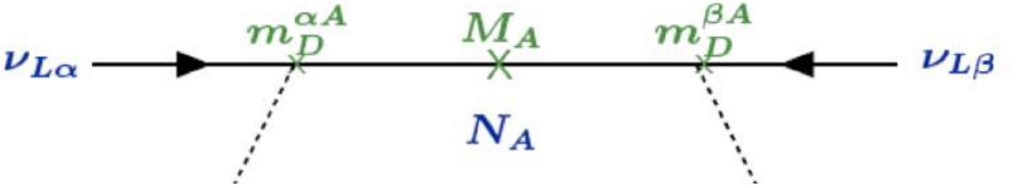
- *B*-number violation
- *CP* violation
- Departure for thermal equilibrium

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**

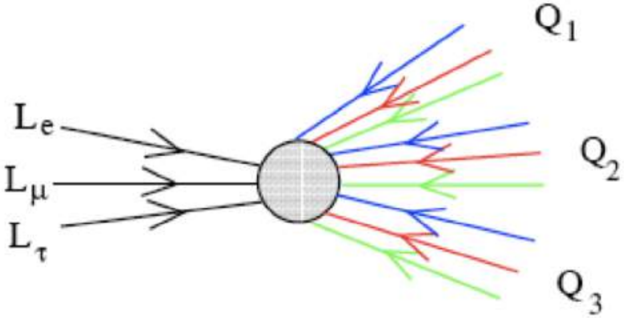
'See-saw': $\mathcal{L} = \mathcal{L}_{SM} + \lambda^*_{\alpha J}\bar{\ell}_\alpha \cdot H N_J - \frac{1}{2}\overline{N_J} M_J N^c_J \qquad \lambda M^{-1}\lambda^{\mathrm{T}}\langle H^0\rangle^2 = [m_\nu]$



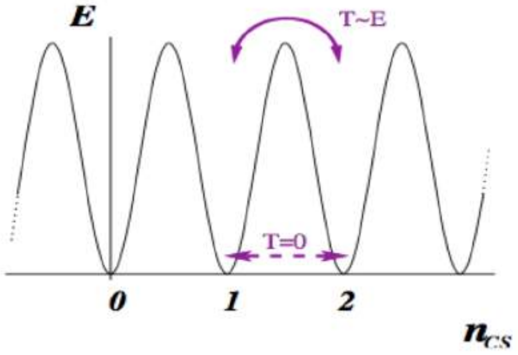


$\Delta m^2_{atm} = m_3^2 - m_2^2 \simeq 2.6 \times 10^{-3}\mathrm{eV}^2 \qquad \Delta m^2_\odot = m_2^2 - m_1^2 \simeq 7.9 \times 10^{-5}\mathrm{eV}^2$

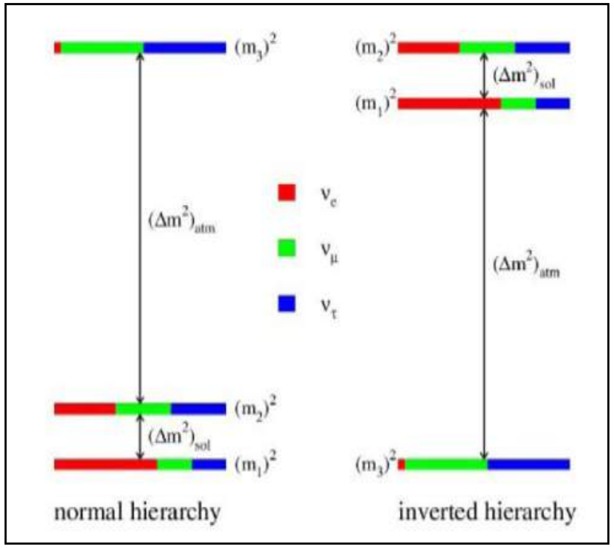
Asymmetric baryonic matter



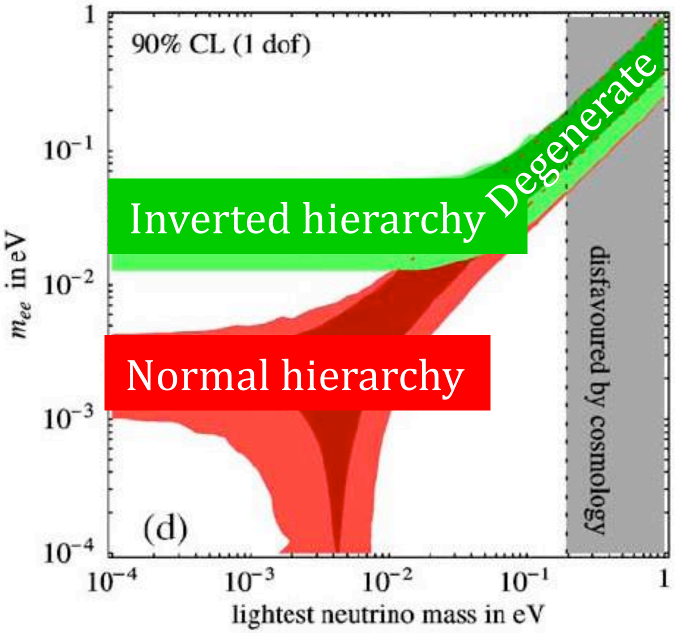
$$\partial_\mu j_i^\mu = \partial_\mu(\bar{\psi}^i \gamma^\mu \psi^i) = \frac{g^2}{8\pi} W^{a\mu\nu} \tilde{W}^a_{\mu\nu}$$



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)



The **Standard $SU(3)_c$ x $SU(2)_L$ x $U(1)_Y$ Model** provides an exact description of all microphysics (up to some high energy cut-off M)

Higgs mass divergence

$$+M^4 + M^2\Phi^2 \quad m_H^2 \simeq \frac{h_t^2}{16\pi^2}\int_0^{M^2} \mathrm{d}k^2 = \frac{h_t^2}{16\pi^2}M^2$$

super-renormalisable

$$\mathcal{L}_{\text{eff}} = F^2 + \bar{\Psi}\,\not{D}\Psi + \bar{\Psi}\Psi\Phi + (D\Phi)^2 + V(\Phi)$$

renormalisable

$$-\mu^2\phi^\dagger\phi + \tfrac{\lambda}{4}(\phi^\dagger\phi)^2, m_H^2 = \lambda v^2/2$$

non-renormalisable

$$+\frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \ldots$$

The effect of new physics beyond the SM (neutrino mass, nucleon decay, FCNC) ⇒ **non-renormalisable operators** suppressed by M^n … which 'decouple' as $M \rightarrow M_P$

But as M is raised, the effects of the **super-renormalisable operators** are exacerbated

One solution for 2nd term → 'softly broken' supersymmetry at $M \sim 1$ TeV

This suggests possible mechanisms for **baryogenesis**, candidates for **dark matter**, …
(as also do other proposed extensions of the SM, e.g. new dimensions @ TeV scale)

For example, the lightest supersymmetric particle (typically the neutralino χ), *if* protected against decay by R-parity, is a candidate for thermal dark matter

But if the Higgs is composite (as in **technicolour** models of **$SU(2)_L$ x $U(1)_Y$** breaking) then there is *no* need for supersymmetry … and light TC states can be dark matter

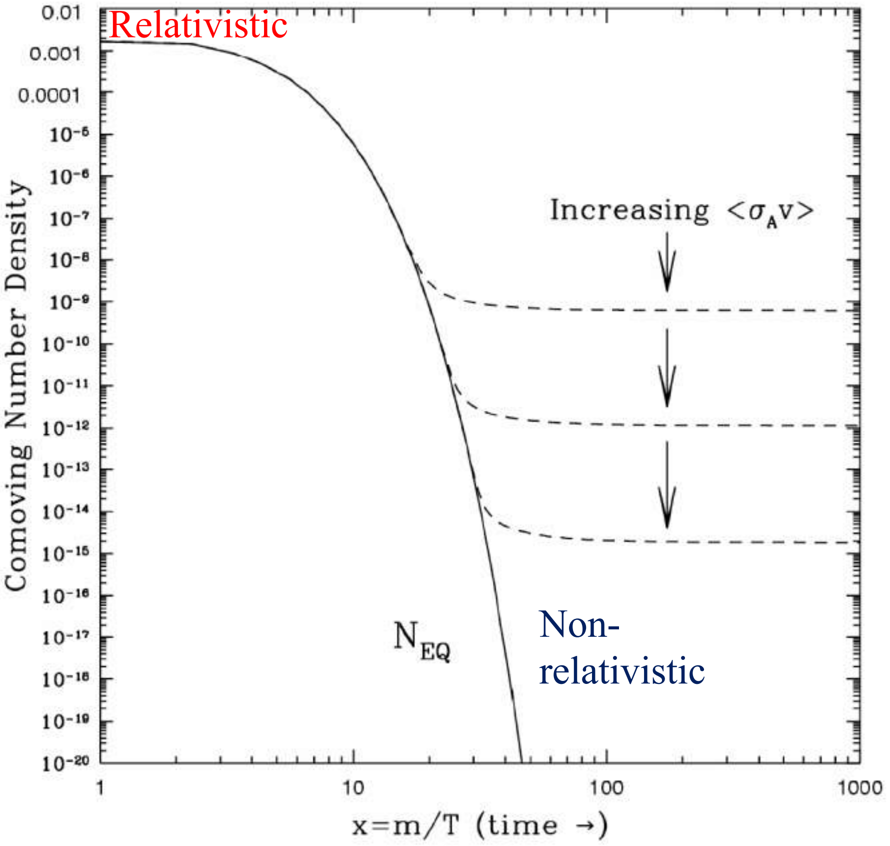
Thermal relics

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

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

'Freeze-out' can occur either when the annihilating particles are:

- Relativistic: $n \sim n_\gamma$
- Non-relativistic: $n \sim n_\gamma \mathrm{e}^{-m/T}$



$$\text{Example 1}: \quad \sum \Omega_\nu h^2 \simeq m_{\nu_i}/93\mathrm{eV}$$

➛ But how might this mass scale arise?

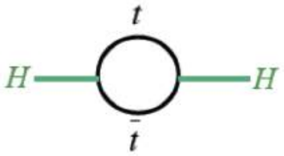
(also disfavoured by structure formation)

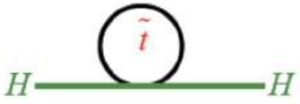
$$\text{Example 2}: \Omega_\chi h^2 \simeq \frac{3\times10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}} v\rangle_{T=T_{\mathrm{f}}}}$$

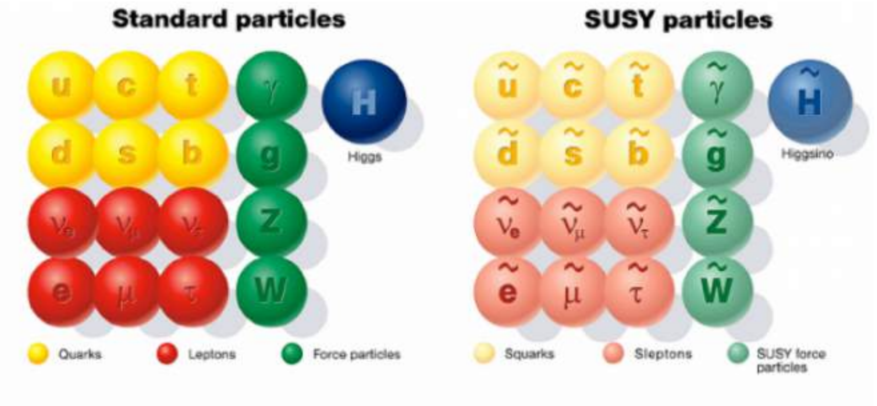
➛ natural for weak scale mass/coupling

What *should* the world be made of?

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







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

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

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

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

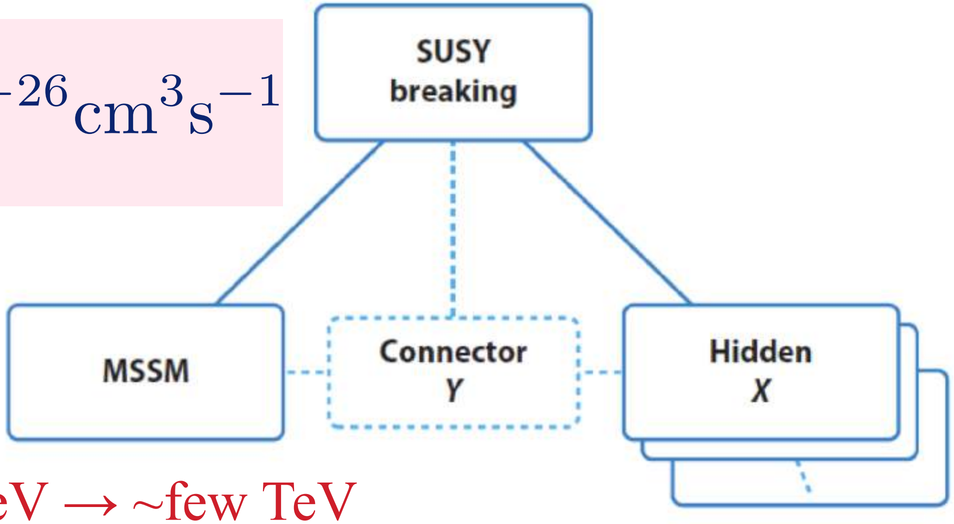
What *should* the world be made of?

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~~	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity?	violated?	‘freeze-out’ from thermal equilibrium	$\Omega_{LSP} \sim 0.3$

This yields the ‘WIMPless miracle’ (Feng & Kumar, PRL **101**:231301,2008) since *generic* hidden sector matter ($g_h^2/m_h \sim g_\chi^2/m_\chi \sim F/16\pi^2 M$) … gives the required abundance as before!

$$\text{since } \langle\sigma_{\rm ann} v\rangle \sim \frac{g_\chi^4}{16\pi^2 m_\chi^2} \approx 3\times 10^{-26}\text{cm}^3\text{s}^{-1}$$

$$\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}\text{cm}^3\text{s}^{-1}}{\langle\sigma_{\rm ann} v\rangle_{T=T_{\rm f}}} \simeq 0.1$$


SUSY breaking

MSSM

Connector Y

Hidden X

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

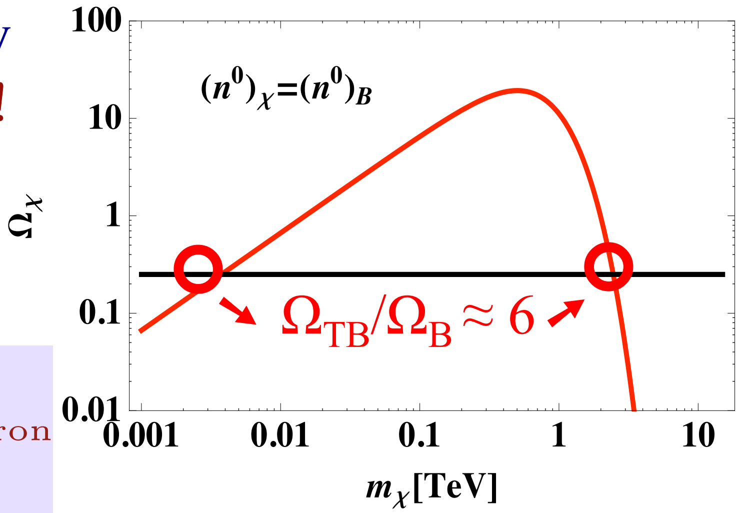
What *should* the world be made of ?

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 $\Omega_B \sim 0.05$
$\Lambda_{\mathrm{QCD'}} \sim 6\Lambda_{\mathrm{QCD}}$	Dark baryon?	$U(1)_{\mathrm{DB}}$	plausible	Asymmetric (like the *observed* baryons)	$\Omega_{\mathrm{DB}} \sim 0.3$
$\Lambda_{\mathrm{Fermi}} \sim G_F^{-1/2}$	Neutralino?	*R*-parity	violated?	'Freeze-out' from thermal equilibrium	$\Omega_{\mathrm{LSP}} \sim 0.3$
	Technibaryon?	(walking) Technicolour	$\tau \sim 10^{18}$ yr e^+ excess?	Asymmetric (like the *observed* baryons)	$\Omega_{\mathrm{TB}} \sim 0.3$

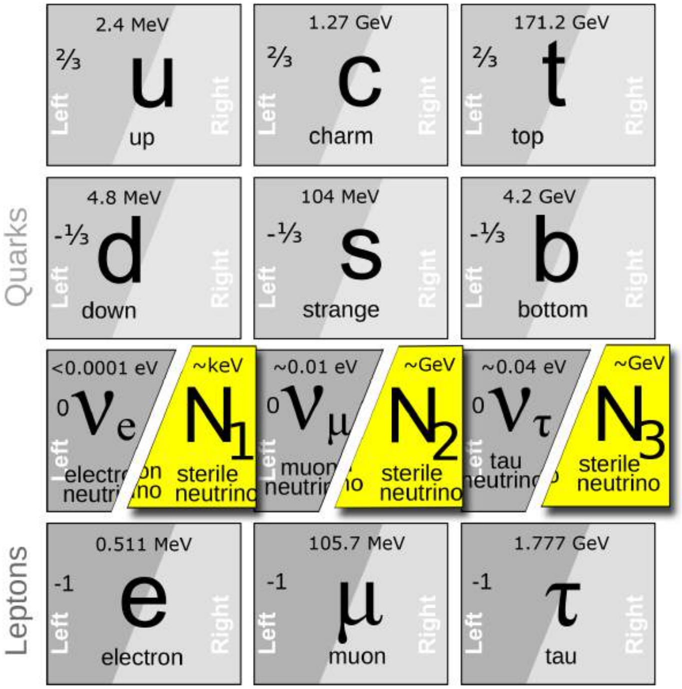
A new particle can naturally *share* in the *B*/*L* asymmetry if it couples to the *W* … linking dark to baryonic matter!

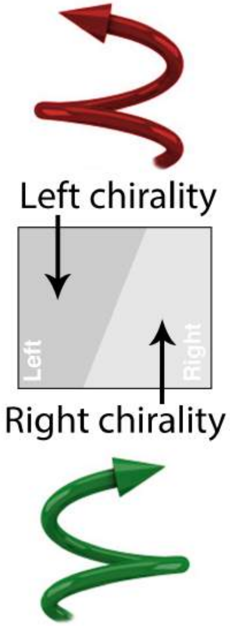
So a *O*(TeV) mass **technibaryon** can be the dark matter … alternatively a ~few GeV mass **'dark baryon'** in a *hidden sector* (e.g. into which the technibaryon decays)

$$\frac{\rho_{\mathrm{DM}}}{\rho_{\mathrm{B}}} \simeq 6 \sim \frac{m_{\mathrm{DM}}}{m_{\mathrm{B}}}\left(\frac{m_{\mathrm{DM}}}{m_{\mathrm{B}}}\right)^{3/2} \mathrm{e}^{-m_{\mathrm{DM}}/T_{\mathrm{dec|sphaleron}}}$$



Sterile neutrino dark matter



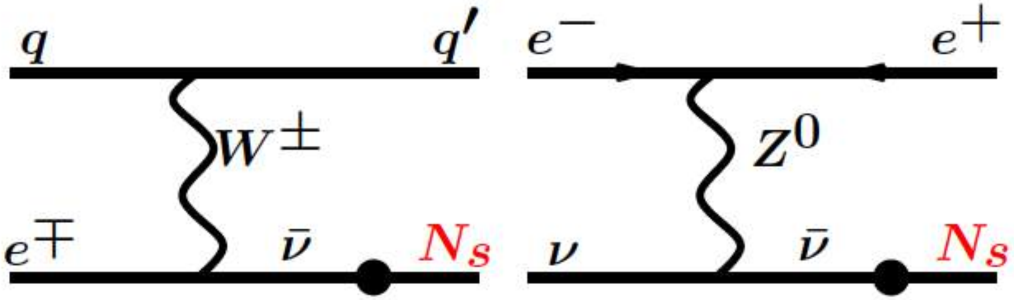


If they mix with the left-handed 'active' neutrinos then would behave as super-weakly interacting particles with an effective coupling: $\theta G_{\rm Fermi}$

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

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

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



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)

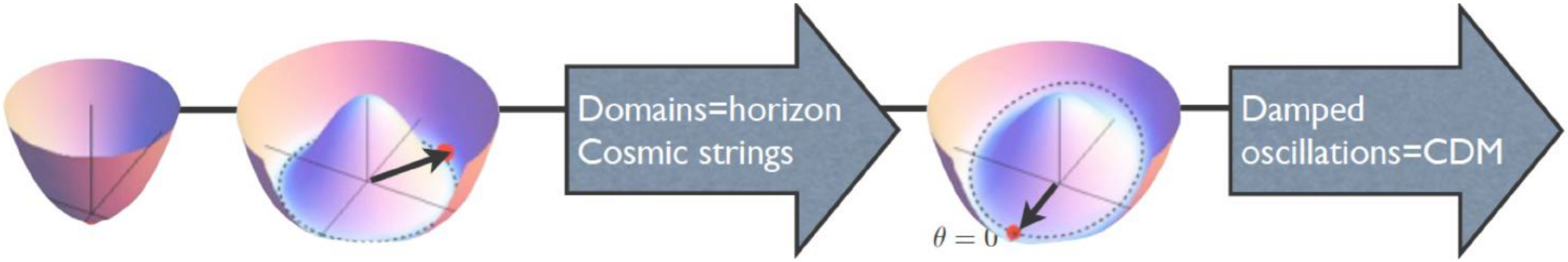
Axion dark matter

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

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 acquires a small mass through its mixing with the pion (the pNGB of QCD): $m_a = m_\pi\,(f_\pi/f_{\rm PQ})$

(Kim, Phys.Rep.**150**:1,1987, Rev.Mod.Phys.**82**:557,2010; Raffelt, Phys.Rep.**198**:1,1990)



Domains=horizon
Cosmic strings

Damped
oscillations=CDM

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 $\Omega_a h^2 \sim 10^{11}$ 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!

Observations indicate that the bulk of the matter in the universe is dark (i.e. dissipationless, ~collisionless, ~cold)

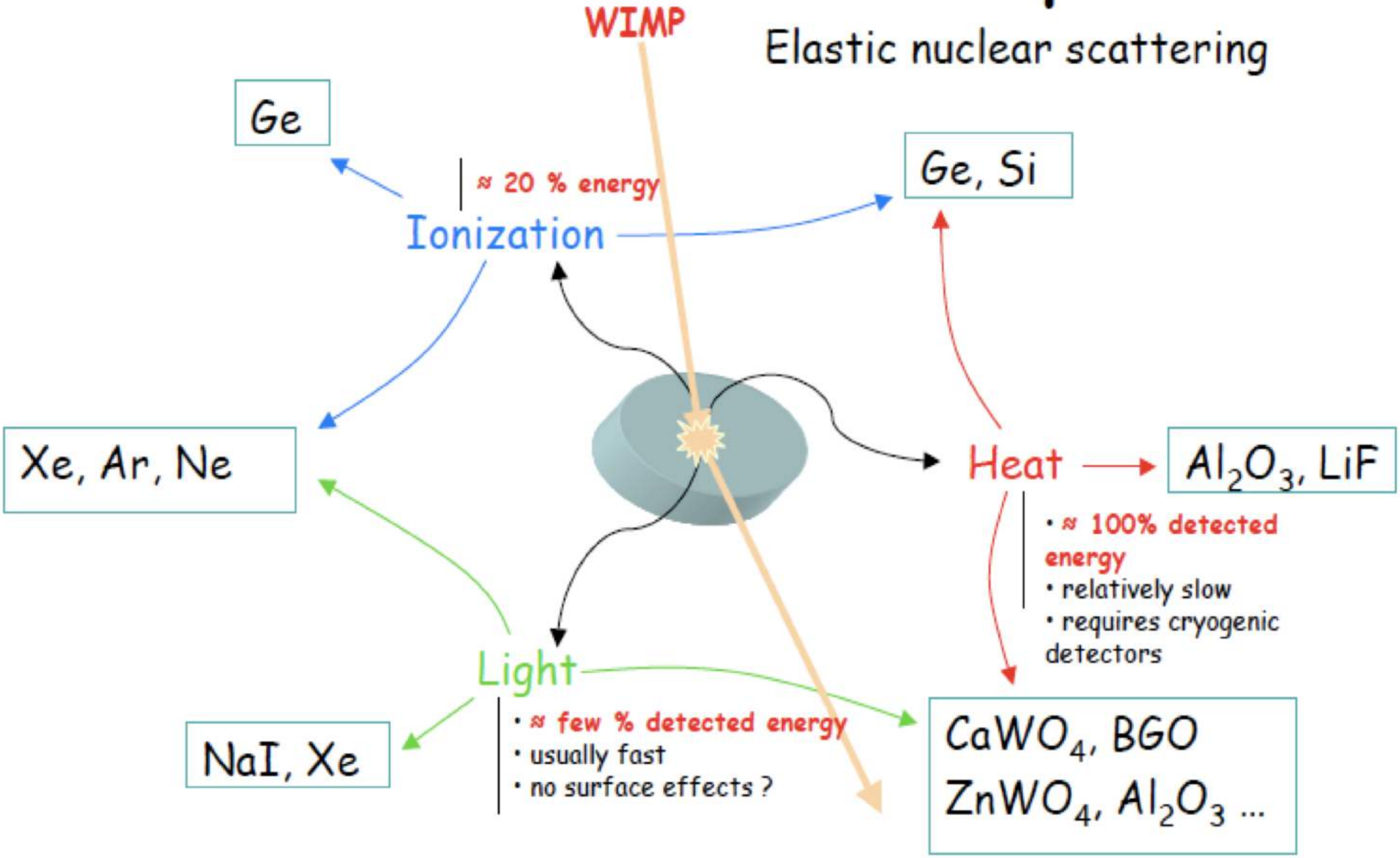
There is a generic expectation that it consists of a new stable particle from physics beyond the Standard Model

… it *cannot* have electric or colour charge (otherwise would bind to ordinary nuclei creating anomalously heavy isotopes → ruled out experimentally at a high level)

… it *cannot* couple too strongly to the Z^0 (or would have been seen already in accelerator searches)

Underground nuclear recoil detectors are placing restrictive bounds on its elastic scattering cross-section with nucleons … while indirect searches for gamma-rays, neutrinos and other products of dark matter annihilations (in the Sun, Milky Way, …) have provided exciting hints!

Direct detection techniques



WIMP

Elastic nuclear scattering

Ge

≈ 20 % energy

Ionization

Ge, Si

Xe, Ar, Ne

Heat

Al_2O_3, LiF

- ≈ 100% detected energy
- relatively slow
- requires cryogenic detectors

Light

NaI, Xe

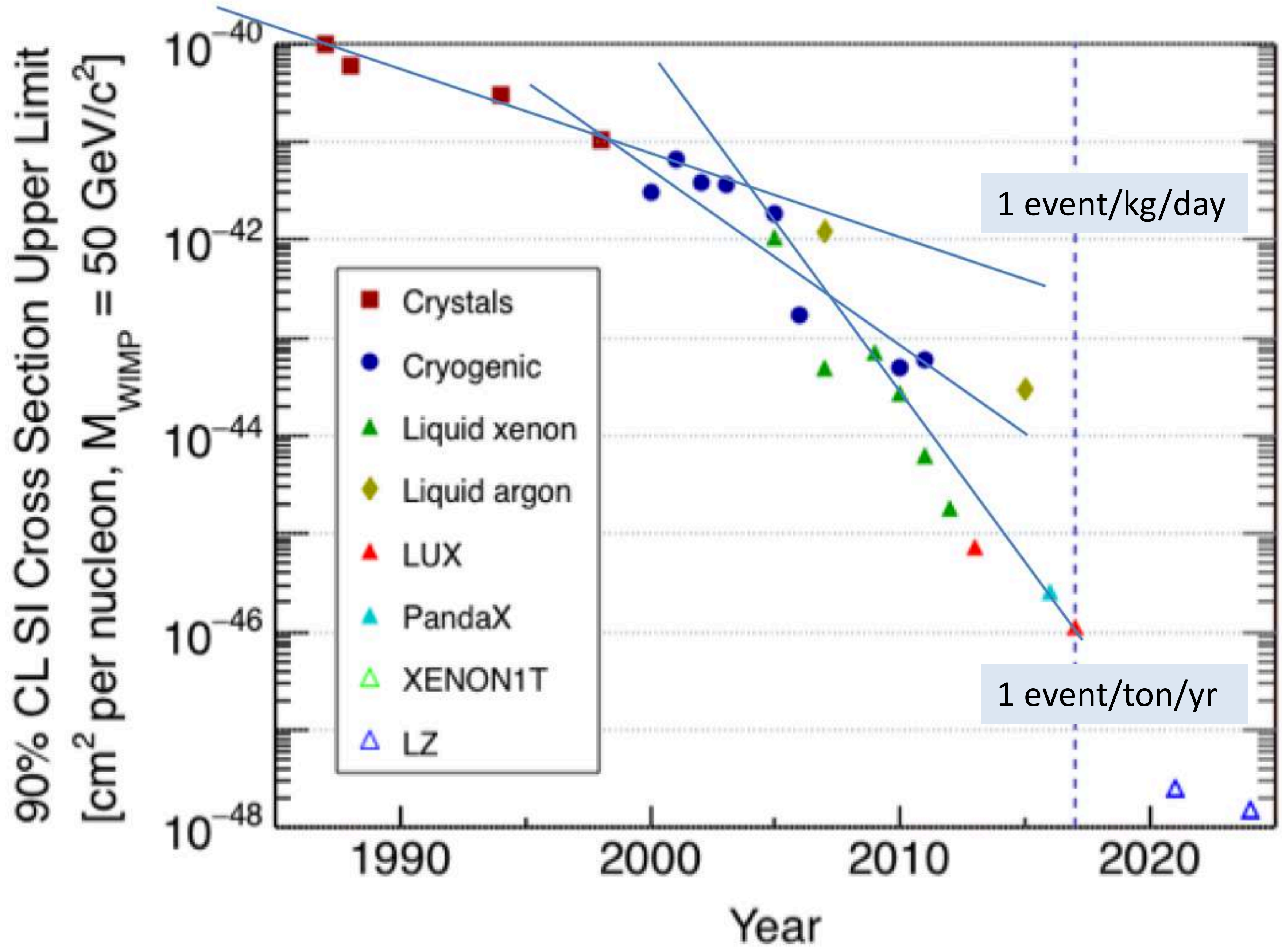
- ≈ few % detected energy
- usually fast
- no surface effects ?

$CaWO_4$, BGO

$ZnWO_4$, Al_2O_3 ...

(Drukier & Stodolsky, PR D**30**:2295,1984; Goodman & Witten, PR D**31**:3059,1985)

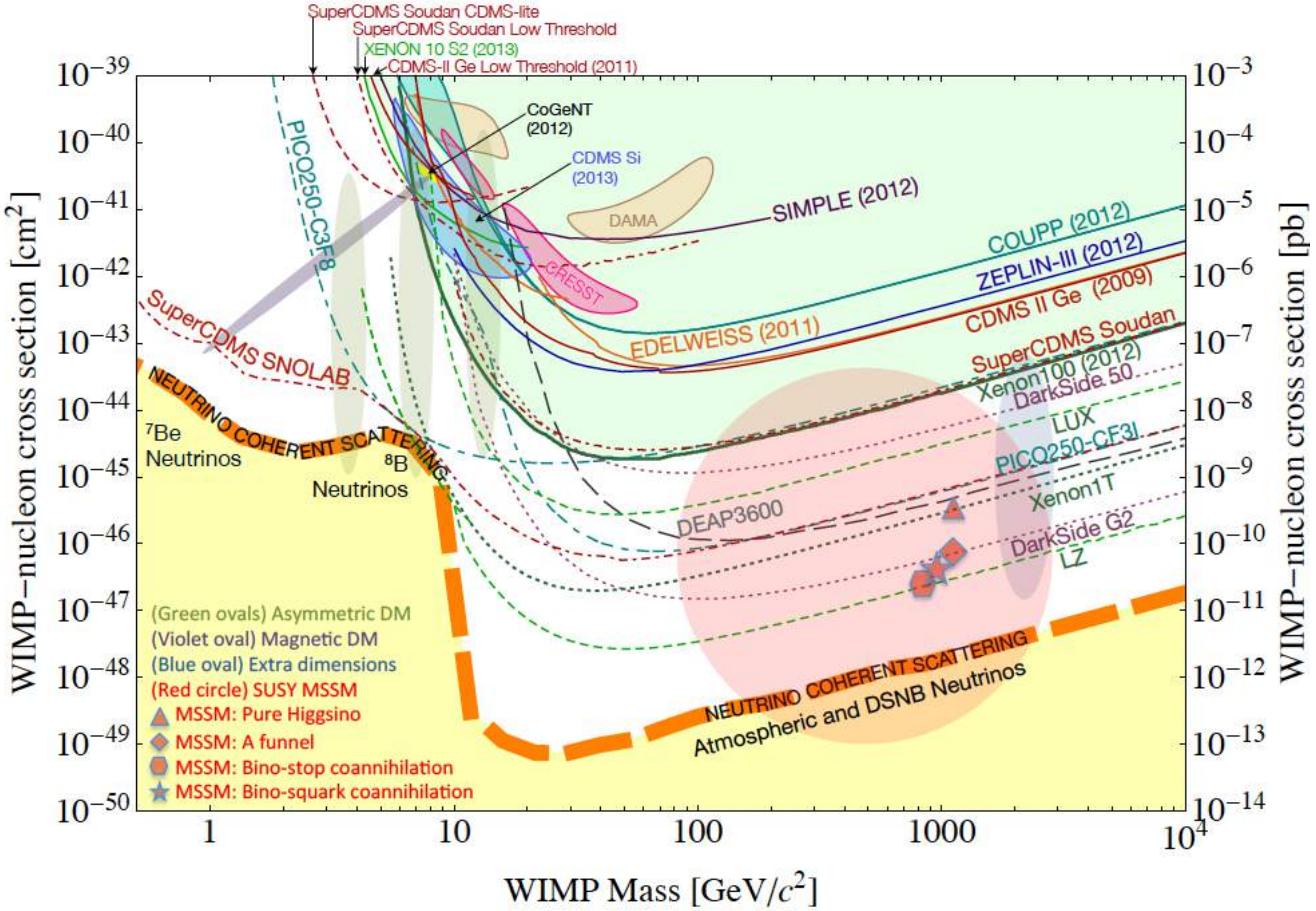
Time evolution of experimental sensitivity



1 event/kg/day

1 event/ton/yr

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



Snowmass CF1 WG summary, 1310.8327

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:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R}(E_R,t) = M_{\mathrm{tar}}\frac{\boxed{\rho_\chi}}{2\,m_\chi\mu^2}\underbrace{\frac{(f_pZ + f_n(A-Z))^2}{f_n^2}\sigma_n}_{\text{Particle physics}}\underbrace{F^2(E_R)}_{\text{Nuclear physics}}\underbrace{\int_{v_{\min}}^{\infty}\mathrm{d}^3v\,\frac{f_{\mathrm{local}}(\vec{v},t)}{v}}_{\text{astrophysics}}$$

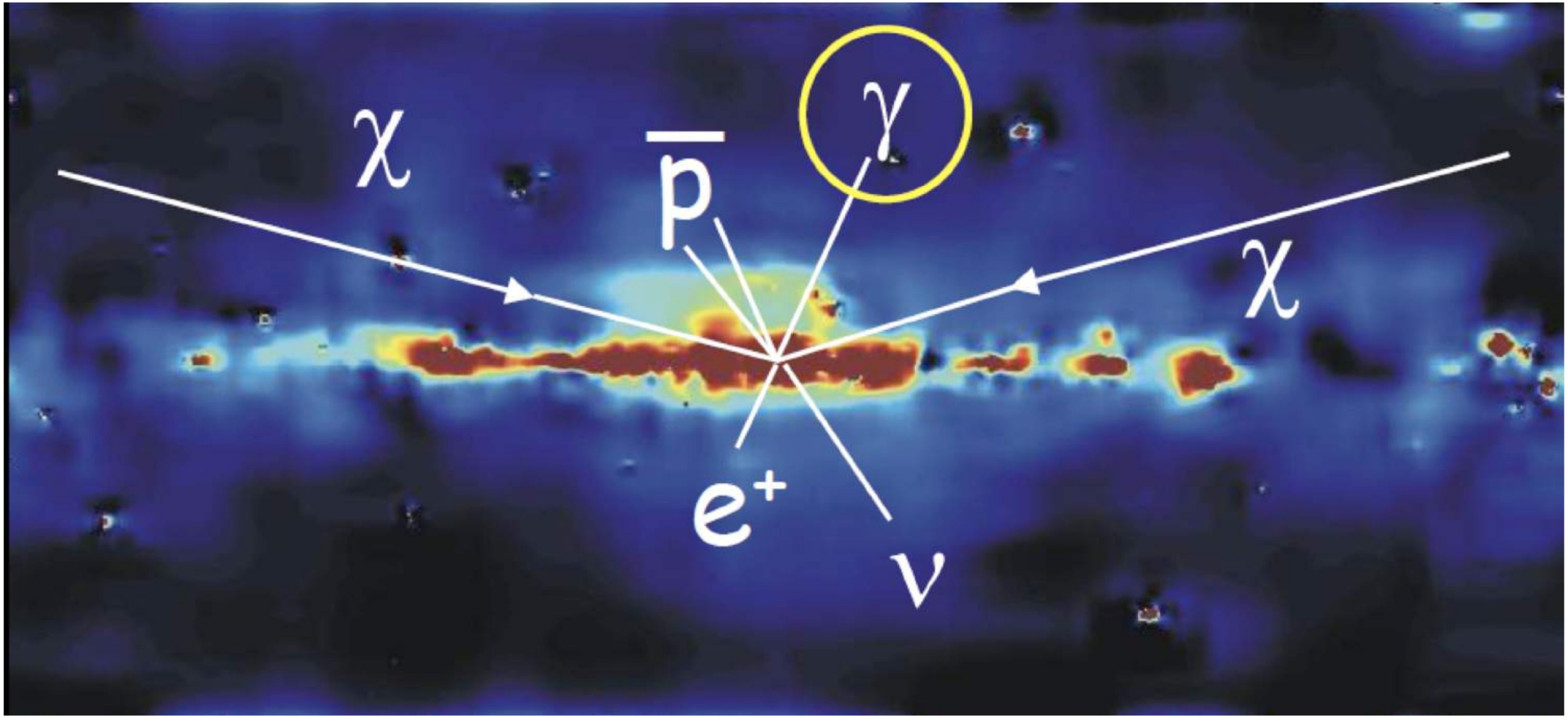
★ Dark matter interacts *differently* with neutrons & protons (Giulani, hep-ph/0504157) if the mediator is a (new) vector boson … so e.g. the events seen by CDMS-Si *can be* consistent with the upper limits set by XENON100 or LUX

★ 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 …

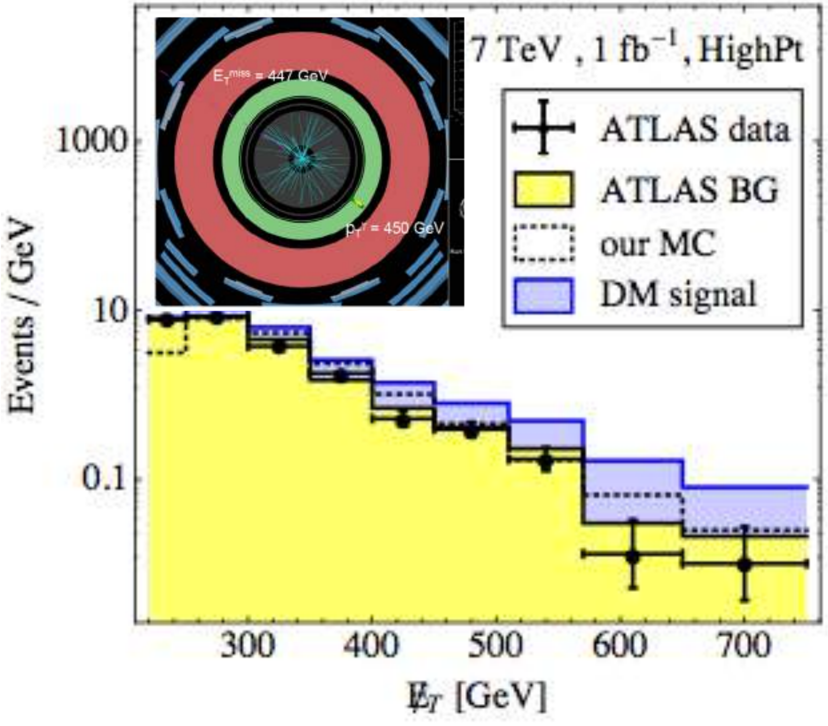
No single experiment can either confirm or rule out dark matter
(and it is *not* a good strategy to look just under the WIMP lamp post!)

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!



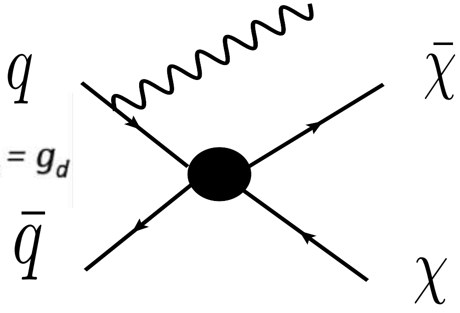
‘Monojet’ events at colliders directly measure the coupling of dark matter to SM particles in an EFT, e.g.

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

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

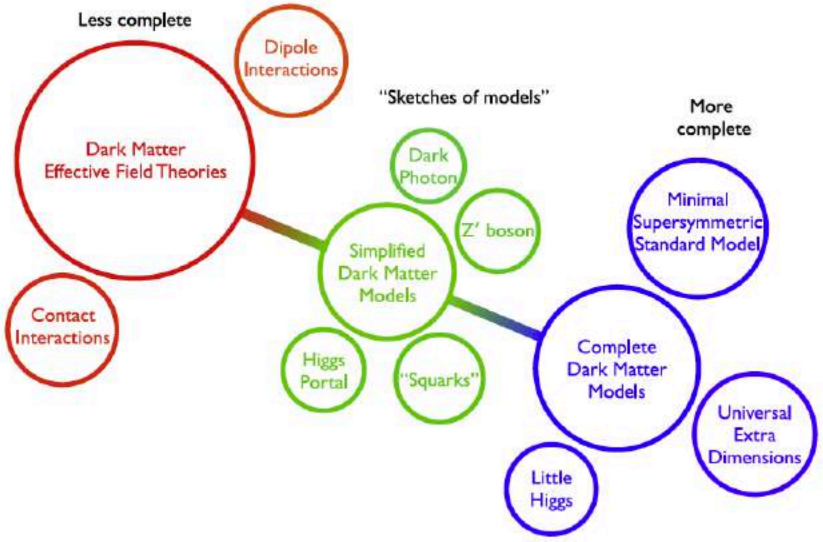
$\Lambda = m_R/\sqrt{g_q g_\chi}$

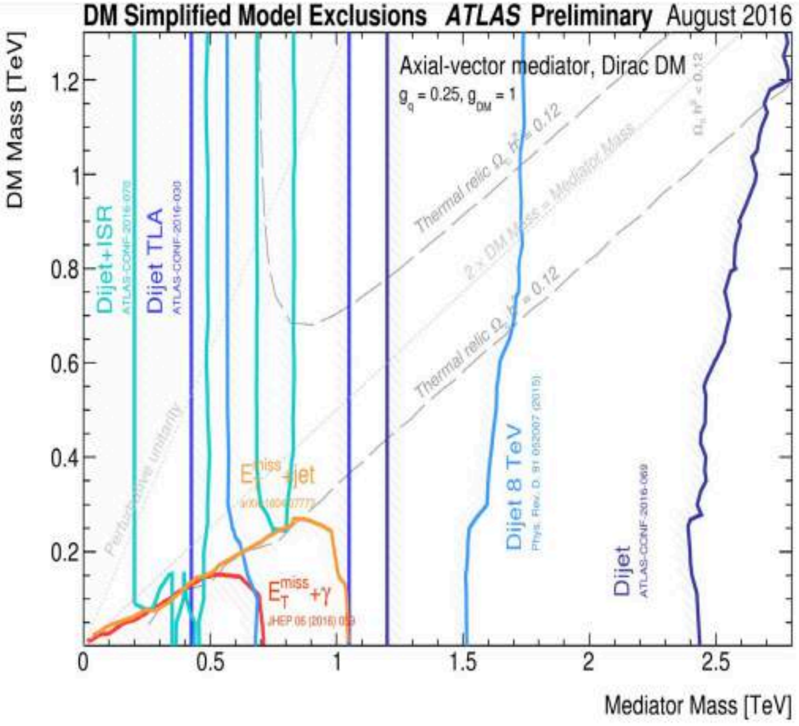
$\rightarrow \sigma\,(j + \mathrm{MET}) \sim 1/\Lambda^4 \sim \sigma_p$



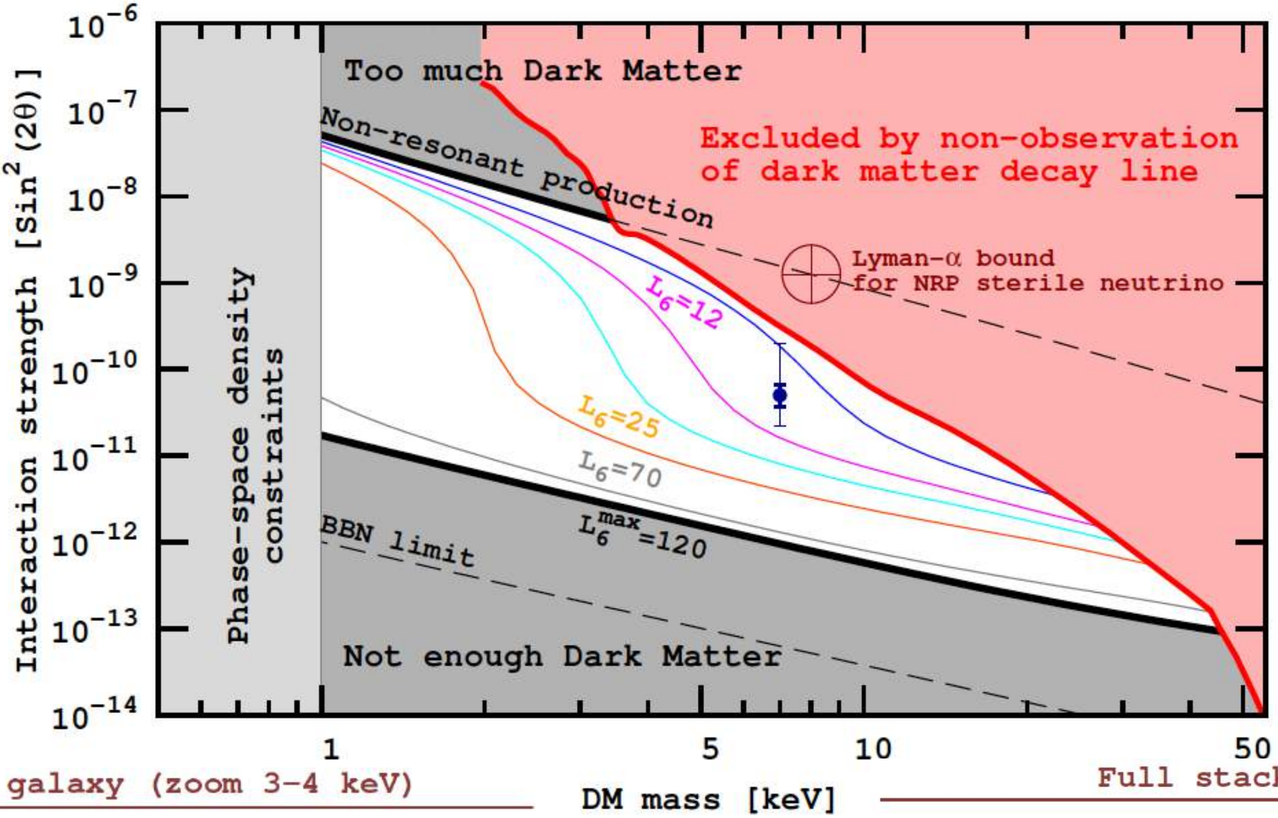
These bounds require the scale Λ to exceed ~0.8 TeV, while perturbative unitarity requires g_q, $g_\chi < \sqrt{4\pi}$ i.e. $m_R < 2$ TeV … so *cannot* rely on EFT description for higher energy collisions (Fox *et al,* 1203.1662)

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)

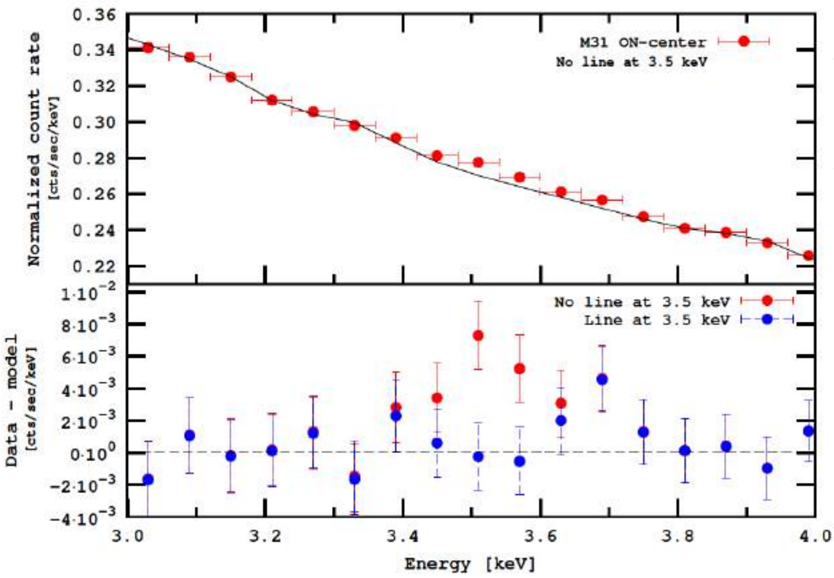




Sterile neutrino and 3.5 keV line



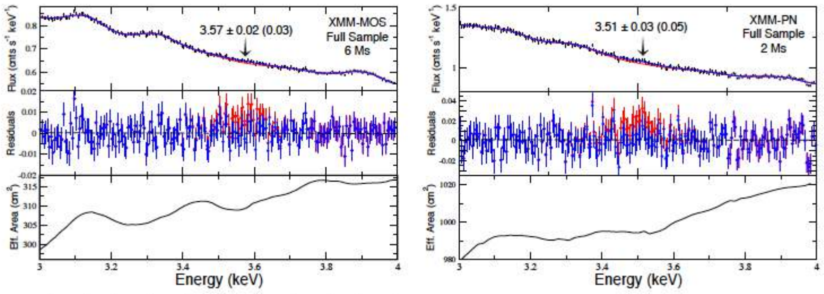
Andromeda galaxy (zoom 3-4 keV)

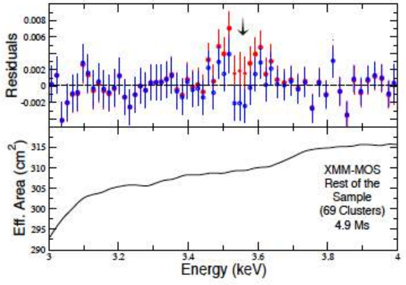


Boyarsky et al, 1402.4119

Full stacked spectra

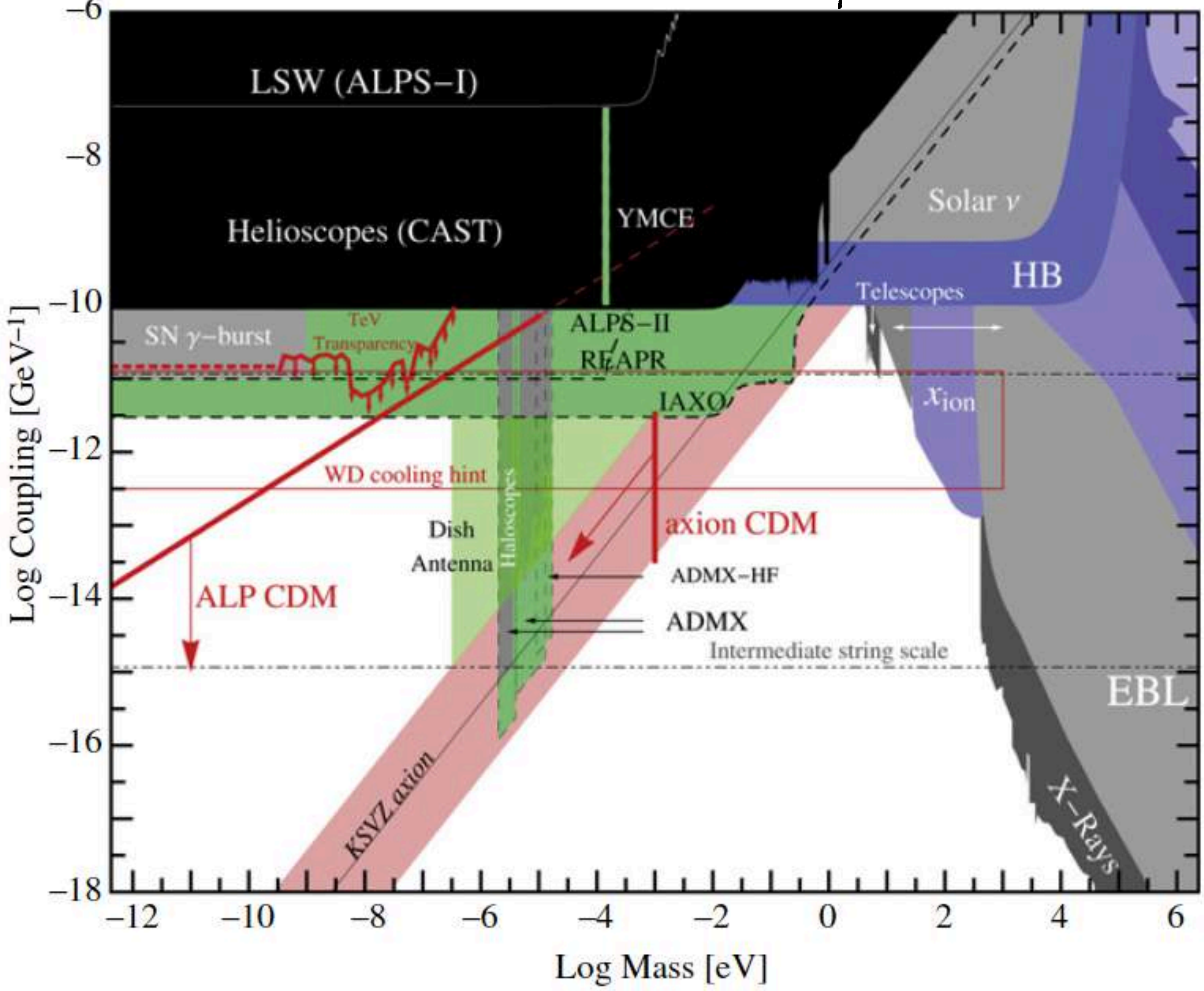
Bulbul et al, 1402.2301





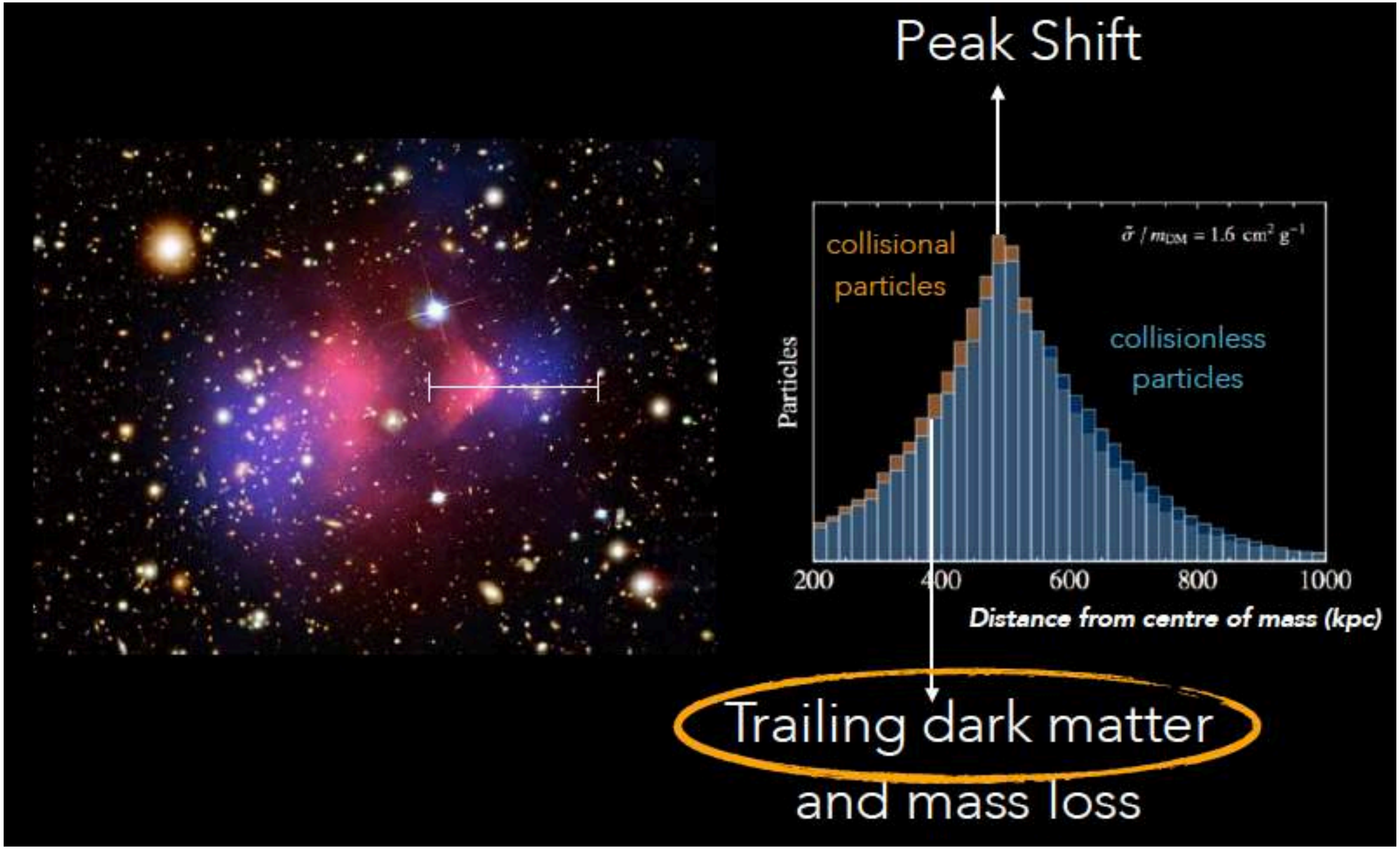
- All spectra blue-shifted in the reference frame of clusters
- Instrumental background processed similarly and **subtracted**

Limits on axions and axion-like particles



Snowmass Intensity Frontier WG summary, 1401.6077

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



A self-interaction cross-section of ~1 cm^2/g would result in an observable separation *between dark matter and galaxies* in colliding clusters (Kahlhoefer *et al,* MNRAS **437**:2865,2014)

If found this would *rule out* nearly all popular DM candidates (neutralinos, axions, neutrinos, …)

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