IDENTIFYING DARK MATTER

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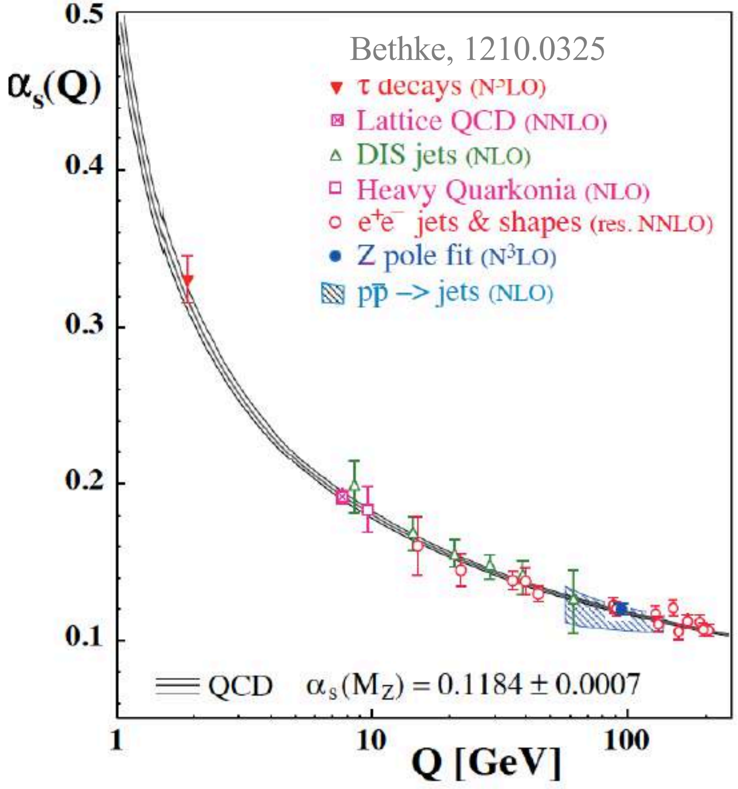
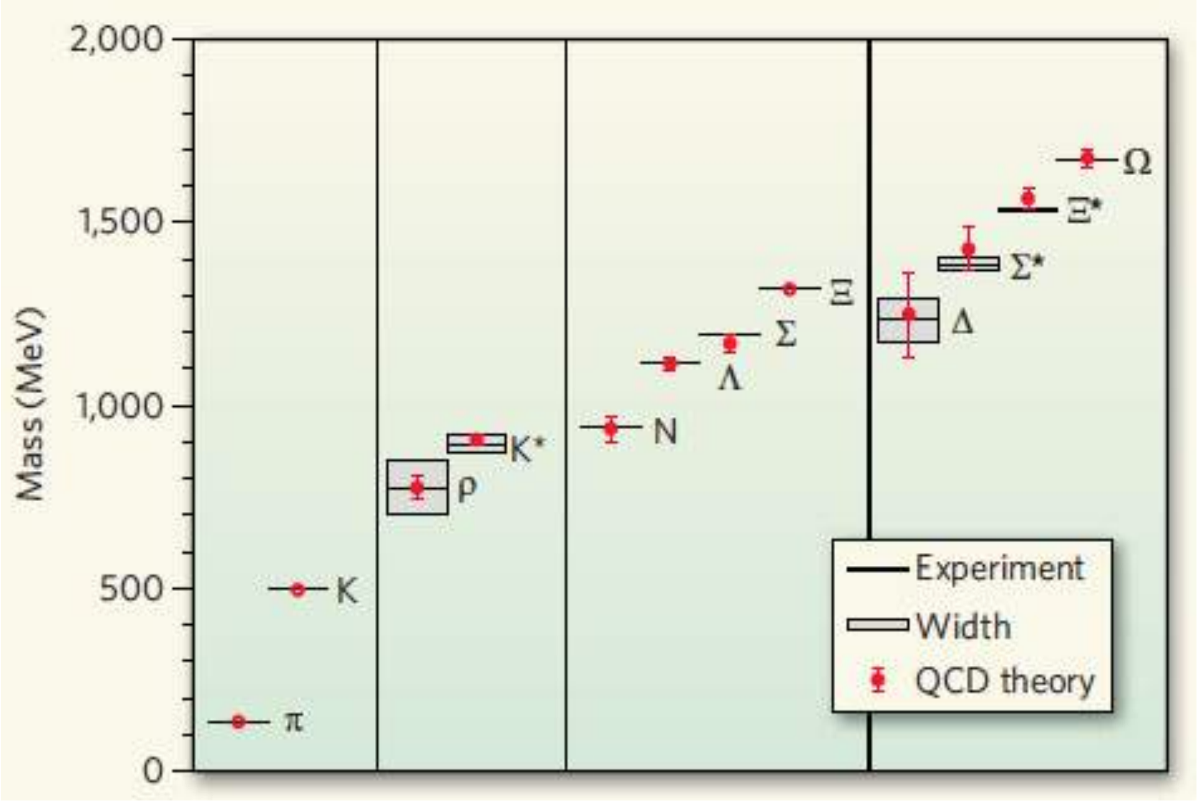
WHAT *SHOULD* THE WORLD BE MADE OF?

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*!

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

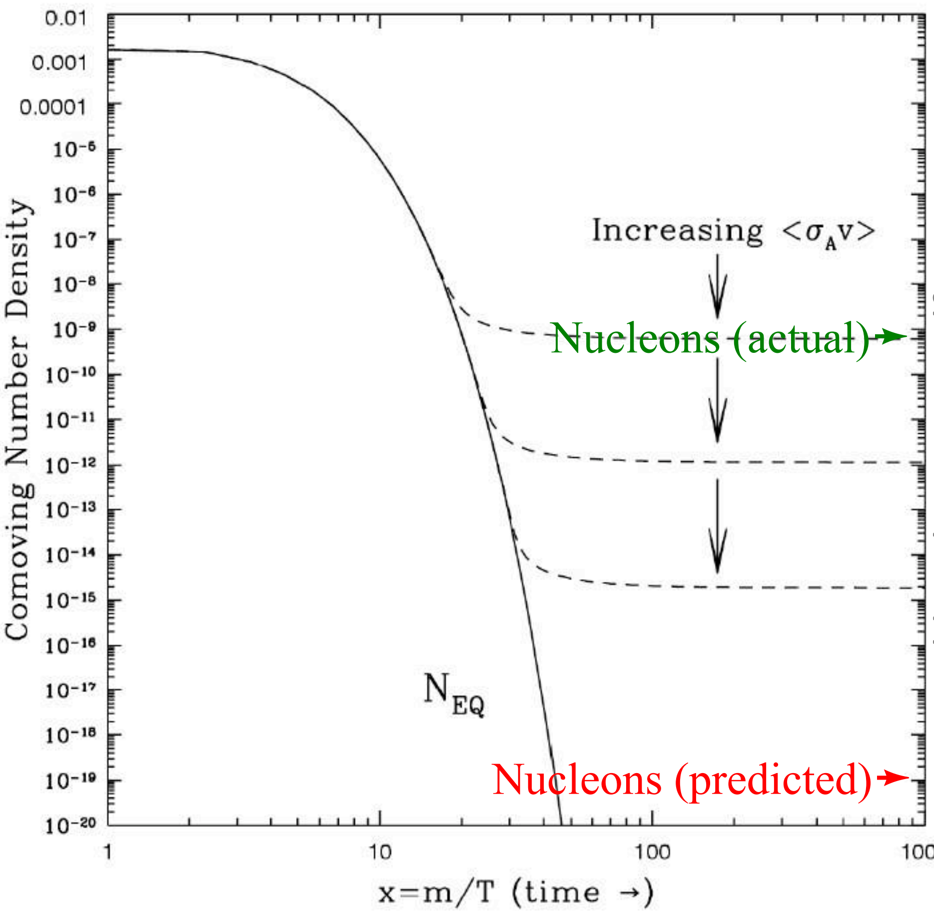
Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate

'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

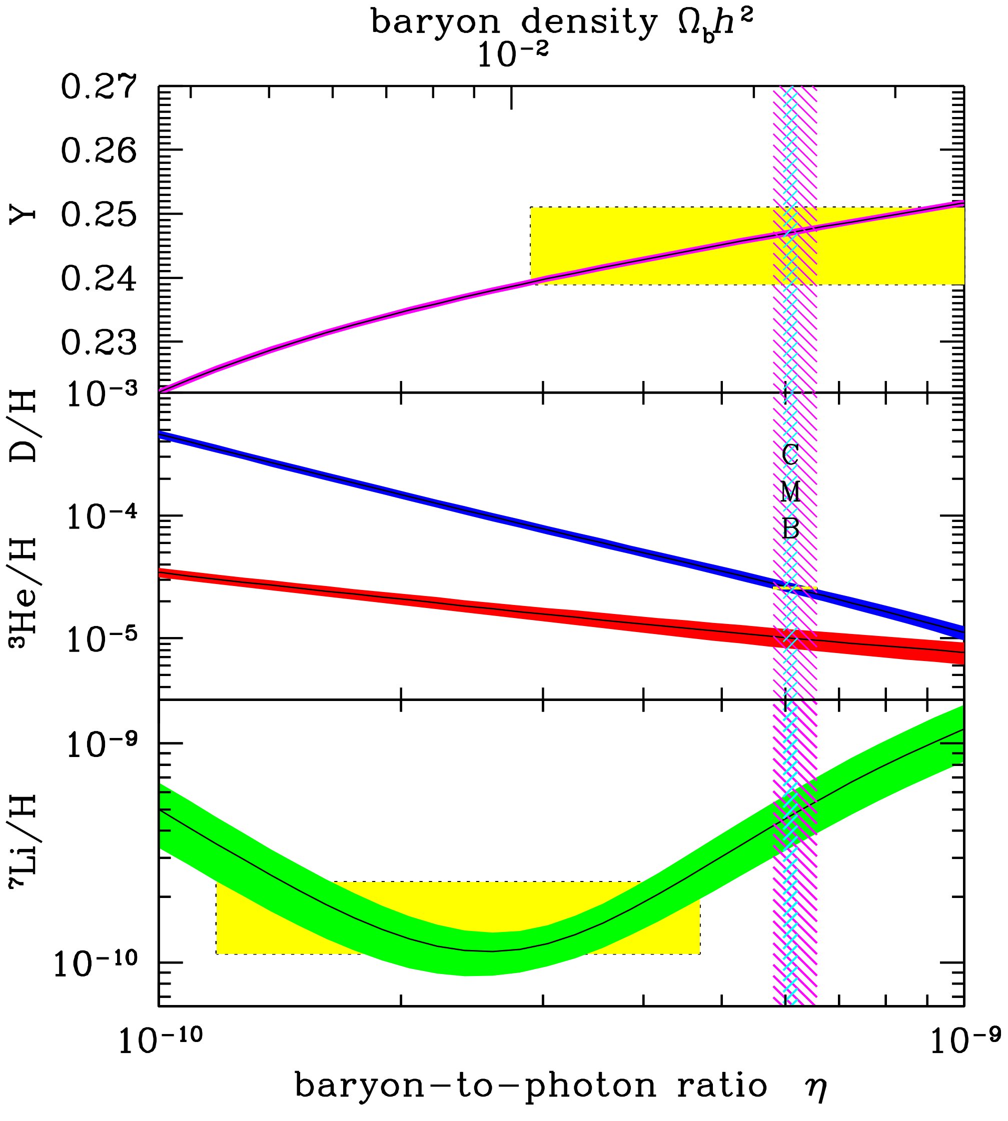
i.e. 'freeze-out' occurs at $T \sim m_N/45$, with: $$\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$$

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

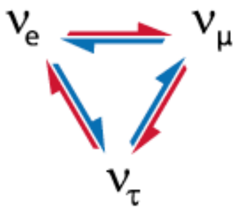
To make the baryon asymmetry requires *new* physics (‘Sakharov conditions’)

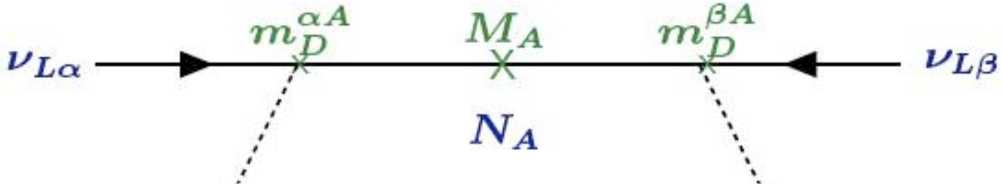
- *B*-number violation
- *CP* violation
- Departure for thermal equilibrium

The SM *allows* *B*-number violation (through non-perturbative – ‘sphaleron-mediated’ – processes) … but *CP*-violation is too *weak* and $SU(2)_L$ 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**

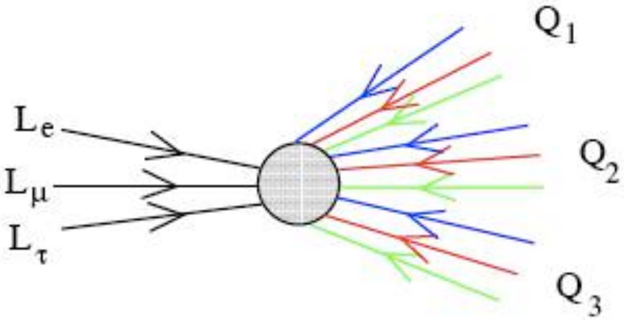
‘See-saw’: $\mathcal{L} = \mathcal{L}_{SM} + \lambda^*_{\alpha J}\bar{\ell}_\alpha \cdot H N_J - \frac{1}{2}\overline{N_J} M_J N^c_J \qquad \lambda M^{-1}\lambda^{\mathrm{T}}\langle H^0\rangle^2 = [m_\nu]$



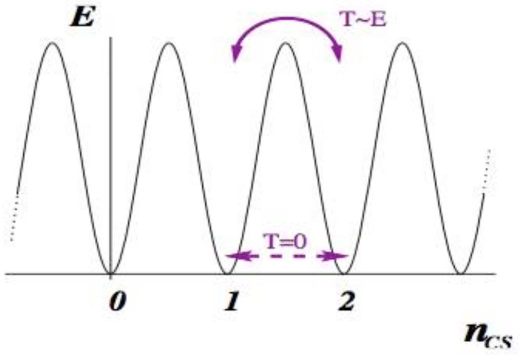


$$\Delta m^2_{atm} = m_3^2 - m_2^2 \simeq 2.6 \times 10^{-3}\mathrm{eV}^2 \qquad \Delta m^2_\odot = m_2^2 - m_1^2 \simeq 7.9 \times 10^{-5}\mathrm{eV}^2$$

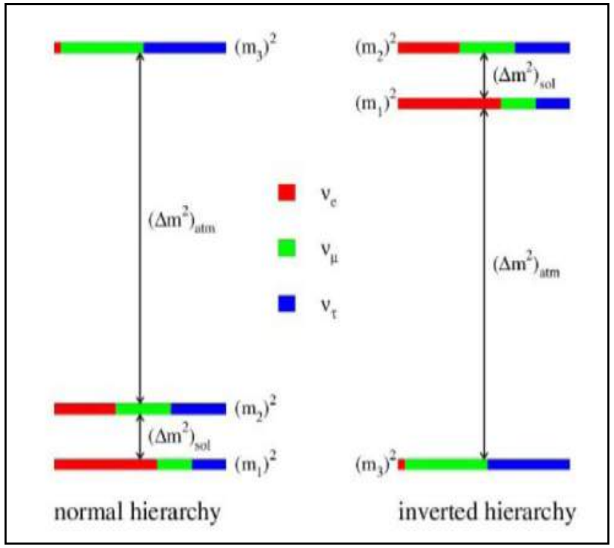
ASYMMETRIC BARYONIC MATTER



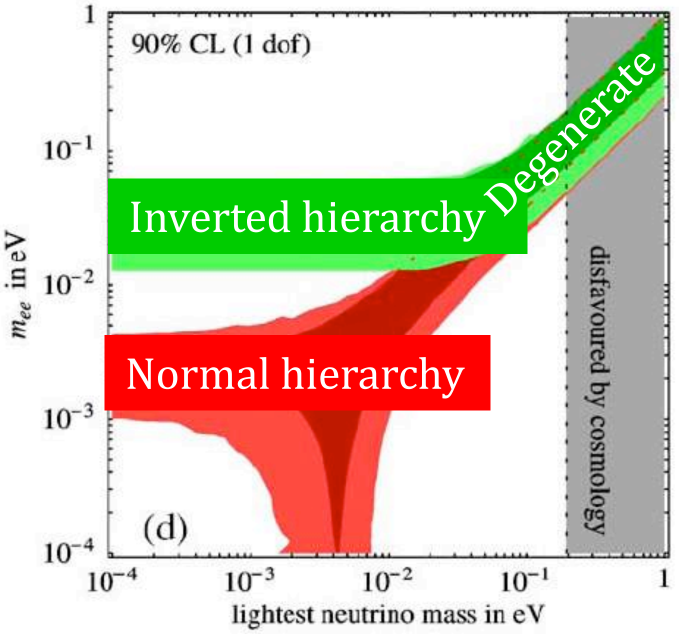
$$\partial_\mu j_i^\mu = \partial_\mu(\bar{\psi}^i \gamma^\mu \psi^i) = \frac{g^2}{8\pi} W^{a\mu\nu} \tilde{W}^a_{\mu\nu}$$



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

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

super-renormalisable

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

renormalisable

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

non-renormalisable

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

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

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

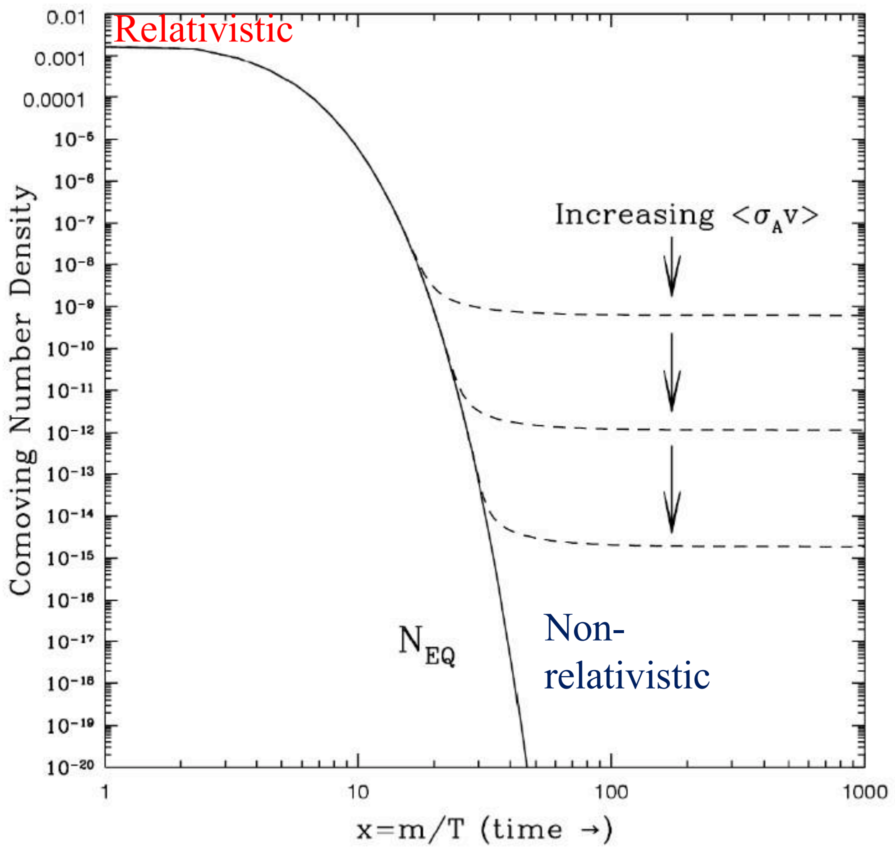
But if the Higgs is composite (as in **technicolour** models of $SU(2)_L$ x $U(1)_Y$ breaking) then there is *no* need for supersymmetry … and light TC states can be dark matter

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?

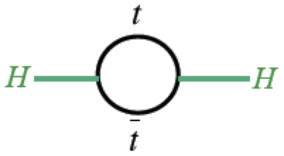
(also disfavoured by structure formation)

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

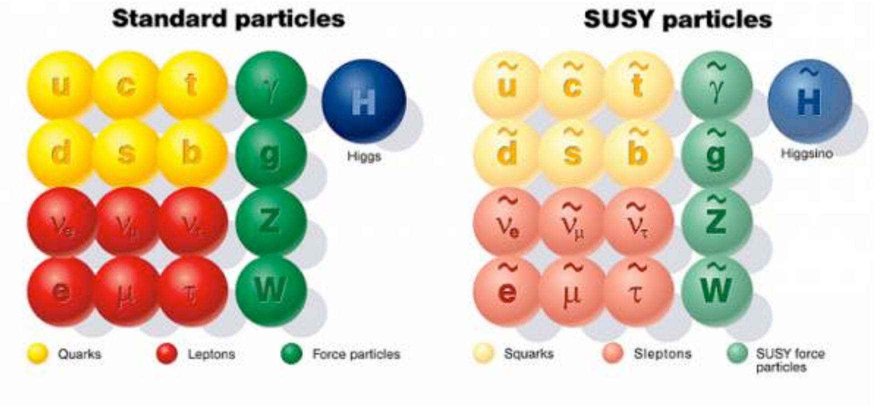
➛ natural for weak scale mass/coupling

WHAT *SHOULD* THE WORLD BE MADE OF?

Mass scale	**Particle**	**Symmetry/ Quantum #**	**Stability**	**Production**	**Abundance**
$\mathbf{\Lambda_{QCD}}$	**Nucleons**	Baryon number	$\tau > 10^{33}$ 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	$\Omega_{LSP} \sim 0.3$



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



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

$$\Omega_\chi h^2 \simeq \frac{3\times10^{-27}{\rm cm}^{-3}{\rm s}^{-1}}{\langle\sigma_{\rm ann} v\rangle_{T=T_{\rm f}}} \simeq 0.1 \quad , \text{ since } \langle\sigma_{\rm ann} v\rangle \sim \frac{g_\chi^4}{16\pi^2 m_\chi^2} \approx 3\times10^{-26}{\rm cm}^3{\rm s}^{-1}$$

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

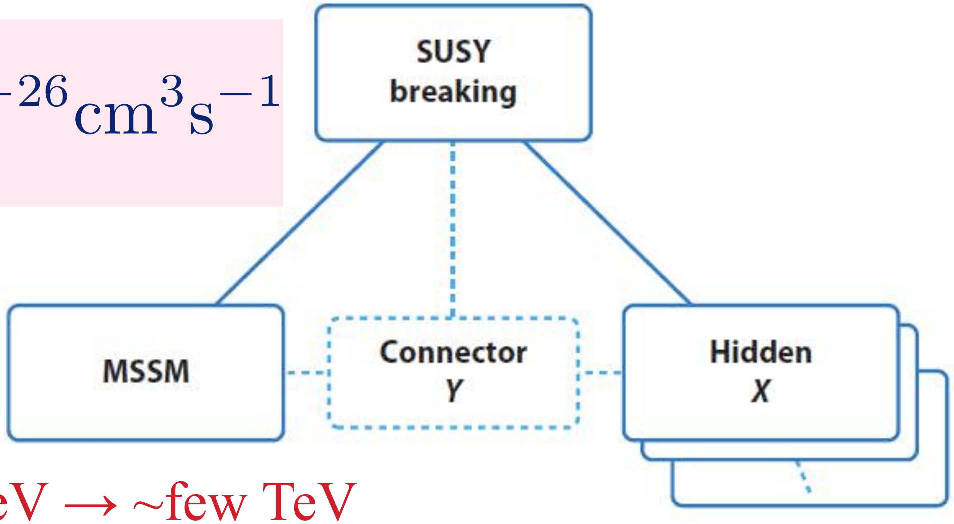
WHAT *SHOULD* THE WORLD BE MADE OF?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	Nucleons	Baryon number	$\tau > 10^{33}$ yr (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!

$$\text{since } \langle\sigma_{\rm ann} v\rangle \sim \frac{g_\chi^4}{16\pi^2 m_\chi^2} \approx 3\times10^{-26}\text{cm}^3\text{s}^{-1}$$

$$\Omega_\chi h^2 \simeq \frac{3\times10^{-27}\text{cm}^3\text{s}^{-1}}{\langle\sigma_{\rm ann} v\rangle_{T=T_{\rm f}}} \simeq 0.1$$



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

WHAT *SHOULD* THE WORLD BE MADE OF ?

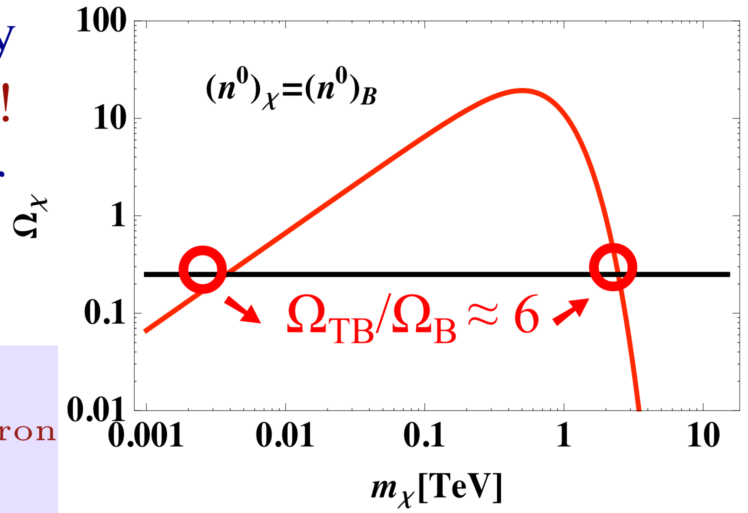
Mass scale	**Particle**	**Symmetry/ Quantum #**	**Stability**	**Production**	**Abundance**
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	~~'Freeze-out' from thermal equilibrium~~ Asymmetric baryogenesis (how?)	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{QCD'} \sim 6\Lambda_{QCD}$	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!

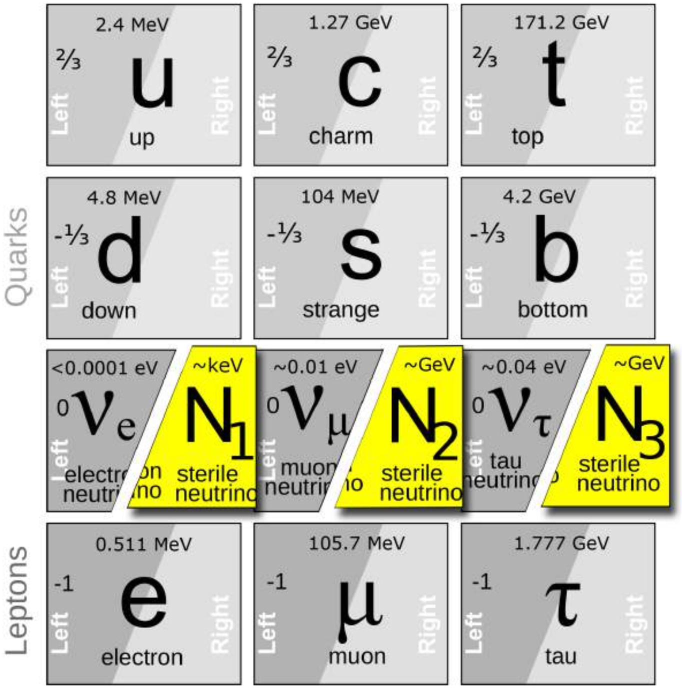
So a *O*(TeV) mass **technibaryon** can be the dark matter

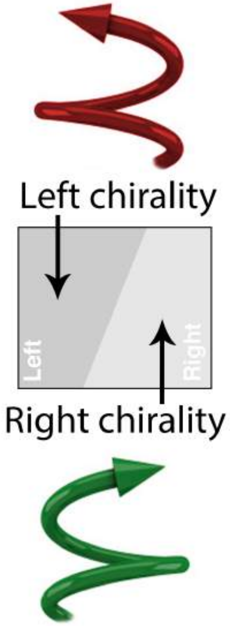
… alternatively a ~few GeV mass **'dark baryon'** in a *hidden sector* (e.g. into which the technibaryon decays)

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



STERILE NEUTRINO DARK MATTER



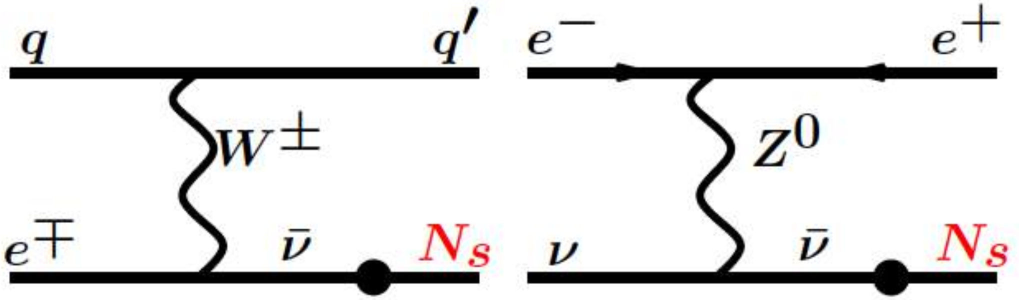


If they mix with the left-handed 'active' neutrinos then would behave as super-weakly interacting particles with an effective coupling: $\theta G_{\rm Fermi}$

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

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

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)

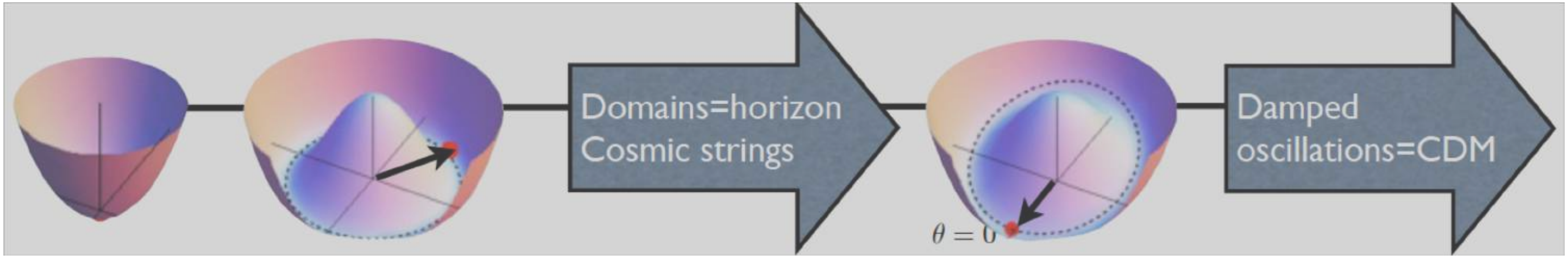
AXION DARK MATTER

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

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 $U(1)_{\text{Peccei-Quinn}}$ 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 (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)



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

No definite indication from theory,
must decide by experiment!

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 $\sigma/m \sim$ barn/GeV)

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