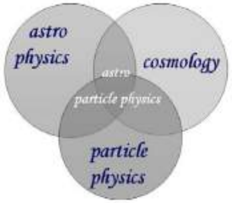
ASTROPARTICLE PHYSICS

Hilary 2021



Oxford Master Course in Mathematical and Theoretical Physics

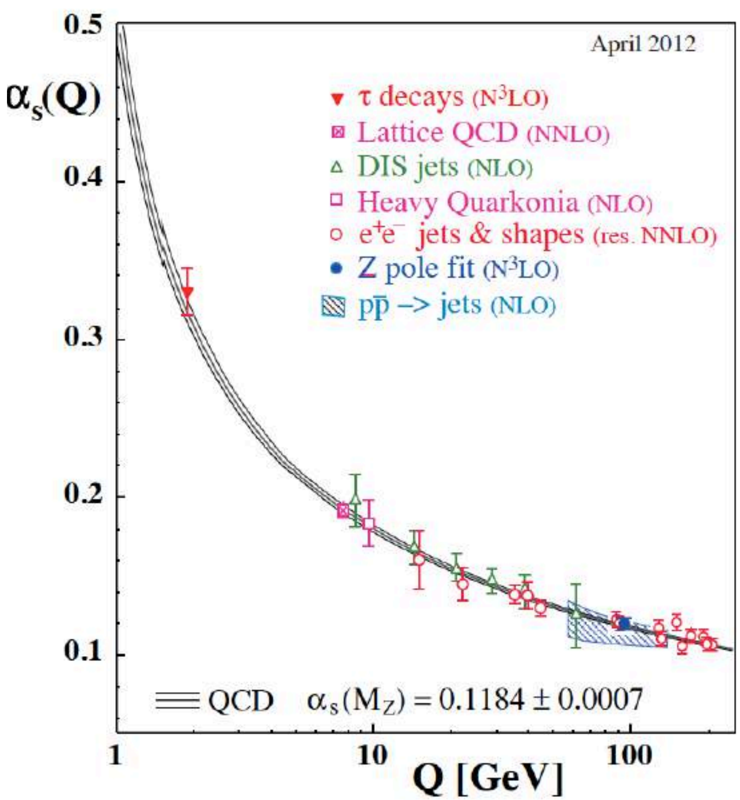
- The universe observed
- Relativistic world models
- Reconstructing the thermal history
- Big bang nucleosynthesis
- Dark matter: astrophysical observations
- Dark matter: relic particles
- Dark matter: direct detection
- Dark matter: indirect detection
- Cosmic rays in the Galaxy
- Antimatter in cosmic rays
- Ultrahigh energy cosmic rays
- High energy cosmic neutrinos
- The early universe: constraints on new physics
- The early universe: baryo/leptogenesis
- The early universe: inflation & the primordial density perturbation
- Cosmic microwave background & large-scale structure

 http://www-thphys.physics.ox.ac.uk/user/SubirSarkar/astropartphys.html

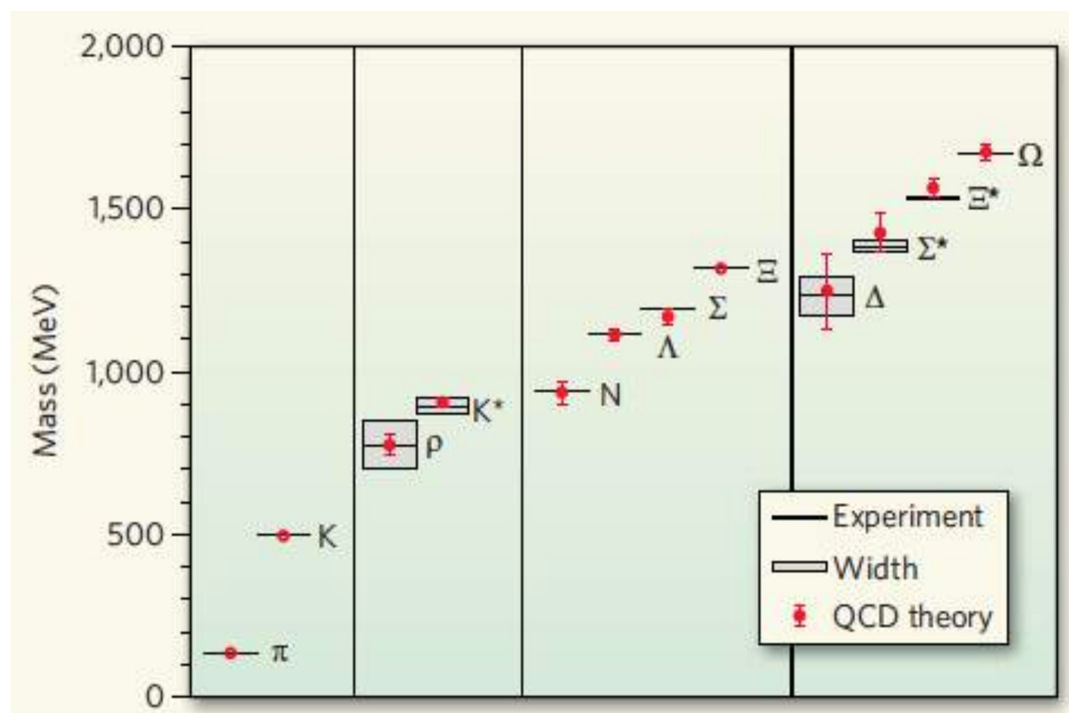
What should the world be made of?

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 $\Omega_B \sim 0.05$

We have a good theory for why baryons are massive and (cosmologically) stable



Bethke, 1210.0325



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

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

What is the expected relic abundance of baryons?

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

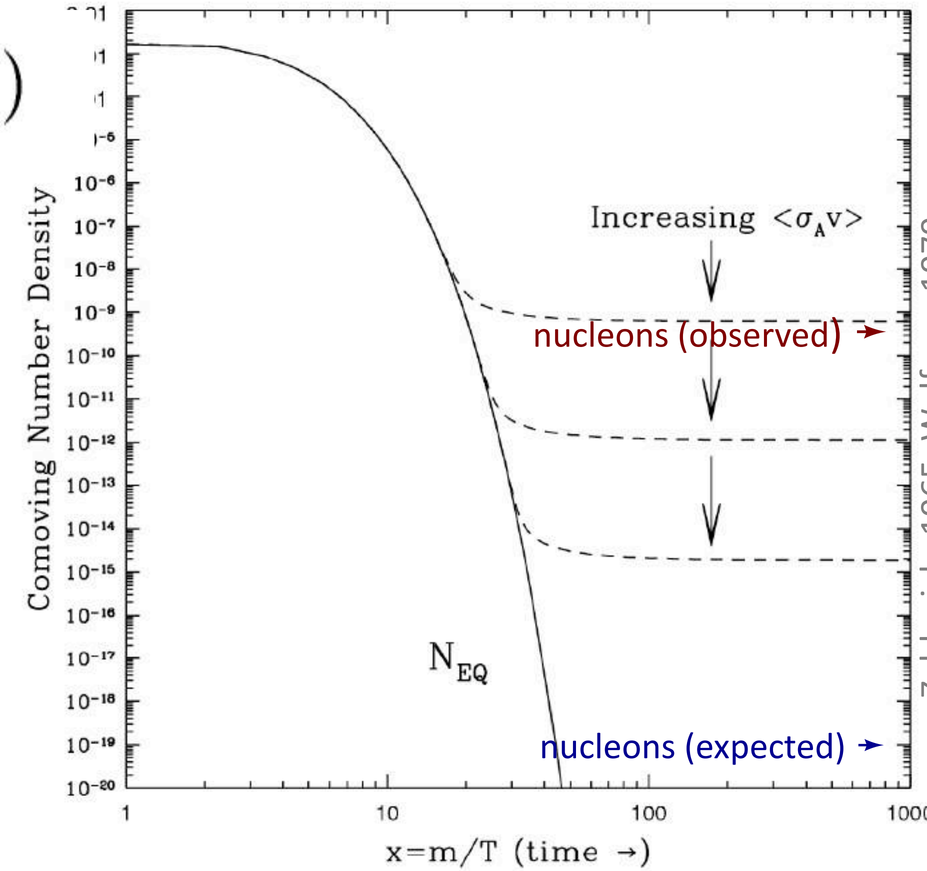
Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate

'Freeze-out' occurs when annihilation rate

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

becomes comparable to the expansion rate

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



Zeldovich, 1965; Wolfram, 1979

i.e. 'freeze-out' occurs at $T \sim m_{\rm N}/45$, 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 are no antibaryons, so we must invoke an **initial *asymmetry***: $$\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$$

(Note: $\Omega_{\rm B}/\Omega_{\rm DM} \sim 1/6$)

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

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

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

non-renormalisable

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

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)

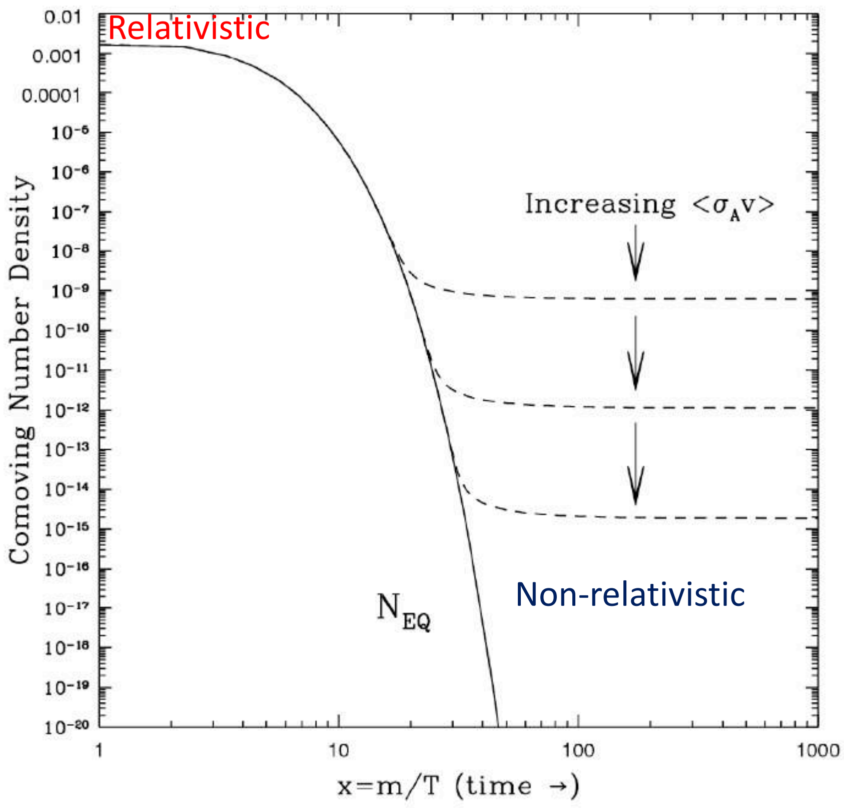
For example, the lightest supersymmetric particle (typically the neutralino χ), *if* protected against decay by *R*-parity, is a candidate for thermal dark matter

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

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

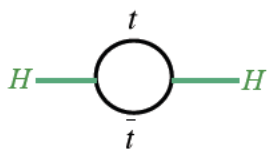
➢ But how might this mass scale arise?

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

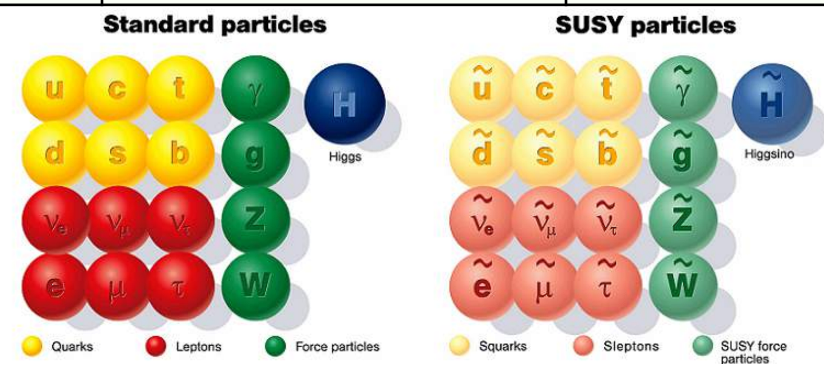
➢ natural for Fermi scale mass/coupling

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	$\Omega_{LSP} \sim 0.3$



$$L^{SM}_{effective} \supset M_A A_\mu A^\mu + m_f \overline{f_L} f_R + M^2_H |H|^2$$

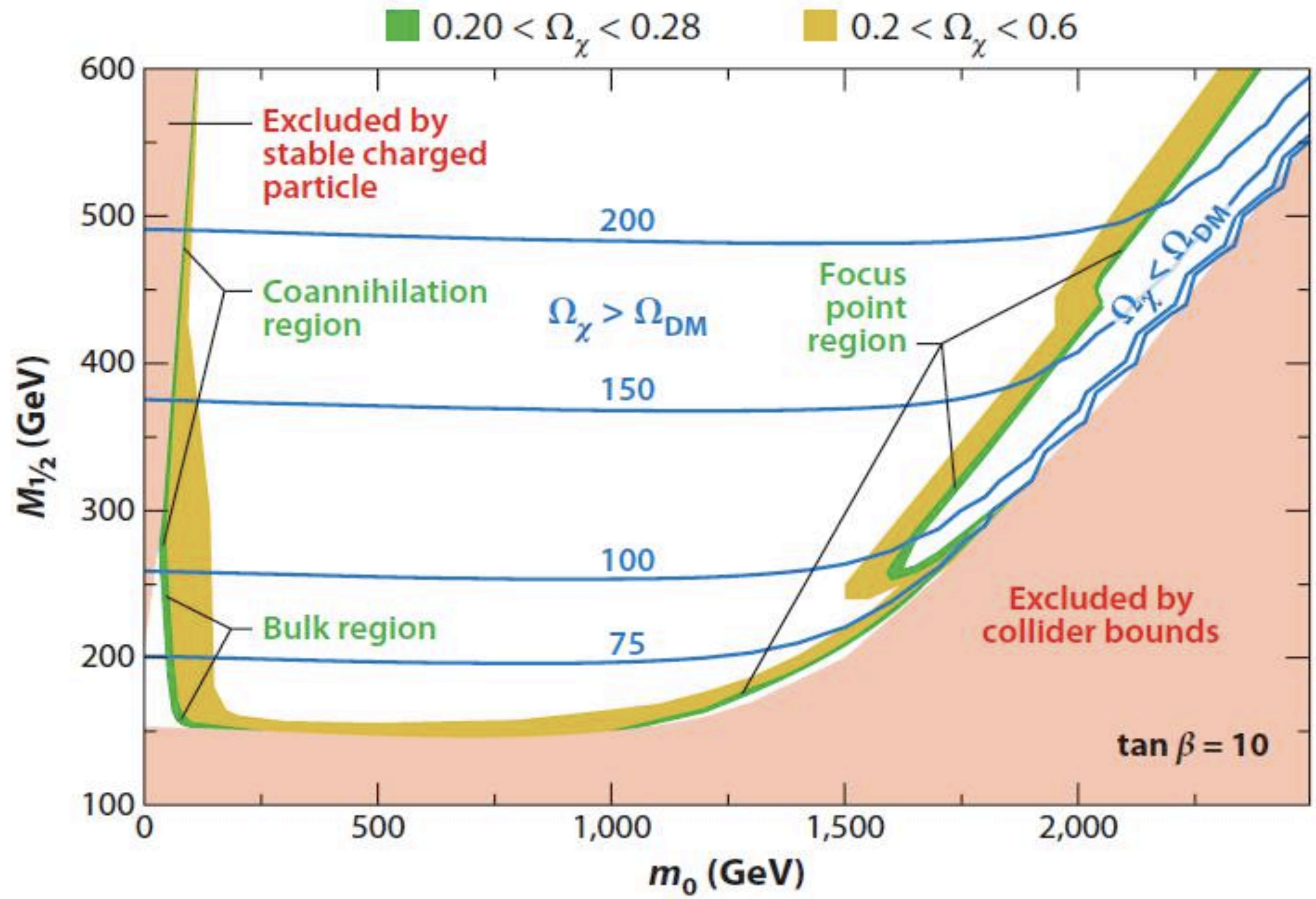


For (softly broken) **supersymmetry** we have the 'WIMP miracle':

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

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

The more we fail to find SUSY particles, the *higher* their relic abundance is expected to be!

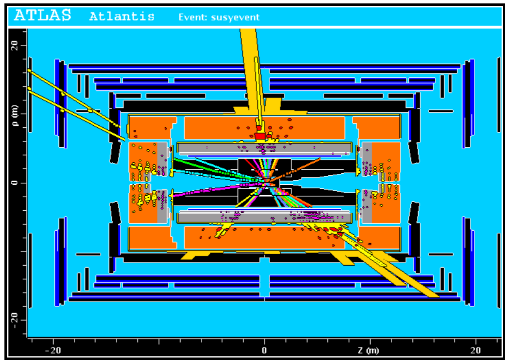


Feng, ARNPS **48**:495,2010

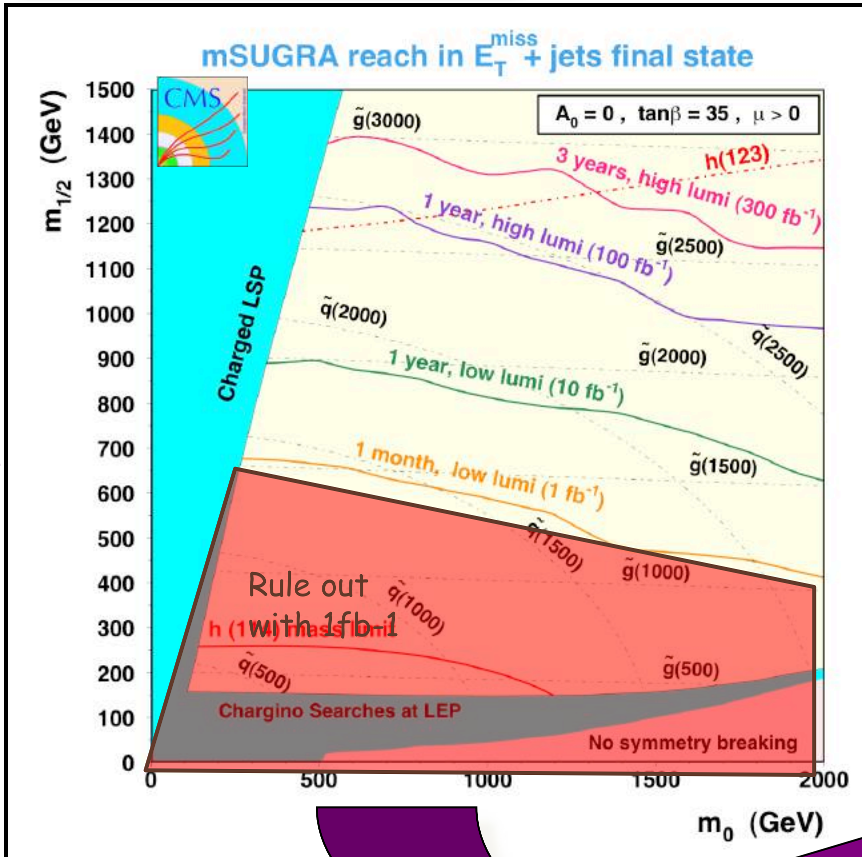
Figure 4

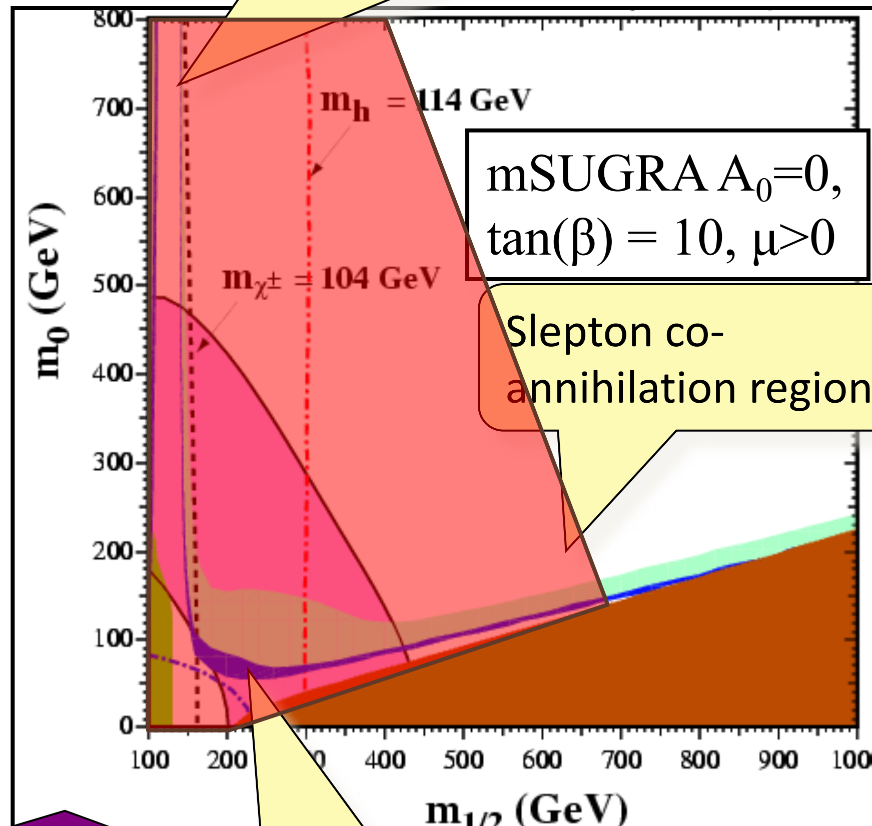
Regions of minimal supergravity (m_0, $M_{1/2}$) parameter space for fixed $A_0 = 0$, $\tan\beta = 10$, and $\mu > 0$. The green (dark yellow) region is cosmologically favored with $0.20 < \Omega_\chi < 0.28$ ($0.2 < \Omega_\chi < 0.6$). The names of cosmologically favored regions (focus point, bulk, and coannihilation) are indicated, along with regions with too much and too little dark matter. The lower right red shaded region is excluded by collider bounds on chargino masses; the upper left red region is excluded by the presence of a stable charged particle. Contours are for neutralino dark matter mass m_χ in gigaelectronvolts. Adapted from Feng, Matchev & Wilczek (2001).

LHC reach for SUSY dark matter



(Courtesey: Alan Barr)





'Focus point' region: annihilation to gauge bosons

Slepton co-annihilation region

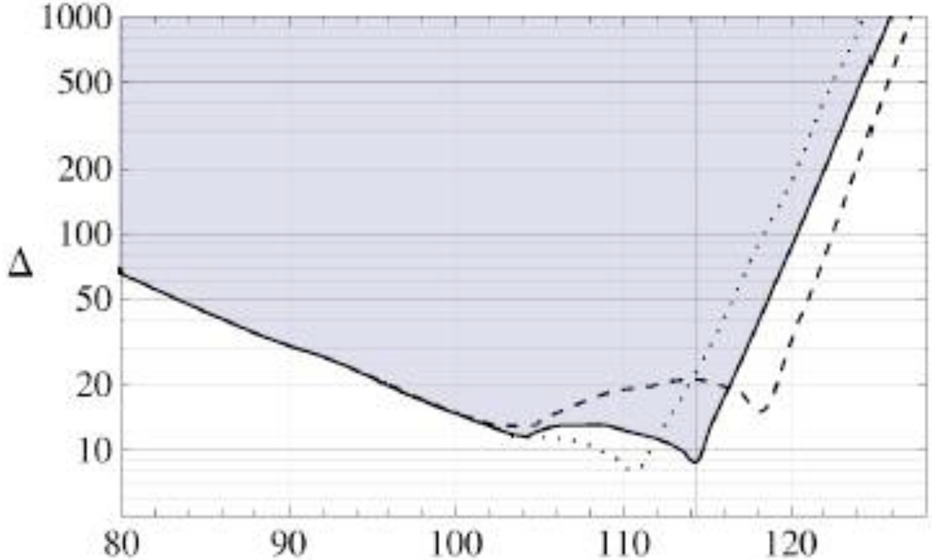
'Bulk' region: t-channel slepton exchange

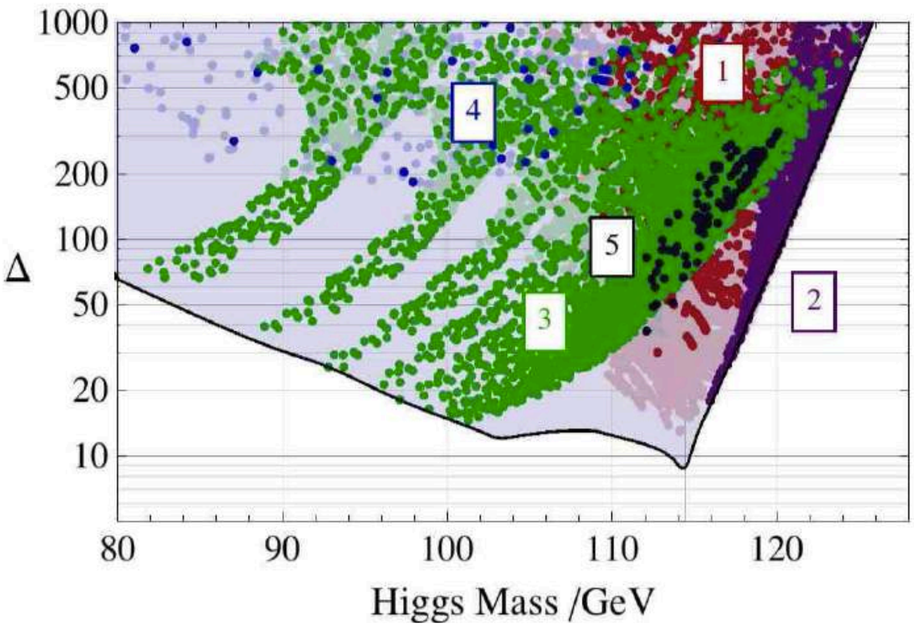
cosmology constraints

‘Natural’ parameter space in the CMSSM

Heavy sparticles → fine tuning of terms … with measure: $\Delta(a_i) = \left| \frac{a_i}{M_Z} \frac{\partial M_Z}{\partial a_i} \right|$

Castell, Ghilencea & Ross, Nucl.Phys. **B835**:110,2010





Relic density unrestricted

SUSY particle masses

$3.20 < 10^4 \,\mathrm{Br}(b \to s\gamma) < 3.84$

$\mathrm{Br}(b \to \mu\mu) < 1.8 \times 10^{-8}$

$\delta a_\mu < 292 \times 10^{-11}$

$-0.0007 < \delta\rho < 0.0012$

$\Delta_{Min} = 9, \quad m_h = 114 \pm 2GeV$

Relic density restricted

1 h^0 resonant annihilation

2 $\tilde{h}$ t-channel exchange

3 $\tilde{\tau}$ co-annihilation

4 $\tilde{t}$ co-annihilation

• 5 A^0 / H^0 resonant annihilation

< 3σ WMAP: $\Delta_{Min} = 18, \quad m_h = 115.9 \pm 2GeV$

What should the world be made of?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
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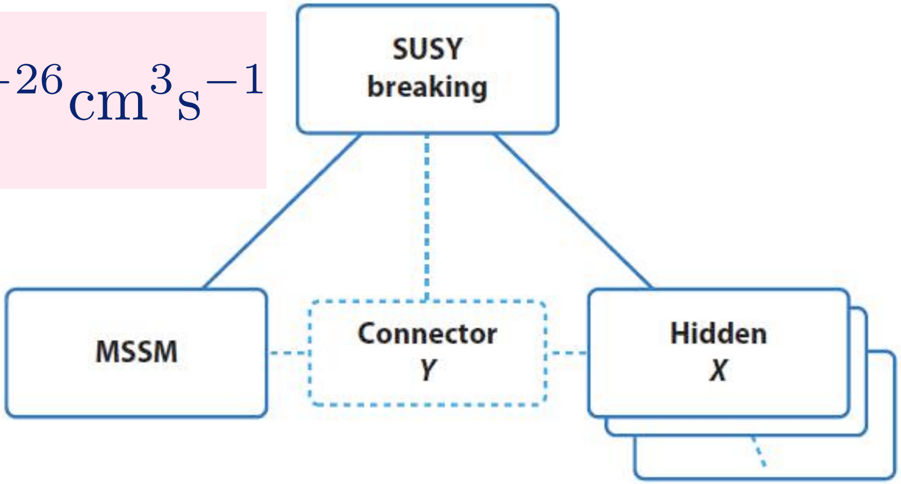
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity?	violated?	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$

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!

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

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



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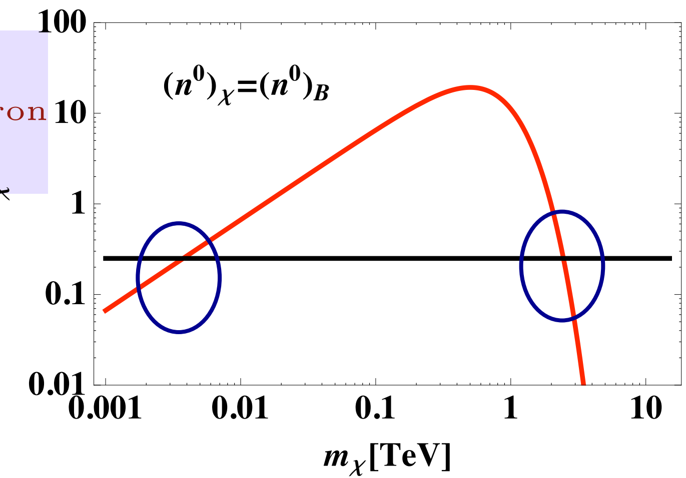
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino? Technibaryon?	R-parity? (walking) Technicolour	violated? $\tau \sim 10^{18}$ yr e^+ excess?!	'freeze-out' from thermal equilibrium Asymmetric (like the observed baryons)	$\Omega_{LSP} \sim 0.3$ $\Omega_{TB} \sim 0.3$

A new electroweak-scale mass particle which shares in this asymmetry (e.g. technibaryon) would have the right abundance to be dark matter … and *explain* the ratio of dark to baryonic matter (Nussinov, PL B**165**:55,1985; Dodelson, Phys.Rev. D40:3252,1989)

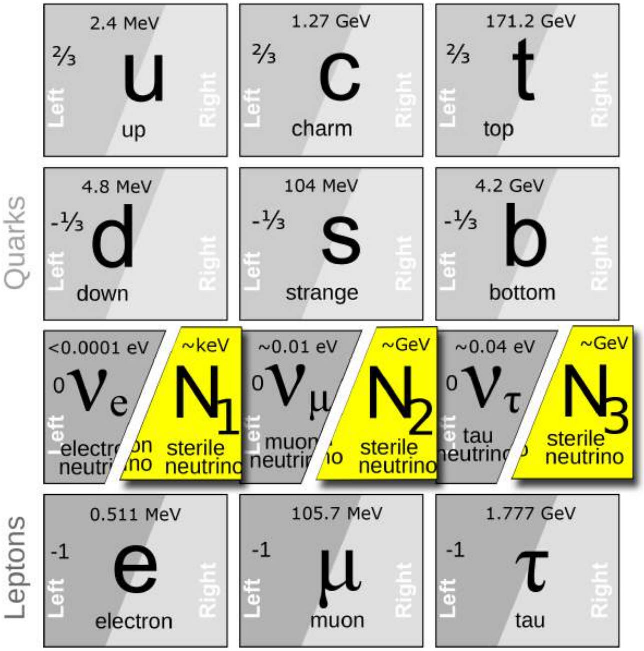
$$\frac{\rho_{\rm DM}}{\rho_{\rm B}} \simeq 6 \sim \frac{m_{\rm DM}}{m_{\rm B}} \left(\frac{m_{\rm DM}}{m_{\rm B}}\right)^{3/2} {\rm e}^{-m_{\rm DM}/T_{\rm dec|sphaleron}}$$

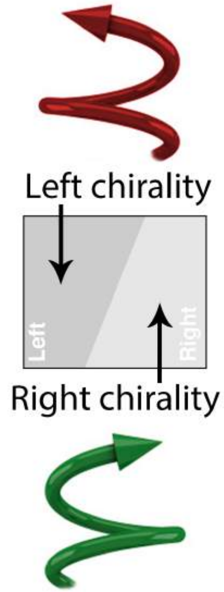
For 'hidden' baryons with mass of a few GeV the required relic abundance is even more natural!

(Gelmini, Hall, Lin, Nucl.Phys.B281:726,1987;
Barr, Chivukula, Farhi, Phys. Lett. B **241**:387,1990)



Sterile (right-handed) neutrinos can also be the dark matter …



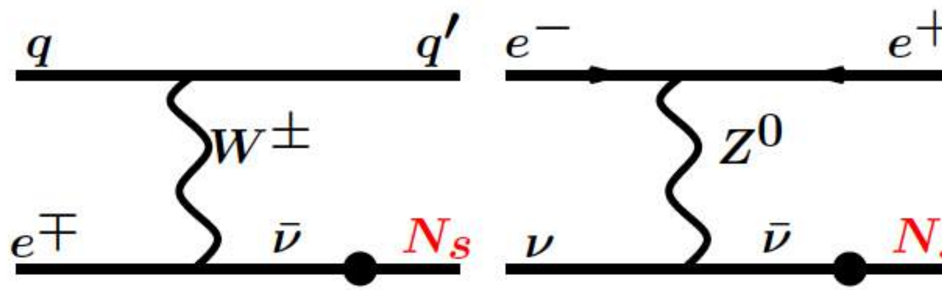


These may mix with the left-handed 'active' neutrinos so would behave as super-weakly interacting particles with an effective coupling: θG_{Fermi}

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

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

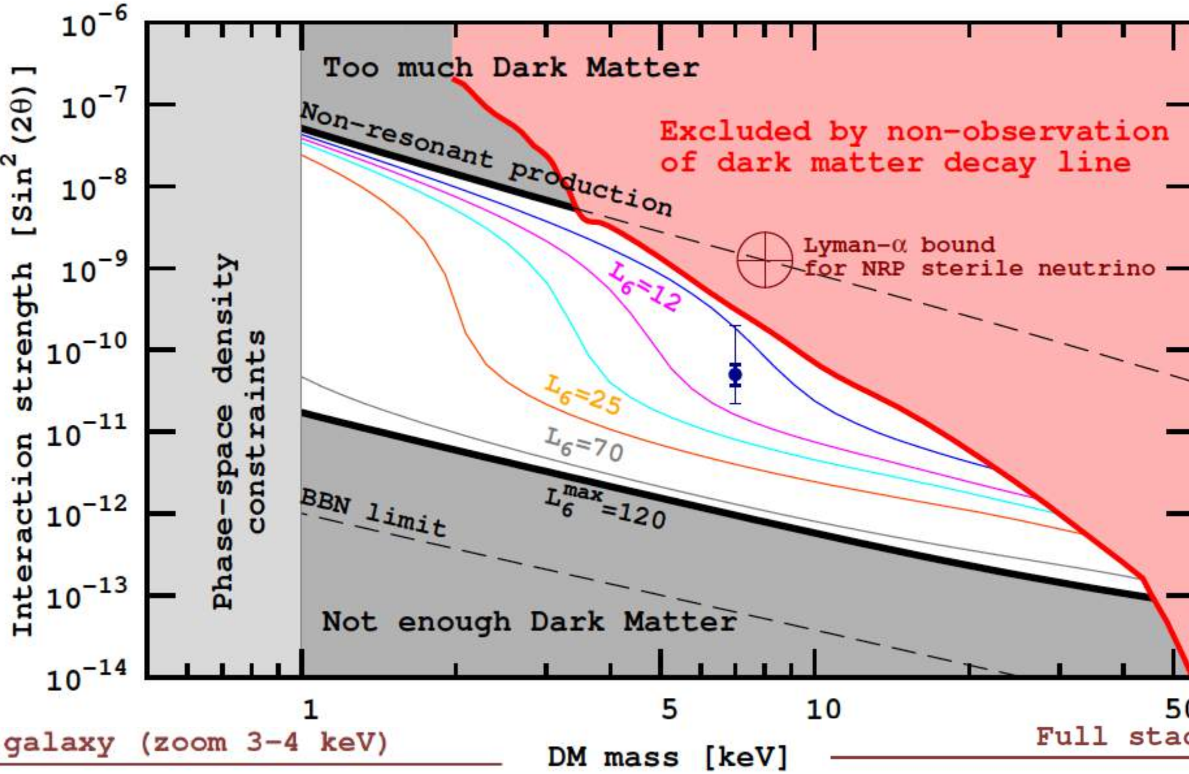
So they will be created when active neutrinos scatter, at a rate $\propto \theta^2 \Gamma_{\text{active}}$



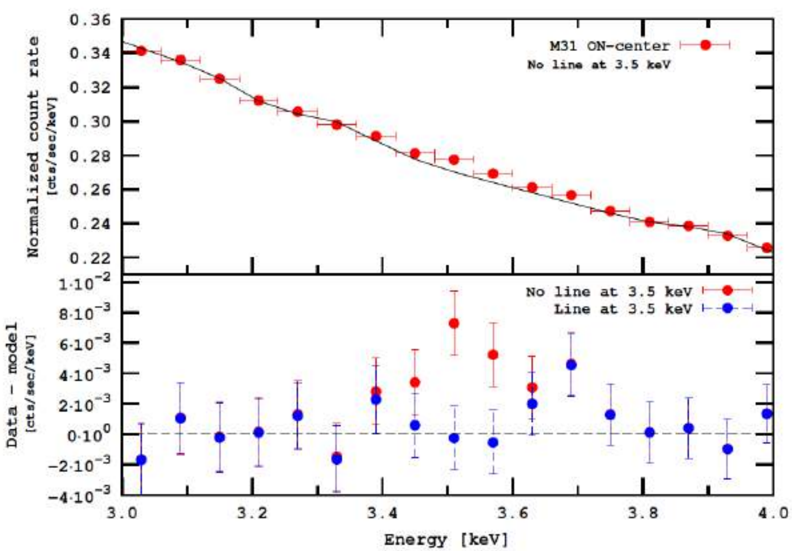
Hence although they may never come into equilibrium, the relic abundance will be of order the dark matter for a mass of order KeV (Dodelson & Widrow, PRL **72**:17,1994)

… however there is no *natural* motivation for such a mass scale

Sterile neutrino and 3.5 keV line

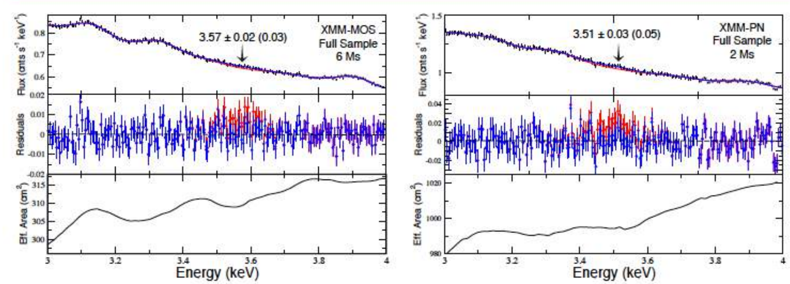


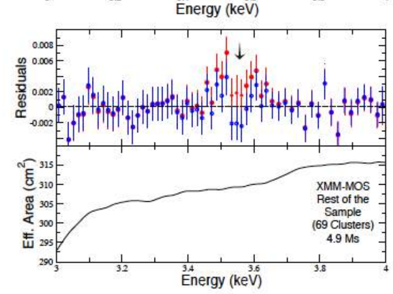
Andromeda galaxy (zoom 3-4 keV)



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

Don't forget the (Oxford) 17 keV anomaly!

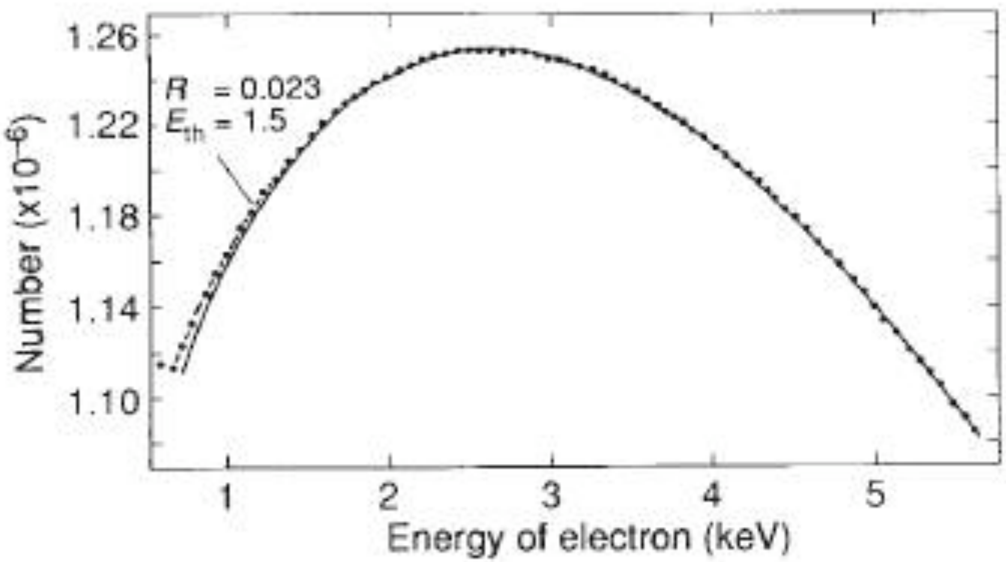
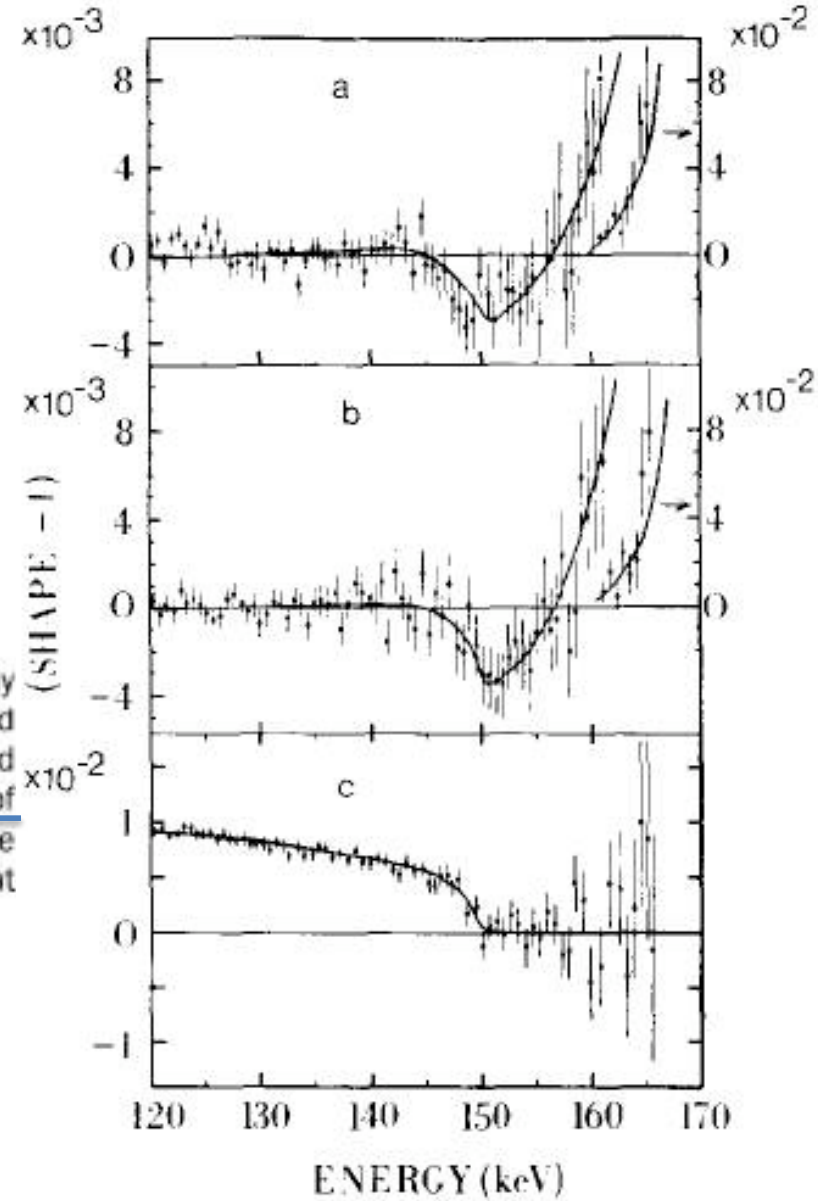


FIG. 2 Part of the distribution of energies of electrons from the β decay of tritium reported by Simpson[1]. The smooth curve is the expected spectrum with only a massless neutrino produced, while the dashed curve shows the expected effect of adding a massive neutrino of 17.1 keV, with a coupling R, of 2.3% rather than the 3% given in the text. The next point to the left of the lowest-energy point is off-scale at 1.6×10^6 counts. E_{th} is the value in keV at the kink.



~7σ evidence from a laboratory experiment that turned out to be a conspiracy of systematic effects!

Axion dark matter

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

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

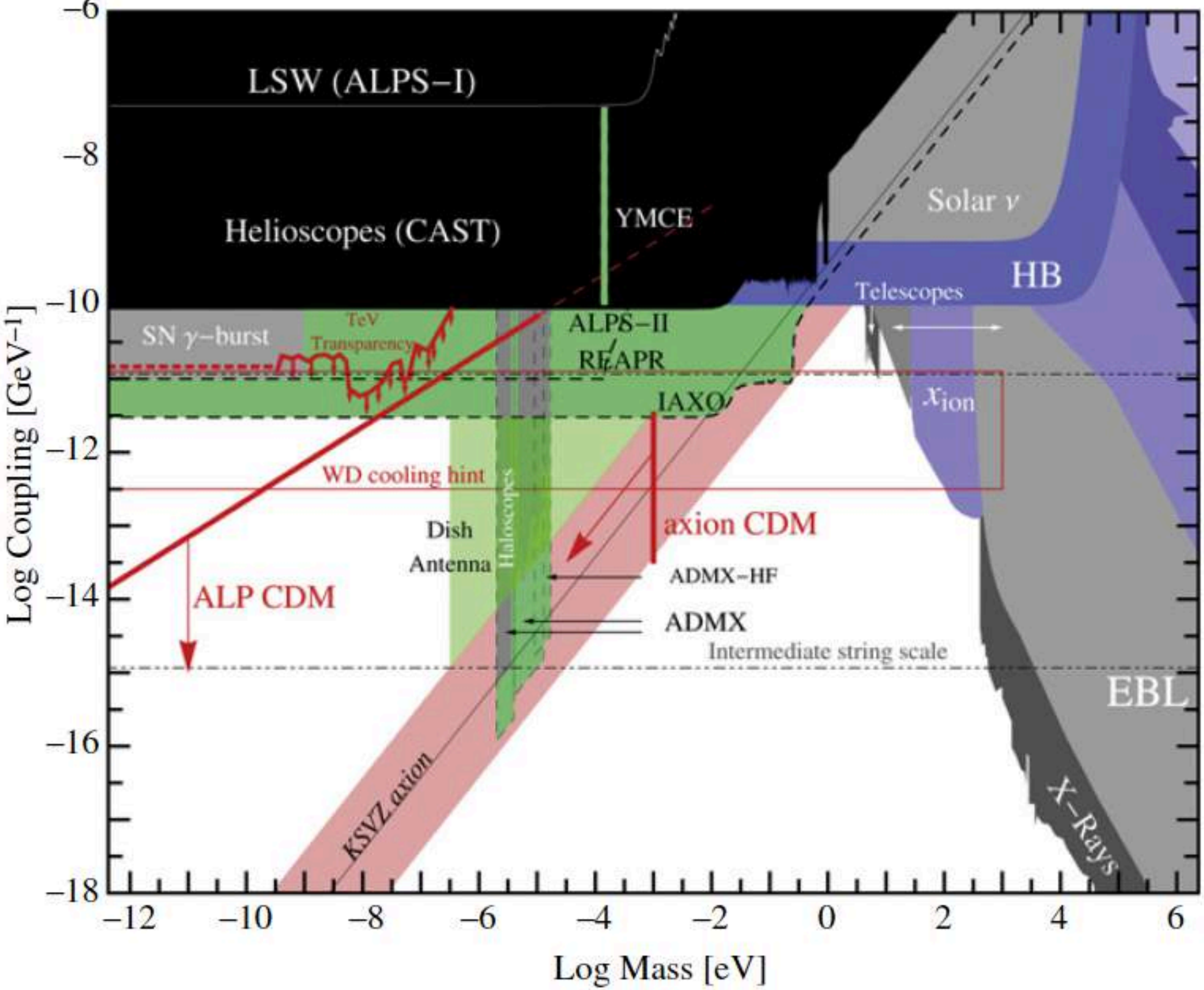
To achieve this without fine-tuning, $\theta_{\rm QCD}$ must be made a dynamical parameter, through the introduction of a new $U(1)_{\text{Peccei-Quinn}}$ symmetry which must be broken … the resulting (pseudo) Nambu-Goldstone boson is the QCD **axion** which later acquires a small mass through its mixing 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 $\Omega_a h^2 \sim 10^{11}$ 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?)

Current limits on axions and axion-like particles



Snowmass Intensity Frontier WG summary, 1401.6077

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 thermal equilibrium Asymmetric baryogenesis (how?)	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{QCD'}$ $\sim 5\Lambda_{QCD}$	Dark baryon	$U(1)_{DB}$	?	Asymmetric (like the observed baryons)	$\Omega_{DB} \sim 0.3$
Λ_{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	Asymmetric (like the observed baryons)	$\Omega_{TB} \sim 0.3$
$\Lambda_{hidden\ sector}$ $\sim(\Lambda_F M_P)^{1/2}$	Crypton? hidden valley?	Discrete (model-dependent)	$\tau \gtrsim 10^{18}$ yr	Varying gravitational field during inflation	$\Omega_X \sim 0.3$?
$\Lambda_{see\text{-}saw}$ $\sim\Lambda_{Fermi}^2/\Lambda_{B-L}$	**Neutrinos**	Lepton number	Stable.	Thermal (like CMB)	$\Omega_\nu > 0.003$
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!