Discovering dark matter

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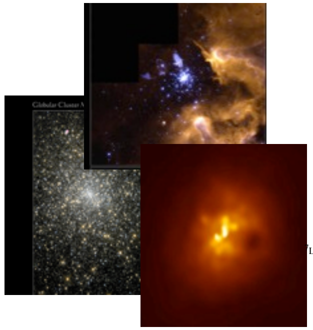
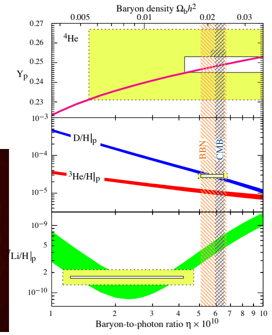
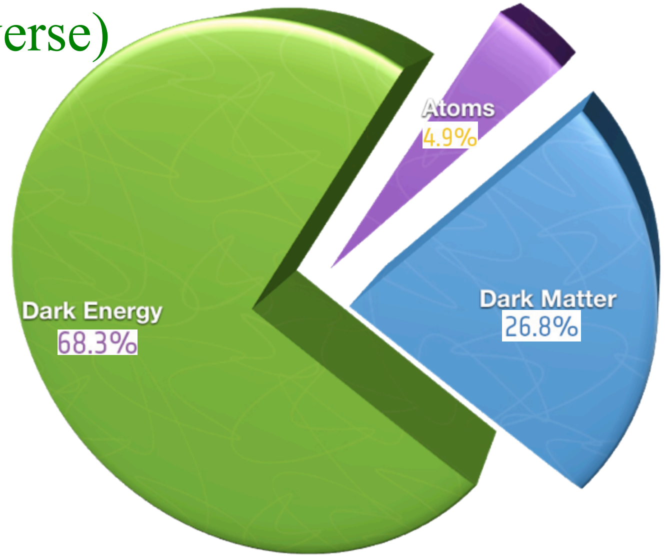
What is the world made of?

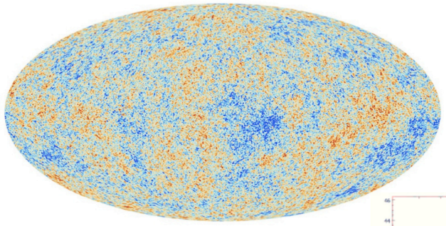
Mainly geometrical evidence:
$\Lambda \sim O(H_0^2)$, $H_0 \sim 10^{-42}$ GeV
… **dark energy** is *inferred* from the
'cosmic sum rule': $\Omega_m + \Omega_k + \Omega_\Lambda = 1$
(*assuming* a homogeneous universe)

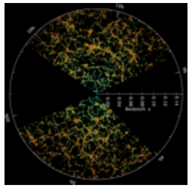


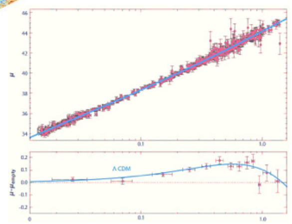


Baryons
(but *no*
anti-baryons)

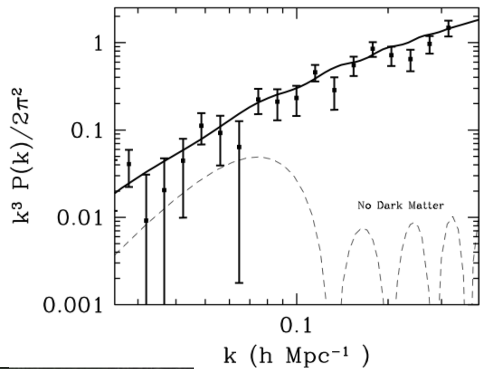




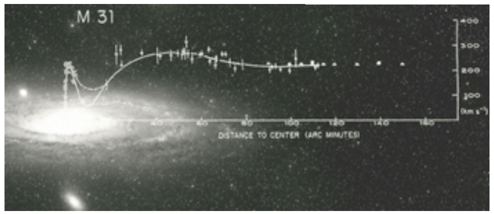


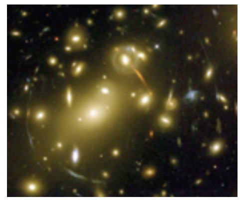


Both geometrical *and*
dynamical evidence for
dark matter (*if* GR is valid)

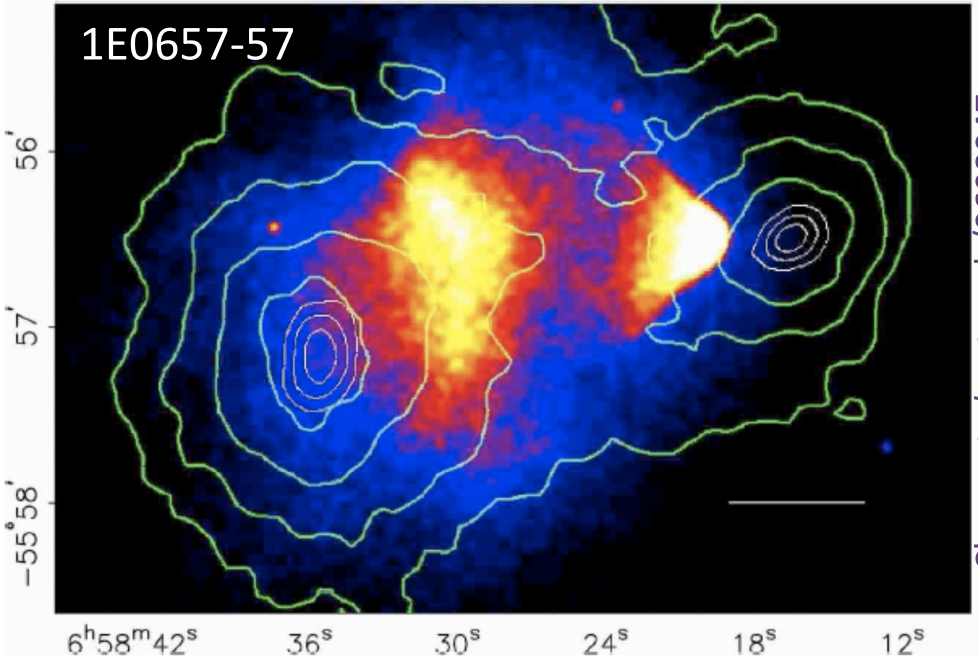


Both the baryon asymmetry and dark matter
require new physics beyond the
Standard $SU(3)_c$x$SU(2)_L$x$U(1)_Y$ Model
… dark energy is even more mysterious
(but still lacks compelling dynamical evidence)





What can astrophysics tell us about dark matter interactions?



Clowe *et al*, astro-ph/0608047

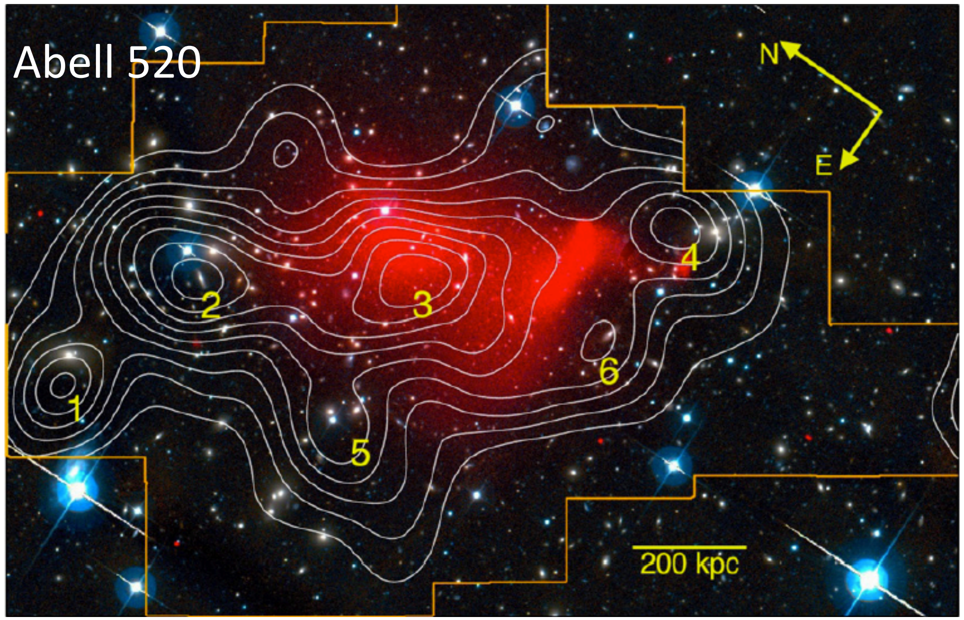
The 'Bullet Cluster' is often cited as evidence that dark matter is *collisionless* … in actual fact it sets a rather *weak* limit on self-interactions: $\sigma \lesssim 2\mathrm{x}10^{-24}$ cm^2/GeV

Moreover it poses a *challenge* for ΛCDM cosmology: why is the relative velocity so high (>3000 km/s on a scale of 5 Mpc)?

Nine other colliding clusters have been found … the odds are *tiny* in a Gaussian density field!

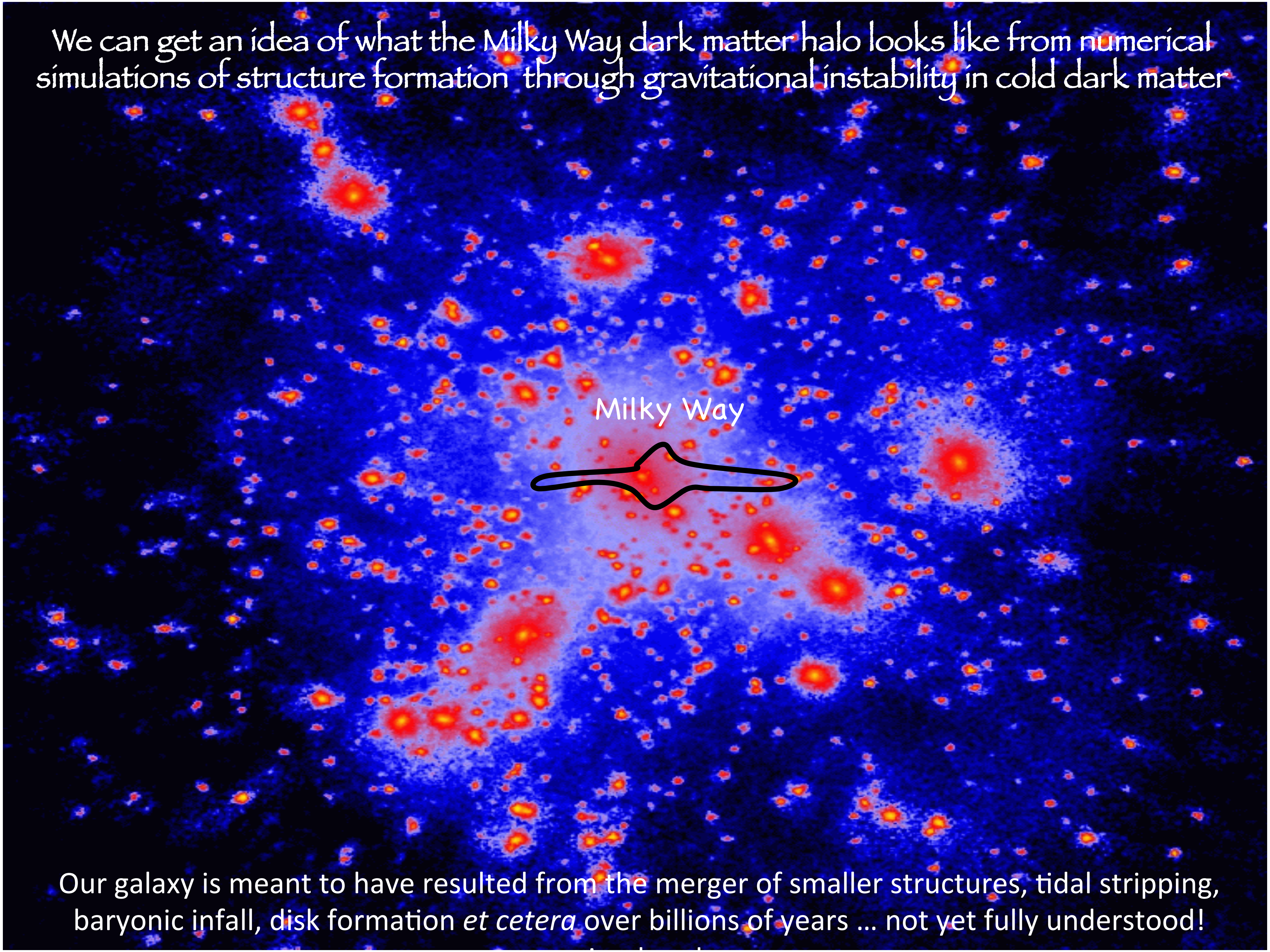
But in Abell 520, the DM concentration is partly *coincident* with the X-ray emitting gas implying that DM is *self-interacting* with: $\sigma \approx 2\ \mathrm{x}10^{-24}$ cm^2/GeV (Jee *et al*, 1401.3356)

This result is contested … in any case the separation between DM and galaxies will be *time-dependent* and sensitive to whether the self-interactions are contact or long-range (Frandsen *et al*, 1308.3419) … so data from gravitational lensing can in principle discriminate between DM particle candidates



Jee *et al*, arXiv:1202.6368

We can get an idea of what the Milky Way dark matter halo looks like from numerical simulations of structure formation through gravitational instability in cold dark matter



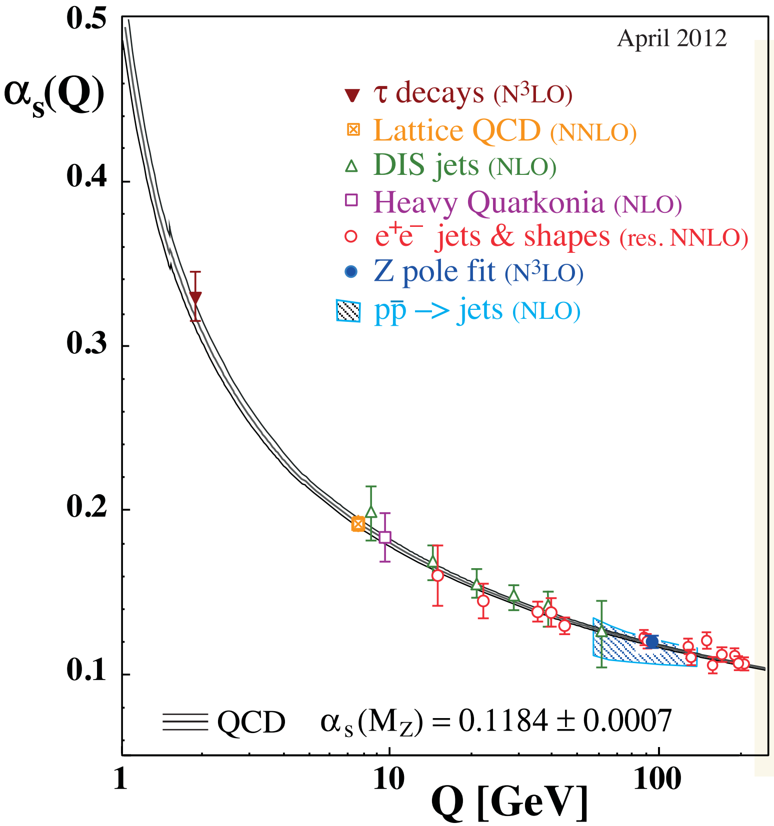
Our galaxy is meant to have resulted from the merger of smaller structures, tidal stripping, baryonic infall, disk formation *et cetera* over billions of years … not yet fully understood!

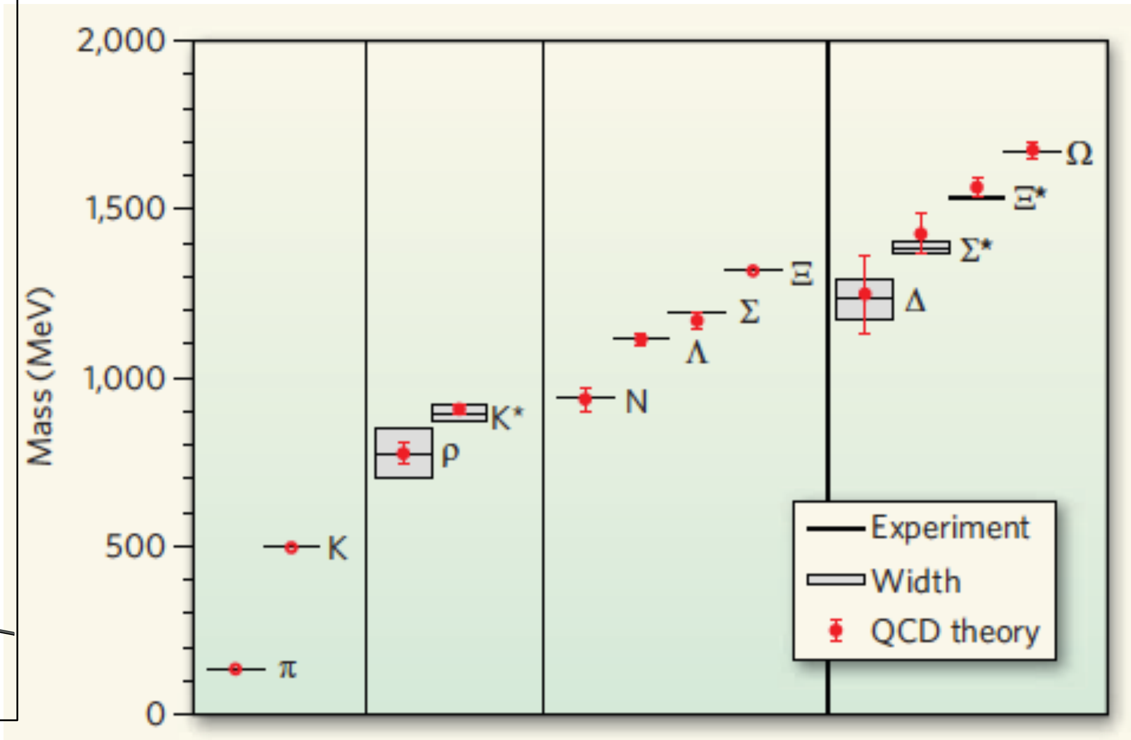
What should the world be made of?

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 *et al* [PDG], 1210.0325





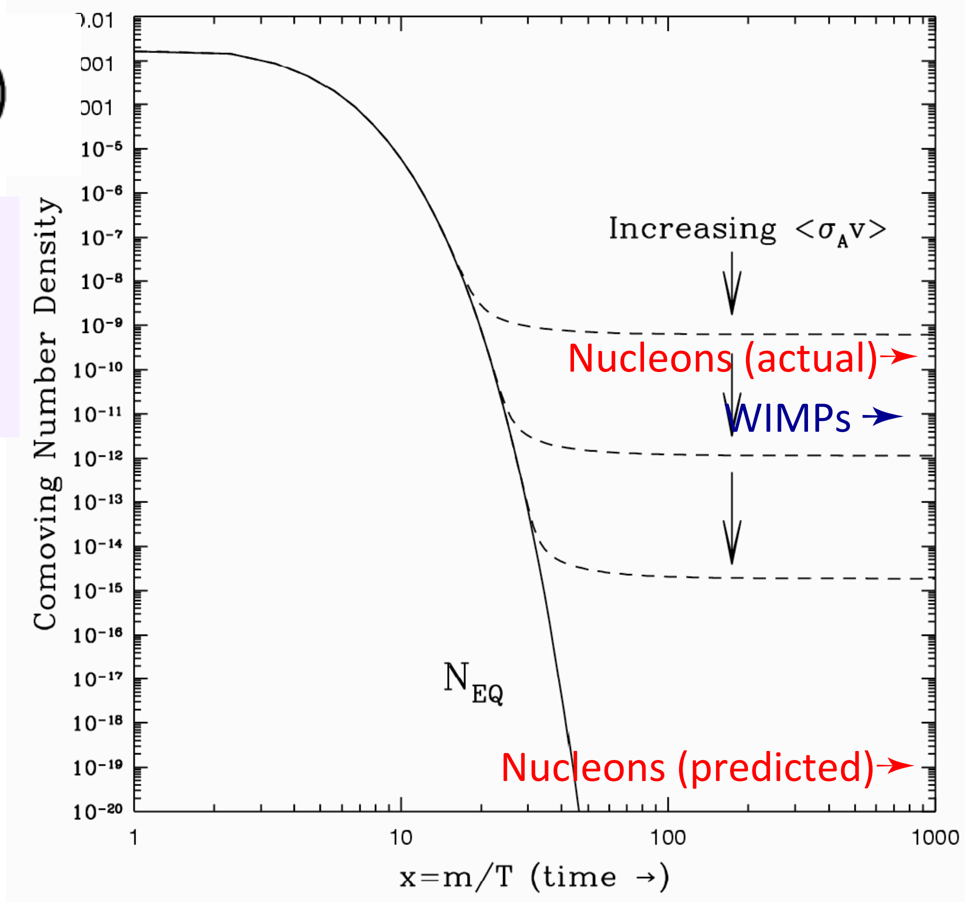
Durr et al, Science 322:2224,2008

We understand the dynamics of QCD … and can calculate the mass spectrum

Nevertheless we get the cosmology of baryons *badly* wrong!

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

Chemical equilibrium is maintained as long as the 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

$$H \sim \frac{\sqrt{g}T^2}{M_{\rm P}}$$ 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 **6×10^9 times *bigger* for baryons**, and there seem to be ***no* antibaryons**, so we must invoke an initial baryon 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'!)

To make the baryon asymmetry requires a lot of new physics:

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

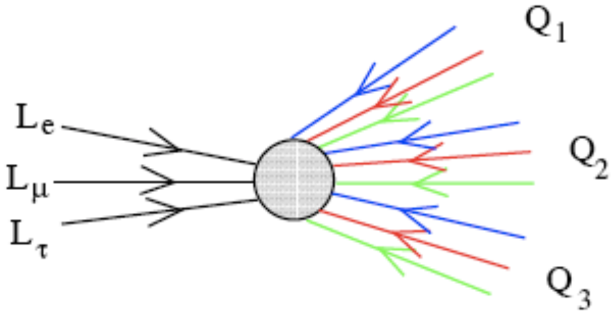
The SM does allow *B*-number violation (through non-perturbative - sphaleron-mediated – processes) … but *CP*-violation is *too weak* and $SU(2)_L \times U(1)_Y$ breaking is a 'cross-over' (*not* out-of-equilibrium)

Hence the generation of the observed matter-antimatter asymmetry *requires* new BSM physics (could be related to neutrino mass **if this arises from violation of lepton number → leptogenesis)**

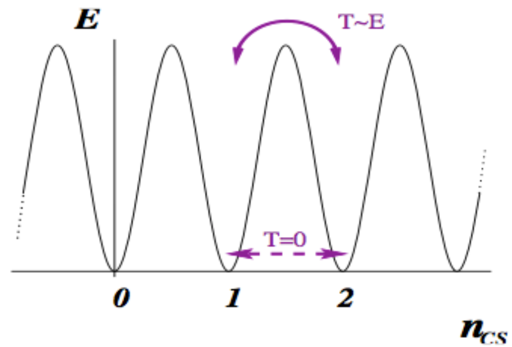
'See-saw': $\mathcal{L} = \mathcal{L}_{SM} + \lambda^*_{\alpha J} \overline{\ell}_\alpha \cdot H N_J - \frac{1}{2}\overline{N_J} M_J N_J^c$ $\quad \lambda M^{-1} \lambda^{\mathrm{T}} \langle H^0 \rangle^2 = [m_\nu]$

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

Asymmetric baryonic matter



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



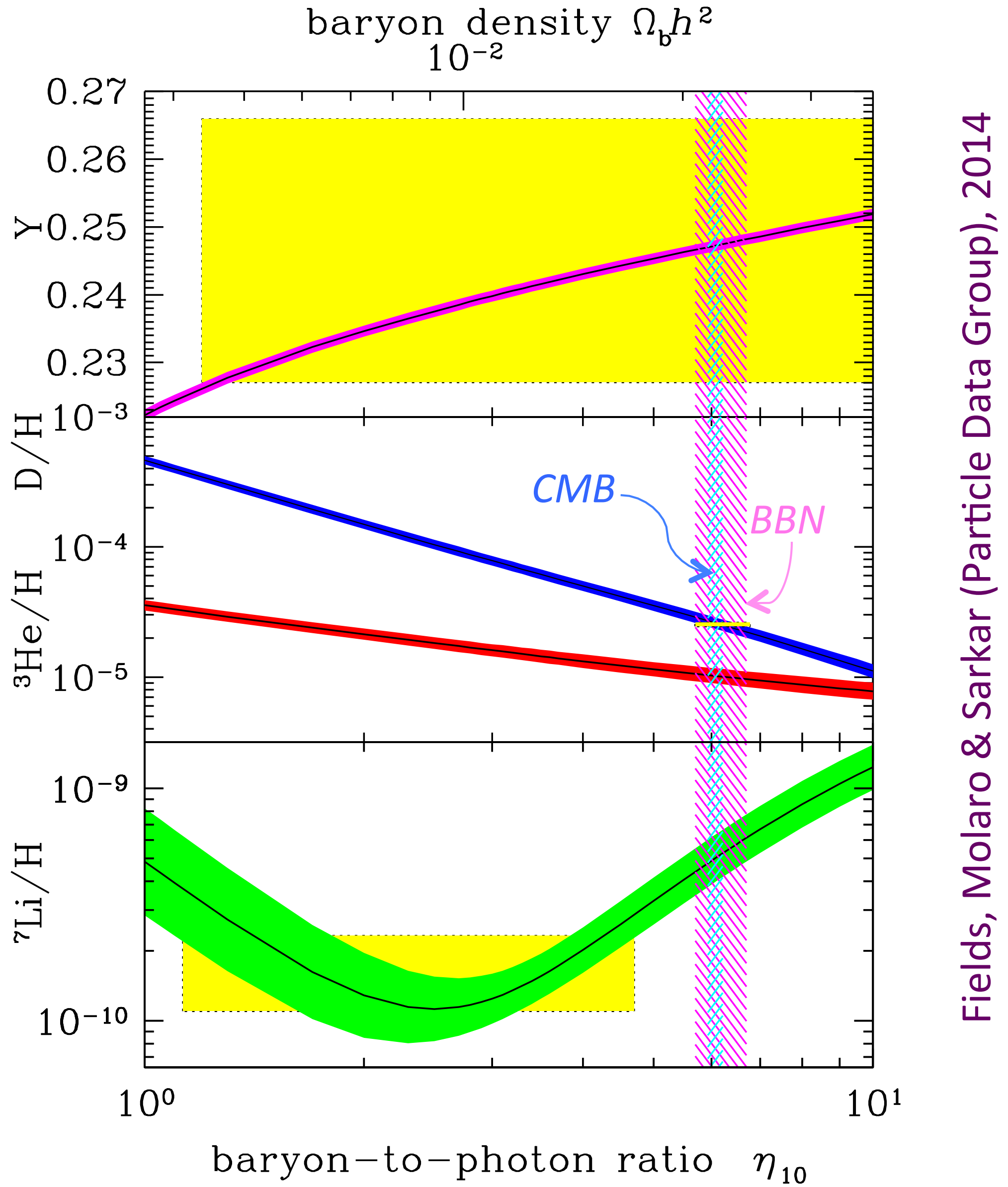
(Barr, Chivukula, Farhi, PLB 241:387,1990)

Any primordial lepton asymmetry (e.g. from *out*-of-equilibrium decays of the right-handed *N*) would be redistributed by *B+L* violating processes in the SM (which *conserve B-L*) amongst *all* fermions – in particular **baryons** - which couple to the electroweak anomaly

Although **leptogenesis** may never be directly testable, evidence for a *Majorana* neutrino mass from observation of neutrino*less* ββ-decay would provide powerful support for the idea

… in any case we accept that the only kind of matter which we are certain *exists*, originated ***non-thermally*** in the early universe

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

The Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ Model (viewed as an effective field theory up to some high energy cut-off scale M) accurately describes *all* microphysics

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

hierarchy problem

super-renormalisable

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

renormalisable

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

neutrino mass — proton decay

non-renormalisable

New physics beyond the SM ⇒ **non-renormalisable operators** suppressed by M^n which 'decouple' as $M \longrightarrow M_P$ (… so **neutrino mass** is small, **proton decay** is slow *etc*)

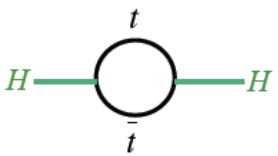
But as *M* is raised, the effects of the **super-renormalisable operators** are *exacerbated*
One solution for Higgs mass divergence ⟶ 'softly broken' supersymmetry at $M \sim 1$ TeV

This provides new possibilities for baryogenesis as well as a good candidate for **dark matter** – the **lightest supersymmetric particle** (typically the neutralino χ), *if* it is cosmologically *stable* because of a conserved quantum number (R-parity)

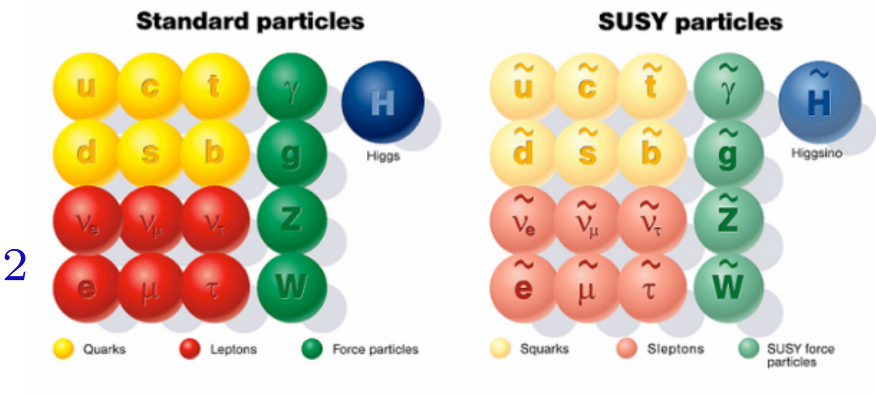
This has been the target of *most* dark matter searches, whether using nuclear recoil detectors or looking for cosmic annihilation products, or missing E_T signals at colliders

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	$\Omega_{\mathrm{B}} \sim 10^{-10}$ *cf.* observed $\Omega_{\mathrm{B}} \sim 0.05$
$\Lambda_{\mathrm{Fermi}} \sim G_{\mathrm{F}}^{-1/2}$	Neutralino?	R-parity?	Violated? (matter parity *adequate* to ensure p stability)	'freeze-out' from thermal equilibrium	$\Omega_{\mathrm{LSP}} \sim 0.3$



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



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?

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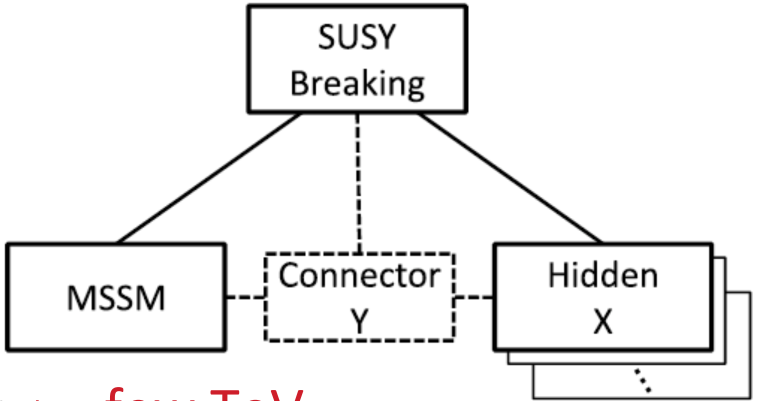
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	*R*-parity?	Violated? (matter parity *adequate* for *p* stability)	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$

(GMSB) Hidden sector matter also provides the '*WIMPless* 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: ~0.1 GeV → ~few TeV

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

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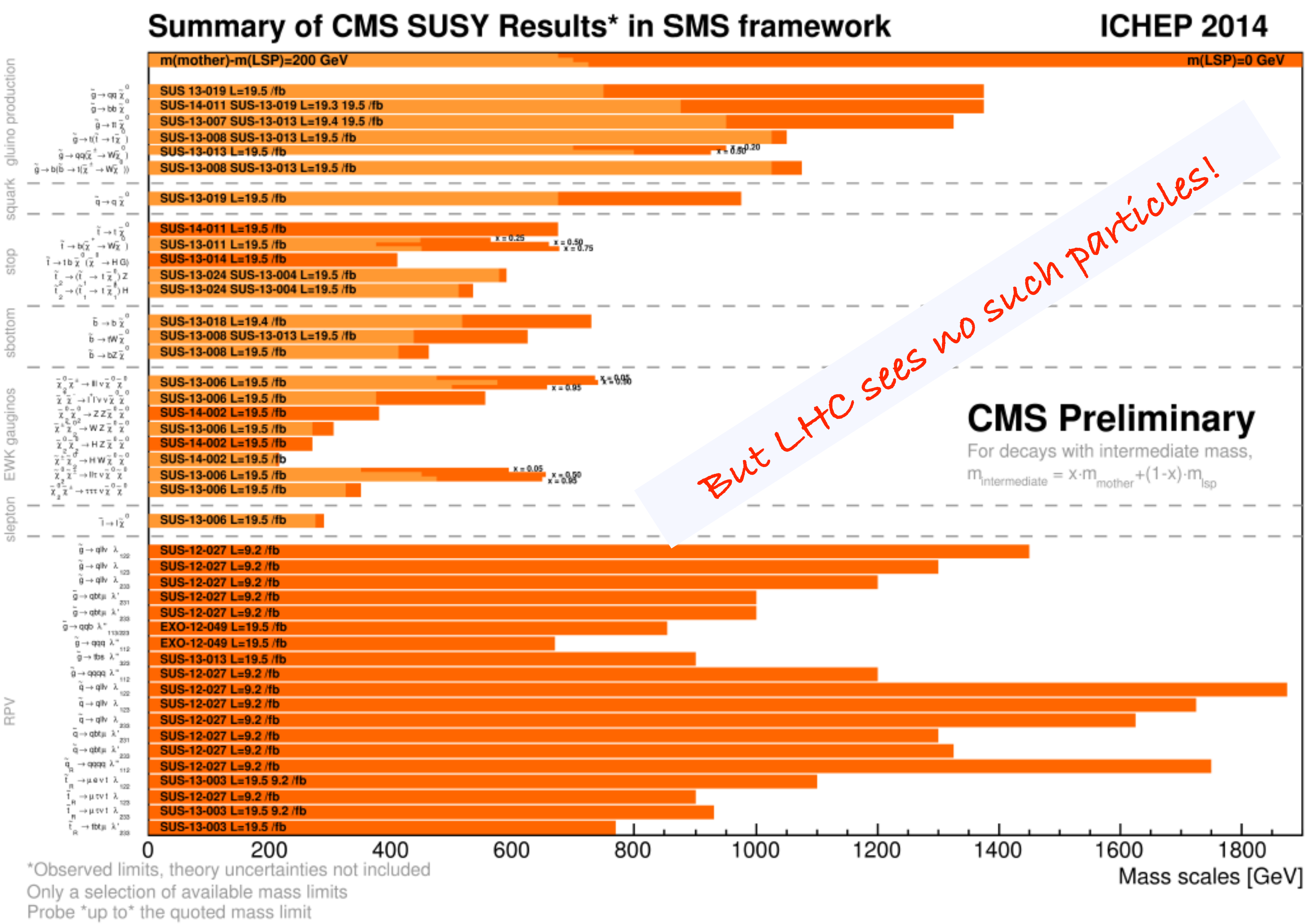
Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
RPV
SUS 13-019 L=19.5 /fb
SUS-14-011 SUS-13-019 L=19.3 19.5 /fb
SUS-13-007 SUS-13-013 L=19.4 19.5 /fb
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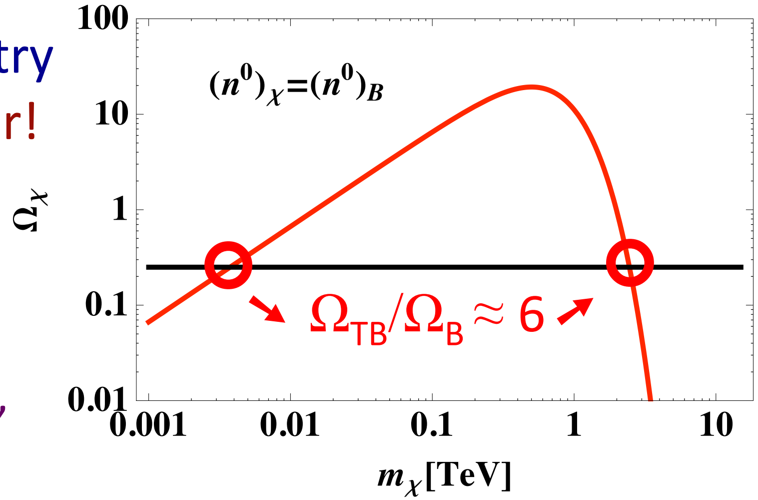
x = 0.25
x = 0.50
x = 0.75
x = 0.95
x = 0.05
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother+(1-x)·m_lsp
But LHC sees no such particles!
0
200
400
600
800
1000
1200
1400
1600
1800
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

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!

For example a *O*(TeV) mass **technibaryon** can be the dark matter (Nussinov 1985) … another possibility is a ~6 GeV mass **'dark baryon'** in a *hidden sector* (Gelmini, Hall & Lin 1986, Kaplan 1992): $\Omega_\chi = (m_\chi \mathcal{N}_\chi / m_B \mathcal{N}_B)\Omega_B$



ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt = (1.0 - 20.3)$ fb^{-1} $\sqrt{s} = 7, 8$ TeV

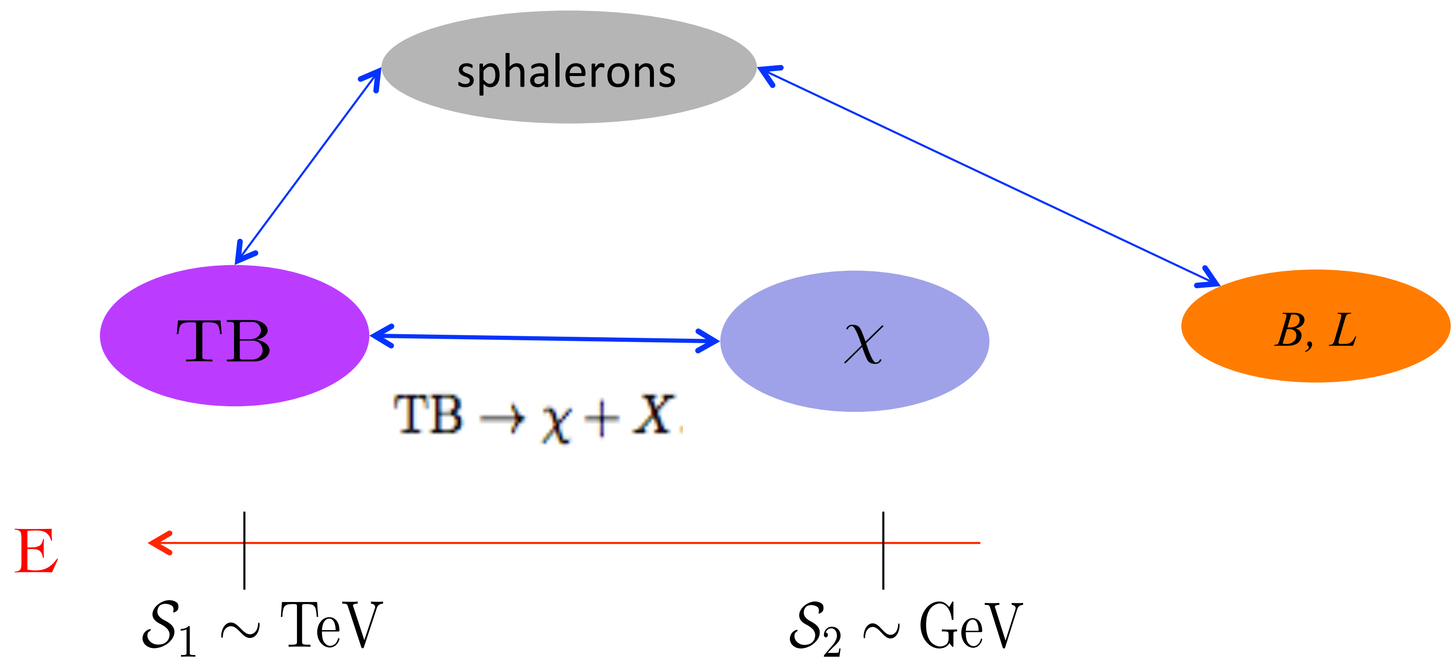
	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt[\text{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	M_S 5.2 TeV	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\ e, \mu$	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to ZZ \to \ell\ell qq$	$2\ e, \mu$	2 j / 1 J	–	20.3	G_{KK} mass 730 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl}$ [illegible]	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 2.0 TeV	BR [illegible]	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\, \ell'\ell'$	$3\ e, \mu$	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	$2\ e, \mu$	2 j / 1 J	–	20.3	W' mass 1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R \to t\bar{b}$	$1\ e, \mu$	2 b, 0-1 j	Yes	14.3	W' mass 1.84 T[illegible]		ATLAS-CONF-2013-050
	LRSM $W'_R \to t\bar{b}$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	W' mass 1.[illegible]		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\ e, \mu$	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	$0\ e, \mu$	1-2 j	Yes	10.5	M_* [illegible]	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	1.0	LQ mass [illegible]eV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	1.0	LQ mass [illegible]85 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	$1\ e, \mu, 1\ \tau$	1 b, 1 j	–	4.7	LQ mass [illegible]34 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	$1\ e, \mu$	≥ 2 b, ≥ 4 j	Yes	14.3	T m[illegible] 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	14.3	[illegible] 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	$2/\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	[illegible] 735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	$2/\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	[illegible] 755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	[illegible] 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\ e, \mu, 1\ \gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \to W\gamma$	$1\ e, \mu, 1\ \gamma$	–	Yes	20.3	a_T mass 960 GeV		to be submitted to PLB
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\ e, \mu$	–	–	5.8	$N^{\pm}$ mass 245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e, \mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g \rvert = 1 g_D$	1207.6411

$\sqrt{s} = 7$ TeV $\sqrt{s} = 8$ TeV

10^{-1} 1   10   Mass scale [TeV]

But LHC sees no such particles either!

Why may we not have seen these particles yet?



Frandsen, Sarkar & Schmidt-Hoberg, 1103.4350

S_1 States (constituents) carry weak charges and are connected to sphalerons

S_2 States are SM singlets (in a hidden sector/hidden valley) but directly connected to the S_1 sector (with scale separation – TeV ➛ GeV – because of different β-function)

$\mathrm{TB} \to \chi + \mathrm{X}$ is in equilibrium until $T \lesssim T_{\mathrm{sph}}$, then χ decouples and becomes DM

The S_1 states *do* couple to the SM (so should show up at LHC14!

NB: Such asymmetric dark matter would naturally have strong self-interactions

Axion dark matter

$$\begin{aligned}\mathcal{L}_{\text{eff}} &= M^4 + M^2\Phi^2 && \text{super-renormalisable}\\ &+ (D\Phi)^2 + \bar{\Psi}\,\not{D}\Psi + F^2 + \bar{\Psi}\Psi\Phi + \Phi^2 \boxed{+\theta_{\text{QCD}} F\tilde{F}} && \text{renormalisable}\\ &+ \frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \ldots && \text{non-renormalisable}\end{aligned}$$

The SM admits a term which would lead to CP violation in strong interactions, hence an (unobserved) electric dipole moment for neutrons → requires $\theta_{\text{QCD}} < 10^{-9}$

To achieve this without fine-tuning, θ_{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 **axion** which acquires a small mass through its mixing with the pion (the pNGB of QCD): $m_a = m_\pi\,(f_\pi/f_{\text{PQ}})$

The coherent oscillations of relic axions contain energy density *that behaves like CDM* with $\Omega_a h^2 \sim 10^{11}\ \text{GeV}/f_{\text{PQ}}$ … however the *natural* P-Q scale is probably $f_{\text{PQ}} \sim 10^{18}$ GeV

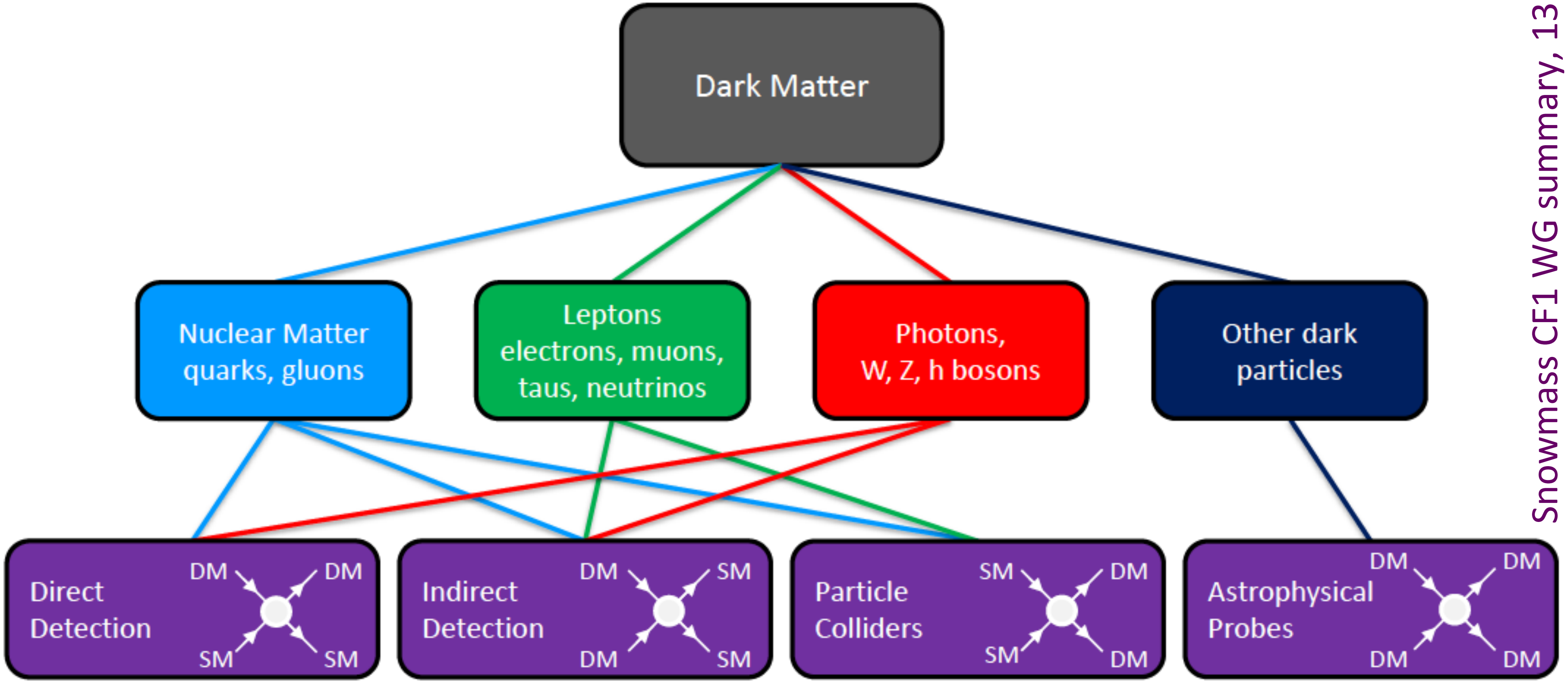
Hence axion dark matter would typically need to be significantly diluted i.e. its relic abundance is *not* predictable (or seek anthropic explanation for why θ_{QCD} is small?)

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 $\Omega_B \sim 0.05$
$\Lambda_{QCD'} \sim 5\Lambda_{QCD}$	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)	$\Omega_{TB} \sim 0.3$
$\Lambda_{\text{hidden sector}} \sim (\Lambda_F M_P)^{1/2}$	Crypton? hidden valley?	Discrete (very model-dependent)	$\tau \gtrsim 10^{18}$ yr	Varying gravitational field during inflation	$\Omega_X \sim 0.3$?
$\Lambda_{\text{see-saw}} \sim \Lambda_{Fermi}^2/\Lambda_{B-L}$	**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	? $\Omega_a \gg 1$!

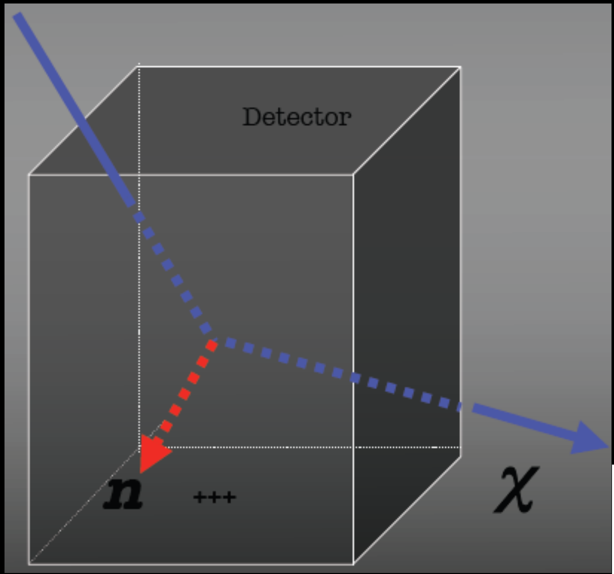
No definite indication from theory
must decide by experiment!

Detecting dark matter particles



The technologies and working environments vary *extremely* widely – from nuclear recoil detectors in shielded underground laboratories, to ground-based + satellite telescopes for detecting annihilation radiation, to searches using collider detectors for missing $E_{T\ \text{signals}}$ + 'monojets', to astronomical gravitational lensing studies of colliding galaxy clusters …

Snowmass CF1 WG summary, 1310.8327

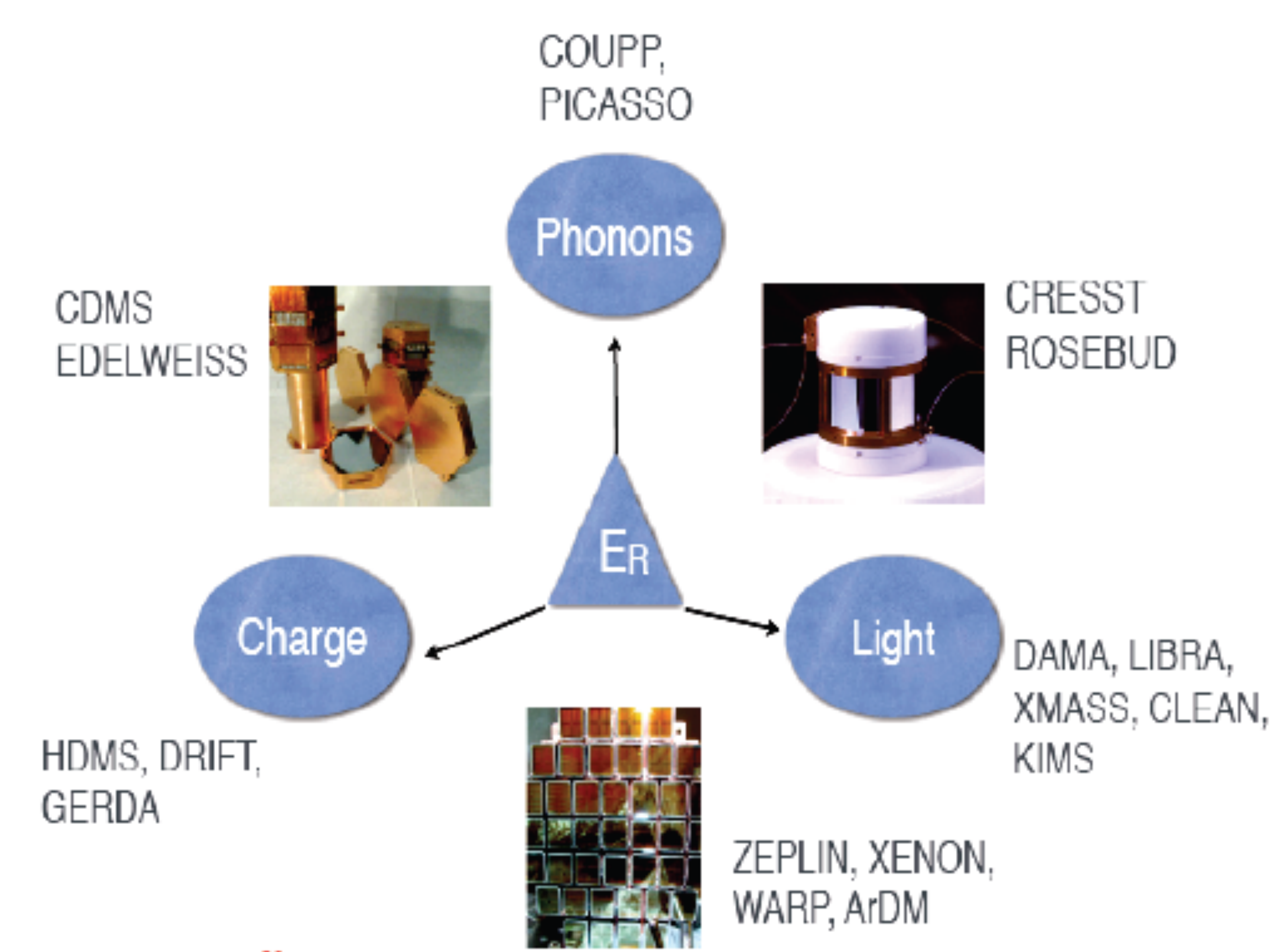


A passing dark matter particle orbiting in the Galaxy (at ~300 km/s) can scatter off a nucleus in an underground detector … the expected rate is *very* low (<< 1 event/kg/yr)

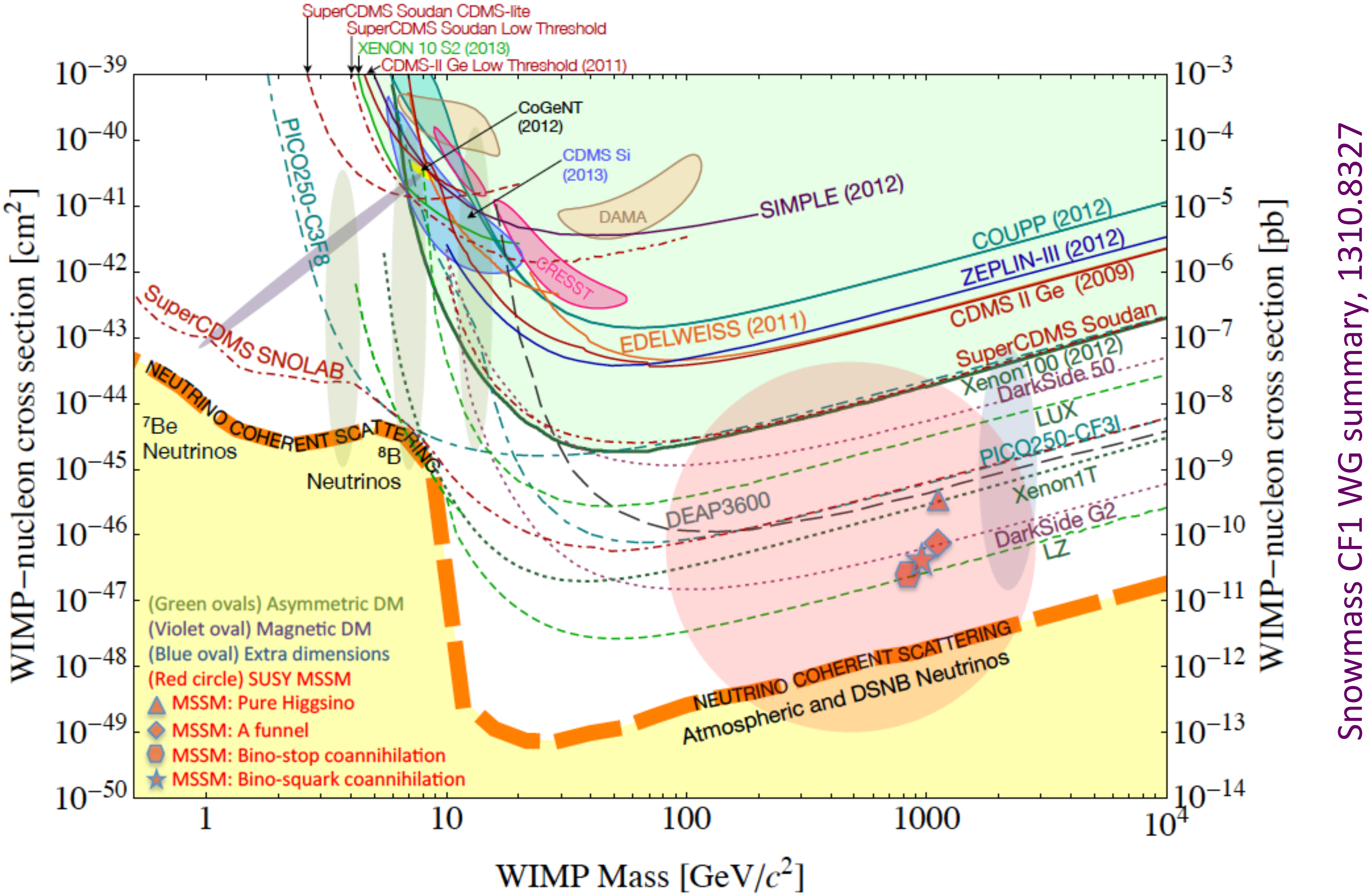
The recoil is detected via the ionization (charge), scintillation (light), and sound (phonons) ➛ heat

Experiments usually measure more than one channel to discriminate against the much bigger electron recoil background

(Very different techniques required to detect axions)



For ~25 years there has been a world-wide race on to detect dark matter



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:

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

Nuclear physics

Particle physics

astrophysics

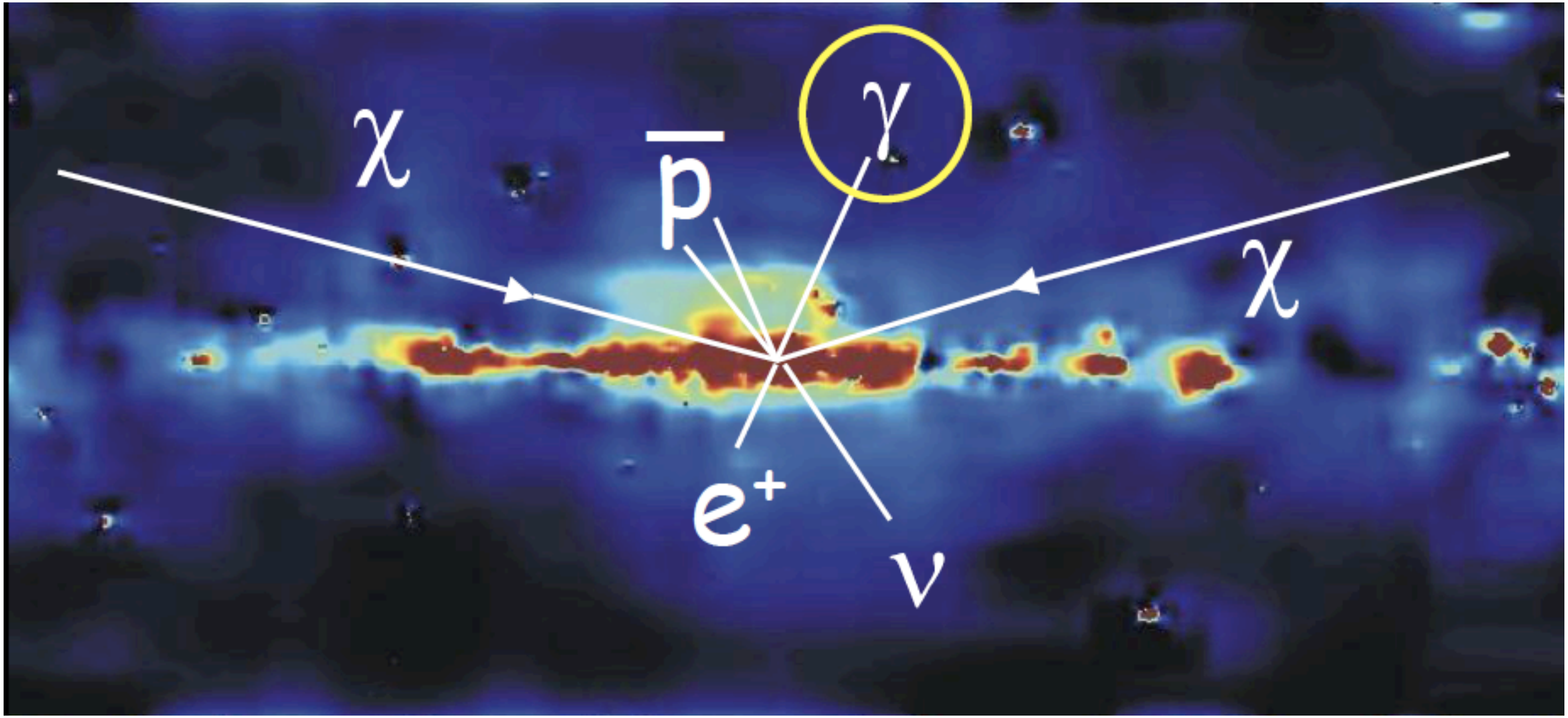
★ Dark matter may interact *differently* with neutrons and protons (Giulani, hep-ph/0504157) if the mediator is a (new) vector boson, so e.g. the events seen by CDMS-Si *can be* quite consistent with the upper limits set by XENON100/LUX.

★ Moreover different experiments are sensitive to *different* regions of the (uncertain) dark matter velocity distribution, hence apparently inconsistent results (e.g. CoGeNT and CRESST) 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 (efficiencies, energy resolution, instrumental backgrounds) … as well as 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
(… also not a good strategy to look just under the supersymmetric lamp post!)

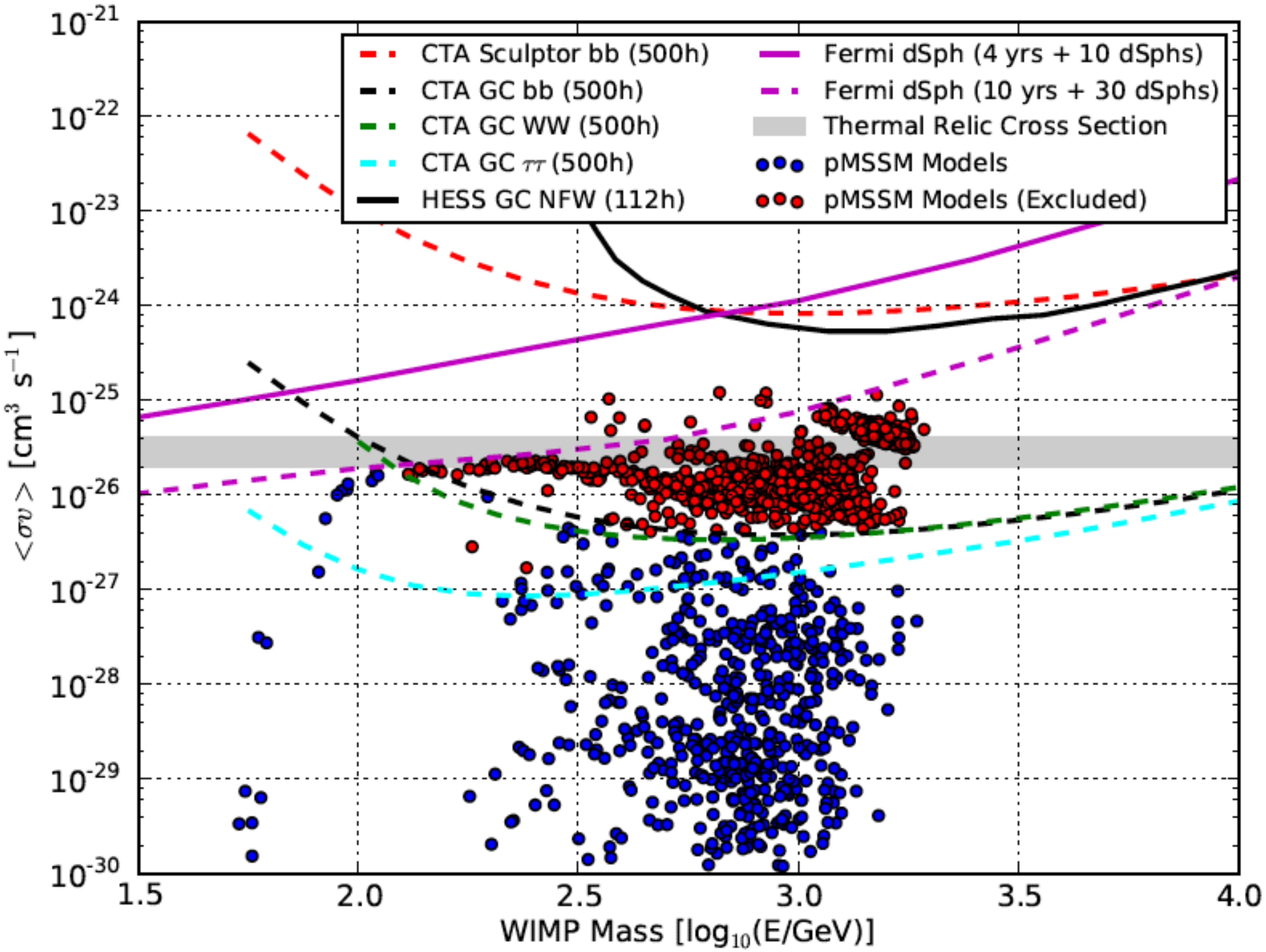
Many techniques for indirect detection … and many claims!



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

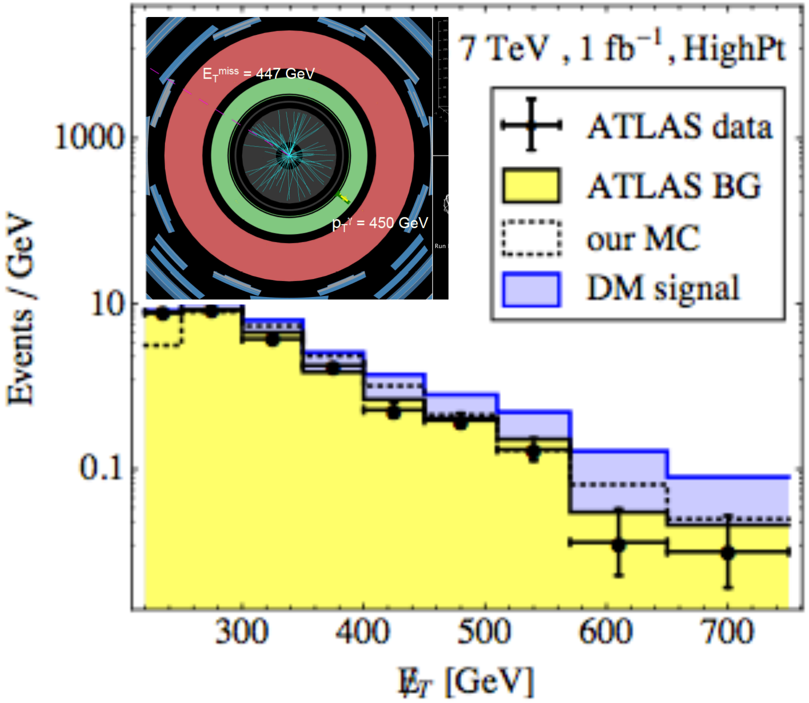
These probe dark matter *elsewhere* in the Galaxy so complement direct detection experiments … but we are just beginning to understand the astrophysical backgrounds

Prospects are good however for probing down to the expected annihilation signal for a thermal relic with Fermi and CTA



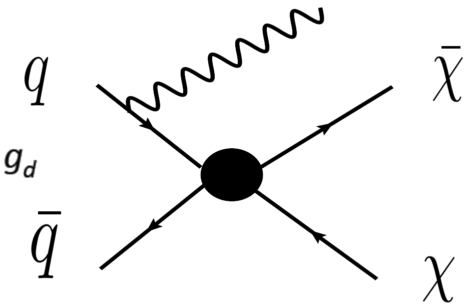
Snowmass CF2 WG Summary, 1310.7040

Moreover low energy extensions of IceCube (*DeepCore*, *PINGU*) will improve the sensitivity for detecting neutrinos from dark matter trapped in the Sun



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

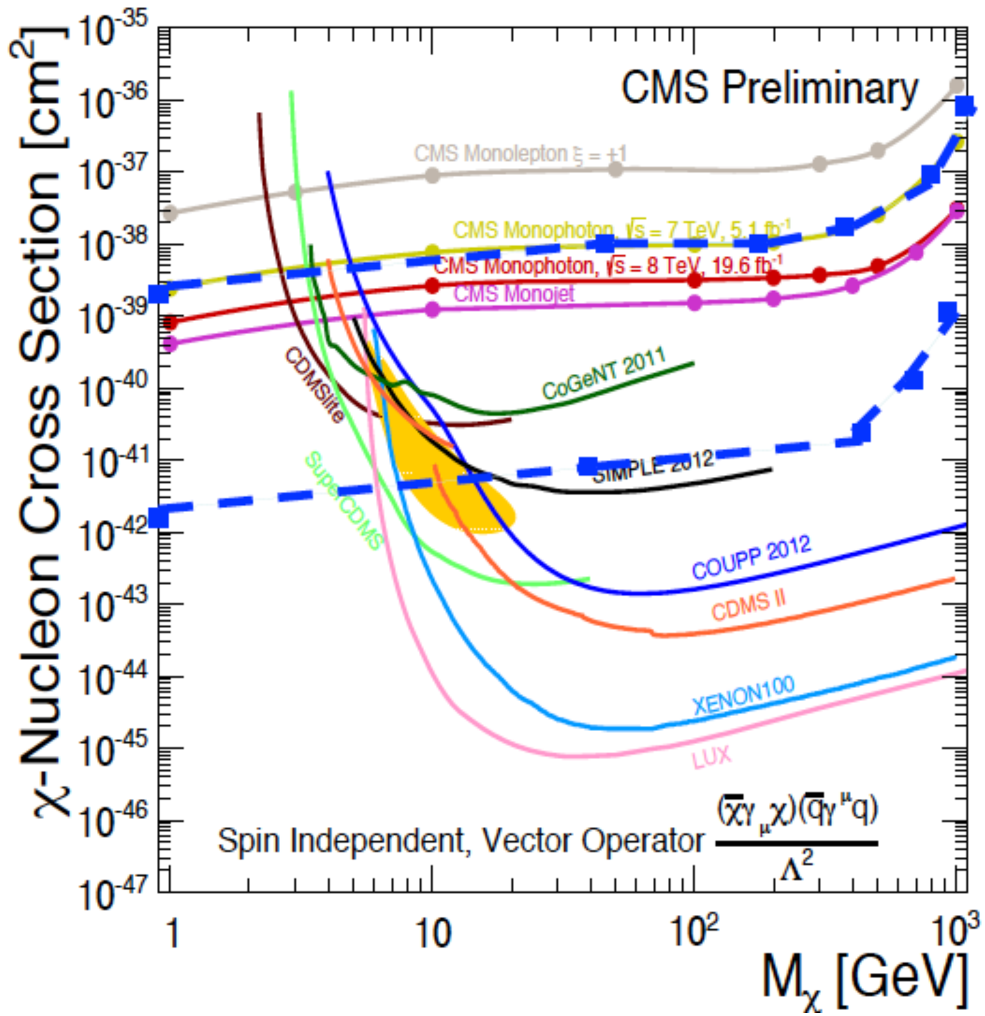
$$\mathcal{L}_\chi^{\rm eff} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$



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

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

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



However these bounds require the scale Λ of the effective operator to exceed ~0.7 TeV, while perturbative unitarity requires $g_q, g_\chi < \sqrt{4\pi}$ i.e. $m_R < 2$ TeV … so for higher energy collisions *cannot* rely on effective operator description (Fox *et al,* 1203.1662)

NB: For scalar-mediated processes, heavy quark loops can significantly enhance the monojet cross-section (Haisch, Kahlhoefer, Unwin, 1208.4605) – very sensitive probe!

Summary

Experimental situation reminiscent of searches in the ’80s for temperature fluctuations in the CMB
… there were clear theoretical predictions but only upper limits on detection (causing near crisis for theory)
Finally breakthrough in 1992 that transformed cosmology!

Theoretical expectations for dark matter are not as clear but there are several *complementary* experimental approaches and there has been impressive recent progress

There are bound to be false alarms but it is a reasonable expectation that the nature of dark matter will soon be determined experimentally