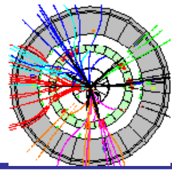
Beyond Standard Model

- Dark matter: WIMPs & axions
- Energy scales & couplings
- Electroweak symmetry breaking
- Grand unified theories
- Supersymmetry
- Extra dimensional models



The Standard Model is a very successful theory of particle interactions

- Electroweak interaction tested at 0.1-1 % level
- Basic strong interaction ingredients are confirmed, however perturbative calculations get very difficult at low Q^2 due to large α_s.
- SM describes well all observed phenomena upto now with the exception of ν oscillations
- Observed interactions are a dynamical consequence of symmetries (”gauge principle”)

Is the Standard Model ”the final theory”? **No, most probably!**

At least since SM doesn’t include gravity!!

Gravity is extremely weak: $m_Z^2 / m_{Pl}^2 \approx 10^{-38}$. WHY?

Why the observed hierarchy of fermion masses ?
Why 3 families of fermions ?
Why this bizarre gauge group combination ?

gauge group $\Rightarrow$ $G = SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$

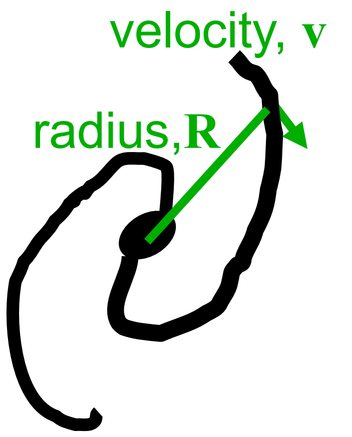
matter fermions $\Rightarrow$

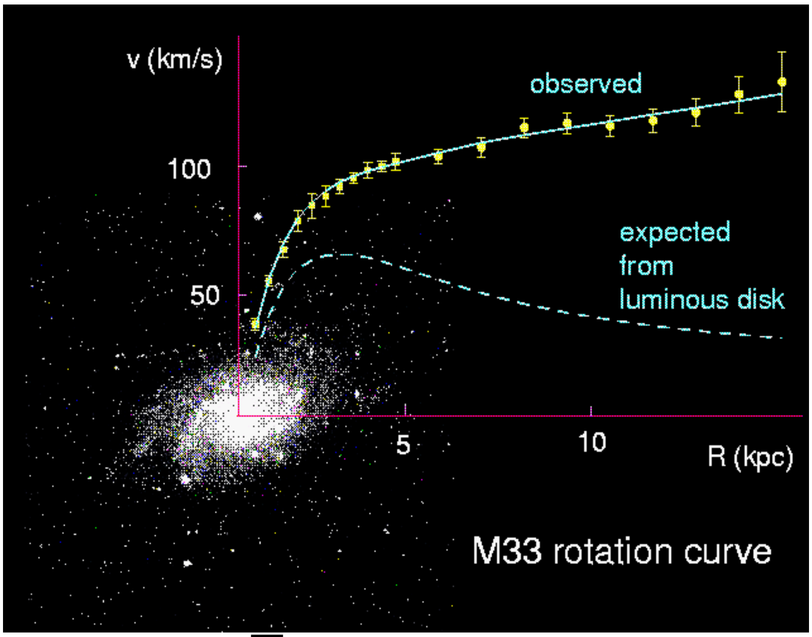
$q_L =$	(2 ,	1/3 ,	3)
$u_R =$	(1 ,	4/3 ,	3)
$d_R =$	(1 ,	−2/3 ,	3)
$l_L =$	(2 ,	−1 ,	1)
$e_R =$	(1 ,	−2 ,	1)

Possible indications of physics beyond SM ?

Dark (i.e. non-luminous & non EM radiation absorbing) **matter** in the universe see e.g. PDG review on dark matter

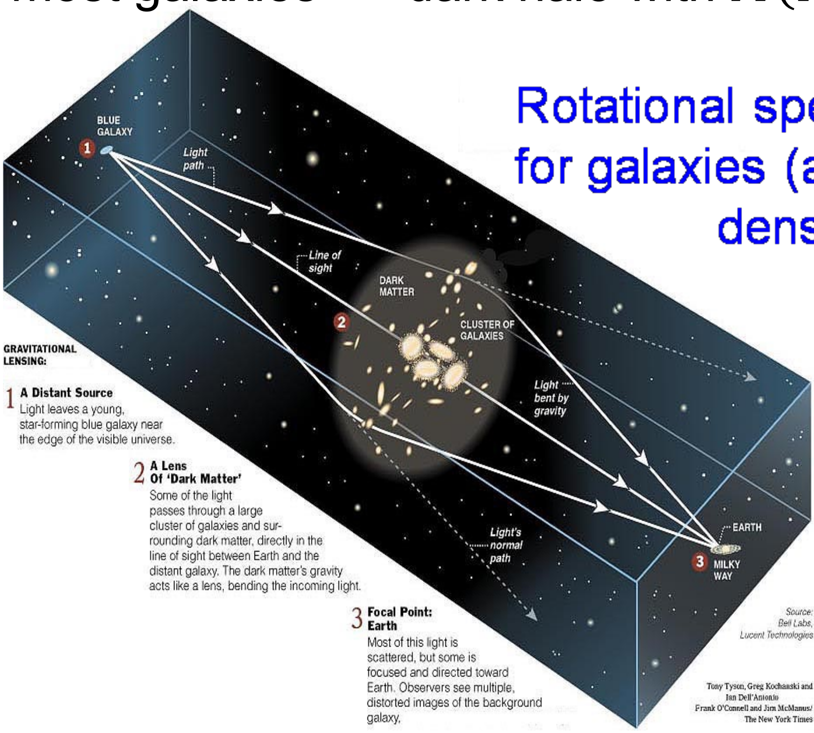
Seen e.g. in galaxy mass distribution





$v(R) \propto \sqrt{M(R)/R}$,
$M(R)$ enclosed mass

Stars & gas predicts $v(R) \propto 1/\sqrt{R}$ but $v(R) \approx$ const. for most galaxies $\Longrightarrow$ dark halo with $M(R) \propto R$ or $\rho(R) \propto R^{-2}$

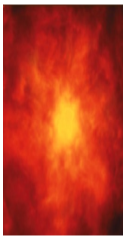


Rotational speed measurements for galaxies (above) and mass density measurements from gravitational lensing (left) indicate $\Rightarrow$

Luminous stars contain only small fraction of total galaxy mass

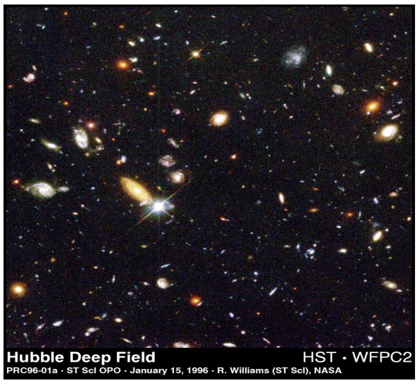
Dark matter & structure formation

Big Bang



gravity

Present Structures



Dark matter dominates matter in our universe ⇒ governs structure formation

2 extreme forms of dark matter possible:

hot (relativistic) and cold (non-relativistic)

Relativistic particles escape from structure formation ⇒ galaxy formation indicate most dark matter cold: CDM

Dark matter must be stable on cosmological time scales, interact weakly with radiation ("electrically neutral") & matter (no strong interaction) plus have right relic density

Baryonic candidates: primordial black holes e.g. Massive Compact Halo Objects (MACHOs) – not sufficient density, stranglets e.g. a uuddss-quark particle with mass < $2m_{\Lambda_0}$.

Non-baryonic candidates: sterile singlet neutrino (ν mixing angle $\theta \ll 1$), dark photons (vector boson with mass < $2m_e$ & only decay to 3γ possible), weakly interacting massive particles (WIMPs), axions – particle physics discoverables

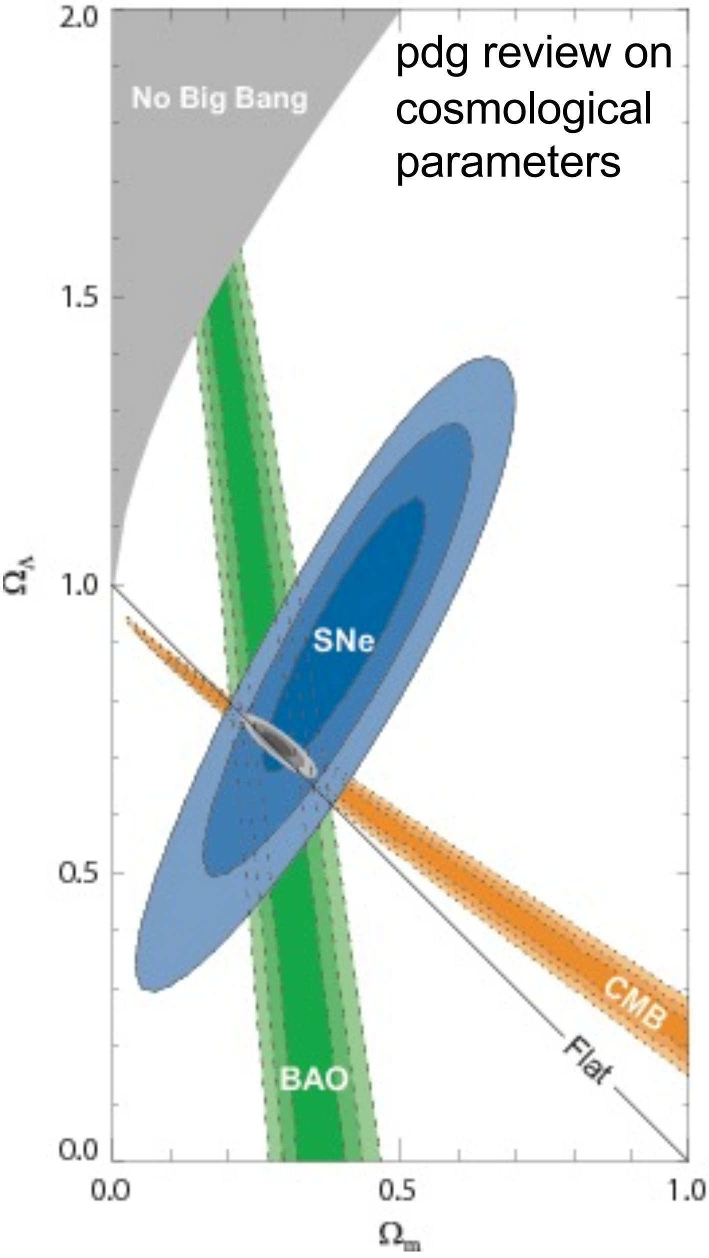
An obvious WIMP would be a heavy neutrino but a SU(2) doublet neutrino ($m_\nu > m_Z/2$) gives too small relic density. Historical candidate: lightest supersymmetric particle (LSP)

Supernova measurements (SNe):

measure brightness $\rightarrow$ distance: $B = L/4\pi d^2$
measure host galaxy redshift $\rightarrow$ recesion velocity
test nonlinearity of Hubbles law at large distances

Cosmic microwave background (CMB):

measure size of CMB anisotropy (last baryon-γ scattering surface) $\rightarrow$ estimate of energy/matter density of universe



Galaxy clustering, baryonic acustic oscillations (BAO):

measure galaxy clustering as "tracer" of dark matter distribution vs redshift $\rightarrow$ estimate of matter density

$\Omega_x = \rho_x / \rho_{critical}$

critical density for flat universe

$\rho_{critical} = 3H^2/8\pi G_N$

$H = h \cdot 100$ km/s/Mpc

<u>CMB + lensing (Planck):</u>

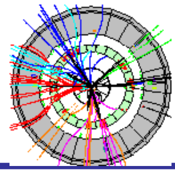
$h = 0.674 \pm 0.005$

$\Omega_{tot} = 1.011 \pm 0.006$ so agrees with flat universe

Cosmological constant:

$\Omega_\Lambda = 0.685 \pm 0.007$

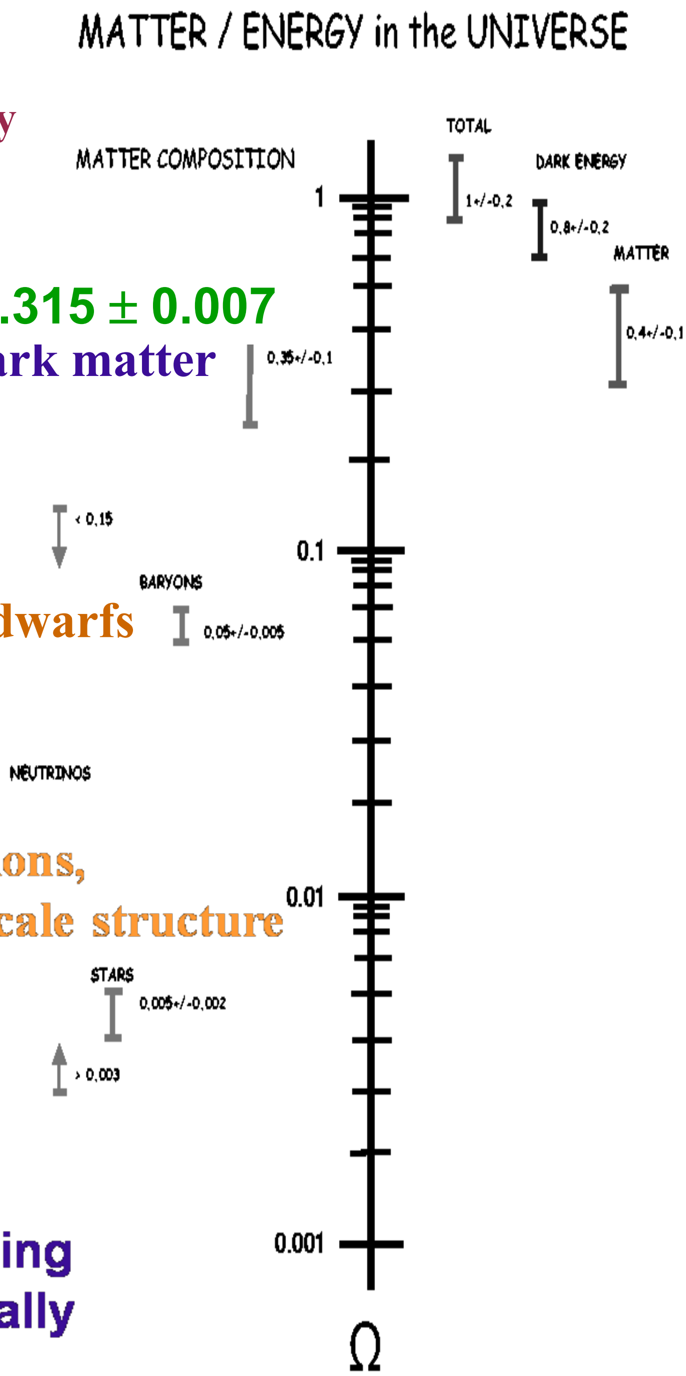
$\Omega_m = 0.315 \pm 0.007$



Dark energy (≡ cosmological constant) constitutes the largest fraction of energy/matter in our universe !!

$$\Omega_{total} = \Omega_M + \Omega_\Lambda \sim 1$$

matter dark energy



Matter:

$$\Omega_M = \Omega_b + \Omega_\nu + \Omega_{CDM} = 0.315 \pm 0.007$$

baryons neutrinos cold dark matter

Baryonic matter :

$$\Omega_b = 0.0492 \pm 0.0008$$

stars, gas, brown & white dwarfs

Neutrinos:

$$0.001 < \Omega_\nu < 0.004$$

lower bound from oscillations,
upper bound from large-scale structure

Cold Dark Matter :

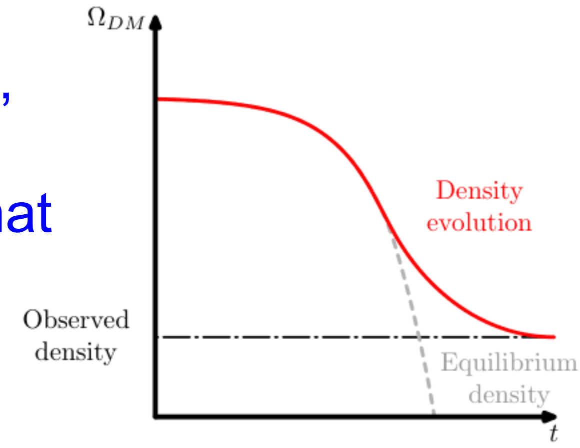
$$\Omega_{CDM} \sim 0.264 \pm 0.005$$

WIMPs (Weakly Interacting Massive Particles), usually neutralinos, or axions

NB! If Planck & BAO is combined, Ω_Λ & h (Ω_{CDM} & Ω_M) increase (decrease) slightly but overall picture looks similar.

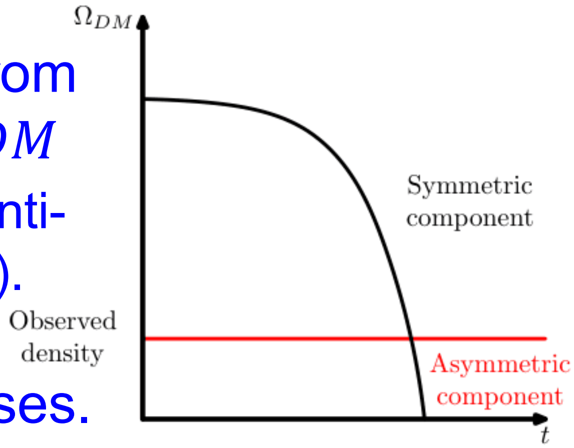
- Freeze-out (DM = dark matter, OM = ordinary matter):

First equilibrium $DM + \overline{DM} \leftrightarrow OM + \overline{OM}$, then $DM + \overline{DM} \rightarrow OM + \overline{OM}$ (when T of universe > m_{DM}), finally expansion of space dilutes density of DM's so that DM collisions happen too rarely and the total number of DM's stops changing.



- Asymmetric DM:

Relic DM abundance arise from asymmetric probabilities of DM & $\overline{DM}$ processes (↔ baryon-anti-baryon asymmetry in universe?). Relic density directly related to these CP violating processes.



- Freeze-in:

Collision processes produce DM's that from start are diluted so that they can graduallly accumulate at cosmic times. E.g. the lightest observable-sector particle decays to DM with a relatively long lifetime.

- Non-thermal production:

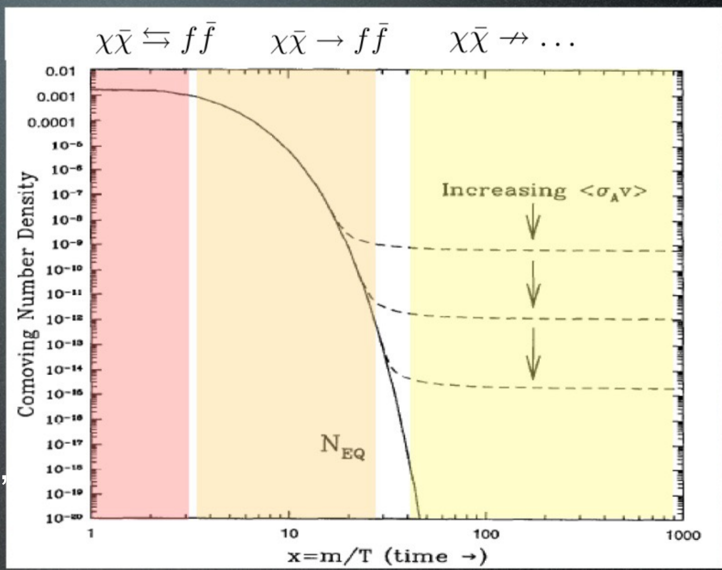
DM production process is out of thermal equilibrium ("non-thermal"). E.g. via decay of "mother" particle, topological defects, moduli or gravitational effects.

A thermal relic from the Early Universe

Consider a particle χ:

- subject to $\chi\bar{\chi} \to \ldots$
- 'heavy' (e.g. 100 GeV)
- 'stable'
- in an expanding Universe
- symmetric abundance

"neutral", very long lived (life time ~cosmological scale), weakly interacting particle, limited self-interactions



Kolb,Turner, The Early Universe, 1995

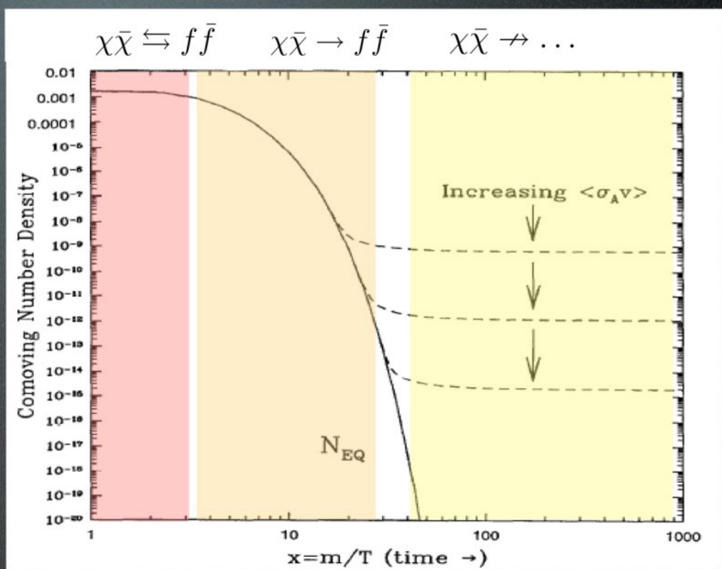
A thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

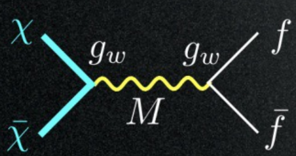
$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}} v\rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$$\langle\sigma_{\mathrm{ann}} v\rangle = 3 \cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$



Weak cross section:

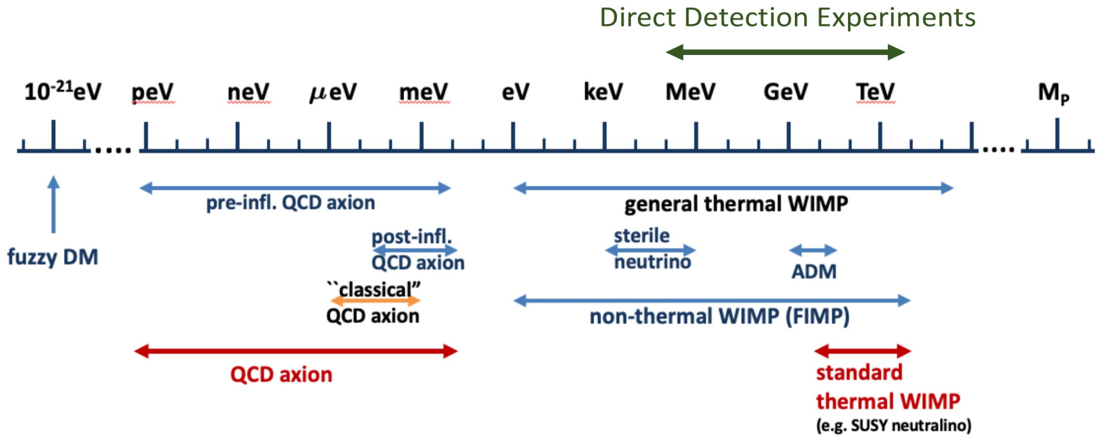


$$\langle\sigma_{\mathrm{ann}} v\rangle \approx \frac{(g_w^2/4\pi)^2}{M^2} \approx 3 \cdot 10^{-26}\mathrm{cm}^3/\mathrm{sec}$$

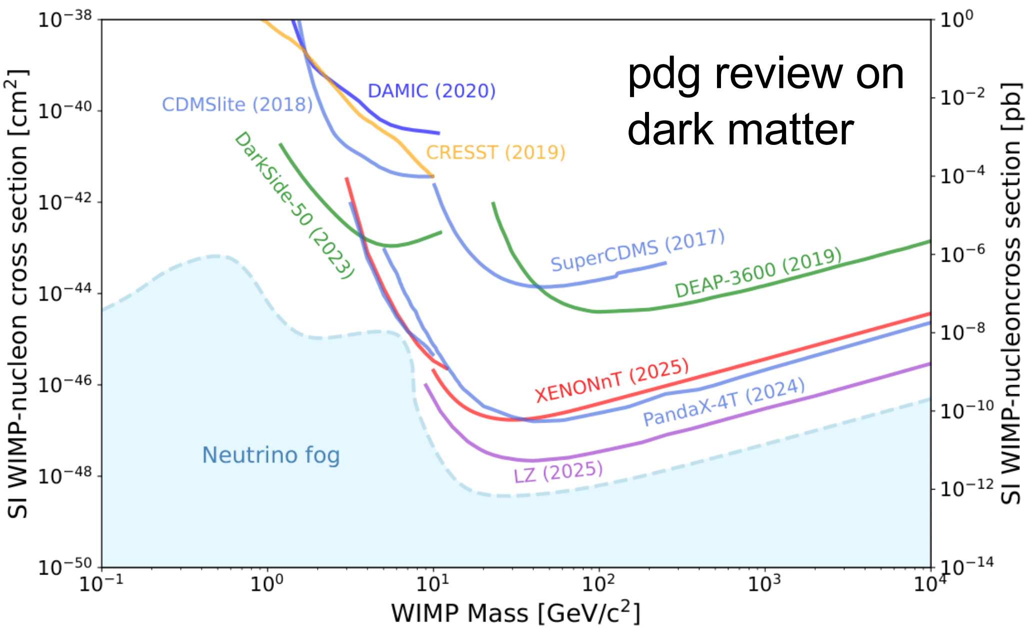
WIMP miracle!

Searches for WIMPs (or other dark matter candidates):

- accelerator-based: (a) missing (transverse) momentum due to WIMP production; (b) excess or bump of jet or lepton pairs produced by a dark mediator
- direct detection of WIMPs from galactic WIMP halo in terrastial detectors; (a) (in)elastic scattering off a target nucleus giving rise to measurable nuclear recoil (b) scattering off bound electrons (for WIMP masses < GeV giving WIMP-nucleus scattering energy transfers below detection threshold) or absorption via “axioelectric” effect (for axions or dark photons, analogous to photoelectric effect)



No WIMP signal observed ⇒ WIMP direct detection limits



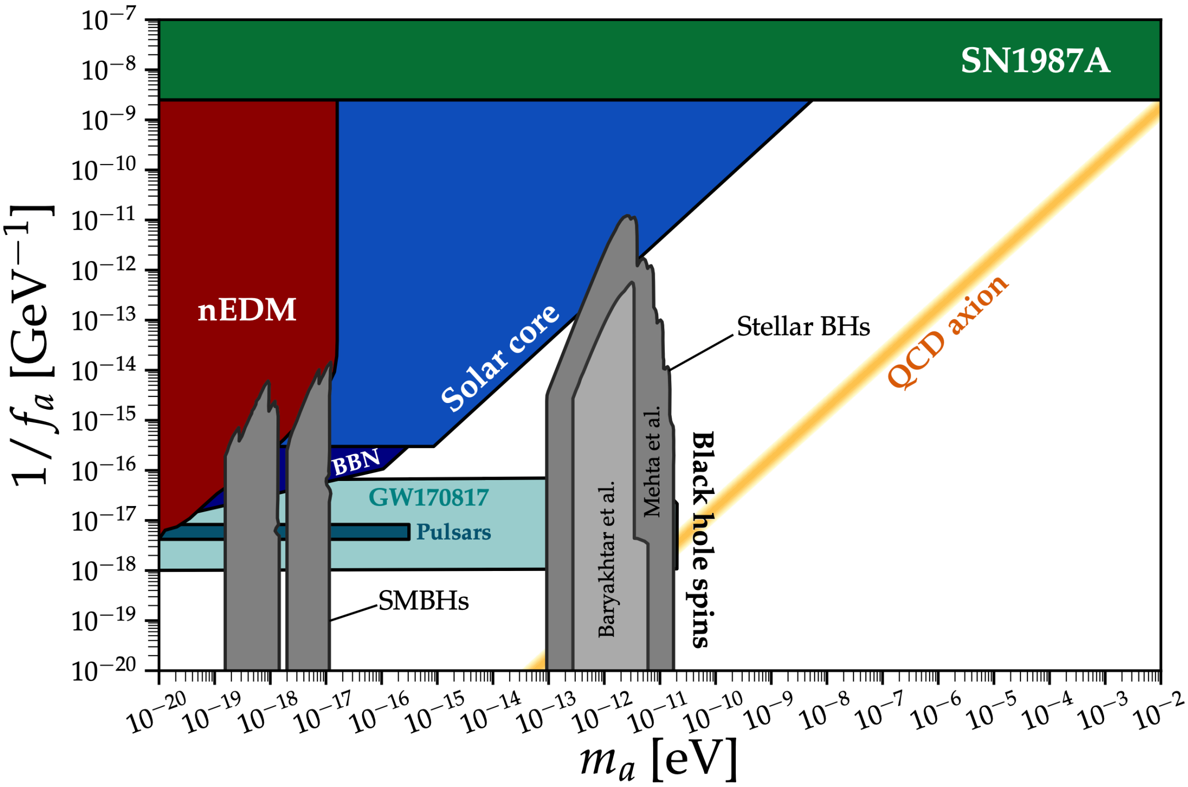
Axion

A very light neutral scalar boson, originally proposed by Peccei & Quinn: pseudo-Goldstone boson from a broken U(1) symmetry introduced to cure CP problem of QCD.

Motivation: CP violation in QCD not observed, stringent limits (< 10^{-10}) from neutron electric dipole moment. Axion field term in the QCD Lagrangian would compensate the CP violating term Θ_i. Coupling $\propto f_A^{-1}$ very small to matter due to the high scale of the U(1) symmetry breaking.

$$\mathcal{L}_{\mathrm{QCD,CPviol}} = (\alpha_s/8\pi)(\Theta_i - \phi_A/f_A)G^{\mu\nu a}\tilde{G}^a_{\mu\nu} \approx 0$$

Axion density contribution (pre-inflation U(1) symmetry breaking): $\Omega_A h^2 \sim 0.12 \cdot (6\ \mu\mathrm{eV}/m_A)^{1.165} \Rightarrow$ masses 10^{-5} to 10^{-3} eV most interesting as dark matter (assuming $\Theta_i \sim 1$ in axion potential); Axions can constitute CDM due to their non-thermal production.



axion would interact weakly with matter (coupling $\propto f_A^{-1}$; very small if $f_A \gg v \rightarrow m_A \ll m_\pi$).

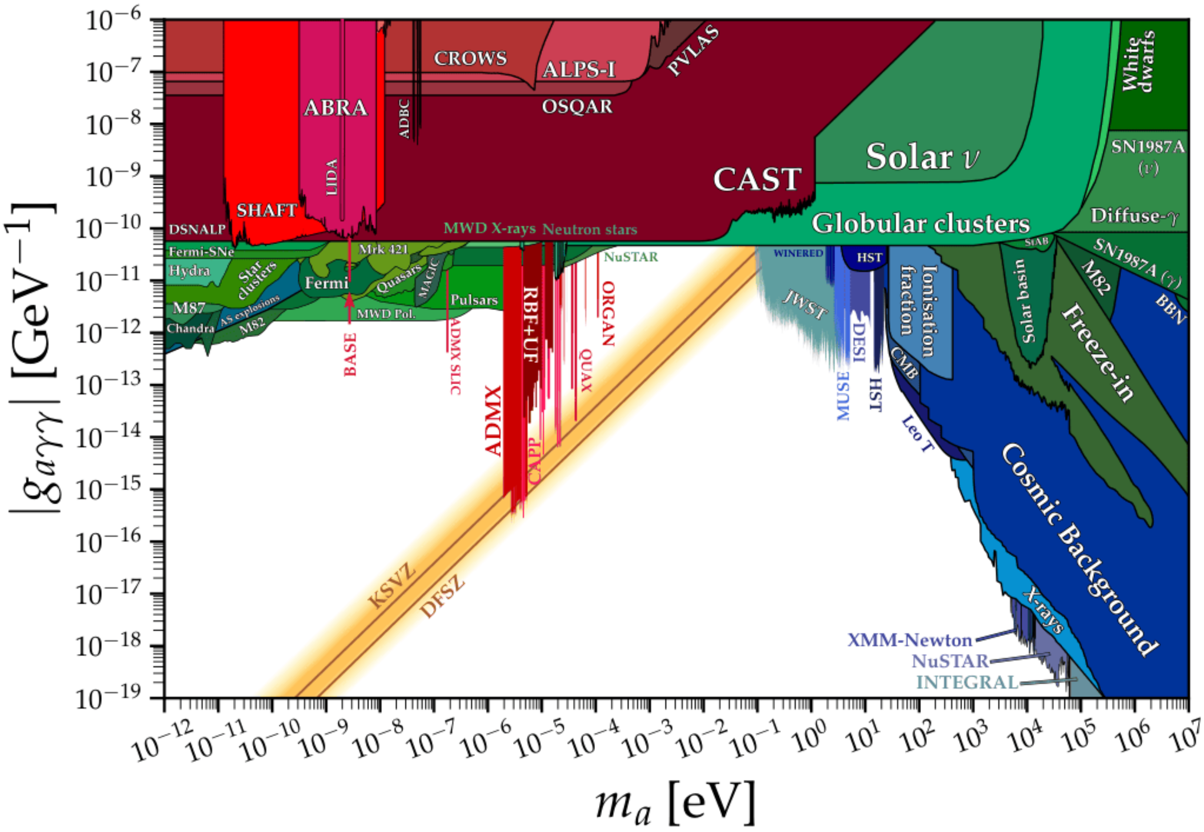
$$\mathcal{L}_{\text{QCD,CPviol}} \propto (\Theta_i - \phi_A / f_A) G^{\mu\nu a} \widetilde{G}^a_{\mu\nu} \approx 0 \xrightarrow{\Theta_i \sim 1} m_A f_A \approx m_\pi f_\pi$$

Next-to-next-to-leading (NNLO) order correction in chiral perturbation theory gives: $m_A = 5.691 \left(\frac{10^9 \text{ GeV}}{f_A}\right)$ meV

Predicted decay $A \rightarrow \gamma\gamma$ in external E/B field presence (coupling $g_{A\gamma\gamma}$ very model dependent).

$$\mathcal{L}_{A\gamma\gamma} = (g_{A\gamma\gamma}/4) F_{\mu\nu} \widetilde{F}^{\mu\nu} \phi_A = -g_{A\gamma\gamma} \mathbf{E} \cdot \mathbf{B} \phi_A$$

Also very small fermion (i.e. electron) coupling g_{Aff} possible



for more details see e.g. PDG review on "Axions"

Physical Energy Scales & Couplings

Ex// scalar field (particle) φ

- most general Lagrangian

$$\mathcal{L} = \partial_\mu\varphi\,\partial^\mu\varphi - m^2\varphi^2 + \lambda_3\varphi^3 + \lambda_4\varphi^4 + \lambda_5\varphi^5 + \lambda_6\varphi^6 + \ldots$$

dimensions

$$\left.\begin{aligned} [\mathcal{L}] &= \frac{E}{L^3} = E^4 \\ [\partial_\mu] &= \frac{1}{L} = E \end{aligned}\right\} \Rightarrow [\varphi] = E$$

couplings

$$[m^2] = E^2$$

$$[\lambda_3] = E$$

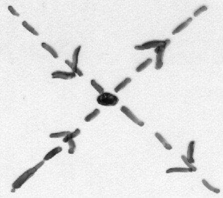
$$[\lambda_4] = E^0 \leftarrow \text{dimensionless}$$

$$[\lambda_5] = E^{-1}$$

$$[\lambda_6] = E^{-2}$$

Energy dependence of amplitudes:

$\lambda_4 \rightarrow$



$\mathcal{A}(2\to 2) \propto \lambda_4$

$\Rightarrow \boxed{\sigma_{2\to 2} \sim \frac{\lambda_4^2}{s}}$

$\lambda_6 \rightarrow$

$\mathcal{A}(2\to 4) \sim \lambda_6 s$

$\Rightarrow \boxed{\sigma_{2\to 4} \sim \lambda_6^2 s}$

$\sigma \propto |\mathcal{A}|^2/\mathcal{F}$, where $\mathcal{F} \propto s$

... more generally

$$[\lambda_i] = E^{d_i} \Rightarrow d_i = 4 - i \text{ (here)}$$

dimensionless quantity ruling perturbative expansion is

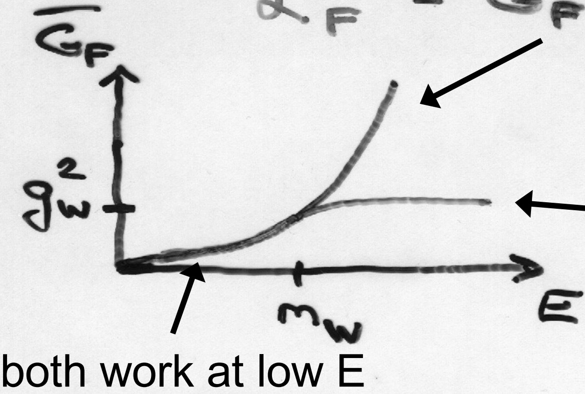
$$\boxed{\bar{\lambda}_i = \lambda_i E^{-d_i}}$$

- weak coupling $\Leftrightarrow$ $\bar{\lambda}_i \ll 1$

* $d_i > 0 \Rightarrow$ relevant at small E ($E \ll m$)
* $d_i = 0 \Rightarrow$ relevant at all E
* $d_i < 0 \Rightarrow$ suppressed at small E; perturbative expansion breaks down at high E

▲ Ex// Fermi Lagrangian

$$\mathcal{L}_F = G_F (\bar{p} \gamma_\mu n)(\bar{e} \gamma^\mu \nu)$$



$$\bar{G}_F = G_F E^2$$

$$\sim g^2 / m_W^2$$

Imagine all couplings with $d_i < 0$ to scale like

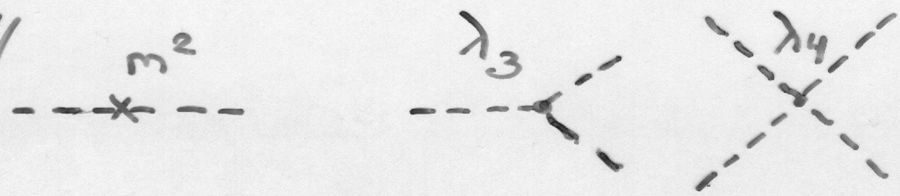
$$\lambda_i \sim \Lambda^{d_i}$$

Ex// $\lambda_5 \sim \frac{1}{\Lambda}$, $\lambda_6 \sim \frac{1}{\Lambda^2}$ ...

⇓

at $E \ll \Lambda$ the dynamics is accurately described by a finite set of couplings with $d_i \geq 0$

Ex//



- $(m^2, \lambda_3, \lambda_4)$ fully describe an elementary (pointlike) particle

- $\lambda_5, \lambda_6 \ldots$ corresponds to inner structure
- to probe structure $E \sim \Lambda$ is needed

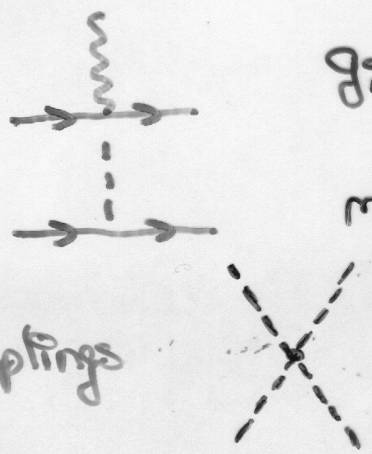
* Ex// e is bound state of size $\sim \frac{1}{\Lambda}$

NB! Customary to assume New Physics couplings to be $g_{\mathrm{SM}}^n/\Lambda^n$, where n depends on order of term

▲ $\lambda_i = 0$ for $d_i < 0$ ⇒ Theory <u>renormalizable</u> (divergencies can be delt with)

Physical meaning: particles have the minimal amount of internal structure

Standard Model couplings:



gauge — g_i

higgs — m_i

self-couplings — λ_i

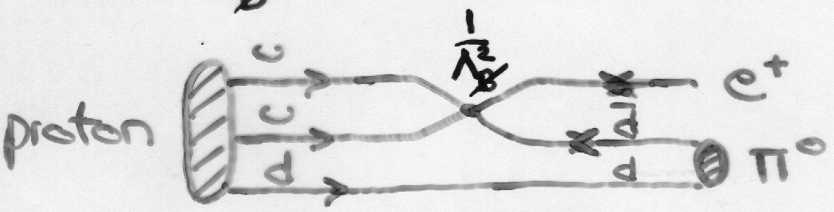
} $d_i = 0$

Higgs mass ---x--- μ^2 $d_i = 2$

- Allowing $d_i < 0$ we would have

1) B- & L-number violation

* $\frac{1}{\Lambda_{\not B}^2} (u_\alpha c \gamma_\mu u_\beta)(e c \gamma^\mu d_\delta)\epsilon^{\alpha\beta\delta}$

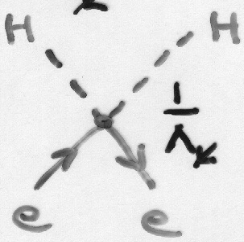


$p \to e^+ \pi^0$

$\tau_p \geq 24 \cdot 10^{33}$ years $\Rightarrow \Lambda_{\not B} \geq 10^{16}$ GeV

tiny neutrino mass can be generated with extended Higgs sector if allowing lepton number violation

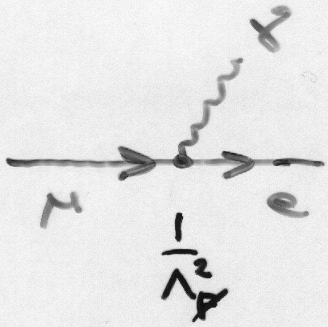
* $\frac{1}{\Lambda_{\not L}} (e_i^A c\, e_j^B) H_A H_B$



$H \leftrightarrow v_F$ $\longrightarrow$ $m_\nu \sim \frac{v_F^2}{\Lambda_{\not L}}$

ν-oscillations: $m_\nu \sim 0.1$ eV $\Rightarrow \Lambda_{\not L} \sim 10^{14}$ GeV

* $\frac{m_\mu}{\Lambda_{\not F}^2} (\bar{e} \gamma_\mu \gamma_\nu \mu) F^{\mu\nu}$



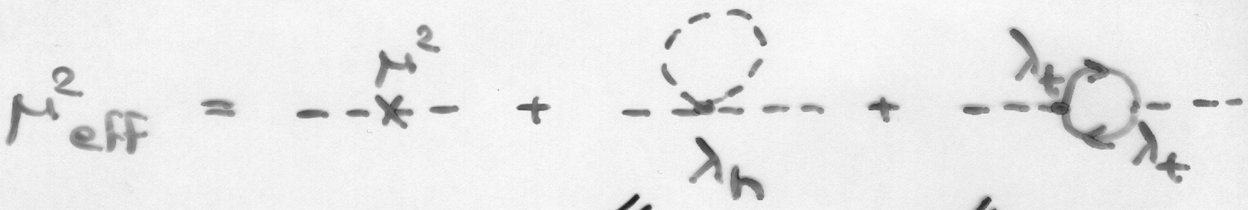
$Br(\mu \to e\gamma) < 3.1 \cdot 10^{-13}$

$\Rightarrow \Lambda_{\not F} \geq 10^7$ GeV

▲ It is tempting to conclude that the scale of "compositness" Λ in the SM is extremely high ... but can we

- $\langle H \rangle \sim$ 125 GeV $\Rightarrow \mu^2 \sim (125\ \text{GeV})^2$
- can $|\mu|$ be $\ll \Lambda$
- have to consider quantum corrections

leading:



cut-off $\int d^4p$ at $p \sim \Lambda$ $\qquad + \frac{\lambda_H}{16\pi^2}\Lambda^2 \qquad - \frac{\lambda_t^2}{16\pi^2}\Lambda^2$

$$\Rightarrow \mu^2_{eff} = \mu^2 + c\Lambda^2$$

▨ μ^2_{eff} does not like to stay small when $\Lambda \to \infty$!!

large Λ $\Rightarrow$ μ^2 must be tuned to make μ^2_{eff} (fine-tuning ~10^{-34})

This is the hierarchy problem!

$p \to e\pi^0$, $\mu \to e\gamma$ $\sim \frac{1}{\Lambda^2}$

effective Higgs mass $\sim \mu^2 + c\Lambda^2$

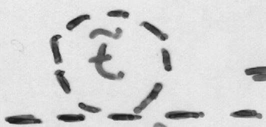
☒ 2 possibilities

1) $\Lambda \gg \mu$
- → B, L conservation naturally follows
- → separation of mass scales mystery

2) SM is not valid for energy $\gtrsim \mu$: it is replaced by more fundamental theory

In New Theory
- no Λ^2 corrections to Higgs mass
- must preserve as much as possible good features of SM

How solve Λ^2 corrections to Higgs mass?

additional  loops cancels if $\lambda_t^2 = \lambda_{\tilde{t}}$

⇒ Need symmetry relating boson to fermions

SUPERSYMMETRY