Plan for 3 lectures

- Introduction. The need for new physics. Portals to new Physics.
- Strong CP problem and axion solutions. Searches for axions and axion-like particles.
- Weakly interacting massive particles. WIMP interaction with Standard Model particles. Some snapshots of WIMP phenomenology.
- Dark mediators. Direct searches of dark mediators at low and medium energies.

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Maxim Pospelov, U of Victoria
Perimeter Inst.

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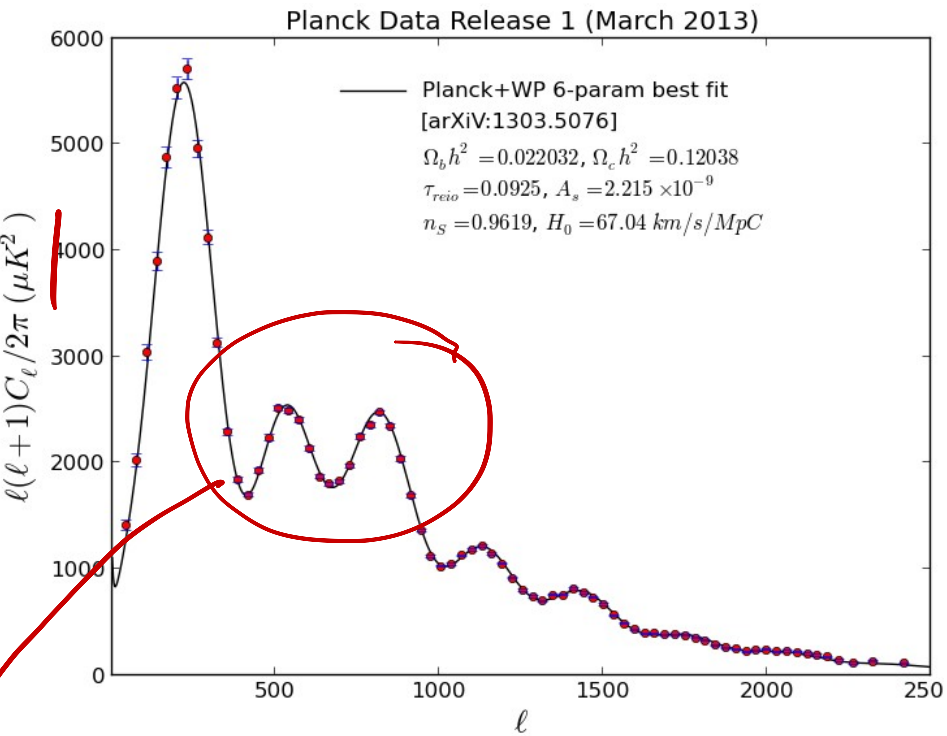
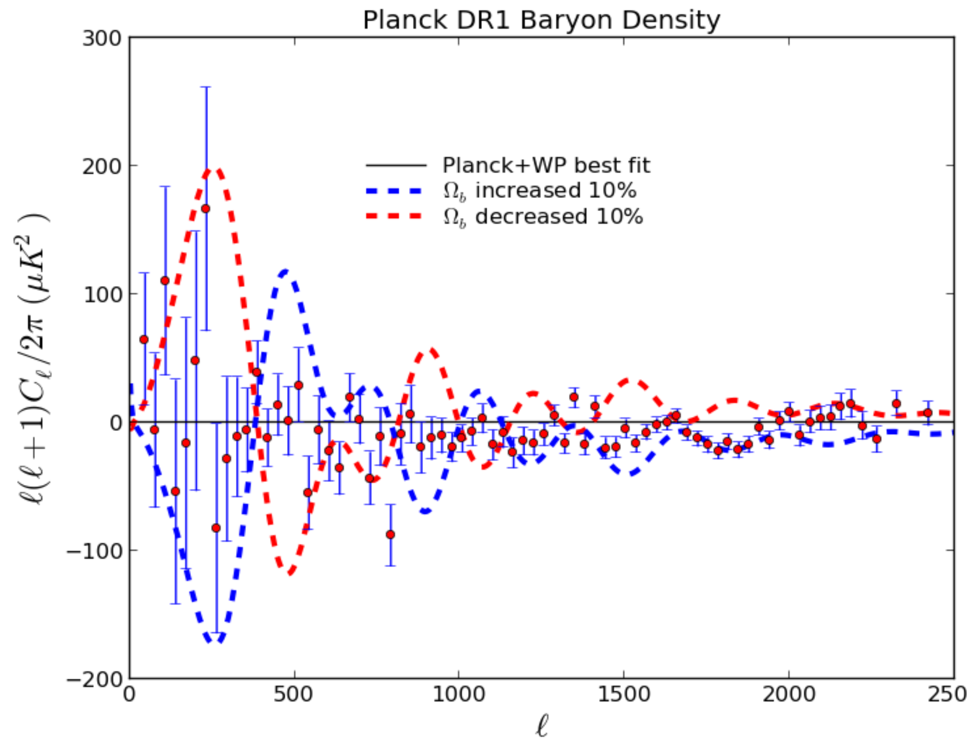
JGC

Evidence for New Physics

- Standard Model based on SU(3)*SU(2)*U(1) interactions is a well-established paradigm
- Evidence for "New Physics" – interactions and particles and fields beyond the SM field content – comes from the neutrino physics and cosmology
- These are enormous subjects to cover in 3 lectures – but a lot of reference literature exists.

Early cosmology is relatively simple





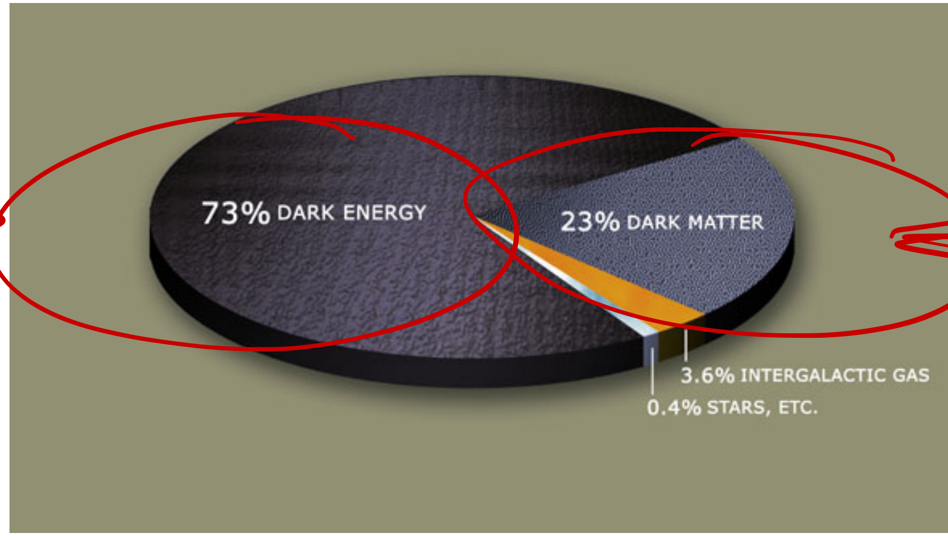
Parameter	Value (68%)
$\Omega_b h^2$	0.02207±0.00027
$\Omega_c h^2$	0.1198±0.0026 (is it high?)
$100\theta_*$ (acoustic scale at recombination)	1.04148±0.00062 (~ 500 parts per million accuracy)
τ	0.091±0.014 (WMAP seeded)
$\ln(10^{10}A_s)$	3.090±0.025
n_s	0.9585±0.0070 (<1 at > 5 σ)

$n_b/n_\gamma = 6.1\times10^{-10}$

$= 1$ HZ

Parameter	Value (95%)
Ω_K	-0.0005±0.006
$\Sigma\, m_\nu$ (eV)	<0.23
N_{eff}	3.30±0.54
Y_P	0.267±0.040

Dark energy, dark matter



does not cluster

$p_{DE}/\varepsilon_{DE} = -1$

$\Omega_{DE} \simeq \Omega_\Lambda$

(cosmological constant)

DM forms structures

particle physics

Astro part

Dark energy, dark matter, dark forces...?

Last few years

Historic examples:

1920s (Z, A)

neutrons + strong force

Dark energy, dark matter, dark forces...?

1860s Maxwell EM theory

1898 ~ radioctivity

1932-35 ~ neutrons, strong force

~1972-4 — weak neutral currents

~2012 — discovery of fundamental Yukawa force

? 2050 - Dark force ?

$n_X \sim n_\gamma$

Possible types of dark matter

WIMPs (weakly interacting massive particles)

Early abundance

Coupling strengths $\sim O(1)$

$\cancel{X \to SM}$ ← forbidden

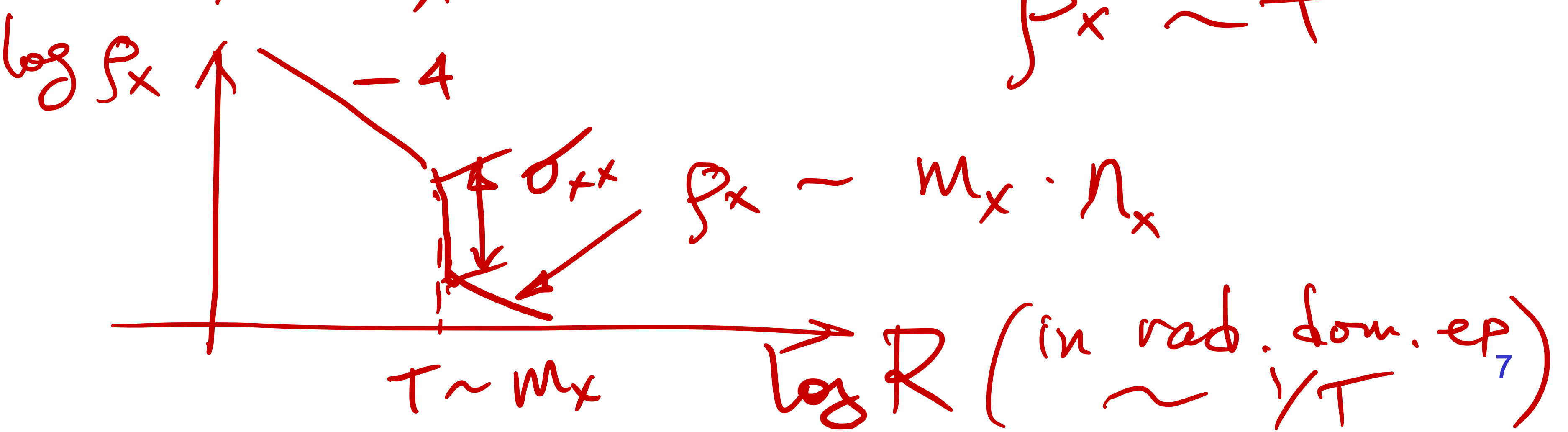
$XX \to SM$ — allowed.

$T \gtrsim m_X$

$n_X \sim T^3 \sim n_\gamma$

$\rho_X \sim T^4$

$\rho_X \sim m_X \cdot n_X$

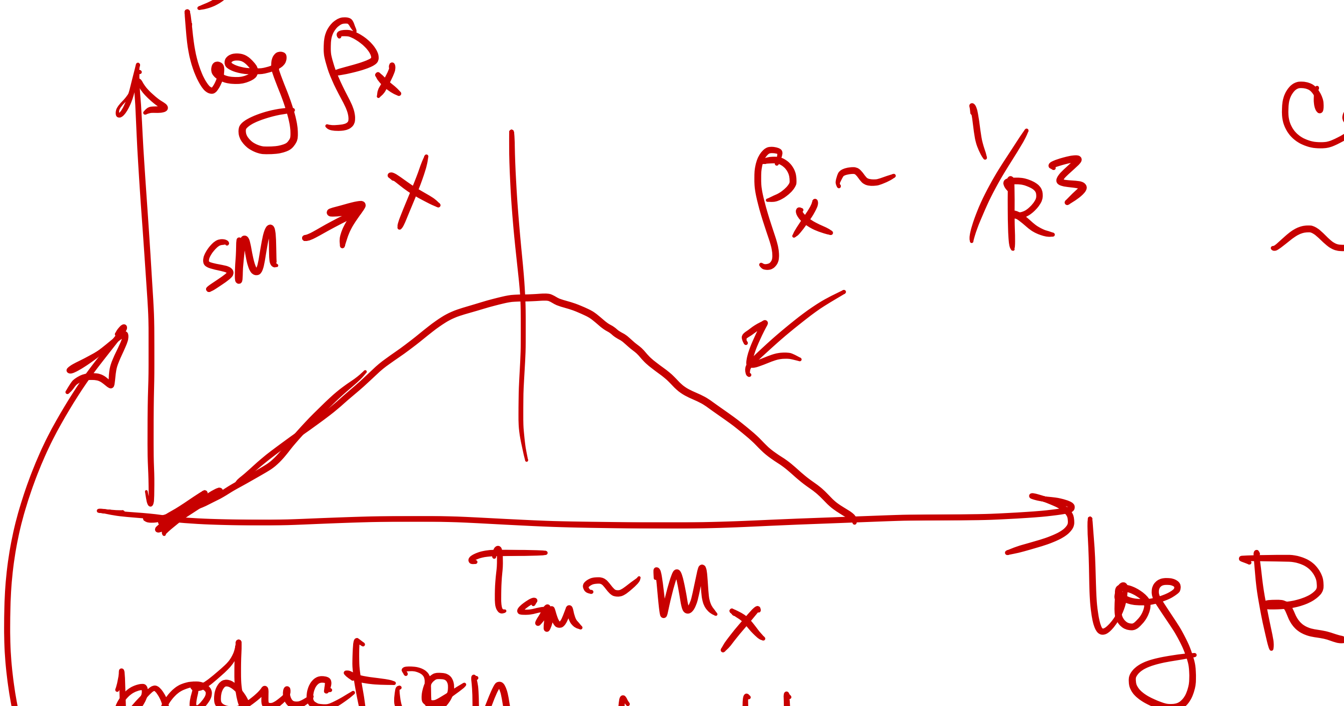


$n_X \ll n_\gamma$

Possible types of dark matter

Super-WIMPs (super-weakly interacting massive particles)

„Right-handed neutrinos", gravitinos etc.



Couplings ~ ~ very small.

production rate $\ll$ Hubble expansion rate

$n_a \gg n_\gamma$

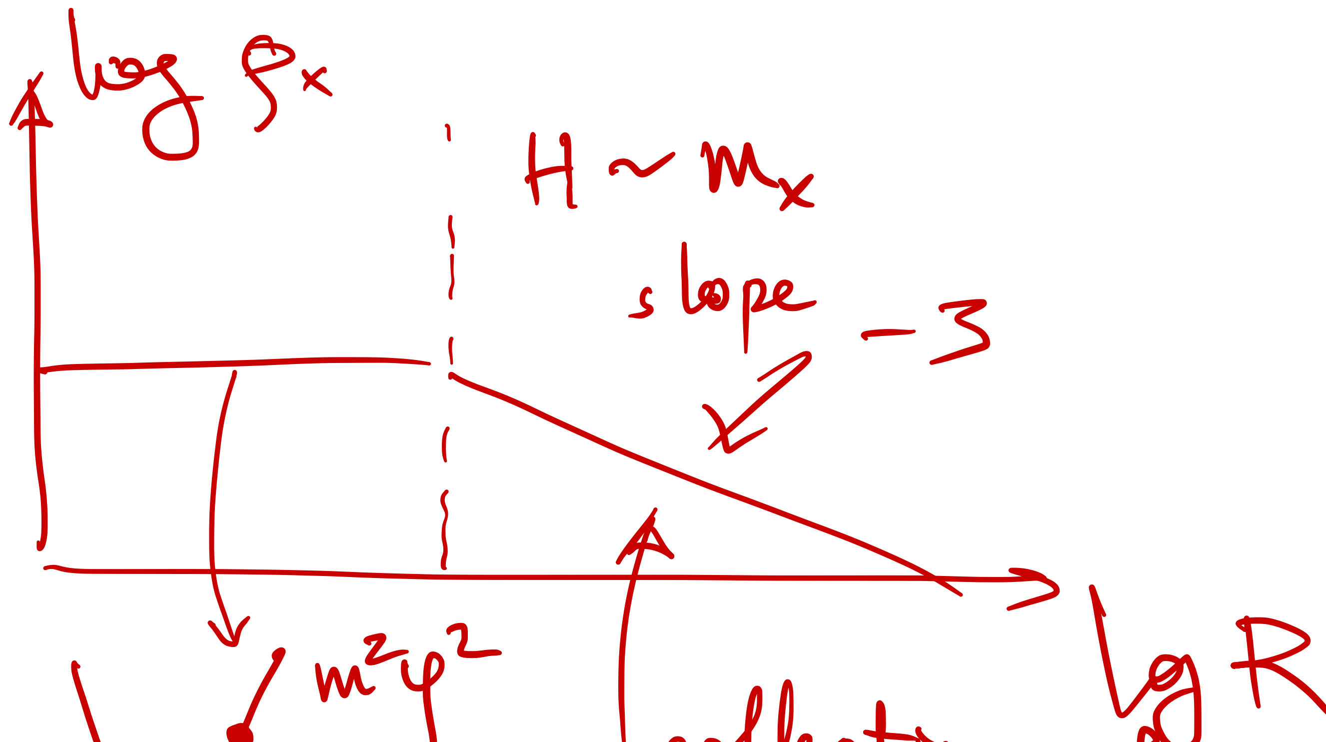
Possible types of dark matter

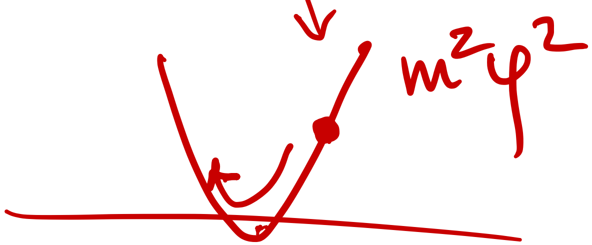
sub-eV particles

Super-cold DM (axions, any other light bosonic field).

fermion, $m_f < 0.5$ keV ← cannot form DM out of it

$$H = \frac{1}{2t} \sim \sqrt{g_*}\,\frac{T^2}{M_{Pl}}$$





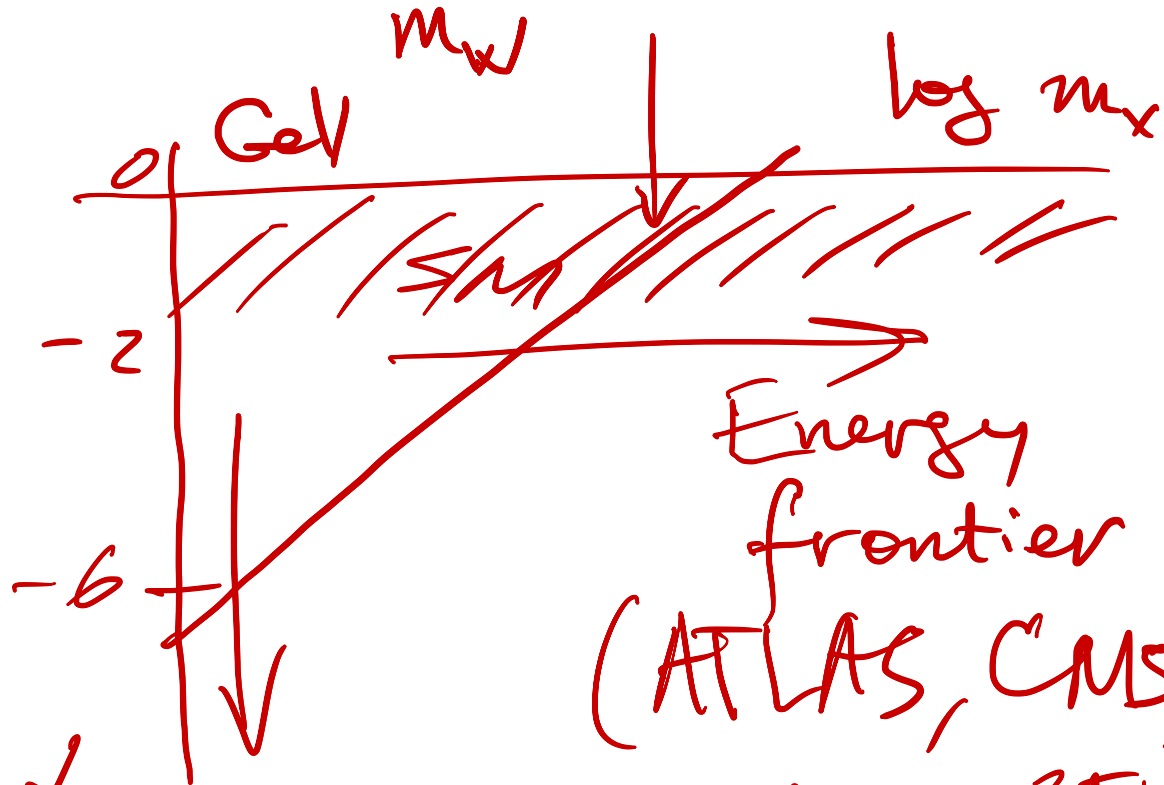
collection of particles or oscillations of classical field

Energy and intensity frontiers

$$V(r) = \frac{\alpha_x}{r} e^{-m_x \cdot r} \qquad (\hbar = c = 1)$$

$$\frac{\alpha_x}{\vec{q}^{\,2} + m_x^2}$$

$$\frac{\alpha_x}{m_x^2} = G_F$$



Energy frontier (ATLAS, CMS $\sim M_{Z'} \sim 3$ TeV)

log α_x

intensity frontier

Portals to New Physics

$\mathcal{L}_{eff} =$

$= \sum_n \frac{O_{SM} O^{ds}}{\Lambda^n}$

look for lowest dimension operators.

$(H^\dagger H)(\lambda S^2 + A \cdot S)$

$B_{\mu\nu} F'_{\mu\nu}$

gauge field strength of U(1)

$(LH)N$

$\bar{\psi} \gamma_\mu \gamma_5 \psi$

A_μ

$\frac{\partial_\mu a}{f_a}$

Portals to New Physics

$(H^\dagger H)(A \cdot S + \lambda S^2)$ Higgs p.

$B_{\mu\nu} F'_{\mu\nu}$ kinetic mixing p.

$(LH) N$ neutrino portal

$(\bar{\psi} \gamma_\mu \psi) A'_\mu$ vector portal

$(\bar{\psi} \gamma_\mu \gamma_5 \psi) \dfrac{\partial_\mu a}{f_a}$ axion portal.

. . . - - - - - - - - $(\bar{\psi} \gamma_\mu \psi)(\bar{\chi} \gamma_\mu \chi)$

Evidence for neutrino portal

$\bar{\nu}\nu \leftarrow$ not SM gauge invariant operator

$$\frac{(LH)(LH)}{\Lambda} \leftarrow \text{effective operator}$$

$\Lambda \leftarrow$ energy scale

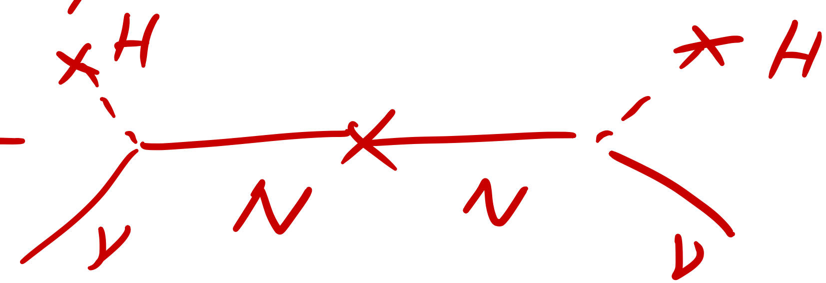
$m_\nu \simeq \frac{v^2}{2\Lambda}$; $v = 246\ \text{GeV}$

$G_F = \frac{1}{2v^2}$

Evidence for neutrino portal

Natural UV completion

$$\frac{(LH)(HL)}{\Lambda} \longleftarrow$$



$$\mathcal{L} = \frac{1}{2}\bar{N}\not{\partial}N - \frac{m_N}{2}\bar{N}N$$

$$+\,y(LH)\underline{\underline{N}} \longleftarrow$$ simplest model for ν-masses

$$\frac{y^2}{M_N}(LH)^2$$

Motivation for axion portal

$$\bar{\psi}\gamma_\mu\gamma_5\psi \;\frac{\partial_\mu a}{f_a} \quad (\dim = 5)$$

Strong CP problem,
axion solution

Summary of Strong CP problem

QCD (and more generically SM) has a non-trivial vacuum structure due to strong dynamics and instantons.

Responsible for $m_{\eta'} \gg m_{\eta,\pi}$

Same condition leads to observability of θ-term.

$$\mathcal{L}_{QCD} = \mathcal{L}_{QCD}^{naive} + \frac{\theta g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}$$

* $G\tilde{G}$ is totally non-perturbative
* $\theta \to \theta + 2\pi$ is absolute symmetry.

Summary of Strong CP problem

θ_{QCD} – quasimomentum for the vacuum configurations with fixed winding number n $\quad \vec{A}=0$

$$|\theta\rangle = \sum_n e^{in\theta}|n\rangle$$

We are forced to introduce θ, because of $|n\rangle \to |n\pm 1\rangle$ transitions, called instantons

$$\frac{g^2}{32\pi^2}\int d^4x_E\, G^a_{\mu\nu}\tilde{G}^a_{\mu\nu} = \frac{g^2}{32\pi^2}\int d^3x\, K_0^{CS}\Big|_{t=-\infty}^{t=+\infty}$$

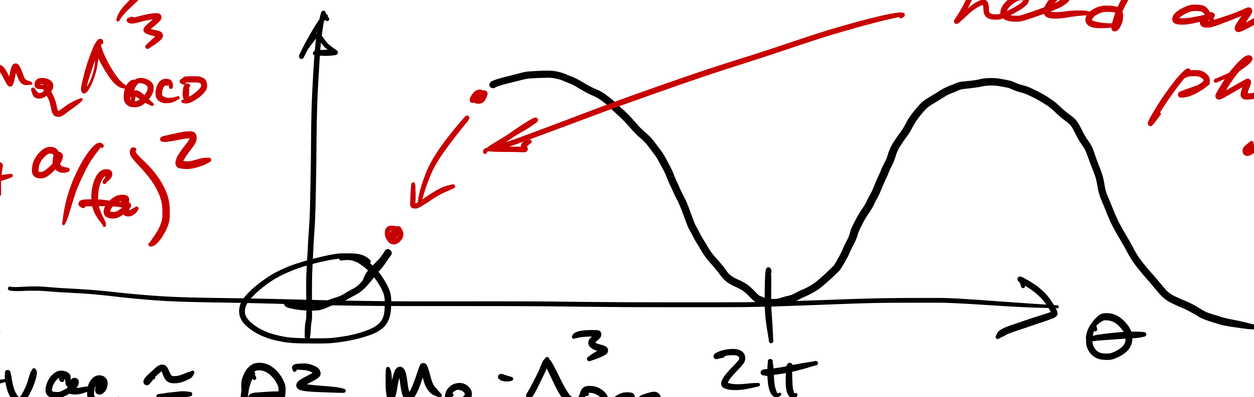
$$= n_+ - n_- \in \mathbb{Z}$$

Summary of Strong CP problem

Energy of QCD vacuum

$E = m_q \Lambda_{QCD}^3 (\theta + a/f_a)^2$

need an actual physical field that "behaves" "like θ"



$E_{vac} \simeq \theta^2 m_q \cdot \Lambda_{QCD}^3$

Superselection rule

$$\langle \theta | O_{\text{gauge invariant}} | \theta' \rangle$$

$$\sim \delta(\theta - \theta')$$

Summary of Strong CP problem

In the full SM $\bar{\theta} = \theta + \arg\det M_u M_d$

$\bar{\theta} \leftarrow$ breaks CP.

Example : $\eta \to \pi^+\pi^-$ decays

$\Gamma \sim \bar{\theta}^2$

More importantly, induces EDMs

$H_{int} = d\,\vec{S}\cdot\vec{E}$

$|d_n| \lesssim 3\times10^{-26}\,\text{cm}\cdot e$

$d_n \simeq \bar{\theta}\,\dfrac{m_q}{(1\,\text{GeV})^2}$ (can be made ~~precise~~)

$|\bar{\theta}| < 10^{-10}$

Solutions to Strong CP

why $\bar{\theta}$ is so small when it could be $O(1)$?

1. By chance.
2. $d_n \to 0$; $m_u = 0$?
   $m_u \to 0$; seems to be not viable, ~~refuted by~~ by lattice QCD
3. Engineer $\bar{\theta} = 0$ at high energies, $\bar{\theta} = 0$
   Parity conserv. mirror symm. models ?
4. Axion solution to strong CP
5. May be we do not understand strong inter.

Axions solve strong CP problem

$$\mathcal{L}_{QCD} \longrightarrow \mathcal{L}_{QCD+a} = \mathcal{L}_{QCD}^{naive} +$$

$$+ \underbrace{\left(\theta + \frac{a}{f_a}\right) G_{\mu\nu}\tilde{G}_{\mu\nu}}_{\text{dim}=5 \text{ operator}} + \frac{1}{2}(\partial_\mu a)^2.$$

$$E_{vac}^{(\theta)} = E_{vac}\left(\theta + \frac{a}{f_a}\right)$$

! Minimum of energy at

$$E_{vac} = 0 \Rightarrow \langle a \rangle_{vac} = -\theta \cdot f_a$$

Effective theta is then

$$\theta_{eff} = \theta + \frac{\langle a \rangle_{vac}}{f_a} = 0.$$ Problem solved.

Axions. Mass ~ coupling

$$m_a \sim \frac{\Lambda_{QCD}^{3/2} \, m_q^{1/2}}{f_a}$$

(more precisely $m_a = \frac{f_\pi}{f_a} \frac{m_u m_d}{(m_u + m_d)^2} m_\pi$)

Substituting in numbers, we get

$$m_a \simeq 6 \text{ meV} \times 10^9 \text{GeV}/f_a$$

f_a small " " " 9

disfavored (excluded) by – , ...

Very light, very weakly coupled particles

Axions. Need for UV completion

Axion-like particles