Axion phenomenology

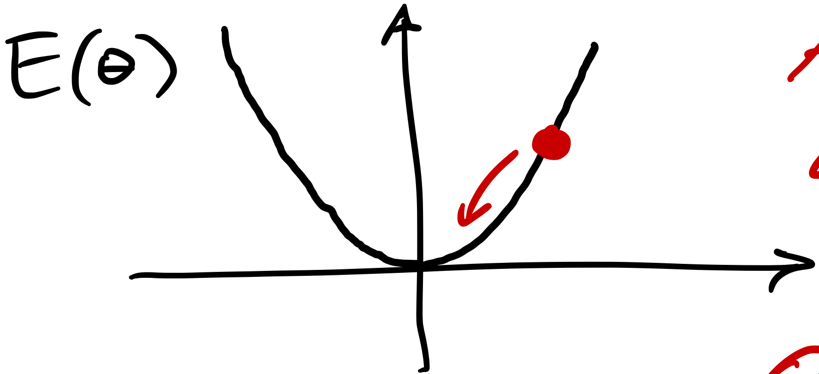
- Recap of Strong CP problems and axions. Peccei-Quinn sectors
- Couplings of axions to photons
- Search for solar axions
- Axions as possible dark matter candidates

Strong CP problem and axions

$$\mathcal{L}_{QCD} \longrightarrow \mathcal{L}_{QCD} + \underbrace{\frac{\bar{\Theta}\, g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}}$$

Breaks CP, induces

d_n ~ 10 orders of m. above limits if $\bar{\Theta} \sim O(1)$. $\quad d_n \sim m_q \bar{\Theta} / m_n^2$



Axions allow to relax θ-dependent QCD vacuum energy → 0.

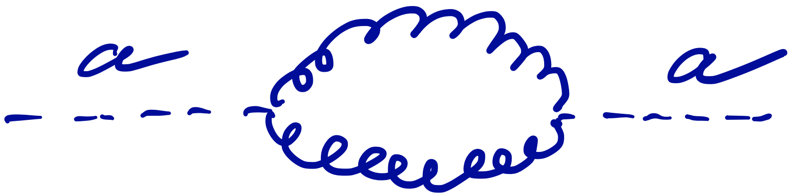
$$\theta_{eff} = \theta_{initial} + \frac{\langle a \rangle}{f_a} = 0.$$

This process of relaxation is not instantaneous, but happens as a function of t ⇒ axions can be DM.

The need for UV completion.

$$\mathcal{L}_a = \frac{a}{f_a}\,\frac{g_s^2}{32\pi^2}\,G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}$$

dim = 5 operator



UV divergent diagram

induces $(\partial_\mu a)^2 \dfrac{\Lambda_{UV}^2}{f_a^2}$ corrections.

A UV completion is needed at energy scale $\lesssim f_a$.

$\Rightarrow$ Peccei-Quinn sectors

Peccei-Quinn symmetry

(Many explicit models exist)

Consider a model of very heavy quark with mass generated by spontaneous symmetry breaking.

$$\mathcal{L}_{PQ} = V(\Phi^*\Phi) + \bar{\psi}_L \not{\partial} \psi_L + \bar{\psi}_R \not{\partial} \psi_R + \bar{\psi}_L \psi_R \Phi + \bar{\psi}_R \psi_L \Phi^*$$

$\Phi \to e^{i\alpha}\Phi$; $\psi_L \to e^{i\alpha}\psi_L$ ⇐ Global PQ symmetry

$V(\Phi) = \lambda(\Phi^*\Phi - f_a^2)^2$. $\Rightarrow$ $m_\psi = f_a$ +

1 Goldstone boson, the phase of Φ.

Integrating out ψ gives $\dfrac{a\, g_s^2}{32\pi^2} G\tilde{G}$

Derivation of axion mass and coupling to EM

You got to use the anomaly equation

$$\partial_\mu(\bar{q}\gamma_\mu\gamma_5 q) = 2m_q\bar{q}i\gamma_5 q + \frac{g^2}{16\pi^2}G\tilde{G} + \frac{\alpha_{EM}}{2\pi}Q_q F\tilde{F}$$

Take a QCD Lagrangian $(\theta = a/f_a)$

$$\mathcal{L}_{QCD} = -\frac{1}{4}G_{\mu\nu}G_{\mu\nu} + \sum_{u,d}\bar{q}(i\not{D} - m)q + \frac{\theta g^2}{32\pi^2}G\tilde{G}$$

and apply chiral rotations $q \to e^{i\theta_q\gamma_5}q$

$$\theta_u = -\frac{1}{2}(m_*/m_u)\theta\ ;\quad \theta_d = -\frac{1}{2}(m_*/m_d)\theta$$

where $m_* = m_u m_d/(m_u+m_d)$.

This removes θ from $G\tilde{G}$ and transfers it to the quark sector.

Derivation of axion mass and coupling to EM

Up to θ^2 terms, you get

$$\mathcal{L} = \theta^0 \text{ terms} + 2m_* (\bar{u} i\gamma_5 u + \bar{d} i\gamma_5 d)\theta$$

$$+ \tfrac{1}{2} m_*^2 \left(\frac{1}{m_d}\bar{d}d + \frac{1}{m_u}\bar{u}u\right)\theta^2 \leftarrow \text{mass for axion}$$

(Remember that we can identify $\theta = \frac{a}{f_a}$)

In QCD $\langle \bar{u}u \rangle = \langle \bar{d}d \rangle = -\frac{m_\pi^2 f_\pi^2}{(m_u + m_d)}$

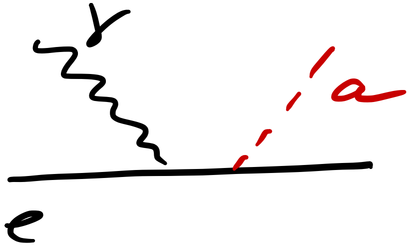
θ^2 term = axion mass, $m_a^2 = m_\pi^2 (f_\pi^2 / f_a^2) \frac{m_*}{m_u + m_d}$

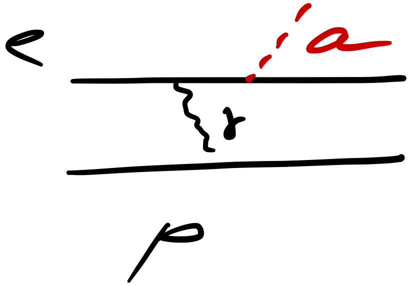
$\left(m_a = 6\,\text{meV} \times \frac{10^9\,\text{GeV}}{f_a} \right)$

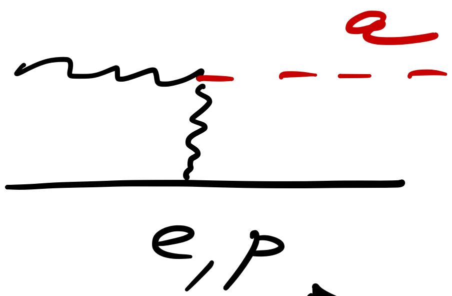
Coupling to $\gamma\gamma$: $\frac{a}{f_a} F_{\mu\nu} \tilde{F}_{\mu\nu} \frac{e^2}{16\pi^2} \frac{4m_d + m_u}{3(m_u + m_d)}$

You can derive this coupling from the same chiral rotation

Stellar energy loss to axions



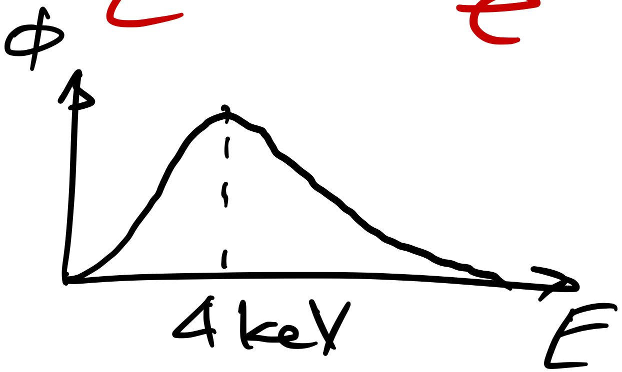




Example: Primakoff process inside the Sun generates

$$\frac{d\Phi_a}{dE} \simeq 6\times10^{10}\,\frac{1}{s\cdot cm^2\,keV}\left(\frac{g_{a\gamma}}{10^{-10}\,GeV^{-1}}\right)^2 E^{2.481}\, e^{-E/1.205}$$

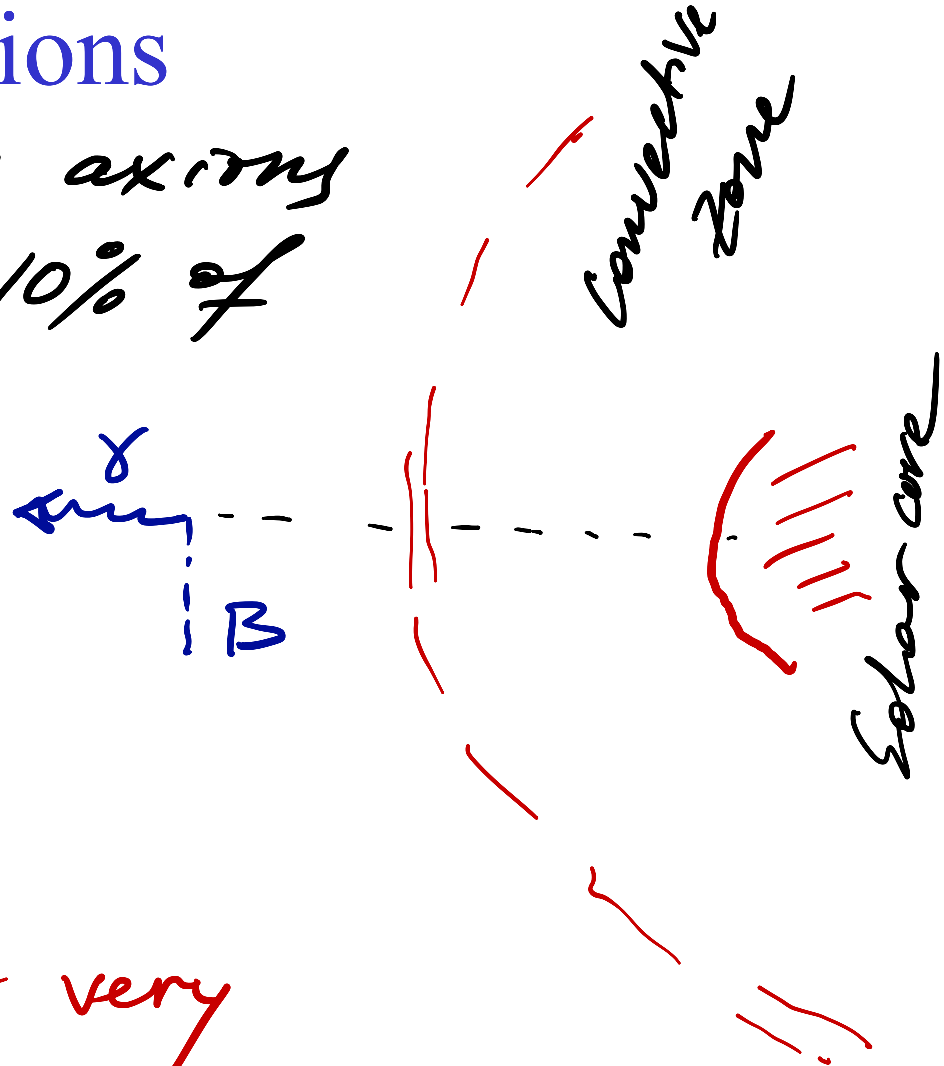
(at Earth)



$$\mathcal{L}_{a\gamma} = -\frac{1}{4}\, g_{a\gamma}\, F\tilde{F}$$

Solar axions

Clearly, luminosity in axions should be less than ~10% of solar luminosity.
(otherwise problems with solar models)



Can we detect solar axions?
(remember, they interact very weakly!)

* Look for extra ionization!
* Look for γ regeneration in magnetic fields

Mixing of axions and photons in external B

$$\frac{1}{4} F\tilde{F} a\, g_{a\gamma} \rightarrow g_{a\gamma}\, a(\vec{E}\vec{B})$$

Create magnetic field perpendicular to axion propagation $\Rightarrow$ a and γ will mix. Propagation of eigenmodes satisfies the equation

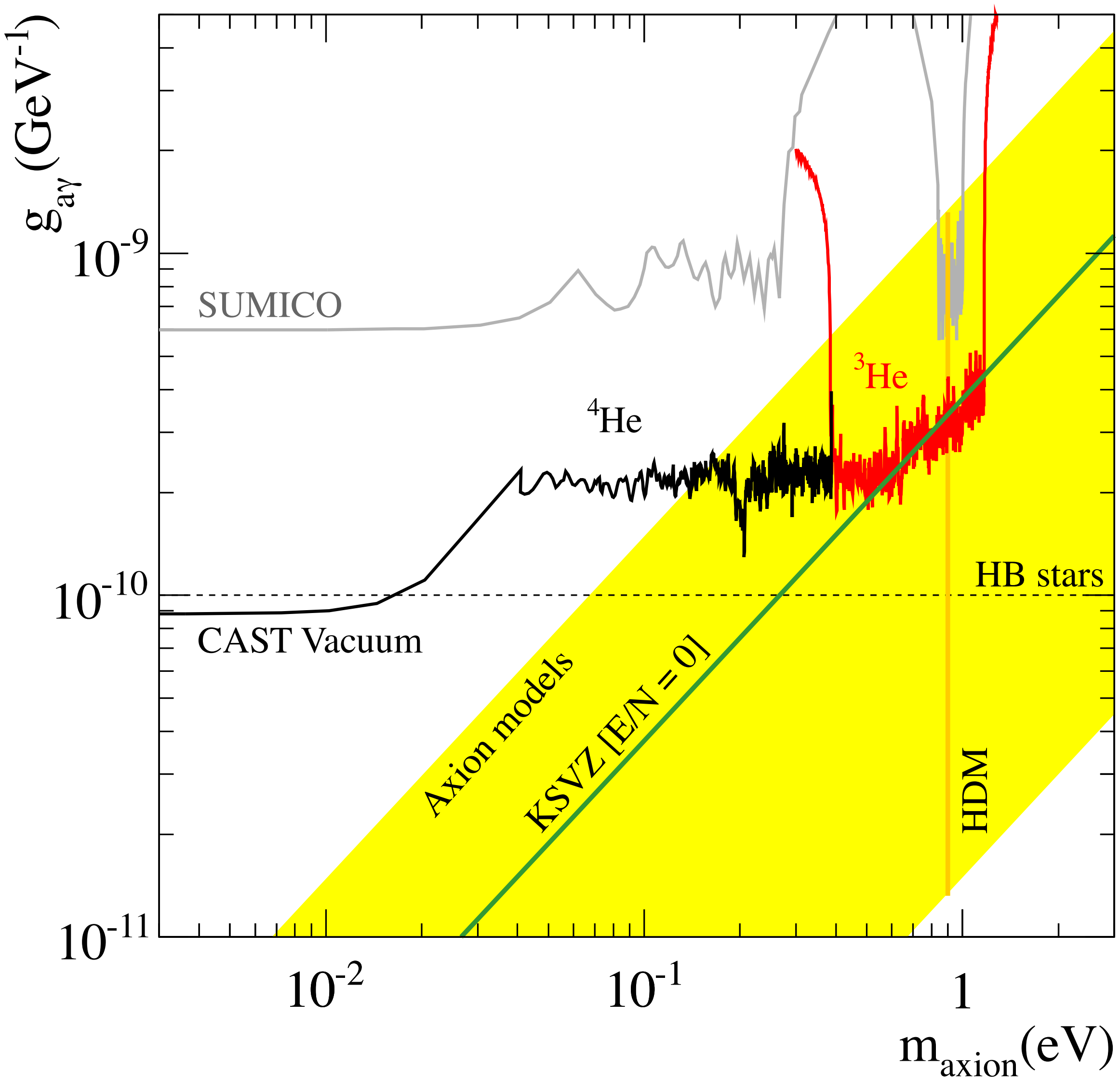
$$i\partial_z \begin{pmatrix} A \\ a \end{pmatrix} = \begin{pmatrix} k - \frac{\omega_{pl}^2}{2k} & \frac{B g_{a\gamma}}{2} \\ \frac{B g_{a\gamma}}{2} & k - \frac{m_a^2}{2k} \end{pmatrix} \begin{pmatrix} A \\ a \end{pmatrix}$$

$$P_{a\to\gamma}(L) = \sin^2(2\theta_{eff}) \sin^2\left(L m_a^2 / 4k_\gamma\right)$$

$$\theta_{eff} = \frac{B g_{a\gamma} \omega}{m_a^2 - \omega_{pl}^2} \quad \Bigg| \quad = \frac{4B^2 g^2 \omega^2}{m_a^4} \sin^2\left(\frac{L m_a^2}{4\omega}\right)$$

CAST limits on $g_{a\gamma}$

Notice additional exclusion from gas filling

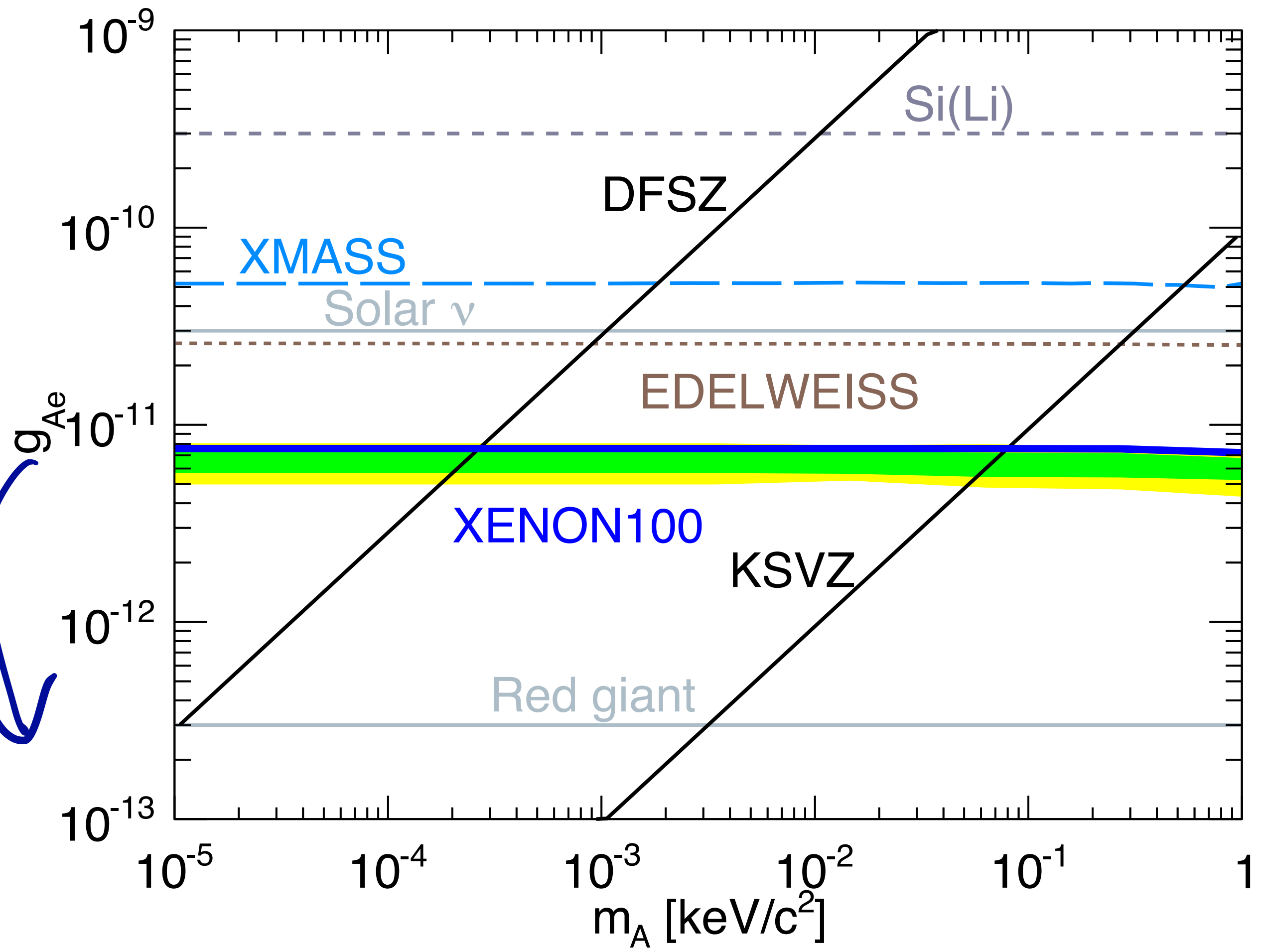


ALP – „axion like particles"

Constraints on solar axions from Xenon 100

Best direct constraints on g_{ae}

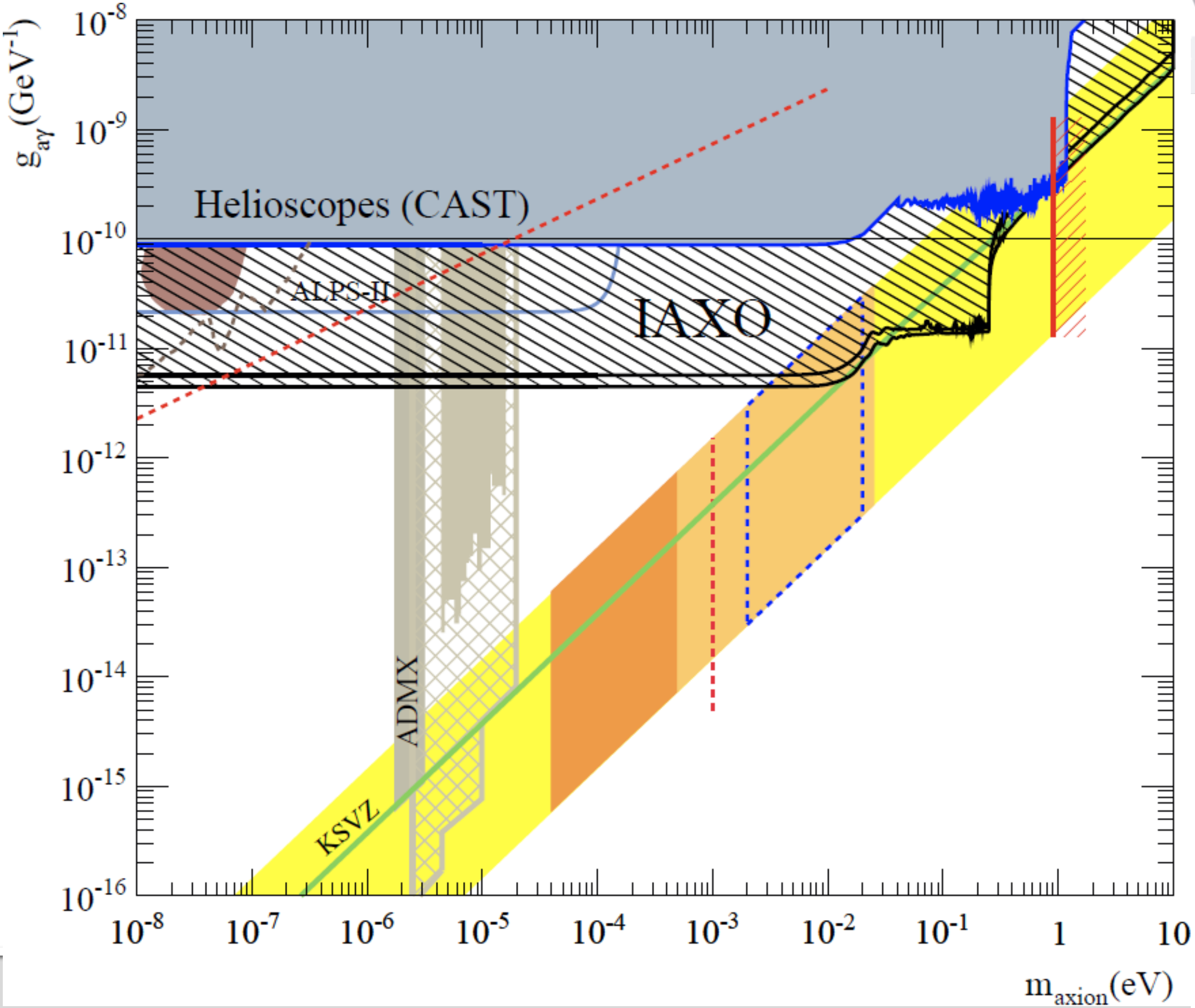
LZ, Xenon 1T

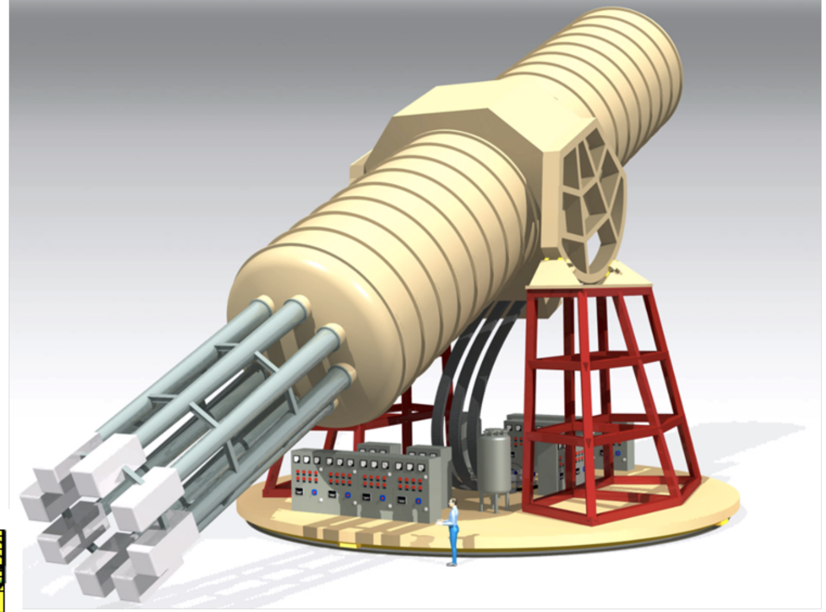


Unfortunately, in all these examples the signal scales as $\sim g_{ay}^4$.

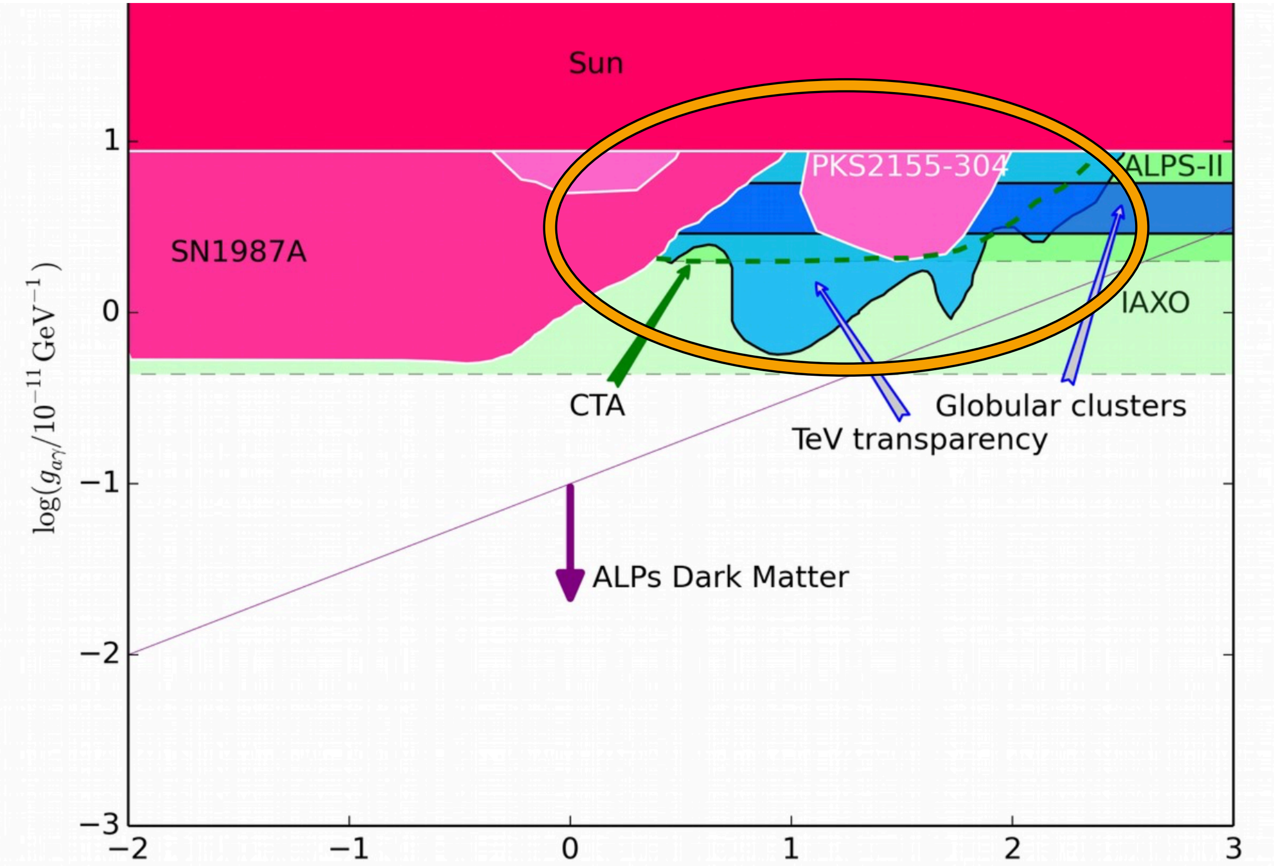
IAXO?

Significant gain over CAST





“Hints” on ALPs and axions



ALPs — axion like particles. (strict relation between ma and fa is relaxed)

[Horns 15]

New hints on ALPs: anomalous transparency of the Universe to the TeV gamma rays; anomalous cooling of neutron star in Cas A(?); preference for extra energy loss channels by comparing HB and RGB stars in globular clusters etc. (After A Ringwald’s talk)

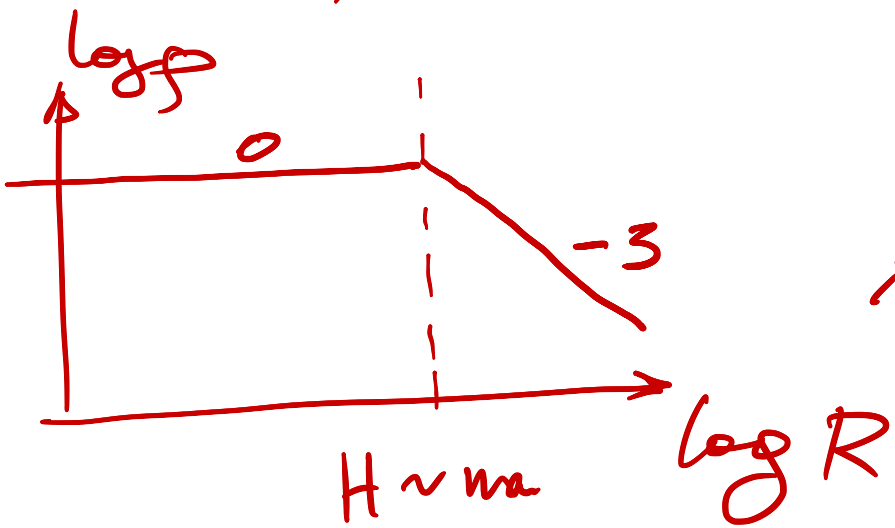
Cosmological evolution of a massive scalar

$$\Box a = -\frac{dV(a)}{da} = -m_a^2 a$$

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

(notice similarity with oscillator with friction)

$$H = \dot{R}/R = 1/2t = \left(\frac{8\pi}{3} G_N \rho_{rad}\right)^{1/2} \sim T^2/M_{pl}$$



$\rho_{initial} = m_a^2 a_{initial}^2$ is getting diluted by Hubble expansion when $H < m_a$

Cosmological evolution of axion field

$m_a = m_a(T)$

Large f_a models

$$\Omega_a h^2 \sim 5\times 10^3 \left(\frac{f_a}{10^{16}\,\mathrm{GeV}}\right)^{3/2} (\theta_{in})^2$$

Smaller f_a

$$\Omega_a h^2 \sim 2\times 10^4 \left(\frac{f_a}{10^{16}\,\mathrm{GeV}}\right)^{7/6} \theta_i^2$$

"Axion window"

$$10^9\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}-10^{13}\,\mathrm{GeV}$$

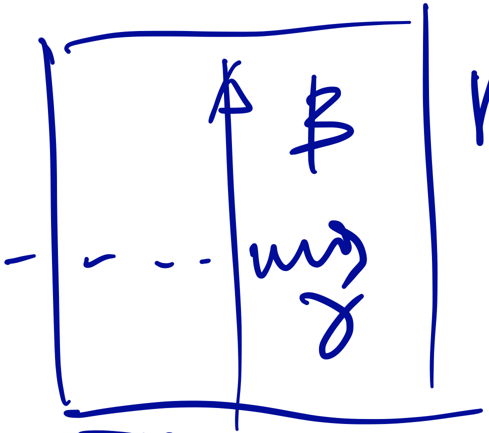
Astrophysics non-negotiable

Cosmology depends on θ_{in}

"Axion haloscopes"

$$m_a \sim 6\,\text{MeV} \times \frac{10^9\,\text{GeV}}{f_a}$$

$\Rightarrow$ meV – $\underline{\underline{\mu\text{eV}}}$ range.



resonator cavities

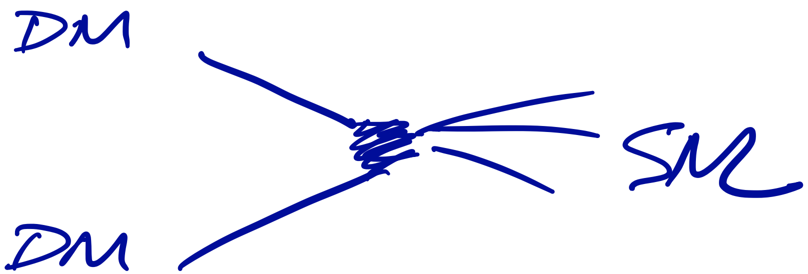
$$\theta = \theta_{in} \to \theta(t) = \frac{a(t)}{f_a}$$

$$\rho^{DM}_{galactic} = 0.3\,\text{GeV}/\text{cm}^3 = m_a^2\, a^2(t)$$

$$\theta_{eff}(t) = \left(4 \times 10^{-19}\right) \sin(m_a t)$$

WIMP phenomenology

- WIMP abundance via the annihilation cross section
- Example with the Higgs-mediated scalar dark matter
- Scattering on nuclei. Perspectives of direct detection.
- WIMPs with extra mediators. Secluded WIMPs



$$T < m_{DM}$$

Expansion-stopped self-annihilation

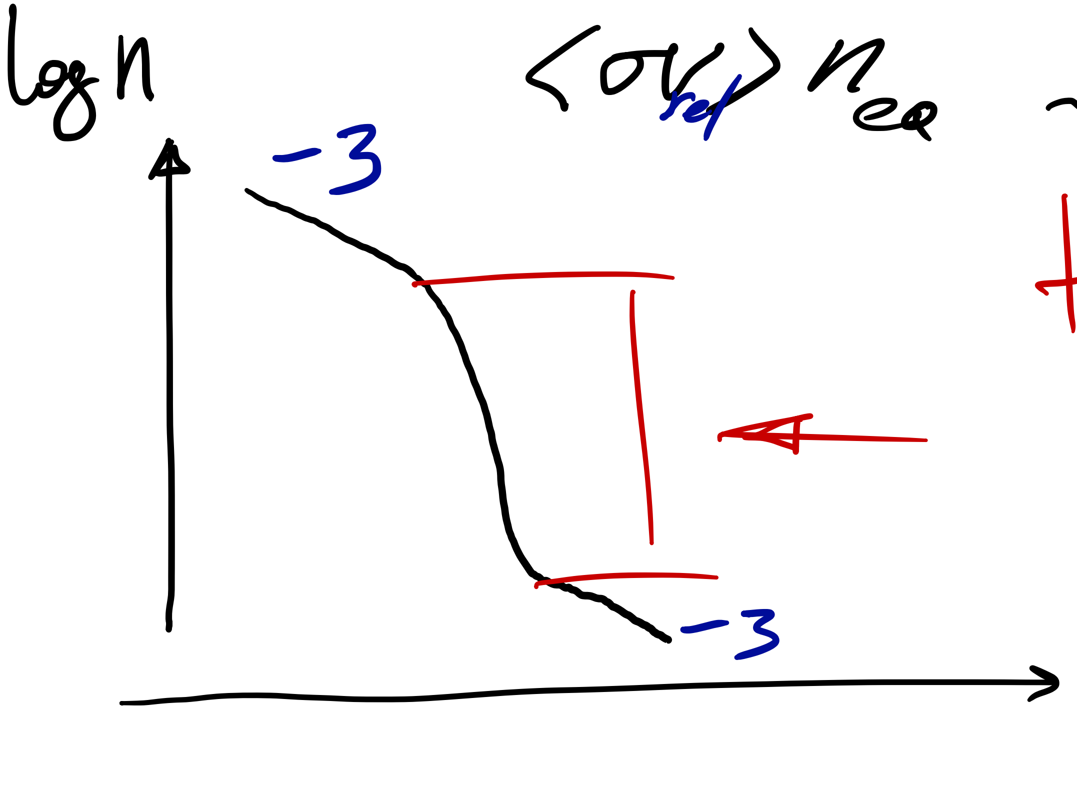
Boltzmann equation

$$R^{-3}\, d(nR^3)/dt = \langle \sigma v \rangle (n_{EQ}^2 - n^2)$$

When R.H.S. $=0$, $n = n_{EQ} \sim e^{-m/T}$ at $T < m$

Annihilation stops when

$\langle \sigma v_{rel} \rangle n_{eq} \lesssim$ Hubble rate



this drop is regulated by $\langle \sigma_{ann} \cdot v \rangle$

Expansion-stopped self-annihilation

$$\Omega_X \simeq \Omega_{DM} \simeq 0.24 \quad \text{if}$$

$$\langle \sigma_{ann} \cdot v \rangle \simeq c \times 1\,\text{pbn} = 10^{-36}\,\text{cm}^2$$

Very similar to many weak-scale cross sections.

Accident?
Or a case for weakly interacting massive particles?

Lee-Weinberg window on WIMPs

Suppose that interactions between WIMPs and SM are mediated by weak-type forces: ← we are going to relax this assumption

$$\langle \sigma v \rangle \simeq G_F^2 \, m_{DM}^2 \sim g_w^4 \frac{1}{m_{DM}^2}$$

small m_{DM}

high m_{DM}

$= 1\,\mathrm{pbn}$

6 GeV → Min $m_{DM} \sim$ few GeV

max $m_{DM} \sim$ tens of TeV

exotic neutrinos

Higgs-mediated dark matter example

One of the simplest WIMP models:

$$\mathcal{L} = \mathcal{L}_{SM} + \tfrac{1}{2}(\partial_\mu S)^2 - \tfrac{1}{2}\underline{m_0^2} S^2$$

$$+ \lambda (H^\dagger H) S^2 \leftarrow \text{Higgs portal}$$

EW symmetry breaking

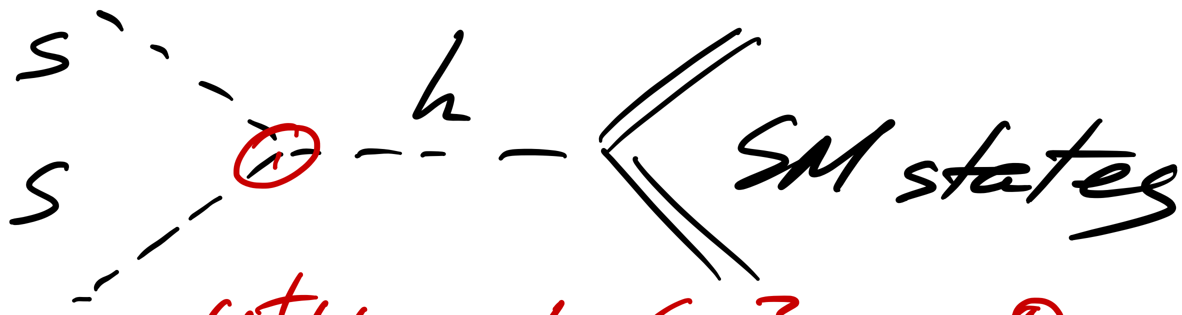
$$H = \frac{v + h}{\sqrt{2}} \qquad \underline{v = 246\ \text{GeV},}$$

$\underline{hS^2}$; $\underline{h^2S^2}$ interaction terms

$$\underline{m_S^2 = m_0^2 + \lambda v^2}$$

$\hookrightarrow \lambda$

$\langle \sigma v \rangle = 1\ \text{pbn}$



$$H^\dagger H = \frac{1}{2}(v^2 + 2vh + h^2).$$

Simplest models of Higgs mediation

Silveira, Zee (1985); McDonald (1993); Burgess, MP, ter Veldhuis(2000)

DM through the Higgs portal – *minimal model of DM*

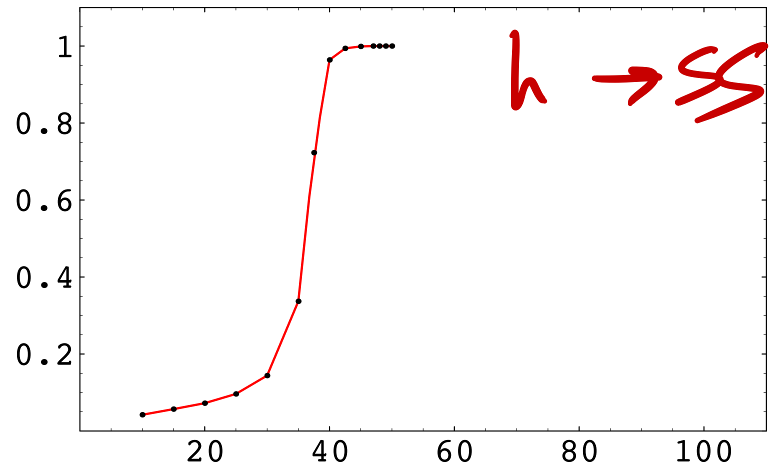
$$-\mathcal{L}_S = \frac{\lambda_S}{4}S^4 + \frac{m_0^2}{2}S^2 + \lambda S^2 H^\dagger H$$

$\langle \sigma v \rangle_{ann} \Rightarrow \lambda$ - coupling

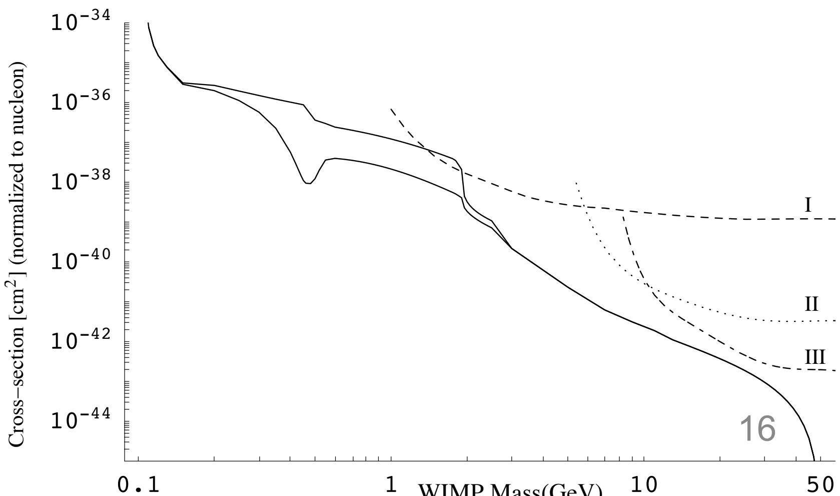
$$= \frac{\lambda_S}{4}S^4 + \underbrace{\frac{1}{2}(m_0^2 + \lambda v_{EW}^2)S^2} + \lambda v_{EW} S^2 h + \frac{\lambda}{2}S^2 h^2.$$

125 GeV Higgs is "very fragile" because its with is ~ y_b^2 – very small

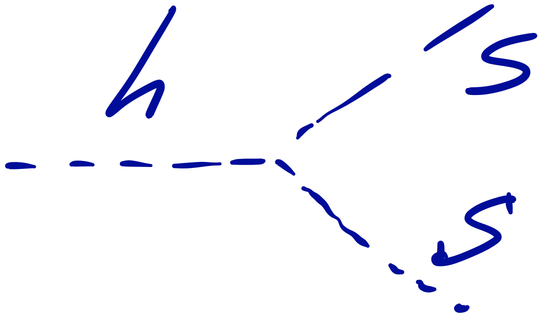
$R = \Gamma_{\text{SM modes}}/(\Gamma_{\text{SM modes}}+\Gamma_{\text{DM modes}})$. Light DM can kill Higgs boson easily (missing Higgs Γ: van der Bij et al., 1990s, Eboli, Zeppenfeld,2000)



$h \to SS$



Higgs-mediated dark matter example



If m_s is below 50 GeV, this process should dominate the Higgs width and dilute observable modes. This does not happen

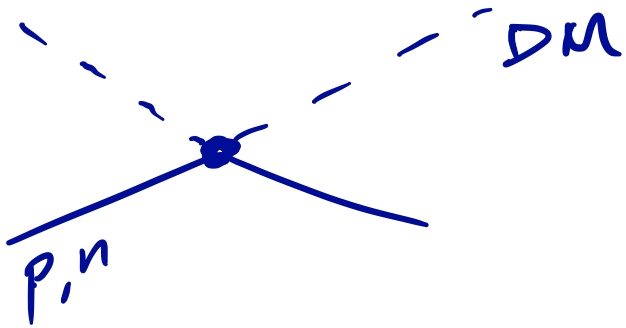
$\Rightarrow$ all masses below 50 GeV are disfavored.

LHC rules out light Higgs-mediated WIMPs

| $m > 300$ GeV are not ruled out

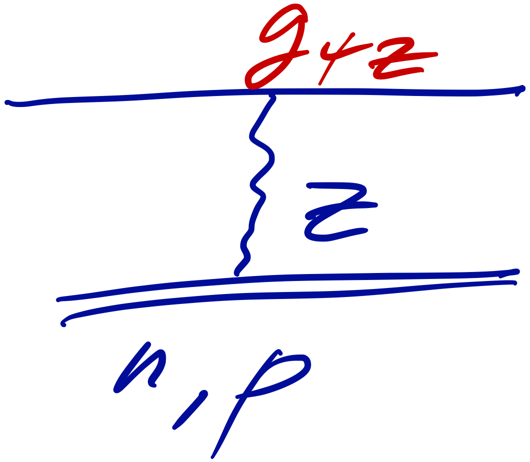
Nuclear recoil from interaction with WIMPs

Typical WIMP galactic velocity $\sim 10^{-3}c$. A 100 GeV particle has $\sim$ 100 keV energy that it can share with nuclei in elastic collisions



If the amplitude has a nuclear spin-independent component, there is an enhancement by A, the number of nucleons inside a nucleus

Nuclear recoil from interaction with WIMPs



ψ_{DM}

$$g_n^Z \simeq -1/2 .$$

$$\sigma_{DM-n} = G_F^2 m_n^2 \left(\mathcal{O}(1)\right)^2$$

$g_{\psi Z}$

$m_{DM} > m_n$

$$\left(10^{-5}\,\frac{1}{GeV^2}\right)^2 \cdot \left(m_N \sim GeV\right)^2$$

$$\frac{1}{GeV} = \frac{1}{5} \times 10^{-13}\,cm$$

$$\sim 10^{-10}\,\frac{1}{GeV^2} \simeq$$

$$\simeq \underline{4 \times 10^{-38}\,cm^2}$$

Updates on the minimal Higgs-mediated model:

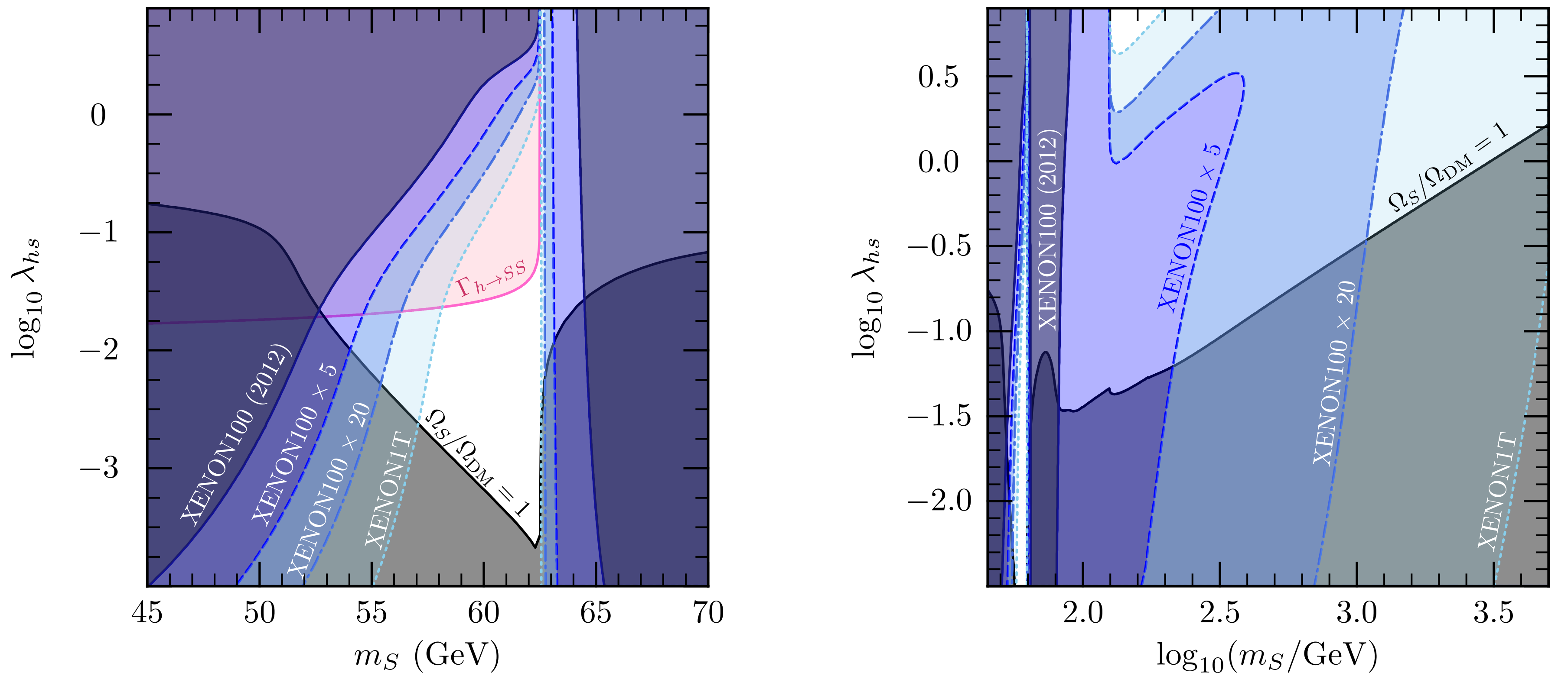
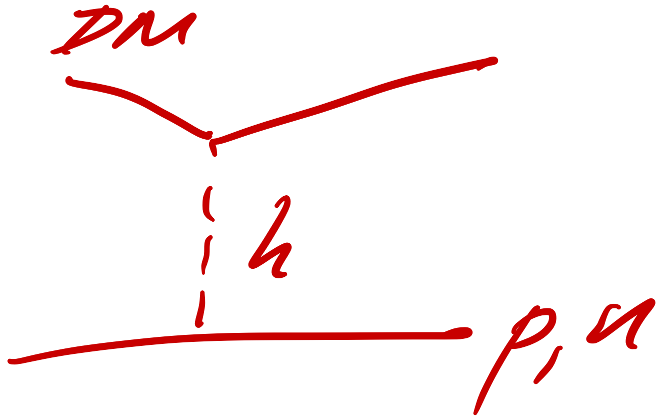


Figure from Cline, Scott, Kainulainen, Weniger, 2013.

Direct detection is competitive with the Higgs constraints.
New generation of direct detection can probe up to TeV scale WIMP masses.

Higgs portal may lead to other forms of dark matter, e.g. based on the non-Abelian “dark group”, Hambye, 2008.

WIMP-nucleon scattering cross section



$$\sigma \simeq G_F^2 m_n^2 \times (g_{hn})^2$$

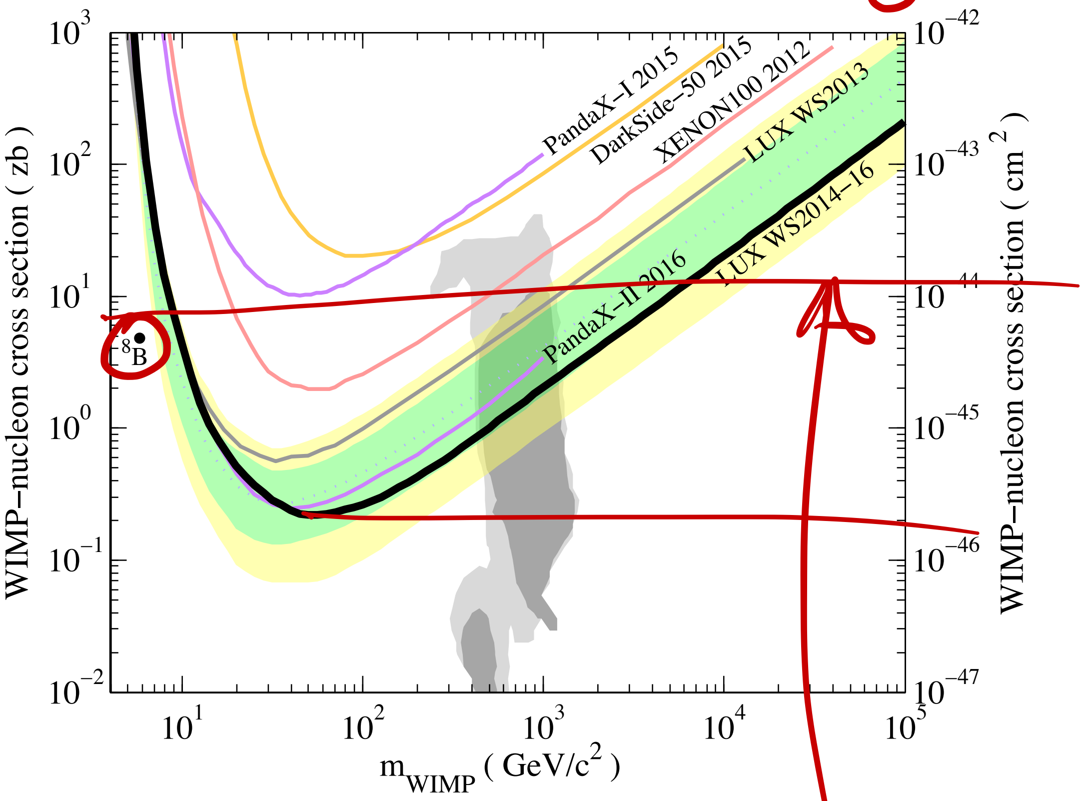
$$g_{hn} \sim \frac{200\ \text{MeV}}{246\ \text{GeV}} \sim 10^{-3}.$$

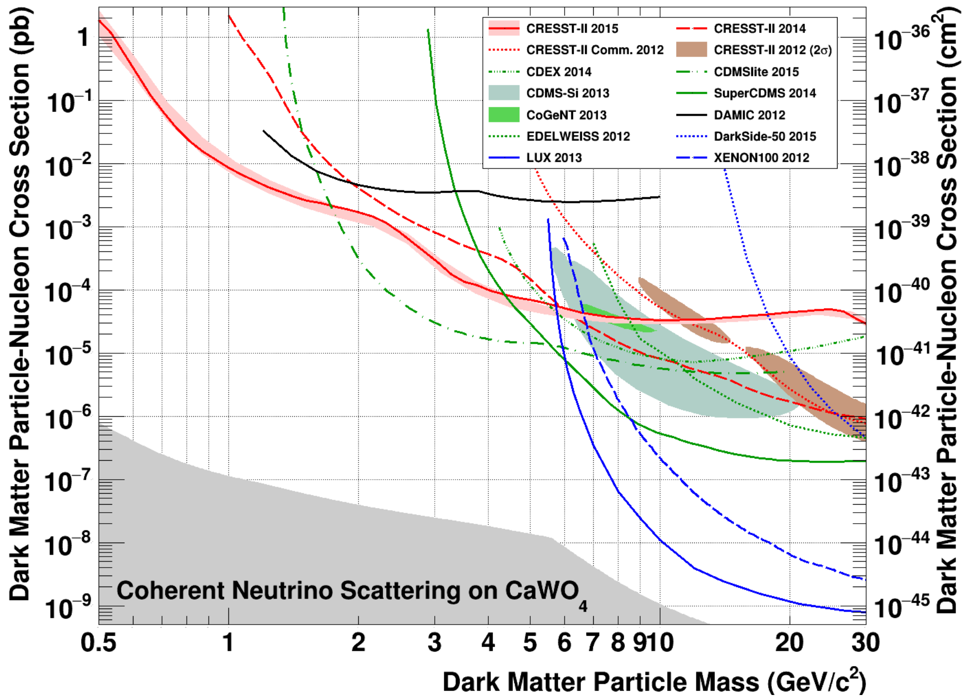
$$\frac{\sigma_{h\text{-mediated}}}{\sigma_{Z\text{-mediated}}} \sim 10^{-6}$$

Progress in direct detection of WIMPs

Lux results, 2016 Z-mediated

CRESST, 2015





higgs-mediated

Direct detection disfavours many H-mediated models in ~ few 100 GeV ~~&~~ mass range.