Pseudo Nambu-Goldstone bosons as dark matter candidates

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MF, Thomas Hambye & Eduard Masso, *PRX 1, 021026 (2011)*
MF, Alex Pomarol, Francesco Riva & Alfredo Urbano, *to appear*

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Outline

- pseudo Nambu-Goldstone Bosons (pNGBs) & the QCD scale; today's talk: pNGBs & the electroweak scale
- pNGBs coupled to the Higgs as dark matter (DM) candidates
- first candidate: a sub-GeV scalar, associated to a symmetry of the neutrino sector
- second candidate: a multi-GeV composite scalar, associated to a symmetry of the electroweak symmetry breaking sector

pNGBs: generalities

- for any global symmetry that is spontaneously broken, there exists a spin-0 field with only derivative interactions, that is, massless and with no potential: an exact Nambu-Goldstone boson (NGB)
- when the global symmetry is explicitly broken (by a coupling, or an anomaly), the NGB acquires a mass and non-derivative interactions, thus becoming a pseudo NGB
- the symmetry is approximate, as long as the scale of spontaneous symmetry breaking (SB) is much larger than the scale of explicit SB

pNGBs associated to the QCD scale

M_{Planck} — Natural cutoff of the gauge theory

$$\alpha_s \sim 1 \; , \quad SU(3)_L \times SU(3)_R \to SU(3)_V$$

Spontaneous breaking of chiral symmetry

Λ_{QCD} — leads to 8 NGBs: the pseudoscalar mesons π's, K's, ...

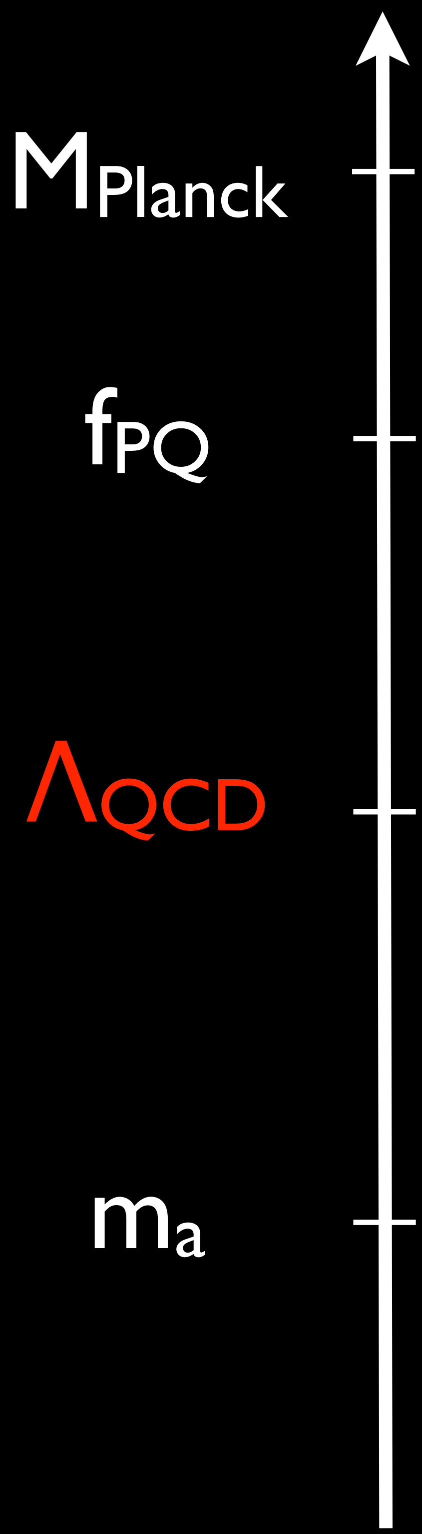
Explicit breaking by quark masses makes them massive

m_π

$$m_\pi^2 = \frac{m_u + m_d}{f_\pi^2} \Lambda_{QCD}^3$$

Pions are unstable under weak/electromagnetic decays: no good dark matter candidate here...

pNGBs associated to the QCD scale



Spontaneous breaking of the Peccei-Quinn U(1) symmetry, introduced to solve the strong CP problem

The axion, the Peccei-Quinn NGB, receives a mass from the anomaly of $U(1)_{PQ}$ w.r.t. $SU(3)_{QCD}$

$$m_a^2 = \frac{m_u m_d}{m_u + m_d} \frac{\Lambda_{QCD}^3}{f_{PQ}^2}$$

The axion can be long-lived, since its interactions can be suppressed by a large f_{PQ}. For $f_{PQ} = (10^{12} - 10^{14})$GeV, the axion is a good dark matter candidate.

EW scale & the hierarchy problem

- M_{Planck} — Natural cutoff of the gauge theory

Around the TeV scale, new physics is required to protect v = 246 GeV from quadratic divergences. Either low energy supersymmetry, or Nature may repeat itself, with a new strongly interacting sector.

- Λ_{EW}

The lightest states of a strong EWSB sector should be the pNGBs associated to its global symmetries

- m_h

$$SO(5) \to SO(4) \qquad H \sim 4_{SO(4)}$$

If a composite Higgs doublet emerges as a pNGB, it is naturally lighter than the new strongly-interacting physics: $v \ll \Lambda_{EW}$

- Λ_{QCD}

Kaplan Georgi '84

Agashe Contino Pomarol '04

- m_π

pNGBs associated to the EW scale

M_{Planck}

M_{seesaw}

Heavy sterile neutrinos are introduced to generate light neutrino masses; their heavy mass may originate from spontaneous SB, e.g. of lepton number $U(1)_L$

Λ_{EW}

The composite pNGBs can include H & a real singlet

$$SO(6) \to SO(5) \qquad (H, \eta) \sim 5_{SO(5)} = (4+1)_{SO(4)}$$

m_H, m_η

Explicit breaking is provided by the gauge couplings g,g' and by the Yukawa couplings y_t, y_b, ...

m_θ

The pNGBs of the sterile neutrino sector can receive mass from the neutrino Yukawa couplings to the Higgs

Motivations for pNGB dark matter

- pNGB couplings to SM particles are suppressed by the spontaneous SB scale f ⇒ the pNGB lifetime grows with f^2

  One needs $\tau_{DM} > \tau_0 = 5 \cdot 10^{17}$s, but also $\tau(DM \to e^+e^-) > 10^{26}$s

- The pNGB mass scale is not chosen ad-hoc: it is induced by a physical scale, e.g. Λ_{EW}, and it can be radiatively stable, even down to scales much below Λ_{EW}

- The same source of explicit SB induces both the pNGB mass, and its couplings that determine its relic density: one-to-one correspondence between m_{DM} and Ω_{DM}

Dark matter as sub-GeV pNGB from the seesaw scale

The Higgs portal to dark matter

Let us assume that (i) a pNGB θ from a large scale f receives a mass below Λ_{EW} from the coupling to the Higgs H:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} - \frac{\lambda}{2}\theta^2 H^\dagger H + \mathcal{O}(\theta^4) \qquad m_\theta^2 = \lambda v^2$$

(ii) a parity $\theta \to -\theta$ is preserved, as a residual global symmetry

(iii) a direct mass term θ^2 is absent, because of the pNGB nature of θ

At temperatures $T \sim m_h$ the interaction λ may or may not thermalize θ

$$\Gamma(h \to \theta\theta) = \frac{1}{16\pi}\lambda^2 \frac{v^2}{m_h}\sqrt{1 - \frac{4m_\theta^2}{m_h^2}} \qquad \text{versus} \qquad \mathcal{H}(T = m_h) \simeq 17\frac{m_h^2}{M_{Planck}}$$

Thermalization for: $\lambda \gtrsim 6 \times 10^{-8}\left(\frac{m_h}{120\ \mathrm{GeV}}\right)^{3/2}$ or $m_\theta \gtrsim 44\ \mathrm{MeV}$

Freeze-out or... freeze-in

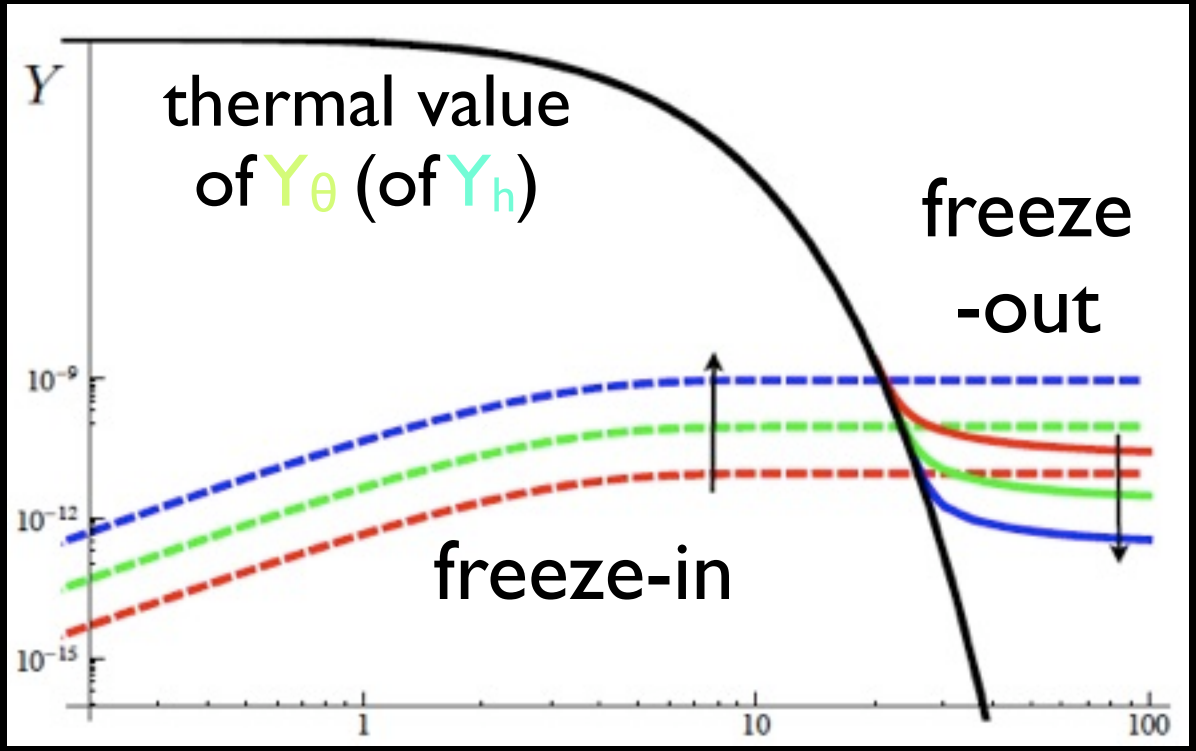
- Freeze-out: θ thermalizes and later, at $T \lesssim m_\theta$, it decouples
  The correct Ω_{DM} is obtained for $<\sigma_{ann} v_{rel}> \approx 10^{-26}$ cm^3 s^{-1}
  Then, the constrained Higgs portal requires $m_\theta \approx 50$ GeV

  Farina, Pappadopulo, Strumia, 2010

- Freeze-in: a less-than-thermal population of θ's is produced by the annihilation/decay of a heavier particle X. The θ number density reaches a plateau at $T \approx m_X$.
  In the case of the Higgs portal, X = h, W, Z, ...

Hall, Jedamzik, March-Russell, West, 2009

$Y_\theta = n_\theta / s$



$z_{f.o.} = m_\theta / T$
$z_{f.i.} = m_h / T$

arrows indicate increasing values of λ

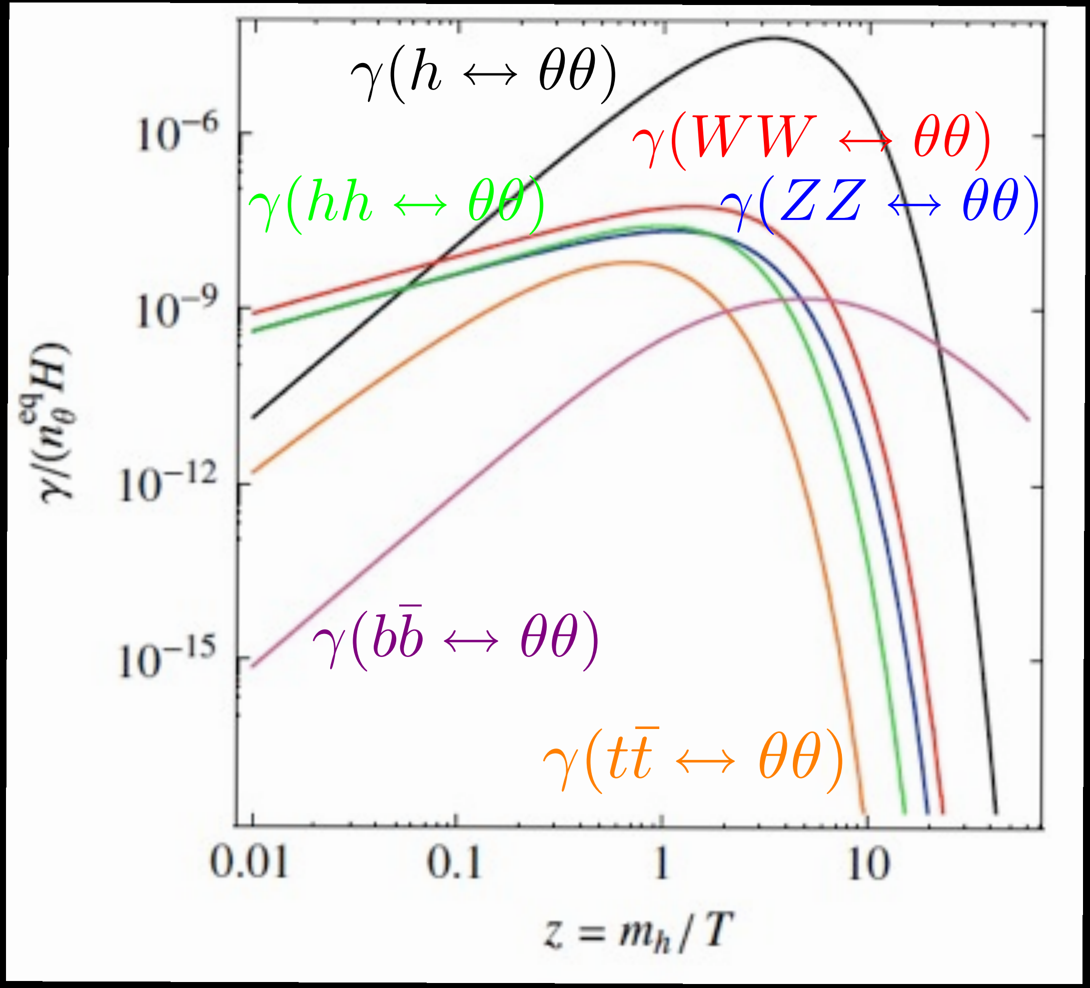
A prediction for m_{DM}

We studied the freeze-in of θ-particles through the Higgs portal

$$z\mathcal{H}(z)s(z)Y'_\theta(z) = \left[1 - \left(\frac{Y_\theta(z)}{Y_\theta^{eq}(z)}\right)^2\right]\sum_i \gamma_i(z)$$

Frigerio, Hambye, Masso, 2011

Here $z = m_h / T$, s is the entropy density, $Y_\theta = n_\theta/s$, and γ_i is the thermalization rate in the channel i



- Decays and inverse decays dominate over annihilations
- The freeze-in is infrared dominated, with Y_θ growing as T^{-3} down to $T \sim m_h$
- The final value of Y_θ depends only on the strength λ of the Higgs portal
- For m_h = 120 (140) GeV, we find that Ω_{DM} requires m_θ = 2.8 (3.0) MeV

pNGBs from the seesaw scale

$$-\mathcal{L}_{\nu^c} = l_\alpha m_{\alpha j} \nu_j^c \left(\frac{H}{v}\right) + \frac{1}{2}\nu_i^c M_{ij} \nu_j^c + \text{h.c.} \qquad \Rightarrow \qquad m_\nu = -m\, M^{-1} m^T$$

M_{ij} break lepton number $U(1)_L$

In the case of spontaneous SB, the NGB is the singlet Majoron θ

$$M = g\Phi \qquad \Phi \equiv \frac{\rho}{\sqrt{2}} e^{i\theta/f} \qquad \langle\rho\rangle = f$$

Majoron as dark matter: its mass must be induced by explicit $U(1)_L$ breaking in another sector of the theory

Akhmedov et al. '92
Rothstein et al. '93
Valle et al. '93,07,08,10
Gu et al. '10

Here we consider instead lepton flavour symmetries broken explicitly by some entries M_{ij} and/or $m_{\alpha j}$
⇒ pNGB masses are controlled be seesaw scales only

$$\mathcal{M} = \begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix}$$

$$V_{eff} \simeq \text{Tr}(\mathcal{M}\mathcal{M}^\dagger)\Lambda^2 + \text{Tr}(\mathcal{M}\mathcal{M}^\dagger\mathcal{M}\mathcal{M}^\dagger)\log\Lambda^2$$

Depending on flavour charges, m_θ^2 may or not receive a Λ^2 contribution

pNGBs from the seesaw scale

Here is an explicit model with no quadratic divergence in the pNGB mass

$$U(1)_X: \qquad X(\nu_1^c) = -1, \quad X(\nu_2^c) = 1, \quad X(\Phi) = 2$$

$$-\mathcal{L}_{\nu^c-\theta} = l_\alpha (m_{\alpha 1}\ m_{\alpha 2}) \frac{H}{v} \begin{pmatrix} \nu_1^c \\ \nu_2^c \end{pmatrix} + \frac{1}{2}(\nu_1^c\ \nu_2^c) \begin{pmatrix} M_{11} e^{i\theta/f} & M_{12} \\ M_{12} & M_{22} e^{-i\theta/f} \end{pmatrix} \begin{pmatrix} \nu_1^c \\ \nu_2^c \end{pmatrix} + \text{h.c.}$$

Explicit breaking in $m_{\alpha j}$ only
⇒ no θθ term is generated

$$V_{eff} = \frac{\lambda}{2} \theta\theta H^\dagger H + \mathcal{O}(\theta^4)$$

$$\lambda \simeq \frac{1}{4\pi^2} \frac{M_{12}(M_{11} + M_{22})}{f^2} \frac{\sum_\alpha m_{\alpha 1} m_{\alpha 2}}{v^2} \log \frac{\Lambda^2}{\mu^2}$$

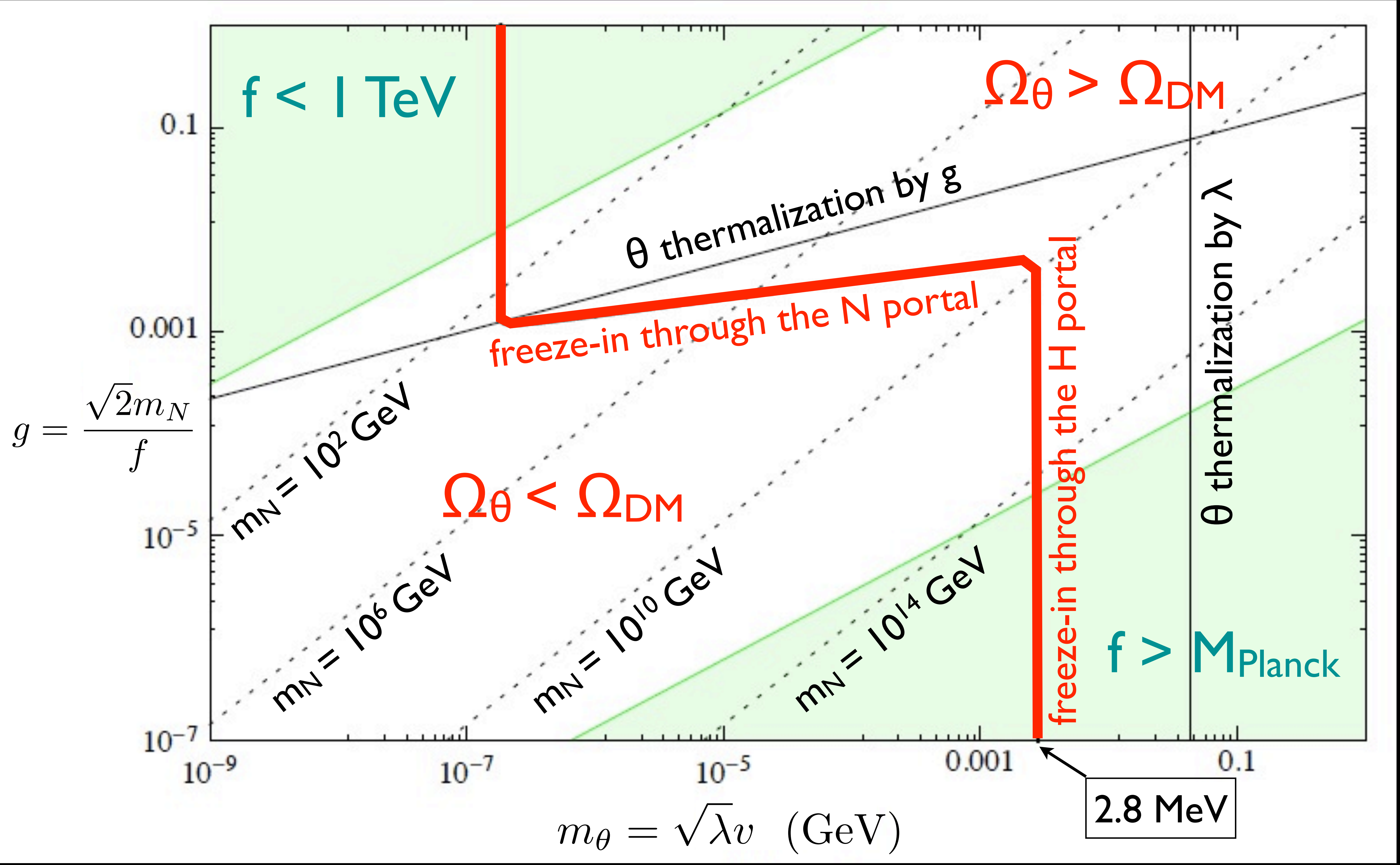
$$m_\theta^2 = \lambda v^2 \sim \frac{M^2 m^2}{f} \sim g^2 m^2 \sim g^2 y^2 v^2$$

The pNGB mass lies (well) below the EW scale

θ-couplings to N and to H

$N \equiv (\nu^c\ \nu^{c\dagger})^T$

$m_\nu = 0.05$ eV



θ-couplings to SM fermions

Since θ has the coupling gθNN, and since N mixes with ν,
θ decays into light neutrinos at tree-level

$$\Gamma(\theta \to \nu\nu) = \frac{1}{16\pi} g^2_{\theta\nu\nu} m_\theta$$

$$g_{\theta\nu\nu} \simeq 10^{-21} \left(\frac{\mathrm{MeV}}{m_\theta}\right)^2 \left(\frac{g}{10^{-3}}\right)^3 \left(\frac{m_\nu}{\mathrm{eV}}\right)^2$$

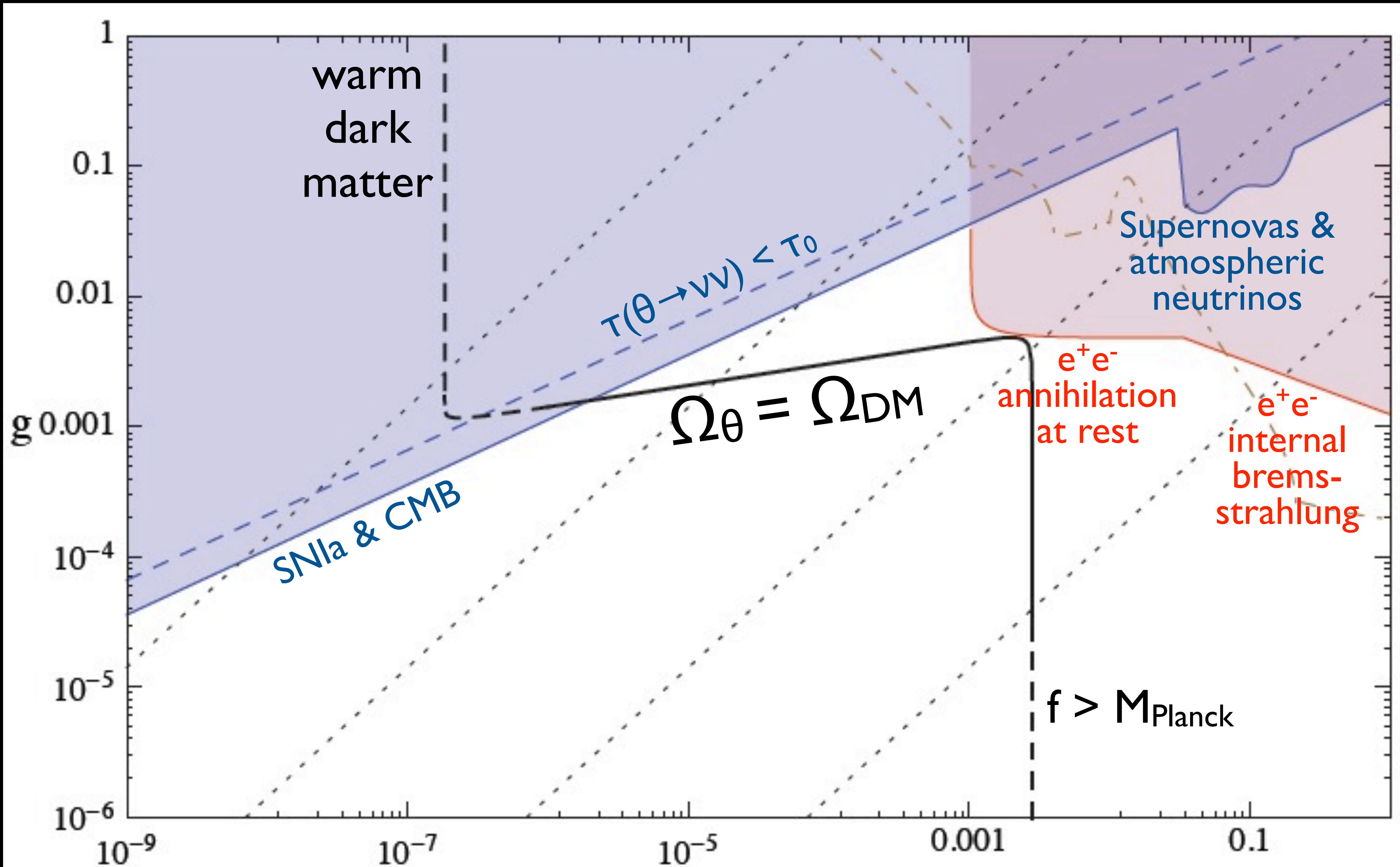
Since ν couples to Z and W, at one-loop θ couples also to charged fermions, both leptons and quarks

$$\Gamma(\theta \to f\bar{f}) = \frac{1}{8\pi} g^2_{\theta f\bar{f}} m_\theta$$

$$g_{\theta f\bar{f}} \simeq 10^{-22} \left(\frac{10^7 \mathrm{GeV}^2 G_F}{16\pi^2}\right) \left(\frac{g}{10^{-3}}\right) \left(\frac{m_f}{\mathrm{MeV}}\right) \left(\frac{m_\nu}{\mathrm{eV}}\right)$$

For θ to play the role of dark matter, one needs,
at the very least, $1 / \Gamma_\theta > \tau_0 \approx 5 \cdot 10^{17}$ s

Allowed regions for θ dark matter



m_ν = 0.05 eV

Dark matter as composite pNGB from the TeV scale

(some equations & plots are preliminary here)

Higgs & DM as composite pNGBs

$$\mathcal{L} = \mathcal{L}^{G_{SM}}_{elementary} + \mathcal{L}^{G \to K}_{composite} + \mathcal{L}^{G_{SM}}_{mixing}$$

SM + a new sector strongly coupled & approximately conformal from M_{Planck} down to $\Lambda_{EW} \sim$ TeV, where strong dynamics breaks conformal & global symmetries: G → K

$$\begin{aligned} G &= SO(6) \times U(1) \\ K &= SO(5) \times U(1) \supset SU(2)_L \times U(1)_Y \text{ with custodial} \end{aligned}$$

$$\rho = \frac{m_W^2}{m_Z^2 \cos\theta_W^2} = 1 \ , \quad \text{without custodial } \Delta\rho \simeq \frac{v^2}{f^2} \lesssim 10^{-3}$$

pNGBs: a gauge singlet accompanies the Higgs doublet

$$SO(6) \to SO(5) \qquad (H, \eta) \sim 5_{SO(5)}$$

symmetry breaking is consistent with the parity $\eta \to -\eta$

More on the composite setup

The coupling of elementary fields with composite operators breaks explicitly (weakly) G, while preserving $G_{SM} \times Z_2$.
E.g. take O_ψ in the 6 of SO(6) for all ψ.

$$\mathcal{L}_{mixing} = g_i A_i^\mu \mathcal{J}_\mu + \lambda_\psi \overline{\psi} \mathcal{O}_\psi$$

$m_\rho = g_\rho f$ — $G \rightarrow K$, composite resonances with mass $m_\rho \approx$ few TeV and inter-composite coupling $1 < g_\rho < 4\pi$

f — Characteristic scale of the pNGBs parametrizing G/K: the Higgs doublet H and the DM singlet η

$v = 246$ GeV — Elementary-composite couplings generate radiatively $V_{eff}(H,\eta)$. At the minimum $\langle H \rangle = v$ realizes EWSB. Departures from the SM Higgs couplings go as $(v / f)^2$.

Giudice-Grojean-Pomarol-Rattazzi '07

Effective lagrangian for h and η

The pNGBs are described by a non-linear σ-model

$$\Sigma = \exp\left(i\frac{\pi^a T^a}{f}\right) = \frac{1}{f}\left(h, 0, 0, 0, \eta, \sqrt{f^2 - h^2 - \eta^2}\right)^T$$

$$\mathcal{L}_{kin} = \frac{f^2}{2}|D_\mu\Sigma|^2 = \frac{(\partial_\mu h)^2}{2} + \frac{(\partial_\mu \eta)^2}{2} + \frac{(h\partial_\mu h + \eta\partial_\mu\eta)^2}{2(f^2 - h^2 - \eta^2)} + \frac{g^2}{4}h^2\left[W^{\mu +}W^-_\mu + \frac{1}{2c_W^2}Z^\mu Z_\mu\right]$$

Gauge and fermion loops generate an effective potential for the pNGBs that breaks EW symmetry with 〈h〉 = v and 〈η〉 = 0

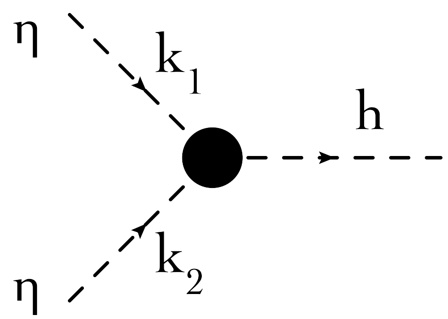
$$V_{eff}(h,\eta) \approx -\frac{\mu_h^2 h^2 + \mu_\eta^2\eta^2}{2} + \frac{\lambda_h h^4 + 2\lambda_m h^2\eta^2 + \lambda_\eta\eta^4}{4} \qquad \lambda_m \sim \frac{N_c}{16\pi^2}\lambda_\psi^4$$

Beside the interactions with h, the dark matter η couples to fermions

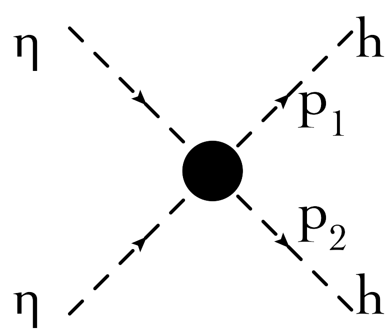
$$\mathcal{L}_{\eta - u} = \frac{\eta^2}{f^2}\left[\frac{\lambda_{u_R}^2}{g_\rho^2}\left(c_u \bar{u}\gamma^\mu P_R\partial_\mu u + \text{h.c.}\right) + \frac{1}{2}m_u\bar{u}u\right]$$

Dark matter composite interactions

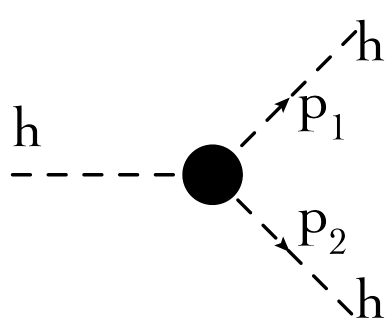
$\xi \equiv (v/f)^2$



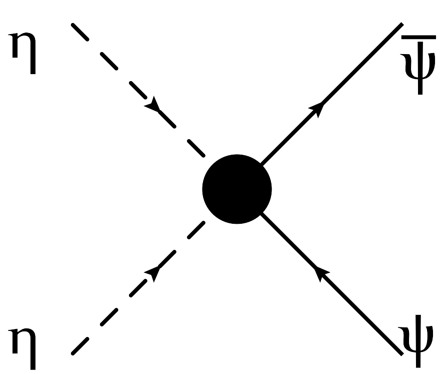
$$-2i\lambda_m v\sqrt{1-\xi} + \frac{iv(k_1+k_2)^2}{f^2\sqrt{1-\xi}}$$



$$-2i\lambda_m(1-\xi) + \frac{i(1+\xi)(p_1+p_2)^2}{f^2(1-\xi)} - \frac{2i\xi p_1\cdot p_2}{f^2(1-\xi)}$$



$$-3i\frac{m_h^2}{v}\sqrt{1-\xi} + \frac{2iv}{f^2\sqrt{1-\xi}}\left[(p_1+p_2)^2 - p_1\cdot p_2\right]$$



$$\frac{2ivy_\psi}{\sqrt{2}f^2}\left(-\tau_3 + \frac{\lambda_{\psi_R}^2}{g_\rho^2}\right) - \frac{2v\kappa y_\psi\lambda_{\psi_R}^2\gamma^5}{\sqrt{2}f^2 g_\rho^2}$$

Couplings in the case SM + singlet with no compositeness

Three effects of compositeness:

- order ξ corrections to Higgs couplings
- new pNGB couplings proportional to p^2 / f^2
- new DM-ψ couplings of order m_ψ / f^2

Relic density from η freeze-out

dashed line: non-composite DM

thick line: b_R mostly elementary

thin line: b_R mostly composite

dotted line: t_R decoupled from η

Bounds from LHC Higgs searches

Two main modifications w.r.t. the SM:

- Higgs couplings modified by $\xi = (v/f)^2$ corrections
- if $2m_\eta < m_h$, invisible Higgs decay into DM: $\Gamma_{tot} = \Gamma_{SM} + \Gamma(h \to \eta\eta)$

SM-like Higgs
with
$m_h \leq 130$ GeV

$$\frac{\sigma(pp \to h \to SM)}{\sigma_{SM}}$$

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- if $2m_\eta < m_h$, invisible Higgs decay into DM: $\Gamma_{tot} = \Gamma_{SM} + \Gamma(h \to \eta\eta)$

Invisible Higgs with $m_h \geq 130$ GeV

$$\frac{\sigma(pp \to h \to SM)}{\sigma_{SM}}$$

Bounds from DM direct detection

DAMA - CoGeNT - CRESST

thick: s_R mostly elementary
thin: s_R mostly composite
dotted: t_R decoupled from η

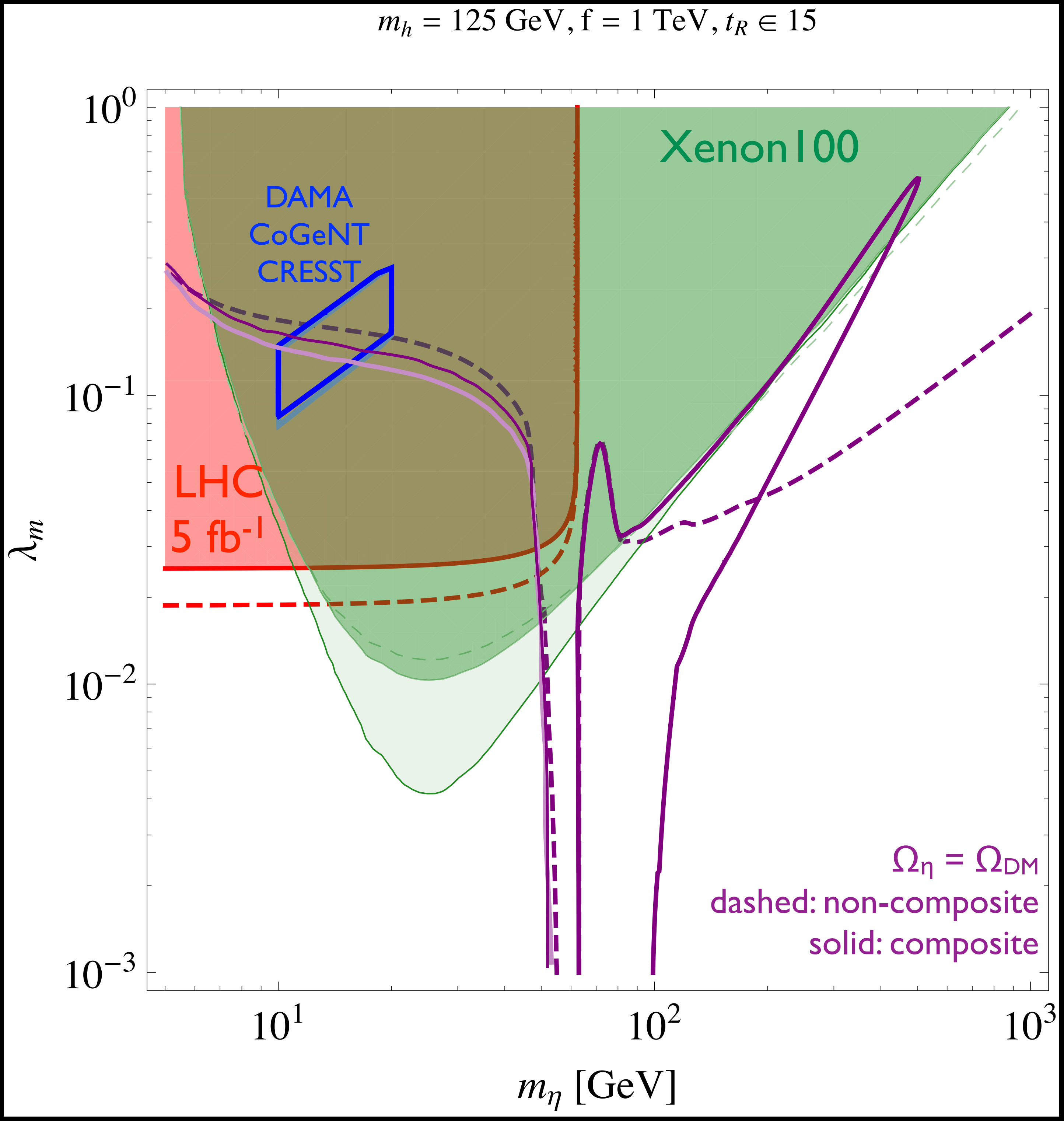
Composite DM-Higgs interplay

- The SM + a real scalar singlet is a minimal but not natural model: the hierarchy problem affects both the Higgs and the DM particle

- Compositeness solves the hierarchy problem and modifies the h and η couplings

- Complementary constraints from LHC Higgs searches, DM direct experiments, and DM relic density

- Putting all together, the allowed parameter space is ...



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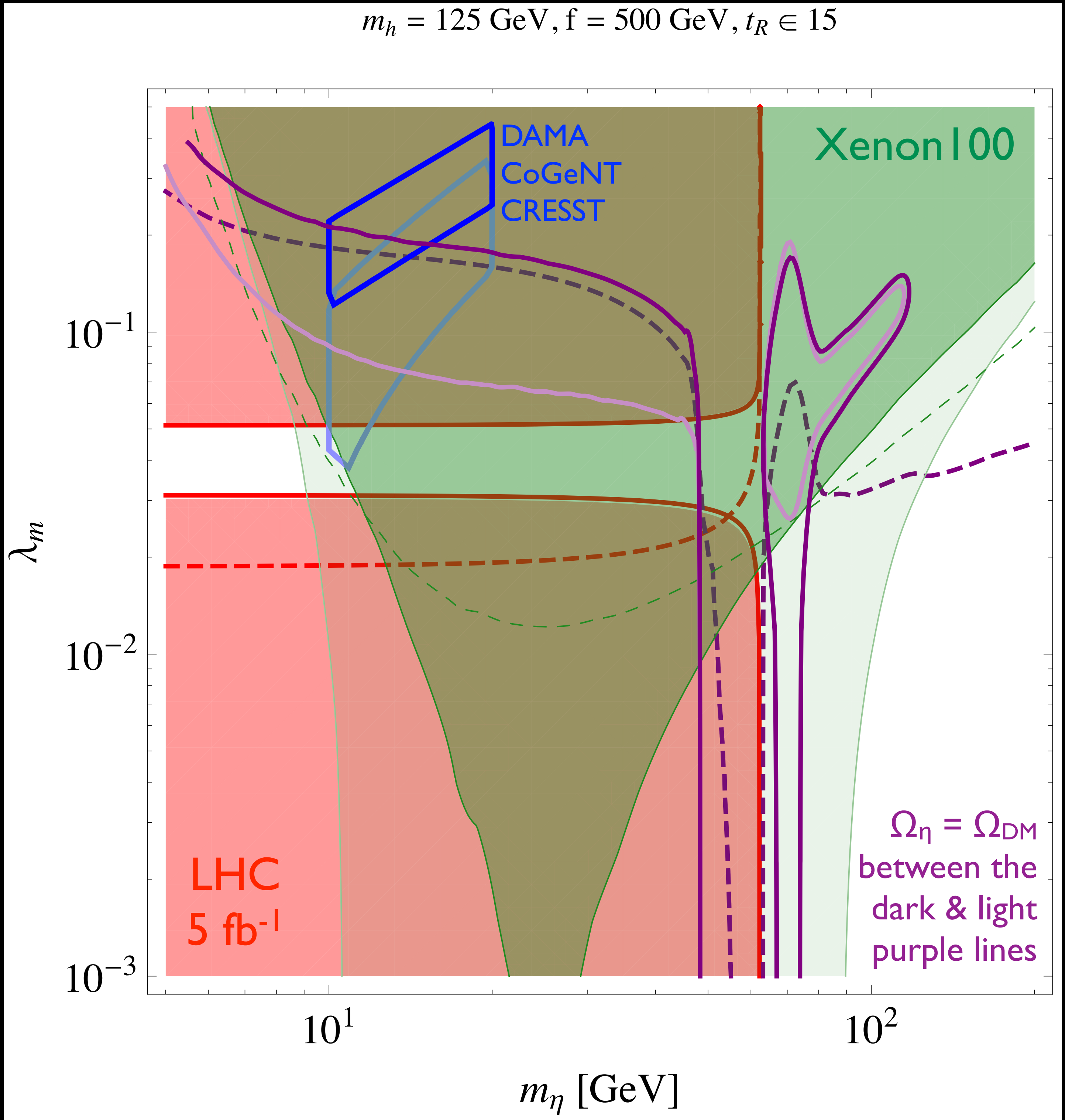

Conclusions

- in this decade we will be able to scrutinize the EW scale
- pNGBs coupled to the EW scale could be a first (the lightest) evidence for new physics
- such pNGBs are natural & promising candidates for dark matter
- a sub-GeV candidate θ emerges from the connection between the EW and the neutrino mass scale: probed in indirect DM searches
- a multi-GeV candidate η emerges from Higgs compositeness: probed in Higgs searches and direct DM searches