Pseudo Nambu-Goldstone bosons as dark matter candidates

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MF, Thomas Hambye & Eduard Massó, *PRX 1, 021026 (2011)*

[MF, Alex Pomarol, Francesco Riva & Alfredo Urbano, *JHEP (2012)*]

18th June 2012 - What is ν? - GGI, Florence

Outline

- pseudo Nambu-Goldstone Bosons (pNGBs) connected to the electroweak scale
- pNGBs coupled to the Higgs as dark matter (DM) candidates
- freeze-in of a sub-GeV scalar DM through the Higgs portal
- pNGBs related to approximate global symmetries of the neutrino 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 is much larger than the scale of explicit symmetry breaking

pNGBs associated to QCD scale (I)

M_{Planck} — Natural cutoff of the gauge theory

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

Λ_{QCD} — Spontaneous breaking of chiral symmetry leads to 8 NGBs: the pseudoscalar mesons π's, K's, ...

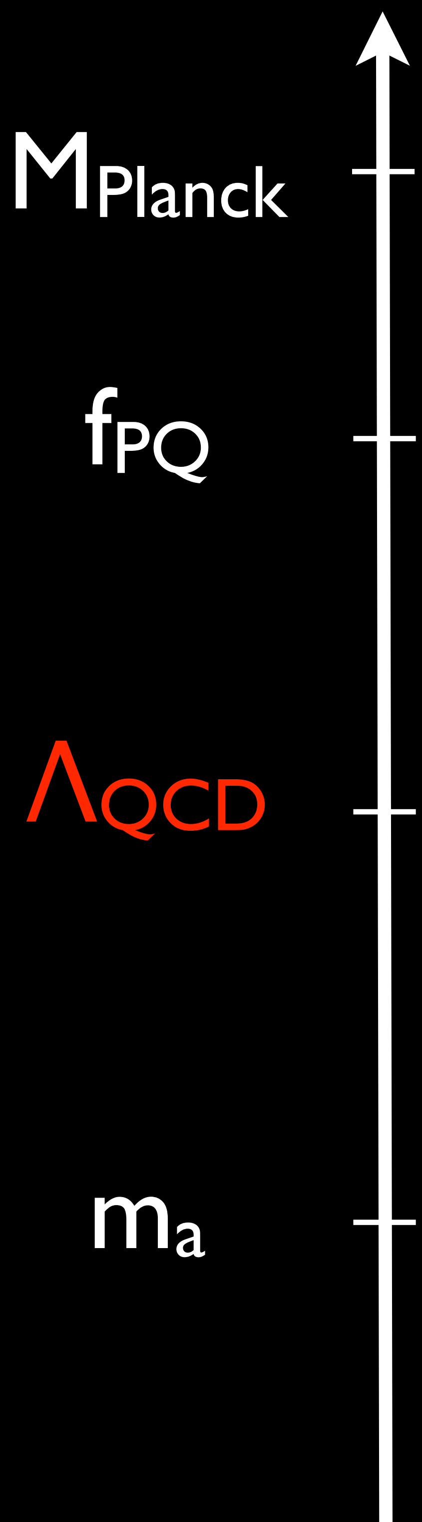
Explicit breaking by quark masses makes them massive

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 DM candidate here...

pNGBs associated to QCD scale (II)



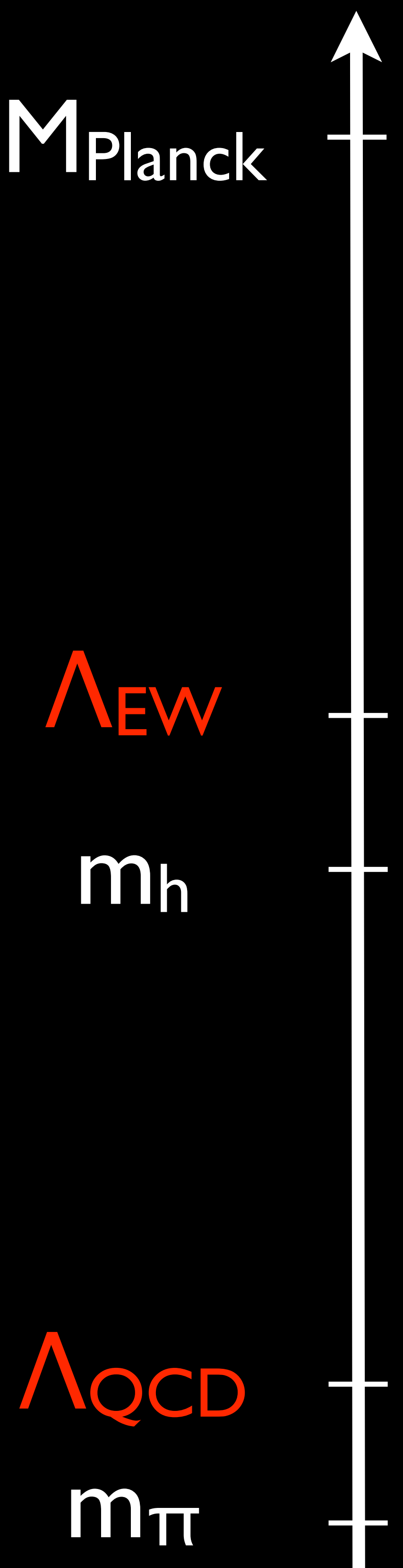
Spontaneous breaking of the Peccei-Quinn U(1) symmetry, introduced to solve the strong CP problem

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 are suppressed by f_{PQ} : for $f_{PQ} = (10^{12} - 10^{14})$GeV the axion is a good DM candidate

EW scale & the hierarchy problem

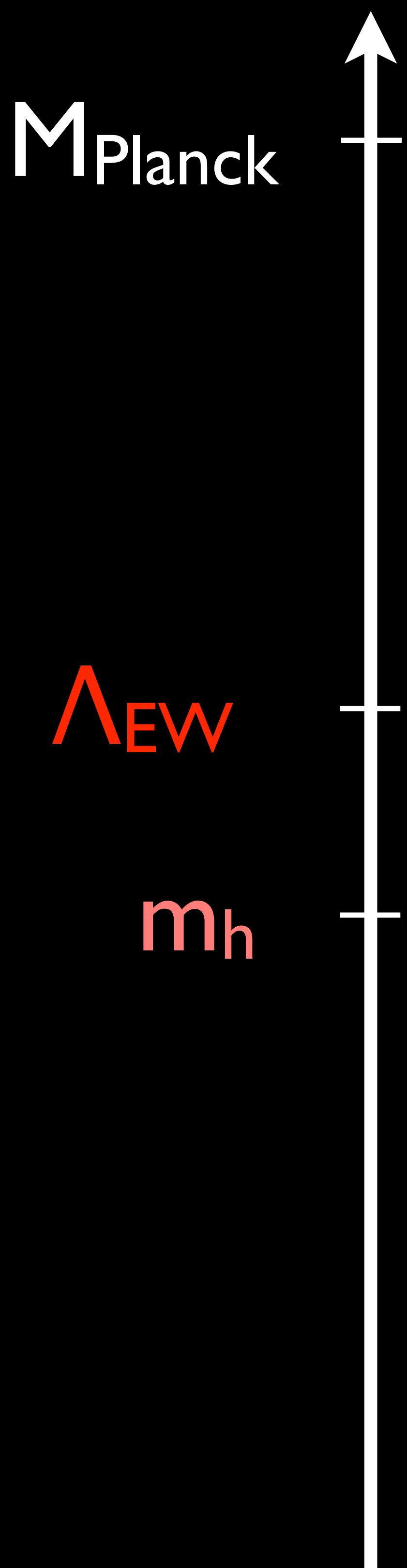


Natural cutoff of the gauge theory

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-coupled sector...

pNGBs associated to EW scale (I)



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

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

A pNGB composite Higgs is naturally lighter than the new strongly-coupled physics: $v \ll \Lambda_{EW}$

Kaplan Georgi '84
Agashe Contino Pomarol '04

Explicit breaking provided by gauge couplings g,g' and Yukawa couplings y_t, y_b, ... ⇒ calculability

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Λ_{EW}

Explicit breaking provided by gauge couplings g,g' and Yukawa couplings y_t, y_b, ... ⇒ calculability

m_η m_h

A larger global symmetry may be spontaneously broken by the strong dynamics.
The composite pNGBs can include the Higgs doublet H and a singlet DM candidate η :

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

Frigerio, Pomarol, Riva, Urbano '12

pNGBs associated to EW scale (II)

Seesaw: heavy sterile neutrinos are introduced to generate small active neutrino masses.
The large mass scale may originate from spontaneous symmetry breaking, $m_N = g \langle\Phi\rangle = g\, f$
(generalization of the singlet Majoron model)

Chikashige, Mohapatra, Peccei '81

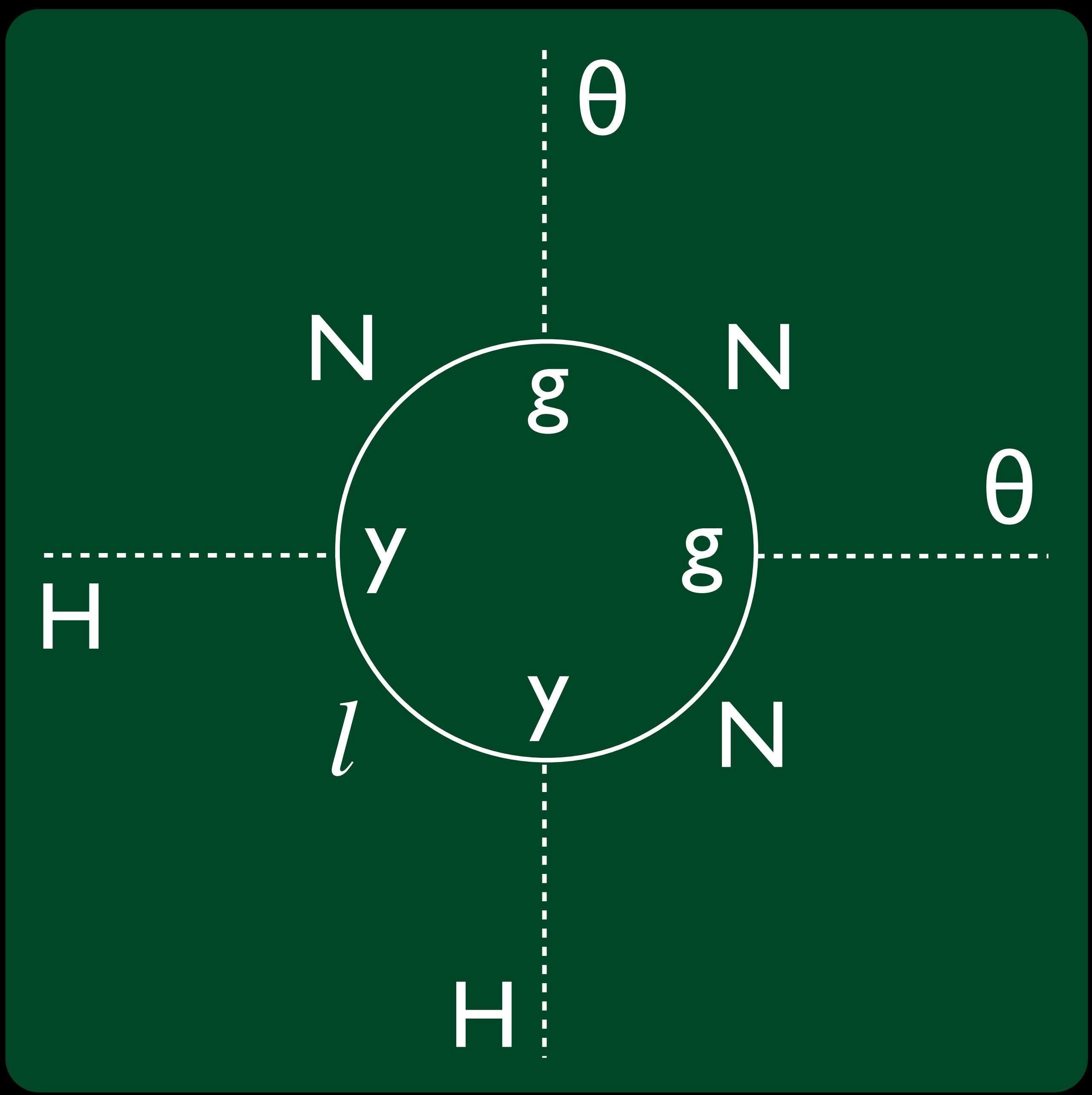
A NGB θ of the sterile neutrino sector can receive mass from the neutrino Yukawa couplings to the Higgs

$$m_\theta^2 \sim \frac{1}{16\pi^2}\frac{m_N^2 y^2}{f^2}\Lambda_{EW}^2$$

Frigerio, Hambye, Masso '11

θ-H coupling in a nutshell

$$-\mathcal{L} \supset l_\alpha (y_{\alpha j} v) N_j \left(\frac{H}{v}\right) + \frac{1}{2} N_i (g_{ij} f) N_j \exp\left(i\frac{\theta}{f}\right)$$



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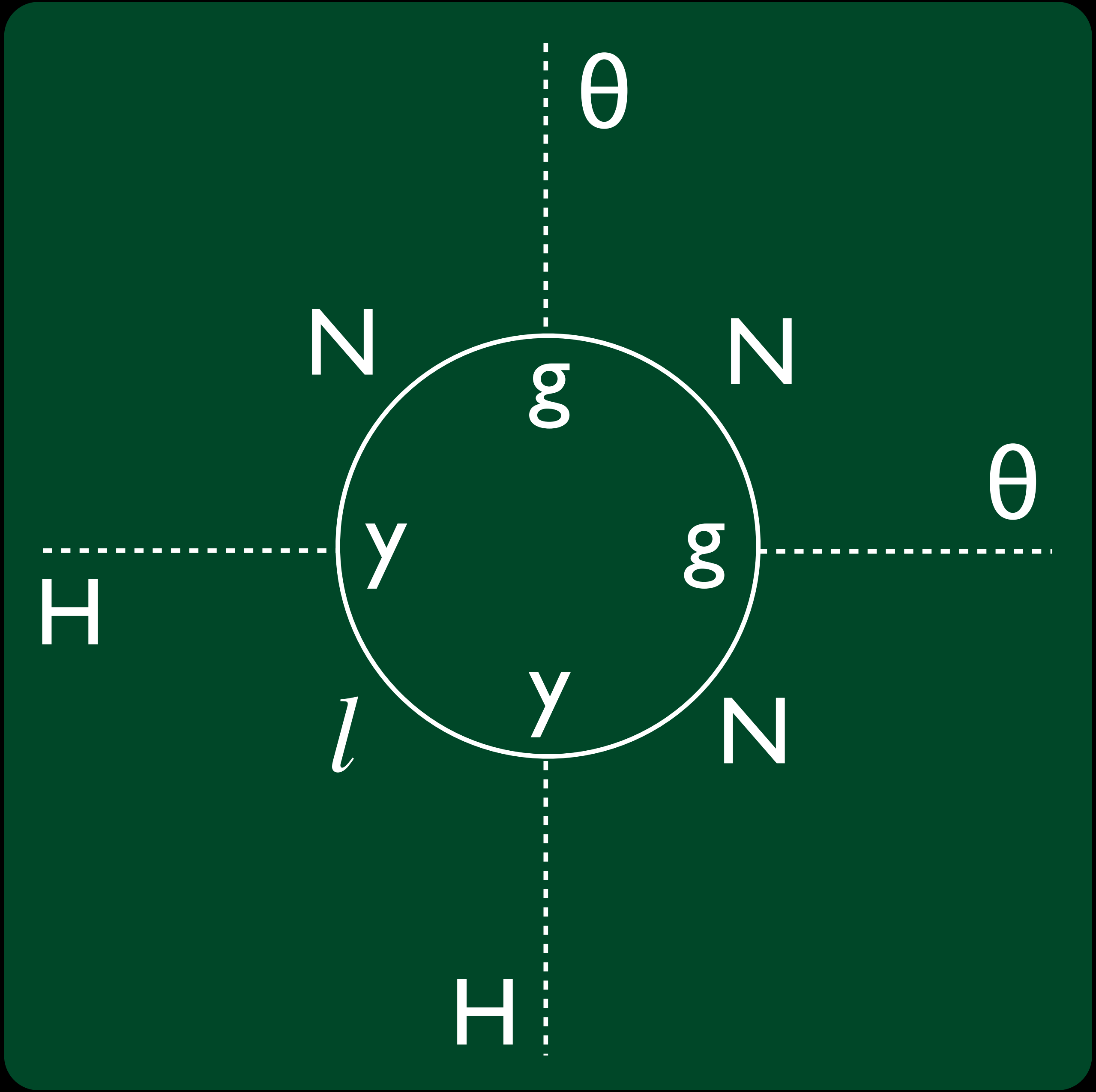


$$-\mathcal{L}_{eff} \supset \lambda \theta^2 H^\dagger H$$

$$\lambda \simeq \frac{1}{16\pi^2} g^2 y^2 \log \frac{\Lambda^2}{f^2}$$

$$m_\theta^2 = \lambda v^2 \ll \Lambda_{EW}^2$$

Details & subtleties later ...

Hill, Ross '88,
Little Higgs models

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 to the SM, that determine its relic density: one-to-one correspondence between m_{DM} and Ω_{DM}

The Higgs portal to dark matter

Let us assume that (i) a pNGB θ receives a mass after EWSB 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: $\lambda \gtrsim 6 \times 10^{-8}\left(\frac{m_h}{120\ \text{GeV}}\right)^{3/2}$ or $m_\theta \gtrsim 44\ \text{MeV}$

Freeze-out or... freeze-in

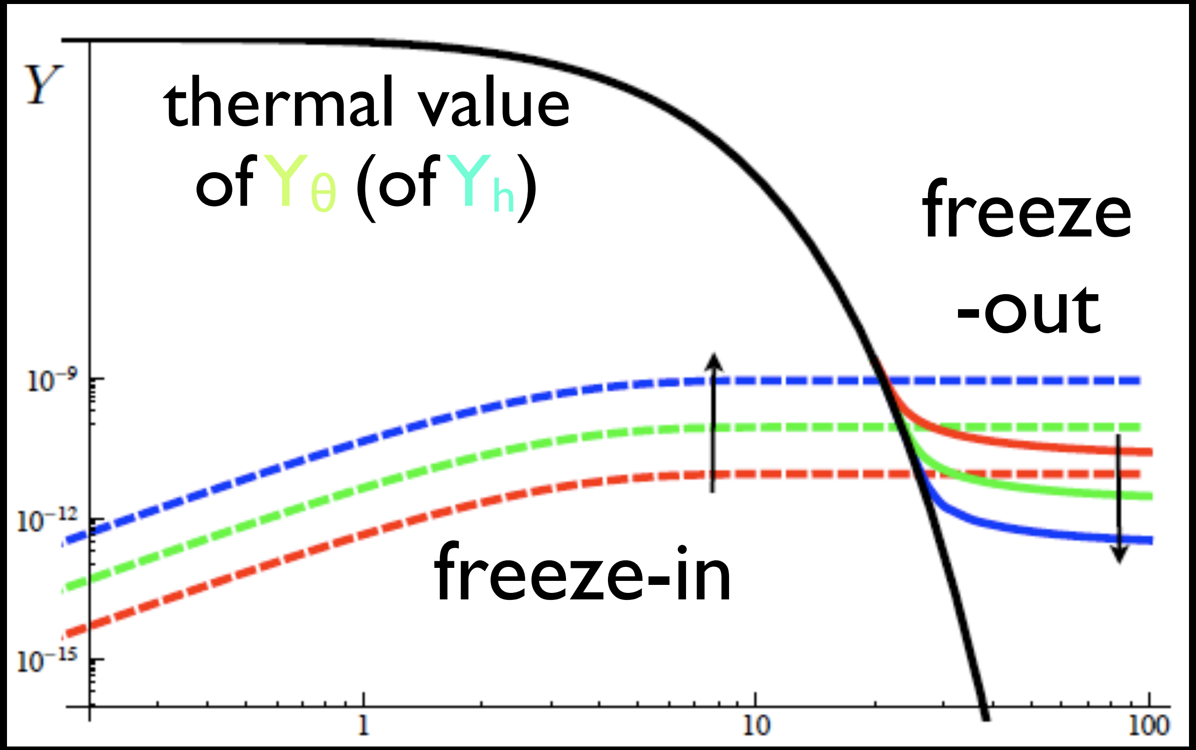
- Freeze-out: θ thermalizes and later decouples, at $T \leq m_\theta$
  The correct Ω_{DM} is obtained for $\langle\sigma_{ann} v_{rel}\rangle \approx 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$
  Then, the constrained Higgs portal requires $m_\theta \approx 50$ GeV

  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

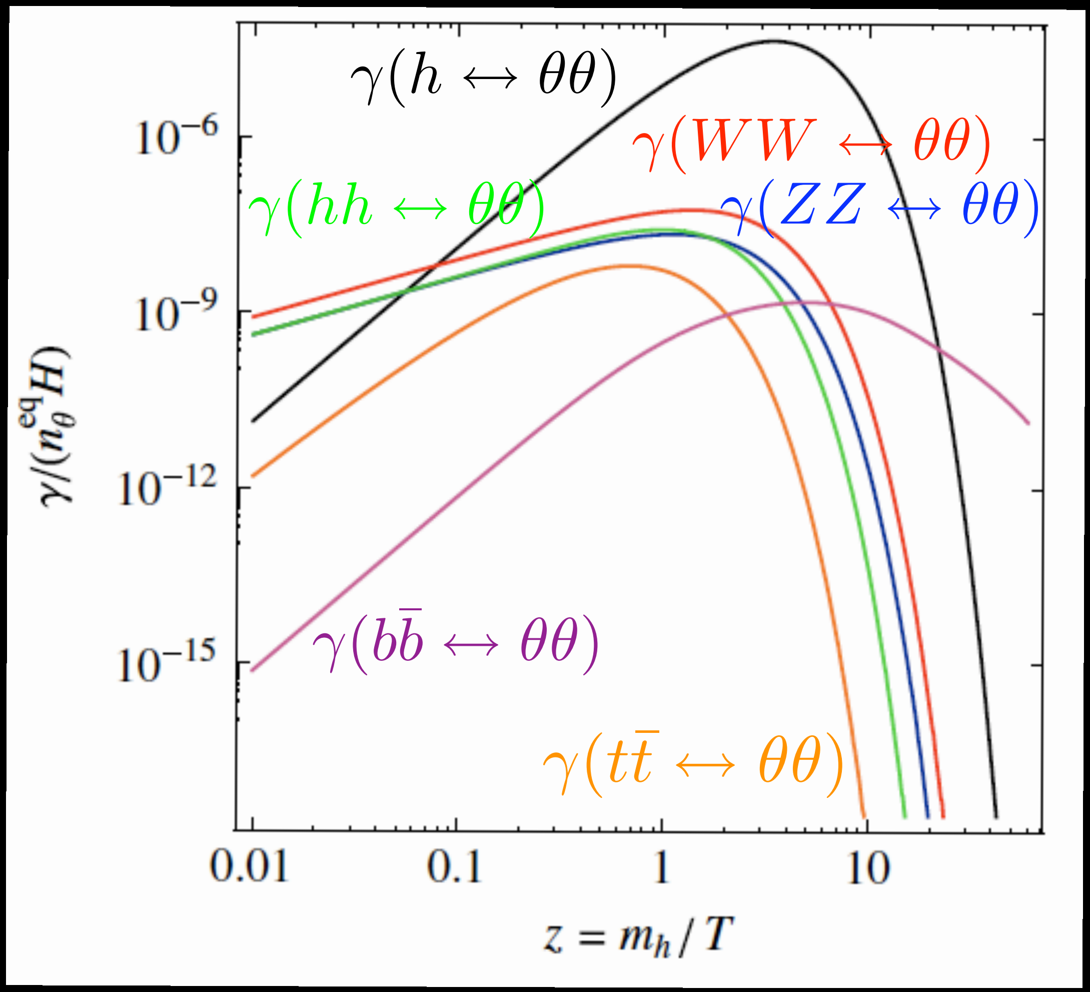
A prediction for the DM mass

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

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

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



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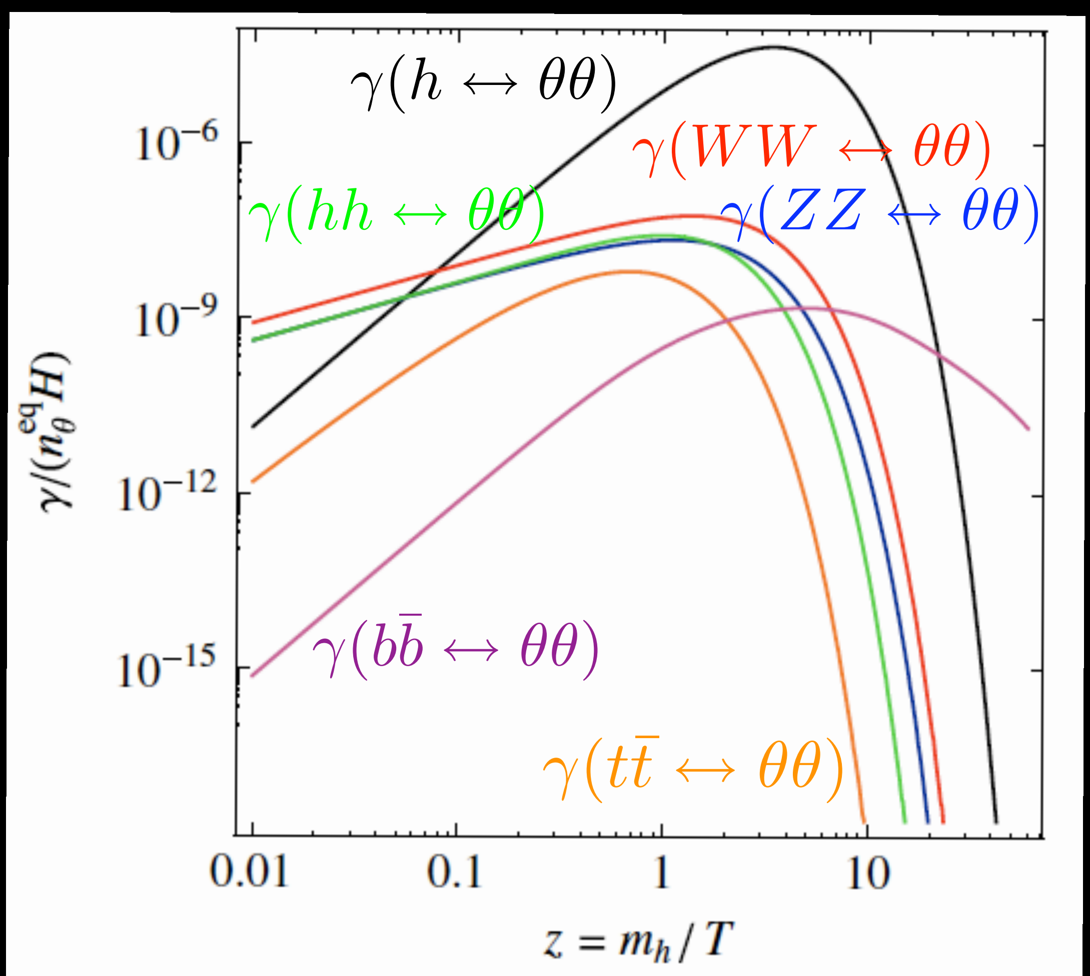
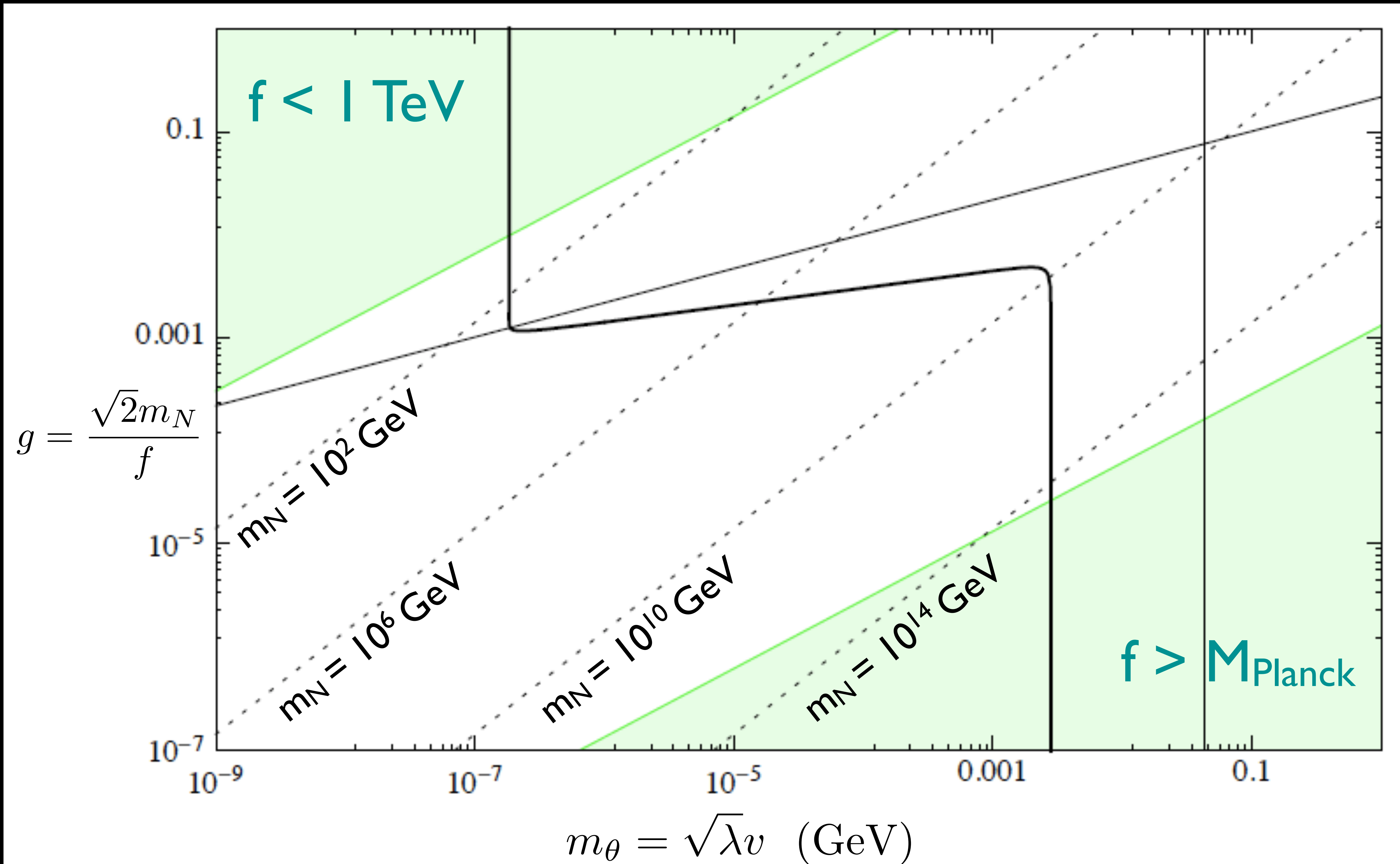


- Decays and inverse decays dominate over annihilations
- The freeze-in is infrared dominated, with Y_θ growing as T^{-3} down to $T \sim m_h$
- The final value of Y_θ depends only on the strength λ of the Higgs portal
- For m_h = 120 (140) GeV, we find that Ω_{DM} requires m_θ = 2.8 (3.0) MeV

θ-couplings to N and to H

m_ν = 0.05 eV



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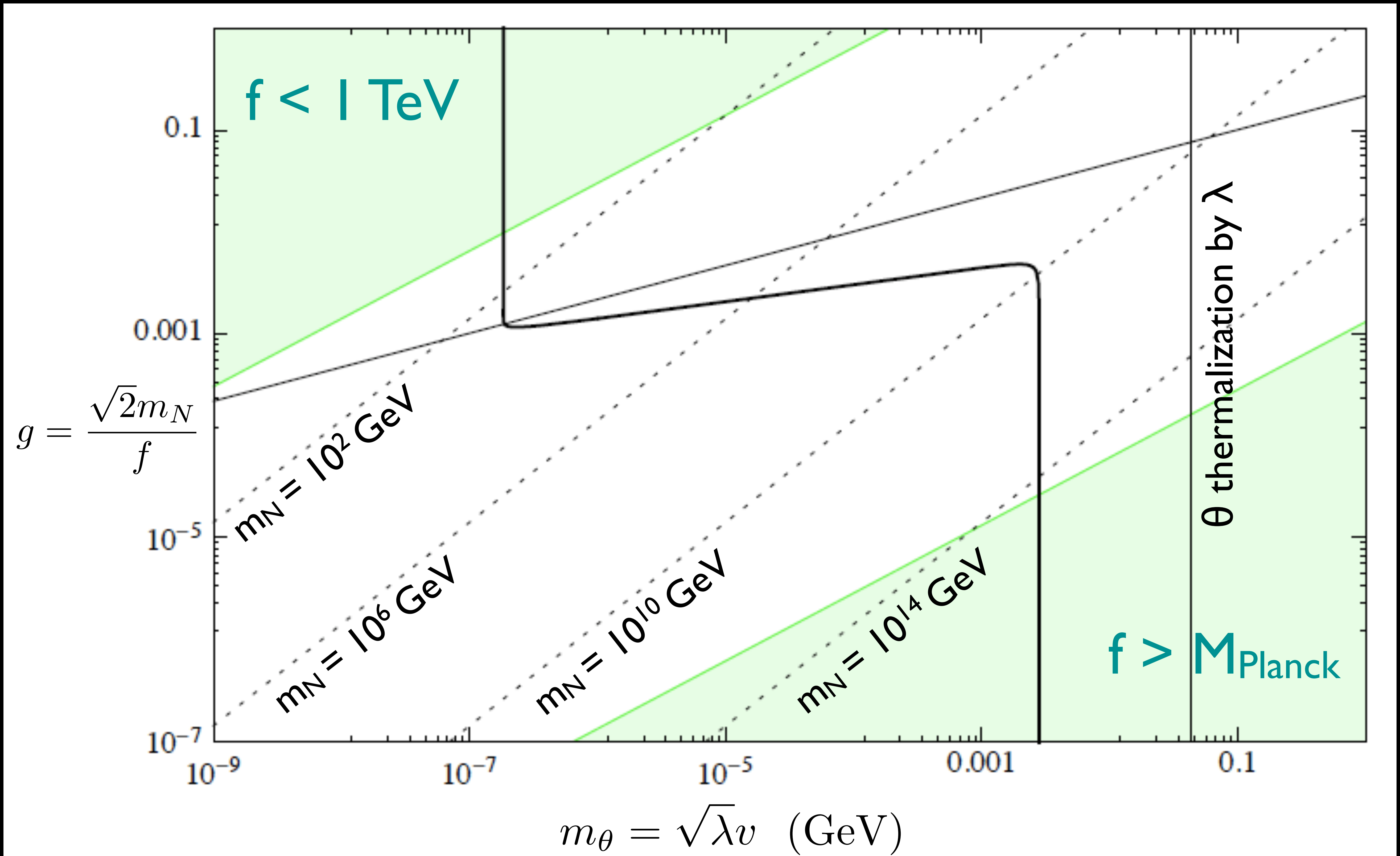

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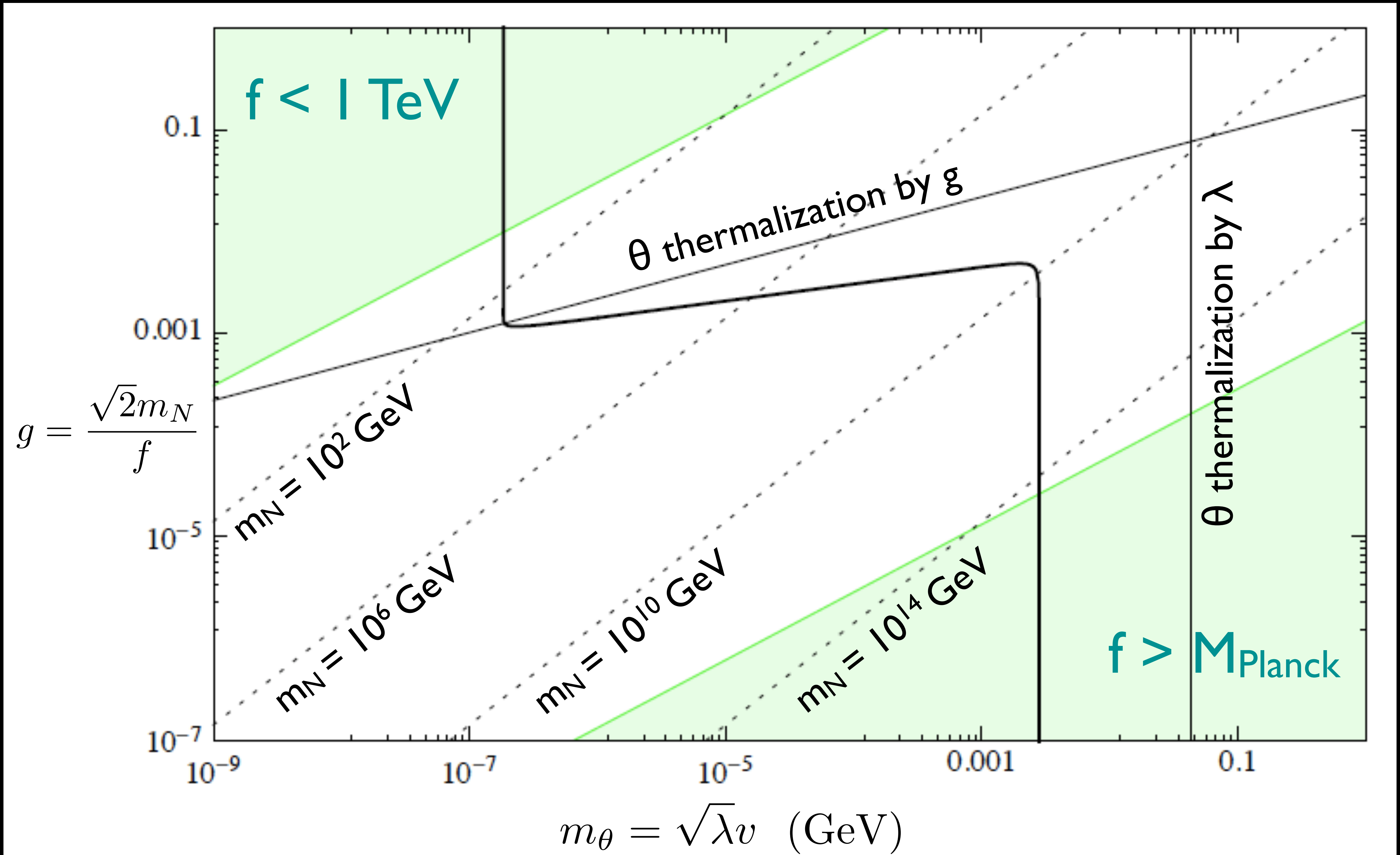

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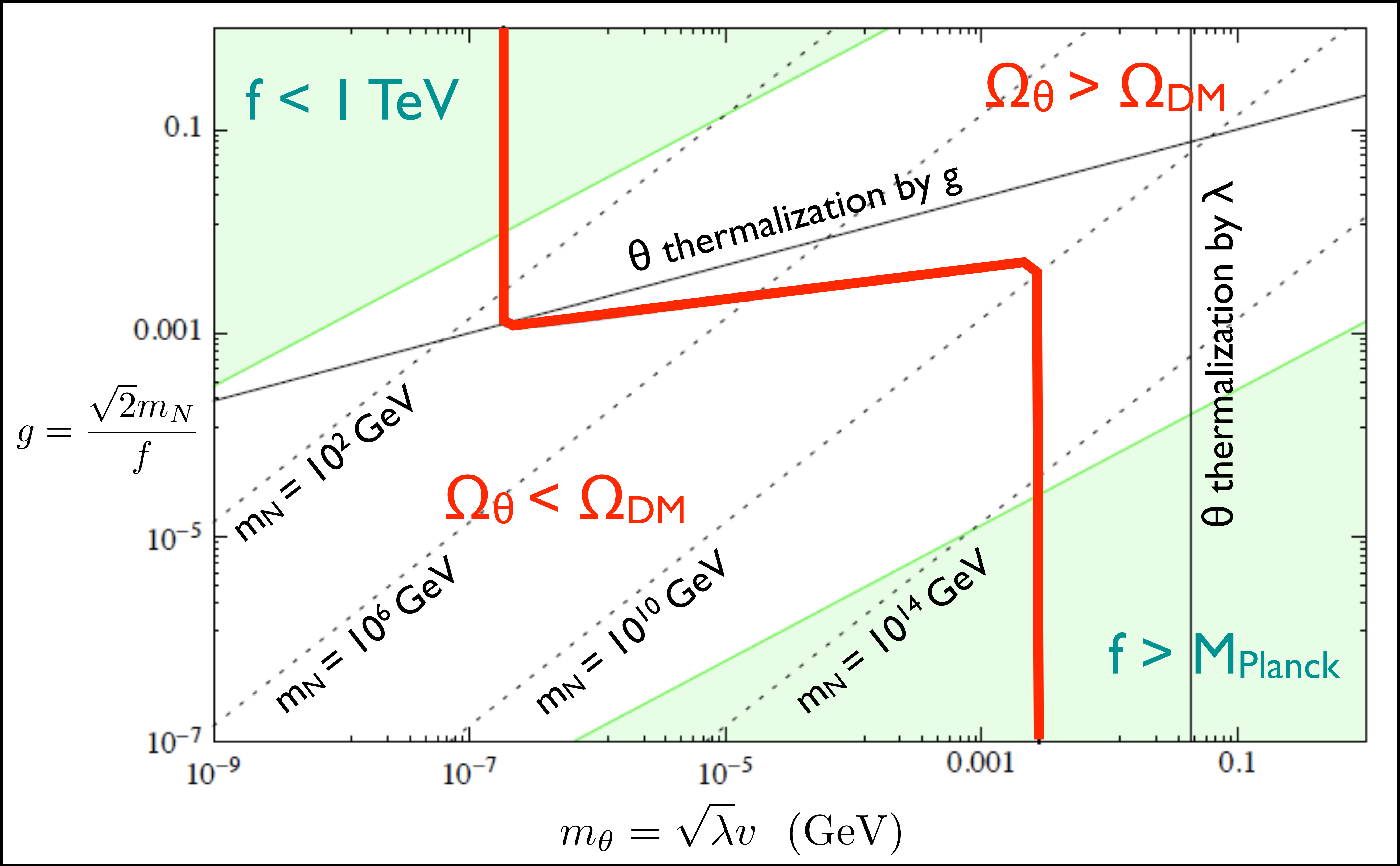

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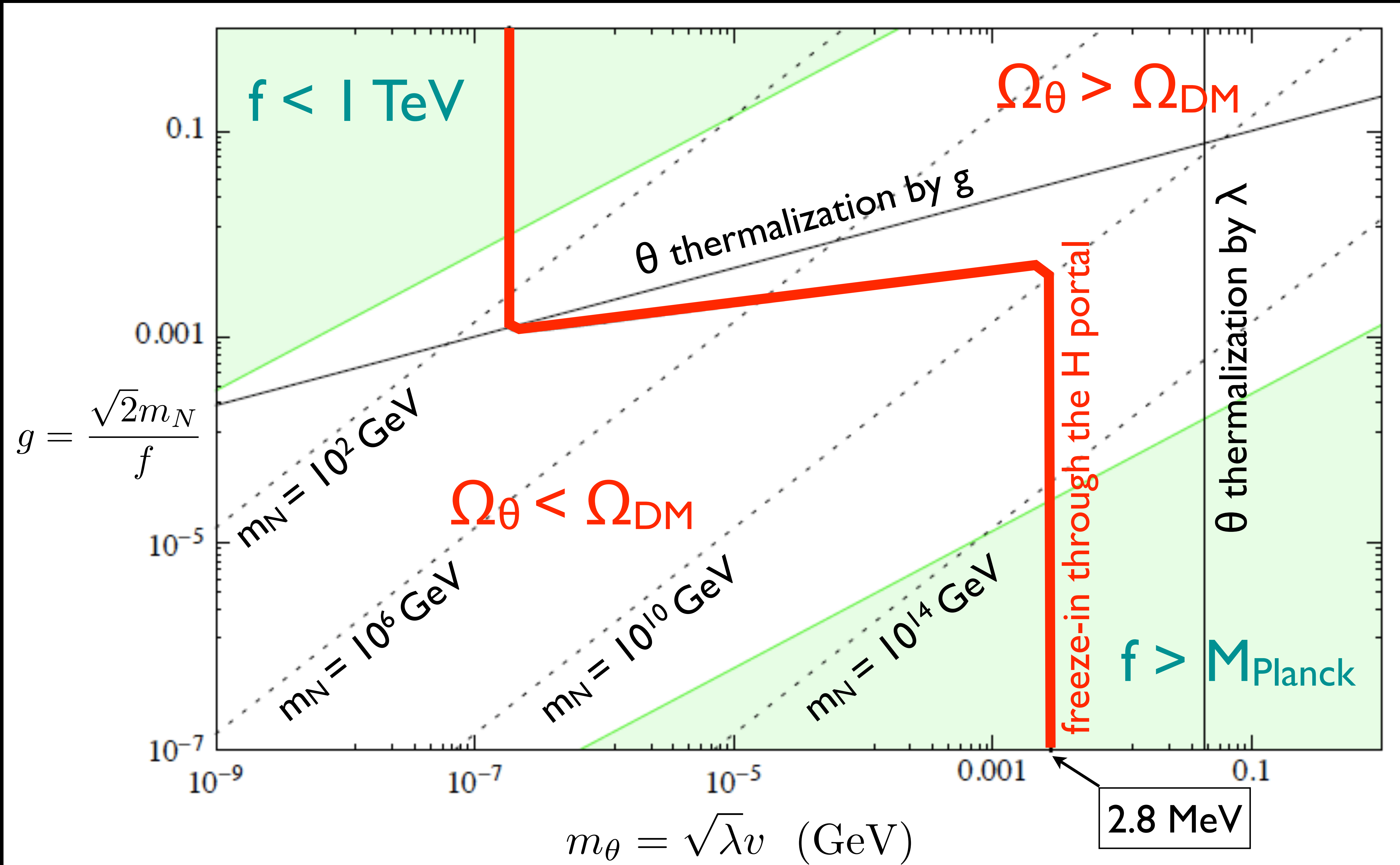

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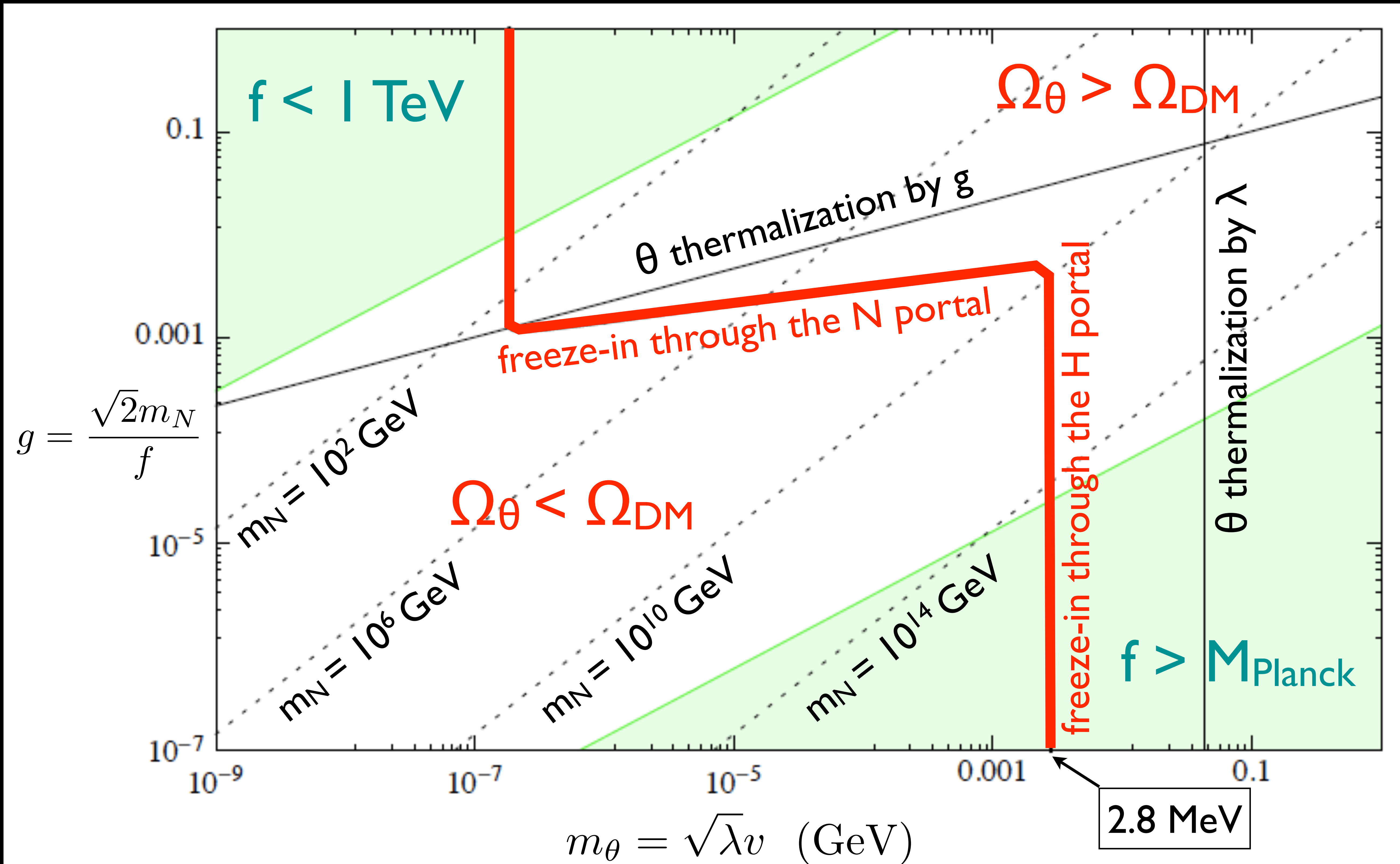


θ-couplings to SM fermions

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

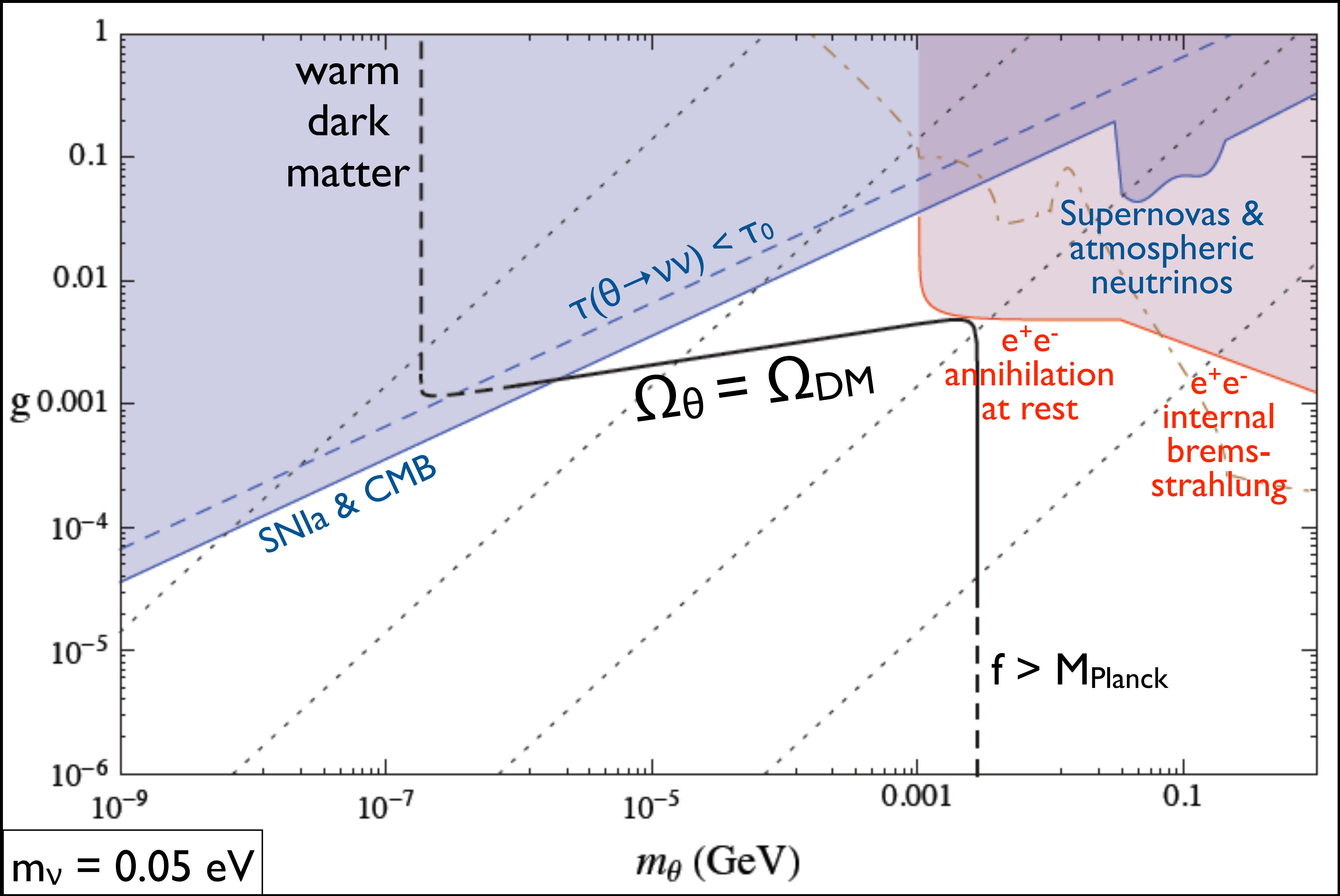
$$\Gamma(\theta \to \nu\nu) = \frac{1}{16\pi} g^2_{\theta\nu\nu} m_\theta \qquad g_{\theta\nu\nu} \simeq 10^{-21} \left(\frac{\mathrm{MeV}}{m_\theta}\right)^2 \left(\frac{g}{10^{-3}}\right)^3 \left(\frac{m_\nu}{\mathrm{eV}}\right)^2$$

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

$$\Gamma(\theta \to f\bar{f}) = \frac{1}{8\pi} g^2_{\theta f\bar{f}} m_\theta \qquad g_{\theta f\bar{f}} \simeq 10^{-22} \left(\frac{10^7 \mathrm{GeV}^2 G_F}{16\pi^2}\right) \left(\frac{g}{10^{-3}}\right) \left(\frac{m_f}{\mathrm{MeV}}\right) \left(\frac{m_\nu}{\mathrm{eV}}\right)$$

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



$m_\nu = 0.05$ eV

pNGBs from the seesaw scale

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

M_{ij} break lepton number $U(1)_L$
In the case of spontaneous SB, the NGB is the singlet Majoron θ

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

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

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

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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

Conclusions

- in this decade we will be able to scrutinize the EW scale
- pNGBs coupled to the EW scale could be the first (the lightest) evidence for new physics
- such pNGBs are natural & promising candidates for dark matter
- a very weakly-coupled sub-GeV scalar θ can freeze-in with the correct DM relic density
- the mass and couplings of θ are determined by the connection between EW and neutrino mass scale
- this class of candidates can be probed in indirect DM searches