A new light DM candidate

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Outline:

- Introduction of the new DM candidate
- Mass and interactions
- Relic density
- Lifetime / decays
- Some theoretical remarks
- Conclusions

Dark matter in the universe

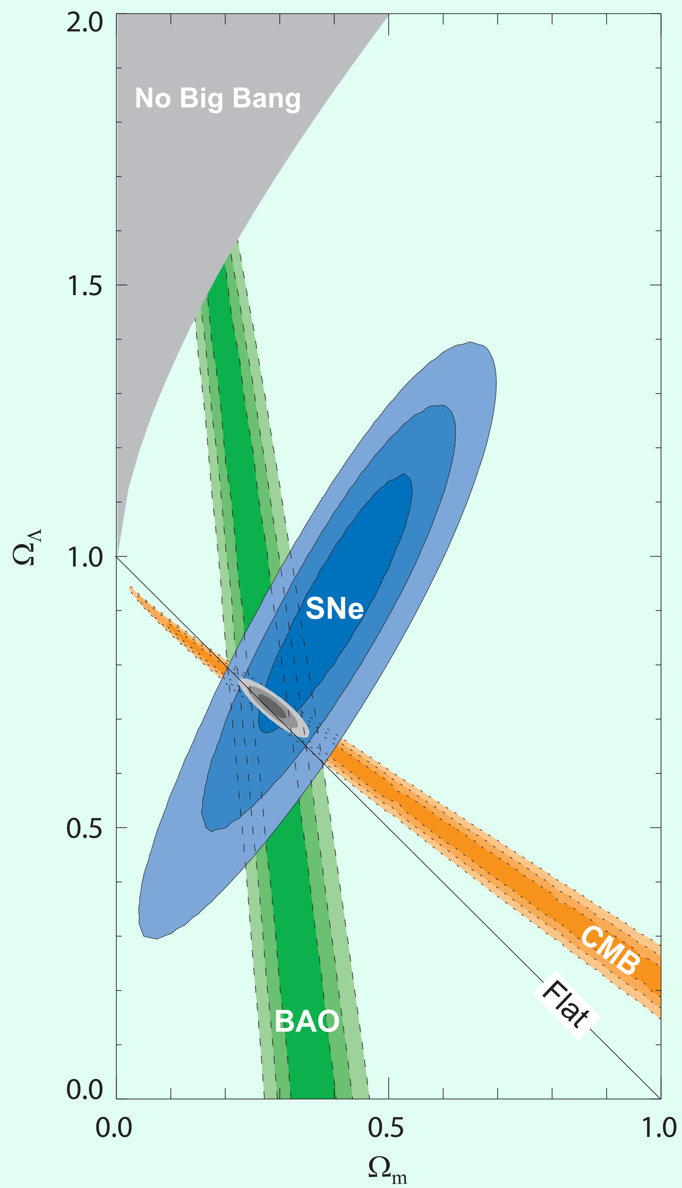

Figure 21.1: Confidence level contours of 68.3%, 95.4% and 99.7% in the Ω_Λ–Ω_m plane from the Cosmic Microwave Background, Baryonic Acoustic Oscillations and the Union SNe Ia set, as well as their combination (assuming $w = -1$). [Courtesy of Kowalski *et al.* [22]]

$$\Omega_{DM} = 0.22 \pm 0.02$$

Many (independent) proofs of DM existence, but dont know yet its nature (apart that we have to go beyond standard physics)

Recently,
some hints of direct detection

Dark matter in the universe

Necessary to explore different possibilities

Context: see-saw as neutrino-mass theory

Scenario:

Explicit breaking → pseudo

global symmetry at see-saw scale → Goldstone boson

pseudo Goldstone boson

Light ~~Massless~~ Spinless

Dark matter in the universe

We propose:

DM as pseudo Goldstone boson

DM mass
and some interactions
from unique source
(explicit breaking)

Global symmetry spontaneously
broken at high energy scale

See-saw scale
(already present
in nu mass theories)

Insures
DM stability
(slow decay)

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θ Mass & Interactions

θ **Mass & Interactions**

1) Goldstone from SSB of global symmetry in neutrino-sector

Example: Majoron

Φ Scalar, charged under B-L $\quad < \Phi >= f$

$$g \; \Phi \; \nu^c \nu^c \;\; \rightarrow \;\; g \; f \; \nu^c \nu^c \; e^{i\theta/f}$$

g = Yuk. coupl.

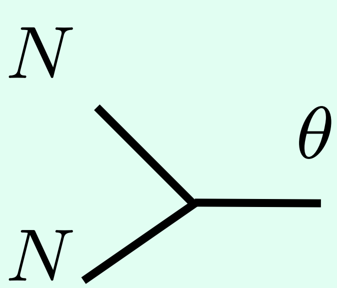
Expand in θ

Get:

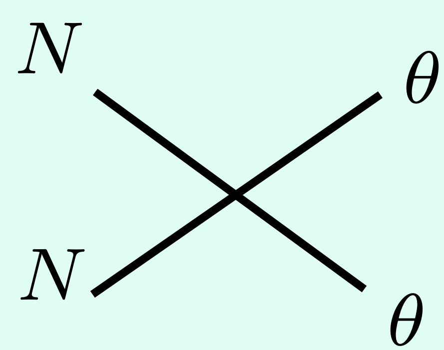
a) Mass of (heavy) sterile neutrino $m_N = gf/\sqrt{2}$

b) Interactions (well defined, no arbitrary couplings) with sterile neutrino N

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



$\sim g(i\gamma_5)$



$\sim g/f$

+ ...

θ Mass & Interactions

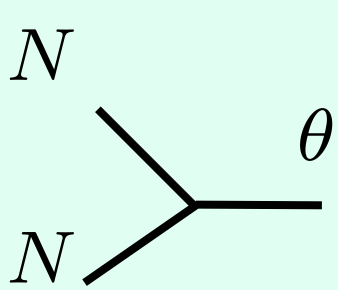
In our model:

θ our DM candidate

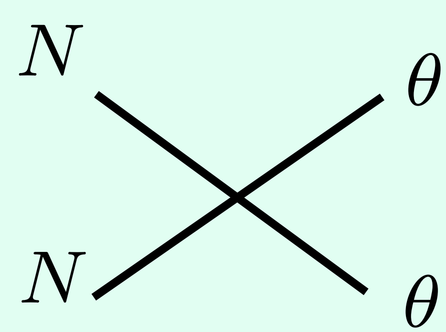
not the Majoron
because need different charges for
different sterile neutrinos

Still:

$$m_N = gf/\sqrt{2}$$



$\sim g(i\gamma_5)$



$\sim g/f$ + ...

θ **Mass & Interactions**

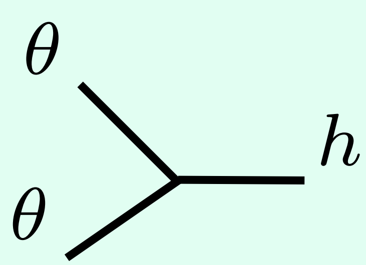
II) Explicit breaking

Involves nu's Dirac Yukawa's, and thus with H=Higgs doublet

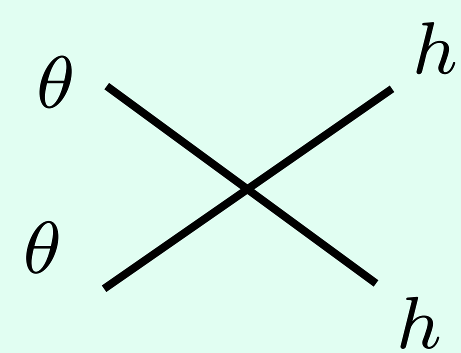
$-\frac{\lambda}{2}\ \theta^2\ H^\dagger H$ Higgs-portal
(in our case related to neutrinos)

EW breaking: a) Mass for θ $m_\theta^2 = \lambda v^2$

b) interactions with physical Higgs h



$\sim \lambda v$



$\sim \lambda$

Explicit breaking -> theta-potential -> pseudoGoldstone
mass and interactions are linked

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θ Mass & Interactions

see-saw: $m_{Dirac} \sim yv$ $m_\nu \sim y^2 v^2 / m_N$

In our model the coupling λ

- involves active nu Yukawa
- is induced radiatively

$$\lambda \simeq g^2 y^2 \frac{\log(\Lambda^2/m_N^2)}{8\pi^2}$$

- involves sterile nu Yukawa

θ Mass & Interactions

We will calculate relic density and lifetime,
and constrain the model using experimental data

However, realistic 3-family case in all generality depends on several parameters

In this first stage,

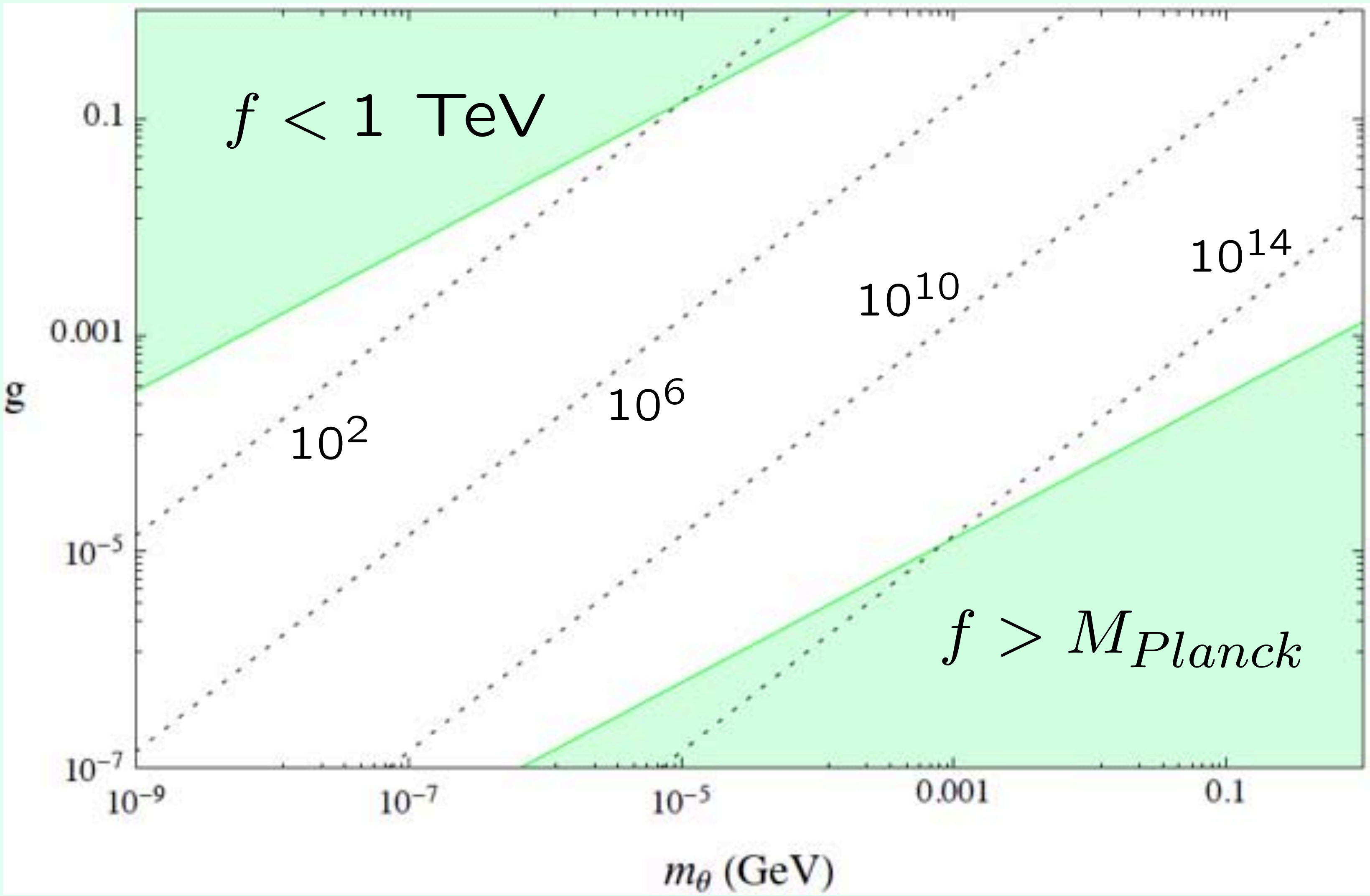
- we simplify formulae to one family case
  (equivalent to not allowing for flavor fine-tuned cancellations or enhancements)
- fix m_ν and take $k \equiv \frac{\log(\Lambda^2/m_N^2)}{8\pi^2} = 1$
  (but these values can be changed any time)

Two parameters: $m_\theta, \; g$

Not the most general model but more predictive

θ Mass & Interactions

Two parameters: $m_\theta, \ g$



$m_N = m_\theta^2/(g^2 m_\nu k)$ $\qquad$ $m_N = 10^2, 10^6, 10^{10}, 10^{14}$ GeV

$(m_\nu = 0.05 \text{ eV})$

θ relic density

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θ **relic density**

Thermalization condition: $\Gamma > H = 1.66\sqrt{g_*^\rho}\,T^2/M_P$ $\qquad g_*^\rho = 106.75$

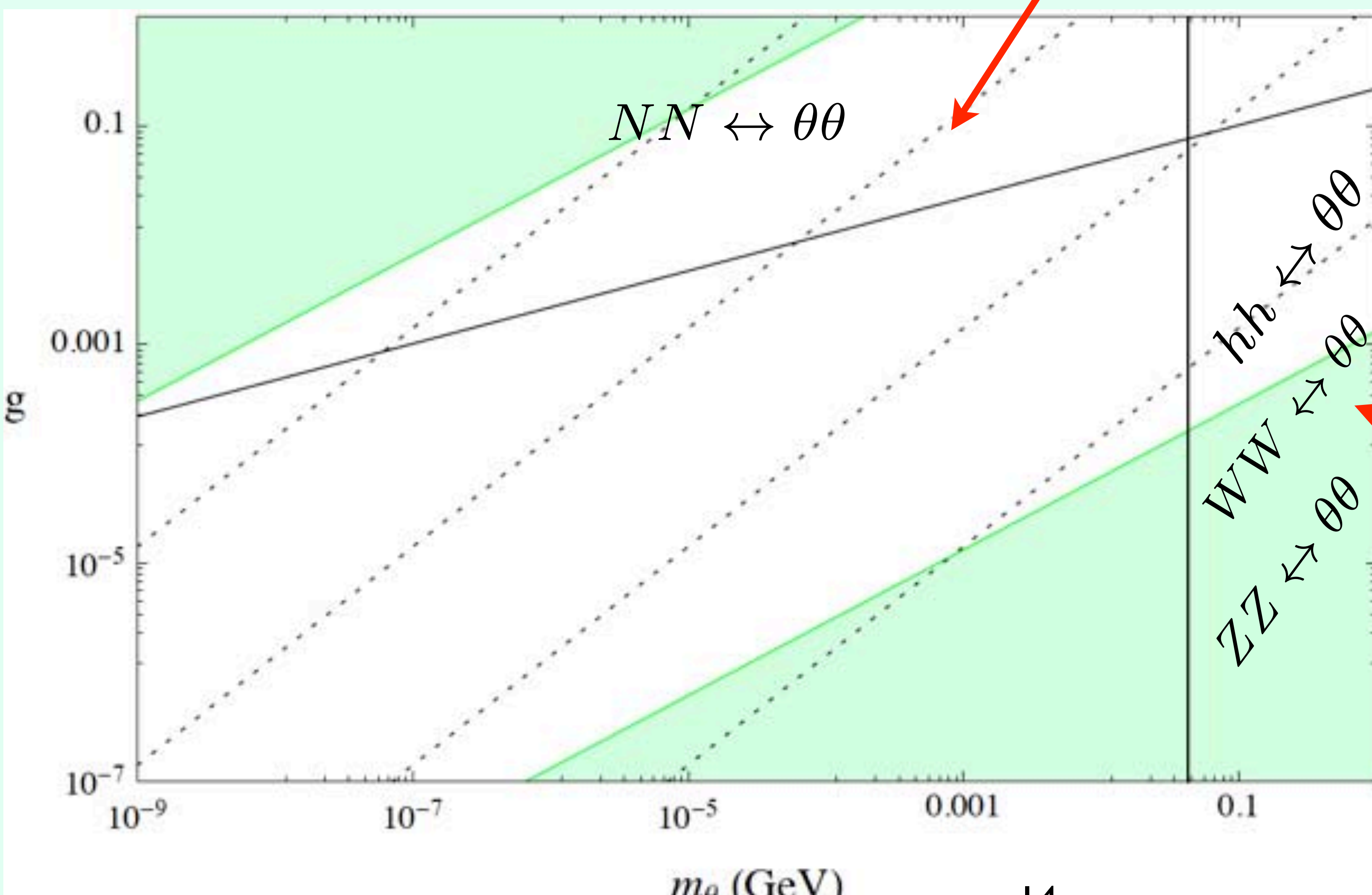
$\sigma \propto g^4$

$T \sim m_N$

$g/m_\theta^{1/3}$ large enough

$\sigma \propto \lambda^2 \propto m_\theta^4$

m_θ large enough



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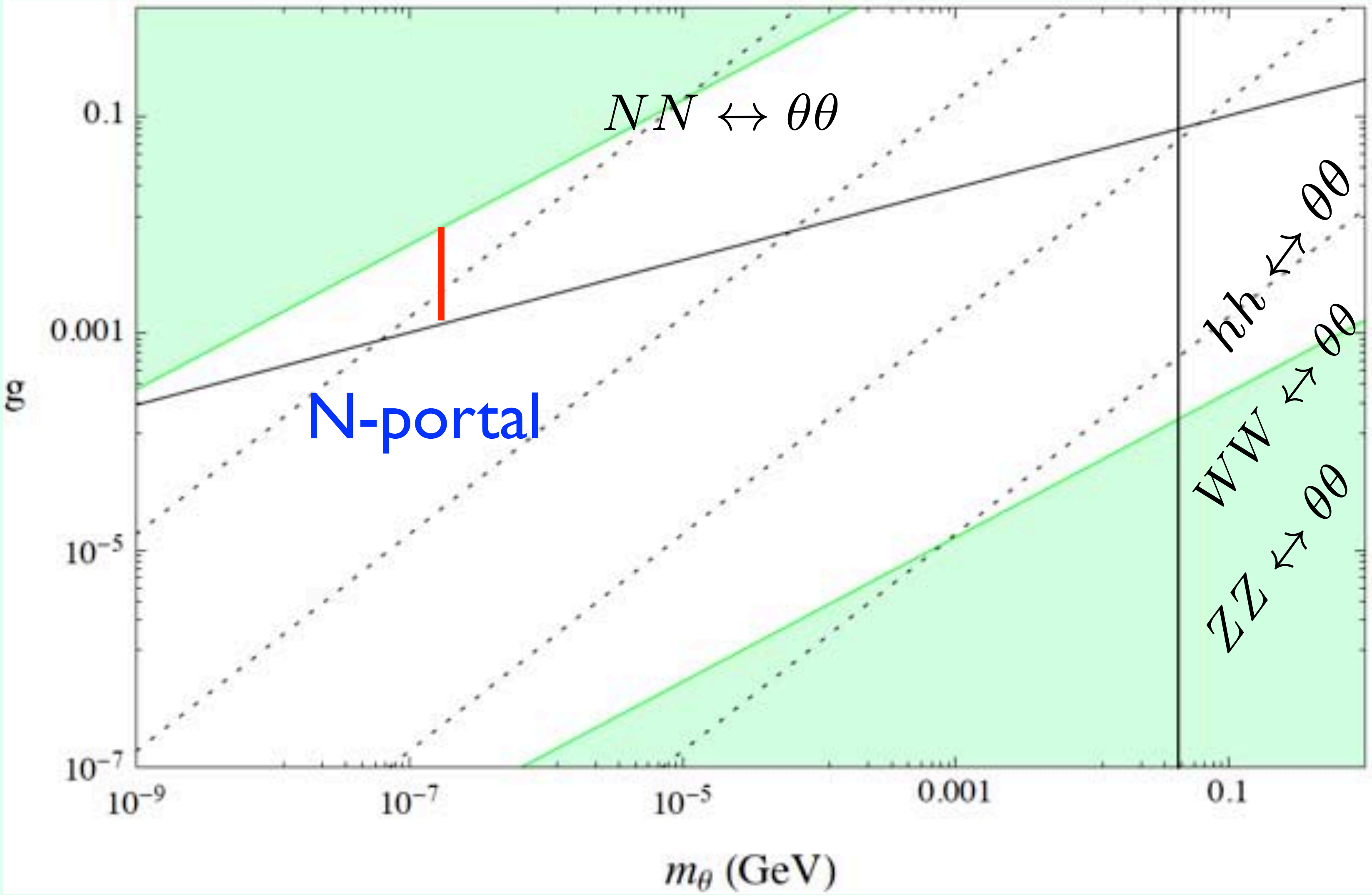
θ relic density

Freeze-out solutions to $\Omega_\theta = \Omega_{DM}$

$m_\theta \simeq 0.15$ keV

$m_\theta = 50 - 70$ GeV
(for $m_h = 120 - 180$ GeV)



Higgs-portal

Farina et al
0912.5038

θ relic density

Regions in parameter space where rate
is too slow to thermalize the DM candidate

$$h \to \theta\theta$$

Some production until T ~ m_h
it may happen that at this moment

$$m_\theta \; n_\theta$$

has a value leading to $\Omega_\theta = \Omega_{DM}$

Freeze-in mechanism

Hall et al
0911.1120

Hall et al
0911.1120

θ relic density

Freeze-in versus freeze-out

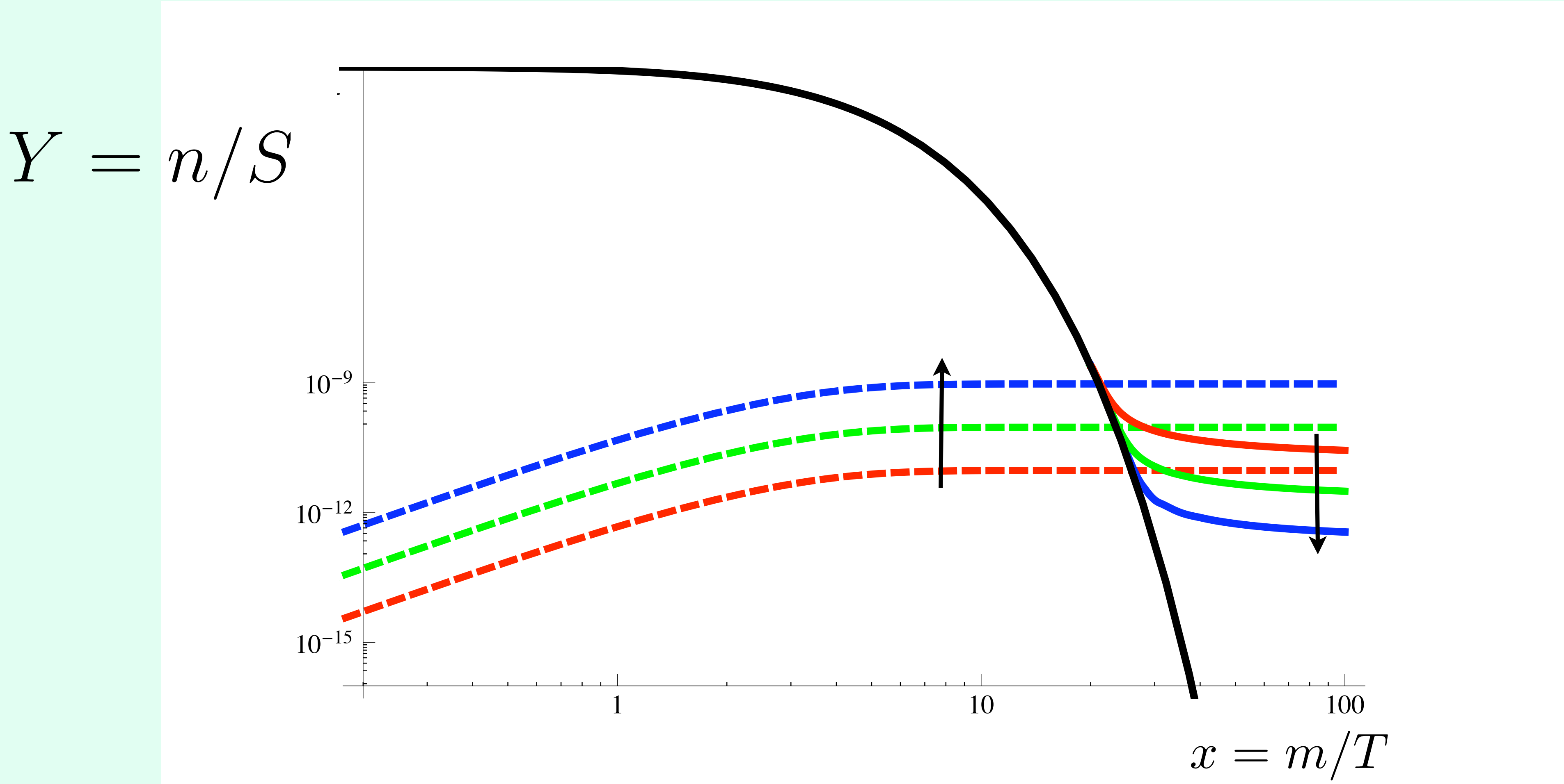


Figure 1: Log-Log plot of the evolution of the relic yields for conventional freeze-out (solid coloured) and freeze-in via a Yukawa interaction (dashed coloured) as a function of $x = m/T$. The black solid line indicates the yield assuming equilibrium is maintained, while the arrows indicate the effect of increasing coupling strength for the two processes. Note that the freeze-in yield is dominated by the epoch $x \sim 2-5$, in contrast to freeze-out which only departs from equilibrium for $x \sim 20-30$.

θ relic density

We integrate Boltzmann eq. numerically

Boltzmann equation in expanding universe:

$$zH(z)s(z)Y'_\theta(z) = \left[1 - \left(\frac{Y_\theta(z)}{Y_\theta^{\text{eq}}(z)}\right)^2\right] \gamma(z)$$

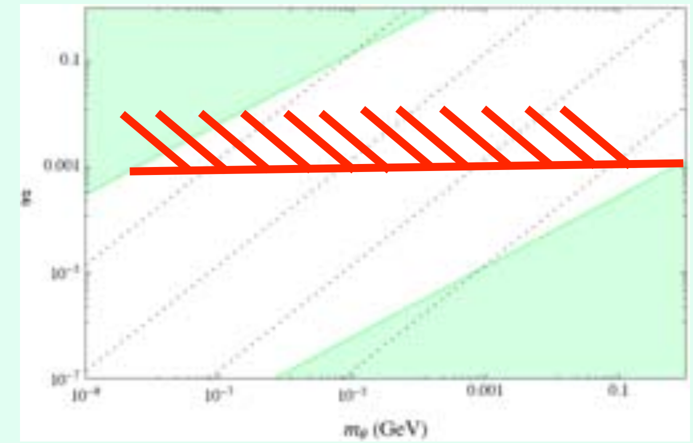
$Y_\theta \equiv n_\theta / s$ $\qquad$ $z \equiv m_h / T$

$s(z)$ entropy dens. $\qquad$ $\gamma(z)$ reaction densities (annihilation + decay)

θ relic density

Consider case $g \to 0$

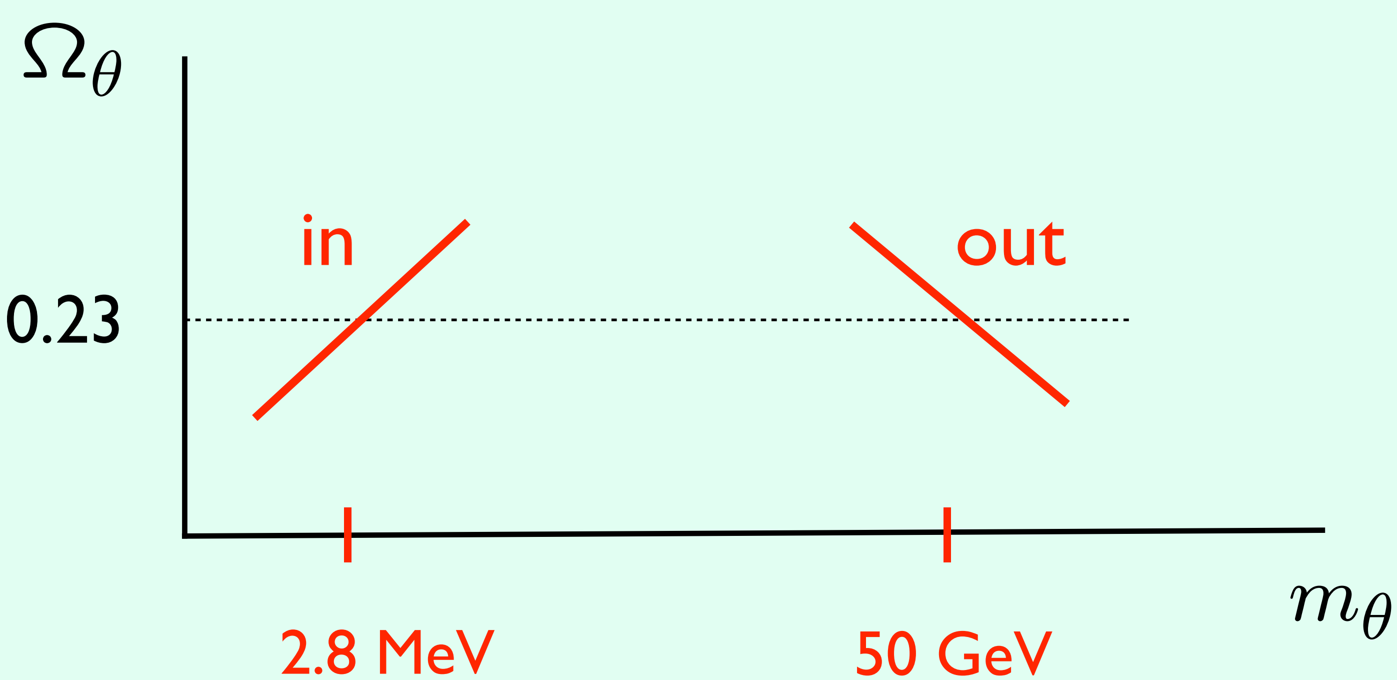
(only Higgs portal at work)



Interaction and mass are related.
Freeze-in solution should fix the mass

$$\boxed{m_\theta = 2.8 \text{ MeV}}$$

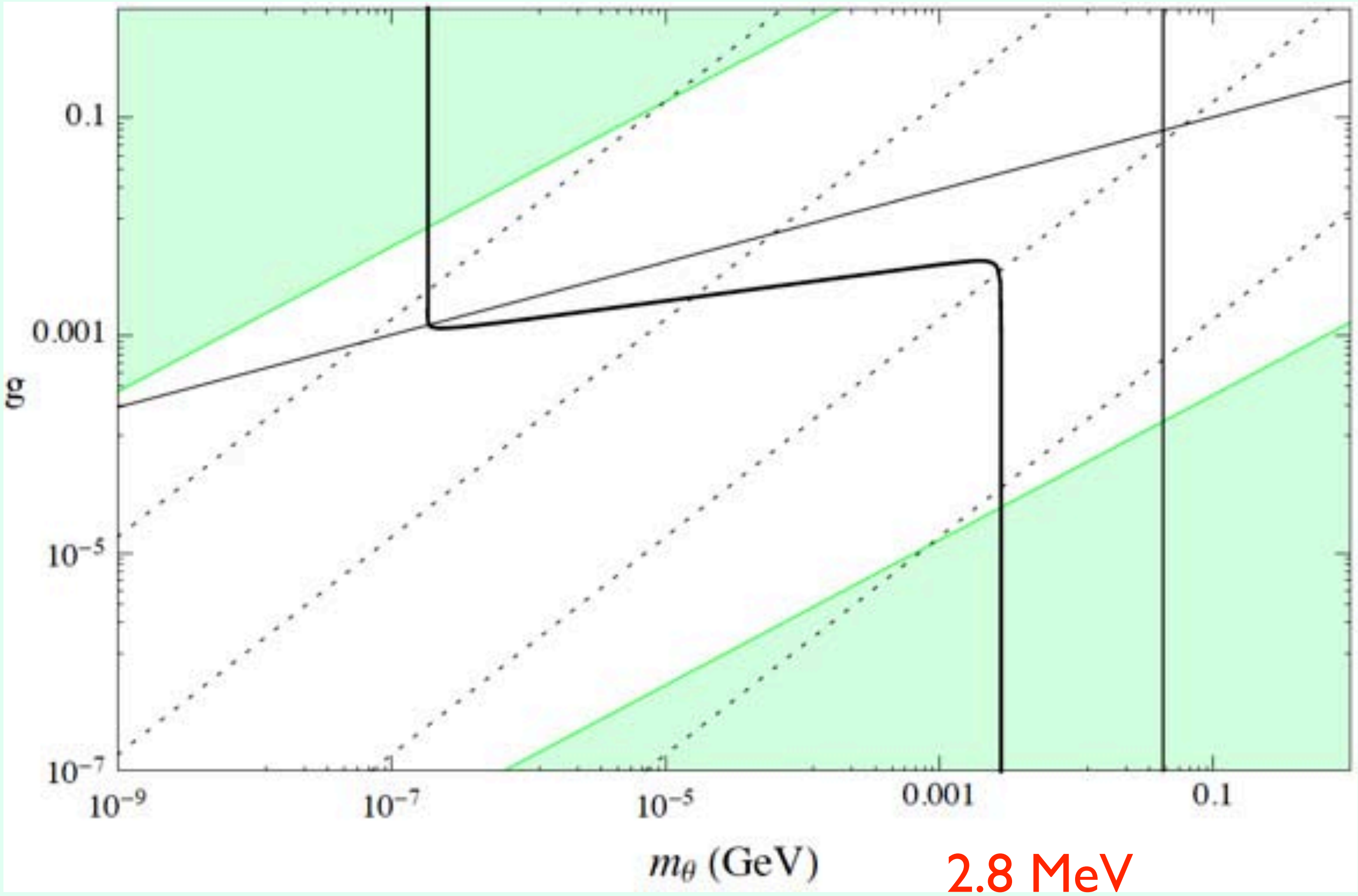
$m_h = 120$ GeV



θ relic density

Freeze-in solution obtained numerically

0.15 keV



2.8 MeV

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θ Lifetime / Decays

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θ Lifetime / Decays

It is the coupling to light fermions what determines lifetime, i.e.

$$\theta \to \nu\nu$$

$$\theta \to e^+e^-$$

PS interaction: $\bar{f}\gamma_5 f\,\theta$

$\theta \to \gamma\gamma$ subdominant

Of course, should require $\tau_\theta > \tau_{universe}$

However, more stringent constraints on

$$\Gamma(\theta \to \nu\nu) \quad \Gamma(\theta \to e^+e^-)$$

due to several astro and cosmo observations

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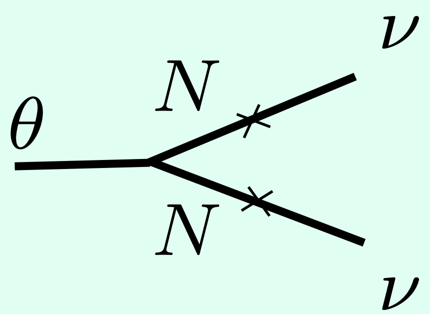
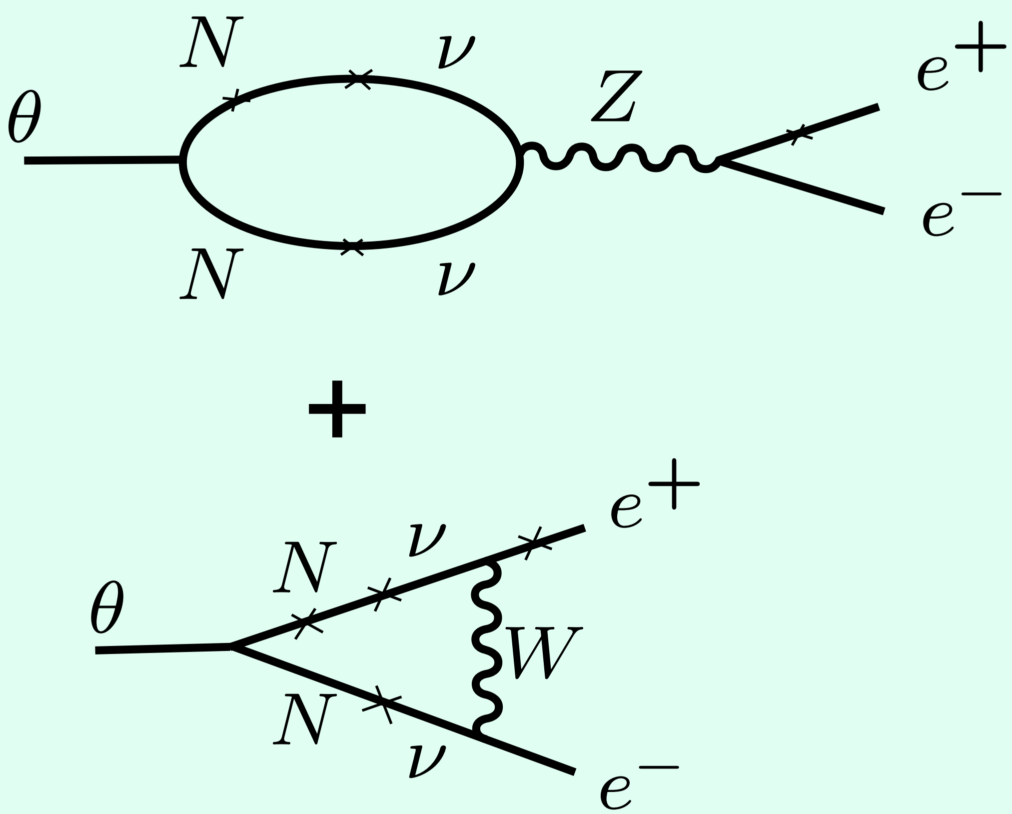
θ Lifetime / Decays



$$\frac{m_\nu}{f}$$



$$\frac{G_F}{(4\pi)^2}\frac{\sqrt{2}m_N}{f}m_e m_\nu$$

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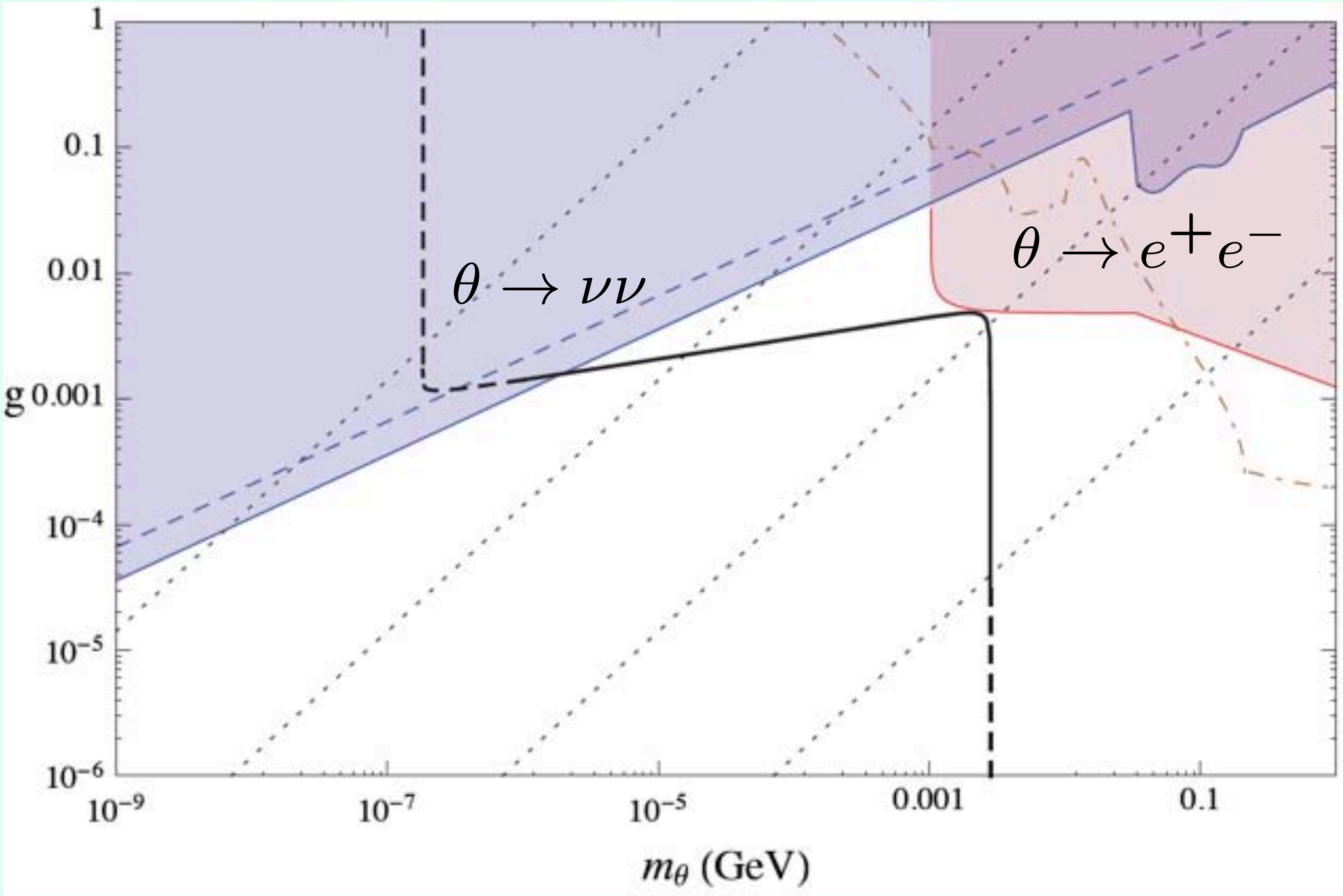
θ Lifetime / Decays



m_nu=0.05 eV

θ Lifetime / Decays

Origin of bounds in relevant region

$\theta \to \nu\nu$

Lattanzi & Valle
0705.2406

Decay implies energy transfer from NR to R;
would change history of universe

$\theta \to e^+e^-$

Bell et al
1004.1008

Annihilation at rest contributing to 511 keV line

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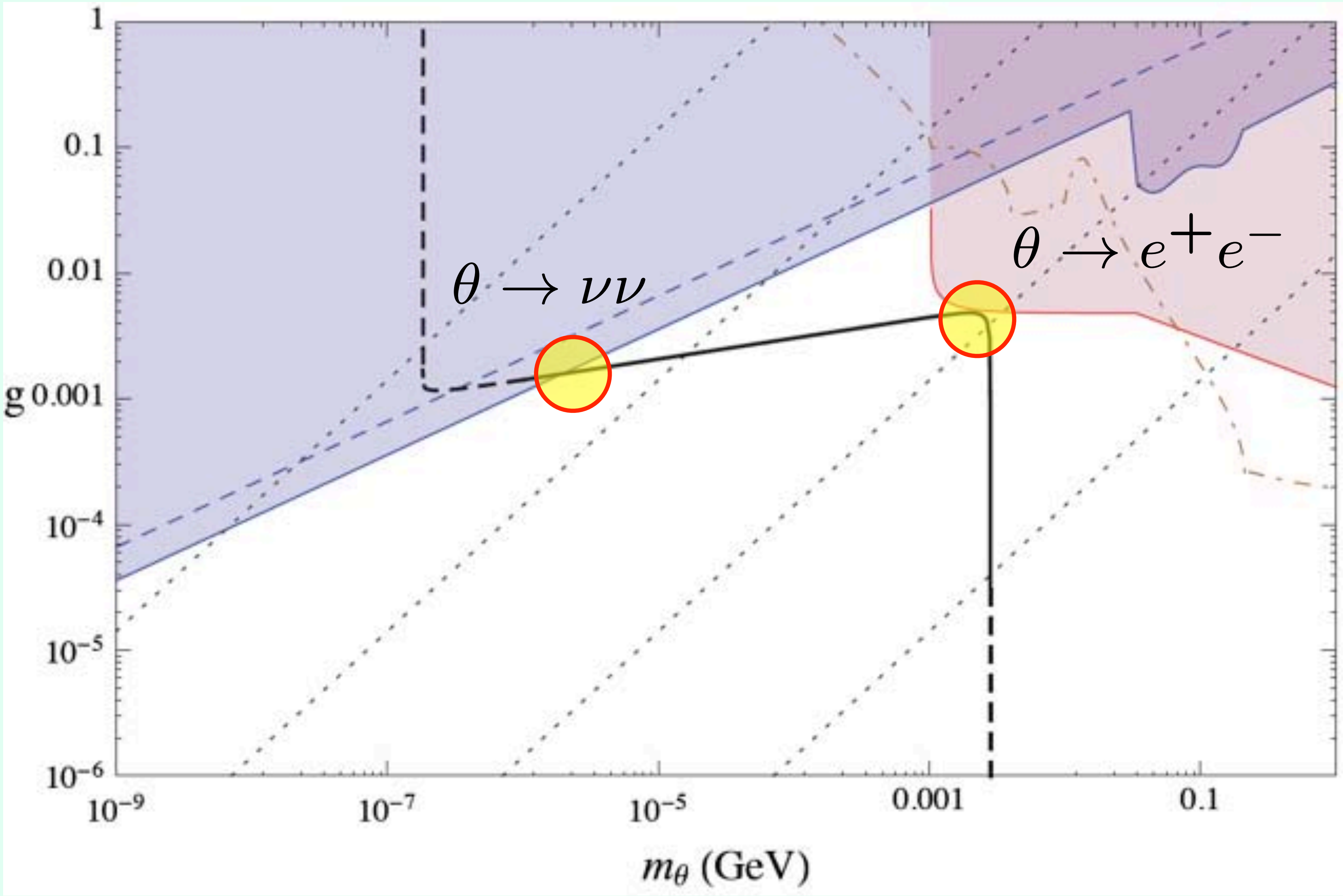
θ Lifetime / Decays

Saturation of bounds, experimental signatures



m_nu=0.05 eV

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Theoretical considerations

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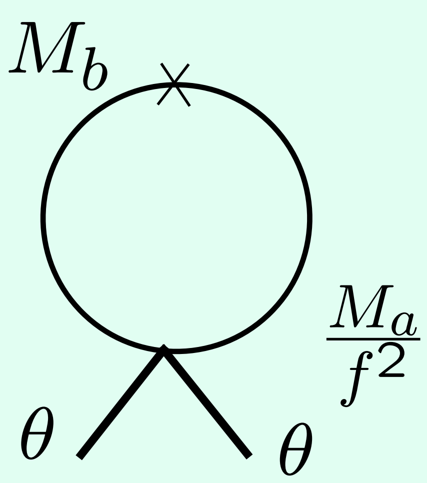
Theoretical considerations

Consider explicit symmetry breaking to give a mass to θ
but wish to protect from large radiative corrections

Not obvious, for example:

$$\frac{1}{2}\nu^c(M_a e^{i\theta/f} + M_b)\nu^c + \text{h.c.}$$
$$= \frac{1}{2}(M_a + M_b)\overline{N}N - \frac{iM_a}{2f}\theta\overline{N}\gamma_5 N - \frac{M_a}{4f^2}\theta^2\overline{N}N + \ldots$$



$$m_\theta^2 \sim \frac{1}{8\pi^2}\frac{M_a M_b}{f^2}\Lambda^2$$

Quadratically divergent,
sensitive to high-energy completion

Theoretical considerations

Hill & Ross
NPB311 ('88)

Hill and Ross worried about explicit (hard) symmetry breaking and goldstones

They worked out (quark) flavor structures reducing the degree of divergence

We apply their ideas to our problem in the neutrino sector; we introduce collective breaking involving neutrino Yukawa couplings

Theoretical considerations

Example: Model with two sterile neutrinos

$$U(1)_X \qquad X(\nu_1^c) = -1, X(\nu_2^c) = 1 \text{ scalar } X(\Phi) = 2$$

SSB ↓

$$+\frac{1}{2}(\nu_1^c\ \nu_2^c)\begin{pmatrix} M_{11}e^{i\theta/f} & M_{12} \\ M_{12} & M_{22}e^{-i\theta/f} \end{pmatrix}\begin{pmatrix} \nu_1^c \\ \nu_2^c \end{pmatrix} + \text{h.c.}$$

allowed ↑ ↑ SSB

$$l_\alpha(m_{\alpha 1}\ m_{\alpha 2})\frac{H}{v}\begin{pmatrix} \nu_1^c \\ \nu_2^c \end{pmatrix} \qquad \alpha = e, \mu, \tau$$

↑

one different from zero necessarily breaks (expl.) the symmetry

Theoretical considerations

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

$m_{\alpha 1} = 0$ or $m_{\alpha 2} = 0$
or
two independent M-entries are zero

→ θ can be absorbed in field redefinitions → true massless Goldstone

mass of θ is proportional to product of several masses and degree of divergence is logarithmic

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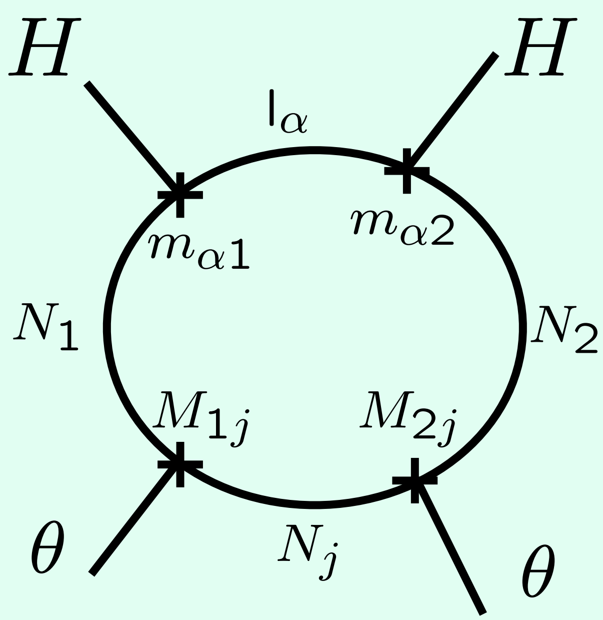
Theoretical considerations

Explicit calculation gives

$$-\frac{\lambda}{2}\ \theta^2\ H^\dagger H$$



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

$$m_\theta^2 = \lambda v^2$$

for our model, need family-dependent $U(1)_X$

but not unique choice, equivalences among different assignments

Theoretical considerations

Can calculate decays in 3-family case
For example, effective vertex $\theta e^+ e^-$

$$i\left(\frac{M_{11}}{f}F_1 - \frac{M_{22}}{f}F_2\right)\frac{2\sqrt{2}\ G_F}{(4\pi)^2}\ m_e \bar{e}\gamma_5 e\,\theta$$

$$F_1 \;=\; m_1^2\left(c^2s^2K + \frac{c^2}{M_1} + \frac{s^2}{M_2}\right) - m_2^2\ c^2s^2K -$$
$$m_1m_2\ cs\left((c^2-s^2)K - \frac{1}{M_1} + \frac{1}{M_2}\right)$$
$$F_2 \;=\; m_2^2\left(c^2s^2K + \frac{s^2}{M_1} + \frac{c^2}{M_2}\right) - m_1^2\ c^2s^2K +$$
$$m_1m_2\ cs\left((c^2-s^2)K + \frac{1}{M_1} - \frac{1}{M_2}\right)$$

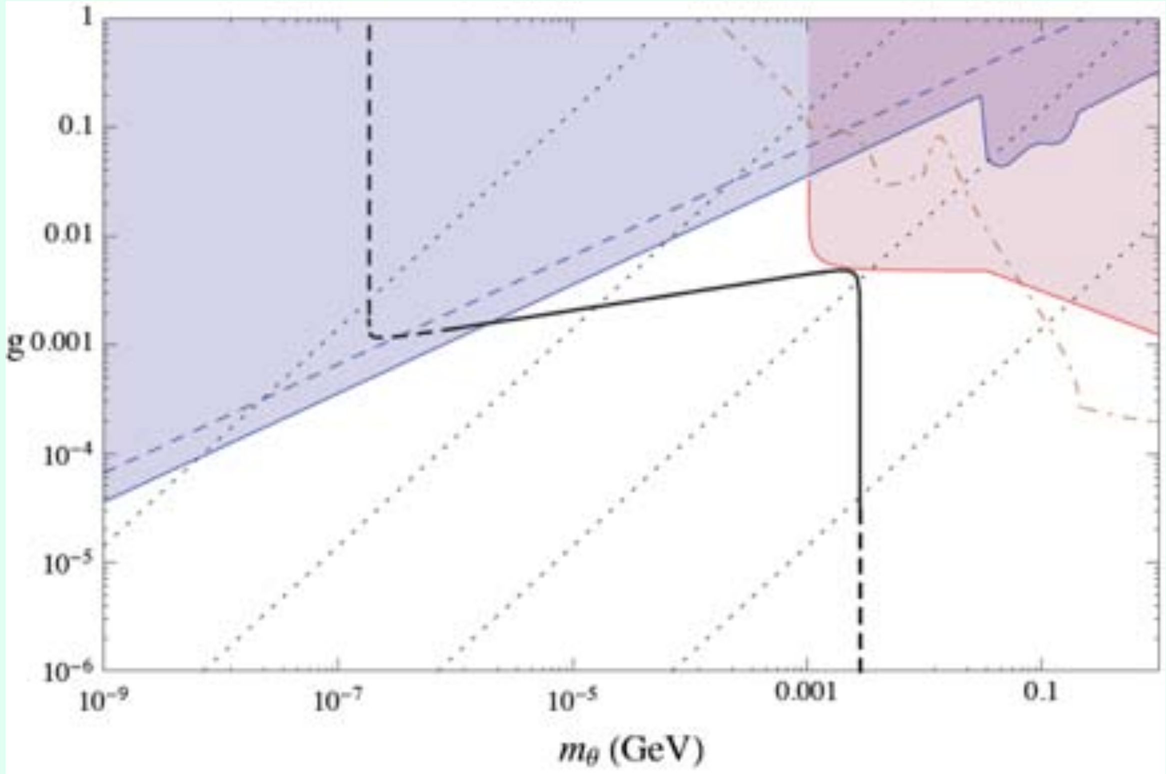
$\tan 2\delta = 2M_{12}/(M_{11}-M_{22})$

$c \equiv \cos\delta$ and $s \equiv \sin\delta$

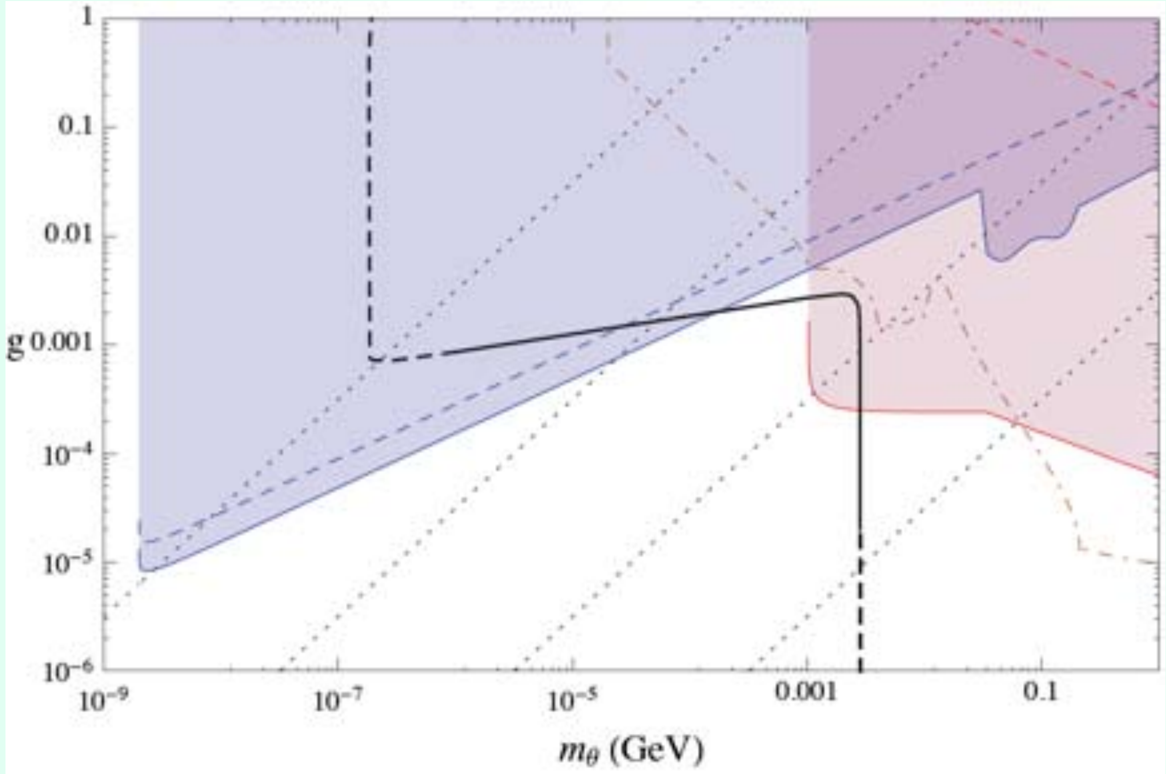
$$K(M_1,M_2) = -\frac{M_1^2 + 4M_1M_2 + M_2^2}{M_1M_2(M_1+M_2)}$$
$$+\frac{4(M_1^2 + M_1M_2 + M_2^2)}{(M_1-M_2)(M_1+M_2)^2}\log\frac{M_1}{M_2}$$

Theoretical considerations

0.05 eV



1 eV



Conclusions

- New pseudoscalar gauge-singlet DM candidate

- Theoretically well motivated
  (related to see-saw scale,
  protected from large radiative corrections)

- Higgs-portal emerges naturally, mass linked to interactions

- Mass in the range keV-MeV

- Relic density from freeze-in

- Decays into neutrinos / e+ e- saturating bounds

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