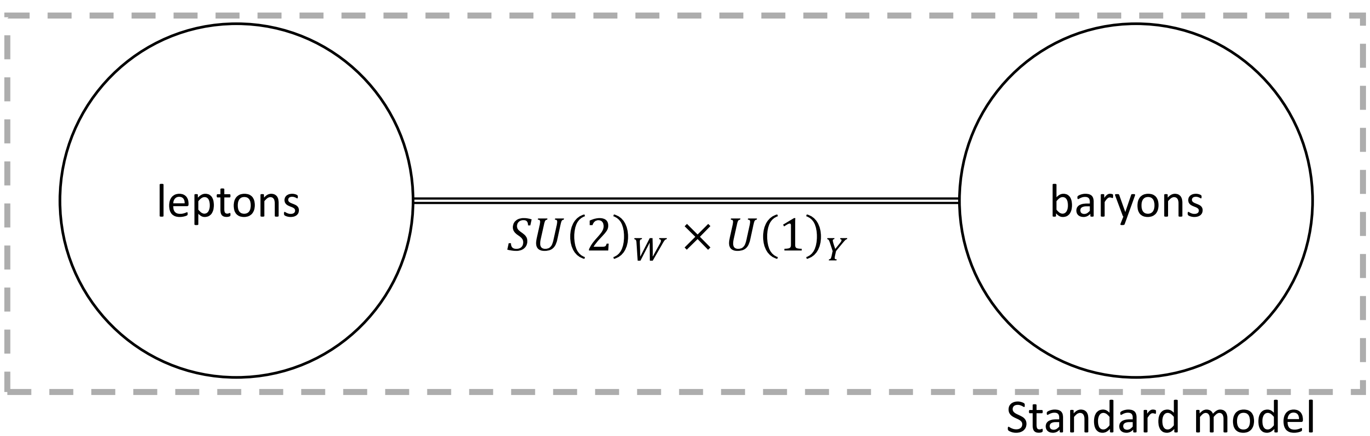
Composite Dirac neutrinos with QCD axion

Tae Hyun Jung

KIAS

Ref S. Chakraborty, THJ, T. Okui, arXiv: 2108.04293

Outline of the model



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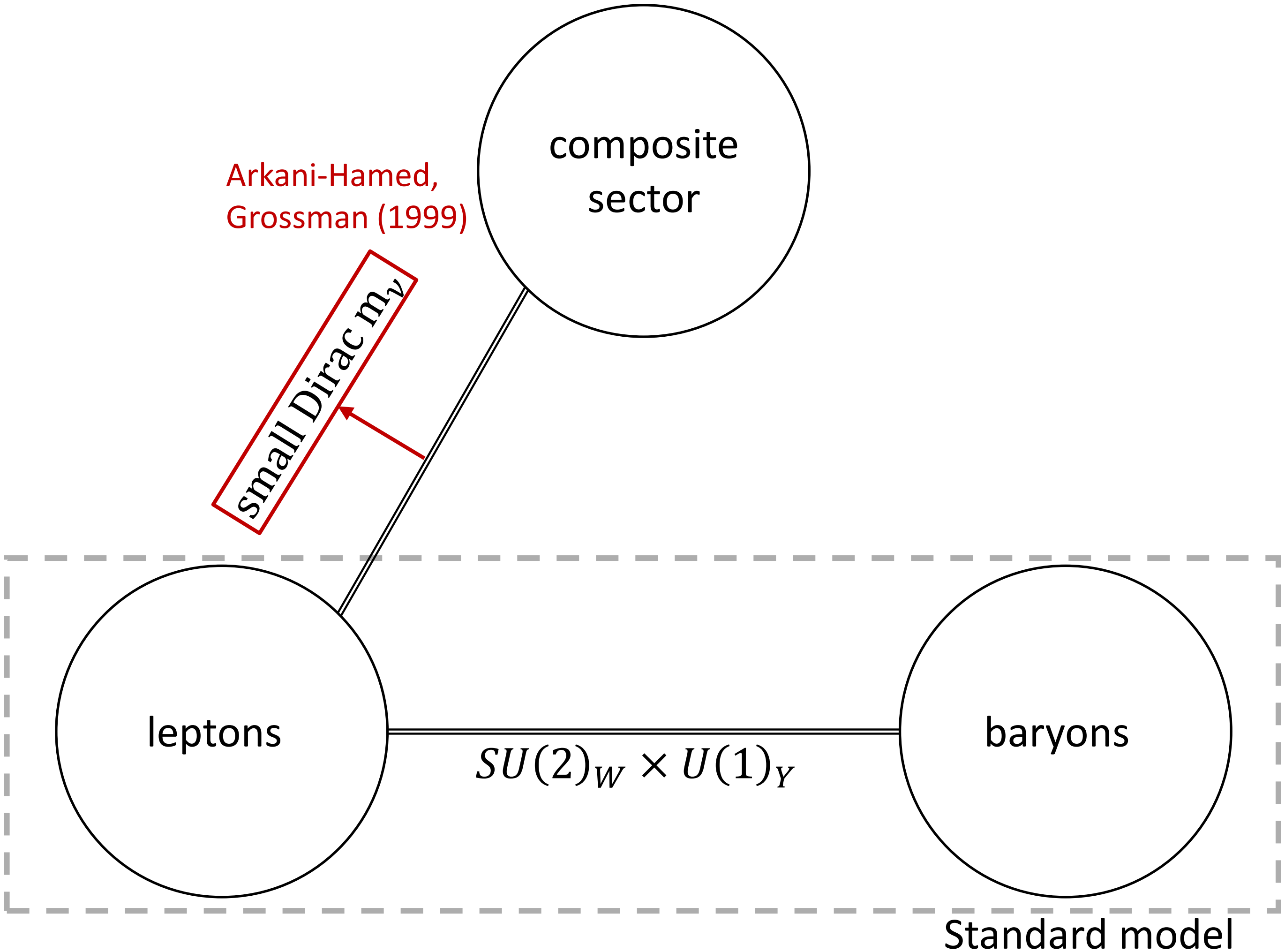

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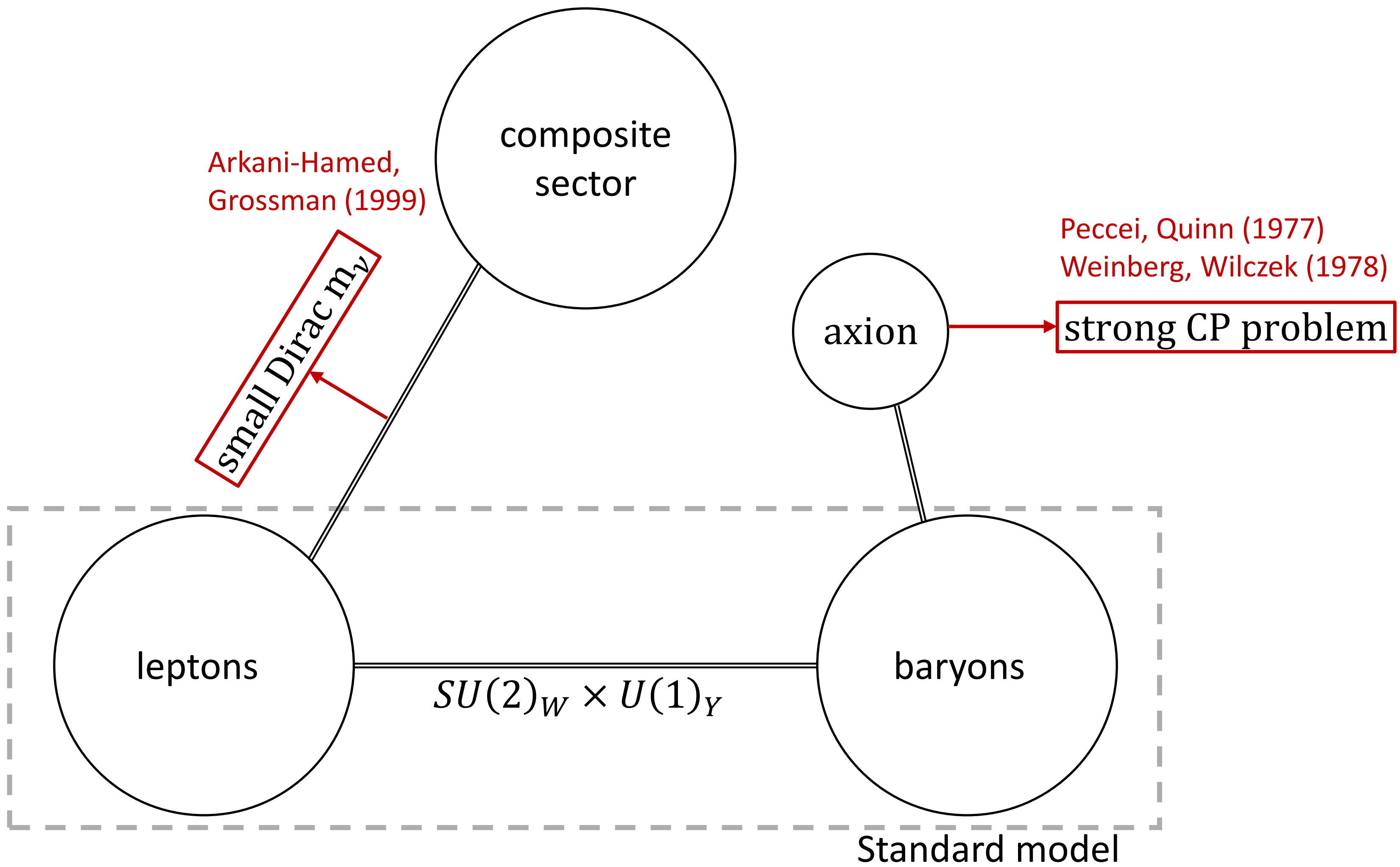

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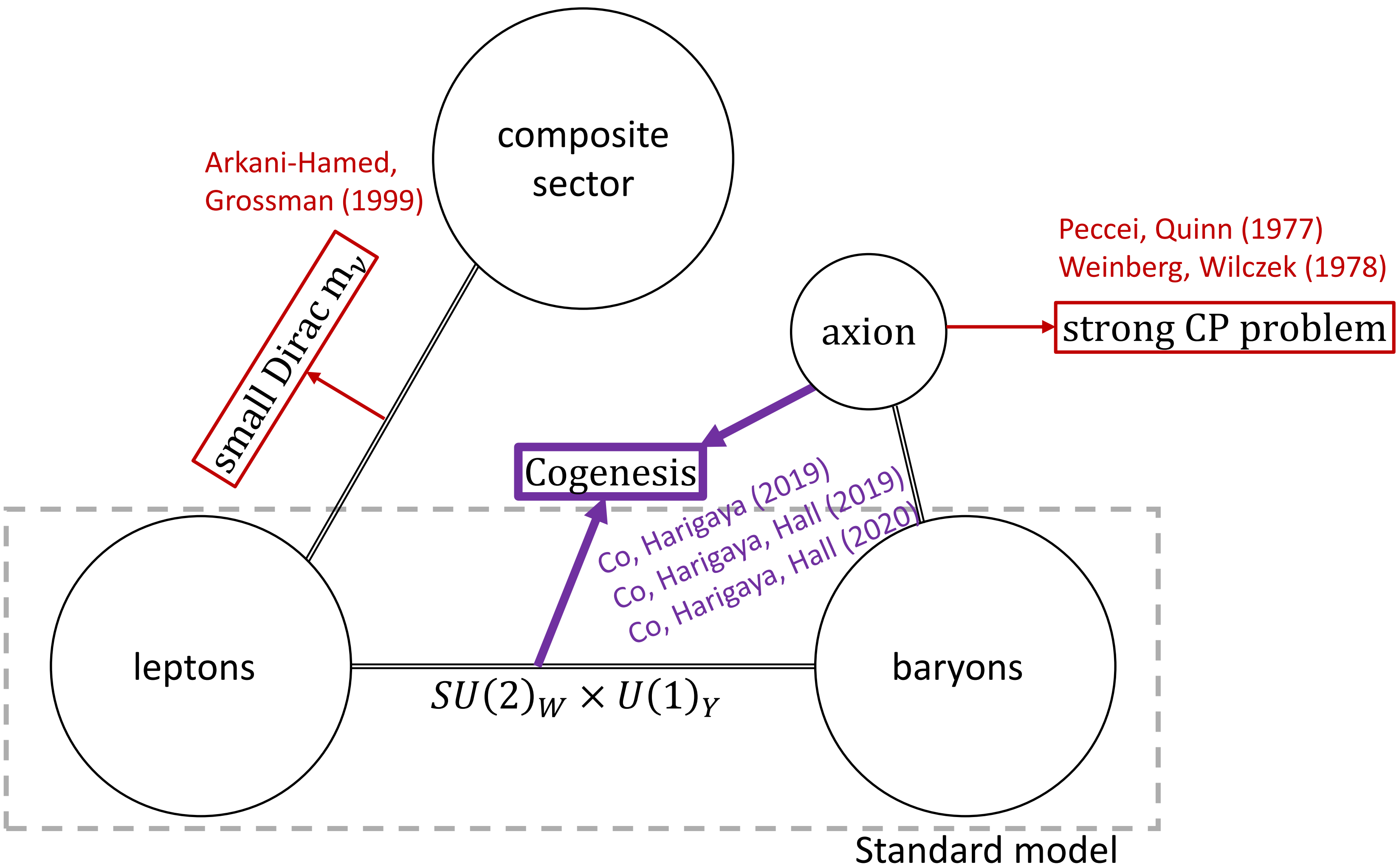

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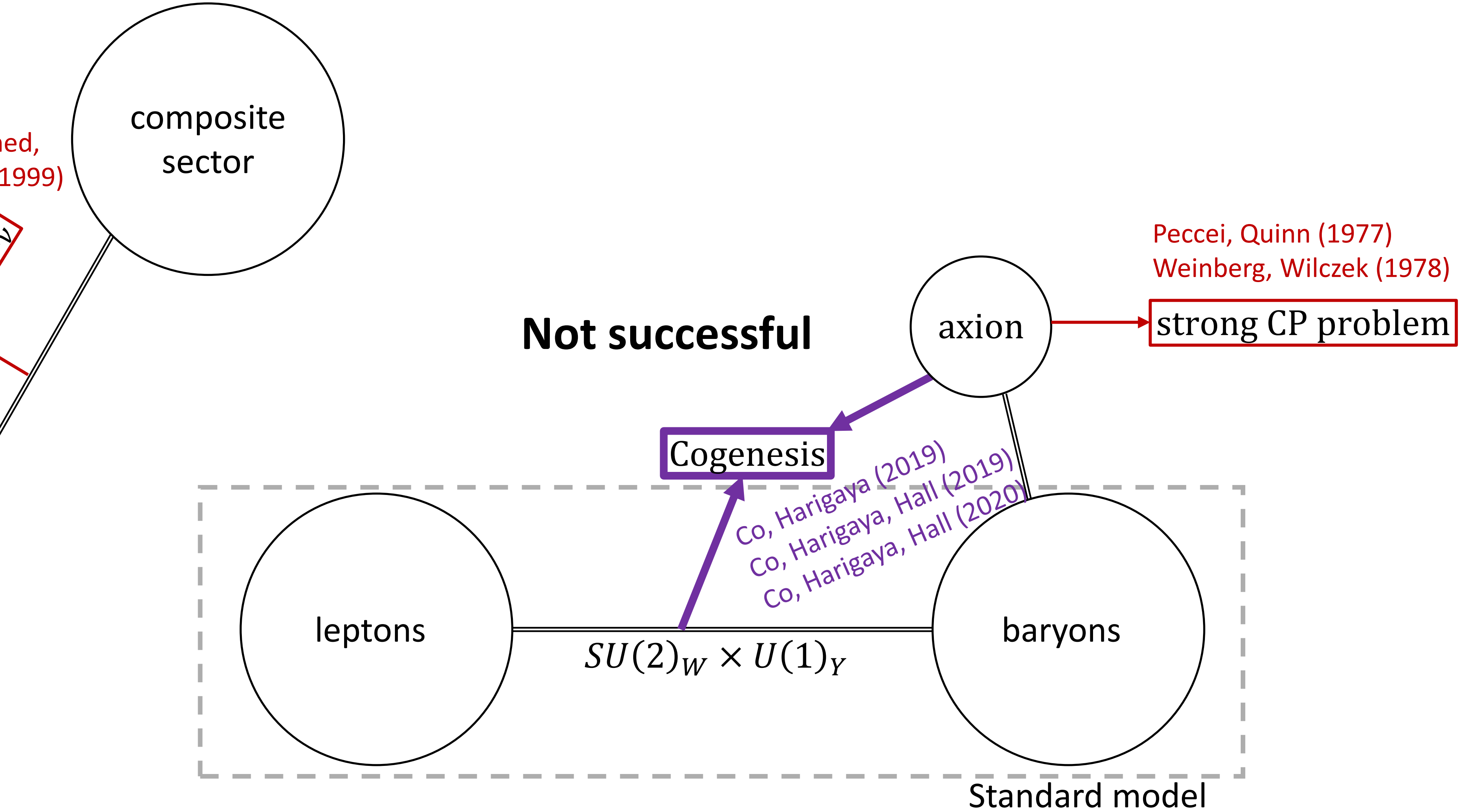

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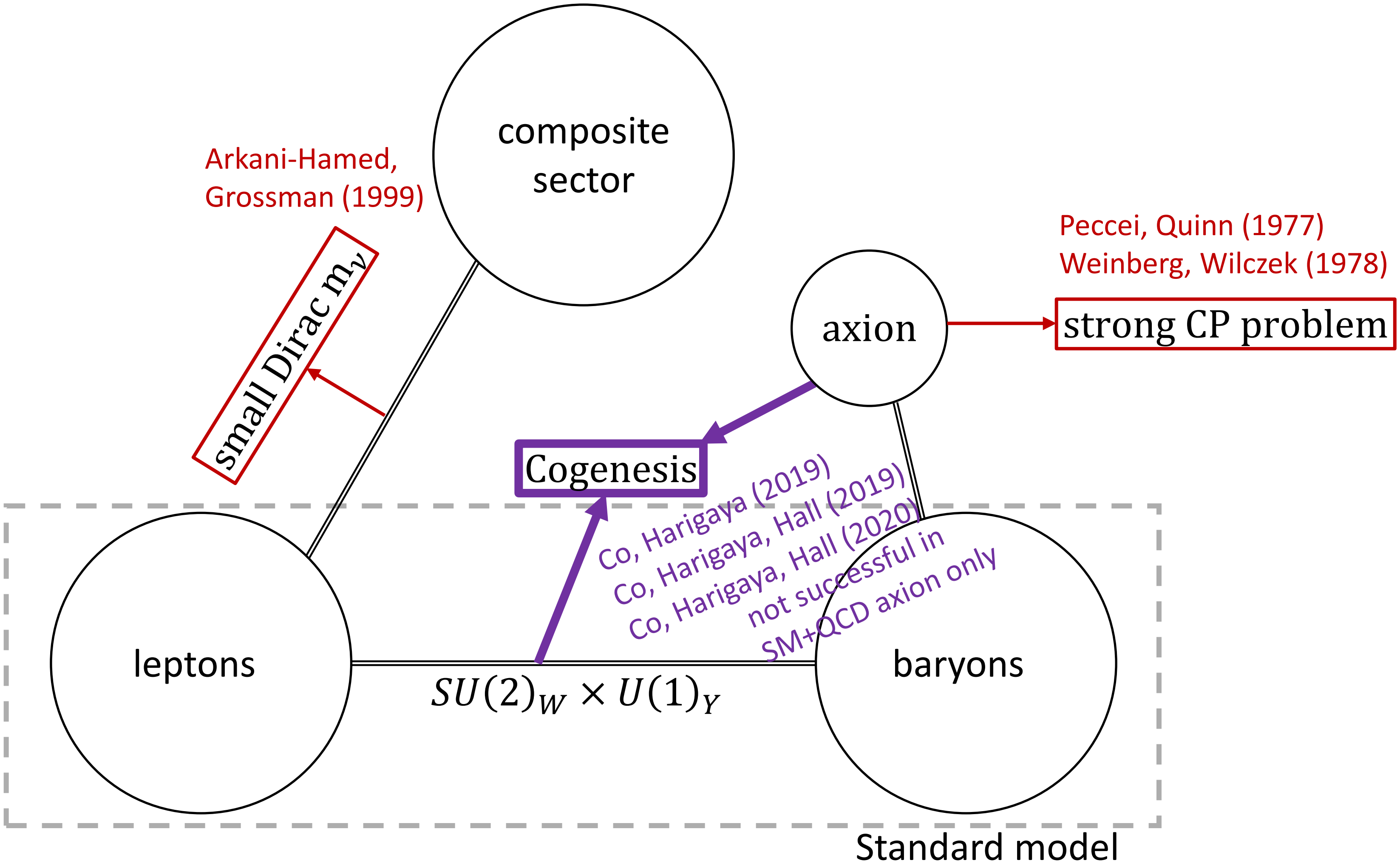

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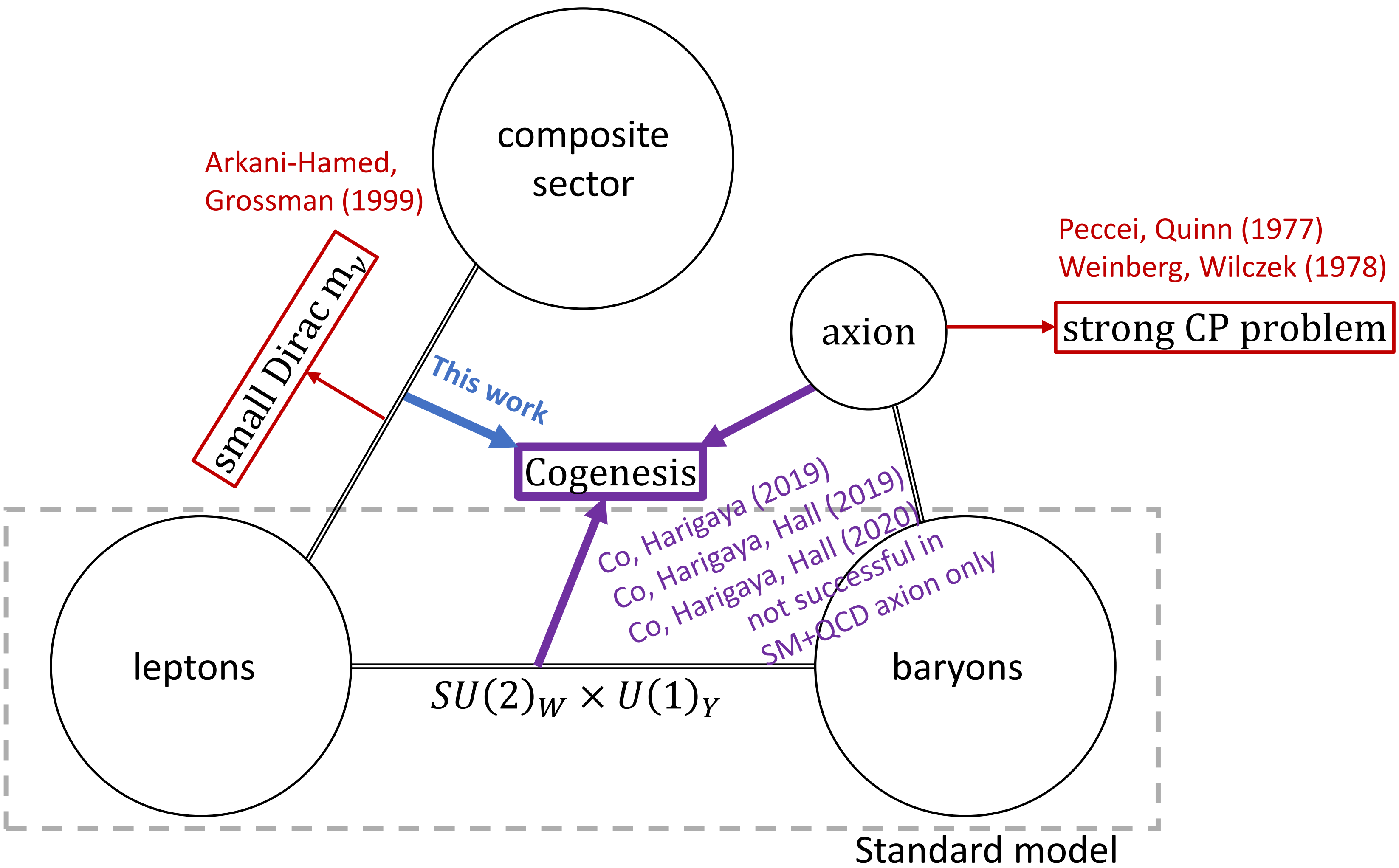
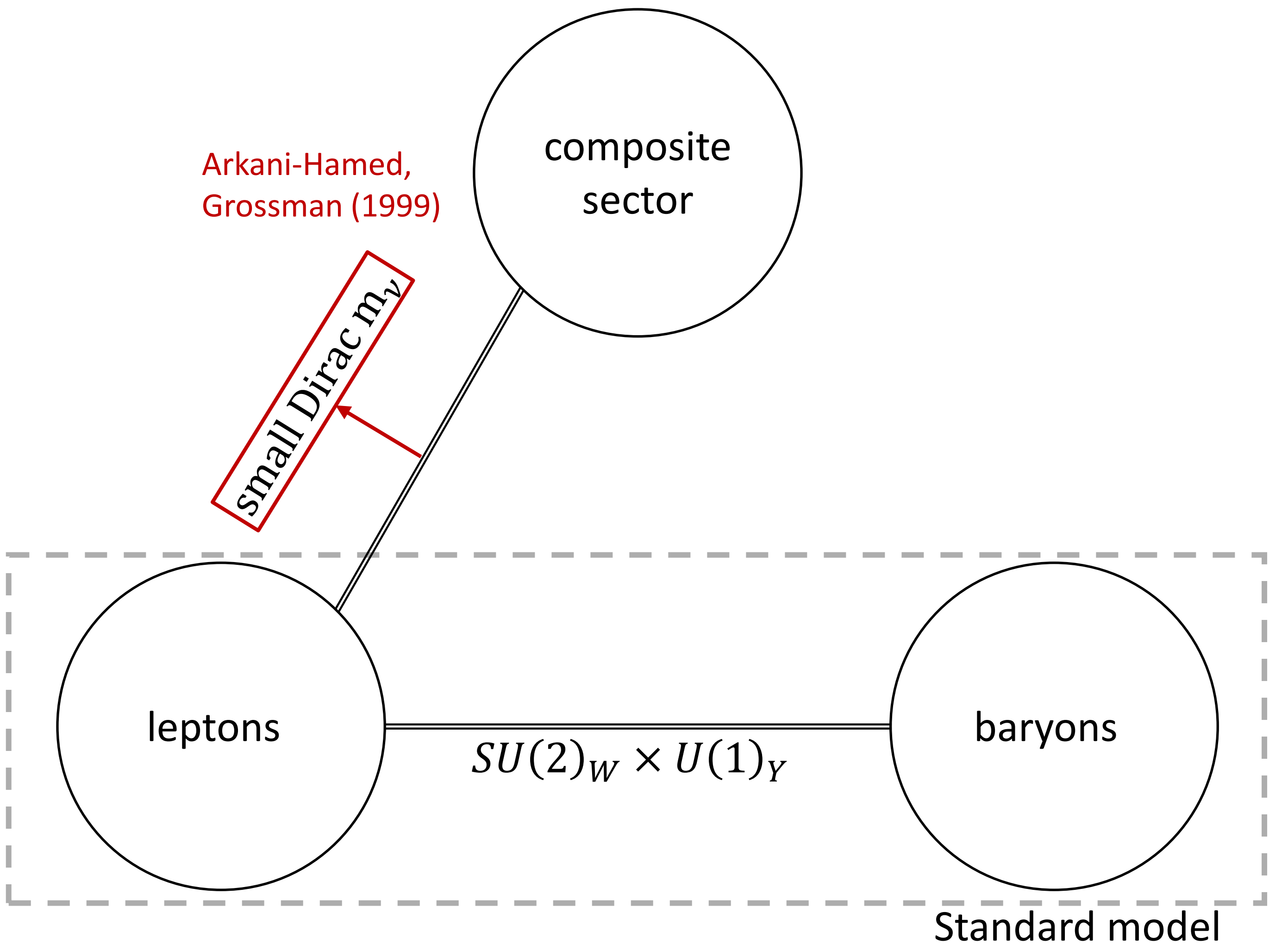


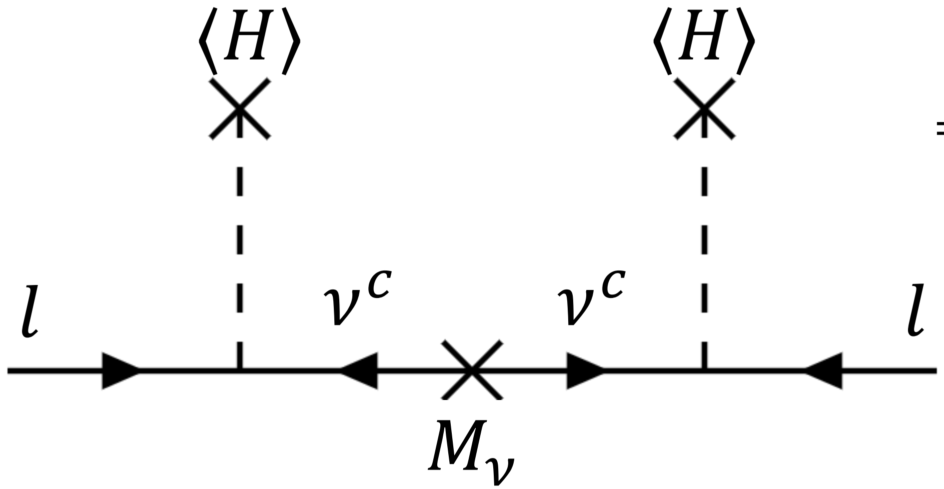
Composite Dirac neutrinos



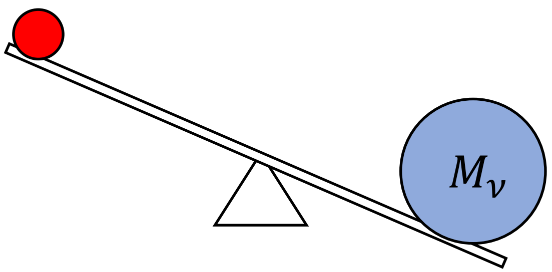
Why are neutrinos so light?

$$y_\nu\, H\, l\, \nu^c + \mathrm{h.c.} + M_\nu \nu^c \nu^c$$

1. See-saw mechanism (Majorana neutrinos): $M_\nu \gg y_\nu v_h$



$\Rightarrow m_\nu \sim \frac{y_\nu^2 v_h^2}{M_\nu}$



2. $\mathbf{0 \neq y_\nu < 10^{-13}}$ **without** $\boldsymbol{M_\nu}$

N. Arkani-Hamed, Y. Grossman (1999)

Composite ν^c

Composite Dirac neutrinos

N. Arkani-Hamed, Y. Grossman (1999)

$$\boldsymbol{\nu^c \propto \psi\psi\chi}$$

ψ, χ: fundamental Weyl fermions charged under a hidden non-Abelian gauge
ν^c: a composite Weyl fermion (like proton/neutron in QCD: $p \propto uud, \quad n \propto udd$)

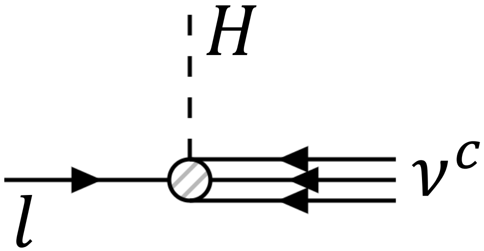
Effective description
after confinement

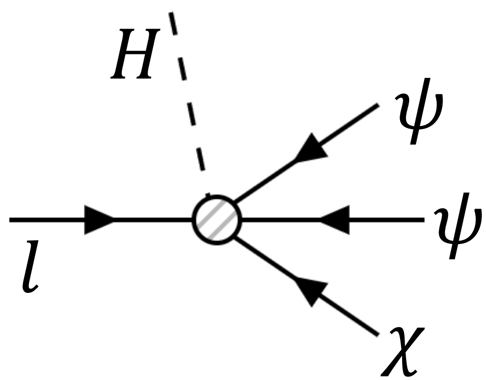
Fundamental description
before confinement

$$H\ l\ \nu^c \quad \leftrightarrow \quad H\ l\ (\psi\psi\chi) \longrightarrow$$ Dim: 7

$(\psi\psi\chi) \sim \Lambda_c^3\ \nu^c$

Dim: $3 \cdot \frac{3}{2}$





$$\boldsymbol{y_\nu \sim \left(\frac{\Lambda_c}{M}\right)^3}$$

$$\frac{\Lambda_c}{M} \sim 10^{-4} \ \Rightarrow\ m_\nu \sim 0.1\ \text{eV}$$

Q: How can those composite fermions remain massless?

cf) protons and neutrons

Composite Dirac neutrinos

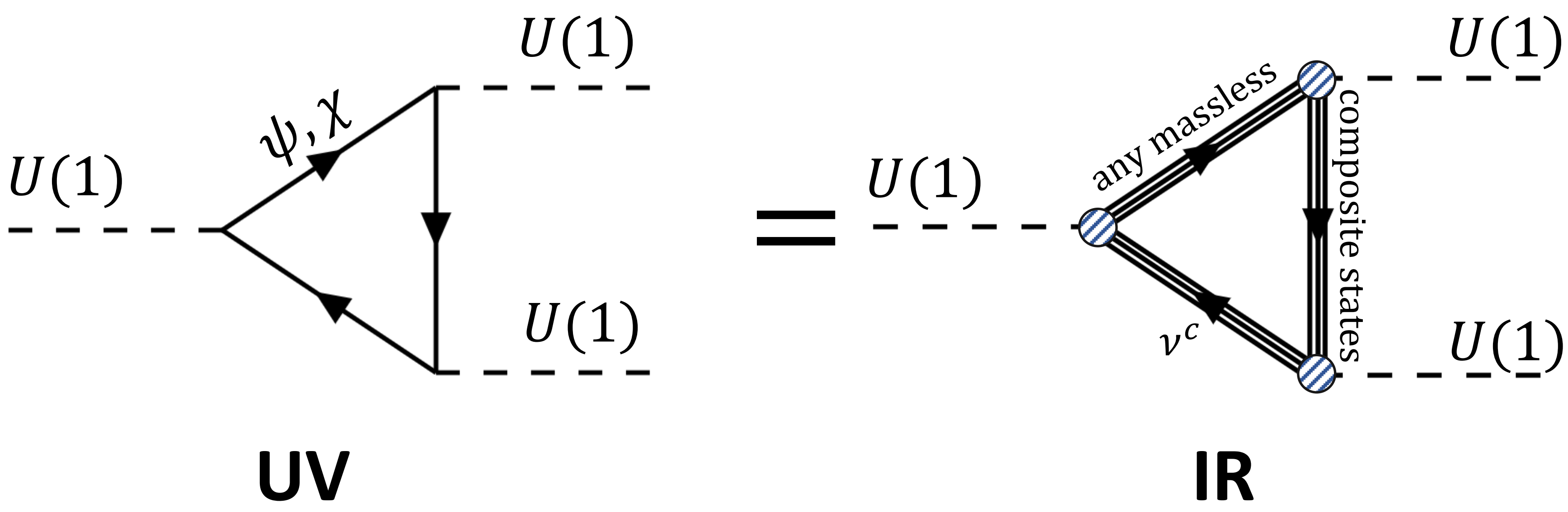
Arkani-Hamed, Grossman (1999)

	Gauge	Global	
	$SU(6)$	$U(1)$	
ψ	$\overline{\mathbf{6}}$	$-2/3$	$\times$ 2 (Two generation)
χ	$\mathbf{15}$	$1/3$	
$\nu^c \propto \psi\psi\chi$	$\mathbf{1}$	-1	$\times$ 3 (Three generation)

How $\nu^c \propto \psi\psi\chi$ can be massless after confinement:

S. Dimopoulos, S. Raby, L Susskind (1980)

't Hooft anomaly matching conditions



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Does not gain mass from the confinement → $\nu^c \propto \psi\psi\chi$

Effective operator with SM: $\frac{1}{M^3} Hl\,(\psi\psi\chi) \rightarrow \frac{\Lambda_c^3}{M^3} Hl\,\nu_c$

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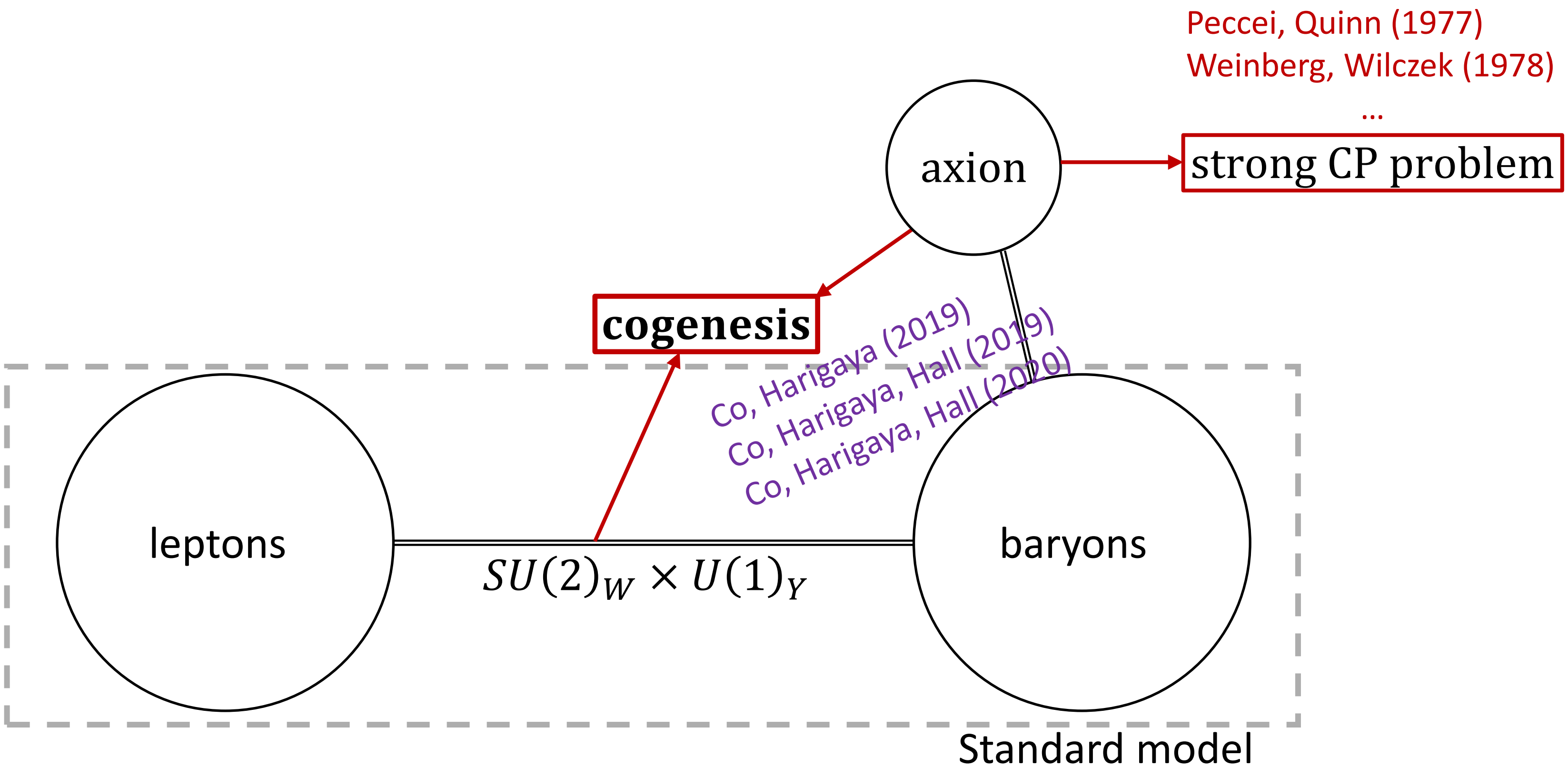
$$m_\nu \sim \left(\frac{\Lambda_c}{M}\right)^3 v_h$$

$$\frac{\Lambda_c}{M} \sim 10^{-4} \;\Rightarrow\; m_\nu \sim 0.1\ \mathrm{eV}$$

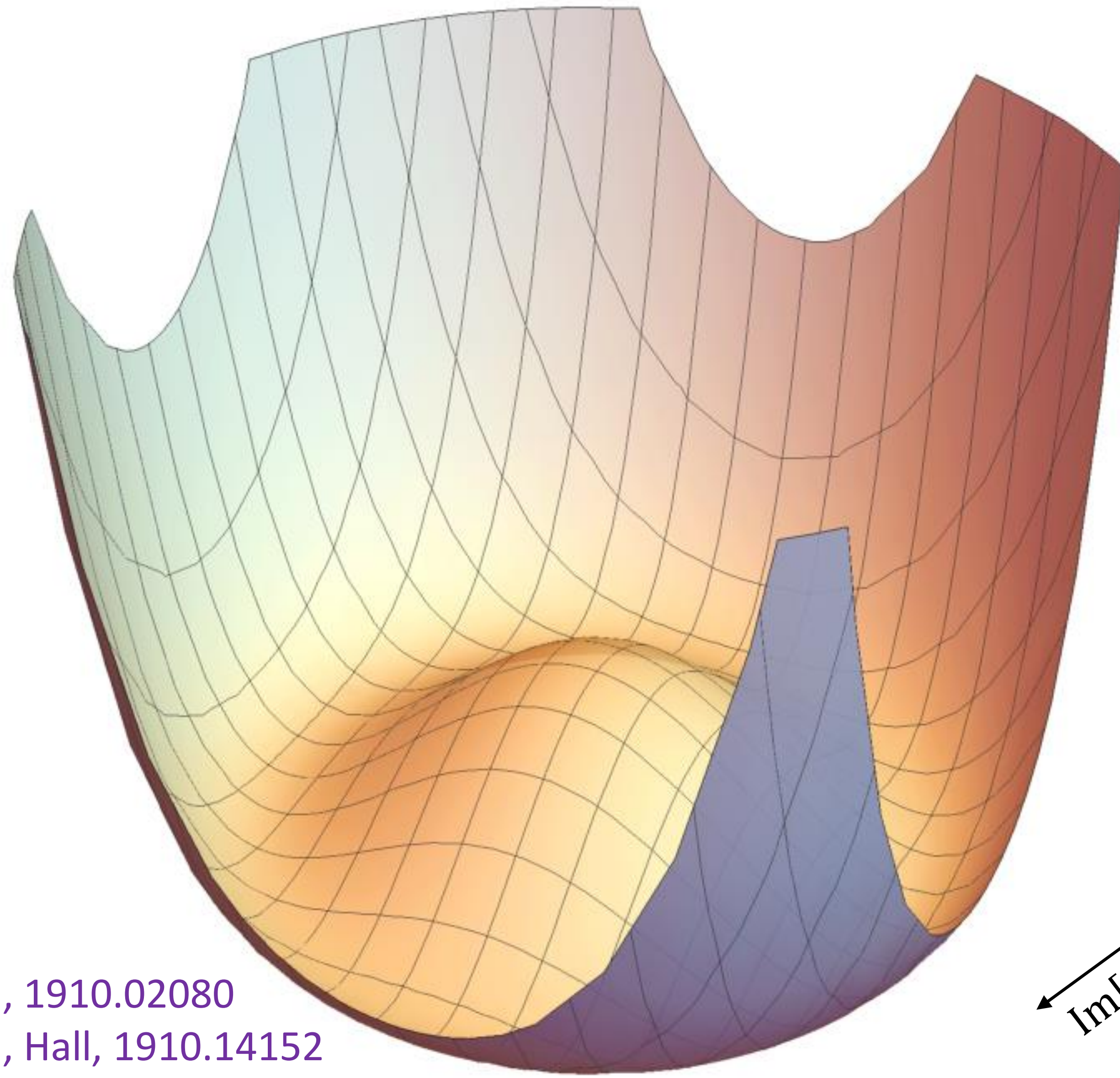
Many ways of UV completion

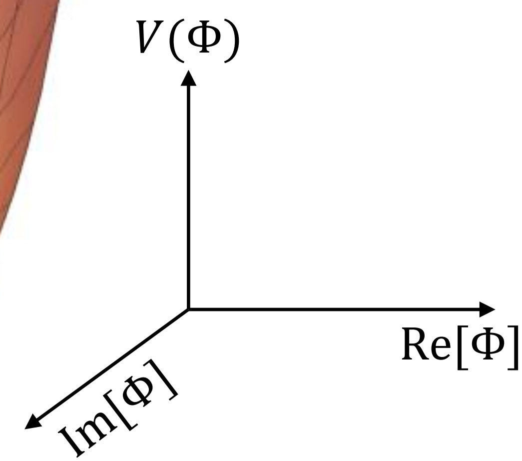
M comes from other particles' mass.

Kinetic misalignment



Kinetic misalignment

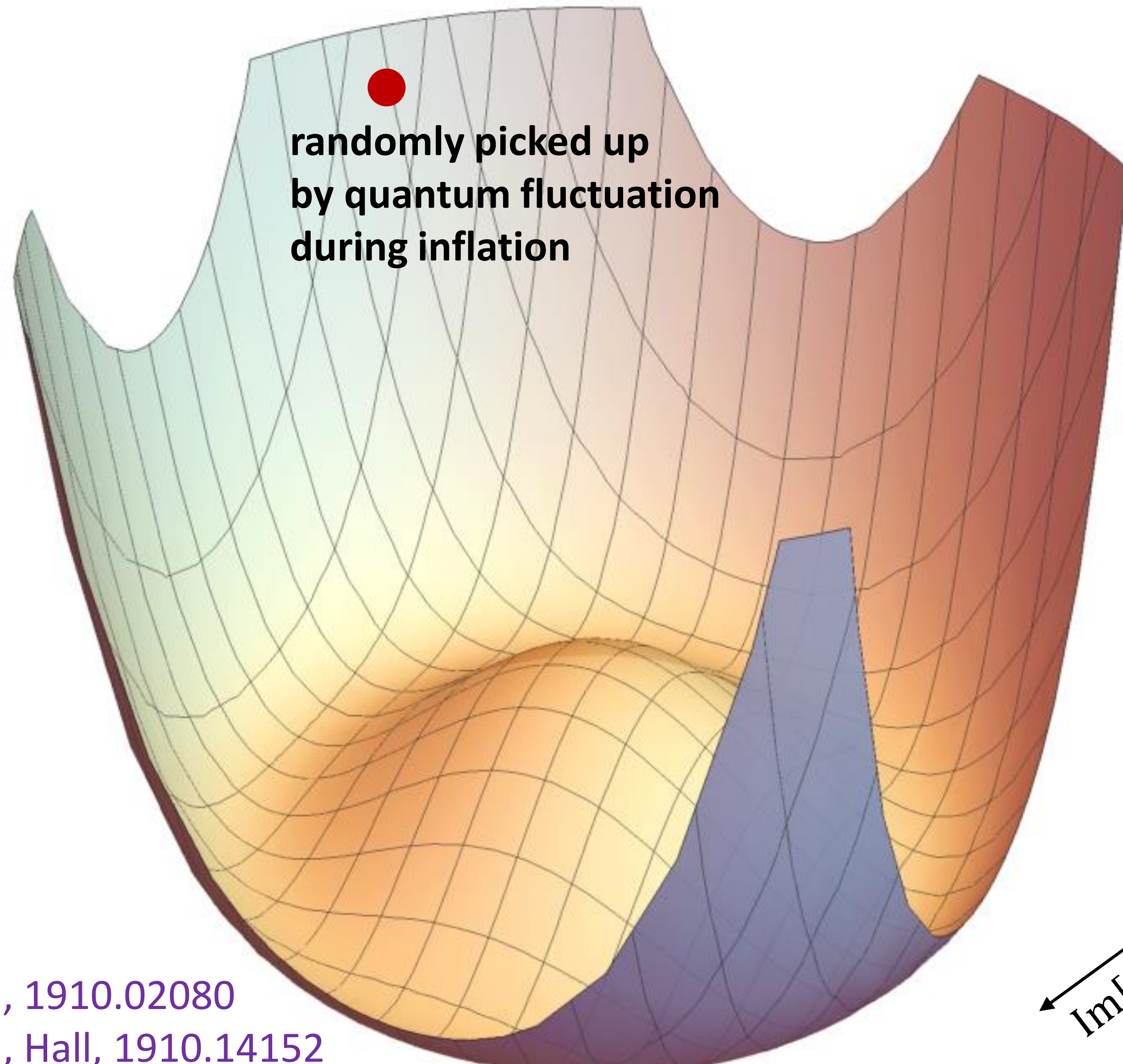


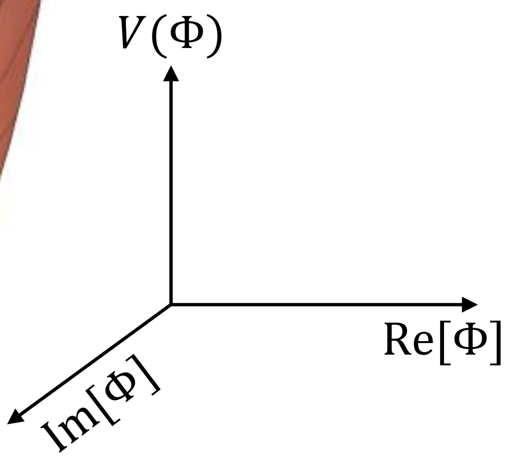


Co, Harygaya, 1910.02080
Co, Harygaya, Hall, 1910.14152

Potential of PQ breaking field Φ

Kinetic misalignment





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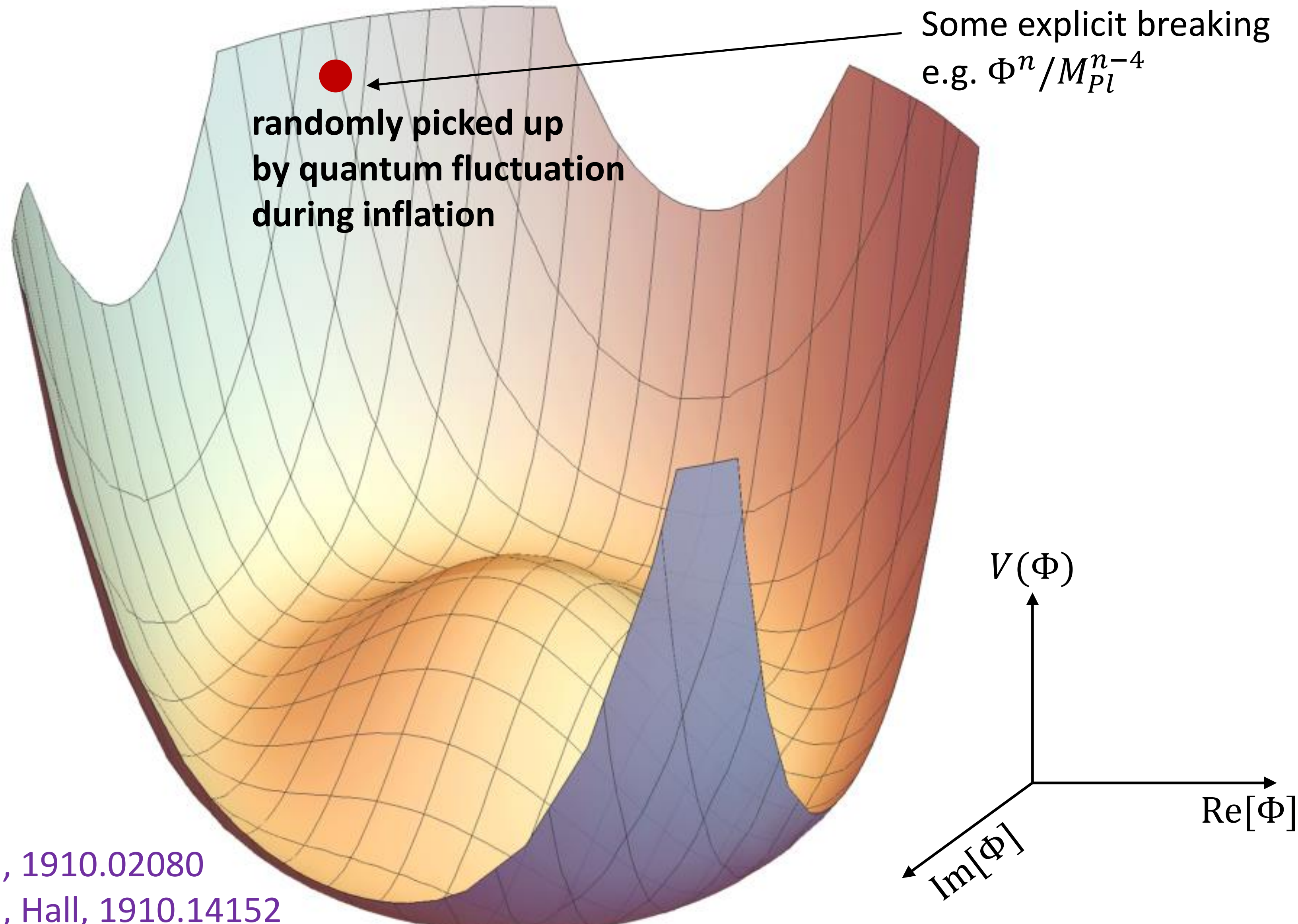

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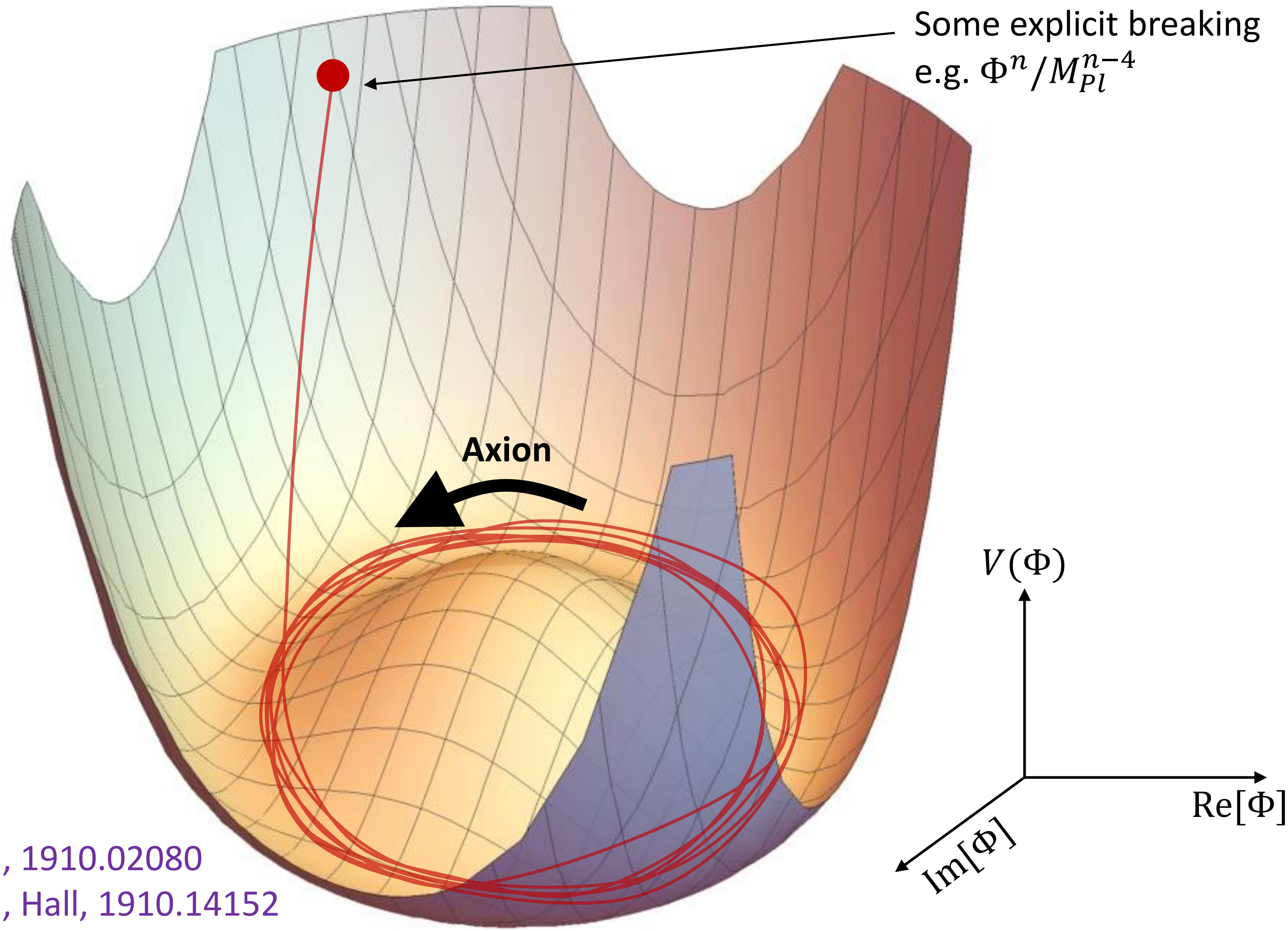

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Potential of PQ breaking field Φ

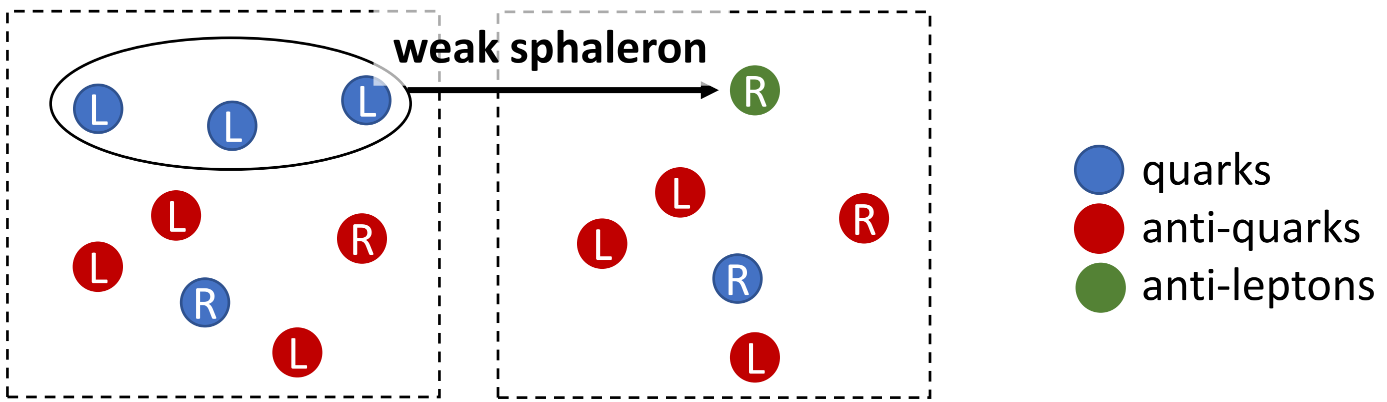
Axiogenesis

Once we have $\dot{a} \neq 0$, baryons and leptons get nonzero chemical potential.

1. Chirality asymmetry is generated by $\dot{a} \neq 0$.

$$\frac{a}{f_a} G\tilde{G} \rightarrow \frac{a}{f_a} \partial_\mu J_A^\mu \rightarrow -\frac{\partial_\mu a}{f_a} J_A^\mu \rightarrow -\frac{\dot{a}}{f_a}(n_L - n_R)$$

2. Weak sphaleron converts only left-handed quarks into (anti-)leptons.



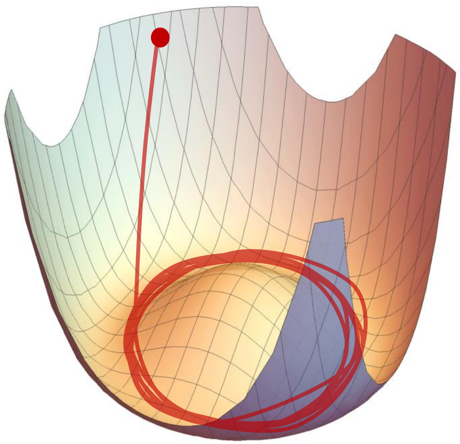
$B = 0, L = 0$
$L_{SM} = 0, L_c = 0$
$\boldsymbol{B - L_{SM} = 0}$

$\boldsymbol{B = -1}, L = -1$
$L_{SM} = 1, L_c = 0$
$\boldsymbol{B - L_{SM} = 0}$

3. $B + L$ asymmetry is generated!

$$n_B \sim \mu_{B+L} T^2 \sim \frac{\dot{a}}{f_a} T^2$$

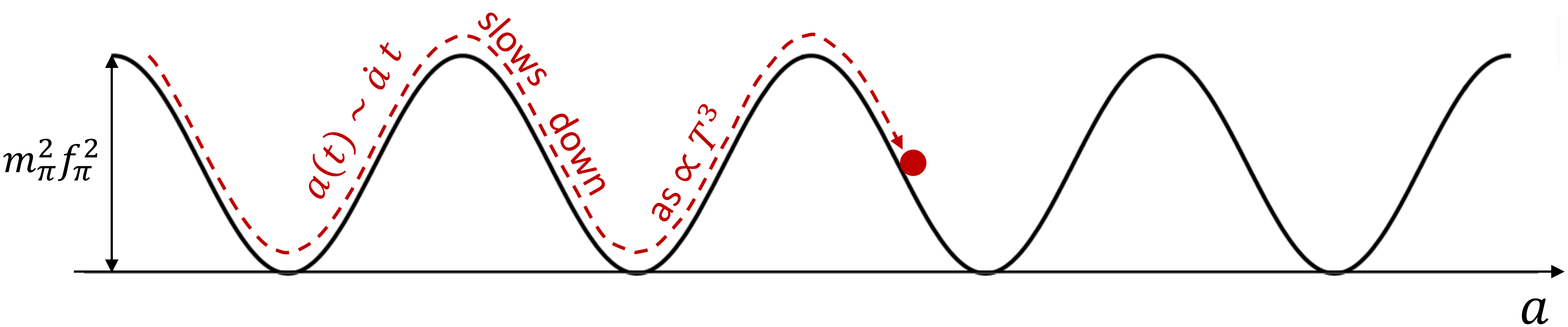
Redshift of the axion motion



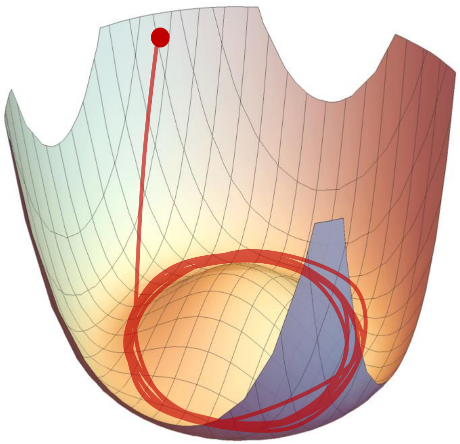
At $T_i \ll f_a$, $\dot{a}(T_i) = \dot{a}_i \neq 0$
PQ charge is approximately conserved, so

$$Y_{PQ} = \frac{n_{PQ}}{s} \simeq \frac{\dot{a}(T) f_a}{s} \simeq \text{const} \;\Rightarrow\; \dot{a}(T) \sim \dot{a}_i \left(\frac{T}{T_i}\right)^3$$

good free parameter



Axion dark matter



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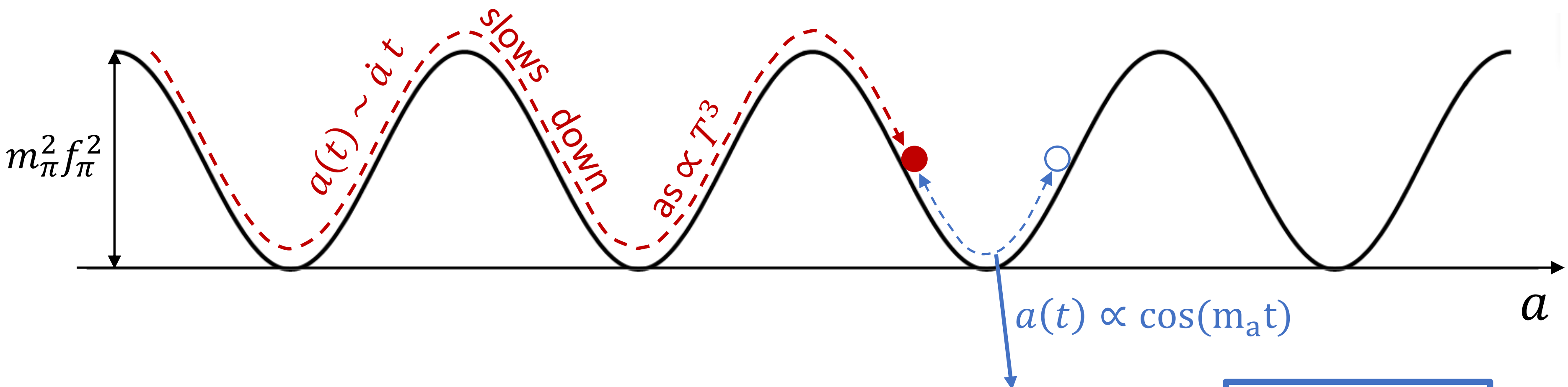


Dark matter $\boldsymbol{\frac{\rho_{DM}}{s} \sim m_a Y_{PQ}}$

$\sim 10^{-10}\mathrm{GeV}$

*Larger abundance compared to the conventional misalignment scenario since we start from nonzero $\dot{a}$.

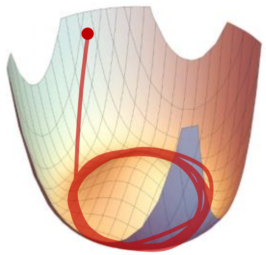
Thermal History

without composite Dirac ν

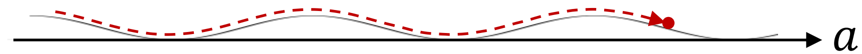
$L = L_{SM}$

T

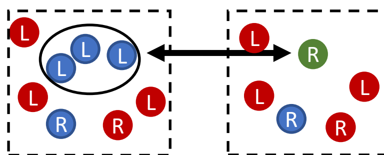
T_i



$\dot{a}_i \neq 0$ is generated



➡ $aG\tilde{G} \sim \dot{a}\, n_{LQ-RQ}$ ➡ $B + L$ asymmetry via weak sphaleron



$$\Rightarrow n_B \sim n_{B+L} \sim n_{PQ} \left(\frac{T}{f_a}\right)^2$$

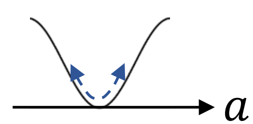
T_{EW}

Weak sphaleron is decoupled: B and L are conserved separately

$$\frac{n_B(T)}{s} \sim Y_{PQ} \left(\frac{T_{EW}}{f_a}\right)^2 \sim 10^{-10}$$

Axion gets trapped by QCD potential and becomes the dark matter

T_{QCD}



$$\frac{\rho_{DM}}{s} \sim m_a Y_{PQ} \sim 10^{-10}\ \mathrm{GeV}$$

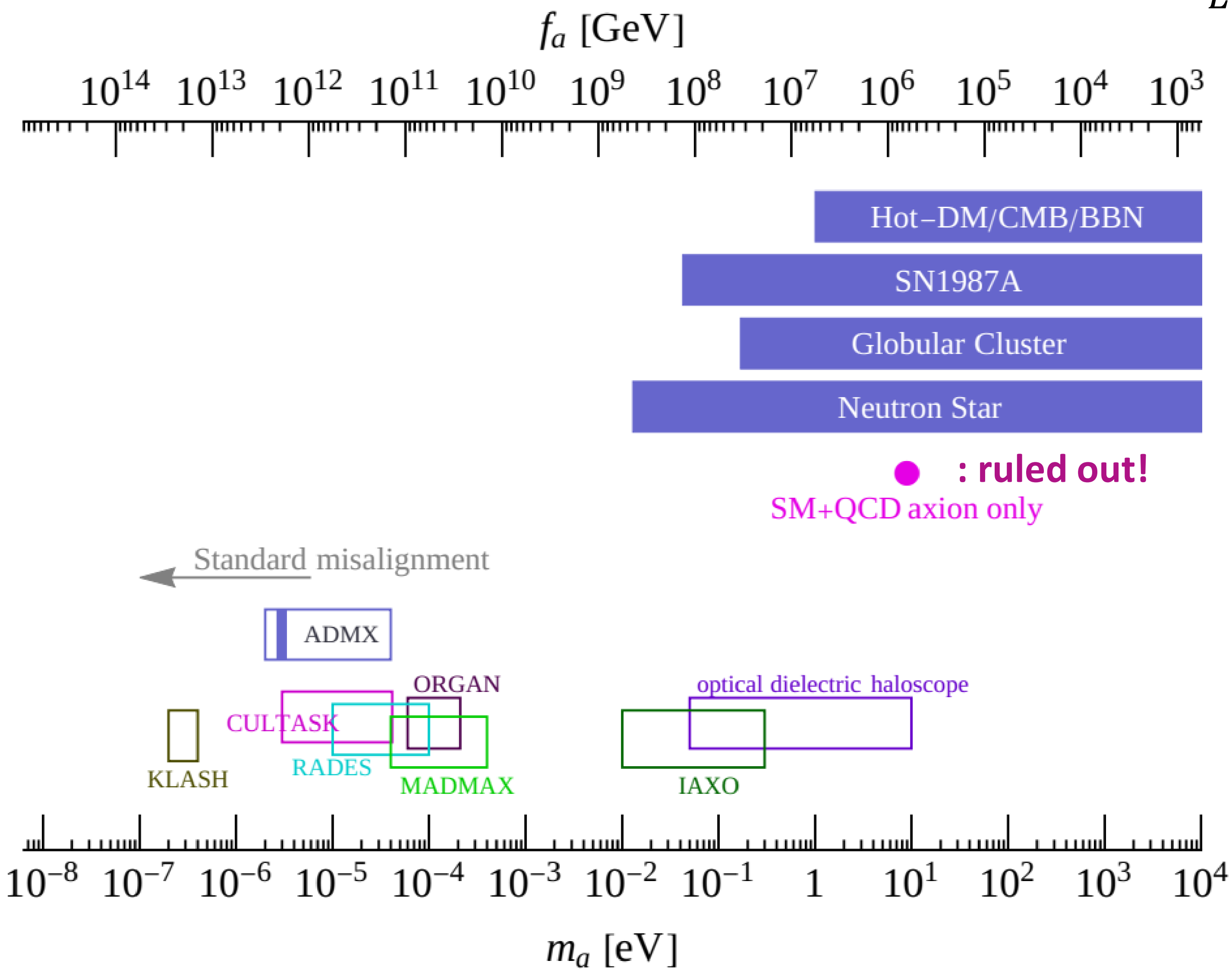
$$m_a \sim m_\pi f_\pi / f_a \sim 10^{-2}\ \mathrm{GeV}^2/\mathrm{f_a}$$

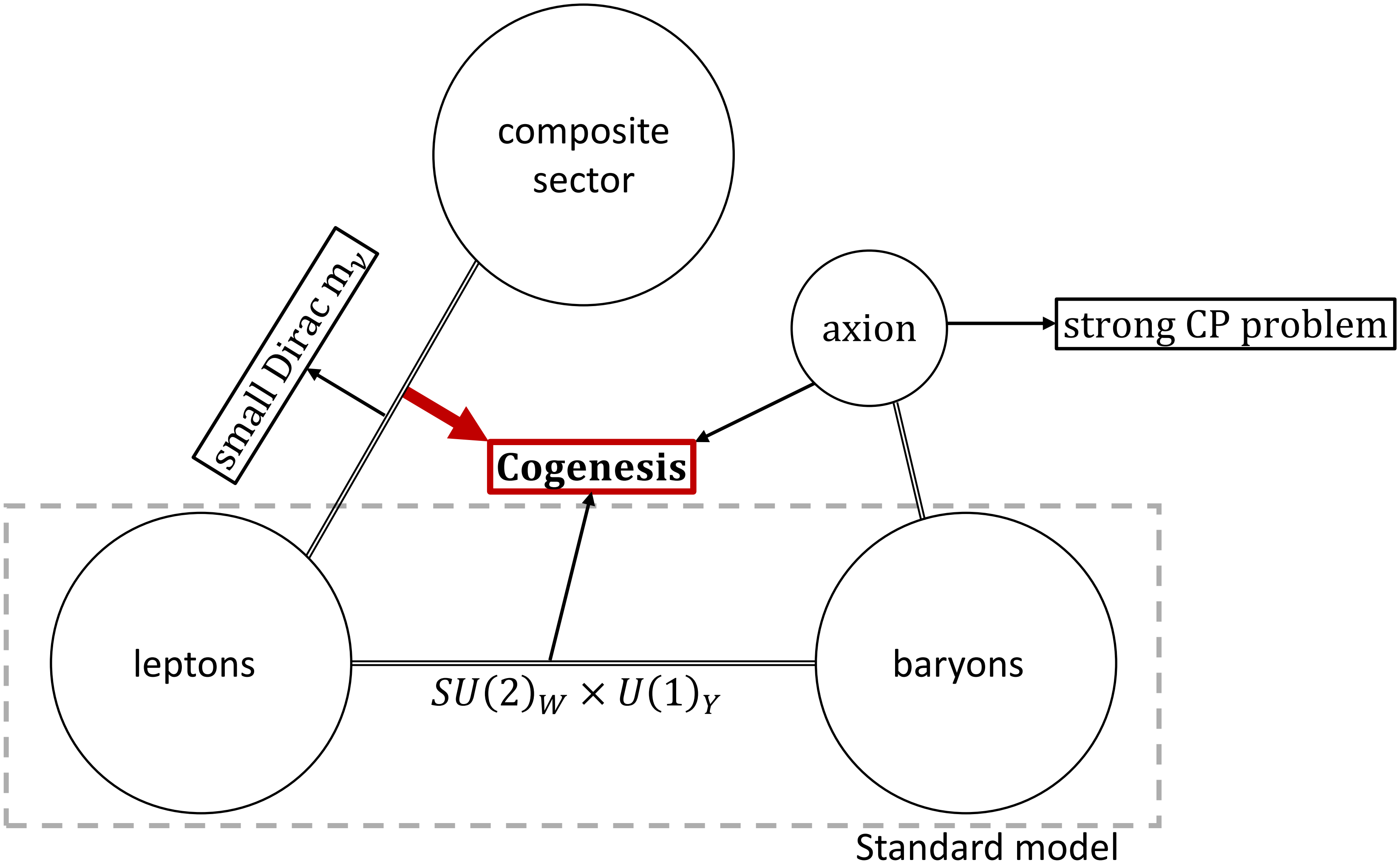
$$f_a \sim 10^6\ \mathrm{GeV}$$

Axiogenesis

without composite Dirac ν

$L = L_{SM}$

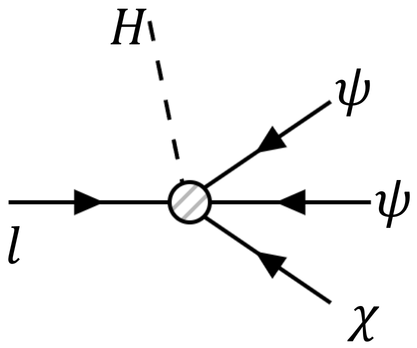



composite sector
small Dirac m_ν
axion
strong CP problem
Cogenesis
leptons
baryons
$SU(2)_W \times U(1)_Y$
Standard model

with composite Dirac ν

$L = L_{SM} + L_c$

	gauge	global	
	SU(6)	$SU(2)_\psi$	$U(1)_L$
ψ	$\bar{\mathbf{6}}$	**2**	$-2/3$
χ	**15**	**1**	$1/3$
$\nu^c \propto \psi\psi\chi$	**1**	**3**	-1



$\frac{1}{M^3} Hl\,(\psi\psi\chi)$

What happens when T is as high as M ?

$L_{SM} \leftrightarrow L_c$ active

with composite Dirac ν

$L = L_{SM} + L_c$

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	SU(6)	$SU(2)_\psi$	$U(1)_L$
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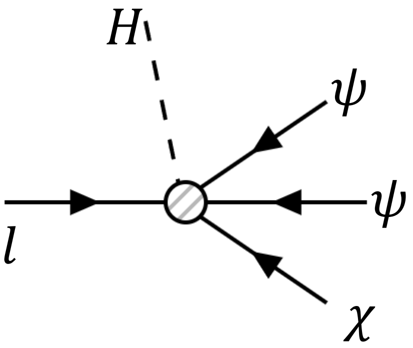


$\frac{1}{M^3} Hl\,(\psi\psi\chi)$

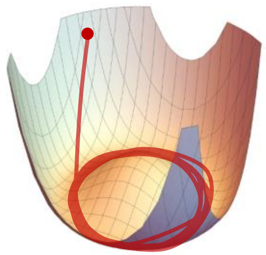
$T > T_{LD} \Rightarrow$ $\boldsymbol{B - L_{SM}}$ **: broken** by $L_{SM} \leftrightarrow L_c$

$T < T_{LD} \Rightarrow$ $\boldsymbol{B - L_{SM}}$: approximately conserved

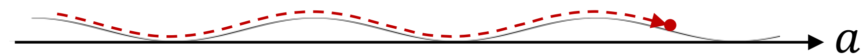
Thermal History with composite Dirac ν

T

T_i



$\dot{a}_i \neq 0$ is generated



$(L_{SM} \leftrightarrow L_c)$ (weak sphaleron)

$$\Rightarrow n_B \sim n_{B-L_{SM}} + n_{B+L_{SM}} \sim \frac{\dot{a}}{f_a} T^2$$

$T_{\rm LD}$

frozen

$$\frac{n_B(T)}{s} \sim \frac{n_{B-L_{SM}}(T_{LD})}{s(T_{LD})} \sim Y_{PQ} \left(\frac{T_{LD}}{f_a}\right)^2 \sim 10^{-10}$$

vs $\frac{n_B(T)}{s} \sim Y_{PQ} \left(\frac{T_{EW}}{f_a}\right)^2$

(without composite ν)

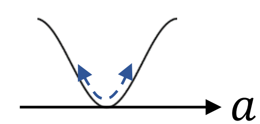
T_{EW}

frozen

$O\left((T_{EW}/T_{LD})^2\right)$ change in final baryon asymmetry, so negligible

T_{QCD}

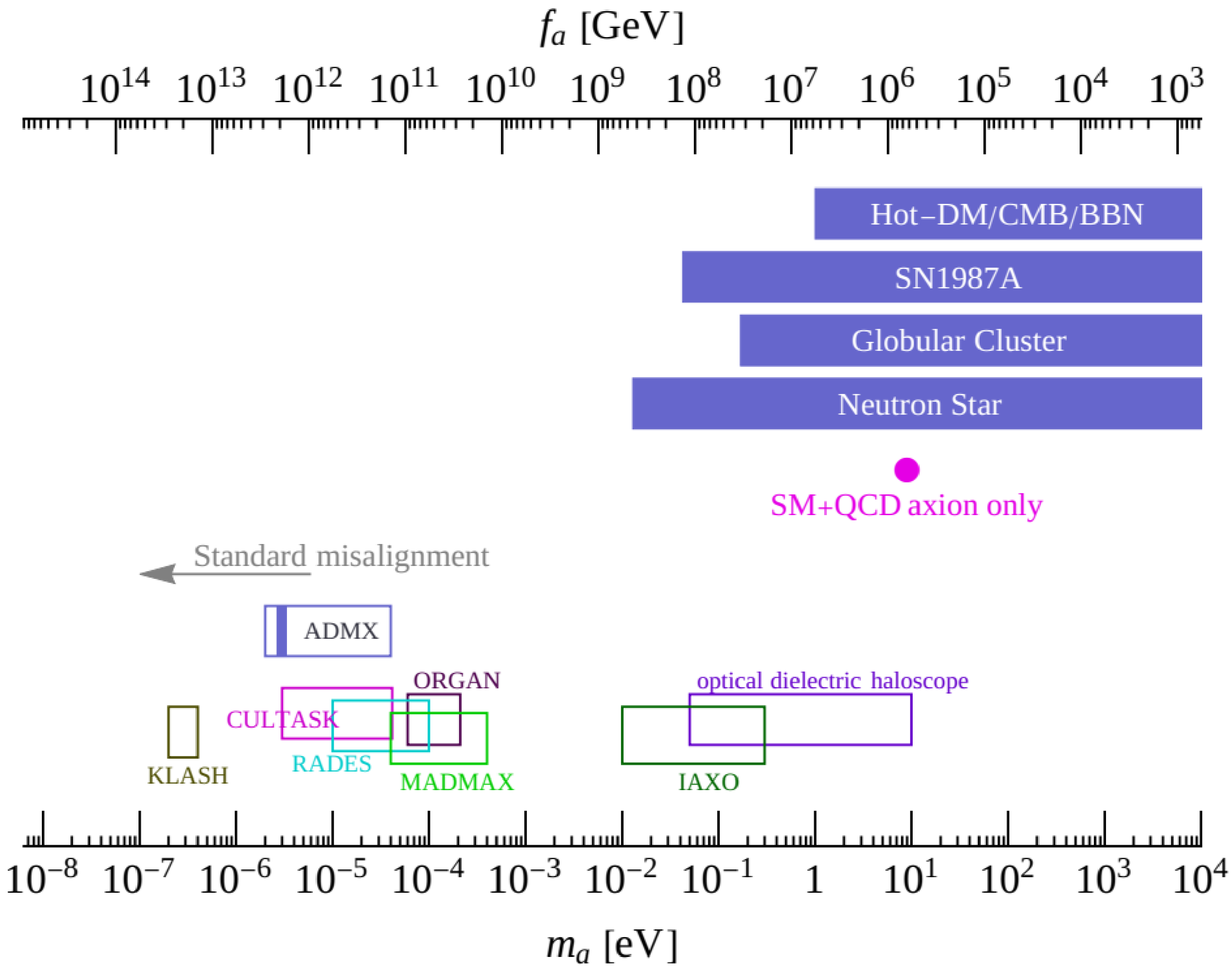
Axion gets trapped by QCD potential and becomes dark matter



$$\frac{\rho_{DM}}{s} \sim m_a Y_{PQ} \sim 10^{-10}\ \text{GeV}$$

$m_a \sim m_\pi f_\pi / f_a$

Baryogenesis with composite Dirac ν



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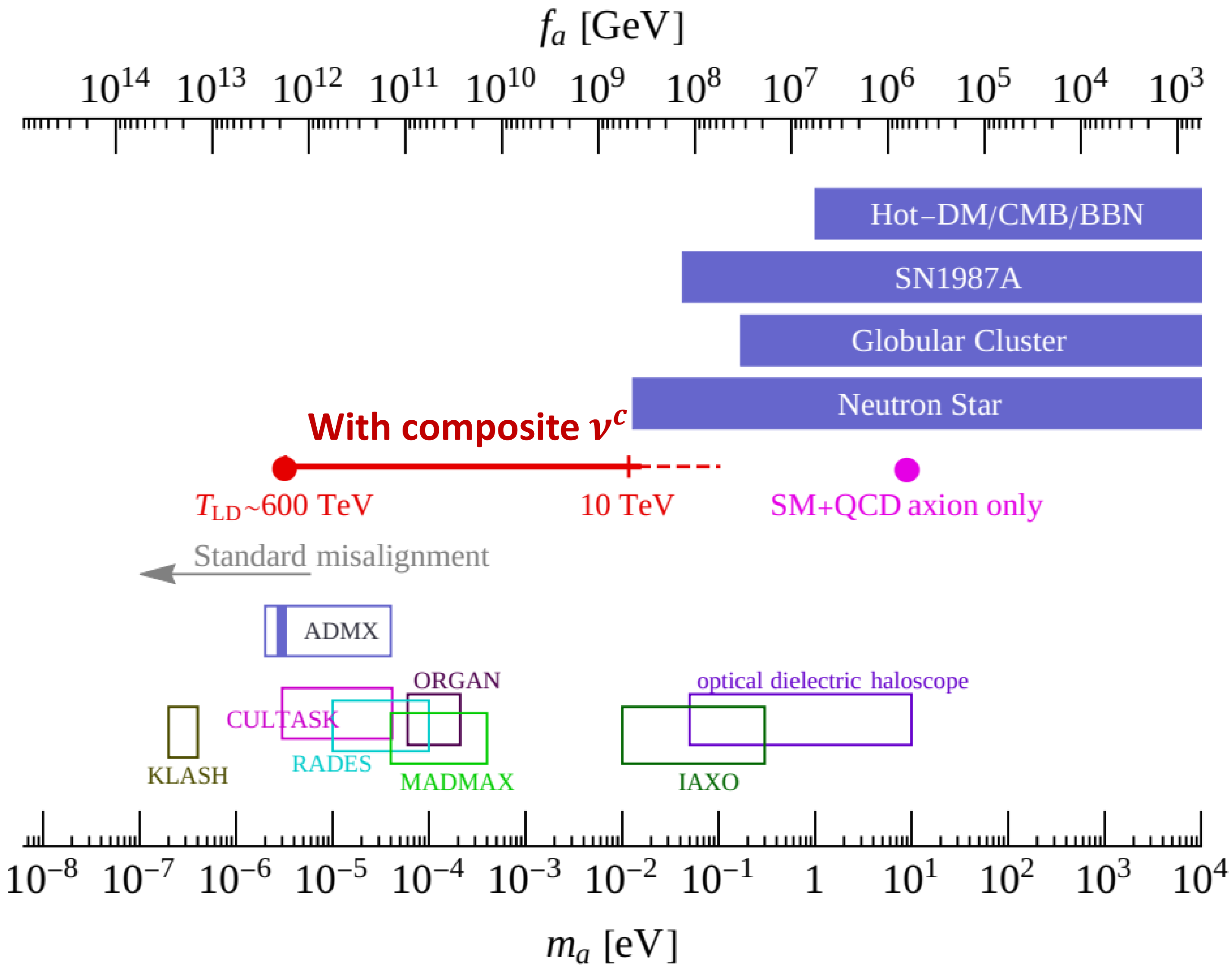

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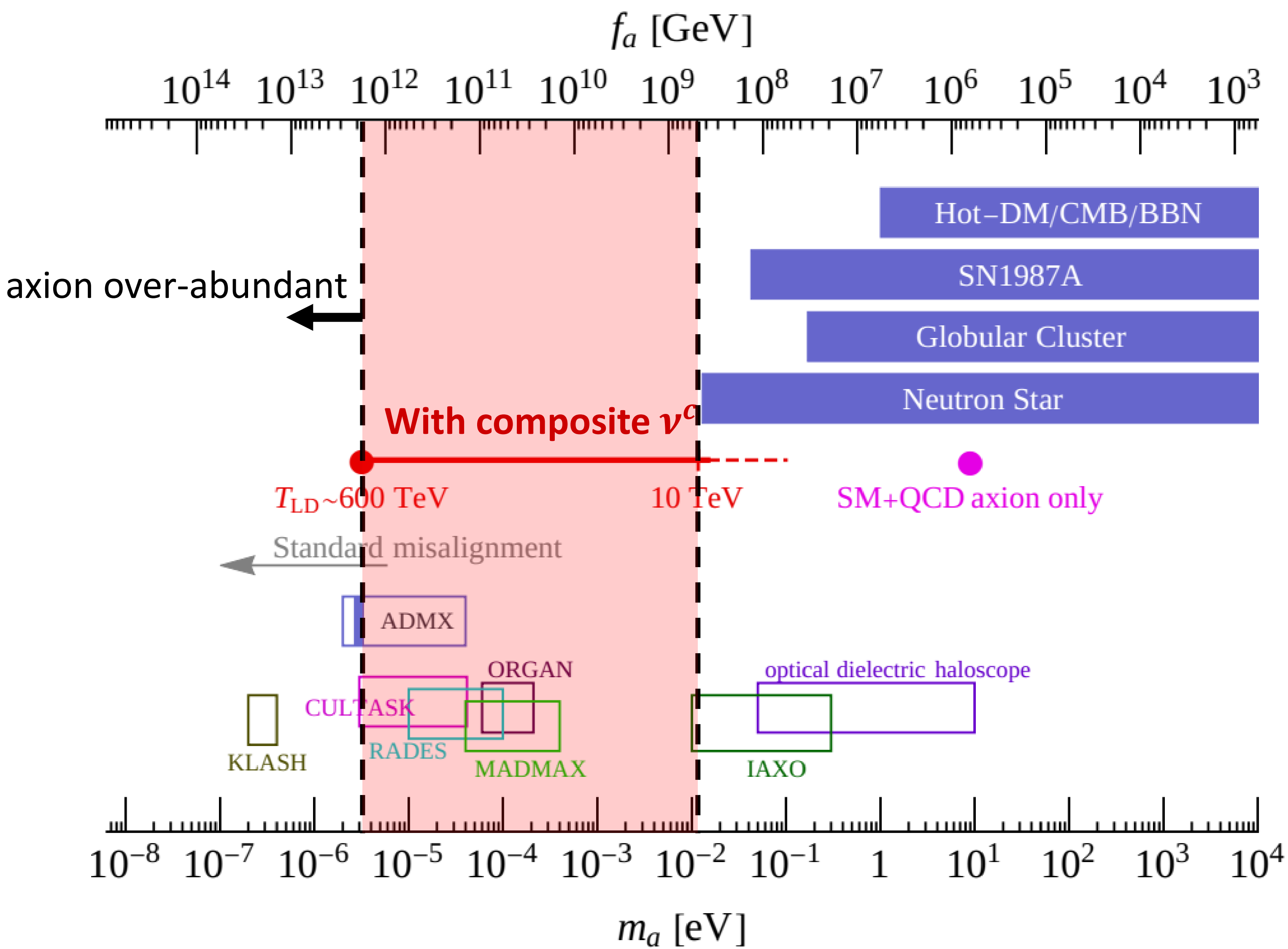


Other prediction?

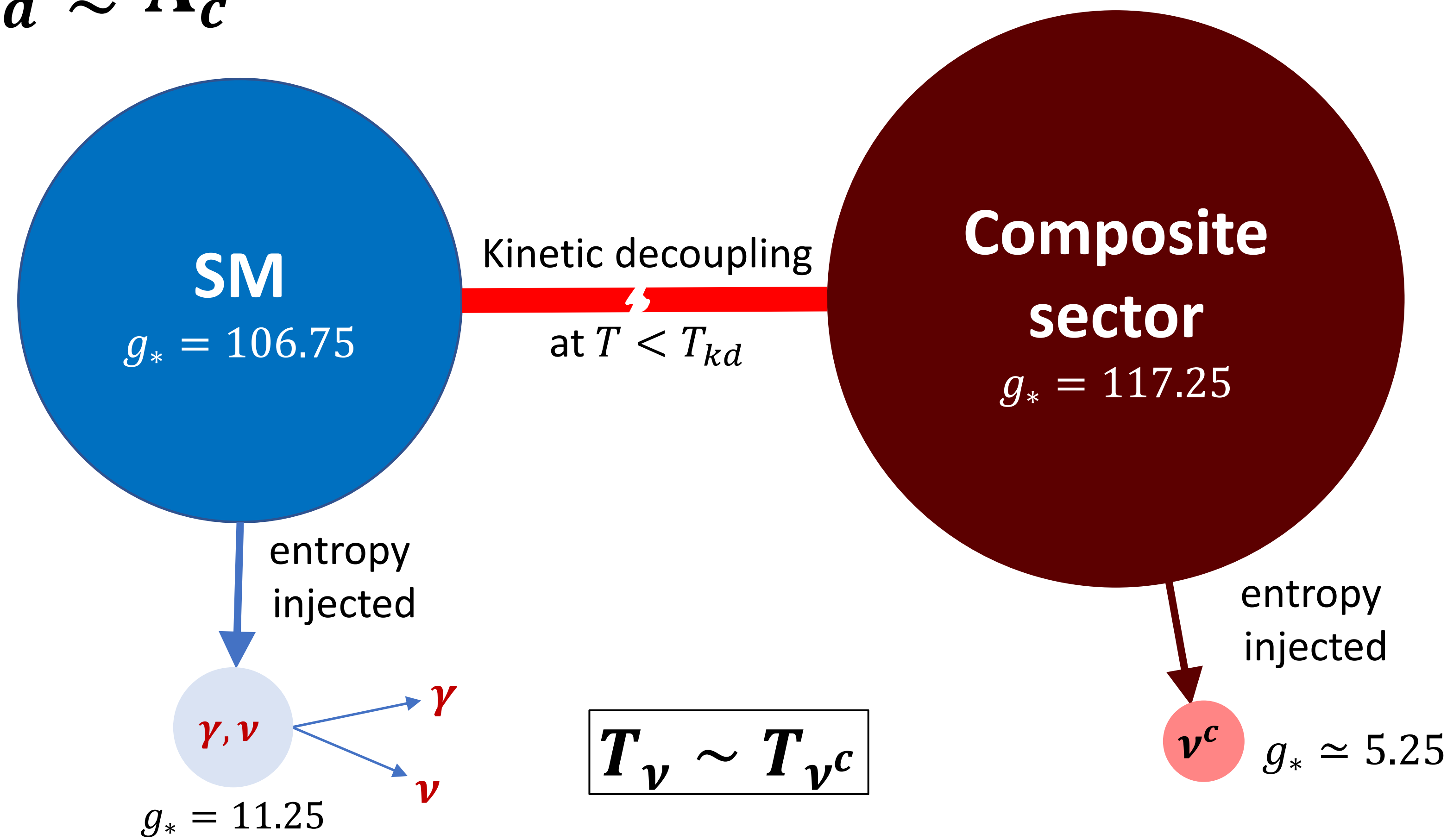
For baryogenesis, the composite sector should be in chemical equilibrium with SM at high temperature. $\Rightarrow$ **Many RH neutrinos in the end?**

$\Delta N_{\text{eff}} =$ additional relativistic abundance
normalized by one generation of SM neutrino

$\boldsymbol{\Delta \mathrm{N}_{\mathrm{eff}} < 0.33}$ **from CMB** at 2σ

ΔN_{eff}

If $T_{kd} \gtrsim \Lambda_c$

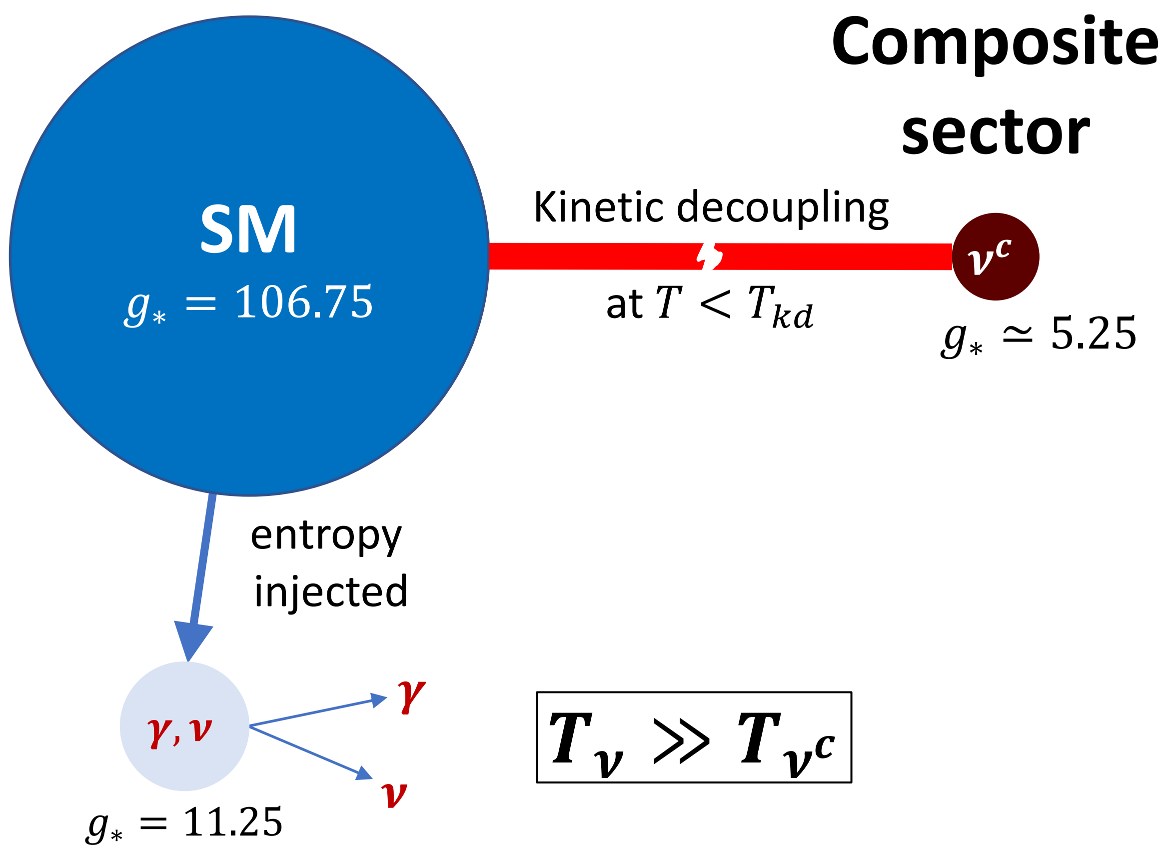


$$\Delta N_{eff} \simeq 8.8$$

ruled out!

$\Delta N_{\rm eff}$

If $T_{kd} \ll \Lambda_c$

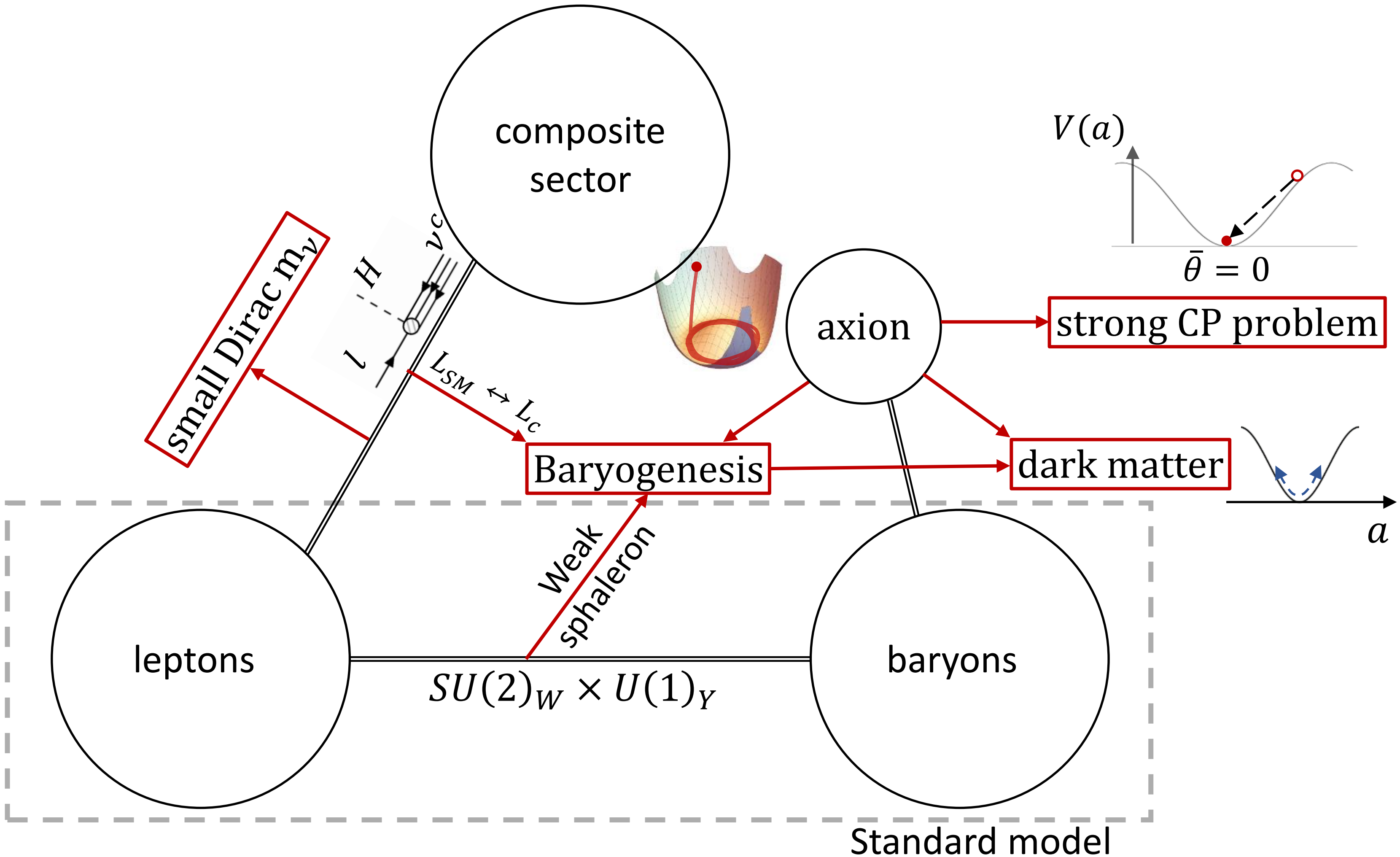


$$\Delta N_{\rm eff} \gtrsim 0.14$$

Not ruled out,
and testable in future

CMB stage IV: $\Delta N_{\rm eff} < 0.03$

Summary


composite sector
axion
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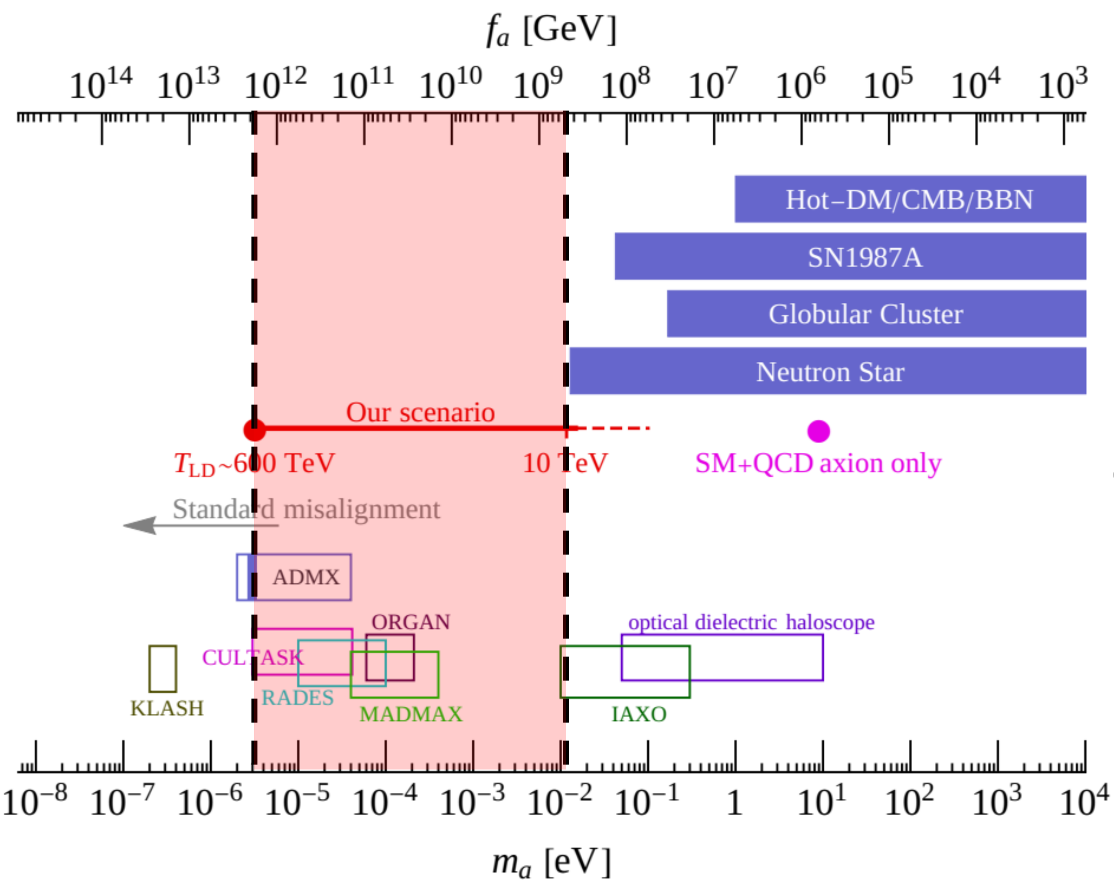
Standard model
small Dirac m_ν
strong CP problem
Baryogenesis
dark matter
Weak sphaleron
$SU(2)_W \times U(1)_Y$
$L_{SM} \leftrightarrow L_c$
H
ν^c
l
$V(a)$
$\bar{\theta} = 0$
a

Summary



& $\boxed{\Delta N_{\mathrm{eff}} \gtrsim 0.14}$