Neutrino Masses without High Scales

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Based on work with: R. Kitano, G. Kribs, and H. Murayama.

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SM:

- Effective field theory, cutoff scale Λ.

- Global (not gauged) symmetries broken at Λ.

- Protect $(B,\, L) \Rightarrow$ Large Λ.

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- Global (not gauged) symmetries broken at Λ.
- Protect $(B, L) \Rightarrow$ Large Λ.

(i) $\tau_p \gtrsim 10^{33}$ *years* $\rightarrow \Lambda \gtrsim 10^{16}$ *GeV* $\quad (\not{B})$

(ii) $m_\nu \lesssim 0.1$ *eV* $\rightarrow \Lambda \gtrsim 10^{14}$ *GeV* $\quad (\not{L})$

Often assumed: $\underset{M_{GUT}}{10^{16}\ \mathit{GeV}} \lesssim \Lambda \lesssim \underset{\bar{M}_P}{10^{18}\ \mathit{GeV}}$

- Quantum Filed Theory, SM probed up to $\sqrt{s} \lesssim 1$ TeV.

$\Lambda \lesssim \bar{M}_P$ a big leap. Lower Λ could resolve hierarchy.

Arkani-Hamed, Dimopoulos, Dvali (1998)
Randall, Sundrum (1999)

- Lowering Λ:

$(B, L) \Rightarrow$ Gauged (anomaly free) symmetries.

Small $m_\nu \neq 0$ from symmetry breaking.

- How low can Λ be?

We consider various bounds on $\Lambda \gtrsim 1$ TeV:

Precision EW, Astrophysics, Cosmology, ...

Protecting (B, L)

- Quarks: Z_A^q ; Leptons: Z_B^ℓ.

Higgs uncharged under $Z_A^q \times Z_B^\ell$ (IR symmetries).

- Anomaly cancellation:

$9a = 0$, mod A $SU(2)$

$3b = 0$, mod B $SU(2)$, gravity

	Q	u^c	d^c	L	e^c
Z_A^q	a	$-a$	$-a$	0	0
Z_B^ℓ	0	0	0	b	$-b$

Choose (a, b) = (1, 1); $Z_9^q \times Z_3^\ell$.

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$\not{B}$, $\not{L}$: $\quad O \sim Q^9 L^3/\Lambda^{14}$

Multi-nucleon $\tau > \tau_p \Rightarrow \Lambda \gtrsim 200$ *GeV.*

Majorana Neutrinos

- $m_\nu \, \nu_L \nu_L \quad \rightarrow \not{Z}_3^\ell$ *spontaneously.*

- Scalar χ , $Z_3^\ell(\chi) = +1$, $\langle\chi\rangle \neq 0$:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + c\,\chi(LH)^2/\Lambda^2 + \ldots, \qquad (c \sim 1)$$

$$\langle H\rangle = v \rightarrow y_\chi \, \chi \, \nu \, \nu \quad ; \quad y_\chi \equiv c(v/\Lambda)^2.$$

- Important Constraint: $0\nu\beta\beta \oplus \chi \rightarrow y_\chi < 3 \times 10^{-5} \Rightarrow \Lambda > 30$ TeV.

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$$m_\nu = y_\chi \langle\chi\rangle = c\,(0.06\text{ eV}) \left(\frac{\langle\chi\rangle}{2\text{ keV}}\right) \left(\frac{30\text{ TeV}}{\Lambda}\right)^2$$

$[\Delta m^2_{\mathrm{atm}} \simeq (0.06)^2\,\mathrm{eV}^2]$

Phenomenology

- *Discrete Symmetry Breaking $\rightarrow$ Domain Walls:*

$\Delta T/T \lesssim 10^{-5}$:

$\langle\chi\rangle^3 \lesssim (400 \text{ keV})^3 \quad \Rightarrow \quad \Lambda \lesssim 400$ TeV.

Frustrated Network: Dark Energy; $w = -2/3$.

- *BBN:*

$m_\nu \gtrsim 10^{-4}$ eV, $T_{BBN} \sim 1$ MeV: $\quad \Gamma \sim y_\chi^2 m_\chi^2/(16\pi T) \sim m_\nu^2/(16\pi T) \gtrsim T^2/M_P$

$\Rightarrow \quad \nu\nu \leftrightarrow \chi$, $\nu\nu \leftrightarrow \chi\chi \ldots$

$\Rightarrow \quad \Delta N_\nu = 8/7 \quad [L(\nu_e) \sim 0.1$, small χ self-coupling].

- *CMB:*

Neutrinos's free stream at decoupling, $T \sim 1$ eV.

Acoustic peaks shifted: $\Delta l_k = -29.3$; $\Delta l_k|_{SM} = -23.3$ (*Planck Experiment*).

Chacko et al. (2003)

- *Supernova:*

$m_\chi \sim \langle\chi\rangle \lesssim 1$ MeV; $T_{SN} \sim 30$ MeV: $\Gamma(\nu_L\nu_L \to \chi\chi) \sim y_\chi^2 T \sim (10^{-12}\,\mathrm{s})^{-1}$

$\delta t(\mathrm{cooling}) \sim 1$ s

$\Rightarrow \chi$'s thermal inside ν-sphere: $\langle\chi\rangle = 0$ and $m_\nu = 0$.

Z_3^ℓ (1^{st} order) phase transition: $E_\nu \sim \langle\chi\rangle \lesssim 1$ MeV ν-flash!

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May help eject the envelope in simulations (work in progress with P. Huber).

Dirac Neutrinos

- Introduce ν_R^i, $i = 1, 2, \ldots, n_R$; $Z_9^q \times Z_3^\ell$ *exact*.
- Forbid $HL\nu_R$ with new gauged symmetries.
- Generate small m_ν from symmetry breaking.

(I) Discrete Gauge Symmetries:

$$\mathcal{L}^R = \lambda^{\alpha i} \left(\frac{H_R}{\Lambda}\right)^n (HL^\alpha)\nu_R^i$$

$$\Rightarrow \langle H_R \rangle \sim 10^{3-\frac{12}{n}} \mathrm{GeV} \left(\frac{\Lambda}{1\ \mathrm{TeV}}\right)$$

	ν_R^1	ν_R^2	ν_R^3	H_R
Z_{3n}^R	n	n	n	-1
Z_3^ℓ	-1	-1	-1	0

BBN:

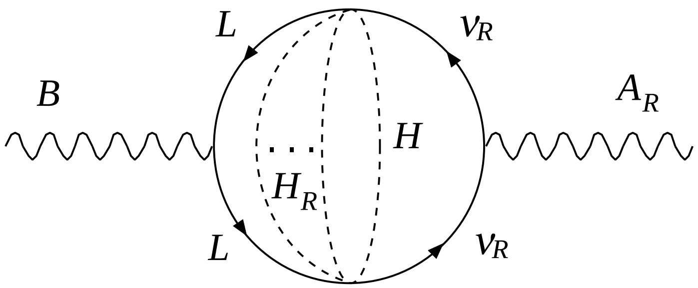
$\nu_L \bar{\nu}_L \to \nu_R \bar{\nu}_R, \ldots \Rightarrow \langle H_R \rangle \gg 1$ MeV (domain walls), unless $\Lambda \gtrsim 10^8$ GeV (hierarchic).

(II) A New U(1) Symmetry:

- ν_R^i charged under U(1)$_R$: $Q = (q_1, \cdots, q_{n_R})$.
- Anomaly free: $\sum_i q_i = 0 \quad ; \quad \sum_i q_i^3 = 0$.

	ν_R^1	ν_R^2	ν_R^3	ν_R^4
Q_R	$+1$	-1	$+1$	-1
Z_3^ℓ	-1	-1	-1	0

- $\mathcal{L}^R = \lambda^{\alpha i} \left(\frac{H_R^{(*)}}{\Lambda} \right)^n (H L^\alpha) \nu_R^i$: $Q(H_R) = -1/n$.
- Dirac $m_\nu \simeq 0.1$ eV: $\langle H_R \rangle \sim m_A / g_R \gtrsim 1$ eV (Short range force).
- U(1)$_Y$–U(1)$_R$ *kinetic mixing:*



$\mathcal{L}^A = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} + F^R_{\mu\nu}F^{R\mu\nu} - 2\,\varepsilon F_{\mu\nu}F^{R\mu\nu}) \quad ; \quad \varepsilon \ll 1$

Diagonalized: $Q_f\,\bar\psi \not{A} \psi \to Q_f\,\bar\psi \not{A} \psi + \varepsilon\, Q_f\,\bar\psi \not{A}_R \psi$.

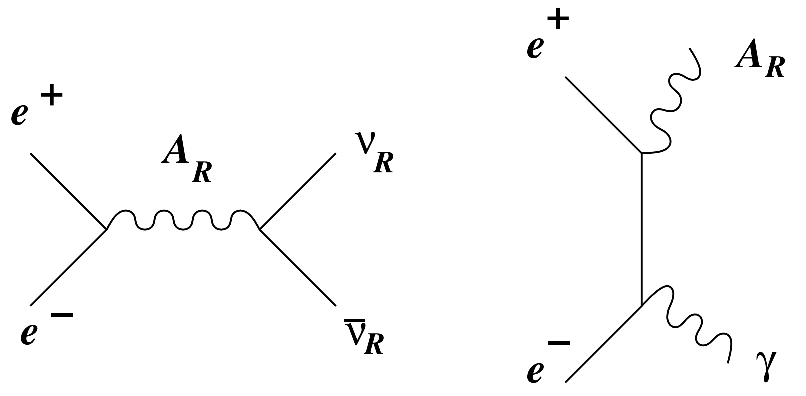
$\varepsilon(\Lambda) = 0 \quad ; \quad \varepsilon_{rad} \sim g_Y g_R / (16\pi^2)^{2+n}$

Phenomenology

- $(g-2)_e$: $\varepsilon^2\alpha/(4\pi) \lesssim 10^{-12} \quad \Rightarrow \quad \varepsilon \lesssim 3\times 10^{-5}$.

- *BBN* $(N_\nu^{eff} < 4)$:

$e^+e^- \to \nu_R\bar{\nu}_R\,,\ e^+e^- \to \gamma A_R\,,\ \ldots$ *constrained.*



- *Astrophysics:*

Red Giant *and* *Supernova* *<u>axion</u>* *bounds:* $g_{aee}^{RG} < 2.5\times 10^{-13}$; $g_{aNN}^{SN} < 3\times 10^{-10}$.

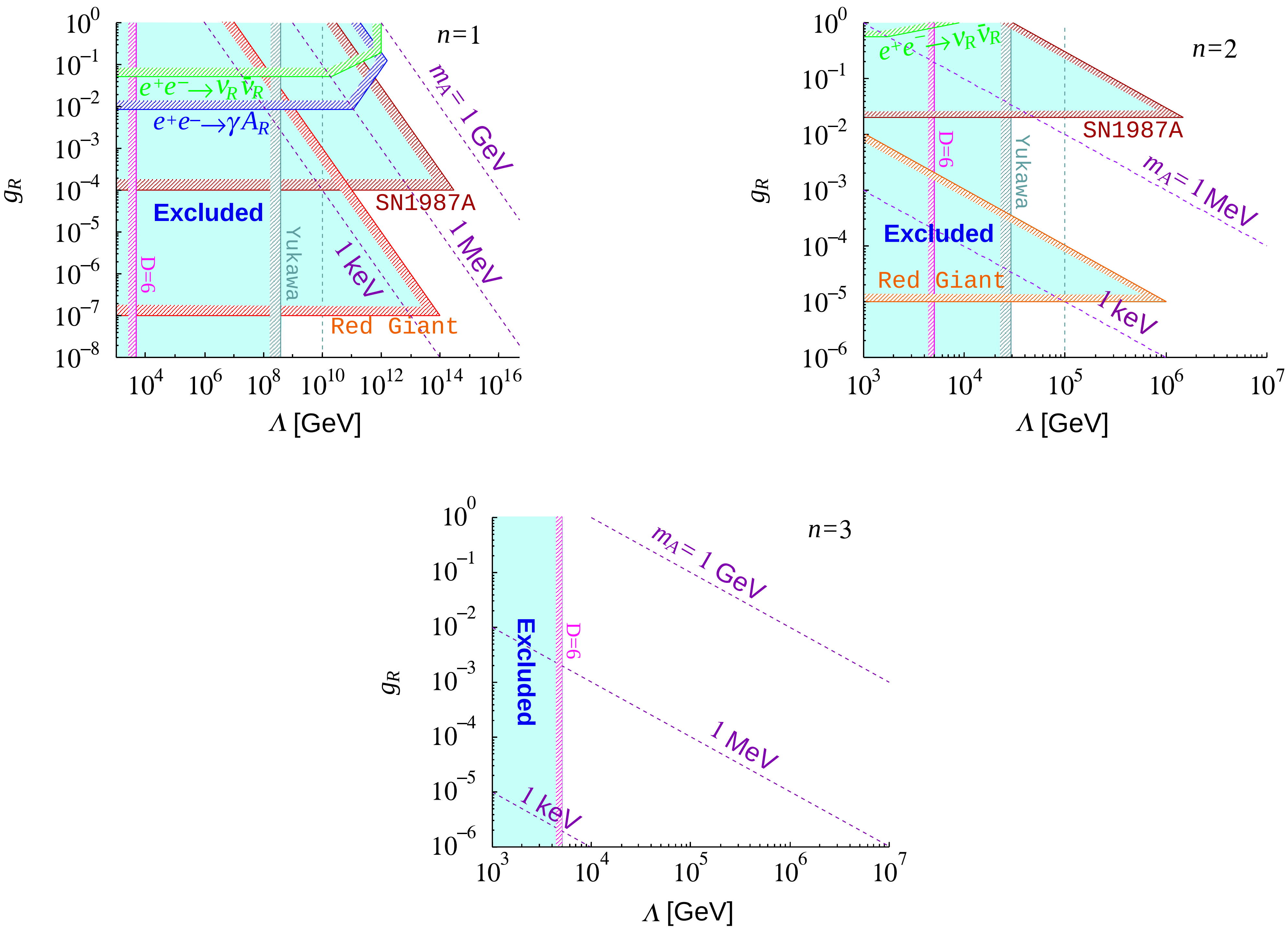
Raffelt, Weiss (1994)
PDG 2004

A_R *coupling enhanced by* $m_f/T_{\rm star} \sim O(10)$.

Constrain $\varepsilon_{rad}(n, g_R)$ unless $m_A(n, g_R, \Lambda) > T_{\rm star}$:

$n=1:\quad g_R \lesssim 10^{-7} \quad$ or $\quad g_R\Lambda \gtrsim 10^7\,$GeV
$n=2:\quad g_R \lesssim 10^{-5} \quad$ or $\quad g_R\Lambda \gtrsim 10\,$GeV (RG)

$n=1:\quad g_R \lesssim 10^{-4} \quad$ or $\quad g_R\Lambda \gtrsim 10^{11}\,$GeV
$n=2:\quad g_R \lesssim 0.02 \quad$ or $\quad g_R\Lambda \gtrsim 50\,$TeV (SN)



n=1
n=2
n=3
g_R
Λ [GeV]
m_A= 1 GeV
1 MeV
1 keV
$e^+e^- \to \nu_R \bar{\nu}_R$
$e^+e^- \to \gamma A_R$
SN1987A
Red Giant
Excluded
Yukawa
D=6

Concluding Remarks

- Lowering the cutoff scale Λ:

$Z_9^q \times Z_3^\ell$ to protect B and L.

- Small $m_\nu \neq 0$:

Spontaneous IR (sub-GeV) symmetry breaking.

- Majorana m_ν from $\not{Z}_3^\ell$:

Domain walls: $\Lambda \lesssim 400$ TeV, $0\nu\beta\beta \oplus \chi$, $\Delta N_\nu^{BBN} \simeq 1$, Supernova ν-flash.

- Dirac m_ν via dim$-d$ operators:

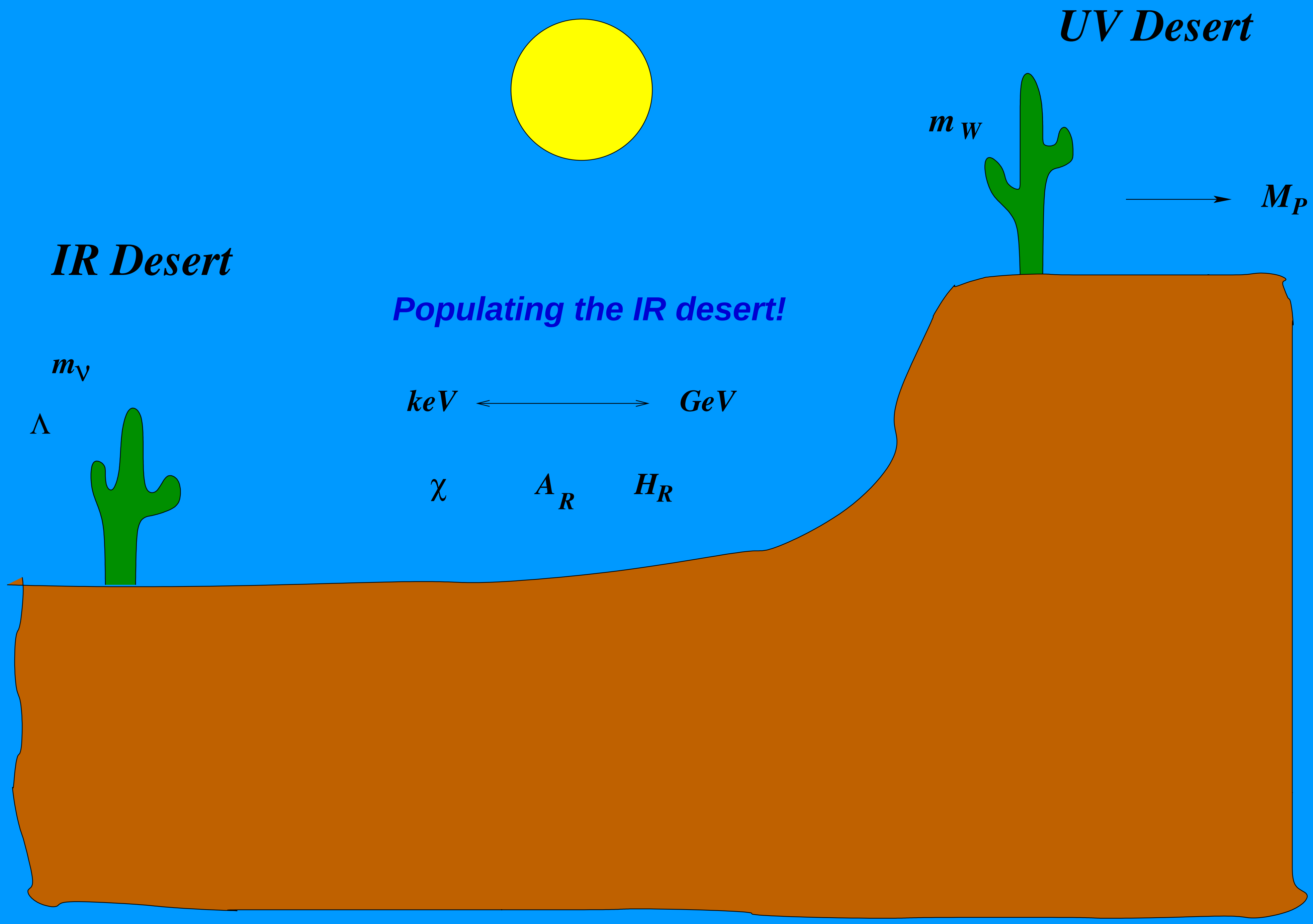
(i) Discrete symmetry: BBN $\rightarrow$ Domain wall problem unless $\Lambda \gtrsim 10^8$ GeV (hierarchic).

(ii) U(1)$_R$ broken by $\langle H_R \rangle \neq 0$: Light (H_R, A_R), ν_R, U(1) kinetic mixing.

$\Rightarrow$ *BBN and astrophysical overcooling constraints: $d = 5, 6, 7 \rightarrow \Lambda \gtrsim 10^9, 50, 5$ TeV.*

- Stabilizing $\langle \chi \rangle$, $\langle H_R \rangle$:

Supersymmetry with sequestering; technicolor ($m_A \sim 10$ GeV).


UV Desert
m_W
M_P
IR Desert
Populating the IR desert!
m_ν
Λ
keV
GeV
χ
A_R
H_R