Axiogenesis from $SU(2)_R$ phase transition

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arXiv: 2107.09679, doi:10.1007/JHEP10(2021)022

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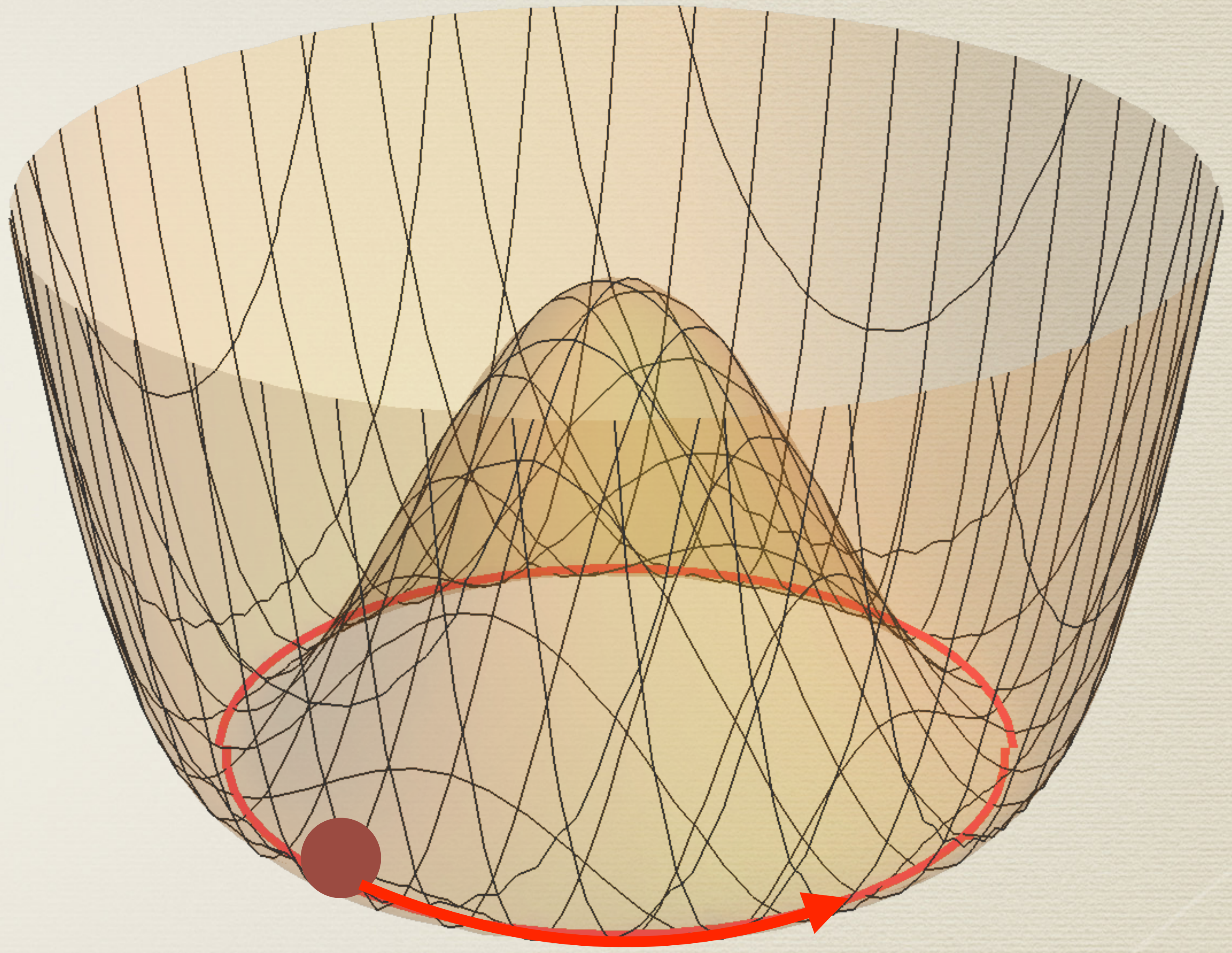
Unsolved Problems in Particle Physics

- Strong CP problem
- Dark matter problem
- Baryogenesis problem
- Neutrino mass problem

Axion

New Dynamics:
Axion rotations

$SU(2)_R$



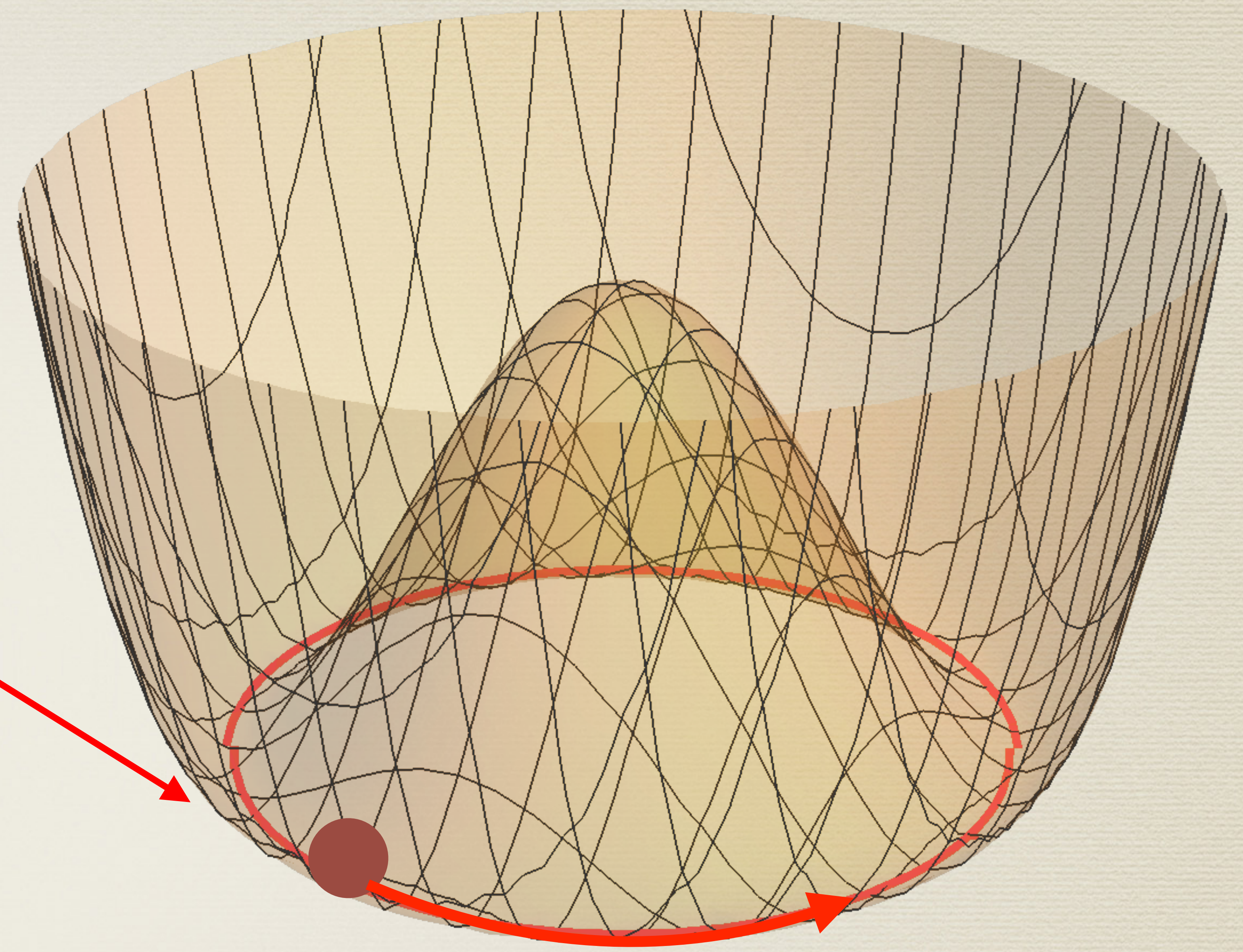
And other frontier problems!

Leads to relationships
between W' boson mass and f_a

Axion Rotations

$$P = \frac{1}{\sqrt{2}}(f_a + \ S\ )\exp(i\frac{a}{f_a})$$

axion



Noether's charge:

$$n_{PQ} = iP\dot{P}^* - iP^*\dot{P} = \dot{\theta}f_a^2,\ \theta \equiv \frac{a}{f_a}$$

Complex field P can be rotating!

Initial velocity $\dot{\theta}$?
Charge transfer?

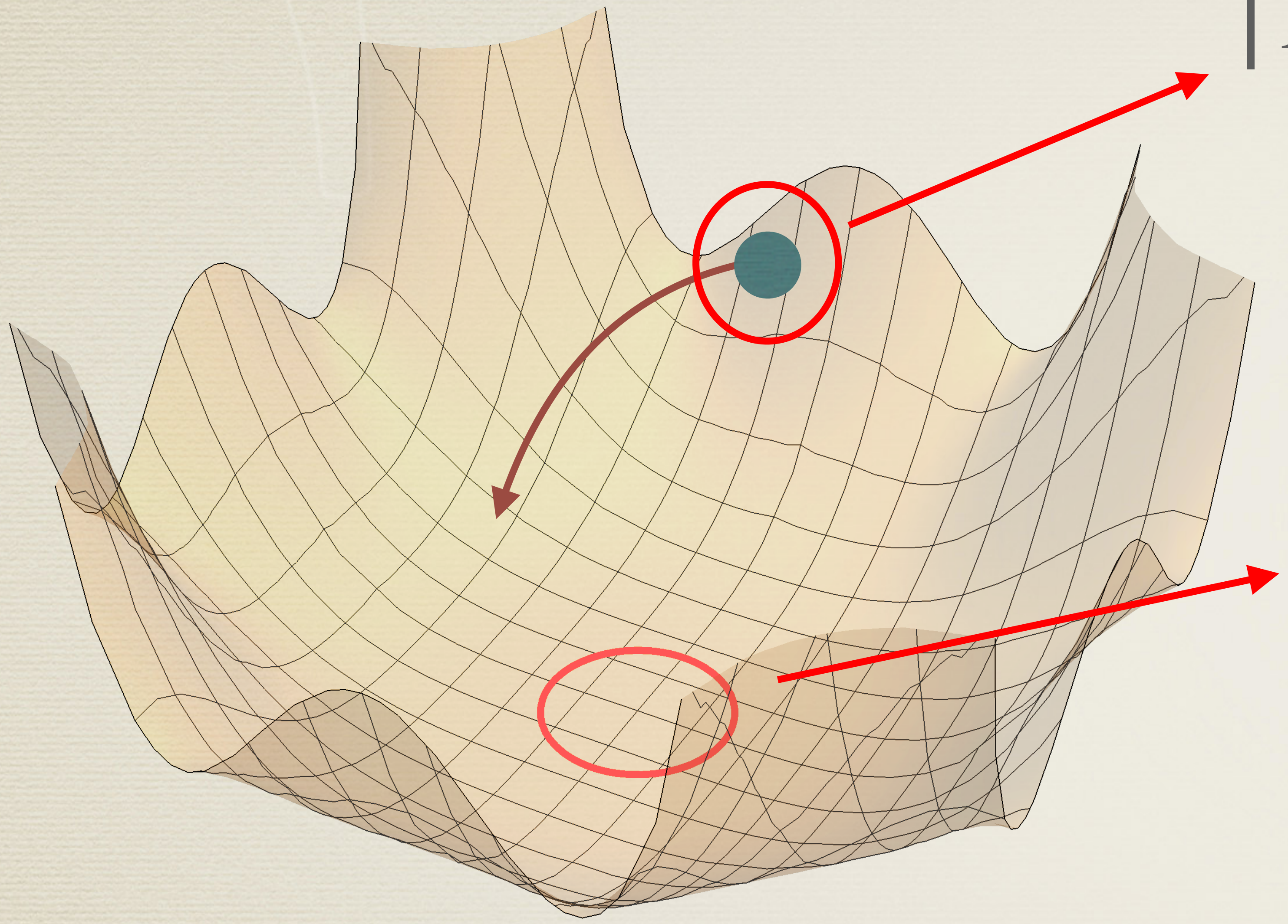
$U(1)$ symmetry in potential:
Peccei-Quinn (PQ) symmetry

R.Co, K.Harigaya: 1910.02080

Axiogenesis

Initial velocity

$|P| \simeq S \gg f_a$
at initial

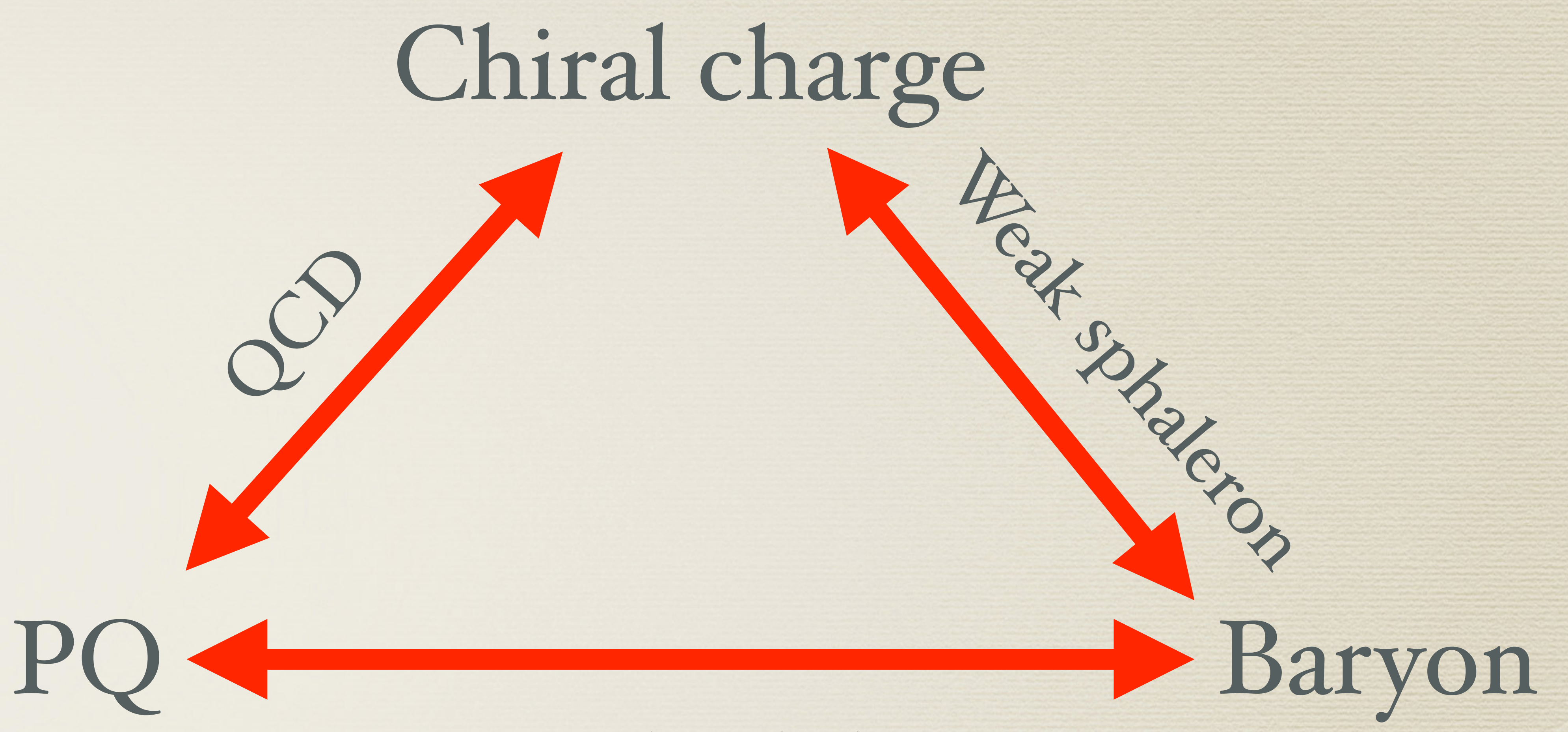


Potential is flat at small field value when temperature is high

Explicit PQ breaking via $V \simeq P^n$ can be effective in early time

$$\frac{\partial V}{\partial \theta} \neq 0$$

Charge transfer



Or: Weak sphaleron

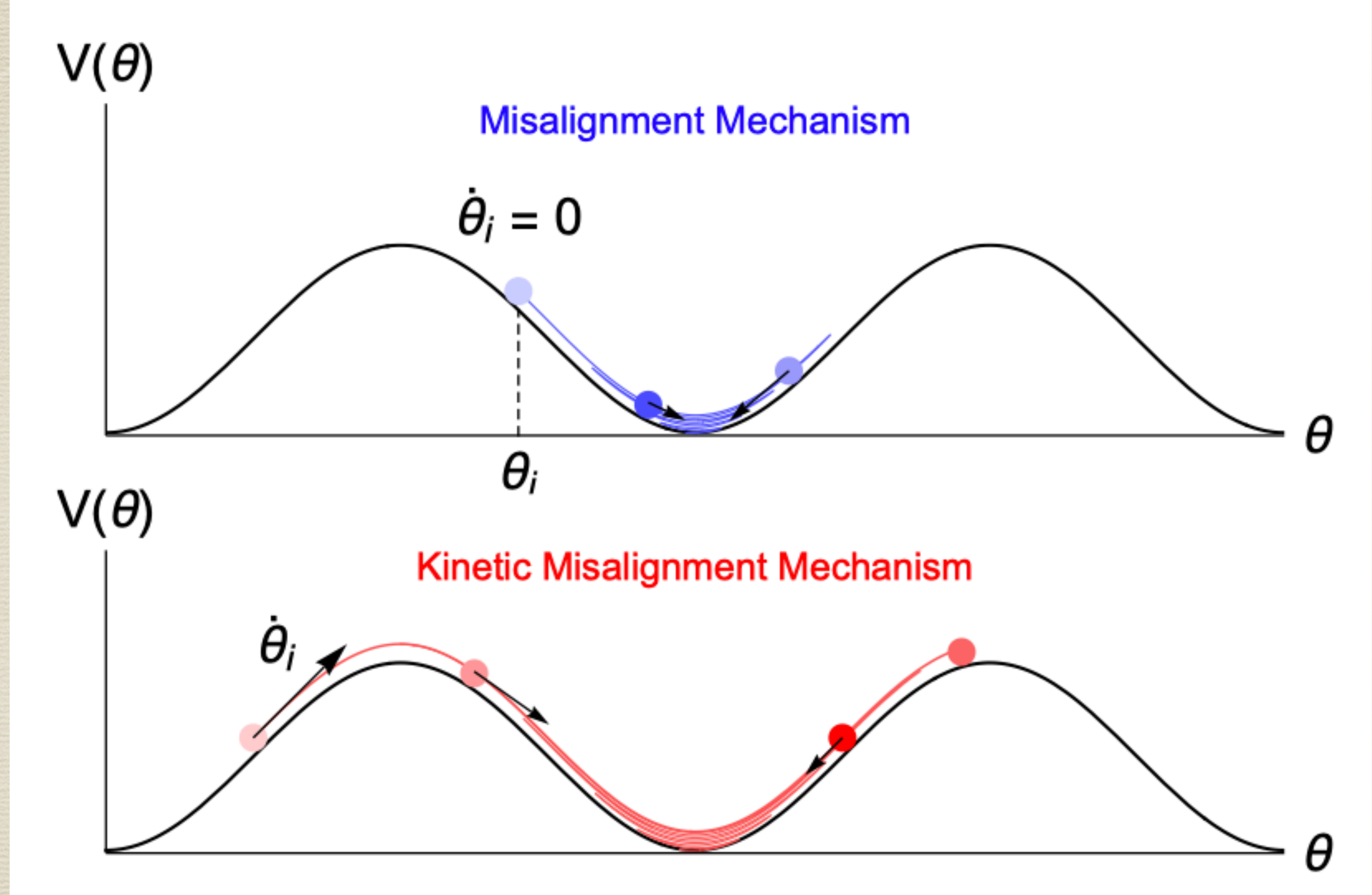
$$n_B = c_B \dot{\theta} T^2, Y_B = 2 \times 10^{-3} \left(\frac{c_B}{0.1} \right) \frac{\dot{\theta}(T_{ws})}{T_{ws}}$$

T_{ws}: weak sphaleron decoupling temperature

R.Co, K.Harigaya: 1910.02080

Similar to Affleck-Dine: I.Affleck & M.Dine: Nucl.Phys.B 249 (1985) 361-380
M.Dine, L.Randall & S.Thomas: hep-ph/9507453

Dark Matter: Kinetic Misalignment



Kinetic energy is now larger than the potential energy at the conventional oscillation temperature T_*

The motion becomes oscillation when the kinetic energy is smaller than the potential barrier at T'

$$\dot{\theta}(T') = 2m_\phi(T')$$

Enhanced DM abundance

Together with axiogenesis:

$$\frac{\Omega_a h^2}{\Omega_{\rm DM} h^2} \simeq 70 \left(\frac{f_a}{10^8\ \mathrm{GeV}}\right)\left(\frac{130\ \mathrm{GeV}}{T_{ws}}\right)^2\left(\frac{0.1}{c_B}\right)$$

DM is overproduced for the required Y_B. But can be solved by higher T_{ws}

R.Co, L.Hall et al: 1910.14152
R.Co, L.Hall et al: 2004.00629

$SU(2)_R$ Phase Transition

$$SU(3)\times SU(2)_L\times SU(2)_R\times U(1)_X$$

$$\bar{\ell}=\begin{pmatrix}\bar{\nu}\\ \bar{e}\end{pmatrix}:(1,1,2,\frac{1}{2}) \qquad \bar{q}=\begin{pmatrix}\bar{u}\\ \bar{d}\end{pmatrix}:(3,1,2,-\frac{1}{6})$$

$$\downarrow$$

$$SU(3)\times SU(2)_L\times U(1)_Y$$

$$\downarrow$$

$$SU(3)\times U(1)_{\rm em}$$

sphaleron:
L+R+QCD

$$n_{\rm PQ} \longrightarrow n_B, n_L$$

$T_{\rm sp,R}$

create $B-L\neq 0$ Need $B-L$ anomaly !

$$B\propto(B-L)\neq 0$$

$T_{\rm sp,L}$

Remember: $B-L$ is non-anomalous in SM
Any B will be washed out if there is no primordial
$B-L$

K.Harigaya & RW: 2107.09679

Avoiding Wash-out

Chiral Matter

$$\partial_\mu j^\mu_{B-L} \neq 0$$

$T_{\rm sp,R}$

$$(B-L) \to (B-L)_{\rm SM} \neq 0$$

Extra particles decay immediately

$$B \propto (B-L)_{\rm SM} \neq 0$$

$T_{\rm sp,L}$

$$n_B$$

Effective Chiral Matter

$$\partial_\mu j^\mu_{B-L} = 0$$

$T_{\rm sp,R}$

$$(B-L)_{\rm SM} \neq 0, L_{\rm exotic} \neq 0$$

$$(B-L)_{\rm SM} - L_{\rm exotic} = 0$$

$$B \propto (B-L)_{\rm SM} \neq 0$$

$T_{\rm sp,L}$

$$n_B$$

Extra particles decay after EWPT

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Example: Effective Chiral Matter

Extra vector-like leptons:

$$\boxed{L = (1,1,2,-\frac{1}{2})_1, \bar{L} = (1,1,2,\frac{1}{2})_{-1}}, \bar{E} = (1,1,1,1)_{-1}, E = (1,1,1,-1)_1$$

Contribute oppositely to $B-L$ anomaly,
but one of them decays after EWPT

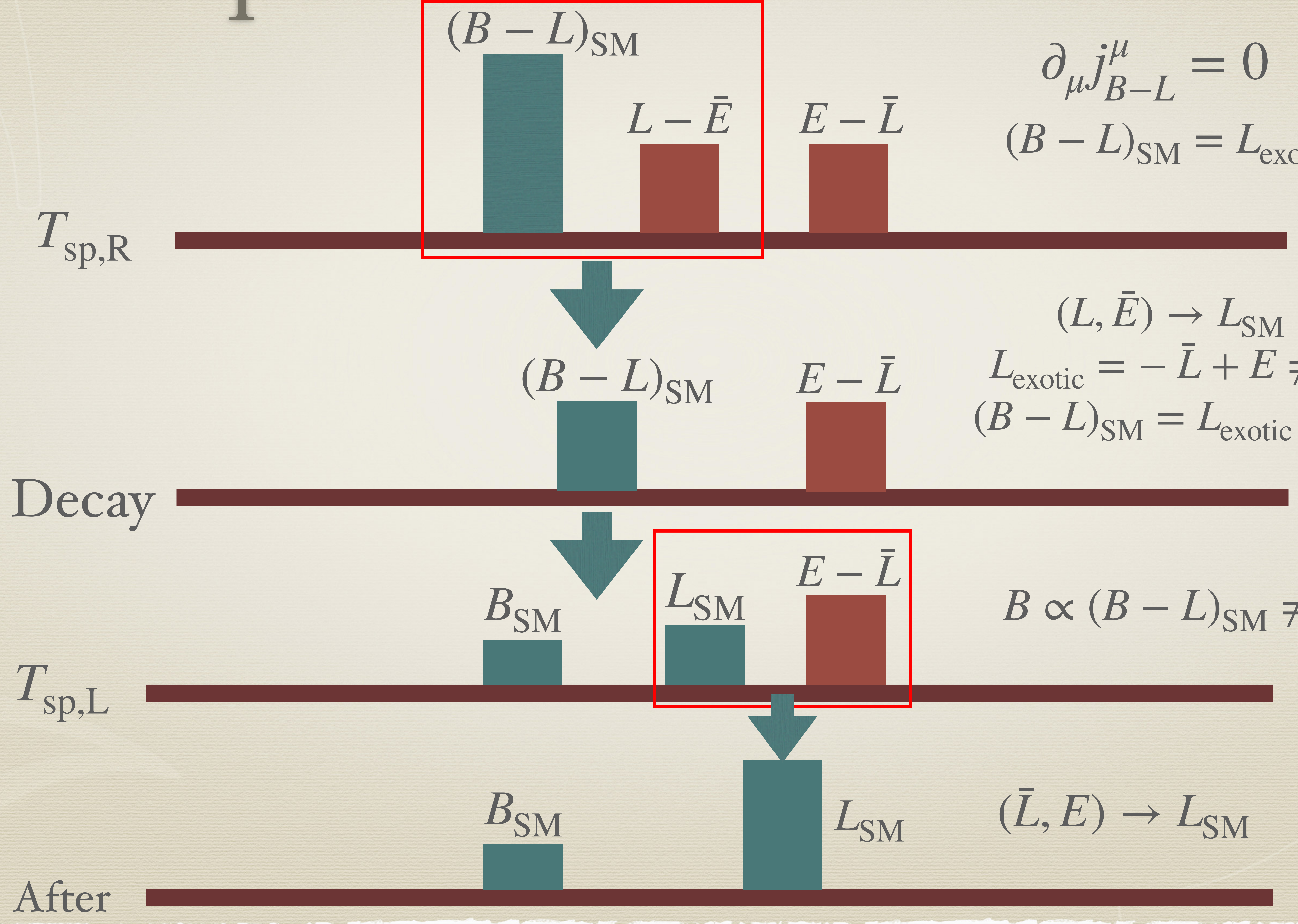
$$\partial_\mu j^\mu_{B-L} = 0$$

Lepton masses: $y_L L H_R^\dagger \bar{E} + y_{\bar{L}} \bar{L} H_R E$

Possible decay terms: $g_L^i \bar{L} \Phi \ell_i$, $g_E^i \bar{\ell}_i H_R E$,
Depends on SM Higgs is Φ or H_L

K.Harigaya & RW: 2107.09679

Example: Effective Chiral Matter



$$\partial_\mu j^\mu_{B-L} = 0$$

$$(B-L)_{\rm SM} = L_{\rm exotic}$$

$$(L, \bar{E}) \to L_{\rm SM}$$

$$L_{\rm exotic} = -\bar{L} + E \neq 0$$

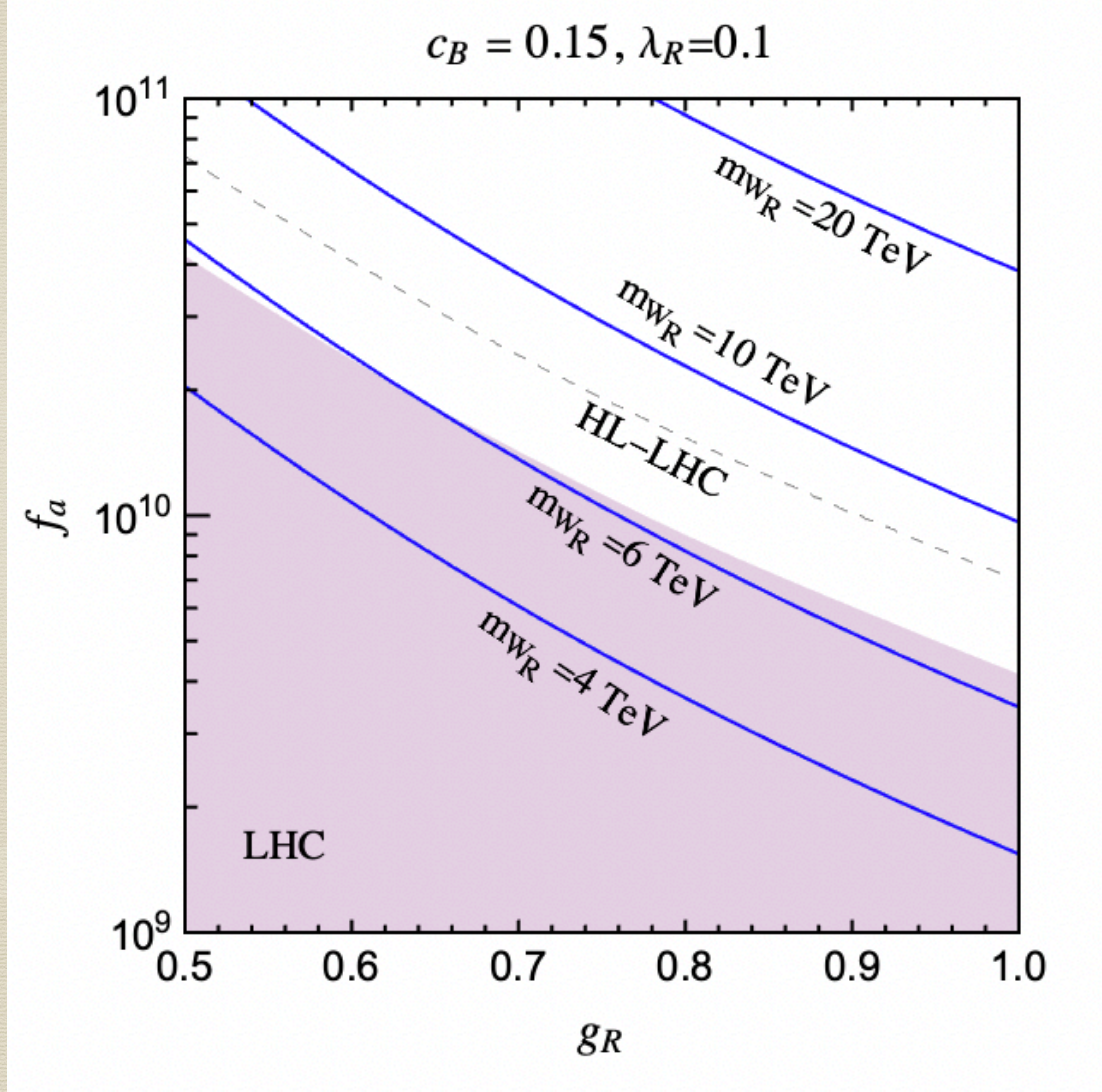
$$(B-L)_{\rm SM} = L_{\rm exotic} \neq 0$$

$$B \propto (B-L)_{\rm SM} \neq 0$$

$$(\bar{L}, E) \to L_{\rm SM}$$

$$\boxed{c_B \simeq 0.15}$$

Heavy W' Detection



Require consistency with DM abundance and baryon asymmetry

$$T_{\mathrm{sp,R}} = (1.1\ \mathrm{TeV})\left(\frac{f_a}{10^8\ \mathrm{GeV}}\right)^{1/2}\left(\frac{0.1}{c_B}\right)^{1/2}$$

Prediction for W' boson mass

$$m_{W_R} = (1.1\ \mathrm{TeV})\left(\frac{g_R}{\sqrt{2}}\right)\left(\frac{v_R(T=0)}{T_{\mathrm{sp,R}}}\right)\left(\frac{f_a}{10^8\ \mathrm{GeV}}\right)^{1/2}\left(\frac{0.1}{c_B}\right)^{1/2}$$

Determined by couplings via phase transition calculation

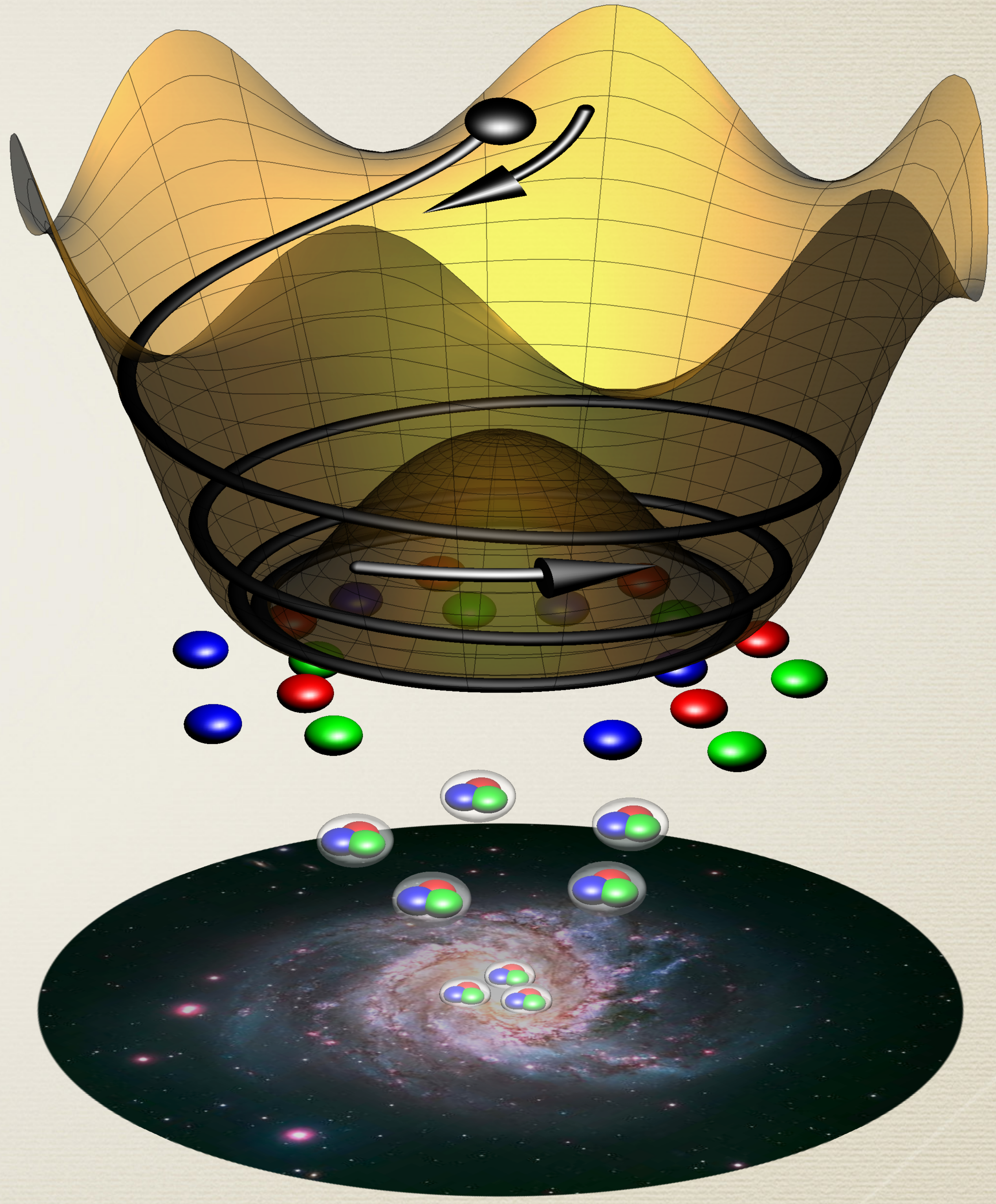
K.Harigaya & RW: 2107.09679

Summary

* Axiogenesis mechanism can generate observed baryon asymmetry via axion rotation.

* Axiogenesis from $SU(2)_R$ phase transition can explain DM abundance and baryon asymmetry consistently.

* A relationship between the decay constant f_a and the W' gauge boson mass is predicted.



Picture by: R. Co, K. Harigaya, and NASA

Back-up

PQ charge not depleted thermally

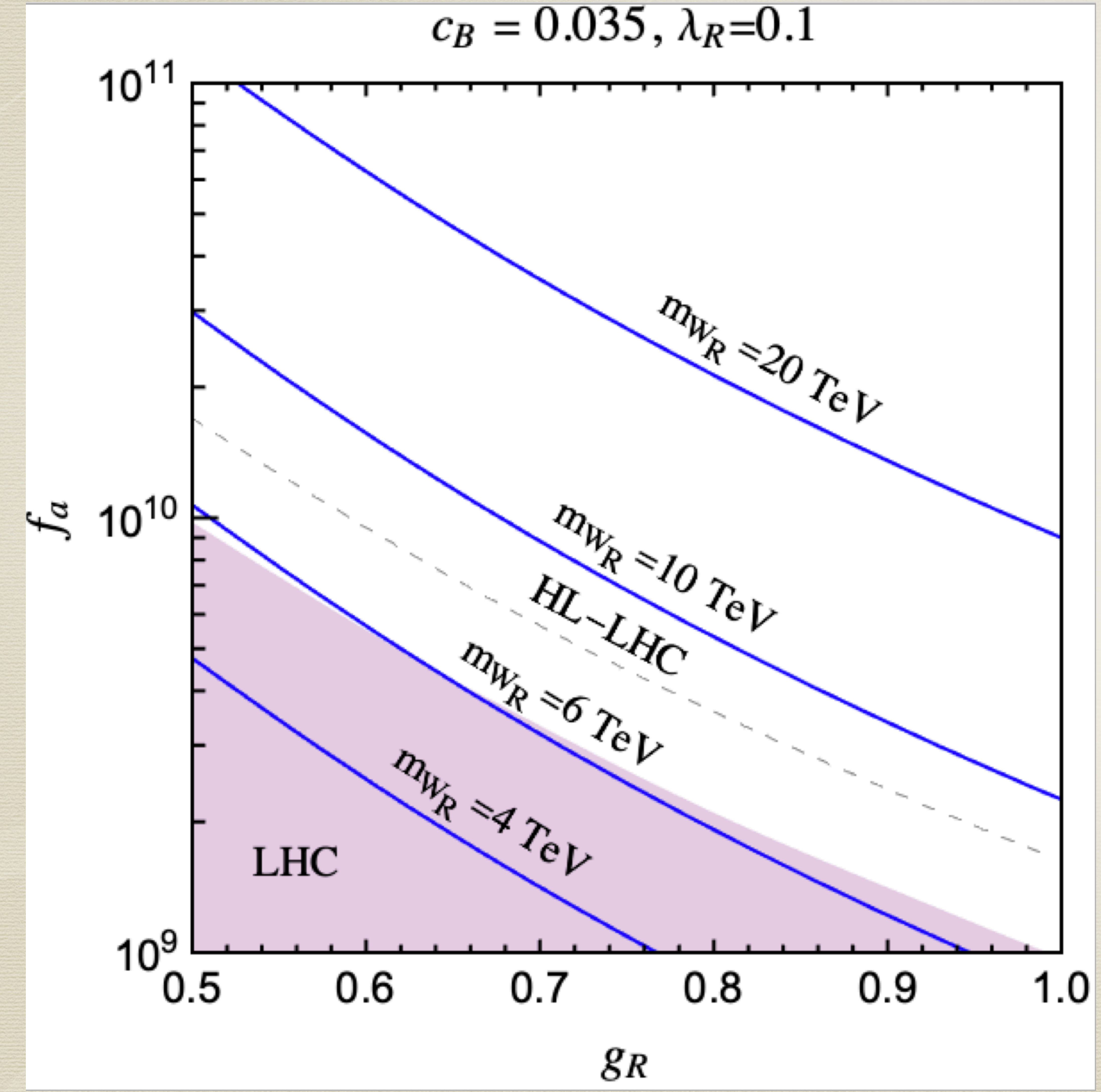
Consider $n_{PQ} \to n_\psi$ in thermal bath, PQ charge is transferred into the fermions ψ

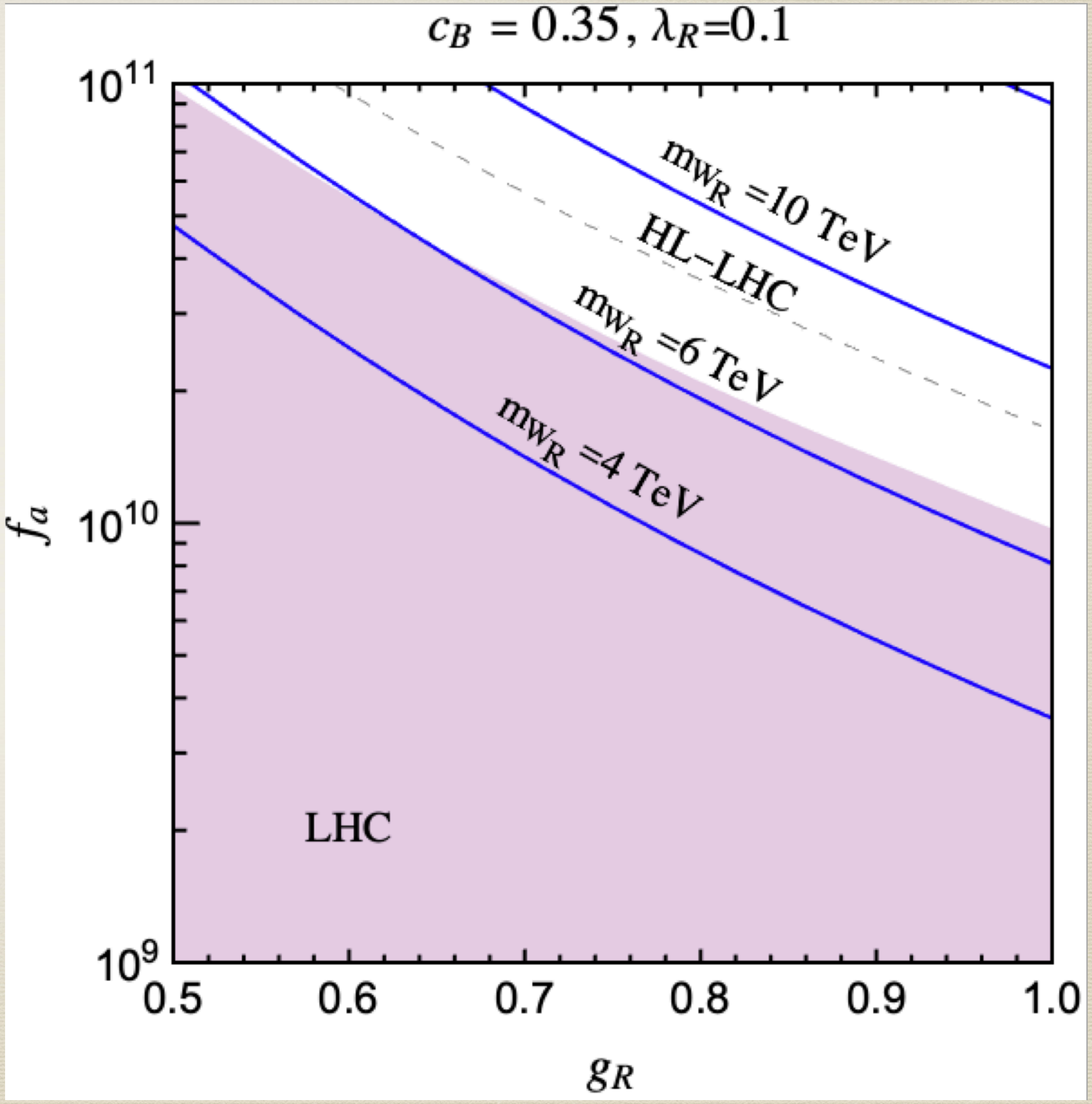
$$\frac{F}{V} = \Delta(\rho - Ts) \simeq -\frac{\pi^2}{90} g_* T^4 + \sum_\psi \frac{n_\psi^2}{T^2}$$

Minimization $\Rightarrow$ $\Delta n_{PQ} = \sum_\psi n_\psi \simeq \dot{\theta} T^2 \ll n_{PQ} = \dot{\theta} f_a^2$

(Suppose $T \ll f_a$)

Predictions: $\lambda_R = 0.1$





Predictions: $\lambda_R = 0.3$