TRIUMF

Beyond Vanilla Electroweak Baryogenesis

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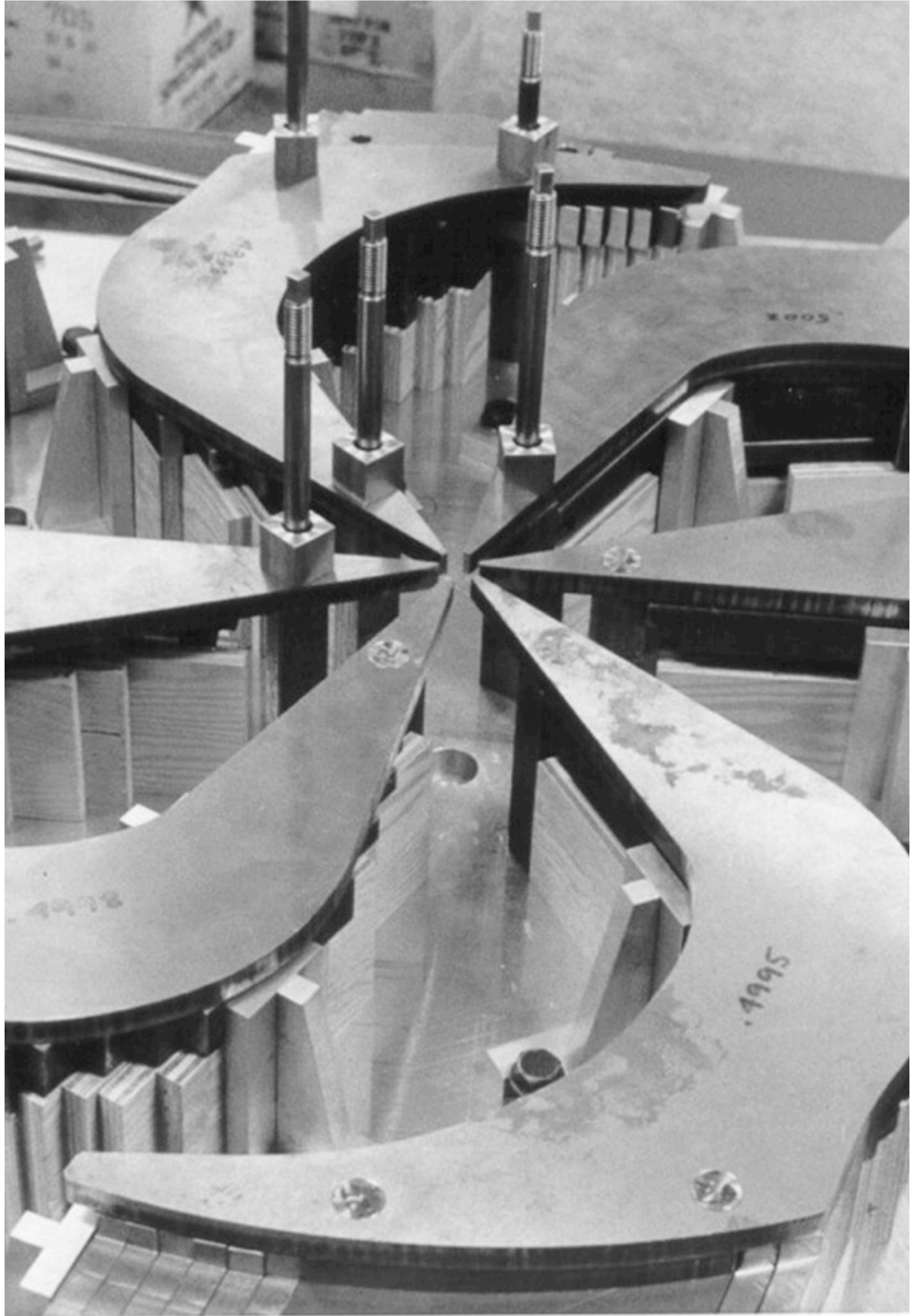
with Sebastian Ellis, Seyda Ipek, David Morrissey, Michael Ramsey-Musolf, Peter Winslow,



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Discovery, accelerated

What wakes me up in the morning

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Literal answer

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← **Literal answer**

- Main: *why is there more matter than anti matter*

- Big bang nucleosynthesis: *low energy injection.*

- Gravitational waves: *Lisa inverse problem*

- Dark matter: *non standard thermal history*

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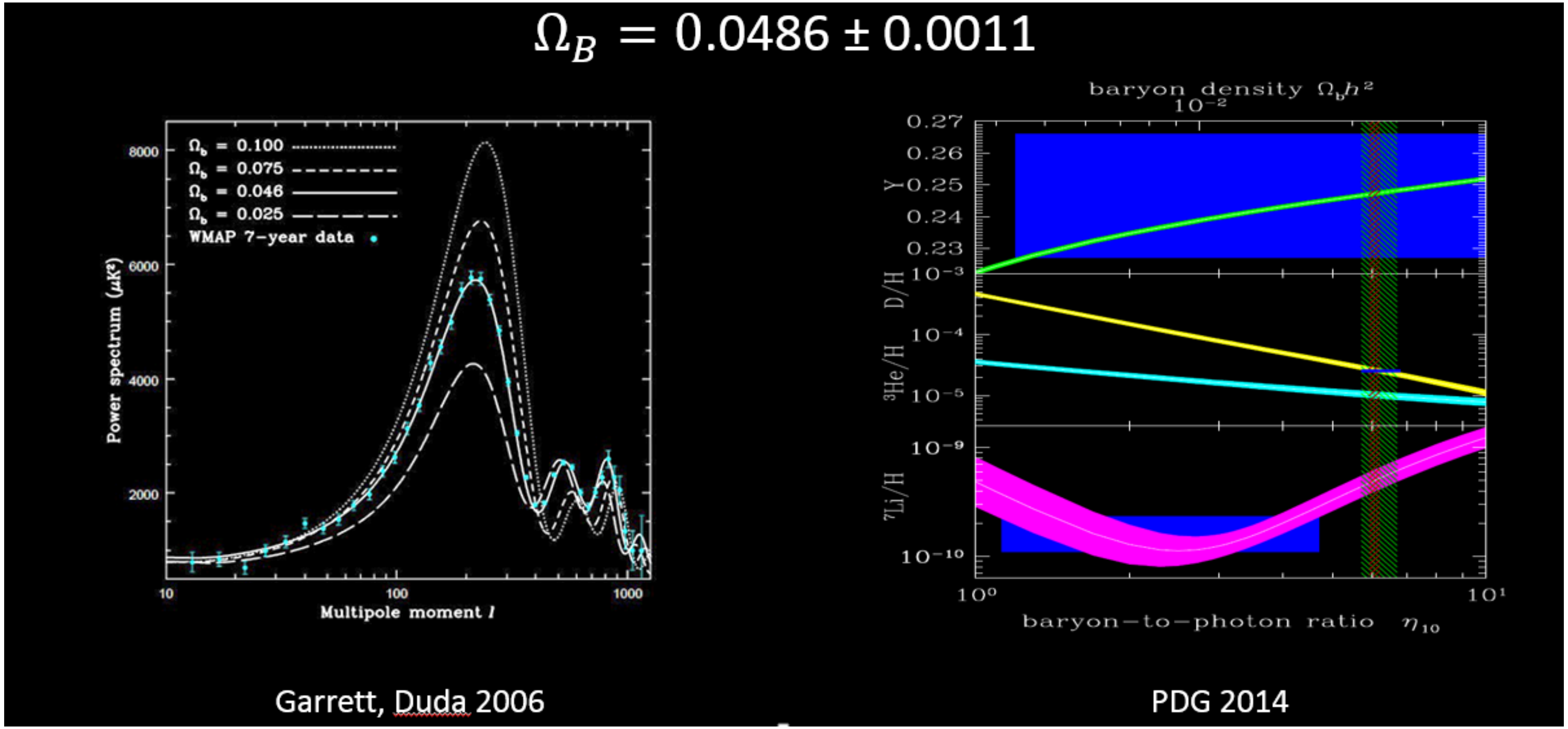
- Dark matter: *non standard thermal history*

Outline

- Review of Electroweak baryogenesis
- Experimental status of vanilla framework
- How to organize extensions to the vanilla framework
- An example of each type of extension
- Summary

Electroweak Baryogenesis

Baryon yield can be measured 2 ways



Electroweak Baryogenesis

Inflation washes out initial baryon asymmetry

Sakharov conditions

B violation
C and CP violation
Departure from Equilibrium

Electroweak Baryogenesis

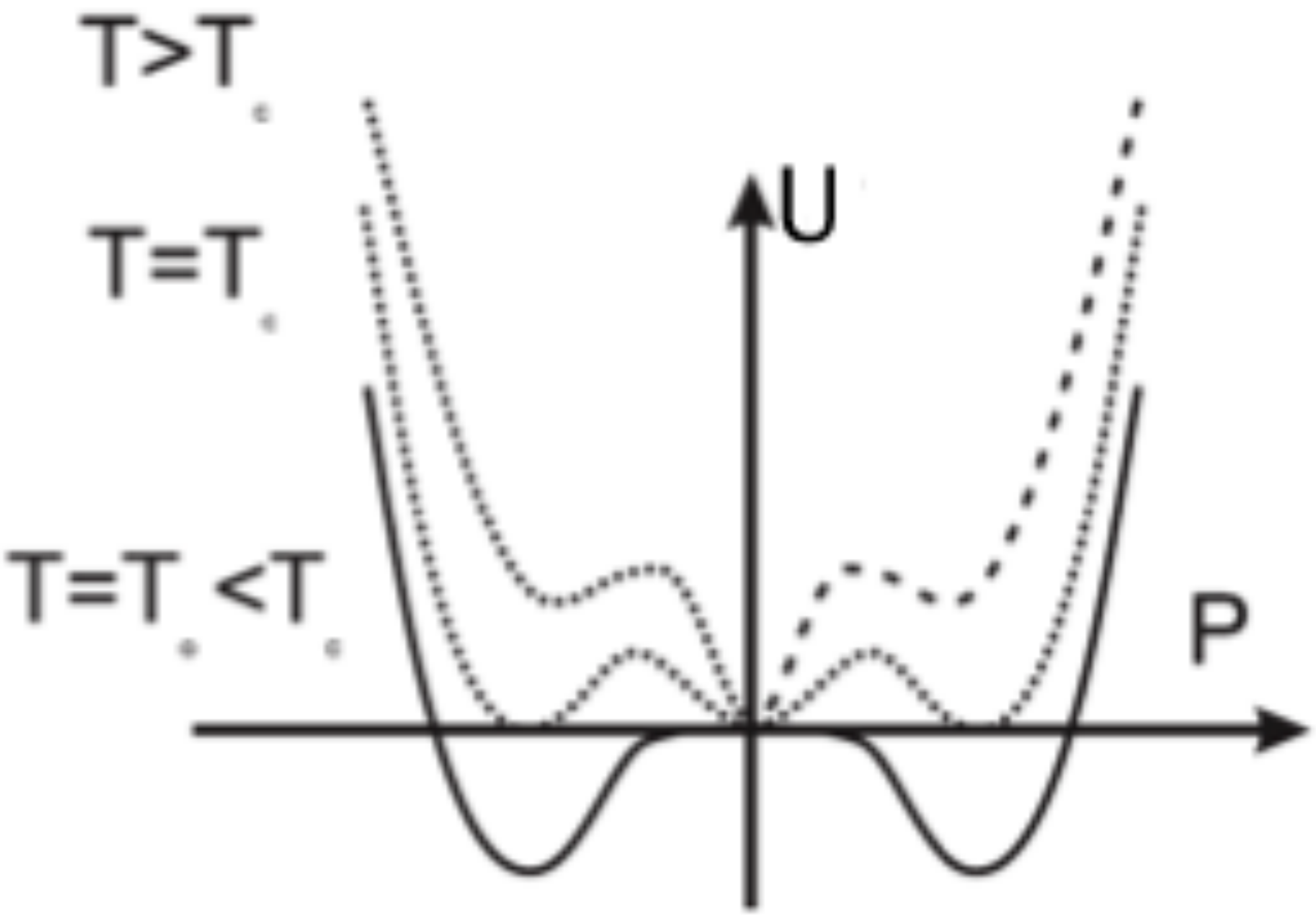
Electroweak baryogenesis

B Violation - Electroweak Sphalerons
CP Violation - CPV interactions with (preferably) Higgs
Departure from equilibrium - EWPT

- most minimal model (if parameters were different would
Require no BSM particles!)

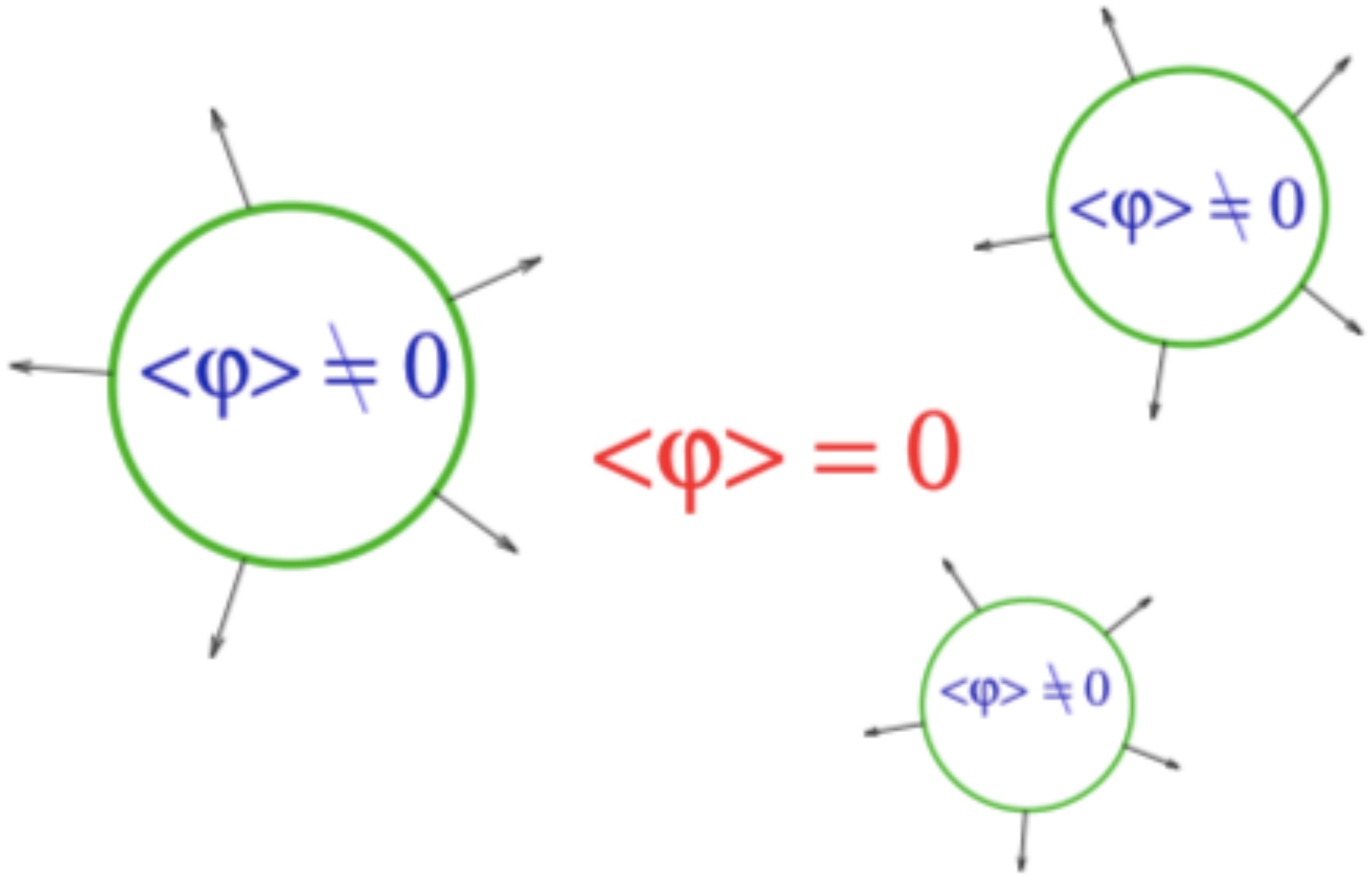
Electroweak Baryogenesis

Electroweak Phase Transition:



Electroweak Baryogenesis

Electroweak Baryogenesis



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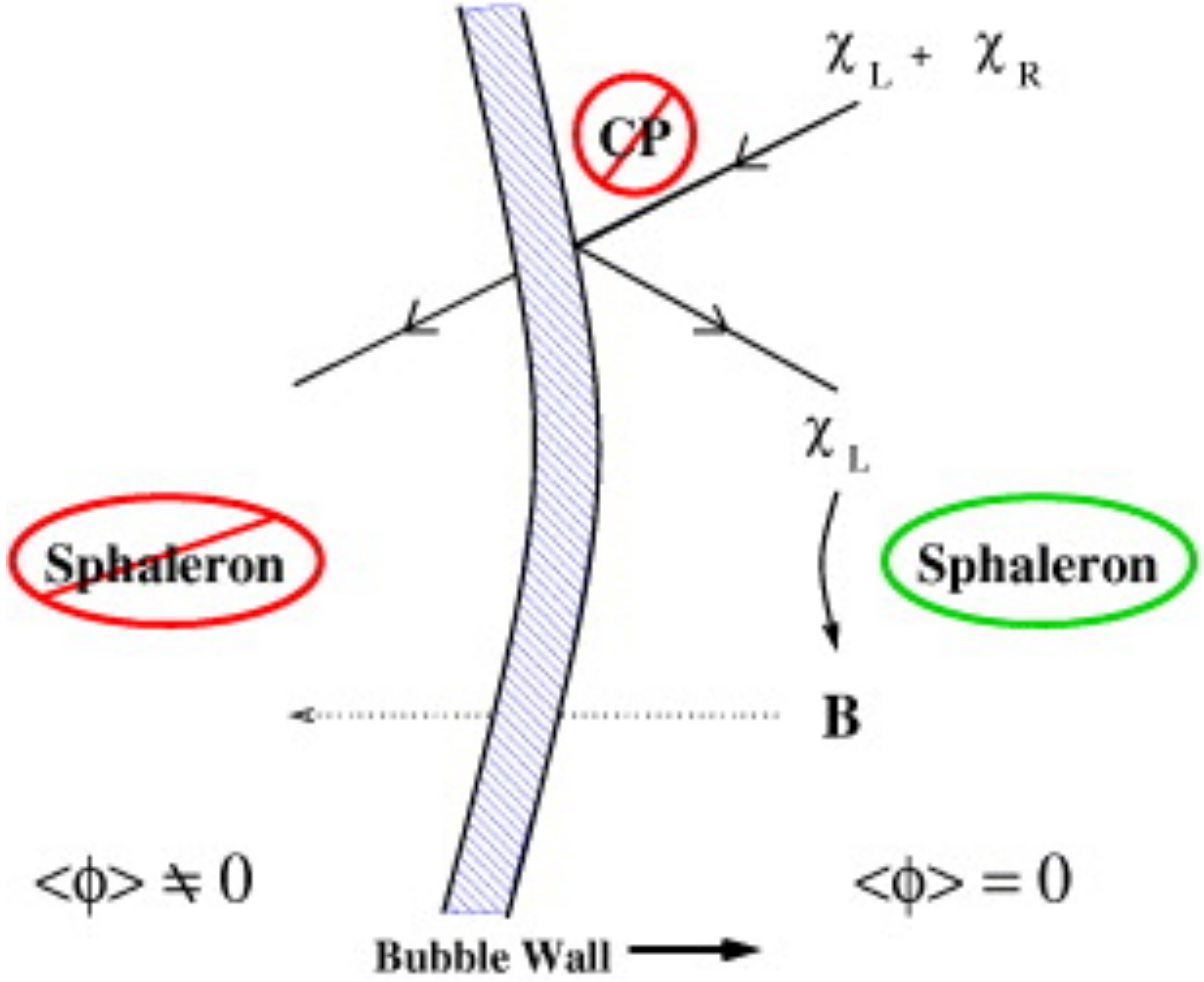
Electroweak Baryogenesis

Electroweak Baryogenesis



Morrissey 1206.2942

Electroweak Baryogenesis

Calculation of baryon asymmetry proceeds in 3 steps

Bubble wall profile
Charged transport and baryon production
Low energy constraints - in particular EDMs!

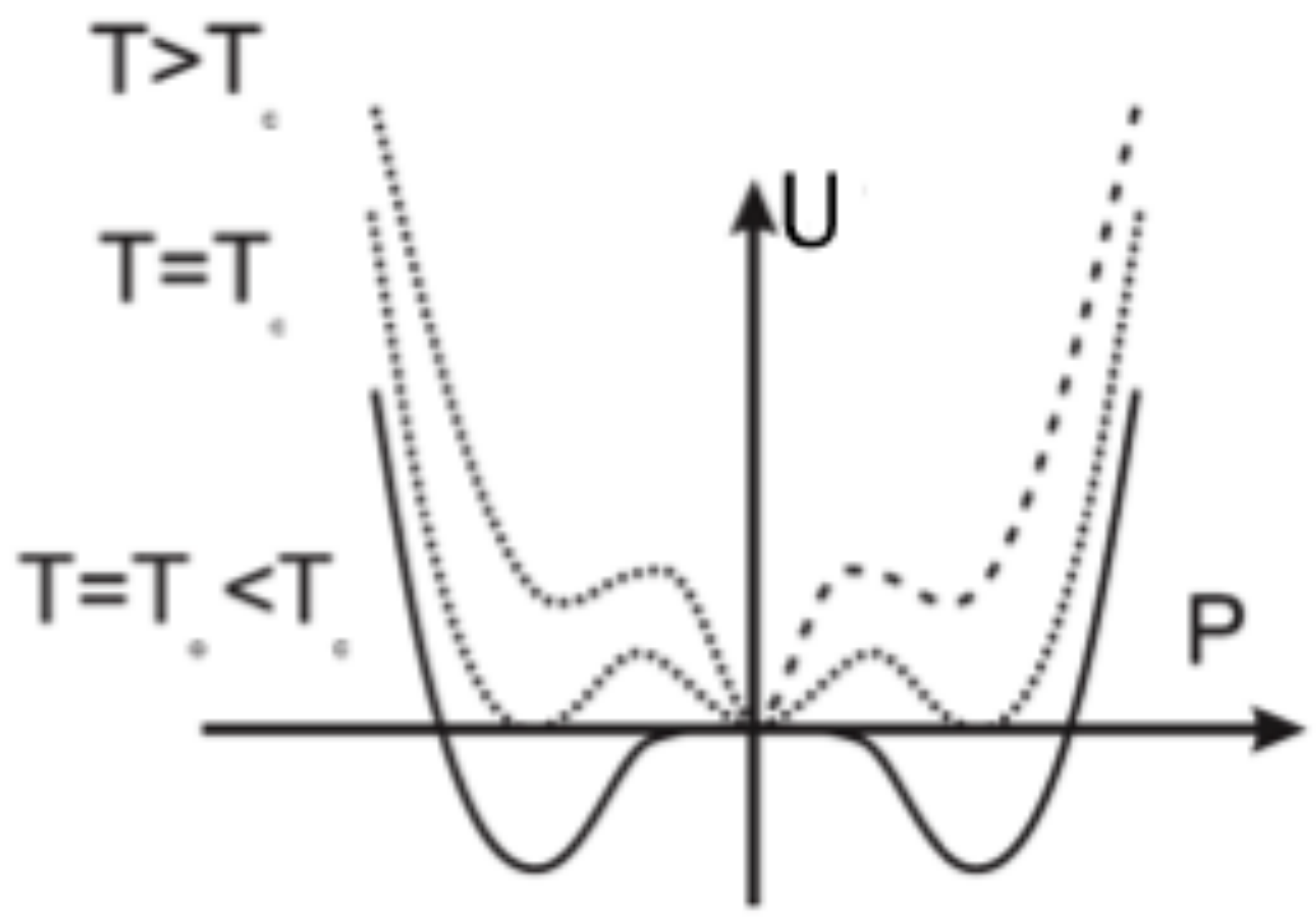
Electroweak Baryogenesis

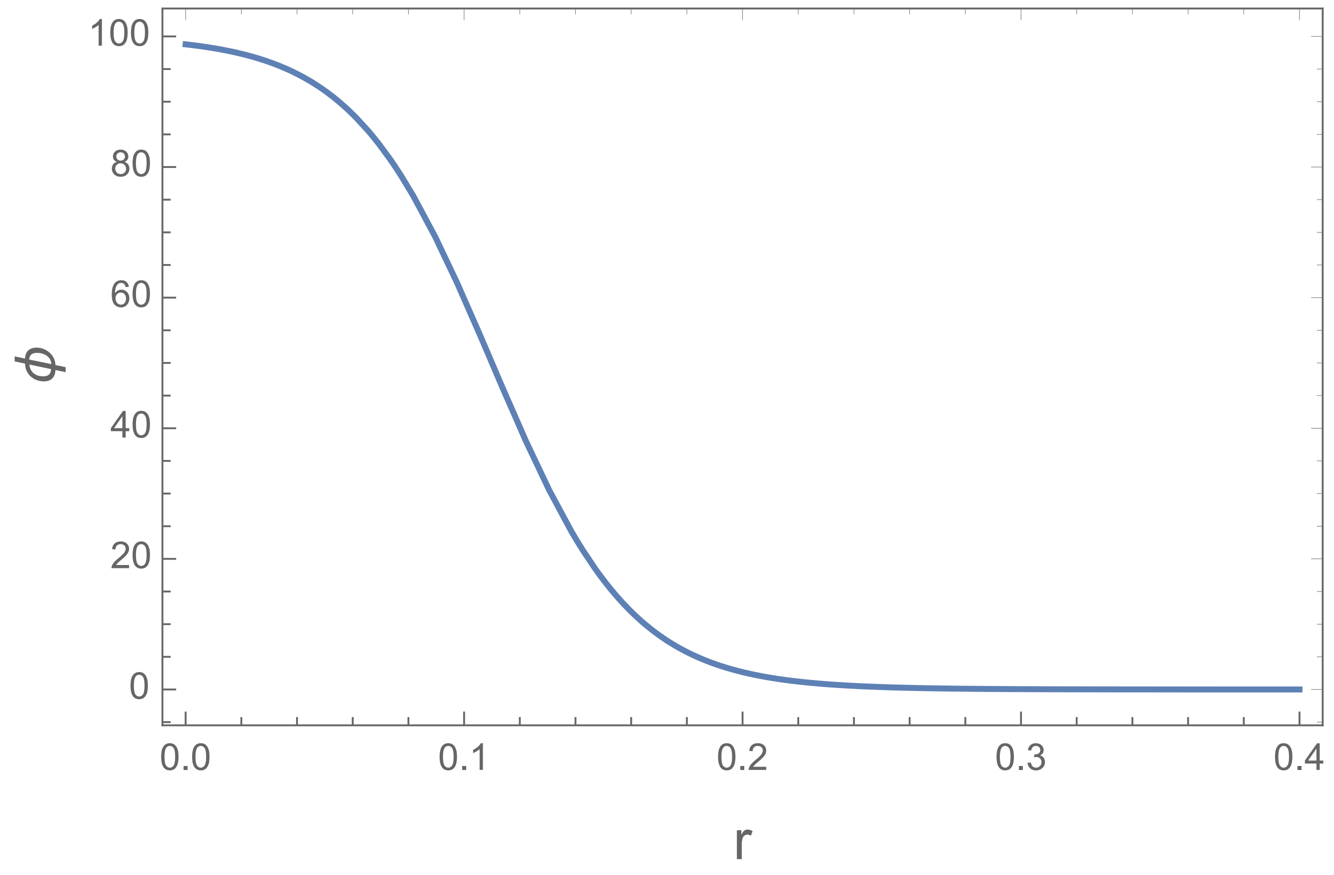
Phase transition calculation

$$\frac{\partial V}{\partial \phi} = 0 \Big|_{T=T_c}, \quad V(\phi_c, T_c) = V(0, T_c)$$

$$\frac{\partial^2 \phi_B}{\partial r^2} + \frac{2}{r}\frac{\partial \phi_B}{dr} = \frac{dV}{d\phi}\Big|_{\phi_B}, \quad \phi_B \approx \frac{\phi_c}{2}\left(1 - \tanh\left[\frac{r-\delta}{L_w}\right]\right)$$

$$S_E = 4\pi \int dr^2 L(\phi_B), \quad \frac{S_E}{T} \approx 140$$





Electroweak Baryogenesis

Transport is done in two steps:

1. **Calculation of a chiral asymmetry (hard part)**
2. **Calculation of the baron asymmetry (easy part)**

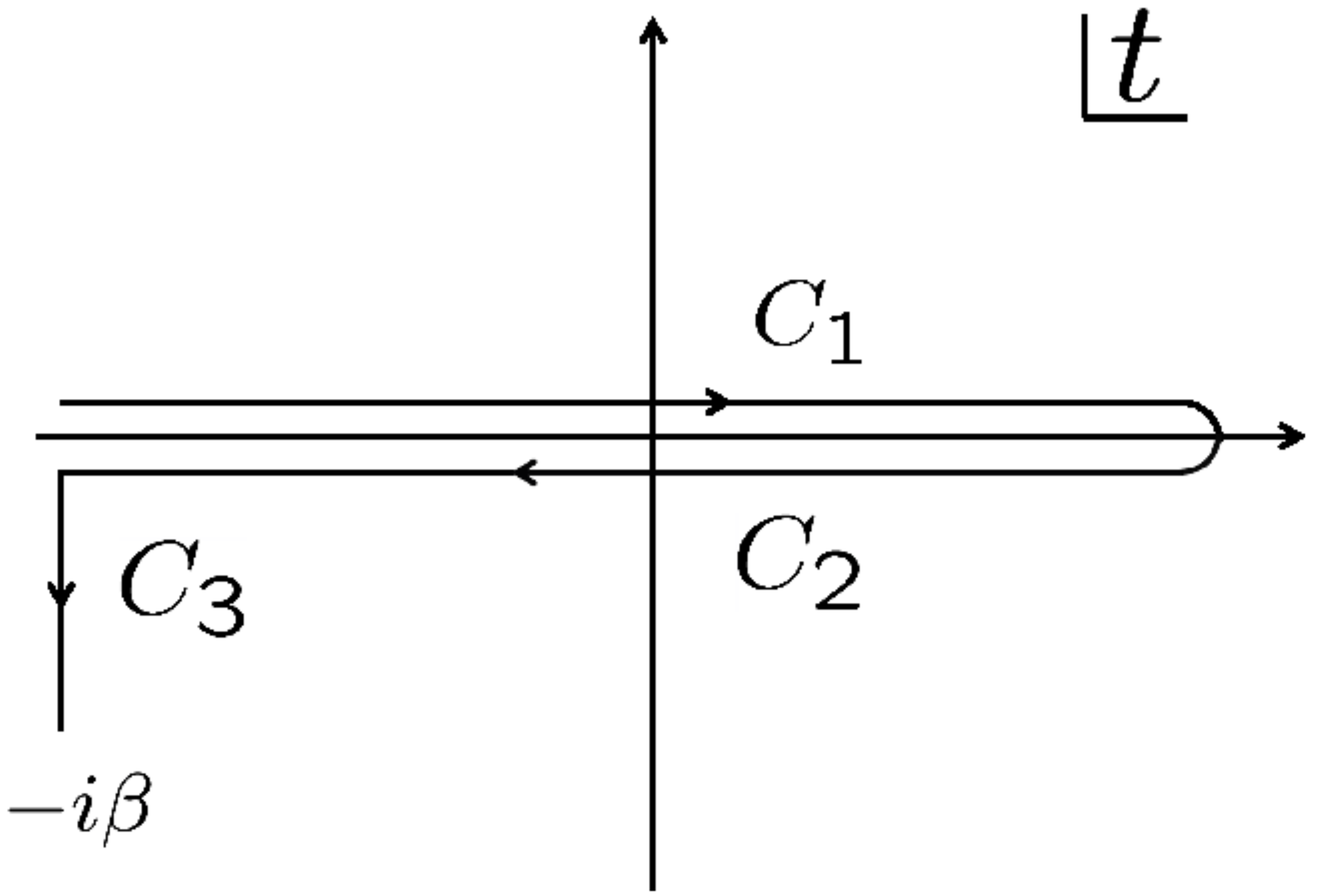
$$D_q \rho_B''(z) - v_w \rho_B' - \Theta[-z]\frac{15}{4}\Gamma_{ws}\rho_B = \Theta[-z]\frac{3}{2}\Gamma_{ws} n_L(z)$$

Electroweak Baryogenesis

Cartoon of thermal field theory

Four types of 2 point correlators

$$G^{++}, G^{+-}, G^{-+} \text{ and } G^{--}$$



Electroweak Baryogenesis

Cartoon of calculation

$$G = G_0 + \Delta G$$

$$\mathscr{E}(x) G_{ij}^{+-}(x,y) - G_{ij}^{+-}(x,y)\mathscr{E}(y) = \mathscr{E}(x)\Delta G_{ij}^{+-}(x,y) - \Delta G_{ij}^{+-}(x,y)\mathscr{E}(y)$$

Space time varying basis!

"Semi Classical force" <—> LHS,
Self-energies <—> RHS

<u>VEV insertion approach:</u>

1. ignore off diagonals
2. Expand around x=y
3. Use electroweak symmetric basis

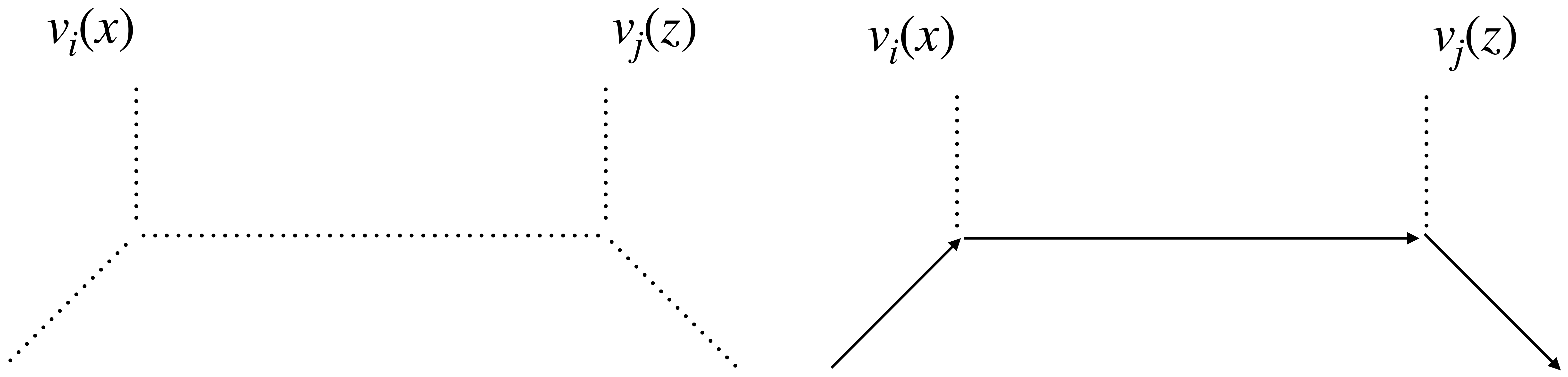
Electroweak Baryogenesis

Vev insertion in words:

Majority of the baryon asymmetry is produced just outside the bubble where the vevs are small compared to the mass splitting and temperature

Electroweak Baryogenesis

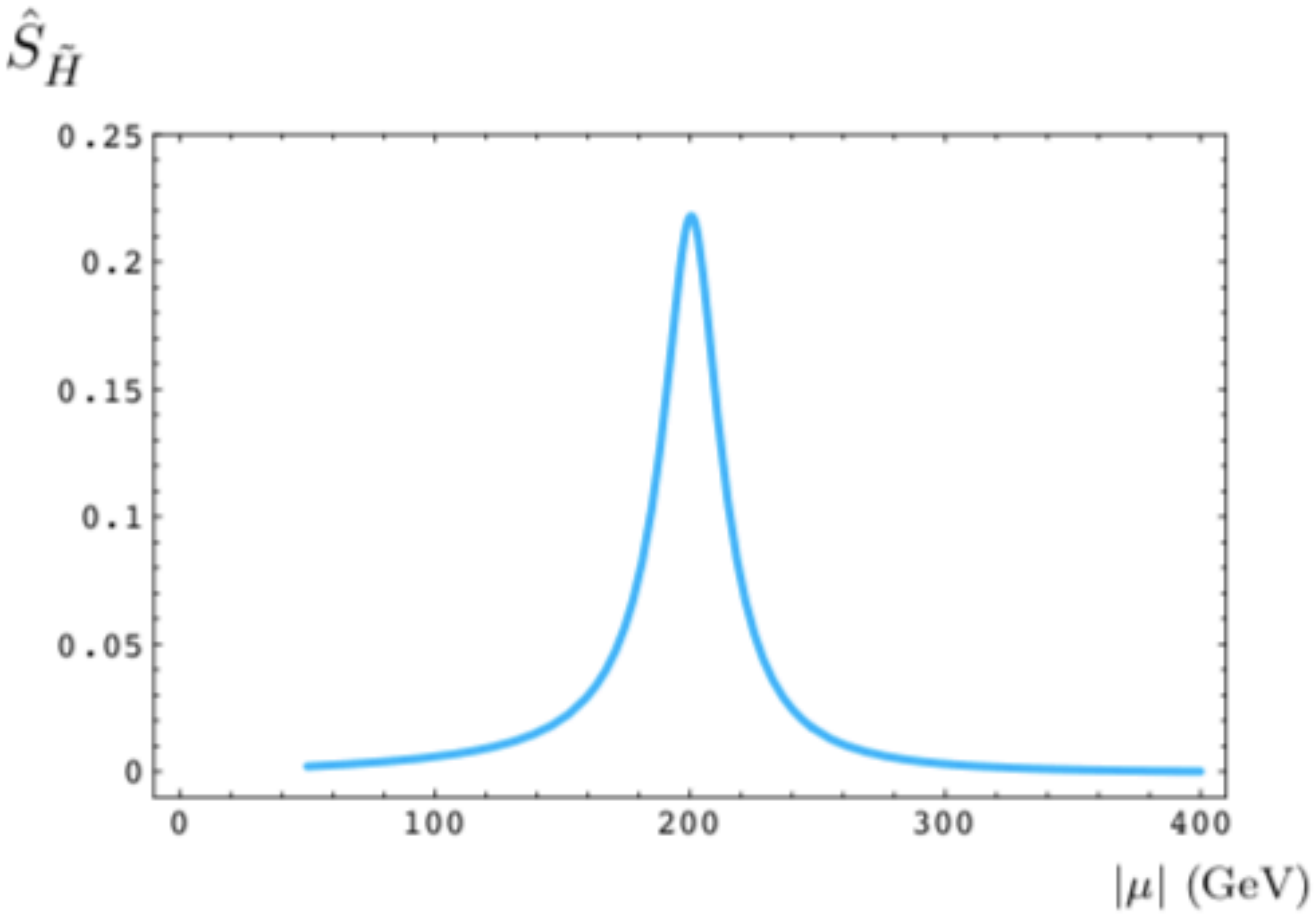
Vev insertion sources

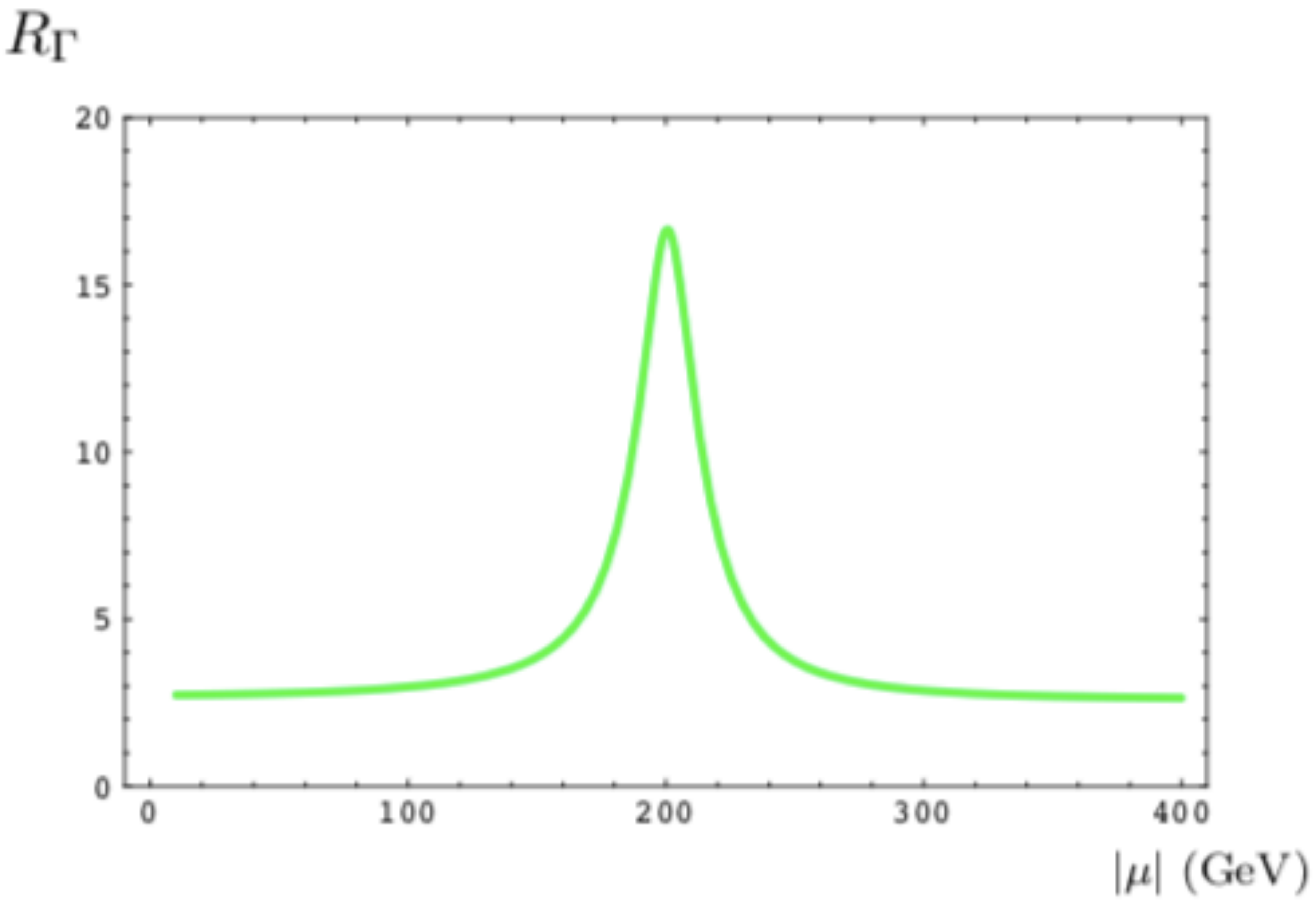


$$\partial_\mu J^\mu = \lim_{y=x} \int d^4 z G^{+-}(x,z)\Sigma^{-+}(z,y) + \cdots$$

Electroweak Baryogenesis

Resonant behaviour of sources





Lee, hep-ph/0412354

Electroweak Baryogenesis

Transport equation for determining chiral asymmetry - Top quark example

$$v_w n_t' - D_Q n_t'' = -\Gamma_m \left(\frac{n_t}{k_t} - \frac{n_Q}{k_Q} \right) - \Gamma_Y \left(\frac{n_t}{k_t} - \frac{n_H}{k_H} - \frac{n_Q}{k_Q} \right) + \Gamma_{ss} \left(\frac{2n_Q}{k_Q} - \frac{n_t}{k_t} + \frac{9(n_Q + n_t)}{k_B} \right) + S_t^{CPV}$$

Strong sphaleron rate
Diffusion rate
Scattering/Decay rate
CP conserving interactions with bubble wall
CPV interations with bubble wall

Electroweak Baryogenesis

Experimental status of EWBG in SM

B violation	✔
CP violation	✗
Departure from Equilibrium	✗

Electroweak Baryogenesis

BSM and Vanilla baryogenesis

MSSM - Light stop + EDMs
NMSSM - $\tilde{S}\tilde{H}H$ still promising
SMEFT - $H^3\bar{\tau}\tau$ still promising
Motivation to look beyond minimal scenario

Extending Electroweak Baryogenesis

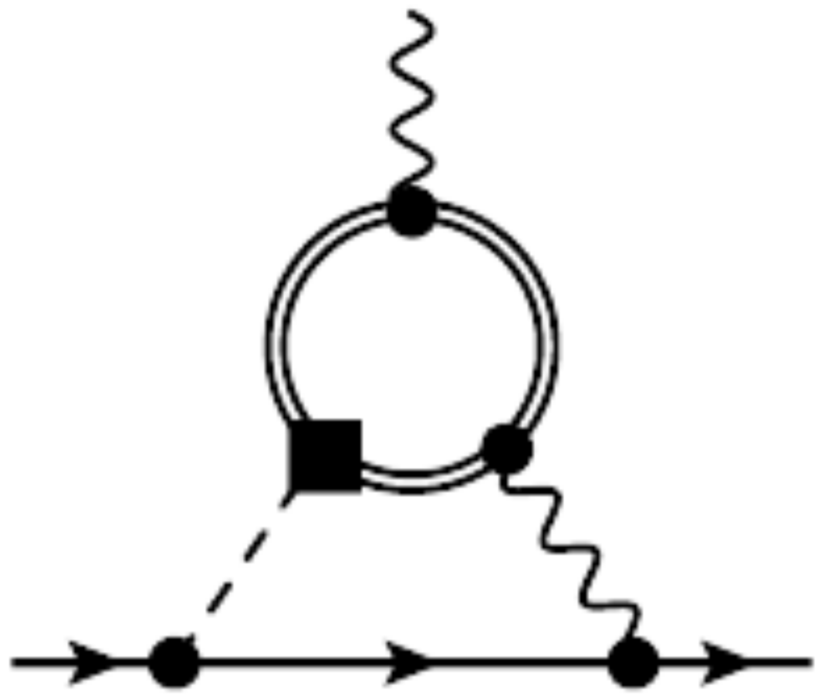
Extensions to minimal scenario based around Sakharov conditions

1. Change how efficiently B is violated
2. Change what sort of CP violating sources one uses
3. Change the way a departure from equilibrium is achieved

Approach 1: New CPV sources

Scaling of tree level CPV sources v scaling of EDMS

$$\exp[-\Lambda_{\mathrm{CPV}}/T] \leftrightarrow \frac{1}{\Lambda_{\mathrm{CPV}}^{N}}$$



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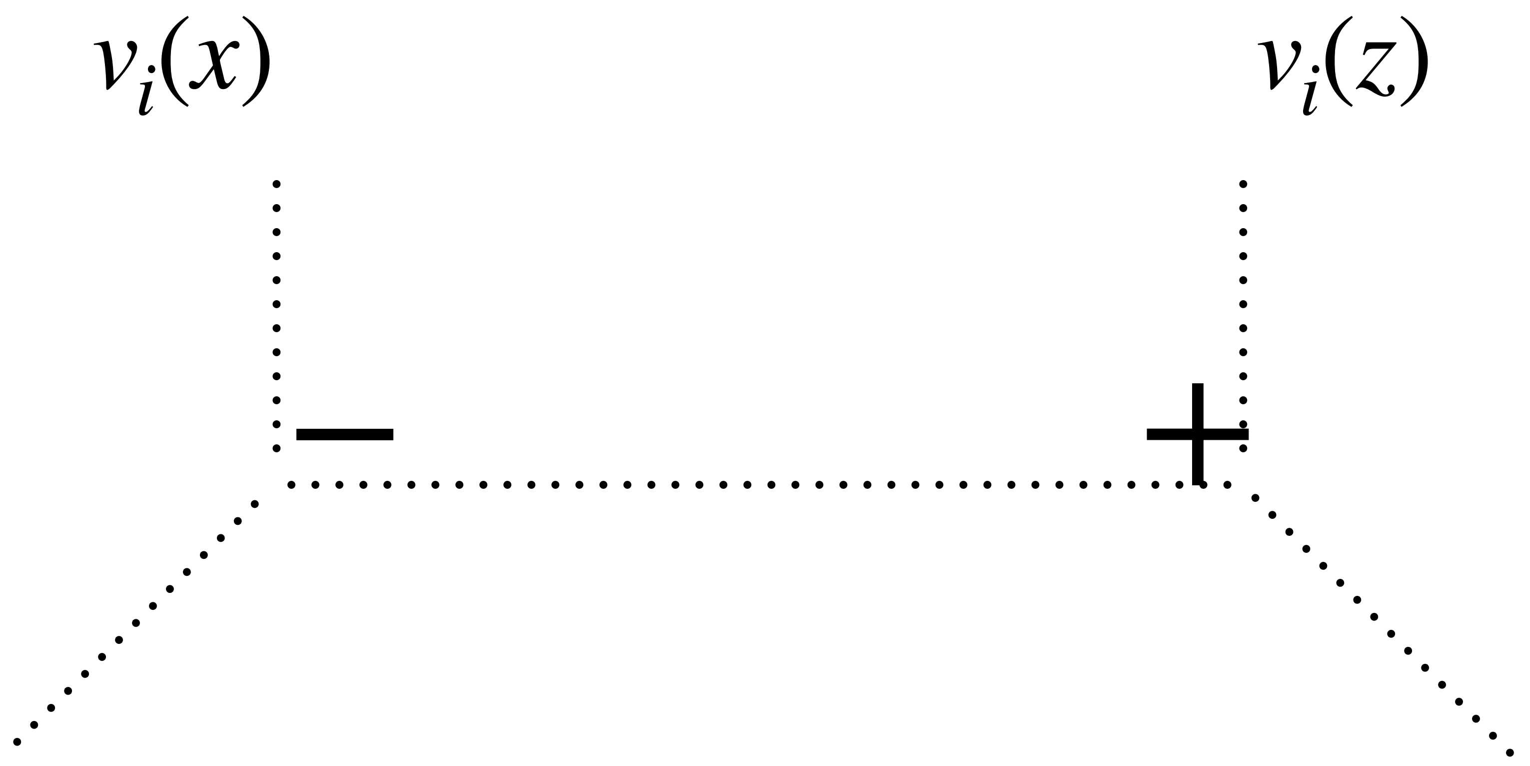
$$\partial_\mu J^\mu = \lim_{y=x} \int d^4z G^{+-}(x,z)\Sigma^{-+}(z,y) + \cdots$$

Approach 1: New CPV sources

Why the Boltzmann supression?

$$G^{\pm\pm} = \approx \pm \frac{1}{M^2} + \mathcal{O}\exp[-M/T]$$

$$G^{\pm\mp} = \approx \mathcal{O}\exp[-M/T]$$



Recall master equation for deriving CPV sources

$$\partial_\mu J^\mu = \lim_{y=x} \int d^4z G^{+-}(x,z)\Sigma^{-+}(z,y) + \cdots$$

Approach 1: New CPV sources

Why the Boltzmann supression?

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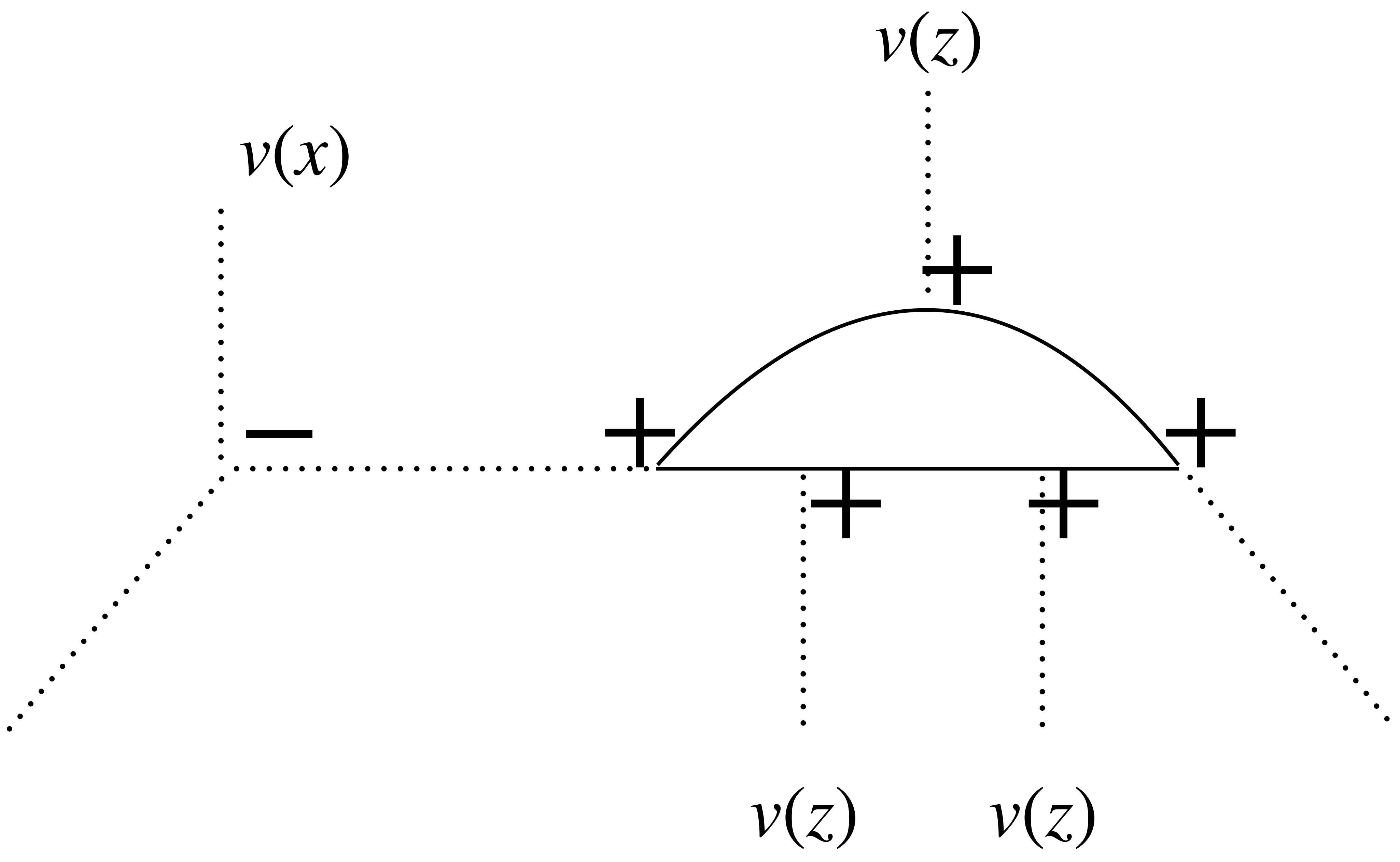
Recall master equation for deriving CPV sources

$$\partial_\mu J^\mu = \lim_{y=x} \int d^4 z G^{+-}(x,z)\Sigma^{-+}(z,y) + \cdots$$

Solution: tree level interfering with loop



Approach 1: New CPV sources

A simple example

$$-\mathscr{L} \ni m_A^2 |A|^2 + m_B^2 |B|^2 + \left[\mu + \frac{\xi |H|^2}{\Lambda}\right] A^\dagger H B + (\kappa |A|^2 + \kappa_B |B|^2) |H|^2 + h.c. + S.B.Ts$$

Quantum numbers

$$A = (1,2,1/2) \quad B = (1,1,0)$$

Approach 1: New CPV sources

Source estimation: tree level

$$-\mathscr{L} \ni A^\dagger \left[\mu_1 H_1 + \mu_2 H_2\right] B$$

$$\sim \mathrm{Im}[\mu_1\mu_2]\beta'(x)v(x)^2 I(m_i, \Gamma_i)$$

$$10^2 \lesssim \mathrm{Max}\left[\frac{Y_B}{Y_B^{\mathrm{obs}}}\right] \lesssim 10^3$$

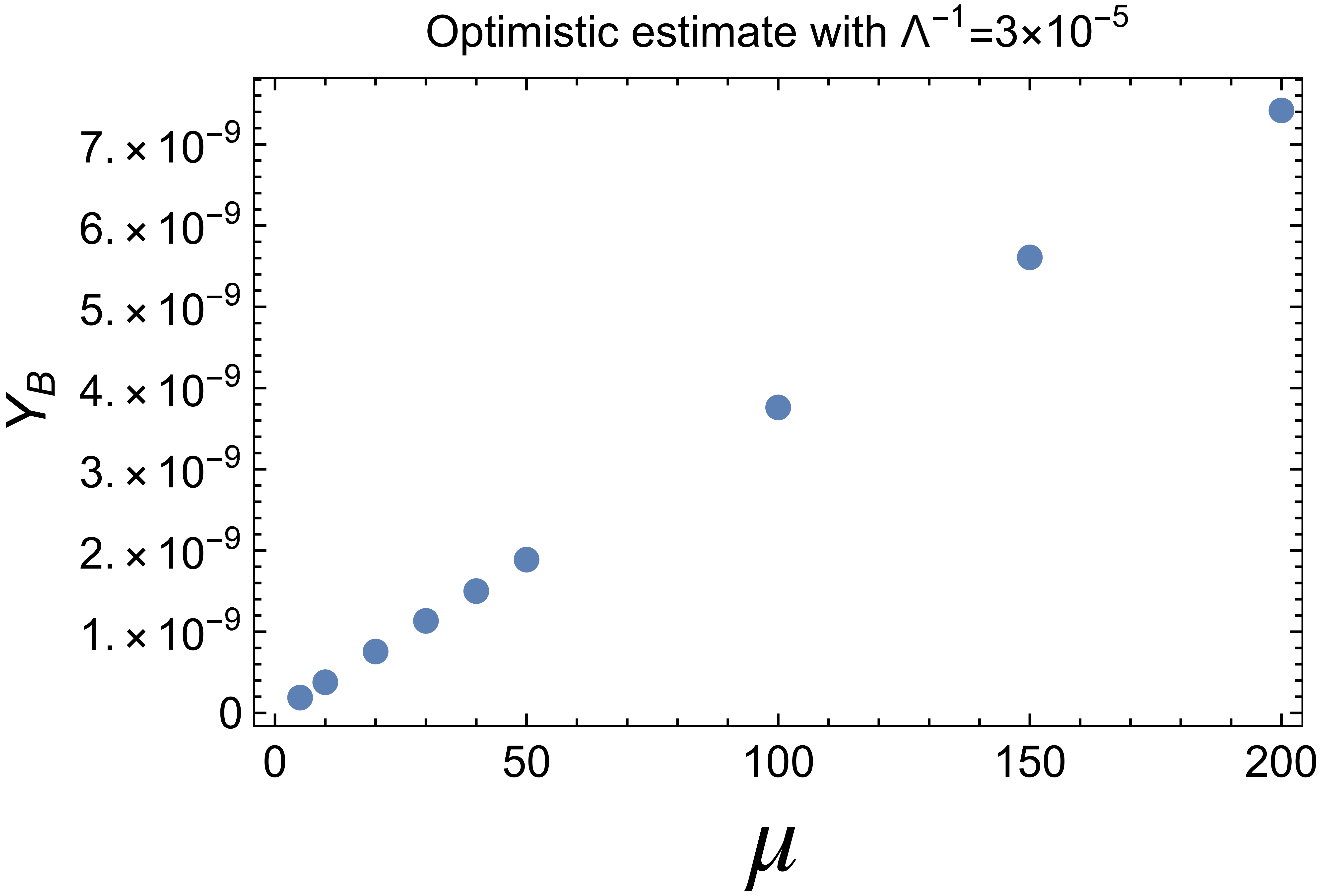
Source estimation: loop

$$-\mathscr{L} \ni \left[\mu + \frac{\xi |H|^2}{\Lambda}\right] A^\dagger H B$$

$$\sim \mathrm{Im}[\mu\xi]\frac{v(x)^2}{\Lambda} v(x)v'(x) I(m_i, \Gamma_i)$$

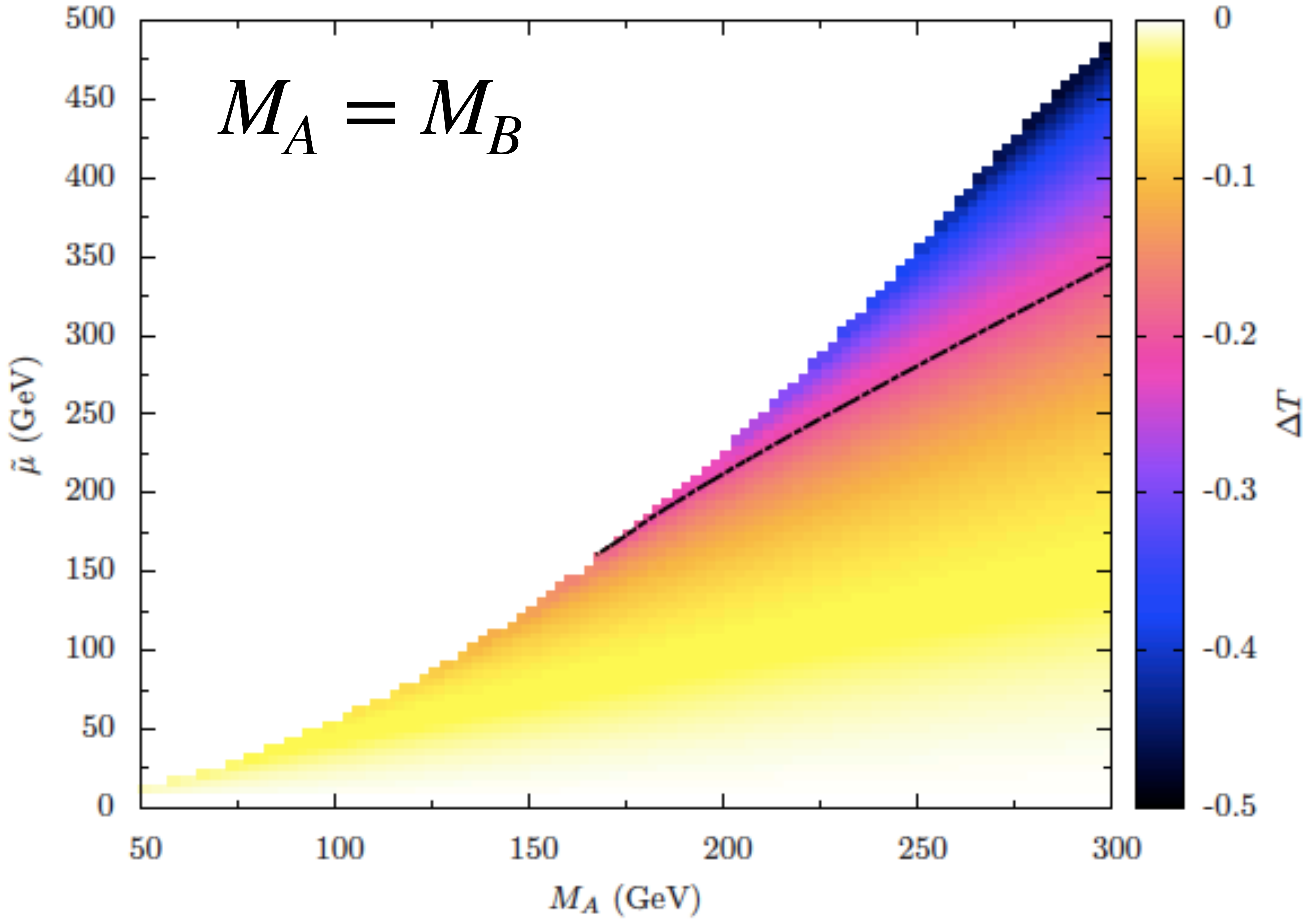
For $\mu \sim 200$ GeV $\quad \mathrm{Max}[\Lambda] \sim \mathscr{O}[1 - 10]$ PeV

Approach 1: New CPV sources



Approach 1: New CPV sources

Electroweak precision



Approach 2: B violation

- Chiral asymmetry generated by CPV interactions with bubble wall
- Weak sphalerons convert chiral asymmetry to B asymmetry

$\Gamma_{ws} = 120\alpha_w^5 T$ **controls efficiency of B violation**

$\Gamma_{ss} = 140\alpha_s^5 T$ **controls efficiency of chiral washout**

Approach 2: B violation

Case 1: Modifying couplings through a PT

$$\mathscr{L} \supset -\frac{1}{4}\left(\frac{1}{g_3^2} + a_\phi \frac{\phi}{\Lambda_\phi}\right) G^{a\,\mu\nu} G^a_{\mu\nu} = -\frac{1}{4}\frac{1}{g_{3_{\rm eff}}^2} G^{a\,\mu\nu} G^a_{\mu\nu} \qquad g_{3_{\rm eff}} = g_3 \left(\frac{\Lambda_\phi}{a_\phi g_3^2 \phi + \Lambda_\phi}\right)^{1/2}$$

UV completion: 1. triangle diagram
2. Dilaton-like field

Approach 2: B violation

Case 2: oscillating dilaton $\alpha_w \to \alpha_w(T)$

$$\delta L = -\frac{1}{4}\left(1 - \frac{d_{gY}}{g_Y^2}\kappa\phi\right)A^{\mu\nu}A_{\mu\nu} - \frac{1}{4}\left(1 - \frac{d_{g2}}{g_2^2}\kappa\phi\right)W^{a\mu\nu}W^a_{\mu\nu}$$

$$\phi \approx \frac{\sqrt{2f_{DM}\rho_{DM}}}{m_\phi}\cos(m_\phi(t - v\cdot x + \cdots) \propto \left(\frac{T}{T_{CMB}}\right)^{3/2}$$

Planck Suppressed coupling
Can be large in the early universe

Approach 2: B violation

Experimental tests

- Variation in α for 1<z<4
- BBN
- E.P.V searches
- 5th force searches (future work)

First three tests are actually sensitive to $d_e = \alpha_Y d_{g_2} + \alpha_2 d_{g_Y}$

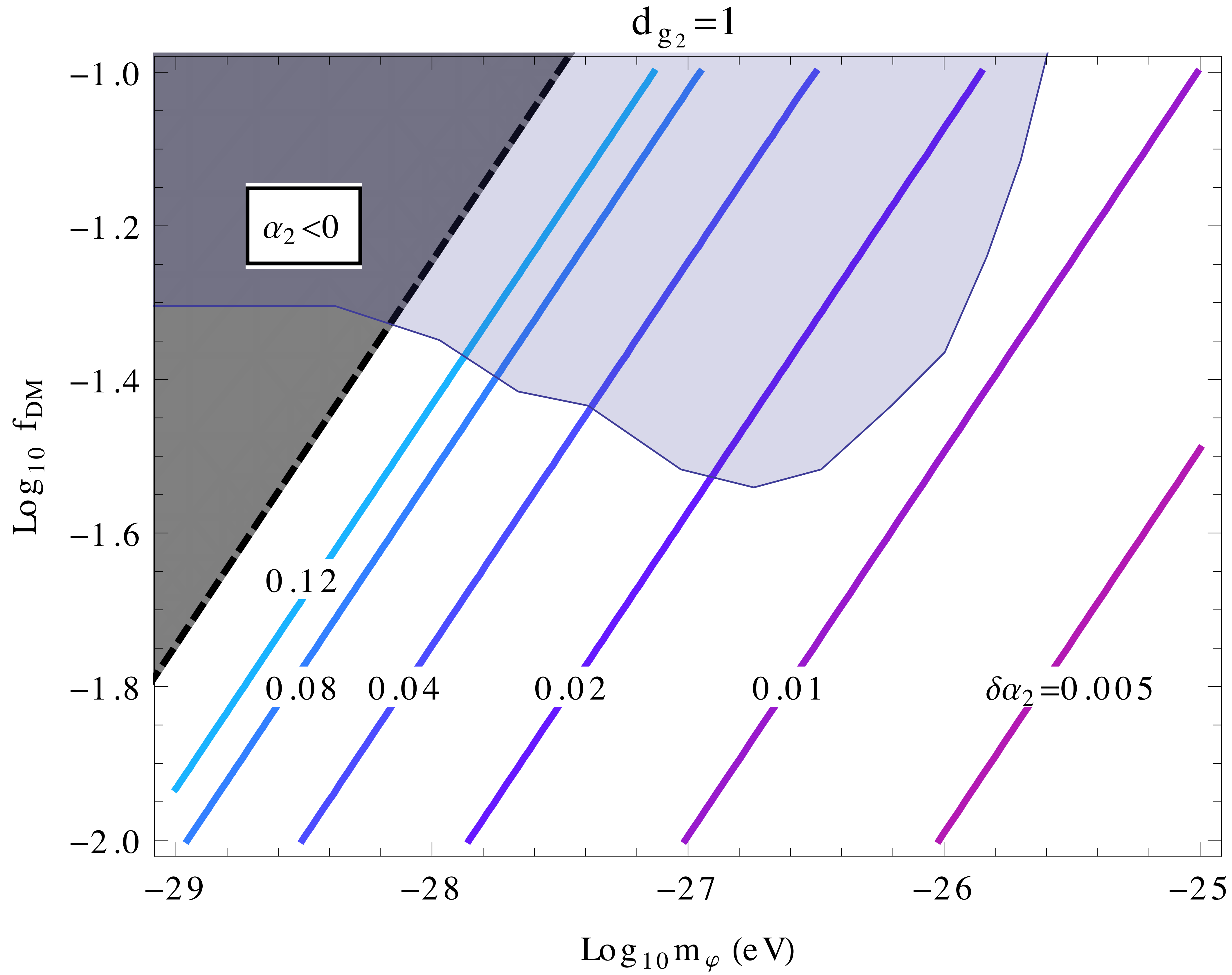
Tuning/Symmetry imposes

$$\frac{d_{g2}}{d_{gY}} = -\frac{\alpha_2}{\alpha_y}$$

If a tuning that is broken by running
it needs to hold reasonably well between z=4 and BBN

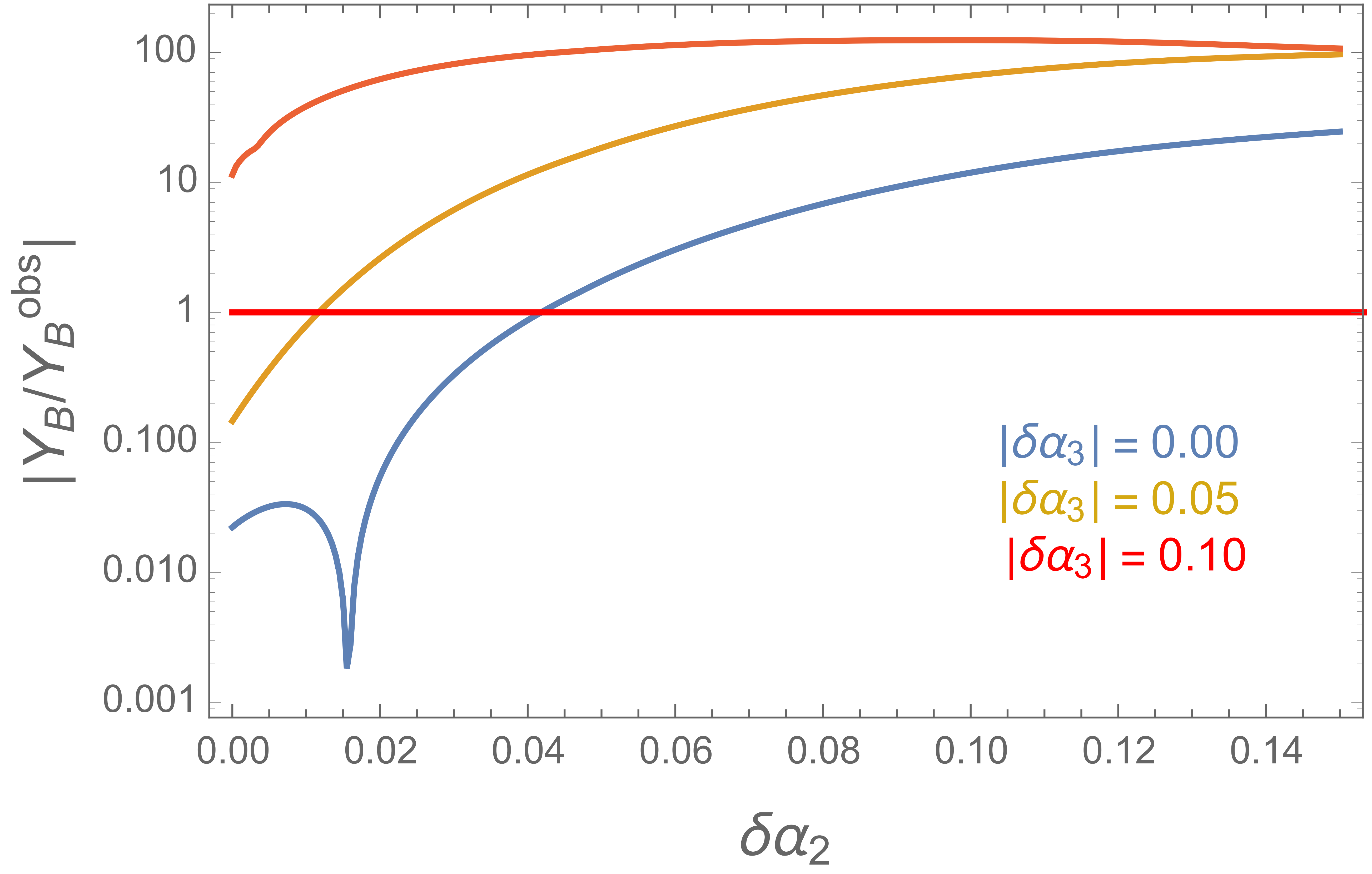
Approach 2: B violation

$$\delta\alpha_2 \approx \alpha_2 \left(\frac{d_{g2}\sqrt{f_{DM}}}{2.5 \times 10^6 m_{\rm pl}^{1/4} - d_{g2}\sqrt{f_{DM}}} \right)$$



Approach 2: B violation

Baryon asymmetry dependence on constants



Approach 2: B violation

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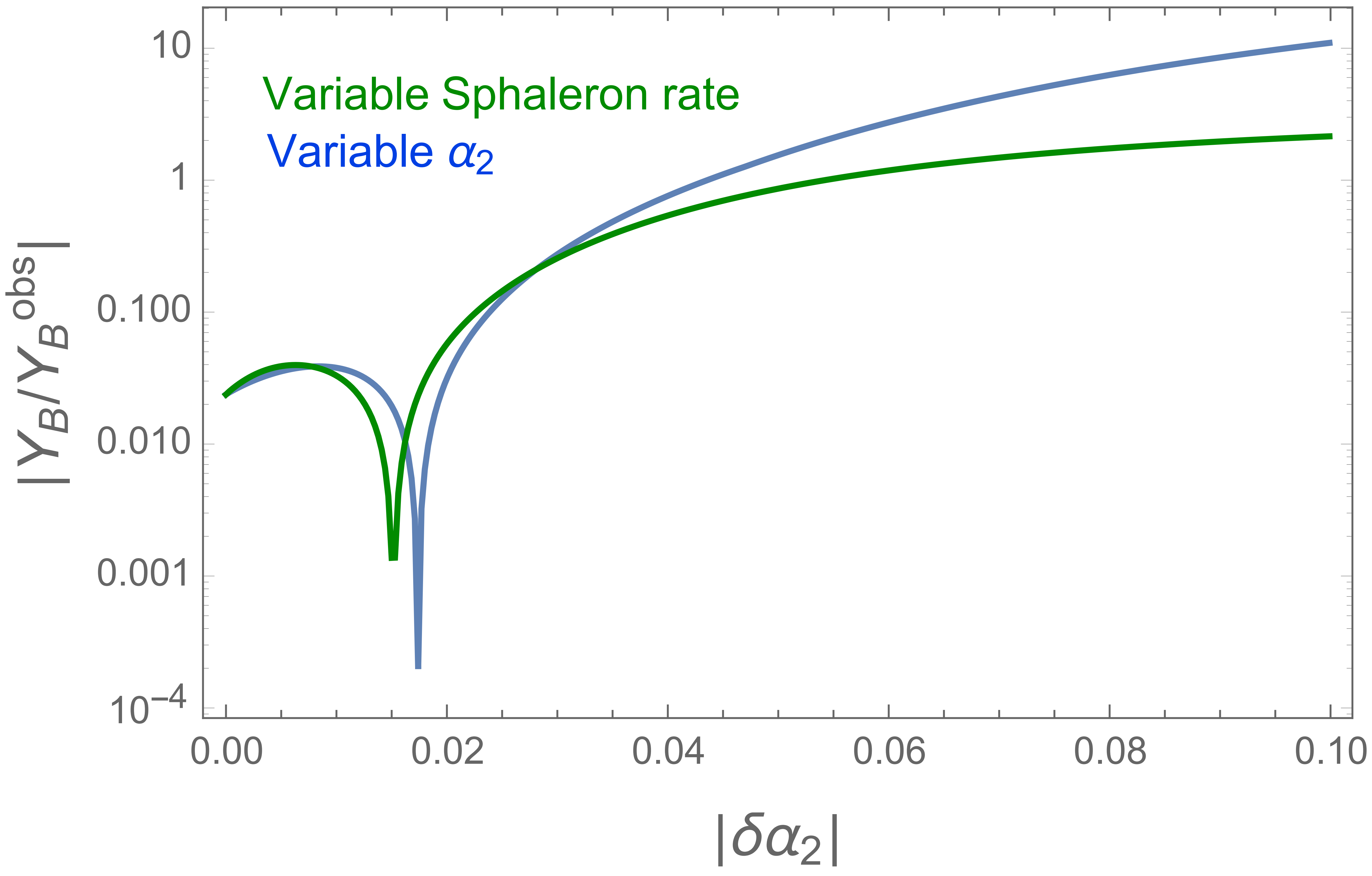
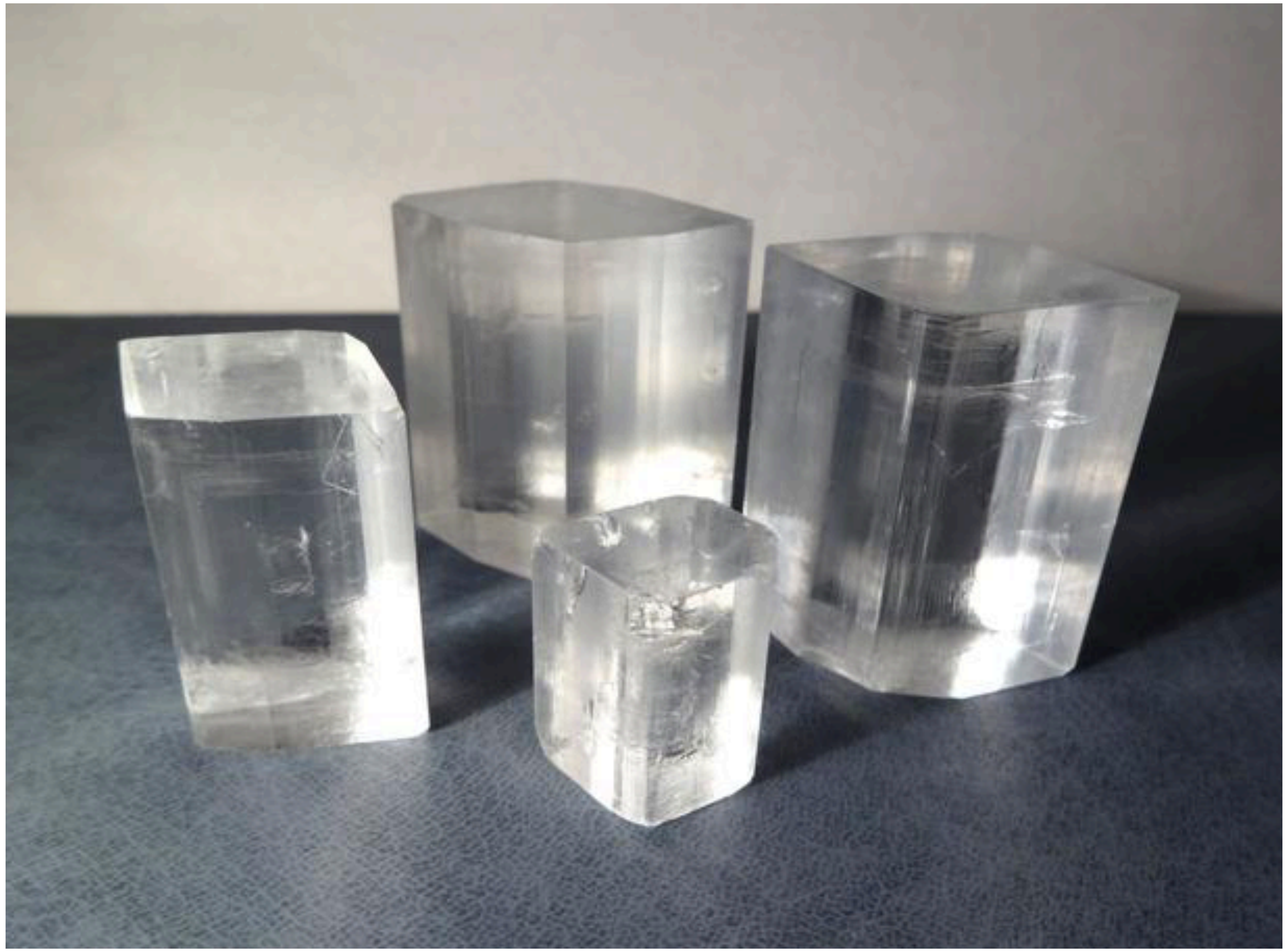


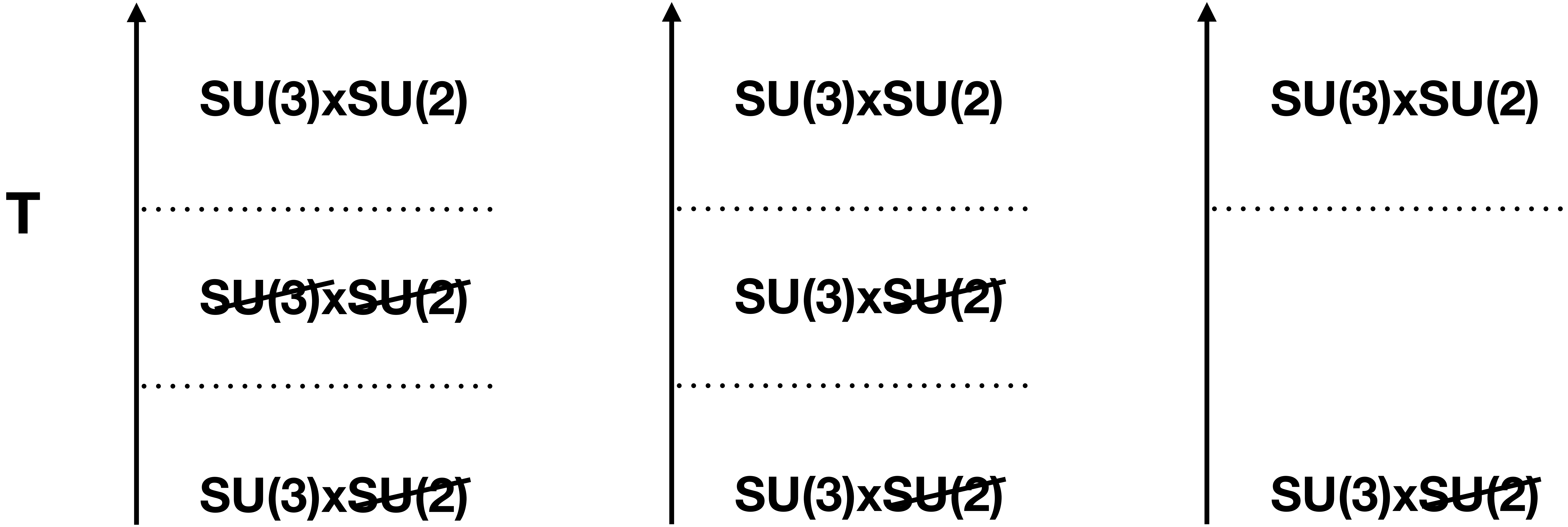
Approach 3: Departure from equilibrium

Heat up Rochelle salt and crystallization increases

Heat further again and the salt will melt



Approach 3: Departure from equilibrium



Approach 3: Departure from equilibrium

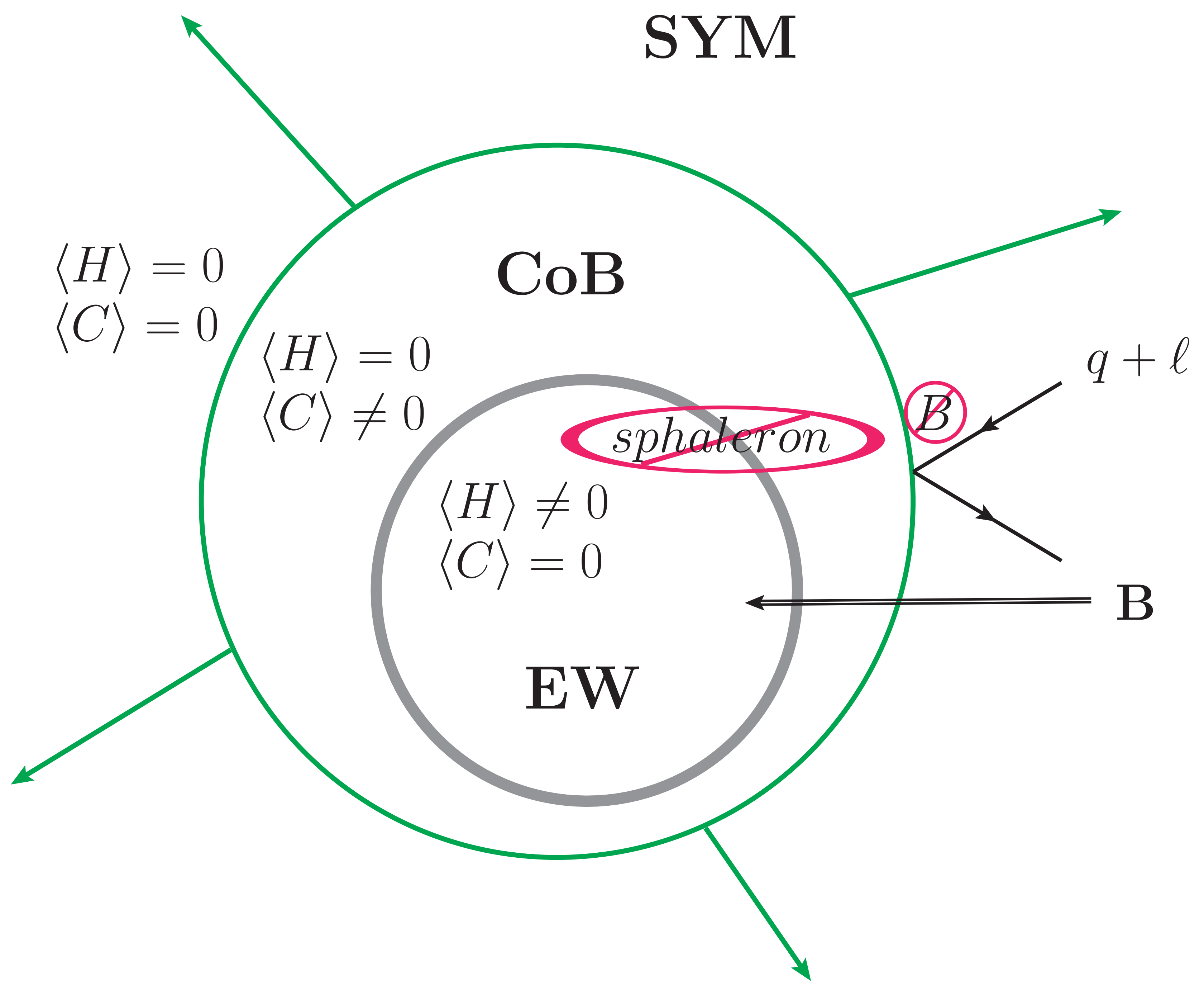
Lagrangian and model for COB

$$L = L_{\mathrm{SM}} + \lambda_i C_i \bar{b}_R L + \Delta V$$

$$C_i = (3,2,1/6)$$

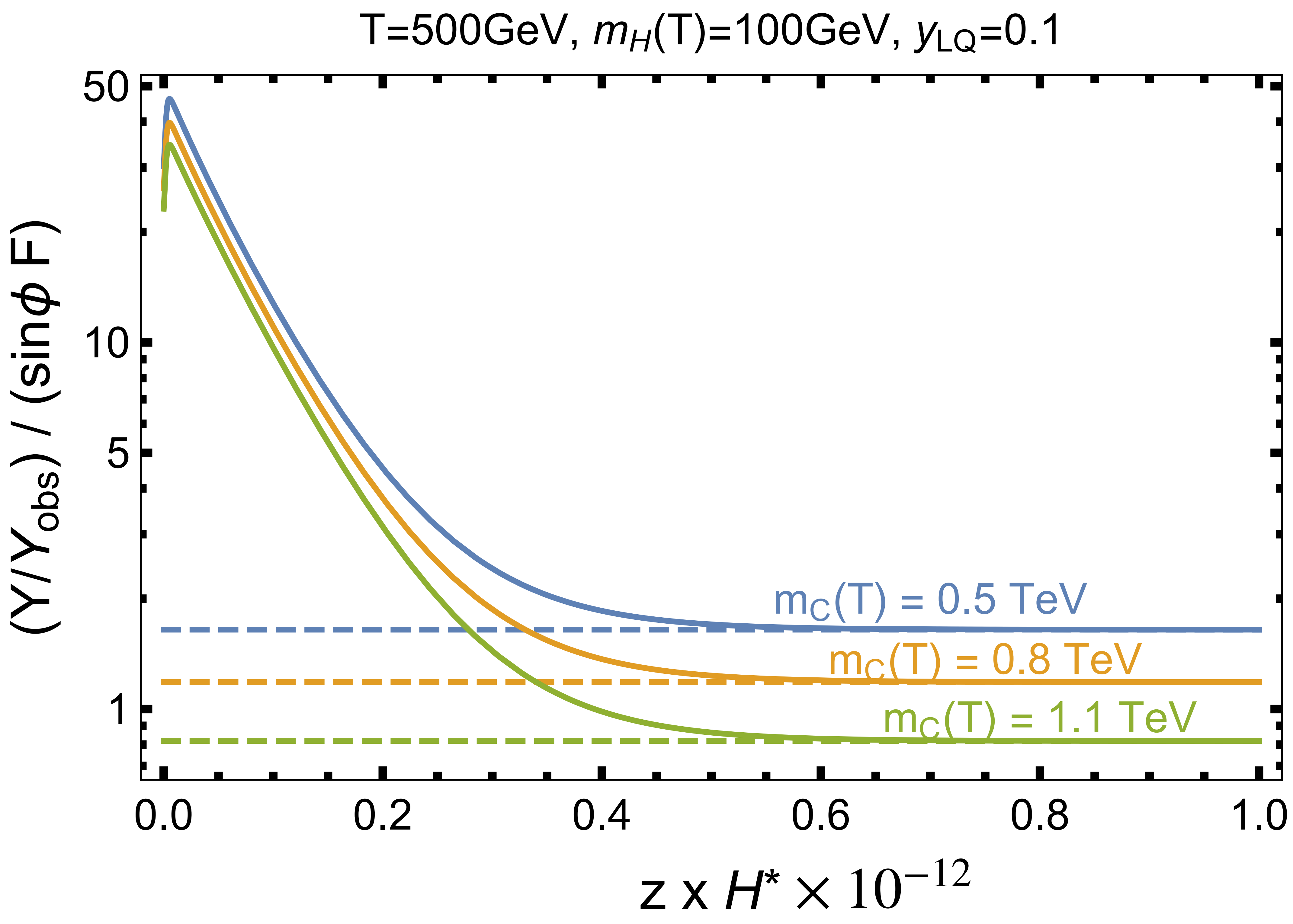
$\langle \not{B} \rangle \rightarrow$ **Spontaneous and Sphalerons**

$\not{CP} \leftrightarrow \lambda_i$ **Restrict to 3rd generation**



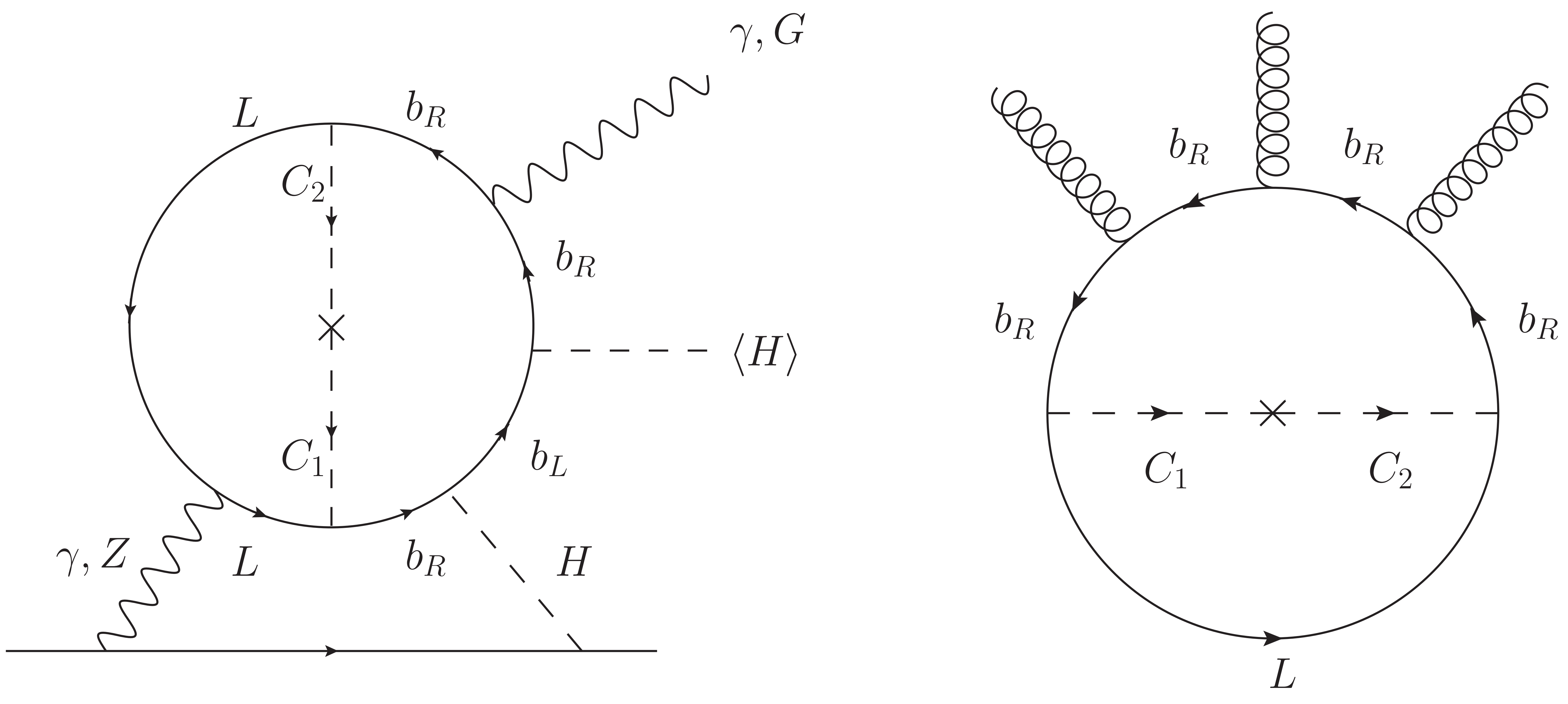
Departure from Equilibrium — Colour breaking phase.
Can happen at multi TeV scale

Approach 3: Departure from equilibrium



Approach 3: Departure from equilibrium

Experimental constraints



(a) (b)

Experimental signal: flavour anomalies, Gravitational waves, neutron EDM, leptoquark production at upgraded LHC?

Summary

While vanilla EWBG is still alive

EDMs motivate extensions to vanilla EWBG

Extensions are quite rich and still testable

Can be organized around Sakharov conditions:

1. **Modify B violation — Temperature dependent gauge constants**
2. **Modify CP violation — Tree level interfering with loop**
3. **Modify Departure from Eq - Richer phase history**

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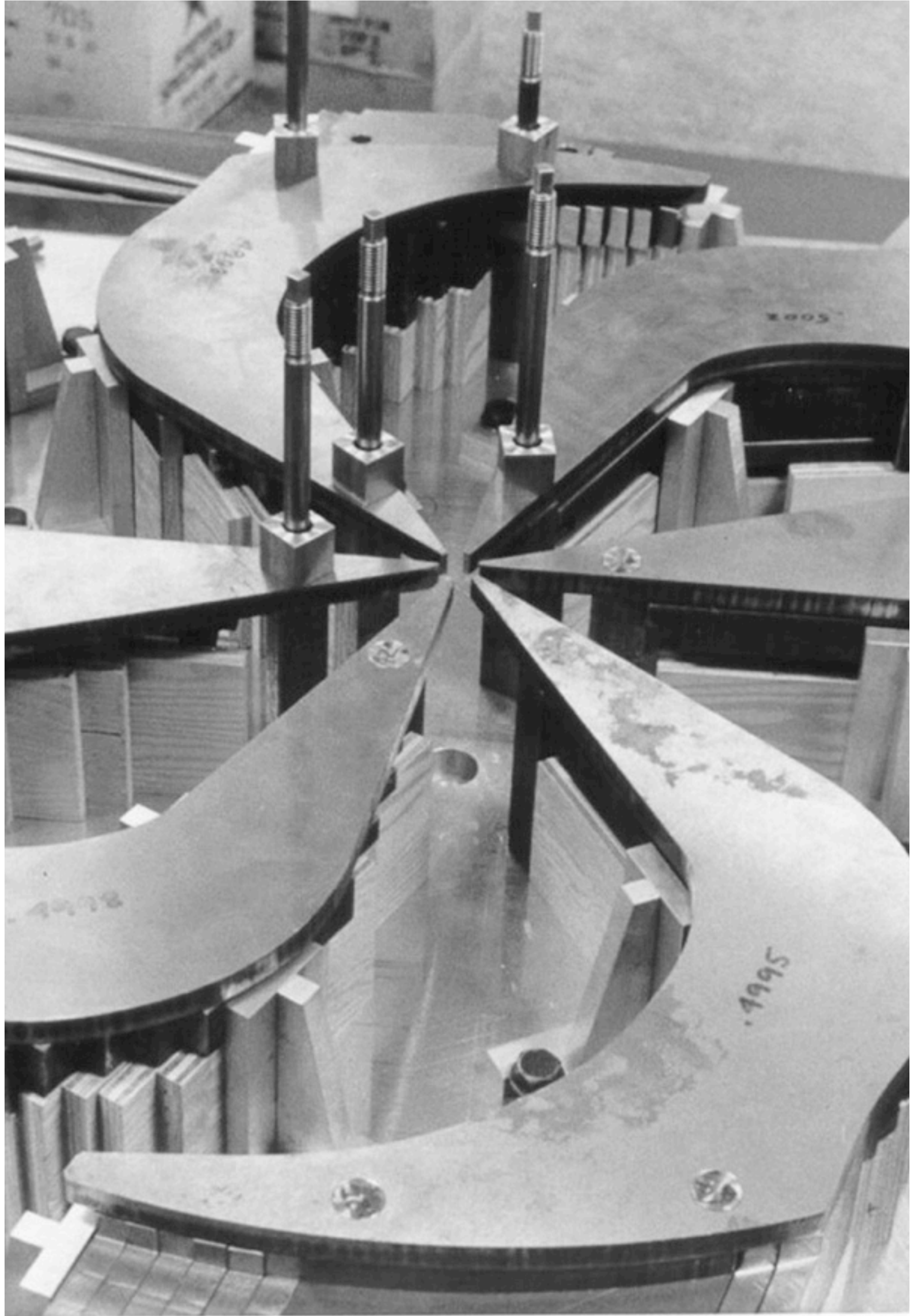
Thank you
Merci



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