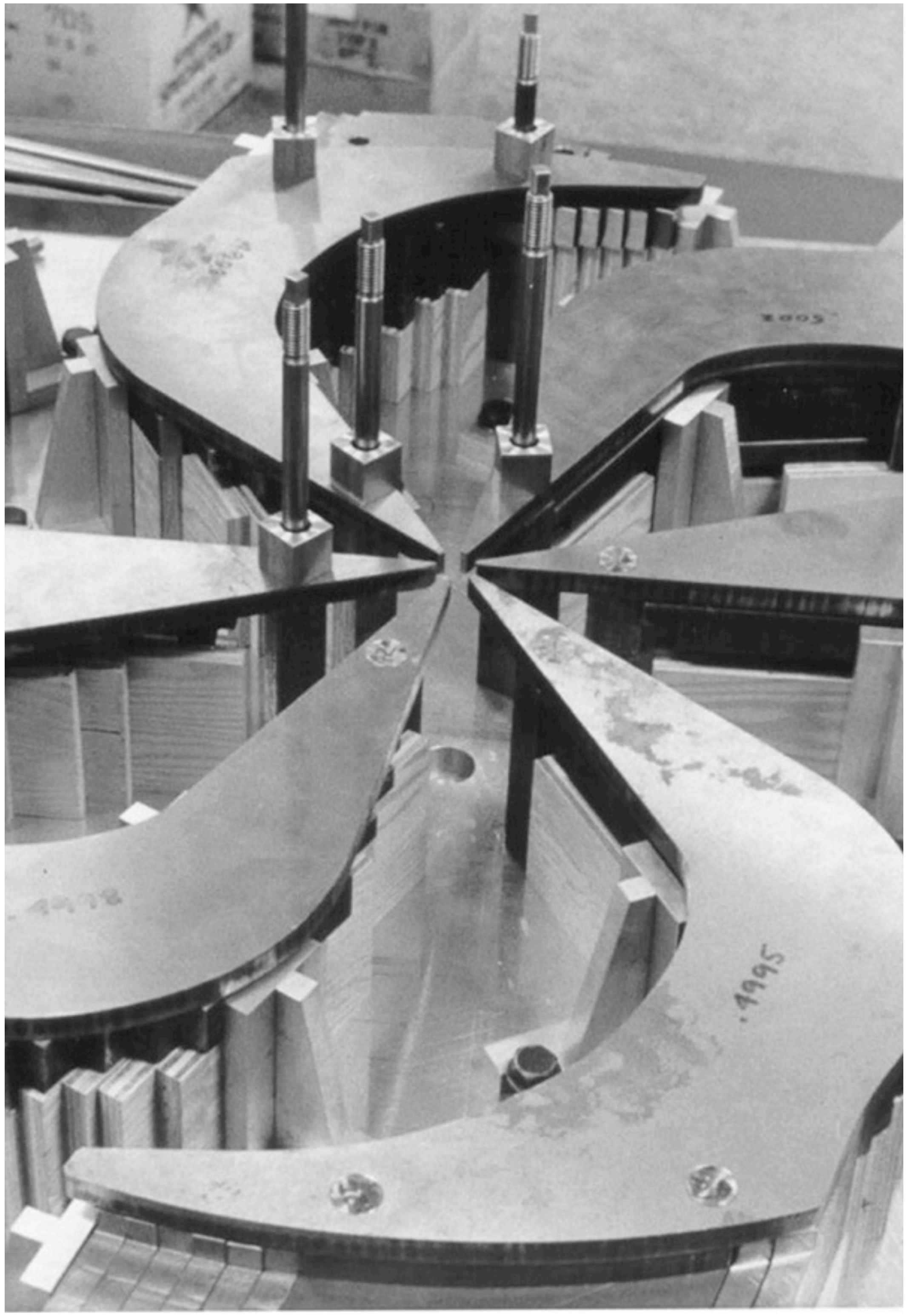
TRIUMF

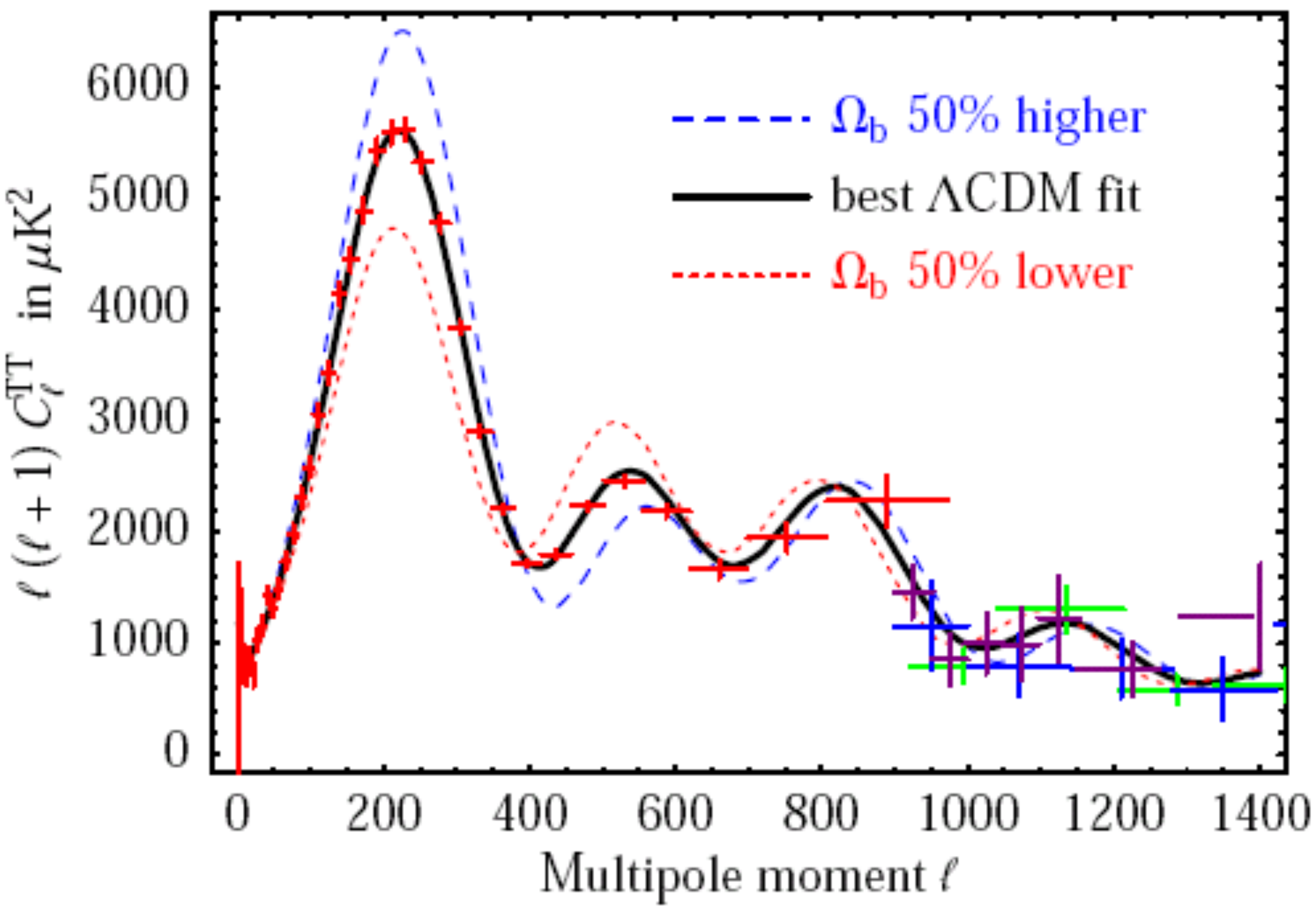
Electroweak baryogenesis, experimental status, progress and extensions

with Csaba Balazs, Michael Ramsey Musolf, David Morrissey, Seyda Ipek, Sebastian Ellis, Joydeep Roy, Jorinde Van de Vis, Jordy De Vries, Marieke Postma, Sujeet Akula, Liam Duncan, Peter Athron, Michael Bardsley, Peter Winslow, Djuna Croon, Toumas Tenkanen and Oli Gould

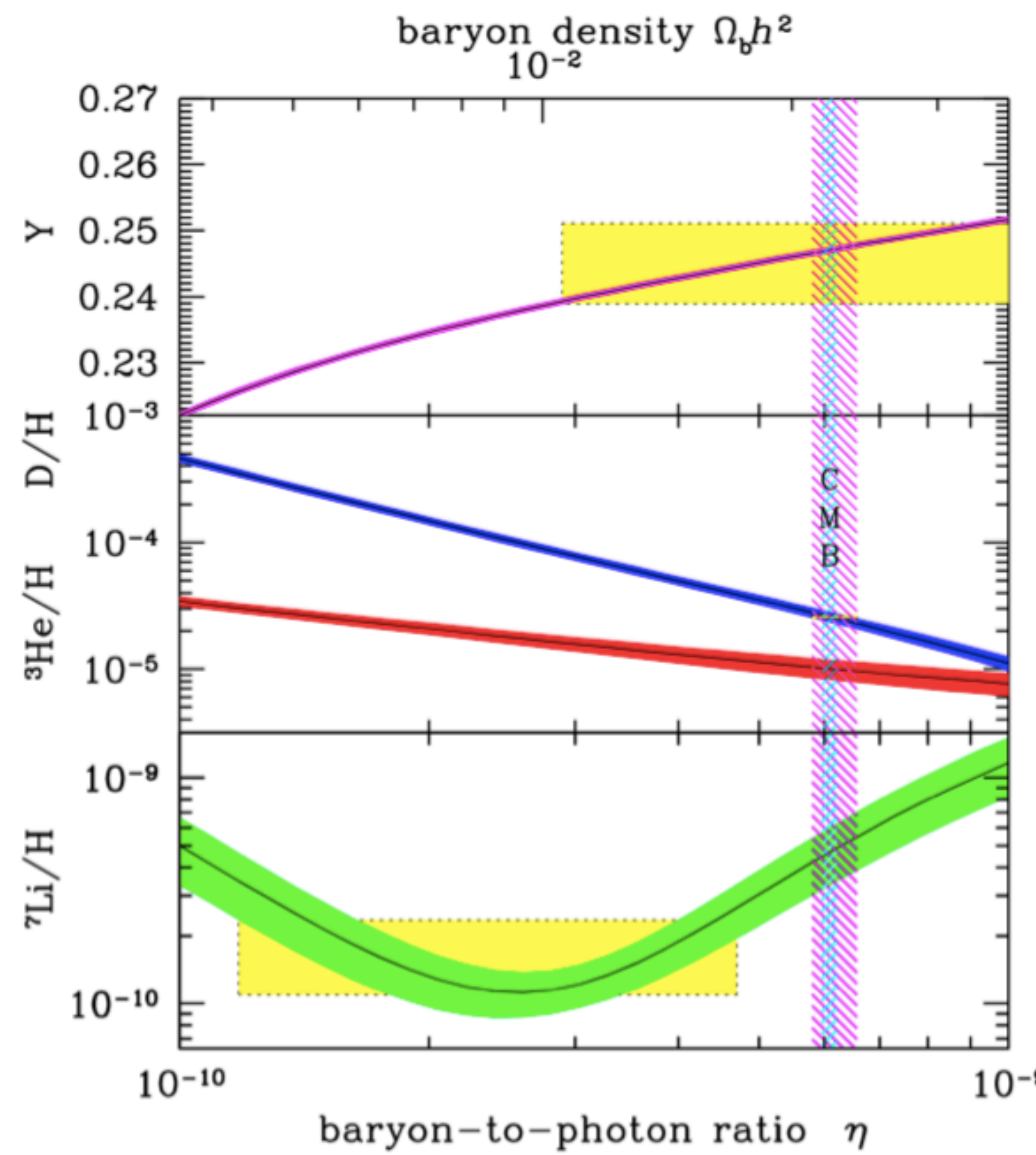


Discovery, accelerated

Baryon asymmetry



Ng. K. Francis (thesis)



Particle data group

Washout and Sakharov conditions

Inflation washes out initial baryon asymmetry (almost) 3

Sakharov conditions

- **C and CP violation**
- **Violation of BNC**
- **Departure from Equilibrium***

Electroweak baryogenesis

How it fulfils the Sakharov conditions

Inflation washes out initial baryon asymmetry (almost)

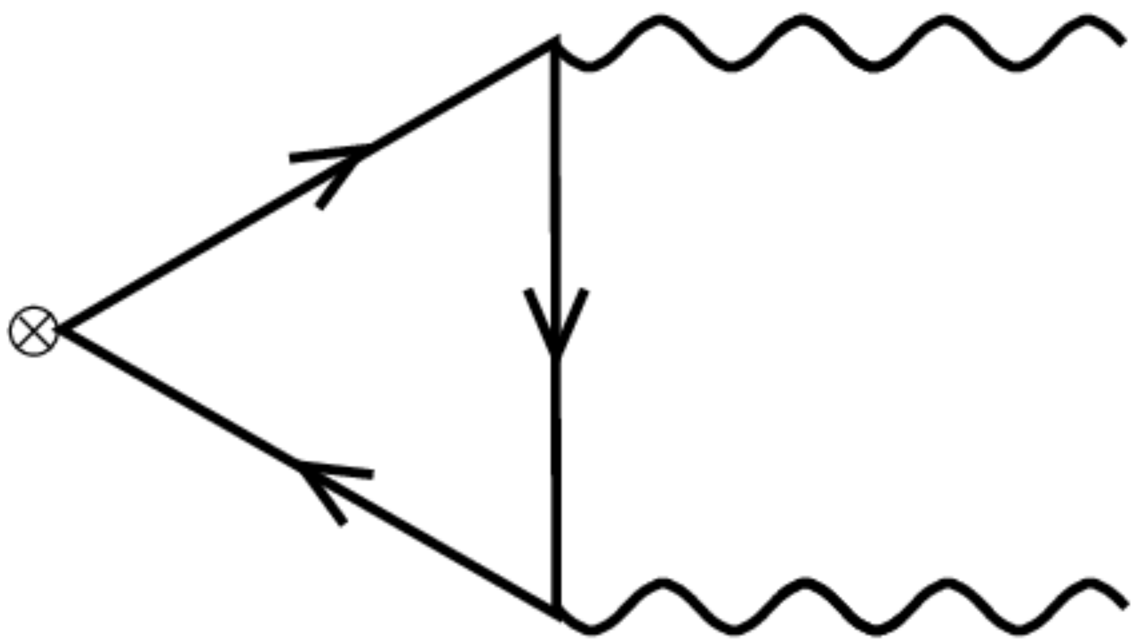
Sakharov conditions

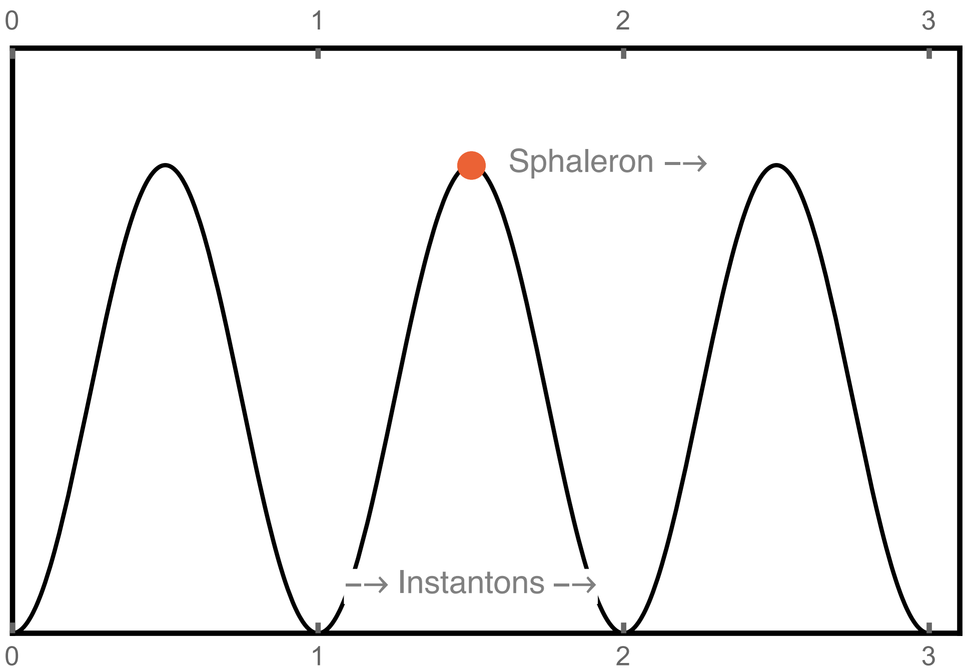
- **C and CP violation** <— — **CPV interactions with Higgs**
- **Violation of BNC** <— — **Non-perturbative processes (sphalerons)**
- **Departure from Equilibrium*** <— — **Electroweak phase transition**

Electroweak baryogenesis

BNC violation: sphalerons

$$\partial_\mu J^\mu_{B+L} \sim W\tilde{W}$$
$$\partial_\mu J^\mu_5 \sim G\tilde{G}$$

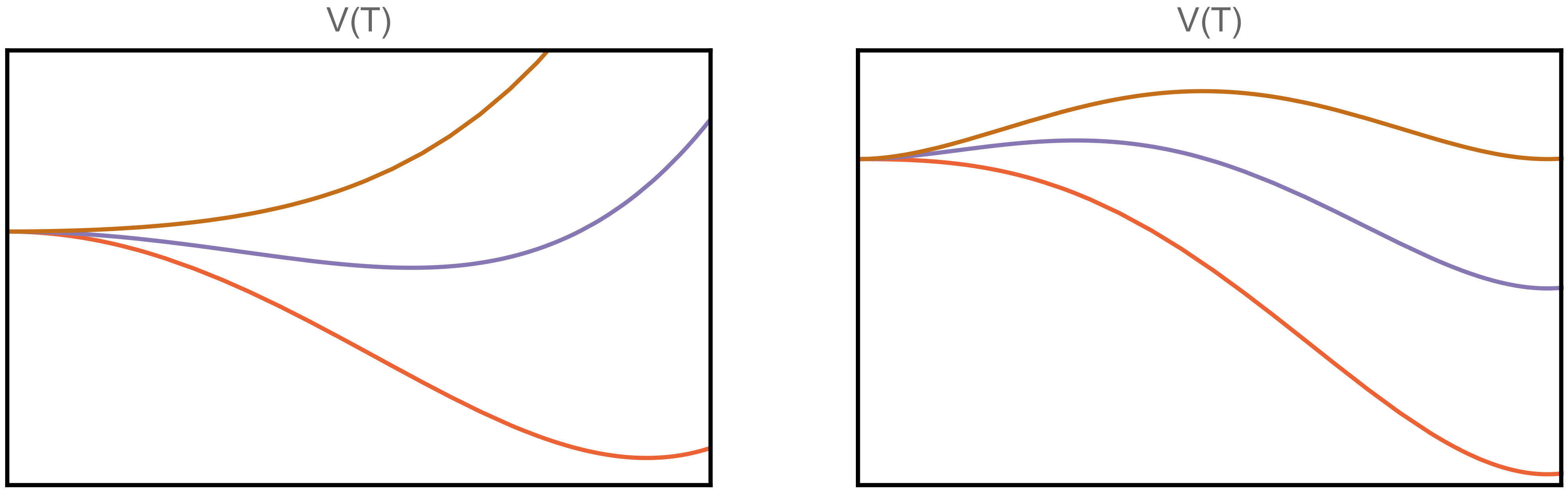




Want more details? read my book!

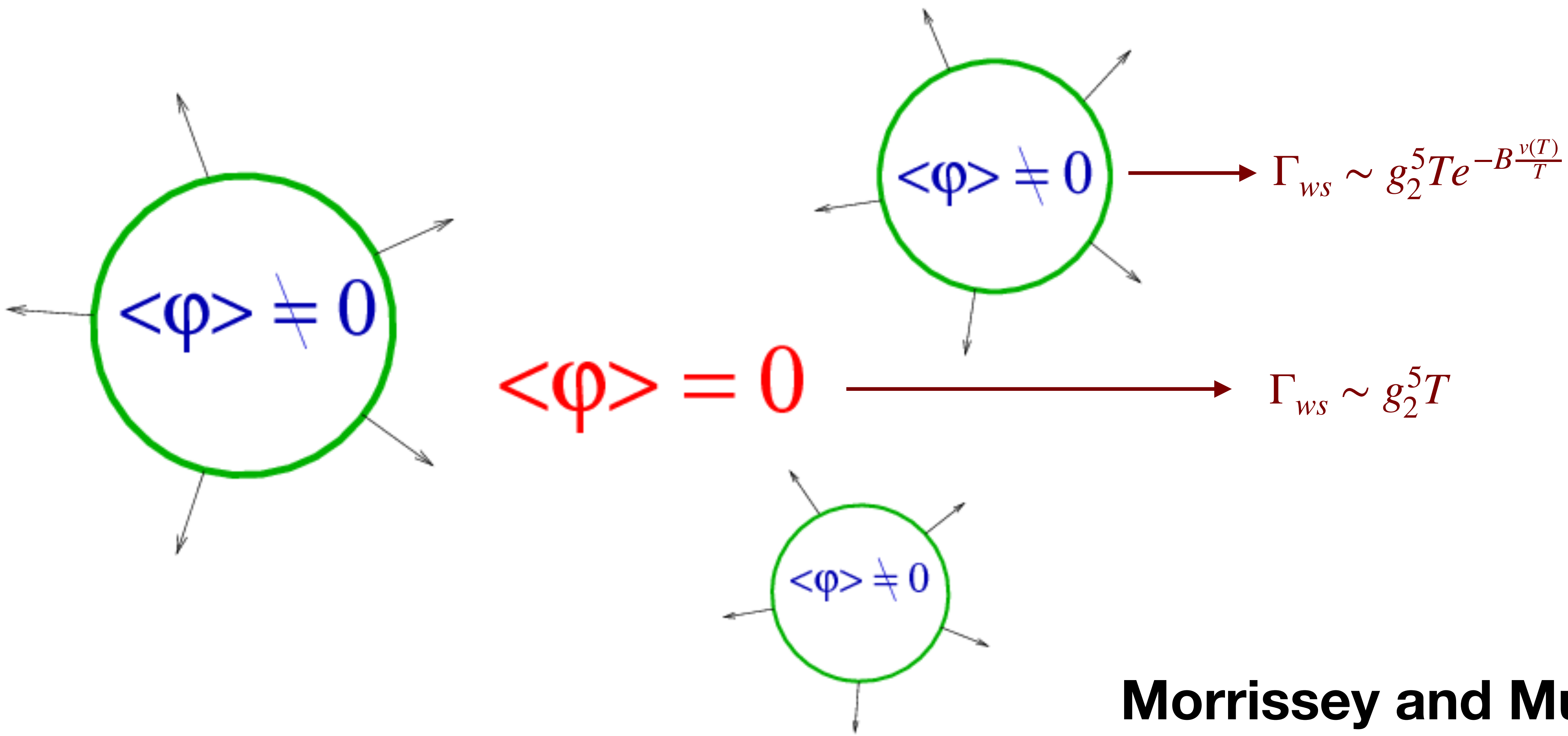
Electroweak baryogenesis

Electroweak symmetry at high temperature



Electroweak baryogenesis

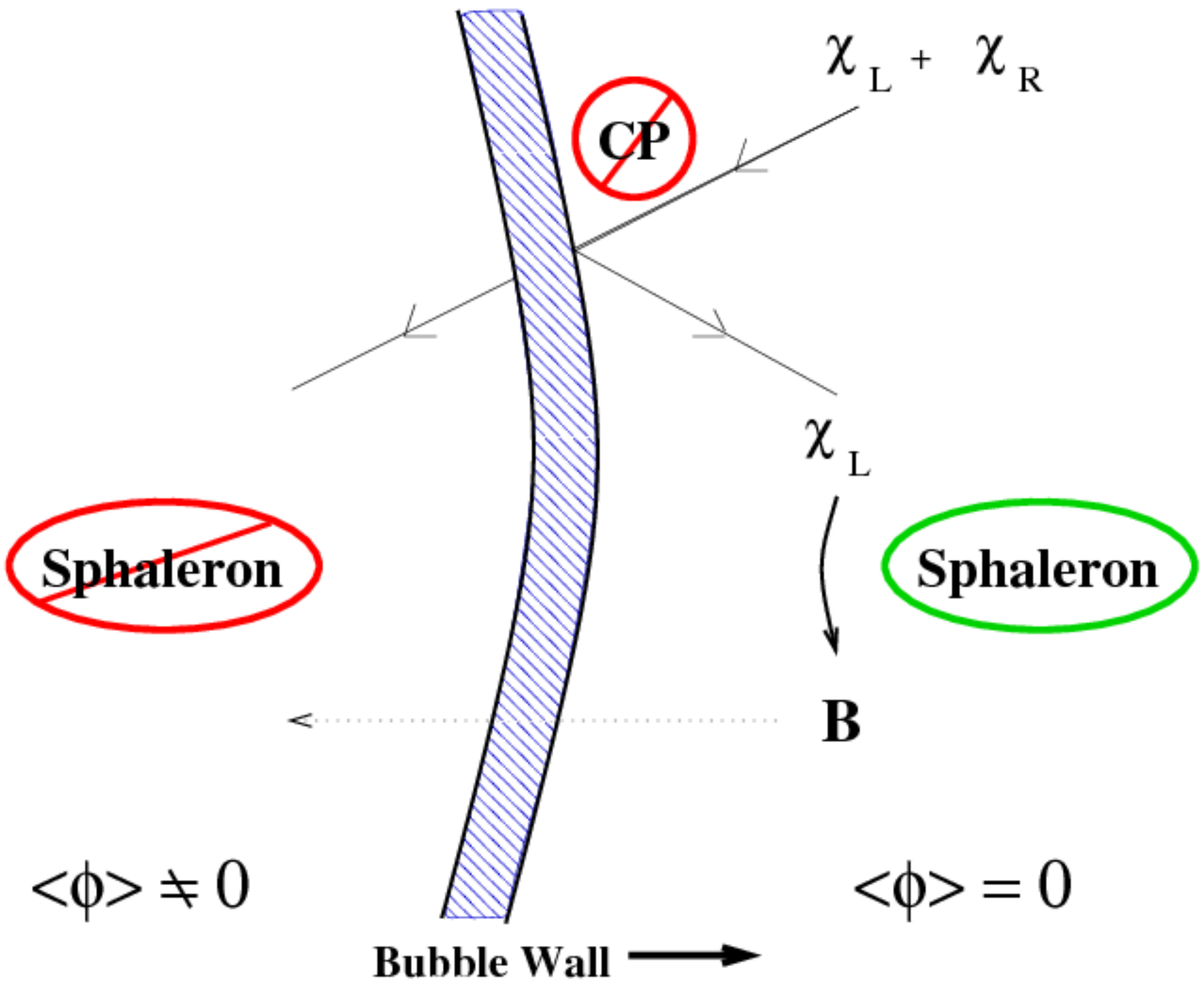
Electroweak symmetry at high temperature



Morrissey and Musolf

Electroweak baryogenesis

Electroweak symmetry at high temperature



$$D_Q \rho_B'' - v_W \rho_B' - R\Gamma_{ws}(z)\rho_B = \frac{n_F}{2}\Gamma_{ws}(z) n_L(z)$$

Morrissey and Musolf

Electroweak baryogenesis

Experimental signatures:

Gravitational waves
Collider signatures
EDMs

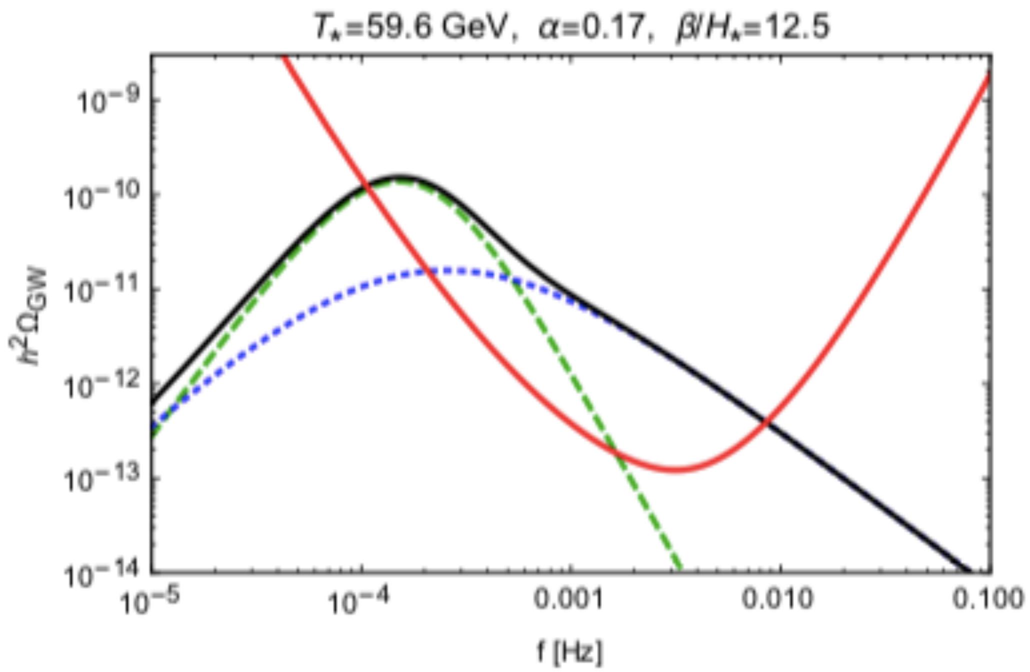
Electroweak baryogenesis

Experimental signatures of PT: GWs 1

1st order transitions have 3 contributions:

- **Acoustic contribution**
- **Turbulent contribution**
- **Bubble collision**

All obey a broken power law



arxiv:1801.04268

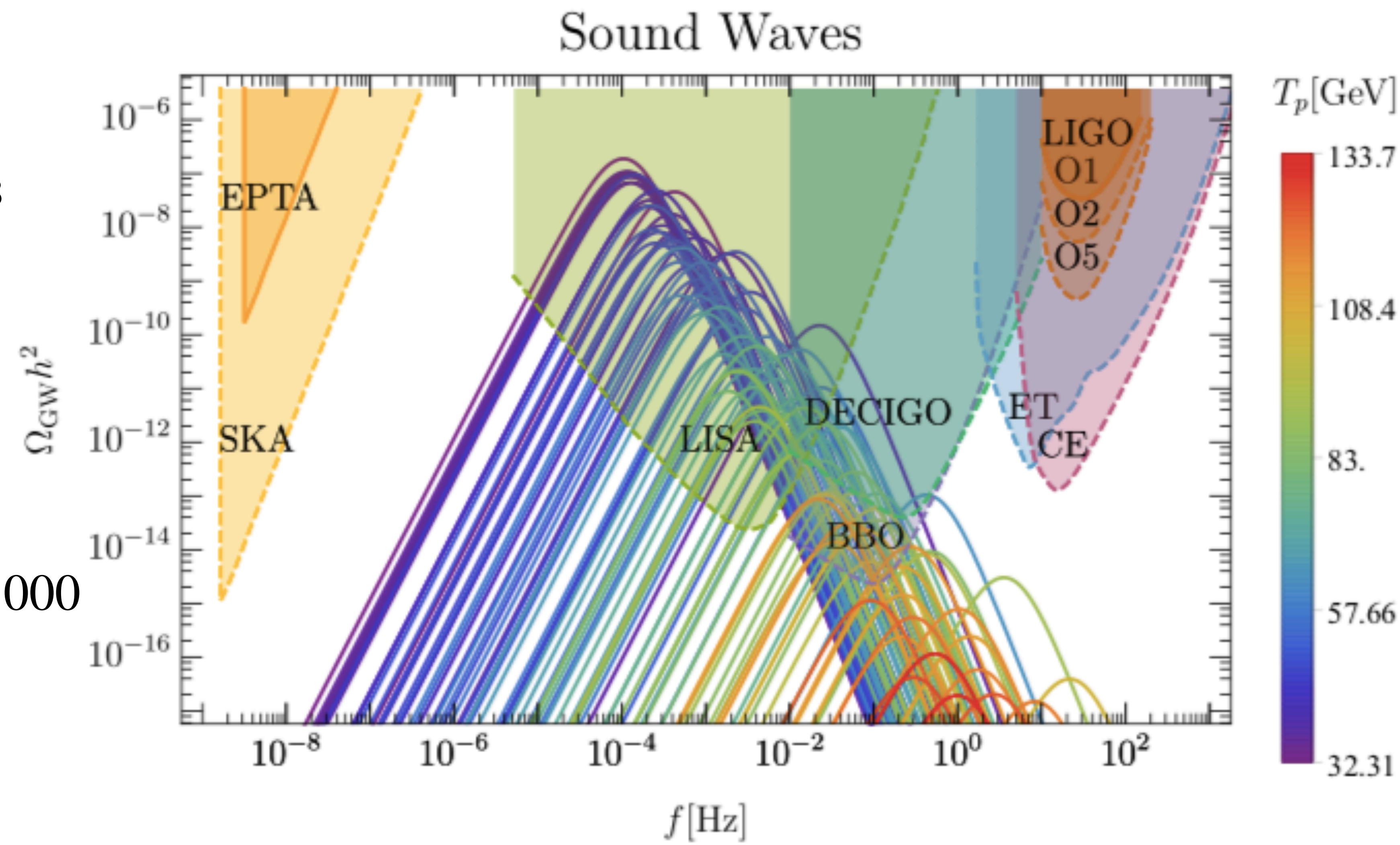
Electroweak baryogenesis

Experimental signatures of PT: GWs 3

$$f_{sw} \sim 0.5 \times \left(\frac{\beta}{H_*}\right) T_*(\text{GeV}) \times 10^{-8}$$

Usually $\left(\frac{\beta}{H_*}\right) \gtrsim 1000$

Supercooled: $10 < \left(\frac{\beta}{H_*}\right) < 1000$

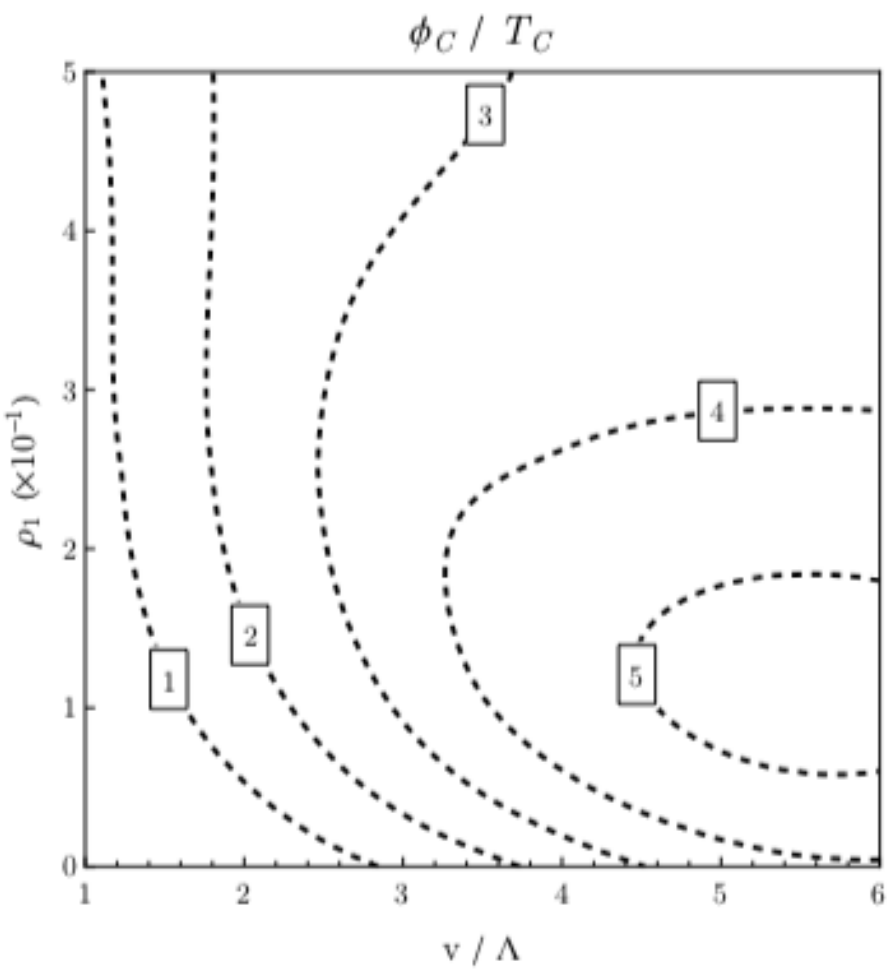


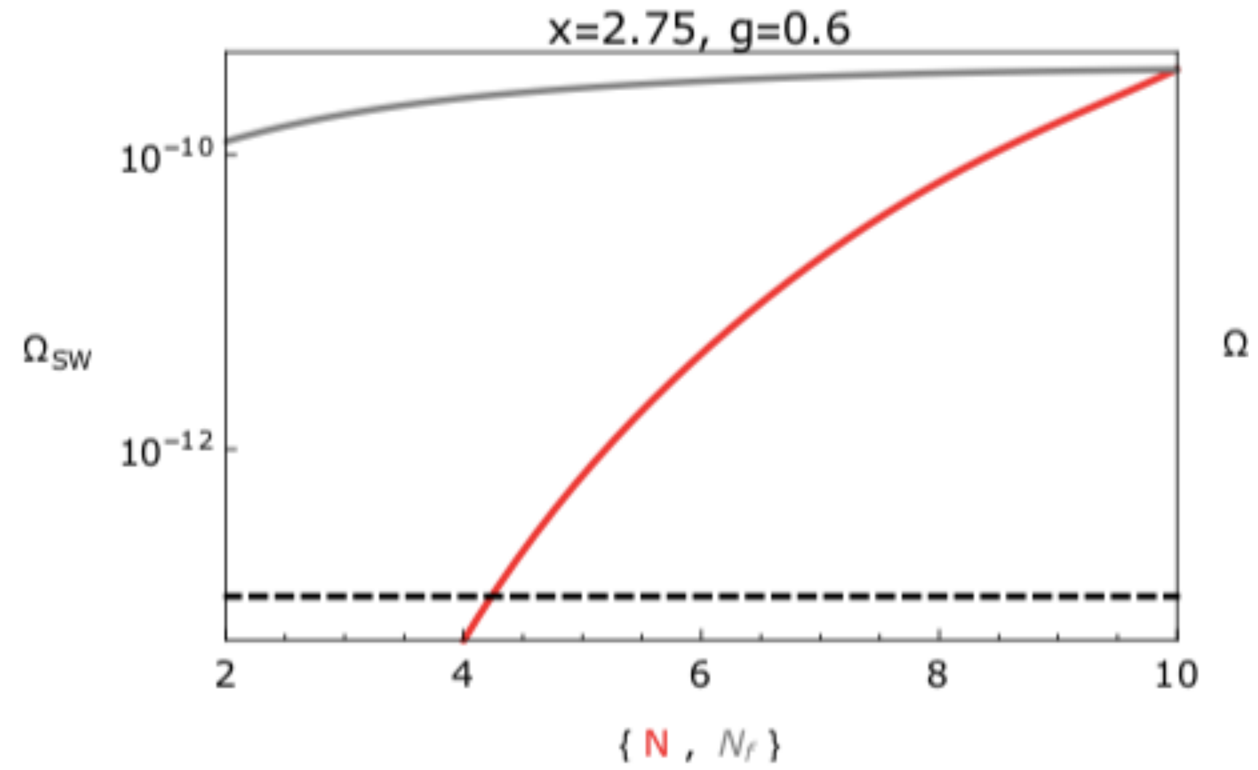
1810.02380

Electroweak baryogenesis

What drives the strength of the GW?

1st case: normal case: $V = \Lambda^4 \left[-\frac{1}{2}\left(\frac{h}{v}\right)^2 + \frac{1}{4}\left(\frac{h}{v}\right)^4 \right]$





SM has N=3, Nf=1, v/Λ=1.6 - not even SFO!

1812.02747,1806.02332

Electroweak baryogenesis

What drives the strength of the GW?

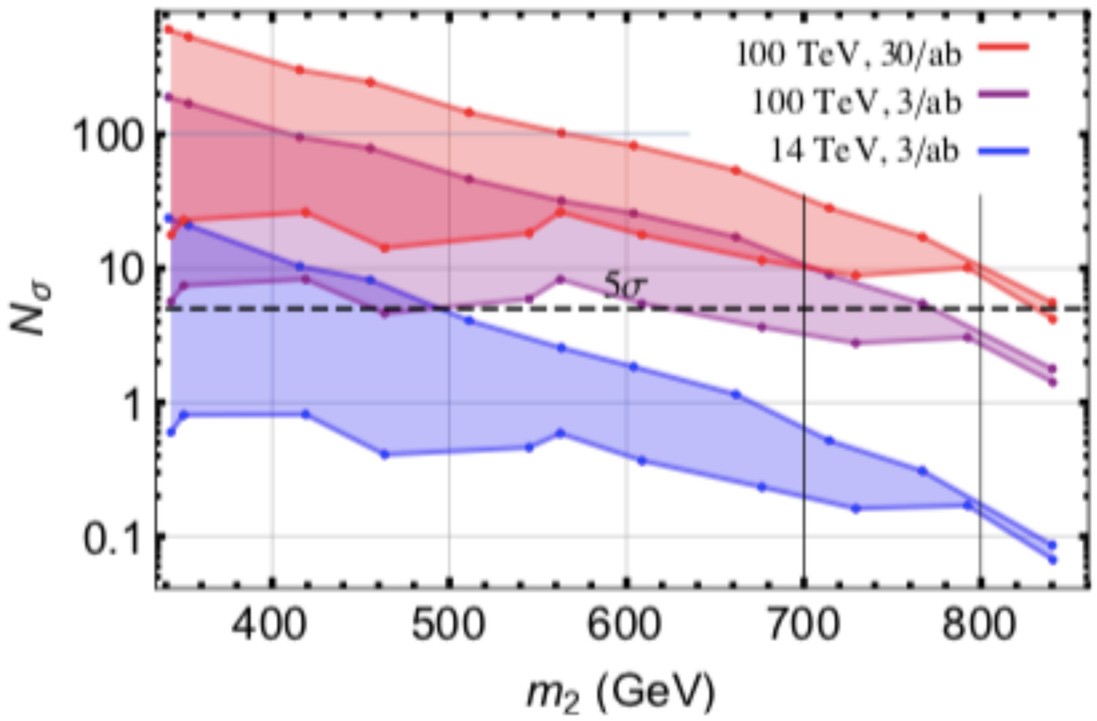
Supercooled case:

$$\phi = ah + bs, \quad V \sim \Lambda(T)^4 \left[\frac{(3 - 4\alpha(T))}{2} \left(\frac{\phi}{v(T)} \right)^2 - \left(\frac{\phi}{v(T)} \right)^3 + \alpha(T) \left(\frac{\phi}{v(T)} \right)^4 \right]$$

$$V = \Lambda(T)^4 \left[(2 - 3\alpha(T)) \left(\frac{h}{v(T)} \right)^2 - \left(\frac{h}{v(T)} \right)^4 + \alpha(T) \left(\frac{h}{v(T)} \right)^6 \right]$$

Electroweak baryogenesis

Experimental signatures of PT: Collider 1

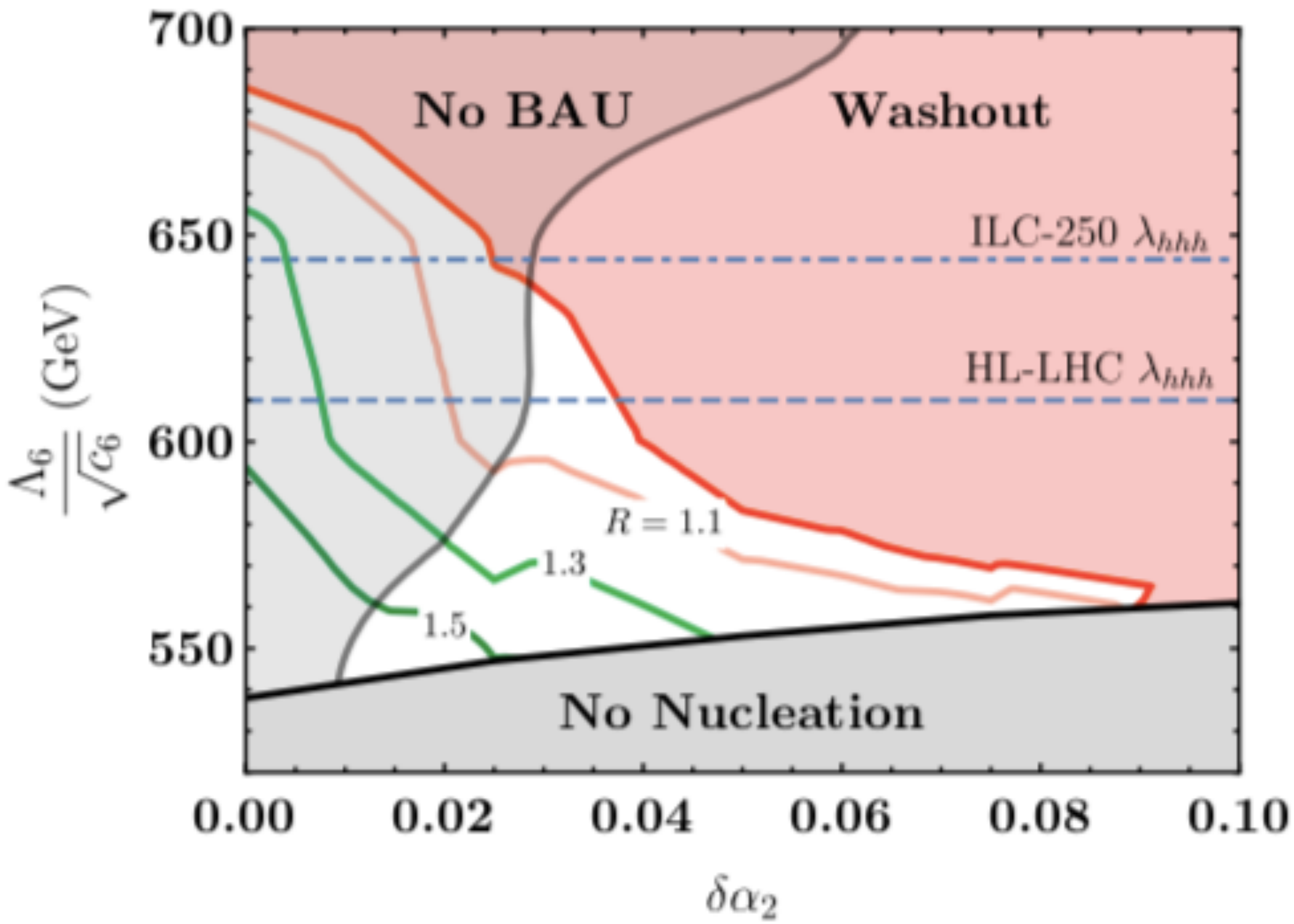


$b\bar{b}\gamma\gamma$ and 4τ final states

1605.06123

Electroweak baryogenesis

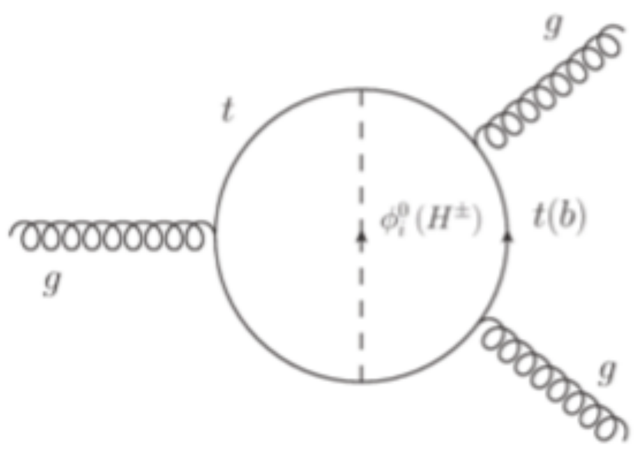
Experimental signatures of PT: Collider 2



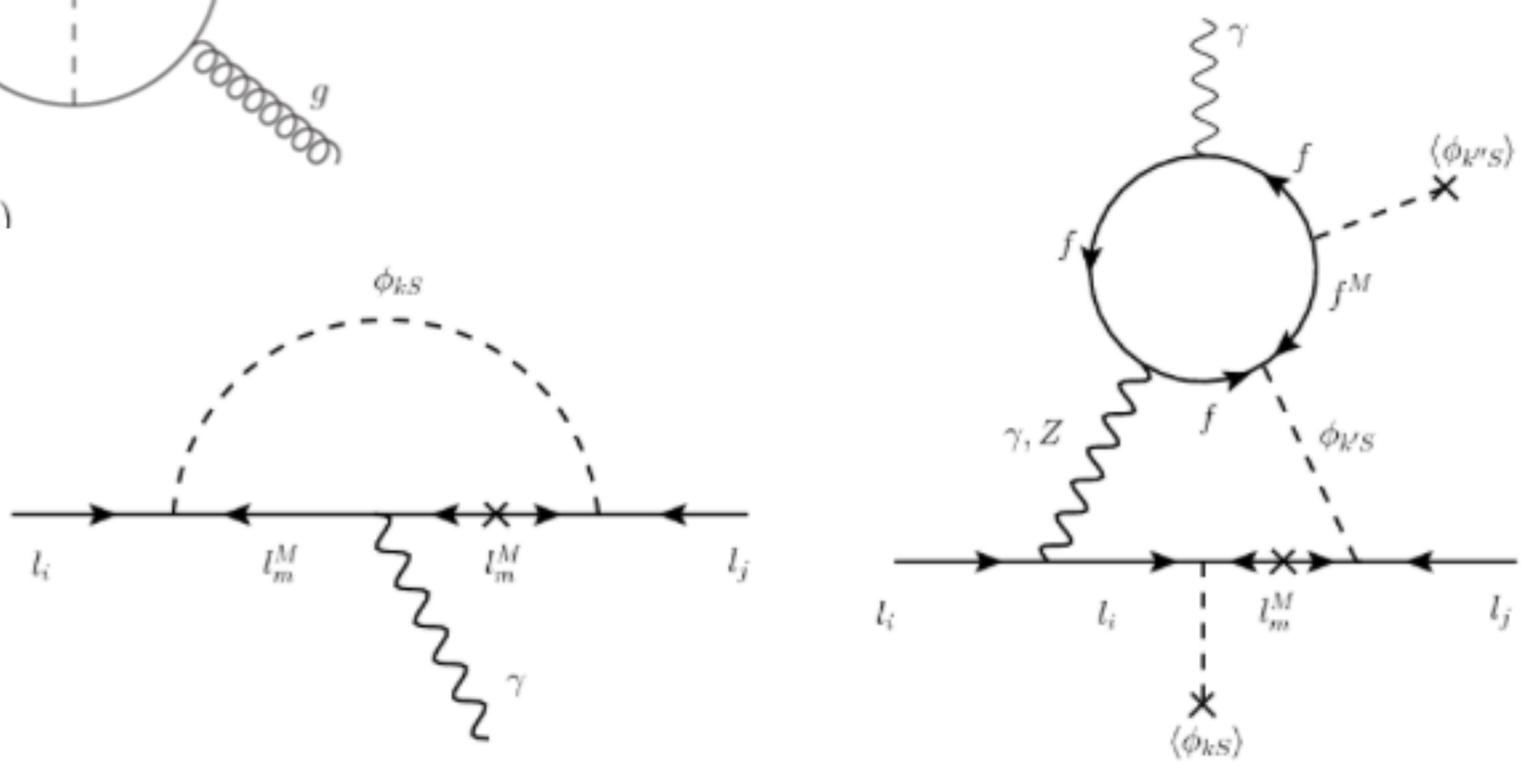
1905.11994

Electroweak baryogenesis

Experimental signatures of CPV: EDMs 2



(a)



(a) (b)

1308.6283 1702.04516

$$d_n \lesssim 3 \times 10^{-26} e \cdot cm$$

$$d_e < 1.1 \times 10^{-29} e \cdot cm$$

Electroweak baryogenesis

Calculation issues:

CP violating source

Electroweak phase transition

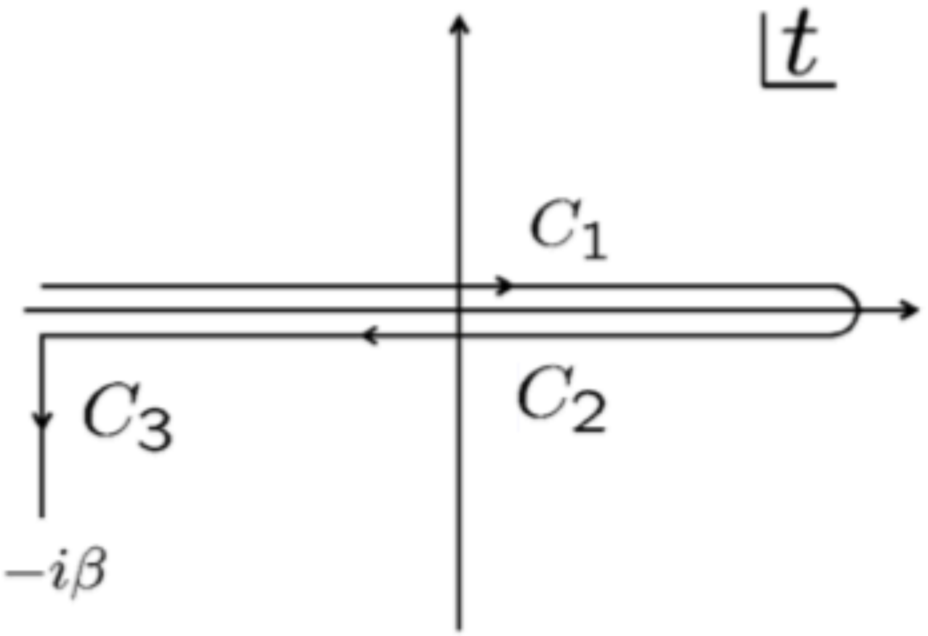
Electroweak baryogenesis

Calculation of CP source

Cartoon of thermal field theory

Four types of 2 point correlators

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



Electroweak baryogenesis

Calculation of CP source

Cartoon of calculation

$$G = G_0 + \Delta G$$

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

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

Space time varying basis!

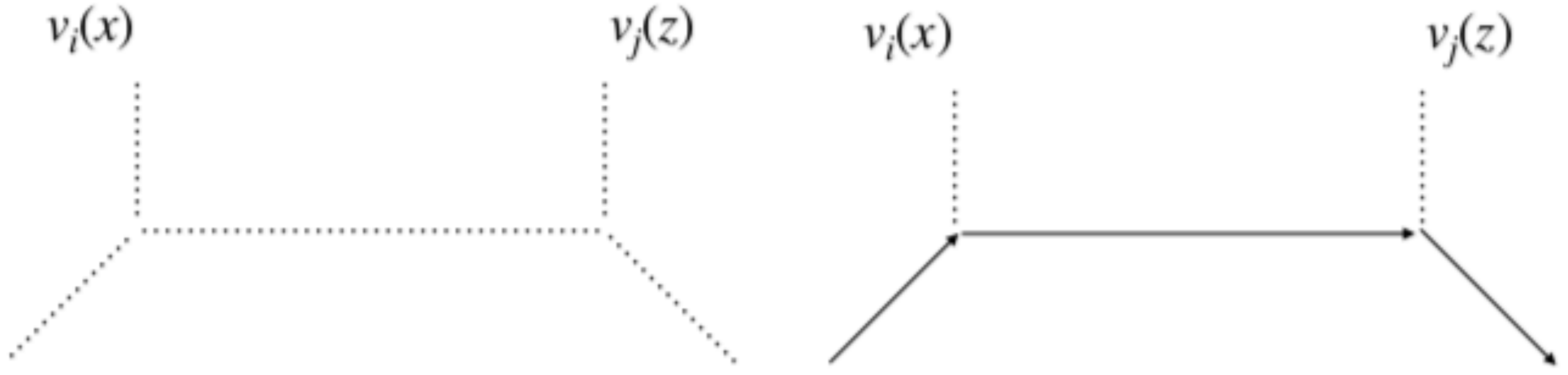
VEV insertion approach:

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

Electroweak baryogenesis

Calculation of CP source

Vev insertion sources

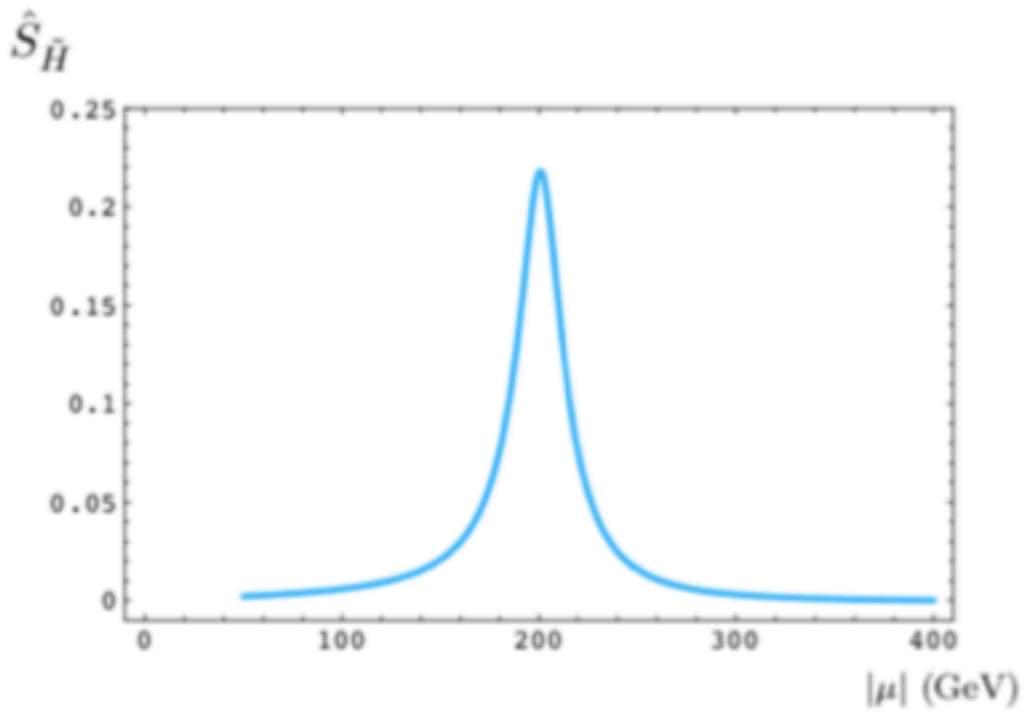


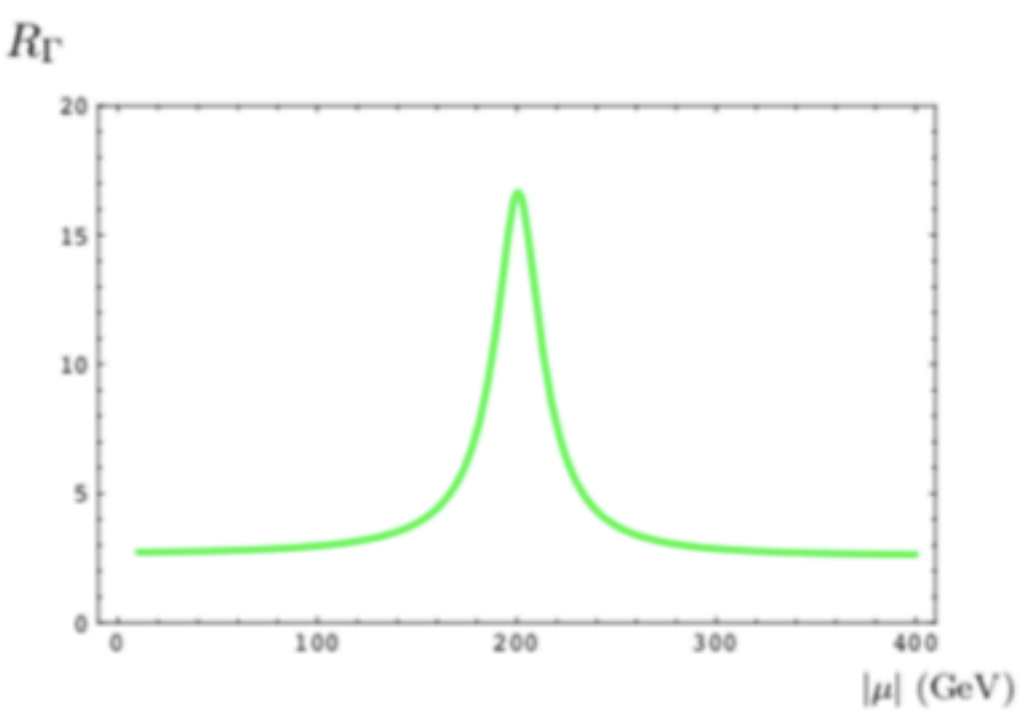
$$\partial_\mu J^\mu = \lim_{y=x} \int d^4z G^{+-}(x,z)\Sigma^{-+}(z,y) + \cdots$$

Electroweak baryogenesis

Calculation of CP source

Resonant behaviour of sources





Lee, hep-ph/0412354

Electroweak baryogenesis

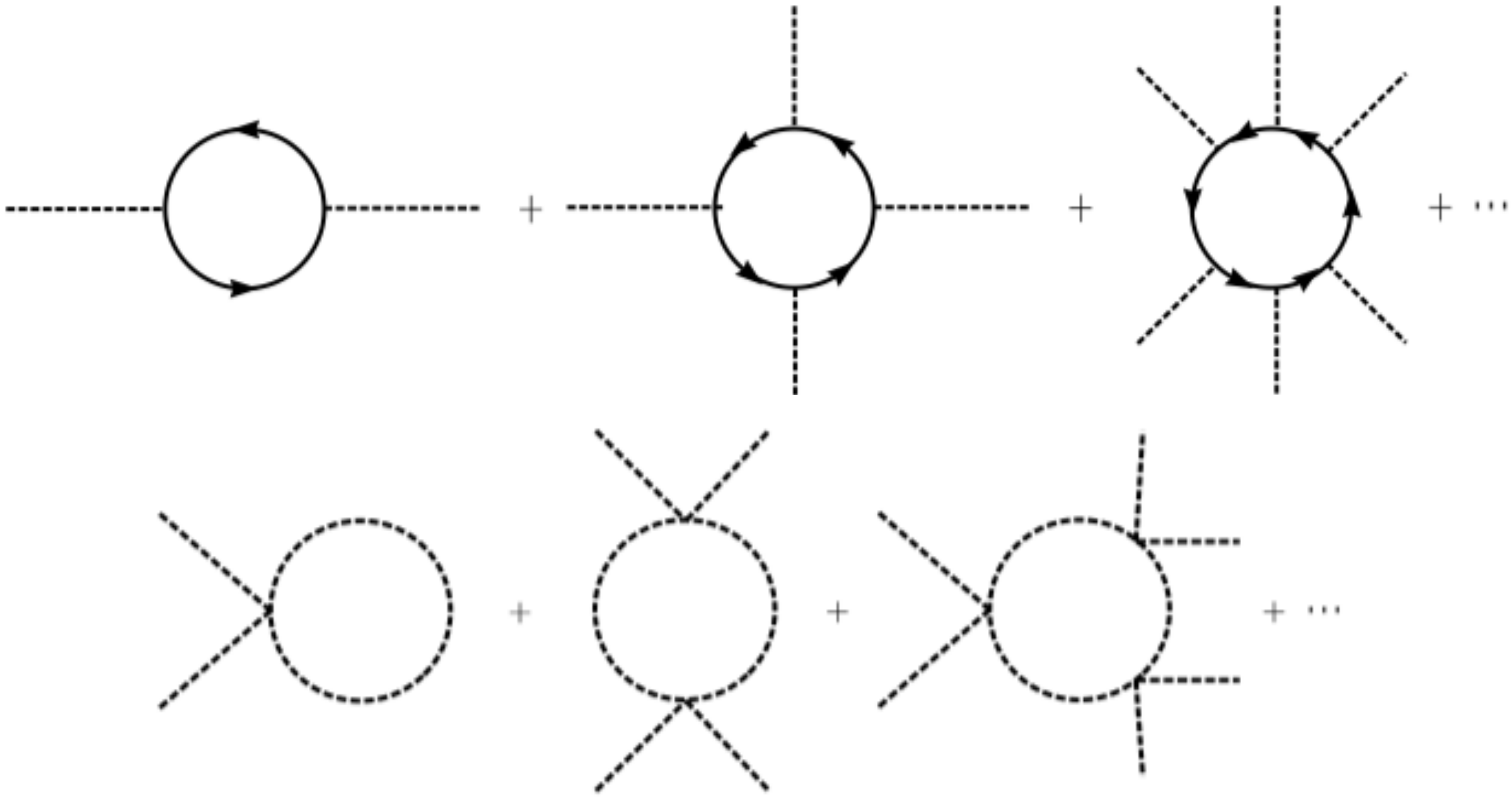
Calculation of CP source

Proper handling of CP sources still an open problem!

Electroweak baryogenesis

Calculation of phase transition (what to calculate)

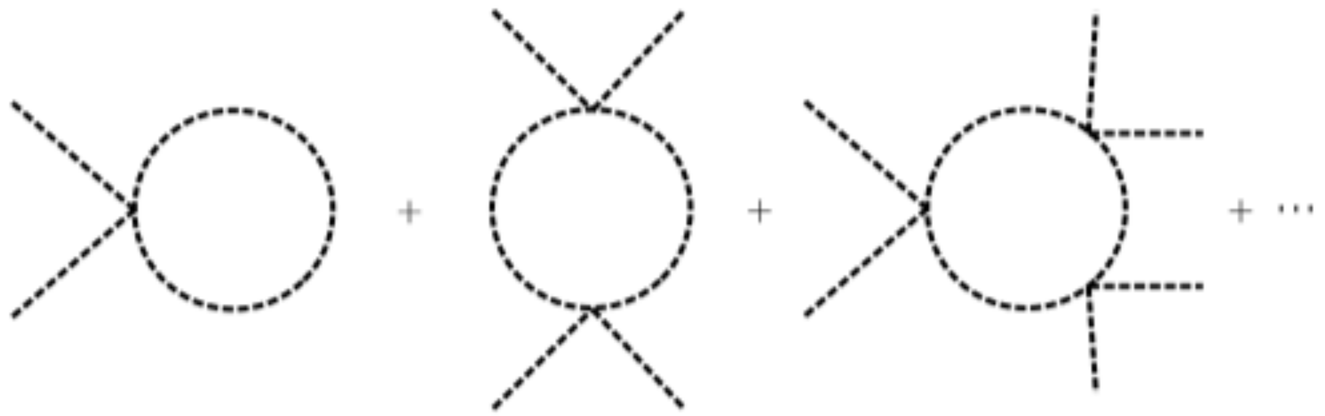
$$V(\phi) \to V_0(\phi) + V_1(\phi, T)$$



Electroweak baryogenesis

Calculation of phase transition (what to calculate)

$V(\phi) \to V_0(\phi) + V_1(\phi, T)$



$$\frac{dV_1}{dm^2} = \int \frac{d^4p}{(2\pi)^4} i\Delta^{++}(p, T)$$

$$\Delta^{++}(p, T) = \Delta^{++}(p,0) + \delta^{++}(p, T)$$

$$V_1(\phi, T) = V_{CW}(\phi) + V_T(\phi, T)$$

Electroweak baryogenesis

Calculation of phase transition (what to calculate)

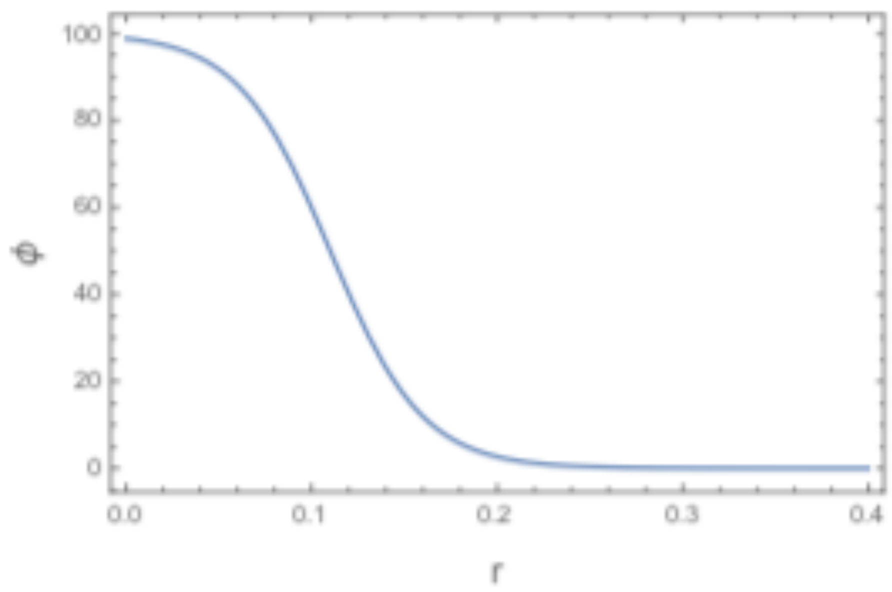
$$\frac{\partial^2 \phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr} = \frac{dV}{d\phi}$$

$$S_E = 4\pi \int r^2 dr \left[\frac{1}{2}(\phi')^2 + V(\phi) \right]$$

$$S_E/T_N \sim 140$$

$$\alpha = \left. \frac{\Delta V - \frac{1}{4} T \Delta(dV/dT)}{\rho_R} \right|_{T_N}$$

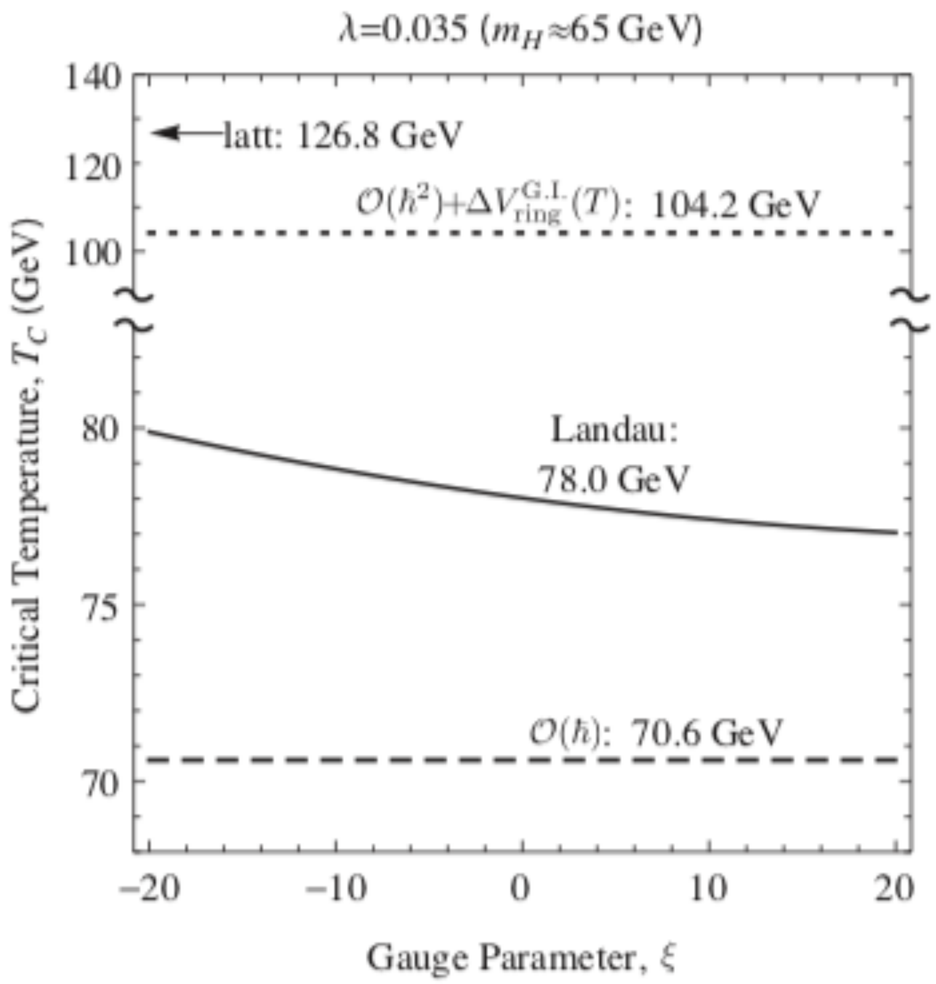
$$\frac{\beta}{H_*} = T \frac{d(S_E/T)}{dT}$$



Electroweak baryogenesis

Calculation of phase transition Issue 1:

Gauge dependence

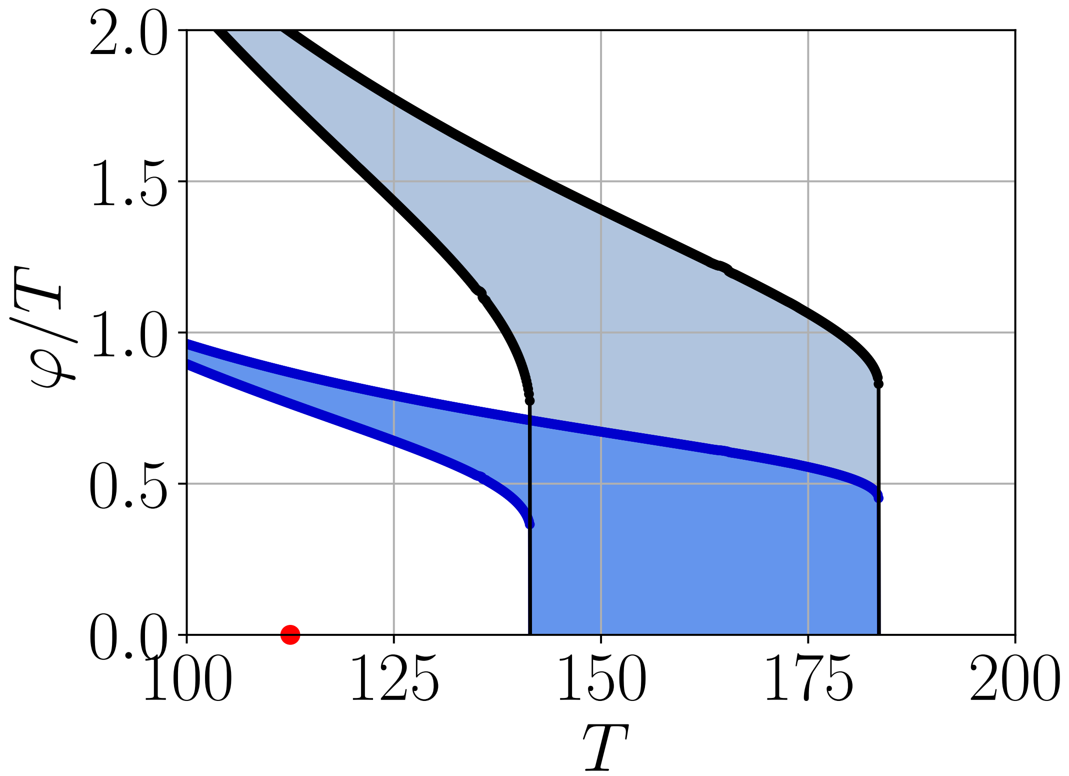


1101.4665

Electroweak baryogenesis

Calculation of phase transition Issue 2:

Renormalization dependence



1904.01329

BM2	1-loop Parwani resum.	142.6 ± 18.0
	1-loop A-E resum.	162.5 ± 21.0
	2-loop $V_{\rm eff}$ in 3d	104.9 ± 2.30
	3d lattice	112.5 ± 0.01

Electroweak baryogenesis

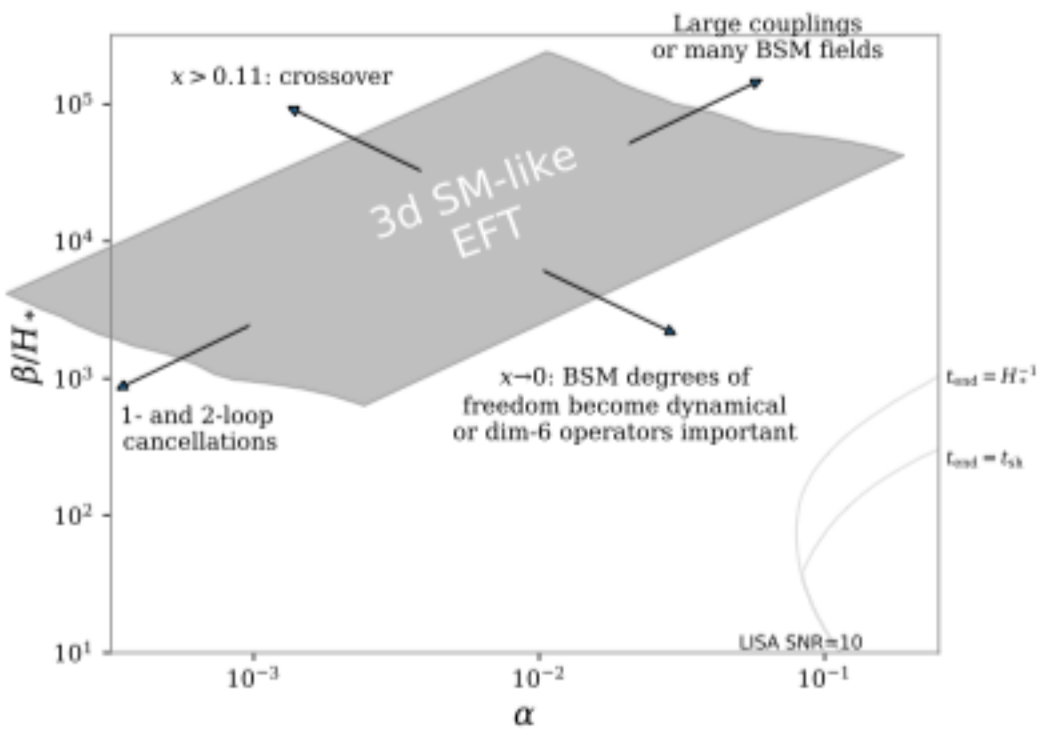
Calculation of phase transition Issue 2:

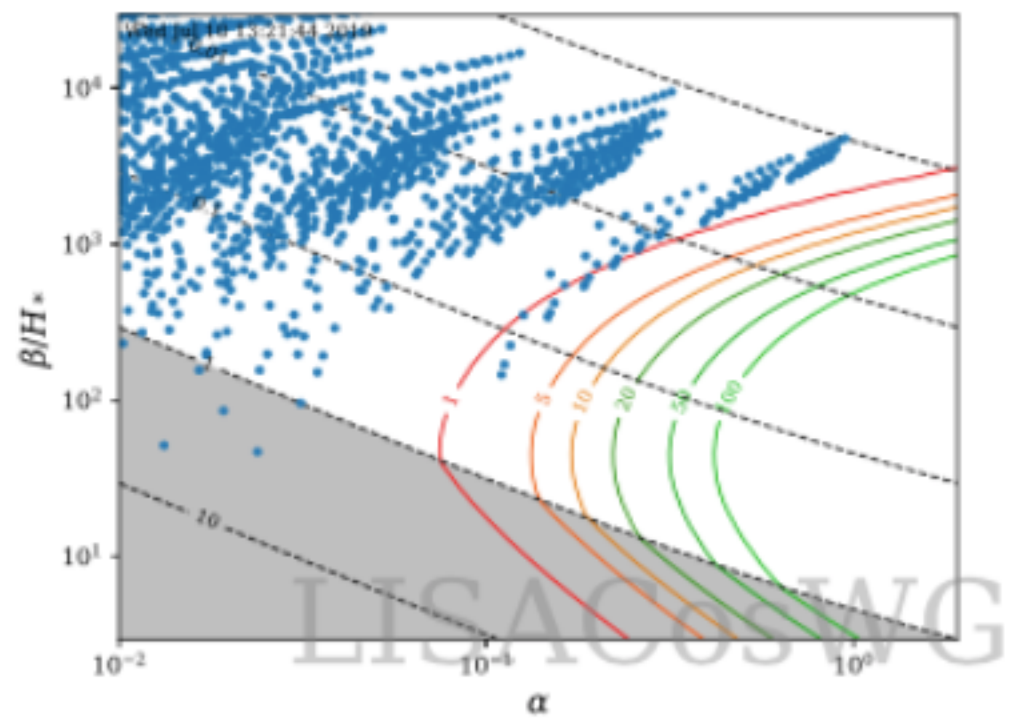
Renormalization dependence

- **3d (dimensional reduction)**
    - **Integrate out heavy matsubara modes**
    - **Manifestly gauge invariant**
    - **Super-renomalizable - only need to go to 2 loop level**
    - **2 loop calculations are easy in 3d**
    - **Includes all order resummations by construction**
    - **Lattice calculations more tractable**
    - **Only works in when HT expansion is valid**

Electroweak baryogenesis

Calculation of phase transition Issue 2:





1903.11604

Croon, Gould, Tenkanen and White, upcoming

Electroweak baryogenesis

Summary of calculation techniques in EWBG:

Great deal of theoretical uncertainty on both the calculation of CP violating sources and phase transitions

Very much a work in progress!

Electroweak baryogenesis

Status of some favourite EWBG models

Electroweak baryogenesis

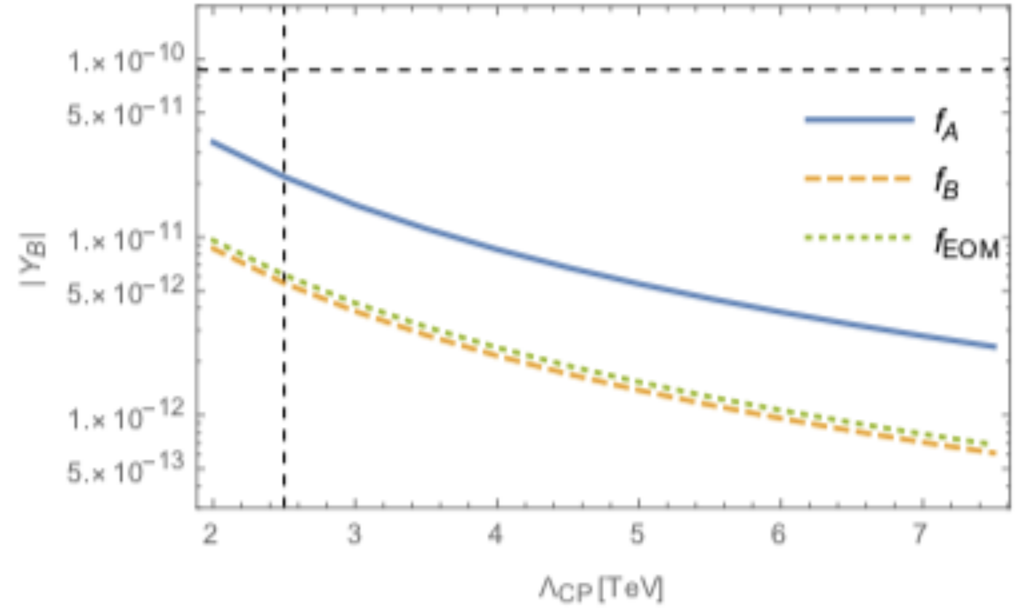
Status of EFT baryogenesis

First an odd feature:
Consider the source generated by 2 dim-6 operators related by eom

$$S^{\not{CP}}_{\mathcal{O}_{DD}} \sim \frac{1}{\Lambda^2}\left[v(x)\partial_t\left(\partial_\mu\partial^\mu v(x)\right) - \partial_t v(x)\left(\partial_\mu\partial^\mu v(x)\right)\right],$$

$$S^{\not{CP}}_{\mathcal{O}_{\partial V/\partial H}} \sim \frac{1}{\Lambda^2}\left[v(x)\partial_t\left(\left.\frac{\partial V_{\rm SM}}{\partial H}\right|_{v(x)}\right) - \partial_t v(x)\left(\left.\frac{\partial V_{\rm SM}}{\partial H}\right|_{v(x)}\right)\right] + \mathcal{O}\left(\frac{1}{\Lambda^4}\right).$$

Degeneracy is broken unless dim 8 piece is included!



1710.04061

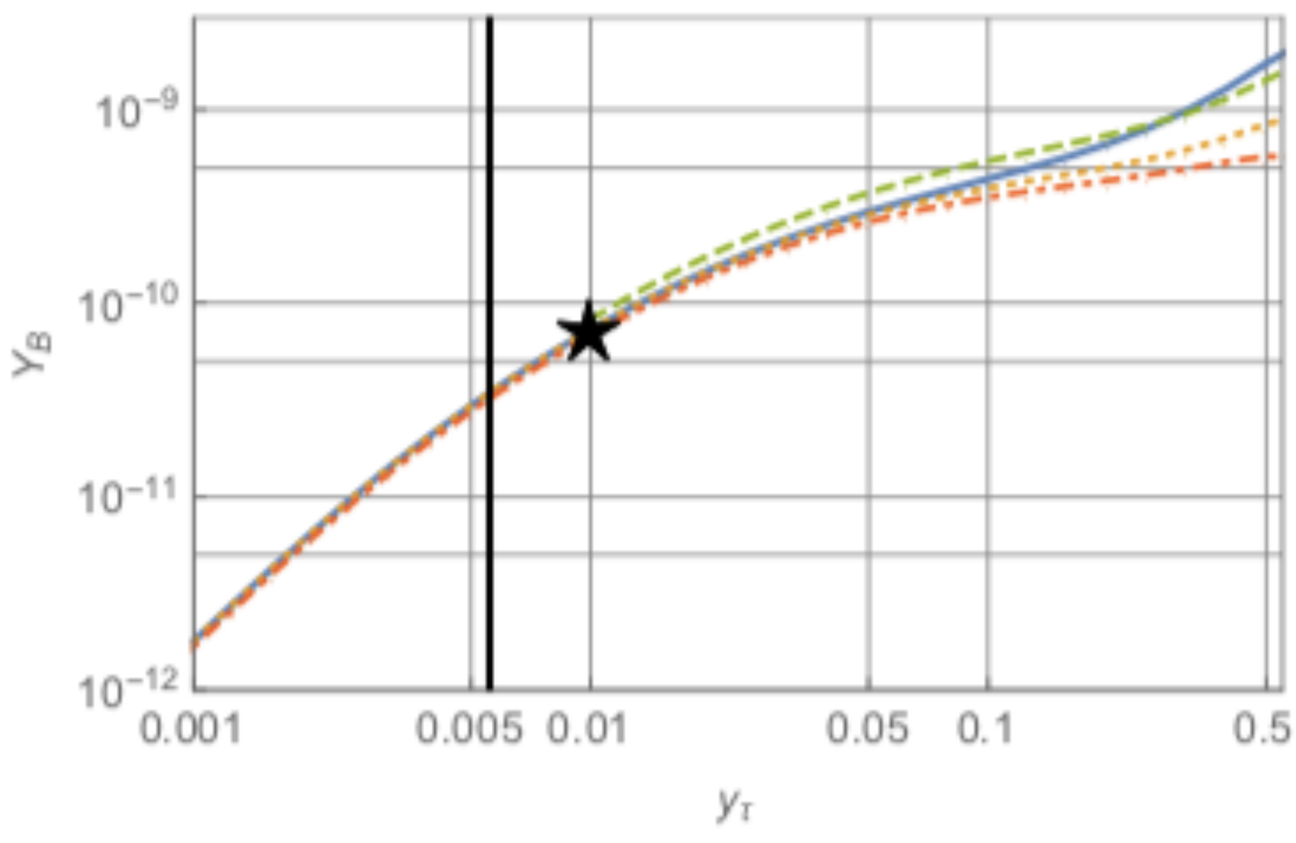
Electroweak baryogenesis

Status of EFT baryogenesis

Appears to be viable with a tau source

$$\delta L = c_6 H^6 + c_{CPV} H^3 \bar{L} \tau$$

Quark transport (unfortunately) killed by EDMs



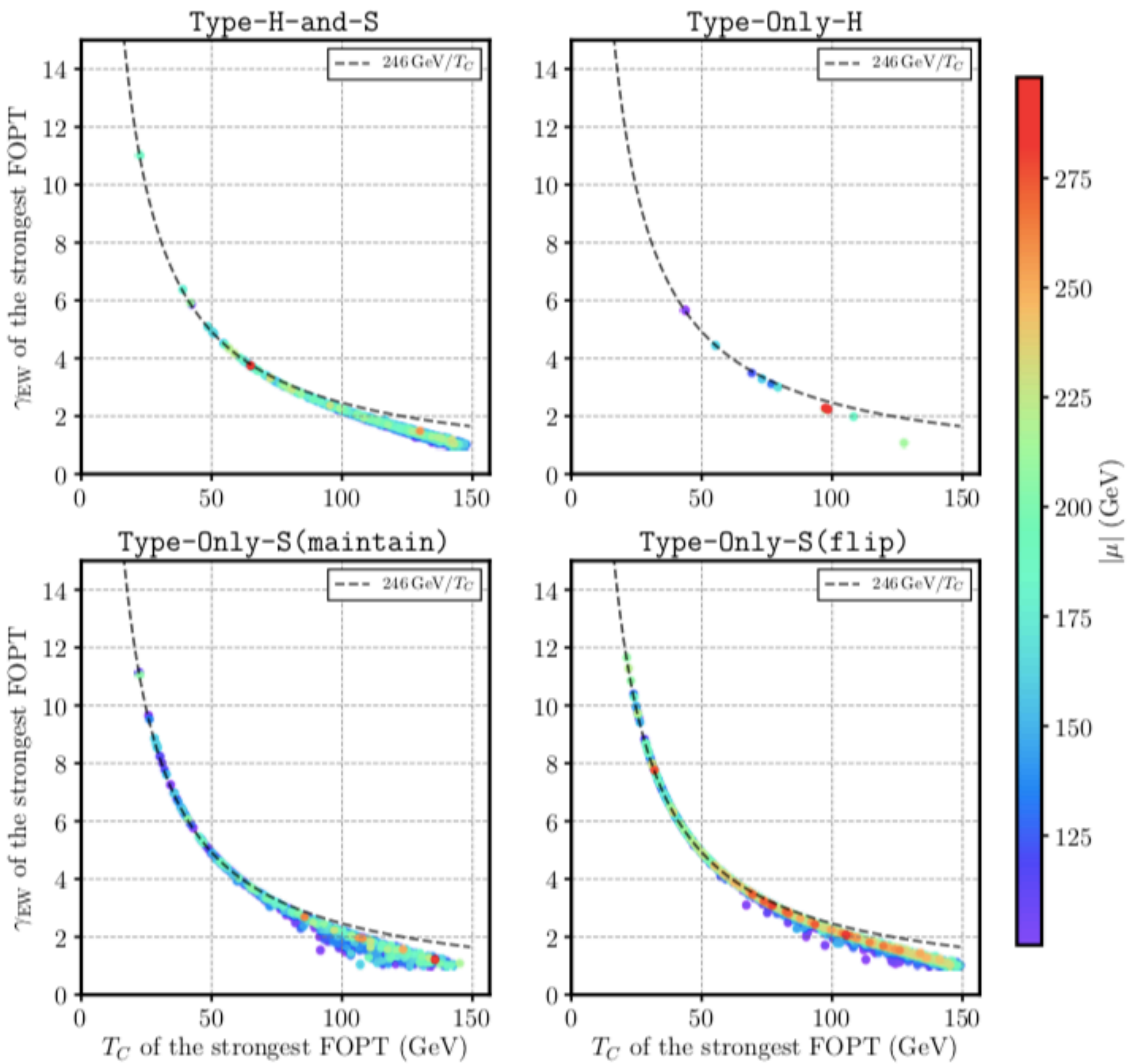
1811.11104

Electroweak baryogenesis

Status of NMSSM baryogenesis

- Z3 invariant potential for simplicity
- Singlet (rather than stop) can catalyze 1st order transition
- Singlino-Higgsino interactions with Higgs can be a weakly constrained CPV source

Electroweak baryogenesis



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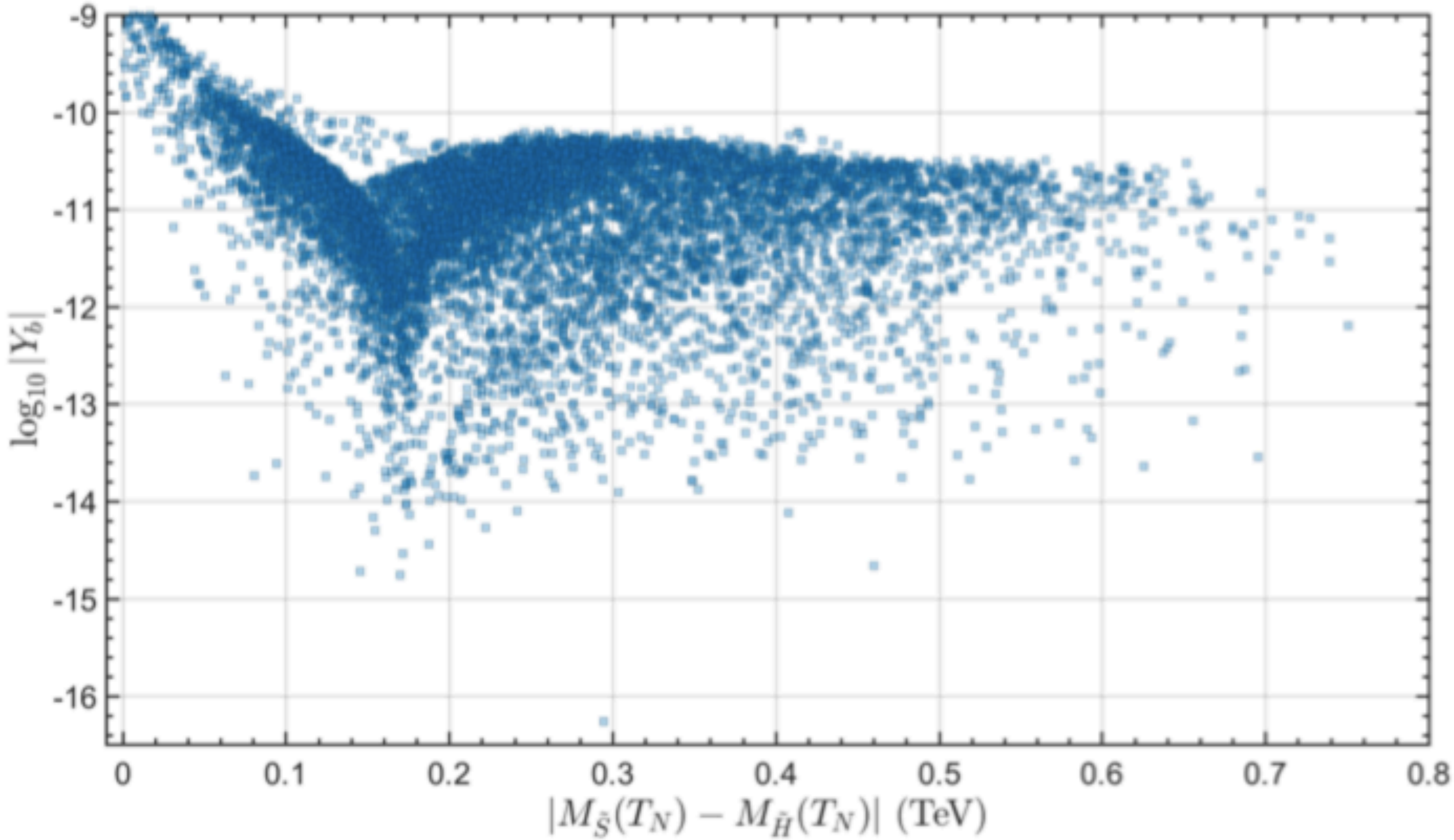
Electroweak baryogenesis

Type H and S is optimal
Type only S means soft terms can be
Large enough for Boltzmann suppression to matter
Even still type only S is viable



1706.09898

Electroweak baryogenesis

How high can the CPV be?

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

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

Electroweak baryogenesis

How high can the CPV be?

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

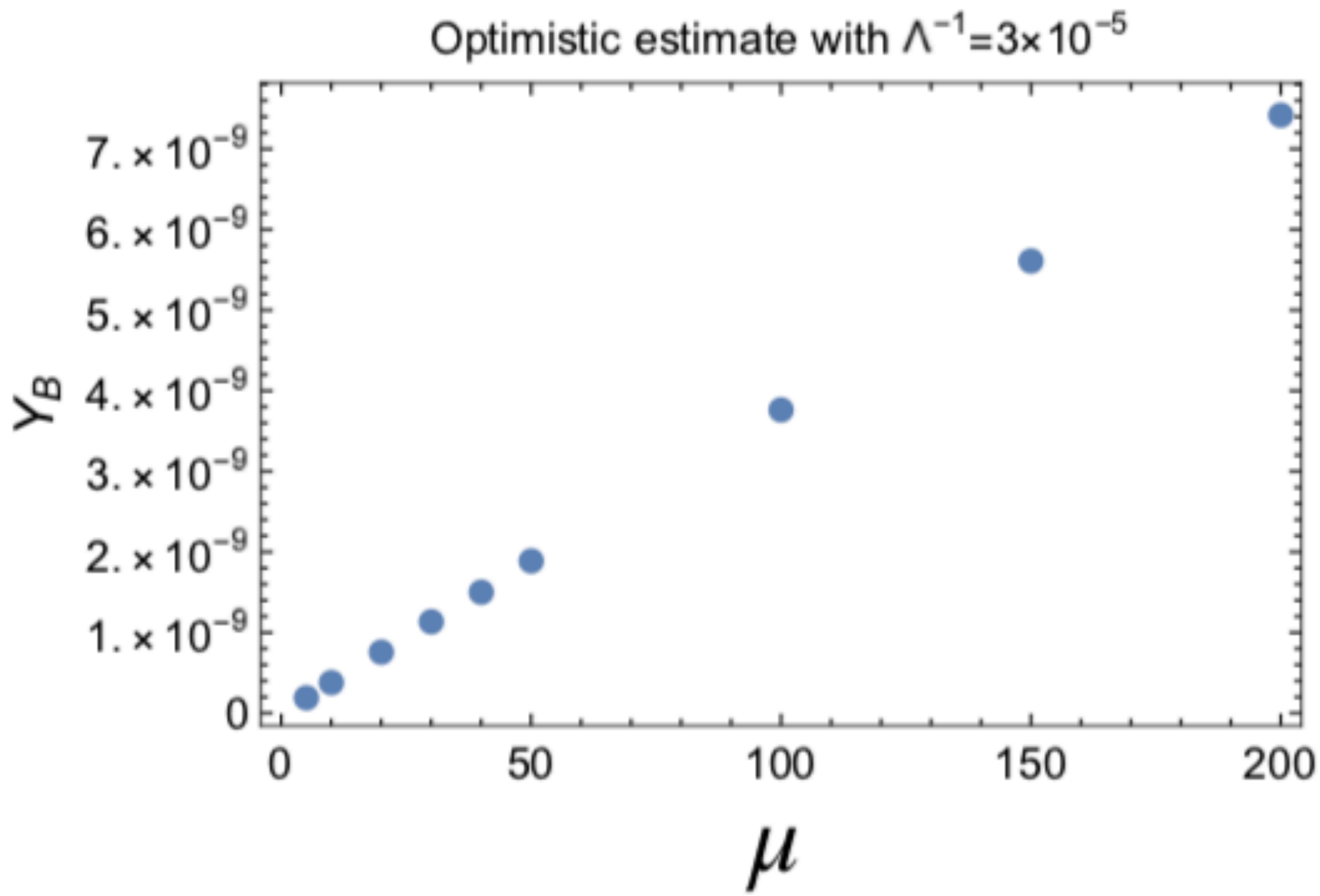
$$-\mathscr{L} \ni \left[\mu + \frac{\xi |H|^2}{\Lambda}\right] A^\dagger H B$$

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

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

Electroweak baryogenesis

How high can the CPV be?



White, Morrissey (preliminary)

Electroweak baryogenesis

Summary of current status

- Many favourite models are still alive and very well
- EDMs usually but not necessarily the most stringent constraint
- Always have the caveat of theoretical uncertainties

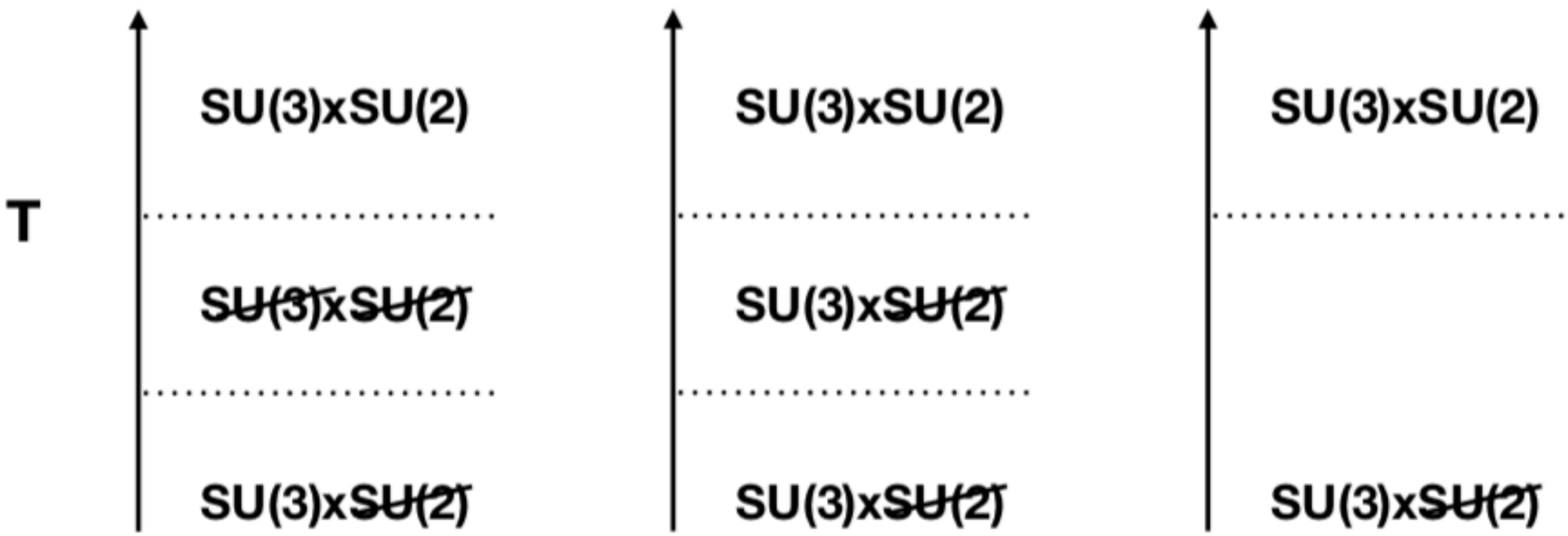
Electroweak baryogenesis

Extensions to the minimal EWBG framework

- **Extensions to ways of realizing CPV**
- **Modify B violation**
- **Modify departure from equilibrium**

Electroweak baryogenesis

Extension 1 departure from equilibrium



Electroweak baryogenesis

Extension 1 colour breaking baryogenesis

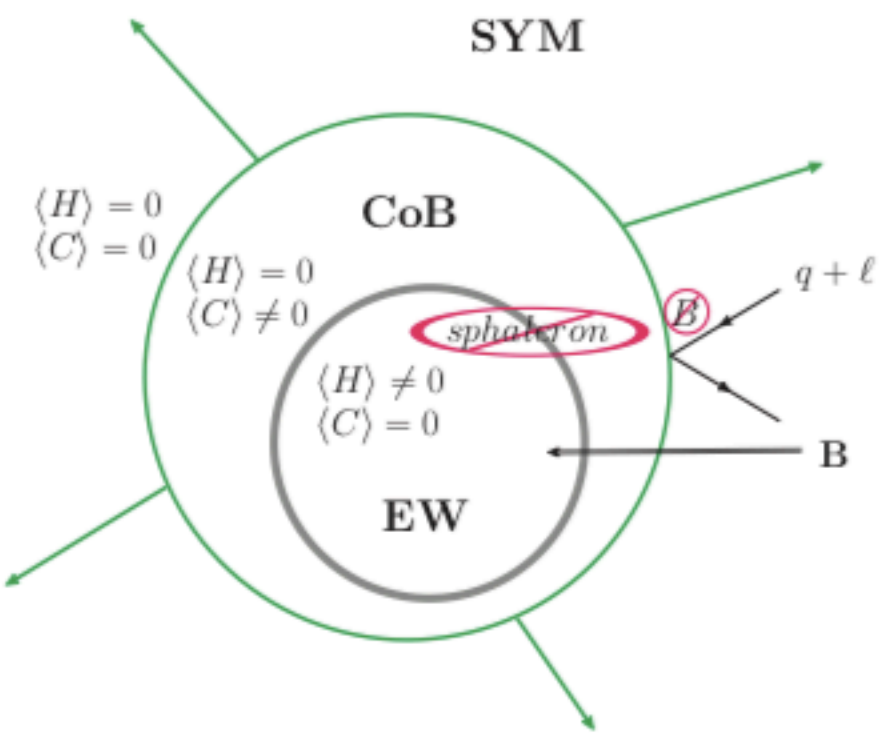
Lagrangian and model for COB

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

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

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

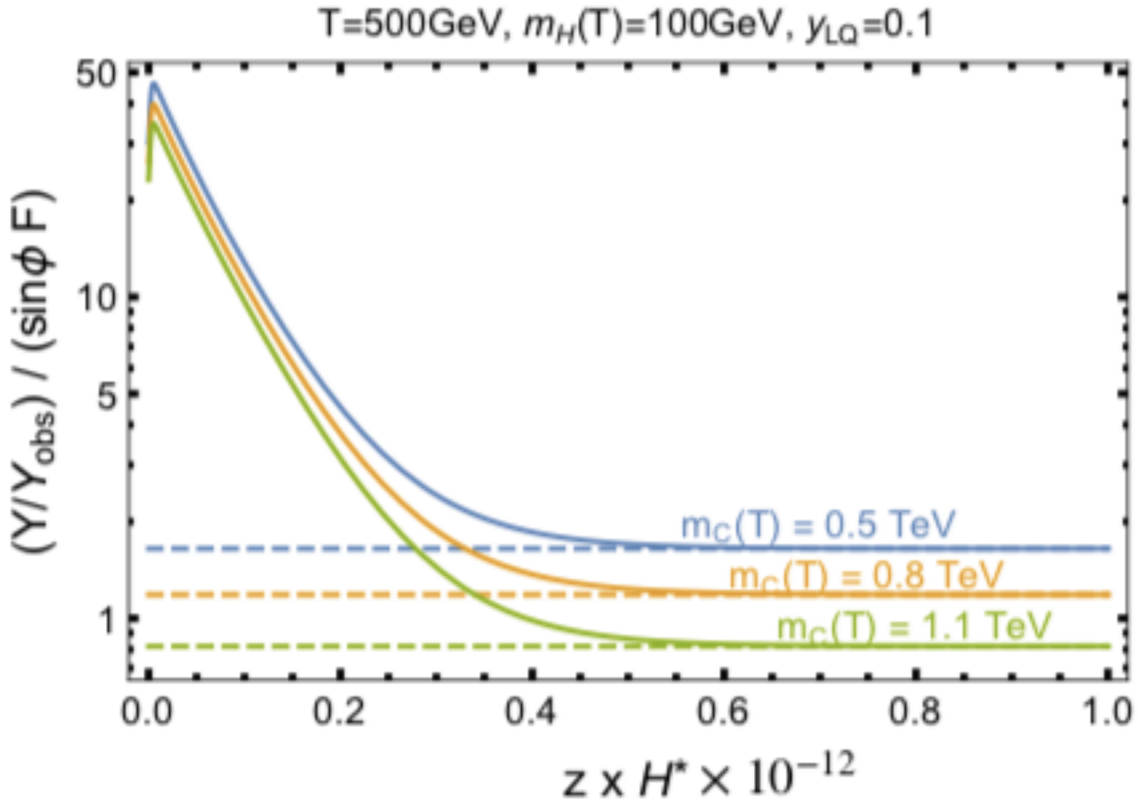
$\not{CP} \leftrightarrow \lambda_i$ **Restrict to 3rd generation**



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

Electroweak baryogenesis

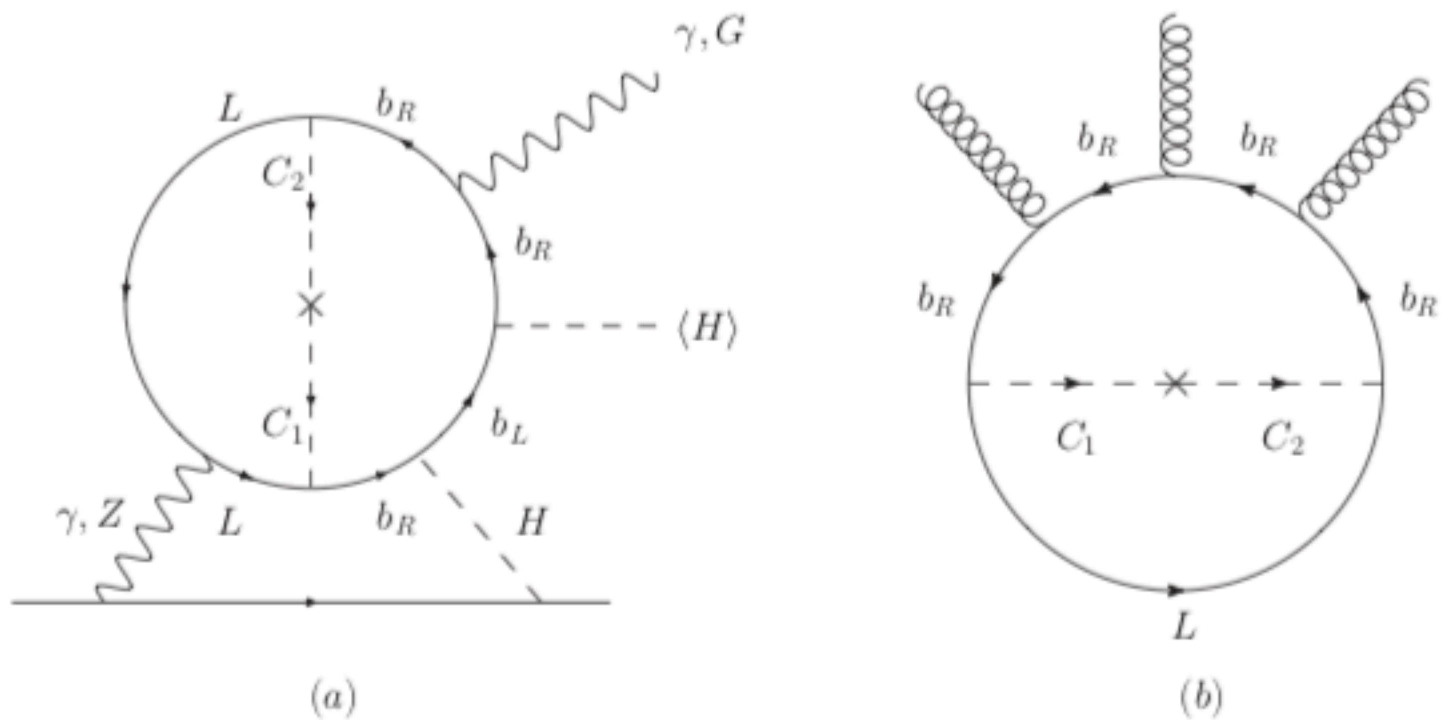
Extension 1 colour breaking baryogenesis



Electroweak baryogenesis

Extension 1 colour breaking baryogenesis

Experimental constraints



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

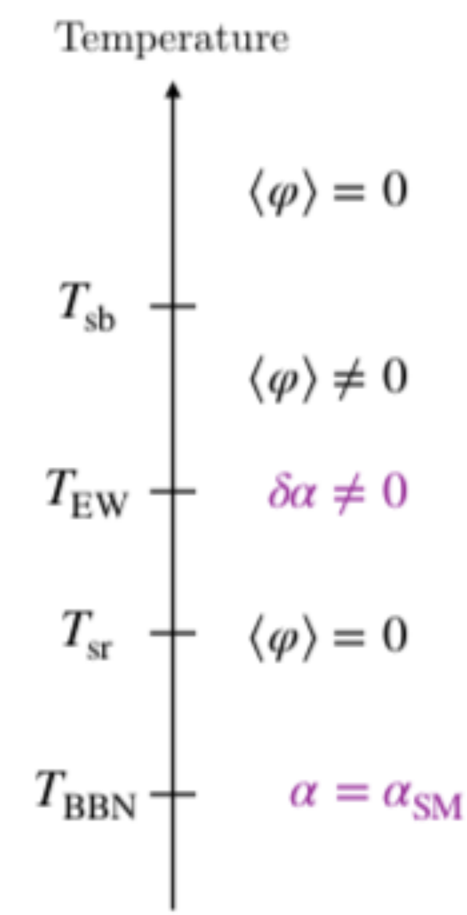
Electroweak baryogenesis

Extension 2 Changing sphalerons

$$\Gamma_{ws} \sim g_2^5$$
$$\Gamma_{ss} \sim g_3^5$$

Case 1: Modifying couplings through a PT

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



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

Electroweak baryogenesis

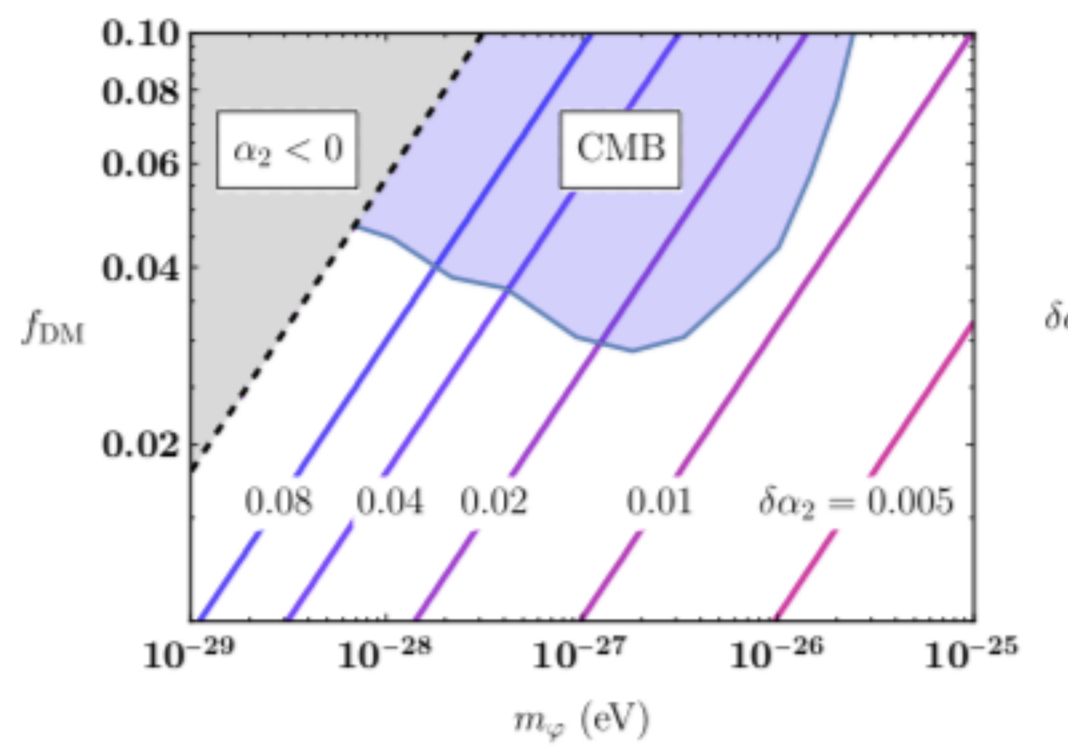
Extension 2 Changing sphalerons

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

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

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

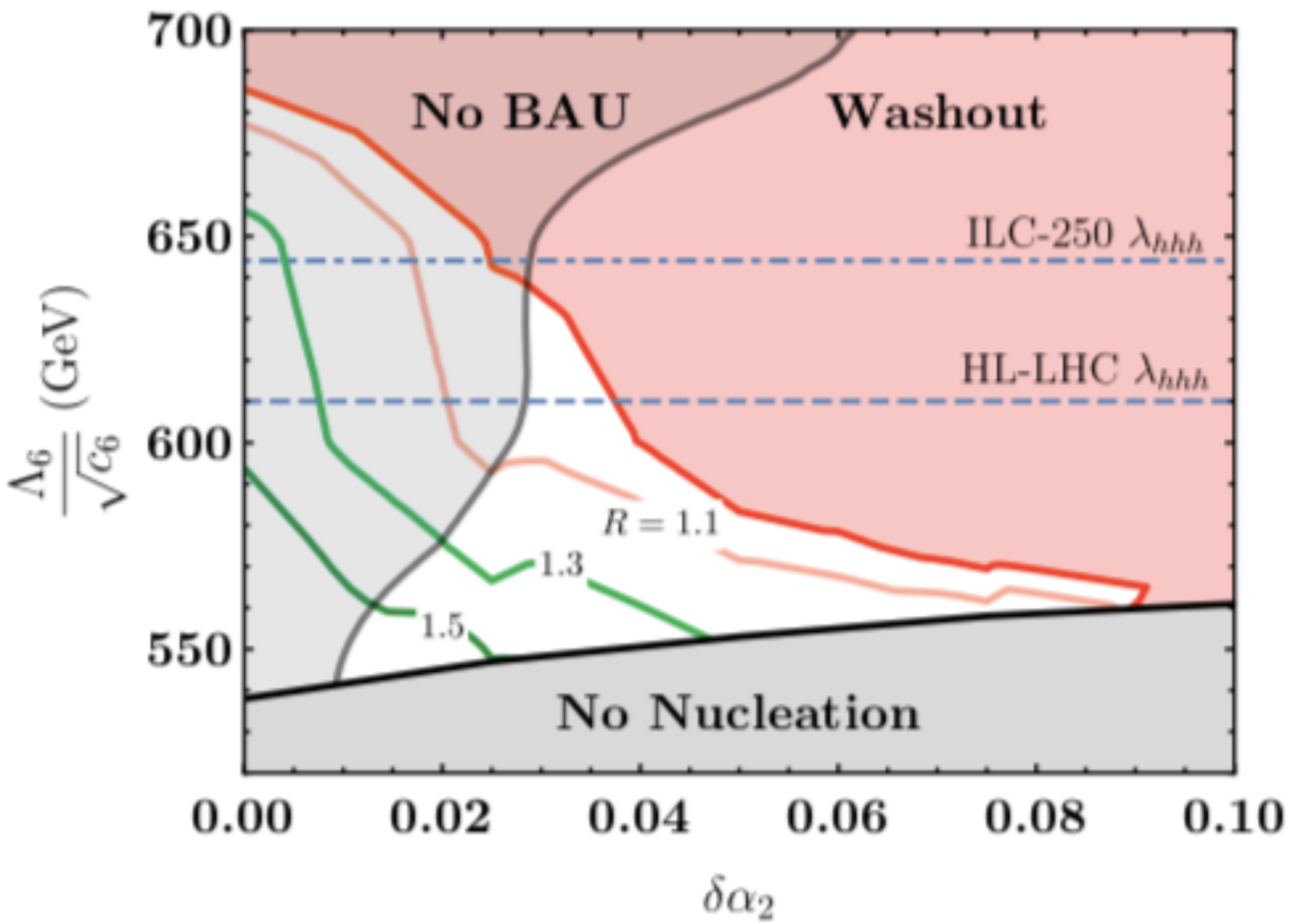
Planck Suppressed coupling
Can be large in the early universe



Electroweak baryogenesis

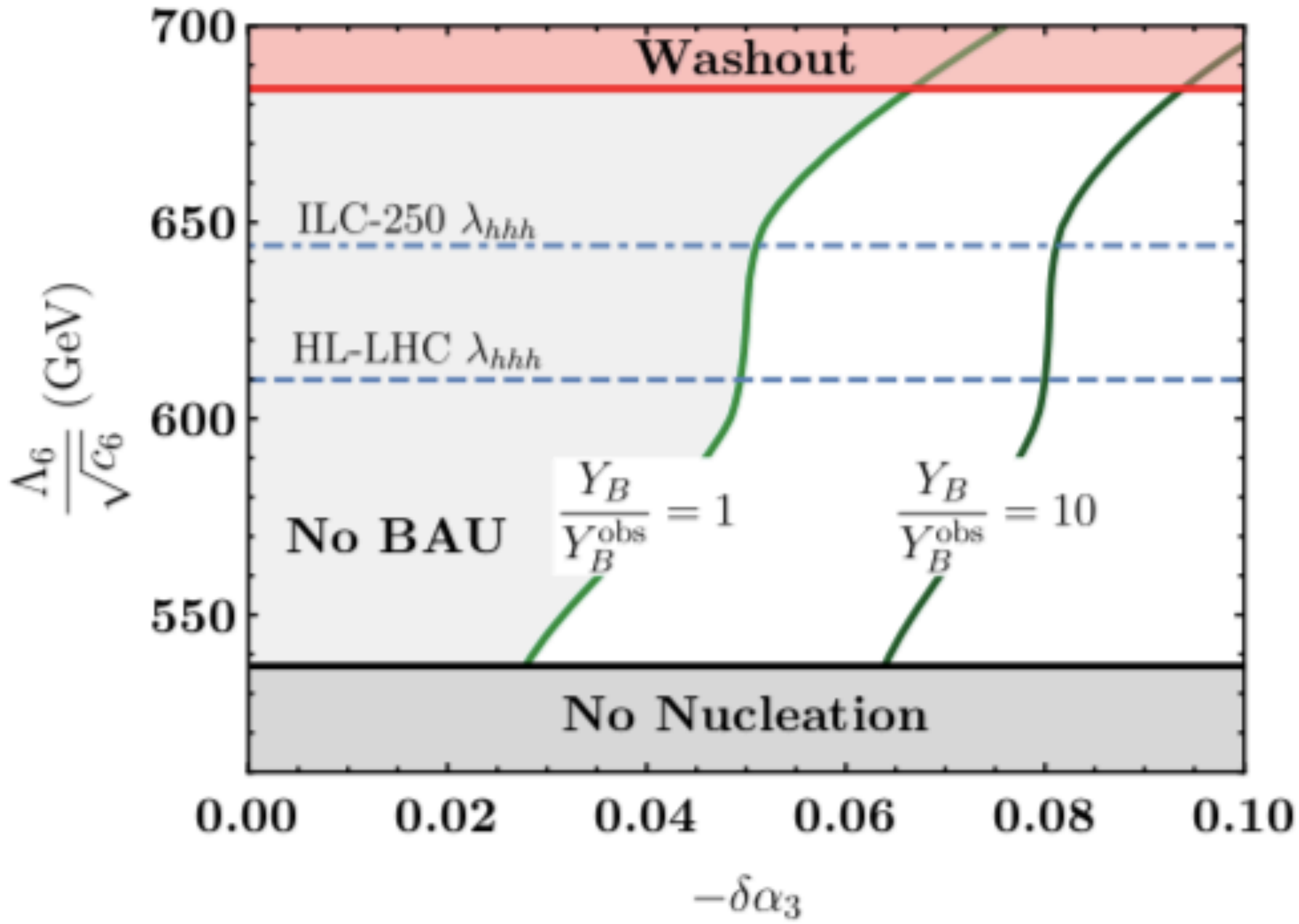
Extension 2 changing sphalerons

Apply paradigm to quark SMEFT



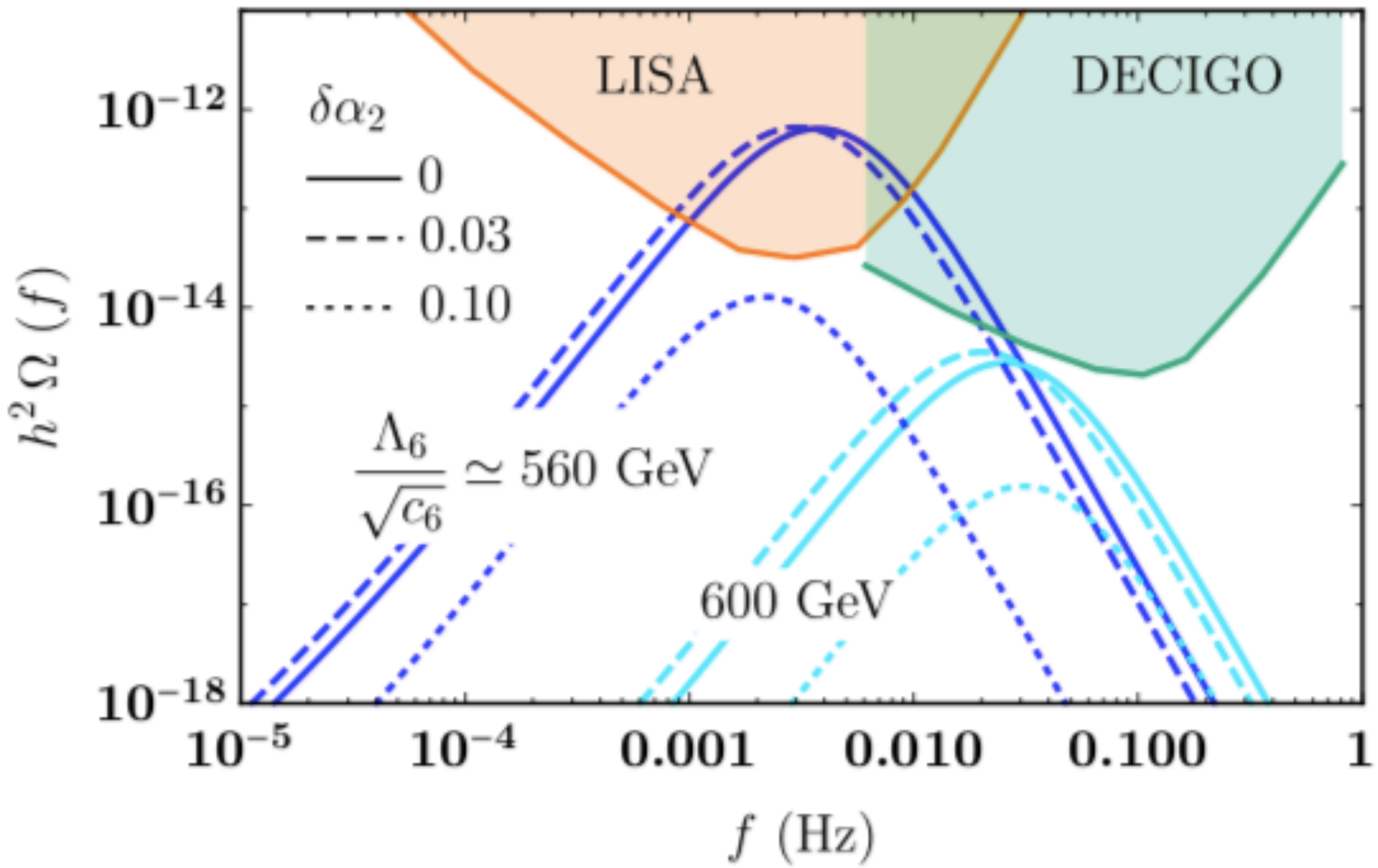
Electroweak baryogenesis

Extension 2 changing sphalerons



Electroweak baryogenesis

Extension 2 changing sphalerons



Electroweak baryogenesis

Extension 3 modified CPV

What if CPV was different in the early Universe compared to today?

Example: CKM can be less suppressed in early Universe if you have dynamical Yukawas

$$L_Y = \left(\frac{S}{M}\right)^{n_i+n_j} \bar{Q}_L^i H q_R^j$$

Electroweak baryogenesis

Extension 3 modified CPV

Original idea: Jarlskog invariant $\sim \left(\frac{S}{M}\right)^{28}$

If S was close to M in the early Universe there would be no suppression

Recent idea: if Yukawas vary during the phase transition, CPV is no longer Loop suppressed

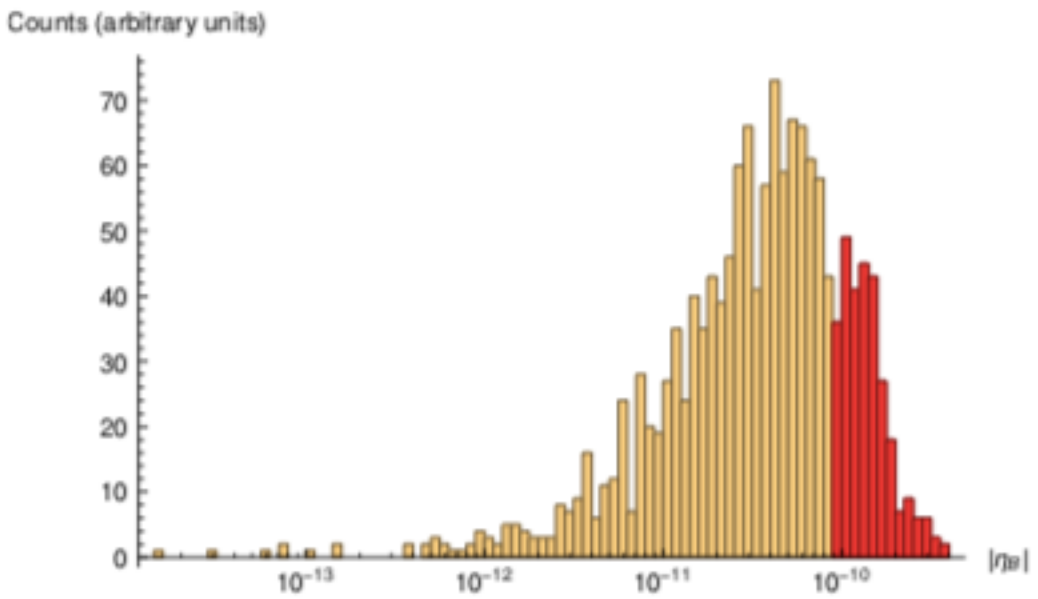
Electroweak baryogenesis

Extension 3 modified CPV

$$y(y_0, y_1, \phi, n) = (y_0 - y_1)\left[1 - \left(\frac{\phi}{v}\right)^n\right] + y_1$$

Varying the up charm yukawas
Can produce enough BAU

1706.08534



Electroweak baryogenesis

Extension 3 modified CPV

Lots to be done on this front:

Both the cases where the Yukawas vary or are simply larger need testing with other methods of calculating the CP asymmetry

Electroweak baryogenesis

Conclusions

Electroweak baryogenesis is a testable and minimal explanation for why we are here
The phenomenology is rich - from colliders to GWs to EDM searches
Much theoretical uncertainty remains
Many of the most popular models are still works in progress
Extensions to the basic paradigm are phenomenologically rich and underexplored