宇宙物质-反物质不对称

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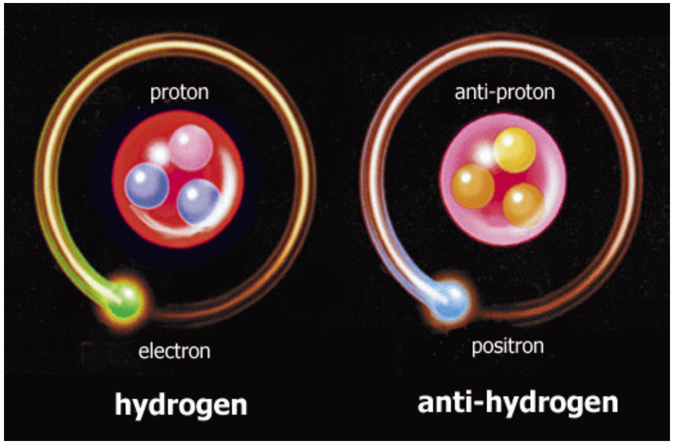
Dirac (1933): a symmetric Universe with matter and antimatter [Nobel Lecture]

positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars



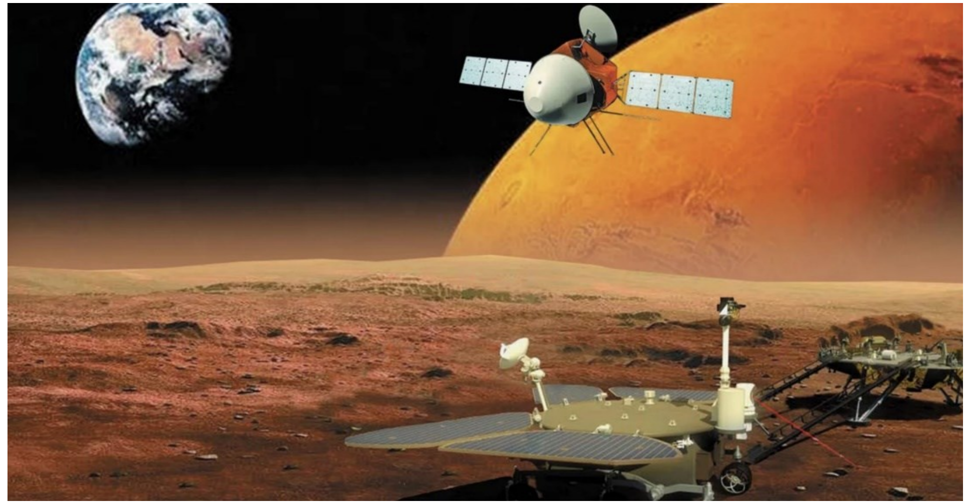
Pauli (1933): letter to Heisenberg

I do not believe in the hole theory, since I would like to have **the asymmetry between positive and negative electricity in the laws of nature** (it does not satisfy me to shift the empirically established asymmetry to one of the initial state). [Quinn & Nir, *The mystery of the missing antimatter*, 2008]

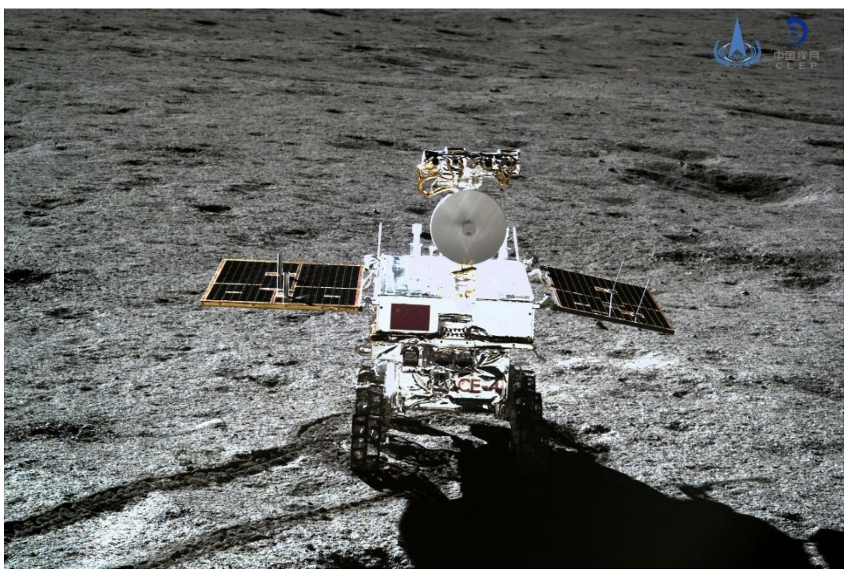
Introduction

Matter-antimatter asymmetry: Empirical observations

Living on the Earth



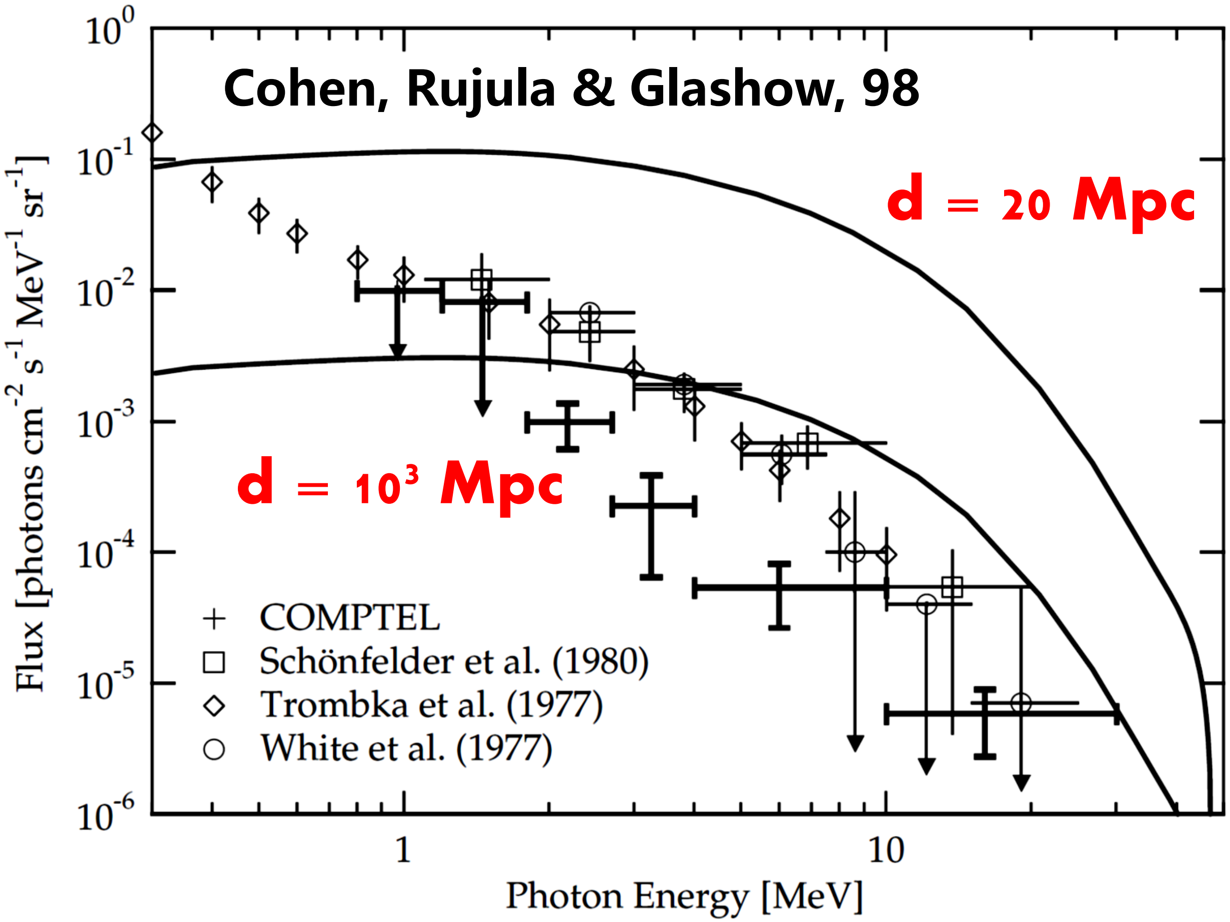
Tianwen on the Mars

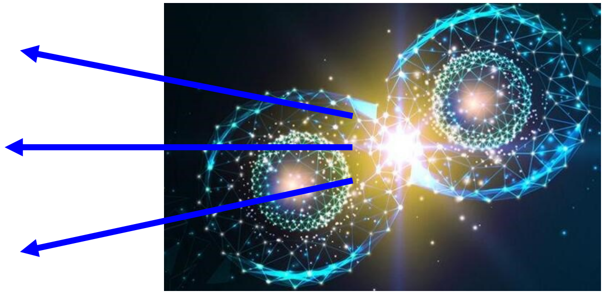


Chang’e on the Moon

Extragalactic UHE cosmic rays

Matter-antimatter asymmetry: Astronomical observations

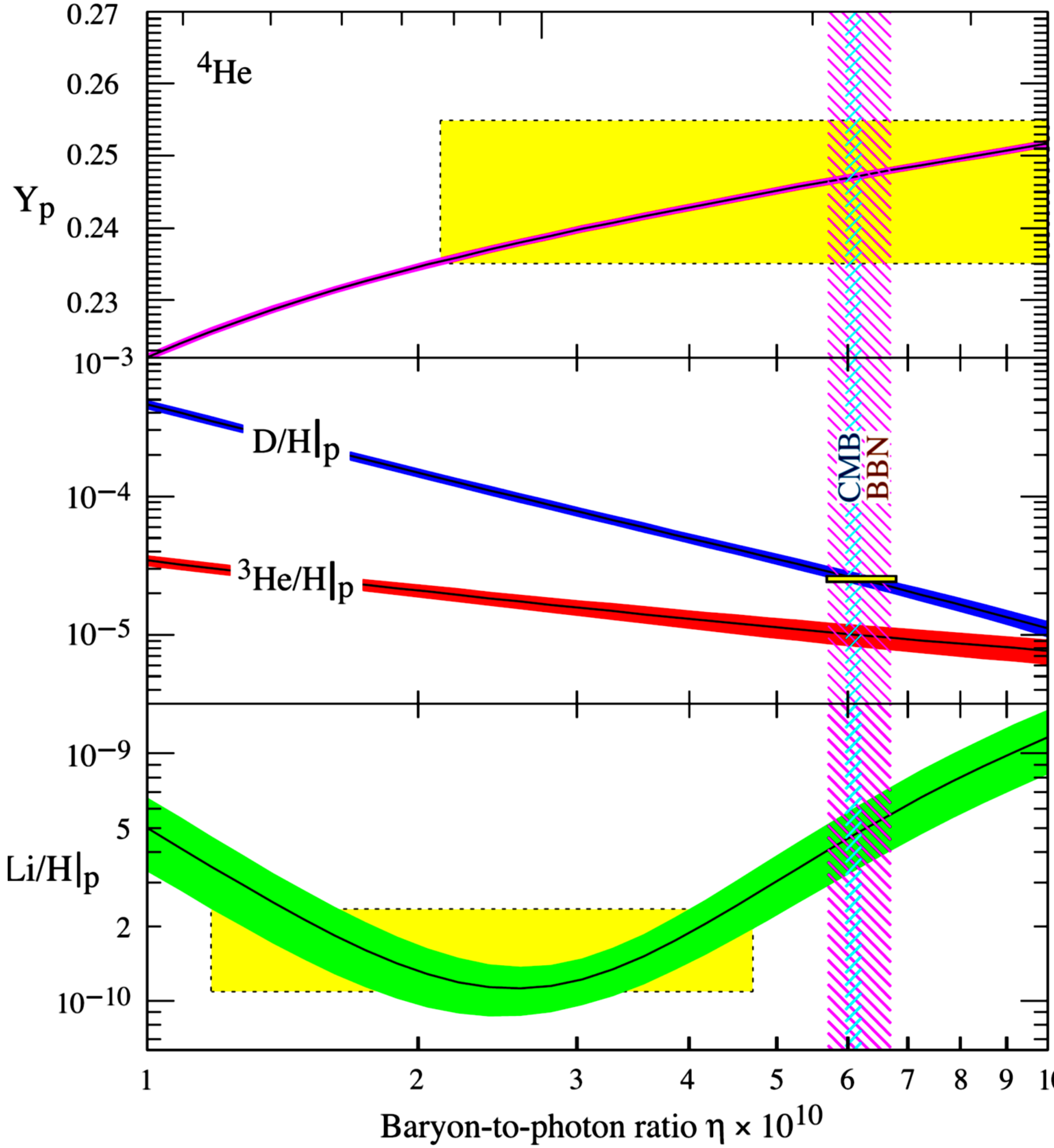




Bounds on the distance d between matter and antimatter regions: >1 Gpc ~ visible universe

Matter-antimatter asymmetry: Cosmological observations

Big Bang Nucleosynthesis & CMB

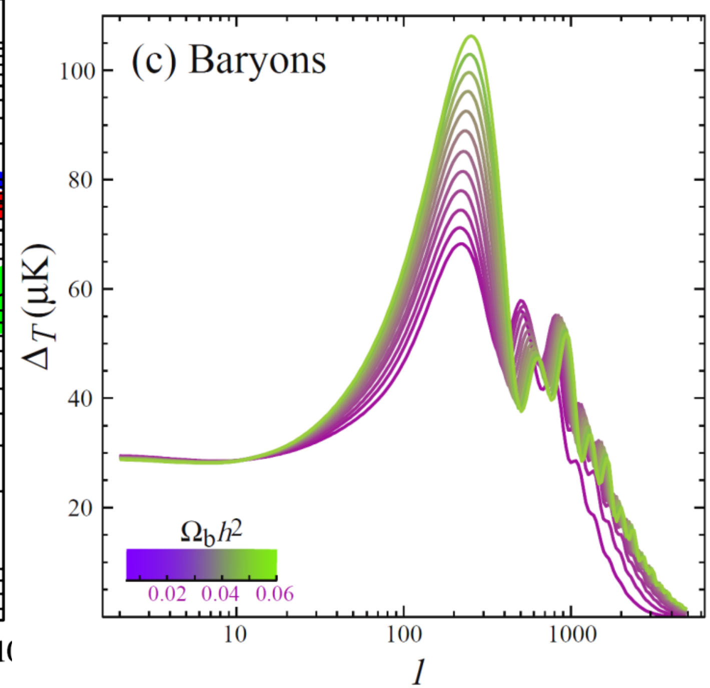


Baryon Asymmetry of Universe (BAU)

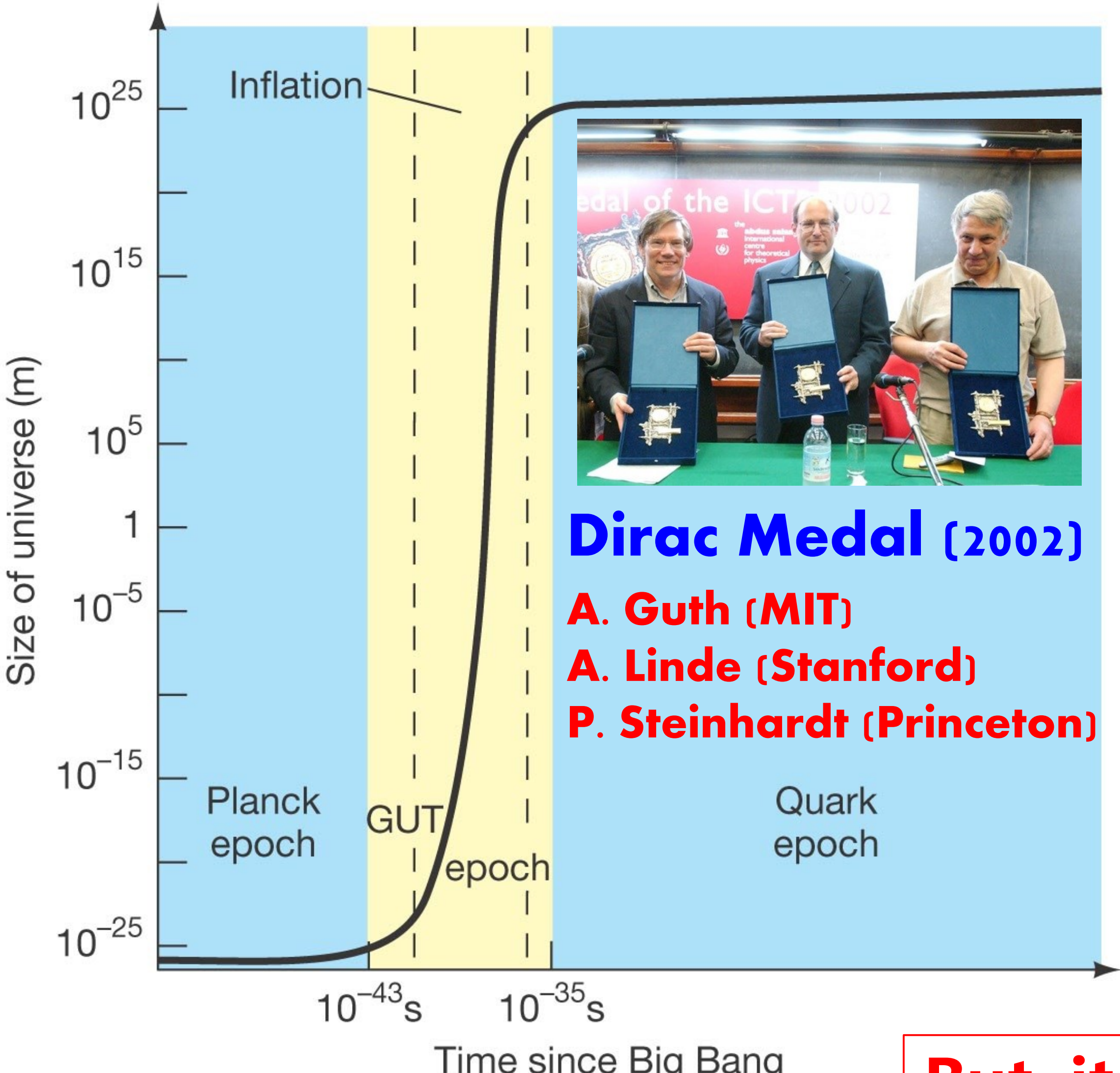
baryon-to-photon ratio

$$\eta_B \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.065 \pm 0.090) \times 10^{-10}$$

Hu, Dodelson, astro-ph/0110401



A naïve answer: Put it as an initial condition!

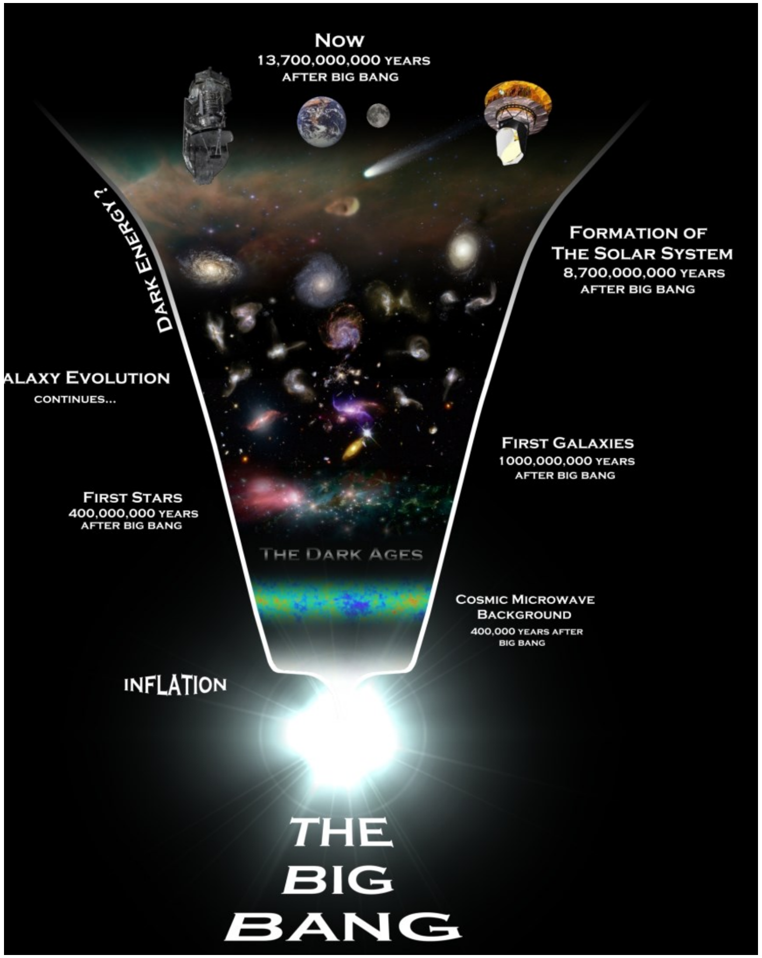


Dirac Medal (2002)

A. Guth (MIT)

A. Linde (Stanford)

P. Steinhardt (Princeton)



But, it will be diluted to zero!

Dynamical Solutions

Pauli (1933): letter to Heisenberg

I do not believe in the hole theory, since I would like to have the asymmetry between positive and negative electricity in the laws of nature (**it does not satisfy me to shift the empirically established asymmetry to one of the initial state**). [Quinn & Nir, *The mystery of the missing antimatter*, 2008]

Quest for dynamical solutions to matter-antimatter asymmetry

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

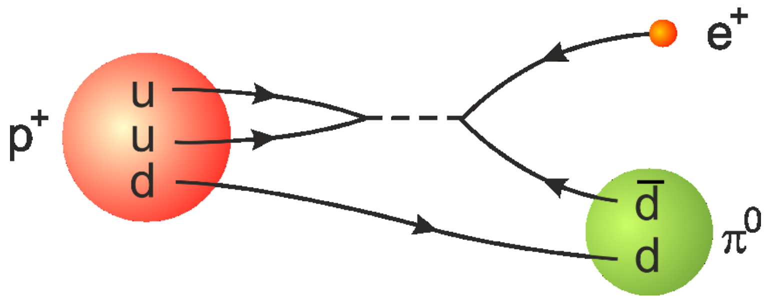
A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

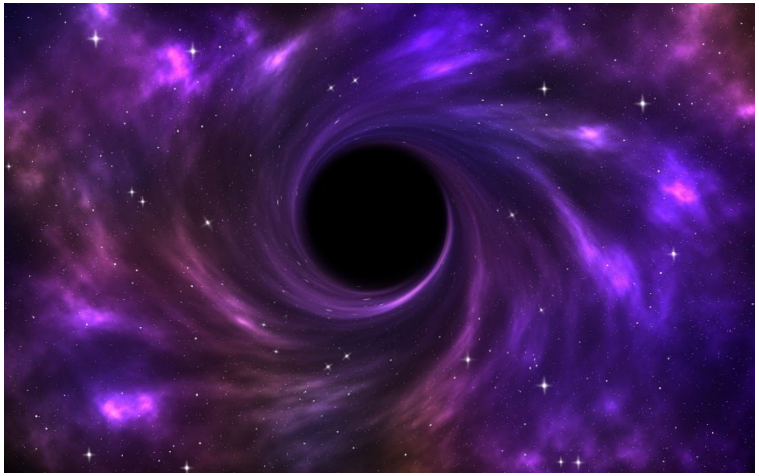
Sakharov Conditions:

- **Baryon number (B) violation**
- **Breaking of CP and C symmetries**
- **Out of thermal equilibrium**

Dolgov, Phys. Rept., 1992
Boedeker & Buchmueller, Rev. Mod. Phys., 2021

Grand unified theories: predictions for baryon number violation (BNV)

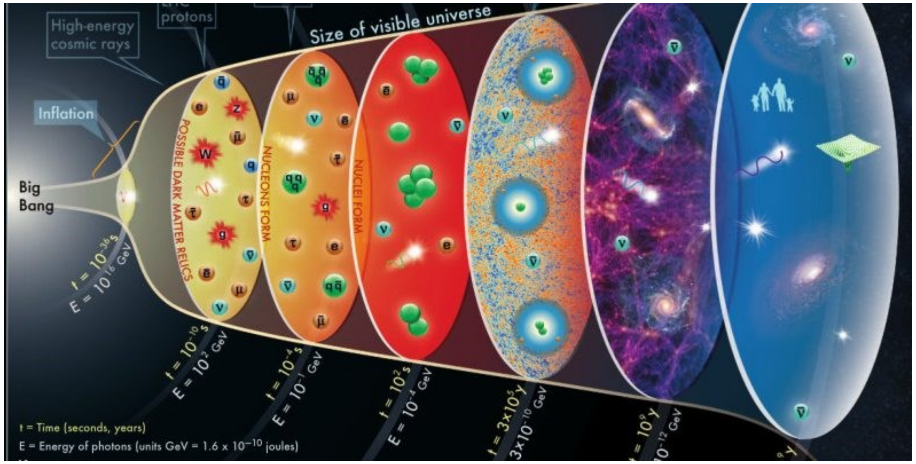




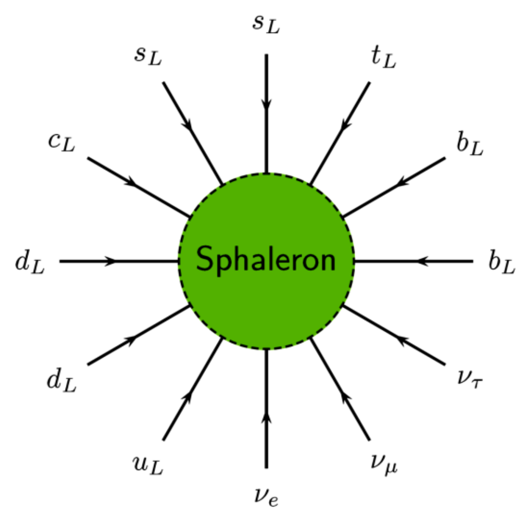
- BNV and lepton number violation (LNV)
- C and CP violation as in weak interactions
- Out-of-equilibrium in expanding universe

Planck/GUT Baryogenesis: dead?

Any global quantum number violated in black-hole physics?



Diluting magnetic monopoles but also BAU

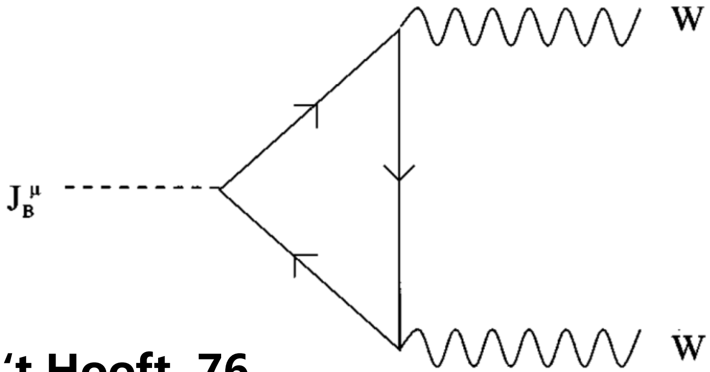


BNV processes in thermal equilibrium will erase all existing BAU

Kuzmin, Rubakov & Shaposhnikov, 85

Electroweak Sphaleron

Accidental Symmetries in the SM: Baryon number & Lepton number



'**t Hooft, 76**

Violated at the quantum level due to the axial anomaly

$$j_B^\mu = \frac{1}{4}[\overline{Q}\gamma^\mu(1-\gamma^5)Q + \overline{Q}\gamma^\mu(1+\gamma^5)Q]$$

$$\partial_\mu j_B^\mu = \partial_\mu j_l^\mu = n_f\left(\frac{g^2}{32\pi^2} W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} - \frac{g'^2}{32\pi^2} F_{\mu\nu}\widetilde{F}^{\mu\nu}\right)$$

Nontrivial topology of the SM vacuum [SU(2) gauge theory]

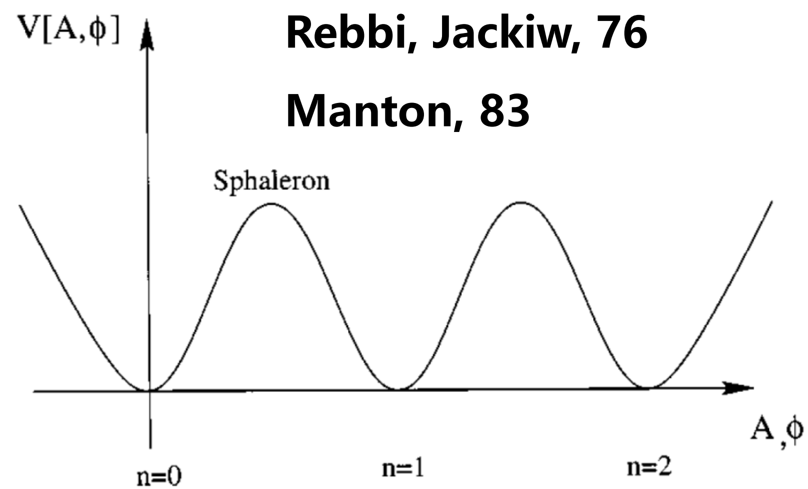
Infinitely degenerate vacua characterized by the Chern-Simons (CS) number

$$U^{(0)}(x) = 1,$$

$$U^{(1)}(x) = \frac{x_0 + i\vec{x}\cdot\vec{\sigma}}{r}, \quad r = (x_0 + |\vec{x}|^2)^{1/2},$$

$$\boxed{\mathcal{G}^{(0)}_{\text{vac}} = \left\{A_i^{(0)} = 0, \Phi^{(0)} = (0, v), N_{\text{CS}} = 0\right\}}$$

$$U^{(n)}(x) = \left[U^{(1)}\right]^n,$$



Rebbi, Jackiw, 76

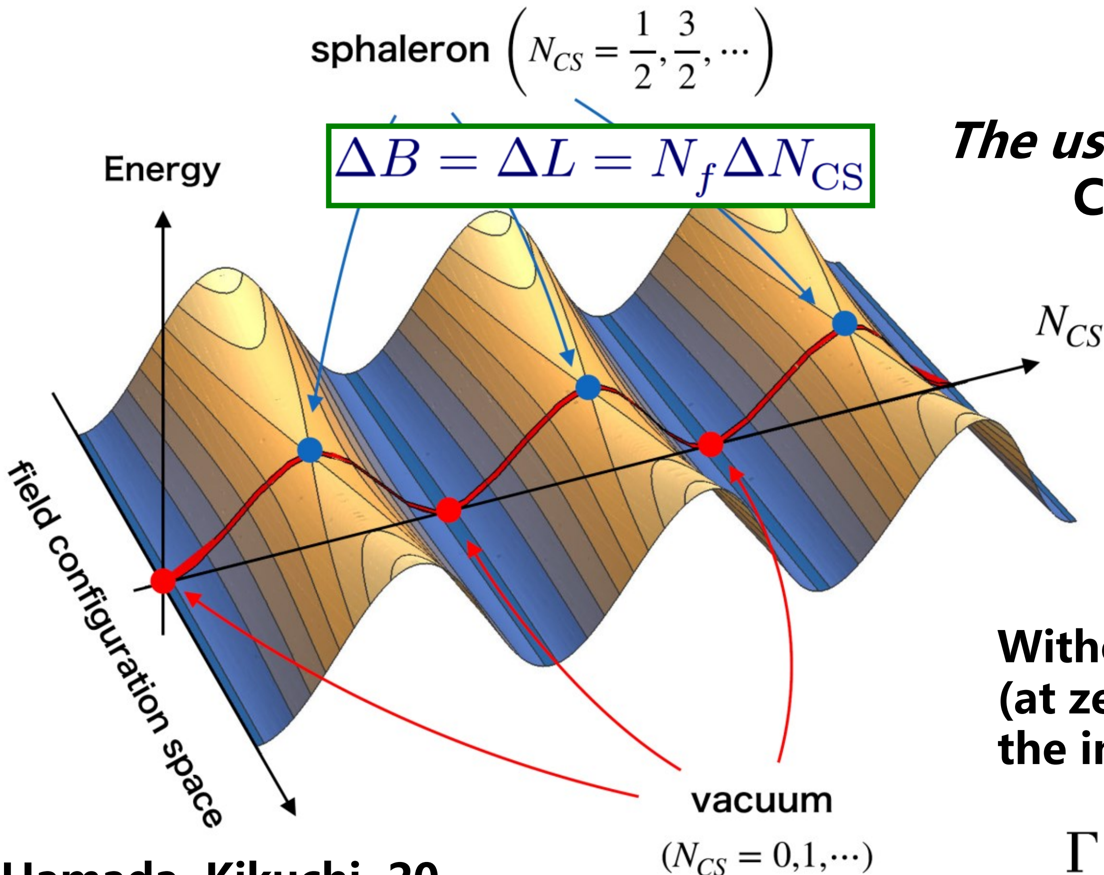
Manton, 83

$$\boxed{\mathcal{G}^{(n)}_{\text{vac}} = \left\{A_i^{(n)} = (i/g_2)(\nabla U^{(n)})(U^{(n)})^{-1}, \Phi^{(n)} = U^{(n)}\Phi^{(0)}, N_{\text{CS}} = n\right\}}$$

Klinkhamer, Manton, 84

Electroweak Sphaleron

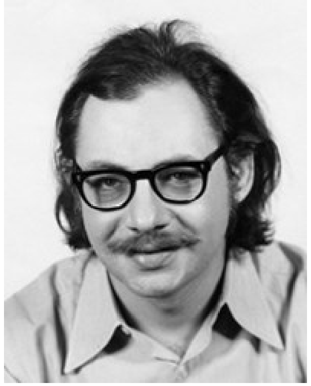
A saddle point solution in the SM: interpolating different vacua



Hamada, Kikuchi, 20

Klinkhamer, Manton, 84

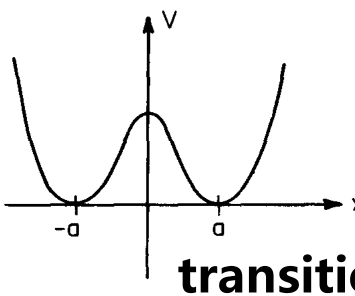
The uses of instantons
Coleman, 77



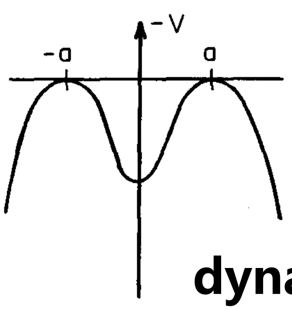
Finite actions are useful for semi-classical calculation of transition rates between different vacua

Without sphalerons, the transition rate (at zero temperature) is determined by the instanton action:

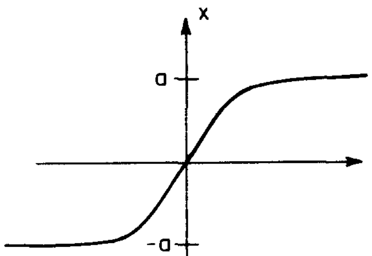
$$\Gamma(T=0) \sim \exp(-2S_E) \sim 10^{-170}$$



transition rate



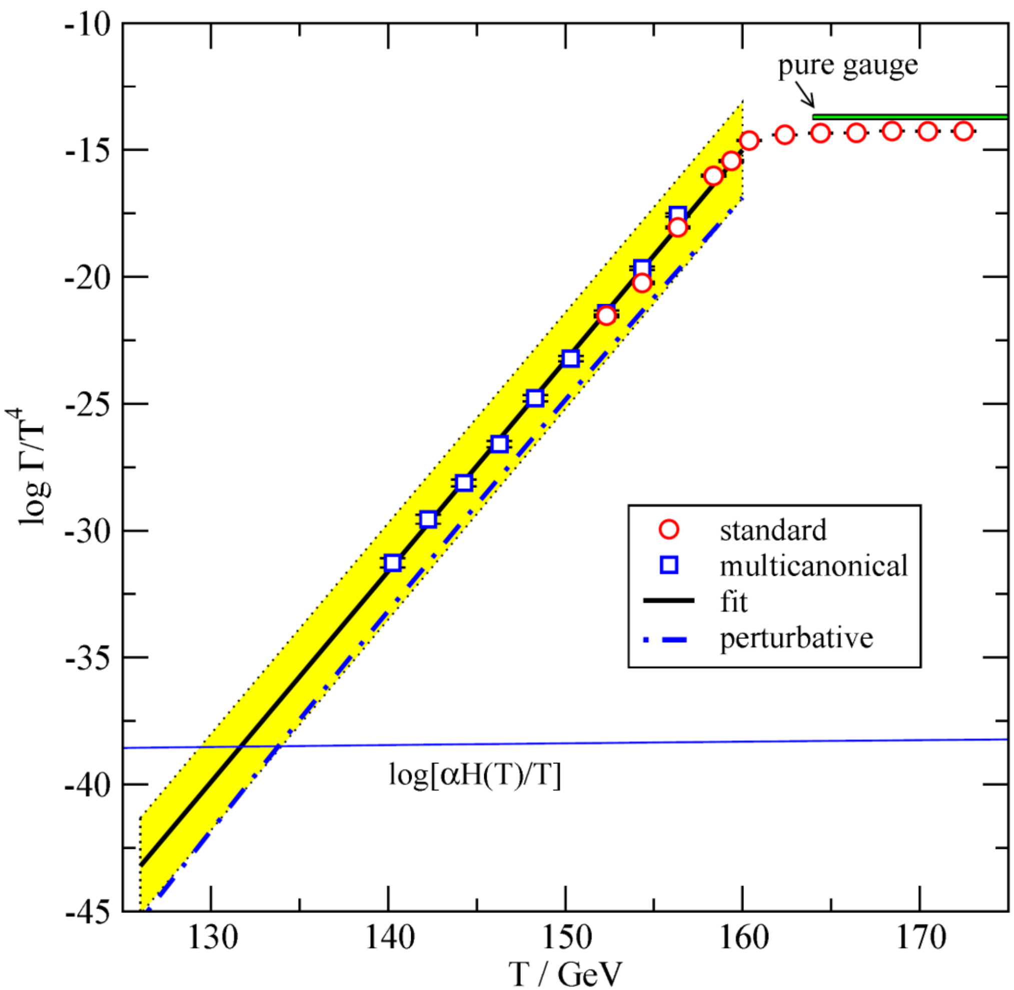
dynamics



solution to the EoM

Electroweak Sphaleron

With sphalerons, the transition rate (at the temperature T) is determined by the sphaleron energy and many other factors [nonperturbative issues]



D'Onofrio, Rummukainen, Tranberg, 14

Sphaleron rate:

$$\Gamma = \lim_{V,t\to\infty} \frac{\langle [N_{cs}(t) - N_{cs}(0)]^2 \rangle}{Vt}$$

Rate in the broken phase

$$\log \frac{\Gamma_{\rm Broken}}{T^4} = (0.83 \pm 0.01)\frac{T}{\rm GeV} - (147.7 \pm 1.9)$$

Rate in the symmetric phase

$$\Gamma_{\rm Symm.}/T^4 = (8.0 \pm 1.3) \times 10^{-7} \approx (18 \pm 3)\alpha_W^5$$

Decoupling temperature:

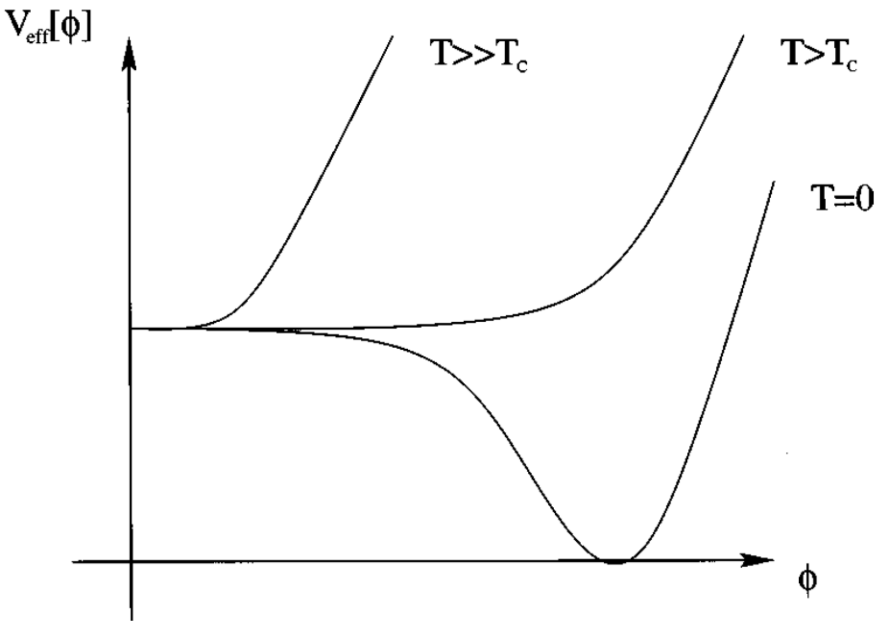
$$\Gamma(T_*)/T_*^3 = \alpha H(T_*)$$

$$\boxed{T_* = (131.7 \pm 2.3)\ \mathrm{GeV}}$$

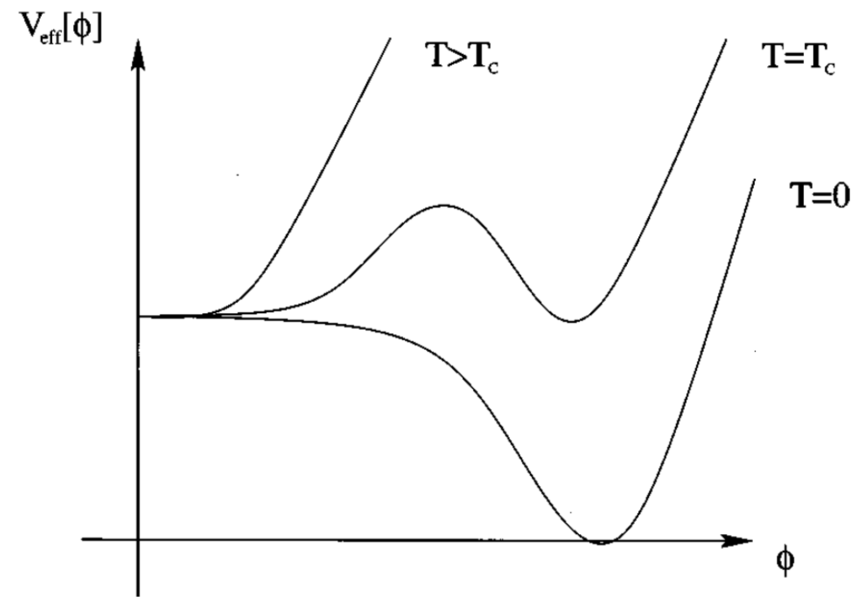
Electroweak Phase Transition

At finite temperatures, the broken symmetries can be restored

Kirzhnits, Linde, 72; Dolan, Jackiw, 74; Weinberg, 74



Second-order phase transition



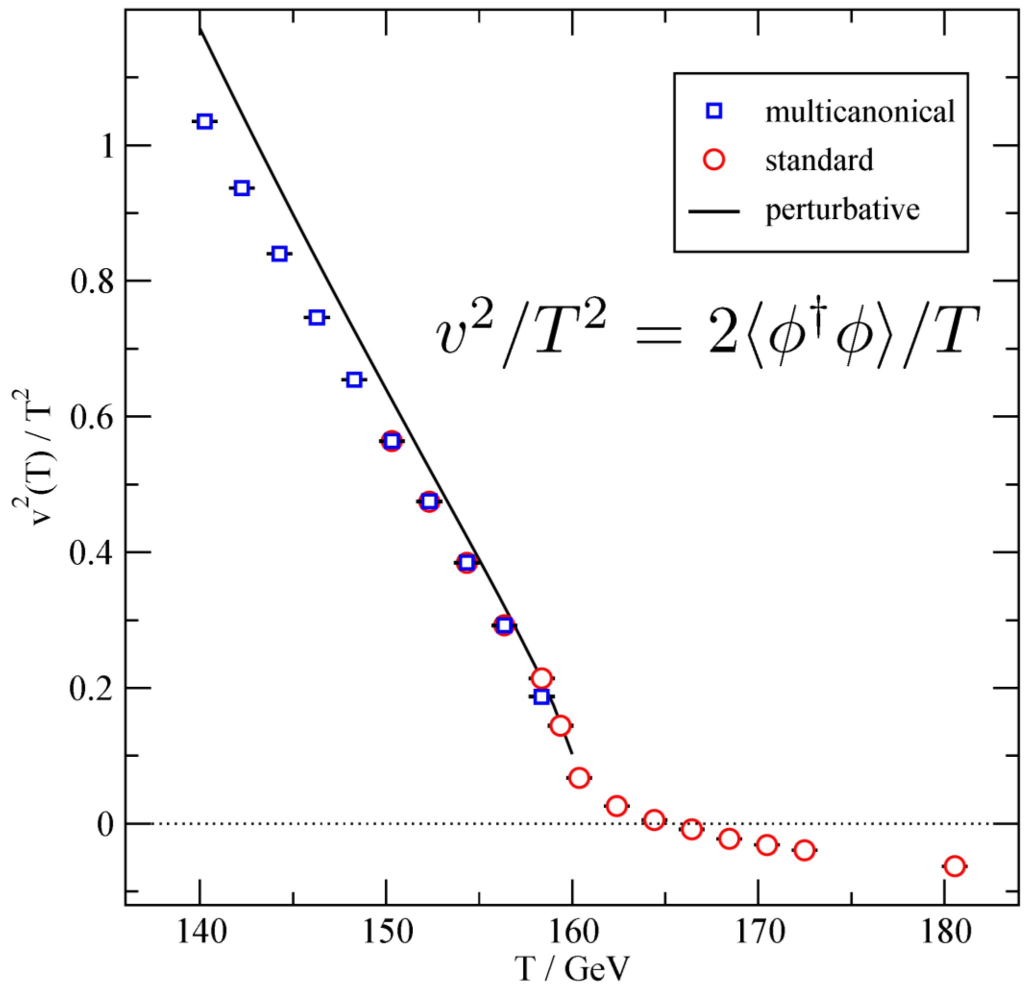
First-order phase transition

- ◆ **Single minimum at nonzero field value**
- ◆ **Classical conversion to the minimum**
- ◆ **No significant deviation from equilibrium**

- ◆ **Degenerate minimum at T_c**
- ◆ **Quantum tunneling occurs**
- ◆ **True-vacuum bubbles**

Strongly first-order phase transitions offer an efficient way to go out of thermal equilibrium, as the third Sakharov necessary condition

The nature of phase transitions in the SM: no proper phase transition!



D'Onofrio, Rummukainen, Tranberg, 14

One-loop effective potential in the SM at high temperature

$$V_{\rm eff}^{(1)}(\varphi;T)=\left(\frac{3}{32}g^2+\frac{\lambda}{4}+\frac{m_t^2}{4v^2}\right)(T^2-T_*^2)\varphi^2$$
$$\boxed{-\frac{3g^2}{32\pi}T\varphi^3}+\frac{\lambda}{4}\varphi^4,$$

The critical temperature

$$T_c=m_H\left(\frac{3}{8}g^2+\lambda-\frac{9}{256\pi^2}g^6+\frac{m_t^2}{v^2}\right)^{-1/2}$$

- **v^2 as a smooth function of T**
- **A sharp cross-over exists at**

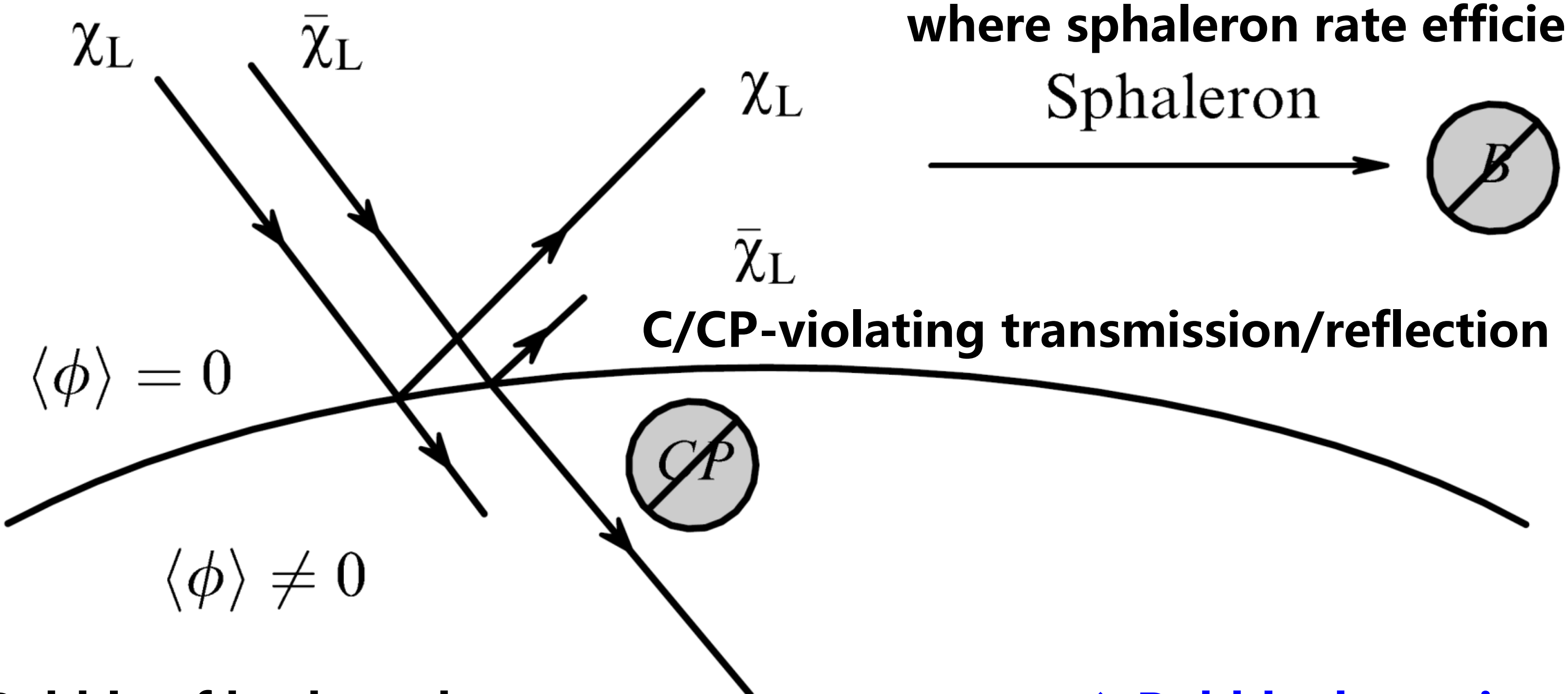
$$\boxed{T_c = 159 \pm 1\,\text{GeV}}$$

Electroweak Baryogenesis

Basic ideas: (1) Sphaleron-BNV; (2) C & CP violation from the CKM matrix; (3) out-of-equilibrium from strongly first-order phase transitions

Fermions with baryon numbers

Region of symmetric phase where sphaleron rate efficient



Bubble of broken phase where sphaleron rate suppressed

- **Bubble dynamics**
- **Charge transport**

SM electroweak baryogenesis: dead; (i) highly-suppressed CP violation; (ii) no first-order phase transition

Electroweak Baryogenesis

- New physics beyond the SM introduced and could be potentially **testable**
- Make use of the **sphaleron-BNV** instead of other exotic BNV interactions

Two-Higgs-Doublet Model Branco et al., 12

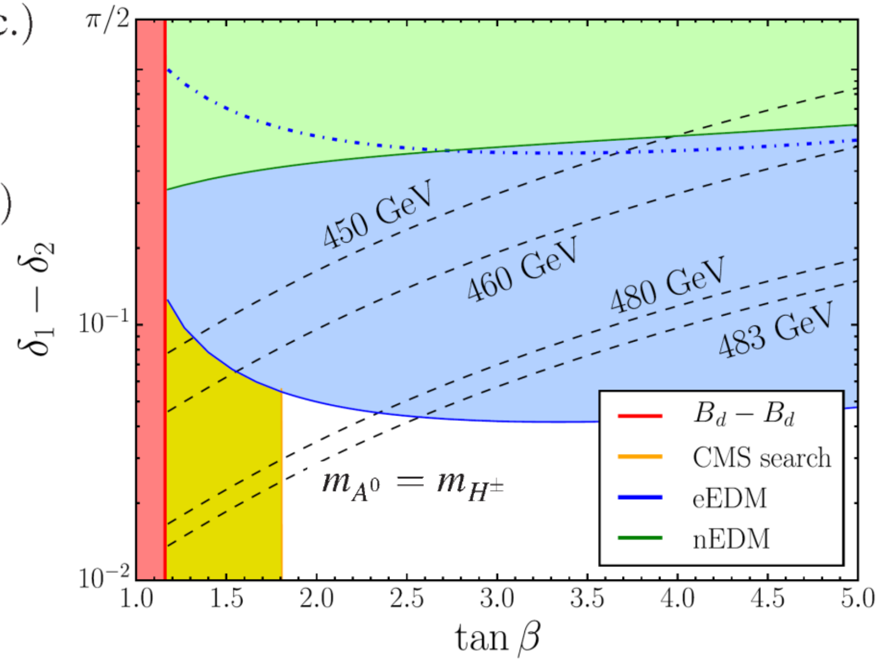
$$V_{\text{tree}}(\Phi_1,\Phi_2) = -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \tfrac{1}{2}(\mu^2\Phi_1^\dagger\Phi_2 + \text{H.c.}) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \tfrac{1}{2}[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{H.c.}].$$

Extra sources of CP violation

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v\cos\beta \end{pmatrix}, \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v\sin\beta e^{i\theta} \end{pmatrix}.$$

$$\delta_1 = \arg[(\mu^2)^2\lambda_5^*], \qquad \delta_2 = \arg(v_1 v_2^* \mu^2 \lambda_5^*)$$

Dorsch et al., 17



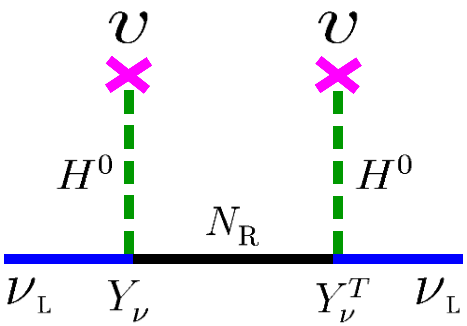
$m_{H^0} = 200$ GeV

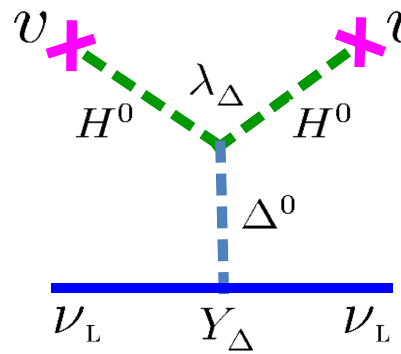
Interesting features of new-physics models for successful EW Baryogenesis:

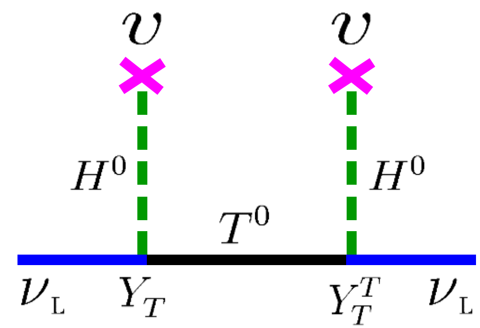
Electron-EDM **Neutron-EDM** **Collider searches** **Gravitational waves**

Baryogenesis via Leptogenesis

Majorana neutrinos: a natural way to understand neutrino masses







$$\boxed{M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T} \qquad \boxed{M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}} \qquad \boxed{M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T}$$

Type-I: SM + 3 right-handed Majorana ν's (Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanovic 79)

Type-II: SM + 1 Higgs triplet (Magg, Wetterich 80; Schechter, Valle 80; Lazarides et al 80; Mohapatra, Senjanovic 80; Gelmini, Roncadelli 80)

Type-III: SM + 3 triplet fermions (Foot, Lew, He, Joshi 89)

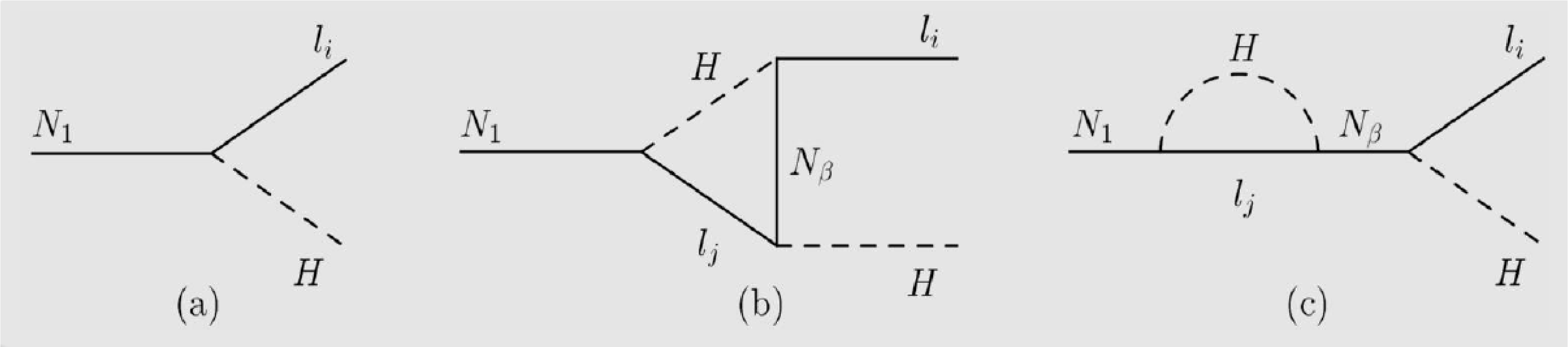
Attractive picture: heavy Majorana neutrinos in the early Universe could successfully generate the BAU

Fukugita & Yanagida (1986)

Baryogenesis via Leptogenesis

Basic ideas: (1) Sphaleron-BNV (in thermal equilibrium 10^2 GeV – 10^{12} GeV)
(2) Yukawa couplings for extra CPV; (3) expanding Universe

Neutrino masses ← **Seesaw** — **Right-handed neutrinos** — **Leptogenesis** → **BAU**



$$\varepsilon_{N_1} = \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to \bar{l}H^\dagger)}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to \bar{l}H^\dagger)}$$

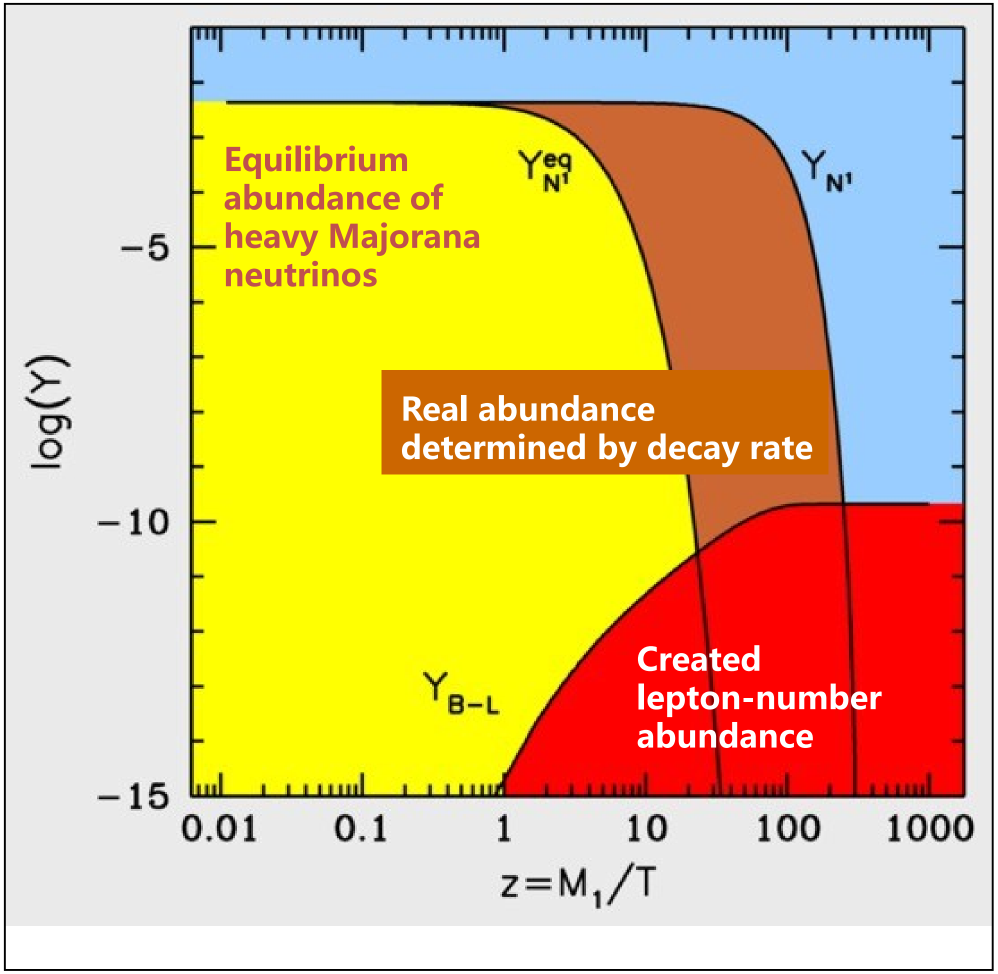
$$= -\frac{1}{8\pi}\sum_{\beta\neq 1}\frac{\Im\left[\left(\lambda^\dagger\lambda\right)^2_{\beta 1}\right]}{(\lambda^\dagger\lambda)_{11}}\left\{\left[-\frac{M_\beta}{M_1}\left(1-\left(1+\frac{M_\beta^2}{M_1^2}\right)\right)\ln\left(1+\frac{M_1^2}{M_\beta^2}\right)\right]+\left[\frac{M_1/M_\beta}{1-(M_1^2/M_\beta^2)}\right]\right\}$$

$$\simeq -\frac{3}{16\pi}\sum_{\beta\neq 1}\frac{\Im\left[\left(\lambda^\dagger\lambda\right)^2_{\beta 1}\right]}{(\lambda^\dagger\lambda)_{11}}\frac{M_1}{M_\beta} \qquad (\text{For } M_1 \ll M_\beta)$$

[L. Covi, E. Roulet and F. Vissani, PLB384 (1996)]

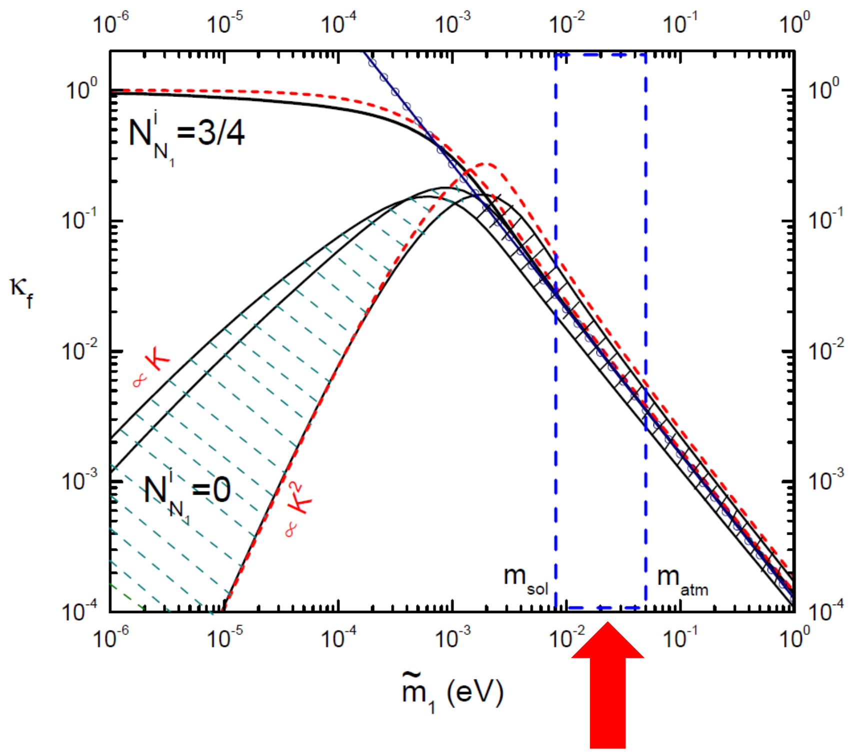
Baryogenesis via Leptogenesis

Solving the Boltzmann equations



$$\eta_B \approx -0.96 \times 10^{-2} \kappa_f \varepsilon_1$$

Buchmueller et al., 2004



Strong washout region: compatible with observed neutrino masses & independent of initial abundances

- ◆ Resonant leptogenesis: enhanced CPV
- ◆ Asymmetry of individual lepton flavor
- ◆ Non-equilibrium thermal field theories

Consider a theory of a complex scalar with baryon number (e.g., squarks)

$$\mathcal{L}_\phi = (\partial^\mu \phi^\dagger)(\partial_\mu \phi) - m^2 \phi^\dagger \phi \qquad J^\mu_{\rm B} = \mathrm{i}(\phi^\dagger \partial^\mu \phi - \phi \partial^\mu \phi^\dagger)$$

Affleck, Dine, 85 **CP & Baryon number conserved**

Introduce the interaction of the complex scalar

$$\mathcal{L}_{\rm int} = \lambda(\phi^\dagger \phi)^2 + \left[\epsilon \phi^\dagger \phi^3 + \delta \phi^4 + \mathrm{h.c.}\right]$$

CP & Baryon number violated

Evolution of the complex scalar in the expanding Universe

$$\frac{\mathrm{d}^2\phi(t)}{\mathrm{d}t^2} + 3H\frac{\mathrm{d}\phi(t)}{\mathrm{d}t} + \frac{\partial V(\phi)}{\partial \phi} = 0$$

For H >> m, the dissipation term dominates & the scalar field frozen; but for H <<m, the scalar field starts to oscillate

$$\phi_{\rm I} = a_r \frac{\mathrm{Im}(\epsilon + \delta)\phi_0^3}{m^2 (mt)^{3/4}} \sin(mt + \delta_r) \qquad \phi_{\rm I} = a_m \frac{\mathrm{Im}(\epsilon + \delta)\phi_0^3}{m^3 t} \sin(mt + \delta_m)$$

Radiation-dominated era **matter-dominated era**

Affleck-Dine Mechanism

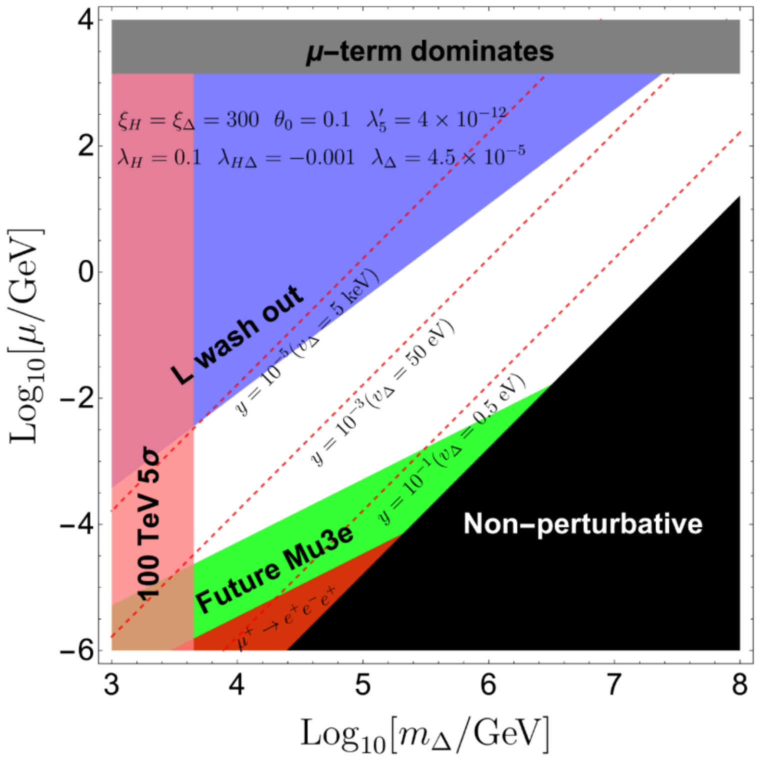
Given the scalar field, calculate the baryon number from the current

$$n_{\rm B} = 2a_r \frac{{\rm Im}(\epsilon+\delta)\phi_0^2}{m^3 t^2}\sin(\delta_r + \pi/8)\ , \qquad ({\rm radiation})\ ,$$

$$n_{\rm B} = 2a_m \frac{{\rm Im}(\epsilon+\delta)\phi_0^2}{m^3 t^2}\sin(\delta_m)\ , \qquad ({\rm matter})\ .$$

Kusenko, Dine, 04

Baryon number asymmetry restored in the scalar condensate, which will be converted into quarks via scalar decays (dynamics & evolution: models)



Affleck-Dine Leptogenesis & type-II seesaw

Barrie, Han, Murayama, 22

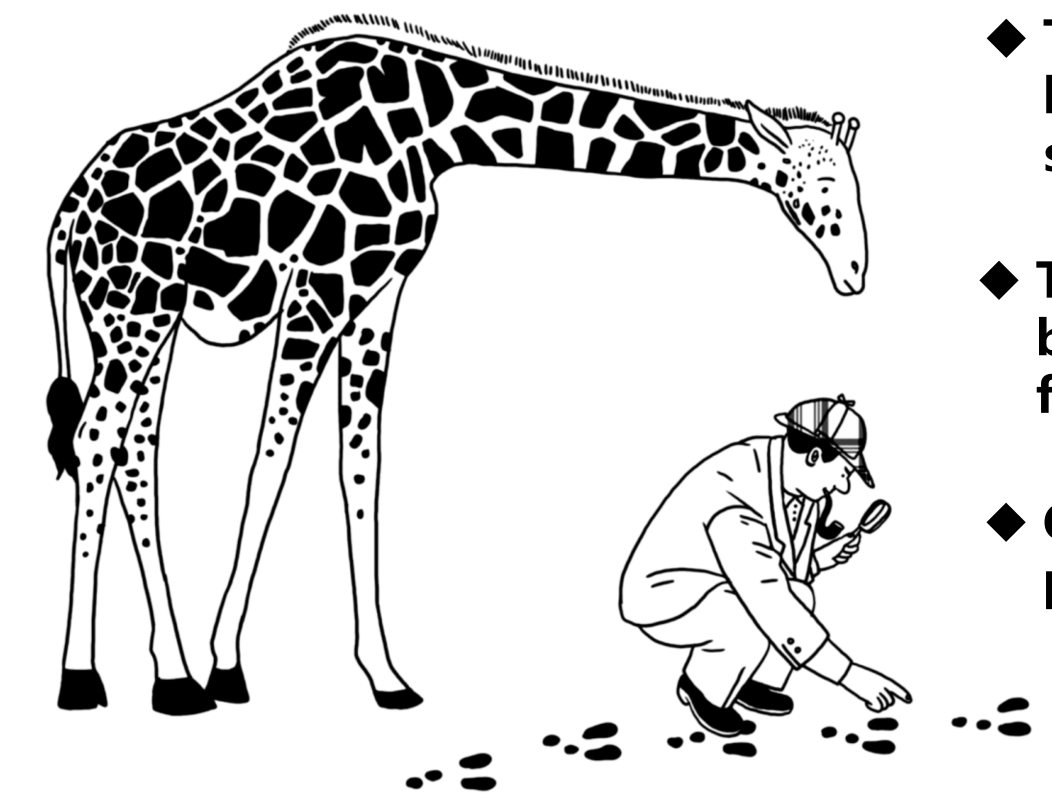
$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}M_p^2 R - F(H,\Delta)R - g^{\mu\nu}(D_\mu H)^\dagger(D_\nu H)$$
$$-g^{\mu\nu}(D_\mu\Delta)^\dagger(D_\nu\Delta) - V(H,\Delta) + \mathcal{L}_{\rm Yukawa}$$

$$\mathcal{L}_{Yukawa} = \mathcal{L}^{\rm SM}_{\rm Yukawa} - \frac{1}{2}y_{ij}\bar{L}_i^c \Delta L_j + h.c.$$

$$V(h,\Delta^0) = -m_H^2|h|^2 + m_\Delta^2|\Delta^0|^2 + \lambda_H|h|^4 + \lambda_\Delta|\Delta^0|^4$$
$$+\lambda_{H\Delta}|h|^2|\Delta^0|^2 + \left(\mu h^2\Delta^{0*} + \frac{\lambda_5}{M_p}|h|^2 h^2 \Delta^{0*}\right.$$
$$\left. + \frac{\lambda_5'}{M_p}|\Delta^0|^2 h^2\Delta^{0*} + h.c.\right) + \ldots$$

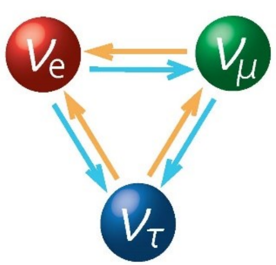
Inflation
+
ν mass
+
BAU

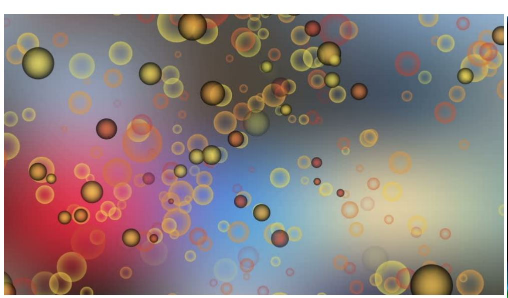
Summary & Outlook

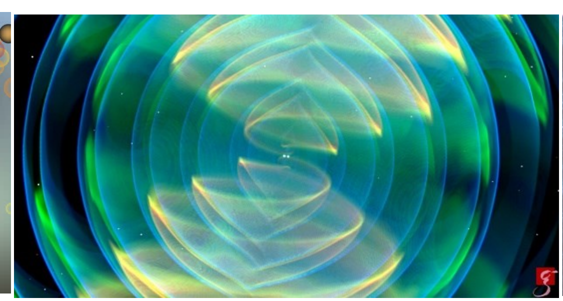


- ◆ The mystery of missing antimatter has not yet been solved, even no single clue exists
- ◆ The SM model with 125 GeV Higgs boson has been excluded as a true framework to solve the problem
- ◆ Currently there are three types of popular scenarios on the market:
  - ➢ Electroweak baryogenesis
  - ➢ Leptogenesis
  - ➢ Affleck-Dine mechanism

◆ Connections to neutrino masses, dark matter, gravitational waves may help to solve one or more these fundamental problems together



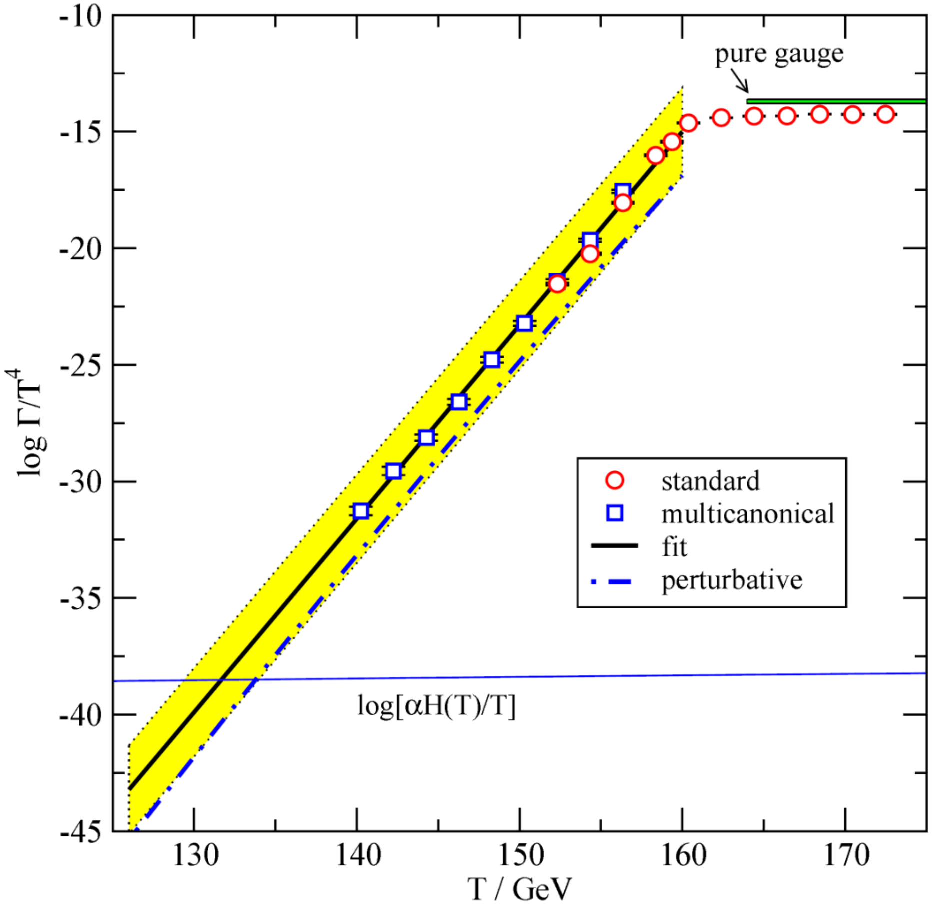


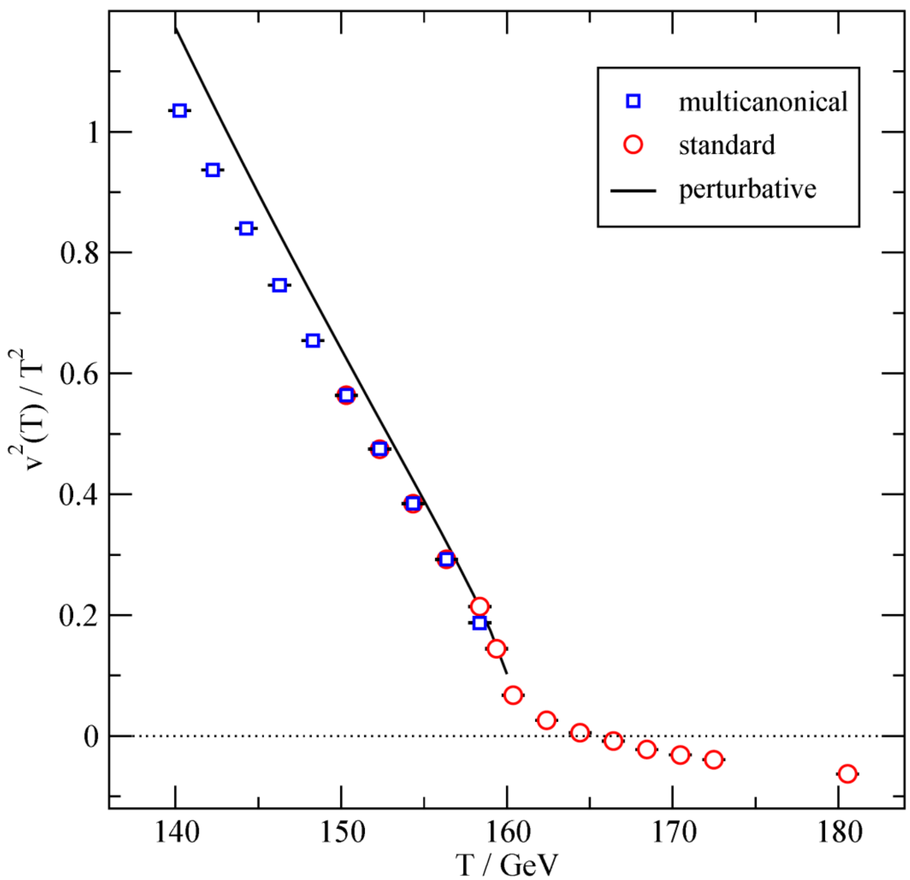


Topics for Further Discussions

1. Electroweak Phase Transition & Sphaleron Rate

D'Onofrio, Rummukainen, Tranberg, 14



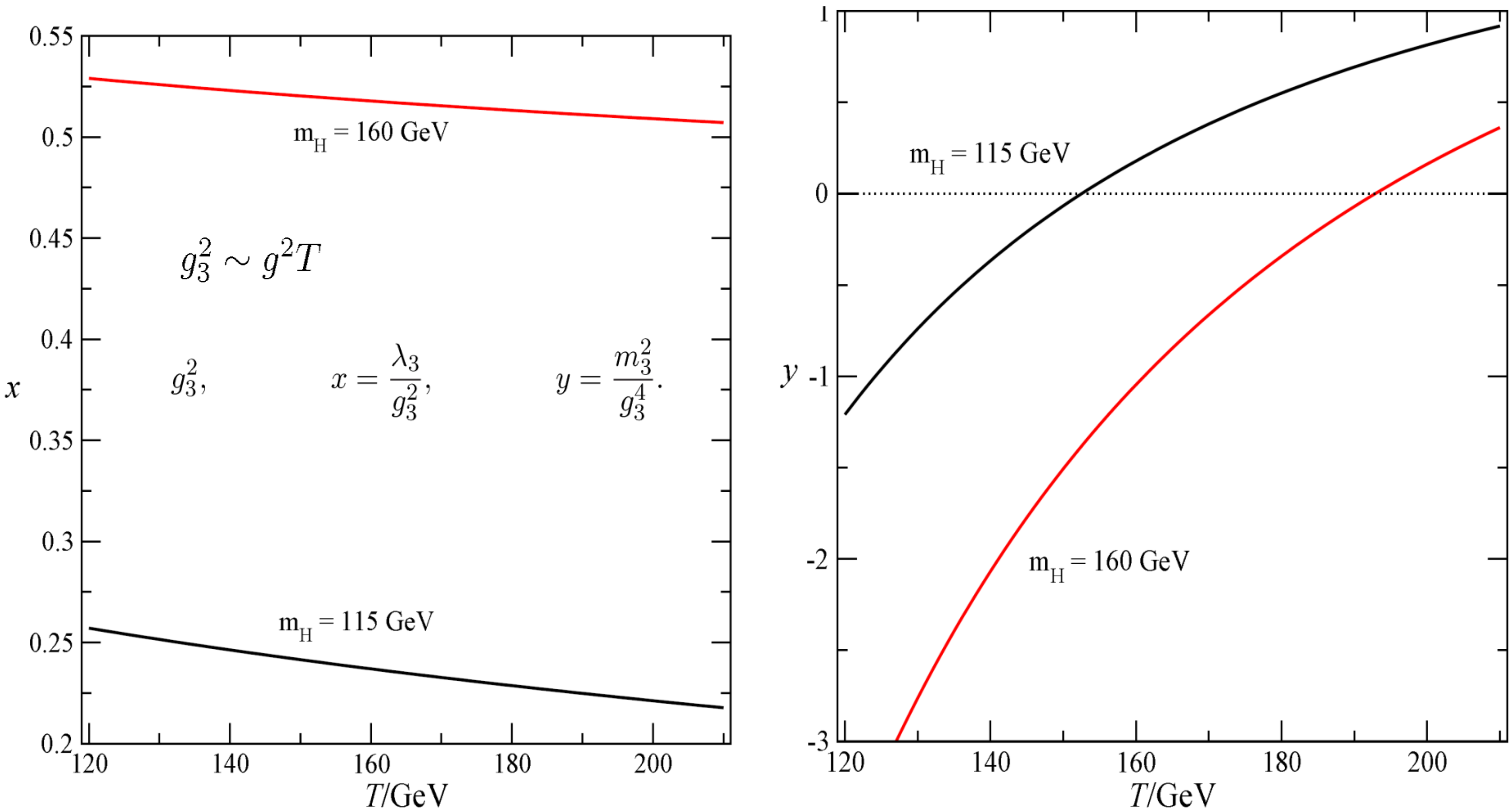


- **Are there any calculations from other groups confirming these results?**
- **Lattice calculations of quantum field theories at finite temperature**

Topics for Further Discussions

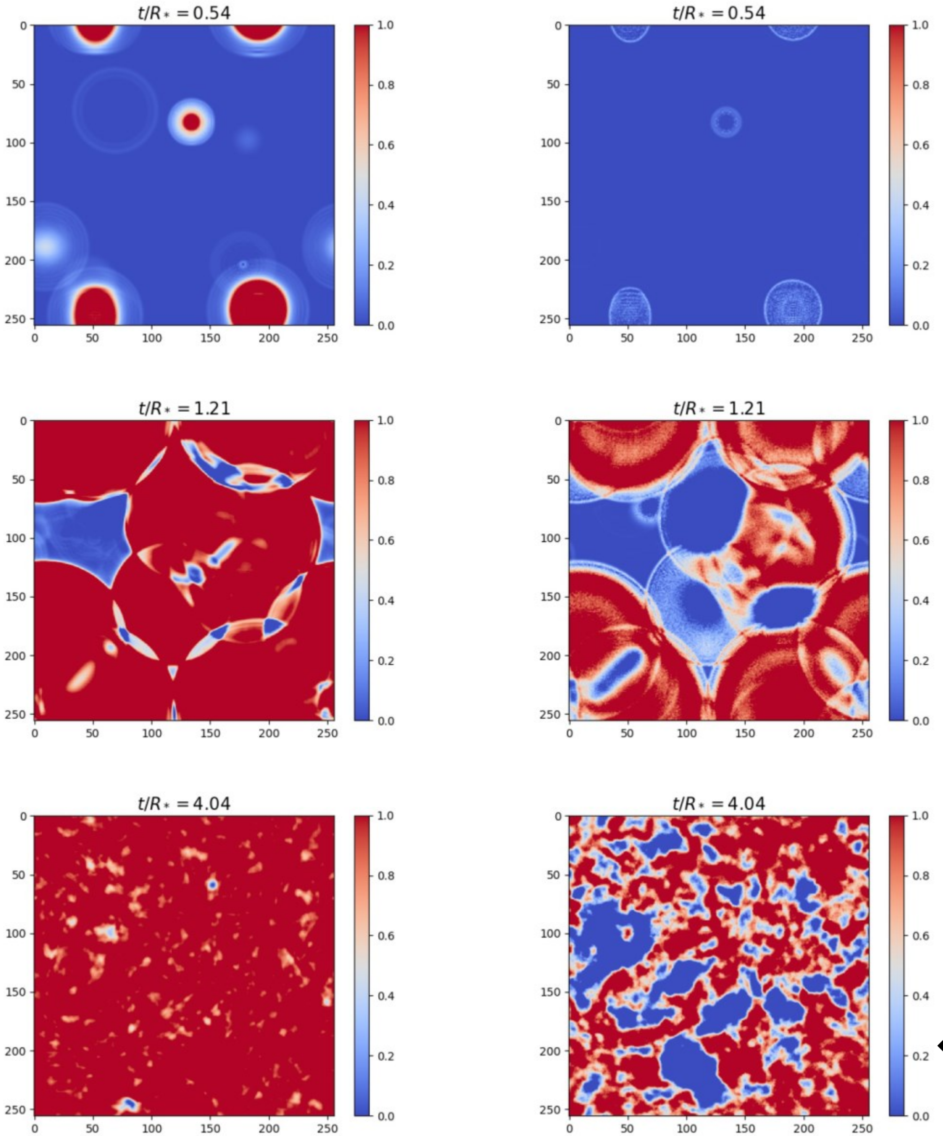
1. Electroweak Phase Transition & Sphaleron Rate

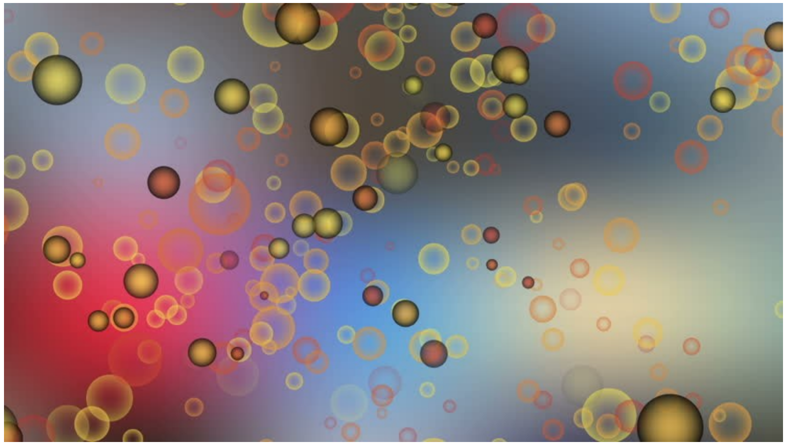
Dimensional reduction $$S = \int d^3x \left(\frac{1}{4} F^a_{ij} F^a_{ij} + (D_i\phi)^\dagger (D_i\phi) + m_3^2 \phi^\dagger \phi + \lambda_3 (\phi^\dagger \phi)^2 \right)$$



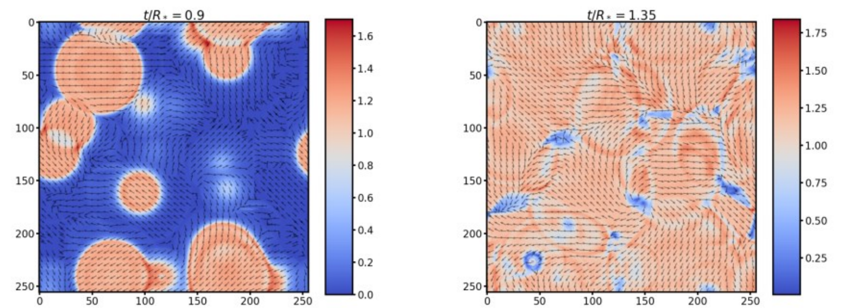
D'Onofrio, Rummukainen, Tranberg, 1207.0685

2. Lattice simulations of EW phase transitions





Zhao, Di, Bian, Cai, 2204.04427



Zhou, Bian, Du, 2203.01561

- ◆ **First-principle simulations for the studies of bubble dynamics?**

3. Sphaleron in the SM extended with scalar multiplets

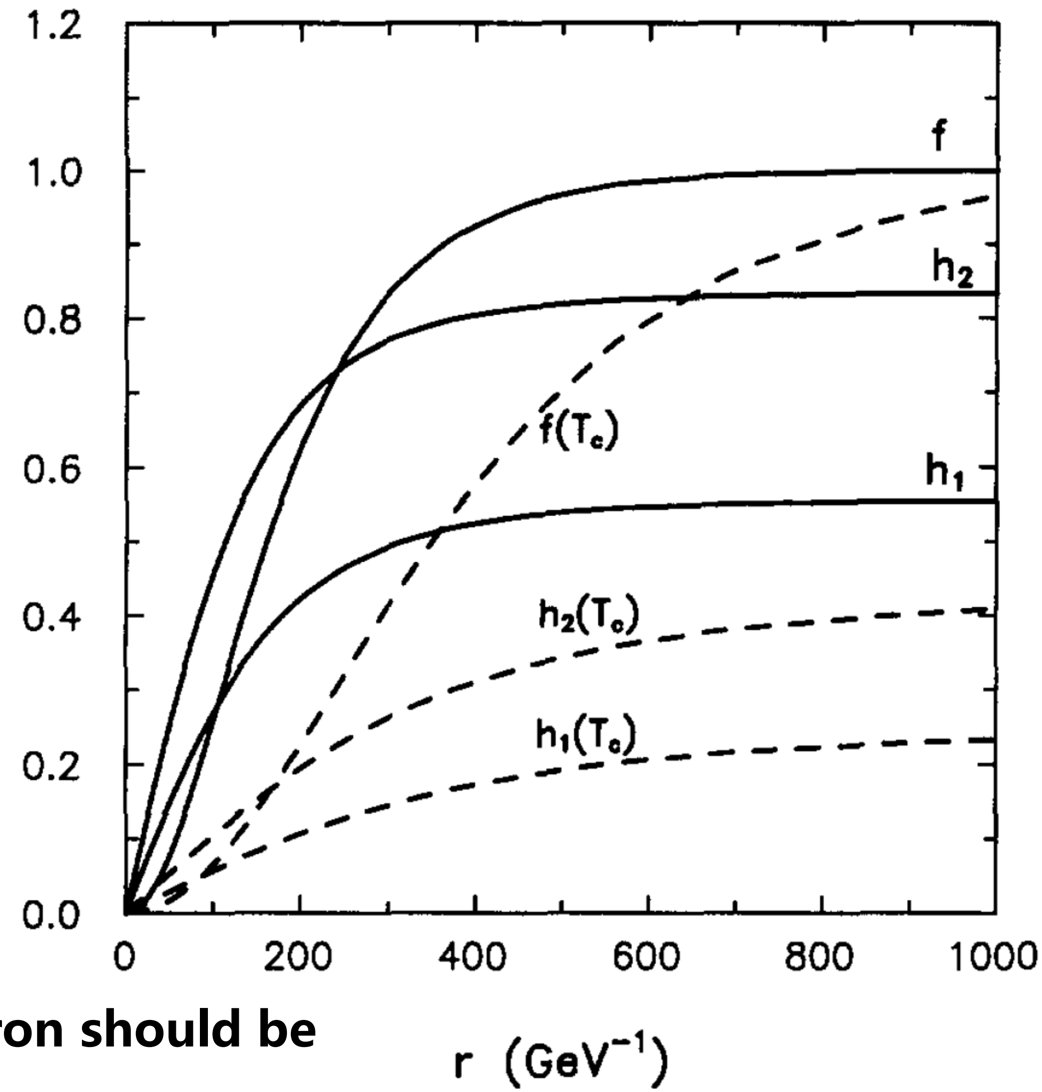
Moreno, Oaknin, Quiros, 97

$$W_j^a(x) = \frac{2f(r)}{gr^2}\epsilon_{ajk}x_k,$$

$$H_1(x) = h_1(r) i\frac{\boldsymbol{\sigma}\cdot\boldsymbol{x}}{r}\begin{bmatrix}1\\0\end{bmatrix}$$

$$H_2(x) = h_2(r) i\frac{\boldsymbol{\sigma}\cdot\boldsymbol{x}}{r}\begin{bmatrix}0\\1\end{bmatrix}$$

for the sphaleron in the MSSM.



- ◆ **If strongly first-order phase transitions are obtained, the sphaleron solution itself may be changed**
- ◆ **Both phase transition & sphaleron should be studied in a self-consistent way**

4. New-physics models should explain neutrino masses as well

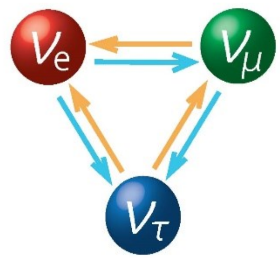
BAU

1^{st} phase transitions

eEDM
nEDM

Sources of CPV

BAU



neutrino masses as well-established evidence for new physics

Stochastic gravitational waves

Dark Matter

BAU

Leptogenesis

BAU

New-physics connecting neutrino masses and BAU should have other signals so as to be completely verifiable or falsifiable