ELECTROWEAK BARYOGENESIS AND STOCHASTIC GRAVITATIONAL WAVES

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COSMOLOGY FRONTIER IN PARTICLE PHYSICS: ASTRO-PARTICLE PHYSICS AND EARLY UNIVERSE

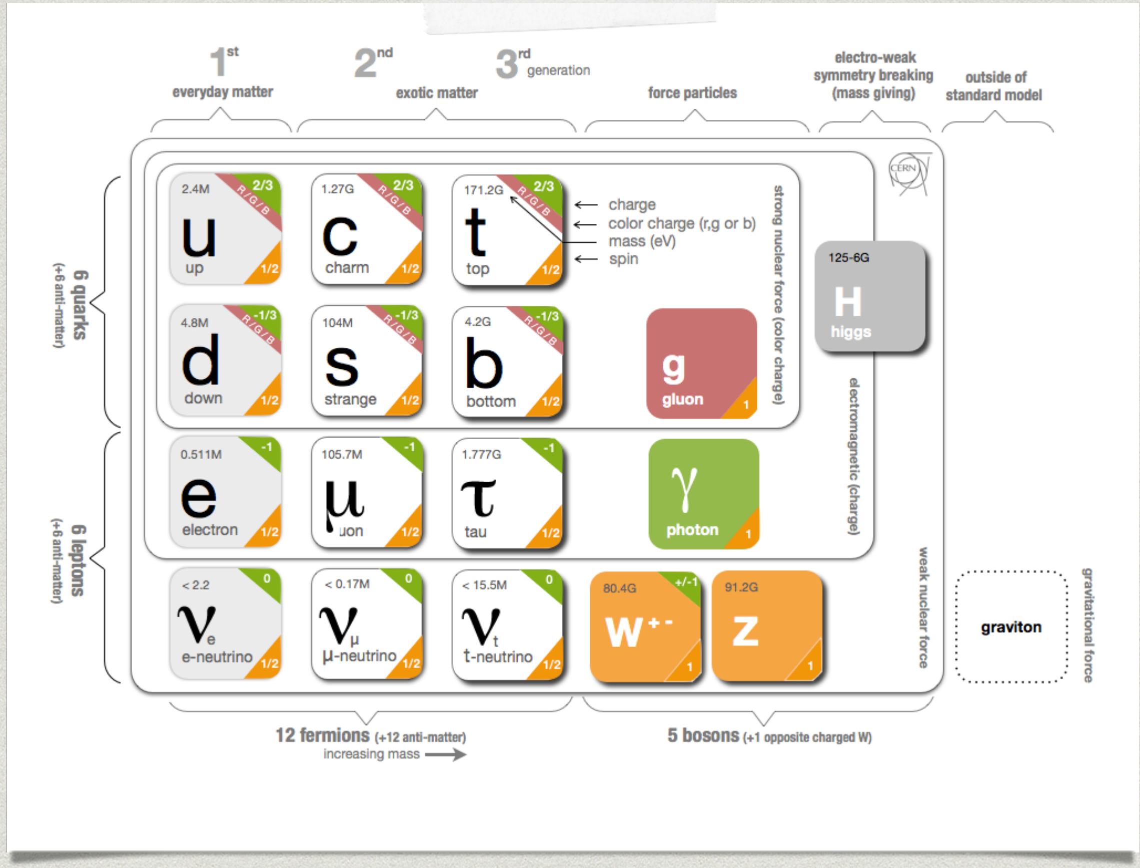
Outline&preview

- **EWBG from spontaneous CPV at the finite T and a two-step phase transition**
- **Stochastic gravitational wave signals from two-step PT**

Preview

- ***Show you how to avoid constraints on the electroweak baryogengesis from the energy and intensity frontiers.***
- ***Show you the space-based interferometer is an efficient facility for the indirect detection of the PT with the stochastic gravitational wave signal.***

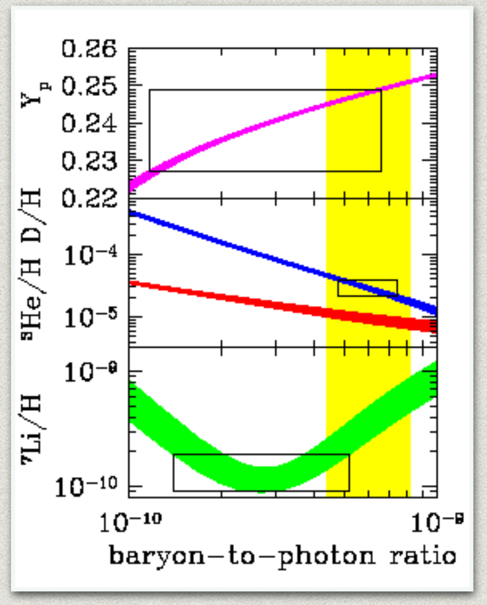
Particle Zoo

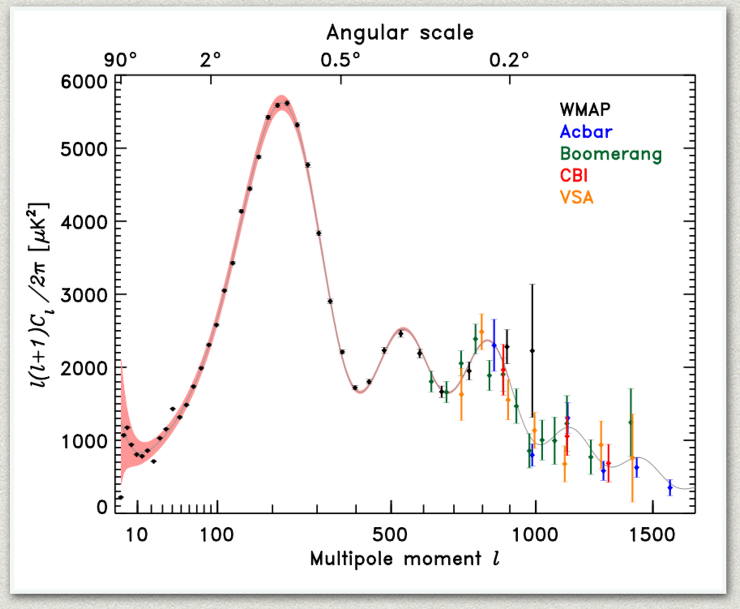


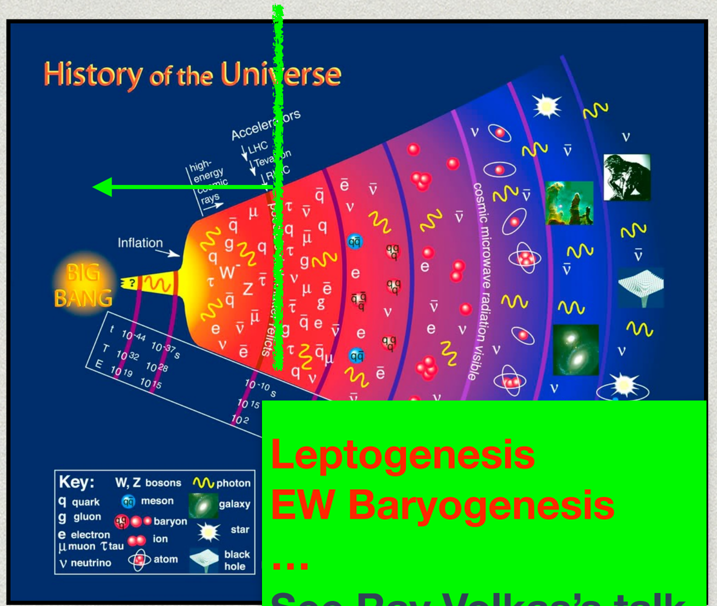
- Neutrino masses
- Dark matter
- Baryon asymmetry

Baryon asymmetry

- No anti-galaxy was observed
- The abundance of the primordial elements and the height of the CMB power spectrum depend on the ratio of of baryon to photons





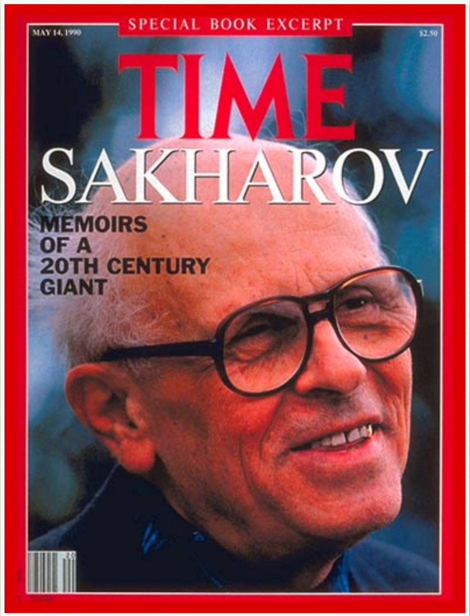


Leptogenesis
EW Baryogenesis
...
See Ray Volkas's talk for a short summary

Baryon asymmetry: $Y_B = \frac{\rho_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$ **(Planck 2015)**

BAU from First order EWPT

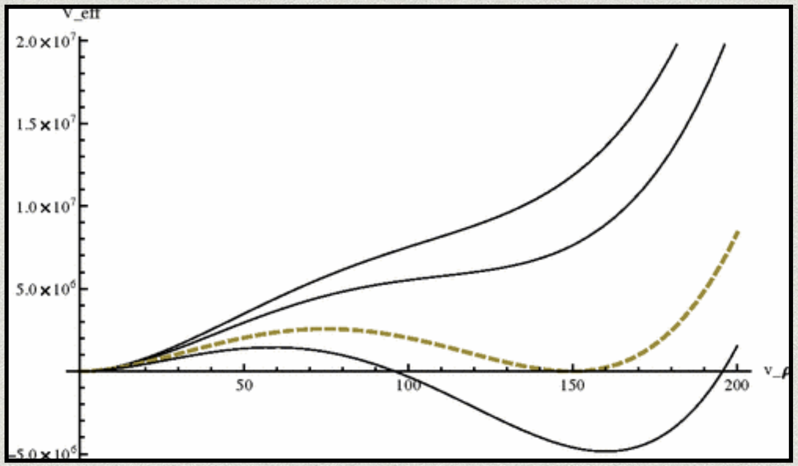
BAU might be generated during the electroweak phase transition

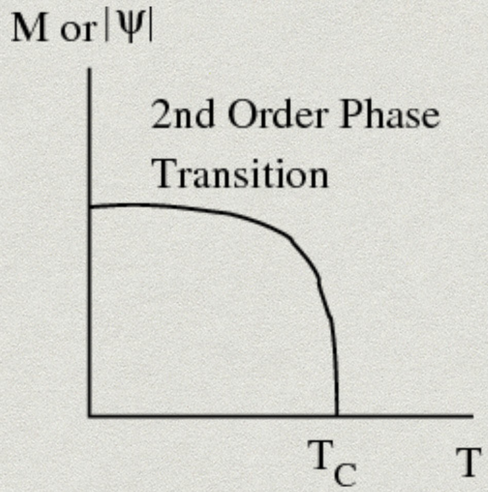


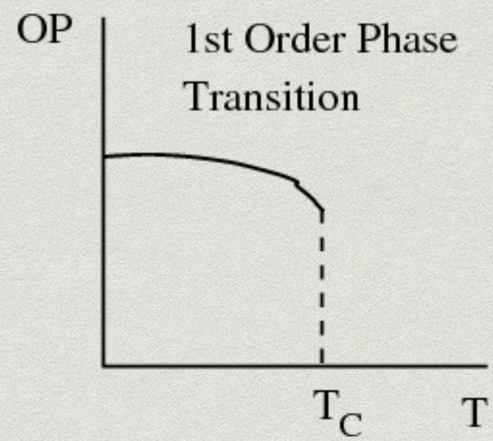
★ **Baryon number violation**
★ **C&CP violation**
★ **Departure from thermal equilibrium**

→

First order electroweak phase transition if baryon asymmetry is generated during the EWPT without CPT violation.

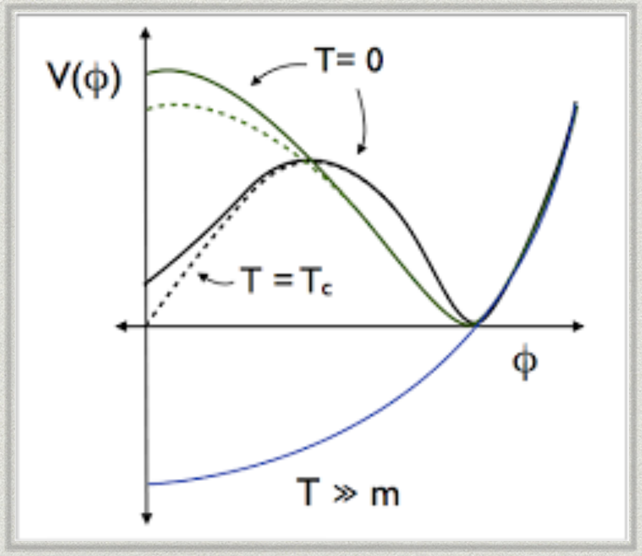


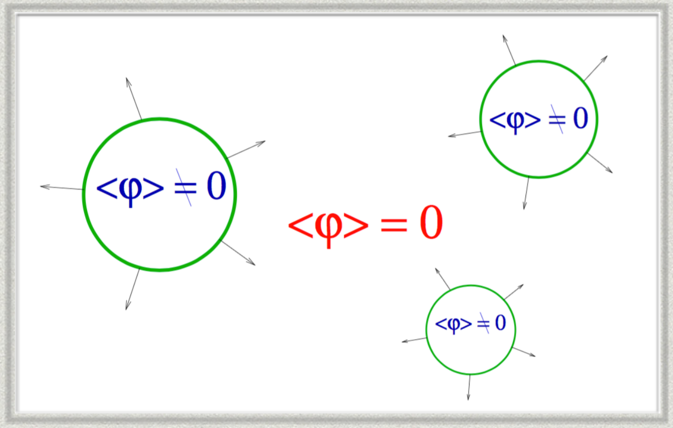




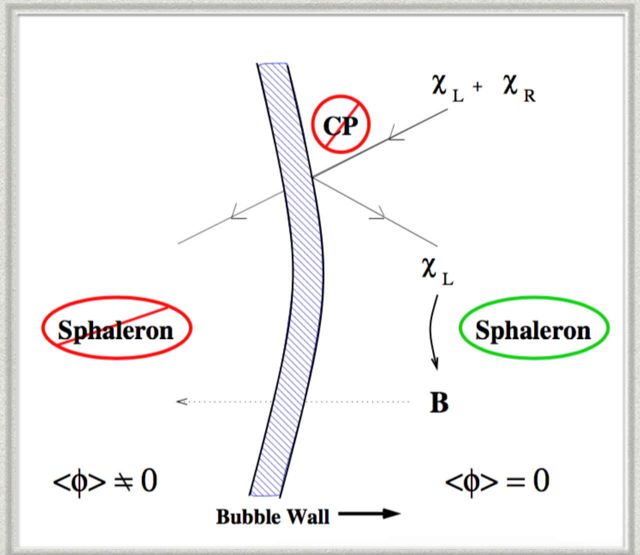
Electroweak Baryogenesis

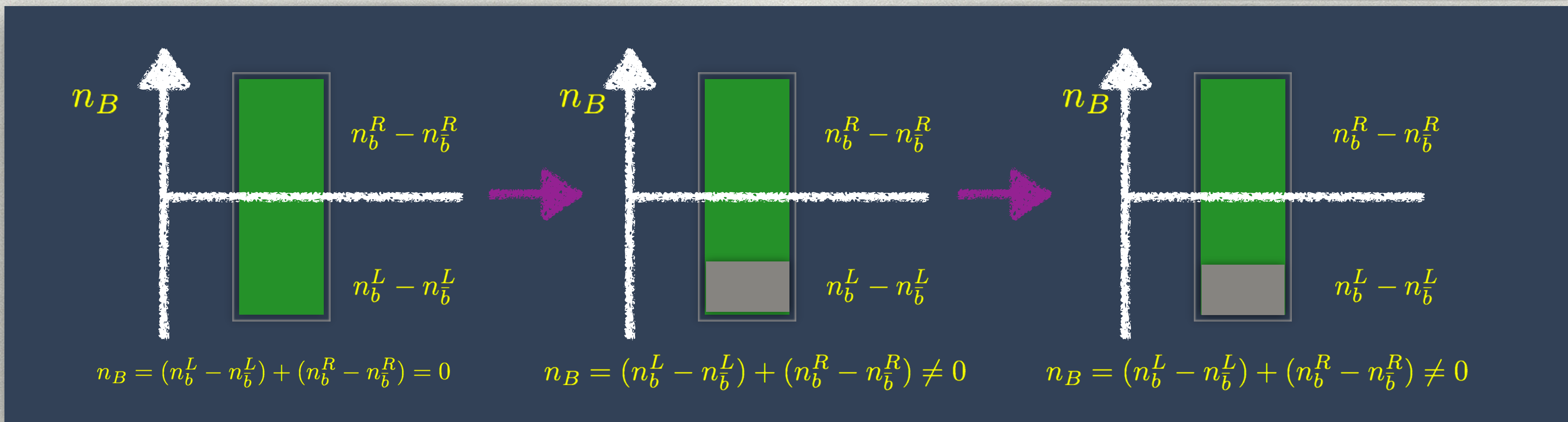
- Generate BAU during the electroweak phase transition





Basic description



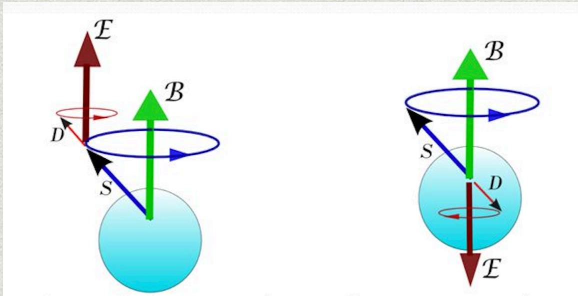


Fate of the EWBG

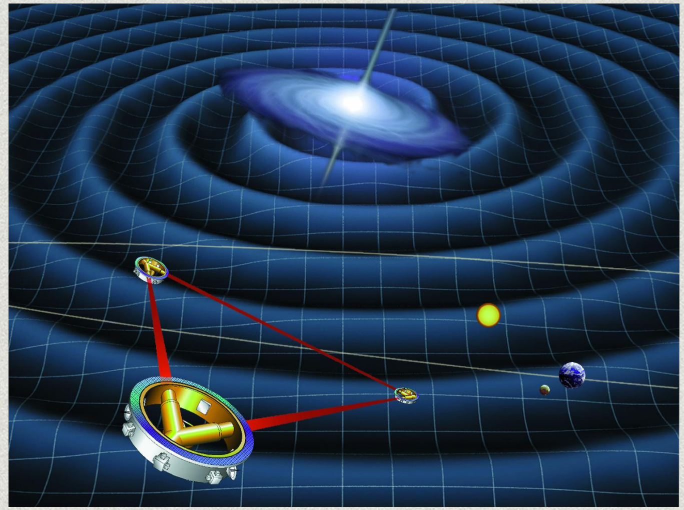
Three Detectives

LHC

EDM



GW



Conventional EWBG mechanism might be found or excluded in the near future when these three detection methods are combined.

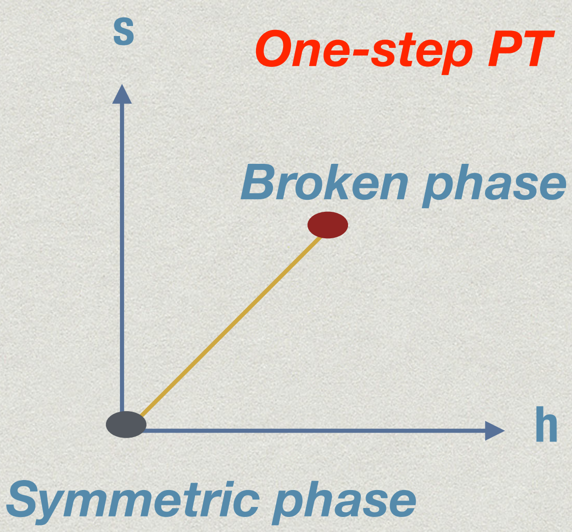
A typical example: Wino-catalyzed EWBG is excluded by the ACME result(intensity frontier) and the Higgs search results at the LHC(energy frontier).

Questions: Is there a mechanism of electroweak baryogenesis that can escape from these hunters?

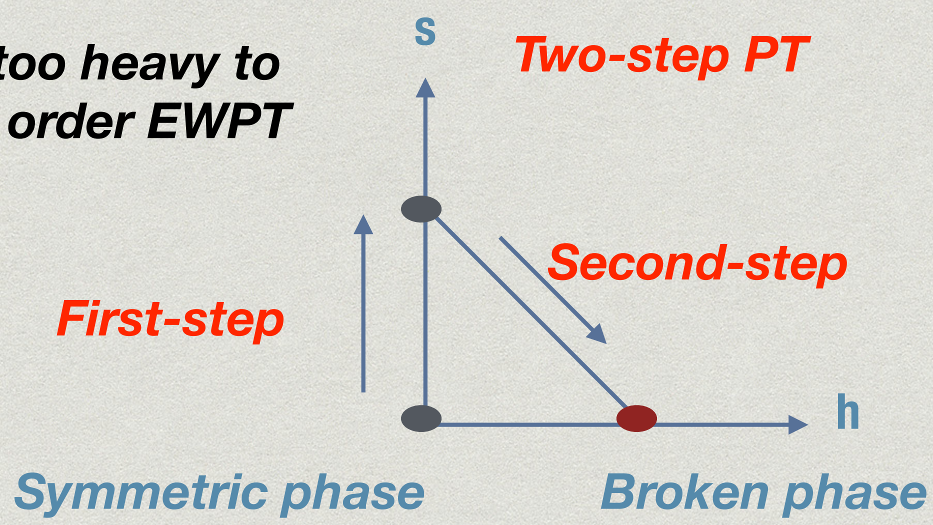
Our little aim: a EWBG with less signature

Exploring the scenario of electroweak baryogenesis that may escape from the combined detection of the cosmic, energy and intensity frontiers.

One observation: **A two-step phase transition may avoid constraint arising from Higgs searches at the LHC**



SM Higgs is too heavy to saturate first order EWPT



The barrier between the symmetric and the broken phase usually comes from radiative corrections

$$V_{\rm eff}(\phi,T)=\mathcal{A}(T)\phi^2+\mathcal{B}(T)\phi^3+\mathcal{C}(T)\phi^4+\cdots$$

The barrier exists at the tree-level

Merits:

1. **No mixing with the SM Higgs**
2. **Correlated with the dark matter**

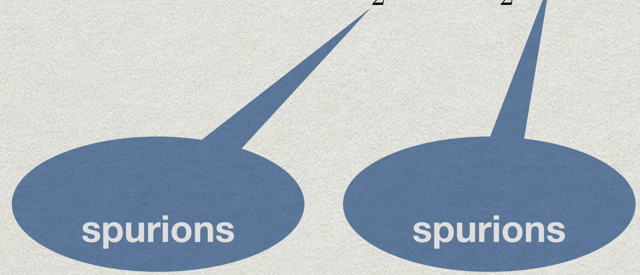
Our little aim: a EWBG with less signature

Another observation: There exists spontaneous CP phase in the scalar singlet sector

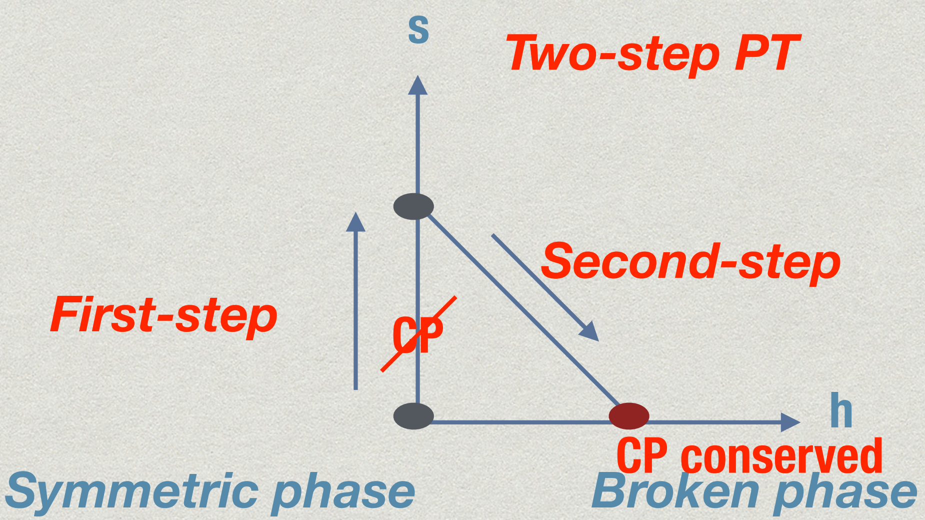
Lemma: Haber, Surujon, 2012

spontaneous CP violation in the theory of one complex scalar field may occur only when the related U(1) is explicitly broken by at least two spurions whose U(1) charges are different in magnitude

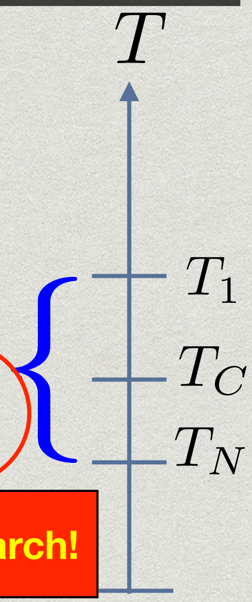
$$V = -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 - \mu_A^2(S^\dagger S) + \lambda_1(S^\dagger S)^2 + \lambda_2(H^\dagger H)(S^\dagger S) - \frac{1}{2}\mu_B^2 S^2 + \frac{1}{2}\lambda_3 S^4 + \text{h.c.}$$



A possible strategy: There might be spontaneous CPV phase only at finite T!



$$\varphi = \pm\frac{1}{2}\arccos\left[\frac{\lambda_1 - \lambda_3}{2\lambda_3}\frac{m_\beta^2 - m_\alpha^2}{\lambda_2 v^2 - m_\alpha^2 - m_\beta^2 + 2\Pi_\alpha}\right]$$



NO constraint of EDM and Higgs search!

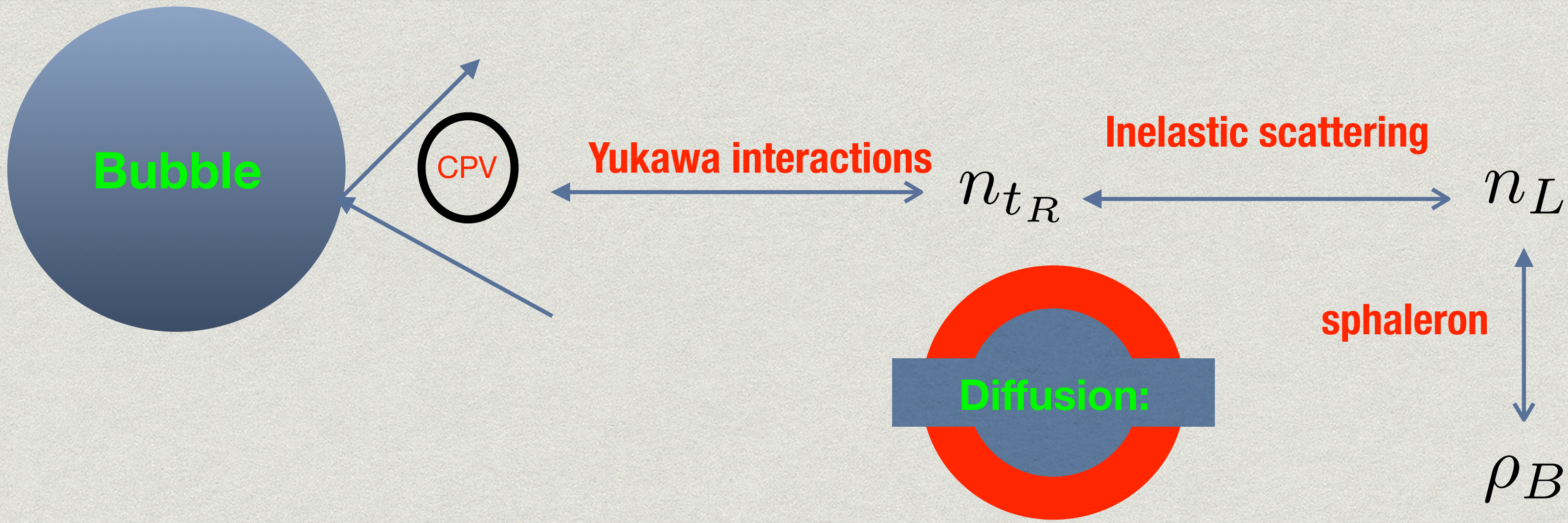
Sketch of the mechanism

Basic description

Sakharov:

- $\not{B}$
- $\not{C}$&$\not{CP}$
- First order EWPT

Sphaleron
Spontaneous CPV
Two-step PT



Transport equation:

$$\partial_t \rho_B(x) - D \nabla \rho_B(x) = -\Gamma_{\rm ws} F_{\rm ws}(x)[n_L(x) - R\rho_B(x)]$$

The model:

SM+ complex scalar singlets

Potential: $V = -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 - \mu_A^2(S^\dagger S) + \lambda_1(S^\dagger S)^2 + \lambda_2(H^\dagger H)(S^\dagger S) - \frac{1}{2}\mu_B^2 S^2 + \frac{1}{2}\lambda_3 S^4 + \text{h.c.}$

Yukawa: $-\mathscr{L} \sim \frac{1}{\Lambda}\overline{Q_L}\tilde{H}St_R + \text{h.c.}$

↑

$-\mathscr{L} \sim \eta\overline{T_L}St_R + M\overline{T_L}T_R + \text{h.c.}$

$T_{L,R}$: vector-like top quark

$$J_{B(F)}(x) = \int_0^\infty dt t^2 \ln\left(1 \mp \exp\{-\sqrt{t^2+x}\}\right)$$

$$V_T = \frac{T^4}{2\pi^2}\left\{\sum_{i\in B} n_i J_B\left[\frac{m_i^2(h,s,\xi)}{T^2}\right] - \sum_{j\in F} n_j J_F\left[\frac{m_j^2(h)}{T^2}\right] - \sum_{k\in G} n_k J_B\left[\frac{m_k^2(h,s,\xi)}{T^2}\right]\right\}$$

- **V_0: The tree-level potential**
- **V_T: Finite temperature contribution**

$$V_{\text{eff}} = V_0 + V_{\text{CW}} + V_T + V_{\text{Daisy}}$$

- **V_{CW}: Coleman-Weinberg term**
- **V_{ring}: The ring contribution**

$$V_{\text{CW}} = \frac{1}{64\pi^2}\sum_i (-1)^{2s_i} n_i m_i^4(h,s,\xi)\left[\log\frac{m_i^2(h,s,\xi)}{\mu^2} - C_i\right]$$

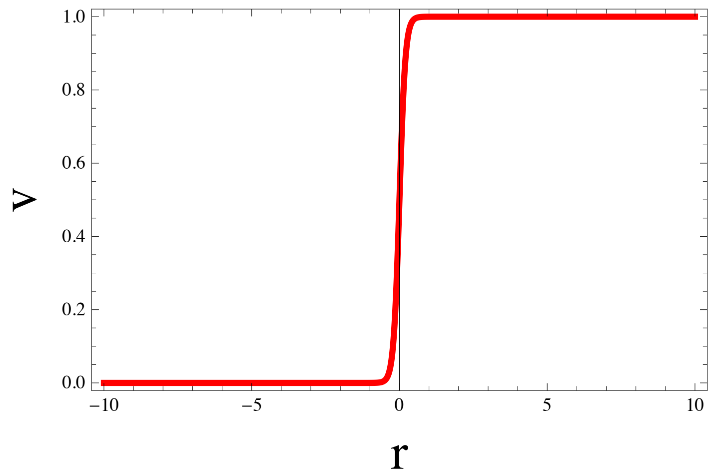
$$V_T^{\text{ring}} = \frac{T}{12\pi}\sum_i n_i\left\{(m_i^2(h,s))^{3/2} - (M_i^2(h,s,T))^{3/2}\right\}$$

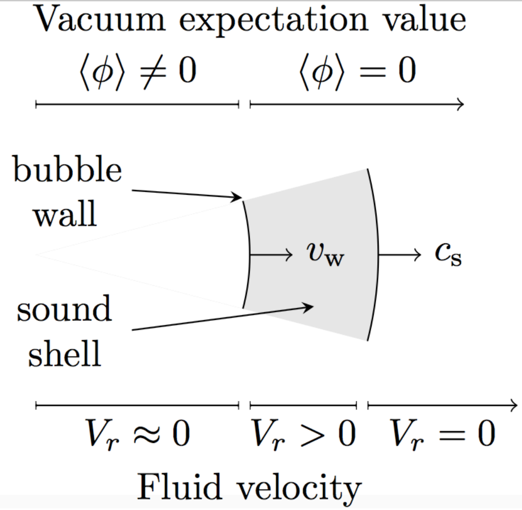
Bubble dynamics

1.Bubble nucleation

Euclidean equation of motion	$$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr} - V''(\phi) = 0$$
Euclidean action for the solution of EoM	$$S_3 = 4\pi \int r^2 dr \left[\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + V(\phi) \right]$$
Bubble nucleation rate per unit time per unit volume	$$\Gamma_n(T) \approx T^4 \left(\frac{S_3(T)}{2\pi T}\right)^{3/2} \exp\left[-\frac{S_3(T)}{T}\right]$$

Bounce solution to the background field	$$V(z) = \frac{1}{2}v(T)\left[1 + \tanh\left(3\frac{z}{L_w}\right)\right]$$





Bubble dynamics

2. Typical temperatures

Critical temperature T_C:	$V_{\text{eff}}(\phi_{\text{symmetric}}, T)\|_{T_C} = V_{\text{eff}}(\phi_{\text{broken}}, T)\|_{T_C}$
Bubble nucleation Temperature T_n:	$\int_0^{t_n} \Gamma V_H(t) dt = \int_{T_n}^{\infty} \frac{dT}{T} \left(\frac{2\zeta M_{\text{pl}}}{T} \right)^4 e^{-S_3/T} = \mathcal{O}(1),$

Γ	Bubble nucleation rate
$V_H(t)$	One-horizon volume

PT completed Temperature T_d:	$f(T_d) = \frac{4\pi}{3} \int_{T_d}^{T_c} \frac{dT}{T} \frac{\Gamma(T)}{H(T)^4} v_w^3 \left(1 - \frac{T_d}{T}\right)^3 \equiv 1$

$H(T)$	Hubble constant
v_w	Bubble wall velocity
$f(T)$	Friction of the universe covered by the broken phase

★**Relationships**

$T_c > T_n > T_d$

Bubble dynamics

3. Physical parameters relating to PT

v_w	*Bubble wall velocity*	*calculated numerically*
l_w	*Bubble wall width*	*calculated numerically*
α	*Released energy to radiation energy*	$\alpha = \Lambda/\rho_{\rm rad}$
κ	*The efficiency factor*	$\kappa = \frac{3}{\varepsilon v_w^3}\int w(\xi)v^2\gamma^2\xi^2 d\xi$
Λ	*Latent heat*	$\Lambda = \Delta\left(V - \frac{dV}{dt}T\right)$

v_w
l_w

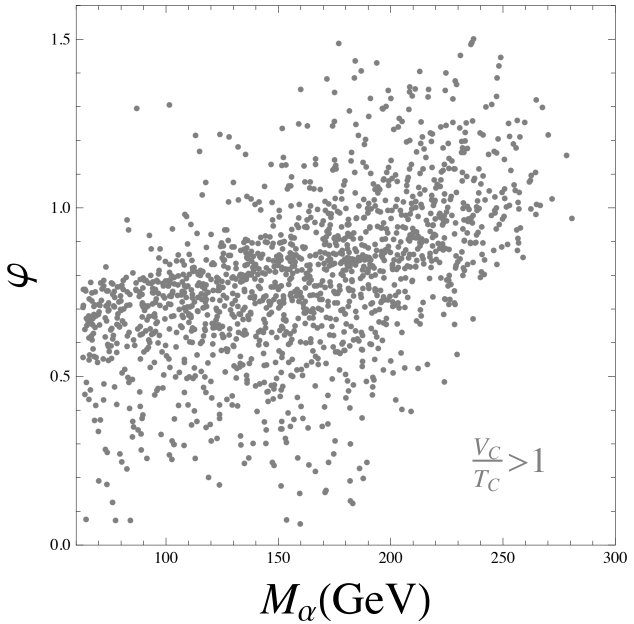
Relevant to the calculation of baryon number density generated during the EWPT

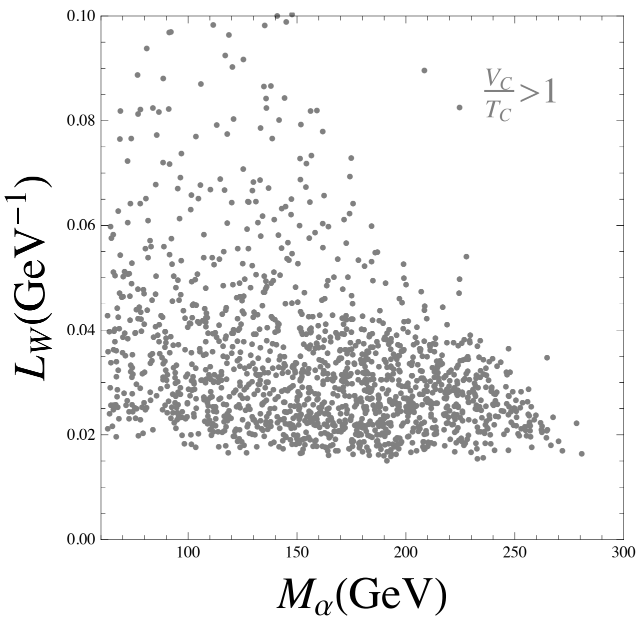
α
κ
Λ

Relevant to the calculation of stochastic gravitational wave spectrum emitted during the EWPT

CP phase and bubble wall width

EoM for three background fields:	$$\frac{d^2\phi_i}{dr^2} + \frac{2}{r}\frac{d\phi_i}{dr} = \bar{V}'(\vec{\phi})$$
Bubble wall width:	$$L_w^2 \approx 1.35 \frac{\lambda + \sqrt{\lambda\lambda_\varrho}}{(\lambda_2 - 2\sqrt{\lambda\lambda_\varrho})[\lambda v_0^2 - \Pi_h(T_C^2)]} \times \left(1 + \sqrt{\frac{\lambda_2^2}{4\lambda\lambda_\varrho}}\right)$$
Spontaneous CP phase:	$$\varphi = \pm\frac{1}{2}\arccos\left[\frac{\lambda_1 - \lambda_3}{2\lambda_3}\frac{m_\beta^2 - m_\alpha^2}{\lambda_2 v^2 - m_\alpha^2 - m_\beta^2 + 2\Pi_\alpha}\right].$$





Transport equations

EWBG

Transport equation

$$\frac{\partial n}{\partial t} + \nabla \cdot j(x) = -\int d^3z \int_{-\infty}^{x_0} dz^0 \mathrm{Tr}[\Sigma^>(x,z)S^<(z,x) - S^>(x,z)\Sigma^<(z,x) + S^<(x,z)\Sigma^>(z,x) - \Sigma^<(x,z)S^>(z,x)]$$

Source term:

$$S_{\rm top}^{\rm CPV} = -2\zeta^2 v_s^2 \dot{\varphi} \int \frac{k^2 dk}{\pi^2 \omega_L \omega_R} \mathrm{Im}\left\{(\varepsilon_L \varepsilon_R^* - k^2)\frac{n(\varepsilon_L) - n(\varepsilon_R^*)}{(\varepsilon_L - \varepsilon_R^*)^2} + (\varepsilon_L \varepsilon_R + k^2)\frac{n(\varepsilon_L) + n(\varepsilon_R)}{(\varepsilon_L + \varepsilon_R)^2}\right\}$$

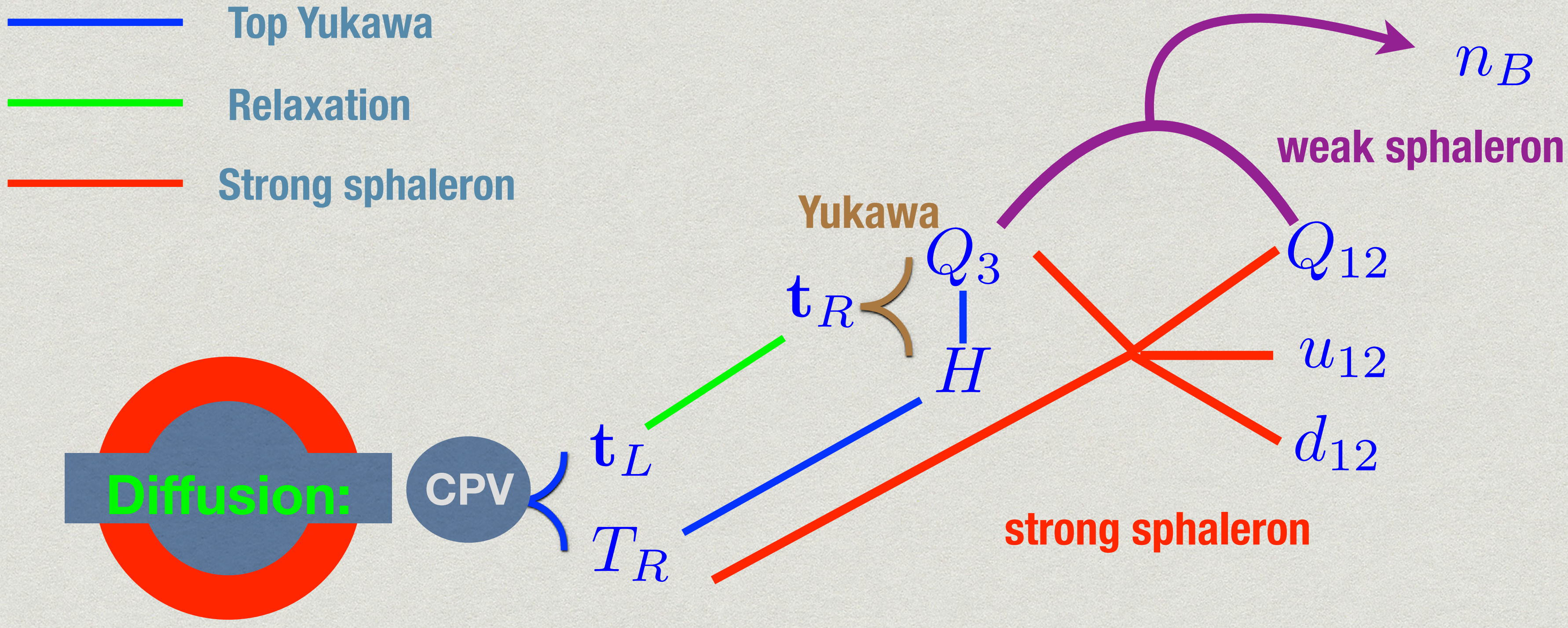
$$\zeta \overline{\mathrm{t}_L} S t_R + (M_\mathrm{t})\overline{\mathrm{t}_L}\mathrm{t}_R + \mathrm{h.c.} \longrightarrow \frac{y_t \zeta}{\Lambda}\overline{Q_3}\widetilde{H} S t_R$$

All equations

$$\begin{aligned}
\partial^\mu Q_\mu &= +\Gamma_{m_t}\mathcal{R}_T^- + \Gamma_{Y_t}\delta_t + \Gamma_{y'}\delta_{t'} + 2\Gamma_s\delta_s \\
\partial^\mu T_\mu &= -\Gamma_{m_t}\mathcal{R}_T^- - \Gamma_{Y_t}\delta_t - \Gamma_s\delta_s - \Gamma_\zeta\delta_\mathrm{t} \\
&\quad +\Gamma_\mathrm{t}^+\mathcal{R}_\mathrm{t}^+ + \Gamma_\mathrm{t}^-\mathcal{R}_\mathrm{t}^- + S_{\rm top}^{\rm CPV} \\
\partial^\mu \mathrm{t}_\mu &= +\Gamma_{m_t}\mathcal{R}_\Lambda^- - \Gamma_\mathrm{t}^+\mathcal{R}_\mathrm{t}^+ - \Gamma_\mathrm{t}^-\mathcal{R}_\mathrm{t}^- + \Gamma_\zeta\delta_\mathrm{t} - S_{\rm top}^{\rm CPV} \\
\partial^\mu \mathrm{t}'_\mu &= -\Gamma_{m_t}\mathcal{R}_\Lambda^- - \Gamma_{y'}\delta_{t'} \\
\partial^\mu S_\mu &= -\Gamma_\zeta\delta_\mathrm{t} \\
\partial^\mu H_\mu &= -\Gamma_{Y_t}\delta_t - \Gamma_{y'}\delta_{t'} \qquad (13)
\end{aligned}$$

Diffusions

EWBG



Baryon number density:

$$\hat{n}_B = -\frac{3\Gamma_{ws}}{2D_Q\lambda_+}\int_{-\infty}^{-L_w/2} dz\, n_L(z) e^{-\lambda_- z}$$

Damping of the domain wall

EWBG

Problems

$+\varphi$ + $-\varphi$ =0

No BAU left

Solution: Adding a Z_2 breaking term to the Higgs potential: Δs+h.c.

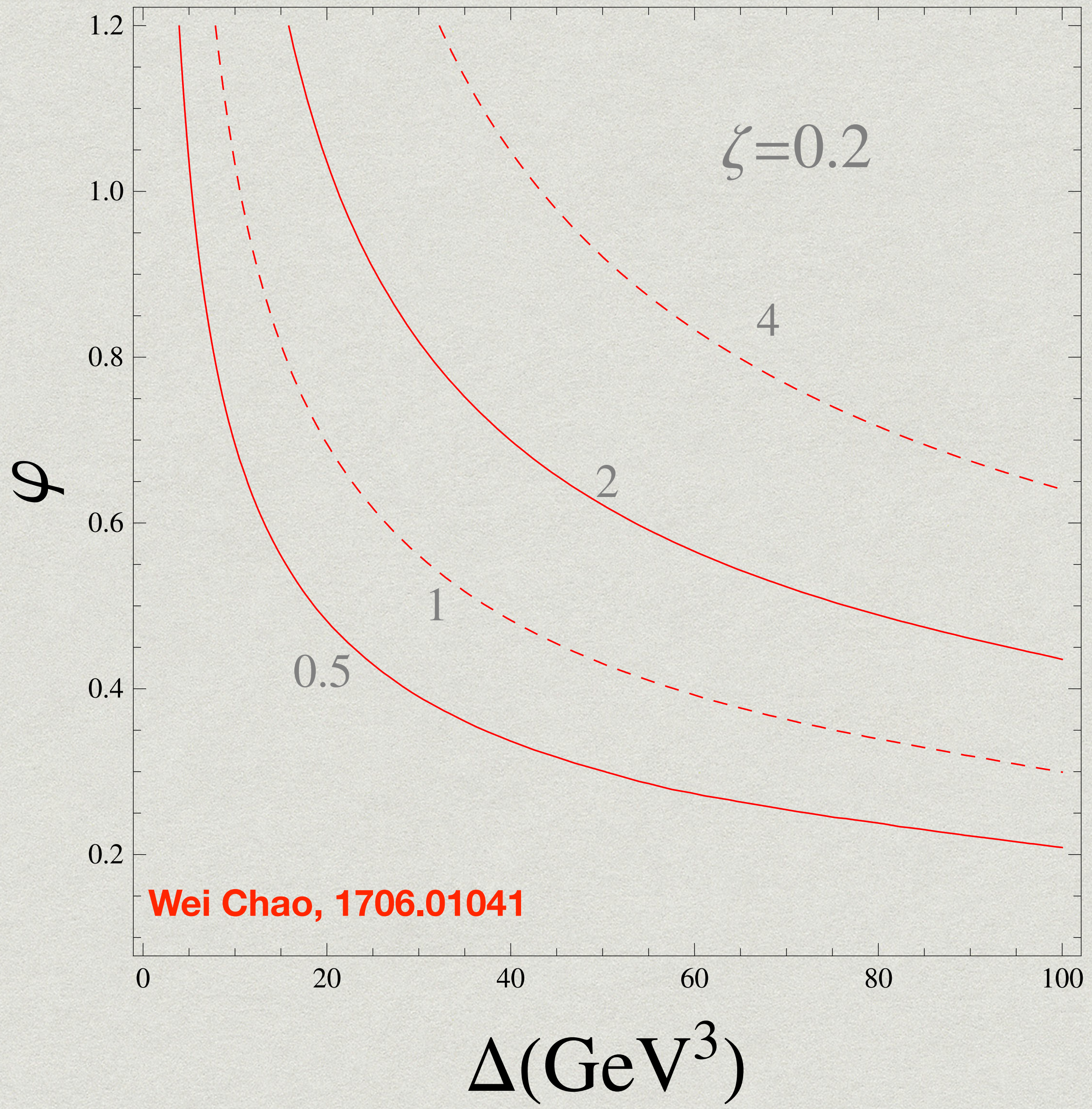
Ratio of bubbles

$$\frac{N_+}{N_-} = \exp\left(\frac{\Delta F}{T}\right)$$

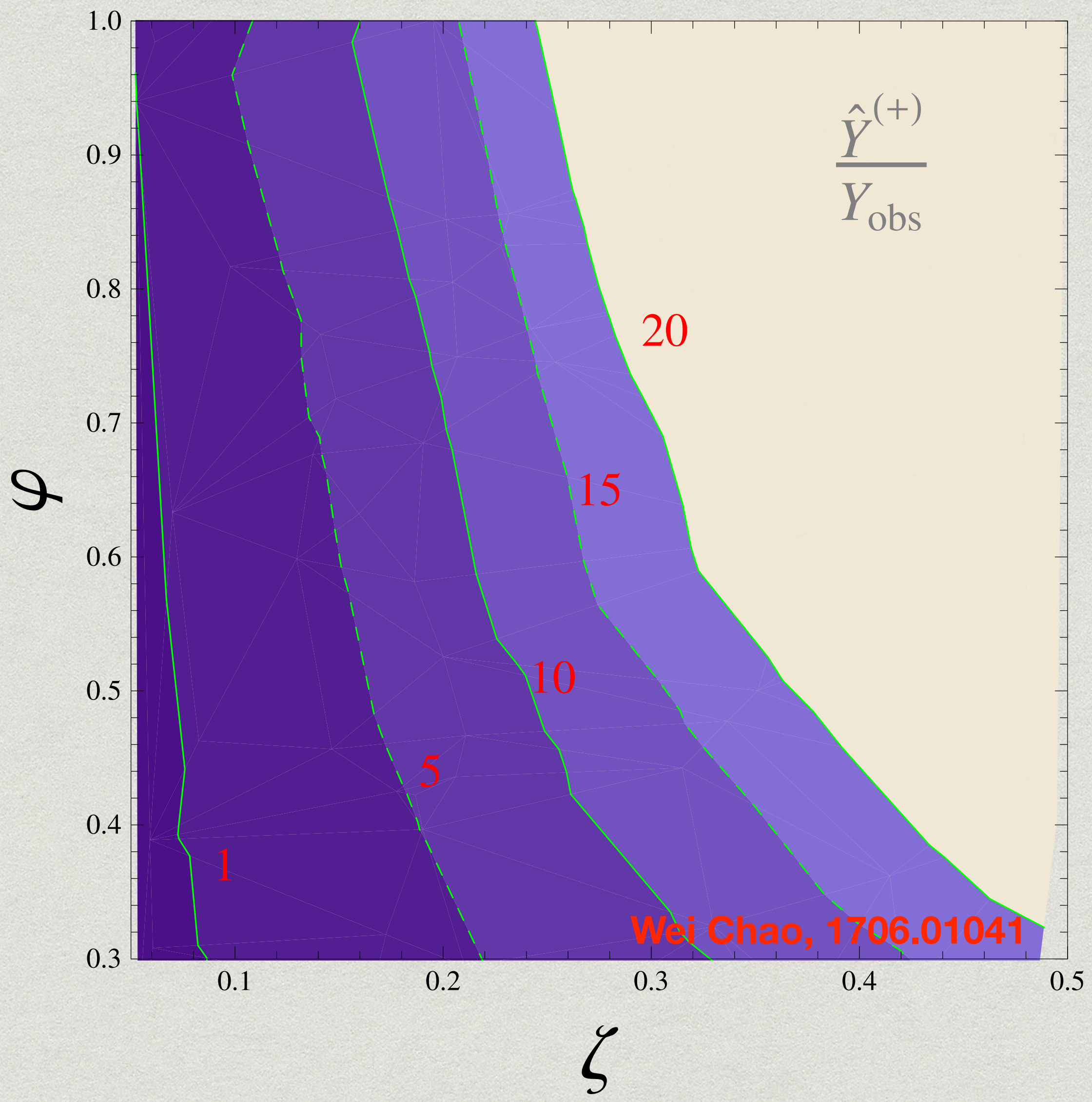
Final BAU

$$n_B = \hat{n}_B^{(+)} \frac{N_+ - N_-}{N_+ + N_-}$$

Numerical results



Numerical results



Outline

- EWBG with two-step PT and spontaneous CPV
- Stochastic gravitational wave from two-step PT

GW from the PT

Basics of gravitational wave from EWPT

Gravitational waves are described by a transverse-traceless gauge invariant perturbation, h_{ij}, in a FRW metric,	$ds^2 = a^2(\tau)[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j]$
Einstein eq for transverse-traceless part	$h''_{ij} - \Delta h_{ij} = 16\pi G[(e+p)\gamma^2 v_i v_j + \partial_i\phi\partial_j\phi]$
Gravitational wave energy density	$\rho_{gw}(t) = \frac{\langle \dot{h}_{ij}(t,\vec{x})\dot{h}_{ij}(t,\vec{x})\rangle}{8\pi G}$
Energy spectrum	$h^2\Omega_{\mathrm{GW}}(f) = \frac{h^2}{\rho_c}\frac{d\rho_{\mathrm{gw}}}{d\log f}$

GW from the PT

Sources of GW from EWPT:

- ✦*Collisions of bubble wall and shocks in the plasma*
- ✦*Sound wave after the collision but before the expansion has dissipated the kinetic energy.*
- ✦*Magnetohydrodynamic turbulence : percolation can also induce MHD turbulence since the plasma is fully ionized.*

Fitted results of GW spectrum

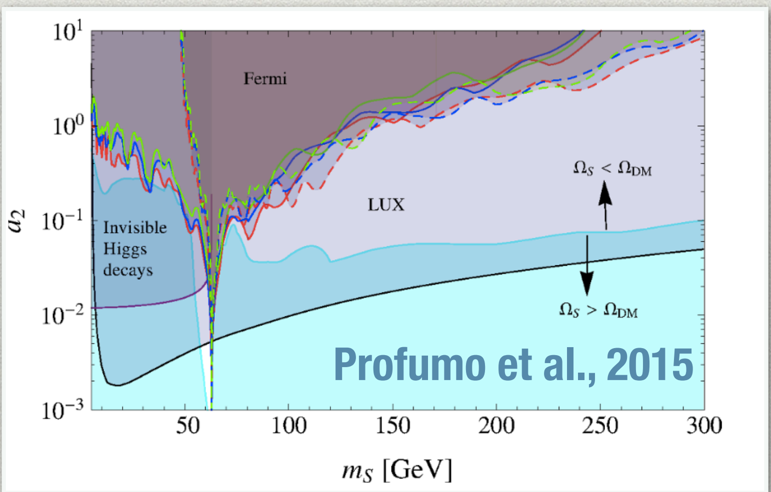
Bubble collision	$h^2\Omega_{\rm coll}(f) = 1.67\times 10^{-5}\left(\frac{H_n}{\beta}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\times\left(\frac{0.11v_w^3}{0.42+v_w^2}\right)\left[\frac{3.8(f/f_{\rm coll})^{2.8}}{1+2.8(f/f_{\rm coll})^{3.8}}\right],$
Sound wave	$h^2\Omega_{\rm sw}(f) = 2.65\times 10^{-6}\left(\frac{H_n}{\beta}\right)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\times v_w\left(\frac{f}{f_{\rm sw}}\right)^3\left[\frac{7}{4+3(f/f_{\rm sw})^2}\right]^{7/2}$
MHD turbulence	$h^2\Omega_{\rm turb}(f) = 3.35\times 10^{-4}\left(\frac{H_n}{\beta}\right)\left(\frac{\kappa_{\rm tu}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\times v_w\frac{(f/f_{\rm tu})^3}{(1+f/f_{\rm tu})^{11/3}(1+8\pi f/h_n)}$

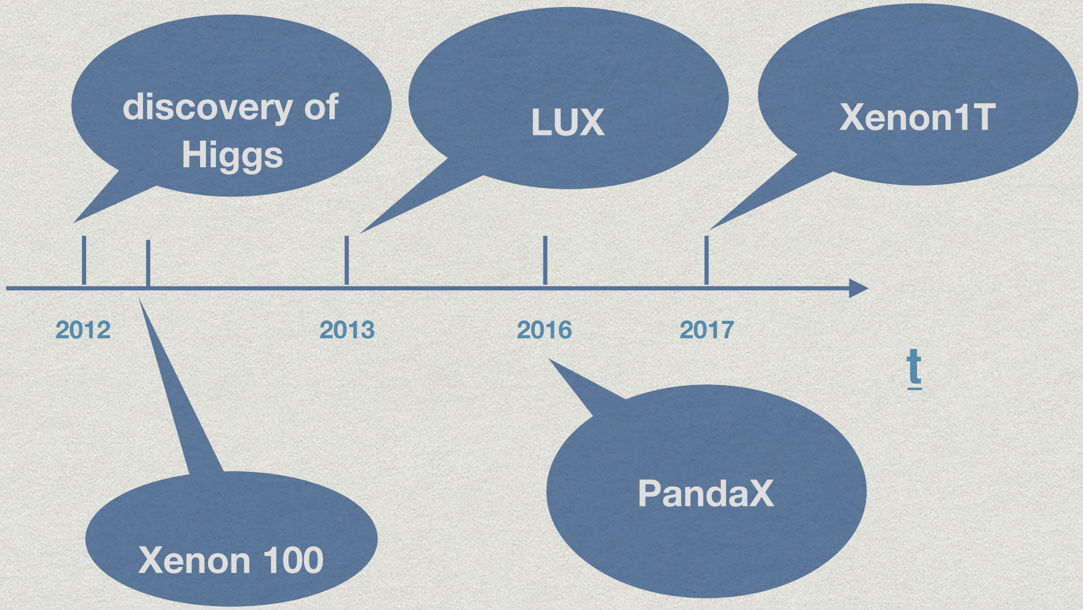
Total energy spectrum:

$$h^2\Omega_{\rm GW}\approx h^2\Omega_{\rm coll}+h^2\Omega_{\rm sw}+h^2\Omega_{\rm turb}$$

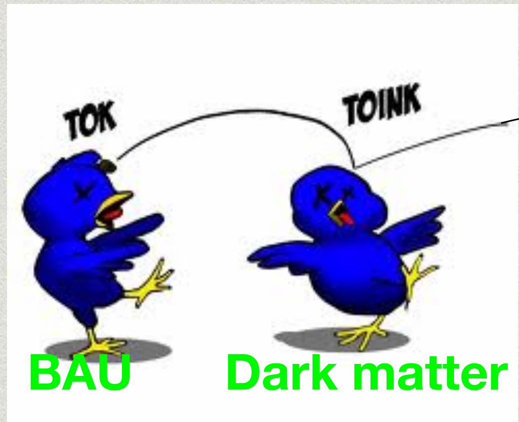
Dark matter in a two-step PT

GW from EWPT, a typical model:





Ordinary Higgs portal is dead since 2013!



Non-minimal Higgs portal

GW from the PT

The model: SM + two real scalar singlets

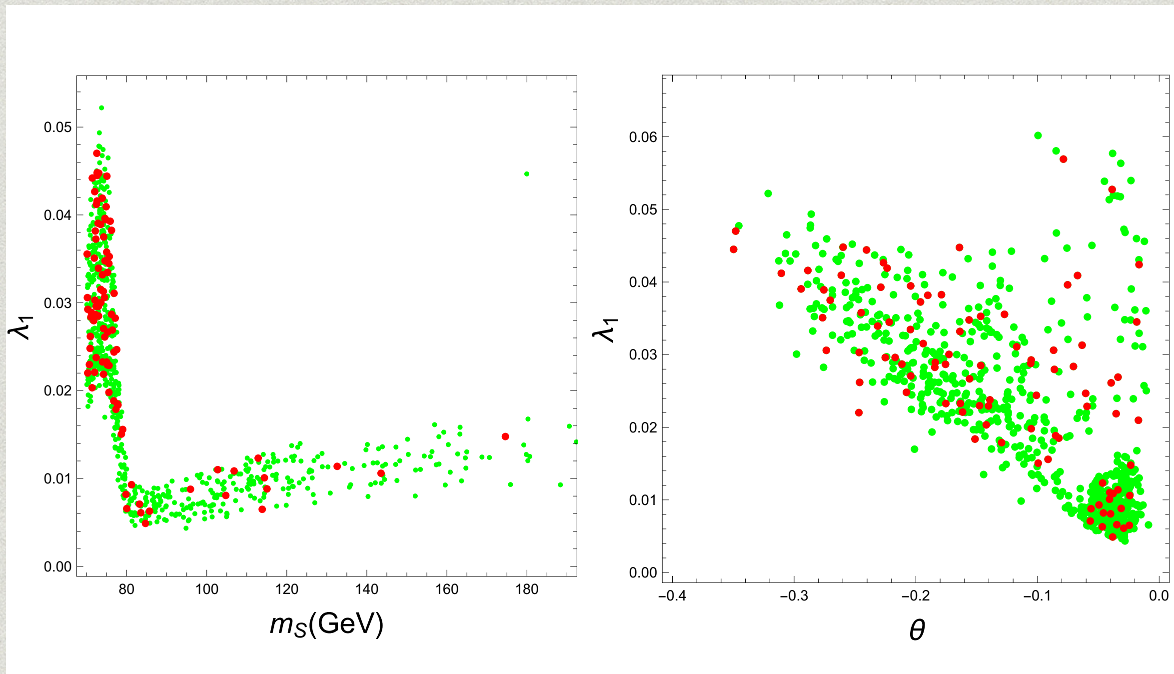
$$V_0 = -\frac{1}{2}\mu_\Phi^2\Phi^2 + \frac{1}{4}\lambda_\Phi\Phi^4 - \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 - \mu^2 H^\dagger H + \lambda(H^\dagger H)^2 + \lambda_1 S^2 H^\dagger H + \lambda_2 \Phi^2 H^\dagger H + \lambda_3 S^2\Phi^2,$$

Real singlet | Dark matter | SM Higgs

Physical parameters: $v_\Phi,\ m_\Phi,\ m_S,\ \lambda_S,\ \theta,\ \lambda_1,\ \lambda_3$

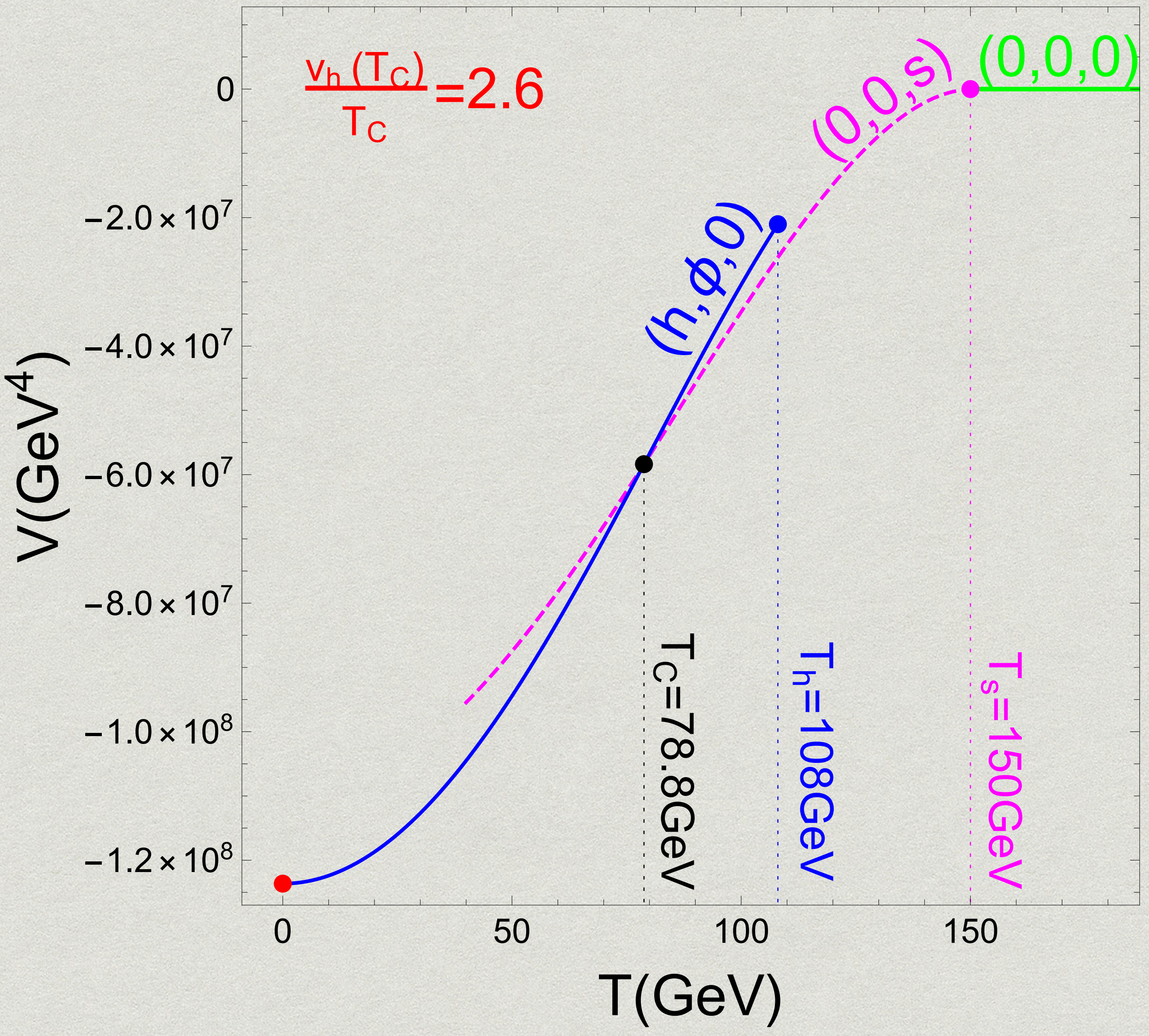
Conditions for a negligible DD cross section:

$$\lambda_3 = \frac{v_{\rm EW}\lambda_1(m_{\hat h}^2\tan\theta + m_{\hat\phi}^2\cot\theta)}{2v_\Phi(m_{\hat h}^2 - m_{\hat\phi}^2)}$$



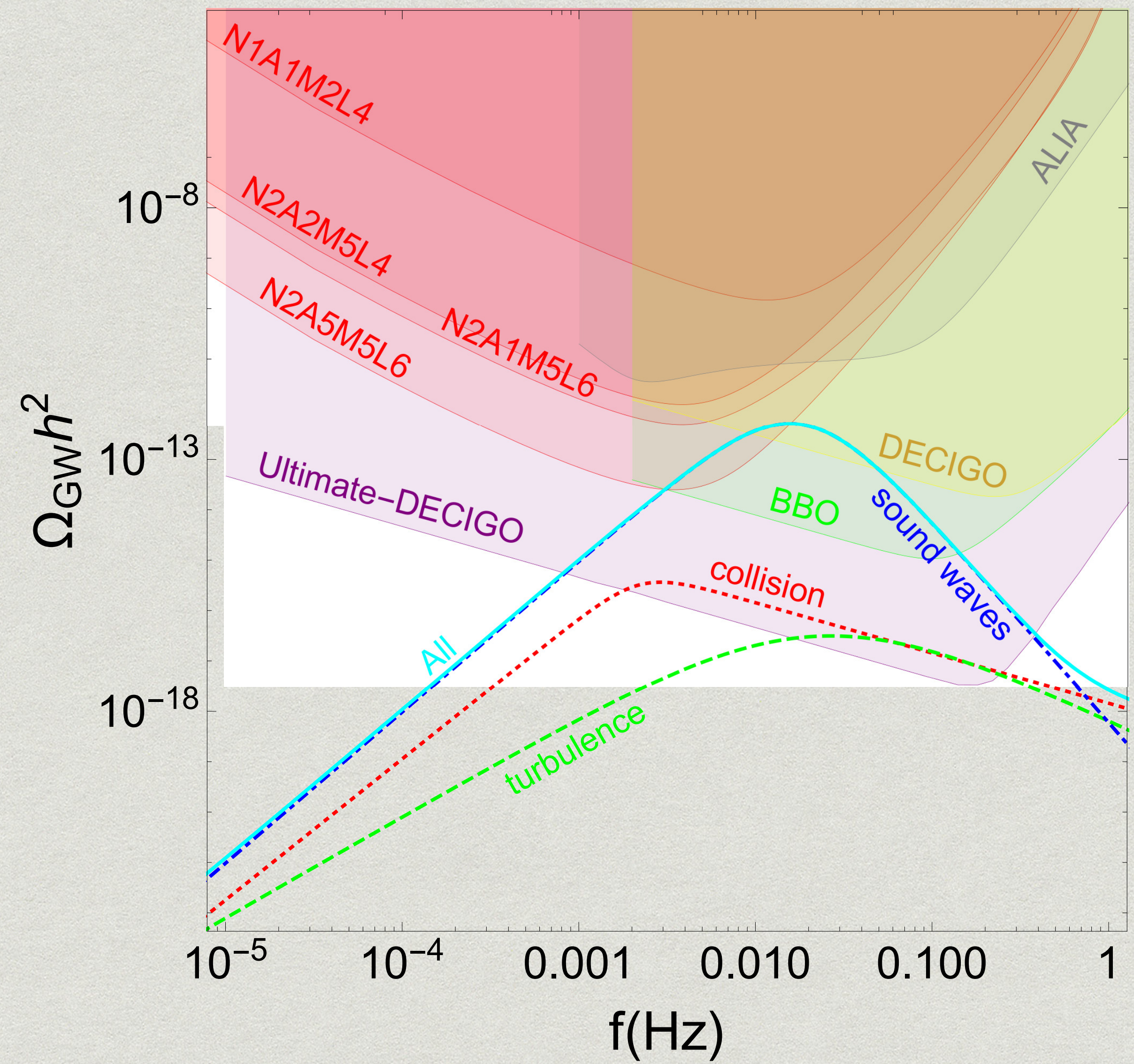
GW from the PT

PT details:



GW from the PT

GW spectrum: (Wei Chao, H. Gu0, J. Shu, JCAP1709,009)



Summary

- ✦ Physics relevant to electroweak phase transition are briefly reviewed.
- ✦ The baryon asymmetry of the universe generated during the first order EWPT is discussed, especially I showed how to generate sufficient BAU with the spontaneous CP phase and a two-step EWPT.
- ✦ Show you stochastic gravitational wave can be taken as an indirect signal of the EWBG.

Thank you