Higgs Physics

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Baryogenesis and Higgs

Baryon Asymmetry of the Universe

$$\frac{n_B}{s} \equiv \frac{n_b - n_{\bar{b}}}{s}$$

n_B Baryon number density

s Entropy density

Observations

Stable Galaxies (~$10^{12}\, M_{\odot}$)

Cosmic Microwave Background

Light Element Synthesis (H, He, Li, ...)

$$\frac{n_B}{s} = (0.67 - 0.92) \times 10^{-10}$$

To explain this number is a big question in particle physics

Baryogenesis Initially n_B=0, then it is generated after inflation

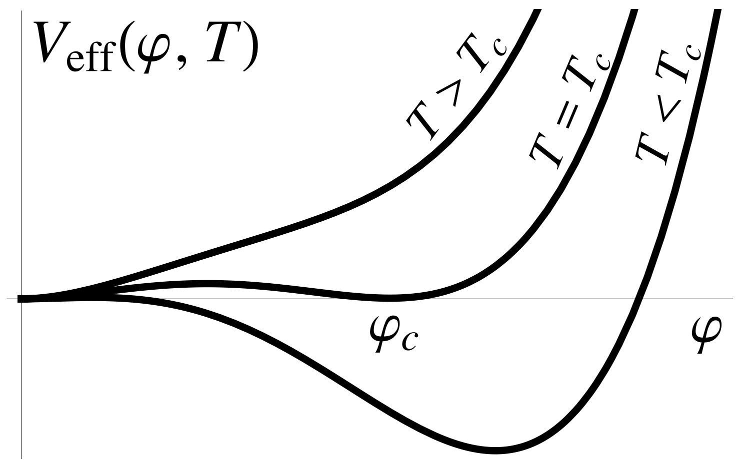
Required to satisfy the Sakharov's 3 conditions

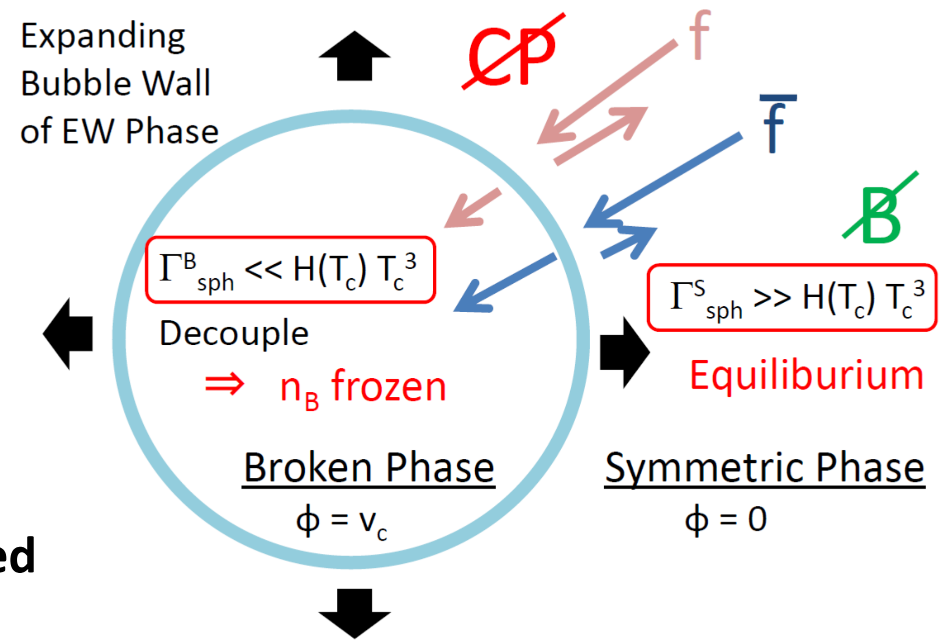
Electroweak Baryogenesis

$$\Gamma \sim e^{-E_{\text{sph}}/T} \quad (T < T_c)$$
$$\Gamma \sim \kappa(\alpha_W T)^4 \quad (T_c < T)$$

Sakharov's conditions:

- B Violation → **Sphaleron transition at high *T***
- C and CP Violation → **CP Phases in extended scalar sector**
- Departure from Equilibrium → **1st Order EW Phase Transition**





Quick sphaleron decoupling is required to retain sufficient baryon number in Broken Phase

(Sphaleron Rate) < (Expansion Rate) ➡ $\boldsymbol{\varphi_c/T_c > 1}$

1-loop effective potential

- **Zero temperature**

$$V_1(\varphi) = n_i \frac{m_i^4(\varphi)}{64\pi^2}\left(\log\frac{m_i^2(\varphi)}{Q^2} - \frac{3}{2}\right)$$

$$(n_W = 6,\ n_Z = 3,\ n_t = -12,\ n_h = n_H = n_A = 1,\ n_{H^\pm} = 2)$$

- **Finite temperature**

$$V_1(\varphi, T) = \frac{T^4}{2\pi^2}\Big[\sum_{i=\text{bosons}} n_i I_B(a^2) + n_t I_F(a)\Big]$$

where $I_{B,F}(a^2) = \int_0^\infty dx\ x^2 \log(1 \mp e^{-\sqrt{x^2+a^2}}),\qquad \left(a(\varphi) = \frac{m(\varphi)}{T}\right)$

▷ **High temperature expansion** $(a^2 \ll 1)$

$$I_B(a^2) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}a^2 - \frac{\pi}{6}(a^2)^{3/2} - \frac{a^4}{32}\left(\log\frac{a^2}{\alpha_B} - \frac{3}{2}\right) + \mathcal{O}(a^6),$$

$$I_F(a^2) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}a^2 - \frac{a^4}{32}\left(\log\frac{a^2}{\alpha_F} - \frac{3}{2}\right) + \mathcal{O}(a^6),\ \left(\log\alpha_{F(B)} = 2\log(4)\pi - 2\gamma_E\right)$$

φ^3-term comes from the "bosonic" loop

Strongly 1st OPT

High Temperature Expansion (just for sketch)

$$V_{\text{eff}}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

Condition of Strongly 1st OPT

$$\frac{\varphi_C}{T_C} \simeq \frac{2E}{\lambda_{T_C}} > 1$$

However, the SM cannot realize the strongly 1st OPT

$$E \simeq \frac{1}{12\pi v^3}\left(6m_W^3 + 3m_Z^3 + \cdots\right) \quad \lambda_{T_C} \sim \frac{m_h^2}{2v^2} + \cdots$$

$$\frac{\varphi_C}{T_C} \simeq \frac{6m_W^3 + 3m_Z^3 + \cdots}{3\pi v m_h^2} \ll 1$$

For m_h = 125 GeV

We need a mechanism to enlarge *E* to realize strongly 1st OPT

1^{st} OPT in extended Higgs sectors

High Temperature Expansion (just for sketch)

$$V_{\rm eff}(\varphi,T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

Condition of Strongly 1^{st} OPT

$$\frac{\varphi_C}{T_C} \simeq \frac{2E}{\lambda_{T_C}} > 1$$

The condition can be satisfied by thermal loop effects of additional scalar bosons Φ (Φ = *H, A, H*$^+$, …) $m_\Phi^2 \simeq M^2 + \lambda_i v^2$

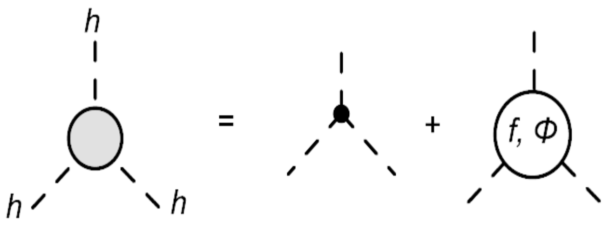
$$\frac{\varphi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2}\left\{6m_W^3 + 3m_Z^3 + \sum_\Phi m_\Phi^3\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\left(1 + \frac{3M^2}{2m_\Phi^2}\right)\right\} > 1$$

In this case, large quantum effects also appear in the *hhh* coupling

$$\lambda_{hhh} \simeq \frac{3m_h^2}{v^2}\left\{1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + \sum_\Phi \frac{m_\Phi^4}{12\pi^2 v^2 m_h^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\right\} > \lambda_{hhh}^{SM}$$

Case of Non-SUSY 2HDM

- **Consider when the lightest *h* is SM-lik[sin(β−α)=1]**
- **At tree, the *hhh* coupling takes the same form as in the SM**
- **At 1-loop, non-decoupling effect m_Φ^4 (If *M* < *v*)**



Φ = *H, A, H*±

SK, Kiyoura, Okada, Senaha, Yuan, PLB558 (2003)

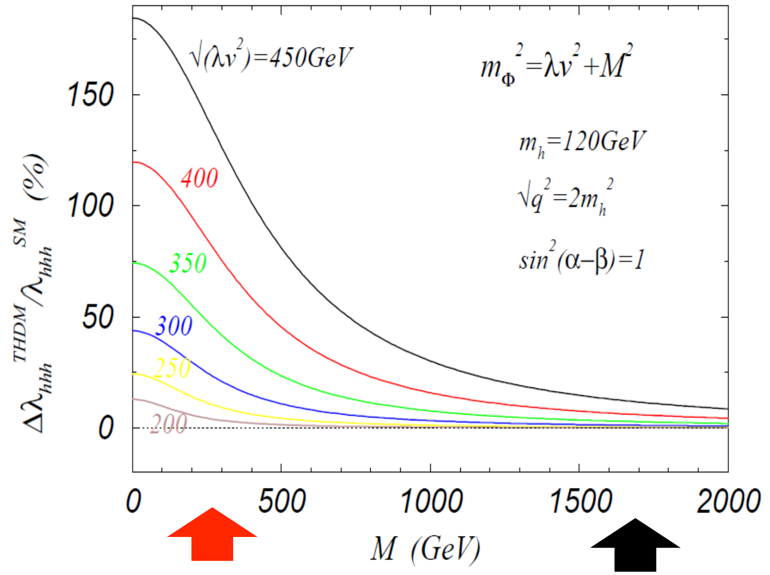
$$\lambda_{hhh}^{\rm 2HDM} \simeq \frac{3m_h^2}{v}\left[1+\frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3-\frac{m_t^4}{\pi^2 v^2 m_h^2}\right]$$

Extra scalar loop **Top loop**

$$m_\Phi^2 = M^2 + \lambda_i v^2$$

(Φ = *H, A, H*±)

Correction can be huge ∼ 100%

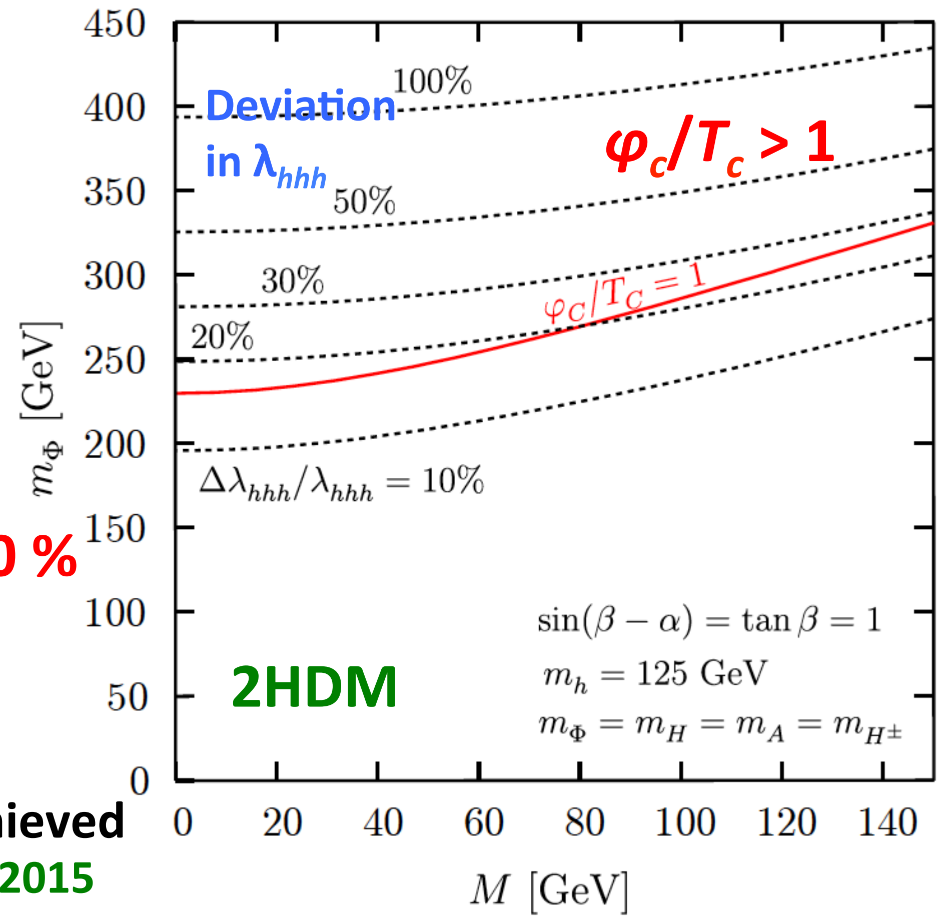


Non-decoupling effect Decoupling

Strong 1st OPT and the *hhh* coupling

Strongly 1st OPT
⇔ Non-decoupling effect
⇔ large deviation in *hhh*

S.K., Y. Okada, E. Senaha (2005)



At LHC, challenging to measure λ_{hhh}

ILC (1 TeV) can measure λ_{hhh} by 10 %

K.Fujii et al., arXiv:1506.05992 [hep-ex]
Great achievement!!!

If Δλ=100%, then Δλ/λ ~ 15% can be achieved at E=500GeV (H20) J. Tian et al. LCWS 2015

Electroweak Baryogenesis can be tested at ILC!

GW : another probe of 1st OPT?

Gravitational Wave Experiments

aLIGO (USA), KAGRA (JPN), aVIRGO (ITA), …

- Trial for first discovery of GWs (Underway)
- GWs from astronomical phenomena (binary of neutron stars, …)

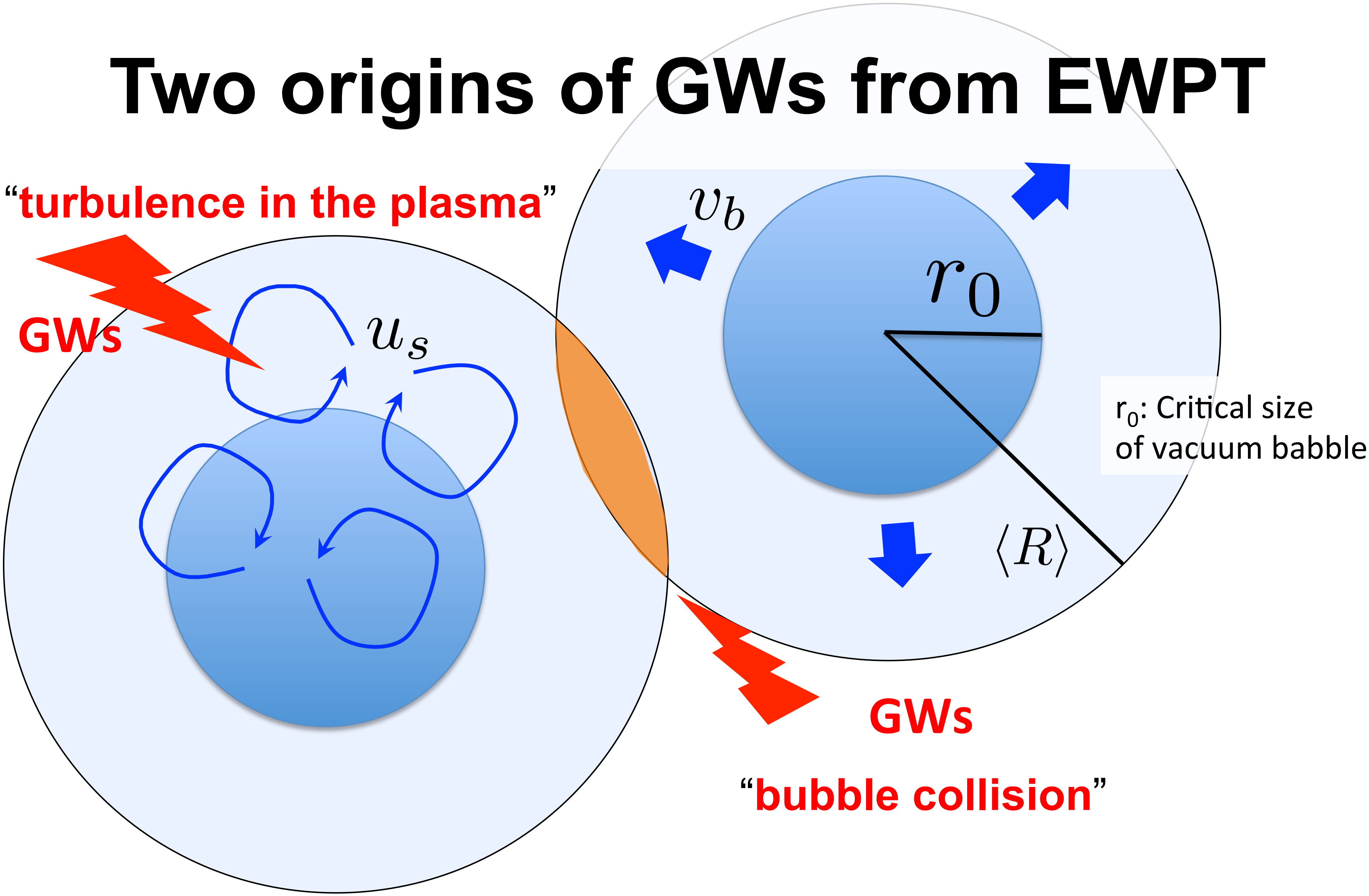
Once, GW is found, era of GW astronomy will come ture

Future exp: eLISA [EUR], DESIGO [JPN], BBO [USA]…

- GWs from very early Universe (Inflation, 1st OPT, …)

GWs may be used for exploration of the Higgs potential, as complementary mean with collider experiments.

Two origins of GWs from EWPT



GW from the EW bubble

Evaluation according to Grojean and Servant

$$\Omega_{\rm GW}(f)h^2 = \Omega_{\rm coll}(f)h^2 + \Omega_{\rm turb}(f)h^2$$

1 Collision of the bubbles

Kamionkowski, et al. (1994)

GW at the peak

$$\tilde{\Omega}_{\rm coll}h^2 \simeq c\kappa^2 \left(\frac{H_t}{\beta}\right)^2 \left(\frac{\alpha}{1+\alpha}\right)^2 \left(\frac{v_b^3}{0.24+v_b^3}\right)$$

$$c = 1.1 \times 10^{-6}$$

Frequency at the peak

$$\tilde{f}_{\rm coll} \simeq 5.2 \times 10^{-3}{\rm mHz} \left(\frac{\beta}{H_t}\right) \left(\frac{T_t}{100{\rm GeV}}\right)$$

2 Plasma Turbulence in the bubbles

Nicolis (2004)

$$\tilde{\Omega}_{\rm turb}h^2 \simeq 1.4 \times 10^{-4} u_s^5 v_b^2 \left(\frac{H_t}{\beta}\right)^2$$

$$\tilde{f}_{\rm turb} \simeq 3.4 \times 10^{-3}{\rm mHz} \frac{u_s}{v_b} \left(\frac{\beta}{H_t}\right) \left(\frac{T_t}{100{\rm GeV}}\right)$$

The spectrum are evaluated by inputting the lattent heat α, variation of the bubble nuclearation rate β and transition temperature T_t

Higgs model with O(*N*) singlet fields

***N*-scalar singlets** $$S^{\mathrm{T}} = (S_1, \cdots, S_N)$$

$$V_0 = -\mu^2|\Phi|^2 + \frac{{\mu_S}^2}{2}|S|^2 + \frac{\lambda}{2}|\Phi|^4 + \frac{\lambda_S}{4}|S|^4 + \frac{c}{2}|\Phi|^2|S|^2$$

Mass of scalar fields: $$m_S^2 = \mu_S^2 + \frac{c}{2}v^2$$

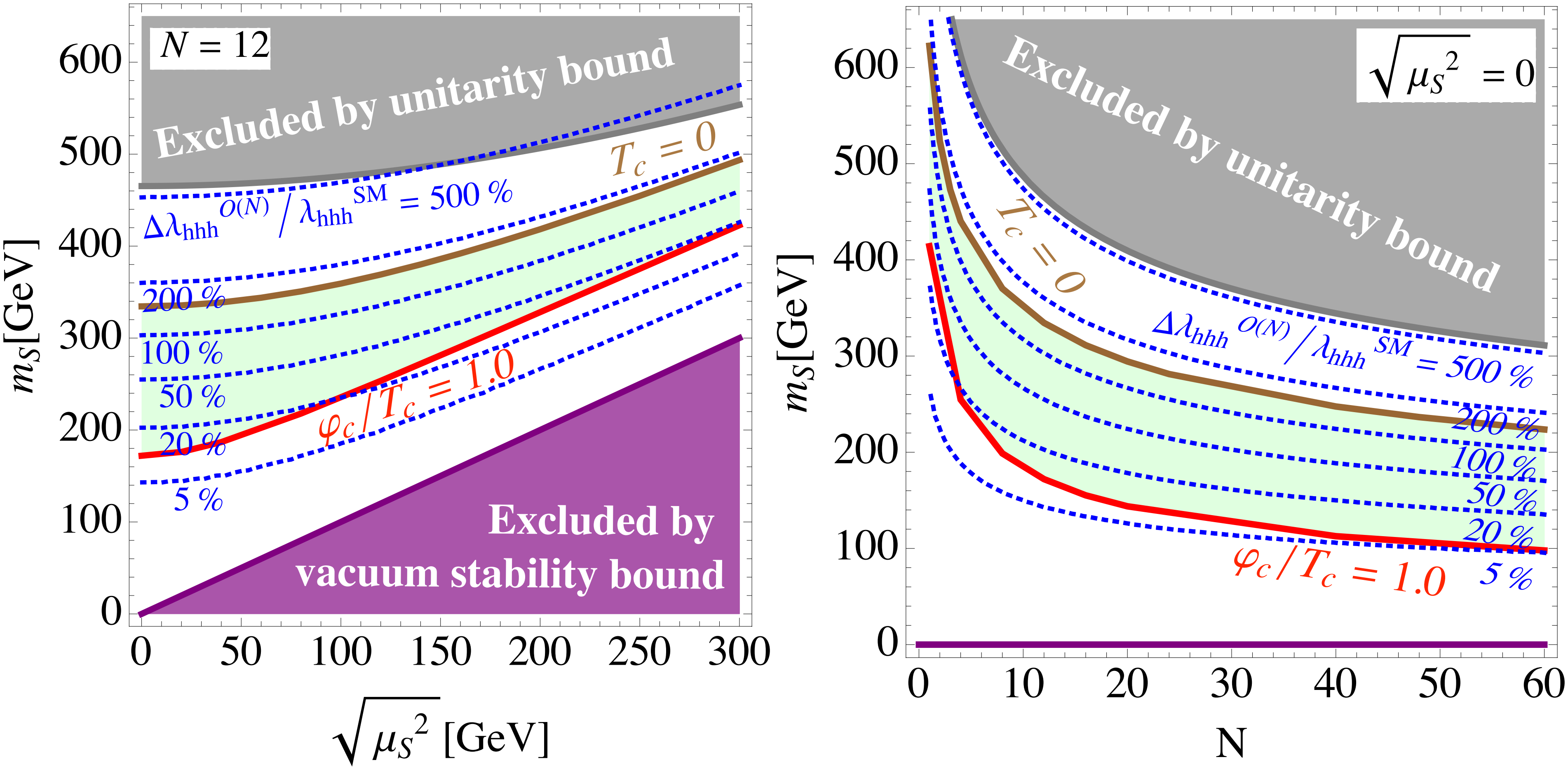
φ_c/T_c > 1 is satisfied by the nondecoupling effect of the singlet fields（compatible with m_h=125GeV）

$$\frac{\varphi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2}\left\{6m_W^3 + 3m_Z^3 + N m_S^3\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3\left(1 + \frac{3\mu_S^2}{2m_S^2}\right)\right\}$$

$$\lambda_{hhh}^{O(N)} \simeq \frac{3m_h^2}{v^2}\left\{1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + N\frac{m_S^4}{12\pi^2 v^2 m_h^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3\right\}$$

Predictions on the *hhh* coupling

M.Kakizaki, S.Kanemura, T.Matsui, arXiv:1509.08394 [hep-ph]

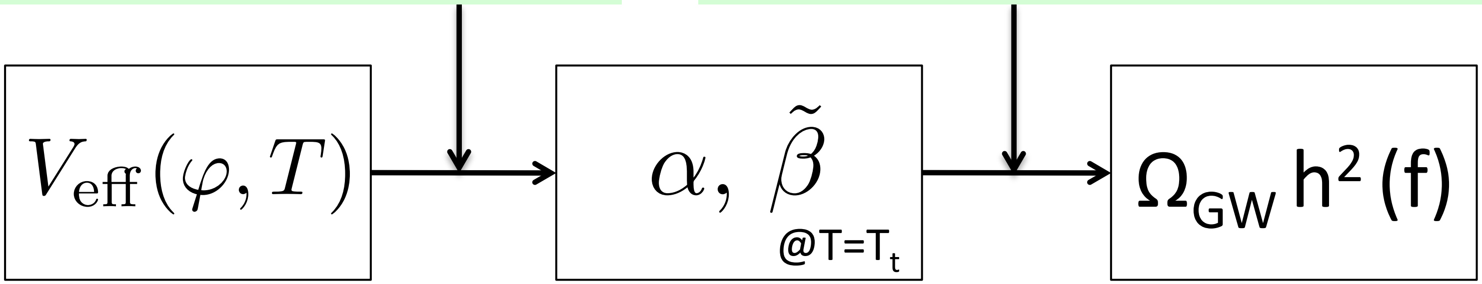


O(10)% deviations in *hhh* coupling

Relic abundance of GWs from EWPT

Numerical calculation
``Overshooting-undershooting method''

Model-independent analysis
C. Grojean and G. Servant, PRD**75,** 043507 (2007)



Relic abundance of GWs is composed of two contributions.

$$\Omega_{\rm GW} h^2(f) \equiv \Omega_{\rm coll} h^2(f) + \Omega_{\rm turb} h^2(f)$$

"bubble collision" $\widetilde{\Omega}_{\rm coll} h^2 \simeq \dfrac{1.1 \times 10^{-6} \kappa^2(\alpha) v_b^3(\alpha)}{0.24 + v_b^3(\alpha)} \times \left(\dfrac{\alpha}{1+\alpha}\right)^2 \tilde{\beta}^{-2}$

$$\tilde{f}_{\rm coll} \simeq 5.2 \times 10^{-6} {\rm Hz} \times (T_t/100{\rm GeV})\tilde{\beta}$$

"turbulence in the plasma"

$$\widetilde{\Omega}_{\rm turb} h^2 \simeq 1.4 \times 10^{-4} u_s^5(\alpha) v_b^2(\alpha) \tilde{\beta}^{-2}$$

$$\tilde{f}_{\rm turb} \simeq 3.4 \times 10^{-6} {\rm Hz} \times (u_s(\alpha)/v_b(\alpha))(T_t/100{\rm GeV})\tilde{\beta}$$

Electroweak Phase Transition

Numerical calculation

``Overshooting-undershooting method''

$$V_{\text{eff}}(\varphi, T)$$

Electroweak Phase Transition

Numerical calculation
``Overshooting-undershooting method''

$$V_{\rm eff}(\varphi, T)$$

``Spherical bubble configuration''

Eq. of motion: $\frac{d^2\varphi}{dr^2} + \frac{2}{r}\frac{d\varphi}{dr} - \frac{dV_{\rm eff}}{d\varphi} = 0 \rightarrow \varphi(r)$

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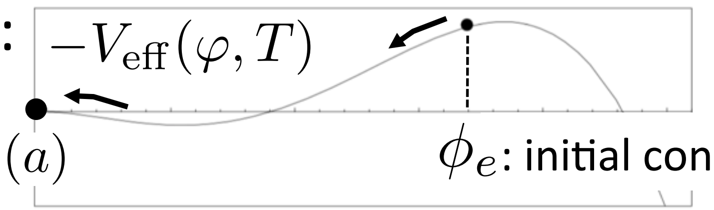
``Overshooting-undershooting method''

$V_{\rm eff}(\varphi, T)$

``Spherical bubble configuration''

Potential:



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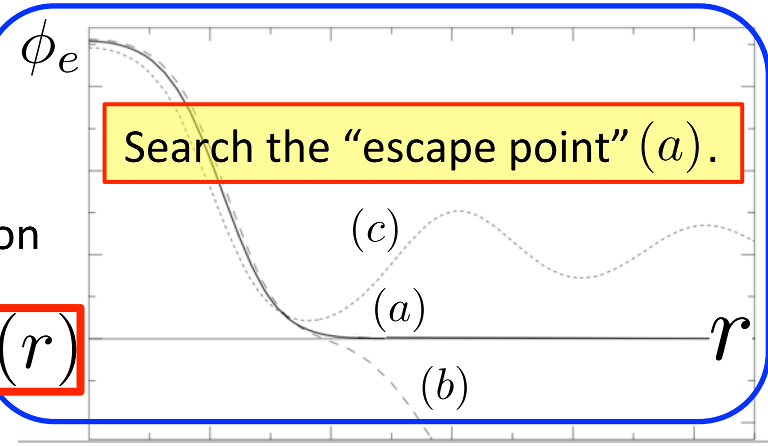

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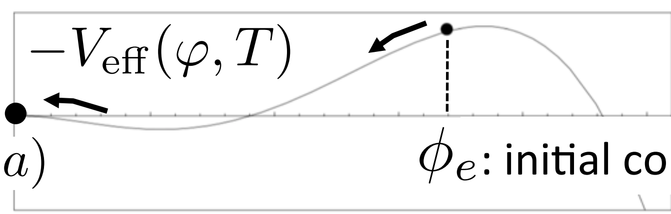

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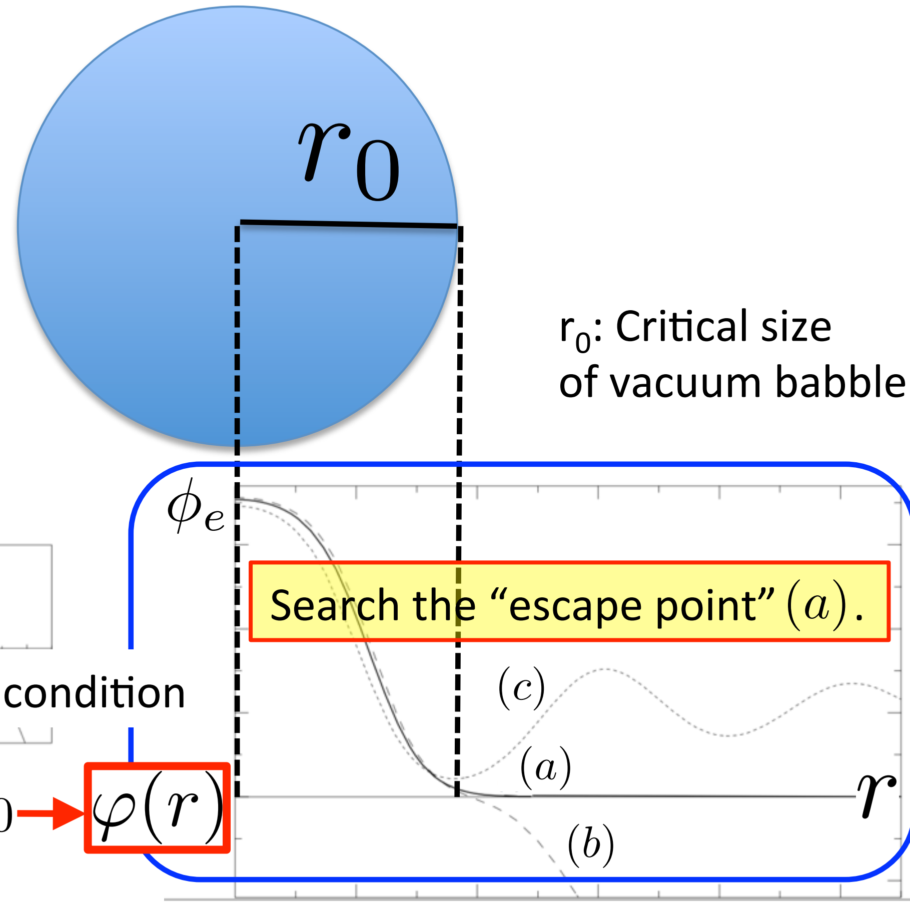

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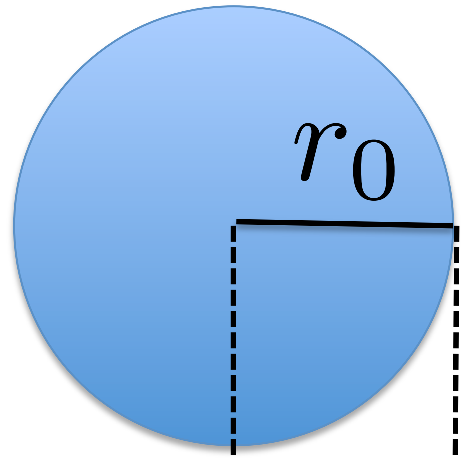
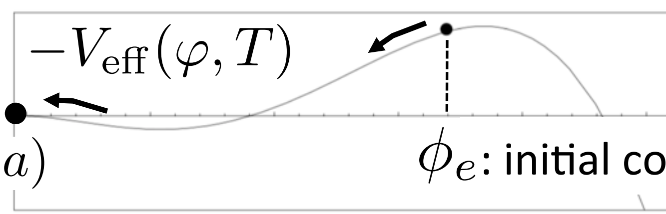


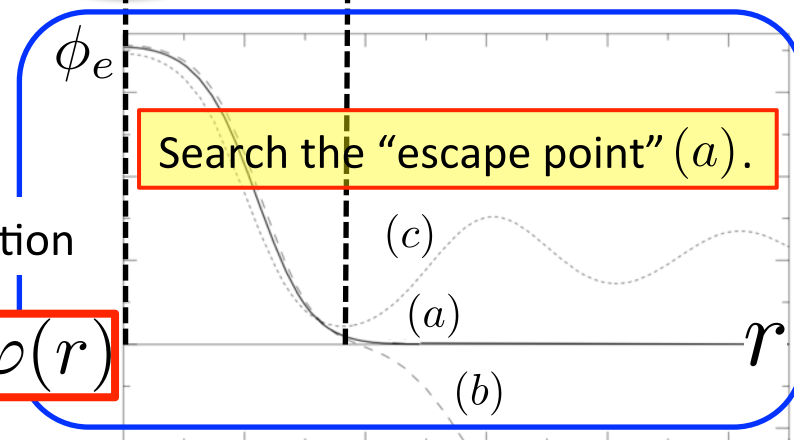
r_0: Critical size of vacuum babble

``Spherical bubble configuration''

Potential:



Eq. of motion: $\frac{d^2\varphi}{dr^2} + \frac{2}{r}\frac{d\varphi}{dr} - \frac{dV_{\rm eff}}{d\varphi} = 0 \rightarrow \varphi(r)$



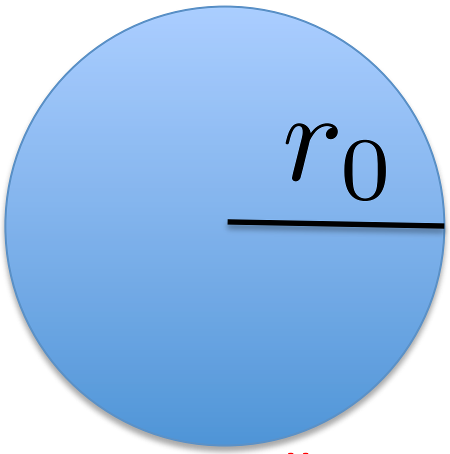
$\varphi(r) \xrightarrow{\text{each}T}$ 3-dim. Euclidean action: $S_3(T) = \int dr^3 \left\{ \frac{1}{2}\left(\vec{\nabla}\varphi\right)^2 + V_{\rm eff}(\varphi, T) \right\}$

Electroweak Phase Transition

Numerical calculation

``Overshooting-undershooting method''

$$V_{\text{eff}}(\varphi, T)$$



r_0: Critical size of vacuum babble

``Definition of phase transition temperature T_t''

$$\left.\frac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1$$

(H: Hubble parameter)

Phase transition completes when the probability for the nucleation of 1 bubble per 1 horizon volume and horizon time is of order 1.

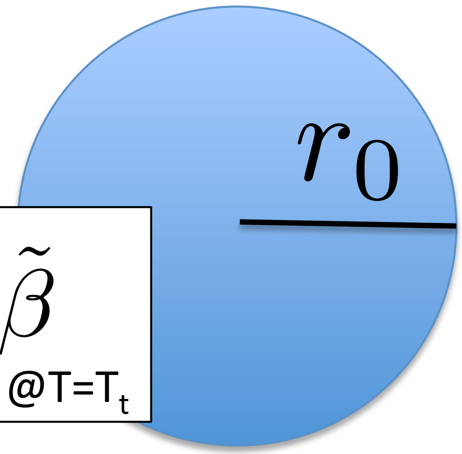
- Bubble nucleation rate: $\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}}$
- 3-dim. Euclidean action: $S_3(T) = \int dr^3 \left\{ \frac{1}{2}\left(\vec{\nabla}\varphi\right)^2 + V_{\text{eff}}(\varphi, T) \right\}$

Electroweak Phase Transition

Numerical calculation

``Overshooting-undershooting method''

$V_{\rm eff}(\varphi, T)$ → $\alpha,\ \tilde{\beta}$ @T=T_t



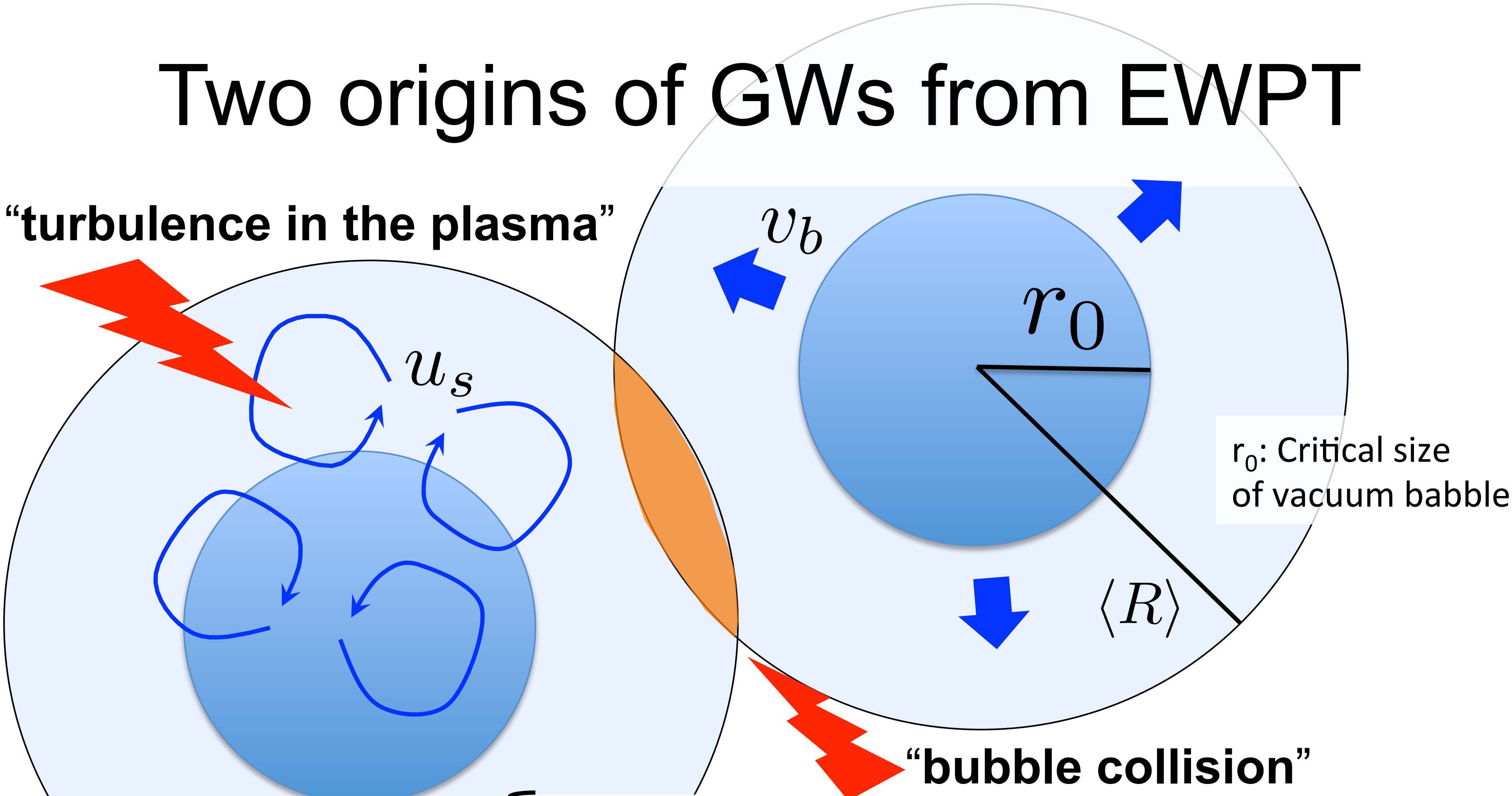
r_0: Critical size
of vacuum babble

``Characteristic parameters of GWs''

- α is defined as $\alpha \equiv \left.\frac{\epsilon}{\rho_{\rm rad}}\right|_{T=T_t}$. ($\rho_{rad}$ is energy density of rad.)
  - Latent heat: $\epsilon(T) \equiv -\Delta V_{\rm eff}(\varphi_B(T), T) + T\frac{\partial \Delta V_{\rm eff}(\varphi_B(T))}{\partial T}$ cf. U=-F+T(dF/dT)
- β is defined as $\beta \equiv \left.\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right|_{t=t_t}$. $\rightarrow$ $\tilde{\beta}\left(\equiv \frac{\beta}{H_t}\right) = T_t \left.\frac{d(S_3(T)/T)}{dT}\right|_{T=T_t}$

(H_t : Hubble parameter @T_t)

Two origins of GWs from EWPT



- Typical radius of the colliding bubbles: $\langle R \rangle \propto v_b \tau$
- Duration of the phase transition: $\tau \simeq \beta^{-1}$
- Bubble wall velocity: $v_b(\alpha)$
- Turbulent fluid velocity: $u_s(\alpha)$

Relic abundance of GWs from EWPT

Numerical calculation
``Overshooting-undershooting method''

Model-independent analysis
C. Grojean and G. Servant, PRD**75,** 043507 (2007)

$V_{\rm eff}(\varphi, T)$ → $\alpha,\ \tilde{\beta}$ @T=T_t → $\Omega_{GW}h^2(f)$

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"bubble collision"

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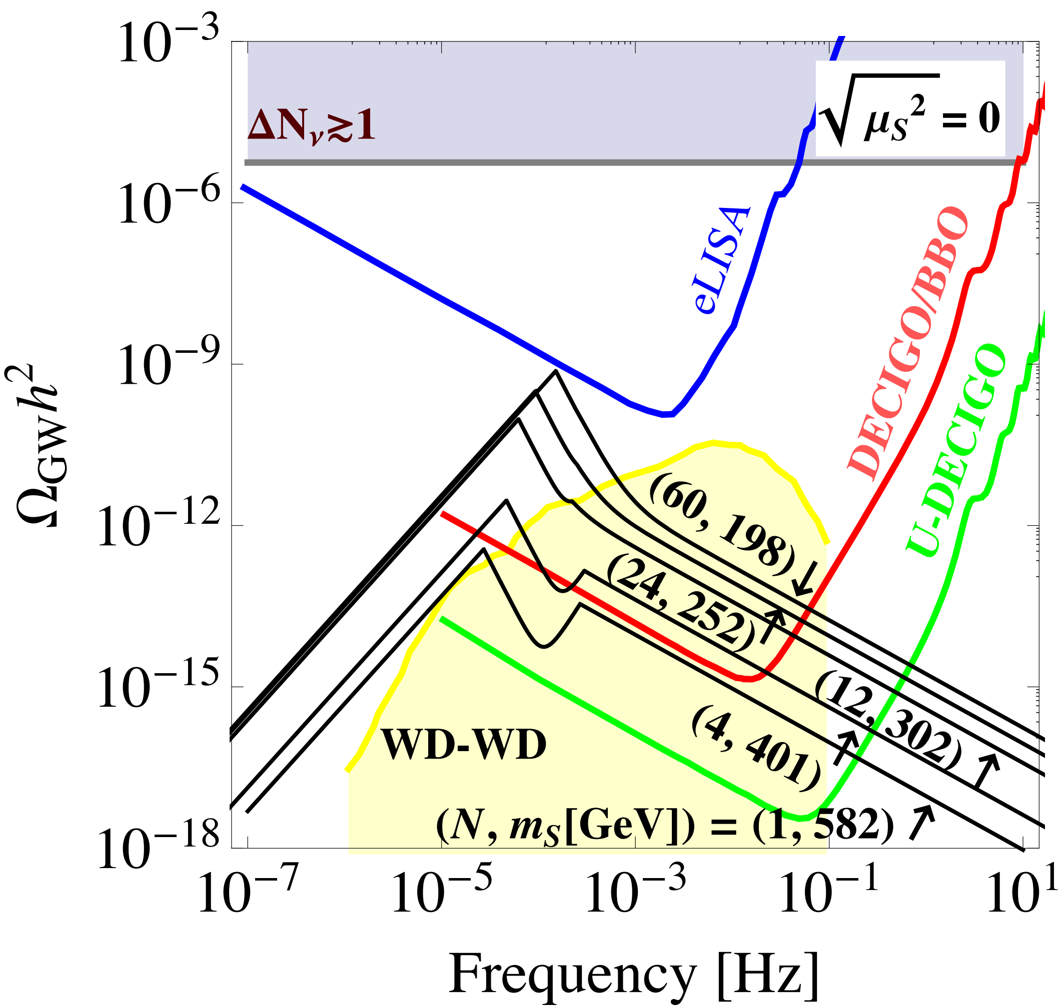
GW spectrum from 1st OPT



Sensitivities

H.Kudoh, *et al.*, PRD73, 064006 (2006)

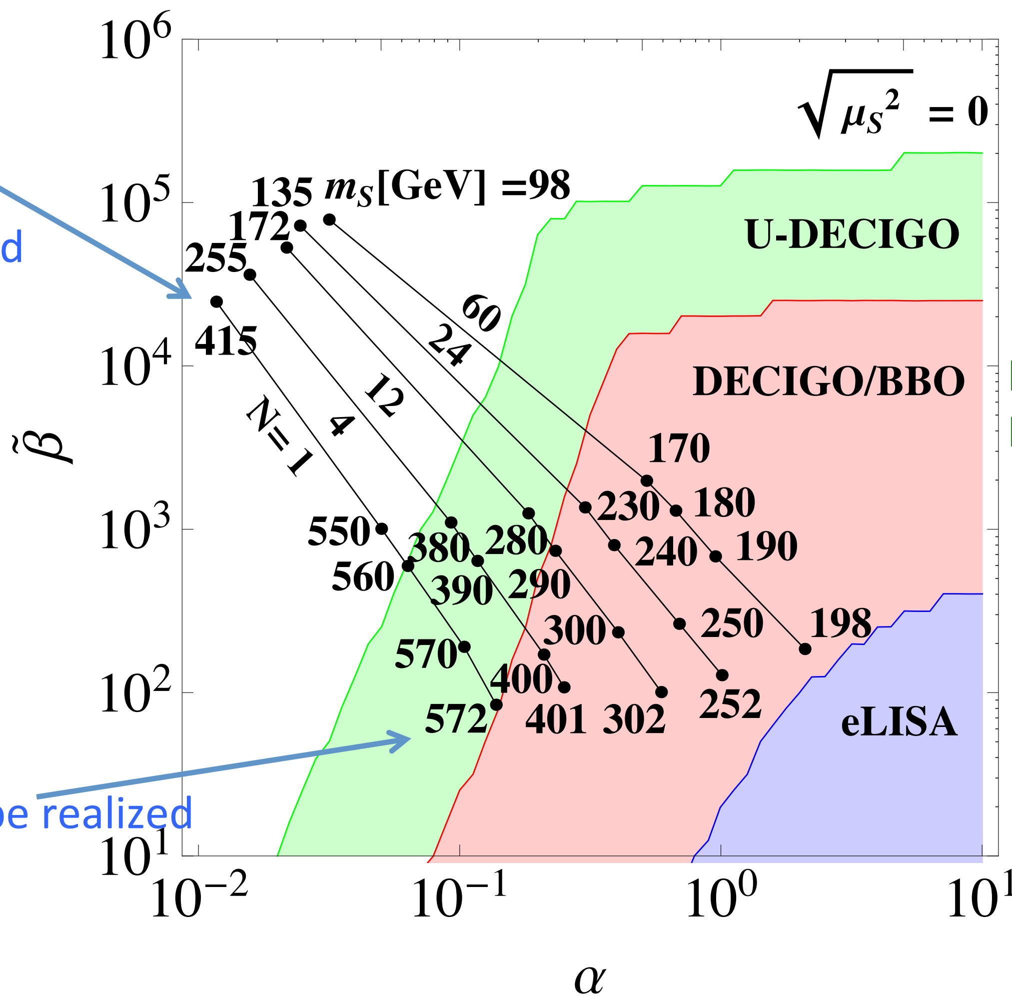
GW from WD-WD

R. Schineider, *et al.*, Class. Quant. Grav. 27, 194007 (2010)

M.Kakizaki, S.Kanemura, T.Matsui, arXiv:1509.08394 [hep-ph]

Dependences on (N, m_s)

For smaller $\boldsymbol{m_s}$
$\boldsymbol{\varphi_c/T_c}$>1
cannot be satisfied



For larger $\boldsymbol{m_s}$
Γ/H^4 = 1 cannot be realized

Sensitivities

H.Kudoh, *et al.*,
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Future improvements

There are uncertainties in evaluation of GW from 1^{st} OPT (babble dynamics, formulas of GW spectrum, …)

Recent detailed analysis of bubble collision

Efficiency factor (rate of GW from latent heat)

Espinosa, et al. (2010), No (2011) **$\kappa(\alpha) \rightarrow \kappa(\alpha, v_w)$**

Which model of plasma turbulence to be used?

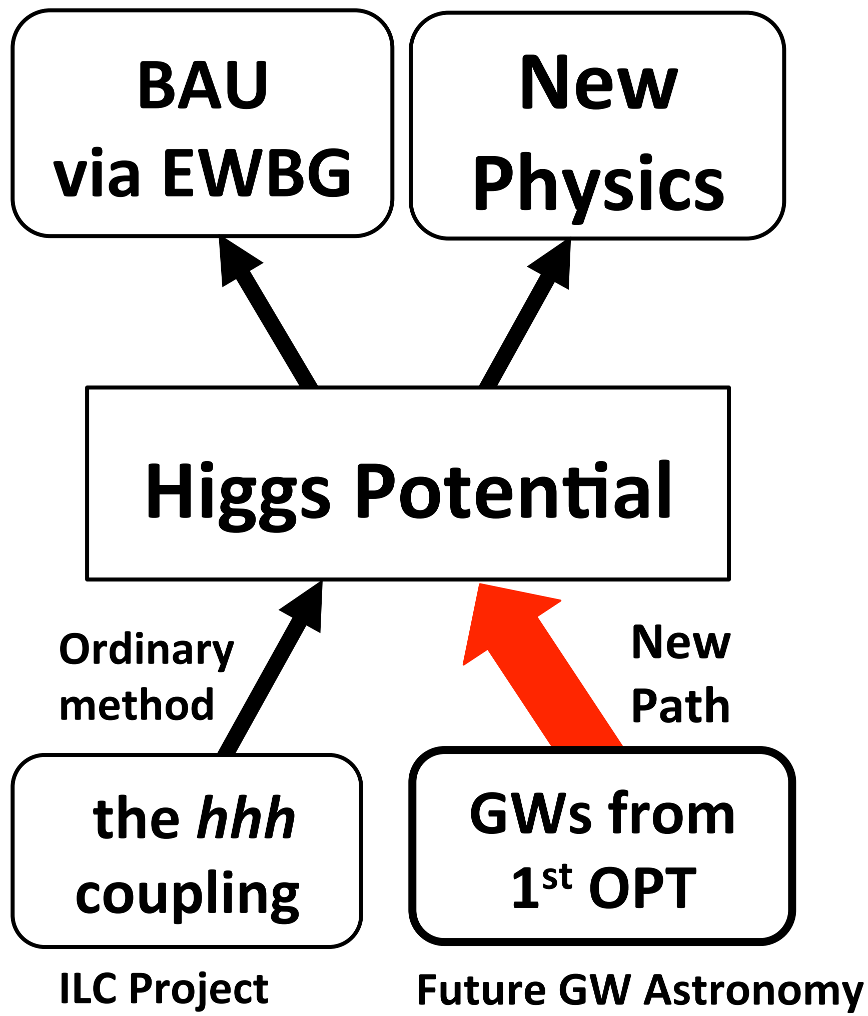
Nicolis (2004)

various fluid modes

Understanding of Foregrouds (ex: WD-WD)

Requirement future GW interferometers

ILC vs LISA/DECIGO



Neutrino and Higgs

Introduction

- Higgs sector remains unknown
  - Minimal/Non-minimal Higgs sector?
  - Higgs Search is the most important issue to complete the SM particle contents.
- We already know BSM phenomena:
  - Neutrino oscillation

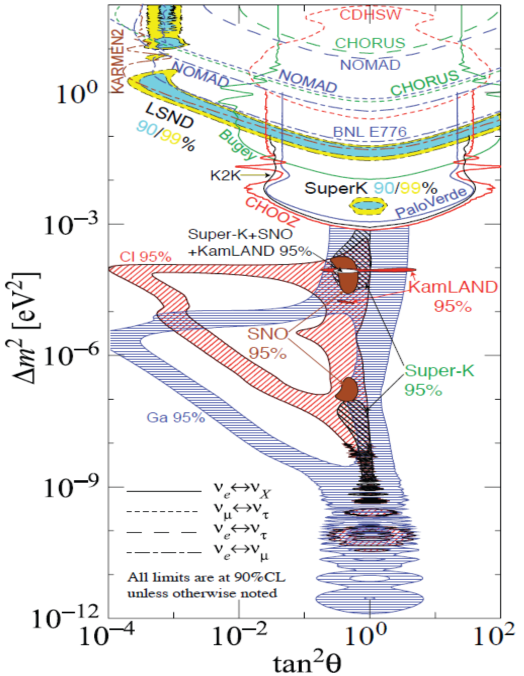
    $\Delta m^2 \sim 8\times10^{-5}\,eV^2, \ \Delta m^2 \sim 3\times10^{-3}\ eV^2$

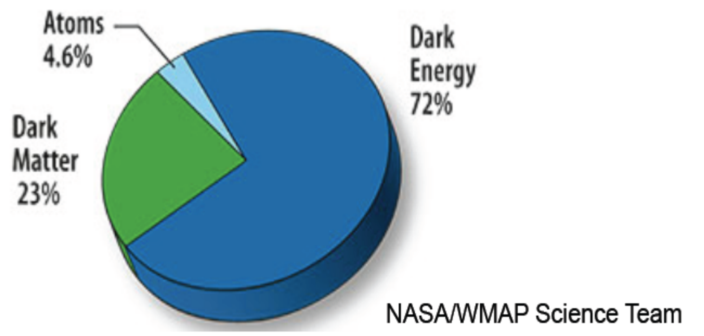
  - Dark Matter

    $\Omega_{DM}h^2 \sim 0.1$

  - Baryon Asymmetry of the Universe

    $n_B/s \ \sim 9\times10^{-11}$





To understand these phenomena, we need to go beyond-SM

Neutrino Oscillation

Two definitions of eigenstates

Mass eigenstates of charged leptons

$$\begin{pmatrix}\overline{e_L} & \overline{\mu_L} & \overline{\tau_L}\end{pmatrix}\begin{pmatrix}m_e & 0 & 0\\ 0 & m_\mu & 0\\ 0 & 0 & m_\tau\end{pmatrix}\begin{pmatrix}e_R\\ \mu_R\\ \tau_R\end{pmatrix}$$

Flavor eigenstates of neutrinos

$$\frac{g}{\sqrt{2}}W_\mu^-\begin{pmatrix}\overline{e_L} & \overline{\mu_L} & \overline{\tau_L}\end{pmatrix}\gamma^\mu\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_{eL}\\ \nu_{\mu L}\\ \nu_{\tau L}\end{pmatrix}$$

Mass eigenstates of neutrinos

$$\begin{pmatrix}\overline{\nu_{1R}} & \overline{\nu_{2R}} & \overline{\nu_{3R}}\end{pmatrix}\begin{pmatrix}m_1 & 0 & 0\\ 0 & m_2 & 0\\ 0 & 0 & m_3\end{pmatrix}\begin{pmatrix}\nu_{1L}\\ \nu_{2L}\\ \nu_{3L}\end{pmatrix}$$

can be **different**

Flavor mixing

$$\nu_\ell = \sum_i (U_{\mathrm{MNS}})_{\ell i}\, \nu_i$$

Flavor eigenstates (weak interaction)

Mass eigenstates (propagation)

Maki-Nakagawa-Sakata matrix (**mixing**)

(quark sector : Cabibbo-Kobayashi-Maskawa matrix)

Neutrino oscillation

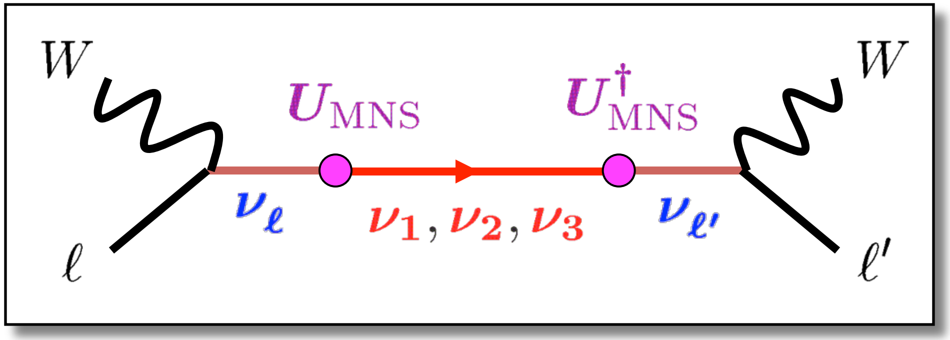
Periodic transition of flavors

$$P(\nu_\ell \to \nu_{\ell'}) = \left| \sum_i (U_{\mathrm{MNS}})_{\ell i} \ \exp\left(i \frac{m_i^2 L}{2E} \right) (U^\dagger_{\mathrm{MNS}})_{i \ell'} \right|^2$$

m_i : **Masses**

L : Distance

E : Energy



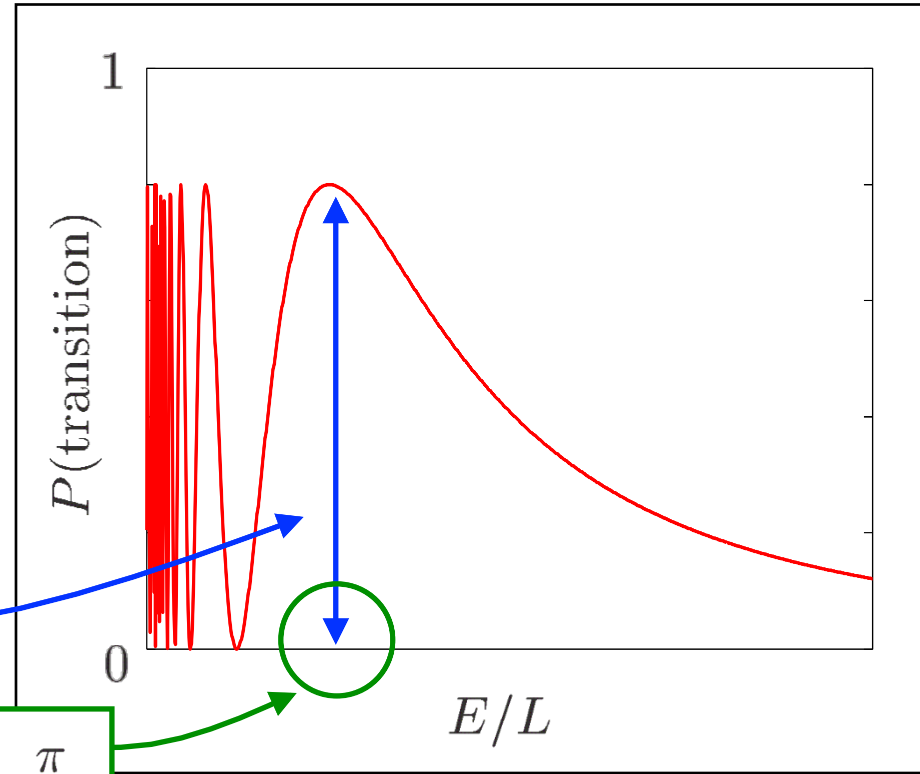
Two-flavor oscillation

$$U_{\mathrm{MNS}} \equiv \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$\boldsymbol{\Delta m^2} \equiv m_2^2 - m_1^2$$

$$\Downarrow$$

$$P = \boldsymbol{\sin^2 2\theta}\ \sin^2\left(\frac{\boldsymbol{\Delta m^2} L}{4E}\right)$$



$$\frac{\boldsymbol{\Delta m^2} L}{4E} = \frac{\pi}{2}$$

First oscillation maximum

$$\frac{\Delta m^2 L}{4E} = 1.27\ \frac{\Delta m^2(\mathrm{eV}^2)\ L(\mathrm{m})}{E(\mathrm{MeV})}$$

- Nobel Prize in Physics 2015 -

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Takaaki Kajita

Director of Institute for Cosmic Ray Research (ICRR)

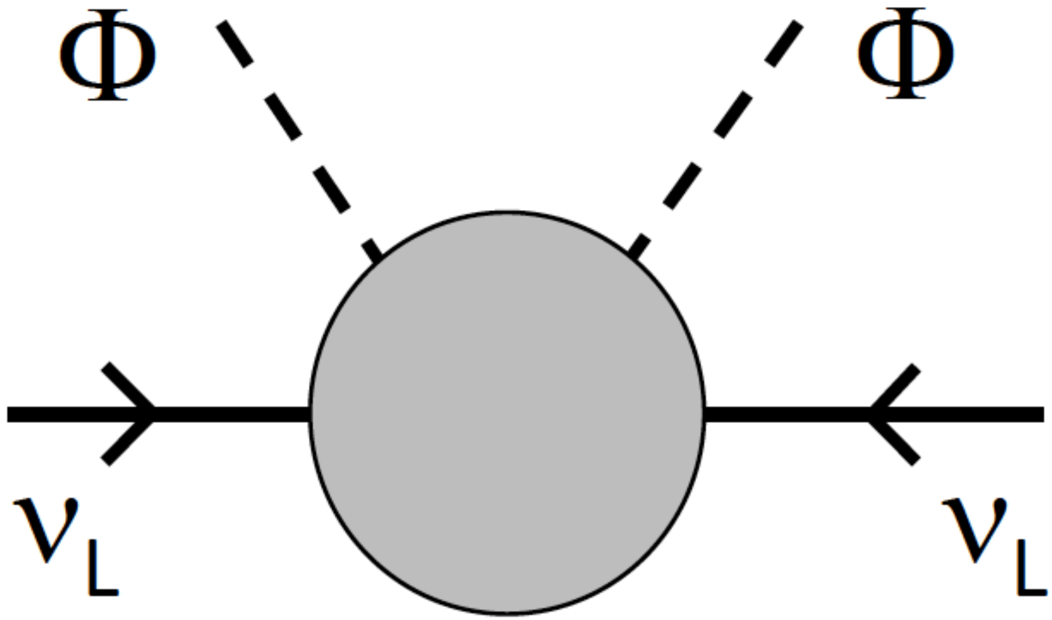
Atmospheric ν oscillation at Super-Kamiokande

Arthur B. McDonald

Professor (emeritus) in Queen's University

Solar ν oscillation at SNO

Neutrinos do have masses



This is a clear signature of BSM

BSM: Neutrino Mass

Neutirno Mass Term (= Effectively Dim-5 Operator)

$$L^{eff} = (c_{ij}/M)\, \nu^i{}_L \nu^j{}_L\, \phi\, \phi$$

$\langle\phi\rangle = v = 246\text{GeV}$

Mechanism for tiny masses:

$$m^\nu{}_{ij} = (c_{ij}/M)\, v^2 \ < 0.1\ \text{eV}$$

Seesaw (tree level)

$$m^\nu{}_{ij} = y_i y_j\, v^2/M$$

$M = 10^{13\text{-}15}\text{GeV}$

Quantum Effects

N-th order of perturbation theory

$$m^\nu{}_{ij} = [1/(16\pi^2)]^N\, C_{ij}\, v^2/M$$

$M = 1$ TeV

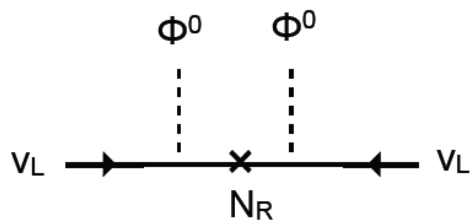
Seesaw Mechanism?

Super heavy RH neutrinos (M_{NR} ~ $10^{10\text{-}15}$GeV)

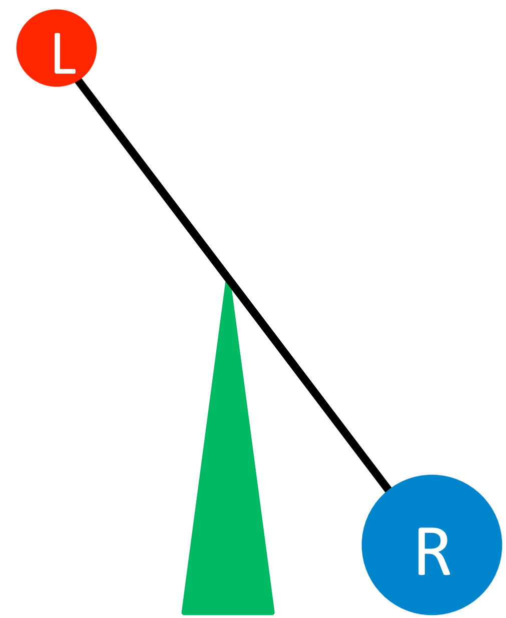
- Hierarchy between M_{NR} and m_D generates that between m_D and tiny m_ν (m_D ~ 100 GeV)

$$m_\nu = m_D{}^2/M_{NR}$$

ννφφ



Minkowski
Yanagida
Gell-Mann et al



- Simple, compatible with GUT etc
- Introduction of a super high scale

Hierarchy for hierarchy!

Far from experimental reach…

BSM: Neutrino Mass

Neutirno Mass Term (= Effectively Dim-5 Operator)

$$L^{eff} = (c_{ij}/M)\ \nu^i{}_L \nu^j{}_L\ \phi\ \phi$$

$\langle\phi\rangle = v = 246\text{GeV}$

Mechanism for tiny masses:

$$m^{\nu}{}_{ij} = (c_{ij}/M)\ v^2 < 0.1\ \text{eV}$$

Seesaw (tree level)

$$m^{\nu}{}_{ij} = y_i y_j\ v^2/M$$

$M = 10^{13\text{-}15}\text{GeV}$

Quantum Effects

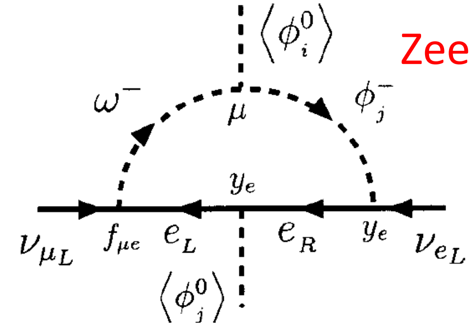
N-th order of perturbation theory

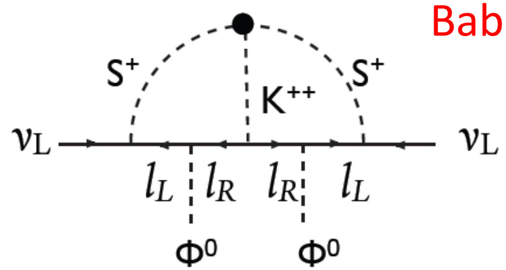
$$m^{\nu}{}_{ij} = [1/(16\pi^2)]^N\ C_{ij}\ v^2/M$$

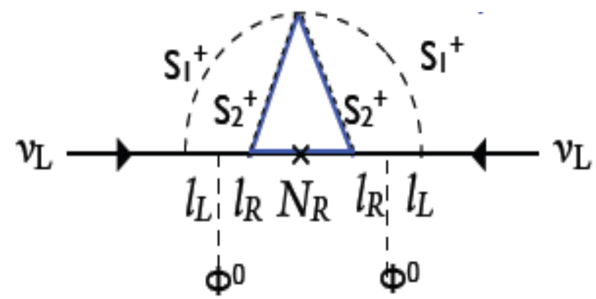
$M = 1\ \text{TeV}$

Scenario of radiative $\nu\nu\phi\phi$ generation

- Tiny ν-Masses come from loop effects
  - Zee (1980, 1985)
  - Zee, Babu (1988)
  - Krauss-Nasri-Trodden (2002)
  - Ma (2006), ...



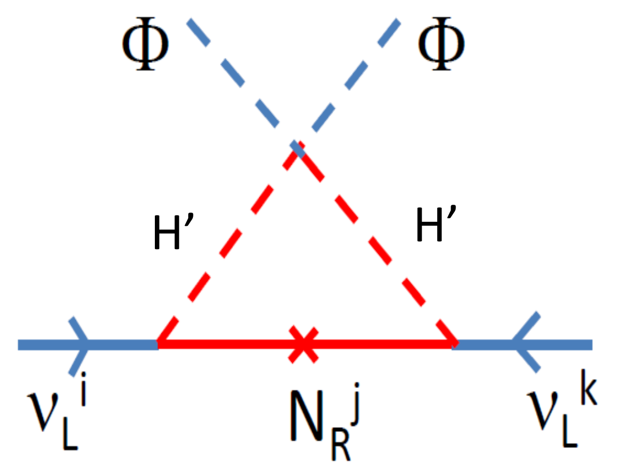




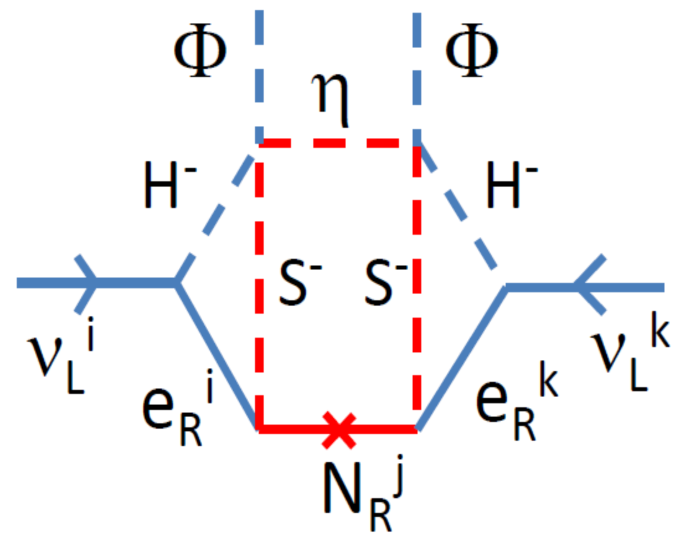
- Merit
  - Super heavy particles are not necessary
    Size of tiny m_ν can naturally be deduced from TeV scale by higher order perturbation
  - Physics at TeV: Testable at collider experiments

Radiative seesaw with Z_2

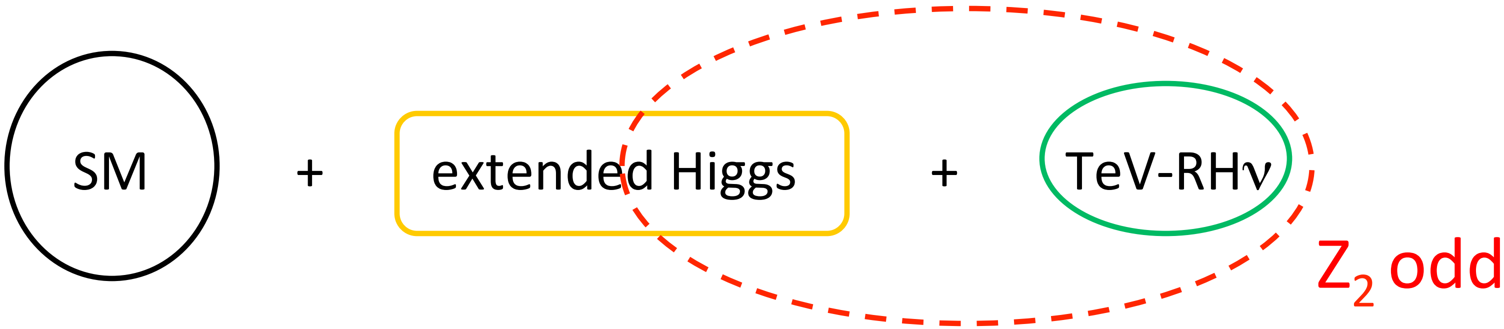
- 1-loop (Ma)
  - Simplest model
  - SM + NR + Inert doublet (H')
  - DM candidate [H' or NR]
    - H' case
    - NR (LFV and MN not compatible)



- 3-loop (Aoki-Kanemura-Seto)
  - Neutrino mass from O(1) coupling.
  - Electroweak Baryogenesis
  - 2HDM + η^0 + S^+ + NR
  - DM candidate [η^0 (or NR)]

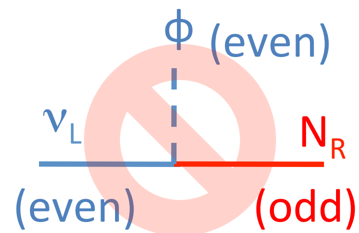


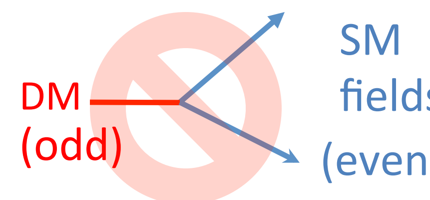
Model by AKS



Exact Z_2 Parity

- No neutrino Yukawa coupling
- Stabilize Dark Matter





RH neutrinos: N_R (M_{NR} = TeV scale)

Extended Higgs: 2HDM (Φ_1, Φ_2) + singlet scalars (η^0, S^+)

Tiny neutrino mass: 3 loop effect (N_R, η^0, S^+, H^+, e_R)
DM candidate: Lightest Z_2-odd particle (η^0)
EW Baryogenesis: Extended Higgs [1st Order PT, Source of CPV]

The Higgs sector

- The Higgs sector

  Φ_1, Φ_2 (2HDM) + S^+, η (singlets)

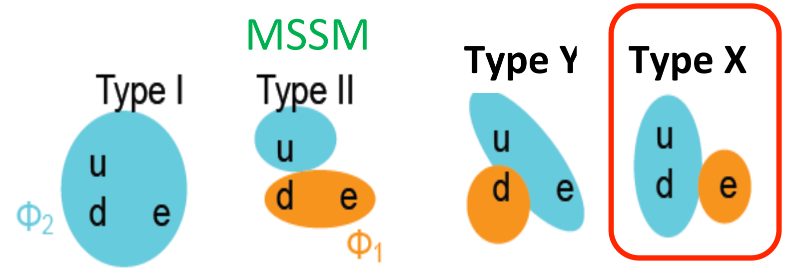
- To avoid FCNC, additional softly-broken Z_2 symmetry is introduced :

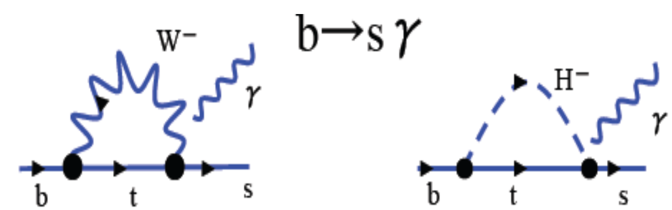
  $$\Phi_1 \to +\Phi_1, \quad \Phi_2 \to -\Phi_2$$

  by which each quark/lepton couples to only one of the Higgs doublets.

- 4 types of Yukawa interactions!

Our model



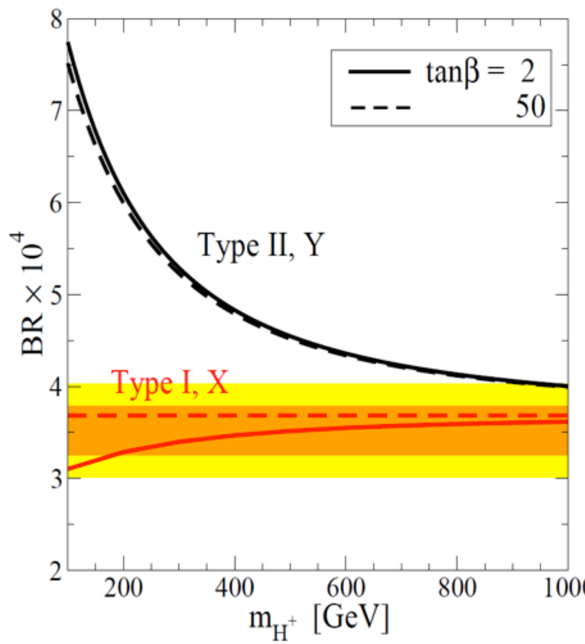


Neutrino data prefer a light H^+(< 200GeV)

- Choose Type-X Yukawa to avoid the constraint from $b \to s\gamma$.

Φ_1 only couples to Leptons
Φ_2 only couples to Quarks

NLO, Ciuchini et al '98,
....
NNLO by
Misial et al. 2006
Becher, Neubert 2006



Aoki, SK, Tsumura, Yagyu, PRD 80, 015017 (2009)

The model

$$SU(3) \times SU(2) \times U(1) \times Z_2 \times \tilde{Z}_2$$

Z_2 (exact) : to forbid ν-Yukawa
to stabilize DM
$\tilde{Z}_2$ (softly-broken): to avoid FCNC

	$SU(2)_L \times U(1)$	Z_2 (exact)	$\tilde{Z}_2$ (softly broken)
Q^i	(2, 1/6)	+	+
u_R^i	(1, 2/3)	+	−
d_R^i	(1, −1/3)	+	−
L^i	(2, −1/2)	+	+
e_R^i	(1, −1)	+	+
Φ_1	(2, 1/2)	+	+
Φ_2	(2, 1/2)	+	−
S^-	(1, -1)	−	+
η^0	(1, 0)	−	−
N_R^α	(1, 0)	−	+

Type-X 2HDM (Q^i through Φ_2)

Z_2-even physical states
h (SM like Higgs)
H, A, H^- (Extra scalars)
Z_2-odd states
η, S^+, N_R

Lagrangian

$$SU(3) \times SU(2) \times U(1) \times Z_2 \times \tilde{Z}_2$$

Z_2 even(2HDM) + Z_2odd(S^+, η^0 , $N_R{}^\alpha$)

Z_2 (exact) : to forbid tree ν-Yukawa and to stabilize DM

$\tilde{Z}_2$ (softly-broken): to avoid FCNC

Potential	
$V = -\mu_1^2\lvert\Phi_1\rvert^2 - \mu_2^2\lvert\Phi_2\rvert^2 - (\mu_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \lambda_1\lvert\Phi_1\rvert^4 + \lambda_2\lvert\Phi_2\rvert^4 + \lambda_3\lvert\Phi_1\rvert^2\lvert\Phi_2\rvert^2 + \lambda_4\lvert\Phi_1^\dagger\Phi_2\rvert^2 + \left\{\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right\}$	Z_2 even 2HDM
$+\mu_s^2\lvert S\rvert^2 + \lambda_s\lvert S\rvert^4 + \frac{1}{2}\mu_\eta\eta^2 + \lambda_\eta\eta^4 + \xi\lvert S\rvert^2\eta^2$	Z_2 odd scalars
$+\sum_{a=1}^{2}\left\{\rho_a\lvert\Phi_a\rvert^2\lvert S\rvert^2 + \sigma_a\lvert\Phi_a\rvert^2\frac{\eta^2}{2}\right\} + \sum_{a,b=1}^{2}\left\{\kappa\epsilon_{ab}(\Phi_a^c)^\dagger\Phi_b S^-\eta + \text{h.c.}\right\}.$	Interaction

RH neutrinos

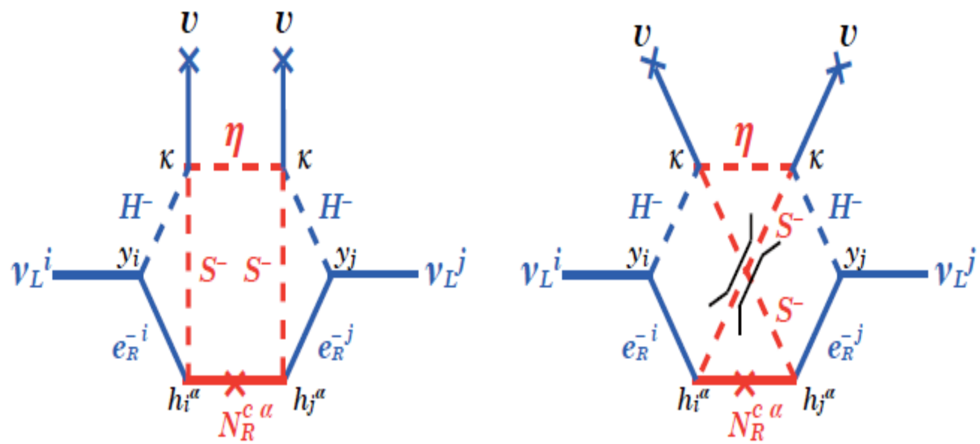
$$\mathcal{L}_Y = -\sum_{\alpha=1}^{2}\sum_{i,j=1}^{3} h_i^\alpha (e_R^i)^c N_R^\alpha S^- + \sum_{\alpha=1}^{2} m_N^\alpha N_\alpha^c N_\alpha + \text{h.c.}.$$

Neutrino Mass

Tree neutrino Yukawa is forbidden by Z_2

$$M_{ij} = \sum_{\alpha=1}^{2} C_{ij}^{\alpha} F(m_H, m_S, m_{N_R^\alpha}, m_\eta)$$

$$F(m_{H^\pm}, m_{S^\pm}, m_{N_R}, m_\eta) = \left(\frac{1}{16\pi^2}\right)^3 \frac{(-m_{N_R} v^2)}{m_{N_R}^2 - m_\eta^2}$$
$$\times \int_0^\infty dx \left[x \left\{ \frac{B_1(-x, m_{H^\pm}, m_{S^\pm}) - B_1(-x, 0, m_{S^\pm})}{m_{H^\pm}^2} \right\}^2 \right.$$
$$\left. \times \left(\frac{m_{N_R}^2}{x + m_{N_R}^2} - \frac{m_\eta^2}{x + m_\eta^2} \right) \right], \quad (m_{S^\pm}^2 \gg m_{e_i}^2),$$



- Universal scale is determined by the 3-loop function factor F
- Mixing structure is determined by

$$C_{ij}^{\alpha} = 4\kappa^2 \tan^2\beta (y_{\ell_i}^{\rm SM} h_i^\alpha)(y_{\ell_j}^{\rm SM} h_j^\alpha)$$

Neutrino data and LFV data require that

H^+ should be light (< 200 GeV)

N_R should be O(1) TeV

We can describe all the neutrino data (tiny masses and angles) without unnatural assumption among mass scales

Solution of ν mass and mixing

Case of 2 generation N_R^{α}

$\Delta m_{sol}^2 \sim 8\times10^{-5}\ \mathrm{eV}^2$
$\Delta m_{atm}^2 \sim 0.0021\ \mathrm{eV}^2$
$\theta_{sol} \sim 0.553$
$\theta_{atm} \sim \pi/4$

$$M_{ij} = U_{is}(M_\nu^{\rm diag})_{st}(U^T)_{tj}$$

$$m_\nu^{\rm diag} \equiv \begin{bmatrix} 0 & 0 & 0 \\ 0 & \sqrt{\Delta m^2_{\rm solar}} & 0 \\ 0 & 0 & \sqrt{\Delta m^2_{\rm atom}} \end{bmatrix}$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\tilde\alpha} & 0 \\ 0 & 0 & e^{i\tilde\beta} \end{bmatrix}$$

$$C_{ij}^{\alpha} = 4\kappa^2 \tan^2\beta (y_{\ell_i}^{\rm SM} h_i^{\alpha})(y_{\ell_j}^{\rm SM} h_j^{\alpha})$$

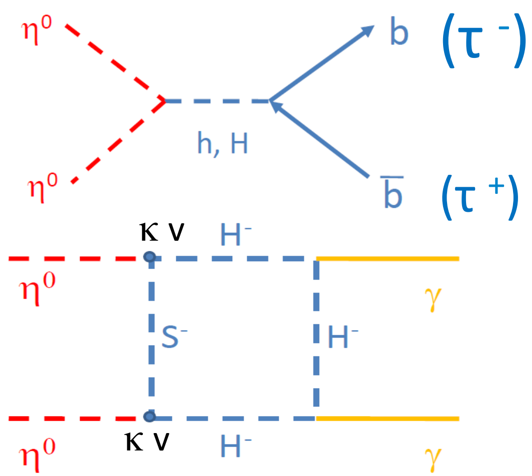
Set	Mass (TeV)				Yukawa couplings						LFV
(hierarchy, $\sin^2 2\theta_{13}$)	m_η	m_S	m_{Ni}	$\kappa\tan\beta$	h_e^1	h_e^2	h_μ^1	h_μ^2	h_τ^1	h_τ^2	$B(\mu\to e\gamma)$
A (normal, 0)	0.05	0.4	3	29	2.0	2.0	0.041	-0.020	0.0012	-0.0025	6.8×10^{-12}
B (normal, 0.14)	0.05	0.4	3	34	2.2	2.1	0.0087	0.037	-0.0010	0.0021	5.3×10^{-12}
C (inverted, 0)	0.05	0.4	3	66	3.8	3.7	0.013	-0.013	-0.00080	0.00080	4.2×10^{-12}
D (inverted, 0.14)	0.05	0.4	3	66	3.7	3.7	-0.016	0.011	0.00064	-0.00096	4.2×10^{-12}

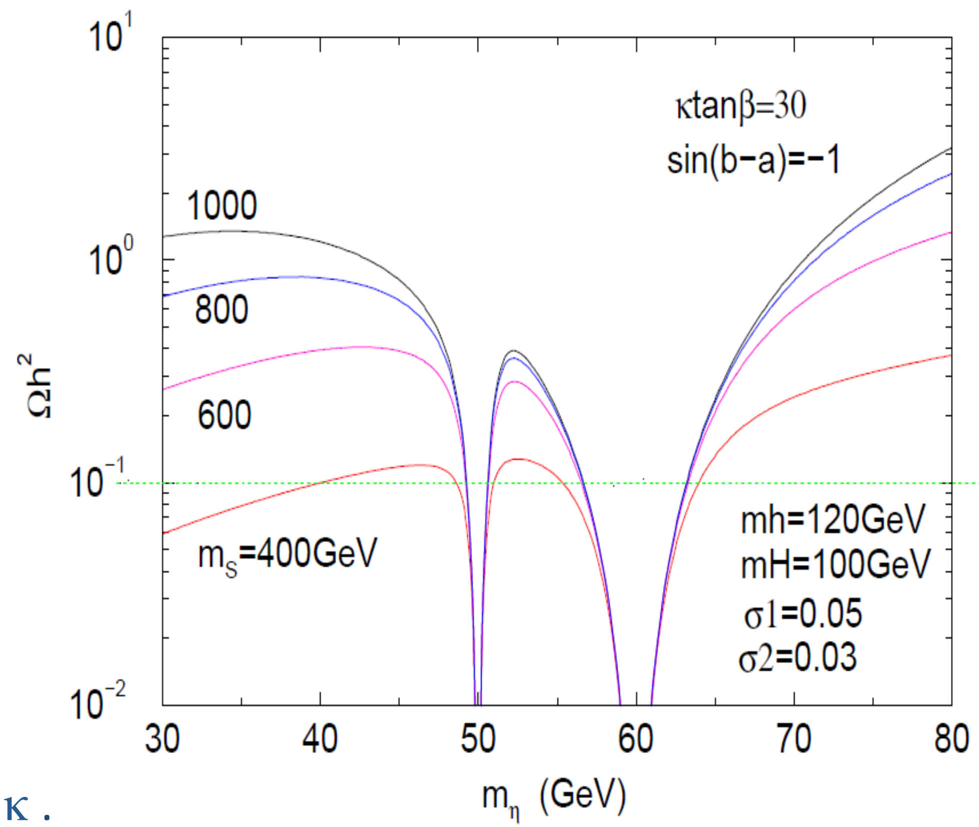
The model can reproduce all the neutrino data

Thermal Relic Abundance of η^0

WMAP data $\Omega_{\rm DM} h^2 \simeq 0.113$

$$\Omega_\eta h^2 = 1.1 \times 10^9 \left. \frac{(m_\eta / T_d)}{\sqrt{g_*} M_P \langle \sigma v \rangle} \right|_{T_d} \quad \text{GeV}^{-1}$$





The 1-loop process γγ can be comparable to the bb and ττ processes, when σ, $Y_f \ll \kappa$.

m_η would be around 40-65 GeV for m_S = 400GeV

Strong 1st Order Phase Transition

Effective Potential at high T

$$V_{\text{eff}} \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4$$

Sphaleron decoupling

$$\frac{\varphi_c}{T_c}\left(= \frac{2E}{\lambda_{T_c}}\right) \gtrsim 1 \qquad \lambda_T \sim \frac{2m_h^2}{v^2}$$

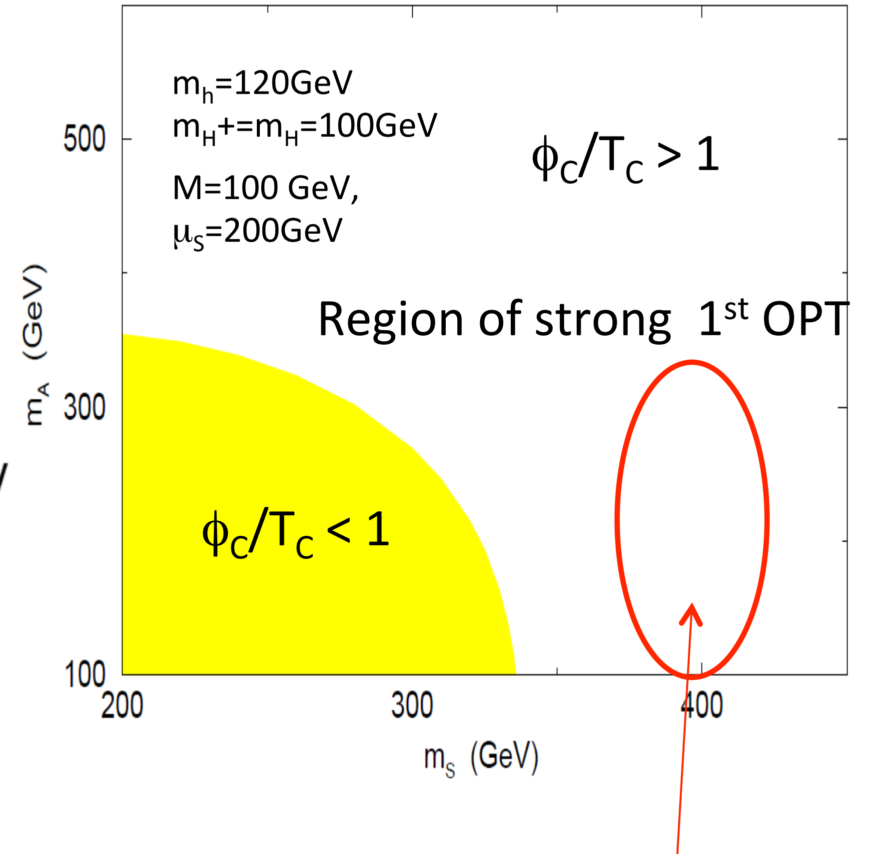
SM $E_{SM} \simeq \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3)$ $m_h \lesssim 65$ GeV

In SM, m_h is too smaller than LEP bound

Our Model

$$E \simeq \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3 + m_A^3 + 2m_{S\pm}^3)$$

The condition can be satisfied with $m_h > 114$ GeV, when A and/or S^+ have non-decoupling property. $m_{S+}^2 \sim \lambda_S v^2$

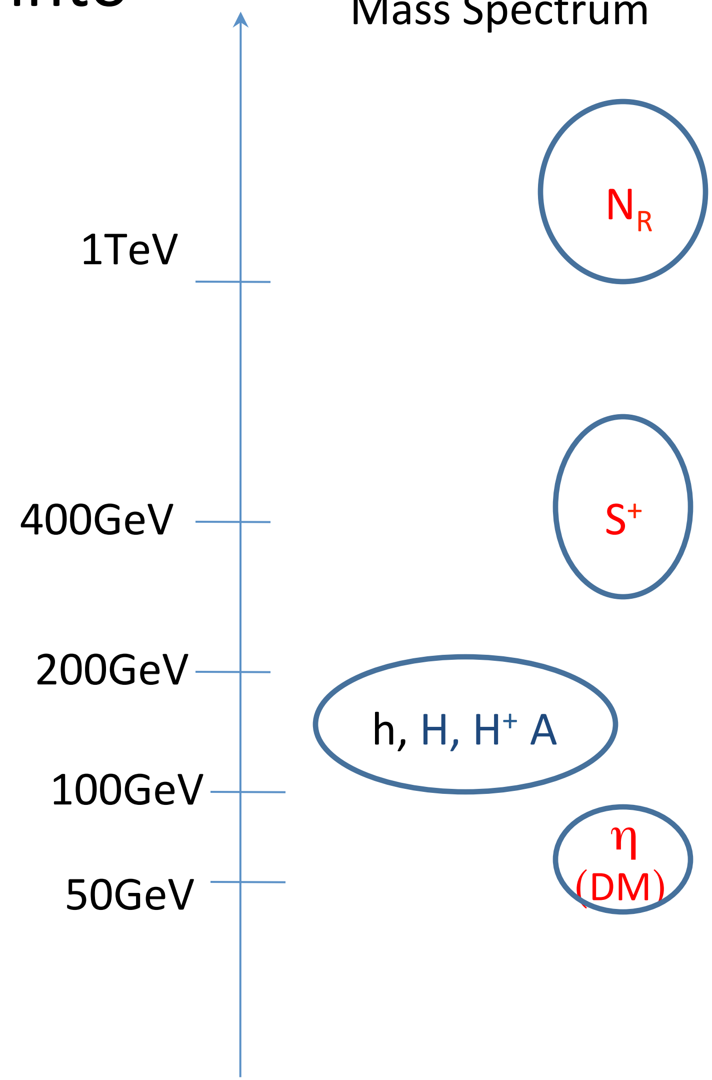


This region is compatible with neutrino data and DM abundance.

Successful scenario under current data

The requirement and data taken into account

- Neutrino Data
- DM Abundance
- Condition for Strong 1[st] OPT
- LEP Bounds on Higgs Bosons
- Tevatron Bounds on m_{H+}
- B physics: $B \rightarrow X_s \gamma$, $B \rightarrow \tau\nu$
- Tau Leptonic Decays, LFV ($\mu \rightarrow e\gamma$), g-2
- Theoretical Consistencies



The mass spectrum is uniquely determined

All masses are O(0.1)-O(1) TeV

Many discriminative predictions !

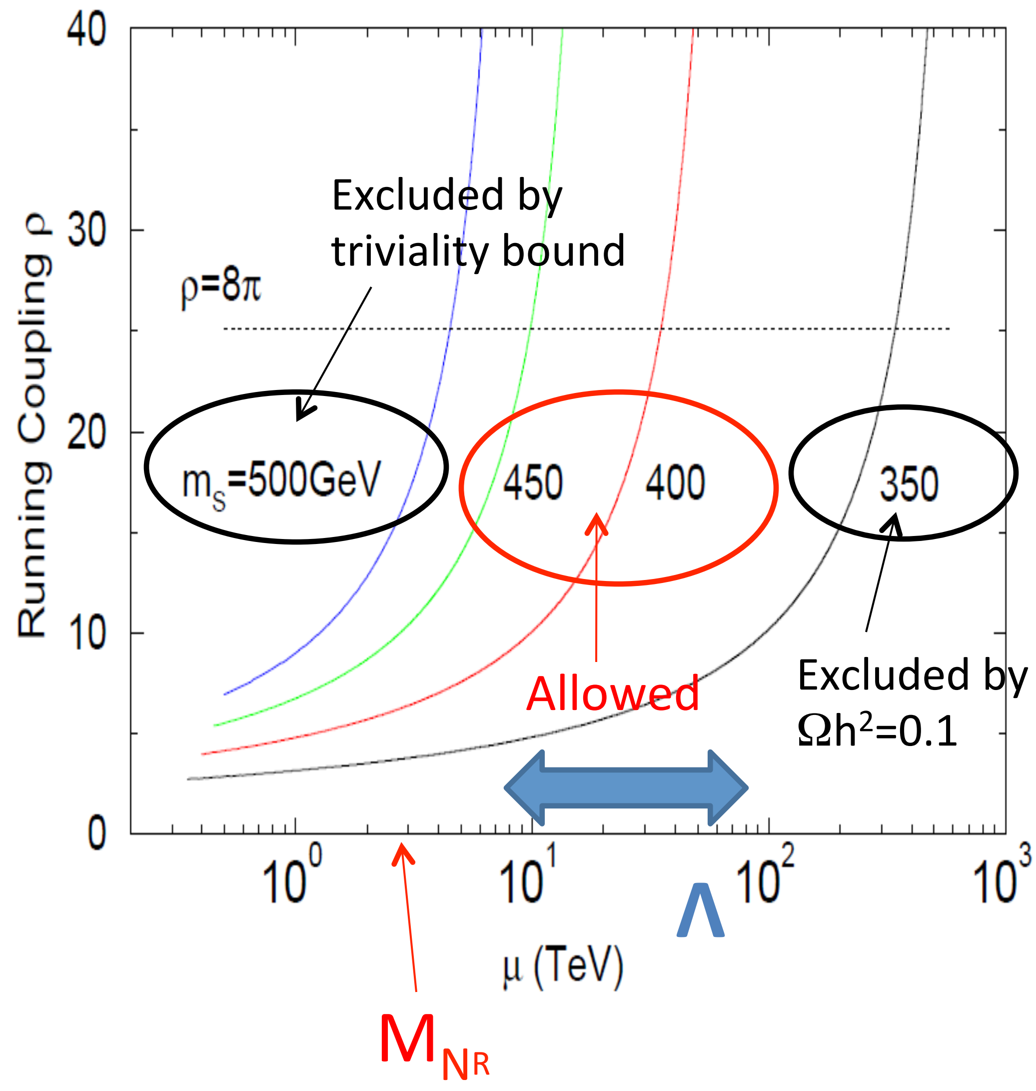
Predictions

- Physics of η (DM)
- Type X THDM with a light H^+.
- Non-decoupling effect of S^+.
- Lamdau Pole at 10-100 TeV
- Direct test for Majorana structure.

Cutoff scale of the model

- This model contains lots of scalars.
- Running couplings become larger for higher energies.
- Our scenario is consistent with the RGE analysis with

  Λ=O(10-100) TeV.

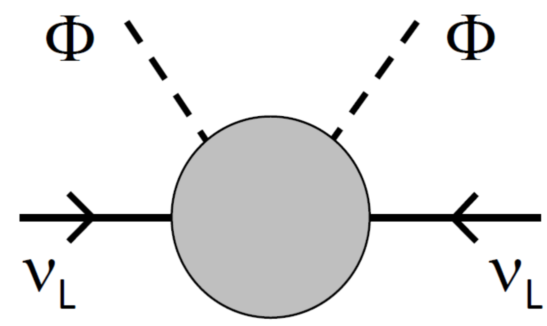


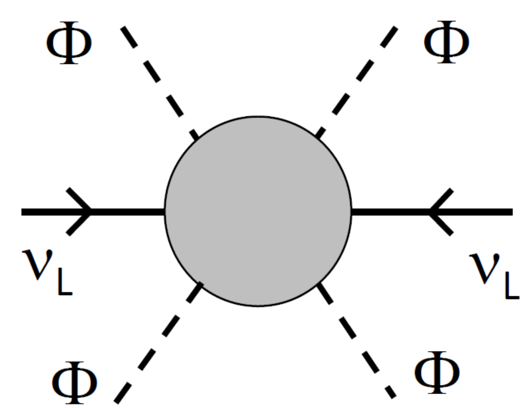
Higher Order Effect

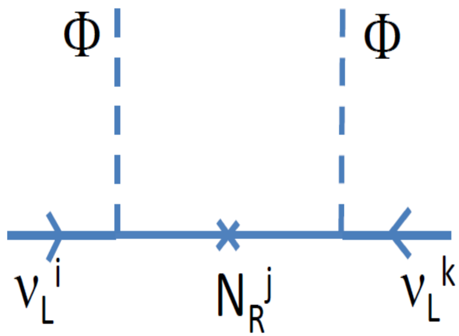
- Majorana mass of LH neutrinos may be generated from dim > 5 operators

- For dim-(5+n) operators, additional suppression $LL\varphi\varphi/\Lambda \times (\varphi\varphi/\Lambda^2)^n$

- Discrete symmetries forbid lower order operators



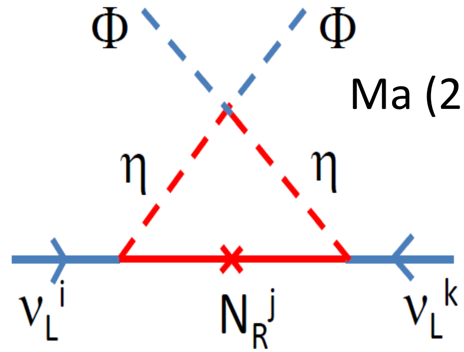




Yanagida; Gell-Mann; Minkowski

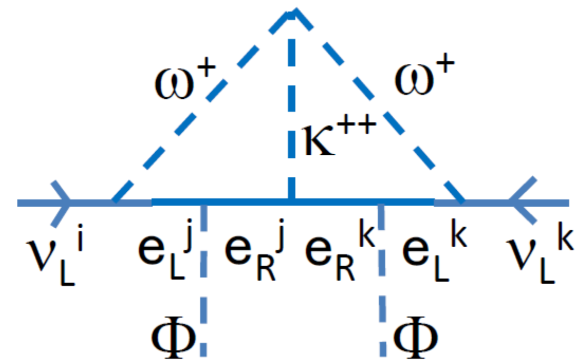
(*m*, *n*)=(0, 0)

Ma (2006)



(1, 0)

Zee; Babu



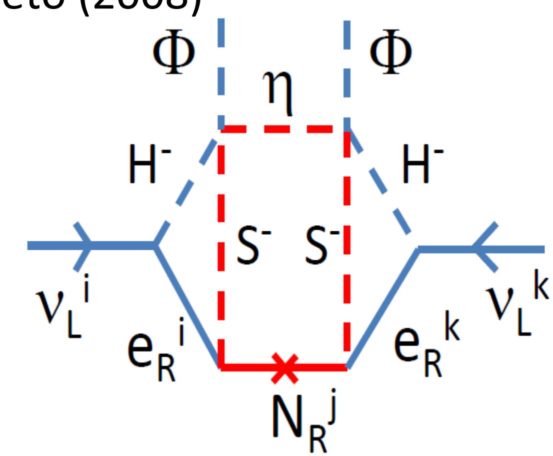
(2, 0)

$$m_\nu \sim c' \left(\frac{1}{16\pi^2}\right)^m \left(\frac{v}{\Lambda}\right)^{2n+1} v$$

Dim 5+*n* Operator

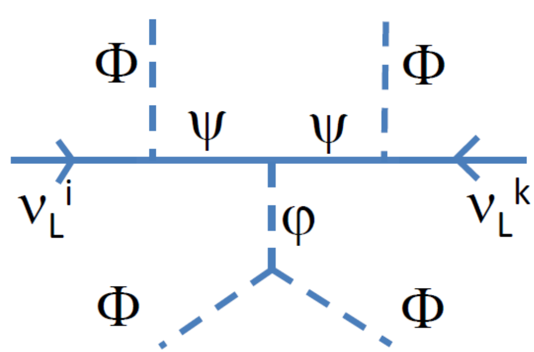
m-loop induced

Aoki, SK, Seto (2008)



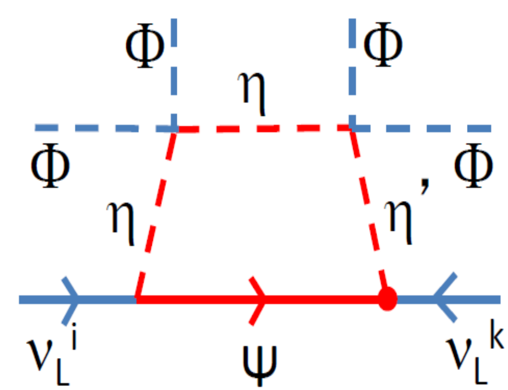
(3, 0)

Bonnet, et al. (2009)



(0, 1)

SK, Ota (2010)



(1, 1)

Summary

- A Higgs boson was found and it turned out to be SM like
- Still, so little is known about the structure of the Higgs sector
- There is a possibility for extended Higgs sectors
- Each extended Higgs sector can be motivated by a new physics model
  - Supersymmetry
  - Composite Higgs models
  - Electroweak Baryogenesis
  - Models of Radiative neutrino mass
  - Dark Matter models
  - …

- Experimental determination of the Higgs sector can be done by direct search and also by indirect search (fingerprinting)
  - LHC good for direct search
  - ILC good for precision measurement
- Higgs sector is the key to new physics beyond the SM