When inverse seesaw meets inverse EWPT:

a novel path to leptogenesis

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With Wen-Yuan Ai and Peisi Huang, 2510.xxxxx

A mystery and an elegant solution

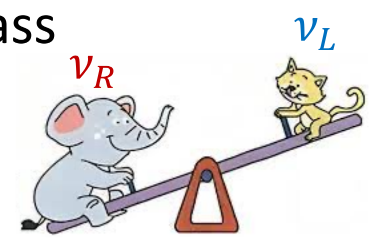
The baryon-matter asymmetry of the Universe

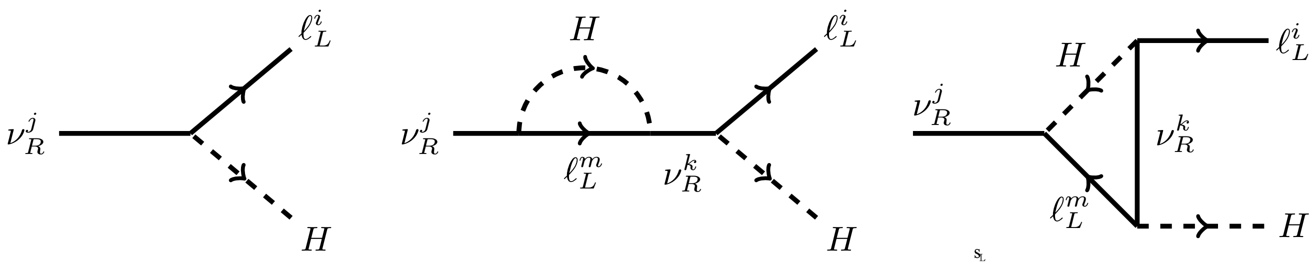
$$Y_B = \frac{n_B}{s} \approx 8.58\times10^{-11}$$

Calling for physics beyond the SM

Leptogenesis Yanagida *et al*, Phys.Lett.B 174 (1986) 45-47

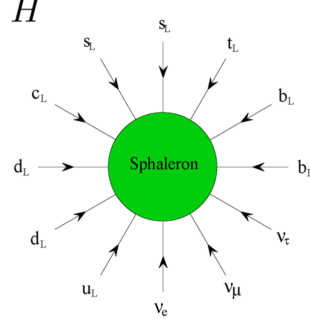
- Right-handed neutrino ν_R, explaining SM neutrino mass
- CP-violating decay, $\Gamma_{\nu_R\to\ell H} > \Gamma_{\nu_R\to\bar{\ell}H^*}$

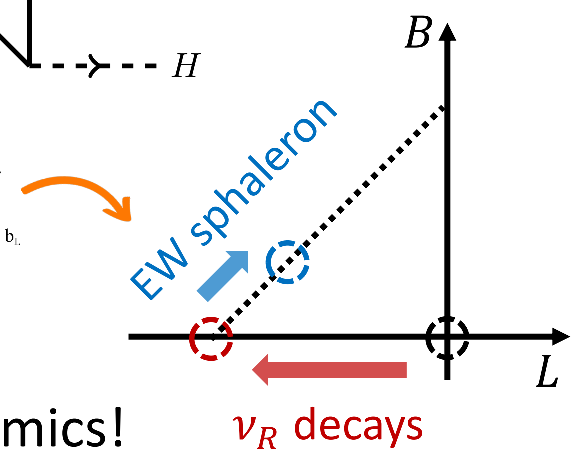




Lepton asymmetry Y_L generated

SM EW sphaleron process partly converts $Y_L \to Y_B$



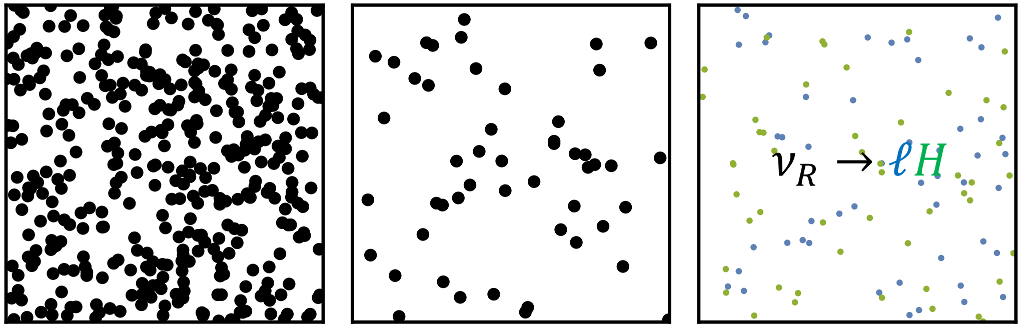


Solving the baryon mystery via the lepton dynamics!

Initial condition

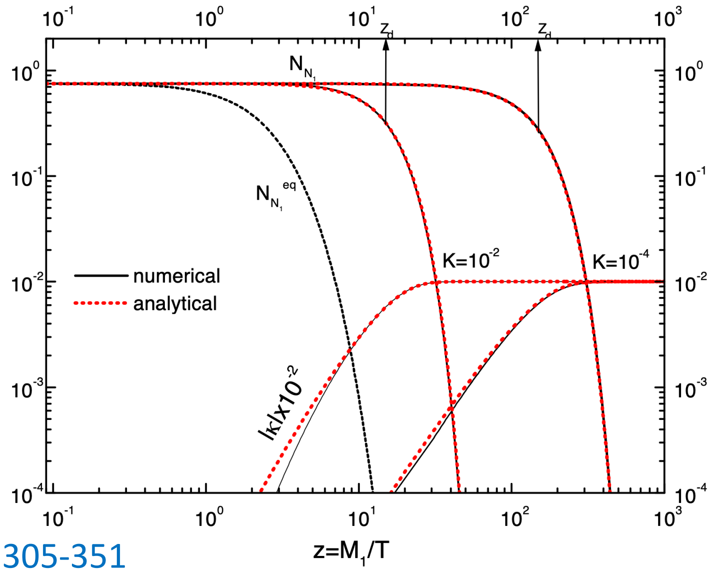
Thermal leptogenesis

$T \gg m_{\nu_R}$,
ν_R in equilibrium



$T \lesssim m_{\nu_R}$,
out-of-eq. decay

Typically described by a set of Boltzmann equations



Buchmuller *et al*,
Annals Phys. 315 (2005) 305-351

Initial condition

Thermal leptogenesis

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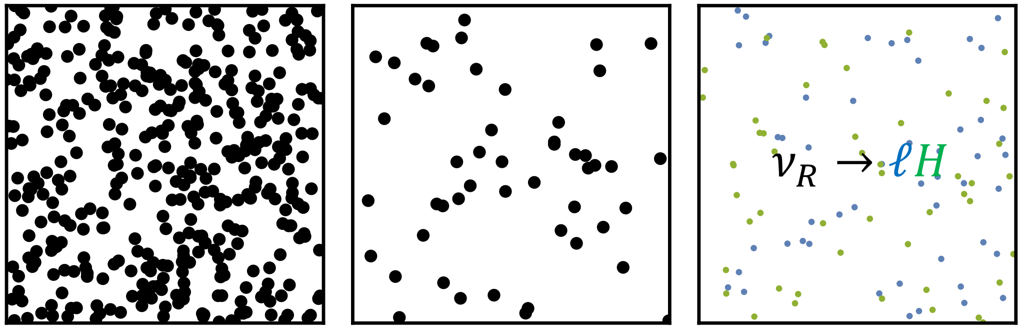
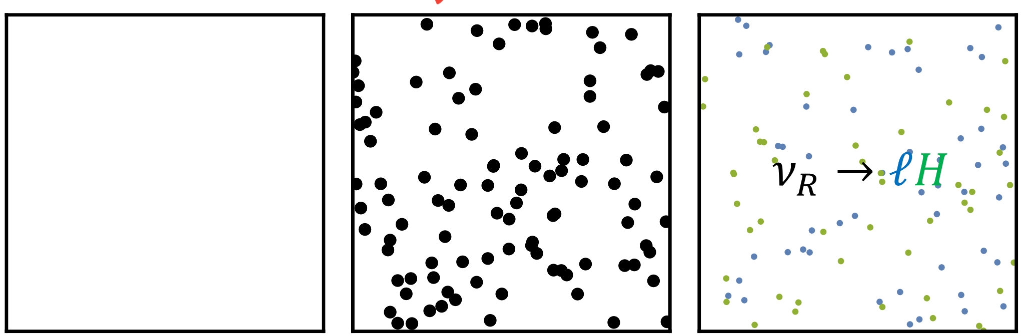


$T \lesssim m_{\nu_R}$,
out-of-eq. decay

Nonthermal leptogenesis

Nonthermal production at $T \ll m_{\nu_R}$

no ν_R in plasma



Instantaneous
out-of-eq. decay

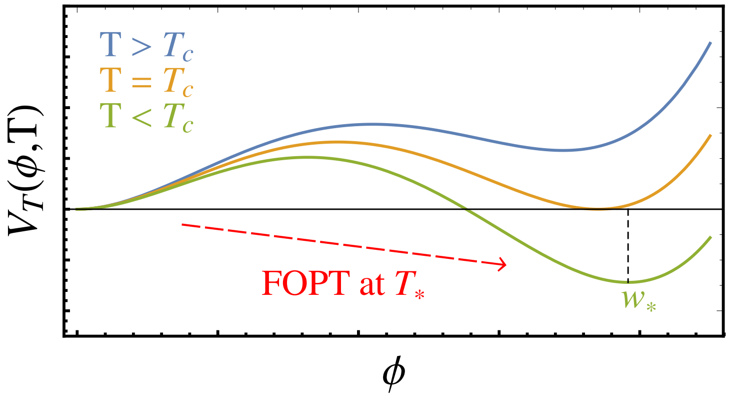
No thermal washout

Scenarios:

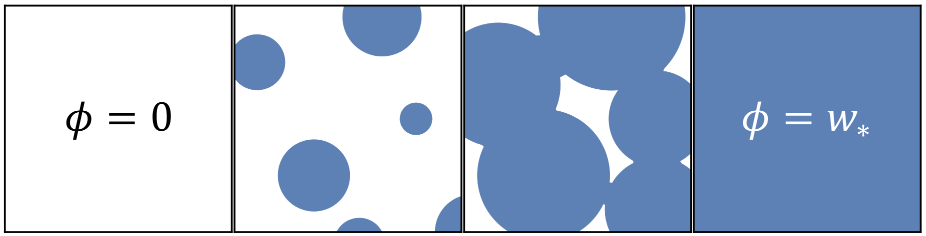
1. Inflaton decay $\phi \to \nu_R \nu_R$ during reheating or preheating
2. Cosmic first-order phase transitions (FOPTs) [this talk]

What is a cosmic FOPT?

Decay of the Universe between two vacuums



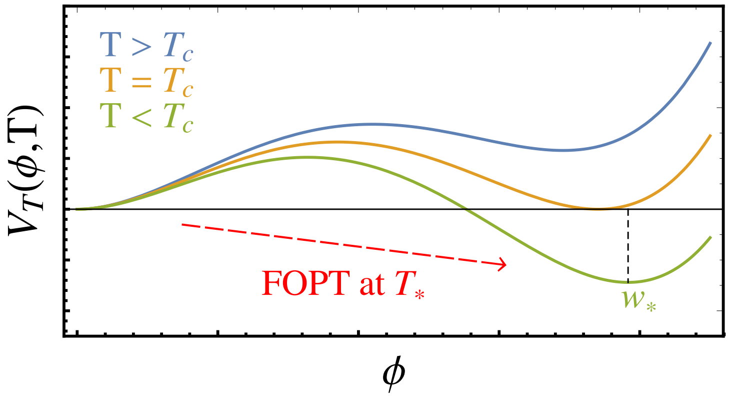
Bubble expansion velocity v_w



Why can it produce heavy particles with $m \gg T_*$?

What is a cosmic FOPT?

Decay of the Universe between two vacuums



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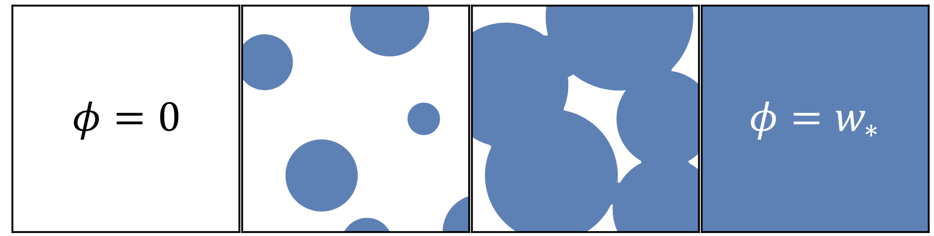
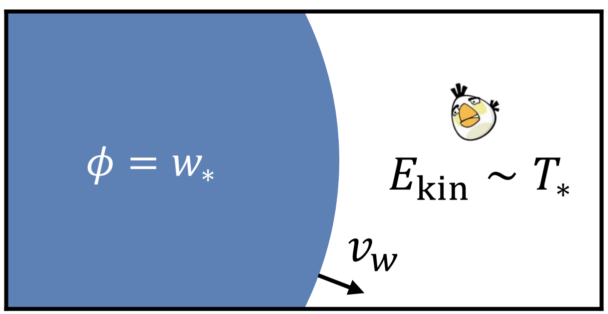
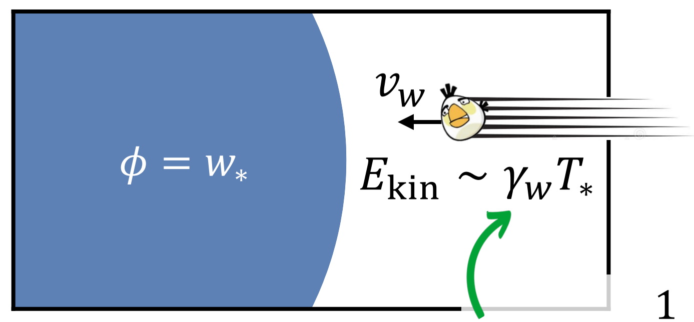


Why can it produce heavy particles with $m \gg T_*$?

Plasma frame



Wall-rest frame



$$\gamma_w = \frac{1}{\sqrt{1 - v_w^2}}$$

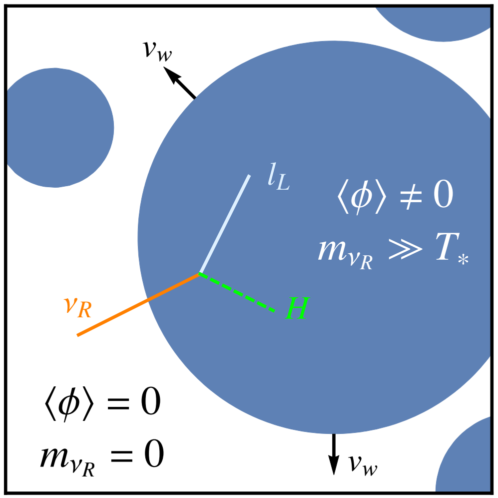
If $v_w \approx 1$, meaning $\gamma_w \gg 1$:

The bubble can touch a scale up to $\gamma_w T_* \gg T_*$!

Bubble-assisted leptogenesis

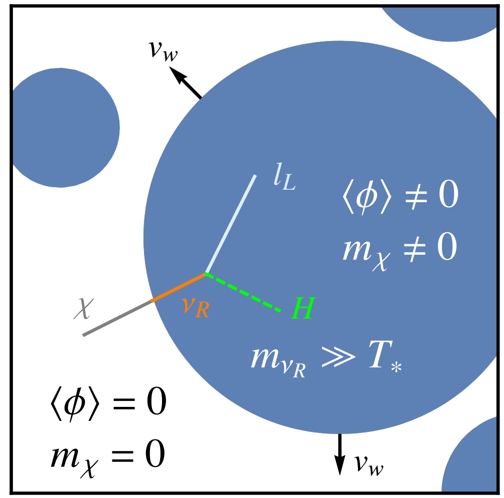
Previous work:

Mass-gain: $\phi\bar{\nu}_R^c\nu_R$



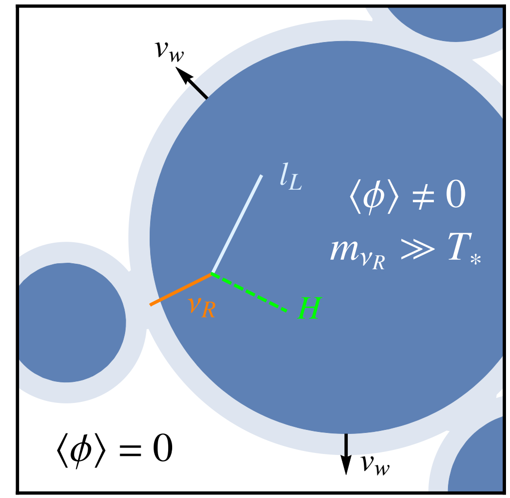
Huang and **KPX**, JHEP 09 (2022) 052

Light-to-heavy: $\phi\bar{\chi}_L\nu_R$



Azatov *et al*, JHEP 10 (2021) 043

Bubble collisions



Cataldi *et al*, JCAP 11 (2024) 047

- New physics scalar ϕ with $T_* \gtrsim 10^7$ GeV
- Supercooling $T_* \ll w_*$, and $\gamma_w \gg 1$ driven by large vacuum energy

Bubble-assisted leptogenesis

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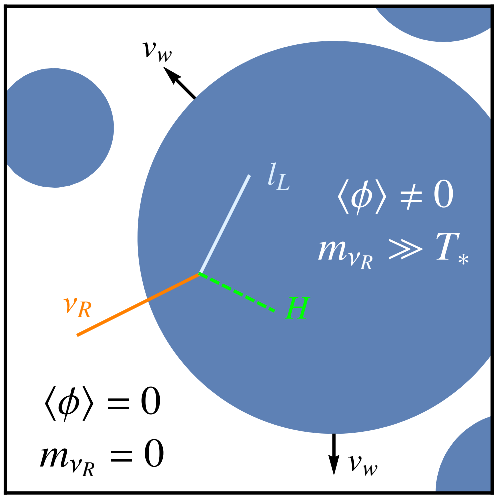

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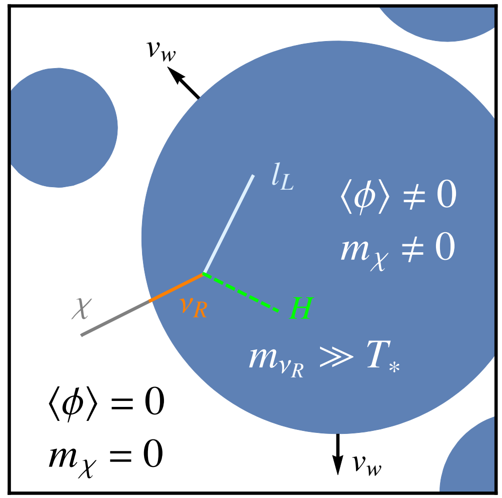

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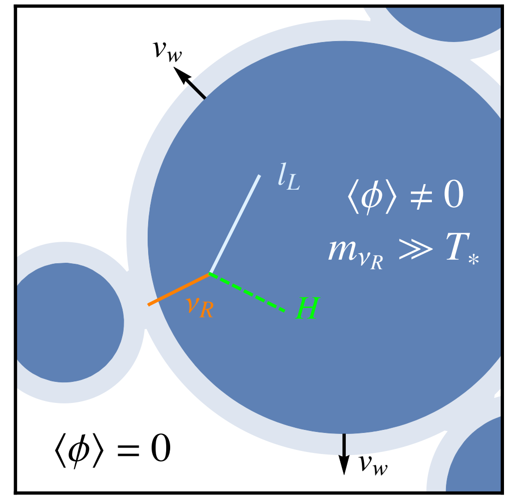
Bubble collisions



Cataldi *et al*, JCAP 11 (2024) 047

- New physics scalar ϕ with $T_* \gtrsim 10^7$ GeV
- Supercooling $T_* \ll w_*$, and $\gamma_w \gg 1$ driven by large vacuum energy

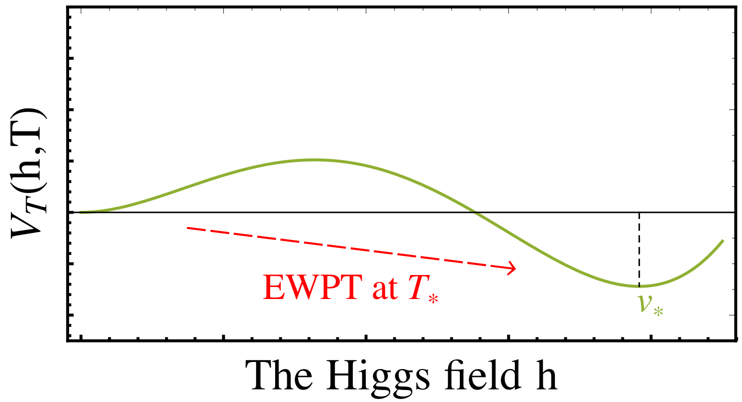
This work:

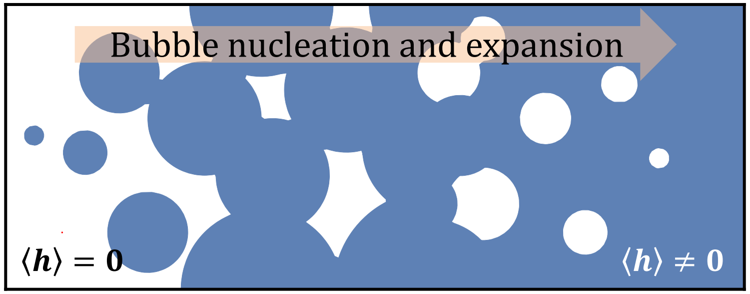
- The SM Higgs h with an EW phase transition at $T_* \sim 10^2$ GeV
- NOT a supercooled transition, but with $\gamma_w \gg 1$

Leptogenesis from an EWPT

A first-order EWPT: triggered by physics beyond the SM

See for example Wang *et al*, Phys.Rev.D 87 (2013) 2, 023509





Fatal difficulty

- EW sphaleron $\mathcal{O}_{\rm eff} = \prod_i \left[\bar{q}_L^{c,i} q_L^i\right]\left[\bar{\ell}_L^{c,i} \ell_L^i\right]$ Kuzmin *et al*, Phys.Lett.B 155 (1985) 36
- Reaction rate $\propto e^{-8\pi\langle h\rangle/(g_W T_*)}$
- Inside the bubble $\langle h \rangle \sim T_*$
- Suppression $\propto e^{-38.8} \approx 10^{-17} \ll 1$
- $Y_L \to Y_B$ forbidden!!

Leptogenesis from an EWPT

A first-order EWPT: triggered by physics beyond the SM

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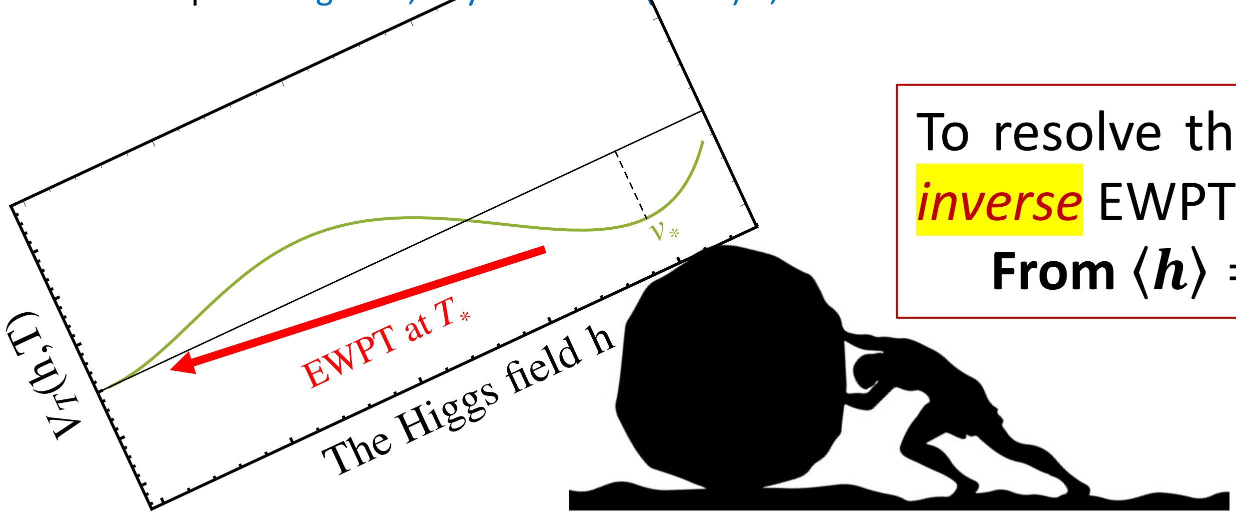

To resolve this, we consider an *inverse* EWPT:

From $\langle h \rangle \neq 0$ to $\langle h \rangle = 0$!

Fatal difficulty

- EW sphaleron $\mathcal{O}_{\text{eff}} = \prod_i [\bar{q}_L^{c,i} q_L^i][\bar{\ell}_L^{c,i} \ell_L^i]$ Kuzmin *et al*, Phys.Lett.B 155 (1985) 36
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Vectorlike lepton (VLL)

Color singlet Dirac fermions

$$F = \begin{pmatrix} F^0 \\ F^- \end{pmatrix} \sim \mathbf{2}_{-1/2}; \quad N \sim \mathbf{1}_0; \quad E \sim \mathbf{1}_{-1}$$

Same charge with ℓ_L Pure singlet Same charge with e_R

Free particle Lagrangain

$$\bar{F}(i\gamma^\mu D_\mu - m_F)F + \bar{N}(i\gamma^\mu \partial_\mu - m_N)N + \bar{E}(i\gamma^\mu D_\mu - m_E)E$$

Gauge kinetic Bare mass term

Yukawa couplings

$$-y_{N_L}\bar{F}_R\tilde{H}N_L - y_{N_R}\bar{F}_L\tilde{H}N_R - y_{E_L}\bar{F}_R H E_L - y_{E_R}\bar{F}_L H E_R$$

After the EWSB: transforming to mass eigenstates

$$(F^0, N) \to (N_1, N_2); (F^-, E) \to (E_1, E_2)$$

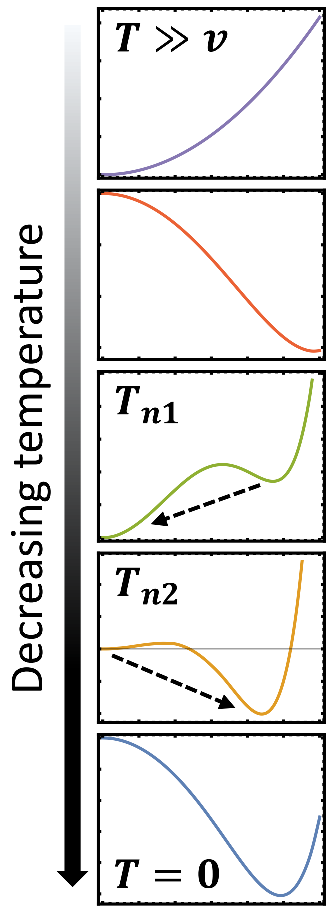
Neutral VLLs Charged VLLs

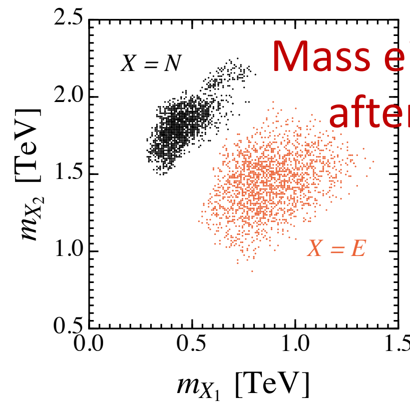
Sizable $y_{N_{L,R}}$ and $y_{E_{L,R}}$: significantly affect the Higgs thermal behavior

The thermal history

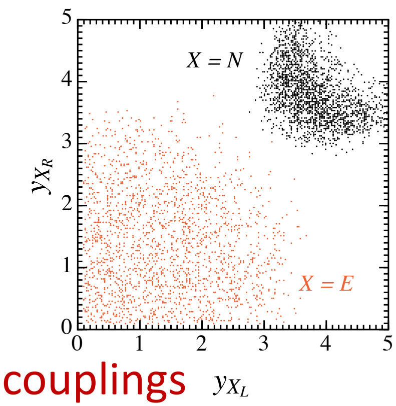
Coupling to the SM Higgs field

$$-y_{N_L}\bar{F}_R\widetilde{H}N_L - y_{N_R}\bar{F}_L\widetilde{H}N_R - y_{E_L}\bar{F}_RHE_L - y_{E_R}\bar{F}_LHE_R$$



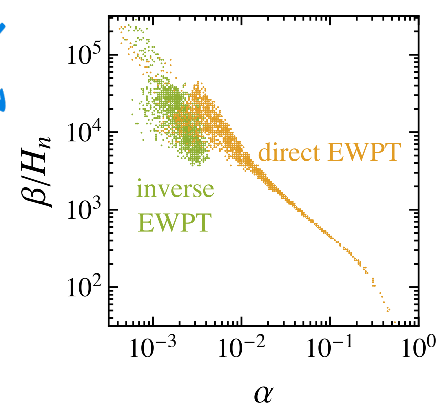


Mass eigenstates after EWSB



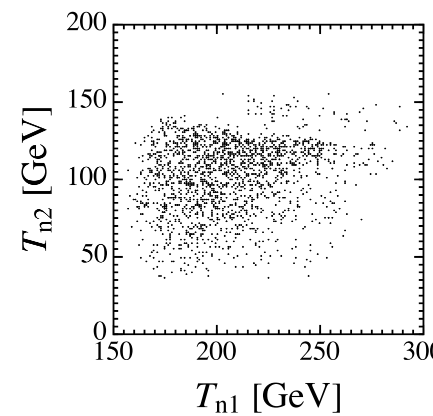
Yukawa couplings

(Hubble time)/(Transition duration)



(Latent heat)/(Radiation energy)

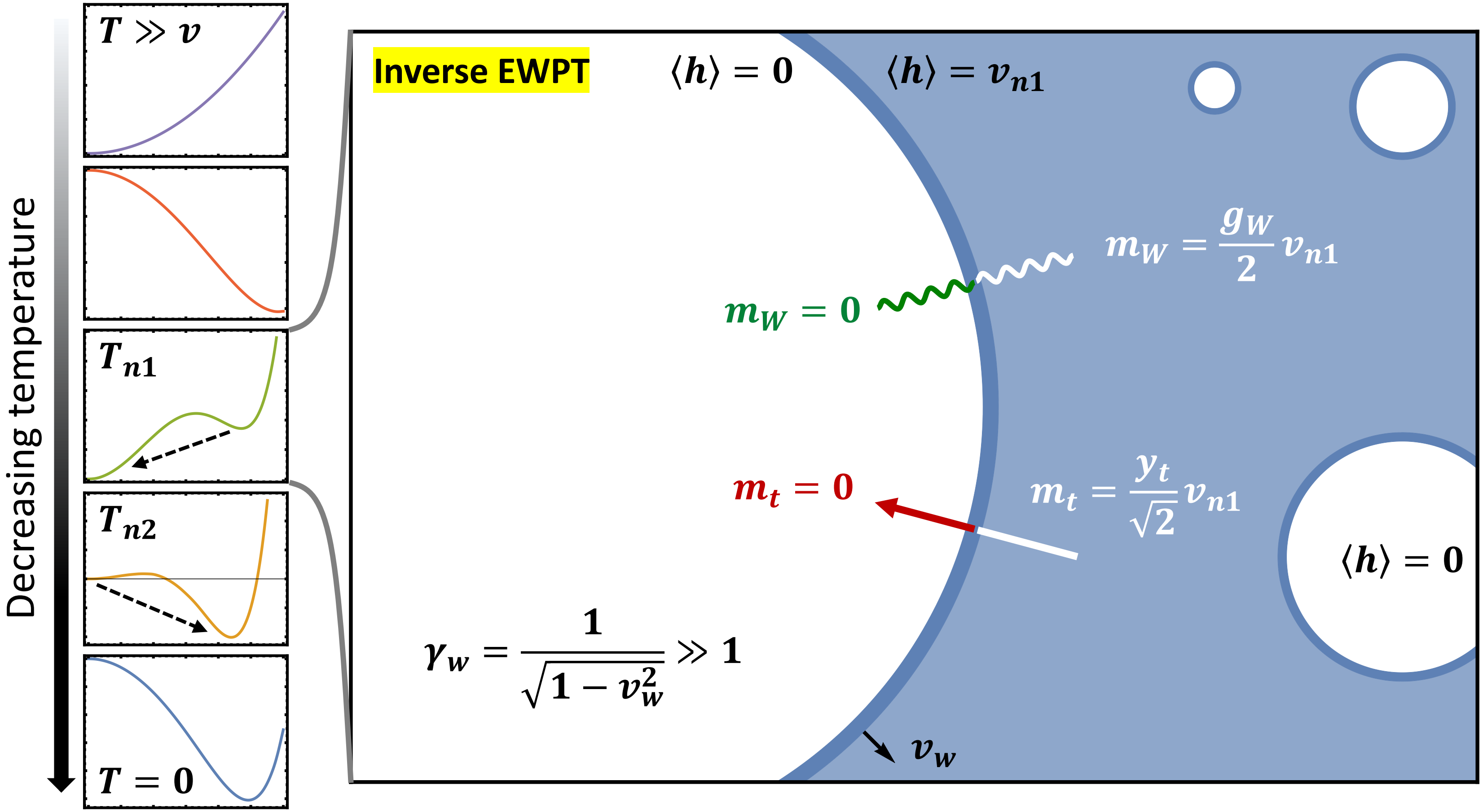
Direct EWPT



Inverse EWPT

The inverse EWPT

Not supercooled ($T_{n1} \approx v_{n1}$), but features relativistic bubble walls



SM particles *aspirated* by the bubble, $v_w \approx 1$

Quantitatively, $\gamma_w \sim 300$ Azatov *et al*, JHEP 12 (2024) 056

The 2nd-generation: VLL′

Higgs portal: $-y'_{N_L}\bar{F}'_R\widetilde{H}N'_L - y'_{N_R}\bar{F}'_L\widetilde{H}N'_R - y'_{E_L}\bar{F}'_R H E'_L - y'_{E_R}\bar{F}'_L H E'_R$

$U(1)_{B-L}$-breaking: $-\frac{\mu_N}{2}\bar{N}'_L N'^c_L - \lambda_N \bar{F}'_L\widetilde{H}N'^c_L$

SM lepton interactions: $-\sum_\alpha y_D^\alpha \bar{\ell}_L^\alpha \widetilde{H}N'_R - \sum_\alpha \mu_D^\alpha \bar{\ell}_L^\alpha F'_R - \sum_\alpha \lambda_D^\alpha \bar{\ell}_L^\alpha H E'_R$

SM lepton doublet

$\alpha = e, \mu, \tau$

Reminder:

$$F' = \begin{pmatrix} F'^0 \\ F'^- \end{pmatrix} \sim \mathbf{2}_{-1/2}; \quad N' \sim \mathbf{1}_0; \quad E' \sim \mathbf{1}_{-1}$$

Same charge with ℓ_L — Pure singlet — Same charge with e_R

The 2nd-generation: VLL′

Higgs portal: $-\, y'_{N_L}\bar{F}'_R\widetilde{H}N'_L - y'_{N_R}\bar{F}'_L\widetilde{H}N'_R - y'_{E_L}\bar{F}'_R H E'_L - y'_{E_R}\bar{F}'_L H E'_R$

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After EWSB, let $N'_R \to \nu_R^1$, $F'^0_R \to \nu_R^2$, and $N'_L \to S_L^1$, $F'^0_L \to S_L^2$

$$-\frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{\nu}_R^c & \bar{S}_L\end{pmatrix}\begin{pmatrix}0_{3\times3} & m_D & 0_{3\times2}\\ m_D^T & 0_{2\times2} & M_R\\ 0_{2\times3} & M_R^T & \mu\end{pmatrix}\begin{pmatrix}\nu_L^c\\ \nu_R\\ S_L^c\end{pmatrix}$$

ν_L^α, with $\alpha = e, \mu, \tau$
ν_R^i and S_L^i, with $i = 1{,}2$

Mass matrices $m_D^{\alpha i} = \begin{pmatrix}\frac{y_D^\alpha v}{\sqrt{2}} & \mu_D^\alpha\end{pmatrix}$, $M_R^{ij} = \begin{pmatrix} m'_N & \frac{y'_{N_R} v}{\sqrt{2}}\\ \frac{y'_{N_L} v}{\sqrt{2}} & m'_F\end{pmatrix}$, and $\mu_{ij} = \begin{pmatrix}\mu_N & \frac{\lambda_N v}{\sqrt{2}}\\ \frac{\lambda_N v}{\sqrt{2}} & 0\end{pmatrix}$

The 2nd-generation: VLL′

Higgs portal: $-y'_{N_L}\bar{F}'_R\widetilde{H}N'_L - y'_{N_R}\bar{F}'_L\widetilde{H}N'_R - y'_{E_L}\bar{F}'_R H E'_L - y'_{E_R}\bar{F}'_L H E'_R$

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SM lepton interactions: $-\sum_\alpha y^\alpha_D \bar{\ell}^\alpha_L \widetilde{H}N'_R - \sum_\alpha \mu^\alpha_D \bar{\ell}^\alpha_L F'_R - \sum_\alpha \lambda^\alpha_D \bar{\ell}^\alpha_L H E'_R$

After EWSB, let $N'_R \to \nu^1_R$, $F'^0_R \to \nu^2_R$, and $N'_L \to S^1_L$, $F'^0_L \to S^2_L$

$$-\frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{\nu}^c_R & \bar{S}_L\end{pmatrix}\begin{pmatrix}0_{3\times3} & m_D & 0_{3\times2}\\ m_D^T & 0_{2\times2} & M_R \\ 0_{2\times3} & M_R^T & \mu\end{pmatrix}\begin{pmatrix}\nu^c_L\\ \nu_R \\ S^c_L\end{pmatrix}$$

ν^α_L, with $\alpha = e,\mu,\tau$
ν^i_R and S^i_L, with $i = 1,2$

Mass matrices $m^{\alpha i}_D = \begin{pmatrix}\frac{y^\alpha_D v}{\sqrt{2}} & \mu^\alpha_D\end{pmatrix}$, $M^{ij}_R = \begin{pmatrix} m'_N & \frac{y'_{N_R}v}{\sqrt{2}} \\ \frac{y'_{N_L}v}{\sqrt{2}} & m'_F\end{pmatrix}$, and $\mu_{ij} = \begin{pmatrix}\mu_N & \frac{\lambda_N v}{\sqrt{2}} \\ \frac{\lambda_N v}{\sqrt{2}} & 0\end{pmatrix}$

Minimal inverse seesaw Xing *et al*, Phys. Lett. B 679 (2009) 242–248

- Lightest SM ν massless, and $m_\nu \sim 0.1\ \mathrm{eV}\times\left(\frac{m_D}{\mathrm{GeV}}\right)^2\left(\frac{\mu}{0.1\ \mathrm{MeV}}\right)\left(\frac{\mathrm{TeV}}{M_R}\right)^2$
- Near-degenerate heavy Majorana neutrinos χ with $m_\chi \sim M_R \pm \frac{\mu}{2}$

The 2[nd]-generation: VLL′

Higgs portal: $-y'_{N_L}\bar{F}'_R\widetilde{H}N'_L - y'_{N_R}\bar{F}'_L\widetilde{H}N'_R - y'_{E_L}\bar{F}'_R H E'_L - y'_{E_R}\bar{F}'_L H E'_R$

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SM lepton interactions: $-\sum_\alpha y^\alpha_D \bar{\ell}^\alpha_L \widetilde{H}N'_R - \sum_\alpha \mu^\alpha_D \bar{\ell}^\alpha_L F'_R$ $-\sum_\alpha \lambda^\alpha_D \bar{\ell}^\alpha_L H E'_R$

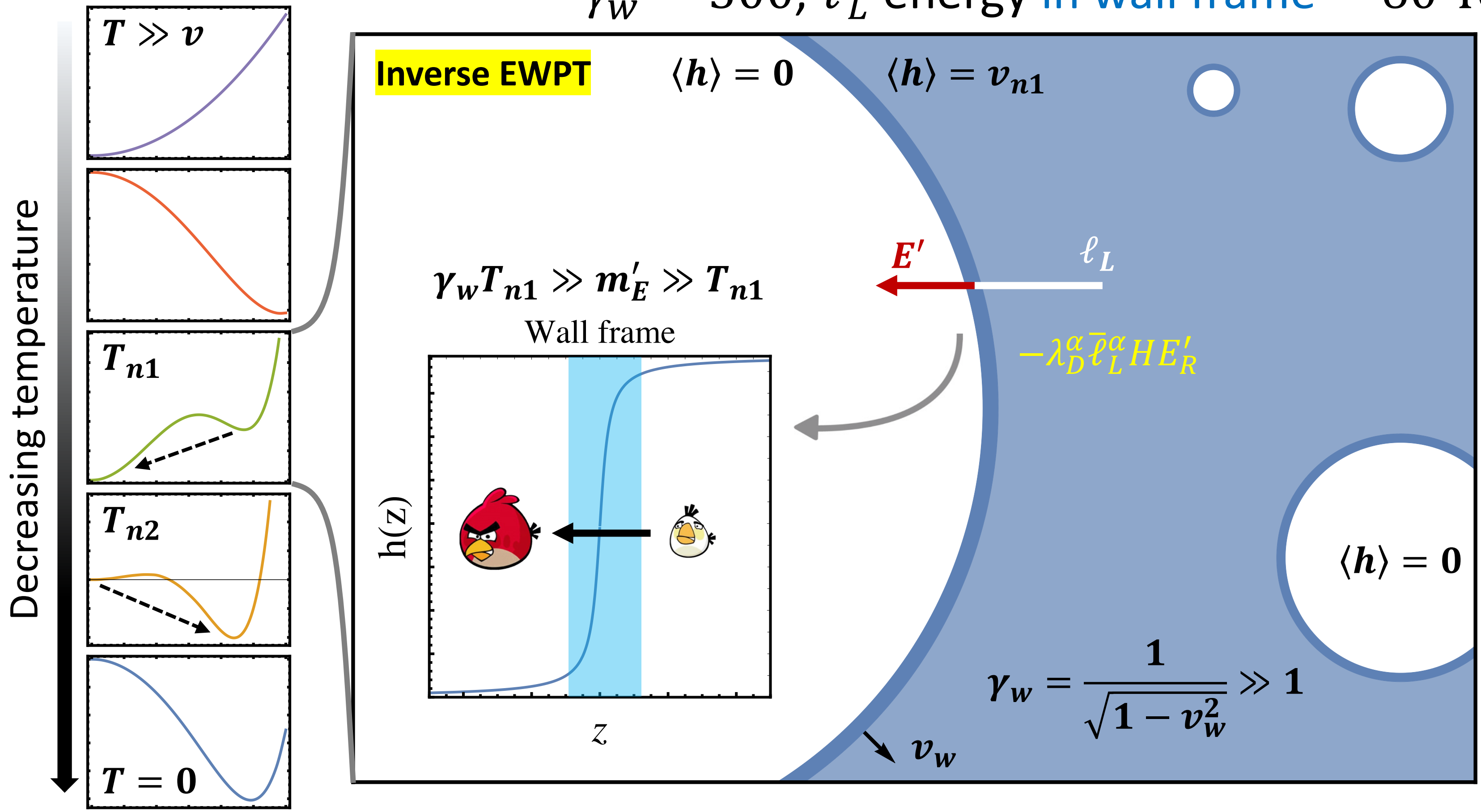
Neutrino mass origin

Crucial for RHN production

Bubble-assisted leptogenesis

Light-to-heavy transition of $\ell_L \to E'_R$ on the wall

$\gamma_w \sim 300$, ℓ_L energy in wall frame ~ 60 TeV

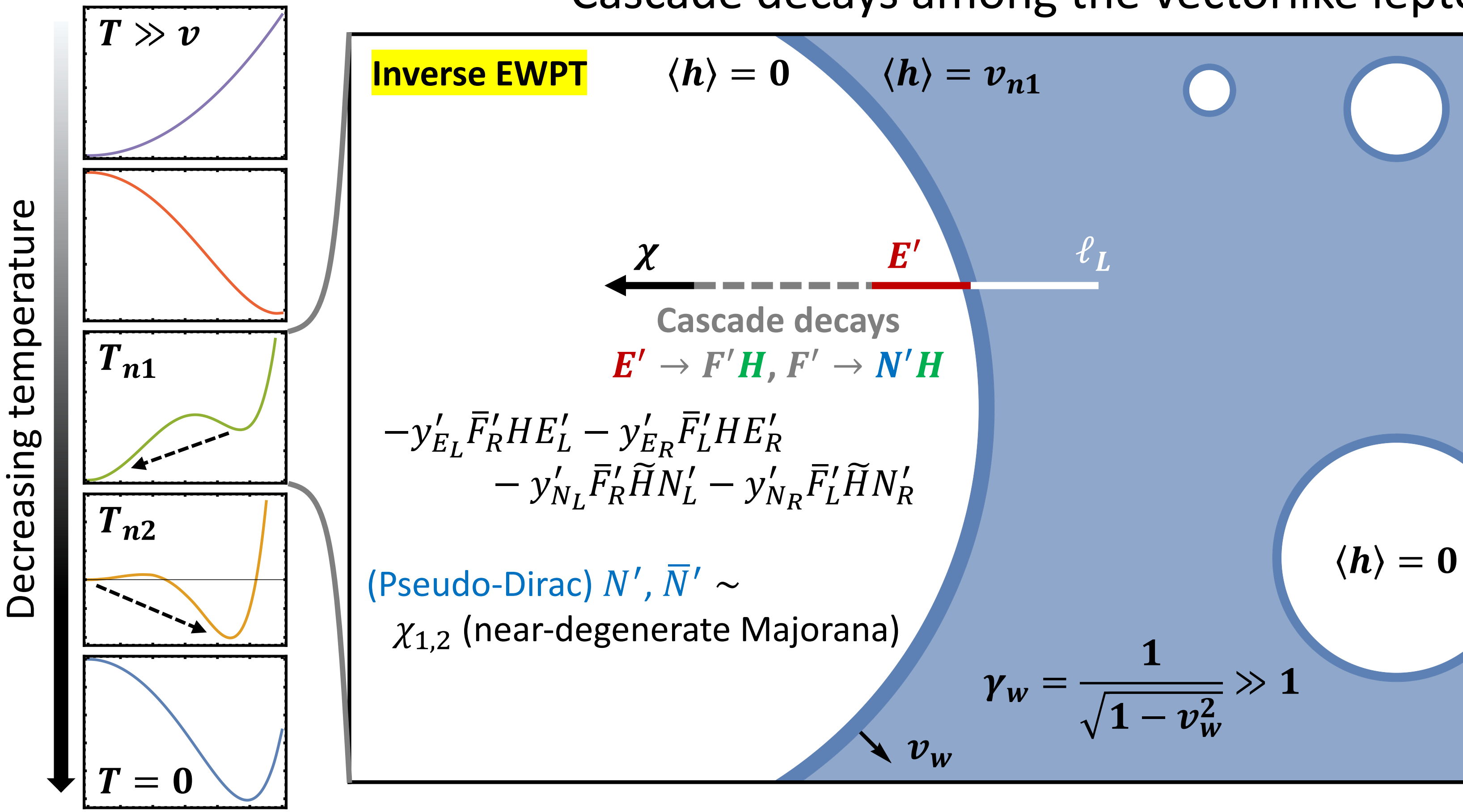


Calculated by the Higgs background field theory Bodeker *et al*, JCAP 05 (2017) 025

Bubble-assisted leptogenesis

Assuming a mass hierarchy $m'_E > m'_F > m'_N$

Cascade decays among the vectorlike leptons

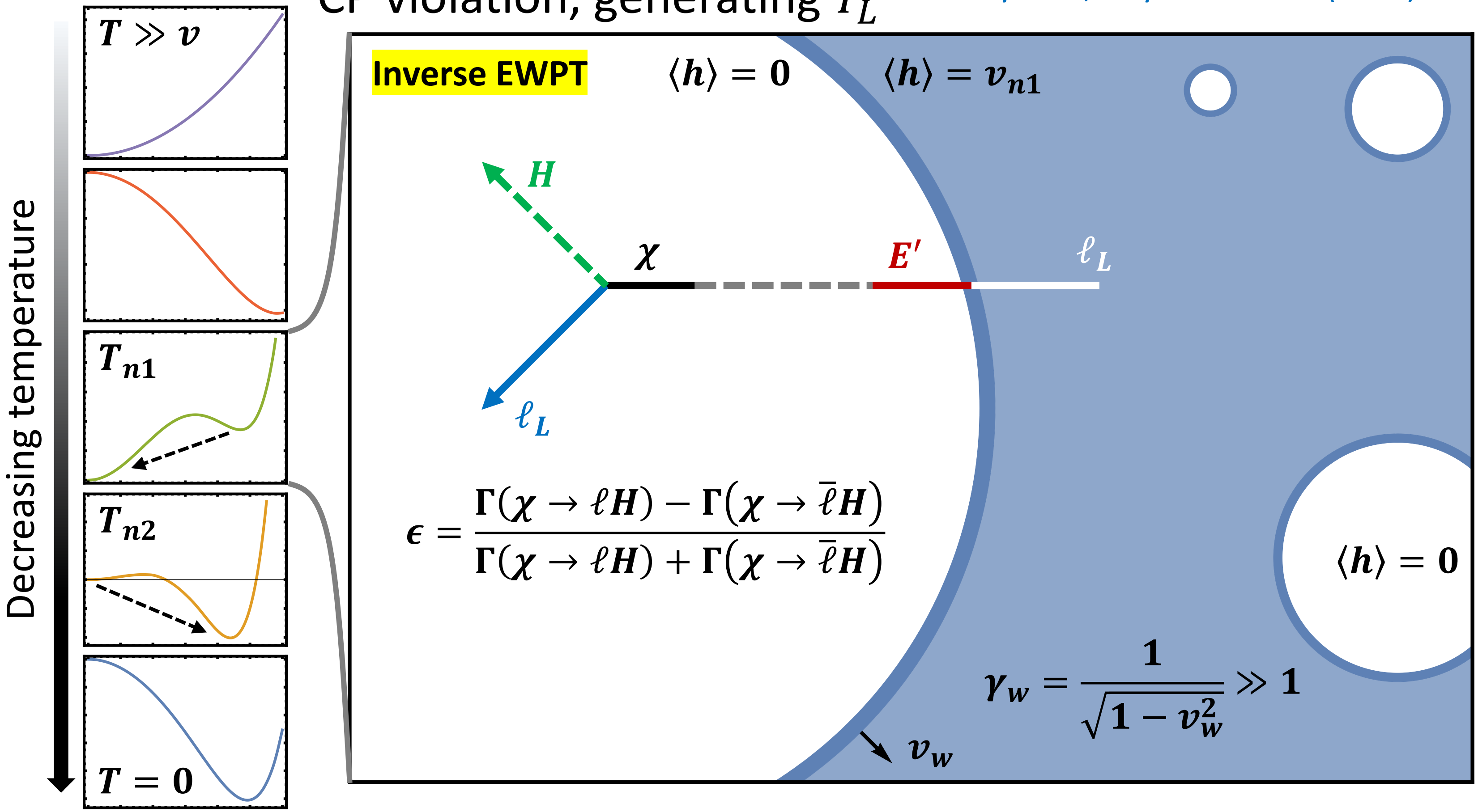


End of the vectorlike lepton decay chain: lightest Majorana $\chi_{1,2}$

Bubble-assisted leptogenesis

$m_\chi \gg T_{n1}$, **instant decay** of $\chi \to \ell H / \bar{\ell} H^*$ via seesaw vertices

CP violation, generating Y_L Adhikary *et al*, Phys. Rev. D 93 (2016) 113001

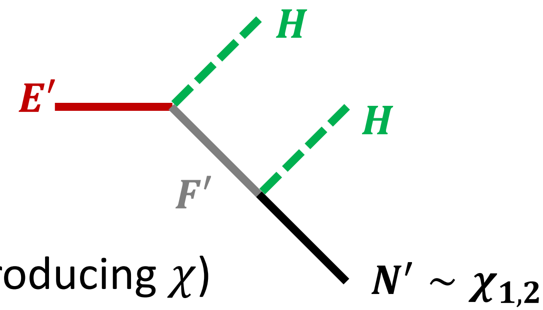


Active EW sphaleron inside the bubble: $Y_L \to Y_B$

χ far away from equilibrium, no thermal washout effects

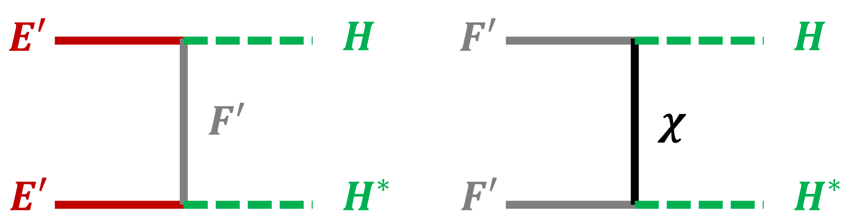
Check list (1)

After the charged VLL production, we want this process

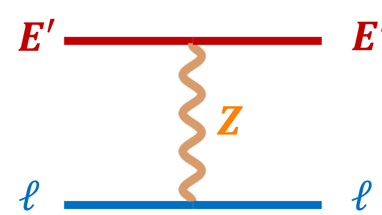


Cascade decay (producing χ)

Not the following processes



Annihilation (no χ produced)

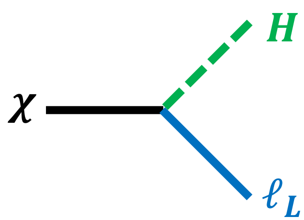


Thermalization
(no χ produced)

Easy to satisfy, as the $1 \to 2$ process has larger phase space

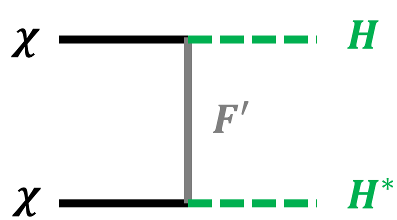
Check list (2)

For the Majorana RHN χ, we want this process



CP-violating decay from seesaw vertices $\sim \mathcal{O}(10^{-5})$
(generating Y_L and then Y_B)

Not the following process



Annihilation from $y'_{N_{L,R}} \sim \mathcal{O}(1)$
(no Y_L generated)

Not easy to satisfy! Need careful check

Yukawa enhancement

- The reason of choosing **inverse seesaw** instead of type-I seesaw
- The reason of first producing E' and then decaying to χ

The direct production rate of χ is too low

Parameter space

Baryon asymmetry generated

Decay asymmetry χ produced via EWPT (inherits from E')

$$Y_B \approx -\frac{28}{79}\epsilon f_{\rm dec}\frac{n_{E'}^{\rm trans.}}{s(T_{n1})}\exp\left\{-\int_{m_N'/T_{n1}}^{m_N'/T_{n2}}\frac{z'^4 dz'}{s(m_N')H(m_N')}\frac{\sum_i \gamma_{\chi_i}(z')}{2Y_\ell^{\rm eq}}\right\}$$

$Y_L \to Y_B$ factor   Fraction of decay   Thermal washout, suppressed by $m_N' \gtrsim 20T_{n1}$

The the decay products ℓ & H thermalize, and experience inverse decay $\ell H \to \chi \to \bar{\ell} H^*$

Need $m_N' \gtrsim 20T_{n1} \sim 4$ TeV to suppress this

Parameter space

Baryon asymmetry generated

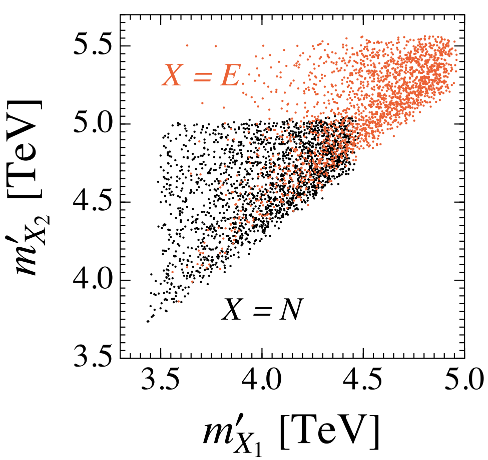
Decay asymmetry — χ produced via EWPT (inherits from E')

$$Y_B \approx -\frac{28}{79}\epsilon f_{\rm dec}\frac{n_{E'}^{\rm trans.}}{s(T_{n1})}\exp\left\{-\int_{m_N'/T_{n1}}^{m_N'/T_{n2}}\frac{z'^4 dz'}{s(m_N')H(m_N')}\frac{\sum_i \gamma_{\chi_i}(z')}{2Y_\ell^{\rm eq}}\right\}$$

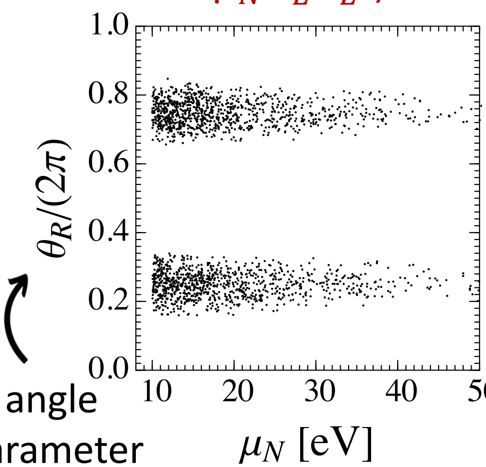
$Y_L \to Y_B$ factor — Fraction of decay — Thermal washout, suppressed by $m_N' \gtrsim 20T_{n1}$

- Casas-Ibarra: $m_D = U_{\rm PMNS} m_n^{1/2} R \mu^{-1/2} M_R^T$, yields oscillation data
- CP violation dominated by the new physics phase from $\mu^{-1/2}$

Mass eigenstates after EWSB

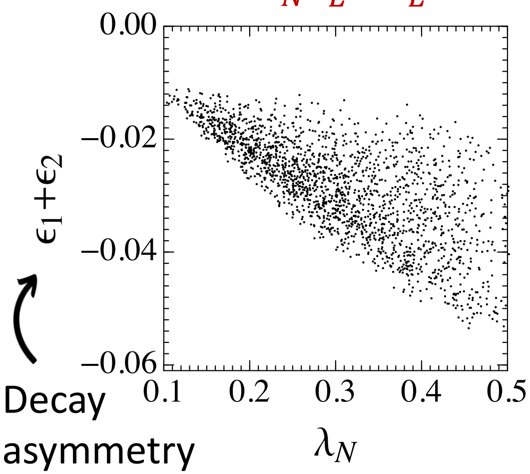


$-\mu_N \bar{N}_L' N_L'^c/2$



CI angle parameter

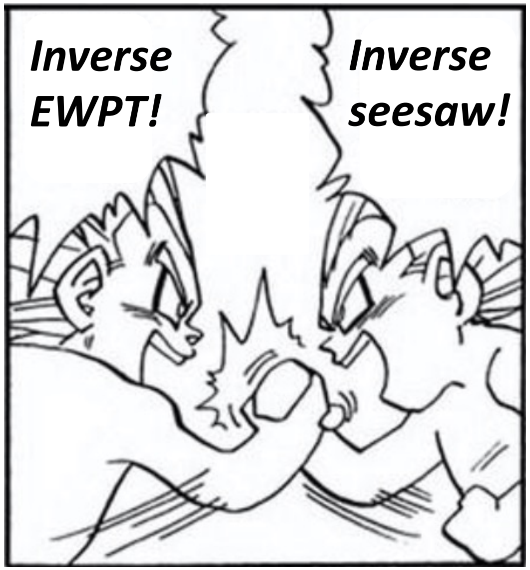
$-\lambda_N \bar{F}_L' \tilde{H} N_L'^c$



Decay asymmetry

Conclusion

A novel leptogenesis mechanism realized by the vectorlike leptons via the Higgs field ***electroweak phase transition***



1st-generation: F, N, and E

- Lighter mass $m_{F,N,E} \sim \text{TeV}$
- Stronger Yukawa $y_{N_{L,R}}, y_{E_{L,R}} \sim 3$
- Inverse EWPT: not supercooled, but $\gamma_w \gg 1$

2nd-generation: F', N', and E'

- Heavier mass $m'_{F,N,E} \sim 4\ \text{TeV}$
- Weaker Yukawa $y'_{N_{L,R}}, y'_{E_{L,R}} \sim 1$
- Inverse seesaw: neutrino mass origin and nonthermal **leptogenesis**

Phenomenology: Higgs measurement (e.g., $h \to \gamma\gamma$, $h \to \tau^+\tau^-$), heavy lepton searches, gravitational waves

Thank you!

Backup: particle production on the wall

In the wall frame, the E' flux injected to the bubble interior

$$J_{E'_R}^{\rm wall} = \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \underbrace{\frac{p^z}{p^0} \frac{1}{e^{\gamma_w(|\mathbf{p}|-v_w p^z)/T_{n1}}+1}}_{\tau_L \text{ flux hitting the wall}} \underbrace{\mathrm{d}\mathbb{P}_{\tau_L\to E'_R}(\mathbf{p})}_{\text{Transformation probability}}$$

According to background field theory

$$\mathrm{d}\mathbb{P}_{\tau_L\to E'_R}(\mathbf{p}) = \frac{1}{2p^z}\int \frac{\mathrm{d}^3 k}{2k^0}\delta(p^0-k^0)\delta^2(\mathbf{p}_\perp-\mathbf{k}_\perp)|\mathcal{M}|^2$$

In the plasma frame, the produced E' number density

$$n_{E'_R}^{\rm plasma} \approx 6.4\times 10^{-7}\times T_{n1}^3\left(\frac{\lambda_D^\tau}{0.1}\right)\left(\frac{v_{n1}}{T_{n1}}\right)^2\left(\frac{25T_{n1}}{m'_E}\right)^2$$

The produced χ density $n_\chi^{\rm in} \approx n_{E'_R}^{\rm plasma}$, with initial $Y_\chi^{\rm in} = n_\chi^{\rm in}/s(T_{n1})$