WHEN YOU SEE A FLYING COW…

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Beyond the SM, From Colliders to the Early Universe
May 29th, 2023

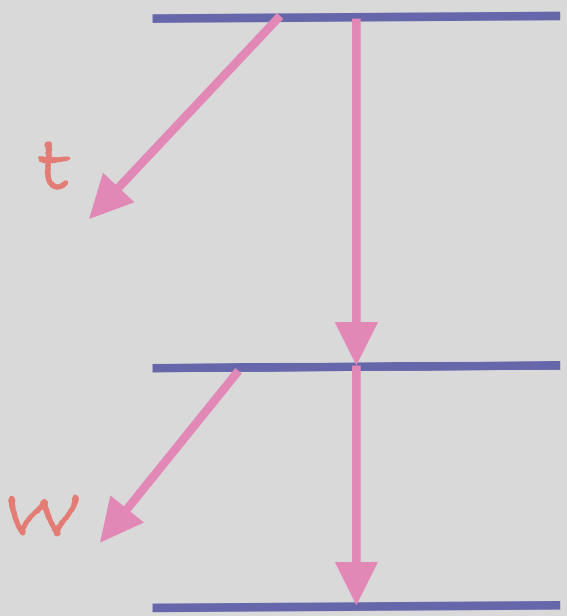

There is a flying cow!!


Are there any flying cows?
Yes!! Look! There is one!


But it is not 5 σ !
OK! Look! There is another one!!

Some of Flying Cows We Were Excited About

When you see a flying unicorn, you claim that is a flying cow….



$\tilde{t}_1 = \tilde{t}_R$;

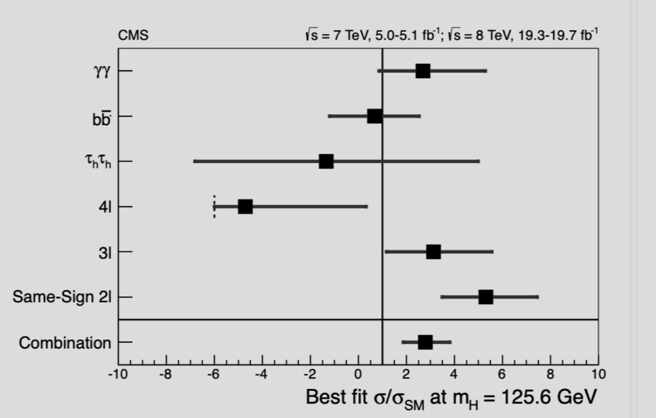
550 GeV, a signal strength for ss2l~ 2.83

$\tilde{\chi}_2^0 = \tilde{B}$;

No decay through a higgs
< 260 + 125, call it 340 GeV

$\tilde{\chi}_1^{\pm} = \tilde{W}^{\pm}$; $\tilde{\chi}_1^0 = \tilde{W}^0$;

260 GeV



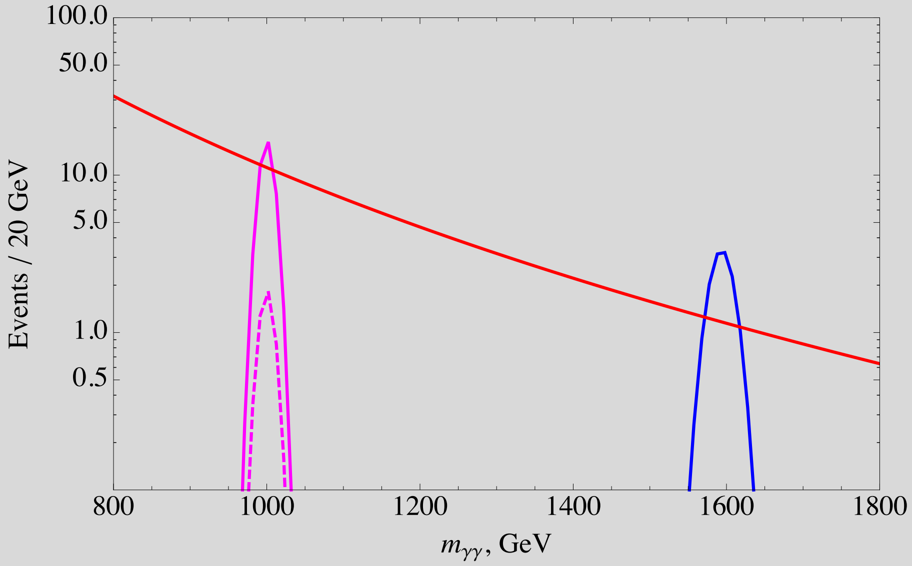
CMS 2014

$$\text{ATLAS} : \mu = 2.8^{+2.1}_{-1.9}$$

$$\text{CMS} : \mu = 5.3^{+2.1}_{-1.8}$$

PH, A. Ismail, I. Low, C. Wagner, 2015

The Fun Doubles with Marcela

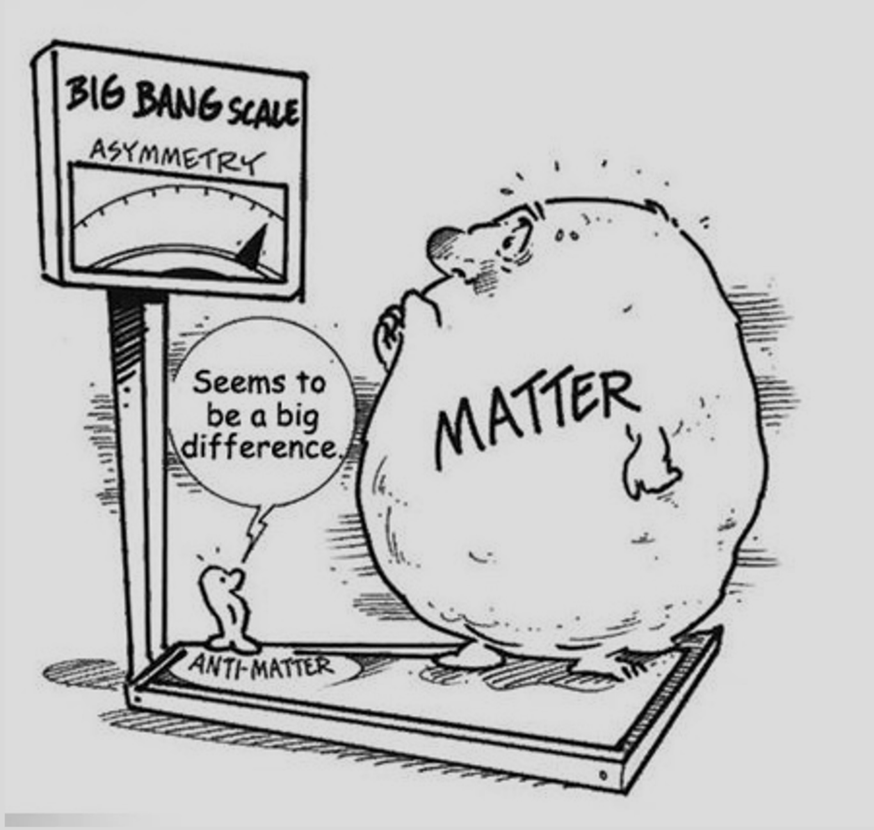


Carena, PH, A. Ismail, I. Low, N. Shah, C. Wagner, 2015


Well, now they are gone...
Incompetent people!!


So, are there flying cows?
Of course! There must be flying cows!!

There Must Be Flying Cows!!!



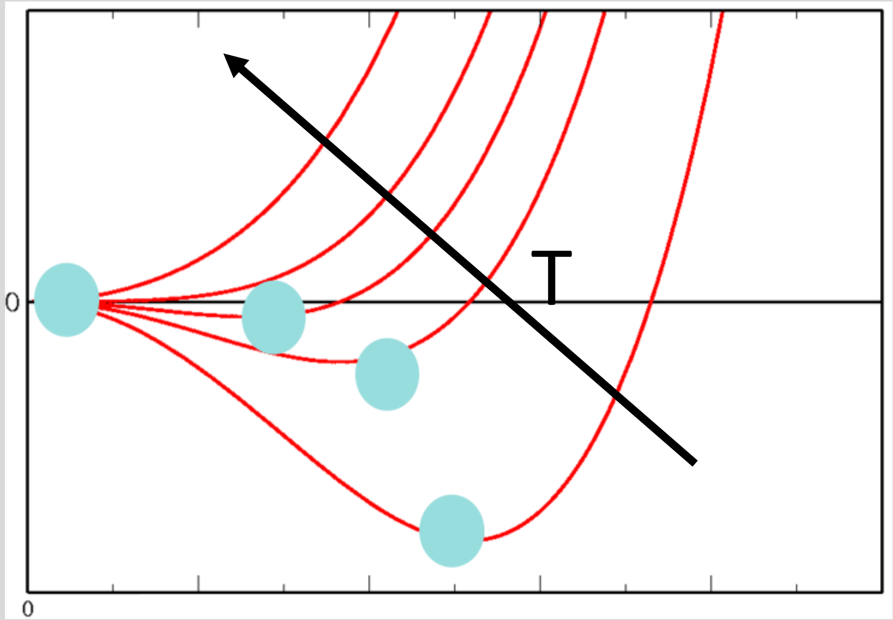
-- Baryon Number Violation
-- CP violation
-- Departure from thermal equilibrium – strong 1st order phase transitions

Sakharov, 1964

Baryon Asymmetry of the Universe (BAU)

There Must Be Flying Cows!!

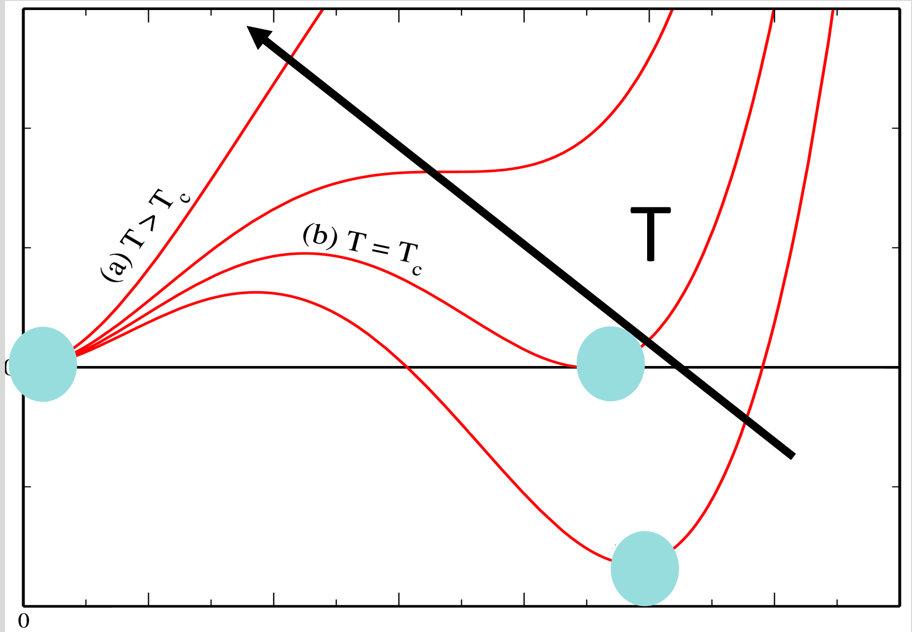
V(ϕ) SM



ϕ

1^{ST} order EWPT

V(ϕ)



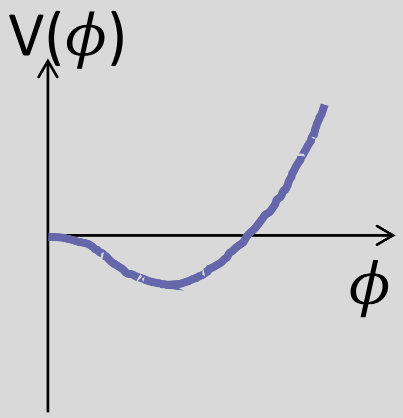
ϕ

Flying cows to generate a barrier

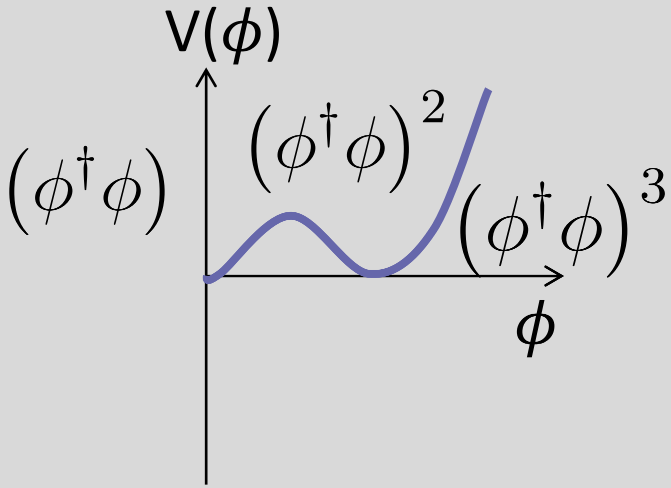
Generating the Barrier

Add non-renormalizable operators to the effective potential

$$V(\phi_h, T) = \frac{-m^2 + a_0 T^2}{2}\left(\phi_h^\dagger \phi_h\right) + \frac{\lambda_h}{4}\left(\phi_h^\dagger \phi_h\right)^2$$



SM



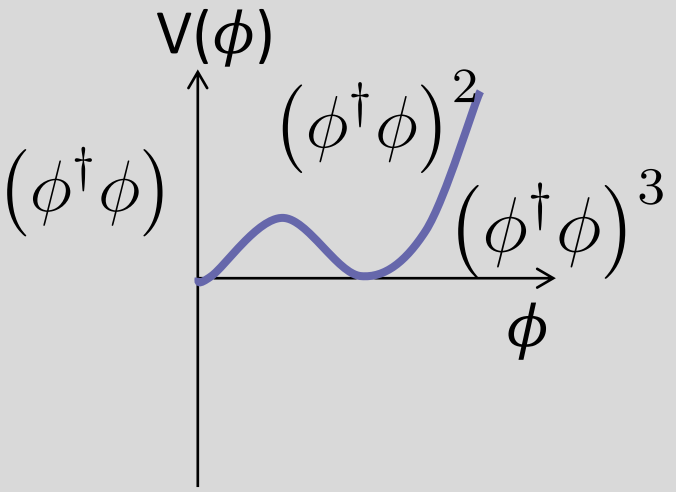
1^{ST} order EWPT

Generating the Barrier

Scalar Singlet,

$$V(\phi_h, \phi_s, T) = \frac{m_0^2 + a_0 T^2}{2}\phi_h^2 + \frac{\lambda_h}{4}\phi_h^4 + a_{hs}\phi_s\phi_h^2 + \frac{\lambda_{hs}}{2}\phi_s^2\phi_h^2 + t_s\phi_s + \frac{m_s^2}{2}\phi_s^2 + \frac{a_s}{3}\phi_s^3 + \frac{\lambda_s}{4}\phi_s^4$$

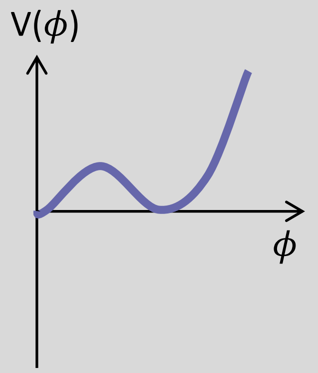
Integrate out the singlet,



$$V_{eff}(H,T) = \frac{m_0^2 + a_0 T^2}{2}H^2 + \left(\frac{\lambda_h}{4} - \frac{z}{2y} - \frac{2m^2 z}{3v^2}\right)H^4 + \left(\frac{8z^2 - 4yz\lambda_h + 3yz\lambda_{hs}}{6v^2 y}\right)H^6.$$

Generates the Barrier

Generates the Barrier



$$\mathcal{L}_{VLL} = \overline{L}(i\gamma_\mu D_L^\mu - m_L)L + \overline{E}'(i\gamma_\mu D_E^\mu - m_E)E' + \overline{N}'(i\gamma_\mu D_N^\mu - m_N)N' - \left[\overline{L}\,H\,(y_{E_L}\mathbb{P}_L + y_{E_R}\mathbb{P}_R)\,E' + \overline{L}\,\widetilde{H}\,(y_{N_L}\mathbb{P}_L + y_{N_R}\mathbb{P}_R)\,N' + \text{h.c.}\right],$$

$$L_{L,R} = \begin{pmatrix} N \\ E \end{pmatrix}_{L,R} \sim (1,2,Y), \quad N'_{L,R} \sim (1,1,Y+\frac{1}{2}), \quad E'_{L,R} \sim (1,1,Y-\frac{1}{2}),$$

$$\begin{aligned} 16\pi^2\mathcal{L}_H^{\text{CP}} \supset &+ \left(-\frac{4}{3} + 2\log\frac{\mu^2}{m^2}\right)\left(|y_N|^2 + |y_E|^2\right)|D_\mu H|^2 \\ &- \left(1 + 3\log\frac{\mu^2}{m^2}\right)\left(|y_N|^2 + |y_E|^2\right)m^2\,\boxed{|H|^2} \\ &+ \left(\frac{16}{3} + 2\log\frac{\mu^2}{m^2}\right)\left(|y_N|^4 + |y_E|^4\right)\boxed{|H|^4}, \\ &- \frac{2\left(|y_N|^6 + |y_E|^6\right)}{15m^2}\boxed{\mathcal{O}_6} \end{aligned}$$

Generates the barrier!!

A. Angelescu, and PH, 2020

S. Ellis, J. Quevillon, P. Vuong, T. You, and Z. Zhang, 2020

How to Look For the Flying Cows?

$$V(\phi, T) = \frac{m^2 + a_0 T^2}{2}\left(\phi^\dagger \phi\right) + \frac{\lambda}{4}\left(\phi^\dagger \phi\right)^2 + \frac{c_6}{8\Lambda^2}\left(\phi^\dagger \phi\right)^3$$

$$\lambda_3 = \left.\frac{\partial^3 V}{\partial \phi^3}\right|_{\phi = v} = \frac{3m_h^2}{v}\left(1 + \frac{2c_6 v^4}{m_h^2 \Lambda^2}\right)$$

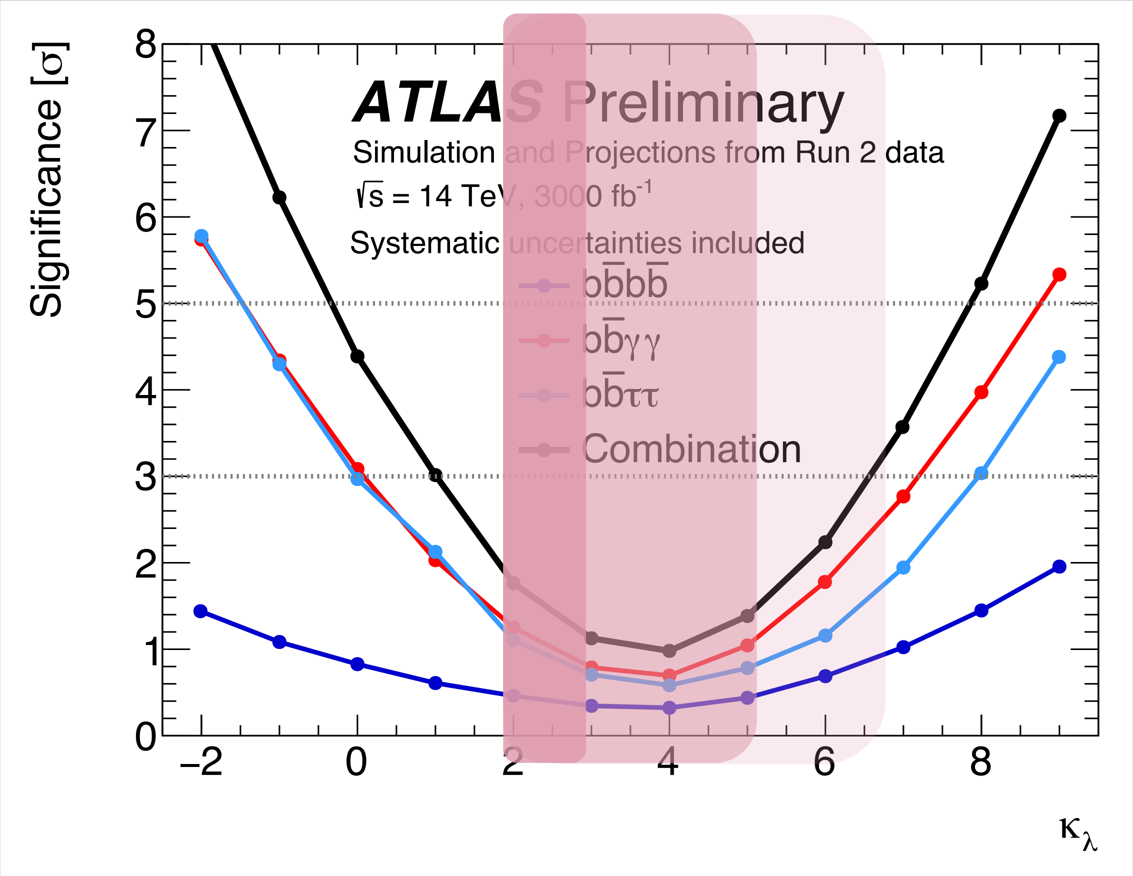
Critical temperature $$T_c^2 = \frac{3c_6}{4\Lambda^2 a_0}\left(v^2 - v_c^2\right)\left(v^2 - \frac{v_c^2}{3}\right).$$

vev at T_c $$\left(\phi_c^\dagger \phi_c\right) = v_c^2 = -\frac{\lambda \Lambda^2}{c_6}.$$

Requiring first order phase transition

$$\frac{5}{3}\lambda_3^{SM} < \lambda_3 < 3\lambda_3^{SM}$$

Collider Probes – Double Higgs Production



$$V(\phi,T) = \frac{m^2 + a_0 T^2}{2}\left(\phi^\dagger\phi\right) + \frac{\lambda}{4}\left(\phi^\dagger\phi\right)^2 + \frac{c_6}{8\Lambda^2}\left(\phi^\dagger\phi\right)^3$$

$$\boxed{\frac{5}{3} < \kappa_\lambda < 3}$$

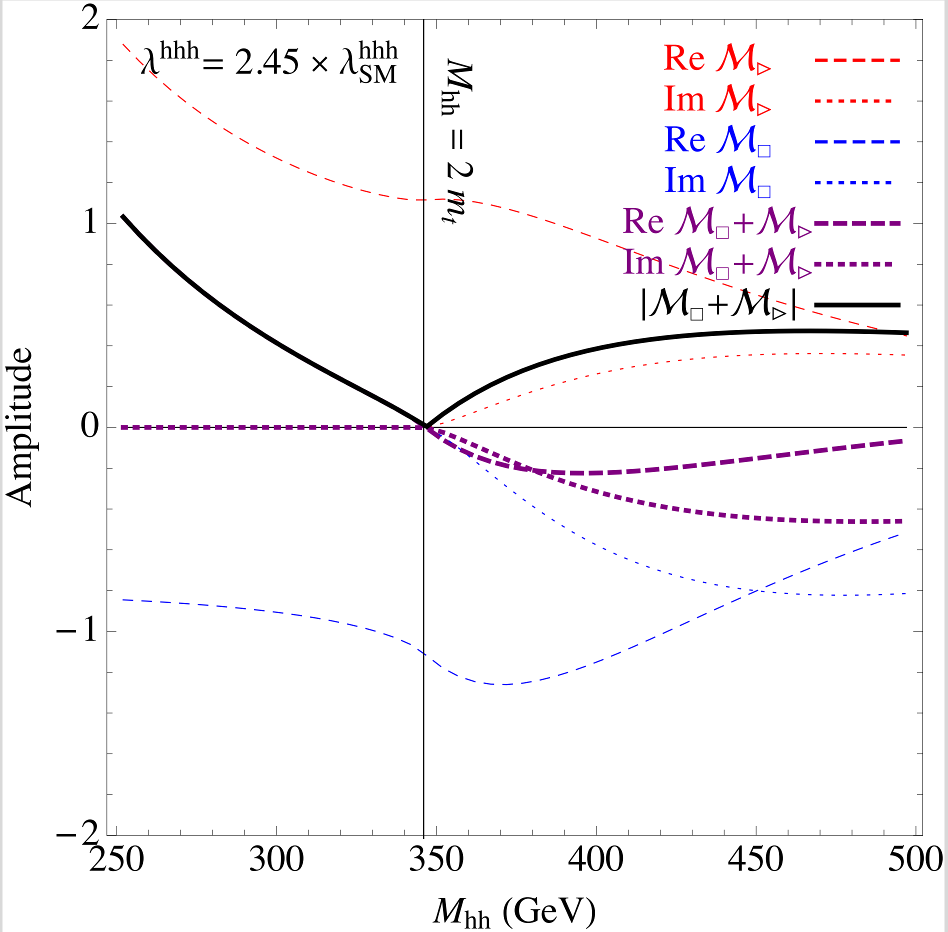
$$V(\phi,0) = \frac{m^2}{2}(\phi^\dagger\phi) + \frac{\lambda}{4}(\phi^\dagger\phi)^2 + \sum_{n=1}^{\infty} \frac{c_{2n+4}}{2^{(n+2)}\Lambda^{2n}}\left(\phi^\dagger\phi\right)^{n+2}$$

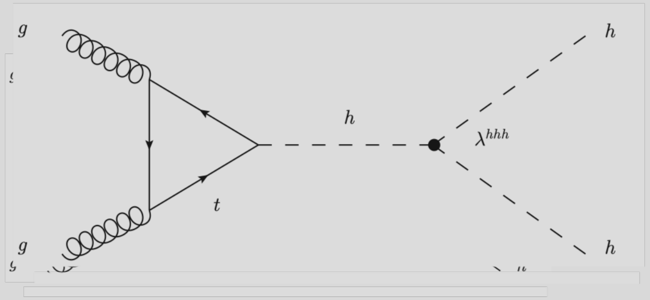
$$\boxed{\lambda_3^{max} \sim 7\lambda_3^{SM}}$$

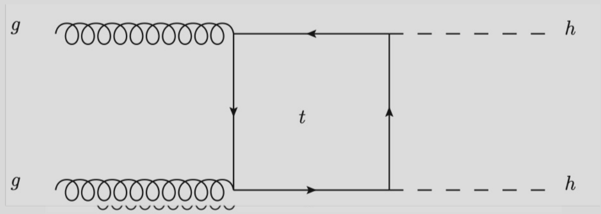
The LHC has a very limited sensitivity in the region where the EWPT can be strongly-first-order.

PH, A. Joglekar, B. Li, and C. Wagner. 2015

Limited sensitivity with large λ_3





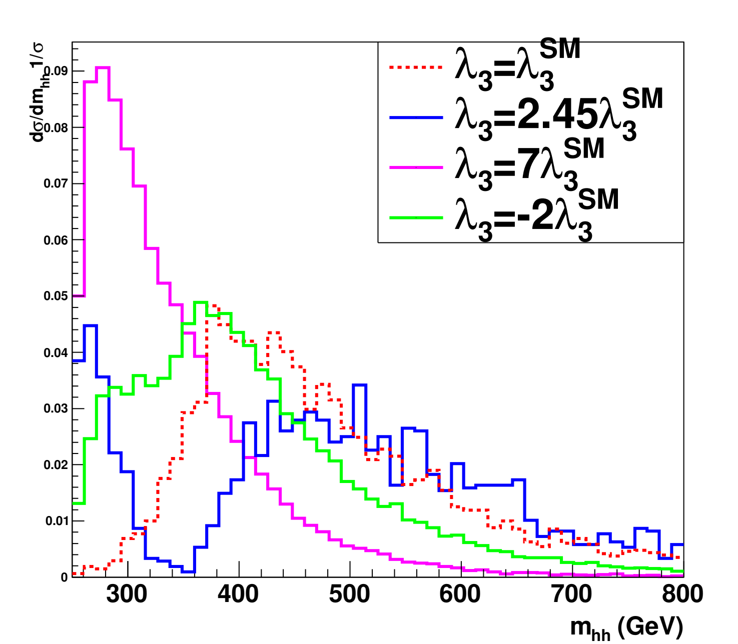


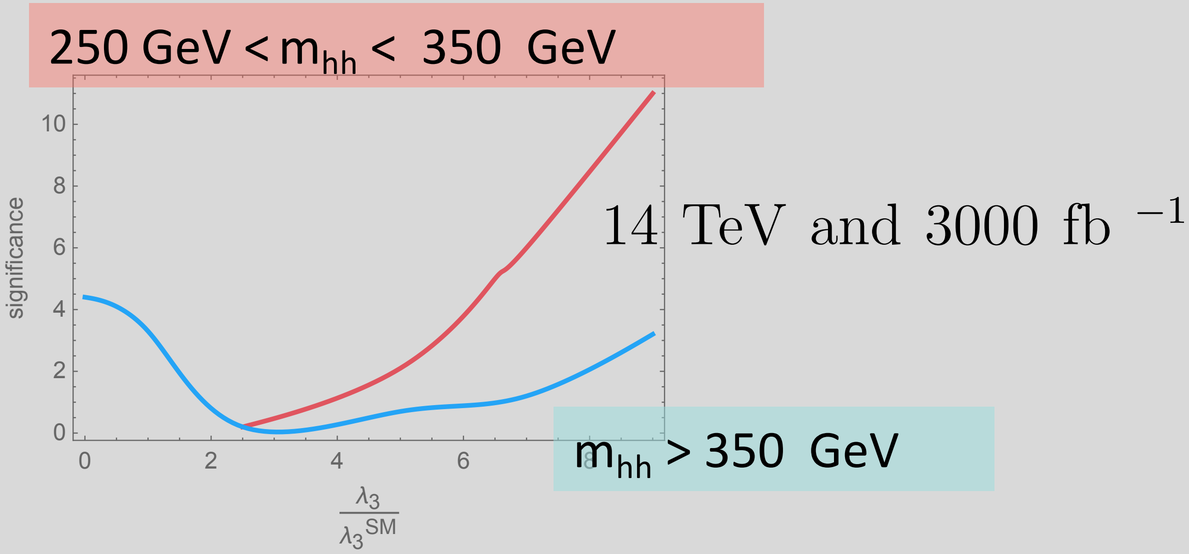
- The destructive interference occurs between the real part of the triangle and the box diagrams
- Above the tt threshold, the amplitudes develop imaginary parts, the cancellation does not occur
- When λ_3 increases, the amplitudes increases more below the tt threshold than above the threshold

- m_{hh} shifts to smaller value for large λ_3

Barger, Everett, Jackson, and Shaughnessy

Limited sensitivity with large λ_3





Big Improvement for New Physics!

SM: peaked at large invariant mass. A cut of $m_{hh} > 2m_{top}$ or something equivalent was used in both experimental and phenomenology studies during that time.

$\lambda_3 > 3\lambda_3^{SM}$, m_{hh} distribution is much softer than the SM case

PH, A. Joglekar, B. Li, and C. Wagner. 2015


But it is still difficult...
Yes, but phase transitions are fun!!

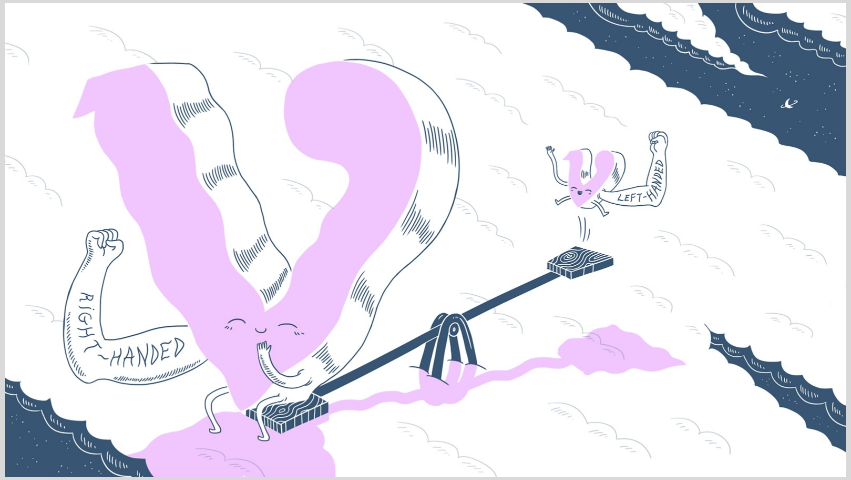
Leptogenesis, Two Birds with One Stone

- Type-I seesaw introduce right-handed neutrinos (mass *M*)

$$\mathcal{L} \supset \sum_i \bar{\nu}_R^i i\gamma^\mu \partial_\mu \nu_R^i - \frac{1}{2}\sum_{i,j}\Big(M^{ij}\bar{\nu}_R^{i,c}\nu_R^j + \text{ h.c. }\Big) - \sum_{i,j}\Big(\lambda_D^{ij}\bar{\ell}_L^i \tilde{H}\nu_R^j + \text{ h.c. }\Big)$$

$$\mathcal{M} = \begin{pmatrix} 0 & \frac{\lambda_D v}{\sqrt{2}} \\ \frac{\lambda_D v}{\sqrt{2}} & M \end{pmatrix}$$

$$m_\nu \simeq \frac{|\lambda_D|^2 v_{EW}^2}{2M} \simeq 0.08 \text{ eV } (\frac{\lambda_D}{0.5})^2(\frac{10^{14} \text{ GeV}}{M})$$



Minkowski, 1977

Leptogenesis

$$\mathcal{L} \supset \sum_i \bar{\nu}^i_R i\gamma^\mu \partial_\mu \nu^i_R - \frac{1}{2}\sum_{i,j}\left(M^{ij}\bar{\nu}^{i,c}_R \nu^j_R + \text{h.c.}\right) \qquad \cancel{L}$$

$$- \sum_{i,j}\left(\lambda^{ij}_D \bar{\ell}^i_L \tilde{H}\nu^j_R + \text{h.c.}\right) \qquad \cancel{CP}$$

~~Thermal Equilibrium~~

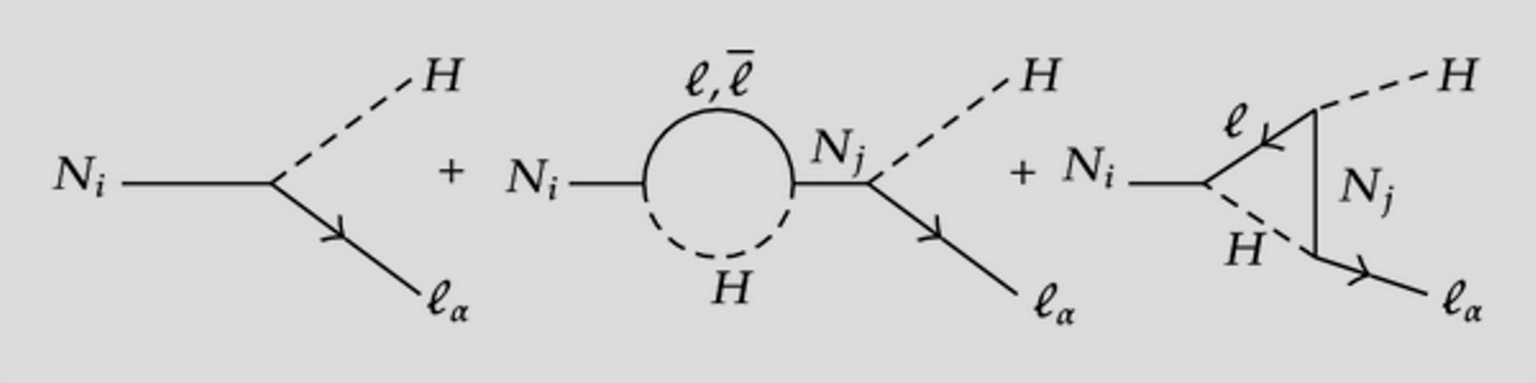
RHN decays

All three Sakharov conditions are satisfied

M. Fukugita, T. Yanagida, 1986
Luty 1992

Leptogenesis

Generate the Baryon asymmetry through the lepton asymmetry



$$\mathcal{L} \supset -\sum_{i,j} \left(\lambda_D^{ij} \bar{\ell}_L^i \tilde{H} \nu_R^j + \mathrm{h.c.} \right)$$

1. The Right Handed Neutrinos, decay (CP violating) asymmetrically

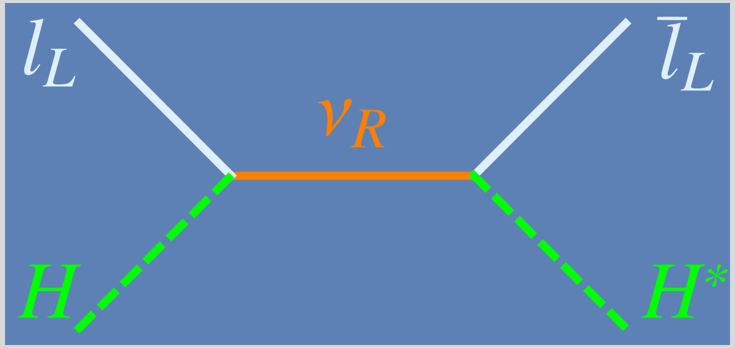
$$\epsilon_i = \frac{\sum_j \Gamma\left(\nu_R^i \to \ell_L^j H\right) - \Gamma\left(\nu_R^i \to \bar{\ell}_L^j H^*\right)}{\sum_j \Gamma\left(\nu_R^i \to \ell_L^j H\right) + \Gamma\left(\nu_R^i \to \bar{\ell}_L^j H^*\right)} \propto \mathrm{Im}\left[\left(\lambda_D \lambda_D^\dagger\right)^2\right]$$

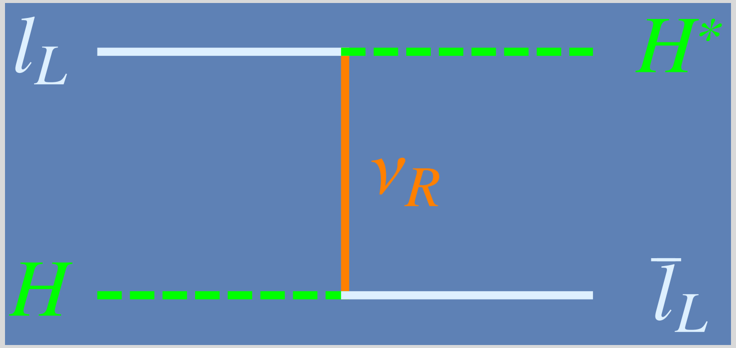
M. Fukugita, T. Yanagida, 1986
Luty 1992

2. Part of the generated asymmetry will be converted to a baryon asymmetry (about order one, detailed calculation gives 28/79)

Difficulties in Leptogenesis

3. Inverse decays and scattering wash out the generated asymmetry





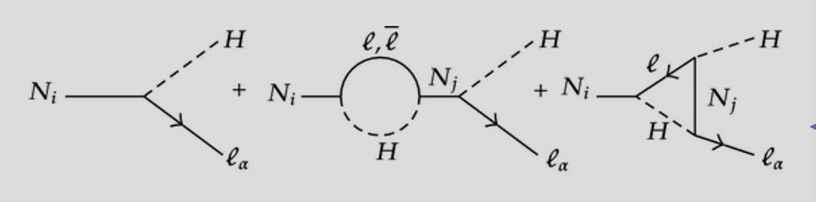
Only 1% of the generated asymmetry will survive

How to fix this?

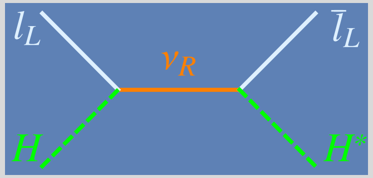
Difficulties in Leptogenesis

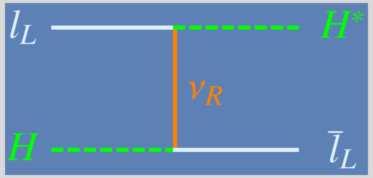
- Naively, the strong washout effect is unavoidable

See for example, Flanz et al, 1996, Pilaftsis, 1997, Dev et al, 2017 ....



Competition





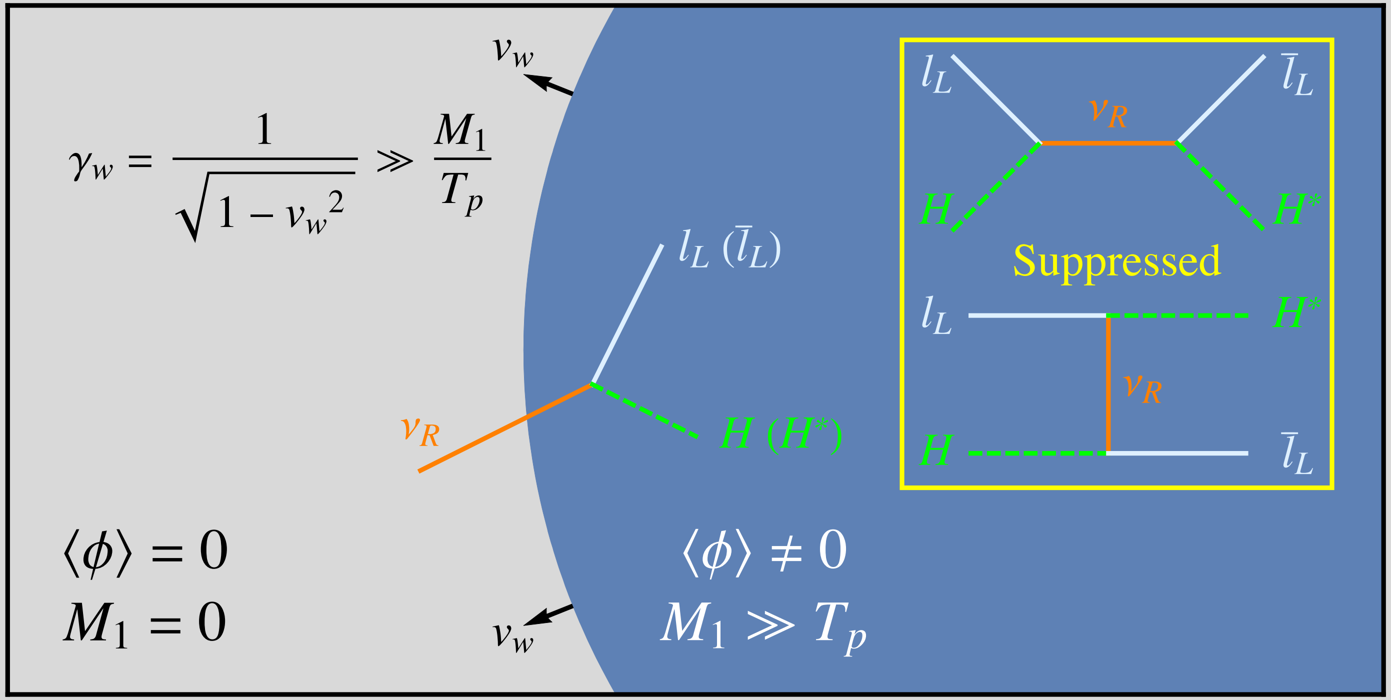
T~M

- The RHN decouples from the thermal bath at T~M
- Only if the cosmic temperature changes discontinuously, the RHN decays, generates the lepton asymmetry. Then the temperature falls T<<M, the washout effects are Boltzmann suppressed

Avoiding the Washout Effects With a Mass Jump

- The cosmic temperature can not change discontinuously, but the mass of the RHNs can -- first-order PT!

$$\mathcal{L} \supset -\sum_{i,j} \frac{1}{2}\left(\lambda_R^{ij}\bar{\nu}_R^{i,c}\nu_R^j\frac{\phi}{\sqrt{2}} + \text{h.c.}\right),$$

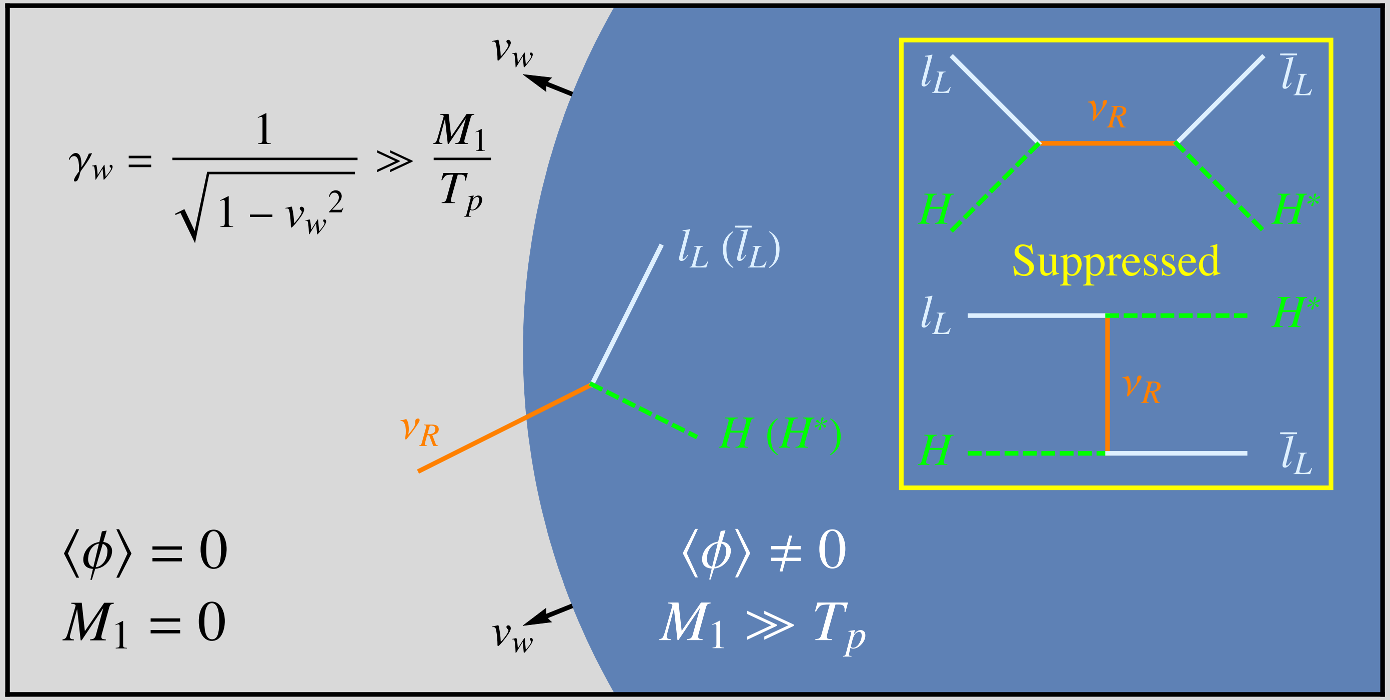


- The RHNs are massless in the old vacuum
- During the PT, the RHN gains mass M_1
- If $M_1 >> Tp$, the washout effects are Boltzmann suppressed

PH, K. P. Xie 2022

Wait – $M_1 >> T_p$, How Can That Happen?

$M_1 >> T_p$, how?

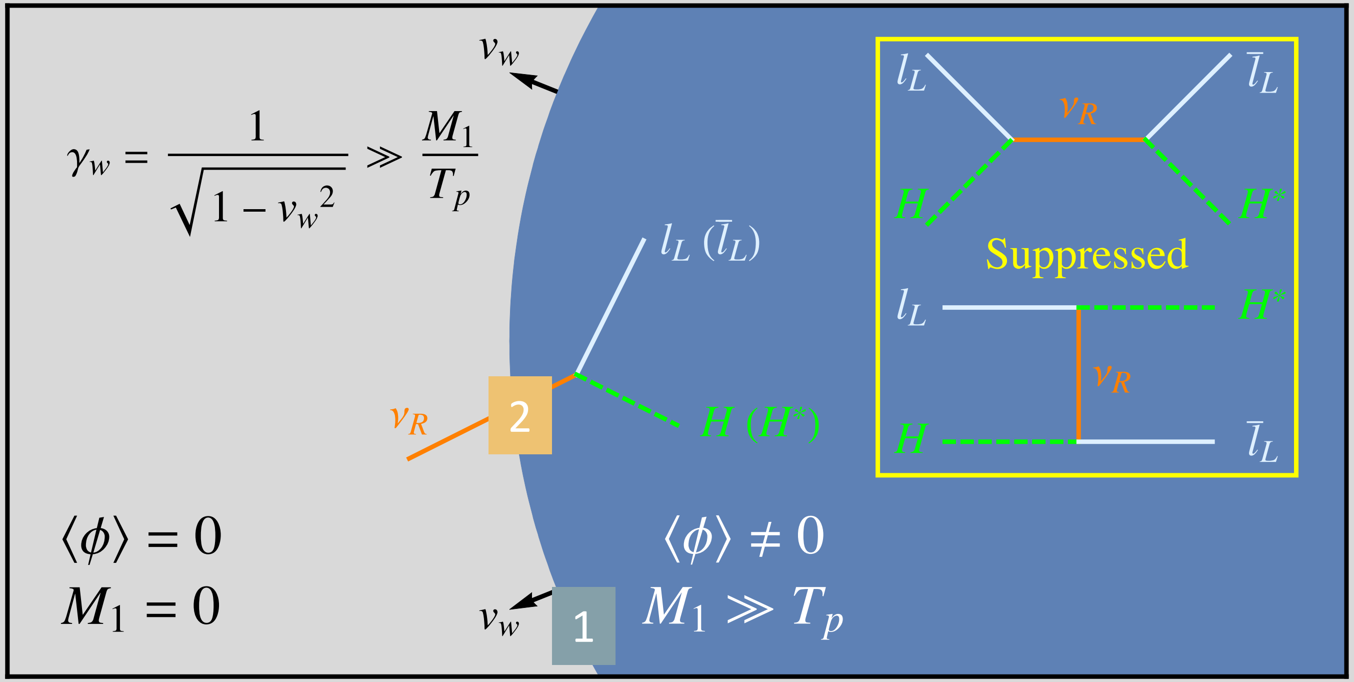


- If the phase transition is very strong, the bubble wall can be relativistic
- Although in the plasma frame, RHNs are in thermal equilibrium, they have very high energy in the wall frame
- They can penetrate into the true vacuum, and decay immediately

PH, K. P. Xie 2022

Leptogenesis with a first-order PT

PH, K. P. Xie 2022



To suppress the wash-out

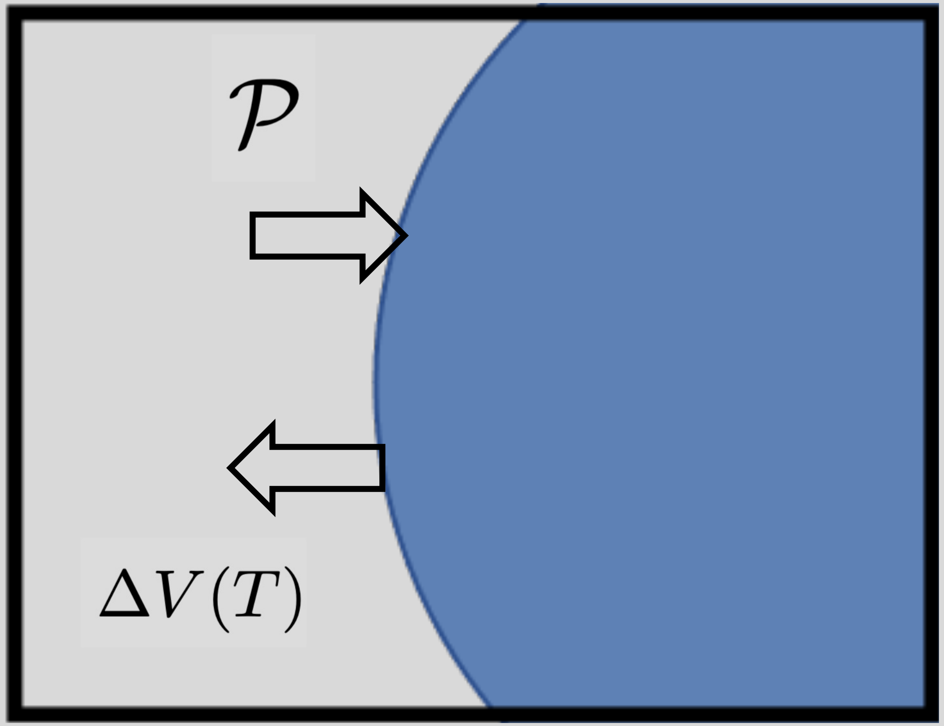
1. $M_1 >> T_p$, easy

$$\mathcal{L} \supset -\sum_{i,j}\frac{1}{2}\left(\lambda_R^{ij}\bar{\nu}_R^{i,c}\nu_R^j\frac{\phi}{\sqrt{2}} + \text{h.c.}\right),$$

2. RHN can penetrate into the new vacuum -> relativistic walls

Model building task: write down the scalar potential for ϕ, that undergoes a strong first-order PT, and the bubble walls are relativistic.

Relativistic Walls



The wall velocity is determined by

$$\Delta V(T) - \mathcal{P}$$

At LO,

Bodeker and Moore, 2009

$$\mathcal{P}_{1->1} = \sum c_i \frac{\Delta m_i^2 T^2}{24}$$

All order resummation,

$$\mathcal{P}_{1\to N} \sim \gamma_w$$

$$\mathcal{P}_{1\to N} \sim \gamma_w^2$$

Gouttenoire, Jinno and Sala, 2021 Hoeche et al, 2021

Terminal wall velocity,

$$\gamma_{\rm eq} = \sqrt{\frac{\Delta V_p - \mathcal{P}_{1\to 1}}{\mathcal{P}_{1\to N}/\gamma_w^2}}; \quad \gamma_{\rm eq} = \frac{\Delta V_p - \mathcal{P}_{1\to 1}}{\mathcal{P}_{1\to N}/\gamma_w}$$

Relativistic Walls

- Relativistic walls can be achieved if

$$\Delta V(T) \gg \mathcal{P}_{1->1} = \sum c_i \frac{\Delta m_i^2 T^2}{24}$$

- This can be easily done in a classical conformal theory,

$$\mathcal{L}_{B-L} = \sum_i \bar{\nu}_R^i i\gamma^\mu D_\mu \nu_R^i - \frac{1}{2}\sum_{i,j}\left(\lambda_R^{ij}\bar{\nu}_R^{i,c}\Phi\nu_R^j + \text{ h.c. }\right) - \sum_{i,j}\left(\lambda_D^{ij}\bar{\ell}_L\tilde{H}\nu_R^j + \text{ h.c. }\right)$$
$$+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu}$$

Iso, Okada, and Orikasa, 2009

$$V_{tree}(\Phi) = \lambda_\phi|\Phi|^4$$

C-W potential, $V(\phi) = V_0 + \frac{B}{4}\phi^4\left(\ln\frac{\phi}{v_\phi} - \frac{1}{4}\right)$

$$M_{Z'} = 2g_{B-L}v_\phi, \quad M_i = \lambda_{R,i}\frac{v_\phi}{\sqrt{2}}, \quad M_\phi = \sqrt{B}v_\phi$$

Relativistic Walls, CC B-L

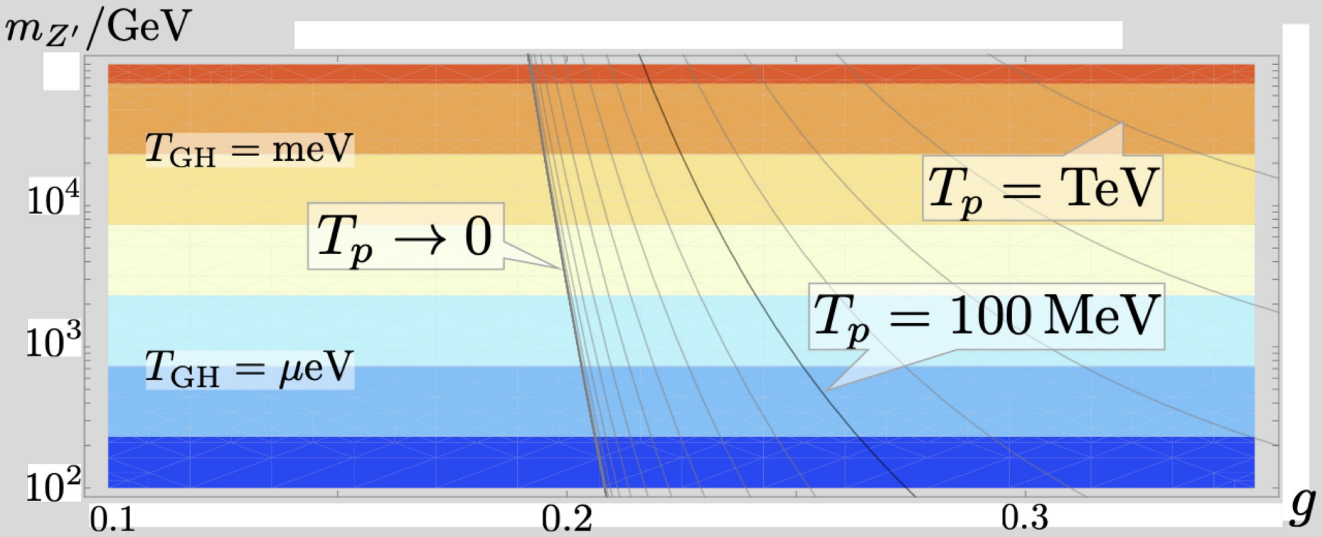


Figure 1: Contour plot of the percolation temperature T_p (black lines) as a function of g and $m_{Z'}$. The horizontal color bands show the temperature $T_{\mathrm{GH}} \equiv \mathcal{H}/2\pi$.

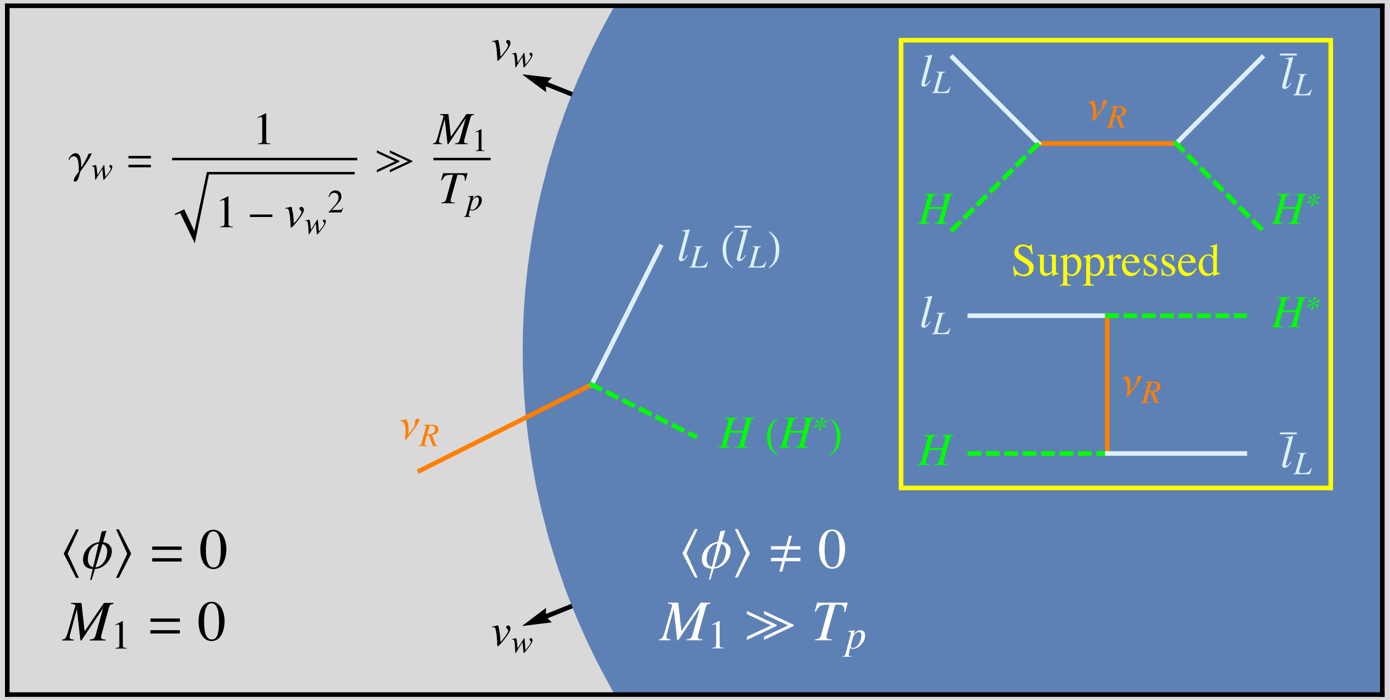
$$V(\phi) \sim \frac{g_{B-L}^2 T^2}{2} + \frac{3 g_{B-L}^4 \phi^4}{4\pi^2}\left[\ln\left(\frac{\phi^2}{v_\phi}\right) - \frac{1}{2}\right]$$

Iso, Serpico, and Shimada, 2017

$$\Delta V(T) \gg \mathcal{P}_{1->1} = \sum c_i \frac{\Delta m_i^2 T^2}{24}$$

Relativistic walls can be achieved

Towards an Actual Model



- RHN in thermal equilibrium

✓ ϕ undergoes a 1st order PT, with relativistic bubble walls.

After penetration…

? Completing processes?

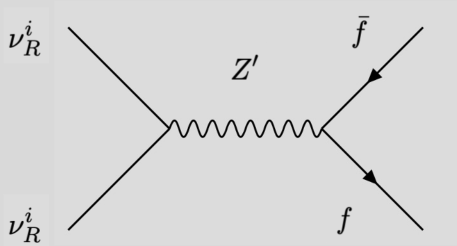
? Additional washouts from the decay products?

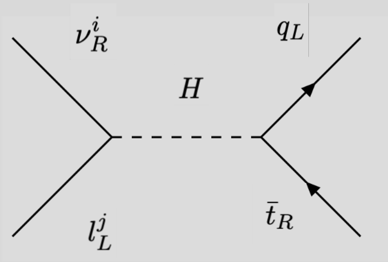
? Strong reheating?

PH, K. P. Xie 2022
Similar ideas in Baldes et al, 2021
Dasgupta, Dev, Ghoshal, Mazumdar 2022

After penetration

Competing processes

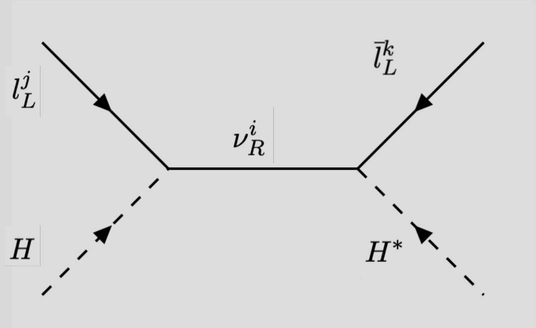




$$\Gamma_D > \Gamma_{\rm ann}\,, \quad \Gamma_D > \Gamma_{\rm sca}\,.$$

No additional washouts

$$E_1 = \gamma_1 M_1 = M_1^2/T_p.$$



$\Gamma_{\rm on}$

$$\Gamma_{\rm th} > \Gamma_{\rm on}\,, \quad \Gamma_{\rm th} > H_p$$

Ensures thermalization is fast enough

Considerations

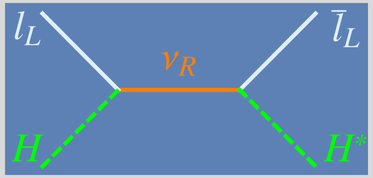
Strong reheating?

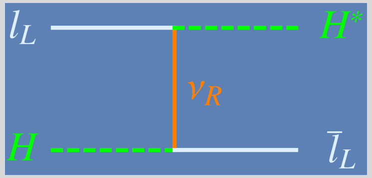
The latent heat released from the PT will reheat the universe to

$$T_{\rm rh} = (1+\alpha)^{1/4} T_p,$$

For the PT to provide ultra-relativistic bubble walls, typically α>>1

With a high reheating temperature,





will become active

The generated asymmetry will be diluted by ~ $(T_p/T_{\rm rh})^3$

Difficulties in the Minimal Model

- The minimal gauged $U(1)_{B\text{-}L}$ model

$$\mathcal{L}_{B-L} = \sum_i \bar{\nu}_R^i i\gamma^\mu D_\mu \nu_R^i - \frac{1}{2}\sum_{i,j}\left(\lambda_R^{ij}\bar{\nu}_R^{i,c}\Phi\nu_R^j + \text{ h.c. }\right) - \sum_{i,j}\left(\lambda_D^{ij}\bar{\ell}_L\tilde{H}\nu_R^j + \text{ h.c. }\right)$$
$$+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu}$$

- The scalar potential $V(\phi) = V_0 + \frac{B}{4}\phi^4\left(\ln\frac{\phi}{v_\phi} - \frac{1}{4}\right)$

- In the minimal gauged $U(1)_{B\text{-}L}$ $B = \frac{6}{\pi^2}\left(g_{B-L}^4 - \sum_i \frac{\lambda_{R,i}^4}{96}\right) = \frac{3}{8\pi^2 v_\phi^4}\left(M_{Z'}^4 - \sum_i \frac{2M_i^4}{3}\right)$

>0, for stability

$$T_{\rm rh} = \left(1 + \frac{Bv_\phi^4/16}{\pi^2 g_* T_p^4/30}\right)^{1/4} \sim g_{B-L}v_\phi \sim M_{Z'} \gtrsim M_1$$

Wash-out unavoidable!!

Extend the Minimal Model

- Wash-out unavoidable

$$T_{\rm rh} = \left(1 + \frac{Bv_\phi^4/16}{\pi^2 g_* T_p^4/30}\right)^{1/4} \cancel{\sim} M_{Z'}$$

- Add a new scalar

$$\mathcal{L}_{B-L} = \sum_i \bar{\nu}_R^i i \not{D} \nu_R^i - \frac{1}{2}\sum_{i,j}\left(\lambda_R^{ij}\bar{\nu}_R^{i,c}\Phi\nu_R^j + \text{h.c.}\right) - \sum_{i,j}\left(\lambda_D^{ij}\bar{\ell}_L^i\tilde{H}\nu_R^j + \text{h.c.}\right)$$
$$+ D_\mu\Phi^\dagger D^\mu\Phi + \boxed{D_\mu S^\dagger D^\mu S} - V(\Phi,S) - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu},$$

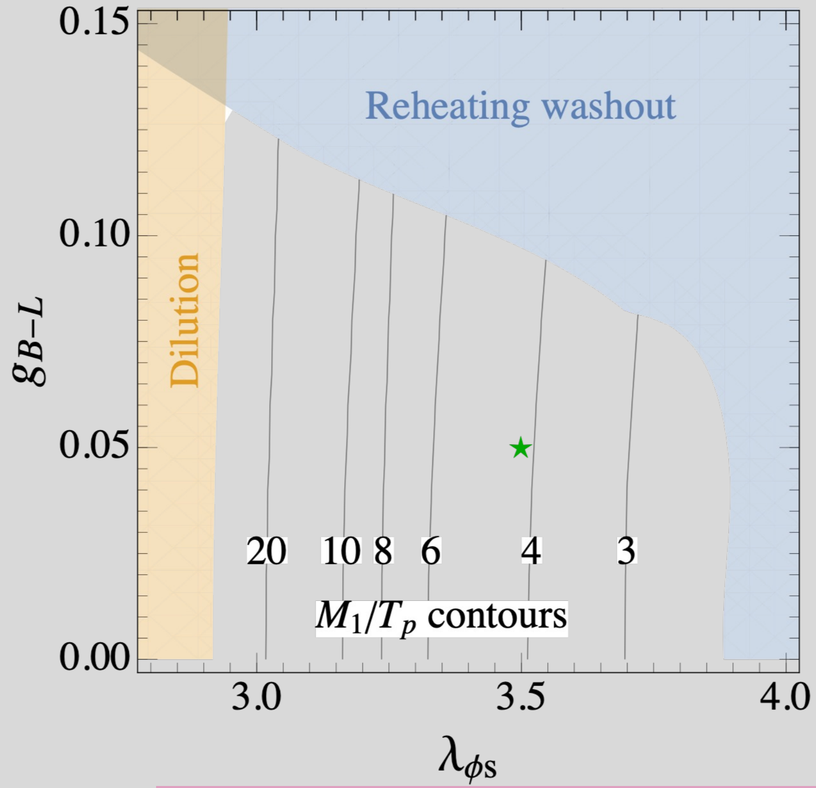
$$V_{\rm tree}(\Phi,S) = \lambda_\phi|\Phi|^4 + \lambda_s|S|^4 + \boxed{\lambda_{\phi s}|\Phi|^2|S|^2},$$

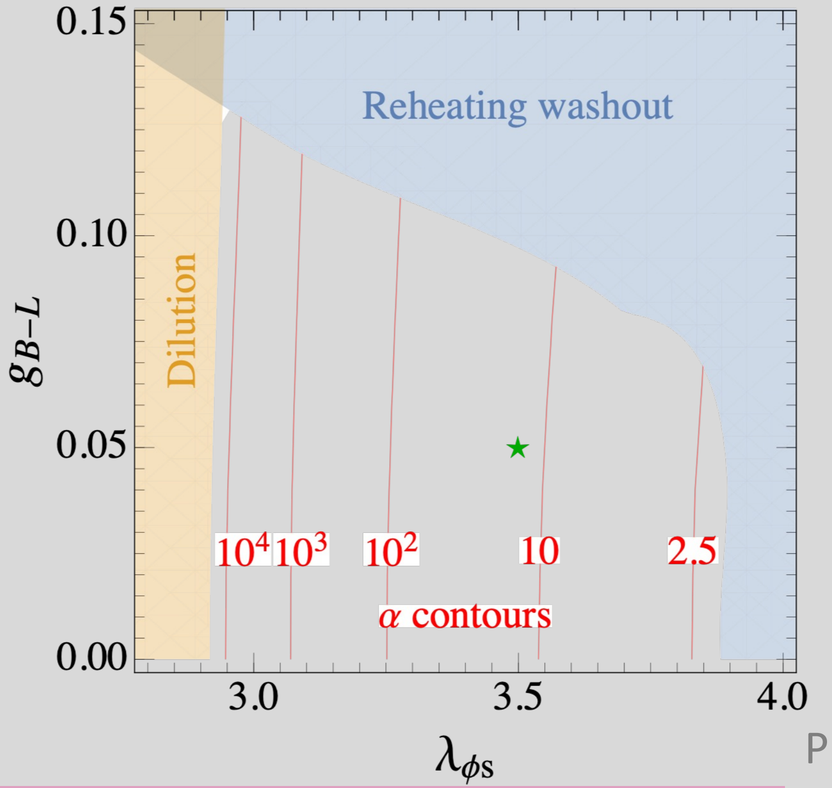
$$B = \frac{6}{\pi^2}\left(\boxed{\frac{\lambda_{\phi s}^2}{96}} + g_{B-L}^4 - \sum_i \frac{\lambda_{R,i}^4}{96}\right),$$

T_{rh} no longer correlated with $M_{Z'}$, wash-out avoidable

Parameter Space

$$M_1 = 2.5 \times 10^{11}\ \text{GeV}, \quad \lambda_{R,1} = 0.3, \quad \lambda_{R,2} = \lambda_{R,3} = 4\lambda_{R,1},$$





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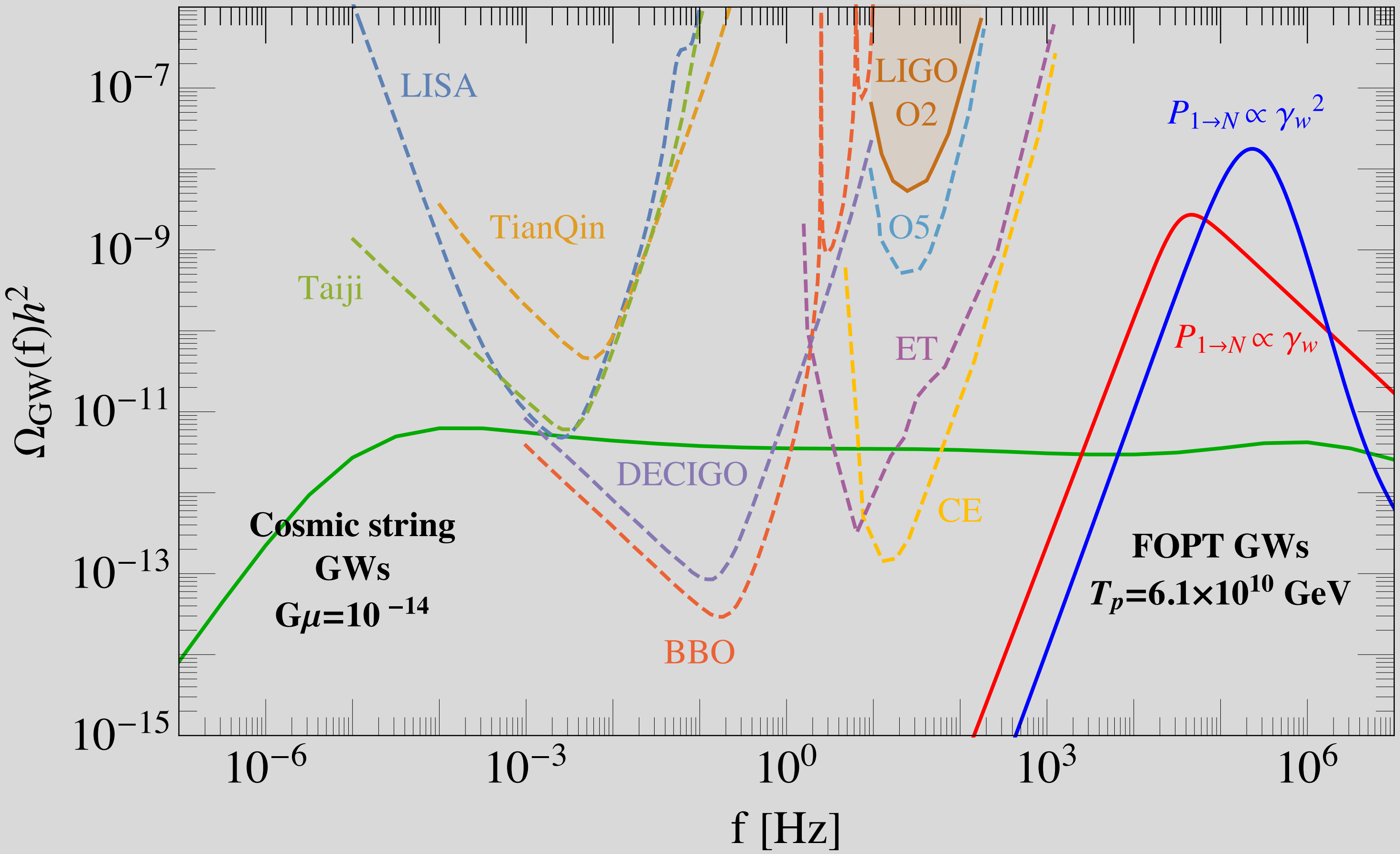
Conventional Leptogenesis needs CPV 30 times stronger

Gravitational Wave signal



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So, what is the most important thing when look for flying cows?
Well, you need a good team, and you need good mentoring skills.

You think it is too difficult?

You think it is too difficult?
Not if you learned from the best!!

With only one short lecture...

This talk is based on true stories

If you see a flying cow, make sure to WOW!

Before that, just work hard now!

On this special day,

Carlos, here are your flying cows !