BUBBLE-ASSISTED LEPTOGENESIS

Eung Jin Chun

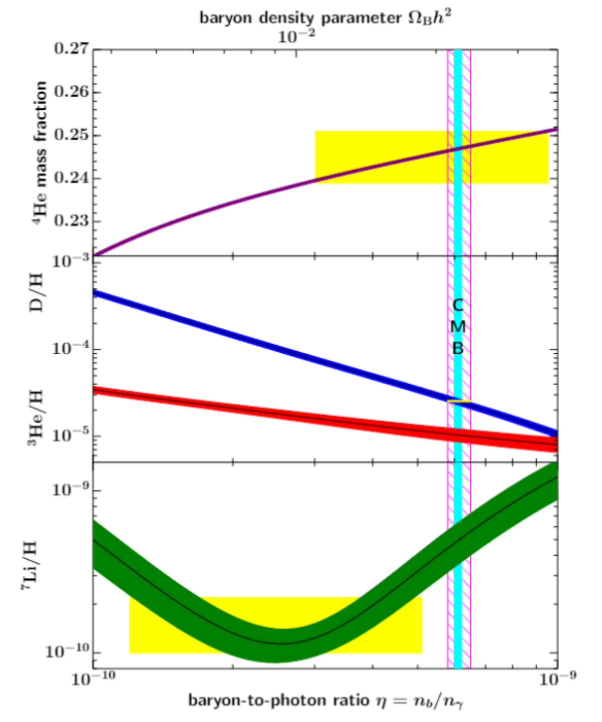
with T. Dutka, T.H. Jung, X. Nagels, M. Vanvlasselaer, 2305.10759

KIAS
KOREA INSTITUTE FOR ADVANCED STUDY

BARYON ASYMMETRY OF THE UNIVERSE

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} \approx 0.9 \times 10^{-10}$$

	Planck TT,TE,EE+lowE+lensing	+BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.1193 ± 0.0009
$100\,\theta_{MC}$	1.0409 ± 0.0003	1.0410 ± 0.0003
n_s	0.965 ± 0.004	0.966 ± 0.004
τ	0.054 ± 0.007	0.056 ± 0.007
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.044 ± 0.014	3.047 ± 0.014
h	0.674 ± 0.005	0.677 ± 0.004
σ_8	0.811 ± 0.006	0.810 ± 0.006
Ω_m	0.315 ± 0.007	0.311 ± 0.006
Ω_Λ	0.685 ± 0.007	0.689 ± 0.006



LEPTOGENESIS

Fukugita, Yanagida, 1986

- Light LH neutrinos with heavy RH neutrinos:
- RHN decays to produce asymmetry in lepton number which converts to baryon asymmetry by EW sphaleron process.
- Dynamical generation of baryon asymmetry:
  - ✓ L and $B+L$ violation: M_N and EW sphaleron
  - ✓ C & CP violation: $\Im(\bar{Y}^2 Y^2) \neq 0$
  - ✓ Out of Equilibrium: decay process

$$\mathcal{L} = Y_D\, \bar{l}\, \bar{H} N + \frac{1}{2} M_N \overline{N^c} N + h.c.$$

$$\Rightarrow \quad M_\nu = Y_D M_N^{-1} Y_D^T v_{EW}^2$$

$$\epsilon_N \equiv \frac{\Gamma(N \to lH) - \Gamma(N \to \bar{l}\bar{H})}{\Gamma(N \to lH) + \Gamma(N \to \bar{l}\bar{H})} \neq 0$$

$$Y_B = Y_N^{\rm eq}\, \epsilon_N\, \kappa_{\rm sph}\, \kappa_{\rm eff}$$

EFFICIENCY FACTOR

- RHN decay becomes active at $T \sim M_N$ to produce the asymmetry.
- Inverse decay could remain in equilibrium till $T \ll M_N$ to wash out the produced asymmetry (Strong washout regime: $K \gg 1$).

$$\Gamma_N = \frac{Y_D^2 M_N}{8\pi} \qquad \tilde{m}_\nu \equiv \frac{Y_D^2 v_{EW}^2}{M_N}$$

$$K \equiv \frac{\Gamma_N}{H(M_N)} = \frac{\tilde{m}_\nu}{\text{meV}}$$

$$K \approx (9, 50) \text{ for } \tilde{m}_\nu = (8.7, 50)\text{ meV}$$

$$\kappa_{\text{eff}} \approx \frac{1}{2K\ln(K)} \sim (0.027, 0.0026)$$

DAVIDSON-IBARRA BOUND

- For non-degenerate RHNs,

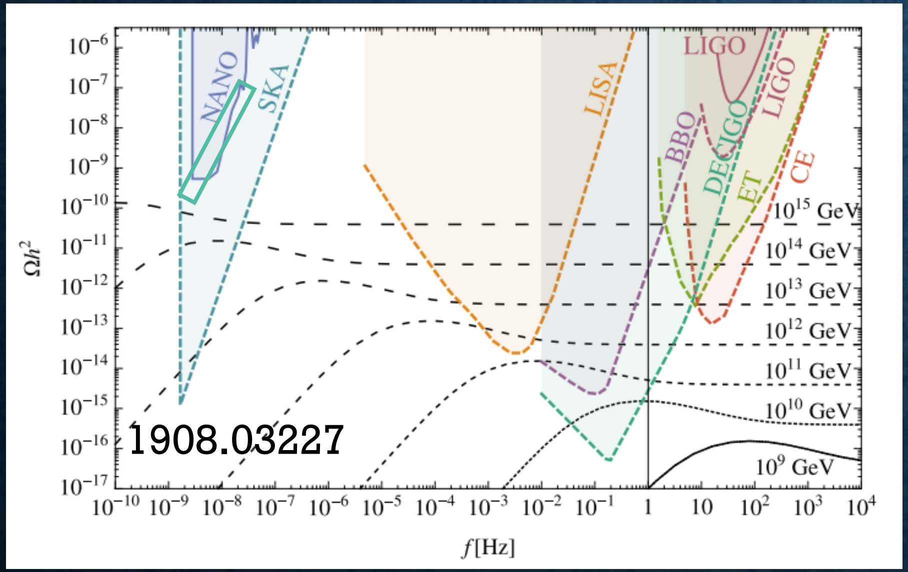
$$\epsilon_N \lesssim \frac{3}{8\pi} \frac{M_N \, m_{\nu_3}}{v_{EW}^2}$$

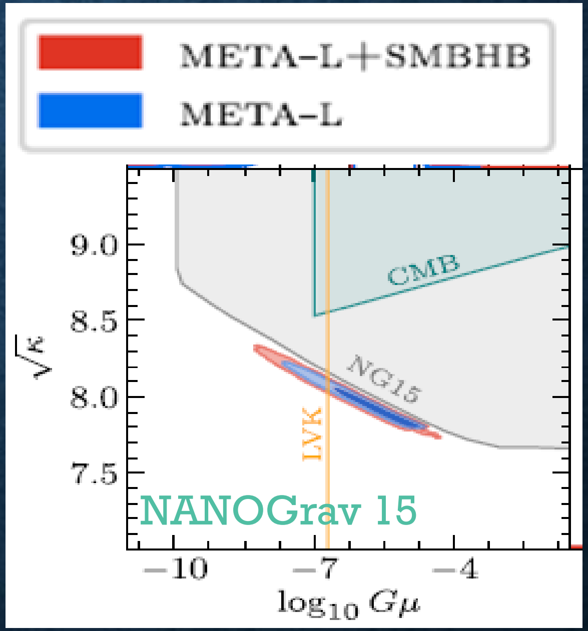
$$Y_B \approx 10^{-10} \quad \Rightarrow \quad M_N \gtrsim 3 \cdot 10^{11} \text{ GeV} \left(\frac{0.0026}{\kappa_{\text{eff}}}\right) \left(\frac{0.05\text{eV}}{m_{\nu_3}}\right)$$

- It can be relaxed significantly in Bubble-assisted Leptogenesis.

SEESAW & GW

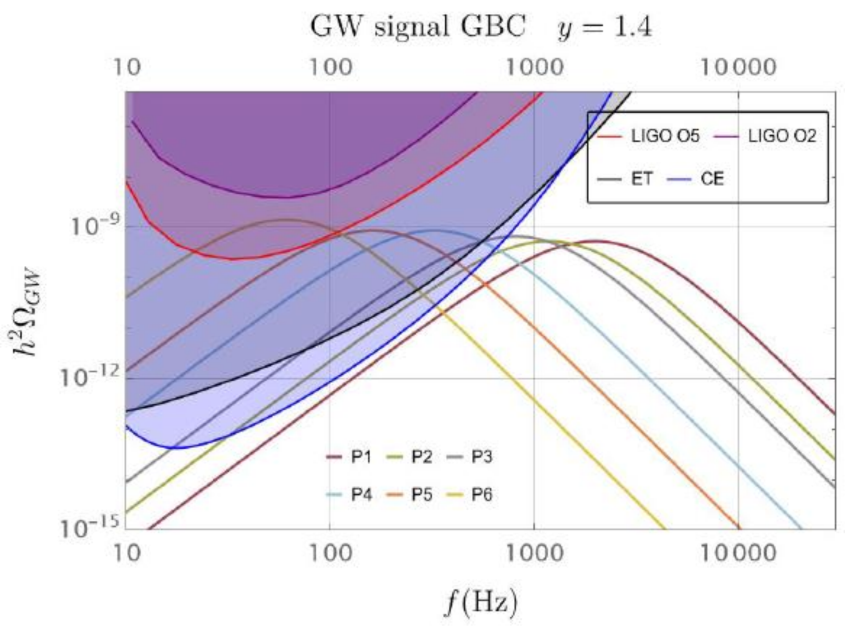
- Gravitational Wave from cosmic strings as a probe of seesaw associated with $U(1)_{B-L}$ breaking at v_{B-L}:





GW FROM BUBBLE-ASSISTED LEPTOGENESIS

- $U(1)_{B-L}$ breaking could be of strong first-order, which enhances the efficiency of leptogenesis and generates observable gravitational wave background:



	GBC		
	$M_N/10^8\text{GeV}$	$\frac{n_B^{FOPT}}{n_B^{\text{thermal}}}$	α_n
P1	60	22	4.8
P2	37	17	5
P3	25	15	9
P4	10	10	9.6
P5	4	5.6	15
P6	1.4	2.9	33

LEPTOGENESIS IN FOPT

- How is the vanilla leptogenesis modified by the bubble dynamics?

2305.10759

Huang, Xie, 2206.04691
Dasgupta, et.al., 2206.07032

Shuve, Tamarit, 1704.01979
Baldes, et.al., 2106.15602

- Study strong FOPT in classically scale-invariant models.

SCALE-INVARIANT $U(1)_{B-L}$ MODEL

- Setup for strong FOPT of $U(1)_{B-L}$ breaking:

$$-\mathcal{L} \ni \frac{1}{2} y_N \Phi N N + Y_D H l N + h.c. + V(\Phi, T)$$

$$V(\Phi, T) = \frac{1}{4}\lambda_\phi \phi^4 + V_{CW}(\phi) + V_T(\phi)$$

$$V_{CW}(\phi) = \sum_i (-1)^{2s_i} g_i \frac{m_i^2(\phi)}{64\pi^2}\left[\ln\left(\frac{m_i^2(\phi)}{\mu^2}\right) - c_i\right]$$

$$V_T(\phi) = \pm \frac{g_i}{2\pi} T^4 J_{B,F}\left(\frac{m_i^2(\phi)}{T^2}\right)$$

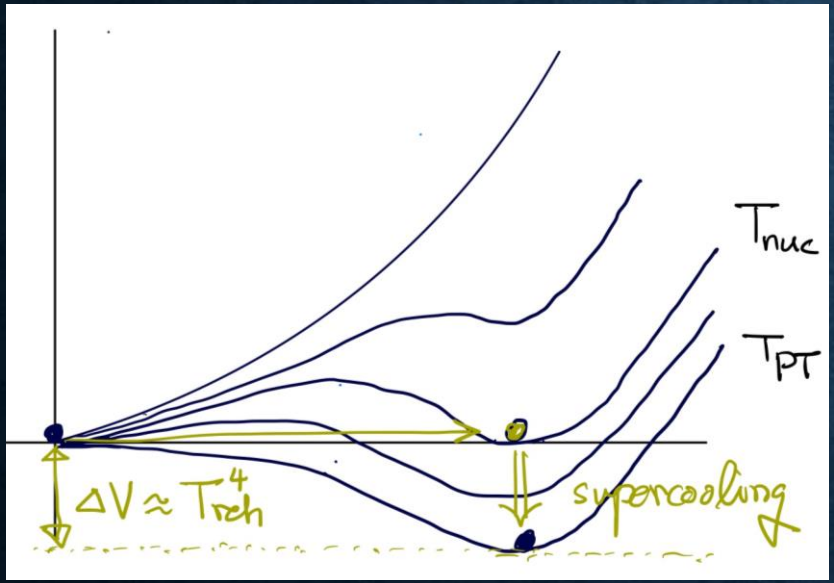
$$\Phi = \frac{\phi}{\sqrt{2}}$$

$$m_N^2(\phi) = \frac{1}{2} y_N^2 \phi^2$$

$$m_{Z_{B-L}}^2(\phi) = 4 g_{B-L}^2 \phi^2$$

$$m_\phi^2(\phi) = 6\lambda_\phi \phi^2$$

BUBBLE DYNAMICS



- Nucleation rate per unit volume per unit time:

$$\Gamma_{\rm nuc}(T) \approx T^4 \left(\frac{S_3}{2\pi T}\right)^{\frac{3}{2}} e^{-\frac{S_3}{T}} = H(T)^4 \ \text{at}\ T = T_{\rm nuc} \qquad H^2 = \frac{\rho(T) + \Delta V}{3 M_P^2}$$

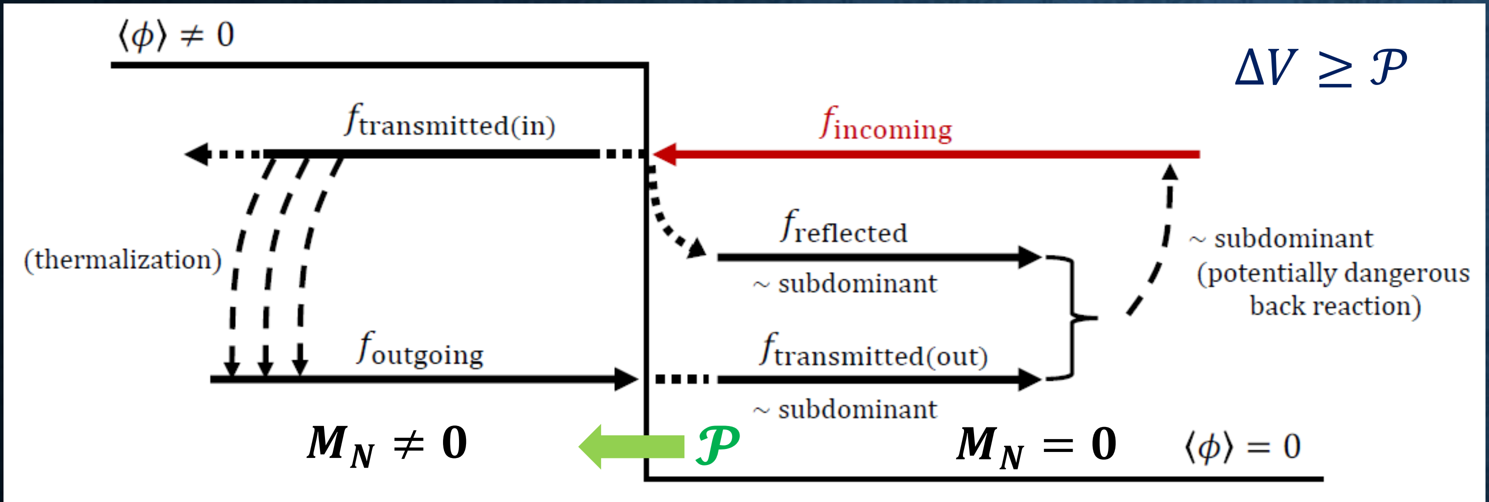
- Time scale between $T_{\rm nuc}$ and $T_{\rm PT}$:

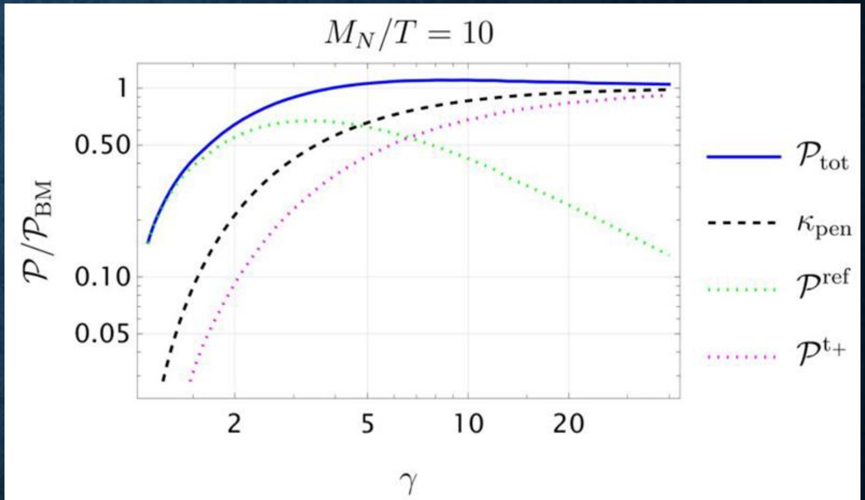
$$\Delta t_{\rm PT} = -\left(\frac{d(S_3/T)}{dt}\right)_{T_{\rm nuc}} \qquad \beta_{\rm PT}^{-1} \equiv \frac{\Delta t_{\rm PT}}{t_{\rm reh}} \ll 1$$

- Strength of FOPT: $\alpha_n \equiv \frac{\Delta V}{\rho(T_{\rm nuc})} = \frac{\rho(T_{\rm reh}) - \rho(T_{\rm nuc})}{\rho(T_{\rm nuc})} \gg 1$

SUDDEN MASS GAIN & PENETRATION RATE

2010.02590



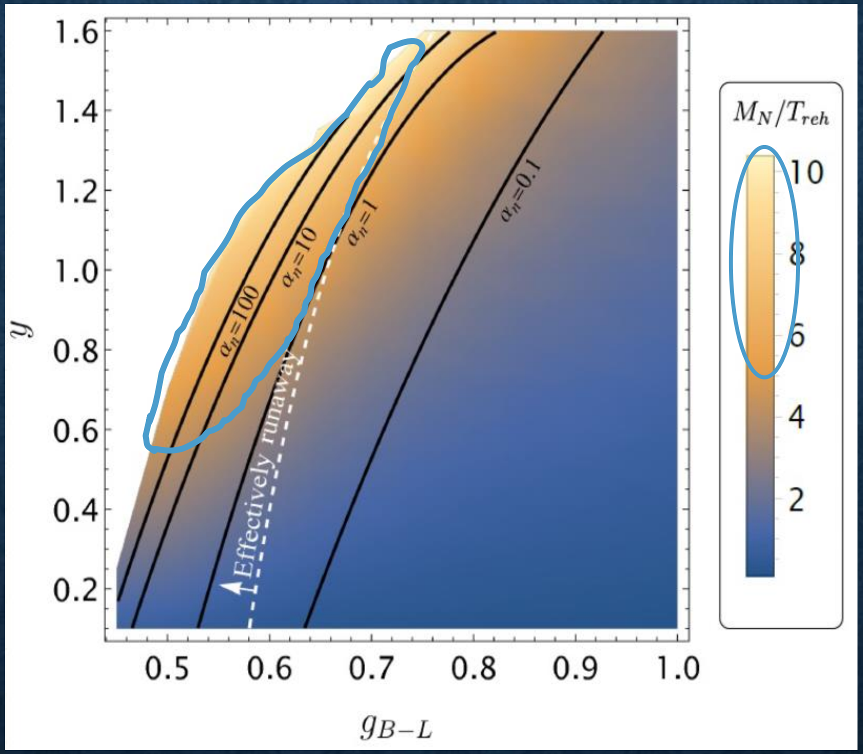


$$\mathcal{P}_{\text{BM}} = \frac{1}{48} g M^2 T^2 \text{ for } v_w \to 1$$

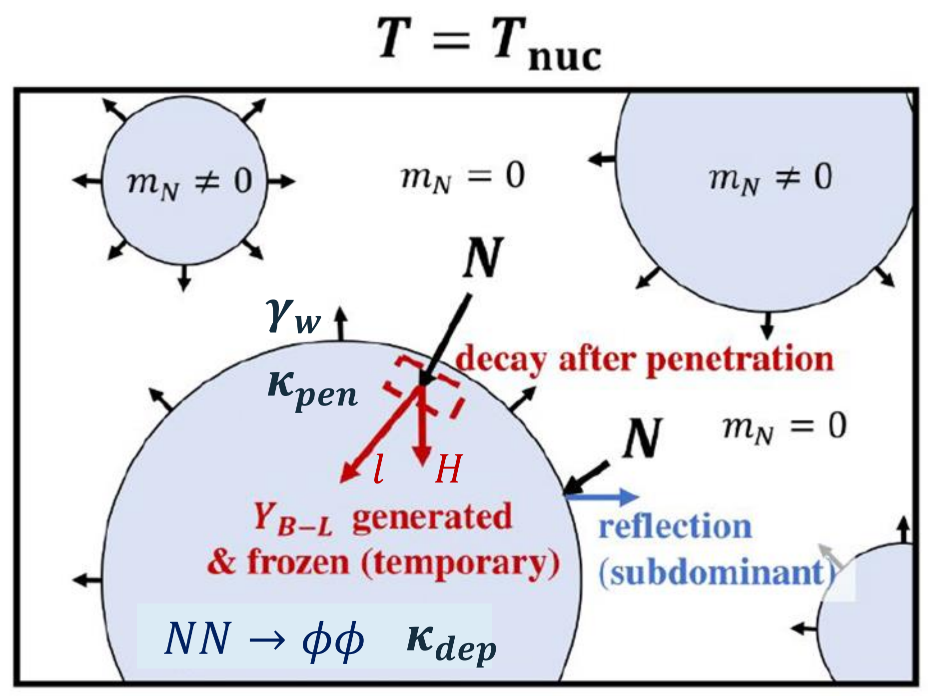
0903,4099

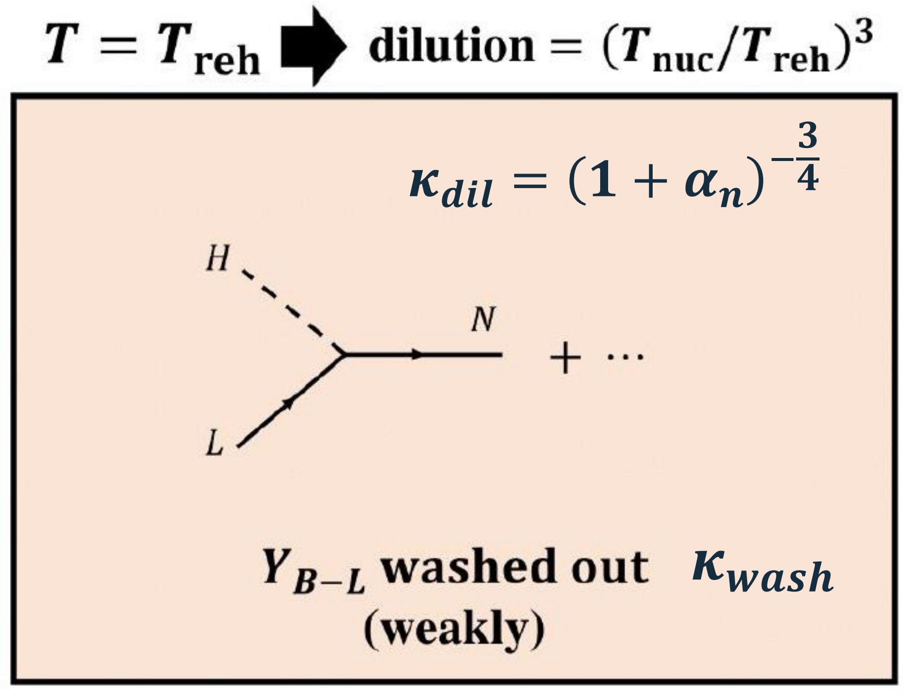
$\kappa_{\text{pen}} \to 1$ for $\gamma_w T \gg M \gg T$

$U(1)_{B-L}$ MODLE AND BUBBLE PARAMETERS



LEPTOGENESIS INSIDE BUBBLE





Require $\gamma_w T_{\rm nuc} \gg M_N \gg T_{\rm reh} > T_{\rm nuc}$

LEPTOGENESIS INSIDE BUBBLE

- RHNs inside bubble decay immediately:

$$\frac{t_{\rm decay}}{t_{\rm PT}} \approx 0.1 \left(\frac{5}{M_N/T_{\rm reh}}\right)^2 \left(\frac{0.05\ {\rm eV}}{\widetilde{m}_\nu}\right)\left(\frac{\beta_{\rm PT}}{100}\right)$$

- Unavoidable depletion $\kappa_{\rm dep}$ by annihilation $\Gamma(NN \to \phi\phi) > H$.

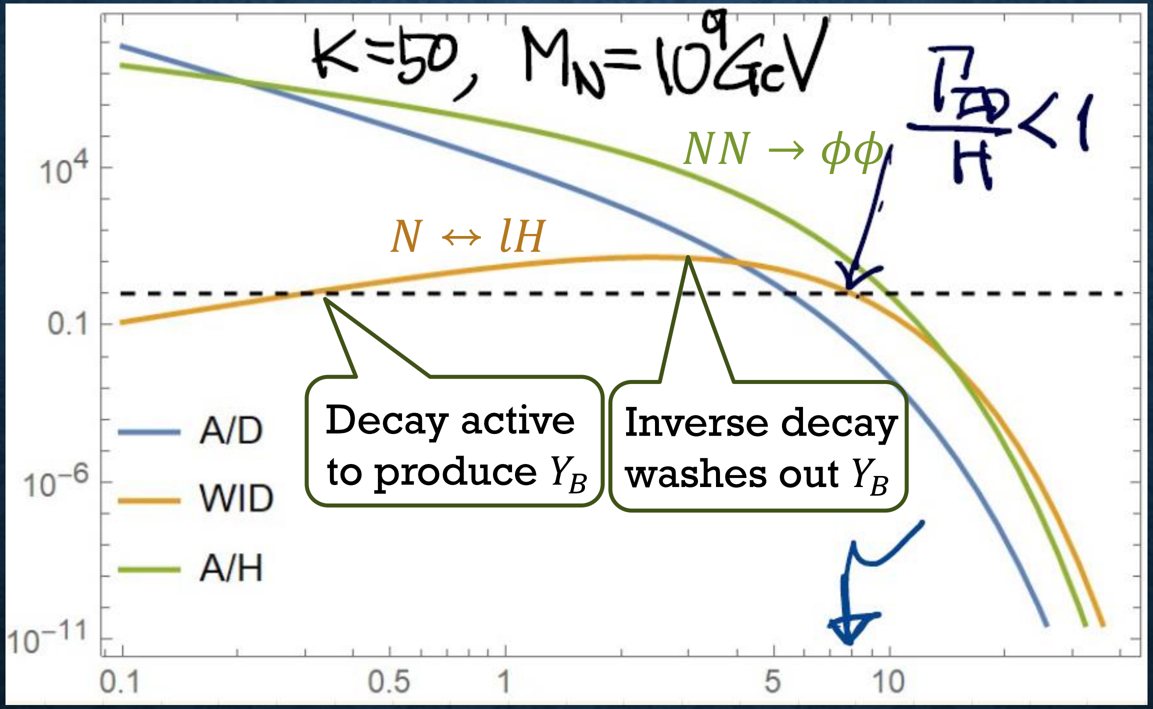
$$n_N^0 = \kappa_{\rm pen}\, n_N^{eq}(M_N = 0)$$

- Partial washout $\kappa_{\rm wash}$ by the inverse decay.
- Dilution $\kappa_{\rm dil}$ by the reheat:

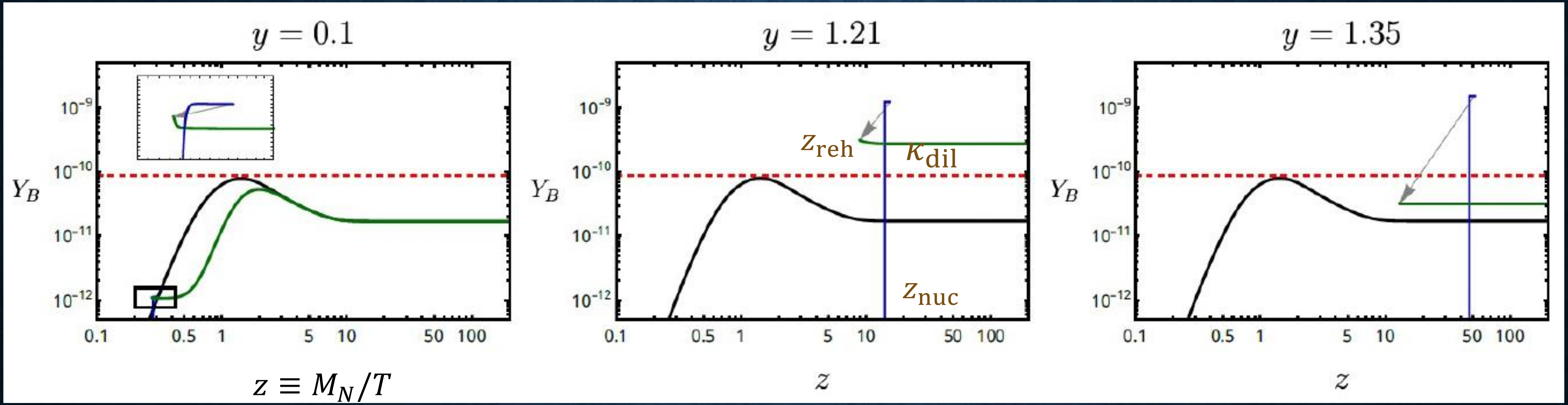
$$\kappa_{\rm dil} = \left(\frac{T_{\rm nuc}}{T_{\rm reh}}\right)^3 = (1+\alpha_n)^{-\frac{3}{4}}$$

$\kappa_{\rm pen} \to 1$ vs. $\kappa_{\rm dil} \downarrow$ for $\alpha_n \uparrow$

DECAY, INVERSE-DECAY & ANNIHILATION

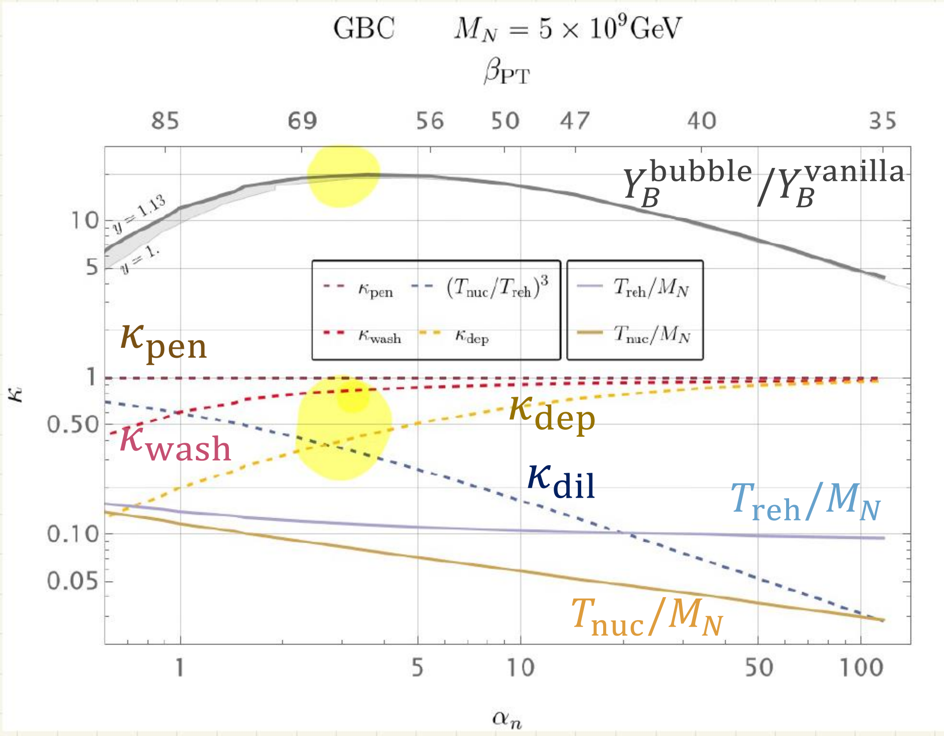


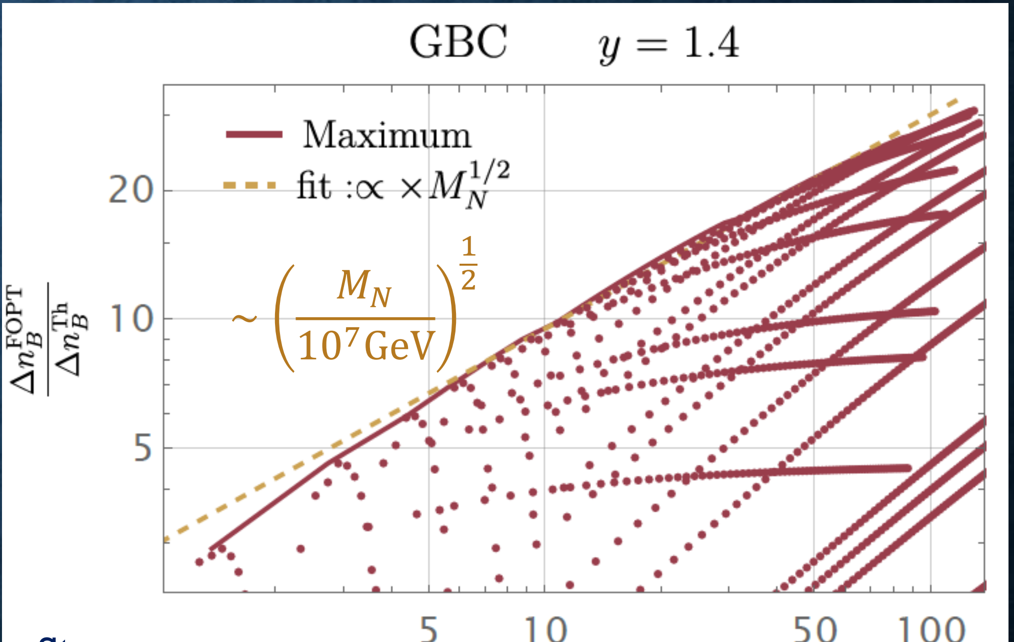
SCHEMATIC BEHAVIOR



$$Y_B^{\rm bubble} = \kappa_{\rm pen}\, Y_N^{eq}(0)\, \epsilon_N\, \kappa_{\rm sph}\, \kappa_{\rm dep}\, \kappa_{\rm wash}\, \kappa_{\rm dil}$$

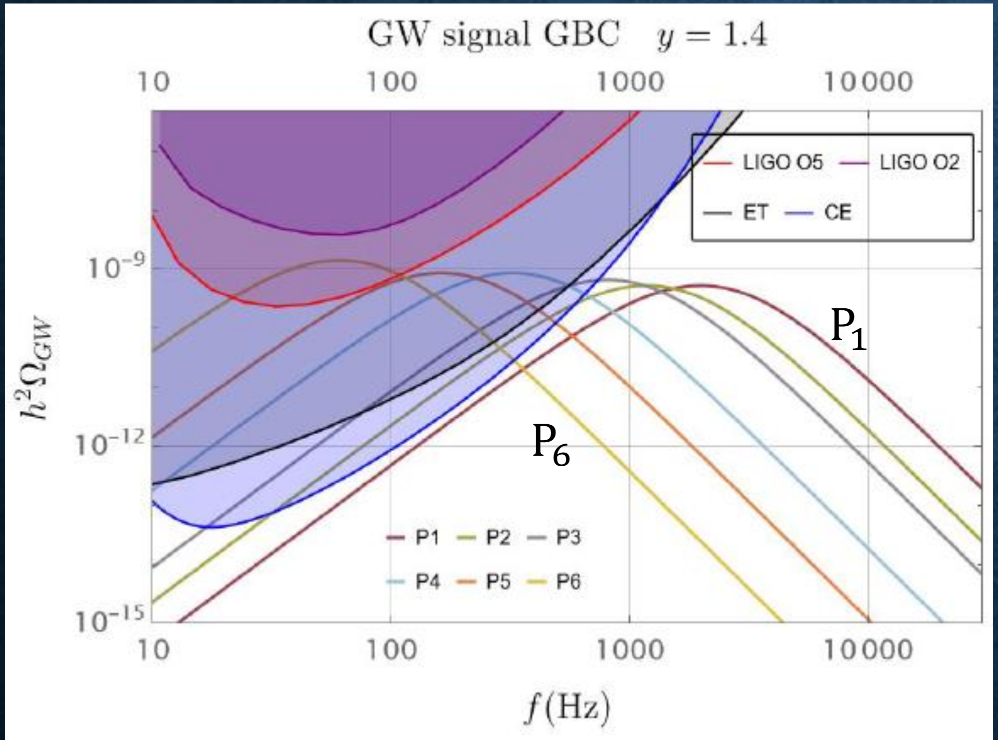
BUBBLE VS. VANILLA





Strong depletion

GRAVITATIONAL WAVE SIGNAL



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CONCLUSION

- Leptogenesis in FOPT can allow for a strong departure from thermal equilibrium:
  - ✓ Conventional washout can be circumvented.
  - ✓ New annihilation channel $NN \to \phi\phi$ opens up to deplete the asymmetry.
  - ✓ Dilution from reheating can be sizable.
- In the strong washout regime, the bubbles help Leptogensis to enhance the efficiency upto $3 \sim 30$ for $M_N = 10^8 \sim 10^{10}$ GeV.
- Observable GW signals are predicted for $M_N \lesssim 5 \cdot 10^9$ GeV.