Baryogenesis via bubble collisions

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The unbearably (finely tuned) baryon asymmetry

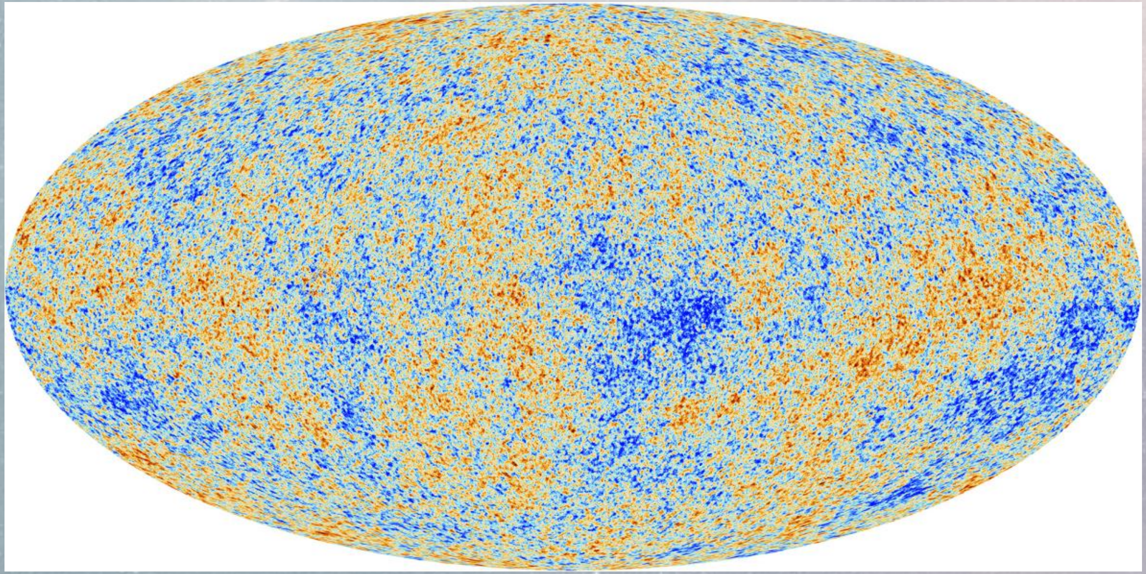
The Universe contains more matter the antimatter as evidenced by the structure around us.
This can be observed in two equivalent ways:

$$\eta \equiv \left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_0 = (6.21 \pm 0.16) \times 10^{-10},$$

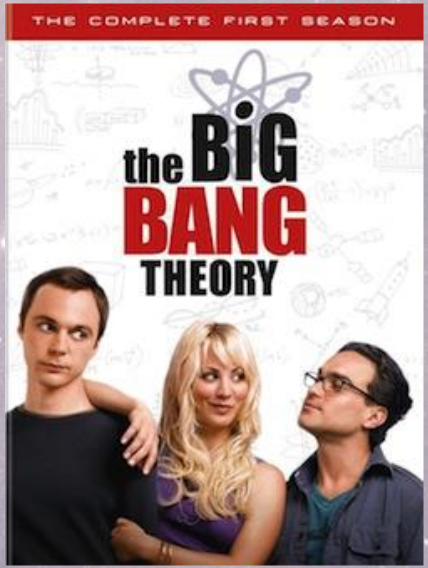
$$Y_{\Delta B} \equiv \left.\frac{n_B - n_{\bar{B}}}{s}\right|_0 = (8.75 \pm 0.23) \times 10^{-11}$$

These values are inferred independently from

1. Enhancement of the odd peaks in CMB
2. Abundances of D, 3He during BBN



Credit: ESA



Credit: Wikipedia

Sakharov conditions

The observed baryon asymmetry should be created dynamically after inflation:

This can be achieved by the 3 Sakharov conditions:

1. Baryon number violation
2. C- and CP- violation
3. Departure from thermal equilibrium

Credit: Wikipedia

Asymmetrizing within the SM

Can we satisfy Sakharov conditions in the SM…? Not really!

$$\Delta B = \Delta L = \pm 3.$$

1. **Sphalerons** conserve B-L but violate B+L
   with ***unsuppressed*** decay rate at **high temperatures**. **OK!**

2.1 Weak interactions **violate C maximally. OK!**

2.2 The CP-violation from the CKM matrix however is ~ 10^{-20}. NOT ENOUGH!

3. EWSB does not give a first order phase transition – Higgs is too heavy! NOT OK!

Look for explanation in connection with other unsolved problems of the SM.

Neutrinos to the rescue

Baryogenesis can be nicely connected with an explanation of neutrino masses.

1. Light neutrino masses from a heavy right-handed neutrino -> ***seesaw mechanism***
2. ***CP violating*** decays of RHN are ***out of equilibrium*** and produce ΔL
3. ΔL is converted into ΔB by ***sphalerons.***

Shortcomings of this simple scenario of LEPTOGENESIS:

1. RHN has to be very heavy mN> 10^9 GeV => High reheating temperatures needed
2. Around T~ 10^{13} GeV strong washout
3. Heavy new physics not very easily testable

We use the mechanism first introduced in

M.Cataldi and B.Shakya, *JCAP* **11** (2024) 047

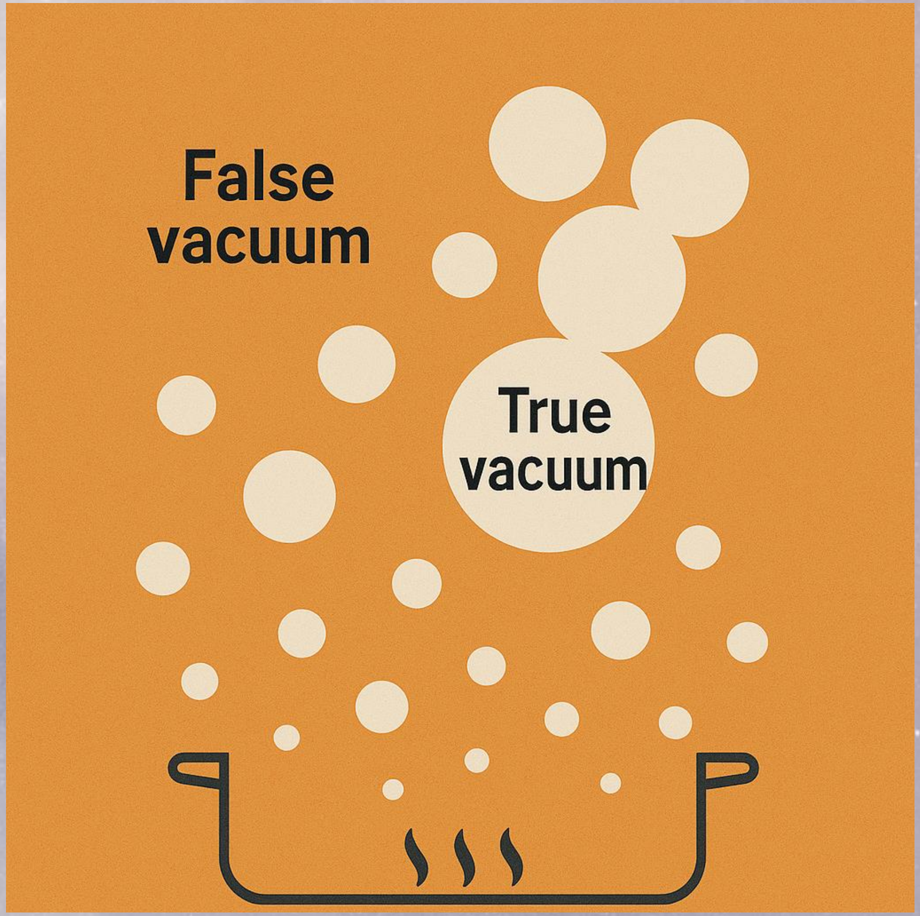
Artwork by Sandbox Studio, Chicago with Ana Kova

The boiling Universe

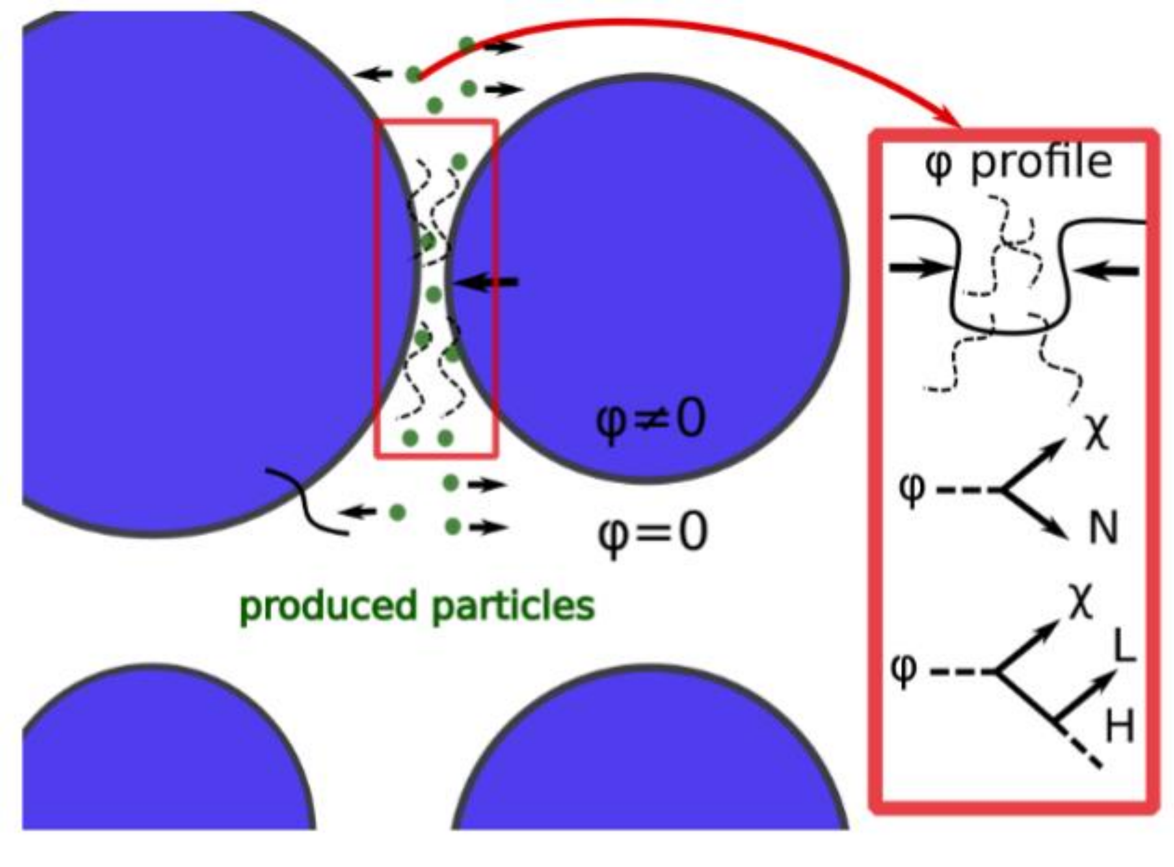
The key observables that we are interested in:

1. **Energy released by** the PT $\boldsymbol{\alpha = \frac{\Delta V}{\rho_{rad}}}$
2. **Inverse duration** of the PT $\boldsymbol{\beta / H}$
3. **Lorentz boost factor** of the bubble $\boldsymbol{\gamma = \sqrt{1 - v_w^2}}$
4. **Bubble wall thickness** $\boldsymbol{l_w \sim O(v)}$
5. **Bubble radius at nucleation** $\boldsymbol{R_* \sim O(T_n^{-1})}$

FOPT often feature **gravitational wave signals**!



From bubbles to particles



For that *runaway bubbles* are needed.

We need to limit the *friction* on the bubble walls

$$\mathcal{P}_{\rm LO} \approx \frac{1}{24} m^2 T^2$$

$$\mathcal{P}_{\rm NLO} \sim g^2 \gamma_w m_V T^3$$

Maximum energy for particle production E ~ γ v

$$\gamma_w^{\rm coll} \sim \frac{2\sqrt{10} M_{\rm pl} T_{\rm nuc} (8\pi)^{1/3} v_w}{\pi \sqrt{g_\star} \beta T_{\rm reh}^2} \approx 5.9 \frac{M_{\rm pl} T_{\rm nuc} v_w}{\sqrt{g_*} \beta T_{\rm reh}^2} .$$

Compared to bubble – plasma collision : vev does not have to be related to the heavy particle mass!

Zooming in on the bubble collisions

The number of particles produced per unit area:

$$\frac{N}{A} = \frac{1}{2\pi^2}\int_{p^2_{\rm min}}^{p^2_{\rm max}} dp^2\, f(p^2)\, {\rm Im}[\tilde{\Gamma}^{(2)}(p^2)]\,.$$

A. Falkowski, J.M.No *JHEP* **02** (2013) 034

The imaginary part of the 1PI 2-point Green function

$${\rm Im}[\tilde{\Gamma}^{(2)}(p^2)] = \frac{1}{2}\sum_k \int d\Pi_k |\bar{\mathcal{M}}(\phi_p^* \to k)|^2$$

R. Watkins and L. M. Widrow, Nuc. Phys B **02** (1992) 347

The Fourier transform has been computed numerically:

$$f_{\rm elastic}(p^2) = f_{\rm PE}(p^2) + \frac{v_\phi^2 L_p^2}{15 m_{\rm t}^2}\exp\left(\frac{-(p^2 - m_{\rm t}^2 + 12 m_{\rm t}/L_p)^2}{440\, m_{\rm t}^2/L_p^2}\right) \quad \text{(elastic collisions)}$$

$$f_{\rm inelastic}(p^2) = f_{\rm PE}(p^2) + \frac{v_\phi^2 L_p^2}{4 m_{\rm f}^2}\exp\left(\frac{-(p^2 - m_{\rm f}^2 + 31 m_{\rm f}/L_p)^2}{650\, m_{\rm f}^2/L_p^2}\right) \quad \text{(inelastic collisions)}$$

H. Mansour, B.Shakya. *Phys.Rev.D* **111** (2025) 2

For very heavy particles only the first part is important

$$f_{\rm PE}(p^2) = \frac{16 v_\phi^2}{p^4}\,{\rm Log}\left[\frac{2(1/l_w)^2 - p^2 + 2(1/l_w)\sqrt{(1/l_w)^2 - p^2}}{p^2}\right]$$

Number of particles produced

$$\frac{n}{s} = \frac{1}{s(T_{\rm reh})}\overbrace{\left.\frac{N}{A}\right|_N}^{\text{production per surface}} \times \overbrace{\frac{3}{2R_{\rm coll}}}^{\text{diffusion}}$$

Introducing the heavyweights

We consider the simplified Lagrangian

$$\mathcal{L} = Y\phi P_R \bar{N}\chi + \frac{1}{2}M_N N\bar{N} + \frac{1}{2}m_\chi \chi\bar{\chi} + \sum_\alpha y_\alpha P_R N(\tilde{H}L_\alpha) - V(\phi, T)$$

with the hierarchy

$$m_N \gg m_\chi \gg T_{\rm reh} \sim v \gg v_{\rm EW}\,.$$

The yield of the heavy particles produced is given by

$$Y_N^{\rm BC} \simeq 0.012 N |Y|^2 \frac{\beta}{v_w}\left(\frac{\pi^2\alpha}{30(1+\alpha)g_* c_V}\right)^{1/4}\frac{v}{M_{\rm pl}}\log\left(\frac{2\gamma_w v}{m_\chi + m_N}\right)$$

which is much less than the yield of light species

$$Y_{\rm rel} \simeq \frac{g}{g_{*,s}}$$

To avoid **backreaction** one needs

$$\rho_N^{\rm BC} \approx 0.03 N |Y|^2 v^5 \frac{T_{\rm nuc}}{T_{\rm reh}^2} \sim 0.03 N |Y|^2 v^3 T_{\rm nuc} \ll \Delta V = c_V v^4$$

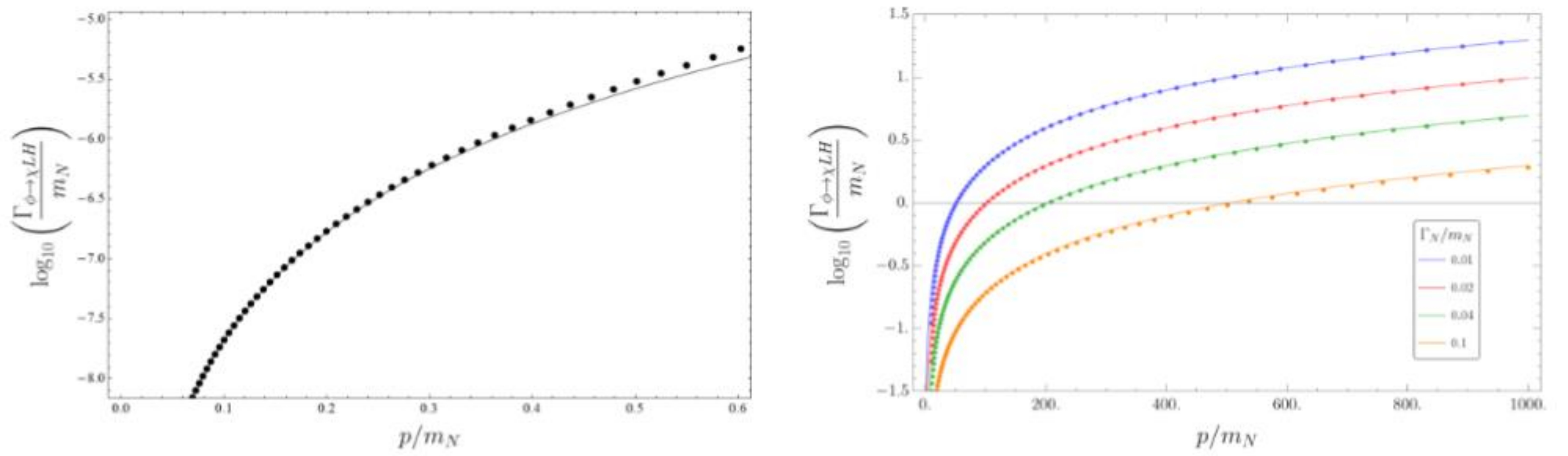
which gives a rough constraint

$$0.03N \times |Y|^2 \frac{T_{\rm nuc}}{v} \ll c_V$$

Boosted light(ning) fast particles

Boosted SM particles can also be produced directly via *off-shell* N

$$\Gamma_{\phi^\star\to HL\chi}(p^2) = \frac{2}{(2\pi)^3}\frac{|y|^2|Y|^2}{32\sqrt{p^6}}\int_{s_{12}^{\min}}^{s_{12}^{\max}}\int_{s_{23}^{\min}}^{s_{23}^{\max}}\frac{m_N^2(s_{23}-m_L^2-m_\chi^2)}{(s_{12}-m_N^2)^2+m_N^2\Gamma_N^2}\mathrm{d}s_{12}\,\mathrm{d}s_{23}\,.$$



The production is always dominated by the mN resonance!

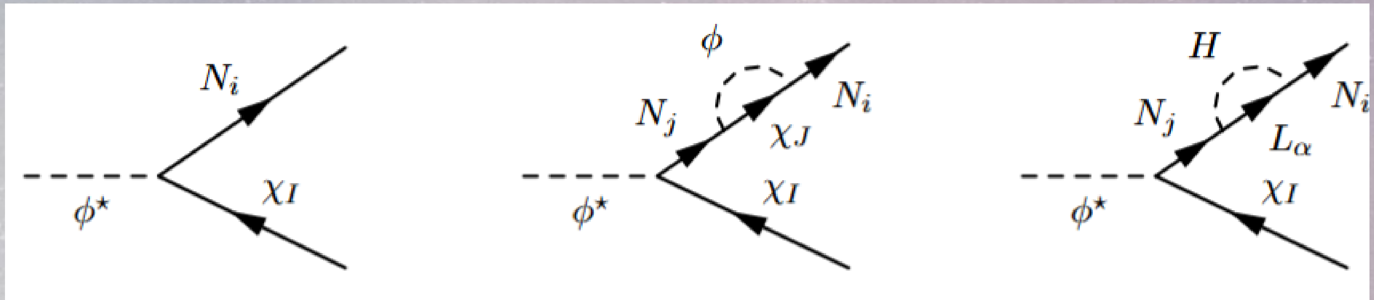
Backreactions can be avoided in all cases.

Low energies $\quad p \ll m_N : \quad \Gamma_{\phi\to HL\chi} \simeq 2\frac{|y|^2|Y|^2}{1536\pi^3}\frac{p^3}{m_N^2}$

High energies $\quad p \gg m_N : \quad \Gamma_{\phi\to HL\chi} \simeq 2\frac{|y|^2|Y|^2 p}{512\,\pi^2}\frac{m_N}{\Gamma_N}$

CP-violation in the *production*

We generalize the Lagrangian to include flavours



$$\mathcal{L} = \sum_{iI} Y_{iI}\phi \bar{N}_i P_R \chi_I + \sum_{i\alpha} y_{i\alpha} P_R N_i (\tilde{H}\bar{L}_\alpha) + \sum_i M_i^N \bar{N}_i N_i + \sum_I M_I^\chi \bar{\chi}_I \chi_I - V(\phi, T) + h.c.$$

Equal and **opposite** asymmetries produced, but **SEPARATED into two sectors**

$$\epsilon_{iI} \equiv \frac{|\mathcal{M}_{\phi\to N_i\chi_I^c}|^2 - |\mathcal{M}_{\phi\to N_i^c\chi_I}|^2}{\sum_{iI}|\mathcal{M}_{iI}|^2 + |\mathcal{M}_{\bar{i}\bar{I}}|^2}$$

$$= \frac{2\sum_{j,J}\mathrm{Im}(Y_{iI}Y^*_{iJ}Y_{jJ}Y^*_{jI})\mathrm{Im}f_{ij}^{(\chi\phi)}}{\sum_{i,I}|Y_{iI}|^2} + \frac{2\sum_{\alpha,j}\mathrm{Im}(Y_{iI}y^*_{i\alpha}y_{j\alpha}Y^*_{jI})\mathrm{Im}f_{ij}^{(HL)}}{\sum_{i,I}|Y_{iI}|^2}$$

$$n_{N_i} - n_{\bar{N}_i} = n^i_{\Delta N_i} \approx \sum_I \epsilon^{iI} n_{N_i} \qquad n_{\chi_I} - n_{\bar{\chi}_I} = n_{\Delta\chi_I} \approx -\sum_i \epsilon^{iI} n_{\chi_I}$$

$$n_{\Delta N} + n_{\Delta\chi} = 0\,.$$

N talks to the SM => **transmits its asymmetry to the SM**

χ talks to a light dark sector => its asymmetry is **secluded** from the SM.

Combining CP violation from *production* and *decay*

$$\frac{n_{L_\alpha} - n_{\bar{L}_\alpha}}{s(T_{\rm nuc})} \approx \frac{1}{s(T_{\rm nuc})} \left(\sum_i \epsilon^{i\alpha} n_{N_i} + \sum_{Ii} \epsilon^{iI} n_{N_i} \right) {\rm Br}[N_i \to H L_\alpha]$$

$$\approx \frac{1}{32\pi} \sum_i \frac{n_{N_i}}{s(T_{\rm nuc})} \left(\frac{\sum_{I, j\neq i} {\rm Im}\left[y^*_{j\alpha} y_{\alpha i} Y_{iI} Y^\star_{jI} \right] \frac{m_j m_i}{m_j^2 - m_i^2}}{\sum_{i,\beta} |y_{i\beta}|^2} + \right.$$

$$\left. 2 \times \frac{\sum_{j\neq i, \beta} {\rm Im}\left[y_{i\beta} y^*_{\beta j} Y^*_{jI} Y_{iI} \right] \frac{m_i m_j}{m_j^2 - m_i^2}}{\sum_{i,I} |Y_{iI}|^2} \right) {\rm Br}[N_i \to H L_\alpha] \, ,$$

← CP-violation from the *production* of N

← Fraction of asymmetry transferred to SM

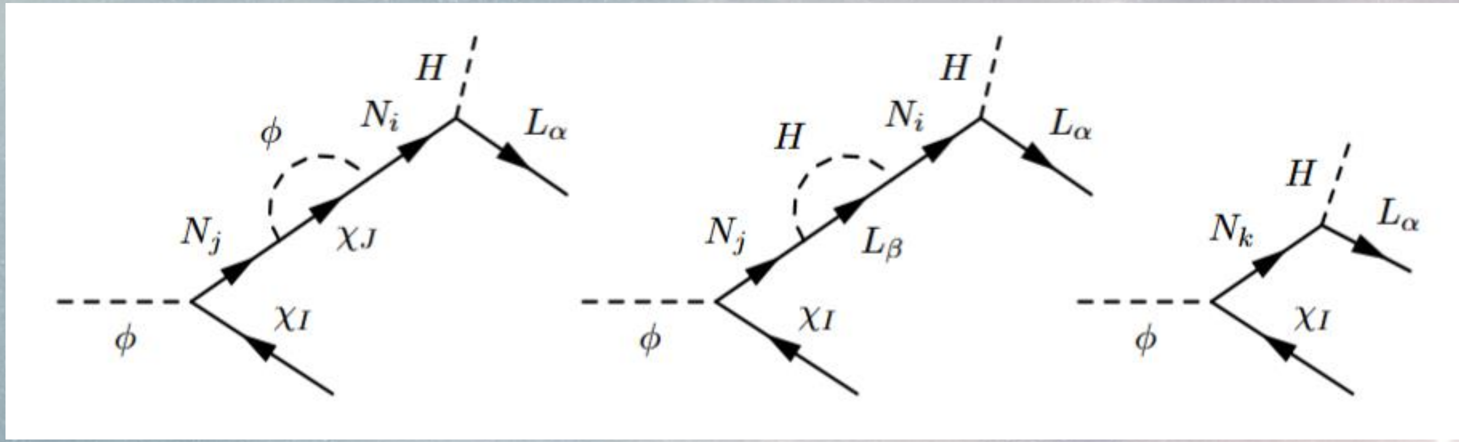
↑

CP violation from the *decay* of N

Bubble wall plasma contribution subdominant due to

$$m_N \gg m_\chi \gg T_{\rm reh} \sim v \gg v_{\rm EW} \, .$$

Production via *off-shell N*



$$\epsilon \equiv \frac{|\mathcal{M}|^2_{\phi\to\bar{\chi}\bar{H}L} - |\mathcal{M}|^2_{\phi\to\chi H\bar{L}}}{|\mathcal{M}|^2_{\phi\to\bar{\chi}\bar{H}L} + |\mathcal{M}|^2_{\phi\to\chi H\bar{L}}} \,.$$

$$\left(\Gamma^{\epsilon}_{\phi^\star\to HL\chi}\right)_{\alpha I} = \frac{1}{(2\pi)^3}\frac{1}{32p^3}\int_{s_{12}^{\min}}^{s_{12}^{\max}}\int_{s_{23}^{\min}}^{s_{23}^{\max}} \left|\mathcal{M}_0^{\alpha I}(s_{12},s_{23})\right|^2 \epsilon_{\alpha I}(s_{12})\mathrm{d}s_{12}\,\mathrm{d}s_{23}$$

The rate of production of the asymmetry

The asymmetry produced as a result:

$$\left.\frac{N_{\Delta L}}{A}\right|_{\phi^*\to\chi HL} \approx \int \frac{dp_z d\omega}{(2\pi)^2}\Gamma_{\phi^*\to\chi HL}(p)|\phi(p^2)|^2 \qquad \Rightarrow n_{\Delta L} \approx \frac{3\beta H}{2} \times \left.\frac{N_{\Delta L}}{A}\right|_{\phi^*\to\chi HL}$$

Two special cases of the *off-shell* production

We focus on 2 generations of N, and assume m1<< m2 and m2>> γv

a. **When $\gamma v \gg$ m1:**

1. N1 resonance dominates the 1->3 production
2. We recover the CP-violation from the production and decay of an *on-shell* N1.

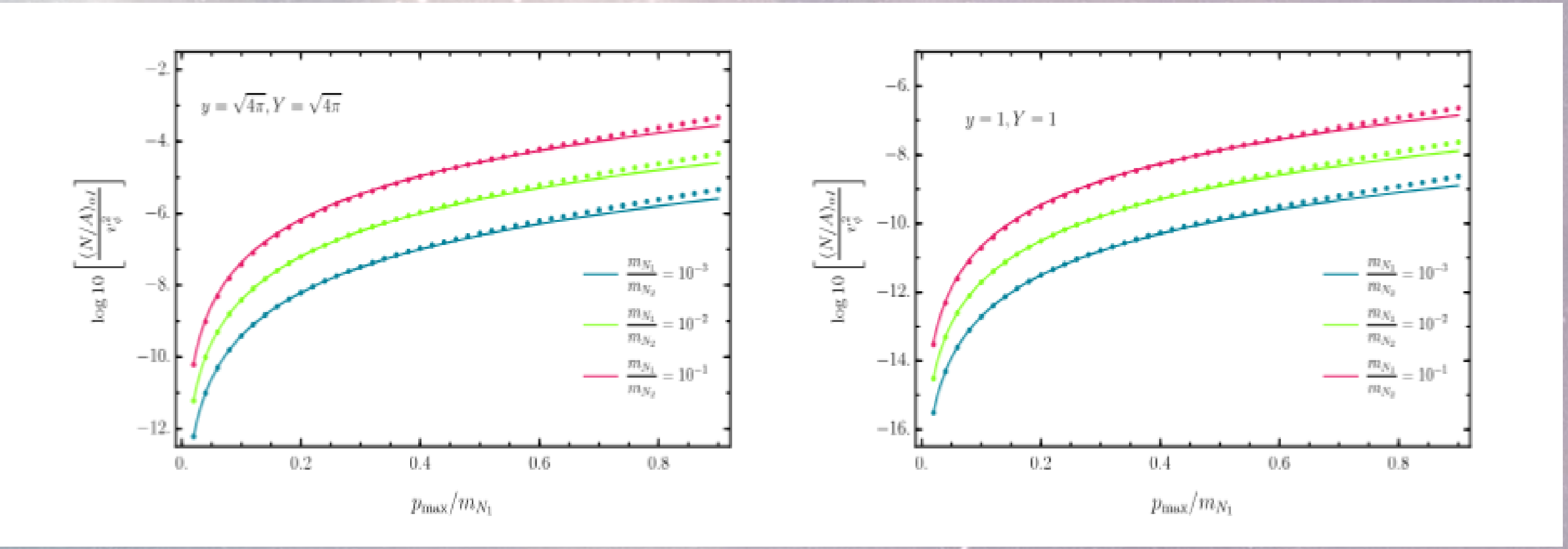
b. **When $\gamma v <$ m1:**

1. CP-violation can still occur via *off-shell production*

Complicated to compute numerically

Excellent analytic approximation:

$$\frac{N_{\Delta L}}{A}\bigg|_{\phi\to\chi HL} \approx 10^{-3}\frac{N\times C}{16\pi^6}\left(|y|^4|Y|^2\frac{m_1}{m_2}+\frac{1}{2}|y|^2|Y|^4\right)\frac{p_{\max}^4 v^2}{m_1^3 m_2}$$



The danger of equilibriation 1

The main danger is the reaction HL $\rightarrow \phi\chi$. This can happen in two ways

1. Non-thermal interactions (boosted H,L)

   a. Can produce N *on-shell* with the rate

$$\Gamma_{HL\to N} \propto \frac{|y|^2}{8\pi}\frac{Tm_N^2}{E_{L,\mathrm{initial}}^2} \times \mathrm{Exp}\left[-\frac{m_N^2}{E_{L,\mathrm{initial}}T}\right]$$

   b. Thermalisation rate via t-channel scatterings

$$\tau_{\mathrm{therm}} \sim \frac{64\pi^3}{g^4}\frac{E_{L,\mathrm{initial}}}{T^2} \, .$$

Another way to understand

nL<< neq!

So the H,L thermalize much before creating appreciable amount of on-shell N.

The danger of equilibration 2

Thus the main process is:

2. Thermal equilibration via off-shell N (we assume massless limit for SM particles)

$$\frac{d\sigma_{HL\to\chi\phi}}{dt} = \frac{1}{2}\frac{1}{|\vec{p_L}|^2}\frac{|\mathcal{M}_{HL\to\chi\phi}|^2}{64\pi s} = \frac{|\mathcal{M}_{HL\to\chi\phi}|^2}{16\pi s^2}$$

$$\gamma(ij\to kl) = \frac{g_i g_j T}{32\pi^4}\int ds s^{3/2} K_1(\sqrt{s}/T)\lambda\left(1, \frac{m_L^2}{s}, \frac{m_H^2}{s}\right)\sigma(s)$$

We consider separately two regimes:

1. Relativistic equilibration

$$\frac{dY_{\Delta L}}{dx} \approx -|y|^2|Y|^2\frac{M_{\rm pl} m_\chi}{0.3\times 64\pi^5 m_N^2 x^2} Y_{\Delta L}$$

resulting in exponential suppression

$$Y_{\Delta L}^{\rm fin} \approx Y_{\Delta L}^{\rm init}\times {\rm Exp}\left[-\frac{|y|^2|Y|^2 M_{\rm pl} T_{\rm reh}}{0.3\times 64\pi^5 m_N^2}\right].$$

2. Non – relativistic equilibration

$$\frac{dY_{\Delta L}}{dx} \approx -|y|^2|Y|^2\frac{M_{\rm pl} m_\chi}{445\pi^4 m_N^2} x^{3/2} e^{-2x} Y_{\Delta L}$$

numerically insignificant

due to the exponential suppression

in the Boltzmann equation!

Two birds with one stone : a tale of *cogenesis*

To explain the *coincidence problem* we slightly extend the Lagrangian

$$\mathcal{L} \supset y_1 \bar{\chi}(\tilde{\chi}\tilde{\phi}) + y_2 \phi\bar{\chi}\chi + \lambda_{\tilde{\phi}H}|H|^2\tilde{\phi}^2 - \frac{1}{2}m_{\tilde{\chi}}\tilde{\chi}\bar{\tilde{\chi}} + h.c.\,,$$

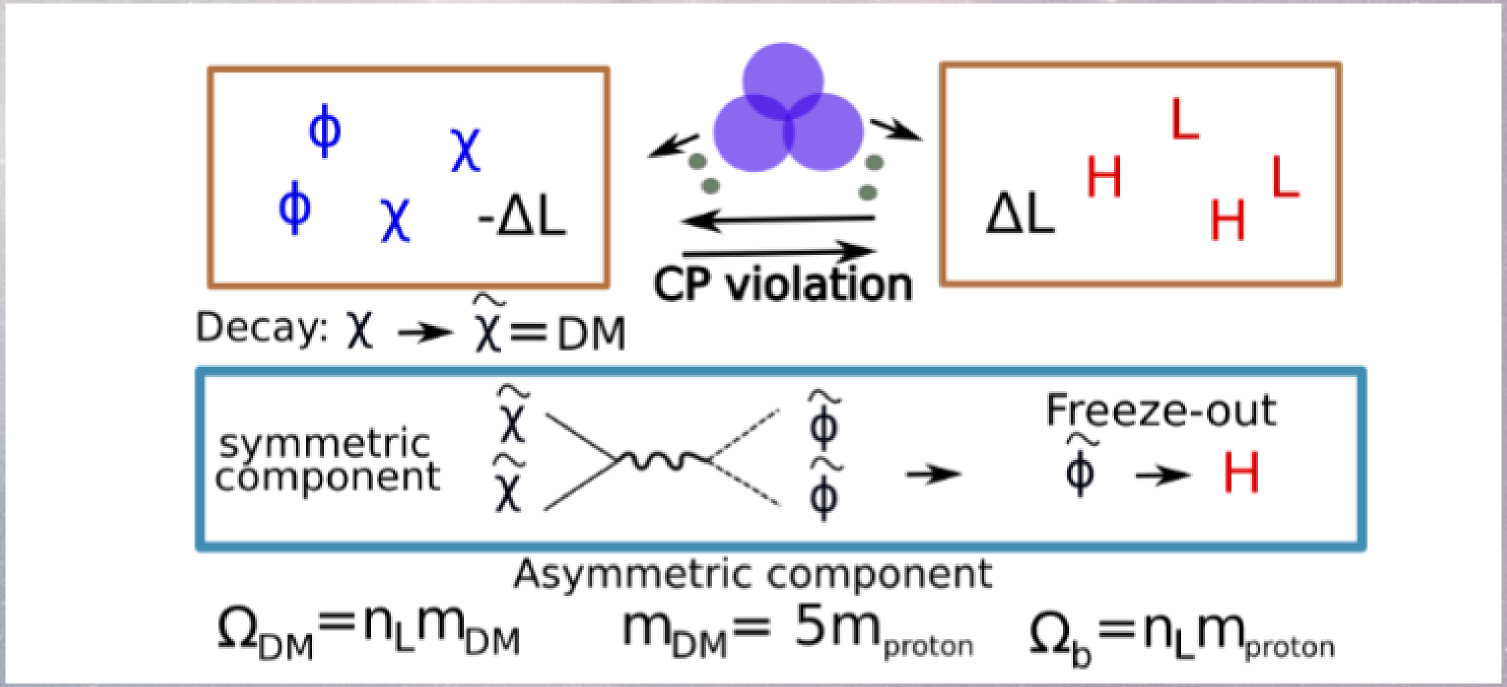
Only connection to the SM

↓

Sizeable Higgs portal

↓

Avoids washout from DS decays to SM



Light from heavy: inverse seesaw mechanism

Introduce lepton number violating terms

$$\mathcal{L} \supset \sum_I \lambda_{N,R}\phi N_{R,I}\bar{N}^c_{R,I} + \lambda_{N,L}\phi N_{L,I}\bar{N}^c_{L,I} + \lambda_{\chi,R}\phi\chi_{R,I}\bar{\chi}^c_{R,I} + \lambda_{\chi,L}\phi\chi_{L,I}\bar{\chi}^c_{L,I}\,.$$

This results in the effective Weinberg operator

$$\mathcal{O}_{\text{Weinberg}} = \sum_{I,\alpha,\beta} \frac{y_{\alpha I} y^*_{\beta I} (\bar{L}^c_\alpha H)(L_\beta H)\lambda_{N,R} v}{m_N^2}\,,$$

Giving a mass to the heaviest light neutrino

↓

$$\text{Max}[m_\nu] \sim \text{Max}\left[\sum_I |y_{\alpha I}|^2\right] \frac{v_{EW}^2 \lambda_{N,R} v}{m_N^2}\,.$$

Resulting in the neutrino mass matrix

$$M = \begin{pmatrix} 0 & 0 & y v_H & 0 & 0 \\ 0 & \lambda_{L,R} v & m_N & 0 & Y v \\ y^T v_H & m_N^T & \lambda_{N,R} v & 0 & 0 \\ 0 & 0 & 0 & \lambda_{\chi,L} v & m_\chi \\ 0 & Y^T v & 0 & m_\chi^T & \lambda_{\chi_R} v \end{pmatrix}$$

Other wash-out channels

$$\Gamma_{HL\to H^c L^c} = \Gamma_{LL\to H^c H^c} \approx \frac{T^3}{4\pi^3}\frac{\sum m_{\nu_i}^2}{v_{\rm EW}^4}, \qquad \Gamma_{2\to 2}^{\Delta L=2} = \frac{T^3}{2\pi^3}\frac{\sum m_{\nu_i}^2}{v_{\rm EW}^4},$$

which decouples for $T \ll T_{\rm dec} \approx 3\times 10^{13}$ GeV.

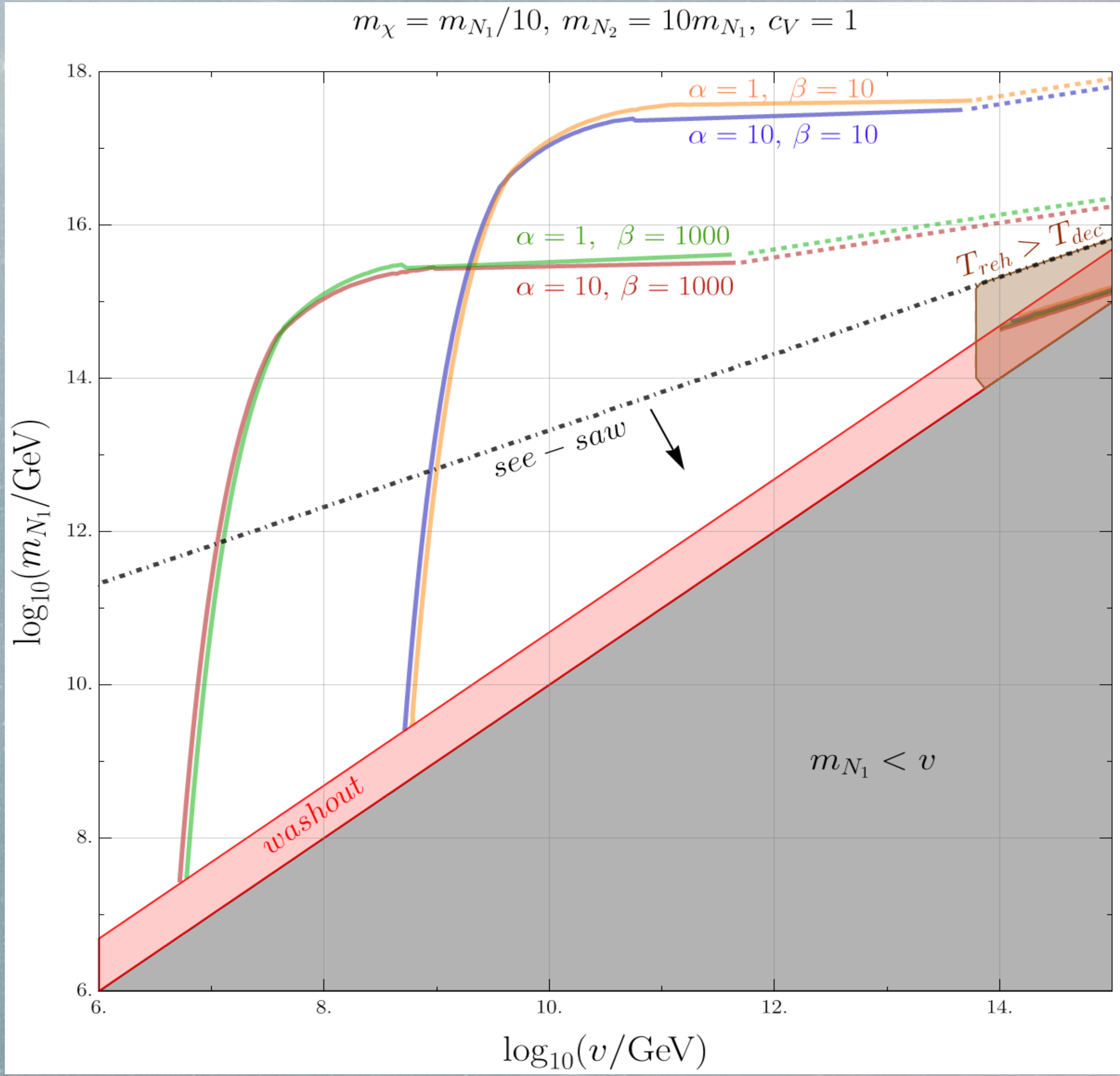
To avoid strong washout we thus require $T_{\rm reh} \sim v \ll T_{\rm dec} \sim 3\times 10^{13}$ GeV

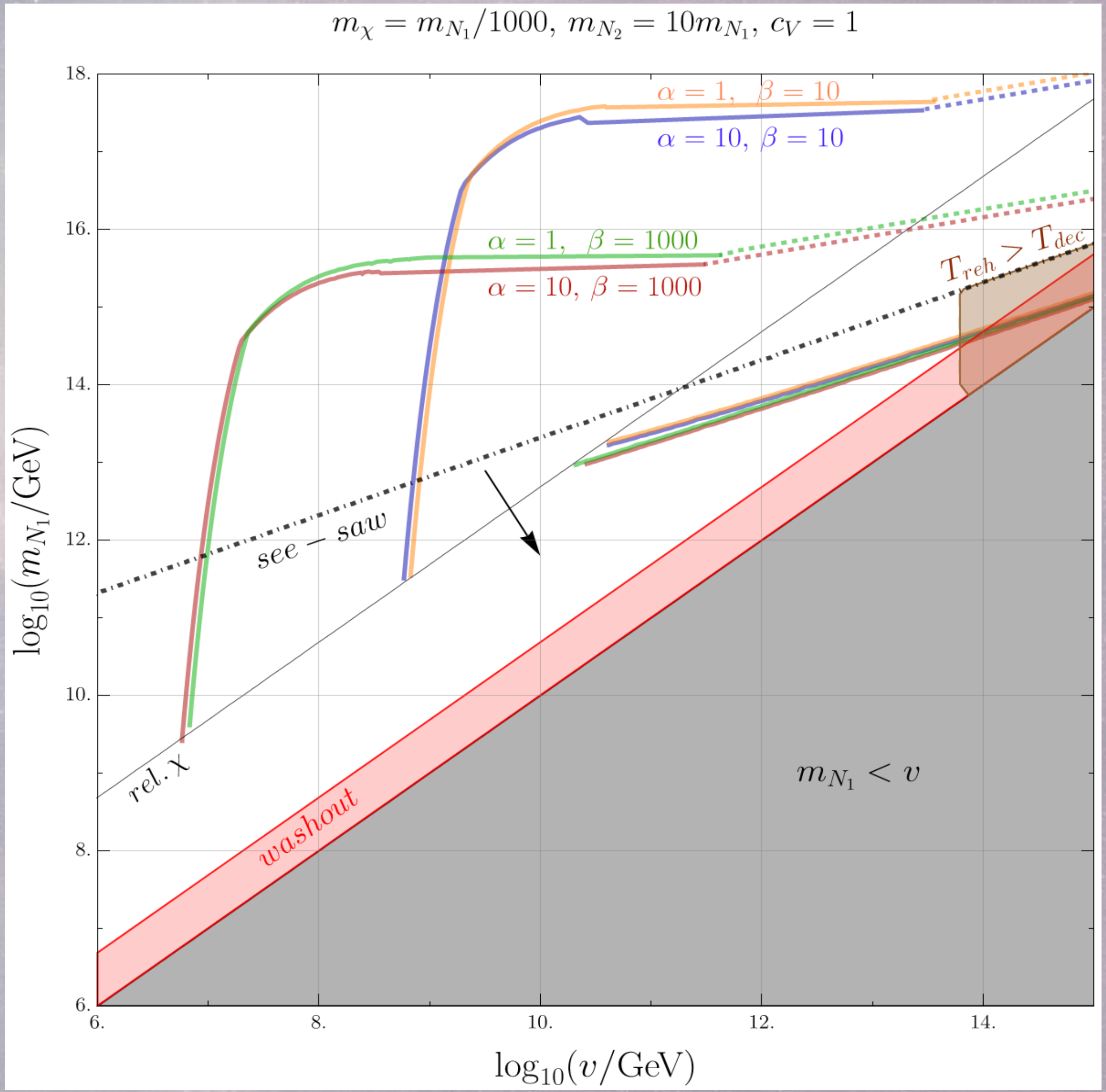
In our construction we can easily avoid this bound since we usually have v<< mN.

$$\Gamma_{\phi\chi\to N} \propto \frac{|Y|^2 m_N}{8\pi} e^{-m_N/T}$$

→ **exponentially suppressed production of N.**

Parameter space for *on-shell* and *off-shell* production





Gravitational wave signal

Since we have $\gamma >> 1$, we will use *bulk flow* model, T.Konstandin, *JCAP* **03** (2018) 047

$$h^2\Omega_{GW}^{today} = h^2\Omega_{peak} S(f, f_{peak}) \qquad S(f, f_{peak}) = \frac{(a+b) f_{peak}^b f^a}{b f_{peak}^{(a+b)} + a f^{(a+b)}}, \qquad (a,b) \approx (0.9, 2.1),$$

energy mostly in the **sound waves**

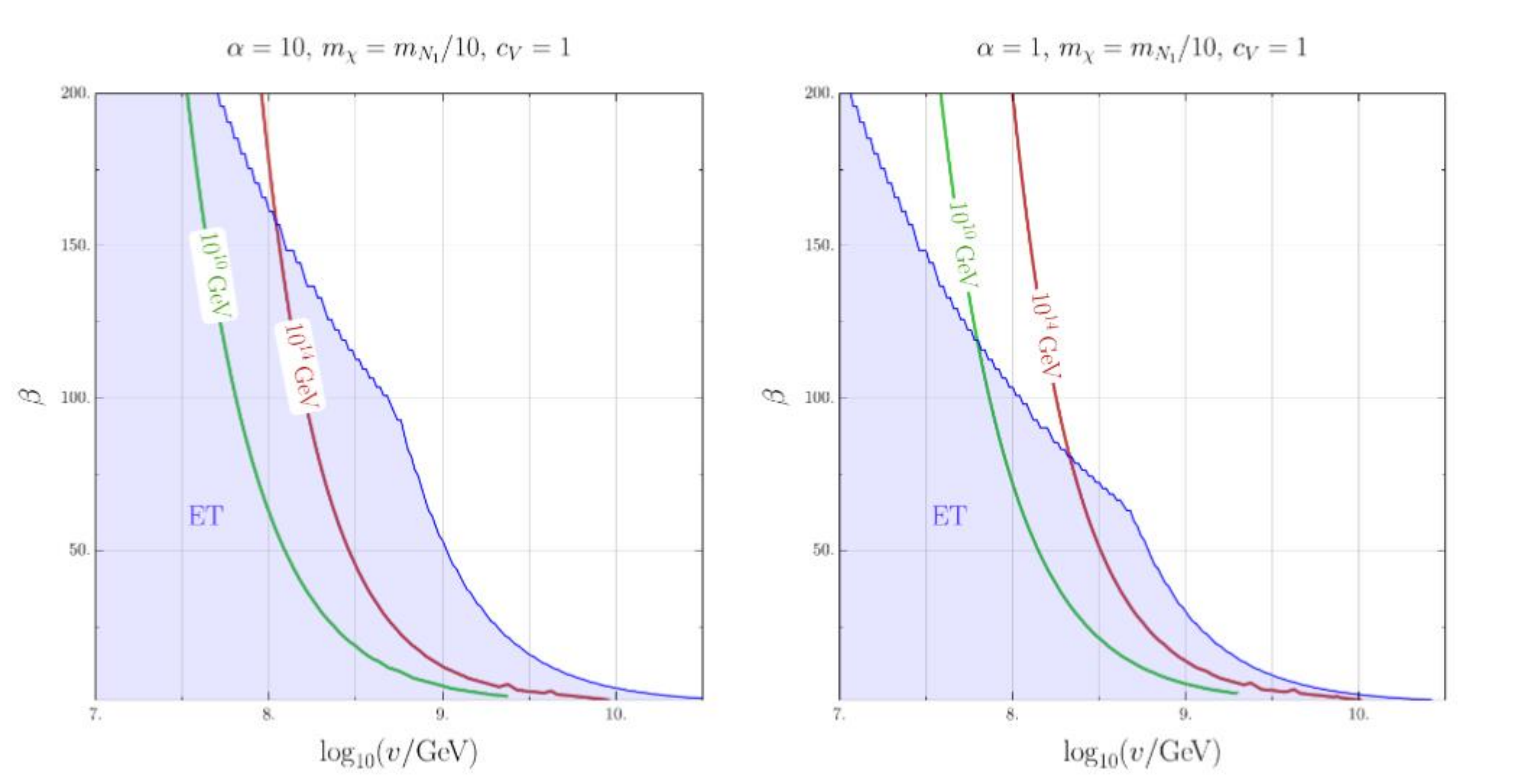
The energy density and the peak frequency are given by

$$h^2\Omega_{peak} \approx 1.06 \times 10^{-6} \left(\frac{H_{reh}}{\beta}\right)^2 \left(\frac{\alpha\kappa}{1+\alpha}\right)^2 \left(\frac{100}{g_\star}\right)^{1/3} \quad \text{and},$$

$$f_{peak} \approx 2.12 \times 10^{-3} \left(\frac{\beta}{H_{reh}}\right) \left(\frac{T_{reh}}{100\text{GeV}}\right) \left(\frac{100}{g_\star}\right)^{-1/6} \quad \text{mHz}.$$

An IR cut-off $f < H(T_{reh})/(2\pi)$ imposed by causality.

Gravitational wave signals for the Einstein telescope



Conclusions

I. Bubble collisions from phase transitions allow to create very heavy particles

II. The same mechanism can also entail CP violation in the production

III. We have applied this observation to a concrete realization of baryogenesis

IV. We computed CP violation both from the on-shell and off-shell production

V. We start with zero asymmetry =|> the asymmetry is separated into two different sectors.

VI. Consequently, we also attempt to explain the DM abundance via *cogenesis*.

VII. Adding lepton violating terms can be used to also explain the neutrino masses

Thank you for attention!