Part 1:
Phase-Separated Leptogenesis

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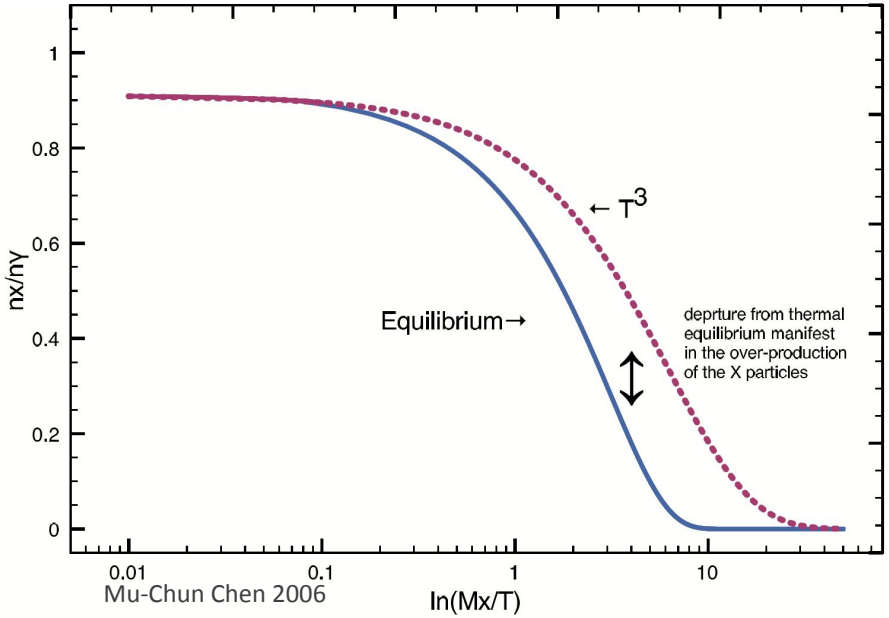
Leptogenesis Overview

Heavy Right-Handed Neutrino population decouples and becomes out of equilibrium

CP-asymmetric decay of RHN satisfies Sakharov conditions

Generated lepton asymmetry converted to baryon asymmetry by sphalerons

Leads to observed Baryon Asymmetry



Resonant Leptogenesis

Standard leptogenesis requires heavy RHN (Davidson-Ibarra):

$$\epsilon_N \gtrsim 10^{-6} \rightarrow M_N \gtrsim 10^9 \text{ GeV}$$

Increased CP asymmetry at resonance:

$$\epsilon_N = \frac{\sum_\alpha \left[\Gamma\left(N_1 \rightarrow \ell_\alpha H\right) - \Gamma\left(N_1 \rightarrow \bar{\ell}_\alpha \bar{H}\right)\right]}{\sum_\alpha \left[\Gamma\left(N_1 \rightarrow \ell_\alpha H\right) + \Gamma\left(N_1 \rightarrow \bar{\ell}_\alpha \bar{H}\right)\right]} \sim \frac{1}{2} \frac{\text{Im}\left(hh^\dagger\right)_{ij}^2}{(hh^\dagger)_{ii}(hh^\dagger)_{jj}} \boxed{\frac{\Delta m_N \, \Gamma_N}{(\Delta m_N)^2 + \Gamma_N^2/4}}$$

More experimentally accessible RHN

$$\epsilon_N \sim \mathcal{O}(1) \rightarrow M_N \gtrsim \text{ TeV}$$

Requires mass difference ~ decay rate, often involves fine-tuning

Lagrangian

RHN couples to Higgs and new scalar

$$\mathcal{L} \supset h_{ij}\overline{N}_i \ell_{L_j} H - \frac{1}{2}(m_N)_{ij}\overline{N}_i^c N_j - \frac{1}{2}(y_R)_{ij}\Phi\overline{N}_i^c N_j + V_{\text{eff}}(\Phi, T) + \text{h.c.}$$

Allows for CP asymmetric $N \rightarrow H\ell$ decays

Scalar undergoes FOPT, providing separated phases

Assume degenerate Majorana masses, thermal mass splittings from SM:

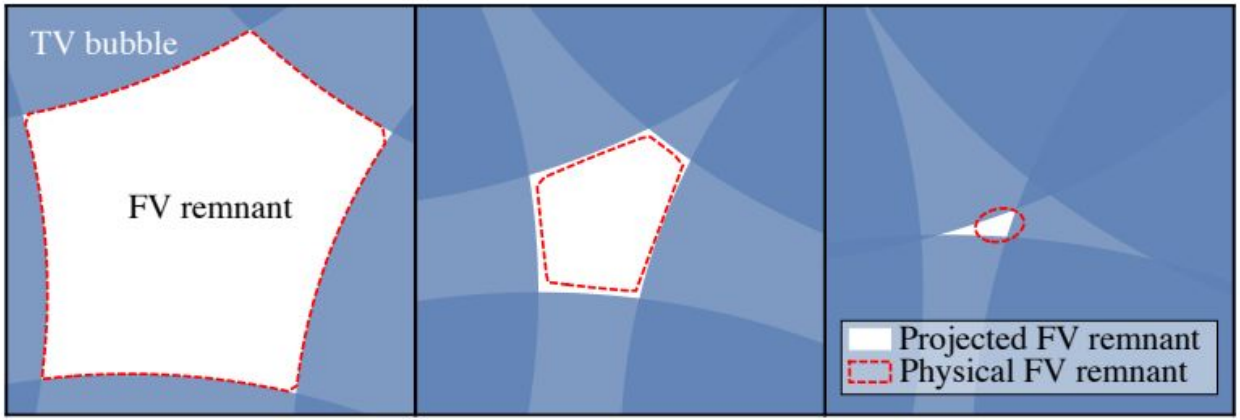
$\Delta m_N \sim \text{Re}[(hh^\dagger)_{ij}]T_{\text{SM}}^2/m_N \sim \Gamma_N/2$ (Resonance!)

First Order Phase Transition

RHN trapped within the false vacuum by mass gap: $m_N{}^{\text{true}} - m_N{}^{\text{false}} = (y_R)_{ii} v_\Phi \gg T_B$

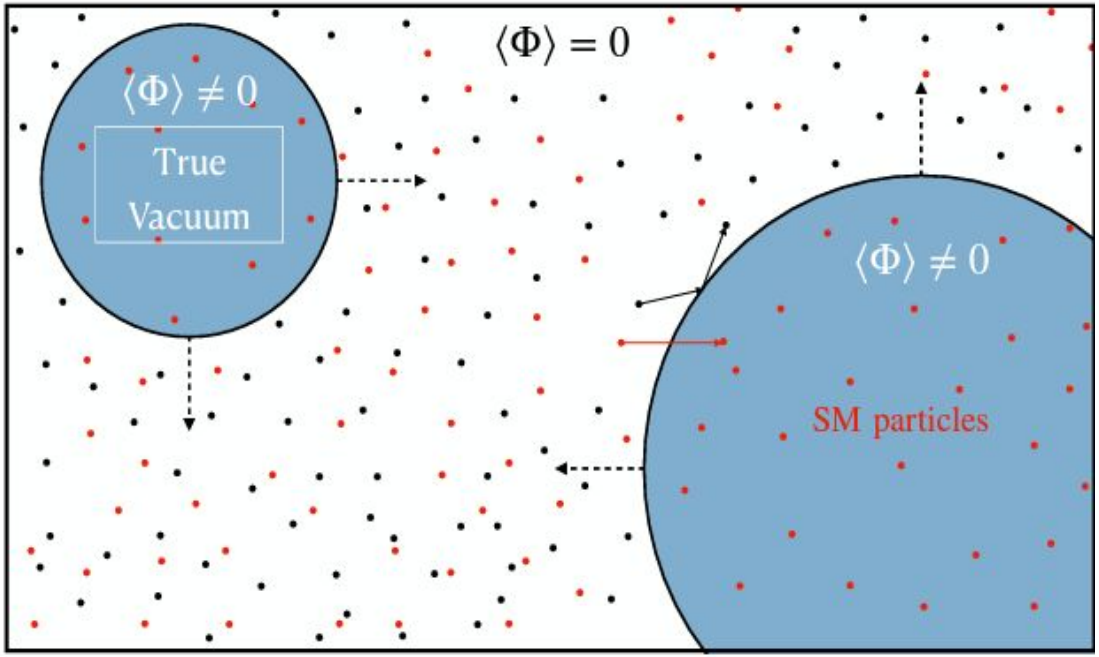
Thermal pressure equilibrium with vacuum pressure

= Thermal ball at fixed temperature: $T_B = (3\alpha_B)^{1/4} T_c$

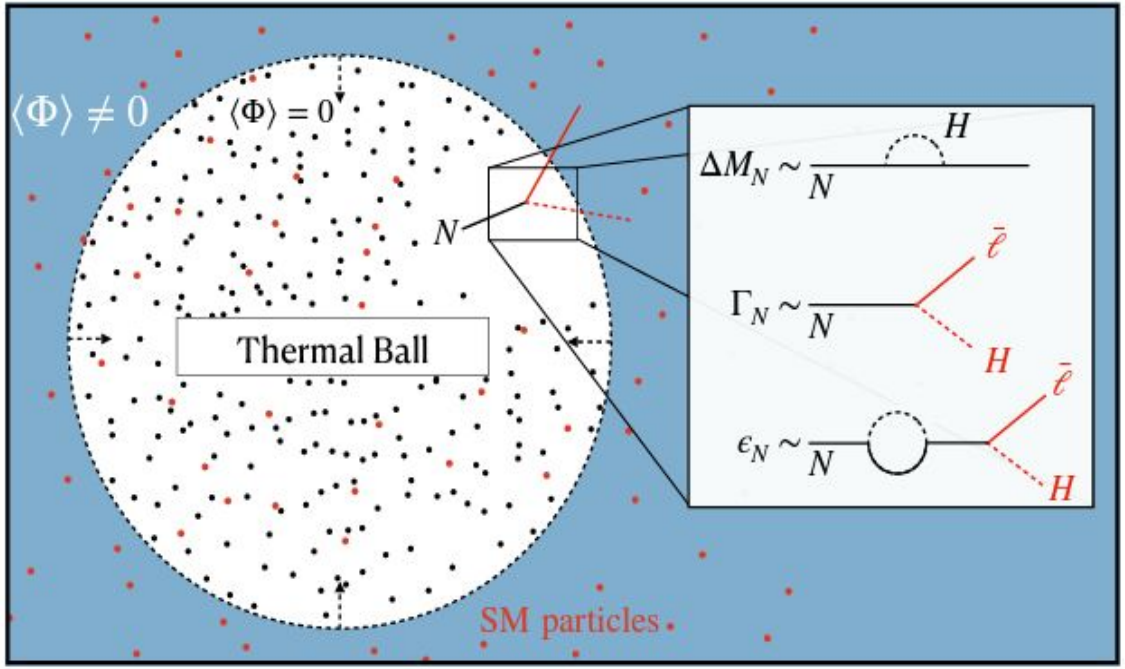


Lu et al. 2022

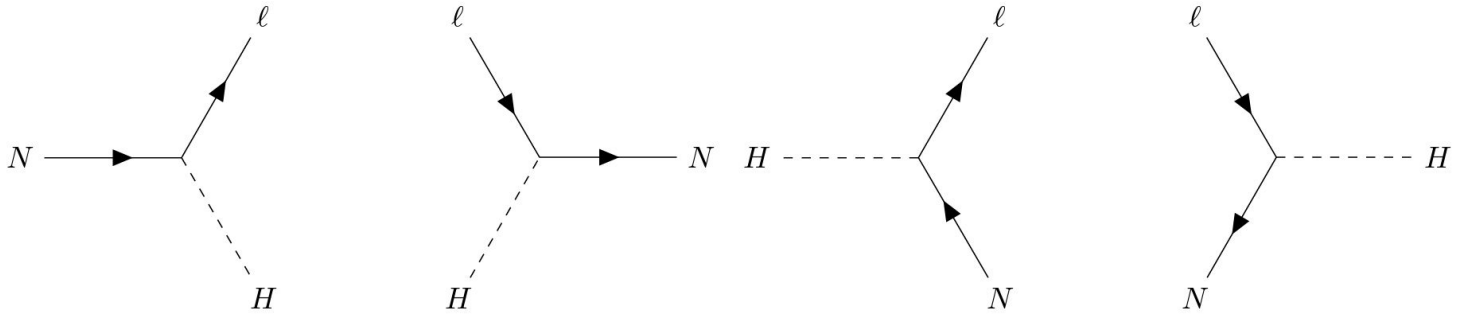
Thermal Ball Formation



Thermal Ball Processes



Thermal Ball Processes



Boltzmann evolution of decay and inverse decay

$$\frac{dn_{\ell-\bar{\ell}}}{dt} + 3Hn_{\ell-\bar{\ell}} \simeq n_B V_B \int \frac{d^3p}{(2\pi)^3 2E_p} \frac{d^3q}{(2\pi)^3 2E_q} \frac{d^3k}{(2\pi)^3 2E_k} (2\pi)^4 \delta^4(p-k-q)$$

$$\times \left\{ |\mathcal{M}|^2_{N_i \to \ell H} [(1-f_\ell)(1+f_H) f_N + f_{\bar{\ell}} f_{\bar{H}} (1-f_N)] \; - \frac{1-\epsilon_N}{1+\epsilon_N} |\mathcal{M}|^2_{N_i \to \ell H} [(1-f_{\bar{\ell}})(1+f_{\bar{H}}) f_N + f_\ell f_H (1-f_N)] \right\}$$

Baryon Asymmetry Generation

Initial thermal ball density:

$$n_B(T) = 1.31 \times 10^5 v_w^{-3} \left(\frac{\beta/H}{100}\right)^3 \frac{g_*(T) g_*(T_c)^{1/2} T^3 T_c^3}{M_{\rm pl}^3}$$

RHN decays deplete thermal balls

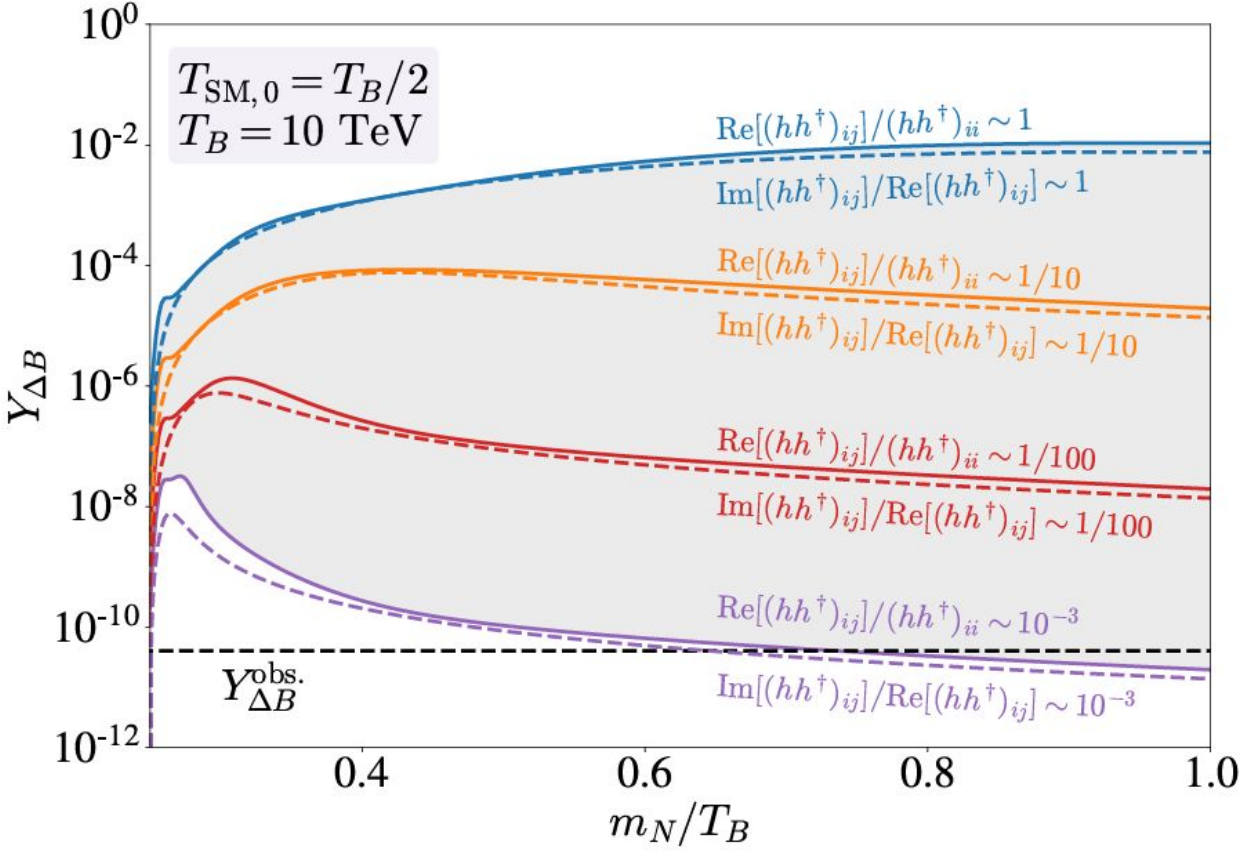
$$\Delta Y_{\ell-\bar{\ell}} = \int \frac{n_B R_0^3}{H(T_{\rm SM}) T_{\rm SM} s(T_{\rm SM})} \exp\left(- \int_{T_{\rm SM}}^{T_N} \frac{\mathcal{I}_N(T'_{\rm SM})}{n_0 T'^3_{\rm SM}} dT'_{\rm SM} \right) \mathcal{I}_{\ell-\bar{\ell}}(T_{\rm SM}) dT_{\rm SM}$$

Baryon asymmetry production includes sphaleron and FOPT parameters

$$Y_{\Delta B} \simeq 1.22 \times 10^{-3} \left(\frac{T_B}{T_c}\right)^3 (1+f_{\rm B})^{-3/4} \left(\frac{1+\alpha_B}{1.16\alpha_B}\right) \epsilon_N(T_d)$$

Suppression from washout factors or small off-diagonal elements

Baryon Asymmetry



Conclusions

1. First order phase transition can trap RHNs and form thermal balls.

2. This separated phase environment naturally induces a thermal mass splitting on the order of the decay width.

3. Resonant leptogenesis produces abundant baryon asymmetry. Suppression factors can reduce to the observed BAU value.

4. Phase separation allows for degenerate masses in the thermal ball, and hierarchical masses in the present-day true vacuum. This realizes resonant leptogenesis with interesting mass textures.

Part 2: Q-balls in the Presence of Attractive Force

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Q-Ball Models

Friedberg-Lee-Sirlin

- One complex + one real scalar
- Symmetric vacuum inside
- “Non-topological Solitons”

Coleman

- One complex scalar
- “Q-ball”

Both

- Conserved charge Q
- Evades Derrick’s Theorem with time-dependent phase
- Stable macroscopic objects

FLS Lagrangian w/ Yukawa Force

Complex scalar Φ with U(1) symmetry

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \chi)^2 + |\partial_\mu \Phi|^2 - V(\chi, \Phi)$$

Quartic interaction promotes stability, new Yukawa interaction destabilizes

$$V(\chi, \Phi) = U(\chi) + \Lambda \chi |\Phi|^2 + \kappa \chi^2 |\Phi|^2$$

Real scalar X potential induces symmetry breaking

$$U(\chi) = \frac{\lambda}{4!}(\chi^2 - v^2)^2$$

Equations of Motion

X EOM enforces constant value inside Q-ball

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\chi}{dr}\right) - \frac{dU(\chi)}{d\chi} - \frac{\Lambda}{2}\phi^2 - \kappa\phi^2\chi = 0$$

Φ sinc function satisfies Helmholtz equation

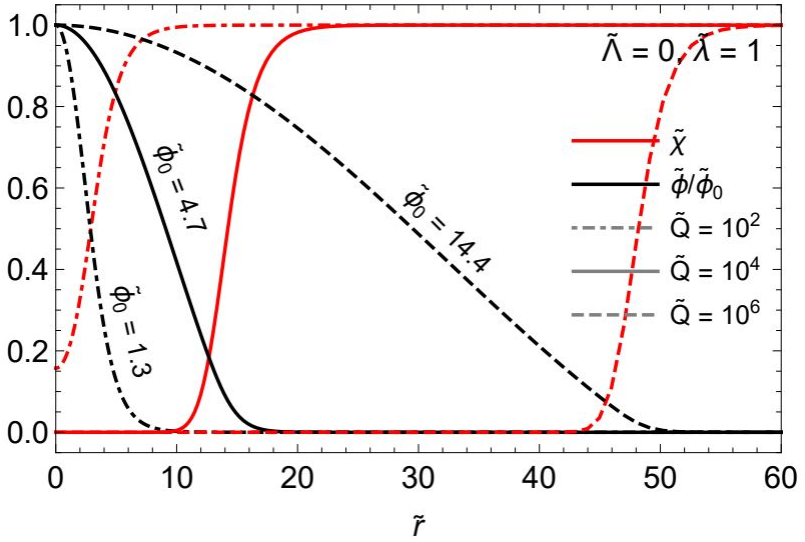
$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\phi}{dr}\right) + \omega^2\phi - (\Lambda\chi + \kappa\chi^2)\phi = 0$$

Conserved charge ensures stability w.r.t. decays

$$Q = 4\pi\omega\int_0^\infty r^2 dr\,\phi^2(r)$$

Approximate Solution

$$\chi(r) \simeq \begin{cases} -\frac{\Lambda}{2\kappa} & r < R_\Lambda \\ -\frac{\Lambda}{2\kappa} + \left(v + \frac{\Lambda}{2\kappa}\right)\left[1 - e^{-m_\chi (r - R_\Lambda)}\right] & r > R_\Lambda \end{cases}, \qquad \phi(r) \simeq \begin{cases} \phi_0 \frac{\sin \omega_\Lambda r}{\omega_\Lambda r} & r < R_\Lambda \\ 0 & r > R_\Lambda \end{cases}$$



Effective radius:

$$\frac{\pi}{R_\Lambda} = \omega_\Lambda = \sqrt{\omega^2 + \Lambda^2/4\kappa}$$

Solving for ω

Total energy of the Q-ball:

$$E = \omega Q + \frac{\lambda\pi^4}{18\omega_\Lambda^3}\left(\frac{\Lambda^2}{4\kappa^2} - v^2\right)^2 + \frac{2\pi^3 v^2 m_\chi}{\omega_\Lambda^2}a_1 + \frac{4\pi^2 v^2}{\omega_\Lambda}a_2 + \frac{4\pi v^2}{m_\chi}a_3$$

Thin wall approximation: drop surface terms

$$\frac{dE}{d\omega} = Q - \frac{\lambda\pi^4\omega}{6\left(\omega^2 + \frac{\Lambda^2}{4\kappa}\right)^{5/2}}\left(\frac{\Lambda^2}{4\kappa^2} - v^2\right)^2 = 0$$

Thick wall approximation: drop volume term

$$\frac{dE}{d\omega} = Q - \frac{\lambda\pi^4\omega}{6\omega_\Lambda^5}\left(\frac{\Lambda^2}{4\kappa^2} - v^2\right)^2 - \frac{4\pi^3 v^2 m_\chi \omega}{\omega_\Lambda^4}a_1 - \frac{4\pi^2 v^2 \omega}{\omega_\Lambda^3}a_2 = 0$$

Minimum and Maximum Charges

Maximum charge scales sharply with interaction strength

$$Q_{\max}^{\text{thin}} = \frac{128\pi^4\kappa^2\lambda}{75\sqrt{5}\Lambda^4}\left(\frac{\Lambda^2}{4\kappa^2} - v^2\right)^2 \qquad Q_{\max}^{\text{thick}} \approx \frac{6\sqrt{3}\pi^3 v^2 m_\chi \kappa^{3/2}}{\Lambda^3}\left(1 + \frac{\Lambda}{2\kappa v}\right)^2$$

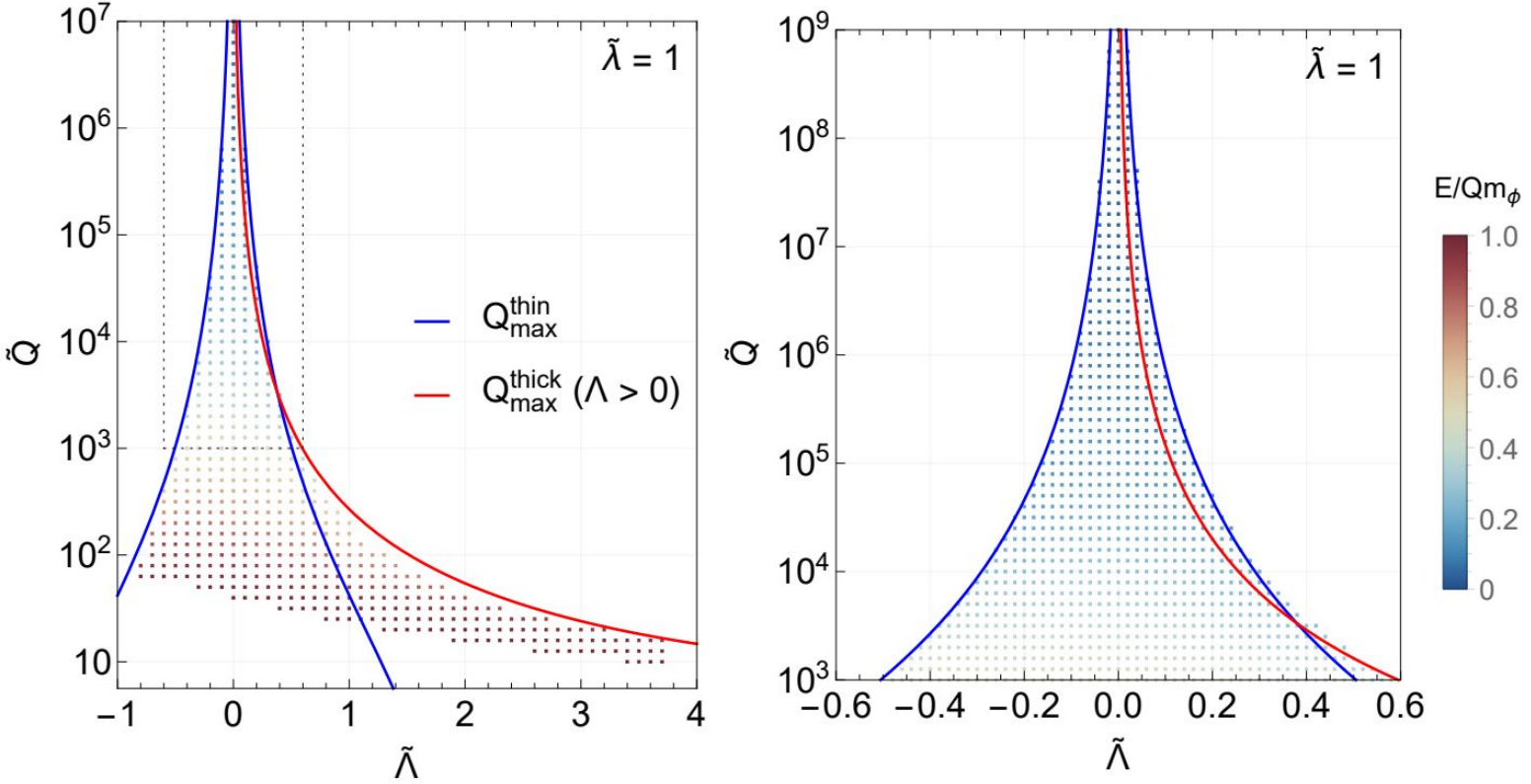
Basic FLS Q-ball has no maximum charge, new restrictive upper limit

Minimum charge can be estimated by energy considerations

$$Q_{\min} \approx \frac{\lambda\pi^4 m_\Phi}{6(m_\Phi^2 + \Lambda^2/4\kappa)^{5/2}}\left(\frac{\Lambda^2}{4\kappa^2} - v^2\right)^2 + \frac{4\pi^3 v^2 m_\chi m_\Phi a_1}{(m_\Phi^2 + \Lambda^2/4\kappa)^2} + \frac{4\pi^2 v^2 m_\Phi a_2}{(m_\Phi^2 + \Lambda^2/4\kappa)^{3/2}}$$

Increased interaction strength results in lighter stable Q-ball configurations.

Maximum Stable Charge



Implications of Instability (Preliminary)

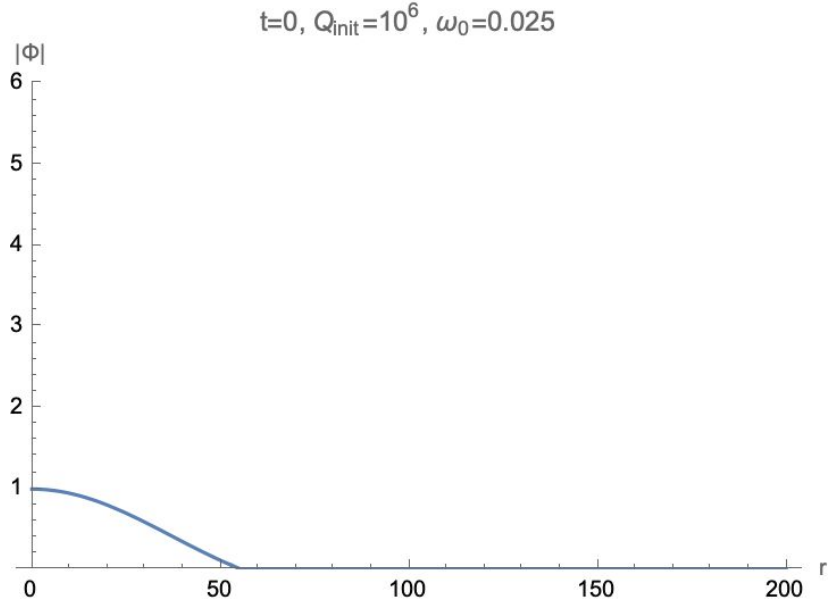
No stationary solution above the maximum charge

$\not\Rightarrow$Collapse into black hole

$\Rightarrow$Exponential Growth

Does growth continue?

Could unstable Q-balls cover the Universe?



Conclusions

1. The inclusion of the Yukawa interaction term alters the Q-ball profile

2. Even at low interaction strengths, a meaningful upper bound on the charge is imposed

3. Unstable Q-balls may not collapse into PBHs, as an attractive interaction would suggest, but could paradoxically expand and grow.