Baryogenesis via relativistic bubble expansion

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Vrije Universiteit Brussel (VUB)

Based on:
Baldes, **SB**, Mariotti, Sevrin, Turbang
[2106.15602] PRD

"How fast does the bubble grow?" 15-17 May 2023, DESY Hamburg

Introduction

Baryon asymmetry of the Universe:

$$Y_B = \frac{n_b - n_{\bar{b}}}{s} \sim 10^{-10}$$

Abundance set by B - $\bar{B}$ annihilation:

$$\frac{n_b}{s} \left(= \frac{n_{\bar{b}}}{s} \right) \sim 10^{-20}$$

Solution: some **initial quark-anti quark asymmetry** prevents strong annihilation, and explains absence of antimatter in our Universe.

Dynamical generation of the asymmetry: **baryogenesis**, a challenge for particle physics!

Introduction

Sakharov conditions

- Baryon number violation
- C and CP violation
- Departure from thermal equilibrium

Introduction

Electroweak baryogenesis

- SM sphalerons violate B+L
- Beyond the SM violation of CP
- First order electroweak phase transition

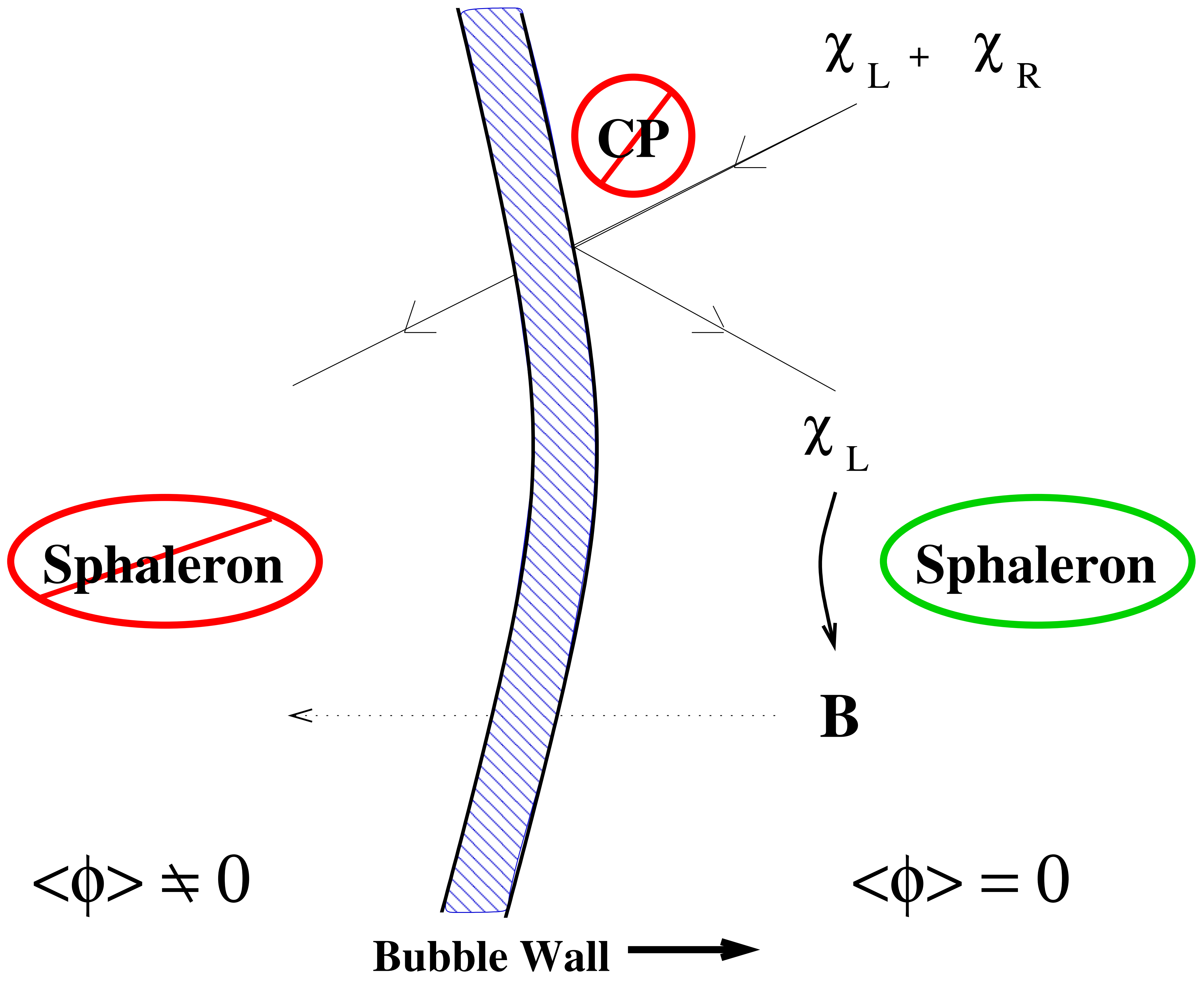


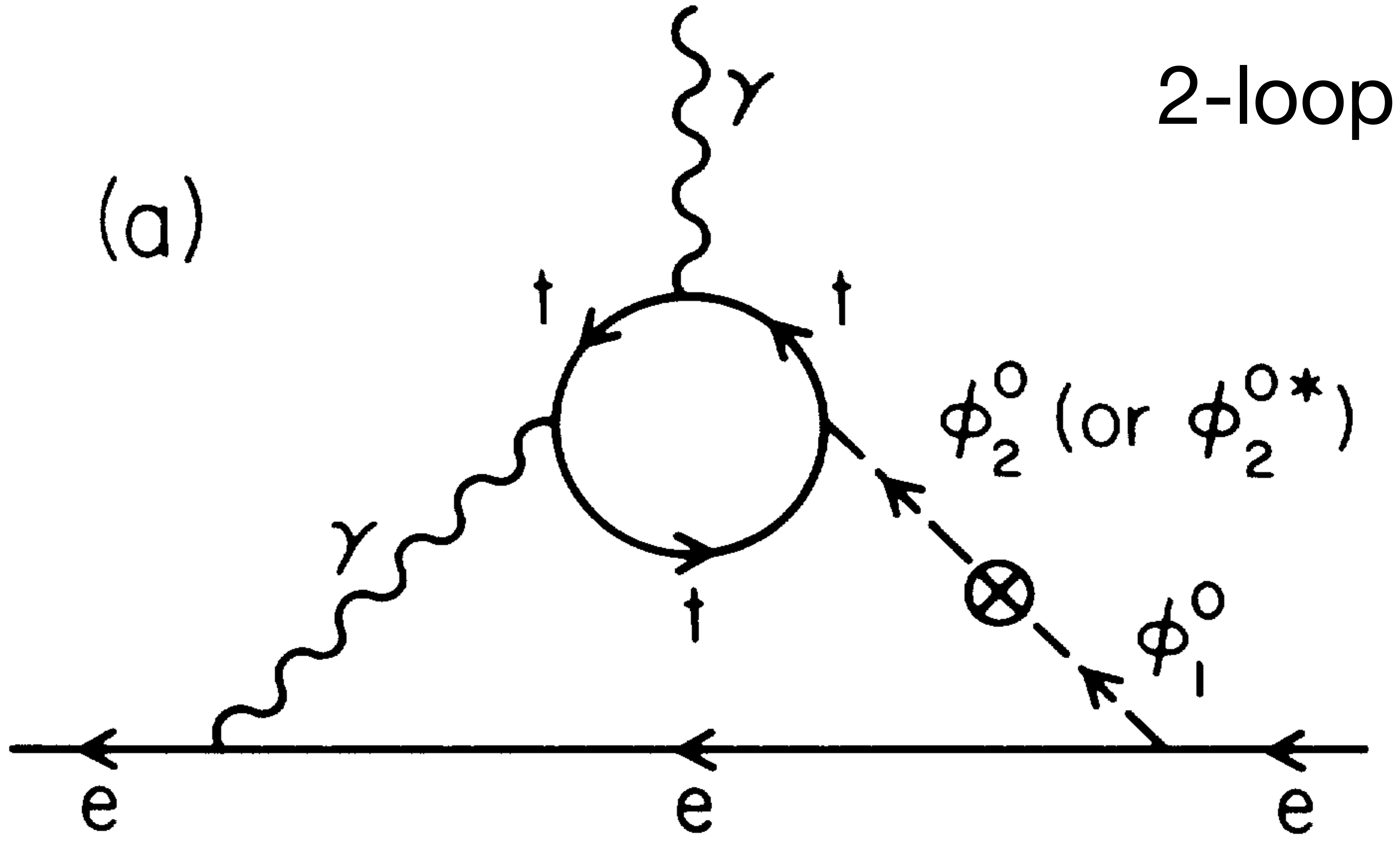
Fig. from Morrissey, Ramsey-Musolf [1206.2942]

Introduction

Successful electroweak baryogenesis

- In tension with electric dipole moment measurement

See also: Postma, van de Vis, White [2206.01120] JHEP



2-loop Zee-Barr

$$|d_e| \sim 10^{-29}\, \theta_{CP} \left(\frac{2.5\,\text{TeV}}{\Lambda}\right)^2 e \cdot cm$$

Glioti, Rattazzi, Vecchi [1811.11740] JHEP

A way out: CP only *temporarily* broken during the phase transition

Introduction

Successful electroweak baryogenesis

- BAU suppressed for $v_w \to 0$ and $v_w \to 1$ (but possible for $v_w > c_s$)

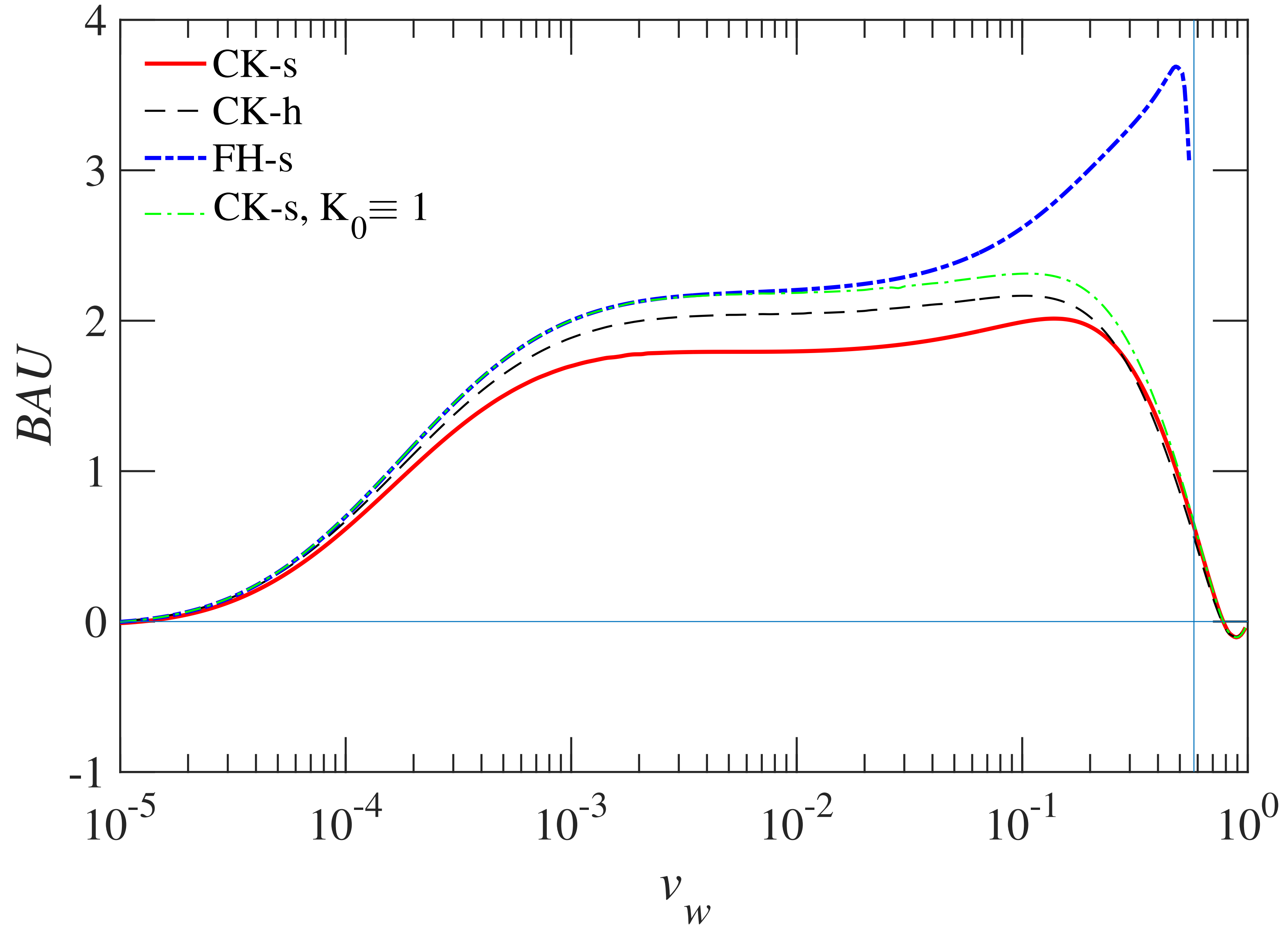


Fig. from Cline, Kainulainen [2001.00568] PRD
See also Dorsch, Huber, Konstandin [2106.06547]

- BAU **and** observable gravitational waves?

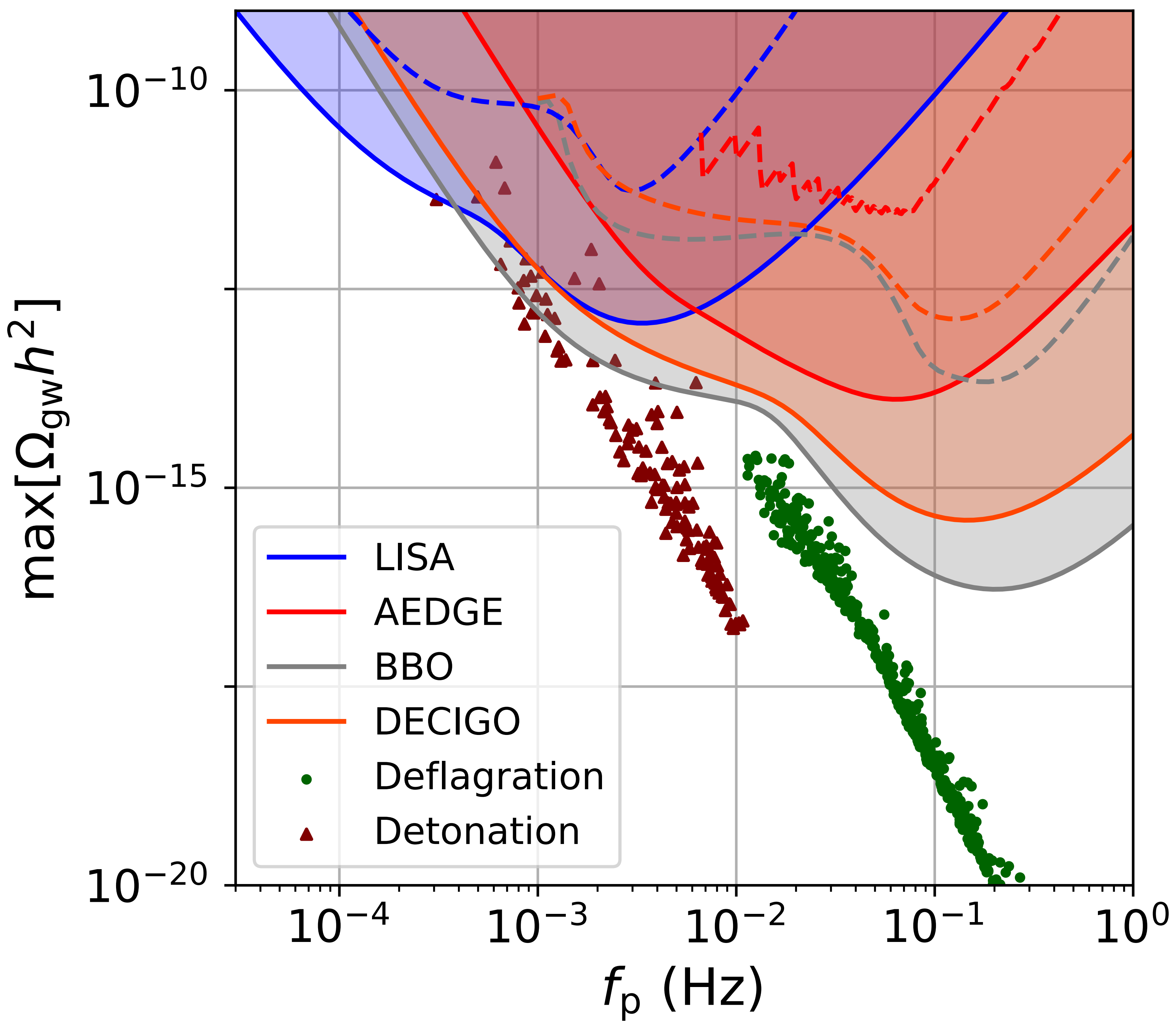


Fig. from Laurent, Cline et al. [2102.12490] PRD

➡ Can we have baryogenesis with (ultra) relativistic bubble walls?

➡ Can this mechanism lead to a large GW signal?

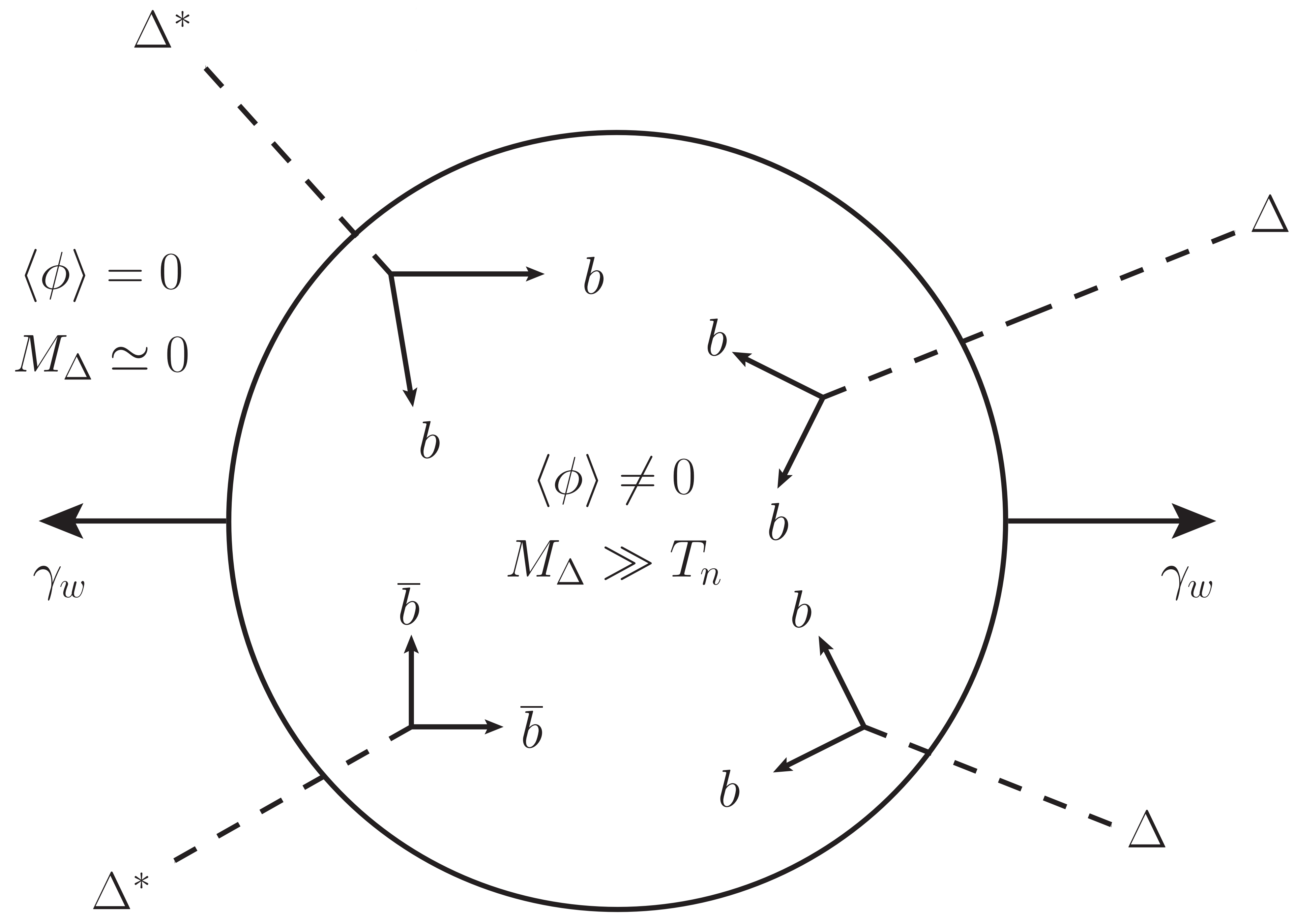
Baryogenesis with relativistic walls

Baldes, **SB**, Mariotti, Sevrin, Turbang
[2106.15602] PRD

Mass gain mechanism

- A particle Δ in thermal equilibrium gains a large mass M_Δ across the wall

$$\mathscr{L} \supset -\frac{\lambda}{2}\phi^2|\Delta|^2$$



Δ particles crossing the ϕ wall and gaining a mass undergo asymmetric decays.

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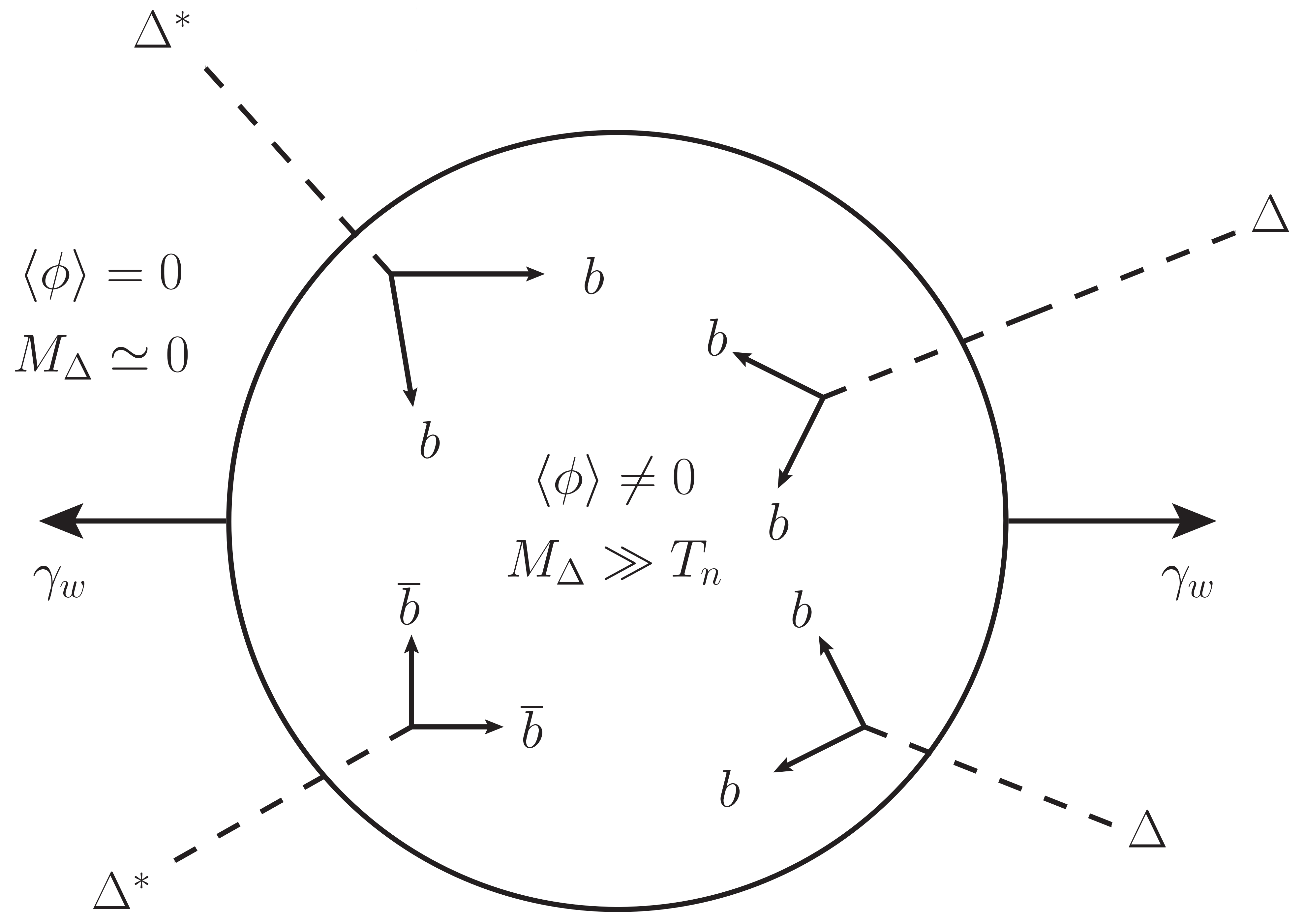
$$\gamma_w > \frac{M_\Delta}{T_n}$$



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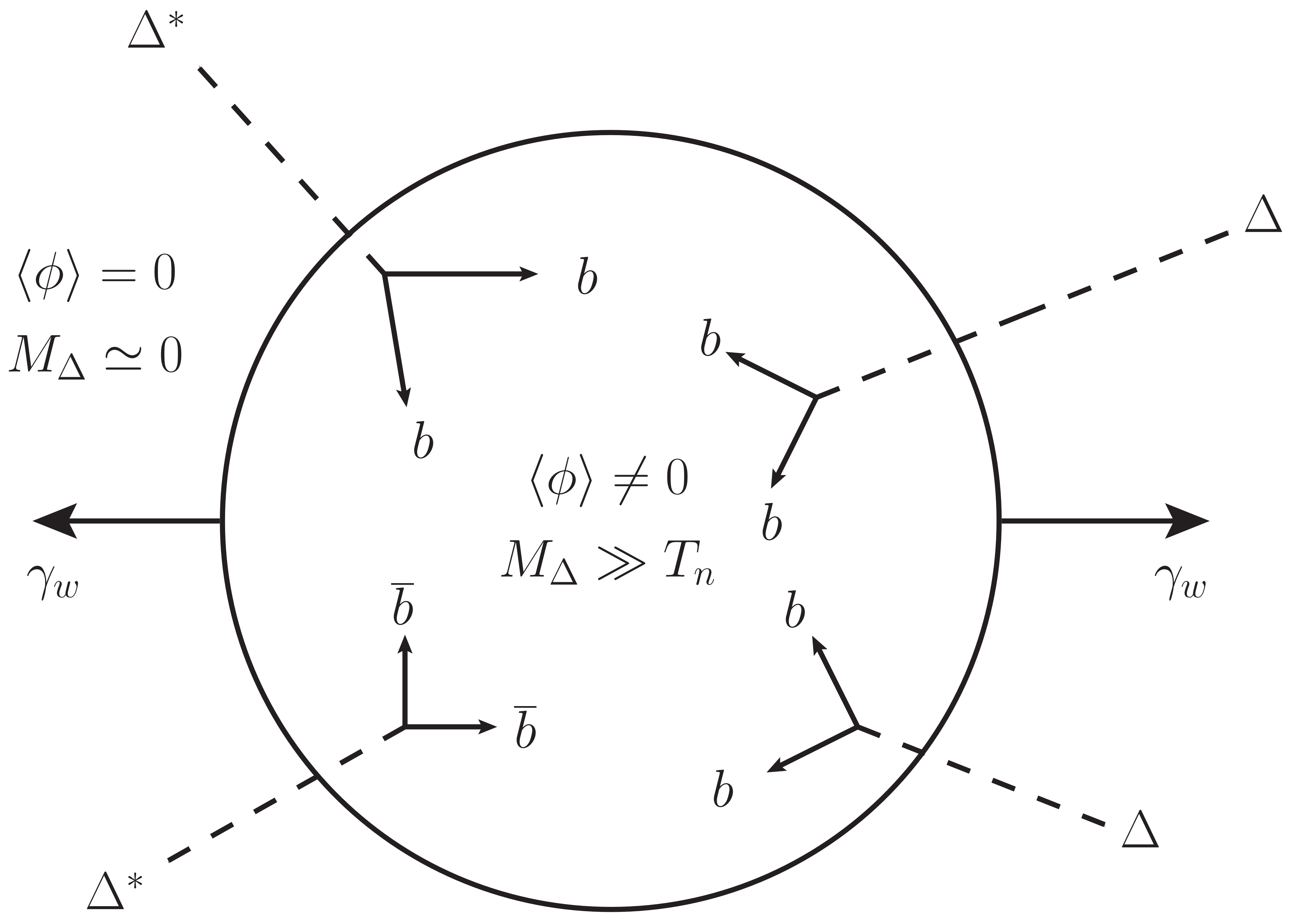
- Δ inside the bubble is out of equilibrium, and undergoes CP and B violating decays



Δ particles crossing the ϕ wall and gaining a mass undergo asymmetric decays.

Baryogenesis with relativistic walls

Mass gain mechanism

$$Y_B = \epsilon_\Delta \cdot \kappa_{Sph.} \left(\frac{n_\Delta(M_\Delta \simeq 0)}{s_e} \right)\Bigg|_{eq} \left(\frac{T_n}{T_{RH}} \right)^3$$

Fraction of asymmetric decays (1-loop effect)

Sphaleron reprocessing factor = 28/79

Large equilibrium abundance

Dilution from reheating (if strong supercooling)

Baryogenesis with relativistic walls

Mass gain mechanism

$$Y_B \sim \left(\frac{100}{g_*}\right)\left(\frac{\epsilon_\Delta}{1/16\pi}\right)\left(\frac{T_n}{T_{RH}}\right)^3 10^5\ Y_{B\ obs.}$$

Baryogenesis with relativistic walls

Baldes, **SB**, Mariotti, Sevrin, Turbang
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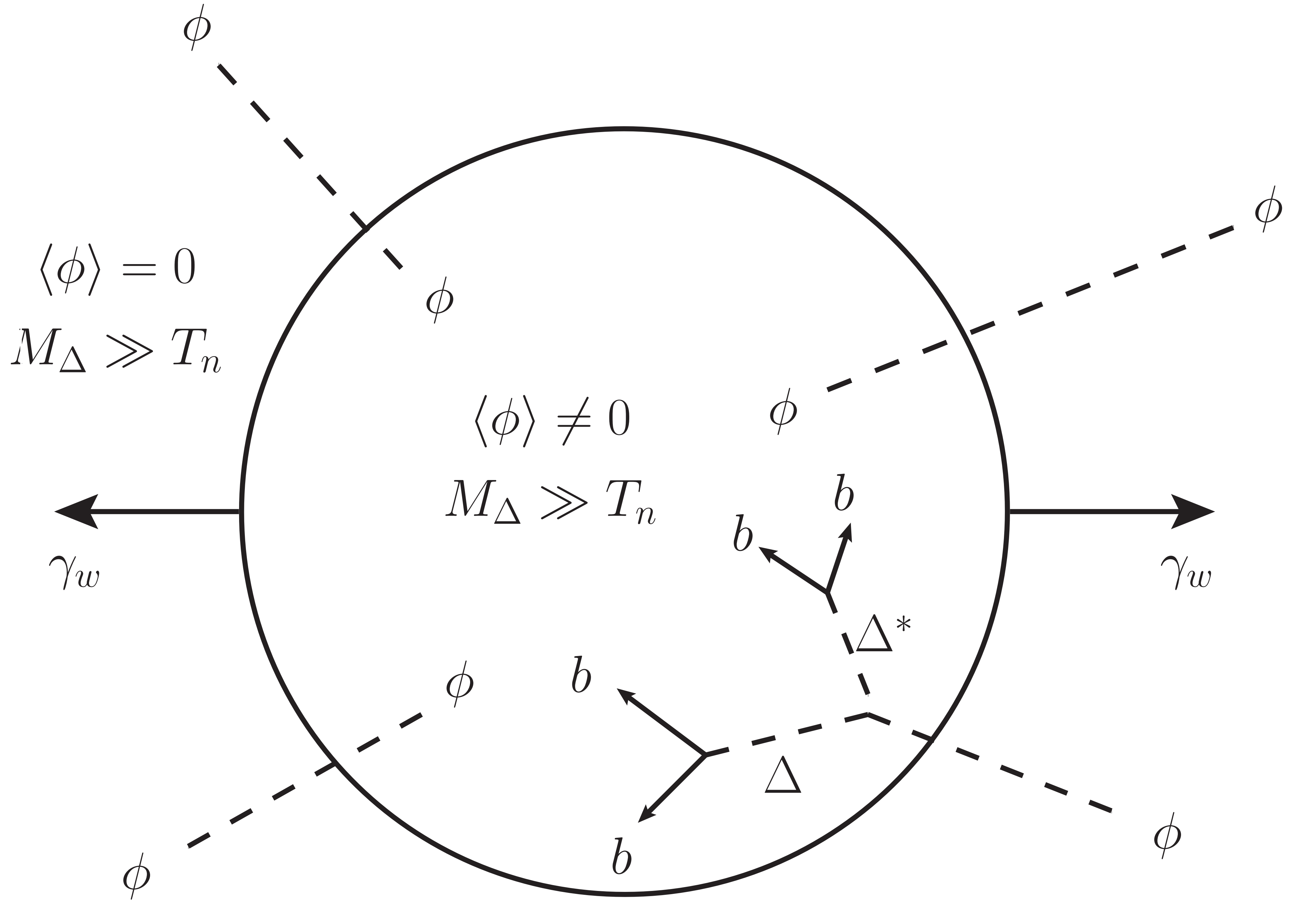
Azatov-Vanvlasselaer mechanism

- Heavy Δ particles are possibly produced from ϕ interacting with the wall

$$\mathscr{L} \supset -\frac{\lambda}{2}\phi^2 |\Delta|^2 - M_\Delta^2 |\Delta|^2$$



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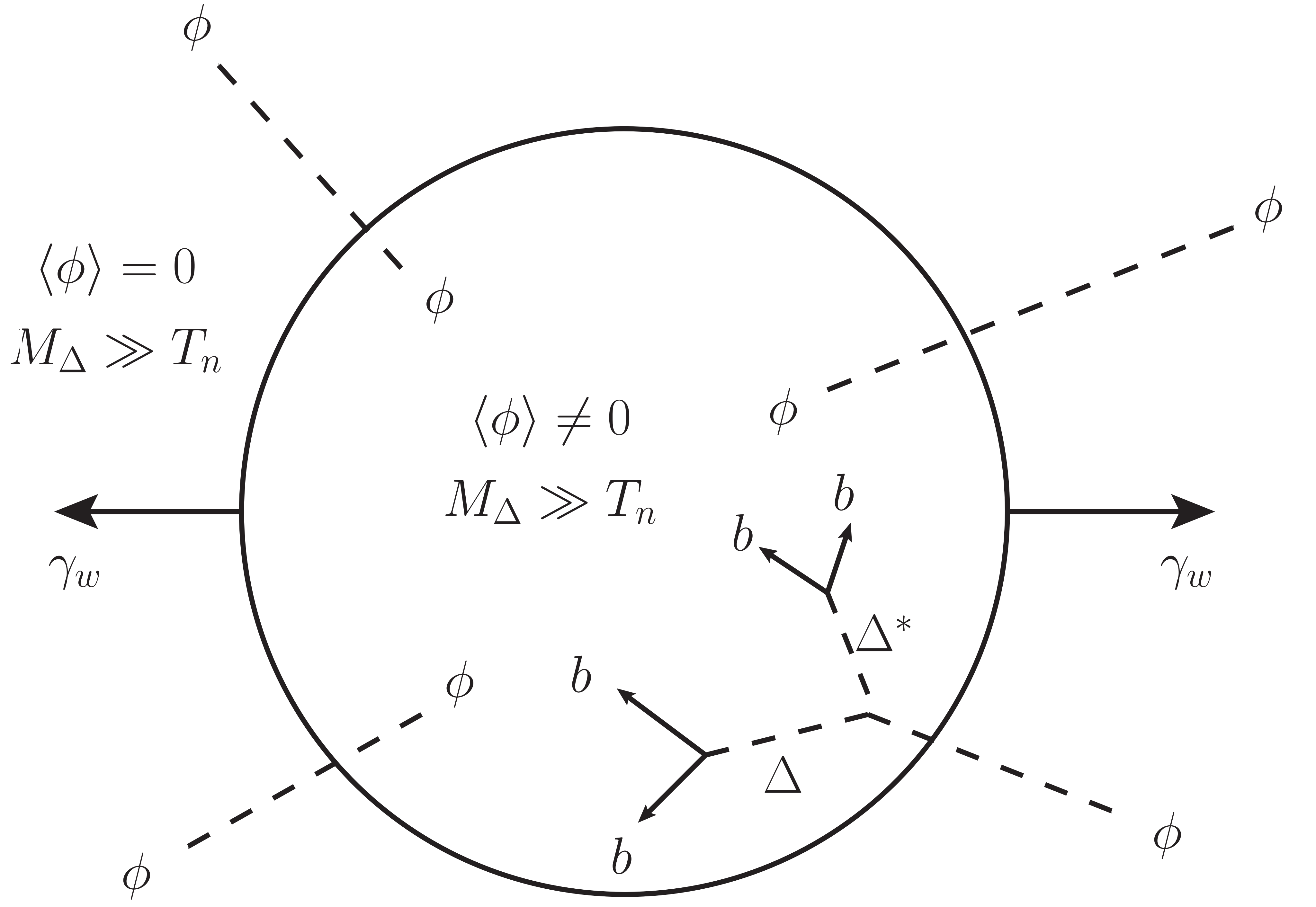
$$\gamma_w > (M_\Delta \delta_w) \cdot \frac{M_\Delta}{T_n}$$



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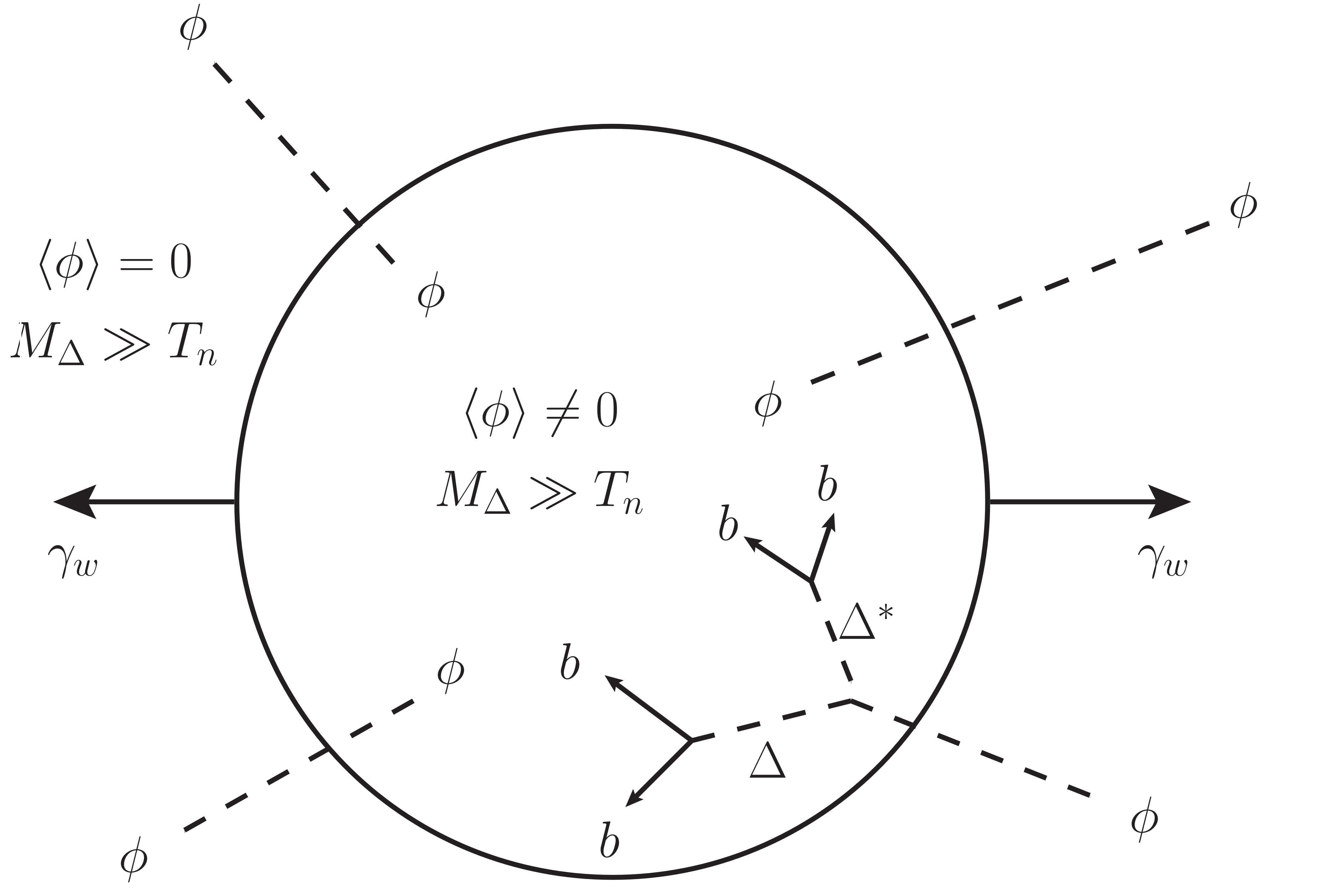
- Δ decays as the "mass gain" mechanism



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Baryogenesis with relativistic walls

Azatov-Vanvlasselaer mechanism

$$Y_B = \epsilon_\Delta \cdot \kappa_{Sph.} \cdot \mathscr{P}\left(\phi \to \Delta\Delta^*\right) \left(\frac{n_\phi}{s_e}\right)\Bigg|_{eq} \left(\frac{T_n}{T_{RH}}\right)^3$$

Prob. of 1 to 2 transition:

$$\mathscr{P} \sim \frac{\lambda^2 v_\phi^2}{96\pi^2 M_\Delta^2}$$

Large equilibrium abundance

Azatov, Vanvlasselaer
[2010.02590] JCAP

Azatov, Vanvlasselaer, Yin
[2101.05721] JHEP

Baryogenesis with relativistic walls

Azatov-Vanvlasselaer mechanism

$$Y_B \sim \left(\frac{100}{g_*}\right)\left(\frac{\epsilon_\Delta}{1/16\pi}\right)\left(\frac{T_n}{T_{RH}}\right)^3 \lambda^2 \left(\frac{v_\phi}{M_\Delta}\right)^2 10^2 \; Y_{B\ obs.}$$

Related work

- Azatov, Vanvlasselaer, Yin [2106.14913] JHEP (see also [2207.02230]): AV mechanism with CP violation at the wall

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- Falkowski, No [1211.5615] JHEP; Katz, Riotto [1608.00583] JCAP: production of heavy particles as a result of elastic wall collisions, leading to DM, BAU and GWs

Bubble wall dynamics

- **Vacuum pressure:**

$$\mathscr{P}_{dr} \sim \Delta V = c_{vac} \cdot v_\phi^4$$

- **Runaway bubbles:** $\Delta V > \mathscr{P}_{LO}, \; \mathscr{P}_{NLO} = 0$

$$\gamma_* \sim \frac{R_*}{R_c} \sim \frac{1}{\beta}\frac{T_n}{H_*} \gg 1$$

- **Pressure from the plasma:**

$$\mathscr{P}_{fr} = \mathscr{P}_{LO} + \gamma \, \mathscr{P}_{NLO}$$

$1 \to 1$ transmission of particles changing mass across the wall

$1 \to 2$ scatterings involving gauge bosons

$$\mathscr{P}_{LO} \sim g_a \frac{v_\phi^2 \, T^2}{24} + \mathcal{O}\left(\gamma^{-1}\right)$$

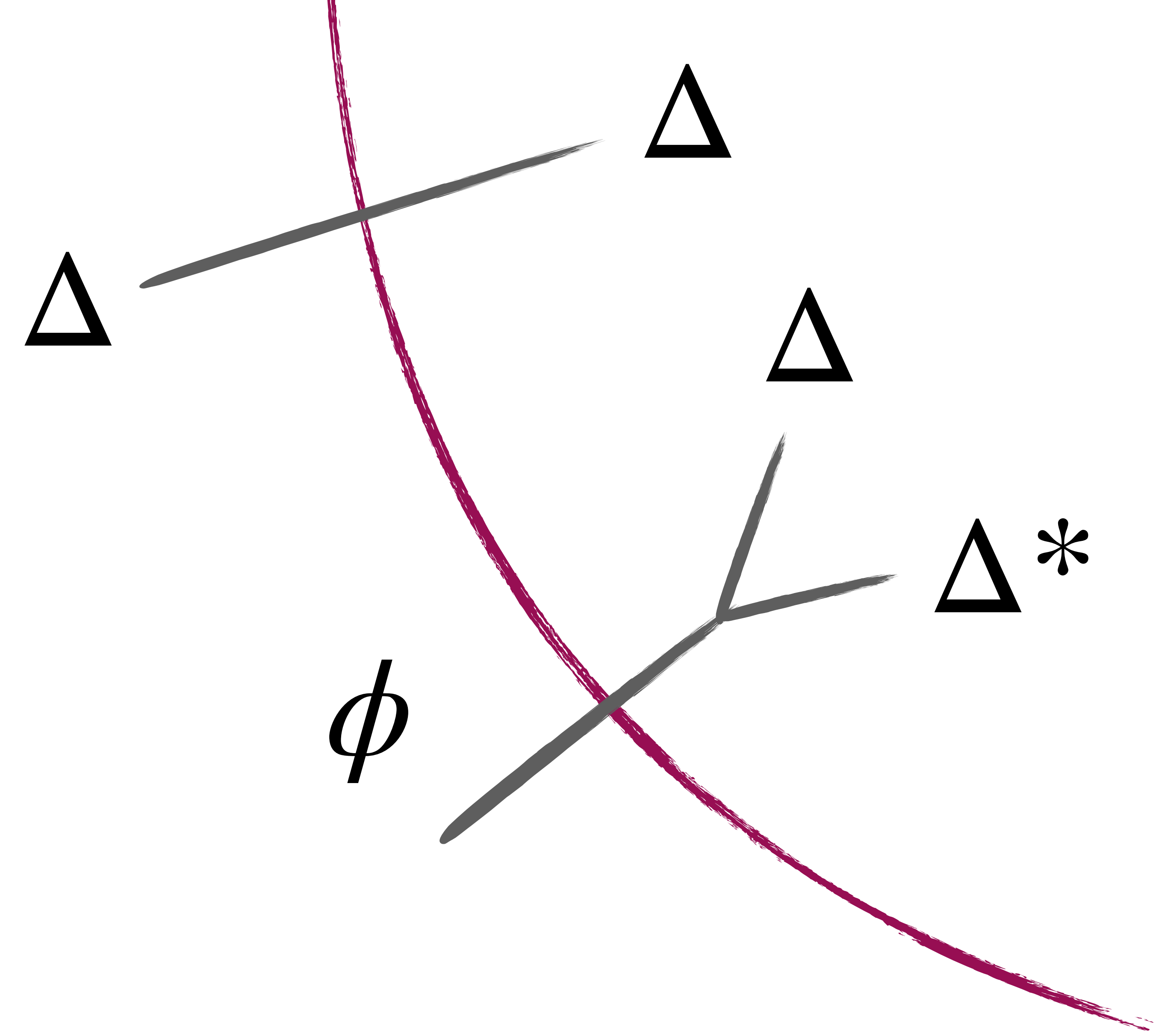
Bodeker, Moore [0903.4099] JCAP

Bodeker, Moore [1703.08215] JCAP

See also Hoche, Kozaczuk, Long, Turner, Wang [2007.10343] JCAP

Summary of kinematic conditions

$$E_\Delta \sim \frac{M_\Delta}{T_n} M_\Delta$$



Moderate supercooling

- **Runaway bubbles:**

$$\frac{T_n}{v_\phi} < 0.5 \left(\frac{c_{vac}}{0.1} \cdot \frac{10}{g_a} \right)^{1/2}$$

- **Efficient Δ crossing or production:**

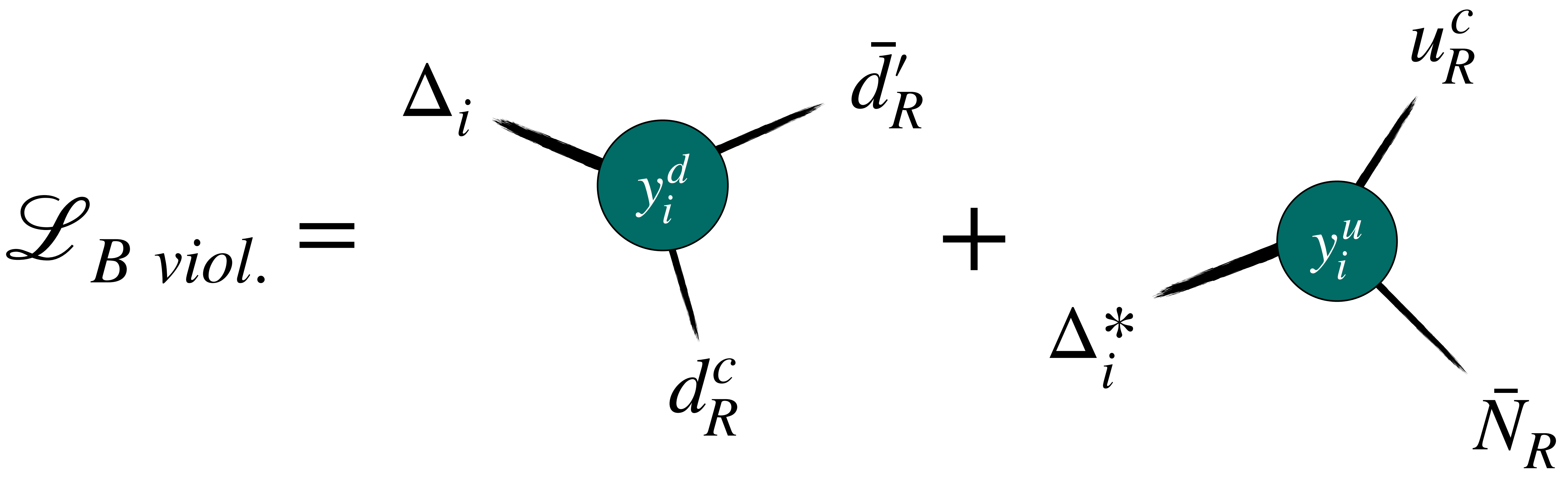
$$\frac{M_\Delta}{T_n} < \left(\frac{1}{\beta} \frac{T_n}{H_*} \right)^a, \quad a = \begin{cases} 1 & MG \\ \frac{1}{2} & AV \end{cases}$$

Anti-adiabatic condition
(taking $v_\phi \sim T_n$)

A model for relativistic baryogenesis

- Two “flavors” $\Delta_{1,2}$ with QCD and hypercharge interactions

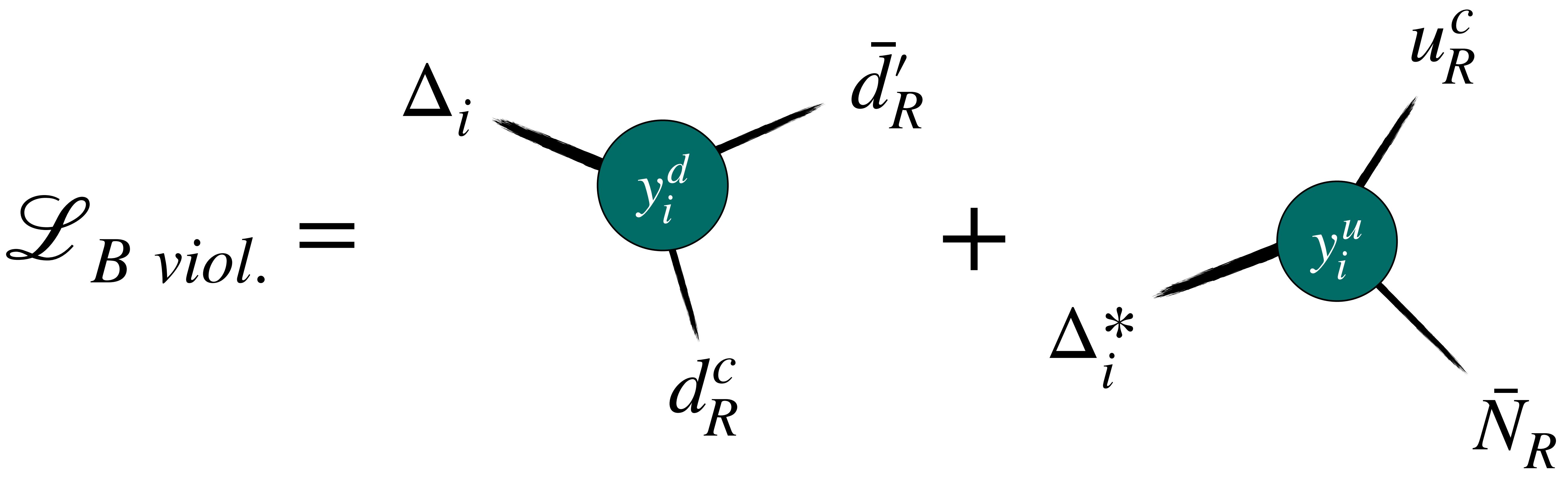
- B violation due to **simultaneous diquark** and **leptoquark** interactions

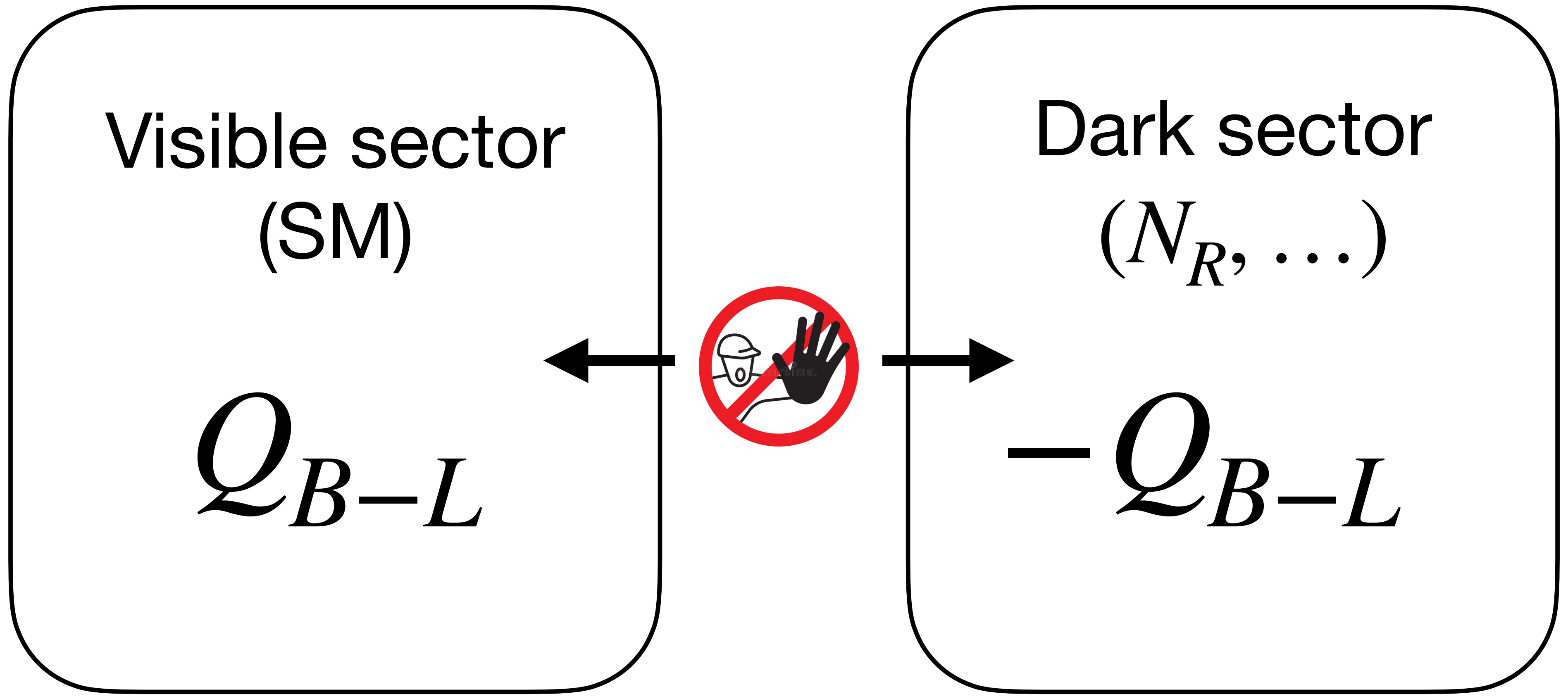


A model for relativistic baryogenesis

- Two “flavors” $\Delta_{1,2}$ with QCD and hypercharge interactions
- B violation due to **simultaneous diquark** and **leptoquark** interactions
- **B-L cons. Δ decays**: charge carried by N_R needs to be “hidden” until T_{EW}

(Explicit B-L interactions may be included as well)





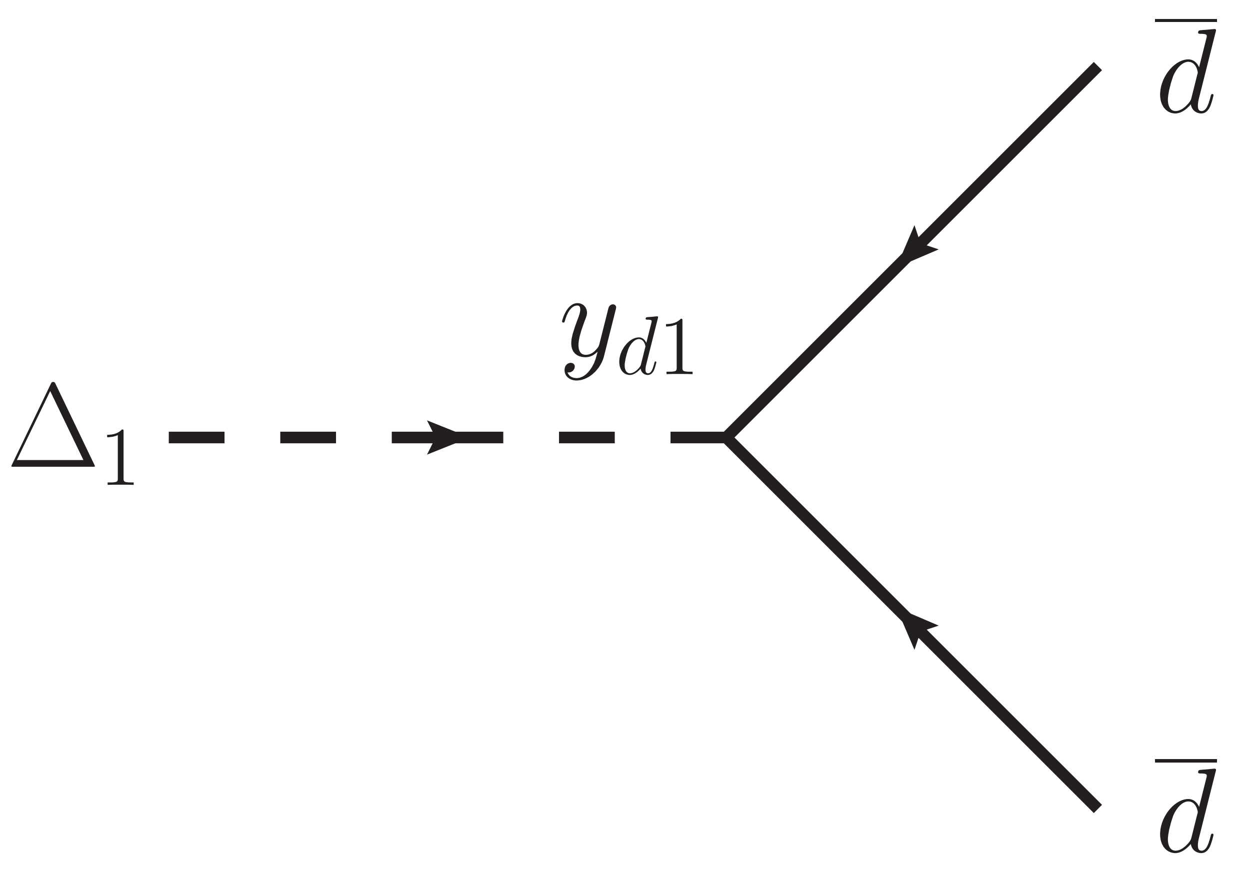
Generating the asymmetry

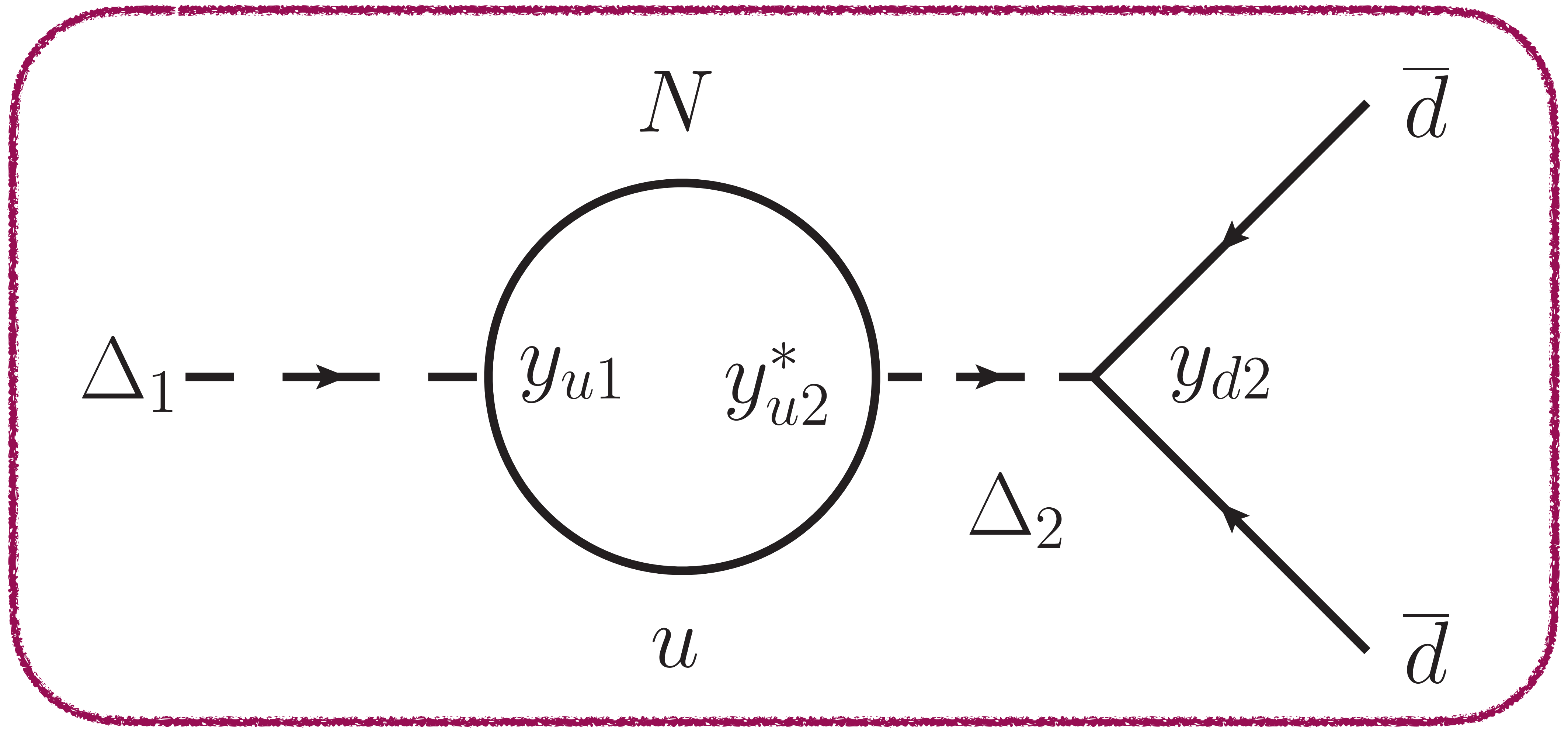
Right after wall crossing:

- CP violating Δ **decays** generate a B-L asymmetry in the visible sector

$$\epsilon_\Delta \sim \frac{Im[y^2]}{6\pi}\left(\frac{M_{\Delta_1}}{M_{\Delta_2}}\right)^2$$

$$\Gamma_\Delta \sim \frac{3y^2}{16\pi}M_\Delta$$





Generating the asymmetry

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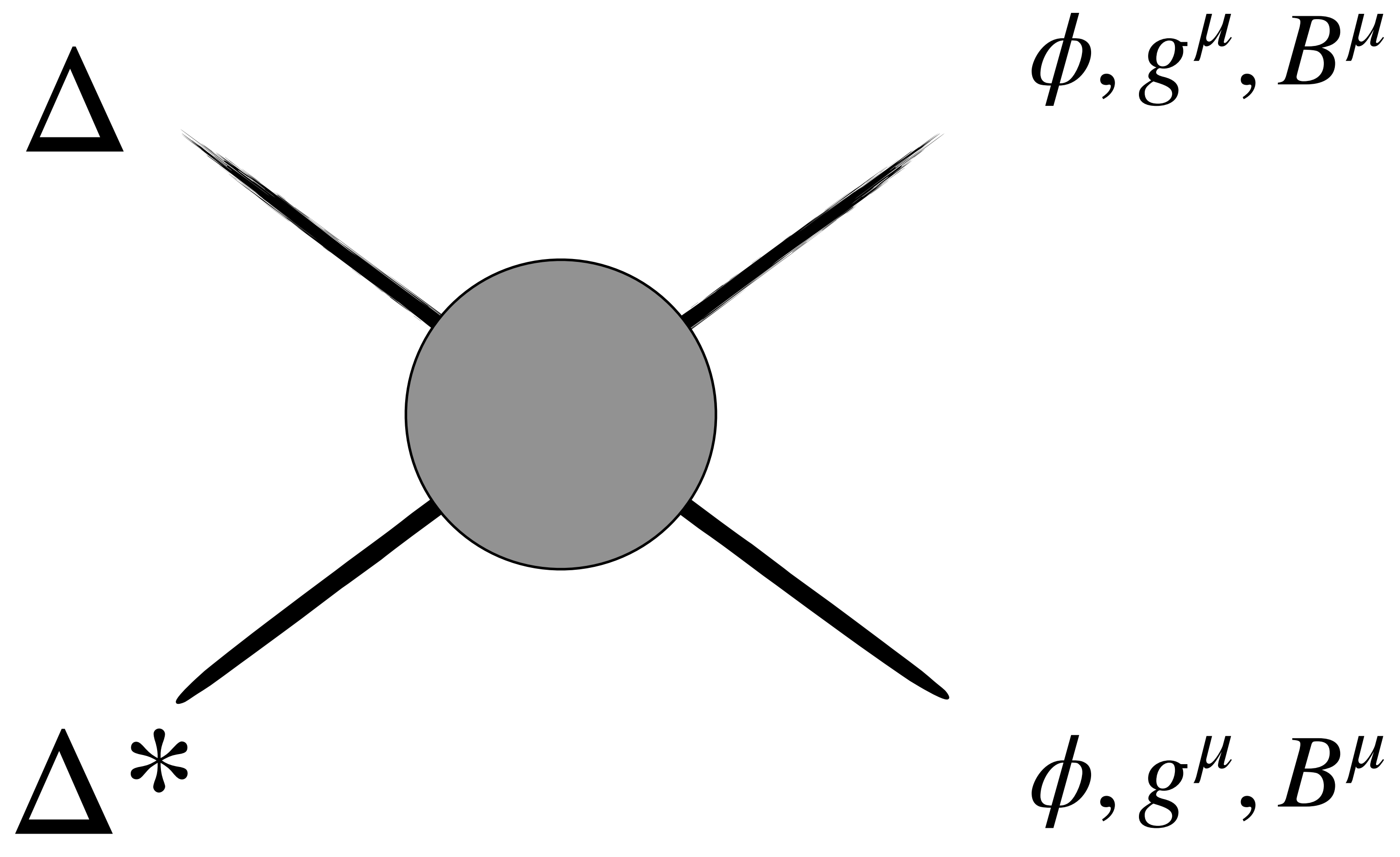
- Δ **should not annihilate** before they undergo asymmetric decays: $\Gamma_{ann} < \Gamma_\Delta$

$$\Gamma_{ann} \sim n_\Delta \langle \sigma \cdot v_{rel} \rangle$$



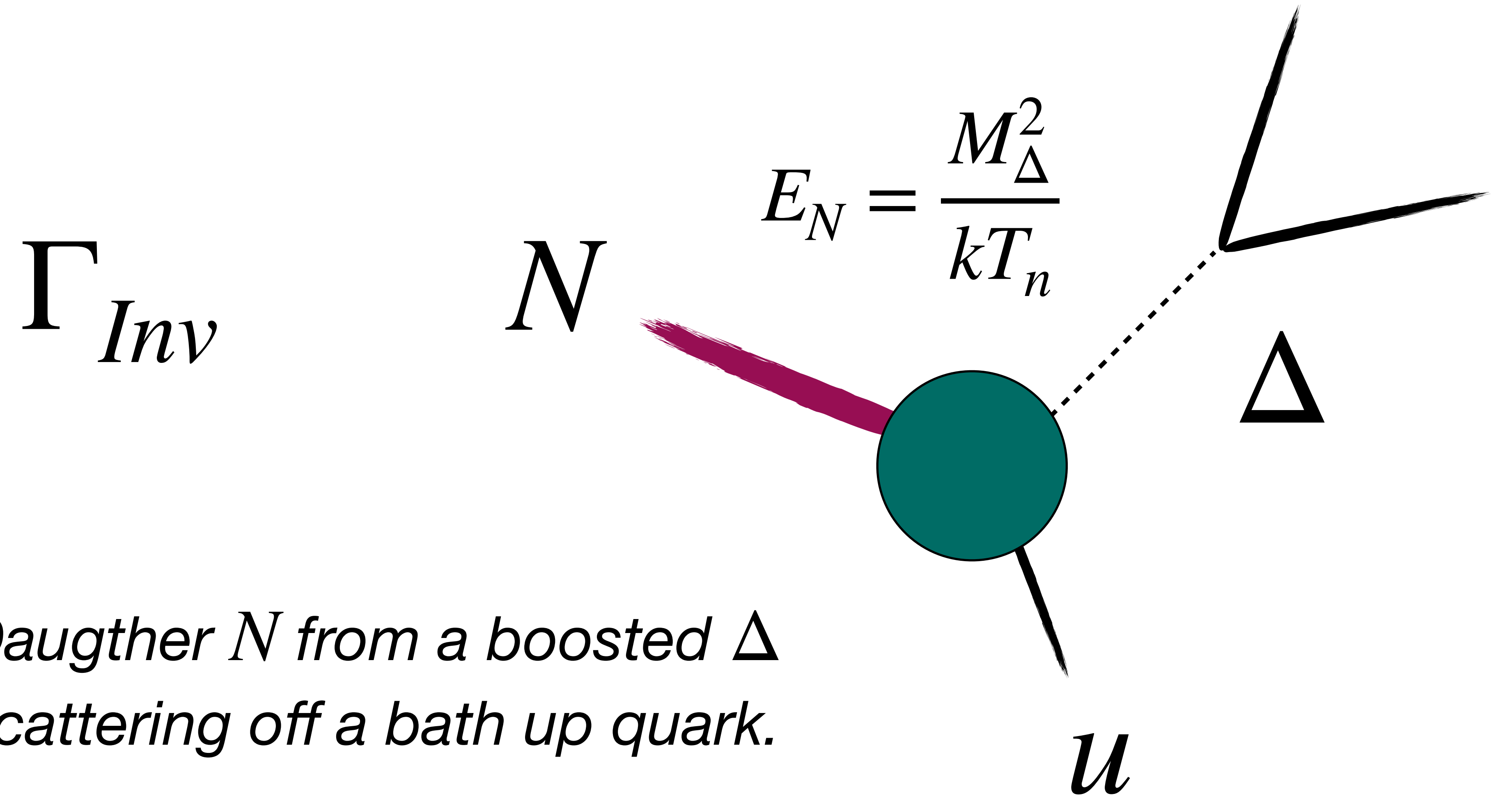
- In their own gas frame, Δ particles are squeezed by a factor M_Δ / T_n

- The MG relative velocity is $v_\Delta \sim T_n / M_\Delta \ll 1$, Sommerfeld enhancement may be relevant

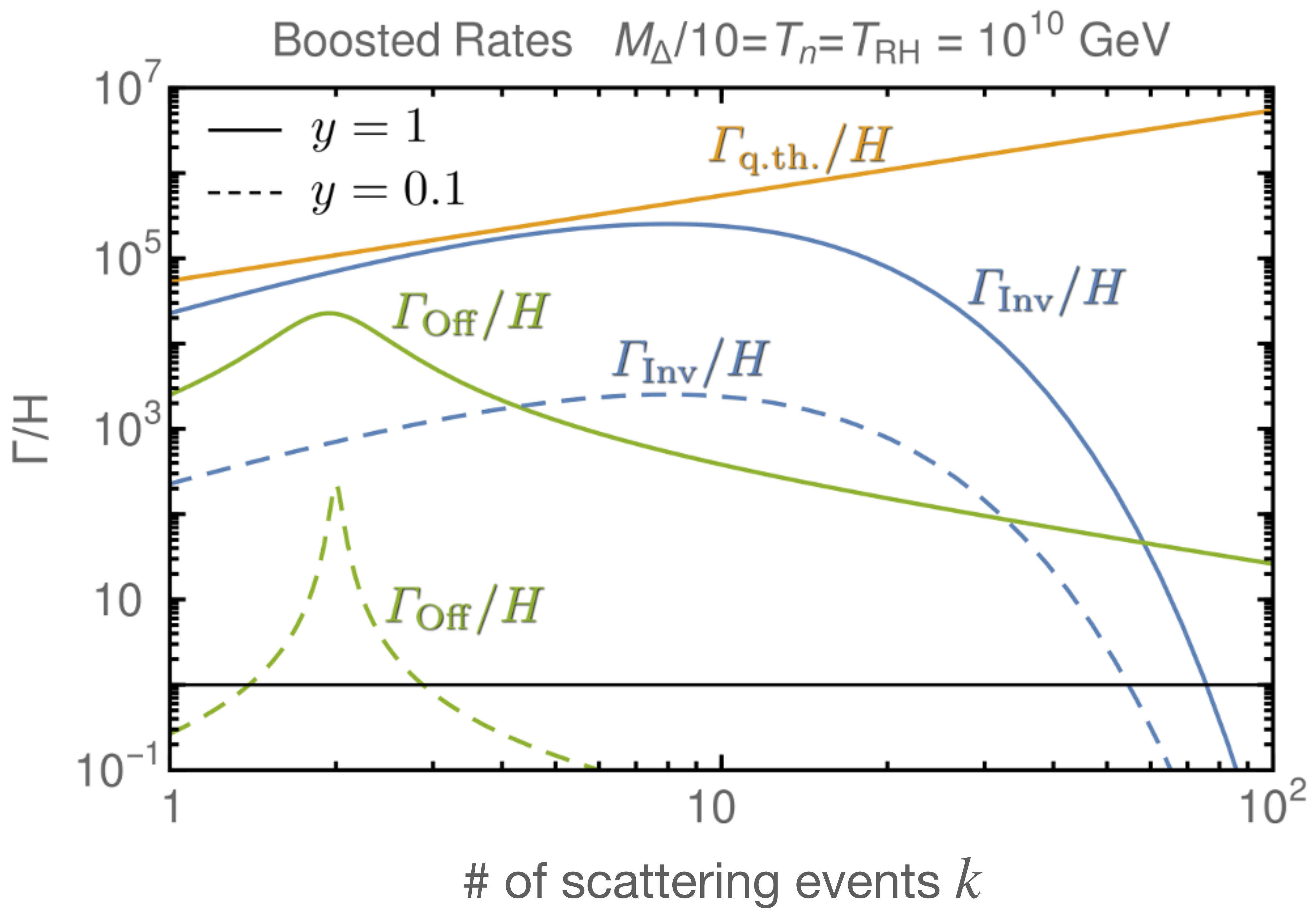
Preserving the asymmetry

Right after decay:

- Δ decay products should not erase the asymmetry on the way to kinetic equilibrium
  - Δ decays with boost $\sim M_\Delta/T_n$ intact



Daugther N from a boosted Δ scattering off a bath up quark.

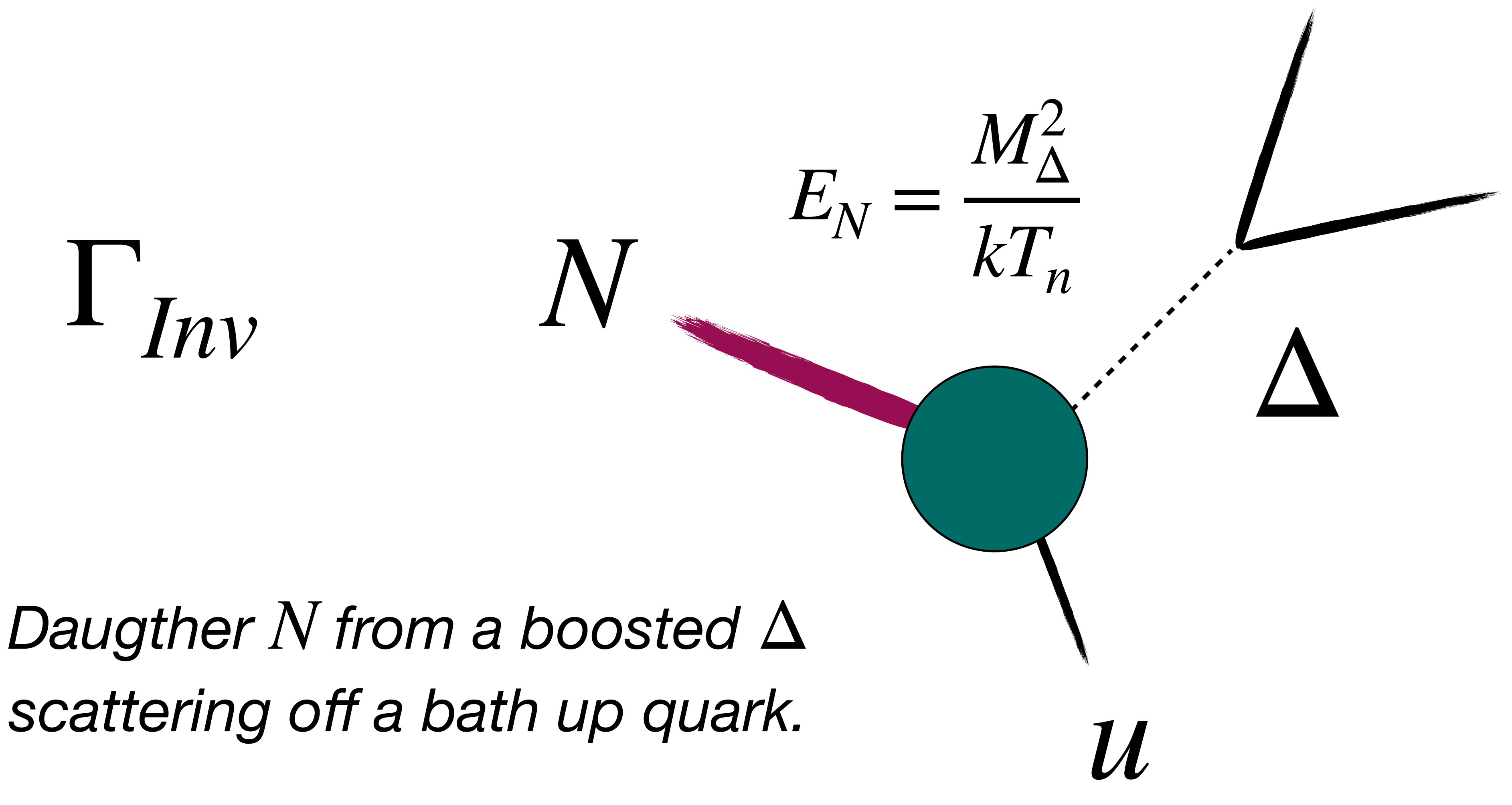


- All the inverse decays are fast, but quarks thermalize faster
- N_R needs to thermalize fast as well to not erase the asymmetry: additional interactions

Preserving the asymmetry

Right after decay:

- Δ decay products should not erase the asymmetry on the way to kinetic equilibrium
  - Δ decays with boost $\sim M_\Delta / T_n$ intact
  - Δ decays at rest



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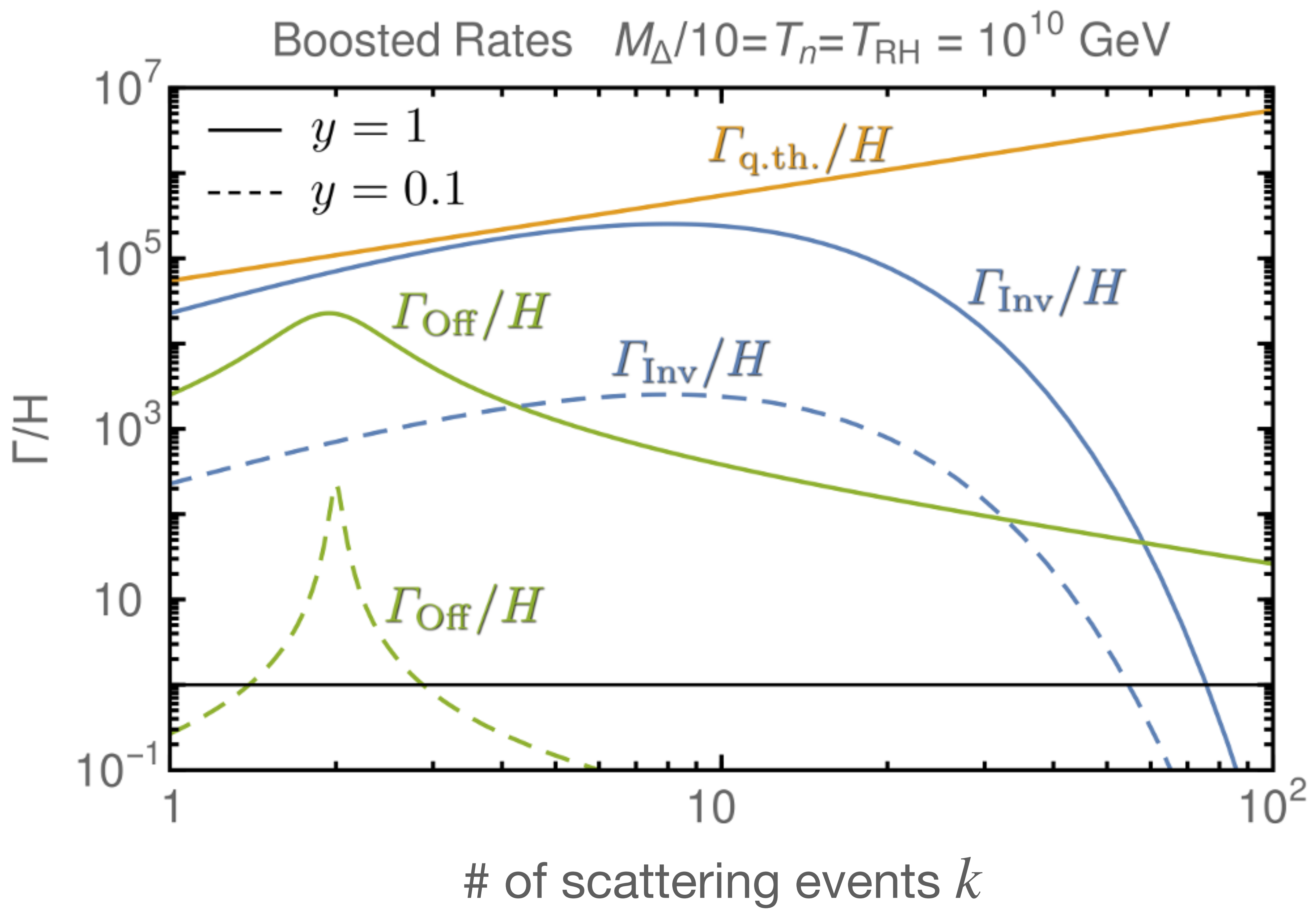

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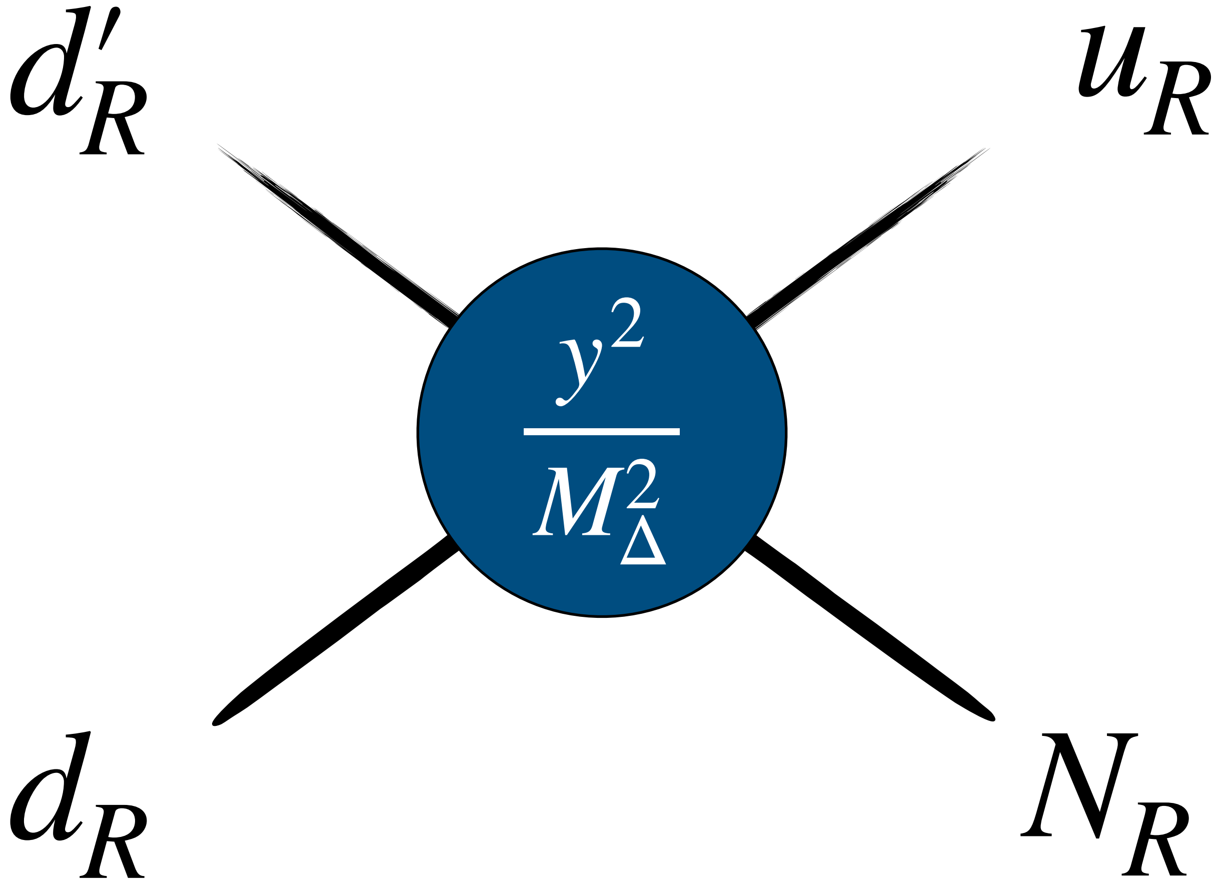
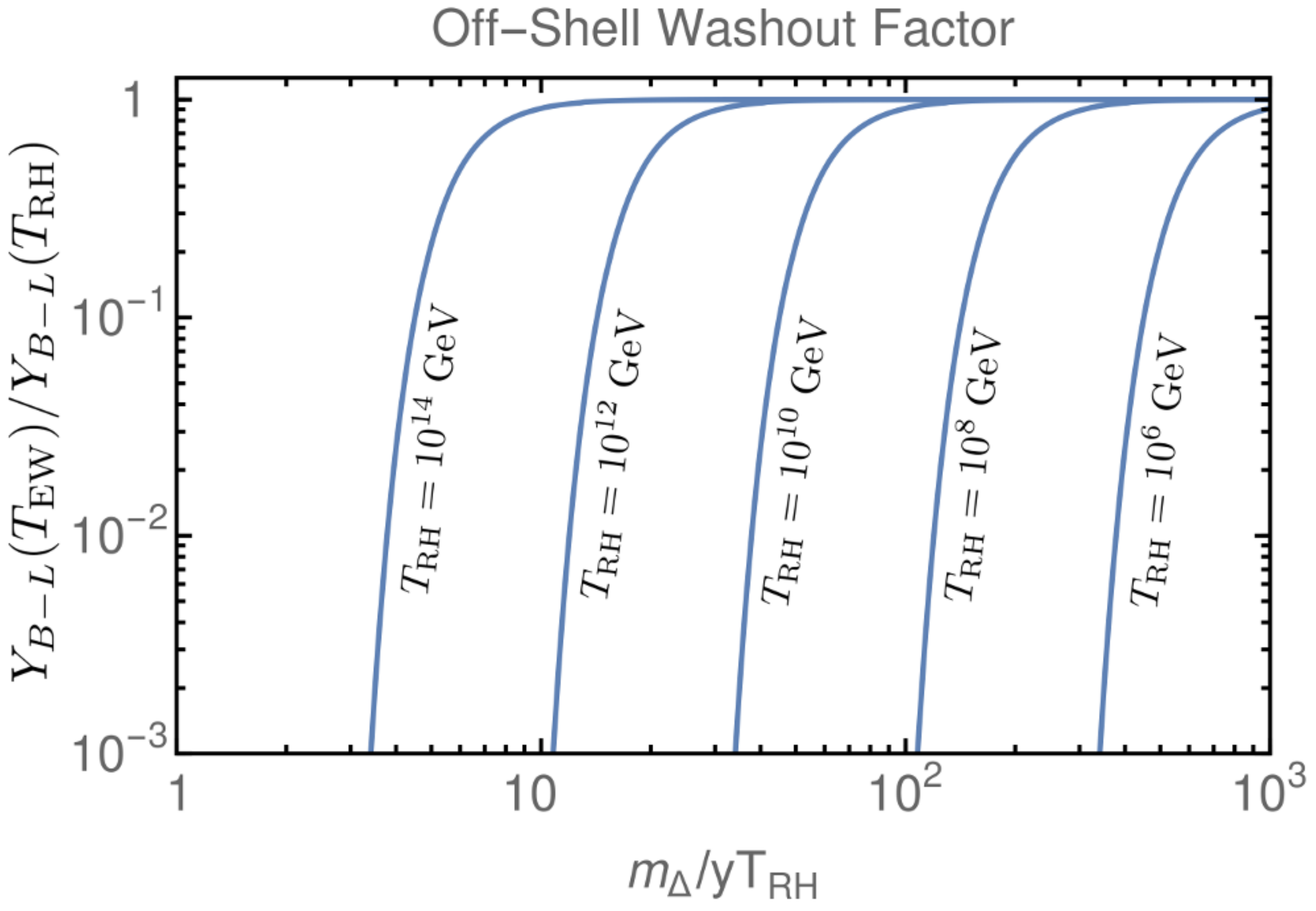
Preserving the asymmetry

After equilibrium is reached at $T = T_{RH}$

- Interactions mediated by Δ can re-equilibrate the B-L charge between dark and visible sector



Effective vertex contributing to the washout from integrating out Δ *at tree level.*



Not shown: wash out from Boltzmann-suppressed inverse decay rates.

Gravitational waves

Runaway bubbles

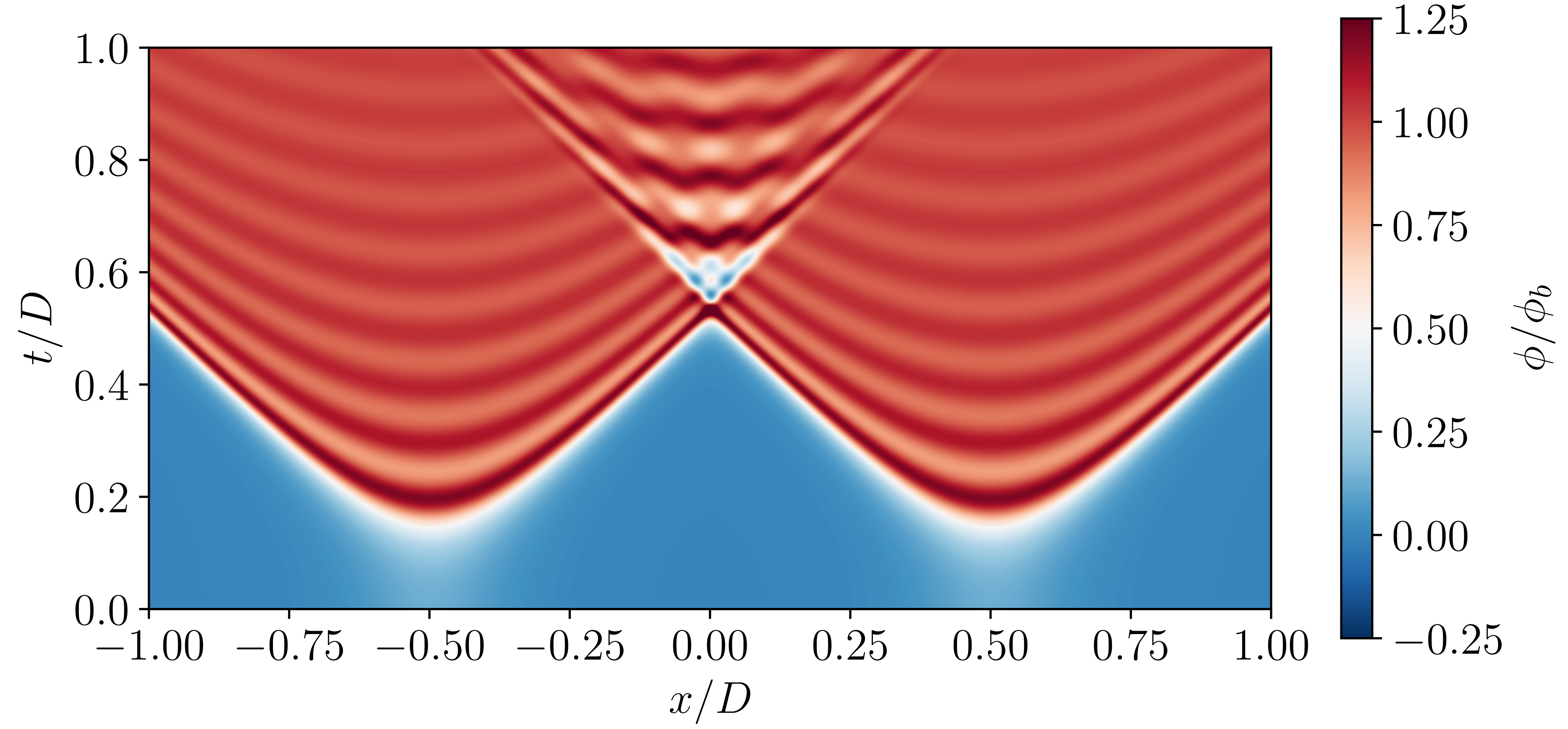
- Latent heat goes into kinetic/gradient energy of expanding scalar field bubbles

- Peak amplitude:

$$h^2\Omega_{GW} \simeq 4 \cdot 10^{-7} \left(\frac{1}{\beta_H}\right)^2 \left(\frac{\alpha}{1+\alpha}\right)^2$$

- Peak frequency:

$$f_{peak} \simeq 260\ Hz\ \left(\frac{T_{RH}}{10^{10}\ GeV}\right)$$



Simulation of thick-walled bubble collisions with $\gamma = 4$.
Fig. from Cutting, Escartin, Hindmarsh, Weir [2005.13537] PRD

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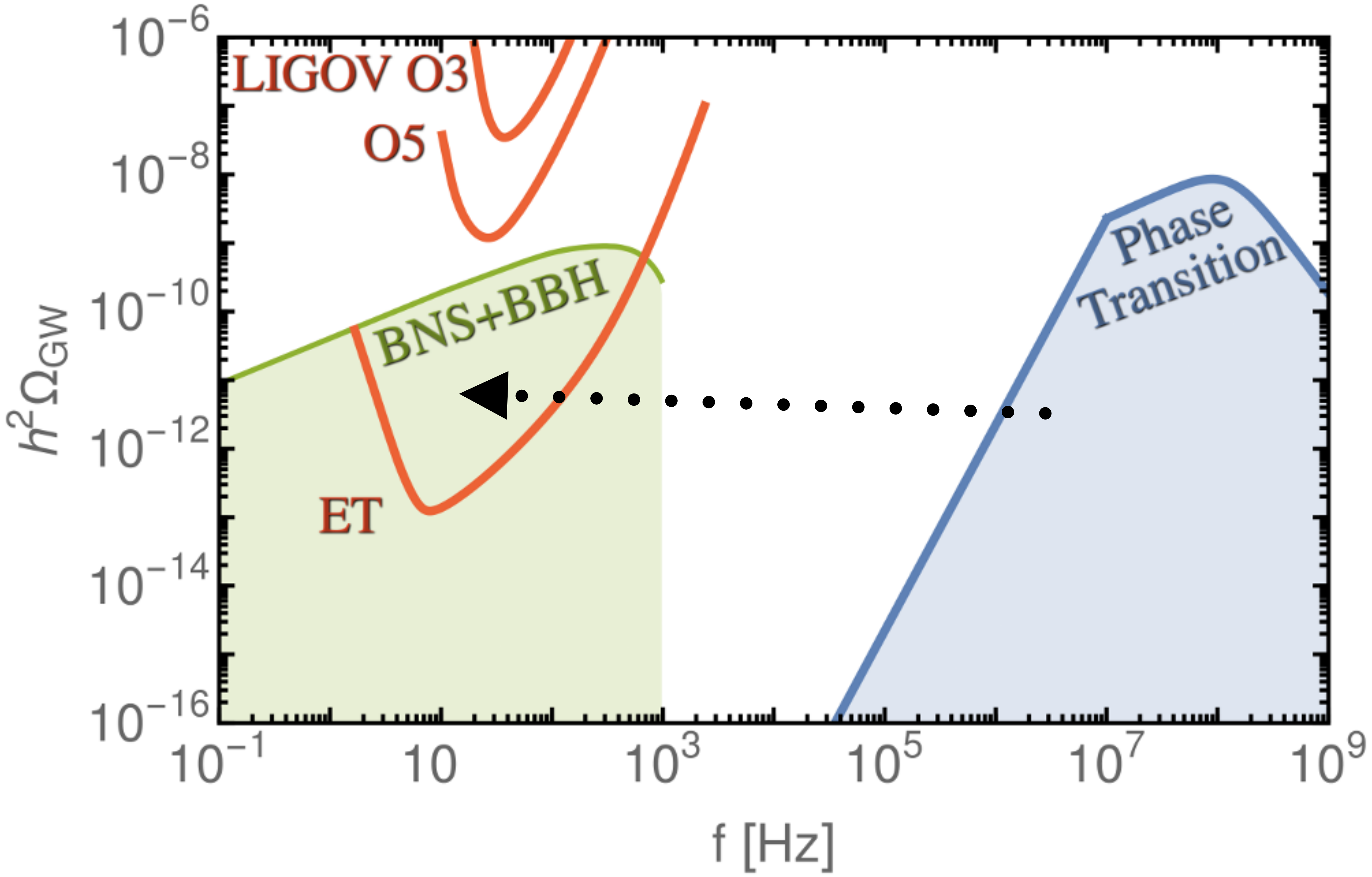
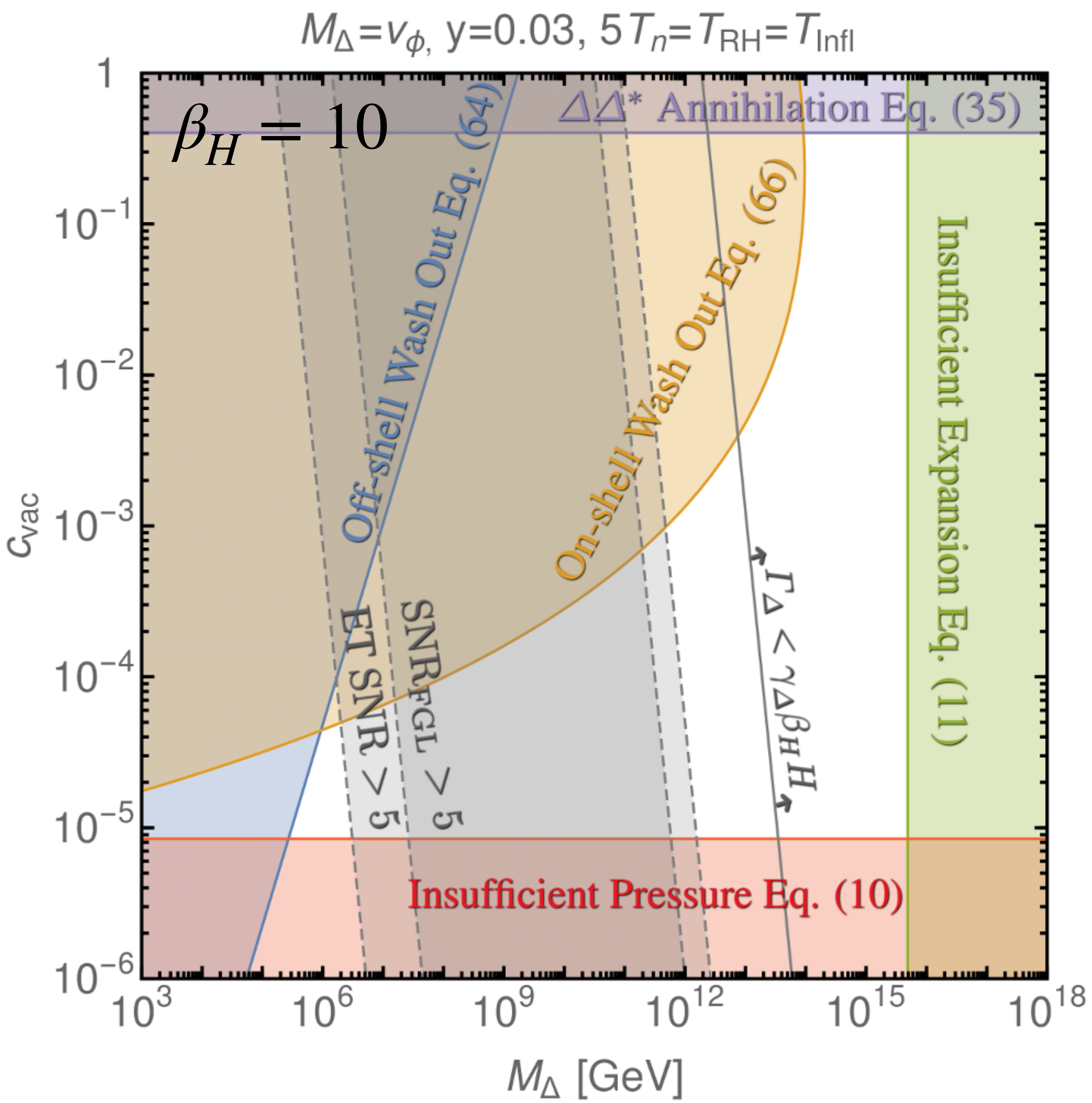
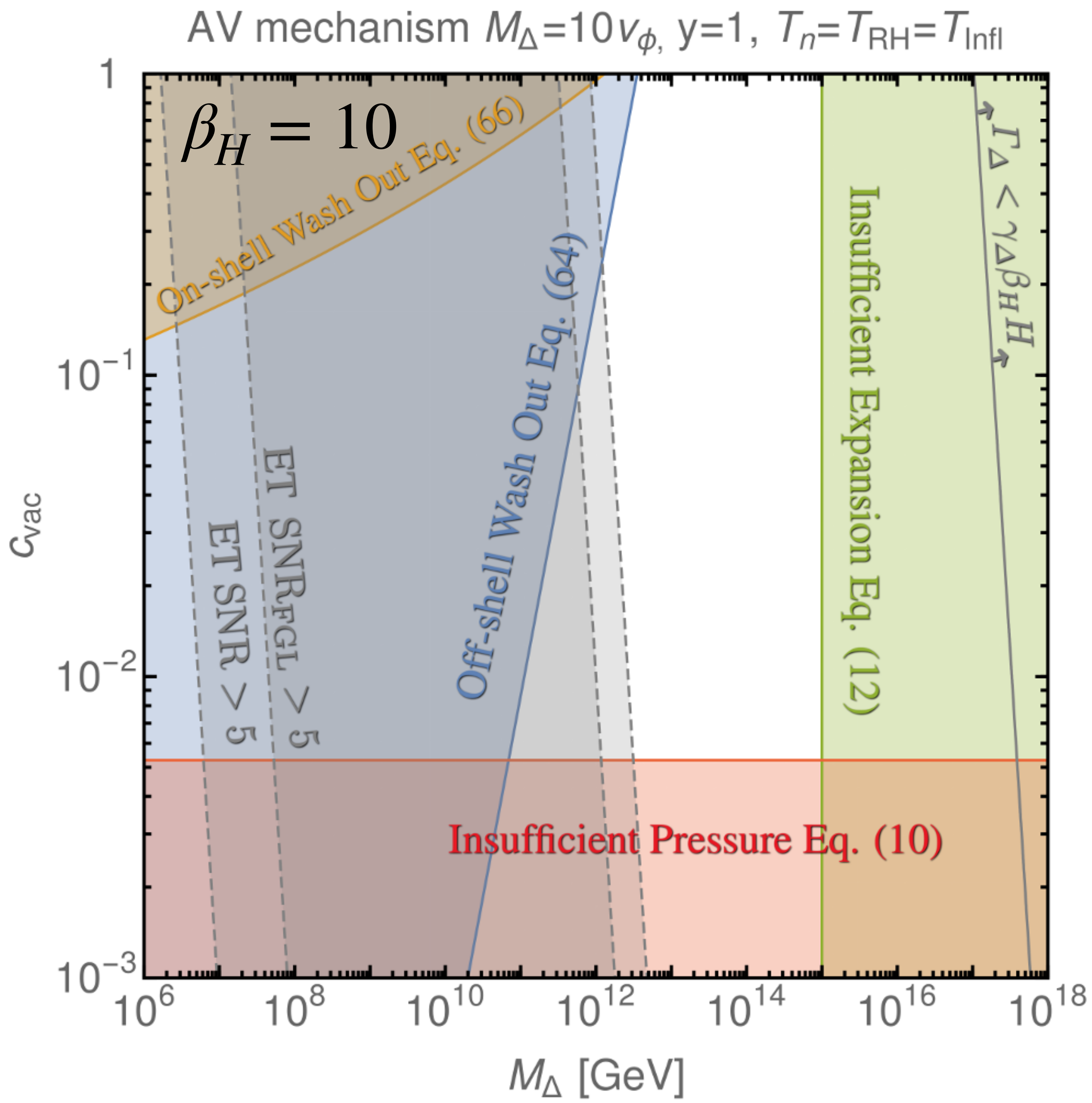


Summary of the results





Conclusion

- We have presented two mechanisms for baryogenesis with (ultra) relativistic bubble walls during FOPTs: mass gain (MG) and Azatov-Vanvlasselaer heavy particle production (AV)
- We have derived requirements on the phase transition properties, mass spectrum, and CP violation for reproducing the observed baryon asymmetry
- Some of the features/challenges of these mechanisms apply beyond our specific choice of the model
- Interesting interplay with gravitational wave production, even though our setups work best at high scales to avoid washout

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Thank you!