

Based on arXiv:2312.09282,

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# The Baryon Asymmetry from Supercooled Confinement

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TAsP Meeting, 18-19 Jan 2024



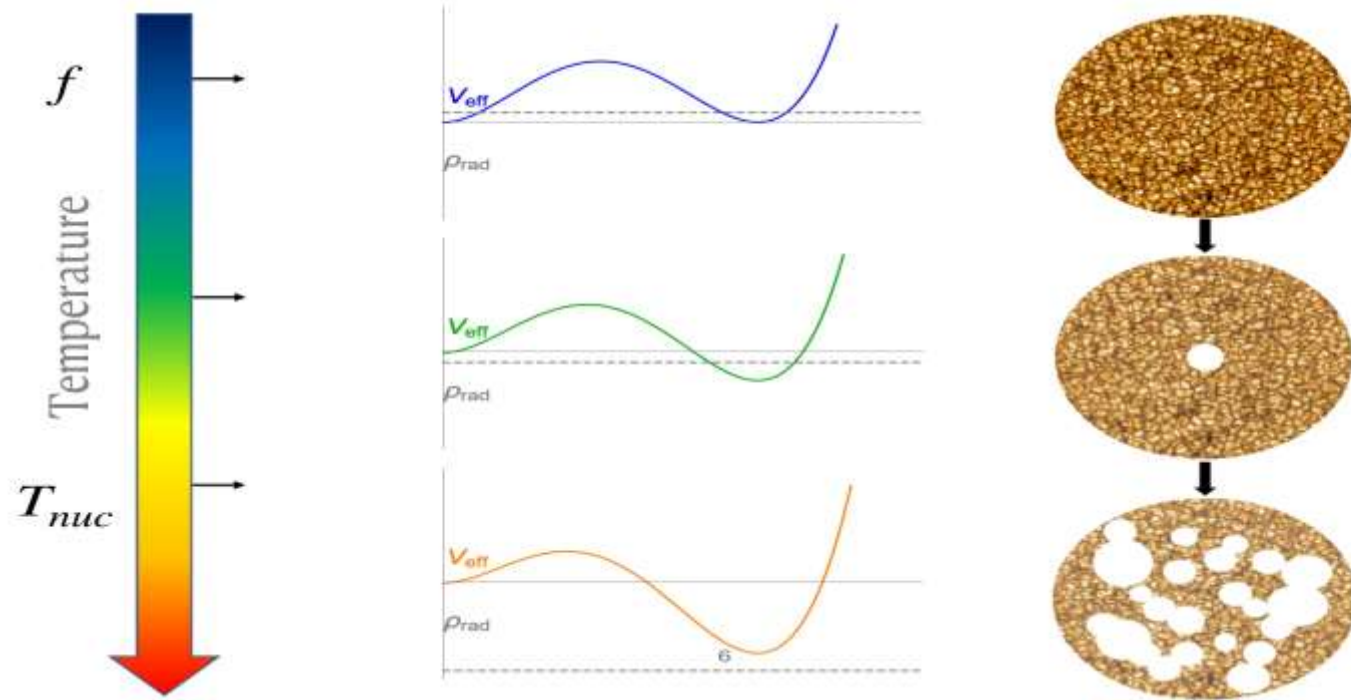
# KEY MESSAGE

New framework for the generation of the **Baryon asymmetry** from **TeV** to much higher scales based on a **first order phase transition of a confining sector**.

# Outline

- Supercooled first order phase transitions
  - Gravitational wave Signal
  - Why is a confining sector interesting?
    - **Enhanced** Baryon Asymmetry
    - **Suppressed** washout processes
- ← Extended parameter space at low scales w.r.t. non confining case
- Model 1: Baryogenesis (Revisiting the model proposed in arXiv:2106.15602)
  - Model 2: Leptogenesis (Inverse seesaw)
  - Conclusions

# First Order Supercooled Phase Transitions



supercooling:  $T_{\text{nuc}} < T_{\text{eq}} \equiv \left( \frac{30 c_{\text{vac}}}{g_* \pi^2} \right)^{1/4} f$

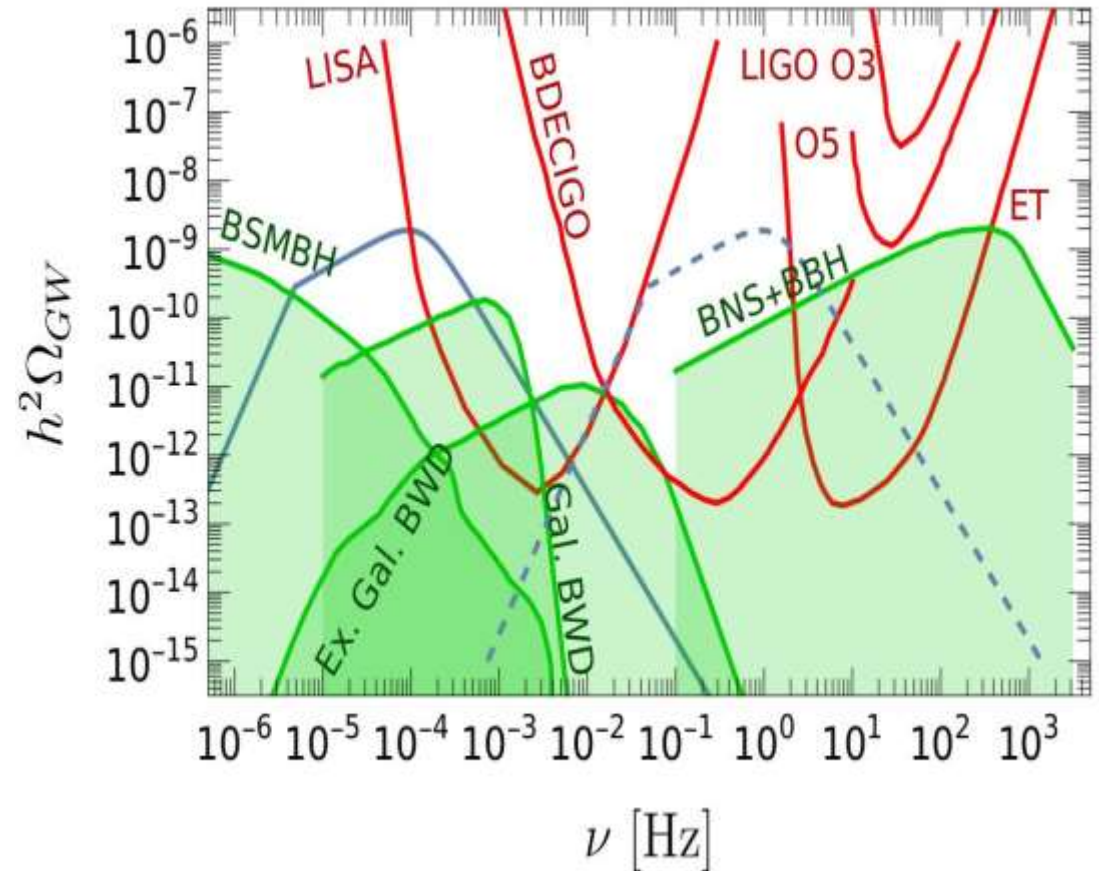
adapted from  
Wang+ arXiv:2003.08892

- 1st order phase transition, **VEV  $f$**
- **Supercooling**, bubbles nucleate at  $T_{\text{nuc}} \ll f$  during **vacuum domination**
- Wall velocity at collision given by  $\gamma_{\text{coll}} > M_{\text{hadr}}/T_{\text{nuc}}$  needed for hadrons enter the bubble and decay

$$\gamma_{\text{coll}} \simeq \text{Min}[\gamma_{\text{run}}, \gamma_{\text{T}}] \simeq \text{Min} \left[ 1.7 \frac{10}{\beta/H} \left( \frac{0.01}{c_{\text{vac}}} \right)^{1/2} \frac{T_{\text{nuc}}}{f} \frac{M_{\text{Pl}}}{f}, 10^{-3} \frac{c_{\text{vac}}}{0.01 g_{\text{TC}}} \left( \frac{f}{T_{\text{nuc}}} \right)^3 \right]$$

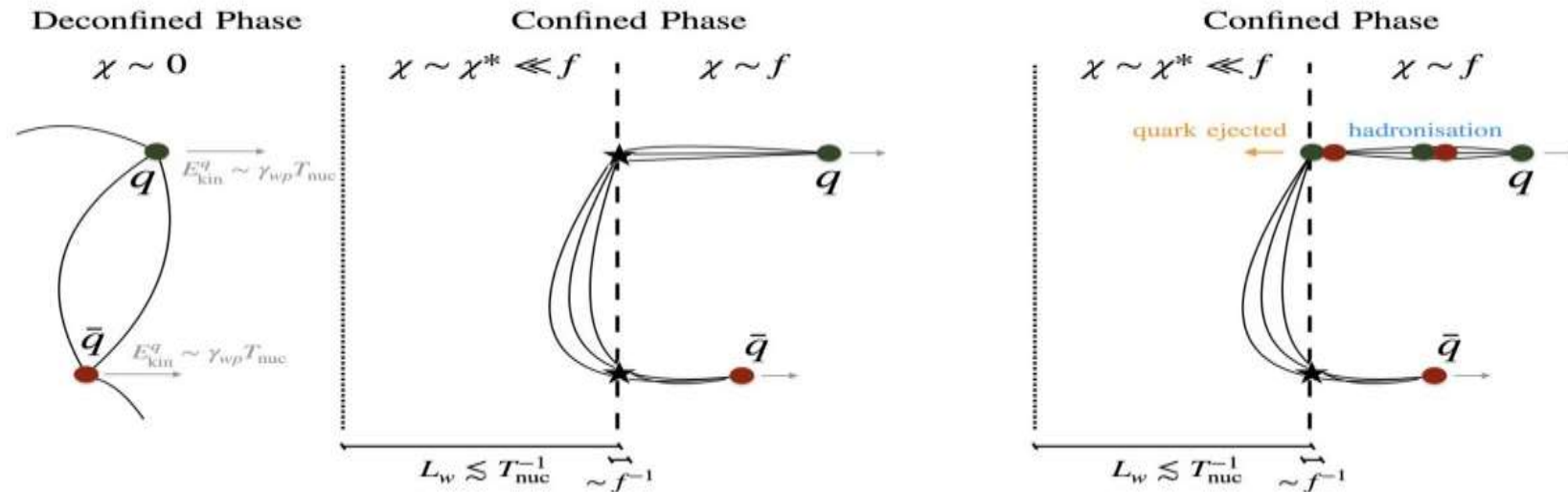
# GW Signal of first order supercooled PTs

- **Astrophysical foregrounds** taken into account
- Benchmark values of  $\{c_{vac, M_\Delta}\} = \{10^{-1}, 10^4 \text{ GeV}\}, = \{10^{-1}, 10^8 \text{ GeV}\}, \text{SNR}=10$
- Spectra computed **assuming thick-wall runaway bubbles**, arXiv:2005.13537
- However our parameter space is also in **Terminal Velocity** regime (sound waves, turbulence).
- There **is uncertainty** on these contributions in **Supercooled PTs**, but **very mild** difference
- Takehome message: **Gravitational Wave signal expected!**



# Confining phase transitions: string fragmentation

I.Baldes,  
Y.Gouttenoire, F.Sala,  
arXiv:2007.08440



- Energy of string minimized if **fluxtubes in  $\chi = f$  point to the bubble wall**, NOT to the closest color charge
- The string inside the wall breaks, producing hadrons and a **quark is ejected** from the wall



Enhanced population of quarks  $\rightarrow$  DIS  $\rightarrow$  Hadrons  $\rightarrow$  Enhanced rate asymmetry!

# General Framework for the Baryon Asymmetry

$$Y_\Psi \simeq Y_{TC} \times 3 \frac{\gamma_{\text{coll}} f m_\phi}{M_{\text{hadr}}^2} Br(\text{hadr} \rightarrow \Psi) \times \left( \frac{T_{\text{nuc}}}{T_{\text{eq}}} \right)^3 \frac{T_{\text{RH}}}{T_{\text{eq}}}$$

$$Y_B = \epsilon_\Psi K_{\text{Sph}} Y_\Psi$$

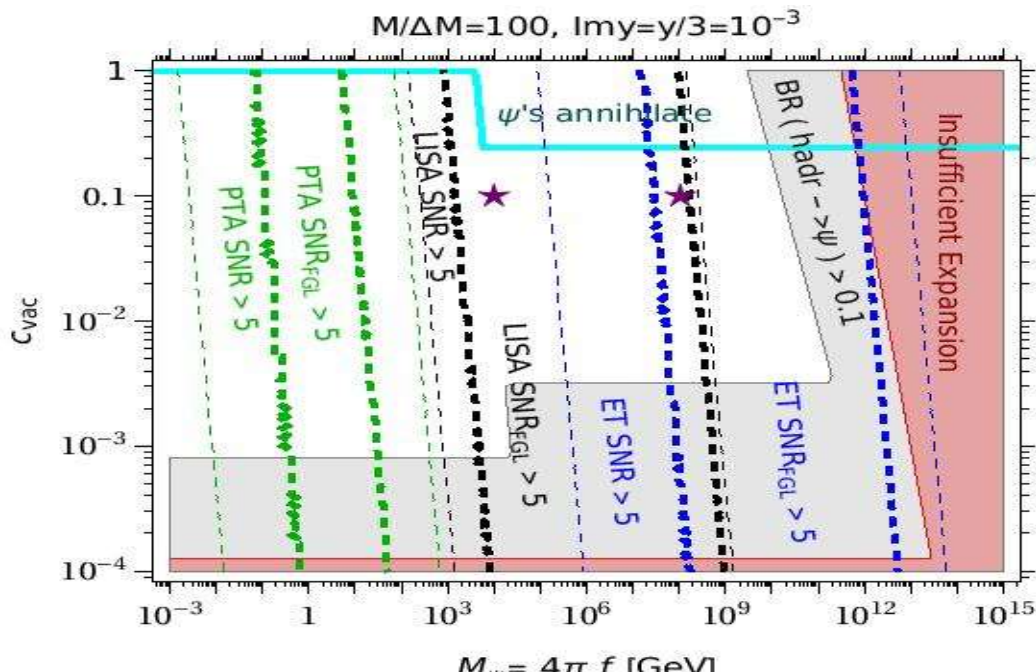
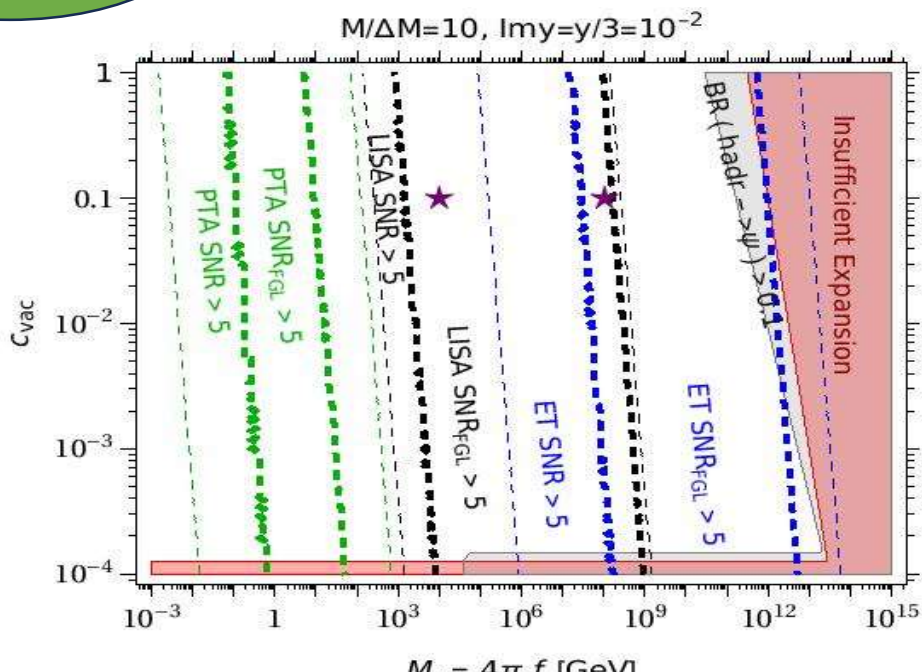
$$\simeq Y_{\text{BAU}} \times \frac{\gamma_{\text{coll}}}{\gamma_{\text{T}}} \frac{\epsilon_\Psi K_{\text{Sph}}}{1.2 \cdot 10^{-4}} \frac{Br(\text{hadr} \rightarrow \Psi)}{10^{-3} Z} \left( \frac{107.75}{g_{\text{RH}}} \right)^{\frac{1}{4}} \left( \frac{c_{\text{vac}}}{0.01} \right)^{\frac{3}{4}} \left( \frac{4\pi f}{M_{\text{hadr}}} \right)^2$$

Thermal equilibrium Yield

Enhanced hadron abundance: Confining sector

Dilution from entropy release

$$\epsilon_\Psi \gtrsim \frac{\text{Im}y^2}{4\pi} \frac{M_\Psi}{\Delta M}$$



# Baryogenesis Scenario: The Model

$$\mathcal{L} \supset y_{di} \Delta_i \bar{d}_R^c d_R + y_{ui} \Delta_i \bar{\chi}_R u_R^c + \text{h.c.} \quad \Delta = (3, 1, 2/3) \quad \chi = (1, 1, 1)$$

$$\Gamma(\Delta_i \rightarrow \bar{d}_R d'_R) \simeq \frac{|y_{di}|^2}{8\pi} M_{\Delta_i},$$

$$\Gamma(\Delta_i \rightarrow \chi u_R) \simeq \frac{|y_{ui}|^2}{16\pi} M_{\Delta_i},$$

$$\Gamma(\Delta_1 \rightarrow \bar{d}_R d'_R) = \Gamma_{1d}(1 + \epsilon_d),$$

$$\Gamma(\Delta_1^* \rightarrow d_R d'_R) = \Gamma_{1d}(1 - \epsilon_d),$$

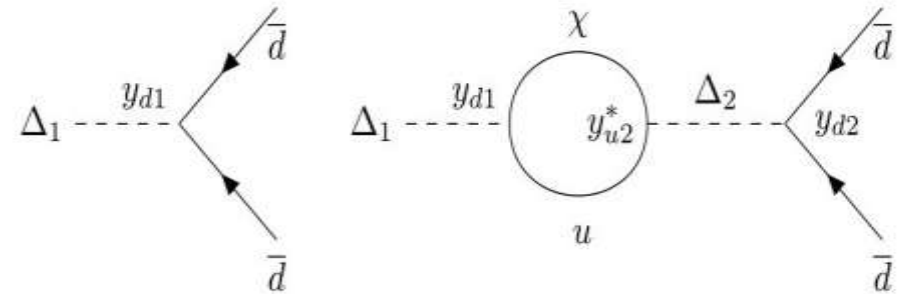
$$\Gamma(\Delta_1 \rightarrow \chi u_R) = \Gamma_{1u}(1 + \epsilon_u),$$

$$\Gamma(\Delta_1^* \rightarrow \bar{\chi} \bar{u}_R) = \Gamma_{1u}(1 - \epsilon_u).$$

CPT theorem

$$\epsilon_d \Gamma_{1d} = -\epsilon_u \Gamma_{1u}$$

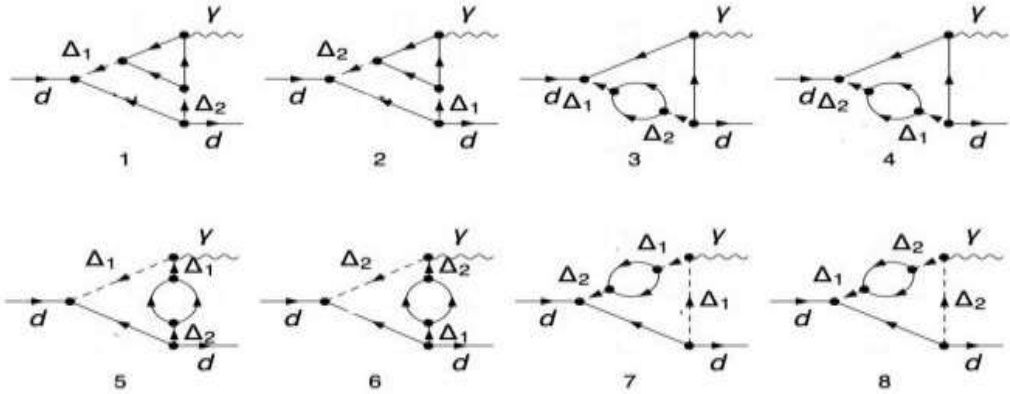
$$\epsilon_\Delta = \frac{1}{2\pi} \frac{\text{Im}(y_{d1}^* y_{u1} y_{u2}^* y_{d2})}{|y_{ui}|^2 + 2|y_{di}|^2} \frac{M_{\Delta_1}^2}{M_{\Delta_2}^2 - M_{\Delta_1}^2} \sim \frac{\text{Im}[y^2]}{6\pi} \frac{M_{\Delta_1}^2}{M_{\Delta_2}^2 - M_{\Delta_1}^2}$$



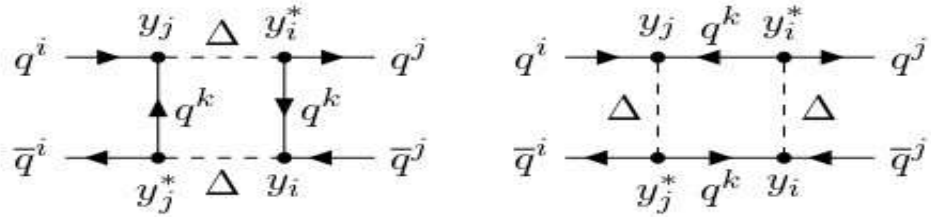
- Minimal setup:  $\chi, \Delta_1, \Delta_2$  couple to a **single up** type quark and **single down** type pair
- $\chi$  needs to be Majorana  $\rightarrow$  (Inverse Decay) and  $M_\chi > m_p - m_{k^+}$  (Nucleon decays)
- X disentangled from neutrino masses



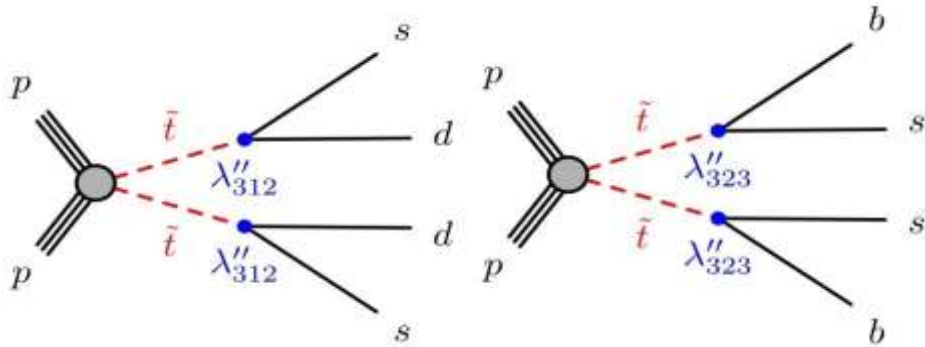
# Baryogenesis Scenario: Phenomenology



No EDM at 2  
Loops,  
 $M_\Delta > \text{few TeV}$



FCNC  $\Delta F = 1,2$   
mediated by  $\Delta$ ,  
 $M_\Delta > \text{few TeV}$

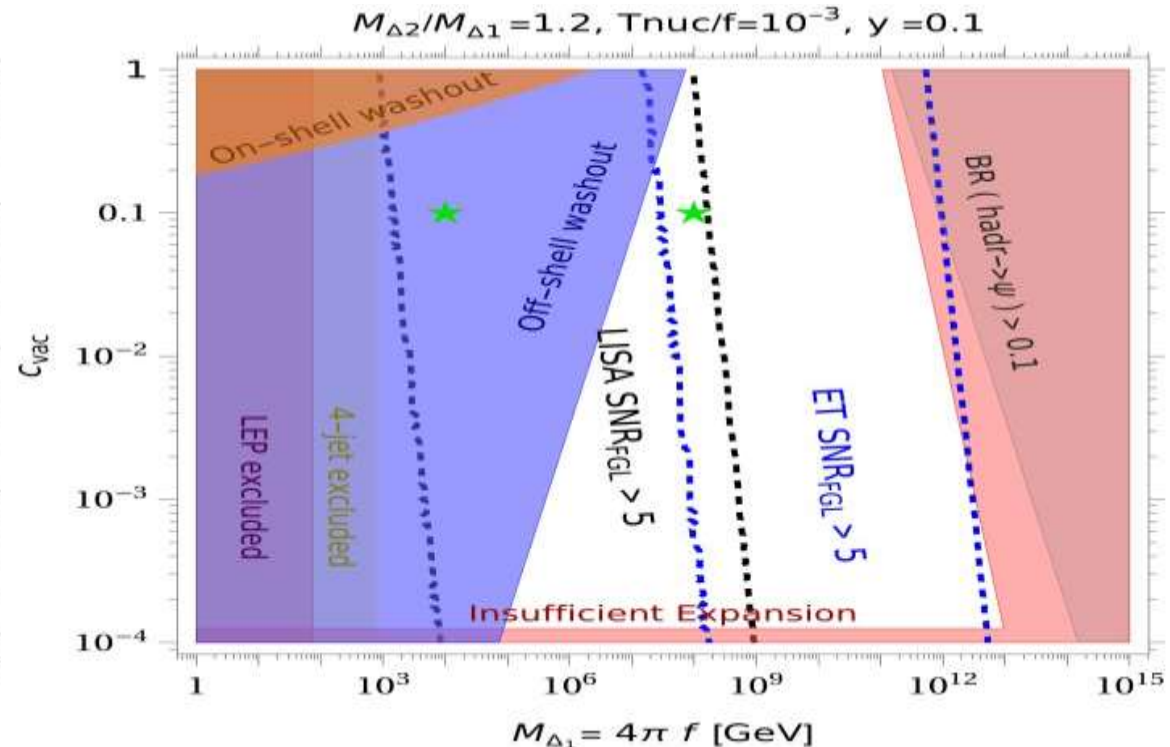
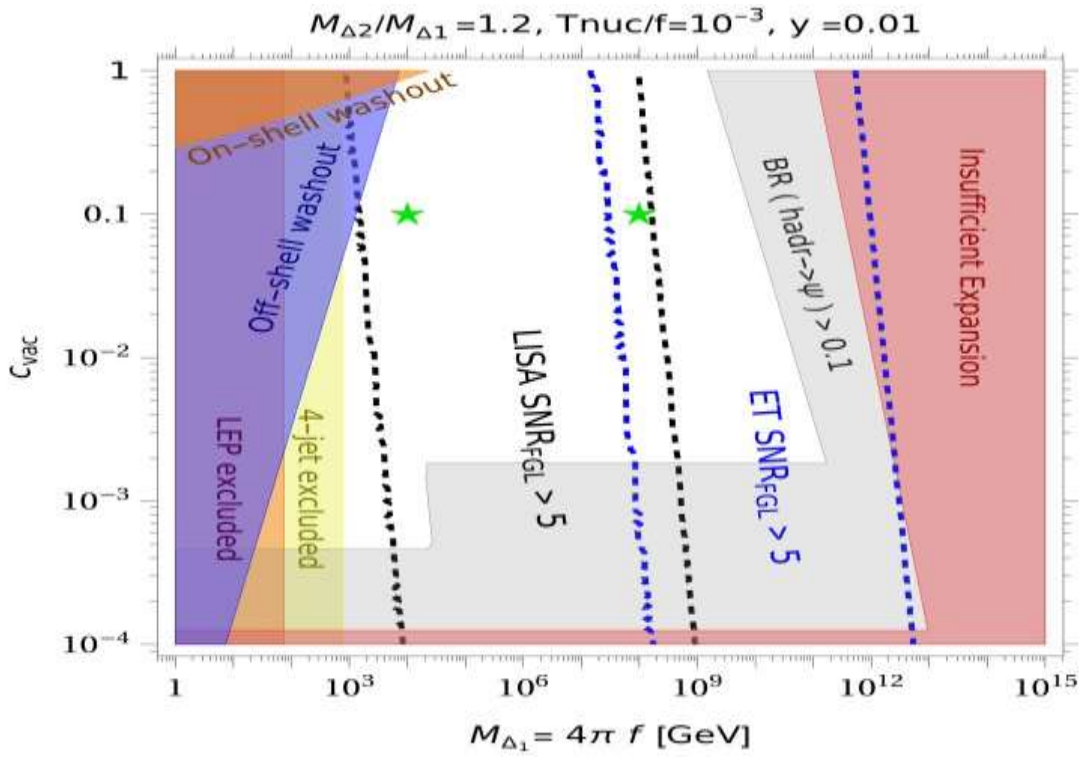
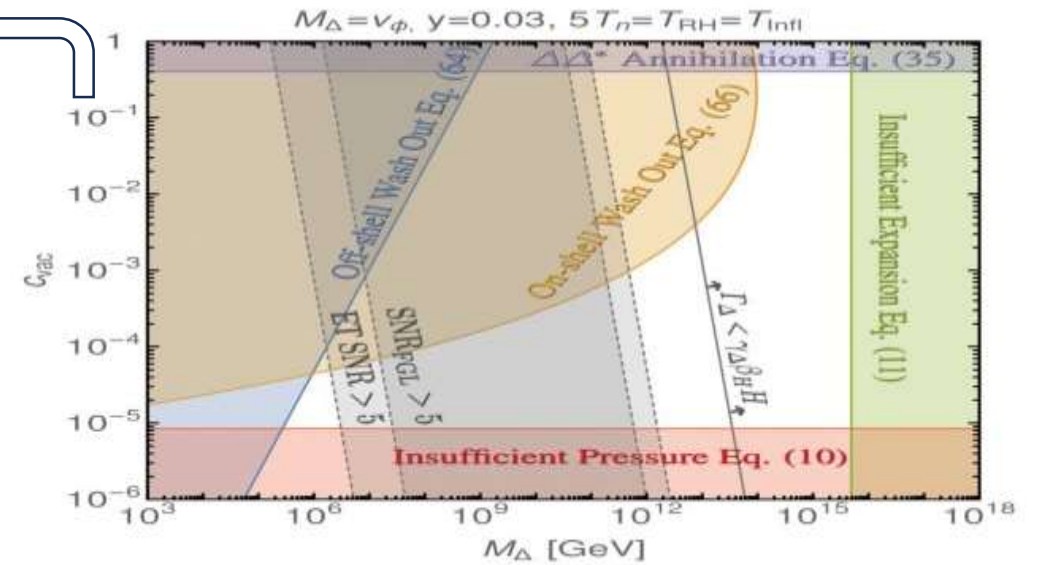


4 Jet Searches at the  
LHC,  $M_\Delta > 770 \text{ GeV}$

From arXiv:  
1710.07171

# Baryogenesis Scenario: Parameter Space

- Comparison with arXiv:2106.15602 where no confining sector, washout suppressed  $M_{hadr} = 4\pi f$
- Gravity waves: in the reach of LISA and of the ET
  - Colliders:  $\Delta$  is partially testable



# Leptogenesis Scenario: Inverse Seesaw (ISS)

$$-\mathcal{L}^{ISS} = y_{a\alpha} \bar{N}_{aR} H L_\alpha + M_{N_a} \bar{N}_a N_a + \frac{\mu_{ab}}{2} \bar{N}_{aL}^c N_{bL} + \text{h.c.},$$

$$\delta \mathcal{L}^{d=5} = c_{\alpha\beta}^{d=5} \left( \bar{L}_\alpha^c \tilde{H}^* \right) \left( \tilde{H}^\dagger L_\beta \right)$$



D=5 Weinberg operator

$$c_{\alpha\beta}^{d=5} = \left( y^T \frac{1}{M_N^T} \mu \frac{1}{M_N} y \right)_{\alpha\beta}$$



$\mu$  is **L breaking** parameter, technically small, **NOT** set by **any fundamental scale!**

$$-\mathcal{L}_{\text{mass}}^{ISS} \supset h_{i\alpha} \bar{N}_i H L_\alpha + \frac{1}{2} M_i \bar{N}_i \tilde{N}_i + \text{h.c.}, \quad \delta_a = \mu / M_{N_a}$$

$$M_1 \simeq M_{N_1} \left( 1 - \frac{\delta_1}{2} \right), \quad h_{1\alpha} \simeq \frac{i}{\sqrt{2}} \left( y_{1\alpha} + \frac{\delta_1}{4} y_{1\alpha} + \bar{\delta}_1 y_{2\alpha} \right)$$

$$M_2 \simeq M_{N_1} \left( 1 + \frac{\delta_1}{2} \right), \quad h_{2\alpha} \simeq \frac{1}{\sqrt{2}} \left( y_{1\alpha} - \frac{\delta_1}{4} y_{1\alpha} - \bar{\delta}_1 y_{2\alpha} \right)$$

$$M_3 \simeq M_{N_2} \left( 1 - \frac{\delta_2}{2} \right), \quad h_{3\alpha} \simeq \frac{i}{\sqrt{2}} \left( y_{2\alpha} + \frac{\delta_2}{4} y_{2\alpha} - \bar{\delta}_2 y_{1\alpha} \right)$$

$$M_4 \simeq M_{N_2} \left( 1 + \frac{\delta_2}{2} \right), \quad h_{4\alpha} \simeq \frac{1}{\sqrt{2}} \left( y_{2\alpha} - \frac{\delta_2}{4} y_{2\alpha} + \bar{\delta}_2 y_{1\alpha} \right)$$

$$\bar{\delta}_i = \frac{\bar{\mu} M_{N_i}}{M_{N_2}^2 - M_{N_1}^2}$$

Key features of confining ISS:

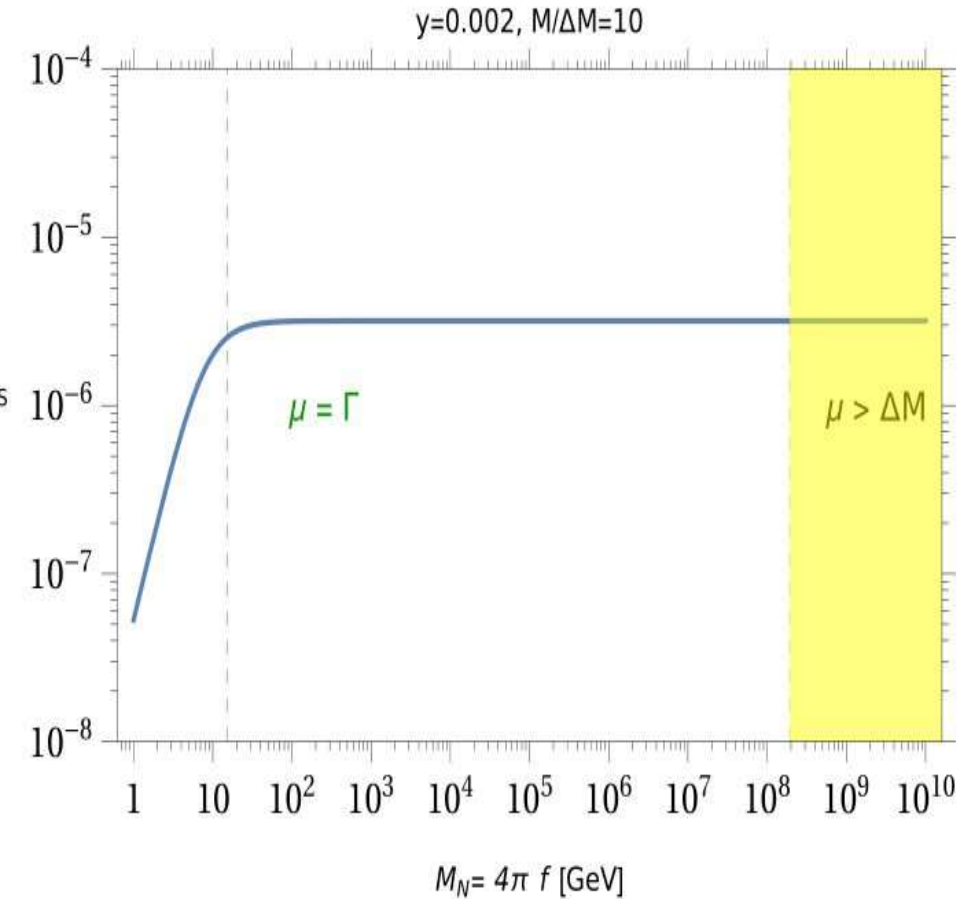
- **Sterile neutrinos** as **hadrons** of the confining sector  $\rightarrow$  **partially composite light neutrinos**
- $\mu$  from dimensional transmutation, physics external to confining sector  $\rightarrow \mu \ll M_N$  is **natural**
- Several **quasi-degenerate hadrons** expected  $\rightarrow$  **Enhancement of rate asymmetry**

# Rate asymmetry in Confining ISS

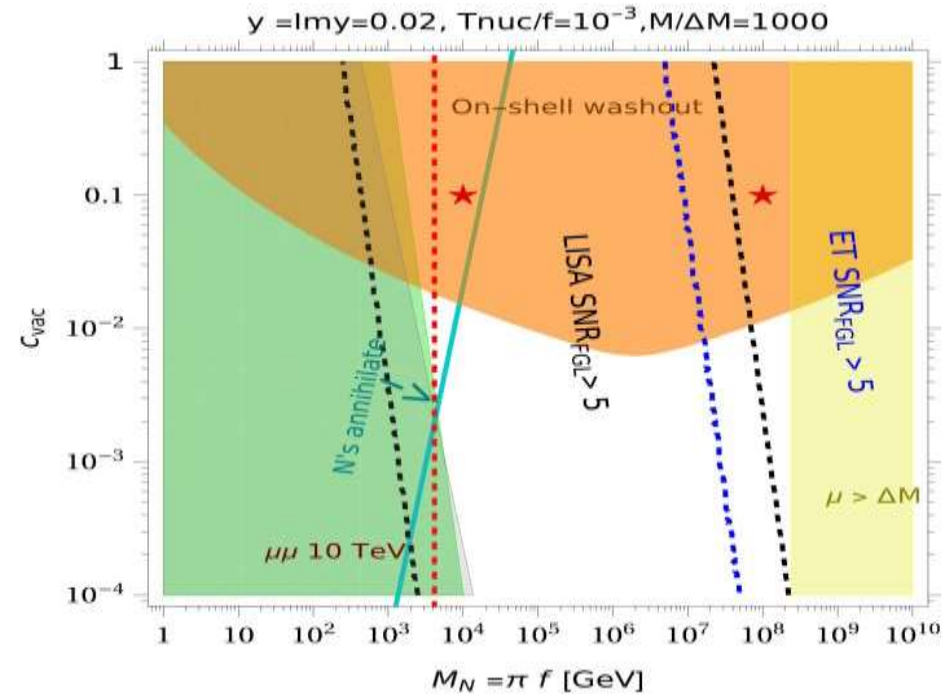
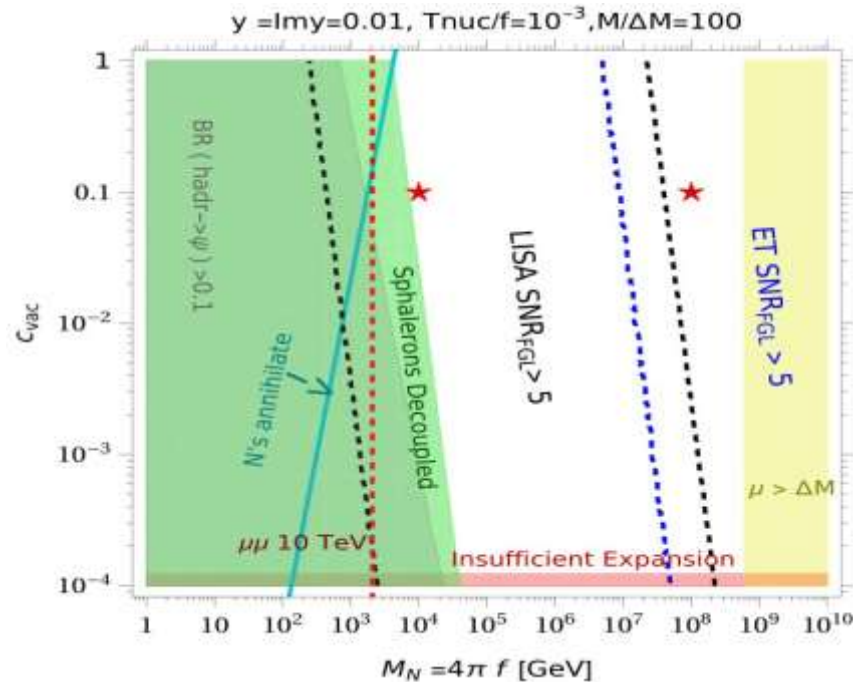
$$\epsilon_a \equiv \frac{\sum_{\alpha} \left[ \Gamma(N_a \rightarrow \ell_{\alpha} H) - \Gamma(N_a \rightarrow \bar{\ell}_{\alpha} H^*) \right]}{\sum_{\alpha} \left[ \Gamma(N_a \rightarrow \ell_{\alpha} H) + \Gamma(N_a \rightarrow \bar{\ell}_{\alpha} H^*) \right]} = \frac{1}{8\pi} \sum_{j \neq i} \frac{\text{Im}[(hh^{\dagger})_{ij}^2]}{(hh^{\dagger})_{ii}} f_{ij}$$

$$\epsilon^{ISS} \simeq 2(\epsilon_1 + \epsilon_2) \simeq \frac{\text{Im}(yy^{\dagger})_{12}}{\pi} \bar{\delta}_1 f_{12}^{\text{self}} \simeq \frac{\text{Im}y^2}{\pi} \left( \frac{\mu}{M_N} \right)^2 \frac{M_N}{\Delta M} \frac{M_N^2}{4\mu^2 + \Gamma^2} \epsilon^{ISS}$$

- Valid if  $\mu, \Gamma \ll M_N, \Delta_{M_N}$ , Natural conditions!
- Degeneracy among hadrons needed to produce enough asymmetry
- 2->2 and inverse decay of N are suppressed by smallness of  $\mu$



# Viability Parameter space in Confining ISS



- Improvement w.r.t. standard thermal leptogenesis in ISS: Leptogenesis at few TeV is possible in confining ISS
  - Obstacle to go to low values of  $f$ : Washout effects+ Electroweak sphalerons
    - Model barely testable by a 10 TeV muon collider

# Summary and Outlook

New framework for the generation of the baryon asymmetry based on a first order supercooled phase transition of a confining sector

## KEY FEATURES:

1. **Enhanced Baryon Asymmetry** due to Hadron production in DIS after bubble percolation
2. **Washout suppressed** by  $M_{hadr} \gg T_{RH}$

1+2)  $\rightarrow$  **Framework testable by GW detectors** (ET, LISA, BDECIGO)

- We discussed two models : parameter space+ testability enlarged w.r.t. non confining realization
- Natural implementation of ISS and LSS + Smallness of neutrino masses

Open question:  $f < \text{TeV}$  is viable in principle. Can we reach the **MeV-GeV** scale? Connection with **PTA signal!**

Thank you for your attention!