Based on arXiv:2312.09282,

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The Baryon Asymmetry from Supercooled Confinement

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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.

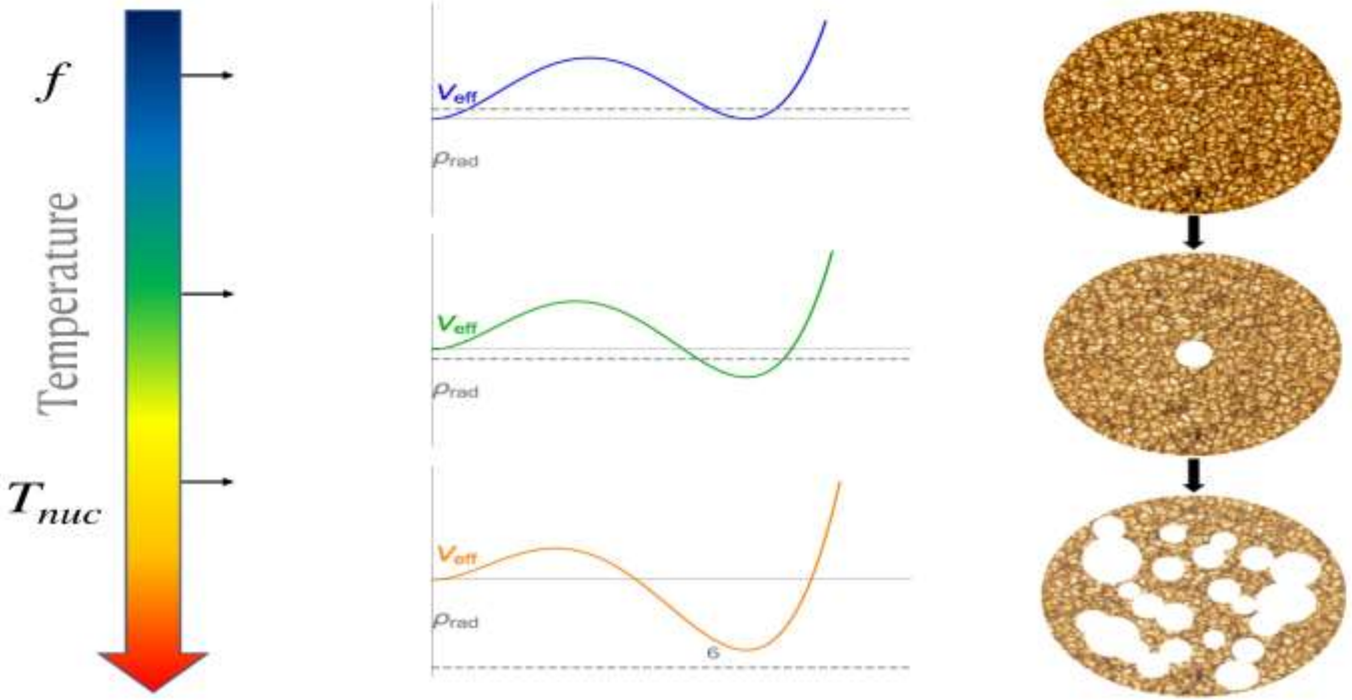
Outline

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

adapted from
Wang+ arXiv:2003.08892

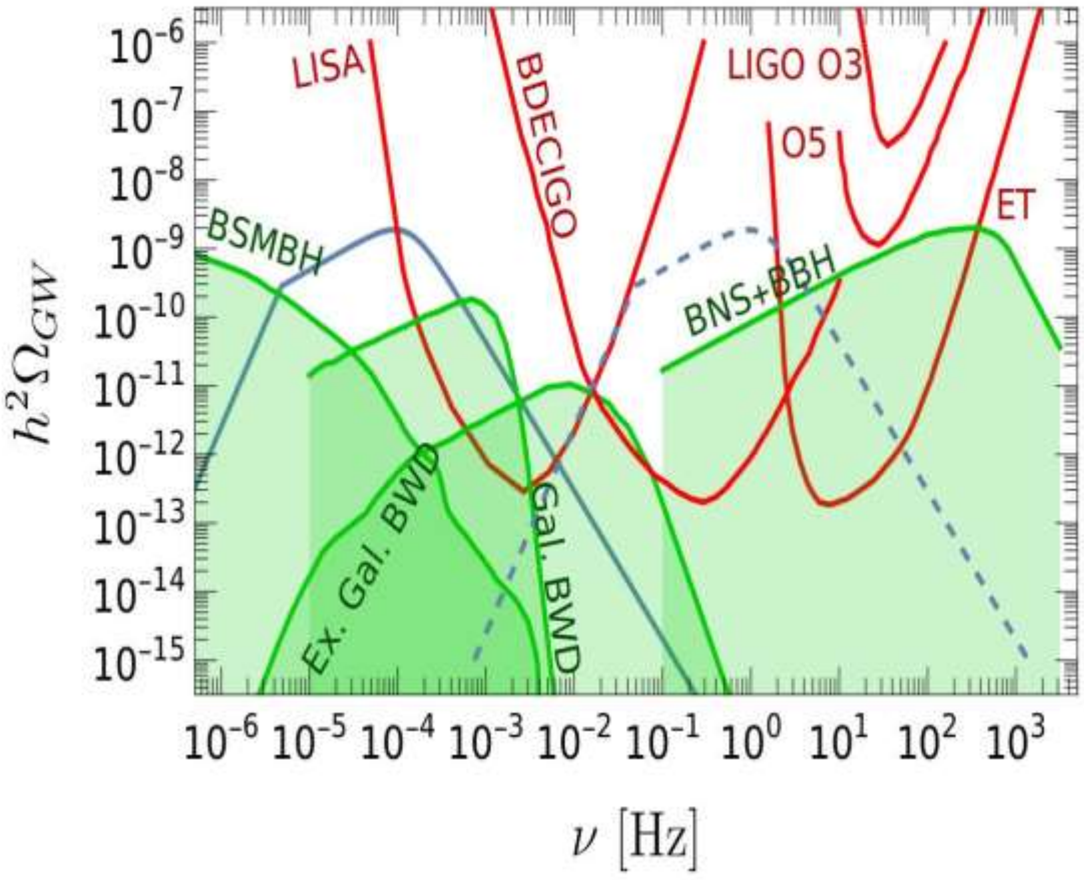
- 1st order phase transition, VEV f
- Supercooling, bubbles nucleate at $T_{nuc} << f$ during vacuum domination
- Wall velocity at collision given by

$\gamma_{coll} > M_{hadr}/T_{nuc}$ needed for hadrons enter the bubble and decay

$$\gamma_{\rm coll} \simeq {\rm Min}\left[\gamma_{\rm run}, \gamma_{\rm T}\right] \simeq {\rm Min}\left[1.7\frac{10}{\beta/H}\left(\frac{0.01}{c_{\rm vac}}\right)^{1/2}\frac{T_{\rm nuc}}{f}\frac{M_{\rm Pl}}{f}, 10^{-3}\frac{c_{\rm vac}}{0.01}\frac{80}{g_{\rm TC}}\left(\frac{f}{T_{\rm nuc}}\right)^3\right]$$

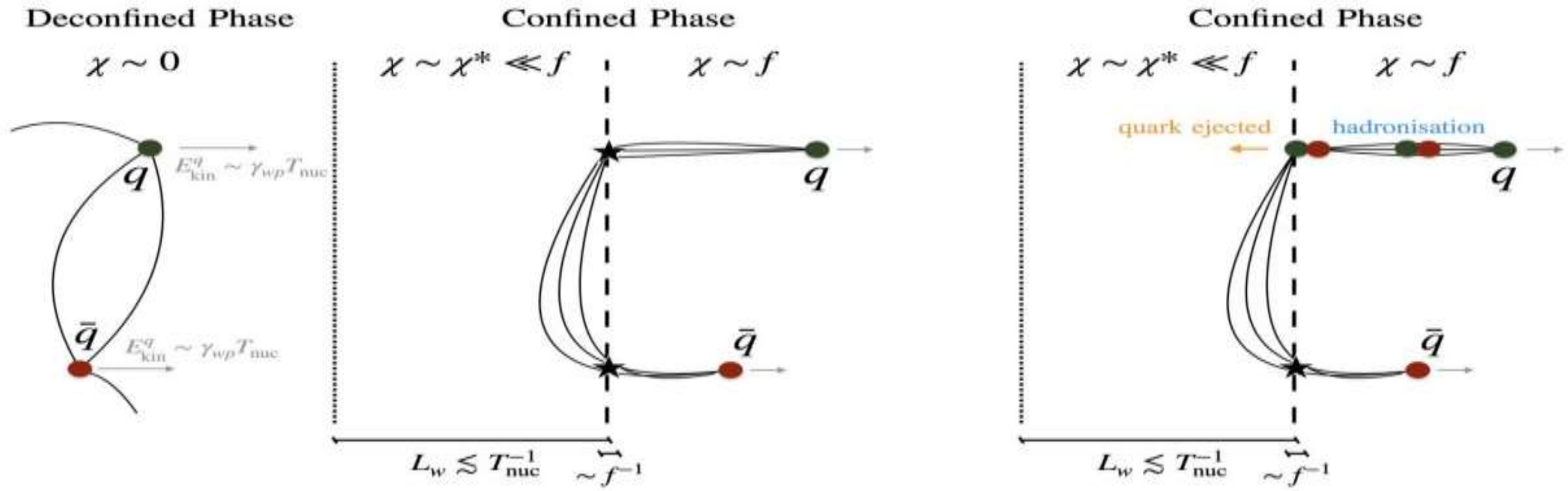
GW Signal of first order supercooled PTs

- Astrophysical foregounds taken into account
- Benchmark values of $\{c_{vac,M_\Delta}\} = \{10^{-1}, 10^4\text{GeV}\}, = \{10^{-1}, 10^8\text{GeV}\}$, 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->DIS->Hadrons->Enhanced rate asymmetry!

General Framework for the Baryon Asymmetry

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

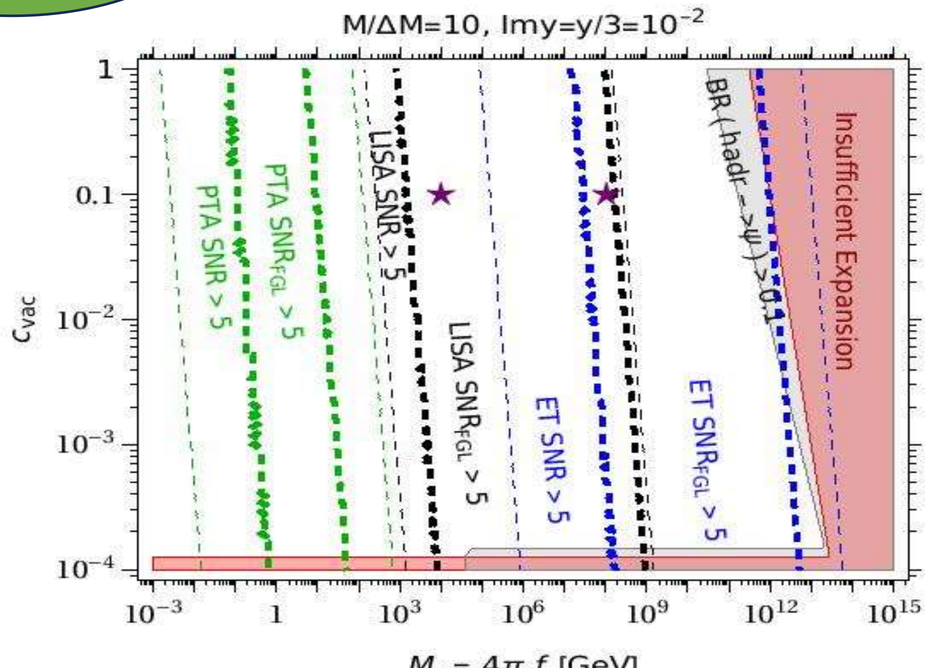
$$Y_B = \epsilon_\Psi K_{\rm Sph} Y_\Psi \simeq Y_{\rm BAU} \times \frac{\gamma_{\rm coll}}{\gamma_T}\frac{\epsilon_\Psi K_{\rm Sph}}{1.2\cdot 10^{-4}}\frac{Br(\text{hadr}\to\Psi)}{10^{-3}Z}\left(\frac{107.75}{g_{\rm RH}}\right)^{\frac{1}{4}}\left(\frac{c_{\rm vac}}{0.01}\right)^{\frac{3}{4}}\left(\frac{4\pi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

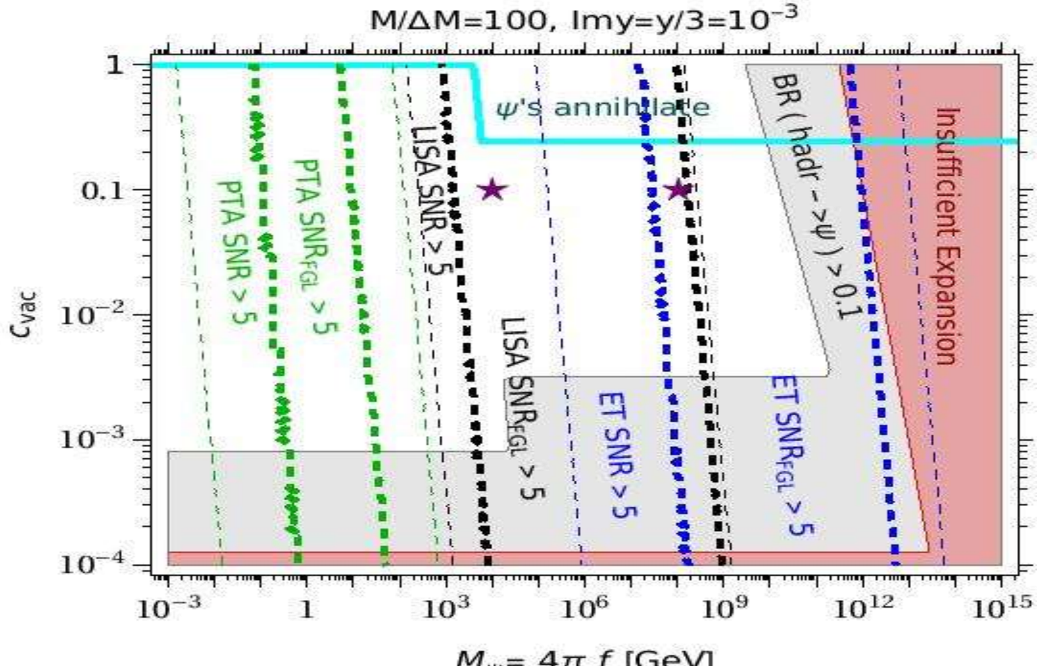
Thermal equilibrium Yield

Enhanced hadron abundance: Confining sector

Dilution from entropy release

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





Baryogenesis Scenario: The Model

$$\mathcal{L} \supset y_{di}\Delta_i \overline{d^c_R}\, d_R + y_{ui}\Delta_i \overline{\chi_R} u^c_R + \text{h.c.}$$ $\Delta = (3, 1, 2/3)$ $\chi = (1, 1, 1)$

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

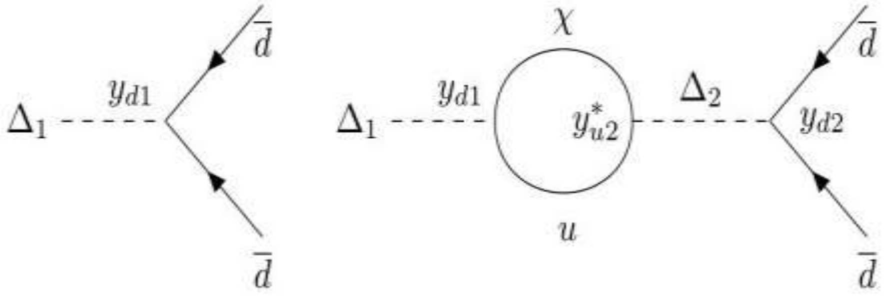
$$\Gamma(\Delta_i \to \chi u_R) \simeq \frac{|y_{ui}|^2}{16\pi} M_{\Delta_i},$$

$$\Gamma(\Delta_1 \to \overline{d_R d'_R}) = \Gamma_{1d}(1+\epsilon_d),$$
$$\Gamma(\Delta_1^* \to d_R d'_R) = \Gamma_{1d}(1-\epsilon_d),$$
$$\Gamma(\Delta_1 \to \chi u_R) = \Gamma_{1u}(1+\epsilon_u),$$
$$\Gamma(\Delta_1^* \to \overline{\chi u_R}) = \Gamma_{1u}(1-\epsilon_u).$$

CPT theorem

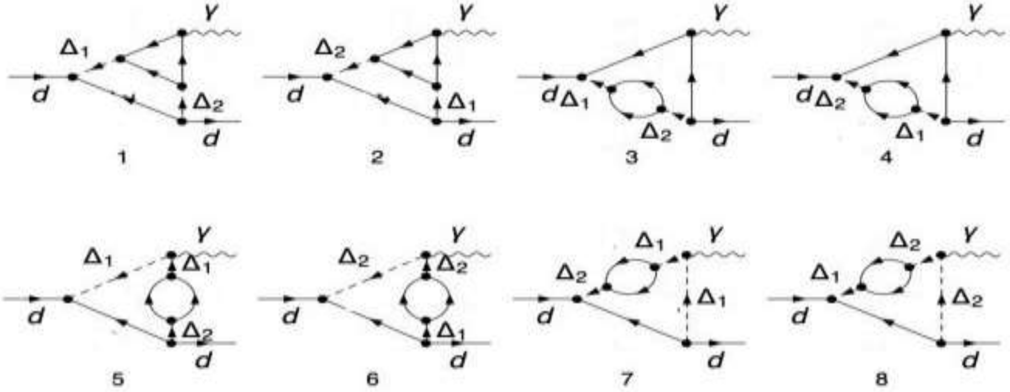
$$\epsilon_d \Gamma_{1d} = -\epsilon_u \Gamma_{1u}$$

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

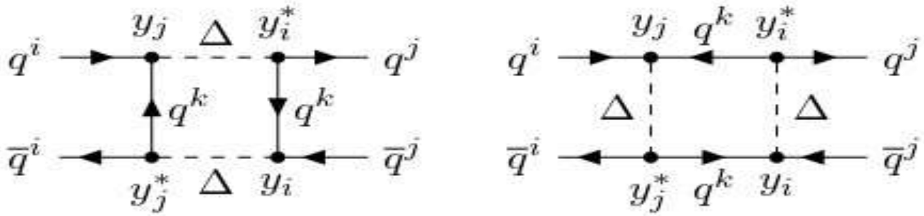


- Minimal setup: χ, Δ_1, Δ_2 couple to a single up type quark and single down type pair
- χ needs to be Majorana-> (Inverse Decay) and $M_\chi > m_p - m_{k^+}$ (Nucleon decays)
- X disentangled from neutrino masses

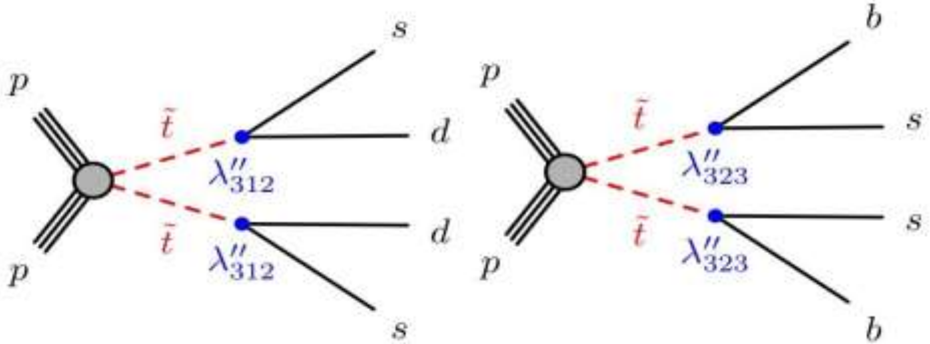
Baryogenesis Scenario: Phenomenology



No EDM at 2 Loops,
M_Δ >few TeV



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

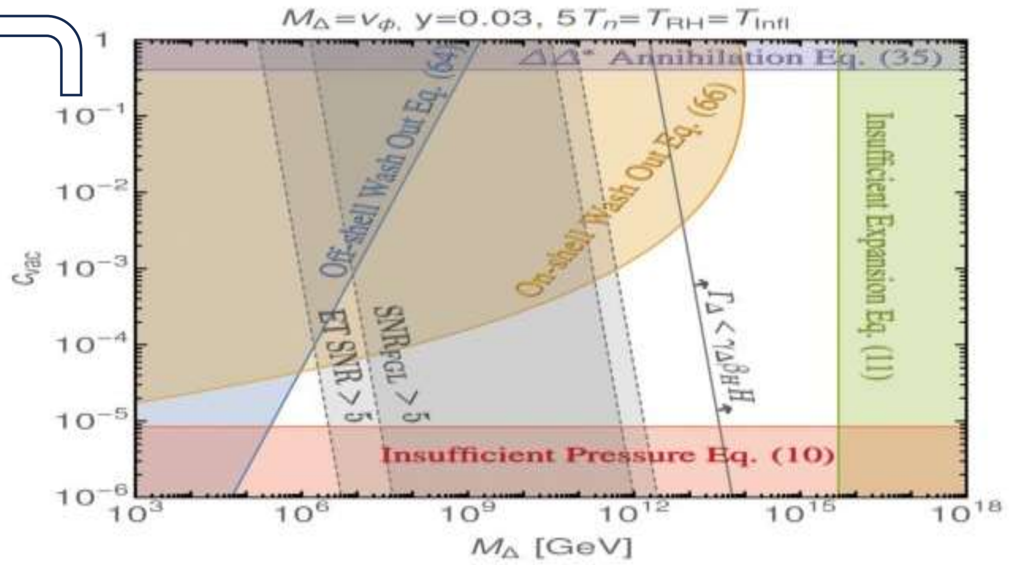


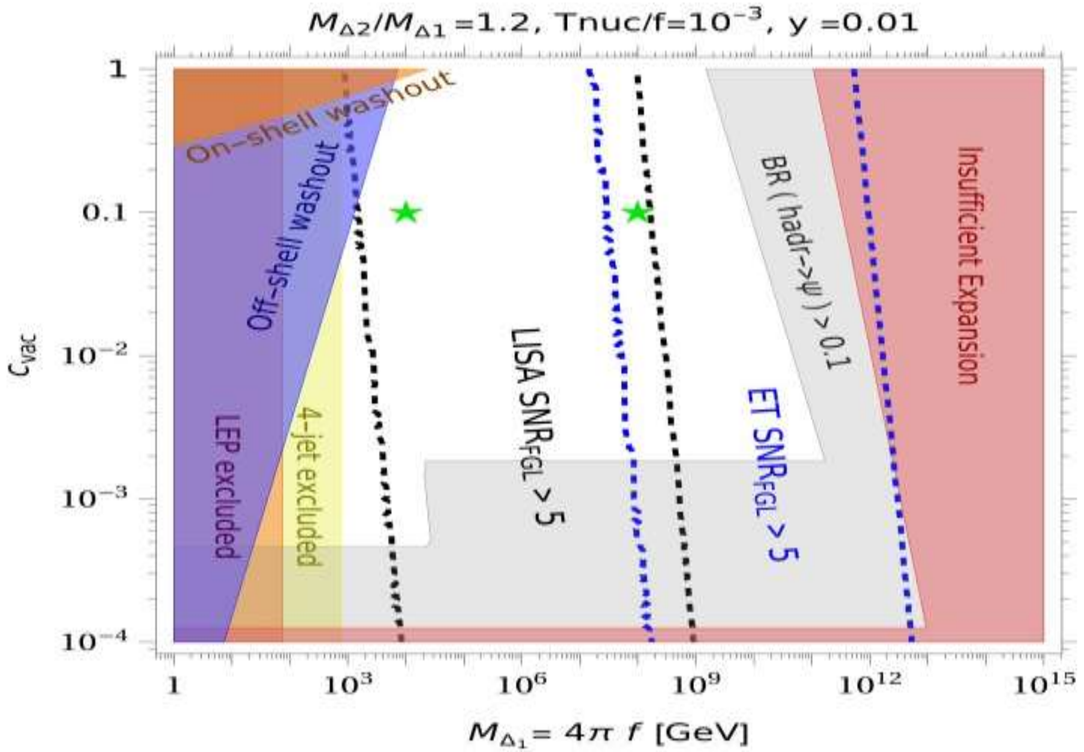
4 Jet Searches at the LHC, $M_\Delta > 770\ GeV$

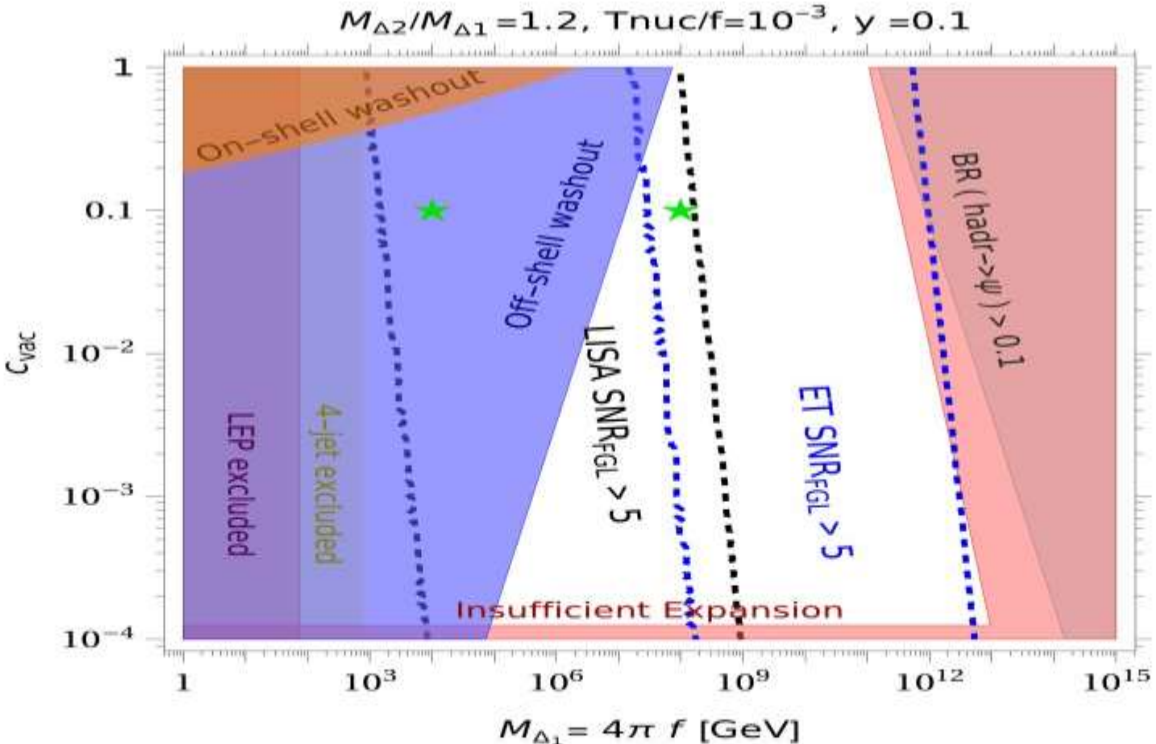
From arXiv: 1710.07171

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: Δ is partially testable







Leptogenesis Scenario: Inverse Seesaw (ISS)

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

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

← D=5 Weinberg operator

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

← μ is L breaking parameter, technically small, NOT set by any fundamental scale!

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

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

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

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

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

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

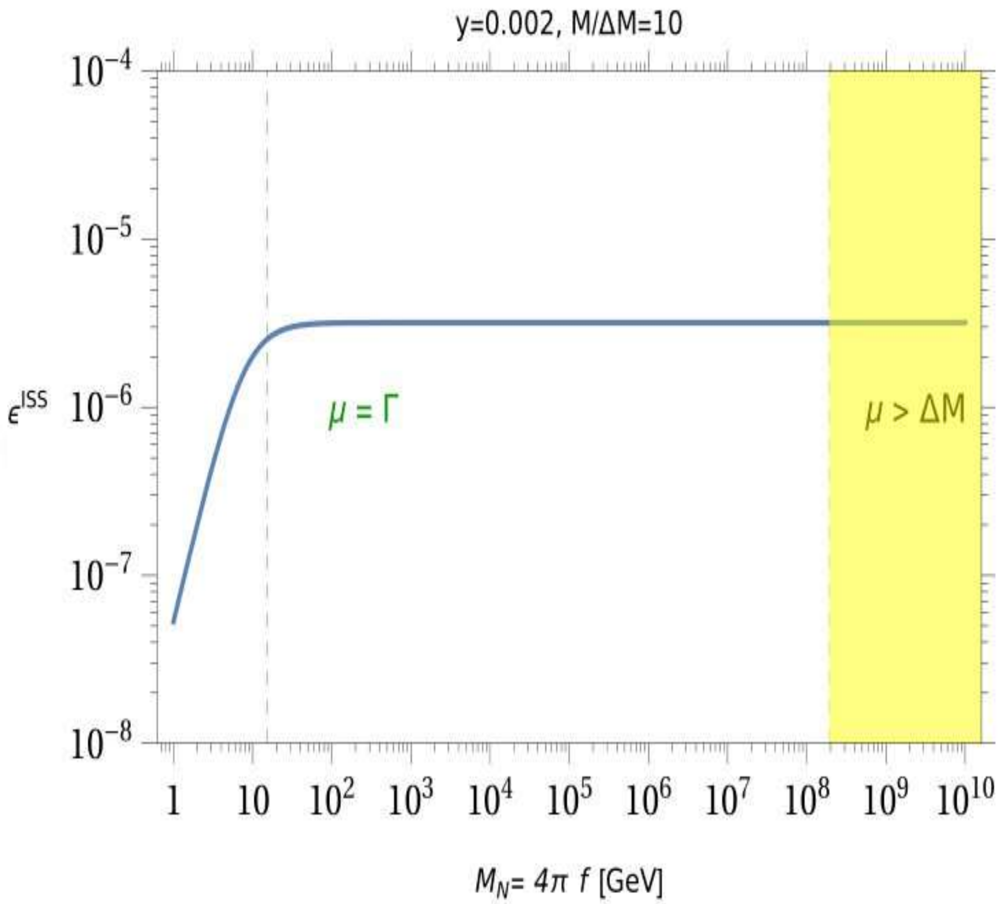
Key features of confining ISS:

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

Rate asymmetry in Confining ISS

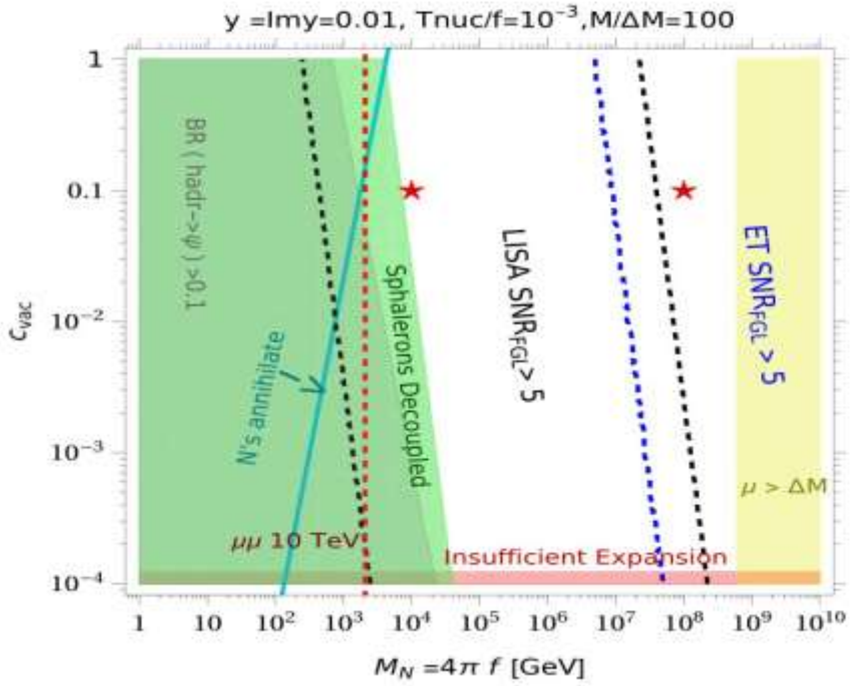
$$\epsilon_a \equiv \frac{\sum_\alpha \left[\Gamma\left(N_a \to \ell_\alpha H\right) - \Gamma\left(N_a \to \overline{\ell_\alpha} H^*\right)\right]}{\sum_\alpha \left[\Gamma\left(N_a \to \ell_\alpha H\right) + \Gamma\left(N_a \to \overline{\ell_\alpha} H^*\right)\right]} = \frac{1}{8\pi} \sum_{j \neq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

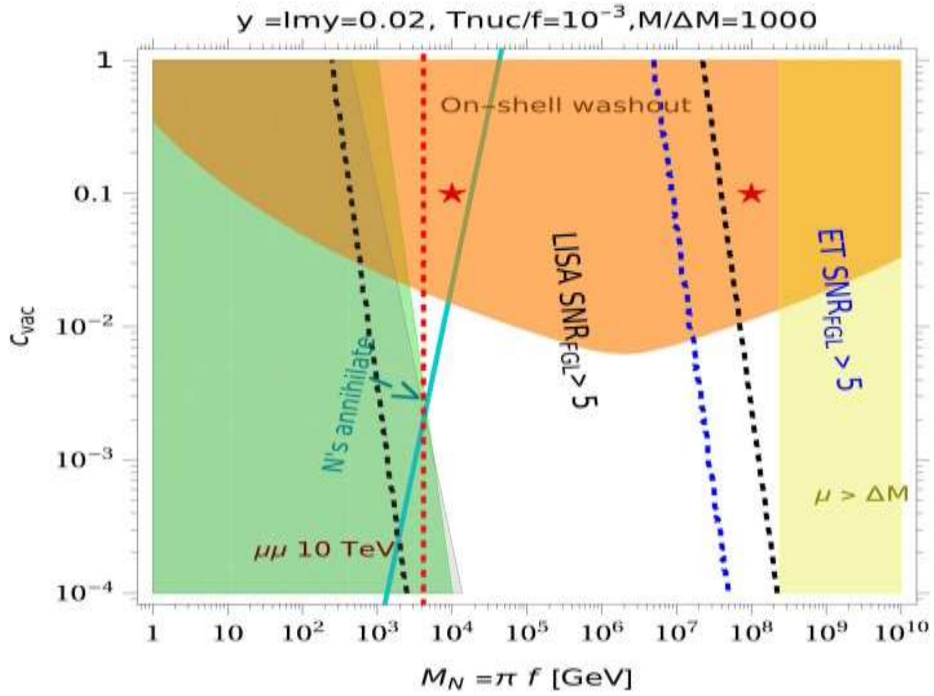
$$\epsilon^{ISS} \simeq 2(\epsilon_1 + \epsilon_2) \simeq \frac{\mathrm{Im}(yy^\dagger)_{12}}{\pi} \bar{\delta}_1 f_{12}^{\mathrm{self}} \simeq \frac{\mathrm{Im} y^2}{\pi} \left(\frac{\mu}{M_N}\right)^2 \frac{M_N}{\Delta M} \frac{M_N^2}{4\mu^2 + \Gamma^2}$$



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

Viable 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) $\longrightarrow$ 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: $f <$ TeV is viable in principle. Can we reach the MeV-GeV scale? Connection with PTA signal!

Thank you for your attention!