

# Leptogenesis and Gravity Waves from a SUSY-breaking Phase Transition

Jim Cline, Benoit Laurent, and Jean-Samuel Roux, McGill U.  
Stuart Raby, OSU

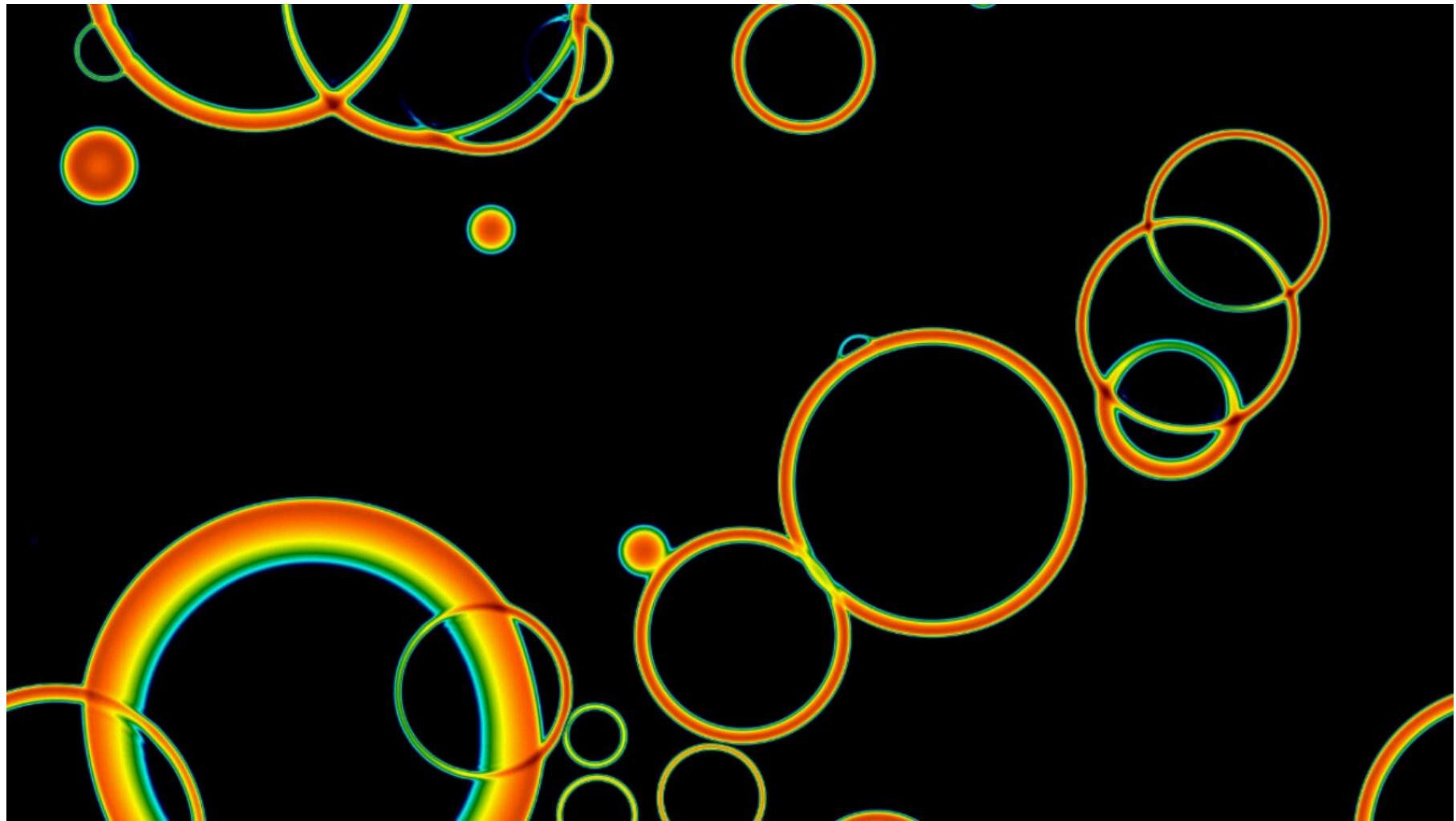
Nanjing Normal University, 25 Oct., 2023

# Outline

- Introduction: PeV-scale ~~SUSY~~ phase transition
- Production of gravity waves and primordial black holes
  - Benoit Laurent
- $\nu$  mass generation and low scale leptogenesis
  - Jean-Samuel Roux
- Conclusions

# I. Introduction

Strong first order phase transitions in the early universe are highly studied.

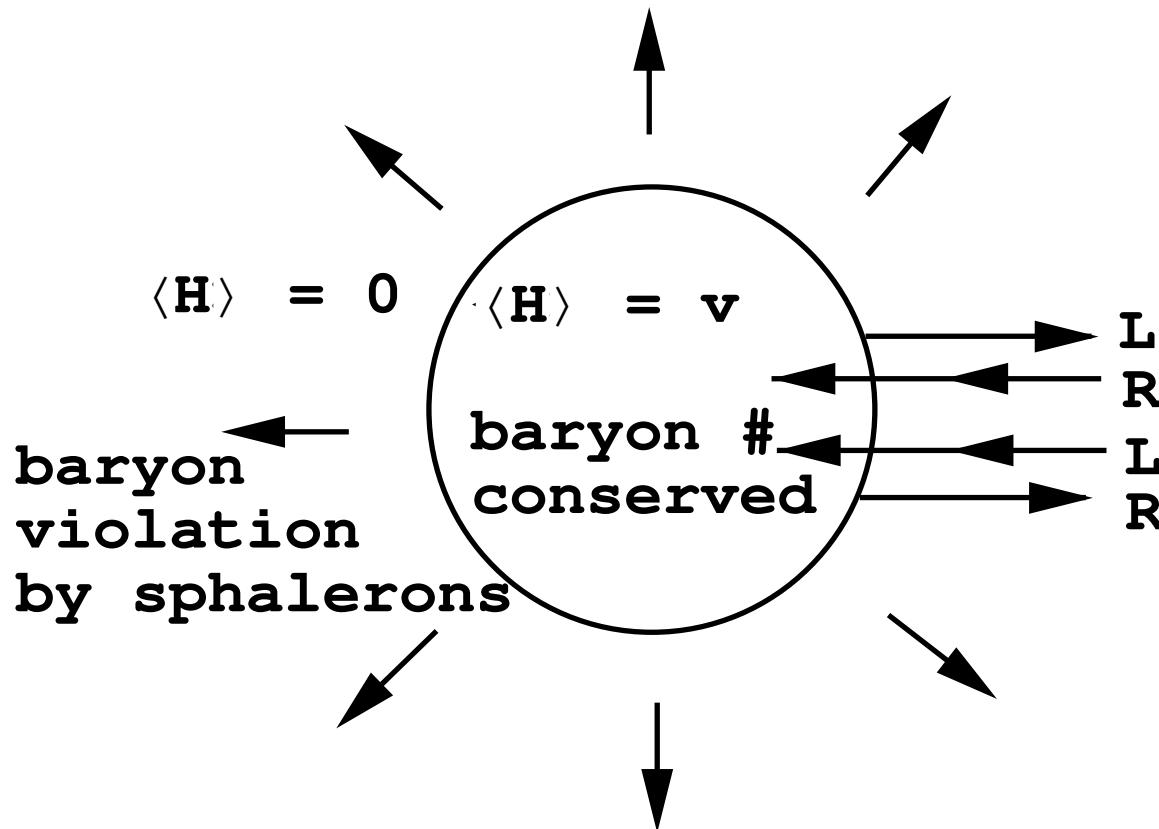


D. Weir, arxiv:1705.01783

# I. Introduction

Strong first order phase transitions can

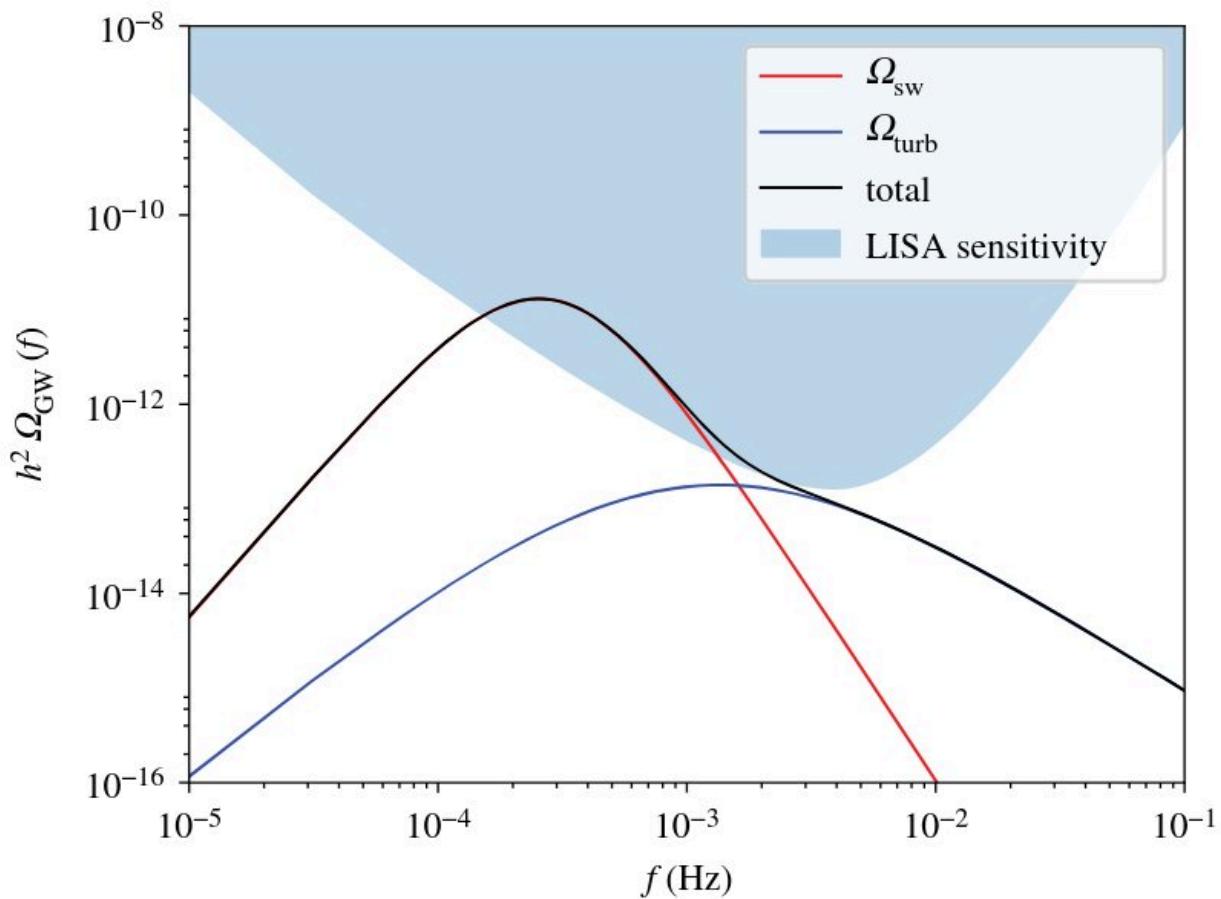
- Enable electroweak baryogenesis



# I. Introduction

Strong first order phase transitions can

- Produce gravity waves, observable in future detectors

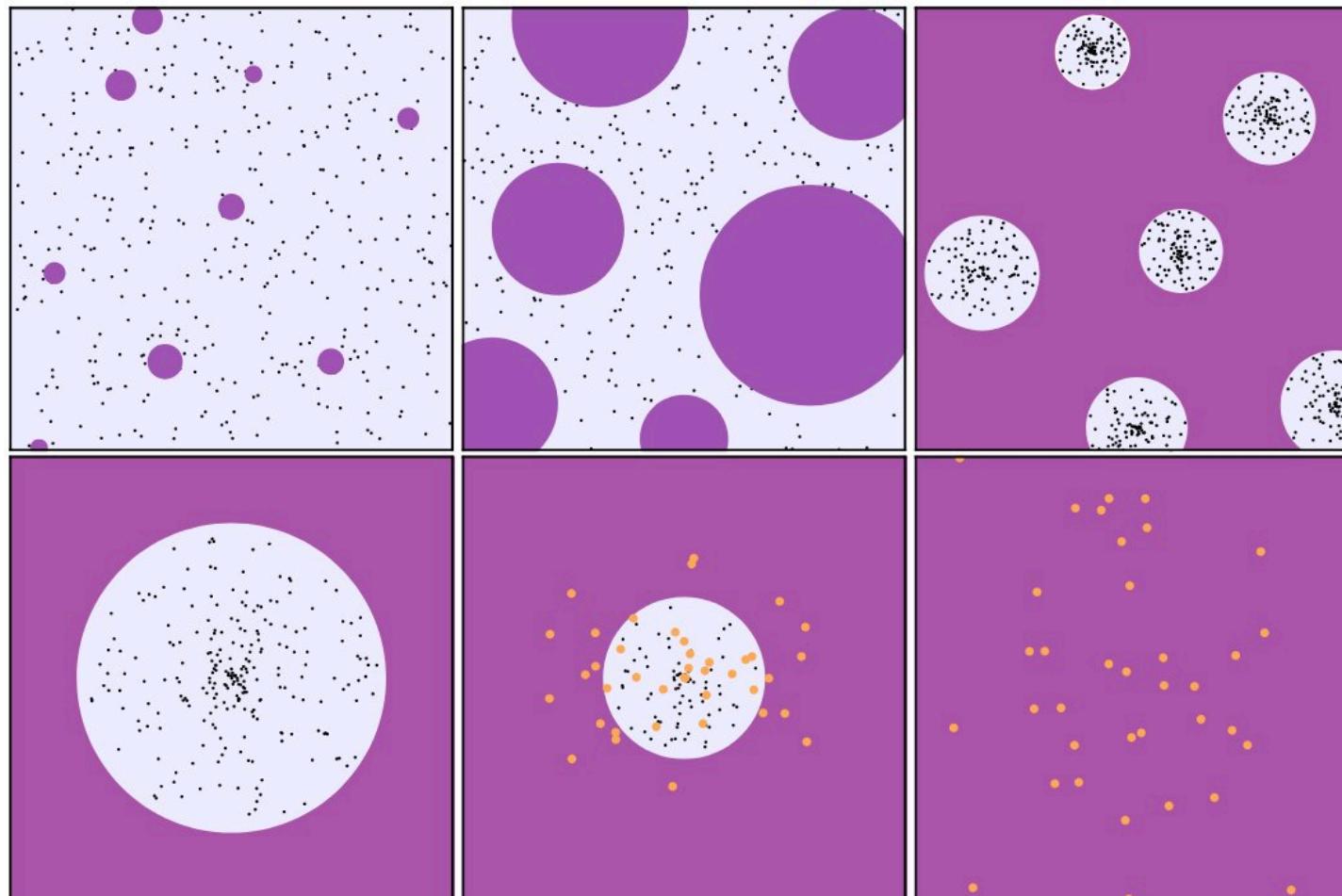


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# I. Introduction

Strong first order phase transitions can

- Have novel effects from squeezing particles in spaces between bubbles, e.g., black hole production

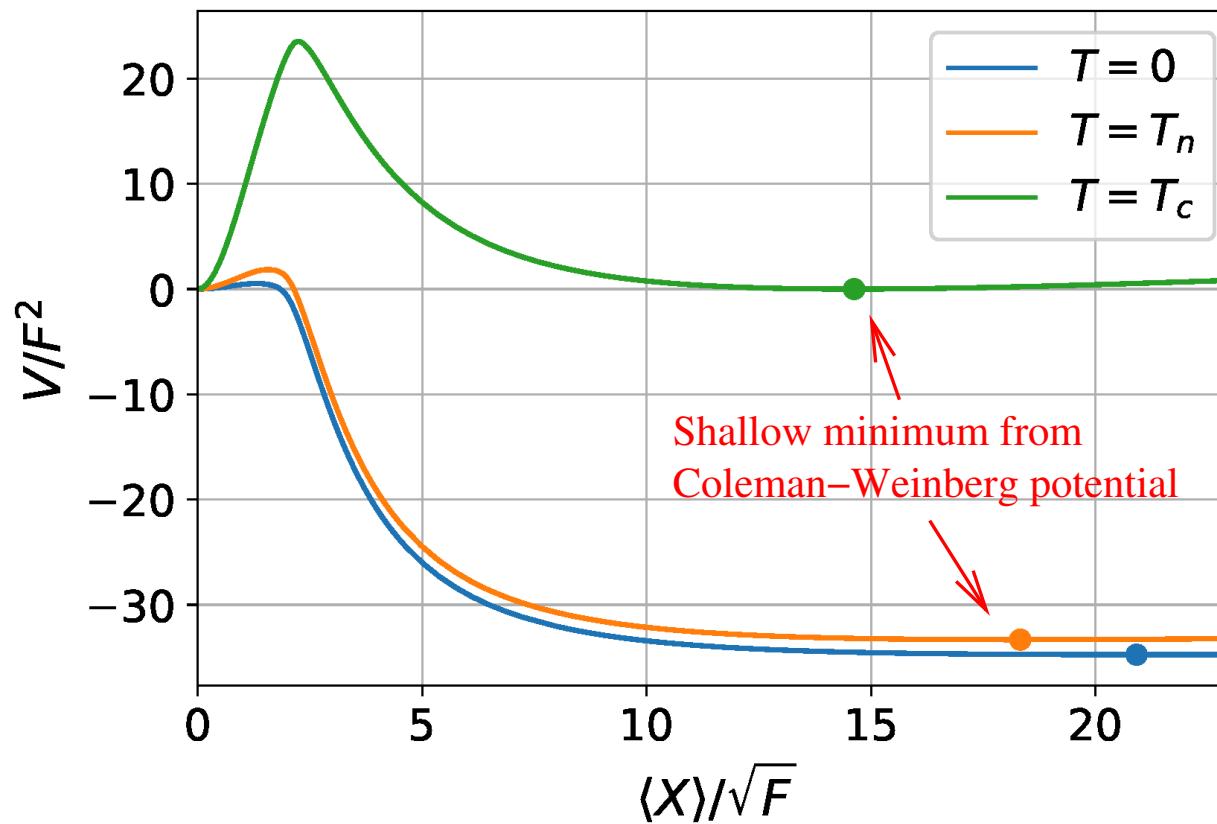


Asadi *et al.*, arxiv:2103.09827

# Beyond electroweak phase transition

EWPT has been widely studied, higher  $T$  transitions less so.

Craig, Levi, Mariotti, Redigolo 2011.13949 considered spontaneous SUSY-breaking at  $T \sim 10$  PeV.

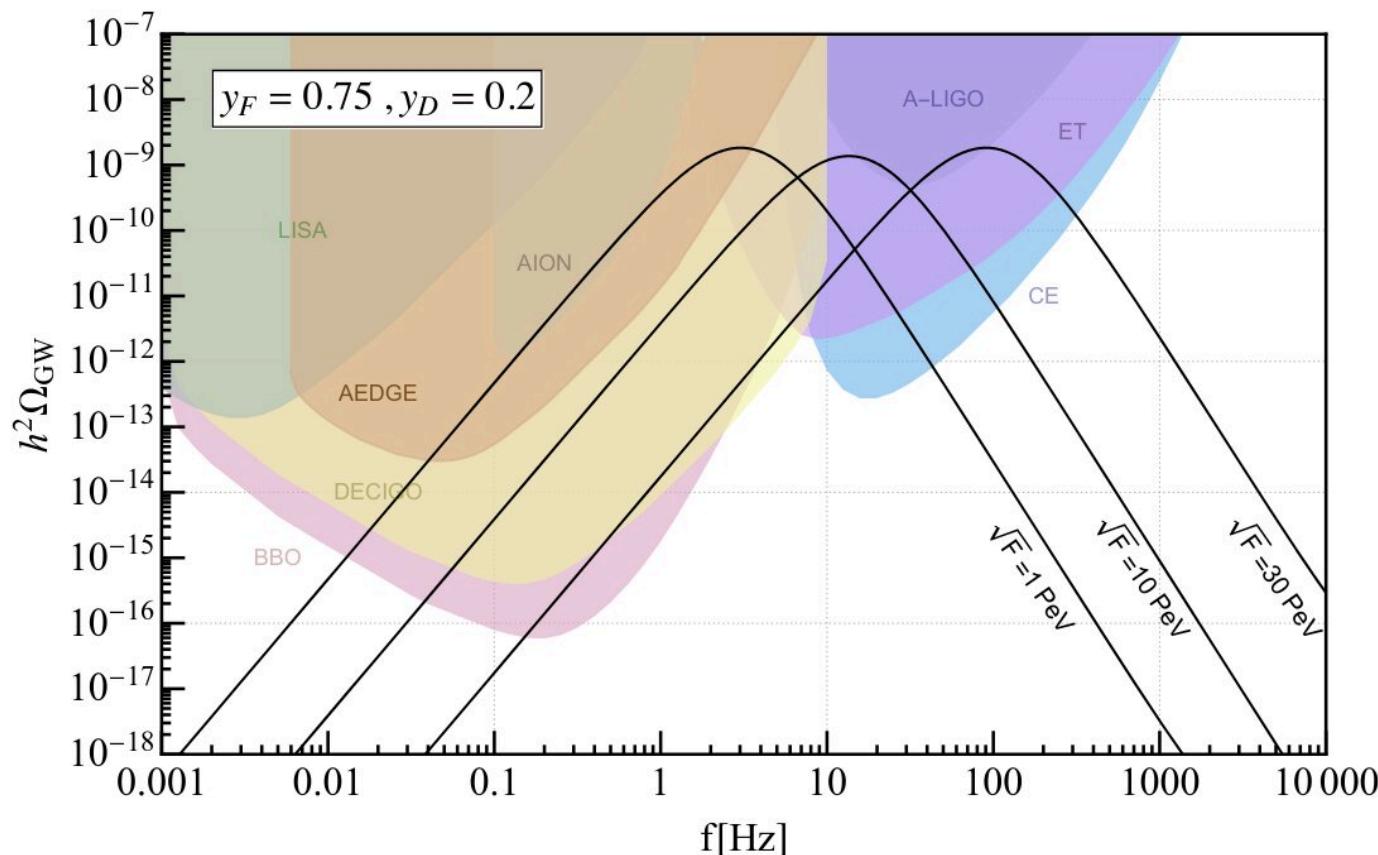


Potential for SUSY-breaking modulus  $X$  develops big barrier, large supercooling, strong phase transition

# Beyond electroweak phase transition

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Gives observable gravity waves for a variety of proposed experiments

# Other motivations for PeV-scale SUSY

There is no experimental hint of SUSY yet.

But SUSY is an attractive framework, suggested by string theory.

J. Wells, [hep-ph/0411041](#): PeV-scale SUSY has all the good features expected of SUSY,

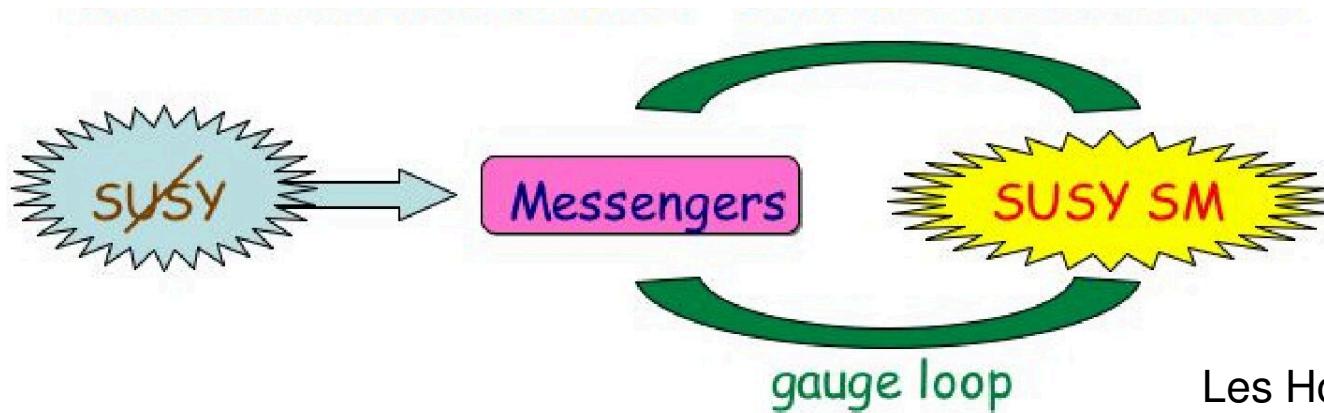
- DM
- $\nu$  mass
- gauge unification
- small FCNCs
- proton stability

Only lacking conventional hierarchy problem solution.  
(Maybe string landscape is the solution.)

With gauge-mediated SUSY, Craig *et al.* show that the PeV scale is favored by LHC gluino limits, and the gravitino problem — cosmological overproduction of gravitinos.

# Gravitino Dark Matter

In gauge mediation, heavy messenger fields  $\Phi$  charged under SM  $SU(3) \times SU(2) \times U(1)$  communicate ~~SUSY~~ from a (hidden) breaking sector to the SM gauginos, squarks, sleptons:



G. Giudice,  
Les Houches 2007

If ~~SUSY~~ scale  $\sqrt{F} \sim 10 \text{ PeV}$ , gravitino is very light:

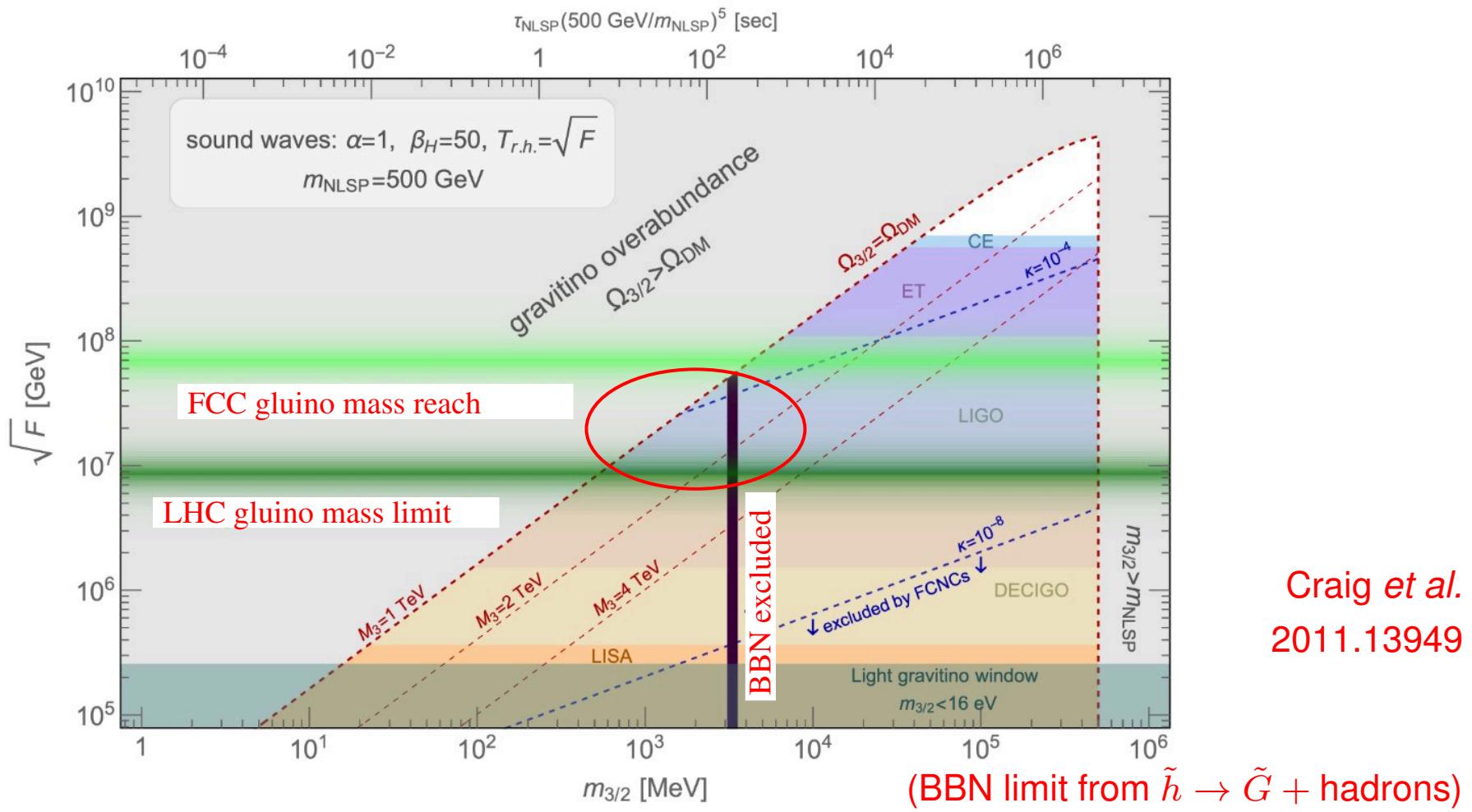
$$m_{3/2} \sim 24 \text{ keV} \left( \frac{F_0}{F} \right) \left( \frac{\sqrt{F}}{10 \text{ PeV}} \right)^2$$

It can be enhanced by additional ~~SUSY~~ sectors that couple only gravitationally to the SM, with scale  $F_0 \gg F$ . But not too much: flavor changing neutral currents in  $\mu \rightarrow e\gamma$  and  $K^0 - \bar{K}^0$  mixing constrain

$$F_0/F \lesssim 10^7, \quad m_{3/2} \lesssim 240 \text{ GeV}$$

# Window for $\sqrt{F} \in [10, 50]$ PeV

Gravitinos ( $\tilde{G}$ ) can be overproduced by  $gg \rightarrow \tilde{g}\tilde{G}$  during reheating after inflation,  $T_{rh} \sim \sqrt{F}$ . Gives constraint  $\sqrt{F} \lesssim 50$  PeV versus gravitino mass  $m_{3/2}$ ,



Gluino mass limit  $m_{\tilde{g}} > 2.3$  TeV gives lower bound,  $\sqrt{F} \gtrsim 10$  PeV\*

\* depending on messenger details: we get  $\sim 30$  PeV

# Model with $\nu$ mass, leptogenesis

We extend previous work by including ingredients for neutrino masses and low-scale leptogenesis:  $N_i$ ,  $N'_i$ , two kinds of heavy neutrinos, each with 2 flavors  $i = 1, 2$

Field	$R$	$U(1)_D$	$SU(5)$	$SU(2)_L$	$U(1)_y$	$L$	$\mathbb{Z}_2^L$
$X$	+2	0	1	1	0	0	+1
$\Phi$	0	+1	1	1	0	0	+1
$\bar{\Phi}$	+2	-1	1	1	0	0	+1
$\Phi'$	+2	+1	1	1	0	0	+1
$\bar{\Phi}'$	0	-1	1	1	0	0	+1
$5_M$	0	0	5	*	+y	0	+1
$\bar{5}_M$	+2	0	5	*	-y	0	+1
$5'_M$	+2	0	5	*	+y	0	+1
$\bar{5}'_M$	0	0	5	*	-y	0	+1
$N_i$	0	0	1	1	0	-1	-1
$N'_i$	+2	0	1	1	0	+1	-1
$L_\alpha$	2	0	1	2	-1	+1	-1
$H_u$	0	0	1	2	+1	0	+1

nonzero X VEV  
breaks SUSY

O'Raighfearaigh  
fields, create  
SUSY-breaking  
potential  $V(X)$

messenger fields,  
transmit SUSY  
breaking to the  
MSSM

PeV scale  
RH neutrinos

Lepton doublet,  
up-type Higgs

$X$  gets SUSY-breaking VEV, which also generates

mass for  $N_i$ . We get novel scenario for  $\nu$  mass and leptogenesis.

provides D-term potential  
embeds  $SU(3) \times SU(2) \times U(1)$  SM gauge group

discrete remnant of lepton symmetry

Define 6-component fields:

$$\Psi = (\Phi, 5_M)^T, \quad \Psi' = (\Phi', 5'_M)^T$$

$$\bar{\Psi} = (\bar{\Phi}, \bar{5}_M)^T, \quad \bar{\Psi}' = (\bar{\Phi}', \bar{5}'_M)^T$$

Superpotential interactions:

$$-FX + \lambda X\Psi\bar{\Psi}' \\ + m(\Psi\bar{\Psi} + \Psi'\bar{\Psi}')$$

Gives SUSY breaking

$$\frac{\lambda'_{ij}}{2} X N_i N_j + M_{ij} N_i N'_j$$

L violating term

$$+ Y_{i\alpha} \epsilon_{ab} N_i L_\alpha^a H_u^b$$

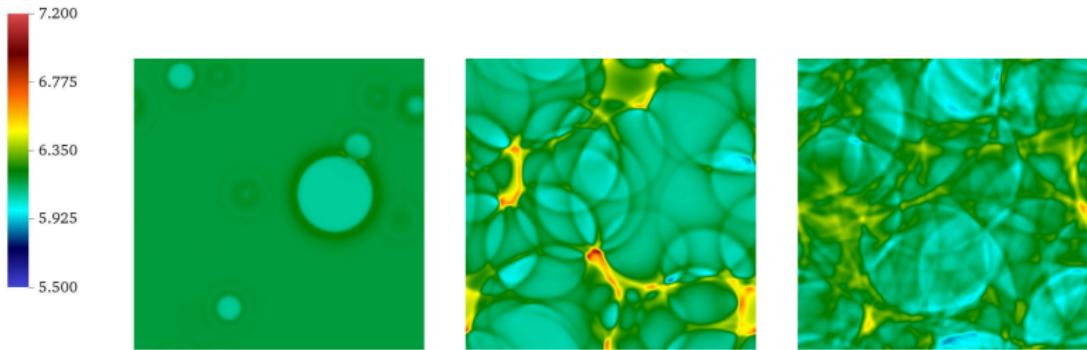
Gives  $\nu$  masses and leptogenesis

D-term potential:

$$V_D = \frac{g^2}{2} \left( \frac{D}{g} + |\tilde{\Phi}|^2 + |\tilde{\Phi}'|^2 - |\tilde{\bar{\Phi}}|^2 - |\tilde{\bar{\Phi}}'|^2 \right)^2$$

leads to strong phase transition

# Gravitational waves



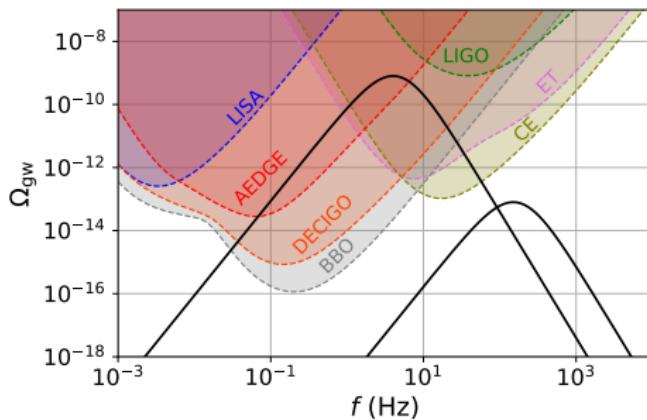
Hindmarsh, Huber, Rummukainen and Weir (arxiv:1304.2433)

# GW prediction

We want to predict the GW energy spectrum  $\Omega_{\text{gw}}(f)$ :

$$\Omega_{\text{gw}}(f) = 2.061 \times \underbrace{F_{\text{gw},0}}_{\text{Redshift}} \times \underbrace{\tilde{\Omega}_{\text{gw}}}_{\text{SW fraction converted in GW}} \times \underbrace{\frac{(HRK)^2}{\sqrt{K+HR}}}_{\text{Energy fraction converted in SW}} \times \underbrace{C(f/f_{\text{p},0})}_{\text{Shape}}$$

$$\int d(\log f) \Omega_{\text{gw}}(f) = \frac{\rho_{\text{gw}}}{\rho_c}$$



# Signal-to-noise ratio (SNR)

The SNR can be used to determine if a signal could be detected:

$$\text{SNR} = \sqrt{\mathcal{T} \int df \left( \frac{\Omega_{\text{gw}}(f)}{\Omega_{\text{sens}}(f)} \right)^2}$$

- $\mathcal{T} \cong 4$  years: mission duration,
- $\Omega_{\text{sens}}(f)$ : detector's sensitivity curve.

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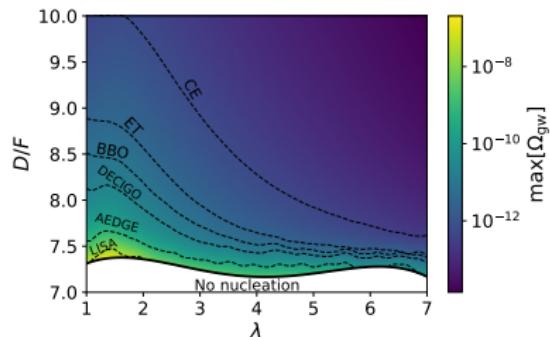
Whenever  $\text{SNR} \geq \text{SNR}_{\text{thr}} \cong 10$ , we conclude that the signal can be detected.

# Results

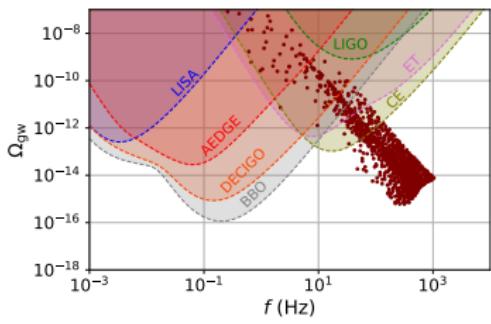
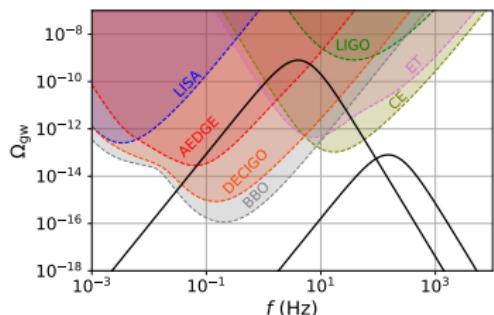
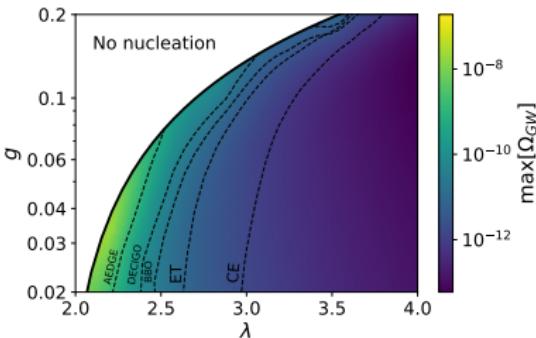
2 scans of the parameter space, both varying  $\lambda$  ( $W \supset \lambda X \Phi \bar{\Phi}'$ )

$F$ : O'Raifeartaigh term

$D$ : Fayet-Iliopoulos term of  $U(1)_D$  symmetry



$g$ :  $U(1)_D$  coupling



# Primordial black holes

# Mass gain mechanism

During a FOPT, if particles gain a large mass  $\Delta m \gg \gamma_w T_n$ , they do not have enough kinetic energy to enter the true-vacuum bubble.

**Every collision with the bubble wall ends in reflection.**

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**Every collision with the bubble wall ends in reflection.**

The density of the trapped particles increases until they collapse into a black hole.



Huang and Xie (arxiv:2201.07243)

# Application to SUSY-breaking PT

Since  $\langle \tilde{X} \rangle$  is very large, the SUSY-breaking PT naturally leads to large variation of mass between the phases.

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## Example: Messenger fields $\Psi$

- Before the PT:  $m_\Psi \cong m$ ,
- After the PT:  $m_{\Psi,1} \cong \lambda \langle \tilde{X} \rangle$  and  $m_{\Psi,2} \cong \frac{m^2}{\lambda \langle \tilde{X} \rangle}$ .

# Schwarzschild criteria

- We assume a spherical false-vacuum bubble with radius  $r$ ,
- We have a gravitational collapse if

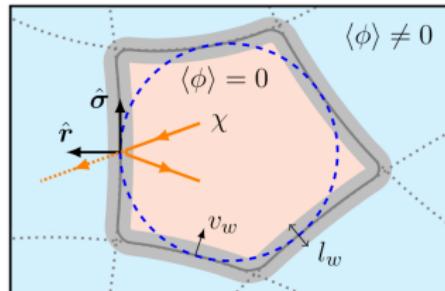
$$r < r_s \equiv 2G E_{\text{tot}},$$

- For slow-moving walls,  $E_{\text{tot}} \propto 1/r$ , which leads to

$$\frac{r_s}{r_H} \cong \sqrt{\frac{g_\Psi}{g_*}} \left( \frac{r_0}{r_H} \right)^2,$$

where  $r_0$  is the initial bubble radius.

- **Example:** For  $r_0 = r_H$ , the bubble only has to shrink by a factor of 2.8.



Baker, Breitbach, Kopp and Mittnacht  
(arxiv:2105.07481)

# Pressure on the wall

There are 3 forces acting on the wall:

- Thermal pressure:

$$P_T \propto -\frac{1}{r^4},$$

- Vacuum pressure:

$$P_V = +\Delta V,$$

- Gravitational pressure:

$$P_G = \frac{dE_G}{dV} = \frac{d}{dV} \left( -\frac{3GE_{\text{tot}}^2}{5r} \right) \propto +\frac{1}{r^6}$$

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To produce a black hole, we must always have  $P_{\text{tot}} > 0$  when  $r > r_s$ .  
The minimal pressure happens at

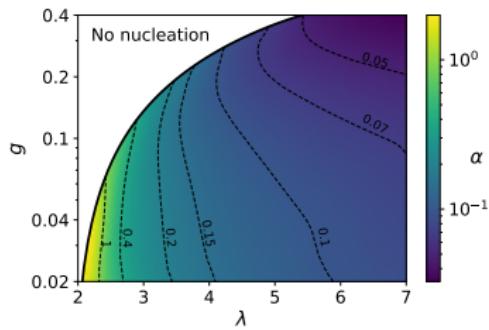
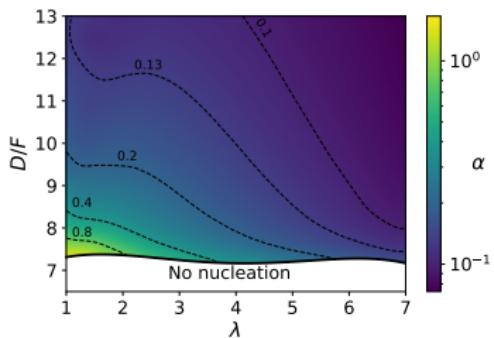
$$r_{\min} \cong 1.16r_s,$$

where the constraint can be written as

$$\alpha \approx \frac{\Delta V}{\rho_\gamma} \gtrsim 0.29 \left( \frac{r_H}{r_0} \right)^4.$$

# Results

$$\text{If } r_0 \cong r_H \quad \rightarrow \quad \alpha \gtrsim 0.29$$



# **Part 3 - PeV-scale leptogenesis**

**Jean-Samuel Roux**

McGill University

August 31 2023

# Superpotential

$$W_{\mathbb{L}} = -FX + \frac{\lambda'_{ij}}{2} X N_i N_j + M_{ij} N_i N'_j + Y_{i\alpha} \epsilon_{ab} N_i L_\alpha^a H_u^b$$

Consider only **2 flavors** each of  $N_i, N'_i$  ( $i = 1, 2$ )  $\Rightarrow$  one massless  $\nu_L$ .

Normal hierarchy (NH)	Inverted hierarchy (IH)
$m_1 = 0$	$m_1 \approx 0.0492$ eV
$m_2 \approx 0.0086$ eV	$m_2 \approx 0.05$ eV
$m_3 \approx 0.05$ eV	$m_3 = 0$

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Minimal Flavor Violation (MFV):  $SO(2)$  symmetry

$$\lambda'_{ij} \rightarrow \lambda' \delta_{ij}; \quad M_{ij} \rightarrow (M \delta_{ij} + i M' \epsilon_{ij}).$$

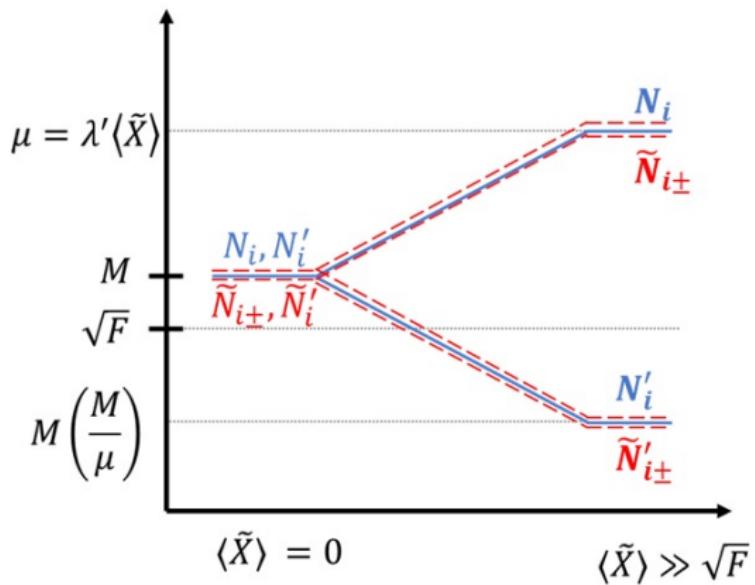
$M_{ij}$  has eigenvalues

$$M_i = M \left( 1 \pm \frac{M'}{M} \right)$$

- Resonant 1-loop flavor mixing with  $M'/M \sim 10^{-7}$ .

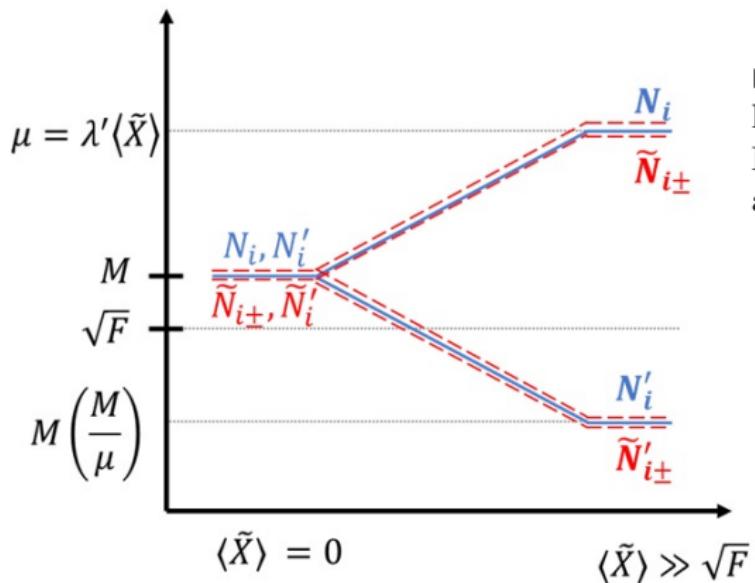
## RH (s)neutrino spectrum

$$\begin{aligned}-\mathcal{L} \supset & \left( |M_i|^2 + |\lambda' \tilde{X}|^2 \right) \left| \tilde{N}_i \right|^2 + \left| M_i \tilde{N}'_i \right|^2 + \left( \lambda' M_i^* \tilde{X} \tilde{N}_i \tilde{N}'_i - \frac{\lambda' F_X^*}{2} \tilde{N}_i \tilde{N}_i + \text{h.c.} \right) \\ & + \left( M_i \overline{N_i^C} N'_i + \frac{\lambda'}{2} \tilde{X} \overline{N_i^C} N_i + \text{h.c.} \right)\end{aligned}$$



## RH (s)neutrino spectrum

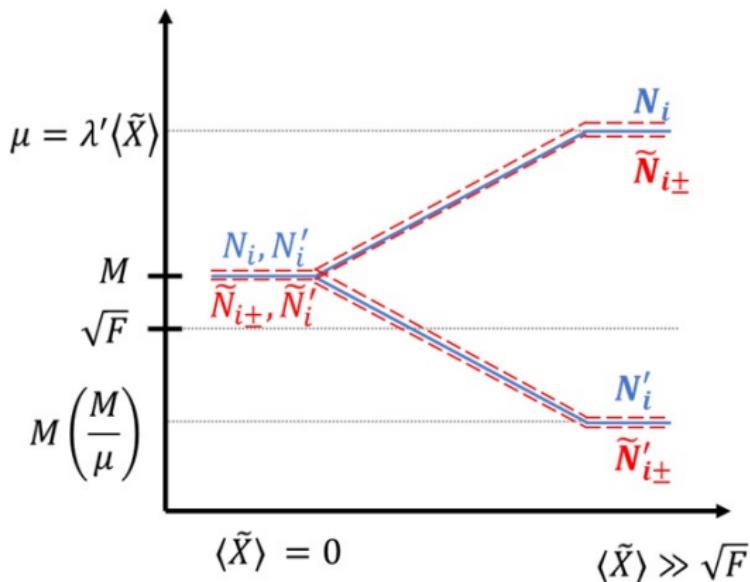
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Induce **light neutrino masses** at one-loop.

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- Decay immediately, but lepton asymmetry washed out. Induce **light neutrino masses** at one-loop.

- Quickly thermalize. Decays lead to **leptogenesis** despite strong washout.

Bound on gluino mass limits the scale of leptogenesis:  $\frac{M^2}{\mu} \gtrsim 500 \text{ TeV}$

## Light neutrino masses

Tree-level mass matrix in  
 $(\nu, N', N)$  basis:

$$\begin{pmatrix} 0 & 0 & m_D \\ 0 & 0 & M_i \\ m_D^T & M_i & \mu \end{pmatrix} \Rightarrow \text{yields } m_\nu = 0$$

where  $m_D = Y \langle H_u \rangle$  and  $\mu = \lambda' \langle \tilde{X} \rangle \gg M$ .

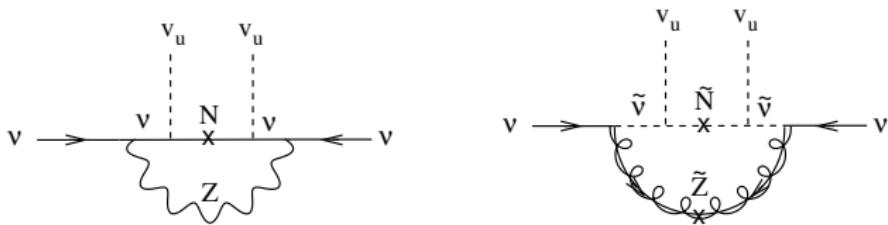
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Radiative terms [Ma *et al.*, hep-ph/0603043; Mohapatra, Okada, 2207.10619]:



$$m_\nu = \frac{g_2^2 Y^T Y (v_u^2/\mu)}{8\pi^2 \cos^2 \theta_W} \left( \frac{\ln(\mu/m_Z)}{1 - m_Z^2/\mu^2} + \frac{\lambda' F_X}{16 \mu m_{\tilde{Z}}} f(s_M) \right) \sim \mathcal{O}(0.1) Y^T Y \frac{v_u^2}{\mu}$$

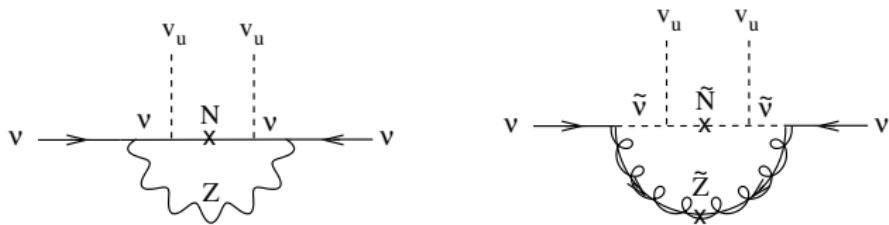
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Yukawa couplings estimate:

$$Y^T Y = 1.6 \times 10^{-6} \left( \frac{\mu}{100 \text{ PeV}} \right) \left( \frac{m_\nu}{0.05 \text{ eV}} \right) \left( \frac{1}{\sin^2 \beta} \right)$$

## Casas-Ibarra parametrization [Casas, Ibarra, hep-ph/0103065]

For normal hierarchy (and similarly for IH):

$$Y_{i\alpha} = \sqrt{C \frac{\mu}{v_u^2}} \mathcal{R} D_{\sqrt{m_\nu}} U_\nu^\dagger, \quad \text{where } C \approx 9.7, \quad D_{\sqrt{m_\nu}} = \text{diag}(0, \sqrt{m_2}, \sqrt{m_3})$$
$$\mathcal{R} = \begin{pmatrix} 0 & \cos \hat{\varrho} & \sin \hat{\varrho} \\ 0 & -\sin \hat{\varrho} & \cos \hat{\varrho} \end{pmatrix}, \quad \hat{\varrho} = a + ib$$

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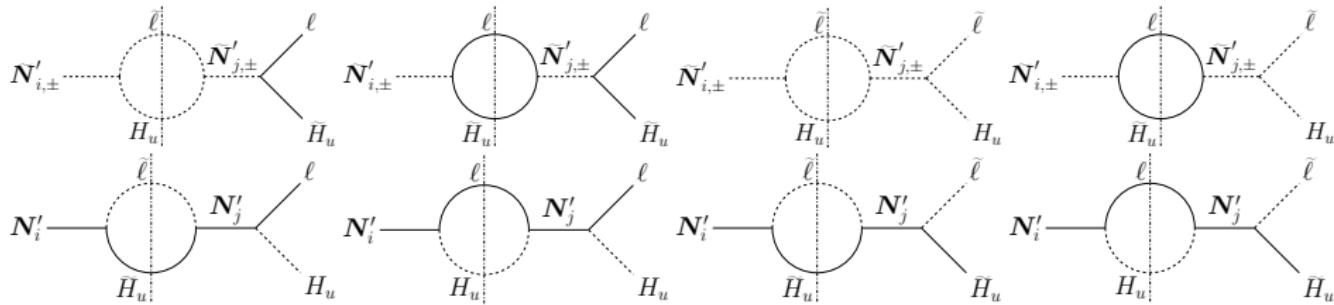
Only  $YY^\dagger$  is relevant for leptogenesis:

$$(YY^\dagger) = C \frac{\mu}{v_u^2} \left( \mathcal{R} D_{m_\nu} \mathcal{R}^\dagger \right) \equiv C \frac{\mu}{2v_u^2} \mathcal{M}$$
$$= C \frac{\mu}{2v_u^2} \begin{pmatrix} \delta \cos 2a + \sigma \cosh 2b & -\delta \sin 2a + i\sigma \sinh 2b \\ -\delta \sin 2a - i\sigma \sinh 2b & -\delta \cos 2a + \sigma \cosh 2b \end{pmatrix},$$

where  $\delta = m_2 - m_3$ ,  $\sigma = m_2 + m_3$ .

$\Rightarrow$  CP violation from complex phases  $\phi_{ij} = \arg(YY^\dagger)_{ij} = \arg \mathcal{M}_{ij}$ .

# One-loop mixing



Mass splitting between flavors:

$$\delta m_{ij}^2 \approx 8M^2 \left(\frac{M}{\mu}\right)^2 \left(\frac{M'}{M}\right) \ll M^2 \left(\frac{M}{\mu}\right)^2 \quad (\sim 1 \text{ part in } 10^6)$$

$\Rightarrow$  Resonant mixing enhances CP asymmetry  $\epsilon \sim 1/\delta m_{ij}^2$ .

## CP asymmetry

CP asymmetry:

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$$\tilde{\epsilon}_i = \frac{\sum_{X_\alpha, \alpha} \Gamma(\widetilde{\mathbf{N}}'_i \rightarrow X_\alpha) - \Gamma(\widetilde{\mathbf{N}}'_i \rightarrow X_\alpha^\dagger)}{\sum_{X_\alpha, \alpha} \Gamma(\widetilde{\mathbf{N}}'_i \rightarrow X_\alpha) + \Gamma(\widetilde{\mathbf{N}}'_i \rightarrow X_\alpha^\dagger)}$$

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Resummation approach [Pilaftsis, hep-ph/9707235]:

$$\epsilon_i = \tilde{\epsilon}_i = \frac{1}{2} \sum_{i \neq j} \frac{\text{Im}[(YY^\dagger)_{ij}^2]}{(YY^\dagger)_{ii}(YY^\dagger)_{jj}} \frac{(m_i \Gamma_j)(\delta m_{ij}^2)}{(\delta m_{ij}^2)^2 + (m_i \Gamma_j)^2} \Rightarrow \text{same as resonant lepto.}$$

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$$m_i \Gamma_j \ll \delta m_{ij}^2 \quad \Rightarrow \quad \epsilon_i \simeq \frac{1}{2} \sum_{i \neq j} \frac{\text{Im}[(YY^\dagger)_{ij}^2]}{(YY^\dagger)_{ii}(YY^\dagger)_{jj}} \frac{m_i \Gamma_j}{\delta m_{ij}^2}$$
$$\simeq \frac{C}{64\pi v_u^2} \left( \frac{M}{M'} \right) \left( \frac{M^2}{\mu} \right) \sum_{j \neq i} \frac{|\mathcal{M}|_{ij}^2 \sin(2\phi_{ij})}{(\mathcal{M})_{ii}}$$

'Quasi-resonant' enhancement yields  $\epsilon \sim 10^{-3}$  at  $M^2/\mu \sim 1\text{PeV}$ .

## Washout parameter

$$K_i = \frac{\Gamma_i}{H(T = m_i)}$$

Indicates how much **out of equilibrium** (s)neutrinos decay and the impact of **inverse decays** on lepton asymmetry.

$$K_i = 1000 \left( \frac{(YY^\dagger)_{ii}}{1.6 \times 10^{-6}} \right) \left( \frac{100 \text{ PeV}}{\mu} \right) \left( \frac{230}{g_*} \right)^{1/2} \gg 1 \Rightarrow \text{Large washout}$$

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Simplifies the analysis:

- ▶ Lepton asymmetry is independent of the initial conditions;
- ▶ Lepton asymmetry coming from the decays of heavy  $N$  and  $\widetilde{N}$  (mass  $\sim \mu$ ) is exponentially suppressed;
- ▶ Thermal effects and  $2 \rightarrow 2$  scattering processes can be ignored  
[Buchmuller *et al.*, [hep-ph/0401240](#)].

## Boltzmann equations

$$\frac{dY_N}{dz} = -Kz \frac{\mathcal{K}_1(z)}{\mathcal{K}_2(z)} (Y_N - Y_N^{\text{eq}})$$

$$\frac{dY_{\tilde{N}}}{dz} = -Kz \frac{\mathcal{K}_1(z)}{\mathcal{K}_2(z)} (Y_{\tilde{N}} - Y_{\tilde{N}}^{\text{eq}})$$

$$\frac{dY_L}{dz} = \epsilon Kz \frac{\mathcal{K}_1(z)}{\mathcal{K}_2(z)} \left( Y_N - Y_N^{\text{eq}} + Y_{\tilde{N}} - Y_{\tilde{N}}^{\text{eq}} \right) - 2 \frac{Kz^3}{4} \mathcal{K}_1(z) Y_L$$

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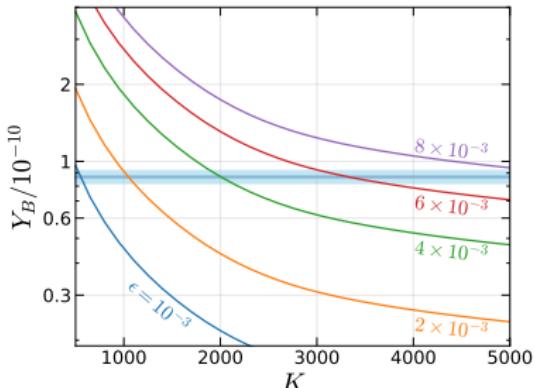
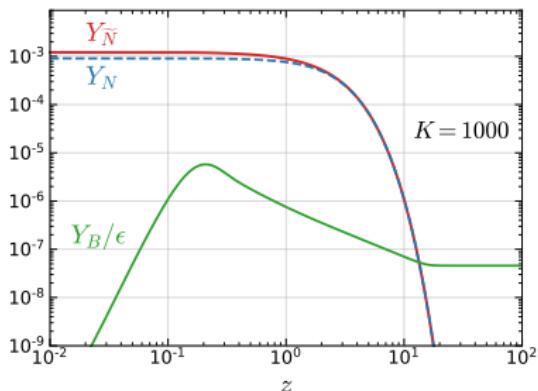
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Numerically we find:  $Y_L \sim 10^{-4} \left( \frac{\epsilon}{K} \right) \sim 10^{-7} \left( \frac{M}{\mu} \right)^2$ .

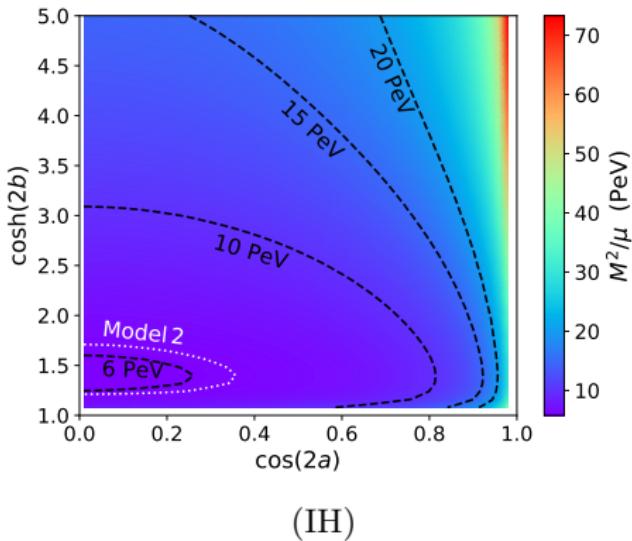
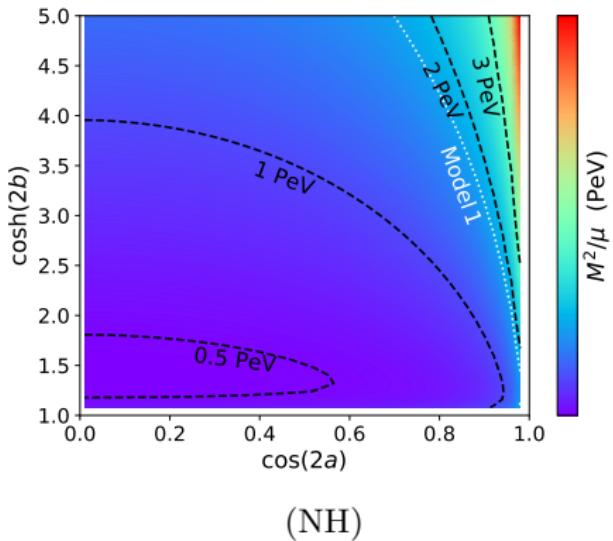
Sphaleron conversion:  $|Y_B| = \frac{8}{23}|Y_L|$  [Fong et al., 1107.5312].

Observations:  $Y_B^{BBN} = (8.7 \pm 0.5) \times 10^{-11}$ ;  $Y_B^{CMB} = (8.69 \pm 0.06) \times 10^{-11}$



## Scan over $\mathcal{M}$ parameters

$$(YY^\dagger) \sim \mathcal{M} = \begin{pmatrix} \delta \cos 2a + \sigma \cosh 2b & -\delta \sin 2a + i\sigma \sinh 2b \\ -\delta \sin 2a - i\sigma \sinh 2b & -\delta \cos 2a + \sigma \cosh 2b \end{pmatrix}$$



- ▶ Need  $(M^2/\mu) \sim 1 - 10$  PeV to get the right BAU.
  - ▶ No fine-tuning of  $YY^\dagger$  necessary.
  - ▶ Difficult to constrain further with e.g. charged lepton flavor violation because  $Y^2 \sim 10^{-6}$ .

## Summary

- ▶ Successful leptogenesis at  $\sim \mathcal{O}(1 \text{ PeV})$  scale;
- ▶ Need two types of sterile neutrinos ( $N, N'$ ) to break SUSY;
- ▶ Light neutrinos acquire their mass radiatively for  $N$ ;
- ▶ Resonant enhancement of CP asymmetry in  $N'$  decays compensates for large washout.

# IV. Conclusions

We constructed an explicit PeV-scale SUSY model with gauge-mediated ~~SUSY~~ and strong first order phase transition

Model is predictive,  $\sqrt{F} \sim 30$  PeV; window could be closed by Future Circular Collider (gluino search)

Dark matter is  $\sim$  GeV gravitino

Observable gravity waves are predicted for many planned experiments.

Primordial black holes can be produced at the end of the phase transition. Additional DM component, or source of LIGO BH's?

We provide a novel mechanism for  $\nu$  mass and low-scale leptogenesis, enabled by a MFV hypothesis.