Leptogenesis and Gravity Waves from a SUSY-breaking Phase Transition

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

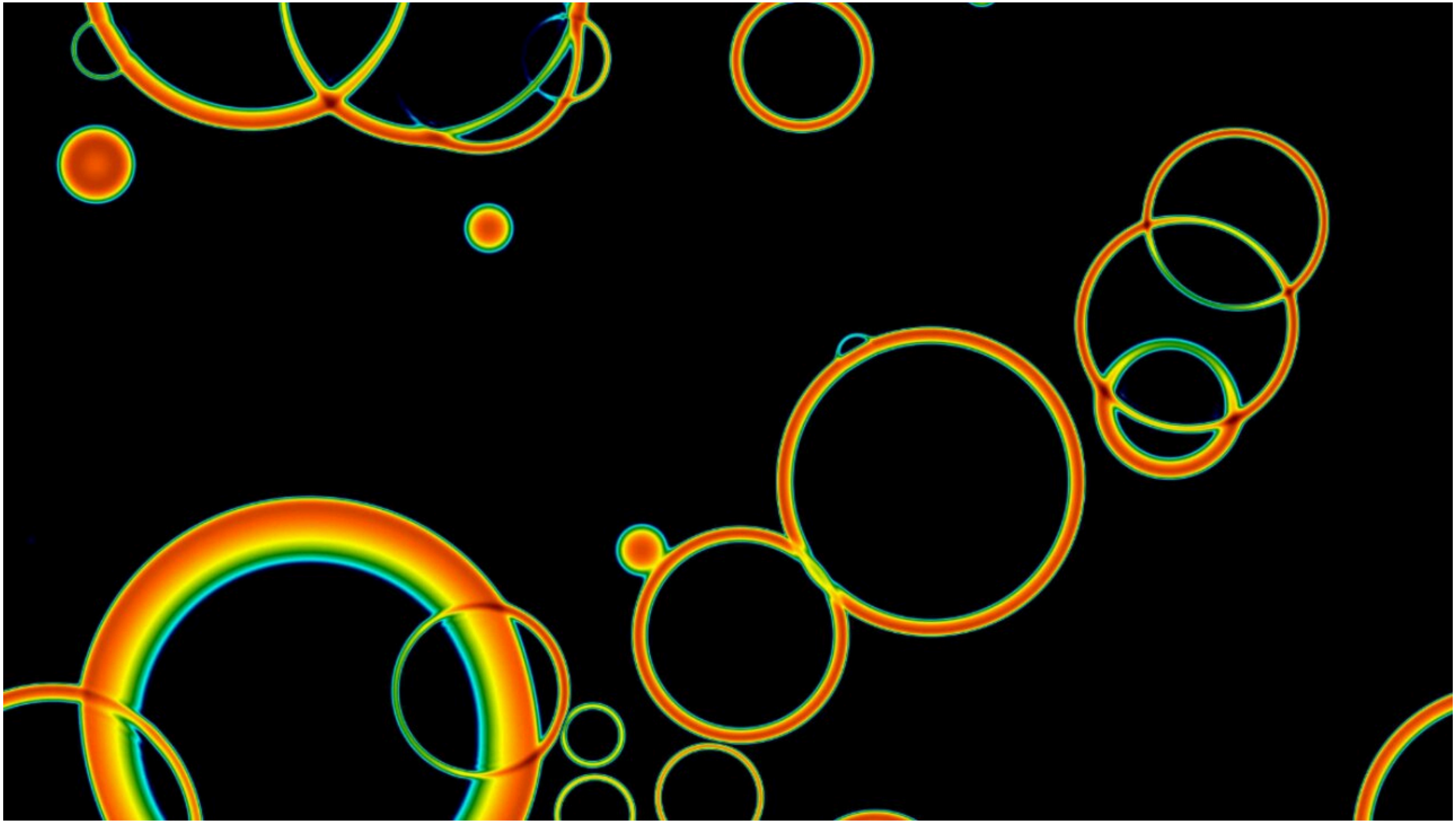
BNL, 31 Aug., 2023

Outline

- Introduction: PeV-scale ~~SUSY~~ phase transition
- Production of gravity waves and primordial black holes
  –Benoit Laurent
- Low scale leptogenesis
  –Jean-Samuel Roux
- Conclusions

I. Introduction

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

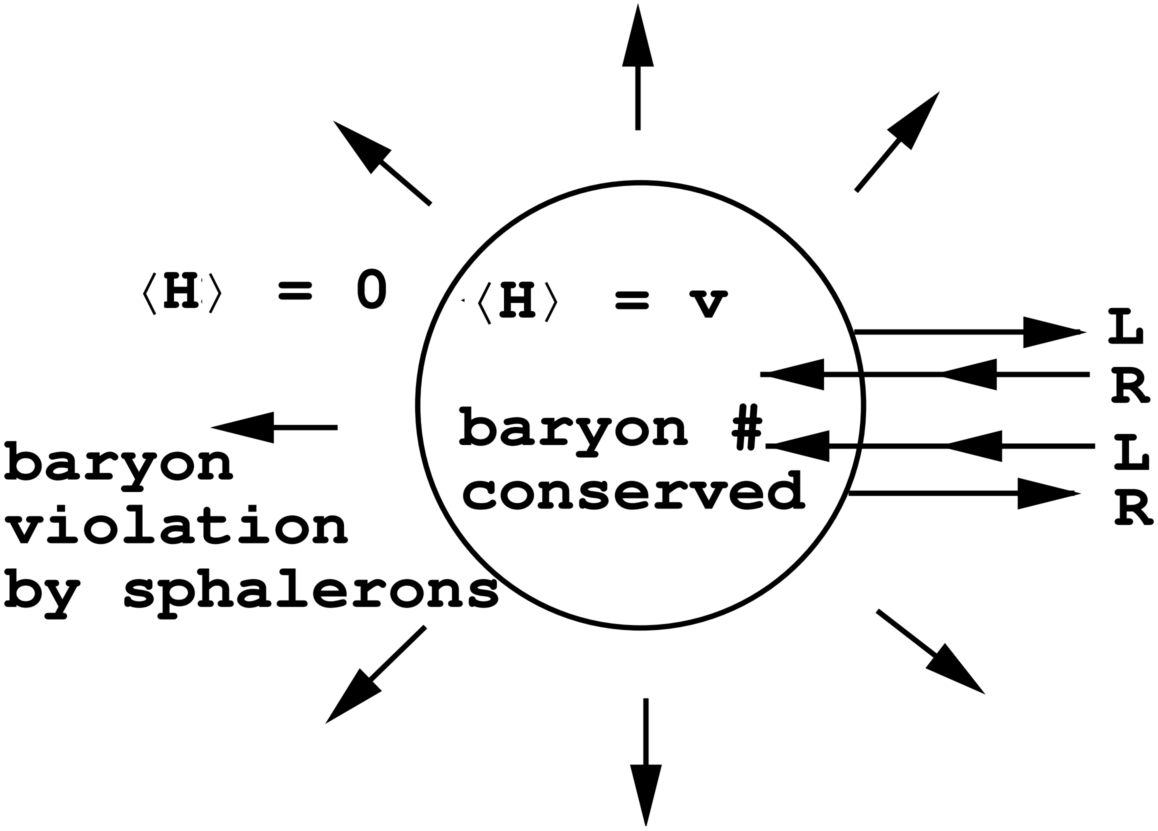


D. Weir, arxiv:1705.01783

I. Introduction

Strong first order phase transitions can

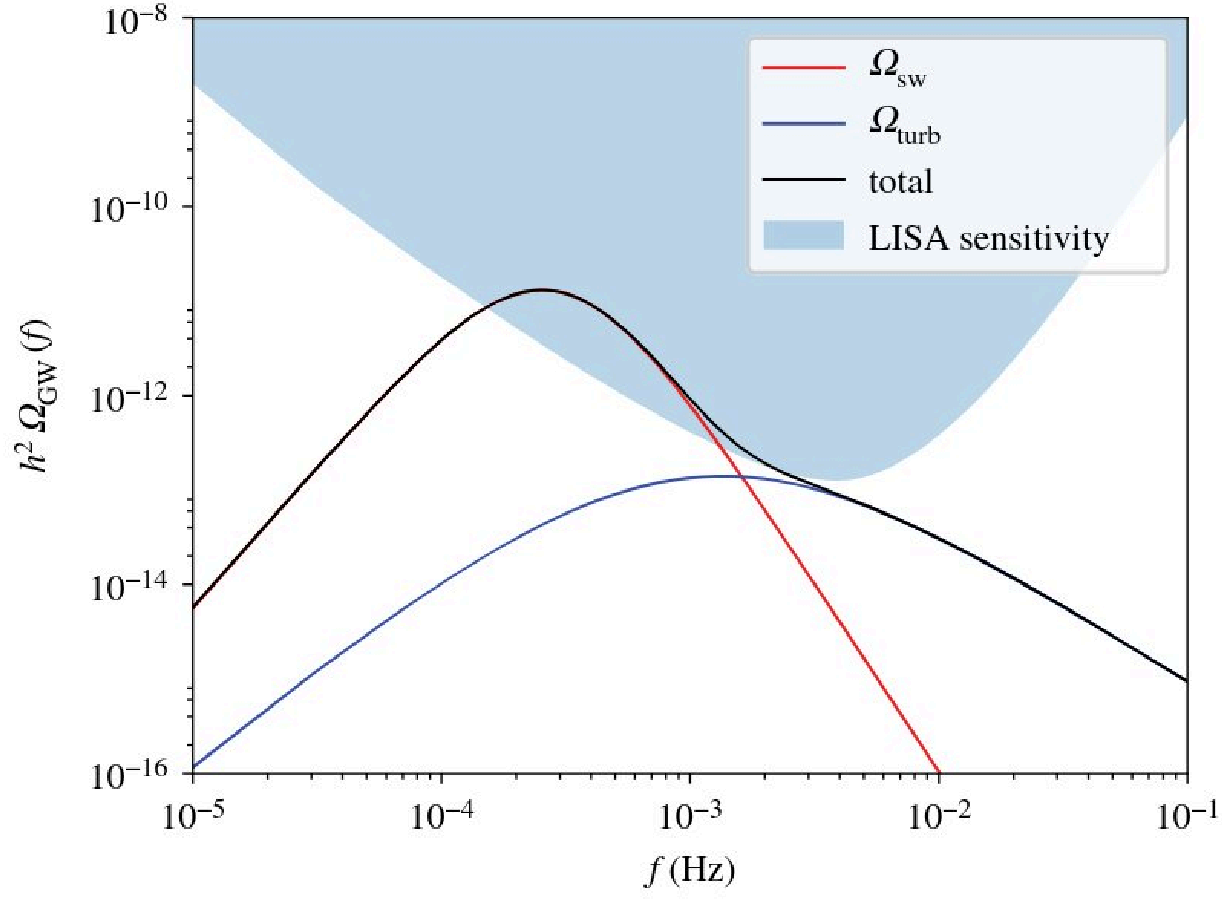
- Enable electroweak baryogenesis



I. Introduction

Strong first order phase transitions can

- Produce gravity waves, observable in future detectors

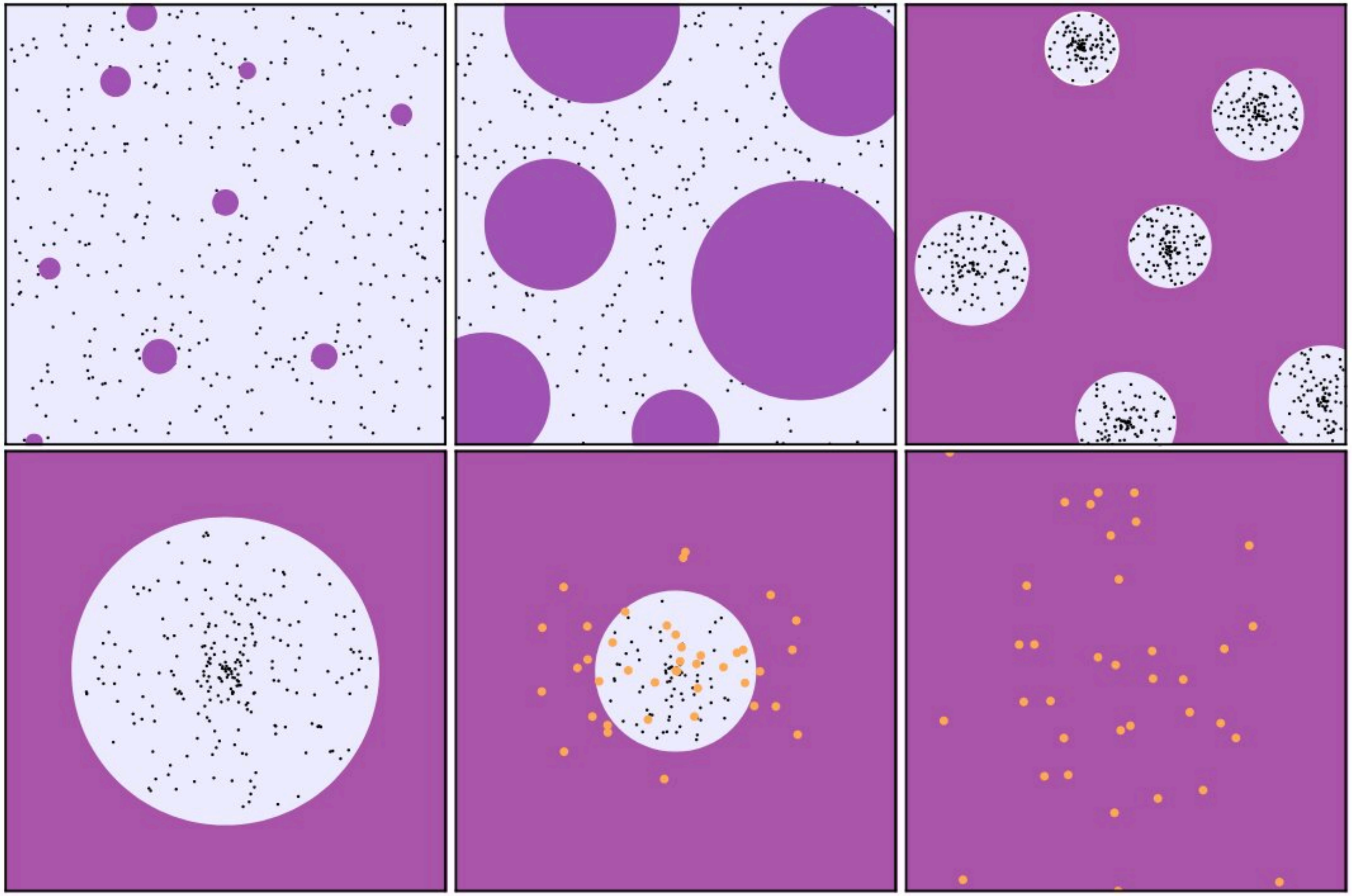


D. Weir, arxiv:1705.01783

I. Introduction

Strong first order phase transitions can

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

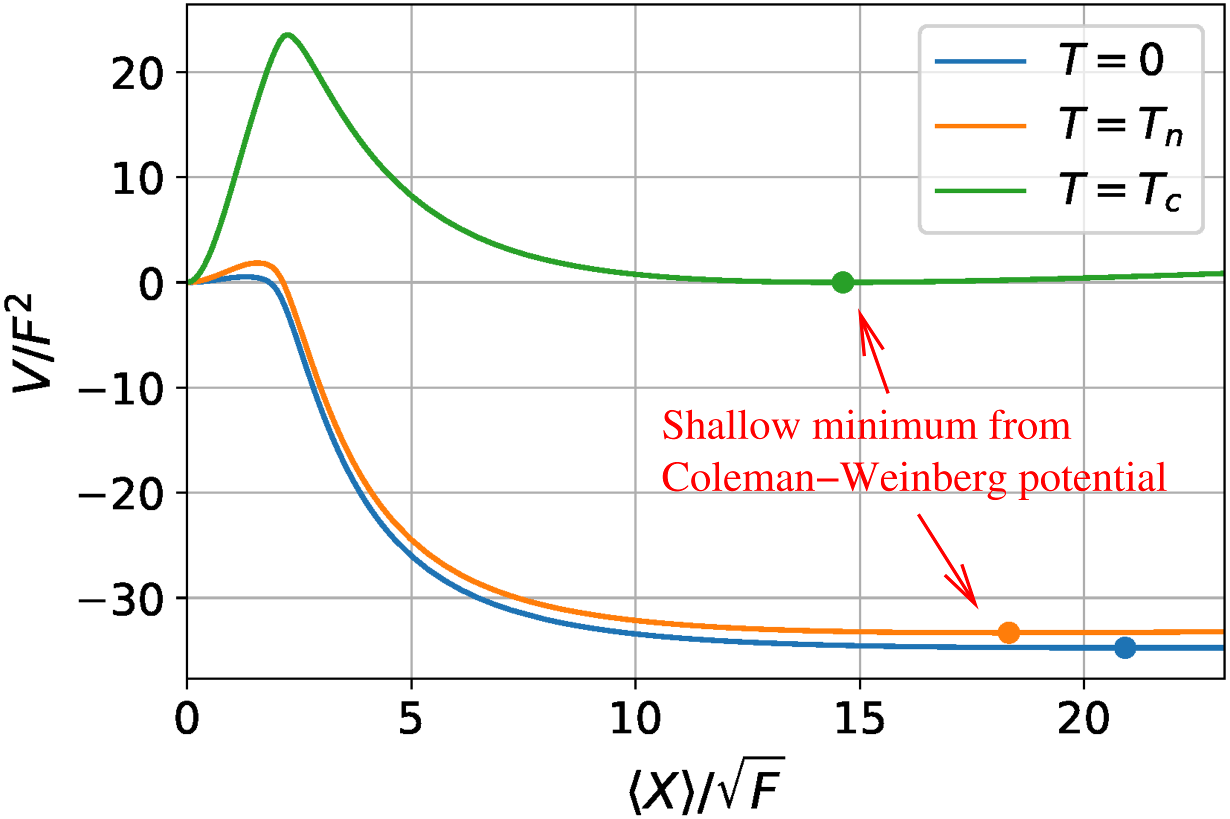


Asadi *et al.*, arxiv:2103.09827

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.



Shallow minimum from Coleman–Weinberg potential

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

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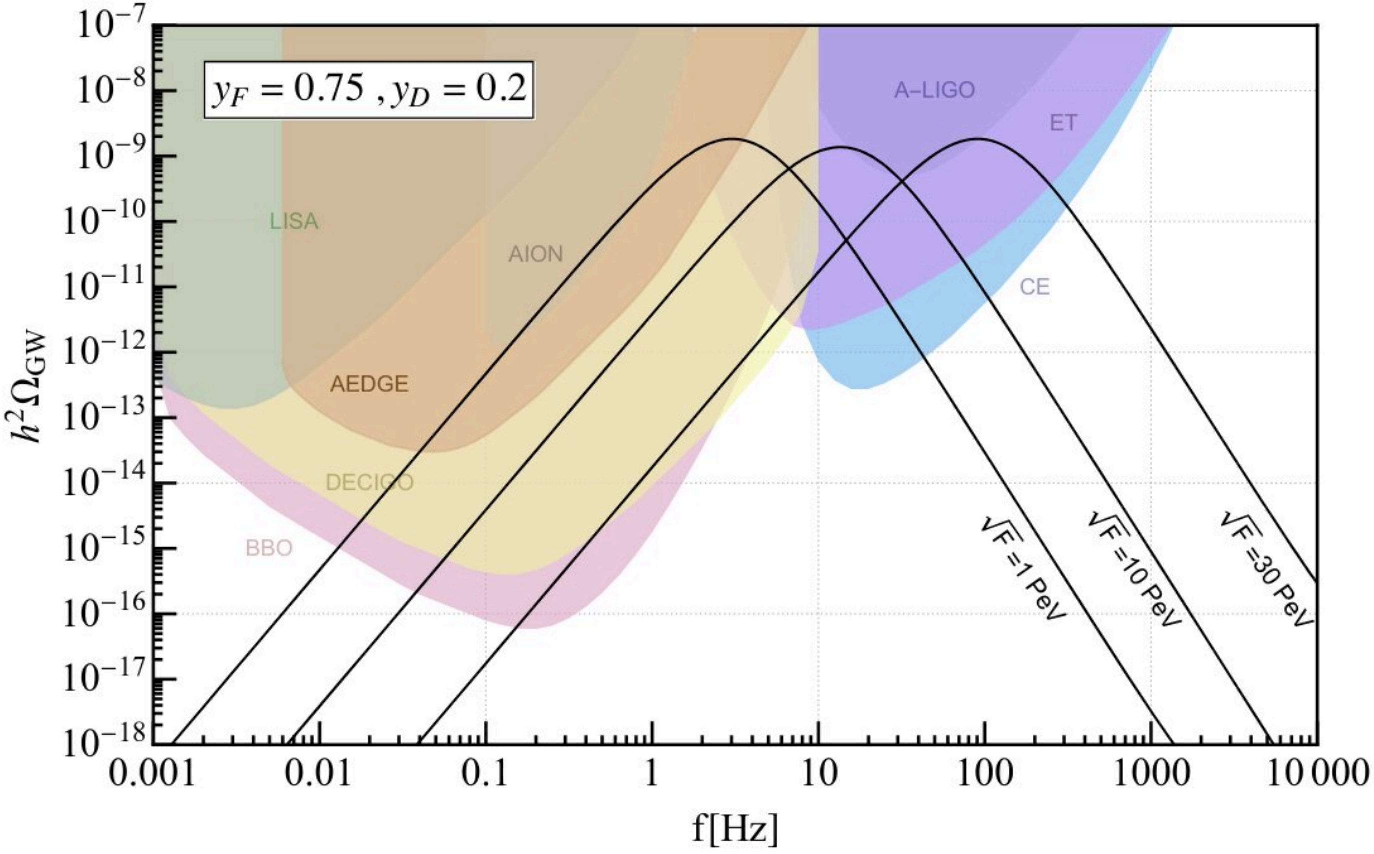


Gives observable gravity waves for a variety of proposed experiments

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,

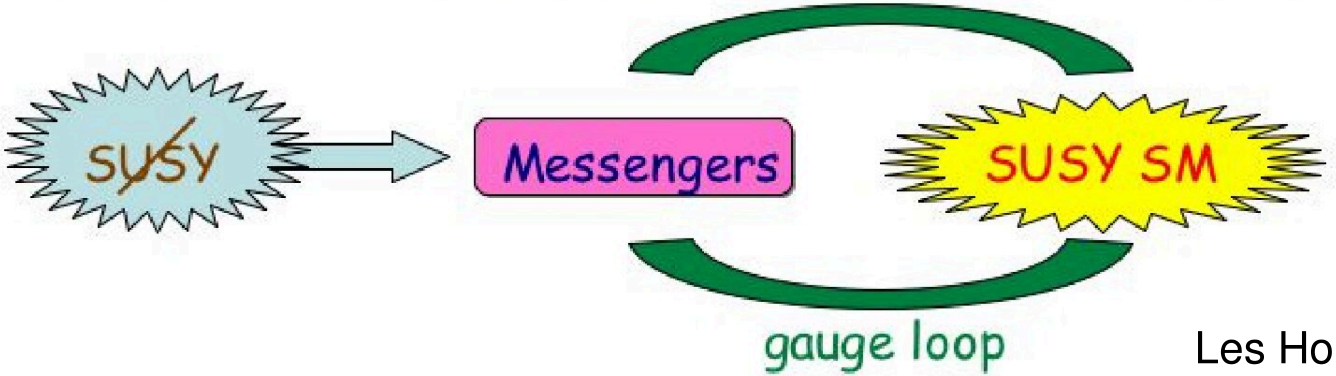
• DM • ν mass • gauge unification • small FCNCs • proton stability

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 Φ charged under SM SU(3)×SU(2)×U(1) communicate ~~SUSY~~ from a (hidden) breaking sector to the SM gauginos, squarks, sleptons:



G. Giudice,
Les Houches 2007

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

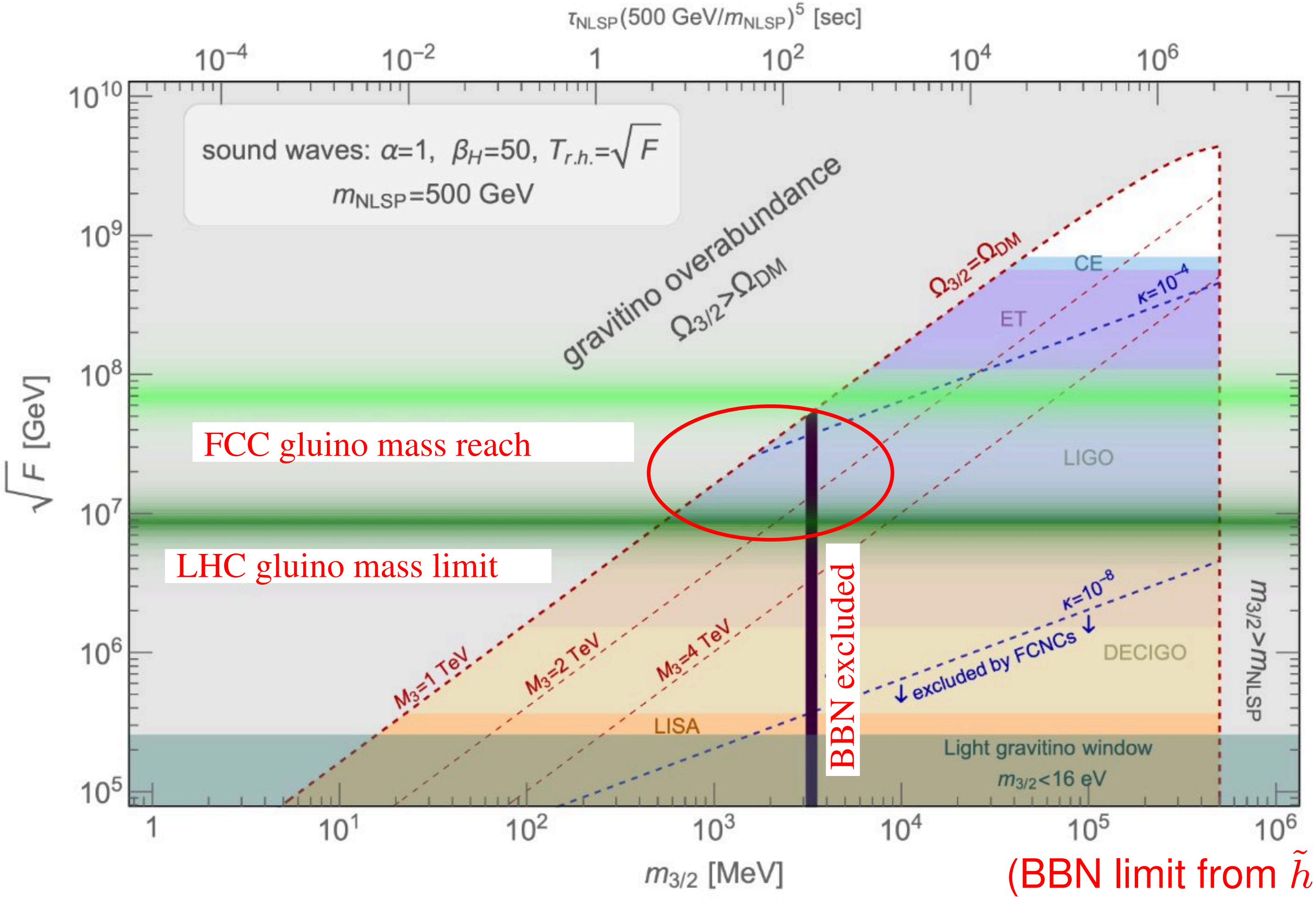
$$m_{3/2} \sim 24\,\mathrm{keV}\left(\frac{F_0}{F}\right)\left(\frac{\sqrt{F}}{10\,\mathrm{PeV}}\right)^2$$

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 $\mu \to e\gamma$ and K^0-$\bar{K}^0$ mixing constrain

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

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

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



Craig *et al.* 2011.13949

(BBN limit from $\tilde{h} \to \tilde{G} + $ hadrons)

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

* depending on messenger details: we get $\sim 30\,\mathrm{PeV}$

Model with ν 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	$\mathrm{U}(1)_D$	SU(5)	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_y$	L	$\mathbb{Z}_2^L$
nonzero X VEV breaks SUSY	X	$+2$	0	1	1	0	0	$+1$
O'Raighfeartaigh fields, create SUSY–breaking potential V(X)	Φ	0	$+1$	1	1	0	0	$+1$
	$\overline{\Phi}$	$+2$	-1	1	1	0	0	$+1$
	Φ'	$+2$	$+1$	1	1	0	0	$+1$
	$\overline{\Phi}'$	0	-1	1	1	0	0	$+1$
messenger fields, transmit SUSY breaking to the MSSM	5_M	0	0	5	$*$	$+y$	0	$+1$
	$\overline{5}_M$	$+2$	0	$\overline{5}$	$*$	$-y$	0	$+1$
	$5_M'$	$+2$	0	5	$*$	$+y$	0	$+1$
	$\overline{5}_M'$	0	0	$\overline{5}$	$*$	$-y$	0	$+1$
PeV scale RH neutrinos	N_i	0	0	1	1	0	-1	-1
	N_i'	$+2$	0	1	1	0	$+1$	-1
Lepton doublet, up–type Higgs	L_α	2	0	1	2	-1	$+1$	-1
	H_u	0	0	1	2	$+1$	0	$+1$

provides D–term potential

embeds SU(3) x SU(2) x U(1) SM gauge group

discrete remnant of lepton symmetry

Define 6–component fields:

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

Superpotential interactions:

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

Gives SUSY breaking

$$\frac{\lambda_{ij}'}{2} \underbrace{X N_i N_j}_{\text{L violating term}} + M_{ij} N_i N_j' + Y_{i\alpha}\epsilon_{ab} N_i L_\alpha^a H_u^b$$

Gives ν masses and leptogenesis

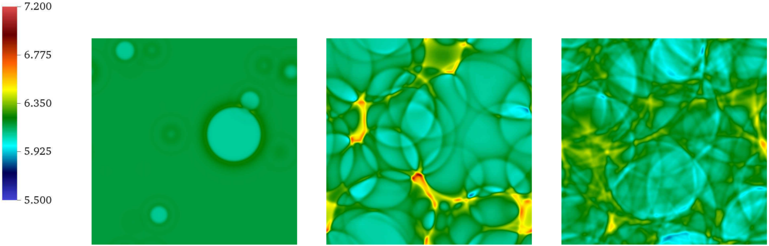
D–term potential:

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

leads to strong phase transition

X gets SUSY-breaking VEV, which also generates mass for N_i. We get novel scenario for ν mass and leptogenesis.

Gravitational waves



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

GW prediction

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

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

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- $R \propto \left[\frac{d}{dT}\left(\frac{S}{T}\right)\right]^{-1}$: mean bubble radius,
- $C(s) = s^3 \left(\frac{7}{4+3s^2}\right)^{7/2}$: shape of the GW spectrum,
- $f_{\text{p},0} = 2.62 \left(\frac{1}{HR}\right) \left(\frac{T_n}{100 \text{ PeV}}\right) \left(\frac{g_*}{100}\right)^{1/6}$ Hz: peak GW frequency,
- $K \propto \Delta V/\rho_\gamma$: fraction of the total energy in kinetic energy,
- $\tilde{\Omega}_{\text{gw}} = 0.012$: fraction of kinetic energy converted in GWs,
- $F_{\text{gw},0} = 3.57 \times 10^{-5} (100/g_*)^{1/3}$: redshift correction.

Signal-to-noise ratio (SNR)

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

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

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

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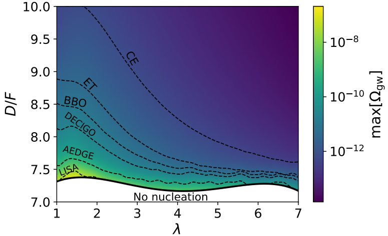
Whenever $\mathrm{SNR} \geq \mathrm{SNR}_{\mathrm{thr}} \cong 10$, we conclude that the signal can be detected.

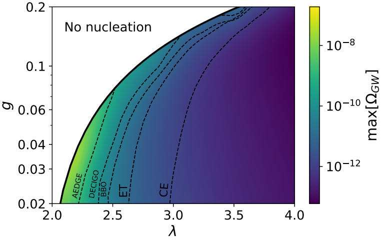
Results

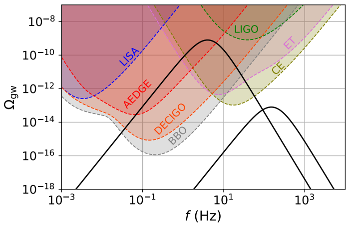
2 scans of the parameter space, both varying λ ($W \supset \lambda X \Phi \overline{\Phi}'$)

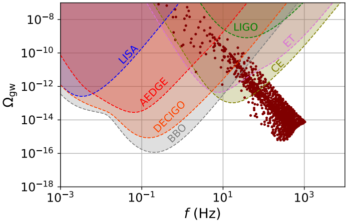
F: O'Raifeartaigh term
D: Fayet-Iliopoulos term of $U(1)_D$ symmetry

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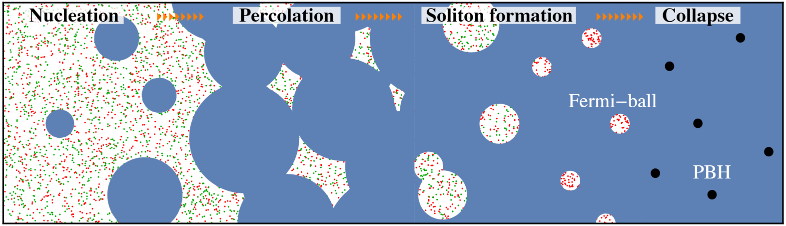
The density of the trapped particles increases until they collapse into a black hole.



Huang and Xie (arxiv:2201.07243)

Application to SUSY-breaking PT

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Example: Messenger fields Ψ

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

Schwarzschild criteria

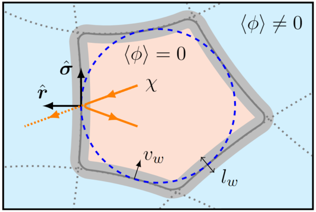
- We assume a spherical false-vacuum bubble with radius r,
- We have a gravitational collapse if

$$r < r_s \equiv 2GE_{\rm tot},$$

- For slow-moving walls, $E_{\rm tot} \propto 1/r$, 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

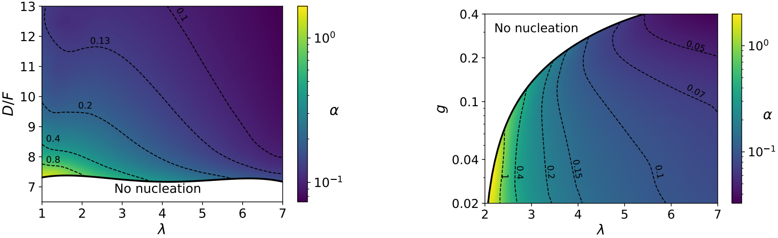
$$r_{\text{min}} \cong 1.16 r_s,$$

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

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



Part 3 - PeV-scale leptogenesis

Jean-Samuel Roux

McGill University

August 31 2023

Superpotential

$$W_{\not{L}} = -FX + \frac{\lambda'_{ij}}{2} X N_i N_j + M_{ij} N_i N'_j + Y_{i\alpha} \epsilon_{ab} N_i L^a_\alpha H^b_u$$

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

$$\lambda'_{ij} \to \lambda' \delta_{ij};\ \ M_{ij} \to (M\delta_{ij} + iM'\epsilon_{ij}).$$

M_{ij} has eigenvalues

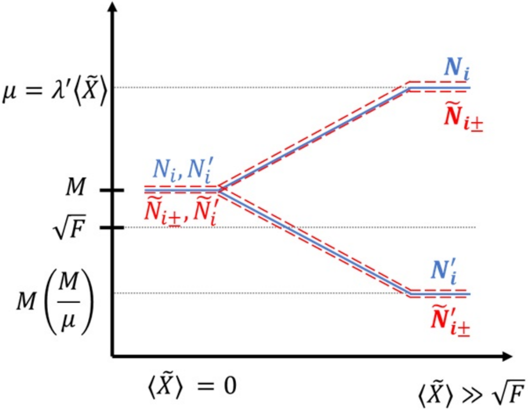
$$M_i = M\left(1 \pm \frac{M'}{M}\right)$$

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

RH (s)neutrino spectrum

$$-\mathcal{L} \supset \left(|M_i|^2 + |\lambda' \widetilde{X}|^2\right) \left|\widetilde{N}_i\right|^2 + \left|M_i \widetilde{N}'_i\right|^2 + \left(\lambda' M_i^* \widetilde{X} \widetilde{N}_i \widetilde{N}'^*_i - \frac{\lambda' F_X^*}{2} \widetilde{N}_i \widetilde{N}_i + \text{h.c.}\right)$$

$$+ \left(M_i \overline{N_i^C} N'_i + \frac{\lambda'}{2} \widetilde{X} \overline{N_i^C} N_i + \text{h.c.}\right)$$



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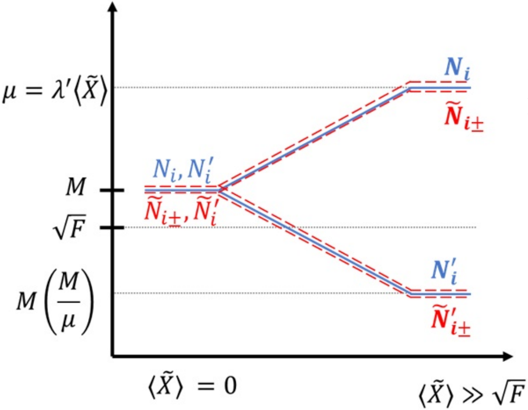

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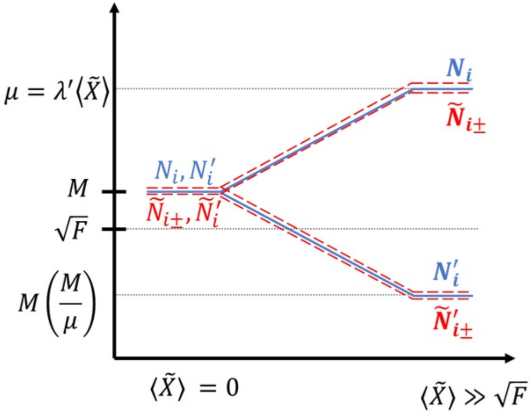

▶ Decay immediately, but lepton asymmetry washed out. Induce **light neutrino masses** at one-loop.

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

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

Light neutrino masses

Tree-level mass matrix in (ν, N', N) basis: $\begin{pmatrix} 0 & 0 & m_D \\ 0 & 0 & M_i \\ m_D^T & M_i & \mu \end{pmatrix}$ $\Rightarrow$ yields $m_\nu = 0$

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

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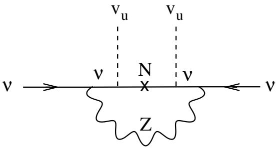
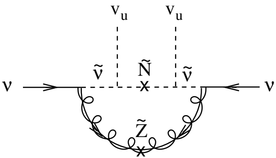
Radiative terms **[Ma *et al.*, hep-ph/0603043; Mohapatra, Okada, 2207.10619]**:





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

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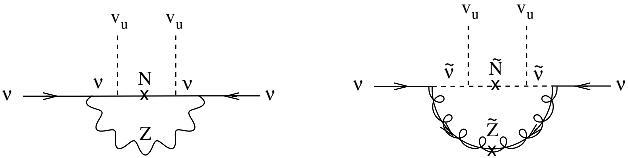

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Yukawa couplings estimate:

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

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

For normal hierarchy (and similarly for IH):

$$Y_{i\alpha} = \sqrt{C\frac{\mu}{v_u^2}}\,\mathcal{R}\,D_{\sqrt{m_\nu}}\,U_\nu^\dagger, \qquad \text{where } C \approx 9.7, \quad D_{\sqrt{m_\nu}} = \mathrm{diag}(0, \sqrt{m_2}, \sqrt{m_3})$$

$$\mathcal{R} = \begin{pmatrix} 0 & \cos\hat{\varrho} & \sin\hat{\varrho} \\ 0 & -\sin\hat{\varrho} & \cos\hat{\varrho} \end{pmatrix}, \qquad \hat{\varrho} = a + ib$$

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

For normal hierarchy (and similarly for IH):

$$Y_{i\alpha} = \sqrt{C\frac{\mu}{v_u^2}}\,\mathcal{R}\,D_{\sqrt{m_\nu}}\,U_\nu^\dagger, \quad \text{where } C \approx 9.7, \quad D_{\sqrt{m_\nu}} = \mathrm{diag}(0, \sqrt{m_2}, \sqrt{m_3})$$

$$\mathcal{R} = \begin{pmatrix} 0 & \cos\hat{\varrho} & \sin\hat{\varrho} \\ 0 & -\sin\hat{\varrho} & \cos\hat{\varrho} \end{pmatrix}, \quad \hat{\varrho} = a + ib$$

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

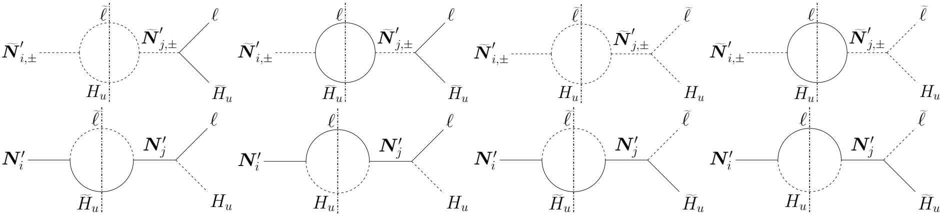
$$(YY^\dagger) = C\frac{\mu}{v_u^2}\left(\mathcal{R}D_{m_\nu}\mathcal{R}^\dagger\right) \equiv C\frac{\mu}{2v_u^2}\mathcal{M}$$

$$= C\frac{\mu}{2v_u^2}\begin{pmatrix} \delta\cos 2a + \sigma\cosh 2b & -\delta\sin 2a + i\sigma\sinh 2b \\ -\delta\sin 2a - i\sigma\sinh 2b & -\delta\cos 2a + \sigma\cosh 2b \end{pmatrix},$$

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

$\Rightarrow$ 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:

$$\epsilon_i = \frac{\sum_{X_\alpha,\alpha} \Gamma(\boldsymbol{N}_i' \to X_\alpha) - \Gamma(\boldsymbol{N}_i' \to X_\alpha^\dagger)}{\sum_{X_\alpha,\alpha} \Gamma(\boldsymbol{N}_i' \to X_\alpha) + \Gamma(\boldsymbol{N}_i' \to X_\alpha^\dagger)}$$

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

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$$\epsilon_i = \frac{\sum_{X_\alpha,\alpha} \Gamma(\boldsymbol{N}'_i \to X_\alpha) - \Gamma(\boldsymbol{N}'_i \to X^\dagger_\alpha)}{\sum_{X_\alpha,\alpha} \Gamma(\boldsymbol{N}'_i \to X_\alpha) + \Gamma(\boldsymbol{N}'_i \to X^\dagger_\alpha)}$$

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

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

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$$m_i\Gamma_j \ll \delta m^2_{ij} \quad \Rightarrow \quad \epsilon_i \simeq \frac{1}{2}\sum_{i\neq j} \frac{\mathrm{Im}[(YY^\dagger)^2_{ij}]}{(YY^\dagger)_{ii}(YY^\dagger)_{jj}} \frac{m_i\Gamma_j}{\delta m^2_{ij}}$$

$$\simeq \frac{C}{64\pi v_u^2}\left(\frac{M}{M'}\right)\left(\frac{M^2}{\mu}\right)\sum_{j\neq i}\frac{|\mathcal{M}|^2_{ij}\sin(2\phi_{ij})}{(\mathcal{M})_{ii}}$$

'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 $\boldsymbol{N}$ and $\widetilde{\boldsymbol{N}}$ (mass $\sim \mu$) is exponentially suppressed;
- Thermal effects and 2 → 2 scattering processes can be ignored **[Buchmuller *et al.*, hep-ph/0401240]**.

Boltzmann equations

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

$$\frac{dY_{\widetilde{N}}}{dz} = -Kz\frac{\mathcal{K}_1(z)}{\mathcal{K}_2(z)}\left(Y_{\widetilde{N}} - Y_{\widetilde{N}}^{\mathrm{eq}}\right)$$

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

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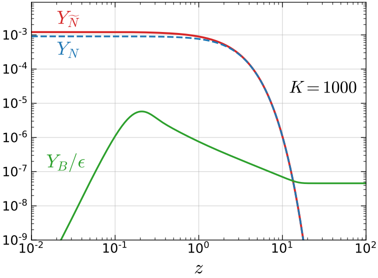
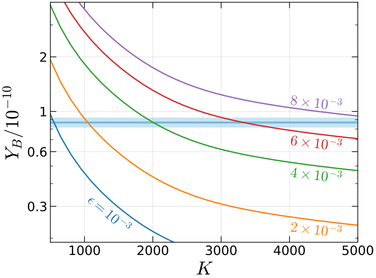
Numerically we find: $Y_L \sim 10^{-4}\left(\frac{\epsilon}{K}\right) \sim 10^{-7}\left(\frac{M}{\mu}\right)^2$.

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

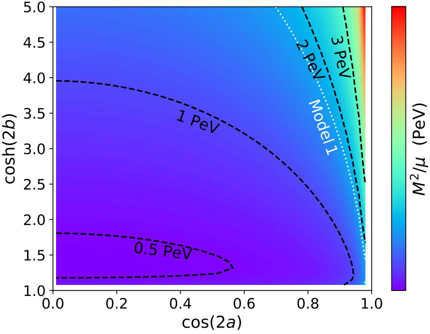
Observations: $Y_B^{BBN} = (8.7\pm0.5)\times10^{-11}$; $Y_B^{CMB} = (8.69\pm0.06)\times10^{-11}$



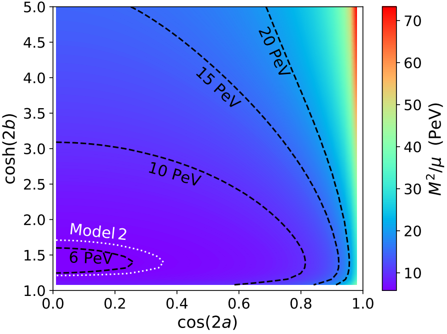


Scan over $\mathcal{M}$ parameters

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



(NH)



(IH)

- 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, $\sqrt{F} \sim 30\,\mathrm{PeV}$; window could be closed by Future Circular Collider

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 ν mass and low-scale leptogenesis, enabled by a MFV hypothesis.