58th Rencontres de Moriond 2024

Electroweak Interactions & Unified Theories 24-31 March

Majorana mass generation gravitational waves and cosmological tensions

Pasquale Di Bari

(University of Southampton)

HIDDeN

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

UNIVERSITY OF Southampton

New physics?

Even ignoring:

- (more or less) compelling theoretical motivations
- Experimental anomalies (e.g., $(g-2)_\mu$, ...)

Standard physics (SM+GR) cannot explain:

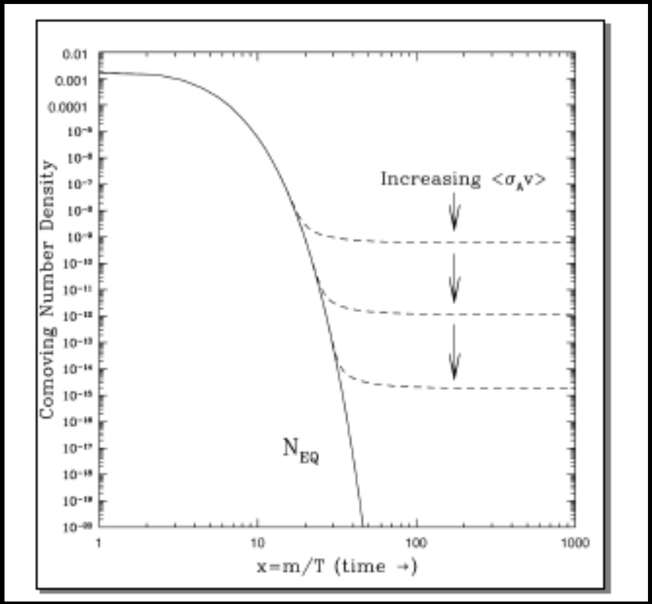
- *Cosmological Puzzles* :

1. Dark matter
2. Matter - antimatter asymmetry
3. Inflation
4. Accelerating Universe at present

problem of the origin of matter in the universe

- *Neutrino masses and mixing*

A natural solution



WIMP miracle

Freeze-out + WIMP ⇒ EW scale (WIMP miracle)

$$< \sigma_{\rm ann} v >_{\rm th} \simeq 3\times 10^{-26} {\rm cm}^3\, s^{-1}$$

$$< \sigma_{\rm ann}^{\rm weak} v > = \frac{\alpha_{\rm weak}^2}{m_X^2} = < \sigma_{\rm ann} v >_{\rm th}$$

$$\Longrightarrow m_X \sim 100 \text{ GeV-1TeV}$$

Electroweak baryogenesis (EWB)

- It requires a strong first order phase transition (FOPT) EWSB
  ⇒ physics beyond the SM at the EW scale
- Great attention focussed on extensions of the SM in SUSY models (MSSM and NMSSM) and in generic extensions of the SM with gauge singlets
- In a strong FOPT a detectable GW production is also possible, though it is not clear whether this is compatible with EWB
- ⇒ EWB + WIMP miracle provide a very attractive and well-motivated natural solution
- However, the strong constraints on new physics at the 100 GeV-TeV scale from LHC+DM searches make WIMP miracle +EW baryogenesis, if not ruled out, certainly less compelling
  ⇒ we live in a kind of *nothing is impossible era:* no prejudice on the scale of new physics

A neutrino solution

(Minkowski '77; Gell-mann,Ramond,Slansky; Yanagida; Mohapatra,Senjanovic '79)

Dirac Majorana

$$-\mathcal{L}^{\nu}_{Y+M} = \bar{L} h^{\nu} \nu_R \widetilde{\Phi} + \frac{1}{2}\overline{\nu^C_R} M \nu_R + \text{h. c.} \overset{EWSB}{\Longrightarrow} -\mathcal{L}^{\nu}_{mass} = \overline{\nu_L} m_D \nu_R + \frac{1}{2}\overline{\nu^C_R} M \nu_R + \text{h. c.}$$

In the *see-saw limit* ($M \gg m_D = v_{ew} h^{\nu}$) the mass spectrum splits into 2 sets:

- 3 light **Majorana neutrinos** with masses (seesaw formula): *talk by Steve King*

$$m_{\nu} = -m_D M^{-1} m_D^T \Rightarrow \text{diag}(m_1, m_2, m_3) = -U^{\dagger} m_{\nu} U^*$$

- $N \geq 3$ heavier "seesaw" neutrinos $N_1, N_2, N_3, \ldots$ with .... $M_3 > M_2 > M_1$
- **matter-antimatter asymmetry from leptogenesis**
- N_1 as dark matter from LH-RH (active-sterile) neutrino mixing

How is the Majorana mass term generated?

Majorana mass generation

SO(10), E6, flavour symmetries, orbifold GUTs,…….

majoron model

Majorana mass generation in the Majoron model

(Y. Chikashige, R. Mohapatra, R. Peccei 1981)

$$-\mathcal{L}^{\nu}_{Y+\phi} = \left(\overline{L_a} h^{\nu}_{aI} N_I \widetilde{\boldsymbol{\Phi}} + \frac{\lambda_I}{2} \phi \overline{N_I^C} N_I + \text{h.c.}\right) + V_0(\phi)$$

$$\xrightarrow{U_L(1)-SSB} \overline{L_a} h^{\nu}_{aI} N_I \widetilde{\Phi} + \frac{1}{2} M_I \overline{N_I^C} N_I + \text{h.c} \xrightarrow{EWSB} -\mathcal{L}^{\nu}_{\text{mass}} = \overline{\nu_L} m_D N_I + \frac{1}{2} \overline{N_I^C} M_I N_I + \text{h.c.}$$

- One can also have U_L (1)-SSB occurring after EWSB
- It is convenient to introduce also the radial component **φ**: $\phi = \frac{\varphi}{\sqrt{2}} e^{i\theta}$
- At the end of the ϕ-phase transition, L is violated and:

$$\phi = \frac{e^{i\theta_0}}{\sqrt{2}} (v_0 + S + i\, J) \qquad\qquad M_I = \lambda_I \frac{v_0}{\sqrt{2}}$$

- Dirac neutrino mass matrix $m_D = v_{ew} h^{\nu}$ generated after EWSB
- after both symmetry breakings: $m_\nu = - m_D M^{-1} m_D^T$
- S is a massive boson, while J is a (pseudo-)Goldstone boson: the majoron (it is an example of ALP)
- DARK SECTOR ≡ N_I 's + J + S   VISIBLE SECTOR ≡ SM particles

Gravitational waves from Majorana mass generation

First order phase transition in the early universe

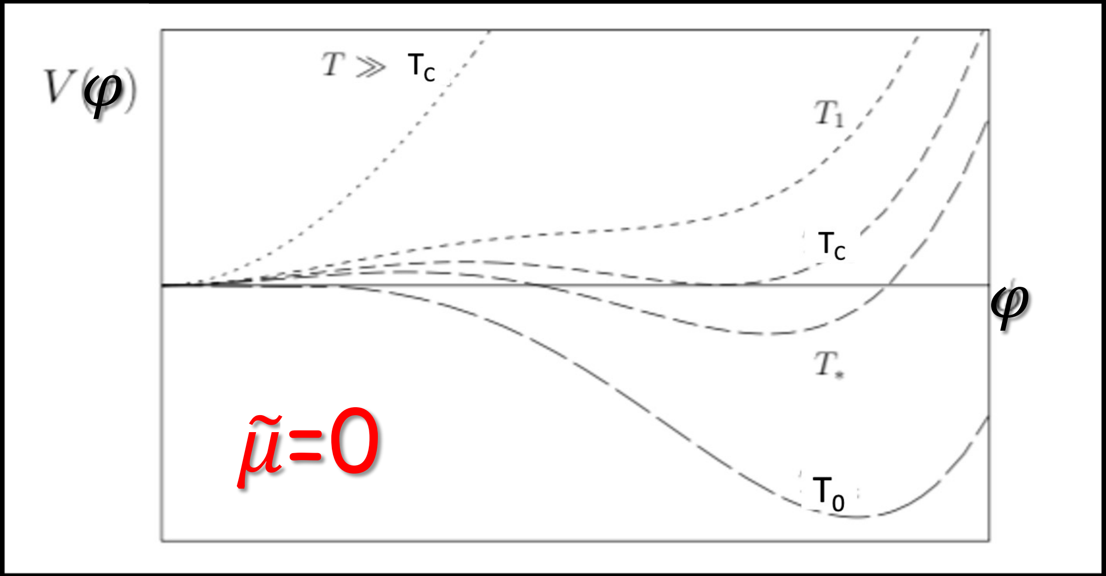
(Kirzhnits,Linde '72; Dolan, Jackiw '74; Anderson, Hall '92; Dine et al. '92; Quiros '98, Curtin et al. 2016)

effective potential
$$V(\phi,T) = V_0(\phi) + \sum_i V^i_{CW}(\phi) + \sum_i V^i_T(\phi,T)$$

1 loop zero T

1 loop thermal potential

$$V(\varphi,T) \simeq D(T-T_0)^2\varphi^2 - (AT+\tilde{\mu})\varphi^3 + \frac{\lambda(T)}{4}\varphi^4 + \ldots$$



This picture relies on the validity of perturbative expansion. In the SM, at the EWSB, this would imply $M_H < M_W$. With the large M_H measured value, there is not even a PT in the SM, just a smooth crossover.

From the effective potential to the Euclidean action

(Coleman '77; Linde '82;)

Probability of bubble nucleation per unit volume per unit time

$$\Gamma(T) = \Gamma_0(T)\, e^{-S_E(T)}$$

$$\begin{cases} \Gamma_0 = \mathcal{O}(1)\, T^4 \\ S_E(T \geq T_c) \to \infty \\ S_E(T \to T_0) \to 0 \end{cases}$$

Euclidean action

$$S_E(\phi) = \int d\tau\, d^3x \left[\frac{1}{2}\left(\frac{d\phi}{d\tau}\right)^2 + \frac{1}{2}\left(\vec{\nabla}\phi\right)^2 + V(\phi) \right]$$

At finite temperatures

$$S_E(\phi, T) = \int_0^{1/T} d\tau\, d^3x \left[\frac{1}{2}\left(\frac{d\phi}{d\tau}\right)^2 + \frac{1}{2}\left(\vec{\nabla}\phi\right)^2 + V(\phi) \right] \xrightarrow{T \gg R^{-1}(0)} \frac{S_3(\phi, T)}{T}$$

Spatial Euclidean action

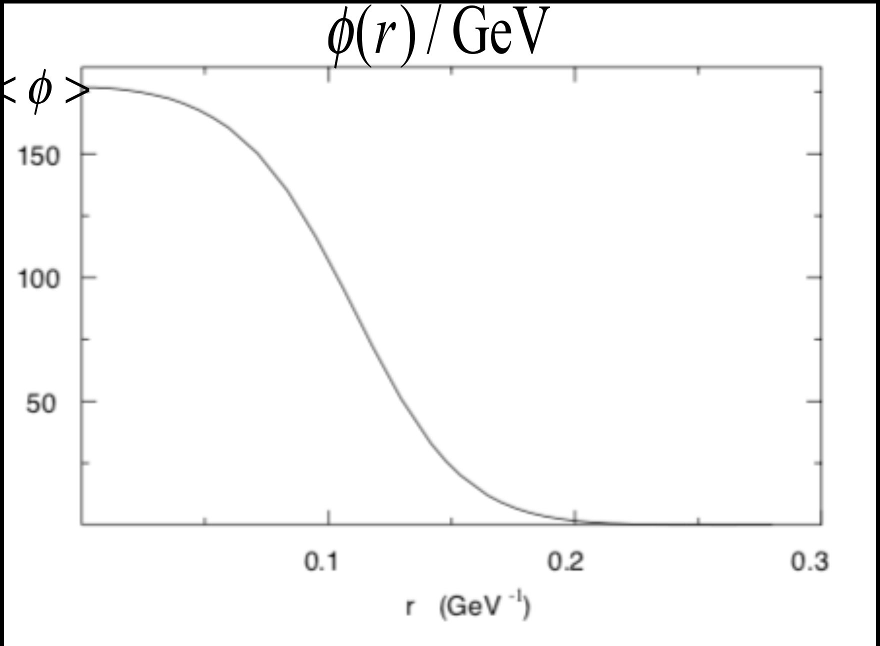
$$S_3(\phi, T) = \int d^3x \left[\frac{1}{2}\left(\vec{\nabla}\phi\right)^2 + V(\phi, T) \right] = 4\pi \int dr\, r^2 \left[\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + V(\phi, T) \right]$$

Euler-Lagrange Equation for the bubble solution

$$\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + \frac{2}{r}\frac{d\phi}{dr} - \frac{\partial V(\phi, T)}{\partial \phi} = 0\,, \qquad \phi(r = \infty) = 0\,, \qquad \left.\frac{d\phi}{dr}\right|_{r=0} = 0$$

In general a bounce solution is found numerically by (overshooting-undershooting) trials and errors procedure.

Typical solution (for T_*~100 GeV)



In the `thin-wall' approximation a kink solution is found analytically:

$$\phi(r,t) = \frac{1}{2} < \phi > \left[1 - \tanh\left(\frac{r - r_n - v_w (t - t_n)}{\Delta_w} \right) \right]$$

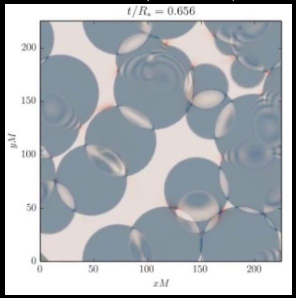
Where v_w and Δ_w are respectively the bubble wall velocity and thickness and t_n is the nucleation time of the bubble.

From the Euclidean action to the GW spectrum

(Kamionkowski,Kosowsky,Turner '93;Apreda et al 2001; Grogejan,Servant 2006; Ellis,Lewicki,No 2020)

time and temperature of nucleation

$$\int_{o}^{t_*} \frac{dt\,\Gamma}{H^3} \sim 1 \Rightarrow \int_{T_*}^{\infty} \frac{dT}{T}\left(\frac{90}{8\pi^3 g_*}\right)^2 \left(\frac{T}{M_{\rm P}}\right)^4 e^{-S_3/T} = 1 \Rightarrow \frac{S_3(T_*)}{T_*} \approx -4\ln\left(\frac{T_*}{M_{\rm P}}\right) \Rightarrow T_*$$



More precisely T_* has to be identified with the *percolation temperature,* slightly more involved definition than the nucleation temperature

$$\beta = \frac{\dot\Gamma}{\Gamma}, \quad \Gamma = \Gamma_0\, e^{-S(t)} \simeq \Gamma_0 e^{-S(t_*)}\, e^{-\left.\frac{dS}{dt}\right|_{t_*}(t-t_*)} \Rightarrow \beta \simeq -\left.\frac{dS}{dt}\right|_{t_*} \Rightarrow \frac{\beta}{H_*} = T_* \left.\frac{d(S_3/T)}{dT}\right|_{T_*}$$

Notice that $\beta/2\pi$ gives the characteristic frequency f_* of the FOPT while $1/\beta$ the time scale of its duration

Latent heat freed in the PT

$$\varepsilon = -\Delta V(\phi) - T\Delta s = V(\phi_{\rm false}) - V(\phi_{true}) + T\frac{\partial V}{\partial T} \Rightarrow \alpha = \frac{\varepsilon(T_*)}{\rho_R(T_*)}$$

Strength of the PT

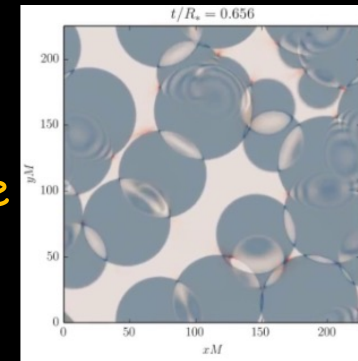
If the temperature of the dark sector $T_D \neq T \Rightarrow \alpha_D = \varepsilon(T_{D*})/\rho_{RD}(T_{D*}) > \alpha$

From α, α_D and β/H_* one can calculate the GW spectrum

Gravitational waves from first order phase transitions

(Hindmarsh et al. 1704.05871; D. Weir 1705.01783; PDB, King, Rahat 2306.4680 ; PDB, Rahat 2307.03184)

GW spectrum $$h^2\Omega_{GW0}(f) \equiv \frac{1}{\rho_{c0}h^{-2}}\frac{d\varrho_{GW0}}{d\ln f}$$



- 3 contributions: bubble wall collisions, sound waves and turbulence

$$\Omega_{GW0}(f) = \Omega_{\mathrm{bwc}\,0}(f) + \Omega_{\mathrm{sw}\,0}(f) + \Omega_{\mathrm{turb}\,0}(f)$$

- FOPT in the dark sector: sound wave contribution dominates

at the production (assuming $T_D = T$ and $\alpha \lesssim 0.1$):

$$\Omega_{GW*}(f) \simeq \Omega_{\mathrm{sw}\,*}(f) = 3h^2\widetilde{\Omega}_{GW}\,\frac{(8\pi)^{\frac{1}{3}}v_w}{\beta/H_*}\left[\frac{\kappa(\alpha)\alpha}{1+\alpha}\right]^2\tilde{S}_{sw}(f)\,\Upsilon(\alpha,\beta/H_*)$$

bubble wall velocity

efficiency factor

normalised spectral function

suppression factor accounting for duration of GW production

$$\widetilde{S}_{\mathrm{sw}}(f) \simeq 0.687\,S_{\mathrm{sw}}(f)$$

$$S_{\mathrm{sw}}(f) = \left(\frac{f}{f_{\mathrm{sw}}}\right)^3\left[\frac{7}{4+3(f/f_{\mathrm{sw}})^2}\right]^{7/2}$$

$$f_{\mathrm{sw}} = 8.9\,\mu\mathrm{Hz}\,\frac{1}{v_{\mathrm{w}}}\frac{\beta}{H_\star}\left(\frac{T_\star}{100\,\mathrm{GeV}}\right)\left(\frac{g_{\rho\star}}{106.75}\right)^{1/6}$$

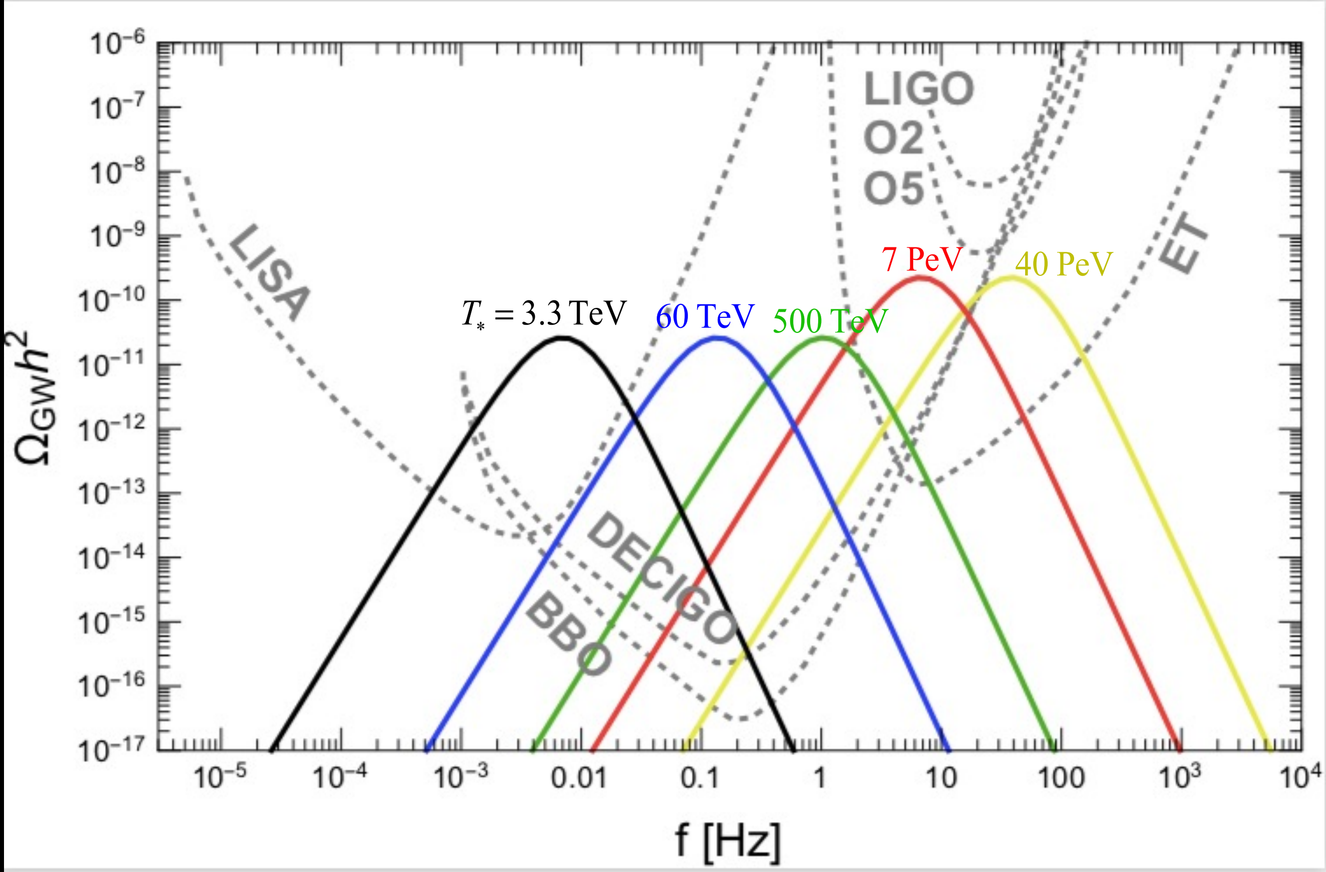
at present: $$\Omega_{\mathrm{sw}\,0}(f) = r_{gw}r(t_*,t_0)\Omega_{\mathrm{sw}\,*}(f)$$

redshift factor $$r_{gw}(t_*,t_0) = \left(\frac{a_*}{a_0}\right)^4\left(\frac{H_*}{H_0}\right)^2$$

numerically: $$h^2\Omega_{\mathrm{sw}0}(f) = 1.45\times10^{-6}\left(\frac{106.75}{g_{\rho\star}}\right)^{\frac{1}{3}}\left(\frac{\widetilde{\Omega}_{\mathrm{gw}}}{10^{-2}}\right)\left[\frac{\kappa(\alpha)\,\alpha}{1+\alpha}\right]^2\frac{v_{\mathrm{w}}}{\beta/H_\star}\widetilde{S}_{\mathrm{sw}}(f)\,\Upsilon(\alpha,\beta/H_\star)\,.$$

GWs from SFOPTs: tuning the knob

(from PDB, D. Marfatia, YL. Zhou 2001.07637)



The minimal model

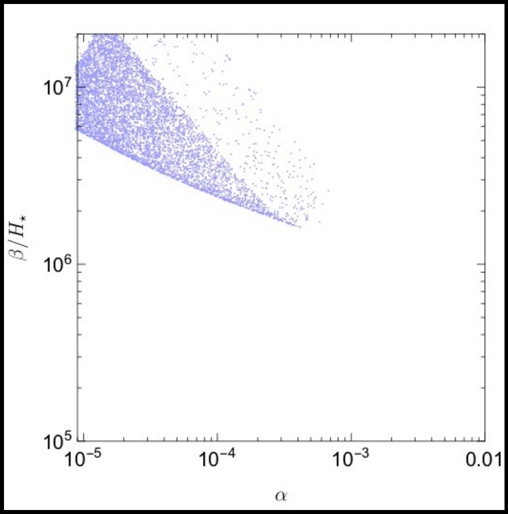
$$V_0(\varphi) = -\frac{1}{2}\mu^2\varphi^2 + \frac{\lambda}{4}\varphi^4 \quad (\lambda, \mu^2 > 0)$$

$$\Rightarrow v_0 = \sqrt{\mu^2/\lambda}\,, \quad m_S^2 = 2\lambda v_0^2\,, \quad m_J = 0$$

One-loop finite temperature effective potential:

$$V(\varphi, T) \simeq D(T - T_0)^2\varphi^2 - (AT + \tilde{\mu})\varphi^3 + \frac{\lambda(T)}{4}\varphi^4$$

The GW signal turns out to be a few orders of magnitude below the experimental sensitivity of any experiment



(from PDB, D. Marfatia, YL. Zhou 2001.07637)

Adding an auxiliary (real) scalar

(Kehayias, Profumo 0911.0687; PDB, D. Marfatia, YL. Zhou 2001.07637; PDB, S.King, M.Rahat 2306.04680)

$$V(\varphi,\eta) = V_0(\varphi) + \zeta\varphi^2\eta^2 - \frac{1}{2}\mu_\eta^2\,\eta^2 + \frac{\lambda_\eta}{4}\eta^4$$

$$v_\eta \gg v_\varphi$$

The scalar field η also undergoes a phase transition settling to its true vacuum prior to the φ phase transition

$$V(\varphi,\mathrm{T}) \simeq D(T-T_0)^2\varphi^2 - (AT+\tilde{\mu})\varphi^3 + \frac{\lambda(T)}{4}\varphi^4$$

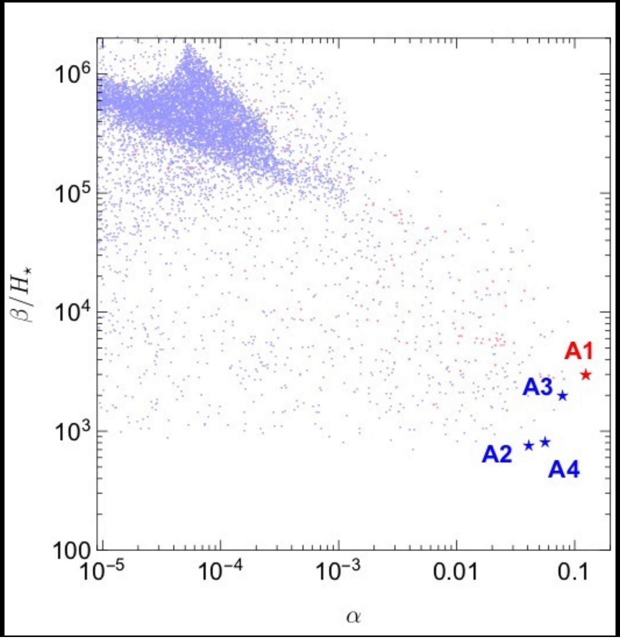
This time one has a non-zero barrier at zero temperature:

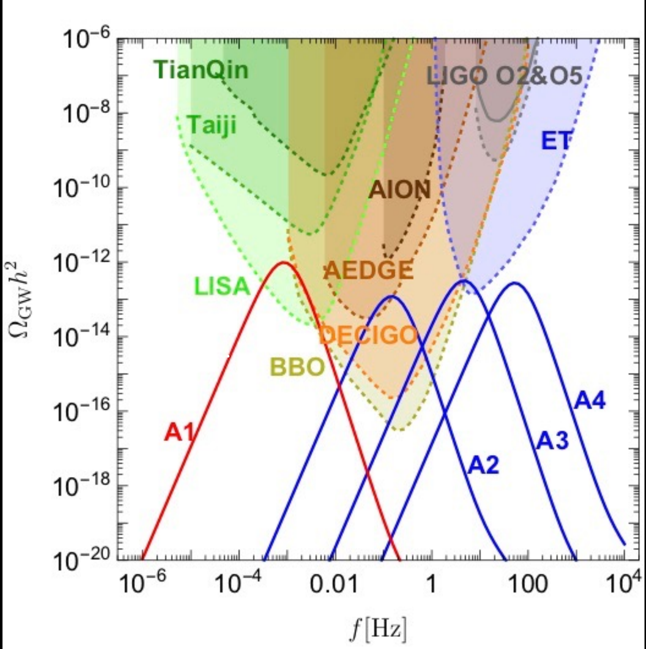
$$\tilde{\mu} = \zeta^2\frac{v_0}{4\lambda_\eta}$$

This greatly enhances the strength of the FOPT and, therefore, the GW spectrum

Adding an auxiliary scalar: GW spectrum

(PDB, D. Marfatia, YL. Zhou 2001.07637)





	Inputs				Predictions			
	m_S/GeV	$\tilde{\mu}$/GeV	M/GeV	v_0/GeV	$T_\star$/GeV	α	$\beta/H_\star$	a_0
A1	0.06190	0.0005857	0.5361	3.5873	0.6504	0.1248	2966	0.05951
A2	156.2	13.15	465.6	1014	721	0.04139	754.8	0.3886
A3	1036	13.72	7977	44424	9180	0.08012	1975	0.06268
A4	43874	1856	181099	567378	247807	0.05611	809.7	0.1944

GeV RH neutrinos can give a signal at LISA
interplay with collider searches (talk by Naredo)

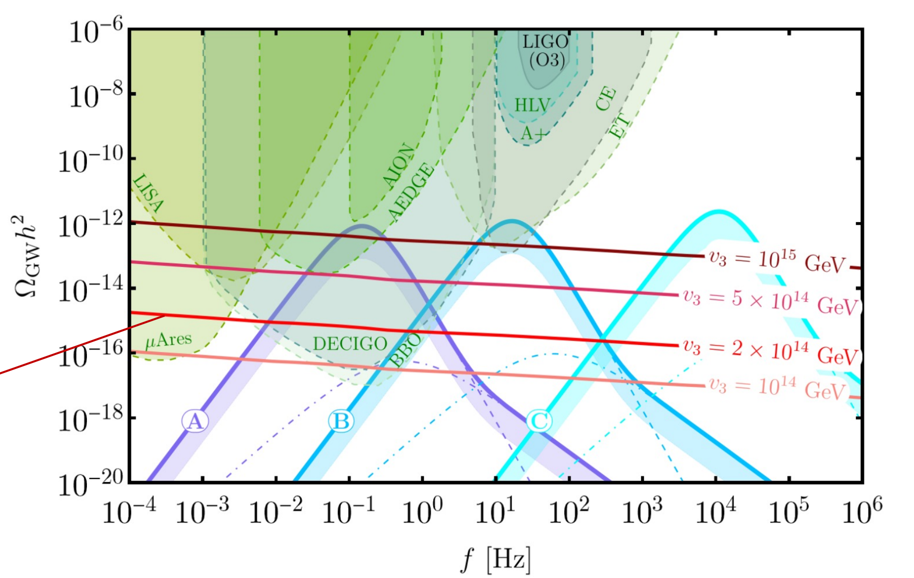
Two-majoron model

(PDB, S.King, M.Rahat 2306.04680)

$$V_0(\phi_1, \phi_3) = -\mu_1^2|\phi_1|^2 + \lambda_1|\phi_1|^4 - \mu_3^2|\phi_3|^2 + \lambda_3|\phi_3|^4 + \zeta|\phi_1|^2|\phi_3|^2$$

At high temperatures it respects a $U(1)_{L_1} \times U(1)_{L_3}$ symmetry

$$v_2 \gg v_1$$



GWs from global cosmic strings

B.P.	λ_1	v_1 [GeV]	M [GeV]	C [GeV]	α	$\beta/H_\star$	$T_\star$ [GeV]	$\langle\varphi_1\rangle_{T_\star}^{\rm true}$ [GeV]
Ⓐ	0.00057	1188.22	186.53	20.79	0.29	244.65	5863.12	1.38×10^5
Ⓑ	0.00061	2.32×10^5	3.63×10^4	3023.02	0.30	204.66	7.81×10^5	1.79×10^7
Ⓒ	0.00036	9.88×10^6	1.08×10^6	2×10^6	0.30	141.48	7.51×10^8	1.92×10^{10}

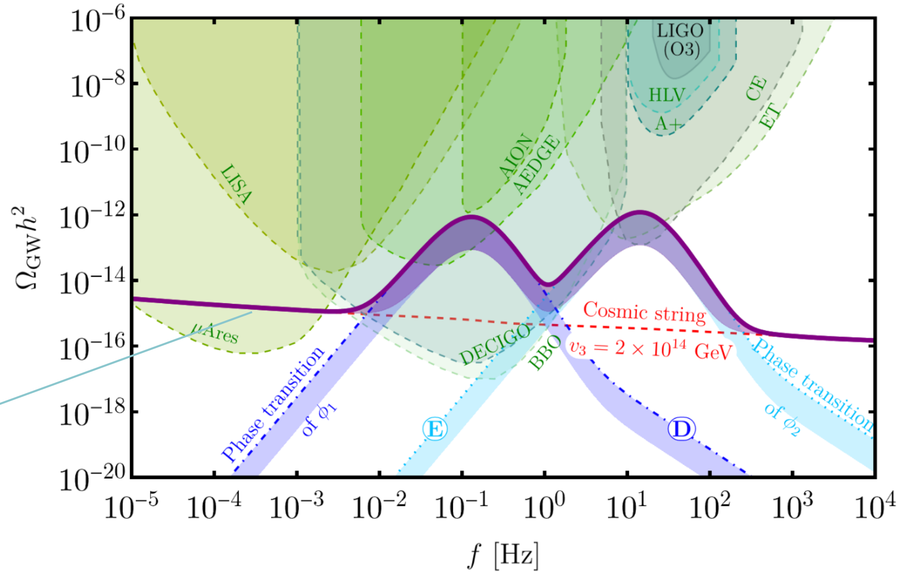
Three-majoron model

(PDB, S.King, M.Rahat 2306.04680)

$$V_0(\phi_1,\phi_2,\phi_3) = \sum_{I=1,2,3}\left[-\mu_I^2\phi_I^*\phi_I + \lambda_I(\phi_I^*\phi_I)^2\right] + \sum_{I,J,I\neq J}^{1,2,3}\frac{\zeta_{IJ}}{2}(\phi_I^*\phi_I)(\phi_J^*\phi_J).$$

At high temperatures it respects a $U(1)_{L_1}\times U(1)_{L_2}\times U(1)_{L_3}$ symmetry

$$v_3 \gg v_2 \gg v_1$$



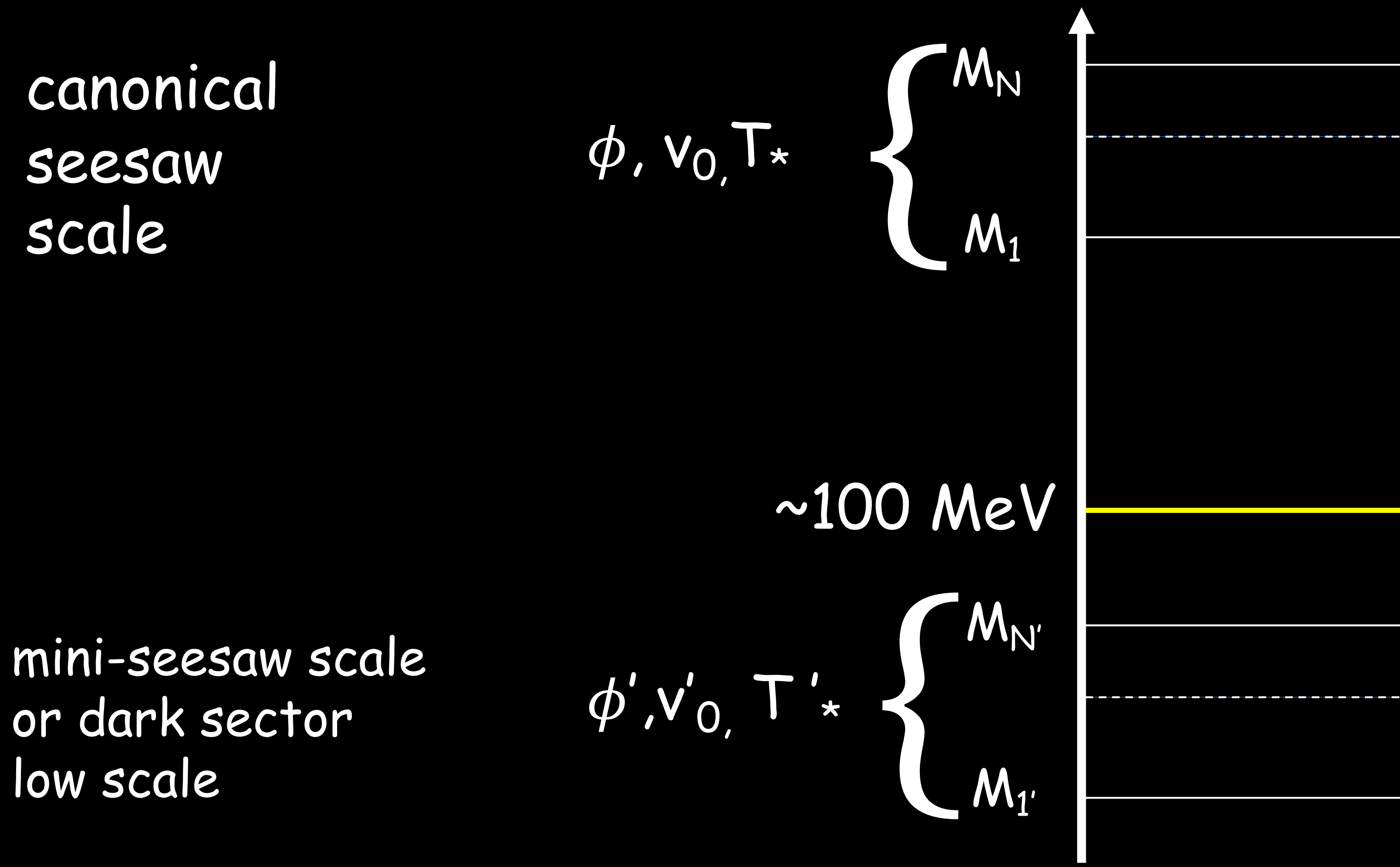
GWs from global cosmic strings

	λ_I	v_I [GeV]	M_I [GeV]	C_I [GeV]	α	$\beta/H_\star$	$T_\star$ [GeV]	$\langle\varphi_I\rangle_{T_\star}^{\rm true}$ [GeV]
Ⓓ	0.00027	1188.2	186.5	10.79	0.30	241.37	5196.52	1.50×10^5
Ⓔ	0.00029	2.32×10^5	3.63×10^4	1523.02	0.30	203.53	6.7×10^5	1.88×10^7

Low scale majoron FOPT and cosmological tensions

Split majoron model

(PDB, Marfatia,Zhou 2106.00025; PDB, Rahat 2307.03184)



for definiteness let us consider N=2 and N′=1 (in this case the lightest RH neutrino could be responsible of the lightest neutrino mass (as in the νMSM model)

Extra (or dark) Radiation

$$\varrho_R(T) = g_\rho(T)\,\frac{\pi^2}{30}\,T^4$$

number of radiation degrees of freedom

$$g_\rho(T) = g_\rho^{SM}(T) + \Delta g_\varrho(T)$$

number of extra (or dark) radiation degrees of freedom

$$\Delta g_\rho(T) \equiv \frac{7}{4}\,\Delta N_\nu(T)\left(\frac{T_\nu}{T}\right)^4$$

effective number of (extra-)neutrino species

$$\Delta N_\nu(T) \equiv N_\nu(T) - N_\nu^{SM}(T)$$

$$N_\nu^{SM}(T \gg m_e) = 3 \qquad N_\nu^{SM}(T \ll m_e) = 3.045$$

three different stages to constraint ΔN_ν:

- $t_{fr} \simeq 1s$, $T_{fr} \simeq 1$ MeV: BBN + $Y_p \Rightarrow \Delta N_\nu(t_{fr}) = -0.1 \pm 0.3 \Rightarrow \Delta N_\nu(t_{fr}) \lesssim 0.5$ (95% C.L.)
- $t_{nuc} \simeq 310s$, $T_{nuc} \simeq 65$ keV : BBN + D/H $\Rightarrow \Delta N_\nu(t_{nuc}) = -0.05 \pm 0.22 \Rightarrow \Delta N_\nu(t_{nuc}) \lesssim 0.4$ (95% C.L.)
- $t_{nuc} \simeq 4\times10^5$yr, $T_{rec} \simeq 0.3$ eV : CMB $\Rightarrow \Delta N_\nu(t_{rec}) = -0.05 \pm 0.17 \Rightarrow \Delta N_\nu(t_{nuc}) \lesssim 0.3$ (95% C.L.)

(*Planck* 2018, ΛCDM)

Split seesaw model with N'=1 and $T'_* = T'_{D*} \sim 10$ MeV $\Rightarrow \Delta N_\nu = 4/7 \simeq 0.6$

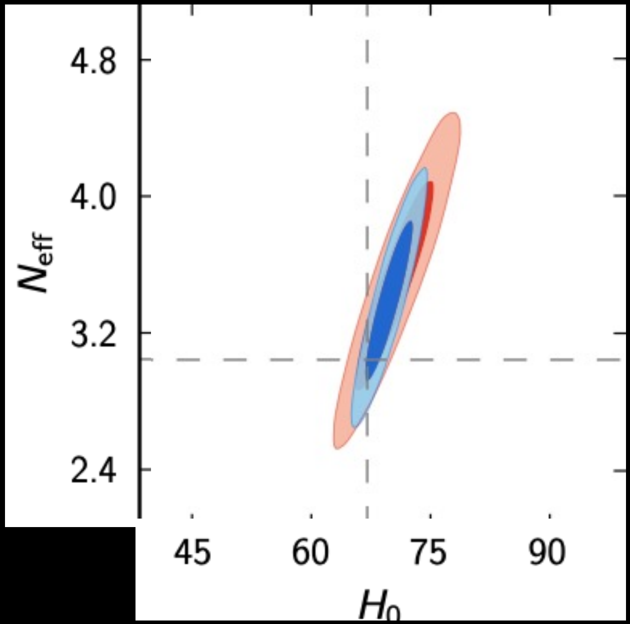
Hubble tension and fractional N_ν

$$H_0^{(Planck13)} = 67.3 \pm 1.2 \text{ km s}^{-1}\text{Mpc}^{-1}$$

$$N_\nu^{(Planck13)} = 3.36 \pm 0.34$$

$$H_0^{(SNe)} = 73.8 \pm 2.4 \text{ km s}^{-1}\text{Mpc}^{-1}$$

$$N_\nu^{(Planck13+SNe)} = 3.62 \pm 0.25$$



(from *Planck* 13 1303.5076)

Many proposed models for $\Delta N_\nu(T_{rec}) \sim 0.5$:

- long-lived particle decays (PDB, S.F. King, A. Merle 1303.6267)
- Axionic dark radiation (J.Conlon, M.C. David Marsh, 1304.1804)
- Goldstone boson: $\Delta N_\nu = 4/7 \simeq 0.6$ (S. Weinberg 1305.1971)
- ………..

Cosmological tensions: beyond a fractional N_ν

Different cosmological tensions tension

- Hubble tension:

$H_0^{(P18)} = 67.66 \pm 0.42$ km s^{-1}Mpc^{-1} $\overset{\sim 5\sigma \text{ tension}}{\longleftrightarrow}$ $H_0^{(SH0ES)} = 73.30 \pm 1.04$ km s^{-1}Mpc^{-1}

- Growth tension
- Cosmic dipoles
- CMB anisotropy anomaly

A model should improve the ΛCDM baseline model rather than solve one tension in isolation.

The majoron model is one of the leading model proposed to ameliorate the cosmological tensions (*silver medal* in *H_0 Olympics*)
(Lesgourgues, Poulin et al. 2107.10291)

Neutrino re-thermalisation

(Chacko,Hall,Okui,Oliver hep-ph 0312267; PDB, Rahat 2307.03184)

- Consider now that the dark sector decouples at high energies and $T_D \ll T$
- Let us consider $T'_\star \lesssim 1$ MeV (after neutrino decoupling)
- This low energy phase transition generates Majorana masses for the N′ light RH neutrinos (minimal case N′ = 1)
- At these temperatures, ordinary neutrinos interact with the majorons J and J′ :

$$-\mathcal{L}_{\nu+\mathrm{D}} = \frac{i}{2}\,\zeta\, J|\phi'|^2 + \frac{i}{2}\sum_{i=2,3}\lambda_i\,\overline{\nu_i}\,\gamma^5\,\nu_i\,J + \mathrm{h.c.}$$

- These interactions couple neutrinos to majorons, so that the dark sector thermalises prior to the phase transition to a common temperature T_D:

$$T_{\nu\mathrm{D}} = T_\nu^{\mathrm{SM}}(T)\left(\frac{3.045}{3.045 + N' + 12/7 + 4\,\Delta g/7}\right)^{\frac{1}{4}}$$

contribution from J and ϕ'

- Minimal case: N′ = 1 and $\Delta g = 0 \Rightarrow T_{\nu D} = 0.815\, T_\nu^{SM}$

Confronting the deuterium constraint

(PDB, Rahat 2307.03184)

$$g_\rho(T) = g_\rho^{\gamma+e^\pm+3\nu}(T) + \frac{7}{4}\Delta N_\nu(T)\left(\frac{T_\nu}{T}\right)^4$$

- Prior to neutrino rethermalisation, above neutrino decoupling, ΔN_ν is negligible
- After the phase transition and the decay of N_h massive particles (S + N′ right-handed neutrinos):

$$\Delta N_\nu \simeq 3.045\left[\left(\frac{3.045 + N' + 12/7 + 4\Delta g/7}{3.043 + N' + 12/7 + 4\Delta g/7 - N_\mathrm{h}}\right)^{\frac{1}{3}} - 1\right]$$

  - For Δg = 0, 1, 2, 3 ⇒ ΔN_ν= 0.46, 0.41, 0.37, 0.33

For $T_* > T_{nuc} \simeq 65$ keV one has to confront BBN+D/H constraint. There are actually 2 different results:

- $\Delta N_\nu(T_{nuc}) = -0.05 \pm 0.22 \Rightarrow \Delta N_\nu(t_{nuc}) \lesssim 0.4$ (95% C.L.) (Pisanti et al. 2011.11537)
- $\Delta N_\nu(T_{nuc}) = 0.3 \pm 0.15$ (Pitrou et al. 2011.11320)

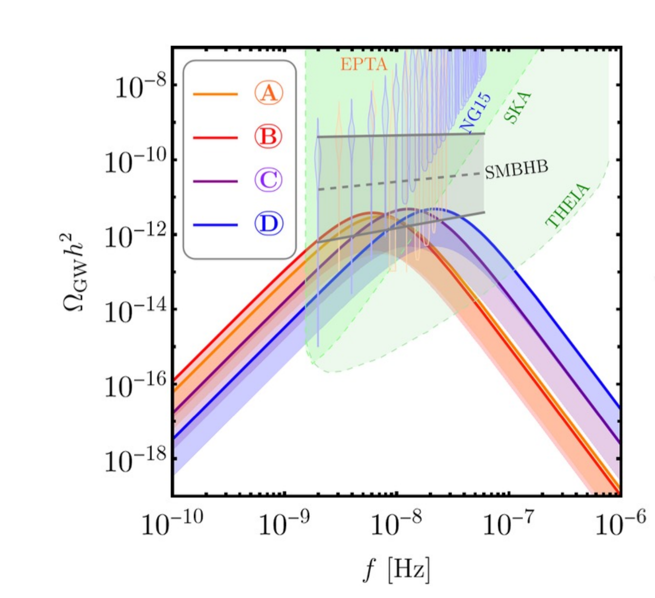
The split majoron model can nicely address this potential *Deuterium problem*

The split majoron model confronts the NANOGrav signal

(PDB, Rahat 2307.03184)

$$h^2\Omega_{\rm sw0}(f) = 1.845\times10^{-6}\,\frac{\widetilde{\Omega}_{\rm gw}}{10^{-2}}\,\frac{v_{\rm w}(\alpha)}{\beta/H_\star}\left[\frac{\kappa(\alpha_{\nu \rm D})\,\alpha}{1+\alpha}\right]^2\left(\frac{15.5}{g'_{s\star}}\right)^{4/3}\left(\frac{g'_{\rho\star}}{15.5}\right)S_{\rm sw}(f)\,\Upsilon(\alpha,\alpha_{\nu\rm D},\beta/H_\star)$$

valid for $\alpha \lesssim 0.1$
At values $\alpha \sim 0.5$
some deviation is
expected….both ways
especially around the peak.
Recently a bump
has been found in certain
conditions
(Caprini et al 2308.12943)



B.P.	N'	λ'	v'_0/keV	M'/keV	C/keV	α	$\alpha_{\nu\rm D}$	$\kappa_{\nu\rm D}$	$\beta/H_\star$	$T_\star$/keV	$v_{\rm w}$	Υ
Ⓐ	1	0.0013	54.85	16.08	0.96	0.45	2.06	0.74	423.93	276.70	0.96	0.014
Ⓑ	1	0.001	71.0	20.0	0.75	0.52	2.40	0.74	424.0	240.58	0.97	0.013
Ⓒ	1	0.001	83.0	23.0	1.70	0.60	2.62	0.75	399.73	515.11	0.97	0.013
Ⓓ	1	0.001	144.0	40.0	3.0	0.59	2.56	0.75	393.63	888.35	0.97	0.013

Conclusions

- The generation of Majorana mass might lead to the production of a stochastic GW cosmological background in the early universe at the seesaw scale or scales in the case of a multiple majoron model
- The split majoron model can motivate a modification of pre-recombination era and be related to the generation of a light Majorana mass
- It can alleviate cosmological tensions and might solve a potential deuterium problem that might be regarded as a kind of signature of the model.
- At the phase transition GWs can be generated with a spectrum that can peak in the NANOGrav frequencies
- It cannot explain the whole signal, but it might contribute marginally in addition to SMBH binaries, and one can hope its contribution could be disentangled if SMBH binary spectrum will be better understood

Confronting the cosmological tensions

(M.Escudero, S. Whitte 1909.04044)

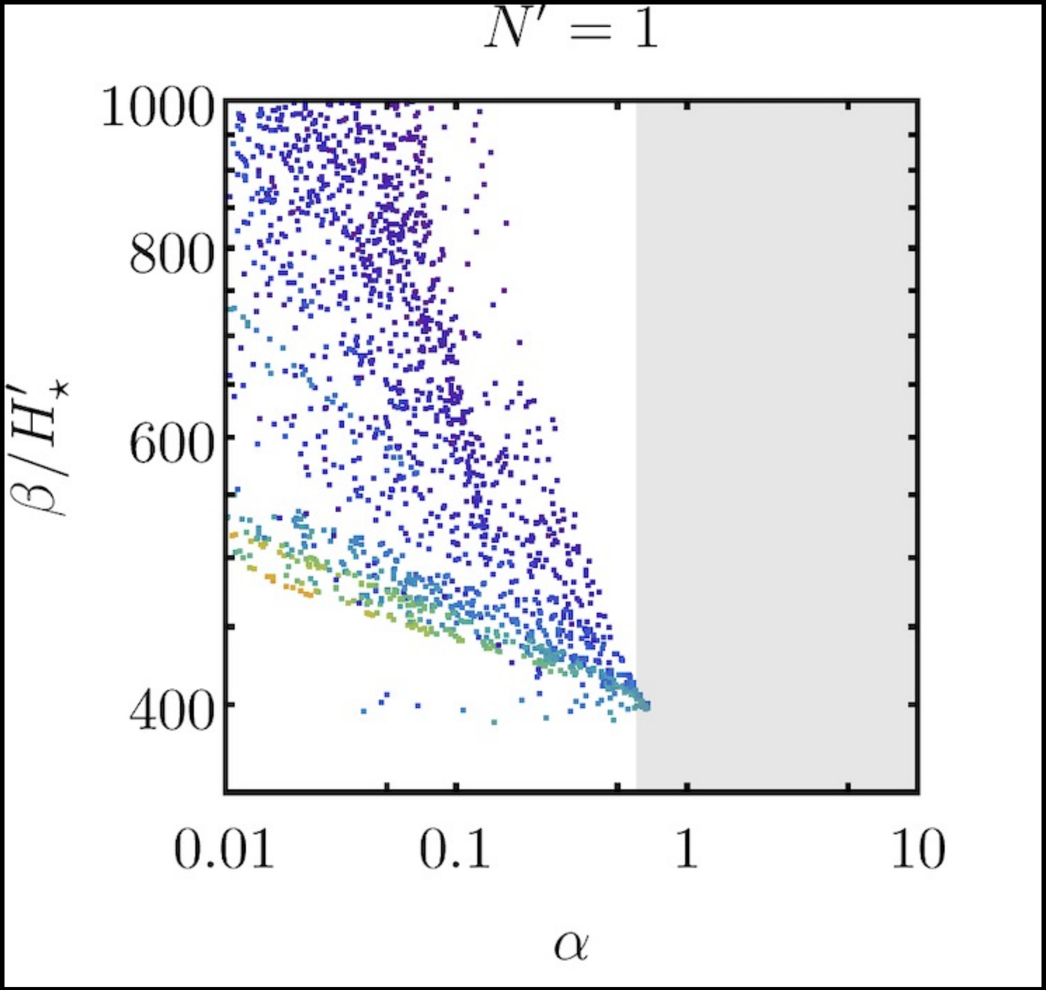
In addition to extra radiation, it also couples the majoron background to neutrinos reducing r_s allowing for larger H_0

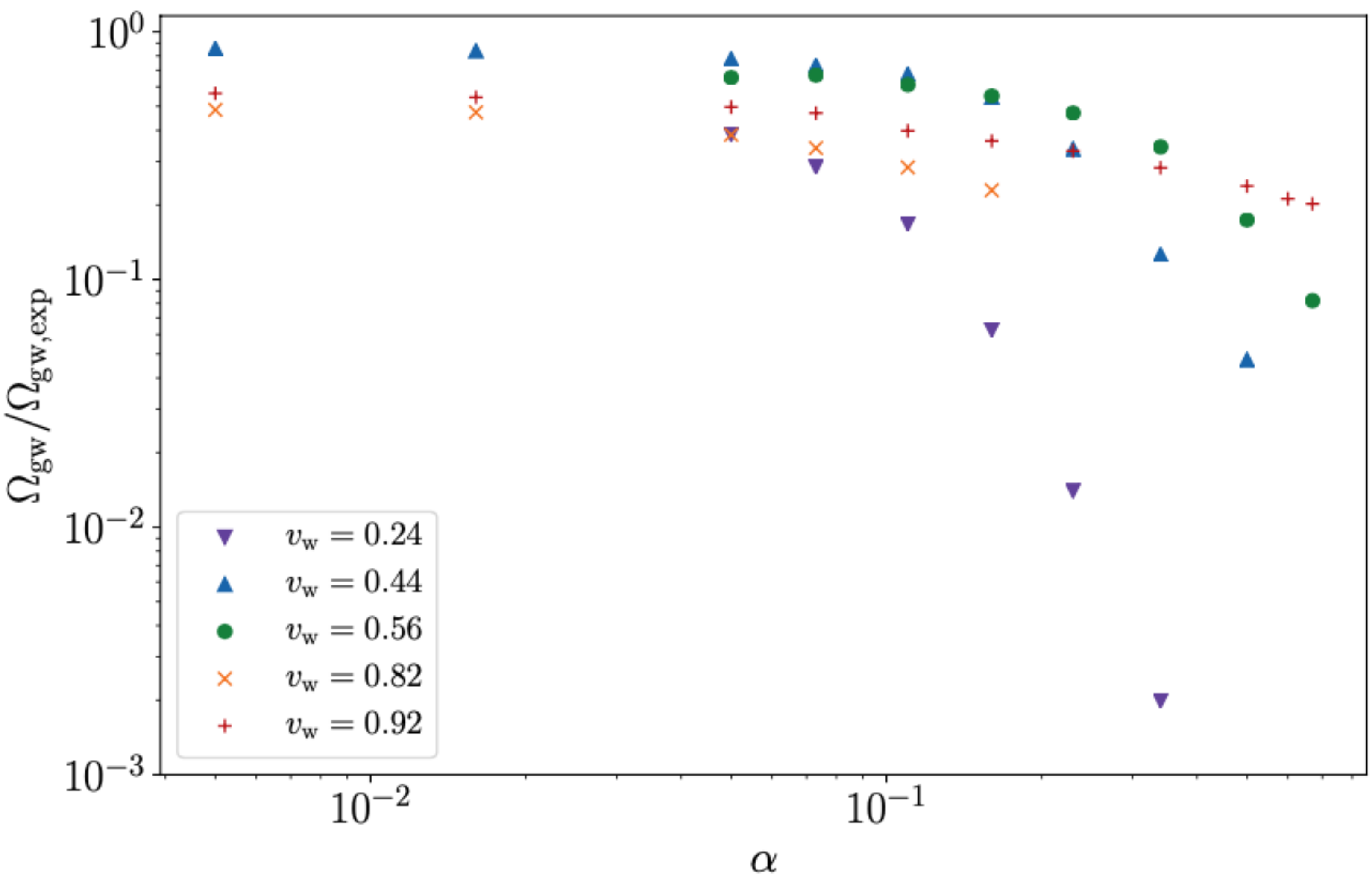
Parameter	ΛCDM	ΛCDM + $\Delta N_{\rm eff}$	Majoron + $\Delta N_{\rm eff}$
$\Delta N_{\rm eff}$	–	0.43 (0.358) ± 0.18	0.52 (0.545) ± 0.19
m_ϕ/eV	–	–	(0.33)
$\Gamma_{\rm eff}$	–	–	(8.1)
$100\,\Omega_b h^2$	2.252 (2.2563) ± 0.016	2.270 (2.2676) ± 0.017	2.280 (2.2765) ± 0.02
$\Omega_{\rm cdm} h^2$	0.1176 (0.11769) ± 0.0012	0.125 (0.1243) ± 0.003	0.127 (0.1279) ± 0.004
$100\,\theta_s$	1.0421 (1.04223) ± 0.0003	1.0411 (1.04125) ± 0.0005	1.0410 (1.04102) ± 0.0005
$\ln(10^{10} A_s)$	3.09 (3.1102) ± 0.03	3.10 (3.072) ± 0.03	3.11 (3.116) ± 0.03
n_s	0.971 (0.9690) ± 0.004	0.981 (0.9780) ± 0.006	0.990 (0.99354) ± 0.010
$\tau_{\rm reio}$	0.051 (0.0500) ± 0.008	0.052 (0.0537) ± 0.008	0.052 (0.0576) ± 0.008
H_0	68.98 (69.04) ± 0.57	71.27 (70.60) ± 1.1	71.92 (71.53) ± 1.2
$(R-1)_{\rm min}$	0.009	0.009	0.03
$\chi^2_{\rm min}$ high-ℓ	2341.56	2345.39	2338.84
$\chi^2_{\rm min}$ lowl	22.45	21.56	20.81
$\chi^2_{\rm min}$ lowE	395.72	395.89	396.40
$\chi^2_{\rm min}$ lensing	9.91	9.21	10.69
$\chi^2_{\rm min}$ BAO	4.74	4.5	4.69
$\chi^2_{\rm min}$ SH$_0$ES	12.34	5.82	3.10
$\chi^2_{\rm min}$ CMB	2769.6	2772.1	2766.7
$\chi^2_{\rm min}$ TOT	2786.7	2782.4	2774.5
$\chi^2_{\rm min} - \chi^2_{\rm min}\|^{\Lambda\rm CDM}$	0	−4.3	−12.2

Significant improvement compared to the ΛCDM model but new calculations neutrino-majoron interaction rate seems to reduce the statistical significance (S. Sandner, M.Escudero, S. Whitte 2305.01692)

Split majoron model

(PDB, Rahat 2307.03184)





10^0
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
α
$\Omega_{\rm gw}/\Omega_{\rm gw,exp}$
$v_{\rm w} = 0.24$
$v_{\rm w} = 0.44$
$v_{\rm w} = 0.56$
$v_{\rm w} = 0.82$
$v_{\rm w} = 0.92$