# Probing leptogenesis with gravitational waves

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**Collab: Pasquale D. Bari, Satyabrata Datta, Ambar Ghosal, Sabir Ramazanov, Federico Urban**

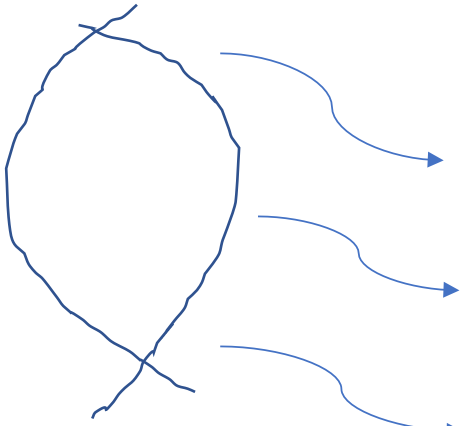
## Subject of this talk:

How to probe **high scale** leptogenesis with gravitational waves.

**High scales =>** beyond the reach of the collider experiments, therefore a shift of attention to GWs.

Typically the heavy neutrinos which are involved in generating lepton asymmetry in various ways, get masses with a dynamical U(1) gauge symmetry breaking. => associated with cosmic strings

Cosmic string loop



Gravitational waves, Amplitude ~ $[VEV_{U(1)}]^2$

Heavy mass: $M_R \sim f(VEV_{U(1)})$

# Basic idea to reconcile light neutrino masses and baryogenesis via leptogenesis

**Minimal scenario: Introduce two RH neutrino field $\nu_{Ri}$**

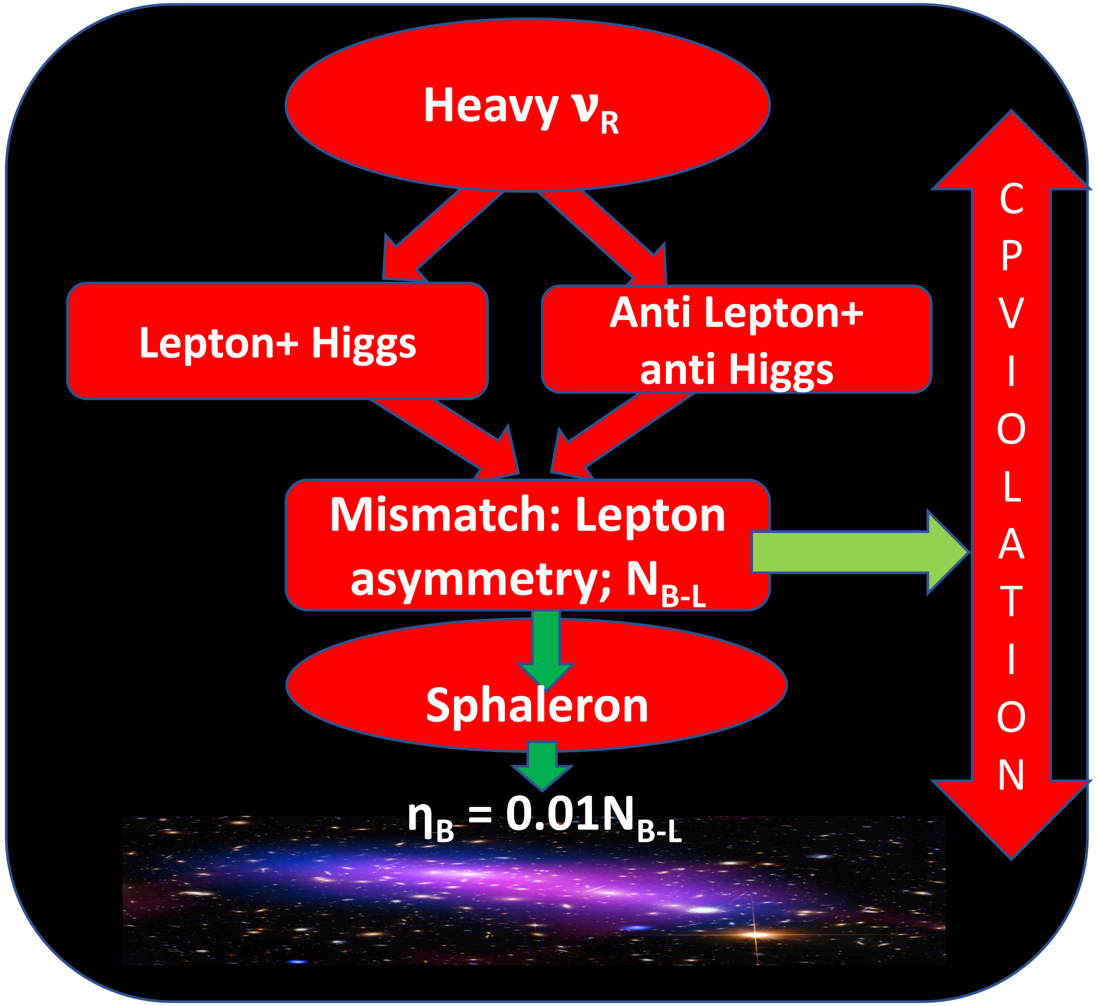
$\overline{\nu_R}\, m_D\, \nu_L$

$\nu_R^T C M_R \nu_R$

Type -1 Seesaw : $m_\nu = m_D^T M_R^{-1} m_D$

$M_R \sim 10^{14}$ GeV $\Longrightarrow m_\nu \simeq 0.1$ eV

Light neutrinos are Majorana type



# Tests:

**Direct:** Colliders => low scale leptogenesis (Temp < TeV).

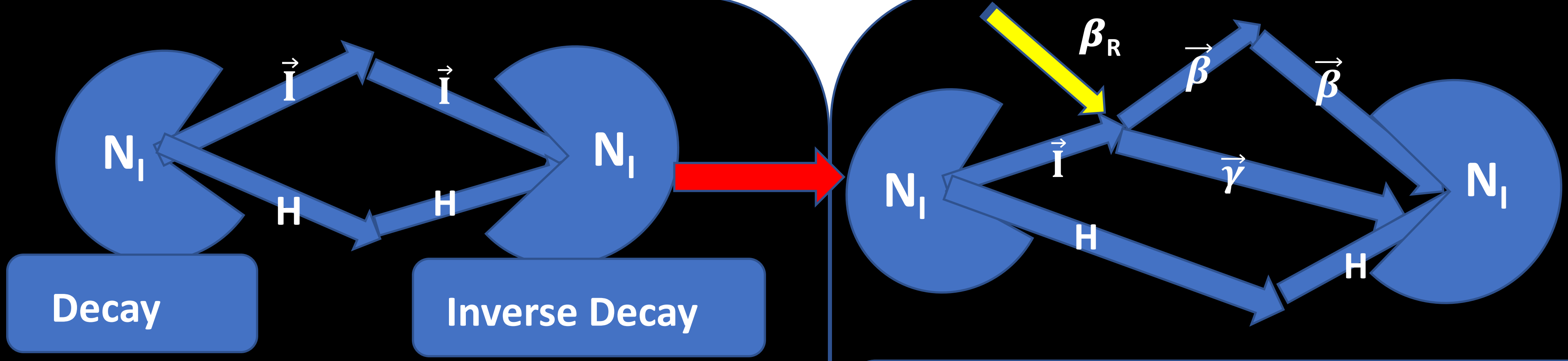
**Examples (Not exhaustive):**

**ARS:** (Heavy neutrino oscillation $N_J$ <-> $N_i$) (**Akhmedov, Rubakov, Smirnov, 1998**).

**Resonant-leptogenesis** (Quassi-degenerate heavy neutrinos enhancement in the CP asymmetry) (**Pifaltsis, Underwood, 2004**).

**Higgs decays:** (**Hambye, Teresi, 2016**)

## Flavour effects : Reduction of N1-washout, Still can not lower the scale significantly but opens up the way of indirect tests in neutrino experiments:



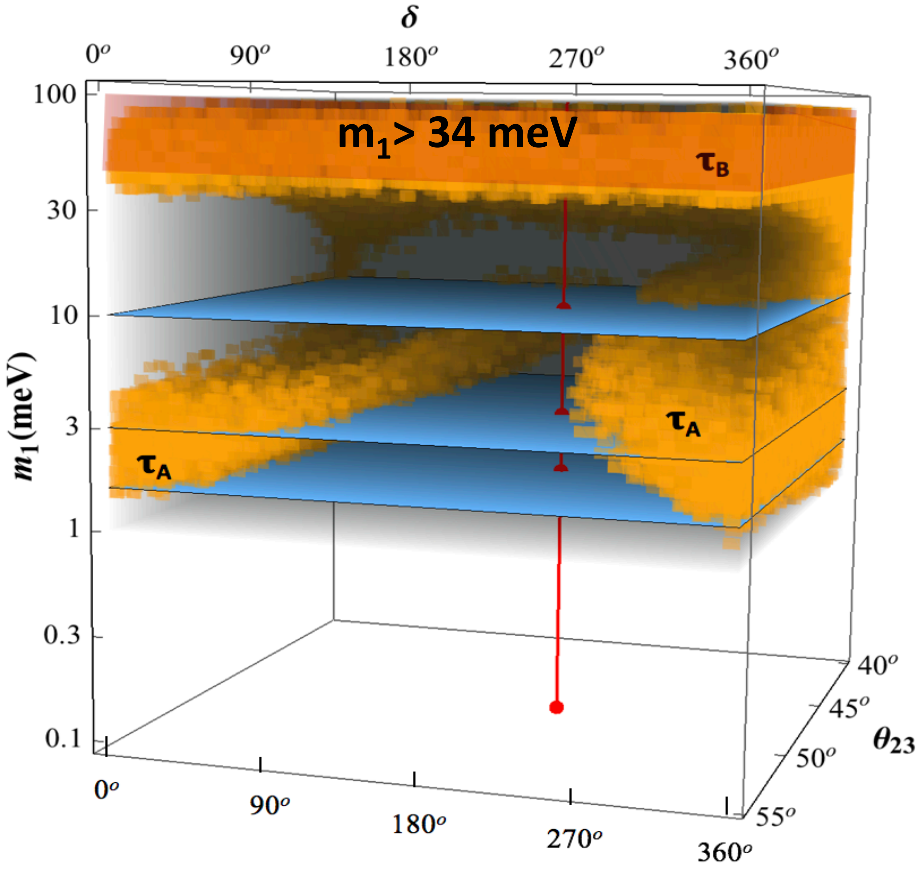

$\vec{l} = P_{l\alpha}\vec{\alpha}$, $\alpha = e, \mu, \tau$, $P_{l\alpha} = K_{i\alpha}/\Sigma_\alpha K_{i\alpha}$

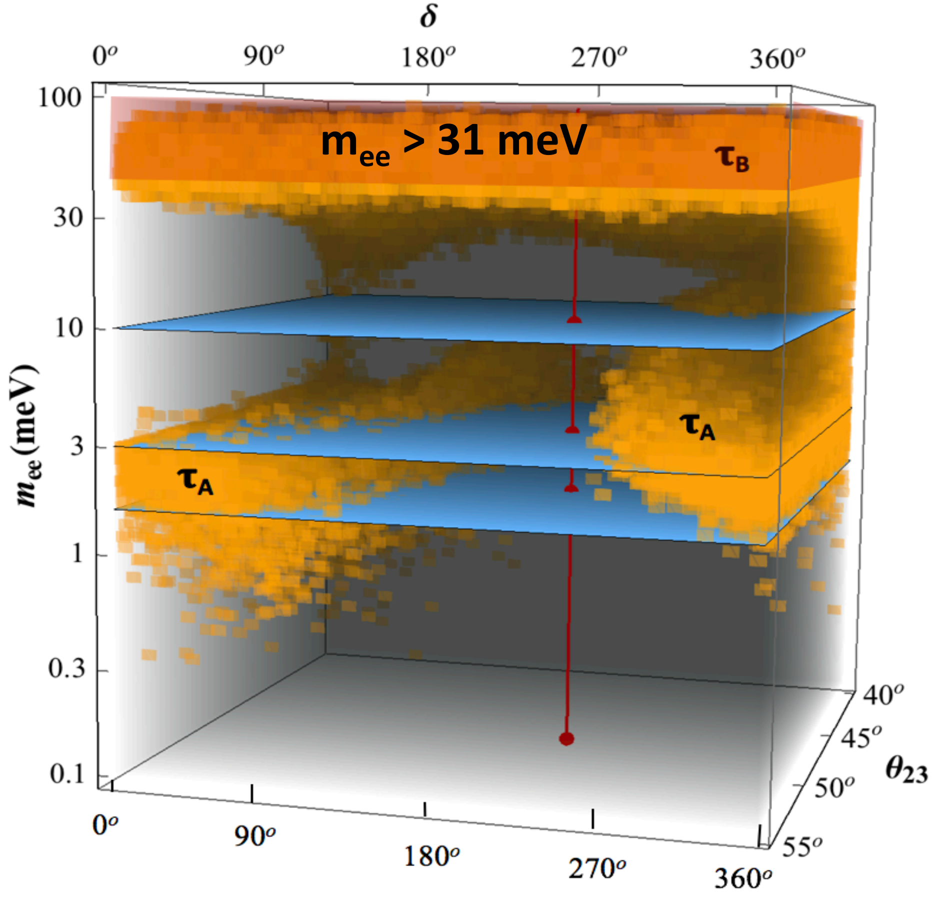
$K_{i\alpha} = P_{l\alpha} K_i$ ← Magnitude of the Decay parameter has been reduced

If $10^9$ GeV < $M_I$ < $10^{12}$ GeV: $\vec{\beta} = \vec{\tau}$ , $\vec{\gamma} = \vec{e} + \vec{\mu}$

$M_I$ < $10^9$ GeV : All the three flavors act individually

# 3D Parameter space : Leptogenesis in SO(10) inspired models-A Prototype




KAMLAND2-ZEN reach: 20 meV

Best fit: ($\theta 23$ ~ $48.6^0$, $\boldsymbol{\delta}$ ~ $221^0$)

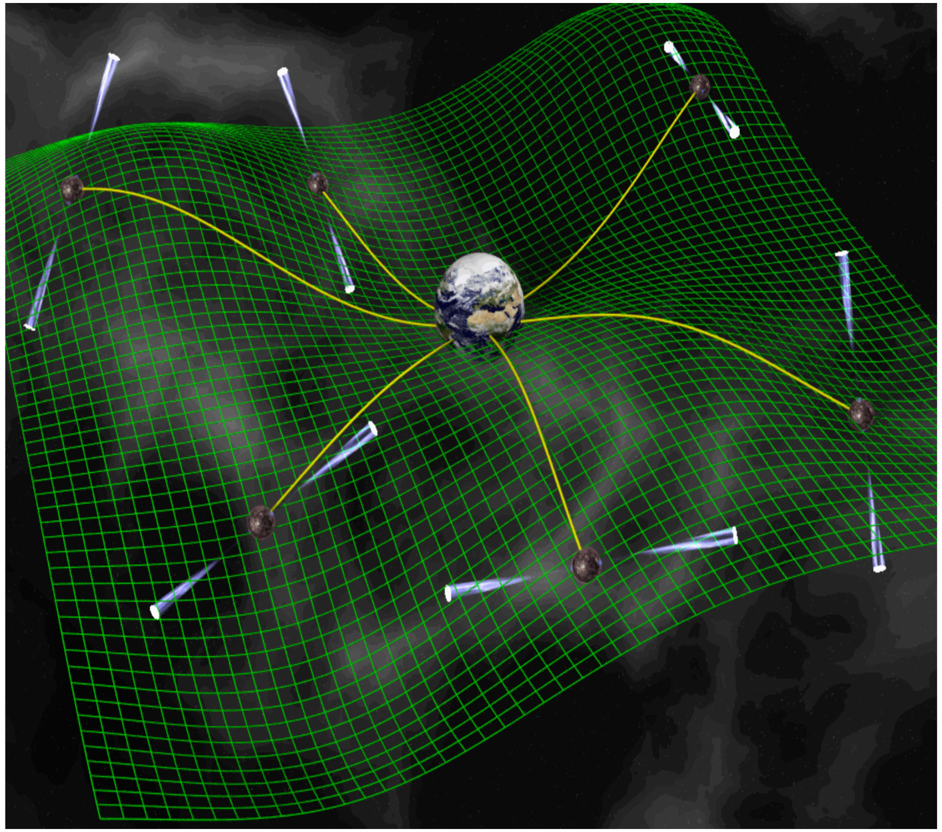
Di. Bari and **Samanta, 2020**

# GWs as a probe of leptogenesis , e.g., PTAs

**Millisecond pulsars (spins ~100 times a second) produce most stable pulses and are used by the PTAs**

When a gravitational wave (a disturbance) passes between the earth and pulsar system, the time of arrival of the signal from the pulsars changes. This induces a change in frequency due to the gravitational wave.

Time residual: $$R(t) = -\int_0^t \frac{\delta\nu}{\nu}\,\mathrm{d}t$$



**Pulsar-Timing-Arrays typically work with high amplitude GWs** => Could be a Detector of High Scale Symmetry breaking theories, e.g., leptogenesis

# Cosmic strings

Cosmological phase transition leads to spontaneous breaking of abelian symmetry
This is associated with topological defect like cosmic strings (CS). (T. Kibble, J. Phys. A 9 (1976)).

They can form close loop and shrink via GW emission.

Still there are debates whether they loose energy via particle radiation or GW emission.

Recent numerical simulation based Nambu-Goto action shows that the dominant emission is GW if the broken symmetry is a local gauge symmetry. (Pillado et al, **PRD 2011**, T. Vachaspati et al ,**PRD**, C. Ringeval et al **JCAP**).

Radiate energy at constant rate $\frac{dE}{dt} = -\Gamma G\mu^2,$

Length dynamics $l(t) = \alpha t_i - \Gamma G\mu(t - t_i)$

G: Newton constant , $\mu$: string tension (~**Square of symmetry breaking scale**), $\alpha$: loop size (max: 0.1)

# Gravitational waves power spectrum and loop number density

Amplitude/energy density

$$\Omega_{GW}(t_0,f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df} = \sum_k \Omega_{GW}^{(k)}(t_0,f).$$

Differential energy density

$$\frac{d\rho_{GW}^{(k)}}{df} = \int_{t_F}^{t_0}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^4 P_{GW}(\tilde{t},f_k)\frac{dF}{df}d\tilde{t},$$

Power spectrum

$$P_{GW}(\tilde{t},f_k) = \frac{2kG\mu^2\Gamma_k}{f_k^2}n(\tilde{t},f_k) = \frac{2kG\mu^2\Gamma_k}{f^2\left[\frac{a(t_0)}{a(\tilde{t})}\right]^2}n\left(\tilde{t},\frac{2k}{f}\left[\frac{a(\tilde{t})}{a(t_0)}\right]\right).$$

$\mu^2/M_{pl}$

Amplitude/energy density

$$\Omega_{GW}^{(k)}(t_0,f) = \frac{2kG\mu^2\Gamma_k}{f\rho_c}\int_{t_{osc}}^{t_0}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^5 n\left(\tilde{t},\frac{2k}{f}\left[\frac{a(\tilde{t})}{a(t_0)}\right]\right)d\tilde{t}.$$

Loop number density

Numerical simulation:

$$n(\tilde{t},l_k(\tilde{t})) = \frac{0.18}{[l_k(\tilde{t})+\Gamma G\mu\tilde{t}]^{5/2}\,\tilde{t}^{3/2}}.$$

# Cosmic archeology, GW spectral shapes and Leptogenesis

| Amplitude sensitivity | Amplitude + spectral shape sensitivity |
|---|---|

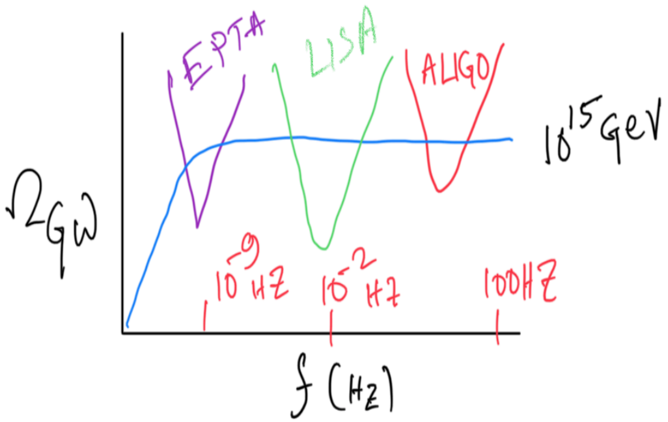
Standard Cosmology ($w=1/3$)

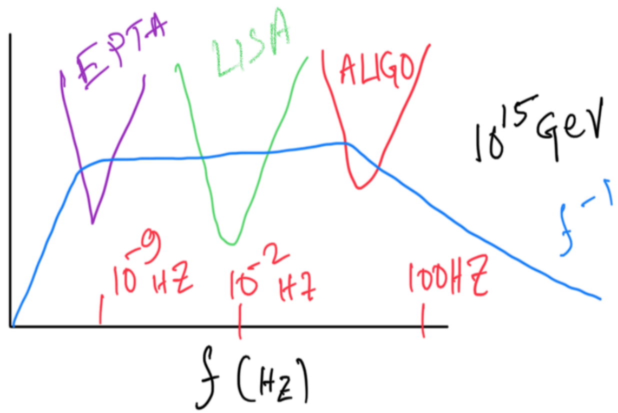
Early Matter domination ($w=0$)

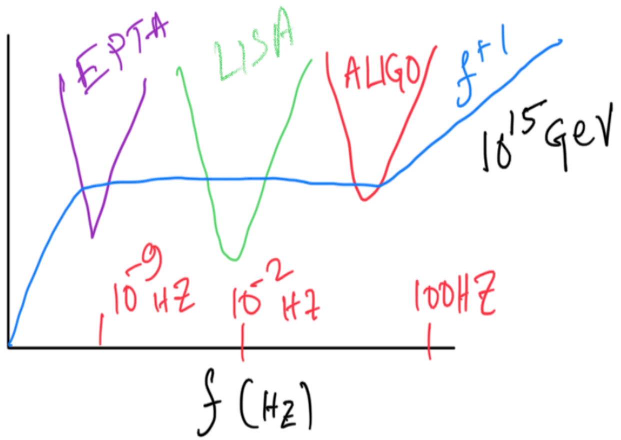
Kination ($w=1$)

A spectral break ($f_*, T_*$)

Fundamental mode ($k=1$):




Standard Leptogenesis

Murayama et al PRL(2020)

**Samanta** et al JHEP(2020)

Leptogenesis from Black holes

**Samanta** et al JCAP(2021)

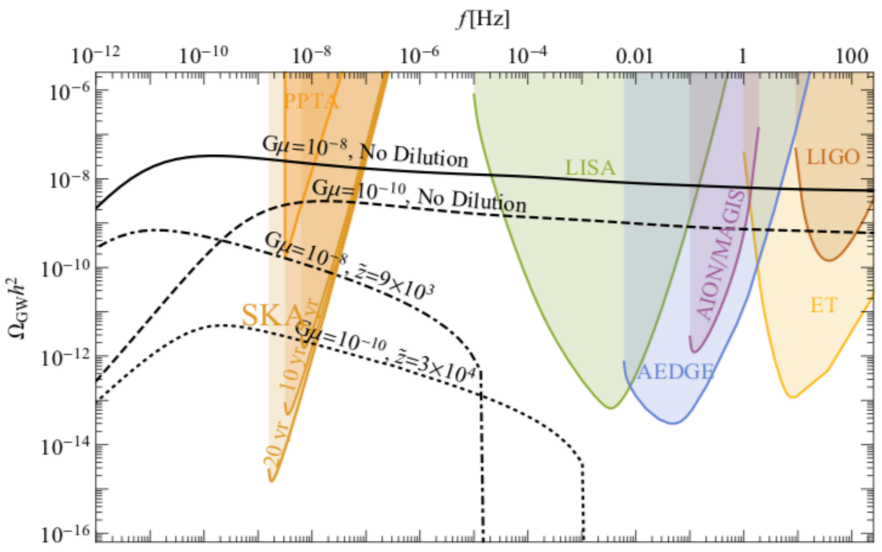
Gravitational Leptogenesis

**Samanta** et al 2108.08359 (2021)

# Some non-standard spectrums

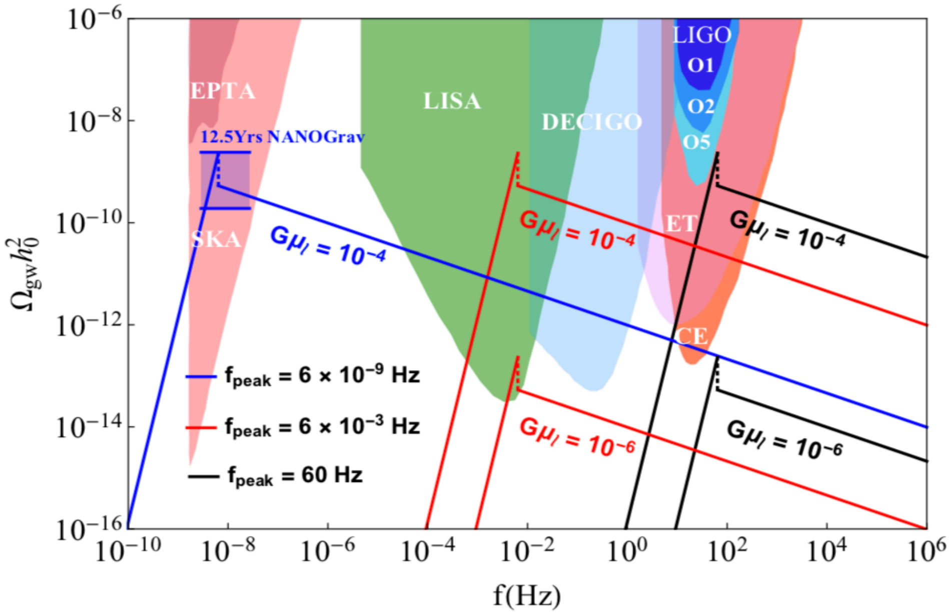
## Cosmic strings with inflation dilution

Cui, Lewicki, Morrissey, PRL, 2020




## Melting cosmic strings

Emond, Ramazanov, Samanta (2108.05377)



# Cosmic archeology, GW spectral shapes and Leptogenesis

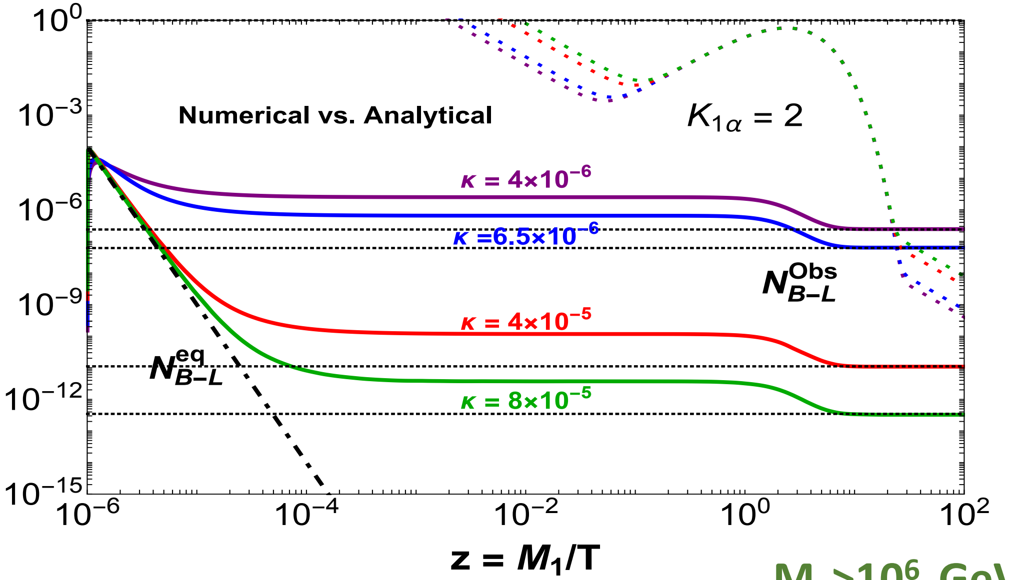
G. Shore et al, JHEP 10 025, (2020) **Samanta** et al JHEP 12 (2020) 67

W =1, $\Omega_{GW}$ (f>f$_*$)~ f$^{+1}$ : Gravitational Leptogenesis => $\partial_\mu R j^\mu / M^2$ generated in seesaw at 2-loops

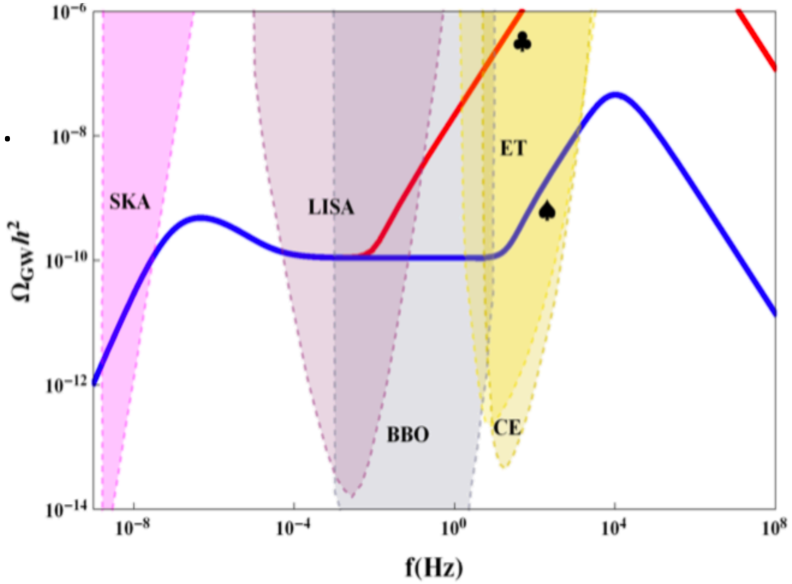
$$N_{B-L}^{eq} = \frac{\pi^2 \dot{R}}{36(4\pi)^4} \sum_{j>i} \frac{\text{Im}\left[k_{ij}^2\right]}{\zeta(3) T M_i M_j} \left(\frac{M_j^2}{M_i^2}\right) \ln\left(\frac{M_j^2}{M_i^2}\right),$$

$$\frac{dN_L}{dz} = -2 W_{\Delta L=2} \left(N_L - N_L^{eq}\right),$$

~ 1-3w ≈ 0

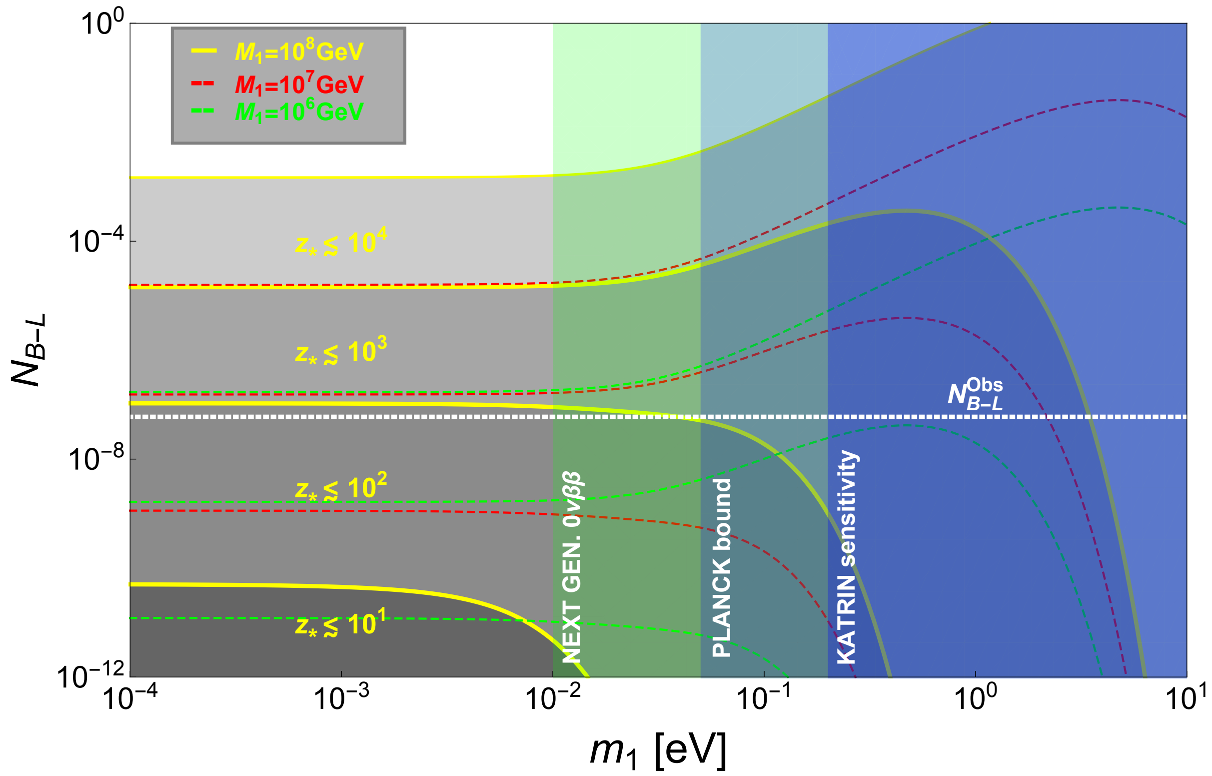


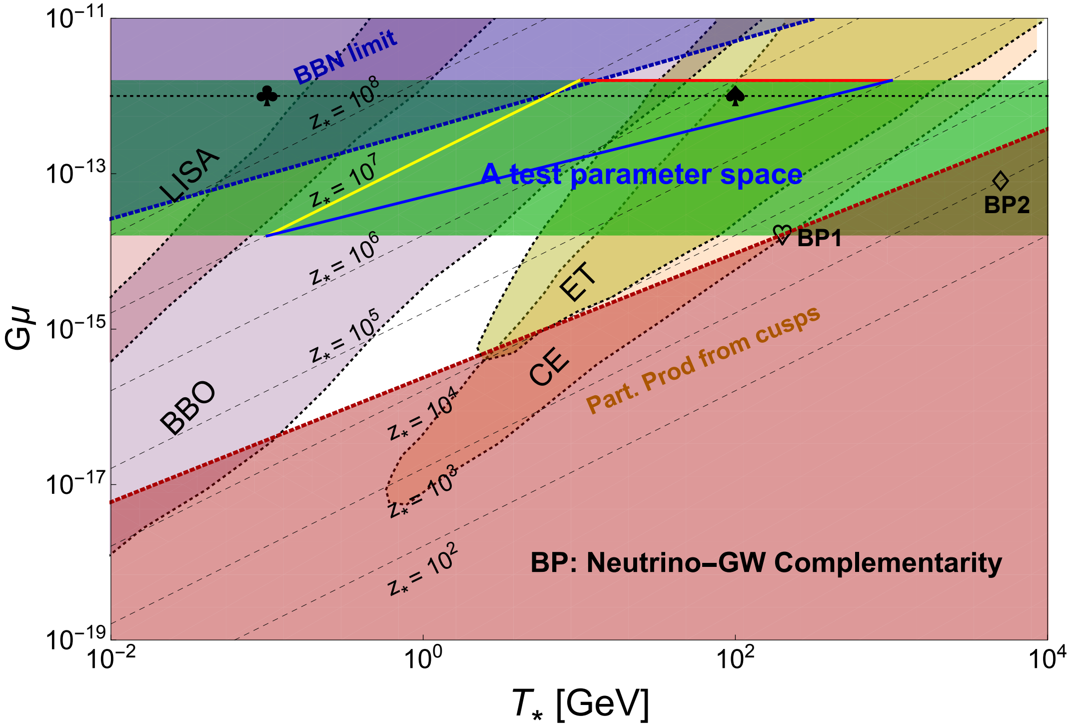

K. Saikawa and S. Shirai, JCAP 05, 035 (2018)




$M_1 > 10^6$ GeV even in 2RH neutrino seesaw model

# Neutrino-Gravitational waves complementarity




Large Yukawa coupling => test point is would be side ET

**Samanta** et al 2108.08359 (2021)

# w = 0, $\Omega_{GW}$ (f>f$_*$)~ $f^{-1}$ Baryogensis from ultra-light primordial black holes (Hawking radiation)

Inflation-> U(1) breaking -> black hole formation-> Heavy neutrino emission (HR)-> baryogenesis

Mass

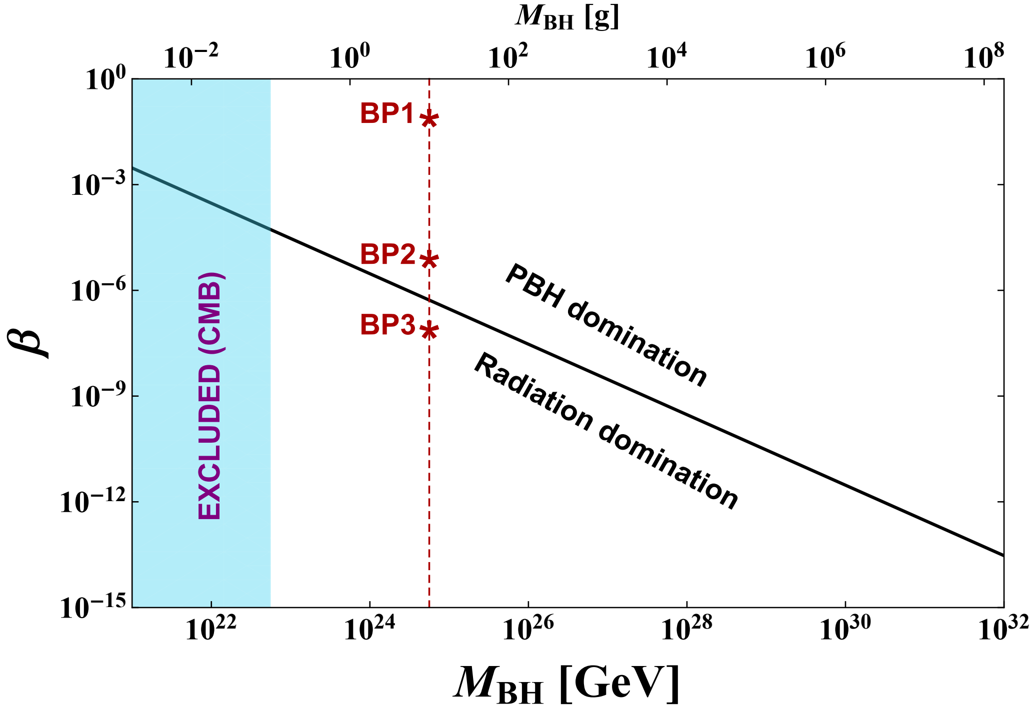
$$M_{BH} = \gamma \frac{4}{3}\pi (H_{Bf}^{-1})^3 \rho_{Bf} \text{ with } \rho_{Bf} = \frac{3H_{Bf}^2 M_{Pl}^2}{8\pi}, \quad H_{Bf} = \frac{1}{2t_{Bf}}.$$

Mass loss

$$\frac{dM_{BH}}{dt} = -\frac{\mathcal{G} g_{*B}(T_{BH})}{30720\pi}\frac{M_{Pl}^4}{M_{BH}^2},$$

Life-time

$$\tau = \int_{t_{Bf}}^{t_{ev}} dt = -\int_{M_{BH}}^{0} dM_{BH}\frac{30720\pi M_{BH}^2}{\mathcal{G} g_{*B}(T_{BH}) M_{Pl}^4} = \frac{10240\pi M_{BH}^3}{\mathcal{G} g_{*B}(T_{BH}) M_{Pl}^4}.$$




$$\beta < \gamma^{-1/2}\left(\frac{\mathcal{G} g_{*B}(T_{BH})}{10240\pi}\right)^{1/2}\frac{M_{Pl}}{M_{BH}}.$$

# w = 0, $\Omega_{GW}$ (f>f$_*$)~ f$^{-1}$ Baryogensis from ultra-light primordial black holes (Hawking radiation)

**Samanta** et al JCAP(2021)

Inflation=> U(1) breaking => black hole formation=> Heavy neutrino emission (HR)=> baryogenesis

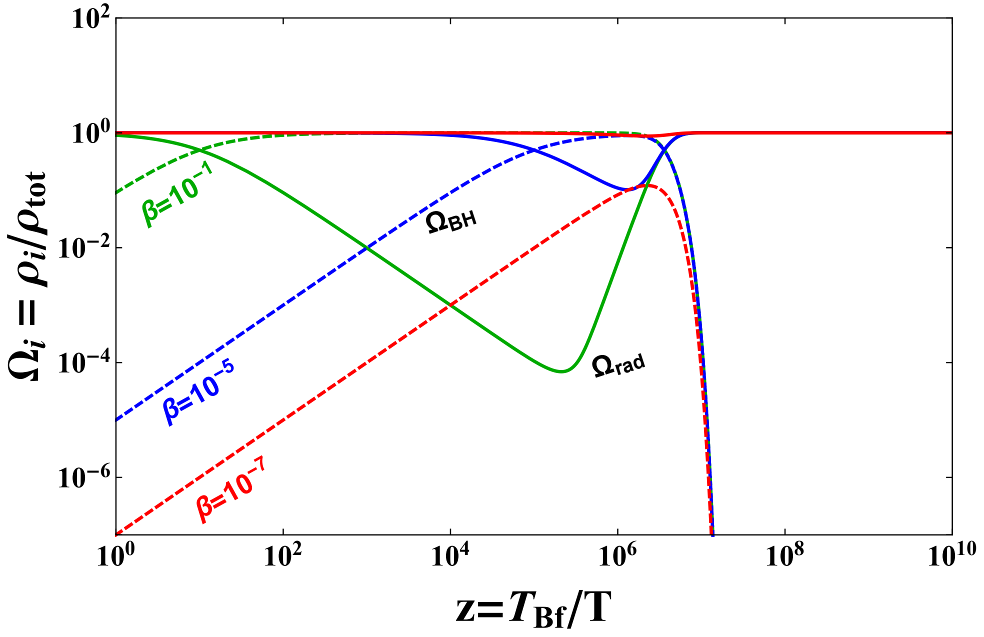
PBH Mass

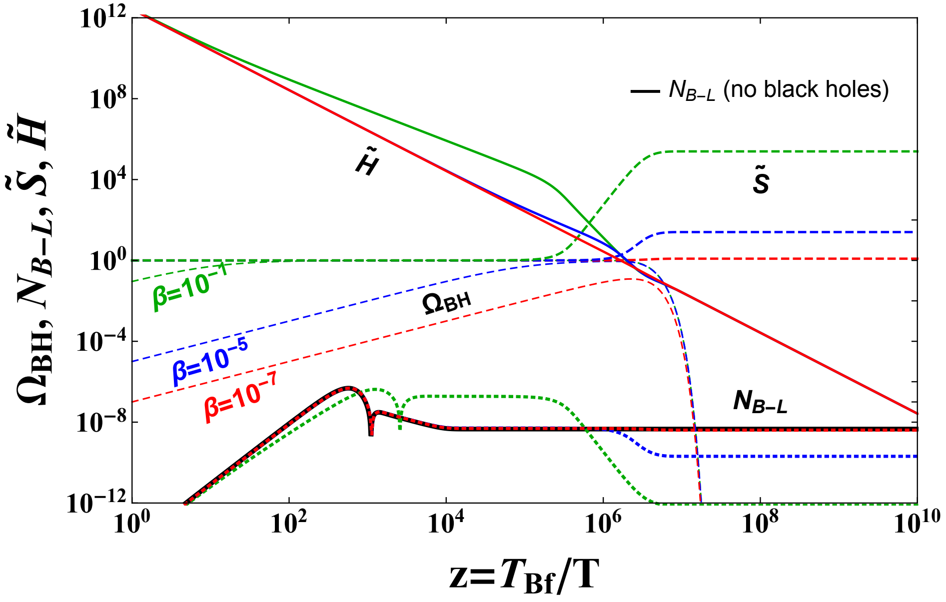
< 0.1 g (CMB)

Leptogenesis

>$10^8$ g (constrained by BBN)

>$10^{15}$ g (Dark matter)



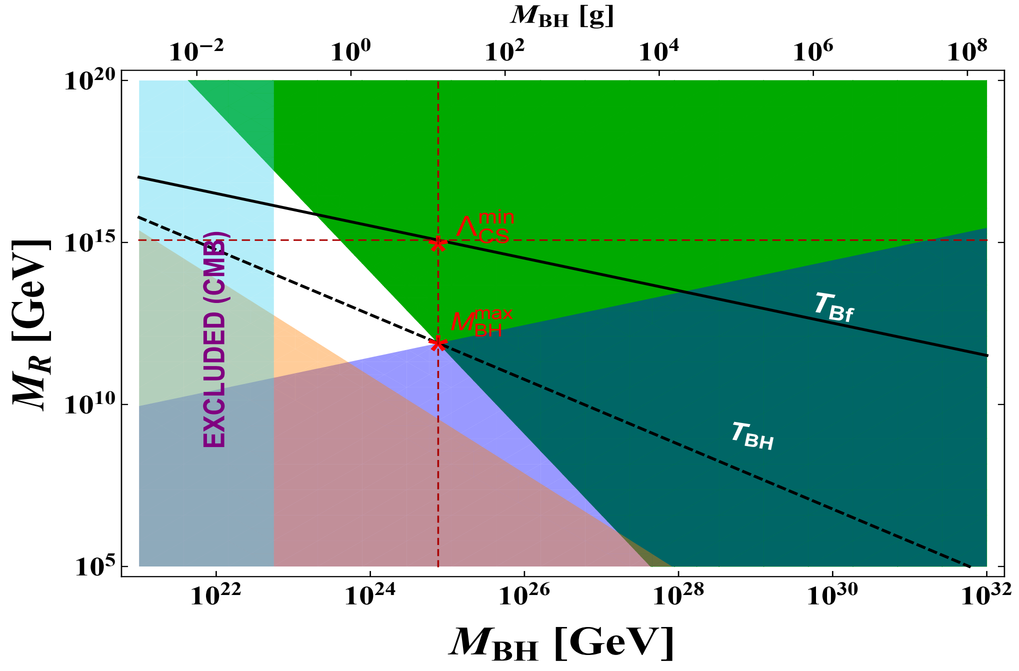



# Cosmic archeology, GW spectral shapes and Leptogenesis

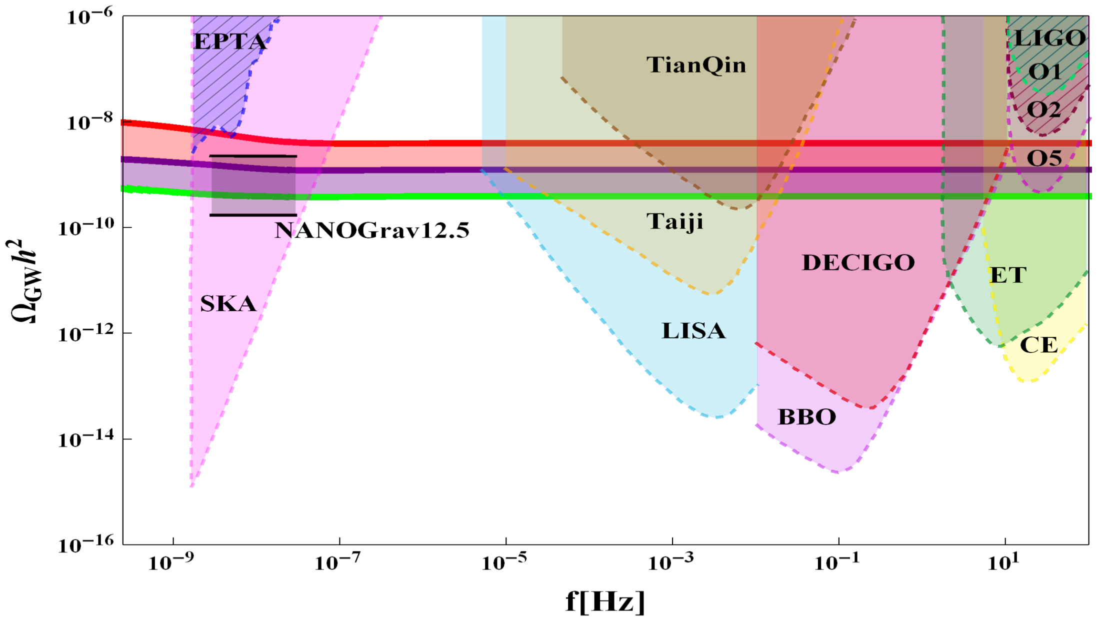
**Number of radiated particles:**

$$\frac{4\pi}{3}\frac{g_X}{g_{*B}}\left(\frac{M_{BH}}{M_{Pl}}\right)^2 \quad \text{for } T_{BH} > M_X, \qquad \frac{1}{48\pi}\frac{g_X}{g_{*B}}\left(\frac{M_{Pl}}{M_X}\right)^2 \quad \text{for } T_{BH} < M_X.$$

Only Ultra light PBHs ($M_{BH}$<13 g) can produce correct baryon asymmetry




Tension with NANOGrav data, with large loops



# Future improvement

We did not consider black hole-string network that could provide spectral distortion.
(**Samanta** et al)

We trying to accommodate **Black** hole generated **R**ight **H**and **N**eutrin**O** **(Black-RHi NOs)** super heavy dark matter in this framework that can be probed with a cosmic ray gravitational waves complementarity.
(**Samanta**, F. Urban et al)

# Summary

Gravitational Waves could be potential probe of High scale leptogenesis which otherwise cannot be probed e.g., in colliders.

Towards a clean probe, one may relate the spectral shapes of the GWs to leptogenesis.

I discussed to concrete models for two types of leptogenesis scenarios

Gravitational Leptogenesis (rising GW spectrum) Black hole leptogenesis (falling GW spectrum)