# Testing Seesaw with Gravitational Waves

*"Prospects of Neutrino Physics"*
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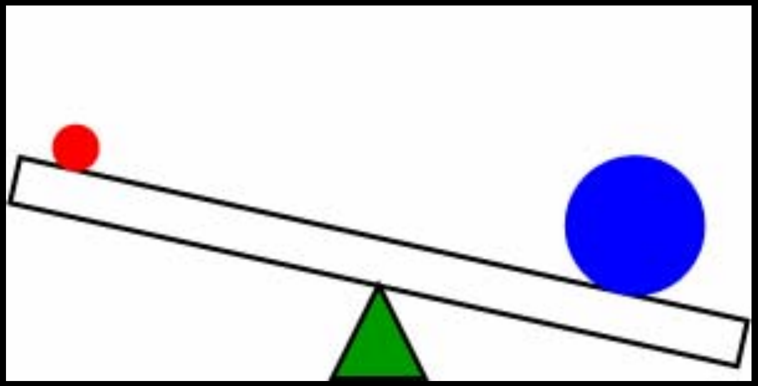
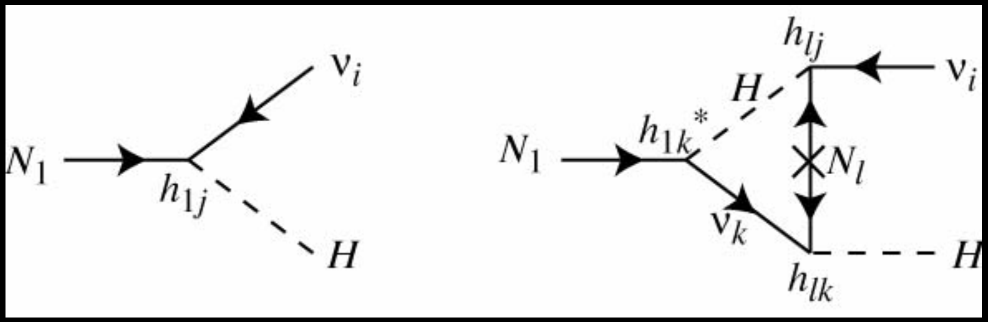
arXiv:1904.xxxxx

# Seesaw



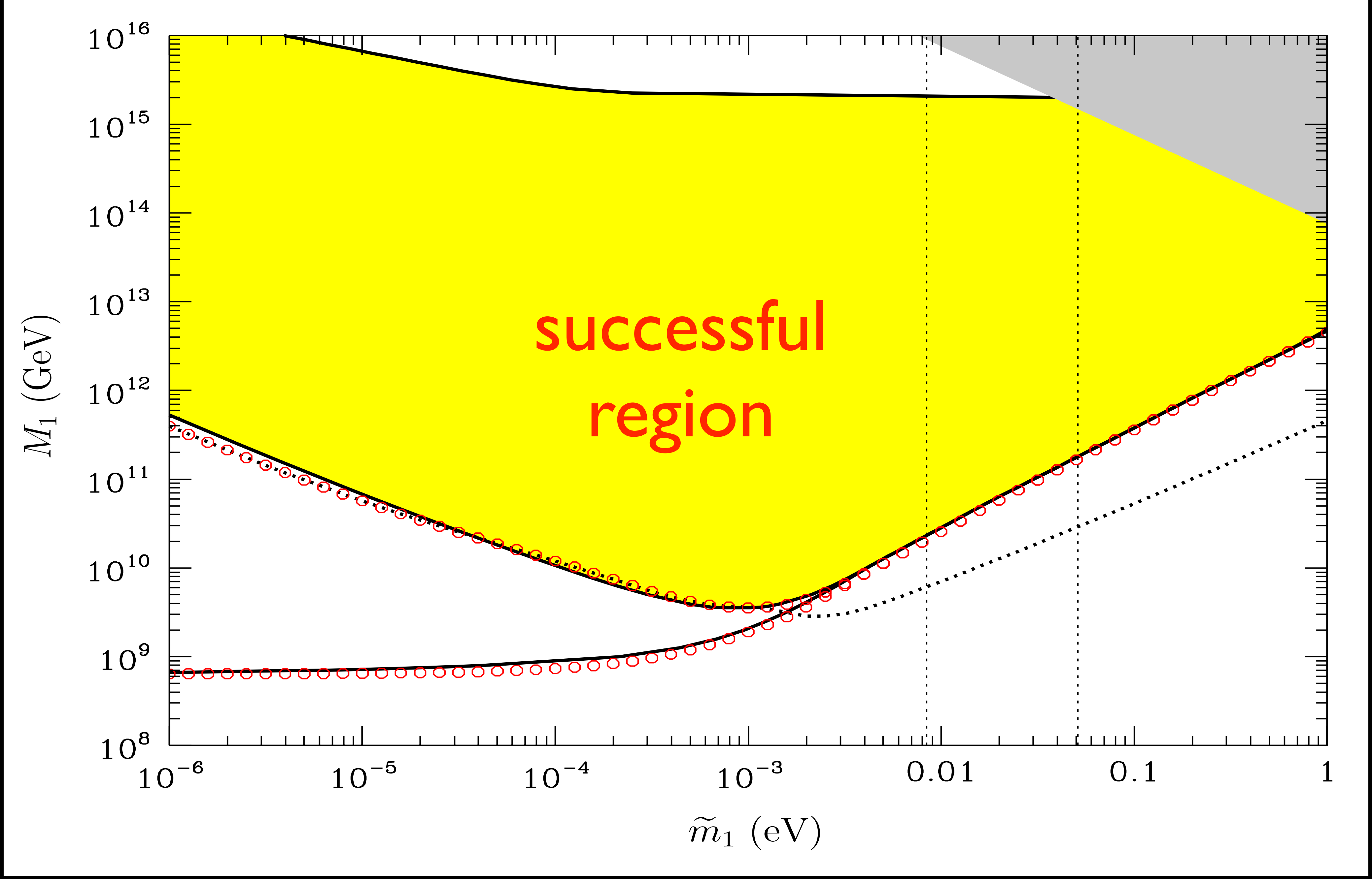
- Seesaw mechanism explains
  - small but finite neutrino masses $m_\nu \sim v^2 / M_R$
  - baryon asymmetry of the Universe through leptogenesis




$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H^*) \propto \Im m(h_{1j} h_{1k} h_{lk}^* h_{lj}^*)$$

- the dominant paradigm in neutrino physics
- probe to very high-energy scale
- notoriously difficult to test

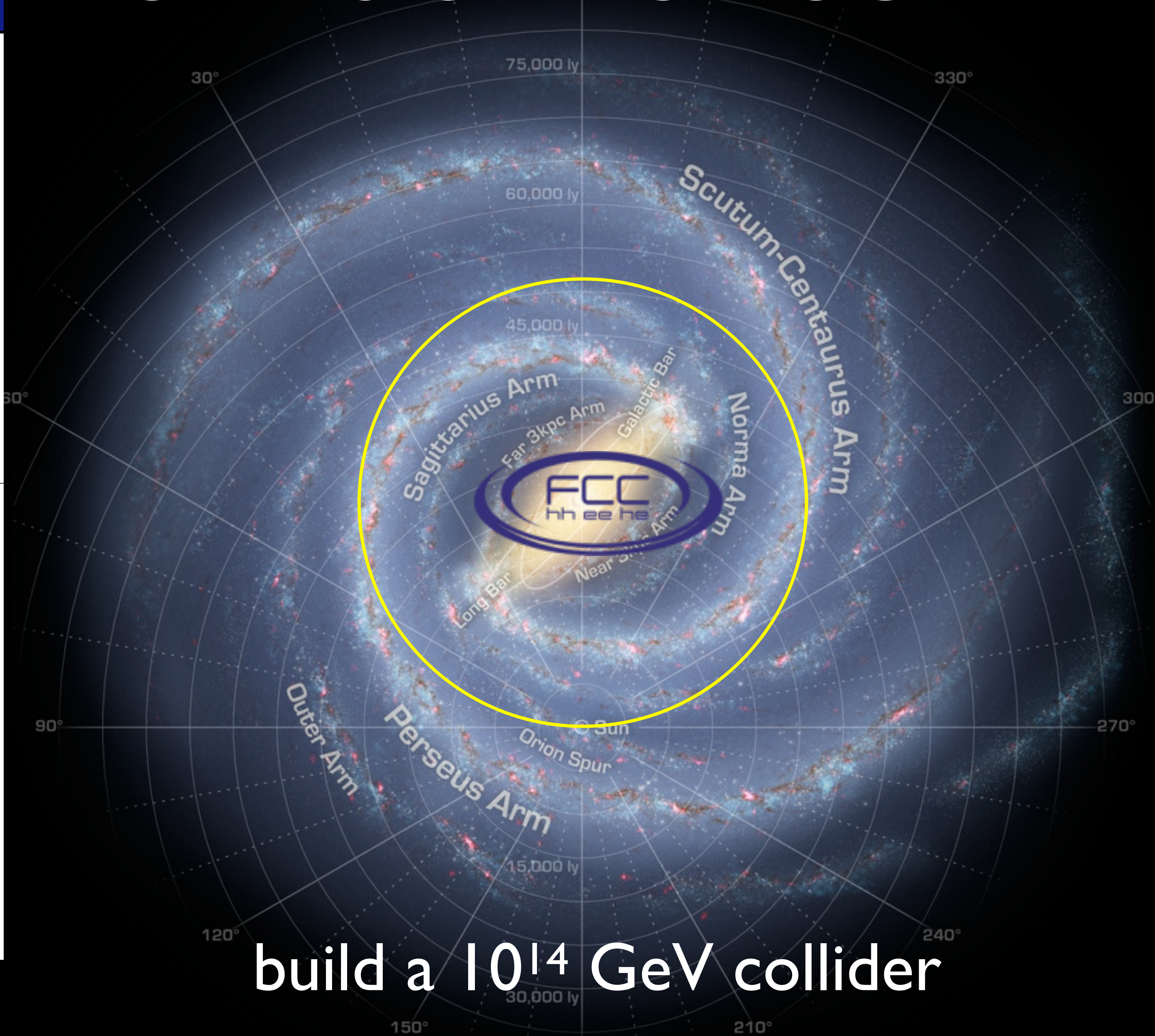
# Leptogenesis




$$\tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1}$$

di Bari, Plümacher, Buchmüller

# How do we test it?




build a $10^{14}$ GeV collider

# how do we test it?

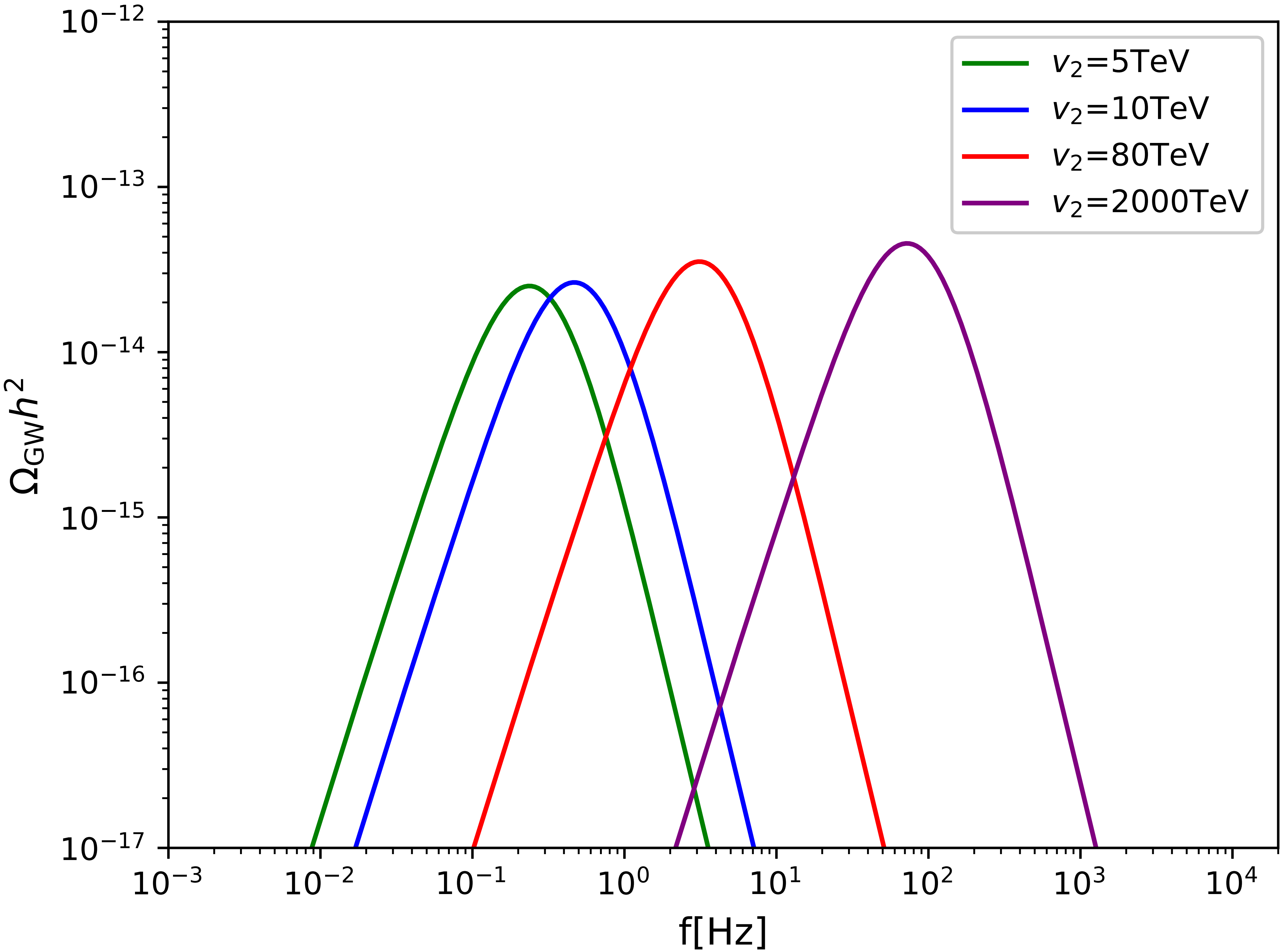
- possible three circumstantial evidences
  - $0\nu\beta\beta$
  - CP violation in neutrino oscillation
  - other impacts e.g. LFV (requires new particles/interactions < 100 TeV)
- *archeology*
- *any more circumstantial evidences?*

# energy scales

- to obtain the correct mass scale of light neutrinos, need $M_R < 10^{14}$ GeV
- to obtain the correct baryon asymmetry via leptogenesis, need $M_R > 10^9$ GeV
- natural that $M_R \gg v_{EW} = 250$GeV because $M_R$ is allowed by SU(2)×U(1)
- but $M_R \ll M_{Pl}$
- Presumably some protection due to a new symmetry
  - e.g., $U(1)_{B-L}$ *s.t.* $<\phi>v_R v_R$ or $<\phi^2>v_R v_R/M_{Pl}$
- implies a phase transition at a high temperature
- any signatures?
- gravitational wave!

# 1st order Phase Transition

Taiki Hasegawa, Nobuchika Okada, Osamu Seto, arXiv:1904.03020

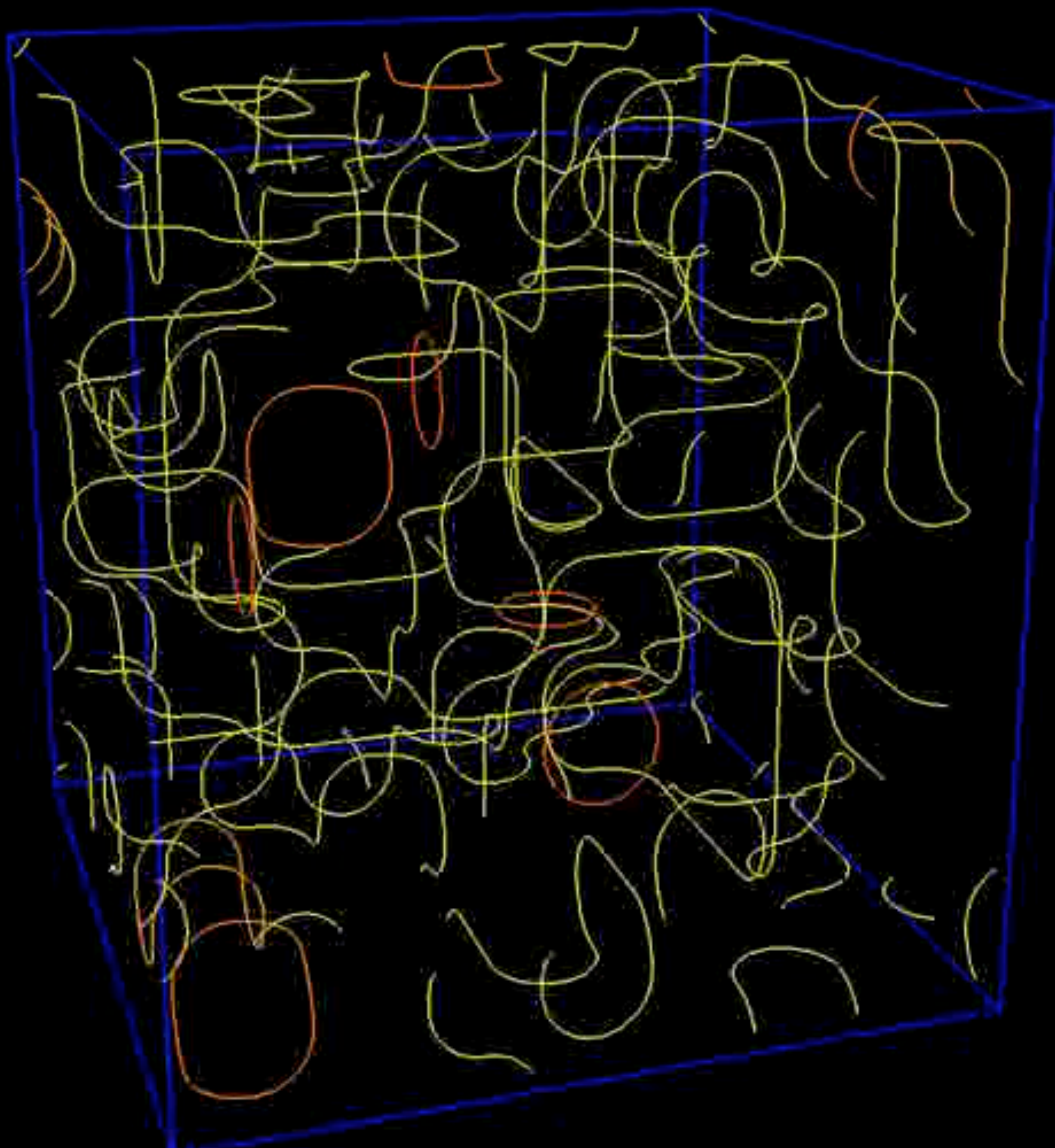


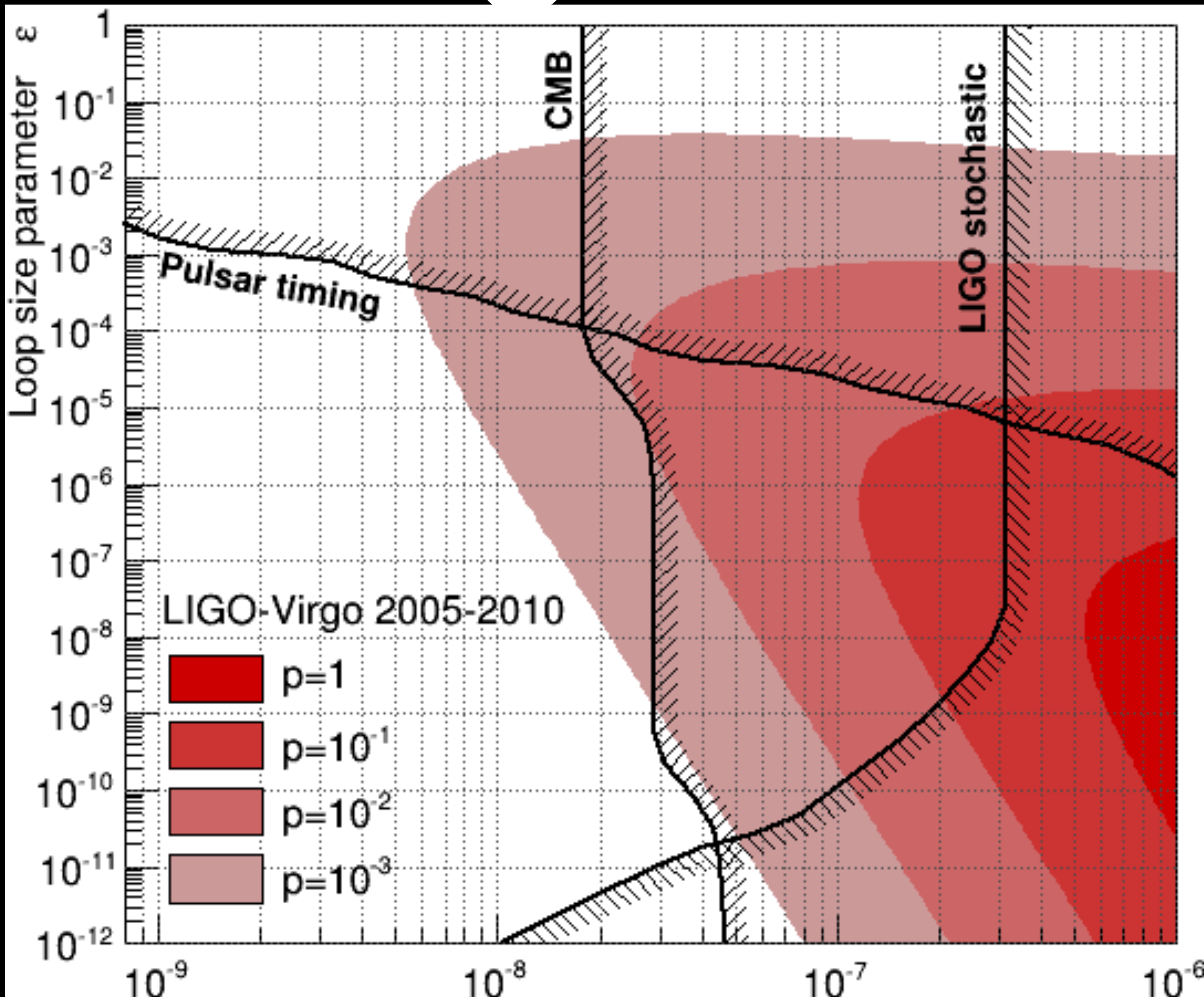
# $U(1)_{B-L}$

- Consider $\langle\phi\rangle\neq 0$
  - $M_R$ from $\langle\phi\rangle v_R v_R$ or $\langle\phi^2\rangle v_R v_R/M_{Pl}$
- U(1) breaking produces cosmic strings because $\pi_1(U(1))=Z$
- nearly scale invariant spectrum
- simplification of the network produces gravitational waves
- stochastic gravitational wave background

https://www.ligo.org/science/Publication-S5S6CosmicStrings/index.php

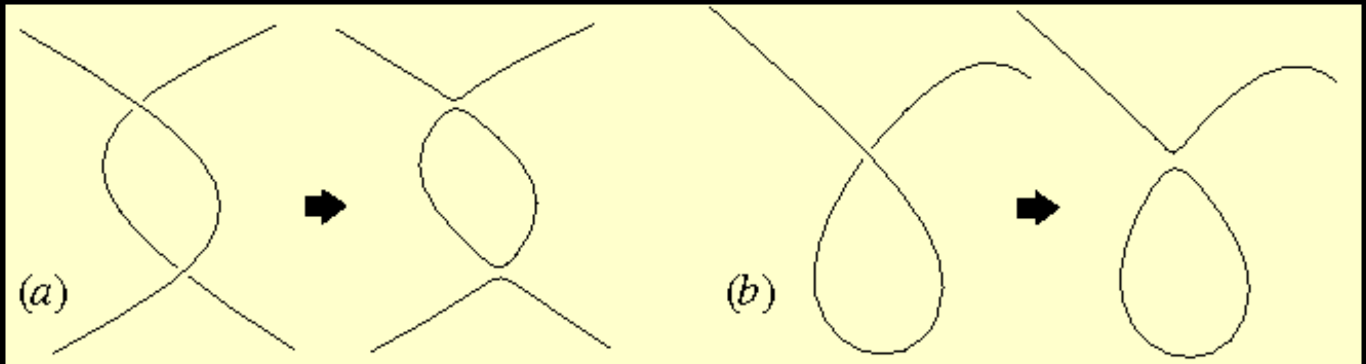
# cosmic strings



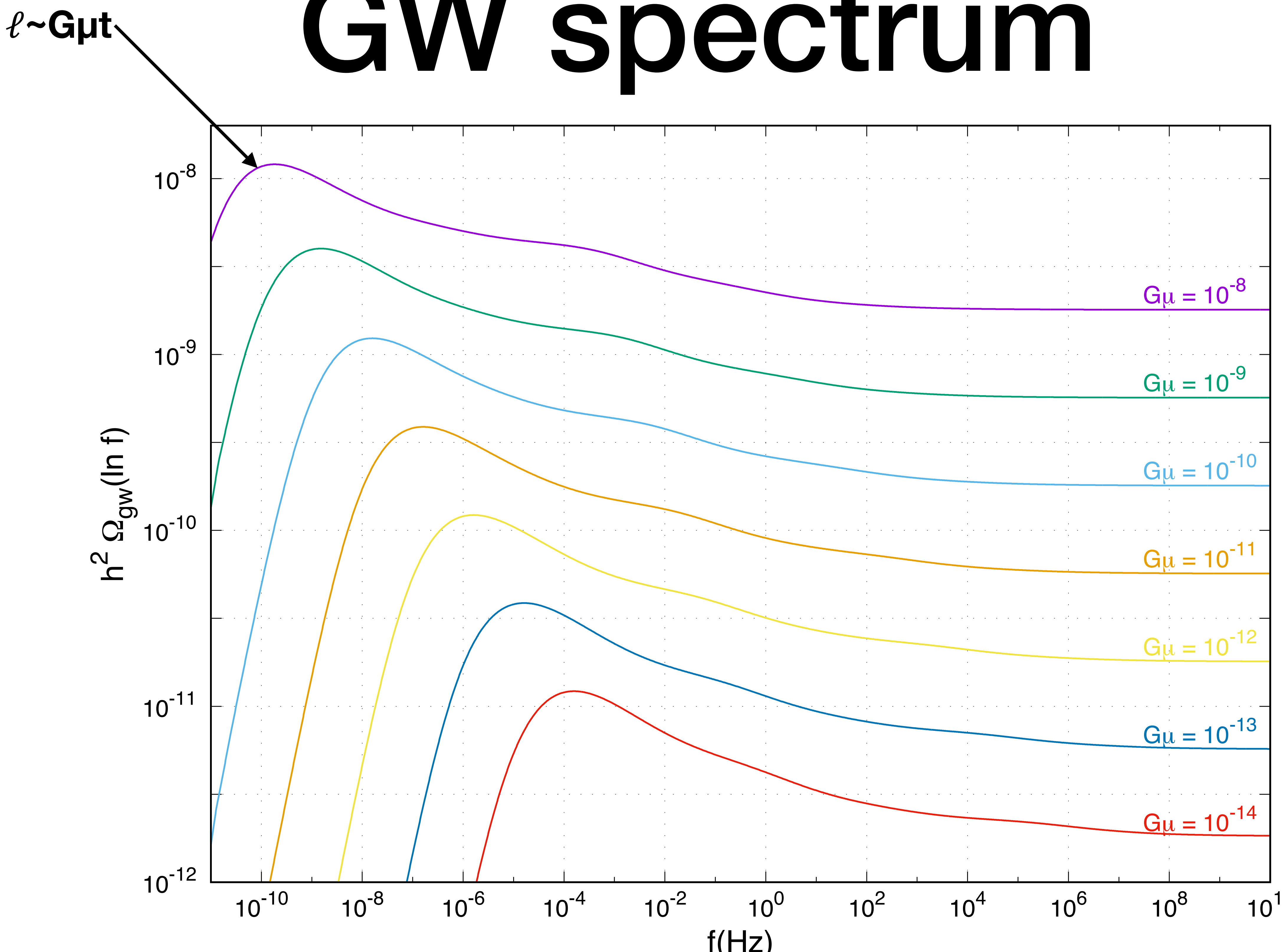



v~$10^{15}$GeV

$G\mu \sim v^2/M_{Pl}^2$

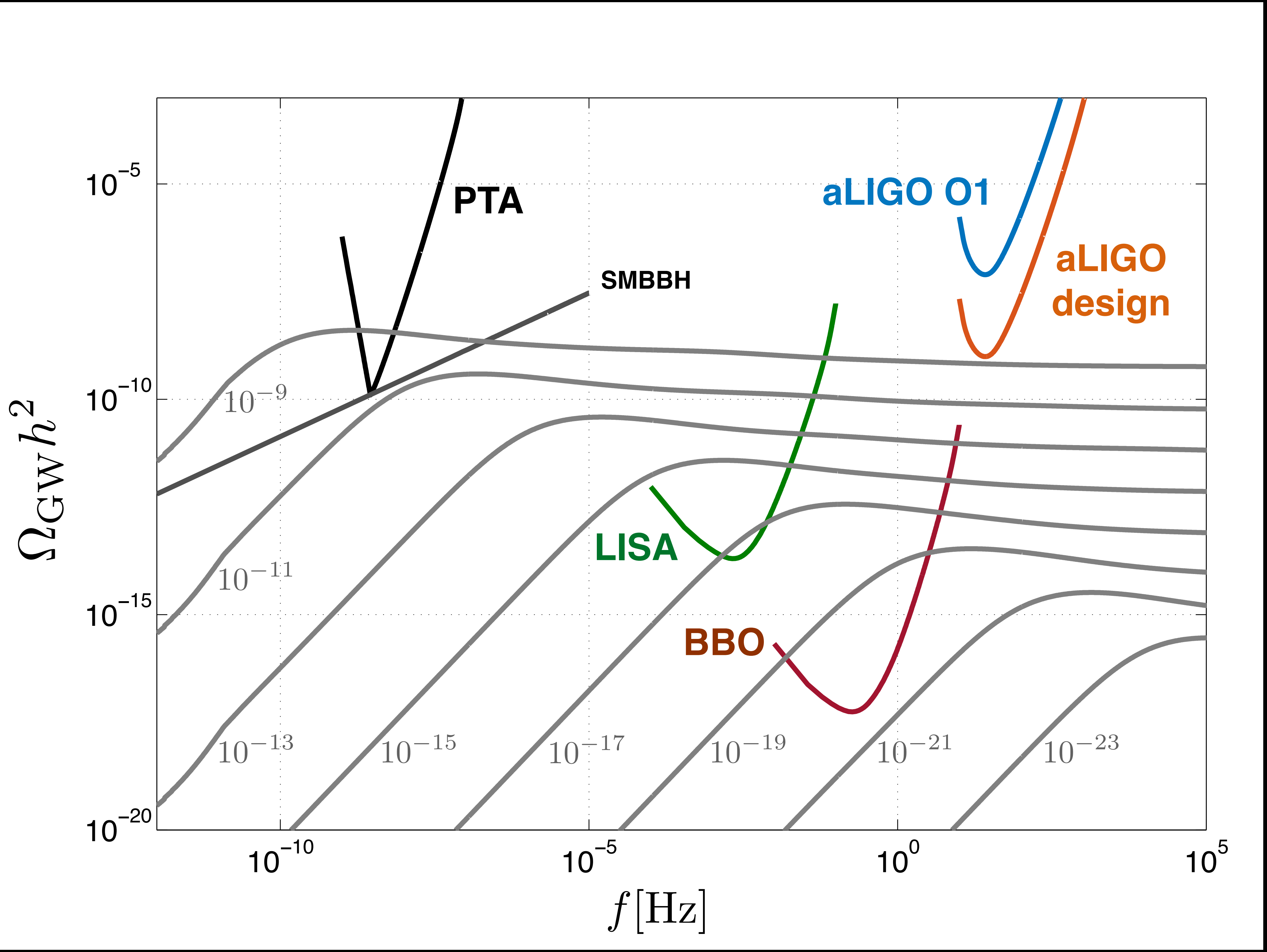


# GW spectrum




Jose J. Blanco-Pillado, Ken D. Olum arXiv:1709.02693

FIG. 6. The stochastic gravitational wave spectrum for string tensions between $G\mu = 10^{-8}$ and $10^{-14}$.




**Future experiments DECIGO/BBO can probe $G\mu \sim 10^{-20}$**

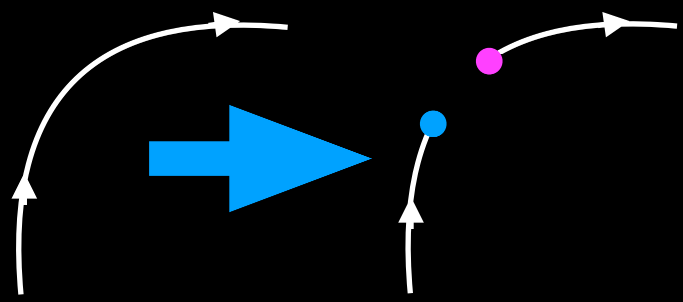
**$v \sim \mu^{1/2} \sim (10^{-20})^{1/2}\, M_{Pl} \sim 10^9$ GeV**

**can probe the whole seesaw/leptogenesis range!**

Jose J. Blanco-Pillado, Ken D. Olum, Xavier Siemens arXiv:1709.02434

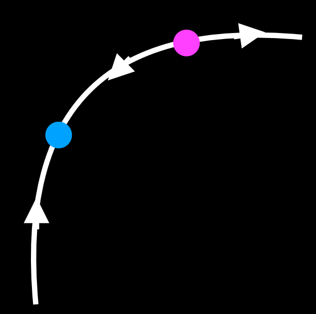
# SO(10)

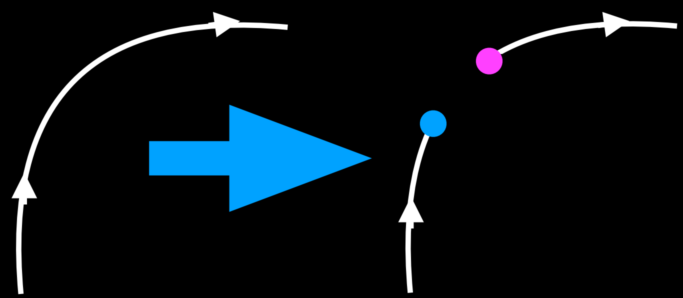
- It is natural to embed $U(1)_{B-L}$ into SO(10)
  - usual gauge coupling unification in SUSY-GUT preserved
- However, SO(10)→SU(3)×SU(2)×U(1) doesn't lead to cosmic strings because $\pi_1(SO(10)/SU(3)\times SU(2)\times U(1))=0$
- SO(10)→SU(3)×SU(2)×U(1)×$U(1)_{B-L}$ produces monopoles
  - SO(10) scale is presumably $V\sim 10^{16}$GeV≫v
  - need inflation below this scale
- SU(3)×SU(2)×U(1)×$U(1)_{B-L}$→SU(3)×SU(2)×U(1) produces strings
  - strings can be *cut* by monopole-anti-monopole pairs through a tunneling process
- If $U(1)_{B-L}$ broken by $\langle\phi(\pm 2)\rangle\neq 0$ (*e.g.* 126), $Z_2$ unbroken
  - $Z_2$ string is stable and discussions not modified
  - obtain *R*-parity for free
- If $U(1)_{B-L}$ broken by $\langle\phi(\pm 1)\rangle\neq 0$ (*e.g.* 16), no stable strings
  - need to estimate probability of monopole pair production



# monopoles

- string from $U(1)_{B-L}$ breaking is basically Abrikosov flux in a superconductor
  - For the Higgs $\phi(\pm Q)$
  - magnetic flux $h/(g\,Q) \times$ integer ($Q$=1, 2, …)
  - minimum monopole charge $h/g$
  - If $Q$=1, monopole can saturate the flux and cut the string
  - If $Q$=2, the minimum string cannot be cut by monopoles





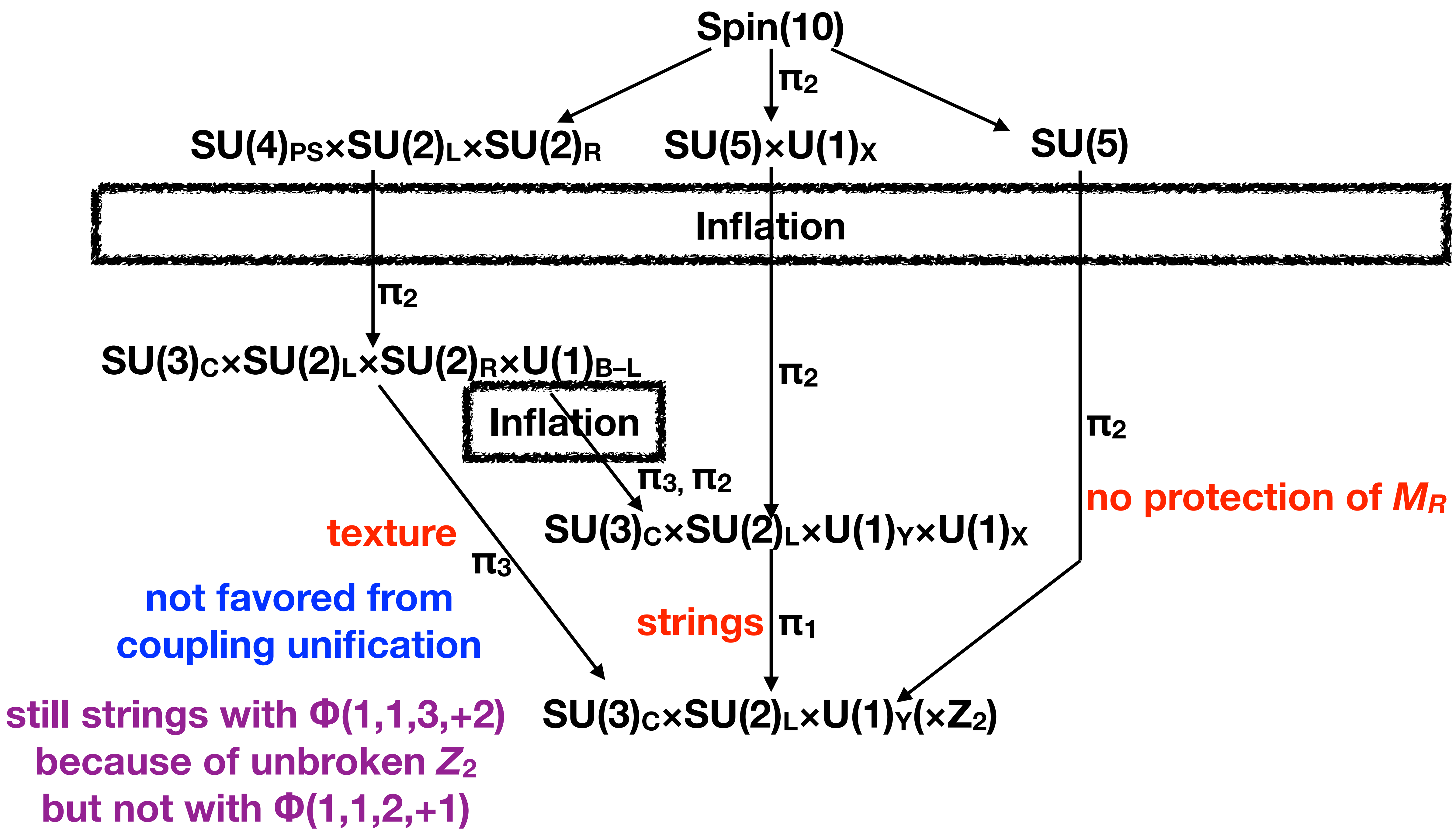
# Schwinger

- Schwinger computed the production of $e^+e^-$ pairs in a constant electric field in 3+1 dimension
- adopt it to 1+1 dimension
- dualize it to magnetic field

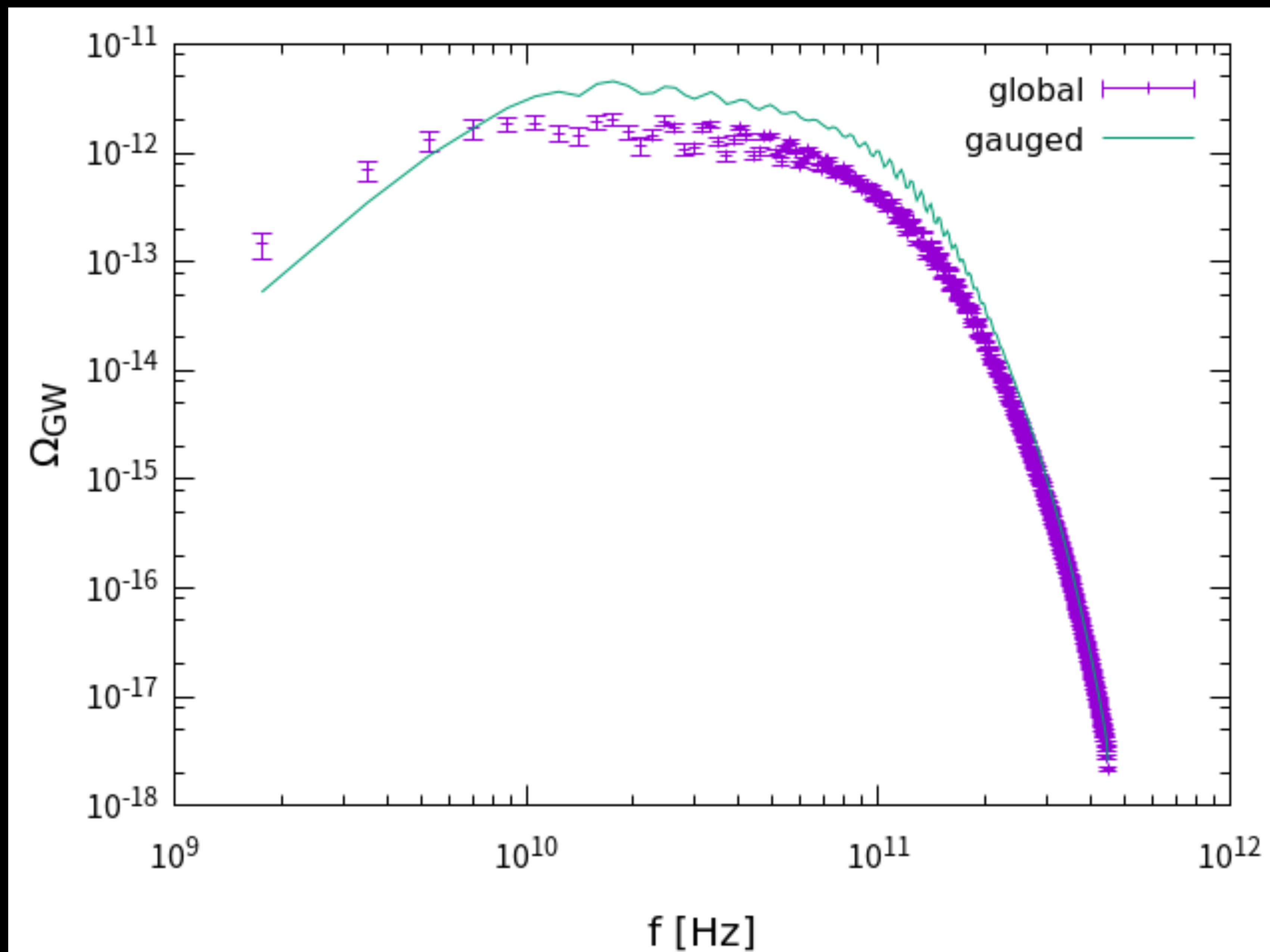
$$\frac{\Gamma}{L} = \frac{eE}{4\pi^2}\sum_{n=1}^{\infty}\frac{1}{n}e^{-\pi m^2 n/eE}$$

- cross section of the string $A \sim (g\,v)^{-2}$
- $B\,A \sim 2\pi/(g\,Q)$
- length of the string $L \sim H^{-1}$
- strings get cut when $H \sim \Gamma/L \times L \sim \Gamma/L \times H^{-1}$
- string network persists until $H^2 \sim (\Gamma/L) \sim (g\,v)^2 \exp(-\pi m^2/gB)$
- monopole mass $m \sim V/g$
- survives to date if $v < 10^{15}$GeV

# Other Breaking patterns?



# texture




Takashi Hiramatsu

**can be probed only when v>$10^{15}$ GeV**

# Conclusions

- stochastic gravitational waves as another possible circumstantial evidence for seesaw+leptogenesis
- for simple $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$, future missions promising to cover most range of seesaw scales
- for $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, texture produces gravitational waves but small and only high frequencies
  - could still have strings with $Z_2$
- if we do detect gravitational waves, helps establish not only seesaw but also the breaking pattern
- *any experimental technique to probe gravitational waves of much higher frequencies?*