Berkeley Week @ IPMU

- bring people from Berkeley to IPMU to mingle scientifically, socially, culturally
- 1 faculty: HM
- 3 postdocs: Hajime Fukuda, Ofri Telem, Kevin Zhang
- 5 students: David Dunsky, Eleanor Hall, Jacob Leedom, Robert McGehee, Liz Wildenhain

University of Tokyo

- Faculty: Masahiro Ibe, Koichi Hamaguchi, Takaaki Kajita, Simeon Hellerman
- Postdocs: Neil Barrie, Tobias Binder, Ipsita Saha, Ippei Obata, Kohei Hayashi, Yevgeny Stadnik
- Students: Daiki Ueda, Eisuke Sonomoto, Hiromasa Nakatsuka, Kaisei Watanabe, Keisuke Yanagi, Kenta Ando, Shih-Yen Tseng, Shin Kobayashi, Shunichi Horigome, So Chigusa, Taichi Ago, Taisuke Katayose
- special talks:
  - *How research may not go as planned*: Takaaki Kajita
  - *How to apply to postdoc positions* Robert McGehee
  - *Life in Japan*: Shih-Yen Tseng, Domenico Orlando+Susanne Reffert
  - *How to succeed outside Japan*: HM

Faculty Guests

- Domenico Orlando (large-Q field theory)
- Susanne Reffert (large-Q field theory)
- Chiaki Kobayashi (chemical evolution)
- Melina Bersten (supernova theory)

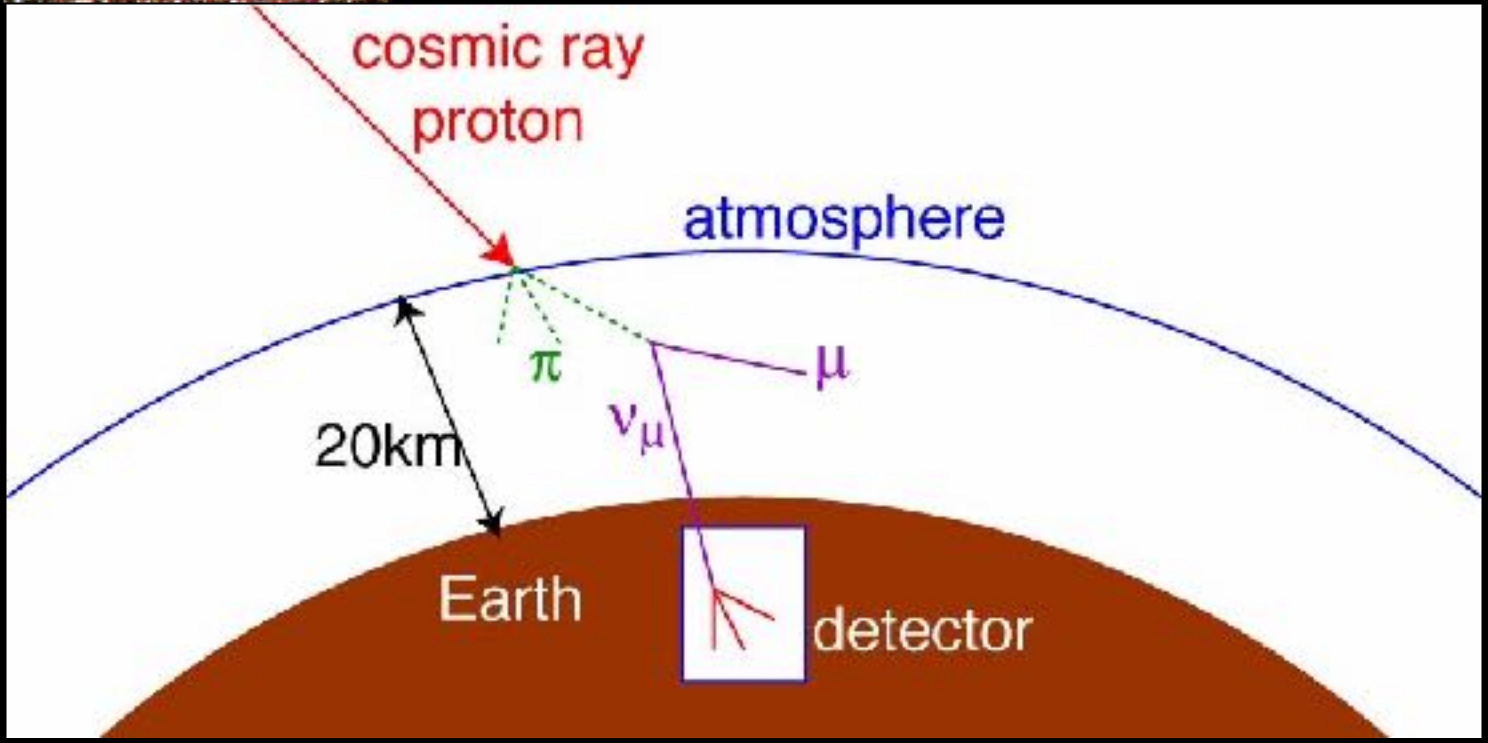
Enjoy

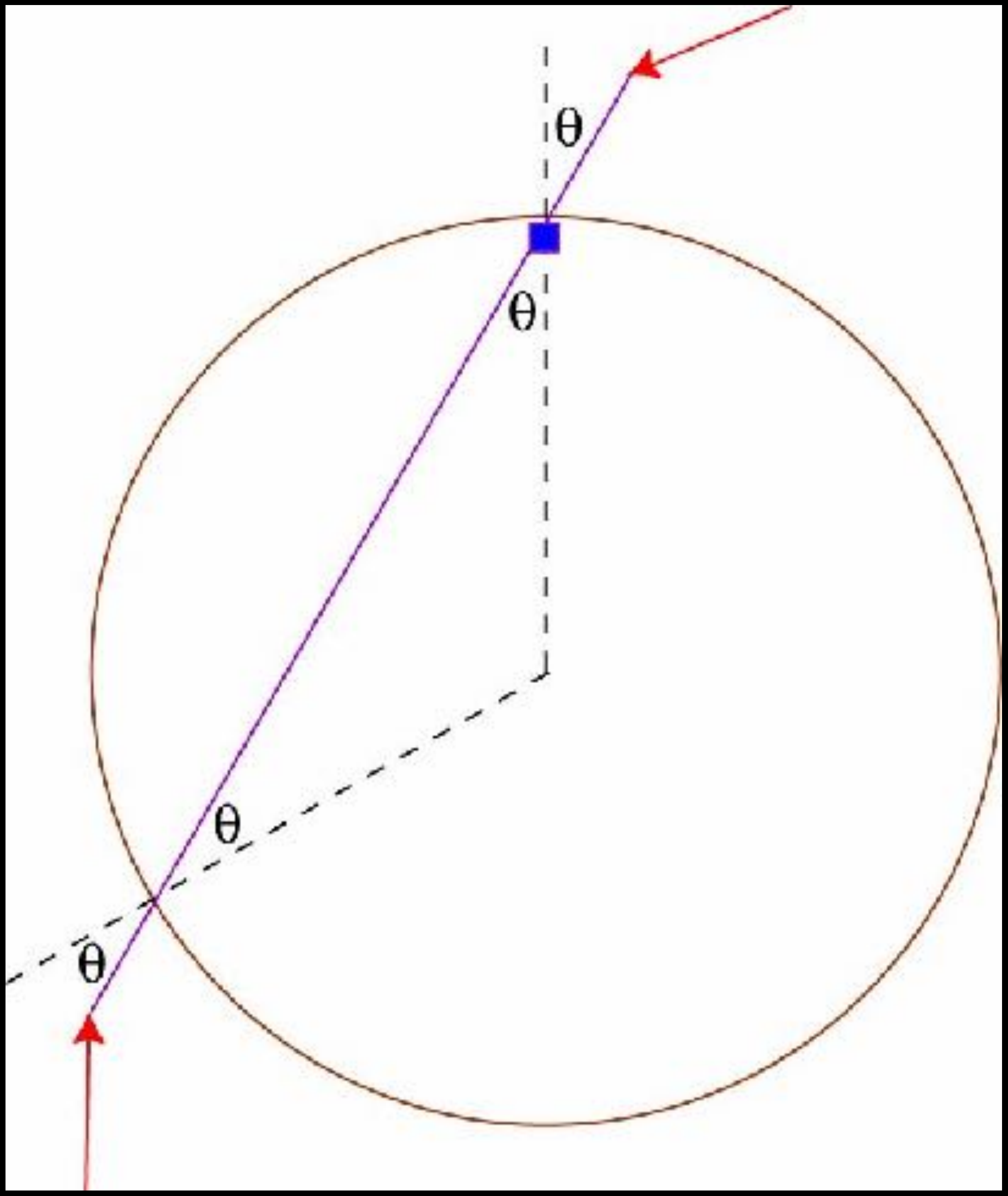
- interact
- ask questions
- discuss
- exchange ideas
- mix cultures

Testing seesaw and leptogenesis by gravitational wave

Hitoshi Murayama (Berkeley, Kavli IPMU)
Berkeley Week, Kavli IPMU, Jan 14, 2020
+Jeff Dror (Berkeley), Takashi Hiramatsu (ICRR), Kazunori Kohri (KEK), Graham White (TRIUMF)
arXiv:1908.03227, accepted for PRL

Atmospheric Neutrinos

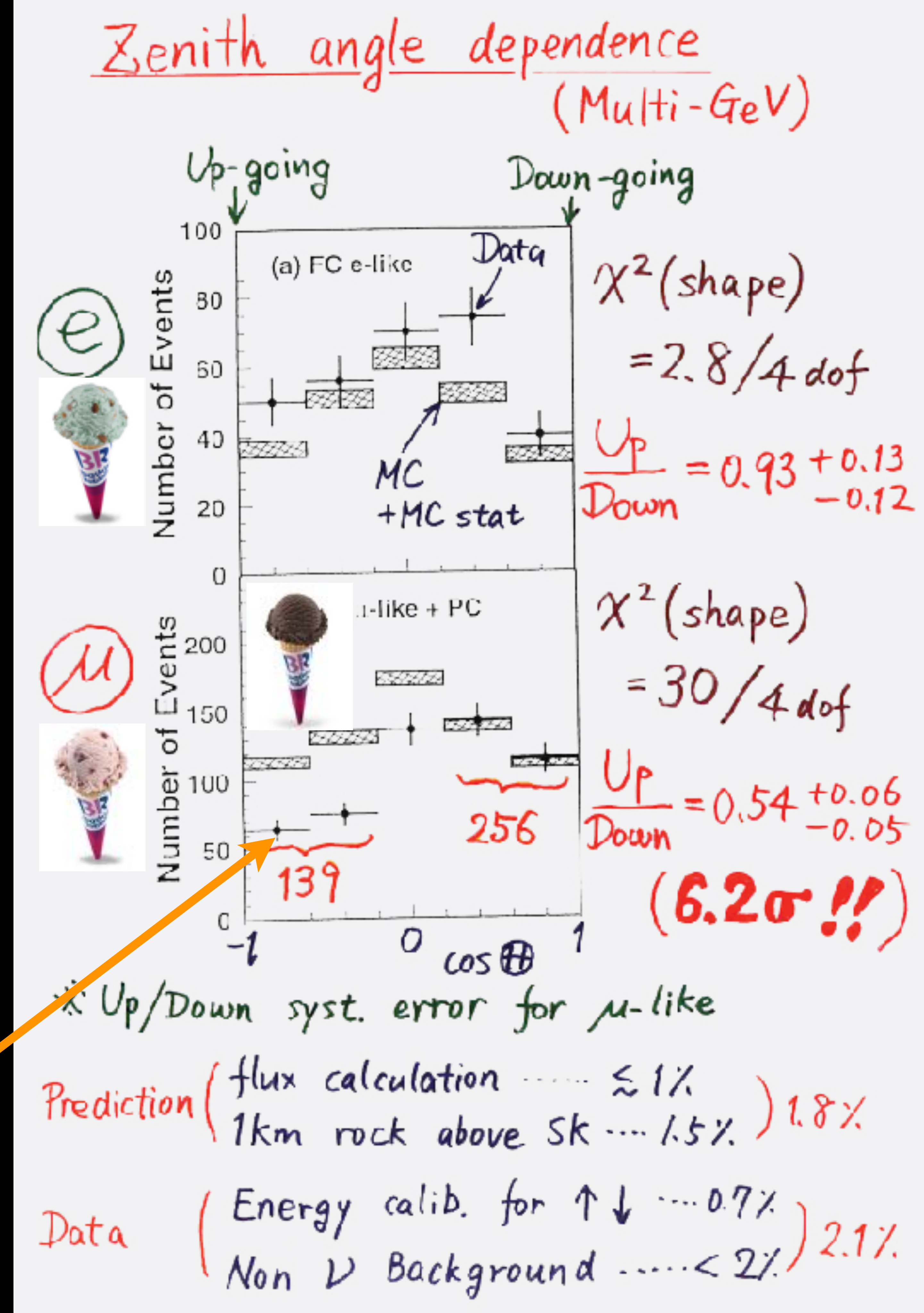




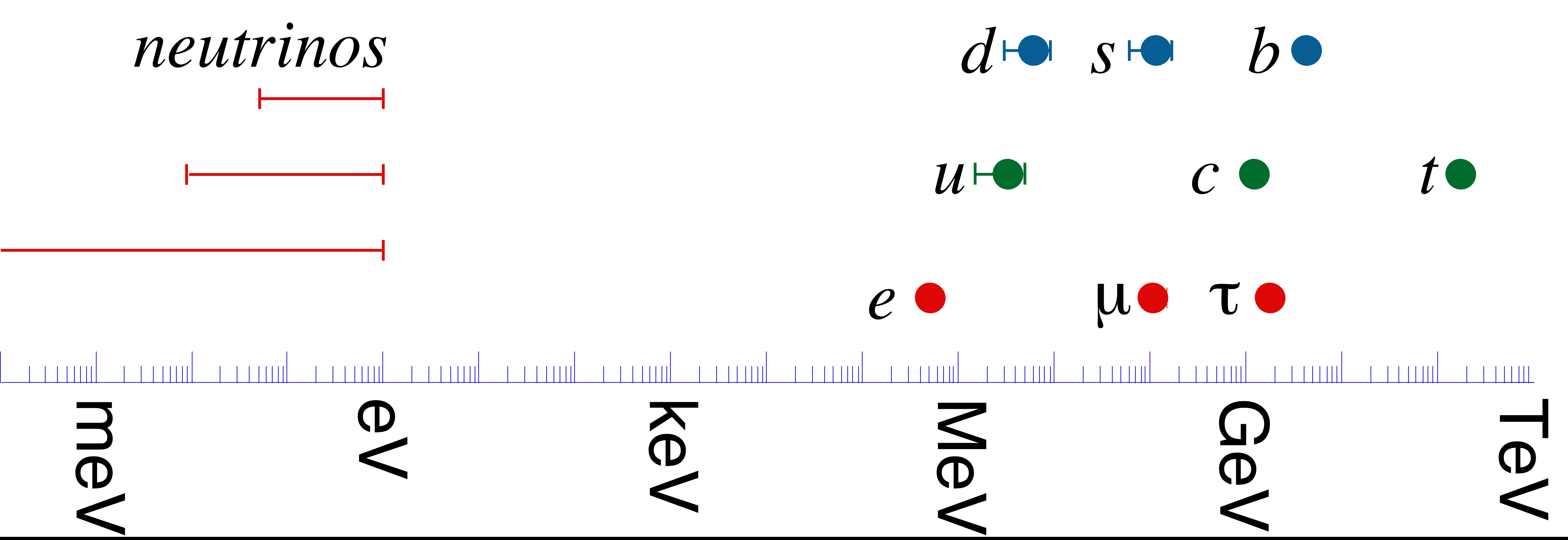
neutrinos morph

1998

a half of expected



very light



Beginning of Universe

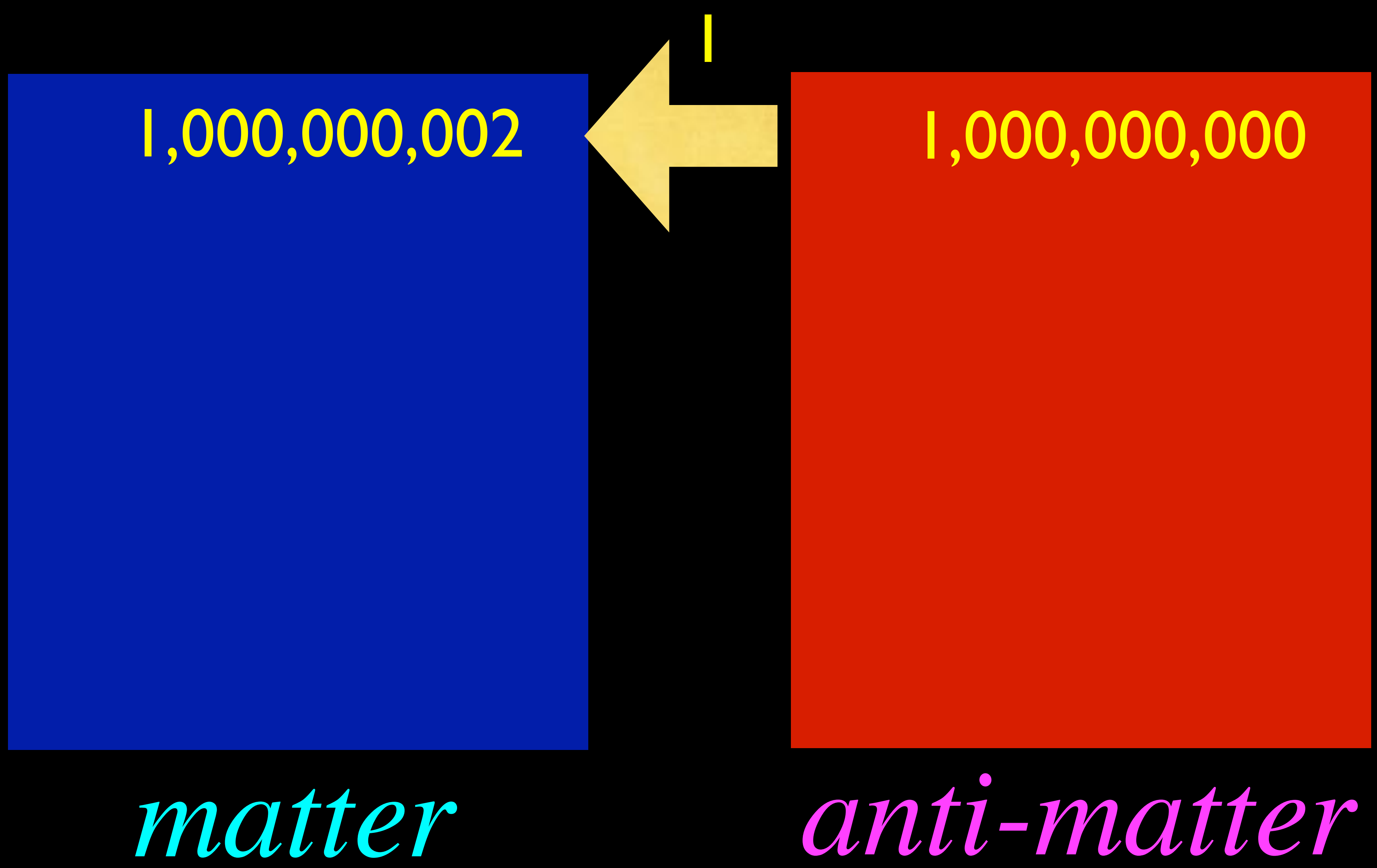
1,000,000,001

matter

1,000,000,001

anti-matter

fraction of second later



turned a billionth of anti-matter to matter

Universe Now

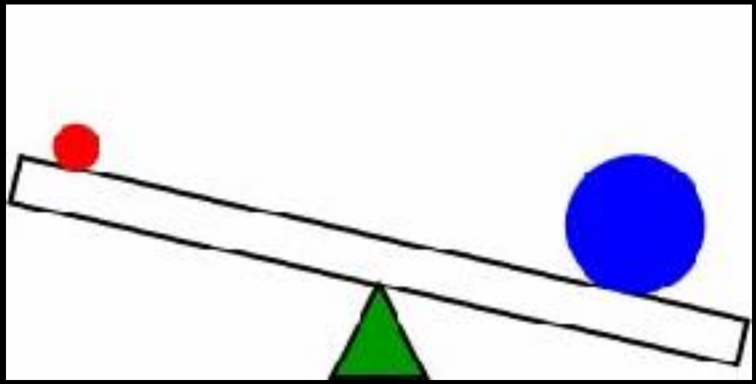
2

us

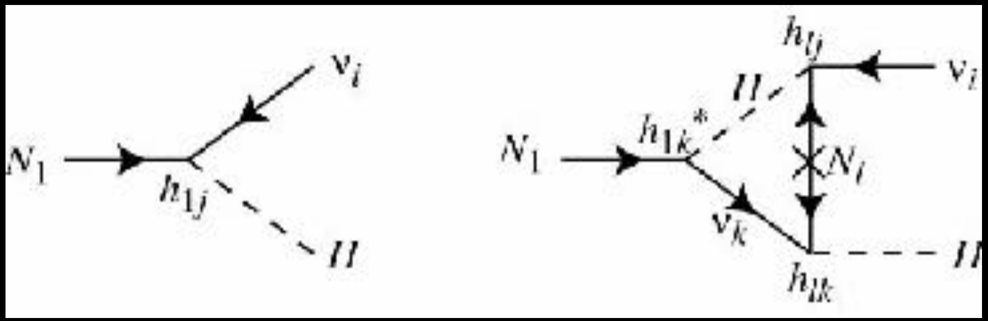
matter *anti-matter*

we were saved from the complete annihilation!

Seesaw



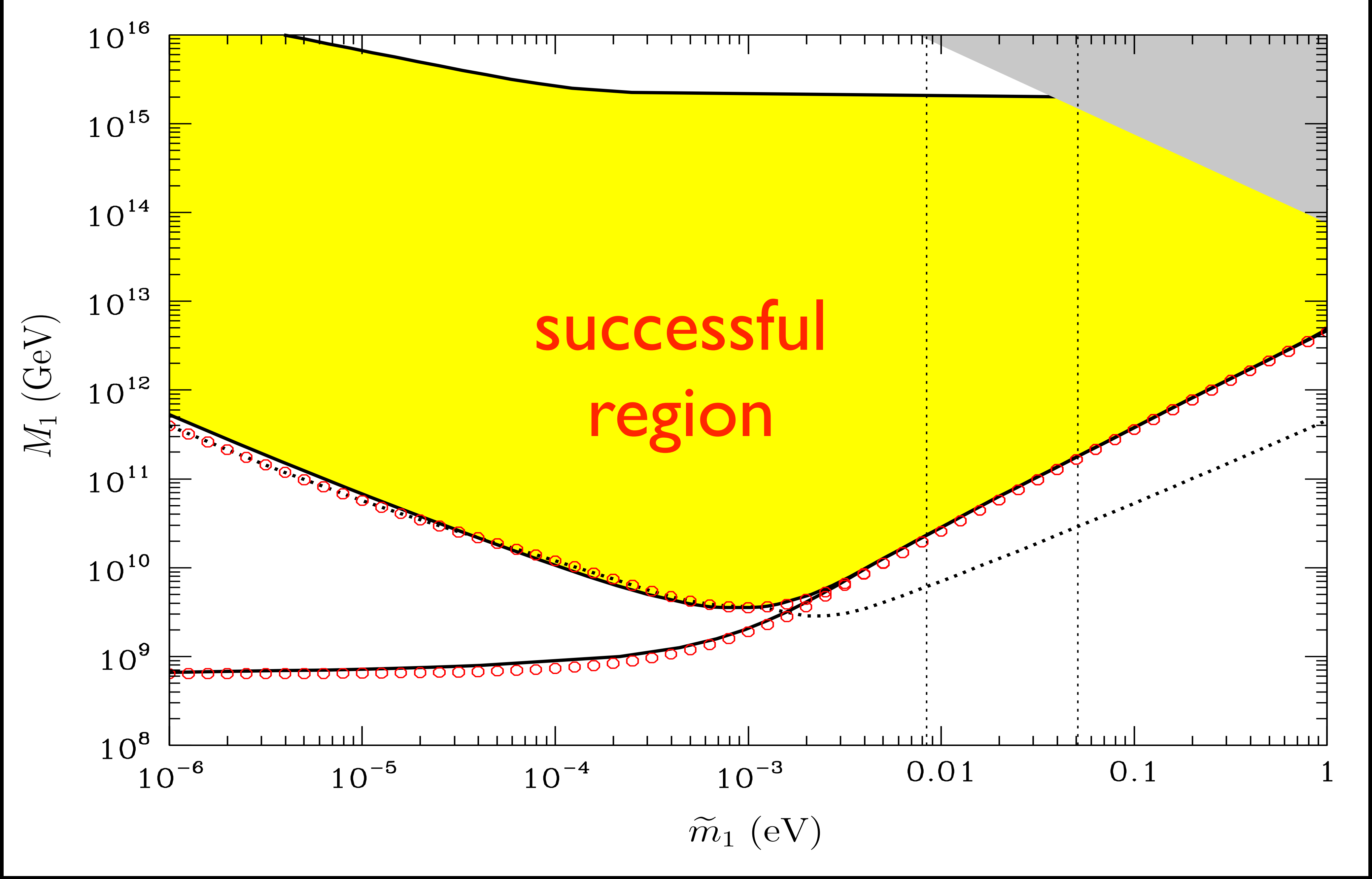
- Seesaw mechanism explains
  - small but finite neutrino masses $m_\nu \sim v^2 / M_R$
  - baryon asymmetry of the Universe through leptogenesis



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

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

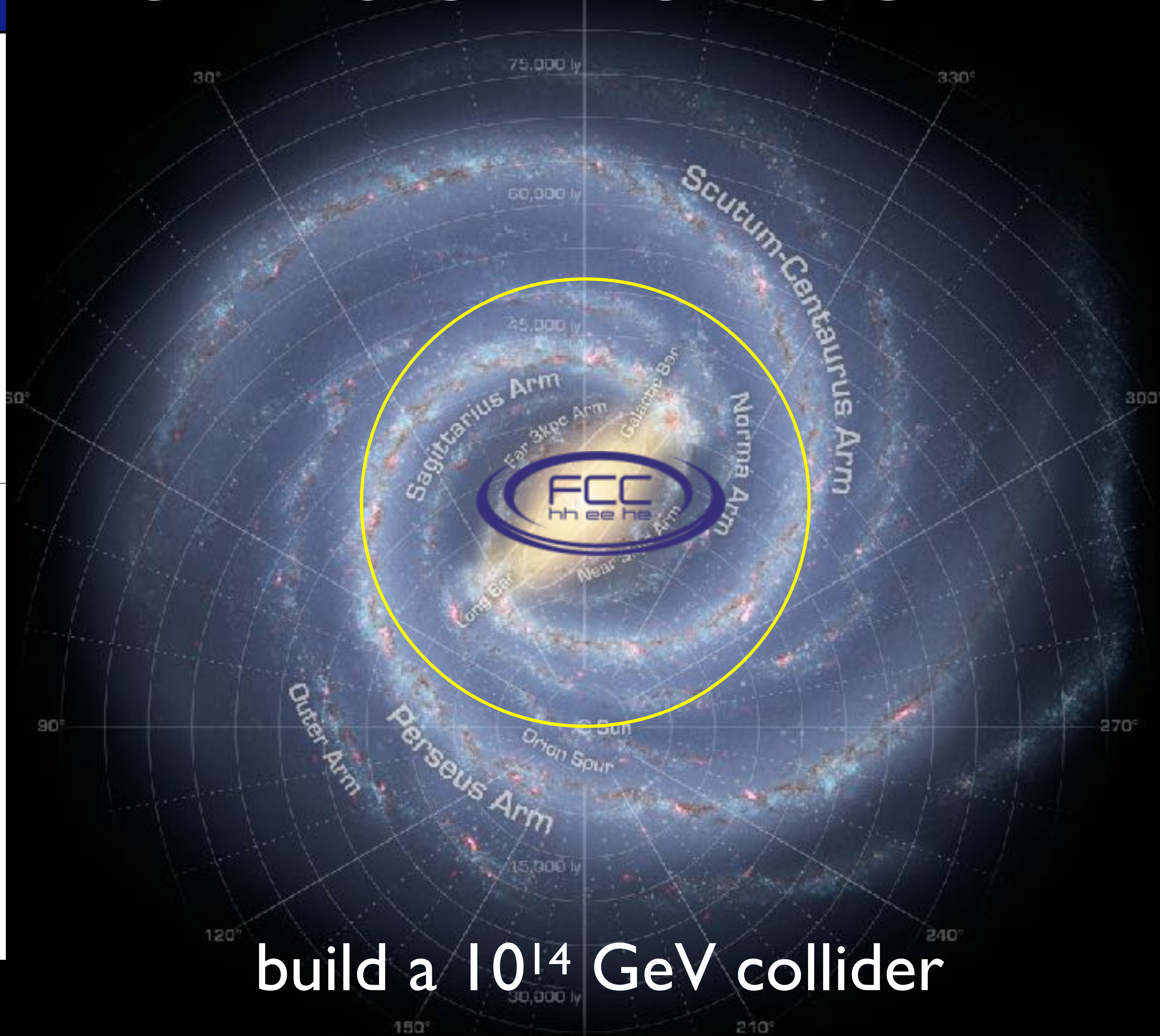
Leptogenesis



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

di Bari, Plümacher, Buchmüller

How do we test it?



build a 10^{14} GeV collider

how do we test it?

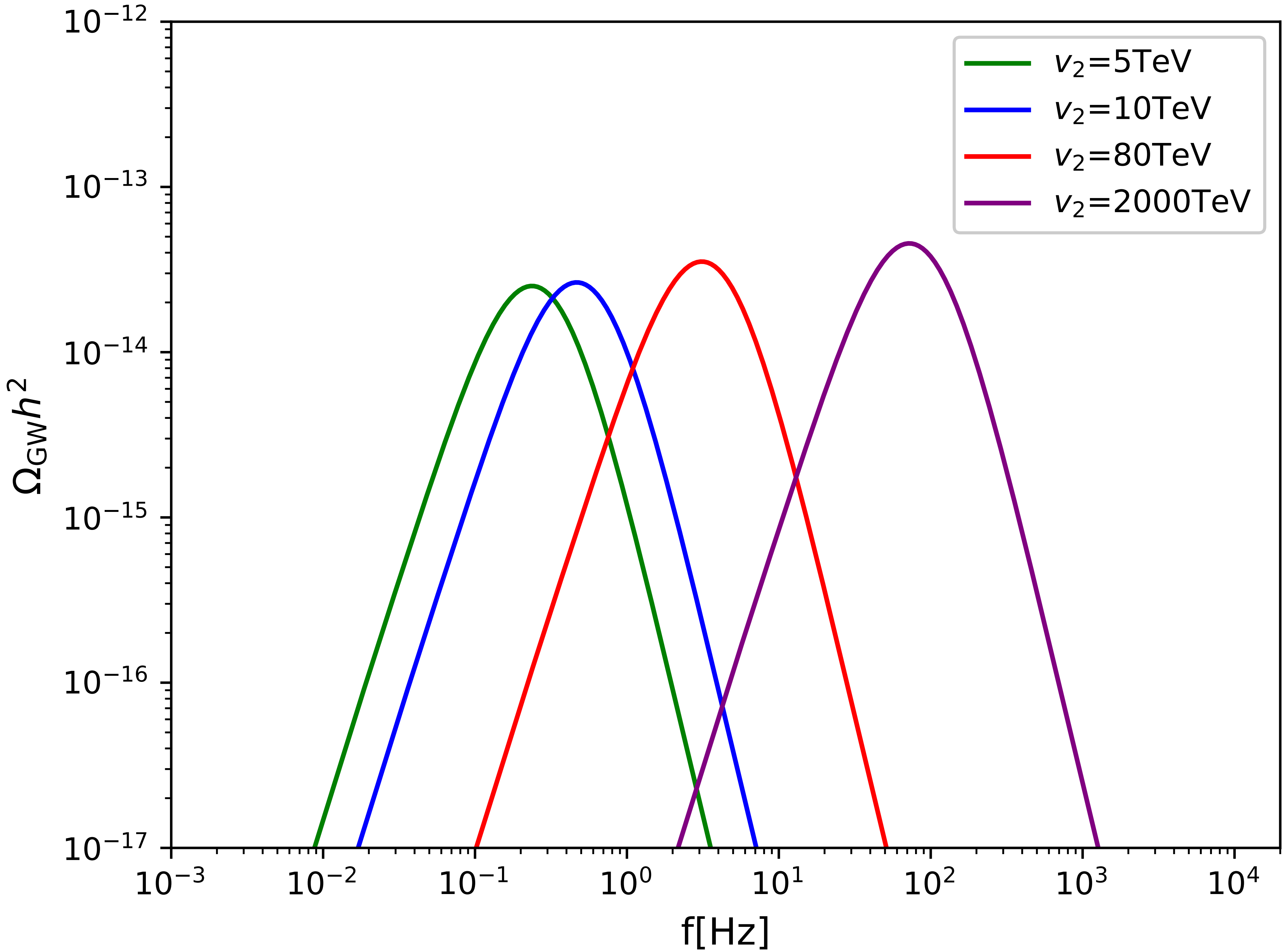
- possible three circumstantial evidences
  - $0\nu\beta\beta$
  - CP violation in neutrino oscillation
  - other impacts e.g. LFV (requires new particles/interactions < 100 TeV)
- *archeology*
- *any more circumstantial evidences?*

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

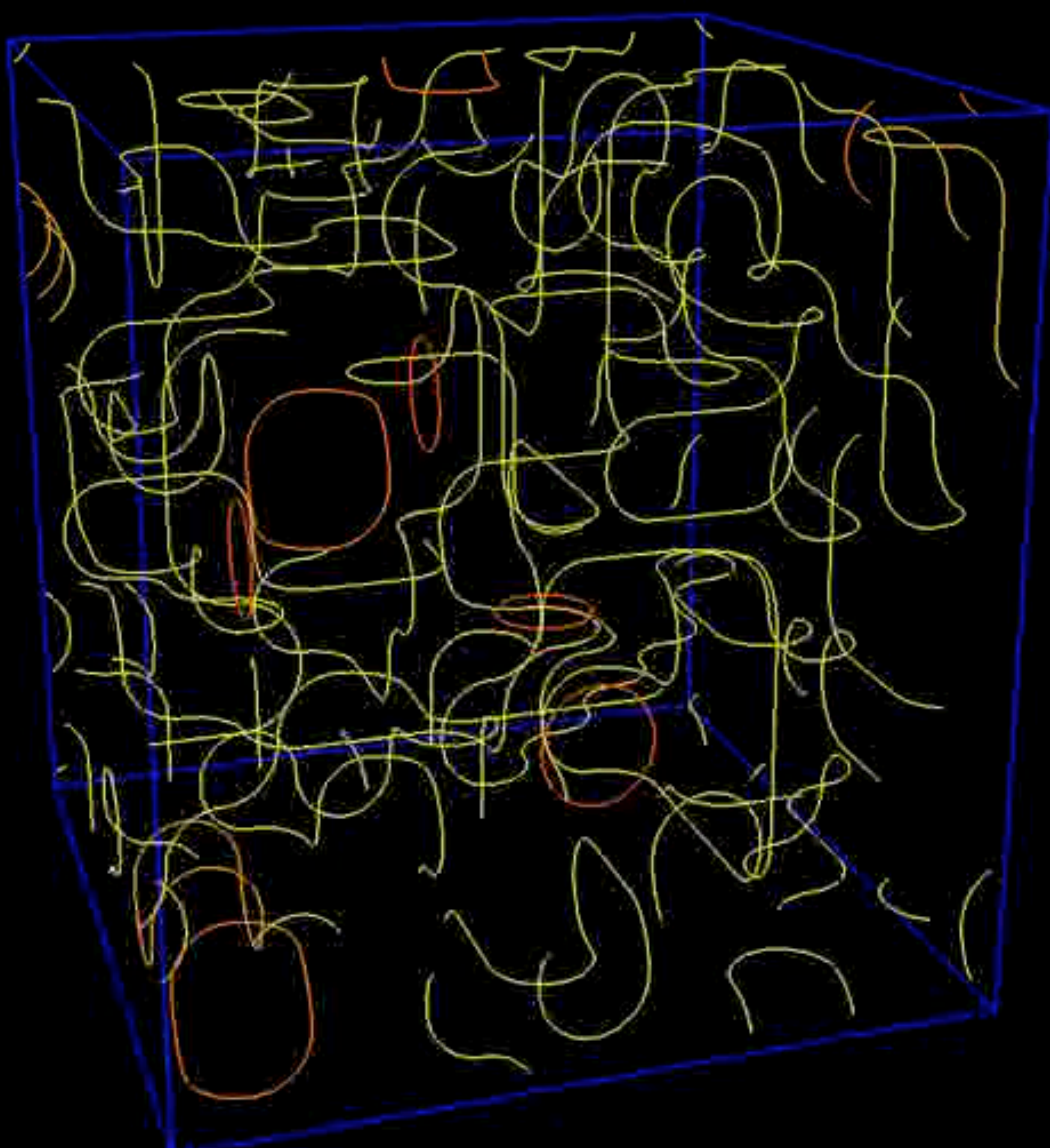


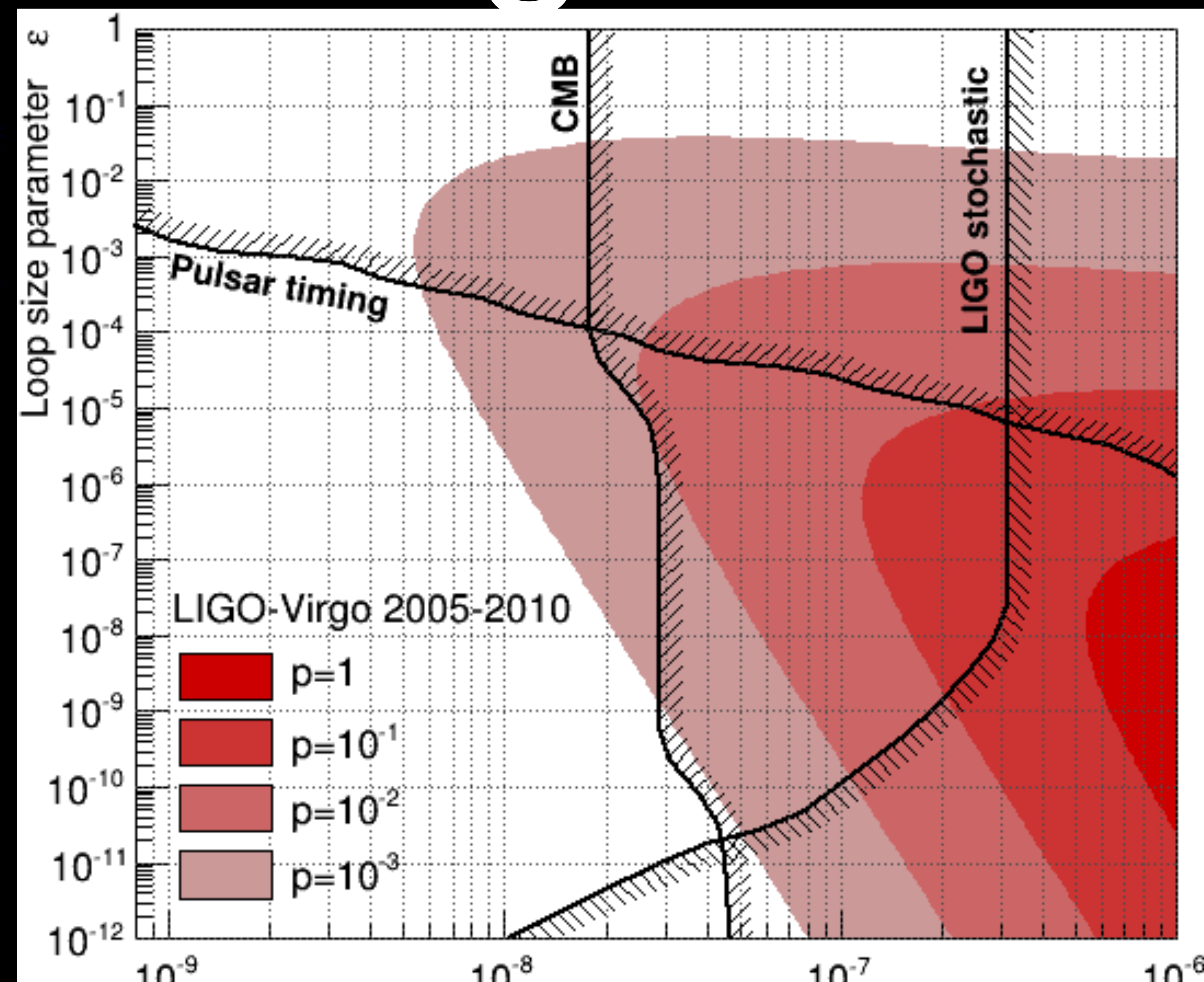
U(1)$_{B-L}$

- Consider $<\phi>\neq 0$
    - M_R from $<\phi>v_R v_R$ or $<\phi^2>v_R v_R/M_{Pl}$
- 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

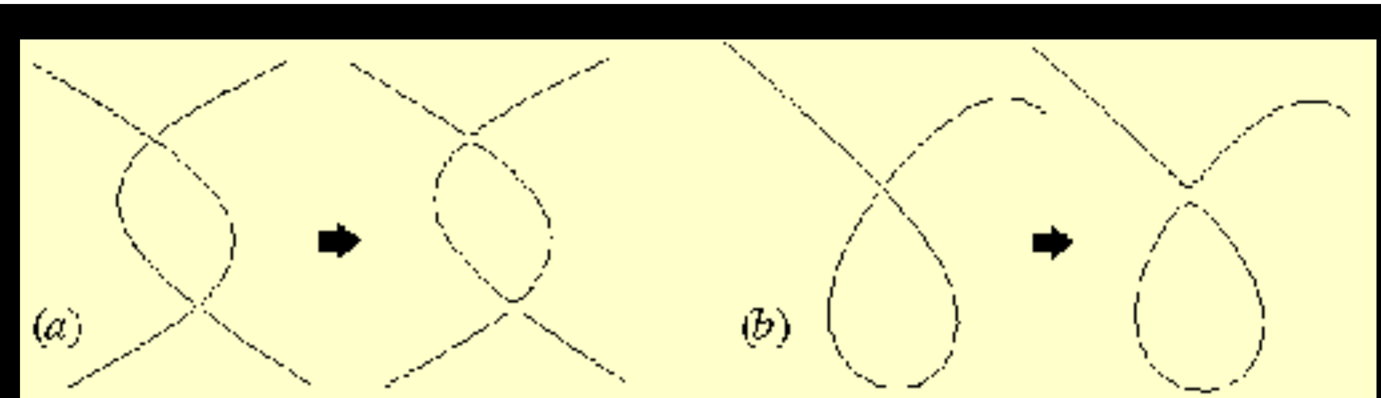
https://www.ligo.org/science/Publication-S5S6CosmicStrings/index.php

cosmic strings





$v \sim 10^{15}$GeV



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

Classification of gauge symmetries

- forbids $M\, \nu_R\, \nu_R$
- anomaly free with $QduLe+\nu_R$
- rank ≤ 5
- no magnetic monopoles

$$G_{\rm disc} = G_{\rm SM} \times \mathbb{Z}_N\,,$$

$$G_{B-L} = G_{\rm SM} \times U(1)_{B-L}\,, \qquad Q(3,2,\tfrac{1}{6},\tfrac{1}{3}), d^c(3^*,1,\tfrac{2}{3},-\tfrac{1}{3}), u^c(3^*,1,-\tfrac{1}{3},-\tfrac{1}{3}), L(1,2,-\tfrac{1}{2},-1), e^c(1,1,+1,+1), \nu_R^c(1,1,1,+1)$$

$$G_{LR} = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}\,, \qquad Q(3,2,1,\tfrac{1}{3}), (d^c+u^c)(3^*,1,2,-\tfrac{1}{3}), L(1,2,1,-1), (e^c+\nu_R^c)(1,1,2,+1$$

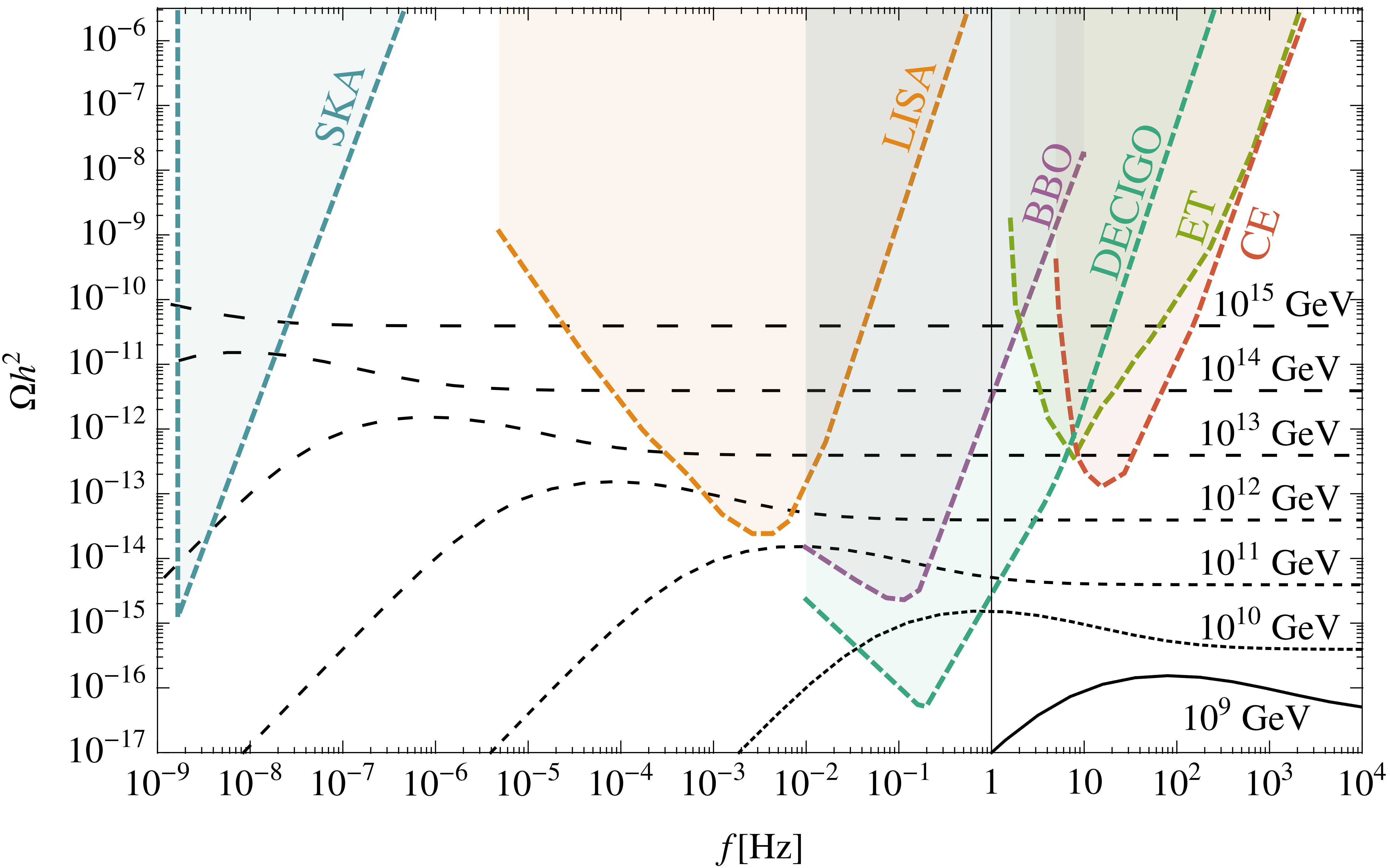
$$G_{421} = SU(4)_{\rm PS} \times SU(2)_L \times U(1)_Y\,, \qquad (Q+L)(4,2,0), (d^c+e^c)(4^*,1,\tfrac{1}{2}), (u^c+\nu_R^c)(4^*,1,-\tfrac{1}{2})$$

$$G_{\rm flip} = SU(5) \times U(1)\,. \qquad (Q+d^c+\nu_R^c)(10,1), (L+u^c)(5^*,-3), e^c(1,5)$$

	$H = G_{\rm SM}$		$H = G_{\rm SM} \times \mathbb{Z}_2$	
G	**defects**	**Higgs**	**defects**	**Higgs**
$G_{\rm disc}$	domain wall*	$B-L=1$	domain wall*	$B-L=2$
G_{B-L}	abelian string*	$B-L=1$	$\mathbb{Z}_2$ string†	$B-L=2$
G_{LR}	texture*	$(\mathbf{1},\mathbf{1},\mathbf{2},\tfrac{1}{2})$	$\mathbb{Z}_2$ string	$(\mathbf{1},\mathbf{1},\mathbf{3},1)$
G_{421}	none	$(\mathbf{10},\mathbf{1},2)$	$\mathbb{Z}_2$ string	$(\mathbf{15},\mathbf{1},2)$
$G_{\rm flip}$	none	$(\mathbf{10},1)$	$\mathbb{Z}_2$ string	$(\mathbf{50},2)$

Z_2 matter parity: flips signs of all fermions

$$0 = \pi_2(G) \to \pi_2(G/H) \to \pi_1(H) \to \pi_1(G) \to \pi_1(G/H) \to \pi_0(H) \to \pi_0(G) = 0$$



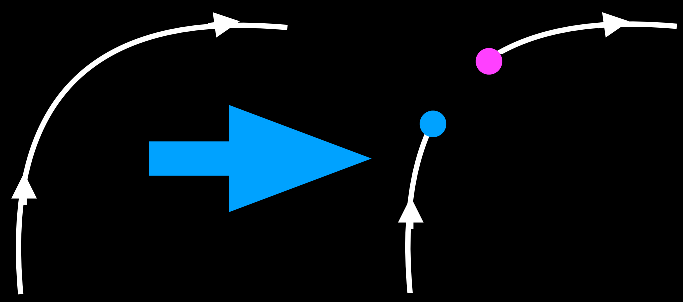
J. Dror, T. Hiramatsu, K. Kohri, HM, G. White, arXiv:1908.03227

covers pretty much the entire range for leptogenesis!

caveat: particle emission from cosmic strings

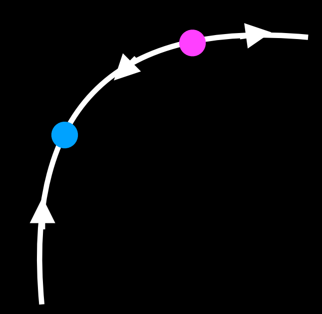
SO(10)

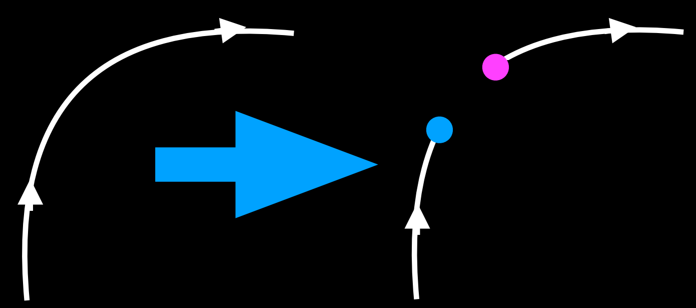
- It is natural to embed $U(1)_{B-L}$ into SO(10)
  - usual gauge coupling unification in SUSY-GUT preserved
- However, SO(10)→SU(3)×SU(2)×U(1) doesn't lead to cosmic strings because $\pi_1(SO(10)/SU(3)\times SU(2)\times U(1))=0$
- SO(10)→SU(3)×SU(2)×U(1)×$U(1)_{B-L}$ produces monopoles
  - SO(10) scale is presumably $V \sim 10^{16}$GeV$\gg$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





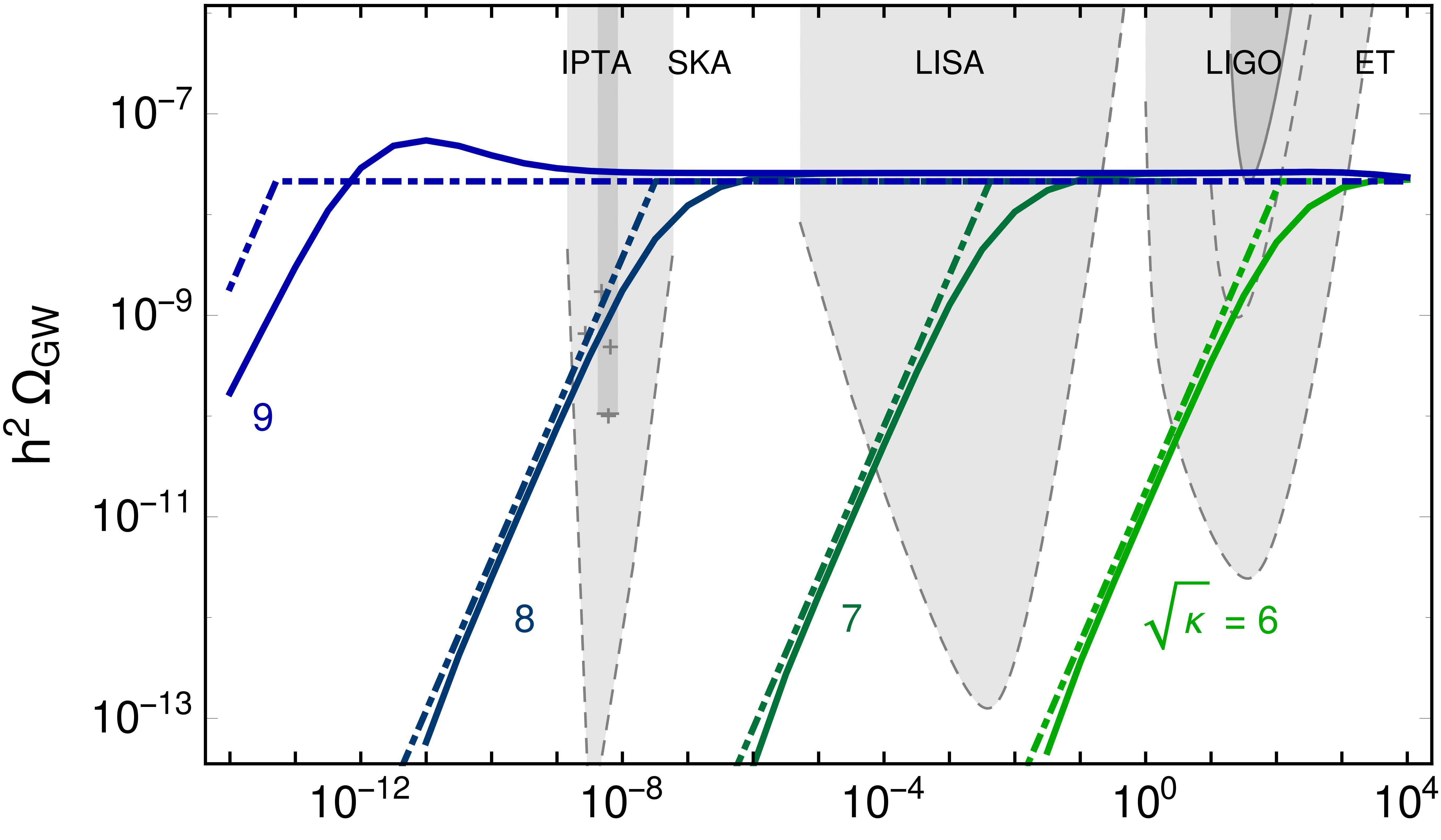
Schwinger

- 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

hybrid inflation



Wilfried Buchmüller, Valerie Domcke, HM, Kai Schmidt, arXiv:1912.03695

Hybrid inflation

- U(1)$_{B\text{-}L}$ broken after inflation

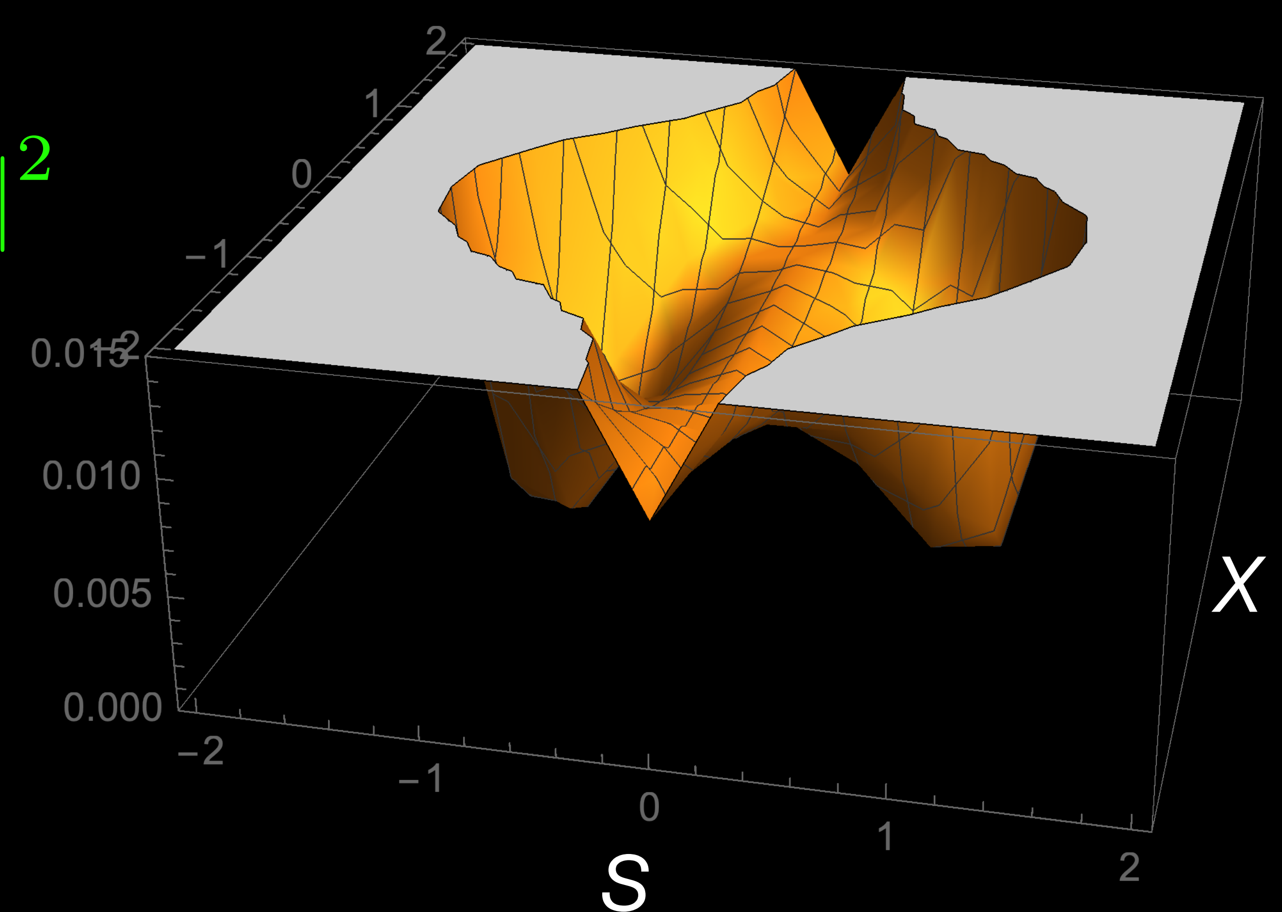
$$W = \lambda X (S^+ S^- - v^2)$$

$$V = \lambda^2 \left|S^+ S^- - v^2\right|^2 + \lambda^2 \left|X\right|^2 (\left|S^+\right|^2 + \left|S^-\right|^2) + \frac{e^2}{2} (\left|S^+\right|^2 - \left|S^-\right|^2)^2$$

- *D*-flat direction $S=S^+=S^-$

$$V = \lambda^2 \left|S^2 - v^2\right|^2 + 2\lambda^2 \left|X\right|^2 \left|S\right|^2$$

- flat: $S=0$, $V=\lambda^2 v^2$
- falls down to $S=v$ near $X\sim0$
- forms cosmic strings
-



Conclusions

- stochastic gravitational waves as another possible circumstantial evidence for seesaw+leptogenesis
- for rank≤5 gauge groups, more than a half of them produce cosmic strings
- future missions promising to cover most range of seesaw scales
- if we do detect scale-invariant gravitational waves, helps establish not only seesaw but also the breaking pattern
- *any experimental technique to probe gravitational waves of much higher frequencies?*

Hongo to Kashiwa

- Students who need support for trips from Hongo to Kashiwa
- Keisuke Yanagi, So Chigusa, Taichi Ago, Shih-Yen Tseng
- ask you to do simple *duties*

	Tu morning 1	Tu morning 2	Tu afternoon	Wed morning 1	Wed morning 2	Wed afternoon 1	Wed afternoon 2
collect slides	Tseng	Yanagi	Kojima	Chigusa	Ago	Tseng	Yanagi
take pictures	Kobayashi	Chigusa	Ago	Tseng	Yanagi	Horigome	Chigusa
	Thu morning 1	Thu morning 2	Thu afternoon	Fri morning 1	Fri morning 2	Fri afternoon 1	Fri afternoon 2
collect slides	Ago	Tseng	Yanagi	Katayose	Chigusa	Ago	Tseng
take pictures	Yanagi	Katayose	Chigusa	Ago	Kojima	Horigome	Katayose

non-theory students

- Aoi Eguchi, Yume Nishinomiya, Yoshitaka Okuyama
- report to Eri Kuromoto to receive support for trips from Hongo
- specify which days you attend

other items

- Banquet, Thursday, 17:30, Ikoi, *free!*
- Group photo: 11am tomorrow