Neutrino mass, leptogenesis, GUT

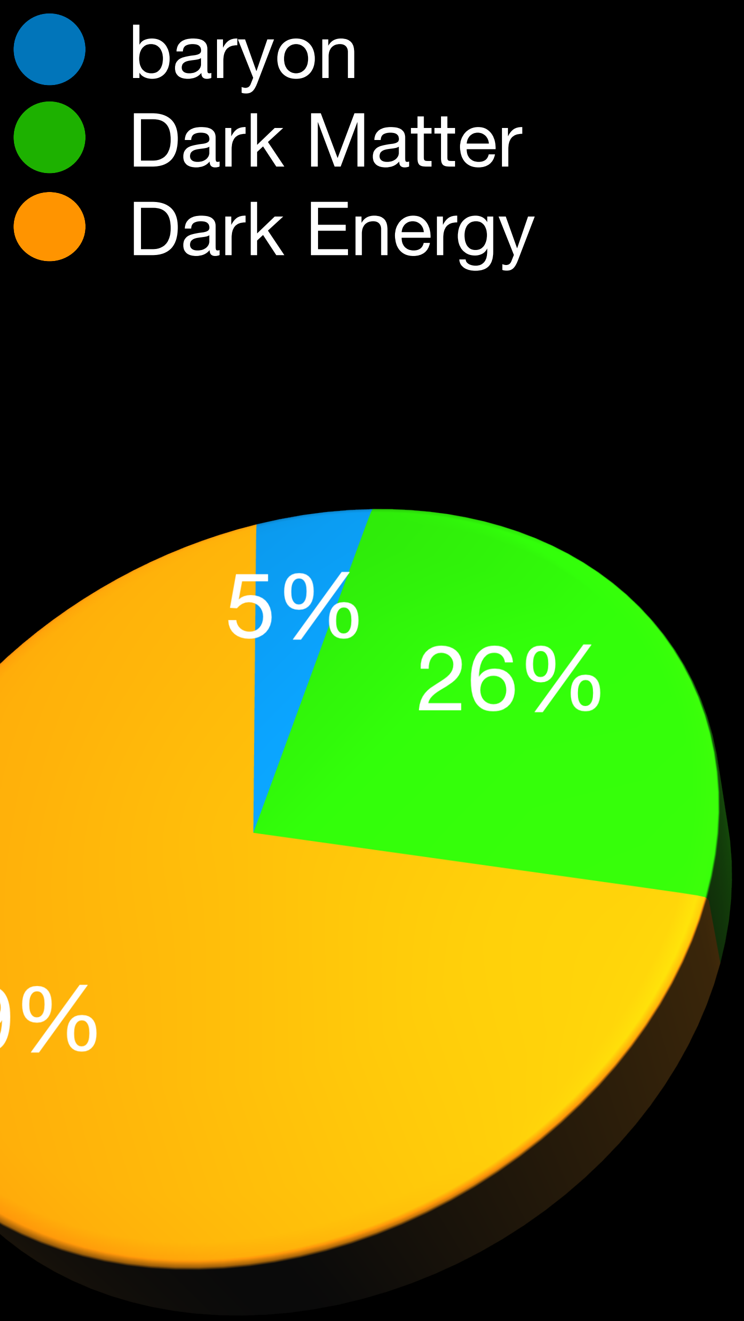
Hitoshi Murayama (Berkeley, Kavli IPMU)

Gravitational Wave Probes of Physics Beyond Standard Model

July 12, 2021

Cosmic mysteries

- We don't know what dark energy is
- We don't know what dark matter is
- We don't know why baryons exist



Sakharov Conditions

- We need to satisfy all three ingredients
- Baryon number violation
  - need a way to change B=0 to B≠0
- CP violation
  - which one is matter? we need distinction
- Departure from equilibrium
  - no net gain as long as detailed balance
- Where and when?

too many theories for a single number

Two tales

- Testing Leptogenesis with gravitational waves
  - +Jeff Dror (Berkeley), Takashi Hiramatsu (ICRR), Kazunori Kohri (KEK), Graham White (TRIUMF)
  - arXiv:1908.03227 accepted for PRL, *Editors' Suggestion*
- Asymmetric Matters from a dark first-order phase transition
  - +Eleanor Hall (Berkeley), Thomas Konstandin (DESY), Robert McGehee (Berkeley)
  - arXiv:1911.12342

Testing seesaw and leptogenesis by gravitational wave

Hitoshi Murayama (Berkeley, Kavli IPMU)
+Jeff Dror (Berkeley), Takashi Hiramatsu (ICRR), Kazunori Kohri (KEK), Graham White (TRIUMF)

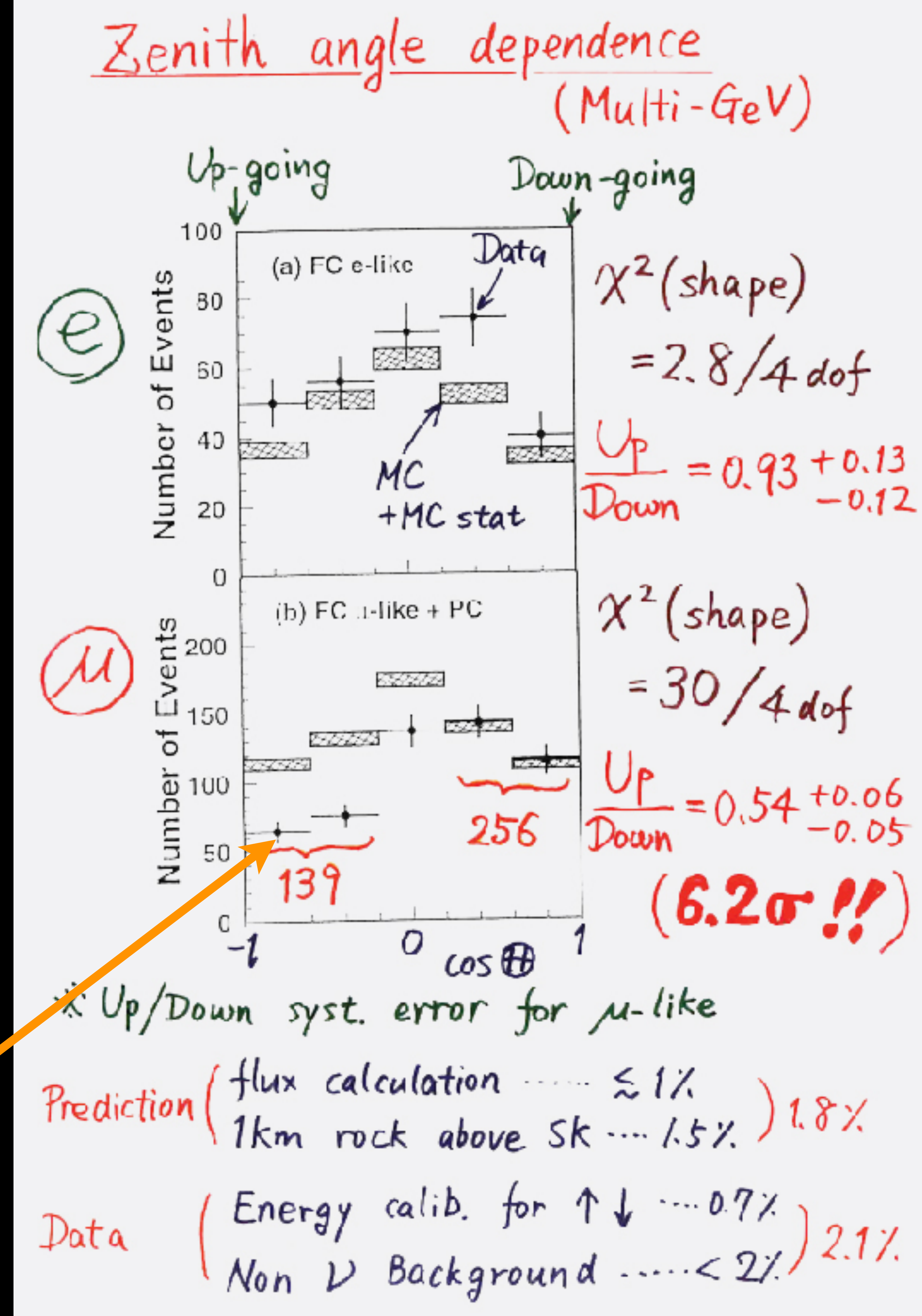
arXiv:1908.03227,
Phys.Rev.Lett. 124 (2020) 4, 041804
Editor's Suggestion

東京大学 THE UNIVERSITY OF TOKYO
UTIAS 東京大学国際高等研究所 THE UNIVERSITY OF TOKYO INSTITUTES FOR ADVANCED STUDY
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
BERKELEY CENTER FOR THEORETICAL PHYSICS
BERKELEY LAB

neutrinos oscillate

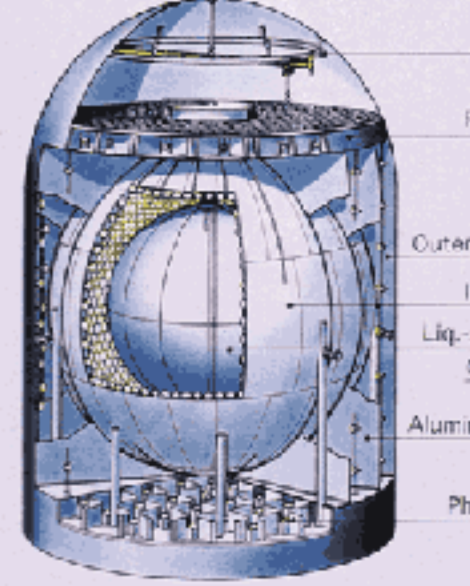
1998

a half of expected

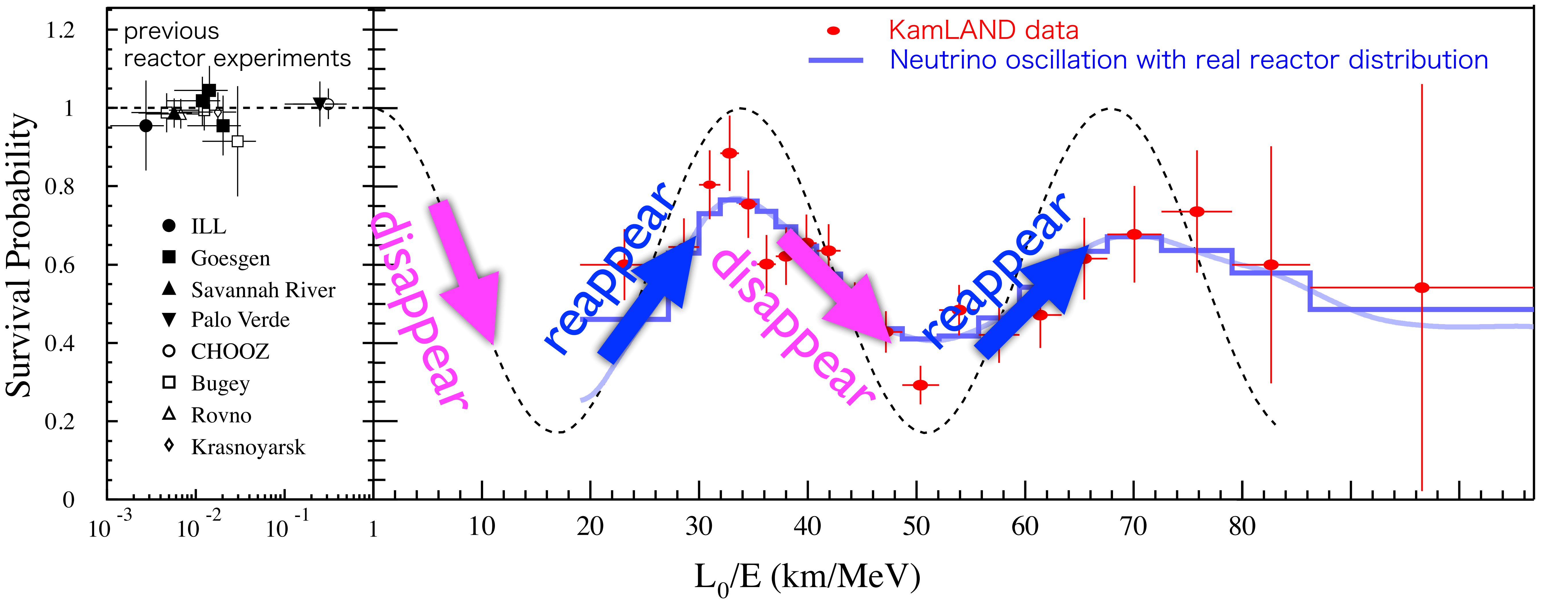


shift inside the mine for KamLAND

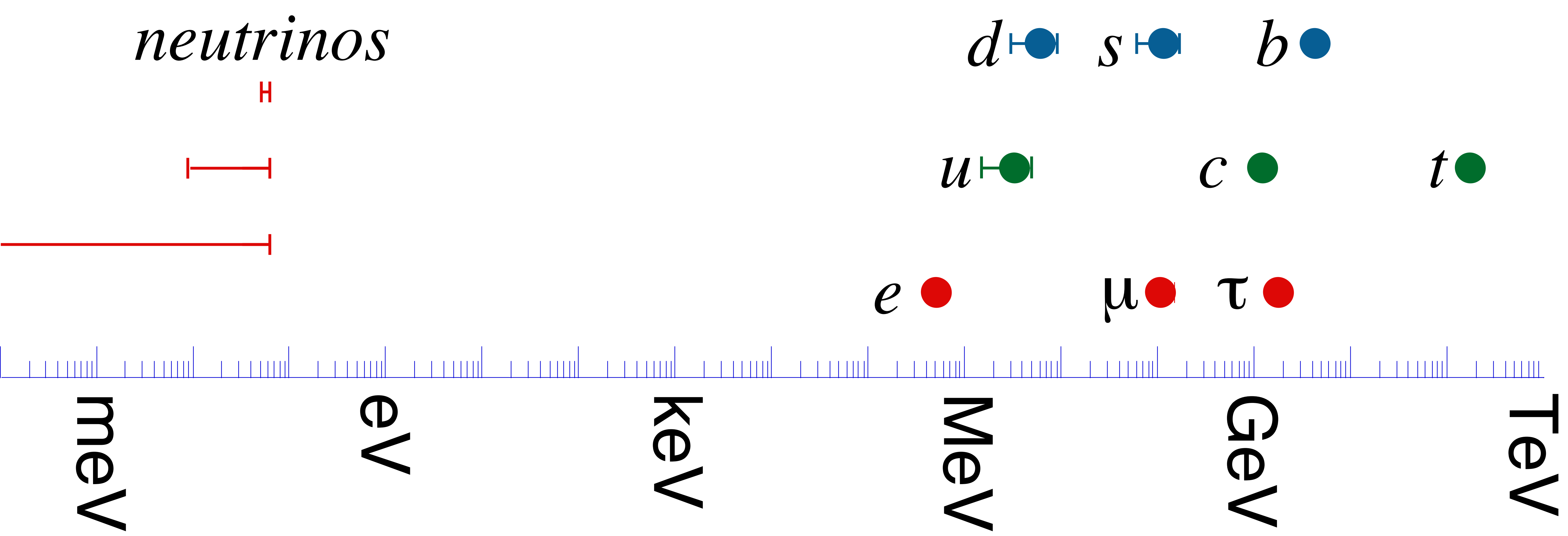
reactor neutrinos



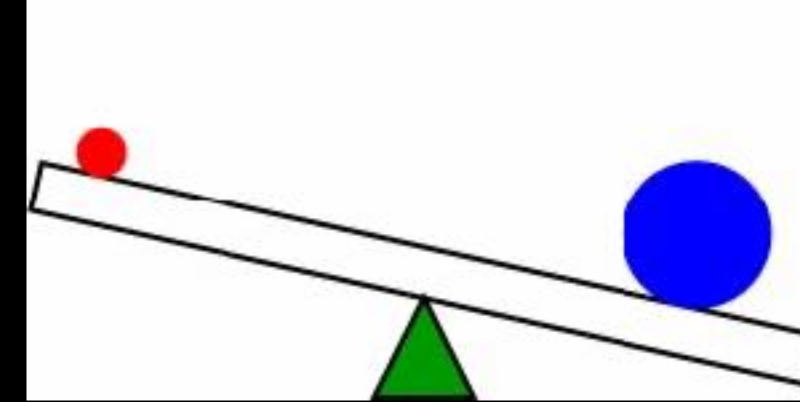
- KamLAND experiment
- a ring of reactors with average *L*~175 km



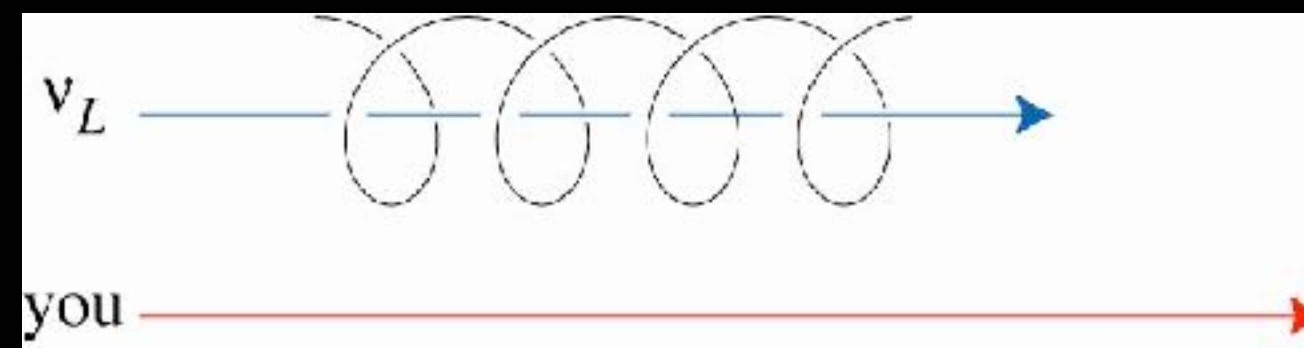
very light



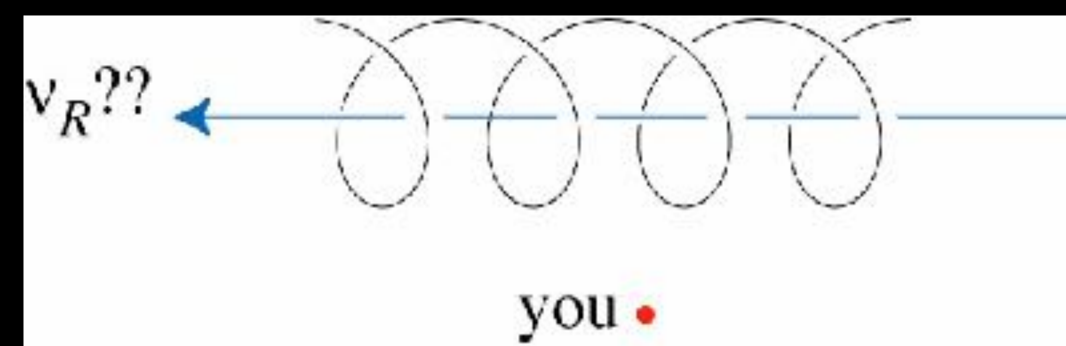
Seesaw



- Why is the neutrino mass so small?
  - neutrinos are left-handed
  - but now they have mass



  - we can overtake and look back
  - looks right-handed!

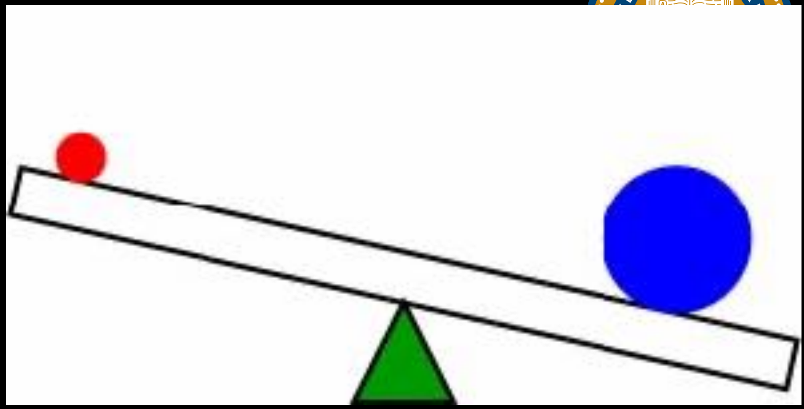


  - introduce right-handed neutrino
  - small but finite neutrino masses $m_\nu \sim (yv)^2 / M$
  - when you look back at a neutrino, you see anti-neutrino

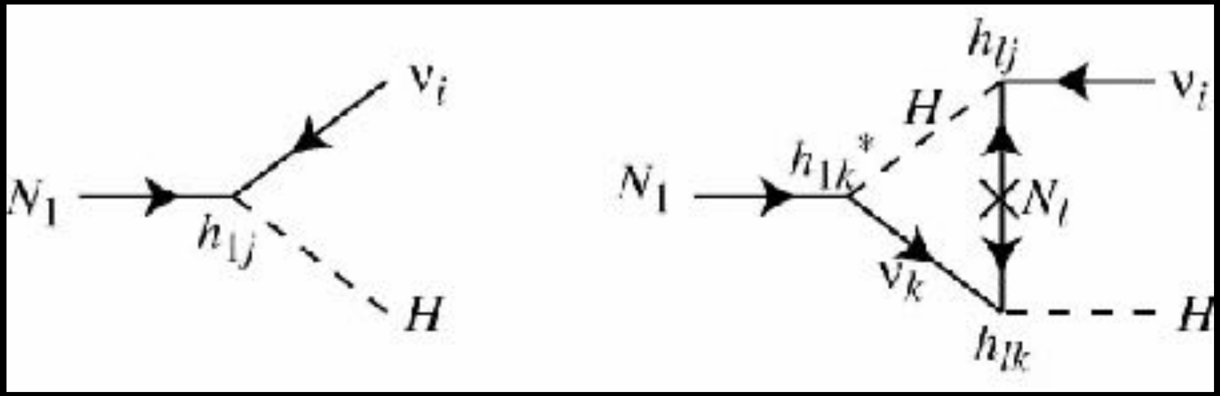
$$\mathcal{L} = -yLNH$$

$$\begin{pmatrix} \nu & N \end{pmatrix} \begin{pmatrix} -\frac{(yv)^2}{M} & 0 \\ 0 & M \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

Leptogenesis



- Right-handed neutrinos in early universe
- when they decay, produce *L*≠0



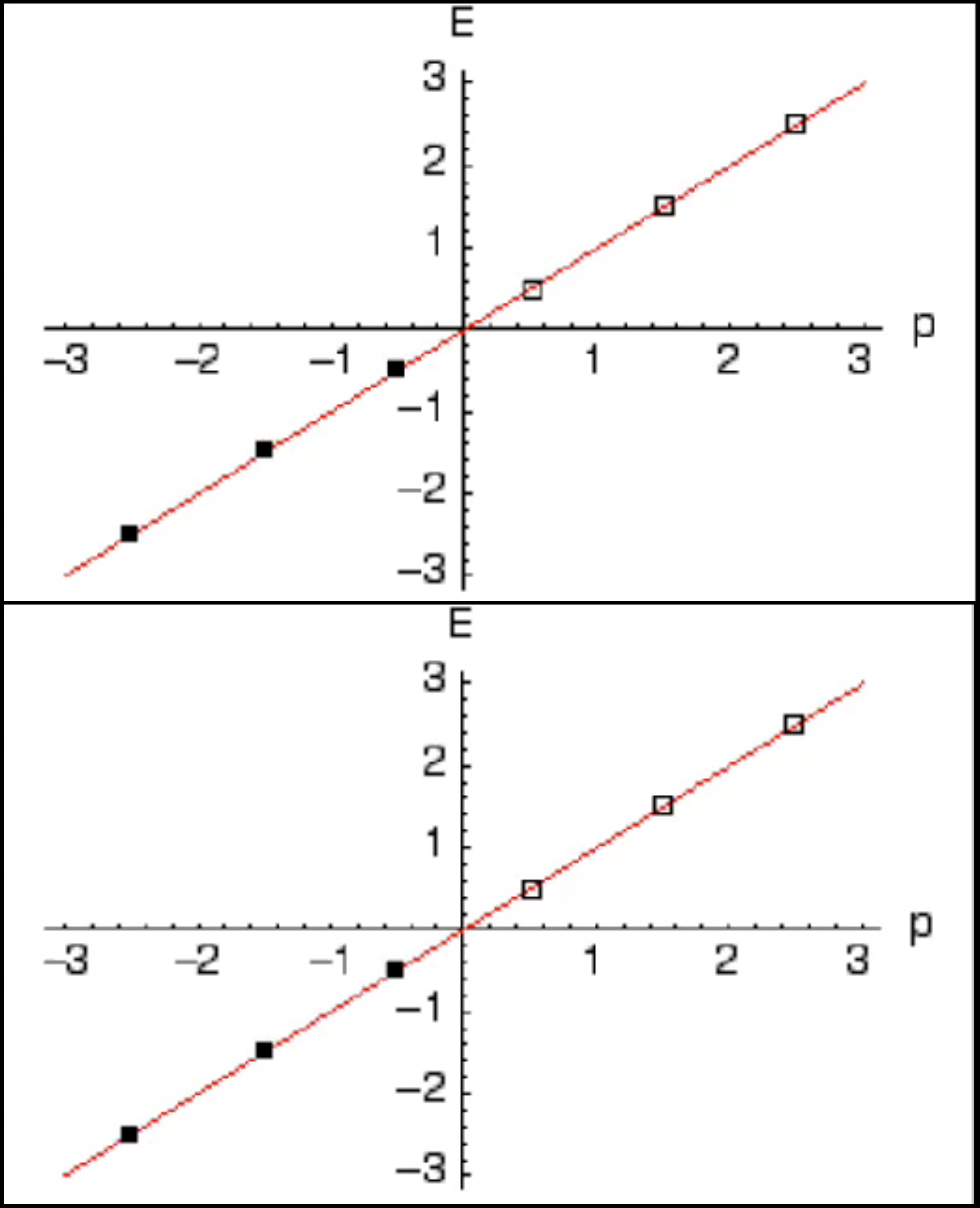
$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H^*) \propto \Im m(h_{1j} h_{1k} h^*_{lk} h^*_{lj})$$

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

Anomaly!

- *W* and *Z* bosons massless at high temperature
- *W* field fluctuates just like in thermal plasma
- solve Dirac equation in the presence of the fluctuating *W* field

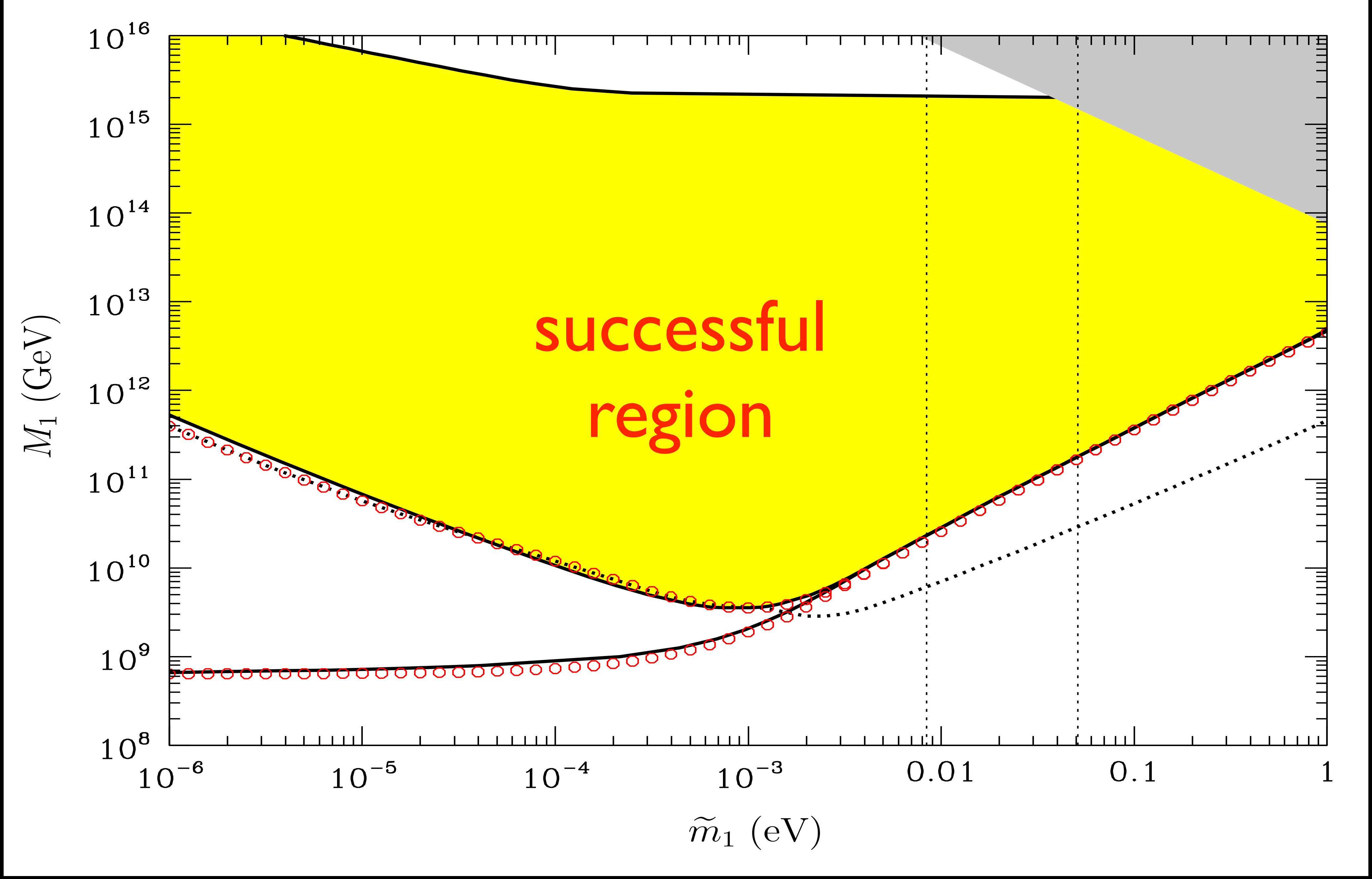
$\Delta q = \Delta q = \Delta q = \Delta L$



Sakharov Conditions

- all three ingredients satisfied
- Baryon number violation
  - lepton number violation + Electroweak anomaly (sphaleron effect)
- CP violation
  - Yukawa couplings $y_{i\alpha} L_i N_\alpha H + M_\alpha N_\alpha N_\alpha$
  - even two generations sufficient
- Departure from equilibrium
  - out-of-equilibrium decay of N_α due to long lifetimes

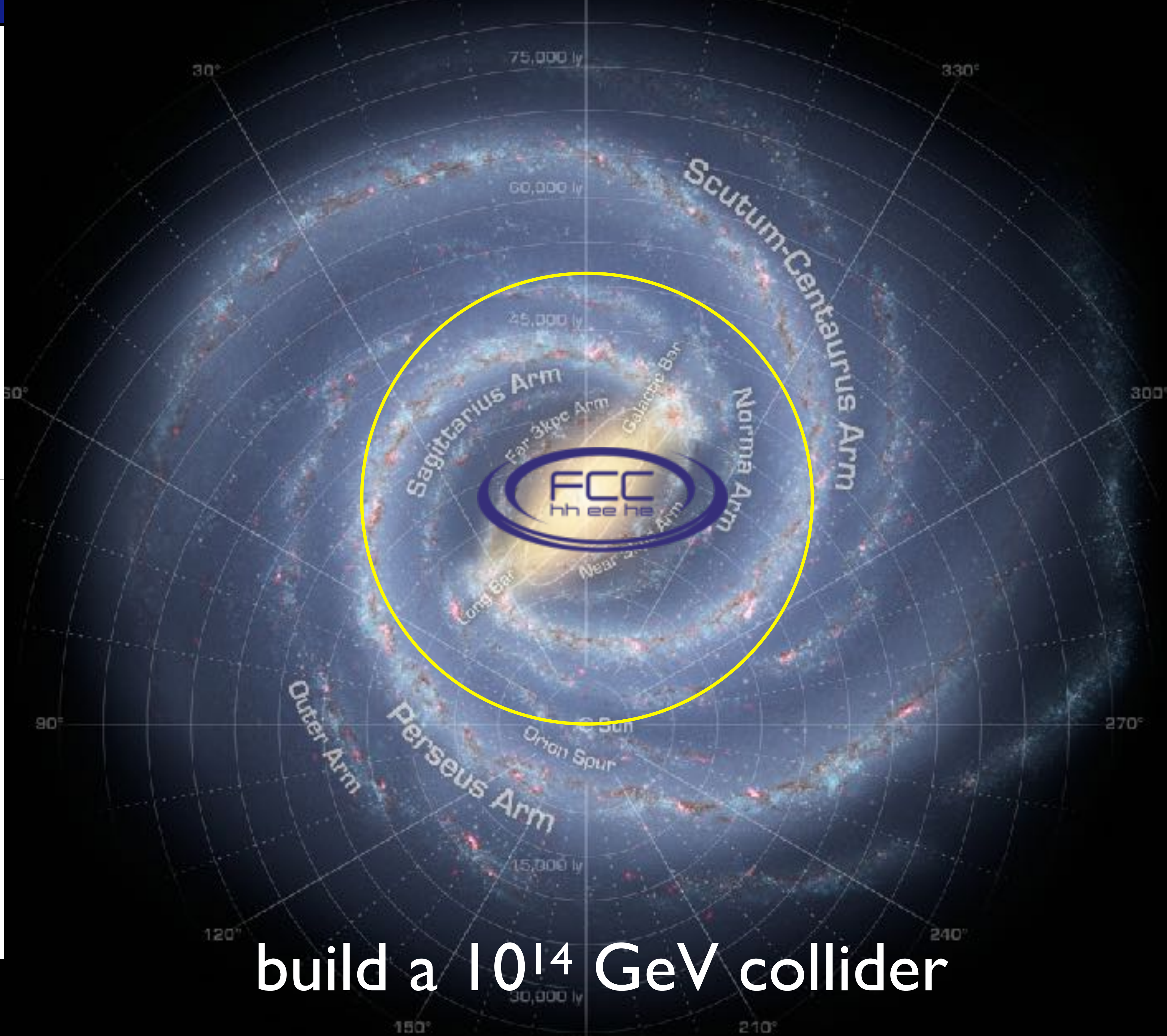
Leptogenesis



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

di Bari, Plümacher, Buchmüller

How do we test it?



build a 10^{14} GeV collider

JAXA
Japan Aerospace Exploration Agency

文部科学省
MEXT
MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

NASA

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NSF

CERN

how do we test it?

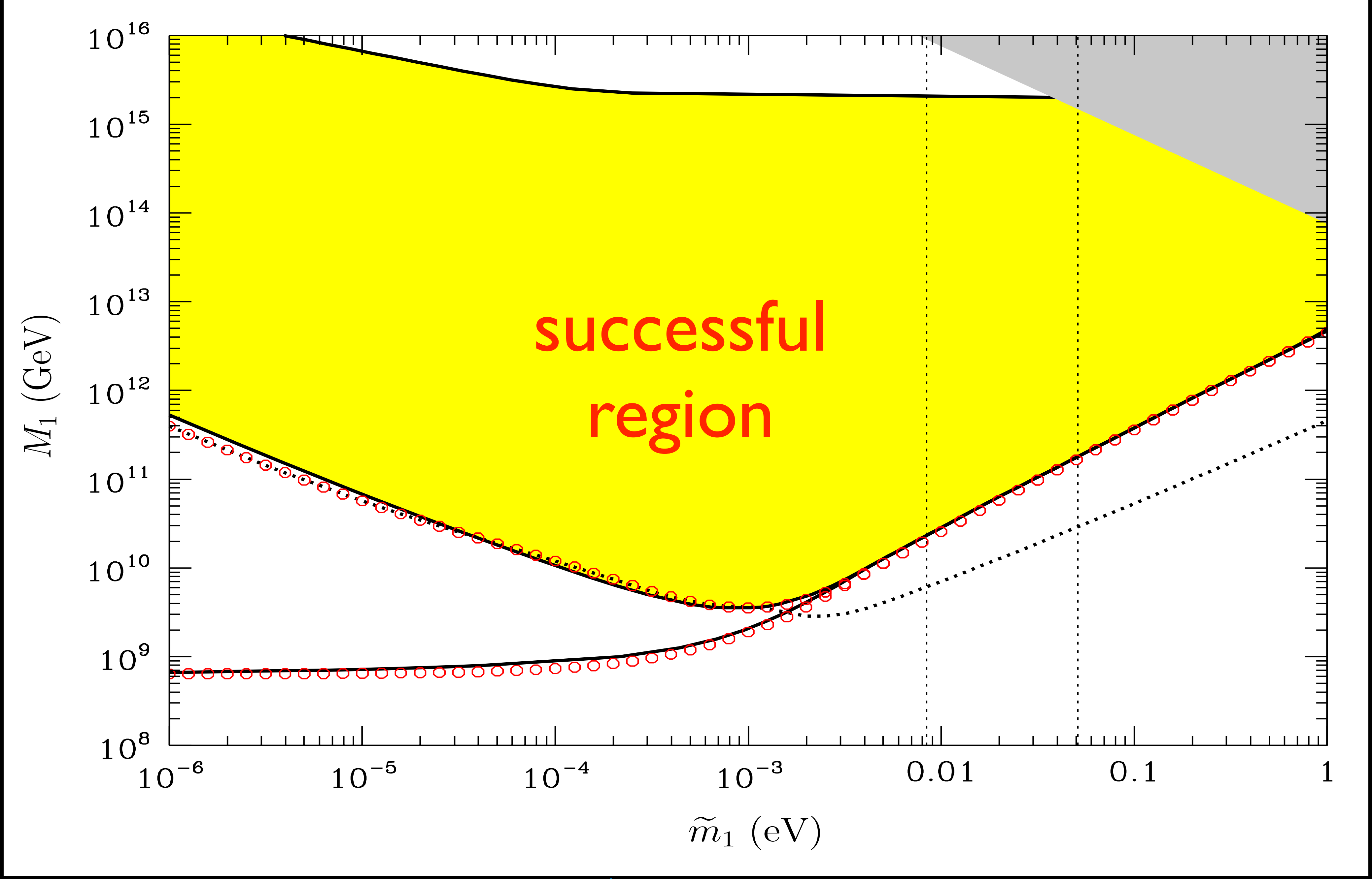
- possible three circumstantial evidences
  - $0\nu\beta\beta$
  - CP violation in neutrino oscillation
  - other impacts e.g. LFV (requires new particles/interactions < 100 TeV)
- *archeology*
- *any more circumstantial evidences?*

M_{Pl}

Natural to think M is induced from symmetry breaking

e.g. $\mathcal{L}=-y\langle\varphi\rangle N\,N$

inflation



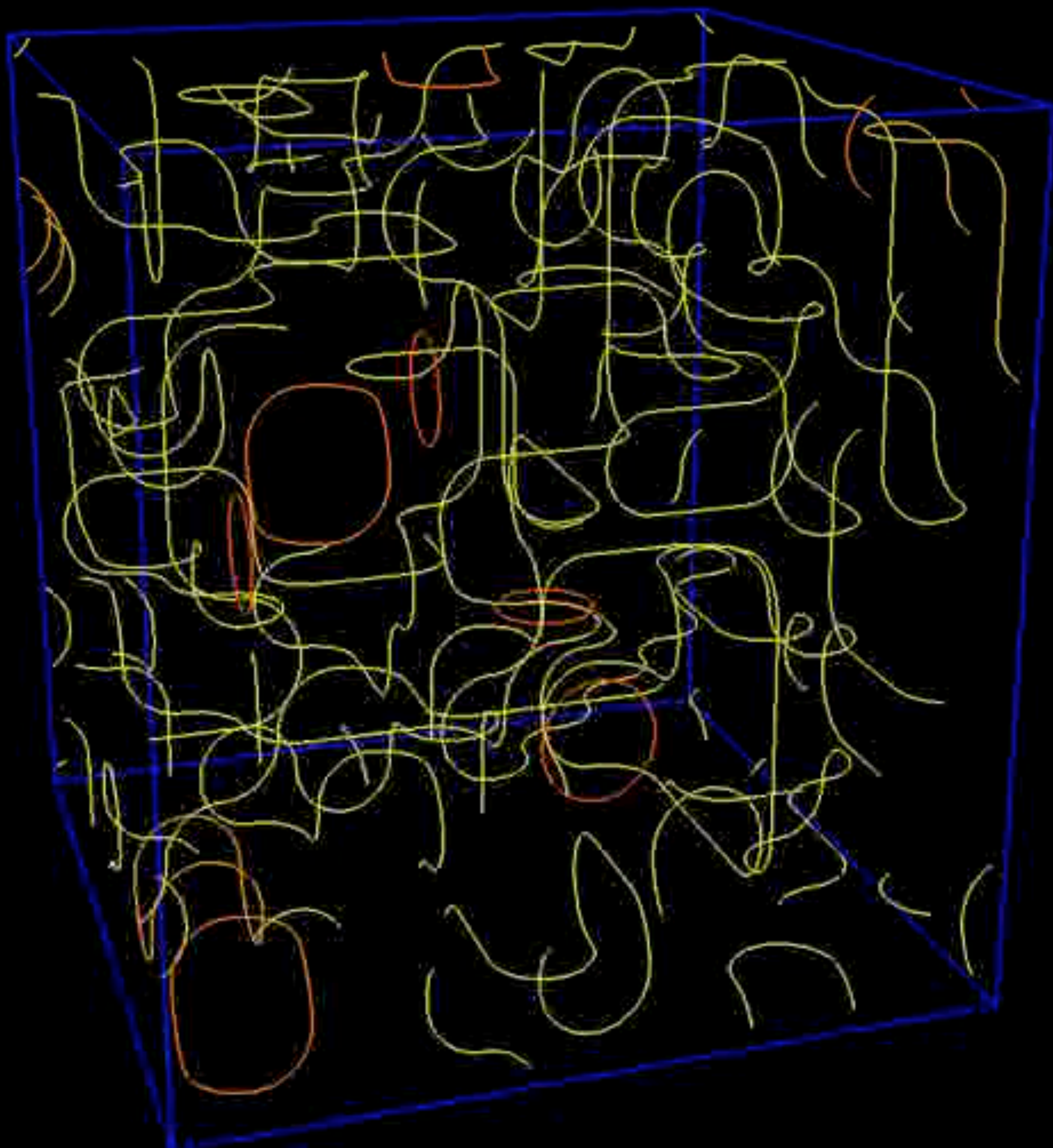
Phase Transition → **Gravitational Waves?**

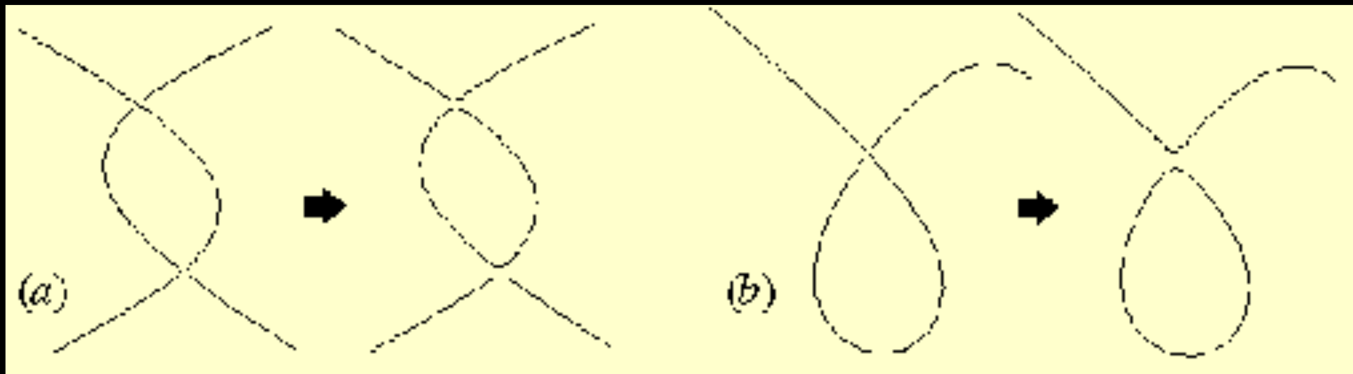
$U(1)_{B-L}$

- Consider $<\phi>\neq 0$
  - M_R from $<\phi>\nu_R\nu_R$
  - 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





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

classification

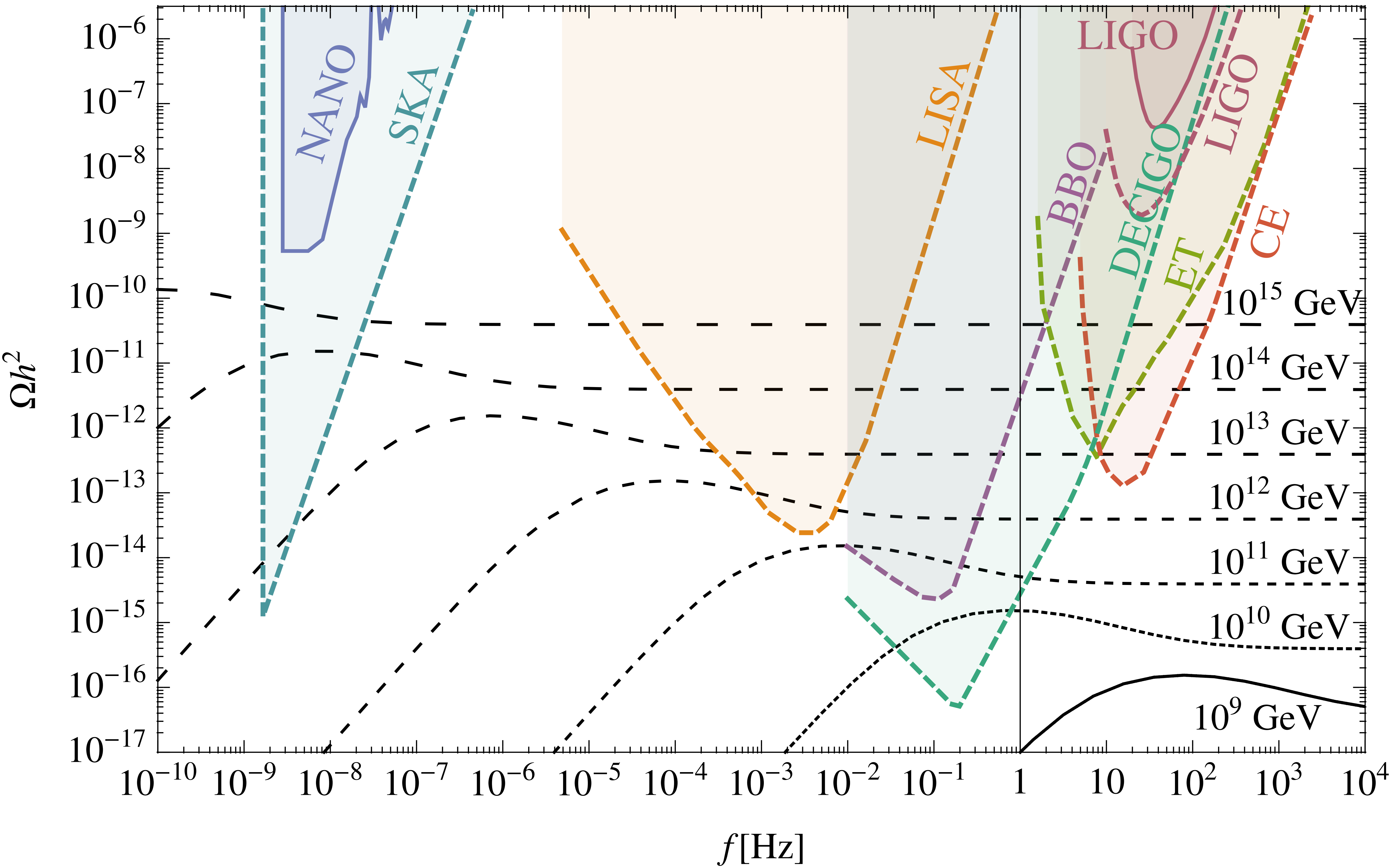
- possible gauge groups
  - forbids $M\, \nu_R\, \nu_R$
  - anomaly-free without additional fermions
  - no magnetic monopoles
  - rank ≤5
- possible Higgs
  - matter parity?
  - e.g. ϕ(+1) or ϕ(+2)
  - $H=G_{SM}$ or $G_{SM}\times Z_2$
- 5 out of 8 have strings

$$
\begin{aligned}
G_{\rm disc} &= G_{\rm SM} \times \mathbb{Z}_N\,, \\
G_{B-L} &= G_{\rm SM} \times U(1)_{B-L}\,, \\
G_{LR} &= SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}\,, \\
G_{421} &= SU(4)_{\rm PS} \times SU(2)_L \times U(1)_Y\,, \\
G_{\rm flip} &= SU(5) \times U(1)\,.
\end{aligned}
$$

$\langle\phi\phi\rangle\, \nu_R \nu_R / M_{Pl}$ $\quad$ $\langle\phi\rangle\, \nu_R \nu_R$

	$H = G_{\rm SM}$		$H = G_{\rm SM}\times\mathbb{Z}_2$	
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*	$(\mathbf{1},\mathbf{1},\mathbf{2},\frac{1}{2})$	$\mathbb{Z}_2$ 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	$(\mathbf{50},2)$

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



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

Hybrid inflation

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

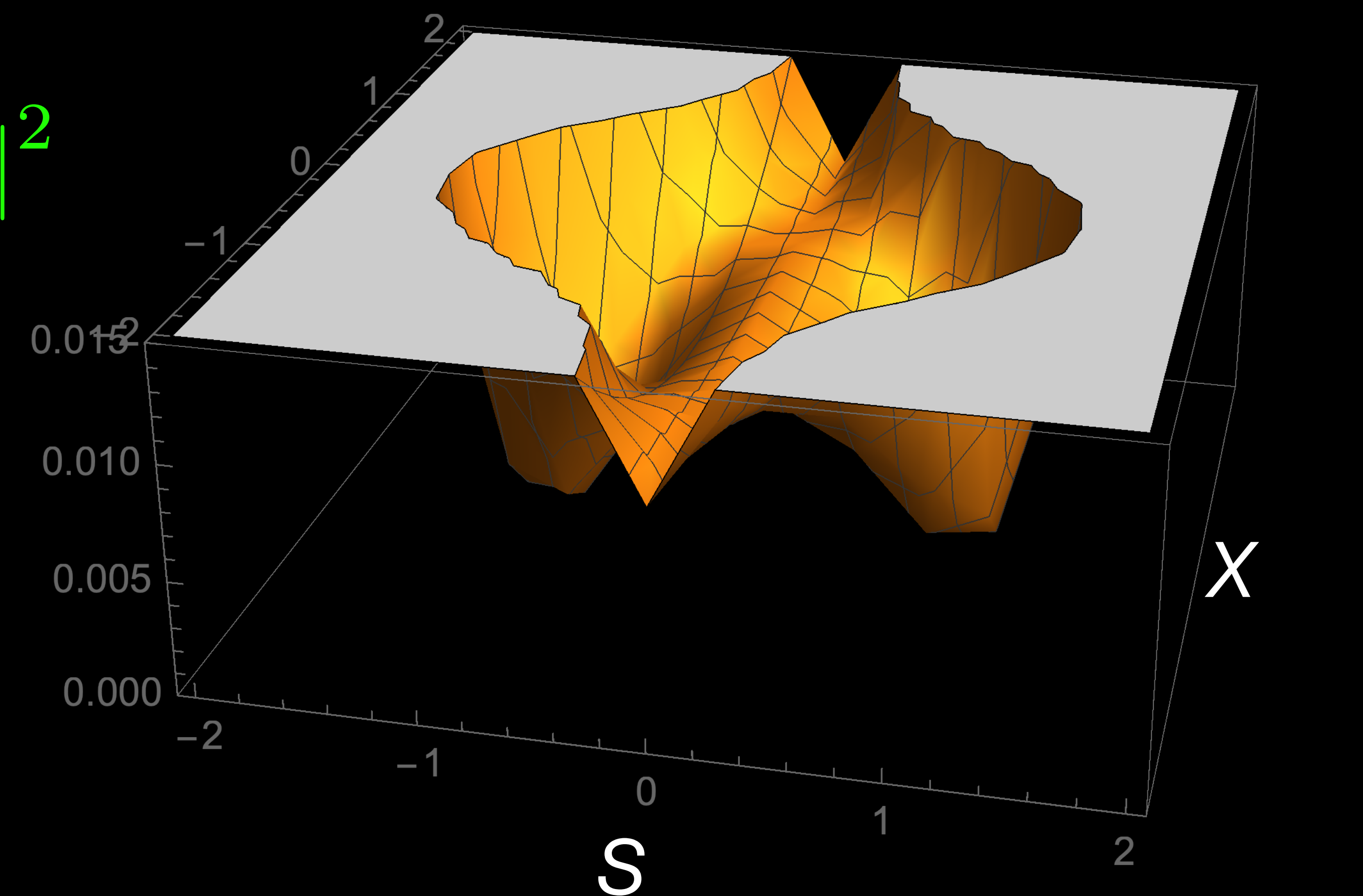
$$W = \lambda X(S^+S^- - v^2)$$

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

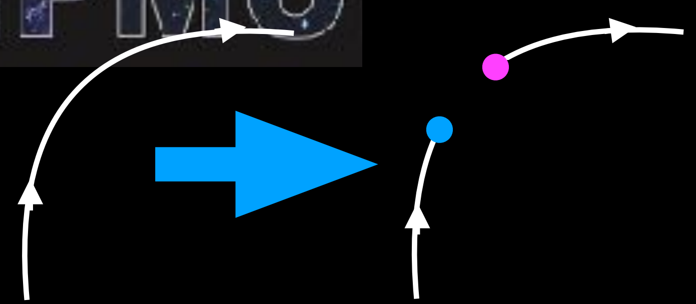
- *D*-flat direction $S=S^+=S^-$

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

- flat: $S=0$, $V=\lambda^2 v^2$
- falls down to $S=v$ near $X\sim 0$
- forms cosmic strings
- requires high $v \geq$ a few 10^{15} GeV
- *excluded* by Pulsar Timing Array?

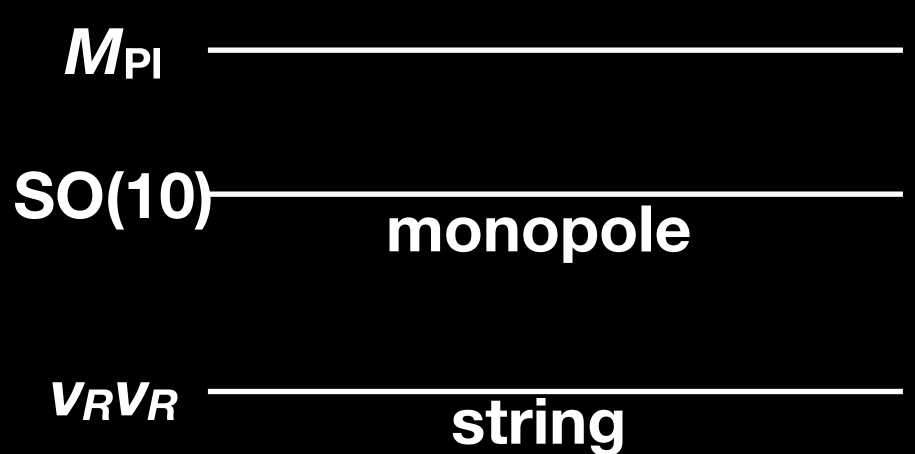


Wilfried Buchmüller, Valerie Domcke, HM, Kai Schmidt, arXiv:1912.03695



SO(10)

- All of them embeddable into SO(10)
- paradox: $\pi_1(SO(10)/G_{SM})=0$
- resolution:



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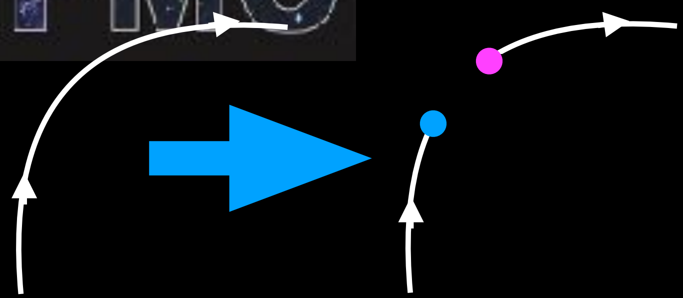
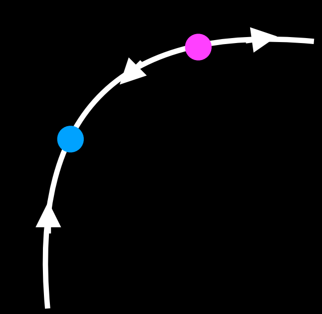
monopoles



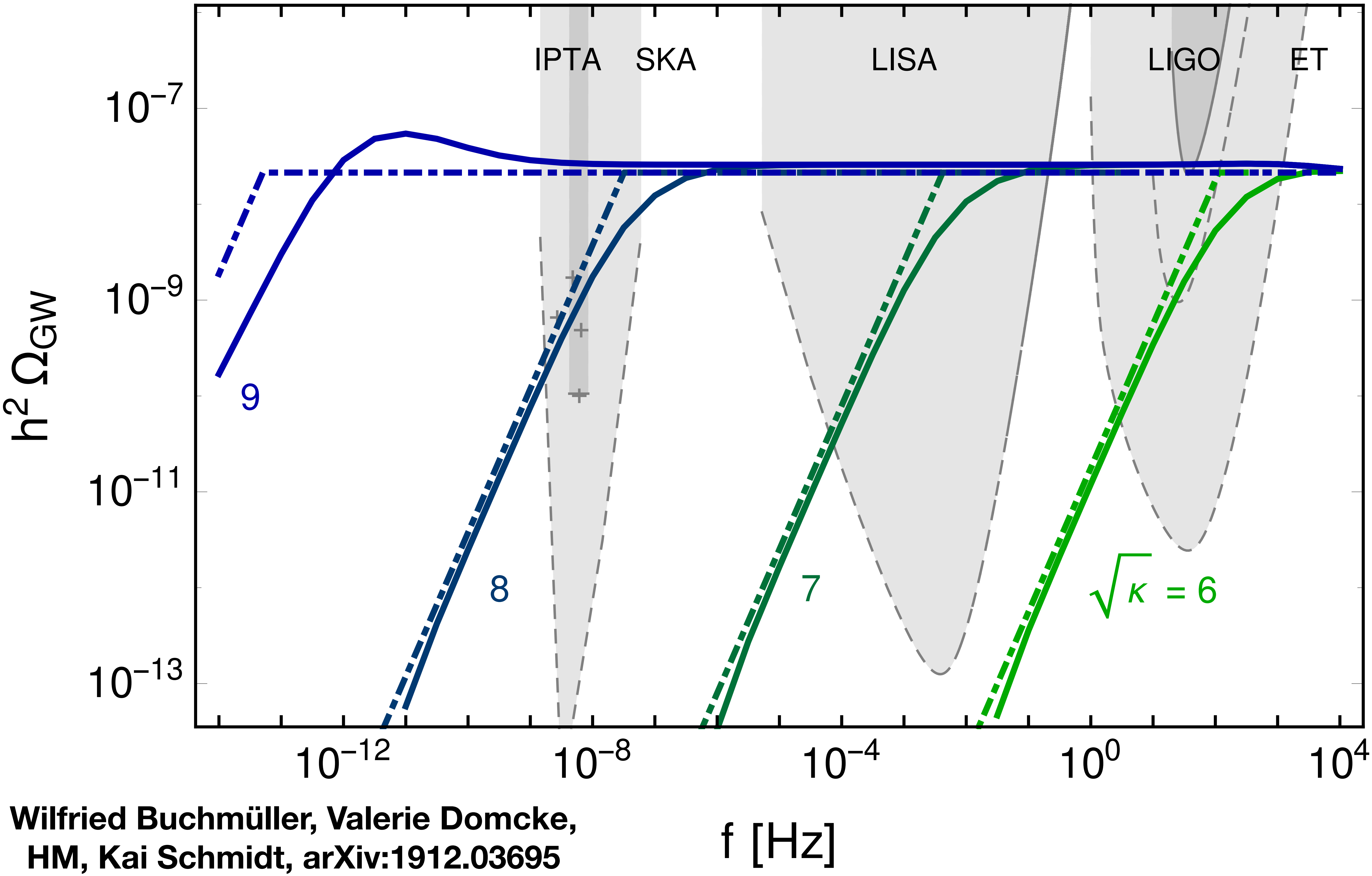
- string from $U(1)_{B-L}$ breaking is basically Abrikosov flux in a superconductor
  - For the Higgs $\phi(\pm Q)$
  - magnetic flux $2\pi\hbar/(e\,Q) \times$ integer (Q=1, 2, …)
  - minimum monopole charge $2\pi\hbar/e$
  - If Q=1, monopole can saturate the flux and cut the string
  - If Q=2, the minimum string cannot be cut by monopoles
  - dual Schwinger process
- survives to date if $v < 10^{15}$GeV

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



hybrid inflation

$\kappa = m^2_{\text{monopole}}/\mu$



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Asymmetric Matters from a dark first-order phase transition

Hitoshi Murayama (Berkeley, Kavli IPMU)
+Nell Hall (Berkeley), Thomas Konstandin (DESY), Robert McGehee (Berkeley)

arXiv:1911.12342

Sakharov Conditions

- Standard Model may have all three ingredients
- Baryon number violation
  - Electroweak anomaly (sphaleron effect)
- CP violation
  - Kobayashi–Maskawa phase

$$J \propto \det[M_u^\dagger M_u, M_d^\dagger M_d]/T_{EW}^{12} \sim 10^{-20} \ll 10^{-10}$$

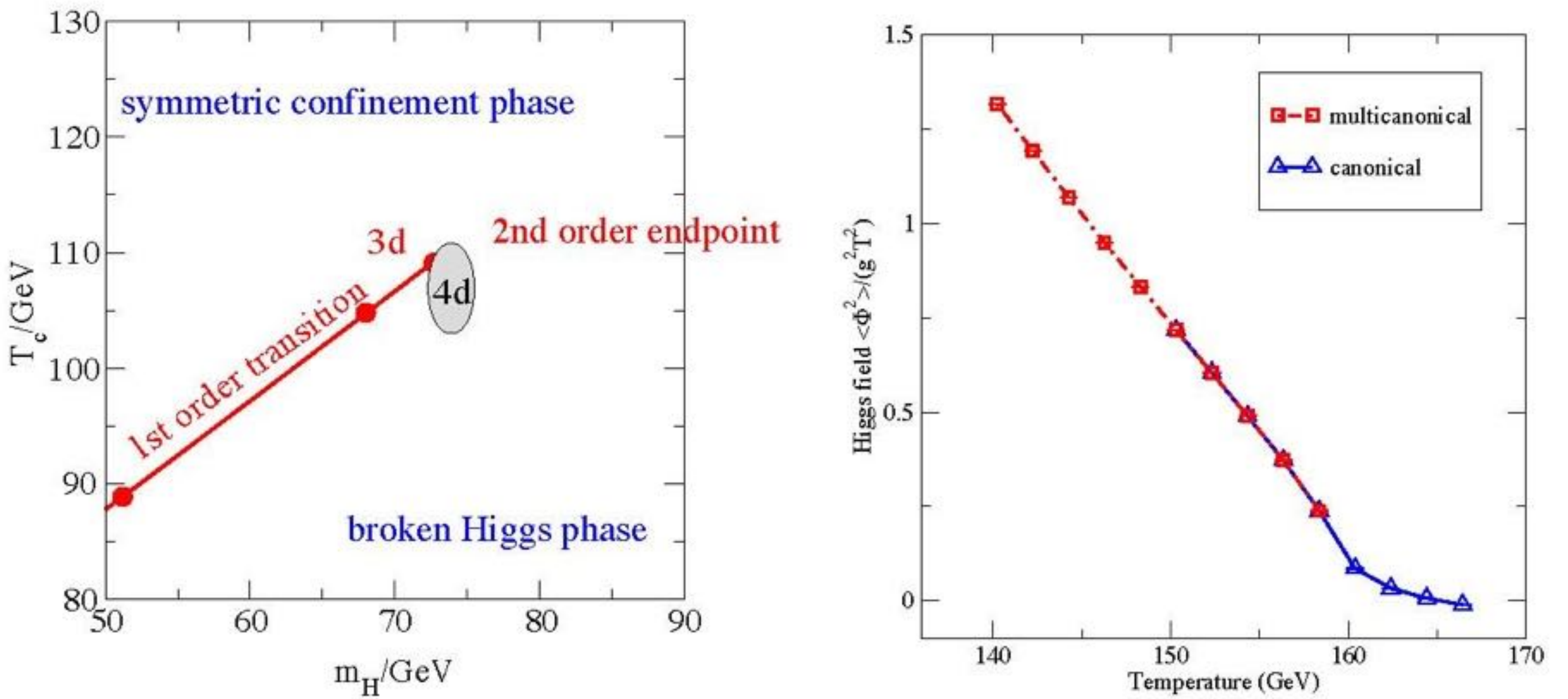
- Departure from equilibrium
  - First-order phase transition of Higgs

requires m_h < 75 GeV

- Experimentally testable?

Mikko Laine (Bern)

Phase diagram for the Standard Model:



$\langle H \rangle$=0 from gauge invariance (Elitzur)

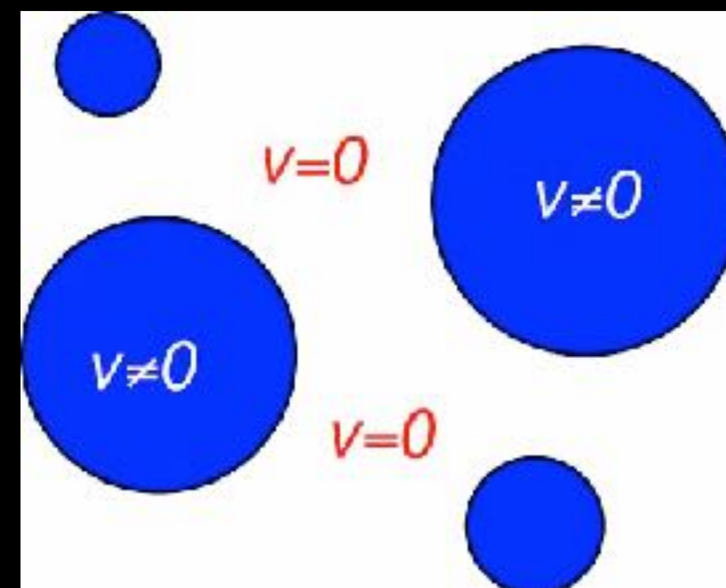
$\langle H^\dagger H \rangle$ is not an order parameter

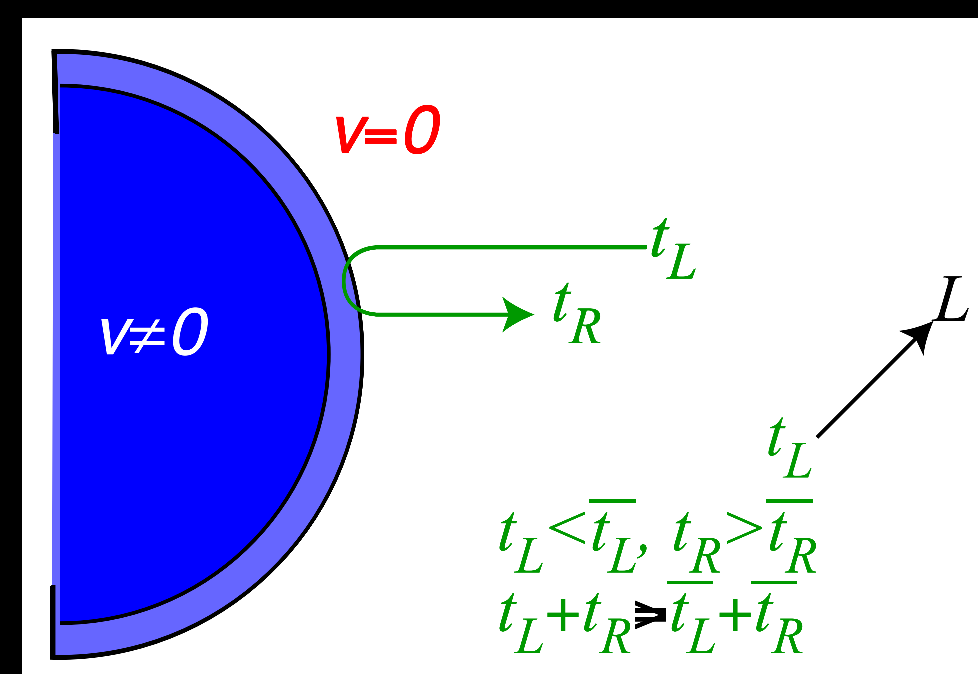
for m_h=125GeV, it is crossover

No phase transition in the Minimal Standard Model

Scenario
Cohen, Kaplan, Nelson

- First-order phase transition
- Different reflection probabilities for t_L, t_R
- asymmetry in top quark
- Left-handed top quark asymmetry partially converted to lepton asymmetry via anomaly
- Remaining top quark asymmetry becomes baryon asymmetry
- need *varying CP phase* inside the bubble wall (G. Servant)
- fixed KM phase doesn't help
- need CPV in Higgs sector





Electric Dipole Moment

- baryon asymmetry limited by the sphaleron rate
  $\Gamma \sim 20\, \alpha_W^5\, T \sim 10^{-6}\, T$

- Can't lose much more to obtain 10^{-9}

- need
  - new physics for 1st order PT at the Higgs scale v=250 GeV
  - CP violation×efficiency ≥10^{-3}

Oct 2018

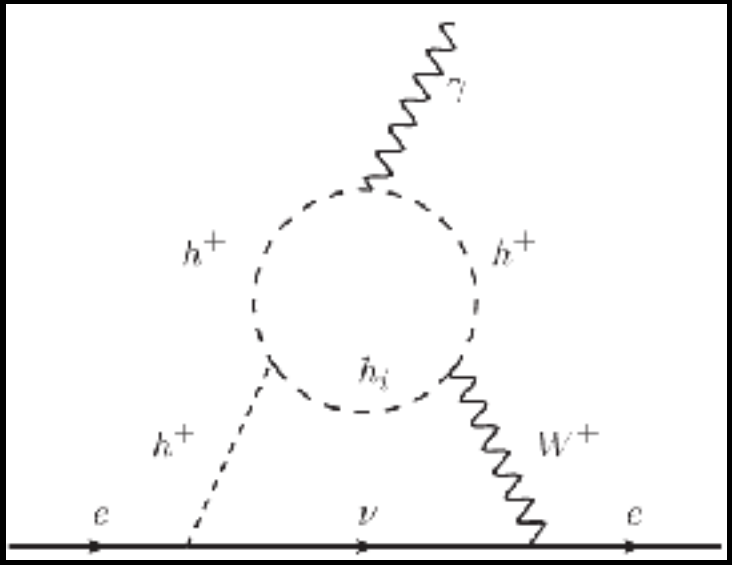
ARTICLE

https://doi.org/10.1038/s41586-018-0599-8

Improved limit on the electric dipole moment of the electron

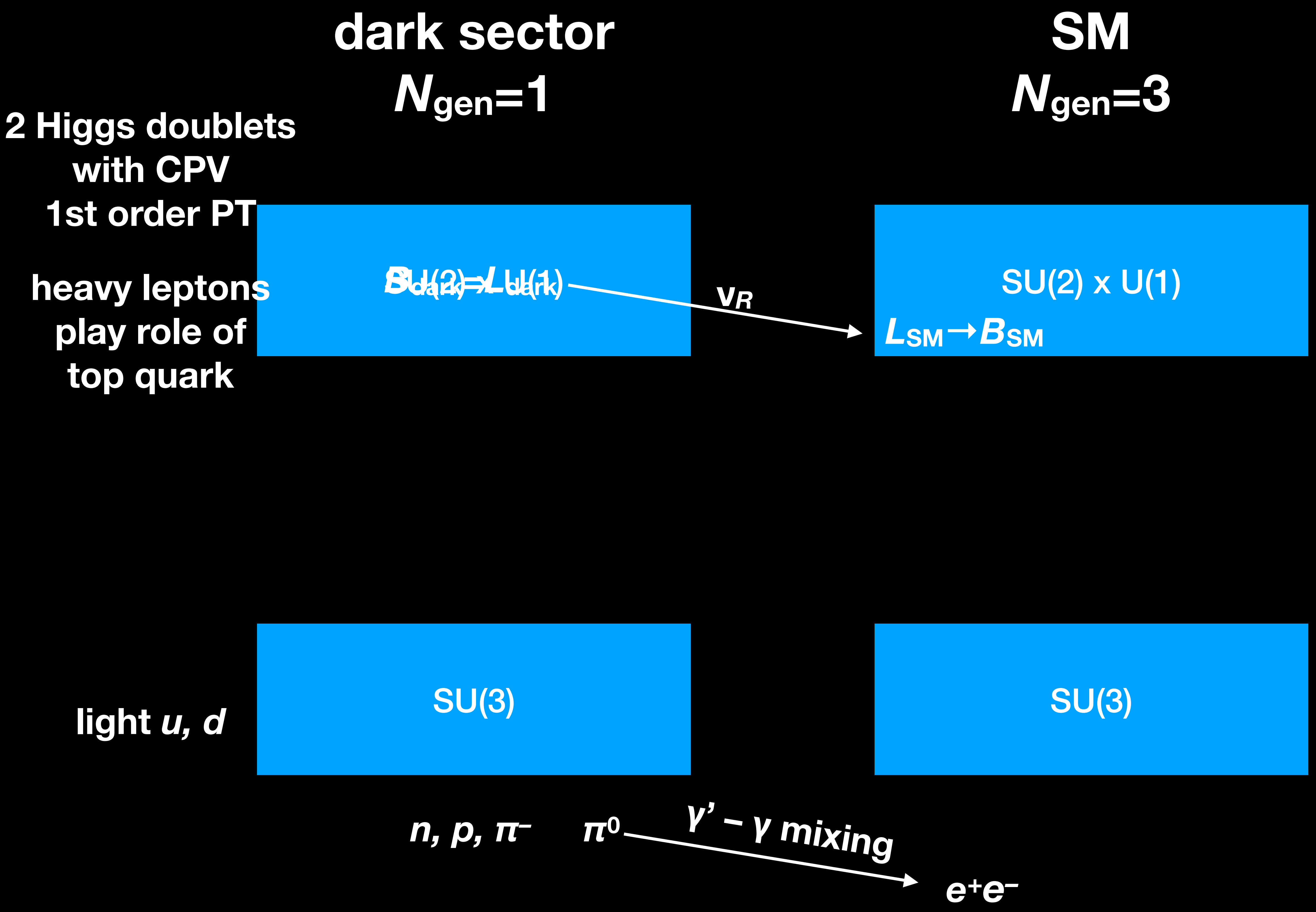
ACME Collaboration*

$d_e \leq 1.1\times10^{-29}\ e$ cm

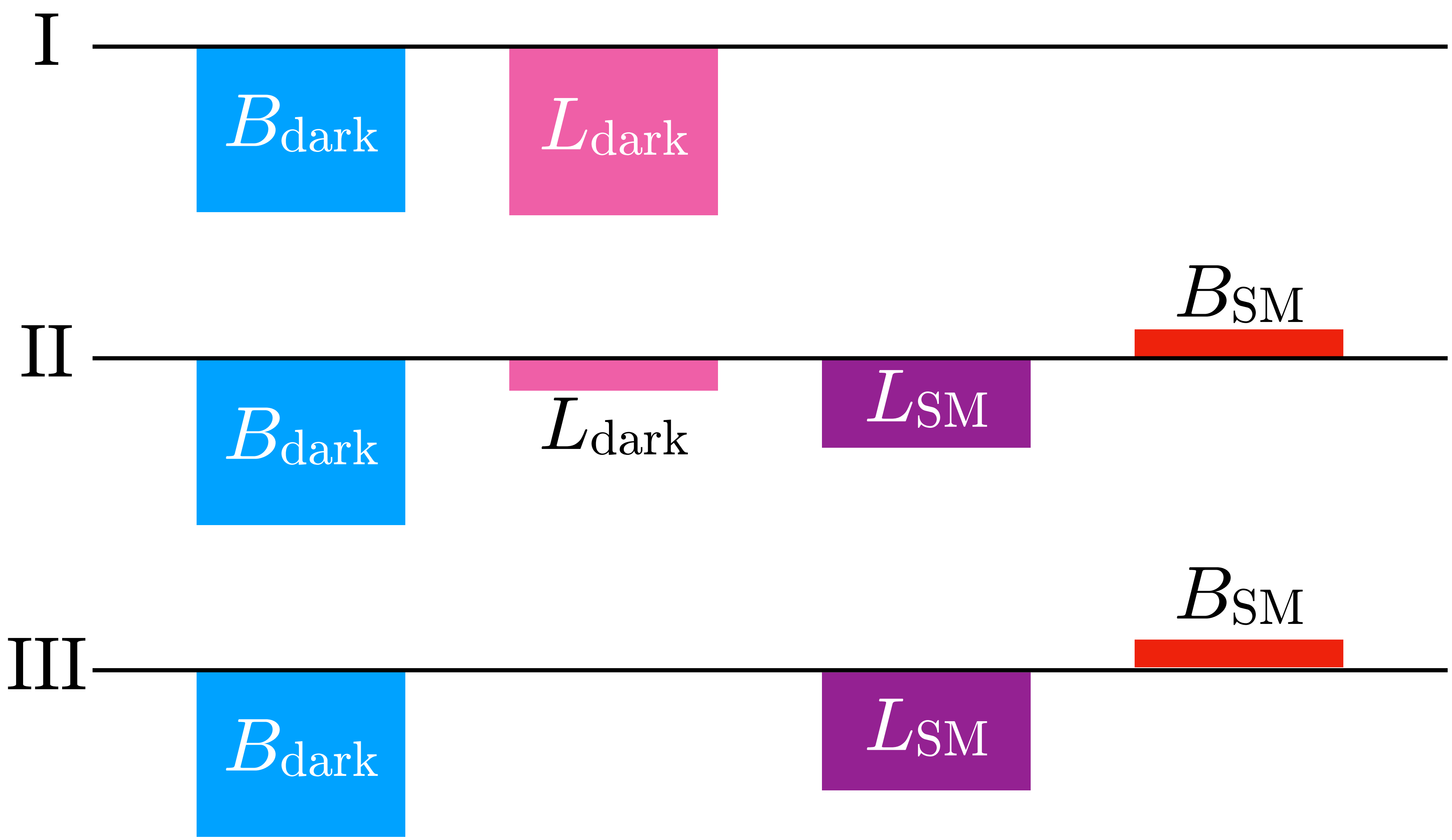


Barr-Zee diagrams

$$d_e \approx \frac{e m_e}{(16\pi^2)^2}\frac{1}{v^2}\sin\delta = 1.6\times10^{-22} e\mathrm{cm}\sin\delta$$



dark sector
N_{gen}=1
SM
N_{gen}=3
2 Higgs doublets
with CPV
1st order PT
heavy leptons
play role of
top quark
ν_R
SU(2) x U(1)
$L_{SM} \to B_{SM}$
light u, d
SU(3)
SU(3)
n, p, π^-
π^0
$\gamma' - \gamma$ mixing
e^+e^-

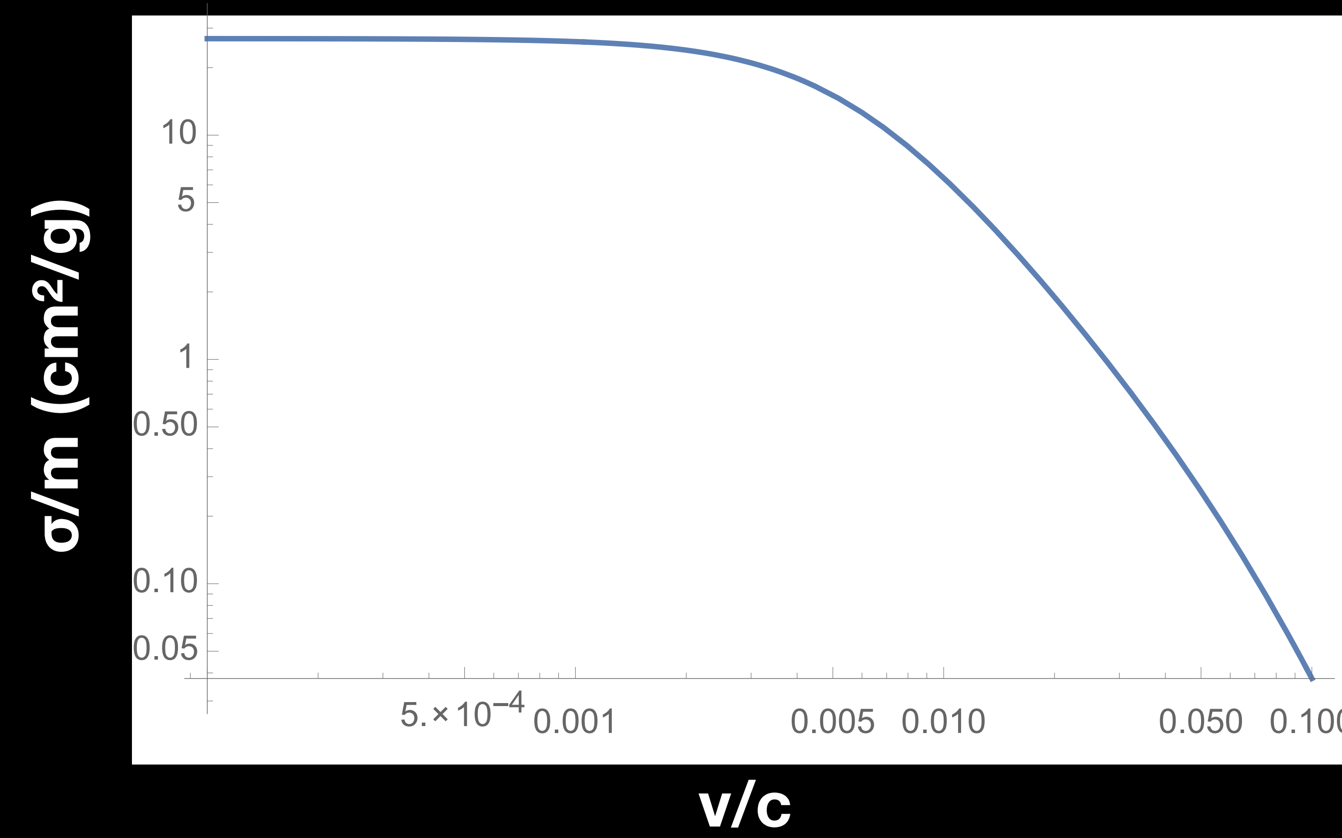


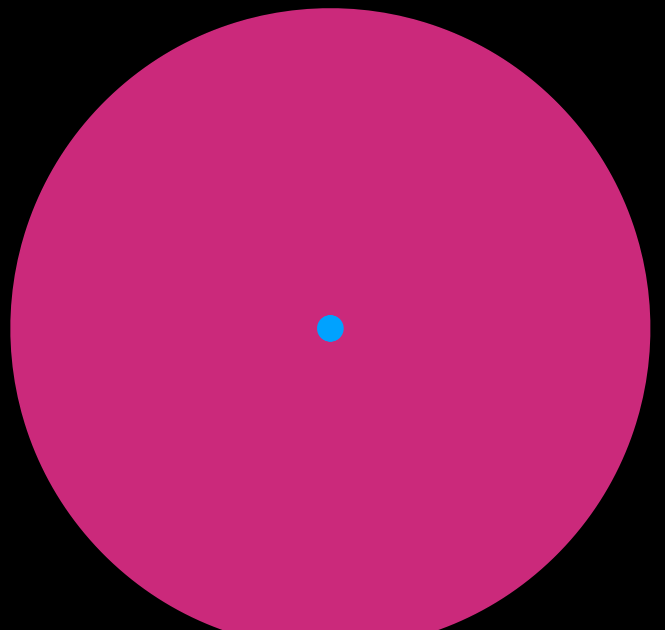
If $M_N > T_{\rm sphaleron}$ $B_{\rm SM} = \frac{36}{133} B_{\rm dark}, \quad L_{\rm SM} = -\frac{97}{133} B_{\rm dark}$ **$m_{n'}$=1.63 GeV**

If $M_N < T_{\rm sphaleron}$ $B_{\rm SM} = \frac{12}{37} B_{\rm dark}, \quad L_{\rm SM} = -\frac{25}{37} B_{\rm dark}$ **$m_{n'}$=1.36 GeV**

n-n scattering

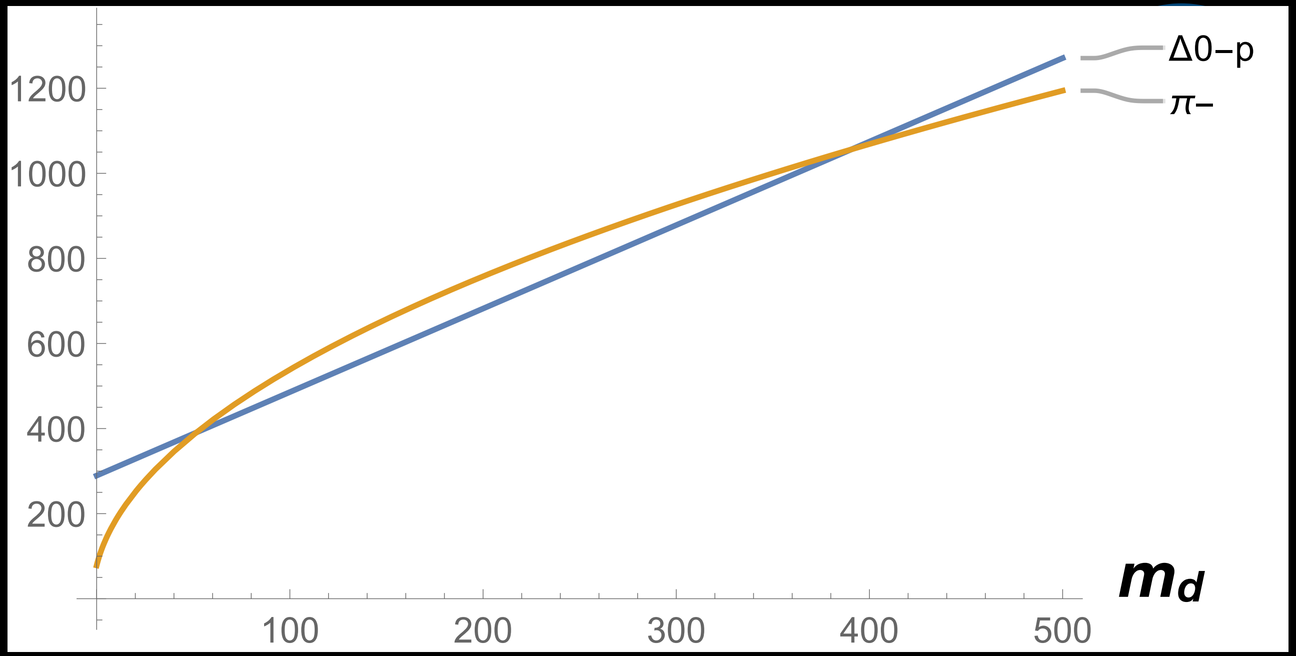
- *n-n* scattering has an anomalously large cross section a=18.9fm
- If so, it violates astrophysical bounds on self-interaction
- a fine cancellation between the bare and one-loop couplings in the pion-less EFT
- According to lattice simulations (HAL QCD), the cross section is more or less of the geometric size if pion mass is not special



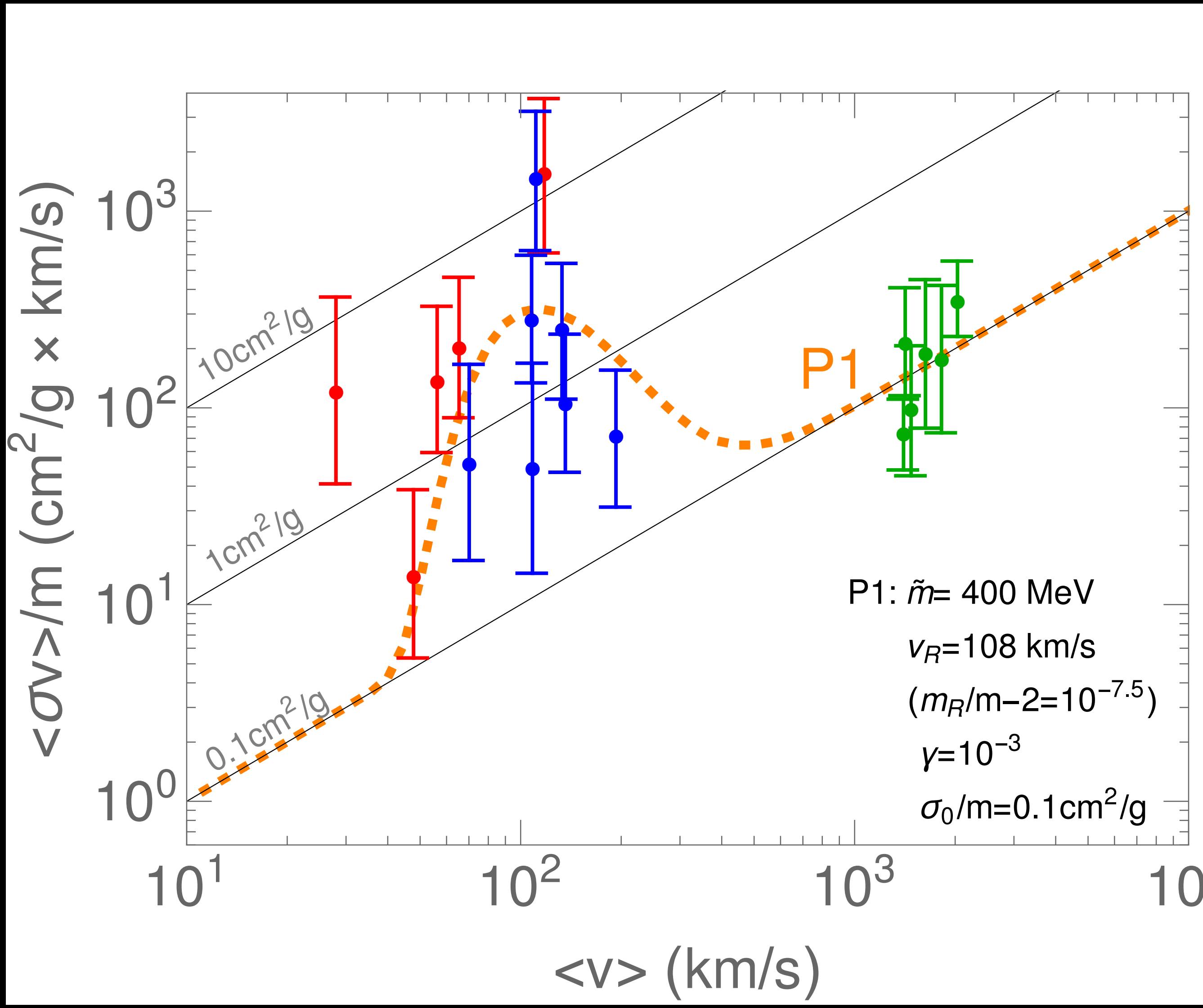


baryon spectrum

- m_u and m_d free parameters
- If $m_d \ll m_u \ll \Lambda_{QCD}$, n' dominates
- If $m_u \ll m_d \ll \Lambda_{QCD}$, p' dominates, together with π'^- for charge neutrality
    - possibly a resonant interaction $\pi'^- p' \to \Delta^0 \to \pi'^- p'$
    - may solve core/cusp problem



Robert McGehee, HM, Yu-Dai Tsai, in prep



Xiaoyong Chu, Camilo Carcia-Cely, HM, Phys.Rev.Lett. 122 (2019) no.7, 071103

some history

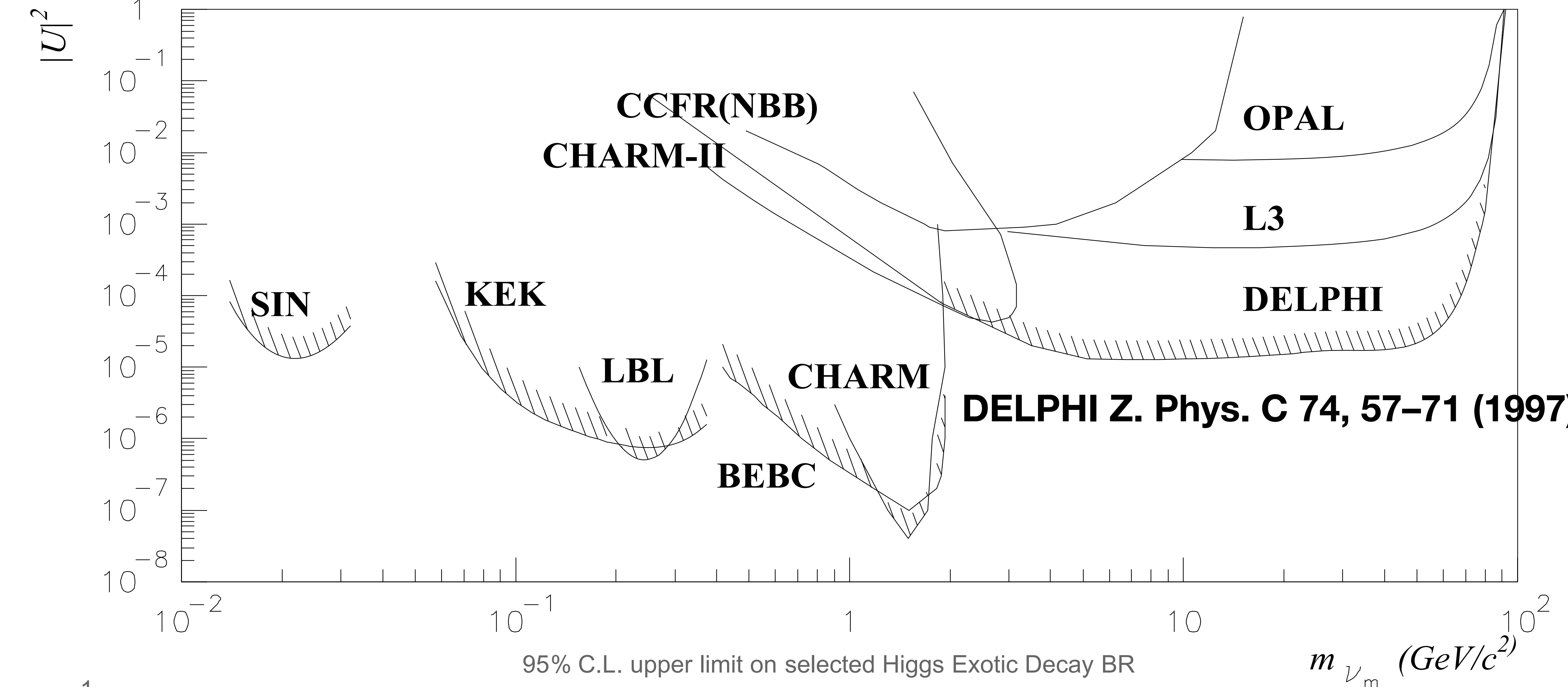
- asymmetric dark matter
  - S. Nussinov, PLB 165, 55 (1985) “technocosmology”
  - R. Kitano, HM, M. Ratz, arXiv:0807.4313, moduli decay
  - D.E. Kaplan, M. Luty, K. Zurek, arXiv:0901.4117
- darkogenesis (= “EW baryogenesis” in the dark sector)
  - J. Shelton, K. Zurek, arXiv:1008.1997

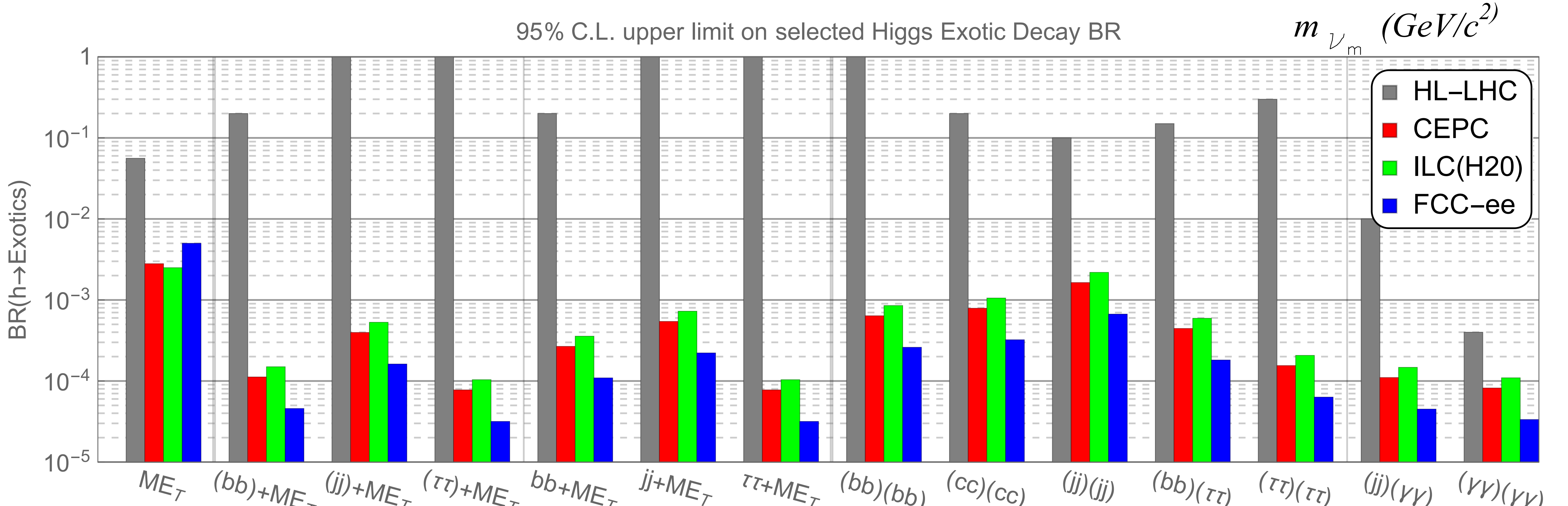
neutrino portal

$$\mathcal{L} = y' \bar{L}' H \nu_R + y_i \bar{L}_i H \nu_R$$

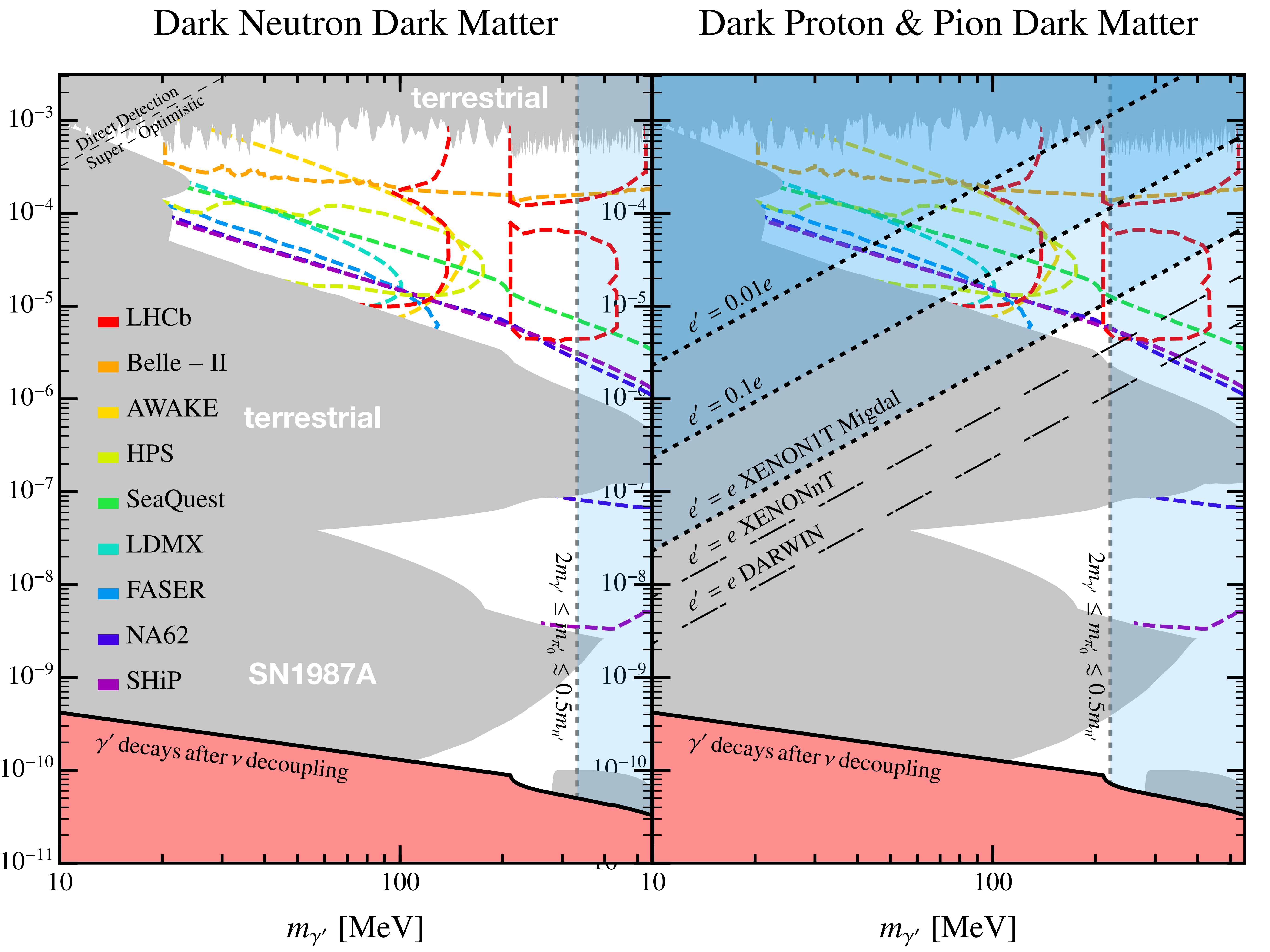
$$\epsilon_i = \frac{y_i}{\sqrt{(y')^2 + (y_i)^2}} \qquad M_\nu = \sqrt{(y')^2 + (y_i)^2} v$$

- charged current universality: $\varepsilon_i^2 < 10^{-3}$
- $\mu \to e\, \gamma$ constraint: $\varepsilon_e\, \varepsilon_\mu < 4\times10^{-5}\ (G_F\, M_\nu)$
- $\tau \to \mu\, \gamma$ constraint: $\varepsilon_e\, \varepsilon_\mu < 0.03\ (G_F\, M_\nu)$
- If $M_\nu < 70$ GeV, $\varepsilon_i^2 < 10^{-5}$ (DELPHI: $Z \to \nu\, \nu_R$, $\nu_R \to l f f$)
- equilibration of asymmetries requires only $\varepsilon_i > 10^{-16}$ or so
- (orders of magnitude estimates so far)



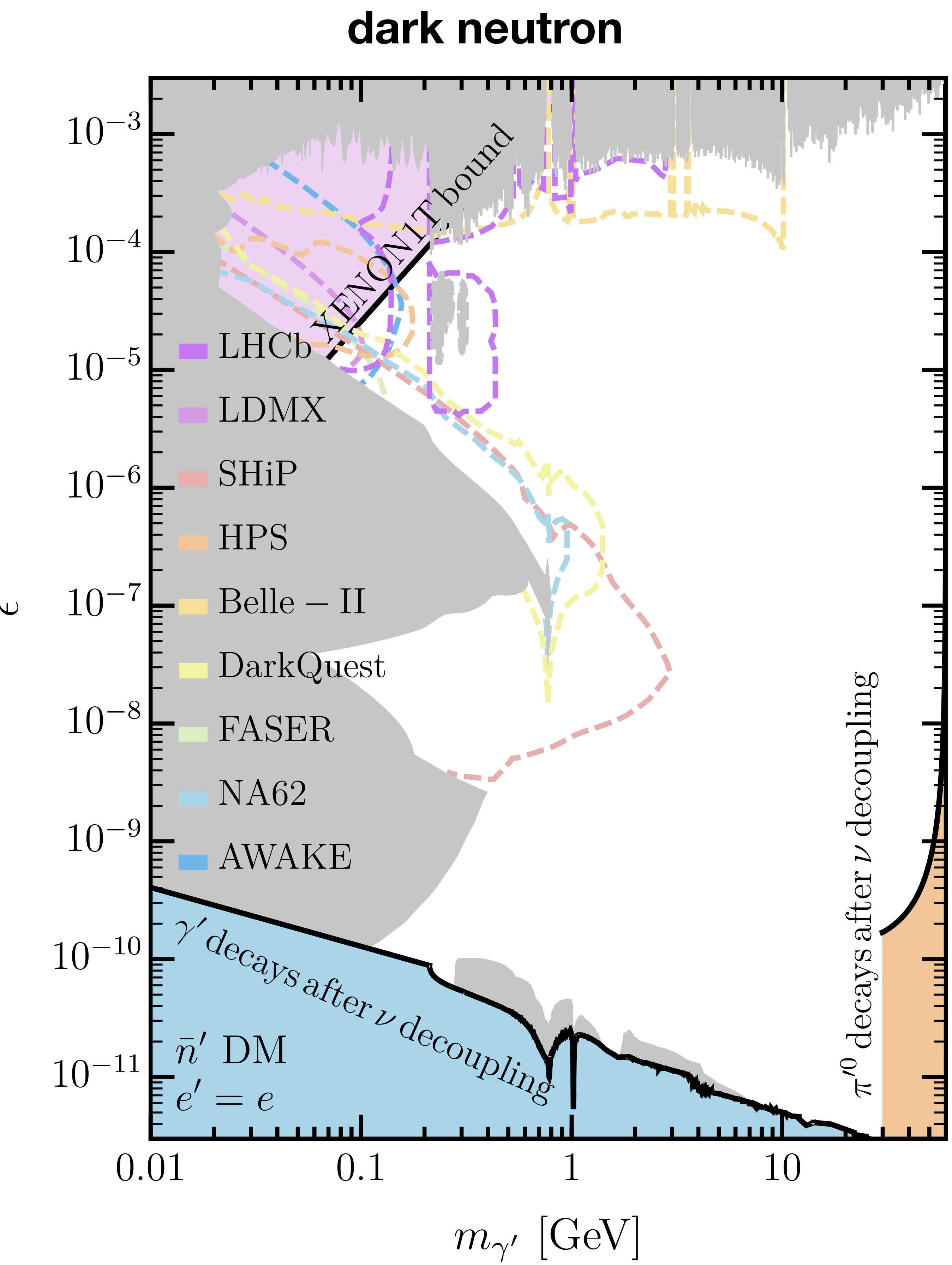


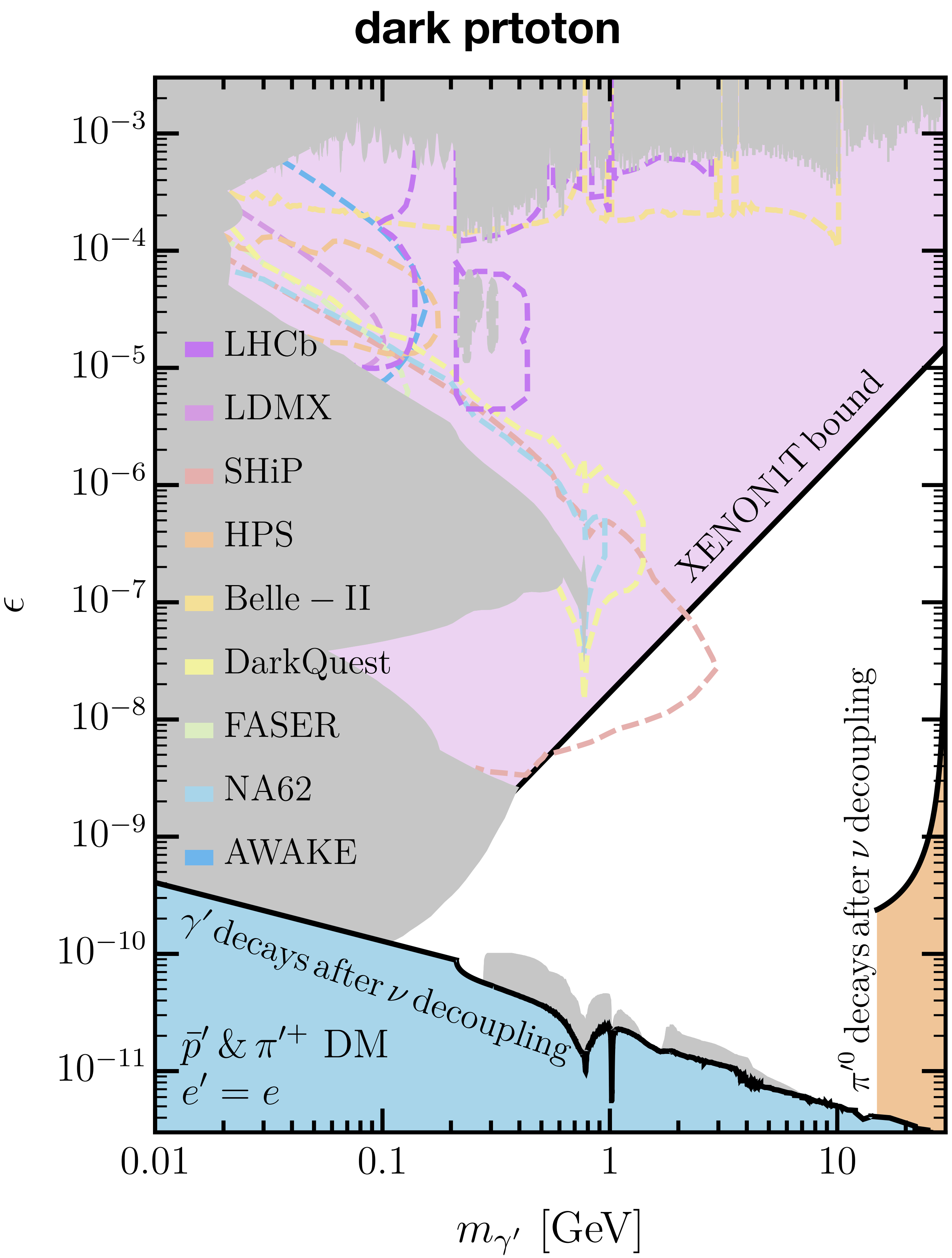
Zhen Liu, Lian-Tao Wang, Hao Zhang, arXiv:1612.09284

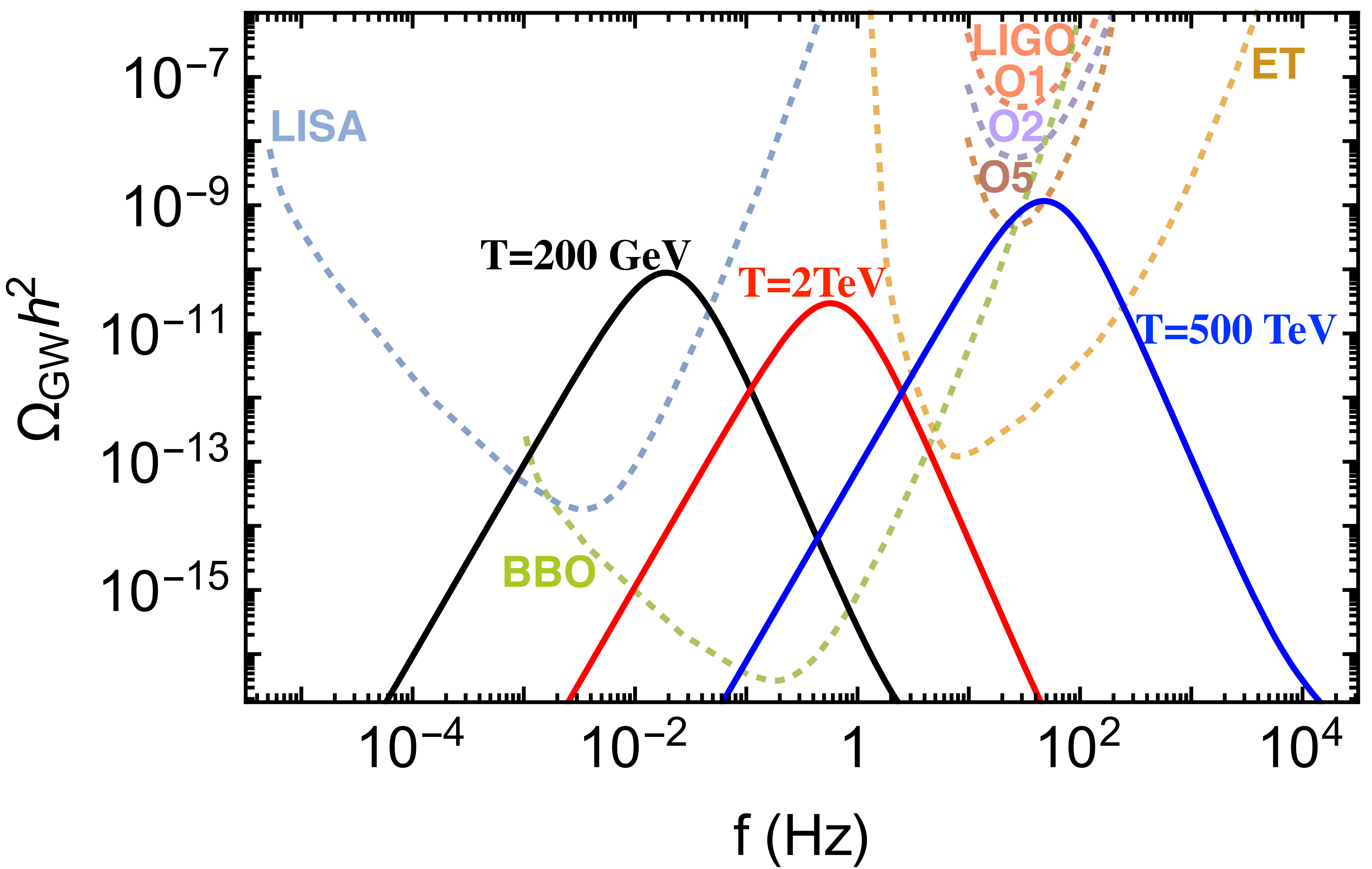


Dark Neutron Dark Matter
Dark Proton & Pion Dark Matter
terrestrial
Direct Detection
Super – Optimistic
LHCb
Belle – II
AWAKE
HPS
SeaQuest
LDMX
FASER
NA62
SHiP
terrestrial
SN1987A
γ' decays after ν decoupling
$2m_{\gamma'} \leq m_{\pi'} \lesssim 0.5 m_{n'}$
$e' = 0.01e$
$e' = 0.1e$
$e' = e$ XENON1T Migdal
$e' = e$ XENONnT
$e' = e$ DARWIN
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10
100
$m_{\gamma'}$ [MeV]

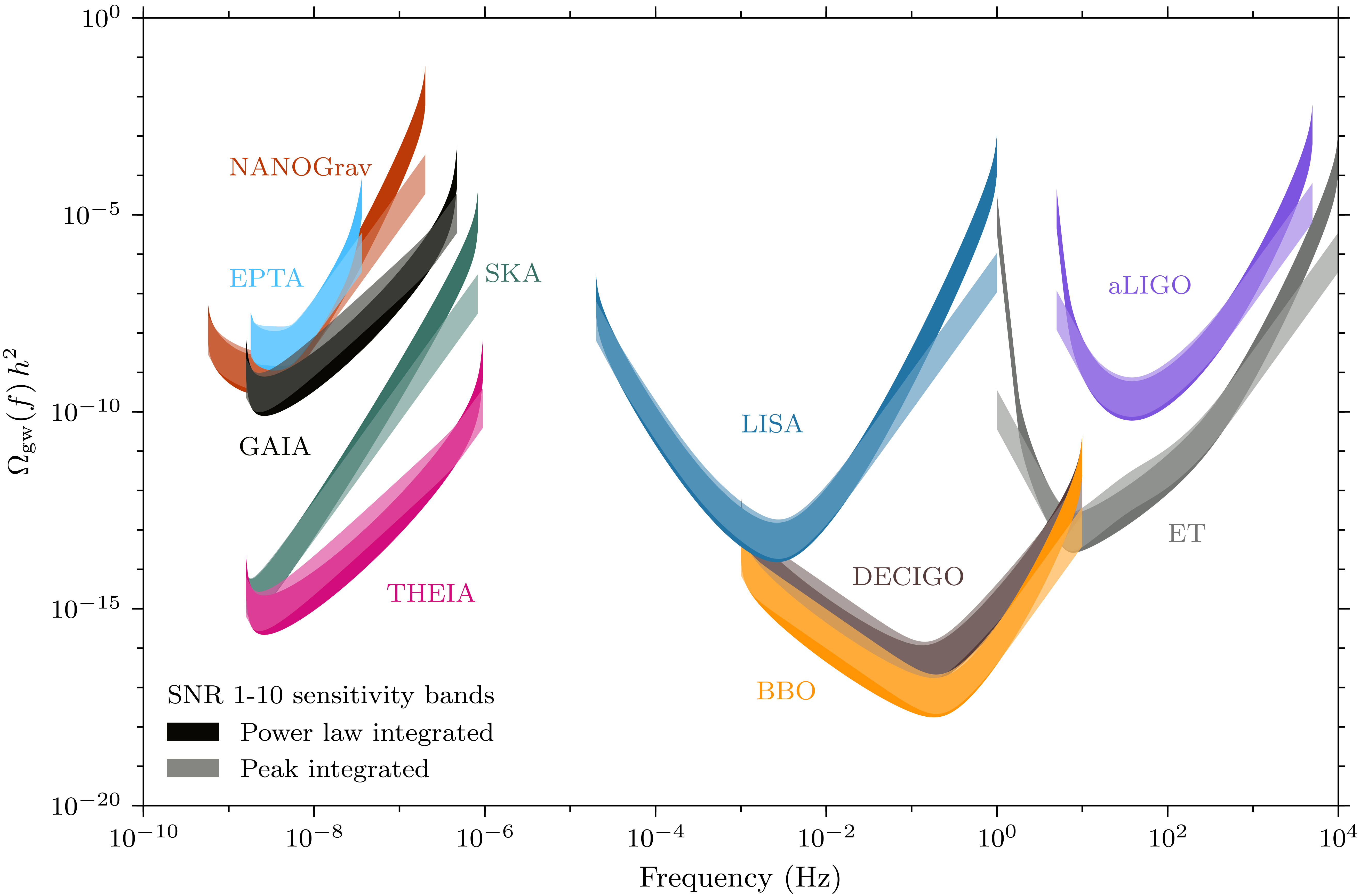
If the asymmetry originates in the SM side transferred to the dark side







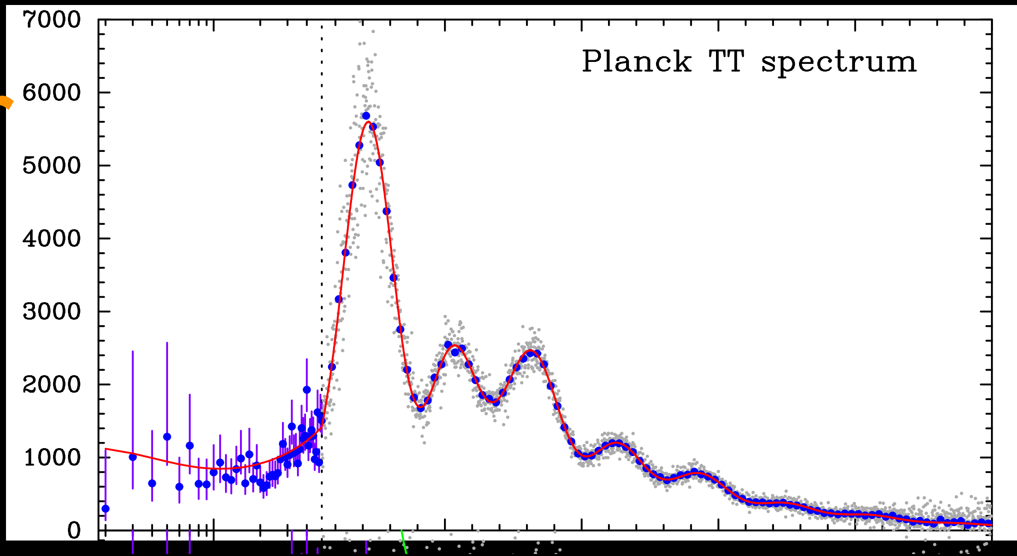
LISA
LIGO
O1
O2
O5
ET
BBO
T=200 GeV
T=2TeV
T=500 TeV
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
$\Omega_{GW}h^2$
10^{-4}
10^{-2}
1
10^{2}
10^{4}
f (Hz)



Juan Garcia-Bellido, Hitoshi Murayama, Graham White, arXiv:2104.04778

Five evidences for physics beyond SM

- Since 1998, it became clear that there are at least five missing pieces in the SM
  - non-baryonic dark matter
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry



We don't really know their energy scales...


many things
to look forward to!