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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

Two Tales of Baryogenesis

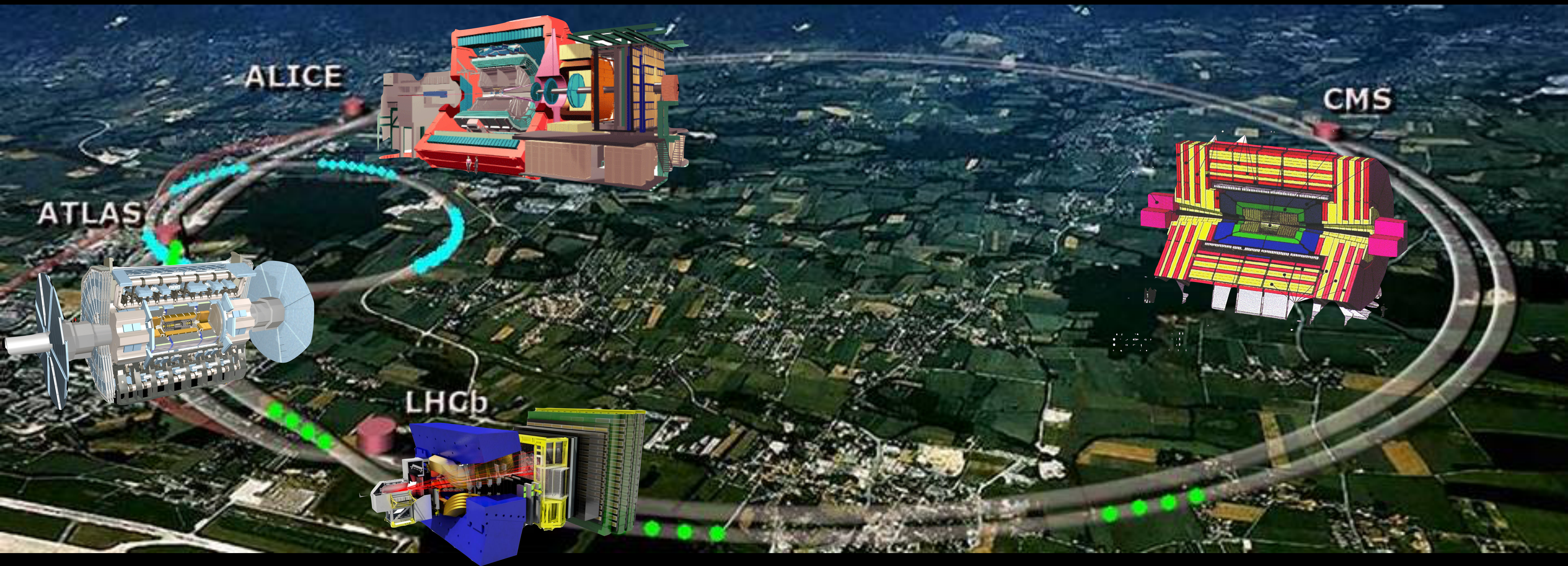
Hitoshi Murayama (Berkeley, Kavli IPMU)

CERN Theory Colloquium, April 8, 2020

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

hierarchy problem



There must be new particles discoverable at the LHC!

The New York Times

July 23, 2011

The Other Half of the Universe Discovered

Geneva, Switzerland

Squarks $J=0?$

The following data are averaged over all light flavors, presumably u, d, s, c with both chiralities. For flavor-tagged data, see listings for Stop and Sbottom. Most results assume minimal supergravity, an untested hypothesis with only five parameters. Alternative interpretation as extra dimensional particles is possible. See KK particle listing.

SQUARK MASS

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
538±10	**OUR FIT**		**mSUGRA assumptions**
532±11	[1]ABBIENDI 11D	CMS	Missing ET with mSUGRA assumptions
541±14	[2]ADLER 11O	ATLAS	Missing ET with mSUGRA assumptions
• • • We do not use the following data for averages, fits, limits, etc • • •			
652±105	[3]ABBIENDI 11K	CMS	extended mSUGRA with 5 more parameters

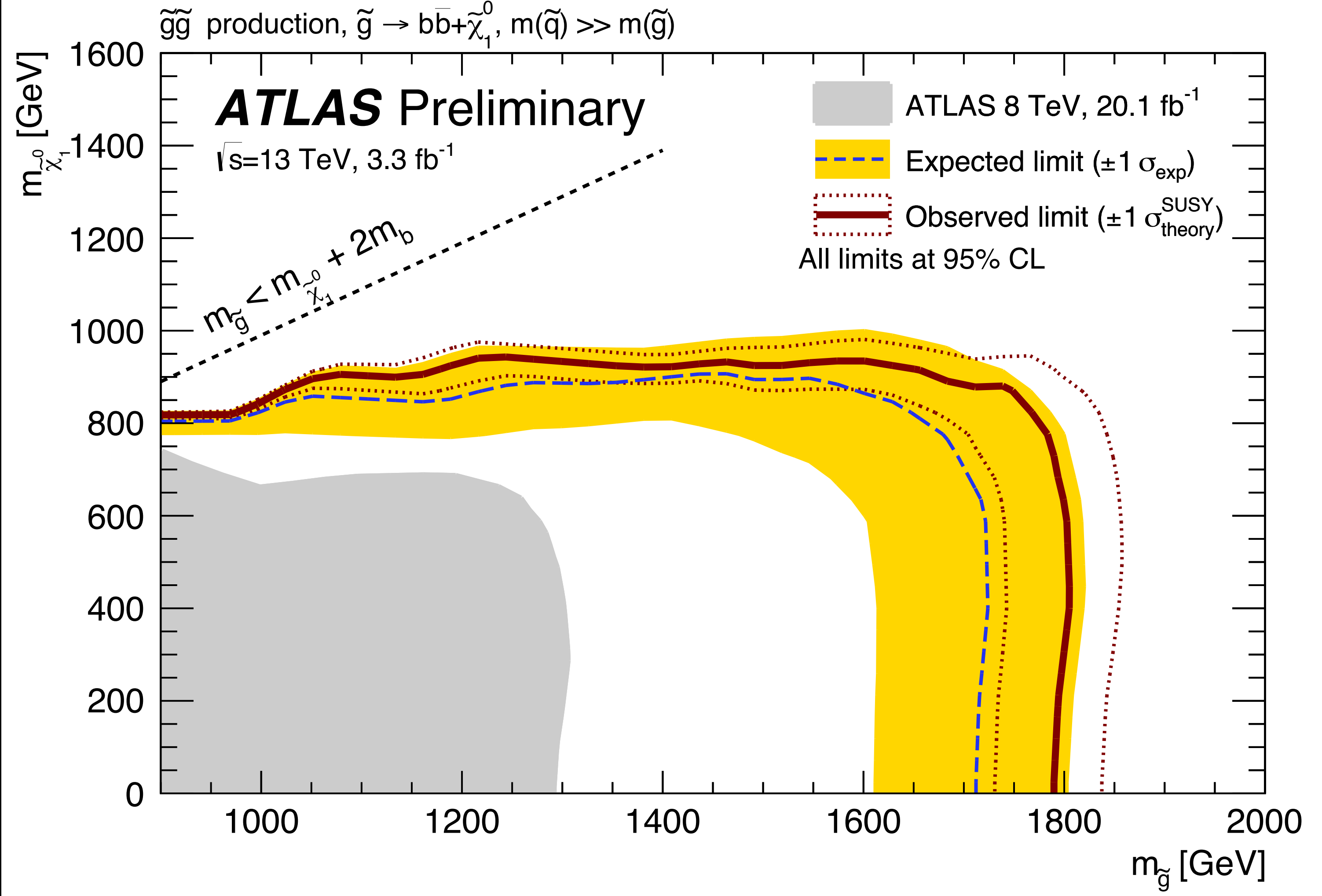
[1]ABBIENDI 11D assumes minimal supergravity in the fits to the data of jets and missing energies and set $A_0=0$ and $\tan\beta = 3$. See Fig. 5 of the paper for other choices of A_0 and $\tan\beta$. The result is correlated with the gluino mass M_3. See listing for gluino.

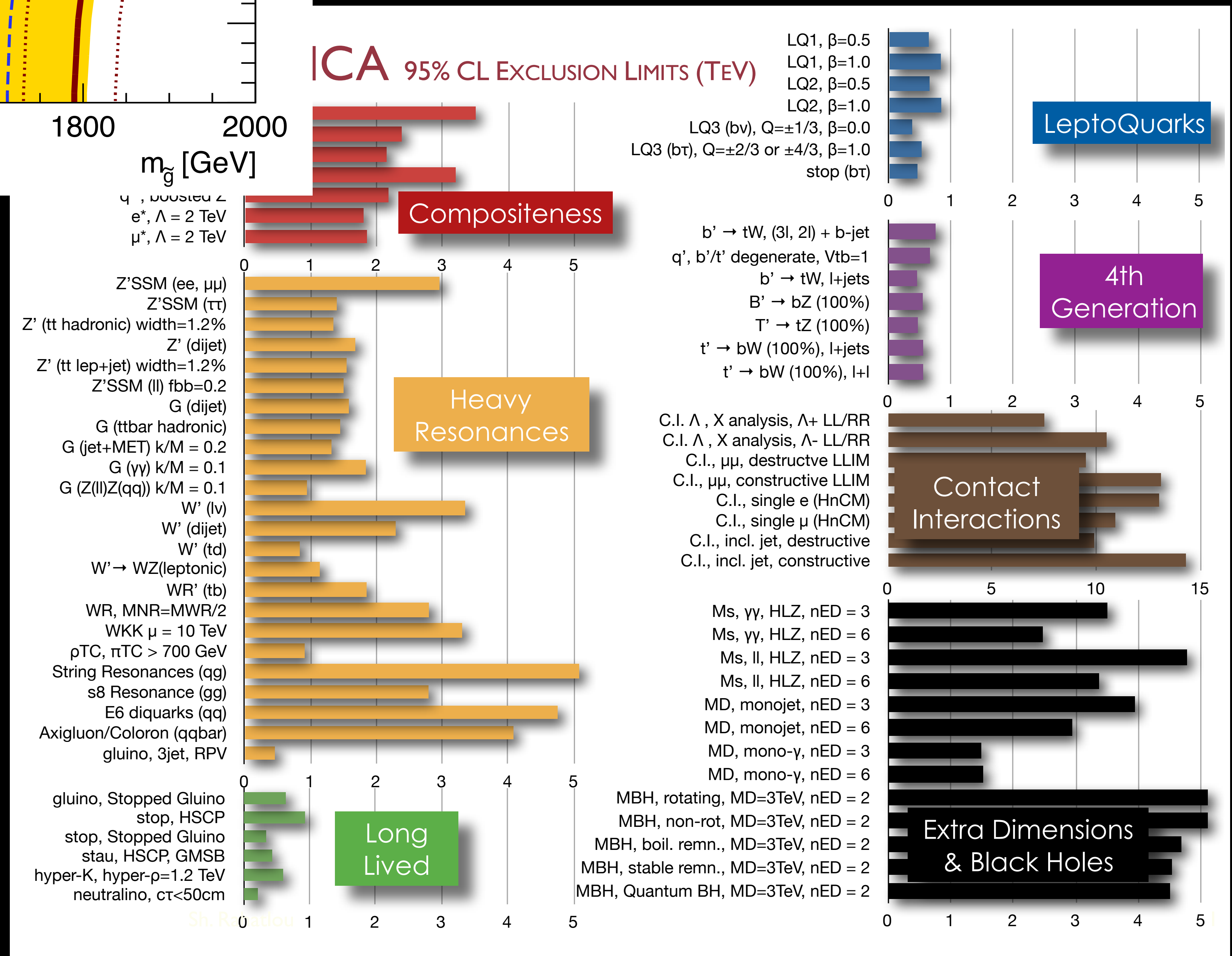
[2]ADLER 11O uses the same set of assumptions as ABBIENDI 11D, but with $\tan\beta = 5$.

[3]ABBIENDI 11K extends minimal supergravity by allowing for different scalar masses-squared for Hu, Hd, 5* and 10 scalars at the GUT scale.

SQUARK DECAY MODES

MODE	BR(%)	DOCUMENT ID	TECN	COMMENT
j+miss	32±5	ABE 10U	ATLAS	
j l+miss	73±10	ABE 10U	ATLAS	lepton universality
j e+miss	22±8	ABE 10U	ATLAS	
j μ +miss	25±7	ABE 10U	ATLAS	
q χ^+	seen	ABE 10U	ATLAS	

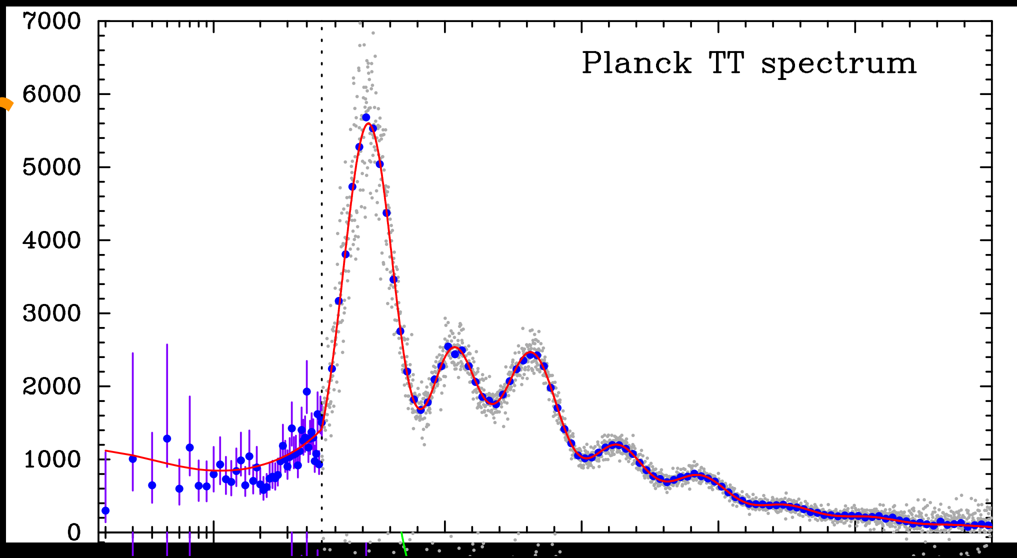




no sign of
new physics that
makes Higgs natural!

Five evidences for physics beyond SM

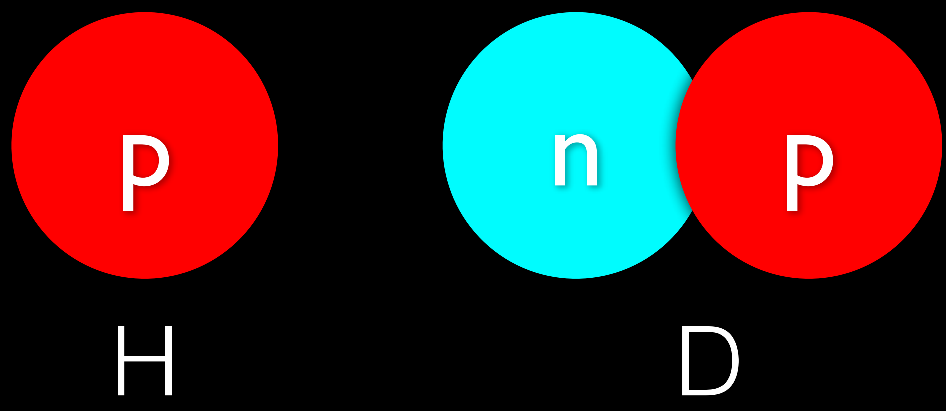
- Since 1998, it became clear that there are at least five missing pieces in the SM
  - non-baryonic dark matter
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry



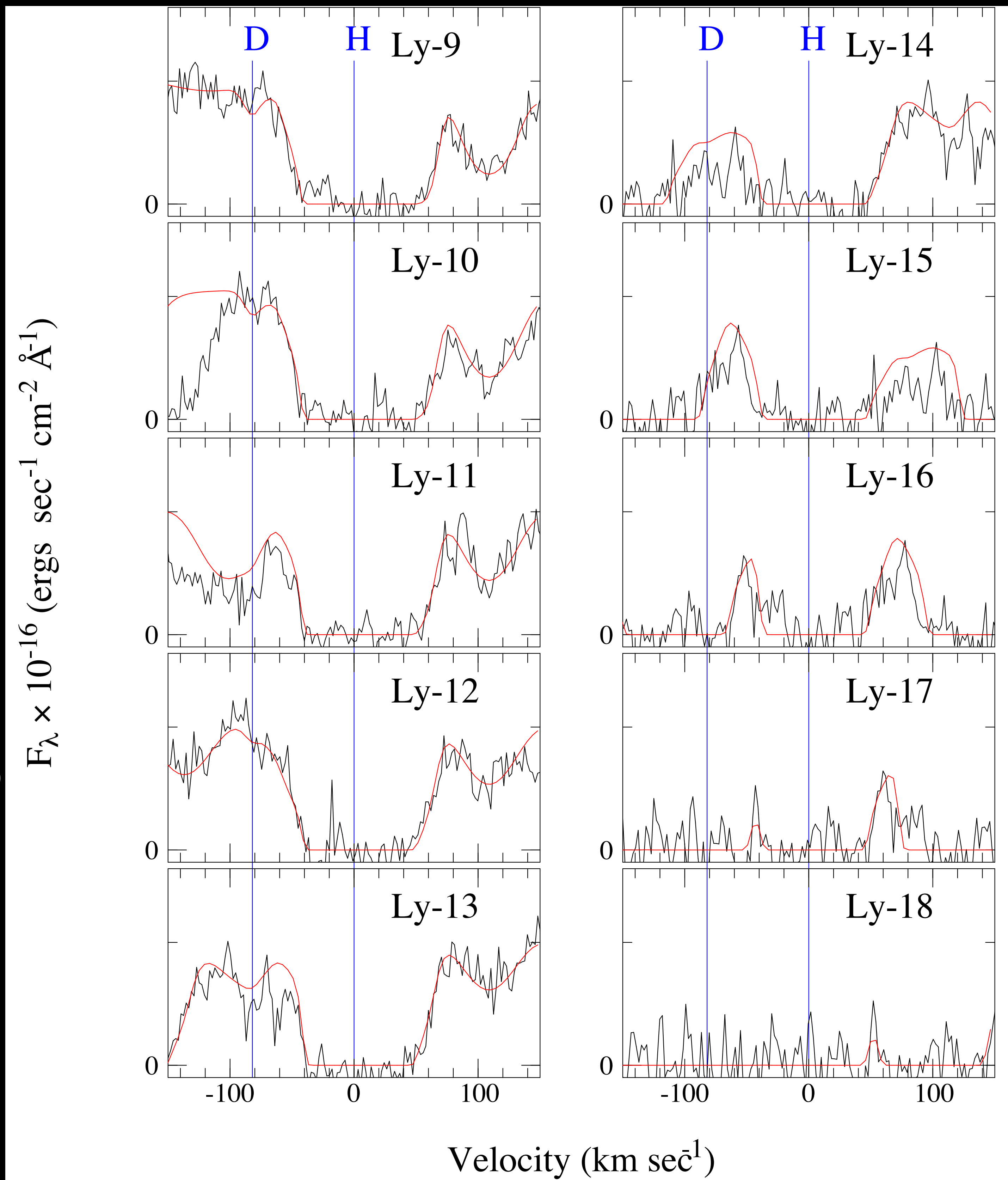
We don't really know their energy scales...

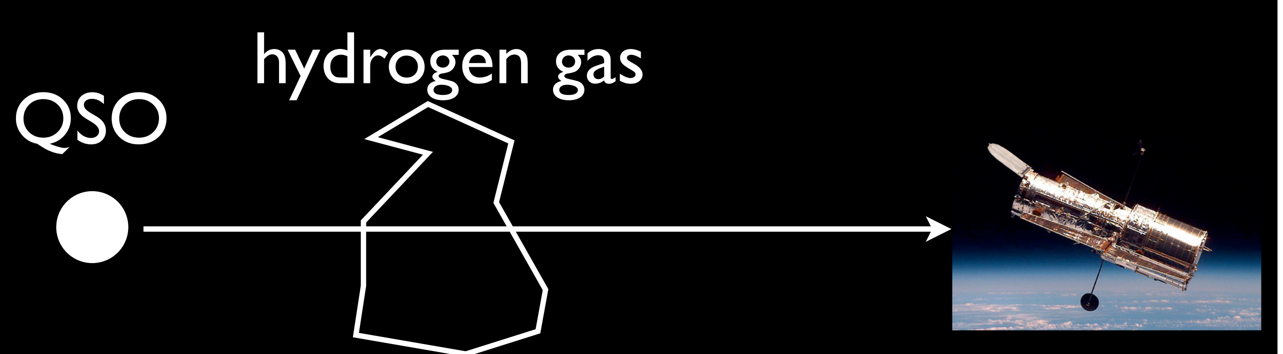
deuterium

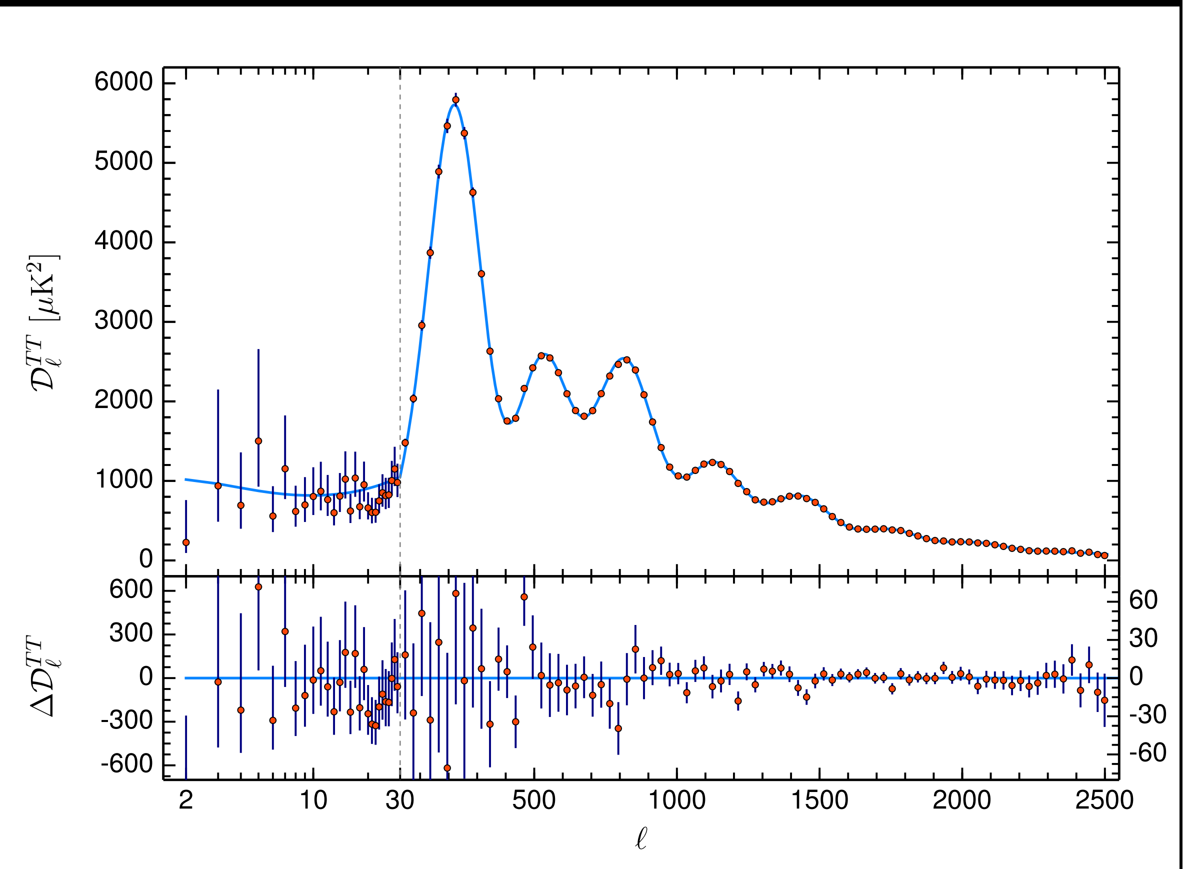
Kirkman, Tytler, Suzuki, O'Meara, Lubin



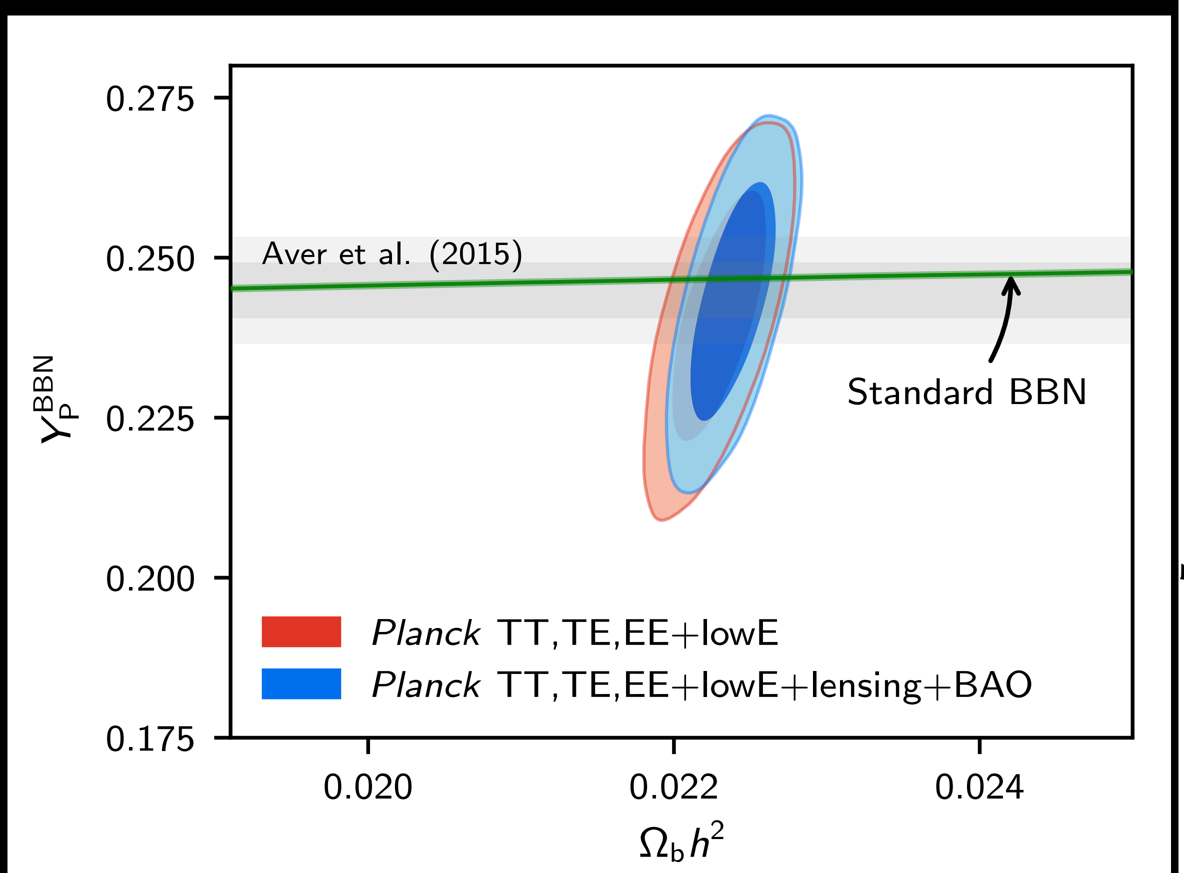
- the same chemically
- energy levels
  $E_n = -\alpha^2 \mu c^2/2$
- reduced mass differs by ~1/4000 between H & D



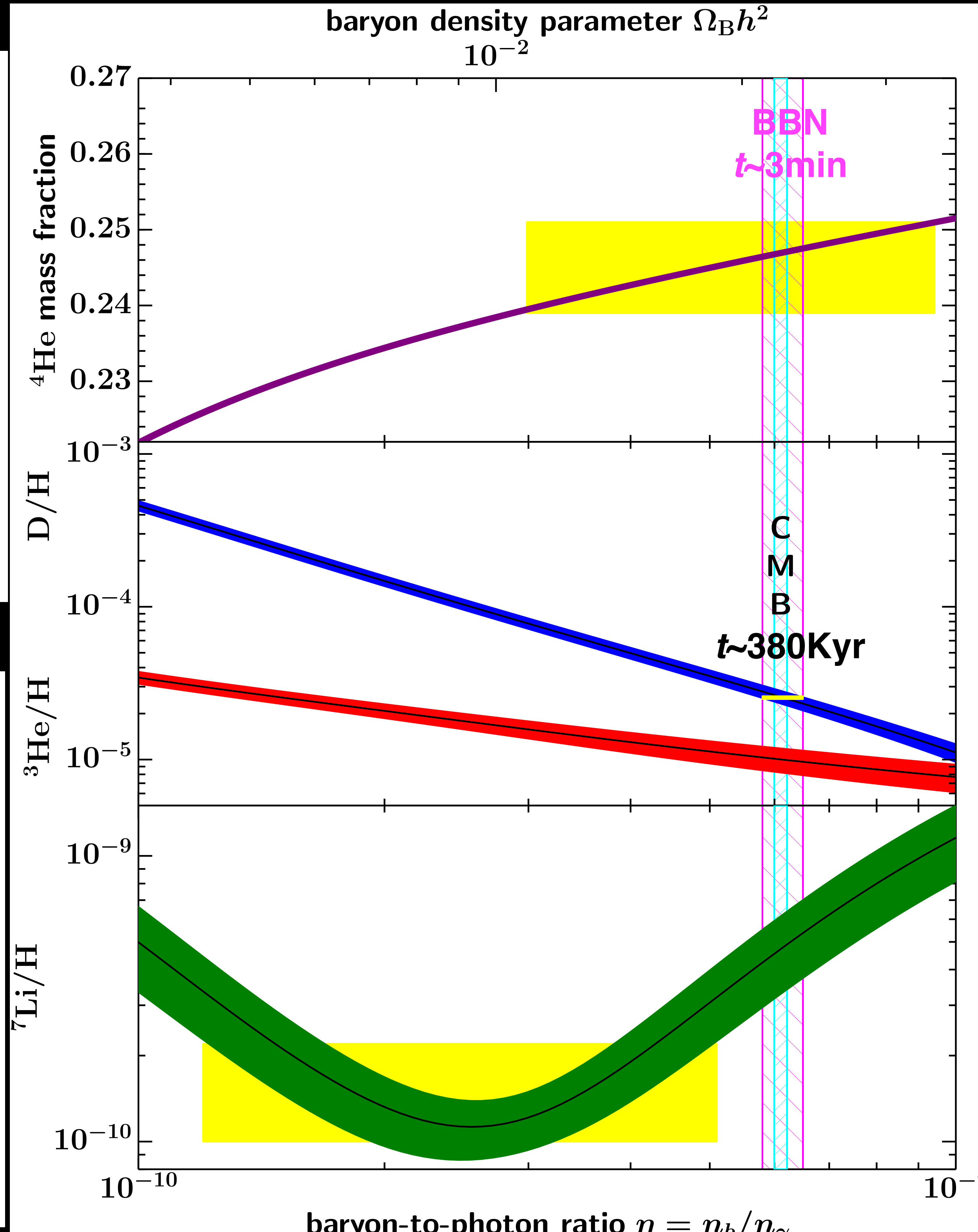




$\mathcal{D}_\ell^{TT}$ [μK^2]
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell^{TT}$
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ



Y_P^{BBN}
0.275
0.250
0.225
0.200
0.175
0.020
0.022
0.024
$\Omega_b h^2$
Aver et al. (2015)
Standard BBN
Planck TT,TE,EE+lowE
Planck TT,TE,EE+lowE+lensing+BAO



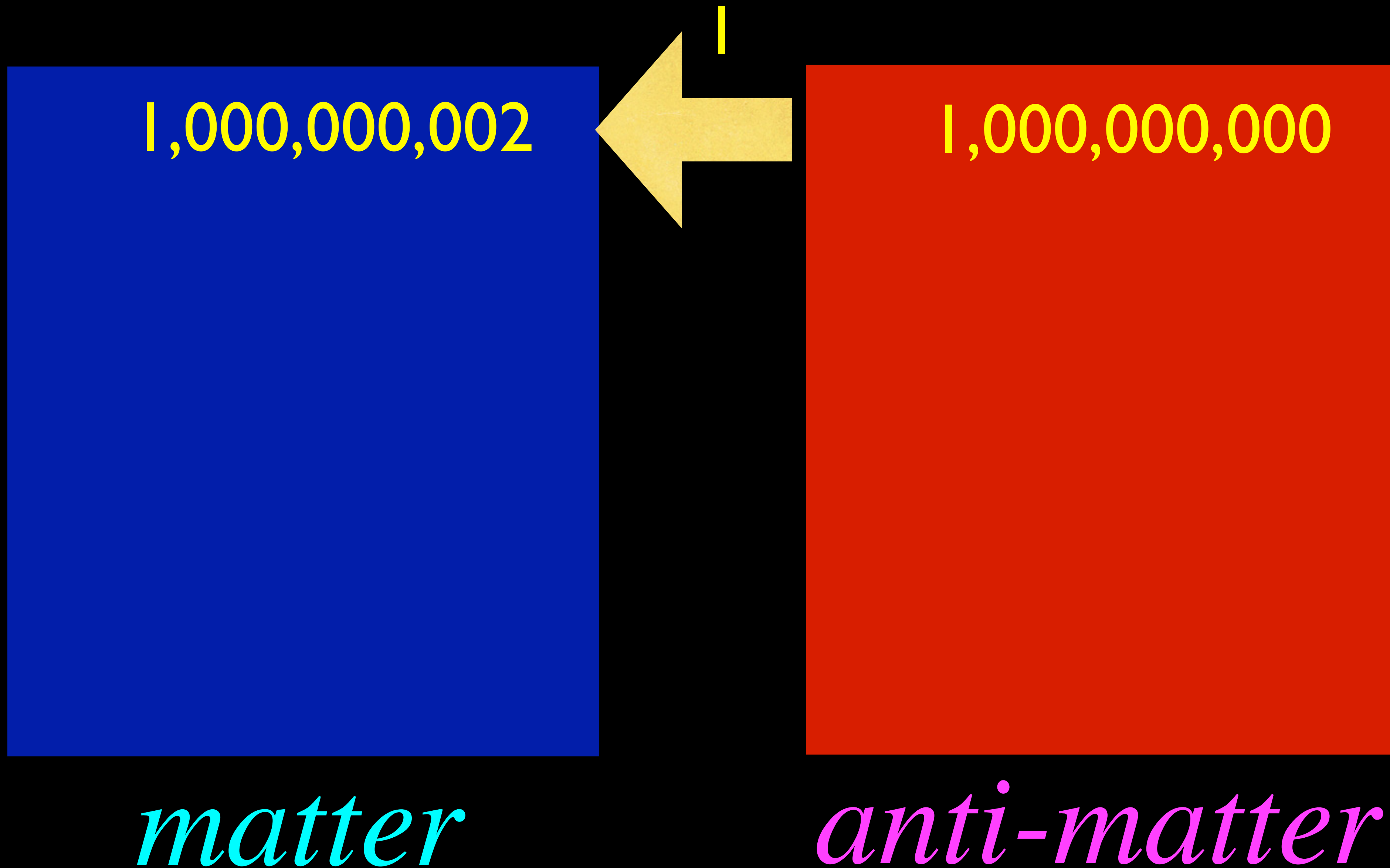
baryon density parameter $\Omega_B h^2$
10^{-2}
^{4}He mass fraction
0.27
0.26
0.25
0.24
0.23
BBN
t~3min
D/H
^{3}He/H
10^{-3}
10^{-4}
10^{-5}
C
M
B
t~380Kyr
^{7}Li/H
10^{-9}
10^{-10}
10^{-10}
10^{-9}
baryon-to-photon ratio $\eta = n_b/n_\gamma$

Beginning of Universe

matter	anti-matter
1,000,000,001	1,000,000,001

matter *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!


Who saved us from
a complete annihilation?

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

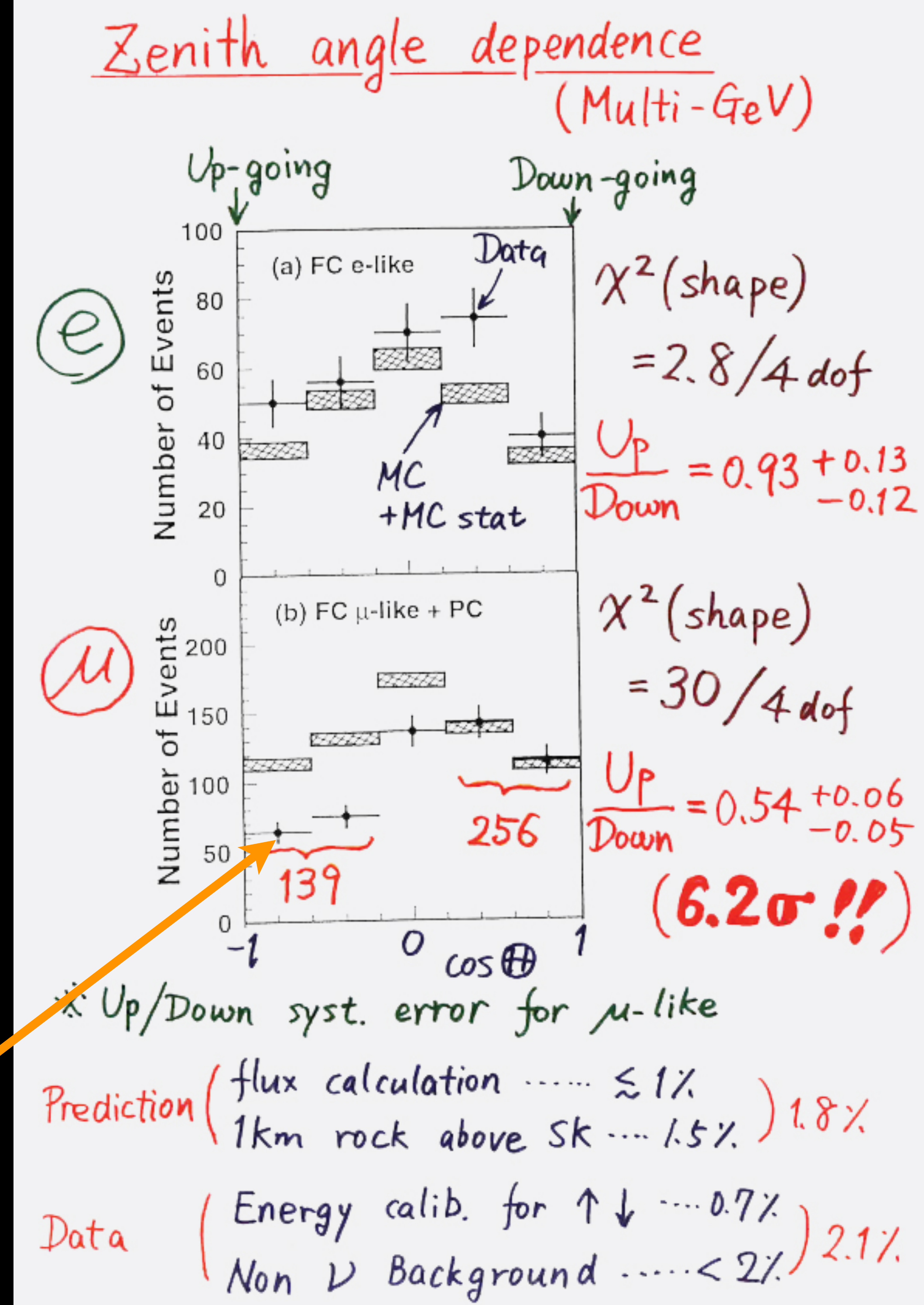
Hitoshi Murayama (Berkeley, Kavli IPMU)
+Jeff Dror (Berkeley), Takashi Hiramatsu (ICRR), Kazunori Kohri (KEK), Graham White (TRIUMF)

arXiv:1908.03227, accepted for PRL

neutrinos morph

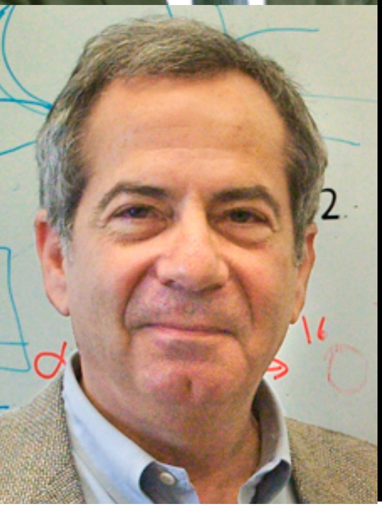
1998

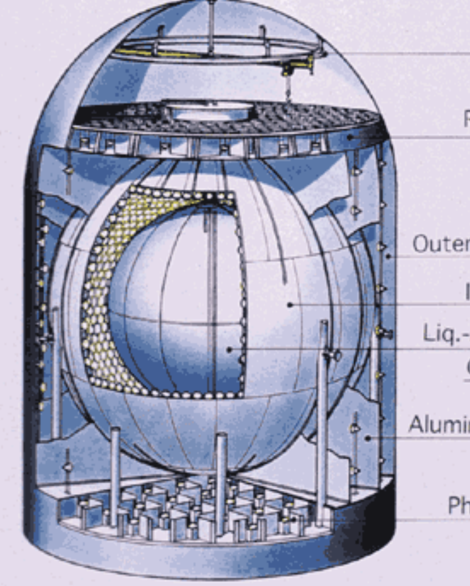
a half of expected



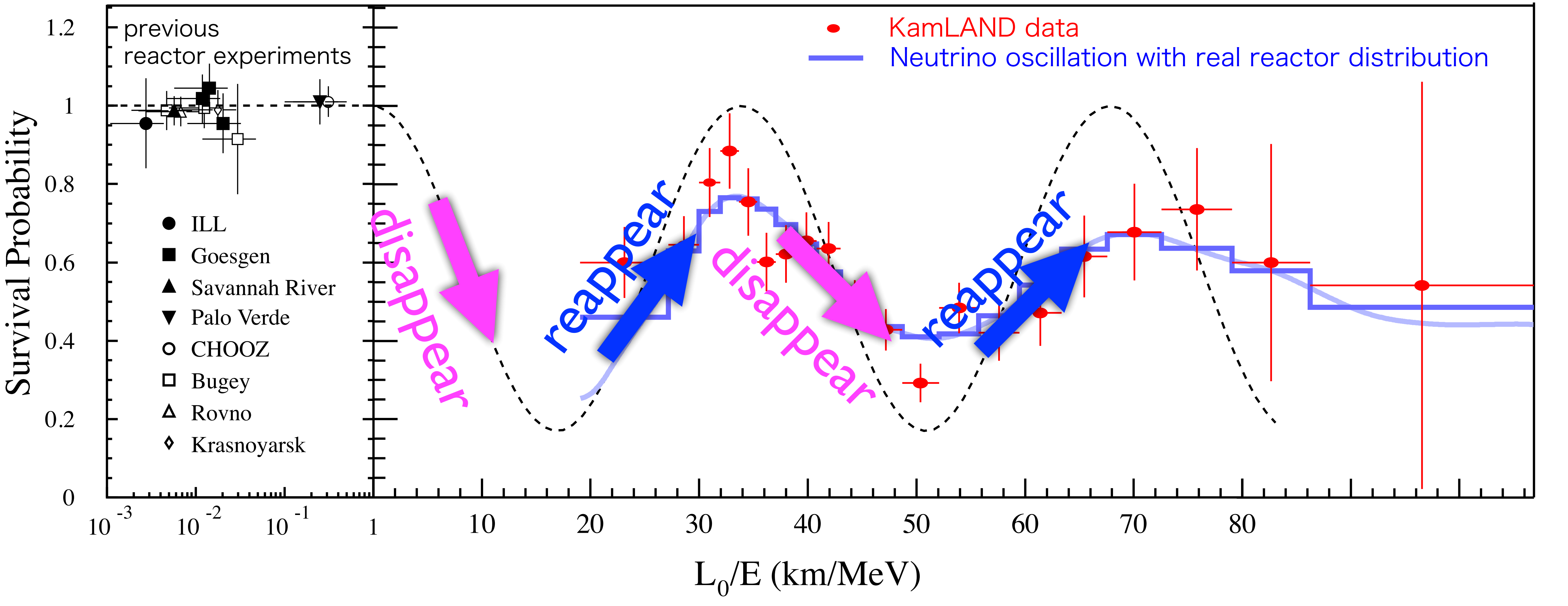
shift inside the mine for KamLAND

reactor neutrinos

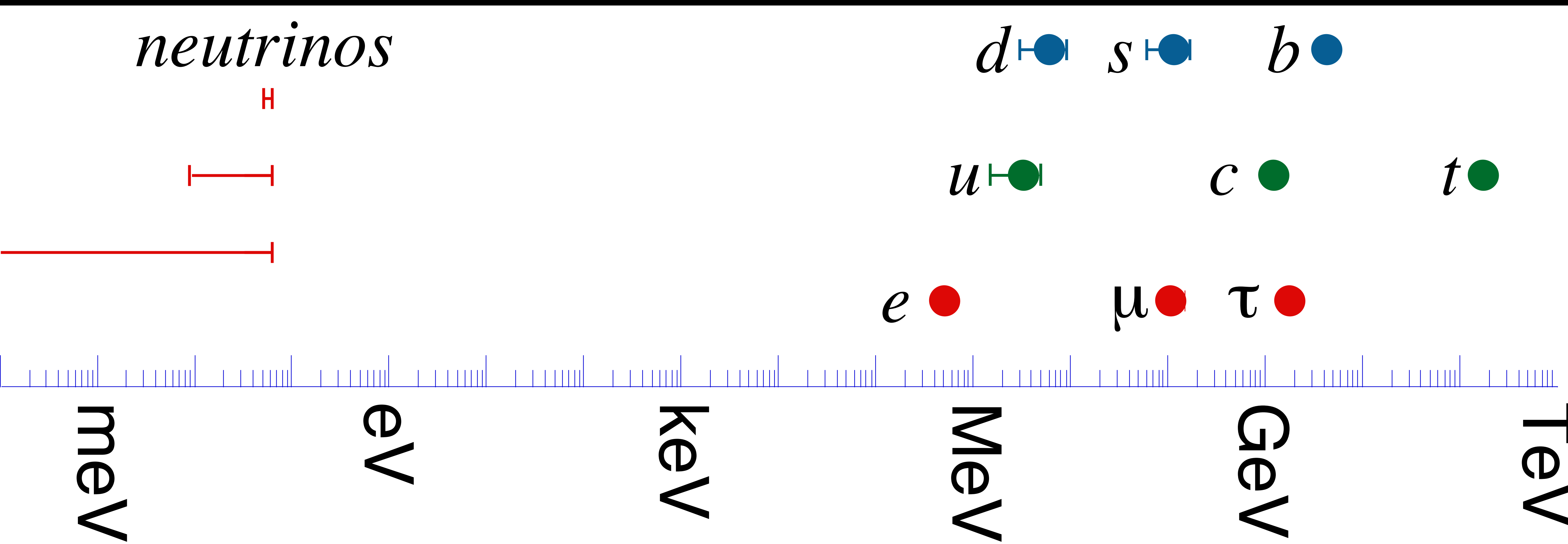




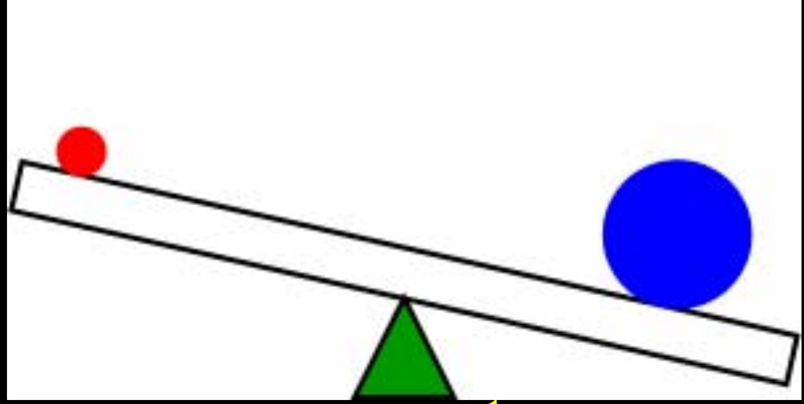
- KamLAND experiment
- a ring of reactors with average L~175 km



very light



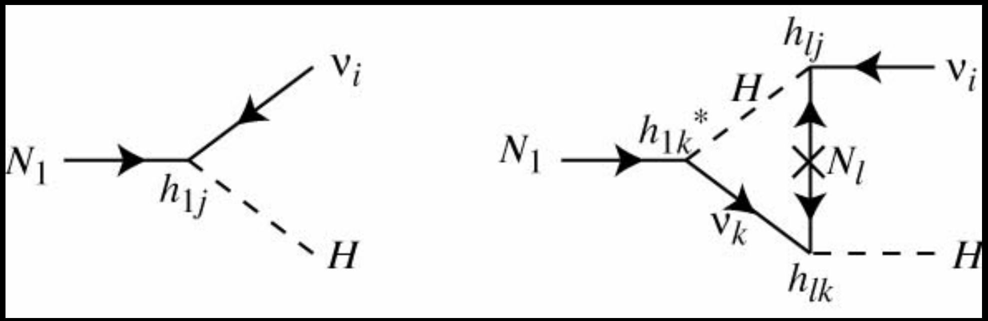
Seesaw



$$\mathcal{L} = -yLNH - \frac{1}{2}MNN$$

$$\begin{pmatrix} \nu & N \end{pmatrix} \begin{pmatrix} 0 & yv \\ yv & M \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

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



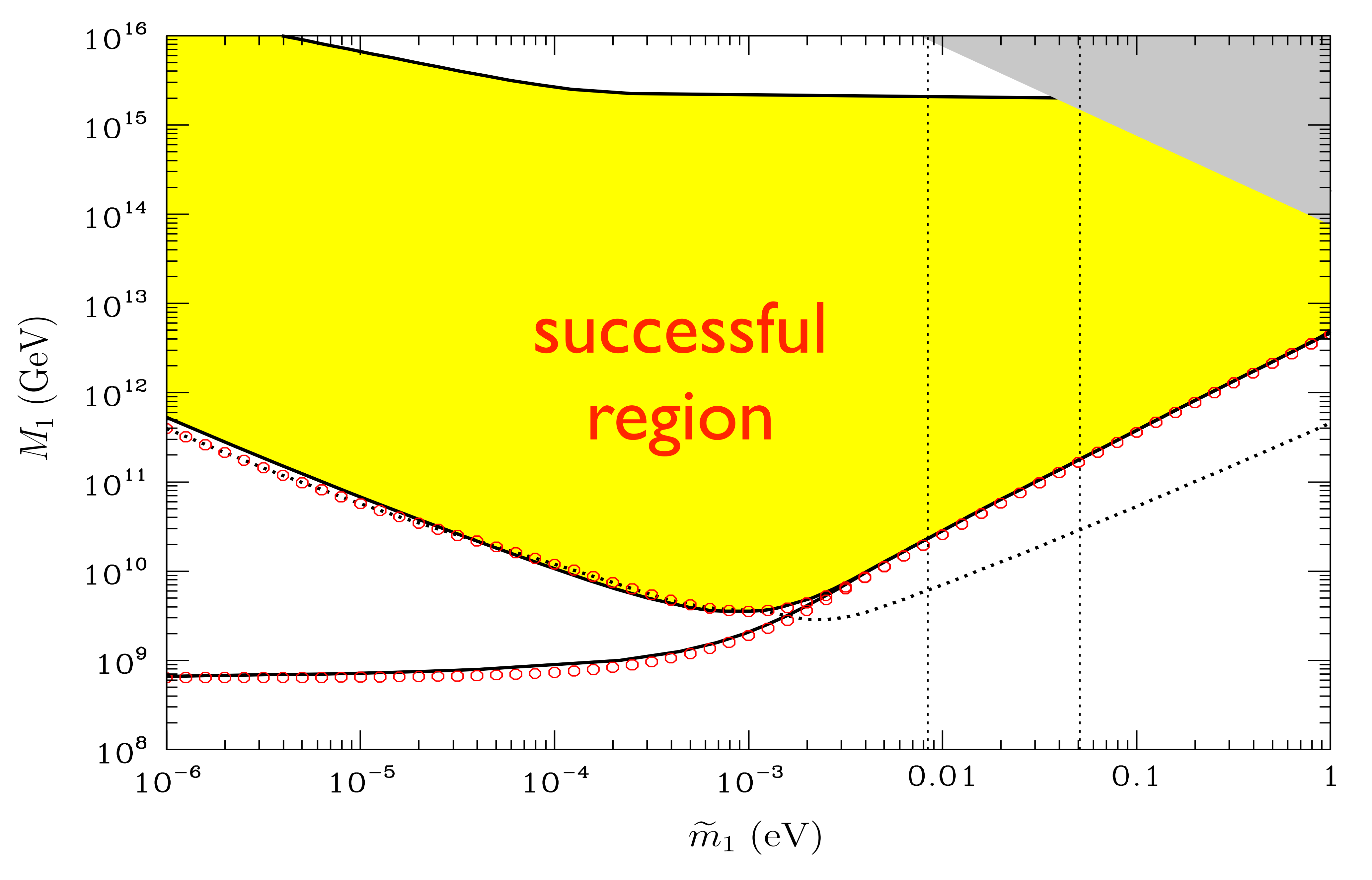
$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H^*) \propto \Im m(h_{1j} h_{1k} h_{lk}^* h_{lj}^*)$$

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

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
- Non-equilibrium
  - out-of-equilibrium decay of N_α due to long lifetimes

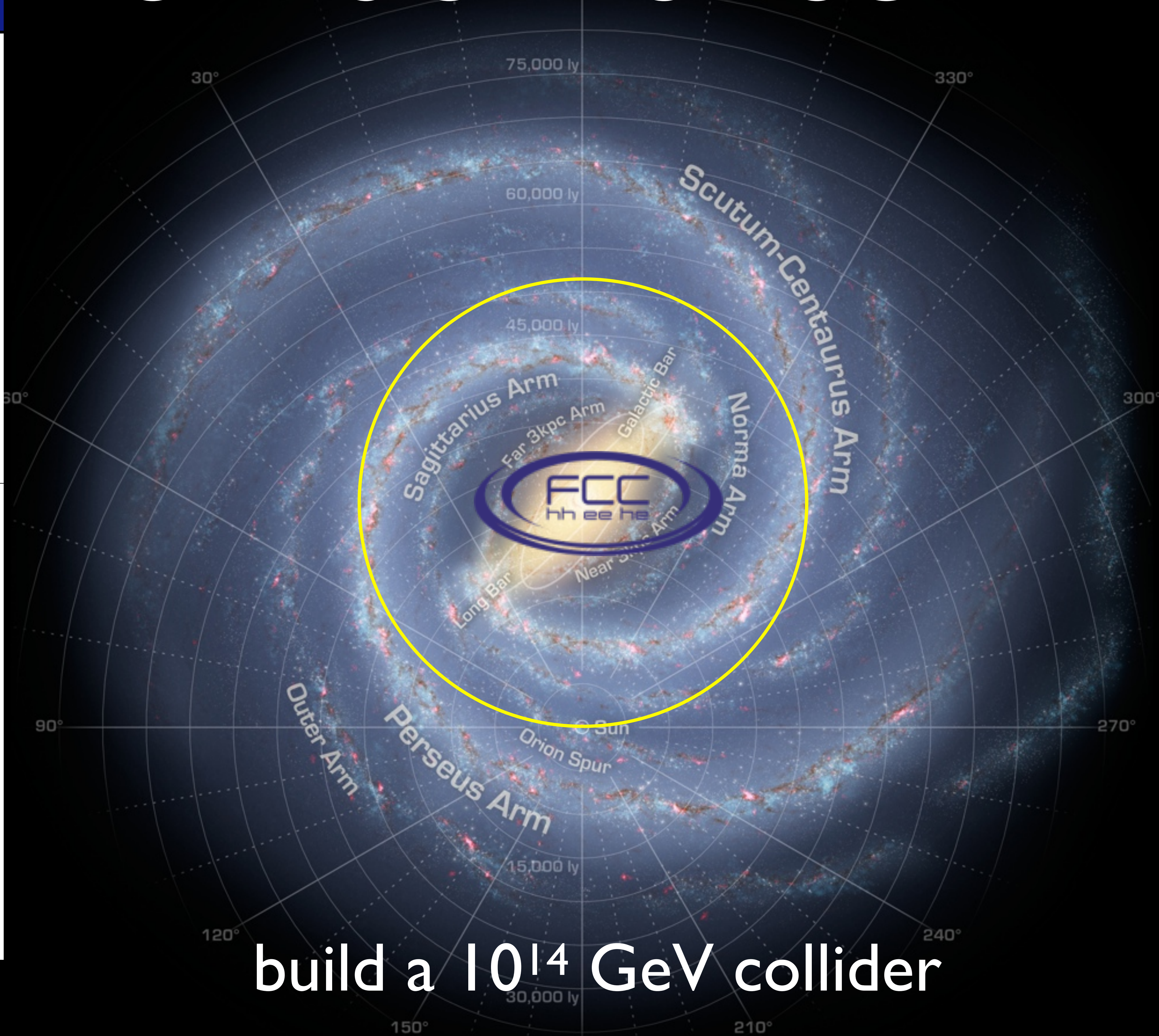
Leptogenesis



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

di Bari, Plümacher, Buchmüller

How do we test it?



build a 10^{14} GeV collider

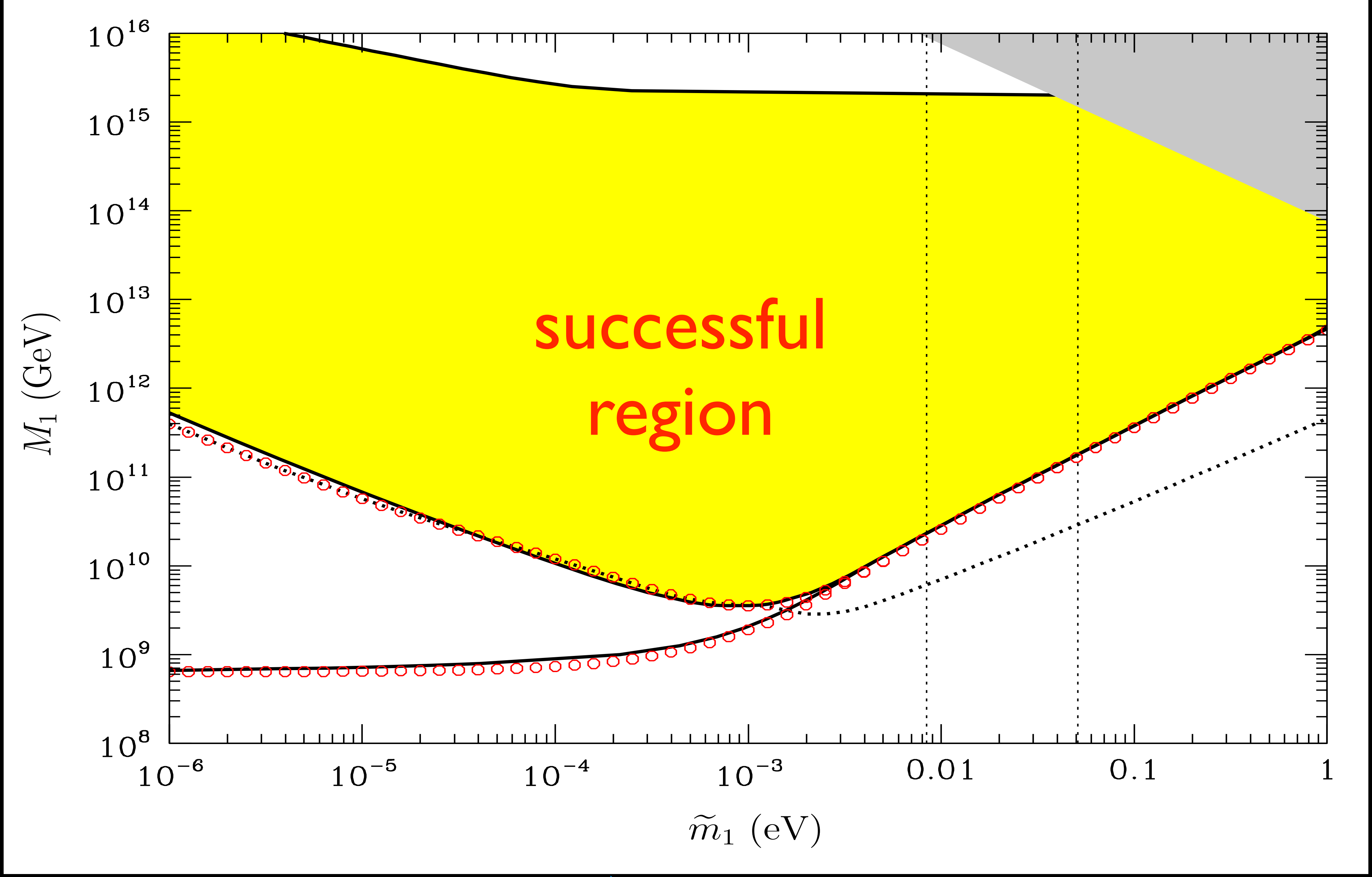
how do we test it?

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

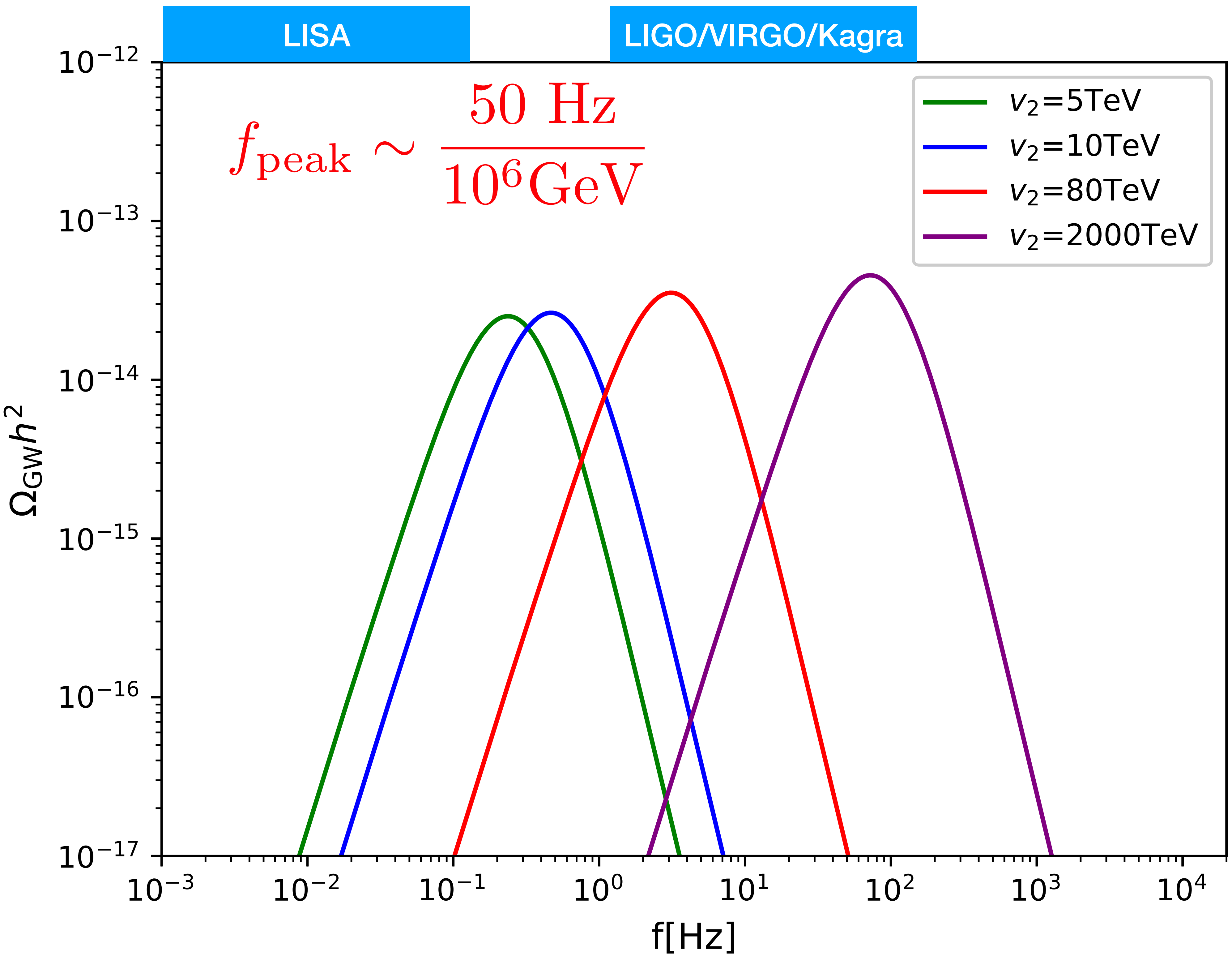
inflation



Phase Transition → **Gravitational Waves?**

1st order Phase Transition

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

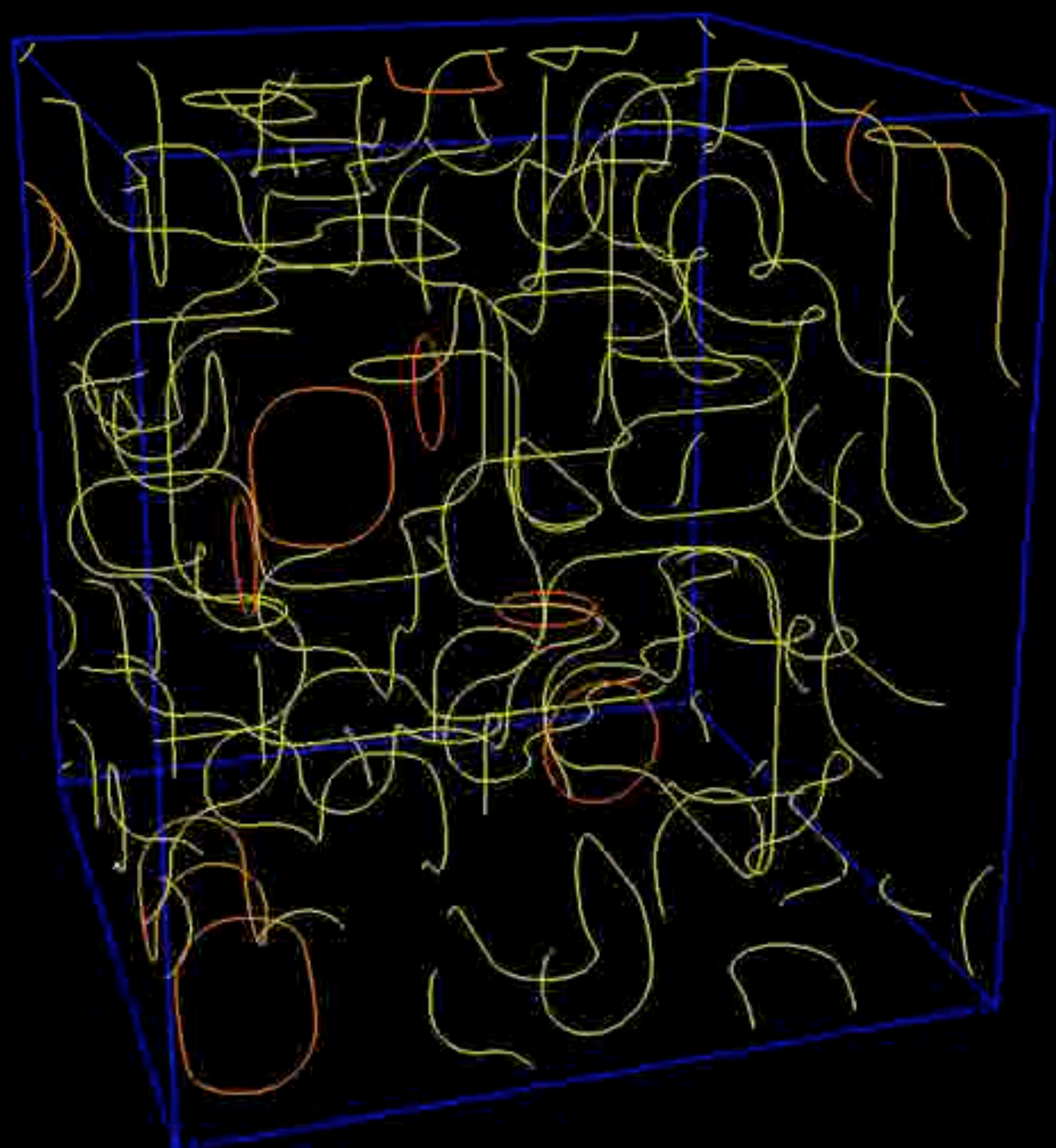


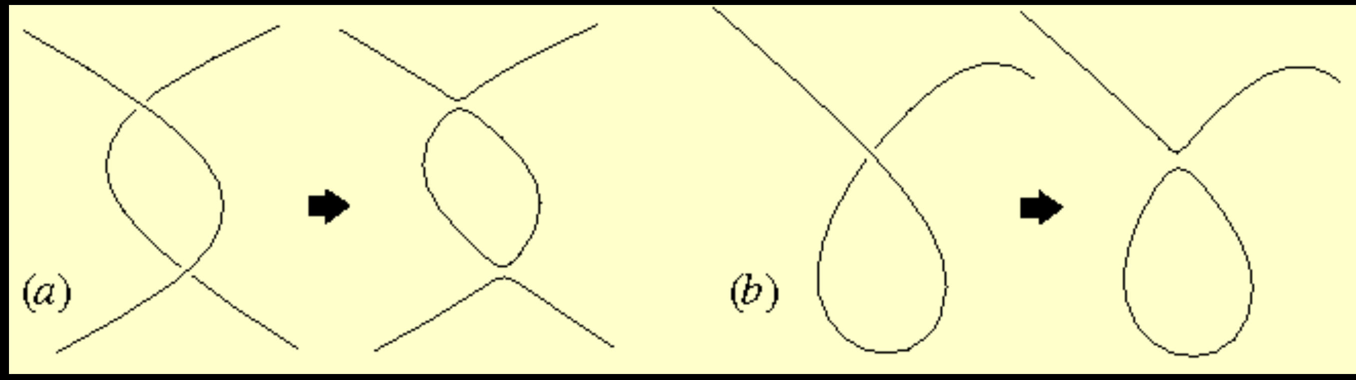
$U(1)_{B-L}$

- 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





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

classification

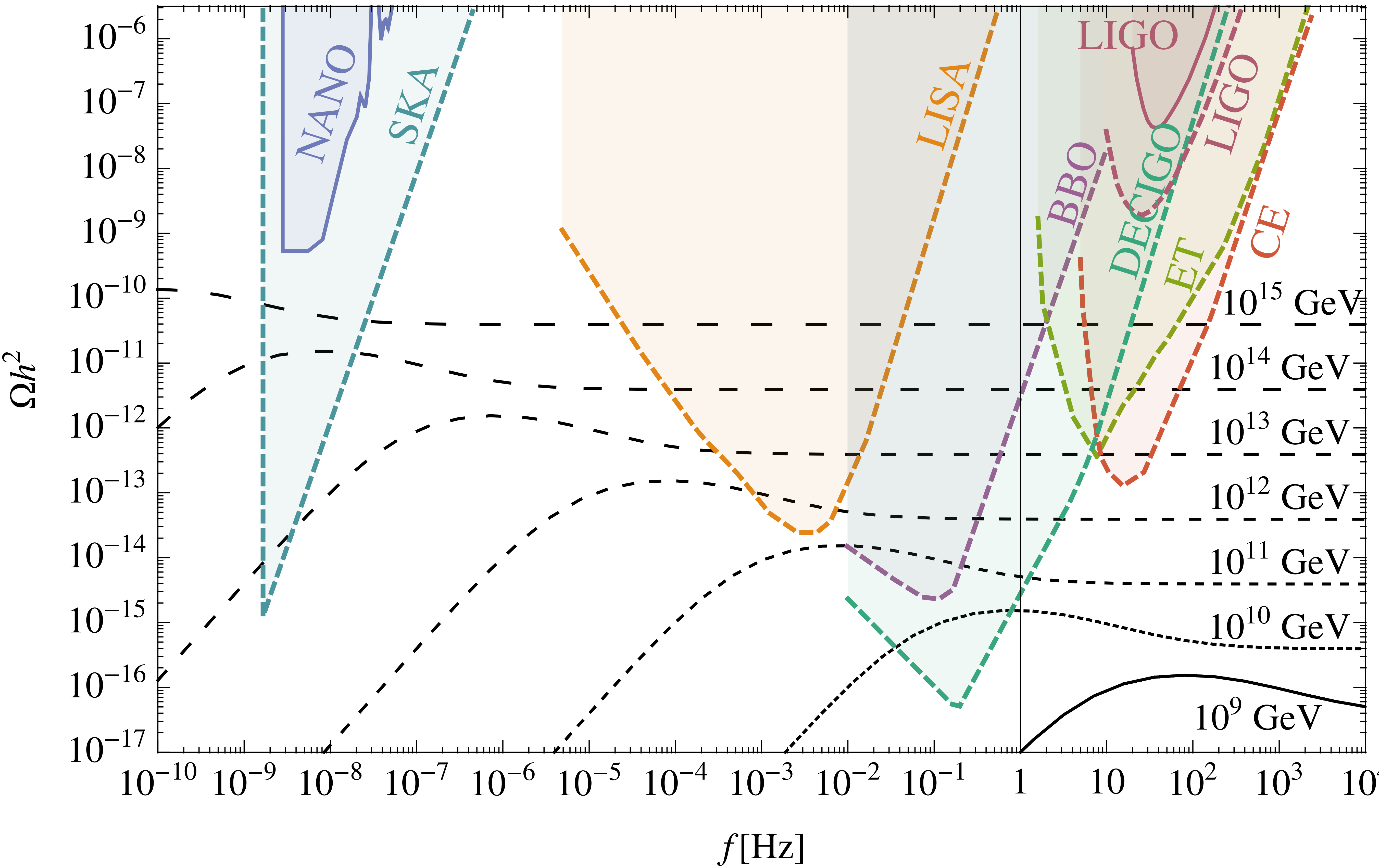
- possible gauge groups
  - forbids $M\,\nu_R\,\nu_R$
  - anomaly-free without additional fermions
  - no magnetic monopoles
  - rank ≤5
- possible Higgs
  - matter parity?
  - e.g. φ(+1) or φ(+2)
  - H=G_{SM} or $G_{SM}\times Z_2$
- 5 out of 8 have strings

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

$\langle\varphi\varphi\rangle\nu_R\nu_R/M_{Pl}$ $\langle\varphi\rangle\nu_R\nu_R$

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

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

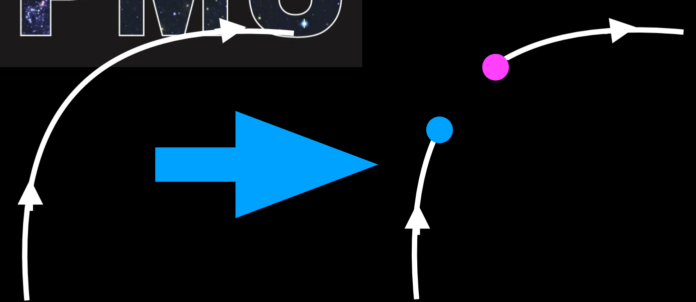


J. Dror, T. Hiramatsu, K. Kohri, HM, G. White, arXiv:1908.03227

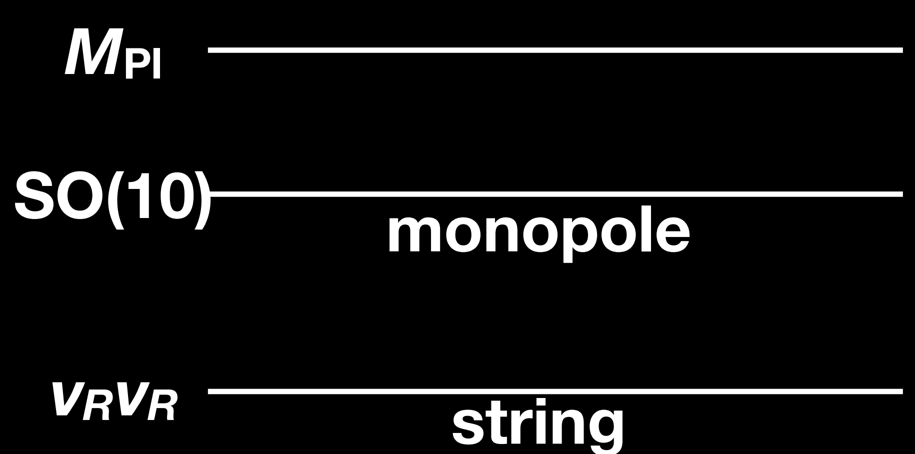
covers pretty much the entire range for leptogenesis!

caveat: particle emission from cosmic strings

SO(10)



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



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

	$\langle\varphi\varphi\rangle\nu_R\nu_R/M_{Pl}$		$\langle\varphi\rangle\nu_R\nu_R$	
	$H = G_{\rm SM}$		$H = G_{\rm SM} \times \mathbb{Z}_2$	
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	$(\mathbf{1},\mathbf{1},\mathbf{3},1)$
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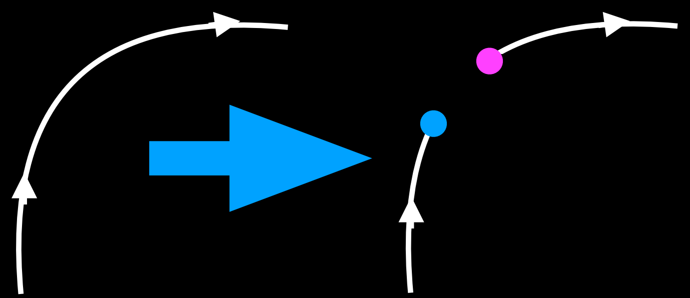
$G_{\rm flip}$	none	$(\mathbf{10},1)$	$\mathbb{Z}_2$ string	$(\mathbf{50},2)$

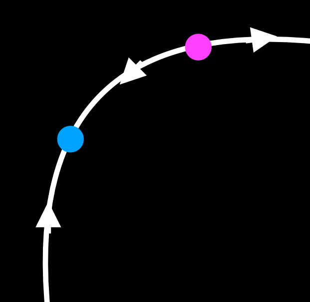
$$0 \to \pi_2(G) \to \pi_2(G/H) \to \pi_1(H) \to \pi_1(G) \to \boxed{\pi_1(G/H)} \to \pi_0(H) \to \pi_0(G) = 0$$



monopoles

- string from $U(1)_{B-L}$ breaking is basically Abrikosov flux in a superconductor
  - For the Higgs $\phi(\pm Q)$
  - magnetic flux $2\pi\hbar/(e\,Q)$ × 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

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

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

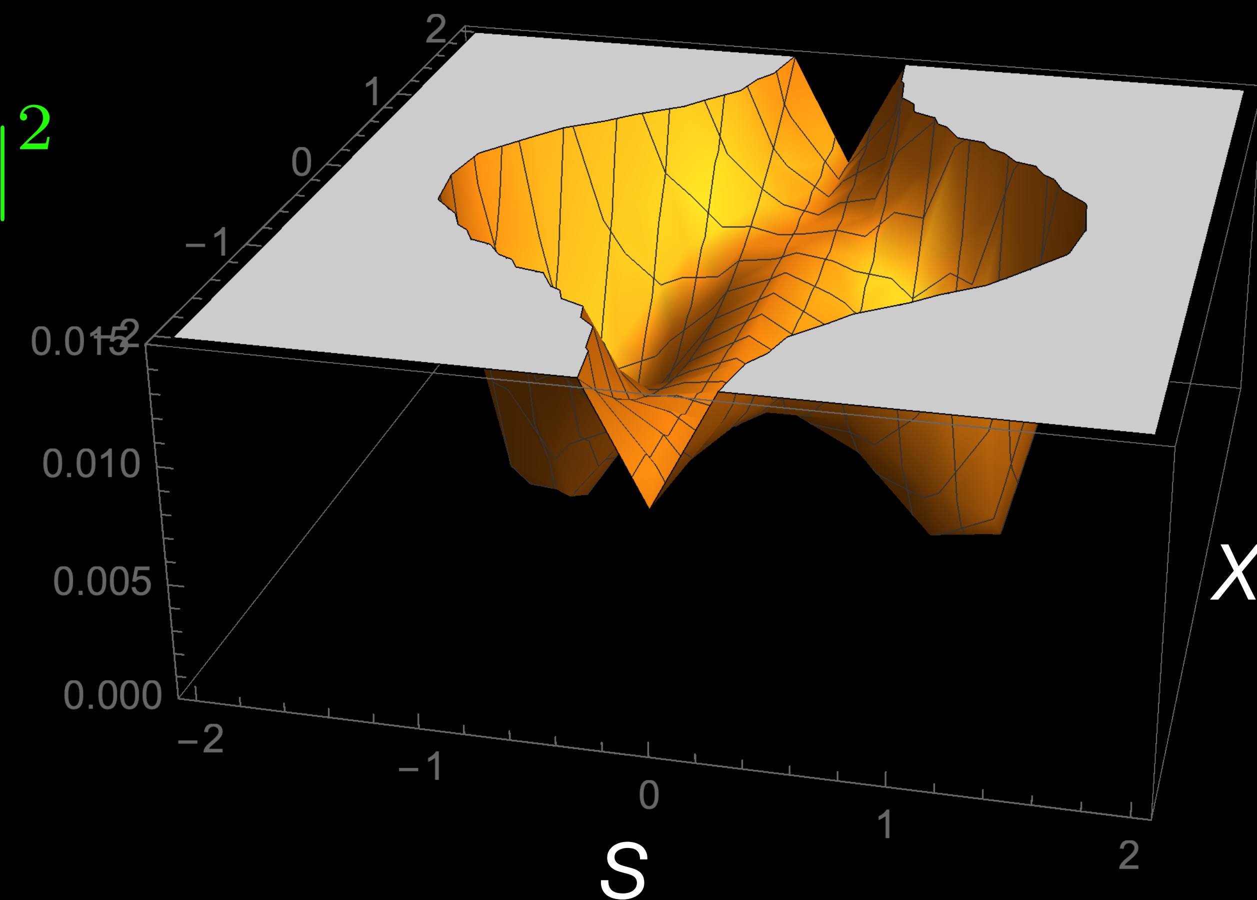
$$V = \lambda^2 \left|S^+S^- - v^2\right|^2 + \lambda^2 |X|^2 \left(|S^+|^2 + |S^-|^2\right) + \frac{e^2}{2}\left(|S^+|^2 - |S^-|^2\right)^2$$

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

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

- flat: $S=0$, $V=\lambda^2 v^2$

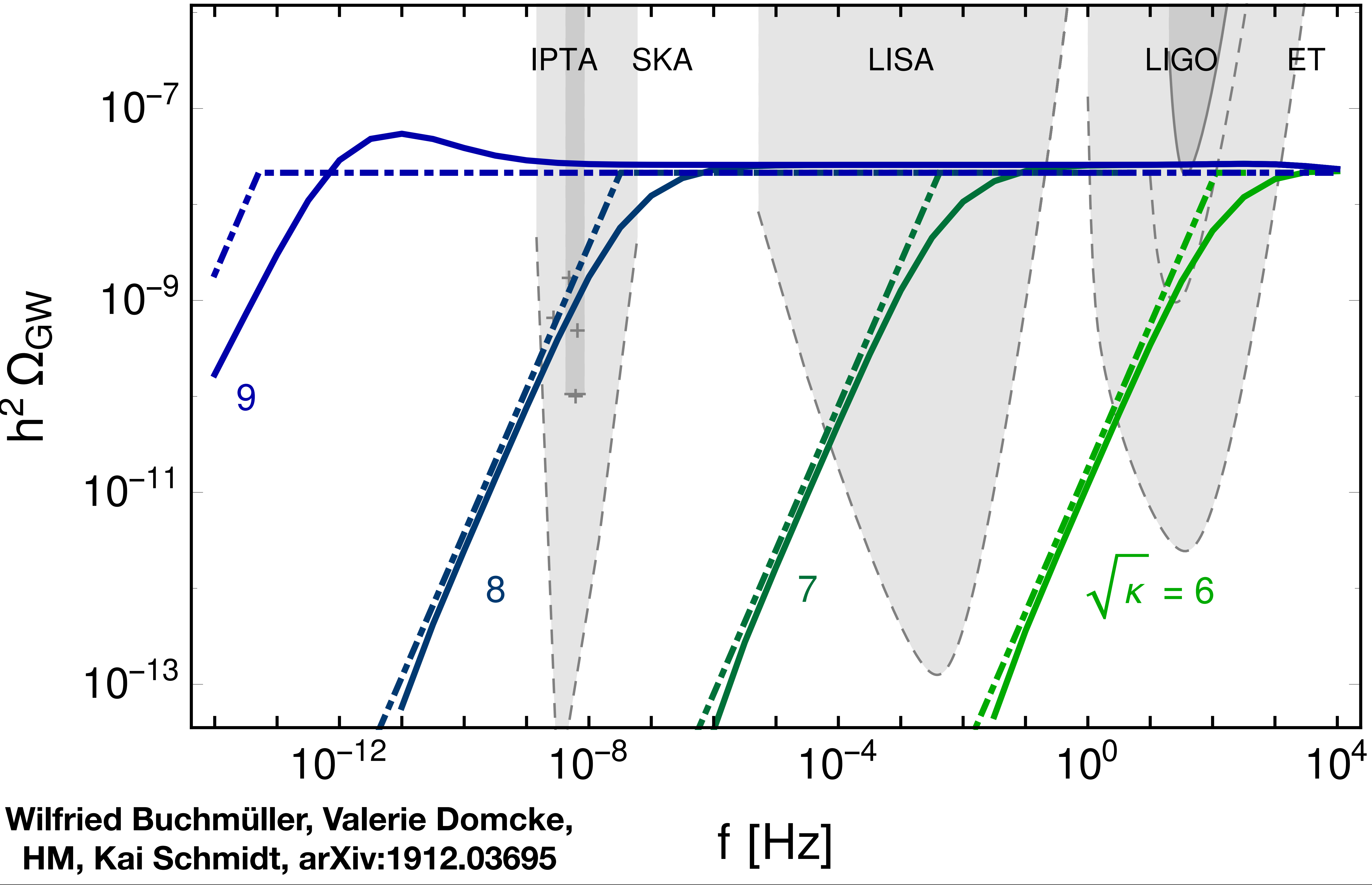
- falls down to $S=v$ near $X\sim 0$
- forms cosmic strings
- requires high $v \gtrsim$ a few 10^{15} GeV



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

hybrid inflation

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



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

Conclusions

- stochastic gravitational waves as another possible circumstantial evidence for seesaw+leptogenesis
- for rank≤5 gauge groups, more than a half of theories produce cosmic strings
- future missions promising to cover most range of seesaw scales
- if we do detect scale-invariant gravitational waves, a smoking gun for strings
- if strings appear to break, evidence for grand unification!
- *any experimental technique to probe gravitational waves of much higher frequencies?*

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

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

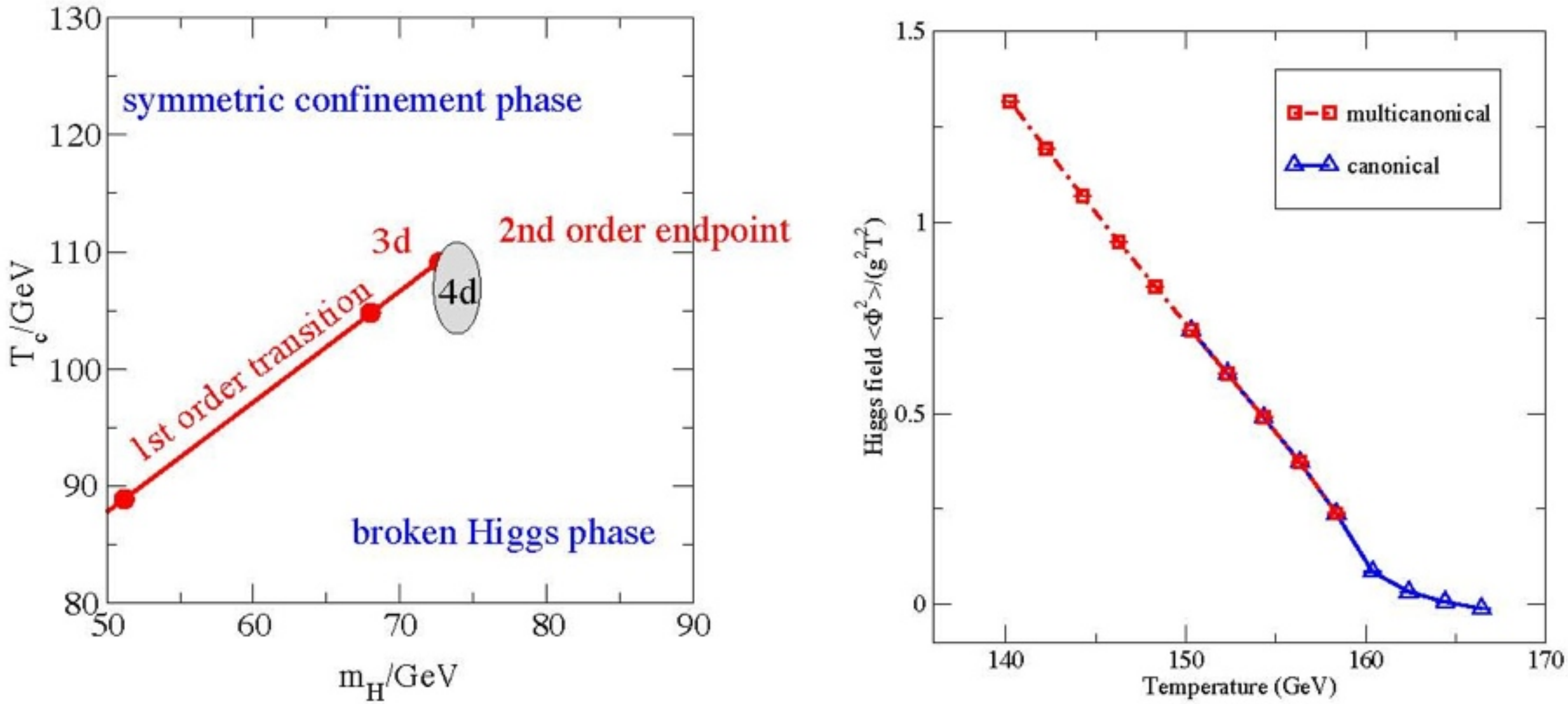
- Non-equilibrium
  - First-order phase transition of Higgs

requires m_h < 75 GeV

- Experimentally testable?

Mikko Laine (Bern)

Phase diagram for the Standard Model:



⟨H⟩=0 from gauge invariance (Elitzur)

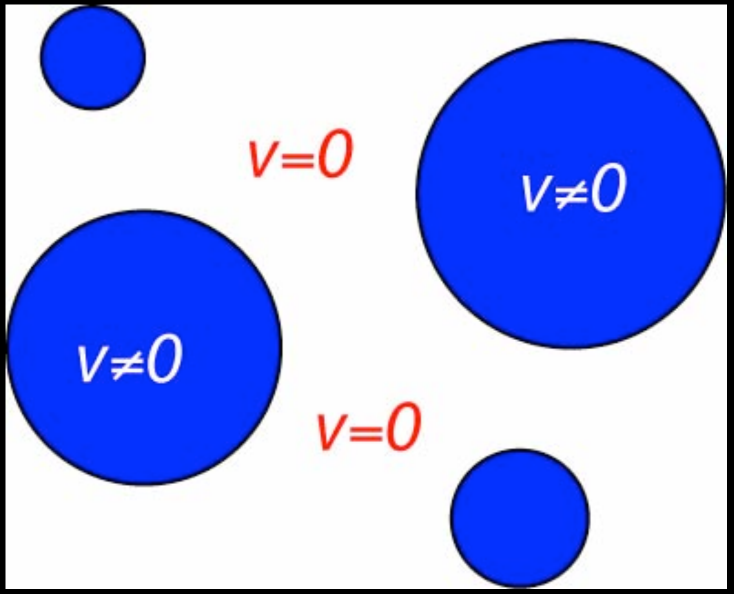
⟨H†H⟩ is not an order parameter

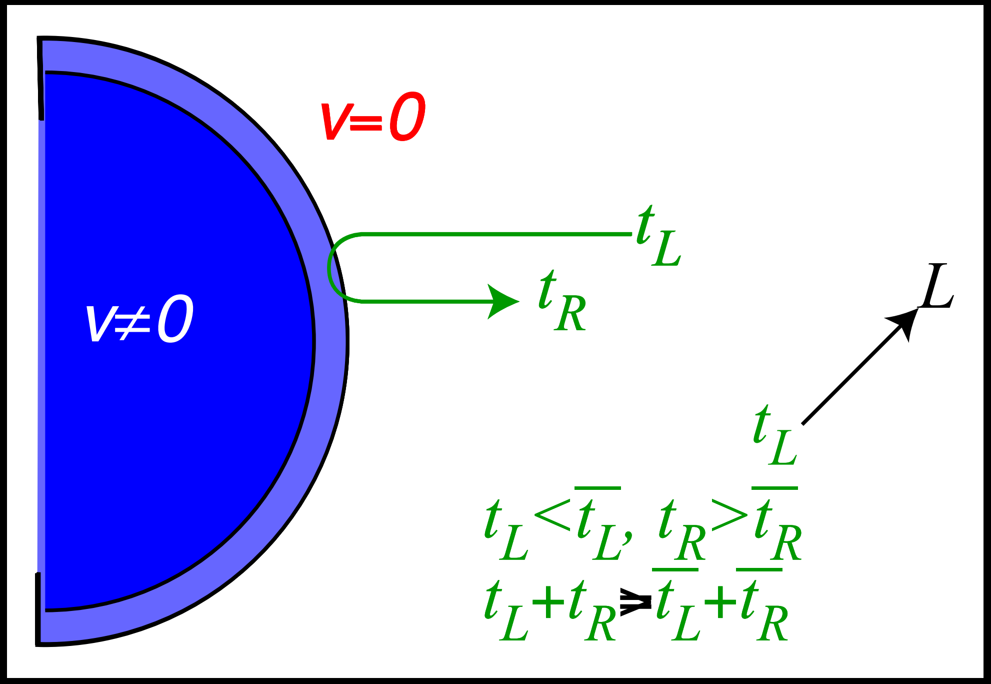
for m_h=125GeV, it is crossover

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 $\geq 10^{-3}$

Oct 2018

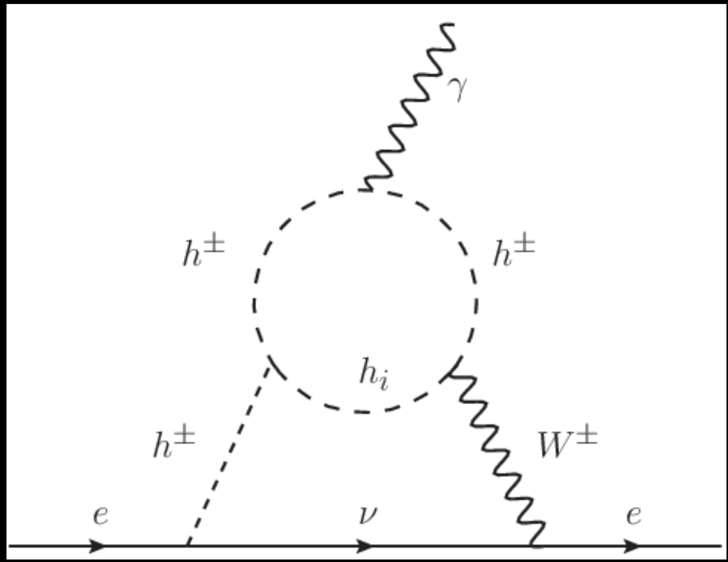
ARTICLE

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

Improved limit on the electric dipole moment of the electron

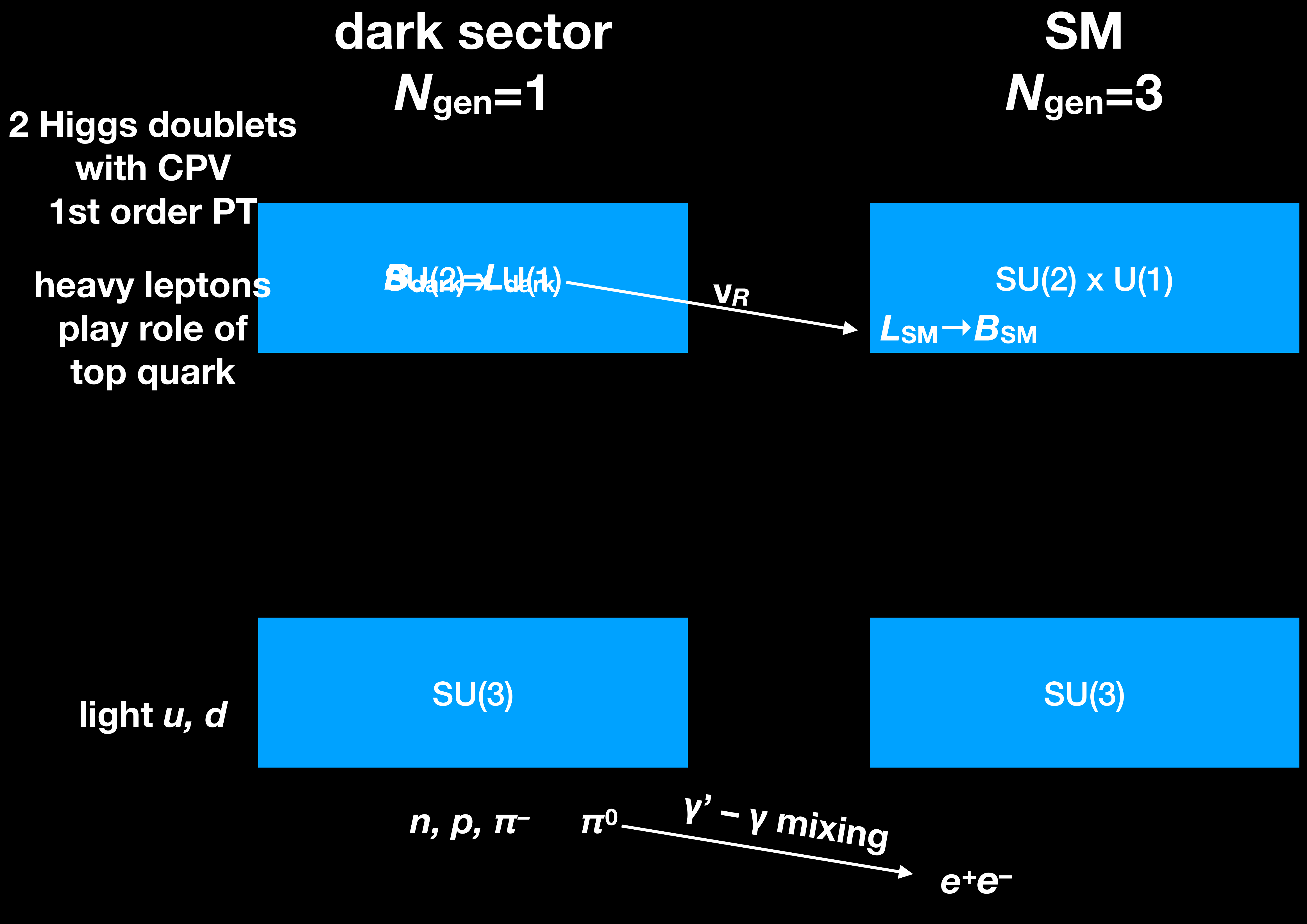
ACME Collaboration*

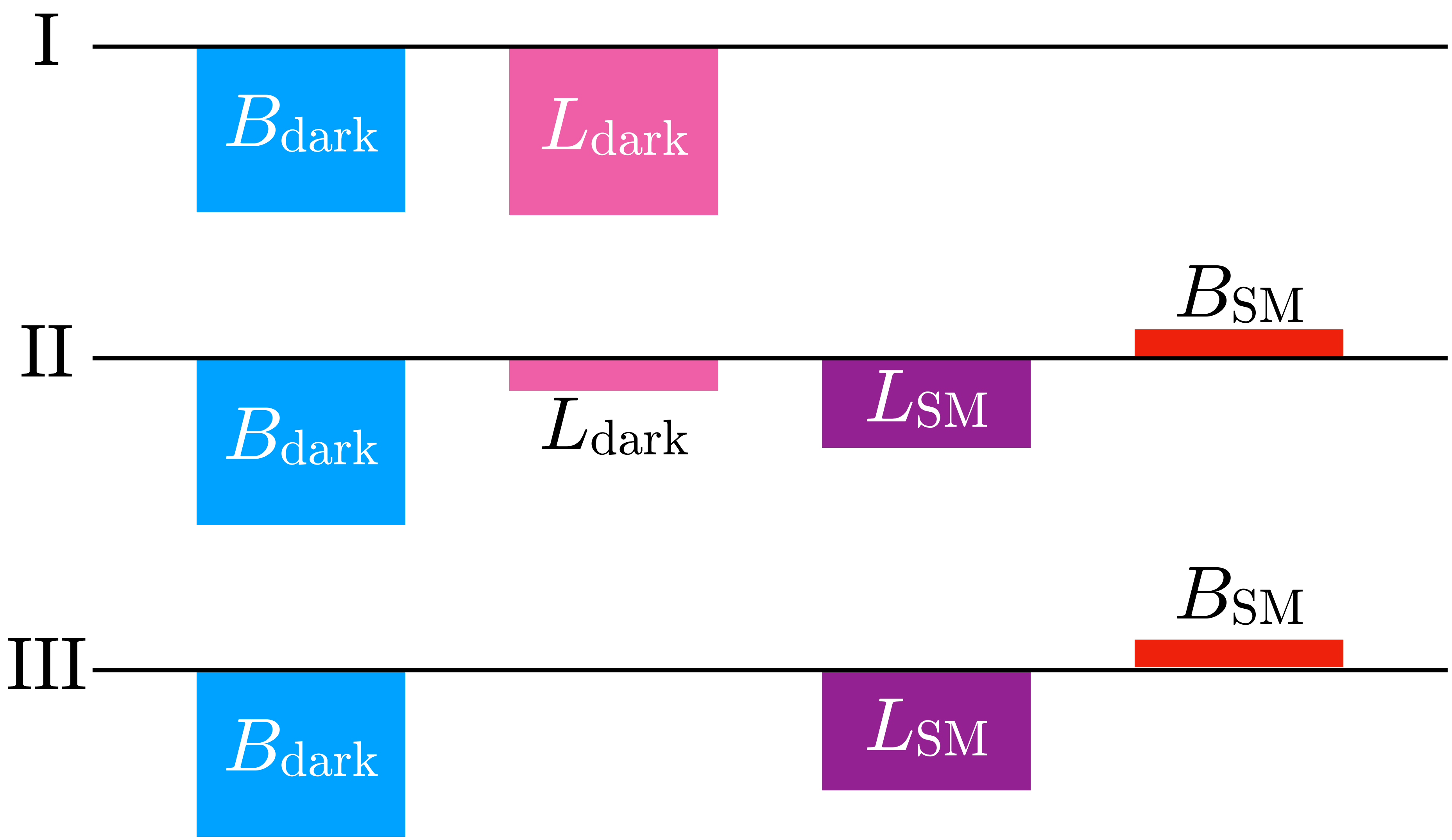
$d_e \leq 1.1\times10^{-29}$ *e* cm



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
SU(2) x U(1)
$B_{dark} \to L_{dark}$
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^-

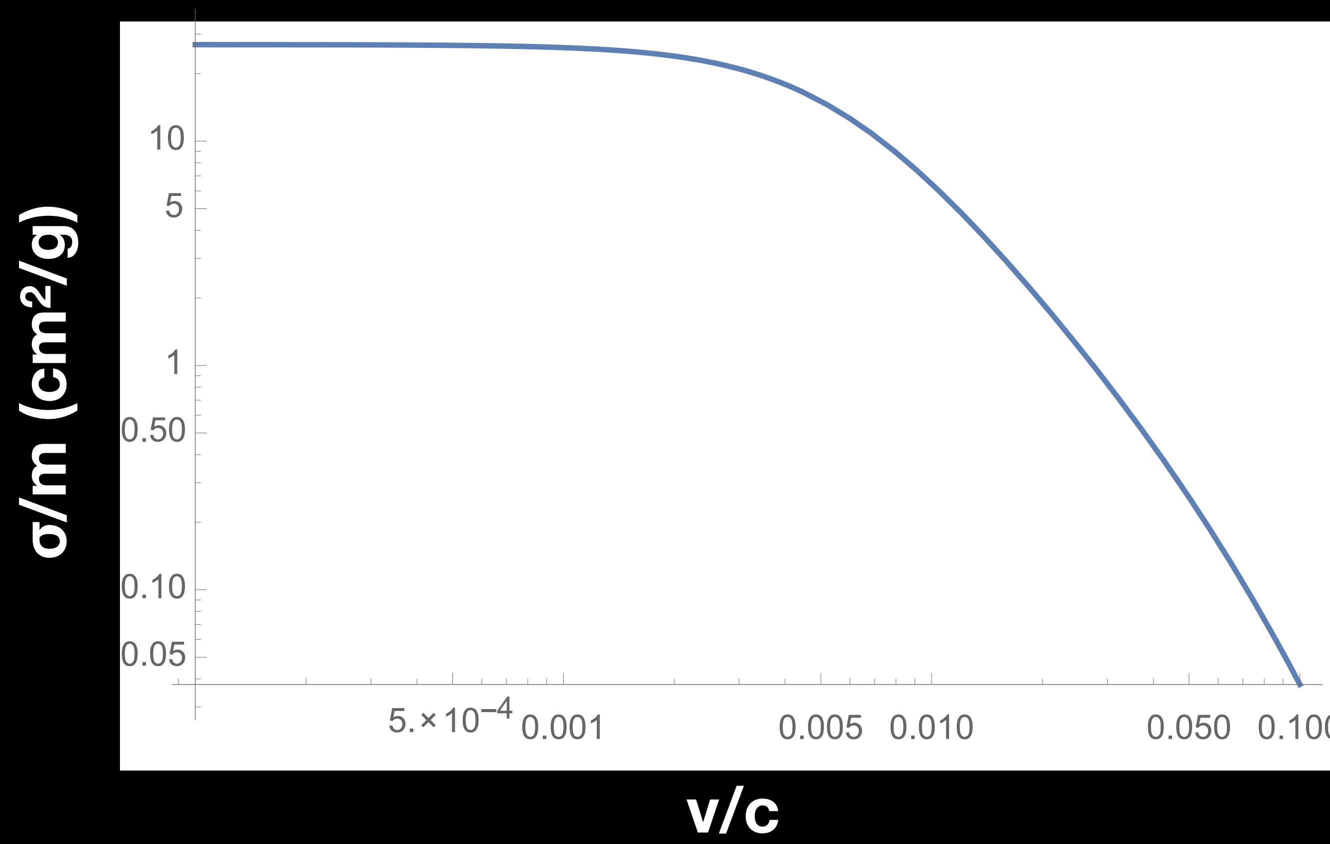


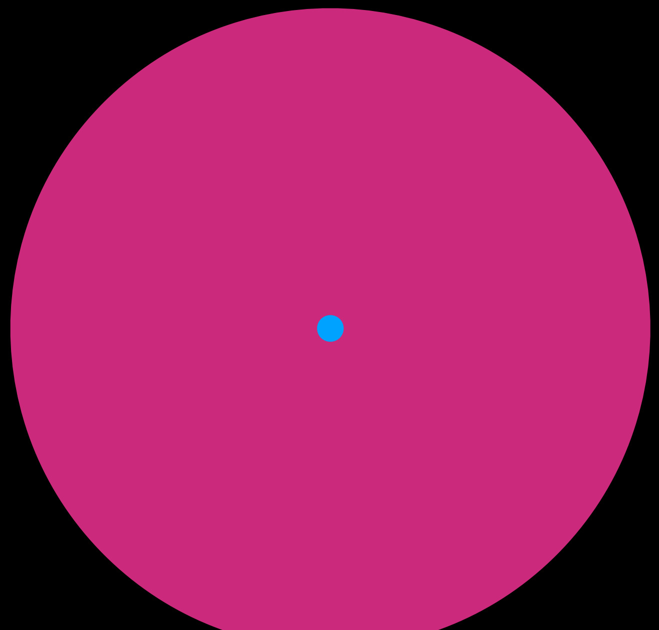
If $M_N > T_{\mathrm{sphaleron}}$ $\quad B_{\mathrm{SM}} = \frac{36}{133} B_{\mathrm{dark}}, \quad L_{\mathrm{SM}} = -\frac{97}{133} B_{\mathrm{dark}}$ $\quad$ **$m_{n'}$=1.58 GeV**

If $M_N < T_{\mathrm{sphaleron}}$ $\quad B_{\mathrm{SM}} = \frac{12}{37} B_{\mathrm{dark}}, \quad L_{\mathrm{SM}} = -\frac{25}{37} B_{\mathrm{dark}}$ $\quad$ **$m_{n'}$=1.33 GeV**

n-*n* scattering

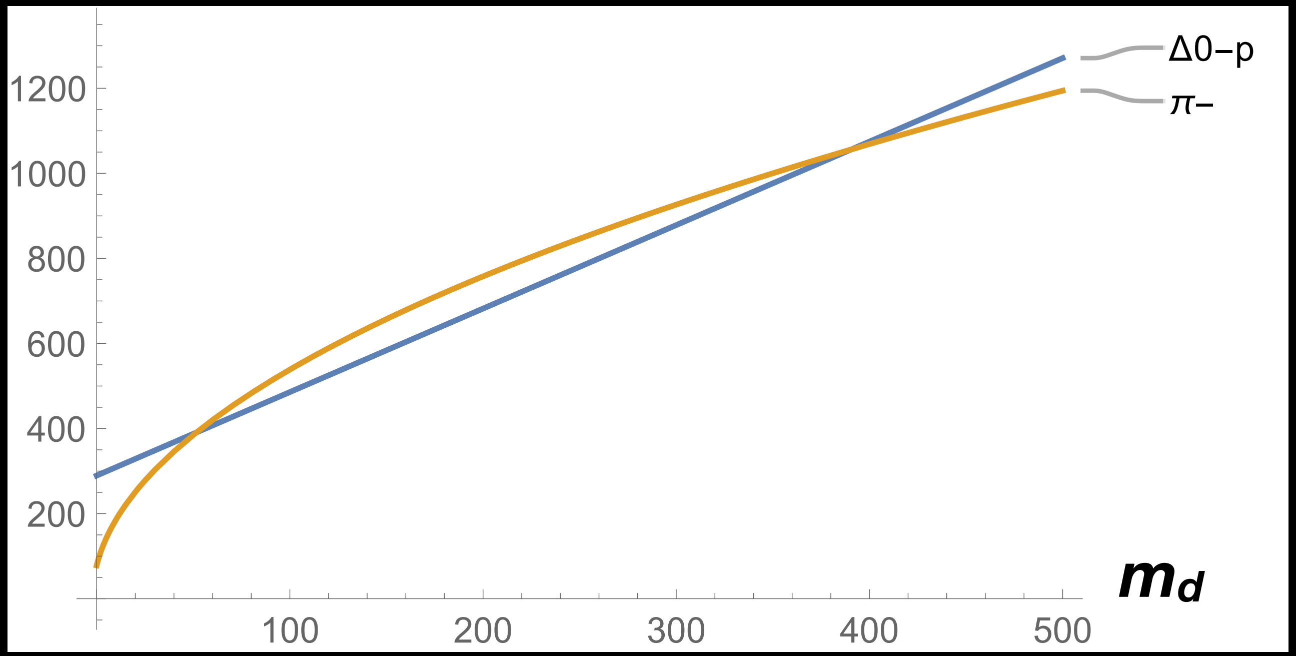
- *n*-*n* scattering has an anomalously large cross section a=18.9fm
- If so, it violates astrophysical bounds on self-interaction
- a fine cancellation between the bare and one-loop couplings in the pion-less EFT
- According to lattice simulations (HAL QCD), the cross section is more or less of the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



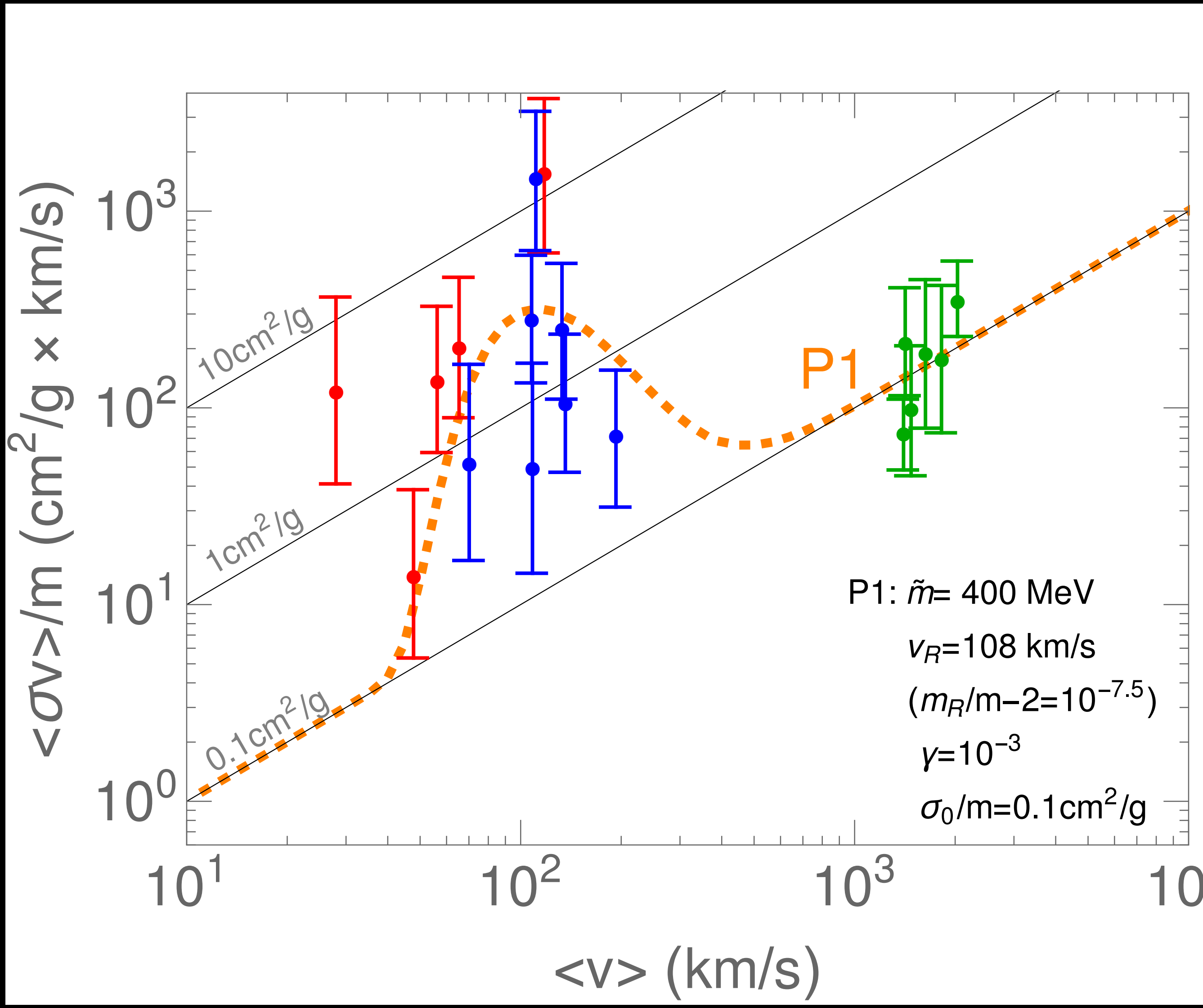


baryon spectrum

- 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

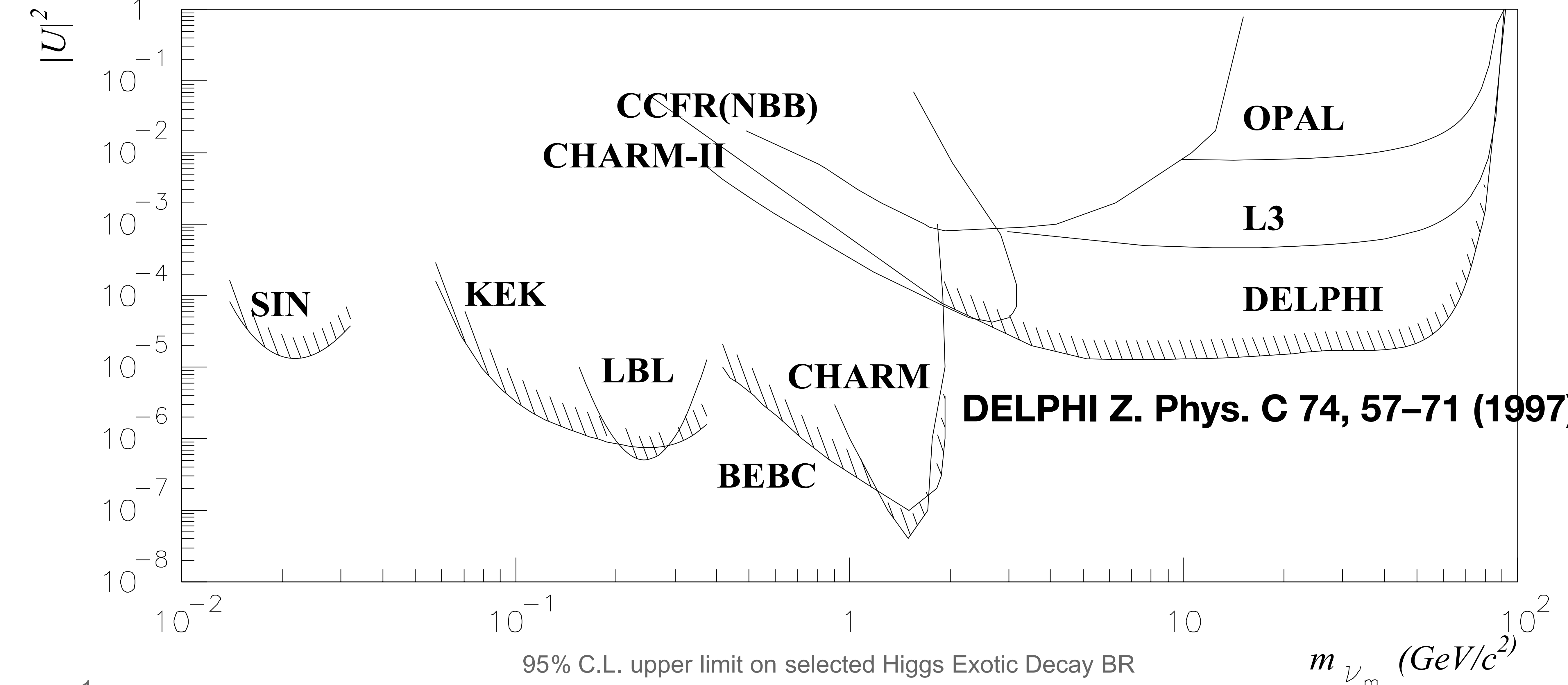
- asymmetric dark matter
  - S. Nussinov, PLB 165, 55 (1985) “technocosmology”
  - R. Kitano, HM, M. Ratz, arXiv:0807.4313, moduli decay
  - D.E. Kaplan, M. Luty, K. Zurek, arXiv:0901.4117
- darkogenesis (= “EW baryogenesis” in the dark sector)
  - J. Shelton, K. Zurek, arXiv:1008.1997

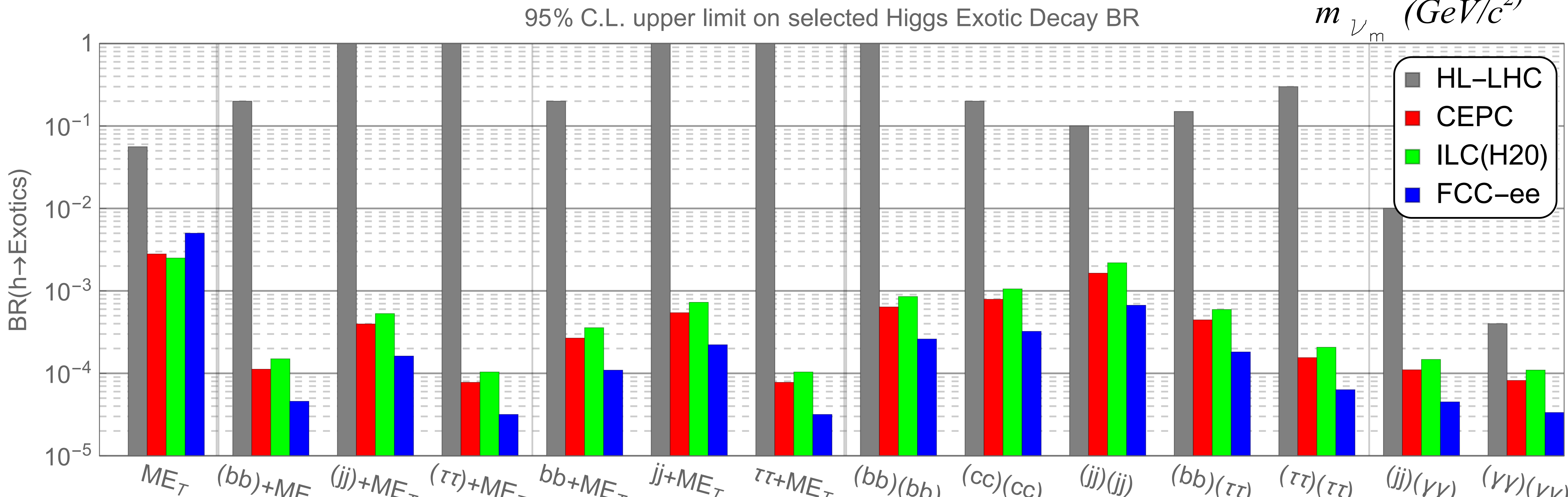
neutrino portal

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

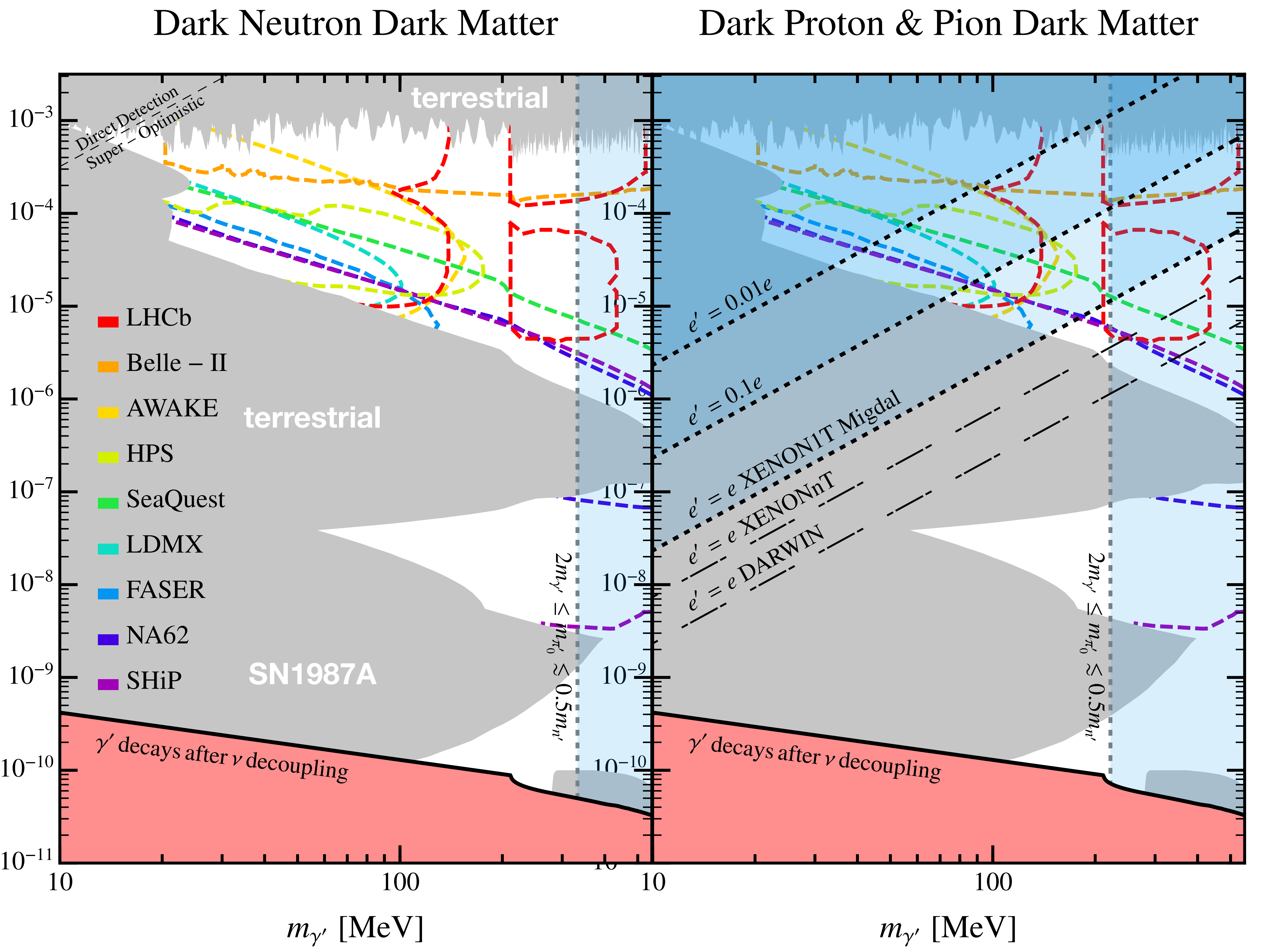
$$\epsilon_i = \frac{y_i}{\sqrt{(y')^2 + (y_i)^2}} \qquad M_\nu = \sqrt{(y')^2 + (y_i)^2} v$$

- charged current universality: $\varepsilon_i^2 < 10^{-3}$
- $\mu \to e\,\gamma$ constraint: $\varepsilon_e\, \varepsilon_\mu < 4 \times 10^{-5}\ (G_F M_\nu)$
- $\tau \to \mu\,\gamma$ 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)

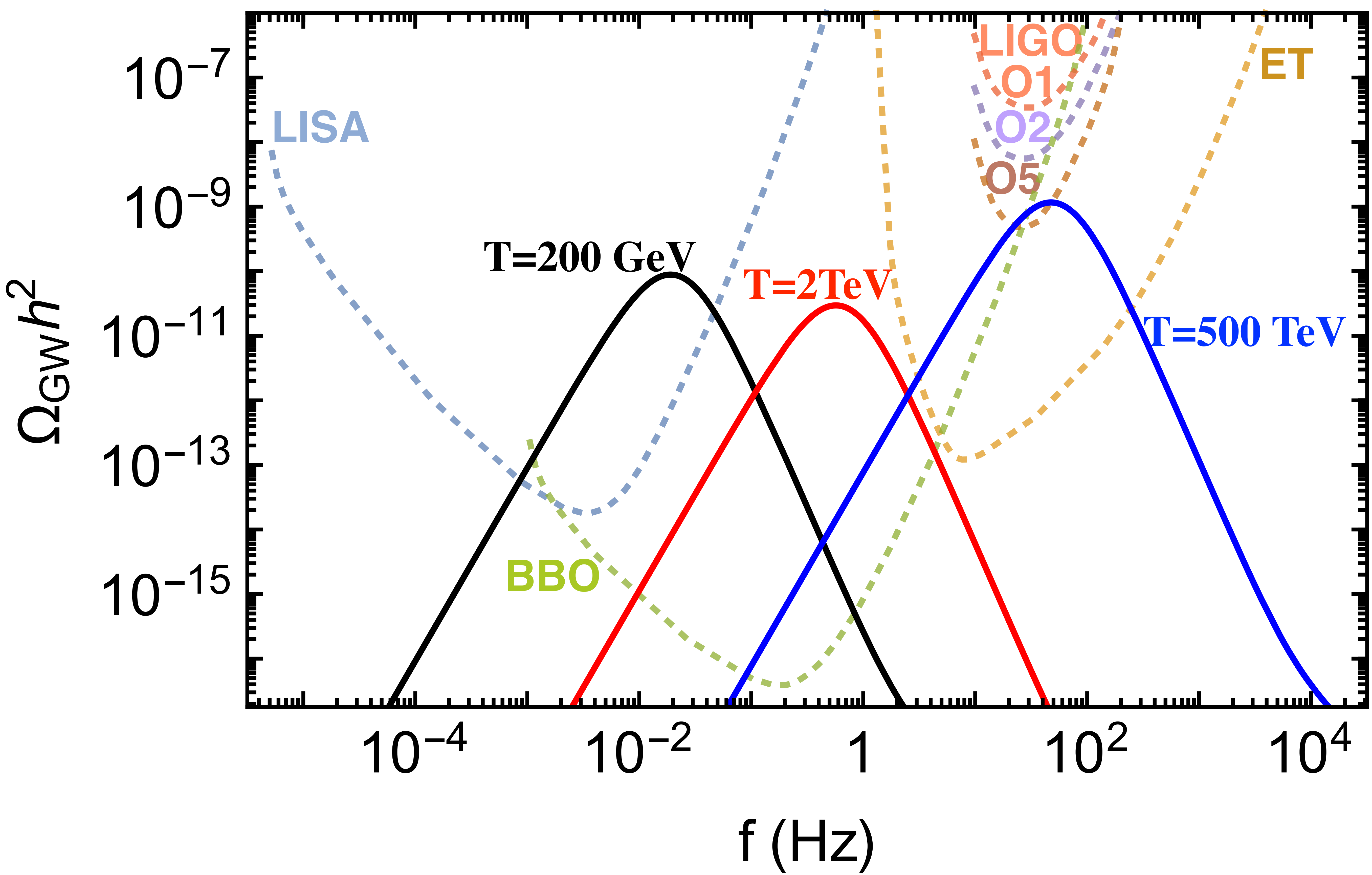




Zhen Liu, Lian-Tao Wang, Hao Zhang, arXiv:1612.09284



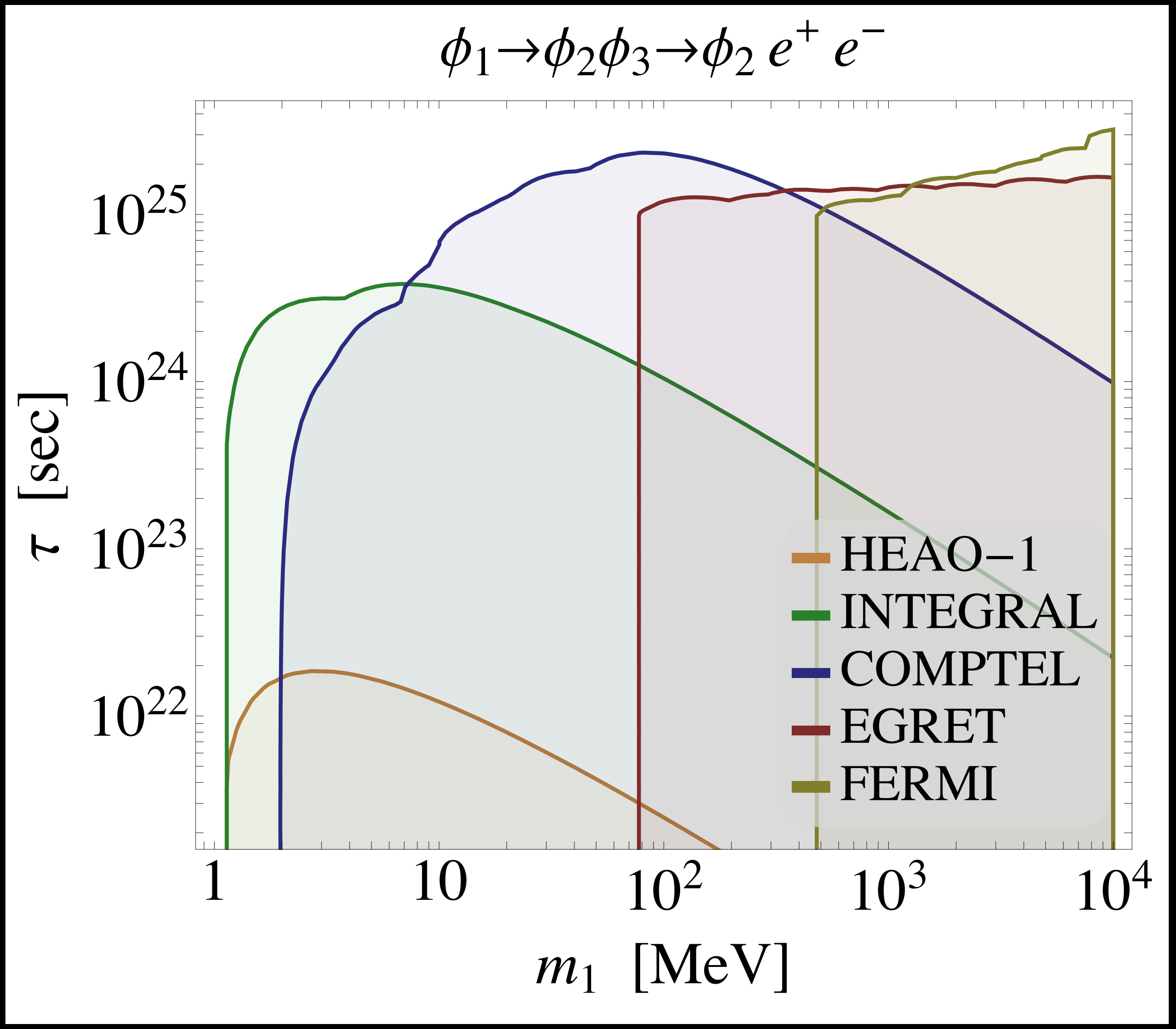
Dark Neutron Dark Matter
Dark Proton & Pion Dark Matter
terrestrial
Direct Detection
Super − Optimistic
LHCb
Belle − II
AWAKE
HPS
SeaQuest
LDMX
FASER
NA62
SHiP
terrestrial
SN1987A
$2m_{\gamma'} \leq m_{\pi'_0} \lesssim 0.5 m_{n'}$
γ' decays after ν decoupling
$e' = 0.01e$
$e' = 0.1e$
$e' = e$ XENON1T Migdal
$e' = e$ XENONnT
$e' = e$ DARWIN
$m_{\gamma'}$ [MeV]



LIGO
O1
O2
O5
ET
LISA
T=200 GeV
T=2TeV
T=500 TeV
BBO
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)

exotic signal

- SU(2)' instanton generates $u' d' d' \boldsymbol{\nu}' e^{-8\pi 2/g2} / v^2$
- dark neutron mixes to dark neutrino to neutrino portal to SM neutrino, decays into SM $\boldsymbol{\ell}$ + (qqbar or $\boldsymbol{\ell\nu}$)
- indirect detection of gamma's from galactic halos $\tau > 10^{25}$sec
- can happen if $\alpha'_W > 0.3$
- not possible when $N_{gen} > 1$



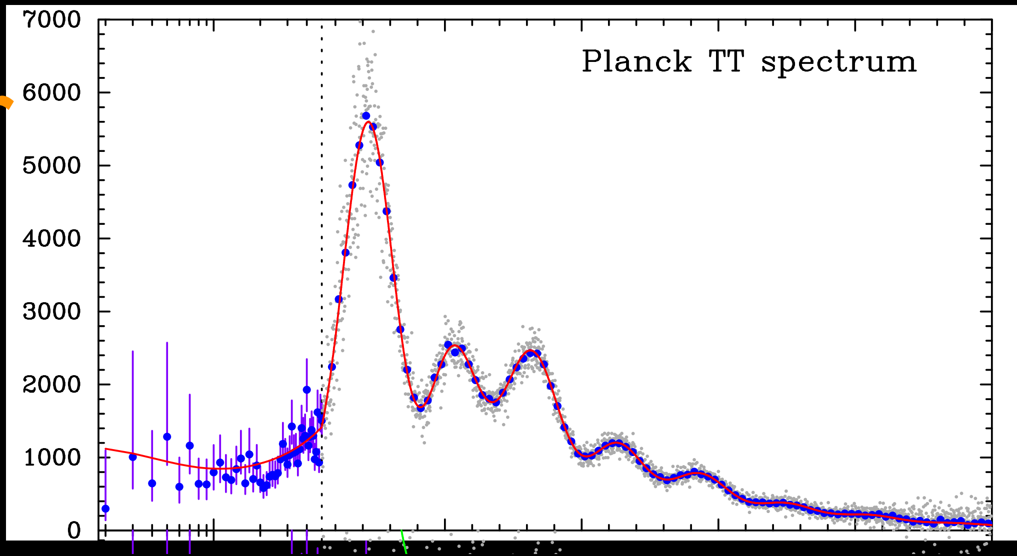
Essig, Kuflik, McDermott, Volansky, Zurek
aarXiv:1309.4091

Conclusions

- Electroweak baryogenesis *too testable*, very tight
  - do it in the dark sector
- dark SU(3)xSU(2)xU(1), one generation
  - two Higgs doublet CPV, 1st order phase transition
  - neutrino portal to transfer asymmetry to SM baryons
- dark neutron 1.33 or 1.58 GeV, or multi-component $p+\pi^-$
- amazingly wide array of experimental signatures
  - dark proton good target for direct detection
  - exotic Z-decay, h-decay (ILC, CEPC, FCC-ee)
  - dark photon search at Belle II, LHC-b, beam dump
  - gravitational wave at LIGO, LISA, Einstein Telescope, etc
  - potential instanton-induced dark neutron decay in halos
- explain coincidence $\Omega_{\rm DM} \sim \Omega_b$ if $N_{\rm gen}=3$ and unification

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...


Still many things
to look forward to!