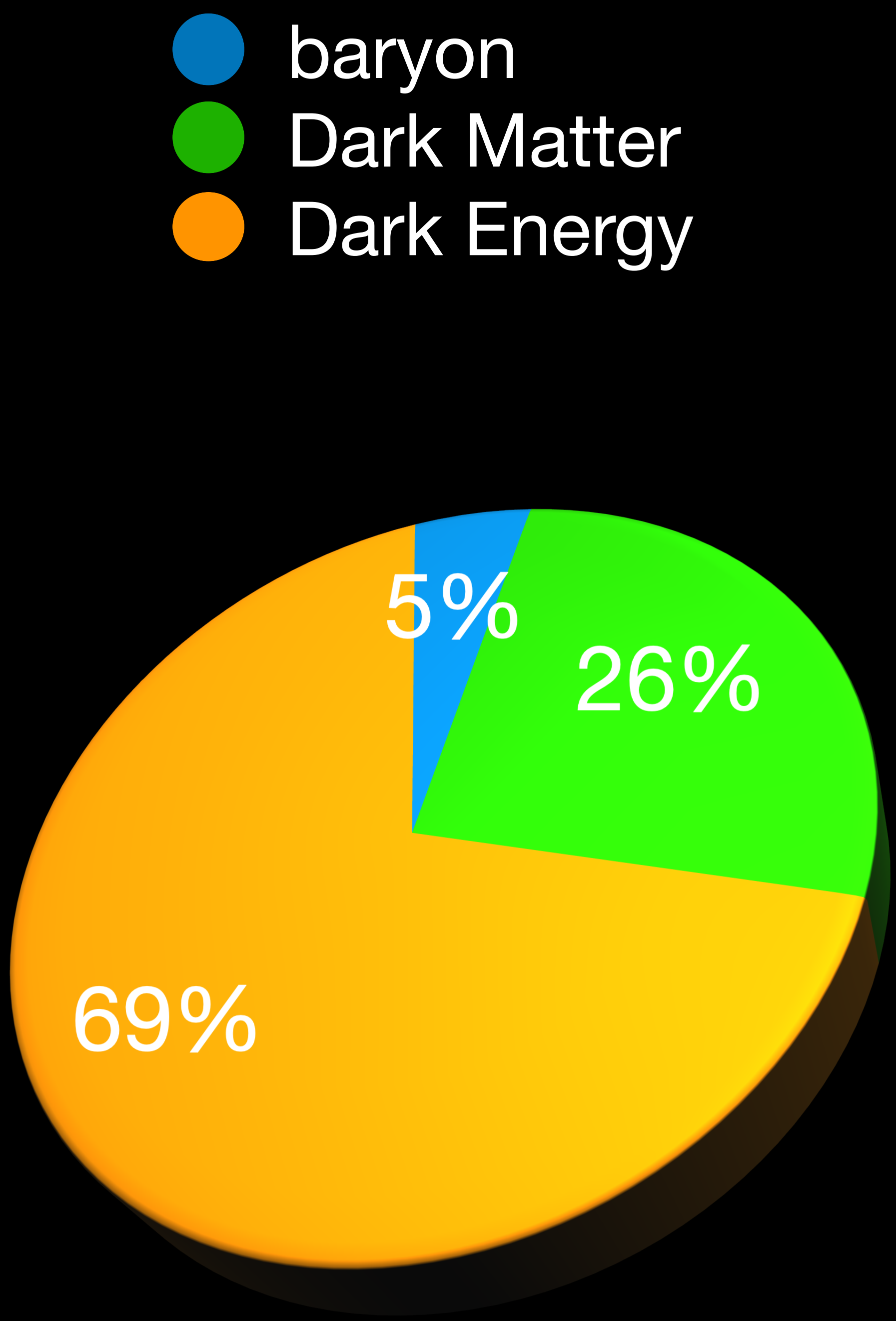
Origin of matter and gravitational wave

Hitoshi Murayama (Berkeley, Kavli IPMU)

University of Zurich, November 23, 2020

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



Beginning of Universe

1,000,000,000

matter

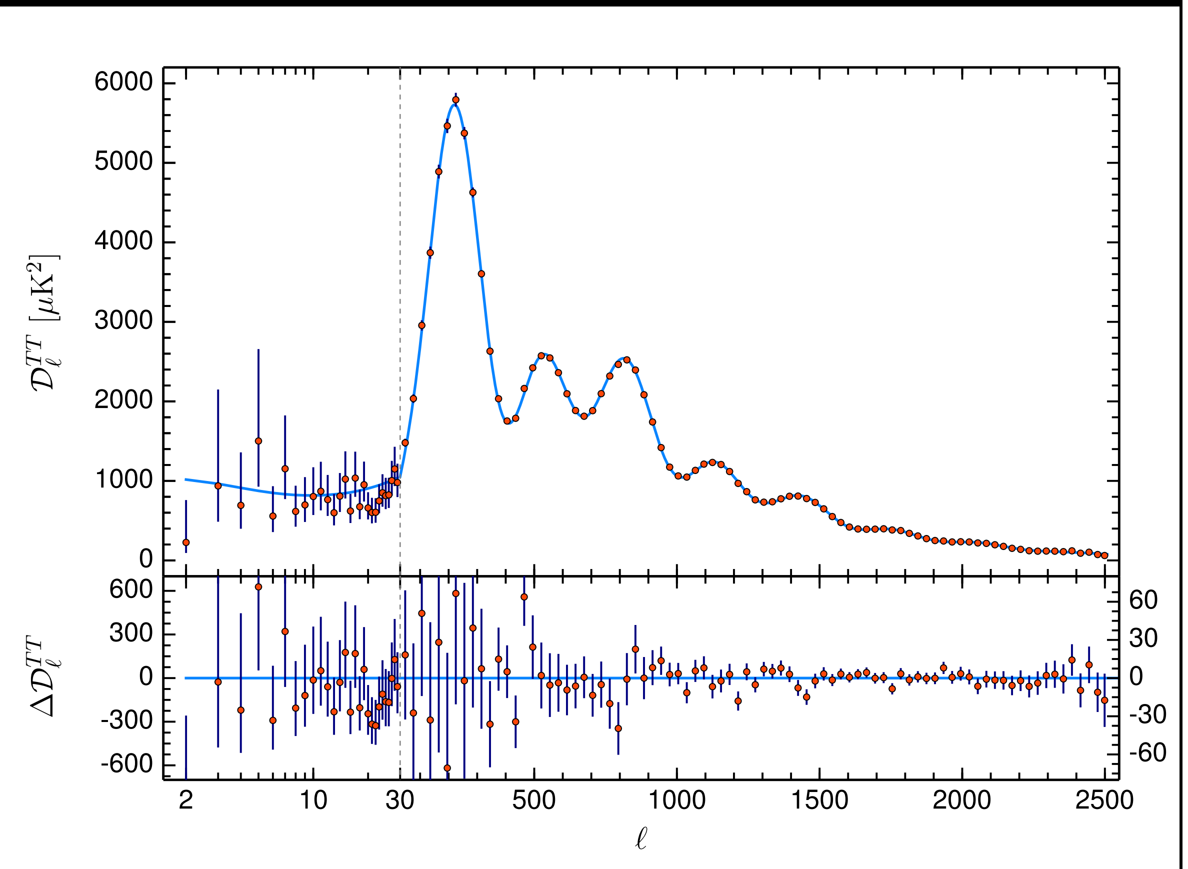
1,000,000,000

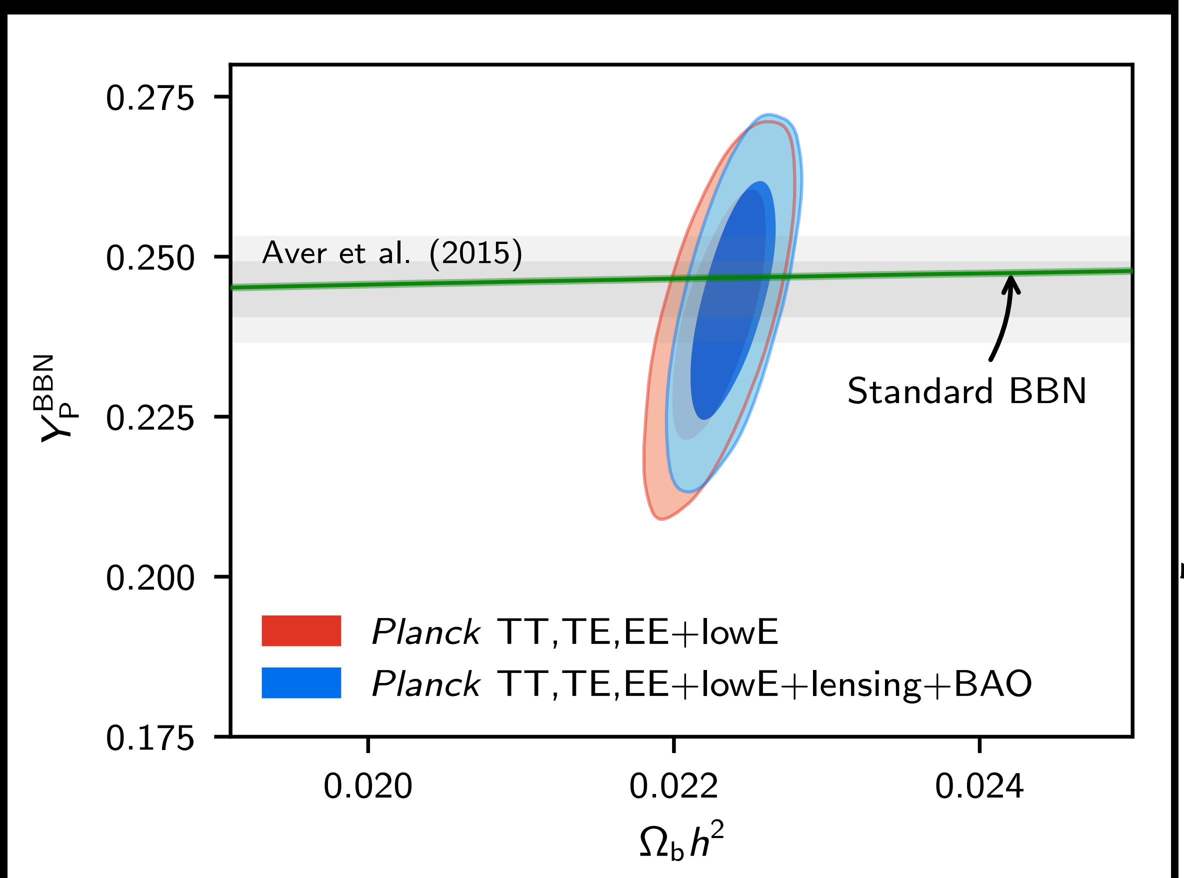
anti-matter

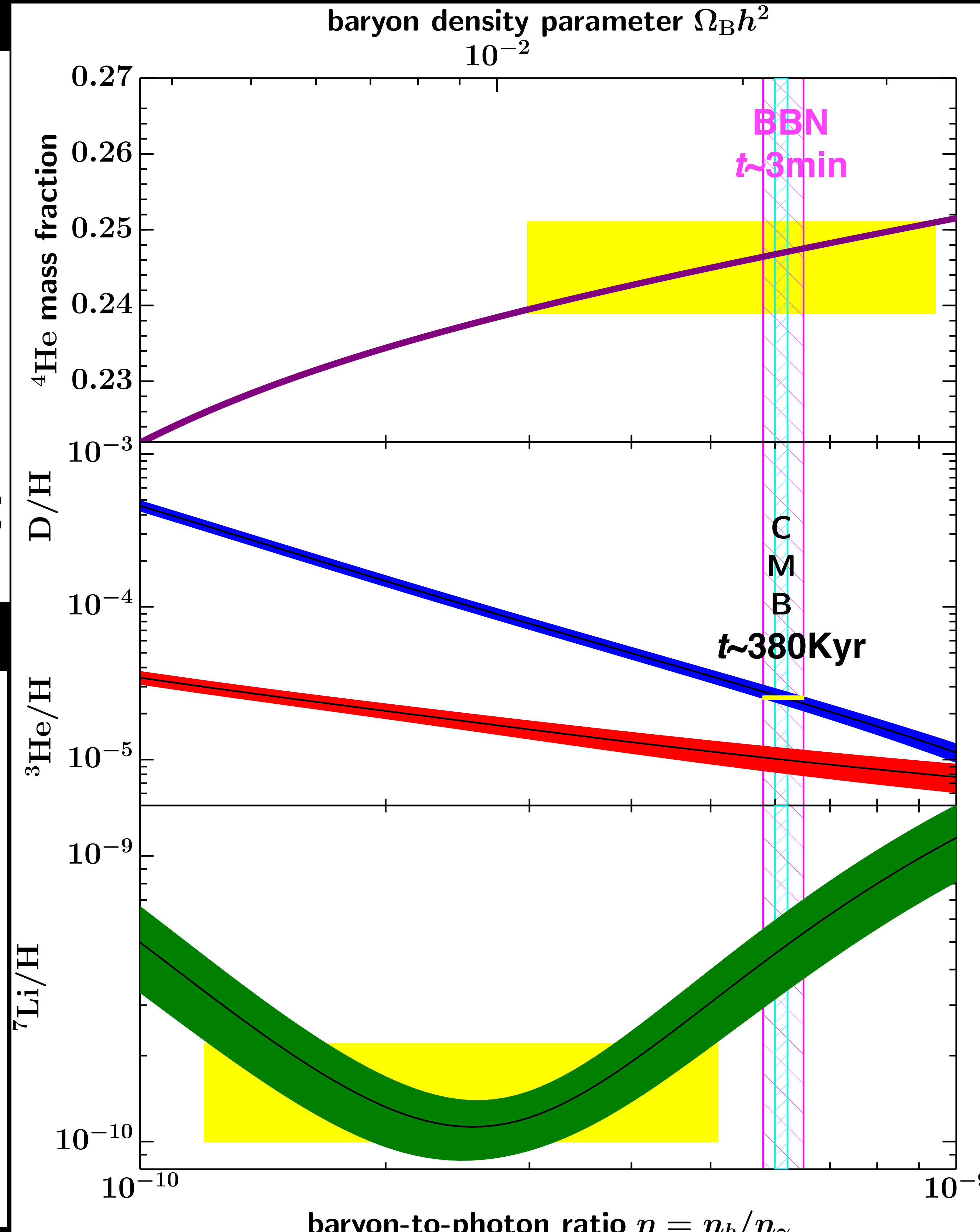
Universe Now?

matter *anti-matter*

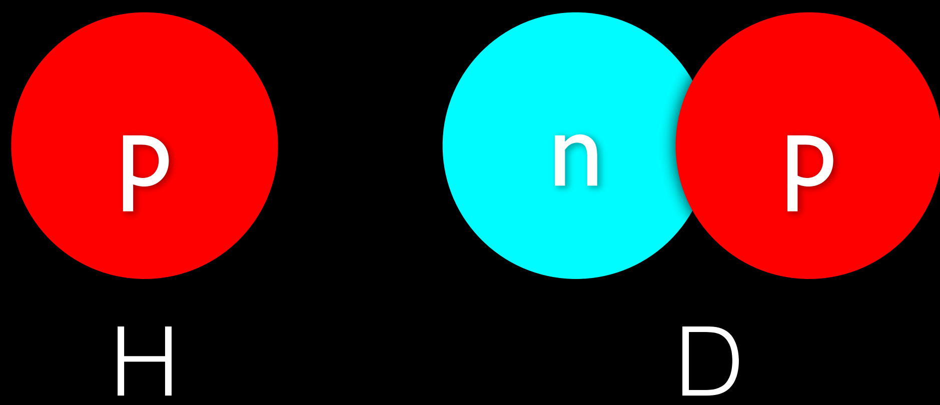
We wouldn't be here to discuss it today!


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

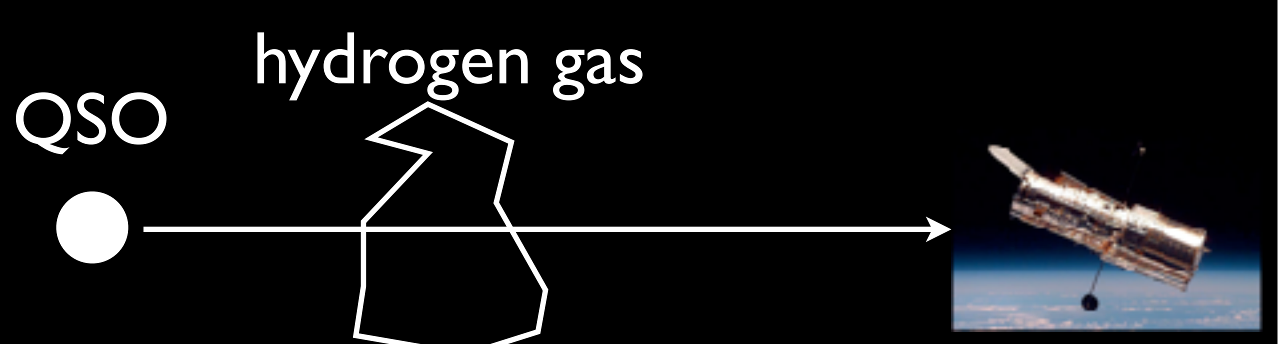

0.275
0.250
0.225
0.200
0.175
$Y_\mathrm{P}^\mathrm{BBN}$
Aver et al. (2015)
Standard BBN
Planck TT,TE,EE+lowE
Planck TT,TE,EE+lowE+lensing+BAO
0.020
0.022
0.024
$\Omega_\mathrm{b}h^2$


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

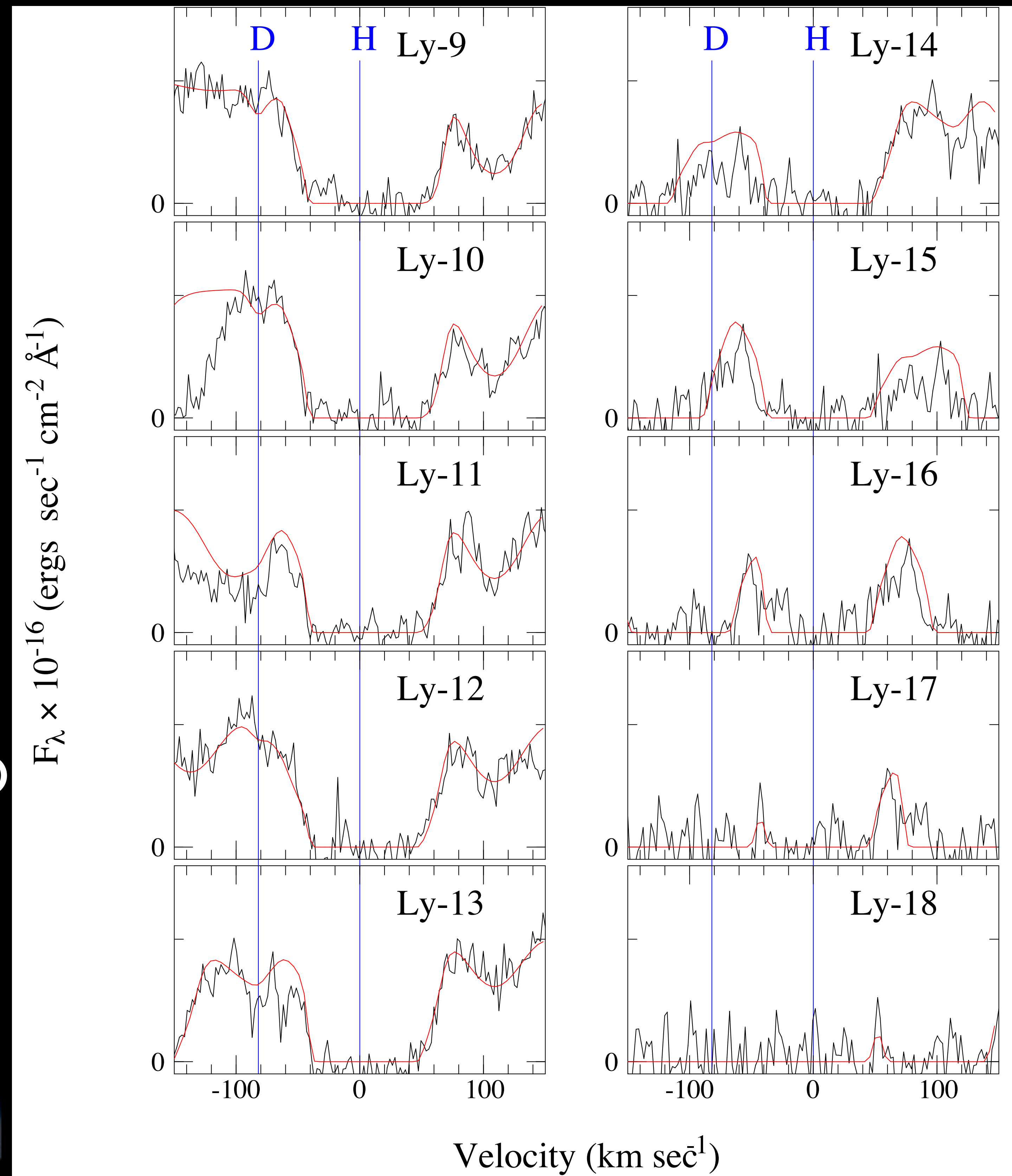
deuterium



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



Kirkman, Tytler, Suzuki, O'Meara, Lubin



fraction of second later

1

1,000,000,002

1,000,000,000

matter

anti-matter

tiny imbalance between matter and anti-matter

Universe Now

2

us

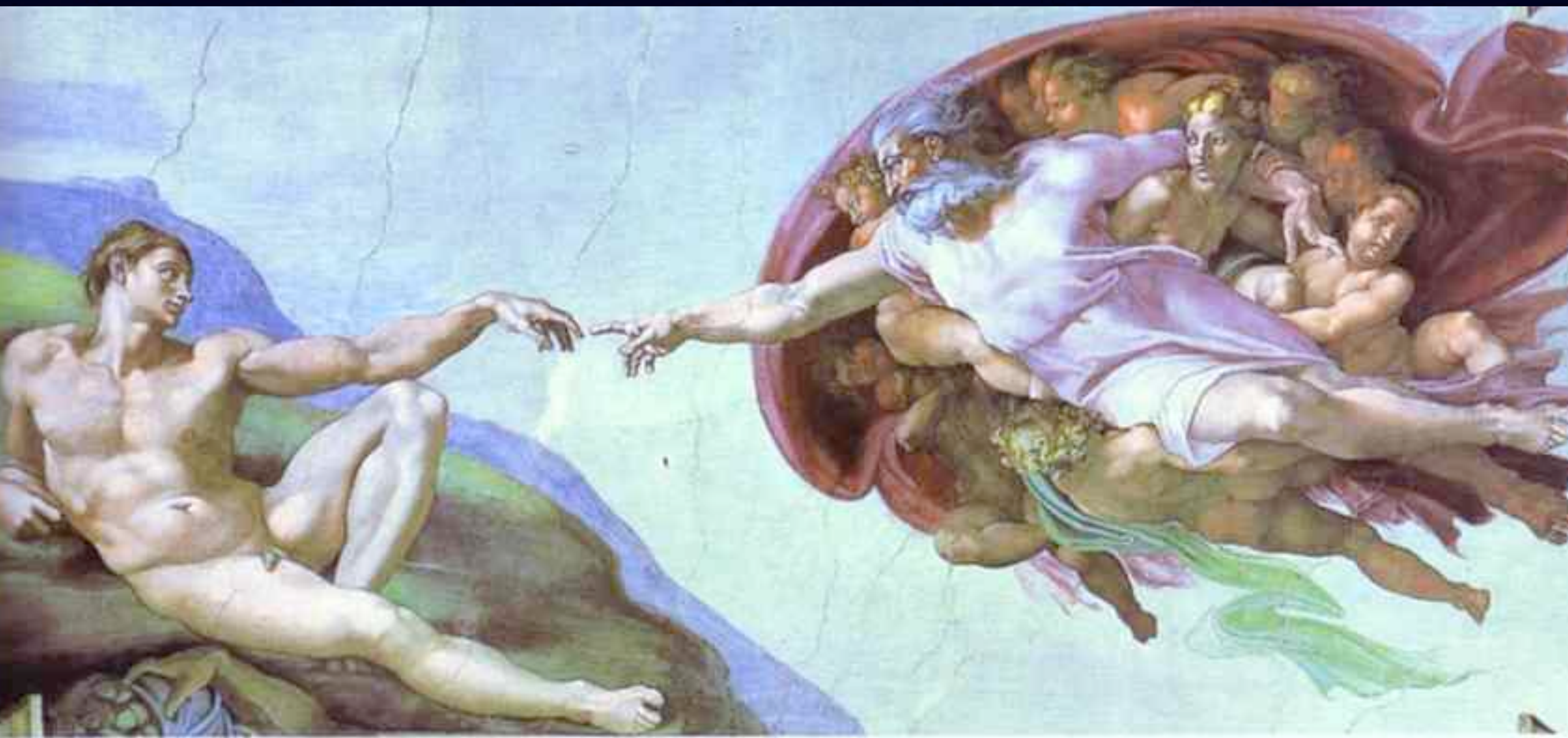
matter

anti-matter

we survived at the expense of a billion friends!

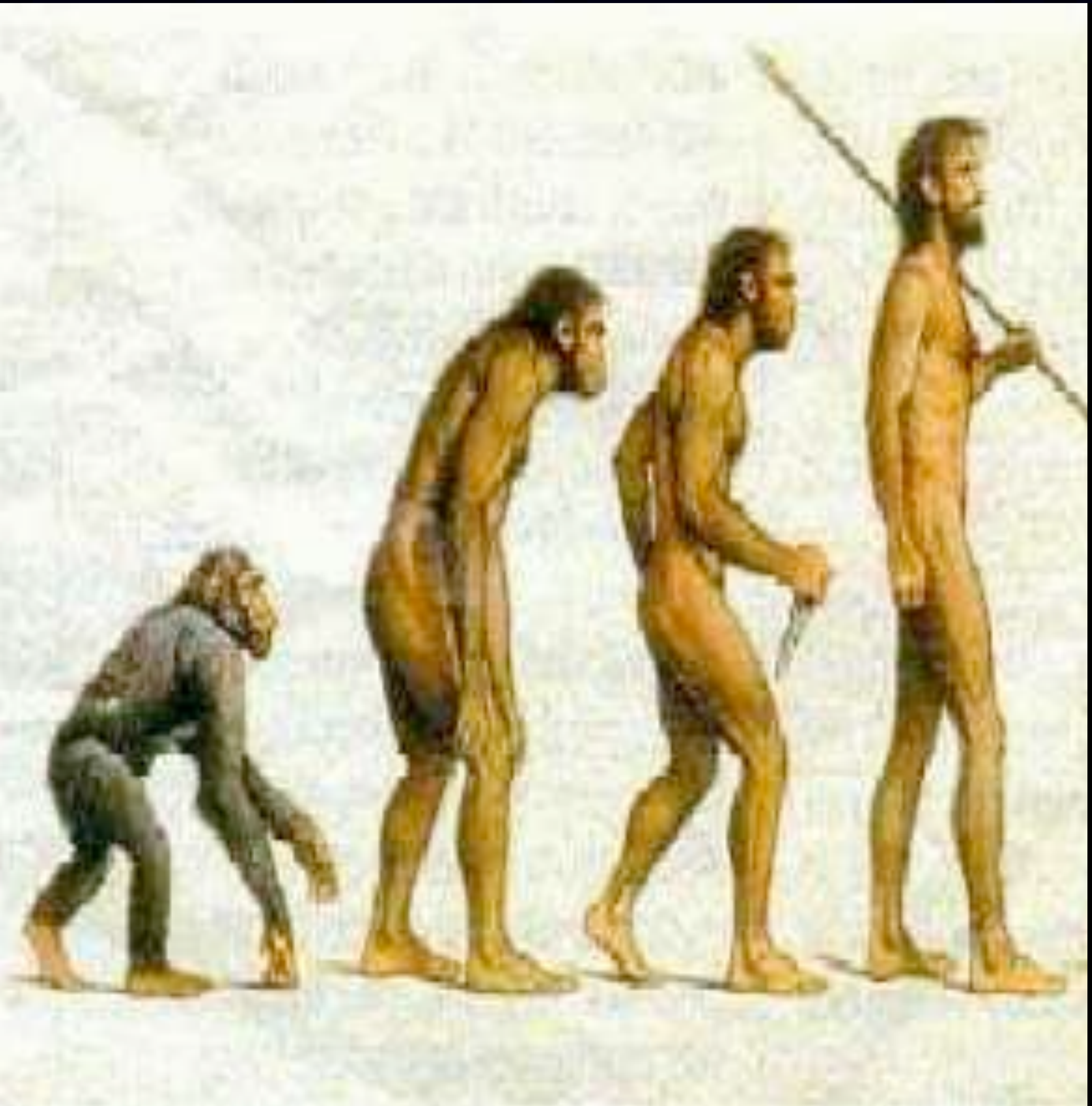
Creation

$n_b(t=0) \neq 0$

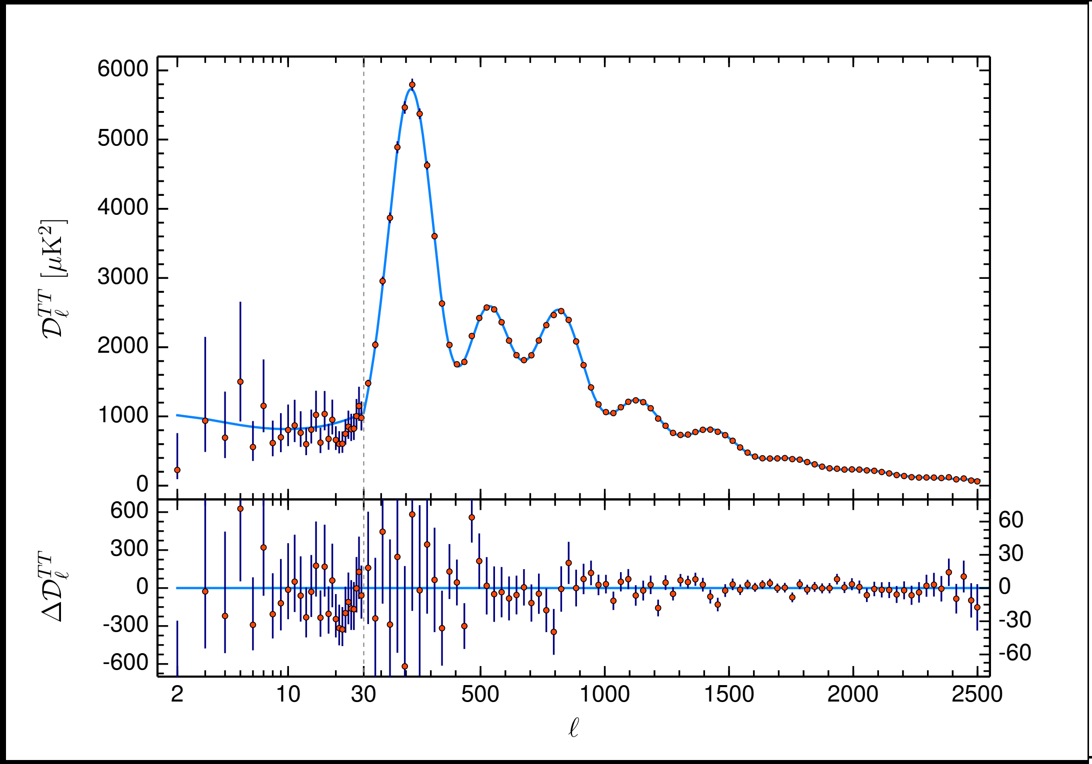


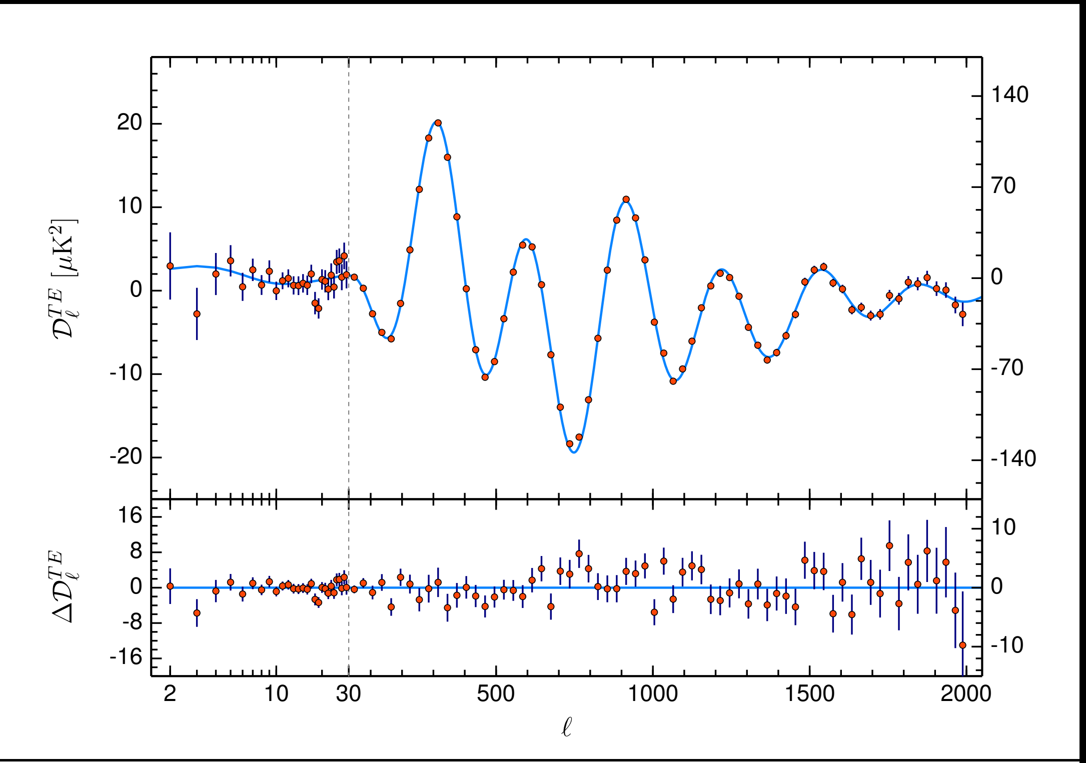
Or Evolution?

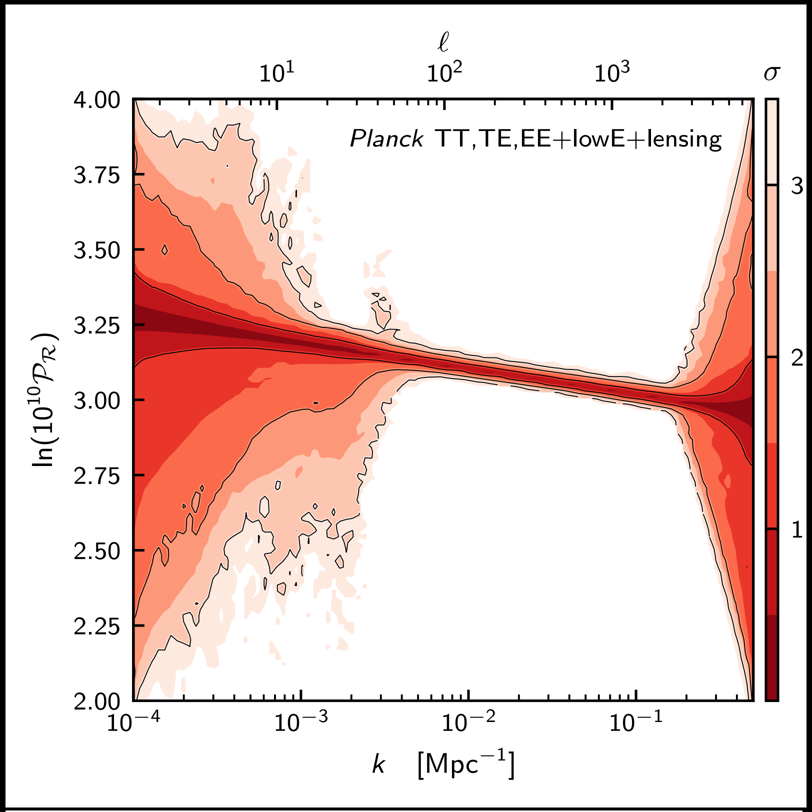
$n_b(t=0)=0 \Rightarrow n_b(t>t_b)\neq 0$

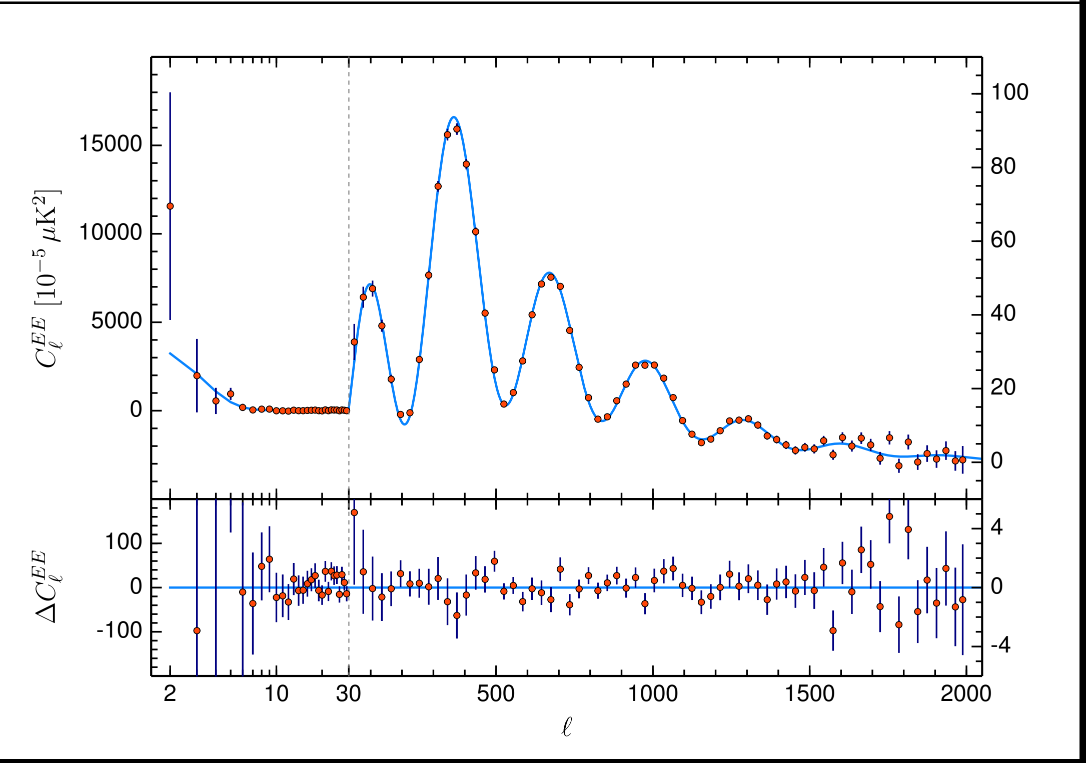


Inflation









Beginning of Universe

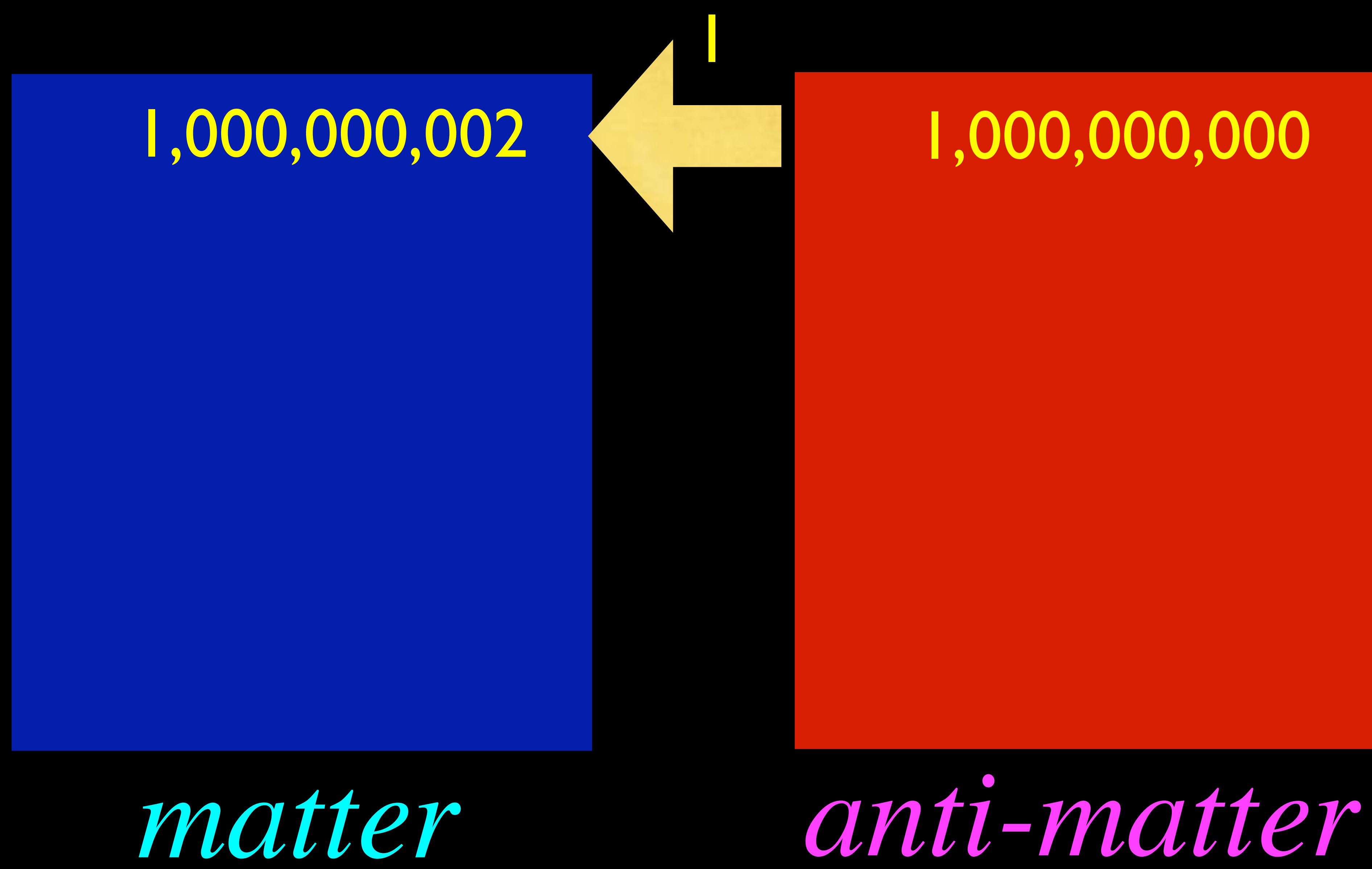
1,000,000,001

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!


Who saved us from
a complete annihilation?

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

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...

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

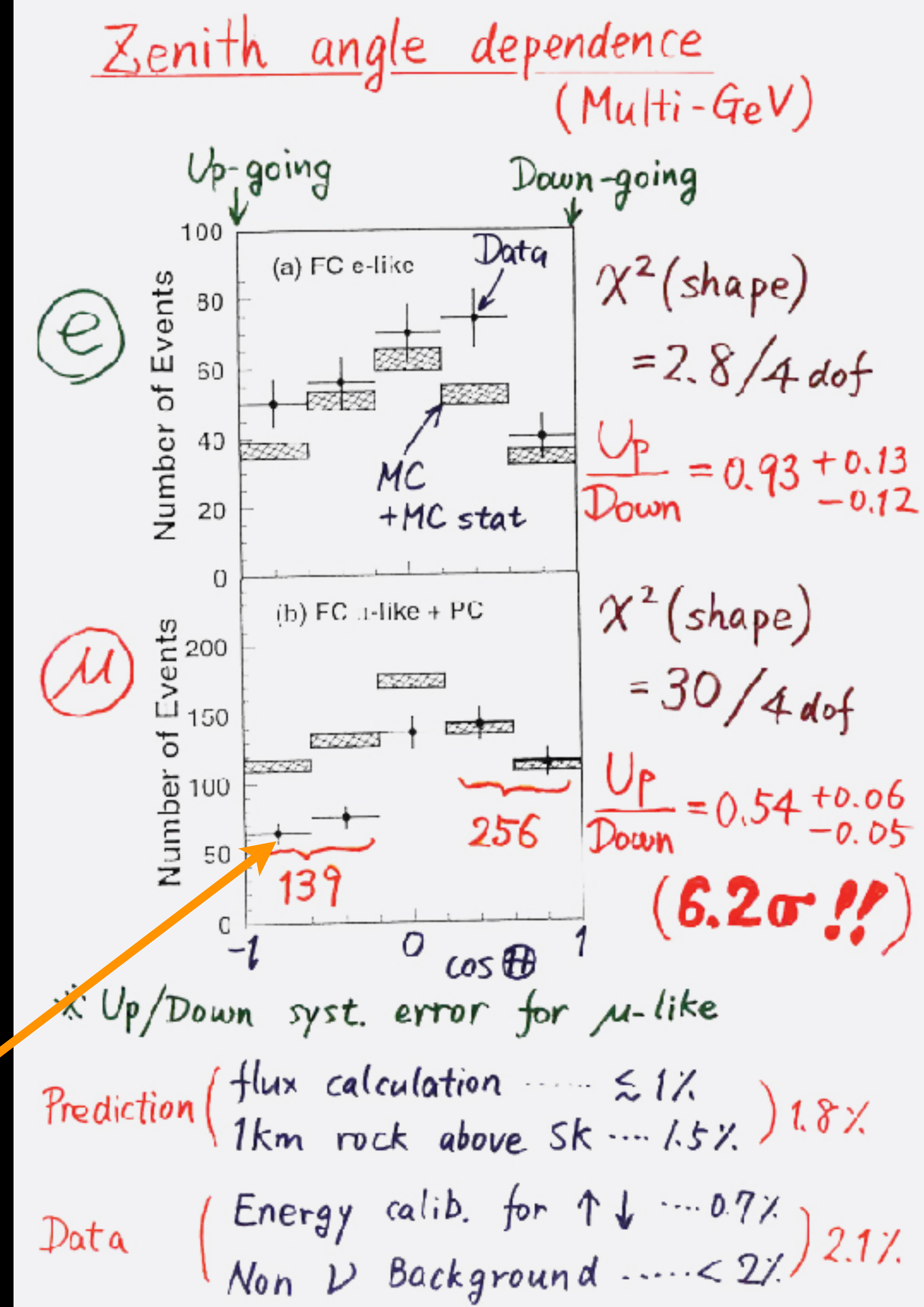
Hitoshi Murayama (Berkeley, Kavli IPMU)
+Jeff Dror (Berkeley), Takashi Hiramatsu (ICRR), Kazunori Kohri (KEK), Graham White (TRIUMF)

arXiv:1908.03227, accepted for PRL

neutrinos oscillate

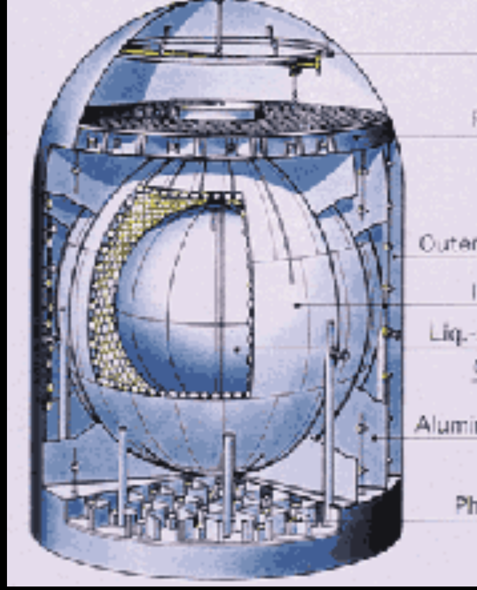
1998

a half of expected

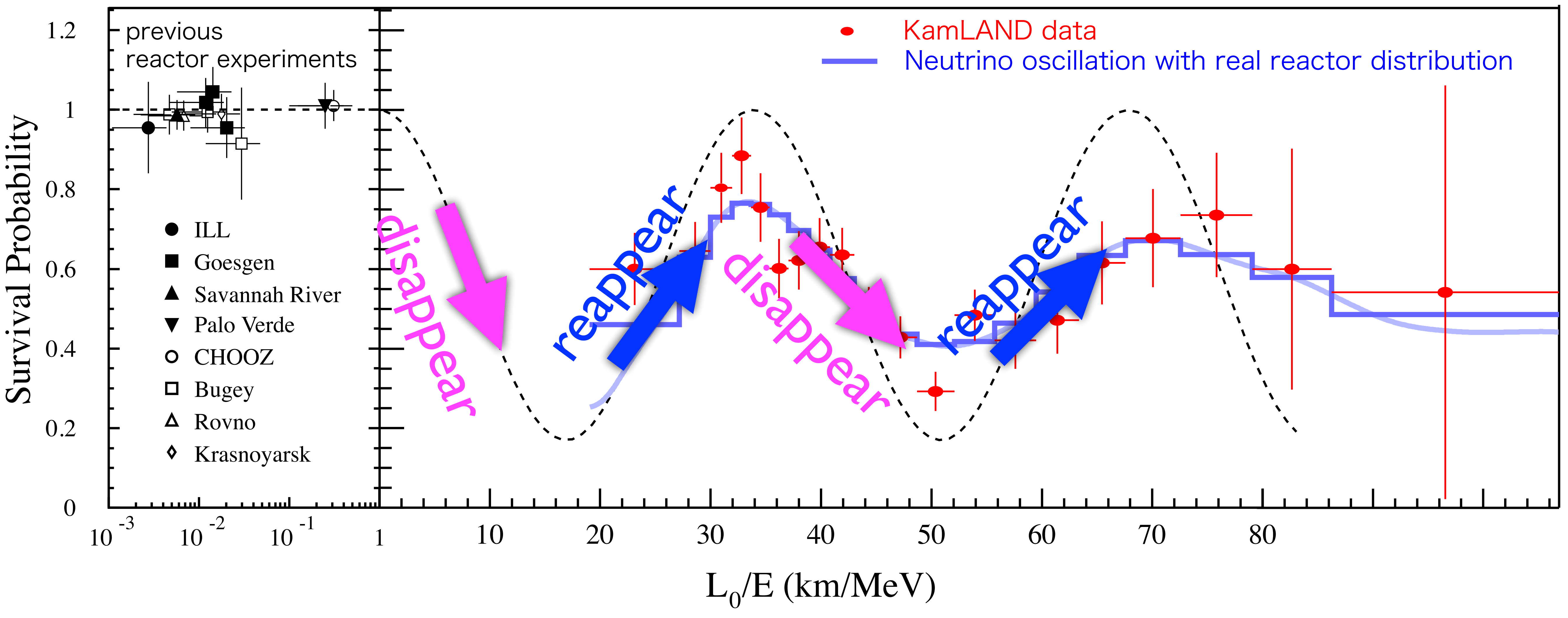


shift inside the mine for KamLAND

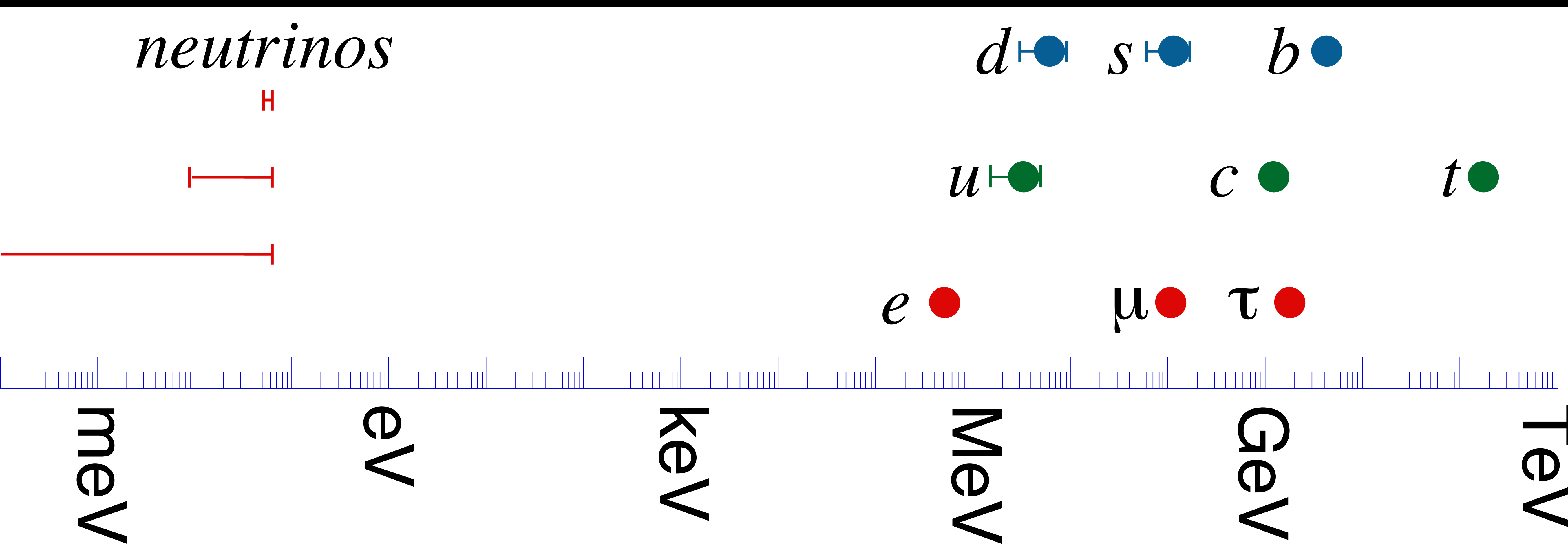
reactor neutrinos



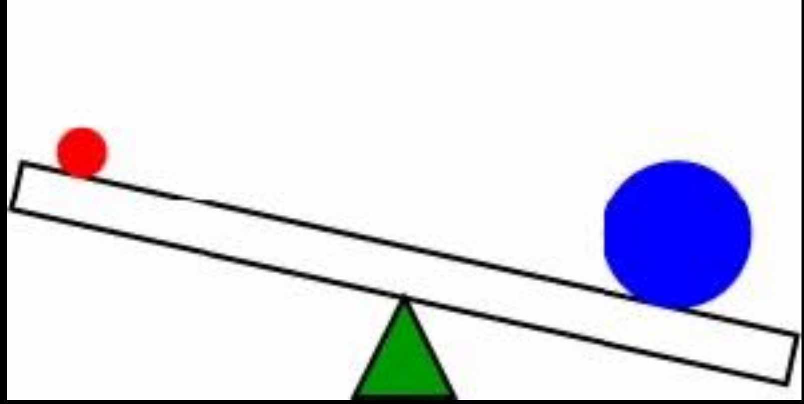
- KamLAND experiment
- a ring of reactors with average L~175 km



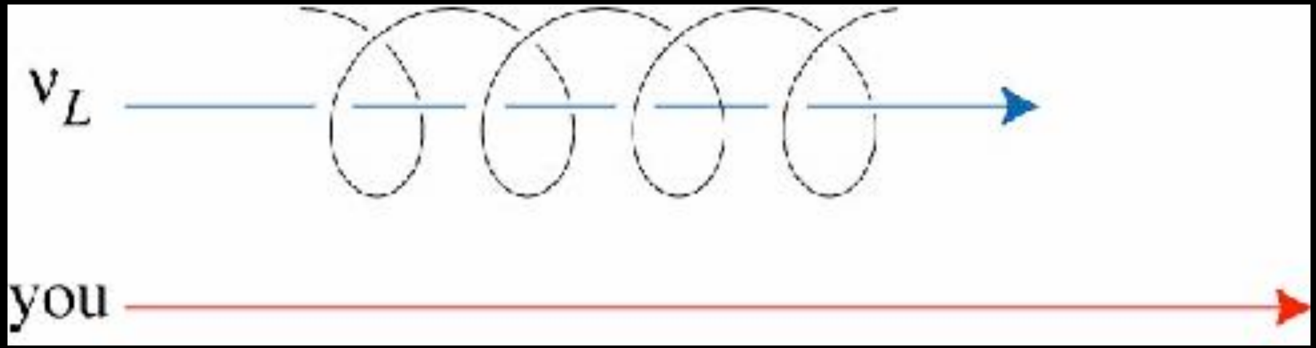
very light

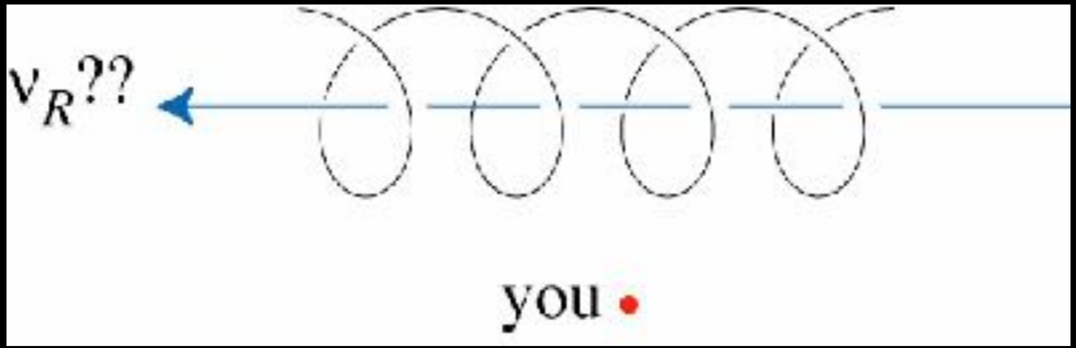


Seesaw



- 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

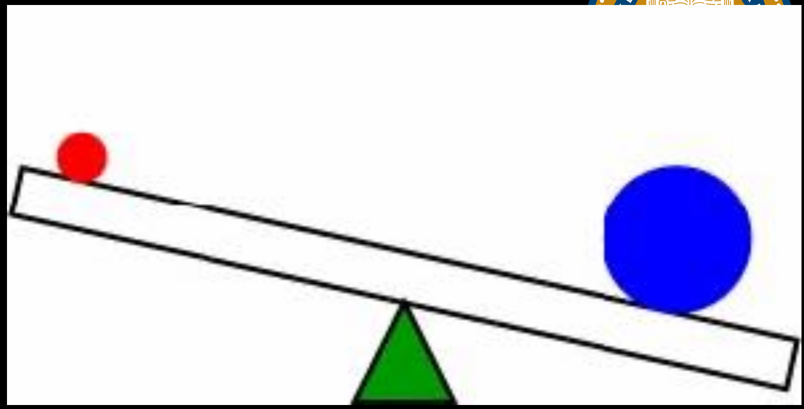




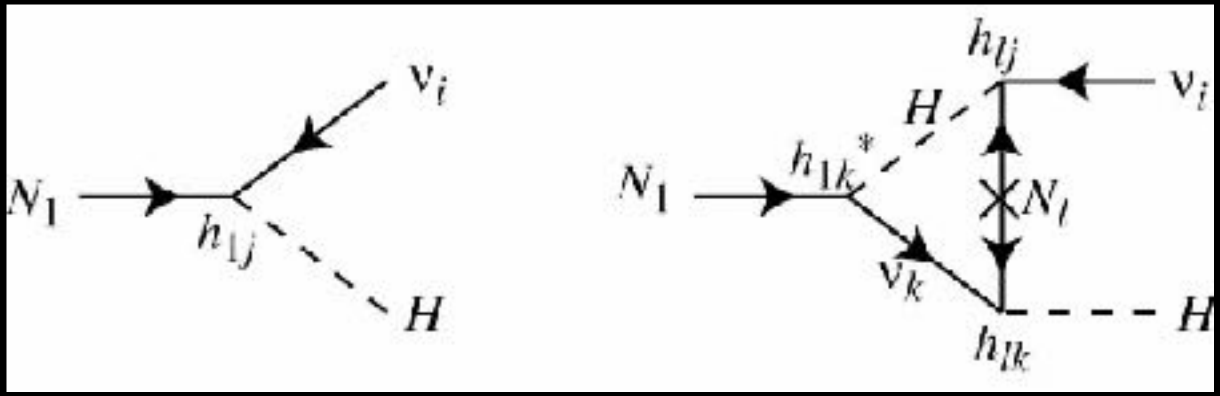
$$\mathcal{L} = -yLNH$$

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

Leptogenesis



- Right-handed neutrinos in early universe
- when they decay, produce $L \neq 0$



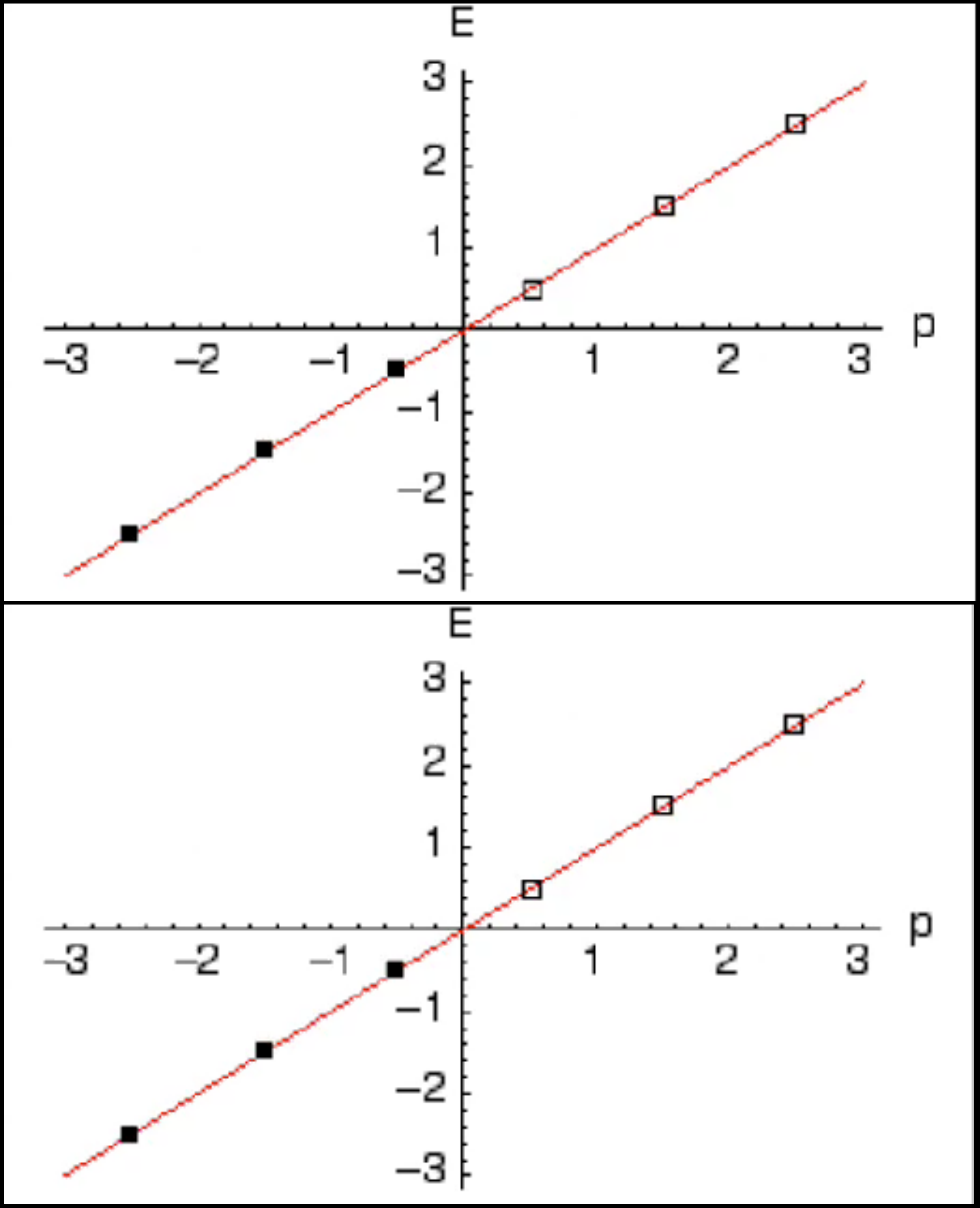
$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H^*) \propto \Im m(h_{1j} h_{1k} h_{lk}^* h_{lj}^*)$$

- 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

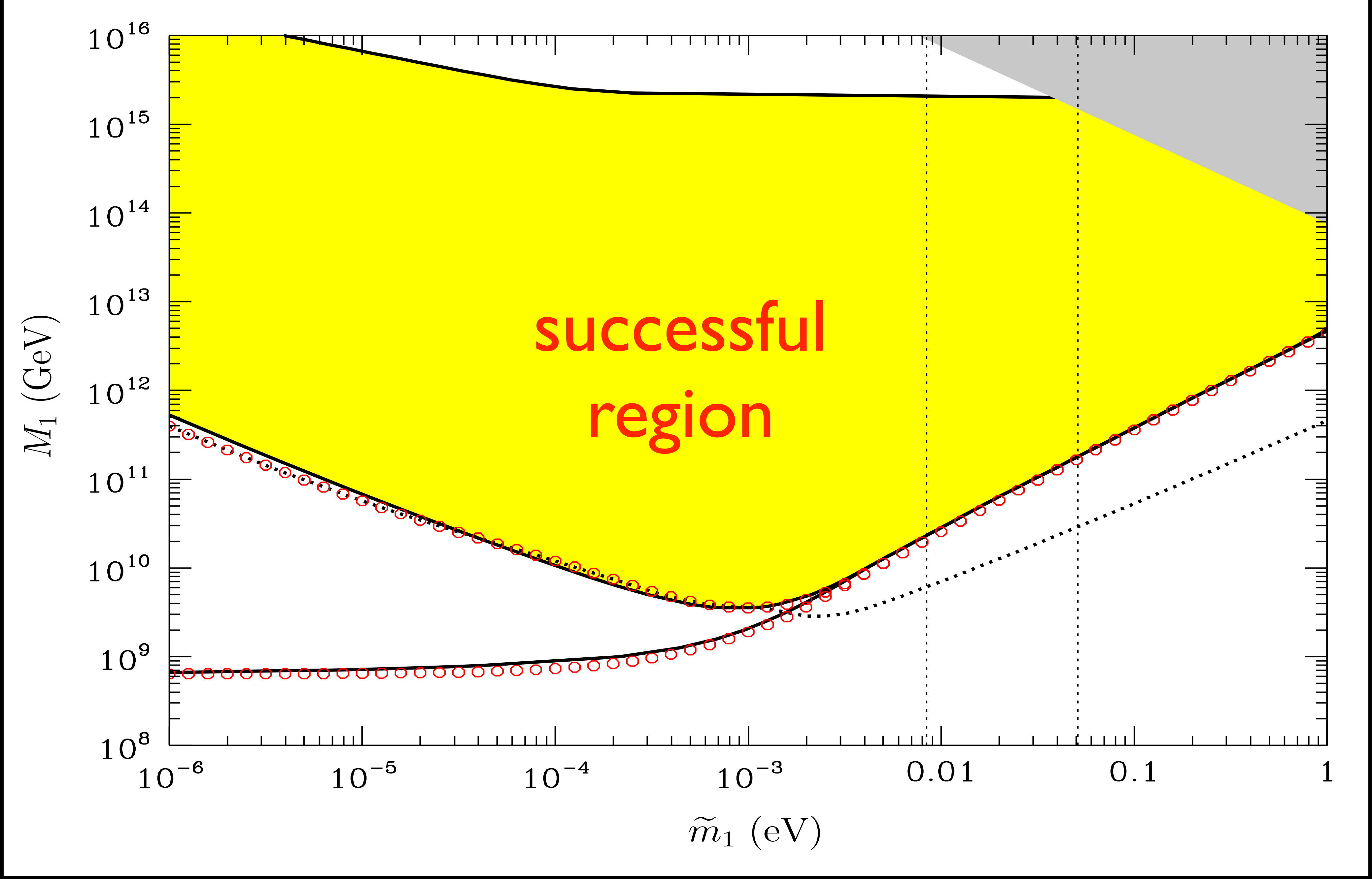
$\Delta q = \Delta q = \Delta q = \Delta L$



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

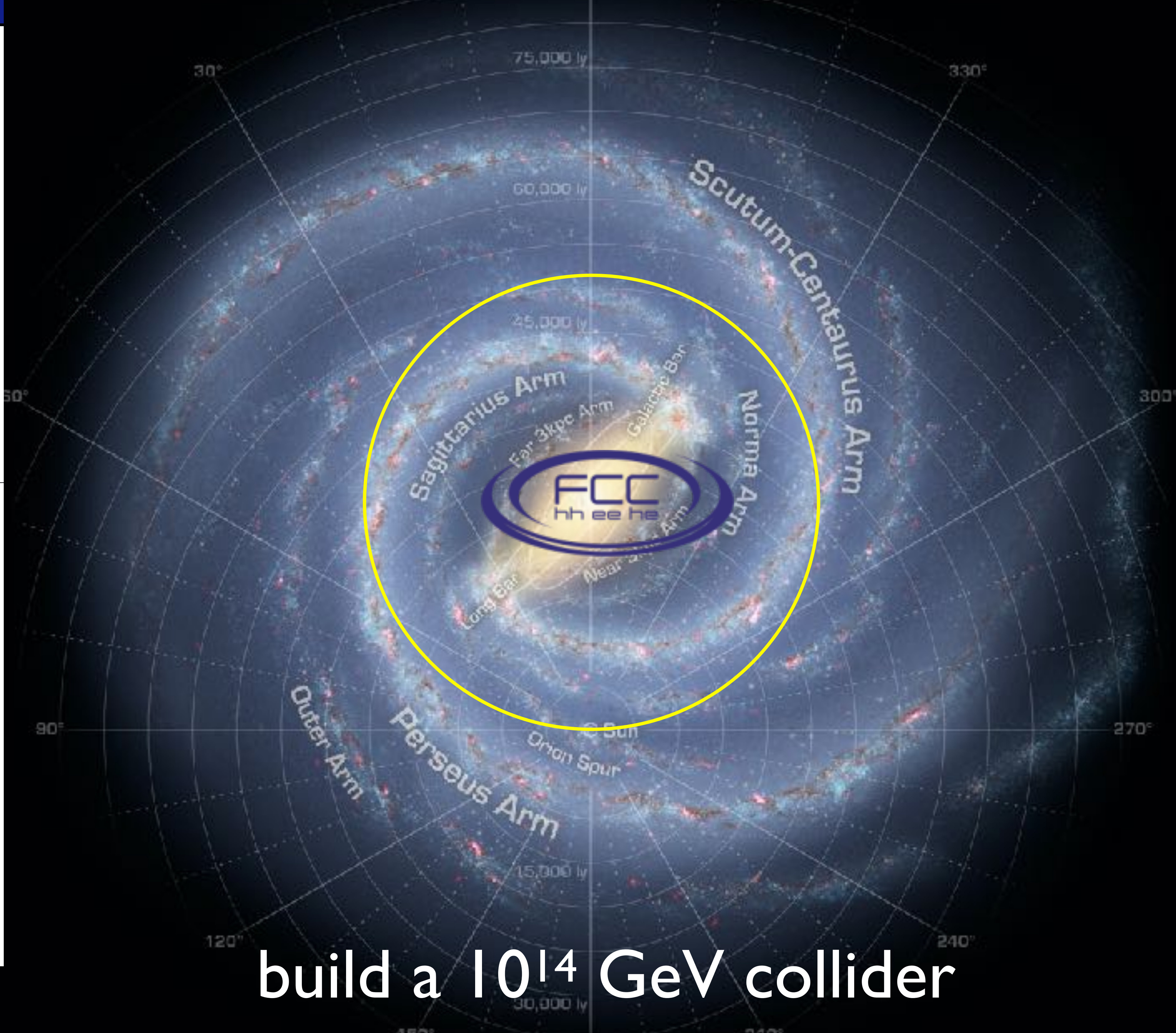
Leptogenesis



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

di Bari, Plümacher, Buchmüller

How do we test it?



build a 10^{14} GeV collider

how do we test it?

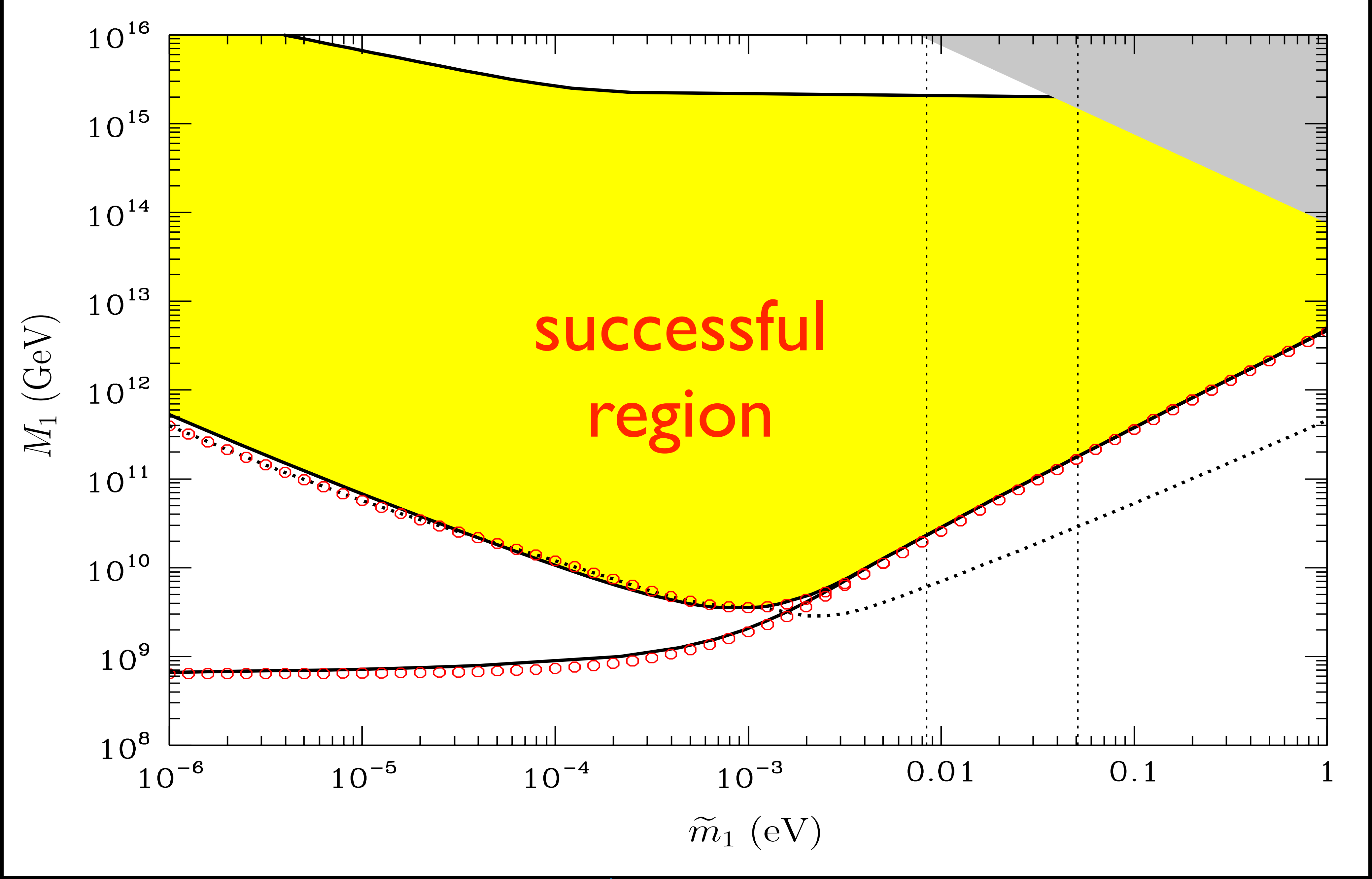
- possible three circumstantial evidences
  - $0\nu\beta\beta$
  - CP violation in neutrino oscillation
  - other impacts e.g. LFV (requires new particles/interactions < 100 TeV)
- *archeology*
- *any more circumstantial evidences?*

M_{Pl}

Natural to think M is induced from symmetry breaking

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

inflation



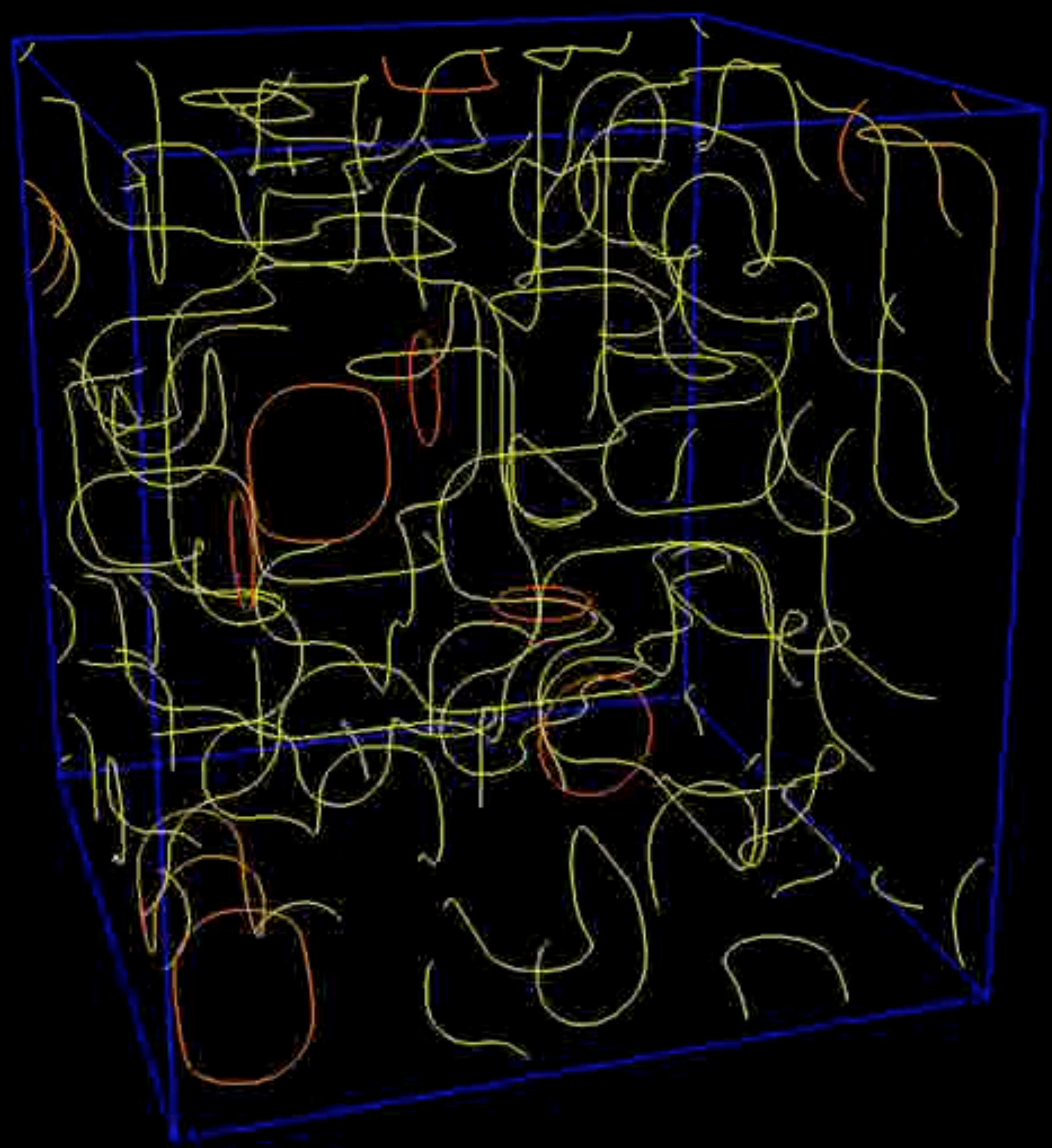
Phase Transition → Gravitational Waves?

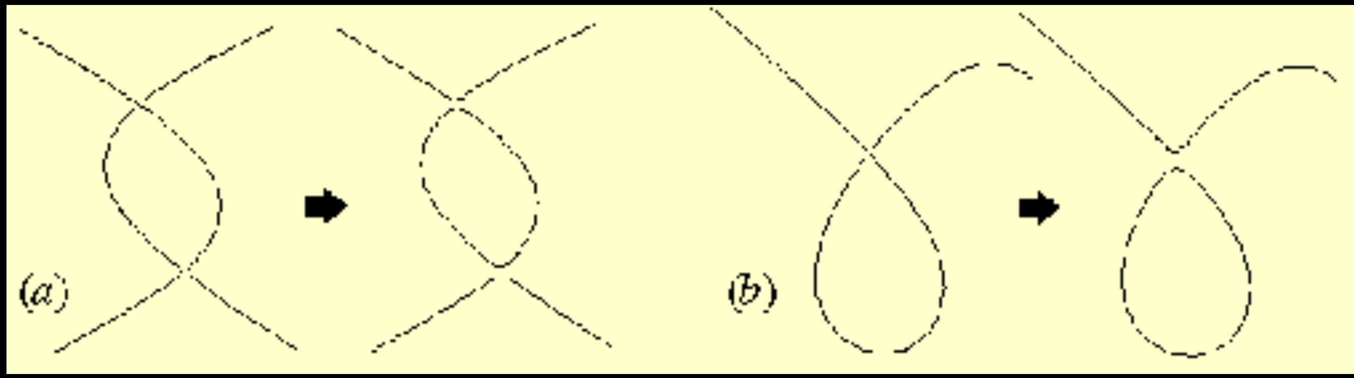
$U(1)_{B-L}$

- 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

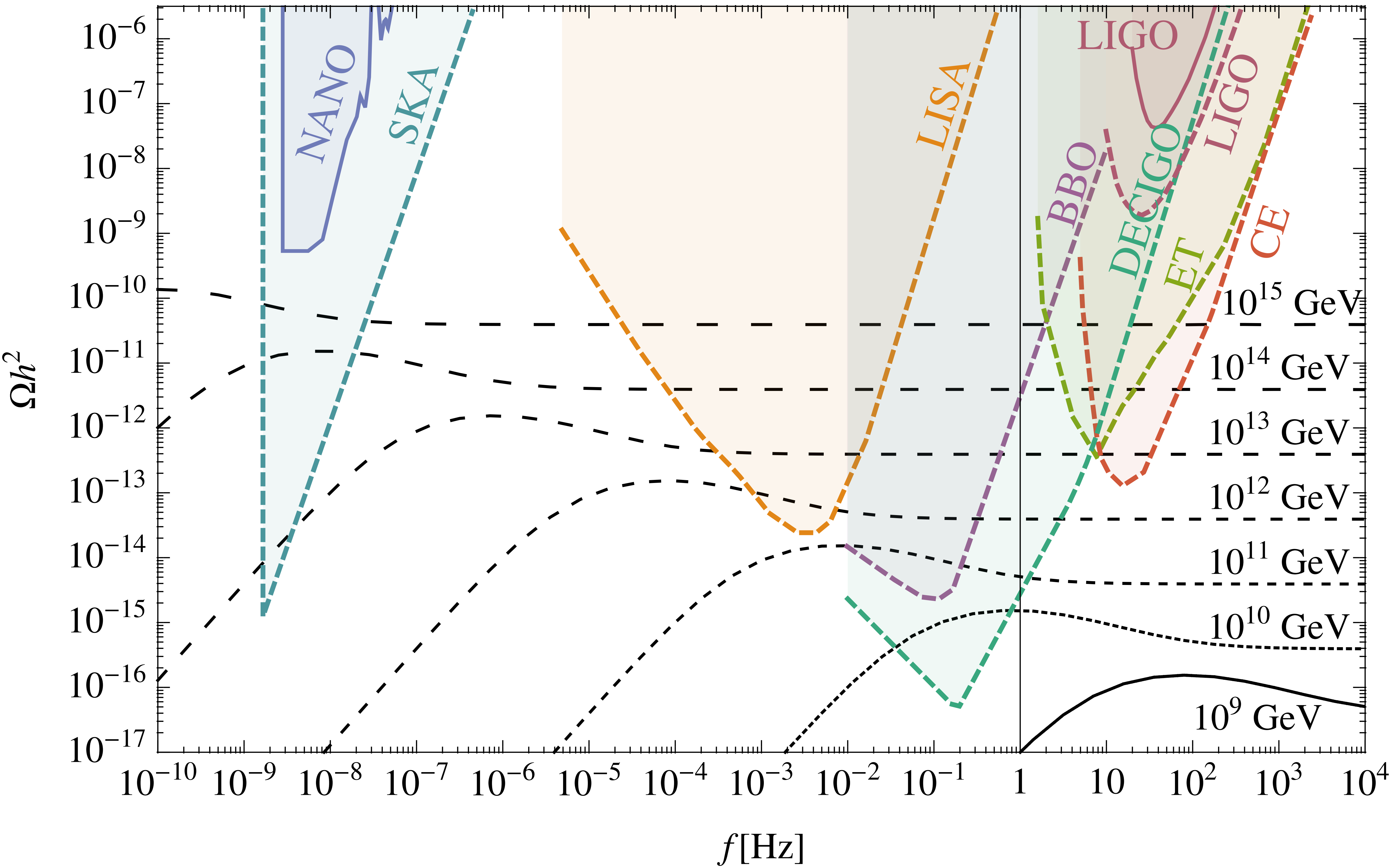
- possible gauge groups
  - forbids $M\,\nu_R\,\nu_R$
  - anomaly-free without additional fermions
  - no magnetic monopoles
  - rank ≤5
- possible Higgs
  - matter parity?
  - e.g. $\varphi(+1)$ or $\varphi(+2)$
  - H=G_{SM} or $G_{SM}\times Z_2$
- 5 out of 8 have strings

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

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

	$H=G_{\rm SM}$		$H=G_{\rm SM}\times\mathbb{Z}_2$	
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

Hybrid inflation

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

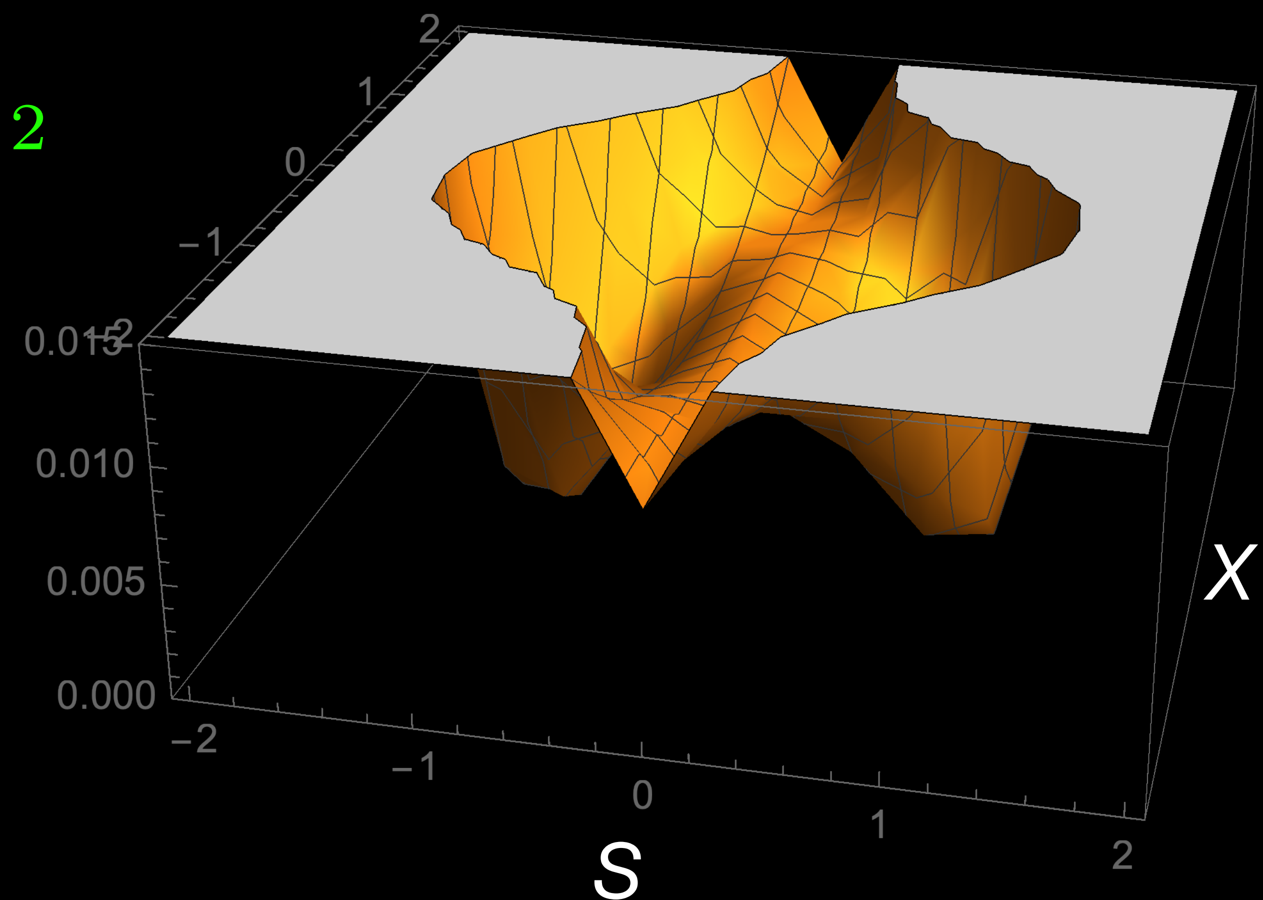
$$W = \lambda X (S^+ S^- - v^2)$$

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

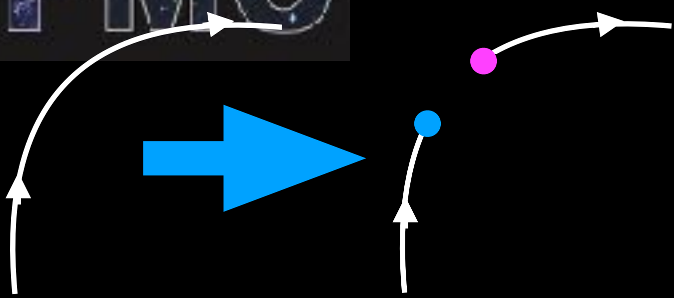
- *D*-flat direction $S=S^+=S^-$

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

- flat: $S=0$, $V=\lambda^2 v^2$
- falls down to $S=v$ near $X\sim0$
- forms cosmic strings
- requires high $v \geq$ a few 10^{15} GeV
- *excluded* by Pulsar Timing Array?

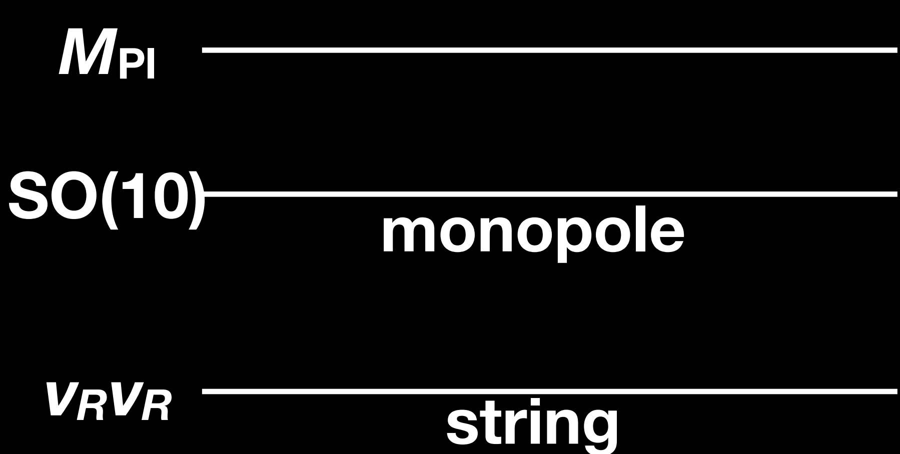


Wilfried Buchmüller, Valerie Domcke, HM, Kai Schmidt, arXiv:1912.03695



SO(10)

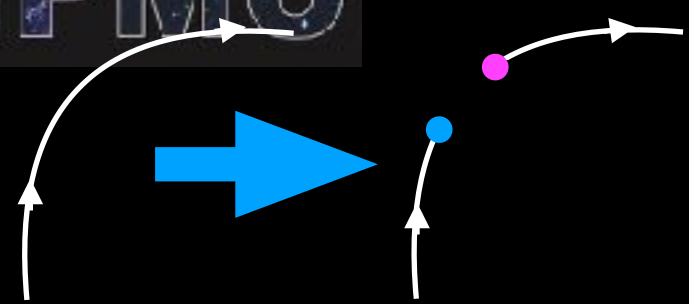
- All of them embeddable into SO(10)
- paradox: $\pi_1(SO(10)/G_{SM})=0$
- resolution:



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

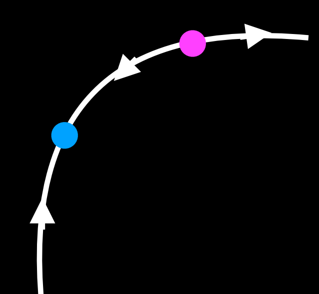
	$\langle\varphi\varphi\rangle v_R v_R/M_{Pl}$		$\langle\varphi\rangle v_R v_R$	
	$H = G_{\rm SM}$		$H = G_{\rm SM} \times \mathbb{Z}_2$	
G	**defects**	**Higgs**	**defects**	**Higgs**
$G_{\rm disc}$	domain wall*	$B-L=1$	domain wall*	$B-L=2$
G_{B-L}	abelian string*	$B-L=1$	$\mathbb{Z}_2$ string†	$B-L=2$
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	$(\mathbf{50},2)$

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



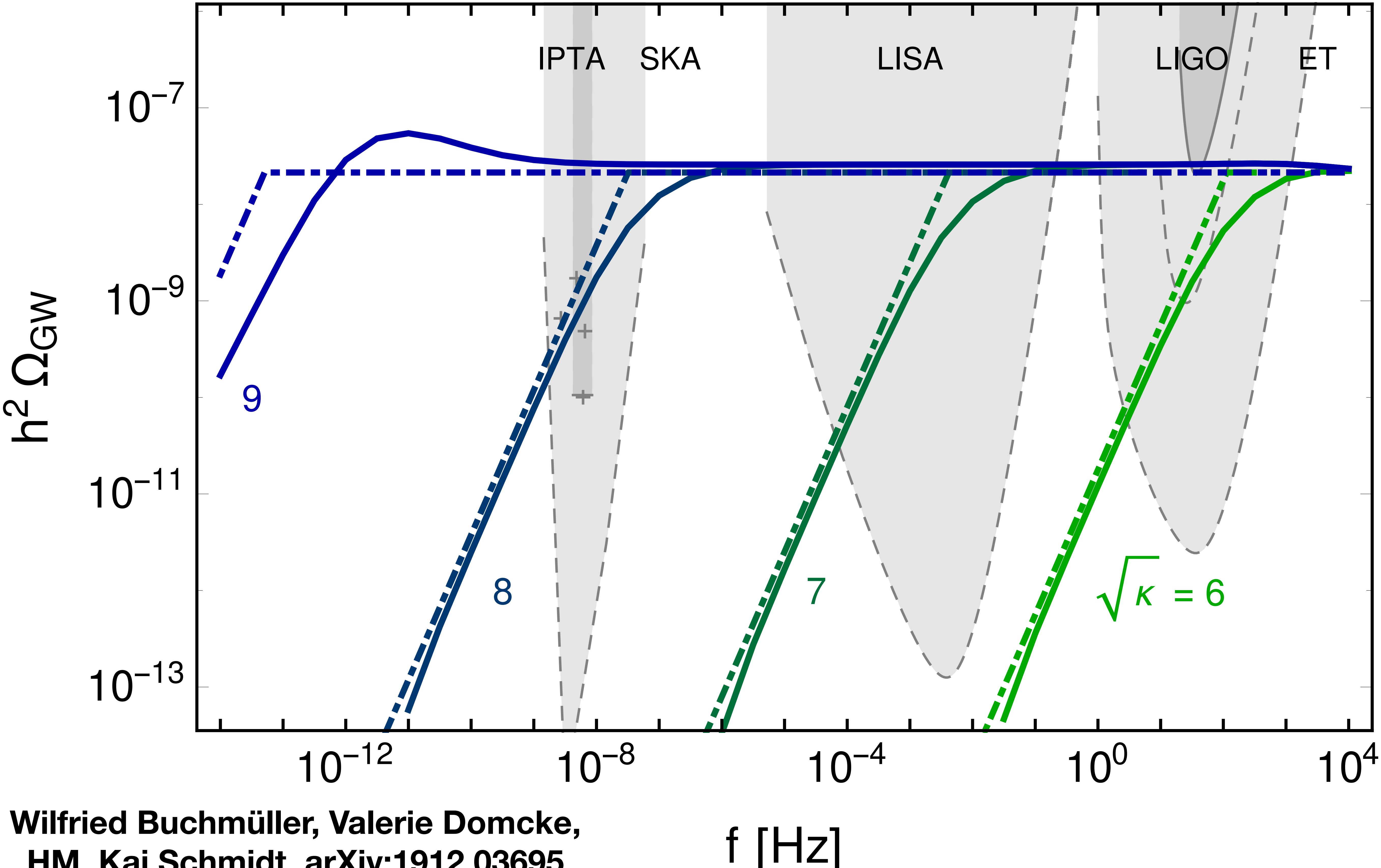
monopoles

- string from U(1)$_{B-L}$ breaking is basically Abrikosov flux in a superconductor
  - For the Higgs ϕ(±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 $$\frac{\Gamma}{L} = \frac{eE}{4\pi^2}\sum_{n=1}^{\infty}\frac{1}{n}e^{-\pi m^2 n/eE}$$
- survives to date if $v < 10^{15}$GeV



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

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

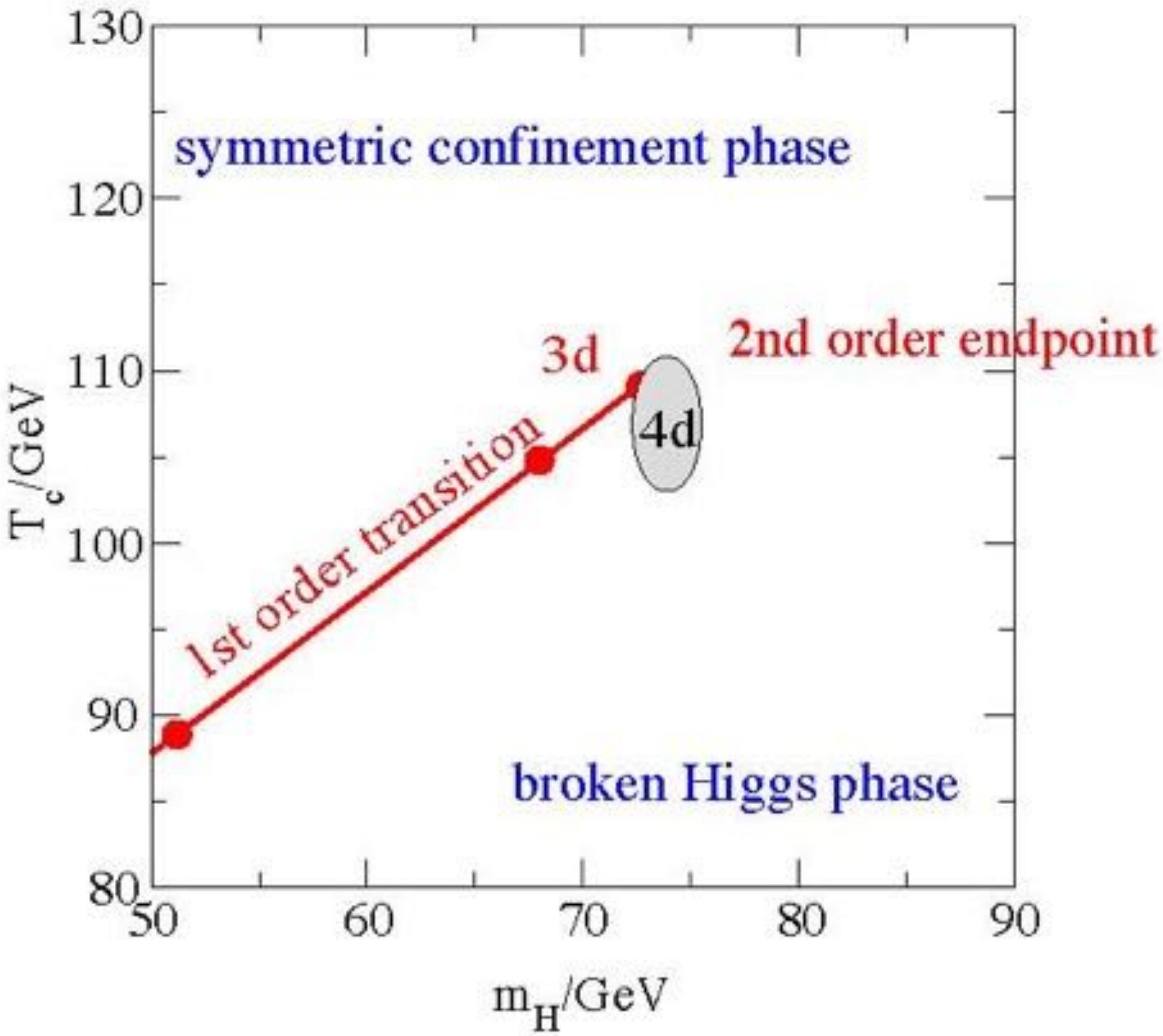
- Departure from equilibrium
  - First-order phase transition of Higgs

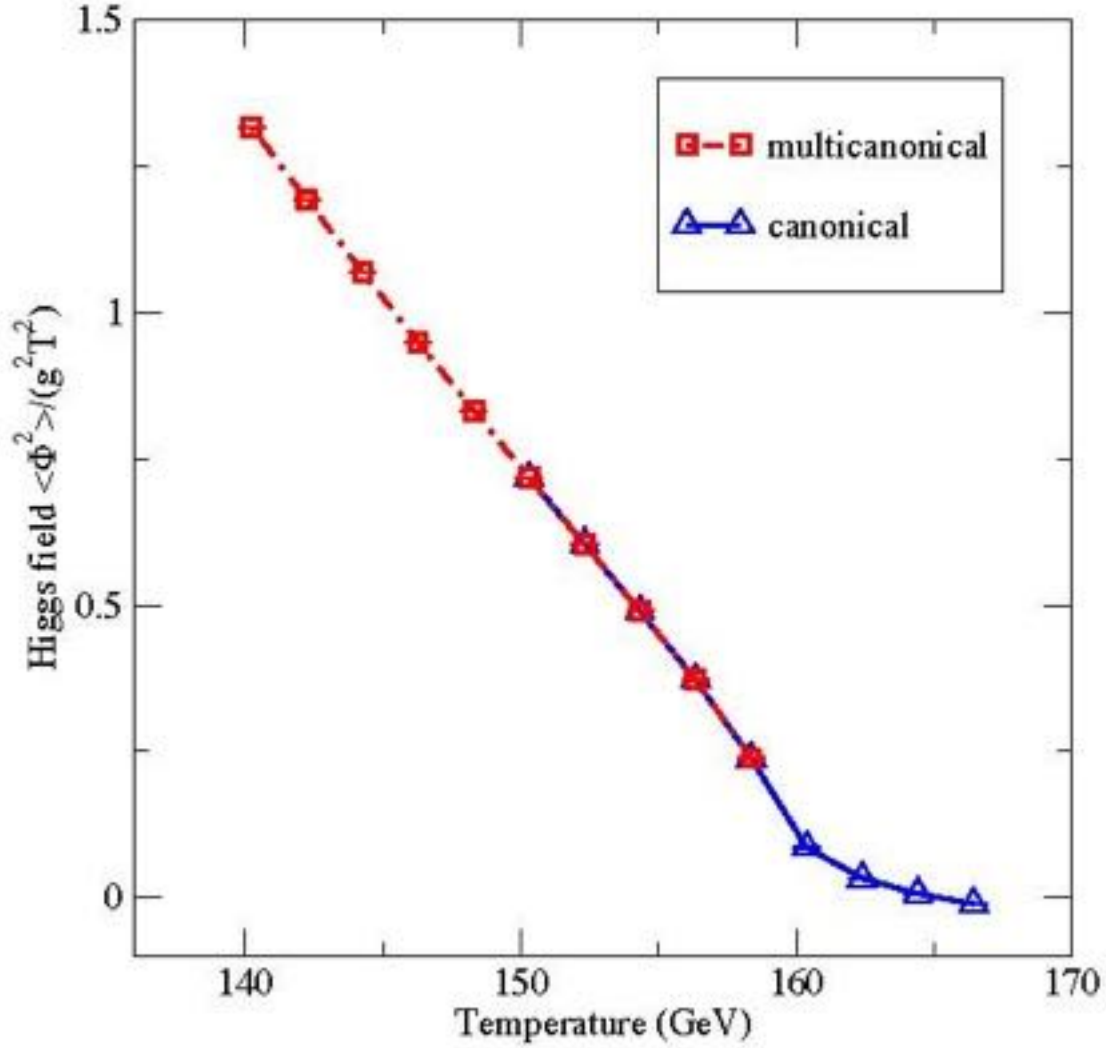
requires $m_h < 75$ GeV

- Experimentally testable?

Phase diagram for the Standard Model:

Mikko Laine (Bern)





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

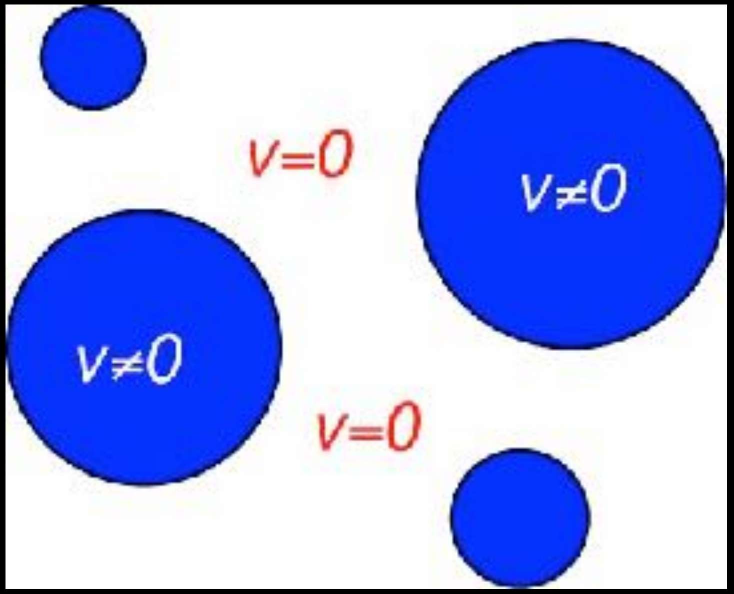
$\langle H^\dagger H \rangle$ is not an order parameter

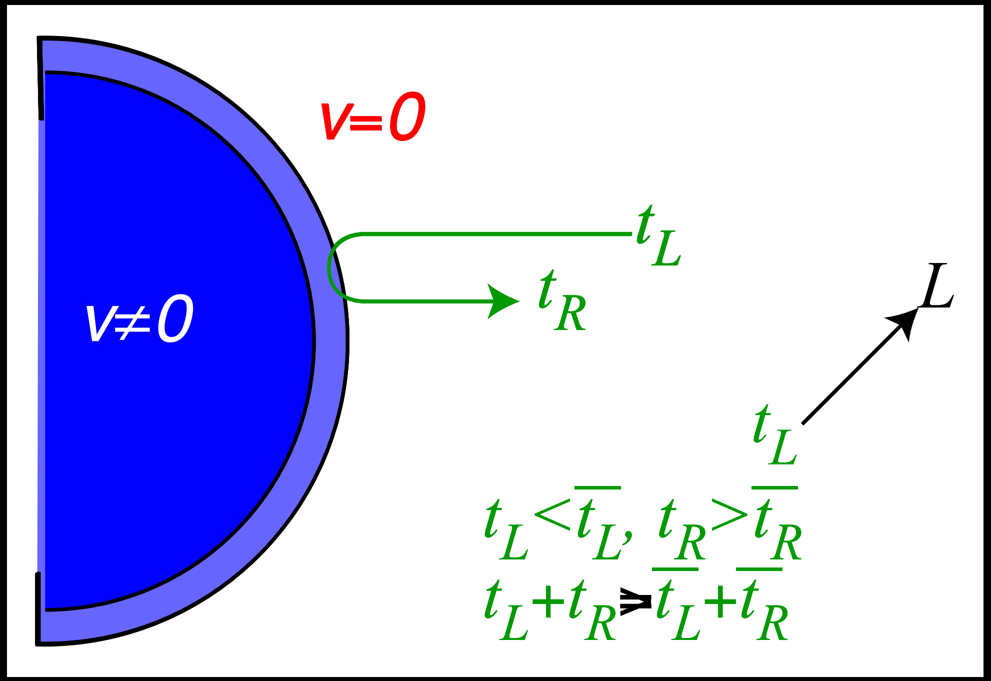
for m_h=125GeV, it is crossover

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


Oct 2018

ARTICLE

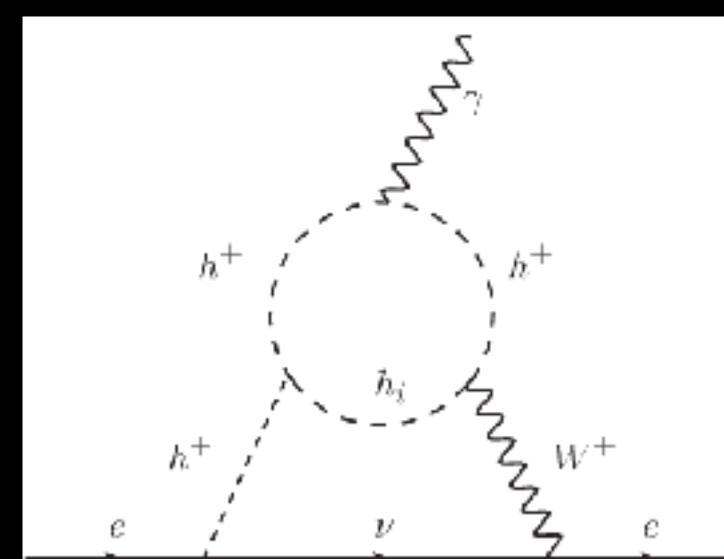
https://doi.org/10.1038/s41586-018-0599-8

Improved limit on the electric dipole moment of the electron

ACME Collaboration*

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

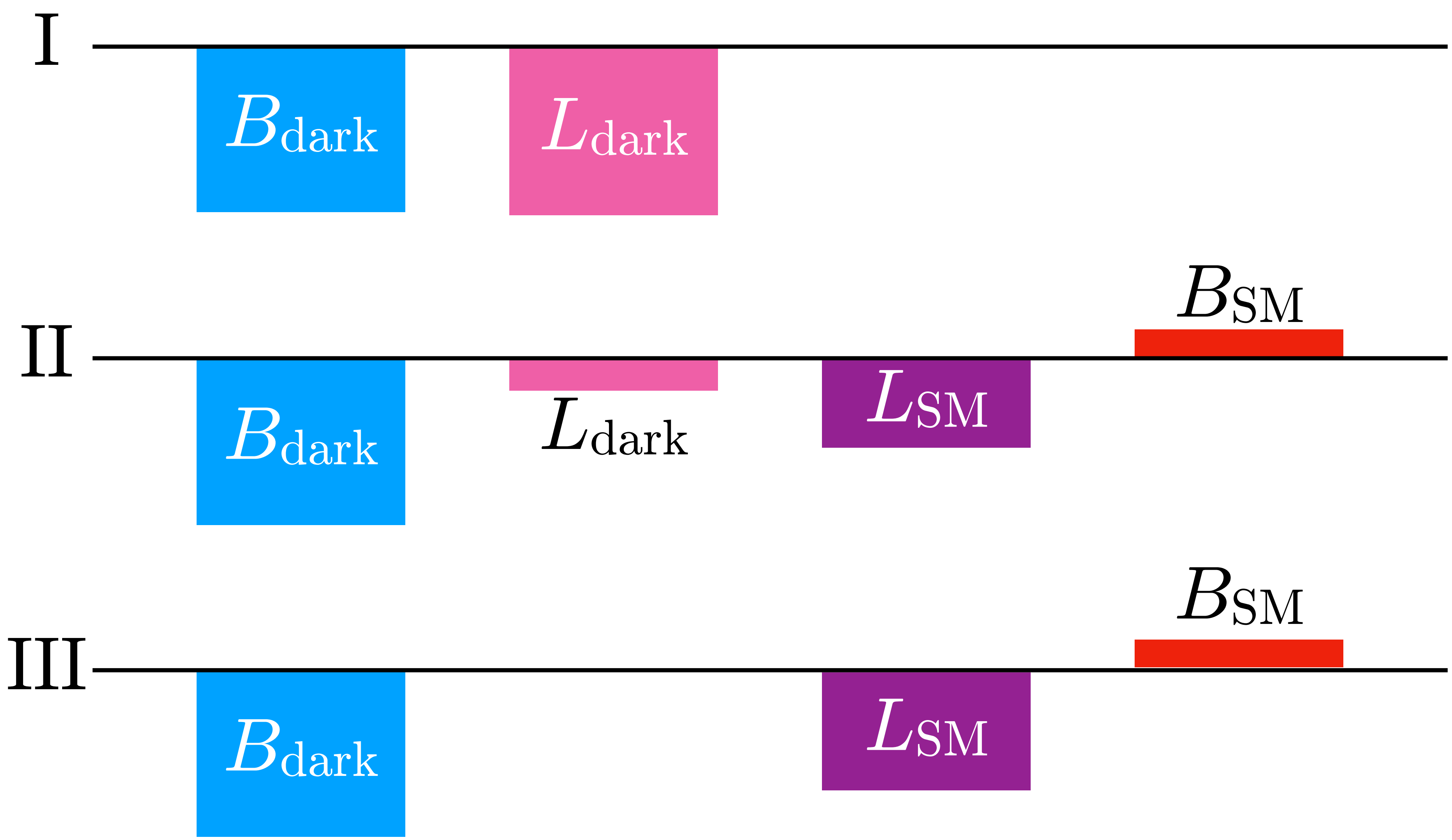
- baryon asymmetry limited by the sphaleron rate
  $\Gamma \sim 20\, \alpha_W^5\, T \sim 10^{-6}\, T$
- Can't lose much more to obtain 10^{-9}
- need
  - new physics for 1st order PT at the Higgs scale v=250 GeV
  - CP violation×efficiency ≥10^{-3}



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

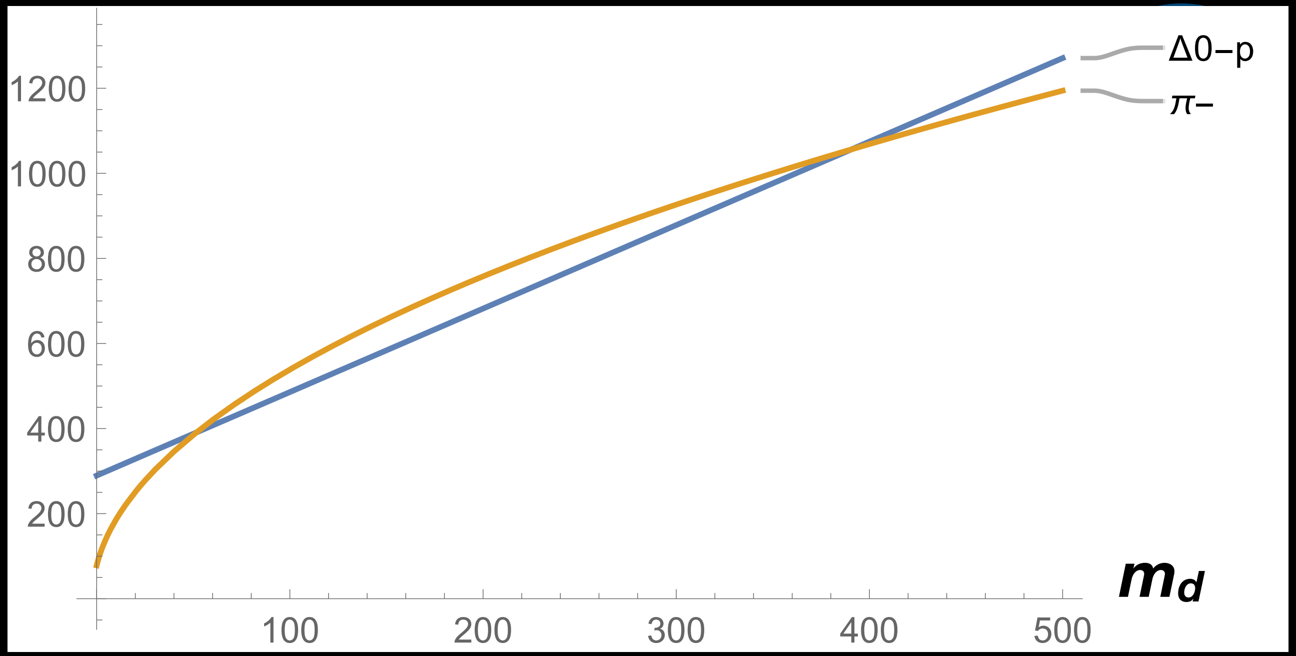


If $M_N > T_{\rm sphaleron}$ $B_{\rm SM} = \frac{36}{133} B_{\rm dark}, \quad L_{\rm SM} = -\frac{97}{133} B_{\rm dark}$ **$m_{n'}$=1.58 GeV**

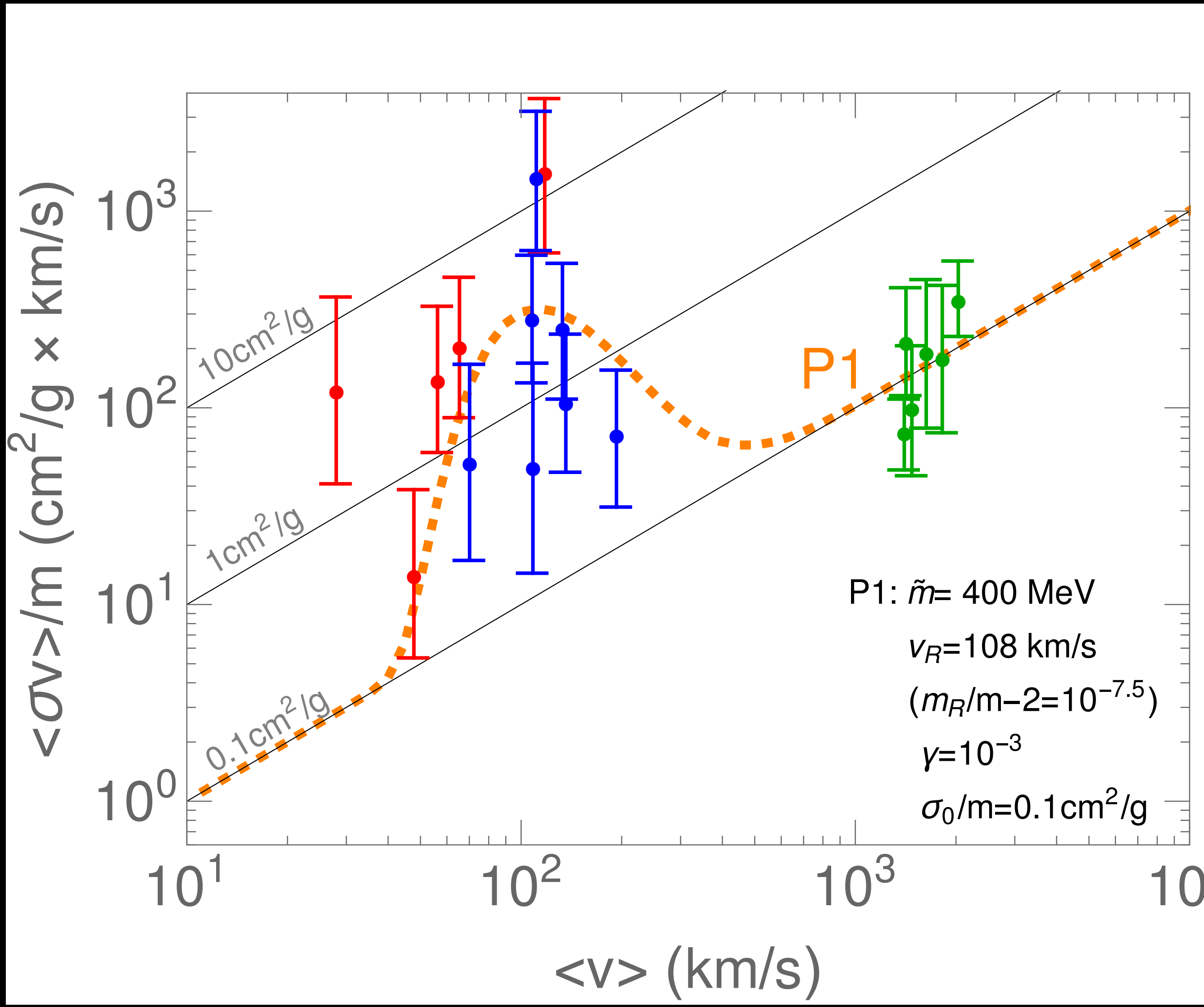
If $M_N < T_{\rm sphaleron}$ $B_{\rm SM} = \frac{12}{37} B_{\rm dark}, \quad L_{\rm SM} = -\frac{25}{37} B_{\rm dark}$ **$m_{n'}$=1.33 GeV**

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

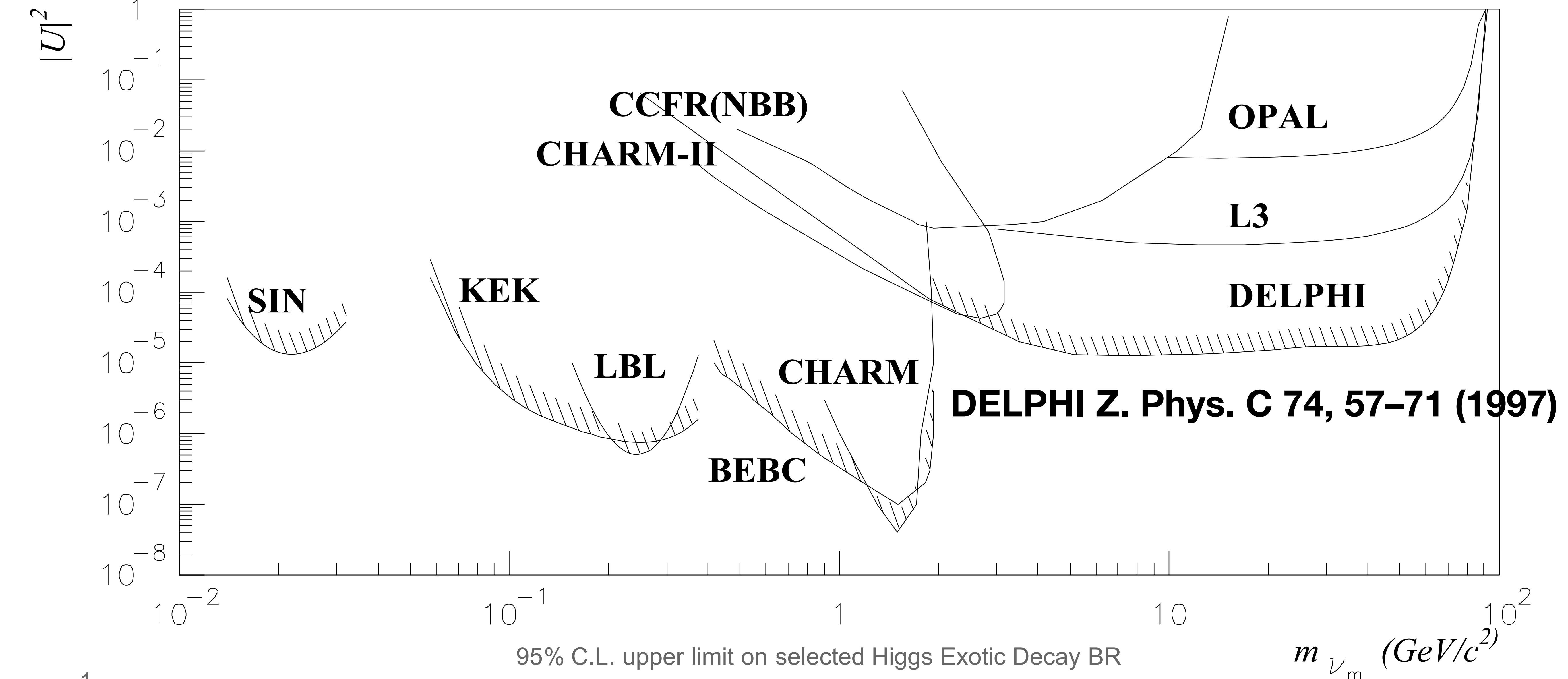
- asymmetric dark matter
  - S. Nussinov, PLB 165, 55 (1985) “technocosmology”
  - R. Kitano, HM, M. Ratz, arXiv:0807.4313, moduli decay
  - D.E. Kaplan, M. Luty, K. Zurek, arXiv:0901.4117
- darkogenesis (= “EW baryogenesis” in the dark sector)
  - J. Shelton, K. Zurek, arXiv:1008.1997

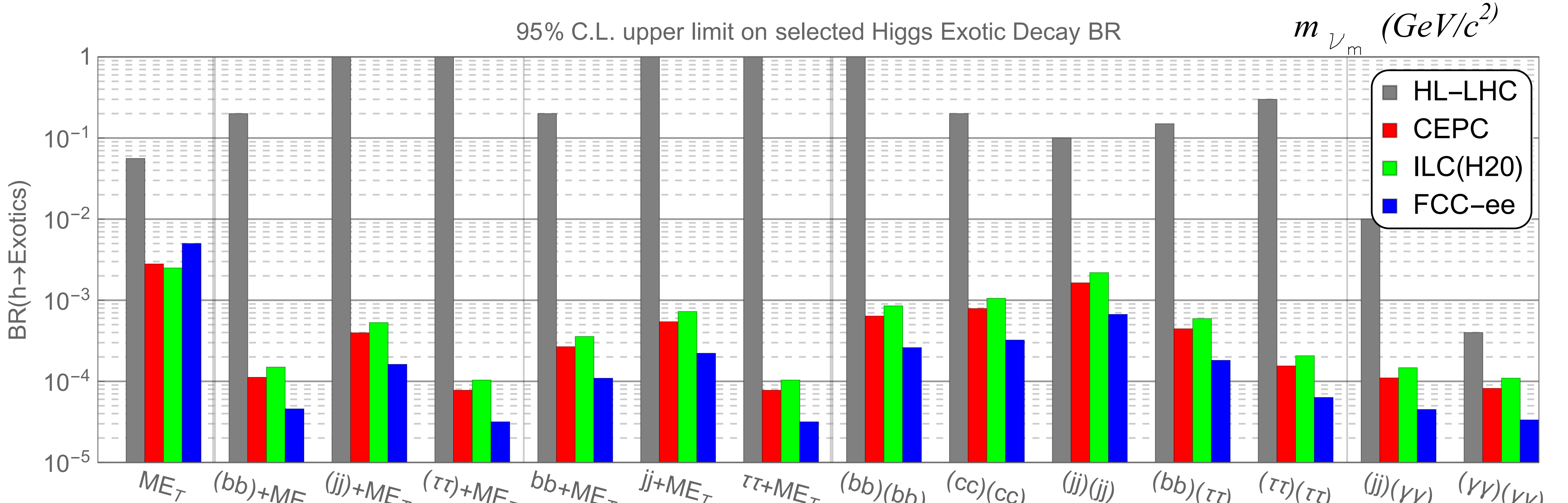
neutrino portal

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

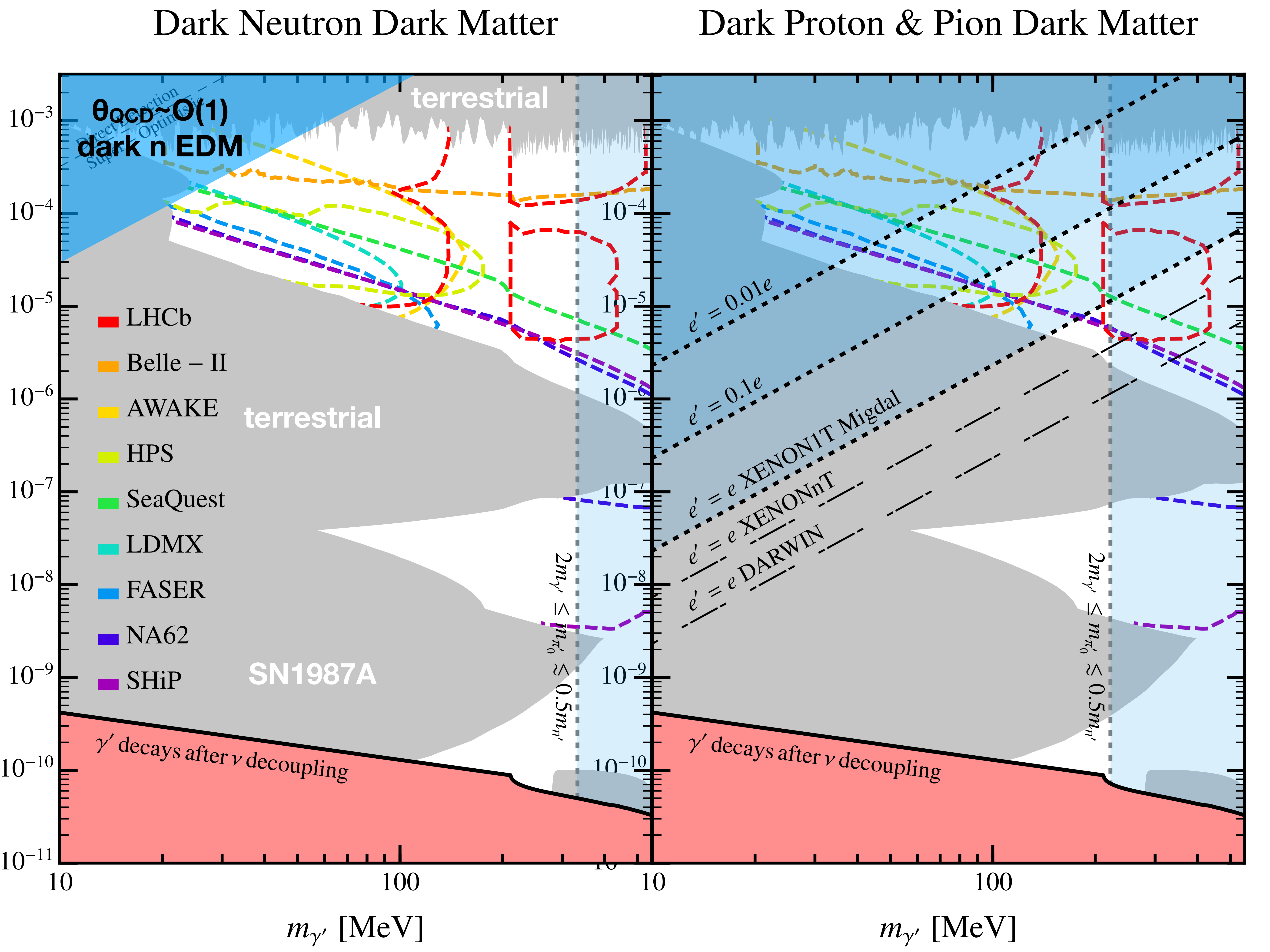
$$\epsilon_i = \frac{y_i}{\sqrt{(y')^2 + (y_i)^2}} \qquad M_\nu = \sqrt{(y')^2 + (y_i)^2} v$$

- 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)

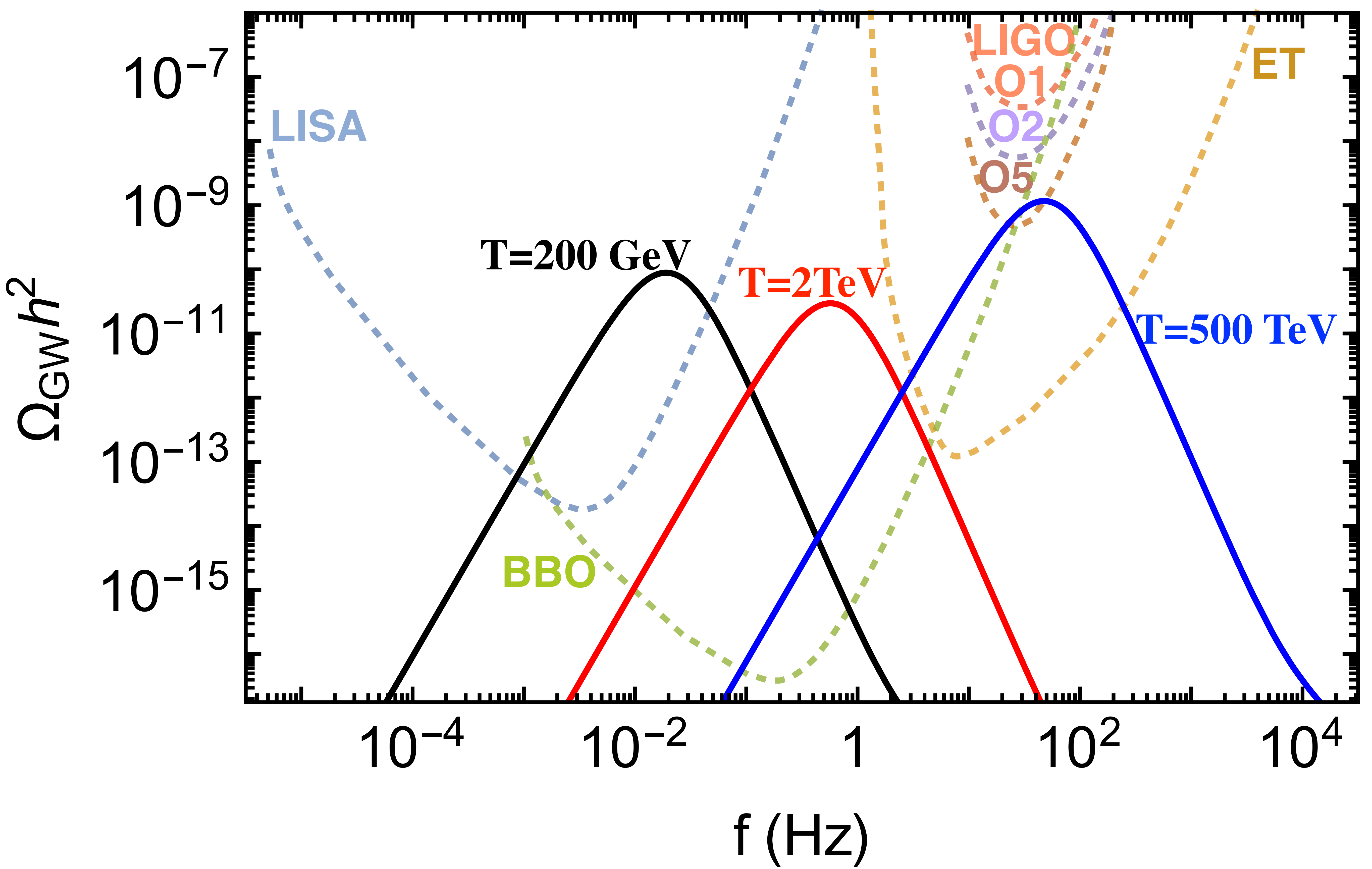




Zhen Liu, Lian-Tao Wang, Hao Zhang, arXiv:1612.09284



Dark Neutron Dark Matter
Dark Proton & Pion Dark Matter
terrestrial
θQCD~O(1)
dark n EDM
Direct Detection
Super Optimistic
LHCb
Belle – II
AWAKE
HPS
SeaQuest
LDMX
FASER
NA62
SHiP
terrestrial
SN1987A
γ′ decays after ν decoupling
2m_γ′ ≤ m_π′0 ≲ 0.5m_n′
e′ = 0.01e
e′ = 0.1e
e′ = e XENON1T Migdal
e′ = e XENONnT
e′ = e DARWIN
10
100
m_γ′ [MeV]



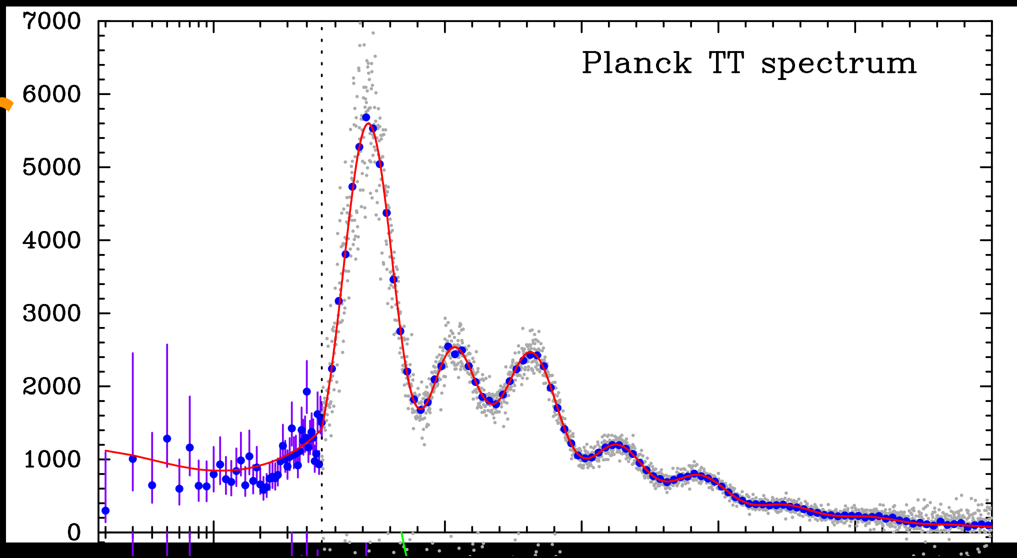
LISA
LIGO
O1
O2
O5
ET
BBO
T=200 GeV
T=2TeV
T=500 TeV
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
$\Omega_{GW}h^2$
10^{-4}
10^{-2}
1
10^{2}
10^{4}
f (Hz)

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+π^-
- amazingly wide array of experimental signatures
  - dark proton good target for direct detection
  - exotic Z-decay, h-decay (HL-LHC, 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 $\Omega_{\rm DM}$~Ω_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...


many things
to look forward to!