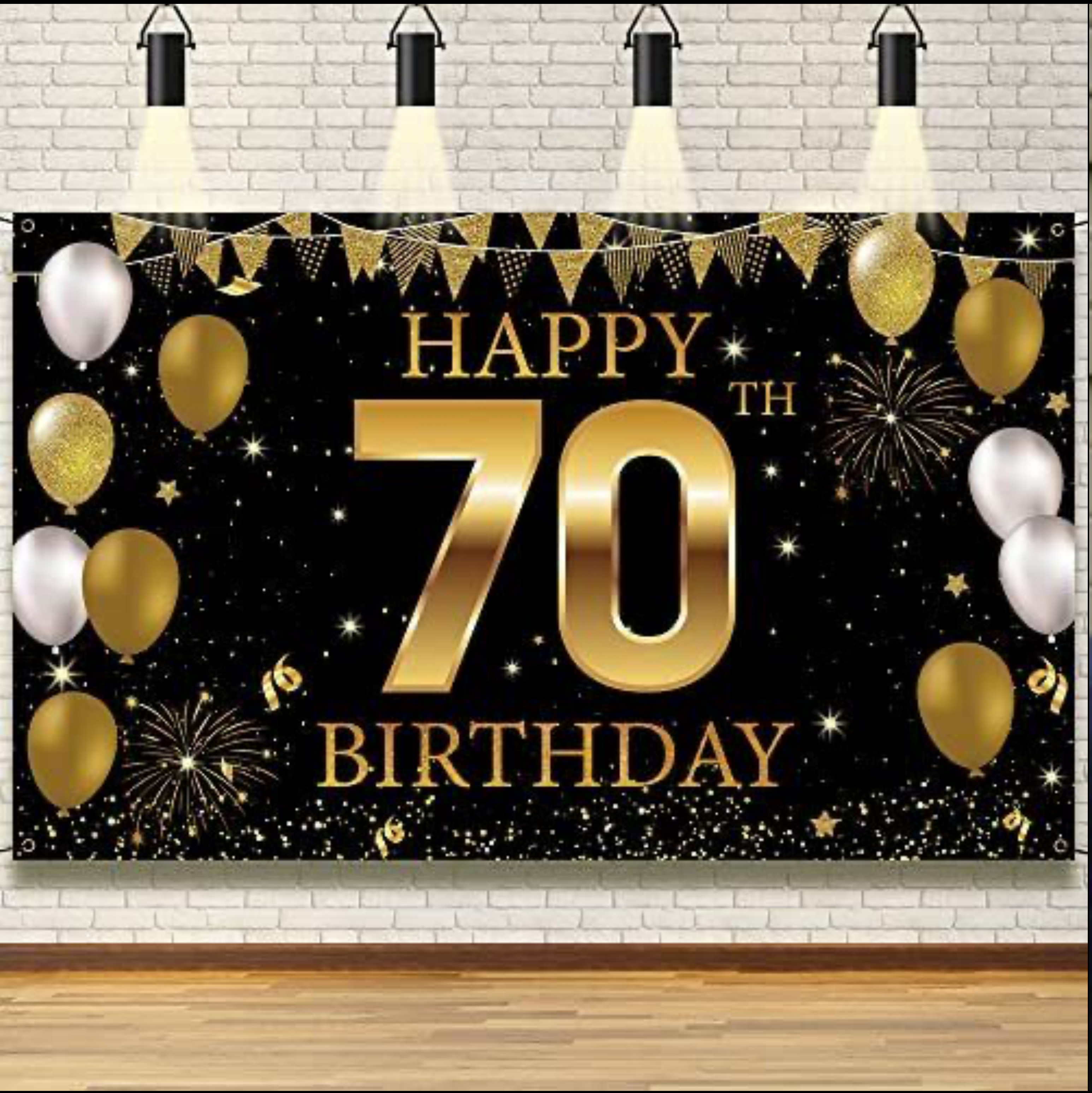
Overview of Neutrino Theory

Hitoshi Murayama (Berkeley, Kavli IPMU)

PetcovFEST, April 24, 2023



Happy Birthday, Serguey!

My encounter with Serguey

Volume 200, number 3 PHYSICS LETTERS B 14 January 1988

EXACT ANALYTIC DESCRIPTION OF TWO-NEUTRINO OSCILLATIONS IN MATTER WITH EXPONENTIALLY VARYING DENSITY

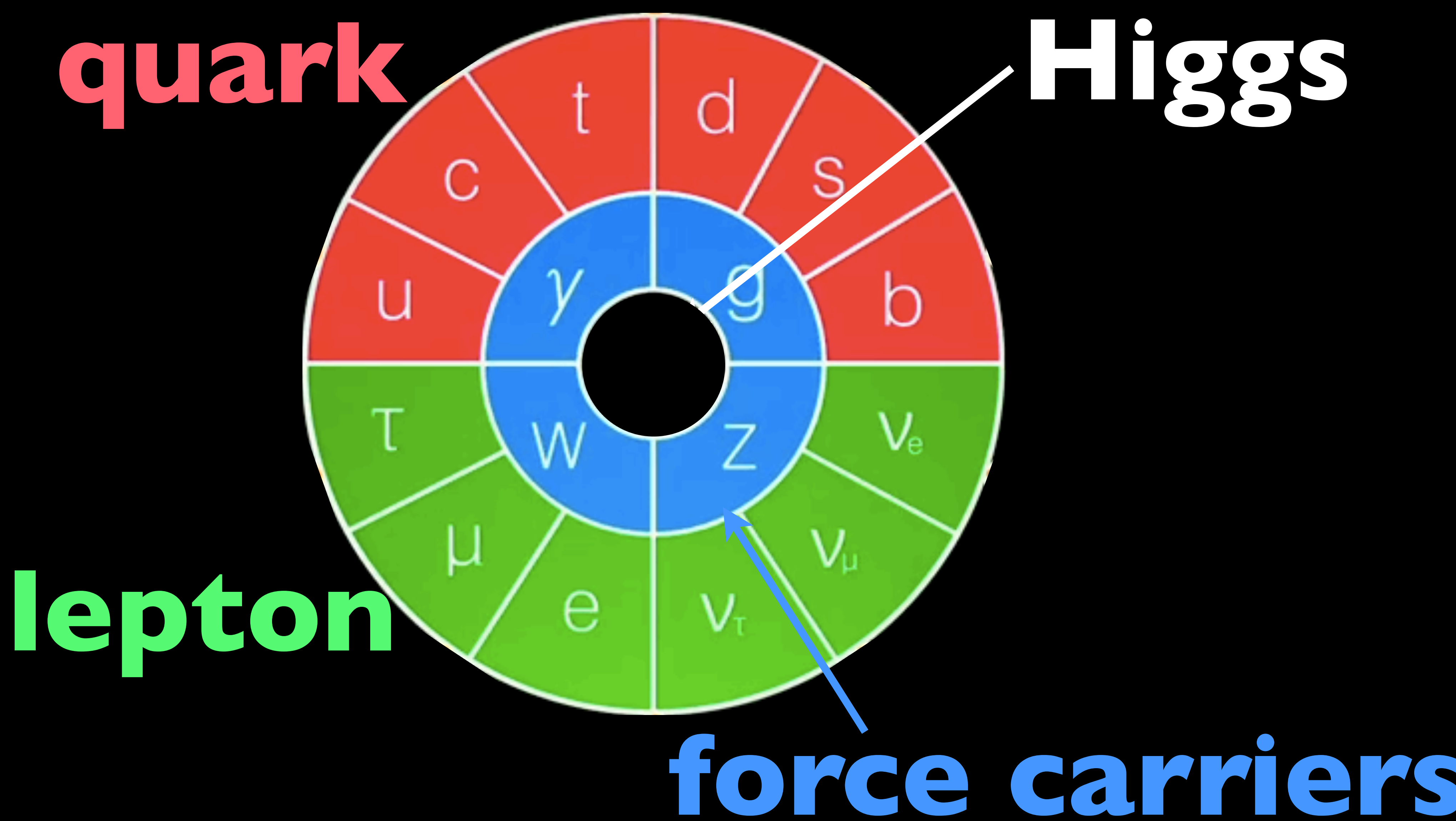
S.T. PETCOV

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria

Received 1 October 1987

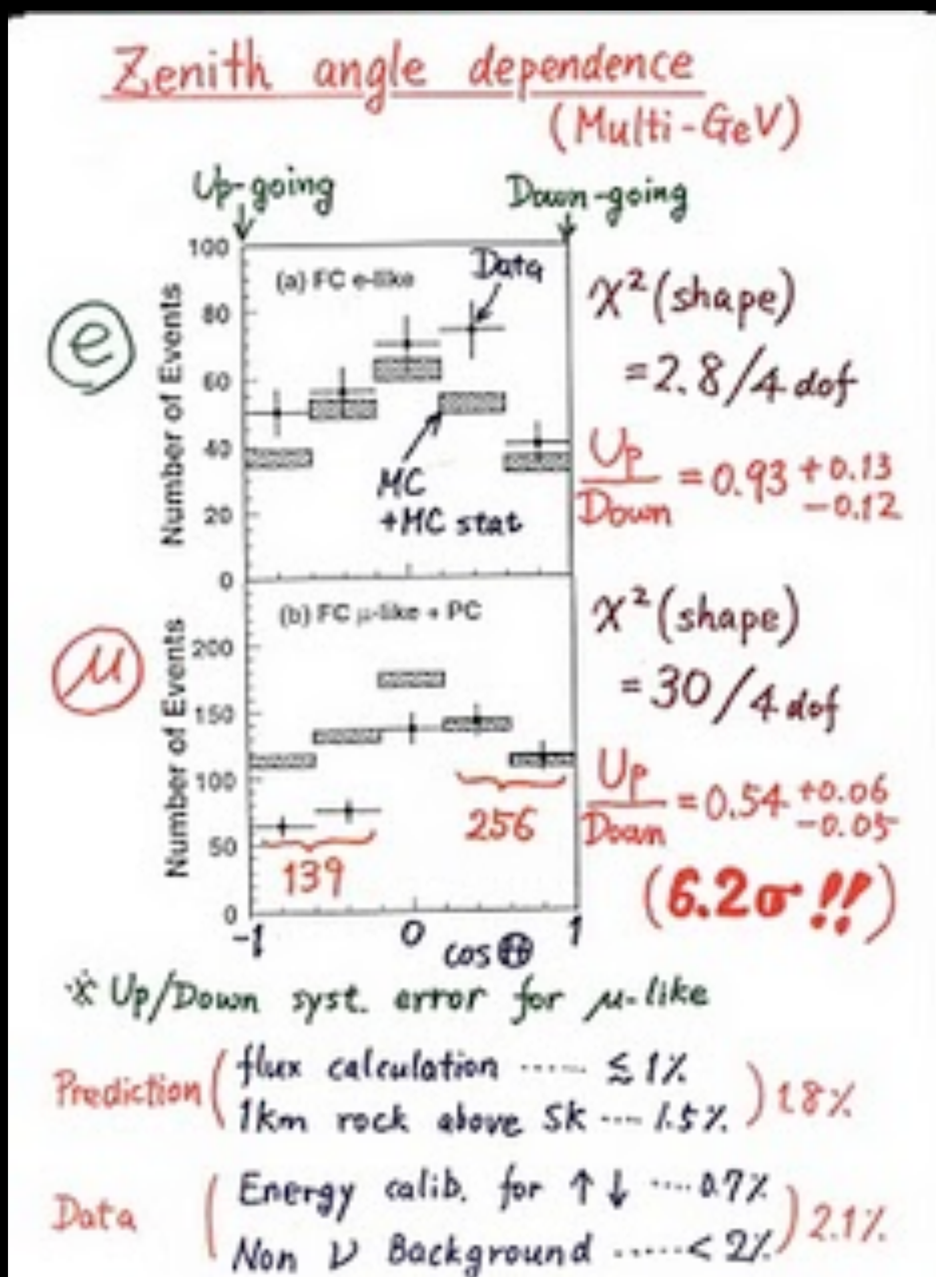
- neutrino oscillation = first experimentally established physics beyond SM
- I studied Serguey's papers intently
  - A giant in neutrino physics
  - First met him at Neutrino 1998
- When I founded IPMU in 2007, I invited Serguey
  - He became a regular presence at IPMU
  - Staff loved him

Standard Model



Standard Model fell!

1998



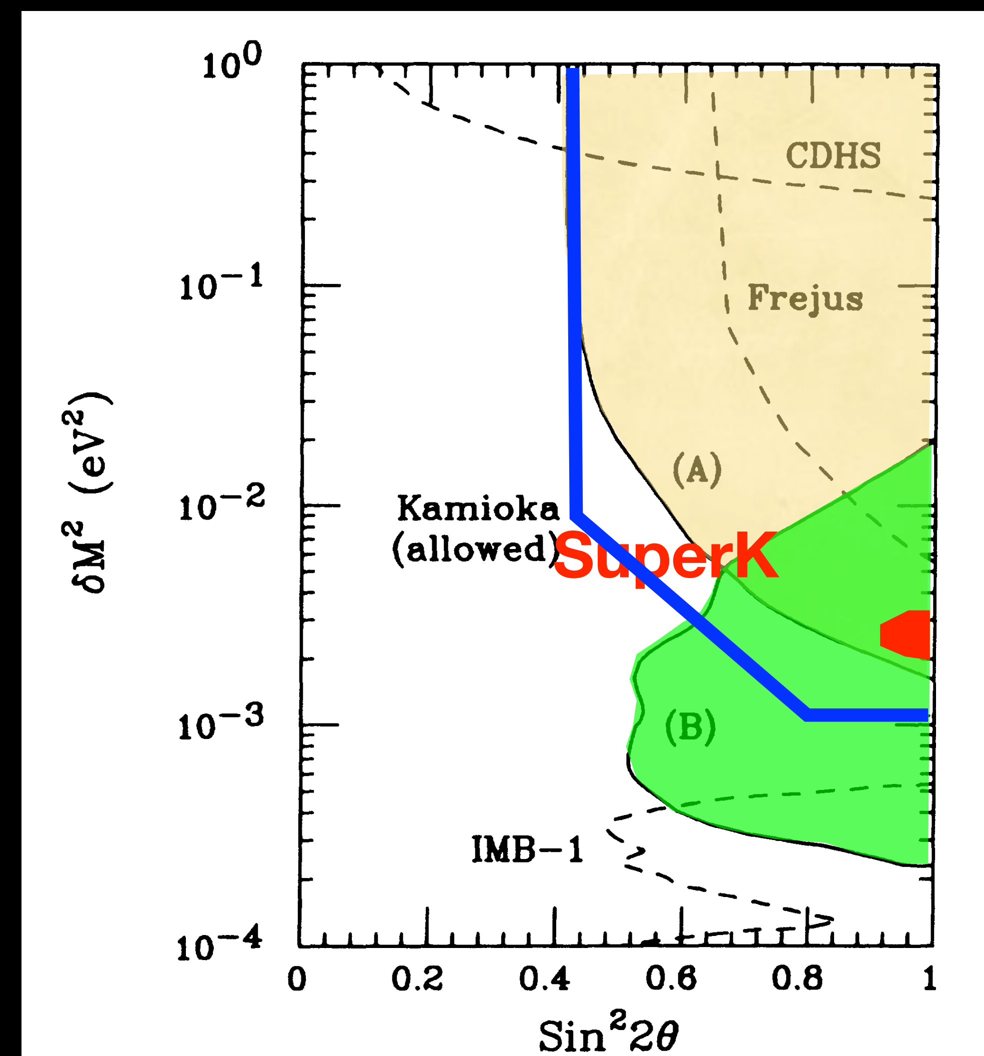


FIG. 2. 90% C.L. limits on ν_μ to ν_τ oscillations from rate (A) and stopping fraction (B). Dashed curves show limits from IMB-1 [14], Frejus [3], and CERN-Dortmund-Heidelberg-Saclay (CDHS) [15]. Dotted curve shows the allowed region from Kamiokande [16]. The Frejus limit is 95% C.L.; others are 90%.

IMB, PRL 69, 1010 (1992)

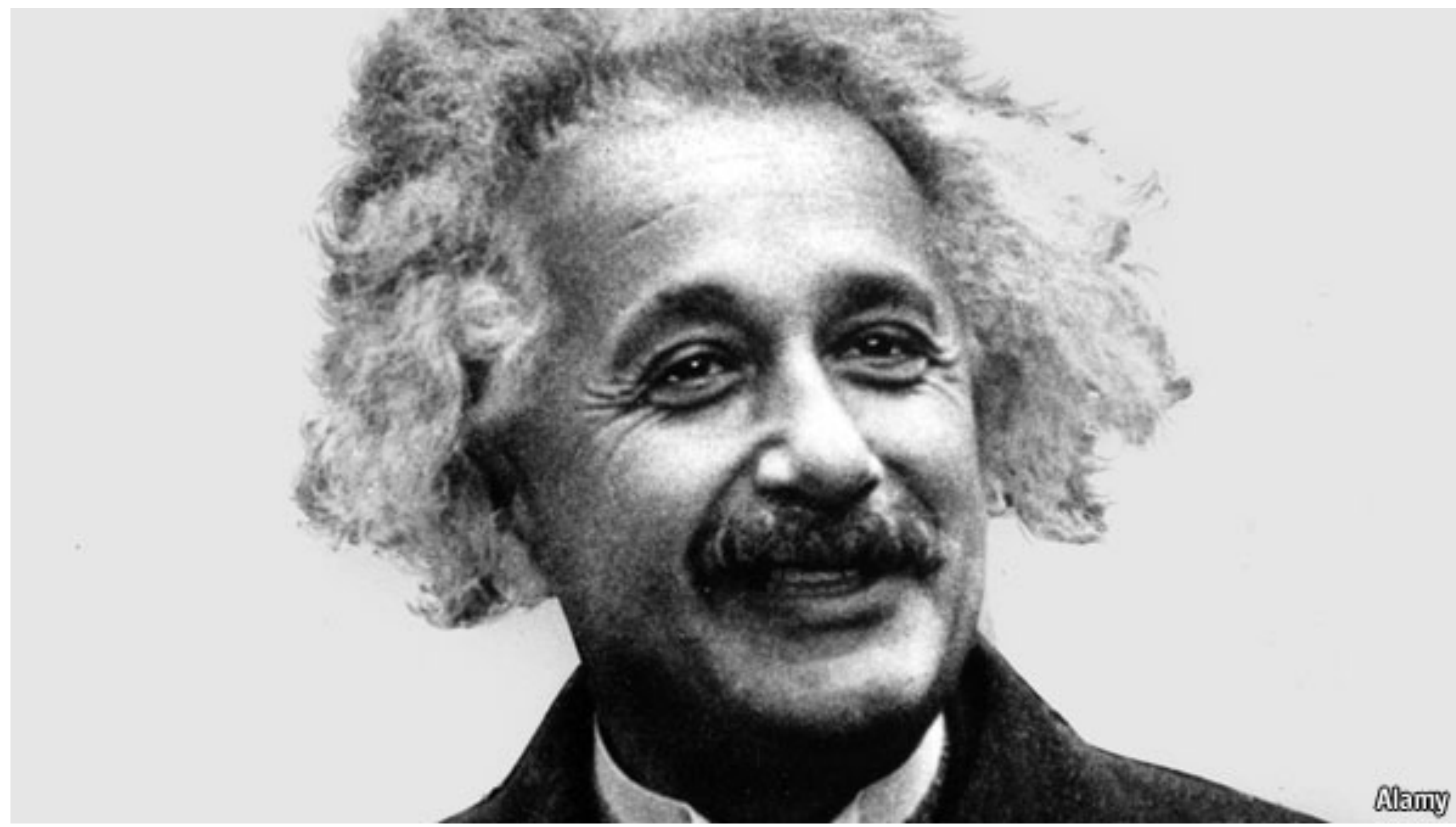
The Economist

Neutrinos and relativity

Faster than the speed of light

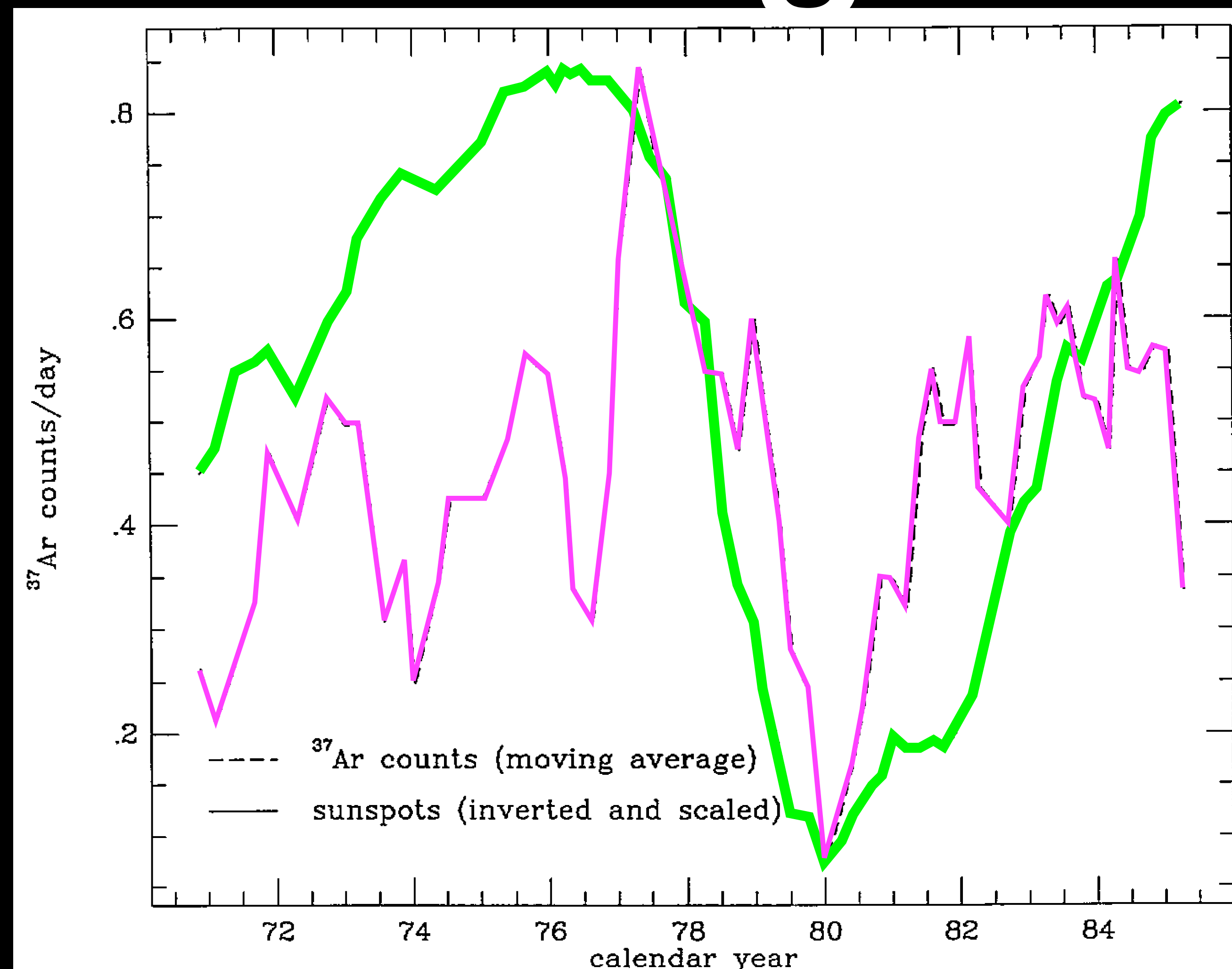
What does an experiment that seems to contradict Einstein's theory of relativity really mean?

Oct 1st 2011 | from the print edition



IN 1887 physicists were feeling pretty smug about their subject. They thought they understood reality well, and that the future would just be one of ever more precise measurements. They could not have been more wrong. The next three decades turned physics on its head, with the discovery of electrons, atomic nuclei, radioactivity, quantum theory and the theory of relativity. But the grit in the pearl for all this was a strange observation made that year by two researchers called Albert Michelson and Edward Morley that the speed of light was constant, no matter how fast the observer was travelling.

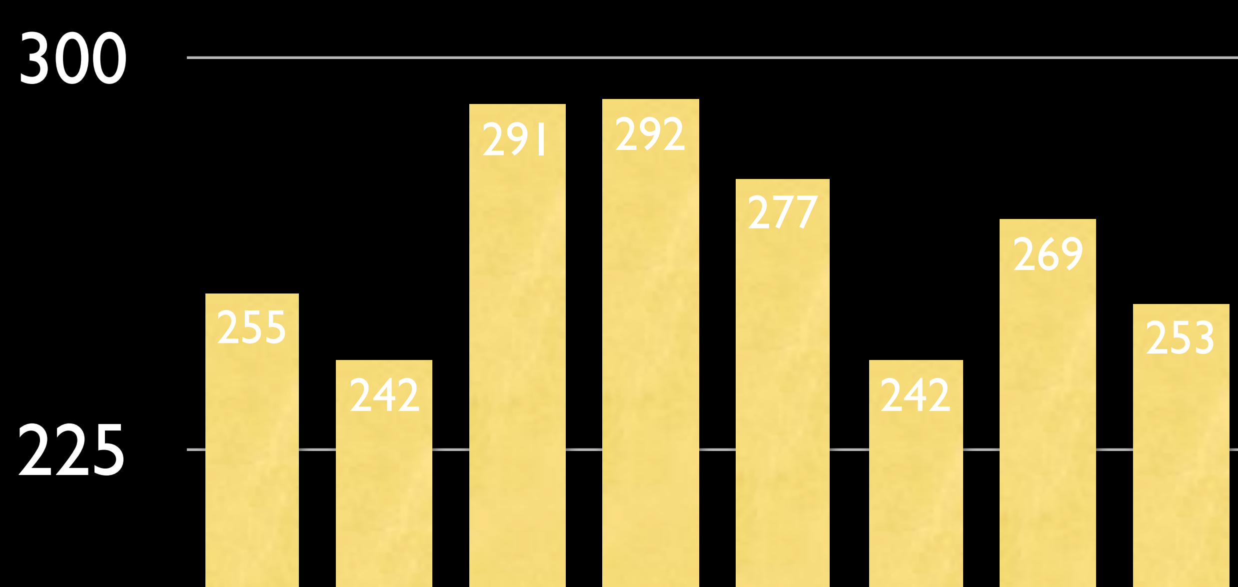
Confusing data



–#sunspot

Homestake

#Democrates in the House



Rare effects from high energies

- Effects of high-energy physics mostly disappear by power suppression

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

- can be classified systematically

$$\mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

$$\mathcal{L}_6 = QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}Hl, \epsilon_{abc}W_\nu^{a\mu}W_\lambda^{b\nu}W_\mu^{c\lambda}, \\ (H^\dagger D_\mu H)(H^\dagger D^\mu H), B_{\mu\nu}H^\dagger W^{\mu\nu}H, \cdots$$

unique role of m_ν

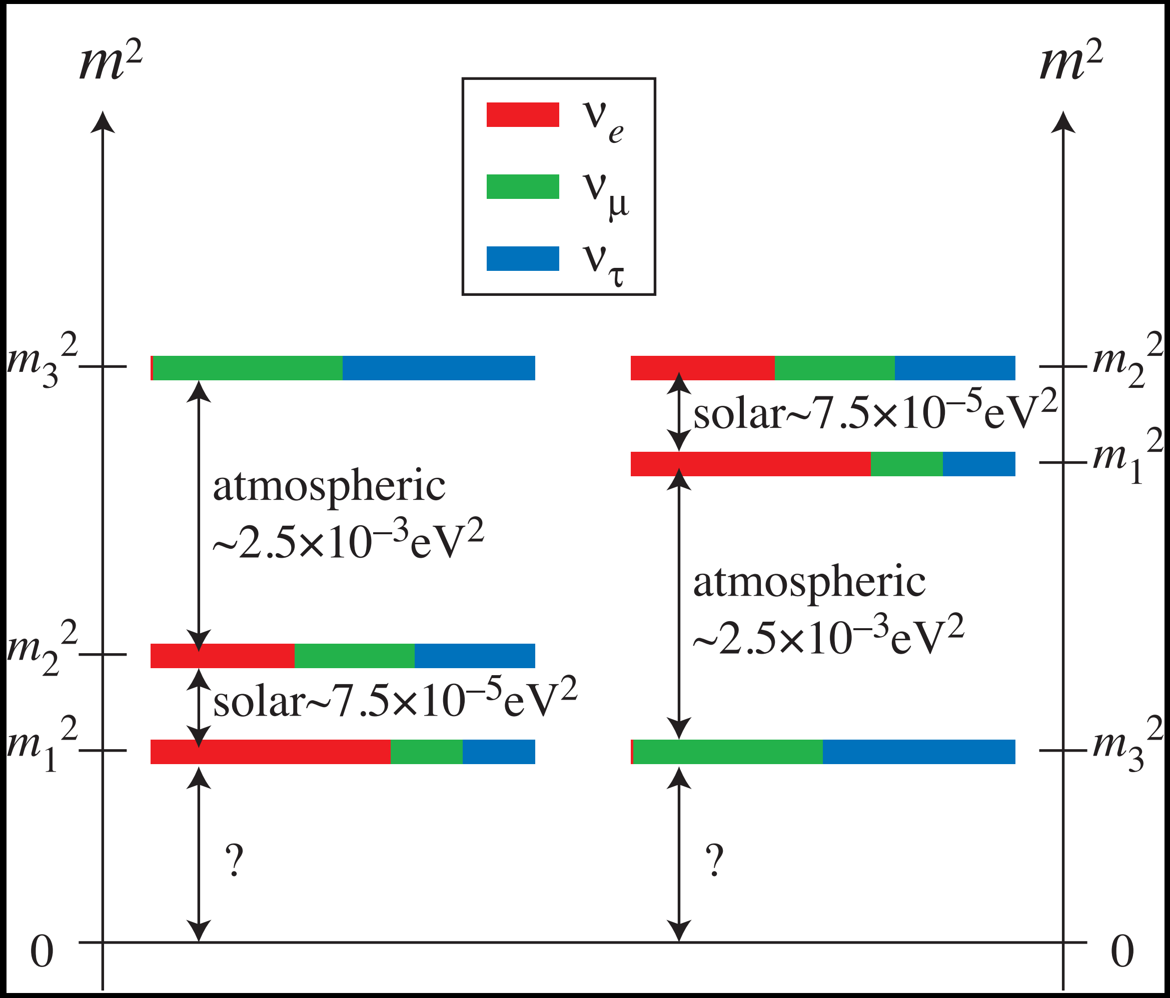
- Lowest order effect of physics at short distances
- tiny effect: $(m_\nu/E_\nu)^2 \approx (0.1\text{eV/GeV})^2 \approx 10^{-20}$!
- interferometry (e.g. Michaelson-Morley)
  - need a coherent source
  - need a long baseline
  - need interference (i.e. large mixing angle)
- Nature was kind to provide them all!
- neutrino interferometry (a.k.a. oscillation) a unique tool to study physics at very high E
- probing up to $\Lambda \approx 10^{14}$ GeV

Typical Theorist's View ca. 1990

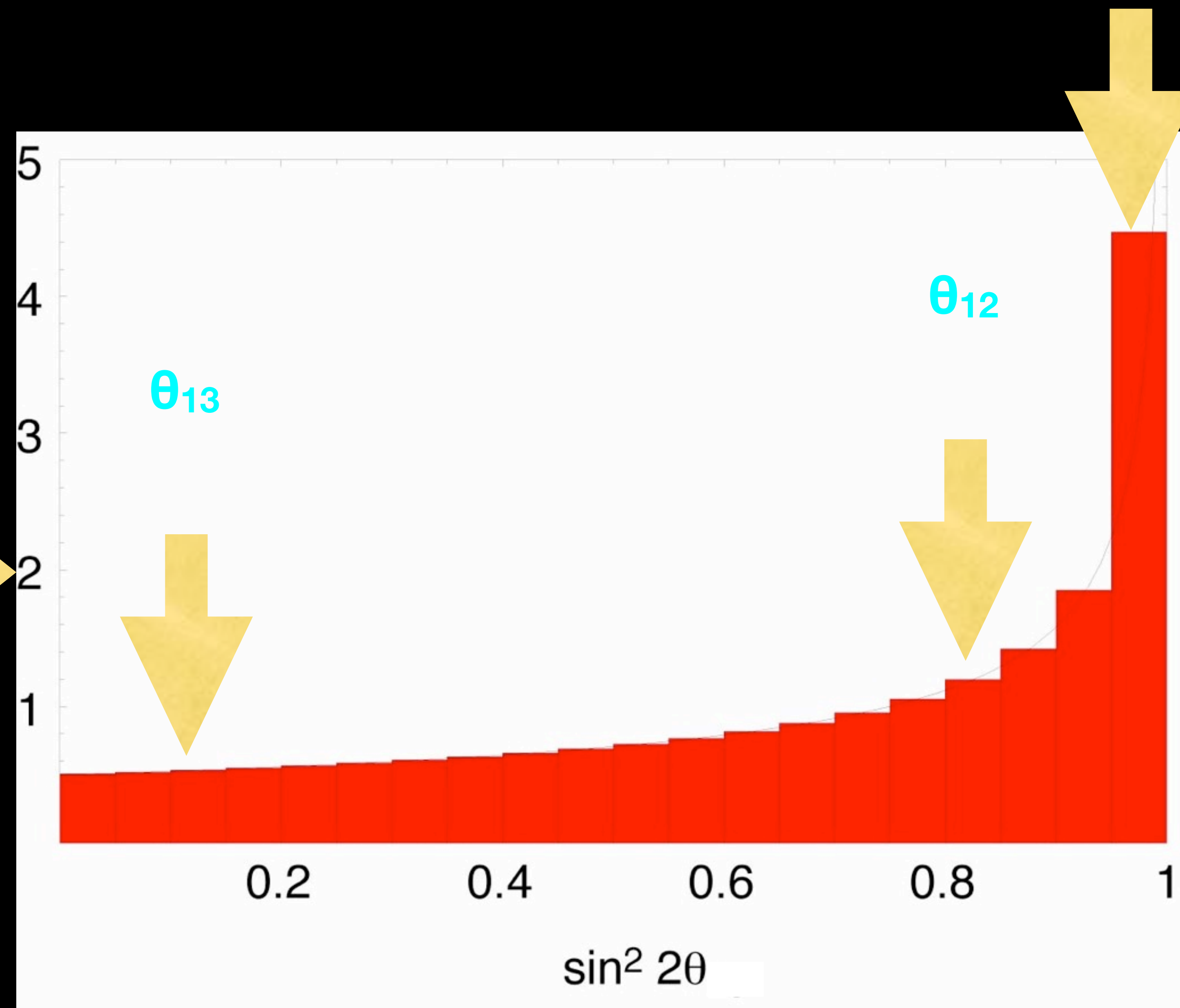
- Solar Neutrino Problem must be solved by Small Angle MSW solution because it is so beautiful *Wrong!*
- Important scale for oscillation is $\Delta m^2 \approx 10\text{-}100$ eV^2 because it may be dark matter *Wrong!*
- θ_{23} must be about $\theta_{23} \approx V_{cb} \approx 0.04$ *Wrong!*
- atmospheric neutrino anomaly must go away because it requires large mixing angle *Wrong!*

Questions

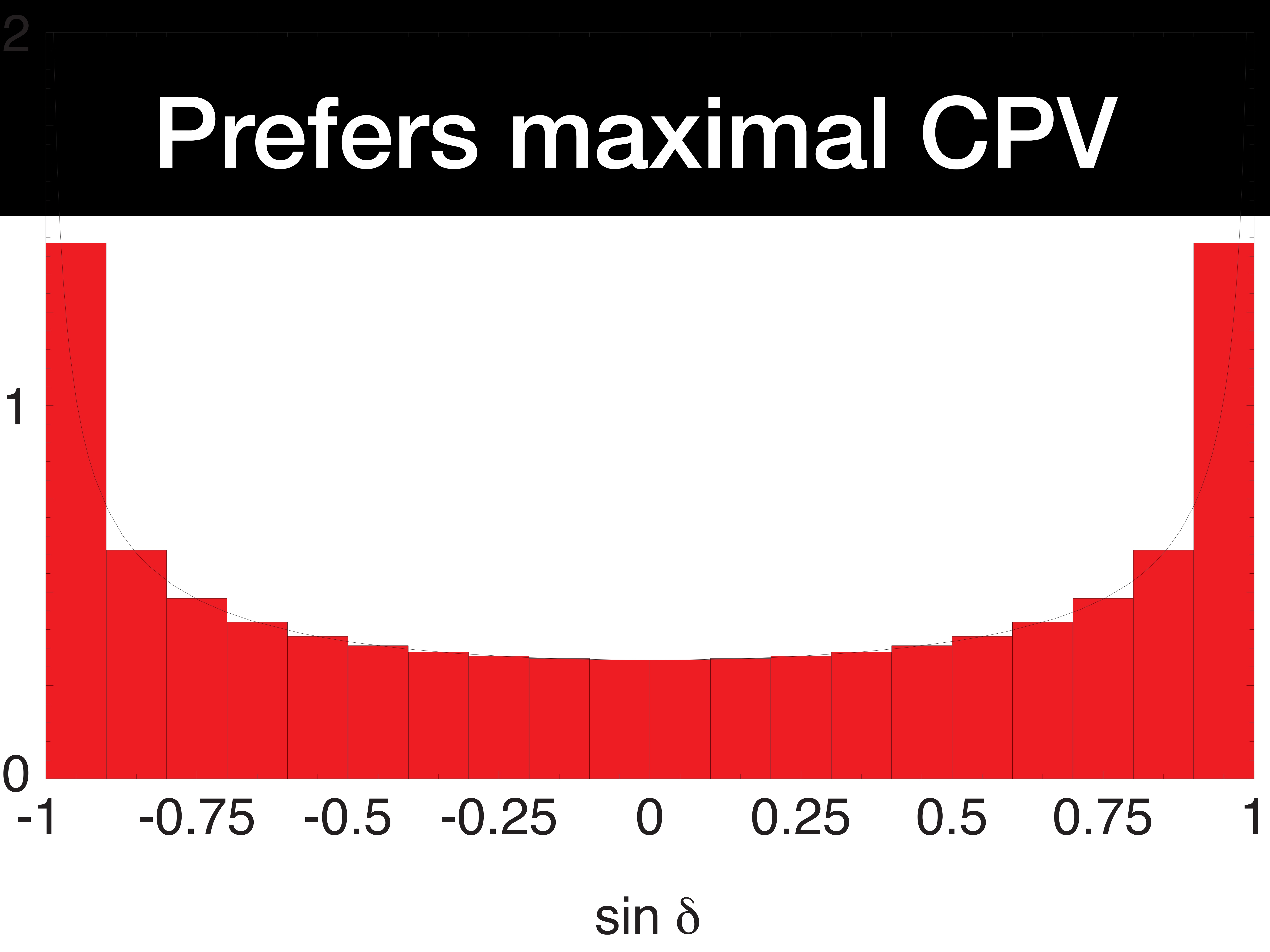
- mass hierarchy?
- mass scale?
- which octant?
- Is θ_{23} maximal?
- CP violation?
- Dirac or Majorana?
- sterile neutrinos?
- non-std interactions?
- origin of neutrino mass?
- seesaw? which type?
- leptogenesis?
- dark matter?



anarchy



Kolmogorov-Smirnov test (de Gouvêa, HM)
nature has 47% chance to choose this kind of numbers

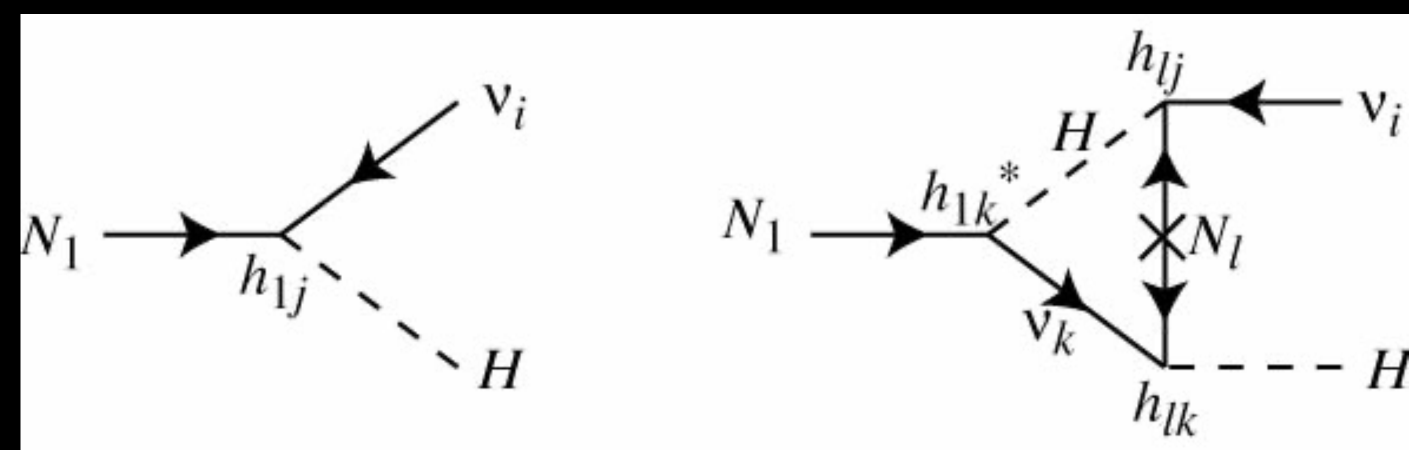

Prefers maximal CPV
2
1
0
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1
sin δ

Leptogenesis

Fukugita

Yanagida

- You generate *Lepton Asymmetry* first.
- Generate *L* from the direct CP violation in right-handed neutrino decay
- *Like ε'/ε!*



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

- *L* gets converted to *B* via EW anomaly

⇒ More matter than anti-matter

⇒ *Neutrinos saved us from complete annihilation*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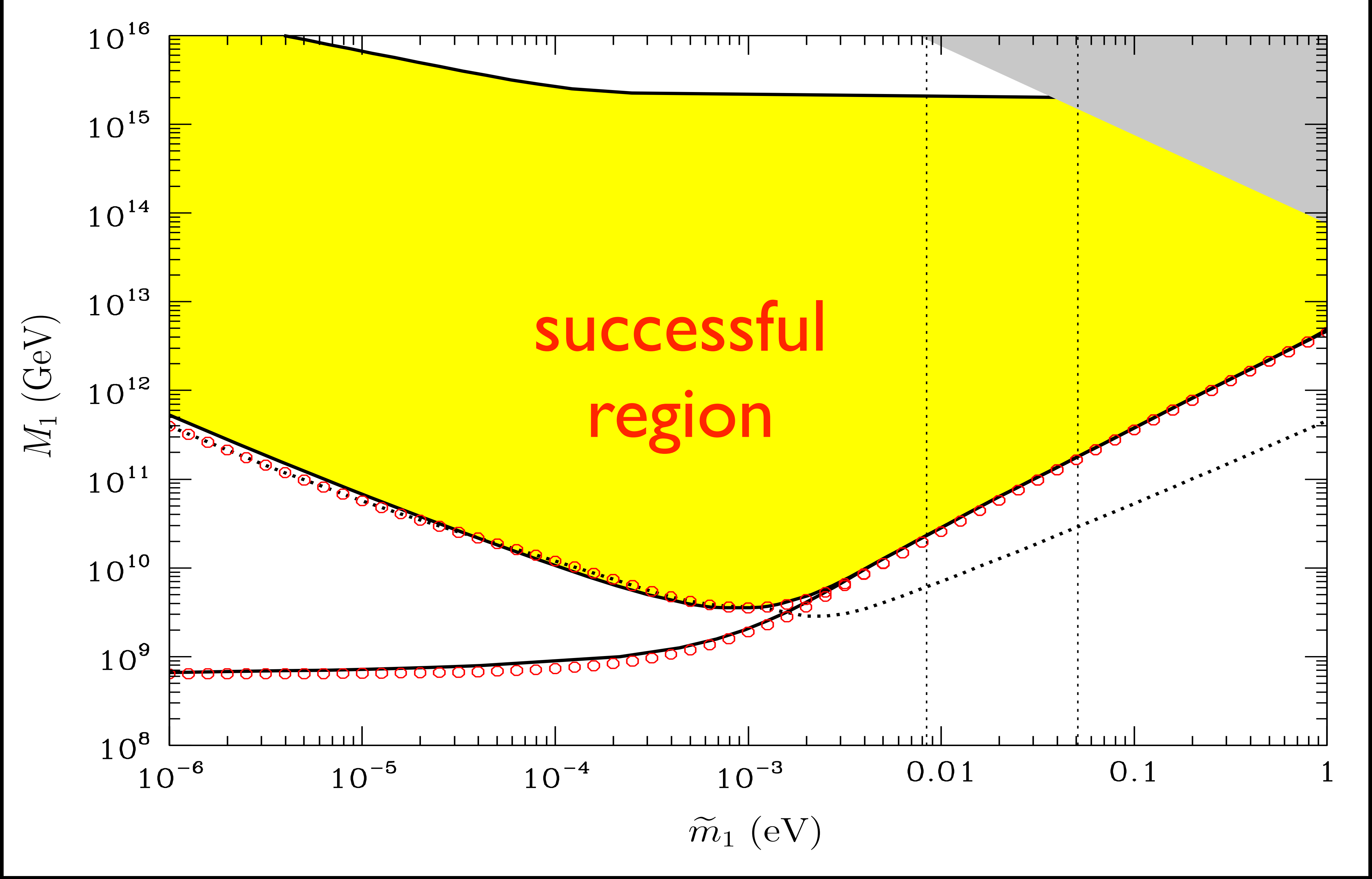
Leptogenesis



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

di Bari, Plümacher, Buchmüller

How do we test it?

build a 10^{14} GeV collider

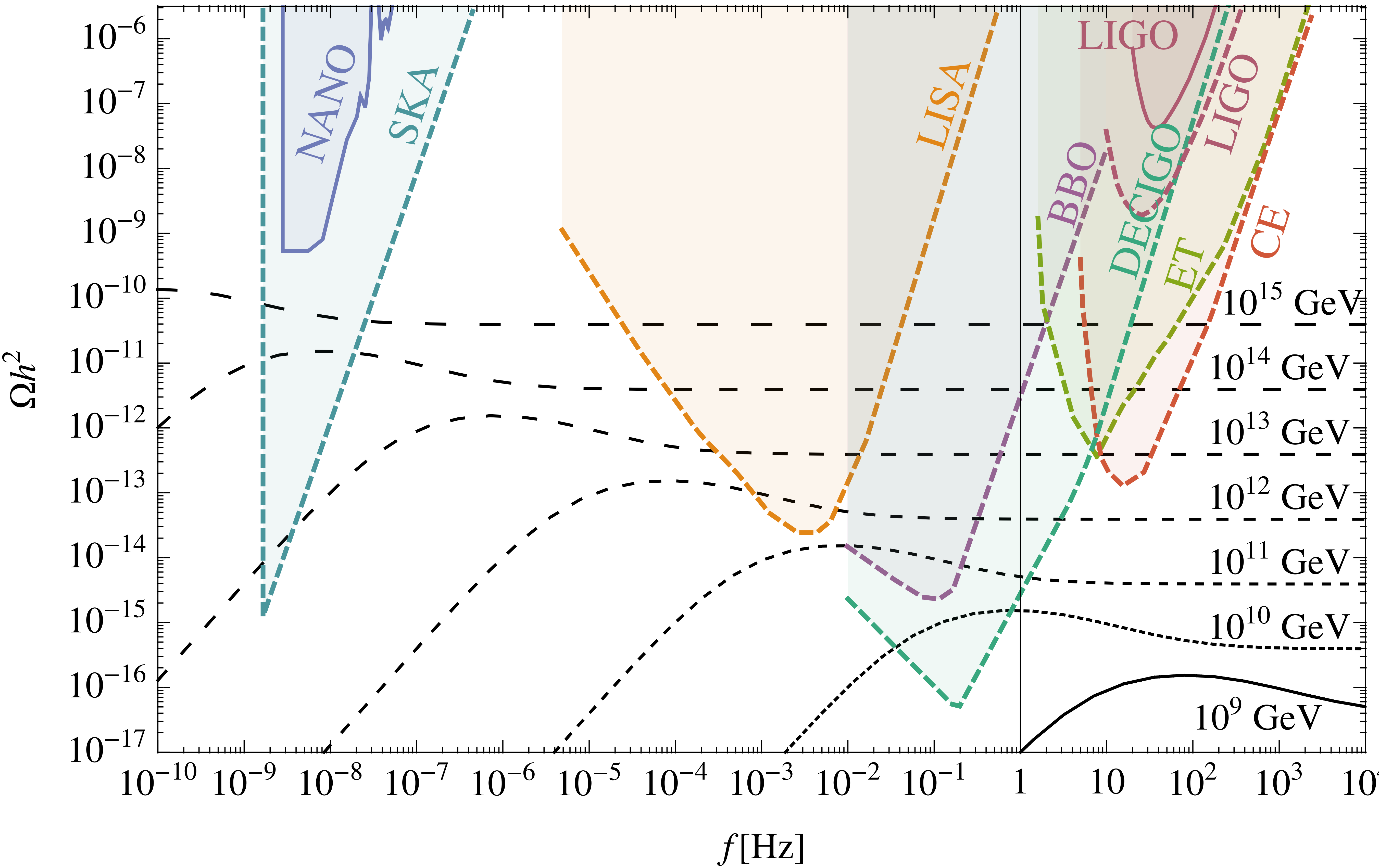
Possible theories

- Any other signals beyond 0νββ and CPV?
- 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

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

	$\langle\phi\phi\rangle\nu_R\nu_R/M_{Pl}$		$\langle\phi\rangle\nu_R\nu_R$	
	$H=G_{\rm SM}$		$H=G_{\rm SM}\times\mathbb{Z}_2$	
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	$(\mathbf{50},2)$

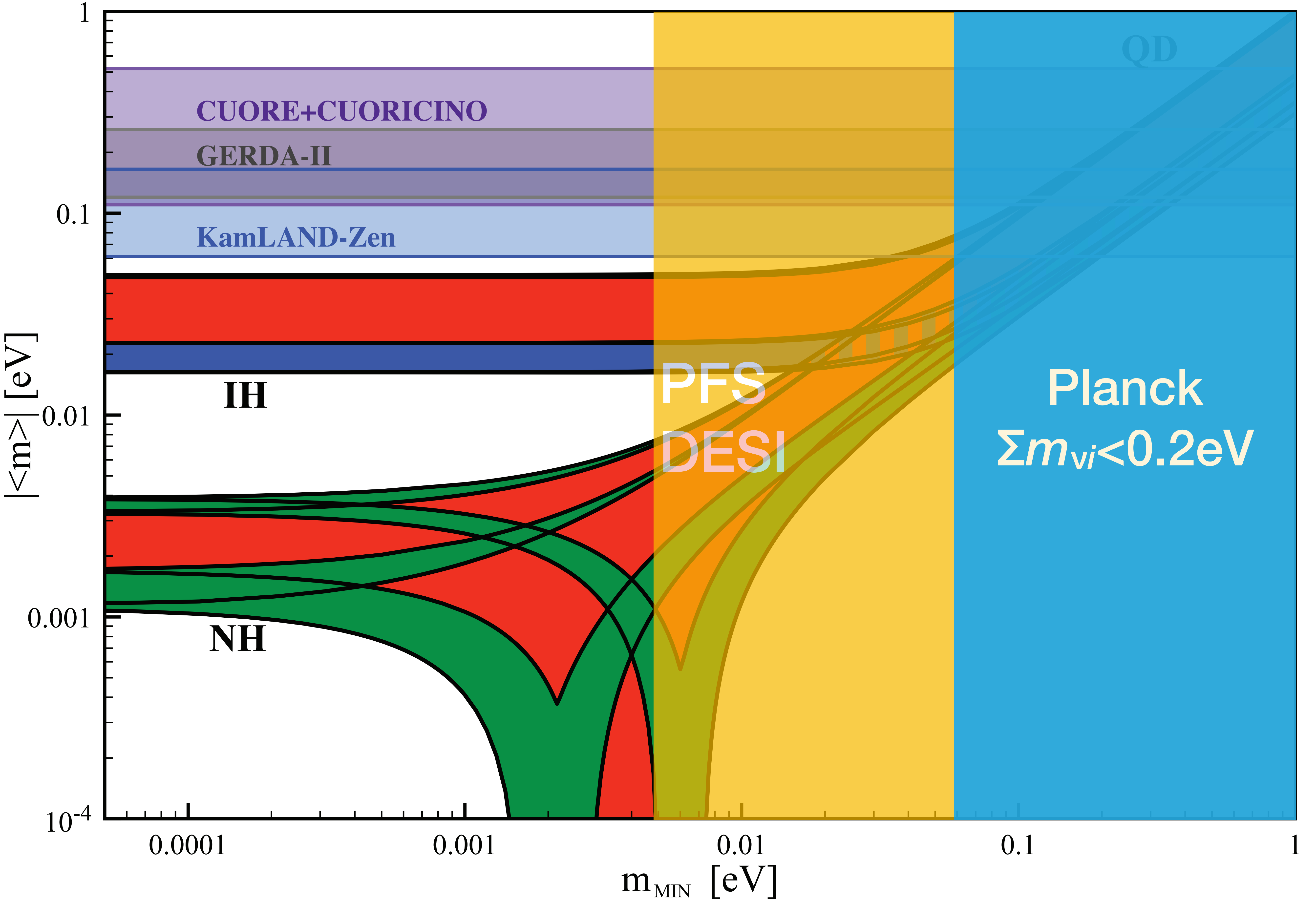
$$0\to\pi_2(G)\to\pi_2(G/H)\to\pi_1(H)\to\pi_1(G)\to\boxed{\pi_1(G/H)}\to\pi_0(H)\to\pi_0(G)=0$$



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

covers pretty much the entire range for leptogenesis!

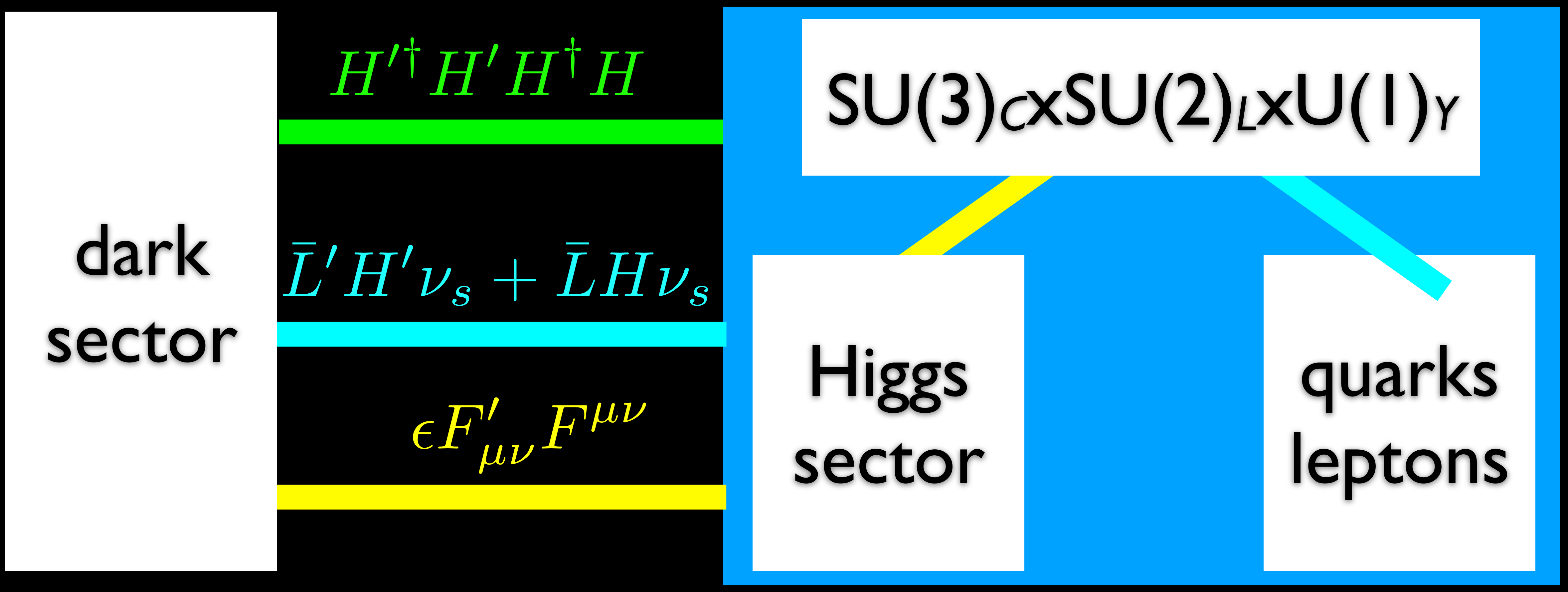
caveat: particle emission from cosmic strings

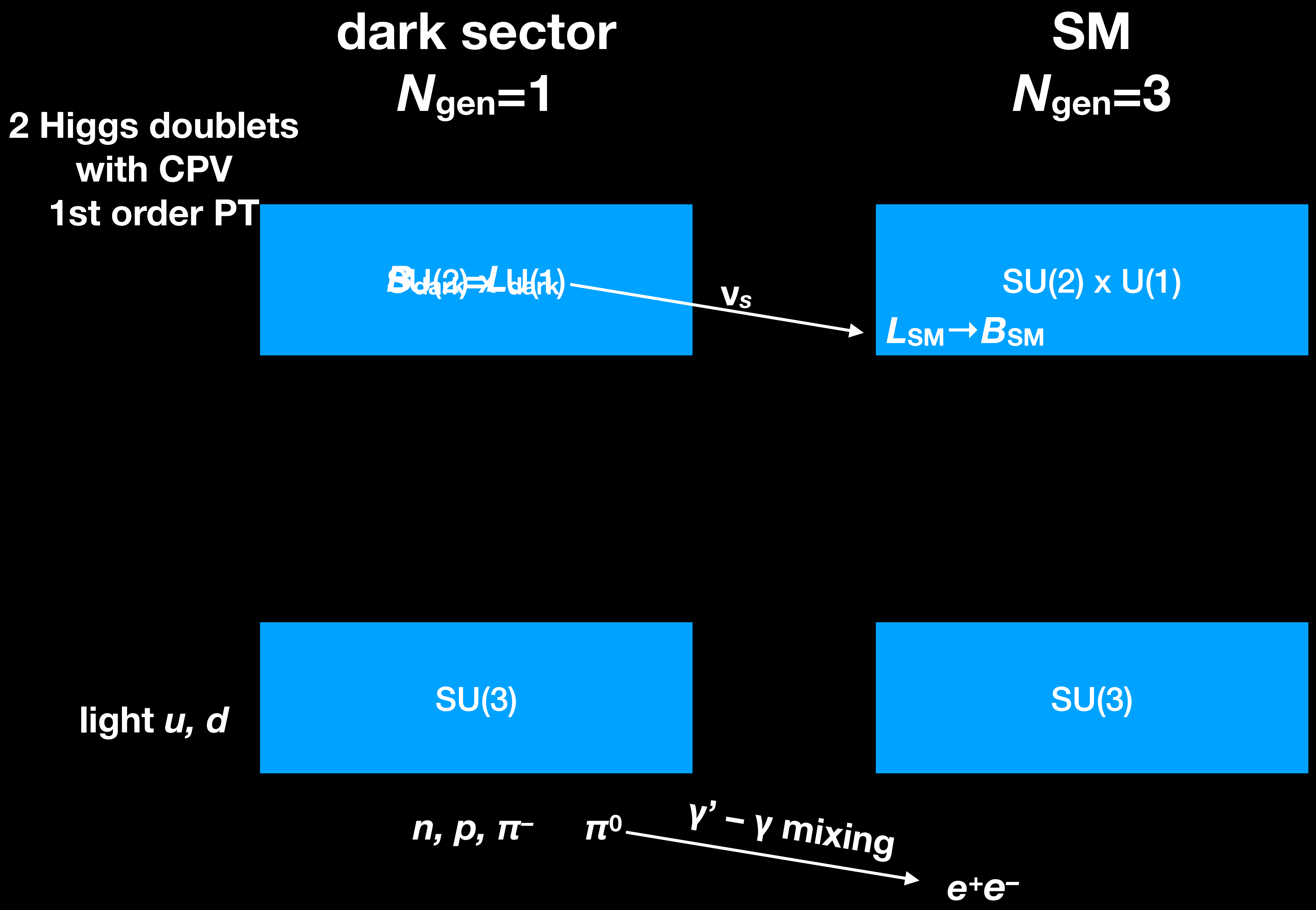


CUORE+CUORICINO
GERDA-II
KamLAND-Zen
QD
IH
NH
PFS
DESI
Planck
$\Sigma m_{\nu i} < 0.2$eV
$|\langle m \rangle|$ [eV]
m_{MIN} [eV]
1
0.1
0.01
0.001
10^{-4}
0.0001
0.001
0.01
0.1
1

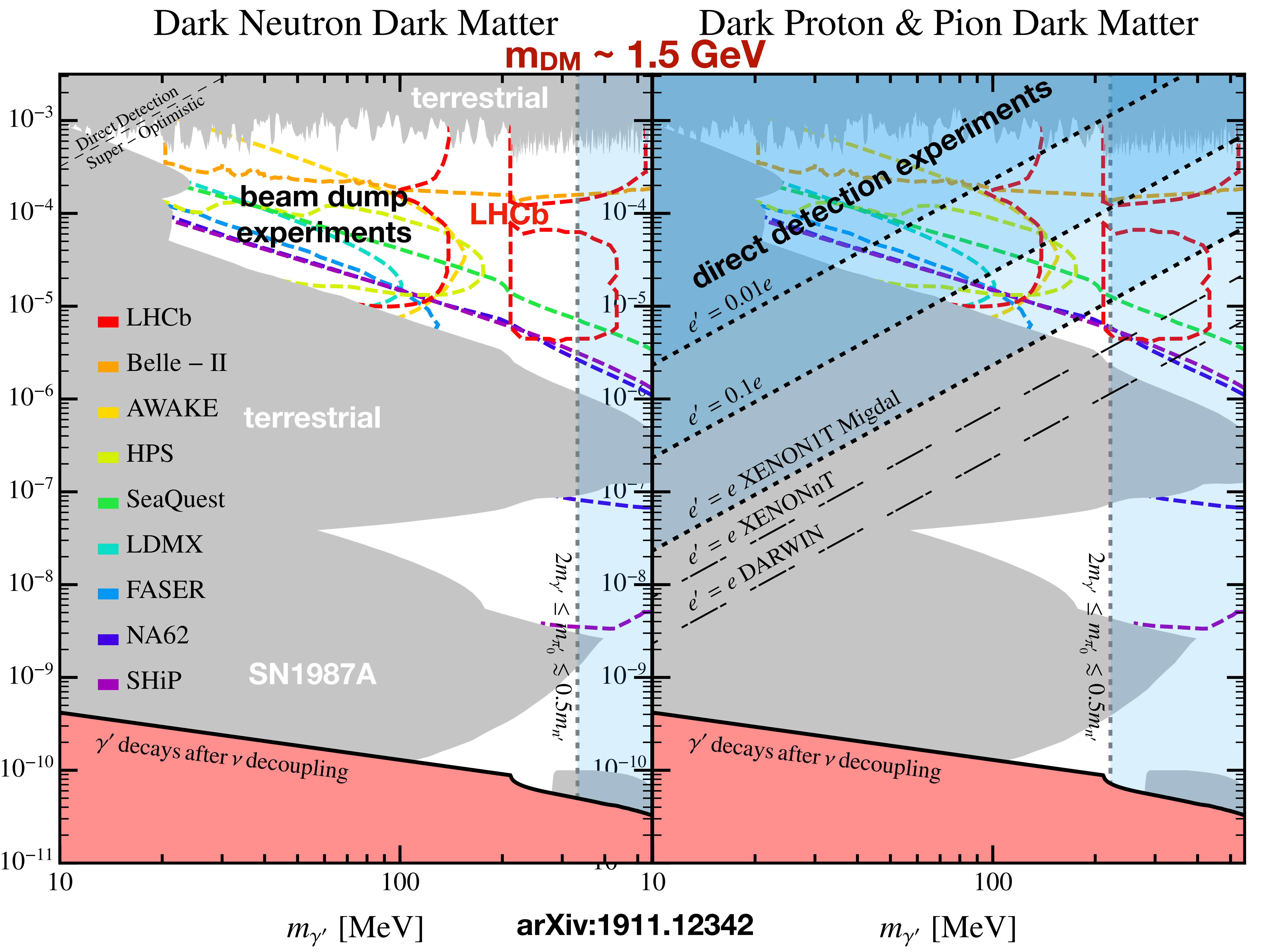
portals

three possible portals in renormalizable theories





+Eleanor Hall, Thomas Konstantin, Robert McGehee, Bethany Suter



Dark Neutron Dark Matter
Dark Proton & Pion Dark Matter
m_DM ~ 1.5 GeV
terrestrial
Direct Detection
Super − Optimistic
beam dump
experiments
LHCb
direct detection experiments
e′ = 0.01e
e′ = 0.1e
e′ = e XENON1T Migdal
e′ = e XENONnT
e′ = e DARWIN
LHCb
Belle − II
AWAKE
HPS
SeaQuest
LDMX
FASER
NA62
SHiP
terrestrial
SN1987A
2m_γ′ ≤ m_π′0 ≲ 0.5m_n′
γ′ decays after ν decoupling
10
100
m_γ′ [MeV]
arXiv:1911.12342

Neutrinos are fun

Thank you, Serguey!