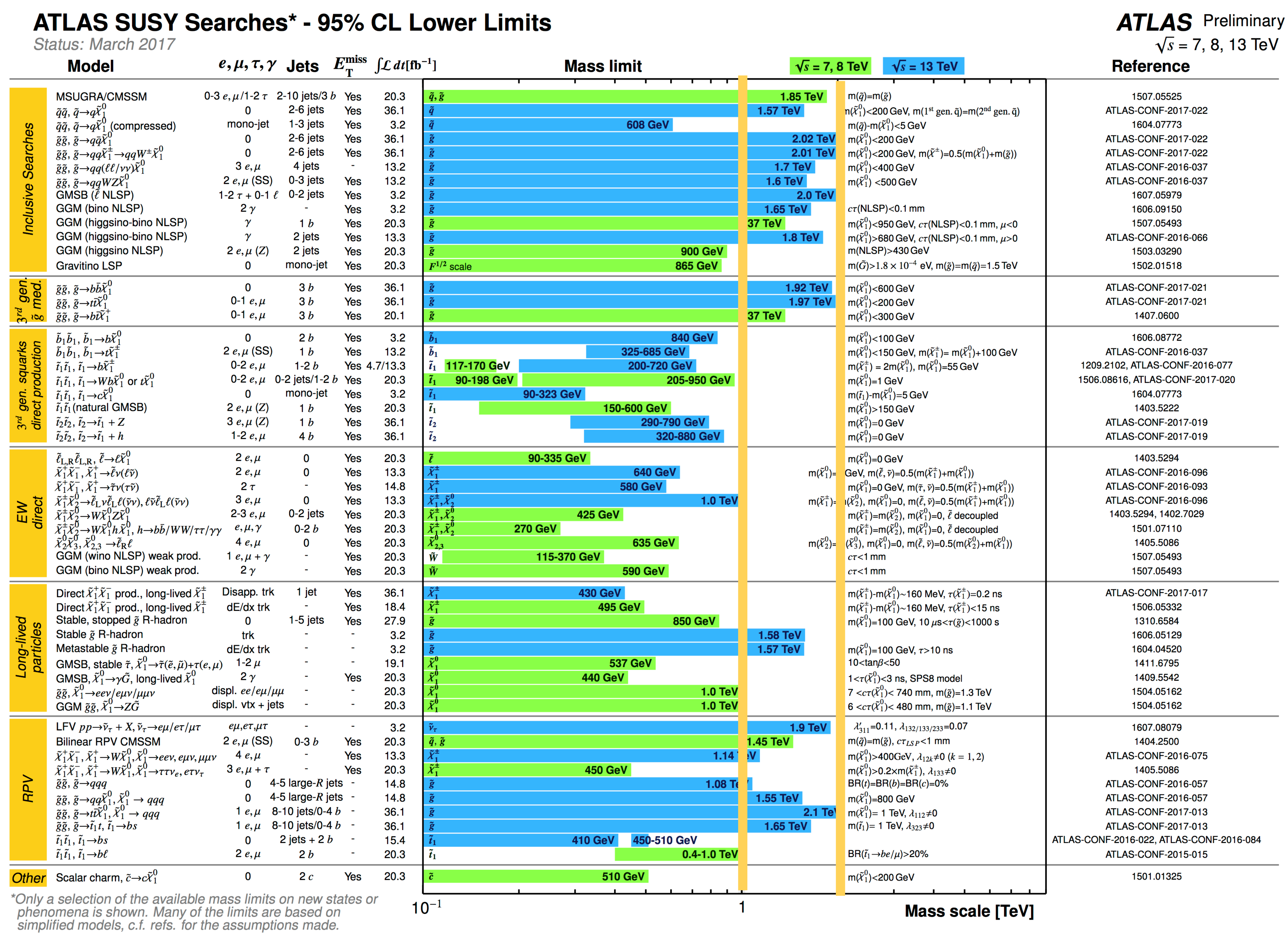
New ideas and signatures in electroweak-scale model building

Hitoshi Murayama (Berkeley, Kavli IPMU)
LHCP 2022, May 19, 2022

東京大学
THE UNIVERSITY OF TOKYO
BERKELEY CENTER for THEORETICAL PHYSICS
BERKELEY LAB
KAVLI IPMU

no new physics



"The 2 TeV line has been reached for some scenarios"

Why SUSY?

- mathematically interesting
- string theory needs it
- rationale for scalars
- helps stabilize inflaton potential
- gauge coupling unification
- dark matter candidate
- hierarchy (naturalness) problem
- *fun for colliders*
- baryogenesis?
- cosmological constant? 10^{-120} to 10^{-60}

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 tanβ = 3. See Fig. 5 of the paper for other choices of A_0 and tanβ. 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 tanβ = 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	

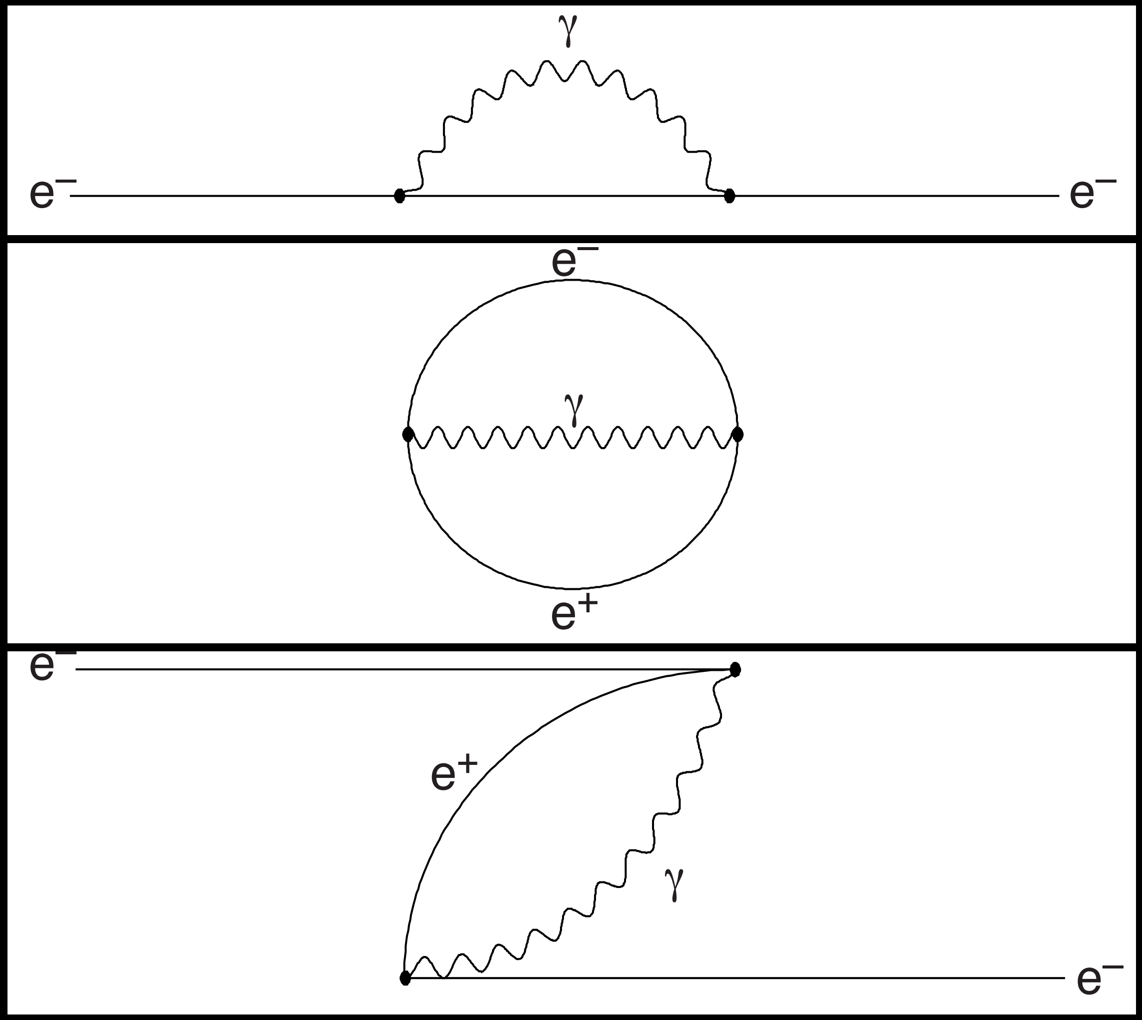
Electron mass is natural by doubling #particles

- Electron creates a force to repel itself

$$\Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \mathrm{GeV}\frac{10^{-17}\mathrm{cm}}{r_e}$$

- 10^{-4} fine-tuning?
- quantum mechanics and anti-matter

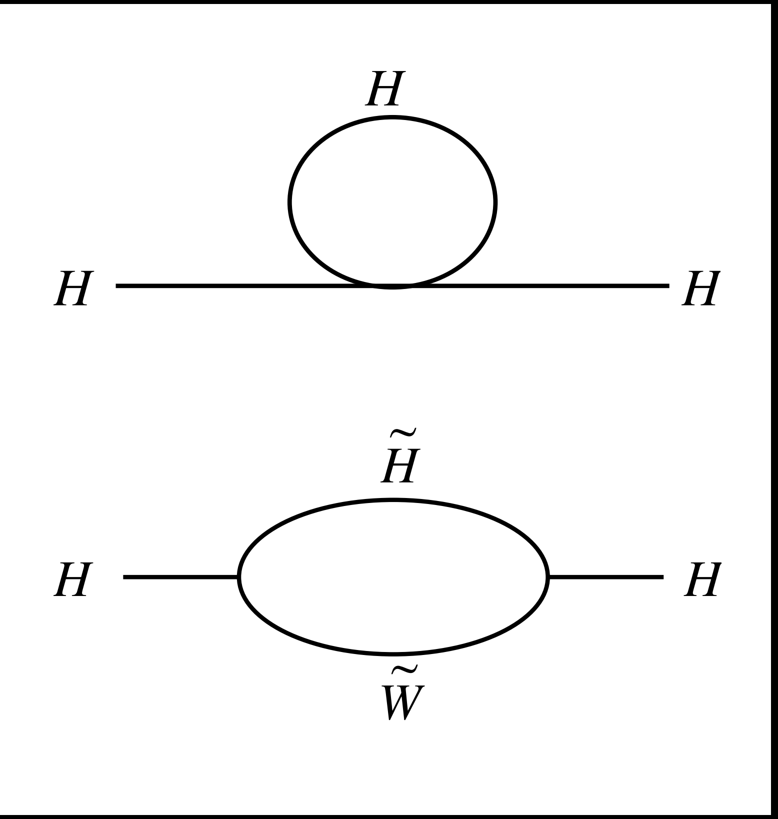
$\Rightarrow$ only 10% of mass even for Planck-size $r_e \sim 10^{-33}$cm



$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

Higgs mass is natural by doubling #particles?

- Higgs also repels itself
- Double #particles again $\Rightarrow$ superpartners
- only log sensitivity to UV
- Standard Model made consistent up to higher energies

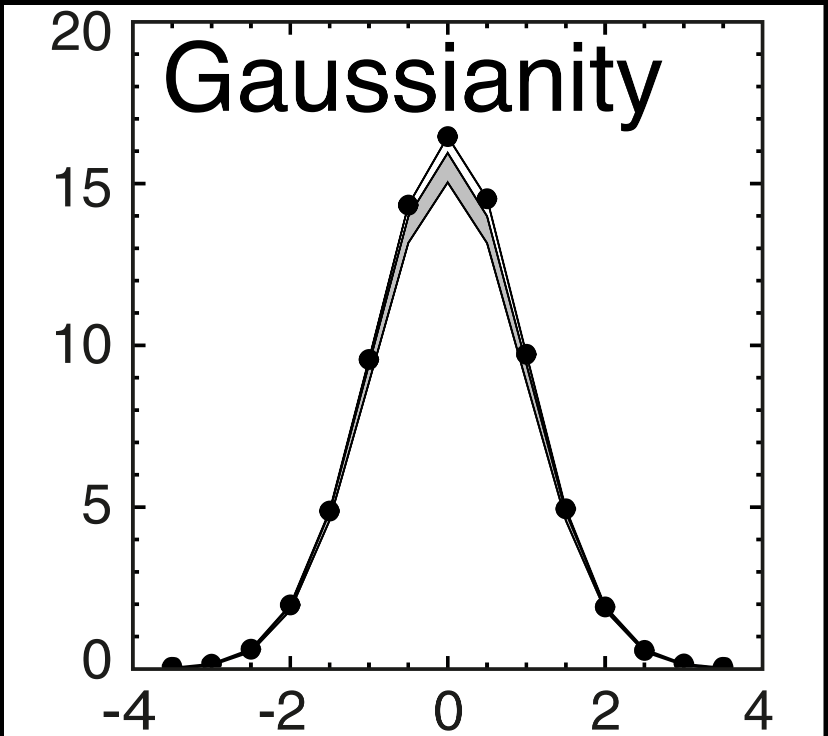


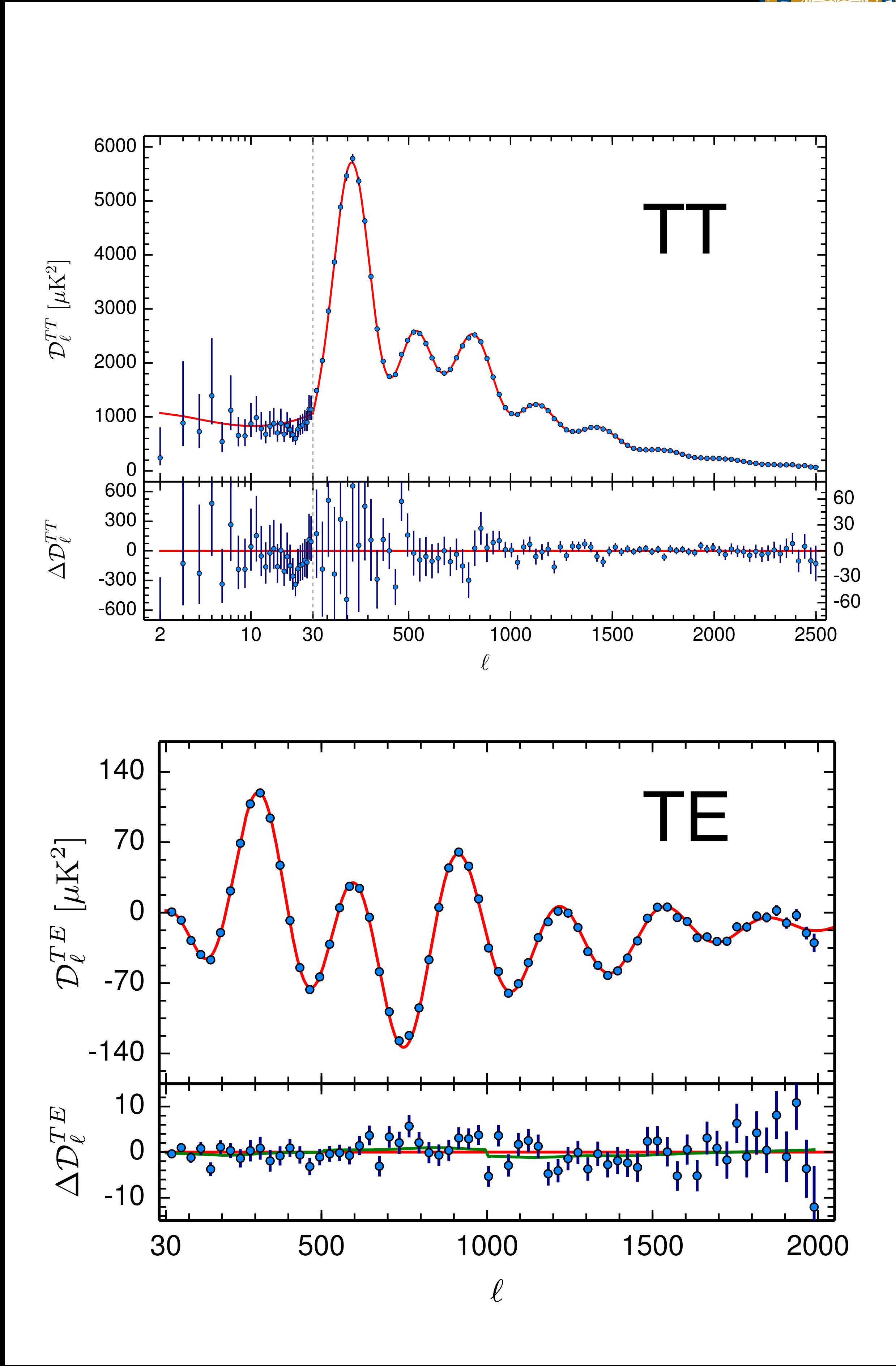
$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

I still take it seriously

Naturalness works!

- Why is the Universe big?
- Inflation
  - horizon problem
  - flatness problem
  - large entropy





ENGINEERING
Machines That Change Shape

MEDICINE
An Off Switch for Cancer

NEUROSCIENCE
How to Reach "Vegetative" Patients

SCIENTIFIC AMERICAN

ScientificAmerican.com

A

IF SUPERSYMMETRY

CRISIS

DOESN'T PAN OUT,

IN

SCIENTISTS NEED A NEW WAY

PHYSICS

TO EXPLAIN THE UNIVERSE

?

0 74470 38527 5
$5.99 U.S.
MAY 2014

been there before

The New York Times

Science

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH

ENVIRONMENT

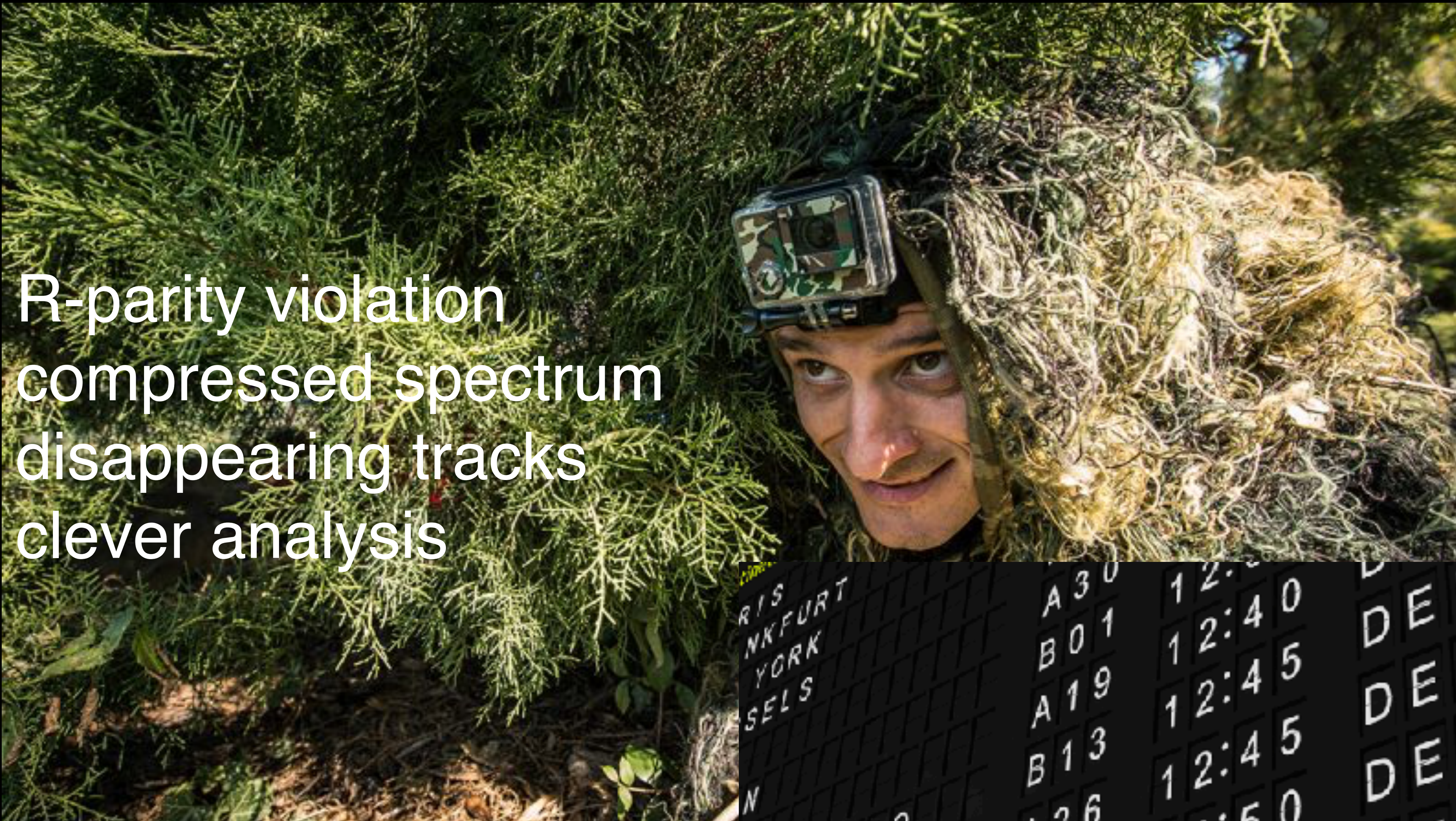
315 Physicists Report Failure In Search for Supersymmetry

By MALCOLM W. BROWNE

Published: January 5, 1993

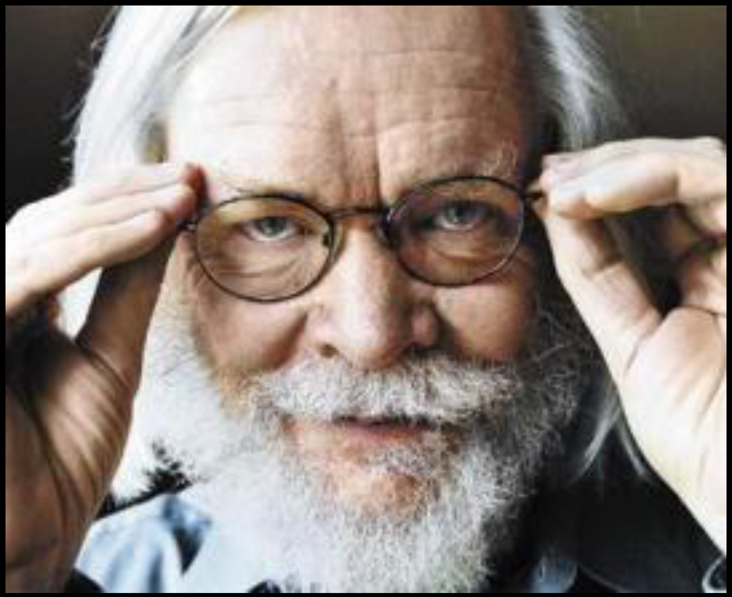
Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as



R-parity violation
compressed spectrum
disappearing tracks
clever analysis

clever analysis
precision Higgs, flavor
HL-LHC
HE-LHC



Better Late Than Never

Even m_{SUSY}~10 TeV ameliorates fine-tuning from 10^{-36} to 10^{-4}

been there before

- CMB anisotropy
- universe younger than oldest stars?
- cosmologists got antsy
- it turned out a little “fine-tuned”
  - low quadrupole
  - dark energy

1% tuning

“

“Ba

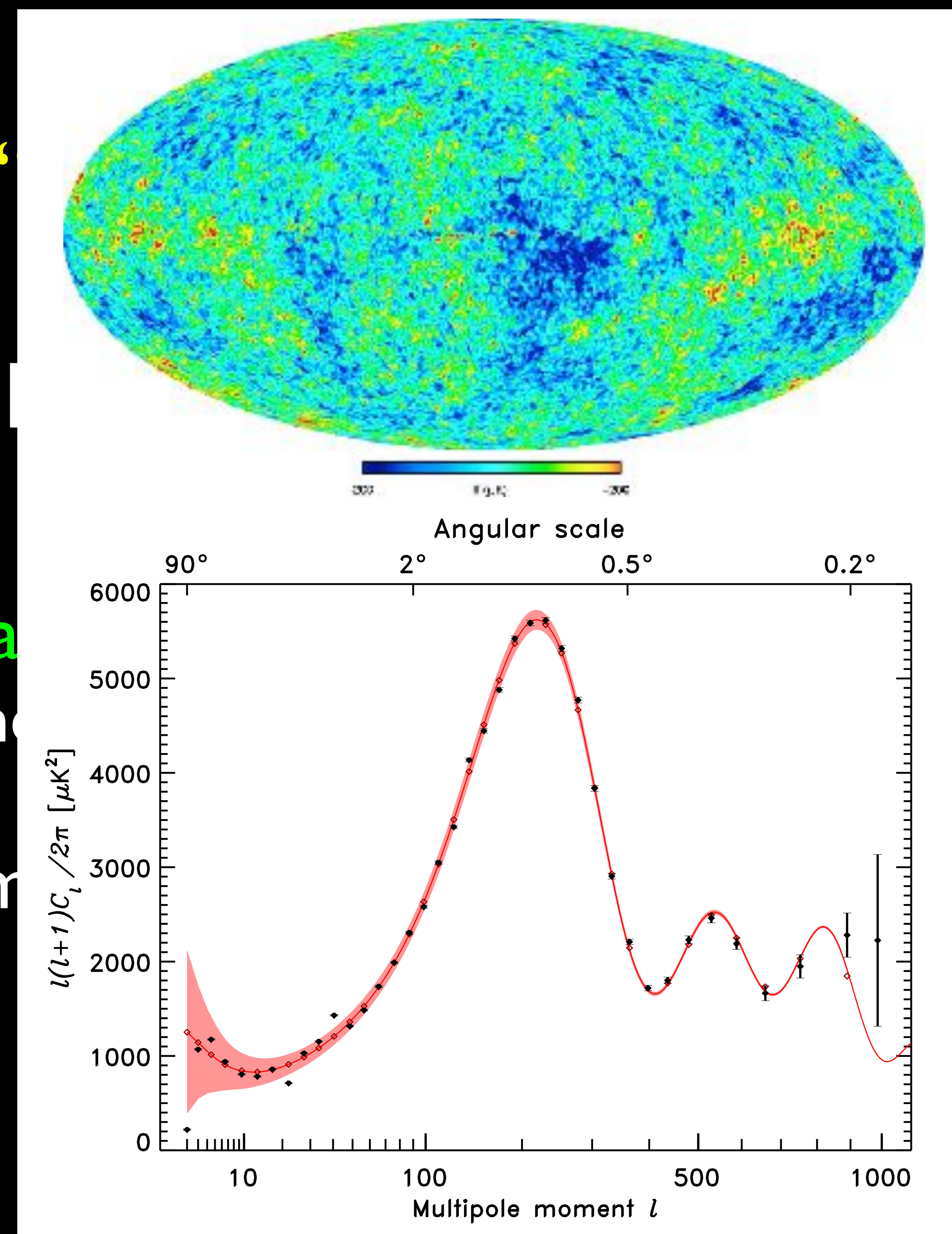
”

A n

e

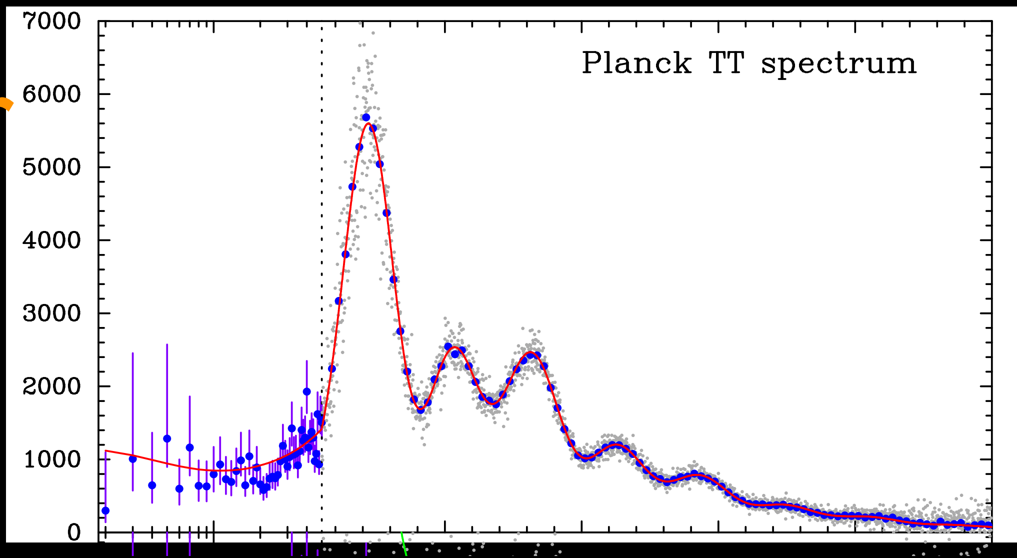
the

Tim

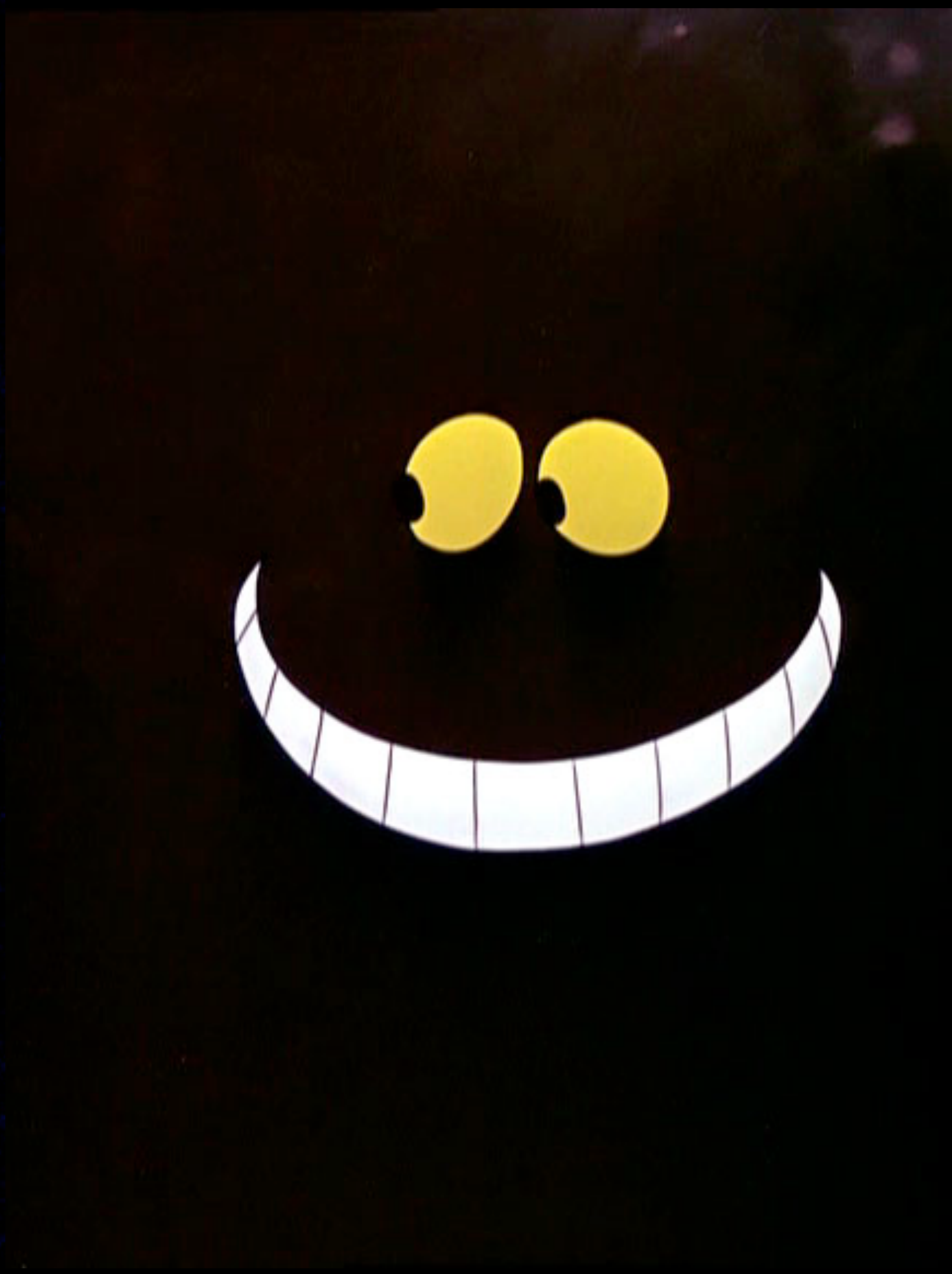


Five empirical evidences for physics beyond SM

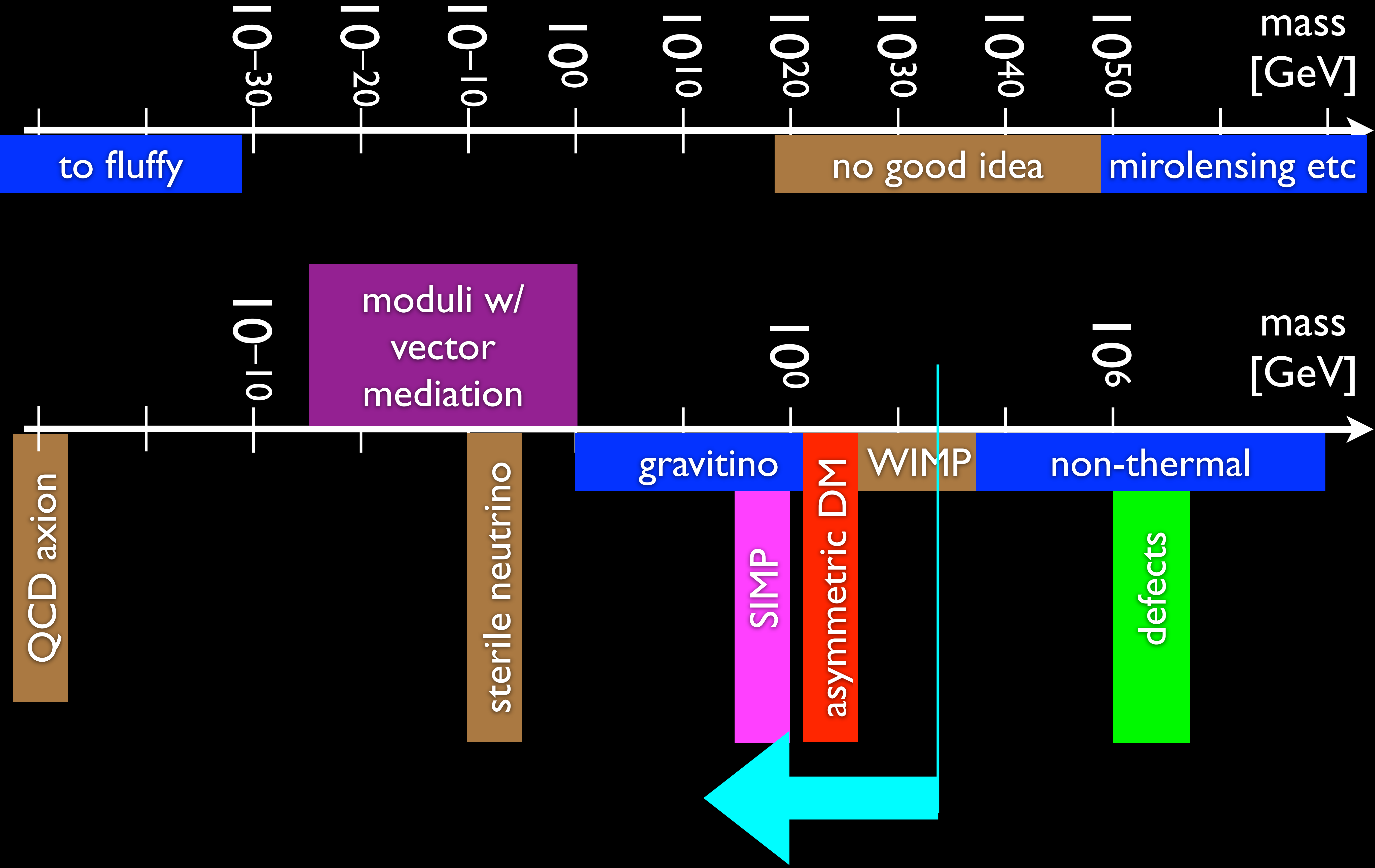
- Since 1998, it became clear that there are at least five missing pieces in the SM
  - non-baryonic dark matter
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry



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

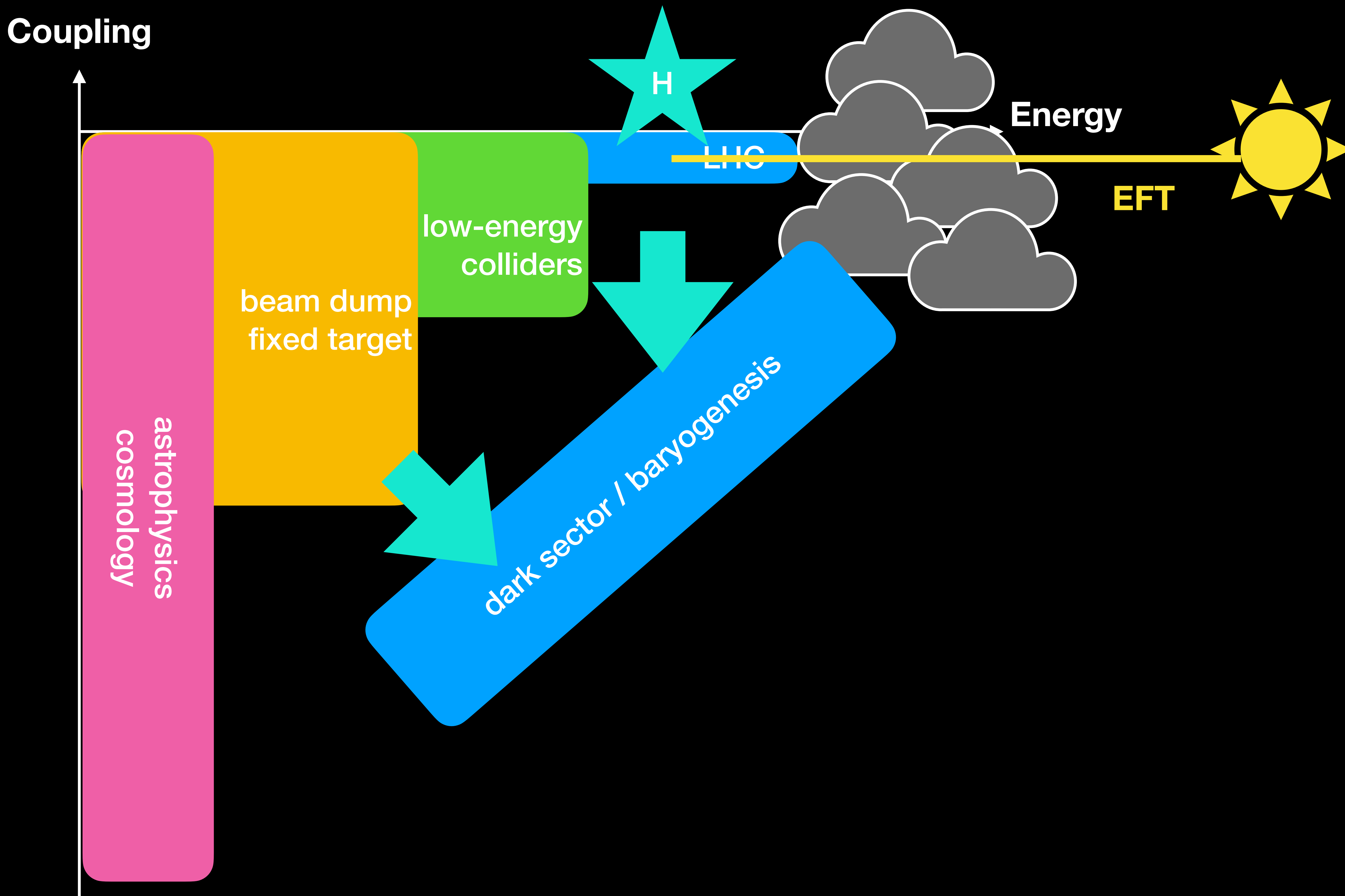
 

Ceshire cat



10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
10^{20}
10^{30}
10^{40}
10^{50}
mass [GeV]
to fluffy
no good idea
mirolensing etc
moduli w/ vector mediation
10^{-10}
10^{0}
10^{6}
mass [GeV]
QCD axion
sterile neutrino
gravitino
SIMP
asymmetric DM
WIMP
non-thermal
defects

another axis



dark baryon asymmetric dark matter

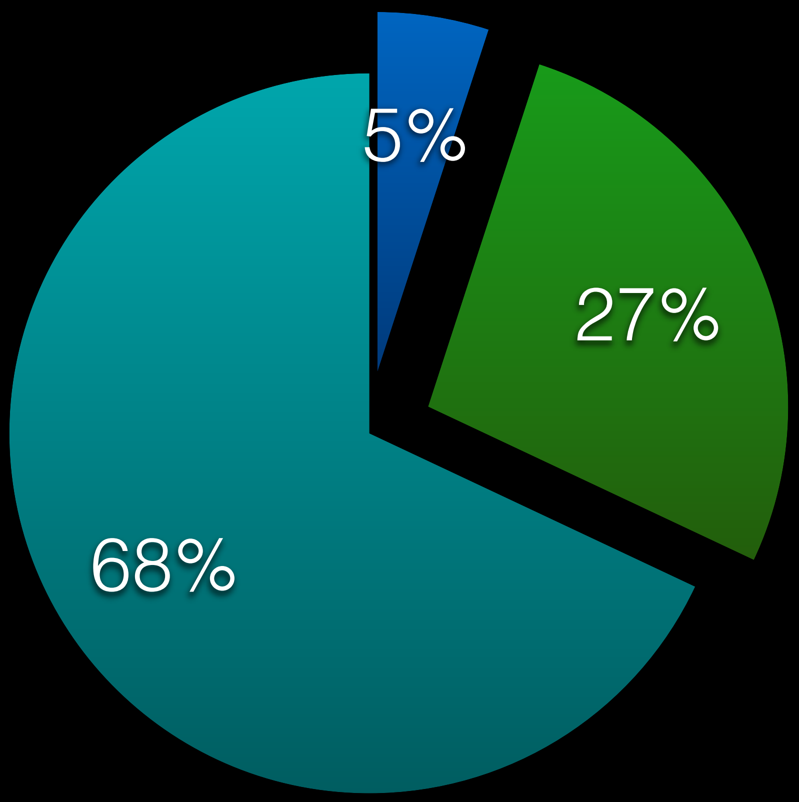
Hitoshi Murayama (Berkeley, Kavli IPMU)
+Nell Hall (Berkeley), Thomas Konstandin (DESY), Robert McGehee (Berkeley)

arXiv:1910.08068, 1911.12342, 2107.03398

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
THE UNIVERSITY OF CALIFORNIA 1868

Cosmic Coincidence

- atoms 5%
- dark matter 28%
- why so close?



Sakharov Conditions

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

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

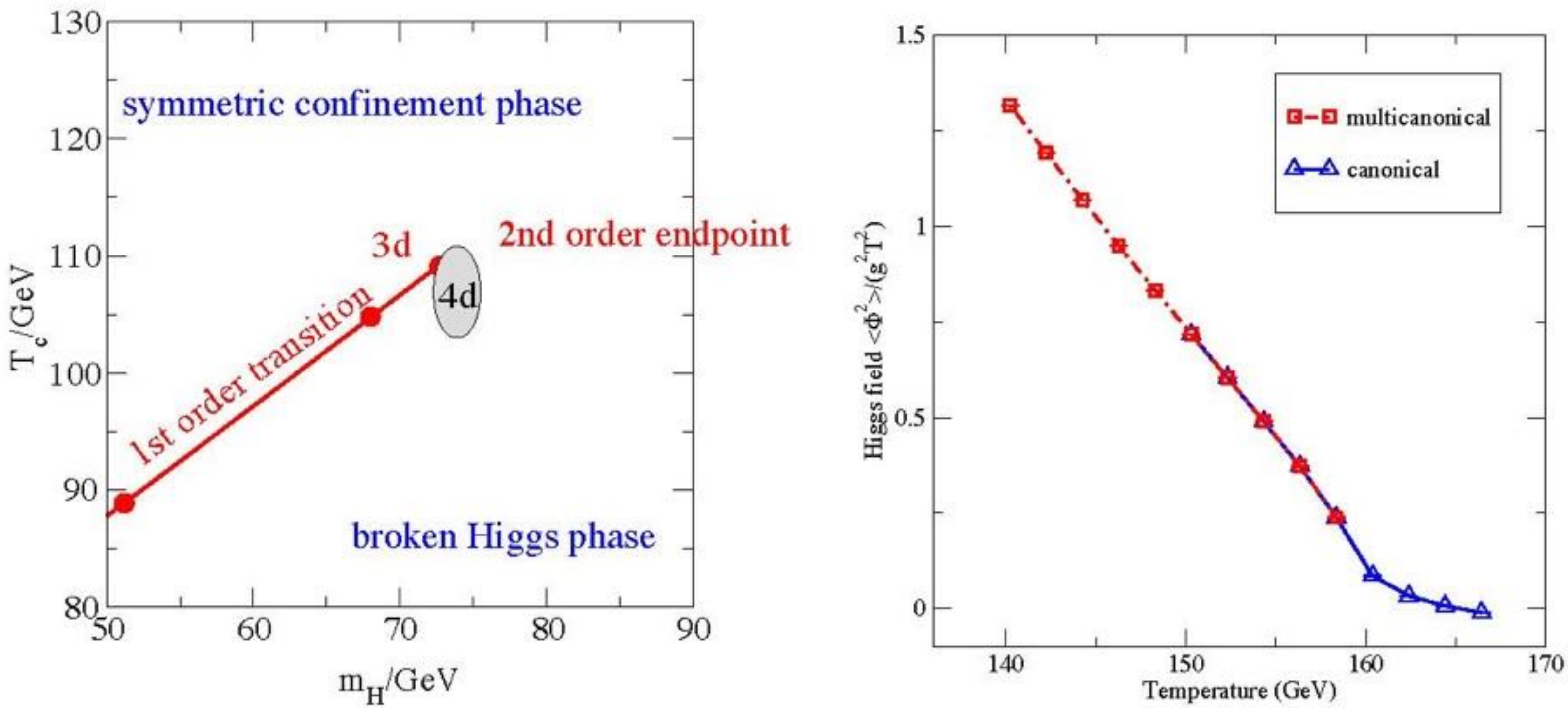
- Departure from equilibrium
  - First-order phase transition of Higgs

requires m_h < 75 GeV

- Experimentally testable?

Phase diagram for the Standard Model:

Mikko Laine (Bern)



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

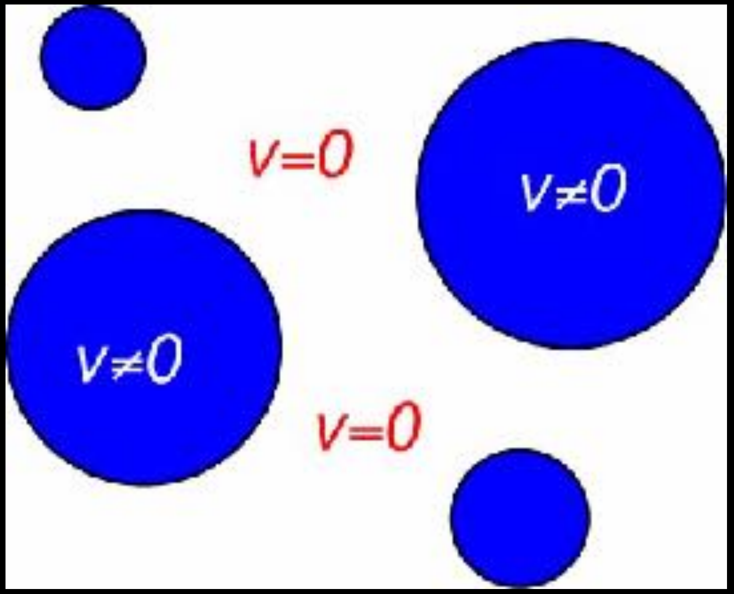
$\langle H^\dagger H \rangle$ is not an order parameter

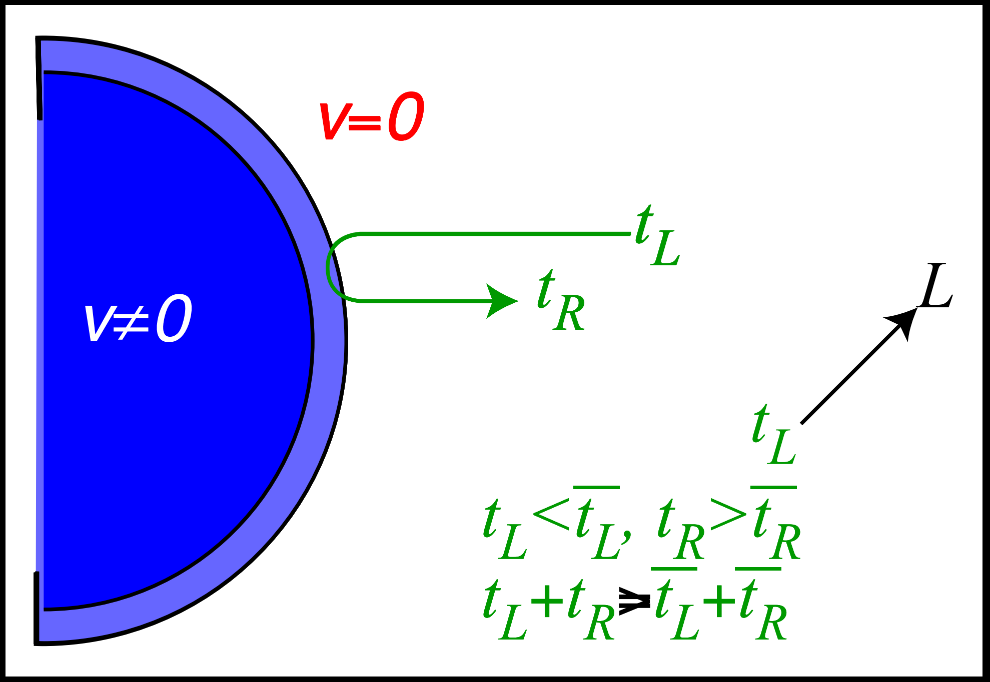
for m_h=125GeV, it is crossover

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

- 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

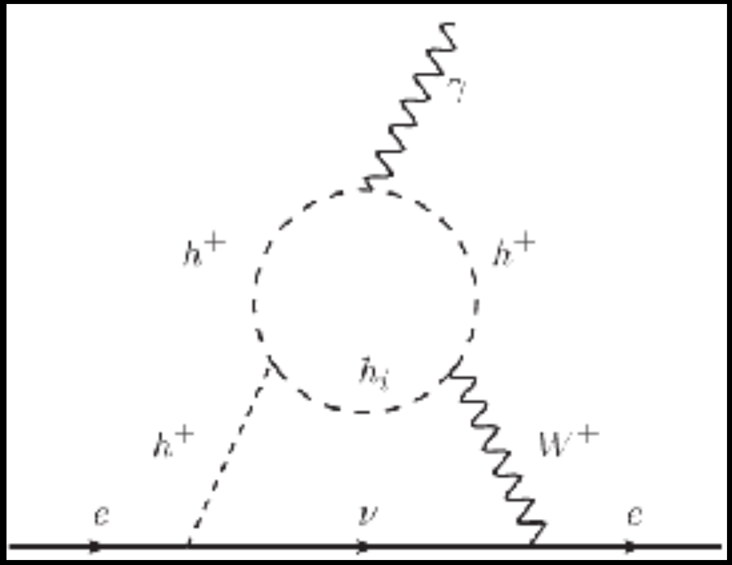
ARTICLE

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

Improved limit on the electric dipole moment of the electron

ACME Collaboration*

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

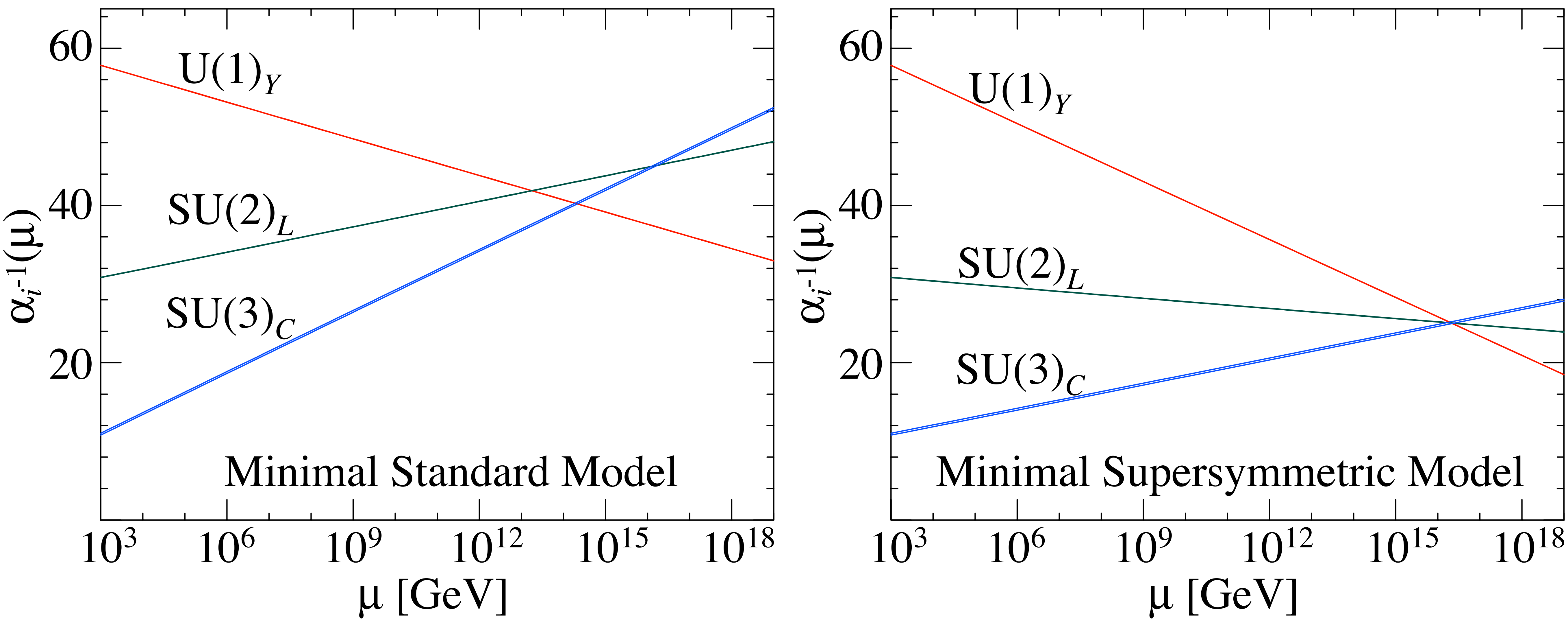


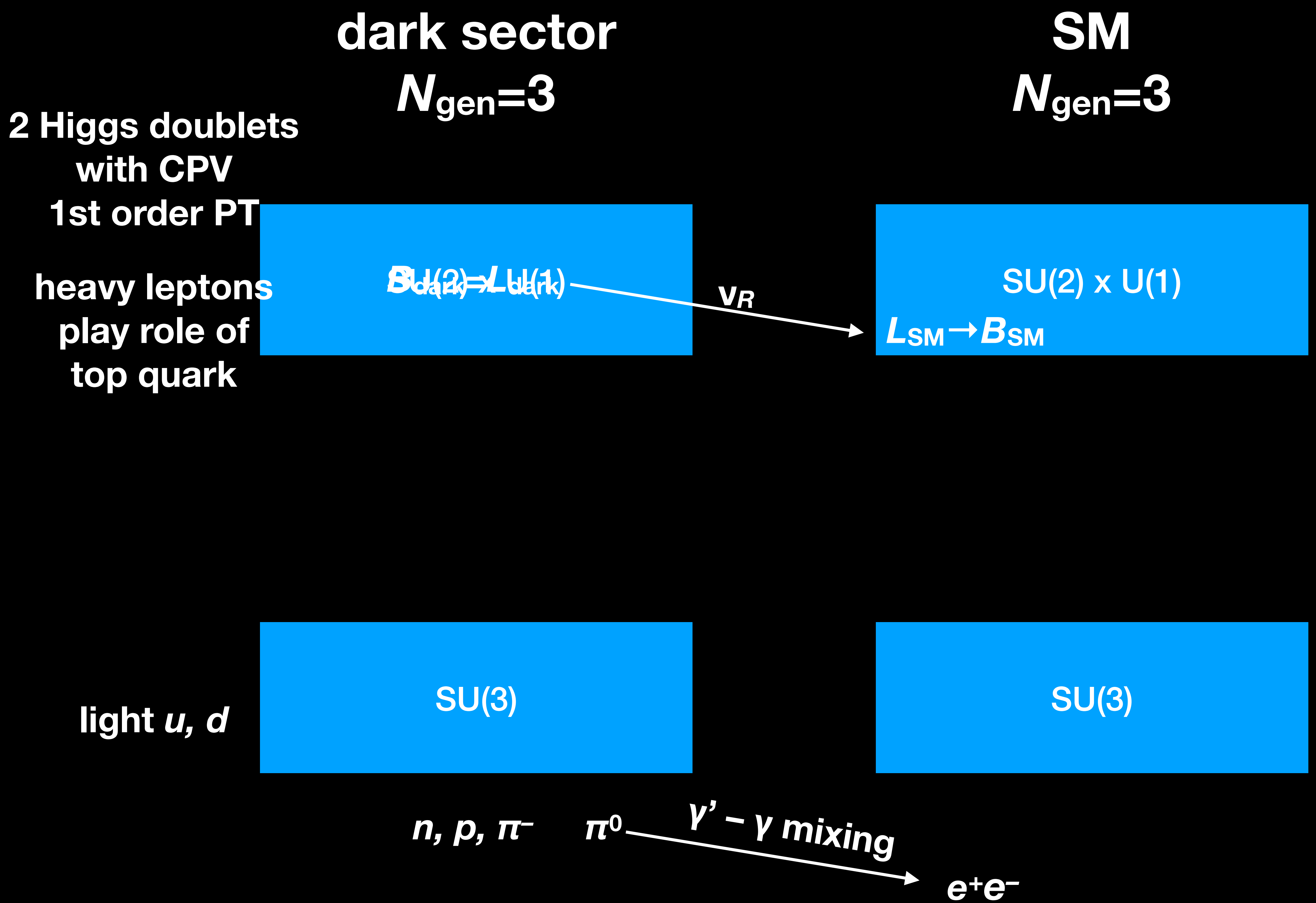
Barr-Zee diagrams

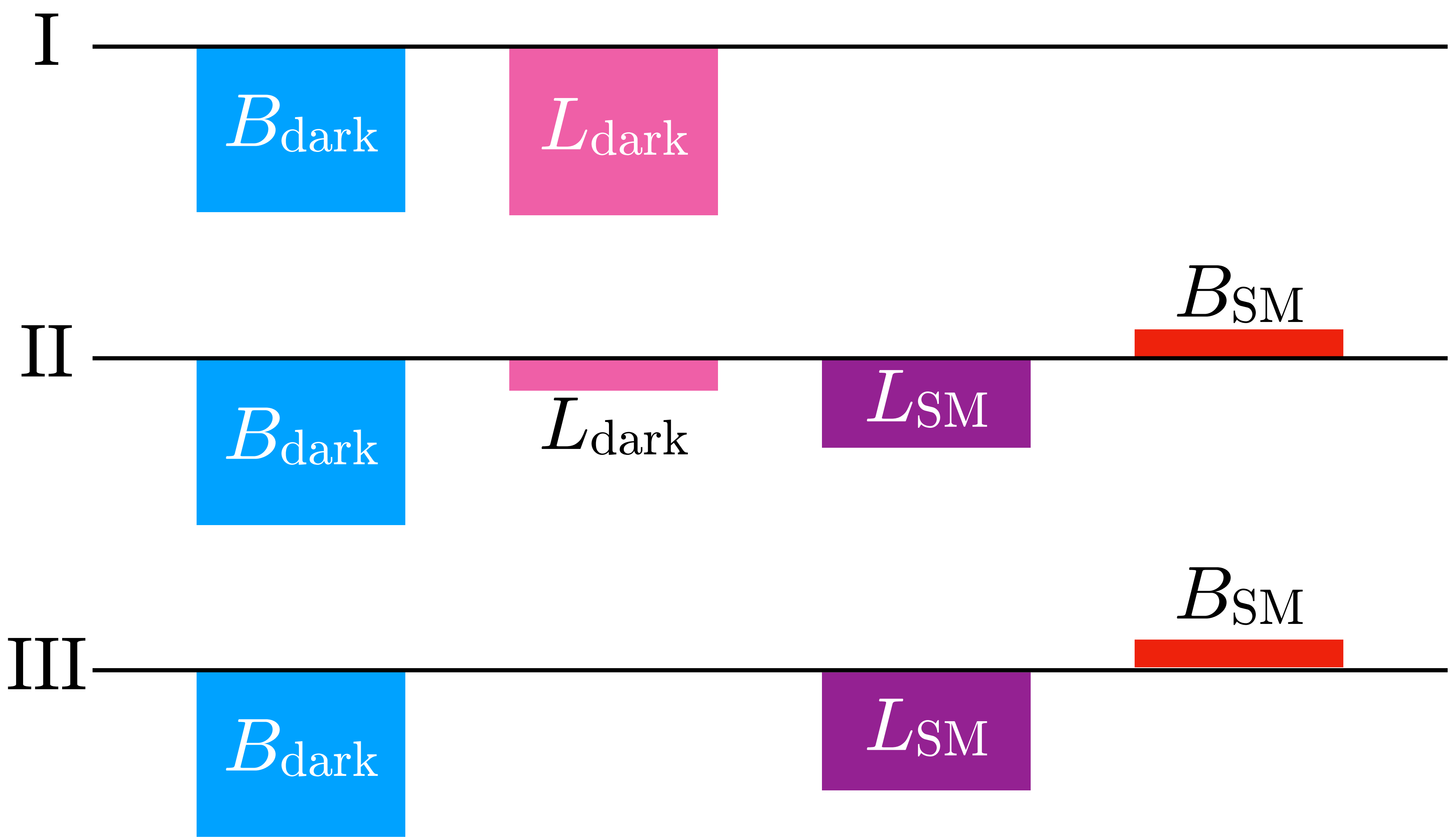
$$d_e \approx \frac{e m_e}{(16\pi^2)^2}\frac{1}{v^2}\sin\delta = 1.6\times10^{-22} e\mathrm{cm}\sin\delta$$

couplings

- unify or not, they start out similar




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

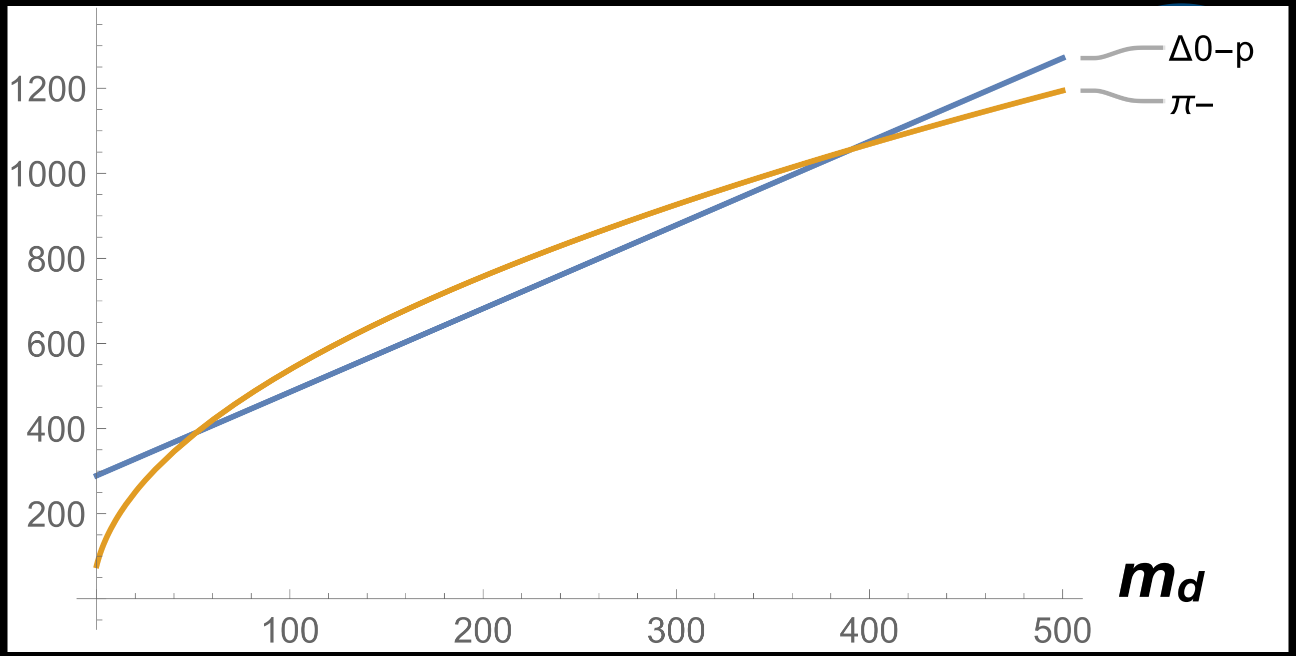


If $M_N > T_{\rm sphaleron}$ $B_{\rm SM} = \frac{36}{133} B_{\rm dark}, \quad L_{\rm SM} = -\frac{97}{133} B_{\rm dark}$ **$m_{n'}$=1.63 GeV**

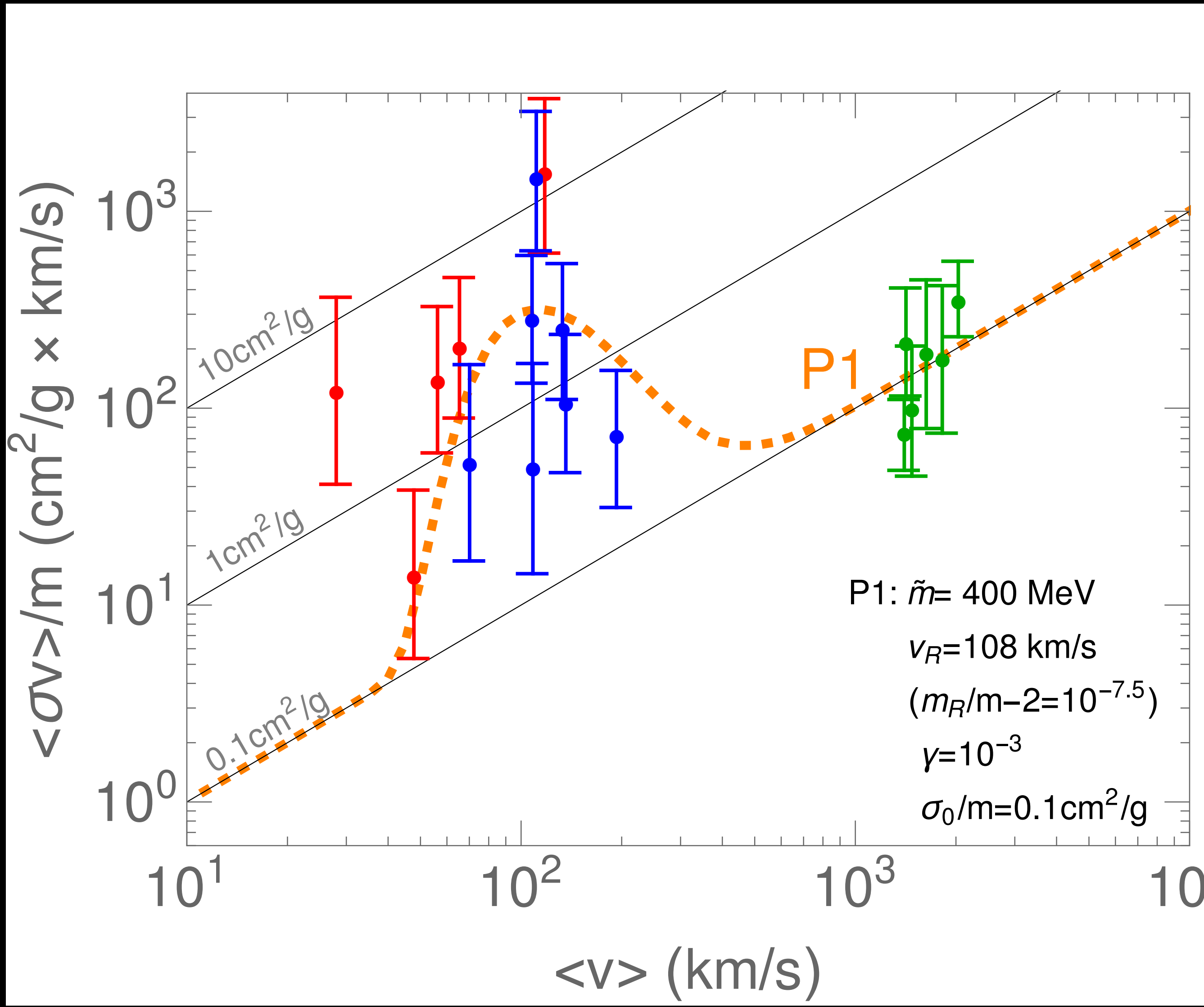
If $M_N < T_{\rm sphaleron}$ $B_{\rm SM} = \frac{12}{37} B_{\rm dark}, \quad L_{\rm SM} = -\frac{25}{37} B_{\rm dark}$ **$m_{n'}$=1.36 GeV**

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

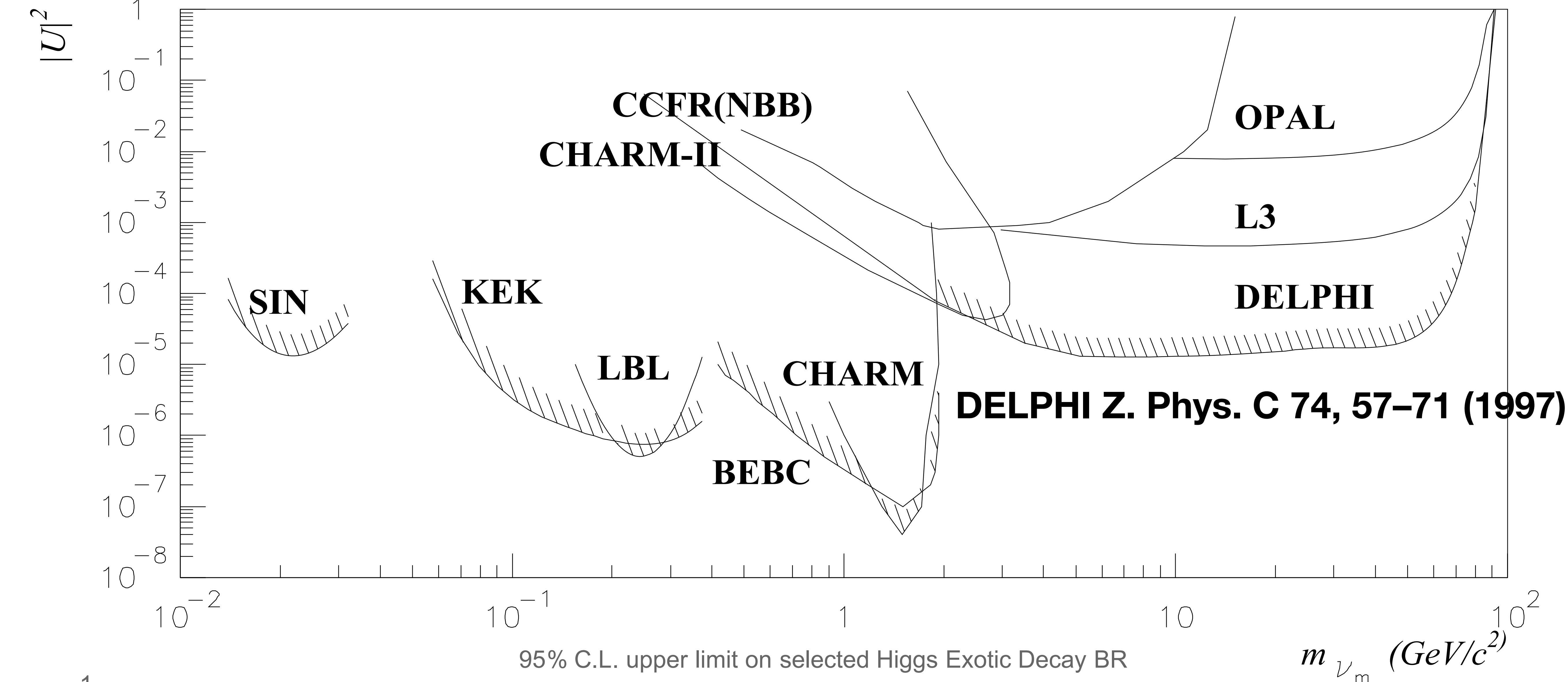
- asymmetric dark matter
  - S. Nussinov, PLB 165, 55 (1985) “technocosmology”
  - R. Kitano, HM, M. Ratz, arXiv:0807.4313, moduli decay
  - D.E. Kaplan, M. Luty, K. Zurek, arXiv:0901.4117
- darkogenesis (= “EW baryogenesis” in the dark sector)
  - J. Shelton, K. Zurek, arXiv:1008.1997

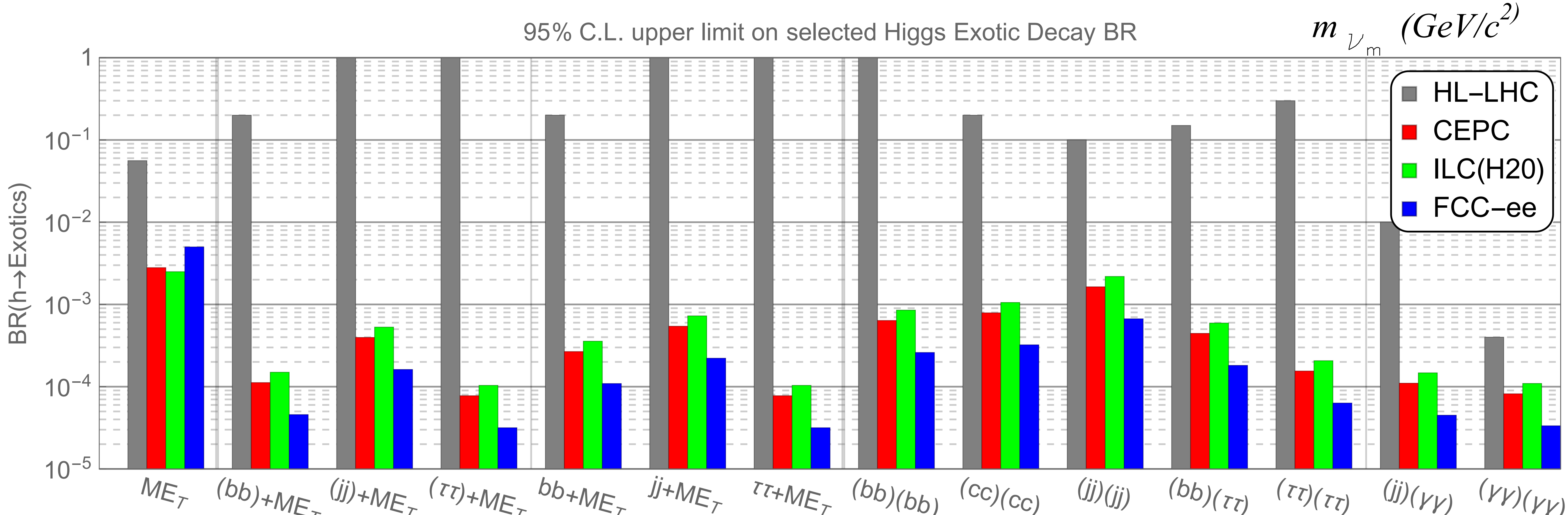
neutrino portal

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

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

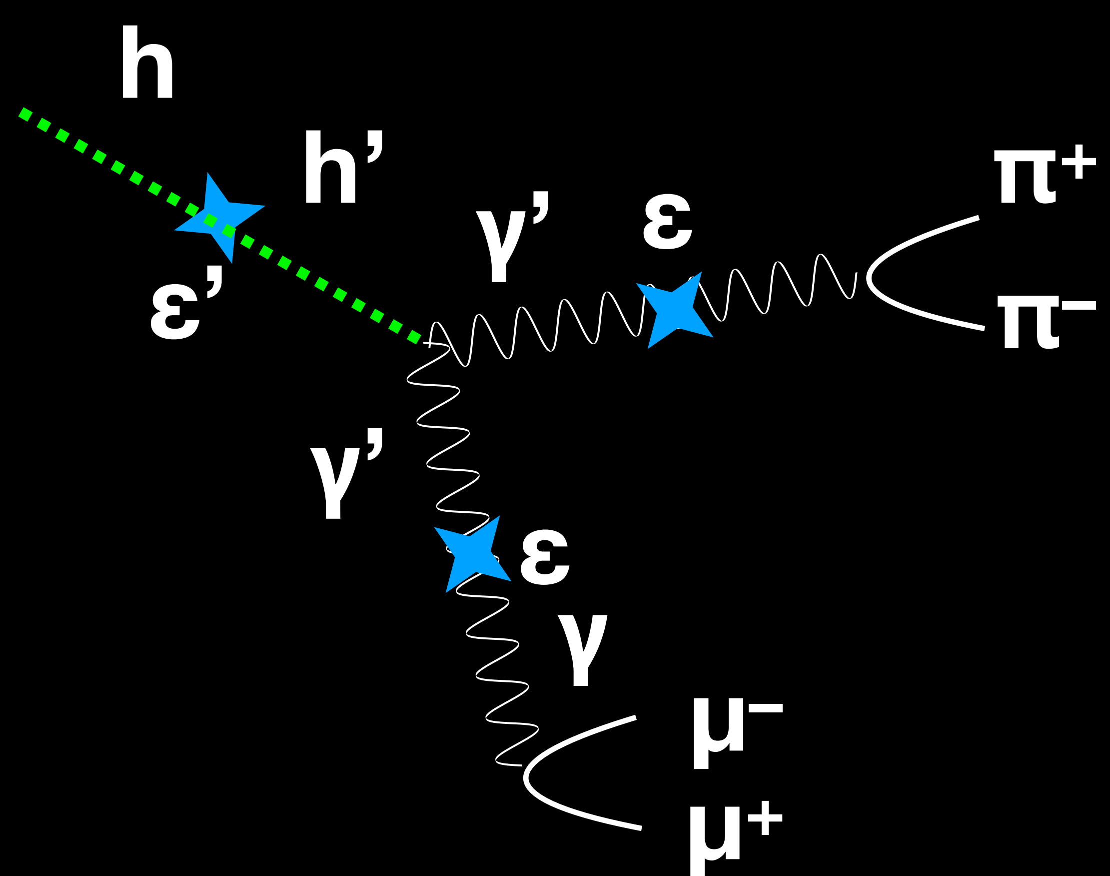
- charged current universality: $\varepsilon_i^2 < 10^{-3}$
- $\mu \to e\,\gamma$ constraint: $\varepsilon_e\,\varepsilon_\mu < 4\times10^{-5}\,(G_F\,M_\nu)$
- $\tau \to \mu\,\gamma$ constraint: $\varepsilon_e\,\varepsilon_\mu < 0.03\,(G_F\,M_\nu)$
- If M_ν <70 GeV, $\varepsilon_i^2 < 10^{-5}$ (DELPHI: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





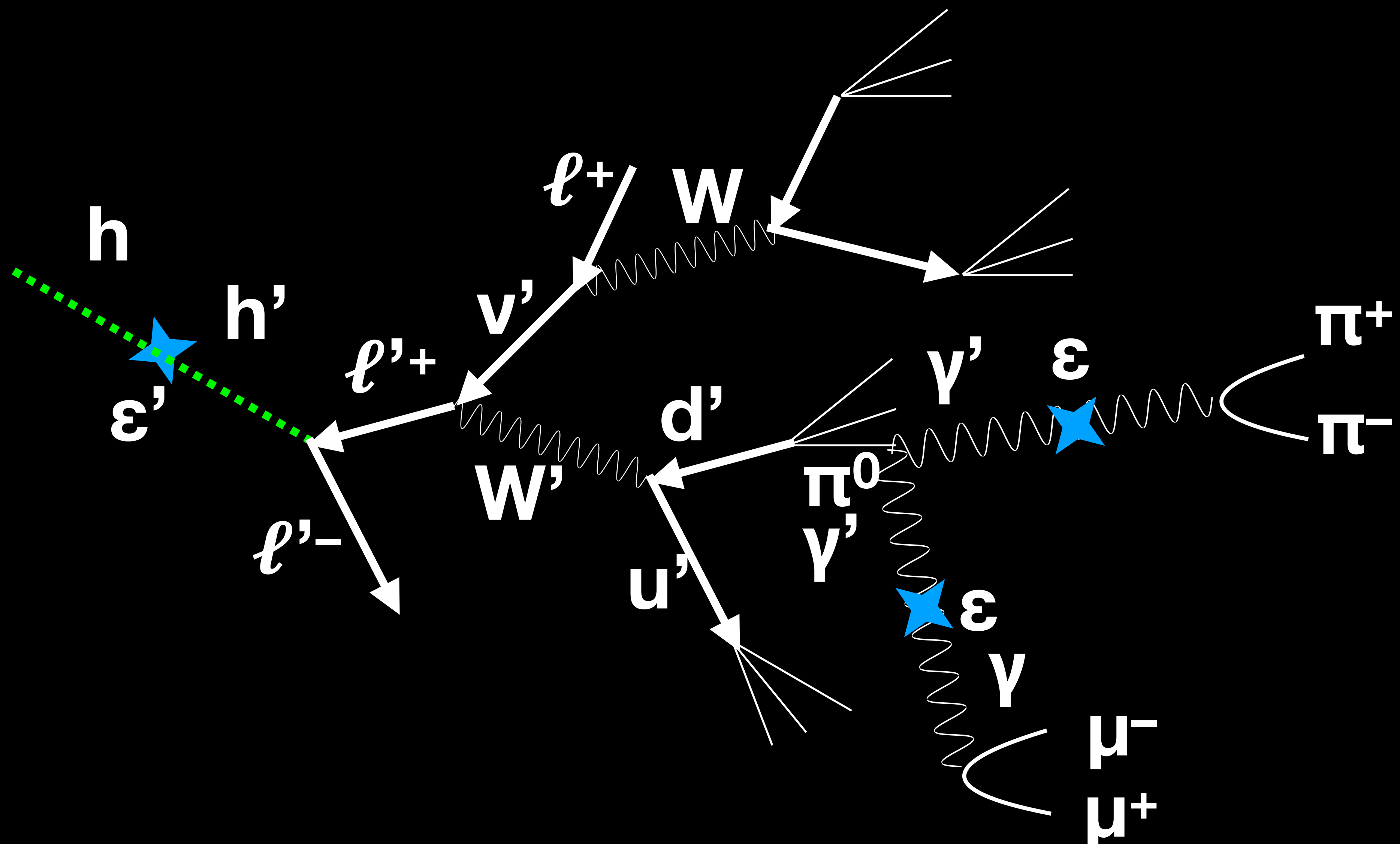
Zhen Liu, Lian-Tao Wang, Hao Zhang, arXiv:1612.09284

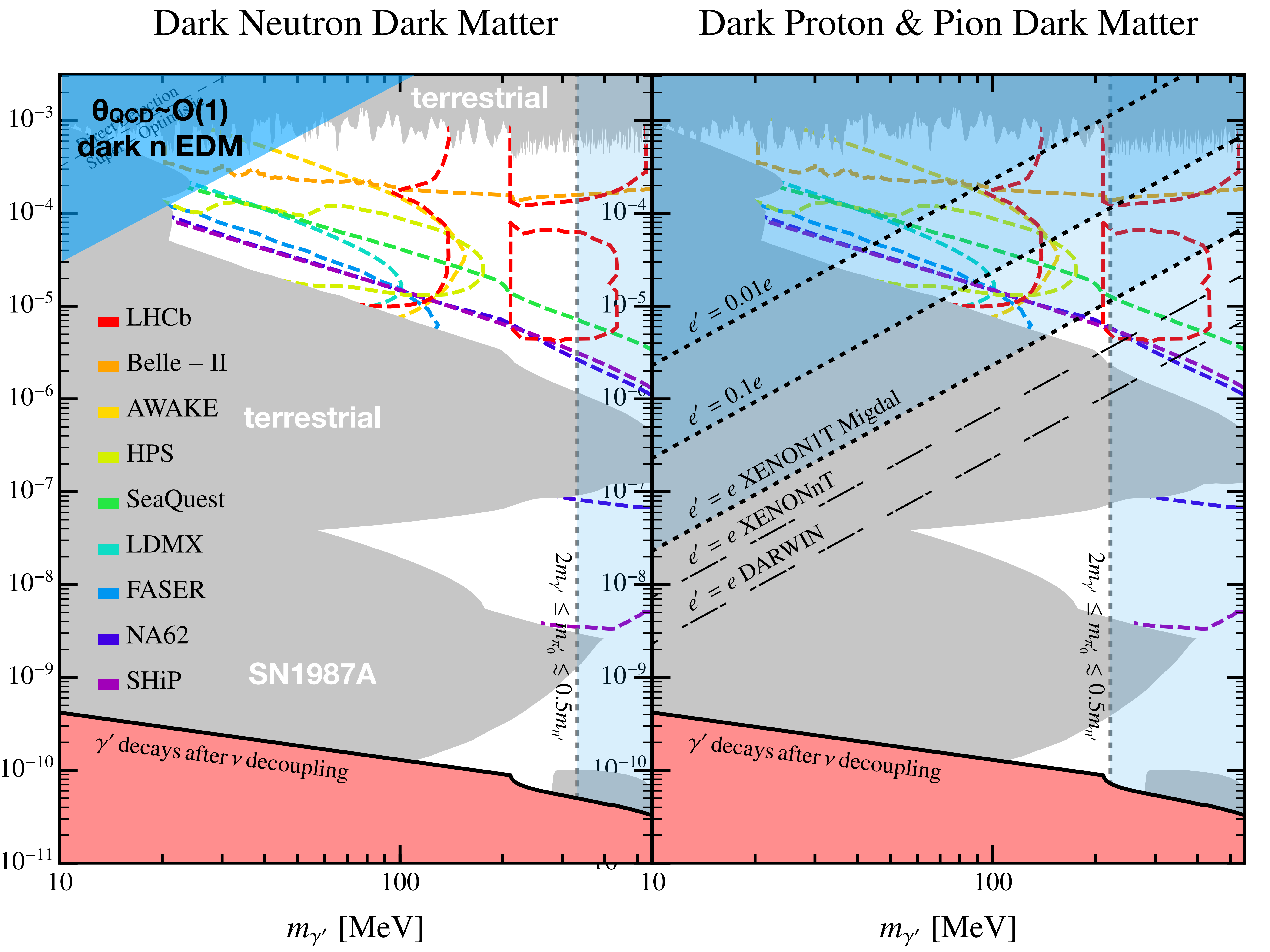
Higgs portal



invisible if decaying
outside the detector

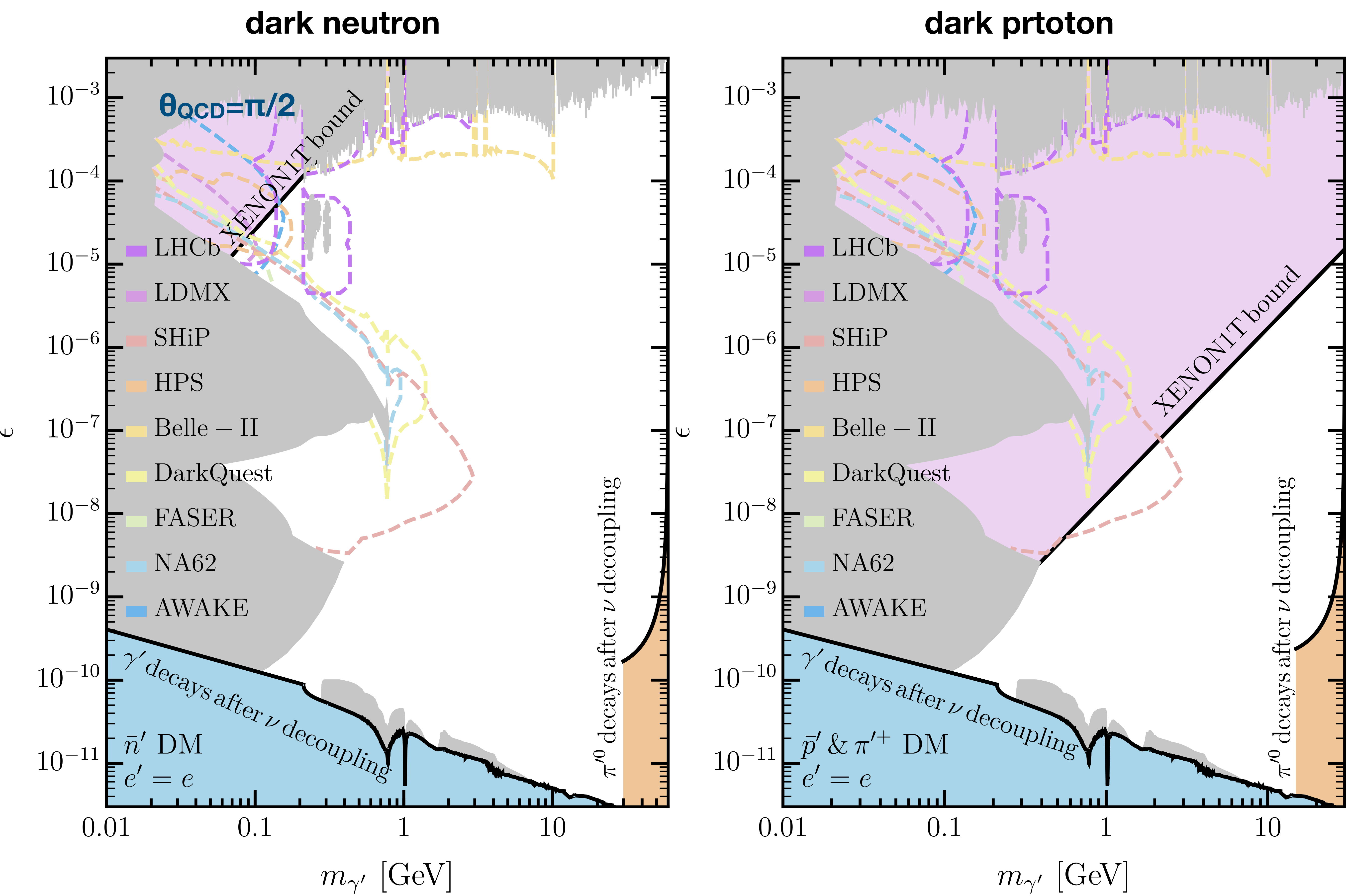
Higgs portal

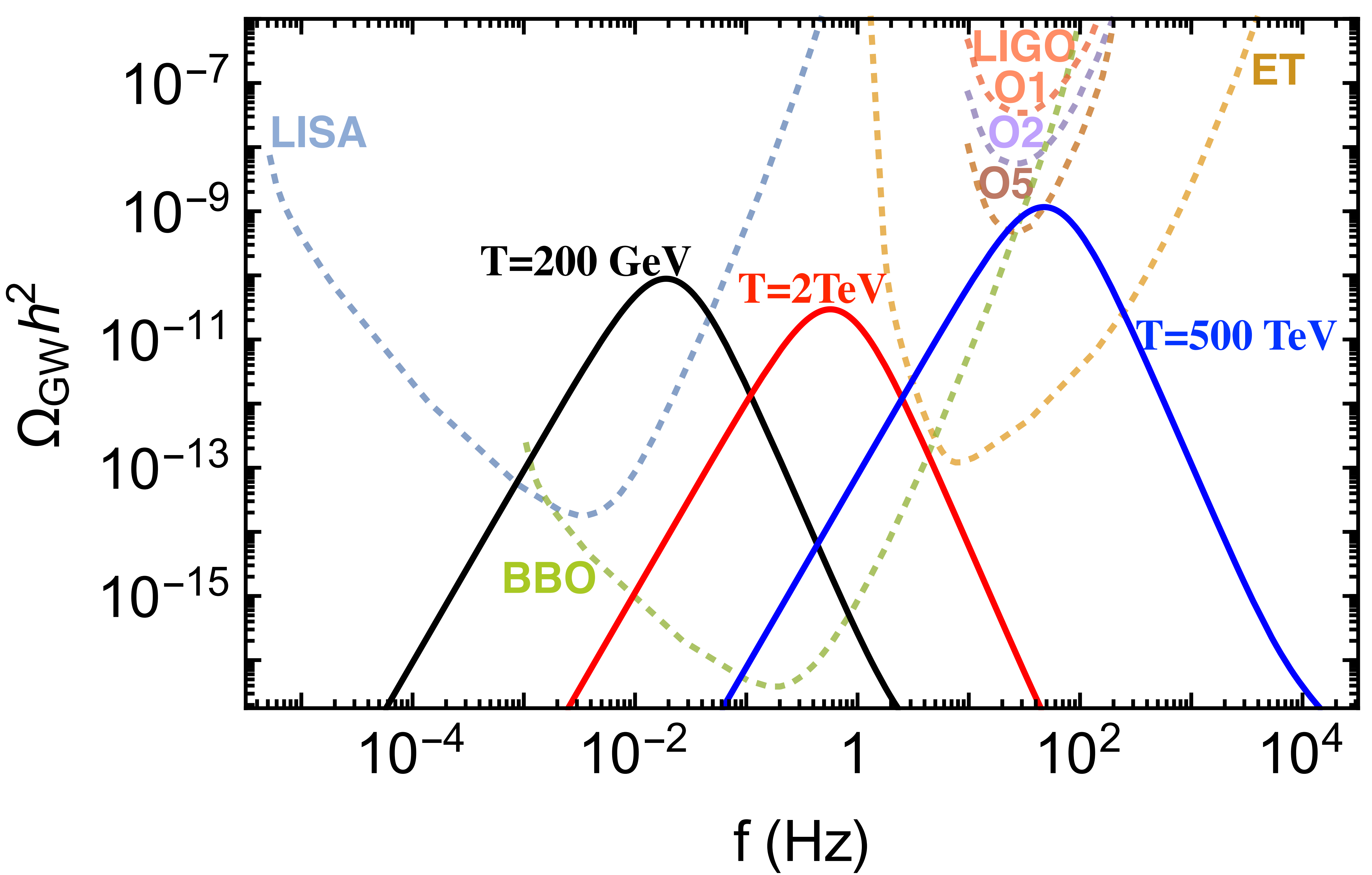




Dark Neutron Dark Matter
Dark Proton & Pion Dark Matter
θ_QCD~O(1)
dark n EDM
terrestrial
SN1987A
LHCb
Belle – II
AWAKE
HPS
SeaQuest
LDMX
FASER
NA62
SHiP
γ′ decays after ν decoupling
2m_γ′ ≤ m_π′0 ≲ 0.5m_n′
e′ = 0.01e
e′ = 0.1e
e′ = e XENON1T Migdal
e′ = e XENONnT
e′ = e DARWIN
m_γ′ [MeV]
10
100

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

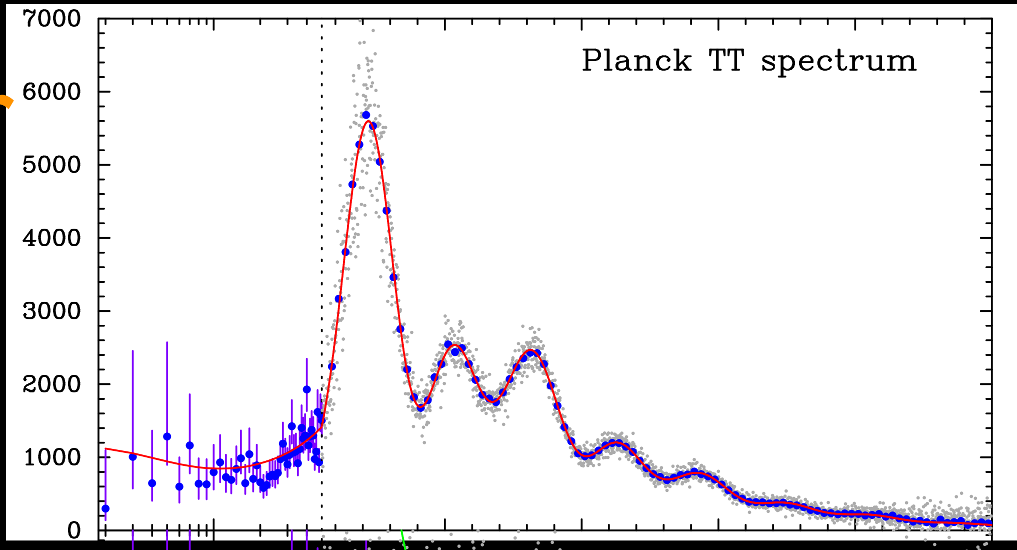




LIGO
O1
O2
O5
ET
LISA
BBO
T=200 GeV
T=2TeV
T=500 TeV
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
$\Omega_{GW}h^2$
10^{-4}
10^{-2}
1
10^{2}
10^{4}
f (Hz)

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!