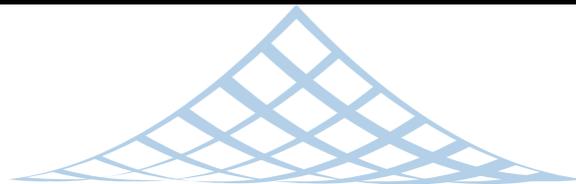


# New ideas and signatures in electroweak-scale model building

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



# no new physics

## ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: March 2017

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13$  TeV

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{miss}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference	
Inclusive Searches	MSUGRA/CMSSM	0-3 $e, \mu/1-2 \tau$	2-10 jets/3 $b$	Yes	20.3	$\tilde{q}, \tilde{g}$	1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	1.57 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(1^{st} \text{ gen. } \tilde{q})=m(2^{nd} \text{ gen. } \tilde{q})$	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$	608 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0) < 5$ GeV	1604.07773
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.02 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0 \rightarrow qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.01 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 $e, \mu$	4 jets	-	13.2	$\tilde{g}$	1.7 TeV	$m(\tilde{\chi}_1^0) < 400$ GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	2 $e, \mu$ (SS)	0-3 jets	Yes	13.2	$\tilde{g}$	1.6 TeV	$m(\tilde{\chi}_1^0) < 500$ GeV	ATLAS-CONF-2016-037
	GMSB ( $\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	3.2	$\tilde{g}$	2.0 TeV	$c\tau(\text{NLSP}) < 0.1$ mm	1607.05979
	GGM (bino NLSP)	2 $\gamma$	-	Yes	3.2	$\tilde{g}$	1.65 TeV	$m(\tilde{\chi}_1^0) < 950$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu < 0$	1606.09150
	GGM (higgsino-bino NLSP)	$\gamma$	1 $b$	Yes	20.3	$\tilde{g}$	37 TeV	$m(\tilde{\chi}_1^0) > 680$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu > 0$	1507.05493
GGM (higgsino-bino NLSP)	$\gamma$	2 jets	Yes	13.3	$\tilde{g}$	1.8 TeV	$m(\text{NLSP}) > 430$ GeV	ATLAS-CONF-2016-066	
GGM (higgsino NLSP)	2 $e, \mu$ (Z)	2 jets	Yes	20.3	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0) > 430$ GeV	1503.03290	
Gravitino LSP	0	mono-jet	Yes	20.3	$R^{1/2}$ scale	865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})=1.5$ TeV	1502.01518	
3 <sup>rd</sup> gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 $b$	Yes	36.1	$\tilde{g}$	1.92 TeV	$m(\tilde{\chi}_1^0) < 600$ GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 $e, \mu$	3 $b$	Yes	36.1	$\tilde{g}$	1.97 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^+$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$	37 TeV	$m(\tilde{\chi}_1^0) < 300$ GeV	1407.0600
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 $b$	Yes	3.2	$\tilde{b}_1$	840 GeV	$m(\tilde{\chi}_1^0) < 100$ GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm$	2 $e, \mu$ (SS)	1 $b$	Yes	13.2	$\tilde{b}_1$	325-685 GeV	$m(\tilde{\chi}_1^0) < 150$ GeV, $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_1^0) + 100$ GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$	0-2 $e, \mu$	1-2 $b$	Yes	4.7/13.3	$\tilde{t}_1$	117-170 GeV	$m(\tilde{\chi}_1^\pm) = 2m(\tilde{\chi}_1^0)$ , $m(\tilde{\chi}_1^0) = 55$ GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $\tilde{t}\tilde{t}^0$	0-2 $e, \mu$	0-2 jets/1-2 $b$	Yes	20.3	$\tilde{t}_1$	90-198 GeV	$m(\tilde{\chi}_1^0) = 1$ GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	$\tilde{t}_1$	90-323 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0) = 5$ GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 $e, \mu$ (Z)	1 $b$	Yes	20.3	$\tilde{t}_1$	150-600 GeV	$m(\tilde{\chi}_1^0) > 150$ GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu$ (Z)	1 $b$	Yes	36.1	$\tilde{t}_2$	290-790 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	ATLAS-CONF-2017-019
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 $e, \mu$	4 $b$	Yes	36.1	$\tilde{t}_2$	320-880 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	ATLAS-CONF-2017-019	
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$	0	Yes	20.3	$\tilde{\ell}$	90-335 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	1403.5294
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu(\tilde{\ell}\bar{\nu})$	2 $e, \mu$	0	Yes	13.3	$\tilde{\chi}_1^\pm$	640 GeV	$m(\tilde{\chi}_1^\pm) = 0$ GeV, $m(\tilde{\ell}, \bar{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2016-096
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu(\tilde{\tau}\bar{\nu})$	2 $\tau$	-	Yes	14.8	$\tilde{\chi}_1^\pm$	580 GeV	$m(\tilde{\chi}_1^\pm) = 0$ GeV, $m(\tilde{\tau}, \bar{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2016-093
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \rightarrow \tilde{\ell}_L\nu\tilde{\ell}_L, \tilde{\ell}(\bar{\nu}\nu), \tilde{\ell}\bar{\nu}\tilde{\ell}_L, \tilde{\ell}(\bar{\nu}\nu)$	3 $e, \mu$	0	Yes	13.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	1.0 TeV	$m(\tilde{\chi}_1^\pm) = 0$ , $m(\tilde{\ell}, \bar{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2016-096
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 $e, \mu$	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	425 GeV	$m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0)$ , $m(\tilde{\chi}_1^0) = 0$ , $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0h, \tilde{h} \rightarrow b\tilde{b}/WW/\tau\tau/\gamma\gamma$	$e, \mu, \gamma$	0-2 $b$	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	270 GeV	$m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0)$ , $m(\tilde{\chi}_1^0) = 0$ , $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0 \rightarrow \tilde{\ell}_R\tilde{\ell}$	4 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_2^0, \tilde{\chi}_3^0$	635 GeV	$m(\tilde{\chi}_1^0) = 0$ , $m(\tilde{\ell}, \bar{\nu}) = 0.5(m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0))$	1405.5086
	GGM (wino NLSP) weak prod.	1 $e, \mu + \gamma$	-	Yes	20.3	$\tilde{W}$	115-370 GeV	$c\tau < 1$ mm	1507.05493
GGM (bino NLSP) weak prod.	2 $\gamma$	-	Yes	20.3	$\tilde{W}$	590 GeV	$c\tau < 1$ mm	1507.05493	
Long-lived particles	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$	430 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0) \sim 160$ MeV, $\tau(\tilde{\chi}_1^\pm) = 0.2$ ns	ATLAS-CONF-2017-017
	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$	495 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0) \sim 160$ MeV, $\tau(\tilde{\chi}_1^\pm) < 15$ ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	850 GeV	$m(\tilde{\chi}_1^0) = 100$ GeV, $10 \mu\text{s} < \tau(\tilde{g}) < 1000$ s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$	1.58 TeV	-	1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$	1.57 TeV	$m(\tilde{\chi}_1^0) = 100$ GeV, $\tau > 10$ ns	1604.04520
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{\ell}, \bar{\mu}) + \tau(e, \mu)$	1-2 $\mu$	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	$10 < \tan\beta < 50$	1411.6795
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ , long-lived $\tilde{\chi}_1^0$	2 $\gamma$	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	$1 < \tau(\tilde{\chi}_1^0) < 3$ ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$7 < c\tau(\tilde{\chi}_1^0) < 740$ mm, $m(\tilde{g}) = 1.3$ TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$6 < c\tau(\tilde{\chi}_1^0) < 480$ mm, $m(\tilde{g}) = 1.1$ TeV	1504.05162
	RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\epsilon\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	$\lambda'_{311} = 0.11, \lambda_{132/133/233} = 0.07$
Bilinear RPV CMSSM		2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{q}, \tilde{g}$	1.45 TeV	$m(\tilde{q}) = m(\tilde{g})$ , $c\tau_{LSP} < 1$ mm	1404.2500
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow ee\nu, e\mu\nu, \mu\mu\nu$		4 $e, \mu$	-	Yes	13.3	$\tilde{\chi}_1^\pm$	1.14 TeV	$m(\tilde{\chi}_1^0) > 400$ GeV, $\lambda_{12k} \neq 0$ ( $k = 1, 2$ )	ATLAS-CONF-2016-075
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tau\nu_e, e\tau\nu_\tau$		3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$	450 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_1^\pm)$ , $\lambda_{133} \neq 0$	1405.5086
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{q}$		0	4-5 large- $R$ jets	-	14.8	$\tilde{g}$	1.08 TeV	$BR(\tilde{g}) = BR(\tilde{b}) = BR(\tilde{c}) = 0\%$	ATLAS-CONF-2016-057
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{q}, \tilde{\chi}_1^0 \rightarrow qq\tilde{q}$		0	4-5 large- $R$ jets	-	14.8	$\tilde{g}$	1.55 TeV	$m(\tilde{\chi}_1^0) = 800$ GeV	ATLAS-CONF-2016-057
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{q}$		1 $e, \mu$	8-10 jets/0-4 $b$	-	36.1	$\tilde{g}$	2.1 TeV	$m(\tilde{\chi}_1^0) = 1$ TeV, $\lambda_{112} \neq 0$	ATLAS-CONF-2017-013
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$		1 $e, \mu$	8-10 jets/0-4 $b$	-	36.1	$\tilde{g}$	1.65 TeV	$m(\tilde{t}_1) = 1$ TeV, $\lambda_{323} \neq 0$	ATLAS-CONF-2017-013
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$		0	2 jets + 2 $b$	-	15.4	$\tilde{t}_1$	410 GeV	$BR(\tilde{t}_1 \rightarrow b\ell/\mu) > 20\%$	ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\ell$		2 $e, \mu$	2 $b$	-	20.3	$\tilde{t}_1$	0.4-1.0 TeV	-	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 $c$	Yes	20.3	$\tilde{c}$	510 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV	1501.01325

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10<sup>-1</sup> 1 Mass scale [TeV]

"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 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.

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## SQUARK MASS

<u>VALUE (GeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>538±10</b>	<b>OUR FIT</b>		<b>mSUGRA assumptions</b>
532±11	<sup>1</sup> ABBIENDI 11D	CMS	Missing ET with mSUGRA assumptions
541±14	<sup>2</sup> ADLER 110	ATLAS	Missing ET with mSUGRA assumptions
••• We do not use the following data for averages, fits, limits, etc •••			
652±105	<sup>3</sup> ABBIENDI 11K	CMS	extended mSUGRA with 5 more parameters

# The New York Times

July 23, 2011

## The Other Half of the Universe Discovered

Geneva, Switzerland

<sup>1</sup>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.

<sup>2</sup>ADLER 110 uses the same set of assumptions as ABBIENDI 11D, but with  $\tan\beta = 5$ .

<sup>3</sup>ABBIENDI 11K extends minimal supergravity by allowing for different scalar masses-squared for  $H_u$ ,  $H_d$ ,  $5^*$  and 10 scalars at the GUT scale.

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## SQUARK DECAY MODES

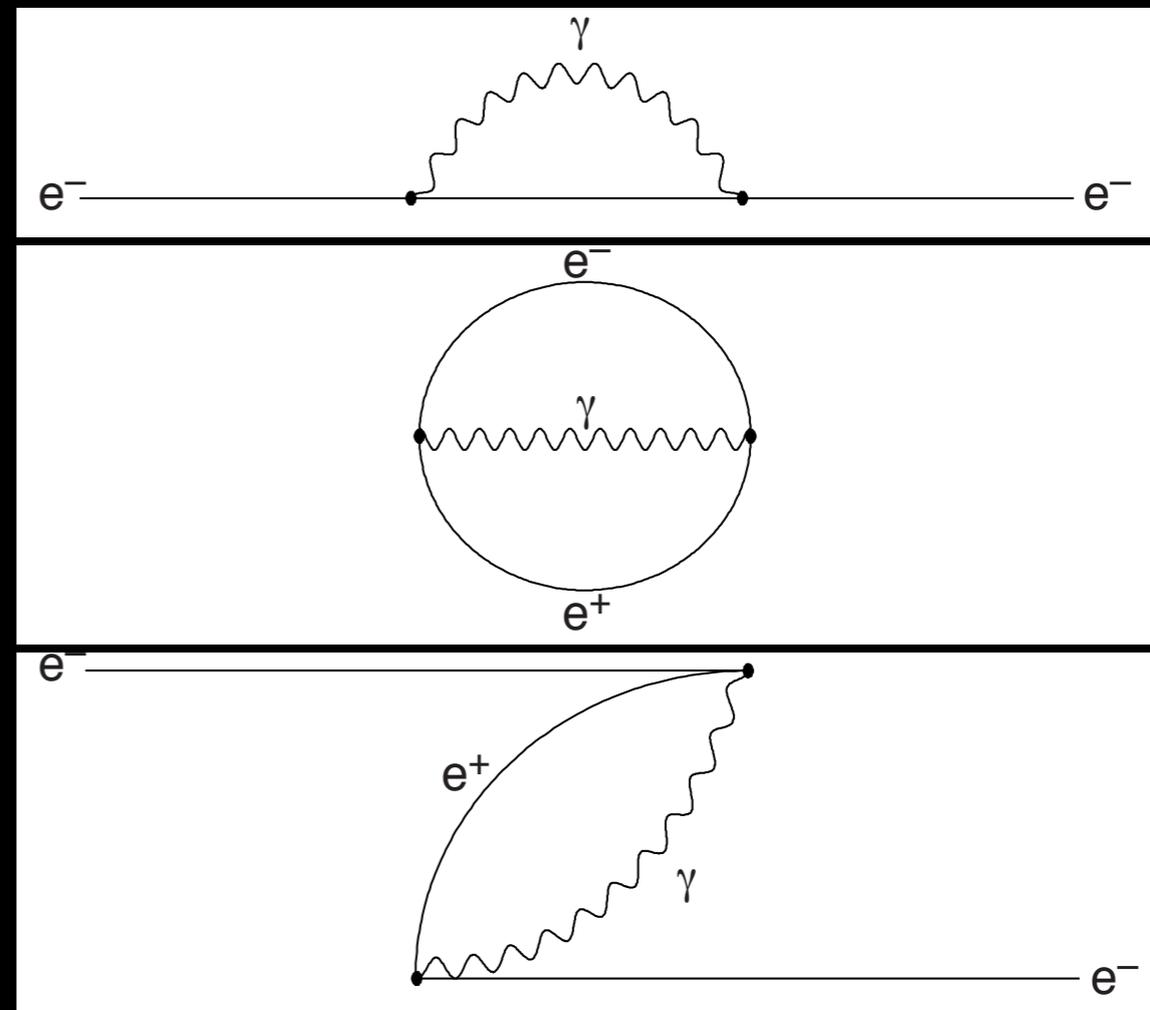
<u>MODE</u>	<u>BR(%)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
j+miss	32±5	ABE 10U	ATLAS	
j l+miss	73±10	ABE 10U	ATLAS	lepton universality
j e+miss	22±8	ABE 10U	ATLAS	
j $\mu$ +miss	25±7	ABE 10U	ATLAS	
q $\chi^+$	seen	ABE 10U	ATLAS	

# Electron mass is natural by doubling #particles

- Electron creates a force to repel itself

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

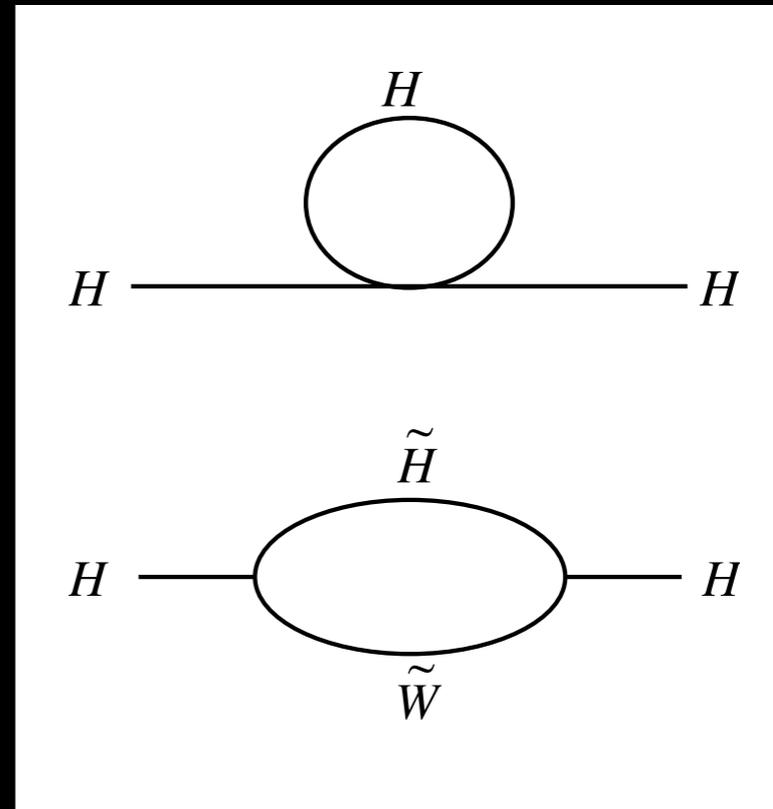
- $10^{-4}$  fine-tuning?
  - quantum mechanics and anti-matter
- ⇒ only 10% of mass even  
for Planck-size  $r_e \sim 10^{-33} \text{cm}$



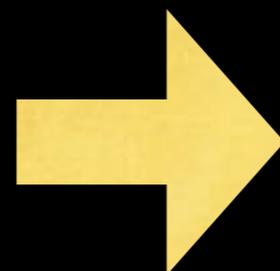
$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

# Higgs mass is natural by doubling #particles?

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



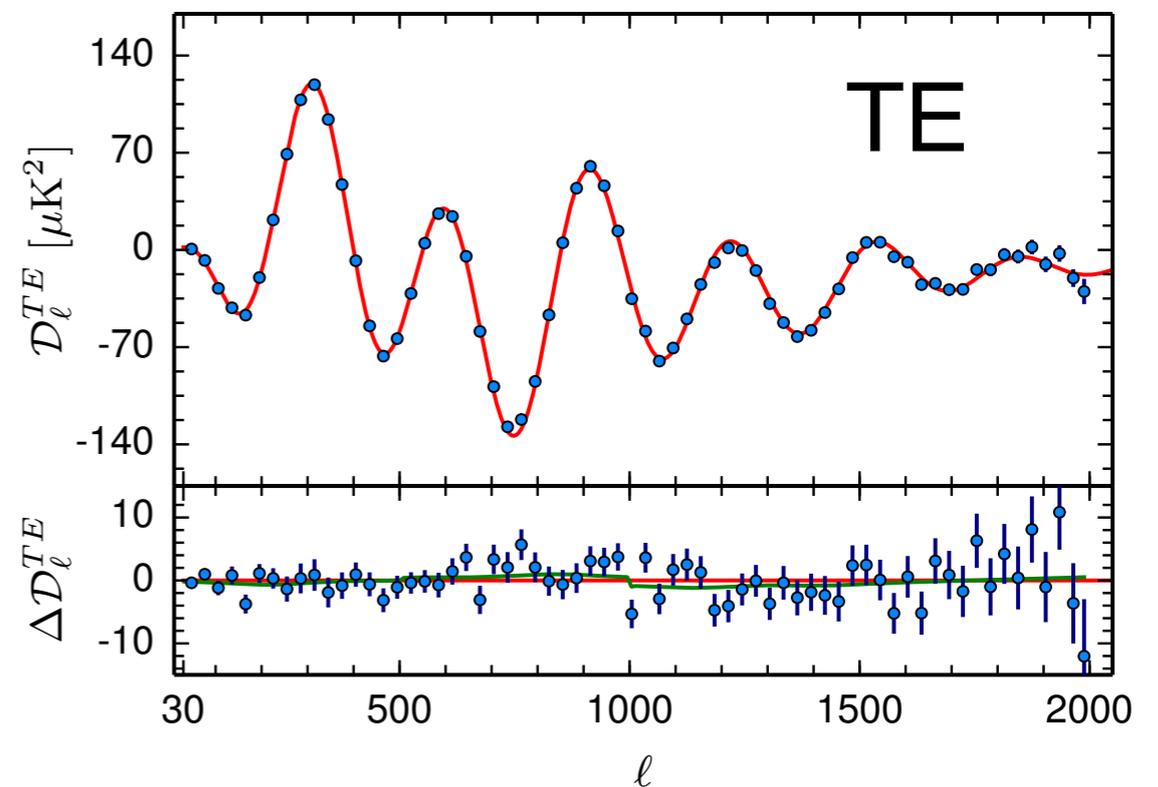
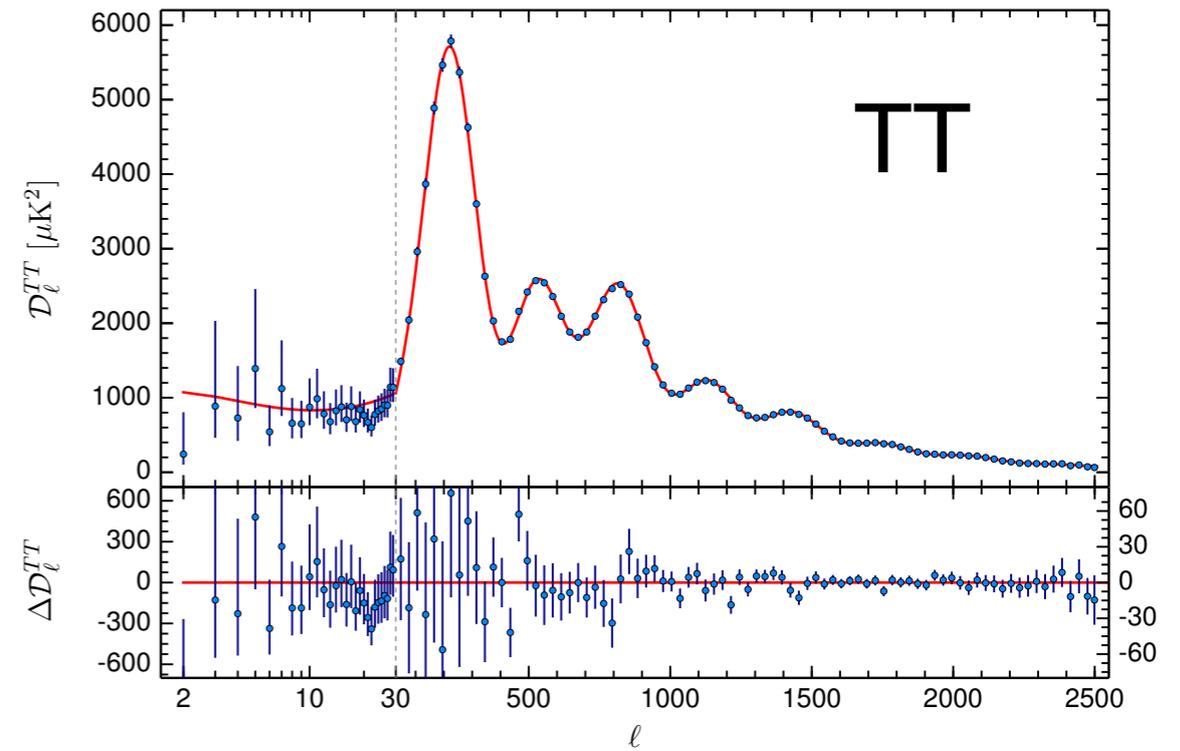
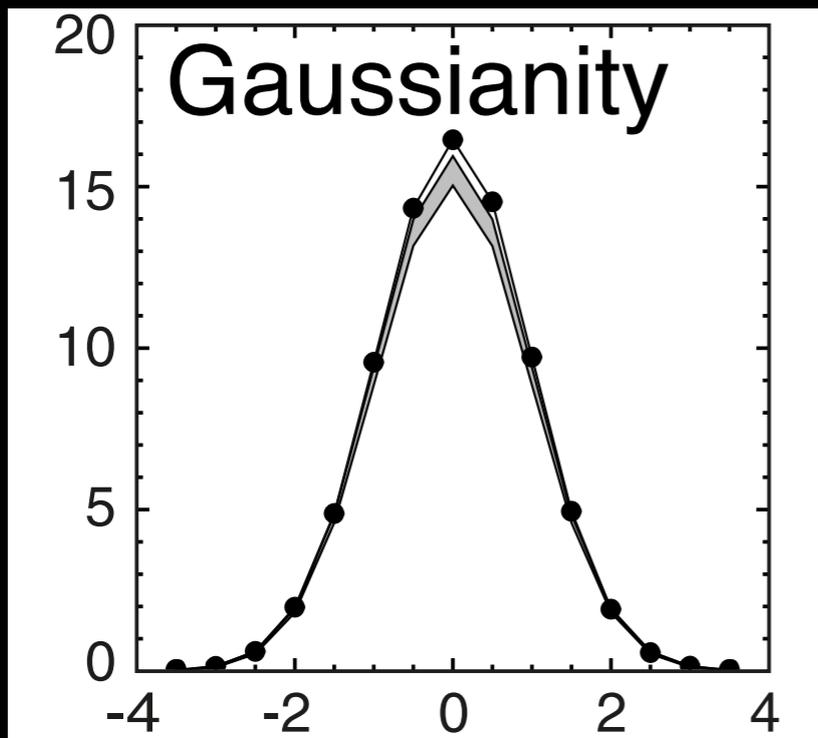
$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$



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

IF SUPERSYMMETRY

# CRISIS

DOESN'T PAN OUT,

# IN

SCIENTISTS NEED A NEW WAY

# PHYSICS

TO EXPLAIN THE UNIVERSE

# ?



\$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.

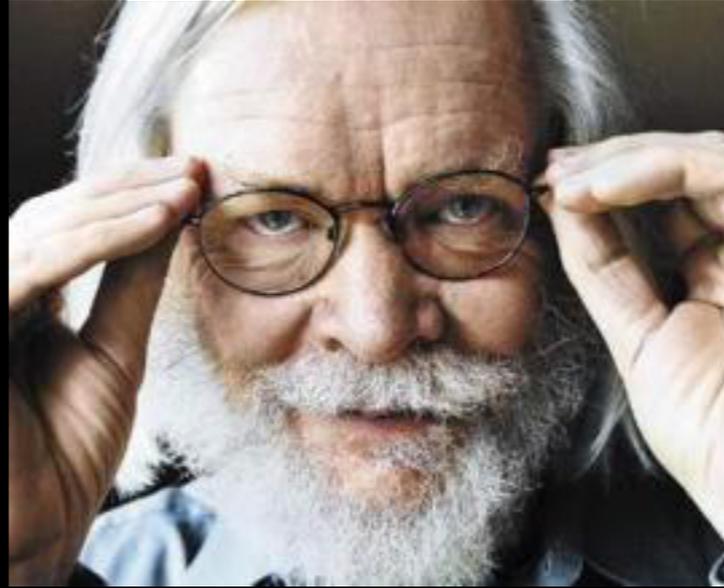
Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a \$65 million detector weighing as

R-parity violation  
compressed spectrum  
disappearing tracks  
clever analysis



RIS	A 30	12:40	DELAYED
NKFURT	B 01	12:40	DELAYED
YORK	A 19	12:45	DELAYED
SELS	B 13	12:45	DELAYED
N	A 26	12:50	DELAYED
V	A 37	13:00	DELAYED
JANEIRO	A 40	13:00	DELAYED
M	A 28	13:10	DELAYED
	A 34	13:15	DELAYED
	A 22	13:20	DELAYED
	B 09	13:30	DELAYED
	A 27	13:30	DELAYED

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



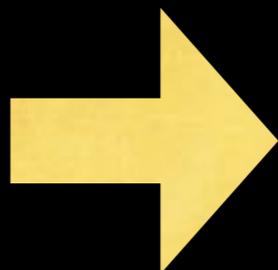
# Better Late Than Never

Even  $m_{\text{SUSY}} \sim 10 \text{ TeV}$  ameliorates fine-tuning  
from  $10^{-36}$  to  $10^{-4}$

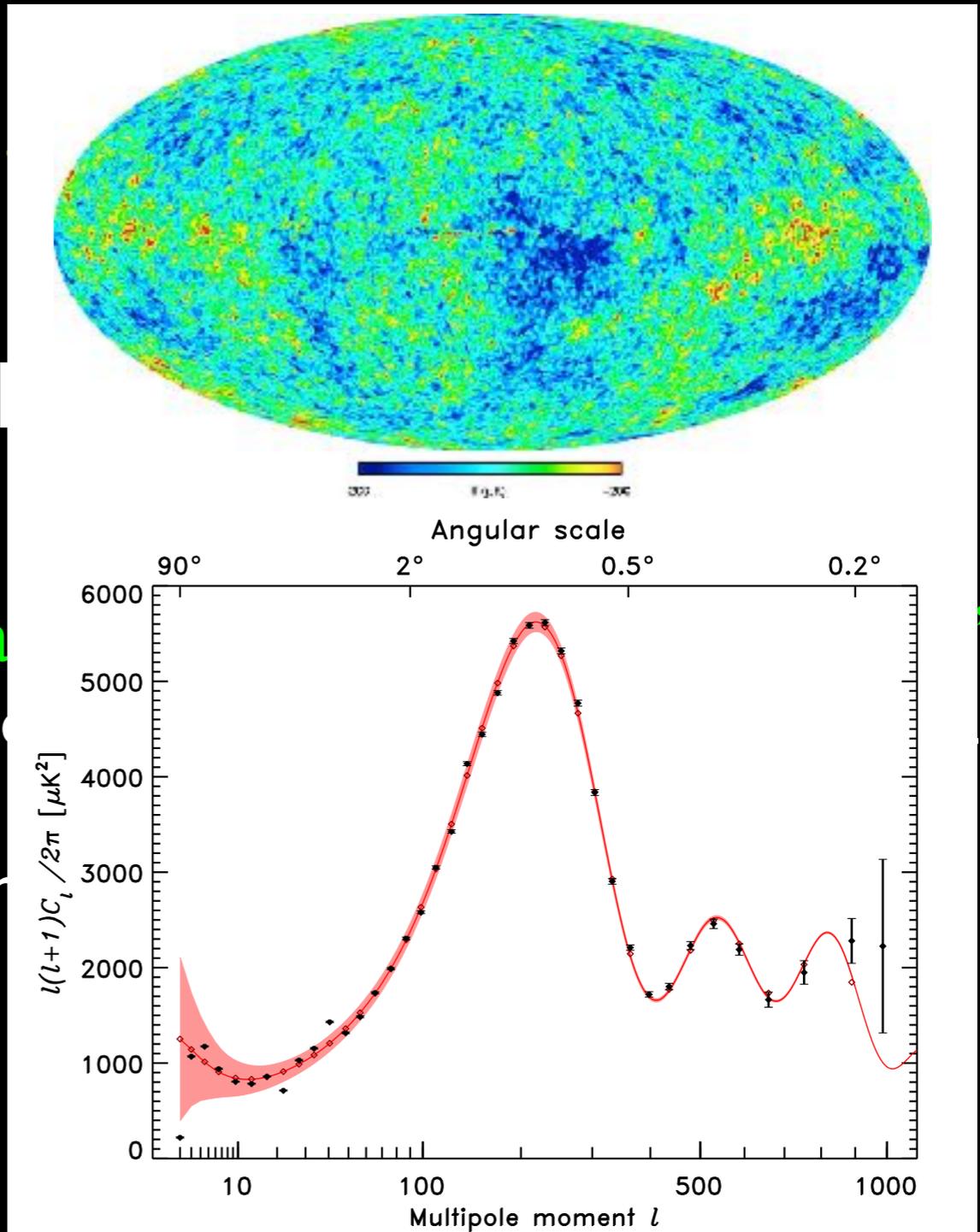
# been there before

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

1% tuning



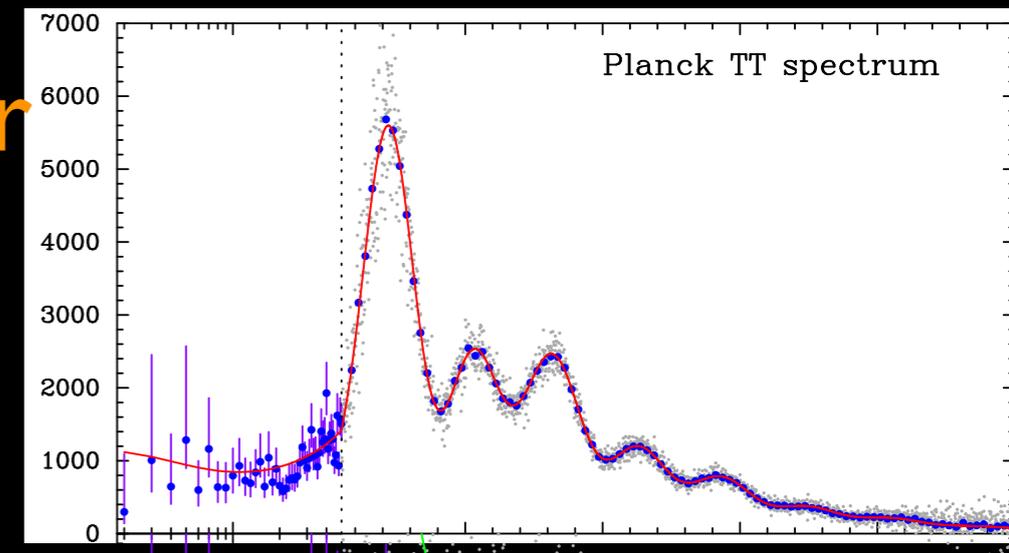
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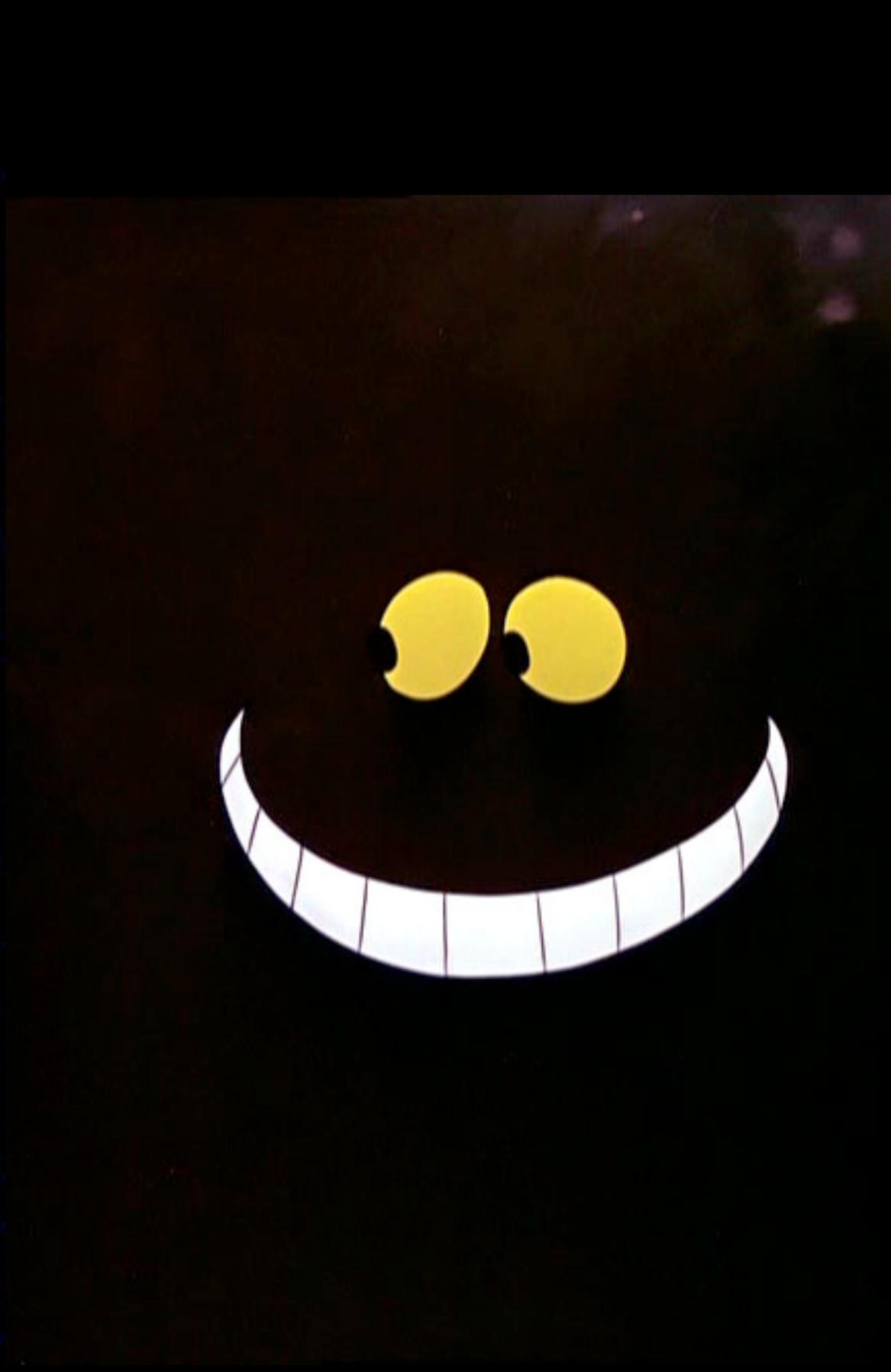
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# Five empirical evidences for physics beyond SM

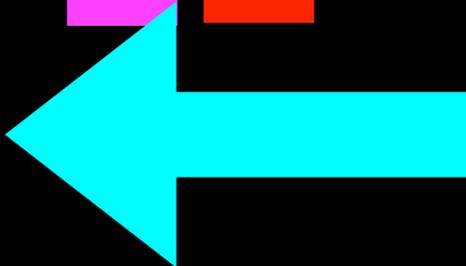
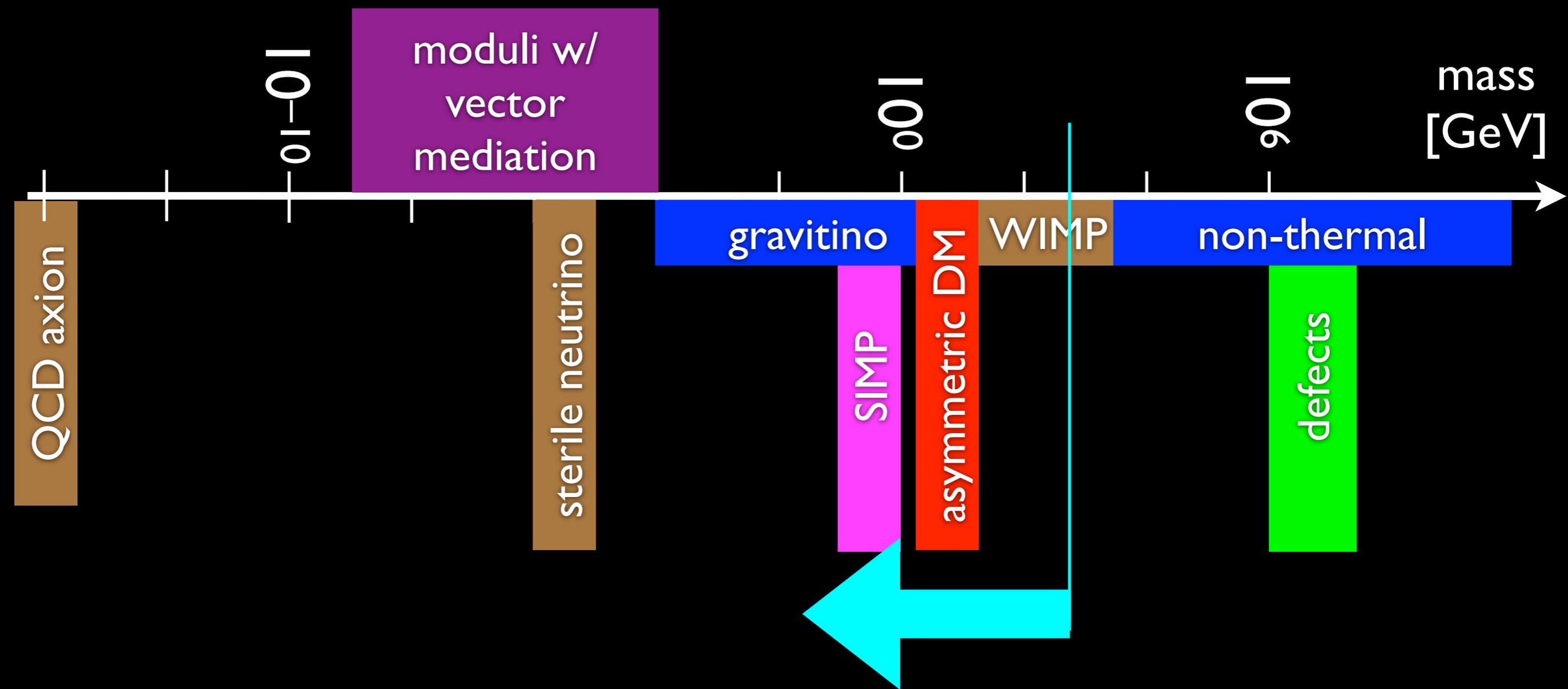
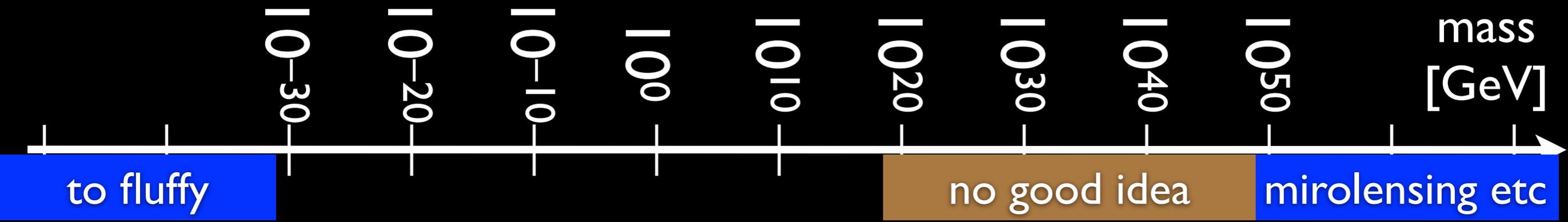
- Since 1998, it became clear that there are **at least five missing pieces in the SM**
  - **non-baryonic dark matter**
  - **neutrino mass**
  - **dark energy**
  - **apparently acausal density fluctuations**
  - **baryon asymmetry**



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

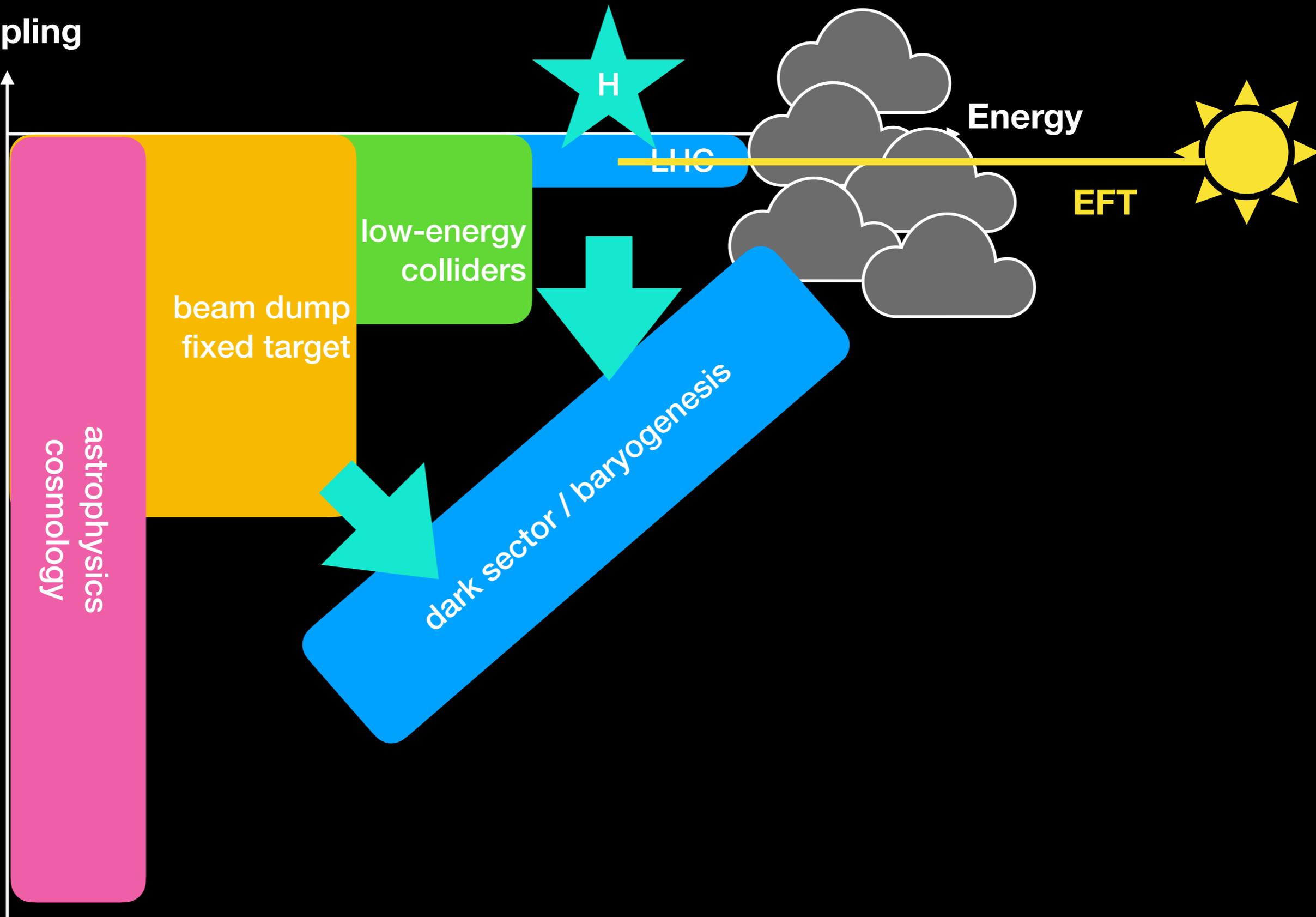


Ceshire cat



# another axis

Coupling

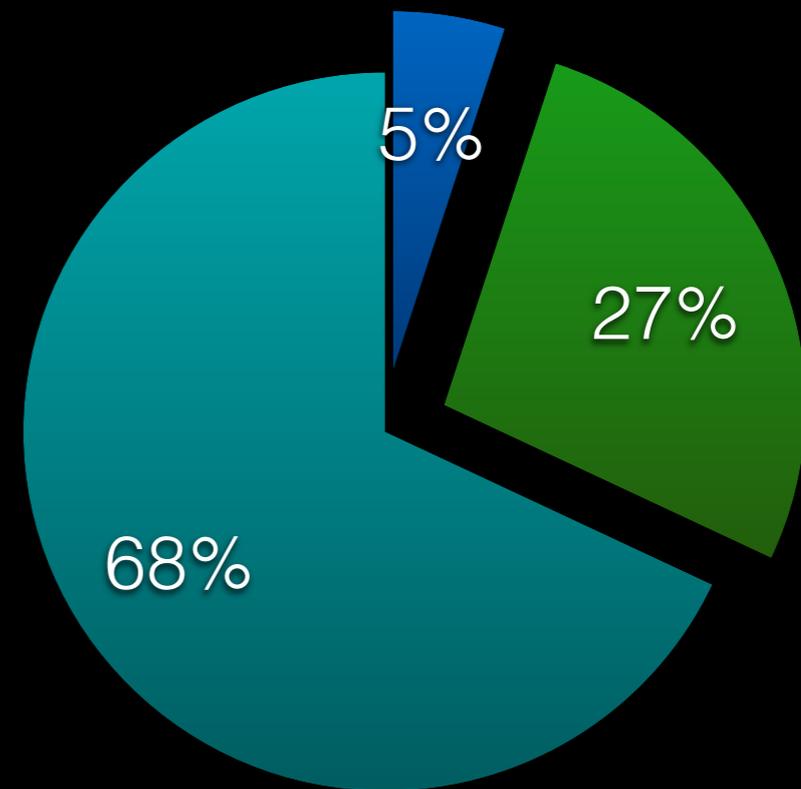


# dark baryon asymmetric dark matter

Hitoshi Murayama (Berkeley, Kavli IPMU)  
+Neil Hall (Berkeley), Thomas Konstandin  
(DESY), Robert McGehee (Berkeley)  
arXiv:1910.08068, 1911.12342, 2107.03398

# 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

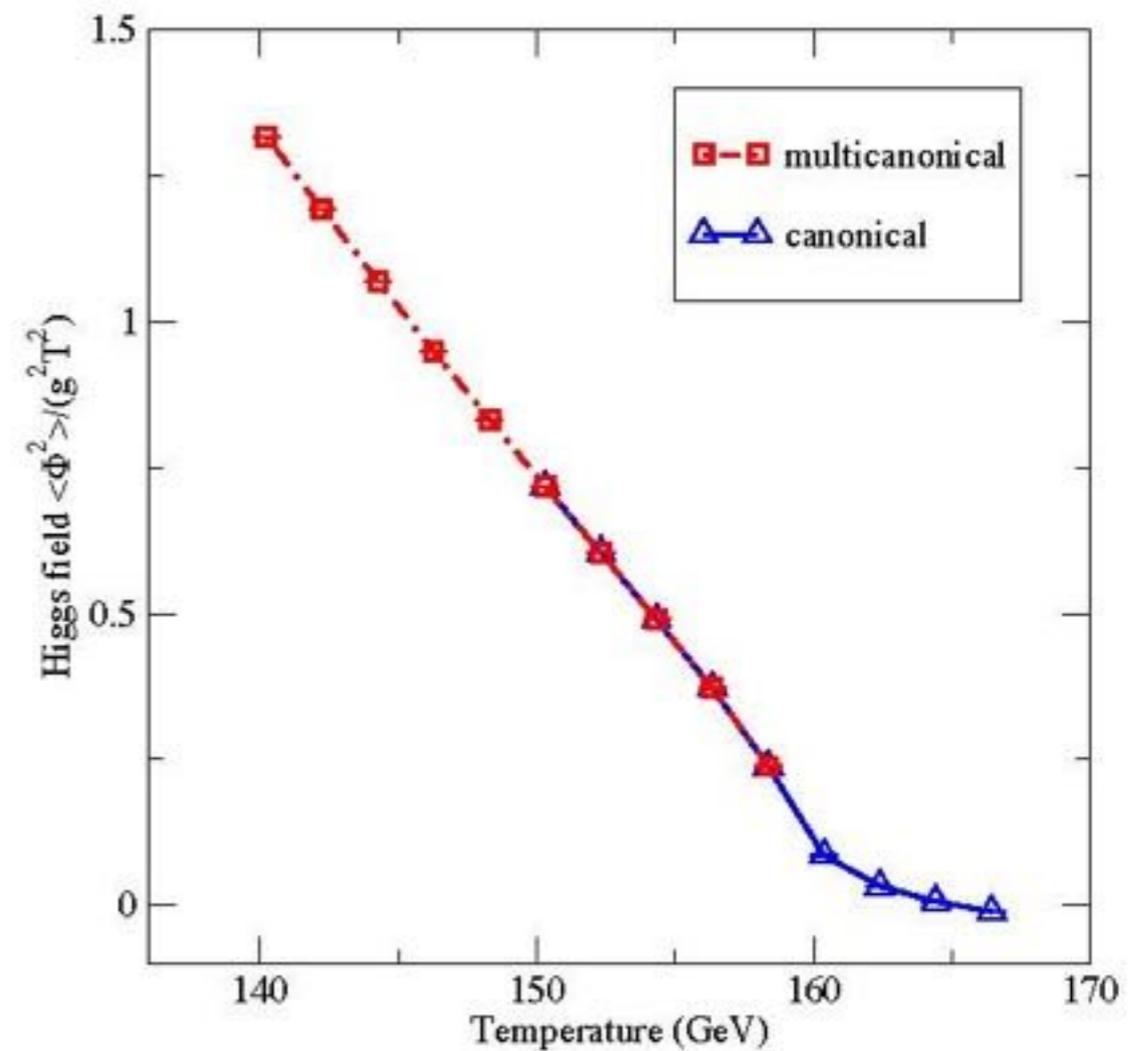
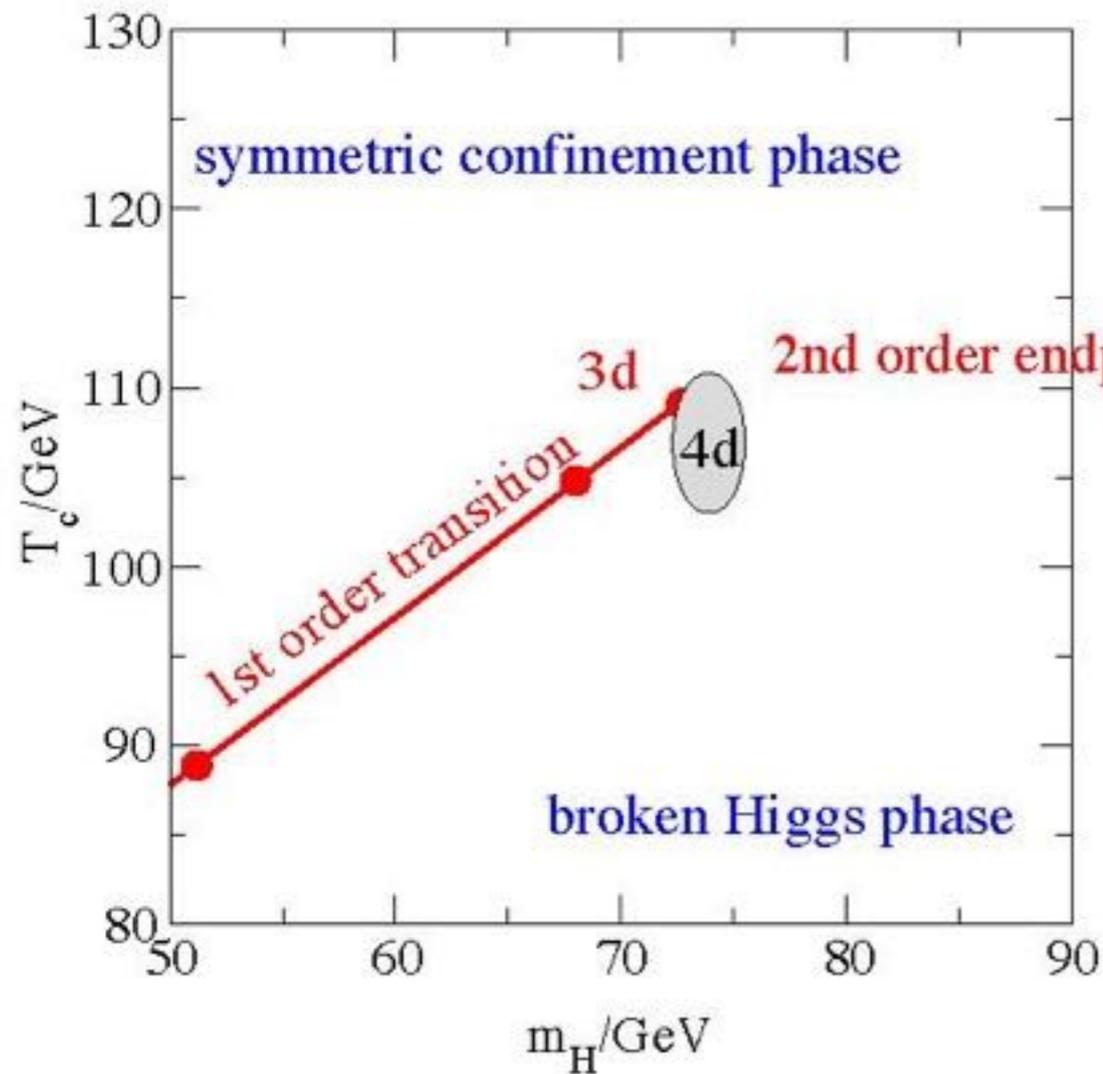
- **Departure from equilibrium**  $J \propto \det[M_u^\dagger M_u, M_d^\dagger M_d] / T_{EW}^{12} \sim 10^{-20} \ll 10^{-10}$

- First-order phase transition of Higgs

**requires  $m_h < 75$  GeV**

- Experimentally testable?

# Phase diagram for the Standard Model:



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

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

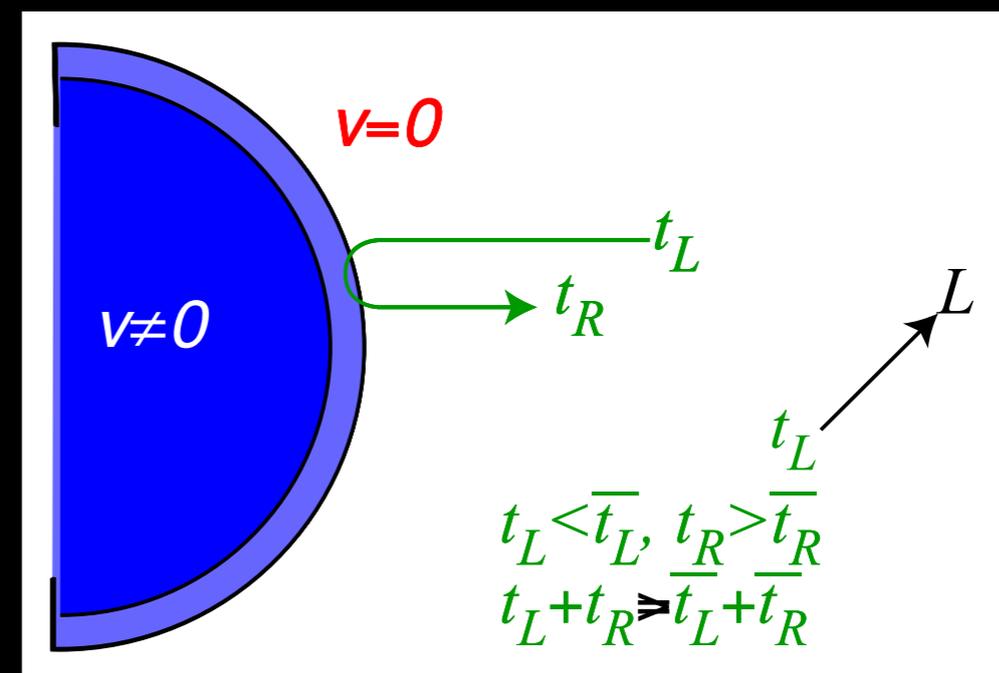
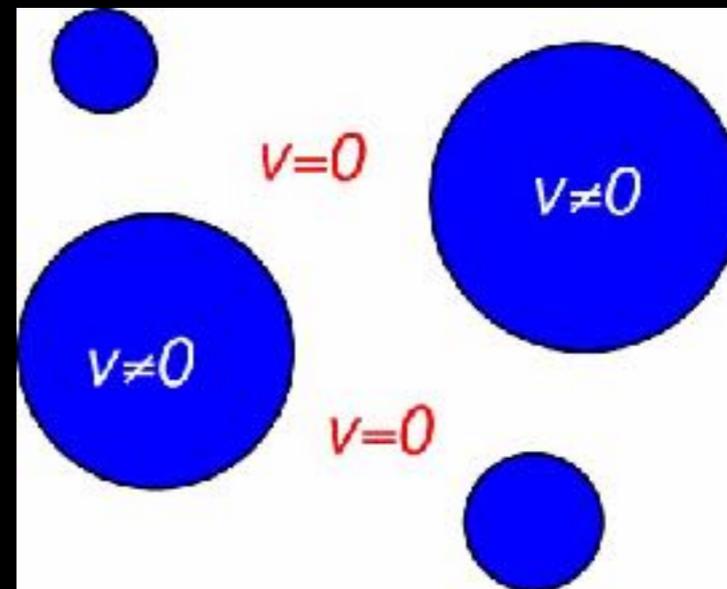
for  $m_h = 125$  GeV, it is crossover

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

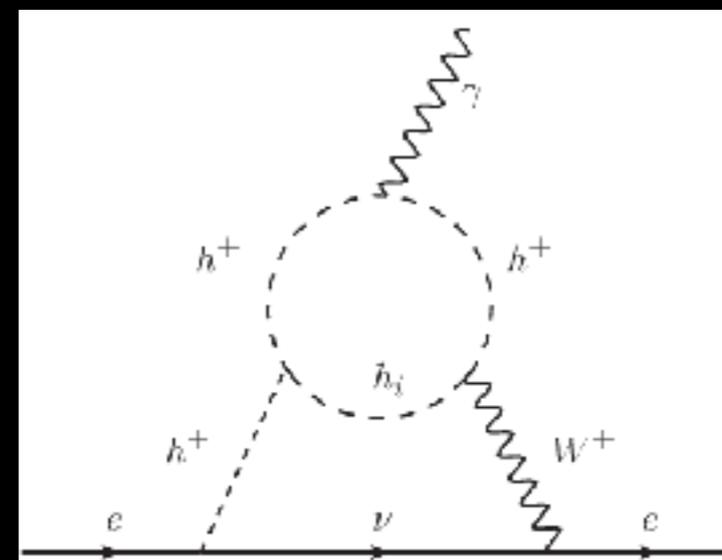
<https://doi.org/10.1038/s41586-018-0599-8>

## Improved limit on the electric dipole moment of the electron

ACME Collaboration\*

- 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  $\times$  efficiency  $\geq 10^{-3}$

$$d_e \leq 1.1 \times 10^{-29} \text{ e cm}$$

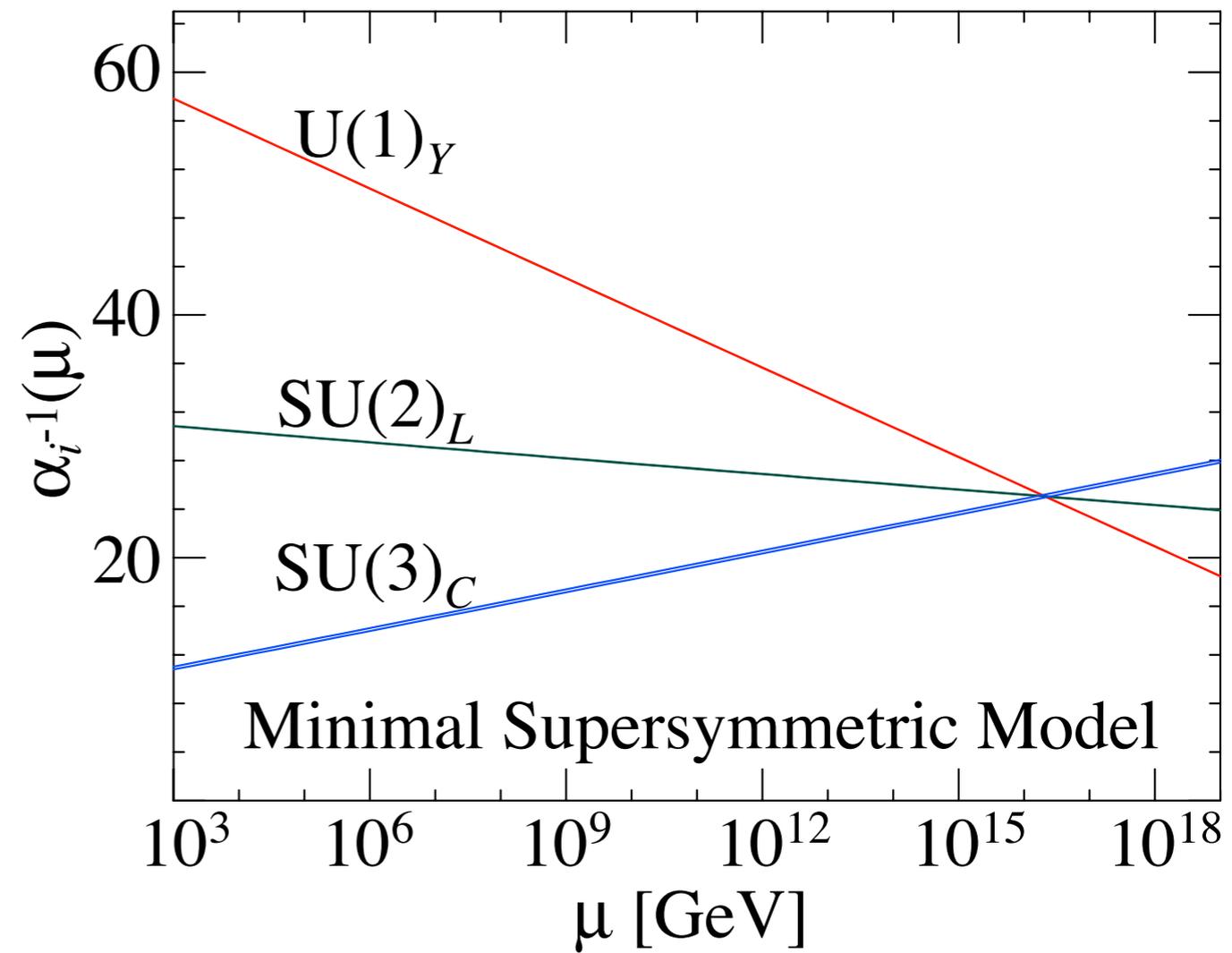
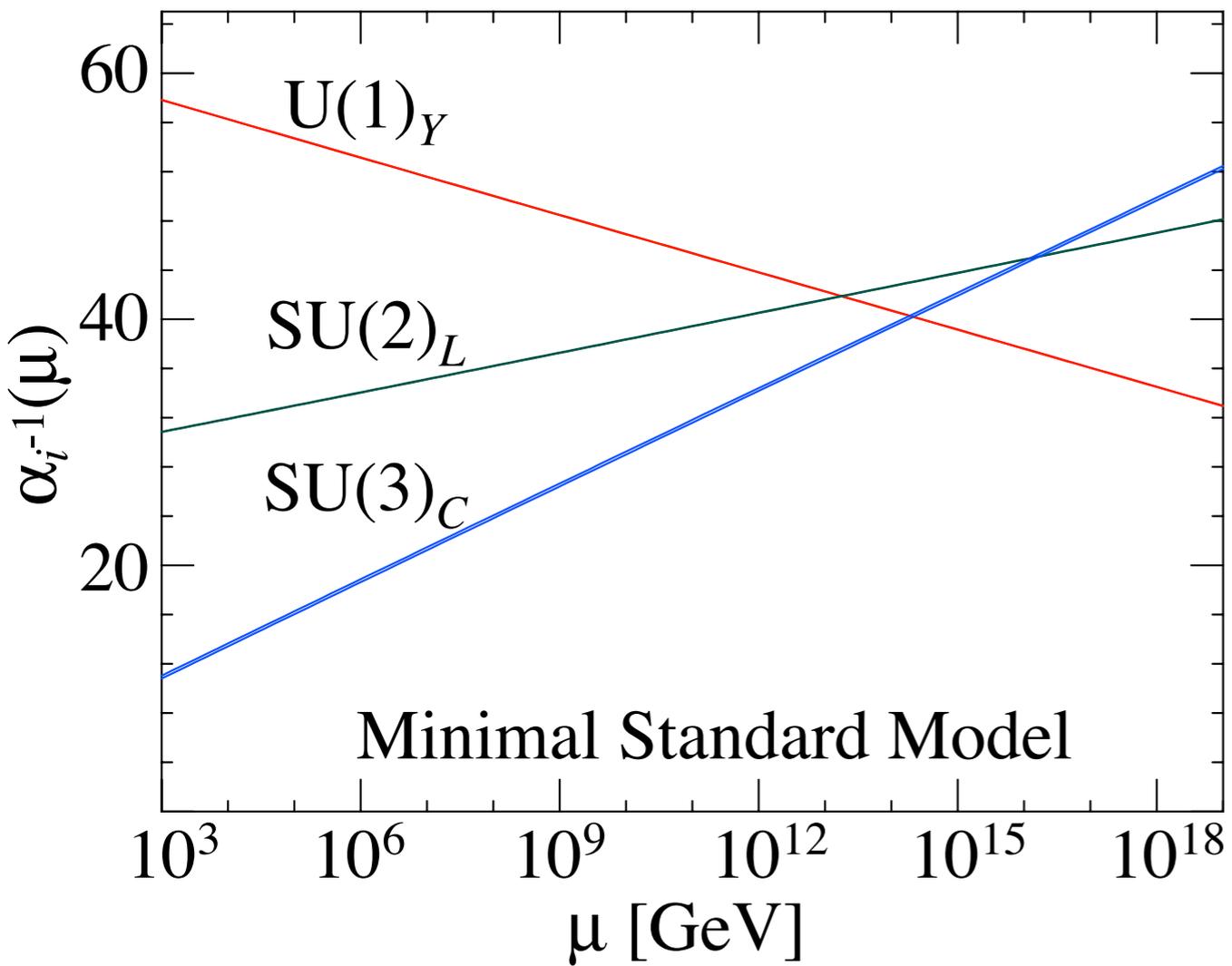


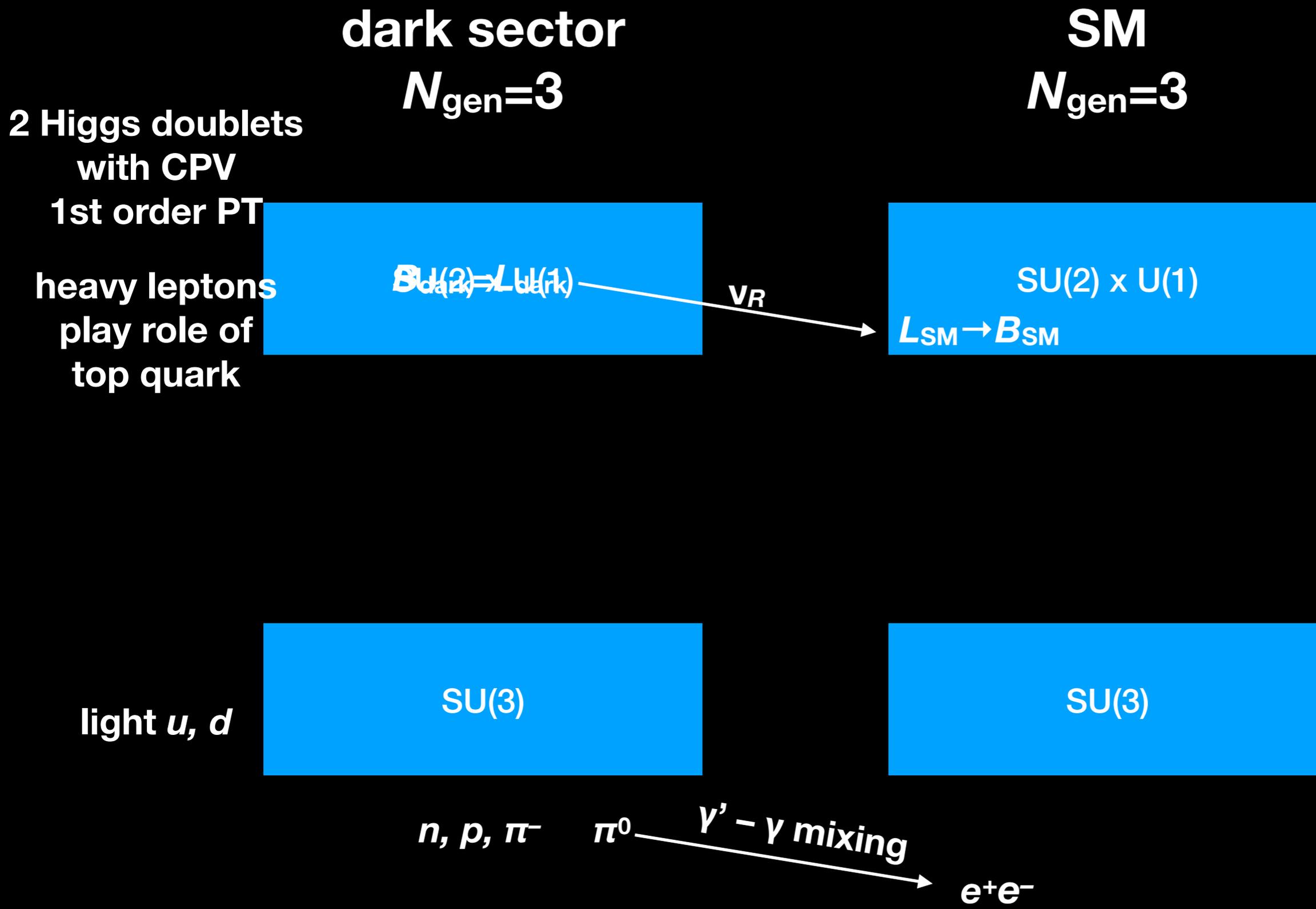
Barr-Zee diagrams

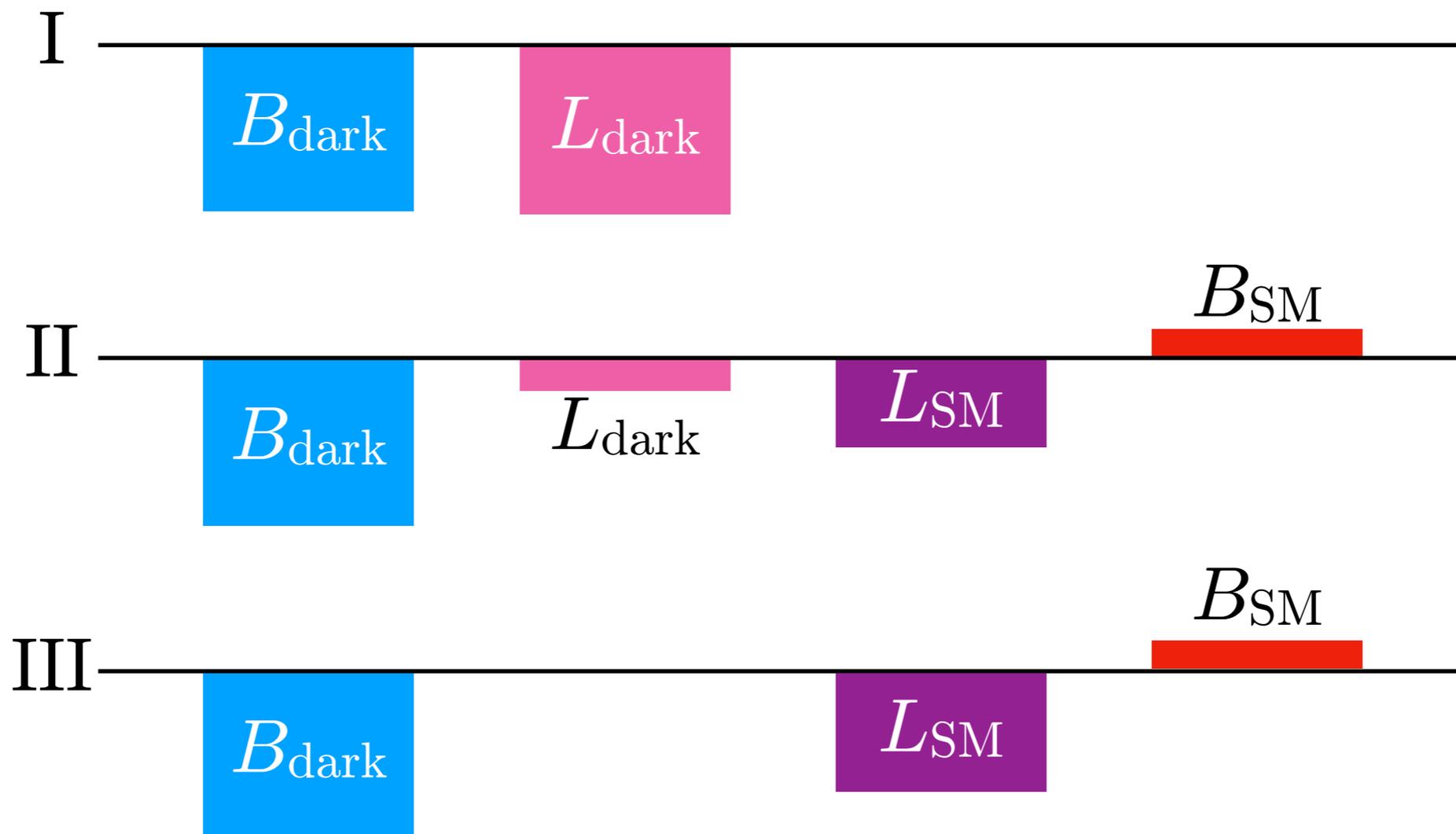
$$d_e \approx \frac{em_e}{(16\pi^2)^2} \frac{1}{v^2} \sin \delta = 1.6 \times 10^{-22} \text{ e cm} \sin \delta$$

# couplings

- unify or not, they start out similar





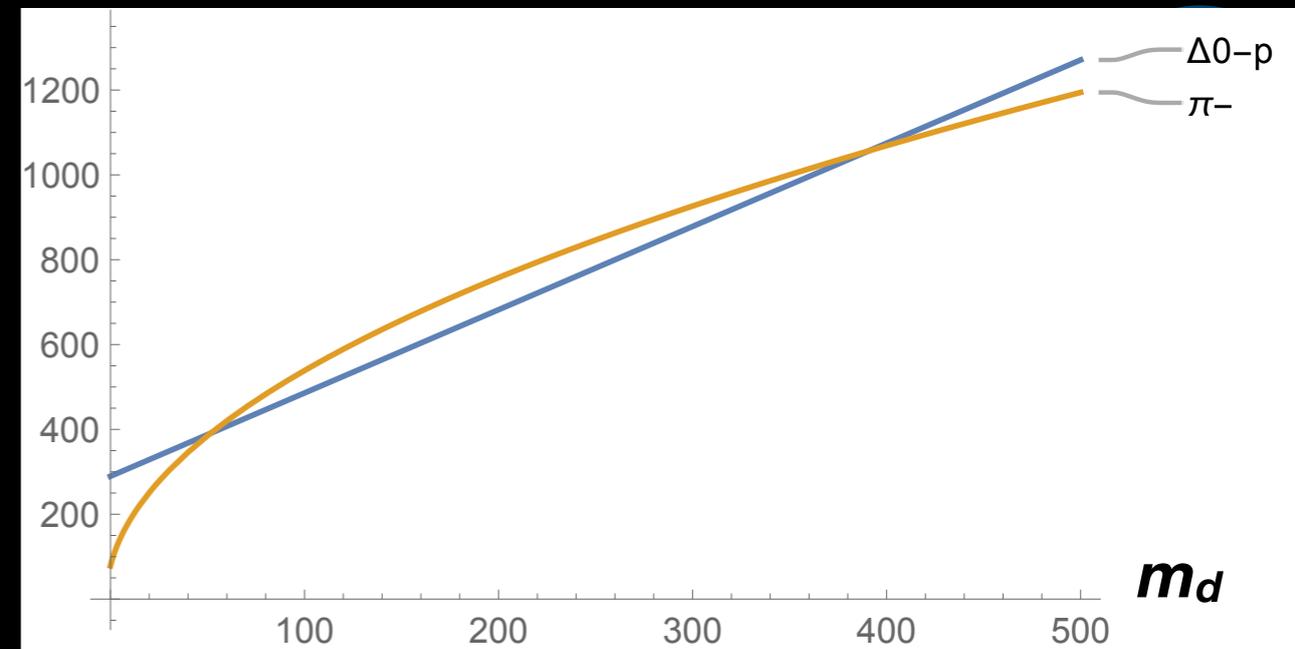


**If  $M_N > T_{\text{sphaleron}}$**   $B_{\text{SM}} = \frac{36}{133} B_{\text{dark}},$   $L_{\text{SM}} = -\frac{97}{133} B_{\text{dark}}$   $m_{n'} = 1.63 \text{ GeV}$

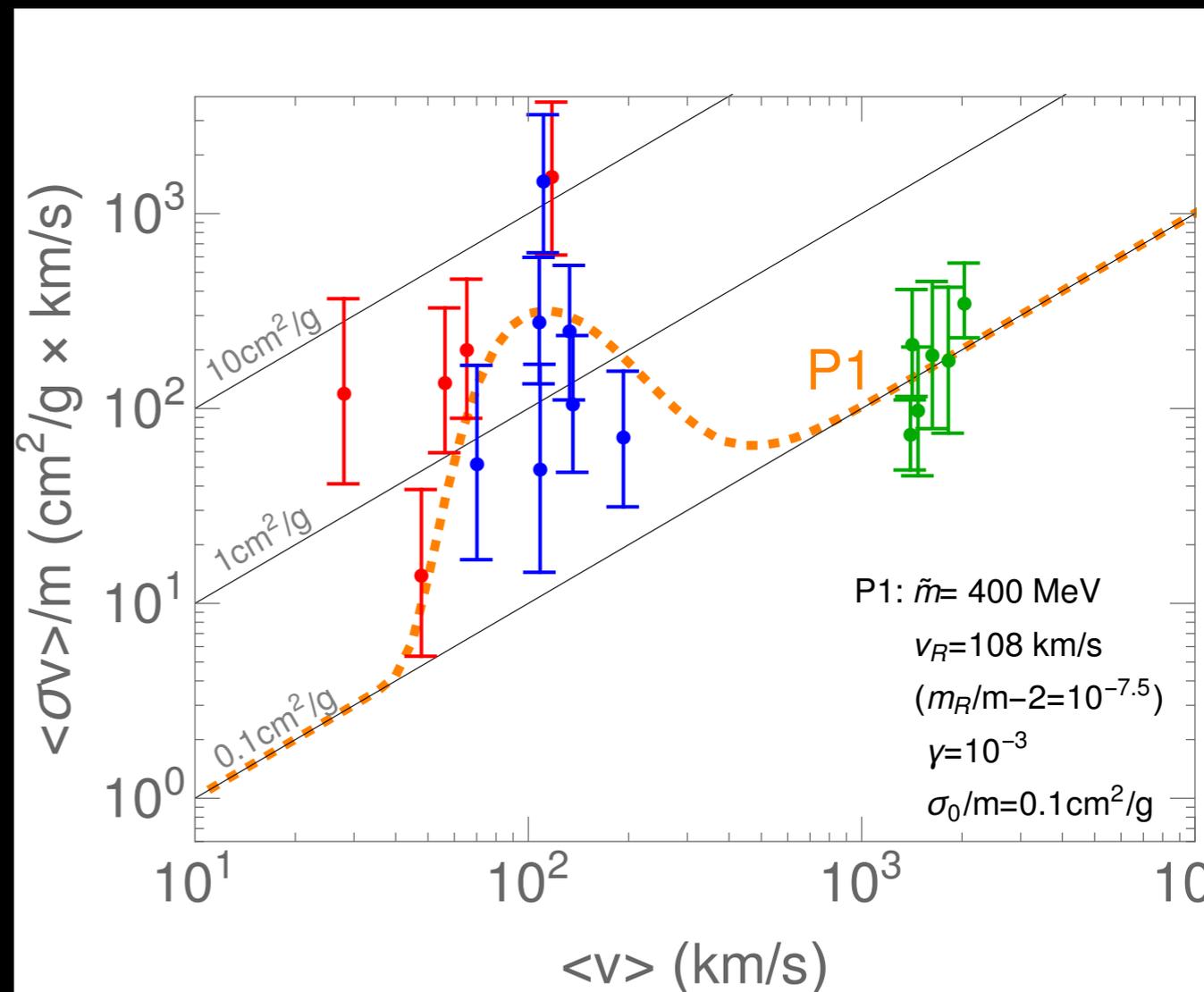
**If  $M_N < T_{\text{sphaleron}}$**   $B_{\text{SM}} = \frac{12}{37} B_{\text{dark}},$   $L_{\text{SM}} = -\frac{25}{37} B_{\text{dark}}$   $m_{n'} = 1.36 \text{ GeV}$

# baryon spectrum

- $m_u$  and  $m_d$  free parameters
- If  $m_d \ll m_u \ll \Lambda_{\text{QCD}}$ ,  $n'$  dominates
- If  $m_u \ll m_d \ll \Lambda_{\text{QCD}}$ ,  $p'$  dominates, together with  $\pi^-$  for charge neutrality
- possibly a resonant interaction  $\pi^- p' \rightarrow \Delta^0 \rightarrow \pi^- p'$
- 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

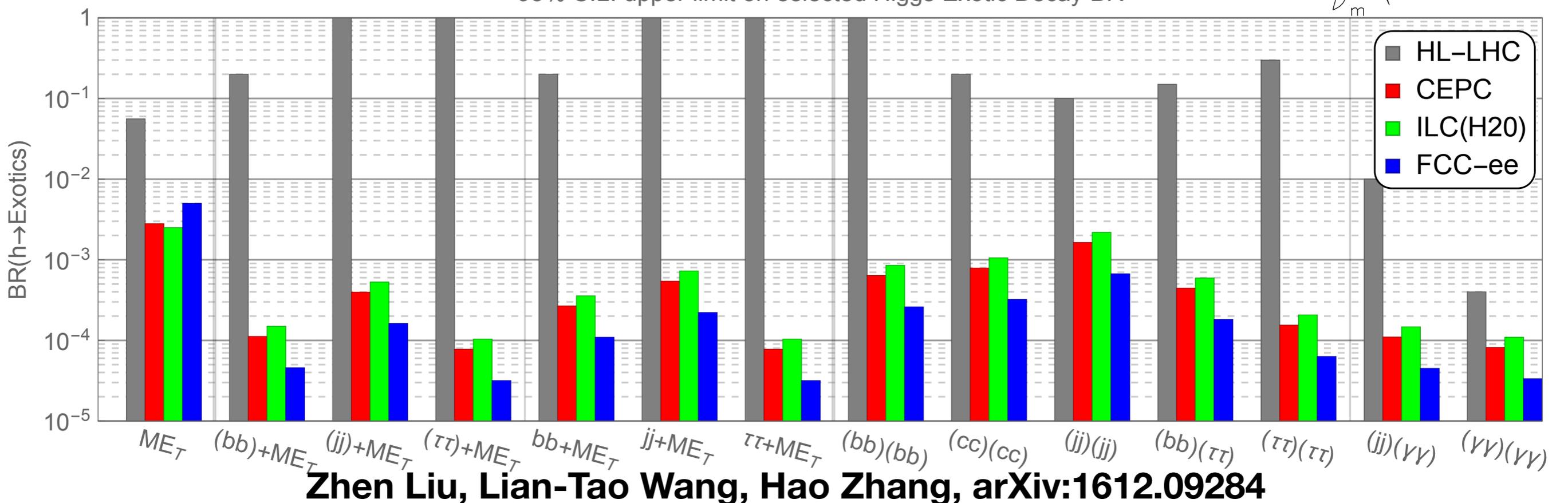
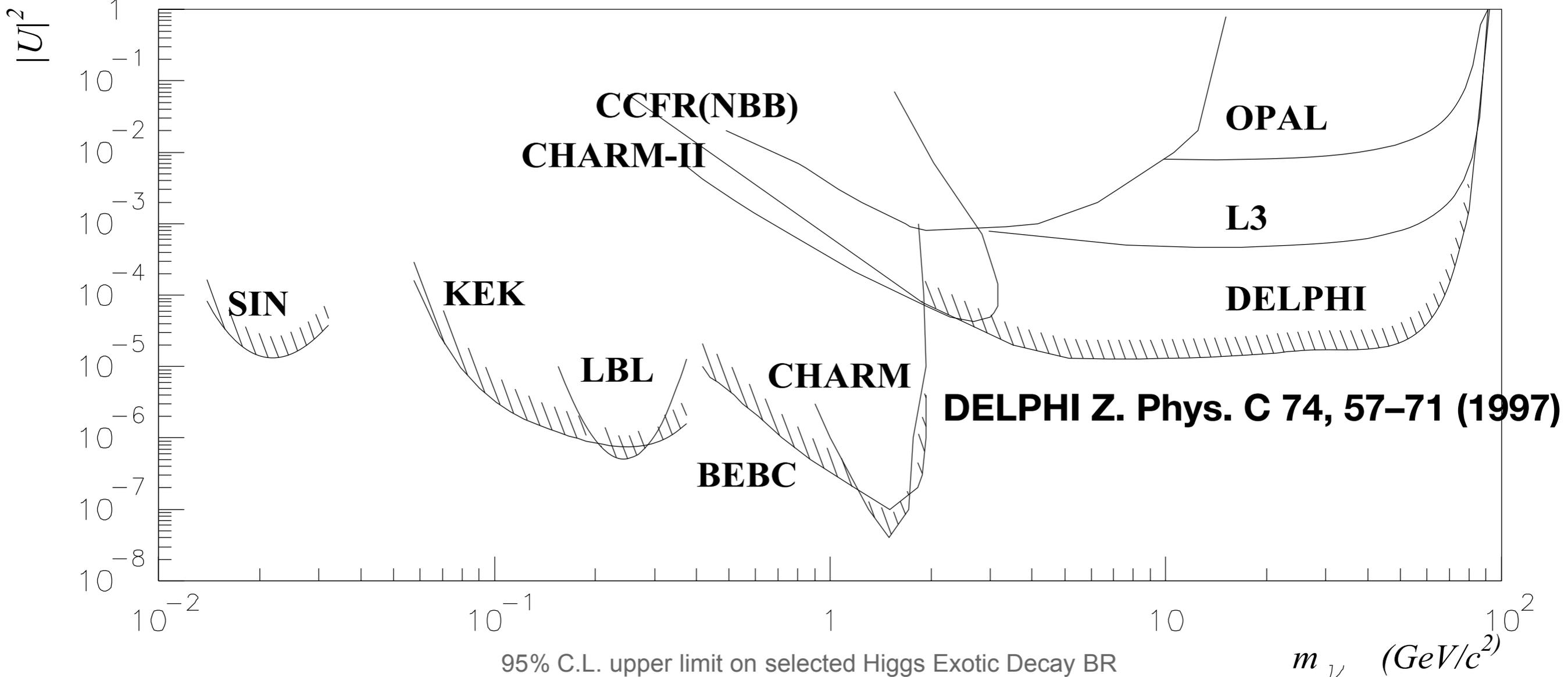
- asymmetric dark matter
  - S. Nussinov, PLB 165, 55 (1985) “technocosmology”
  - R. Kitano, HM, M. Ratz, arXiv:0807.4313, moduli decay
  - D.E. Kaplan, M. Luty, K. Zurek, arXiv:0901.4117
- darkogenesis (= “EW baryogenesis” in the dark sector)
  - J. Shelton, K. Zurek, arXiv:1008.1997

# neutrino portal

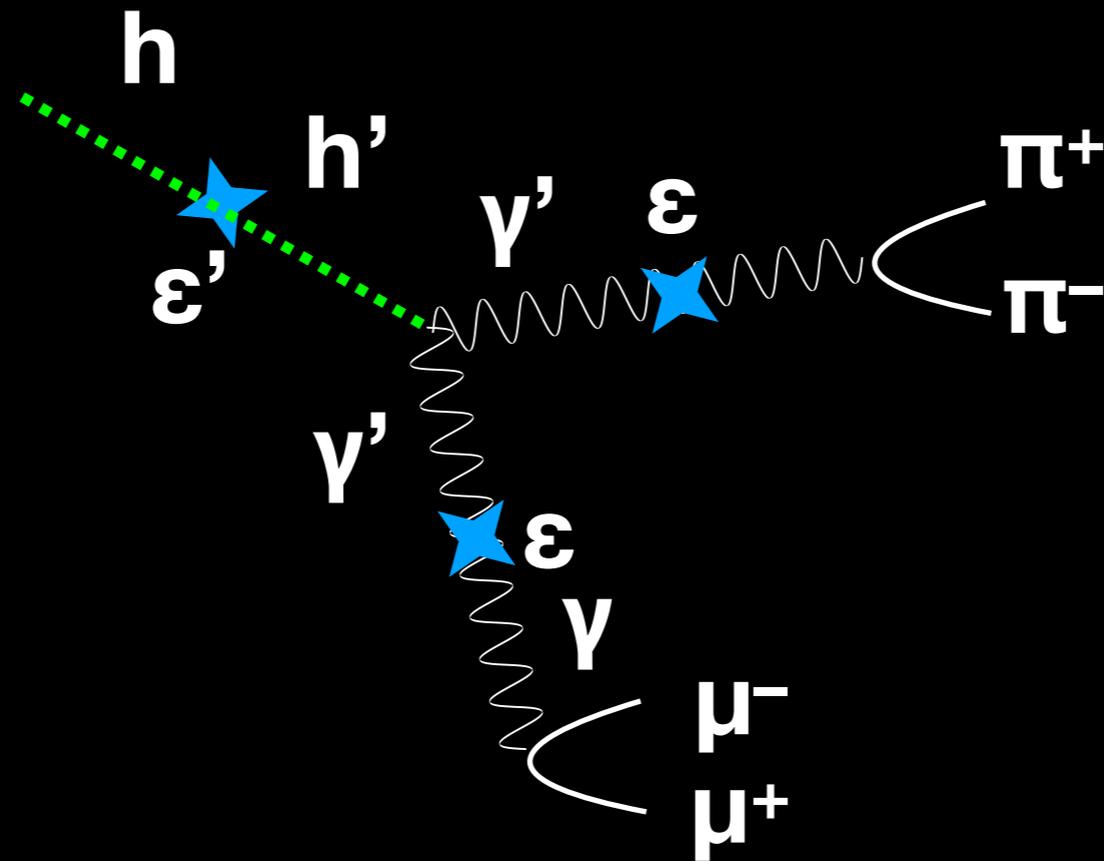
$$\mathcal{L} = y' \bar{L}' H \nu_R + y_i \bar{L}_i H \nu_R$$

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

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

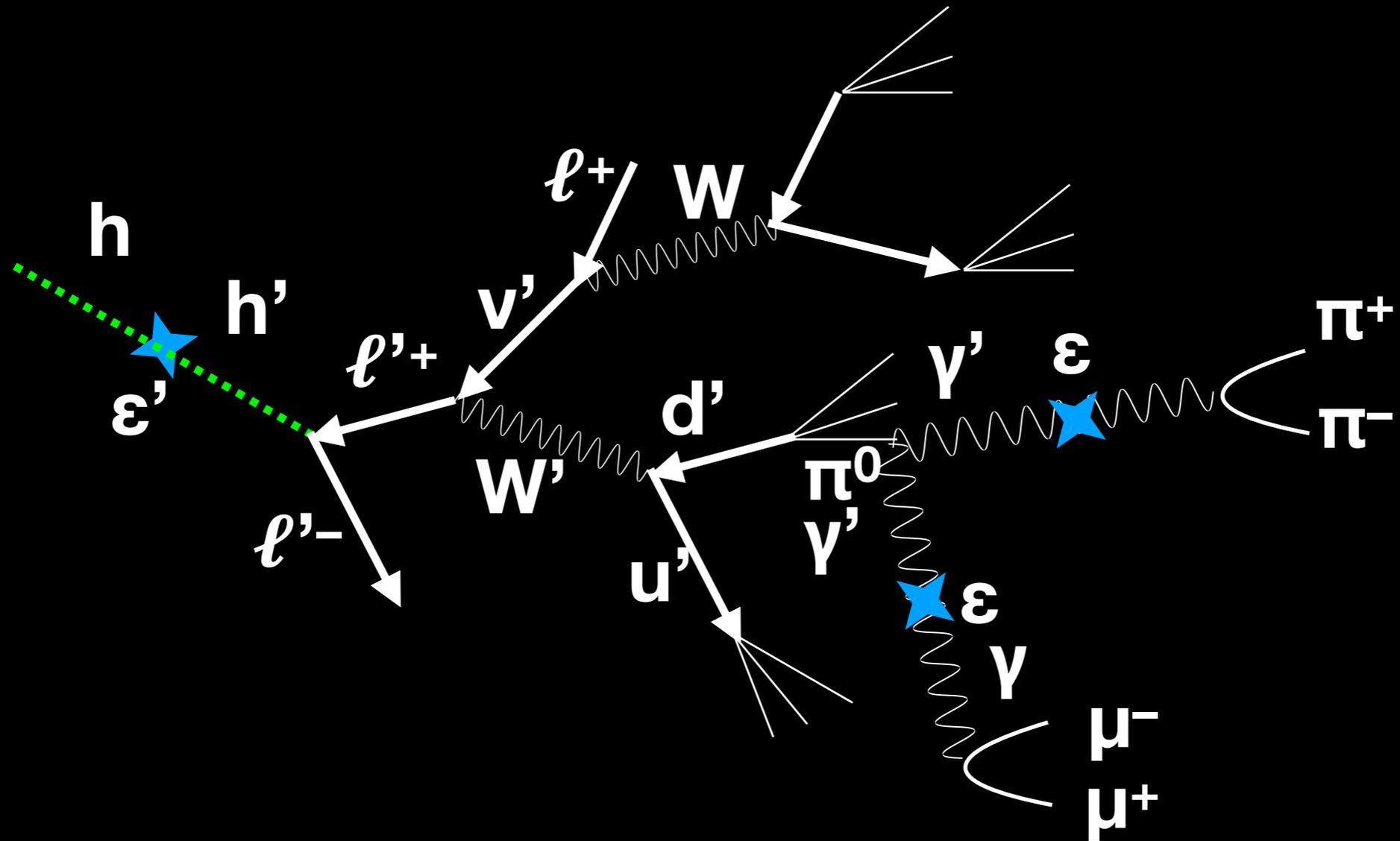


# Higgs portal



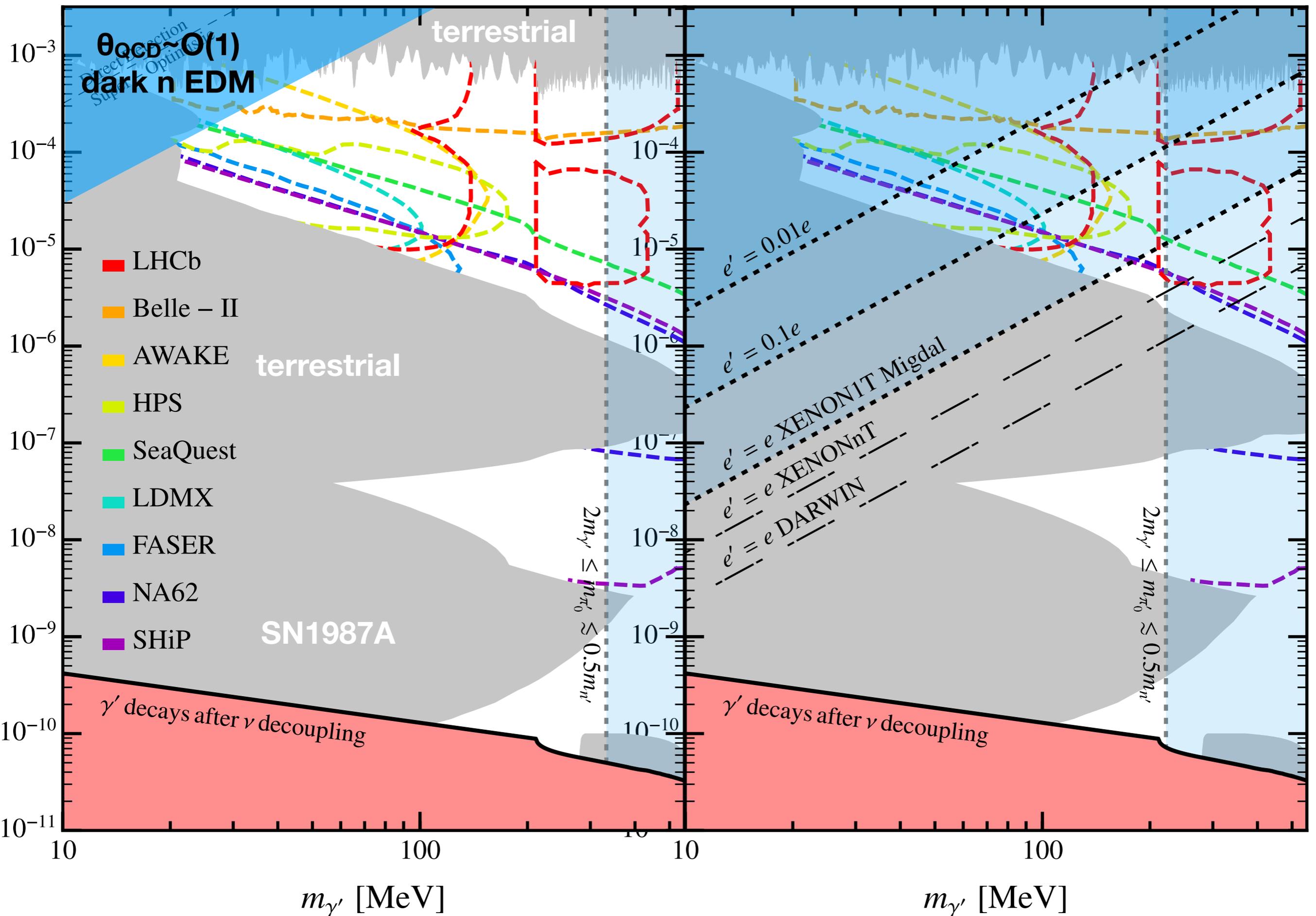
invisible if decaying  
outside the detector

# Higgs portal



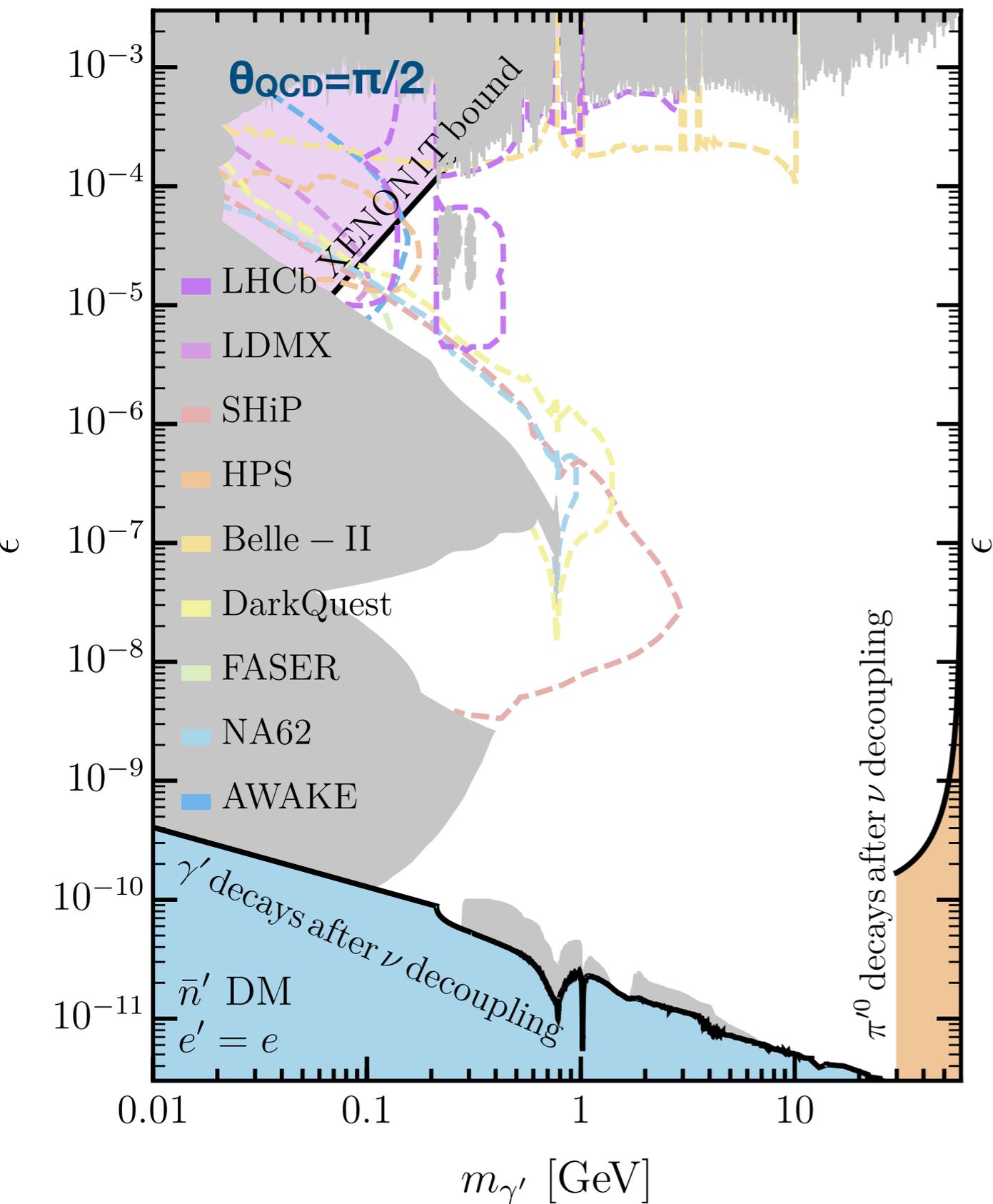
# Dark Neutron Dark Matter

# Dark Proton & Pion Dark Matter

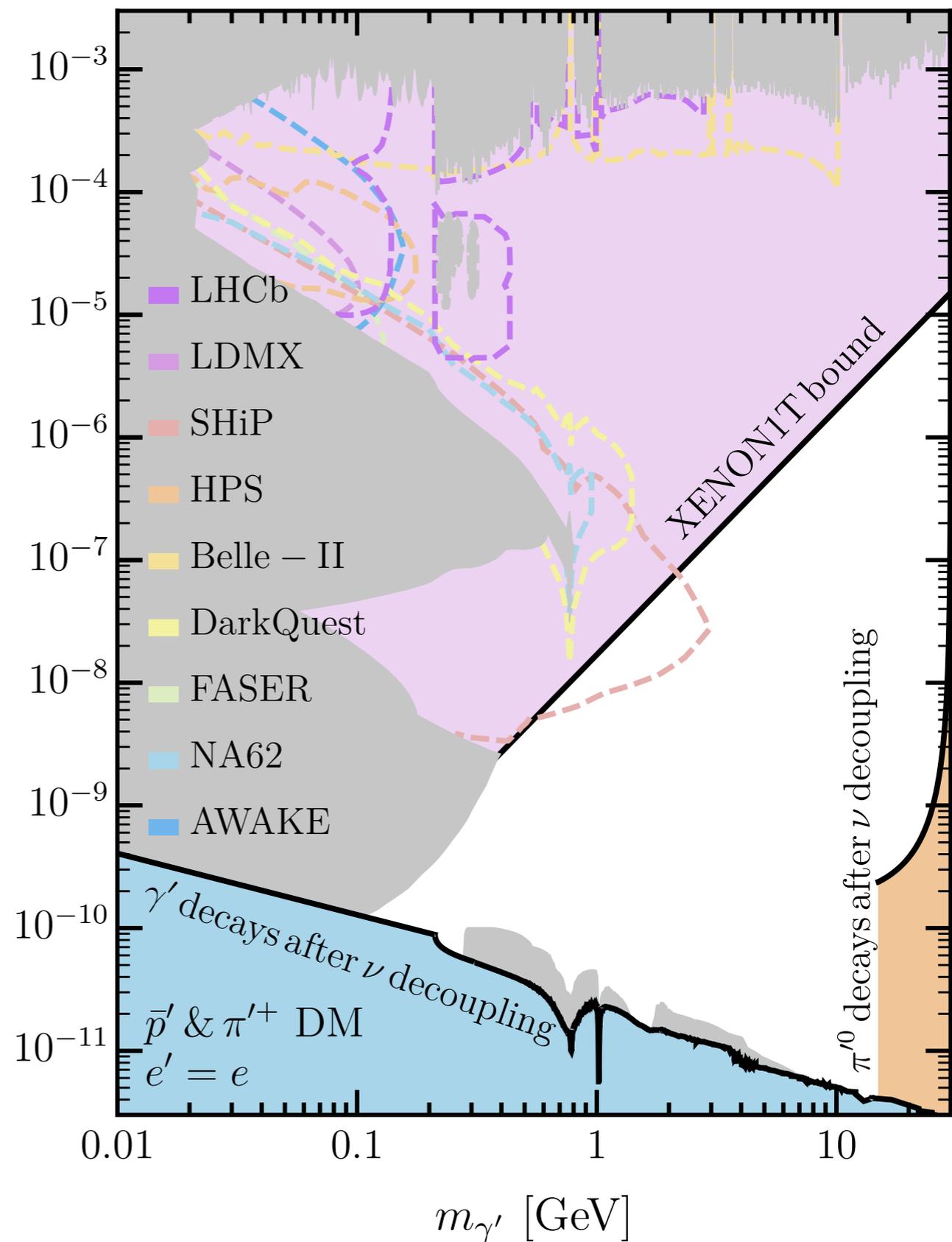


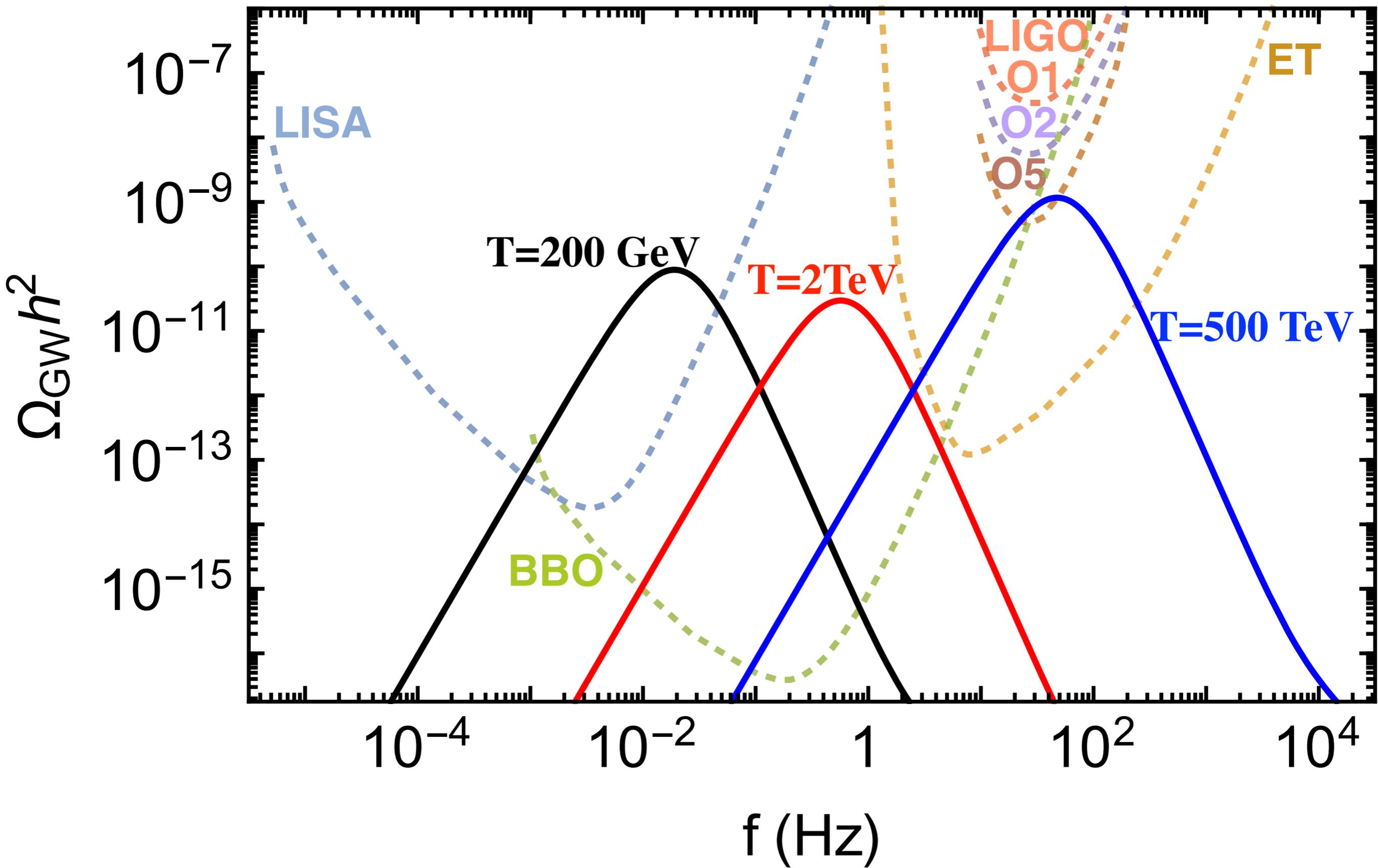
# If the asymmetry originates in the SM side transferred to the dark side

## dark neutron



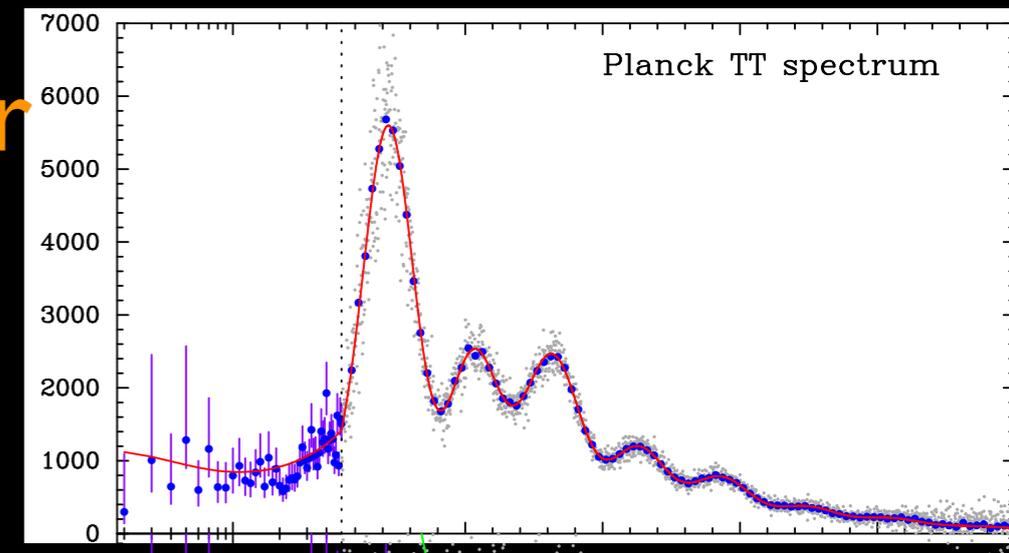
## dark prtoton





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



*many things  
to look forward to!*