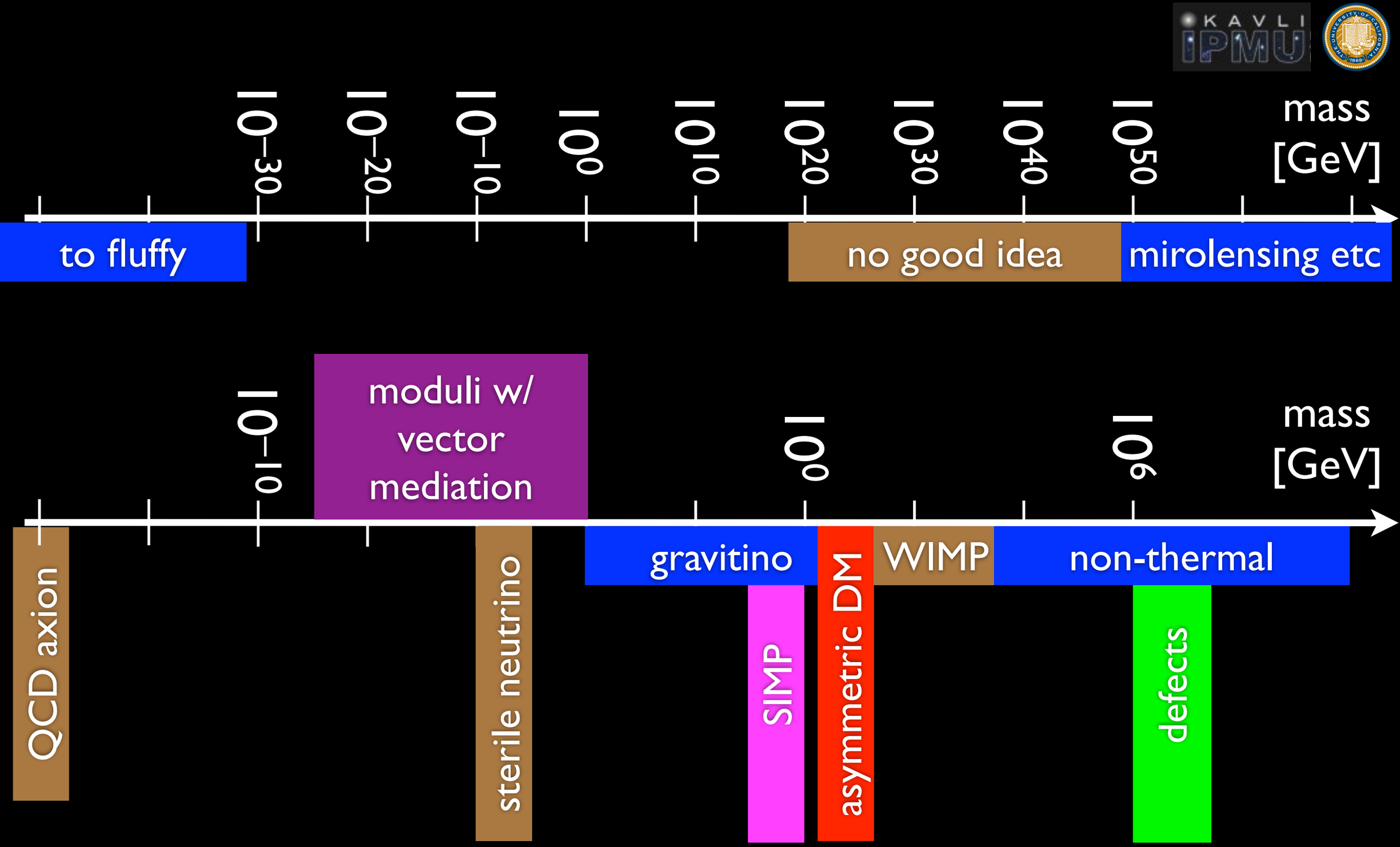


discuss various possibilities

highly biased list

most references are *mine*

QCD axion

- An old puzzle: Why doesn't strong interaction violate CP?
- periodic in $\theta \to \theta + 2\pi$ $\quad \mathcal{L}_\theta = \dfrac{\theta}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$
- leads to $H_{eff} = d_e \, \vec{s}_n \cdot \vec{E}$
- $\theta < 10^{-10}$ $\quad d_e \approx \dfrac{e m_u \sin\theta}{m^2_{\rm constituent}} < 2.9 \times 10^{-26} e \text{ cm}$
- blow up neutron to Earth size: allowed separation of electric charge <3μ

QCD axion

- Promote θ-parameter to a dynamical field

$$\mathcal{L}_{eff} = \frac{1}{64\pi^2}\left(\theta_0 + \frac{a}{f_a}\right)\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}$$

- effect on pion Lagrangian in low energy:

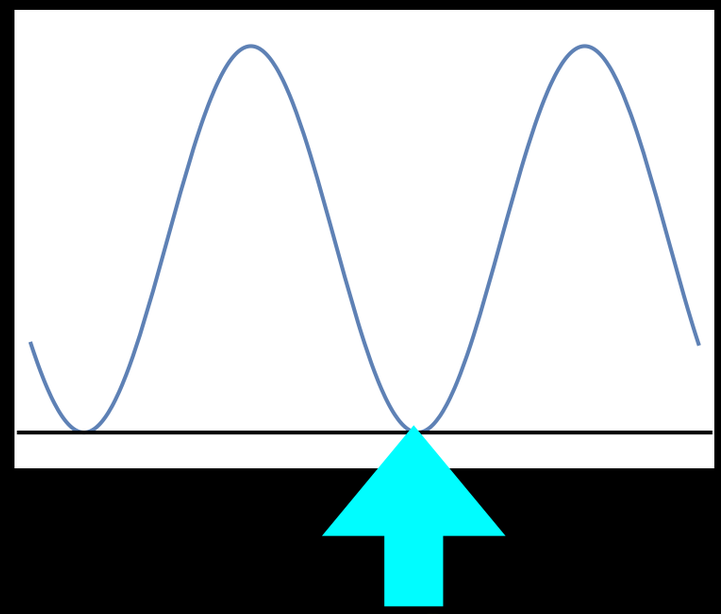
$$\mathcal{L}_\chi = f_\pi^2 \mathrm{tr}\partial U^\dagger \partial U + \mu^3 \mathrm{tr} M e^{i(\theta_0 + a/f_a)}U + \mathrm{c.c.}$$

- potential for axion ($U=1$)

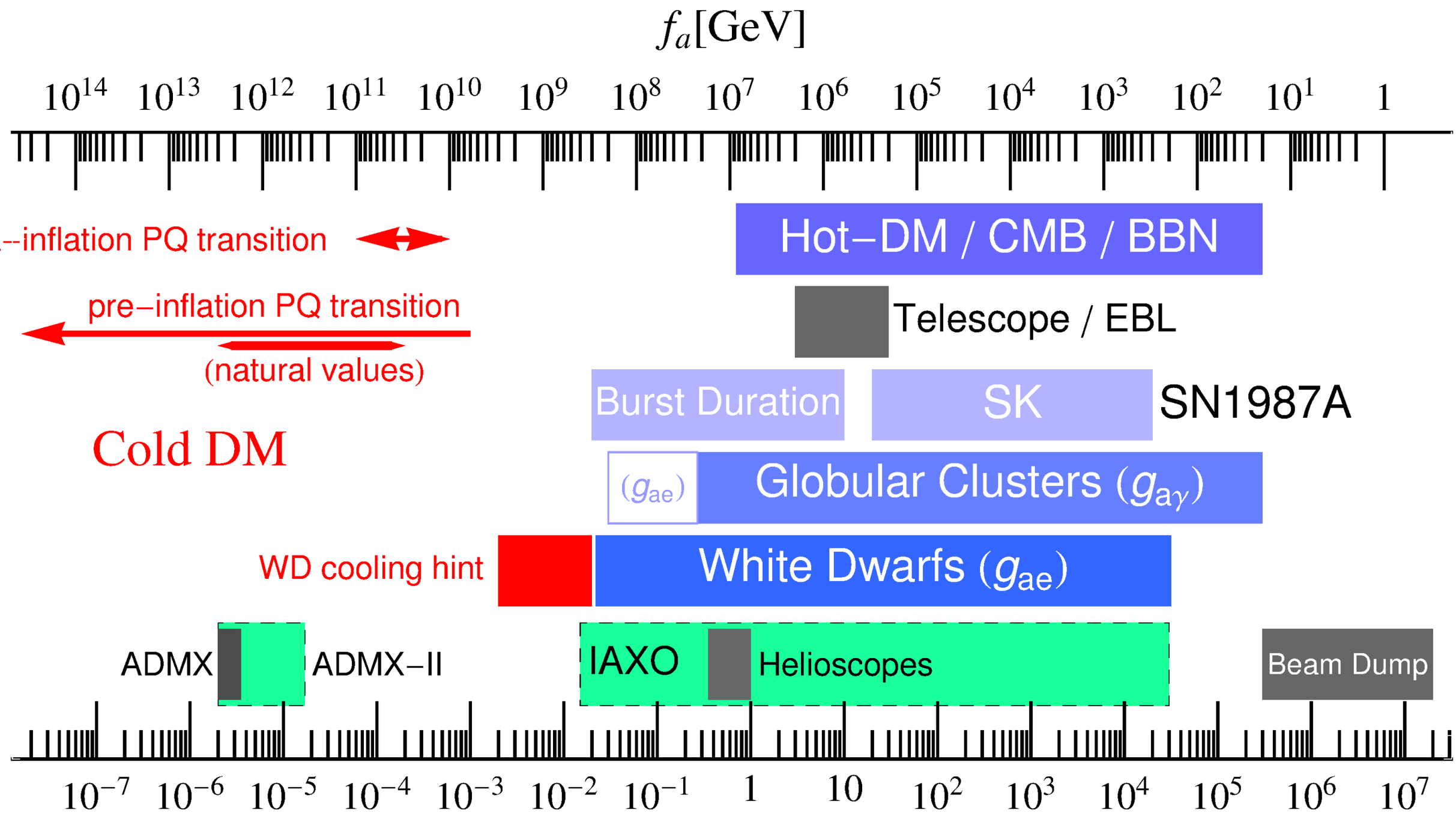
$$V = -m_\pi^2 f_\pi^2 \cos\left(\theta_0 + \frac{a}{f_a}\right)$$

- it settles $a=-\theta_0 f_a$, canceling θ_0
- no CP violation at the minimum!

$$m_a = \frac{m_\pi f_\pi}{f_a}$$

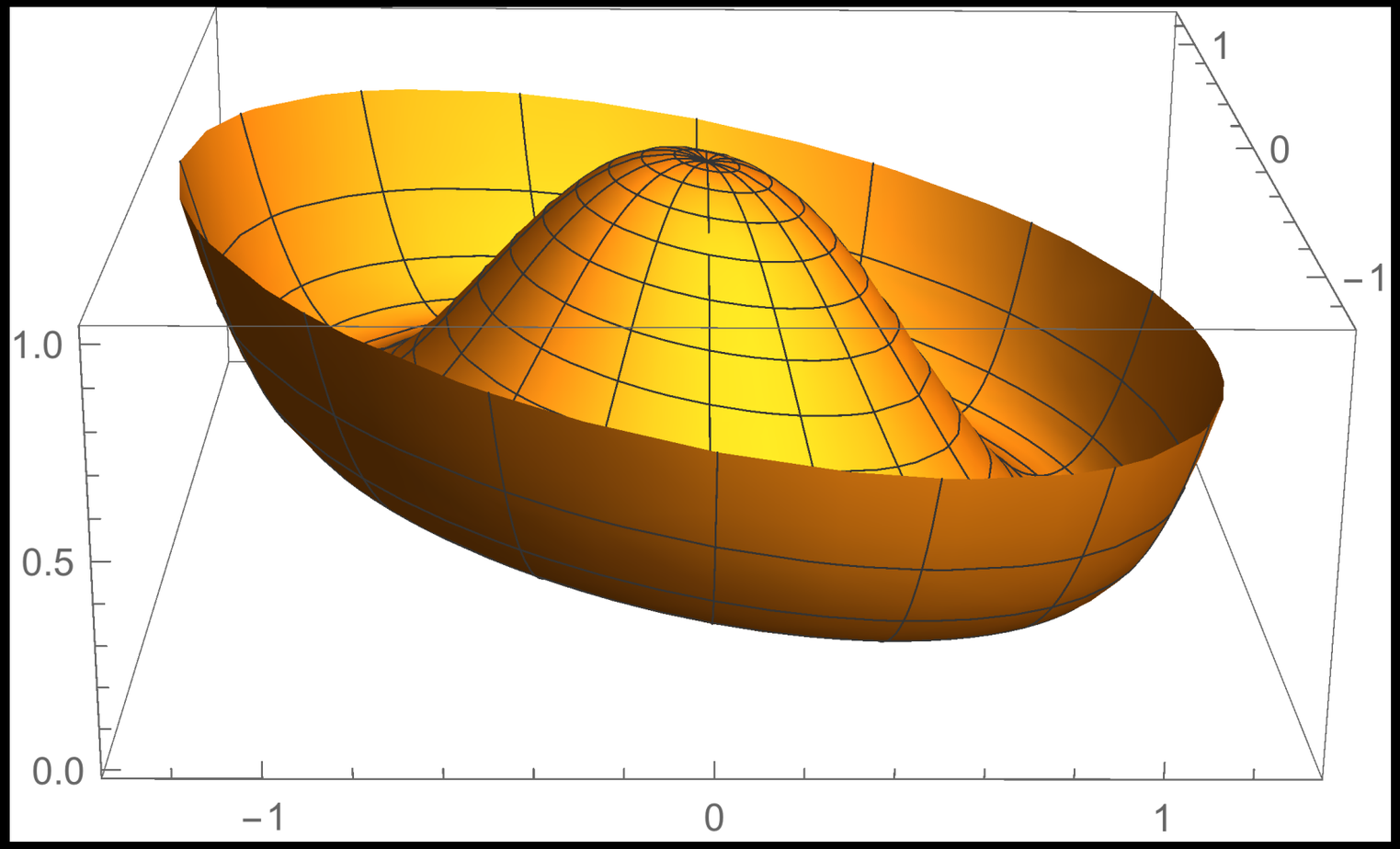


Limits


f_a[GeV]
10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 1
post--inflation PQ transition
Hot–DM / CMB / BBN
pre–inflation PQ transition
(natural values)
Cold DM
Telescope / EBL
Burst Duration
SK
SN1987A
(g_{ae})
Globular Clusters ($g_{a\gamma}$)
WD cooling hint
White Dwarfs (g_{ae})
ADMX
ADMX–II
IAXO
Helioscopes
Beam Dump
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
$m_a=m_\pi f_\pi/f_a$ [eV]

very flat potential

- in early universe, axion doesn't know where the minimum is
- starts to oscillate around minimum



$(100\text{MeV})^4$

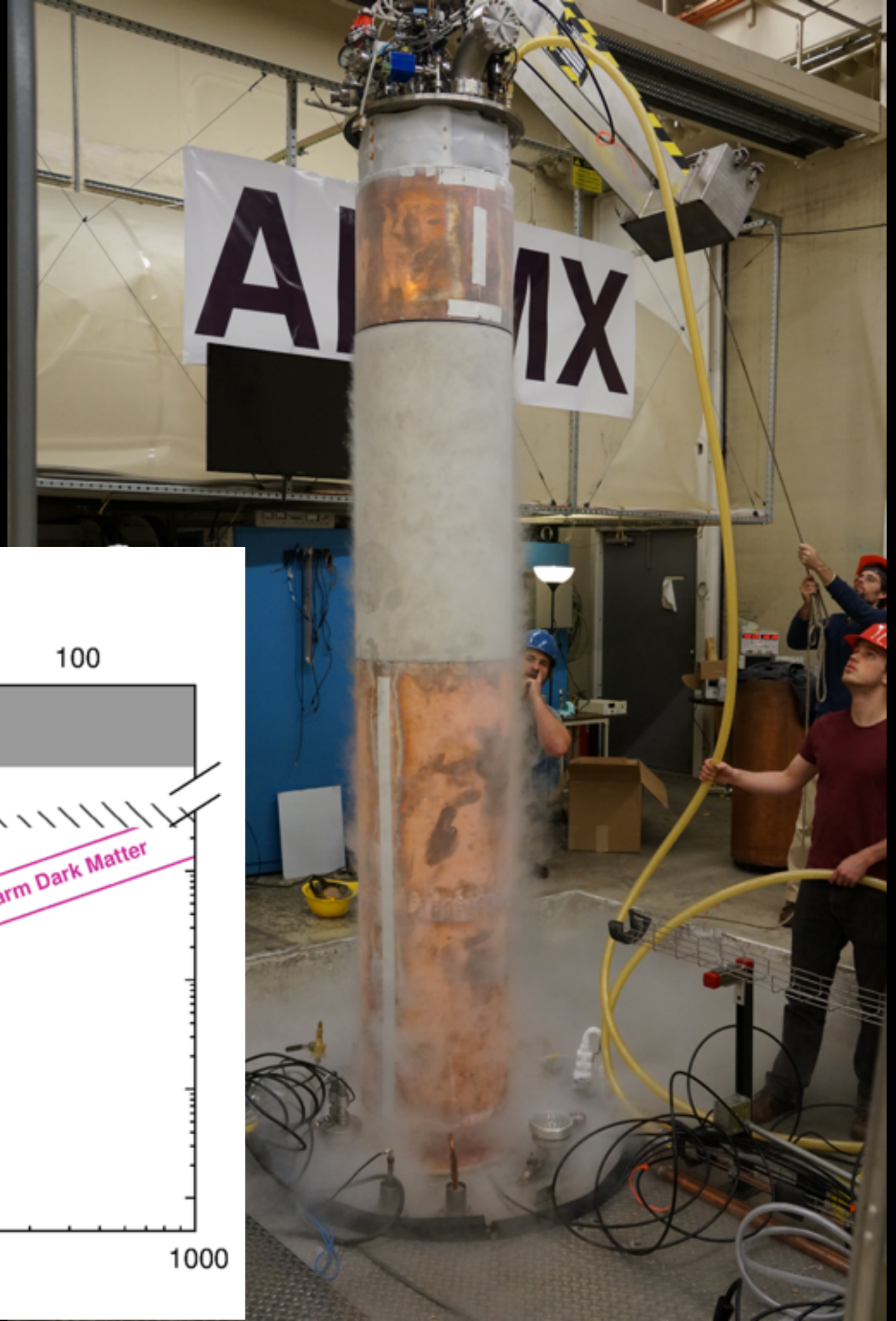
$$\frac{\Omega_a}{\Omega_c} = \left(\frac{f_a}{0.45 \times 10^{12}\text{GeV}}\right)^{1.184} \theta_0^2$$

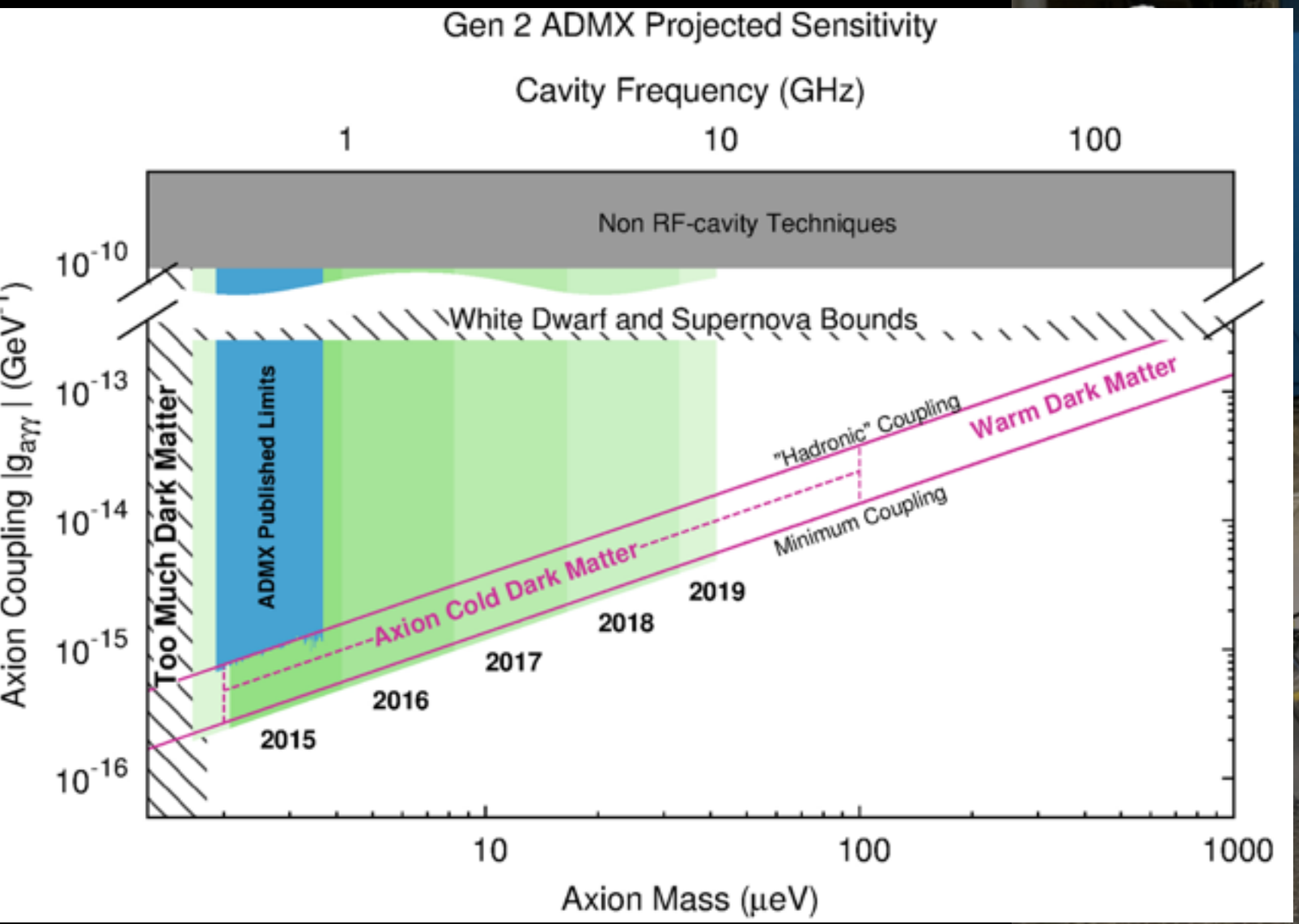
f_a=10^{12}GeV

ADMX

Use the effective coupling

$$\mathcal{L}_{eff} \sim \frac{e^2}{4\pi^2}\frac{a}{f_a}\vec{E}\cdot\vec{B}$$

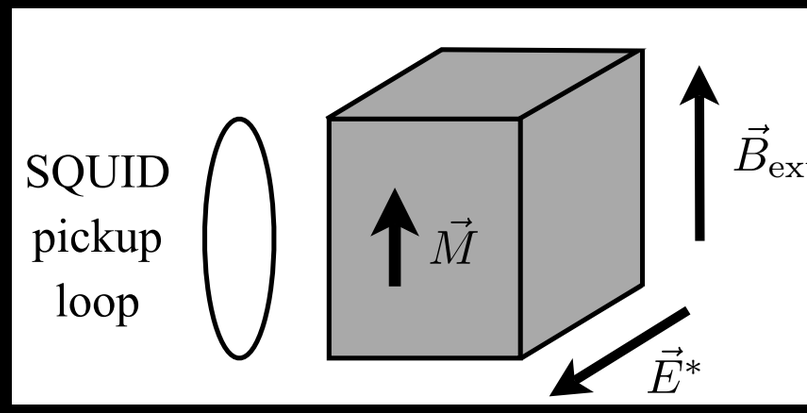




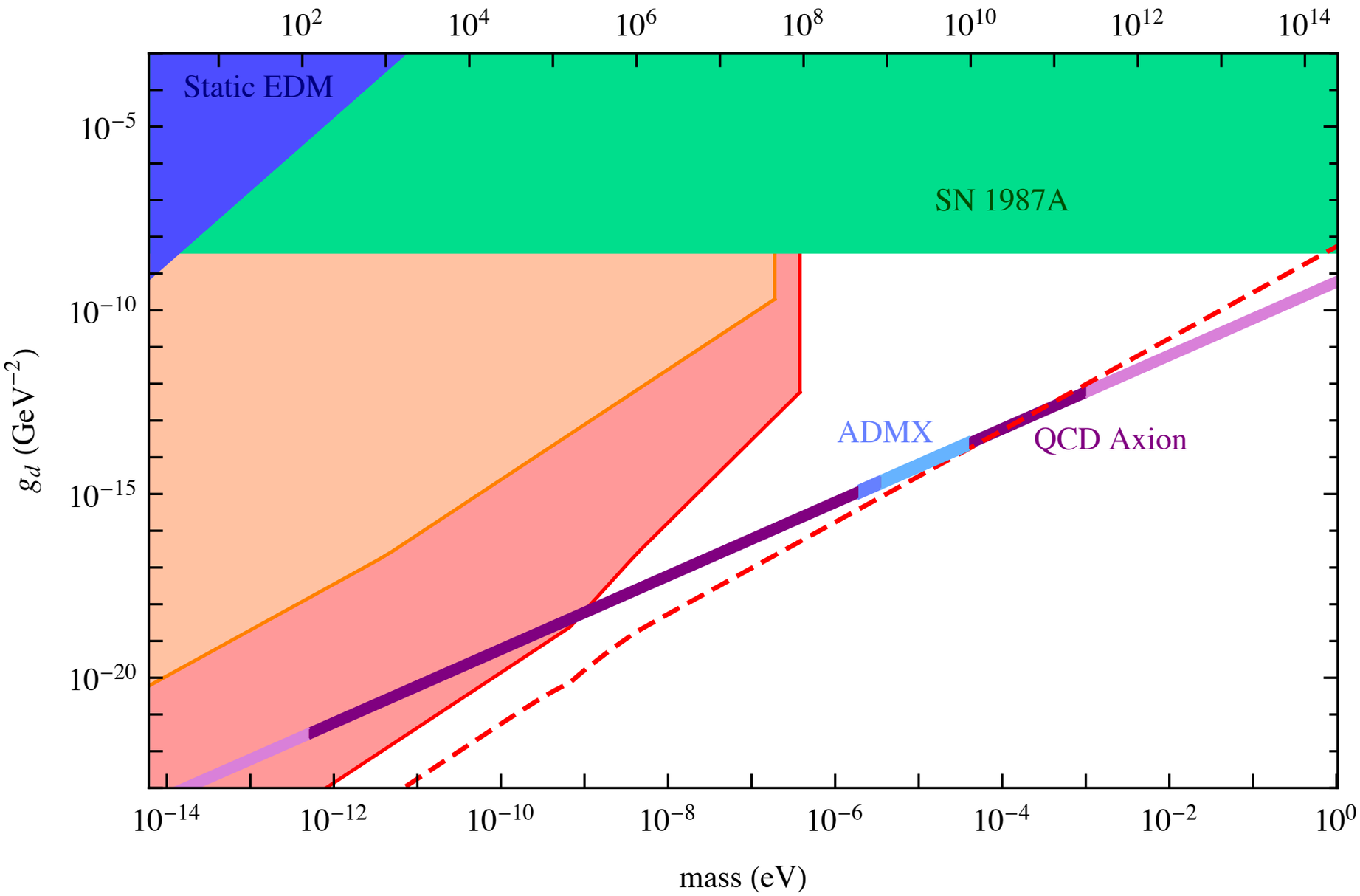
Cosmic Axion Spin Precession

$$H_{eff}(t) = -\vec{\mu}\cdot\vec{B} - \frac{m_u}{m_{\text{const}}^2}\sin(m_a t)\times\vec{s}_n\cdot\vec{E}$$

resonance @ μ*B*=m_a



Budker et al
arXiv:1306.6089



atom

electron

Higgs boson

neutron

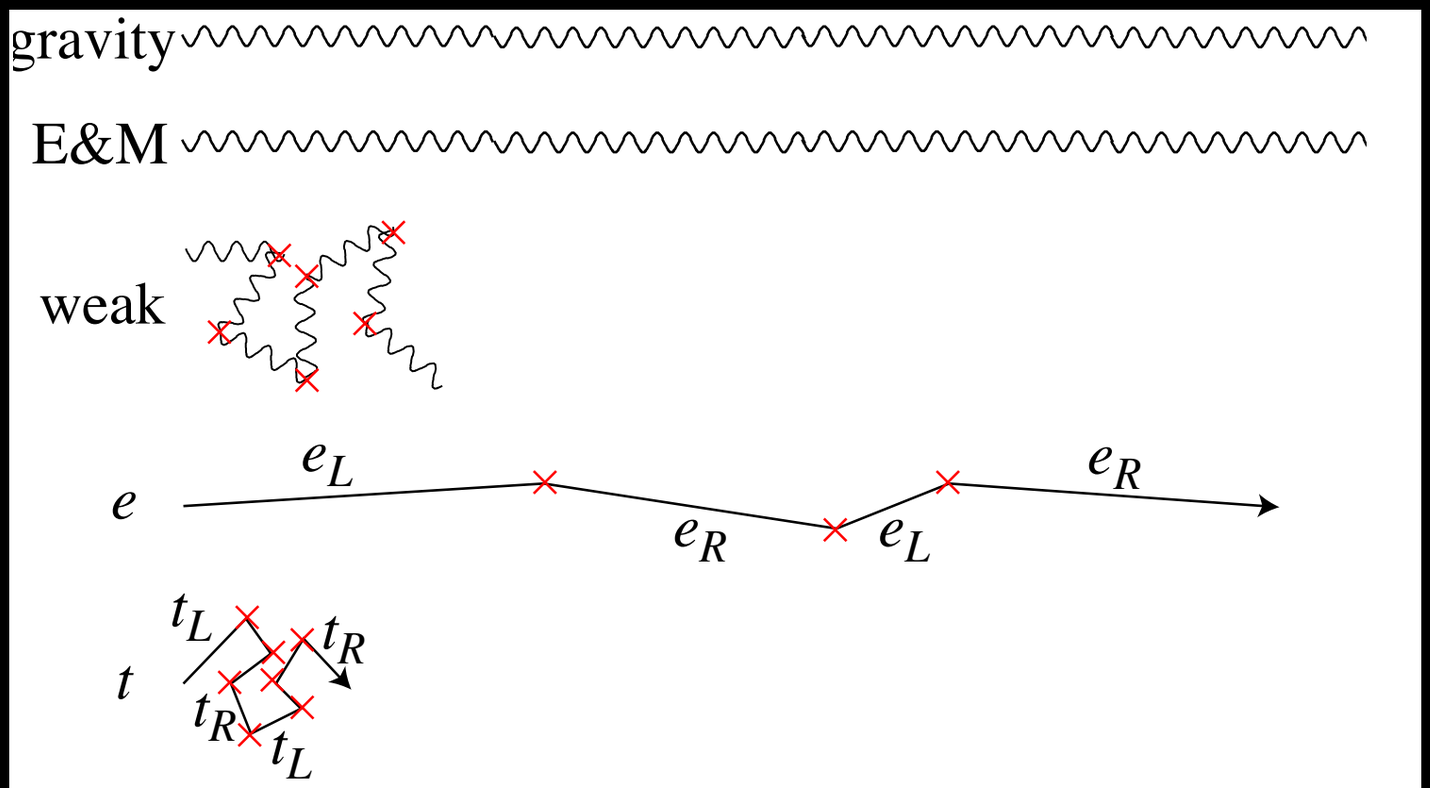
proton

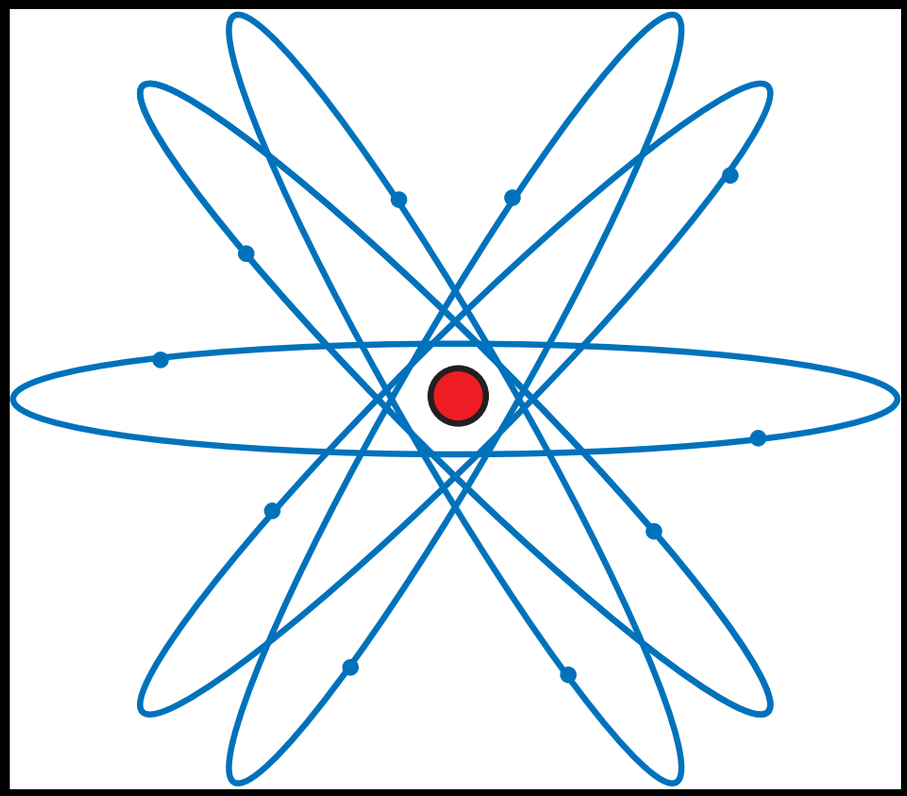
nucleus

quarks

we came from ancient stars
born from dark matter

Universe is filled with Higgs





Particles slow down

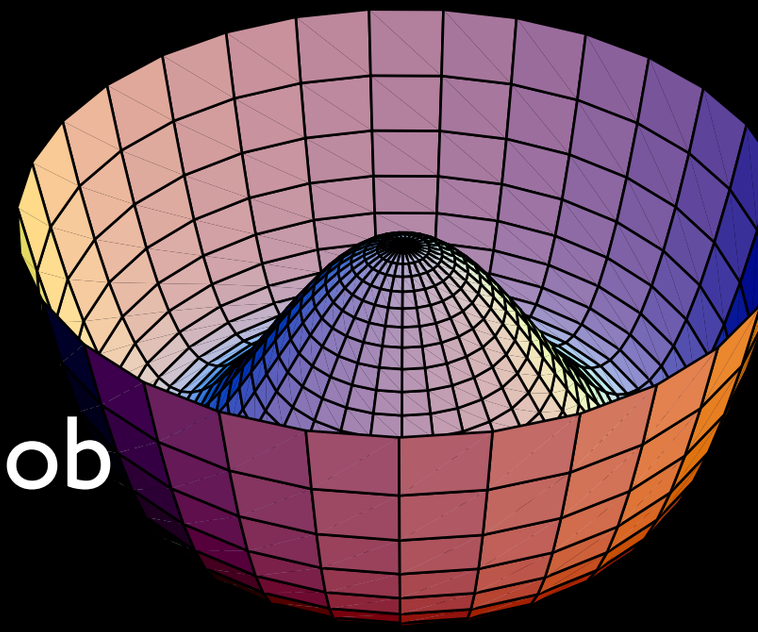
$$\frac{i}{\not{p}-m} = \frac{i}{\not{p}} + \frac{i}{\not{p}}(-im)\frac{i}{\not{p}} + \frac{i}{\not{p}}(-im)\frac{i}{\not{p}}(-im)\frac{i}{\not{p}} + \cdots$$

Without Higgs,
we evaporate in
a billionth of a second

naturalness

What is Higgs?
Is it alone?
Any siblings?
Any relatives?
Why frozen?

- Higgs boson is the *only spin 0 particle* in the standard model
  - it is *faceless*
  - one of its kind, no context
  - but does the most important job
- looks very artificial
- we still don't know *dynamics* behind the Higgs condensate
- *Higgsless theories*: now dead



Electron mass is natural by doubling #particles

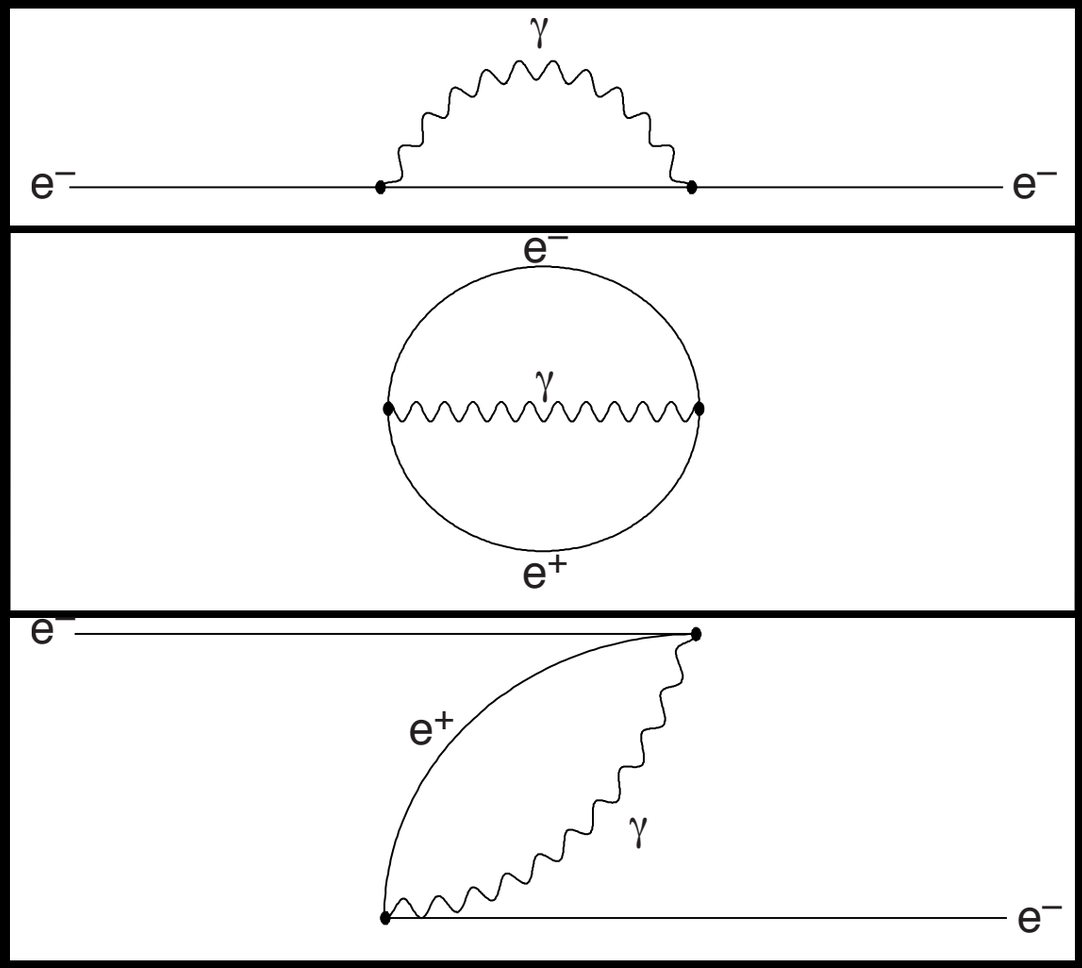
- Electron creates a force to repel itself

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

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

⇒ only 10% of mass even

for Planck-size $r_e \sim 10^{-33}$cm

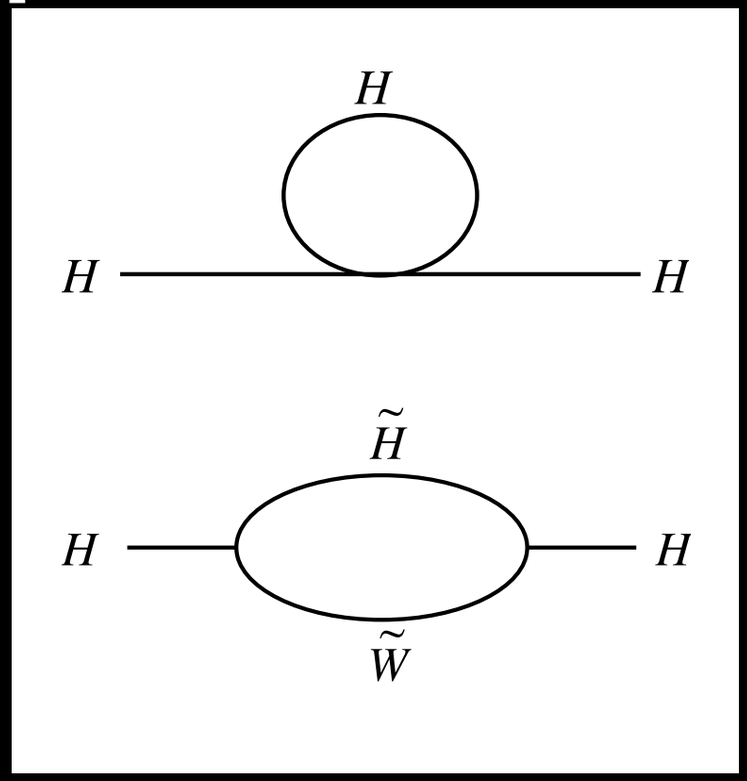


$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

HM hep-ph/0002232

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

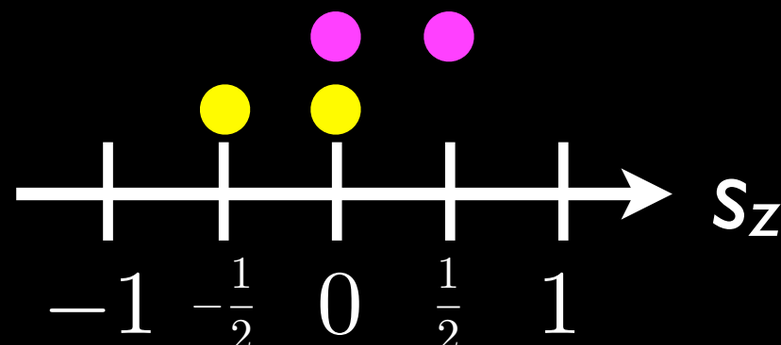
HM hep-ph/0002232

Supersymmetry

- Theorem:
  - the only space-time symmetry beyond Lorentz and translation invariance possible in *S*-matrices
  - interchanges bosonic & fermionic states, spins different by 1/2
  - possibly *unifies* matter (fermions) and forces (bosons)

supersymmetrize SM

- All quarks and leptons are Weyl fermions



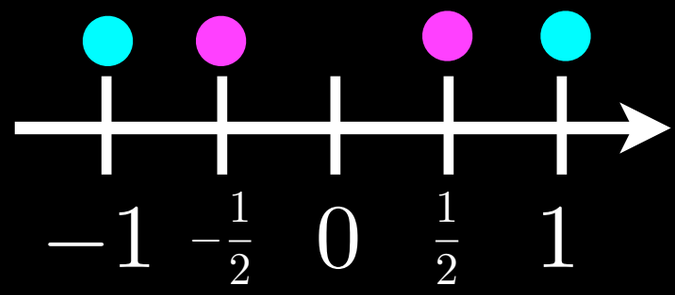
- add their scalar partners
- Naming convention: add "s" as a prefix, which stands for supersymmetry or scalar

terrible convention!

- e.g., selectron, smuon, stop, sup, sstrange

supersymmetrize SM

- Gauge fields are vector bosons
- namely add massless Majorana fermions "gauginos"

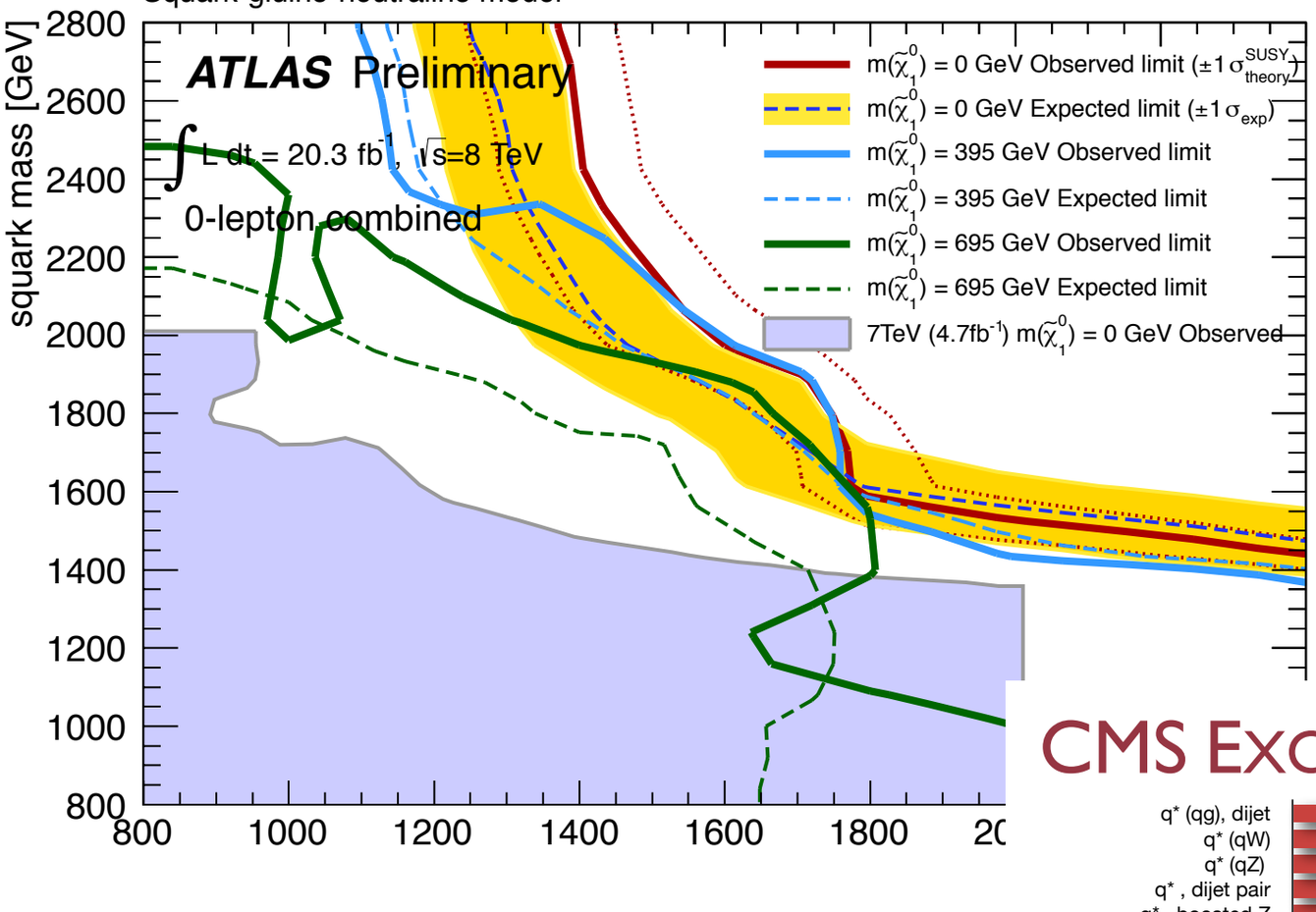


- Naming convention: add "ino" as a suffix, which doesn't mean "small" in any sense

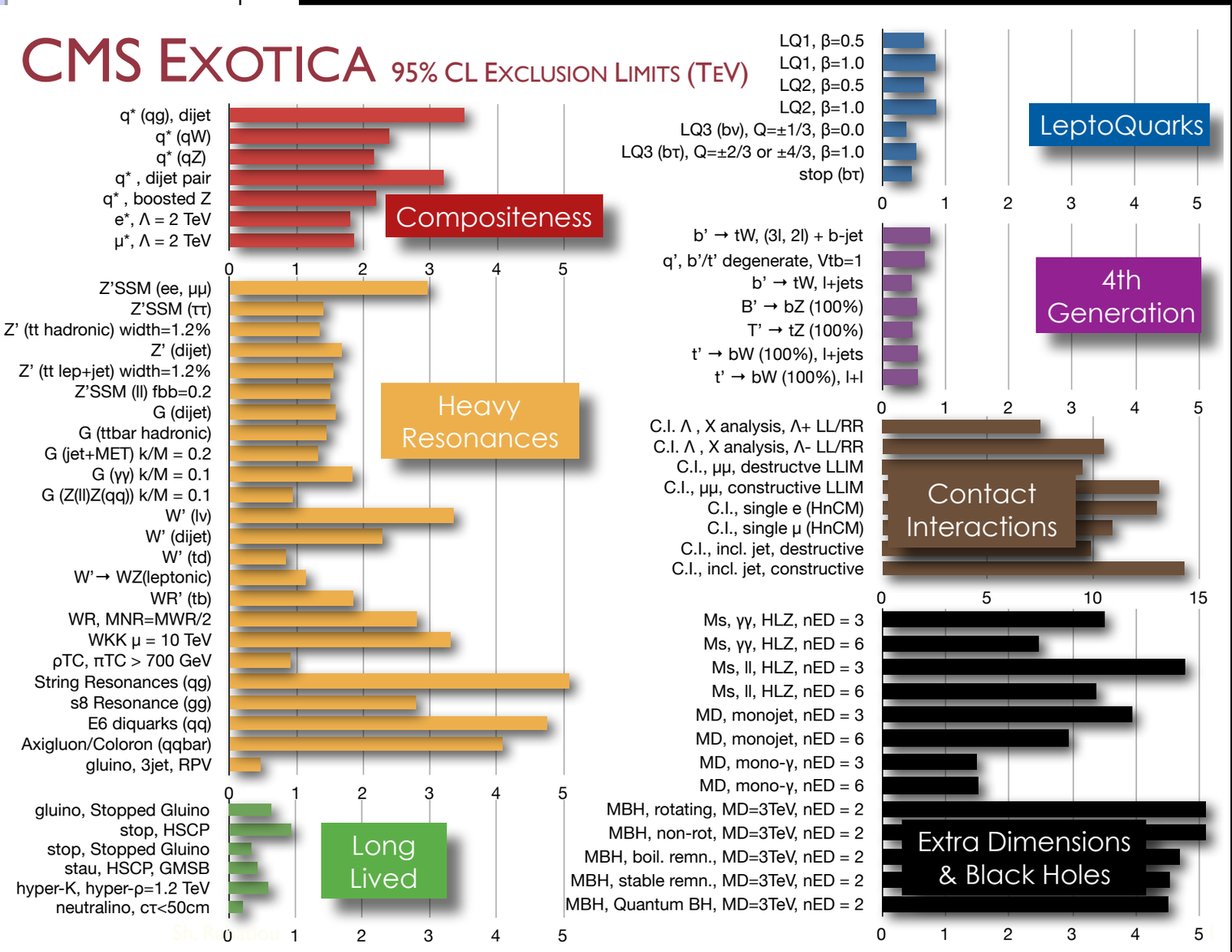
terrible convention!

- e.g.: gluino, wino, photino, zino, bino

gluissimo



no sign of
new physics
that explains
mass of the Higgs!



SCIENTIFIC AMERICAN™

Permanent Address: http://www.scientificamerican.com/article/supersymmetry-and-the-crisis-in-physics/

Scientific American Volume 310, Issue 5

Supersymmetry and the Crisis in Physics

For decades physicists have been working on a beautiful theory that has promised to lead to a deeper un

stand at a crossroads: prove it right in the next year or confront an epochal paradigm shift

By Joseph Lykken and Maria Spiropulu

At dawn on a summer morning in 2012, we were on our third round of espresso when the video link connected our office at the California Institute of Technology to the CERN laboratory near Geneva. On the monitor we saw our colleagues on the Razor team, one of many groups of physicists analyzing data from the CMS

premature obituary

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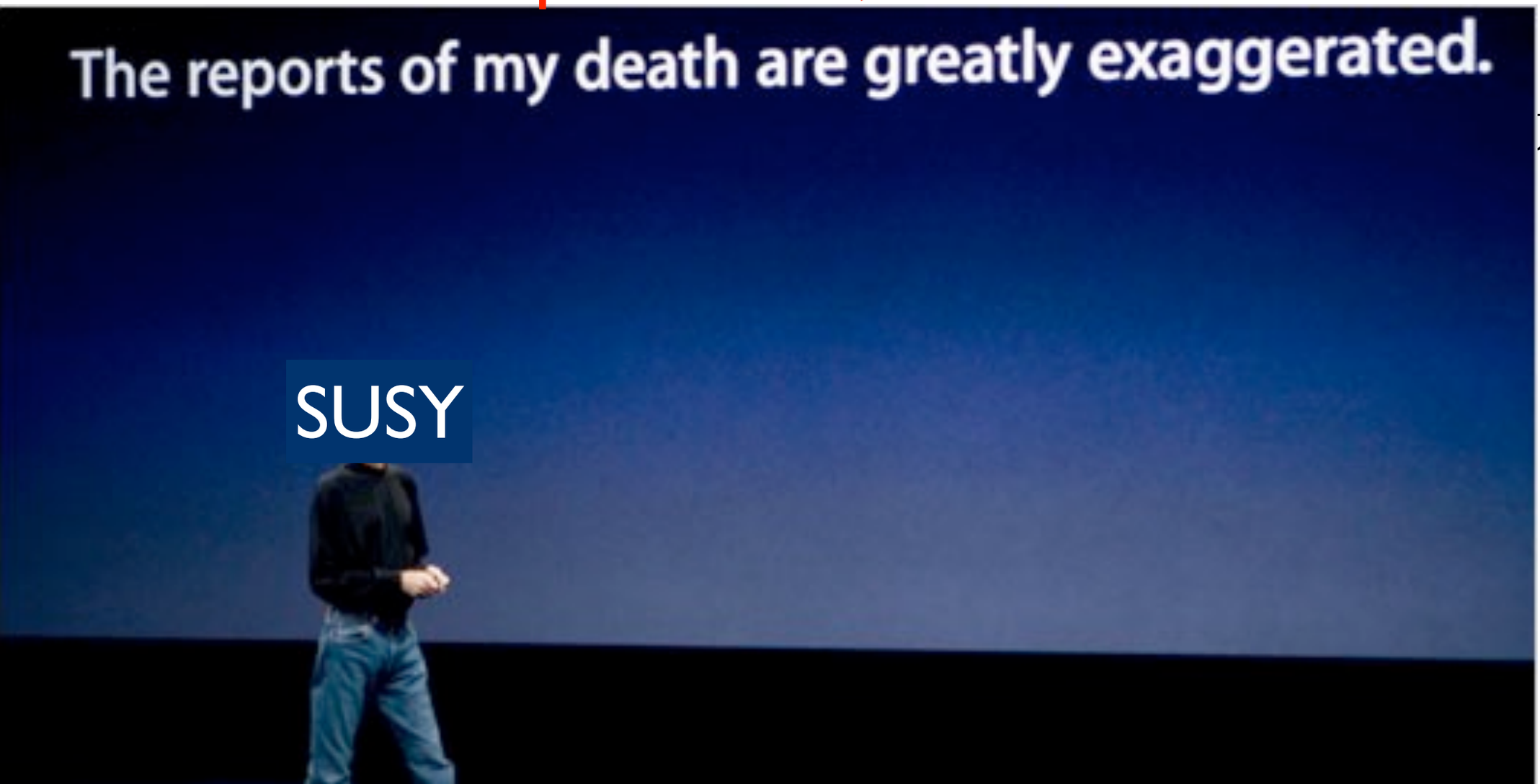
JOB, STEVE. APPLE FOUNDER, TECH VISIONARY. UPDATED AUGUST 2008

September 9, 2008



D NOT USE

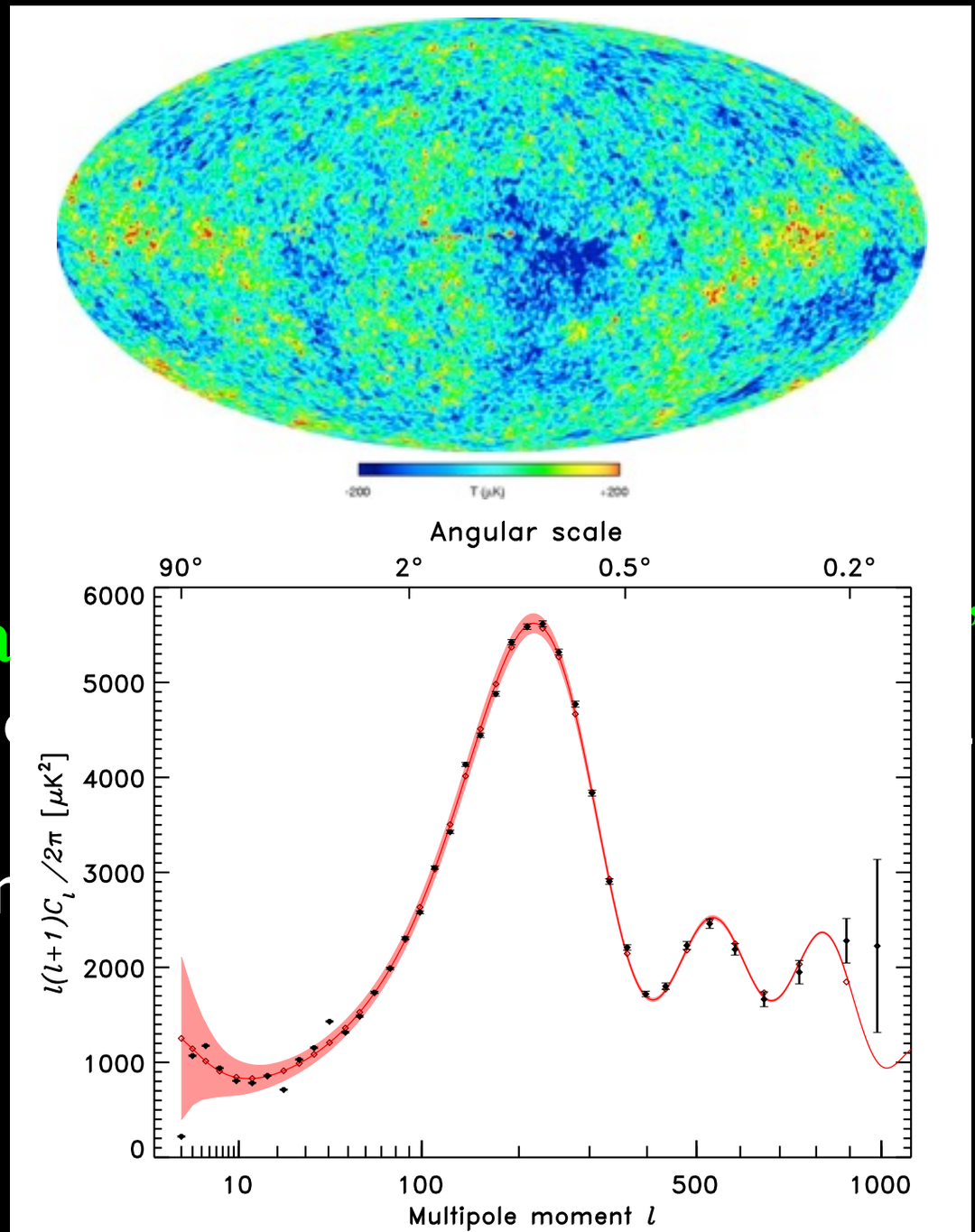
SUSY

October 5, 2011

uneasiness in cosmology

- Before COBE, upper limit on CMB anisotropy kept getting better and better
- cosmologists got antsy
- "crisis in standard cosmology"
- it turned out a little "fine-tuned"
  - low quadrupole

2% tuning



Rationale for Scalar Bosons?

Supersymmetry

- Higgs just one of *many* scalar bosons
- SUSY loops make m_h^2 negative

composite

- spins cancel among constituents
- condensate by a strong attractive force, holography

Extra dimension

- Higgs spinning in extra dimensions
- new forces from particles running in extra D

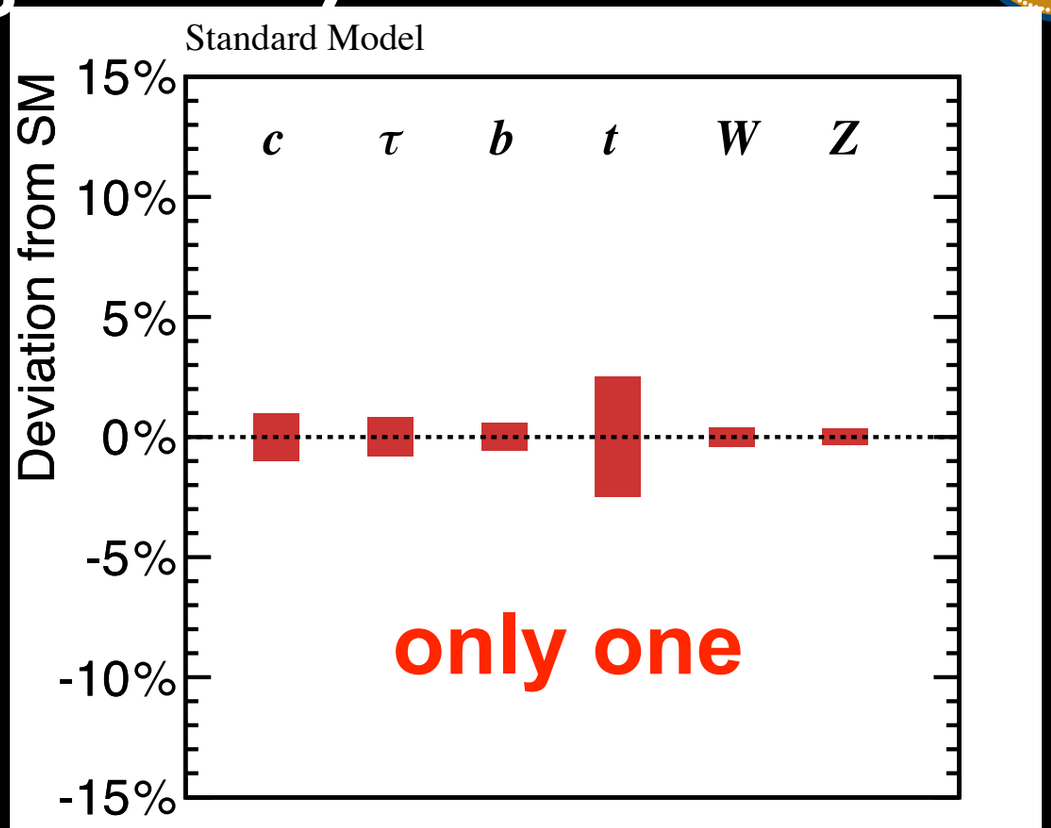
not the usual "naturalness" argument

What is Higgs really?

Only one? (SM)
has siblings? (2DHM)
not elementary?

ILC

Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV



History of the Universe

a trillionth sec

10–10 sec

3min

380k yrs

13.8Bzyrs

BIG BANG

Inflation

?

Higgs

CMB

high-energy cosmic rays

possible dark matter relicts

cosmic microwave background radiation visible

t 10-44 10-37 s 10-10 s 10-5 s 102 s 3x105 y 109 y 12x109 y (sec,yrs)

T 1032 1028 1015 1015 102 109 3000 15 2.7 (Kelvin)

E 1019 1015 102 1012 10-4 3x10-10 10-12 2.3x10-13 (GeV)

Today

Key:

- q quark
- g gluon
- e electron
- μ muon τ tau
- ν neutrino
- W, Z bosons
- qq meson
- qqq baryon
- ion
- atom
- photon
- galaxy
- star
- black hole

atom

electron

Higgs boson

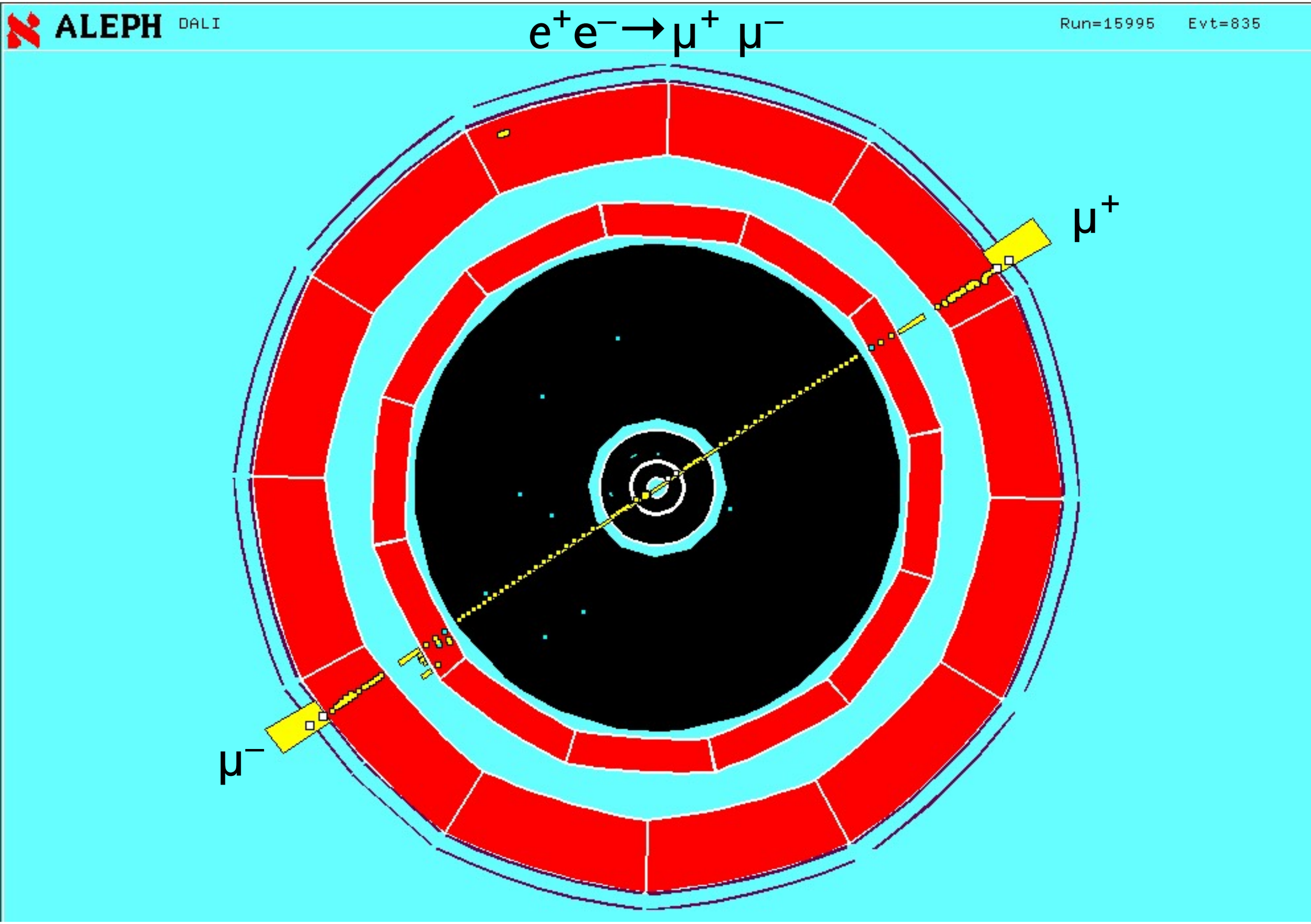
neutron

proton

nucleus

quarks

We still need quarks to get started


ALEPH
DALI
$e^+e^- \rightarrow \mu^+ \mu^-$
Run=15995 Evt=835
μ^+
μ^-

Early Universe

1,000,000,000

matter

1,000,000,000

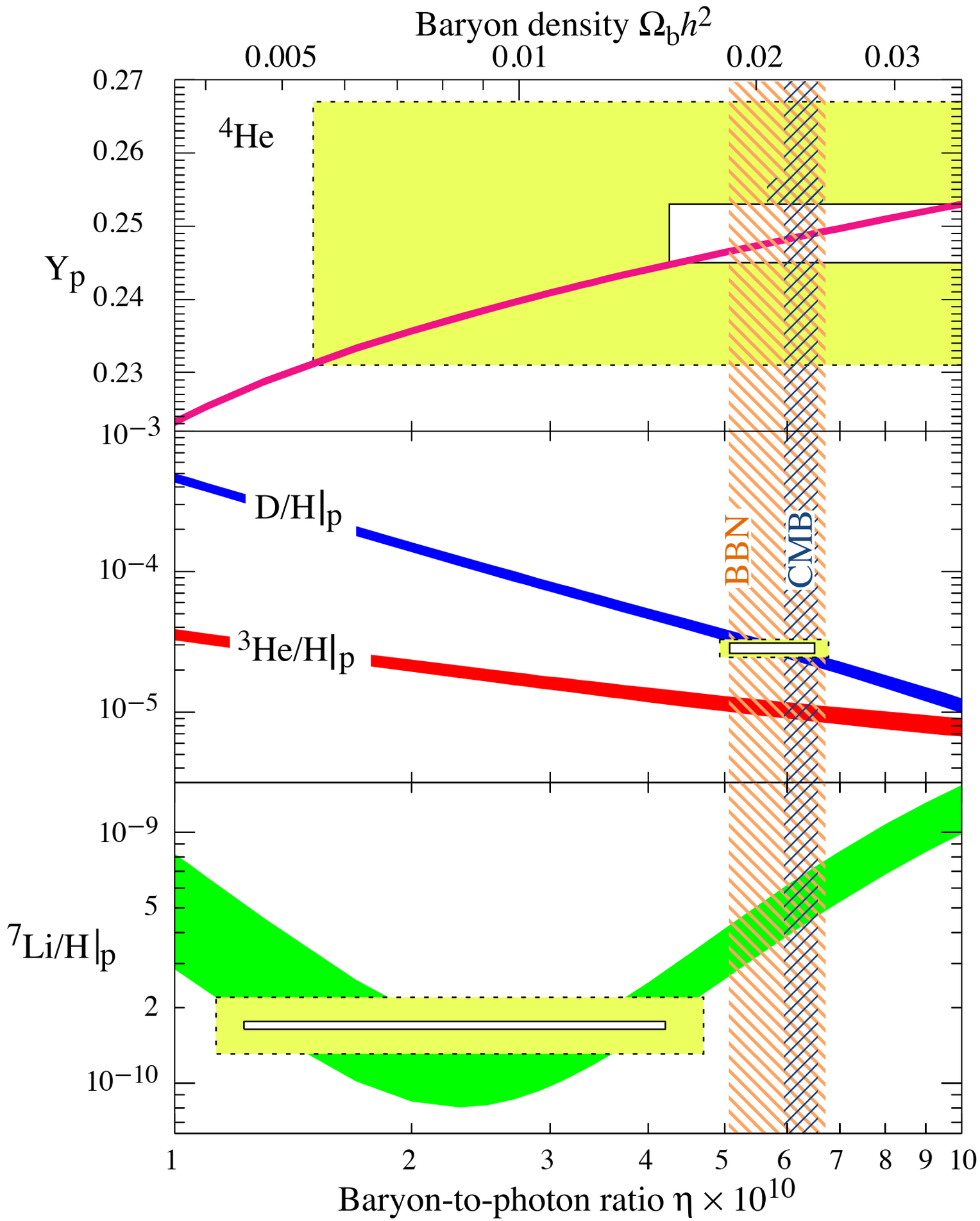
anti-matter

Current Universe

matter *anti-matter*

We wouldn't exist!

PDG



$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$

Early Universe

1,000,000,002

1,000,000,000

matter

anti-matter

Current Universe

2

•

us

matter *anti-matter*

We won! But *why*?

Beginning of Universe

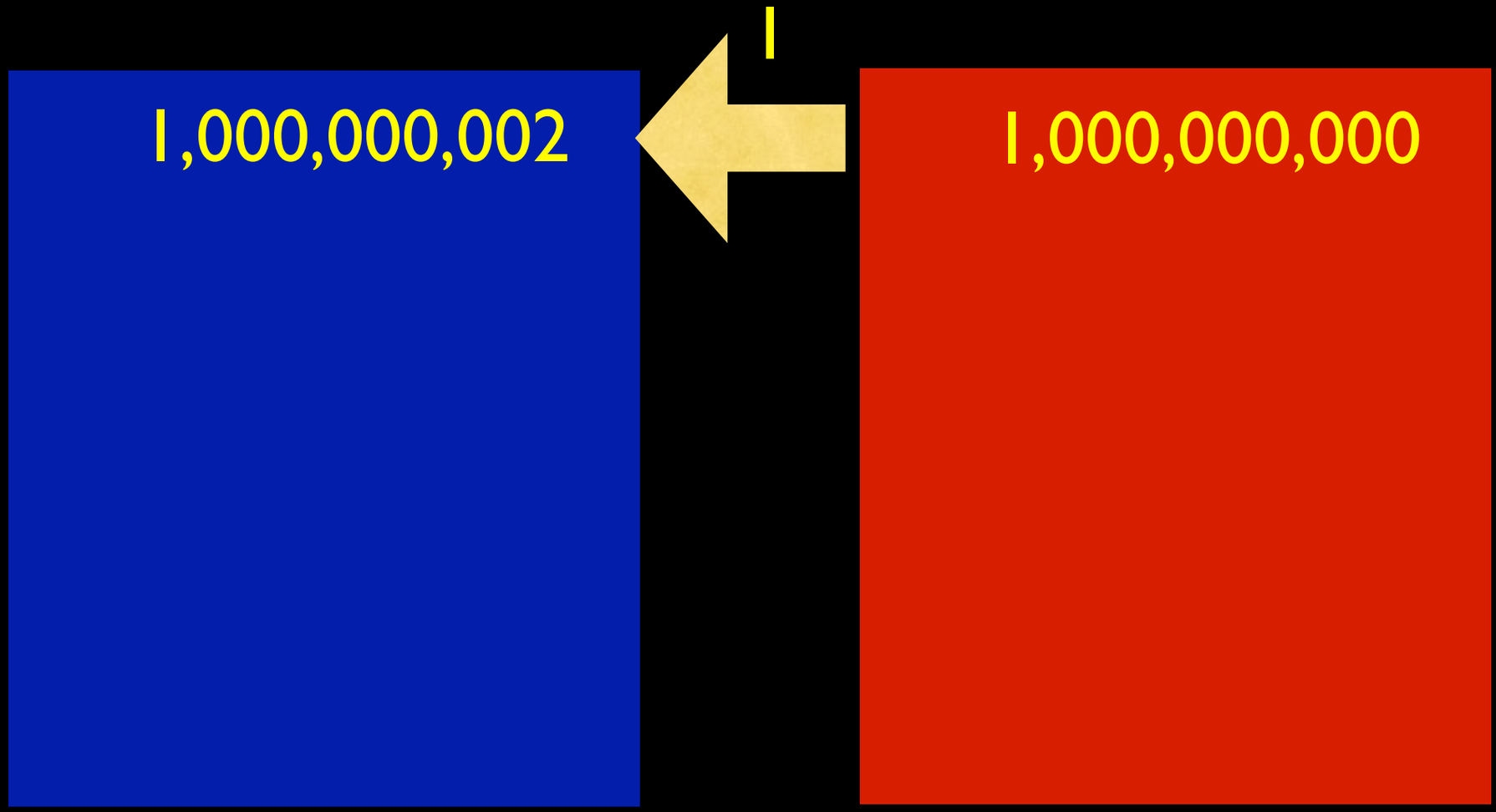
1,000,000,001

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*

This must be how we survived the Big Bang!

Sakharov's conditions

- Need to reshuffle matter and anti-matter
  - baryon-number violation
- need to prefer matter over anti-matter
  - CP violation
- need process but not inverse process
  - departure from equilibrium

Electroweak Baryogenesis

Standard Model

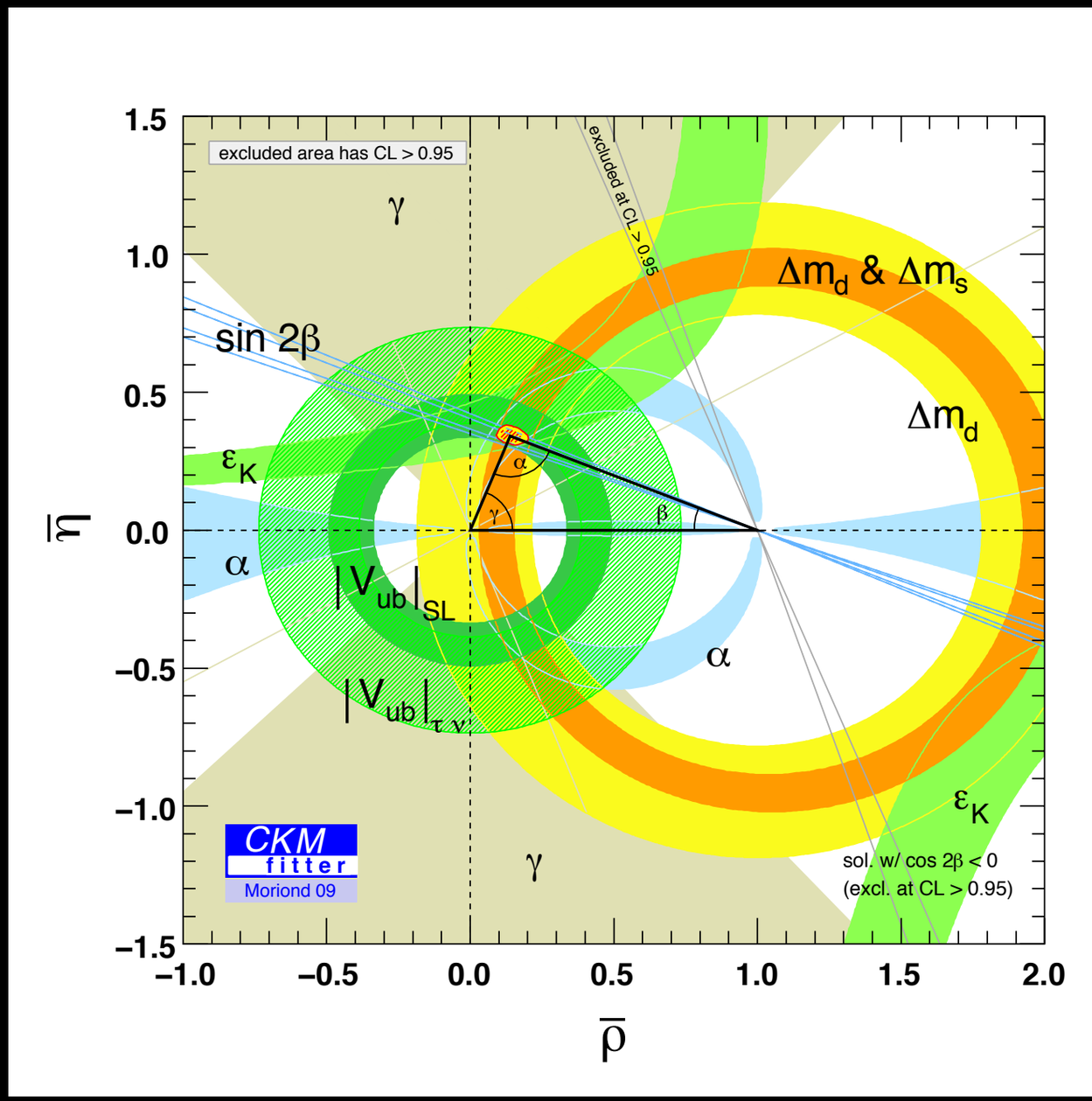
- Standard Model has all three ingredients
- Baryon number violation
  - Electroweak anomaly (sphaleron effect)
- CP violation
  - Kobayashi–Maskawa phase
- Non-equilibrium
  - First-order phase transition of Higgs Bose–Einstein condensate

Kobayashi-Maskawa

- Known CP-violating phenomena can all be explained by Kobayashi-Maskawa theory
- There is only a single CP-violating phase (Jarlskog inv.)

$$J = \Im m \, \det[Y_u^\dagger Y_u, Y_d^\dagger Y_d]$$
$$= (y_c^2 - y_u^2)(y_t^2 - y_u^2)(y_t^2 - y_c^2)$$
$$(y_s^2 - y_d^2)(y_b^2 - y_d^2)(y_b^2 - y_s^2)$$
$$\Im m(V_{us} V_{cb} V_{ub}^* V_{cs}^*) \sim 10^{-20}$$

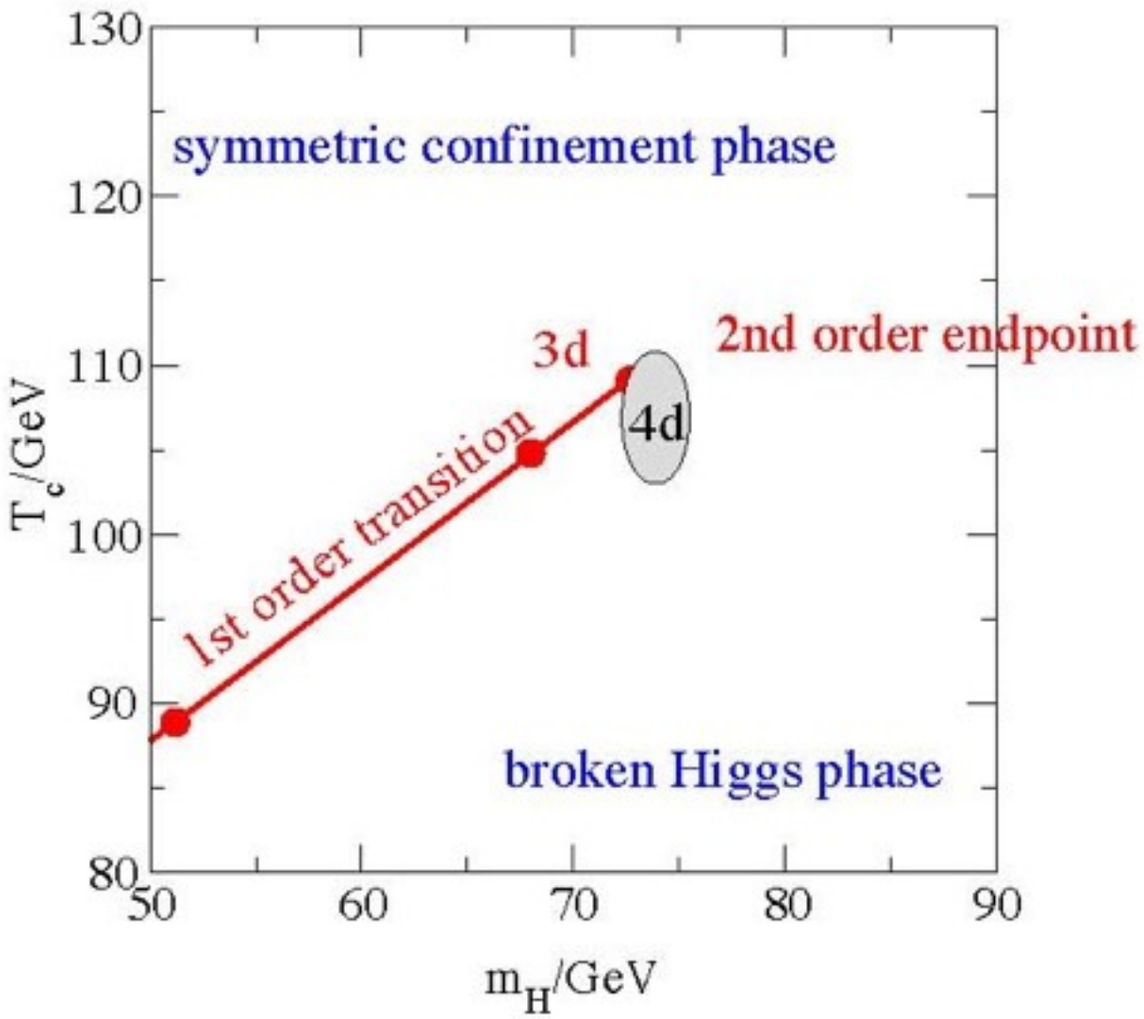
- Not enough! Can't create excess quarks over anti-quarks

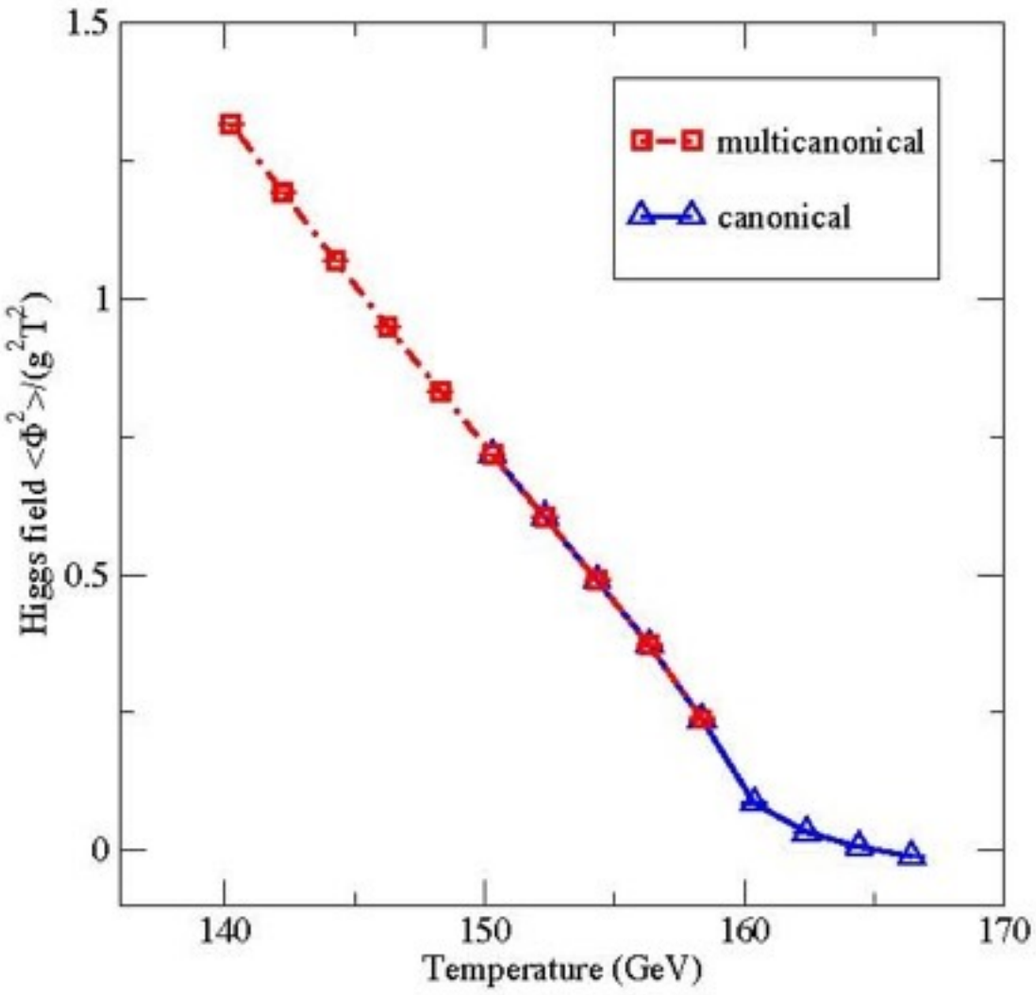


Need new source of CP violation!

Mikko Laine (Bern)

Phase diagram for the Standard Model:





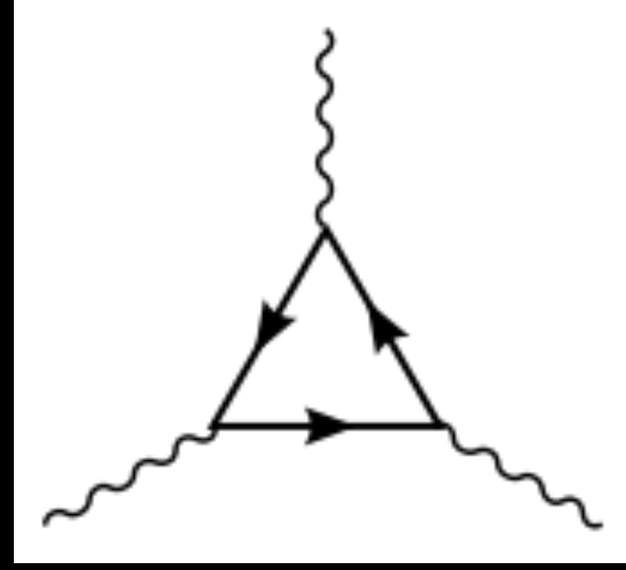
<H>=0 from gauge invariance (Elitzur)

<H†H> is not an order parameter

for m_h=126GeV, it is crossover

No phase transition in the Minimal Standard Model

‘t Hooft



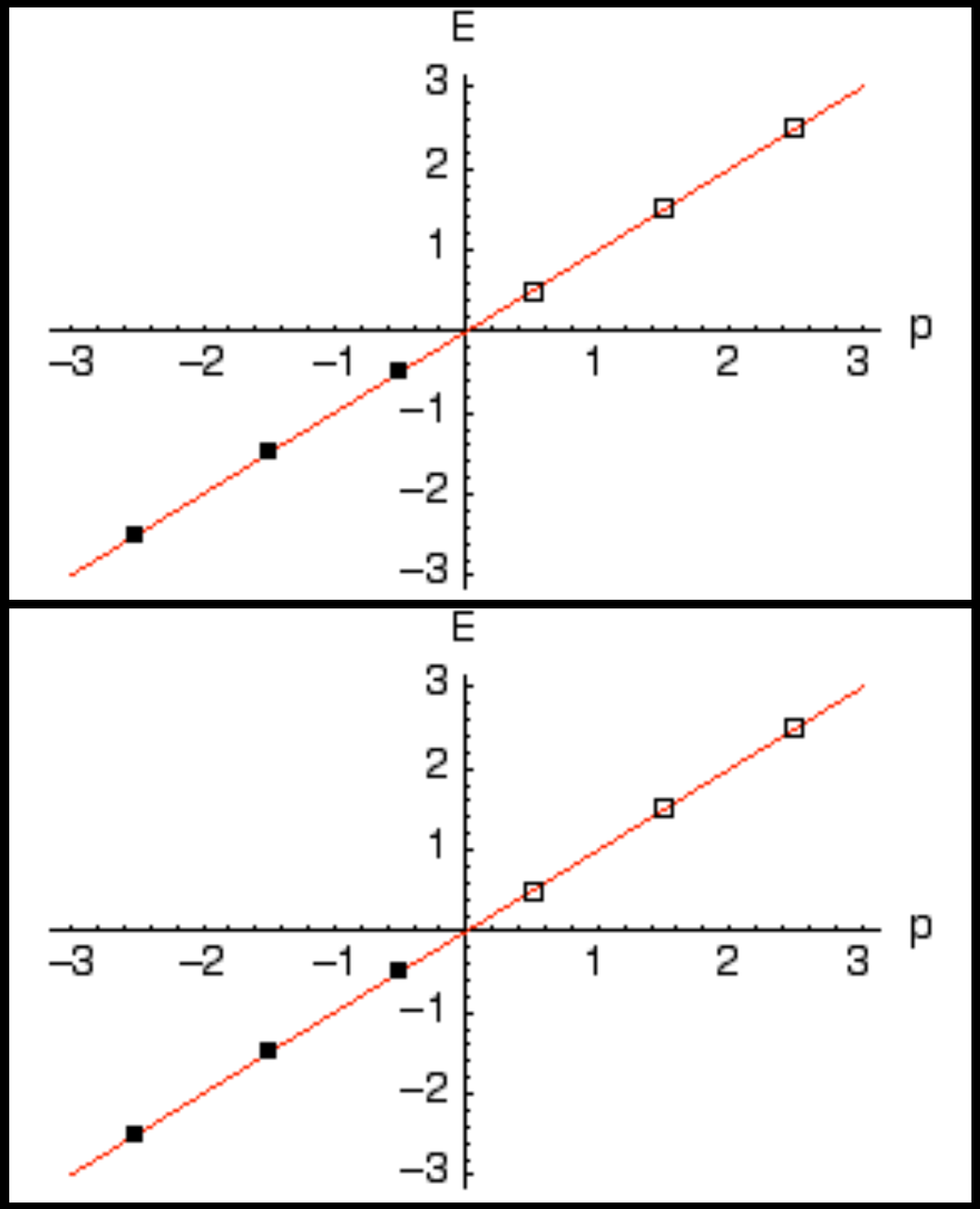
$$\partial_\mu j^\mu_L = \partial_\mu j^\mu_B = \frac{N_g}{64\pi^2}\epsilon^{\mu\nu\rho\sigma} W^a_{\mu\nu} W^a_{\rho\sigma}$$

- Standard Model actually violates the baryon number from the triangle anomalies
- conserves *B*–*L*
- can in principle lead to $^3\mathrm{He} \rightarrow e^+\mu^+\nu_\tau$
- my back-on-envelope estimate $\tau \sim 10^{150}$ yrs
- but can have impact in early universe

Electroweak Anomaly

- In Early Universe (T>200GeV), *W*-boson is massless and fluctuate in *W* plasma

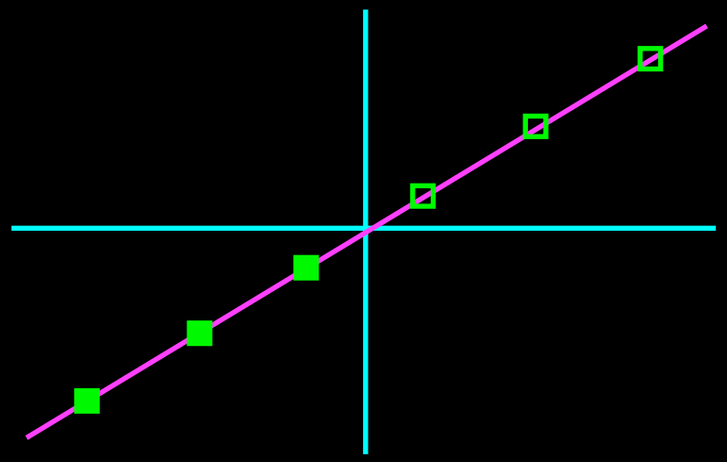
- Energy levels for left-handed quarks/leptons fluctuate correspondingly



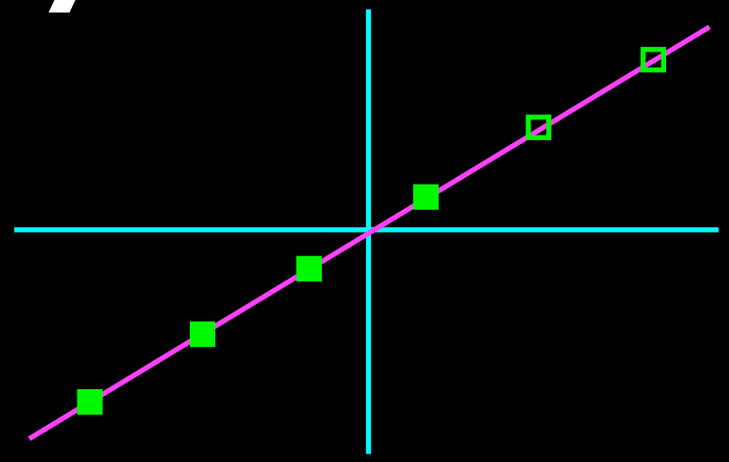
$$\Delta L=\Delta Q=\Delta Q=\Delta Q=1$$

$$\Delta(B-L)=0$$

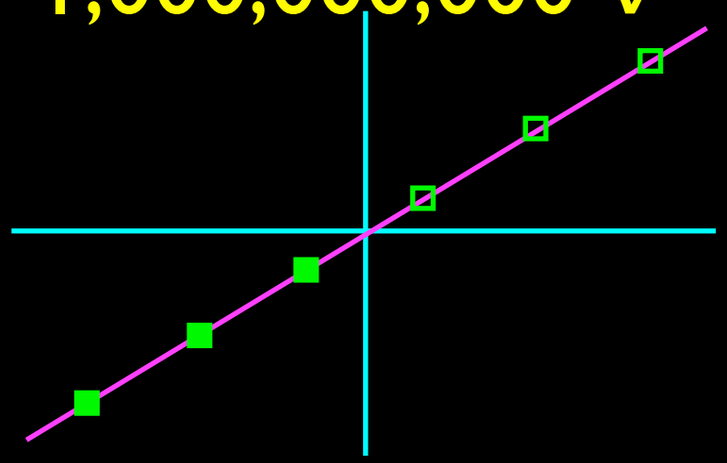
What anomaly can do

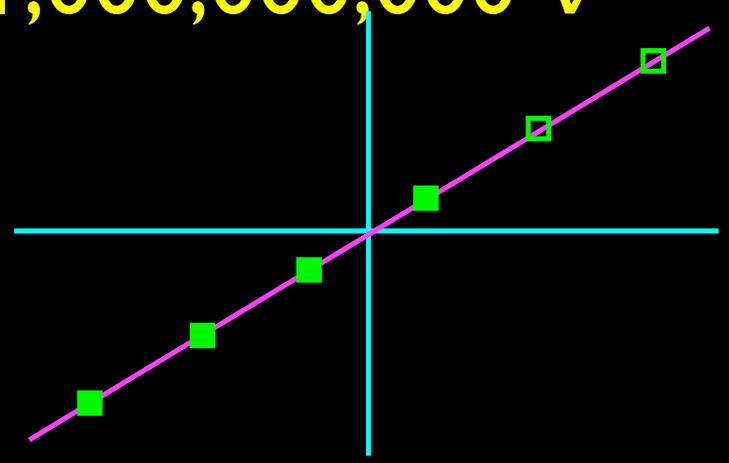


- 1,000,000,000 q
- 1,000,000,000 $\bar{q}$
- 1,000,000,000 ν
- 1,000,000,000 $\bar{\nu}$



- 1,000,000,001 q
- 1,000,000,000 $\bar{q}$
- 1,000,000,001 ν
- 1,000,000,000 $\bar{\nu}$

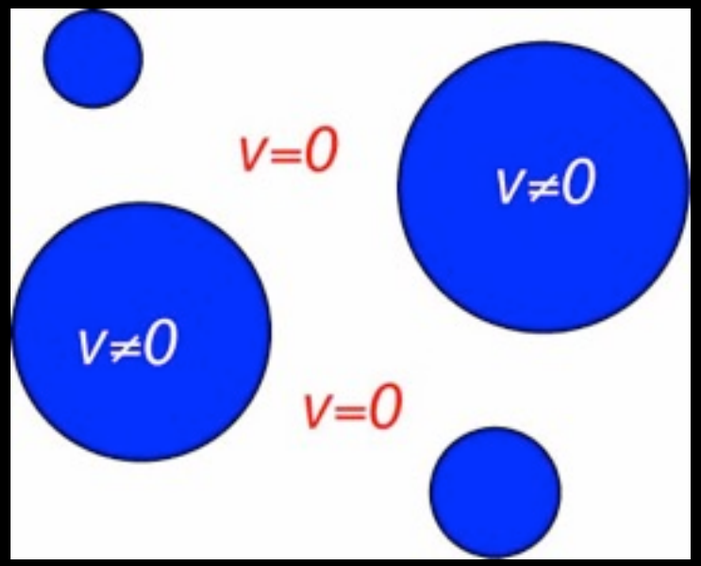


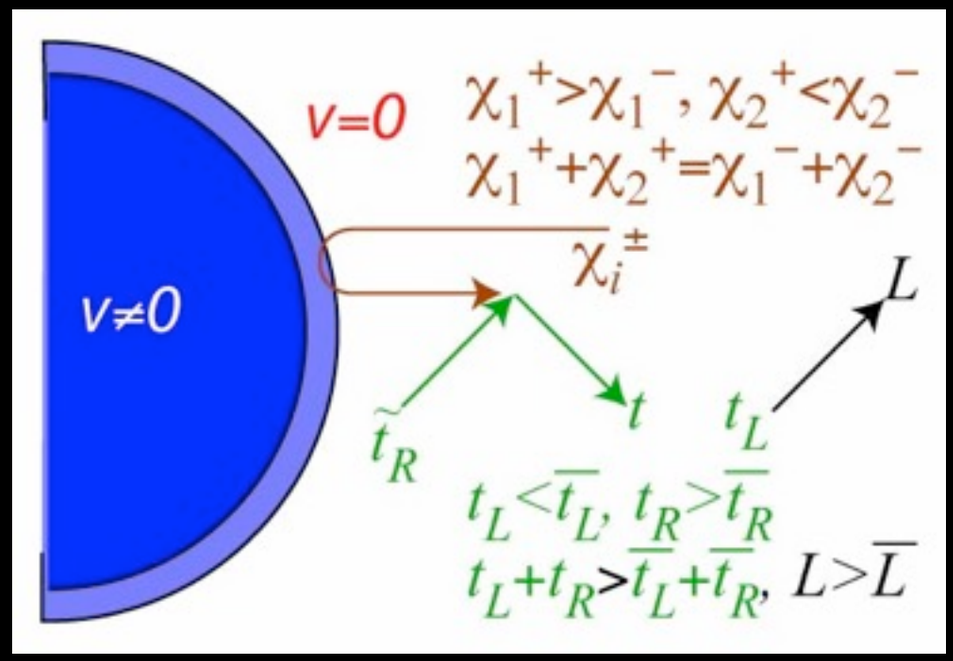



FASTEN
SEAT
BELT

Scenario in MSSM

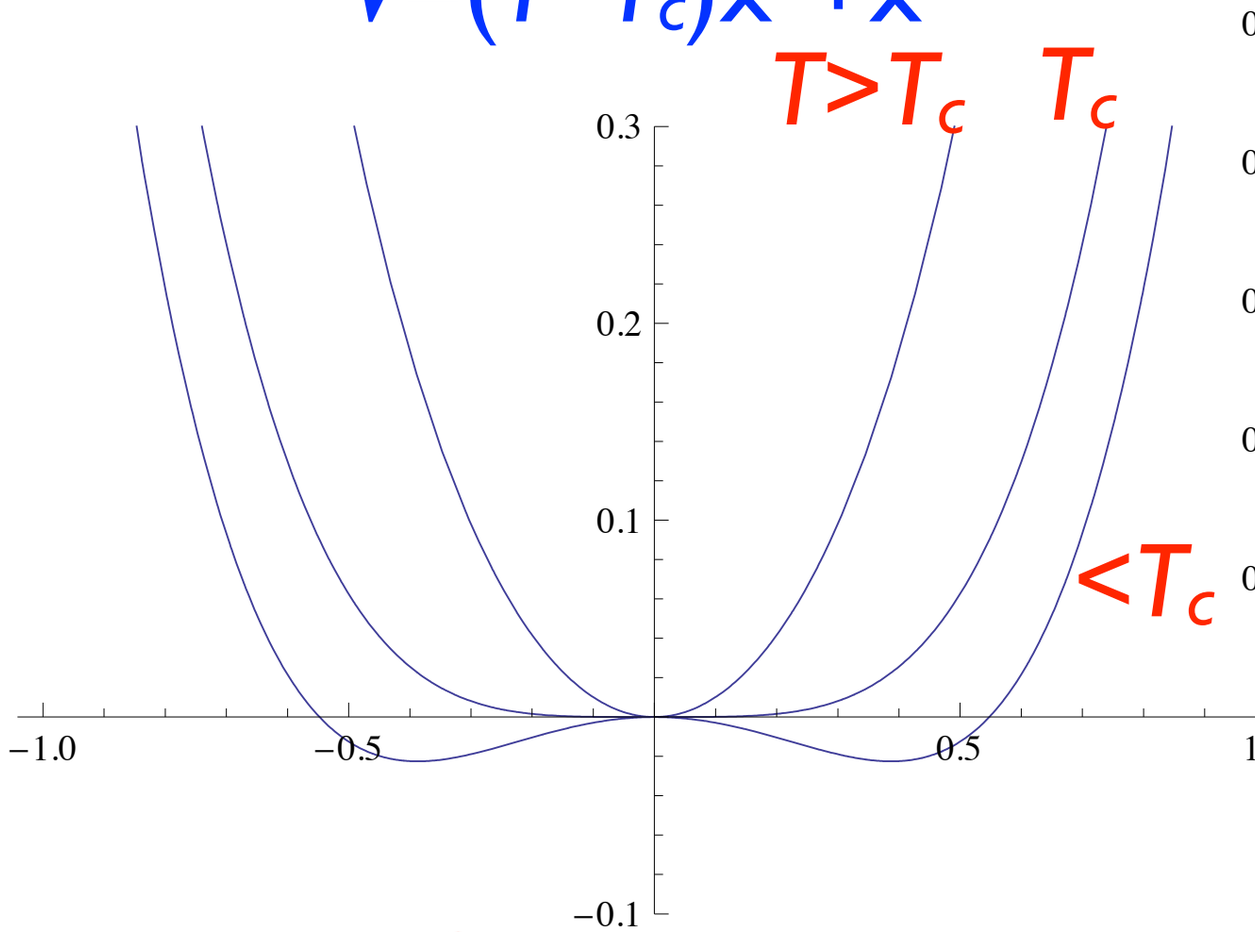
- $\mathrm{Im}(M_2\mu^*)\neq 0$ violates CP
- First order phase transition
- Different reflection probabilities for chargino species
- Chargino interaction with thermal bath produces an asymmetry in top quark
- Left-handed top quark asymmetry partially converted to lepton asymmetry via anomaly
- Remaining top quark asymmetry becomes baryon asymmetry





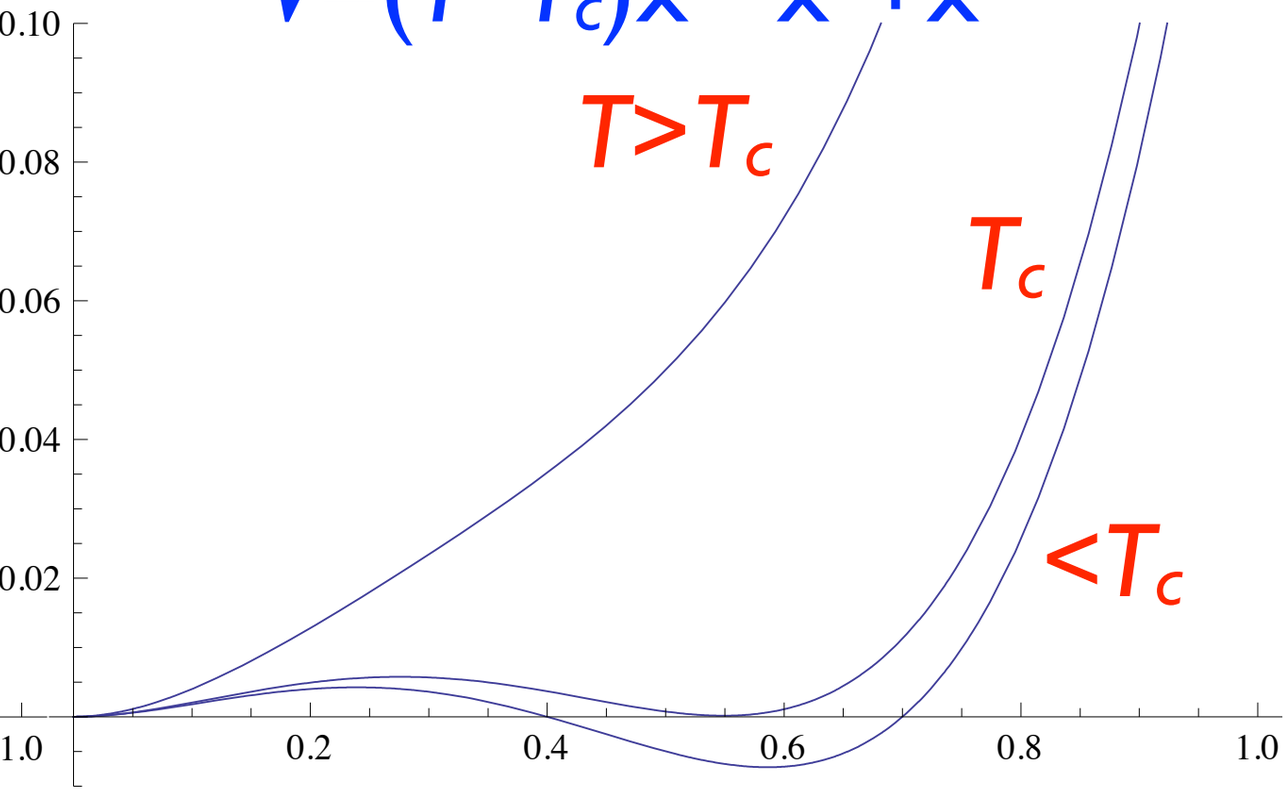
Order of phase transition

$V=(T-T_c)x^2+x^4$



2nd order

$V=(T-T_c)x^2-x^3+x^4$

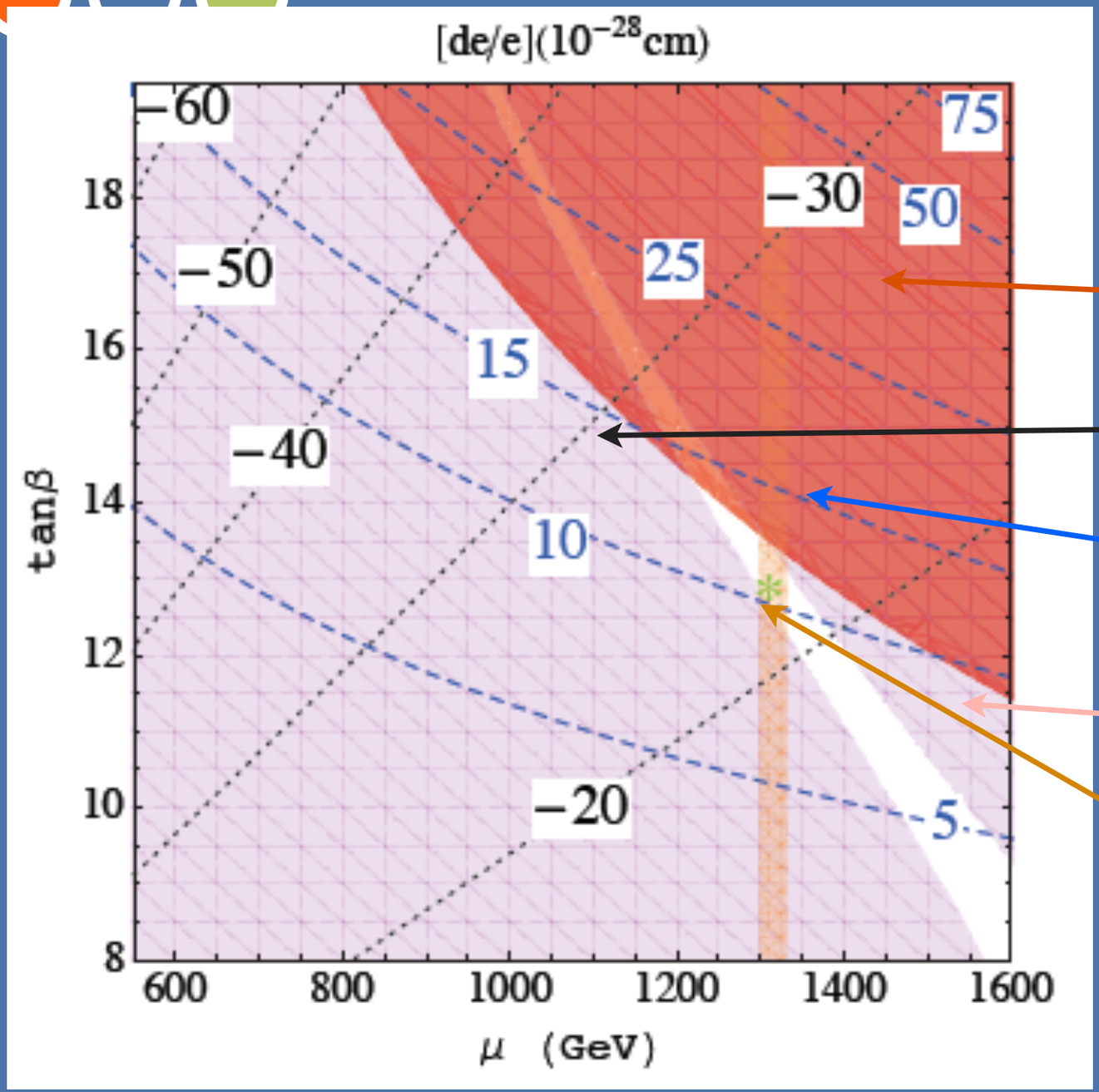


1st order

need some modification to Higgs potential
measure Higgs self-coupling ⇒ ILC, FCC

In MSSM, need m(stop)<160GeV, pratically dead

Final Results



Open the Heavy Higgs CPV search

Mercury exclusion

Chargino contour

Stau contour

ACME exclusion $|d_e|<8.7\times10^{-29}$ ecm

Preferred by EWBG

LG. Bian, T. Liu, J. S, 1411.6695

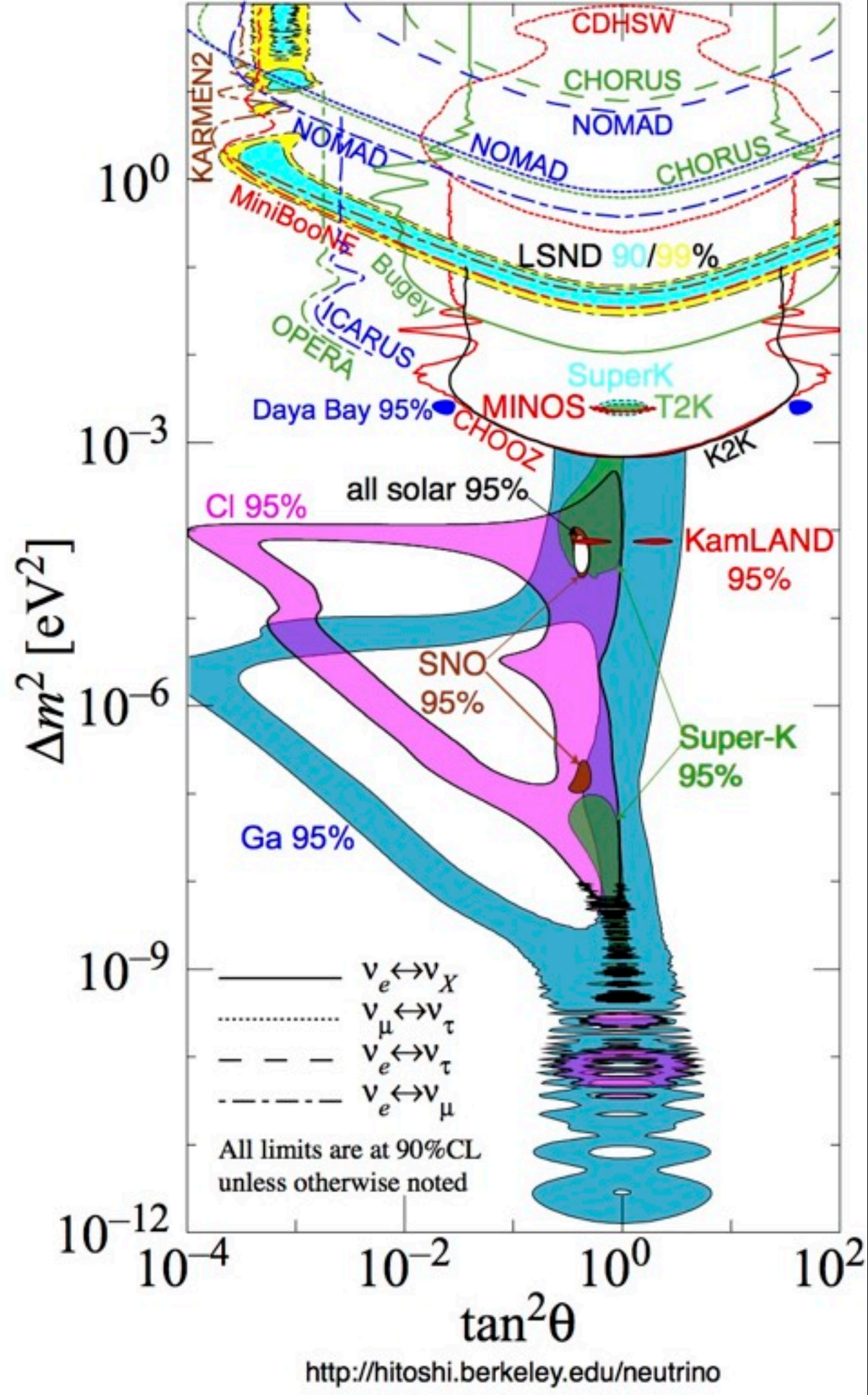
Leptogenesis

Neutrinos?

- Now we know they have mass

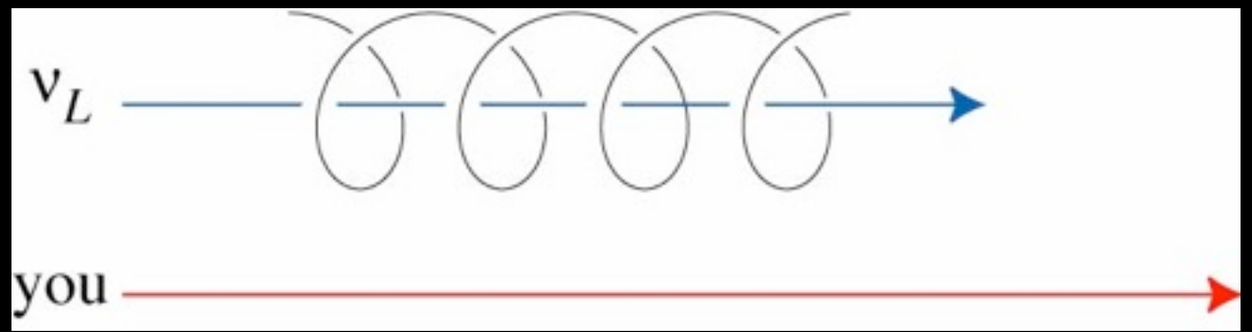
- The only matter particles that are electrically neutral

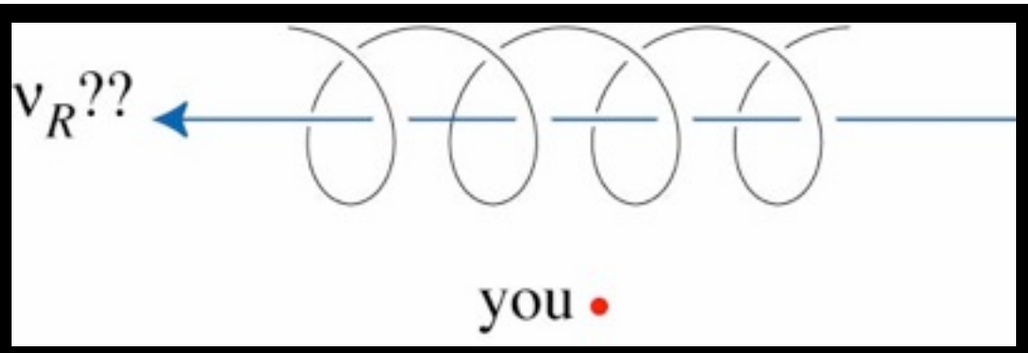
- may reshuffle matter and anti-matter?



Neutrinos have mass

- They have mass. Can't go at speed of light.





What is this right-handed particle?

New particle: right-handed neutrino (Dirac)

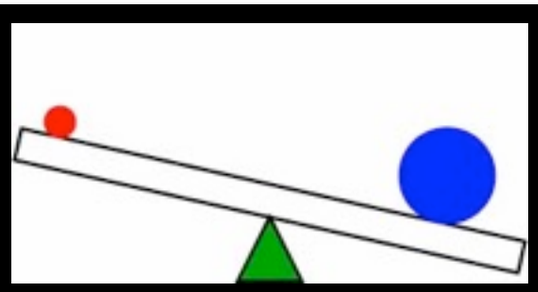
Old anti-particle: right-handed anti-neutrino (Majorana)

Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass, but ν_R SM neutral

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

$$m_\nu = \frac{m_D^2}{M} << m_D$$



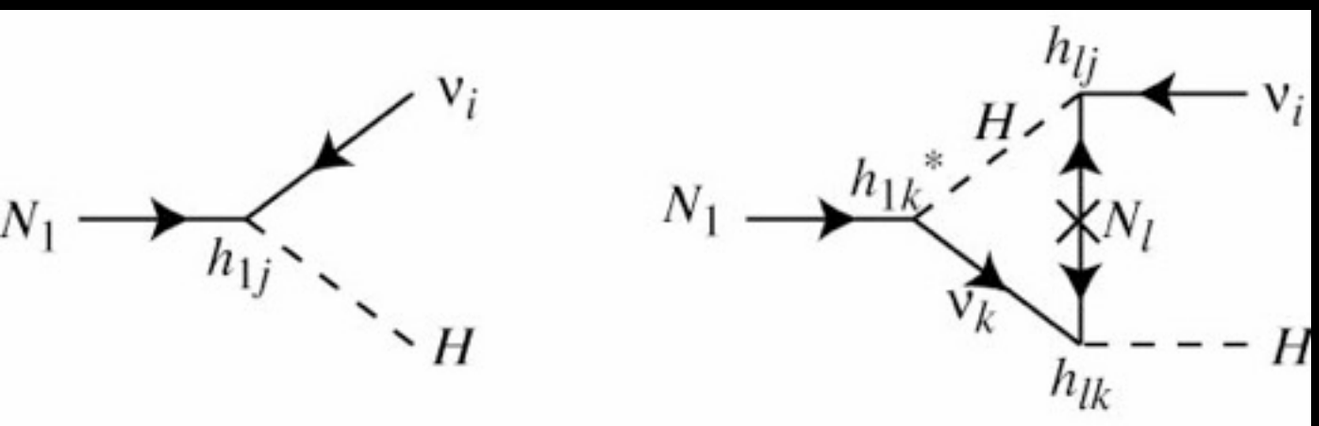
To obtain $m_3 \sim (\Delta m^2_{\text{atm}})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{14}$GeV

Leptogenesis

- Presumably three ν_R
- One of them lives long and decays late
- Majorana: $\nu_R = \bar{\nu}_R$

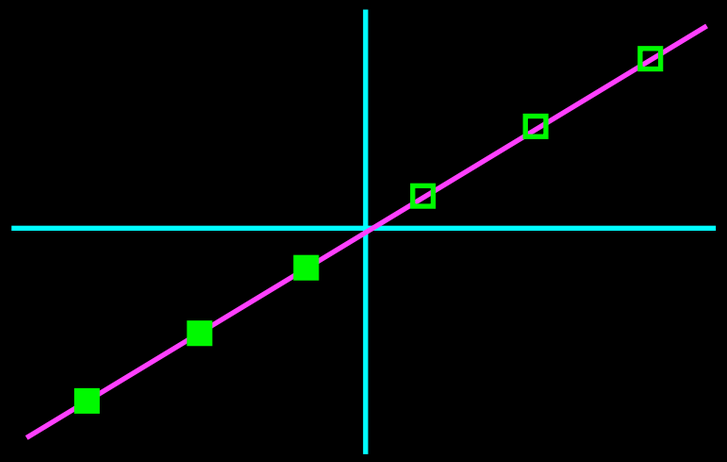
- @tree-level, decays 50:50 to ν_L+h, $\bar{\nu}_L$+h^*
- @one-loop,

$$\Gamma(\nu_R \to \nu_L + h) \propto 1 - \epsilon$$
$$\Gamma(\nu_R \to \bar{\nu}_L + h^*) \propto 1 + \epsilon$$

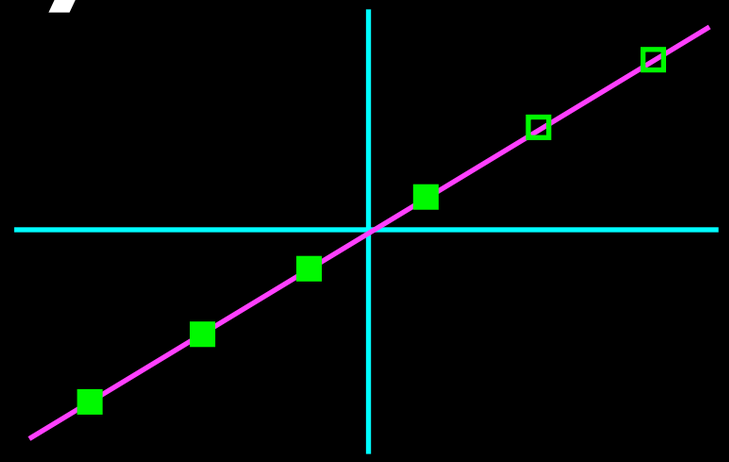


$$\epsilon \propto \Im m(h_{1j} h_{1k} h_{lk}^* h_{lj}^*)$$

What anomaly can do

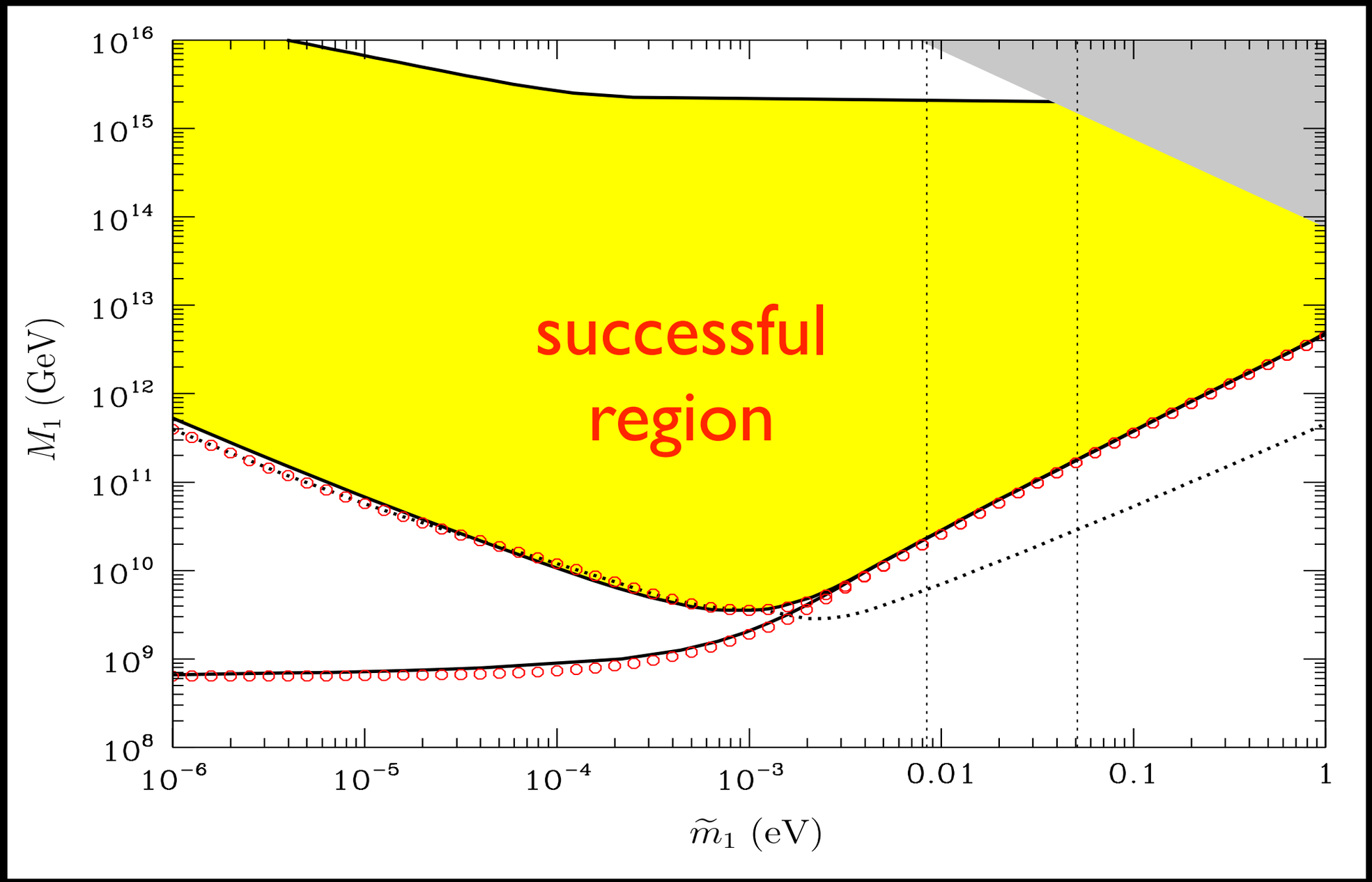


- 1,000,000,000 q
- 1,000,000,000 $\bar{q}$
- 1,000,000,000 ν
- 1,000,000,002 $\bar{\nu}$



- 1,000,000,001 q
- 1,000,000,000 $\bar{q}$
- 1,000,000,000 ν
- 1,000,000,001 $\bar{\nu}$

Non-trivial success!



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

di Bari, Plümacher, Buchmüller

How do we test it?

build a 10^{14} GeV collider

Japan Aerospace Exploration Agency

文部科学省

MEXT

MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

indirect evidences

- Are all mixing angles large-ish?
- Is CP violated in neutrino sector?
- Is neutrino Majorana?
- collect archaeological evidences

Excitement

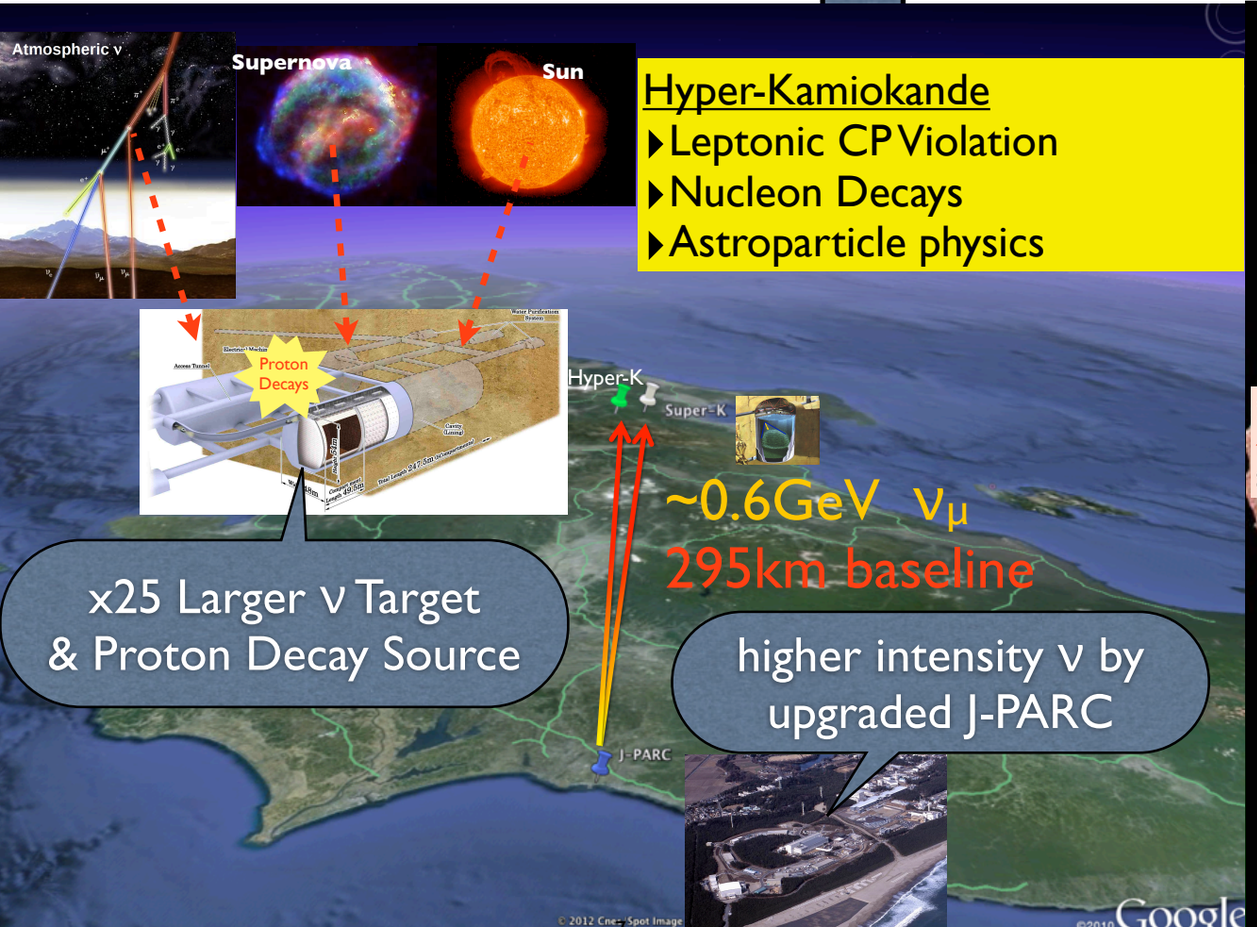
- CP violation in neutrino sector may be observable with conventional technique

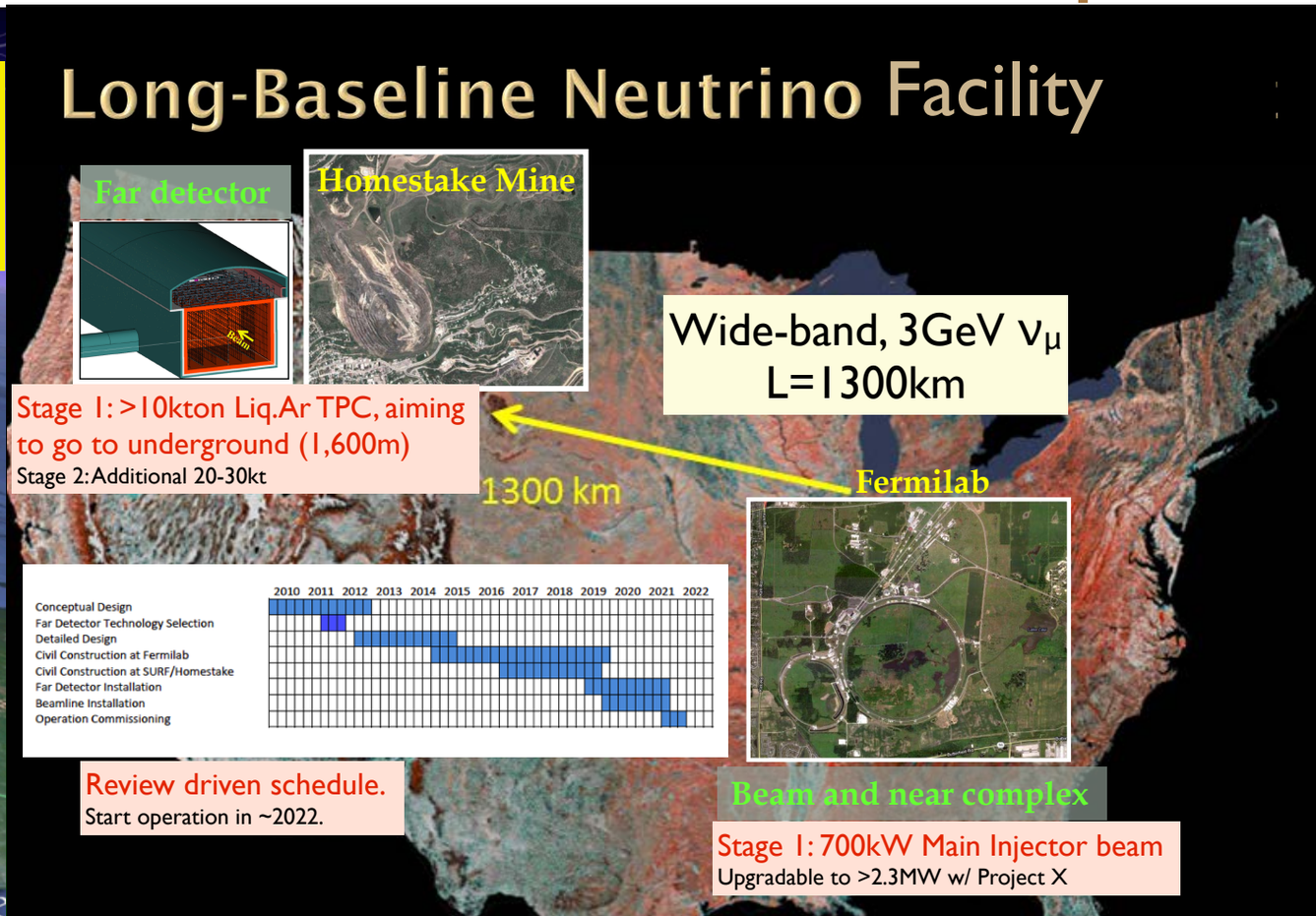
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\frac{\Delta m^2_{12} L}{4E} - \sin\frac{\Delta m^2_{13} L}{4E} - \sin\frac{\Delta m^2_{23} L}{4E} -$$

2002 KamLAND SNO

2012 Daya Bay

1998 Super-K

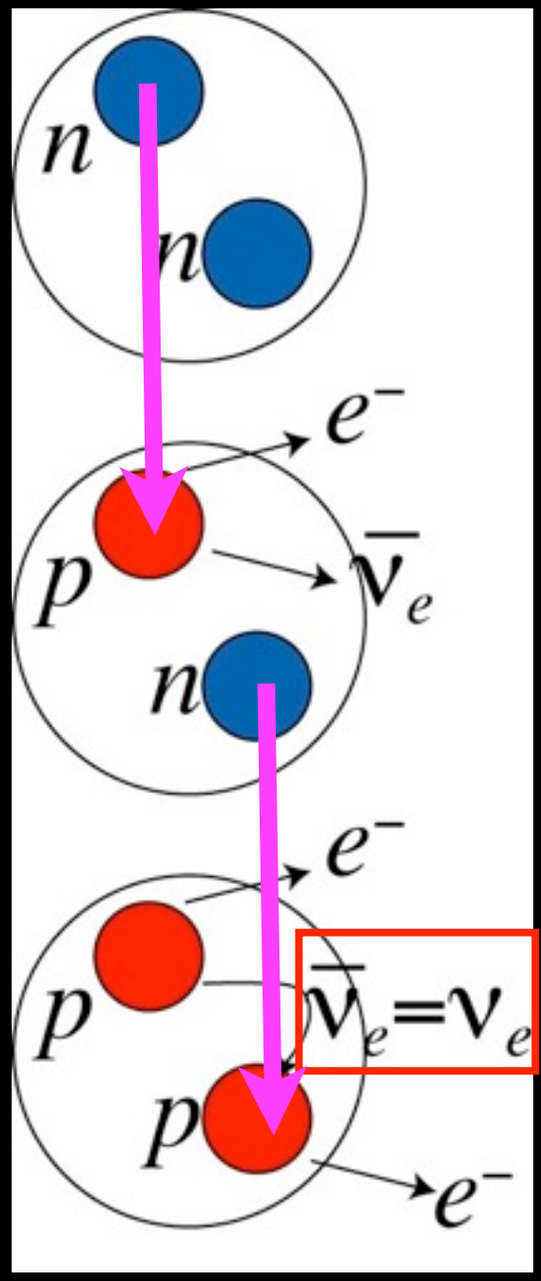




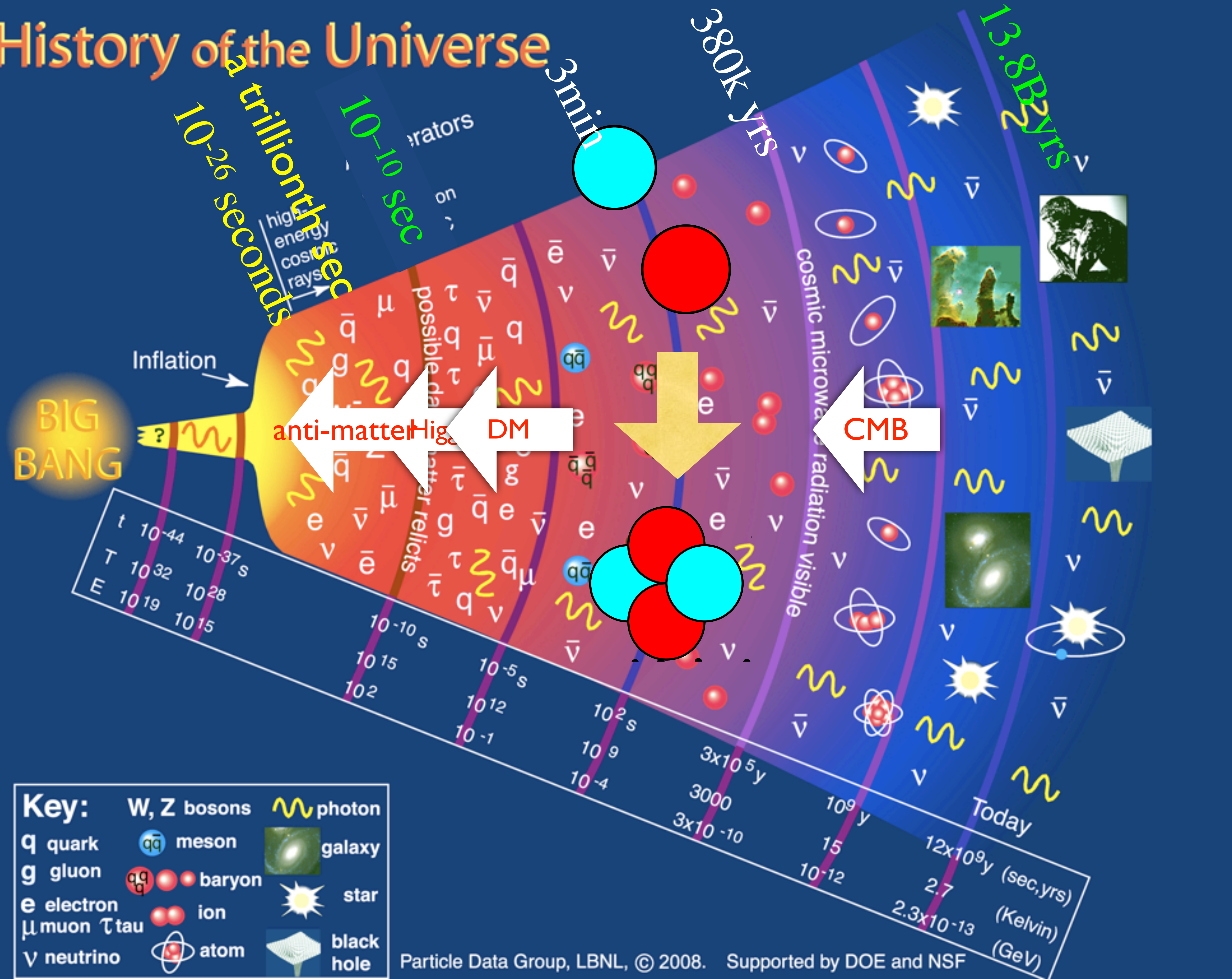
Turn anti-matter into matter

- Can anti-matter turn into matter?
- Maybe anti-neutrino can turn into neutrino because they don't carry electricity!
- $0\nu\beta\beta$: $nn \rightarrow ppe^-e^-$ with no neutrinos
- can happen only once 10^{24} years

patience!



History of the Universe



Physicists ask simple and profound questions

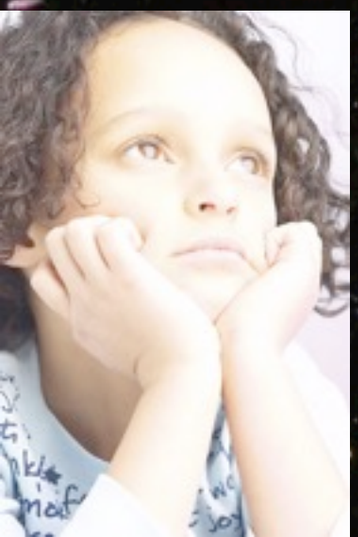
How did the Universe begin?

What is its fate?

What is it made of?

How does it work?

Where do we come from?



invisibles

neutrinos, dark matter & dark energy physics

Disney PRESENTS A PIXAR FILM

THE INCREDIBLES

NOW PLAYING