Why Are We Here?

Matter-Antimatter Asymmetry Of The Universe

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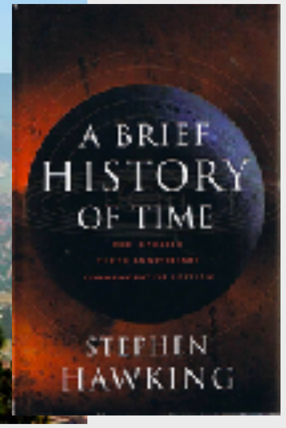
Cluster of Excellence
PRiSMA+
Precision Physics,
Fundamental Interactions
and Structure of Matter

Carleton
UNIVERSITY
Canada's Capital University



Karabuk, Turkey

Bilkent University, Ankara

Fermilab, Batavia

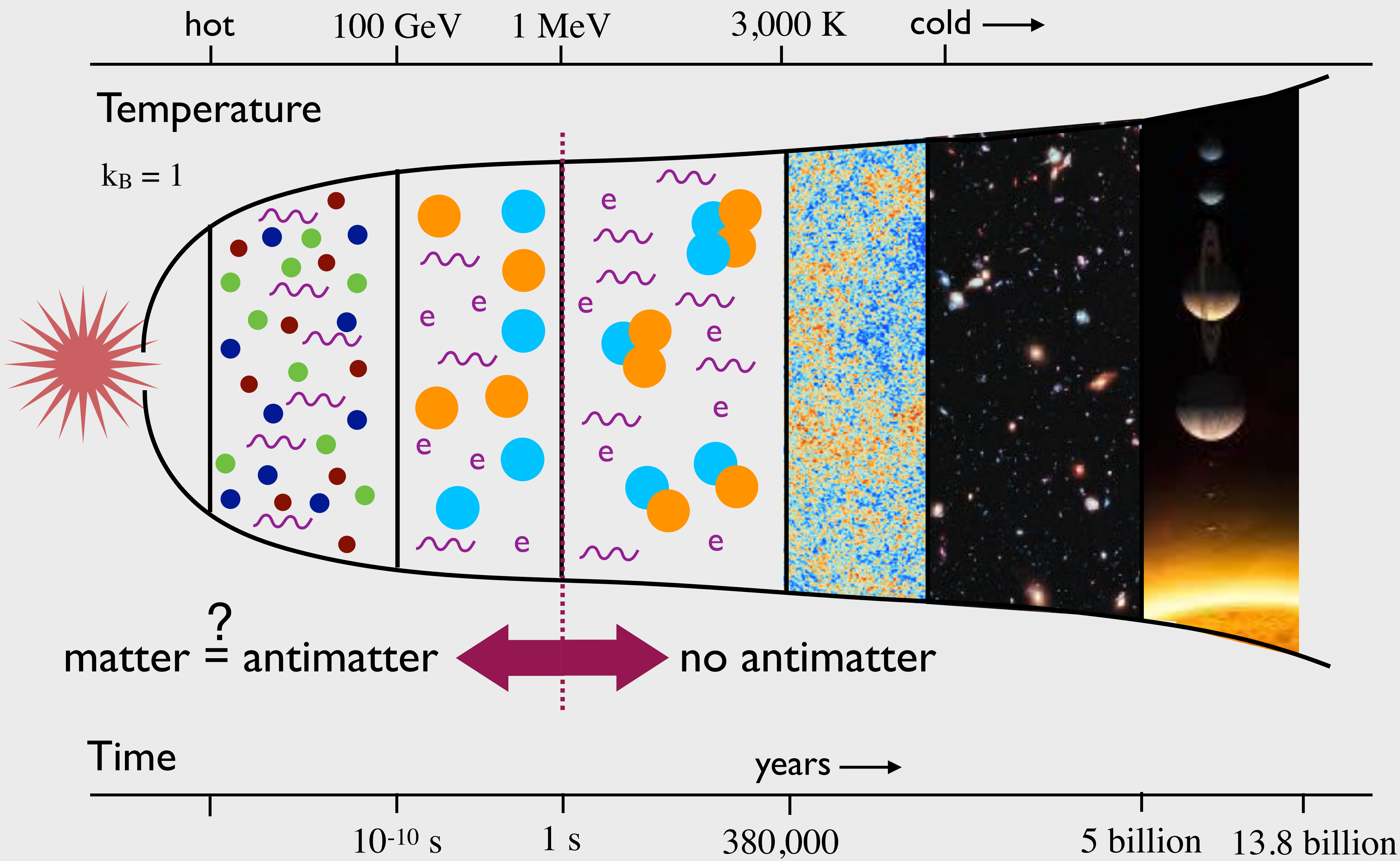
U of Washington, Seattle

Koc University, Istanbul

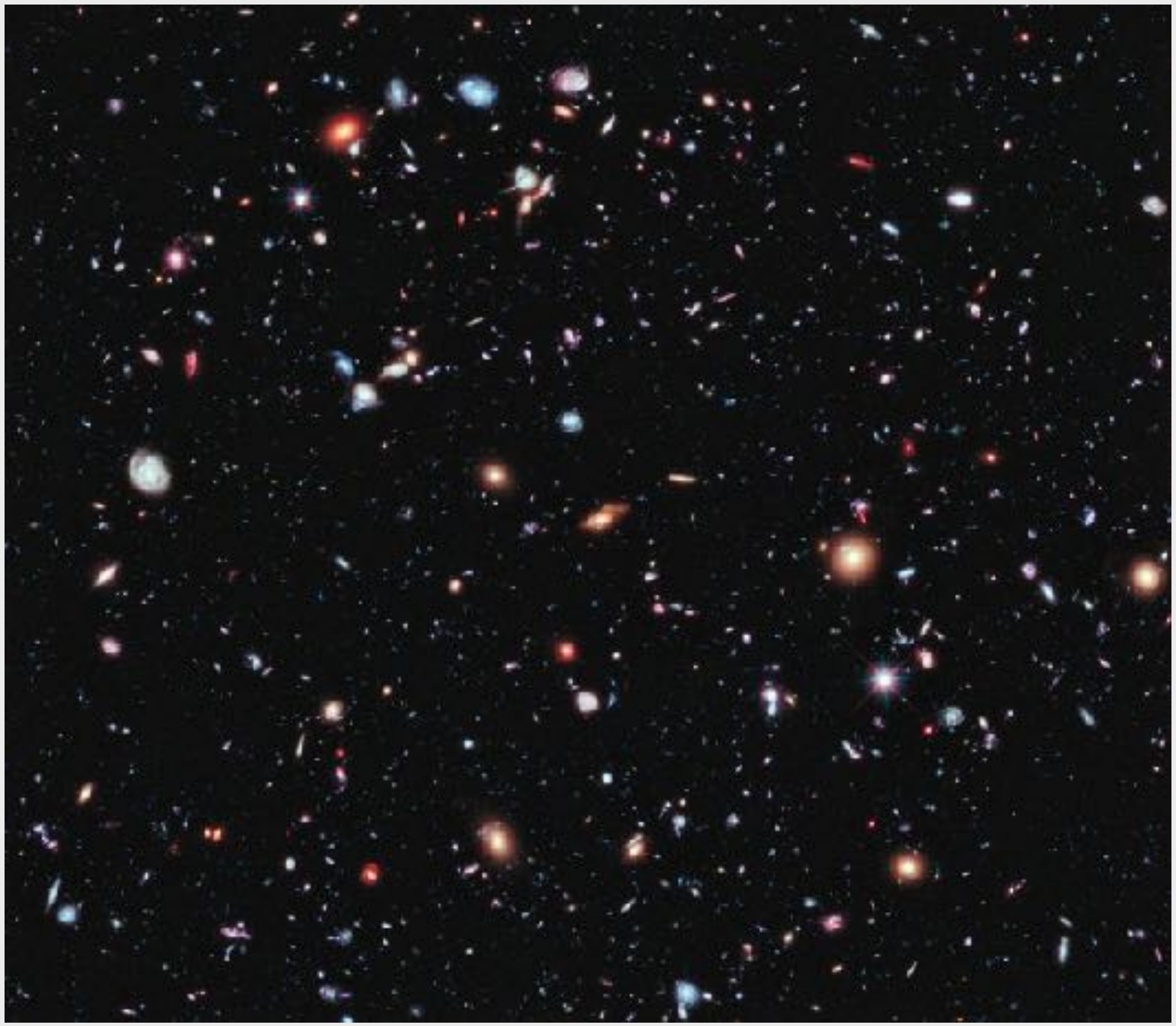
U of California, Irvine

Carleton U, Ottawa

A Brief History Of Our Universe



What is in our Universe?

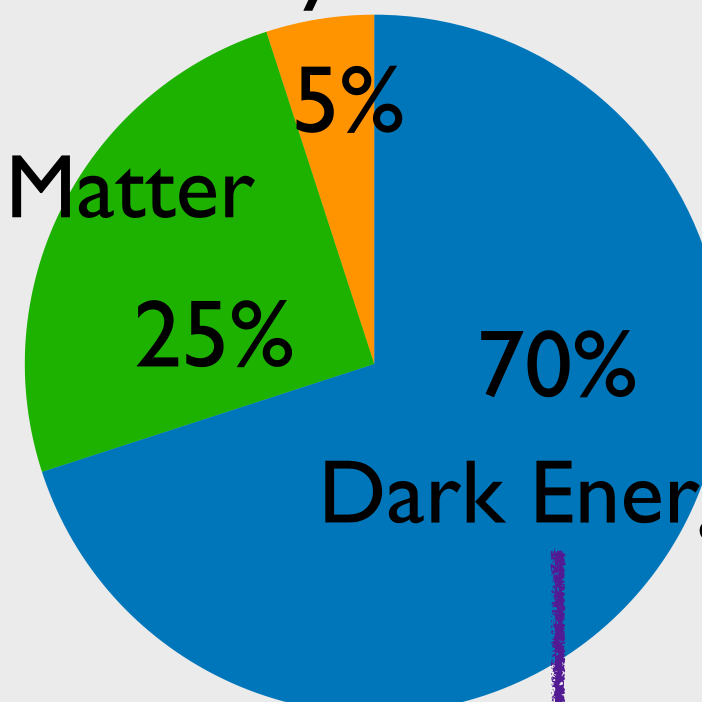


Our Universe (a few hundred millions years old)
image from Hubble Space Telescope

Ordinary Matter

Dark Matter

???

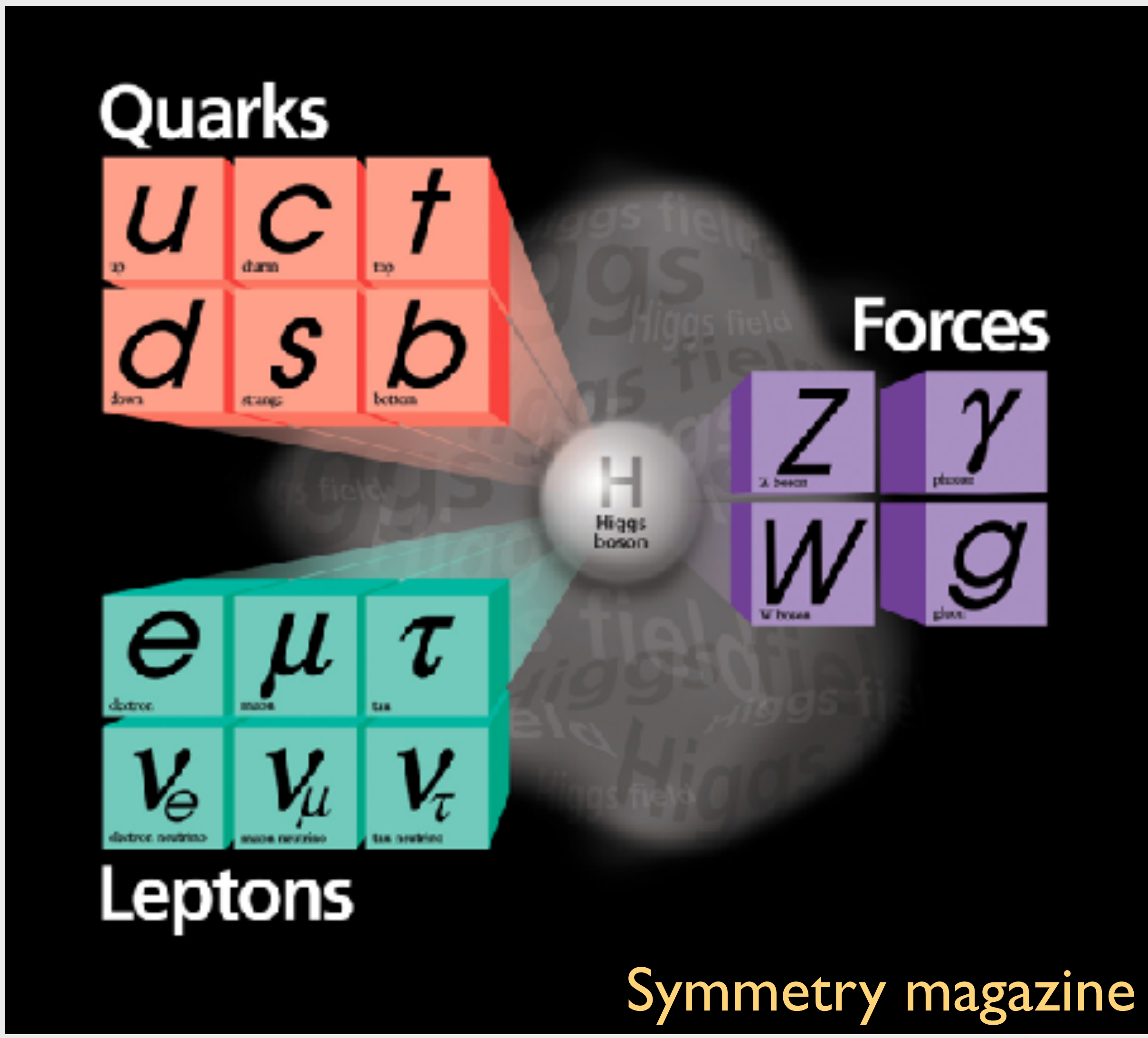


Dark Energy

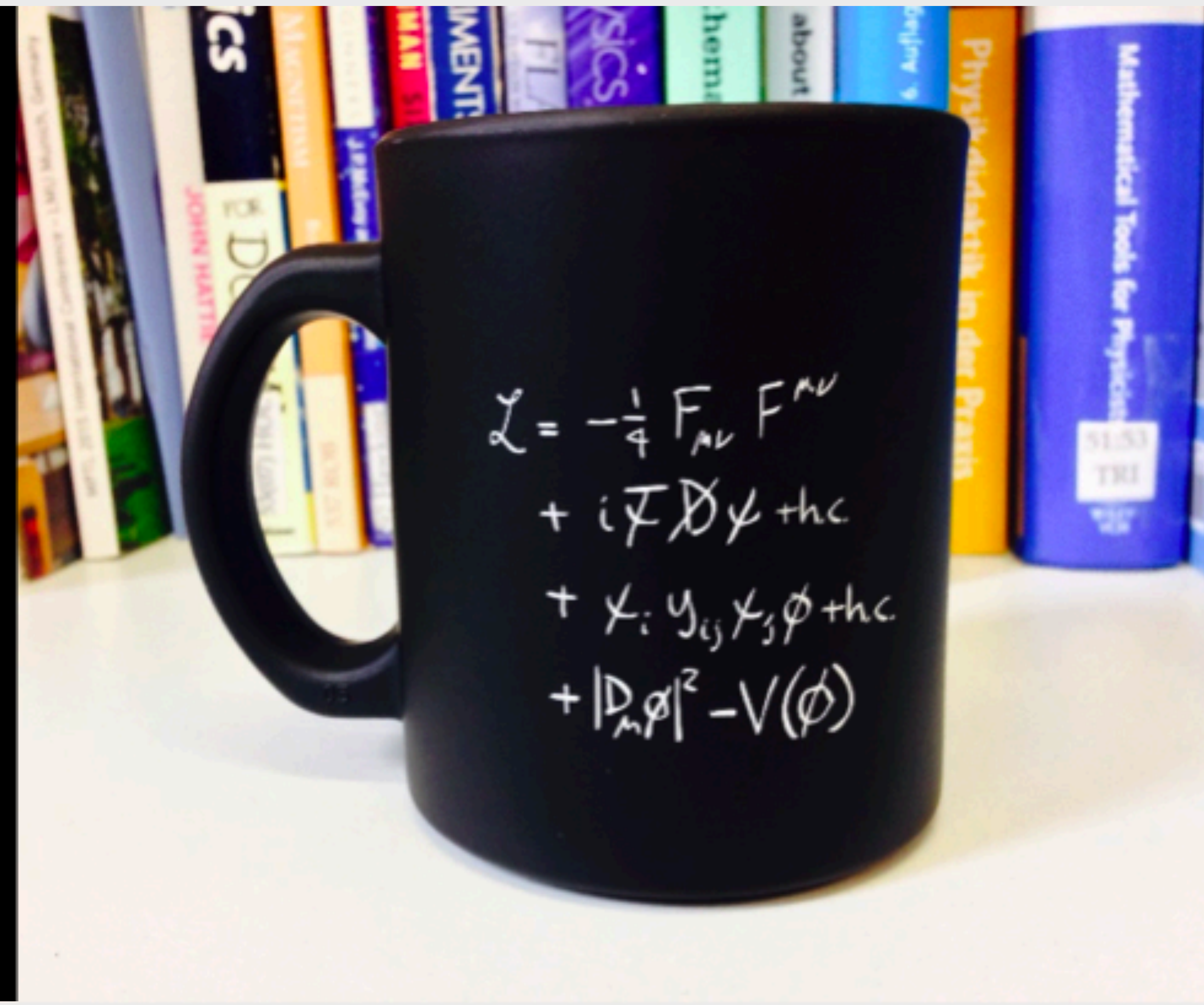
???

Elementary particles are described by the Standard Model (SM) of particle physics

$$SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{EM}$$



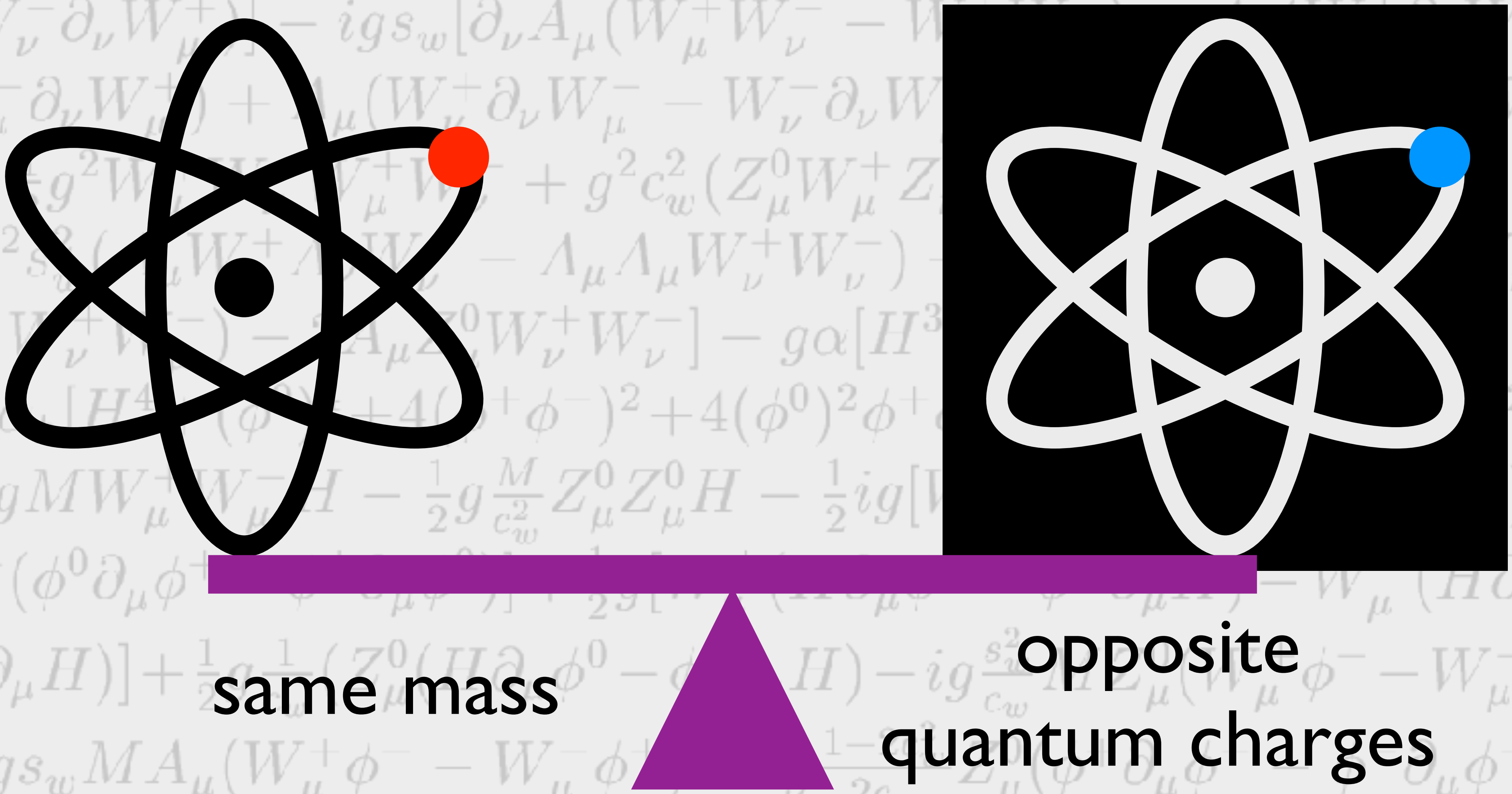
Symmetry magazine



Standard Model also has "antimatter"

proton + electron
=
hydrogen

anti-proton + positron
=
anti-hydrogen

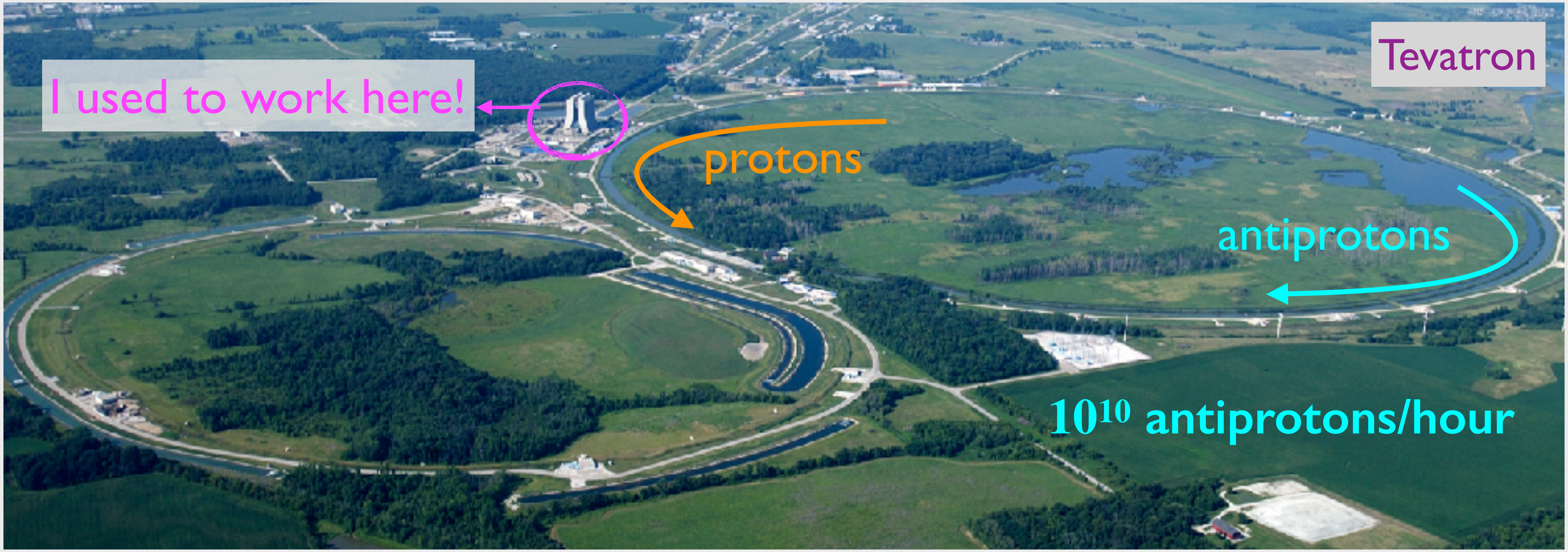


same mass

opposite
quantum charges

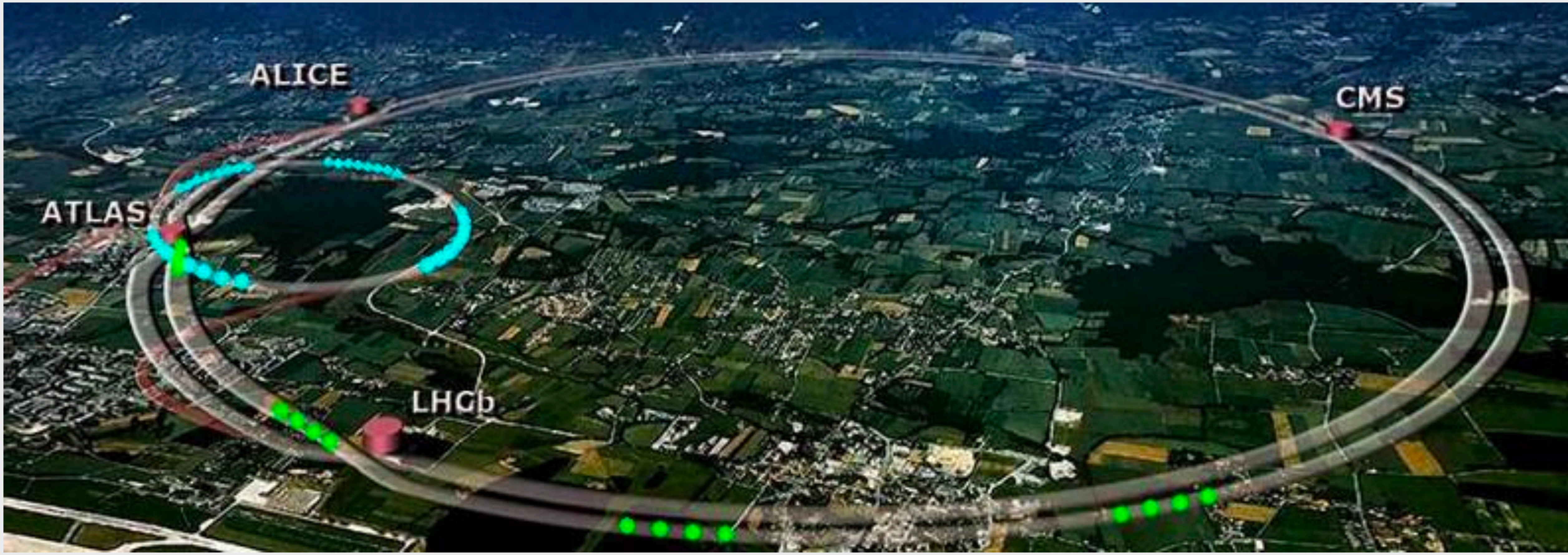
Antimatter is very normal!

Fermilab used to make a lot of antimatter!



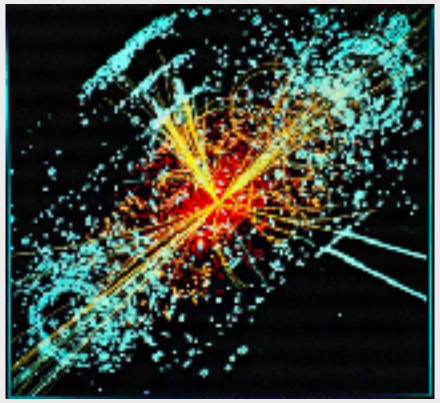
Batavia, IL USA

Large Hadron Collider at CERN



(France-Switzerland border)

Collides protons with protons → both matter and antimatter is produced!



Matter and Antimatter annihilate when they meet!

It's good NOT to have an anti-Seyda around!

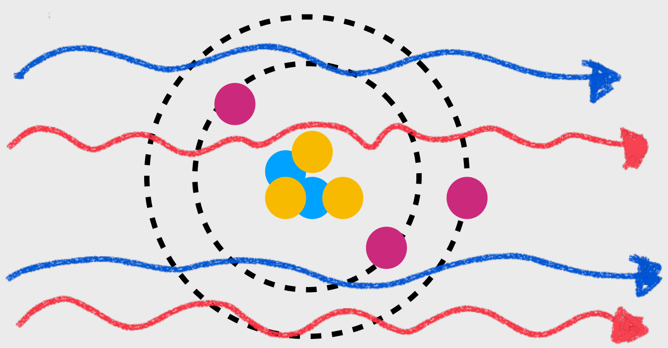
But here we are…

Thanks to a matter—antimatter asymmetry!

Cosmic Microwave Background

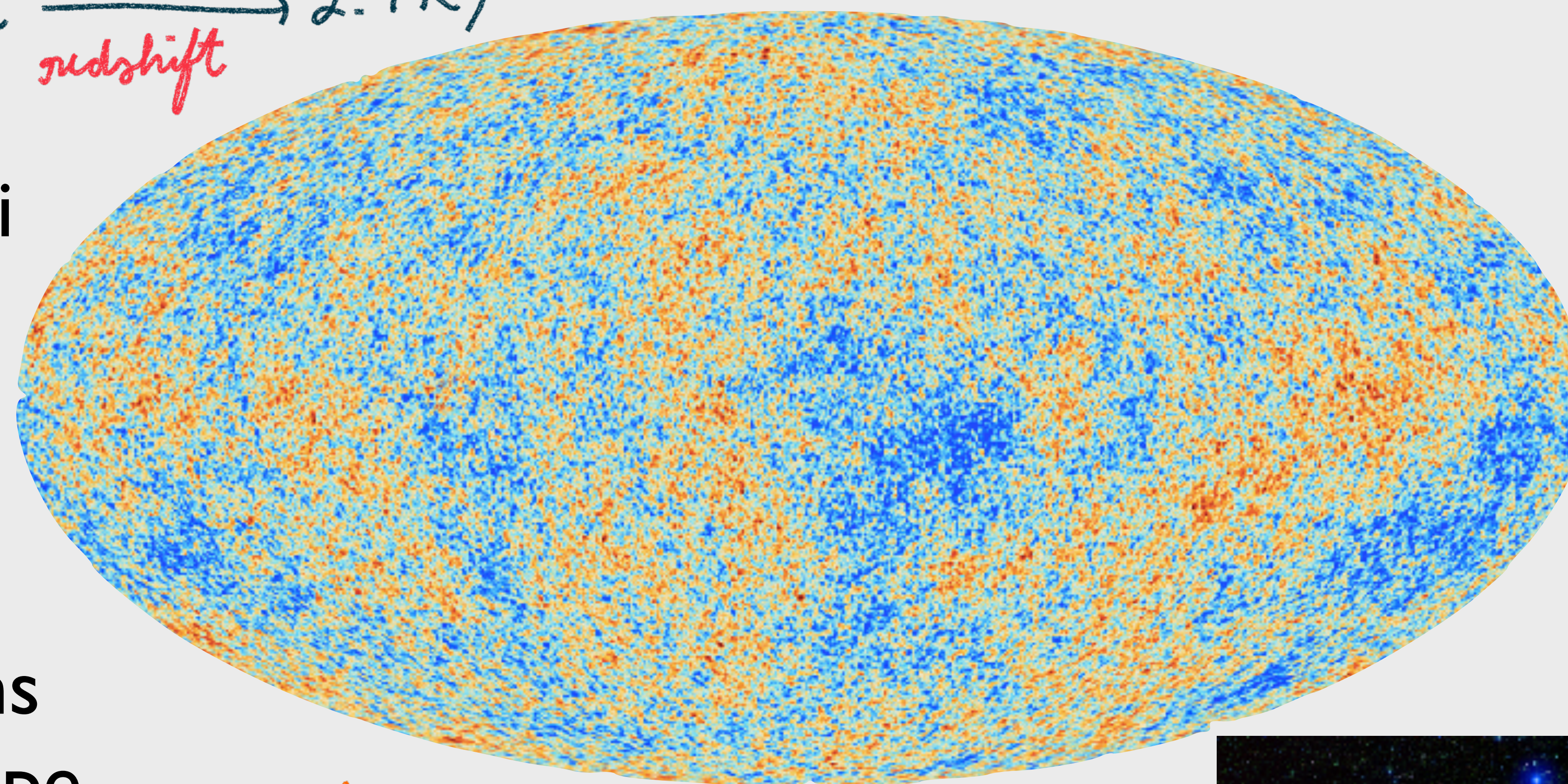
~380,000 years $(3000\text{ K} \xrightarrow[\text{redshift}]{} 2.7\text{K})$

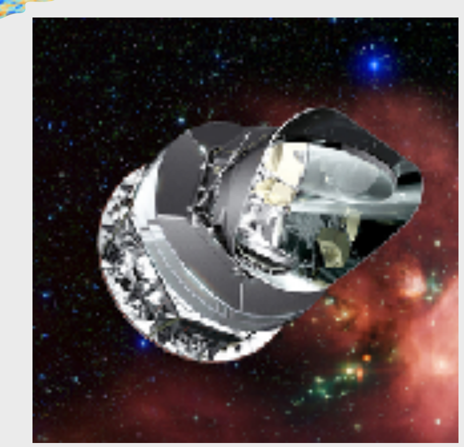
Electrons bind into nuclei



Universe is neutral

Photons can escape





Planck 2015

protons and neutrons

Baryon-to-photon ratio

number density of (anti-)baryons

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

number density of photons

Big Bang Nucleosynthesis

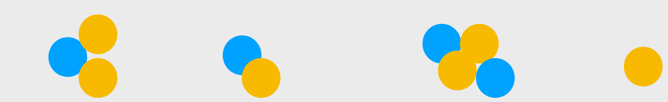
Universe is ~ a min old (10 MeV)

Protons and neutrons start binding to form light nuclei

$$p + n \rightarrow D + \gamma$$

Fun fact: Pretty much all of the deuterium in the universe comes from this era

$$D + D \rightarrow {}^{3}\mathrm{He} + n$$

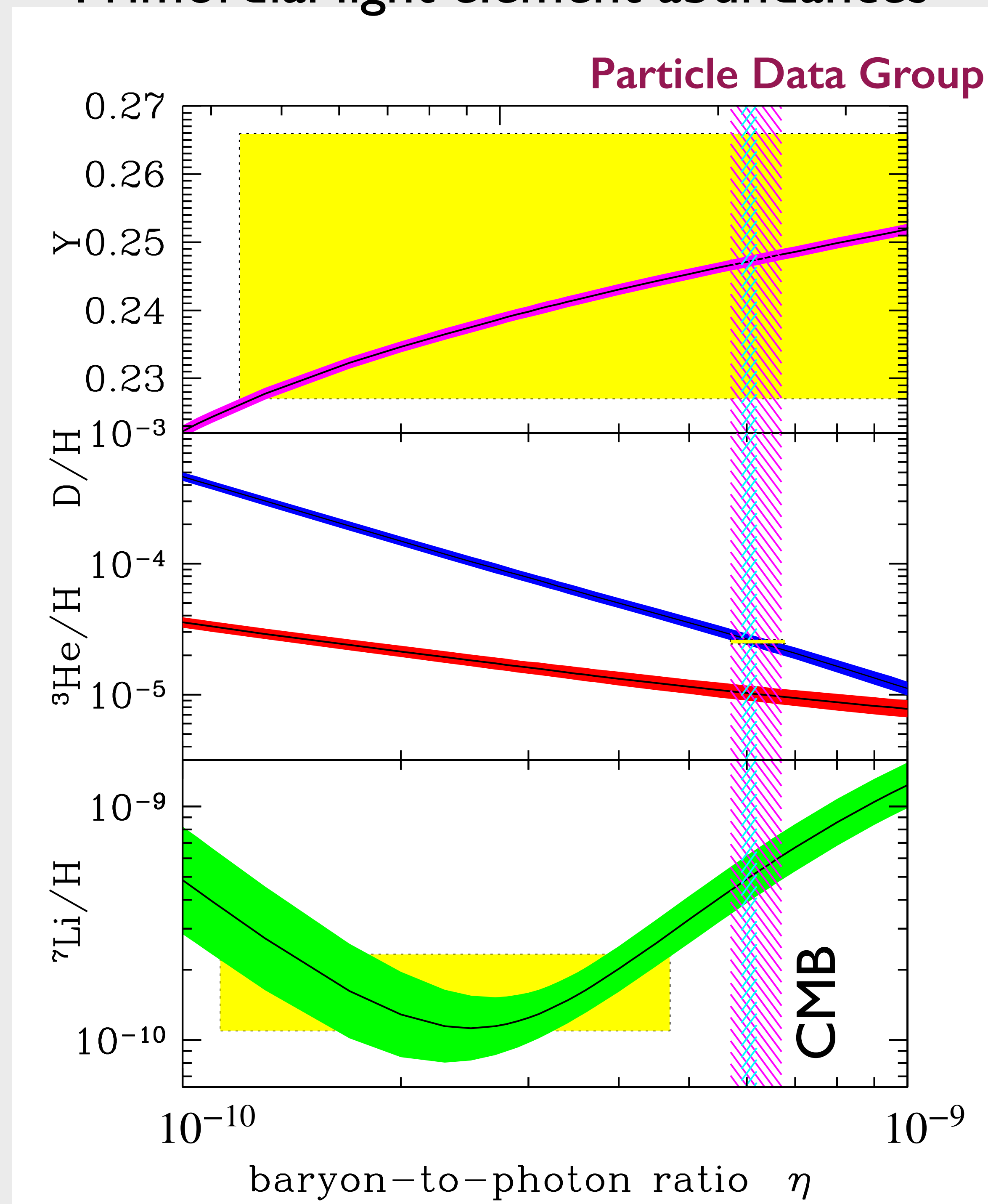


$${}^{3}\mathrm{He} + D \rightarrow {}^{4}\mathrm{He} + p$$

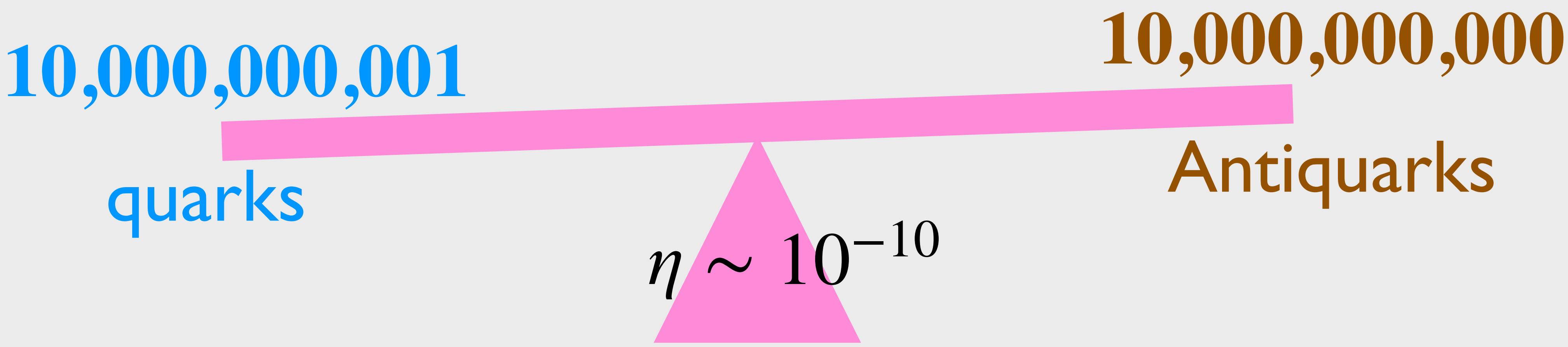
Helium-4 is the most abundant element

Small amounts of Li-7 and Be-8

Primordial light element abundances



How do we make sure there are more quarks than antiquarks in the early Universe?



Physics need to be a little bit different between matter and antimatter!

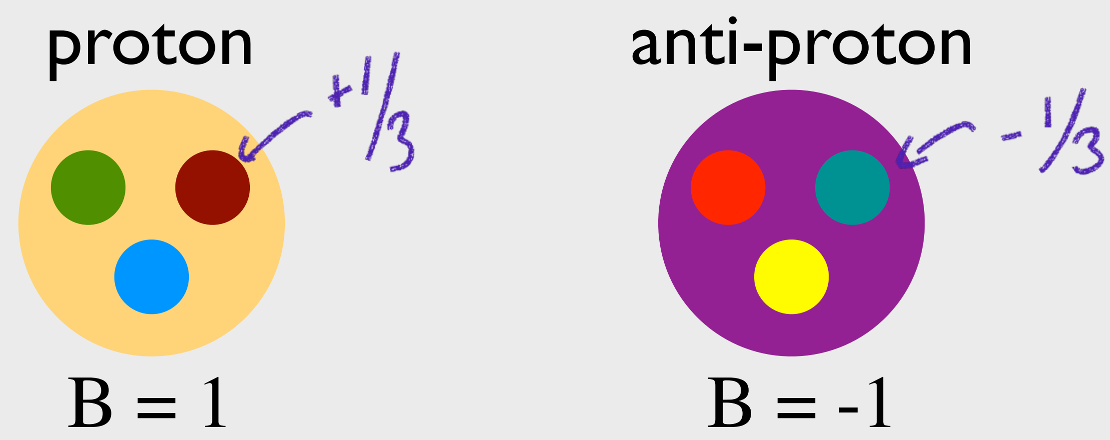
Andrei Sakharov
1921-1989

JETP Lett. 6 (1967) 4

Sakharov conditions

1. Baryon (matter) number cannot be a conserved quantity
2. Charge and Charge-Parity (CP) symmetries must be violated
3. Out-of-equilibrium processes

Baryon number is a quantum number/charge



Net baryon number:

$$\boxed{\Delta_B = n_B - n_{\bar{B}}}$$

Inflation

At the beginning:

$$n_q = n_{\bar{q}}$$

$t=0$: $\Delta_B = 0$

time flies

$\Delta_B \neq 0$

Δ_B cannot be a conserved quantity! It needs to change with time

Baryon number violation

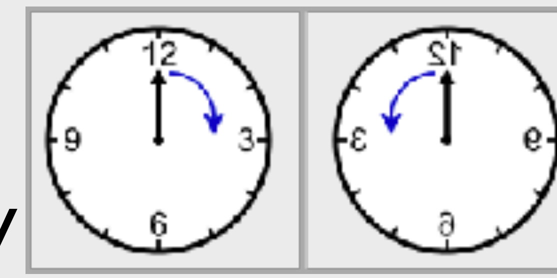
Time

How can physics laws tell the difference between a particle and an antiparticle?

We look at some (a)symmetries under certain transformations

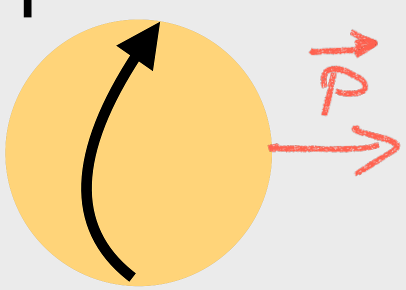
Handedness

Parity



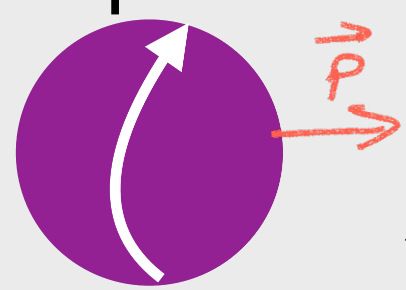
different physics laws!

Left-handed proton



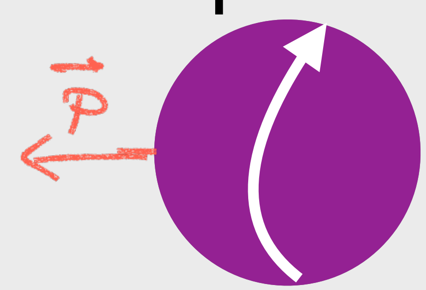
Charge transformation

Left-handed anti-proton



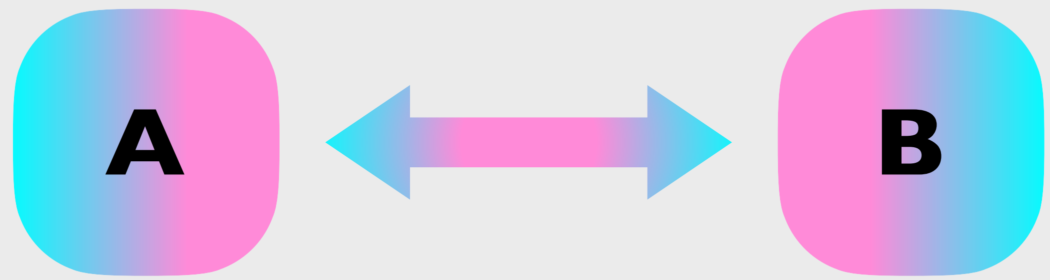
Parity transformation

Right-handed anti-proton

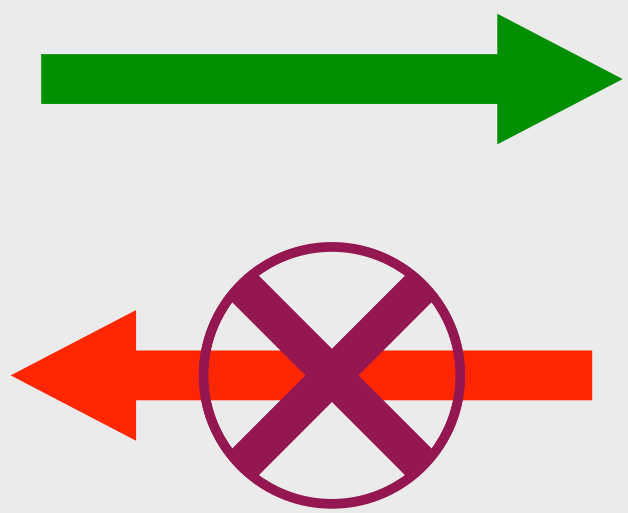


Charge-parity violation

Nothing interesting happens in thermal equilibrium



Zero baryon asymmetry



Some baryon asymmetry

Pillars of Creation,
Eagle Nebule,
Hubble Space Telescope

Being out of equilibrium

Can the Standard Model of particle physics explain the baryon asymmetry of the Universe?

Does the Standard Model satisfy the Sakharov Conditions?

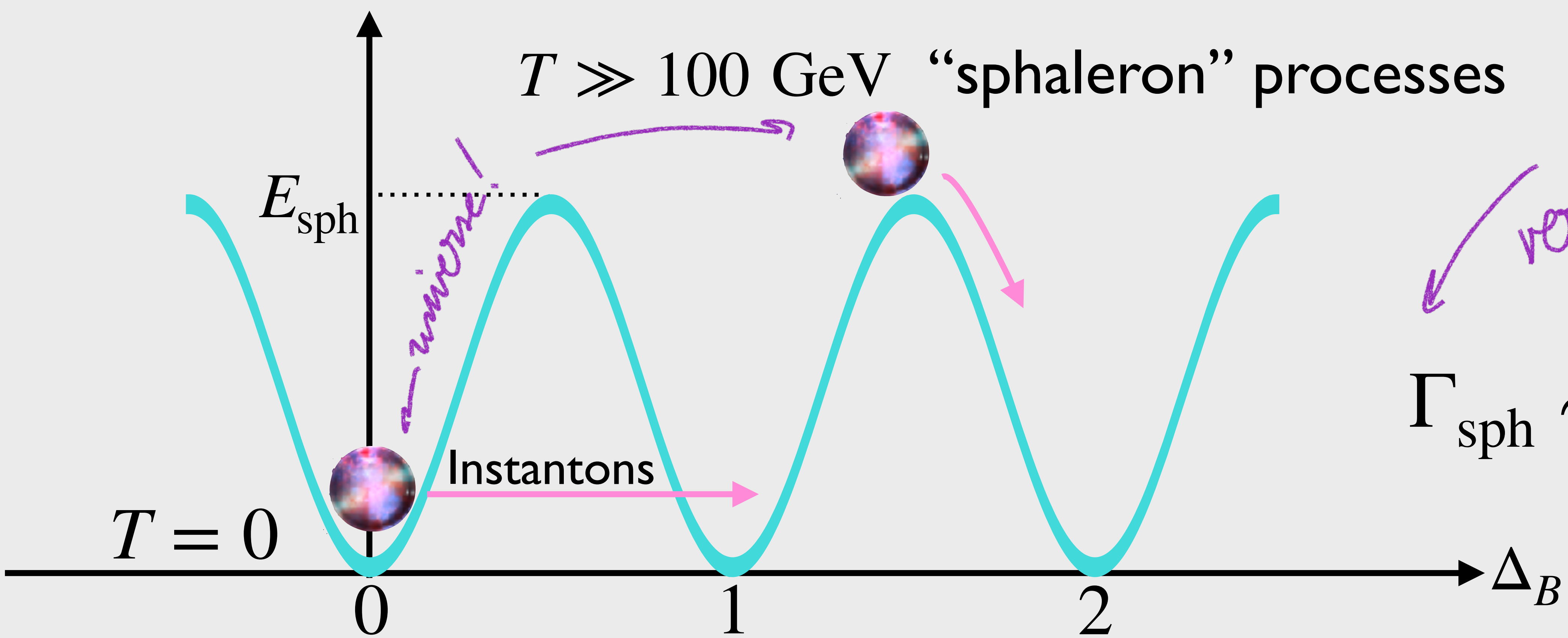
Baryon number is violated in weak interactions 😃

$$\partial^\mu j^B_\mu = 3\,\partial^\mu j^{L_i}_\mu = 3\frac{g^2}{32\pi^2}W^{\mu\nu,a}\tilde{W}^a_{\mu\nu}$$

only left-handed particles interact via the weak nuclear force

$$\Delta_B = \int d^4x\,\partial^\mu j^B_\mu = 3\frac{g^2}{32\pi^2}\int d^4x\,W^{\mu\nu,a}\tilde{W}^a_{\mu\nu}$$

$$\alpha_W \sim \frac{1}{30}$$



very efficient

$$\Gamma_{\rm sph} \sim 25\,\alpha_W^5 T^4$$

Quantum tunneling is hard!

$$\Gamma \sim e^{-4\pi/\alpha_W} \sim e^{-160}$$

$$E_{\rm sph} \sim \frac{M_W}{\alpha_W} \sim 10\ \text{TeV}$$

The Standard Model is a "chiral" theory

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Charge-Parity violation

$$e_L^- \xrightarrow{C} e_L^+$$

Weak nuclear interactions are not allowed

$$e_L^- \xrightarrow{P} e_R^-$$

Weak nuclear interactions are allowed

$$e_L^- \xrightarrow{C} e_L^+ \xrightarrow{P} e_R^+$$

allowed but tiny bit different

Cronin, Fitch, Turlay got the Nobel Prize!

$$K_L \to 2\pi \quad \text{AND} \quad K_L \to 3\pi$$

A historical review: Cronin, *Eur. Phys. J. H* 36 (2012) pp.487-508

Entirely because there is a complex phase in the CKM matrix

Great! BUT not enough 😐

handwavey:

$$\eta \sim J \prod_i \left(\frac{m_i}{M_W} \right)^2$$

more detailed calculations:

$$\eta_{\mathrm{SM\ CP}} \sim 10^{-20}$$

Gavela, Hernandez, Orloff, Pene, CERN 93/7081

How about the neutrino sector? Maybe PMNS CP violation?

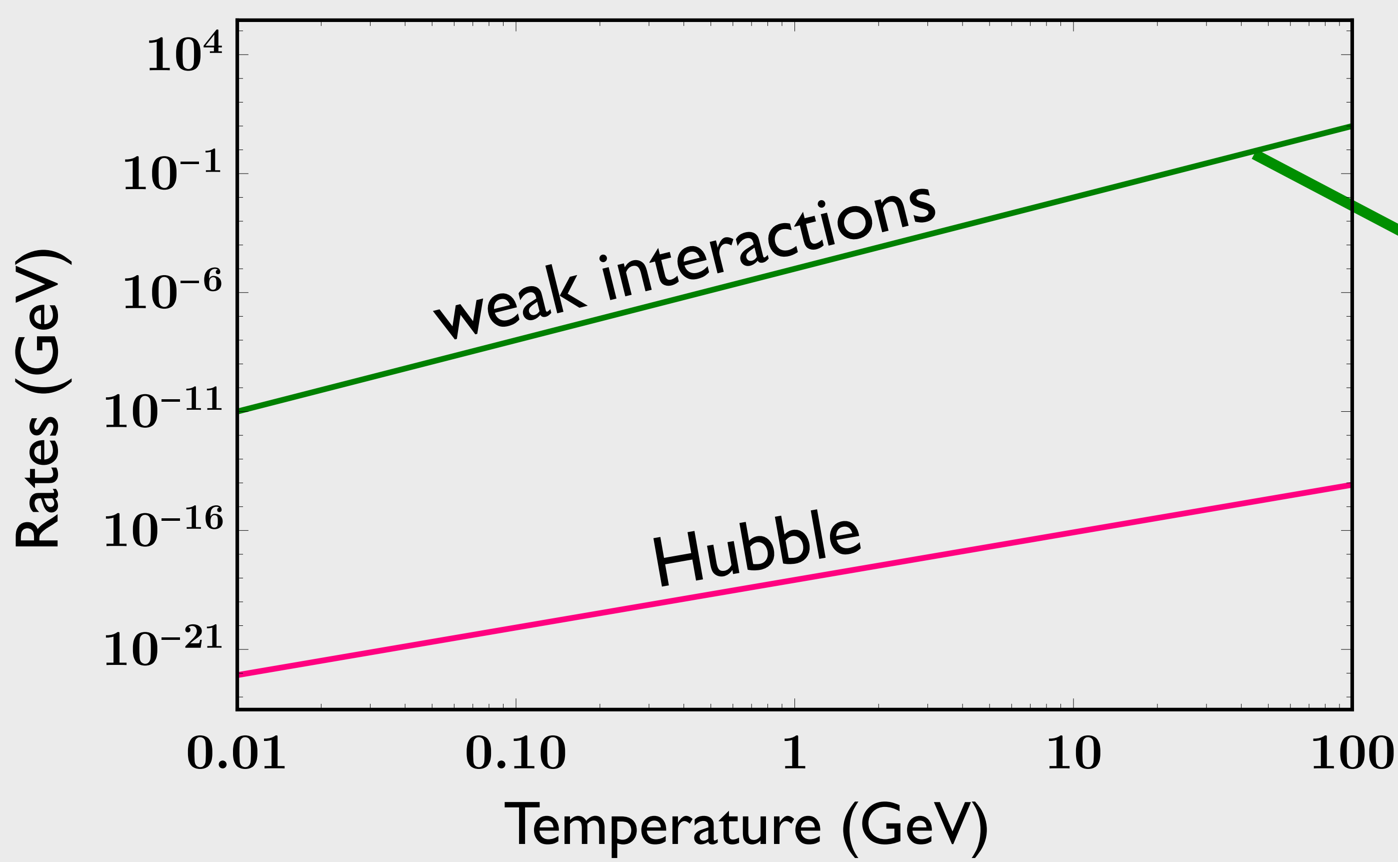
Look out for DUNE and HyperK!

Equilibrium?

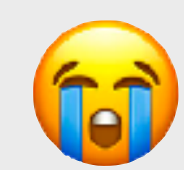
Rate of (weak) interactions **vs** Expansion rate of the universe

$$\Gamma_{\text{weak}} \sim G_F^2 \times T^3 \sim \frac{T^3}{10^{10}\ \text{GeV}^2}$$

$$H \sim \frac{T^2}{M_{\text{Planck}}} \sim \frac{T^2}{10^{19}\ \text{GeV}}$$



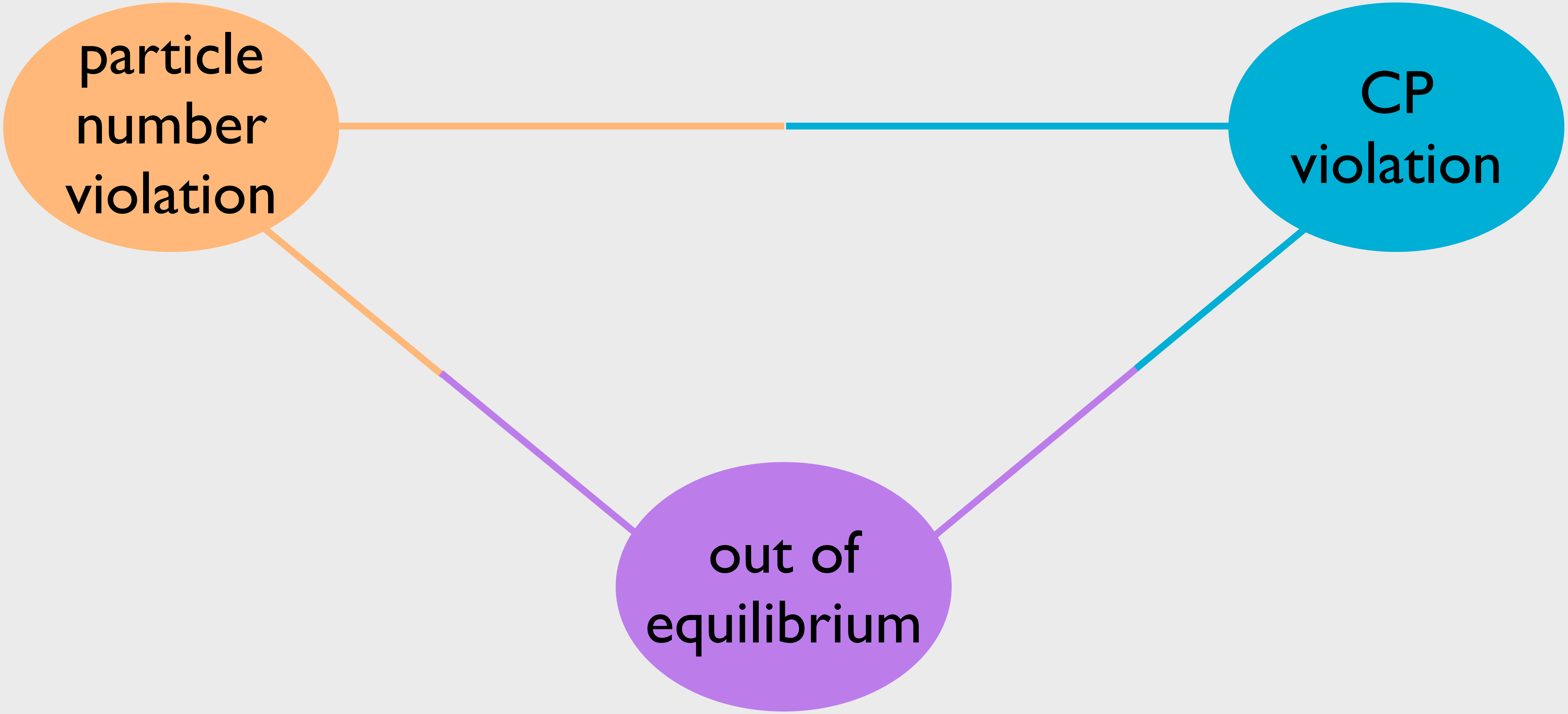
Too fast!



SM Universe always equilibriates!

Standard Model can NOT explain the matter-antimatter asymmetry of the universe!

We need some new physics…

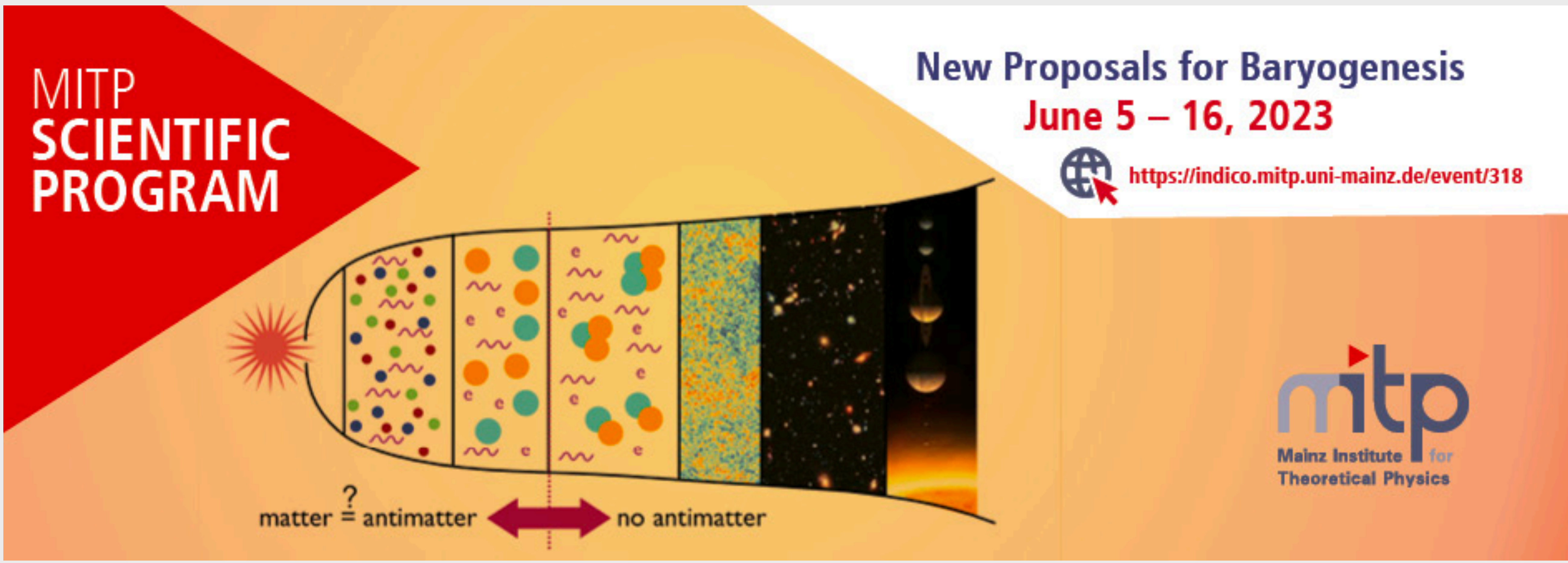


…that interacts with the Standard Model!

New Ideas in Baryogenesis: A Snowmass White Paper

Editors: Gilly Elor,[1] Julia Harz,[2] Seyda Ipek,[3] Bibhushan Shakya.[4]

Authors: Nikita Blinov,[5] Raymond T. Co,[6] Yanou Cui,[7] Arnab Dasgupta,[8] Hooman Davoudiasl,[9] Fatemeh Elahi,[1] Gilly Elor,[1] Kåre Fridell,[2] Akshay Ghalsasi,[8] Keisuke Harigaya,[10] Julia Harz,[2] Chandan Hati,[2] Peisi Huang,[11] Seyda Ipek,[3] Azadeh Maleknejad,[10] Robert McGehee,[12] David E. Morrissey,[13] Kai Schmitz,[10] Bibhushan Shakya,[4] Michael Shamma,[13] Brian Shuve,[14] David Tucker-Smith,[15] Jorinde van de Vis,[4] Graham White.[16]



How to think about particle number violation?

SM

$B - L$ — conserved

$\cancel{B + L}$ — sphalerons

Explicit L violation:

Lepton asymmetry turns into a baryon asymmetry via sphalerons

Leptogenesis!

Right-handed Majorana neutrinos $\Rightarrow$ neutrino masses + lepton asymmetry

B, L can be conserved

dark sector $\longrightarrow$ SM

Neutrino portal,
Higgs portal,
neutron portal,…

Particle number violation

$\Updownarrow$

Global $U(1)$ symmetries

$\Updownarrow$

Baryon asymmetry

At this workshop: Rob McGehee, Jerome Vandecasteele, Can Kilic,…

C.S. Fong, arXiv:2012.03973

CP violation can be easy or hard

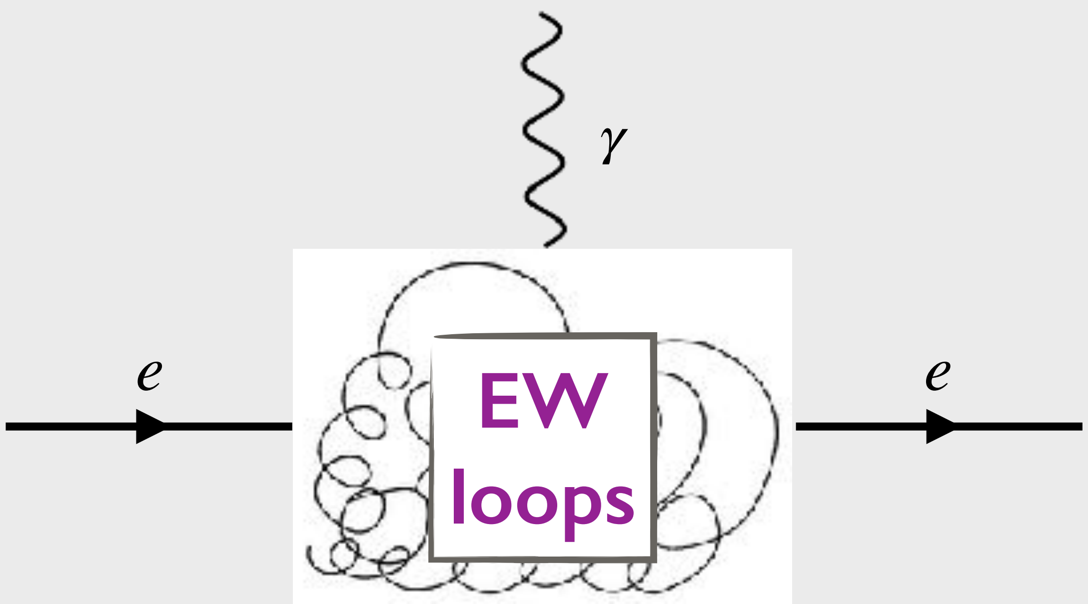
JILA, arXiv:2212.11841

Electron electric dipole moment: $d_e \leq 4.1\mathrm{x}10^{-30}\ e{\cdot}\mathrm{cm}$

Could come down to 10^{-32} !

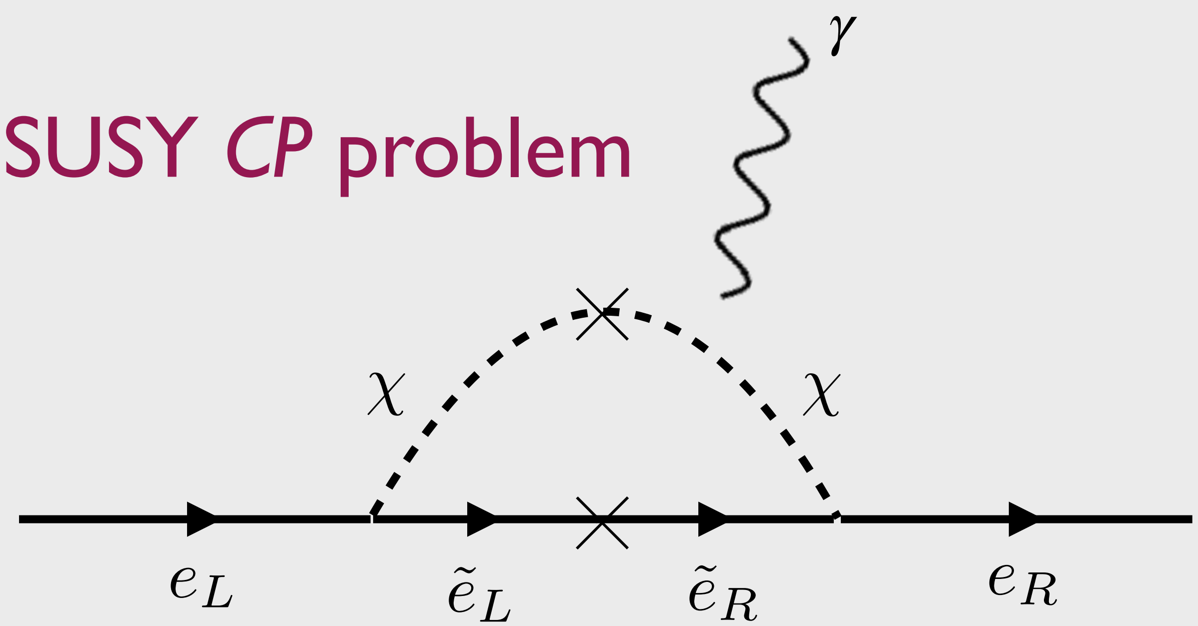
Fleig, DeMille, arXiv:2108.02809

What we have in the SM:



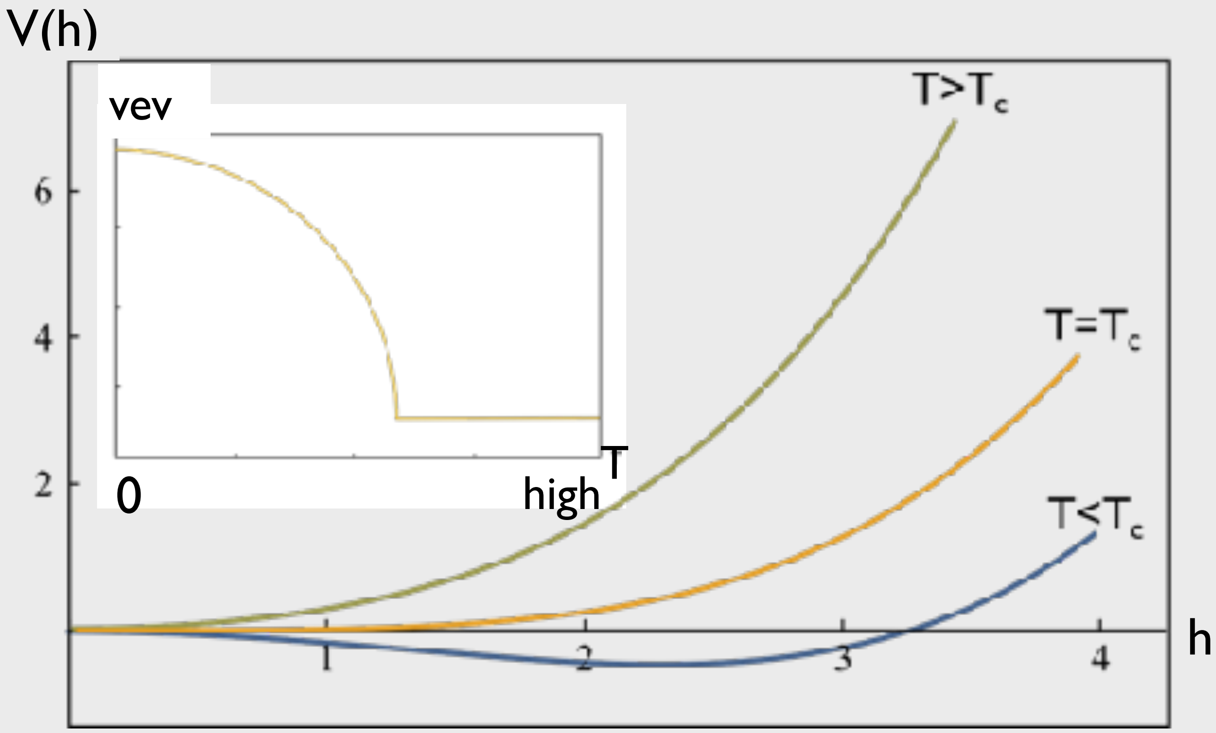
$d_e \leq 10^{-38}\ e{\cdot}\mathrm{cm}$

SUSY *CP* problem



PMNS CP phase? Maybe! Hernandez, et al, arxiv:2305.14427

Out of equilibrium: cosmological phase transitions???

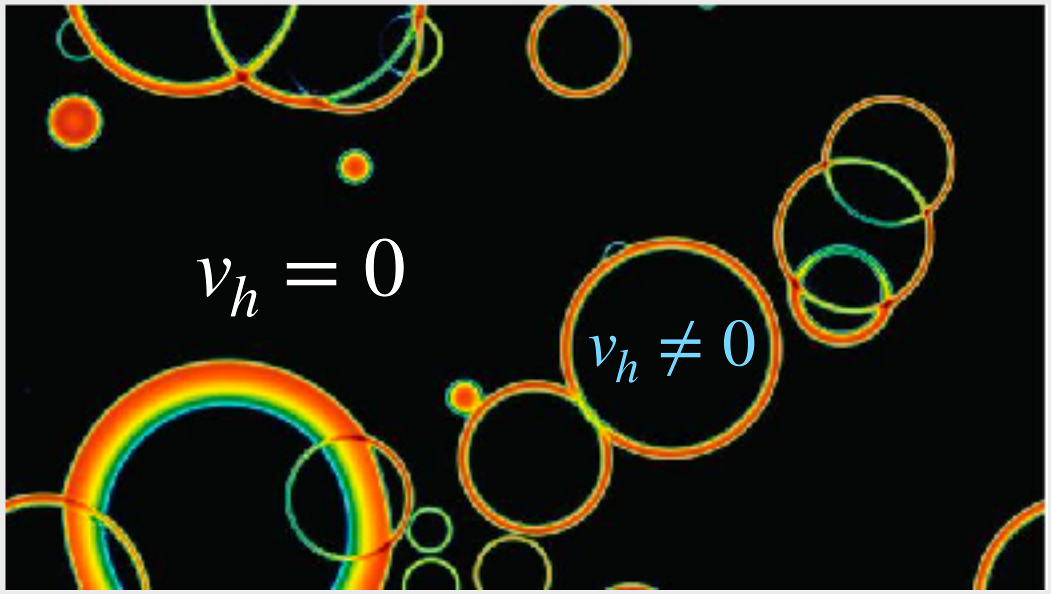


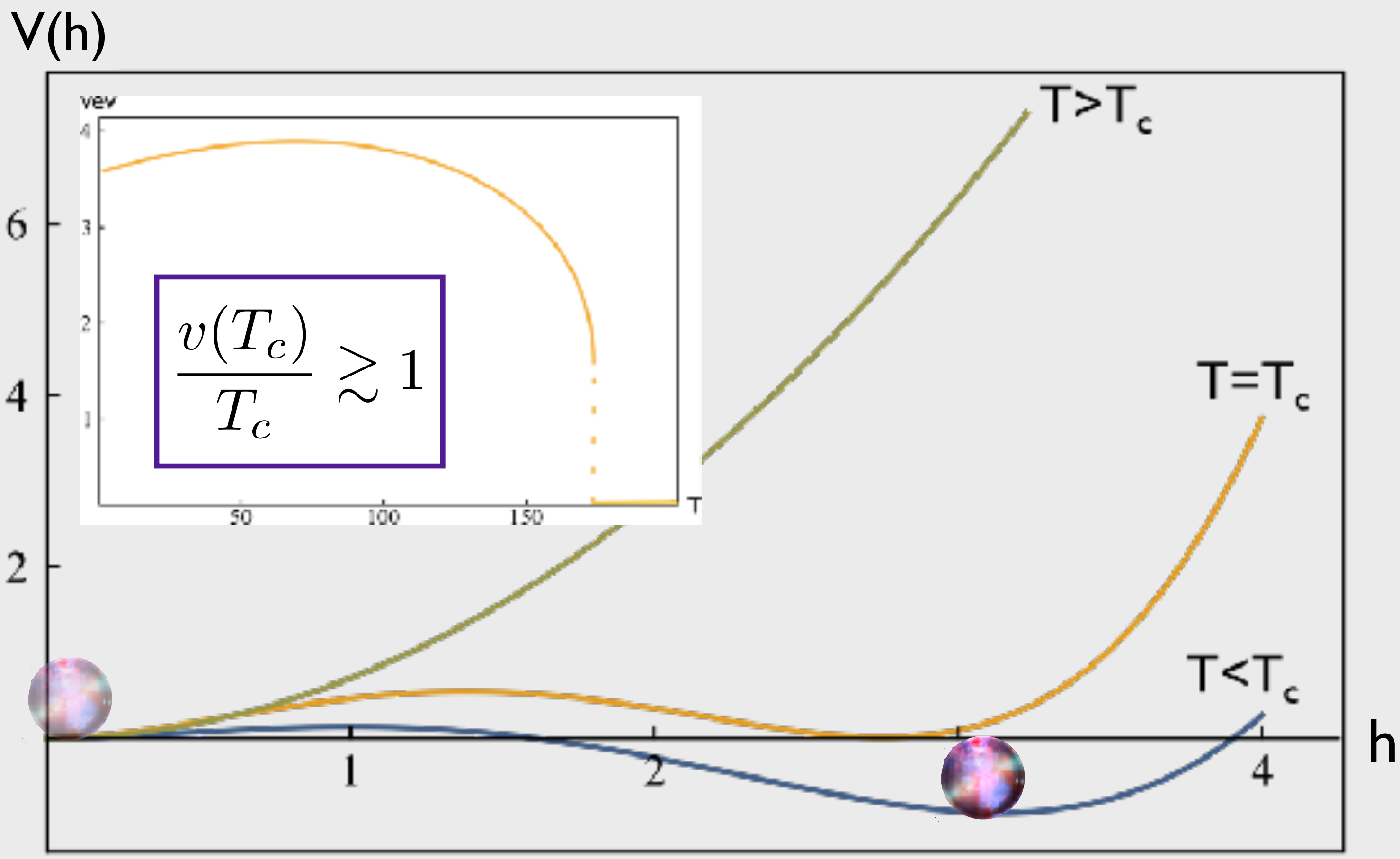
SM EW transition is a crossover

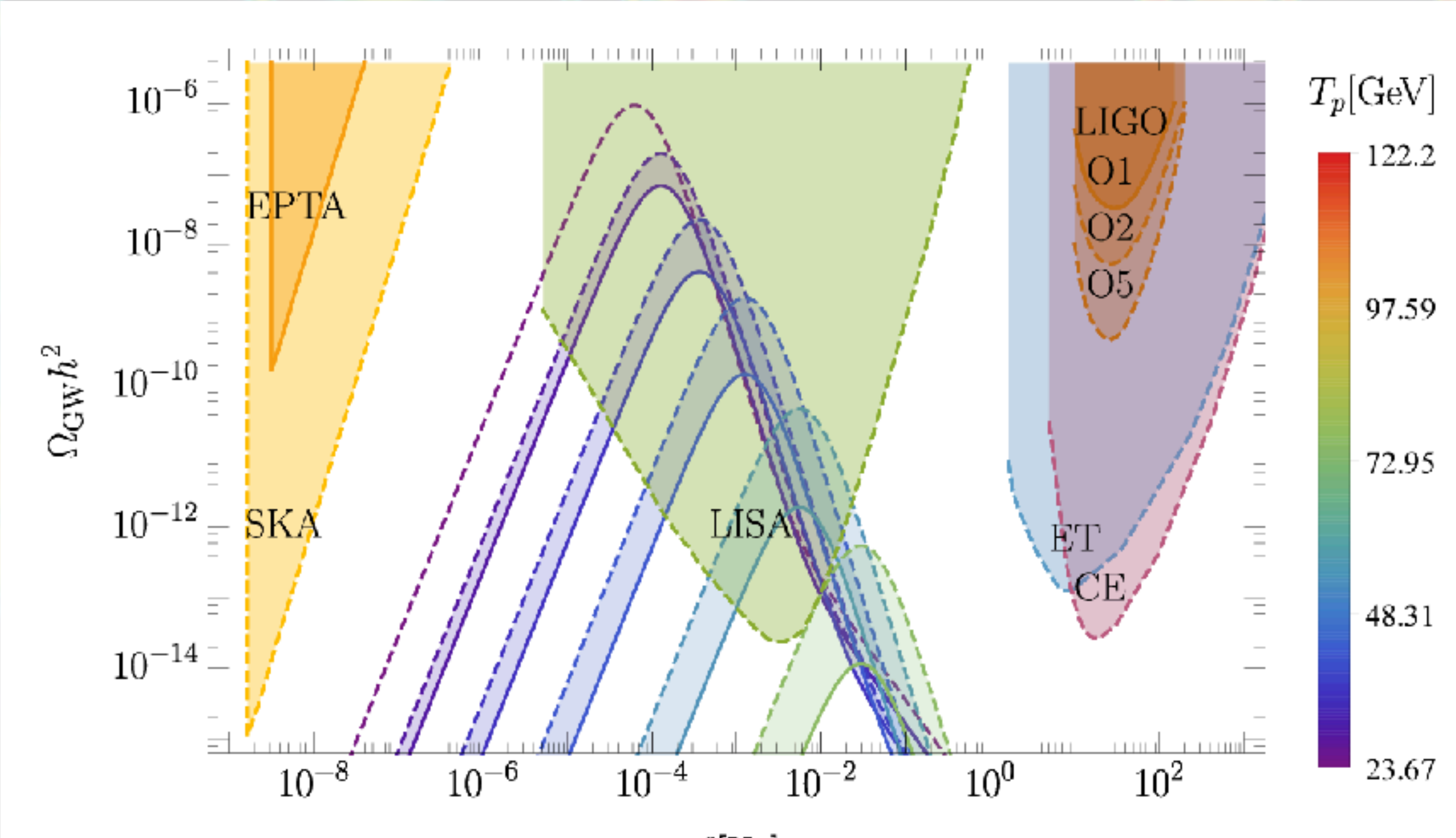
$$m_h \gtrsim 75 \text{ GeV}$$

Always in equilibrium

First-order Phase Transition







J. Ellis, et al, arXiv:1809.08242

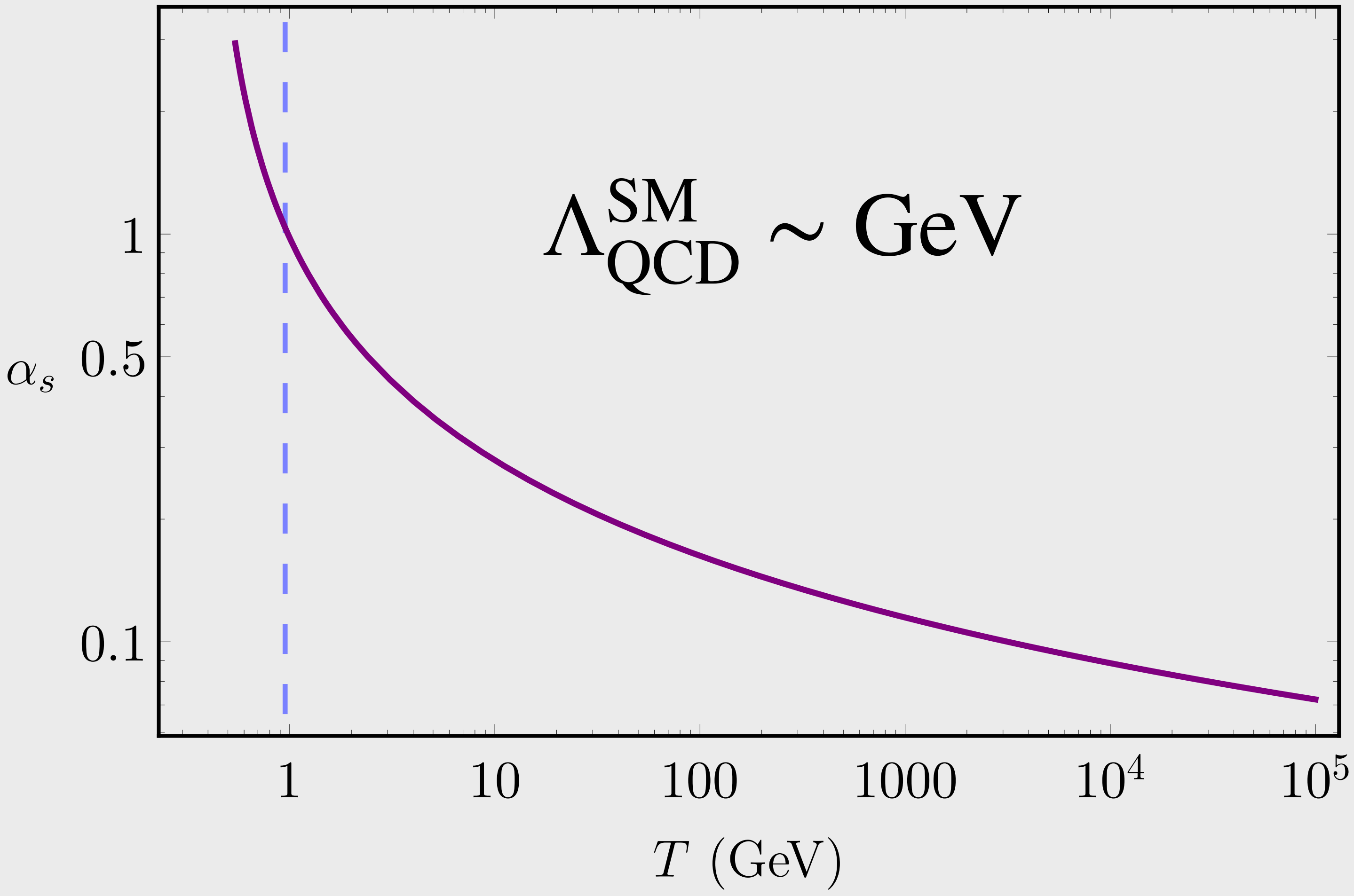
At this workshop: Anish Ghoshal, Oleksii Matsedonskyi, Carlos Wagner, Marcela Carena, Andrew Long, Miguel Vanvlasselaer, …

How about strong interactions?

SI, T. Tait, PRL (2019), 122, 112001

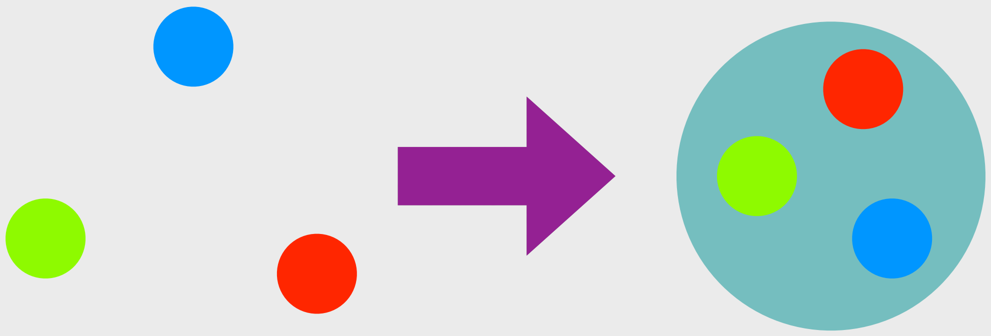
D. Croon, J. Howard, **SI**, T. Tait, *arXiv:1911.01432*

QCD is asymptotically free at high energies, but becomes strongly interacting at low energy



$$\alpha_s = \frac{g_s^2}{4\pi}$$

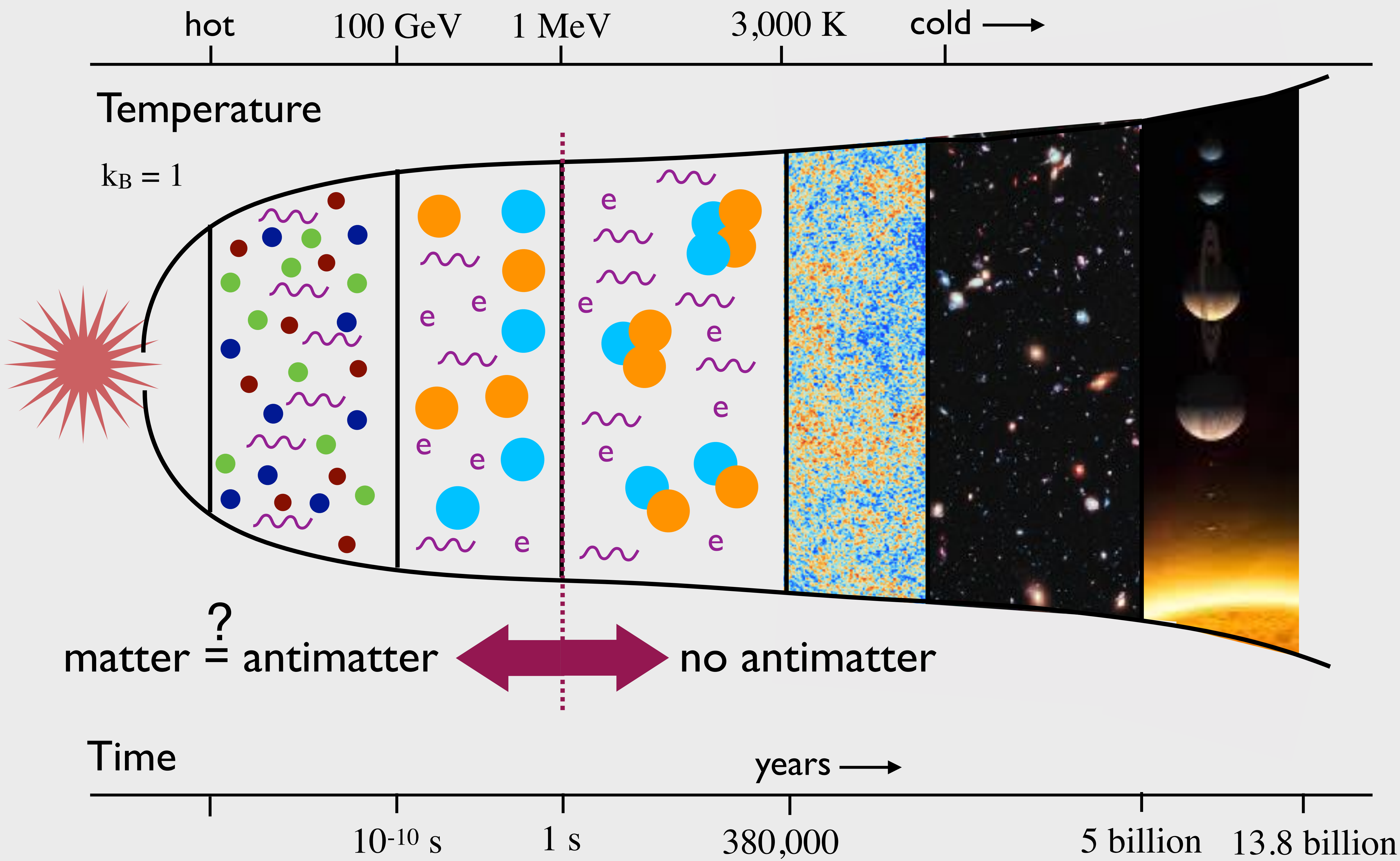
Quarks confine into hadrons when the strong coupling becomes "large"



QCD Phase Transition

Was QCD the same in the early universe?

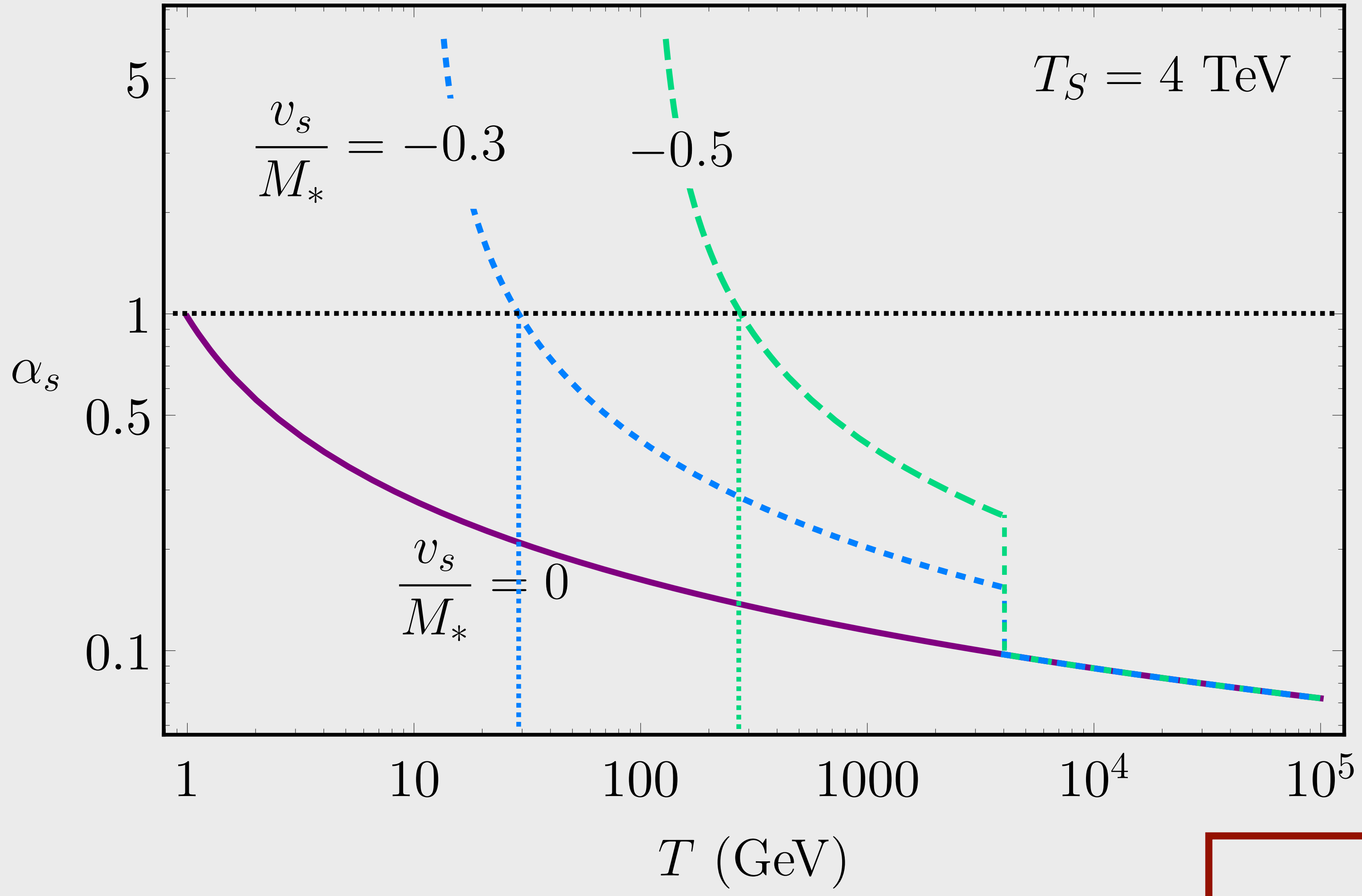
Who knows what happened before BBN!



Was QCD the same in the early universe?

Who knows what happened before BBN!

Confinement scale changes with new particles if they interact via strong interactions!



$$\mathscr{L} \supset \left(\frac{1}{g_s^2} + \frac{S}{M_*} \right) G^{\mu\nu} G_{\mu\nu}$$

$$\frac{1}{g_{\rm eff}^2} = \frac{1}{g_s^2} + \frac{v_s}{M_*}$$

$$\boxed{\Lambda_{\rm QCD} \simeq \Lambda_{\rm QCD}^{\rm SM} \exp \left(\frac{24\pi^2}{2N_f - 33} \frac{v_s}{M_*} \right)}$$

SM QCD

confinement ~ 400 MeV

mass of up/down quarks $< \Lambda_{\rm QCD}^{\rm SM}$

pion masses: $m_{\pi 0}^2 = \dfrac{2\kappa_0(m_u + m_d)}{f_{\pi 0}^2}$

QCD quantities:

$$\kappa_0 \simeq (225\ \mathrm{MeV})^3$$

$$f_{\pi 0} \simeq 94\ \mathrm{MeV}$$

New physics QCD

confinement ~ 400 GeV

all quarks are lighter than $\Lambda_{\rm QCD}^{\rm new}$

pions are heavier:

Higgs vev at ~$\Lambda_{\rm QCD}$

$$m_\pi^2 \simeq m_{\pi 0}^2 \left(\frac{\boxed{v_h}}{v_h^{\rm SM}}\right) \xi$$

$$\kappa \simeq \kappa_0\, \xi^3$$

$$f_\pi \simeq f_{\pi 0}\, \xi$$

with $\xi \equiv \dfrac{\Lambda_{\rm QCD}^{\rm new}}{\Lambda_{\rm QCD}^{\rm SM}}$

$$\mathscr{L} \supset \left(\frac{1}{g_s^2} + \frac{S}{M_*} \right) G^{\mu\nu} G_{\mu\nu}$$

$$\boxed{\begin{aligned} V_{\text{scalar}} = & -\mu^2 |H|^2 + \lambda_h |H|^4 \\ & + a_2 S^2 + a_3 S^3 + a_4 S^4 \\ & - b_1 S |H|^2 + b_2 S^2 |H|^2 \end{aligned}}$$

New scalar sector

$\Downarrow$

Interesting dynamics

$\Downarrow$

New QCD

$\Downarrow$

Baryogenesis!

Standard Model

$v_h = 0$

$T_{\mathrm{EW}}^{\mathrm{SM}}$ 150 GeV

$v_h \neq 0$

$\Lambda_{\mathrm{QCD}}^{\mathrm{SM}} \sim \mathrm{GeV}$

QCD confined

T_{BBN}

New Universe

$v_s = 0,\ v_h = 0$

T_S not important

$v_s \neq 0,\ v_h = 0$

150 GeV

$v_s \neq 0,\ v_h = 0$

confinement temp $\rightarrow T_c$

QCD confined

$v_s \neq 0,\ v_h \neq 0$

de-confinement temp $\rightarrow T_d$

$v_s = 0,\ v_h = v_h^{\mathrm{SM}}$

QCD deconfines $\longleftrightarrow$ SM

$\Lambda_{\mathrm{QCD}}^{\mathrm{SM}} \sim \mathrm{GeV}$

SM QCD - confined

T_{BBN}

$v_s = 0,\ v_h = 0$

T_S

$v_s \neq 0,\ v_h = 0$

$T_{\rm EW}^{\rm SM}$

$v_s \neq 0,\ v_h = 0$

finite temperature corrections
the usual: gauge bosons, quarks,…

T_c

QCD confined
$v_s \neq 0,\ v_h \neq 0$

no quarks,
but hadrons!

T_d

$v_s = 0,\ v_h = v_h^{\rm SM}$

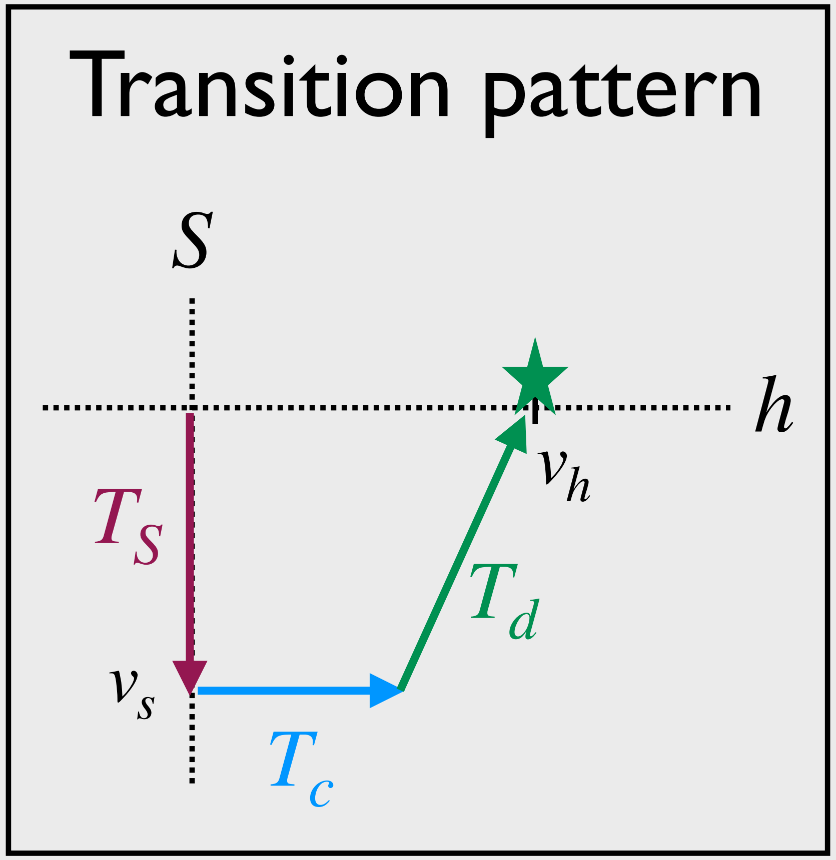
QCD deconfines

return to the SM

$\Lambda_{\rm QCD}^{\rm SM} \sim$ GeV

QCD confined

$T_{\rm BBN}$



- Higgs gets a tadpole term from the meson mass-term

$$V_{\rm tad}(v_h) \simeq \kappa \frac{y_t}{\sqrt{2}} v_h \simeq -0.0158\ \mathrm{GeV}^3 \left(\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm QCD}^{\rm new}}\right)^3 v_h$$

- Thermal corrections to the Higgs potential from mesons

$$V_{\rm meson}(v_h, T) = \sum_{i=25...35} \frac{T^4}{2\pi^2} J_B\left(\frac{m_i^2}{T^2}\right)$$

$$J_B(m^2) = \int_0^\infty dx x^2 \log\left(1 - e^{-\sqrt{x^2+m^2}}\right)$$

- The gluon condensate contributes to the singlet potential

$$\frac{S}{M_*}\langle GG\rangle \Longrightarrow V_{\rm GC}(v_s) \simeq \frac{v_s}{4M_*}\Lambda_{\rm QCD}^4$$

High temperature

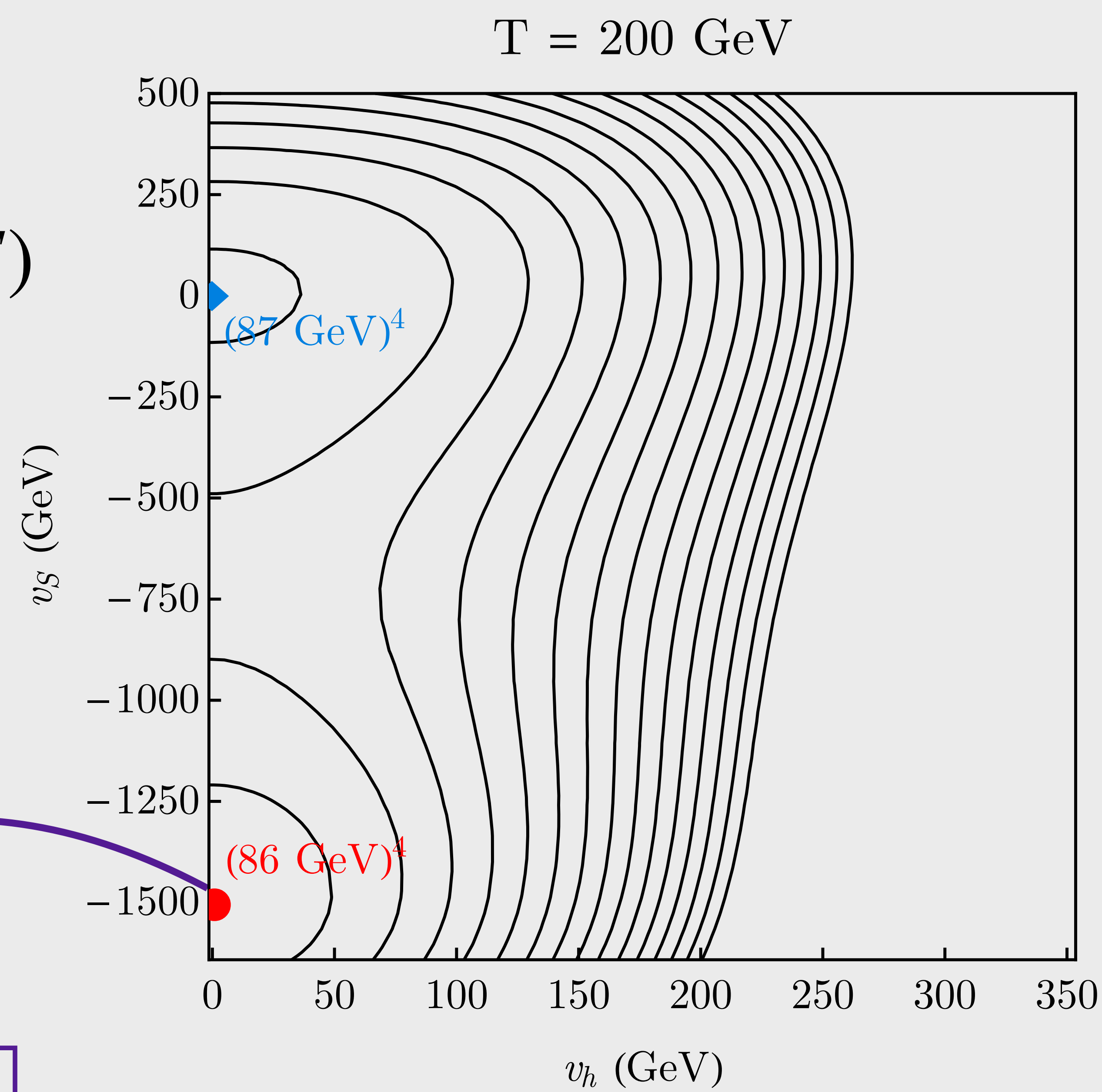
$$\boxed{T > T_{\rm EW} > T_c}$$

Finite temperature potential:

$$V(v_h, v_s, T) = V_0(v_h, v_s) + V_{\rm gauge}(v_h, T)$$
$$+V_{\rm top}(v_h, T)$$

$$V_0 = -\mu^2 |H|^2 + \lambda_h |H|^4$$
$$+a_2 S^2 + a_3 S^3 + a_4 S^4$$
$$-b_1 S |H|^2 + b_2 S^2 |H|^2$$

$b_1 = 0.7$ GeV, $b_2 = 10^{-3}$
$a_2 = 108$ GeV^2, $a_3 = 0.15$ GeV, $a_4 = 5 \times 10^{-5}$



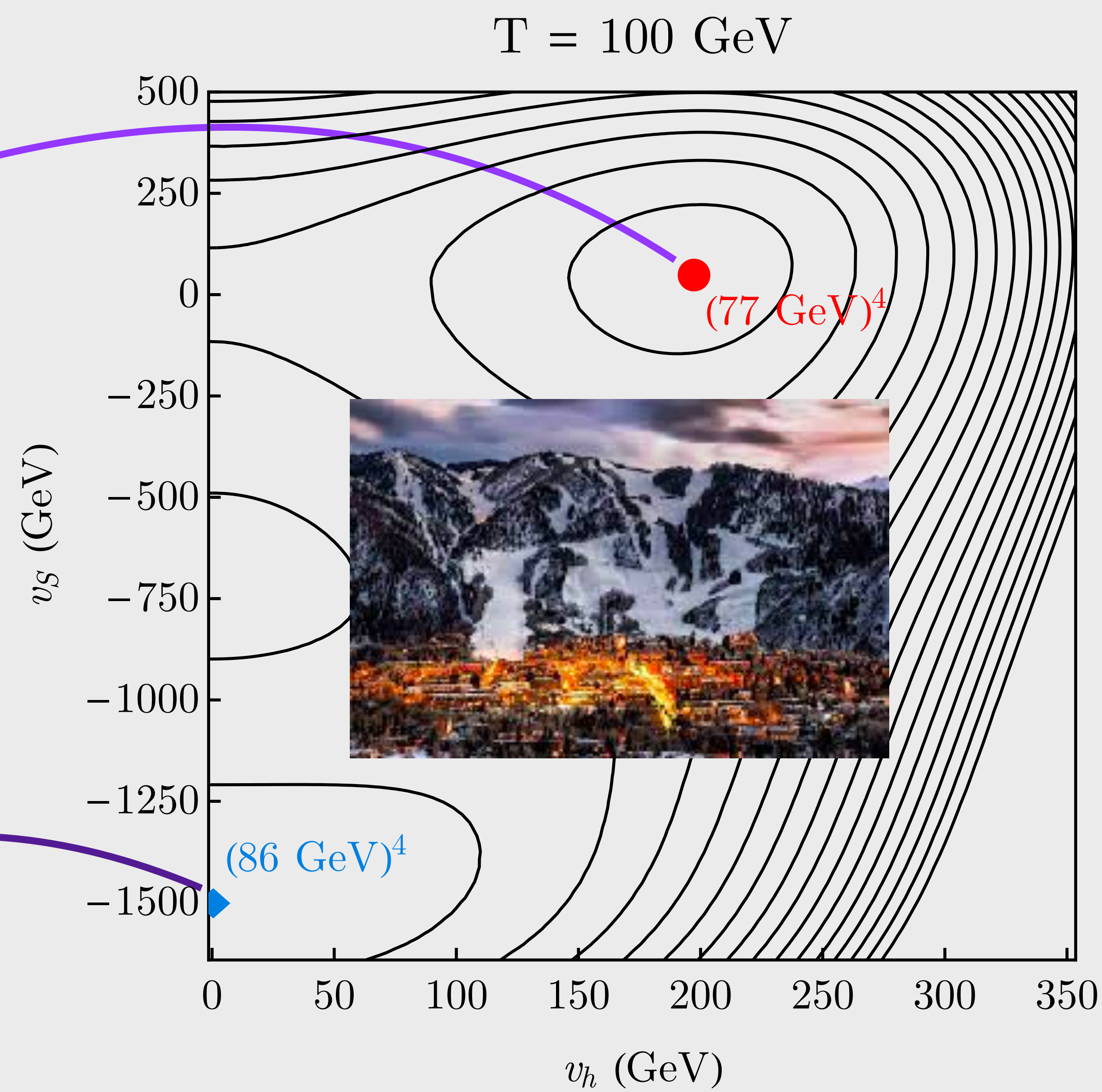
vacuum is at $v_s \neq 0,\ v_h = 0$

● global minimum

Below EW scale

$$\boxed{T_{\mathrm{EW}} > T > T_c}$$

$b_1 = 0.7$ GeV, $b_2 = 10^{-3}$
$a_2 = 108$ GeV^2, $a_3 = 0.15$ GeV, $a_4 = 5 \times 10^{-5}$



Global minimum is SM-like

There is an impenetrable barrier between the two vacua!

Euclidean bounce action

$$\frac{S_E}{T} \sim \left(\frac{\Delta v_s}{\Delta V(v_s)}\right)^4 \sim 10^{-8}$$

$$\boxed{\text{Universe is stuck at } v_s,\ v_h = 0}$$

We require: $m_h = 125$ GeV

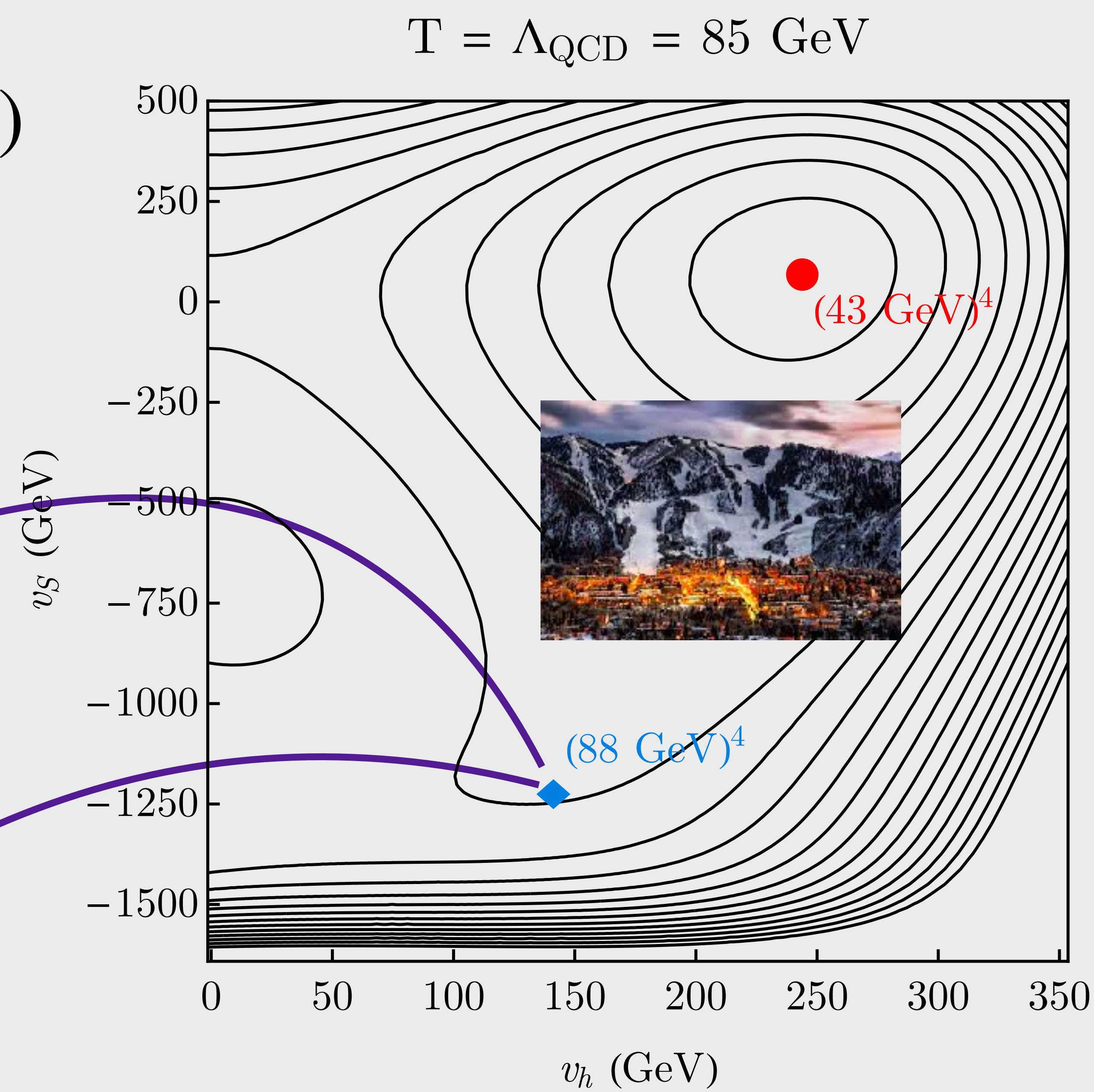
$v_h^0 = 246$ GeV

Below QCD confinement

$$\boxed{T_c \gtrsim T > T_d}$$

$b_1 = 0.7$ GeV, $b_2 = 10^{-3}$
$a_2 = 108$ GeV^2, $a_3 = 0.15$ GeV, $a_4 = 5 \times 10^{-5}$

$$V(v_h, v_s, T) = V_0(v_h, v_s) + V_{\rm gauge}(v_h, T) + V_{\rm tad}(v_h) + V_{\rm GC}(v_s) + V_{\rm meson}(v_h, T)$$



QCD confinement tips this vacuum towards finite v_h
(but not towards the SM value)

But there is still a barrier between the two vacua!

Universe is stuck at $v_s,\ v_h < v_h^{\rm SM}$

Back to the SM

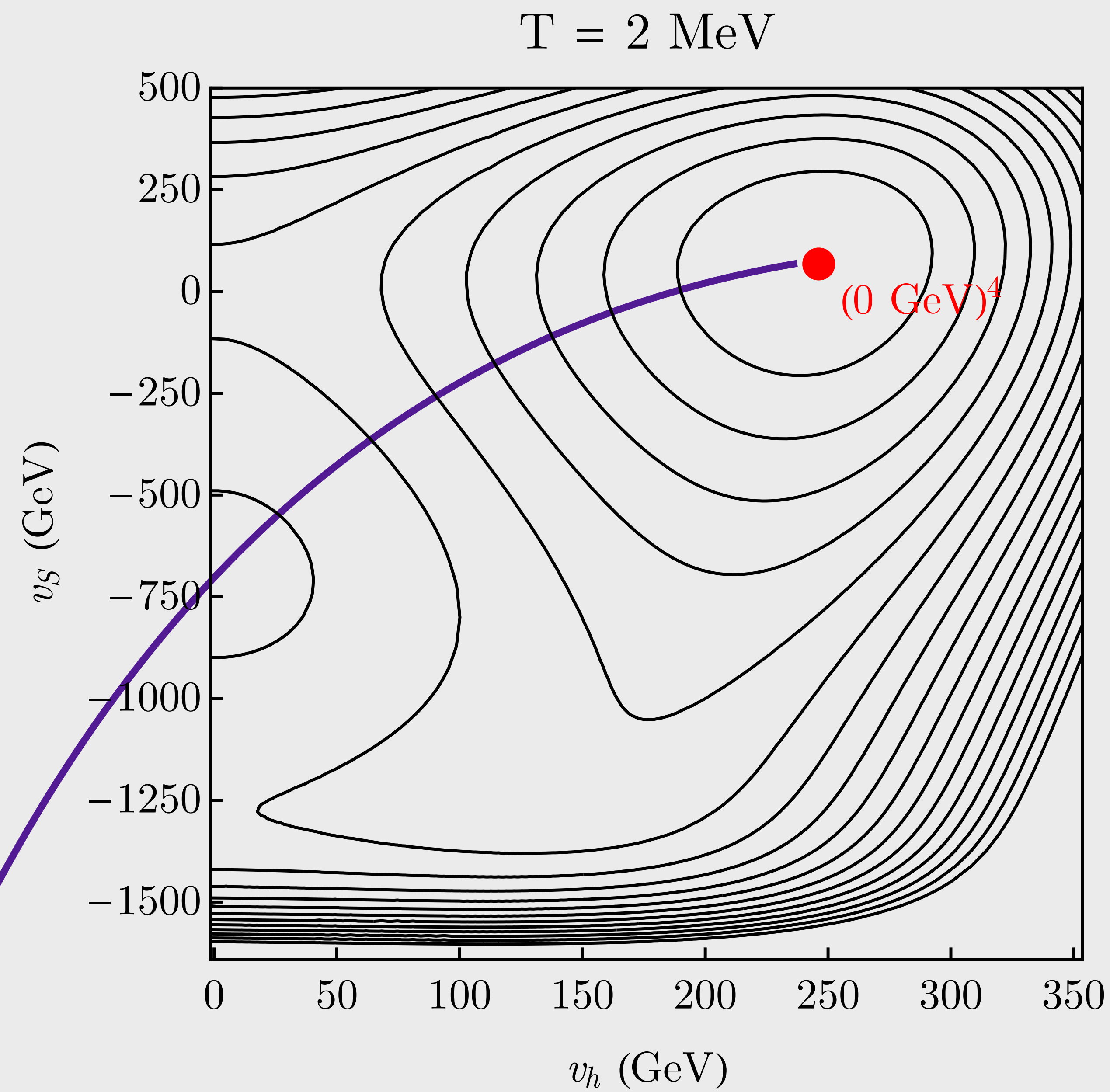
$\boxed{T_c > T_d > T}$

Universe has the right Higgs vev and Λ_{QCD}

The barrier disappears

The universe can roll over instead of tunneling

$b_1 = 0.7$ GeV, $b_2 = 10^{-3}$
$a_2 = 108$ GeV^2, $a_3 = 0.15$ GeV, $a_4 = 5 \times 10^{-5}$



SM-like vacuum before BBN!

CP violation

$\boxed{T = T_c}$

QCD has CP violation!

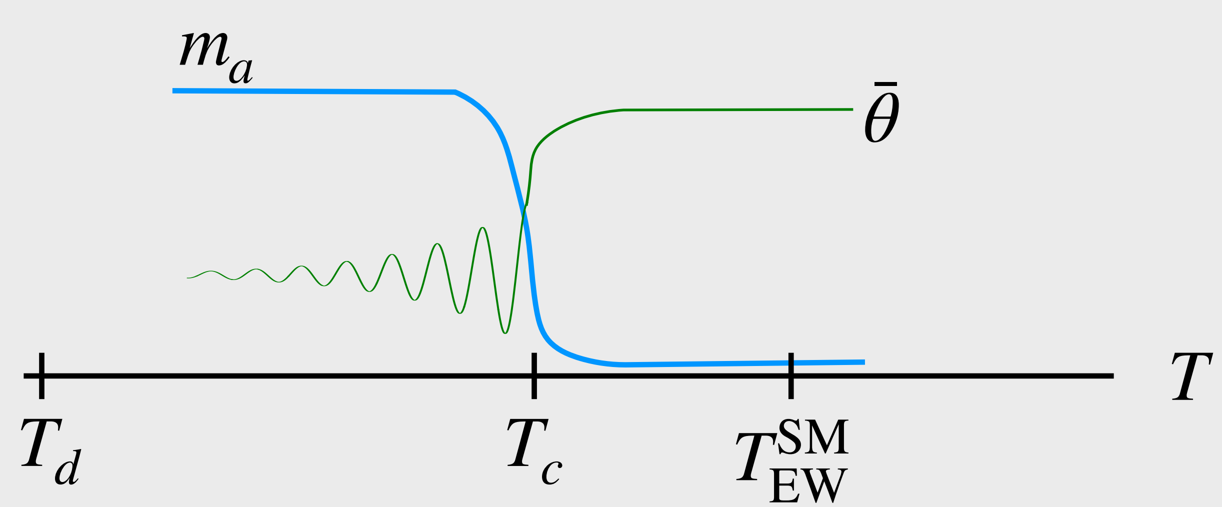
$$\mathscr{L} \supset \bar{\theta}\, G^{\mu\nu}\tilde{G}_{\mu\nu}$$

Axions!

$$m_a^2(T) f_a^2 \simeq \begin{cases} m_\pi^2 f_\pi^2\, \zeta \left(\dfrac{\Lambda_{\rm QCD}}{T}\right)^n & T > T_c \\ m_\pi^2 f_\pi^2 & T < T_c \end{cases}$$

has small mass at high T

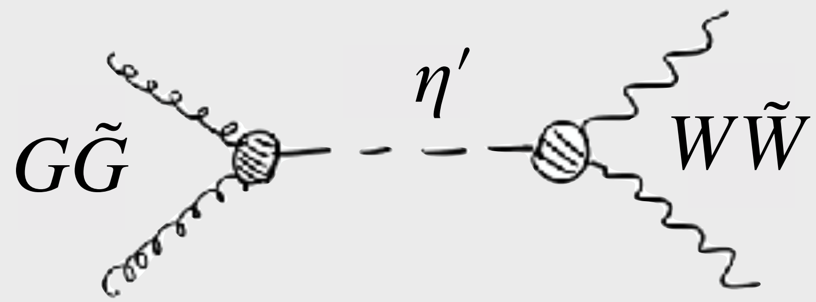
T-dependence given by number of light flavors, etc



How about B violation?

Baryon number violation

$\boxed{T = T_c}$



$$\partial_\mu j^\mu_B = \frac{\alpha_W}{8\pi}\mathrm{Tr}[W\tilde{W}]$$

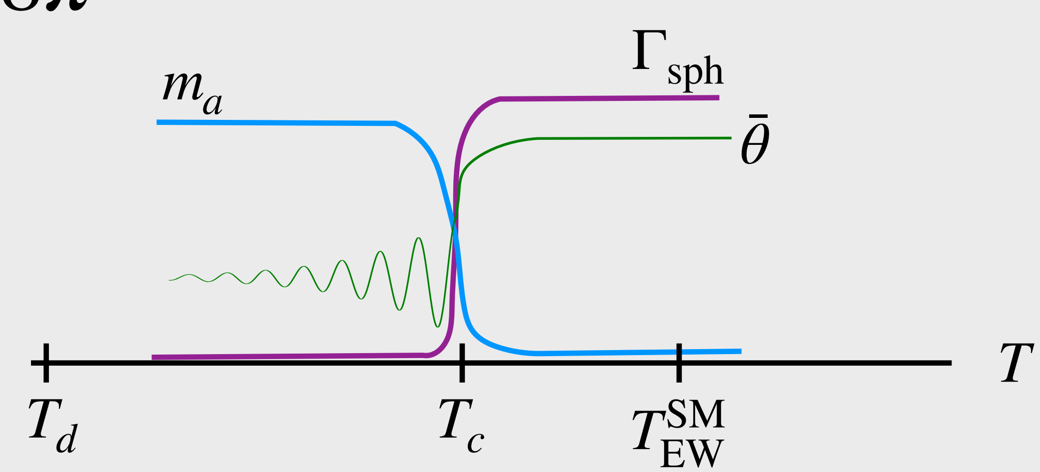
$$\Gamma_B \sim 25\alpha_W^5 T^4$$

$$\mathscr{L}_{\rm eff} = \frac{10}{f_\pi^2 m_{\eta'}^2} \boxed{\frac{\alpha_s}{8\pi}\langle G\tilde{G}\rangle} \boxed{\frac{\alpha_W}{8\pi} W\tilde{W}}$$

anomalous baryon current

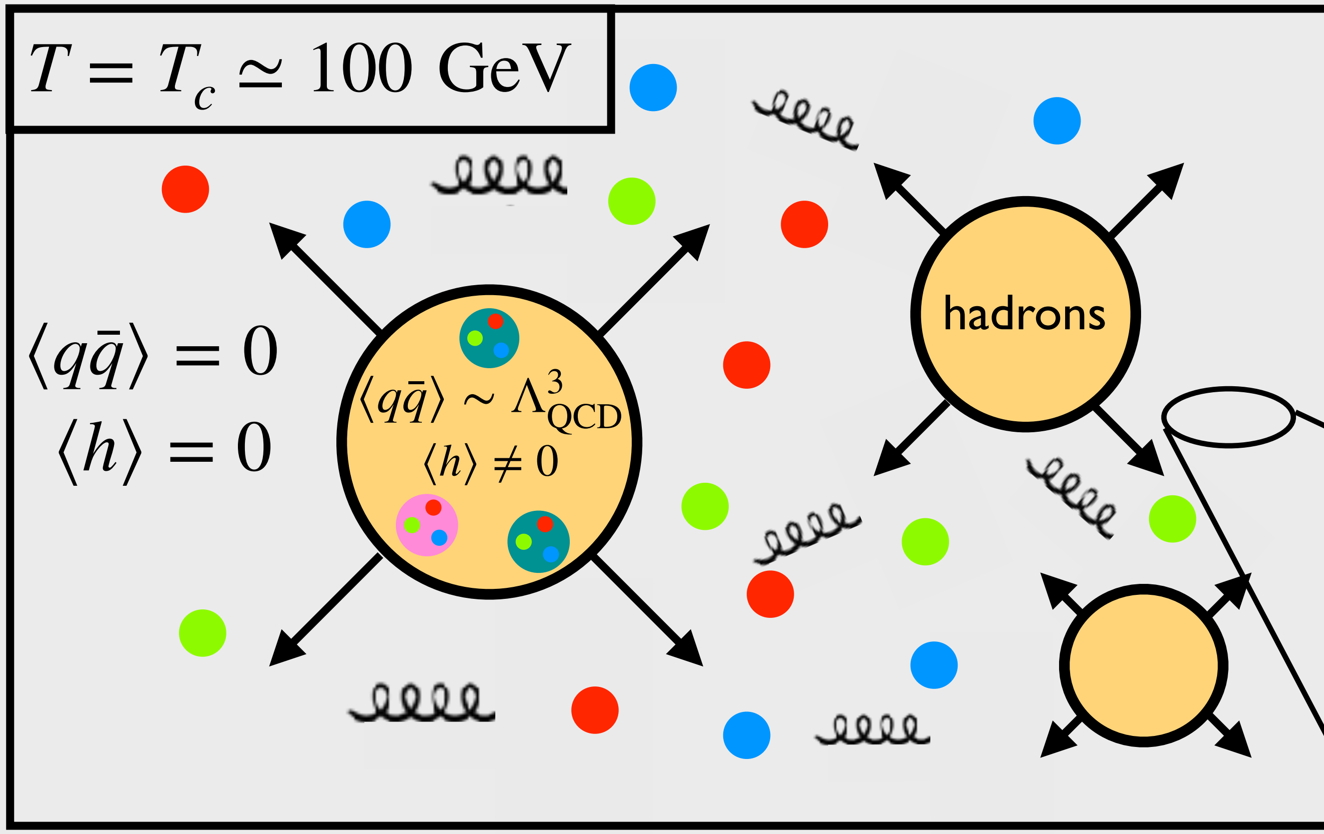
generates a chemical potential

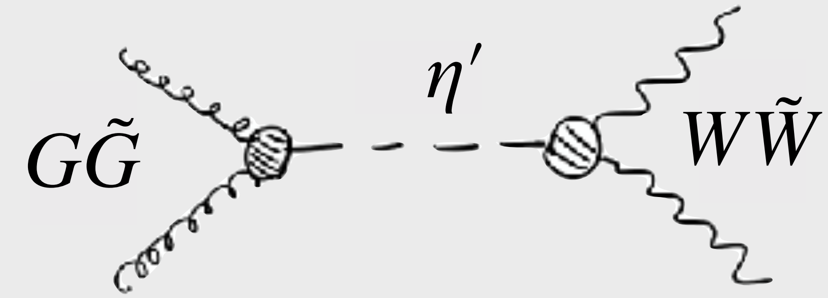
$$\frac{\alpha_s}{8\pi}\langle G\tilde{G}\rangle = m_a^2(T) f_a^2 \sin\bar{\theta} \quad \Rightarrow \quad \mu = \frac{10}{f_\pi^2 m_{\eta'}^2}\frac{d}{dt}\left[m_a^2(T) f_a^2 \sin\bar{\theta}(T)\right]$$

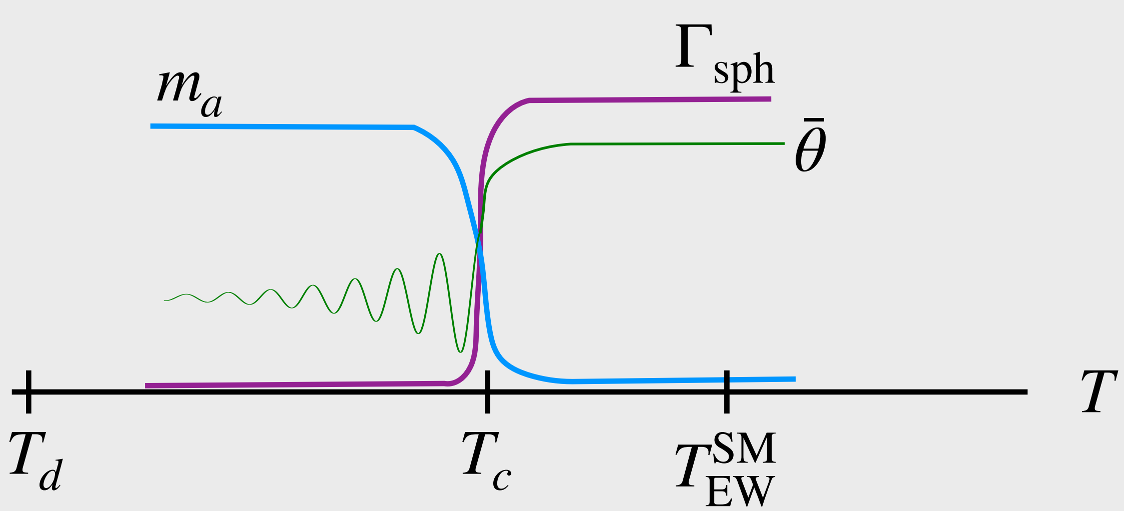


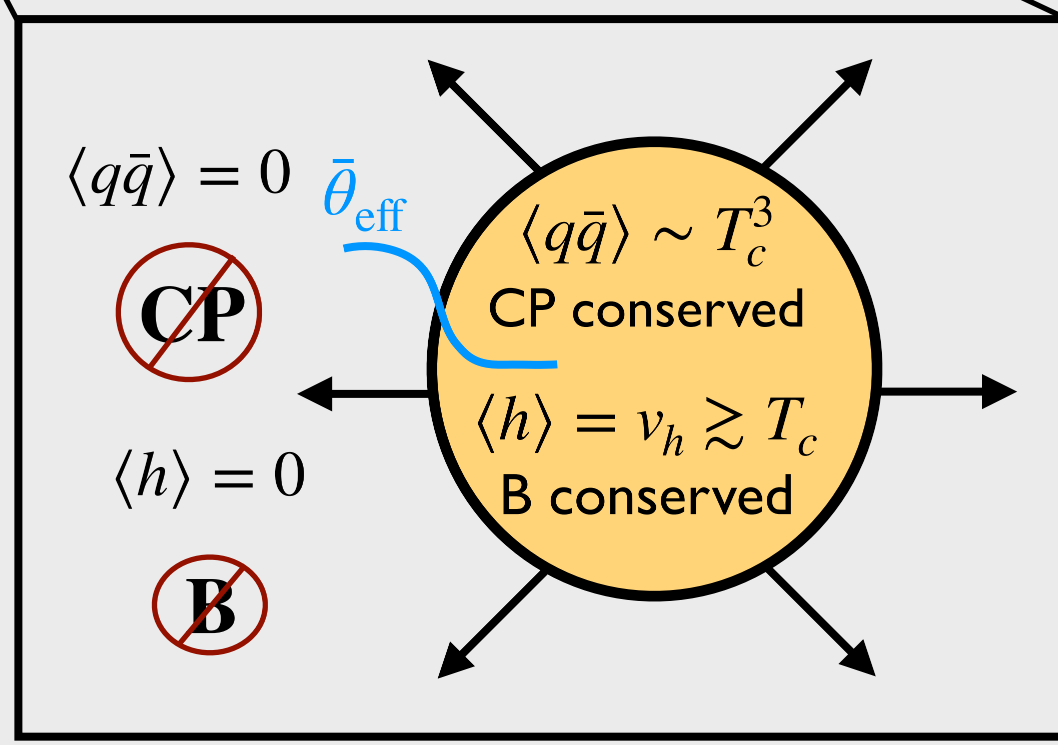
Spontaneous baryogenesis

A. Cohen, D. Kaplan, Nucl. Phys. B308 (1988) 913–928


$T = T_c \simeq 100$ GeV
$\langle q\bar{q}\rangle = 0$
$\langle h\rangle = 0$
$\langle q\bar{q}\rangle \sim \Lambda^3_{QCD}$
$\langle h\rangle \neq 0$
hadrons


$G\tilde{G}$
η'
$W\tilde{W}$


m_a
$\Gamma_{\rm sph}$
$\bar{\theta}$
T
T_d
T_c
$T^{\rm SM}_{\rm EW}$

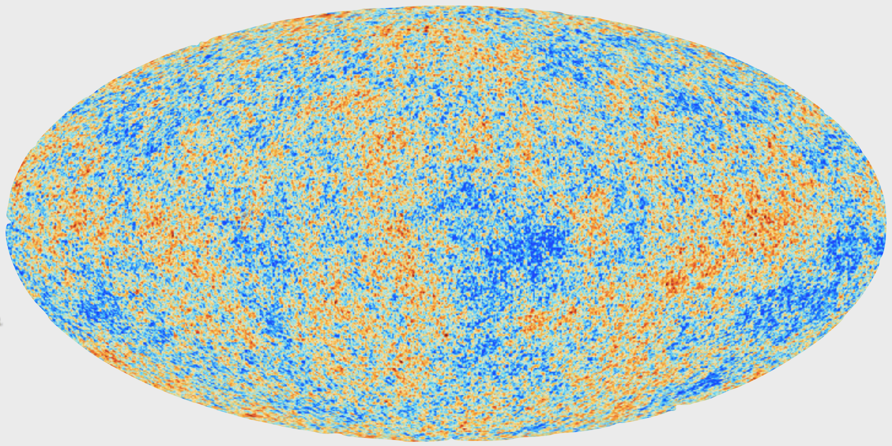

$\langle q\bar{q}\rangle = 0$
$\bar{\theta}_{\rm eff}$
CP
$\langle h\rangle = 0$
B
$\langle q\bar{q}\rangle \sim T_c^3$
CP conserved
$\langle h\rangle = v_h \gtrsim T_c$
B conserved

Number of baryons: $n_B = \int_{t_i}^{t_f} dt \frac{\Gamma_B}{T}\mu$

Baryon-to-entropy ratio

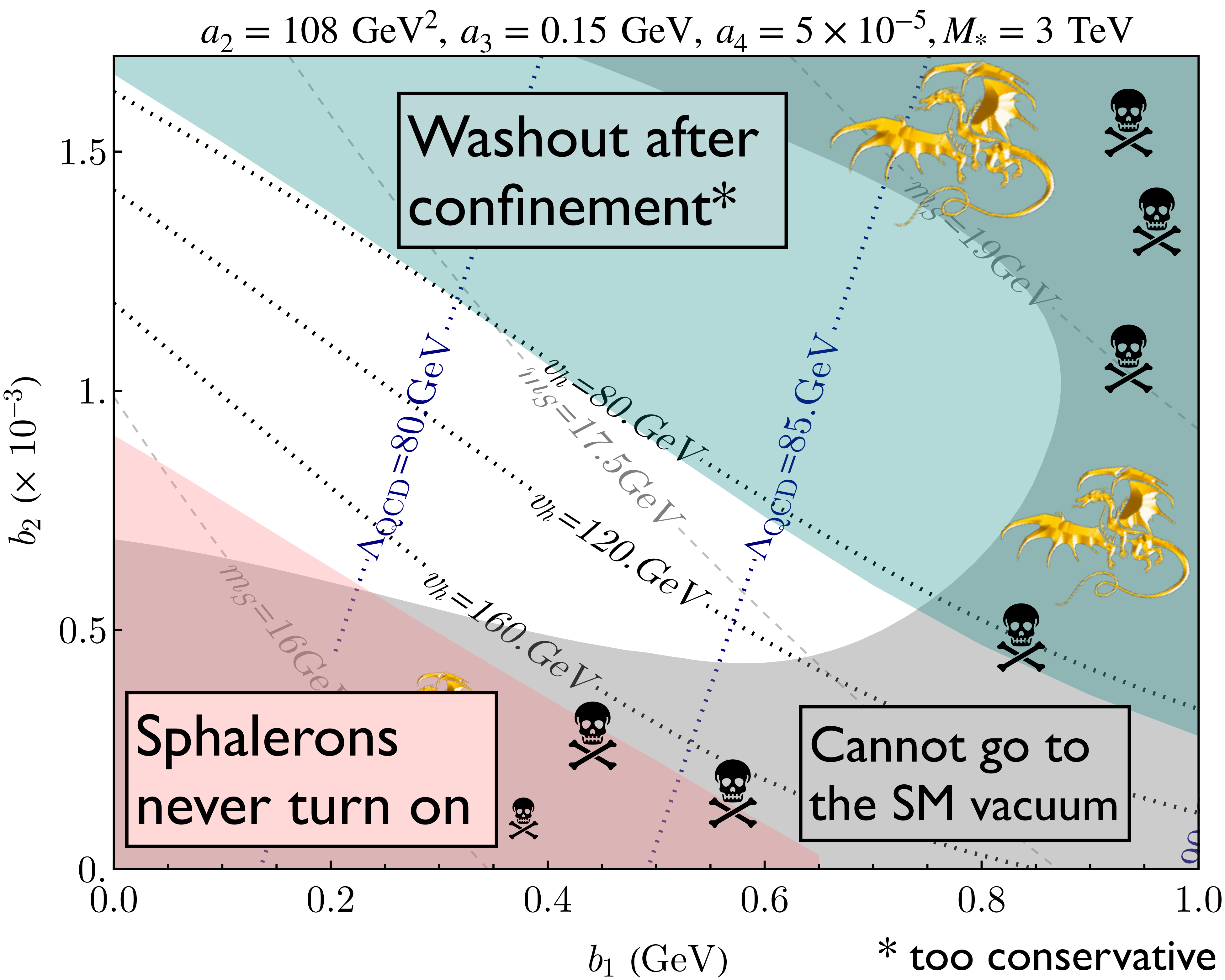
$$\eta = \frac{n_B}{s} \simeq \underbrace{\frac{5625}{2\pi^2 \underbrace{\boxed{g_*(T_{\rm reh})}}_{\sim 45}} \alpha_w^5 \sin\bar{\theta}\, \frac{\overbrace{\boxed{\Delta\left[m_a^2(T) f_a^2\right]}}^{\sim m_\pi^2 f_\pi^2}}{f_\pi^2 m_{\eta'}^2} \left(\frac{T_{\rm sph}}{T_{\rm reh}}\right)^3}_{4.4\times 10^{-9}\sin\bar{\theta}\left(\frac{v_h}{v_h^0}\right)\left(\frac{\Lambda_{\rm QCD}^{\rm SM}}{\Lambda_{\rm QCD}}\right)}$$

$$\boxed{\eta \sim 10^{-11}\, \overbrace{\sin\bar{\theta}}^{\sim 1}\, \overbrace{\frac{v_h}{\Lambda_{\rm QCD}}}^{\sim 4} \left(\overbrace{\frac{T_{\rm sph}}{T_{\rm reh}}}^{>1}\right)^3 \qquad \eta_{\rm obs} \simeq 8.5\times 10^{-11}}$$



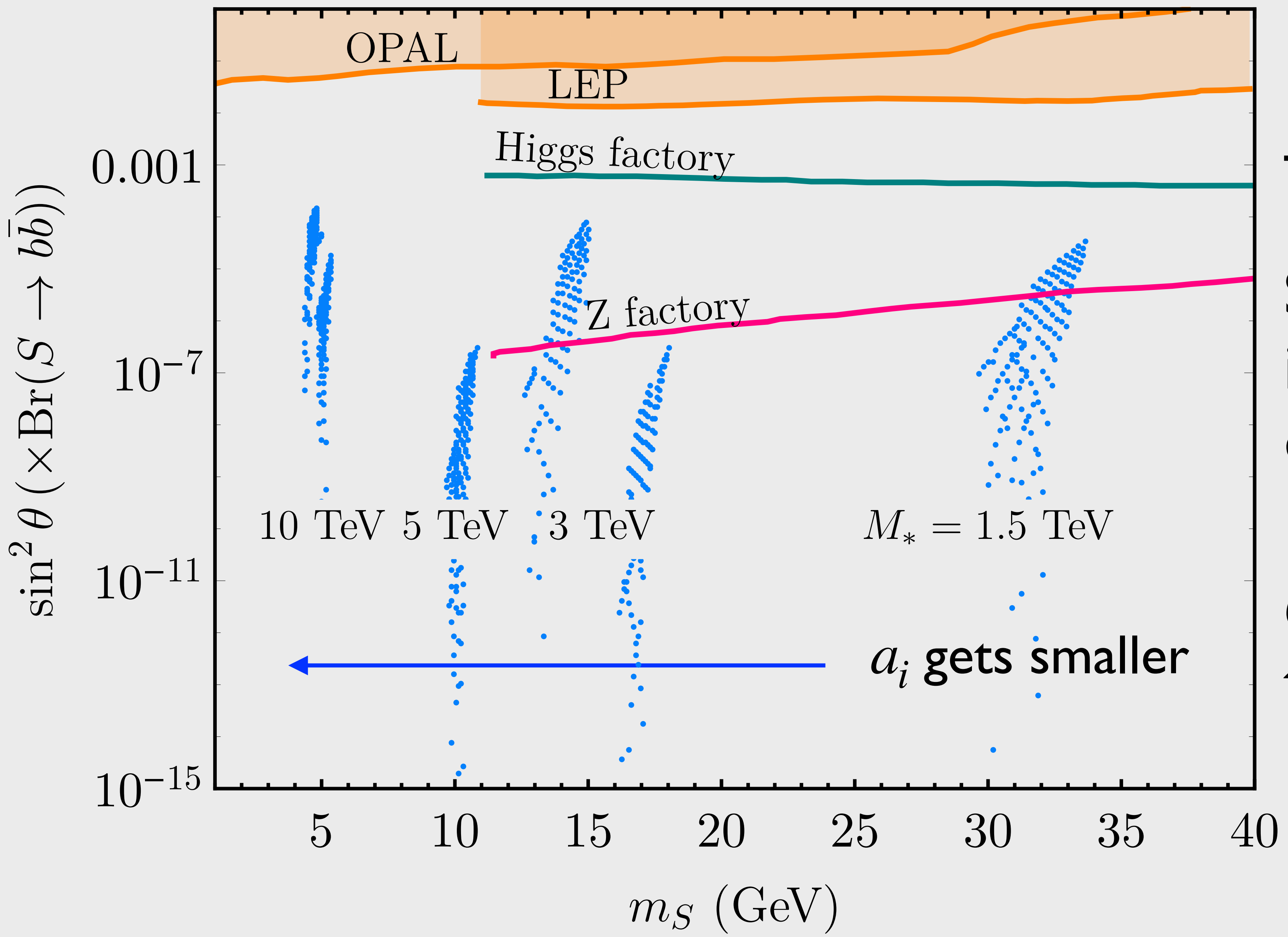
fix (6 benchmark scenarios) vary

$$V_0 = \boxed{-\mu^2|H|^2 + \lambda_h|H|^4 + a_2 S^2 + a_3 S^3 + a_4 S^4} - \boxed{b_1 S|H|^2 + b_2 S^2|H|^2}$$



* too conservative

Constraints - Higgs mixing



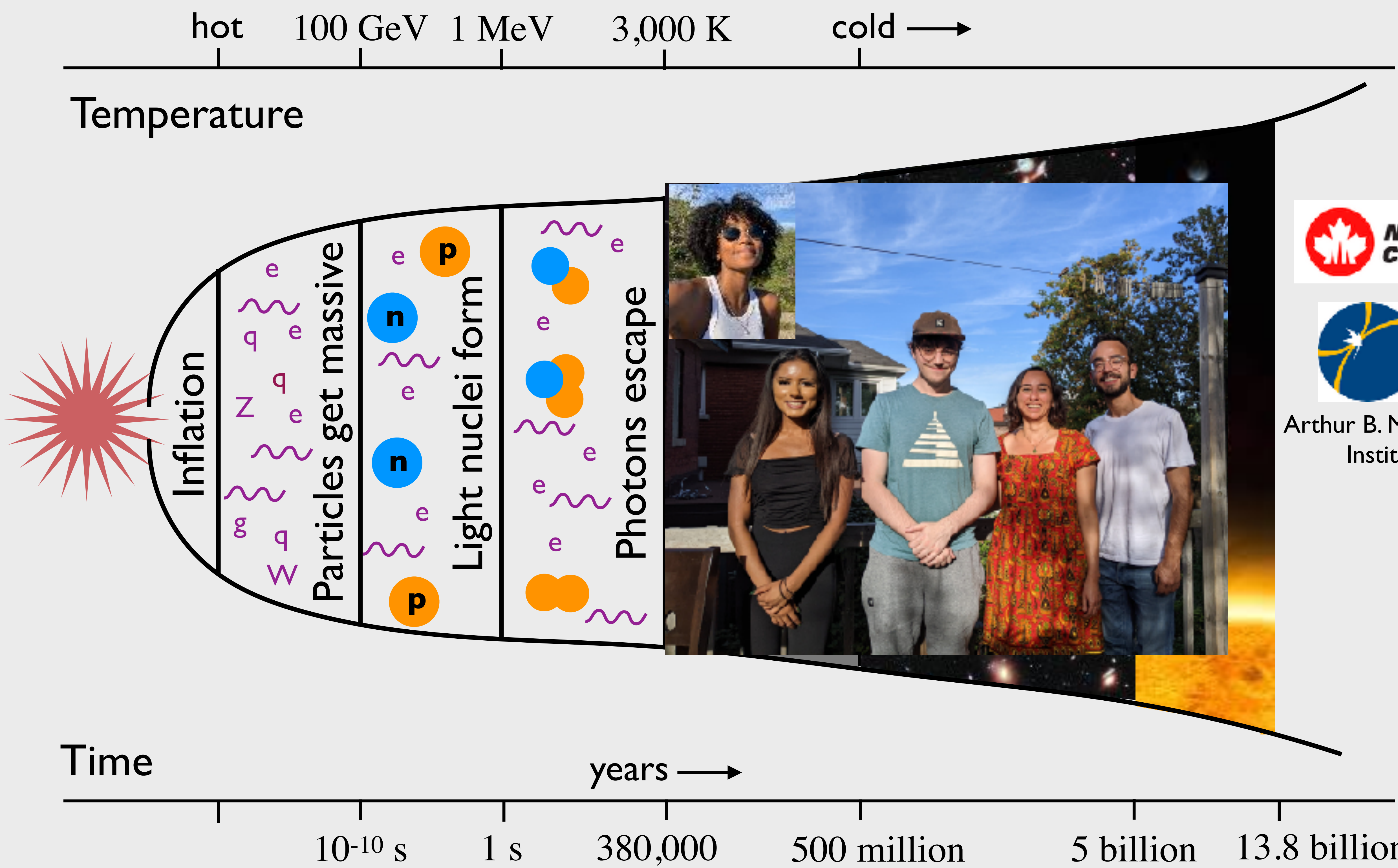
Mixing angle is too small for current searches

Singlet lighter than ~10GeV is hard to constrain since it decays primarily to gluons

6 benchmark scenarios, there will be more!

Multi-step 1^{st} order phase transitions → $f \sim 10^{-3}$ Hz Interesting GW signatures!

We want to understand the universe!



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