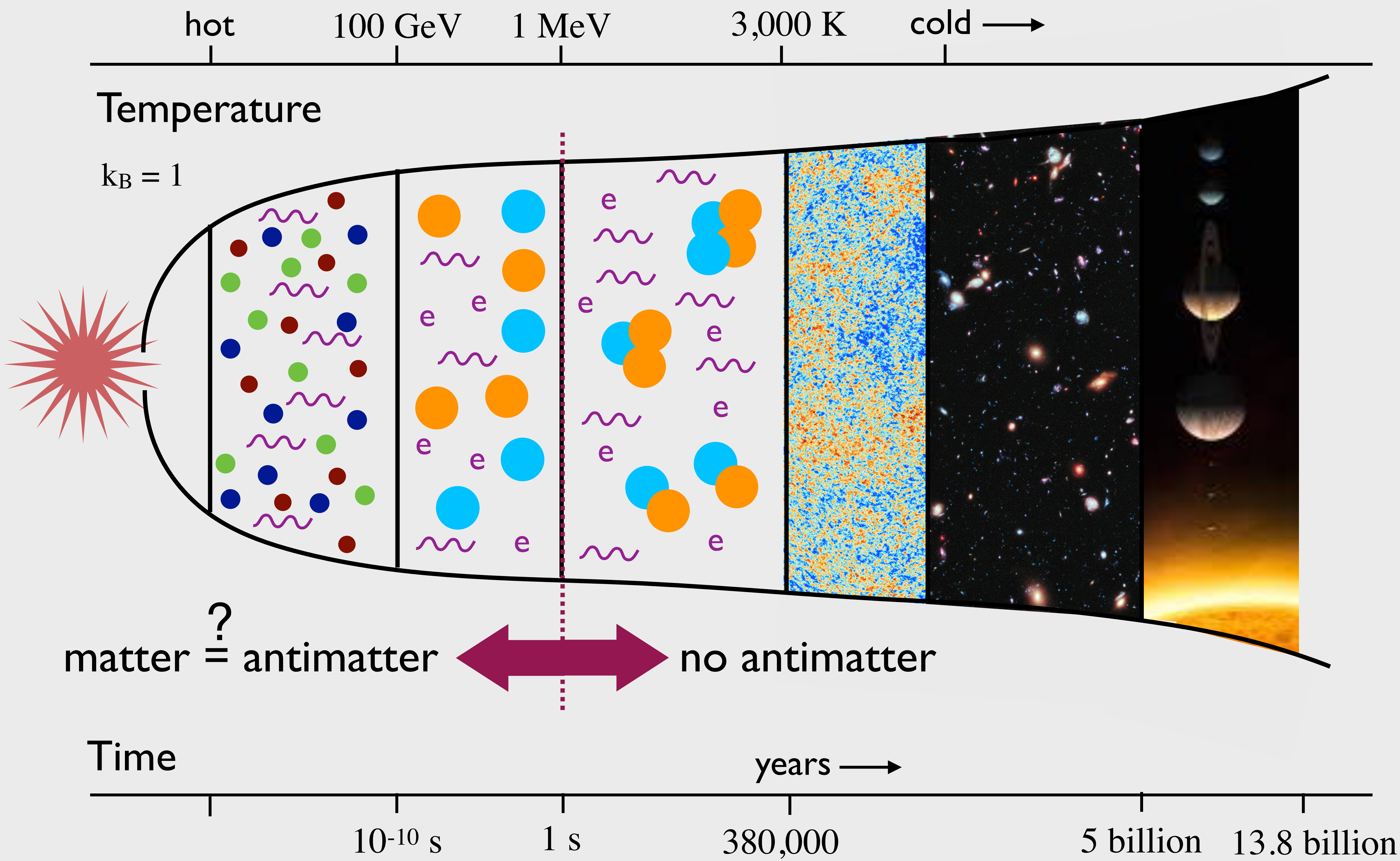
New Physics for Baryogenesis And Where to Find It

Seyda Ipek
Carleton University

WNPPC 2024

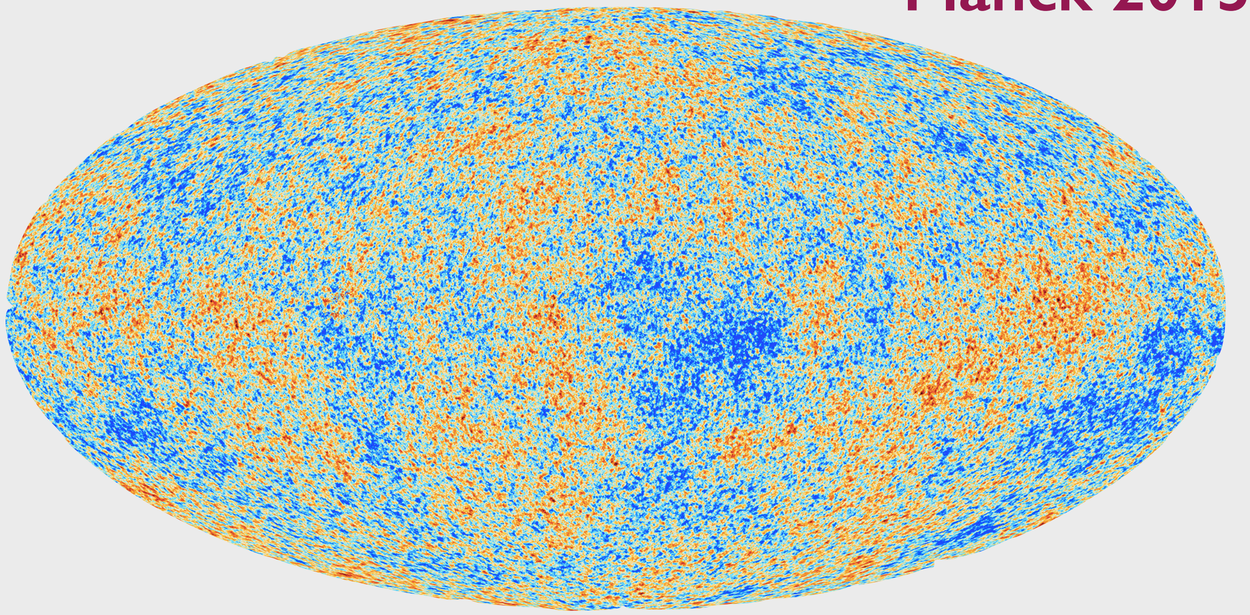
Carleton UNIVERSITY
Canada's Capital University

A Brief History Of Our Universe



Cosmic Microwave Background

Planck 2015

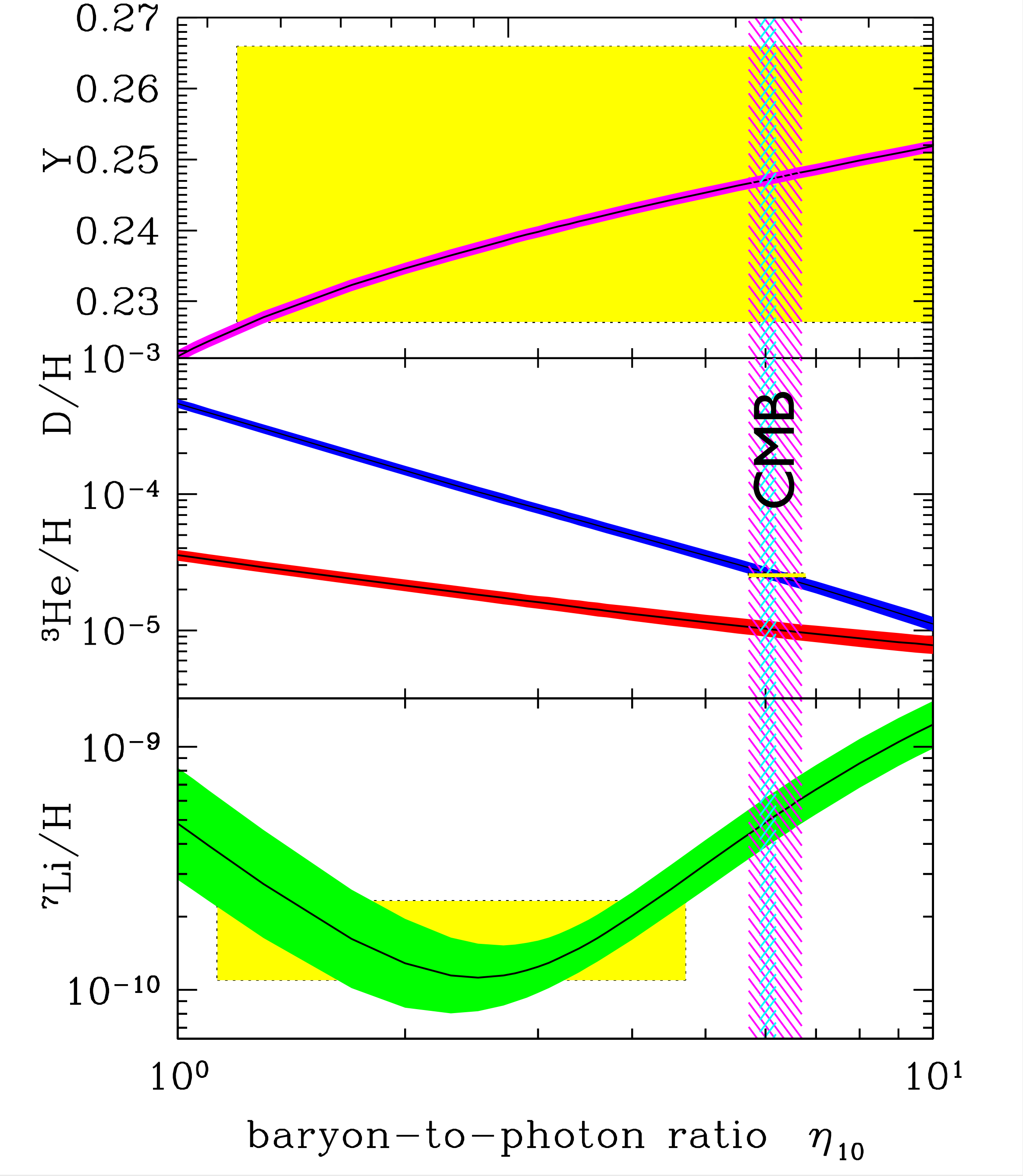


Baryon-to-photon ratio:

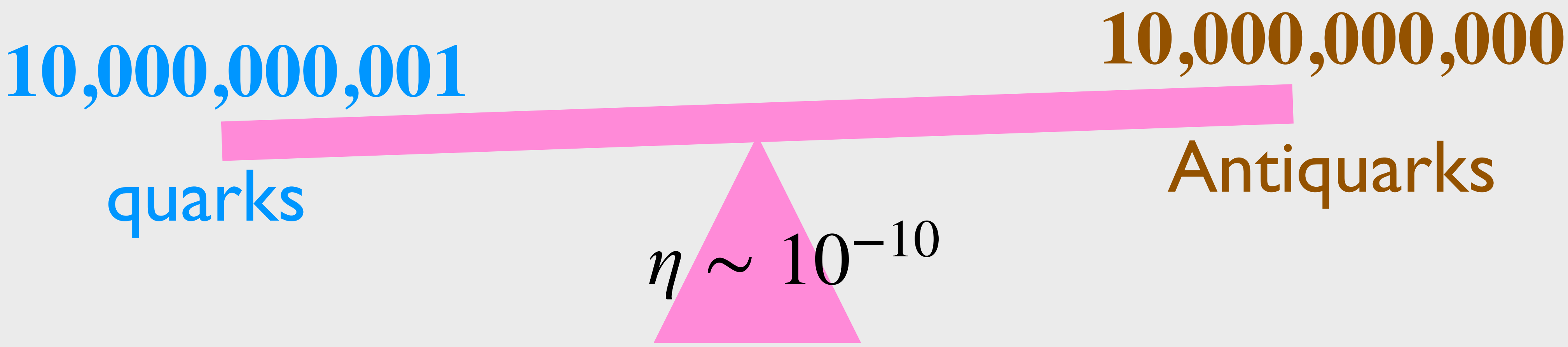
$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

Primordial light element abundances

Particle Data Group



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!

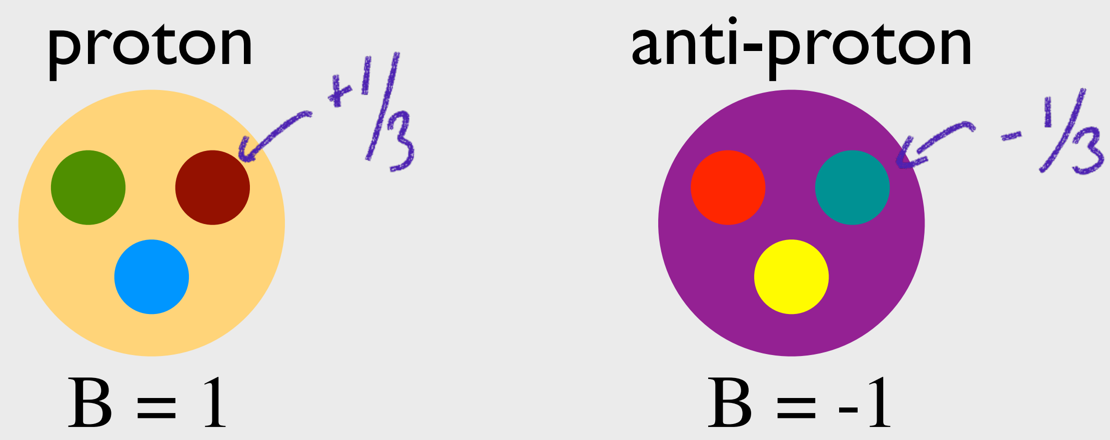
Andrei Sakharov
1921-1989

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:

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

Inflation

At the beginning:

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

$t = 0$: $\Delta_B = 0$ → time flies → $\Delta_B \neq 0$

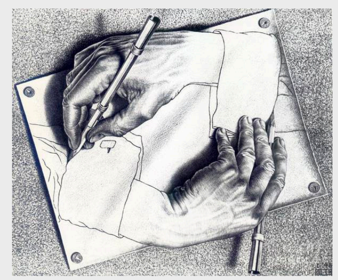
Δ_B cannot be a conserved quantity! It needs to change with time

Baryon number violation

Time

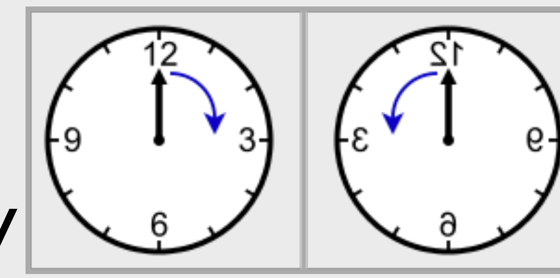
How can physics laws tell the difference between a particle and an antiparticle?

We look at some (a)symmetries under certain transformations



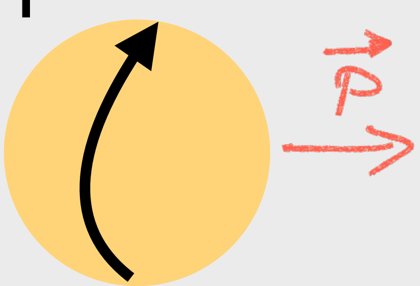
Handedness

Parity



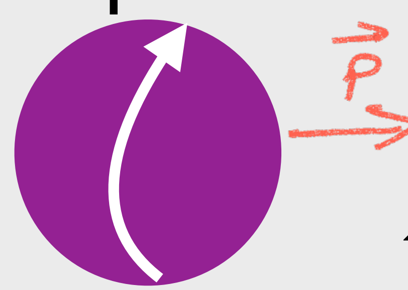
different physics laws!

Left-handed proton



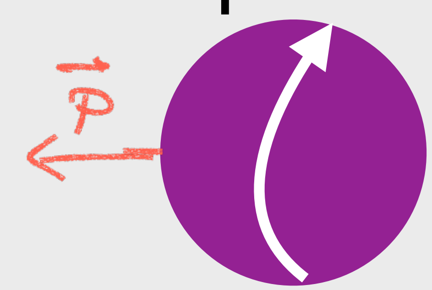
Charge transformation

Left-handed anti-proton



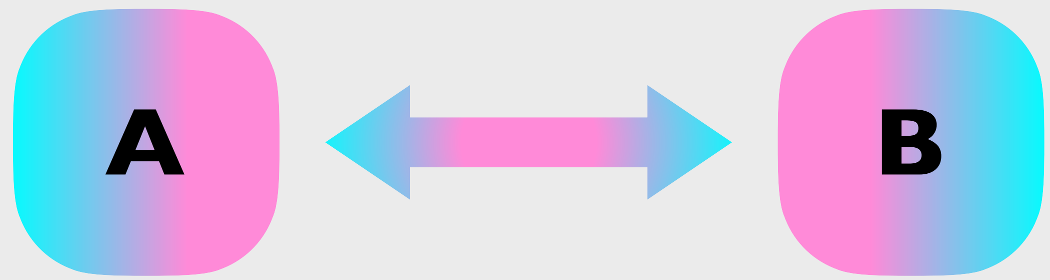
Parity transformation

Right-handed anti-proton



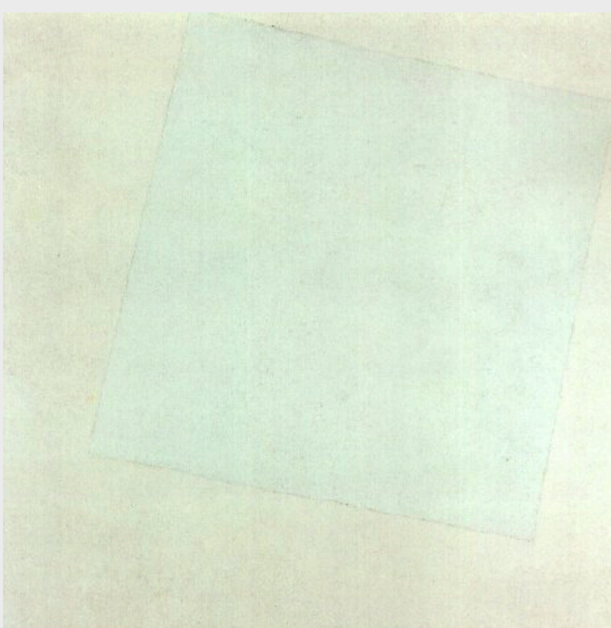
Charge-parity violation

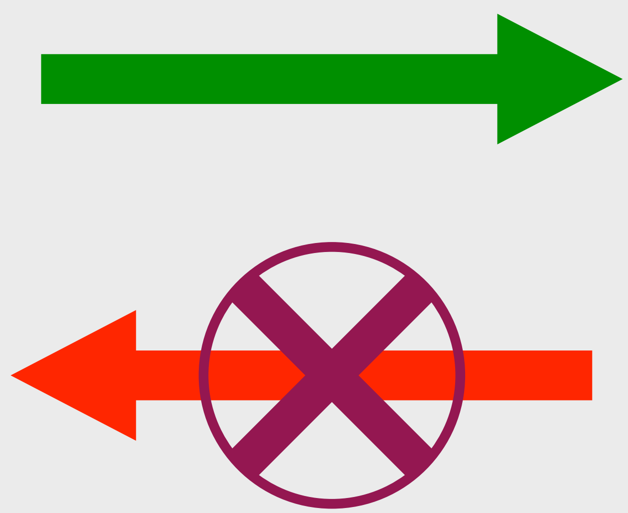
Nothing interesting happens in thermal equilibrium

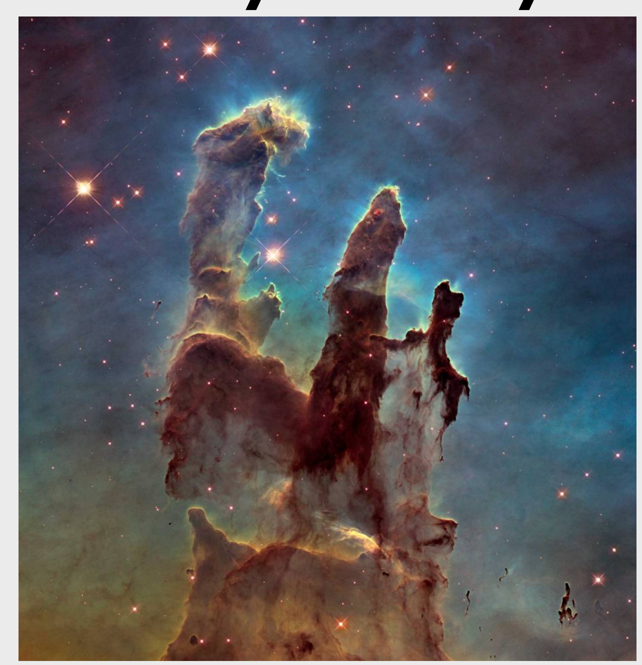


Zero baryon asymmetry

Some baryon asymmetry







Pillars of Creation,
Eagle Nebule,
Hubble Space Telescope

Being out of equilibrium

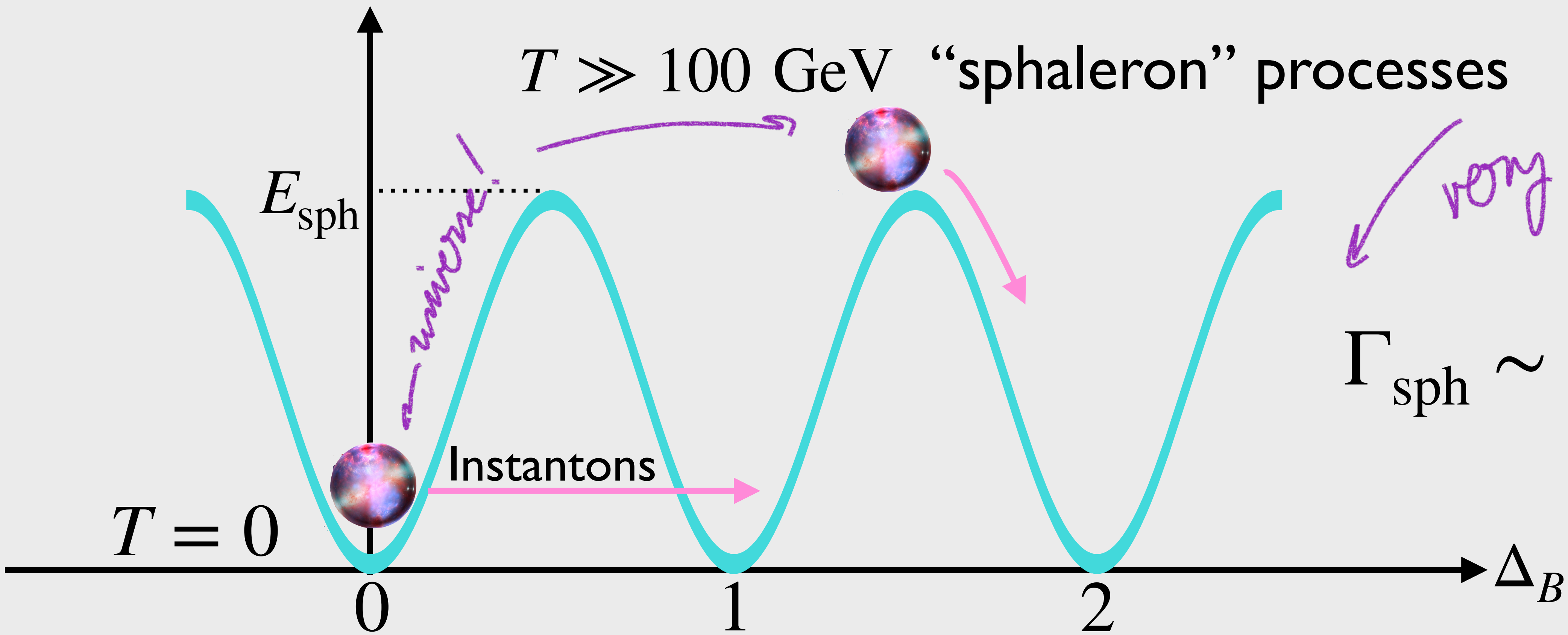
Can the Standard Model of particle physics explain the baryon asymmetry of the Universe?

Does the Standard Model satisfy the Sakharov Conditions?

Baryon number is violated in weak interactions 😃

only left-handed particles interact via the weak nuclear force

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



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

Quantum tunneling is hard!

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

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

CP is also violated in weak interactions $K_L \to 2\pi$ AND $K_L \to 3\pi$

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

Entirely because there is a complex phase in the CKM matrix

$\begin{pmatrix} u & c & t \end{pmatrix}$

$\begin{pmatrix} d \\ s \\ b \end{pmatrix}$

"Joke" from one of my first talks (2013)

Great! BUT not enough for the baryon asymmetry

handwavey:

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

more detailed calculations:

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

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

Equilibrium?

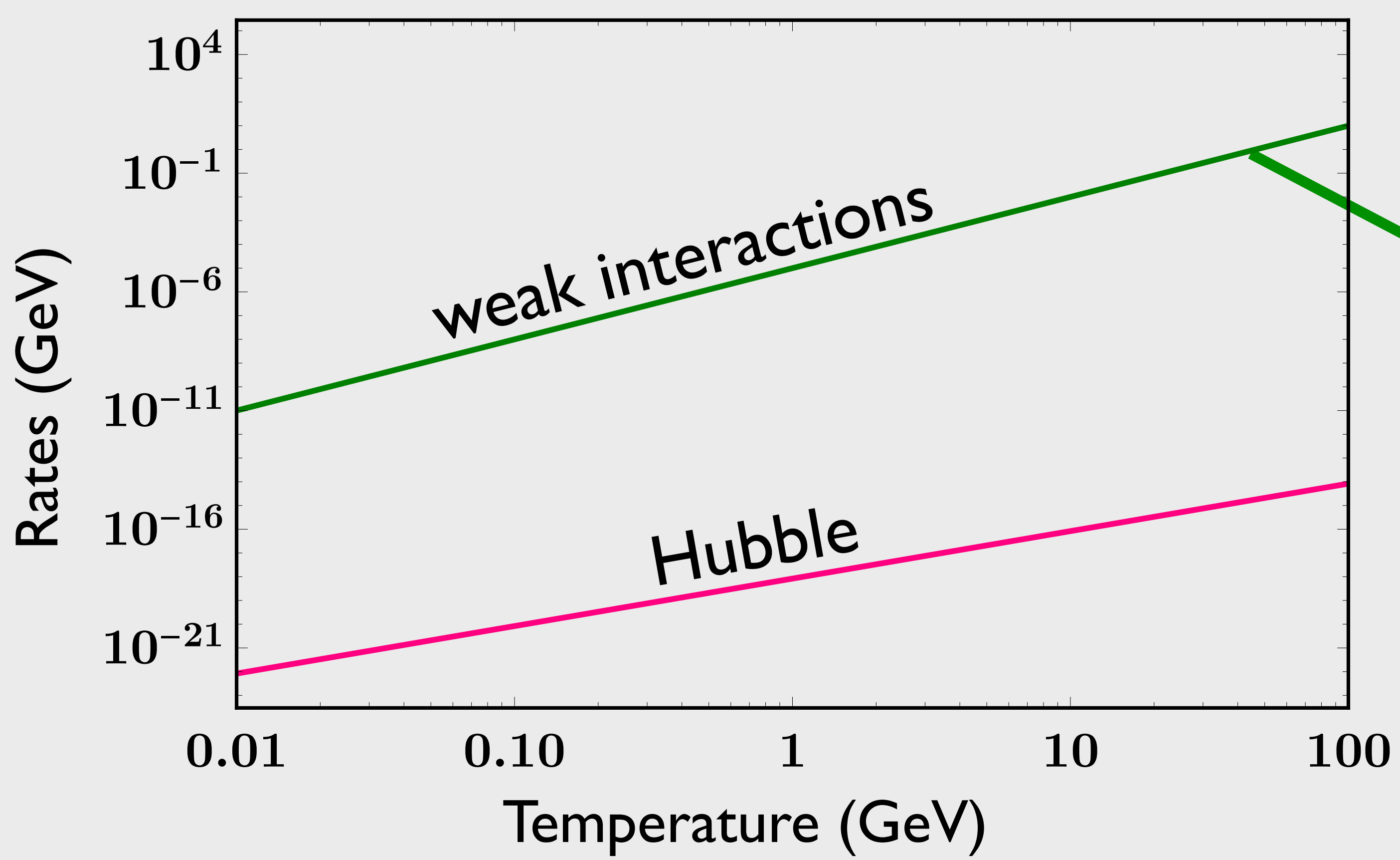
Rate of
(weak) interactions

vs

Expansion rate
of the universe

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

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

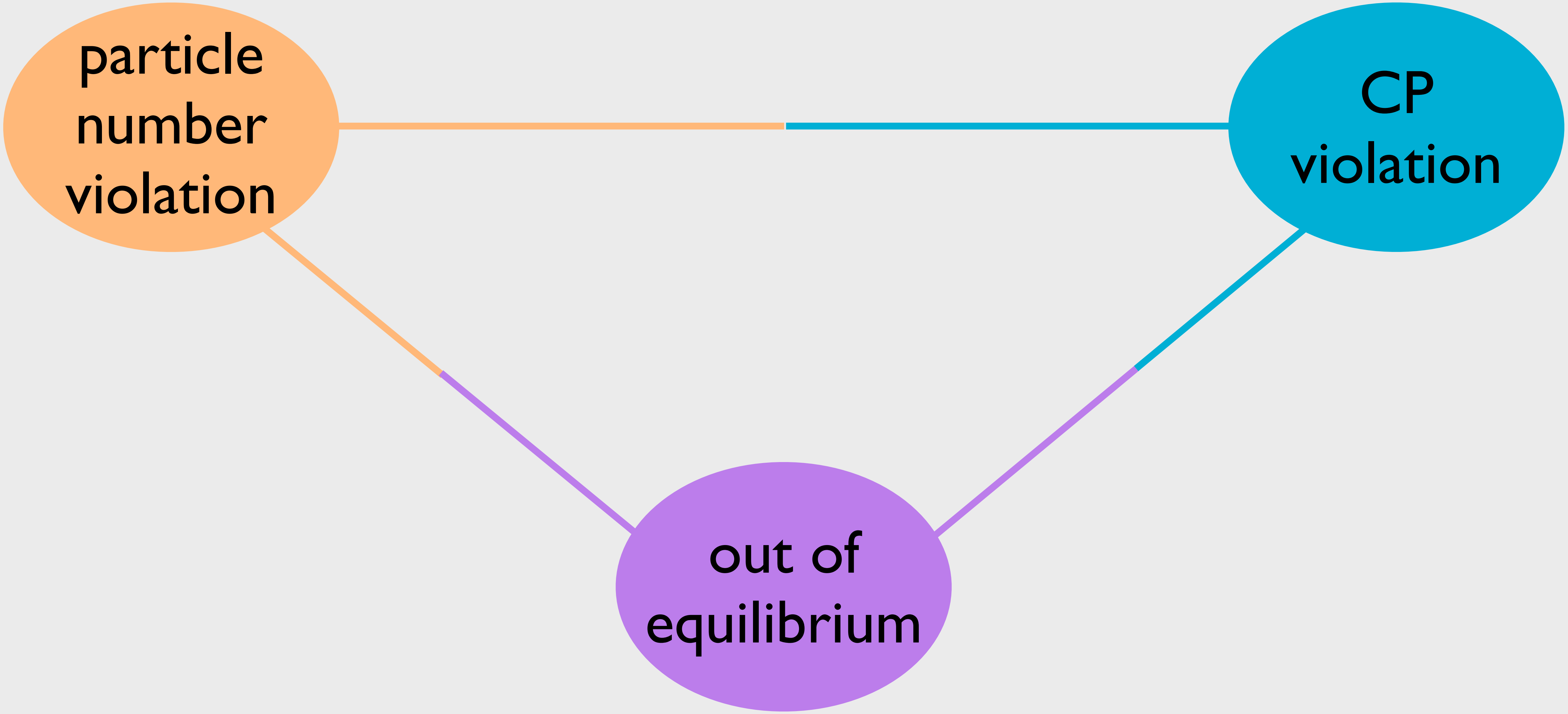


Too fast!

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!

particle number violation

Explicit L violation is an option

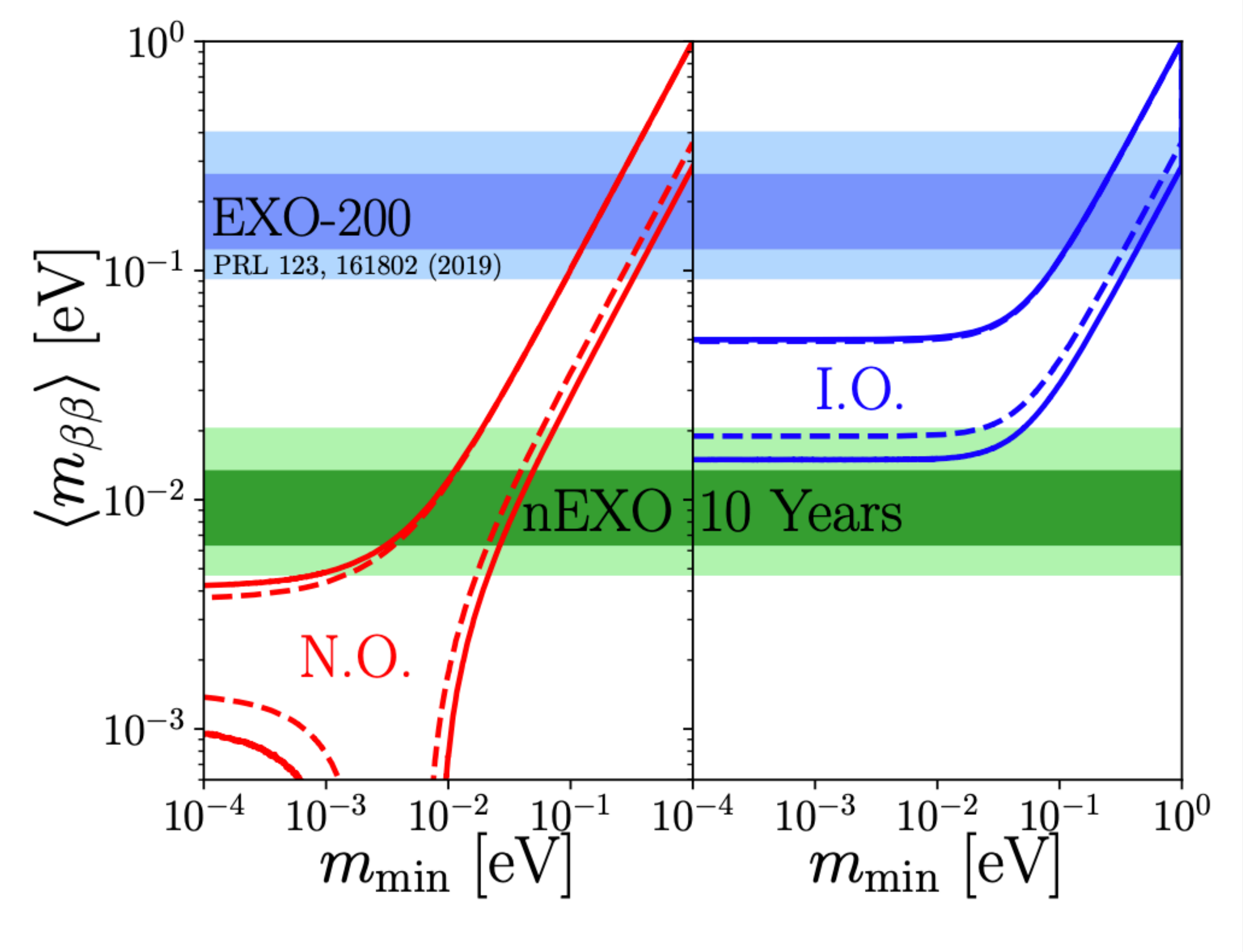
Leptogenesis!

Right-handed Majorana neutrinos → neutrino masses + lepton asymmetry

How about $0\nu\beta\beta$?

Would be very interesting if the SM neutrinos are Majorana!

But not directly related to the baryon asymmetry :(



particle number violation

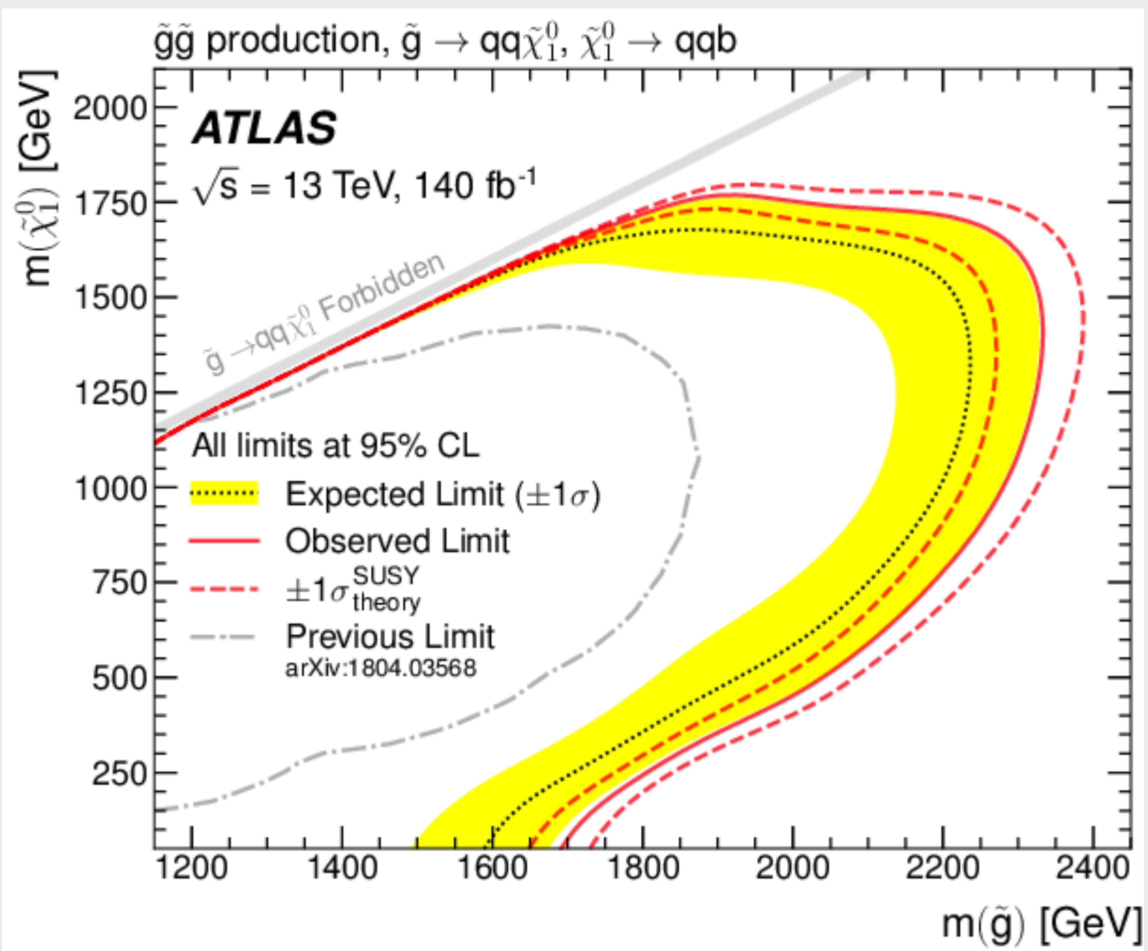
Explicit B violation is also an option

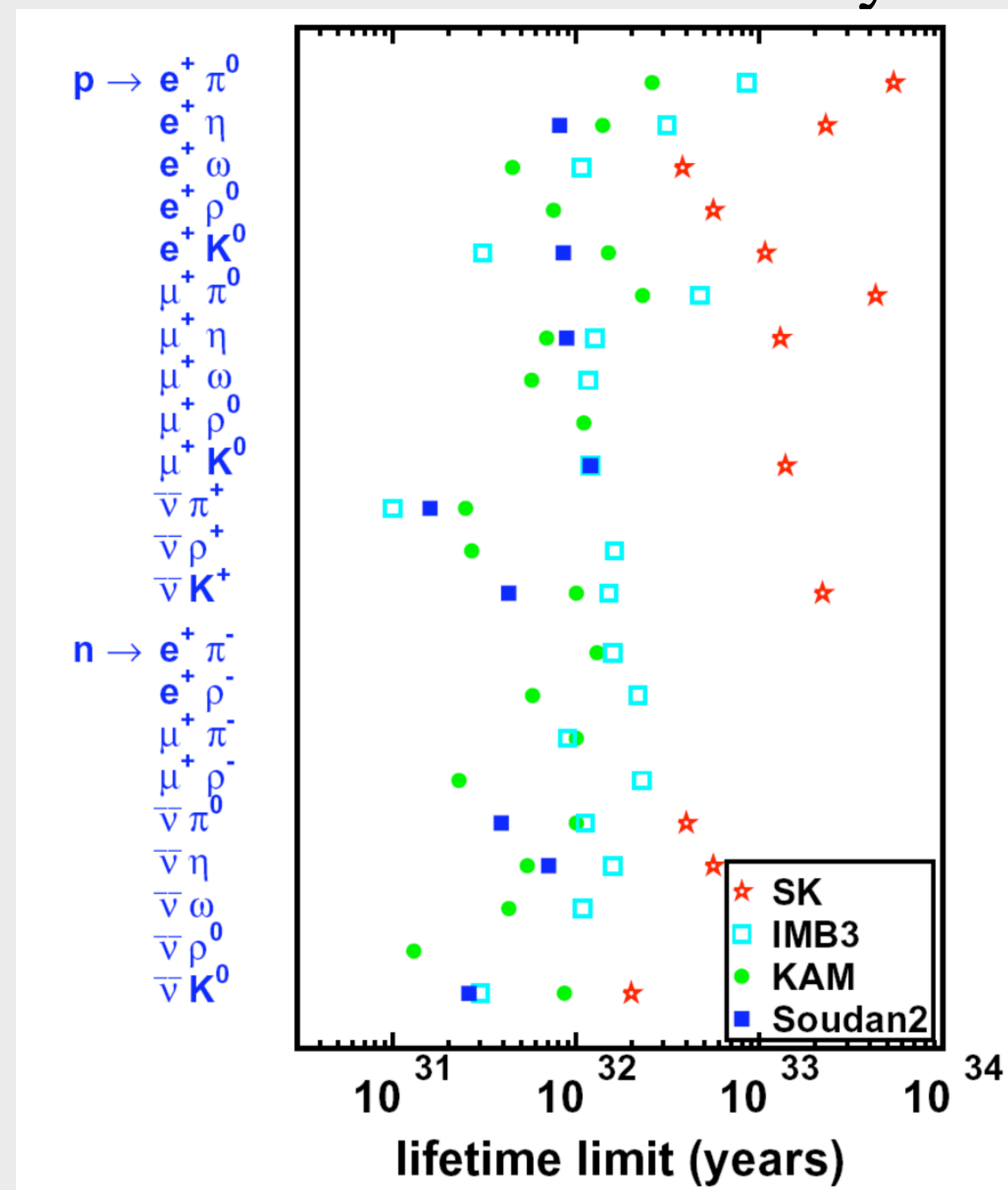
proton decay??? $\frac{g}{\Lambda^2} qqq\ell$

$\tau > 10^{34}$ years

R-parity violating SUSY

$$\lambda_{ijk} L_i L_j L_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k$$





2003, M. Shiozawa 28th International Cosmic Ray Conference

Baryon asymmetry from pseudo-Dirac binos

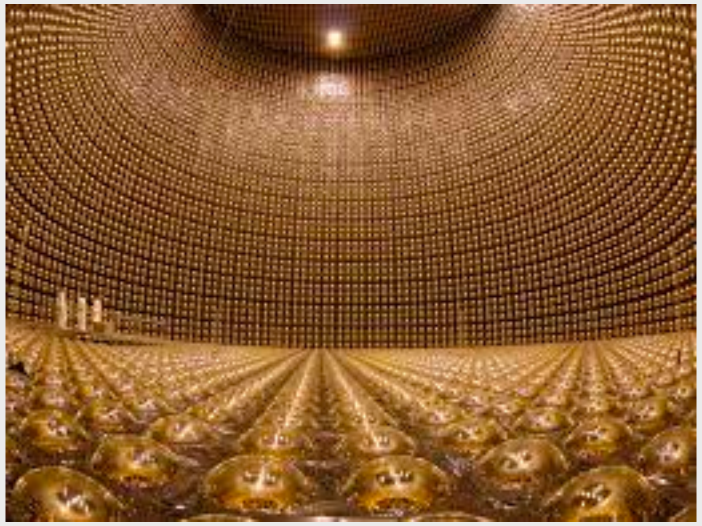
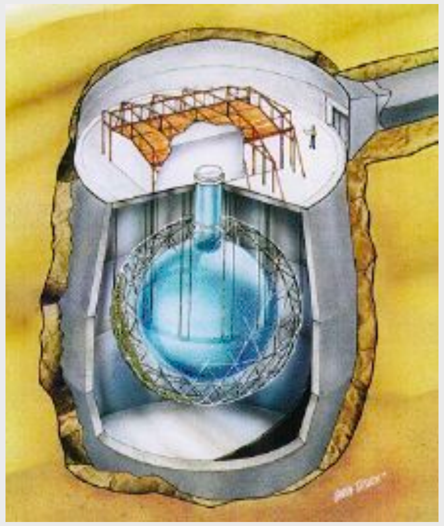
SI, J. March-Russell, PRD 93 (2016), no.12

particle number violation

Explicit B violation is also an option

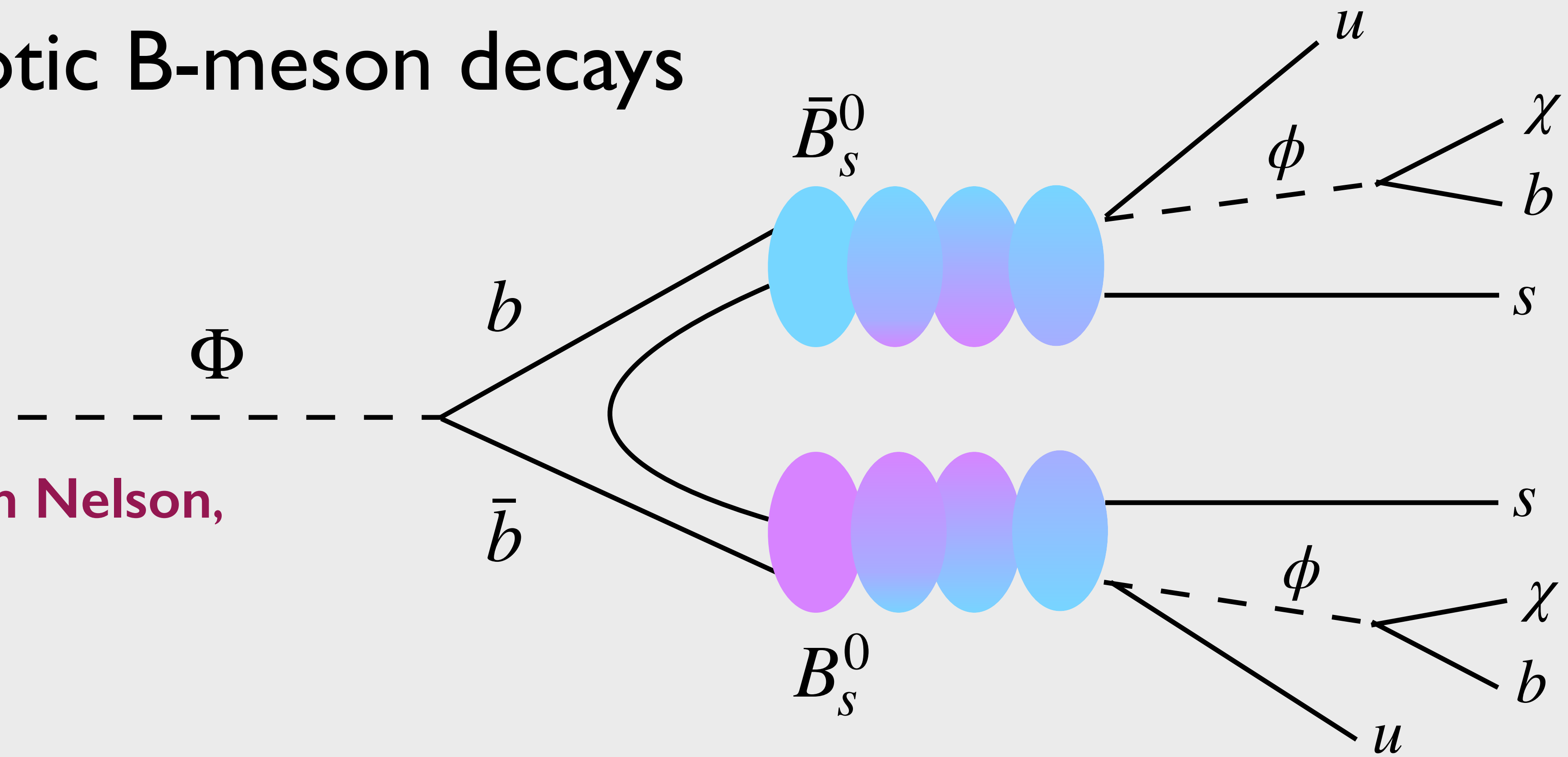
$\Delta B = 2$

$n - \bar{n}$ oscillations! $\frac{g}{\Lambda^5} QQQQQQ$

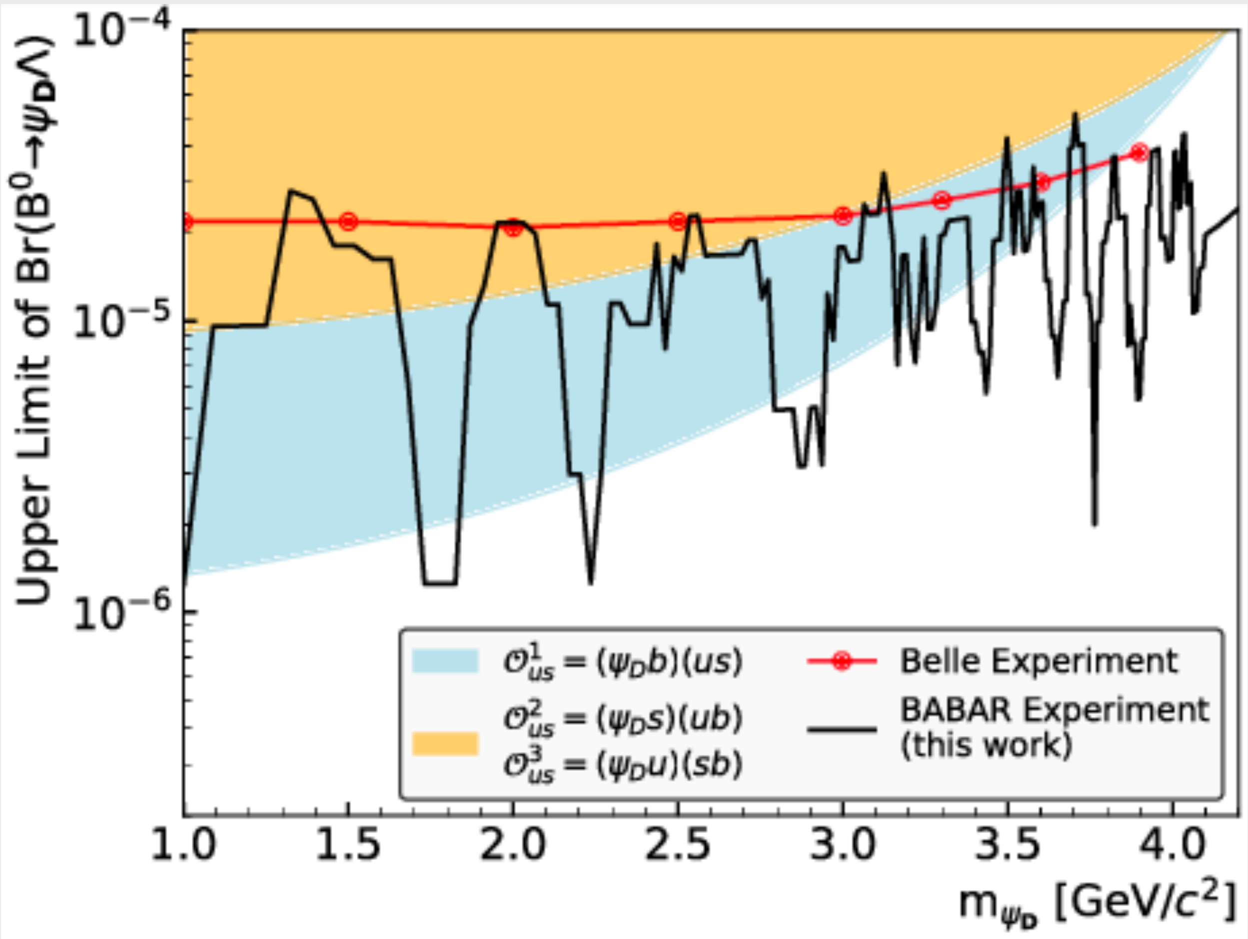
Super-K	Soudan-II	SNO
		
In ^{16}O	In ^{56}Fe	In deuteron
$\tau_{n-\bar{n}} > 2.7 \times 10^8\ s$	$\tau_{n-\bar{n}} > 1.3 \times 10^8\ s$	$\tau_{n-\bar{n}} > 1.23 \times 10^8\ s$

particle number violation

Exotic B-meson decays



Gilly Elor, Miguel Escudero, **Ann Nelson**, arXiv: 1810.00880



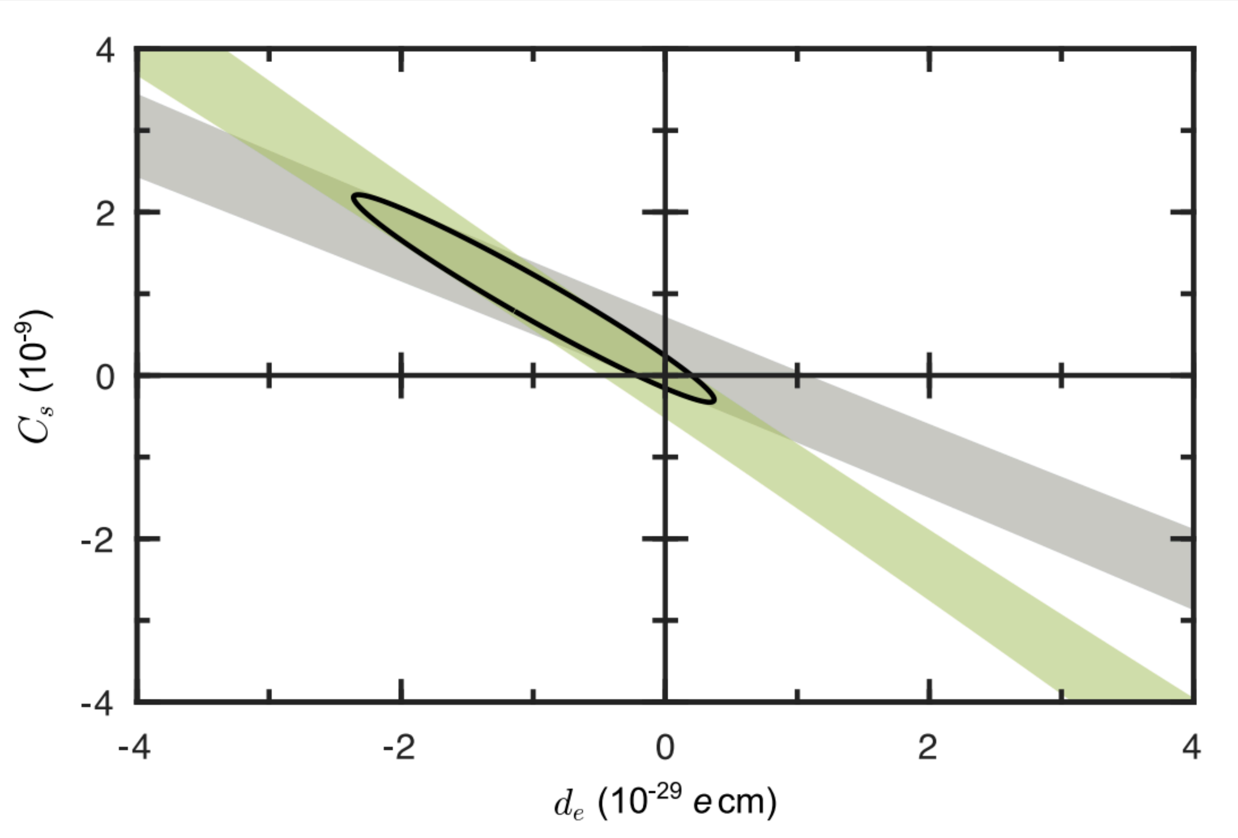
BABAR

BaBar, *Phys.Rev.D* 107 (2023) 9, 092001, 2302.0028

CP violation

Electron electric dipole moment

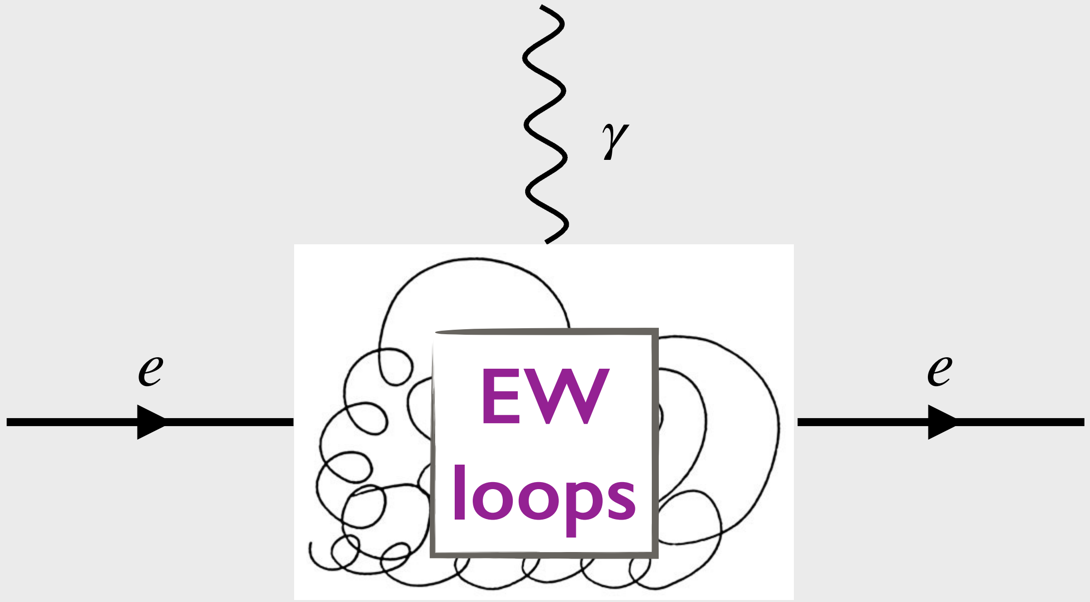
$$d_e \sim \frac{e a_0 \alpha}{2} \frac{g^2}{2\pi} \frac{m_2^2}{M^2} \sin\phi_{CP}$$



JILA, arXiv:2212.11841

$d_e \leq 4.1\text{x}10^{-30}\ e{\cdot}\text{cm}$

What we have in the SM:



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

Could come down to 10^{-32} !

Fleig, DeMille, arXiv:2108.02809

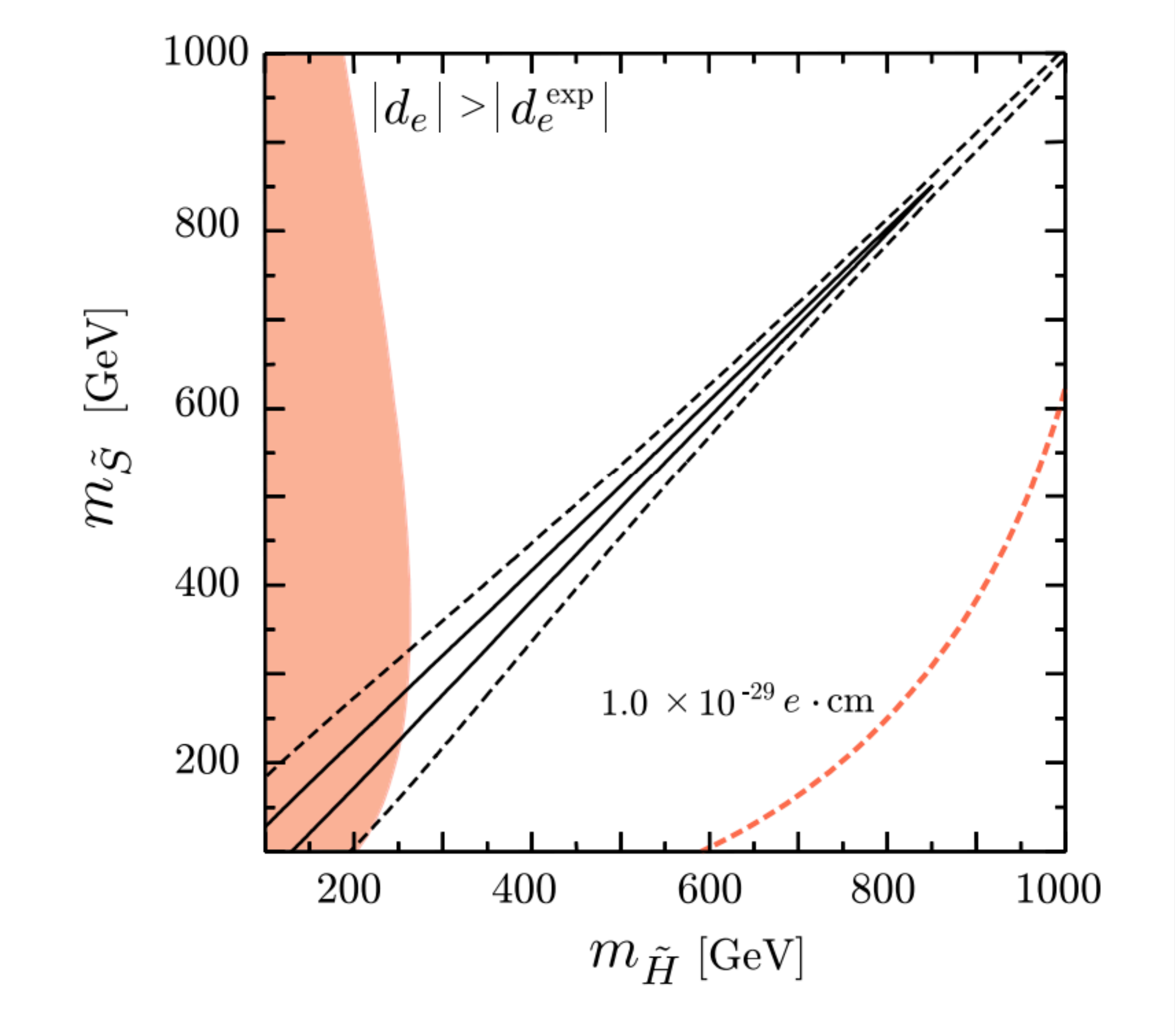
CP violation

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

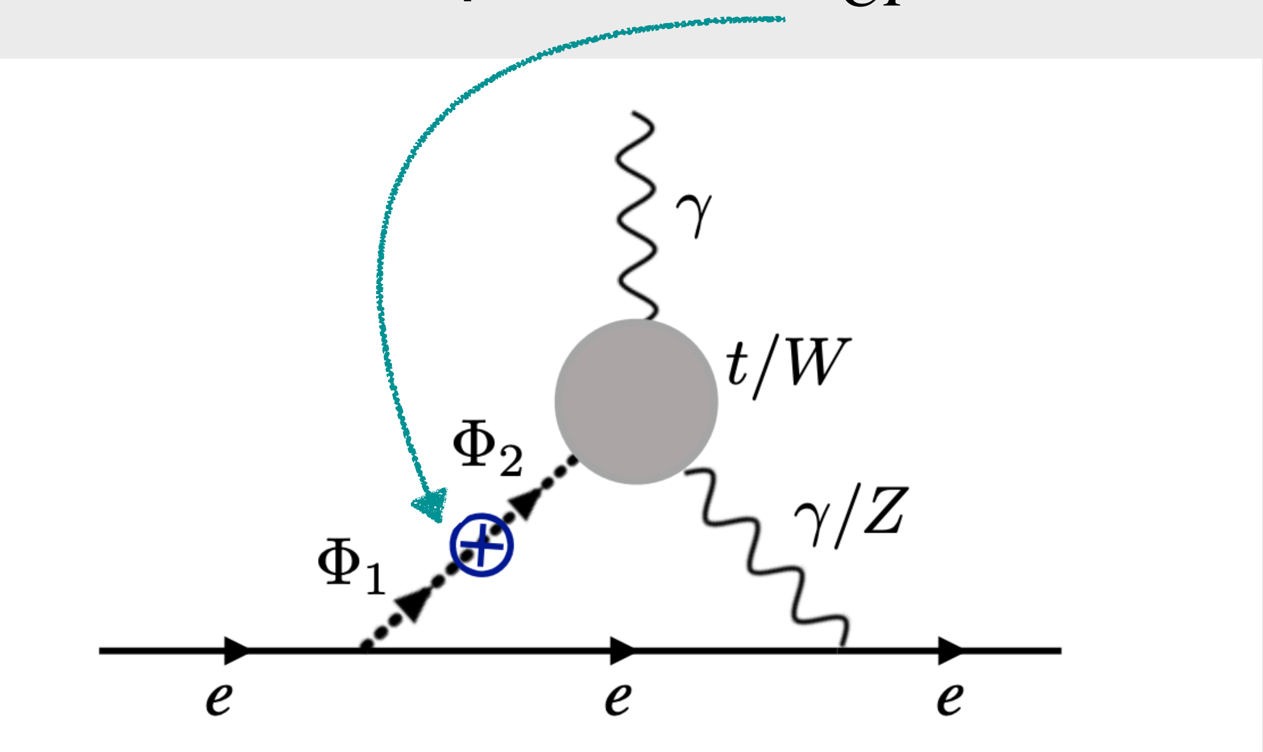
JILA, arXiv:2212.11841

2HDM + CP violation

K. Fuyuto, et al, arXiv:1510.04485



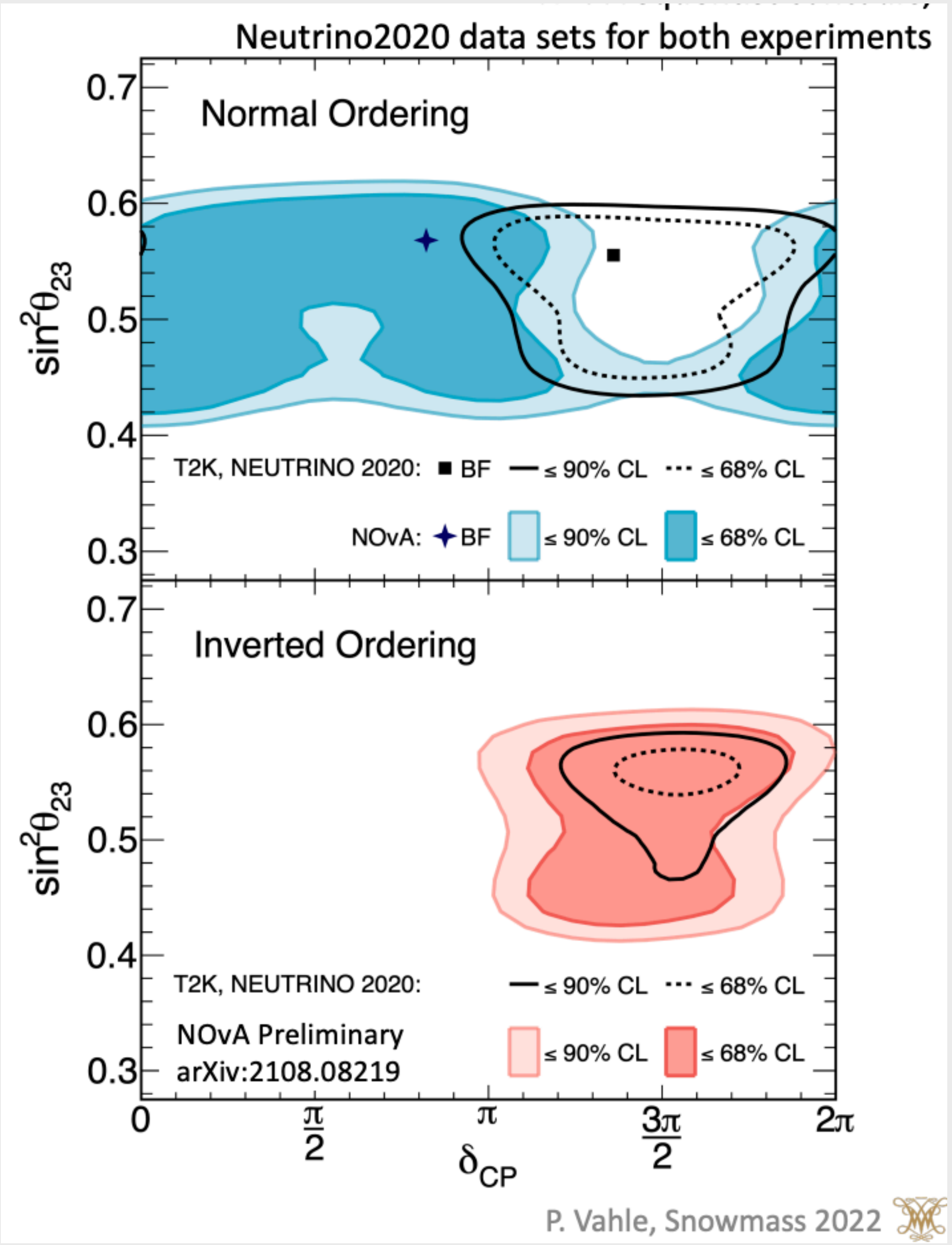
$\eta \sim 10^{-8}\, \xi_{CP}$

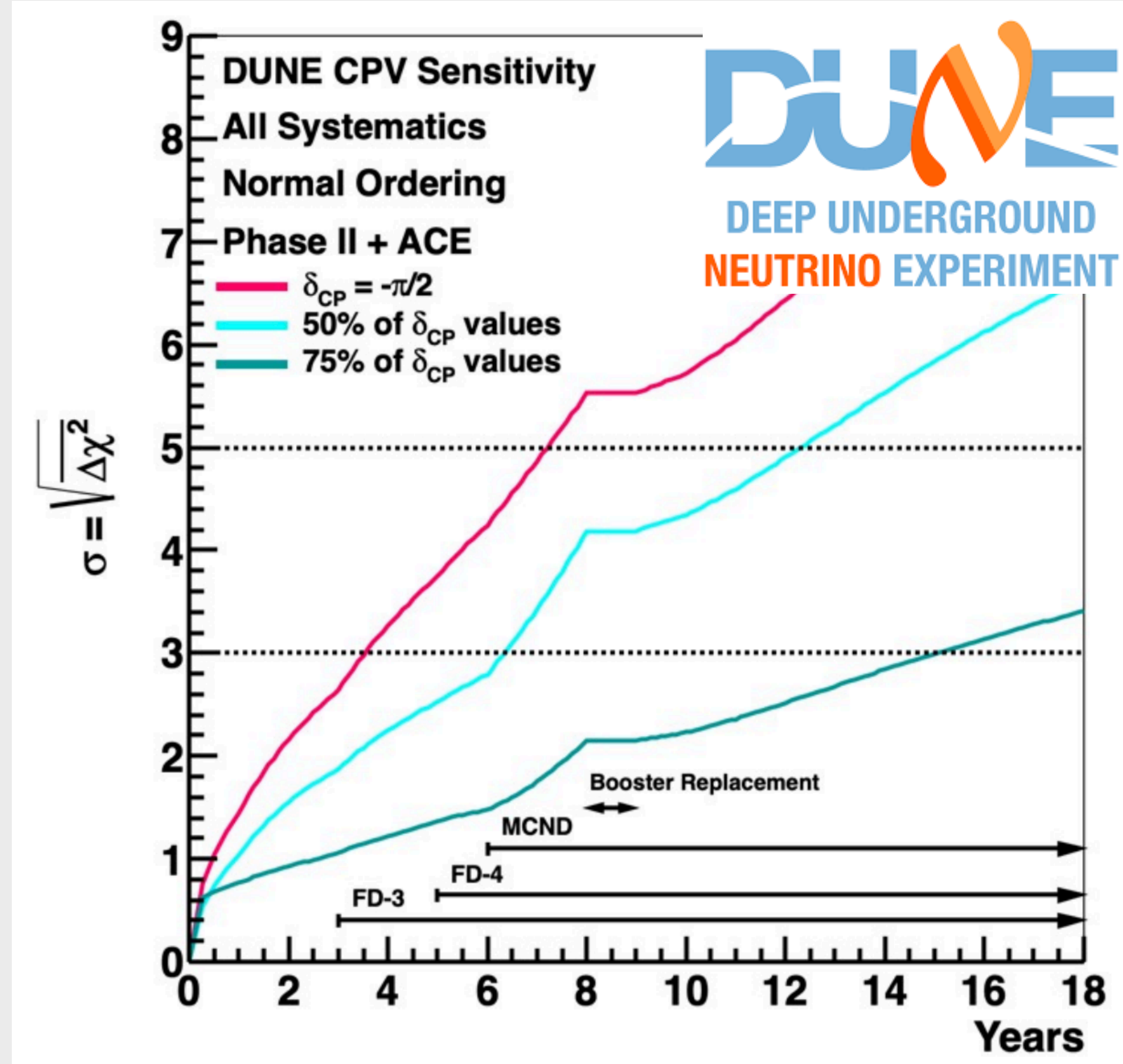


eEDM is very bad news for a lot of models :(

CP violation

How about the PMNS CP violation?





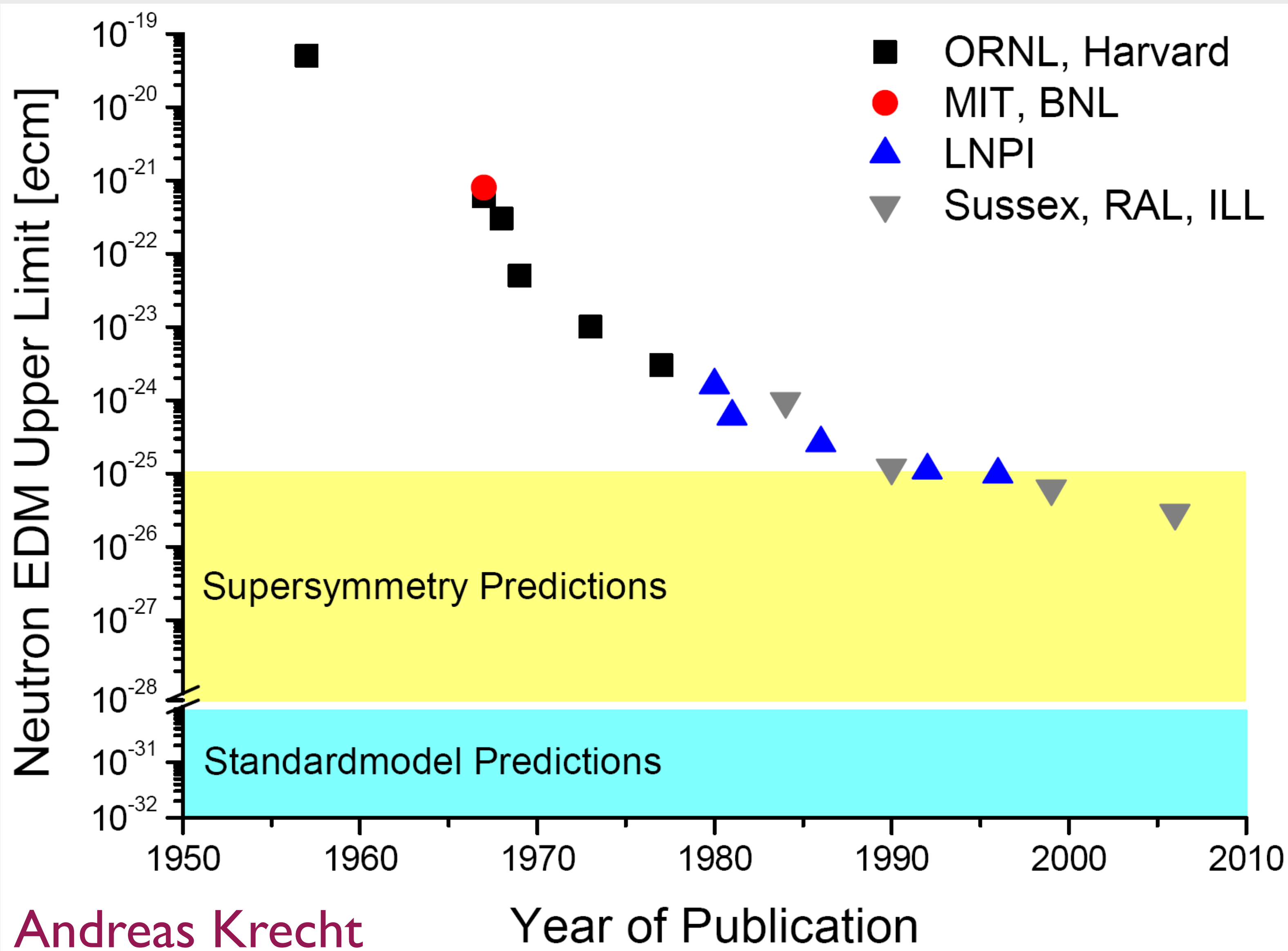
Chris Marshall, P5 Townhall, 21 March 2023

Also look out for:

Hyper-Kamiokande

CP violation

How about the the $\bar{\theta}$ angle? $\mathscr{L} \supset \bar{\theta}\, G^{\mu\nu}\tilde{G}_{\mu\nu}$



Andreas Krecht

$$|d_n| < 1.8 \times 10^{-26}\ \mathrm{e \cdot cm}$$

PSI, PRL 124, 081803 (2020)

$$\bar{\theta} \lesssim 10^{-10}$$

TUCAN Collaboration

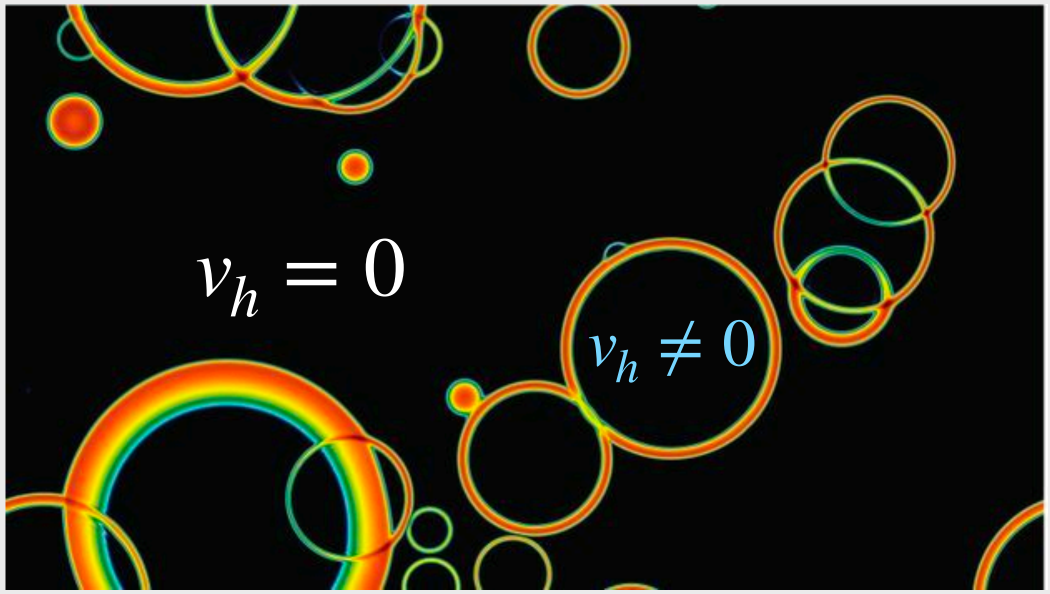
Should get down to 10^{-27} e cm

! Not clear how to connect to baryogenesis !

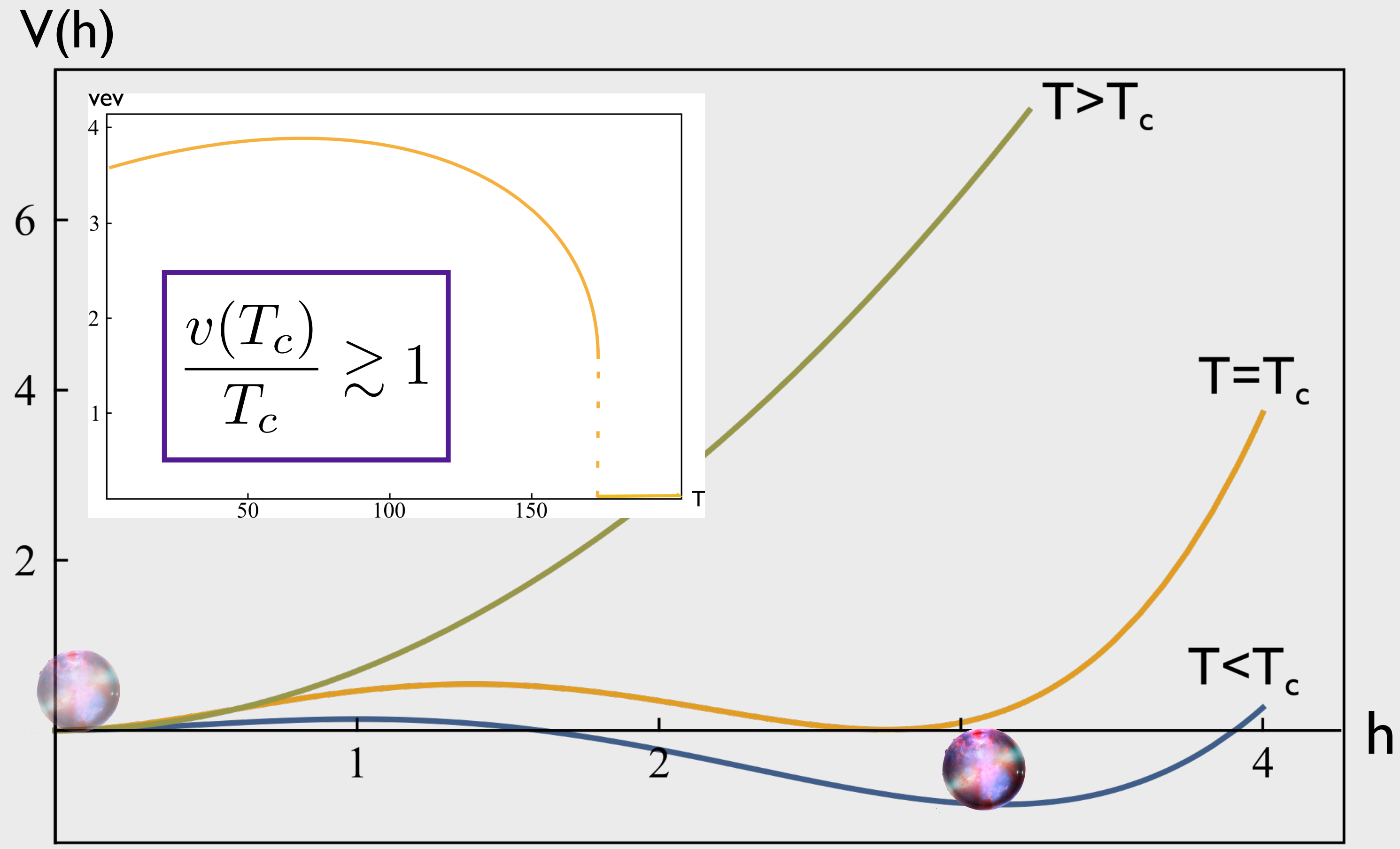
out of equilibrium

Cosmological (first order) phase transitions

First-order Phase Transition



Credit: David Weir



SM EW transition is a crossover

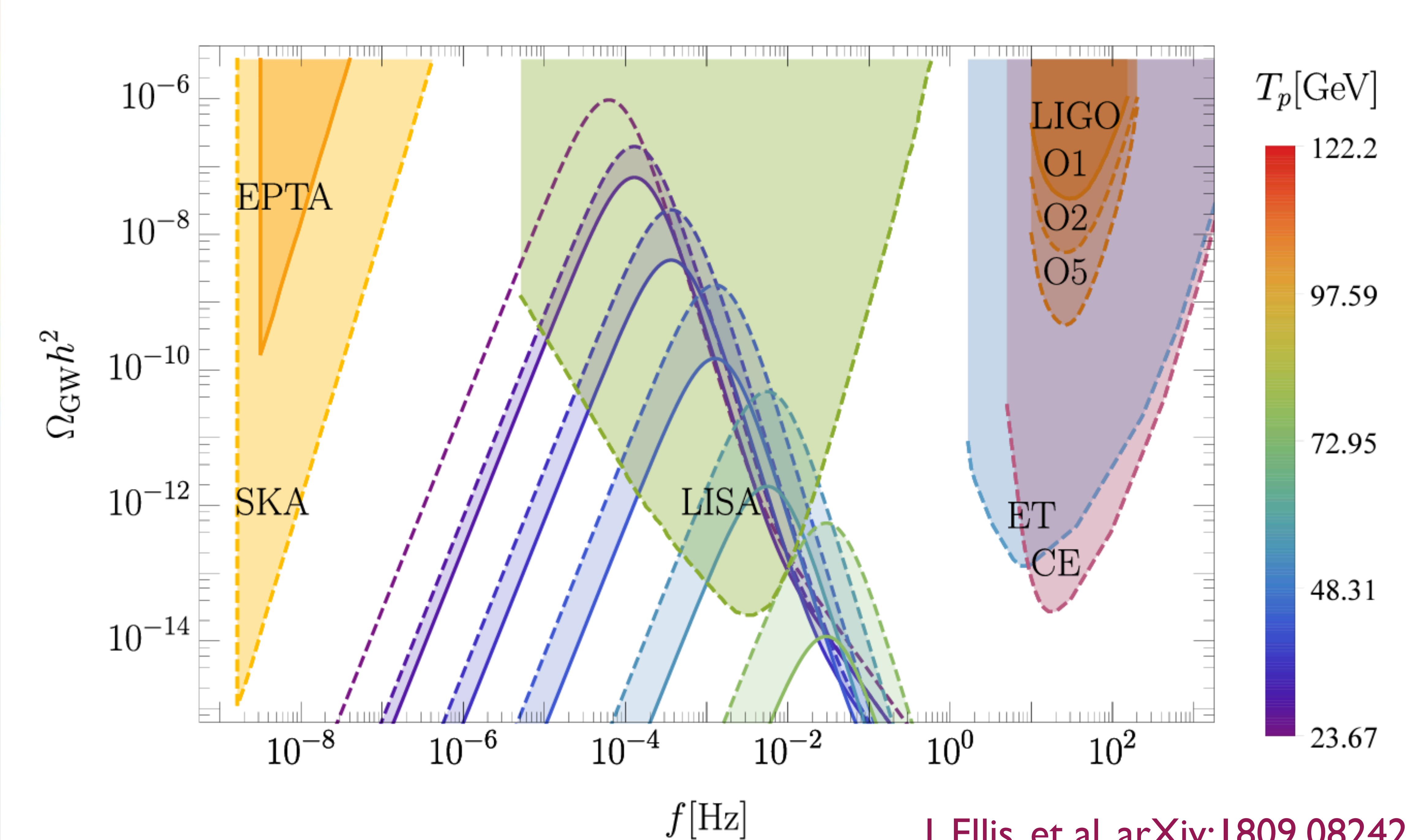
$$m_h \gtrsim 75 \text{ GeV}$$

Always in equilibrium :(

Not too hard to get with extra (light) scalars

out of equilibrium

bubbles → gravitational waves!



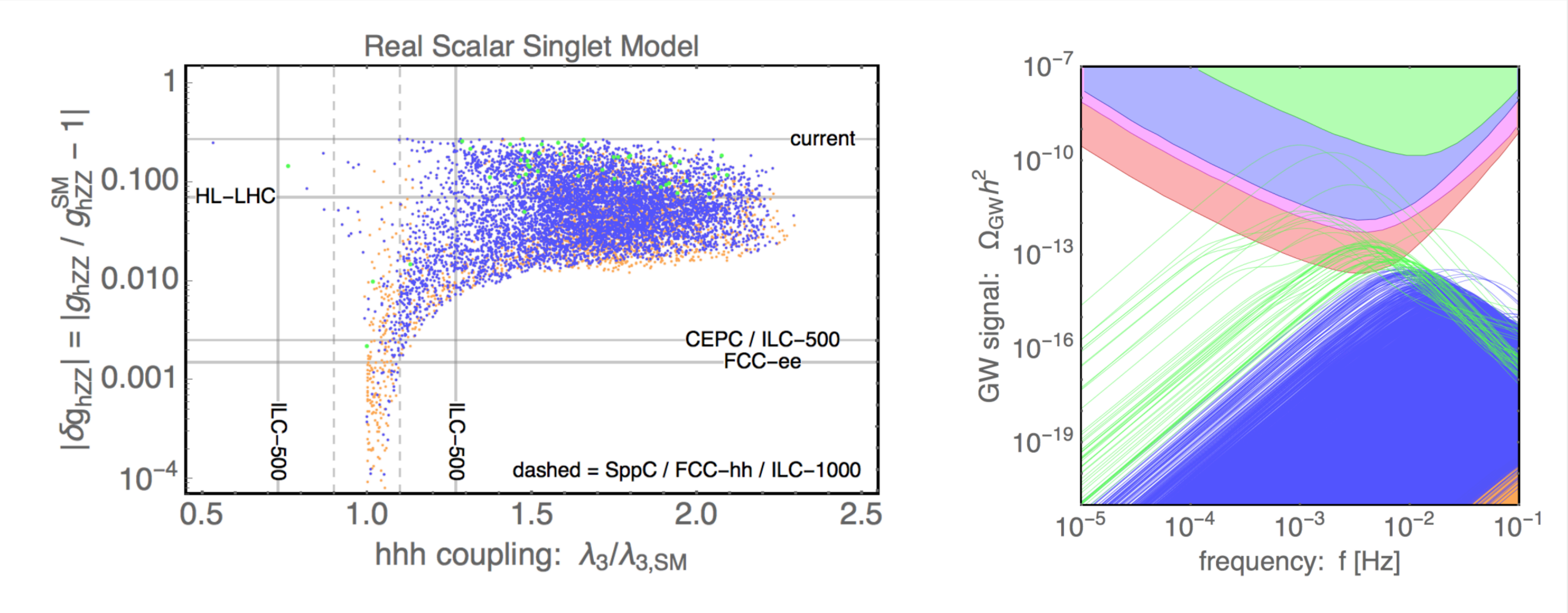
J. Ellis, et al, arXiv:1809.08242

out of equilibrium

New scalars + first order phase transition (FOPT)

Collider signals in the Higgs sector

P. Huang, et al, arXiv:1608.06619

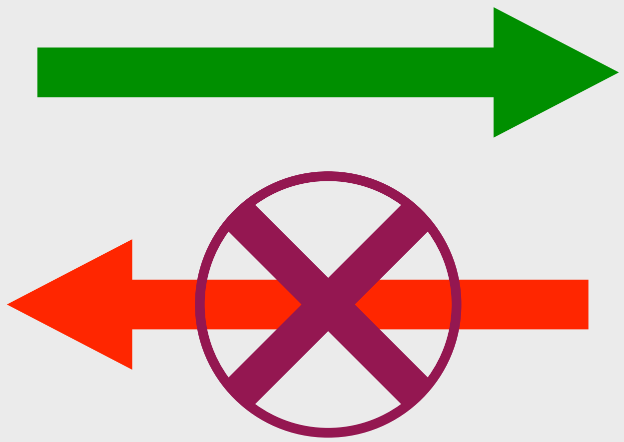


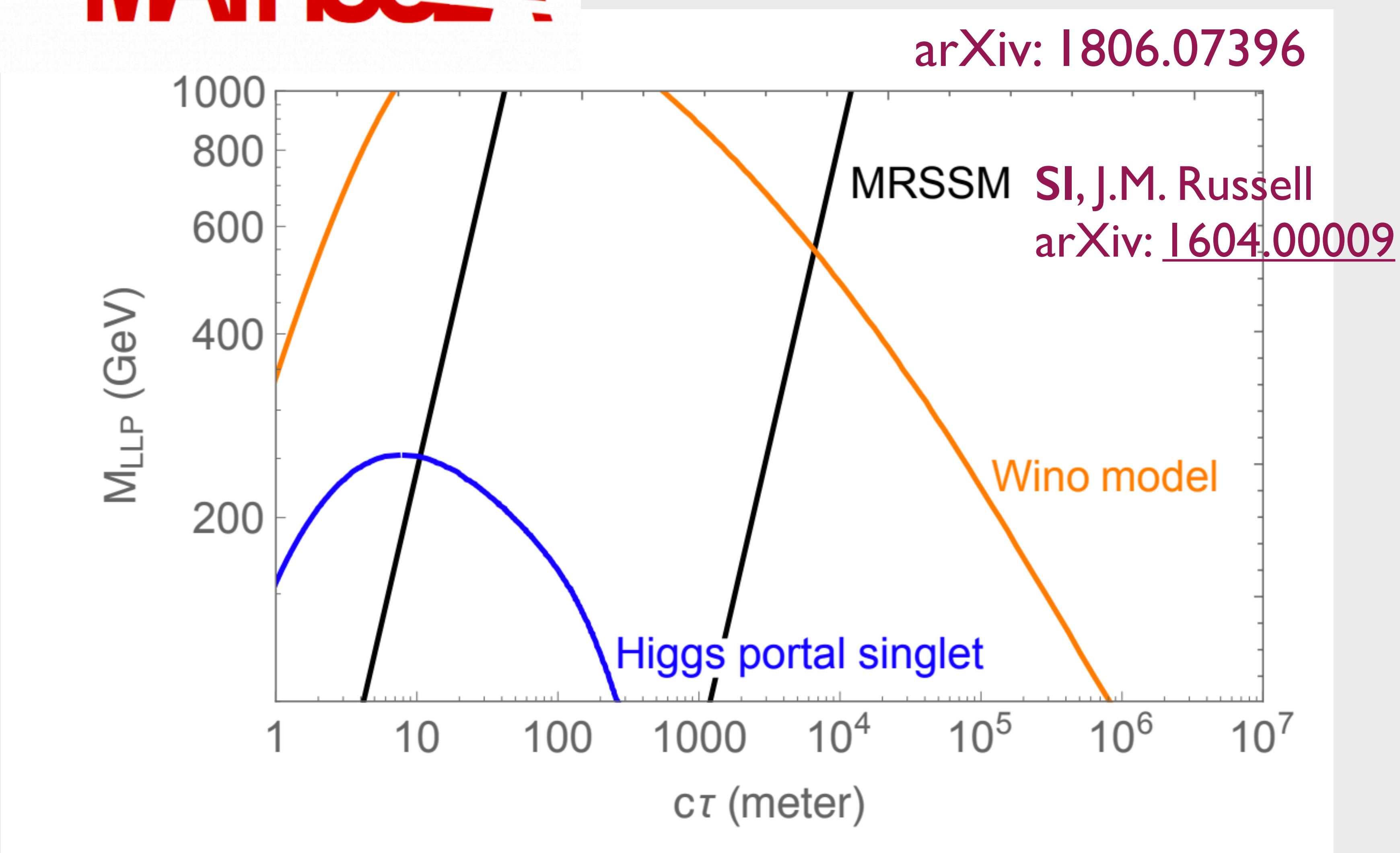
orange = FOPT   blue = strong FOPT   green = very strong FOPT

out of equilibrium

Long-lived particles? $\Gamma_X < H(T = M_X)$

$\tau \lesssim 1\ \mathrm{s}$ (BBN) → $c\tau \lesssim 10^8\ \mathrm{m}$





LLP searches at ATLAS/CMS

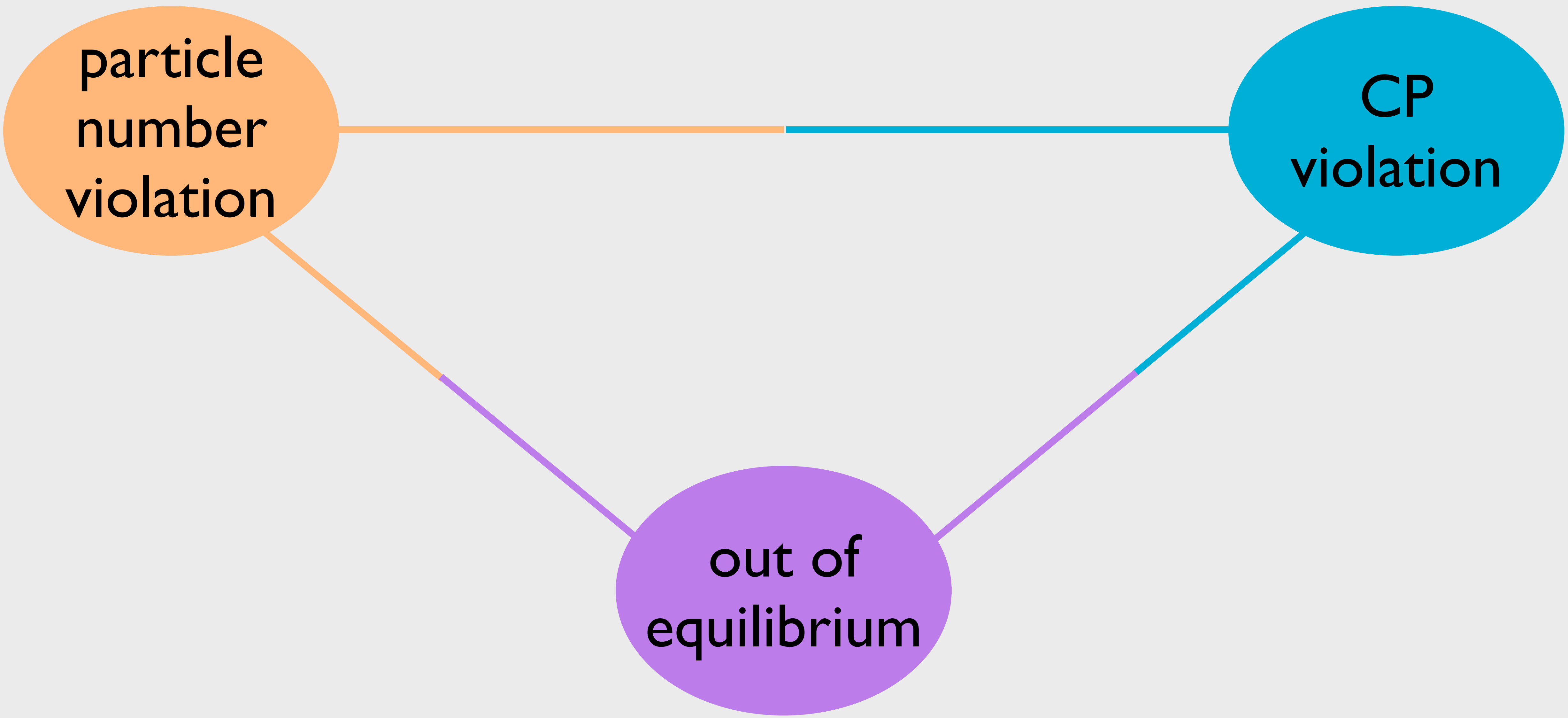
CODEX-b

SHiP

…

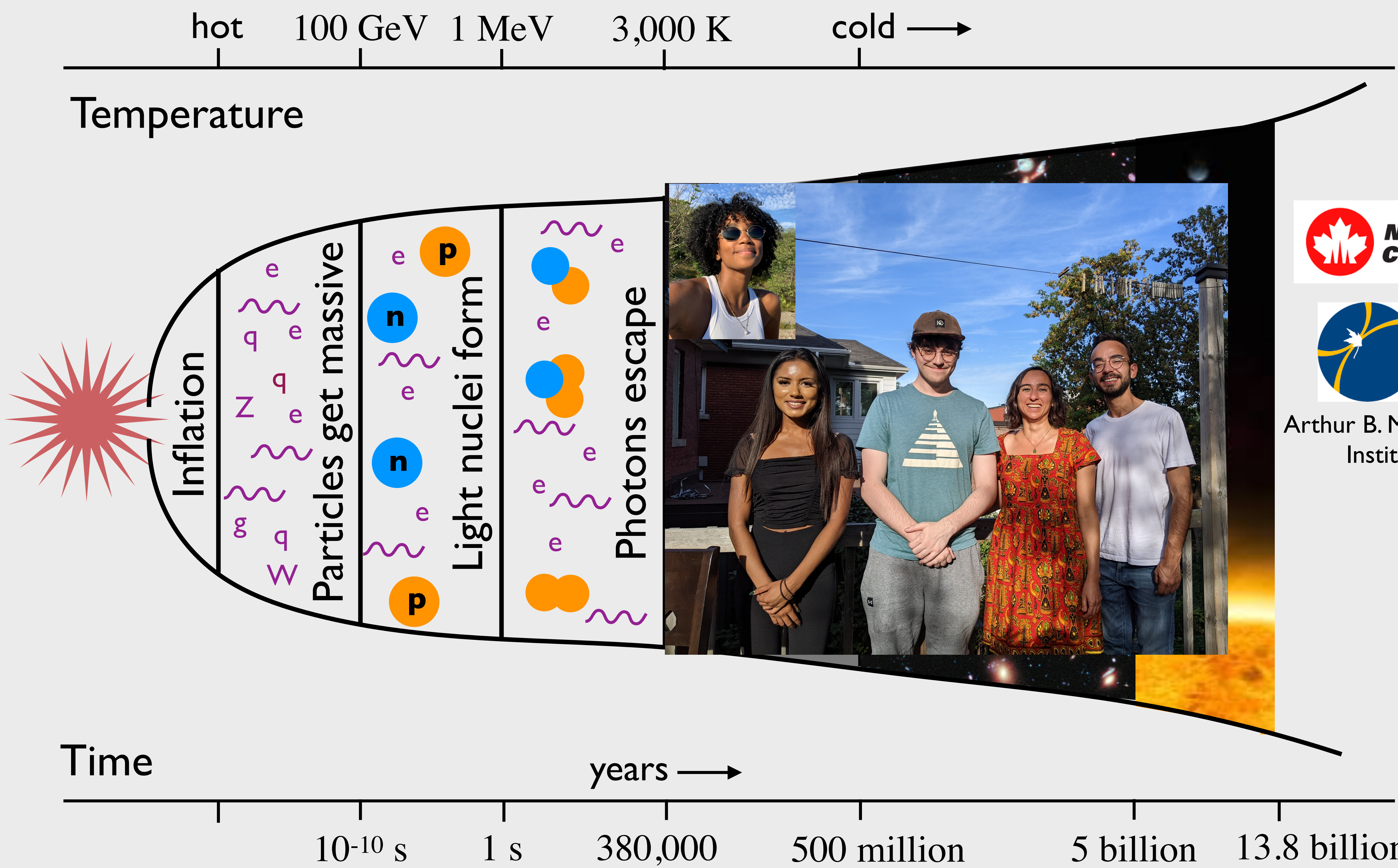
Standard Model can NOT explain the matter-antimatter asymmetry of the universe!

We need some new physics…



…that interacts with the Standard Model!

We want to understand the universe!



NSERC CRSNG

Arthur B. McDonald Institute