The Experimentalist's Guide to Leptogenesis

Jessica Turner

Neutrino Seminar Series

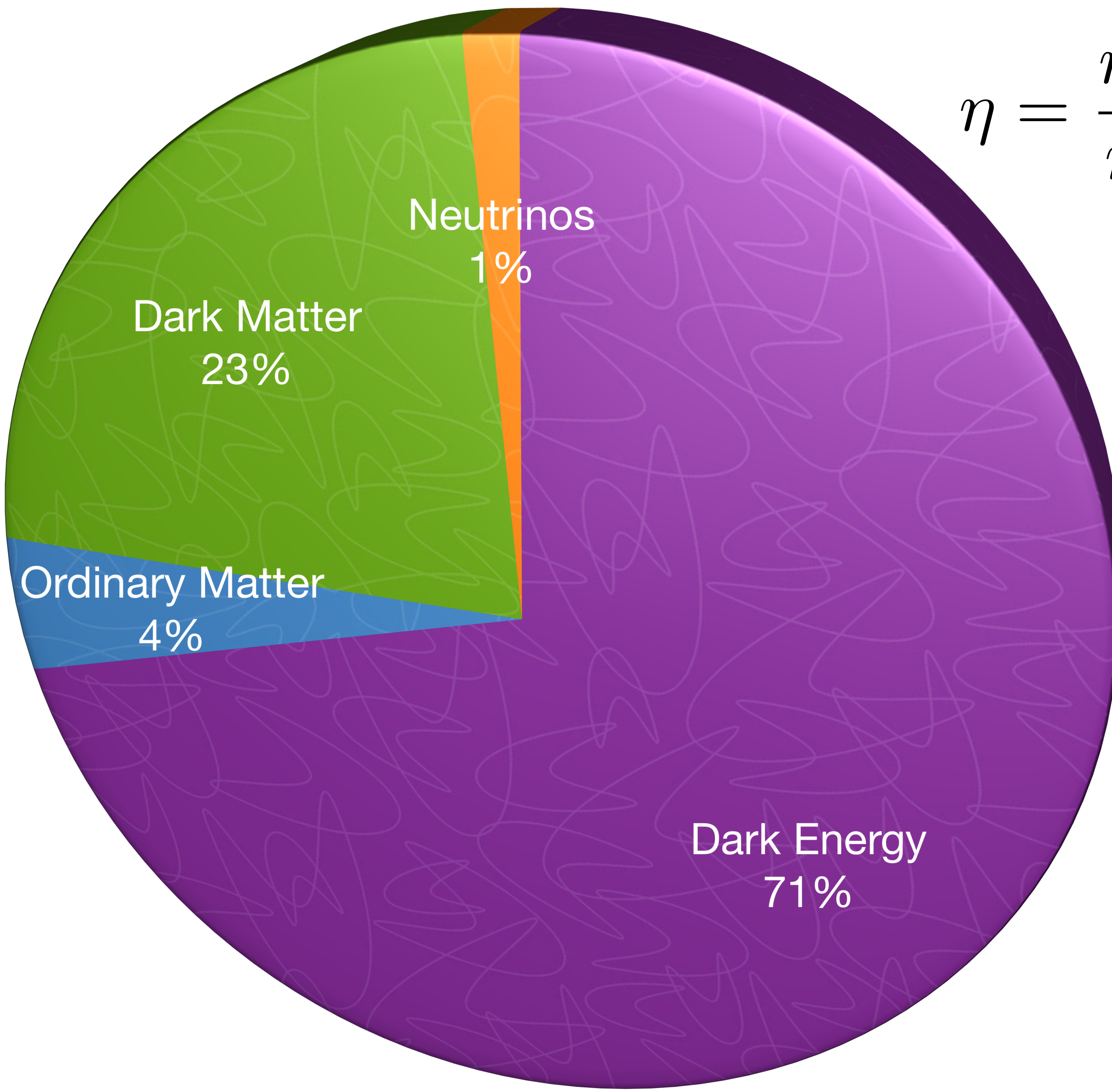
18th October 2018

Fermilab

Outline

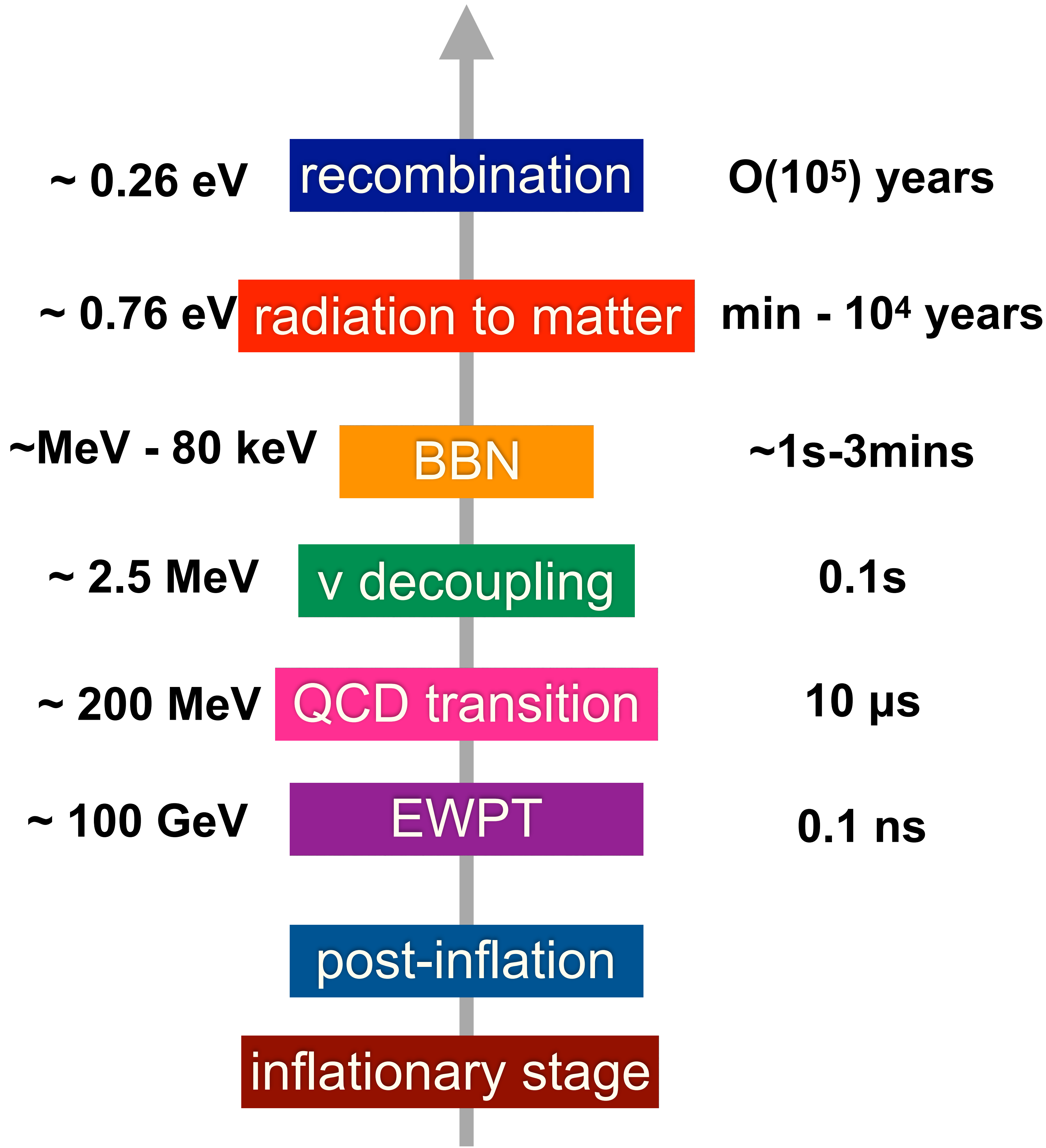
- What is the baryon asymmetry?
- How is it measured?
- Sakharov's Conditions
- Two Leading Explanations
- Leptogenesis with Type-I Seesaw Mechanism
- Connecting Measurable Parameters with the BAU

Energy Budget of the Universe

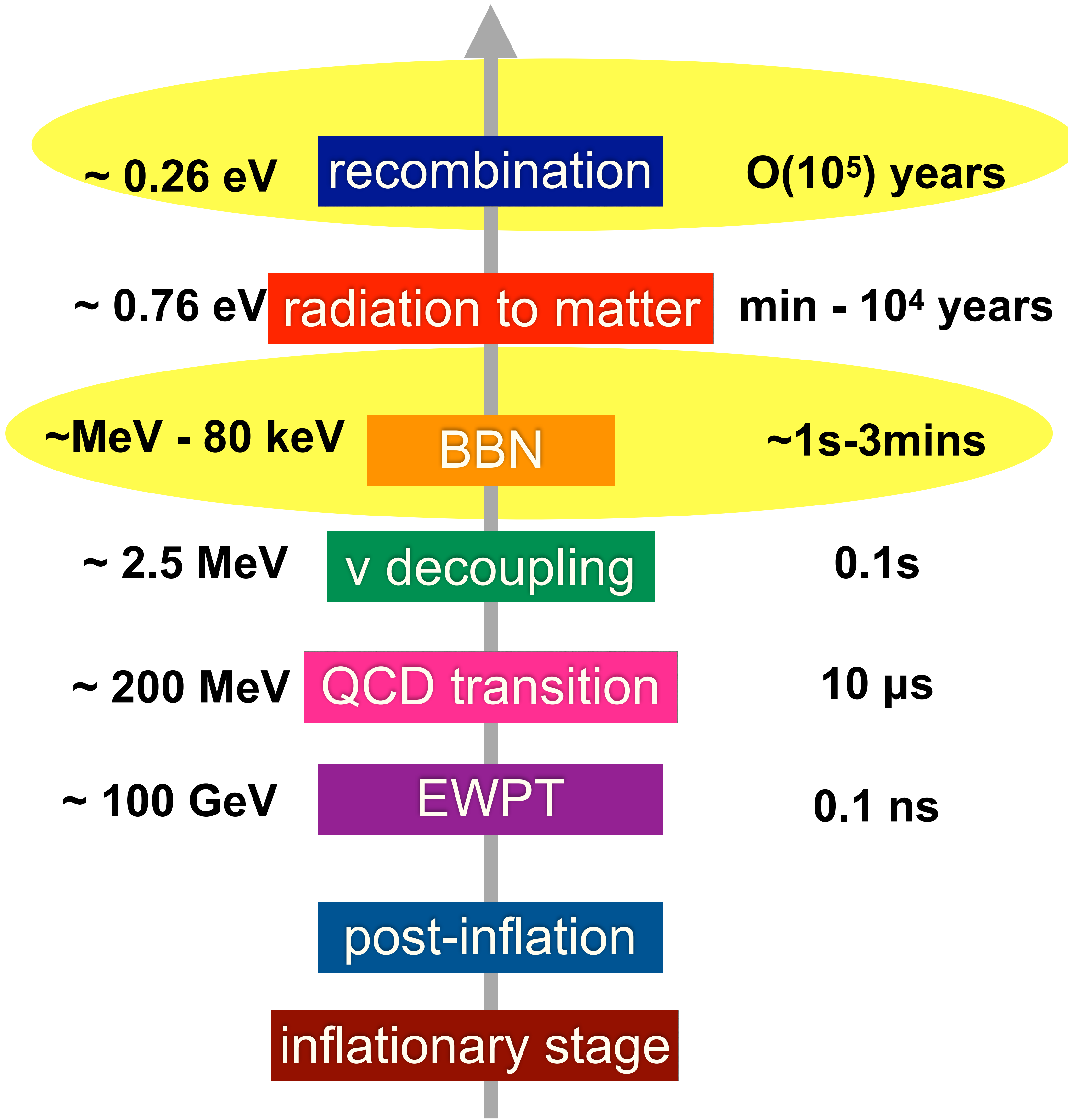


$$\eta = \frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$$

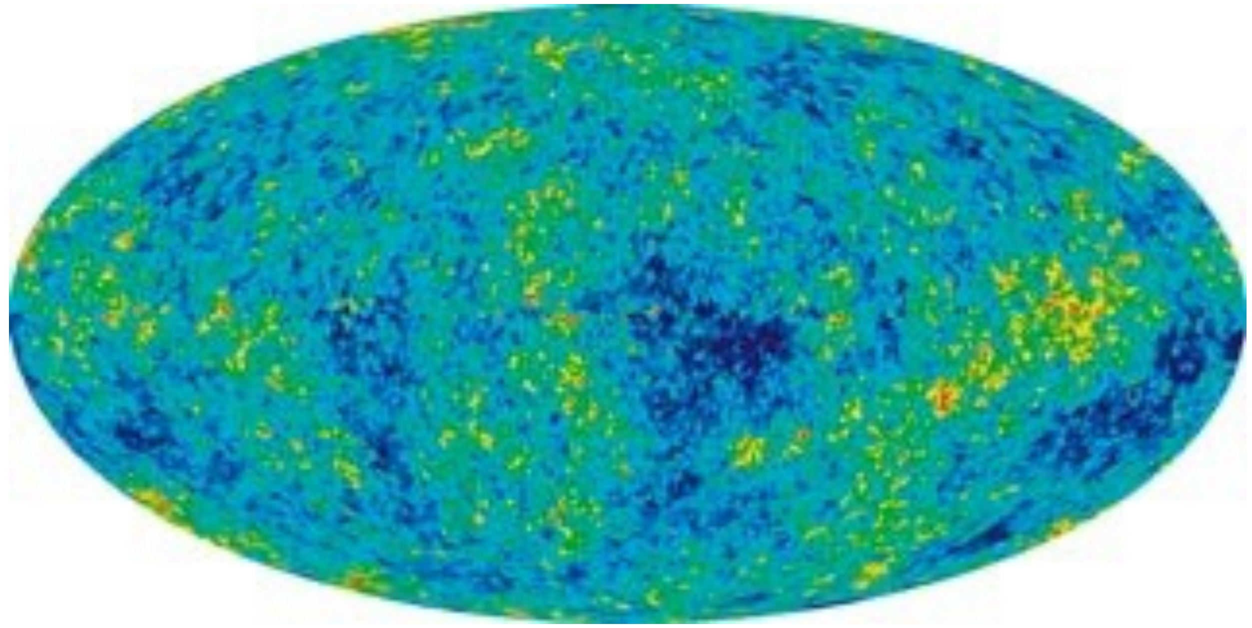
Measuring the Baryon Asymmetry

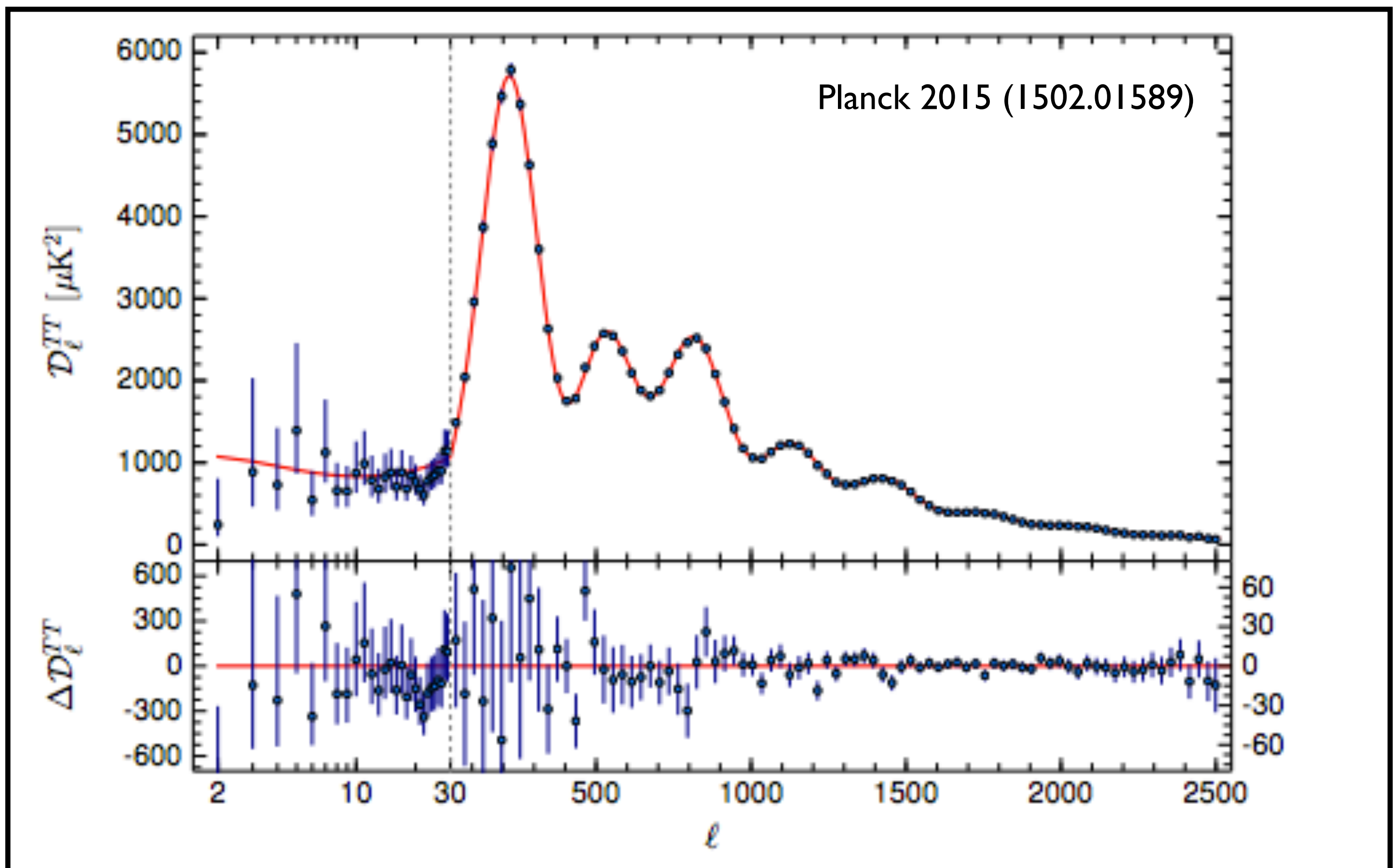


Measuring the Baryon Asymmetry



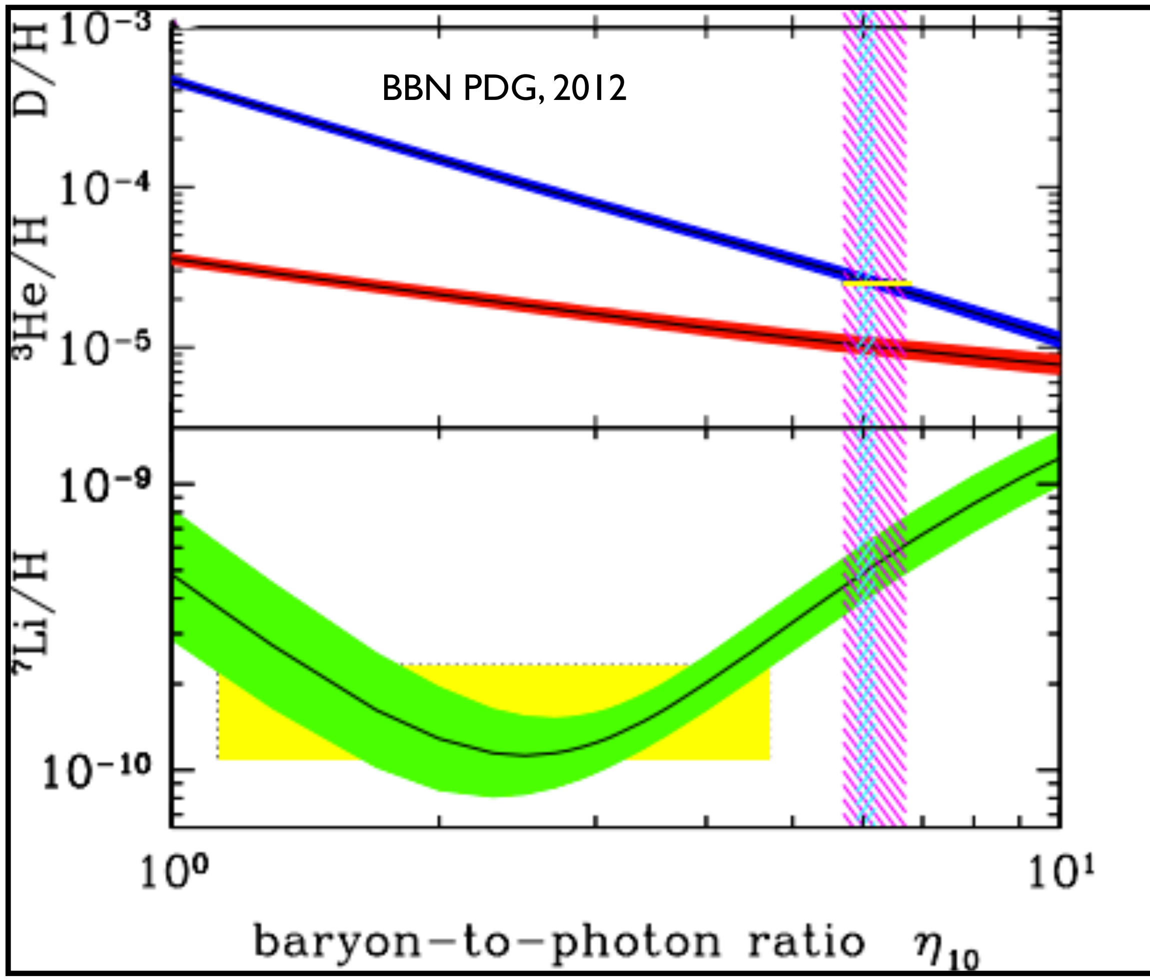
Cosmic Microwave Background



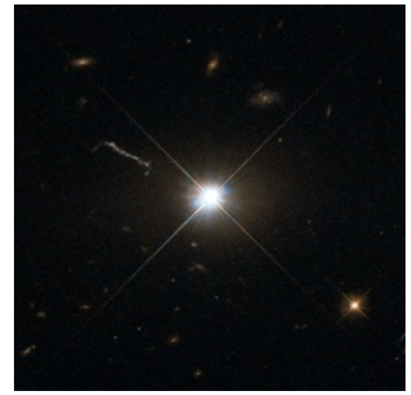


$\eta_{CMB} = (6.23 \pm 0.17) \times 10^{-10}$

Big Bang Nucleosynthesis

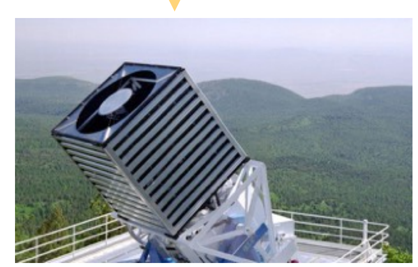


$$\eta_{BBN} = (6.08 \pm 0.06) \times 10^{-10}$$

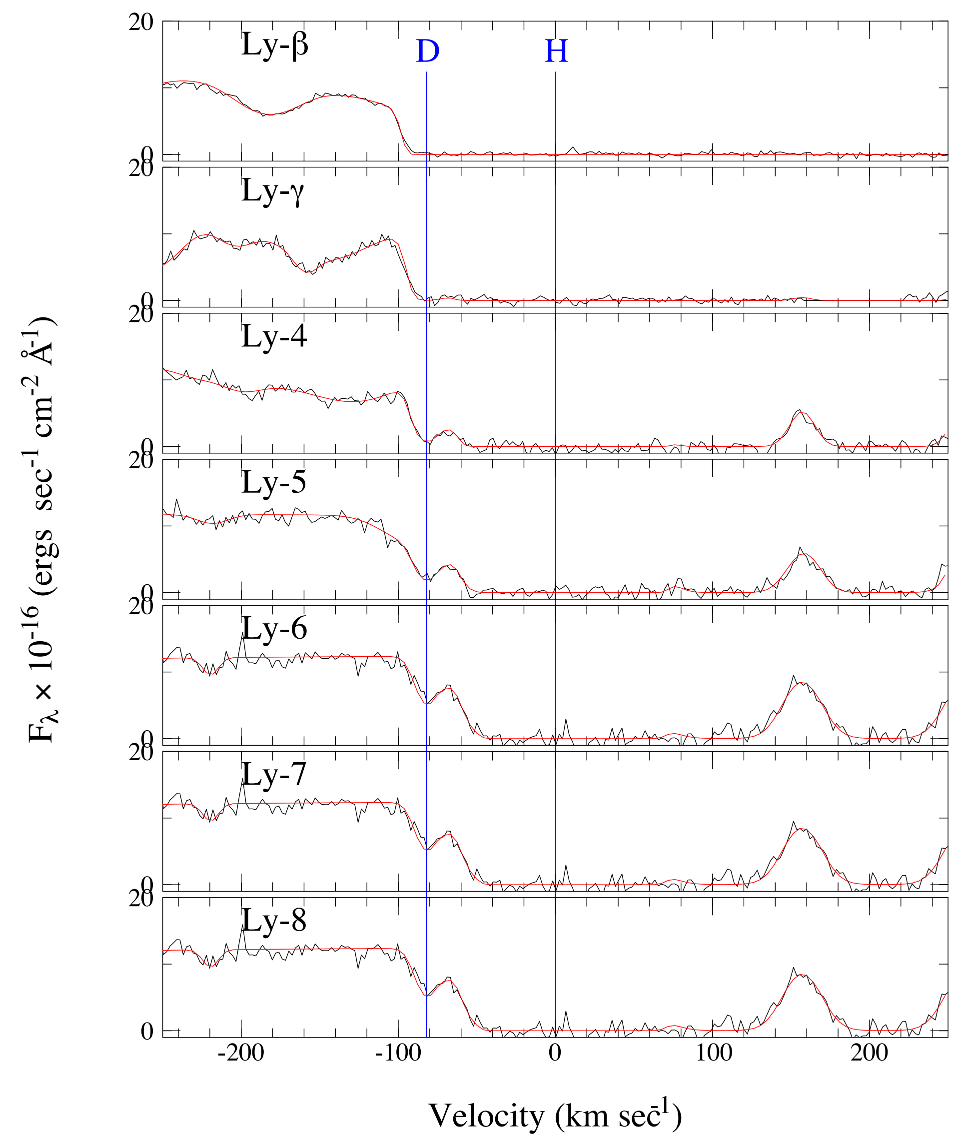


bright quasar 3C 273:
Hubble Space
Telescope

Dust Cloud

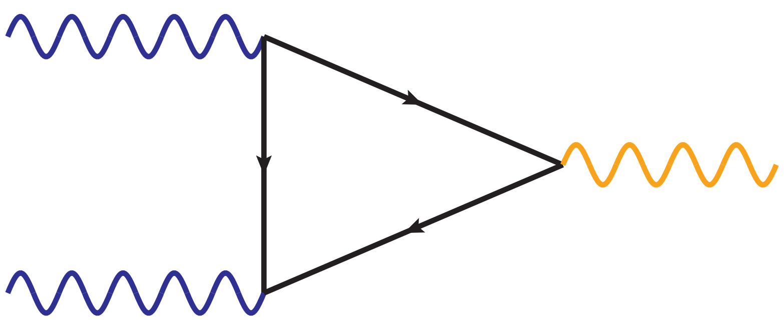


0302006



Sakharov's Conditions

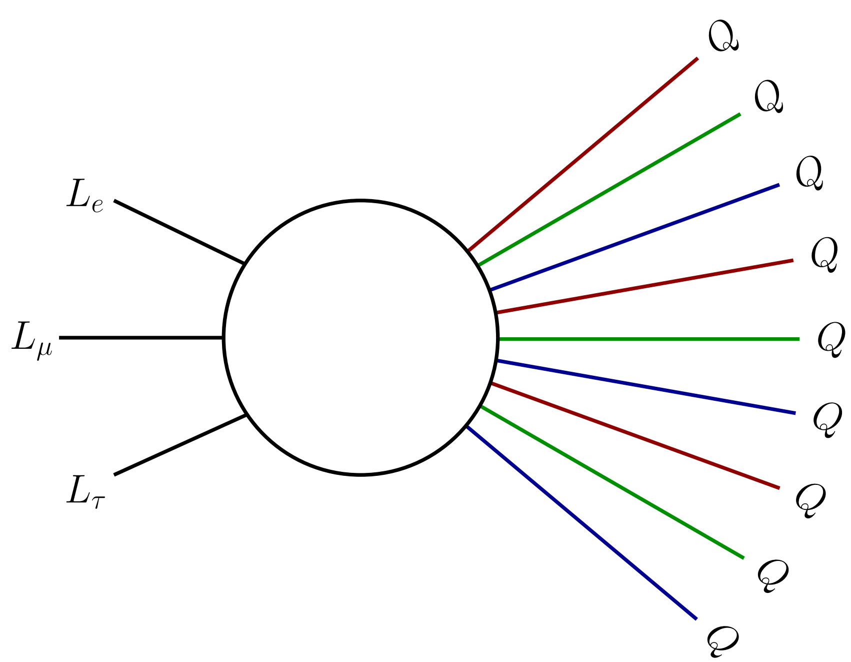
1. Baryon/Lepton Number Violation



- **B and L accidental symmetries of SM**
- **B+L violate by SU(2)L anomaly**
- **B-L conserved**

$$\partial_\mu j^\mu_{B+L} = \frac{N_f g^2}{32\pi^2} \epsilon^{\alpha\beta\gamma\delta} F^a_{\alpha\beta} F^a_{\gamma\delta}$$

$$\partial_\mu j^\mu_{B-L} = 0$$



- **sphalerons are non-perturbative field configurations**
- **T > EW scale, sphalerons rates are unsuppressed**

Kuzmin, Rubakov and Shaposhnikov

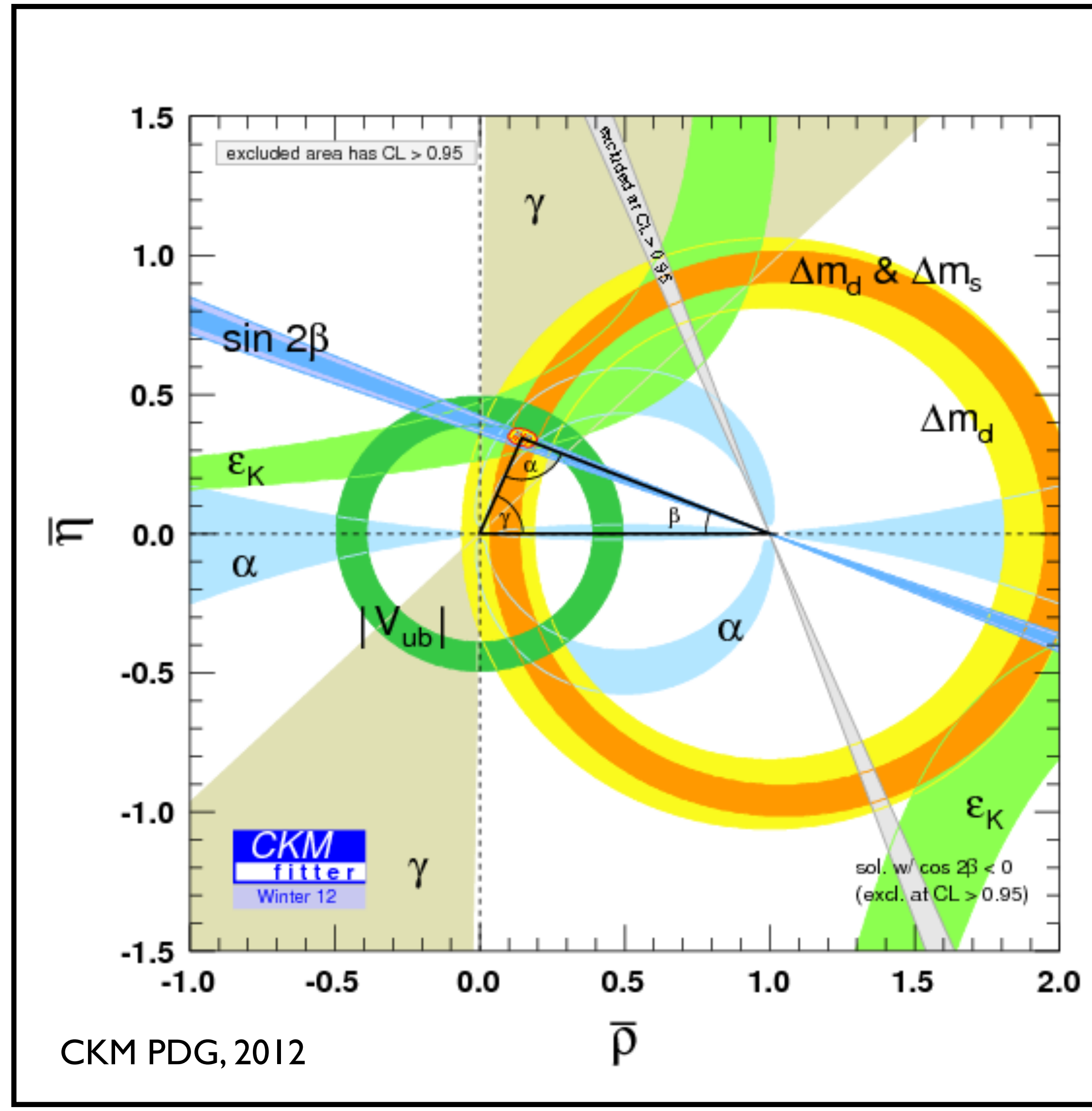
Baryon and Lepton Number Violation

2. CP Violation

- **Require interactions to prefer matter over anti-matter**

- **CPV in SM quark sector produces an asymmetry $O(10^{7})$ too small.**

- **Require new sources of CPV**



CKM PDG, 2012

Kuzmin, Rubakov and Shaposhnikov

☑ **Baryon and Lepton Number Violation**

☒ **Insufficient CP Violation**

Gavela, Hernandez, Orloff, Pene; Huet and Sather

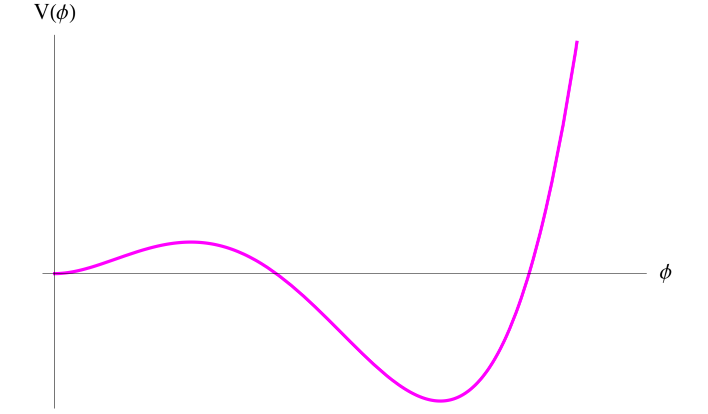
3. Departure from Thermal Equilibrium (Irreversibility)

- In thermal equilibrium: process and its inverse proceed at the same rate.

- Interaction rate of a process drops below the expansion rate of the Universe, process comes out of equilibrium $\Gamma < H$

- The EWPT of the SM is a crossover not strongly first order

- Need alternative mechanism to provide OEE condition.



Kuzmin, Rubakov and Shaposhnikov

Baryon and Lepton Number Violation

Insufficient CP Violation

Gavela, Hernandez, Orloff, Pene; Huet and Sather

Kajantie, Laine, Rummukainen, Shaposhnikov

No departure from thermal equilibrium

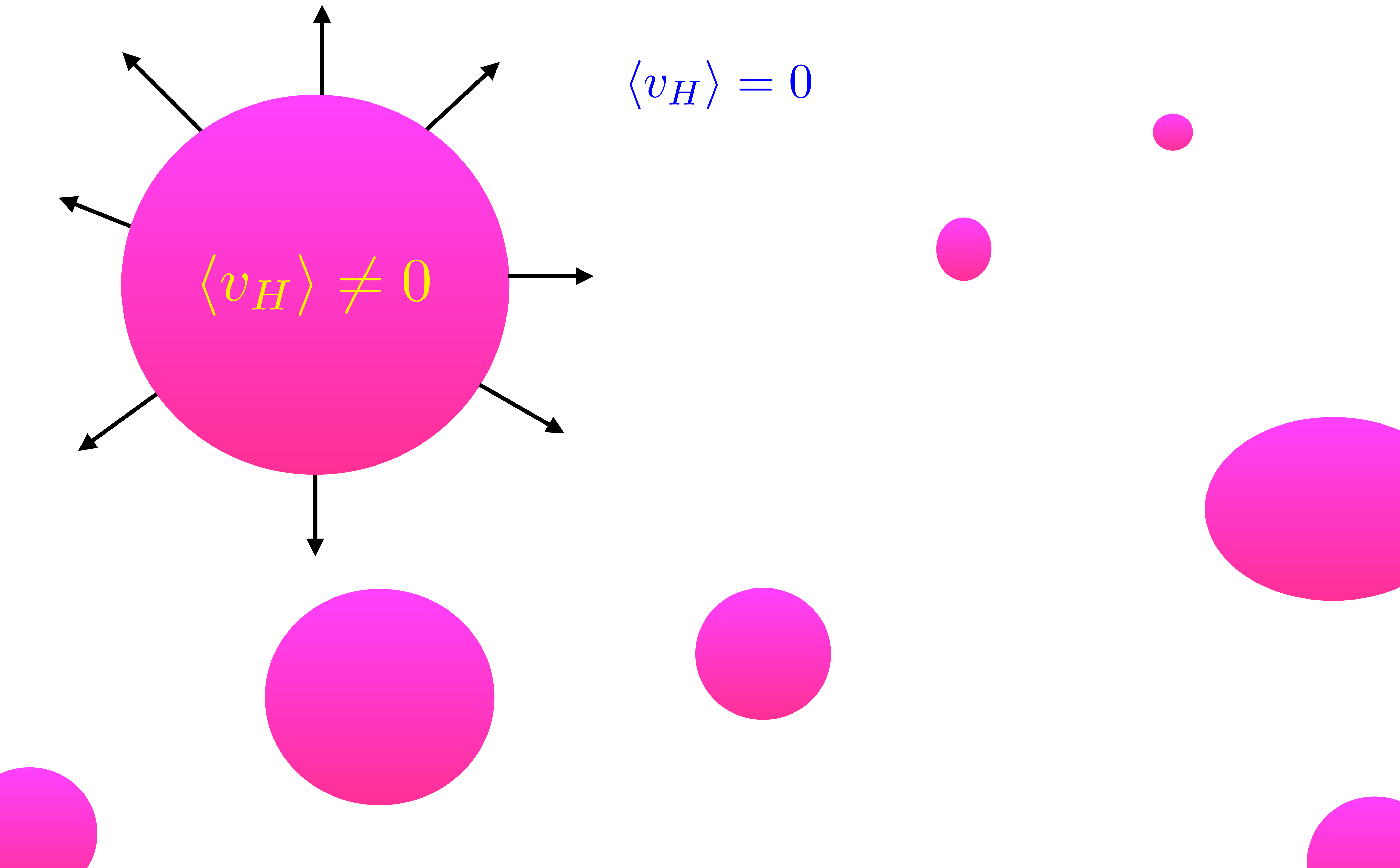
Leading Explanations

1. BAU produced during EWPT via EWBG.

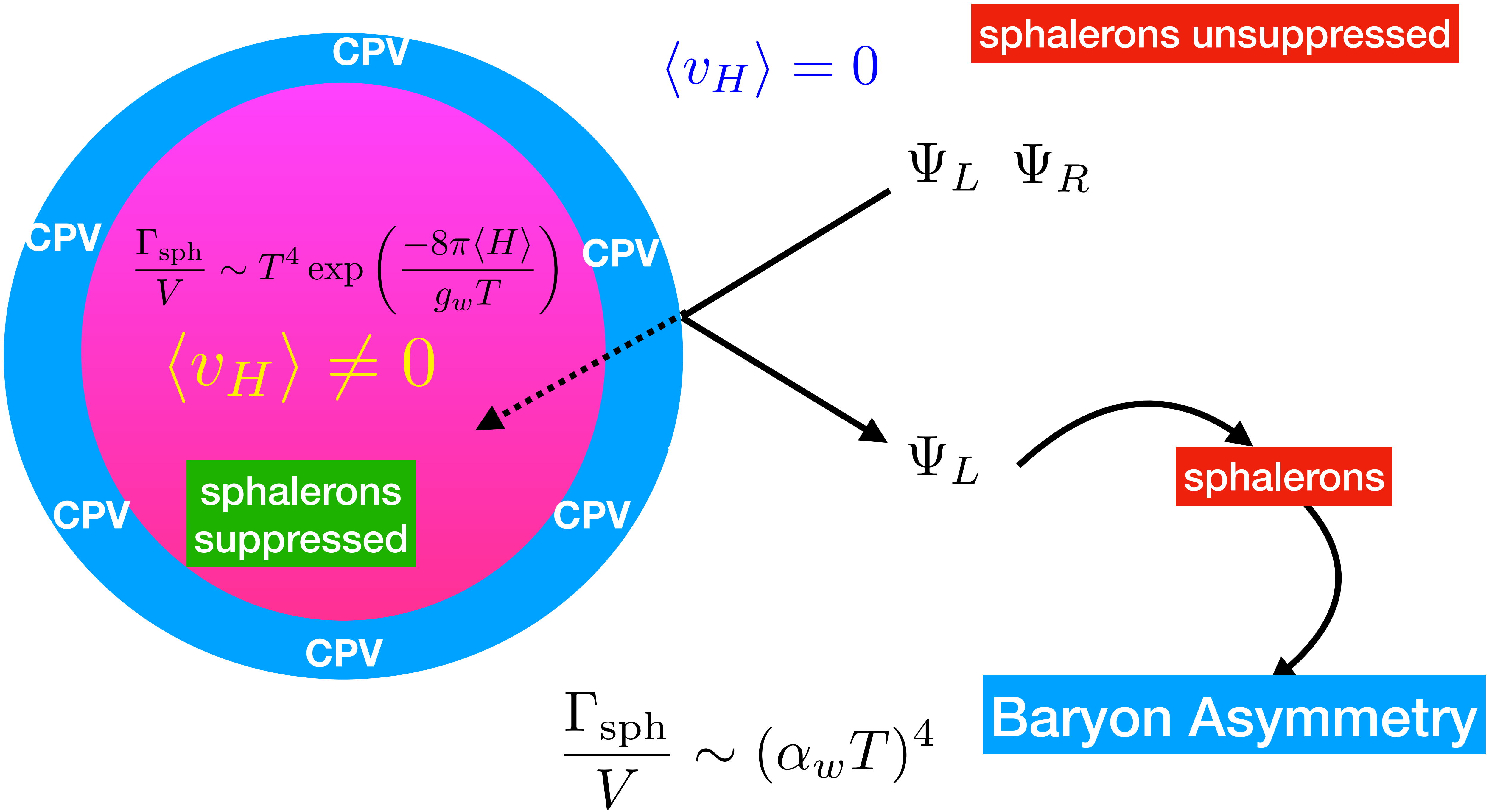
2. BAU produced before EWPT via Leptogenesis

3. BAU produced after EWPT via exotic decays

Electroweak Baryogenesis

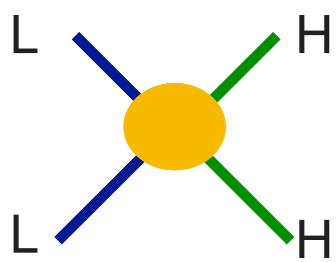


Electroweak Baryogenesis



Seesaw Mechanism

- **Most theories of leptogenesis assume neutrinos are Majorana (of course there are exceptions*)**

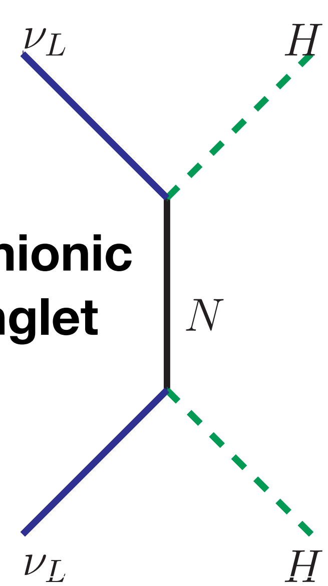


$$-\mathcal{L}_{D=5} = \lambda \frac{L.HL.H}{M} = \frac{\lambda v^2}{M} \nu_L^T C^\dagger \nu_L$$

type-I SS	type-II SS	type-III SS

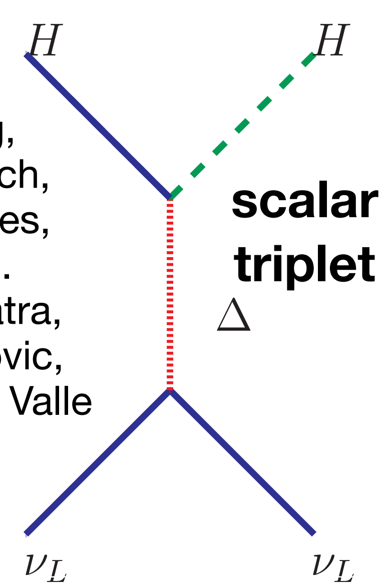
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

fermionic singlet

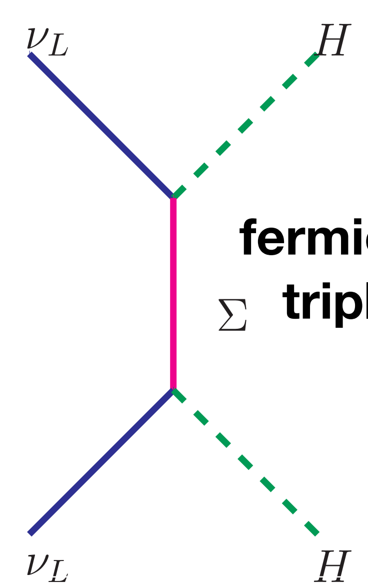


Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

scalar triplet



fermionic triplet



Ma, Roy, Senjanovic, Hambye

$$\mathcal{L} = -Y_\nu \overline{N} L H - \frac{1}{2} \overline{N^C} M_N N$$

*Dirac Leptogenesis, Dick, Lindner, Wright, Ratz

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

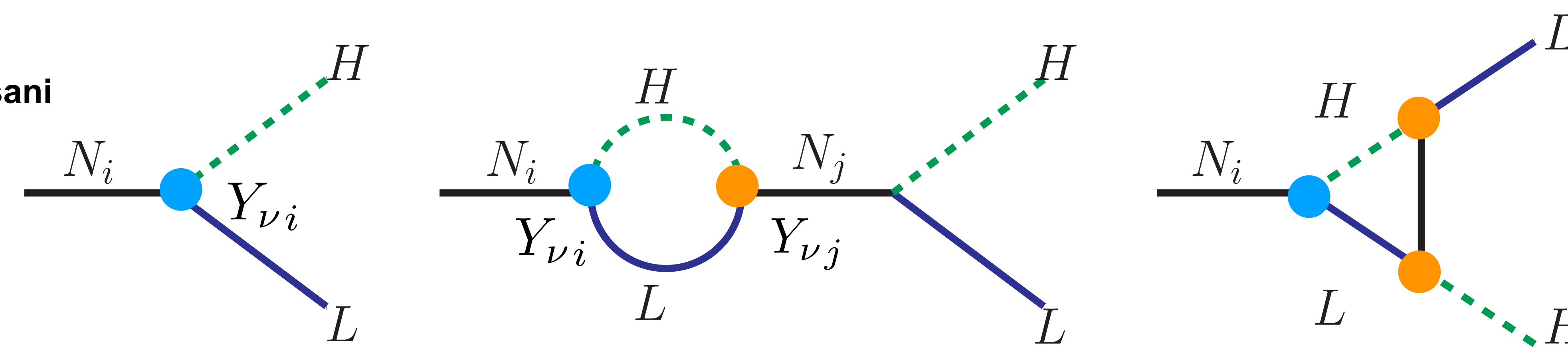
$$m_\nu = \frac{Y_\nu^2 v^2}{M_N} \sim 0.1\,\mathrm{eV}$$

Leptogenesis via Decays

Fukugida, Yanagida

Decay asymmetry from interference between tree and loop level diagrams

Covi, Roulet, Vissani

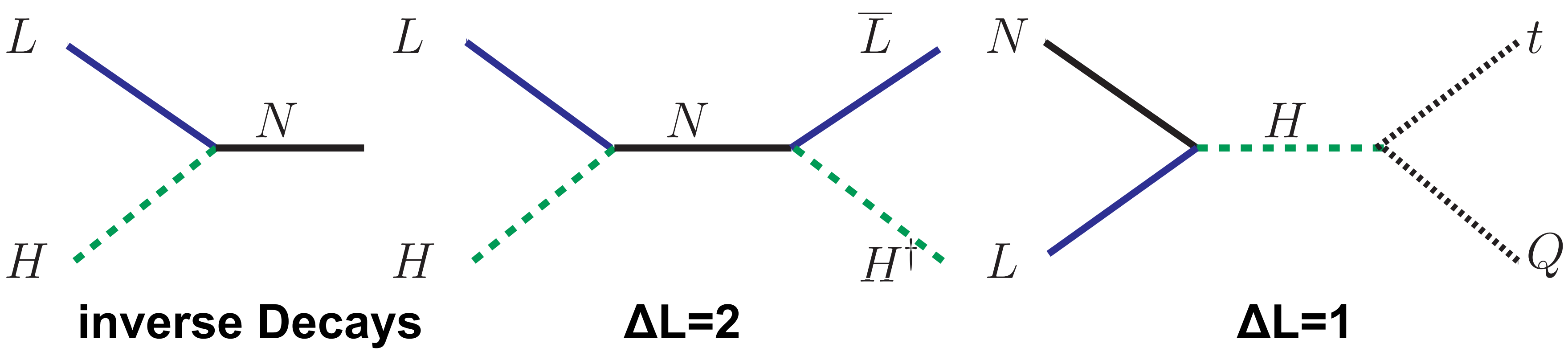


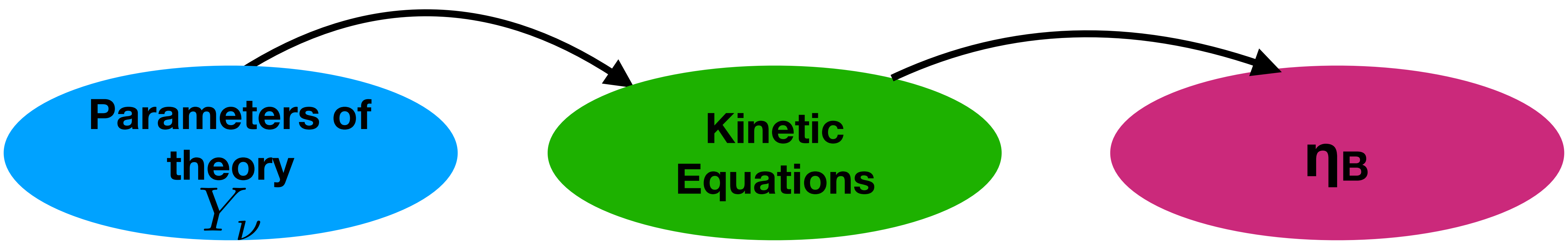
Decay Asymmetry

$$\epsilon = \frac{\Gamma\left(N_1 \to HL\right) - \Gamma\left(N_1 \to H^\dagger \overline{L}\right)}{\Gamma\left(N_1 \to HL\right) + \Gamma\left(N_1 \to H^\dagger \overline{L}\right)}$$

Basic Mechanism

Washout and Scattering processes





Add refinements: flavour effects, finite density effects, spectator processes etc

Model Parameter Space

$$Y_\nu = \frac{1}{v} U_{\rm PMNS} \sqrt{m} R^T \sqrt{M}$$

Model Parameter Space

$$Y_\nu = \frac{1}{v} U_{\mathrm{PMNS}} \sqrt{m} R^T \sqrt{M}$$

Neutrino Oscillation constraints

3 mixing angles
3 phases

sum of neutrino masses and neutrino oscillation

3 parameters

Complex, orthogonal matrix

6 real parameters

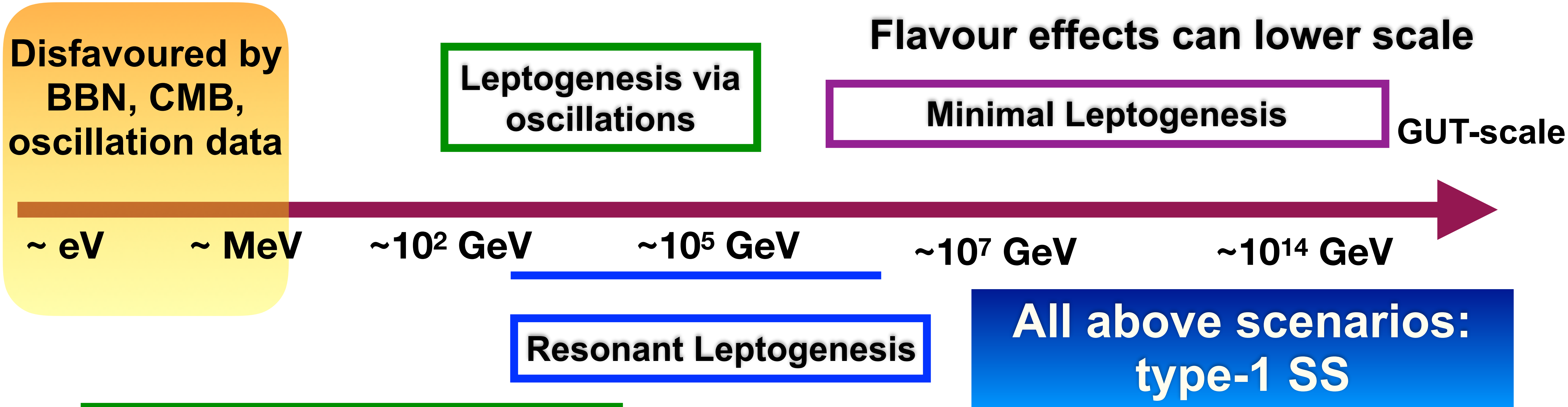
Unconstrained

3 masses
ensure at least mild hierarchy

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\omega_1} & s_{\omega_1} \\ 0 & -s_{\omega_1} & c_{\omega_1} \end{pmatrix} \begin{pmatrix} c_{\omega_2} & 0 & s_{\omega_2} \\ 0 & 1 & 0 \\ -s_{\omega_2} & 0 & c_{\omega_2} \end{pmatrix} \begin{pmatrix} c_{\omega_3} & s_{\omega_3} & 0 \\ -s_{\omega_3} & c_{\omega_3} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{\omega_i} = \cos\omega_i,\ s_{\omega_i} = \sin\omega_i,\ \omega_i = x_i + iy_i$$

η_B is a function of up to 18 parameters.



Leptogenesis via oscillations

- neutrinos masses + BAU
- Minimal: 2 heavy RHN
- LFV, LNV colliders and meson decays
- Minimal models fine-tuned

Leptogenesis via decays

- neutrinos masses + BAU
- Minimal: 2 heavy RHN
- Natural UV completions
- Harder to test (maybe in future depends on scale)

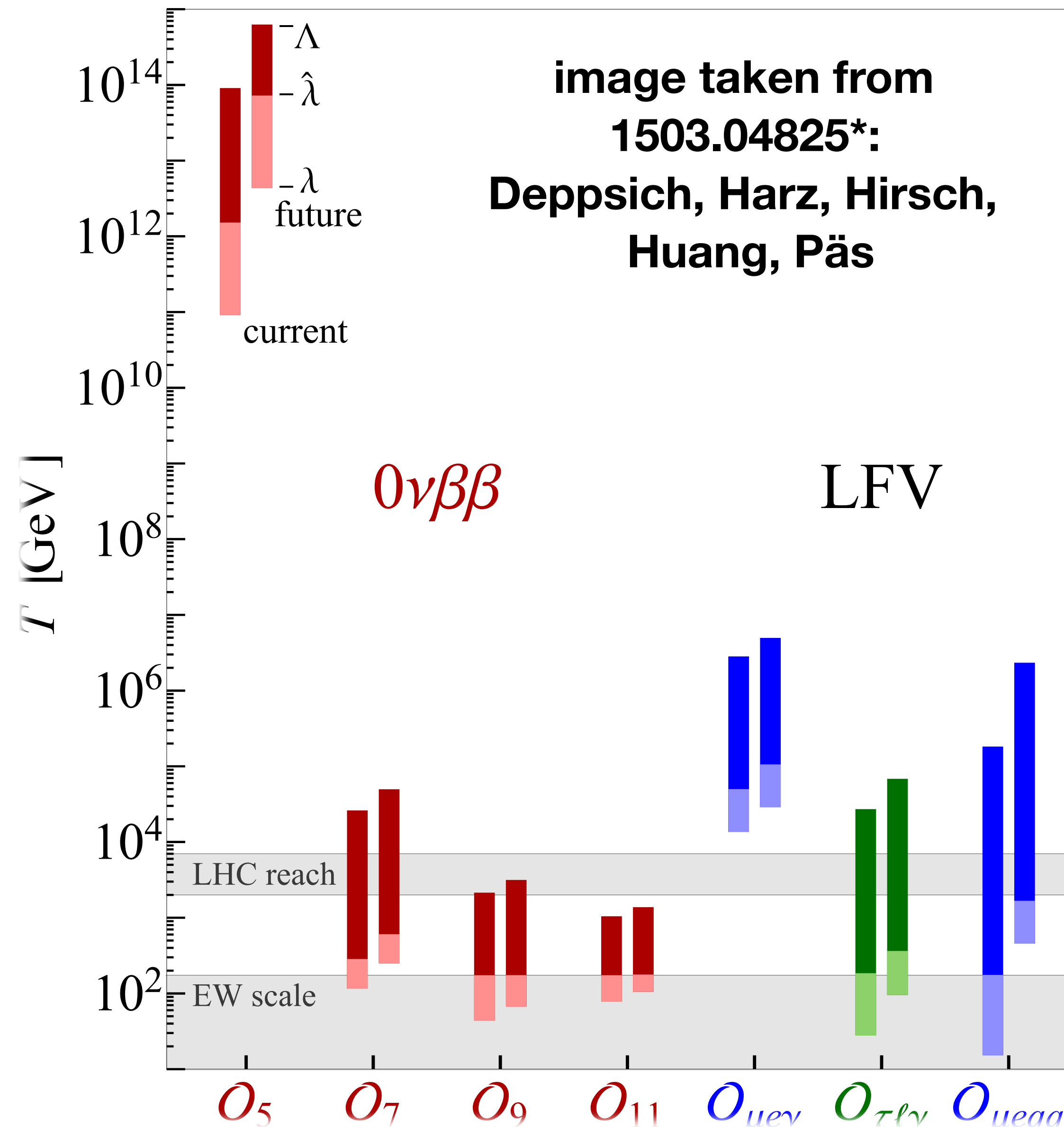
Falsifiable

It would be ideal if the physics explaining neutrinos masses + BAU was at the GeV scale.

BUT we should consider the possibility this is not the case, it may be higher → harder to test

There are issues if the mass scale of the RHN is too high: Higgs vacuum stability, increased F.T Higgs mass

Still falsifiable colliders and NDBD: observe new physics to exclude new physics!



* see also 0806.0841, 1312.4447

Standard Paradigm: Leptogenesis via decays cannot produce BAU below 10^9 GeV

Davidson-Ibarra Bound

Can we lower the scale?

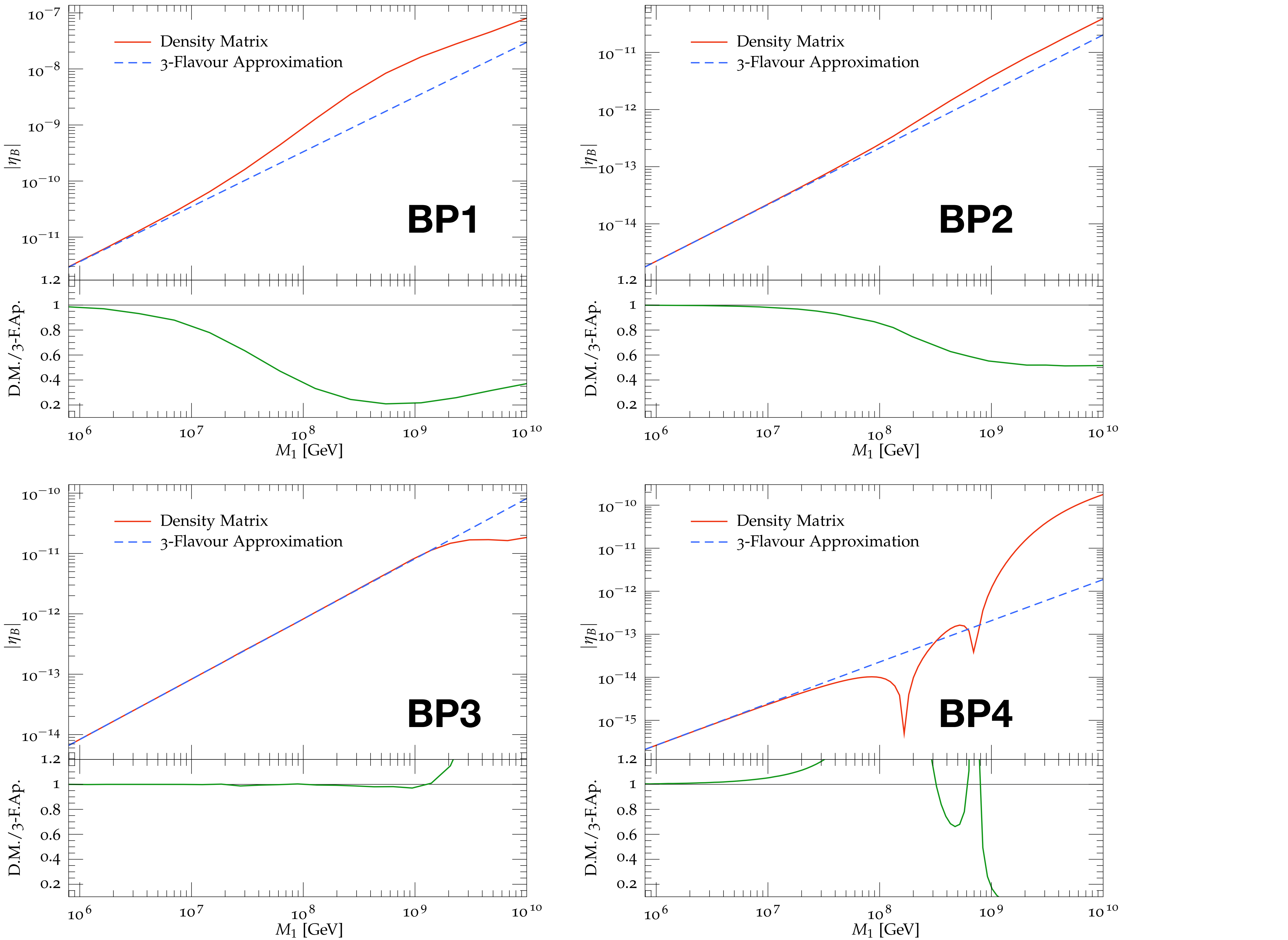
Three-flavored nonresonant leptogenesis at intermediate scales

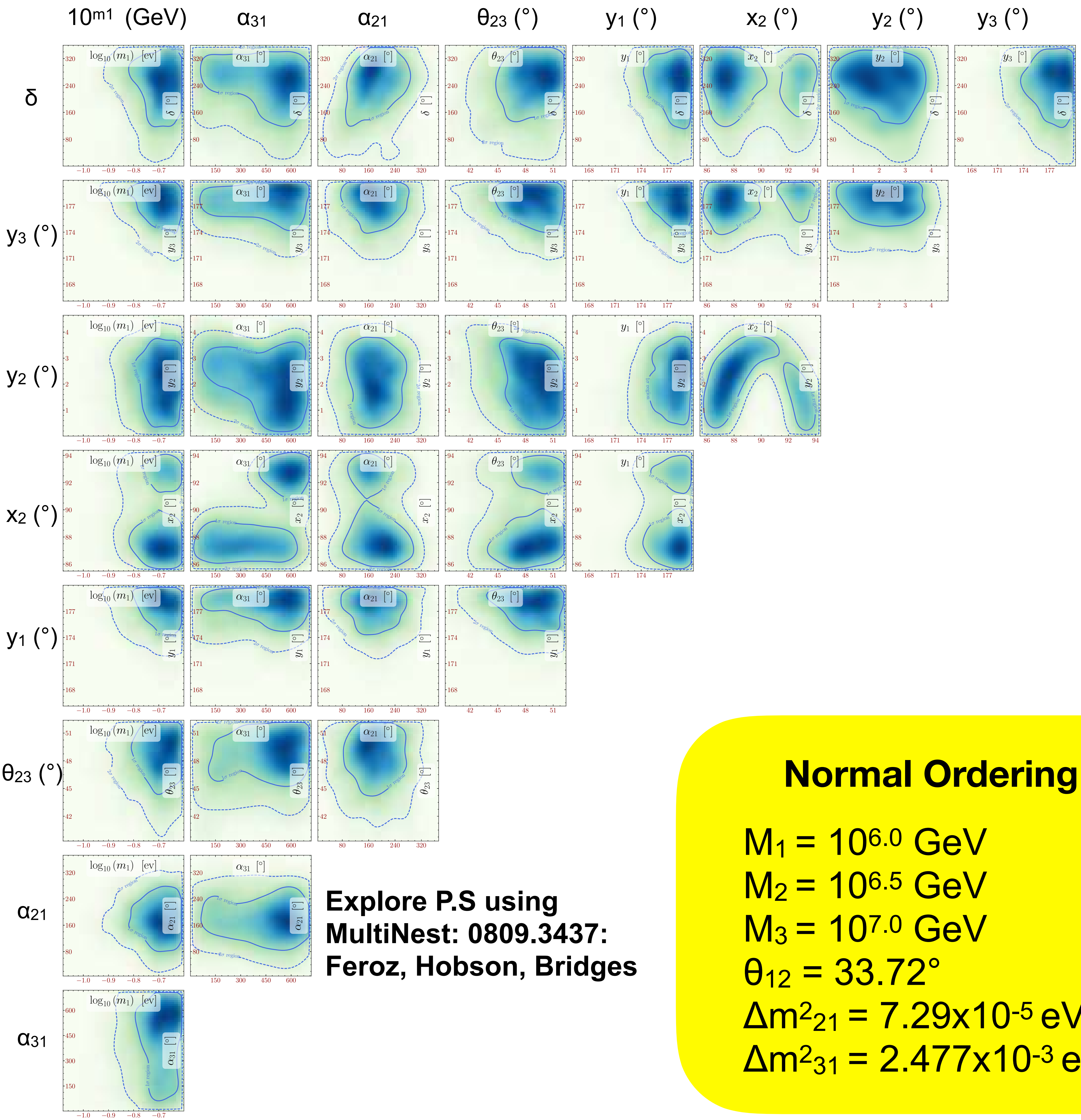
Work in collaboration with K. Moffat, S. Pascoli, S. Petcov, H. Schulz (1804.05066)

Use flavour effects to lower the scale

	δ	α_{21}	α_{31}	$x_1(^\circ)$	$y_1(^\circ)$	$x_2(^\circ)$	$y_2(^\circ)$	$x_3(^\circ)$	$y_3(^\circ)$
BP1	π	0	0	10	45	15	25	65	35
BP2	$\frac{\pi}{2}$	$\frac{\pi}{2}$	0	20	0	45	25	75	15
BP3	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	60	10	45	90	65	0
BP4	$\frac{3\pi}{2}$	$\frac{\pi}{2}$	0	5	180	5	90	65	135

TABLE II. Benchmark points used to test the three-flavoured equations against the density matrix equations.

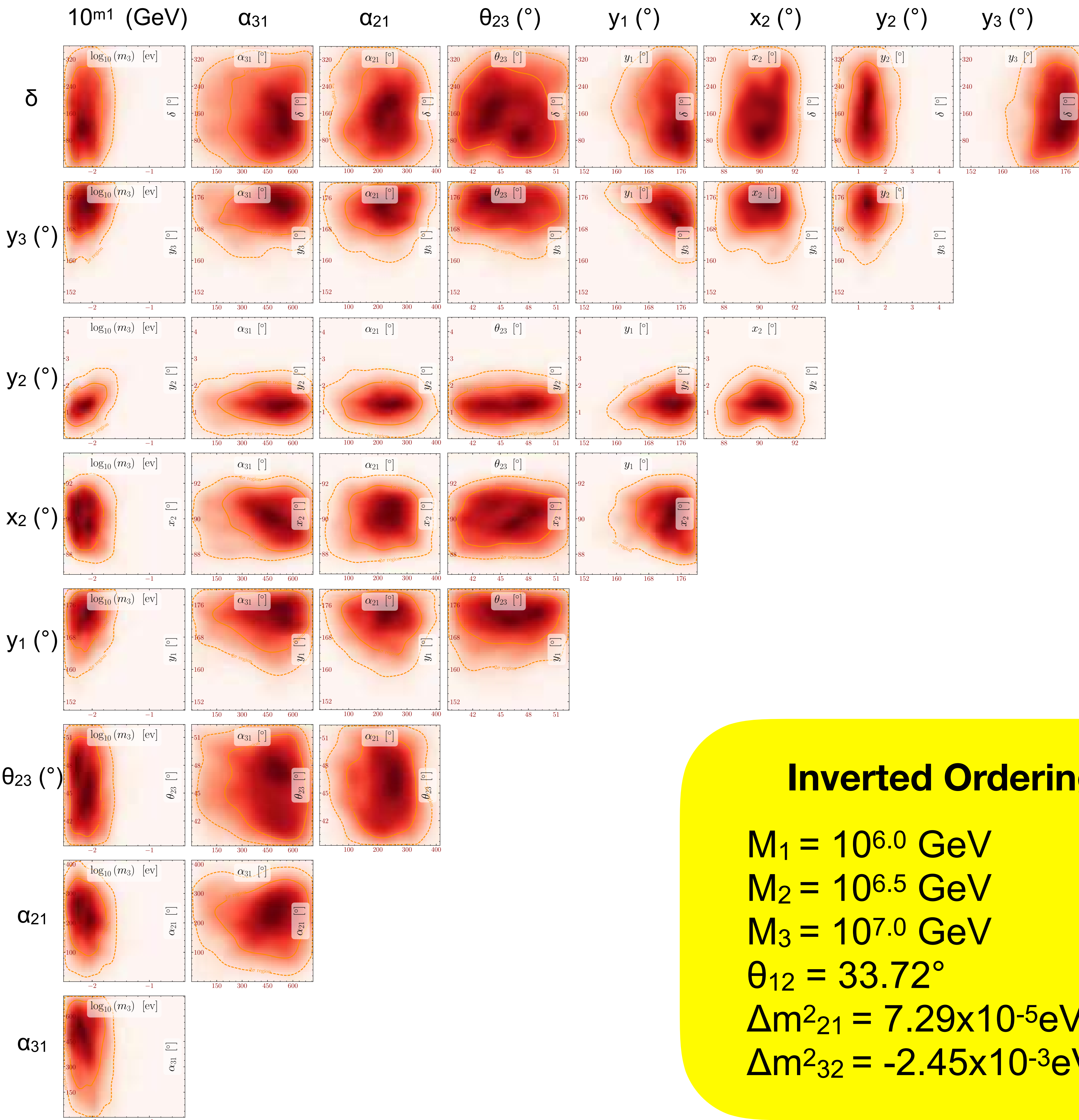




Explore P.S using MultiNest: 0809.3437: Feroz, Hobson, Bridges

Normal Ordering

$M_1 = 10^{6.0}$ GeV
$M_2 = 10^{6.5}$ GeV
$M_3 = 10^{7.0}$ GeV
$\theta_{12} = 33.72°$
$\Delta m^2_{21} = 7.29\text{x}10^{-5}\ \text{eV}^2$
$\Delta m^2_{31} = 2.477\text{x}10^{-3}\ \text{eV}^2$



Inverted Ordering

$M_1 = 10^{6.0}$ GeV
$M_2 = 10^{6.5}$ GeV
$M_3 = 10^{7.0}$ GeV
$\theta_{12} = 33.72°$
$\Delta m^2_{21} = 7.29\times10^{-5} \mathrm{eV}^2$
$\Delta m^2_{32} = -2.45\times10^{-3} \mathrm{eV}^2$

Scale can be lowered through flavour effects and thorough P.S exploration

What if all CPV came from low-energy phases?

Originally addressed by Pascoli, Petcov, Riotto

Lets revisit this question
with more sophisticated machinery
and incorporate of flavour effects,
radiative corrections etc

Leptogenesis from Low Energy CP Violation

Work in collaboration with K. Moffat, S. Pascoli, S. Petcov (1809.08251)

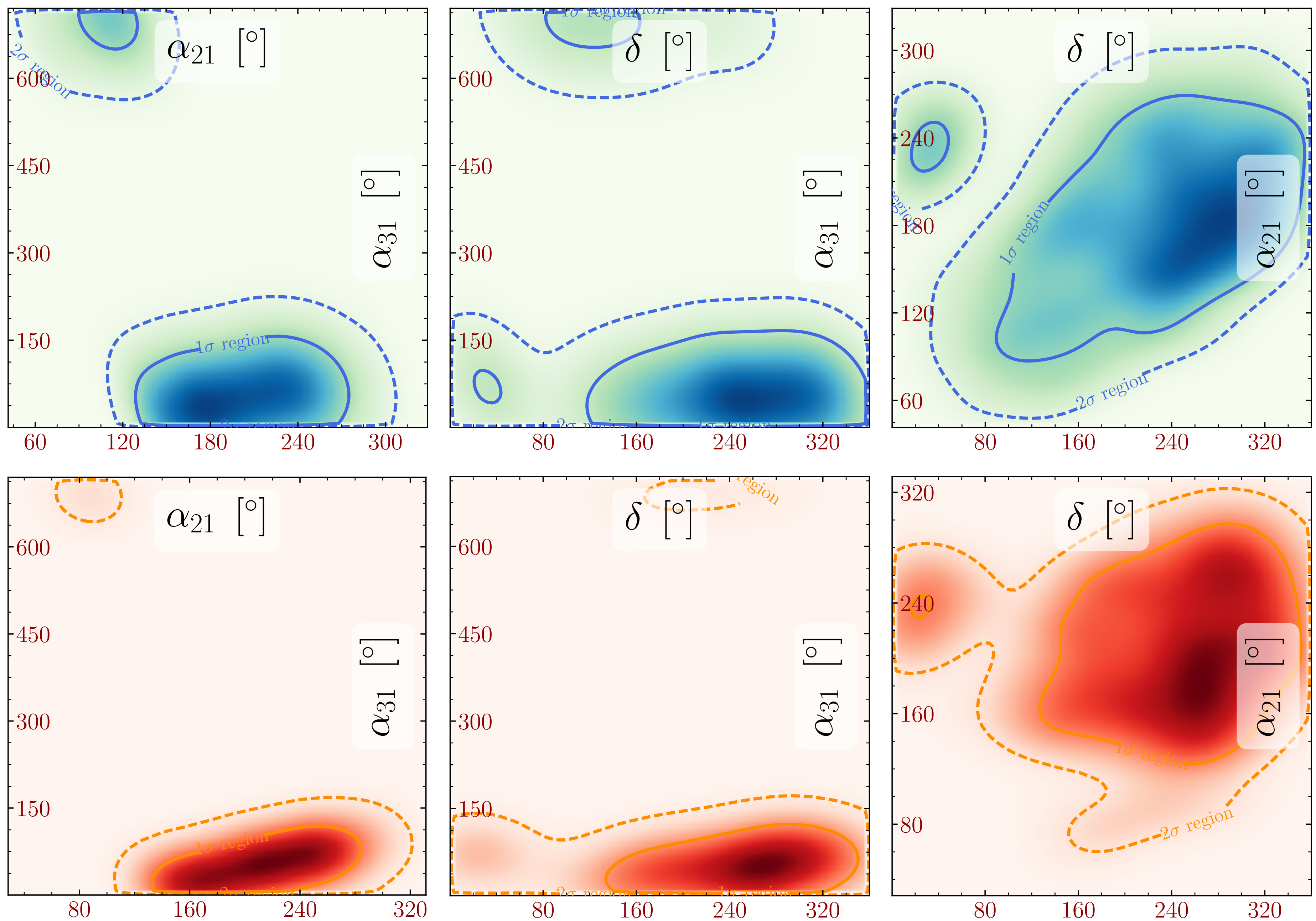
Can BAU be produced at "intermediate" scales with low energy phases?

Need to assume (although there are theoretical motivations) that high scale phases are CP conserving

$$\cos x_2 \approx 0 \text{ and } y_2 = 0,$$
$$|\cos x_1| = 0 \text{ or } 1,$$
$$|\cos x_3| = 0 \text{ or } 1,$$

Solve kinetic equations using this assumption over 7 orders of magnitude in the scale

Leptogenesis at intermediate scales using low-energy phases

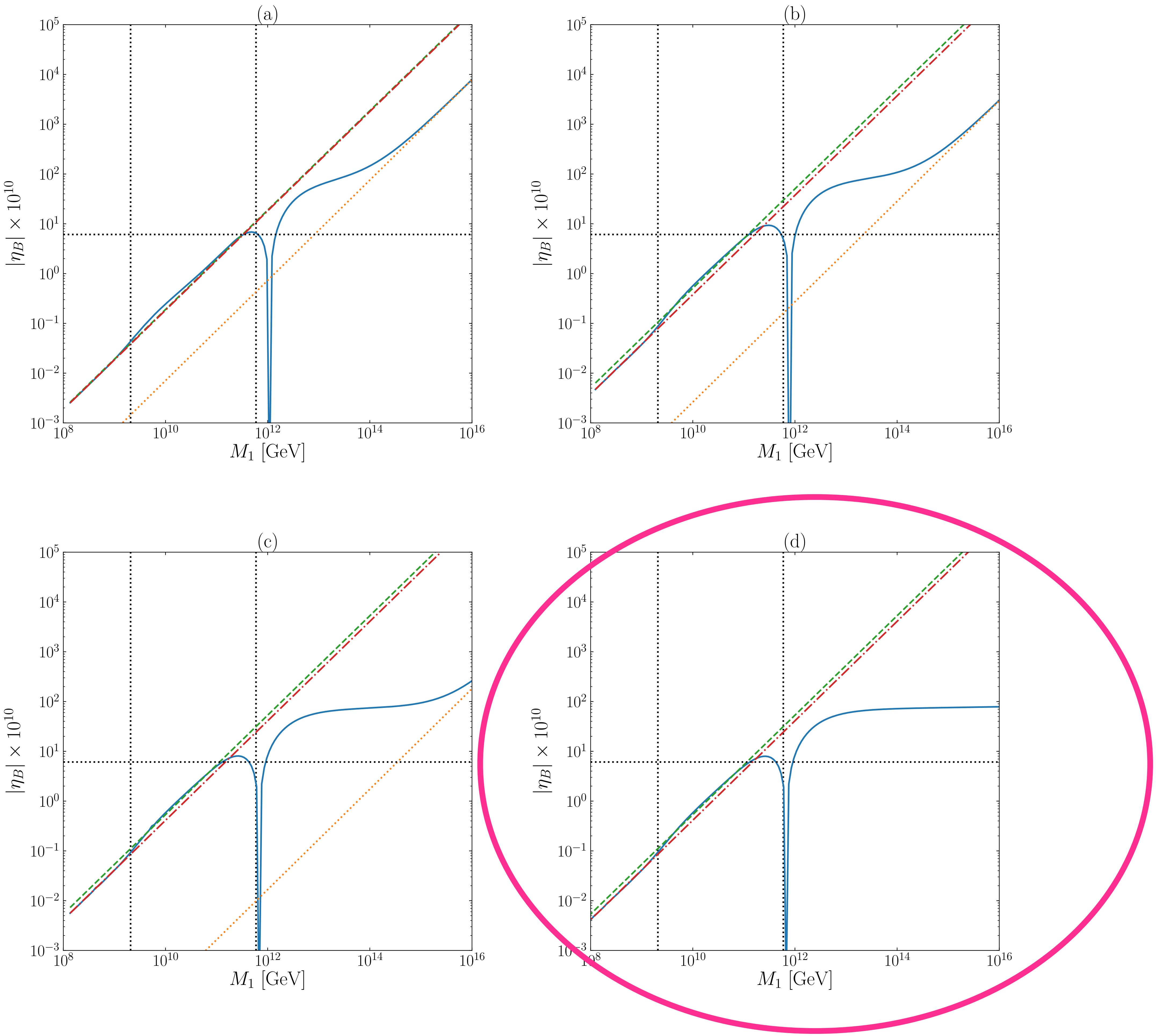


$M_1 = 10^{6.5}$ GeV
$M_2 = 10^{7.0}$ GeV
$M_3 = 10^{7.5}$ GeV

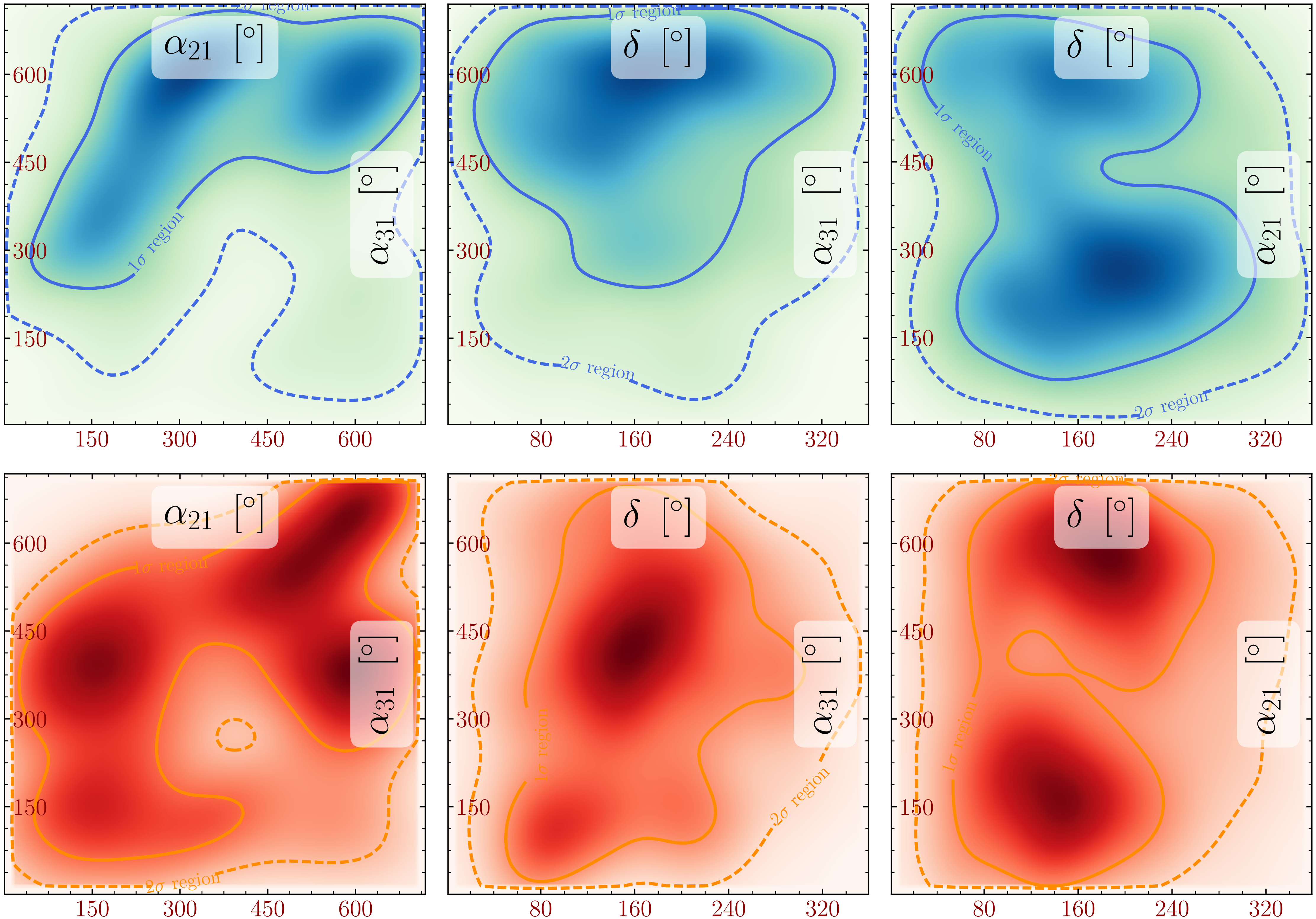
It was thought that at high high scales leptogenesis with low energy CPV could not produce the BAU

It was thought that at high high scales leptogenesis with low energy CPV could not produce the BAU

We found this to be incorrect



(a)
(b)
(c)
(d)
$|\eta_B| \times 10^{10}$
M_1 [GeV]
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}



$M_1 = 10^{13.0}$ GeV
$M_2 = 10^{13.5}$ GeV
$M_3 = 10^{14.0}$GeV

In the very high scale regime, the one-flavoured limit is never fully reached which means a lepton asymmetry can still be generated. The contrary conclusion was a misconception.

Leptogenesis via decays can produce the BAU from CPV phases measurable at neutrino oscillation experiments over 7 orders of magnitude.

CAVEAT

But one has to assume the high-scale phases are CP conserving (although there are theoretical motivations to do so).

Summary

- **Observation of the BAU is empirical evidence of Physics beyond the Standard Model.**

- **Leptogenesis is a simple and compelling mechanism to address neutrino masses and the BAU.**

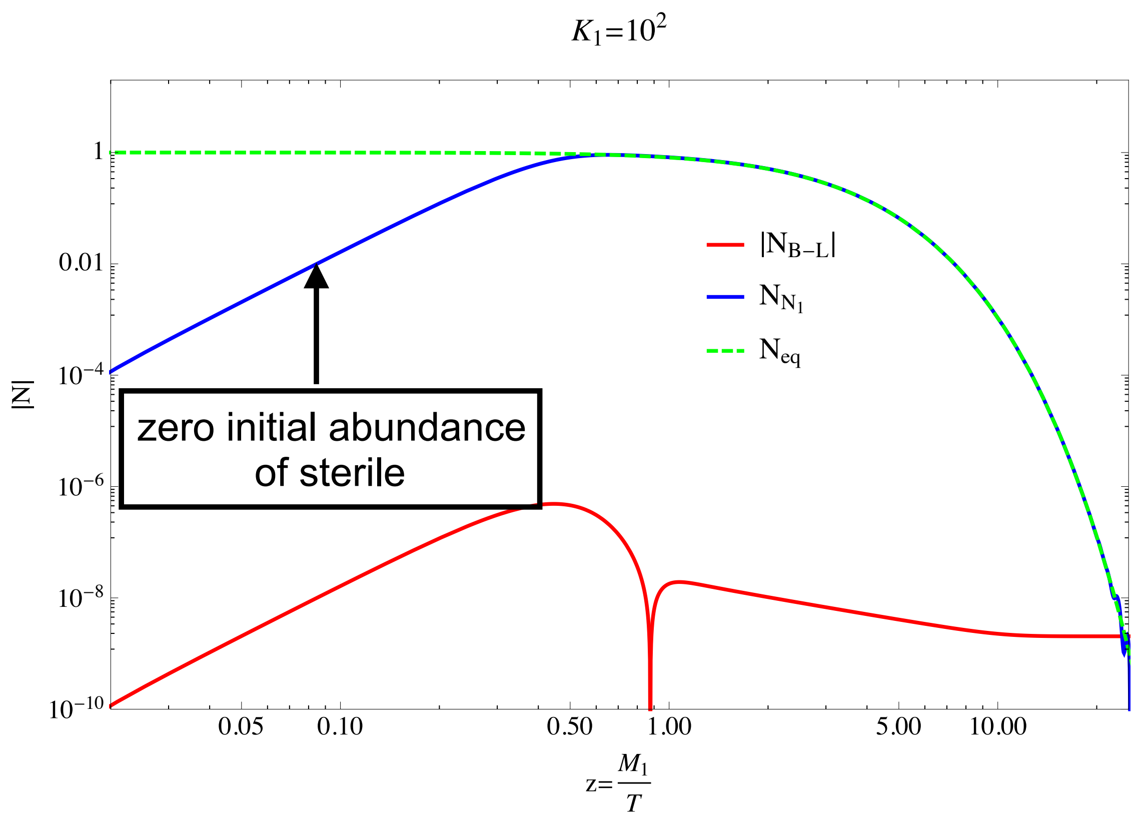
"Observation of low-scale leptonic CP violation and positive determination of the Majorana nature of the massive neutrinos, would make more plausible, but will not be a proof, of the existence of thermal leptogenesis. These remarkable discoveries would indicate that thermal leptogenesis could produce the BAU with the requisite CP violation provided by the Dirac CP-violating phase in the neutrino mixing matrix."

Thank you for your attention

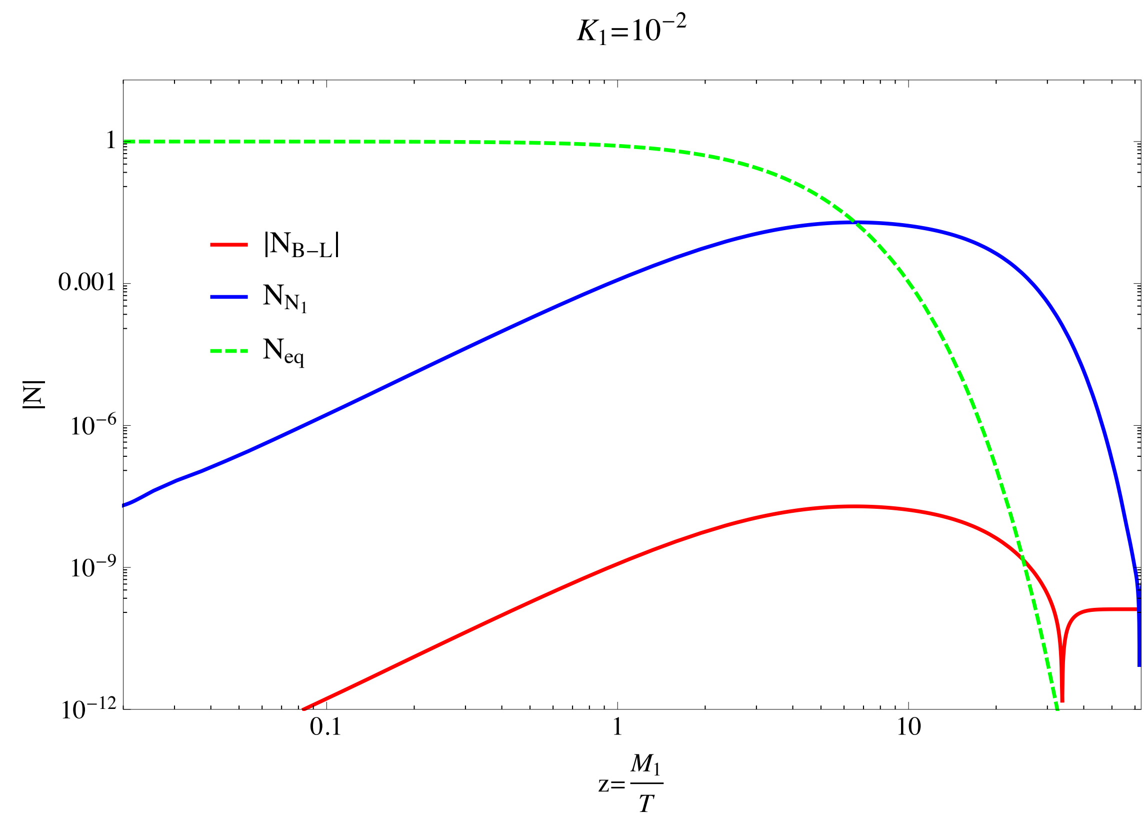
Basic Mechanism

$$\frac{dN_{N_1}}{dz} = -D_1(N_{N_1} - N_{N_1}^{\rm eq})$$
$$\frac{dN_{B-L}}{dz} = \epsilon_1 D_1(N_{N_1} - N_{N_1}^{\rm eq}) - W_1 N_{B-L}$$

B.E do not consider spectator effects or thermal corrections



Strong washout



Weak washout

These kinetic equations do not account for the fact leptons have flavour

Flavour Effects

$\Gamma_\alpha(T) \simeq 10^{-2} h_\alpha^2 T$

Temperature

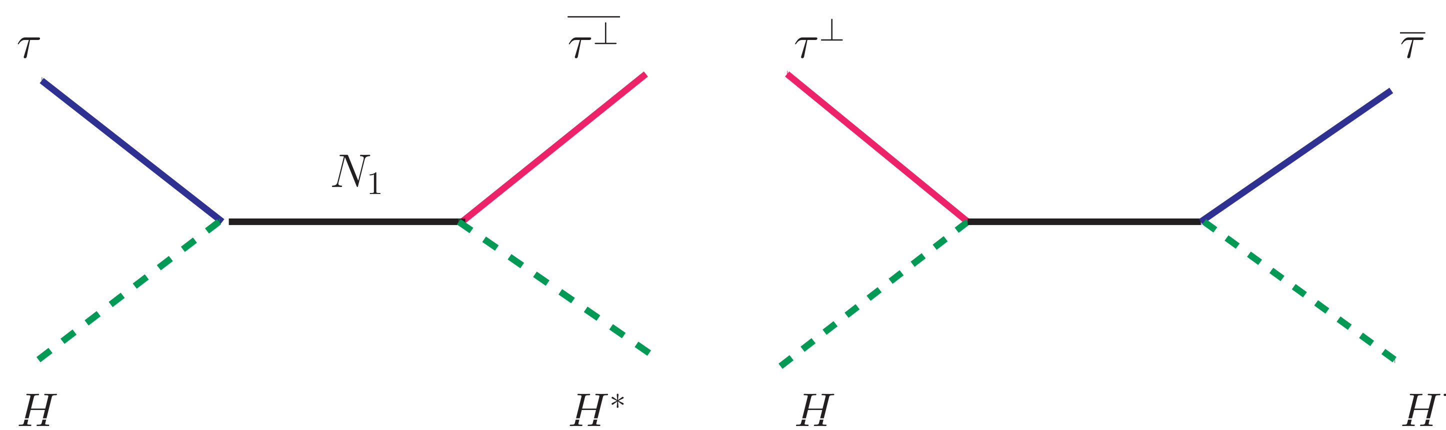
$T_e \simeq 4 \times 10^4\,\mathrm{GeV}$ $T_\mu \simeq 2 \times 10^9\,\mathrm{GeV}$ $T_\tau \simeq 5 \times 10^{11}\,\mathrm{GeV}$

$$|\ell_1\rangle = \sum_{\alpha=e,\mu,\tau} c_{1\alpha}|\ell_\alpha\rangle, \quad c_{1\alpha} = \langle\alpha|\ell_1\rangle,$$

$\propto Y_\nu$

$$|\overline{\ell_1}\rangle = \sum_{\alpha=e,\mu,\tau} \overline{c_{1\alpha}}|\overline{\ell_\alpha}\rangle, \quad \overline{c_{1\alpha}} = \langle\overline{\ell_\alpha}|\overline{\ell_1}\rangle.$$

$(10^9\,\mathrm{GeV} < T < 5 \times 10^{11}\,\mathrm{GeV})$



Using flavour effects the scale of thermal leptogenesis may be lowered several orders of magnitude

If the era of leptonenesis occurs T < 10⁹ GeV, three flavours become distinct

$$U_{CP} N_i(x) U_{CP}^{\dagger} = i\rho_i^N N_i(x'),$$
$$U_{CP} \nu_i(x) U_{CP}^{\dagger} = i\rho_i^{\nu} \nu_i(x'),$$

$$Y_{\alpha i}^* = Y_{\alpha i} \rho_i^N$$

CP invariant transformation of PMNS matrix

$$U_{\alpha j}^* = U_{\alpha j} \rho_j^{\nu}, \;\; j \in \{1,2,3\},$$

CP invariant transformation of R matrix

$$R_{ij}^* = R_{ij} \rho_i^N \rho_j^{\nu}, \quad i,j \in \{1,2,3\}.$$