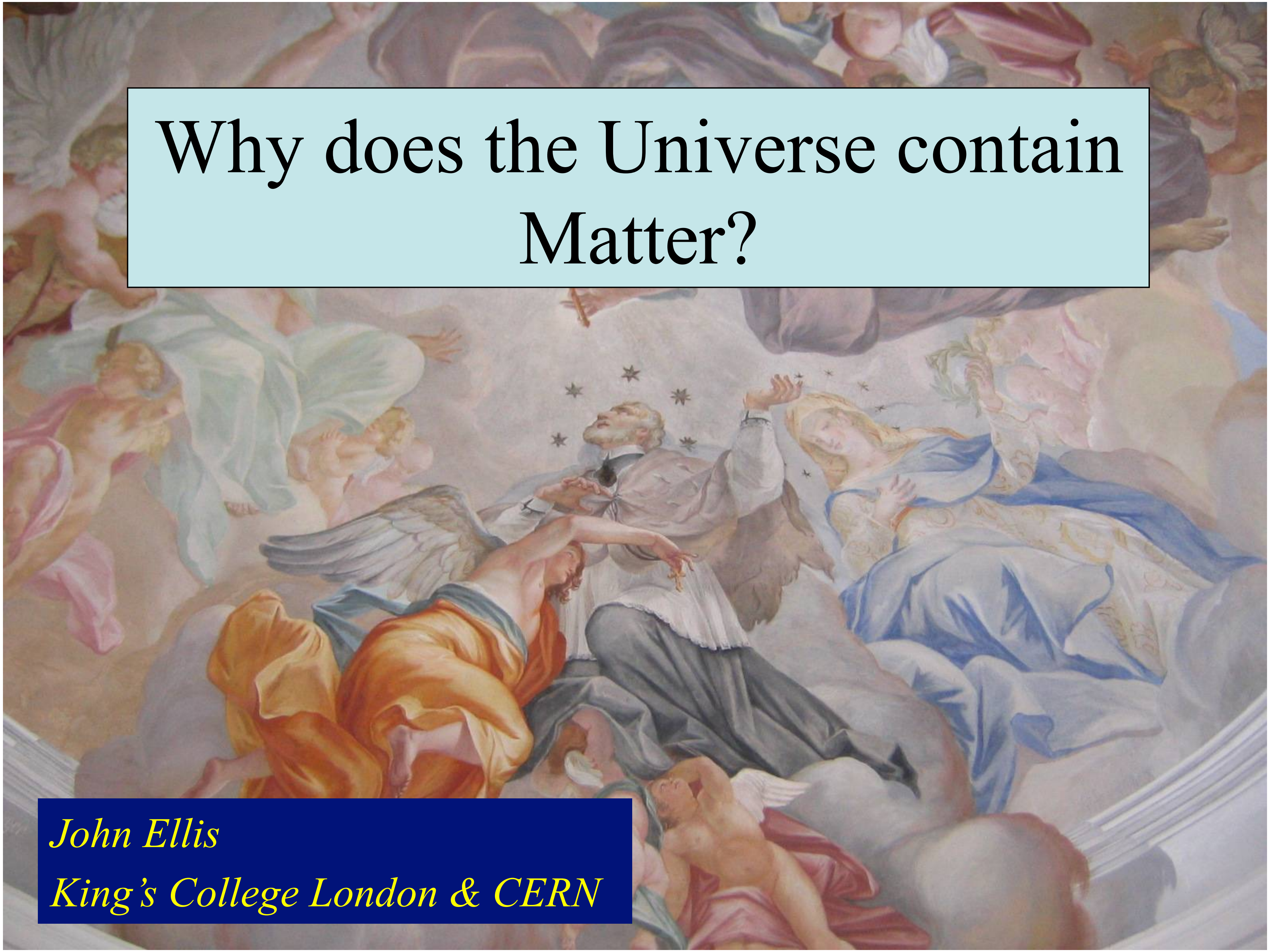
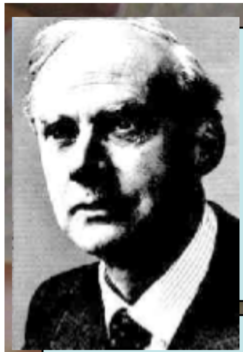
Why does the Universe contain Matter?

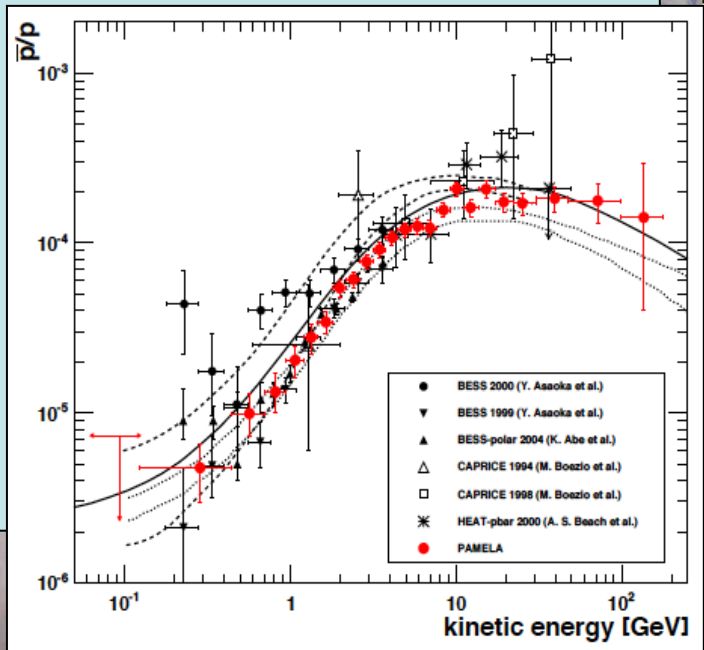


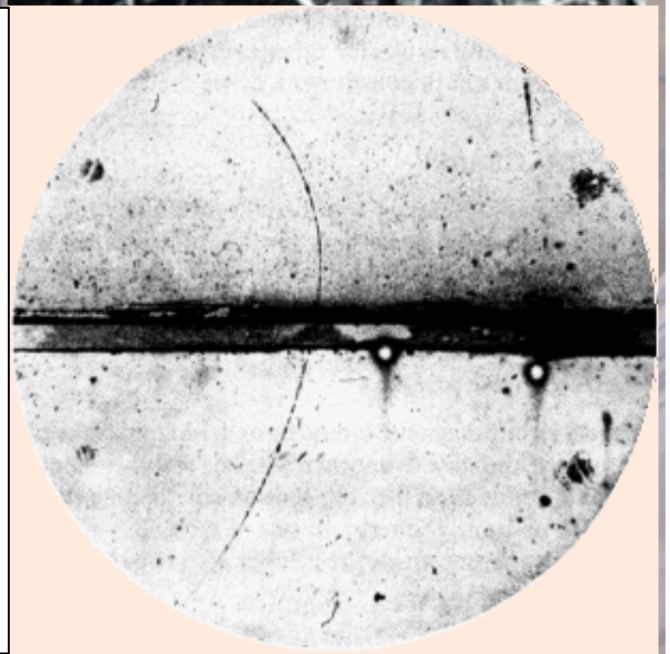
John Ellis
King's College London & CERN



Antimatter in the Universe

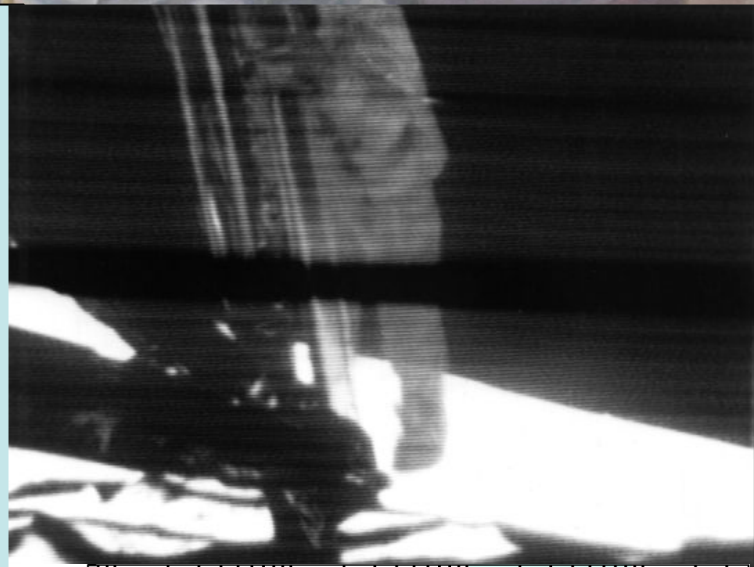
- Predicted by Dirac in 1928
- Positron discovered in cosmic rays by Anderson in 1932
- Antiprotons also seen
- Consistent with matter primaries

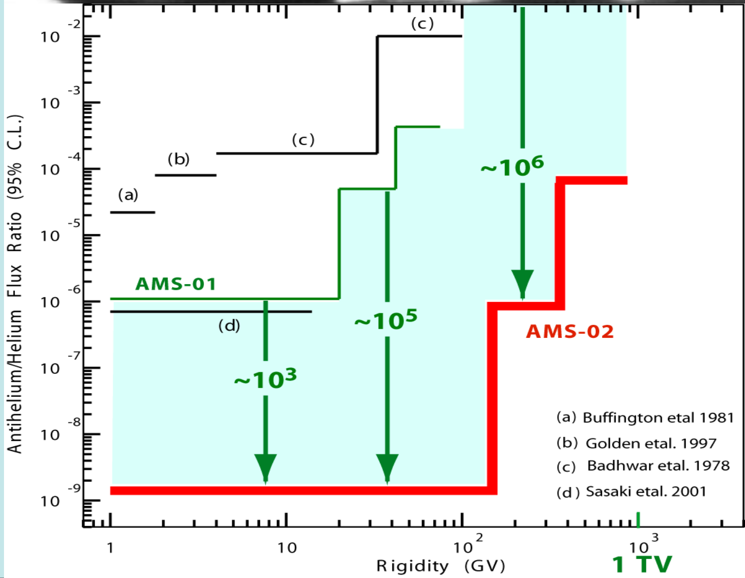




Matter-Antimatter Asymmetry

- Moon made of matter:
  astronauts got back OK
- No excess γ-rays from matter-antimatter annihilation within our cluster of galaxies
- No distortion of cosmic microwave background
- No antinuclei detected in cosmic rays
- **➔No lumps of antimatter within visible Universe**





Outline

- The Sakharov conditions for generating the matter in the Universe
- Why the Standard Model is not enough
- Beyond the Standard Model:
  - At the electroweak scale?
    - Supersymmetry? Composite model?
  - At some higher scale?
- Out-of-equilibrium decays of heavy neutrinos?
  - Also responsible for cosmological inflation?

Where did the Antimatter go?

Dirac predicted existence of antimatter:

same mass

opposite internal properties:

electric charge, …

Discovered in cosmic rays

Studied using accelerators

Matter and antimatter not quite equal and opposite: WHY?

Is this why the Universe contains matter, not antimatter?

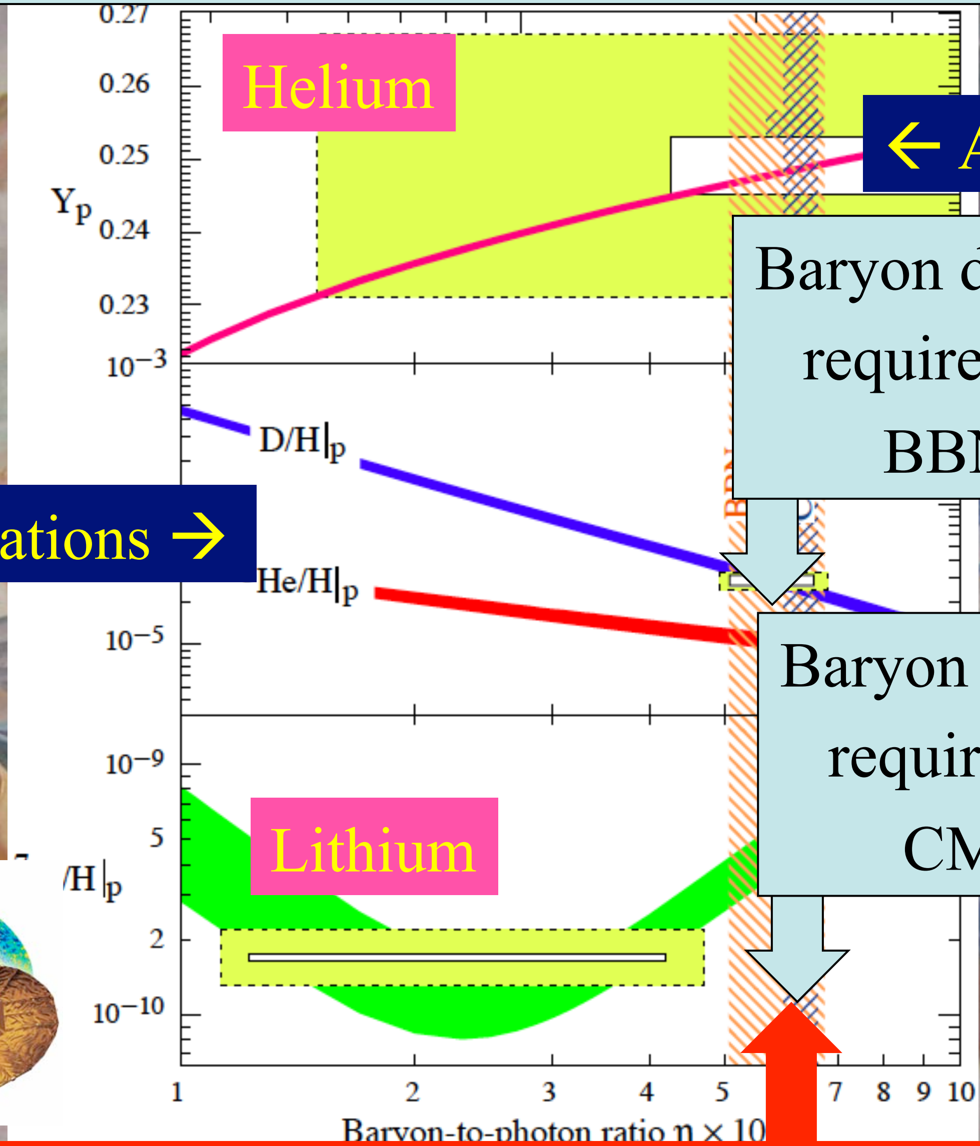
Can experiments reveal how matter was created?

Evolution of Baryon Asymmetry

- Suppose quark asymmetry generated before quark-hadron phase transition:

  #(quarks)/#(antiquarks) = 1 + $O(10^{-9})$
- At transition:
  - all antibaryons annihilate with baryons, yielding radiation, neutrinos
- After transition:
  - baryon excess ~ $O(10^{-9})$ survives
- Small baryon-to-photon ratio in Universe today

Baryon-to-Photon Ratio in Universe

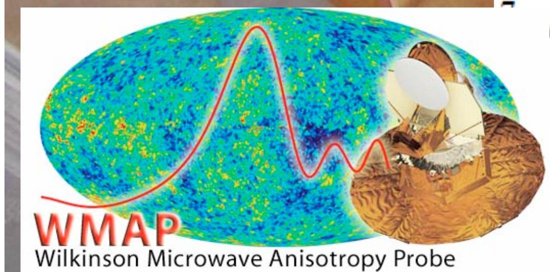


← Agree with data

Theoretical calculations →

Baryon density required by BBN

Baryon density required by CMB



Baryon/photon ratio ~ few × 10^{-9}: need dark matter, dark energy

How to Create the Matter in the Universe?

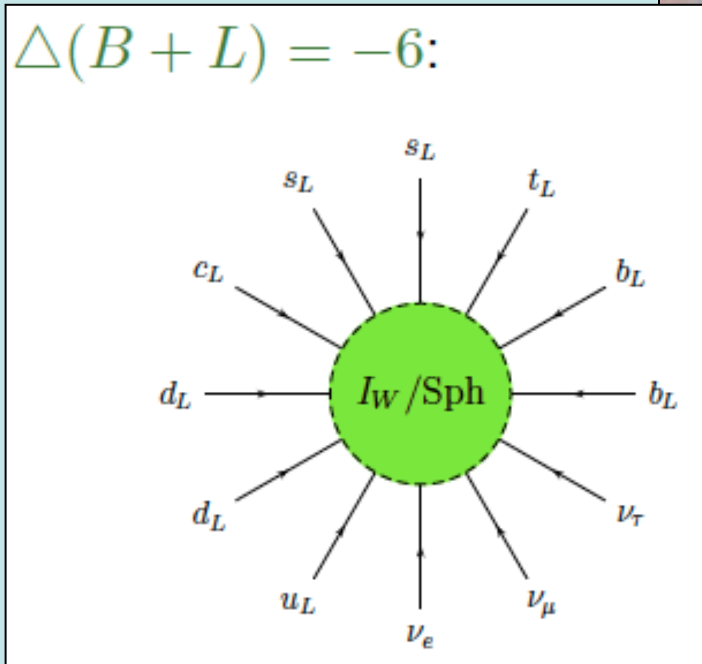
Sakharov

- Need a difference between matter and antimatter
  C, CP violation observed
- Need interactions creating matter
  present in unified theories
  not yet seen by experiment
- Must break thermal equilibrium
  First-order phase transition?
  Decays of heavy particles?

Will we be able to calculate using laboratory data?

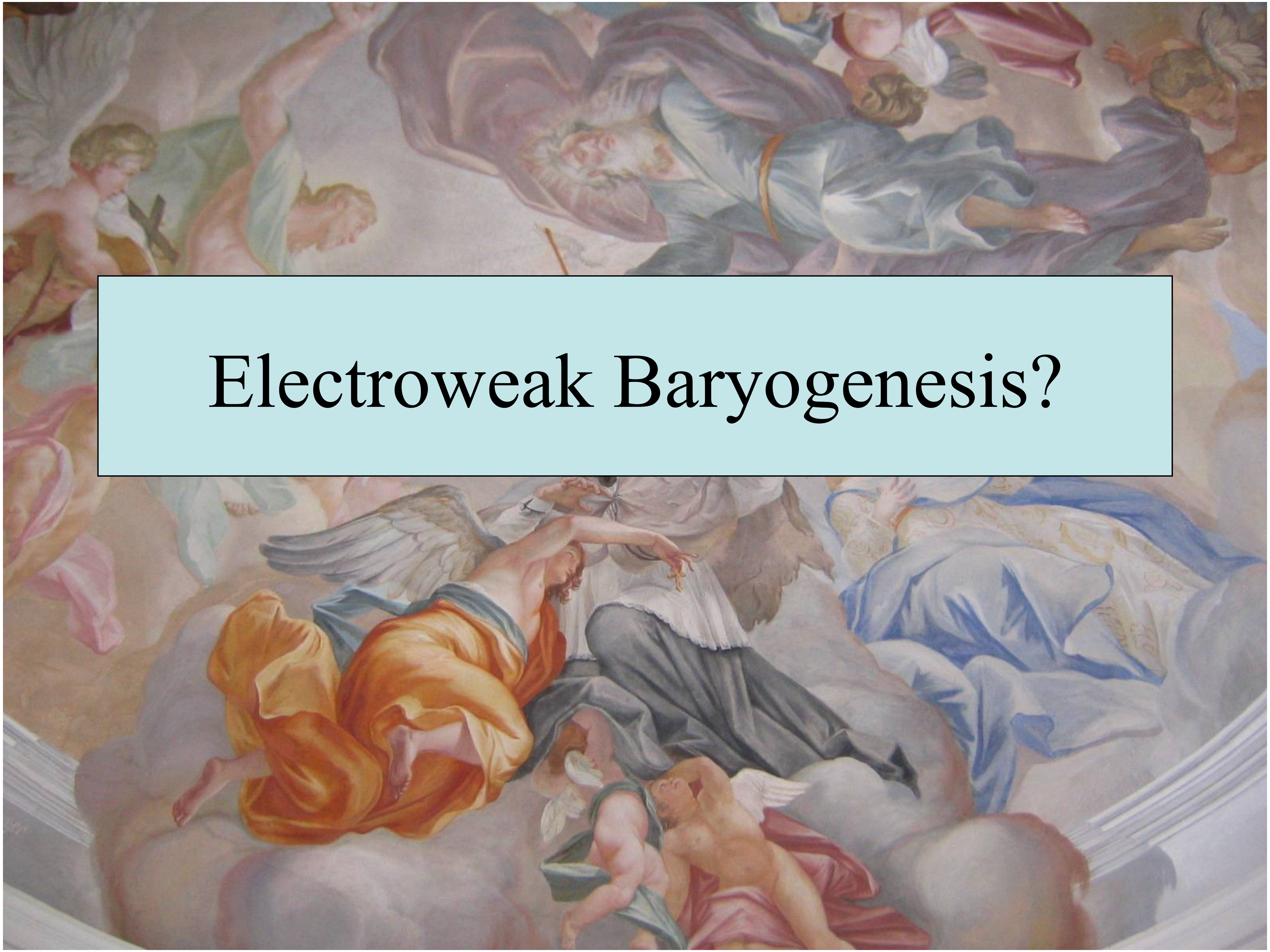
Interactions Creating Matter?

- B-violating interactions in GUTs: p ➔ $e^+\nu$
  - But proton decay not seen
- Non-perturbative electroweak interactions:
  - instantons/sphalerons
- Violate B, L but conserve B-L



- Sphaleron transitions would have been in equilibrium in the early Universe

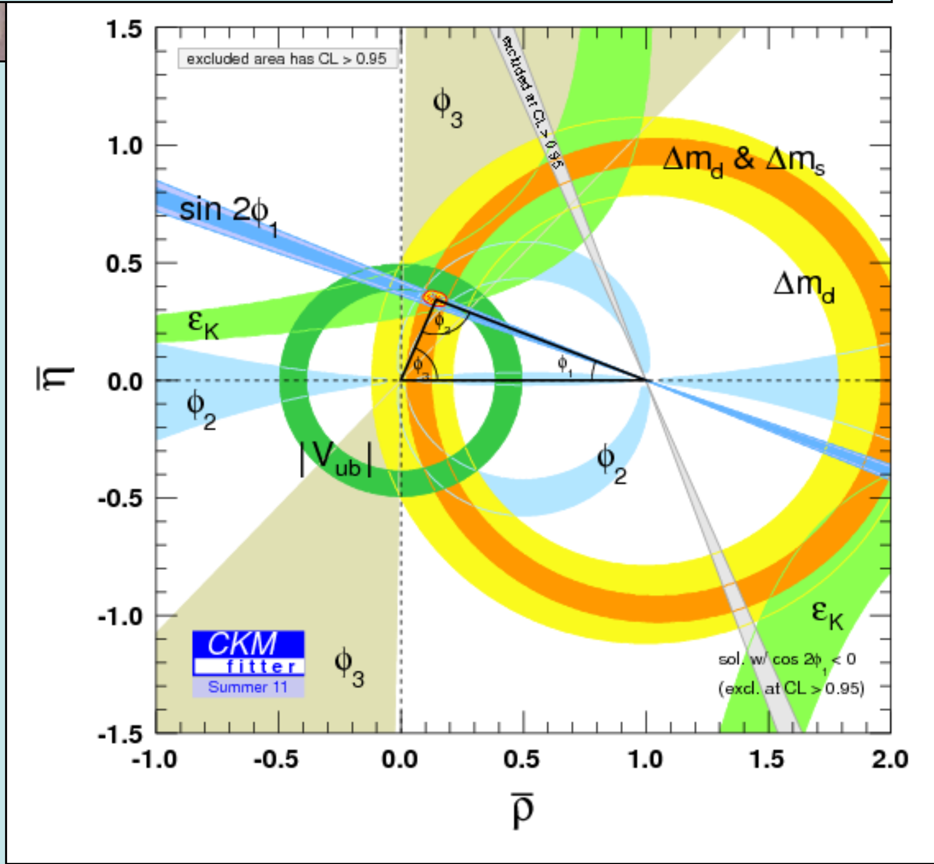
Electroweak Baryogenesis?



The Standard Model is not enough

- Maximal C violation ☺
- CP violation ☺
- Well described by Kobayashi-Maskawa ☺
- Too small to explain baryon asymmetry ☹

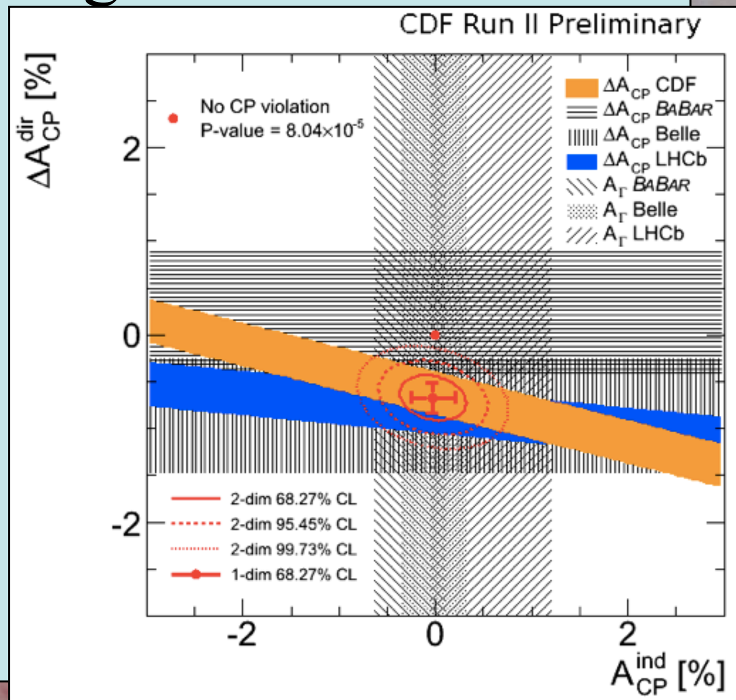
$J \sim \Pi(\delta m_q^2/M_W^2)\Pi(\text{angles})$



- Cosmological phase transition not 1st order, certainly not if $M_H \sim 125$ GeV ☹

Is there life beyond Kobayashi & Maskawa?

- Many consistency checks
- Successful prediction of CP violation in B decays from CP-conserving processes
- Discrepancies in B decays, but not significant?
- Recent: CP violation in D decays:
  – $A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \neq 0$
- Standard Model predicted ~ 0.1%
  – Measurement ~ 0.6%
- Failure of Standard Model, or of theoretical calculations?
- **New frontier in CP violation**



New Physics at Electroweak Scale?

- Electroweak symmetry breaking?
- "Any" non-minimal scenario ➔ more CP ✕
- Elementary Higgs boson or composite?
- In former case: need new physics to make light Higgs boson "natural"
- In latter case: need new physics to give fermion masses
- **Both offer more opportunities for CP ✕**

Minimal Supersymmetric Extension of Standard Model (MSSM)

- Particles + spartners

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell \; (lepton) \\ \tilde{\ell} \; (slepton) \end{pmatrix} \; or \; \begin{pmatrix} q \; (quark) \\ \tilde{q} \; (squark) \end{pmatrix} \begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma \; (photon) \\ \tilde{\gamma} \; (photino) \end{pmatrix} \; or \; \begin{pmatrix} g \; (gluon) \\ \tilde{g} \; (gluino) \end{pmatrix}$$

- 2 Higgs doublets, coupling μ, ratio of v.e.v.s = $\tan\beta$
- Unknown supersymmetry-breaking parameters:

  Scalar masses m_0, gaugino masses $m_{1/2}$,
  trilinear soft couplings A_{λ}, bilinear soft coupling B_{μ}
- Assume universality? constrained MSSM = CMSSM

  Single m_0, single $m_{1/2}$, single A_{λ}, B_{μ}: not string?
- Even this simplest scenario has many possibilities for extra CP-violating phases

Maximal CP Violation with Minimal Flavour Violation (MCPMFV)

- Minimal flavour violation (MFV)
- All squark mixing due to CKM matrix
- Universal scalar masses for sparticles with same quantum numbers, parametrization:

$$M_{1,2,3}\,, \quad M^2_{H_{u,d}}\,, \qquad \widetilde{\mathbf{M}}^2_{Q,L,U,D,E} \;=\; \widetilde{M}^2_{Q,L,U,D,E}\,\mathbf{1}_3\,, \qquad \mathbf{A}_{u,d,e} \;=\; A_{u,d,e}\,\mathbf{1}_3$$

- Maximally CP-violating MFV (MCPMFV) model has 19 parameters, of which **6 violate CP**:

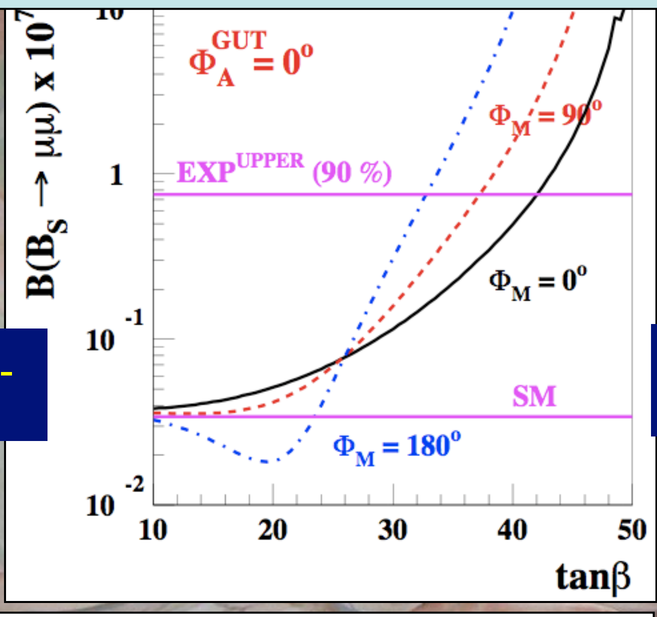
$$\mathrm{Im}\, M_{1,2,3} \text{ and } \mathrm{Im}\, A_{u,d,e}$$

- Often assume universal ImM_a, ImA_f, but non-universality compatible with MFV: **MCPMFV**

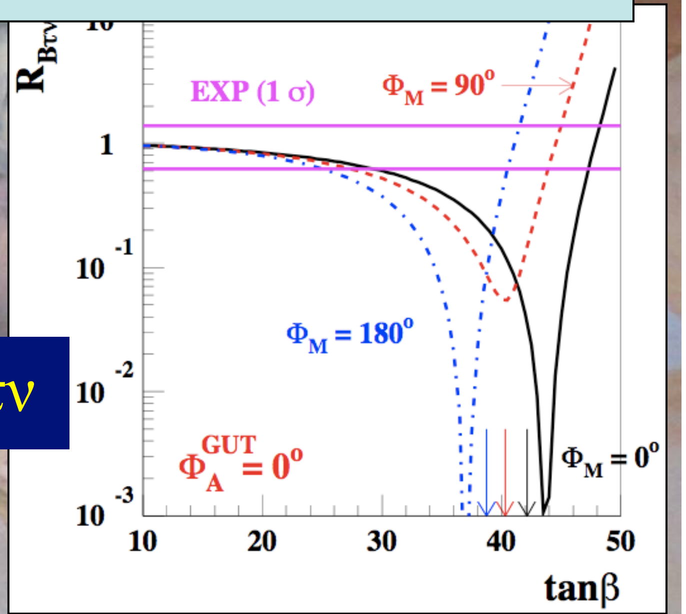
J.E. + Lee + Pilaftsis

Effects of CP Phases in MCPMFV

$B_s \rightarrow \mu^+\mu^-$

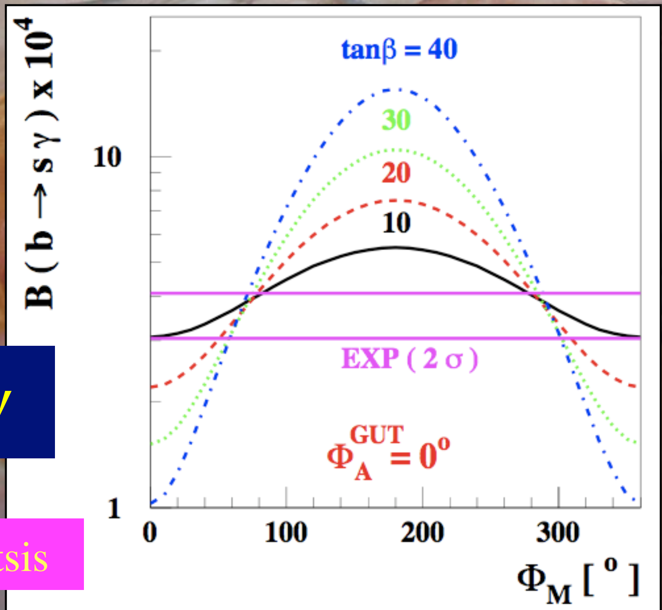


$B_u \rightarrow \tau\nu$

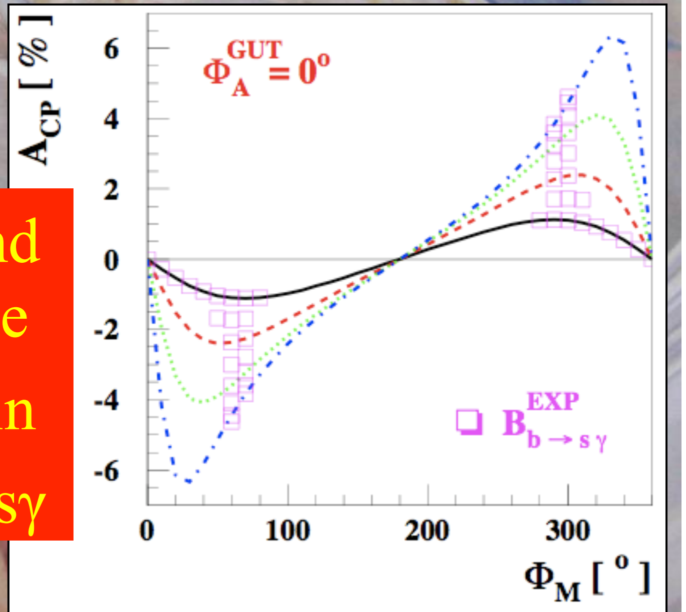


Different regions allowed for different phases …

$b \rightarrow s\gamma$



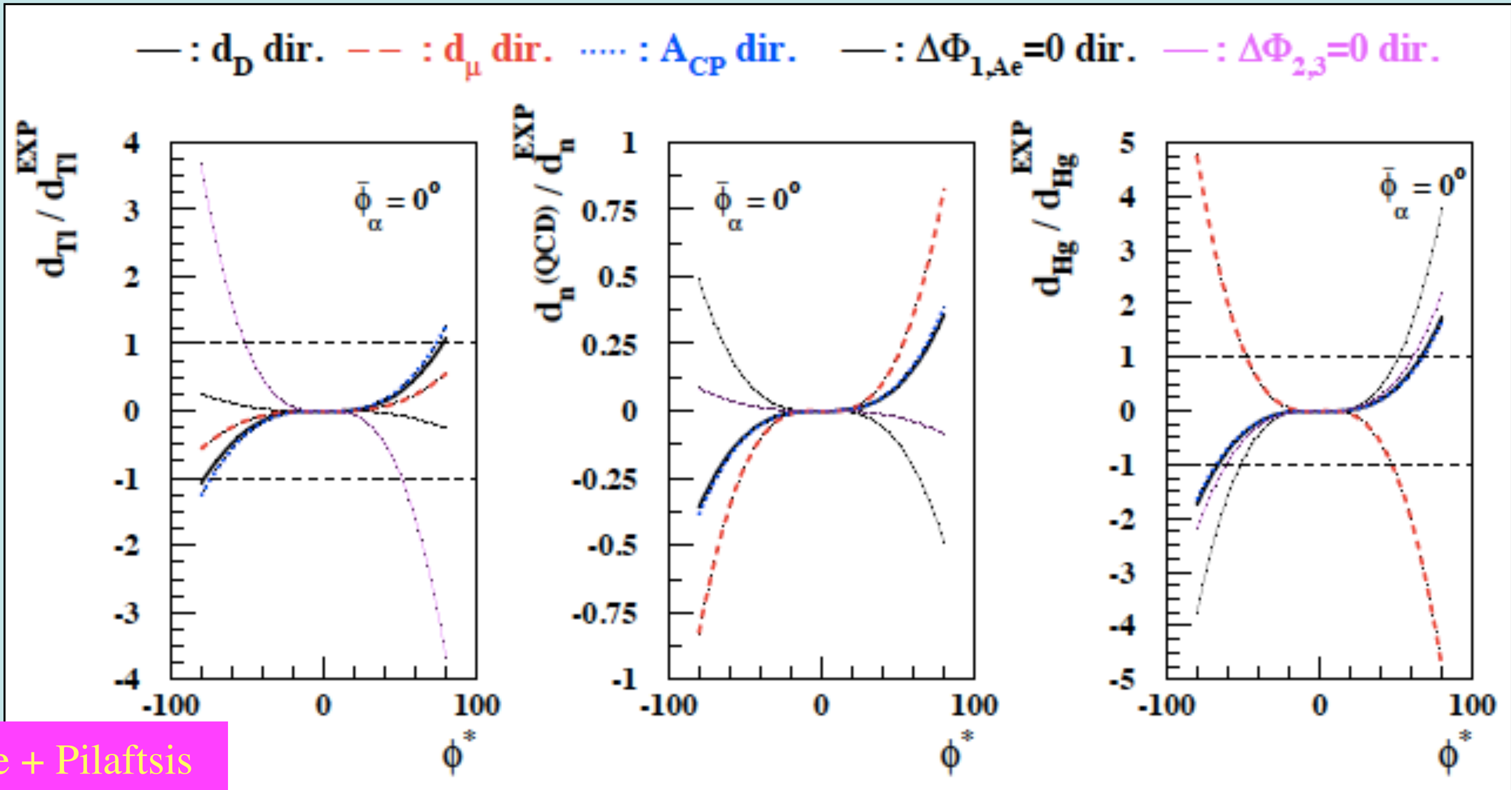
… and hence A_{CP} in $b \rightarrow s\gamma$



J.E. + Lee + Pilaftsis

How Large could the CP Phases be?

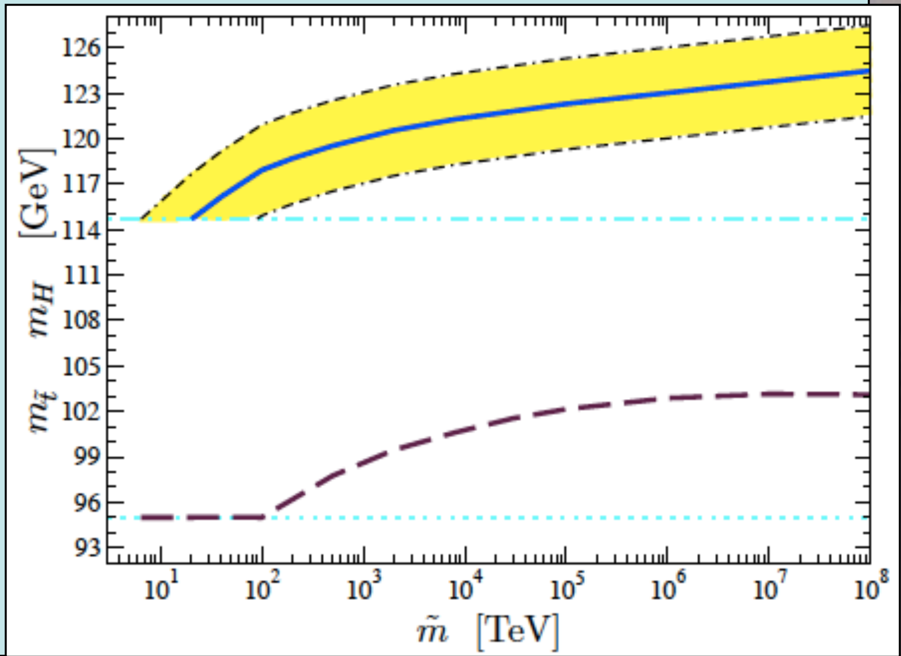
- 6 phases, 3 bounds from electric dipole moments
- There are directions in parameter space where phases may be large: good for baryogenesis ☺



J.E. + Lee + Pilaftsis

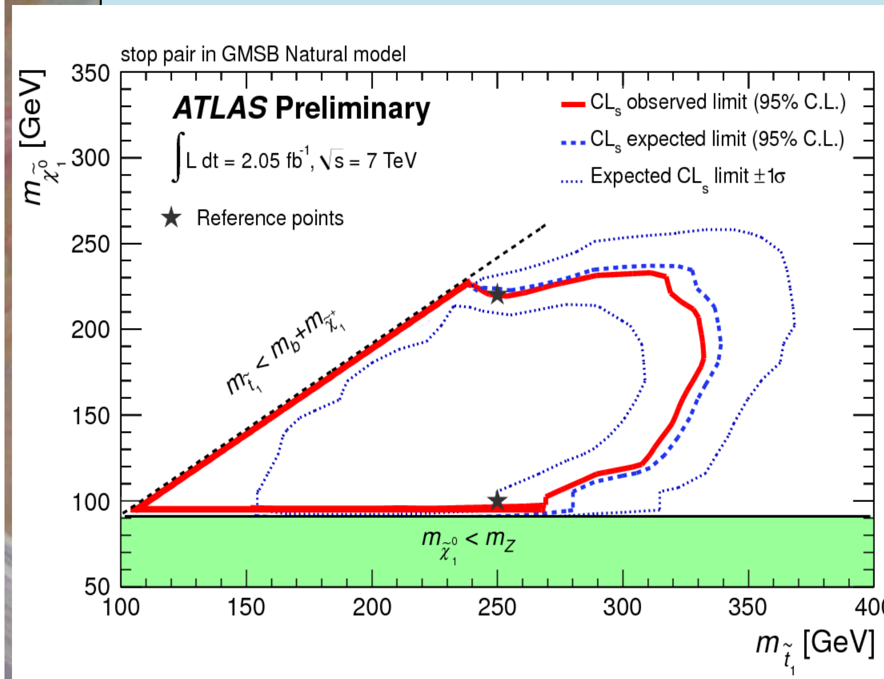
What about First-Order Phase Transition?

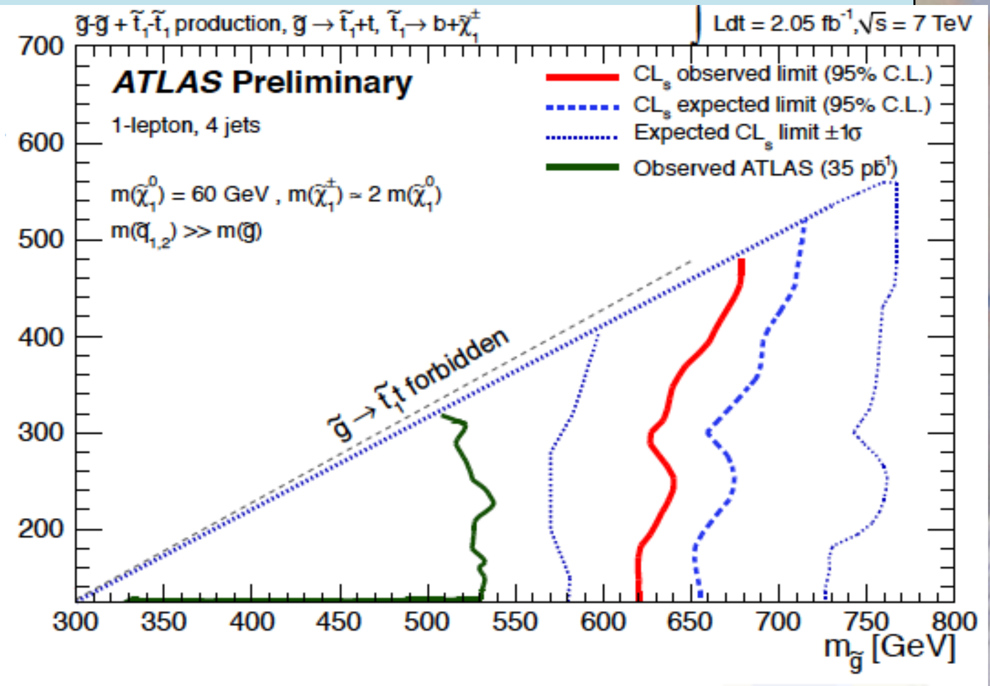
- Not the case in Standard Model for $M_H > 50$ GeV
- Would require additional light scalar particle(s)
- Candidate in supersymmetry: lighter stop squark
- Expected to be lighter than other squarks: could it be light enough?
- Strong limits from LHC & scenario disfavoured by $M_H \sim 125$ GeV
- RIP Supersymmetric electroweak baryogenesis?



Stop Searches @ LHC

- No sign of a light stop
- Searches in two sample scenarios





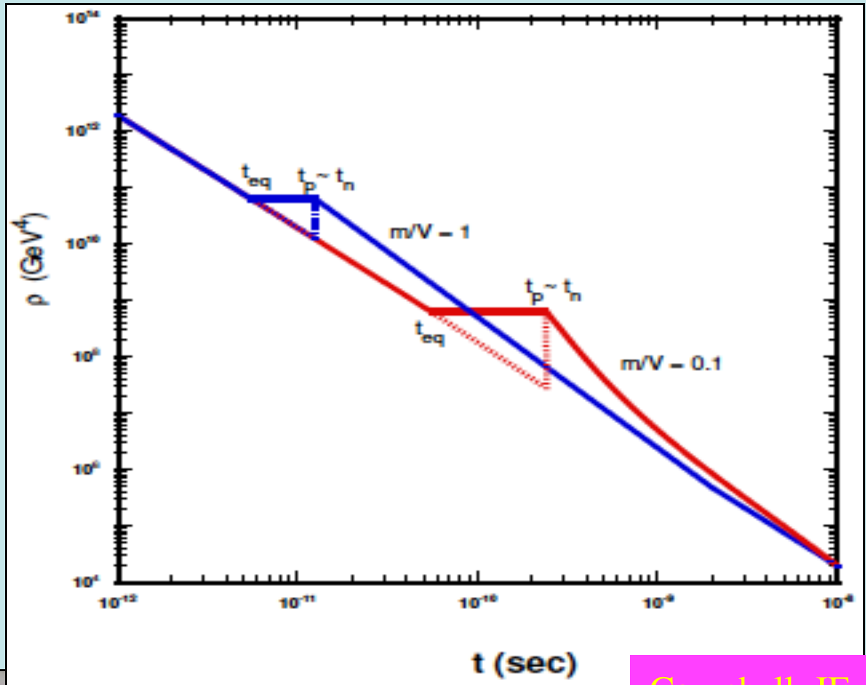
- But all possible signatures not yet studied

Electroweak Baryogenesis in Composite Model?

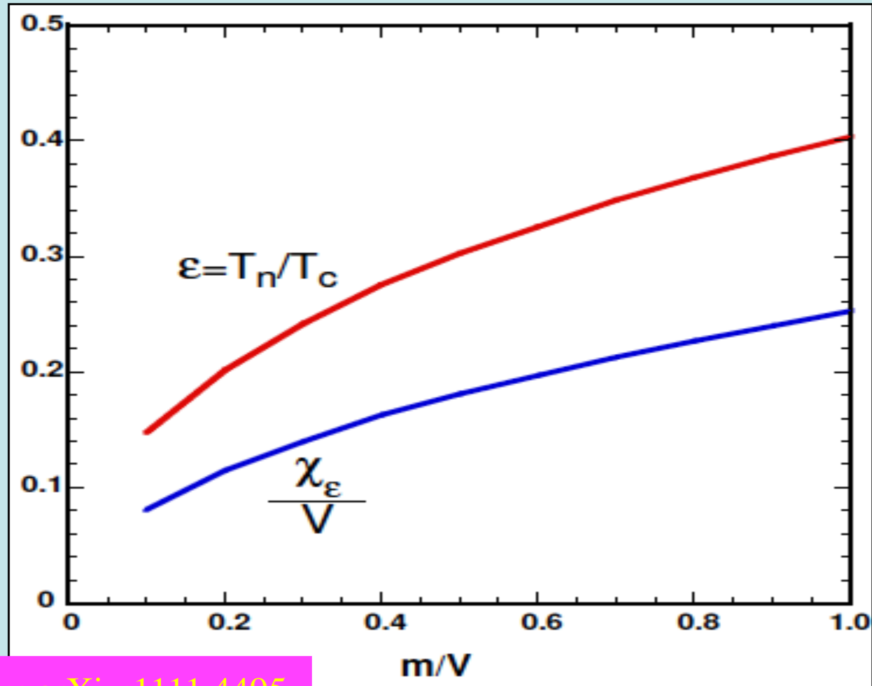
- Extra CP violation associated with fermion masses
- e.g., near-conformal composite model with light pseudo-dilaton (maybe at 125 GeV?)
- Fermion masses: $\mathcal{L}_Y = -\frac{\chi}{f}\sum_{\psi} m(z)\bar{\psi}\psi$: $z = \hat{\lambda}(\chi/f)^{\Delta-4}$
- Independent of couplings:
$$\begin{aligned} m_\psi &= m(0) + \hat{\lambda}m'(0), \\ Y_\psi &= \frac{1}{f}\left[m(0) + \hat{\lambda}(\Delta-3)m'(0)\right] \end{aligned}$$
- Extra source of CP violation
- BUT electroweak baryogenesis would need first-order electroweak phase transition

Evolution of the Universe in Light Dilaton Scenario

- Universe supercoools
- Briefly dominated by field energy



- First-order transition
- Ingredients for baryogenesis

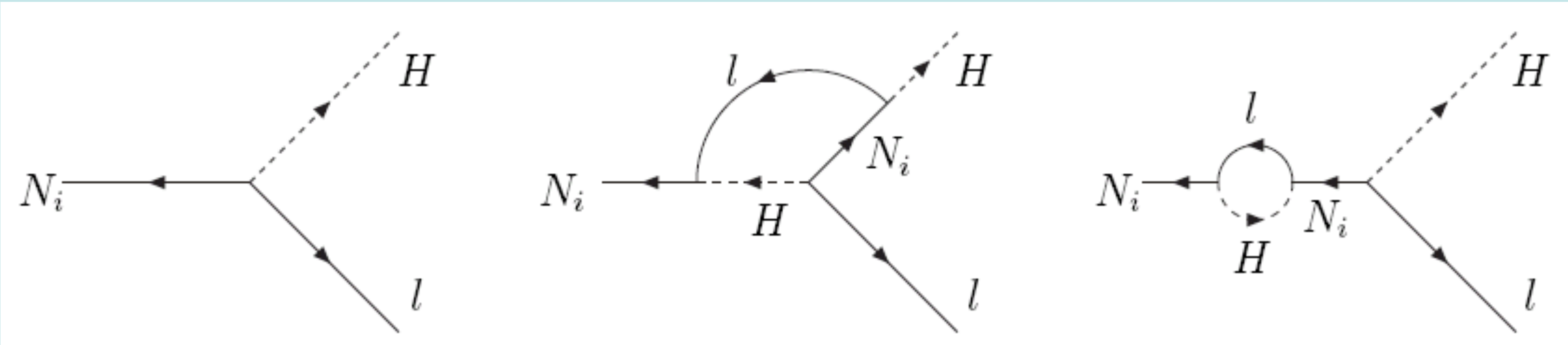


Campbell, JE, Olive: arXiv:1111.4495

Baryogenesis via Leptogenesis?

Scenario for Leptogenesis

- Early Universe contained heavy Majorana neutrinos
- Decays could have created lepton asymmetry



- Non-perturbative weak interactions would convert (partly) to baryon asymmetry

Requirements for Leptogenesis

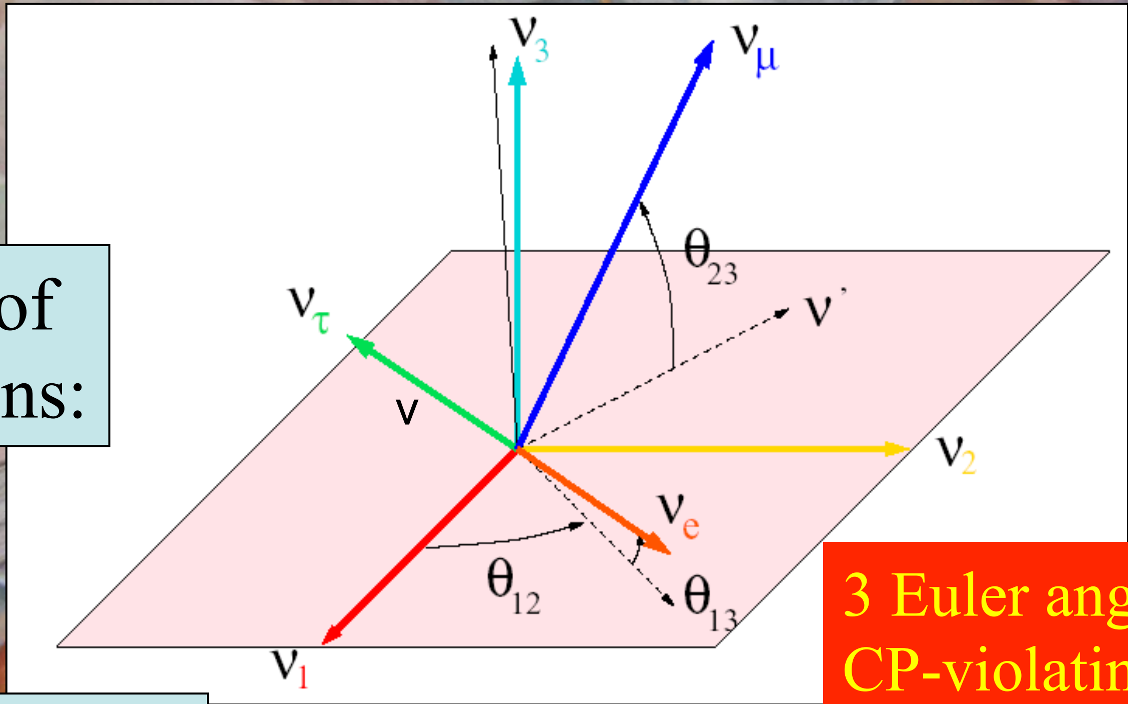
- Three essential conditions:
  - Neutrino mixing (oscillations) ✓
  - CP violation ?
  - Majorana neutrino masses ($\Delta L = 2$) ?
- These generate lepton asymmetry $\Delta L \neq 0$
- Sphalerons with $\Delta(B - L) = 0$ convert

  part of lepton asymmetry $\Delta L \neq 0$

  to baryon asymmetry $\Delta B \neq 0$

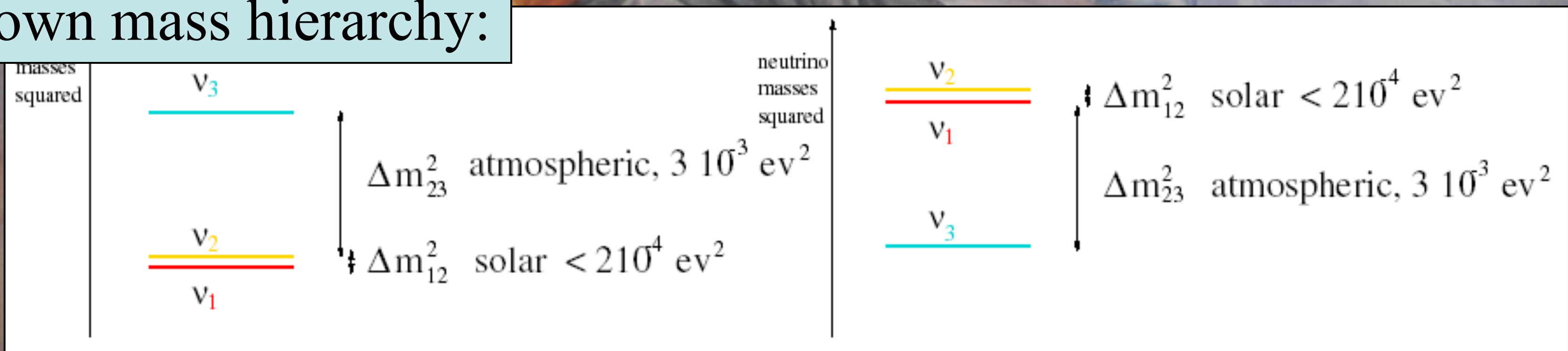
ν Oscillation Parameters

Geometry of ν oscillations:



3 Euler angles + CP-violating phase

Unknown mass hierarchy:



Neutrino Mixing

- Diagonalize neutrino mass matrix in flavour space:

$$U^T M_\nu U = M_\nu^d \quad \text{where} \quad M_\nu = Y_\nu^T \frac{1}{M} Y_\nu v^2$$

- Two 'observable' Majorana phases as well as Maki-Nakagawa-Sakata (MNS) mixing matrix:

$$U = U_\nu P_0 : \; P_0 \equiv \mathrm{Diag}\left(e^{i\phi_1}, e^{i\phi_2}, 1\right)$$

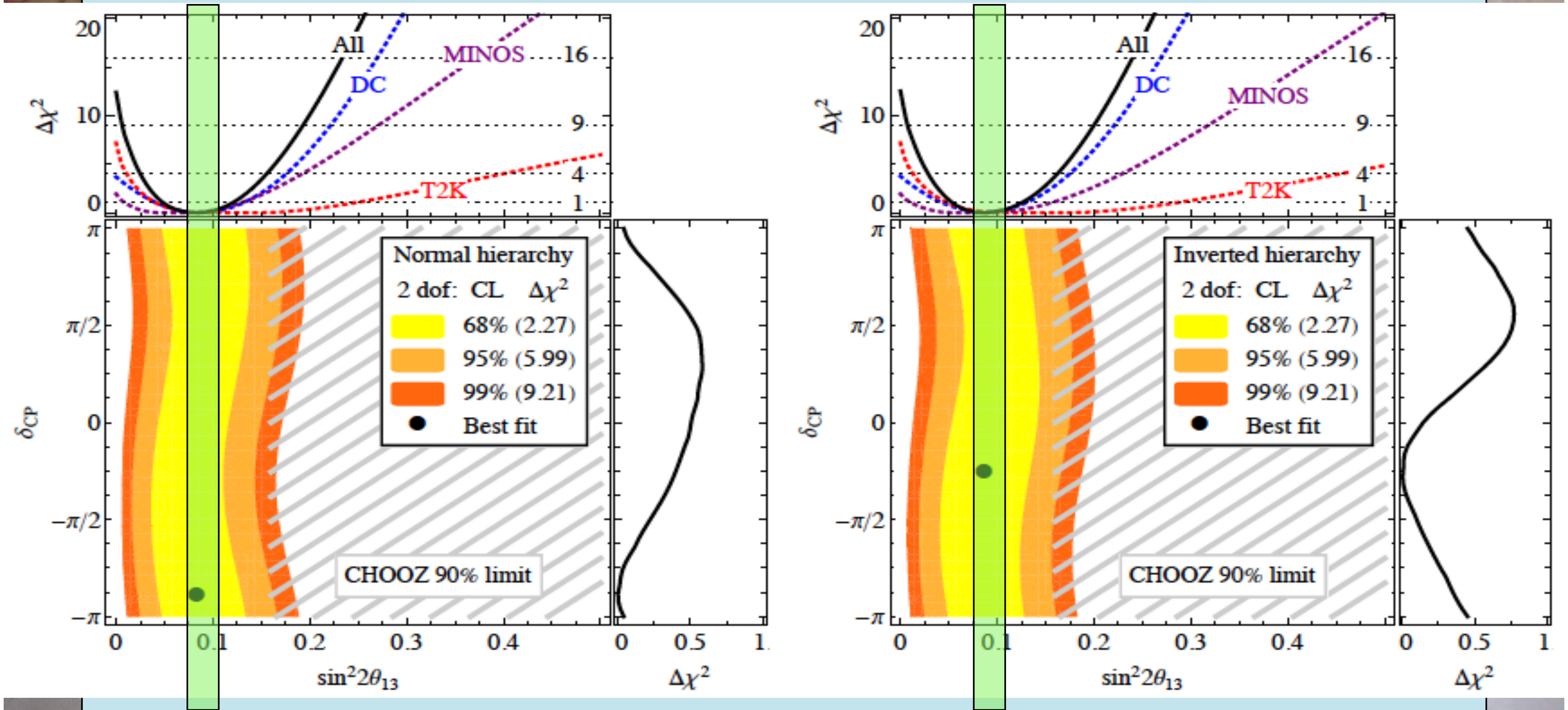
- MNS matrix has 3 real angles and 1 phase:

$$U_\nu = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13}e^{-i\delta} \end{pmatrix}$$

- **But that is not all!**

Update on θ_{13}

- Global fit to T2K, MINOS, Double Chooz



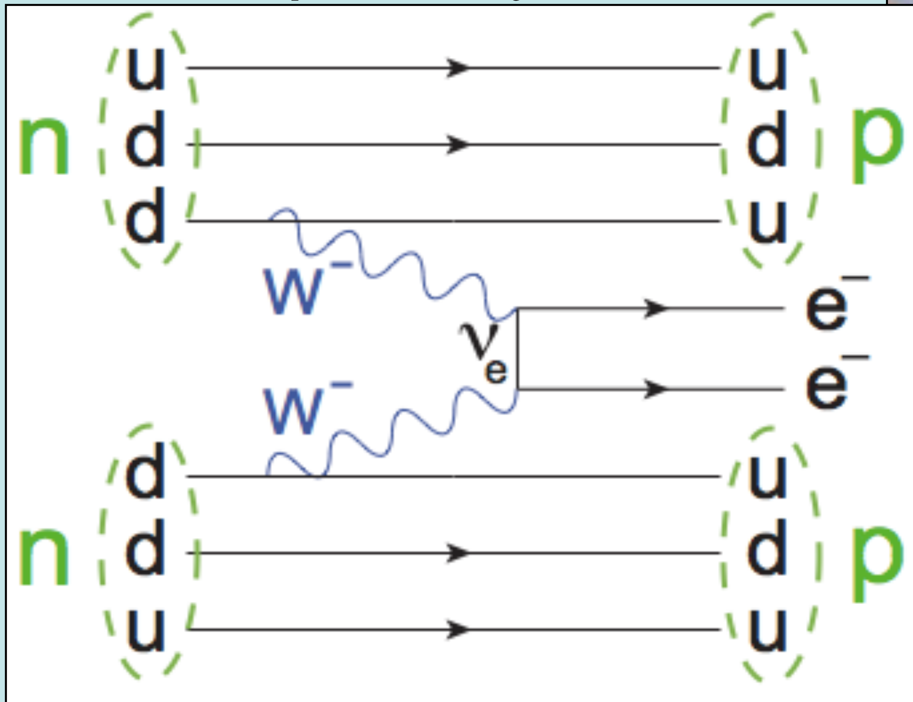
- New Daya Bay result superposed

Majorana Neutrino Masses?

- Search for neutrinoless double-β decay
- Rate given by weighted sum of Majorana ν masses:

$$\Gamma = \quad G|M|^2|m_{\beta\beta}|^2$$

$$m_{\beta\beta} = \sum_{i=1}^{3} m_i U_{ei}^2$$



- Experimental searches underway

Parameters in Minimal Seesaw Model

- Effective light-neutrino theory

$$-\mathcal{L}_\nu \supset (Y_\nu)_{ij}\, H \bar{N}_i \begin{pmatrix} \nu \\ L \end{pmatrix}_j + \frac{1}{2} \bar{N}_i \mathcal{M}_{ij} \bar{N}_j$$

- 3 Dirac masses, 3 angles, 3 CP-violating phases
- Additional 9 parameters associated with heavy singlet 'right-handed' neutrinos:

  3 Majorana masses, 3 more mixing angles,

  3 more CP-violating phases
- 12 contribute to leptogenesis, not MNS phase δ
- If supersymmetric, 16 parameters contribute to renormalization of soft susy-breaking m_0

Leptogenesis in Seesaw Model

- Asymmetry in decay of heavy neutrino, due to one-loop diagrams: $\epsilon_{ij} = \frac{1}{8\pi} \frac{1}{\left(Y_\nu Y_\nu^\dagger\right)_{ii}} \mathrm{Im}\left(\left(Y_\nu Y_\nu^\dagger\right)_{ij}\right)^2 f\left(\frac{M_j}{M_i}\right)$
- Possible in 2-generation seesaw model, with no δ
- Scenario for determining baryon asymmetry in supersymmetric seesaw model:

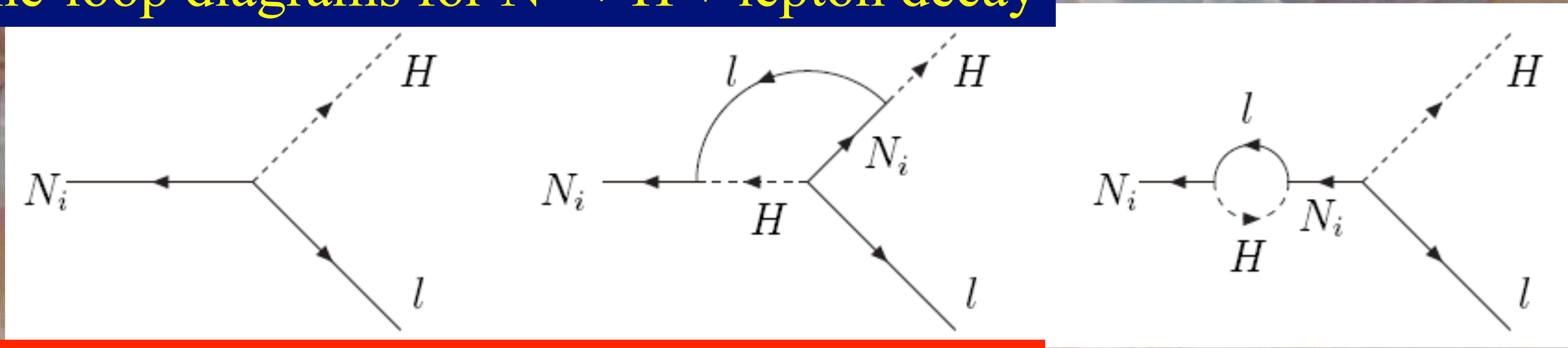
  Measure δ and low-E Majorana phases $\varphi_{1,2}$

  Measure susy renormalization effects

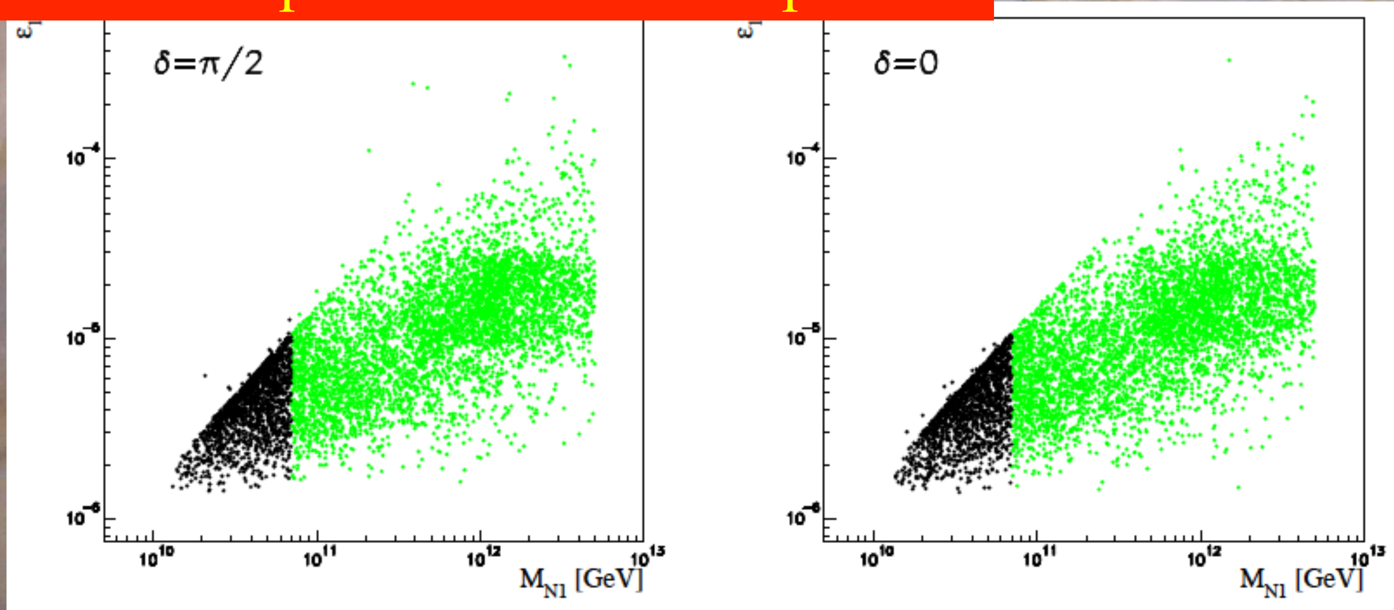
  Subtract contributions of δ, $\varphi_{1,2}$
- Remaining effect due to leptogenesis parameters

Leptogenesis independent of δ !

One-loop diagrams for N → H + lepton decay



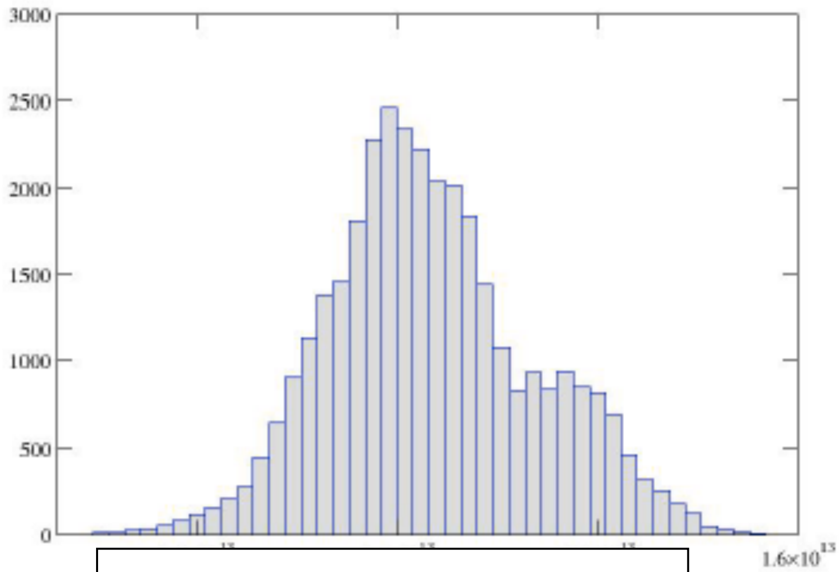
Result does not depend on oscillation phase δ



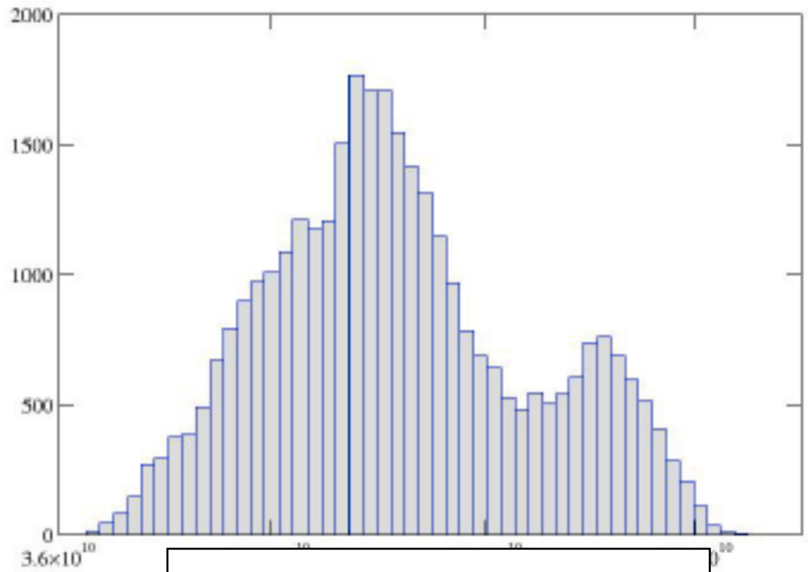
Leptogenesis with 2 Generations

- Two sneutrino species contributing to cosmological perturbations, baryon asymmetry
- Large mixing angle
- Sneutrino Masses

JE, Fairbairn & Sueiro



$M_1 \sim 1.4 \times 10^{13}$ GeV



$M_2 \sim 4 \times 10^{10}$ GeV

How to Measure Neutrino Parameters?

7 measurable:
$m_{1,2,3}$, θ_{12}, θ_{13}, θ_{23}, δ
not $\varphi_{1,2}$?

Seesaw mechanism
M_ν
9 effective parameters

$$(\delta m^2_{\tilde{L}})_{ij} \ni -\frac{1}{8\pi^2}\left(3m_0^2 + A_0^2\right)\left(Y_\nu^\dagger Y_\nu\right)_{ij} \mathrm{Ln}\left(\frac{M_{GUT}}{M}\right),$$

$$\epsilon_{ij} = \frac{1}{8\pi}\frac{1}{\left(Y_\nu Y_\nu^\dagger\right)_{ii}}\mathrm{Im}\left(\left(Y_\nu Y_\nu^\dagger\right)_{ij}\right)^2 f\left(\frac{M_j}{M_i}\right)$$

Y_ν , M_{N_i}
15+3 physical parameters

CP violation in decays of heavy neutrinos

Induces flavour-changing decays of charged leptons, CP violation

Leptogenesis
$Y_\nu Y_\nu^\dagger$, M_{N_i}
9+3 parameters

Renormalization
$Y_\nu^\dagger L Y_\nu$, M_{N_i}
13+3 parameters

Renormalization of Soft Supersymmetry-Breaking Parameters

- Flavour violation due to ν Yukawa couplings in minimal seesaw model:

$$\left(\delta m^2_{\tilde{L}}\right)_{ij} \approx -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(Y_\nu^\dagger Y_\nu + Y_e^\dagger Y_e)_{ij} \log\frac{M_{GUT}}{M_N}$$

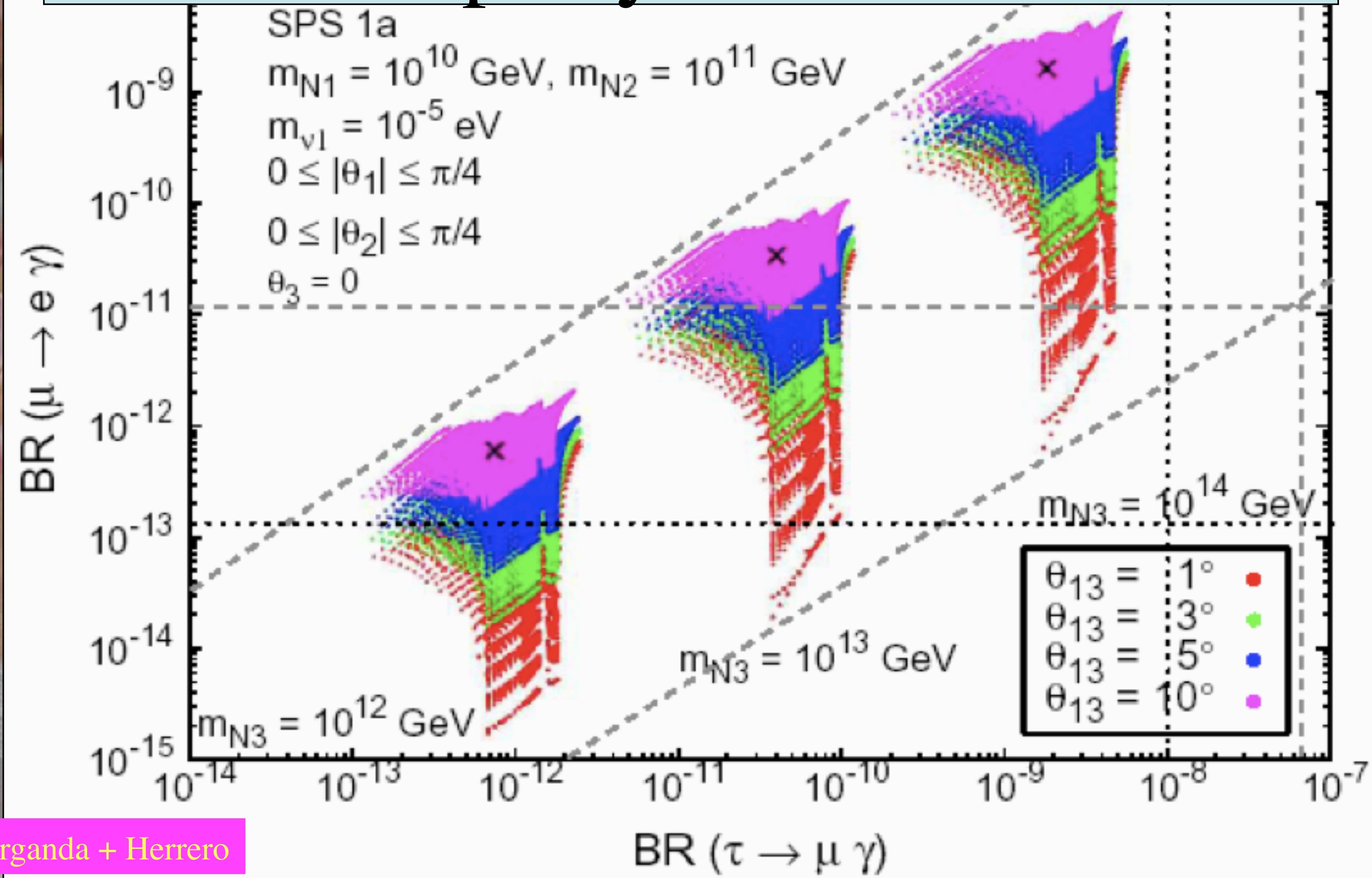
- Single ‘Jarlskog invariant’ for CP violation

$$J_{\tilde{L}} = \mathrm{Im}\left[\left(m^2_{\tilde{L}}\right)_{12}\left(m^2_{\tilde{L}}\right)_{23}\left(m^2_{\tilde{L}}\right)_{31}\right]$$

- More CP-violating invariants if heavy neutrinos non-degenerate

$$\left(\tilde{\delta} m^2_{\tilde{L}}\right)_{ij} \approx -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(Y_\nu^\dagger L Y_\nu)_{ij}. : L \equiv \log\frac{M_N}{M_{N_i}}\delta_{ij}$$

Flavour in the LHC Era: LFV in Supersymmetric Seesaw?



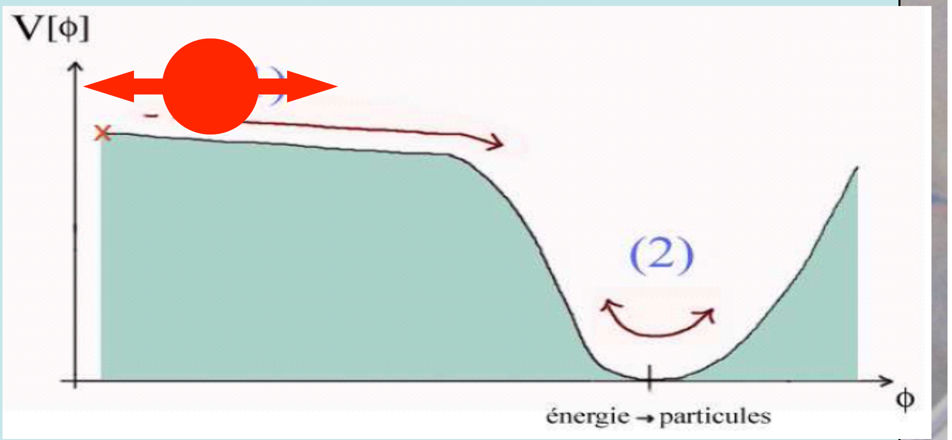
Arganda + Herrero

Cosmological Inflation

- Theory to explain the size, age & uniformity of the Universe
- Period of (near) exponential expansion driven by scalar field energy (1)
- Quantum effects →

  CMB anisotropies,

  origins of structures



- Subsequent reheating → matter (2)
- Then matter-antimatter asymmetry generated

Sneutrino Inflation?

- Supersymmetric partners of heavy singlet neutrinos have simple potential:

$$V = \tfrac{1}{2}\, m^2 \varphi^2$$

- Can be used to drive cosmological inflation if

$$m \sim 2 \times 10^{13}\ \text{GeV}$$

- Predictions for CMB observables:

  Scalar spectral index: $n_s = 0.96$

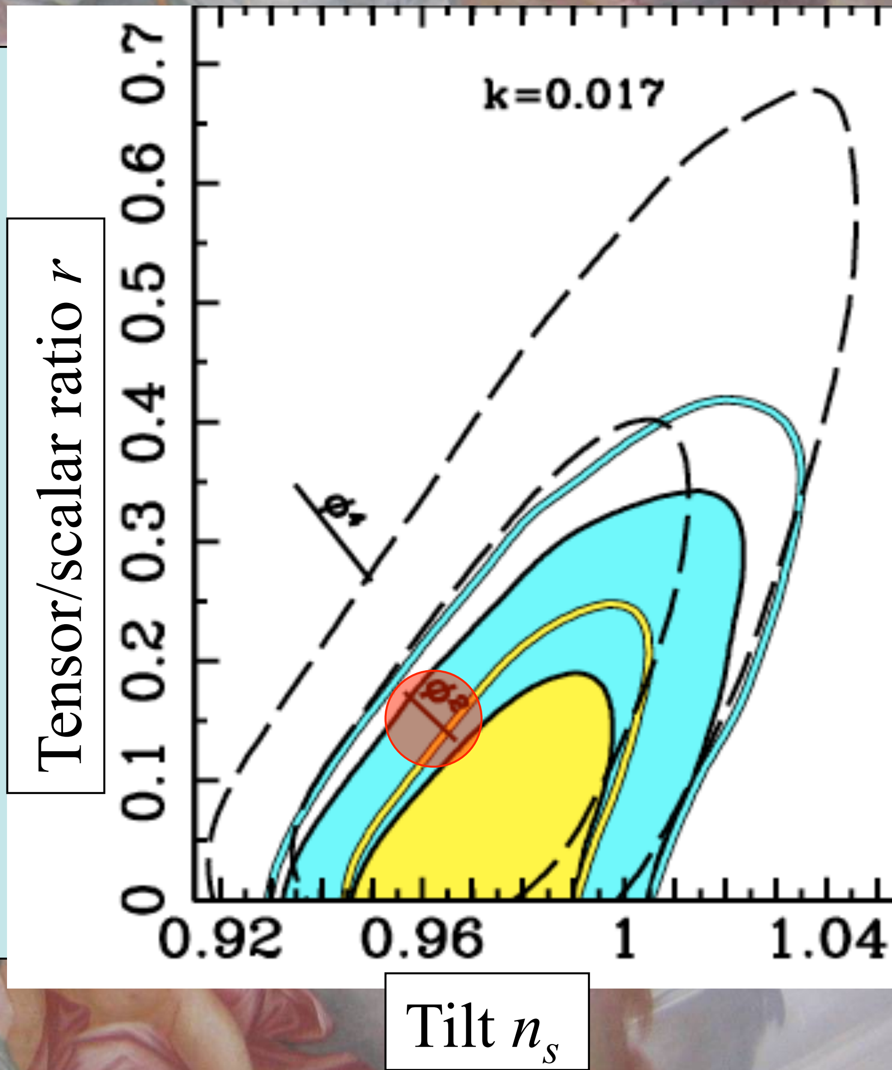
  Tensor/scalar ratio: $r = 0.16$

- Leptogenesis in sneutrino inflaton decay

JE + Raidal + Yanagida

Tests of Sneutrino Inflation

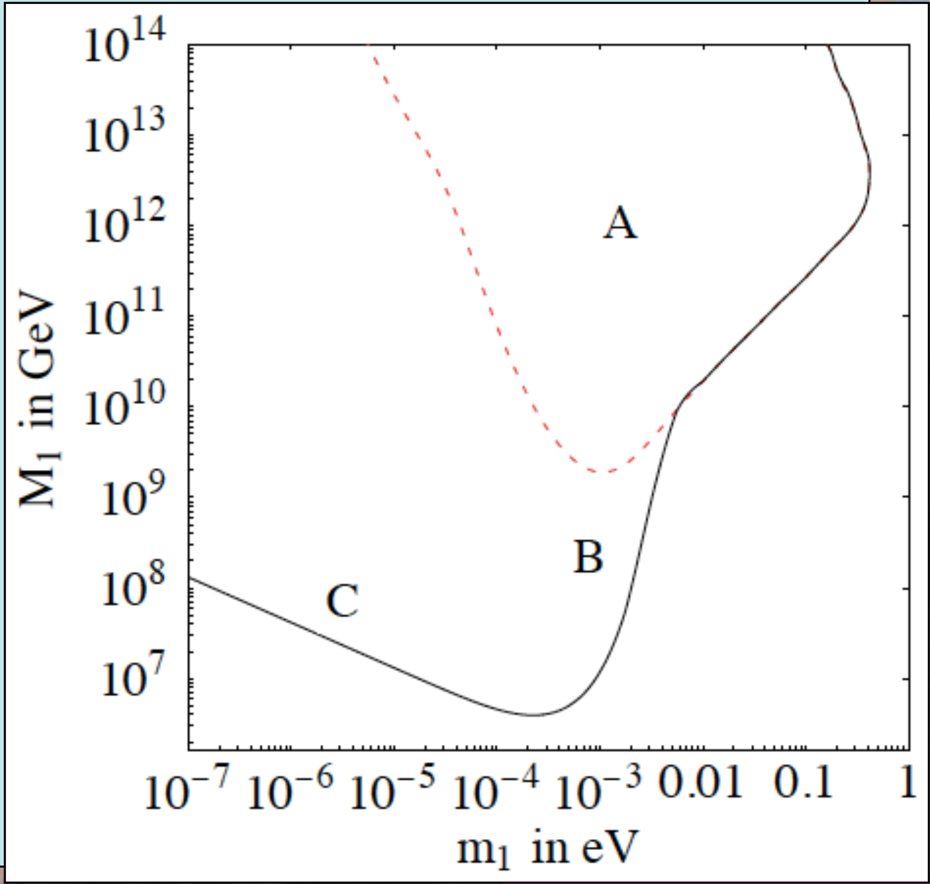
- Consistent with measurements of tilt n_s in spectrum of adiabatic fluctuations
- Predicts tensor perturbations close to present upper limit
- Expect definitive test from Planck satellite



Allowed Regions for Leptogenesis

- May be thermal: region A, or non-thermal: region C
- Reheating temperature after inflation could be small ~ 10^6 GeV
- Needed in some supersymmetric models
- Constraints on couplings

$$\tilde{m}_1 = (Y_\nu Y_\nu^\dagger)_{11} v^2 \sin^2\beta / M_{N_1}$$



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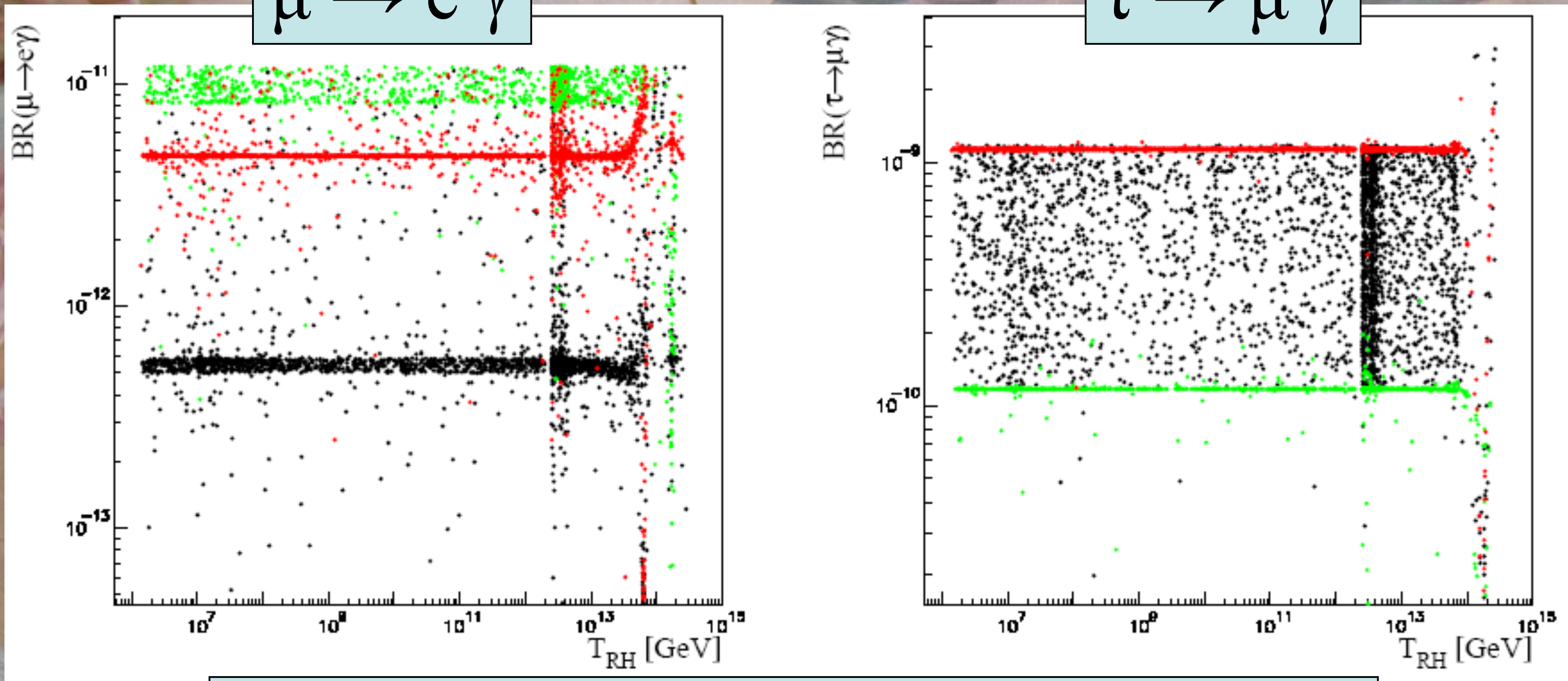
Flavour-Changing Charged-Lepton Decays

$\mu \rightarrow e\,\gamma$ | $\tau \rightarrow \mu\,\gamma$



Close to present experimental limits

JE + Raidal + Yanagida

Outlook

- Sakharov mechanism for baryogenesis promising in general
- No concrete evidence for any specific scenario
- Not possible within Standard Model
- Tough to realize at electroweak scale
  - Possibilities in some extensions of Standard Model
- Leptogenesis a promising possibility
  - May be linked to other cosmological observables