Baryogenesis, Leptogenesis and Lepton Flavor Violation

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- Status: Evidence for the baryon asymmetry
- Requisites: Sakharov conditions for baryogenesis
- Realization: Particle physics scenarios
- Focus: Leptogenesis and the seesaw mechanism
- Work out: LFV and the seesaw mechanism

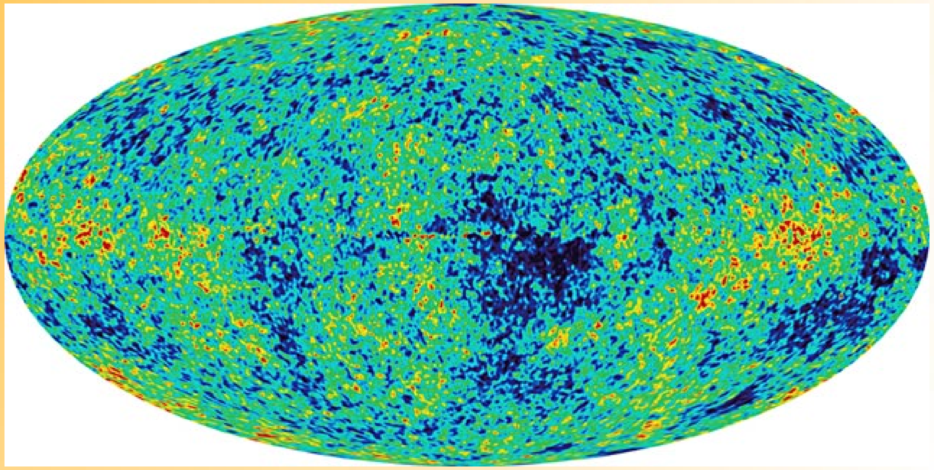
Observation: there are more baryons than anti-baryons in the universe

- Spectrum of anti-protons in cosmic radiation (BESS/balloon in 35 km altitude) consistent with generation from cosmic primaries

- no anti-nuclei found in cosmic radiation (AMS spectrometer/Discovery)

Evidence for the baryon asymmetry

- no aniihilation radiation detected in the local galaxy cluster



- no distortion of cosmic microwave background from particle-anti-particle annihilation in the observable universe

big bang nucleosynthesis:
$\sim 0.1 - 180s$ after big bang

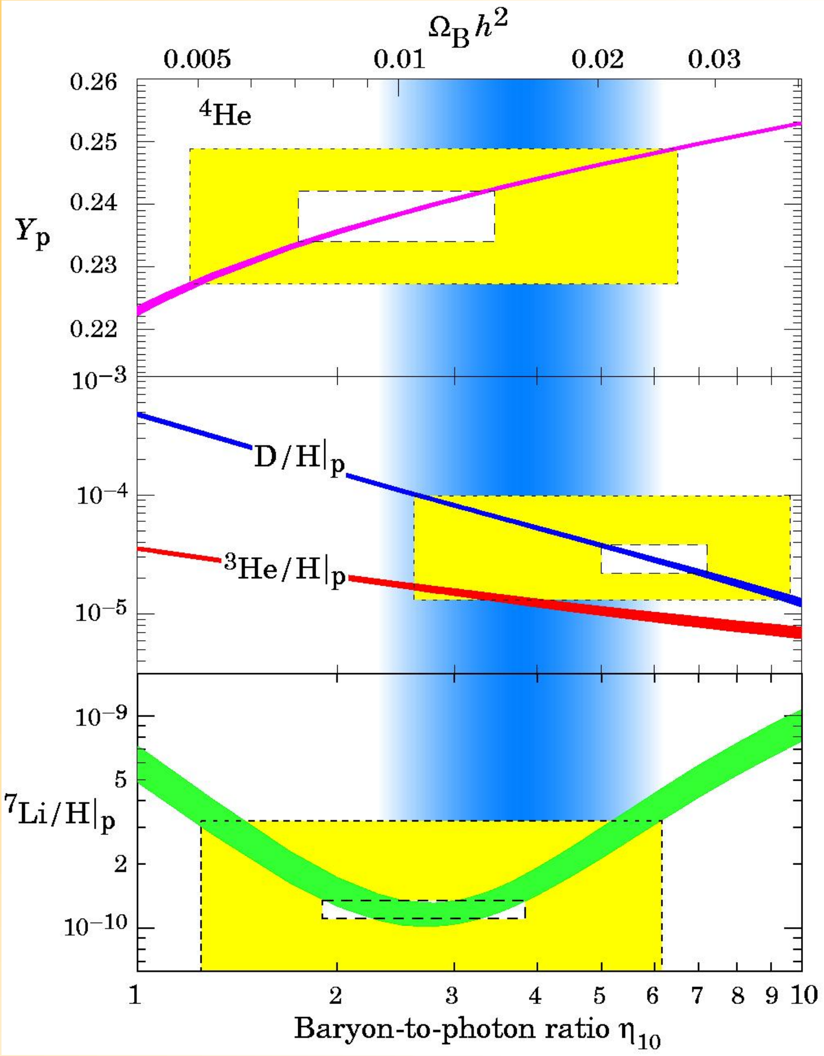
Synthesis $p, n \to D,^3He,^4He,^7Li$ dissociated by collisions with high-energetic γ's

$\Rightarrow$ sensitive to:

$$\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

Search for $\mathrm{D},^3He,^4He,^7Li$ in gas clouds and stars with small metallicity

$\Rightarrow$ $2.6 \cdot 10^{-10} < \eta_B < 6.2 \cdot 10^{-10}$

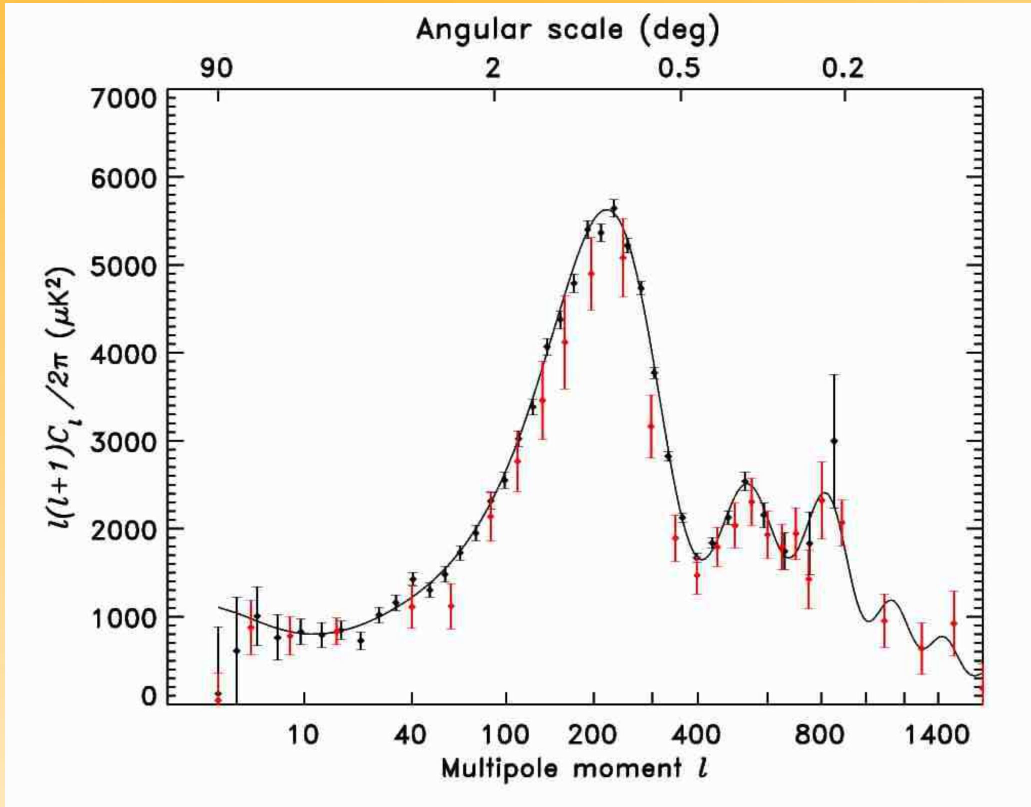


S. Sarkar, astro-ph/0205116

Anisotropies in the CMB:

Atomic synthesis $\sim 380000y$ after big bang

D.N. Spergel, Astrophys. J. Suppl. 148 (2003) 175



Acustic oscillations in the early universe

Comparison 1st peak
(fundamental wave: gravity $\Rightarrow$ / $\Rightarrow$ gas pressure)

to 2nd peak
(overtone: gravity $\Leftrightarrow$ gas pressure)

$\Rightarrow$ Ratio baryons (gravity + gas pressure)/ cold dark matter (gravity)

$\Rightarrow$ Ratio ρ_B/ $\rho_\gamma \simeq 1$

$\Rightarrow$ $$\eta_B = 6.1^{+0.3}_{-0.2} \cdot 10^{-10}$$

Baryon asymmetry as initial condition?

Possibility: $\eta_B = 6 \cdot 10^{-10}$ as initial condition?

Inflationary epoch:

$$ds^2 = dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right)$$

$$\boxed{R(t) \propto \exp(\sqrt{\Lambda/3}t)}$$

- $\rho_\Lambda = \Lambda/8\pi G$: Vacuum energy of inflaton field
- $\Rightarrow$ flat, homogenous und empty universe!
- $\Rightarrow$ end of inflation: decay of inflaton field into thermal plasma
- $\Rightarrow$ particles and anti-particles in equal abundances
- $\Rightarrow$ Necessity of baryogenesis after inflationary epoch

Sakharov-Bedingungen for baryogenesis

- Baryon number violation:
  Interactions, which generate or annihilate B
- Non-Equilibrium:
  $\Gamma(i(\vec{p}_i,\vec{s}_i) \to f(\vec{p}_f,\vec{s}_f)) \neq \Gamma(f(\vec{p}_f,\vec{s}_f) \to i(\vec{p}_i,\vec{s}_i))$
  $\Rightarrow$ arrow of time
- C violation:
  $\Gamma(i(\vec{p}_i,\vec{s}_i) \to f(\vec{p}_f,\vec{s}_f)) \neq \Gamma(\bar{i}(\vec{p}_i,\vec{s}_i) \to \bar{f}(\vec{p}_f,\vec{s}_f))$
  $\Rightarrow$ different process rates for particles and anti-particles
- CP violation:
  $\Gamma(i(\vec{p}_i,\vec{s}_i) \to f(\vec{p}_f,\vec{s}_f)) \neq \Gamma(\bar{i}(-\vec{p}_i,\vec{s}_i) \to \bar{f}(-\vec{p}_f,\vec{s}_f))$
  $\Rightarrow$ different process rates for particles and anti-particles of different parities

A.D. Sakharov, 1967; V.A. Kuzmin, 1970

How can the

Sakharov conditions

be realized in a

particle physics model?

Baryon number violation?

1st Model: GUT Baryogenesis

Standard Model

Quarks

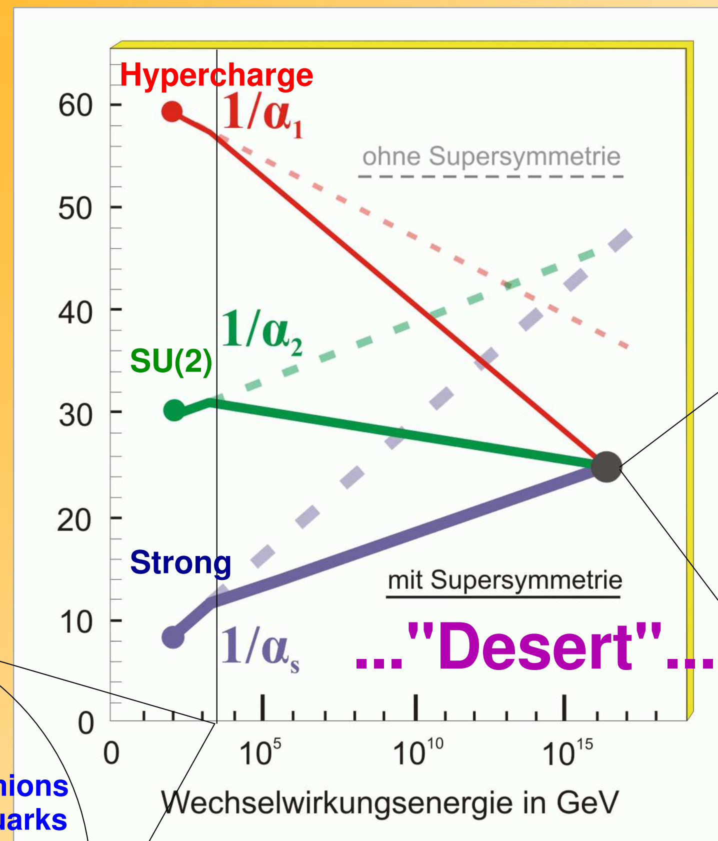
$\begin{pmatrix}u\\d\end{pmatrix}_L \begin{pmatrix}c\\s\end{pmatrix}_L \begin{pmatrix}t\\b\end{pmatrix}_L$

$u_R, d_R, c_R, s_R, t_R, b_R$

Leptons

e_R, μ_R, τ_R

$\begin{pmatrix}\nu\\e\end{pmatrix}_L \begin{pmatrix}\nu\\\mu\end{pmatrix}_L \begin{pmatrix}\nu\\\tau\end{pmatrix}_L$



Grand Unified Theory

quarks and leptons in the same multiplet

Unification of forces

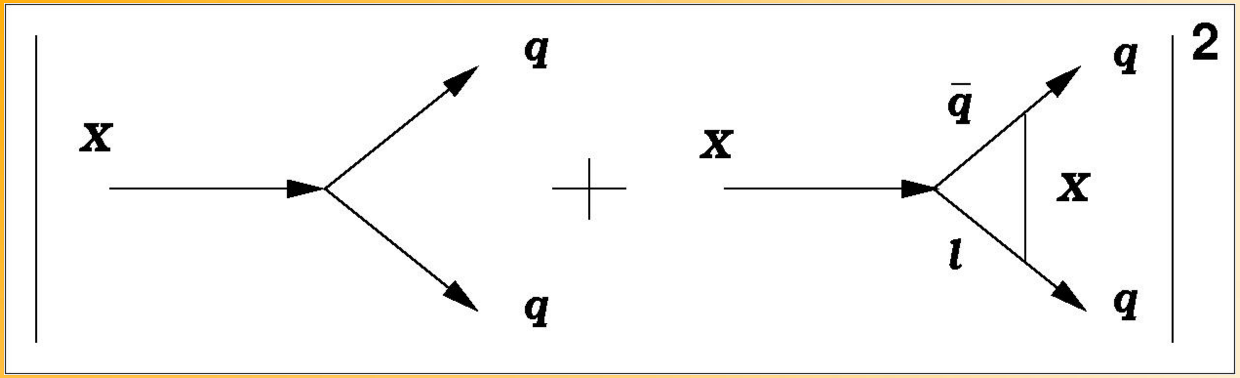
Right handed neutrinos?

Supersymmetry

symmetry: bosons <–> fermions
quarks <–> (scalar) squarks
leptons <–> (scalar) sleptons
bosons <–> (s=1/2) bosinos

benefits: coupling unification
cancels divergencies
dark matter candidate
necessary for gravity

1st Model: GUT Baryogenesis



- Baryon number violationen: GUT multiplet
- Non-equilibrium decay of heavy X-bosons for $M_X > T_{\text{universe}}$
- CP-violation: $\Gamma(X \to qq) > \Gamma(\overline{X} \to \overline{qq})$
- Problem: thermal generation of X bosons with $m_X \sim M_{GUT}$ $\to$ high reheating temperature after inflation $T_{reh} \sim M_{GUT} \simeq 10^{16}$ GeV $\to$ powerful generation of weakly interacting superpartners (gravitinos) in SUSY scenarios $\to$ decay products prevent successful BBN

Ingnatiev, Krasnikov, Kuzmin, Tavkhelidze, 1978; Yoshimura, Weinberg, 1979

2nd Model: Elektroweak baryogenesis

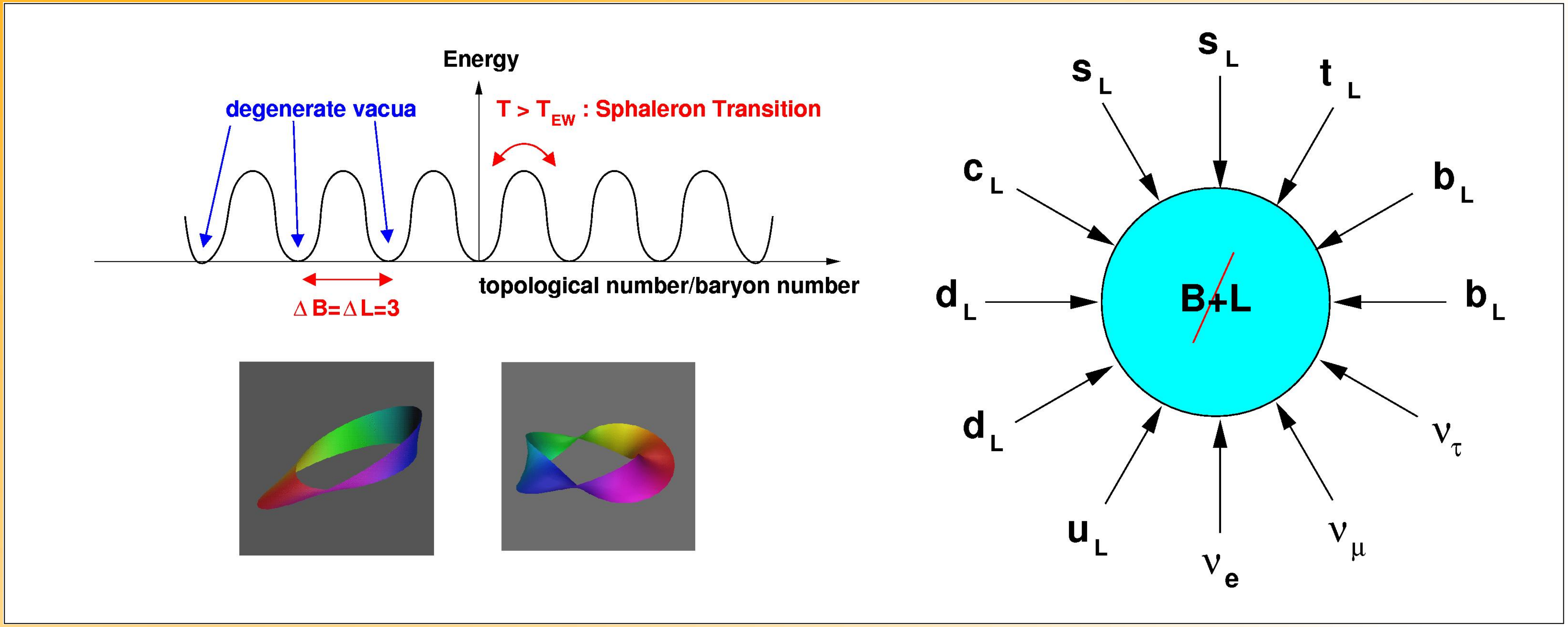
Baryon number violation

already

in the

Standard Model?

Sphalerons: B violation in the Standard Model

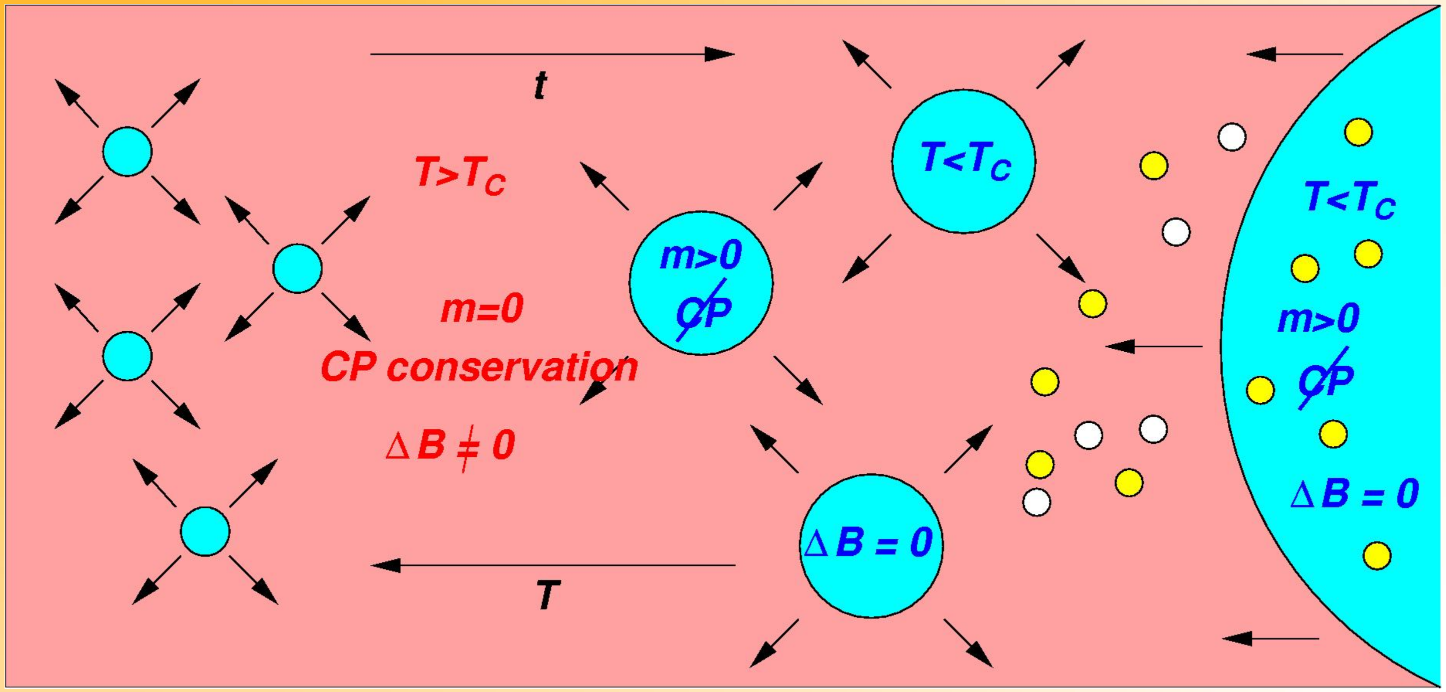


Topologically different field configurations $\Rightarrow$ degenrated vacua with different baryon numbers t'Hooft 1976

$T > T_{EW} \Rightarrow$ Transitions between vacua, Baryon number violation

Kuzmin, Rubakov, Shaposhnikov, 1985

Electroweak phase transition $\sim 10^{-10}$ s after big bang
Condensation of the Higgs field: $\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = v(T < T_c)$
$\Rightarrow$ Mass generation, CP violation
Non-equilibrium: analogy water-steam transition



Requirement: 1st order transition $\Leftrightarrow$ competing ground states
dependent of Higgs potential $\Rightarrow$ depending on Higgs self interaction
$\lambda \Rightarrow m_H = v(T=0)\sqrt{2\lambda} < 70$ GeV
$m_H > 114$ GeV bei LEP too small!

Combination of

Non-equilibrium decay

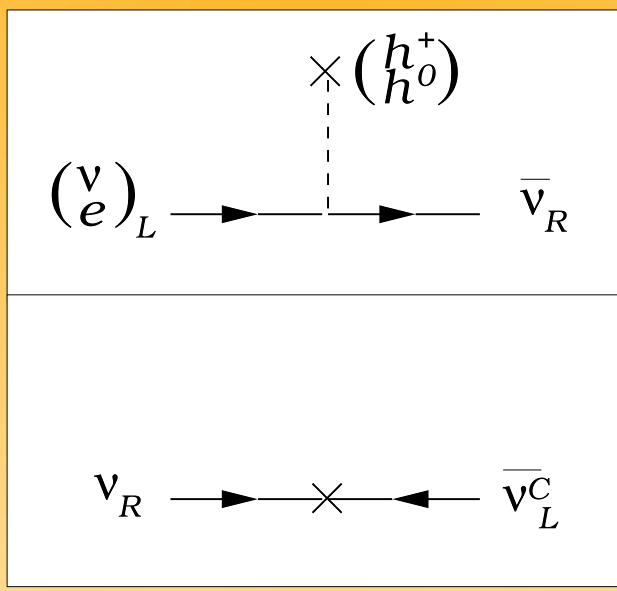
and

baryogenesis at low energies?

3rd Modell: Leptogenesis

Neutrino mass generation in the seesaw mechanism

Motivation: $m_\nu \ll m_{u,d,e}$, Standard Model: $m_\nu \equiv 0$, since no right-handed neutrino



Assumption: $\exists$ right-handed neutrino N_R:
“Normal” Dirac mass term $m^D \overline{\nu_L} N_R$

However: N_R is a SM singlet!
$\Rightarrow$ Majorana mass term $\overline{N}_R M^R (N_R)^C$, $M_R \gg m_D$

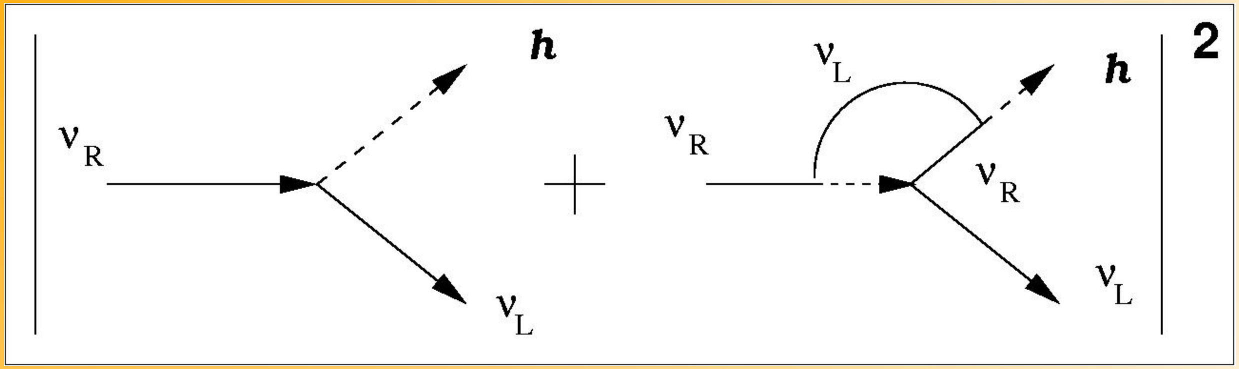
E. Majorana 1937

$$m^{\mathrm{D+M}} \equiv \overline{\begin{pmatrix} \nu_L^c \\ (N_R) \end{pmatrix}} \begin{pmatrix} 0 & m^{\mathrm{D}} \\ m^{\mathrm{D}} & M^R \end{pmatrix} \begin{pmatrix} \nu_L \\ (N_R)^c \end{pmatrix}$$

$$m^D \ll m^R \Rightarrow m_{\mathrm{light}} \simeq -(m^D)^2/M^R \ll m^D$$

$\Rightarrow$ $\exists$ right-handed Neutrino N_R with L violating mass $M_R \sim 10^{14}$ GeV

N_R decays in the early universe



- Non-equilibrium decay of heavy neutrinos for $M_R > T_{\text{universe}}$
- CP violation

$$\Gamma(N_R \to \bar{h} + \bar{\nu_L}) > \Gamma(N_R \to h + \nu_L)$$

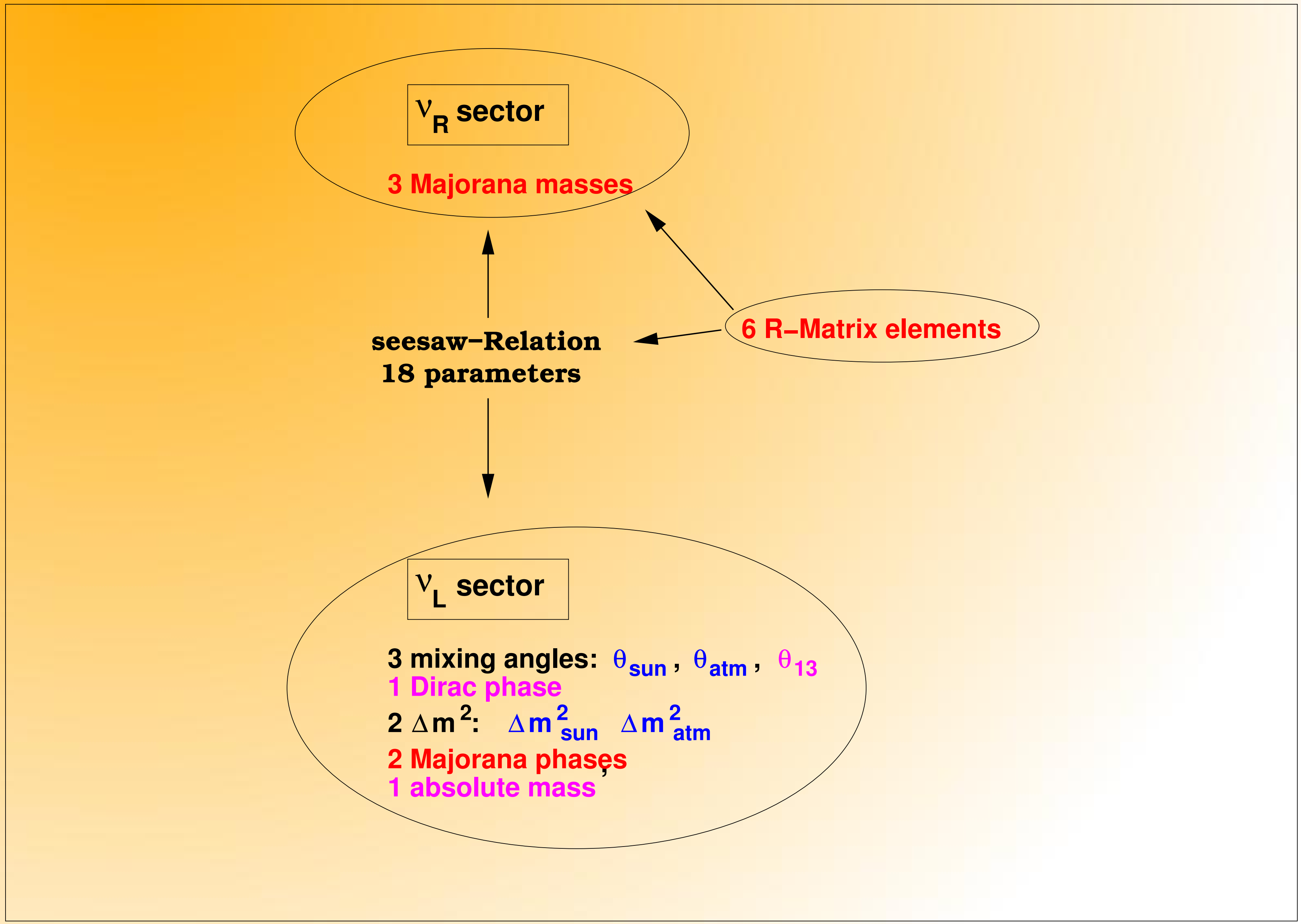
$\Rightarrow$ L-violation

- B-violation: L-violation + $B + L$ violating sphaleron processes $\to$ B violation

$\Rightarrow$ Relations to neutrino physics + lepton flavor violation!

Fukugita, Yanagida, 1986

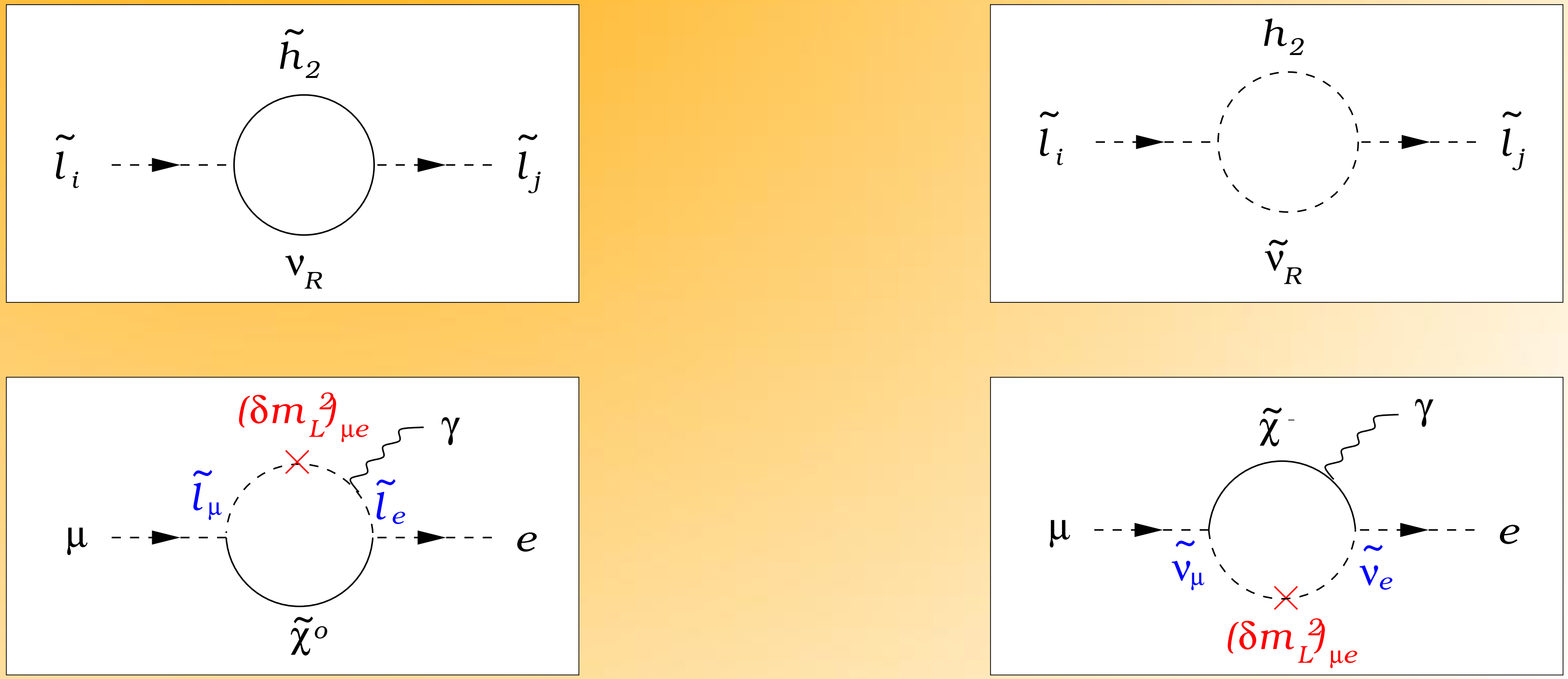
3rd Modell: Leptogenesis



Inverting the seesaw matrix: $Y_\nu^\dagger Y_\nu \propto (m^D)^2 \propto M_R$ ($\sim M_3$)

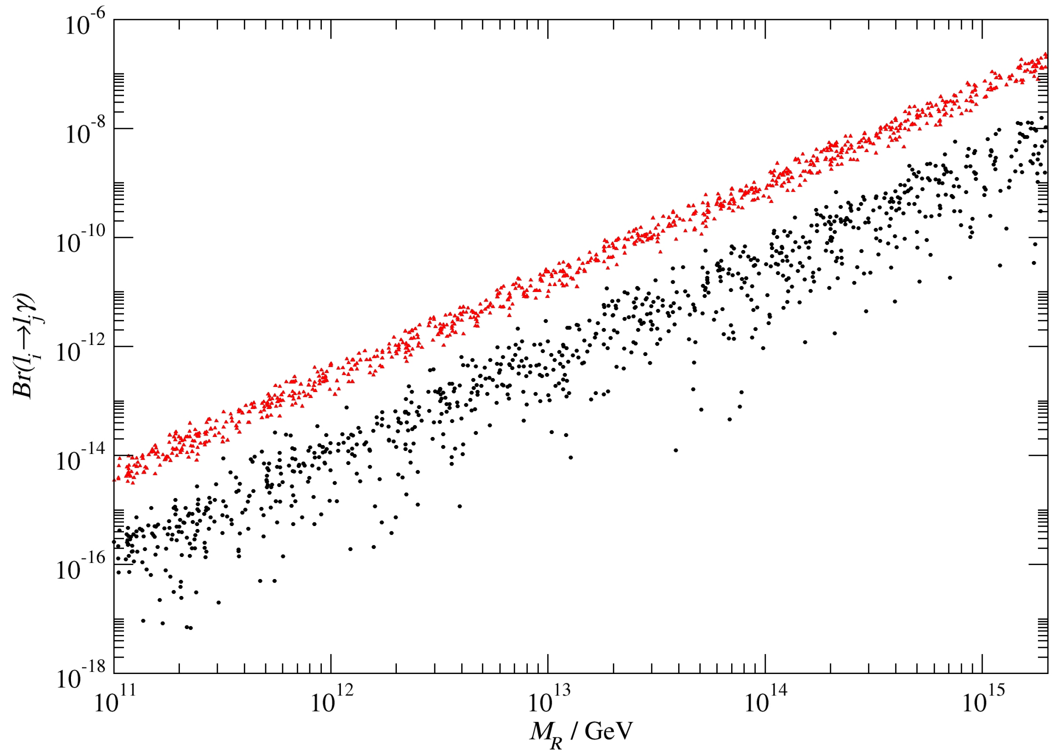
$\Rightarrow$ Look for processes $\propto Y_\nu^\dagger Y_\nu$

$\Rightarrow$ Lepton Flavor violating corrections to slepton masses!



$Br(\mu \to e\gamma)$ and $Br(\tau \to \mu\gamma)$

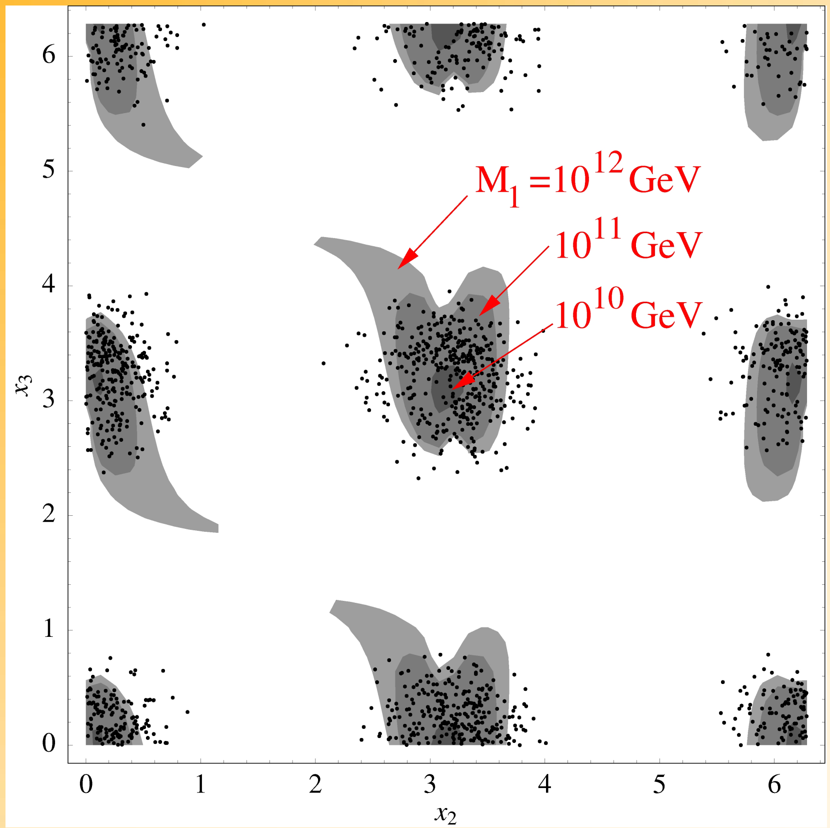
SUSY scenario SPS1, $m_1 < 0.03$ eV



PDG: $Br(\mu \to e\gamma) < 1.2 \cdot 10^{-11}$ $(90\% C.L.) \Rightarrow M_R < 10^{14} - 10^{15}$ GeV
$Br(\tau \to \mu\gamma) < 10^{-8}$ $(90\% C.L.)$: determination accuracy factor 2!

F. Deppisch, H. Päs, A. Redelbach, R. Rückl, Y. Shimizu, Eur.Phys.J. C28 (2003) 365-374

mSUGRA problem: overabundance of gravitinos for $T_R > 10^{10}$ GeV ($m_{3/2} \simeq 1$ TeV)
$\Rightarrow M_1 < 10 T_R < 10^{11}$ GeV $\Rightarrow x_{2,3} \simeq 0,\ \pi,\ 2\pi$



Contours: $y_i = 0.1$, best fit ν_L

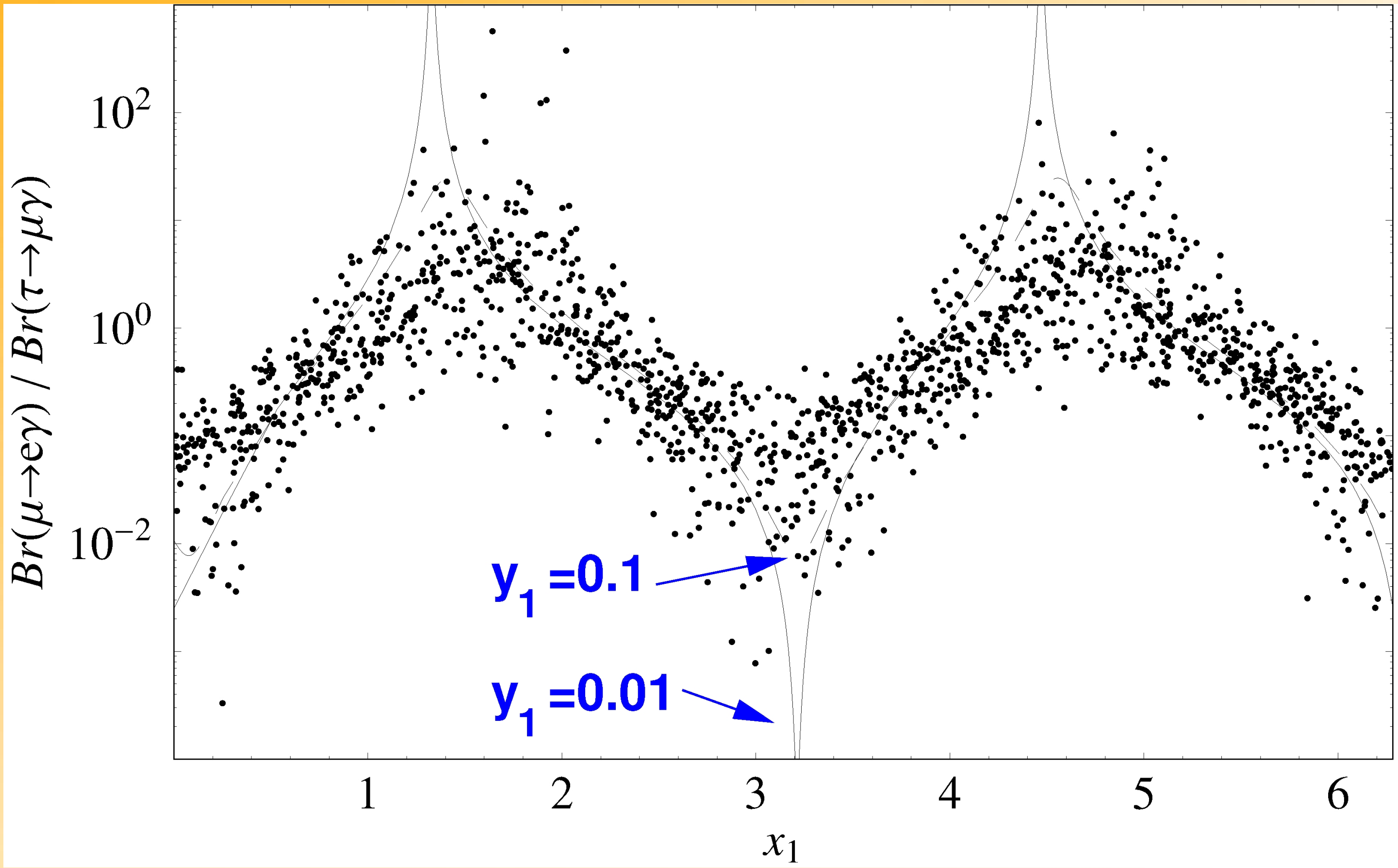
F. Deppisch, H. Päs, A. Redelbach, R. Rückl, in preparation

$Br(\mu \to e\gamma / Br(\tau \to \mu\gamma$ and x_1

Strong variation of $Br(\mu \to e\gamma)/Br(\tau \to \mu\gamma)$ with x_1

SuperB: $Br(\tau \to \mu\gamma) \simeq 10^8$

$\Rightarrow$ Sensitivity: $Br(\mu \to e\gamma)/Br(\tau \to \mu\gamma) < \mathcal{O}10^{-3}$



F. Deppisch, H. Päs, A. Redelbach, R. Rückl, in preparation

Conclusions

- Cosmological evidence for baryon asymmetry
- Inflation destroys initial asymmetry
- Sakharov conditions: B violation, C- and CP violation, thermal Non-equilibrium
- GUT baryogenesis: overproduction of gravitinos
- Elektroweak baryogenesis: Phase transition too weak
- Leptogenesis: decays of heavy neutrino $\Rightarrow L$ violation $\Rightarrow B$ violation
  - Seesaw mechanism: 18 parameters
  - $\Rightarrow$ Neutrino mass constraints
  - $\Rightarrow$ Lepton flavor violations of charged leptons: $\tau \to \mu\gamma$
  - $\Rightarrow$ constraints on right-handed neutrino masses
  - Seesaw benchmark model, learn GUT scale physics!

Martin Heidegger: "Das Nichts nichtet (the nothing noths)"

CP-Verletzung und komplexe Phasen

Massenbasis: $(d, s, b)^T$
Wechselwirkungsbasis: $(d', s', b')^T$
Unitäre Transformation: $(d, s, b)^T = U(d', s', b')^T$
U: Mischungsmatrix
Quarkstrom: $J^\mu = (\overline{u}, \overline{c}, \overline{t})\mathcal{O}U(d, s, b)^T$

Amplitude für Prozess($ab \to cd$):
$\mathcal{M} \sim J^\mu_{ca} J^\dagger_{\mu bd} \sim U_{ca} U^*_{bd} (\overline{u}_c \mathcal{O} u_a)(\overline{u}_d \mathcal{O} u_b)^\dagger$

Amplitude für CP-gespiegelten Prozess:
$\mathcal{M}^{CP} \sim CP(J^\mu_{ca}) CP(J^\dagger_{\mu bd}) \sim U_{ca} U^*_{bd} (\overline{u}_a \mathcal{O} u_c)(\overline{u}_b \mathcal{O} u_d)^\dagger$

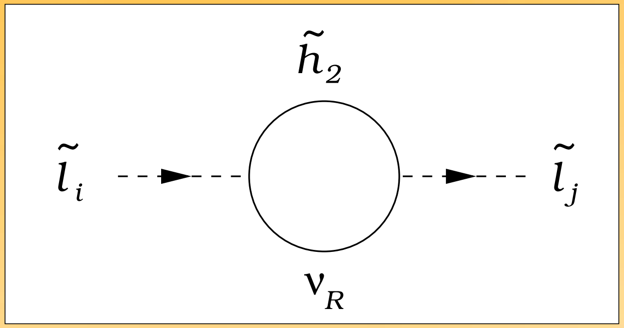
Beobachtung: $\mathcal{M}^{CP} = \mathcal{M}^\dagger \Leftrightarrow U$ reell

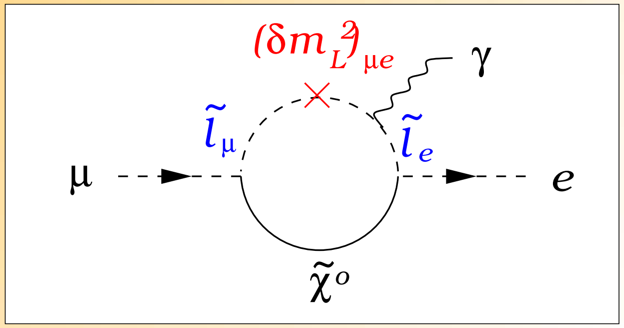
$\Rightarrow CP$-Verletzung $\Leftrightarrow$ komplexe Phasen in Kopplungen $\Rightarrow CP$-Verletzung erfordert nichtverschwindende Massen!

- Affleck-Dine Baryogenese: Skalare Superpartner von Baryonen erhalten VEVs
  Supersymmetrie: flache Richtungen im Potential
- Baryogenese an topologischen Defekten
- Baryogenese in schwarzen Löchern
  Schwarze Löcher sind vollständig durch Masse, Ladung, Drehimpuls beschrieben (“No-hair”)
  $\Rightarrow$ Quantengravitation verletzt alle globalen Symmetrien B, L
- Sneutrino ist das Inflaton: Nichtthermische Leptogenese im Inflatonzerfall
  Neutrinophysik $\Leftrightarrow$ Inflation

Beziehungen zur Neutrinophysik

- Niedrige Reheatingtemperatur $\Rightarrow$ kleine M_R-Masse
  Davidson, Ibarra, 2002
- CP-Verletzung in Neutrinooszillationen $\Rightarrow$ Neutrino Factories und Superbeams
- Lepton Flavor Verletzung in Prozessen mit geladenen Leptonen (seltene Zerfälle, Beschleuniger)





Borzumati, Masiero, 1986; Casas, Ibarra, 2001

- Washout für zu große Leptonenzahlverletzung: Grenze auf die Neutrinomasse im minimalen Modell $m_\nu \lesssim 0.1$ eV
  Buchmüller, di Bari, Plümacher, 2002