

Lepton-Flavour Violation

Charged in the context of the seesaw model
+ supersymmetry

1 - Introduction

to LFV and the seesaw

2 - Renormalization of soft susy X
heavy neutrinos \rightarrow electroweak scale

3 - Examples of LFV + CPX

$\mu \rightarrow e\gamma$, $\tau \rightarrow \mu e \gamma$ lepton edm's, ...

sphaleron decays

GUT-induced effects in B decays?

4 - Relation to leptogenesis

indirect ...

5 - sneutrino inflation?

consistent with WMAP

constraints parameters $\mu \rightarrow e\gamma$ "soon"?

- Lepton-Flavour Violation

Generic GUT Seesaw Model

↑
no new gauge int^{us} needed

$$(\nu_L, \nu_0) \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_0 \end{pmatrix}$$

Dirac mass = $O(m_q, m_l)$
singlet ✓
Majorana mass

diagonalization:

$$m_\nu = m_D \frac{1}{M_M} m_D^T \quad \ll m_{q,l} \text{ if } M_M \gg m_W$$

each mass matrix in flavor space

flavor diagonalization:

$$V_{MNS} = V_L V_L^+ \quad \text{diagonalize } L_L \quad \nu_L \leftarrow m_D \frac{1}{M_M} m_D^T$$

different structure from quark mixing

$$V_{CKM} = V_d V_u^+ \leftarrow m_q$$

✓ mixing might be very different from q

$V(l)$ models? $\begin{pmatrix} e^m & e^q & e^b \\ e^{q'} & e^r & e^s \\ e^p & e^s' & e^t \end{pmatrix}$ GUTs? extra dimensions?
non-Abelian flavor symmetry?

2.2 - Neutrino Oscillations

Neutrino Mixing Matrix

Maki+Nakagawa+Sakata

$$\begin{aligned}
 U_{\text{MNS}} &= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \xrightarrow{\text{charged lepton flavors}} \begin{matrix} \text{mass eigenstates} \\ \xrightarrow{\text{CPX}} \end{matrix} \\
 &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13} e^{i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \xrightarrow{\text{CPX}} \begin{matrix} \text{solar } \nu \text{ oscillations} \\ \text{atmospheric } \nu \text{ oscillations for the future} \end{matrix}
 \end{aligned}$$

measurable in double- β decay

+ 2 Majorana phases

$$\begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

CP-Violating Observable

$$P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$$

$$= 16 S_{12} C_{12} S_{13} C_{13}^2 S_{23} C_{23} \sin S$$

$$\times \sin\left(\frac{\Delta m_{12}^2}{4E}L\right) \sin\left(\frac{\Delta m_{31}^2}{4E}L\right) \sin\left(\frac{\Delta m_{23}^2}{4E}L\right)$$

possible **only if**

Δm_{12}^2 , S_{12} large enough: LMA \leftarrow established

θ_{13} large enough \nwarrow

we need to know!

Windows on leptogenesis?

Heavy Singlet Neutrino Mass Scale?

basic seesaw mass formula:

$$m_\nu = \frac{m_D^2}{m_M} \quad \text{cf } m_a, m_c$$

$\sim 10^{-2} \text{ eV} = 10^{11} \text{ GeV}$?

$\sim (10 \text{ GeV})^2$?

from oscillation data

⇒ heavy neutrino mass

$$m_M \sim 10^{13} \text{ GeV}$$

± few orders of magnitude

comparable to GUT scale?

do not need new gauge interactions ...

Beyond the Neutrino Sector

Parameter Counting in Seesaw Model

$$\mathcal{L}_\nu = (\nu)_{ij}^H \bar{N}_i (\nu)_j + \frac{1}{2} \bar{N}_i M_{ij} \bar{N}_j$$

physical parameters = 18

$$3m_\nu + (\delta, \phi_1, \phi_2) + \Theta_{12, 23, 13} + 3M_\nu + \underbrace{3\alpha_H + 3\beta_H}_{\text{matrix } R}$$

$\underbrace{\qquad\qquad\qquad}_{CP \times} \qquad \underbrace{\qquad\qquad\qquad}_{CP \times}$

9 'observable' @ low energies 9 heavy sector
 4 'known'
 + renormalization
 of susy x

Total of 6 CP-violating parameters

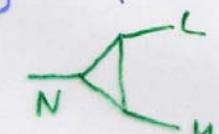
MNS phase + 2 Majorana phases \leftarrow P.P. or

3 extra phases control leptogenesis

Origin of baryon asymmetry?

$$\Gamma(N \rightarrow L + H) \neq \Gamma(N \rightarrow \bar{L} + H) ?$$

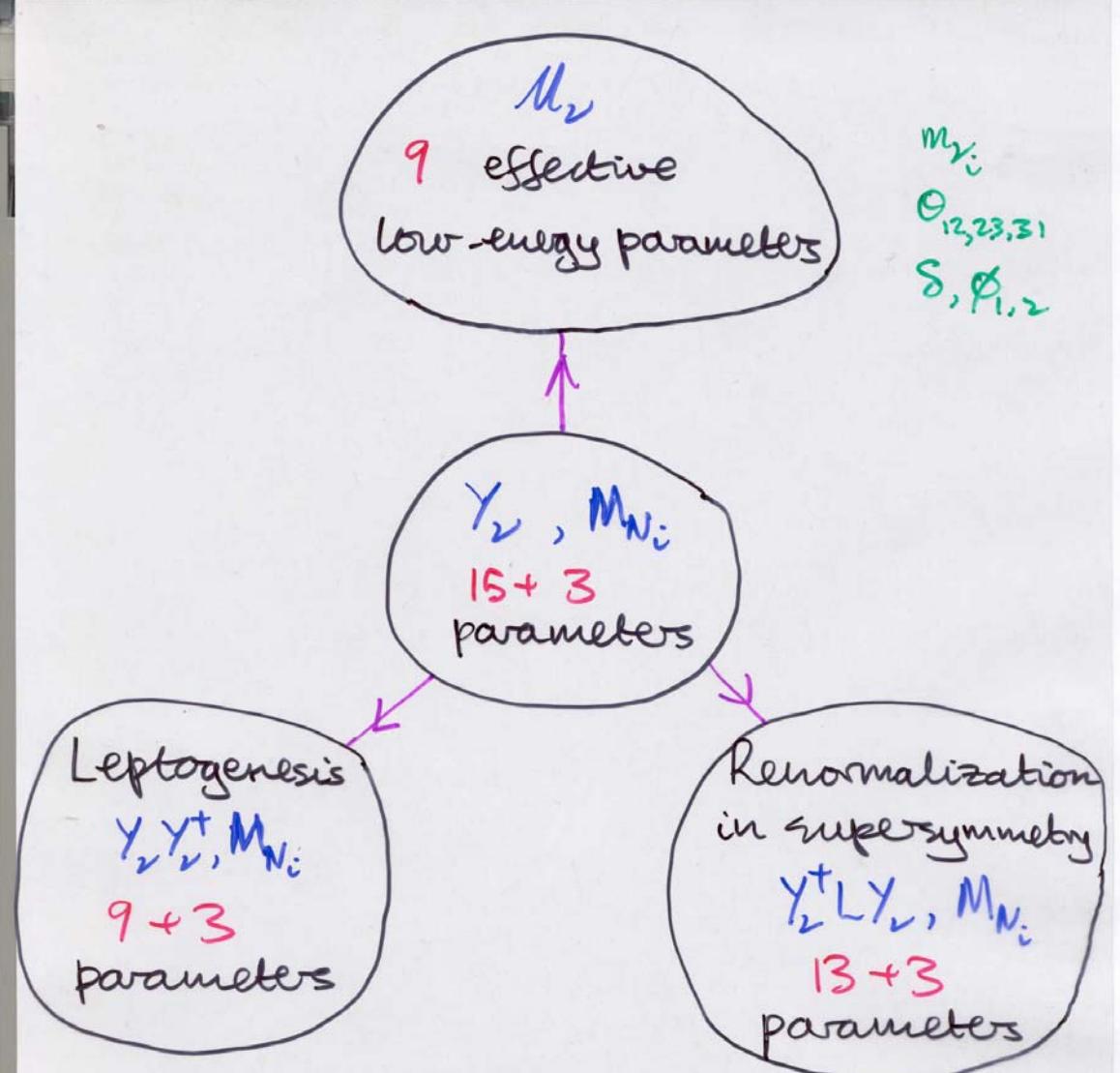
possible via 1-loop CPx diagrams



Lepton asymmetry \rightarrow baryon asymmetry

via non-perturbative electroweak interactions

Ppt



Experimental programme to determine
 all parameters, calculate leptogenesis?

Seesaw Parametrization

(S.E. + Hisano
+ Lola + Raidal)

diagonalize masses of charged leptons:

$$(Y_e)_{ij} = Y_e^\Delta \delta_{ij}$$

and heavy neutrinos:

$$M_{ij} = M_i^\Delta \delta_{ij}$$
3 masses

parametrize Y_ν :

$$Y_\nu = Z^* Y_\nu^\Delta X^+$$

$Z = P_1 \bar{Z} P_2$

$P_{1,2} = \text{diag}(e^{i\theta_{1,3}}, e^{i\theta_{2,3}}, 1)$

Y_ν^Δ real, diagonal of CKM matrix

X of CKM matrix

\rightarrow 3 eigenvalues

\rightarrow 1 phase, 3 angles

4 phases

leptogenesis $\propto Y_\nu Y_\nu^+ = P_1^* \bar{Z}^* (Y_\nu^\Delta)^2 \bar{Z}^T P_1$

3 phases, 3 angles

leading renormalization of sparticle masses

if N_i degenerate $\propto Y_\nu^+ Y_\nu = X (Y_\nu^\Delta)^2 X^+$

1 phase, 3 angles

if N_i non-degenerate: 3 phases

assuming universality @ input (Sugra GUT) scale

2-Renormalization of soft susy X parameters

$$\begin{aligned} (\delta m_L^2)_{ij} &\Rightarrow -\frac{1}{8\pi^2} (3m_0^2 + A_0^2) (Y_\nu^\dagger Y_\nu)_{ij} \ln\left(\frac{M_{\text{GUT}}}{M_N}\right) \\ i \text{---} \text{---} j & \\ (\delta A_e)_{ij} &\Rightarrow -\frac{1}{8\pi^2} A_0 Y_e (Y_\nu^\dagger Y_\nu)_{ij} \ln\left(\frac{M_{\text{GUT}}}{M_N}\right) \end{aligned}$$

in leading-log approximation: degenerate

$$M_{N_i} \ll M_{\text{GUT}}$$

single 'Janus' invariant

$$\mathcal{J}_\Sigma = \ln \left[(M_L^2)_{12} (M_L^2)_{23} (M_L^2)_{31} \right] \quad 1 \text{ phase}$$

additional contribution for non-degenerate N_i

$$(\tilde{\delta} m_L^2)_{ij} \approx -\frac{1}{8\pi^2} (3m_0^2 + A_0^2) (Y_\nu^\dagger L Y_\nu)_{ij} : L \equiv \ln \frac{M_N}{M_{N_i}} S_{ij}$$

$$\text{where } M_N = \sqrt[3]{M_{N_1} M_{N_2} M_{N_3}}$$

contains matrix factor

$$Y^\dagger L Y = X Y^D P_2 \bar{Z}^\dagger L \bar{Z}^* P_2^* Y^D X^\dagger$$

introduces dependence on phases in $\bar{Z} P_2$

now a total of 3 phases

\uparrow
not P_1
(EHLR)

Two-generation model

(J.E. + Hisano
+ Lola + Raidal)

$$M_\nu^D = \begin{pmatrix} M_{\nu_1} & 0 \\ 0 & M_{\nu_2} \end{pmatrix}, \quad M^D = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}$$

$$R = \begin{pmatrix} \cos(\theta_r + i\theta_i) & \sin(\theta_r + i\theta_i) \\ -\sin(\theta_r + i\theta_i) & \cos(\theta_r + i\theta_i) \end{pmatrix}$$

leptogenesis

$$\propto \text{Im}\left[\left(Y_\nu Y_\nu^+\right)^{21} \left(Y_\nu Y_\nu^+\right)^{21}\right] = - \frac{(M_{\nu_1}^2 - M_{\nu_2}^2) M_1 M_2}{2 v^2 \sin^2 \beta} \sinh 2\theta_i \sin 2\theta_r$$

one phase unrelated to Majorana, no oscillation S

renormalization

$$\text{assuming maximal mixing } U = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} e^{-i\phi} & 0 \\ 0 & 1 \end{pmatrix}$$

$$\text{Re}\left[\left(Y_\nu^+ Y_\nu\right)^{12}\right] = \dots - \frac{(M_{\nu_2} - M_{\nu_1})}{4 v^2 \sin^2 \beta} (M_1 + M_2) \cosh 2\theta_i$$

$$\text{Im}\left[\left(Y_\nu^+ Y_\nu\right)^{12}\right] = \frac{\sqrt{M_{\nu_1} M_{\nu_2}}}{2 v^2 \sin^2 \beta} (M_1 + M_2) \cos \phi \sinh 2\theta_i - \dots$$

$$\beta\beta_{02} \Rightarrow \phi$$

$$\text{Re, Im}(Y^+ Y) \Rightarrow \theta_r, \theta_i$$

low-energy renormalization $f(S, \phi, \text{leptag})$

+ determine low- E_T phases (S, ϕ)

\Rightarrow can calculate leptogenesis

(Casas + Ibarra / Davidson + Ibarra

Convenient phenomenological parametrization

(J.E.+Hisano+Raidal+Shimizu
hep-ph/0206110)

incorporates 9 low-energy parameters:

$$m_{\nu_1, 2, 3}; \theta_{12, 13, 23}; \delta, \phi_1, \phi_2$$

3 phases

3 charged-lepton masses

remaining 9 parameters in Hermitian matrix

$$H = Y^T D Y$$

\uparrow real diagonal: \pm or L

utilization: calculate

$$H' = \sqrt{M^D} U^T H U \sqrt{M^D}$$

$$\text{diagonalize: } H' = R'^T M'^D R' : R'^T R' = I$$

calculate remaining physical parameters:

$$(M_\nu, H) \xrightarrow[\text{model}]{} (M_\nu, M'^D, R') \xrightarrow[\text{experiment}]{} (Y_\nu, M_{N_i})$$

can suppress $\mu \rightarrow e\gamma$ $D = L, H'^2 = 0$

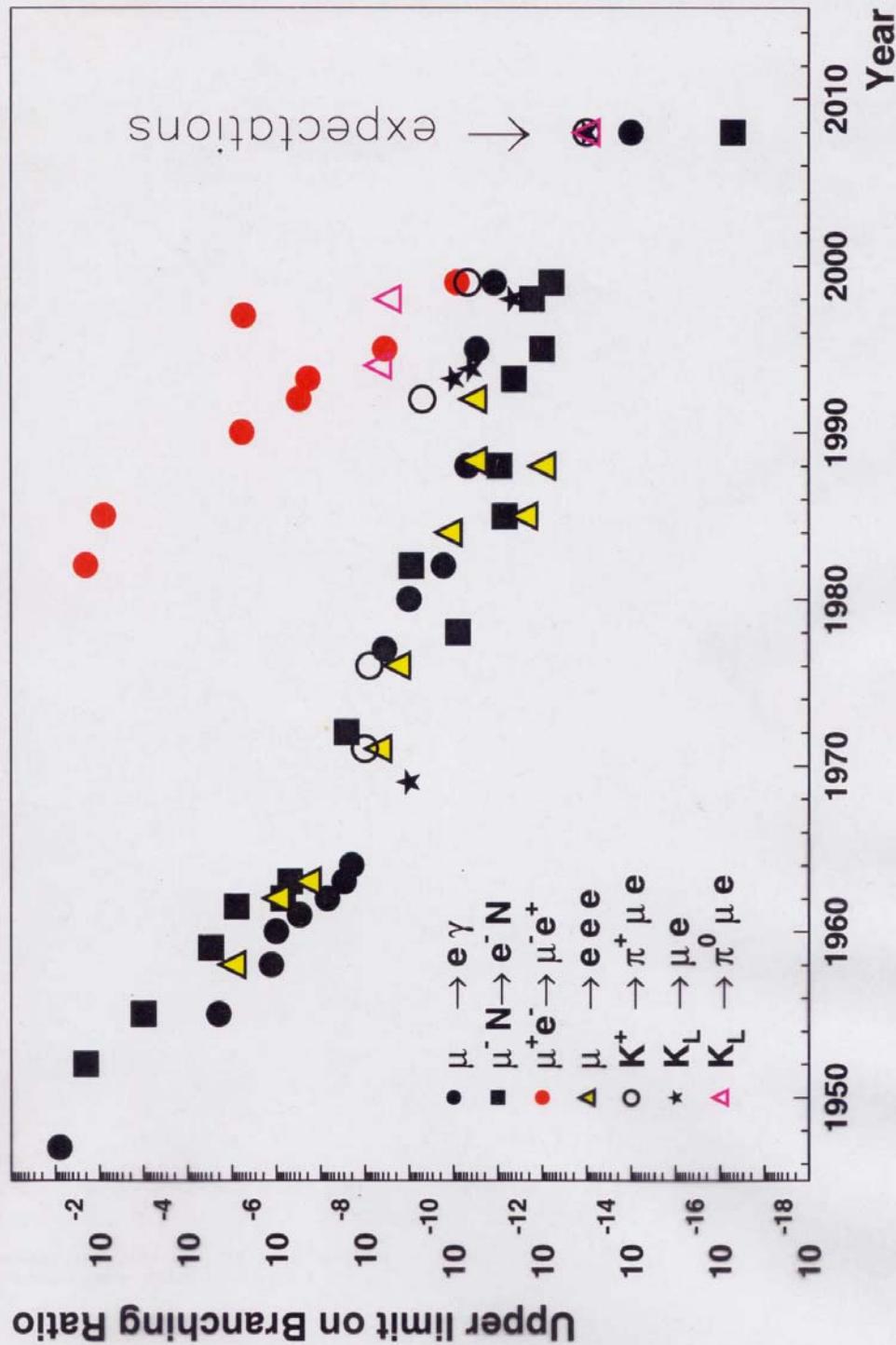
limiting choices of parameters:

$$H' = \begin{pmatrix} a & 0 & 0 \\ 0 & b & d \\ 0 & d^+ & c \end{pmatrix} \quad H^2 = \begin{pmatrix} a & 0 & d \\ 0 & b & 0 \\ d^+ & 0 & c \end{pmatrix}$$

favours $\tau \rightarrow \mu\gamma$

favours $\tau \rightarrow e\gamma$

5.3- Searches for Lepton Number Violation



$\tau \rightarrow \mu \gamma$ decay

in texture H_1

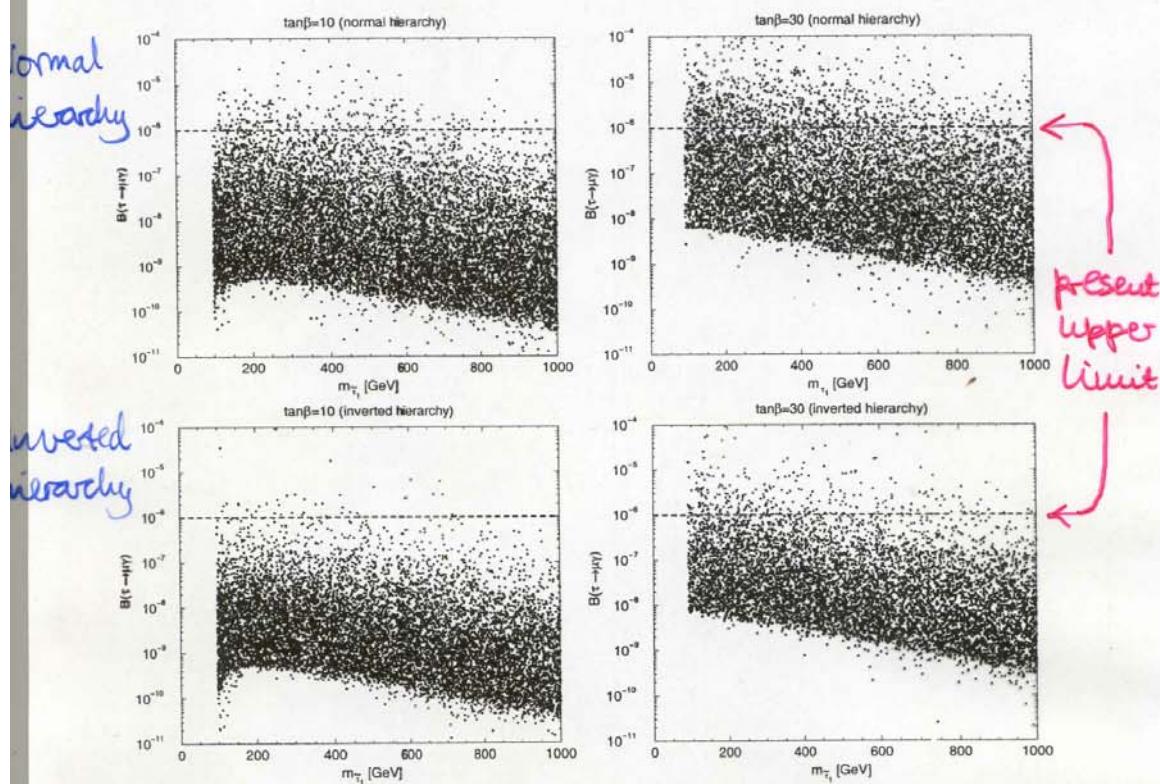
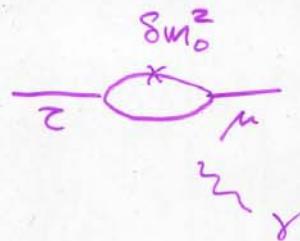


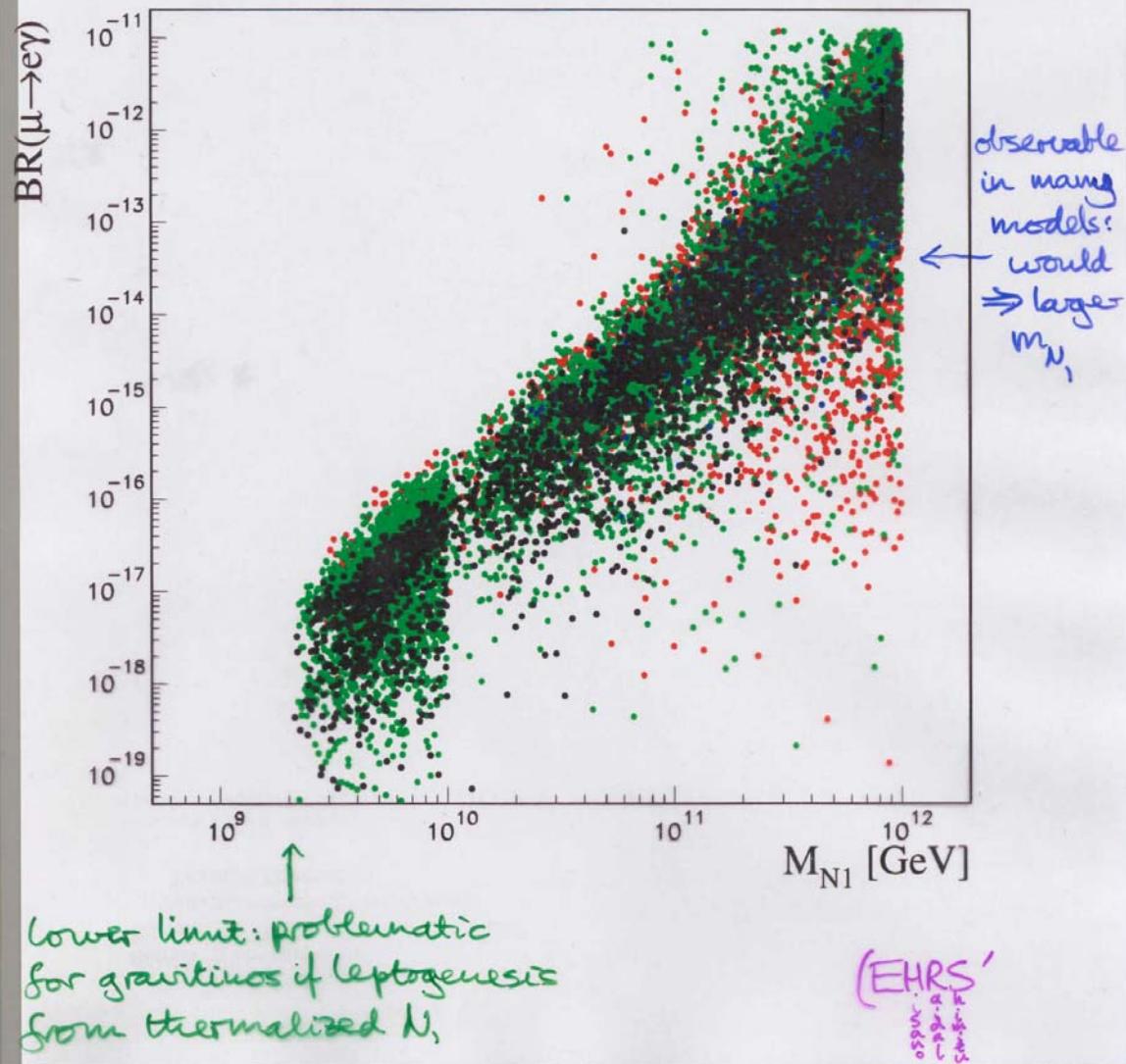
Figure 2: Scatter plot of $Br(\tau \rightarrow \mu\gamma)$ against the lightest stau mass for the ansatz H_1 . We take the $SU(2)$ gaugino mass to be 200 GeV, $A_0 = 0$, $\mu > 0$, and $\tan \beta = 10$ and 30. We consider both the normal and inverted hierarchies for the light neutrino mass spectrum.

(J.E.+Hisano+Raidal+Shimizu)
hep-ph/0206110

$\mu \rightarrow e\gamma$ vs lightest heavy ν

in texture H'

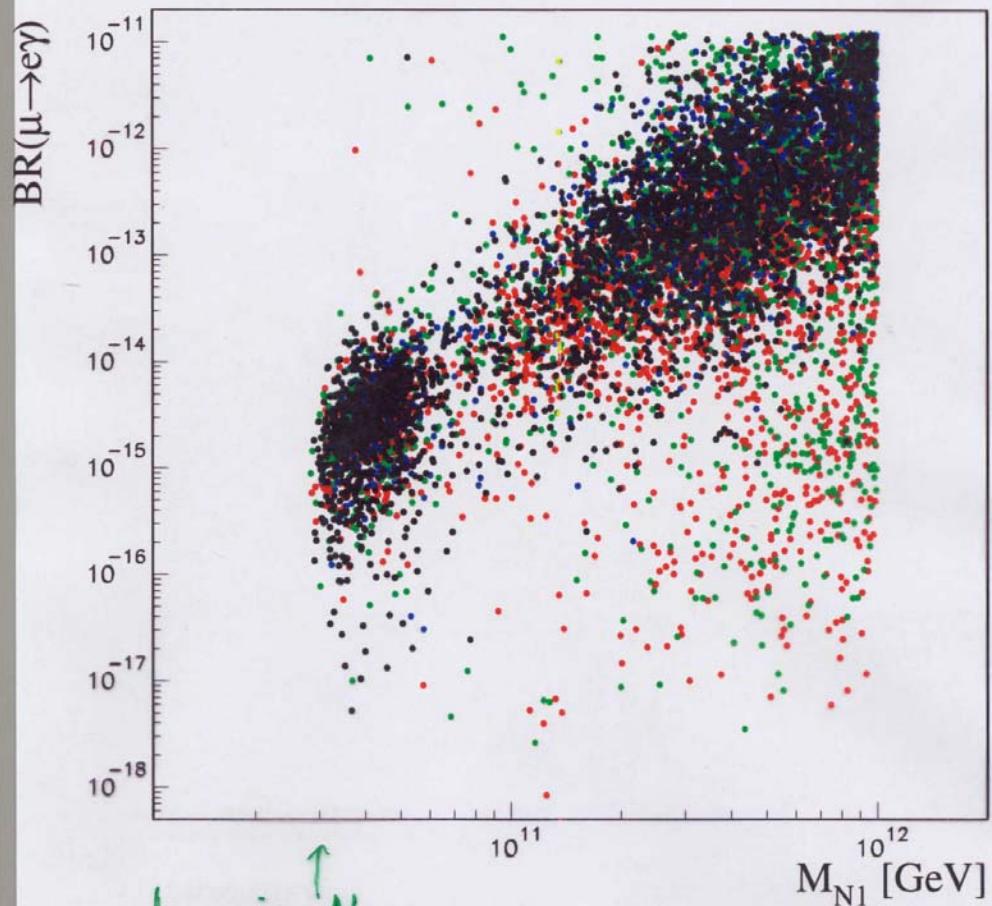
$$\text{for } 10^{-11} \leq Y_B \leq 3 \times 10^{-10}$$



$B(\mu \rightarrow e\gamma)$ vs lightest heavy ν

in texture H^2

for $10^{-11} \leq Y_B \leq 3 \times 10^{-10}$



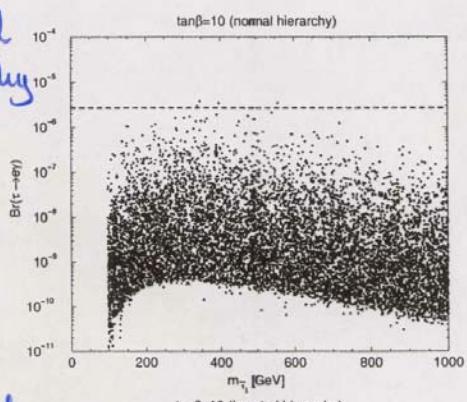
heavier N_1 :
even more of a
gravitino problem?

(EHRS)
SUSY
at
LHC

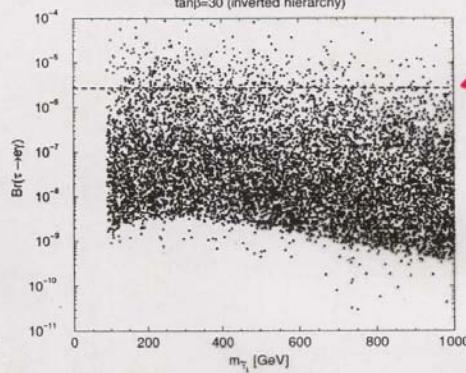
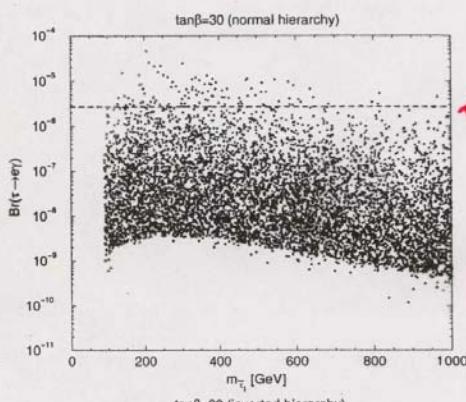
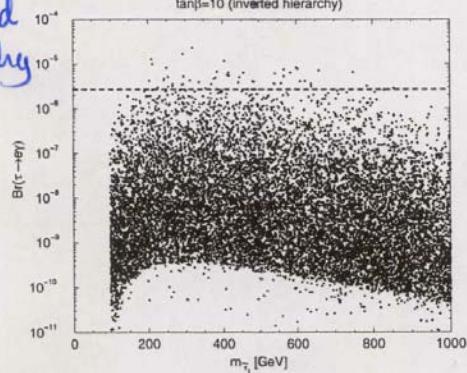
$\tau \rightarrow e\gamma$ decay

in texture H_2

Normal
hierarchy



Inverted
hierarchy



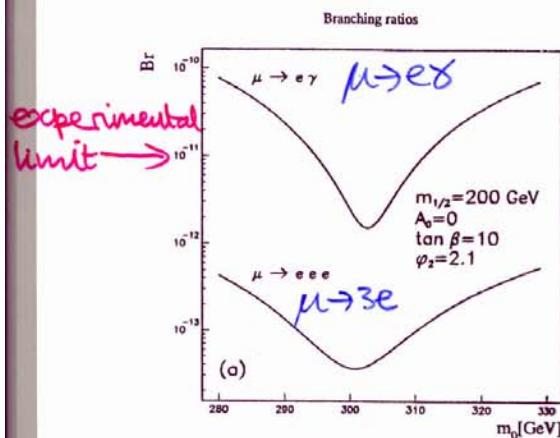
present
upper
limit

Figure 3: Scatter plot of $Br(\tau \rightarrow e\gamma)$ against the lightest stau mass for the ansatz F_2 . The input parameters for the supersymmetry-breaking parameters are the same as in Fig. 2.

(S.E.+Kisano+Raidal+Shimizu'
hep-ph/0206110

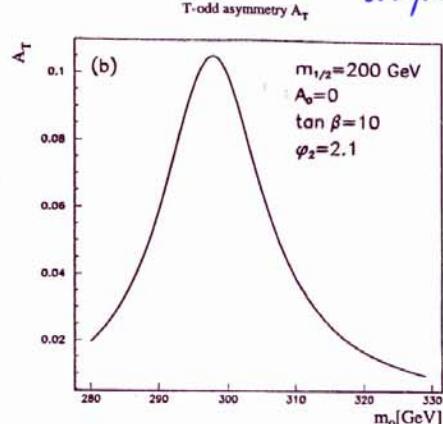
μ LFV and CP Violation

B Ratios



experimental limit →

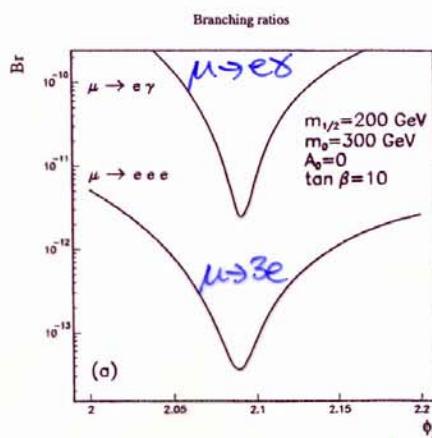
T-odd Asymmetry in $\mu \rightarrow 3e$



m_0 dependence

Figure 3: (a) Branching ratios for the decays $\mu^+ \rightarrow e^+\gamma$ and $\mu^+ \rightarrow e^+e^+e^-$ and (b) the T-odd asymmetry A_T in $\mu^+ \rightarrow e^+e^+e^-$ decay, as functions of the common soft mass m_0 , for the fixed choice of neutrino parameters described in the text.

B Ratios



ϕ_2 dependence

T-odd Asymmetry in $\mu \rightarrow 3e$

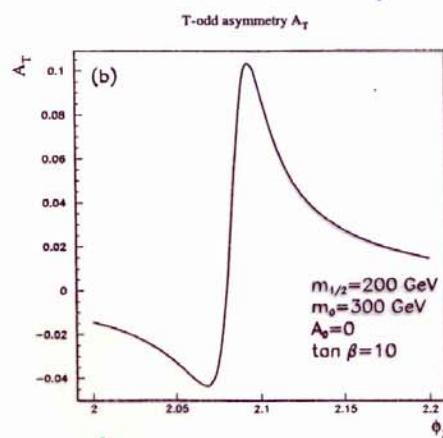


Figure 4: (a) Branching ratios of the decays $\mu^+ \rightarrow e^+\gamma$ and $\mu^+ \rightarrow e^+e^+e^-$ and (b) the T-odd asymmetry A_T in $\mu^+ \rightarrow e^+e^+e^-$ decay, as functions of the Majorana phase ϕ_2 for $m_0 = 300$ GeV. All other parameters are fixed as in Fig. 3.

5.E.+Hisano+Lola+Raidal

Lepton Electric Dipole Moments

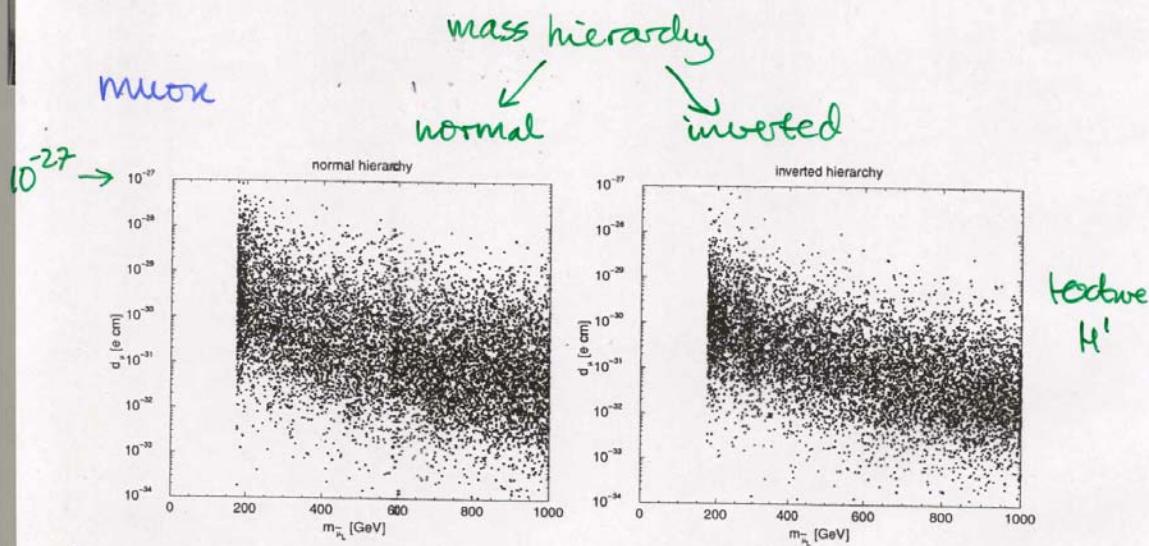


Figure 4: Scatter plot of the muon EDM against the left-smuon mass for the ansatz H_1 , taking the $SU(2)$ gaugino mass to be 200 GeV, $A_0 = -3m_0$, $\mu > 0$, and $\tan\beta = 10$. We assume the normal hierarchy for the light neutrino mass spectrum in (a) and the inverted hierarchy in (b).

electron

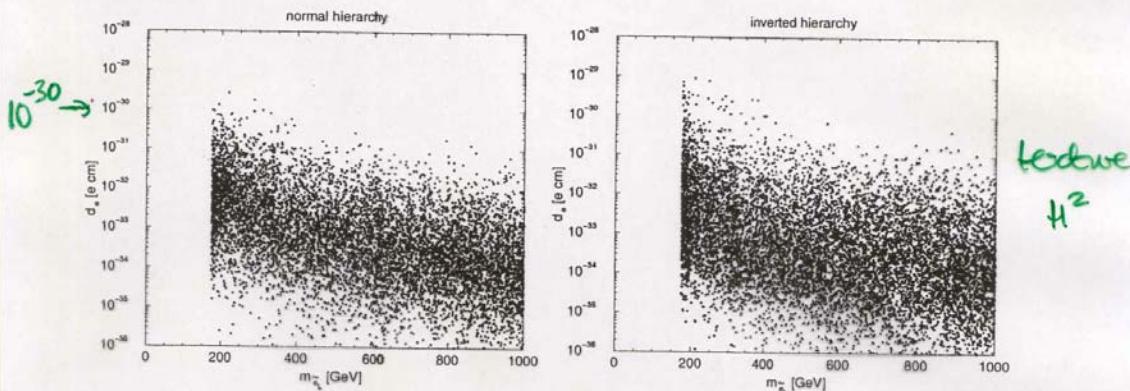


Figure 5: Scatter plot of the electron EDM against the left-selectron mass for the ansatz H_2 . Other input parameters are the same as in Fig. 4.

Electric Dipole Moments

(J.E. + Hisano +
Raidal + Shimizu)

- strongly enhanced if heavy neutrinos non-degenerate
- violate naive relation $d_\nu \propto m_\nu$
- depend strongly on A_0

$$(\tilde{\delta} m_\nu^2)_{ij} \approx \frac{18}{(4\pi)^4} (M_0^2 + A_0^2) \left\{ Y_\nu^\dagger L Y_\nu, Y_\nu^\dagger Y_\nu \right\} \ln\left(\frac{M_{GUT}}{m_N}\right)$$

$$(\tilde{\delta} A_e)_{ij} \approx \frac{1}{(4\pi)^4} A_0 Y_e \left[11 \left\{ Y_\nu^\dagger L Y_\nu, Y_\nu^\dagger Y_\nu \right\} + 7 \left[Y_\nu^\dagger L Y_\nu, Y_\nu^\dagger Y_\nu \right] \right]_{ij}$$

where $L_{ij} = \ln\left(\frac{M_N}{m_{N_i}}\right)_{ij}$

- dependence on new phases (leptogenesis)
- possible even in 2-generation case

$$\mathcal{L} = -\frac{i}{2} d_\nu \bar{L} \sigma_{\mu\nu} \gamma_5 L F^{\mu\nu} \quad \text{cf } -\frac{e}{2} m_i A_{L,R} \bar{l}_i \sigma^{\mu\nu} l_i F_{\mu\nu}$$

$$d_\nu \approx d_\nu^{x+} + d_\nu^{x0}$$

for $l_i \rightarrow l_j \gamma$

present bounds \longrightarrow future?

$$d_e < 1.6 \times 10^{-27} \text{ e.cm}$$

$d_e \rightarrow 10^{-53} \text{ e.cm}$?
(Lamoreaux)

$$d_\nu < 7 \times 10^{-19} \text{ e.cm}$$

$d_\nu \rightarrow 10^{-24} \text{ e.cm}$?
(PRISM)
 $5 \times 10^{-26} \text{ e.cm}$?
(2 factories)

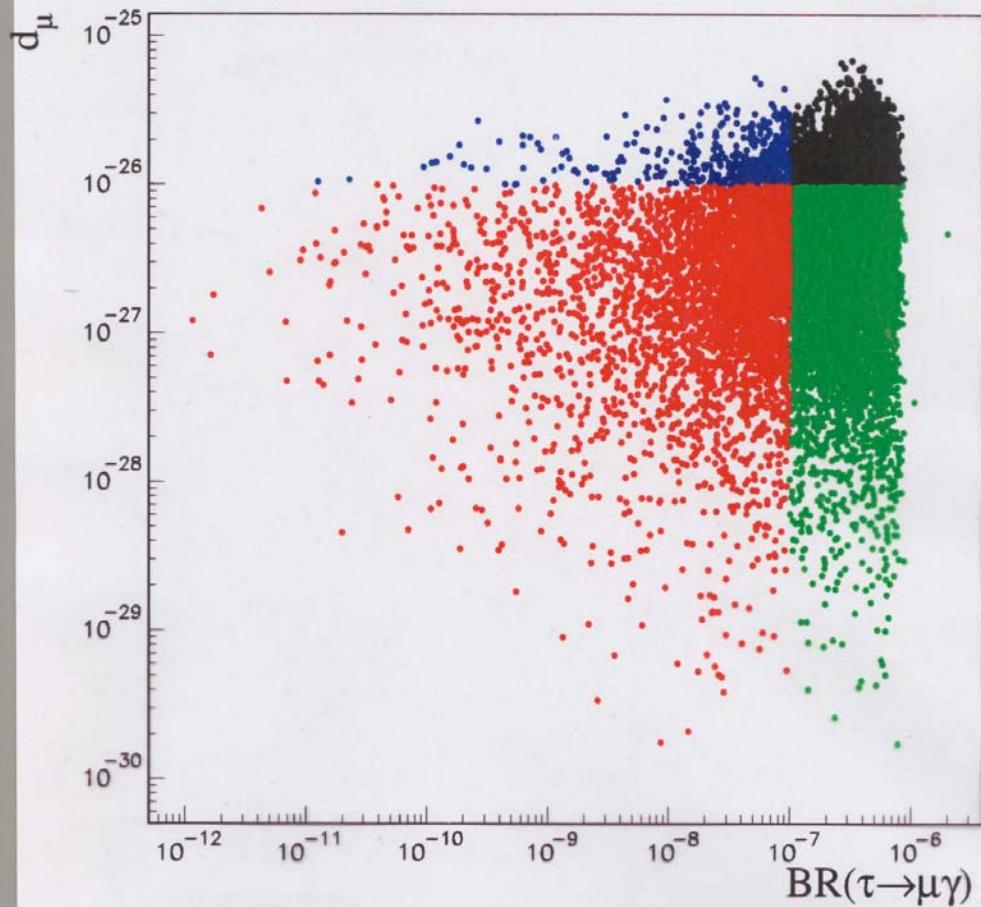
Muon EDM vs $\tau \rightarrow \mu \gamma$

in texture H'

Benchmark CMSSM parameters:

$$m_{1/2} = 300 \text{ GeV}, m_0 = 100 \text{ GeV}, A_0 = -300 \text{ GeV}$$

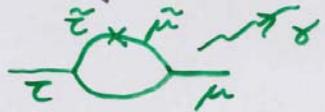
$$\tan\beta = 10, \mu > 0$$



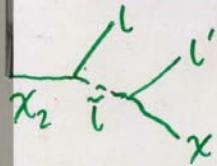
(J.E. + Hisano + Raidal + Shimizu')

(Not so) Rare Sparticle Decays

- suppression of rare $\tau \rightarrow \mu$ decay due to large sparticle masses, loop effects
not necessarily small intrinsic slepton mixing
- lepton flavor violation could be large in sparticle decays? (Hinchliffe + Paige, ...)
most accessible @ LHC:
 $\chi_2 \rightarrow \chi (l^+ l^-)$
(Cavalcanti + SE. + Gomez + Lola + Romao)
- largest LFV effects potentially in $\chi_2 \rightarrow \chi (\tau^\pm \mu^\mp)$, $\chi_2 \rightarrow \chi (\tau^\pm e^\mp)$
- most important in 'coannihilation' region
- complementary to searches for $\tau \rightarrow \mu \gamma, \tau \rightarrow e \gamma$



Lepton Flavour Violation in Sparticle Decay



$$\tilde{\chi}_2^0 \rightarrow (e\mu)\tilde{\chi}$$

$m_{\tilde{\chi}_2^0} = 300 \text{ GeV}$
 $m_0 = 100 \text{ GeV}$
 $\tan\beta = 2.1$

$\mu = 498 \text{ GeV}$
 (CMSSM
 $\equiv mSUGRA$)

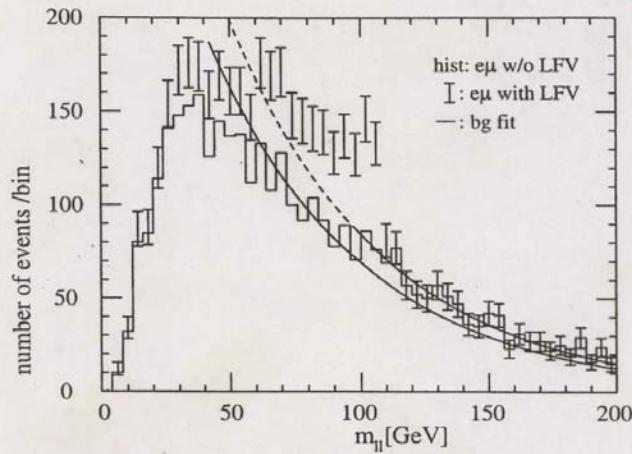


Figure 5: The $m_{e\mu}$ distribution for point I). The data corresponds to integrated luminosity of 95 fb^{-1} and standard cuts are applied (see text). The histogram shows the distribution without LFV, while bars are number of events and the error with $\tilde{\mu}\tilde{e}$ mixing. In the plot, $1/30$ of $\tilde{\chi}_2^0 \rightarrow \tilde{l}'l, \tilde{l}' \rightarrow \tilde{\chi}_1^0 l'$ decay chain is assumed to go to the $e\mu$ channel. Two curves are fits to the background distribution in the region $m_{ll} = 40-200 \text{ GeV}$ (solid) and $m_{ll} = 100-200$ (dashed then solid). We use $c = 12.1$.

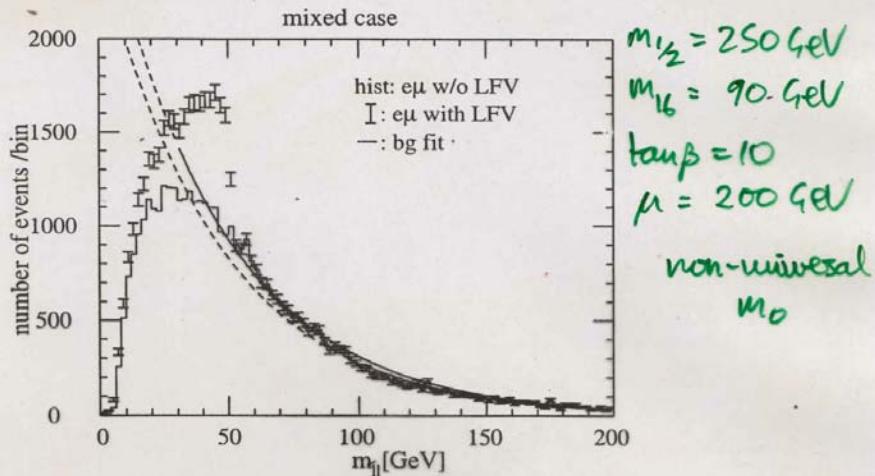
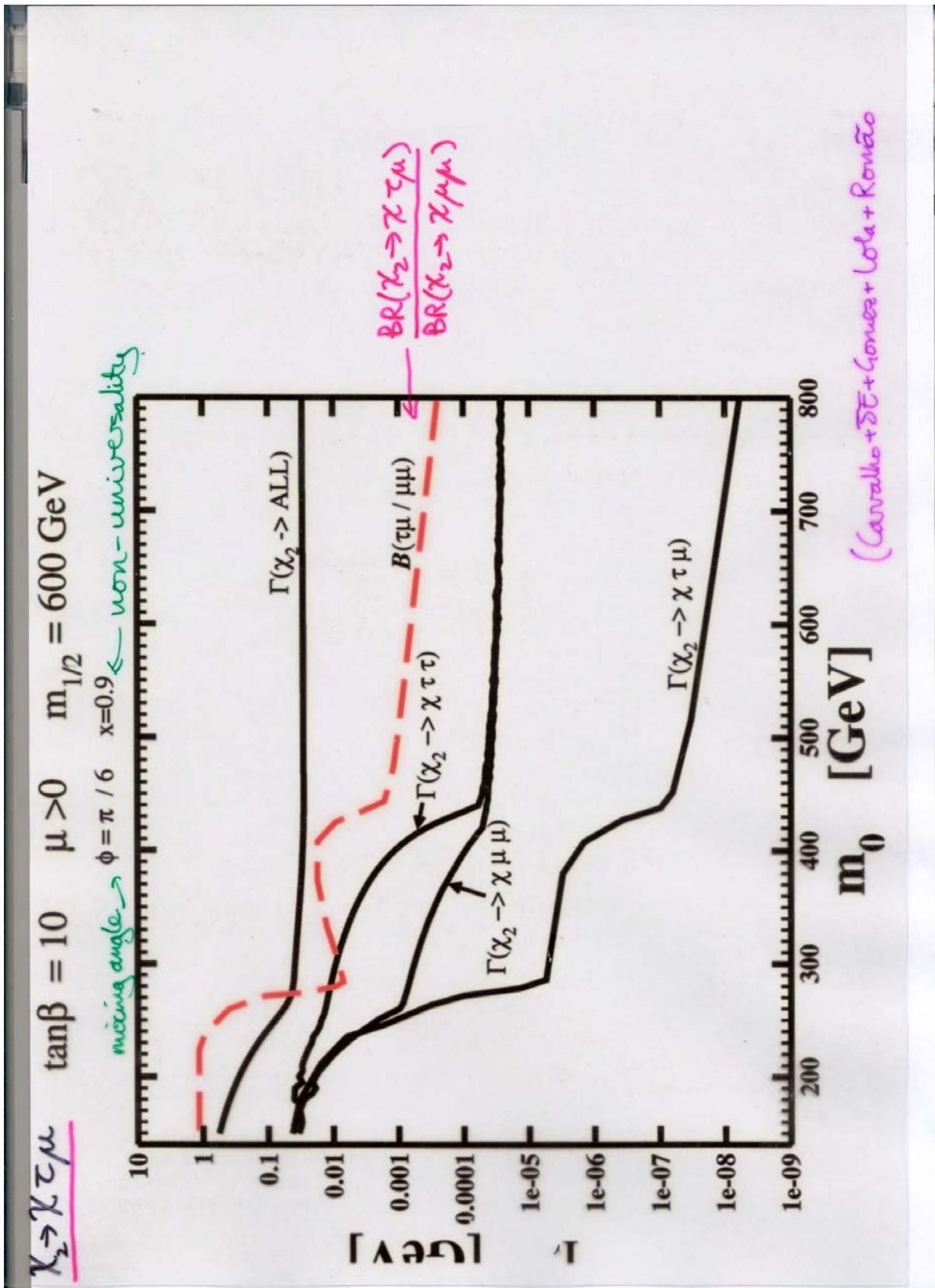
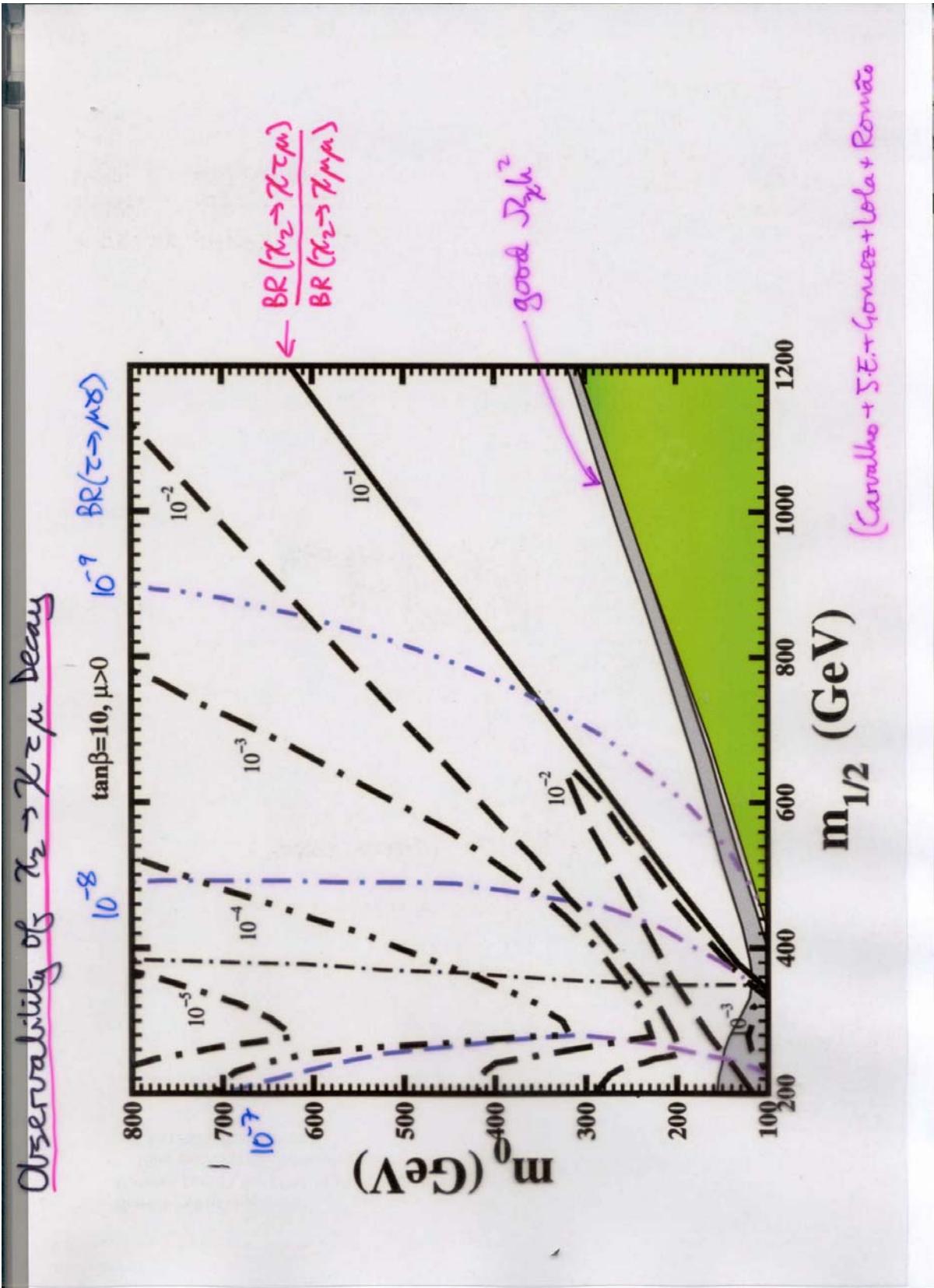


Figure 6: Same as Fig. 5, but for point II). The integrated luminosity is 196 fb^{-1} , and $c = 13.7$.





GUT Relation to Hadronic FCNC?

Neutrino Dirac coupling $\gamma_\nu H \bar{N} L$ \leftarrow lepton doublet
becomes (in SU(5)) $\gamma_\nu H_5 \bar{N} F$ $\leftarrow (d^c, d^c, d^c, e^-, \nu)^T$

induces FCNC via renormalization

$$(\delta m_{d^c})_{ij} \propto (\gamma_\nu^\dagger \gamma_\nu)_{ij} \ln \left(\frac{m_{\text{gravity}}}{m_{\text{GUT}}} \right)$$

assuming universality at some supergravity

scale: $m_{\text{gravity}} > m_{\text{GUT}}$

⇒ Correlation between d^c mixing and LFV, CPX

observable effect in $B \rightarrow \phi K_s ??$

(Hisano+Shimizu:

hep-ph/0303071

BUT

possible magnitude of effect constrained by
edmu of ^{199}Hg

(H+S: hep-ph/0308255

Possible Correlation: $\tau \rightarrow \mu\gamma \Leftrightarrow A_{CP} (B \rightarrow \phi K_S)$

induced by GUT renormalization between

$$m_{\text{gravity}} - m_{\text{GUT}}$$

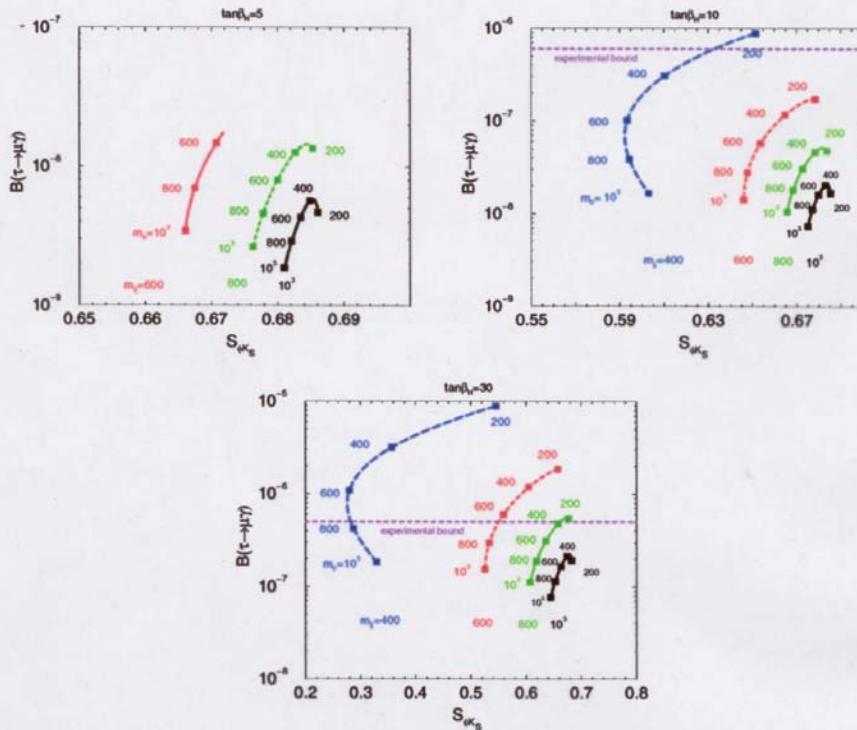


Figure 1: $Br(\tau \rightarrow \mu\gamma)$ as a function of $S_{\phi K_S}$ for fixed gluino masses $m_{\tilde{g}} = 400, 600, 800$, and 1000 GeV. $\tan \beta_H$ is 5, 10, and 30. Also, 200 GeV $< m_0 < 1$ TeV, $A_0 = 0$, $m_{\nu_\tau} = 5 \times 10^{-2}$ eV, $M_N = 5 \times 10^{14}$ GeV, and $U_{32} = 1/\sqrt{2}$. $(\varphi_{d_2} - \varphi_{d_3})$ is taken for the deviation of $S_{\phi K_S}$ from the SM prediction to be maximum. The constraints from $b \rightarrow s\gamma$ and the light-Higgs mass are imposed.

(Misano + Shimizu:
hep-ph/0303071)

BUT

Constrained by Strange Quark Contribution
to EDM of ^{199}Hg

similar
diagrams

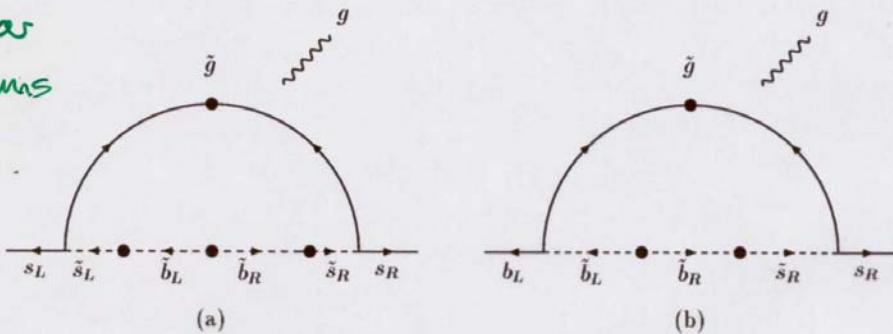


Figure 1: a) The dominant diagram contributing to the CEDM of the strange quark when both the left-handed and right-handed squarks have mixings. b) The dominant SUSY diagram contributing to the CP asymmetry in $B \rightarrow \phi K_s$ when the right-handed squarks have a mixing.

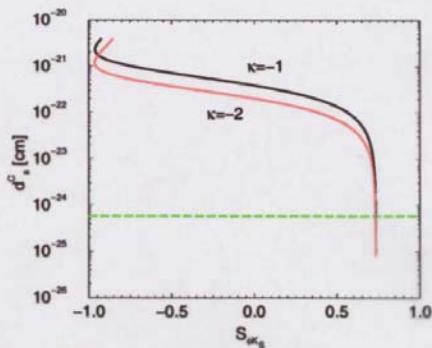


Figure 2: The correlation between d_s^C and $S_{\phi K_s}$, assuming $d_s^C = -m_b/(4\pi^2)\text{Im}[(\delta_{LL}^{(d)})_{23}C_8^R]$. Here, $(\delta_{LL}^{(d)})_{23} = -0.04$ and $\arg[C_8^R] = \pi/2$. κ comes from the matrix element of chromomagnetic moment in $B \rightarrow \phi K_s$. The dashed line is the upperbound on d_s^C from the EDM of ^{199}Hg atom.

(Hisano + Shimizu: hep-ph/0308255

4 - Leptogenesis

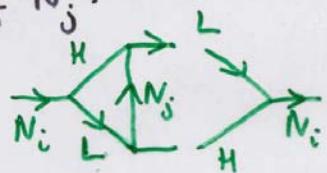
(Fukugita + Yanagida,
...)

asymmetry in decays of heavy neutrinos

total decay rate: $\Gamma_i = \frac{1}{8\pi} (Y_\nu Y_\nu^*)_{ii} M_i$ (no Σ)

asymmetry due to exchange of N_j :

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



where

known kinematic function

$$(Y_\nu Y_\nu^*) = (\sqrt{M^d} R^d R^+ \sqrt{M^d})$$

sum over light leptons \Rightarrow

independent of MNS $S, \phi_{1,2}$

compact expression:

$$(Y_\nu Y_\nu^*)_{ii} = M_i (R^d R^+)^{ii}$$

$$((Y_\nu Y_\nu^*)_{ij})^2 = M_i M_j ((R^d R^+)^{ij})^2$$

decay asymmetry:

$$\epsilon_{ij} = \frac{1}{8\pi} M_j f\left(\frac{M_j}{M_i}\right) \frac{\text{Im}((R^d R^+)^{ij})^2}{(R^d R^+)^{ii}}$$

depends only on β_i ← extra phases

How to measure them?

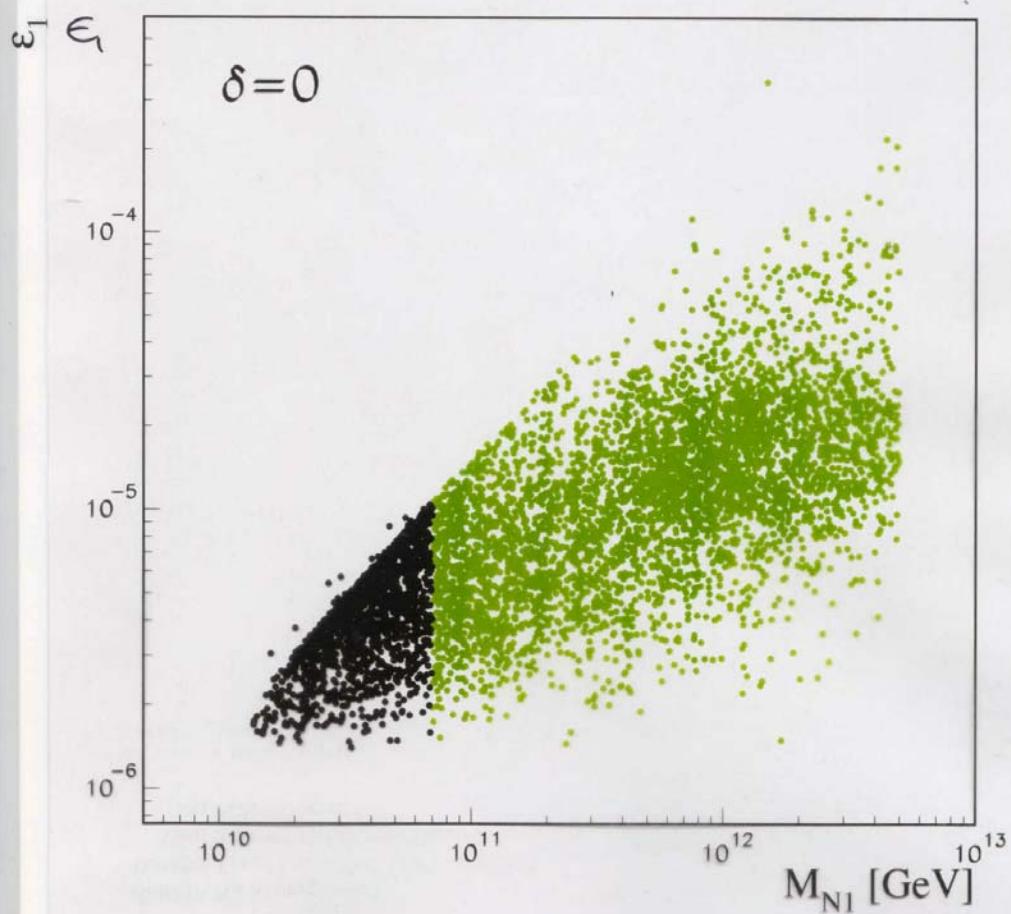
in minimal supersymmetric seesaw model

Leptogenesis Asymmetry

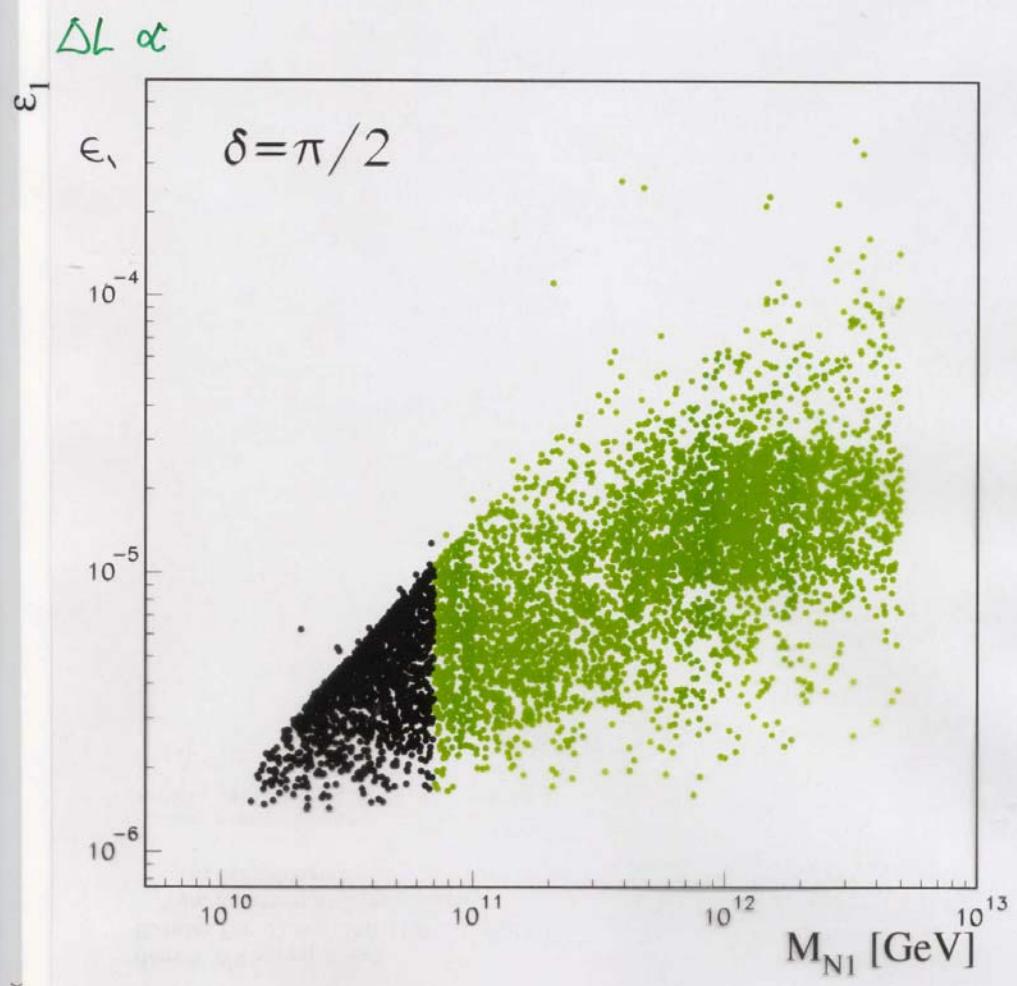
without CP violation in ν oscillations

in decays of heavy neutrinos

$\Delta L \propto$



with CP violation in ν oscillations



Possibilities for Leptogenesis

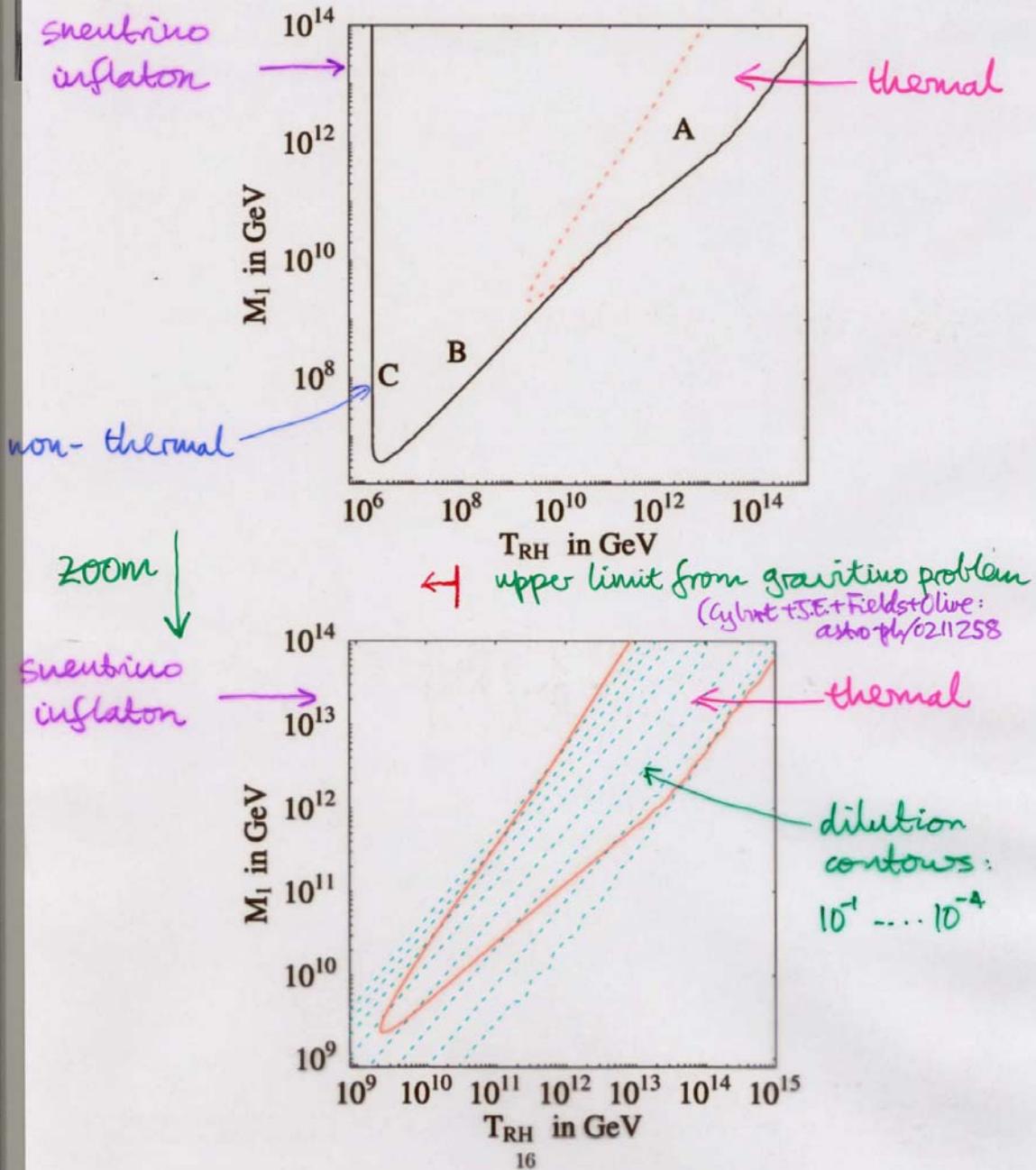
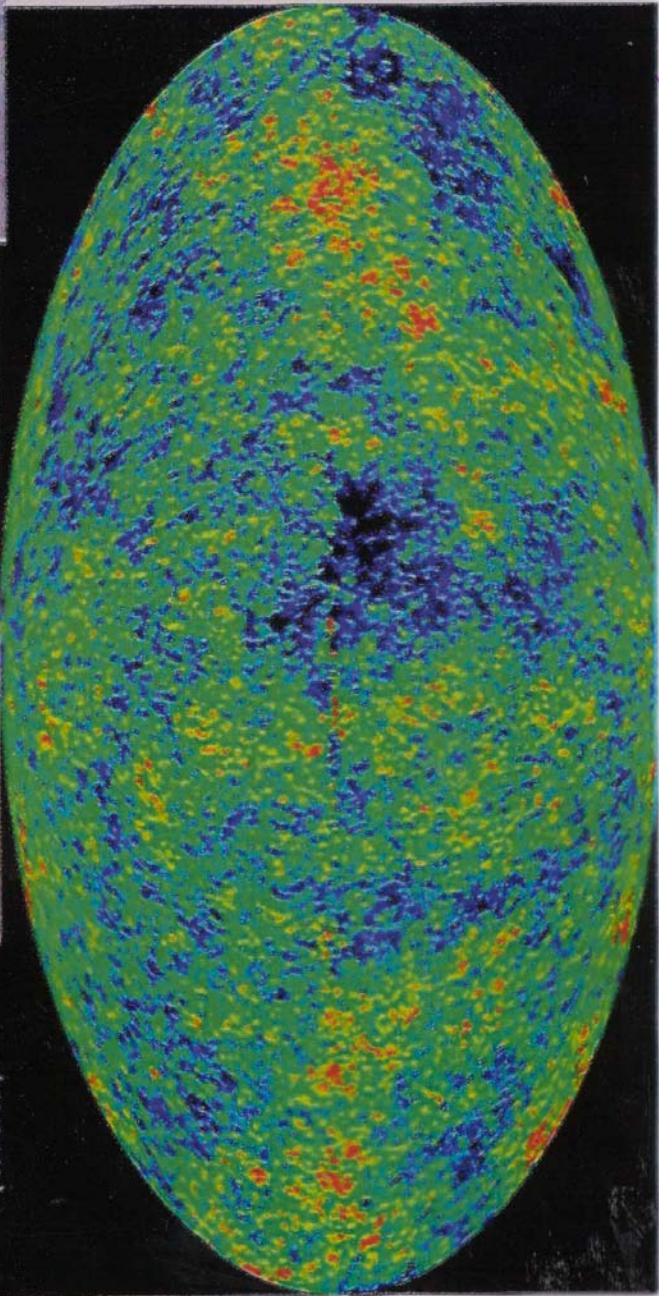


Figure 2: Left: The solid curve bounds the region allowed for leptogenesis in the (T_{RH}, M_{N_1}) plane, again obtained assuming $Y_B > 7.8 \times 10^{-11}$ and the maximal CP asymmetry $\epsilon_1^{\max}(M_{N_1})$. In the area bounded by the red dashed curve leptogenesis is entirely thermal. Right: The dashed lines are isocontours of the efficiency parameter $\eta = 10^{-1, -2, -3, -4}$; they have meaning only inside the solid curve, which bounds the region where leptogenesis is thermal.
 (J.E. + Raidal + Yanagida: hep-ph/0303242)

**MAP OF THE UNIVERSE
AT A SIMPLER TIME
(400,000 YRS)**

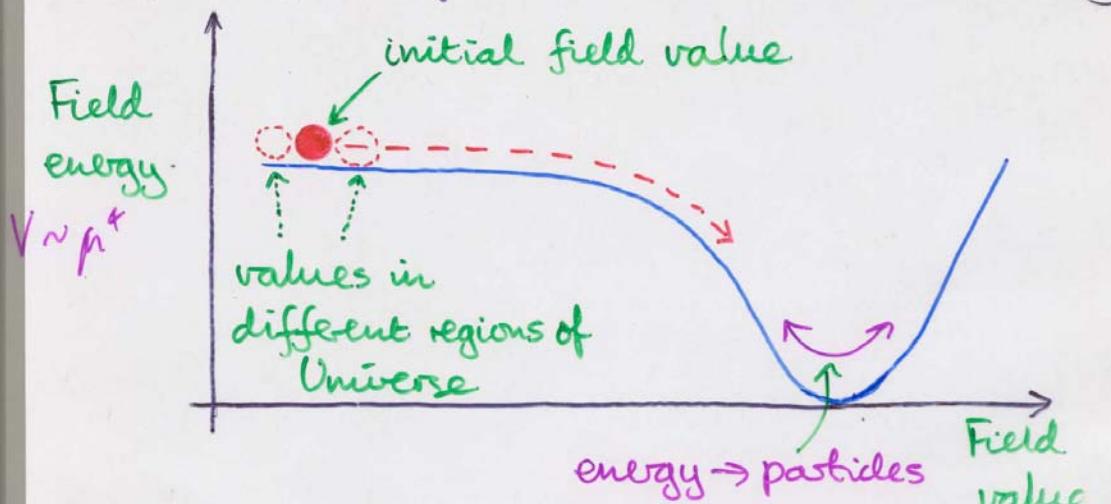


Turner

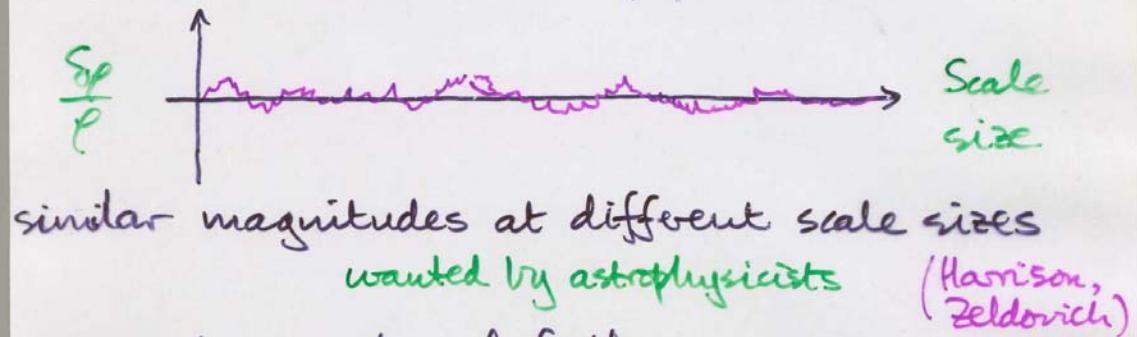
Density Perturbations

GUT Higgs?

quantum/thermal fluctuations in scalar field
⇒ different parts of Universe expand differently



⇒ Gaussian random field of perturbations



magnitude \leftrightarrow value of field energy

$$\left(\frac{S_T}{T}\right) \sim \frac{S_T}{\mu} \propto \mu^2 G_N$$

consistent with COBE data

$$\frac{S_T}{T} \sim 10^{-5}$$

$\mu \sim 10^{16} \text{ GeV}$: GUT energy?

Spectral Index from WMAP + 2dFGRS + Lyman α
 combination prefers scale dependence in spectral index
 BUT consistent with constant spectral index
 $n_s \sim 1.0$

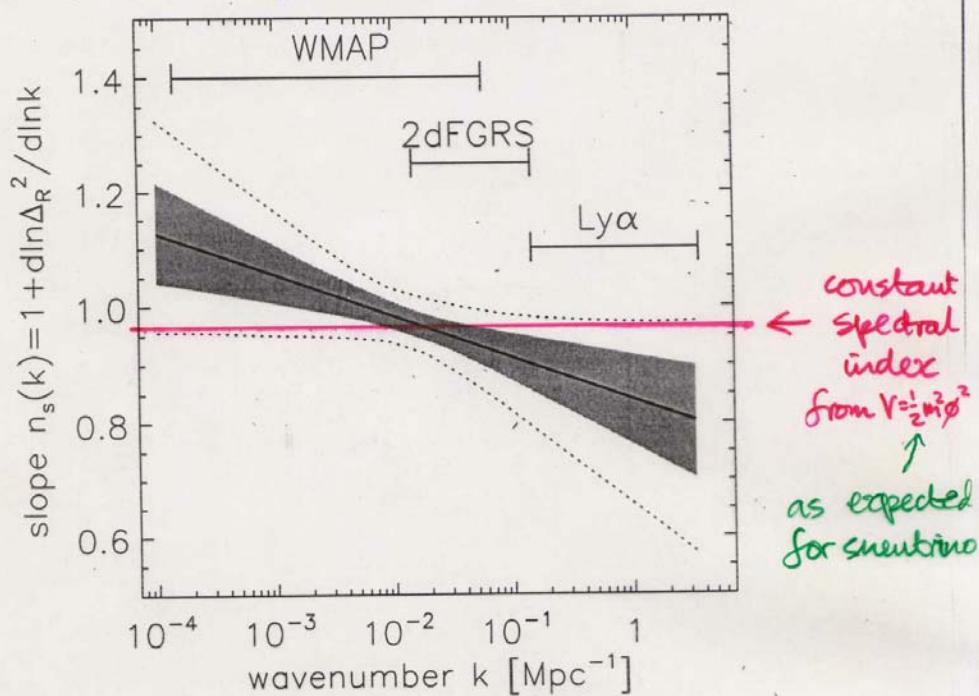


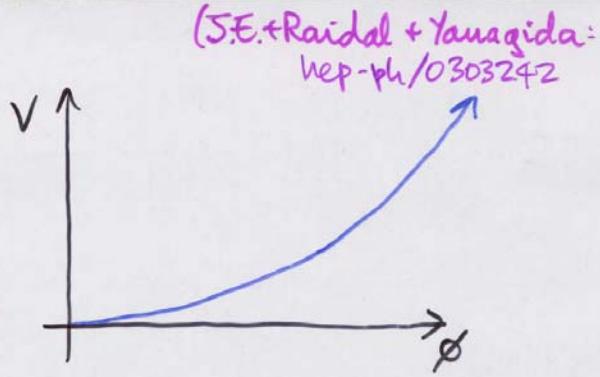
Fig. 2.— This figure shows n_s as a function of k for the WMAPext+2dFGRS+Lyman α data. The mean (solid line) and the 68% (shaded area) and 95% (dashed lines) intervals are shown. The scales probed by WMAP, 2dFGRS and Lyman α are indicated on the figure.

(WMAP)

Toy Model

$$V = \frac{1}{2} m^2 \phi^2$$

$$V' = m^2 \phi, \quad V'' = m^2$$



slow-roll parameters: $\epsilon = \frac{2m_{Pl}^2}{\phi^2} = \gamma$ $m_{Pl} = (8\pi G_N)^{\frac{1}{2}}$
 $\approx 2 \cdot 4 \times 10^{18}$ GeV

COBE normalization:

$$(1.94 \times 10^{-5}) = \sqrt{\frac{1}{75\pi} m_{Pl}^6} \frac{V^3}{V'^2}$$

magnitude of potential:

$$V^{\frac{1}{4}} = 0.027 \epsilon^{\frac{1}{4}} m_{Pl} \quad < \text{Planck scale}$$

in simple model: $\phi \sqrt{m} \approx 0.04 \times m_{Pl}^{\frac{3}{2}}$

need about 60 e-folds of expansion:

$$N = 2\pi G_N \phi^2 \approx 60 \Rightarrow \phi^2 \approx 240 m_{Pl}^2$$

↑ somewhat > Planck scale

inflaton mass:

$$m \approx \frac{(0.04)^2 m_{Pl}^3}{\phi^2} \approx 1.8 \times 10^{13} \text{ GeV}$$

spectral index: $n_s = 1 + 2\gamma - 4\epsilon \approx 1 - \frac{8m_{Pl}^2}{\phi^2} \approx 0.96$

tensor mode: $\approx 16\epsilon \approx 0.16 \leftarrow$ only monomial compatible with WMAP?
 $(V \sim \phi^4 \text{ excluded by } \sim 3\sigma)$

5- Could the Inflaton be a Sneutrino?

(Miwajima + Suzuki + Yanagida + Yokoyama: 1993,
1994)

need massive scalar $m \sim 10^{10} - 10^{15}$ GeV
without gauge interactions (\rightarrow potential \neq flat)

sounds like heavy singlet sneutrino \tilde{N}

mass in correct range

need not have gauge interactions (\times SO(10)?)

tailor-made for leptogenesis?

if so, inflation \leftrightarrow rest of physics

can calculate baryon density via
leptogenesis in inflaton decay

Predictions for lepton flavour violation

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

(J.E. + Raidal
+ Yanagida
hep-ph/0303242)

Constraints from WMAP et al

on inflation observables

(E+Raidal+Yanagida)

$$V = \frac{1}{2} m^2 \phi^2 \quad (\text{sneutrino model})$$

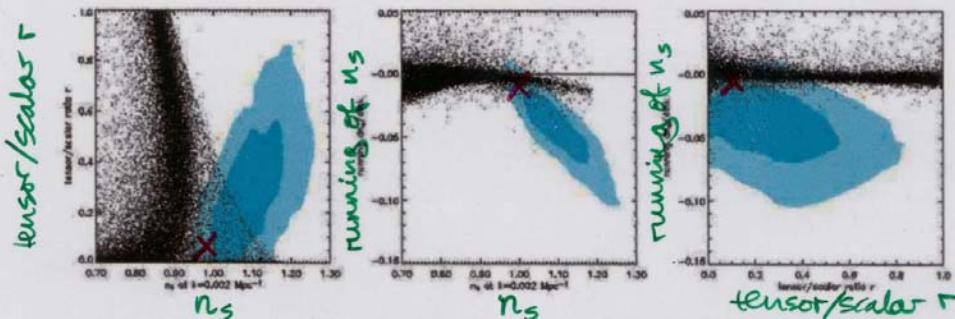


Fig. 3.— This set of figures shows part of the parameter space spanned by viable slow roll inflation models, with the WMAPext+2dFGRS+Lyman α 68% confidence region shown in dark blue and the 95% confidence region shown in light blue.

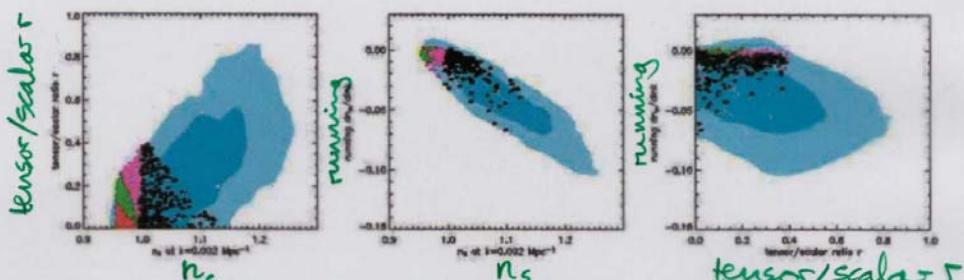


Fig. 4.— This set of figures compares the fits from the WMAPext+2dFGRS+Lyman α data to the predictions of specific classes of physically motivated inflation models. The color coding shows model classes referred to in the text: (A) red, (B) green, (C) magenta, (D) black. The dark and light blue regions are the joint 1- σ and 2- σ regions for the WMAPext+2dFGRS+Lyman α data. We show only Monte Carlo models that are consistent with 2- σ regions in all panels. This figure does not imply that the models not plotted are ruled out.

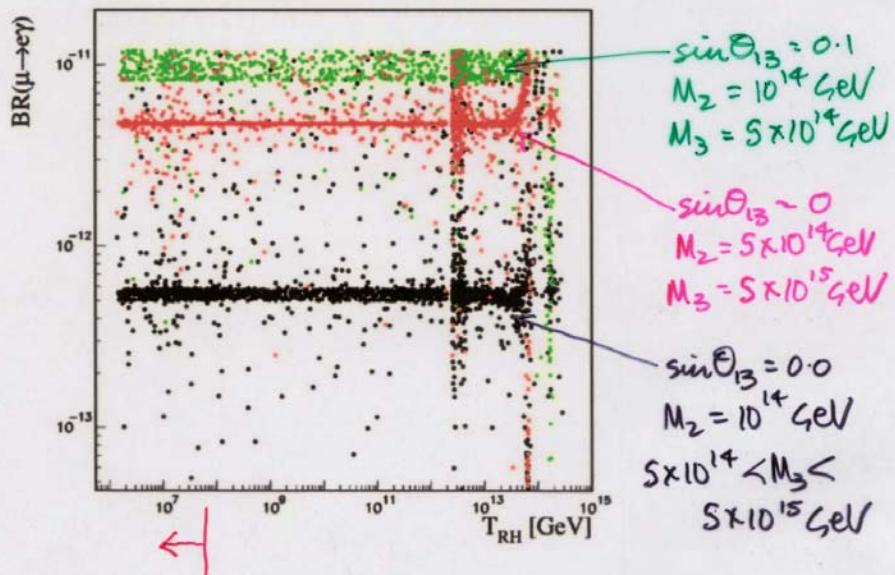
Lepton Flavour Violation

assuming sneutrino inflation, leptogenesis

$\mu \rightarrow e\gamma$

$\tan\beta = 10$,
 $m_{\tilde{\chi}_2^0} = 800 \text{ GeV}$,
 $M_0 = 170 \text{ GeV}$,

$\mu > 0$



$\tau \rightarrow \mu \gamma$

reheating
temperature
may be low

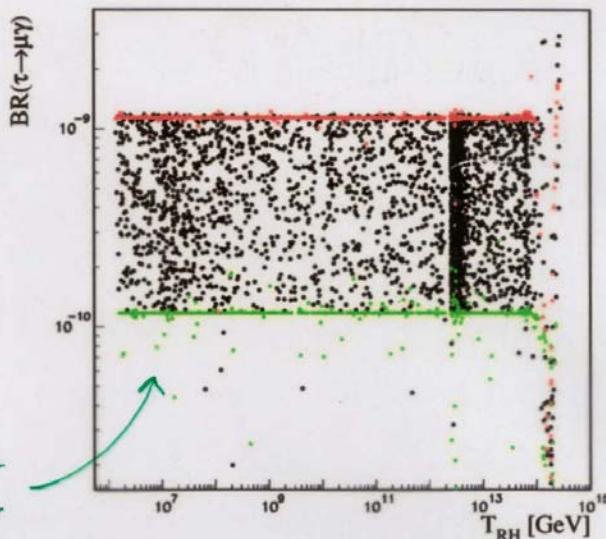


Figure 3: Calculations of $BR(\mu \rightarrow e\gamma)$ and $BR(\tau \rightarrow \mu\gamma)$ on left and right panels, respectively. Black points correspond to $\sin\theta_{13} = 0.0$, $M_2 = 10^{14} \text{ GeV}$, and $5 \times 10^{14} \text{ GeV} < M_3 < 5 \times 10^{15} \text{ GeV}$. Red points correspond to $\sin\theta_{13} = 0.0$, $M_2 = 5 \times 10^{14} \text{ GeV}$, and $M_3 = 5 \times 10^{15} \text{ GeV}$, while green points correspond to $\sin\theta_{13} = 0.1$, $M_2 = 10^{14} \text{ GeV}$, and $M_3 = 5 \times 10^{14} \text{ GeV}$.

(J.E.+Raidal+Yanagida:hep-ph/0303292)