3 – Physique des Neutrinos (et al.)

3.1 – Masses et oscillations des ν

3.2 – Au-delà des ν : violations des N_L ?

3.3 – Désintégrations de sparticules qui violent les N_L

3.4 – Leptogenèse

3.5 – Inflation sleptonique

-Neutrino Masses

Setting the Neutrino Mass Scale

irect

Tritium β decay: $m_{\nu_e} < 2.5\,\text{eV}$

$\rightarrow$ 0.2 eV possible?

$\pi \to \mu\nu$ decay: $m_{\nu_\mu} < 190\,\text{keV}$

$\tau \to n\pi\nu$ decay: $m_{\nu_\tau} < 15.5\,\text{MeV}$

$\rightarrow$ 3 MeV possible?

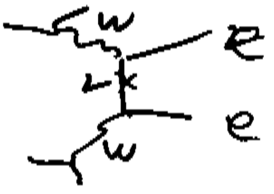
Cosmology

WMAP

CMB ⊕ large-scale structure: $\boxed{\sum_\nu m_\nu \lesssim 0.7\,\text{eV}}$

$\rightarrow$ fraction eV possible?

Neutrinoless Double-β Decay



measures $\langle m_\nu \rangle_e = \sum_i m_{\nu_i} U_{ei}^2 \lesssim 0.5\,\text{eV}$

most stringent limit, prospects for improvement

sensitive to Majorana phases ϕ_1, ϕ_2

as well as MNS parameters

Upper Limit on Neutrino Relic Density

combining WMAP and 2dFGRS data

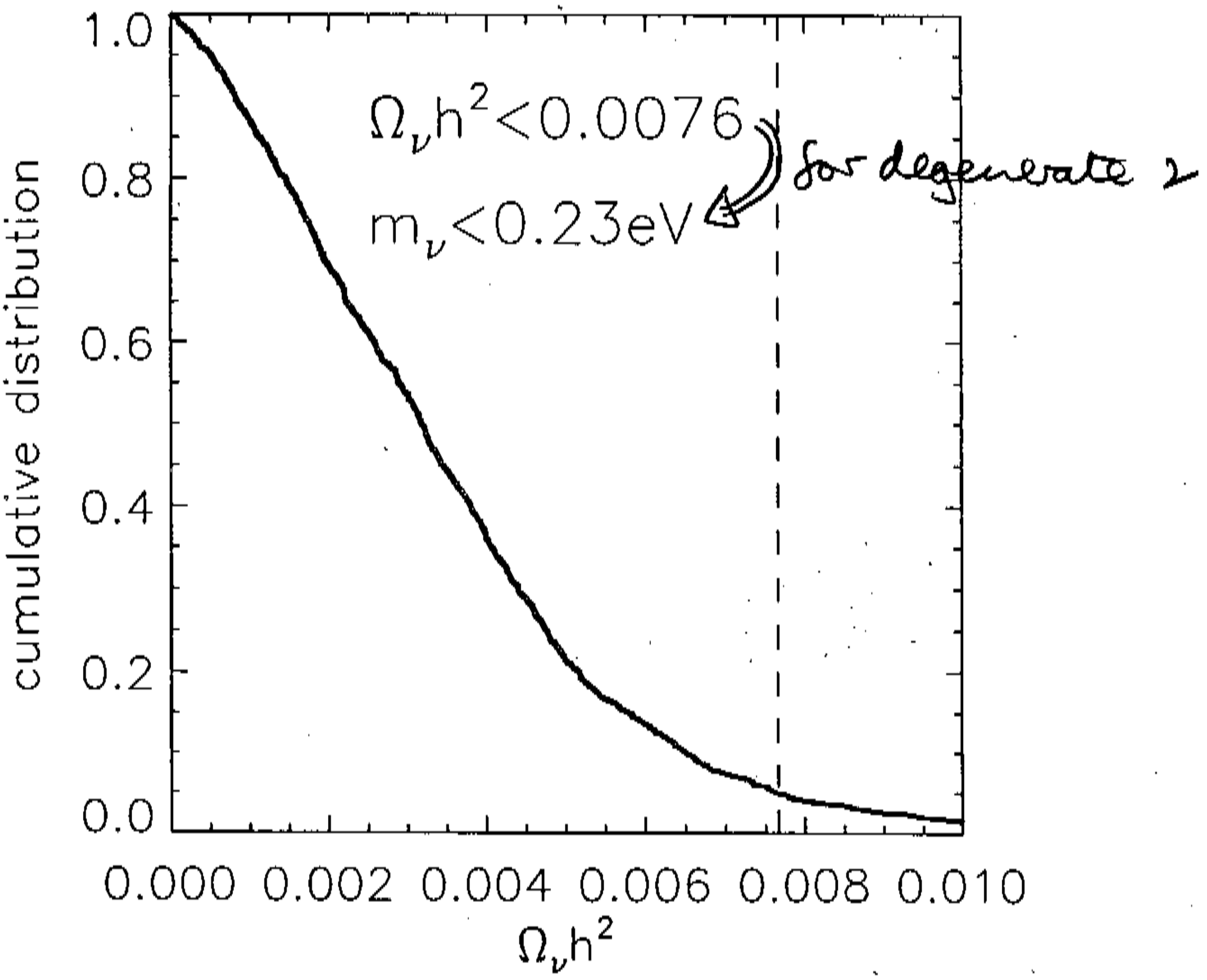
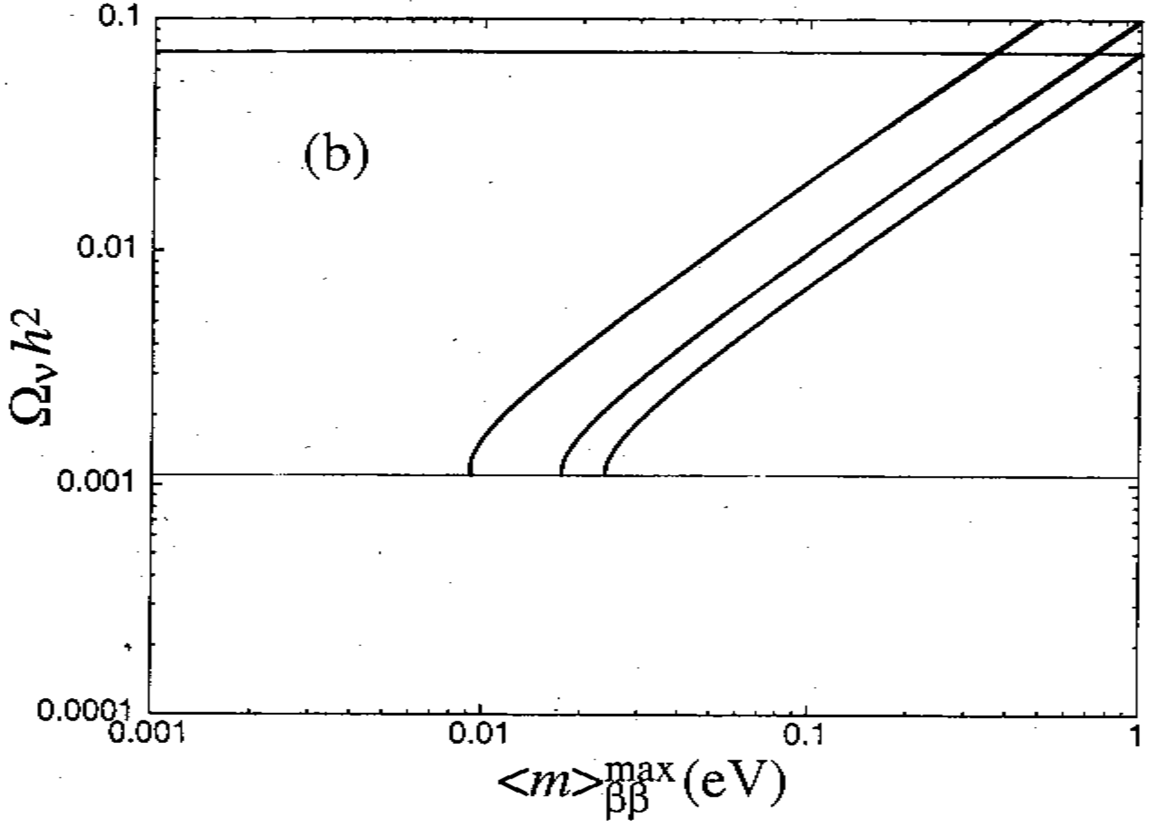


Fig. 14.— This figure shows the marginalized cumulative probability of $\Omega_\nu h^2$ based on a fit to the WMAPext+ 2dFGRS data sets.

(WMAP

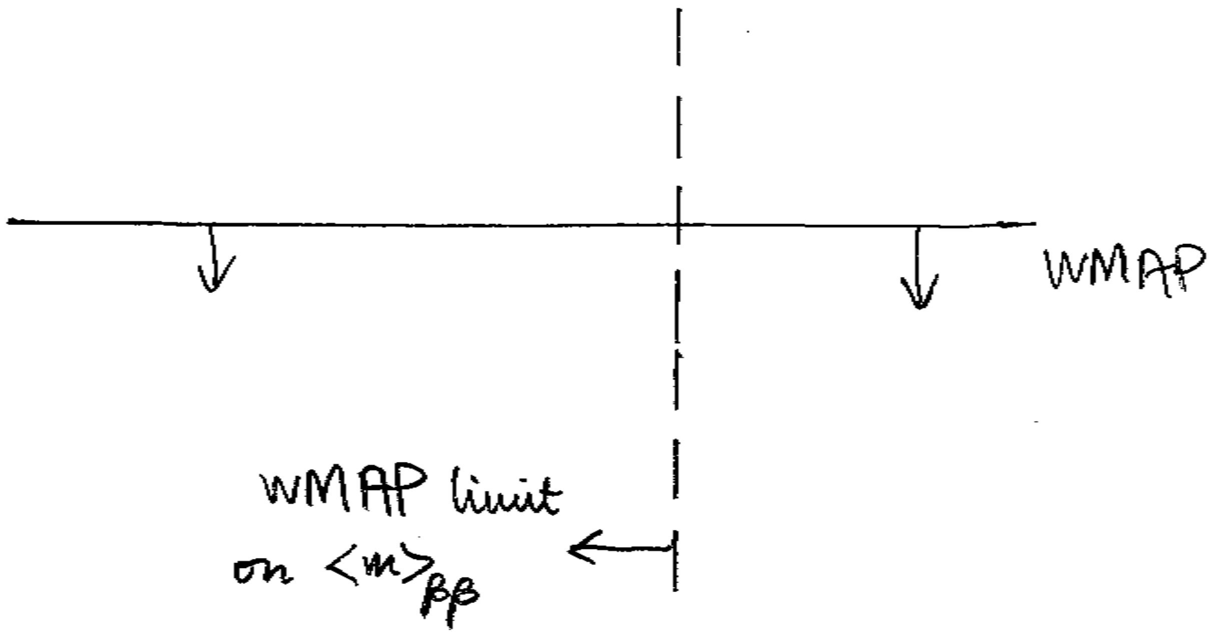
Ω_ν vs Neutrinoless $\beta\beta$ Decay



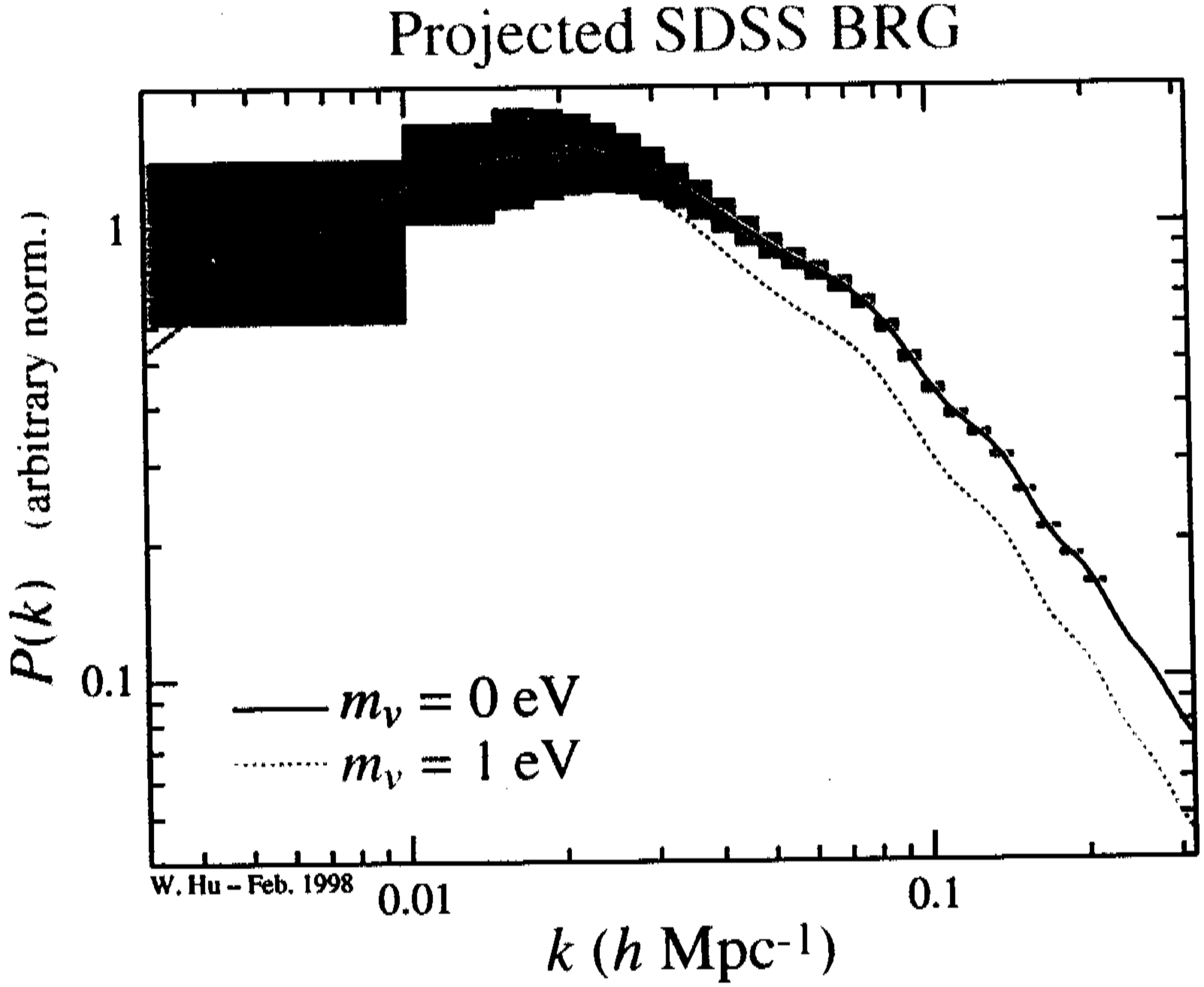
range allowed
by oscillation
measurements

(Minakata +
Sugiyama:
hep-ph/0212240

Figure 8: *Correlation between $\Omega_\nu h^2$ and $\langle m_\nu \rangle_e$, taking into account the measurements by KamLAND and other experiments [28].*


WMAP
WMAP limit
on $\langle m \rangle_{\beta\beta}$

Possible future data



(Hu

Neutrino Masses
+ Lepton Flavour Violation

$m_\nu \neq 0$

$\Delta L \neq 0$

Why not?

vanishing masses ⟺ exact symmetries

e.g. photon [illegible] gauge symmetry [illegible]

no gauge symmetry for Lepton # L

Seen in ν!

oscillations ⟺ different ν flavours

Needs no GUTs!

m_ν possible with Standard Model fields

$$m_\nu \nu\cdot\nu \Leftarrow \frac{1}{M}\nu H\cdot\nu H : \quad m_\nu = \frac{\langle 0|H|0\rangle^2}{M}$$

non-renormalizable interaction with

large mass scale M ← origin?

Seesaw model:

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

Negligible for charged leptons?

in minimal seesaw model with

no extra light particles ← Supersymmetry

Generic GUT Seesaw Model

no new gauge int^ns 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:

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

each mass matrix in flavour space

flavour diagonalization:

$$V_{MNS} = V_l V_\nu^\dagger$$

$$\text{diagonalize } l_L \qquad \nu_L \leftarrow m_D \frac{1}{M} m_D^T$$

different structure from quark mixing

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

ν mixing might be very different from q

U(1) models? $\begin{pmatrix} \epsilon^m & \epsilon^q & \epsilon^p \\ \epsilon^{q'} & \epsilon^r & \epsilon^s \\ \epsilon^{p'} & \epsilon^{s'} & \epsilon^t \end{pmatrix}$ GUTs? extra dimensions

non-Abelian flavour symmetry

Barbieri

The Basis of Particle Physics

$$
\begin{aligned}
L = & -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\psi \\
& + \psi_i\lambda_{ij}\psi_j h + h.c. \\
& + |D_\mu h|^2 - V(h) \\
& + \frac{1}{M}L_i\lambda^{\nu}_{ij}L_j h^2 \text{ or } L_i\lambda^{\nu}_{ij}N_j
\end{aligned}
$$

The gauge sector (1)

The flavor sector (2)

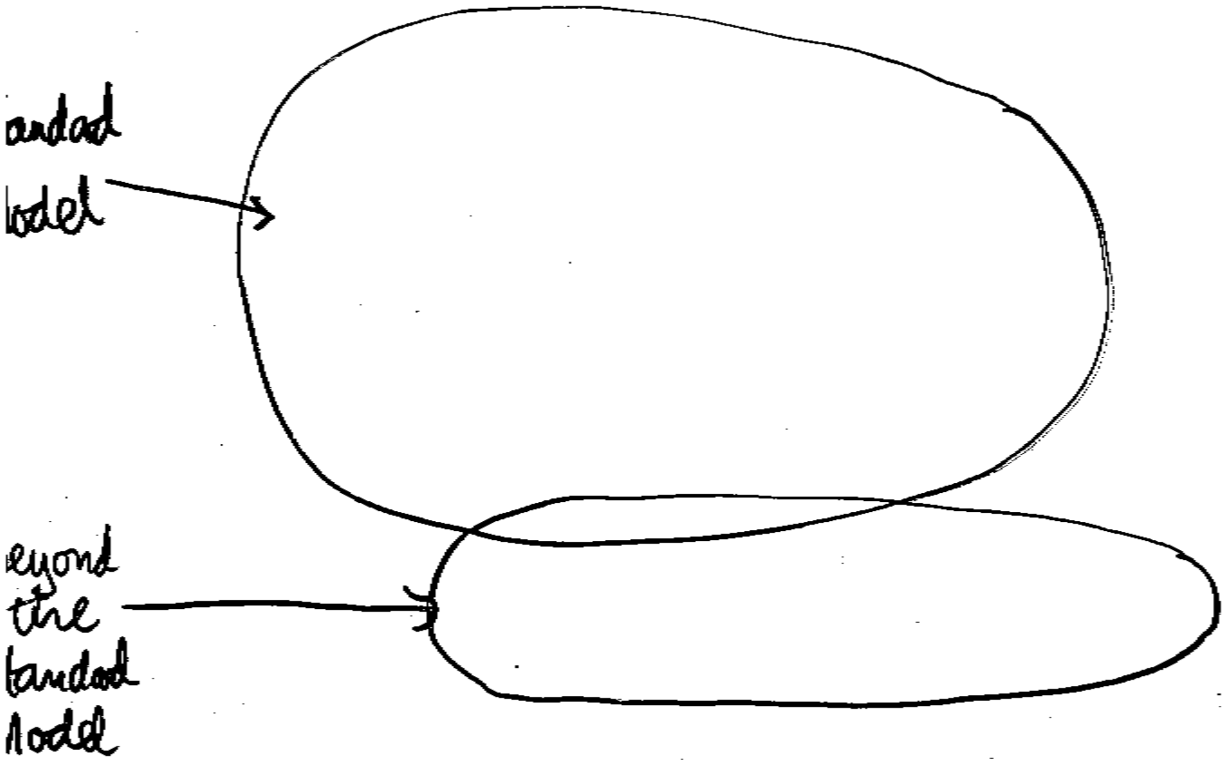
The EWSB sector (3)

The ν–mass sector (4)

String theory

Cosmology

Future accelerators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Heavy Singlet Neutrino Mass Scale?

basic seesaw mass formula:

$$m_\nu = \frac{m_D^2}{m_M}$$

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

cf m_q, m_l

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

from oscillation data

$\Rightarrow$ heavy neutrino mass

$m_M \sim 10^{13}$ GeV

± few orders of magnitude

comparable to GUT scale?

do not need new gauge interactions ...

suitable for lepto → baryogenesis?

inflation?

Neutrino Oscillations

Neutrino Mixing Matrix

(Maki + Nakagawa + Sakata

$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

harged
epton flavours →

← mass eigenstates ← eigenvalues?

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

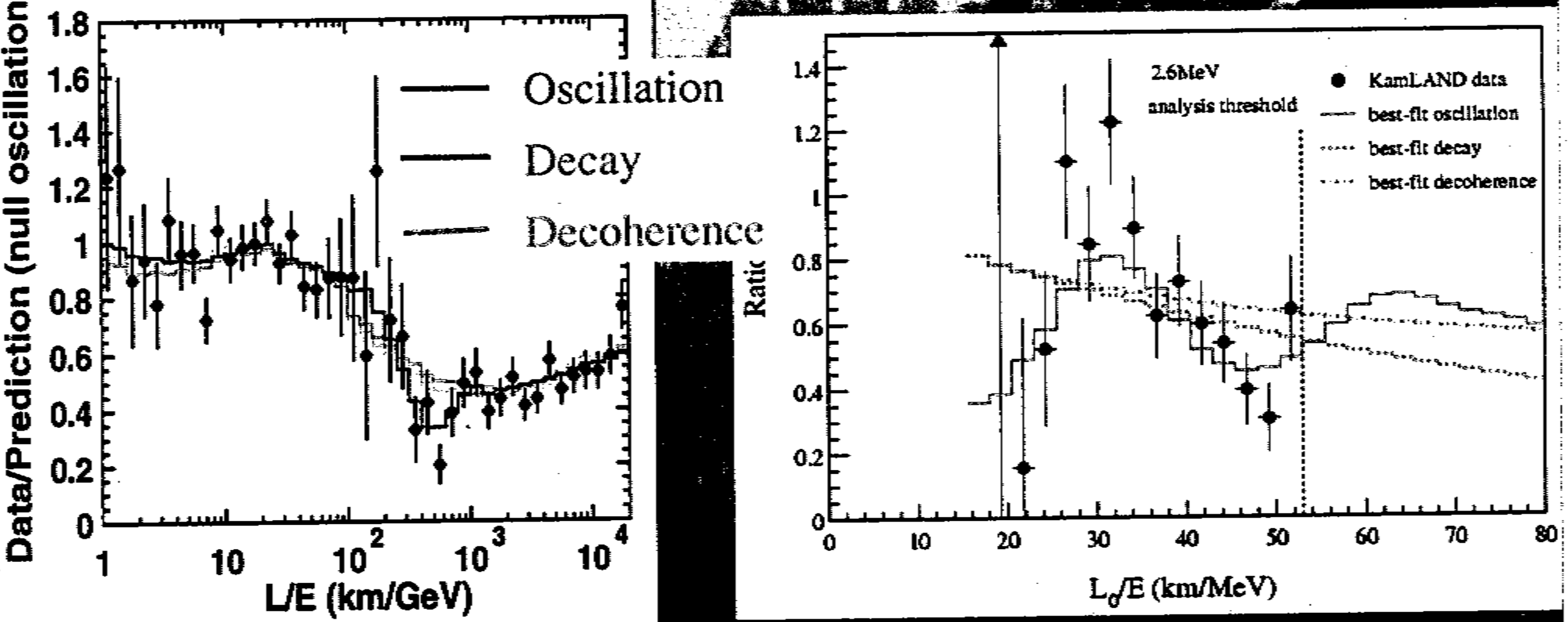
$\boxed{\text{CPX}} \rightarrow s_{13}e^{-i\delta}$

↑ atmospheric ν oscill^ns ↑ for the future ↑ solar ν oscill^ns

$$+ \ 2 \text{ Majorana phases } \boxed{\text{CPX}} \rightarrow \begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

measurable in double-β dec

Evidence for Neutrino Oscillation Pattern from Super-Kamiokande & KamLAND



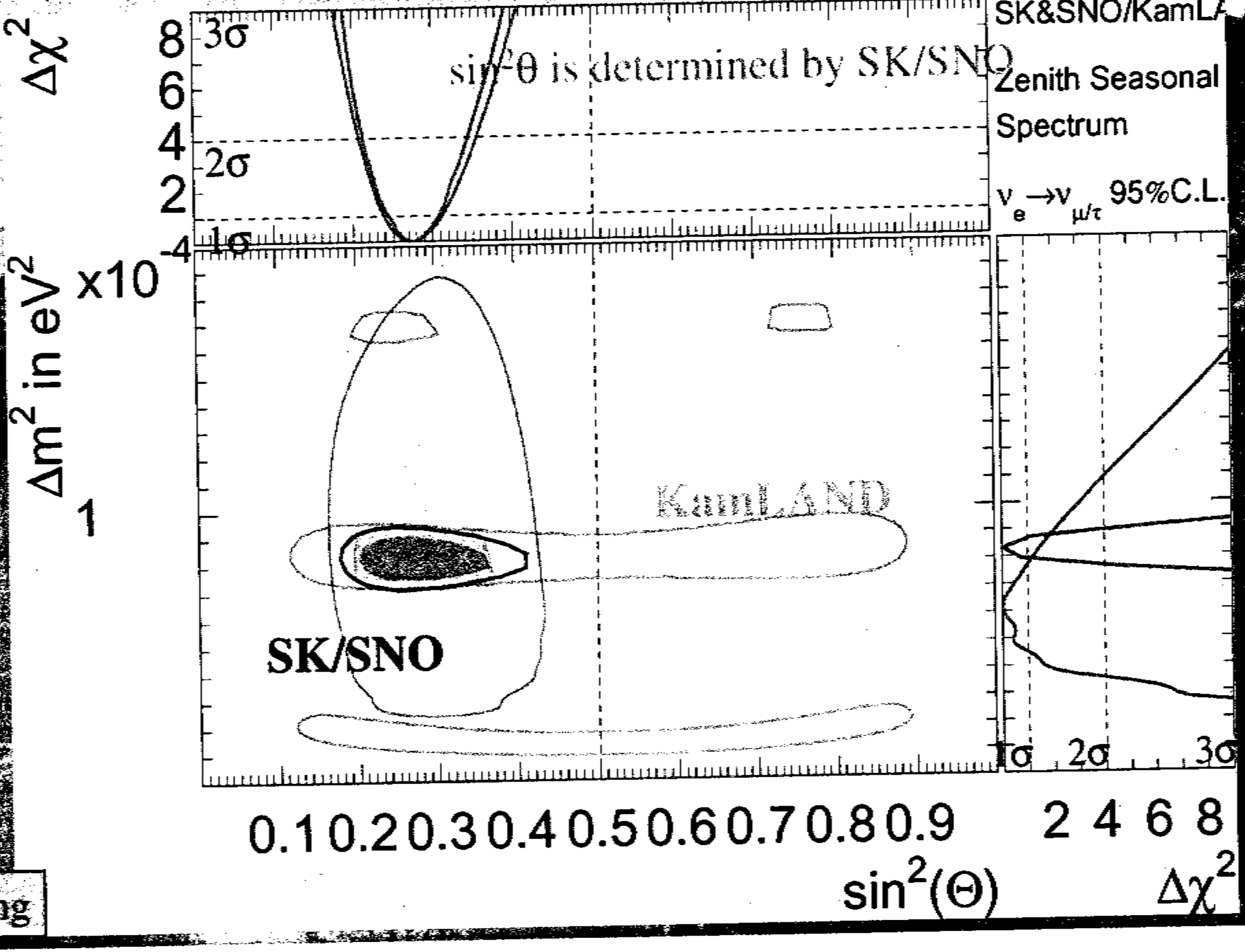
$\Delta\chi^2$ (neutrino decay – oscillation) $=11.4 \rightarrow 3.4\ \sigma$

$\Delta\chi^2$ (neutrino decoherence – osc'n) $=14.6 \rightarrow 3.8\ \sigma$

The dips in the data cannot be explained by other models

Wang

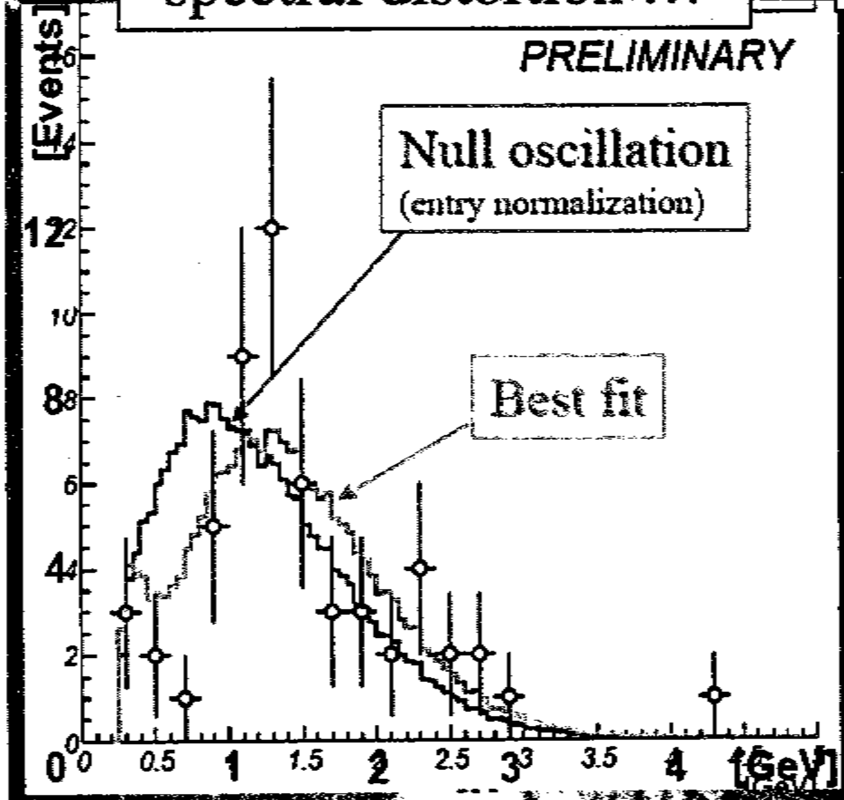
KamLAND consistent with SK/SNO



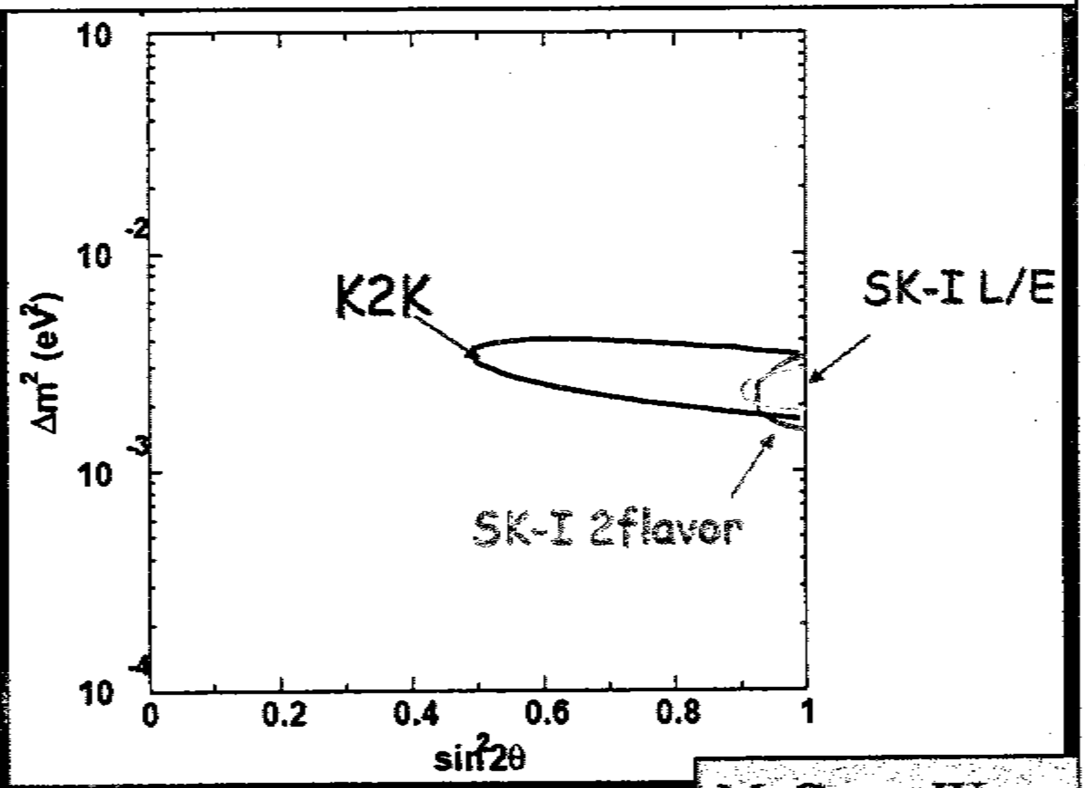
Wang

K2K confirms Super-Kamiokande

K2K Rate suppression
and
spectral distortion …



… agree with SK azimuthal distributions
and
L/E analysis



McGrew, Wang

Emerging Default Option

- Three light neutrinos
- Hierarchical masses
- ~ Bimaximal mixing

$$U_{MNS} \simeq \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -1/\sqrt{2} \\ \frac{1}{2} & \frac{1}{2} & 1/\sqrt{2} \end{pmatrix}$$

- Majorana masses
- small dipole moments
- long lifetimes

$\Rightarrow$ Questions

also ν_s? MiniBooNE

or $\left\{ \begin{array}{l} \text{degenerate? cosmolog} \\ \text{inverse hierarchy?} \end{array} \right.$

size of θ_{13} JPARC?
reactor?

$\theta_\odot + \theta_c = \pi/4$?

CP violation?
ν factory?

$\beta\beta_{0\nu}$ decay

Sun??

cosmology??

CP-Violating Observable

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

$$= 16\, s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta$$

$$\times \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

possible only if

Δm_{12}^2, s_{12} large enough: LMA ← established

θ_{13} large enough ↖ we need to know!

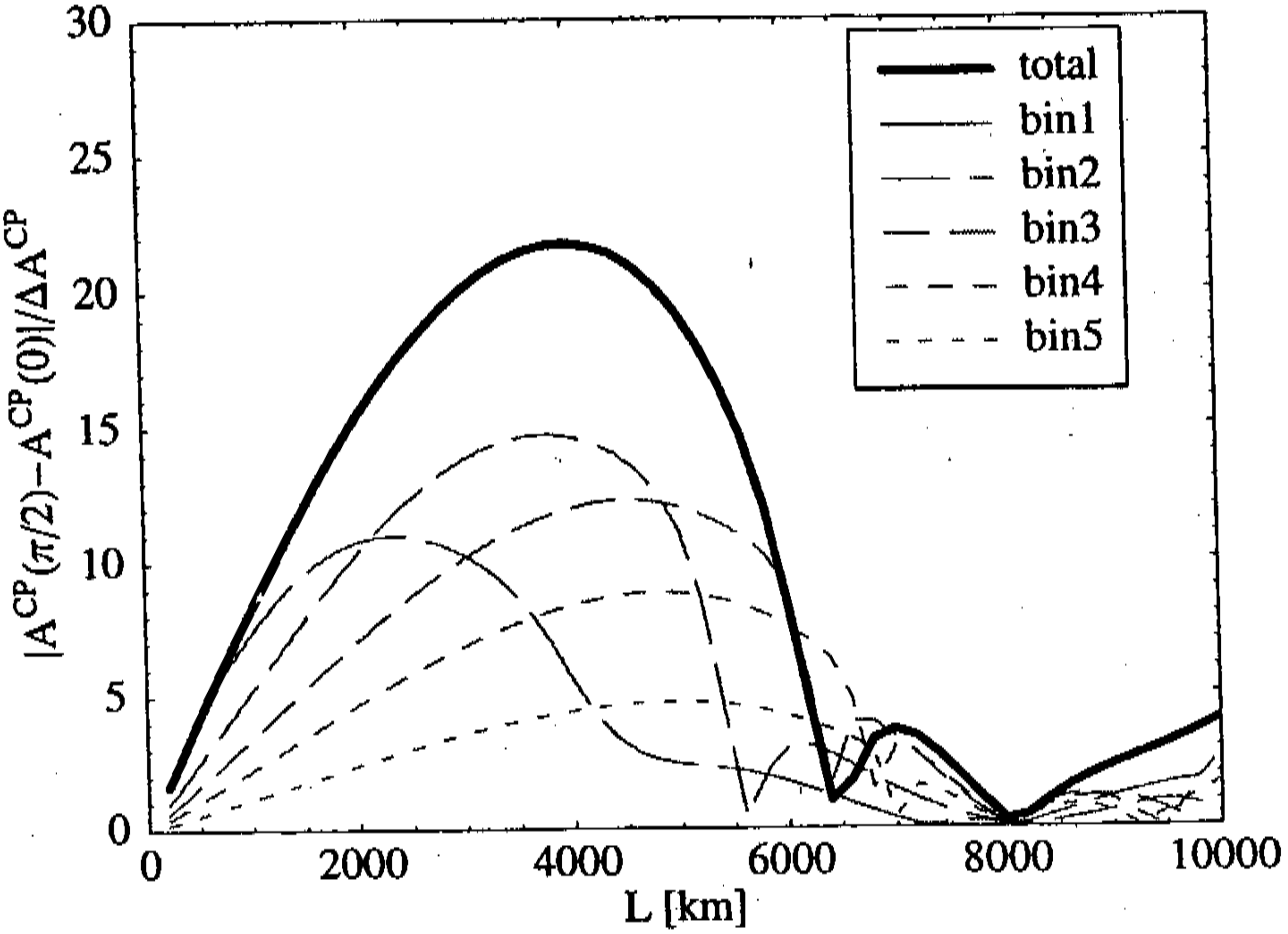
Window on leptogenesis?

Signal/Noise for CP-Violating Asymmetry

@ ν factory

$\Delta m^2_{23} = 2.8 \times 10^{-3}\ \mathrm{eV}^2$ $\theta_{12} = 22.5°$ $\theta_{13} = 13°$

$\Delta m^2_{12} = 1 \times 10^{-4}\ \mathrm{eV}^2$ $\theta_{23} = 45°$ $\delta = 90°$



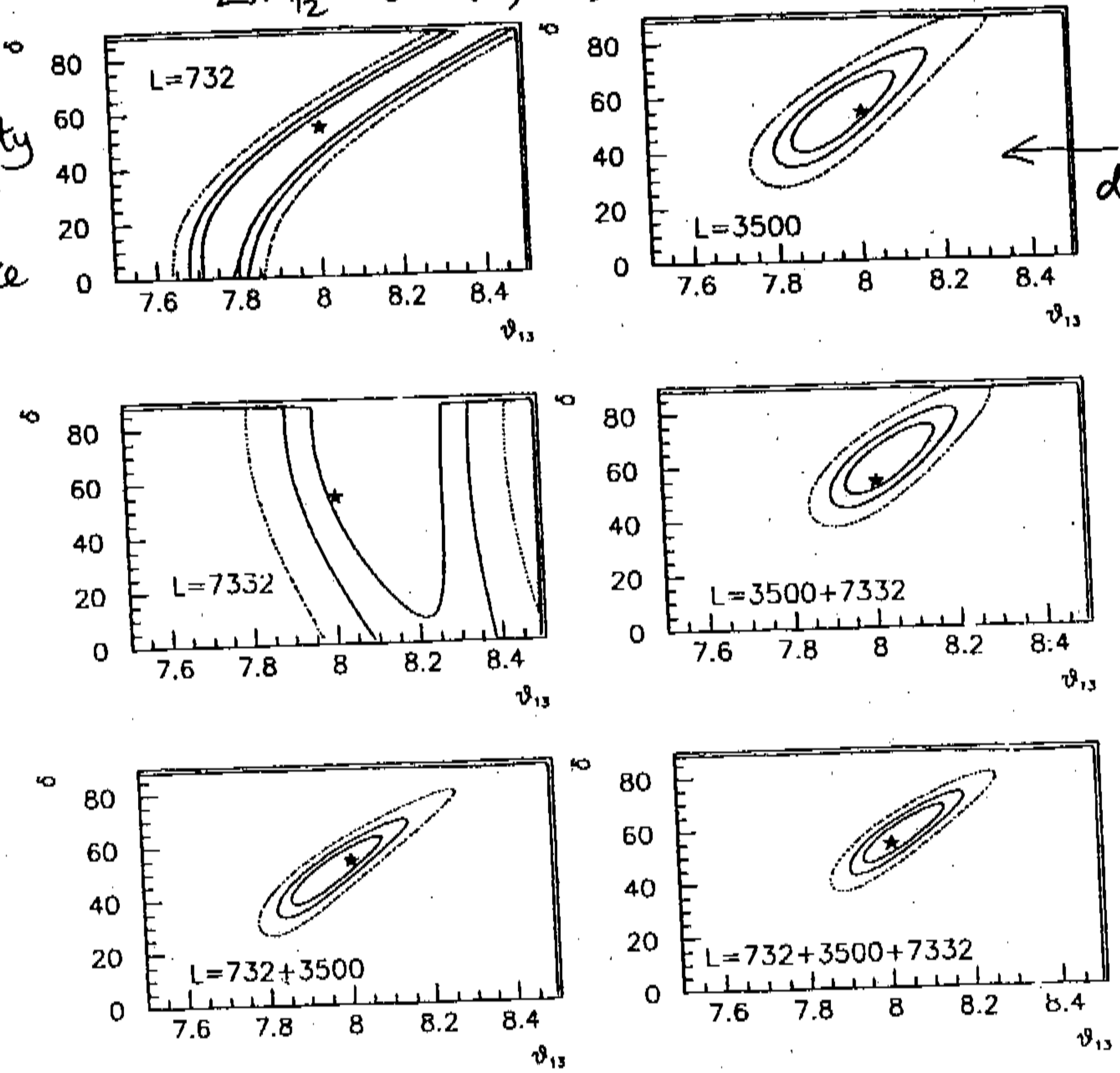
(Cervera et al.

CP-Violating Phase Measurements

@ ν factory

$\Delta m^2_{12} = 10^{-4}\,eV^2$, $\theta_{13} = 8^\circ$, $\delta = 54^\circ$

mbiguity
f just
one
istance



← good distance

including backgrounds, efficiencies

(Cervera et al.

Another Accelerator Concept for ν Physics

(Zucchelli

β beams

↳ from decays of radioactive nuclei

e.g. $^6He: n \to p e^- \bar{\nu}_e$

$^{18}Ne: p \to n e^+ \nu_e$

accelerate nuclei to ~ 150GeV/nucleon

↳ $E_\nu = \mathcal{O}(1)$ GeV

make direct comparison of pure beams:

$P(\nu_e \to \nu_e) \Leftrightarrow P(\bar{\nu}_e \to \bar{\nu}_e)$

distance ~ 130km: CERN → Fréjus ?

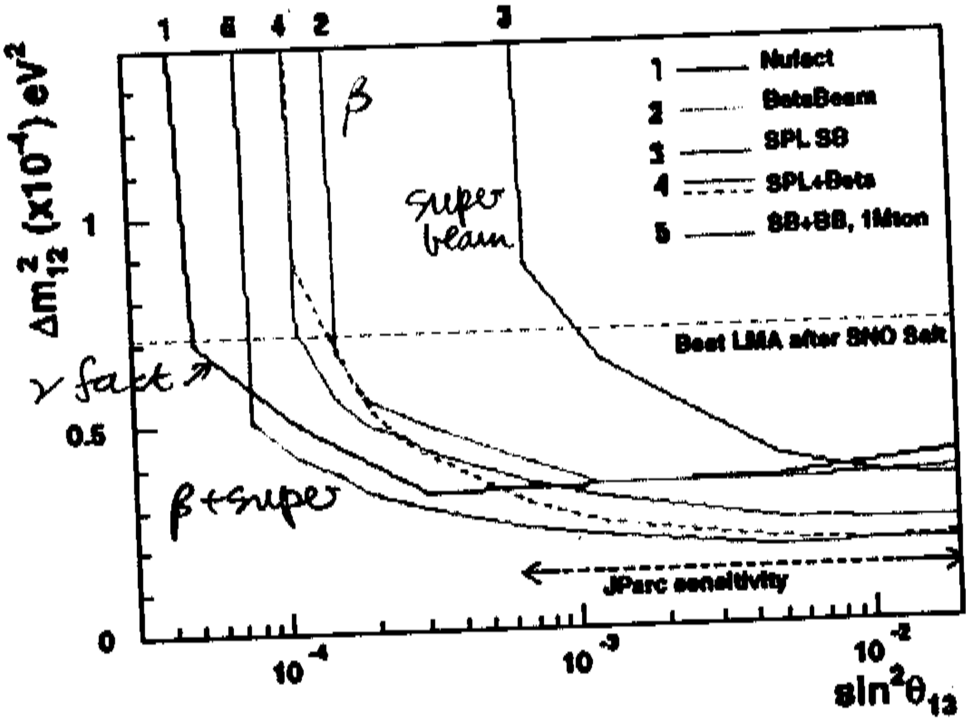
↙

routine production of radioactive ions (ISOLDE)

accelerated ion beams planned (REX-ISOLDE)

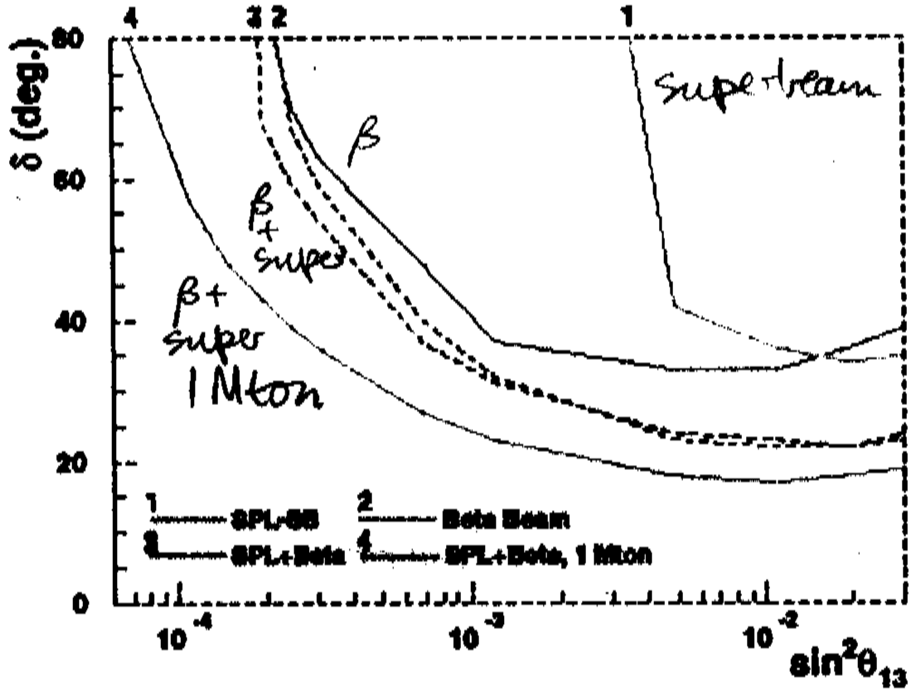
routine acceleration of stable ions in SPS

Sensitivity to θ_{13}
of different ν oscillation projects



(Bouchez + Lindroos + Mezzetto:
hep-ex/0310059

Sensitivity to θ_{13} and δ of different ν oscillation projects



(Bouchez + Lindroos + Mezzetto:
hep-ex/0310059

Parameter Counting in Seesaw Model

$$\mathcal{L}_\nu = (Y_\nu)_{ij} H \bar{N}_i \begin{pmatrix} \nu \\ l \end{pmatrix}_j + \frac{1}{2} \bar{N}_i M_{ij} \bar{N}_j$$ (Casas +Ibarra

physical parameters = 18

$$\underbrace{3m_\nu + \underbrace{(\delta, \phi_1, \phi_2)}_{CP\times} + \theta_{12,23,13}}_{9 \text{ 'observable' @ low energies}} + \underbrace{3M_\nu + \overbrace{3\alpha_H + 3\underbrace{\beta_H}_{CP\times}}^{\text{matrix } R}}_{9 \text{ heavy sector}}$$

4 'known'

+ renormalization of susy ×

Total of 6 CP-violating parameters

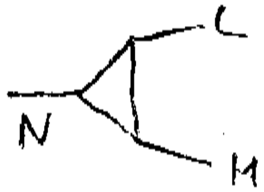
MNS phase + 2 Majorana phases ← $\beta\beta_{0\nu}$

3 extra phases control leptogenesis

Origin of baryon asymmetry?

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

possible via 1-loop CP× diagrams



Lepton asymmetry → baryon asymmetry

via non-perturbative electroweak interactions

HPt

Seesaw Parametrization

(S.E. + Hisano + Lola + Raidal

diagonalize masses of charged leptons:

$$(Y_e)_{ij} = Y^D_{e_i}\,\delta_{ij}$$

and heavy neutrinos:

$$\mathcal{M}_{ij} = \mathcal{M}^D_i\,\delta_{ij}$$

3 masses

parametrize Y_ν:

$$Y_\nu = Z^* Y^D_{\nu_k} X^\dagger$$

cf CKM matrix

1 phase
3 angles

real, diagonal

3 evalues

$$Z = P_1\,\bar{Z}\,P_2$$

cf CKM matrix

1 phase
3 angles

$$P_{1,2} = \mathrm{diag}(e^{i\theta_{1,3}}, e^{i\theta_{2,4}}, 1)$$

4 phases

leptogenesis $\propto Y_\nu Y_\nu^\dagger = P_1^*\,\bar{Z}^*(Y_\nu^D)^2\,\bar{Z}^T P_1$

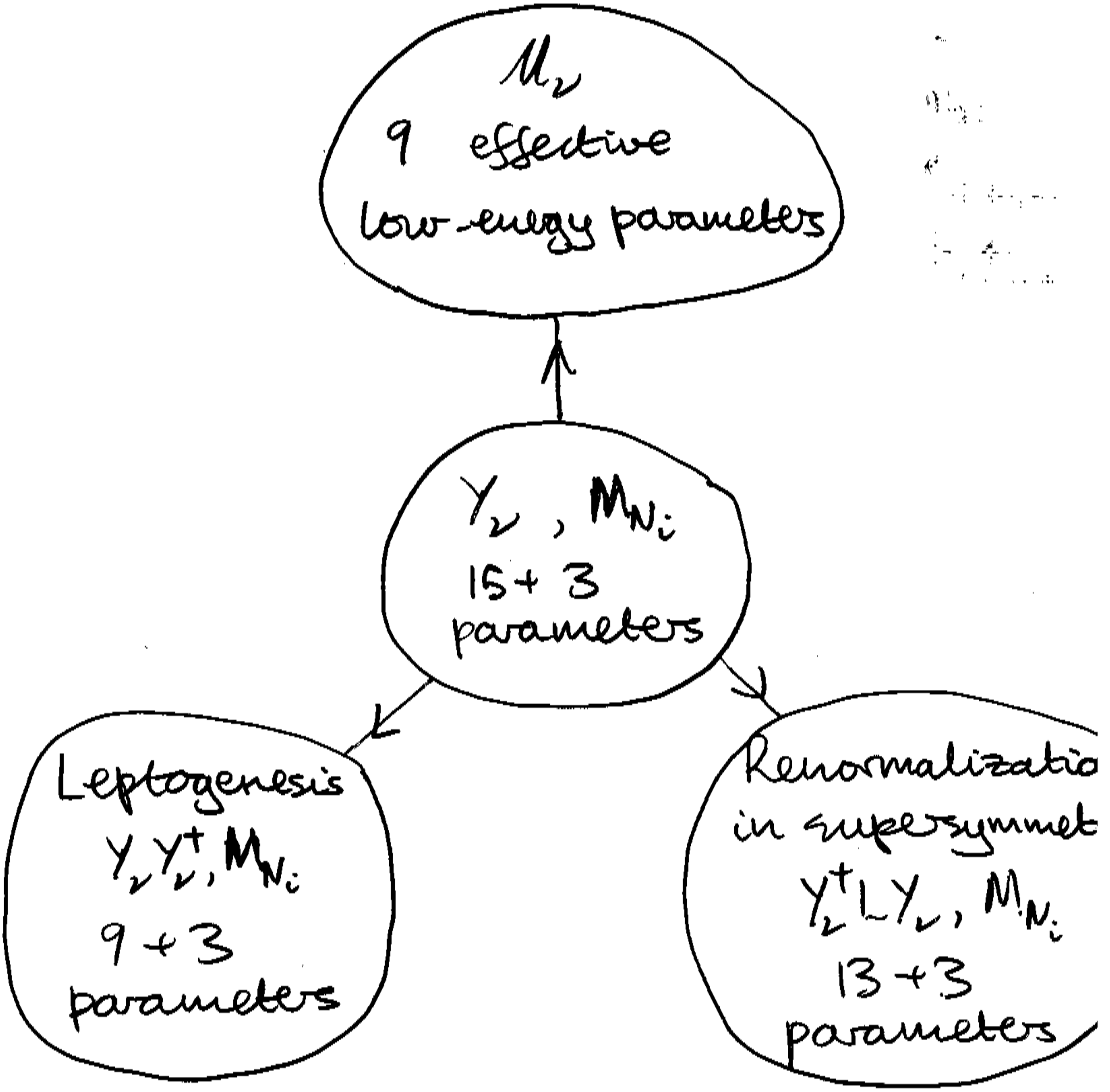
3 phases, 3 angles

leading renormalization of sparticle masses

if N_i degenerate $\propto Y_\nu^\dagger Y_\nu = X (Y_\nu^D)^2 X^\dagger$

1 phase, 3 angles

if N_i non-degenerate: 3 phases



Experimental programme to determine all parameters, calculate leptogenesis?

assuming universality @ input (Sugra/GUT) scale

Renormalization of soft susy X parameters

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

$$(\delta A_e)_{ij} \ni -\frac{1}{8\pi^2}A_0 Y_{e_i}(Y_\nu^\dagger Y_\nu)_{ij}\ln\left(\frac{M_{GUT}}{M_N}\right)$$

in leading-log approximation: degenerate

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

single 'Jarlskog' invariant

$$J_{\tilde L} = \mathrm{Im}\left[(m^2_{\tilde L})_{12}(m^2_{\tilde L})_{23}(m^2_{\tilde L})_{31}\right] \qquad 1 \text{ phase}$$

additional contribution for non-degenerate N_i

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

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

contains matrix factor

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

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

$\uparrow$ not P_1

now a total of 3 phases

(EHLR

(S.E.+Hisano+Lola+Raida
hep-ph/0109125

Slepton Mass Renormalization

assume degenerate universal $m_{\tilde{l}}^2$ @ M_{GUT}

renormalization: $\delta m_{\tilde{l}}^2 = -\frac{1}{8\pi^2}(3m_0^2+A_0^2)(Y_\nu^\dagger Y_\nu)_{ij}\ln\left(\frac{M_{GUT}}{M_N}\right)$

$\delta A_e = -\frac{3}{8\pi^2}A_0 Y_{e_i}(Y_\nu^\dagger Y_\nu)_{ij}\ln\left(\frac{M_{GUT}}{M_N}\right)$

non-universal ⇒ lepton flavour violation

e.g.

$\propto \quad (Y_\nu^\dagger Y_\nu)_{ij}$

$= \left(U\sqrt{m^d}R^\dagger M^d R\sqrt{m^d}U^\dagger\right)_{ij}$

depends on 6 phases: $\beta_i, \delta, \phi_{1,2}$

+ 6 real angles: α_i, θ_{MNS}

many low-energy observables:

$\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$; $\mu N \to eN$;

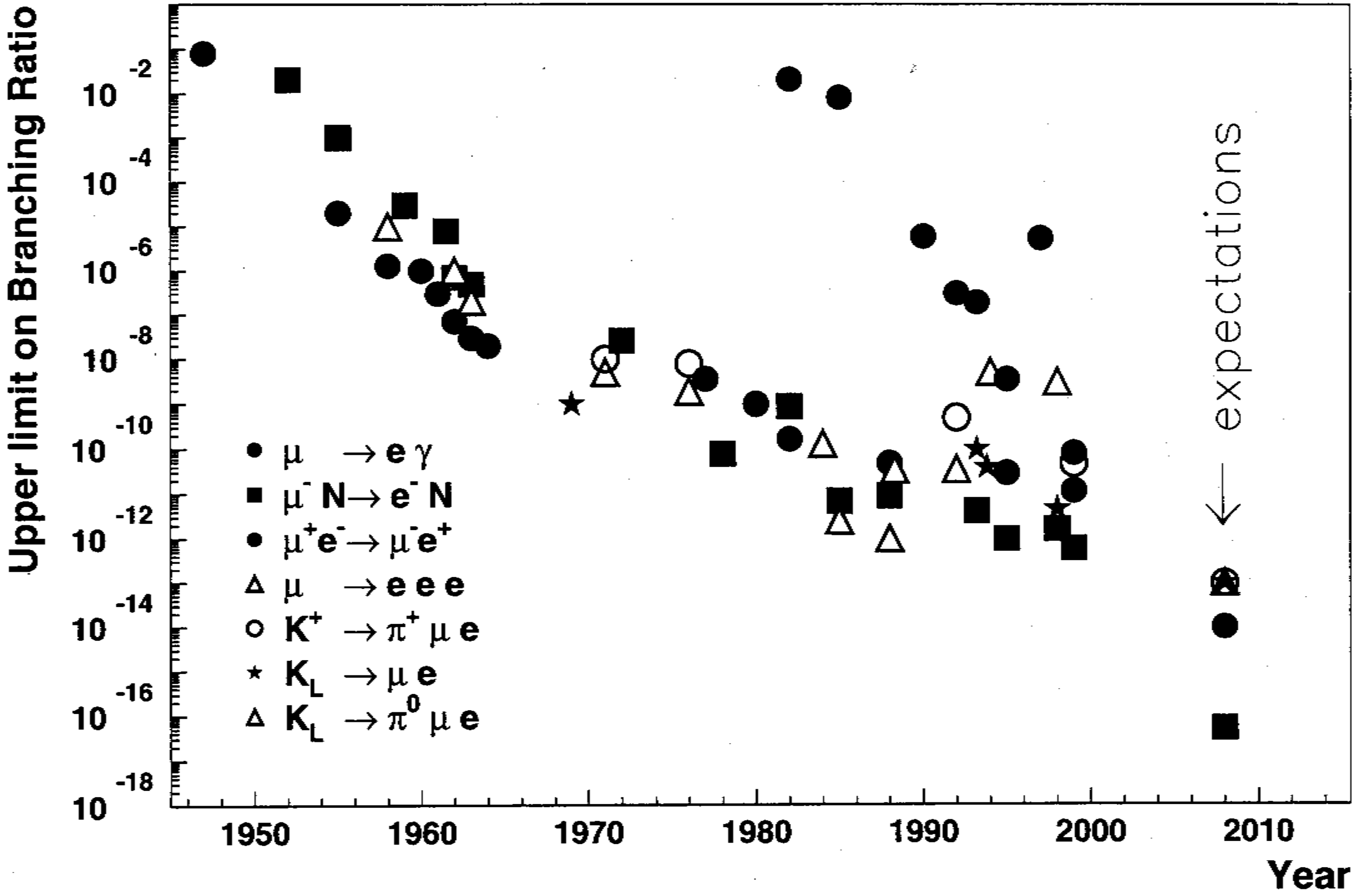
$\mu \to 3e$, $\tau \to 3e$, $e2\mu$, $2e\mu$, 3μ

many CP-violating observables:

EDM_e, EDM_μ;

$A_T(\mu \to 3e)$, ...

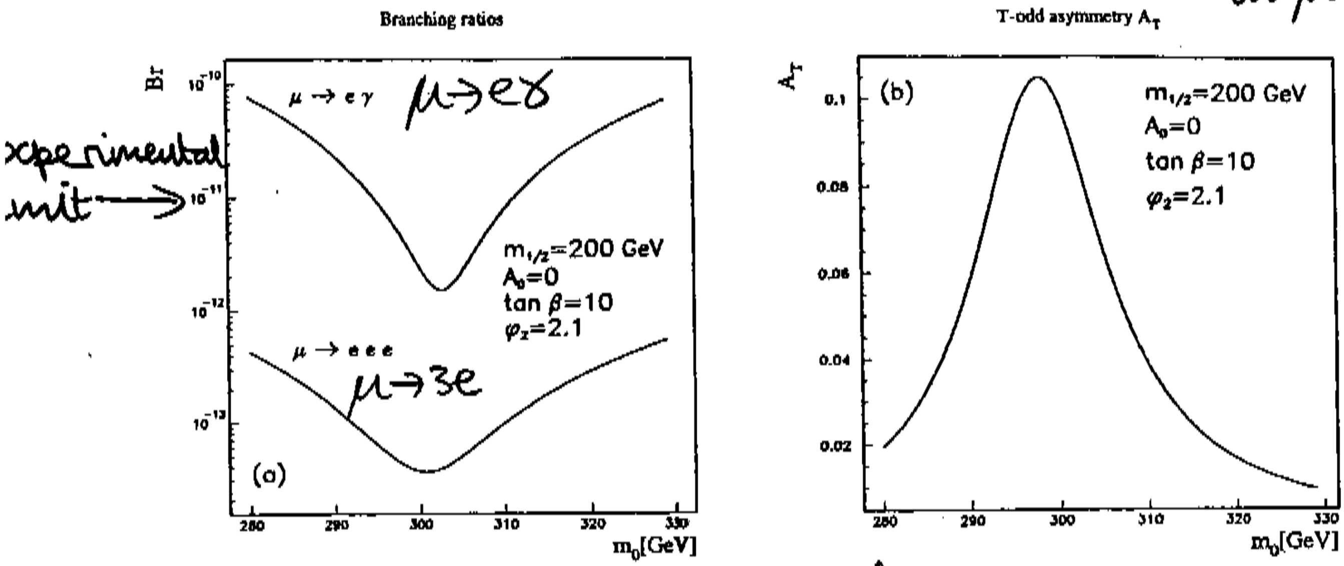
2 - Searches for Lepton Number Violation



μ LFV and CP Violation

B Ratios

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

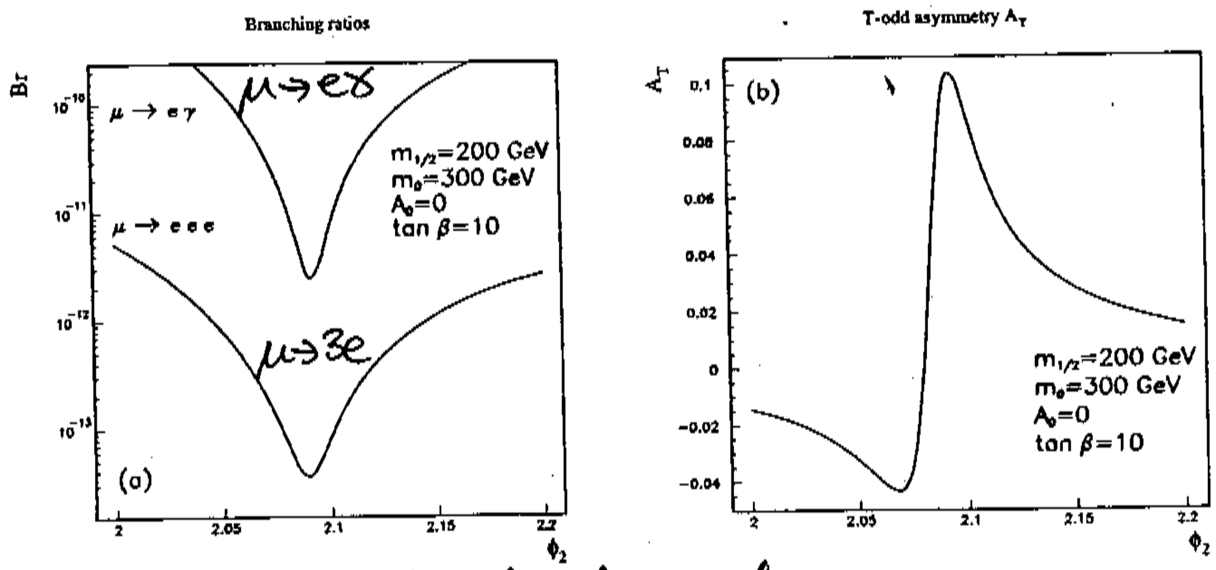


m_0 dependence

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

B Ratios

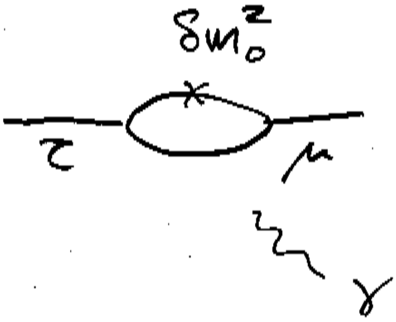
T-odd Asymmetry in $\mu \to 3e$



ϕ_2 dependence

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

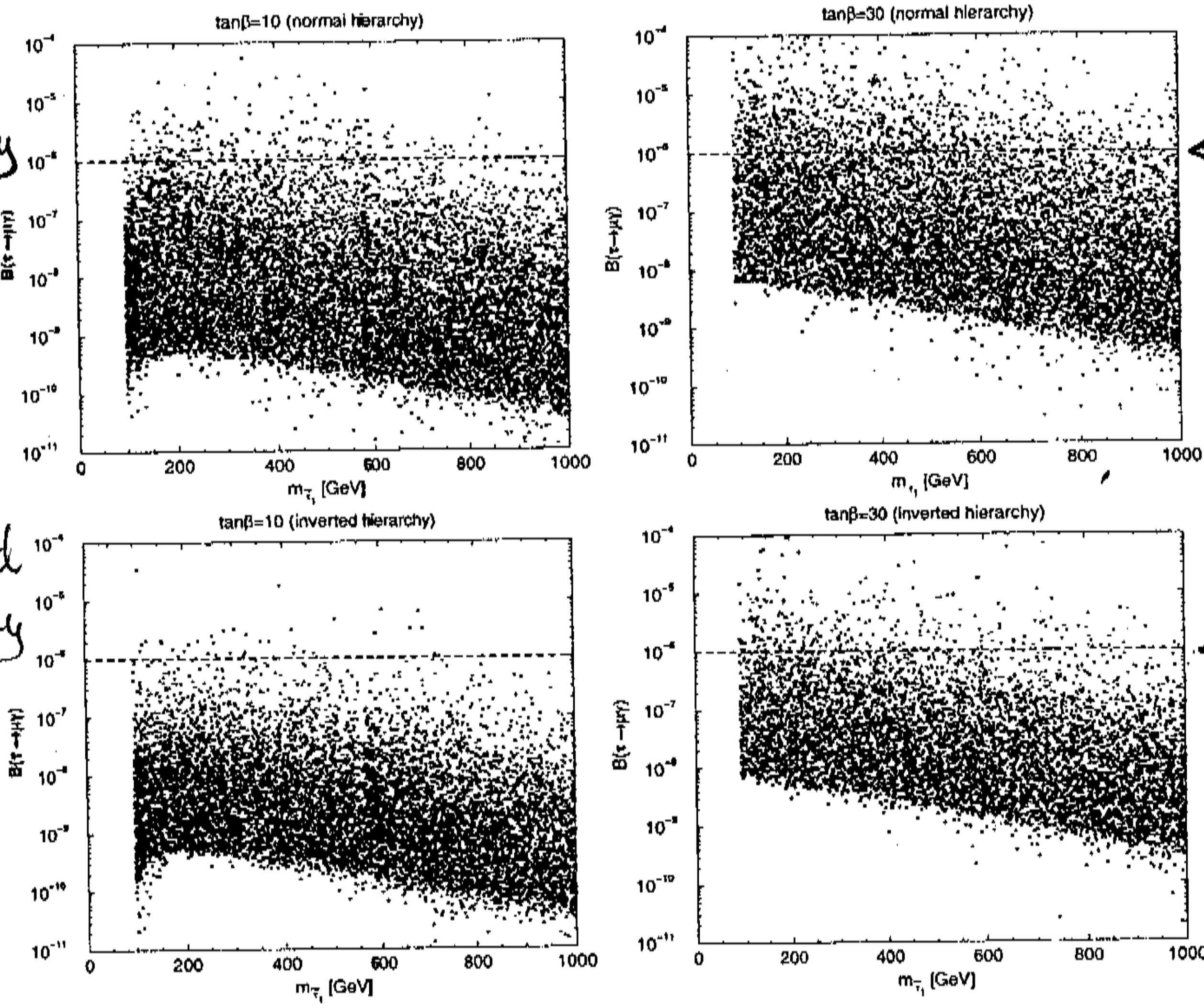
$\tau \to \mu\gamma$ decay



in texture H_1

ormal
ierarchy

nverted
ierarchy



present
upper
limit

Figure 2: *Scatter plot of* $Br(\tau \to \mu\gamma)$ *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

$\tau \to e\gamma$ decay

in texture H_2

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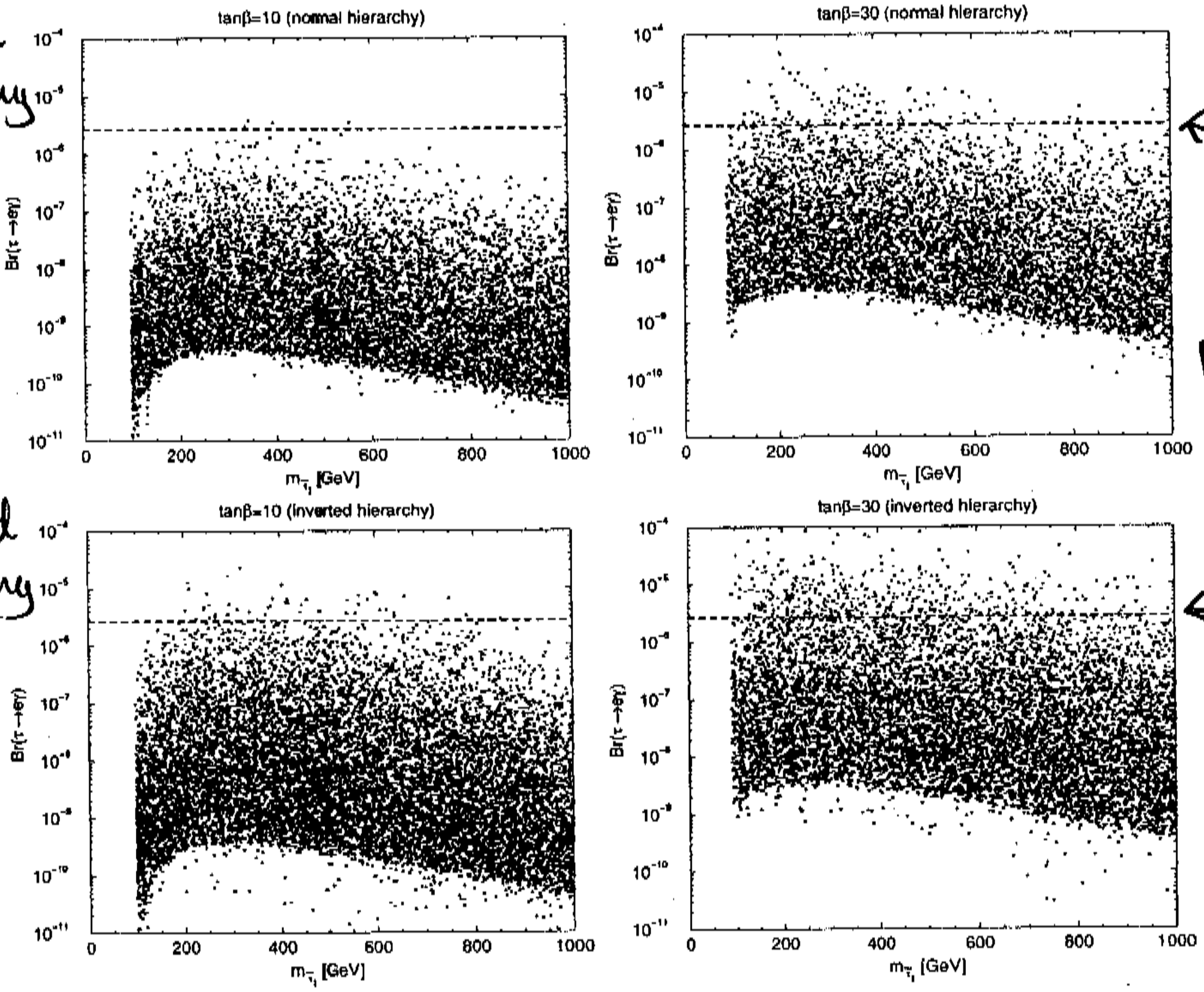
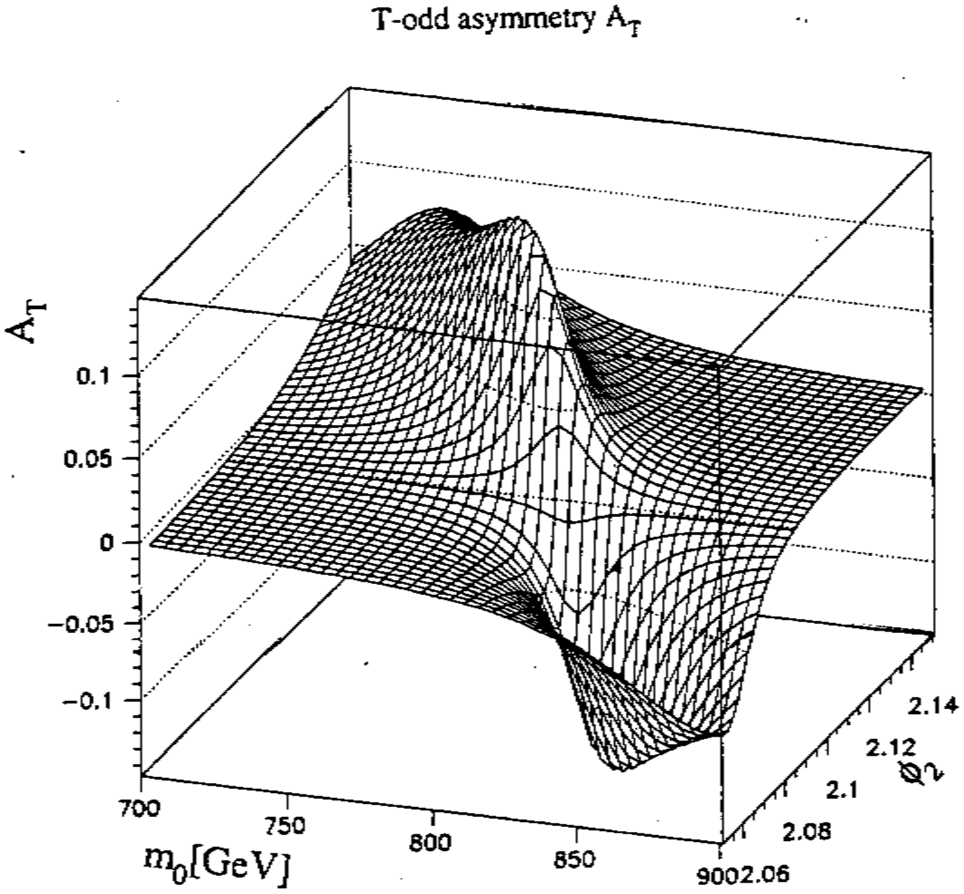


Figure 3: *Scatter plot of* $Br(\tau \to e\gamma)$ *against the lightest stau mass for the ansatz* E_2. *The input parameters for the supersymmetry-breaking parameters are the same as in Fig. 2.*

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

T-odd asymmetry in $\mu \to 3e$ decays



larger when
$B(\mu \to e\gamma)$
consistent
with experiment!

Figure 2: *The T-odd asymmetry A_T in polarized $\mu^+ \to e^+e^+e^-$ decay for the same set of parameters as in Fig. 1.*

(J.E. + Hisano + Lola + Raidal

Electric Dipole Moments

(J.E. + Hisano +
Raidal + Shimizu

- strongly enhanced if heavy neutrinos non-degenerate
- violate naive relation $d_l \propto m_l$
- depend strongly on A_0

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

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

where $L_{ij} \equiv \ln(M_N/M_{N_i})_{ij}$

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

$$\mathcal{L} = -\frac{i}{2} d_l \bar{l} \sigma_{\mu\nu} \gamma_5 l F^{\mu\nu}$$

cf $-\frac{e}{2} m_i A_{L,R} \bar{l}_j \sigma^{\mu\nu} l_{i_{L,R}} F_{\mu\nu}$
for $l_i \to l_j \gamma$

$$d_l \simeq d_l^{\chi^+} + d_l^{\chi^0}$$

present bounds ⟶ future?

$d_e < 1{\cdot}6 \times 10^{-27}$ e.cm

$d_e \to 10^{-33}$ e.cm ?
(Lamoreaux

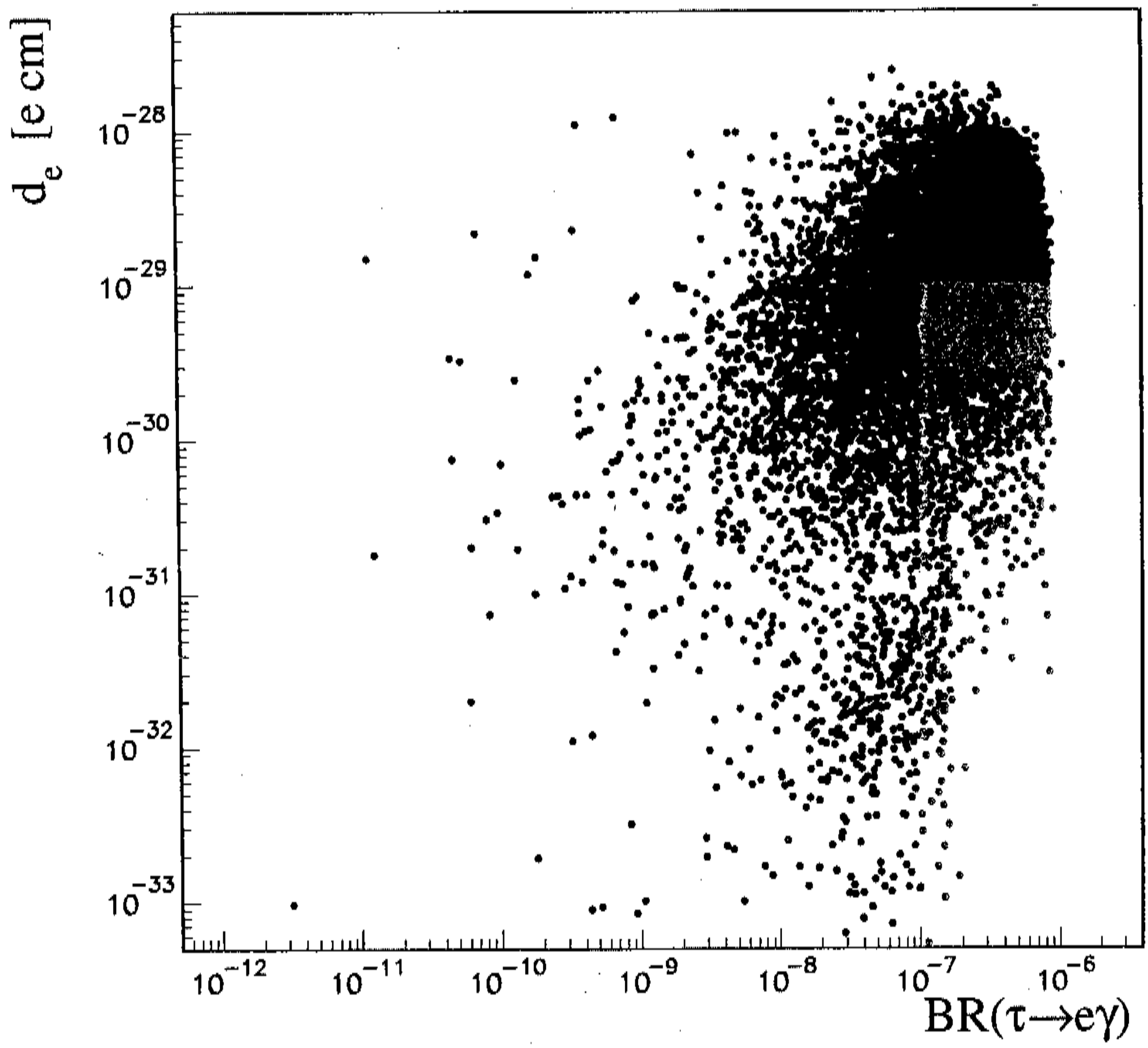
$d_\mu < 7\times10^{-19}$ e.cm

$d_\mu \to 10^{-24}$ e.cm ?
(PRISM
5×10^{-26} e.cm ?

Electron EDM vs $\tau \to e\gamma$

in texture H^2
with inverted masses

ppt



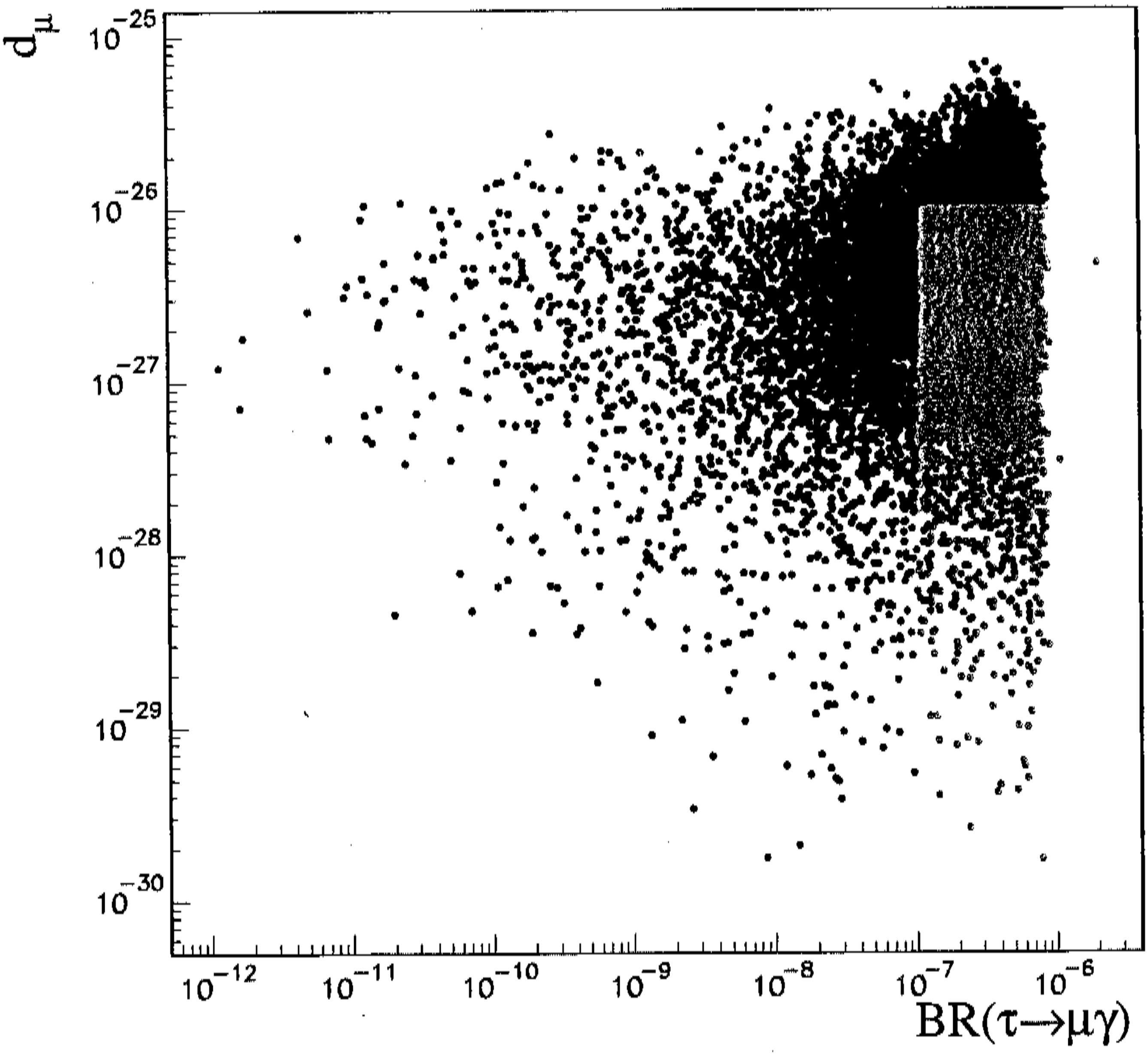
Muon EDM vs $\tau \to \mu\gamma$

in texture H'

Benchmark CMSSM parameters:

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

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



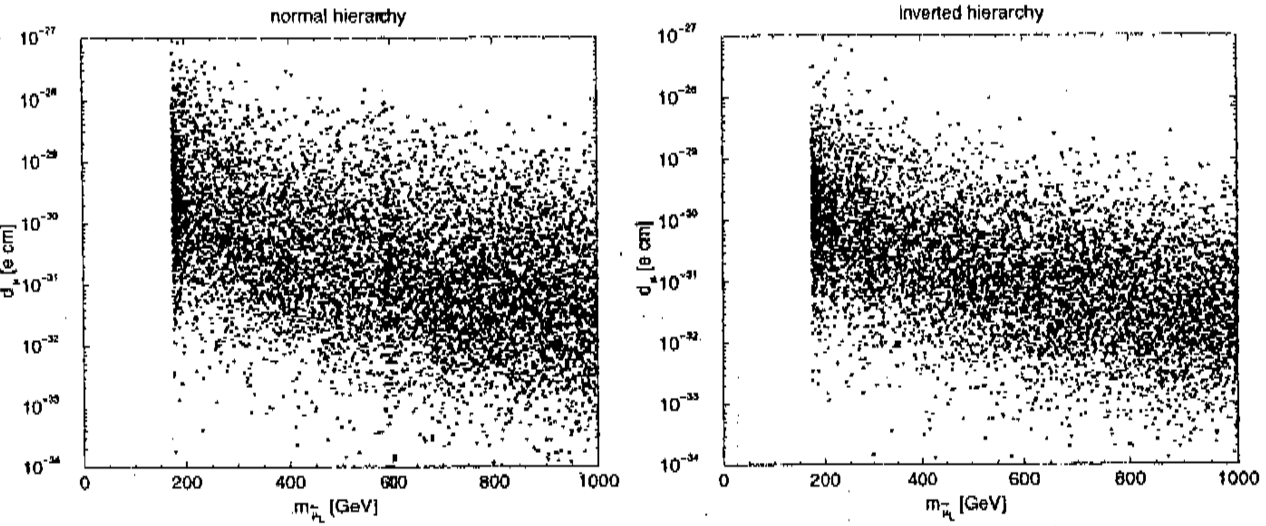
(J.E. + (Hisano) + Raidal + (Shimizu ')

Lepton Electric Dipole Moments

mass hierarchy

muon — normal — inverted

$10^{-27} \rightarrow$

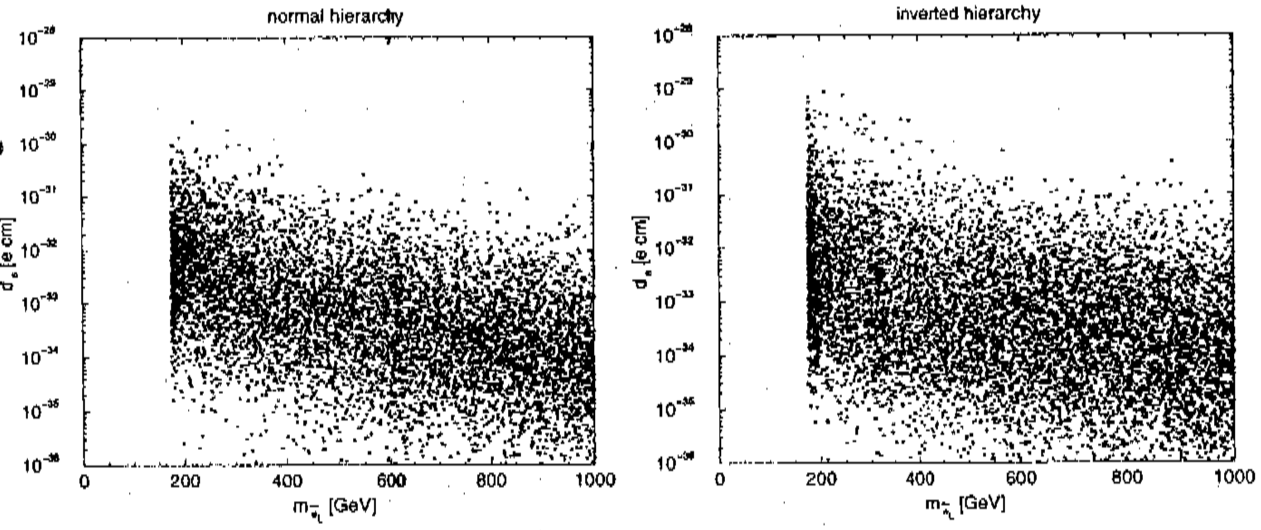


texture H^1

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

$10^{-30} \rightarrow$



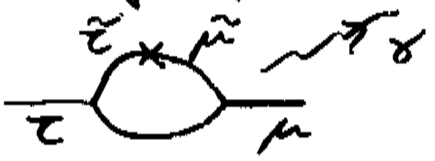
texture H^2

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.*

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

3.3 - (Not so) Rare Sparticle Decays

- suppression of rare τ (μ) decays due to large sparticle masses, loop effects



not necessarily small intrinsic slepton mixing

- lepton flavour violation could be large in sparticle decays? (Hinchliffe + Paige, ...

  most accessible @ LHC:

$$\chi_2 \to \chi \; (l^+ l^-)$$

(Carvalho + J.E. + Gomez + Lola + Romão

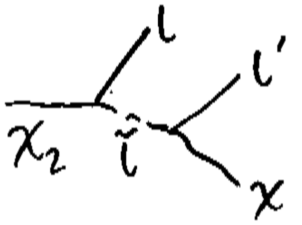
- largest LFV effects potentially in

$$\chi_2 \to \chi \; (\tau^\pm \mu^\mp) \; , \; \chi_2 \to \chi \; (\tau^\pm e^\mp)$$

- most important in 'coannihilation' region

- complementary to searches for $\tau \to \mu\gamma$, $\tau \to e$

Lepton Flavour Violation in Sparticle Decay



$$\chi_2 \to (e\mu)\,\chi$$

$m_{1/2} = 300$ GeV
$m_0 = 100$ GeV
$\tan\beta = 2.1$
$\mu = 498$ GeV
(CMSSM
≡ mSUGRA)

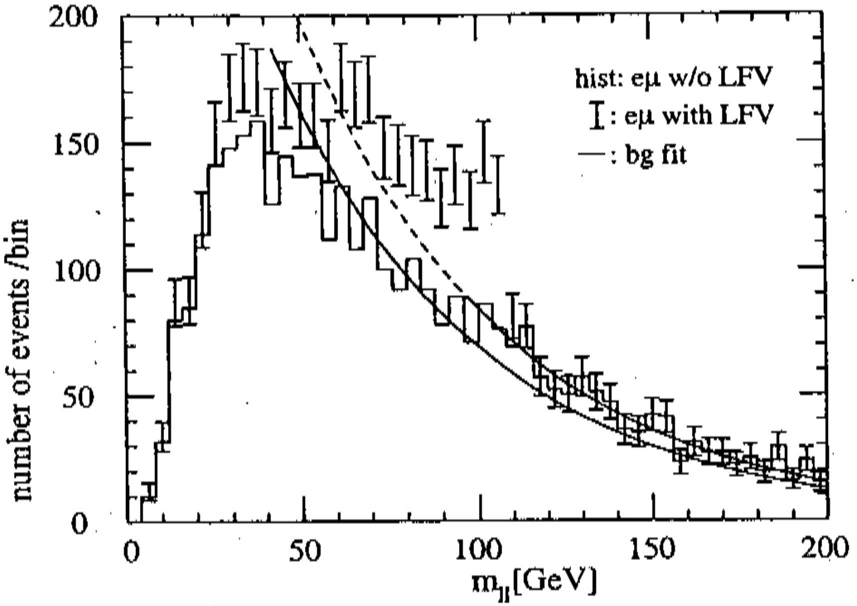
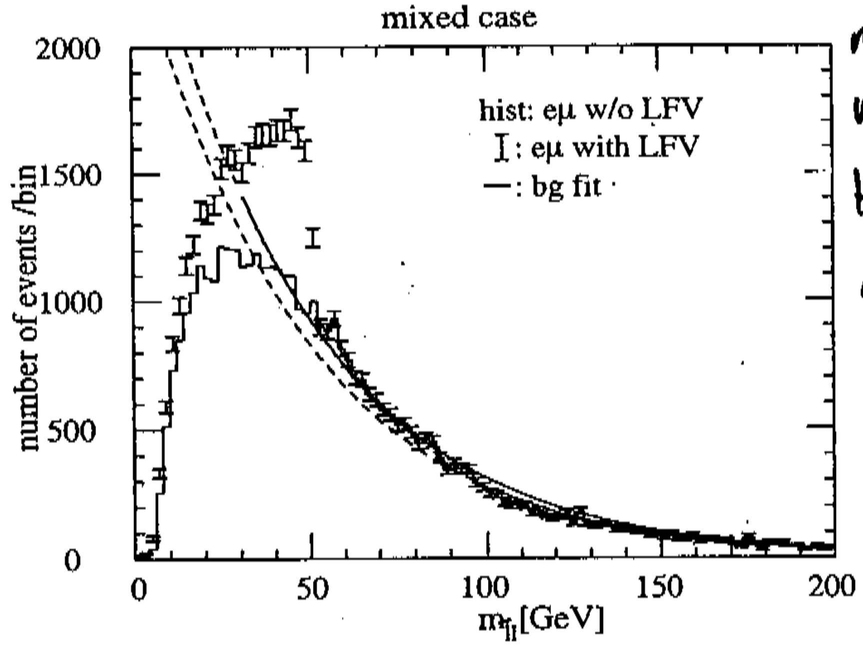


Figure 5: The $m_{e\mu}$ distribution for point I). The data corresponds to integrated luminosity of 95 fb^{-1} and standard cuts are applied (see text). The histogram shows the distribution without LFV, while bars are number of events and the error with $\tilde{\mu}$-$\tilde{e}$ mixing. In the plot, 1/30 of $\tilde{\chi}_2^0 \to \tilde{l}'' l$, $\tilde{l}'' \to \chi_1^0 l'$ 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 GeV(solid) and m_{ll} = 100–200(dashed then solid). We use $c = 12.1$.



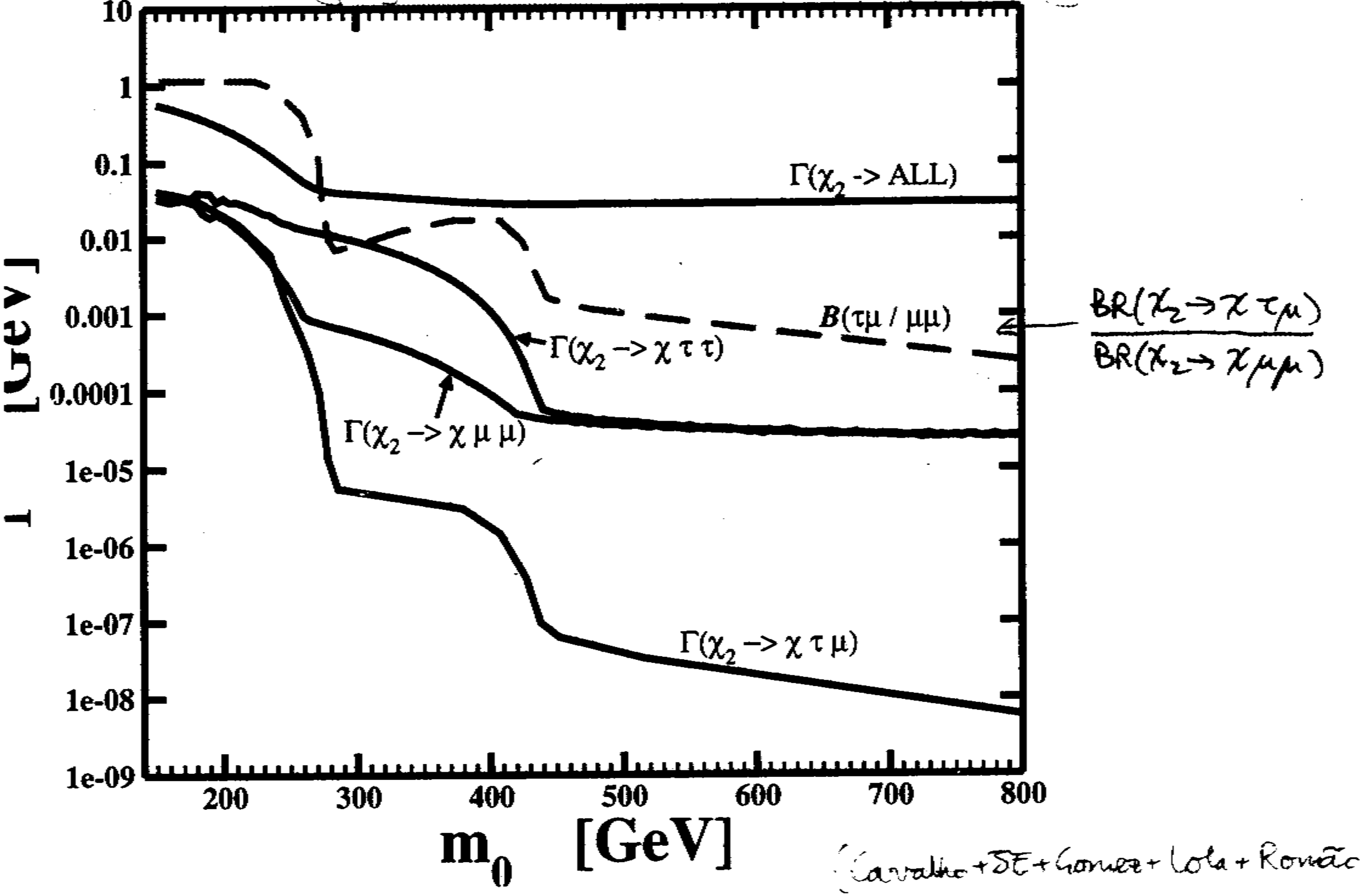
$m_{1/2} = 250$ GeV
$m_{16} = 90$ GeV
$\tan\beta = 10$
$\mu = 200$ GeV
non-universal
m_0

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

(Hisano+Kitano+Nojiri : hep-ph/0202129

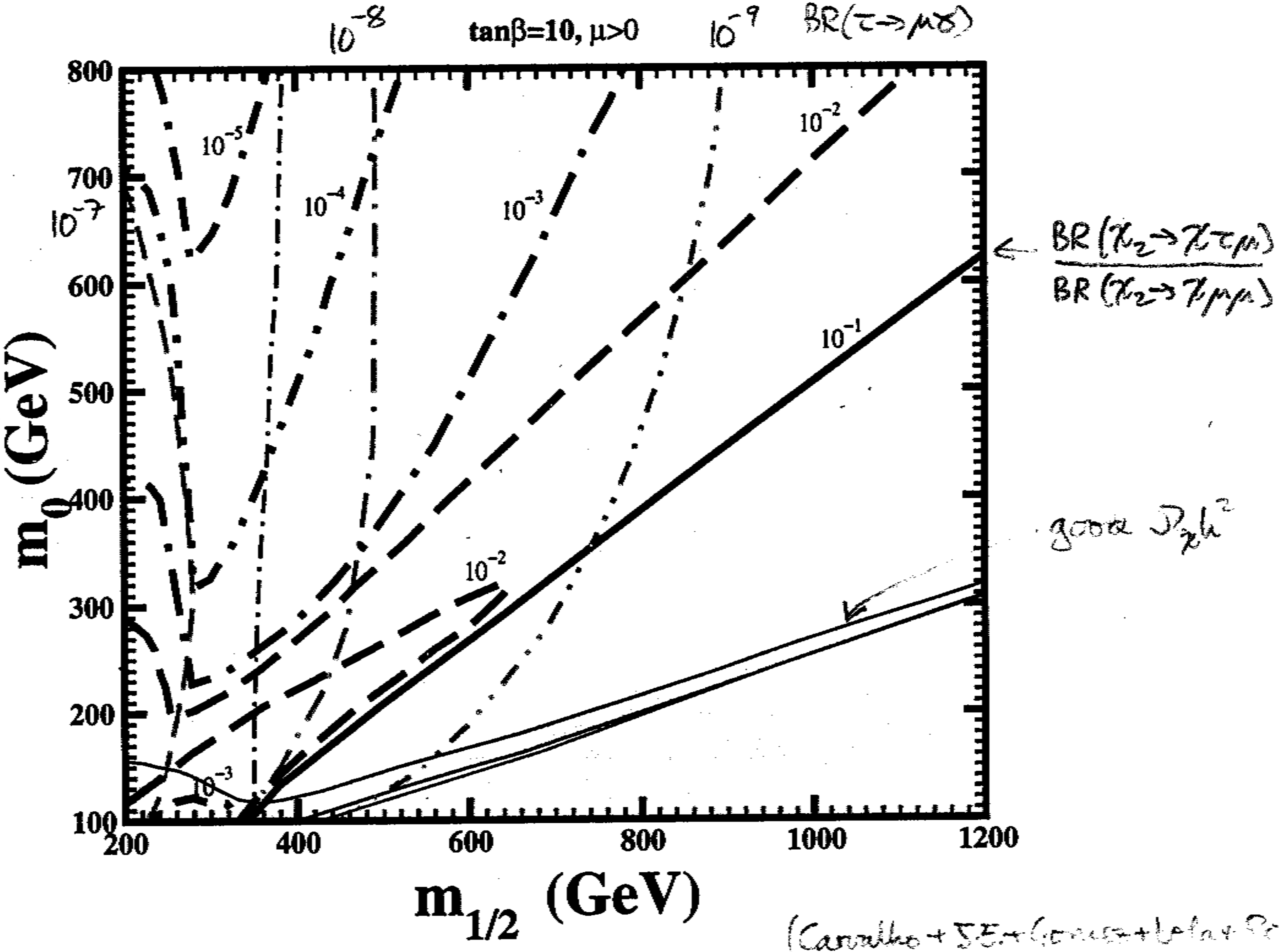
$\chi_2 \to \chi \tau \mu$ $\tan\beta = 10$ $\mu > 0$ $m_{1/2} = 600$ GeV

mixing angle → $\phi = \pi / 6$ $x=0.9$ ← non-universality



Carvalho + ΣE + Gomez + Lola + Romão

Observability of $\chi_2 \to \chi \tau \mu$ Decay



(Carvalho + J.E. + Gomez + Lola + Romão

The Origin of Matter? (Sak[illegible])

Why is there matter in the Universe, but no antimatter?

Need small matter excess in early Universe

$$\# q > \# \bar{q}$$

th[illegible] $\bar{q}$ annihilated [illegible] us

3 necessary conditions for creating matter excess

1) diffeent interactions for matter, antimatter
   ↑ fo[illegible]d [illegible] Mod
2) interactions changing quark number
   ↑ i[illegible]
   ↑ non-pe[illegible] effects in St[illegible]
   p[illegible] effects [illegible] Theory
3) breakdown of thermal equilibrium
   ↑ at breaking of [illegible]

$t \sim 10^{-35}$ to 10^{-10} seconds

If matter excess due to electroweak interactions

Then possible direct link between laboratory measurements and density of matter in Universe

1985 in Gorki

(Sakharov

(Fukugita + Yanagida,
....

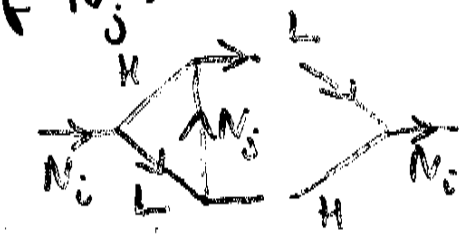
Leptogenesis

asymmetry in decays of heavy neutrinos

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

asymmetry due to exchange of N_j:

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



known kinematic function

where

$$(Y_\nu Y_\nu^\dagger) = \left(\sqrt{M^d}\, R\, m^d R^\dagger \sqrt{M^d} \right)$$

sum over light leptons ⇒

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

compact expression:

$$(Y_\nu Y_\nu^\dagger)_{ii} = M_i \,(R m^d R^\dagger)_{ii}$$

$$((Y_\nu Y_\nu^\dagger)_{ij})^2 = M_i M_j \,((R m^d R^\dagger)_{ij})^2$$

decay asymmetry:

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

depends only on β_i ← extra phases

How to measure them?

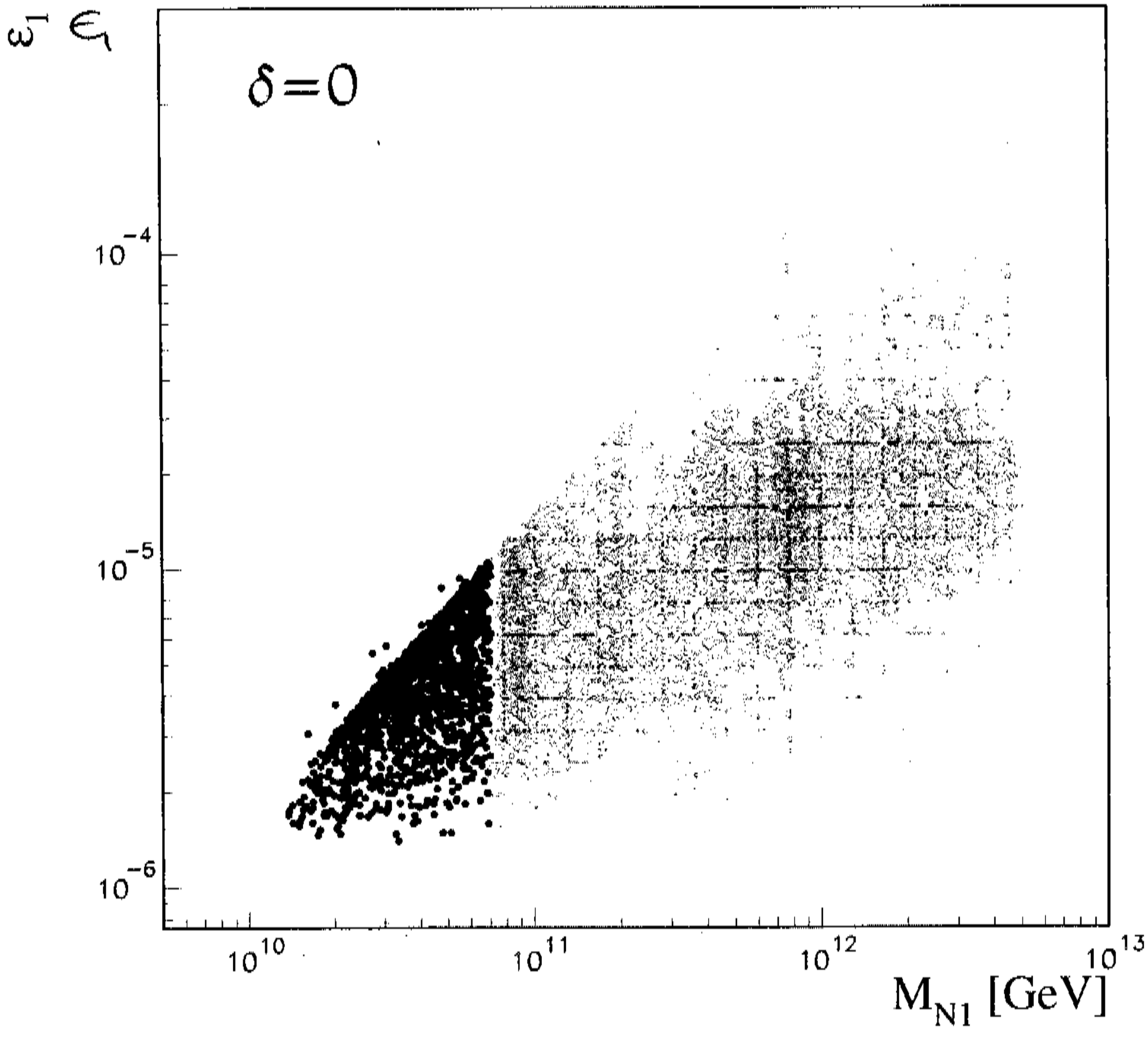
in minimal supersymmetric seesaw model

Leptogenesis Asymmetry

without CP violation in ν oscillations

in decays of heavy neutrinos

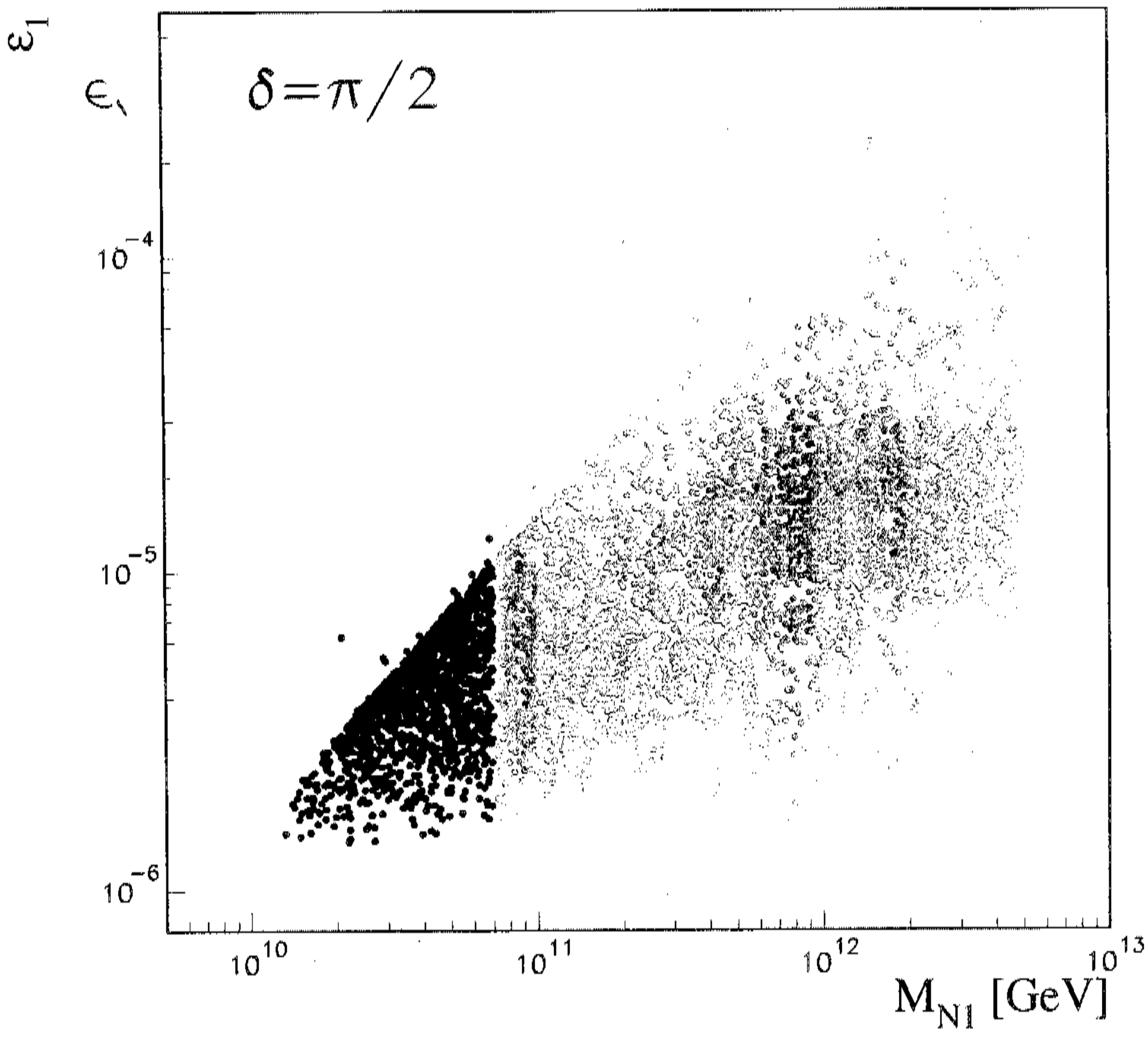
$\Delta L \propto$



(J.E. + Raidal: hep-ph/0206174

with $\not{C}\not{P}$ violation in ν oscillations

ΔL. α



(J.E. + Hisano
+ Lola + Raidal

Two-generation model

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

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

leptogenesis

$$\propto \mathrm{Im}\left[(Y_\nu Y_\nu^\dagger)^{21} (Y_\nu Y_\nu^\dagger)^{21} \right] = - \frac{(m_{\nu_1}^2 - m_{\nu_2}^2) M_1 M_2}{2 v^4 \sin^4\beta} \underset{\uparrow}{\sinh 2\theta_i} \sin 2$$

one phase unrelated to Majorana, no oscillation δ

renormalization

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

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

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

$$\beta\beta_{0\nu} \Rightarrow \phi$$

$$\mathrm{Re}, \mathrm{Im}\, (Y^\dagger Y) \Rightarrow \theta_r, \theta_i$$

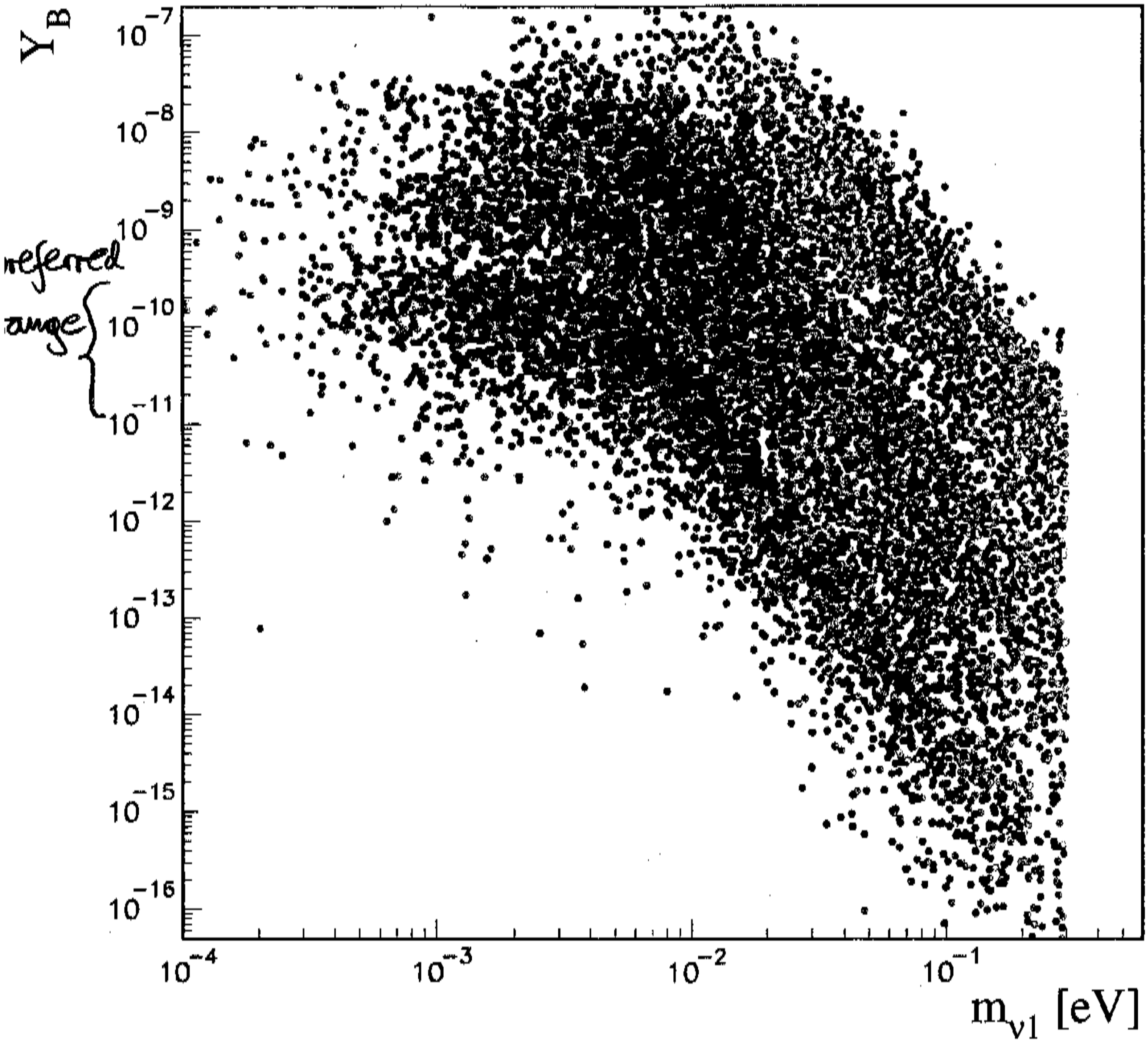
low-energy renormalization $f(\delta, \phi, \text{Leptog})$

+ determine low-E ν phases (δ, ϕ)

$\Rightarrow$ can calculate leptogenesis

Y_B vs m_{ν_1}

in texture H'

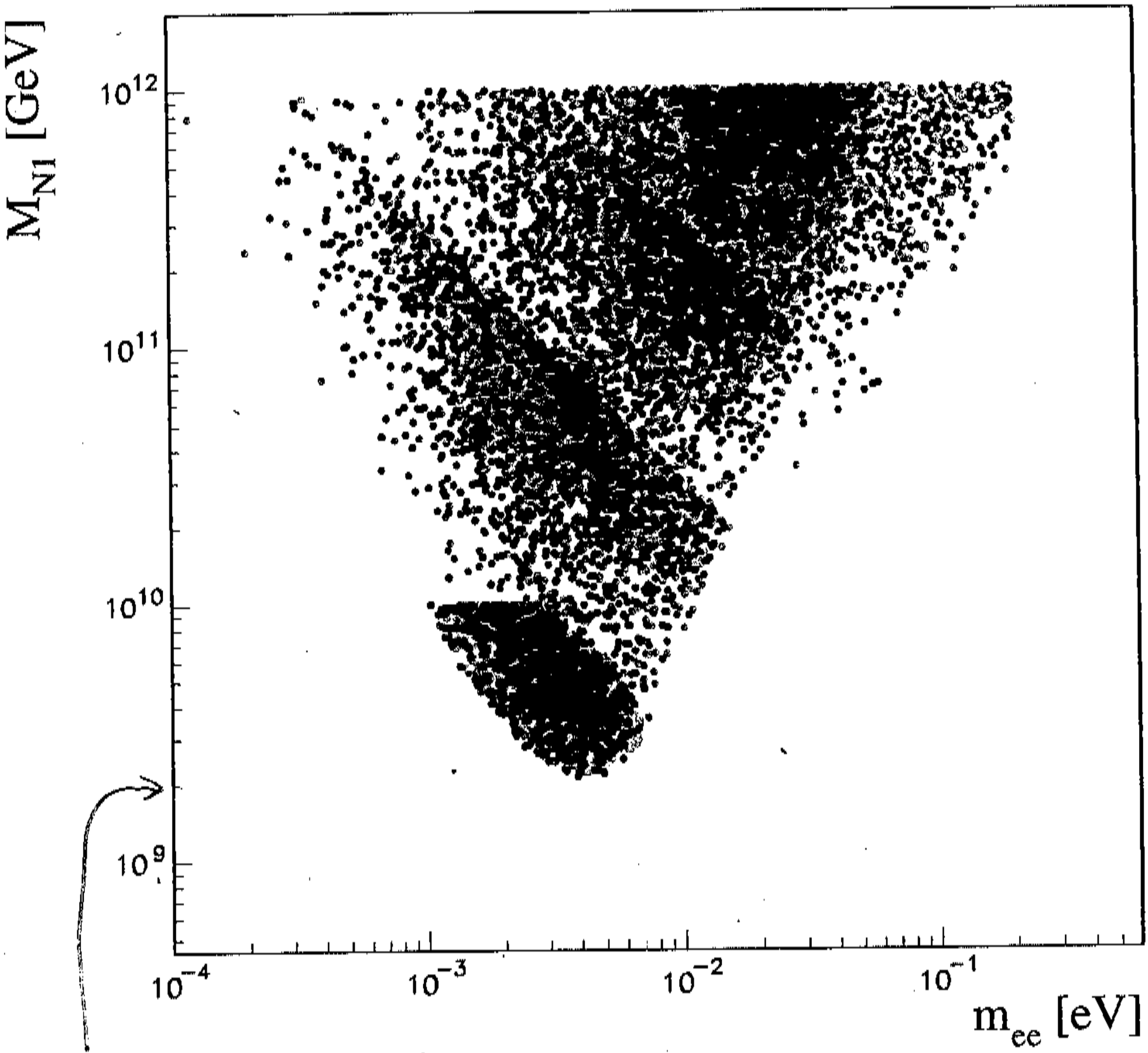


(E(H)R(S'))

Lightest heavy ν vs $\beta\beta_{0\nu}$ decay

in texture H'

for $10^{-11} \lesssim Y_B \lesssim 3\times10^{-10}$



experimental limit

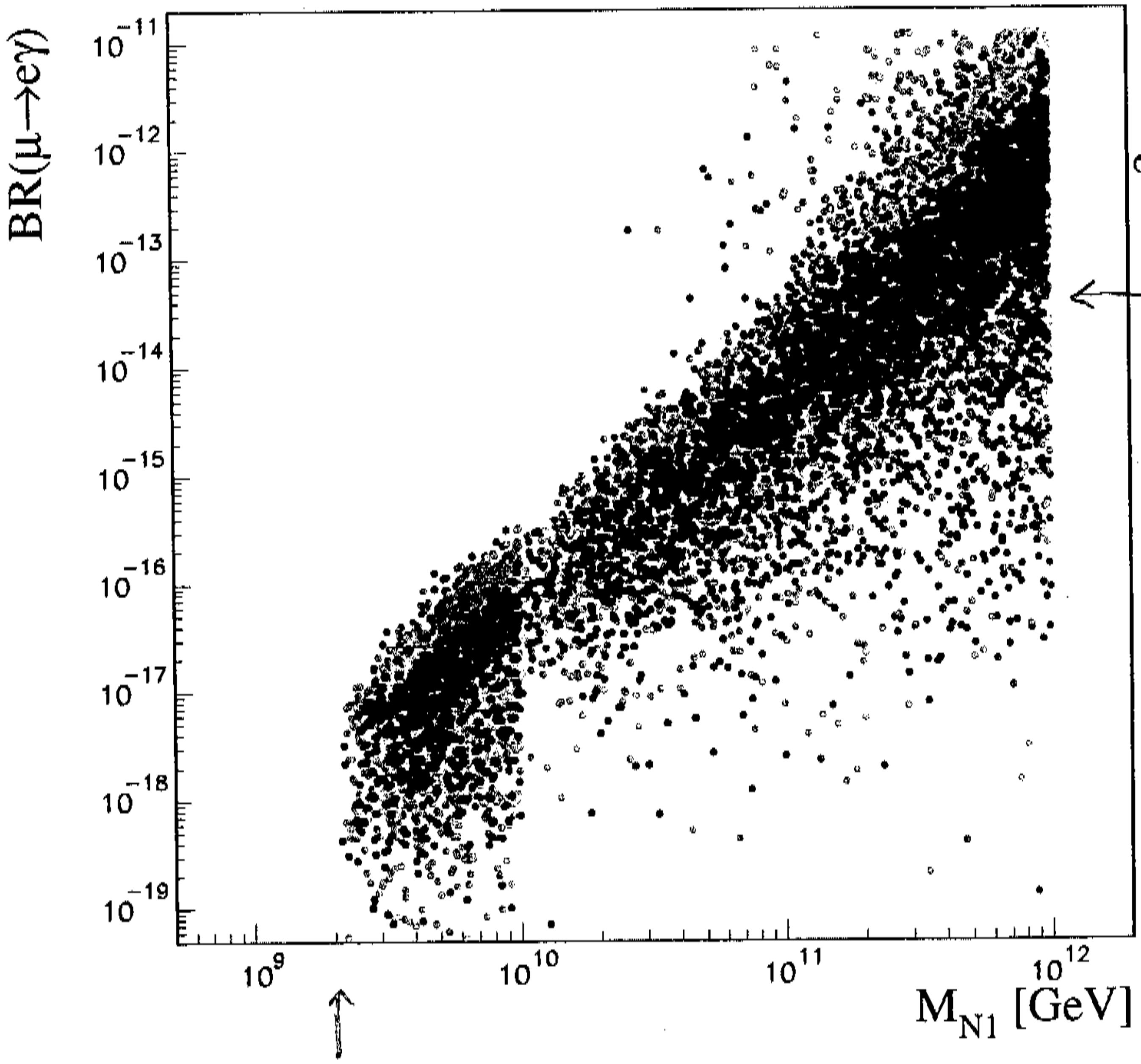
lower limit: problematic for gravitinos if leptogenesis from thermalized N_1

(JE + Raidal: hep-ph/0206174)

$\mu \to e\gamma$ vs lightest heavy ν

in texture H'

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



observable in many models: would ⇒ large m_{N_1}

lower limit: problematic for gravitinos if leptogenesis from thermalized N_1

(EHRS'

35 Could the Inflaton be a Sneutrino?

(Murayama + Suzuki + Yanagida + Yokoyama: 1993, 1994

need massive scalar $m \sim 10^{10} - 10^{15}$ GeV

without gauge interactions (⇔ potential flat)

sounds like heavy singlet sneutrino $\tilde{N}$.

mass in correct range

need not have gauge interactions (X SO(10)?)

tailor-made for leptogenesis?

if so, inflation ⟷ rest of physics

can calculate baryon density via

leptogenesis in inflaton decay

Predictions for lepton flavour violation

$\mu \to e\gamma$, $\tau \to \mu\gamma$, ...

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

WMAP combining 5 bands

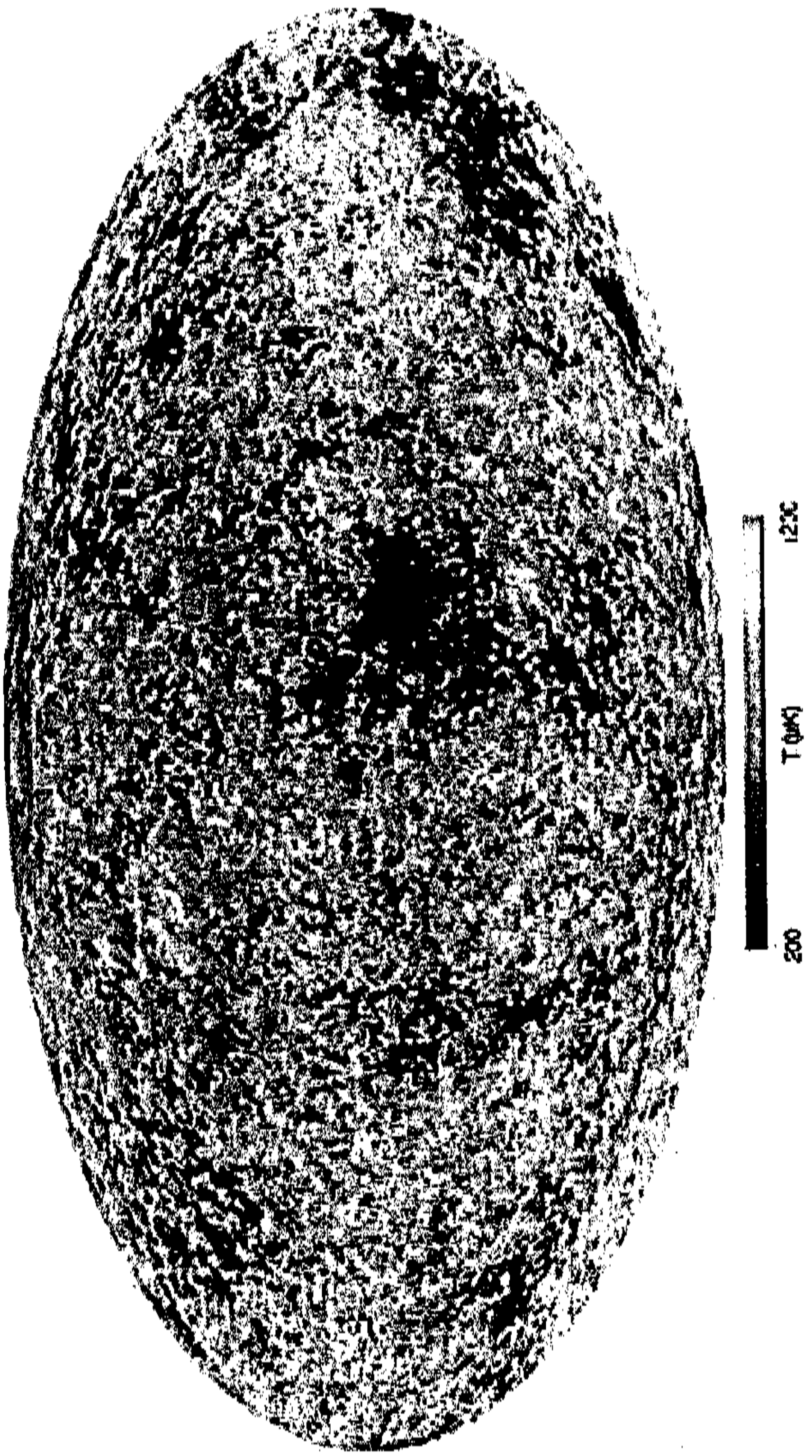


Fig. 11. This "internal linear combination" map combines the five band maps in such as way as to maintain unity response to the CMB while minimizing foreground foreground contamination. For a more detailed description see Bennett et al. (2003c). For the region that covers the full sky outside of the inner Galactic plane, the weights are 0.109, −0.684, −0.096, 1.921, −0.250 for K, Ka, Q, V, and W bands, respectively. Note that there is a chance alignment of a particularly warm feature and a cool feature near the Galactic plane. As discussed in Bennett et al. (2003c), the noise properties of this map are complex, so it should not generally be used for cosmological analyses. *A higher quality rendering is available on the LAMBDA web*

Basic Idea of Inflation

At some early epoch, energy density may have been dominated by ≃ constant term:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N \rho}{3} - k/a^2 \quad : \quad \rho = V$$ [illegible]

⇒ epoch of exponential expansion:

$$a = a_i \exp(Ht) \quad : \quad H = \sqrt{\frac{8\pi G_N}{3} V}$$

⇒ Horizon

expanded exponentially

all observable Universe within pre-inflationary horizon ⇒ homogeneity could have been established

"real" horizon ≫ "apparent" horizon

$$a_i e^{H\tau} \gg a_H = c t_0$$

[illegible]

Platness

$-k/a^2$ term negligible

[illegible]

Entropy

Universe very big

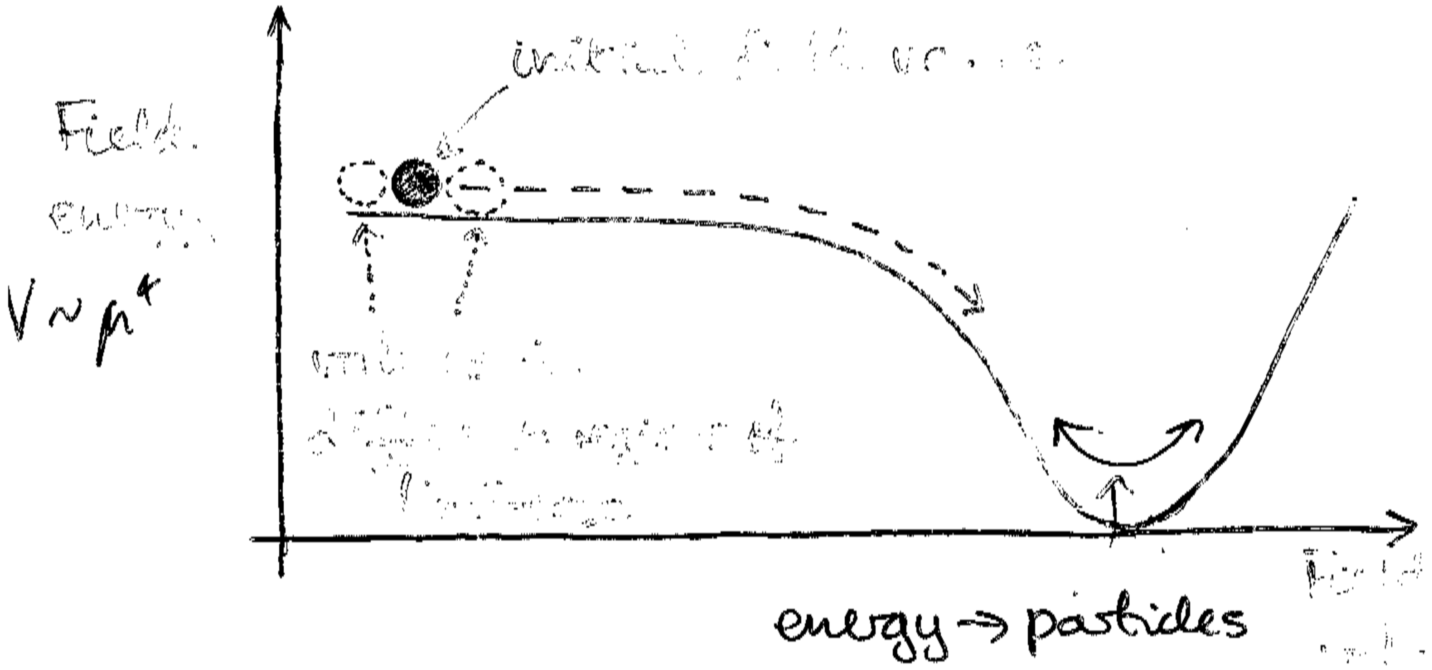
Monopoles

closest one beyond CMB

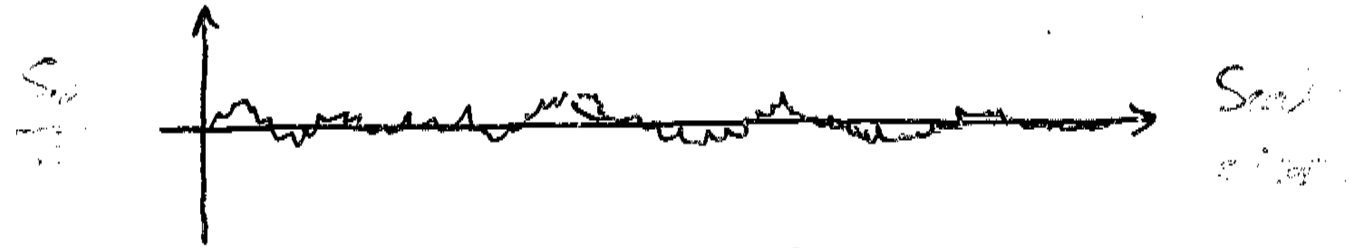
Density Perturbations

quantum/thermal fluctuations in scala-field

⇒ different parts of Universe expand differently



⇒ Gaussian random field of perturbations



similar magnitudes at different scale sizes

[illegible] (Harrison, Zeldovich)

magnitude ⇔ value of field energy

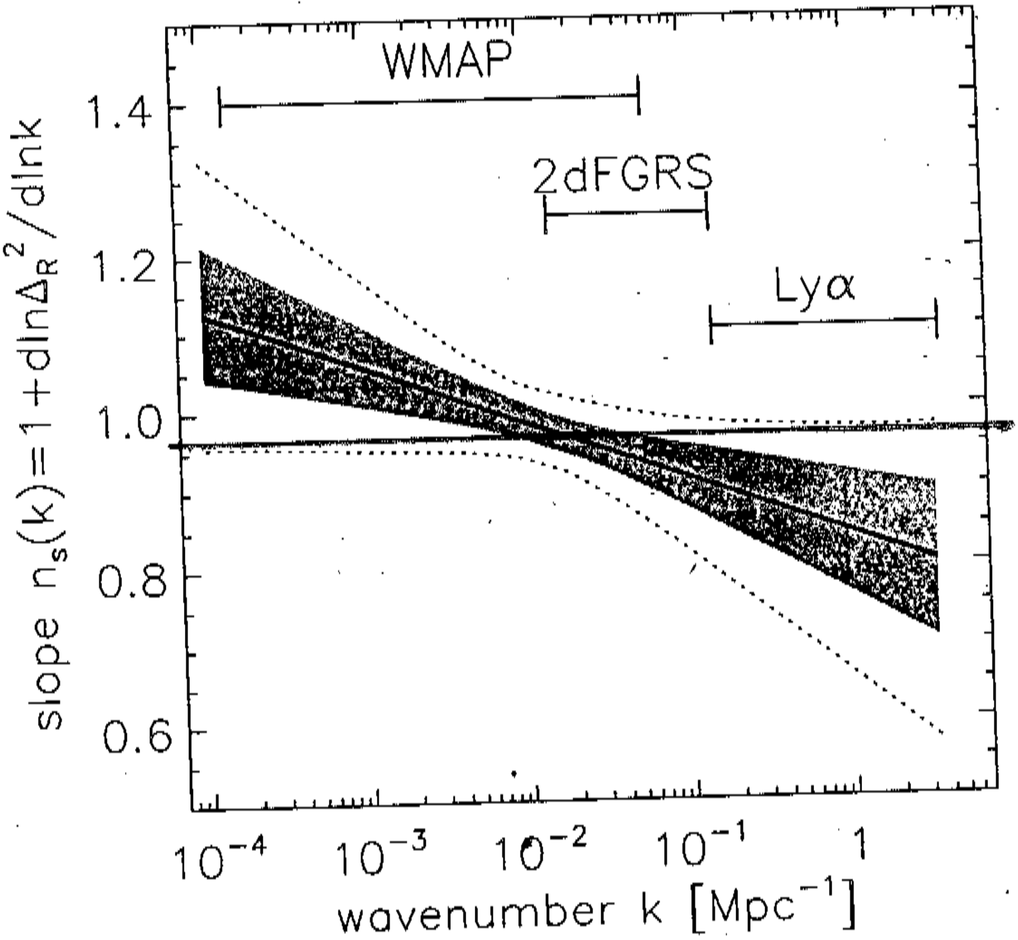
$$\left(\frac{\delta T}{T}\right) \sim \frac{\delta\rho}{\rho} \propto \mu^2 \cdot G_N$$

consistent with COBE data $\delta T / T \sim 10^{-5}$

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

Spectral Index from WMAP + 2dFGRS + Lyman α

mbination prefers scale dependence in spectral index
BUT consistent with constant spectral index
$n_s \sim 1.0$ ← Harrison-Zeldovich.



← constant spectral index from $V=\frac{1}{2}m^2\phi^2$
↑
as expecte
for sneutrin

Fig. 2.— This figure shows n_s as a function of k for the *WMAP*ext+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.

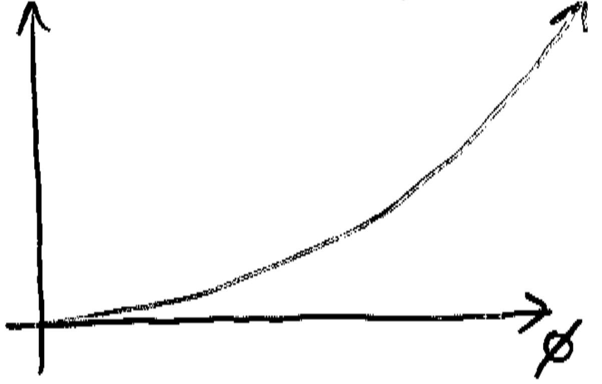
(WMAP

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

Toy Model

$V = \frac{1}{2}m^2\phi^2 \leftarrow$ e.g. $\tilde{N}$

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



slow-roll parameters: $\epsilon = \frac{2m_{Pl}^2}{\phi^2} = \eta$ $\quad m_{Pl} \equiv (8\pi G_N)^{-\frac{1}{2}} \simeq 2.4\times10^{18}$ GeV

COBE normalization:

$$(1.94\times10^{-5}) = \sqrt{\frac{1}{75\pi m_{Pl}^6}\frac{V^3}{V'^2}}$$

magnitude of potential:

$$V^{1/4} = 0.027\,\epsilon^{1/4}\,m_{Pl}$$ < Planck scale

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

need about 60 e-folds of expansion:

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

somewhat > Planck scale

inflaton mass: $m \simeq \frac{(0.04)^2 m_{Pl}^3}{\phi^2} \simeq \boxed{1.8\times10^{13}\text{ GeV}}$

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

tensor mode: $\simeq 16\epsilon \simeq \boxed{0.16} \leftarrow$ only monomial compatible with WMAP?

$(V \propto \phi^4$ excluded by $\sim 3\sigma)$

Constraints from WMAP et al
on inflation observables

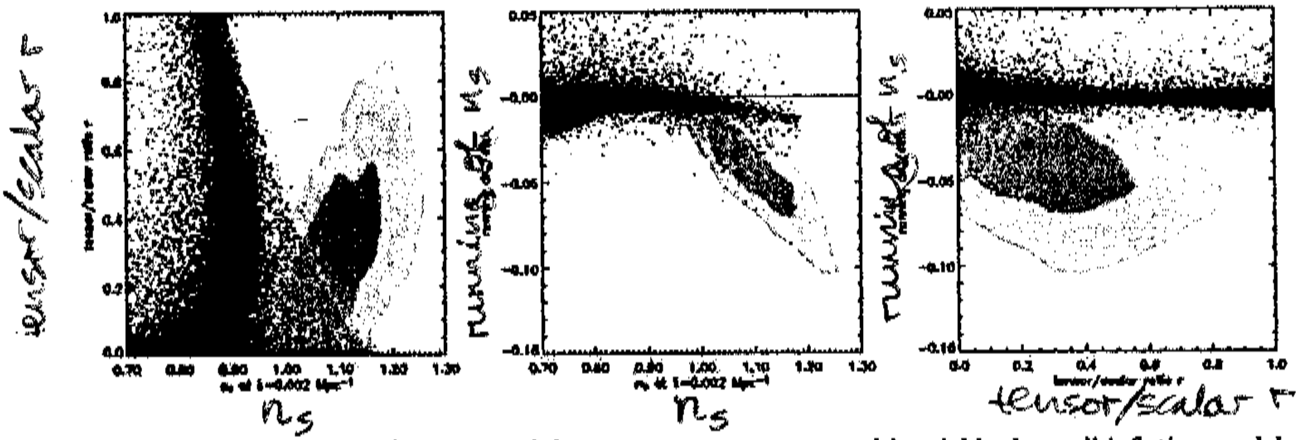


Fig. 3. This set of figures shows part of the parameter space spanned by viable slow roll inflation models, with the *WMAP*ext+2dFGRS+Lyman α 68% confidence region shown in dark blue and the 95% confidence region shown in light blue.

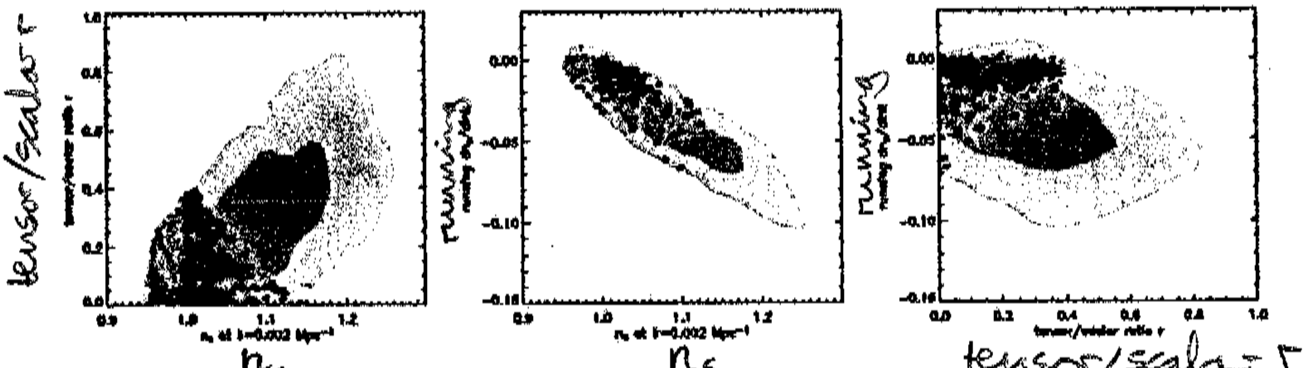


Fig. 4. This set of figures compares the fits from the *WMAP*ext+2dFGRS+Lyα data to the predictions of specific classes of physically motivated inflation models. The color coding shows model classes referred to in the text: (A) red, (B) green, (C) magenta, (D) black. The dark and light blue regions are the joint 1-σ and 2-σ regions for the *WMAP*ext+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.

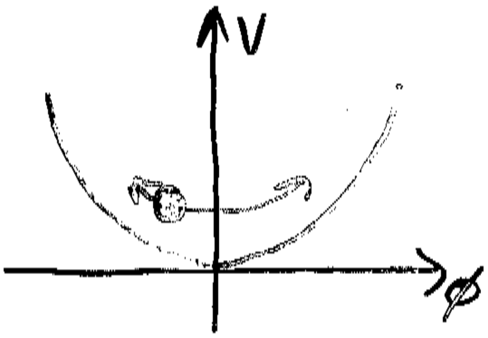
(J.E + Raidal + Yanagida

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

X X

X

Following Inflation



ends when $H \sim m$

field then oscillates about minimum

energy density ≃ non-relativistic matter

$$\rho_\phi \simeq \rho_{\text{initial}} \left(\frac{a_{\text{initial}}}{a}\right)^3$$

inflaton decays when $H \sim \Gamma_\phi$

inflaton decay rate

decay products thermalize rapidly ⇒ reheating

$$\rho_{\text{reheating}} \simeq \rho_\phi$$

reheating temperature:

$$n\, T_{RH}^4 \simeq \left(\frac{g_\phi^2}{8\pi} m_\phi\right)^2 m_{Pl}^2$$

$$T_{RH} \lesssim 10^{14}\,\text{GeV}$$

want low T_{RH} to suppress relic gravitinos?

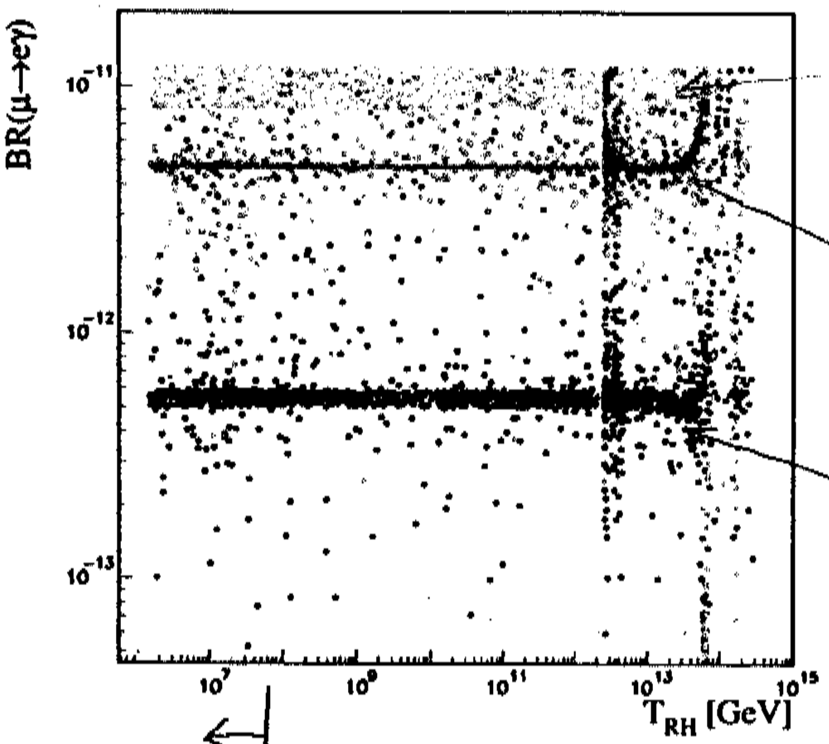
⇒ approximate decoupling

ERY

Lepton Flavour Violation

assuming sneutrino inflation, leptogenesis

$\mu \to e\gamma$



$\sin\theta_{13} = 0.1$
$M_2 = 10^{14}$ GeV
$M_3 = 5\times10^{14}$ GeV

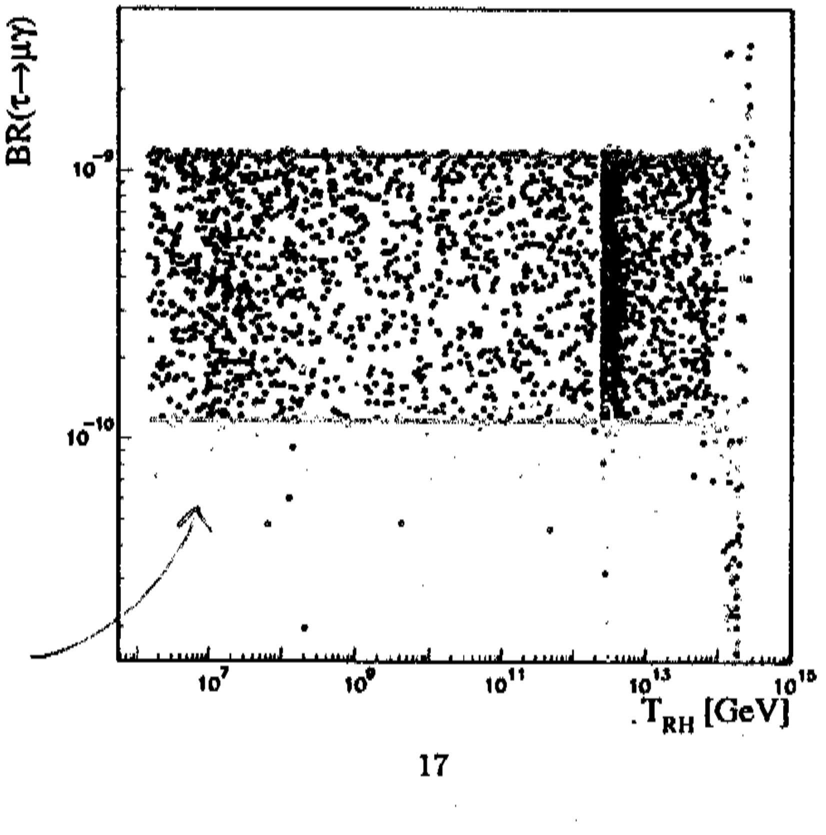
$\sin\theta_{13} \sim 0$
$M_2 = 5\times10^{14}$ GeV
$M_3 = 5\times10^{15}$ GeV

$\sin\theta_{13} = 0.0$
$M_2 = 10^{14}$ GeV
$5\times10^{14} < M_3 < 5\times10^{15}$ GeV

$\tan\beta = 10$,
$m_{1/2} = 800$ GeV,
$m_0 = 170$ GeV,
$\mu > 0$

upper limit from gravitino problem
(Cyburt + JE + Fields + Olive: astro-ph/0211258

$\tau \to \mu\gamma$



reheating temperature may be low

Figure 3: *Calculations of $BR(\mu \to e\gamma)$ and $BR(\tau \to \mu\gamma)$ on left and right panels, respectively. Black points correspond to $\sin\theta_{13} = 0.0$, $M_2 = 10^{14}$ GeV, and 5×10^{14} GeV $< M_3 < 5\times10^{15}$ GeV. Red points correspond to $\sin\theta_{13} = 0.0$, $M_2 = 5\times10^{14}$ GeV, and $M_3 = 5\times10^{15}$ GeV, while green points correspond to $\sin\theta_{13} = 0.1$, $M_2 = 10^{14}$ GeV, and $M_3 = 5\times10^{14}$ GeV.*

(JE + Raidal + Yanagida hep-ph/0302

Motiv:

"We are all made of stars"

astrophysical/cosmological nucleosynthesis?

Here:

"We are all made of neutrinos"

leptogenesis? inflation?

"The rest is made of neutralinos"

LHC? direct detection?