

BARYOGENESIS & DARK MATTER

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OUTLINE

(1) Matter-Antimatter Asymmetry

(2) Electroweak Baryogenesis

(3) Affleck-Dine Baryogenesis

(4) Thermal Leptogenesis

(5) Gravitino Dark Matter

(1) Matter-Antimatter Asymmetry

A matter-antimatter asymmetry can be dynamically generated if particle interactions and cosmological evolution satisfy **Sakharov's conditions** [1967],

- baryon number violation ,
- C and CP violation ,
- deviation from thermal equilibrium .

Sakharov's model for baryogenesis: CP violating decays of 'maximons' with mass $\mathcal{O}(M_{\text{P}})$ at temperature $T_i \sim M_{\text{P}}$, connection with CP violation in K^0 -meson system, ..., proton lifetime $\tau_p > 10^{50}$ years predicted. In general, baryogenesis provides important relationship between the standard model of cosmology and the standard model of particle physics as well as its extensions.

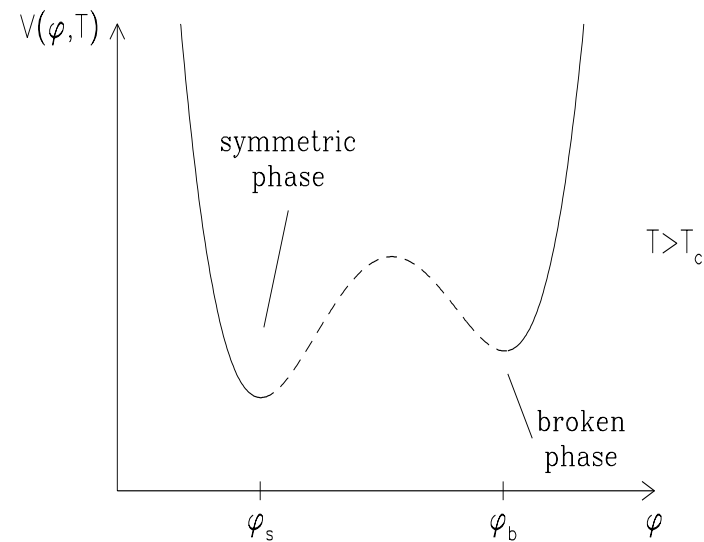
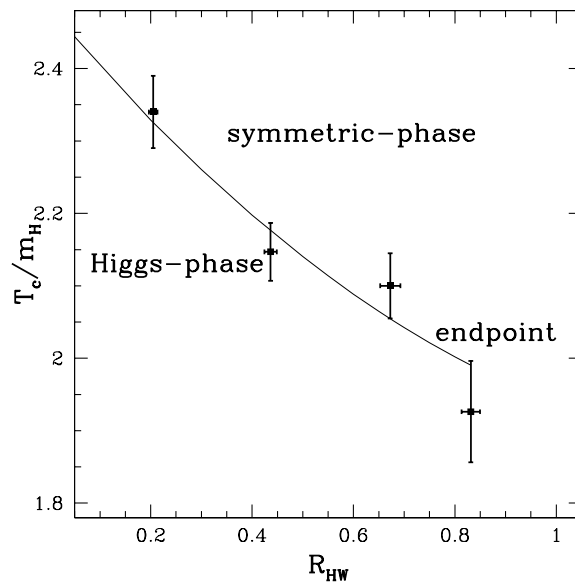
Scenarios for baryogenesis: classical GUT baryogenesis, leptogenesis, electroweak baryogenesis, Affleck-Dine baryogenesis (scalar field dynamics).

Theory of baryogenesis depends crucially on nonperturbative properties of standard model,

- **electroweak phase transition:** ‘symmetry restoration’ at high temperatures, $T > T_{EW} \sim 100$ GeV, smooth transition for large Higgs masses, $m_H > m_H^c \simeq 72$ GeV (LEP bound $m_H > 114$ GeV).
- **sphaleron processes:** relate baryon and lepton number at high temperatures, only $B - L$ conserved; detailed analytical and numerical studies have led to consistent picture for high-temperature phase; $B - L$ violating processes in thermal equilibrium for $T > T_{EW}$.

Finite temperature potential and phase diagram for electroweak theory: endpoint of critical line of first-order phase transitions, critical Higgs mass

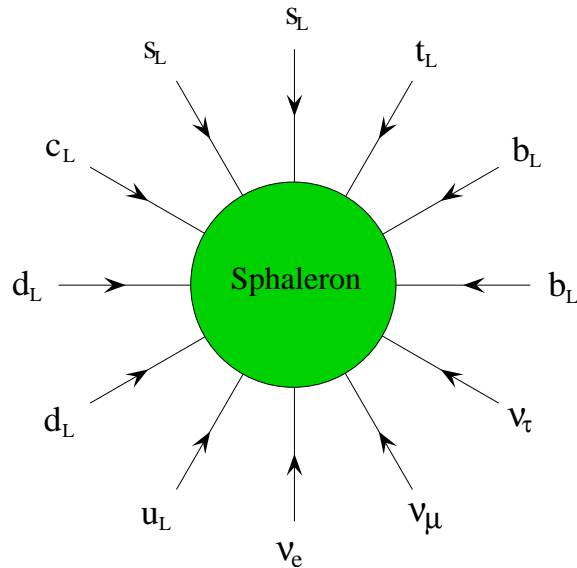
Csikor, Fodor, Heitger '99, → M. Laine



$$R_{HW,c} = \frac{m_H^c}{m_W}, \quad m_H^c = 72.1 \pm 1.4 \text{ GeV}$$

Baryon and lepton number violating sphaleron processes

't Hooft '76; Kuzmin, Rubakov, Shaposhnikov '85, → J. Smit



$$O_{B+L} = \prod_i (q_{Li} q_{Li} q_{Li} l_{Li}),$$

$$\Delta B = \Delta L = 3\Delta N_{CS},$$

$B - L$ conserved

Processes are in thermal equilibrium above electroweak phase transition, for temperatures

$$T_{EW} \sim 100\text{GeV} < T < T_{SPH} \sim 10^{12}\text{GeV}.$$

Sphaleron processes have a profound effect on the generation of cosmological baryon asymmetry. Analysis of chemical potentials of all particle species in the high-temperature phase yields relation between the baryon asymmetry (B) and L and $B - L$ asymmetries,

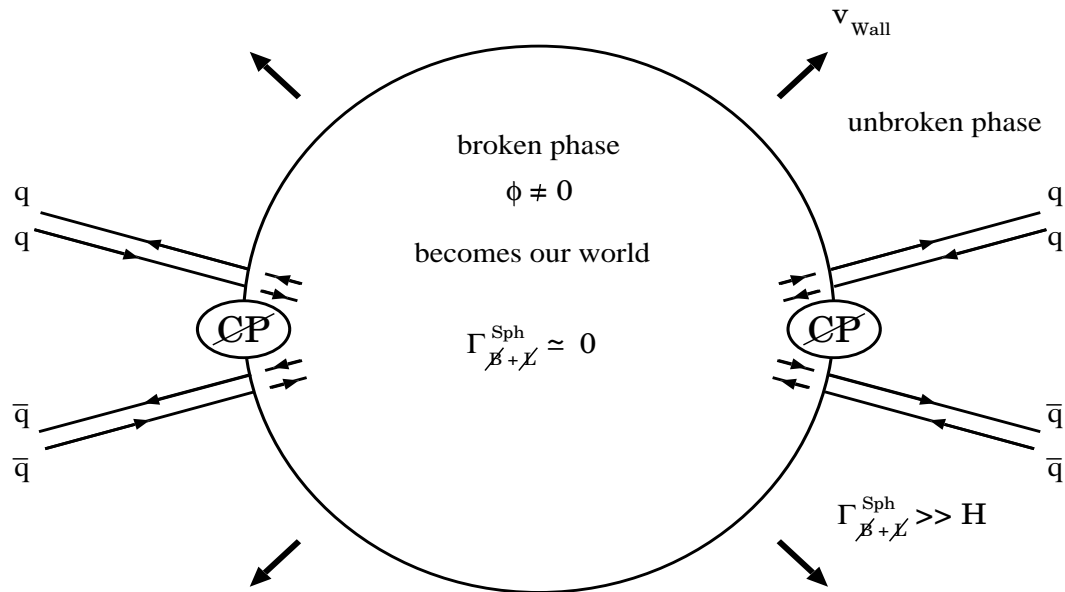
$$\langle B \rangle_T = c_S \langle B - L \rangle_T = \frac{c_S}{c_S - 1} \langle L \rangle_T ,$$

with c_S number $\mathcal{O}(1)$; in standard model $c_S = 28/79$.

This relation suggests that **lepton number violation is needed to explain the cosmological baryon asymmetry**. However, it can only be weak, since otherwise any baryon asymmetry would be washed out. The interplay of these conflicting conditions leads to important constraints on neutrino properties and on extensions of the standard model in general.

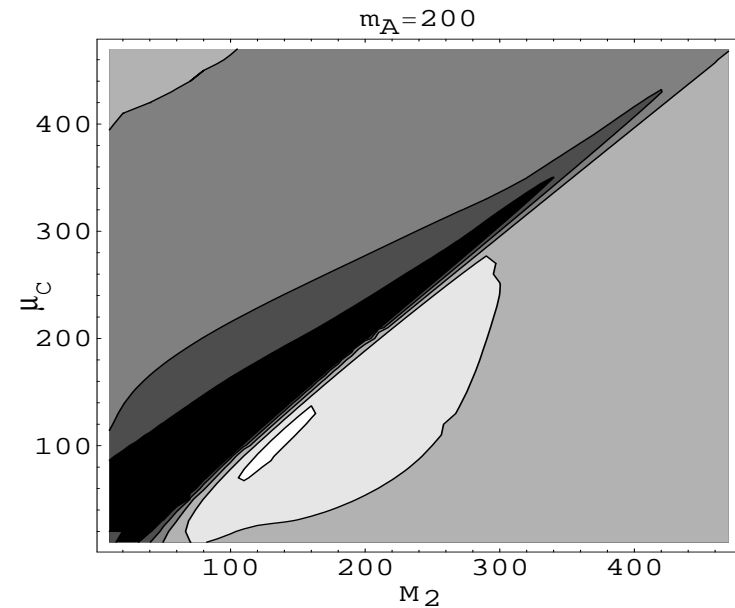
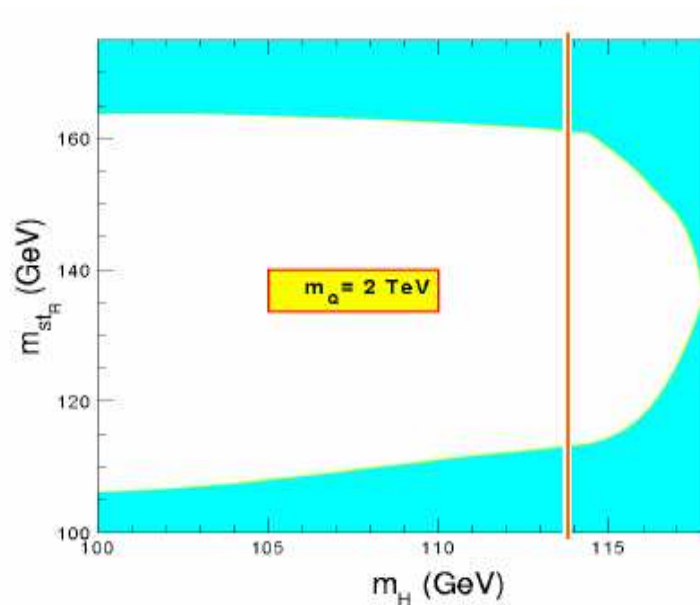
(2) Electroweak Baryogenesis (cf. Rubakov, Shaposhnikov '96)

First-order electroweak phase transition: nucleation and growth of bubbles,



departure from thermal equilibrium; CP violating reflection and transmission generate baryon asymmetry; phase transition has to be sufficiently strong to avoid washout in 'true vacuum'; **standard model EWBG excluded!**

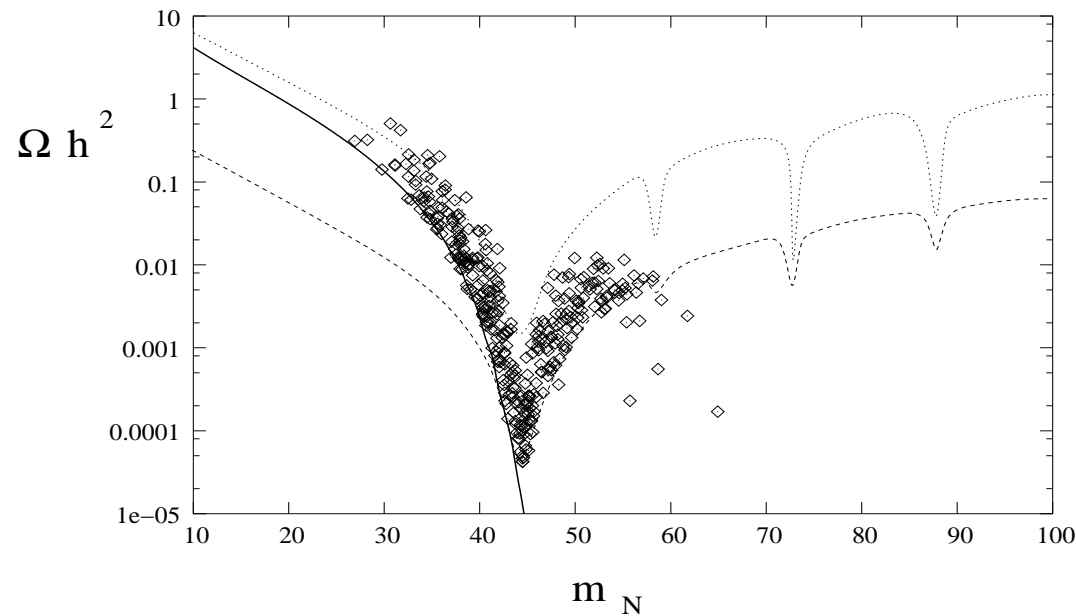
Extensions still viable: 2 Higgs doublet models, MSSM,..., but **strong constraints on parameters!**



'exceptional' SUSY mass spectrum: $m_{\text{stop}} < m_{\text{top}}, \dots$, other squarks very heavy (left) (Carena, Quiros, Wagner,...); light wino and higgsino masses,...(right; black region allowed) (Huber, Konstandin, Prokopec, Schmidt)

Neutralino Dark Matter in NMSSM (Menon, Morrisey, Wagner '04, ...)

constraints on mass spectrum more relaxed in NMSSM, extension with additional singlet



EWBG and WIMP dark matter possible; clear predictions: $\tan\beta = \mathcal{O}(1)$, very light LSP (mostly higgsino) \rightarrow EWBG will soon be tested at LHC!

(3) Affleck-Dine Baryogenesis

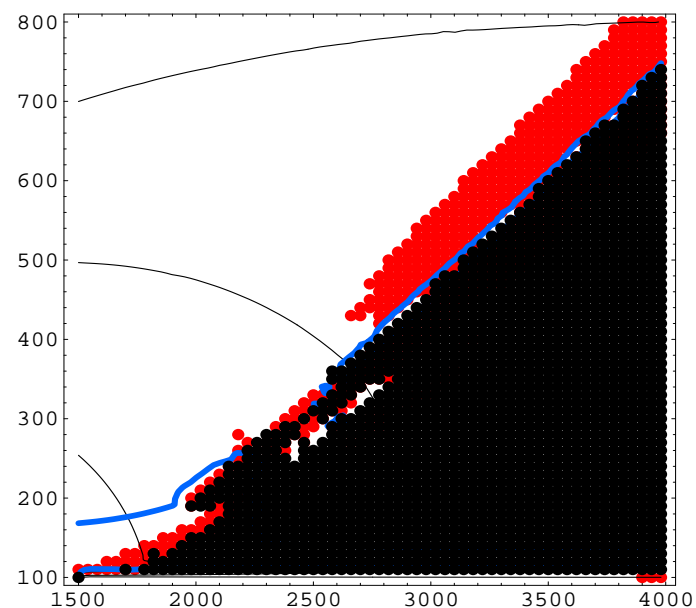
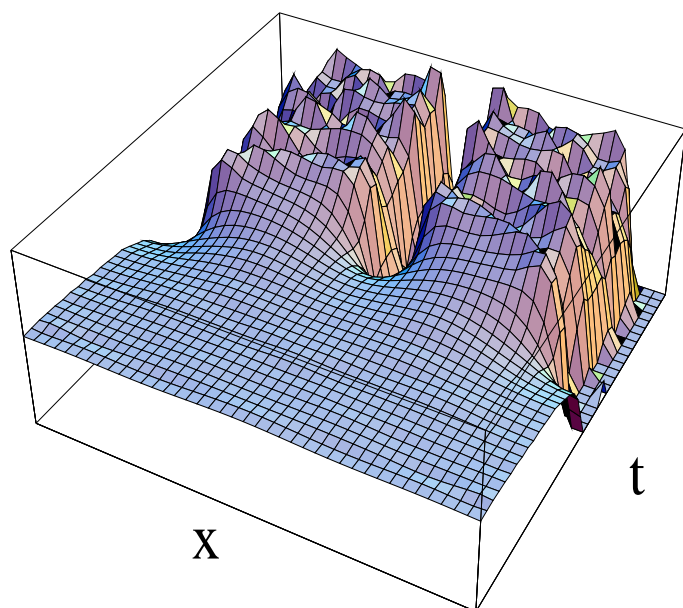
Supersymmetric theories: complex scalar fields can carry baryon or lepton number; typical feature: flat directions in scalar potential of MSSM, e.g.,

$$(LH_u), \quad (U^c D^c D^c),$$

L : lepton doublet, H_u : Higgs doublet (... Kawasaki et al '07); U, D : quark fields.

During inflation formation of large scalar condensate ϕ_0 ; after inflation coherent oscillation, can store large baryon/lepton number (CP violating phases assumed); decay of condensate leads to ordinary baryon/lepton number; example of non-thermal baryogenesis; AD mechanism difficult to falsify, no 'standard model'; characteristic forms of dark matter could provide 'evidence' for AD baryogenesis, also isocurvature density fluctuations (Takahashi '01).

For $U^c D^c D^c$ flat direction, Q-balls can form (left) (Dine, Kusenko '04), stable macroscopic objects, e.g., $B_Q \sim 10^{26}$, $M_Q \sim 10^{24}$ GeV.



alternative: decay of unstable Q-balls, with non-thermal production of higgsino dark matter (right, vertical: $m_{1/2}$, horizontal: m_0 , red: allowed) (Fujii, Hamaguchi '02), inconsistent with thermally produced DM \rightarrow possibly striking signatures at ICECUBE, Super-Kamiokande, or hints from LHC!

(4) Thermal Leptogenesis (Fukugita, Yanagida '86, → Davidson, Nardi, Nir '08)

The **seesaw mechanism** explains smallness of the light neutrino masses by largeness of the heavy Majorana masses; predicts six mass eigenstates,

$$\begin{aligned} N &\simeq \nu_R + \nu_R^c : & m_N &\simeq M ; \\ \nu &\simeq \nu_L + \nu_L^c : & m_\nu &= -m_D^T \frac{1}{M} m_D . \end{aligned}$$

Yukawa couplings of third generation $\mathcal{O}(1)$, like the top-quark, yields heavy and light neutrino masses,

$$M_3 \sim \Lambda_{GUT} \sim 10^{15} \text{ GeV} , \quad m_3 \sim \frac{v^2}{M_3} \sim 0.01 \text{ eV} ;$$

neutrino mass m_3 is compatible with $(\Delta m_{sol}^2)^{1/2} \sim 0.008 \text{ eV}$ and $(\Delta m_{atm}^2)^{1/2} \sim 0.05 \text{ eV}$ from neutrino oscillations, i.e. **GUT scale physics !!**

Ideal candidate for baryogenesis: lightest (heavy) Majorana neutrino, N_1 ; no SM gauge interactions, hence out-of-equilibrium condition o.k.; N_1 decays to lepton-Higgs pairs yield lepton asymmetry $\langle L \rangle_T \neq 0$, partially converted to baryon asymmetry $\langle B \rangle_T \neq 0$ (work by several groups since about 1996; expectation $m_i < 1$ eV before experimental results on Δm_{atm}^2 ; afterwards leptogenesis boom).

The generated baryon asymmetry is proportional to the CP asymmetry in N_1 -decays (simplest case $m_D = h\langle\phi\rangle$, seesaw mass relation),

$$\begin{aligned}\varepsilon_1 &= \frac{\Gamma(N_1 \rightarrow l\phi) - \Gamma(N_1 \rightarrow \bar{l}\bar{\phi})}{\Gamma(N_1 \rightarrow l\phi) + \Gamma(N_1 \rightarrow \bar{l}\bar{\phi})} \\ &\simeq -\frac{3}{16\pi} \frac{M_1}{(hh^\dagger)_{11}v^2} \text{Im} (h^* m_\nu h^\dagger)_{11} ;\end{aligned}$$

rough estimate for ε_1 in terms of neutrino masses,

$$\varepsilon_1 \sim \frac{3}{16\pi} \frac{M_1 m_3}{v^2} \sim 0.1 \frac{M_1}{M_3} .$$

Order of magnitude of CP asymmetry is given by the mass hierarchy of the heavy Majorana neutrinos, e.g. $\varepsilon_1 \sim 10^{-6}$ for $M_1/M_3 \sim m_u/m_t \sim 10^{-5}$.

Baryon asymmetry for given CP asymmetry ε_1 ,

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = -d \varepsilon_1 \kappa_f \sim 10^{-9},$$

with dilution factor $d \sim 0.01$ (increase of photon number density), efficiency factor $\kappa_f \sim 0.1$ (Boltzmann equations); baryogenesis temperature $T_B \sim M_1 \sim 10^{10}$ GeV.

The **observed value** of the baryon asymmetry, $\eta_B \sim 10^{-9}$, is obtained as consequence of the hierarchy of the heavy neutrino masses, leading to a small CP asymmetry, and the kinematical factors d and κ_f (WB, Plümacher '96).

Solving the Boltzmann equations

Heavy neutrinos are (not) in **thermal equilibrium** if the decay rate satisfies $\Gamma_1 > H$ ($\Gamma_1 < H$), with $H(T)$ Hubble parameter, i.e.,

$$\tilde{m}_1 > m_* \quad (\tilde{m}_1 < m_*),$$

with ‘effective neutrino mass’,

$$\tilde{m}_1 = \frac{(m_D m_D^\dagger)_{11}}{M_1}, \quad m_1 \leq \tilde{m}_1 (<) m_3,$$

and ‘equilibrium neutrino mass’ ($M_{pl} = 1.2 \times 10^{19}$ GeV, $g_* = 434/4$),

$$m_* = \frac{16\pi^{5/2}}{3\sqrt{5}} g_*^{1/2} \frac{v^2}{M_{pl}} \simeq 10^{-3} \text{ eV}.$$

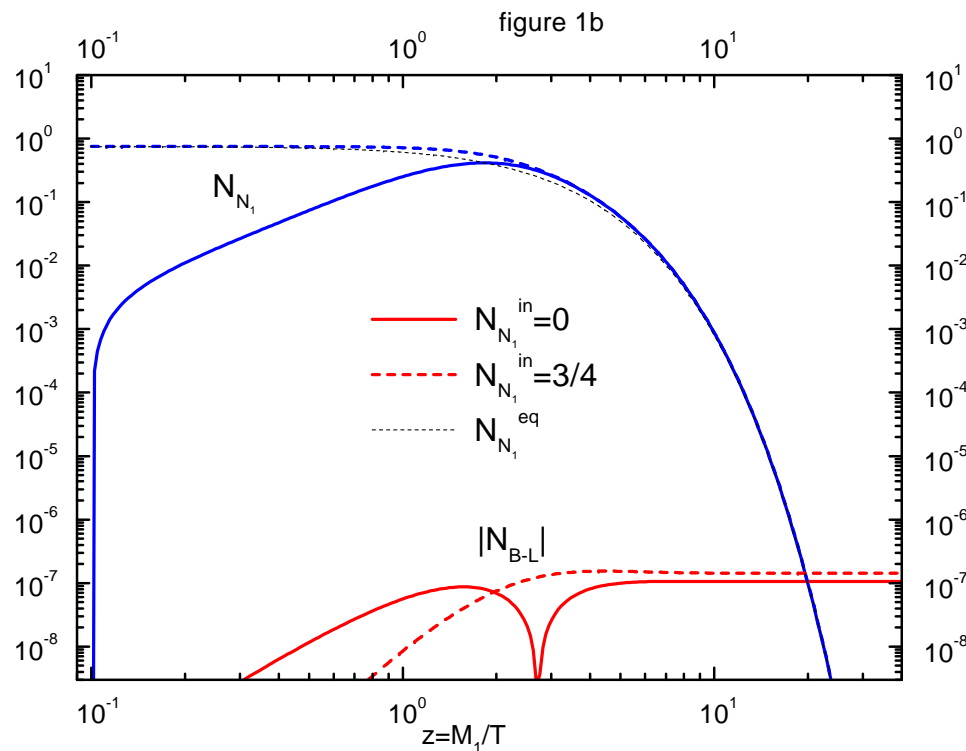
Note: equilibrium neutrino mass m_* close to neutrino masses $\sqrt{\Delta m_{\text{sol}}^2} \simeq 8 \times 10^{-3}$ eV and $\sqrt{\Delta m_{\text{atm}}^2} \simeq 5 \times 10^{-2}$ eV; **hope:** baryogenesis via leptogenesis process close to thermal equilibrium ?!

Boltzmann equations for leptogenesis, competition between production and washout,

$$\begin{aligned} \frac{dN_{N_1}}{dz} &= -(D + S) (N_{N_1} - N_{N_1}^{\text{eq}}) , \\ \frac{dN_{B-L}}{dz} &= -\varepsilon_1 D (N_{N_1} - N_{N_1}^{\text{eq}}) - W N_{B-L} . \end{aligned}$$

N_i : number densities in comoving volume, $z = M_1/T$, D : decay rate, S : scattering rate, W : washout rate (sum over lepton flavours!); in relevant of neutrino masses, solution essentially **analytically** !

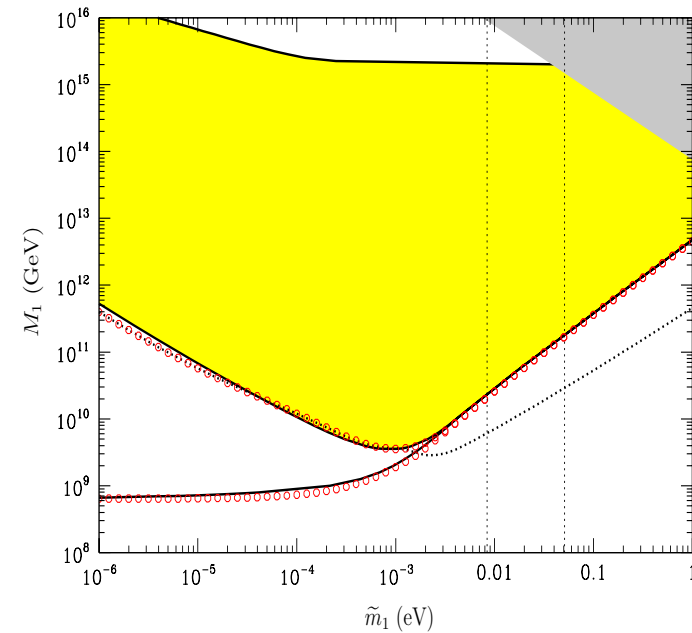
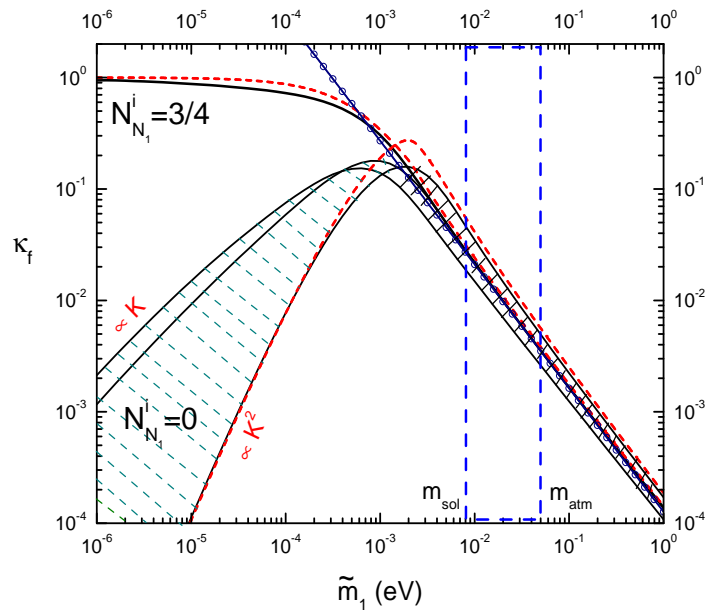
Evolution of number densities and $B - L$ asymmetry



Generation of a $B - L$ asymmetry for different initial conditions, zero and thermal N_1 abundance; Yukawa interactions are strong enough to bring the heavy neutrinos into thermal equilibrium; **observed asymmetry:** $\eta_B \simeq 0.01 \times N_{B-L} \sim 10^{-9}$.

Parameters: $M_1 = 10^{10}$ GeV, $\tilde{m}_1 = 10^{-3}$ eV, $\bar{m} = 0.05$ eV, $|\epsilon_1| = 10^{-6}$.

Quantitative analysis: Upper bound on CP asymmetry (Hamaguchi et al; Davidson, Ibarra '02) together with 'washout effects' lead for simplest scenario to **neutrino mass window** and lower bound on reheating temperature (WB, Di Bari, Plümacher '02,...,Giudice et at. '03, Pilftsis, Underwood '03,...):



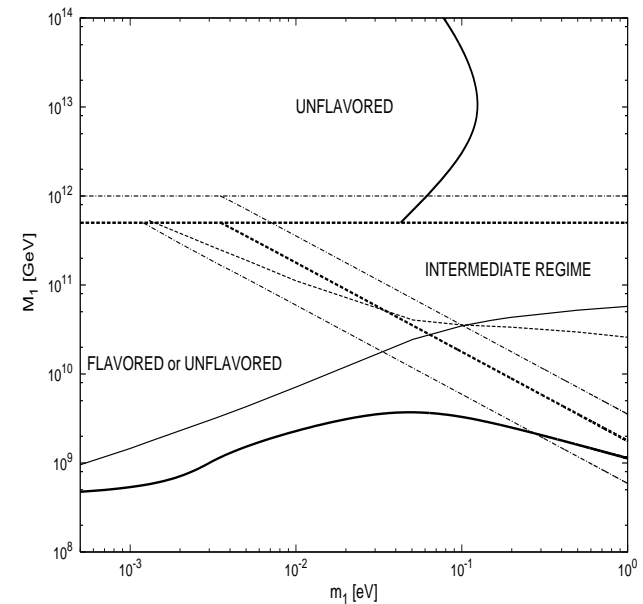
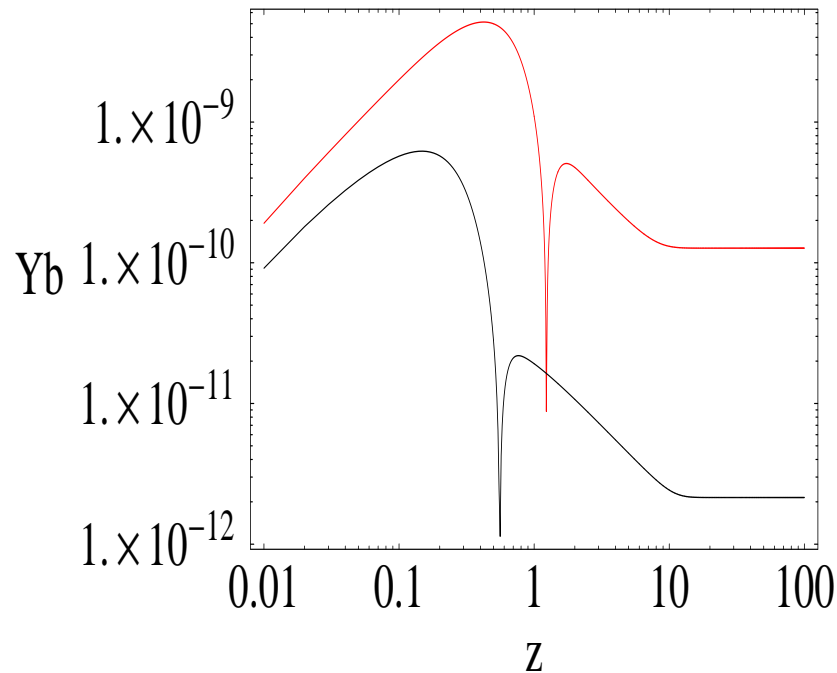
$$10^{-3} \text{ eV} < m_i < 0.1 \text{ eV} ,$$

$$T_i > 2 \times 10^9 \text{ GeV} .$$

(lower bound on m_i : independence of initial conditions)

Recent development: dependence on lepton flavour mixing

Upper bound on light neutrino masses can be avoided in seesaw models with $SU(2)$ triplets, 'Dirac leptogenesis' (...Underwood'07), ..., but also via **flavour effects** in 'minimal' leptogenesis (Abada et al '06, Nardi et al '06, ..., Antusch et al '07) !?



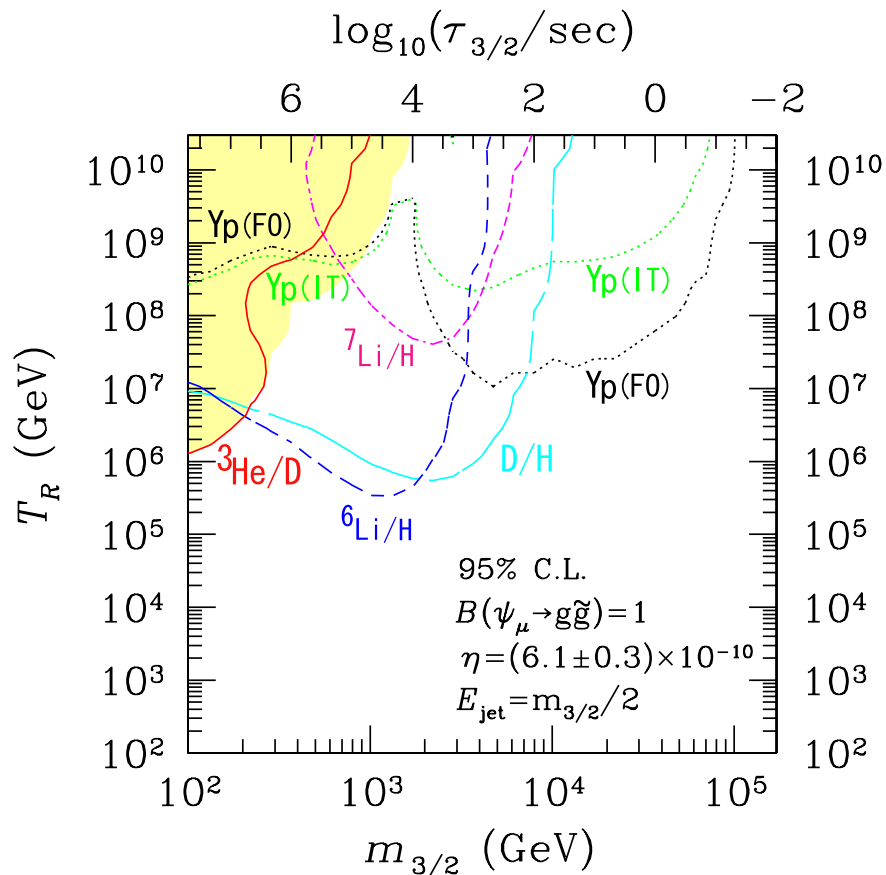
Flavour effects can enhance CP asymmetries and baryon asymmetry (left) [Abada et al '06], but status of neutrino mass bound still unclear (right) [Blanchet, Di Bari, Raffelt '06] \rightarrow quantum mechanical treatment required...

Leptogenesis as a problem in statistical mechanics

What is the theoretical error of the computed baryon asymmetry for given neutrino masses and mixings? Needed: full quantum mechanical description of nonequilibrium process, a **challenging problem!** Aspects of a 'theory of leptogenesis':

- quantum mechanical framework, e.g., Kadanoff-Baym equations; present conceptual problem: Boltzmann equations classical, 'collision terms' quantum mechanical (WB, Fredenhagen '00, De Simone, Riotto '06, Lindner, Müller '07);
- wanted: systematic expansion around solution of Boltzmann equations; one expects: relativistic corrections, off-shell effects, 'memory effects', higher order loop corrections etc; much work for the coming years!
- present understanding of high temperature region, $T > M_1$ insufficient; improvement also important for other topics in particle cosmology, like gravitino production, axino production...

(5) Gravitino Dark Matter



Gravitino problem: thermally produced gravitino number density grows with reheating temperature after inflation,

$$\frac{n_{3/2}}{n_\gamma} \propto \frac{\alpha_3}{M_{\text{p}}^2} T_R.$$

Most stringent upper bound on T_R (Kawasaki, Kohri, Moroi '05):

$$T_R < \mathcal{O}(1) \times 10^5 \text{ GeV},$$

hence standard mSUGRA with neutralino LSP incompatible with thermal leptogenesis !!

Possible way out: Gravitino LSP (Bolz, WB, Plümacher '98); strong constraints for $\tilde{\tau}$ -NLSP (Feng et al '03; Ellis et al '03; Steffen '06;...; Pospelov '06;...) → unstable gravitino LSP

Thermal production of gravitino dark matter

Can one understand the amount of dark matter, $\Omega_{DM} \simeq 0.23$, with $\Omega_{DM} = \rho_{DM}/\rho_c$, if gravitinos are dominant component, i.e. $\Omega_{DM} \simeq \Omega_{3/2}$?

Production mechanisms: (i) 'Super-WIMPs' (Feng, Rajaraman, Takayama '03), i.e., gravitinos from WIMP decays,

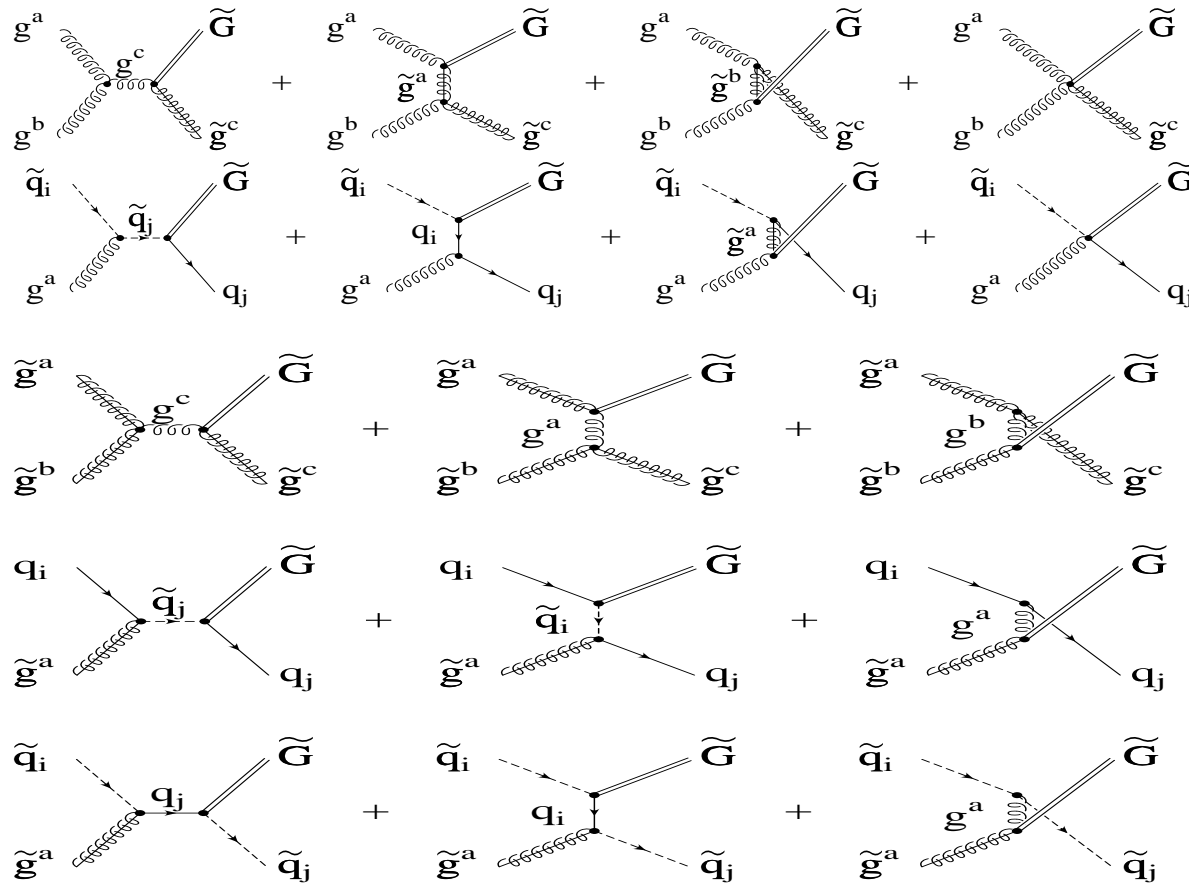
$$\Omega_{3/2} = \frac{m_{3/2}}{m_{\text{NLSP}}} \Omega_{\text{NLSP}} ,$$

independent of initial temperature T_R (!!), but disfavoured by BBN constraints; (ii) Thermal production, from $2 \rightarrow 2$ QCD processes,

$$\Omega_{3/2} h^2 \simeq 0.3 \left(\frac{T_R}{10^{10} \text{GeV}} \right) \left(\frac{100 \text{GeV}}{m_{3/2}} \right) \left(\frac{m_{\tilde{g}}(\mu)}{1 \text{TeV}} \right) .$$

$\Omega_{DM} h^2$ for typical parameters of **supergravity** and **leptogenesis!**

Gravitino production from thermal bath of gluons and quarks:



calculations should be improved (...Bolz, Brandenburg, Plümacher '00; Pradler, Steffen '06; Rychkov, Strumia '07); resummation of thermal masses?

Unstable gravitino LSP (WB, Covi, Hamaguchi, Ibarra, Yanagida '07)

BBN, leptogenesis and gravitino dark matter are all consistent in case of a small 'R-parity' breaking, which leads to processes $\tilde{\tau}_R \rightarrow \tau \nu_\mu, \mu \nu_\tau$, $\tilde{\tau}_L \rightarrow b^c t$ or $\psi_{3/2} \rightarrow \gamma \nu, \dots$, possible. Models with sufficiently small R-parity breaking can be constructed,

$$\lambda \sim h^{(e,d)} \Theta \lesssim 10^{-7}, \quad \Theta \sim \frac{v_{B-L}^2}{M_{\text{P}}^2}.$$

The NLSP lifetime becomes sufficiently short (decay before BBN),

$$c\tau_{\tilde{\tau}}^{\text{lep}} \sim 30 \text{ cm} \left(\frac{m_{\tilde{\tau}}}{200 \text{ GeV}} \right)^{-1} \left(\frac{\lambda}{10^{-7}} \right)^{-2}.$$

BBN, thermal leptogenesis and gravitino dark matter are consistent for $10^{-14} < \lambda, \lambda' < 10^{-7}$ and $m_{3/2} \gtrsim 5 \text{ GeV}$.

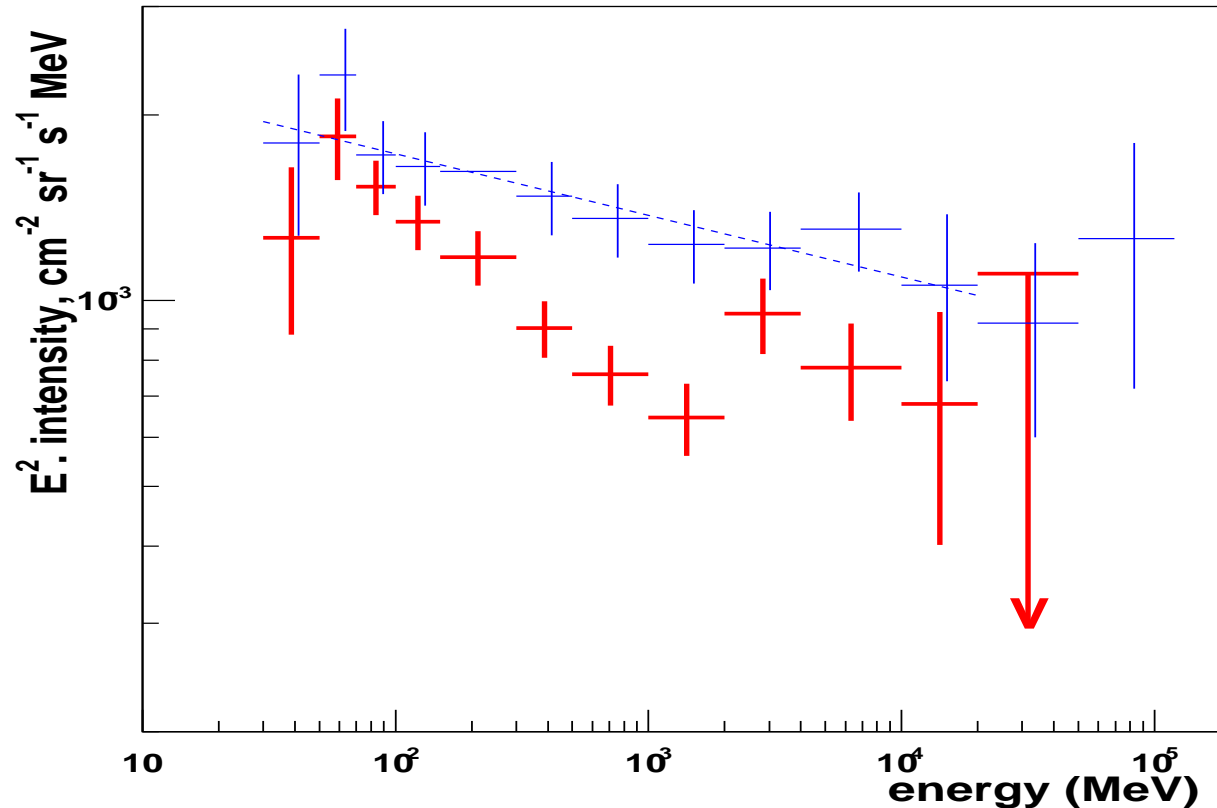
At **LHC** one should see spectacular signal with strongly ionising macroscopic charged tracks, followed by a muon track or a jet and missing energy, corresponding to $\tilde{\tau} \rightarrow \mu\nu_{\tau}$ or $\tilde{\tau} \rightarrow \tau\nu_{\mu}$.

The gravitino decay $\psi_{3/2} \rightarrow \gamma\nu$ is suppressed both by the Planck mass and the small R-parity breaking couplings, so the lifetime is much longer than the age of the universe (Takayama, Yamaguchi '00),

$$\tau_{3/2} \sim 10^{26} \text{s} \left(\frac{\lambda}{10^{-7}} \right)^{-2} \left(\frac{m_{3/2}}{10 \text{ GeV}} \right)^{-3},$$

Decaying gravitino dark matter leads to an **extragalactic diffuse gamma-ray flux** with a characteristic energy spectrum, corresponding to a red shifted monochromatic line. In addition there is an **anisotropic halo contribution** of comparable magnitude. Consistent with EGRET data?

Extragalactic diffuse gamma-ray flux from EGRET data (1998)



analysis of Strong, Moskalenko and Reimer ([astro-ph/0406254](#), [astro-ph/0506359](#));
subtraction of galactic component difficult ([astro-ph/0609768](#))

Gamma-Rays from Decaying Gravitinos

Decaying gravitino dark matter leads to extragalactic diffuse gamma-ray flux with energy spectrum of red shifted monochromatic line; photon with measured energy $E = m_{3/2}/(2(1+z))$ was emitted at comoving distance $\chi(z)$, with $d\chi/dz \simeq (1+z)^{-3/2}/(a_0 H_0 \sqrt{\Omega_M(1+3(1+z)^{-3})})$ (a_0 : scale factor, H_0 : Hubble parameter, $\Omega_M \simeq 0.25$); photon flux ($\tau_{3/2} \gg H_0^{-1}$):

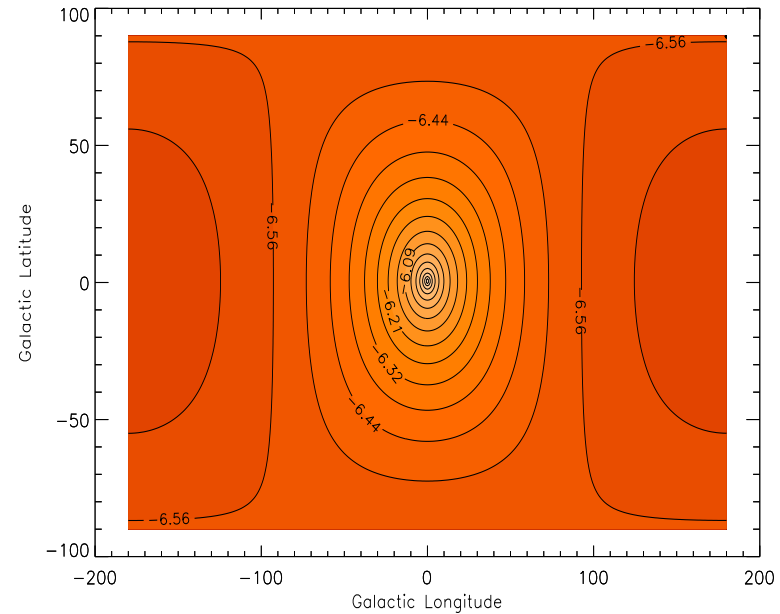
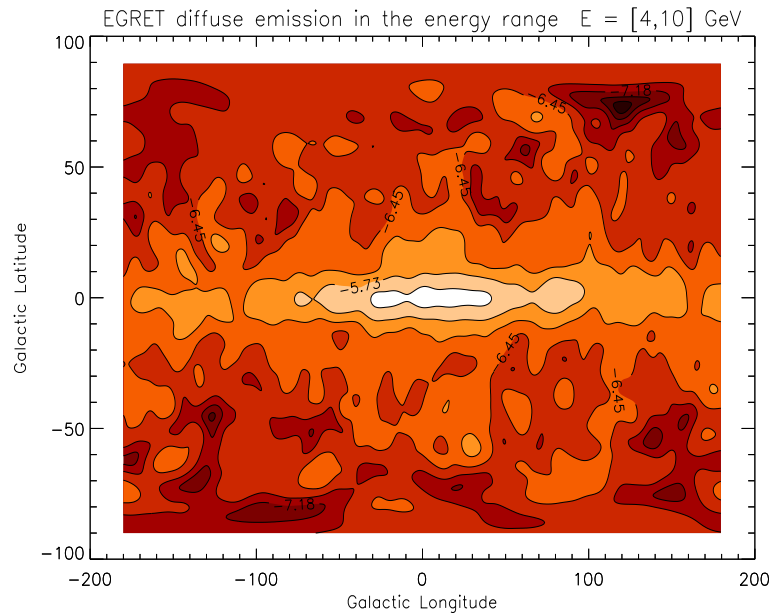
$$E^2 \frac{dJ_{eg}}{dE} = C_\gamma \left(1 + \kappa \left(\frac{2E}{m_{3/2}} \right)^3 \right)^{-1/2} \left(\frac{2E}{m_{3/2}} \right)^{5/2} \theta \left(1 - \frac{2E}{m_{3/2}} \right),$$

with

$$C_\gamma = \frac{\Omega_{3/2} \rho_c}{8\pi \tau_{3/2} H_0 \Omega_M^{1/2}} = 10^{-6} (\text{cm}^2 \text{str s})^{-1} \text{GeV} \left(\frac{\tau_{3/2}}{10^{27} \text{s}} \right)^{-1};$$

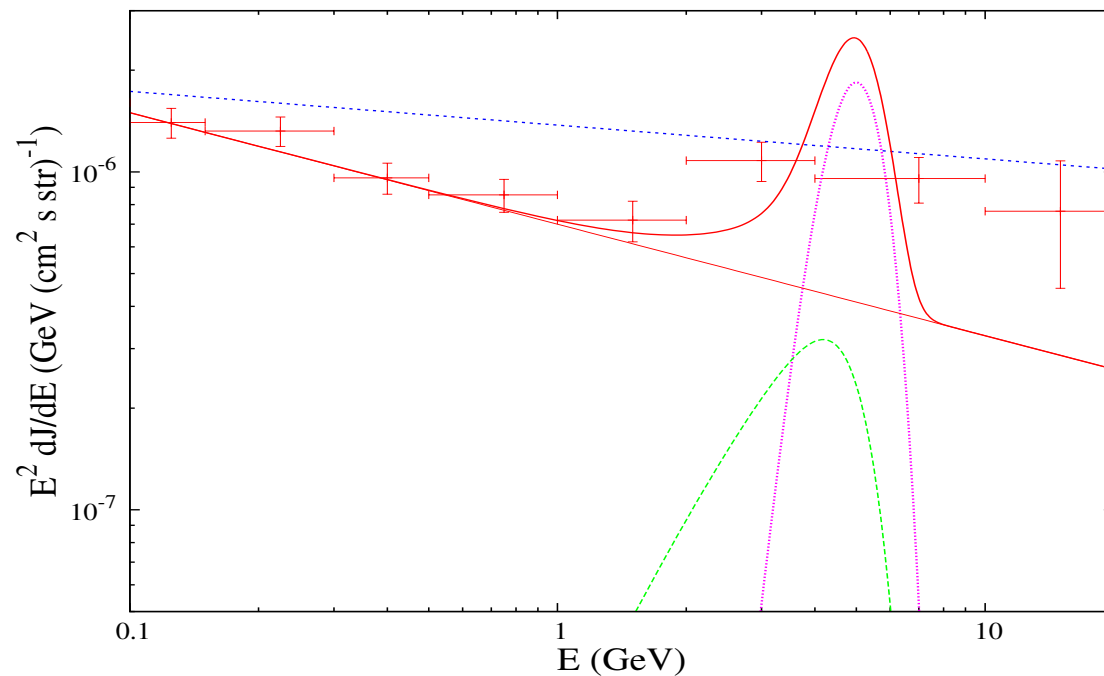
flux is normalized to expectation from theoretical model; in addition anisotropic halo contribution of comparable magnitude.

Extragalactic diffuse gamma-ray flux from EGRET



Left: EGRET diffuse emission in the energy range $E = [4,10]$ GeV. *Right:* Sum of the Galactic and extra-galactic contributions to the gamma-ray flux from gravitino decay.

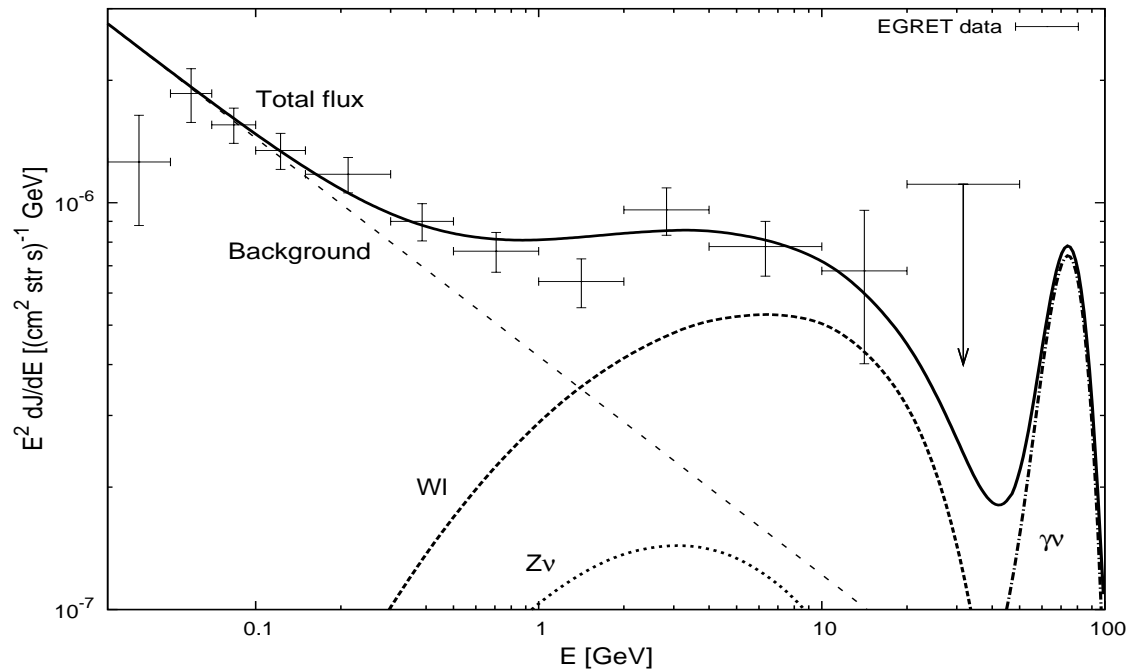
Energy spectrum of diffuse gamma-ray flux (I)



EGRET data from analysis of Strong, Moskalenko and Reimer, [astro-ph/0406254](#) (2004), [astro-ph/0506359](#) (2005); photons from gravitino decay $\psi_{3/2} \rightarrow \gamma\nu$ with $m_{3/2} \simeq 10 \text{ GeV}$; halo component may partly be hidden in anisotropic galactic gamma-ray flux

Energy spectrum of diffuse gamma-ray flux (II)

(Ibarra, Tran '07)



EGRET data from analysis of Strong, Moskalenko and Reimer; gravitino decays: $BR(\psi_{3/2} \rightarrow \gamma\nu) = 0.05$, $BR(\psi_{3/2} \rightarrow Z\nu) = 0.24$, $BR(\psi_{3/2} \rightarrow WI) = 0.71$, with $m_{3/2} \simeq 150$ GeV \rightarrow wait for GLAST !!

SUMMARY

Theoretical developments over almost two decades concerning electroweak phase transition and sphaleron processes have established connection between baryon and lepton number in high-temperature phase of the SM.

Electroweak baryogenesis will soon be tested at **LHC** !

Evidence for AD baryogenesis from Q-balls (ICECUBE, Super-Kamiokande), or hints for non-thermal WIMP dark matter from **LHC** ?

Leptogenesis provides elegant explanation of observed baryon asymmetry in terms of neutrino properties; perfect cosmological observation: $\sum m_\nu \sim 0.07$ eV; further theoretical development beyond Boltzmann equations required

Discovery of **mSUGRA** at **LHC** could falsify (standard) thermal leptogenesis; evidence for gravitino dark matter from **LHC** and **GLAST** ?