WB, DESY, 9-04

THERMAL HISTORY OF THE EARLY UNIVERSE

current picture:

de Sitter (inflaton)

↓

(Re/Pre) Heating ↓

↓

Hot Phase (radiation dominated)

↓

Cold Phase (matter dominated) ↑

↓

Structure Formation, CMB

↓

de Sitter' ($\Omega \simeq \Omega_\Lambda$)

↓ ?

temperature/time

1 eV	10^{13} s	decoupling of photons, CMB → Durrer
1 MeV	1 s	decoupling of neutrinos
0.1 ... 10 MeV	10^{2} ... 10^{-2} s	{BBN}, important constraints on particle physics new results
10^{2} MeV	10^{-4} s	QCD phase transition, quark gluon plasma cf heavy ion collisions
~ 10 GeV	10^{-8} s	{WIMP} decoupling, SUSY dark matter
100 GeV	10^{-10} s	Electroweak transition
⋮		
10^{6} ... 10^{10} GeV	10^{-18} ... 10^{-26} s	Baryogenesis, {gravitino} (axino) dark matter
~ 10^{12} GeV		'maximal' temperature ?

– Processes in early universe

expansion (FRW metric):

$$ds^2 = dt^2 - R^2(t)\,(dr^2 + r^2 d\Omega^2) \quad ,$$

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\,\rho$$

Hubble parameter

energy density

flat universe ($k=0$) , CMB

energy density:

$$\rho = \rho_r + \rho_M + \rho_\Lambda$$

radiation matter 'vacuum' (cosm. constant)

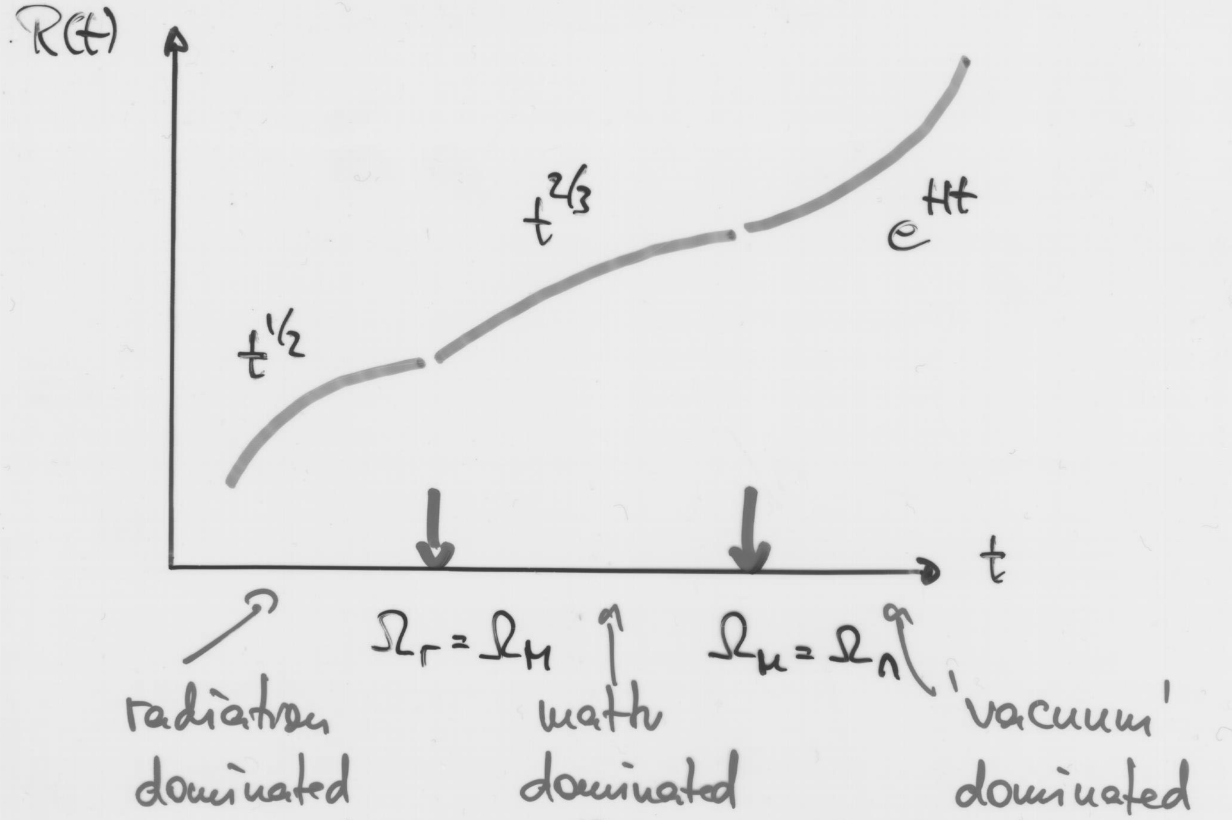
$$\Omega = \frac{\rho}{\rho_c} \quad , \quad \rho_c = \frac{3H_0^2}{8\pi G}$$

today

$$H^2 = H_0^2\left(\Omega_r\left(\frac{R_0}{R}\right)^4 + \Omega_M\left(\frac{R_0}{R}\right)^3 + \Omega_\Lambda\right)$$

different scaling with R !

flat universe ($k=0$) : $\Omega_r + \Omega_M + \Omega_\Lambda = 1$



$t_{eq} \simeq 2 \times 10^{12}$ s → structure formation

Radiation dominated phase :

$$n(p) = \frac{1}{e^{\frac{E-\mu}{T}} \pm 1}$$ equilibrium particle number distributions, μ: chemical potential

relativistic particles :

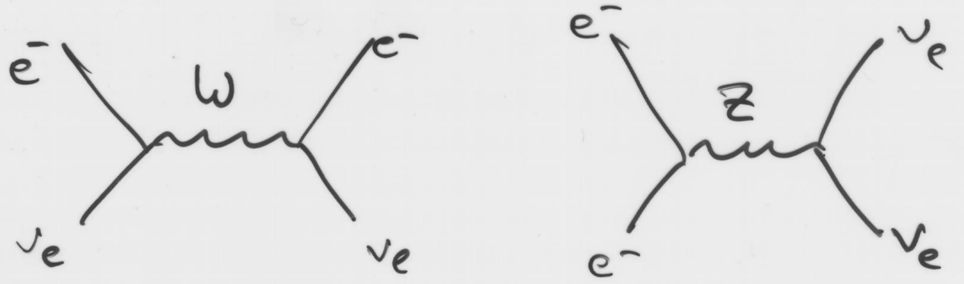
$$\rho = \frac{\pi^2}{30} g_* T^4 \quad , \quad g_* = \underset{\text{bosons}}{g_B} + \frac{7}{8} \underset{\text{fermions}}{g_f}$$

$$p = \rho/3$$

$$t = \frac{1}{2H} \simeq 0.3 \frac{M_p}{g_*^{1/2} T^2} \quad , \quad M_p = G^{-1/2} = 1.2 \times 10^{19} \text{ GeV}$$

$$t[s] \sim T[\text{MeV}]^{-2}$$

• Neutrino decoupling



average collision rate:

$$\Gamma = \langle \sigma n v \rangle$$

↑ relative velocity

process in equilibrium: $\Gamma > H$;

decoupling temperature:

$$H \Big|_{T=T_D} = \Gamma \Big|_{T=T_D}$$

$\Gamma \sim G_F^2 T^5$ yields $T_D \sim 1$ MeV; precise calculation ($\to$ Hannestad): $T_D(\nu_e) = 2.4$ MeV, $T_D(\nu_{\mu,\tau}) = 3.7$ MeV $> m_e$; at $T \sim m_e/3$ annihilation $e^+e^- \to 2\gamma$; entropy conservation:

$$\left[g_\gamma + \frac{7}{8}(g_{e^-} + g_{e^+}) \right] T_\nu^3 = g_\gamma T_\gamma^3$$

$$\to \quad \frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{1/3} = 0.71$$

1% accuracy **measurement!**

• Nucleosynthesis (BBN)

predicts abundances of light elements D, ^3He, ^4He, ^7Li ; crucial quantity is neutron/proton ratio,

$$\frac{n_n}{n_p} \simeq e^{-\frac{m_n-m_p}{T}} ,$$

at neutron freeze out decoupling temperature

$$T_D(\nu n \leftrightarrow e p) \simeq 0.5\, \underset{\uparrow}{g_*}^{1/6} \text{ MeV}$$

$$\left.\frac{n_n}{n_p}\right|_{T_D} \simeq \frac{1}{6}$$

(almost) all neutrons are processed into ^4He; resulting mass fraction:

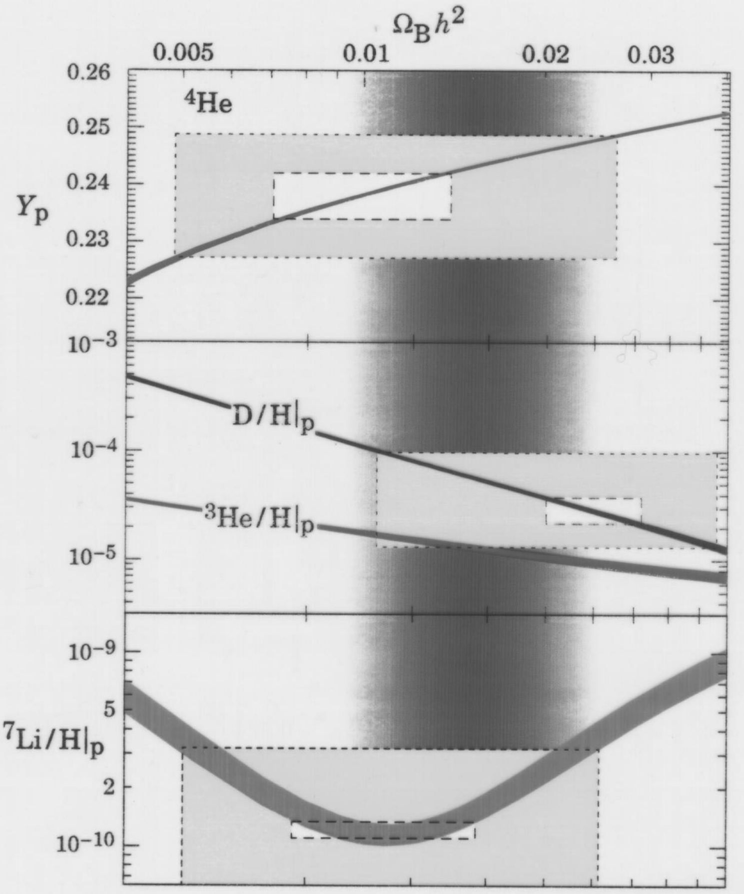
$$Y \simeq \frac{4\, n_{4He}}{n_n + n_p} \simeq \frac{4\,\frac{n_n}{2}}{n_n + n_p} = \frac{2\,\frac{n_n}{n_p}}{\frac{n_n}{n_p}+1} \simeq \frac{1}{4}$$

Detailed calculations constrain baryon asymmetry:

$$\eta_B = \frac{n_B}{n_\gamma} \simeq \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq (2.6-6.2)\times 10^{-10} \quad F$$

Fields, Sarkar '03

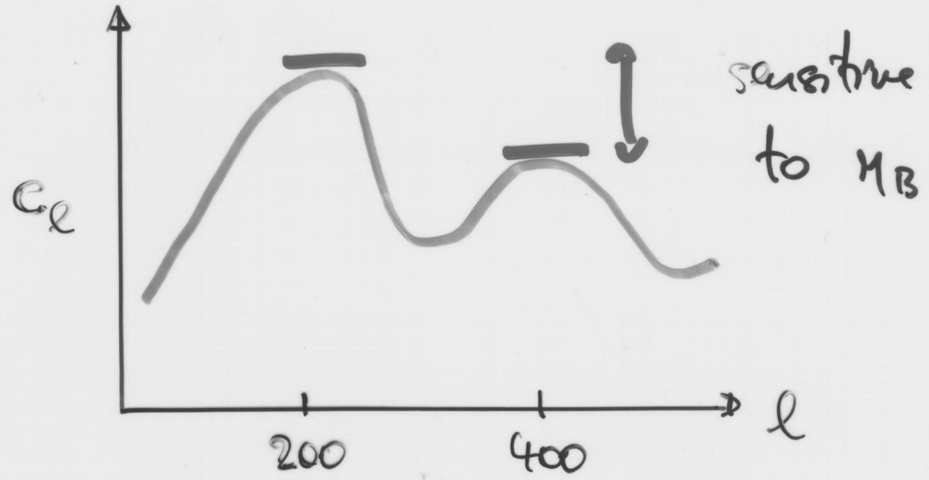
Primordial abundances from BBN



smaller boxes : 2σ statistical errors

larger " : 2σ statistical + systematic errors

for comparison : CMB



WMAP : $\eta_B^{CMB} = (6.3 \pm 0.3) \times 10^{-10}$

'precision measurement', consistency of hot BB up to temperatures $T \sim 1$ MeV !

constraints on number of neutrinos

neutron decoupling temperature depends on total # of degrees of freedom (g_*), yields bound on # of ν's :

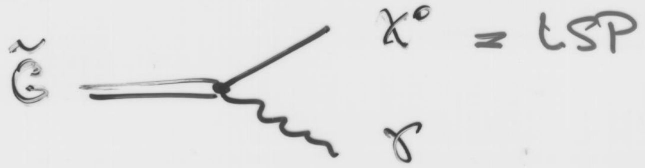
$$1.7 \leq N_\nu \leq 3.0 \quad (95\% \text{ cl})$$

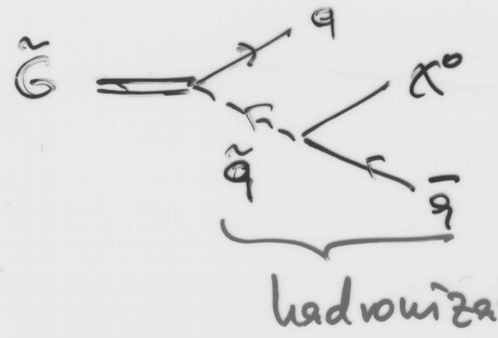
cf. review by Hannestad

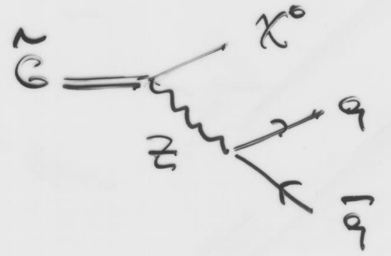
Constraints on long-lived massive particles

problem : late decays, after BBN, destroy successful prediction of abundances

example : gravitino







dangerous processes : photodissociation, ...

$\gamma + D \to n + p$, $\gamma + {}^3He \to p + p + n$, ... ,

excludes regions in $m_X n_X - \tau_X$ - plane

(→ Kawasaki et al. , astro-ph/0408426) ;

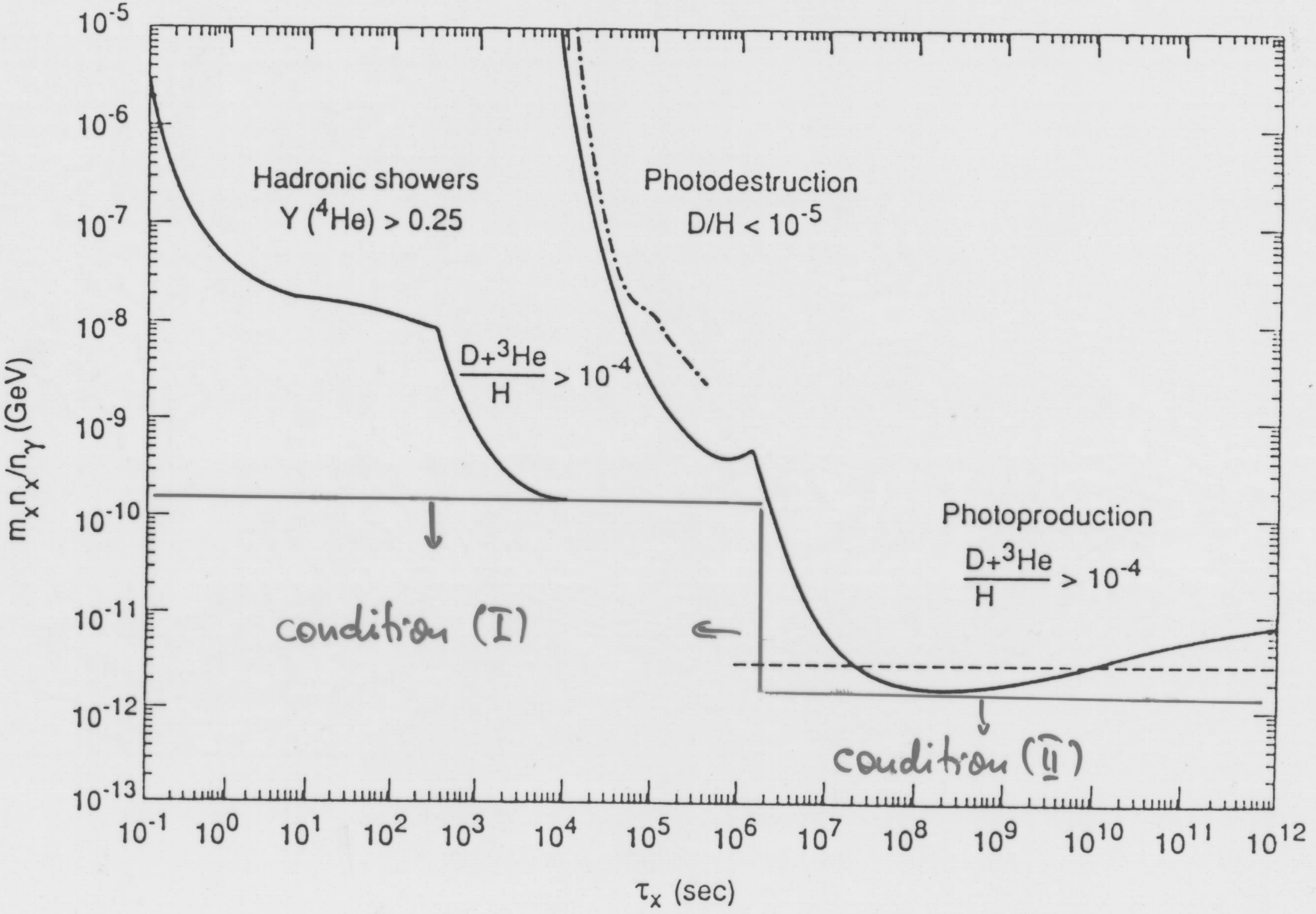
F_S

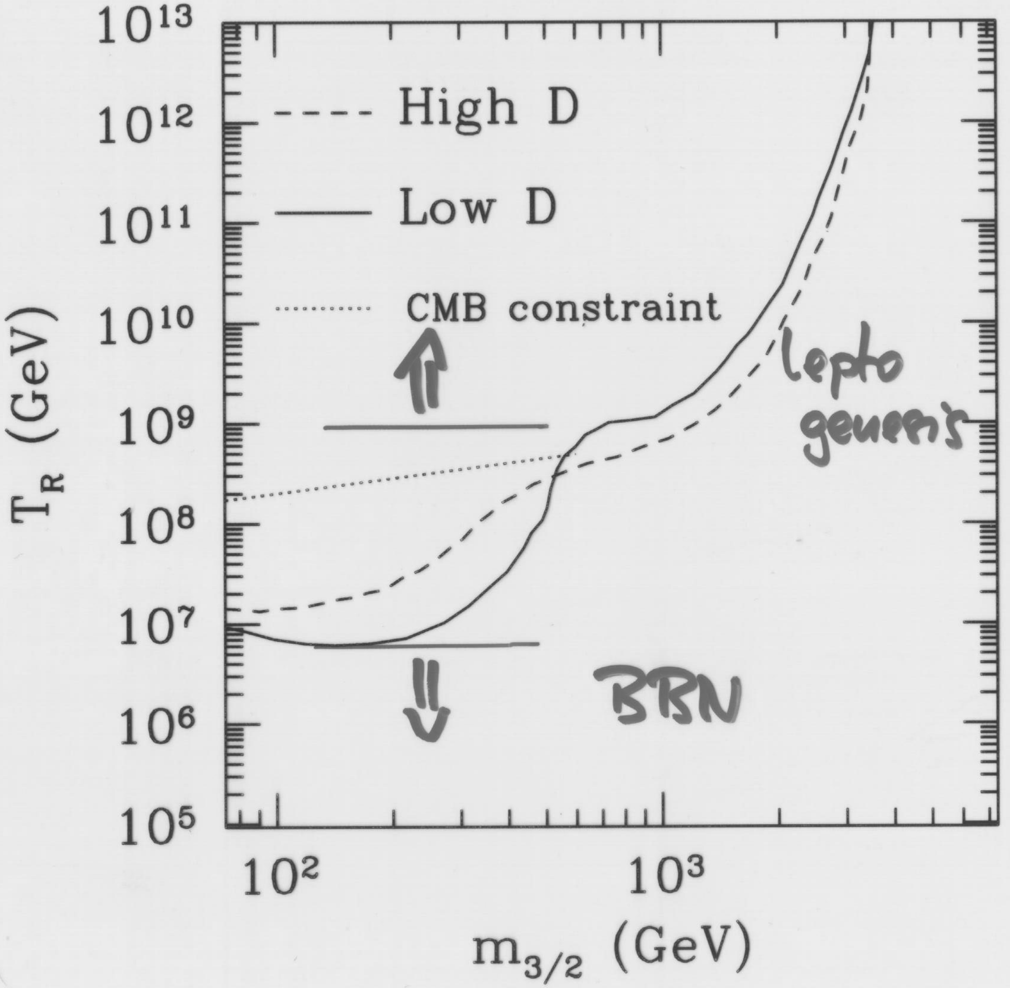
for gravitinos :

$$\frac{n_{\tilde G}}{n_\gamma} \propto T_R \quad ,$$

yields bound on reheating temperature, $T_R < 10^6$ GeV

Ellis, Gelmini, Lopez, Nanopoulos, Sarkar, NP '92





Kawasaki,
Kohri, Moroi '01

• Quark gluon plasma

at critical energy density,

$$\varrho_c = (0.6 \pm 0.3)\,\frac{GeV}{fm^3} \sim \Lambda_{QCD}^4 ,$$

transition from hadronic matter to quark-gluon plasma; much work in LGT (→ Petrecky, hep-lat/0409139); transition flavour dependent, most likely smooth crossover (→ no relic gravitational waves!); transition temperature $T_c \simeq 160$ MeV.

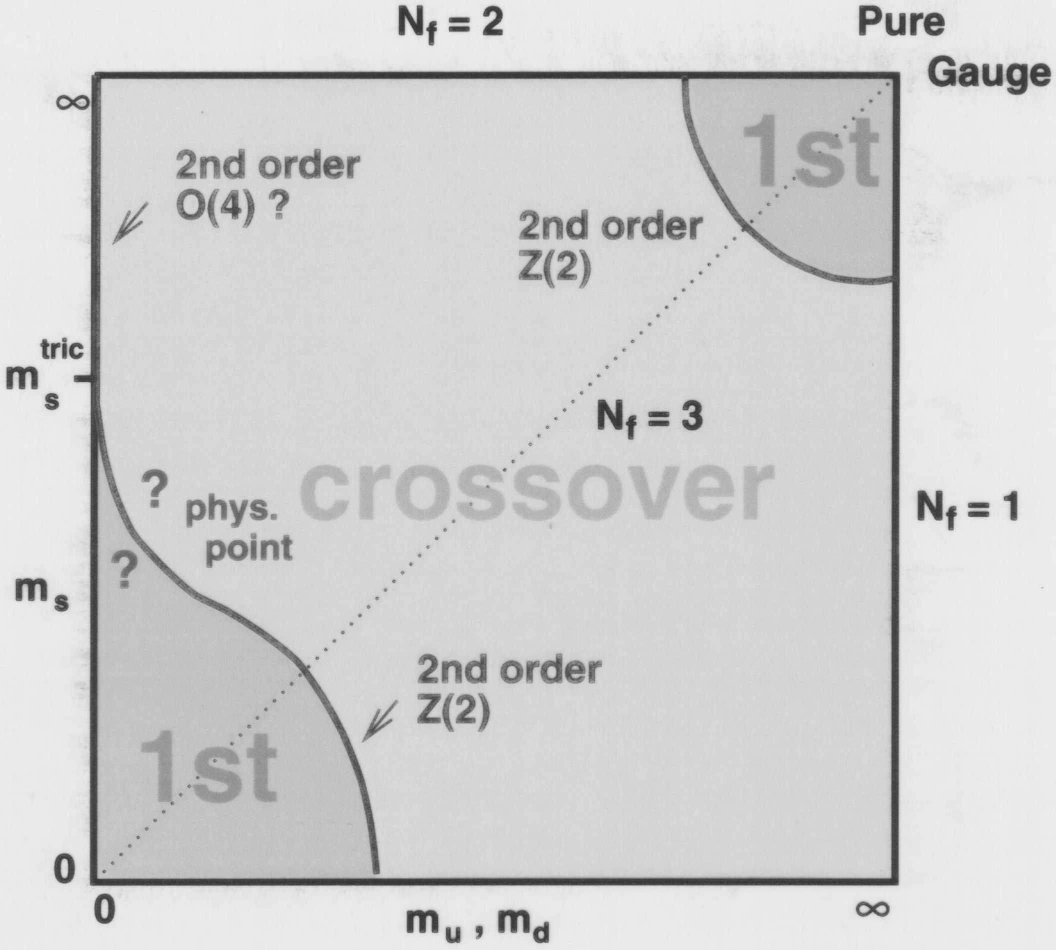
QG plasma interesting and difficult!

typical particle wavelength	T^{-1}
" separation	T^{-1}
Debye screening length	$(gT)^{-1}$
magnetic "	$(g^2T)^{-1}$

(nonperturbative!)

'perturbative' calculations possible for $(g^2T)^{-1} \gg (gT)^{-1} \gg T^{-1}$; QCD: $g \gg 1$

→ heavy ion collisions; photon radiation of QGP, quasi-particle picture? $(m \sim gT)$



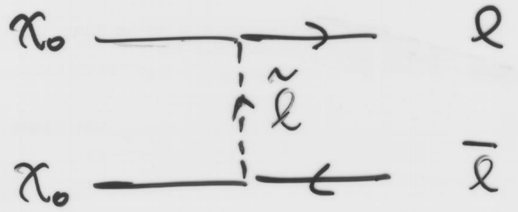
P. Petreczky , Lattice 04

hep-lat/0409139

- **WIMP dark matter**

Weakly Interacting Massive Particles (LSP)

annihilate in plasma, e.g.



$\ell = e, \mu, \tau$, ...

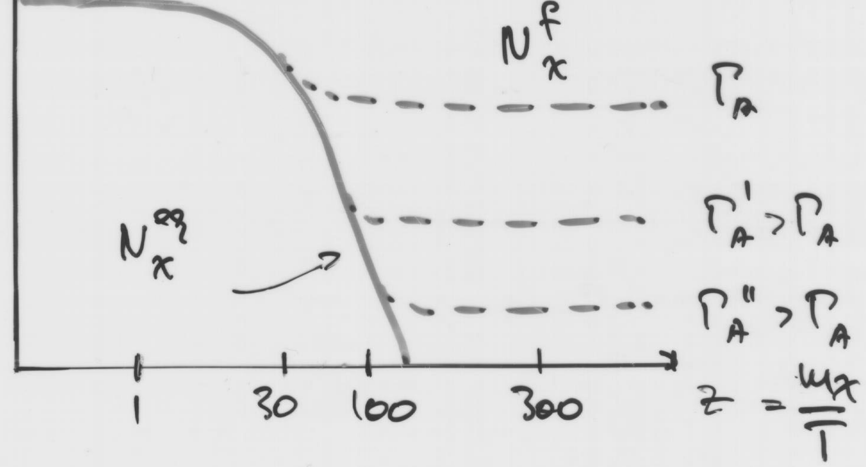
Boltzmann eqs. describe decoupling :

$$\frac{dn_\chi}{dt} + \underset{\uparrow \ \text{expansion}}{3H}\, n_\chi = -\underset{\uparrow \ \text{thermal average}}{\langle \sigma_A v \rangle} \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

$n_\chi \to N_\chi$ (# in comoving volume) ,

$t \to z = m_\chi / T$, $\langle \sigma_A v \rangle \to \Gamma_A$

$$\frac{1}{N_\chi} \frac{dN_\chi}{dz} = -\frac{\Gamma_A}{Hz} \left[\left(\frac{N_\chi}{N_\chi^{eq}} \right)^2 - 1 \right]$$



many detailed studies ! (→ Drees, Gerbier RPP '04)

- decoupling temperature :

$$T_D \sim \frac{1}{20} m_\chi$$

i.e., $T_D \sim 10$ GeV for $m_\chi \sim 200$ GeV

- WIMP density in SUGRA (part of parameter space) :

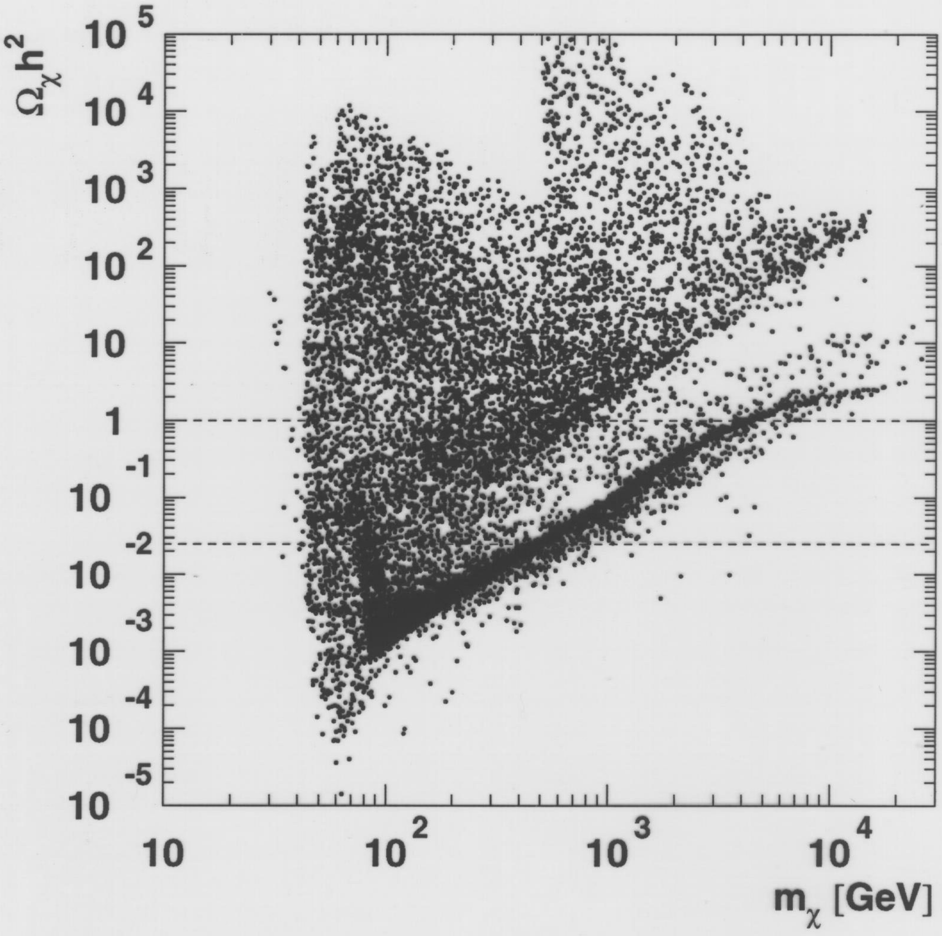
$$\Omega_\chi h^2 \simeq \frac{(m_\chi^2 + m_{\tilde{\ell}_R}^2)^2}{10^6 \,\mathrm{GeV}^2\, m_\chi^2 \,(m_{\tilde{\ell}_R}^2 + m_\chi^2)}$$

$\Omega h^2 < 0.2$ then implies for SUSY scale :

$$m_\chi,\, m_{\tilde{\ell}_R} < 200 \,\mathrm{GeV} .$$

neutralino, $\chi = \alpha \tilde{b} + \beta \tilde{w}_3 + \gamma \tilde{h}_1^0 + \delta \tilde{h}_2^0$, natural DM candidate ; complete parameter space rather complex ! strong constraints from global analyses in CMSSM F

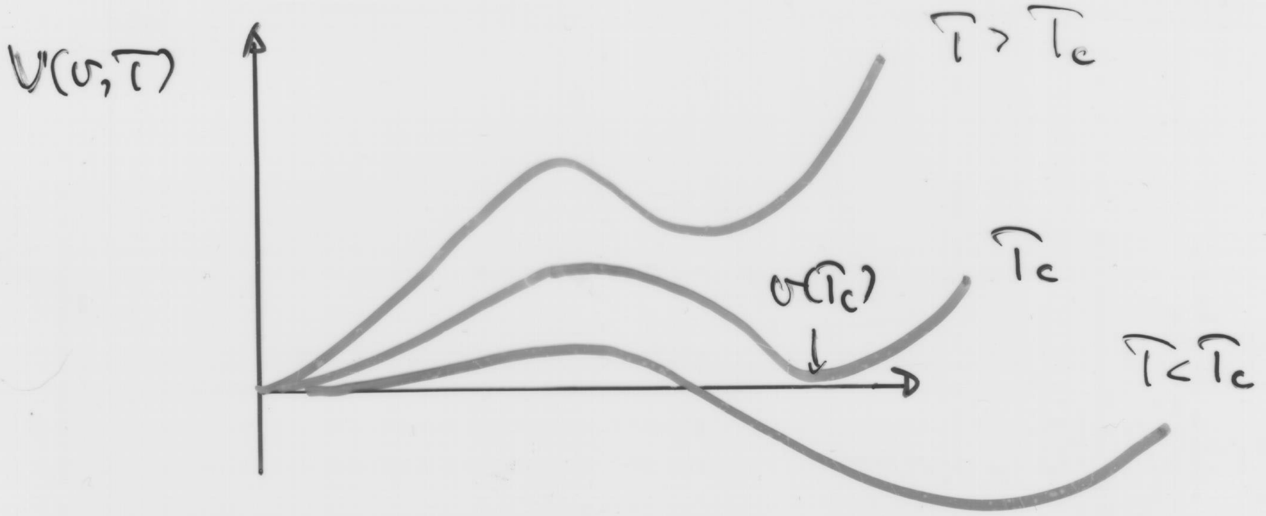
Edsjö, Gondolo, PRD '97



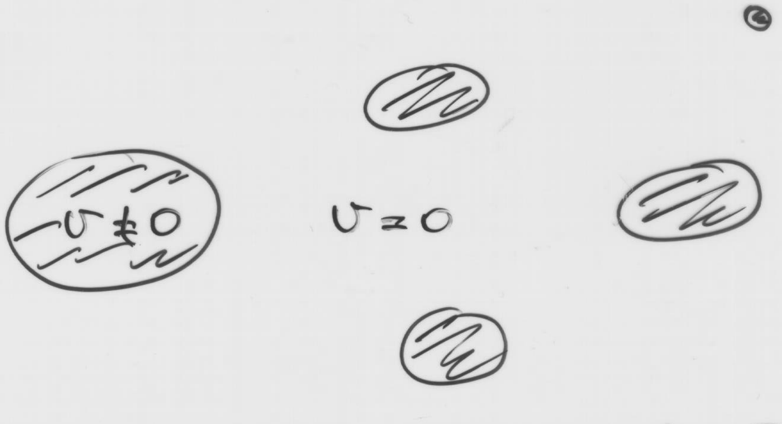
- **Electroweak transition**

crucial quantity of electroweak theory:
Higgs vacuum expectation value $v_T = \langle \phi \rangle_T$, evaporates at critical temperature

$$T_c \sim v_0 \sim 100 \text{ GeV}$$



leads to first-order phase transition
electroweak baryogenesis



dynamics near bubble wall generates B-asymmetry
(review : Rubakov , Shaposhnikov '97)

Necessary condition for EWB (Shaposhnikov):

$$\frac{v_T}{T} > 1 \quad ,$$

sufficiently strong transition (sphaleron washout), yields bound on Higgs mass

$$m_H < 45 \text{ GeV} .$$ F

Detailed (lattice) studies have determined phase diagram of electroweak theory; F
crossover at critical Higgs mass

$$m_H^c = 72.1 \pm 1.4 \text{ GeV}$$

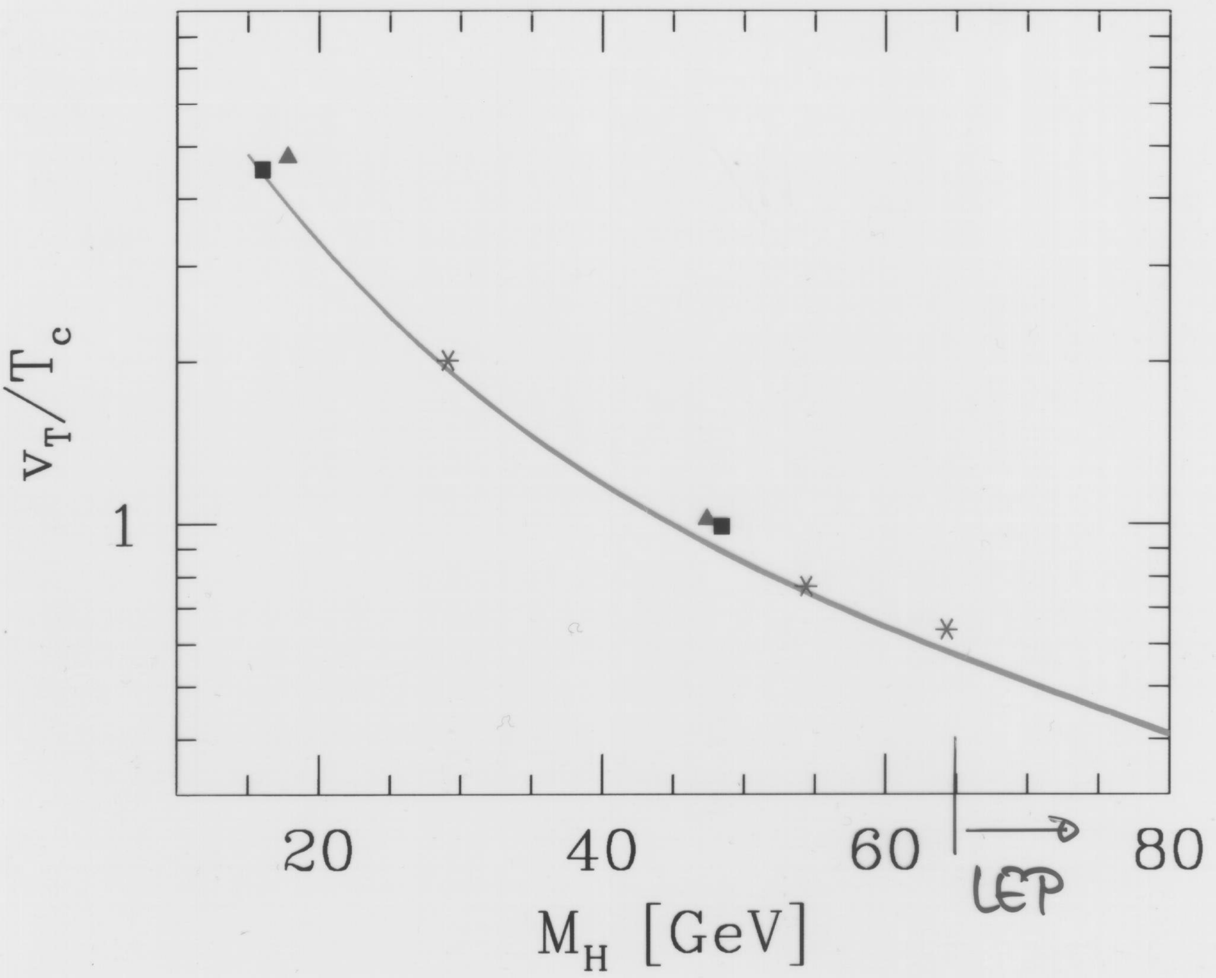
Rough estimate (compare m_W in Higgs phase with $m_{MS} = C g^2 T$, $C \simeq 0.35$ in symm. ph.):

$$m_H^c = \left(\frac{3}{4\pi C}\right)^{1/2} m_W \simeq 74 \text{ GeV}$$

extrapolation to MSSM: $m_h^c < 130 \ldots 150$ GeV

→ no EWB in SM; MSSM still possible (Carena et al., Schmidt et al.), also 'cold' EWB, etc → Shaposhnikov

Jansen , LATTICE '95



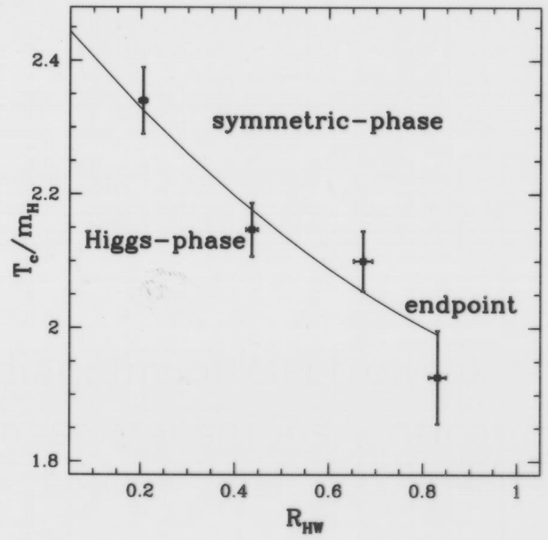
■, ▲ Fodor, Hein, Jansen, Jaster, Montvay, Nucl. Phys. B '95 , d=4

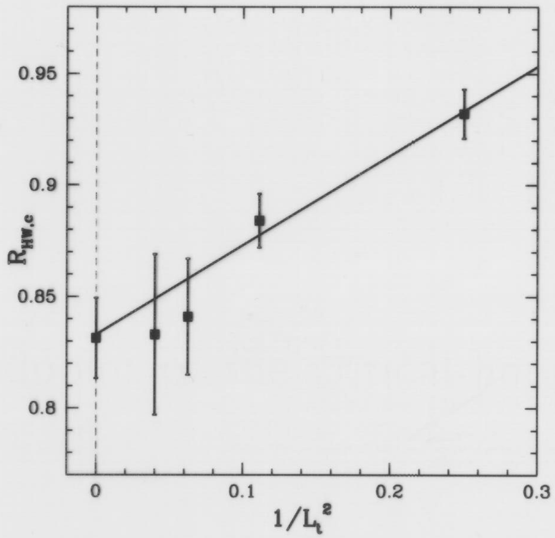
* Farakos, Kajantie, Rummukainen, Shaposhnikov, to appear , d=3 , Nucl. Phys. B '96

— WB , Fodor , Hebecker , Nucl. Phys. B '95

Phase diagram of electroweak theory, endpoint of the critical line of first-order phase transitions, critical Higgs mass m_H^c

Csikor, Fodor, Heitger '99





lattice: $L_t L_s^3 = 2 \times 5^3 \ldots 5 \times 50^3$, $R_{HW,c} = \frac{m_H^c}{m_W}$, $m_H^c = 72.1 \pm 1.4$ GeV

Sphaleron processes

Baryon and lepton number not conserved in SM:

$$\partial_\mu J_B^{\mu} = \partial_\mu J_L^{\mu} = n_f \frac{g^2}{32\pi^2} W^I_{\mu\nu} \tilde{W}^{I\mu\nu}$$

instantons / sphalerons generate effective 12-fermion interaction in SM:

$$O_{B+L} = \underset{(i=1\ldots n_f)}{\prod_i} \left(q_{Li} q_{Li} q_{Li} l_{Li} \right)$$

F

sphaleron rate near T_c from semiclassical calculation; for $T > T_c$ diffusion process:

$$\Gamma \propto \lim_{\substack{V \to \infty \\ t \to \infty}} \frac{1}{Vt} \left\langle \int_t \int_V \frac{g^2}{32\pi^2} W\tilde{W} \right\rangle_T$$

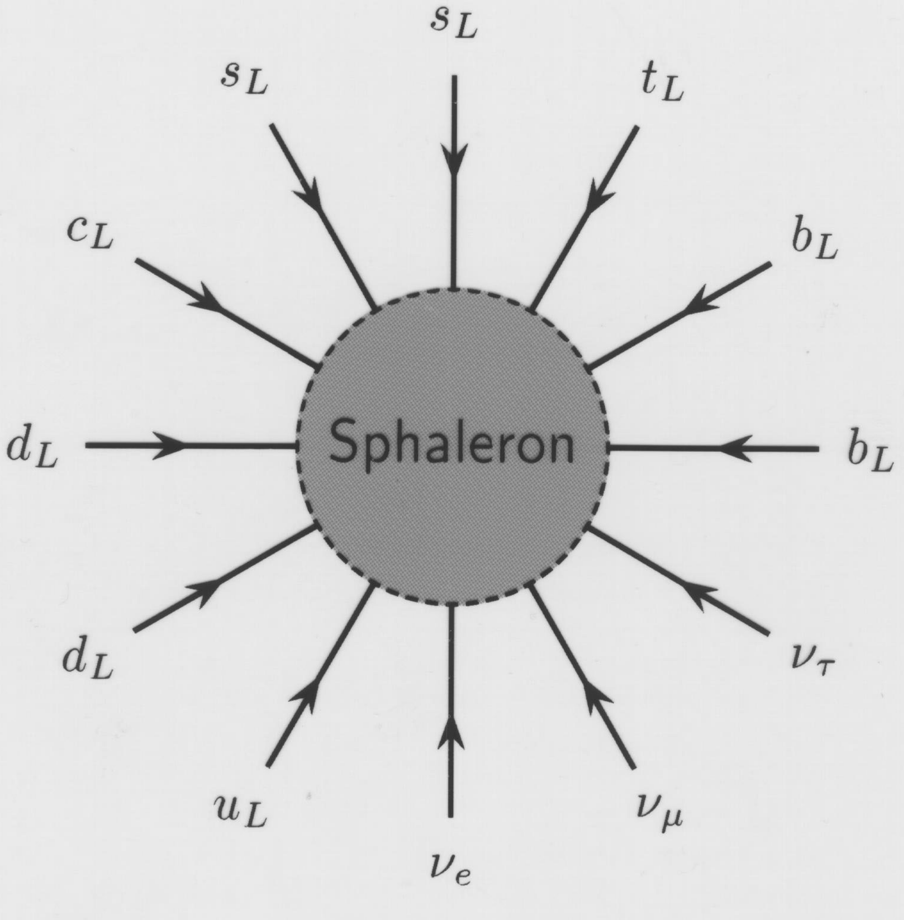
$$\simeq (14.3 \pm 0.3) \frac{1}{\sigma} (\alpha T)^5 ,$$

F

σ: colour conductivity; experts agree that $\Gamma > H$ for

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

$$\longrightarrow \left\{ \boxed{\langle B \rangle_T = c \langle B-L \rangle_T = \frac{c}{c-1} \langle L \rangle_T} \right\} \text{ in equil.}$$


s_L
s_L
t_L
c_L
b_L
d_L
Sphaleron
b_L
d_L
ν_τ
u_L
ν_μ
ν_e

G. Moore , hep-ph/0009161

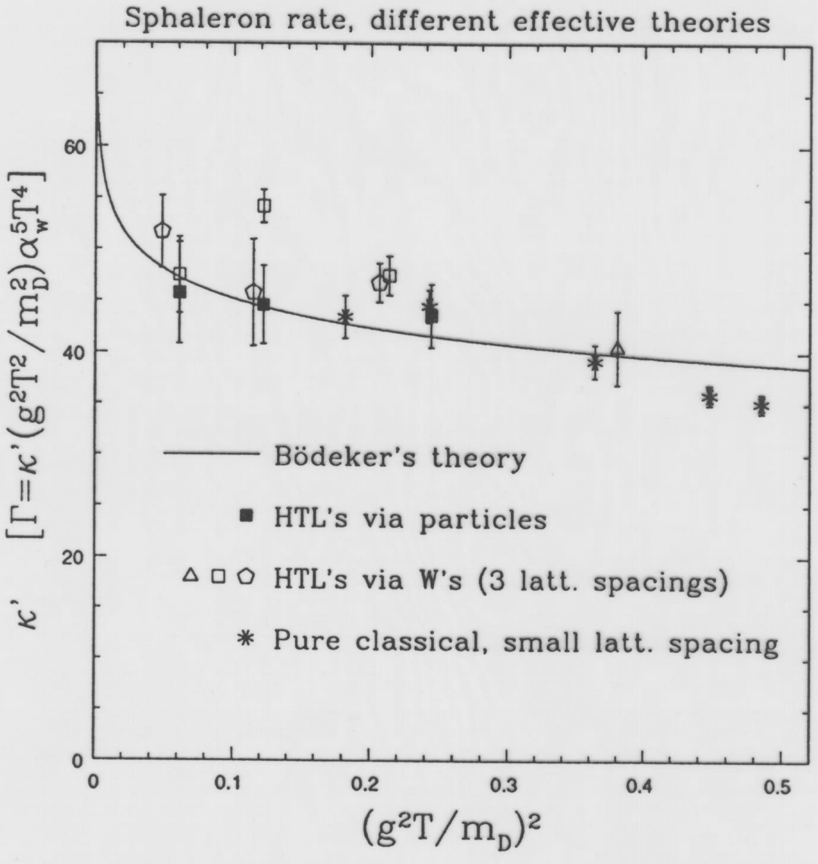
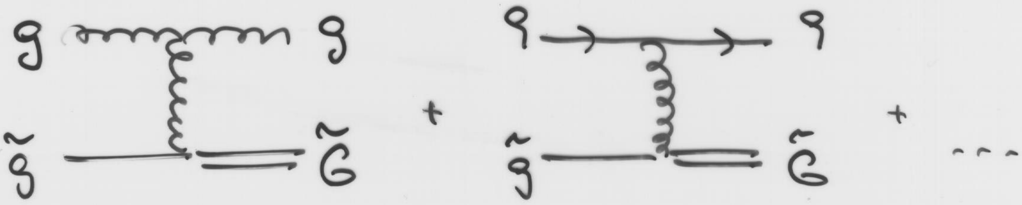


Figure 2: Sphaleron rate in Bödeker's effective theory, two lattice implementations of HTL effective theory [14,15], and pure lattice theory interpreted as HTL effective theory (see [24]).

• Gravitinos

cosmology for $T > T_{EW} \sim 100$ GeV depends on assumptions on physics beyond the SM !

Important problem in SUGRA : thermal production of gravitinos (Ellis et al., Moroi et al.):



$$\Gamma(T) \propto \frac{g_3^2}{M_P^2}\left(1 + \frac{m_{\tilde{g}}^2}{3 m_{3/2}^2}\right) T^3$$

production dominated by largest (re)heating temperature (similar discussion: axinos) ; unstable (stable) $\tilde{G}$: BBN (overclosure)

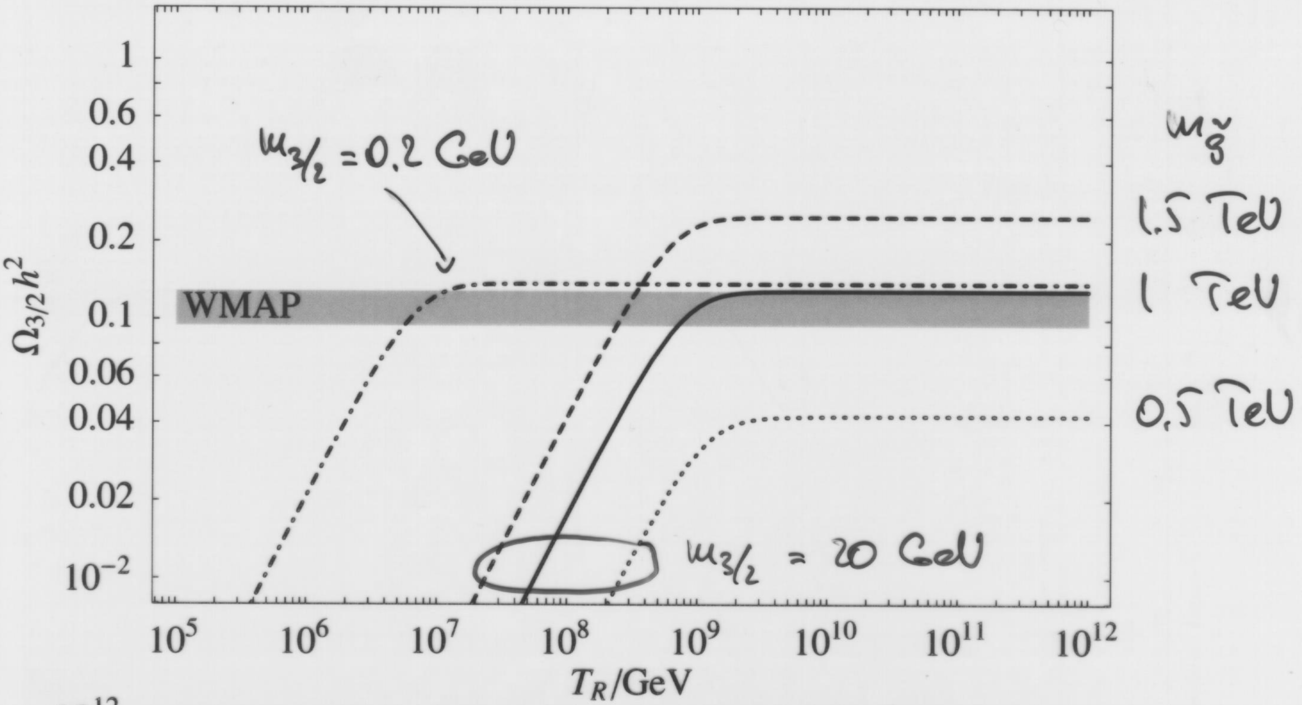
dynamical gauge coupling (WB, Hamaguchi, Ratz '08)

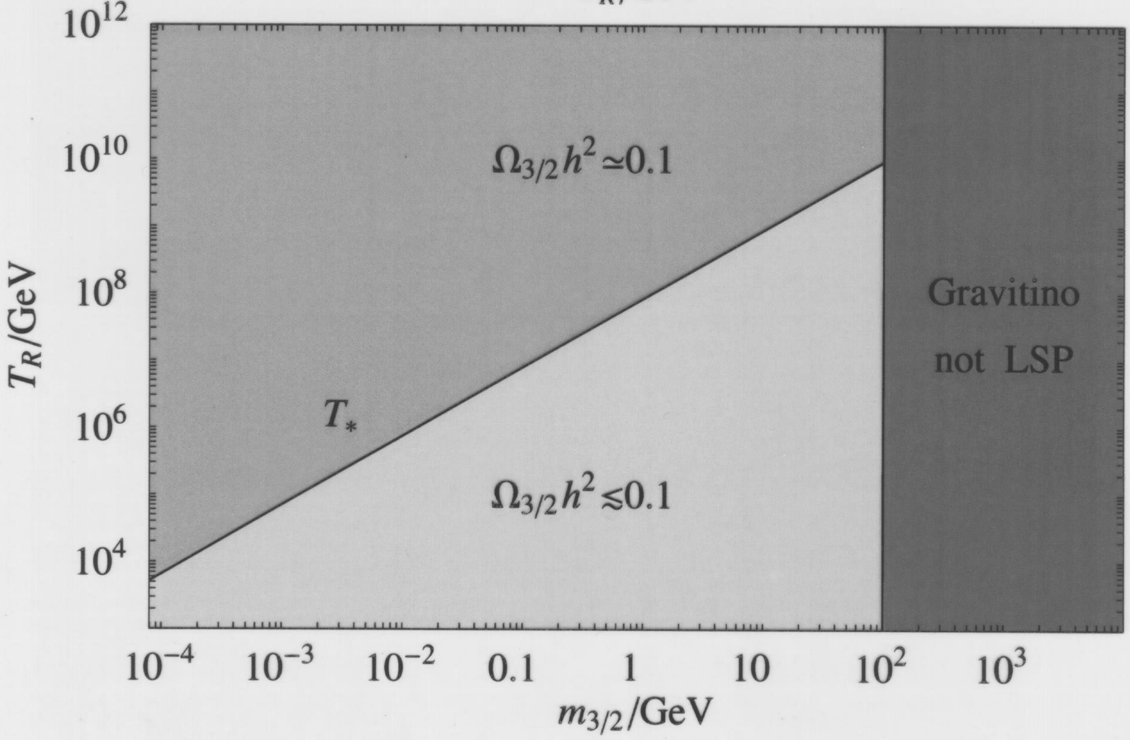
$$L = g_0 \frac{\Phi}{M}\left(-\frac{1}{4} F_{\mu\nu}F^{\mu\nu}\right) + \dots$$

→ $g(T)$ decreases for $T > T_* \sim m_{3/2}\left(M_P/m_{\tilde{g}}\right)^{1/2}$, with

$$\left\{ \boxed{\Omega_{3/2} h^2 \simeq (0.05-0.2)\left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^{3/2}\left(\frac{\xi}{M}\right)^{1/4}} \right\} \quad F$$

Gravitino dark matter





$m_{\tilde g} = 1$ TeV , $\frac{\xi}{\eta^2} = 1$

WB, Hamaguchi, Ratz , hep-ph/0307181

• Baryogenesis

many scenarios involving dynamics of scalar fields (Affleck-Dine, ...), require very different reheating temperatures T_R (cf. 'gravitino problem')

Non-thermal leptogenesis (inflaton)

(Shafi et al., Asaka et al., Giudice et al...)

inflaton decays into heavy Majorana neutrinos:

$$\phi \to N_1 N_1 \quad (B_R) \qquad m_\phi > 2M_1$$

$$\hookrightarrow \begin{cases} l\,\Phi \\ \bar{l}\,\bar{\Phi} \end{cases} , \quad B_R = \begin{matrix} (1+\varepsilon_1)/2 \\ (1-\varepsilon_1)/2 \end{matrix}$$

$$\frac{n_{N1}}{s} \simeq \frac{\rho_{rad}}{s}\,\frac{n_\phi}{\rho_\phi}\,\frac{n_{N1}}{n_\phi} \quad \text{(after reheating)}$$

$$= \frac{3}{4} T_R \, \frac{1}{m_\phi} \, 2B_R$$

$$\longrightarrow \frac{n_{B-L}}{s} \simeq 3\times 10^{-10} B_r \left(\frac{T_R}{10^6\,\mathrm{GeV}}\right) \frac{M_1}{m_\phi} \left(\frac{m_{\nu 3}}{0.05\,\mathrm{eV}}\right) \delta_{eff}$$

requires $T_R > 10^6$ GeV ✓ (cf. Hamaguchi hep-ph/0212305)

Thermal leptogenesis

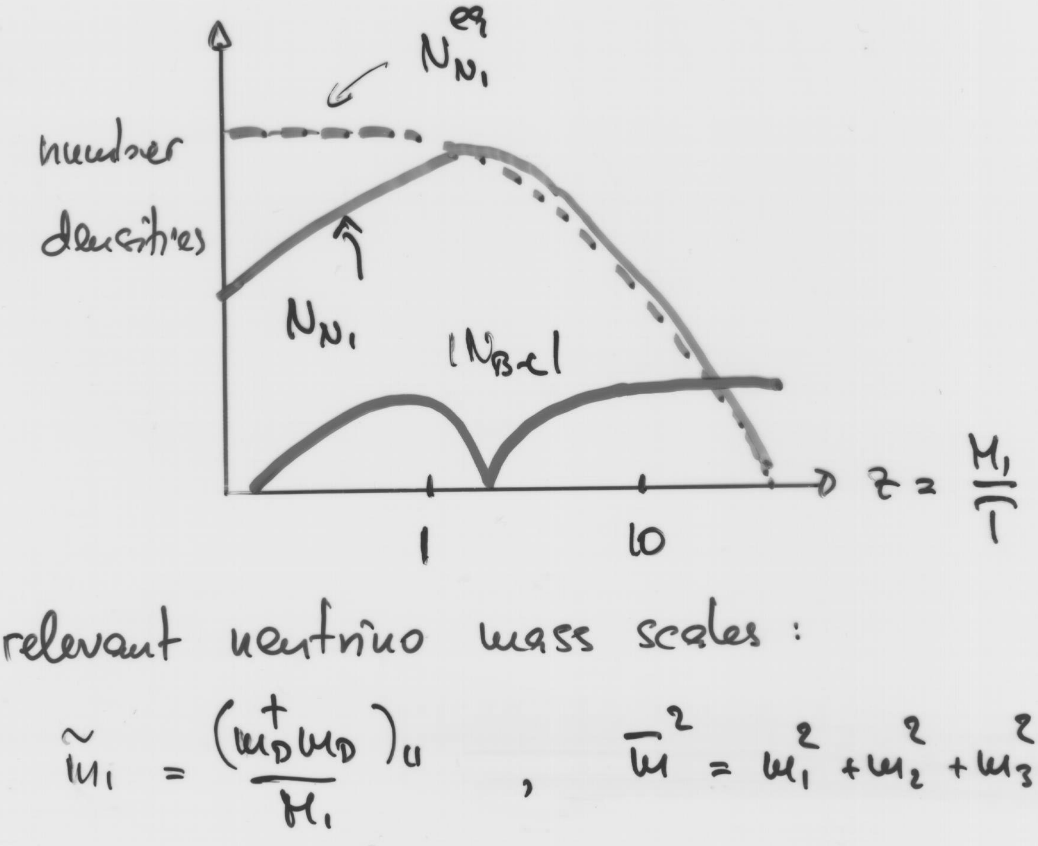
Fukugita, Yanagida '86 → Di Bari

closely related to seesaw mechanism :

$N \simeq \nu_R + \nu_R^c$: $m_N \simeq M$ heavy

$\nu \simeq \nu_L + \nu_L^c$, $m_\nu = - m_D \frac{1}{M} m_D^T$ light

simplest out-of-equilibrium decay scenario



relevant neutrino mass scales :

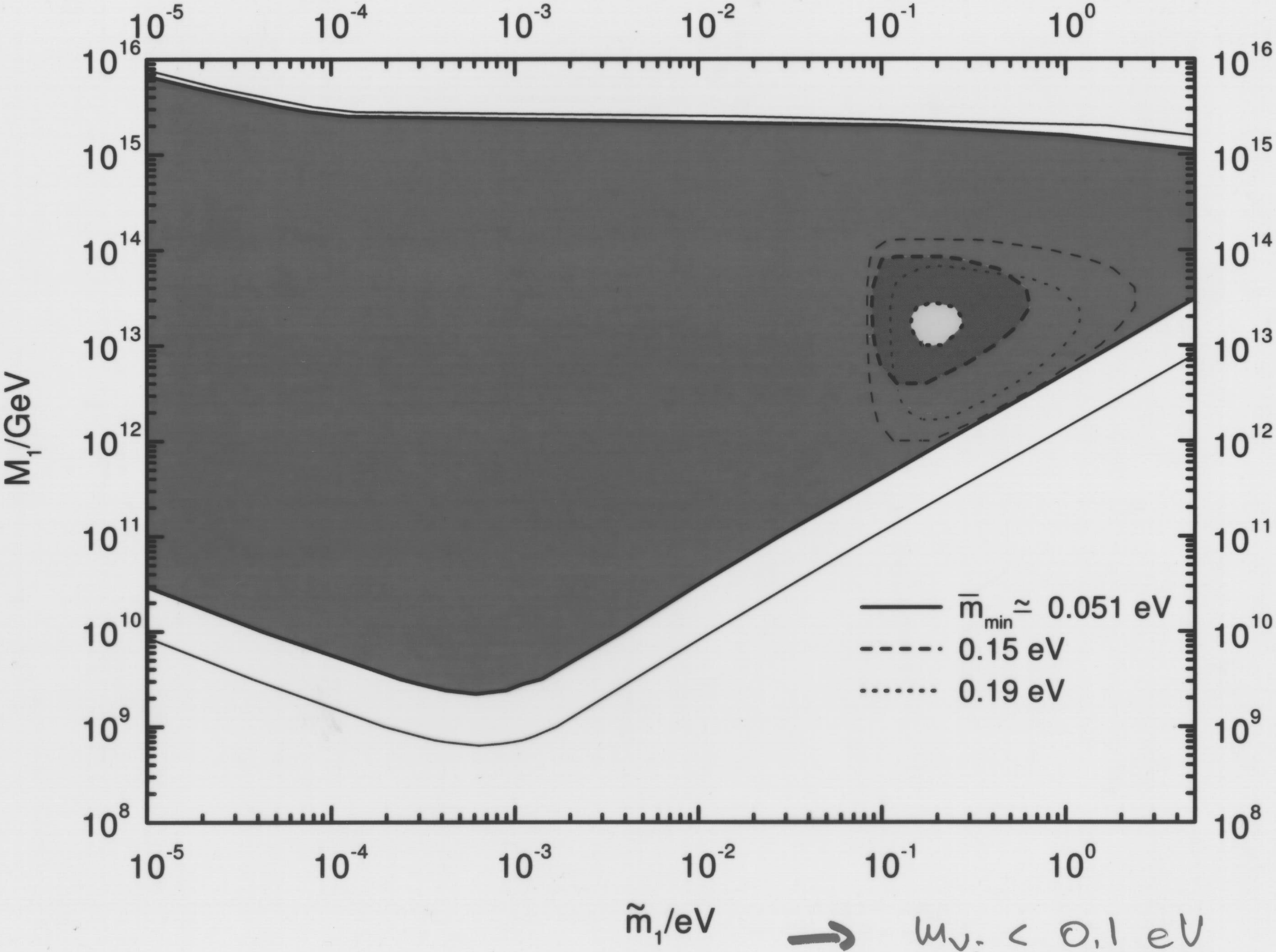
$$\tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1} , \quad \bar{m}^2 = m_1^2 + m_2^2 + m_3^2 ,$$

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

quantitative analysis yields ν-mass window :

$$\boxed{m_* < m_{\nu_i} < 0.1 \text{ eV}} , \quad T_R > \underset{(?)}{10^9} \text{ GeV}$$

WB, Di Bari, Plümacher



→ $m_{\nu_i} < 0.1$ eV

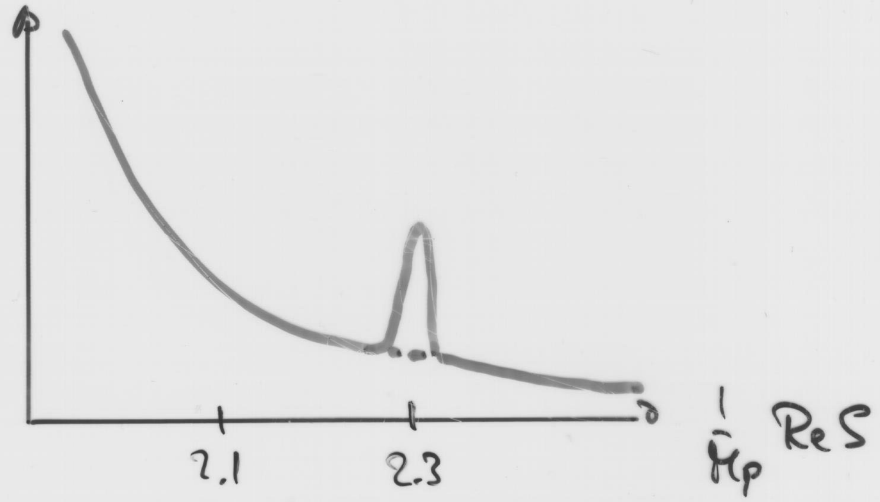
- **Maximal temperature ?**

(WB, Hamaguchi, Lebedev, Ratz, hep-th/0404168)

In superstrings compactification from 10 dim to 4 dim; gauge coupling determined by value of dilaton field :

$$L = \frac{1}{M_p} \mathrm{Re}S \left(-\frac{1}{4} F_{\mu\nu} F^{\mu\nu}\right) + \dots$$

stabalized run-away potential :



racetrack, Kähler (or flux?) stabilization ...

$\langle -\frac{1}{4} F^2 \rangle_T > 0$ generates negative linear term in effective potential, leads to destabilization at critical temperature

$$T_{crit} \sim \sqrt{m_{3/2}} \left(\frac{3}{\beta}\right)^{3/4} \left(\frac{\xi}{K''}\right)^{1/4} \sim 10^{12}\ \mathrm{GeV}$$

→ decompactification to 10 dim (?)