E-WIMPs and Gravitino DM

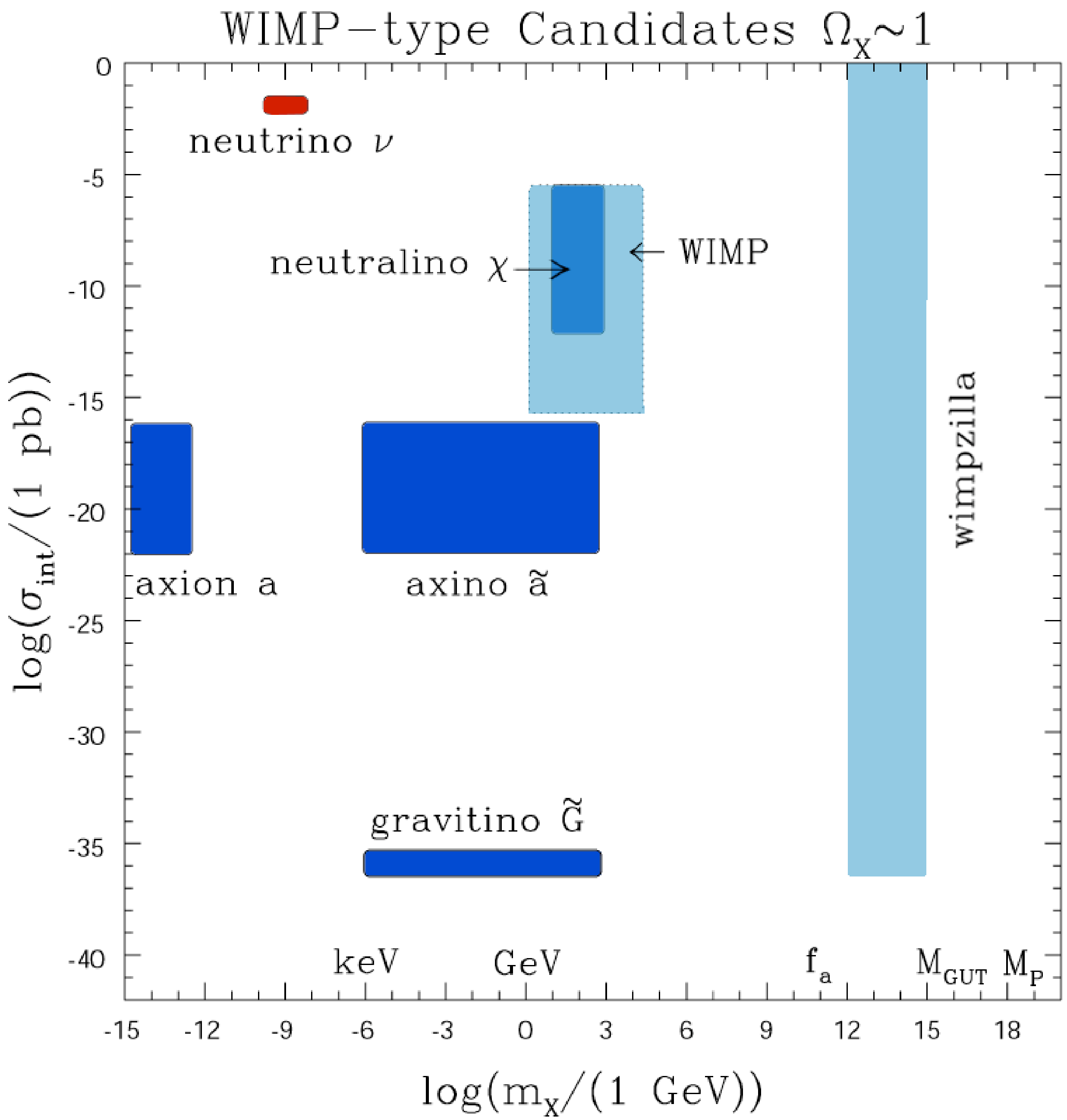
Ki Young Choi
(Pusan National University, Korea)

20th May 2010

GGI Conference The Dark Matter connection: Theory & Experiment

(Dark Matter: Its Origin, Nature and Prospects for Detection)

1. E-WIMPs
2. Gravitino and the production
   : Thermal and non-thermal production
3. Gravitino LSP as Dark Matter and cosmological constraints
4. Gravitino Dark Matter in the CMSSM
5. Beyond CMSSM
6. E-WIMPs and LHC
7. Summary

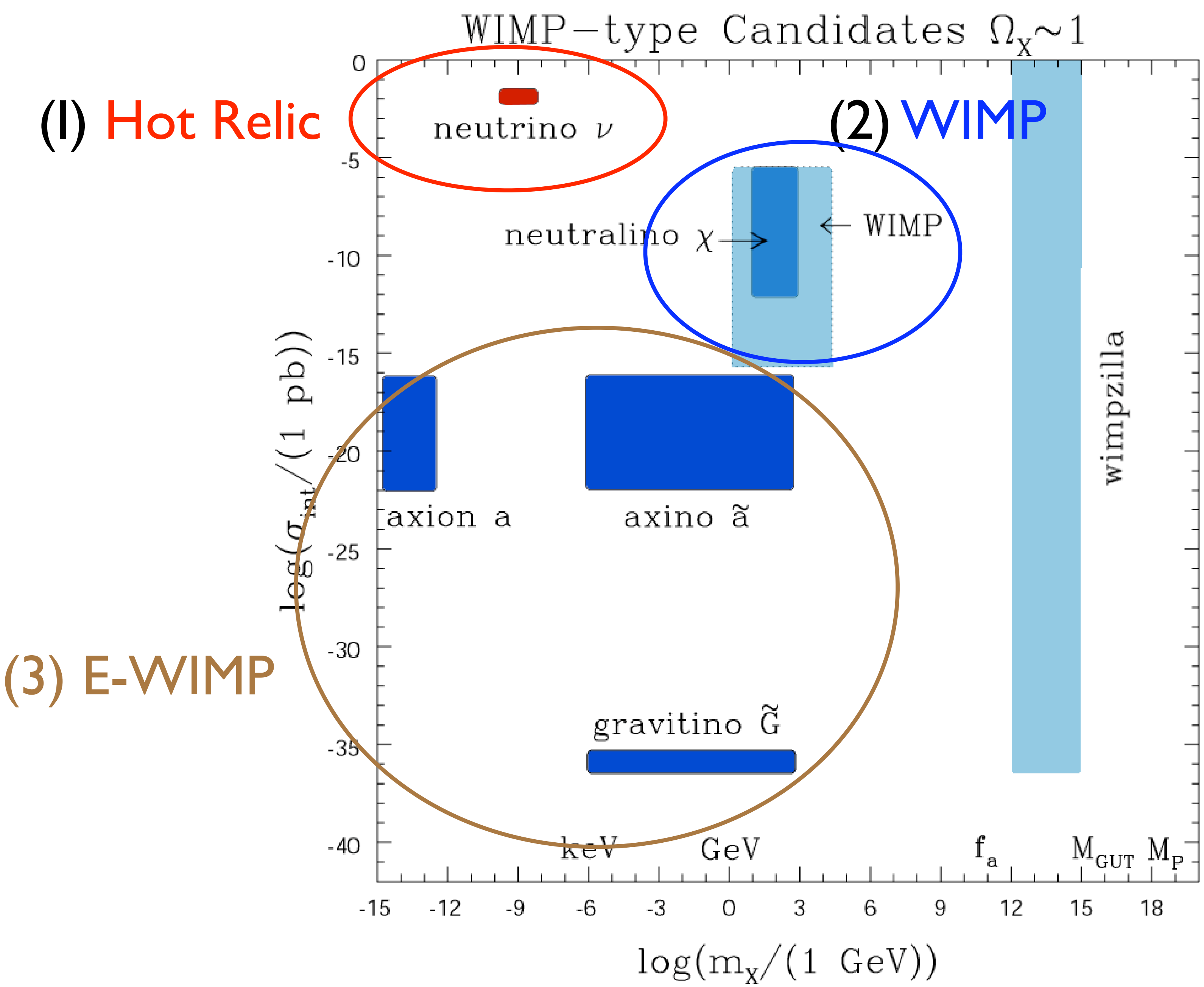


[Leszek]

T_f : freeze-out temperature

from $n_{eq}\langle\sigma_A v\rangle = H$

$T_{\rm reh}$: reheating temperature after inflation



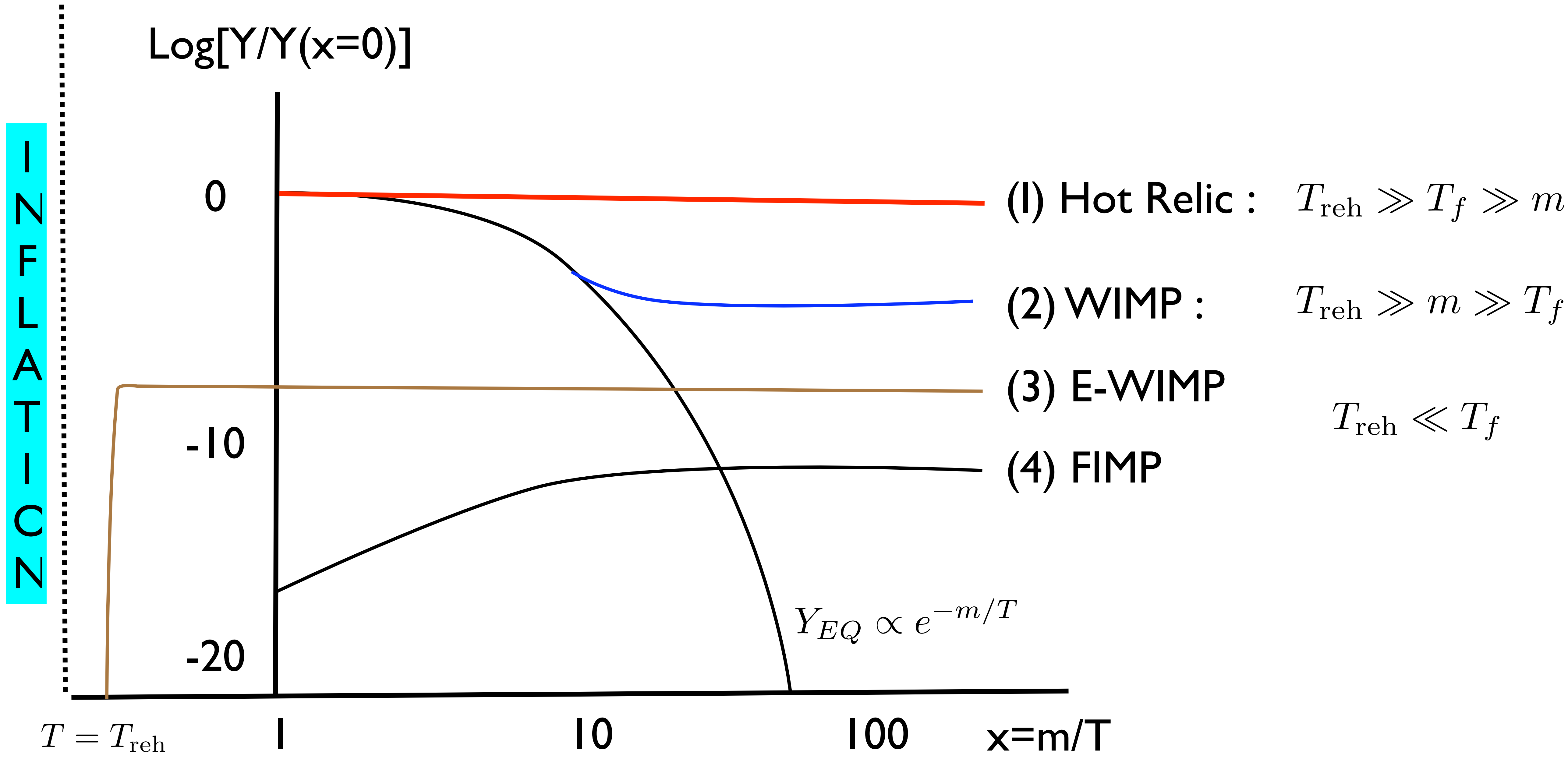
[Leszek]

T_f : freeze-out temperature

from $n_{eq}\langle\sigma_A v\rangle = H$

$T_{\rm reh}$: reheating temperature after inflation

• Thermal production of (meta-)stable relics

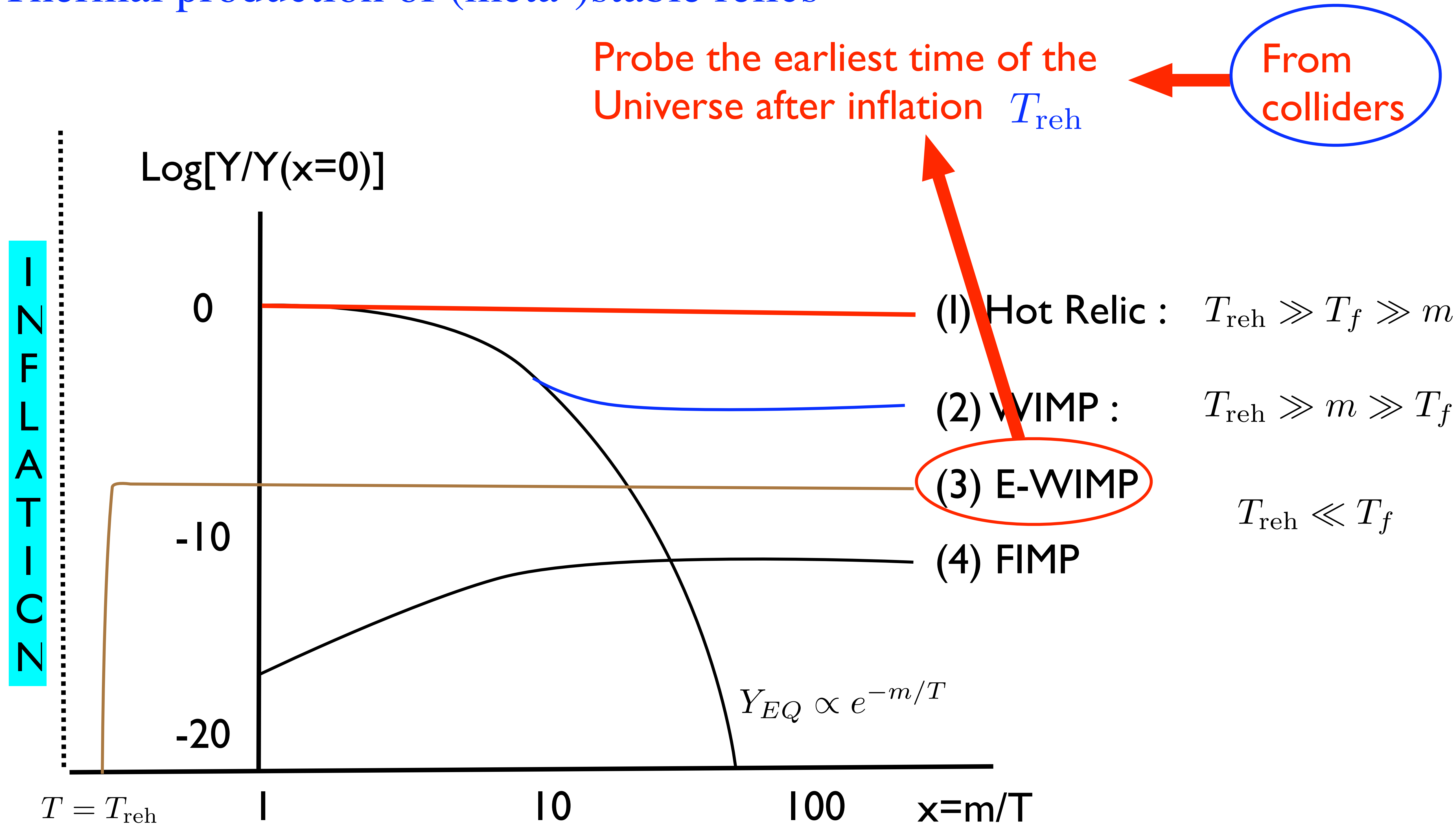


$$Y \equiv \frac{n}{s}$$

n : number density
s : entropy density
EQ : equilibrium

m : mass
T : temperature
Treh : reheating temperature
Tf : freeze-out temperature

- Thermal production of (meta-)stable relics



$$Y \equiv \frac{n}{s}$$

n : number density
s : entropy density
EQ : equilibrium

m : mass
T : temperature
Treh : reheating temperature
Tf : freeze-out temperature

- E-WIMPs : Extremely-Weakly Interacting Massive particles

  - Interactions to Standard Model particles are highly suppressed compared to WIMP

Gravitino $M_{\rm Pl} \sim 10^{18}\,{\rm GeV}$

Axion and Axino $f_a \sim 10^{11}\,{\rm GeV}$ ⟶ In the talk tomorrow

- Gravitino

SUSY + Gravity ⟶ Supergravity (SUGRA) : Gravitino (spin 3/2 supartner of gravtion)

$*$ The properties of gravitino are completely fixed by SUGRA

- Mass : $m_{\tilde{G}} = \langle W e^{K/2} \rangle = \dfrac{F_X}{M_P}$ from SUSY breaking (F_X : SUSY breaking scale)

from eV to TeV depending on the SUSY breaking mechanism (GMSB, Gravity-MSB, gaugino-MSB, anomaly-MSB ...)

- Couplings : given by SUGRA, suppressed by Planck scale

for light gravitino, Goldstino spin 1/2 interaction is dominant

$$-\frac{1}{M_{\rm Pl}}\bar{\psi}_\mu \sigma^{\nu\rho}\gamma^\mu \lambda^a F^a_{\nu\rho} - \frac{1}{\sqrt{2}M_{\rm Pl}} D_\nu \phi^* \bar{\psi}_\mu \gamma^\nu \gamma^\mu \chi_R - \frac{1}{\sqrt{2}M_{\rm Pl}} D_\nu \phi \bar{\chi}_L \gamma^\mu \gamma^\nu \psi_\mu + h.c.$$

$$\Rightarrow \quad \frac{i m_\lambda}{8\sqrt{6} m_{\tilde{G}} M_P} \bar{\psi}\left[\gamma_\mu, \gamma_\nu\right] \lambda F_{\mu\nu} + \frac{m_\chi^2 - m_\phi^2}{\sqrt{3} m_{\tilde{G}} M_P} (\bar{\psi \chi_L}) \phi^* + h.c$$

where $\psi_\mu \sim i\sqrt{\frac{2}{3}}\frac{1}{m_{\tilde{G}}}\partial_\mu \psi$ (ϕ, χ) chiral multiplet (A_μ, λ) gauge multiplet

- Light gravitinos could be in the thermal equilibrium

$$T_f \simeq 1\,\mathrm{TeV}\left(\frac{g_*}{230}\right)^{1/2}\left(\frac{m_{\widetilde{G}}}{10\,\mathrm{keV}}\right)^2\left(\frac{1\,\mathrm{TeV}}{m_{\tilde{g}}}\right)^2$$

[Fujii, Yanagida '02]

and freeze-out: Hot or warm Dark Matter

- LSP with R-parity is automatically stable and good DM candidate
- Gravitinos less than keV was in the thermal equilibrium in the early Universe if T_R is bigger than TeV

$$\Omega_{\widetilde{G}} h^2 \simeq \left(\frac{m_{\widetilde{G}}}{1\,\mathrm{keV}}\right)\left(\frac{100}{g_*}\right)$$

: If it is the dominant DM,
it has problems with large scale structure formation,

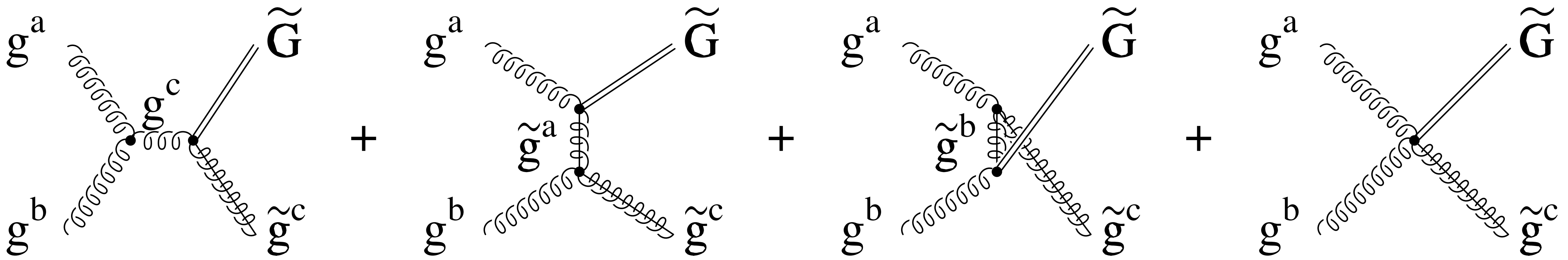
$\longrightarrow$ $m_{\widetilde{G}} \lesssim 30\,\mathrm{eV}$ or $m_{\widetilde{G}} \gtrsim 2\,\mathrm{keV}$ [Viel et al 2005]

(too small) (too large relic density)

: not the main component of DM or new mechanism is needed
: more on collider signatures [Feng, Kamionkowski, Lee 1004.4213]

- Heavy Gravitinos : nevr in the thermal equilibrium in the early Universe
  - Thermal production : the gravitinos are produced from the 2->2 scatterings after inflation [Ellis, Kim, Nanopoulos 1984]

$$g^a + g^b \to \tilde{g}^c + \widetilde{G}$$



Thermal production is proportional to the reheating temperature

$$\Omega^{TP}_{\widetilde{G}} h^2 \simeq 0.27 \left(\frac{100\,\mathrm{GeV}}{m_{\widetilde{G}}}\right)\left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^2\left(\frac{T_{\mathrm{reh}}}{10^{10}\,\mathrm{GeV}}\right)$$

[Bolz, Brandenburg, Buchmuller 2000]

∗ Including electroweak contribution, enhancement by abount 30 % [Pradler, Steffen 2007]

∗ Production by 1-> 2 decays allowed by thermal masses, factor 2 enhancement [Rychkov, Strumia 2007]

- If the gravitino is not LSP

- then they will decay with decay temperature less than 1 MeV, the epoch of BBN, and disrupt the light element abundances

$$T_{\rm reh} < 10^9 \sim 10^{10}\ {\rm GeV}$$ [Ellis, Kim, Nanopoulos 1984]

- Recently developments with hadronic decay gives

$$T_{\rm reh} \lesssim 10^6 \sim 10^8\ {\rm GeV}$$ [Jedamzik 2004]
[Kawasaki, Kohri, Moroi 2004]

If gravitino is LSP with R-parity, they are stable and DM candidate
(or small R-parity violation and have long lifetime)

- However the Next LSP (NLSP) decay very late and have problems with light nuclei element

- Non-thermal production : all supersymmeric particles decay to NLSP and later NLSP decay to gravitino. By R-parity conservation the number densities of R odd particles are conserved

$$\Omega_{\widetilde{G}}^{NTP} h^2 = \frac{m_{\widetilde{G}}}{m_{NLSP}} \Omega_{NLSP} h^2$$

- Total relic density of gravitino : TP+NTP

$$\Rightarrow \quad \Omega_{\widetilde{G}} h^2 = \Omega_{\widetilde{G}}^{TP} h^2 + \Omega_{\widetilde{G}}^{NTP} h^2$$

∗ Also there are model dependent non-thermal productions (inflaton decay, moduli decay ...)

- What is LSP and Dark Matter?
  - Neutralino

    Neutral, stable, massive and weakly interacting particles
    Relic density determined from thermal freeze-out with right order
    Detectability in the near future at colliders, direct and indirect detection exp.

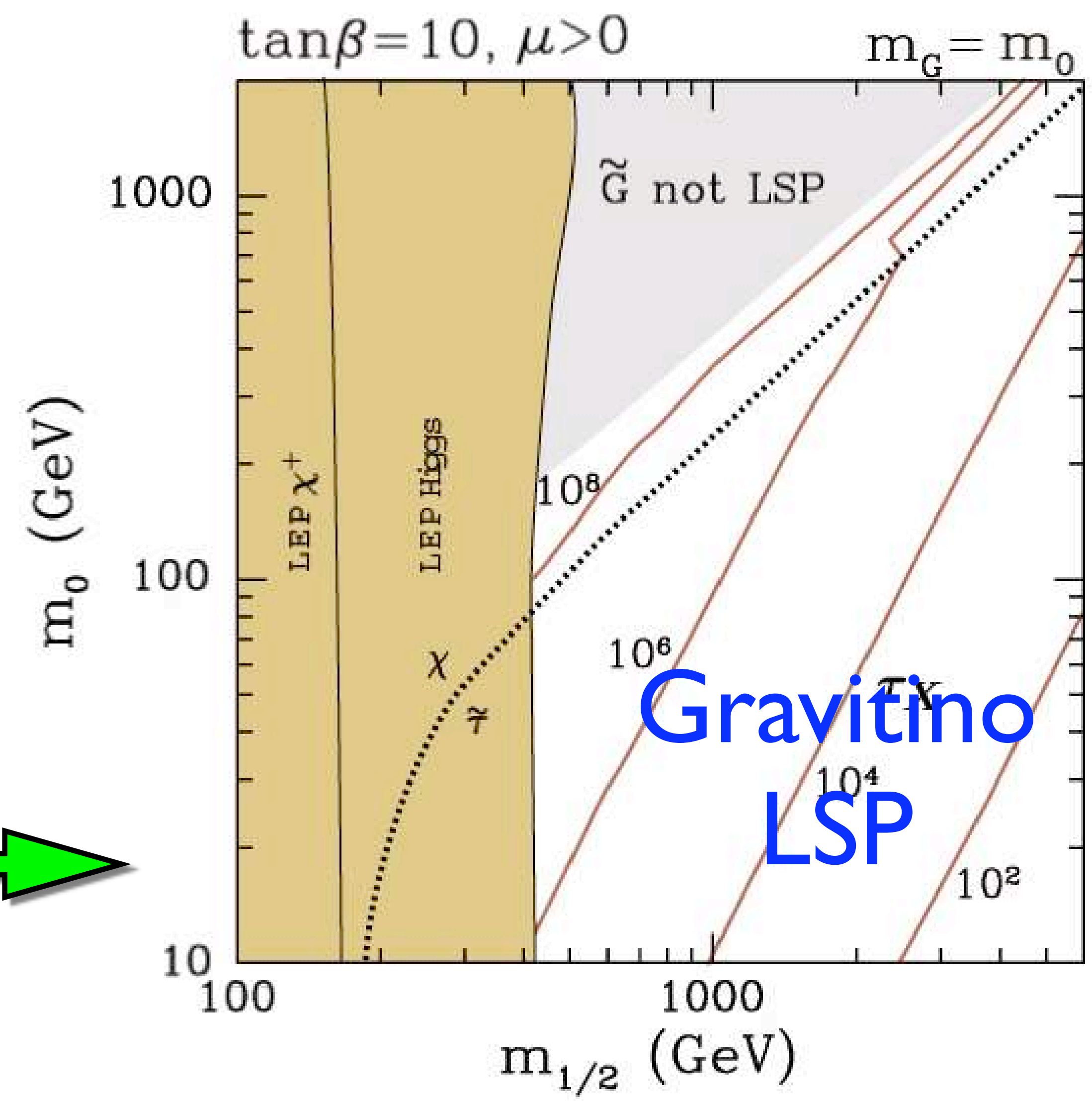
⇨ Most favored

- What is the lightest?

However there is no fundamental reason for neutralino to be the lightest

In many SUSY breaking scenarios, gravitino is the lightest SUSY particle

eg) CMSSM (m0,m1/2,tan\beta,A,sgn mu)
with mG=m0



⇨ Gravitino LSP is natural!

NLSP can be neutralino, stau, sneutrino, stop, ...
[Feng etal, Ellis, Olive etal, Kohri etal, Roszkowski etal, Steffen etal, ...]

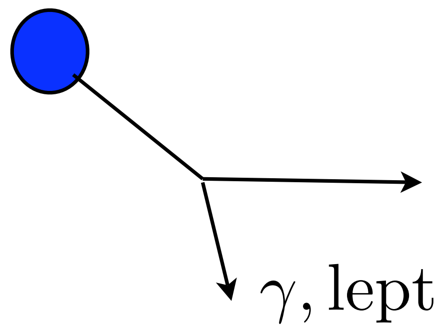
Gravitino can be naturally LSP and gives correct relic density for dark matter!

Cosmological constraints

- Total relic abundance: $\Omega h^2 \sim 0.1$
- Structure formation : cold or warm
- Late NLSP decays (t > 0.1 sec)
  - Cosmic Microwave Background (CMB) distortion
  - BBN constraints : EM and hadronic showers from NLSP decay disrupt the light element abundances
  - Catalyzed BBN : charged NLSP make bound state with nuclei

NLSP(neutralino, stau ...) decay at 1 sec – 10^{12} sec

m_X



Gravitino E ~ mX/2

$$p_i = \frac{m_X^2 - m_{LSP}^2}{2m_X}$$

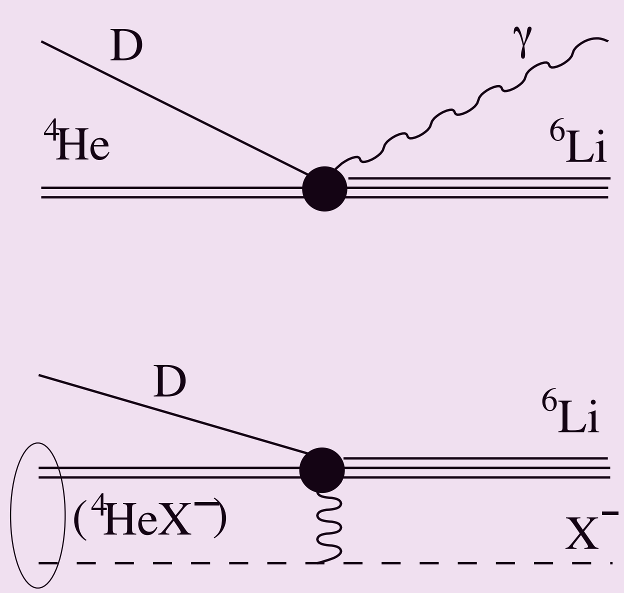
erase small scale perturbation
: affects LSS at small scale

γ, leptons, $q\bar{q}$

E ~ mX/2 : interact with

if negatively charged

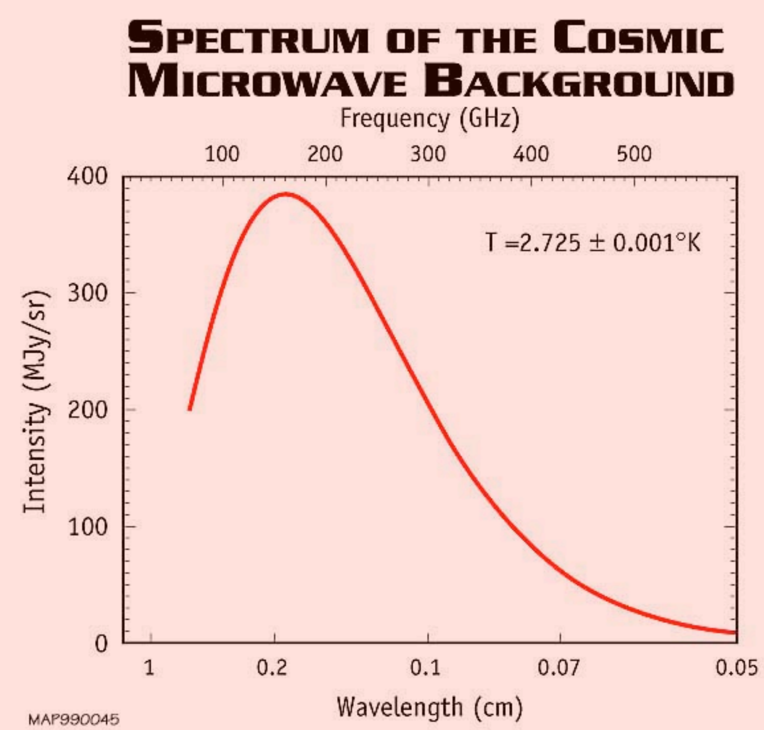
Bound with nuclei
: change BBN



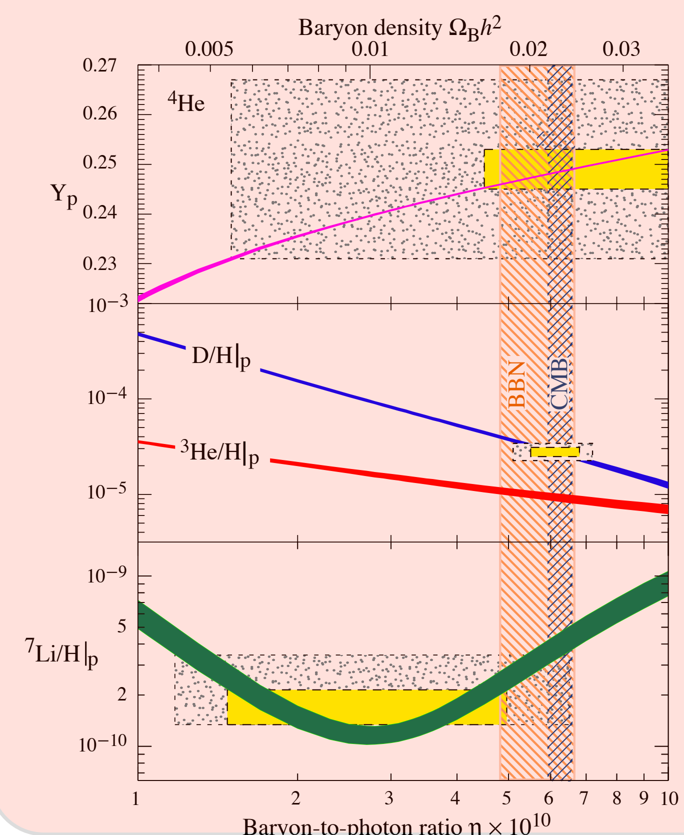
$$Y \equiv \frac{n}{s} \lesssim 10^{-15} - 10^{-14}$$

$\Rightarrow \tau_{\tilde{\tau}} \lesssim 5 \times 10^3$ sec
(not always)

Background photons
: CMB distortion



Background nuclei
: BBN disruption

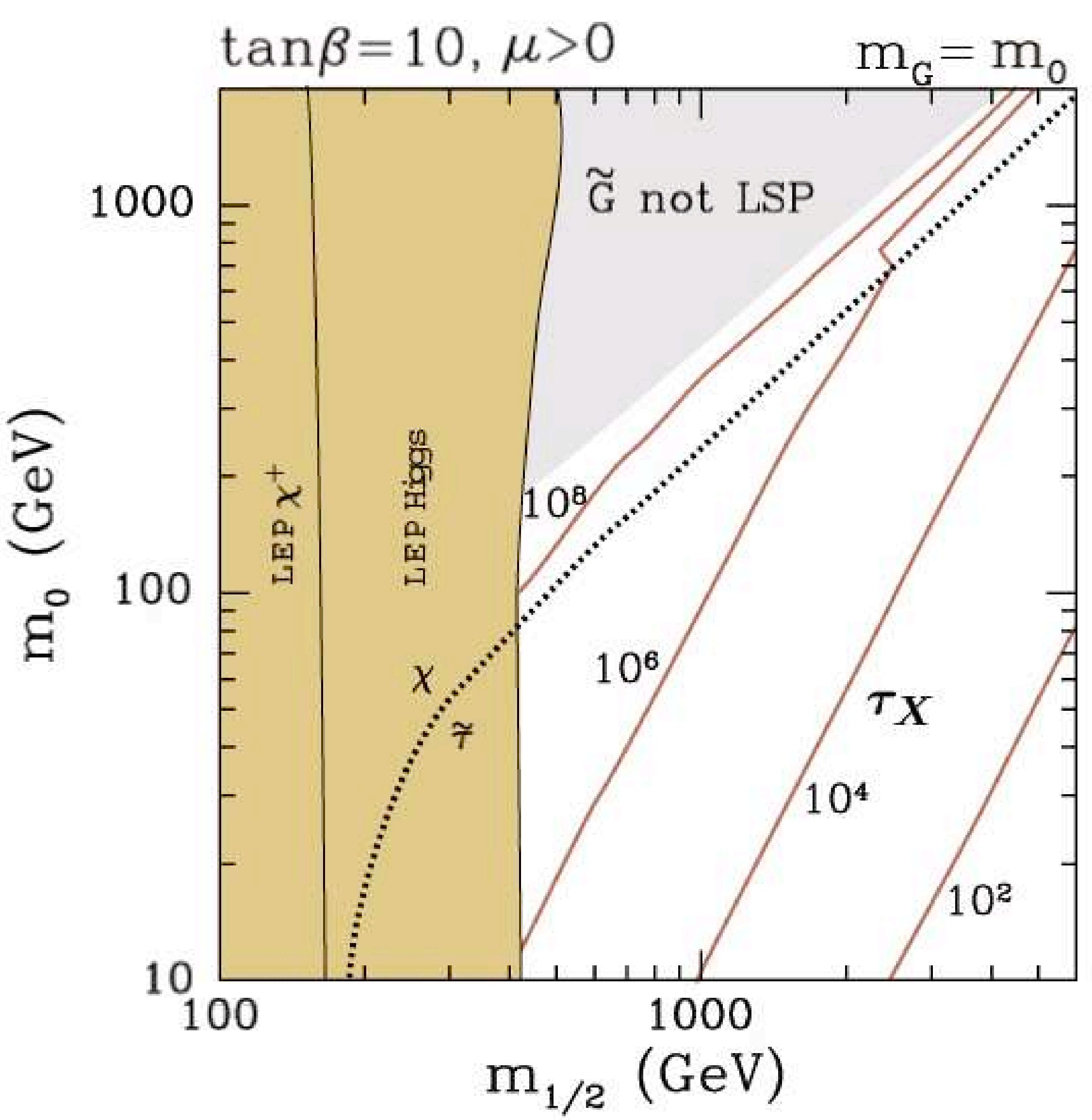


EM and HAD showers

- Heavy Gravitino Dark Matter (with NLSP decays)

  - NTP of gravitinos in the MSSM [Feng et al., 2003; 2004]
    in the CMSSM [Ellis et al., 2004]
  - TP of gravitinos in the MSSM [Fujii et al., 2004]
  - TP + NTP of gravitinos in the CMSSM [Leszek et al., 2005; Cerdeno et al., 2006]
    and confirmed later with similar analysis [Steffen 2006; Pradler et al., 2007]
  - Solution to cosmic Lithium problems [Jedamzik et al., 2006; Bailly 2009]
  - Catalyzed BBN with gravitino [Cyburt et al., 2006; Kawasaki et al., 2007; Pradler et al., 2007; 2008, Kersten et al., 2008]
  - Complete analysis in the CMSSM [Bailly et al., 2009]

• Gravitino Dark Matter in the CMSSM : Most up to date and complete



[Roszkowski, Ruiz de Austri, KYC 2005]

[Cerdeno,KYC,Jedamzik, Roszkowski, Ruiz de Austri 2006]

[Bailly, KYC, Jedamzik, Roszkowski 2009]

At each point of

$$m_0, m_{1/2}, A, \tan_\beta, \mathrm{sgn}(\mu) \quad \text{and} \quad m_{\tilde{G}}$$

↓ RGE running : Suspect

Low Energy spectrums

$\Omega_{NLSP}h^2$ micrOmega — Treh → TP, NTP $\Omega_{\tilde{G}}h^2$

↓ CalcHEP, PYTHIA

Energy specrums of the decay products → τ_X

EM and Hadronic spectrums

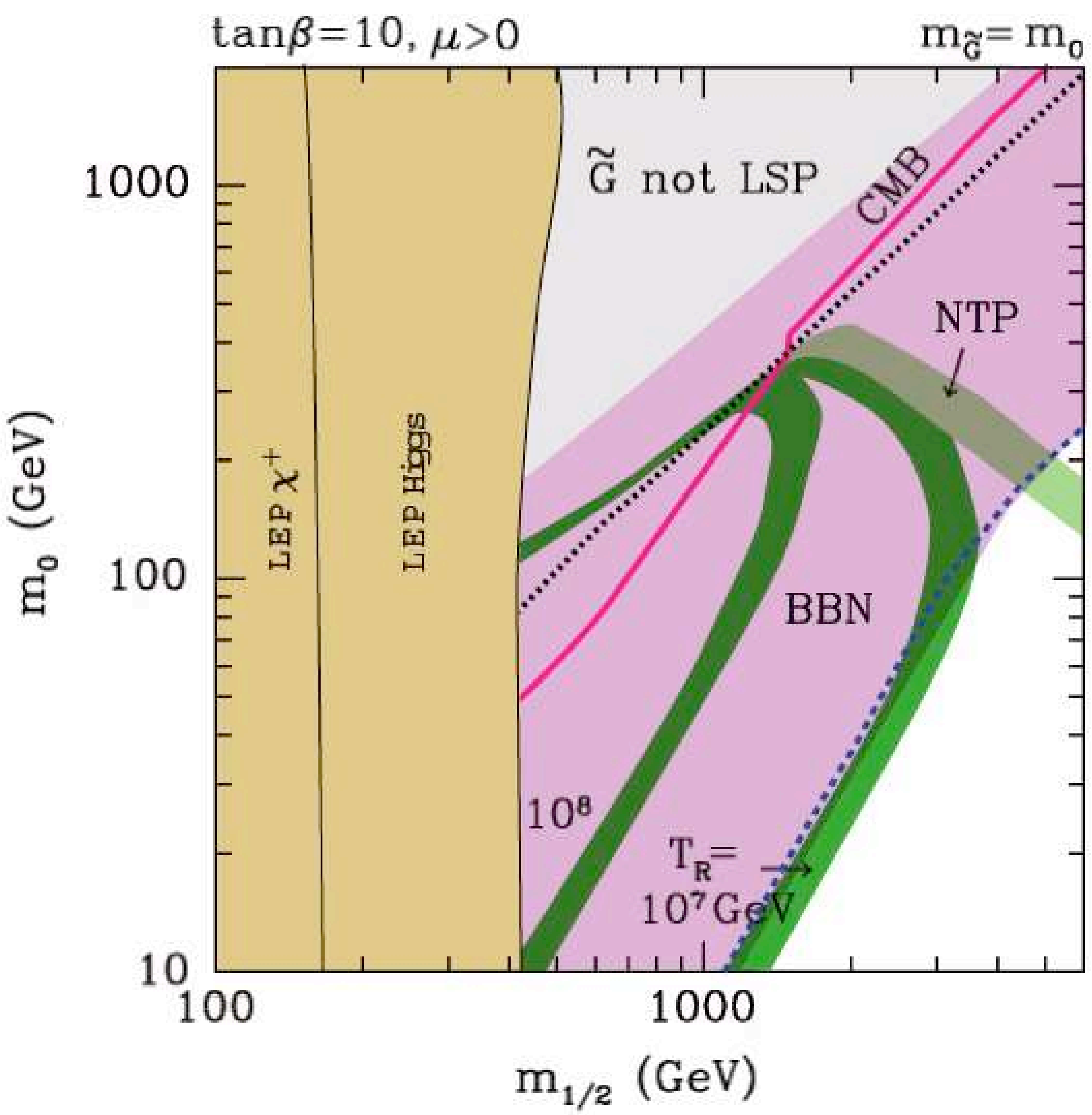
↓ BBN code [K.Jedamzik]

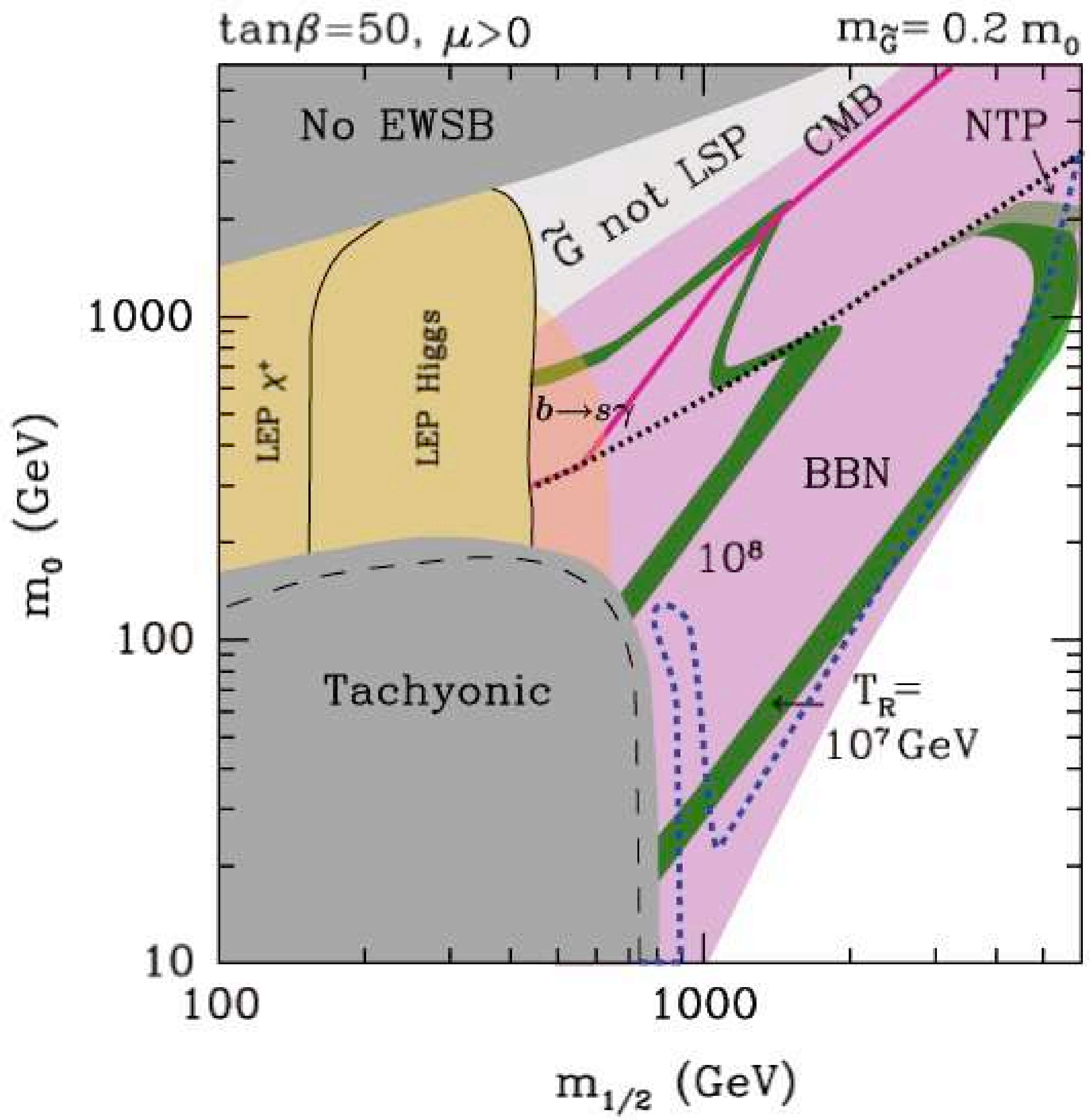
Light element abundances

→ compare with observation

[Roszkowski, Ruiz de Austri, KYC 2005]
[Cerdeno,KYC,Jedamzik, Roszkowski, Ruiz de Austri 2006]
[Bailly, KYC, Jedamzik, Roszkowski 2009]

• Gravitino DM in the CMSSM





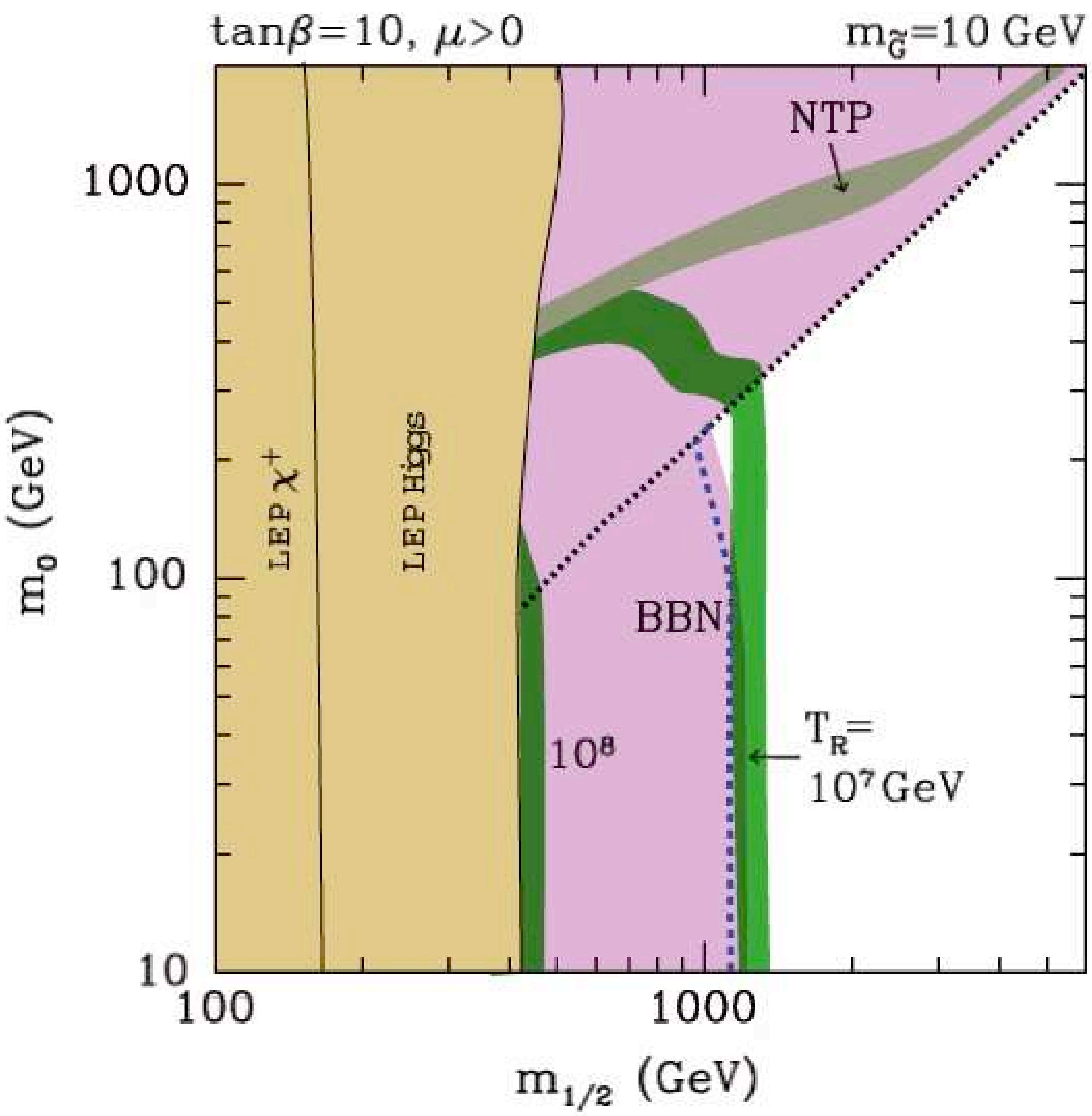
$$
\begin{array}{rll}
1.2\times10^{-5} < & D/H & < 5.3\times10^{-5} \\
 & Y_p & < 0.258 \\
8.5\times10^{-11} < & {}^7\mathrm{Li}/H & \\
 & {}^3\mathrm{He}/D & < 1.52 \\
 & {}^6\mathrm{Li}/{}^7\mathrm{Li} & < 0.1\,(0.66).
\end{array}
$$

[Jedamzik 2006]

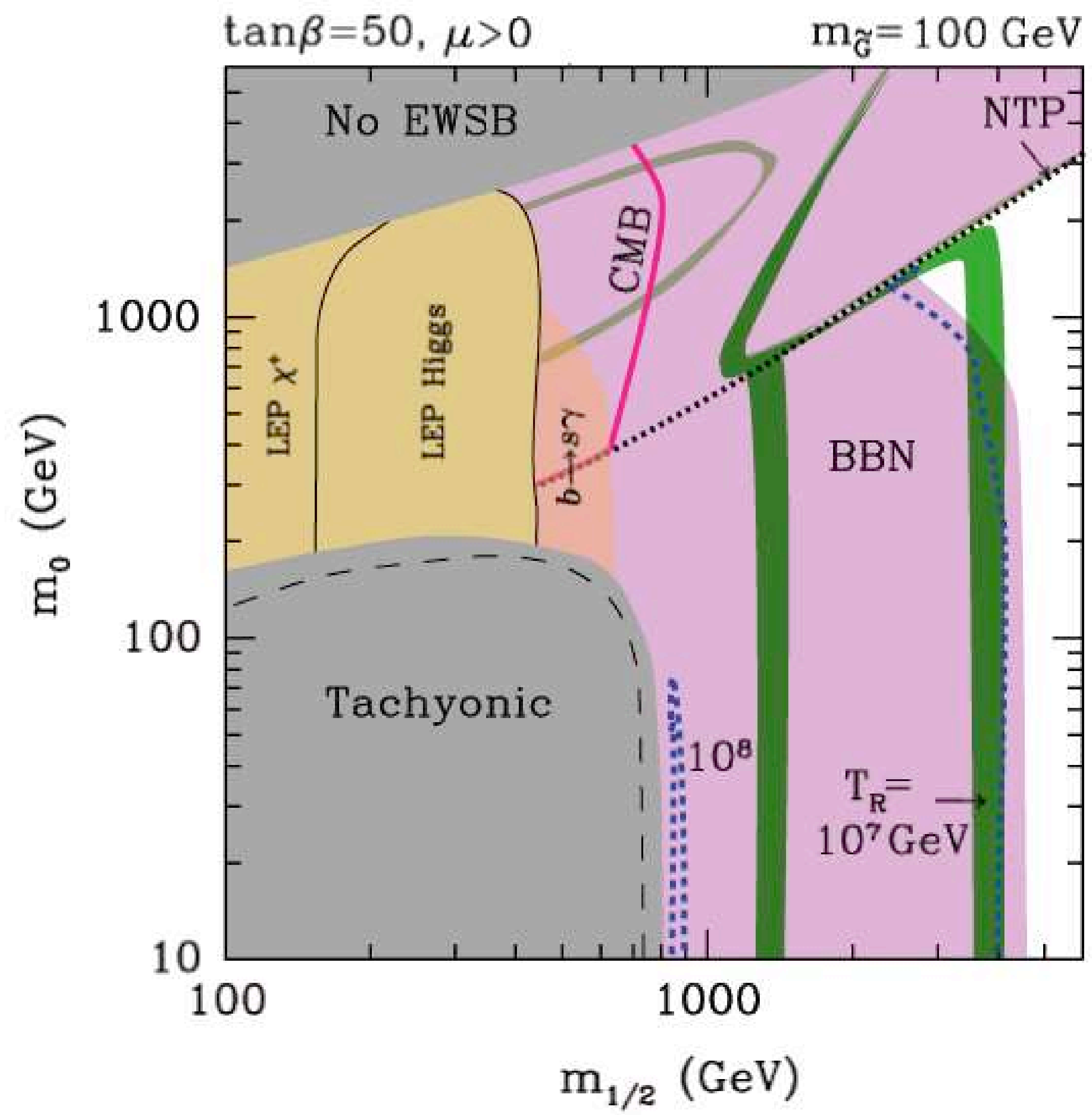
Neutralino NLSP is difficult
Stau NLSP is available with heavier than 1 TeV
(stau NLSP around 100 GeV with conservative Li6/Li7 < 0.66)

- With fixed gravitino mass

$m_{\widetilde{G}} = 10\,\mathrm{GeV}$



$m_{\widetilde{G}} = 100\,\mathrm{GeV}$



[Bailly, KYC, Jedamzik, Roszkowski 2009] excluded by EM decay products

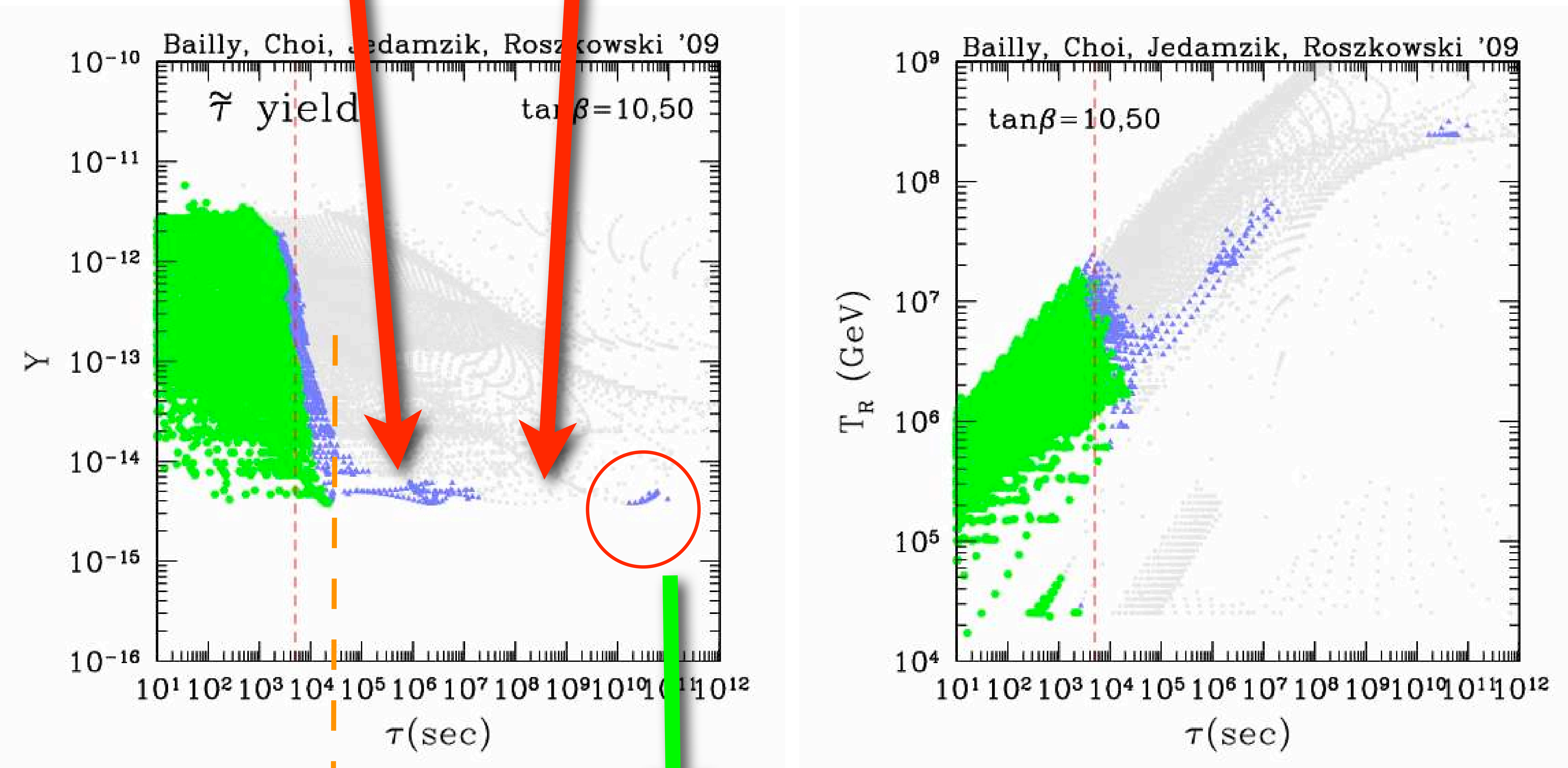
$^3\mathrm{He}/\mathrm{D}$

excluded by CBBN

green : allowed

blue : allowd with conserve 6Li/7Li

grey : allowed by collider but
disallowed by cosmology



$\tau = 3 \times 10^4$ sec

scans for

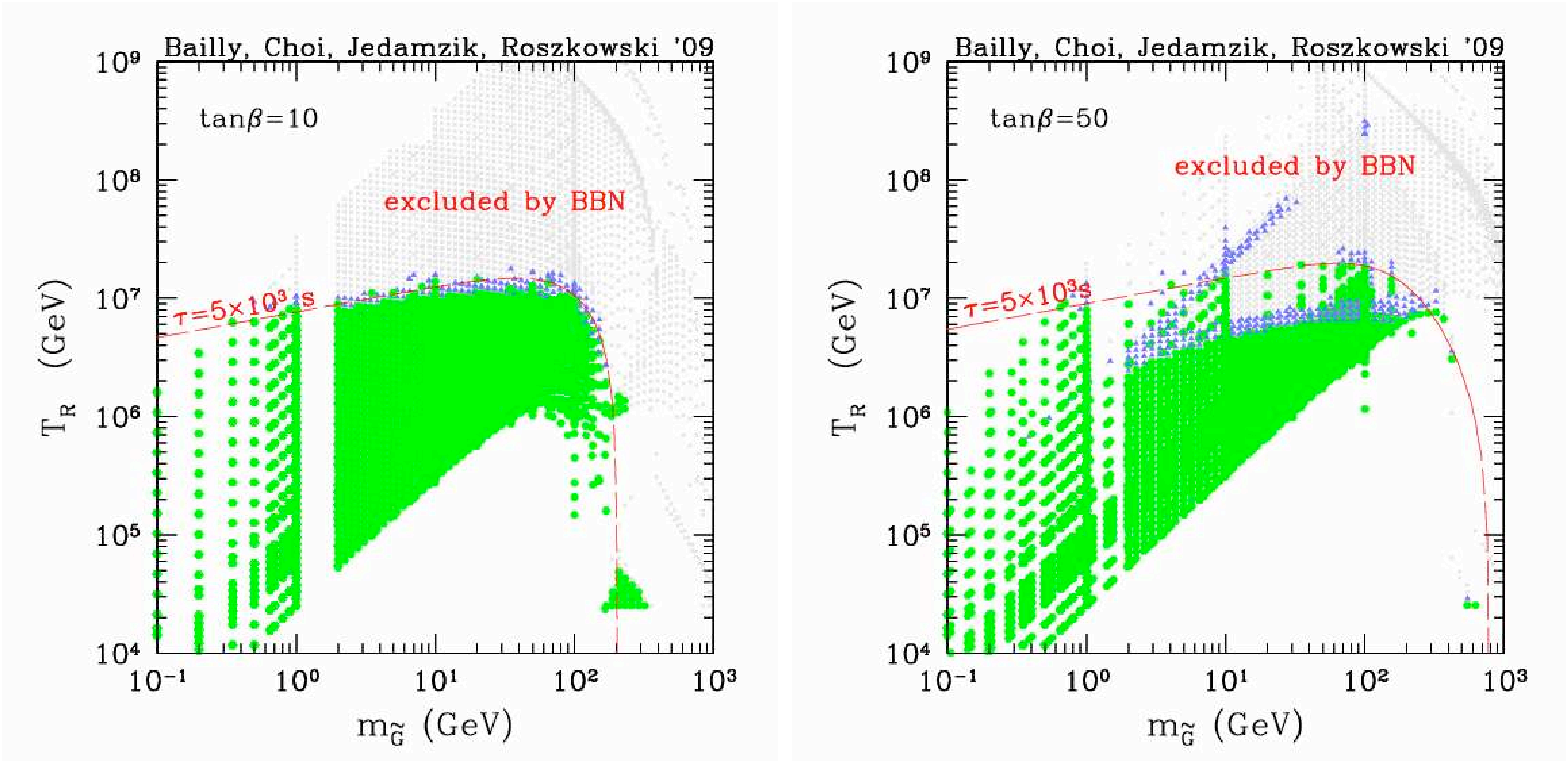
$m_{\widetilde{G}} = 0.2m_0, 0.4m_0$

$0.2m_{1/2}, 0.4m_{1/2}$

0.1 GeV....100 GeV

allowed due to the degenerate stau and gravitino mass
around 100 GeV, accessible to the LHC
-> longer lifetime with small energy of decay products

• Reheating temperature in the CMSSM



scans for

$m_{\widetilde{G}} = 0.2 m_0, 0.4 m_0$

$0.2 m_{1/2}, 0.4 m_{1/2}$

$0.1\,\mathrm{GeV} \ldots 100\,\mathrm{GeV}$

$T_{\rm reh} <$ a few $\times\, 10^7$ GeV $\quad (\lesssim 3 \times 10^8\,\mathrm{GeV})$

with stau NLSP

- Cosmic Lithium problems

Li7 : SBBN prediction

$$^{7}\mathrm{Li/H} = (5.24 + 0.71 - 0.67) \times 10^{-10}$$

[Cyburt, Fields, Olive 2008]

larger than the observed one

$$^{7}\mathrm{Li/H} = (1.23^{+0.68}_{-0.32}) \times 10^{-10}$$

[Ryan et al 1999, Holsford et al 2008]

Li6 : SBBN prediction is negligible

$$^{6}\mathrm{Li}/^{7}\mathrm{Li} \sim 10^{-4} - 10^{-3}$$

compared to observed

$$^{6}\mathrm{Li}/^{7}\mathrm{Li} \sim 0.05$$

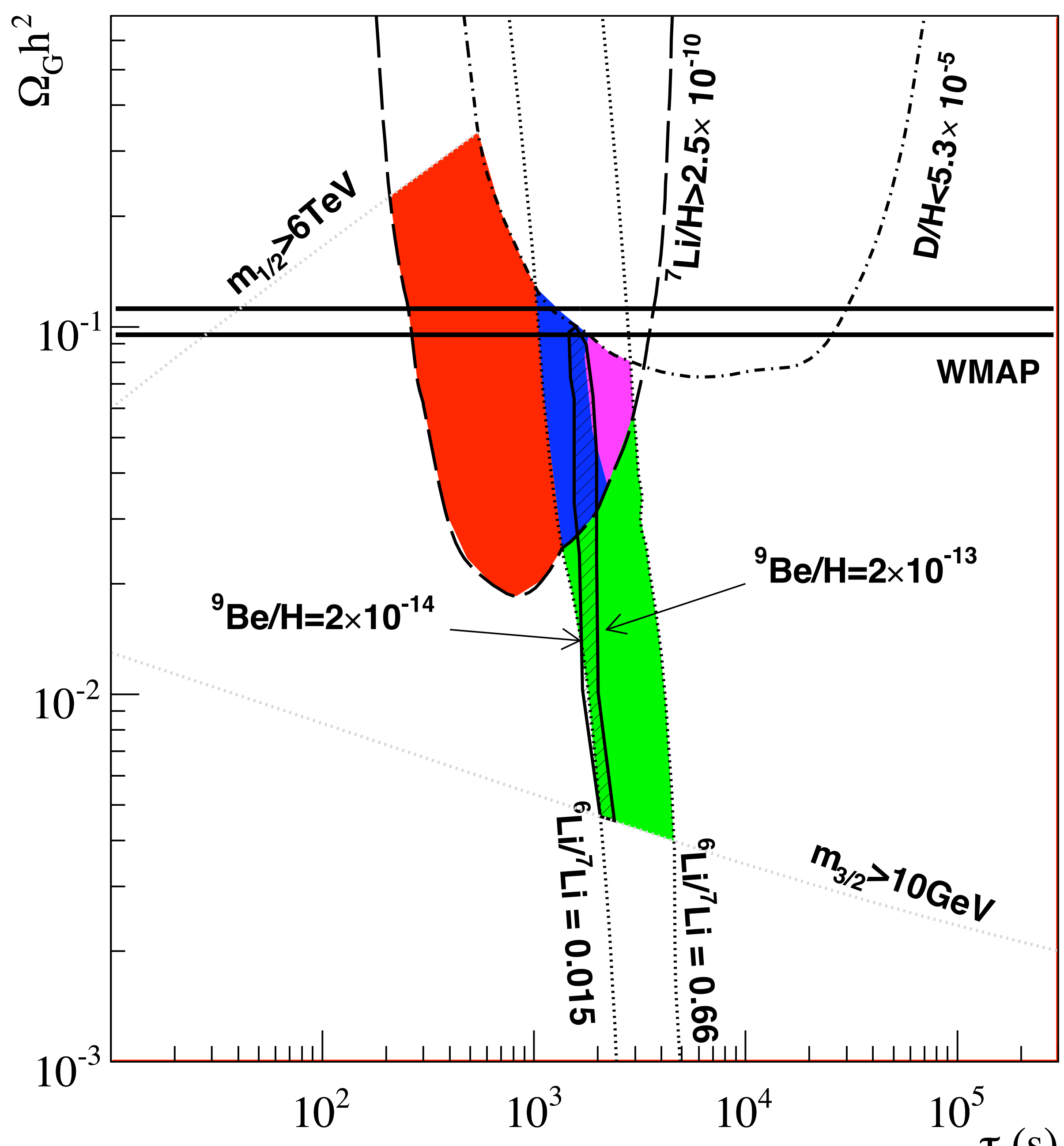
[Asplund et al 2006]

Both can be solved with late decaying particles

[Jedamzik, KYC, Roszkowski, Ruiz de Austri 2006]

[Bailly, Jedamzik, Moultaka 2009]

In the CMSSM



[Bailly, Jedamzik, Moultaka 2009]

solves

green : Li6 only

red : Li7 only

blue : both

- Gravitino DM not compatible with neutralino NLSP? or lighter stau NLSP?
  - Degenerate mass $\Delta M \equiv m_{NLSP} - m_{\tilde{G}} \ll m_{\tilde{G}}$
    - released energy from decay is small : reduce BBN constraints
    - increases the stau lifetime : gets stronger constraints from
      - CMB distortation - Difuse gamma-ray background
    - could solve the MeV gamma-ray access [Cembranos, Feng, Strigari 2007]
    - to find possible high reheating temperature

      Treh ~ 10^8 GeV for stau NLSP with $\Delta M \sim 10\,\mathrm{GeV}$

      [Bailly, KYC, Jedamzik, Roszkowski 2009]

      Treh ~ 10^9 GeV for general NLSP with $\Delta M \lesssim 10^{-2}\,\mathrm{GeV}$

      lifetime is much longer than the age of the Universe

      possible indirect signatures

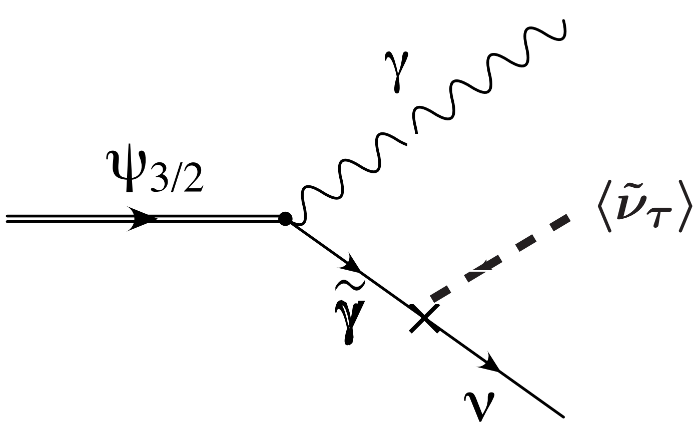
      [Boubekeur, KYC, Ruiz de Austri, Vives 2010]
  - Beyond CMSSM [Berger et al. 2008; Ratz et al. 2008; Pradler et al. 2009]
  - Non standard cosmology: dilute NLSP with entropy production

- R-parity violation and gravitino DM
  - NLSPs decay before BBN
  - Gravitinos can decay with lifetime much longer than the age of our universe

    : candidate for DM + indirect signatures [in the talk of Ibarra, Grefe and Bomark]
  - In the bilinear R-parity violation, gravitino decay is dominated 2-body decays $\widetilde{G} \to \gamma + \nu, \quad Z^0 + \nu, \quad W^{\pm} + l_{\rm P}^{M}$
  - 3-body decays can dominate 2-body decay when $m_{\widetilde{G}} < m_W$ [KYC, C. Yaguna 2010]

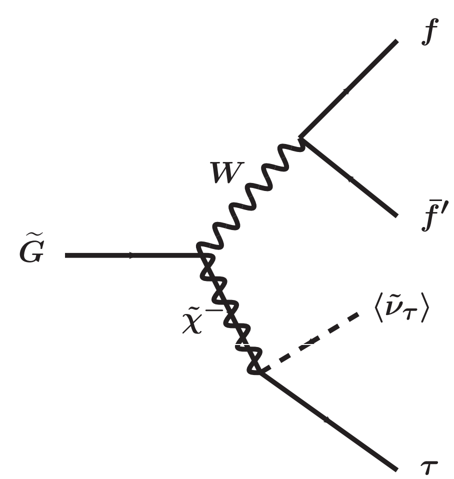
2-body decay $\widetilde{G} \to \gamma + \nu$

3-body decay $\widetilde{G} \to \tau^- W^{+*} \to \tau^- f \bar{f}'$

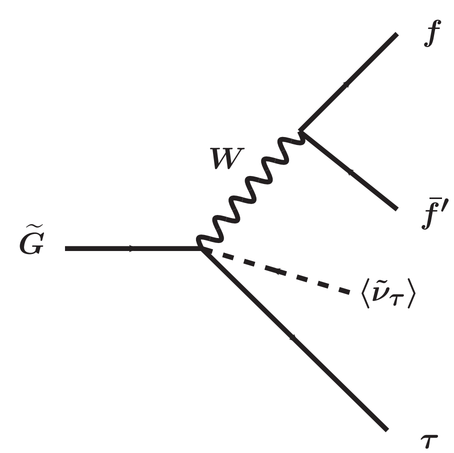


$$\Gamma(\widetilde{G}\to\gamma\nu_\tau) = \frac{\xi_\tau^2 m_{\widetilde{G}}{}^3}{64\pi M_P^2}|U_{\tilde{\gamma}\tilde{Z}}|^2 \propto \left(\frac{M_W}{M_2}\right)^2$$

with $\xi_\tau \equiv \dfrac{\langle\tilde{\nu}_\tau\rangle}{v}$



$$\xi_\tau^2 |U_{\widetilde{W}\widetilde{W}}|^2 \propto \xi_\tau^2 \left(\frac{M_W}{M_2}\right)^2$$

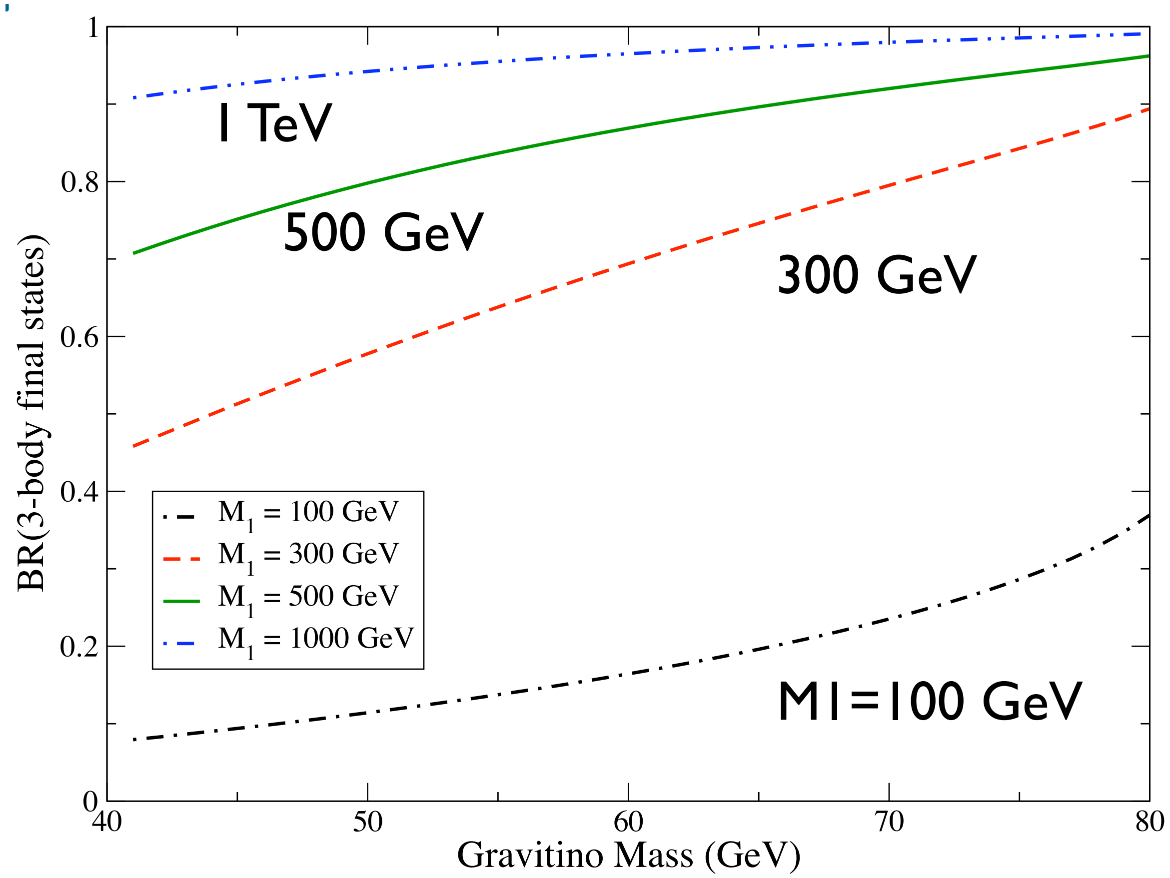


$\propto \xi_\tau^2$

No suppression by the gaugino masses!

- R-parity violation and gravitino DM

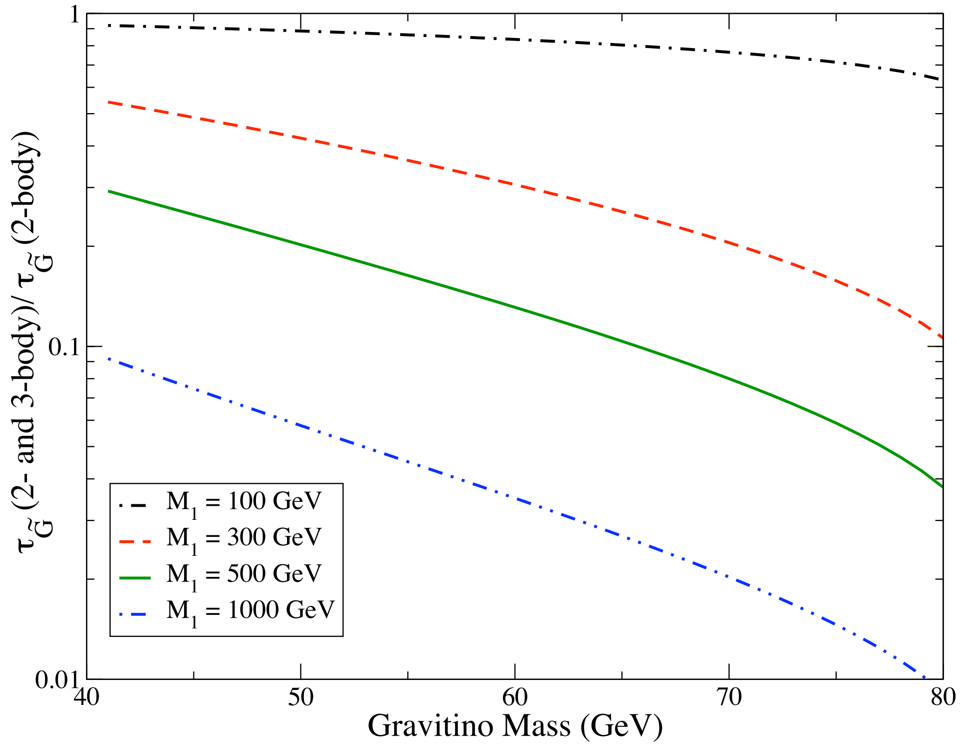
[KYC, C. Yaguna 2010]

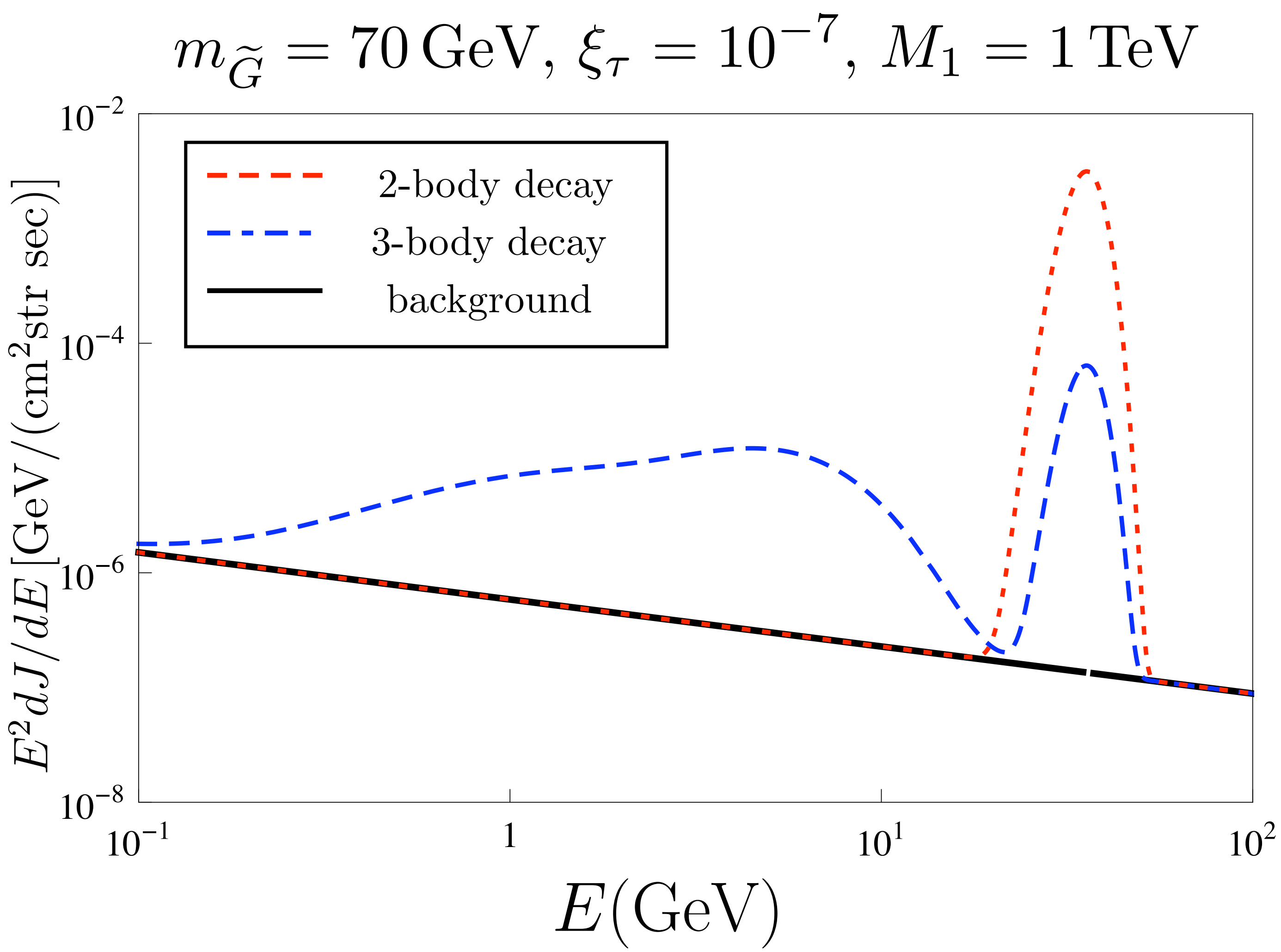


with M2 = 1.9 M1 at weak scale assuming unification at GUT

- 3-body can dominate over a wide range of gravitino mass
- The effect is significant even for small gaugino mass
- For large gaugino mass, $\widetilde{G} \to \gamma\nu$ is negligible

• The lifetime changes : becomes shorter
- could be 100 times smaller





• Indirect detection of decaying gravitino DM is severly affected

: suppressed photon, line neutrino signals

: new continuum photon lines

: new antimatter signals

[KYC, D. Restrepo, C. Yaguna, O. Zapata, Work in progress]

- At LHC

It is expected to find several superpartners and determine their properties

Assume we have found SUSY particles and neutralinos as stable(-like) and obtain the mass and relic density with some uncertainties

If direct detection and/or indirect detection find signatures with same parameters such as mass and relic density, neutralino might be declared to be a dark matter

If we have No direct detection, No Indirect detection, then neutralino might not be a main DM component, possibly decayed to much weakly interacting particles

Or discovery of (apparently) stable charged massive particle at the LHC will immediately imply that there is lighter particle

Even worse the derived relic density of neutralino can be far outside of WMAP DM range.

- Non standard cosmology can save neutralino DM

  [Salati 2003, Rosati 2003, Profumo et al. 2003, Catena et al. 2004, Pallis 2005, Rosenfeld 2005, Barenboim et al. 2006, Chung et al, 2007]

- Gravitino or Axino Dark Matter with standard cosmology

- E-WIMPs can explain any anomalous situations with the standard cosmology

(1) $\Omega_X^{coll} < \Omega_{DM}$

(2) $\Omega_X^{coll} > \Omega_{DM}$

$$\Omega^{TP} + \frac{m_{LSP}}{m_X}\Omega_X^{coll} = \Omega_{DM}$$

- Opportunity to probe the earliest time of the Universe's history

$$\Omega_{\widetilde{G}}^{\mathrm{TP}} h^2 \simeq 0.27 \left(\frac{T_{\mathrm{R}}}{10^{10}\,\mathrm{GeV}}\right) \left(\frac{100\,\mathrm{GeV}}{m_{\widetilde{G}}}\right) \left(\frac{m_{\tilde{g}}(\mu)}{1\,\mathrm{TeV}}\right)^2$$

$$\Omega_{\tilde{a}}^{\mathrm{TP}} h^2 \simeq 5.5\, g_s^6 \ln\left(\frac{1.108}{g_s}\right) \left(\frac{m_{\tilde{a}}}{0.1\,\mathrm{GeV}}\right) \left(\frac{10^{11}\,\mathrm{GeV}}{f_a}\right)^2 \left(\frac{T_{\mathrm{R}}}{10^4\,\mathrm{GeV}}\right)$$

- Gravitino or Axino Dark Matter with standard cosmology

- E-WIMPs can explain any anomalous situations with the standard cosmology

(1) $\Omega_X^{coll} < \Omega_{DM}$

(2) $\Omega_X^{coll} > \Omega_{DM}$

$$\Omega^{TP} + \frac{m_{LSP}}{m_X}\Omega_X^{coll} = \Omega_{DM}$$

- Opportunity to probe the earliest time of the Universe's history

$$\Omega_{\widetilde{G}}^{\rm TP} h^2 \simeq 0.27 \left(\frac{T_{\rm R}}{10^{10}\,{\rm GeV}}\right)\left(\frac{100\,{\rm GeV}}{m_{\widetilde{G}}}\right)\left(\frac{m_{\tilde{g}}(\mu)}{1\,{\rm TeV}}\right)^2$$

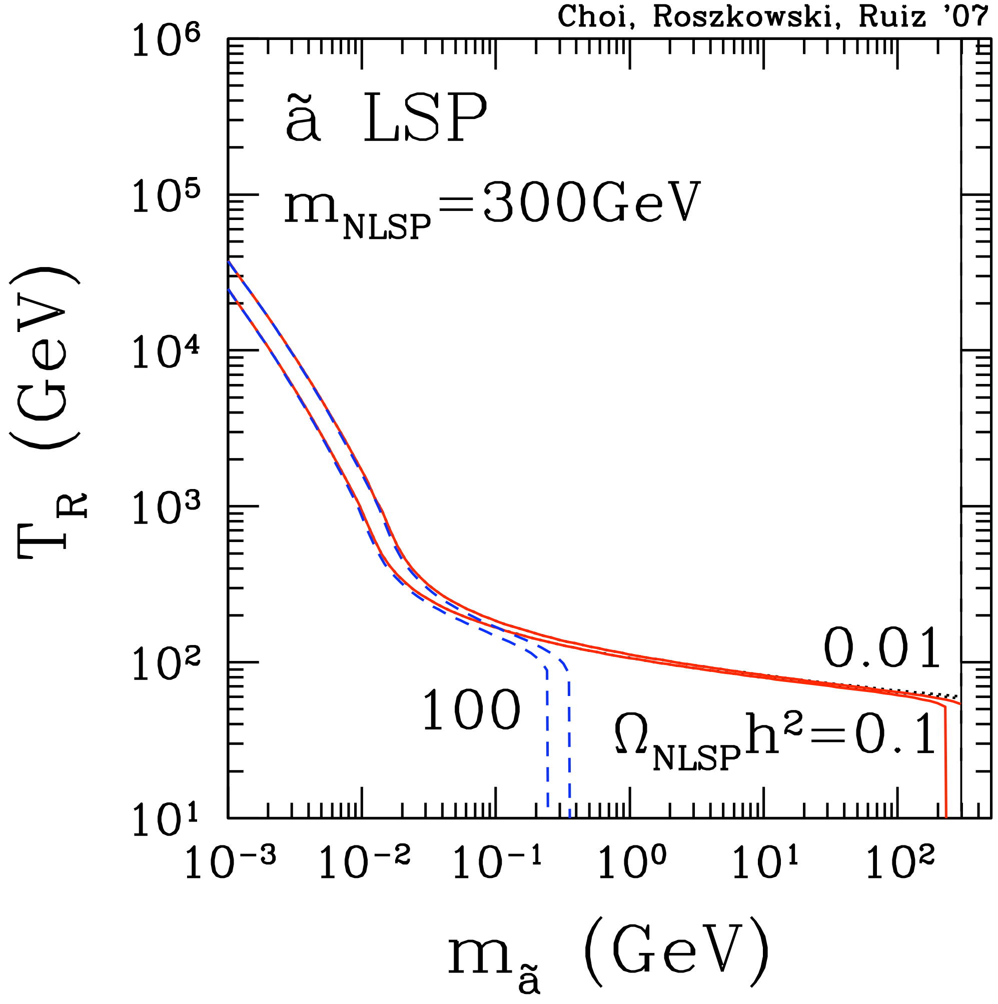
$$\Omega_{\tilde{a}}^{\rm TP} h^2 \simeq 5.5\, g_s^6 \ln\left(\frac{1.108}{g_s}\right)\left(\frac{m_{\tilde{a}}}{0.1\,{\rm GeV}}\right)\left(\frac{10^{11}\,{\rm GeV}}{f_a}\right)^2\left(\frac{T_{\rm R}}{10^4\,{\rm GeV}}\right)$$

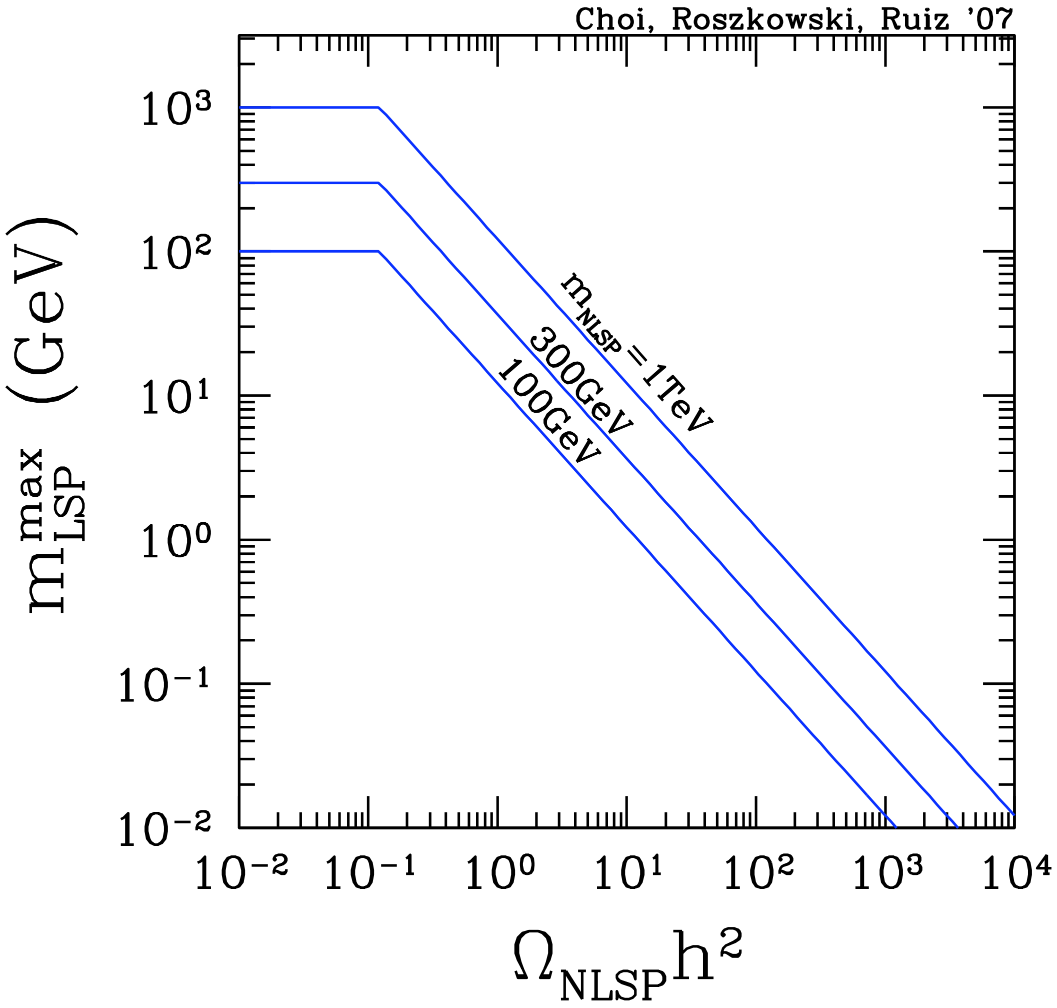
• Reheating temperature from collider measurements

[K.Y.Choi, Roszkowski, Ruiz de Austri 2007]

$$\Omega^{TP}_{LSP}(T_{\rm reh}, m_{LSP}, m_{\tilde{g}}, m_{NLSP}, \ldots)h^2 + \frac{m_{LSP}}{m_{NLSP}}\Omega^{coll}_{NLSP}h^2 = \Omega_{DM}h^2 \simeq 0.1$$

Axino LSP



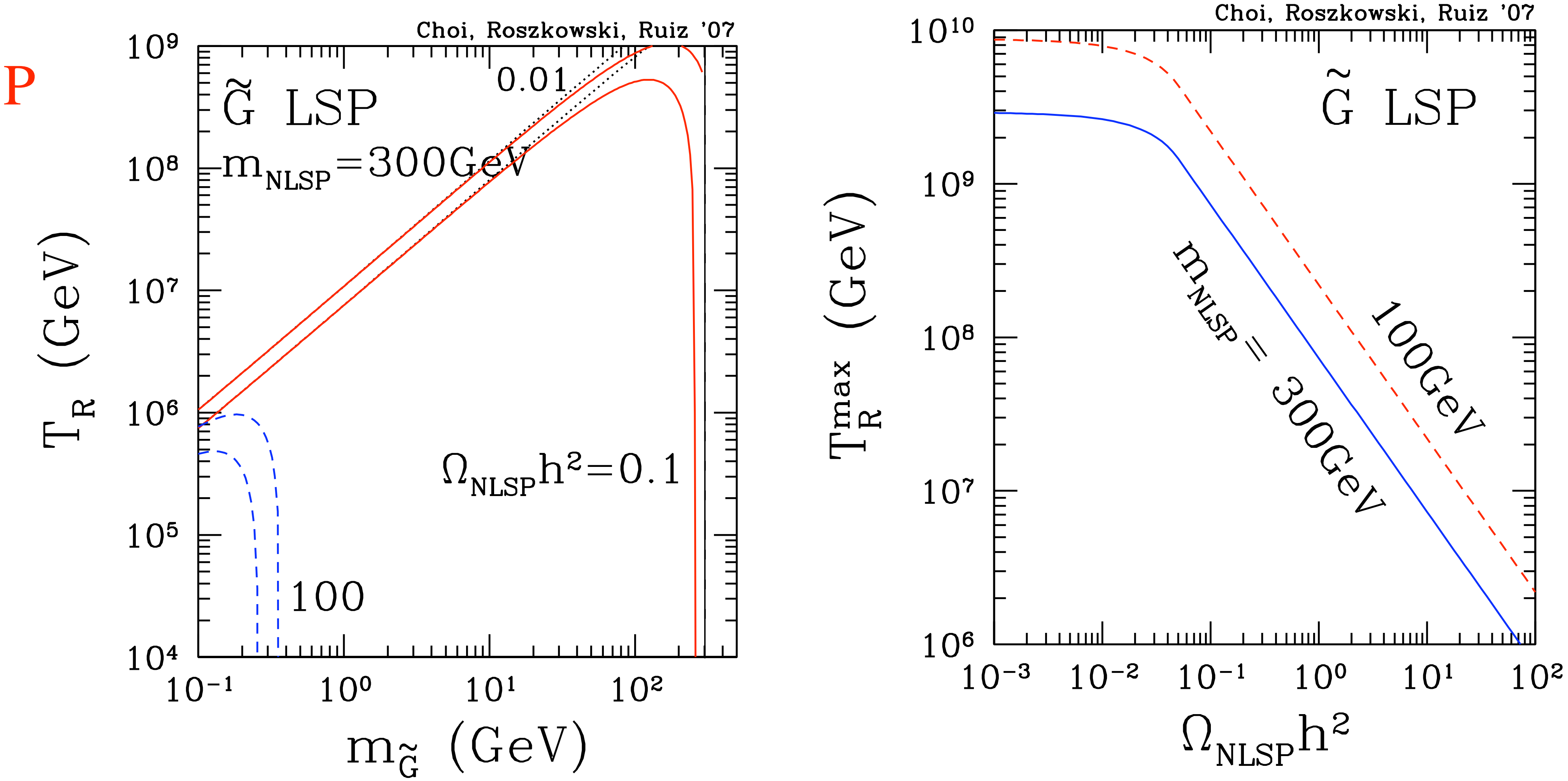


• Upper bound the axino mass and the reheating temperature

• Reheating temperature from collider measurements

[K.Y.Choi, Roszkowski, Ruiz de Austri 2007]

Gravitino LSP



• $m_{\rm NLSP}$ and $\Omega_{NLPS}h^2$ gives relation between $T_{\rm reh}$ and $m_{\widetilde{G}}$

• Upper bound the gravitino mass and the reheating temperature are obtained

• For stau NLSP, considering BBN,

$m_{\widetilde{\tau}} = 300\,{\rm GeV}$ ➡ $m_{\widetilde{G}} \lesssim 2\,{\rm GeV},\ T_{\rm reh} \lesssim 9\times 10^6\,{\rm GeV}$

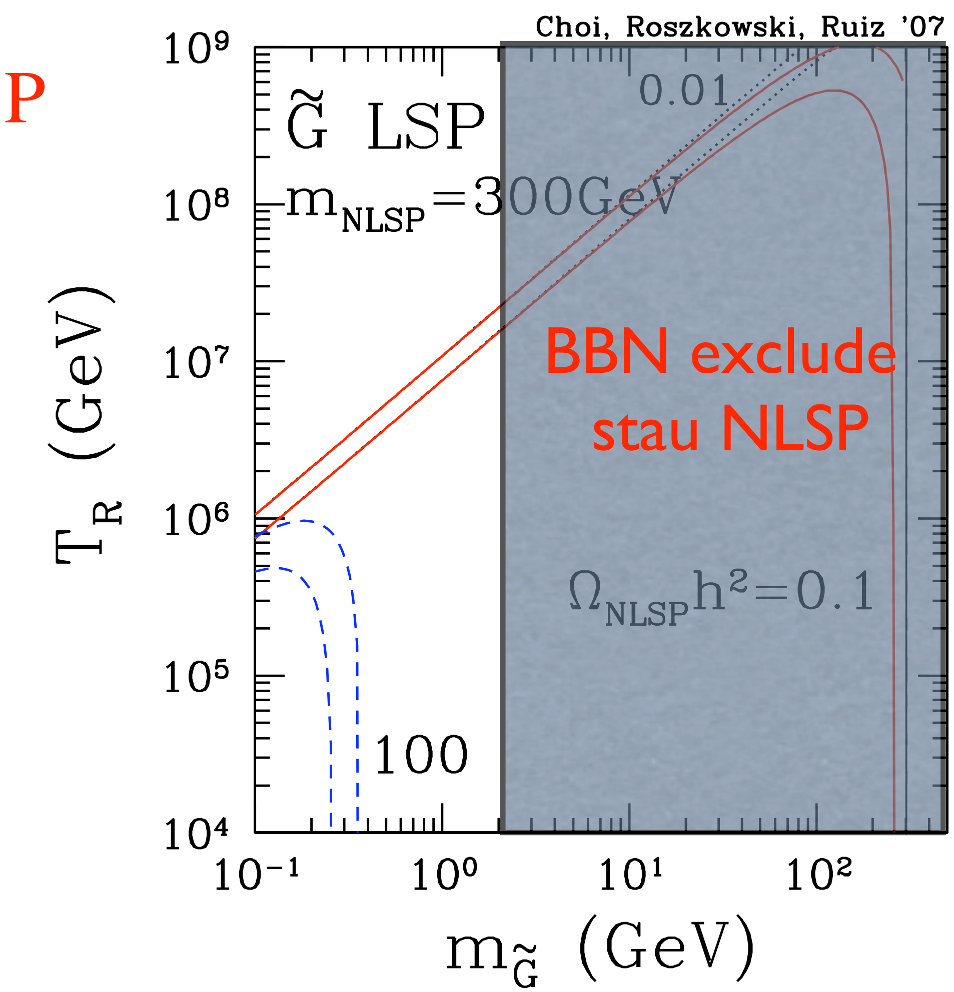
$m_{\widetilde{\tau}} = 1\,{\rm TeV}$ ➡ $m_{\widetilde{G}} \lesssim 40\,{\rm GeV},\ T_{\rm reh} \lesssim 4\times 10^8\,{\rm GeV}$

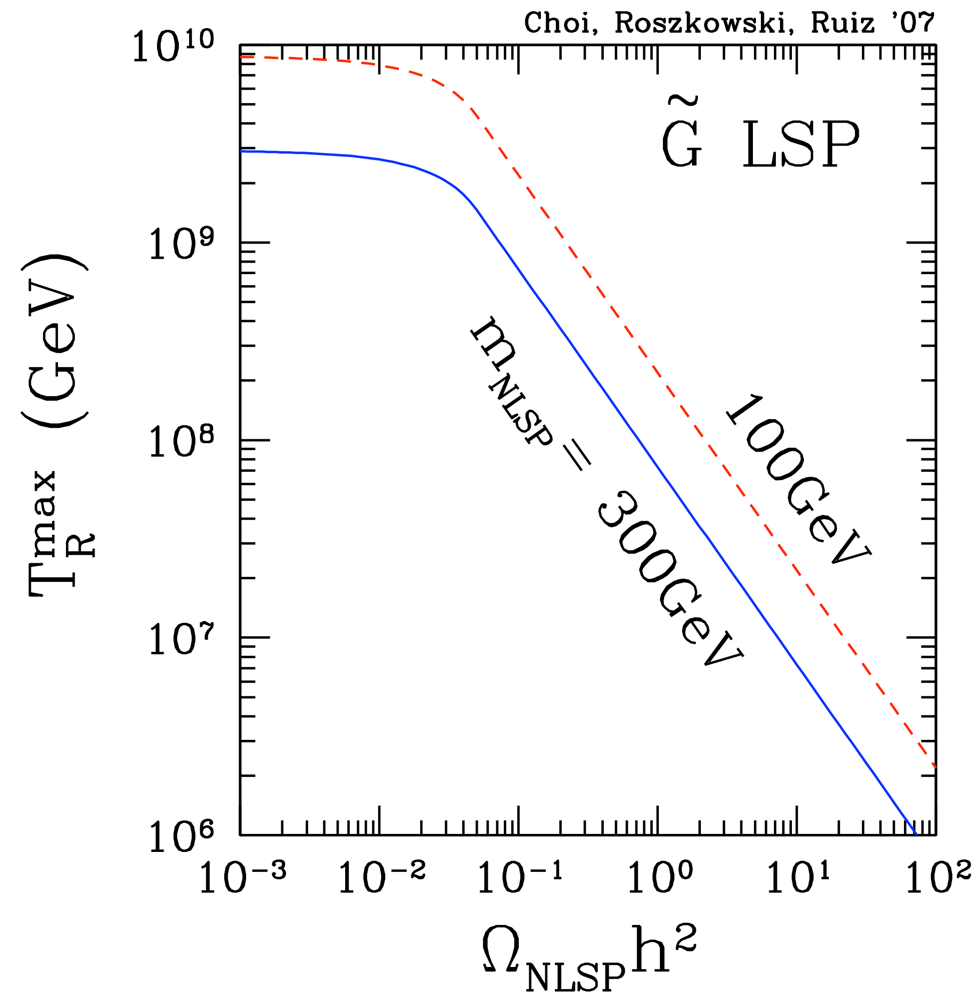
confirmed later by with different parameterization [Steffen 2008]

• Reheating temperature from collider measurements

[K.Y.Choi, Roszkowski, Ruiz de Austri 2007]

Gravitino LSP





• $m_{\rm NLSP}$ and $\Omega_{NLPS}h^2$ gives relation between $T_{\rm reh}$ and $m_{\widetilde{G}}$

• Upper bound the gravitino mass and the reheating temperature are obtained

• For stau NLSP, considering BBN,

$m_{\widetilde{\tau}} = 300\,{\rm GeV}$ ➡ $m_{\widetilde{G}} \lesssim 2\,{\rm GeV},\ T_{\rm reh} \lesssim 9\times10^6\,{\rm GeV}$

$m_{\widetilde{\tau}} = 1\,{\rm TeV}$ ➡ $m_{\widetilde{G}} \lesssim 40\,{\rm GeV},\ T_{\rm reh} \lesssim 4\times10^8\,{\rm GeV}$

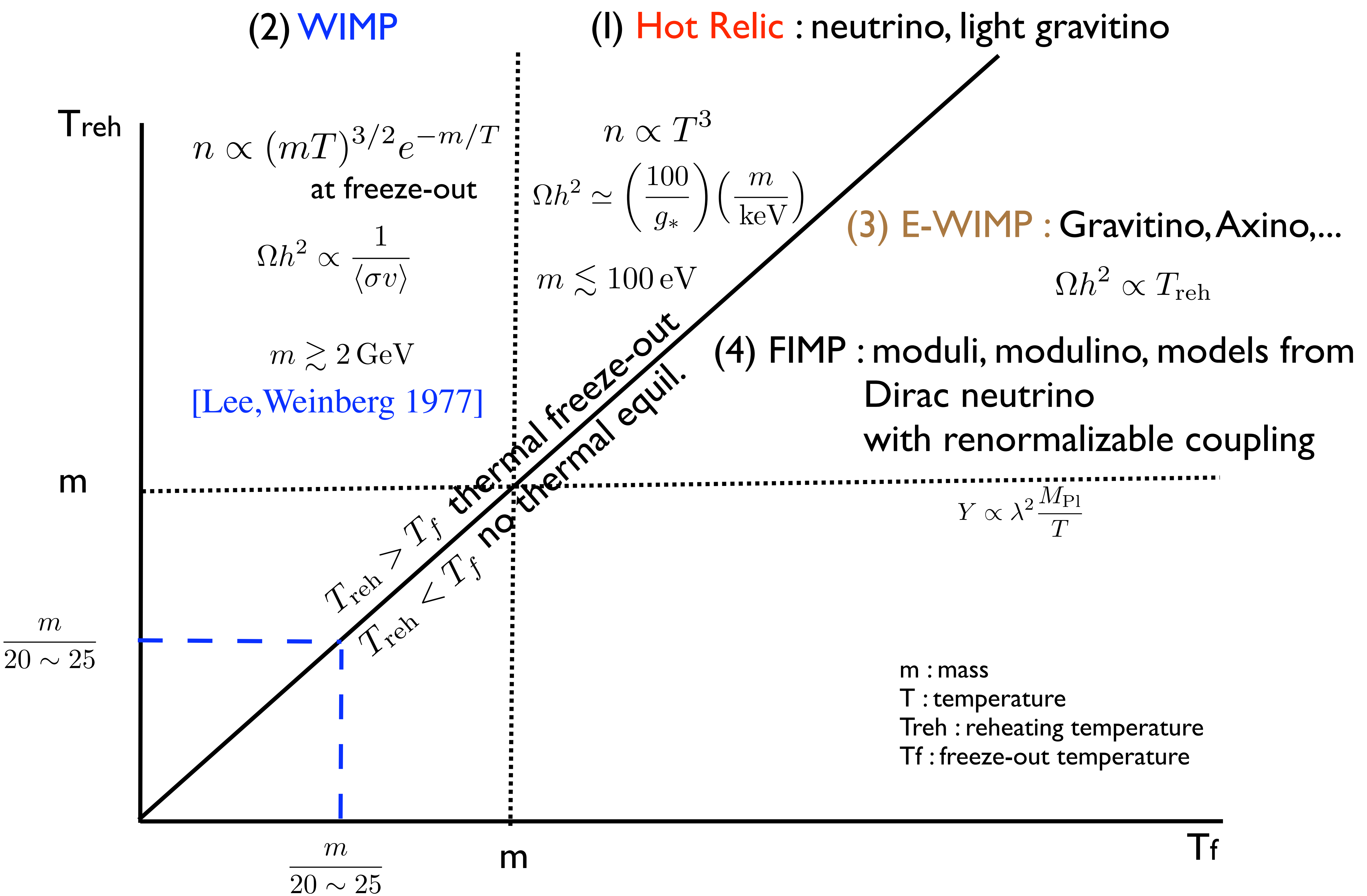
confirmed later by with different parameterization [Steffen 2008]

Summary

- In sugravity gravitinos exist and become a good candidate for dark matter
- Gravitinos are produced by thermal and non-thermal productions
- The cosmological constraints on gravitino DM are strong
  - Neutralino NLSP (100 GeV) is difficult as gravitino DM (> 1 GeV)
  - Stau NLSP is a viable NLSP for gravitino DM
    - Rather heavy stau NLSP (> TeV) for 100 GeV gravitino DM
    - Degenerate gravitino and stau ~ 100 GeV with conservative 6Li/7Li
- Conservative upper bound on the reheating temperature with gravitino DM

$$T_{\rm reh} < \text{a few} \times 10^7\,\text{GeV} \quad (\lesssim 10^8\ \text{GeV})$$

- Determination of the reheating temperature and the mass of gravitino or axino from the LHC collider measurements



(2) WIMP
(I) Hot Relic : neutrino, light gravitino
Treh
$n \propto (mT)^{3/2} e^{-m/T}$
at freeze-out
$\Omega h^2 \propto \frac{1}{\langle \sigma v \rangle}$
$m \gtrsim 2\,\mathrm{GeV}$
[Lee,Weinberg 1977]
$n \propto T^3$
$\Omega h^2 \simeq \left(\frac{100}{g_*}\right)\left(\frac{m}{\mathrm{keV}}\right)$
$m \lesssim 100\,\mathrm{eV}$
(3) E-WIMP : Gravitino, Axino,...
$\Omega h^2 \propto T_{\rm reh}$
(4) FIMP : moduli, modulino, models from
Dirac neutrino
with renormalizable coupling
thermal freeze-out
no thermal equil.
$T_{\rm reh} > T_f$
$T_{\rm reh} < T_f$
m
$Y \propto \lambda^2 \frac{M_{\rm Pl}}{T}$
$\frac{m}{20 \sim 25}$
$\frac{m}{20 \sim 25}$
m
Tf
m : mass
T : temperature
Treh : reheating temperature
Tf : freeze-out temperature

- # Gravitino Problem (Before 1980's)

: Big Bang hot Universe started from very high temperature

- Stable gravitino

If Gravitino is light enough to be stable: possibly dominant constitunent

$$\Omega_{\tilde{G}} h^2 \simeq 1.17 \left(\frac{100}{g_*}\right) \left(\frac{m_{\tilde{G}}}{1\,\mathrm{keV}}\right)$$

leading to the upper bound on the mass from the observational bound

$$m_{\tilde{G}} \lesssim 1\,\mathrm{keV}$$ [Pagels, Primack, PRL'82]

- Unstable gravitino

If Gravitino is heavy enough so that almost all gravitinos would have decayed, it should be before Big Bang Nucleosynthesis not to disrupt the successful genesis of light elements

$$m_{\tilde{G}} \gtrsim 10\,\mathrm{TeV}$$ [Weinberg, PRL'82]

⇒ Between 1 keV and 10 TeV of gravitino appears to be ruled out

- ## Gravitino Problem (After 1980's)

"Inflation can save the gravitino" analogous to the familiar monopole problem

[Ellis, Linde, Nanopoulos, 1982]

However after inflation, gravitinos are reproduced from the scatterings of ordinary particles, and the abundance depends on the reheating temperature after inflation.

Now the constraints on gravitino mass are reduced into the gravitino mass and reheating temperature.

We can have O(100 GeV) mass Gravitino but now the reheating temperature should be lower than around 10^{6-8} GeV for either stable or unstable Gravitino

→ Problematic for thermal leptogenesis, which need TR > 10^9 GeV

Way-out : soft leptogenesis [Chun, Scopel '06]
non-thermal leptogenesis [Lazarides, Shafi '91]
resonant leptogenesis [Pilatfsis, Underwood '04]

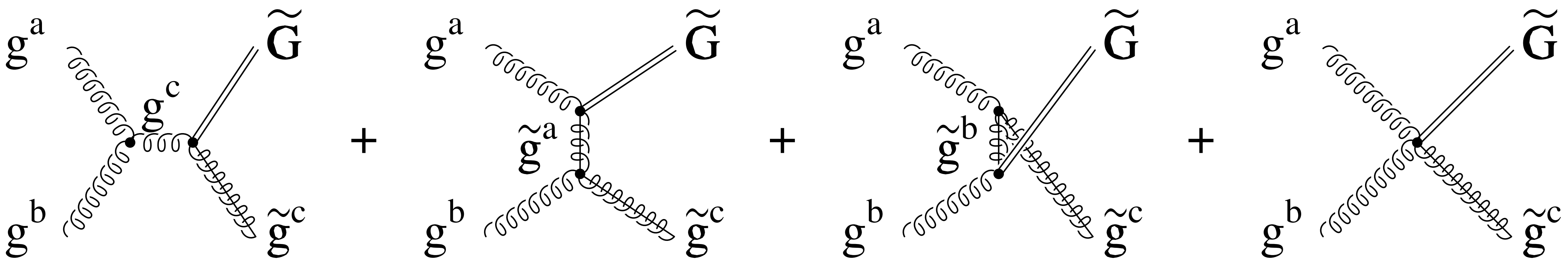
.... or by the new sources of CP violation from non-leptonic sector [Chung, Garbrecht, Ramsey-Musolf '09]

- # Gravitino Production (Thermal production)
  - 2 -> 2 sctterings

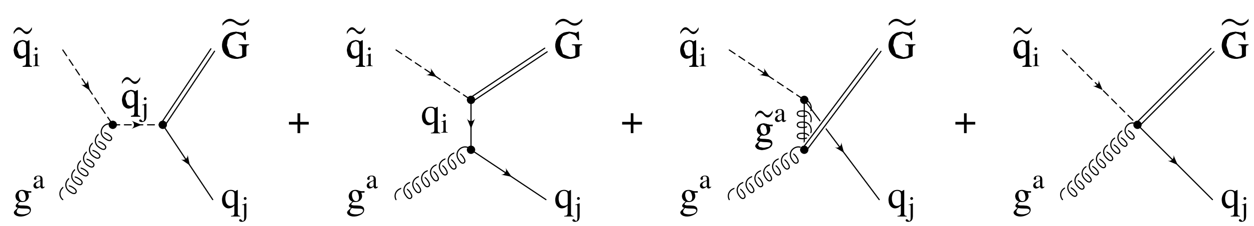
    The gravitino abundance is created in the reheating phase after inflation with reheating temperature TR, dominantly by 2-2 gravitino production process

[Ellis, Kim, Nanopoulos, 1984]
[Kawasaki, Moroi, 1995]
[Bolz, Brandenburg, Buchmuller, 2000]

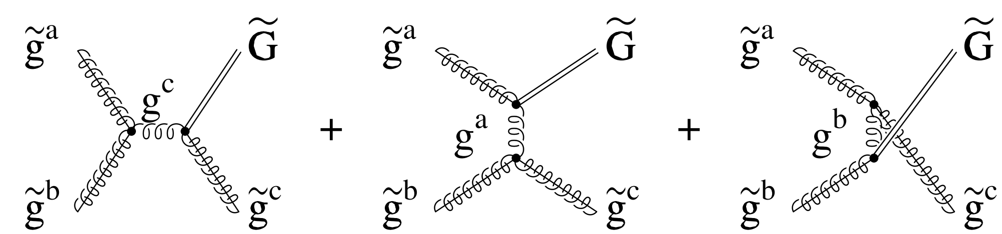
$$g^a + g^b \longrightarrow \tilde{g}^c + \tilde{G}$$



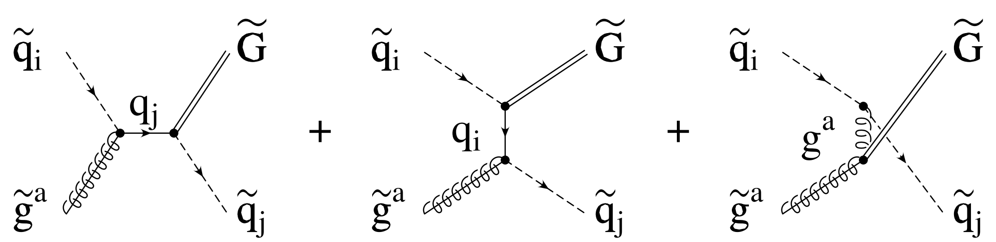
$\tilde{q}_i + g^a \longrightarrow \tilde{q}_j + \tilde{G}$



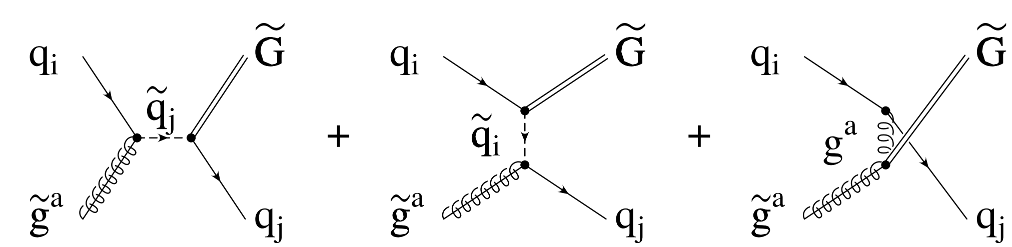
$\tilde{g}^a + \tilde{g}^b \longrightarrow \tilde{g}^c + \tilde{G}$



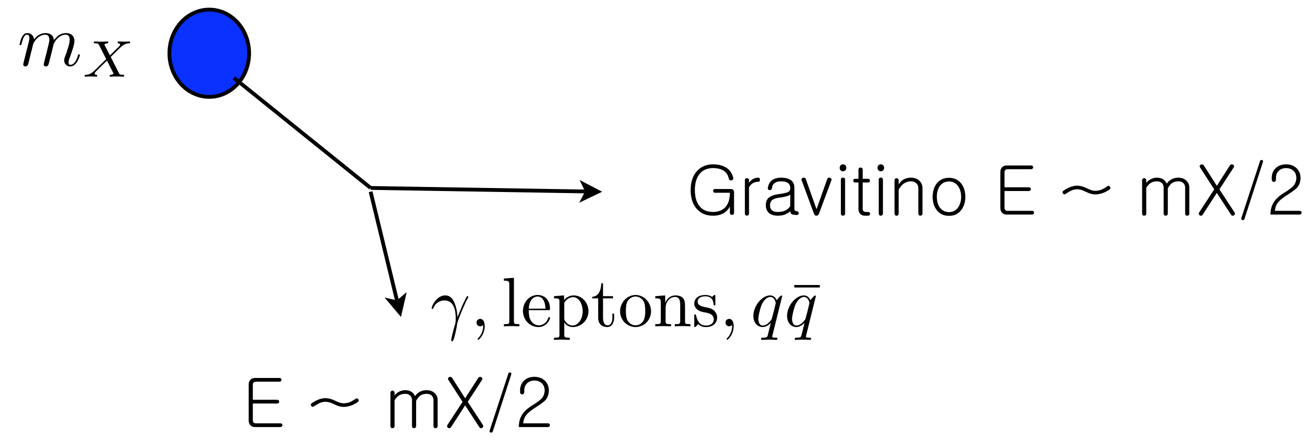
$\tilde{q}_i + \tilde{g}^a \longrightarrow \tilde{q}_j + \tilde{G}$



$q_i + \tilde{g}^a \longrightarrow q_j + \tilde{G}$



CMB distortion



- $\tau < 10^6\,\text{sec}$

  Additional EM energies are completely thermalized

- $10^6\,\text{sec} < \tau < 4 \times 10^{11}\Omega_b h^2\,\text{sec}$

  Number changing processes are not efficient
  : kinetic equilibrium but not chemical

  ➡ Bose-Einstein distribution with chemical potential

  $$|\mu| < 9 \times 10^{-5} \quad (95\%\text{CL})$$ [Hu et al. '93, Fixen et.al., '96]

- $\tau > 4 \times 10^{11}\Omega_b h^2\,\text{sec}$

  No longer Bose-Einstein sectrum
  : constraints on compton parameter $y \equiv 4\delta\epsilon/\epsilon$

  $$|y| < 1.2 \times 10^{-5} \quad (95\%\text{CL})$$ [Hagiwara et.al., '02]

★ However it is weaker constraint than BBN

[Roskowski et al. '05, Cerdeno et al. 06', et.al., '02]
[Lamon, Durrer '06]

BBN with Gravitino DM

Neutralino NLSP

$$\chi \to \tilde{G} + \gamma$$

$$\chi \to \tilde{G} + Z(h, \gamma^*/Z^*) \to \tilde{G} + q\bar{q}$$

$$B_h \sim 10^{-3}$$

Stau NLSP ★ Catalyzed BBN

$$\tilde{\tau} \to \tilde{G} + \tau$$

$$\tilde{\tau} \to \tilde{G} + \tau + Z(\gamma^*/Z^*) \to \tilde{G} + \tau + q\bar{q}$$

$$\tilde{\tau} \to \tilde{G} + \nu_\tau + W \to \tilde{G} + \nu_\tau + q\bar{q}$$

$$B_h \sim 10^{-5} - 10^{-2}$$

★ High energetic EM and Hadronic showers are generated and interact with nuclei

- n-p conversion by mesons $(t < 100\,\mathrm{s})$: increase of D and He4
- Hadronic dissociation $(100\,\mathrm{sec} - 10^7\,\mathrm{sec})$: increase of D and Li6

$$n + \alpha_{\mathrm{BG}} \to \mathrm{D} + \mathrm{T} \qquad p(n) + \alpha_{\mathrm{BG}} \to \begin{cases} \mathrm{T} + \cdots \\ {}^3\mathrm{He} + \cdots, \end{cases}$$

$$\mathrm{T} + \alpha_{\mathrm{BG}} \to {}^6\mathrm{Li} + n,$$

$${}^3\mathrm{He} + \alpha_{\mathrm{BG}} \to {}^6\mathrm{Li} + p.$$

- Electromagnetic dissociation $(10^4\,\mathrm{sec} - 10^{12}\,\mathrm{sec})$

$$\gamma + D \to n + p \quad (t \lesssim 10^6\,\mathrm{s}) \qquad \gamma + {}^4He \to n + {}^3He \quad (t \gtrsim 10^6\,\mathrm{s})$$

$$\gamma + {}^4He \to p + n + D$$

[Jedamzik 2004]

[Kohri, Kawasaki, Moroi '04]

- Charged particle during BBN : Catalyzed BBN

$$\tau(\tilde{\tau} \to \tilde{G}\tau) \simeq 6 \times 10^3\,\mathrm{sec} \left(\frac{1\,\mathrm{TeV}}{m_{\tilde{\tau}}}\right)^5 \left(\frac{m_{\tilde{G}}}{100\,\mathrm{GeV}}\right)^2 \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^{-4}$$

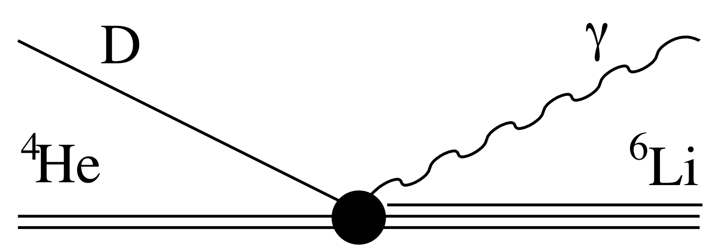
staus still exist during BBN epoch

"The existence of metastable, tau > 10^3 sec, negatively charged EW scale particles (X−) alters the predictions for lithium and other primordial elemental abunances via the formation of bound states with nuclei during BBN"

[M.Pospelov, PRL 2007]

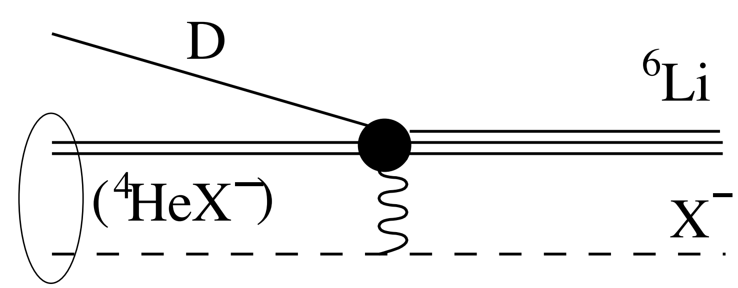
Standard BBN

$$^4\mathrm{He} + \mathrm{D} \to \ ^6\mathrm{Li} + \gamma;$$



Catalyzed BBN

$$(^4\mathrm{He}X^-) + \mathrm{D} \to \ ^6\mathrm{Li} + X^-;$$



requires $Y_X \lesssim 10^{-14}$ for $\tau_X \gtrsim 5 \times 10^3\,\mathrm{sec}$

CBBN may dominate had input for $5 \times 10^3\,\mathrm{sec} < \tau_X < 10^7\,\mathrm{sec}$