Experimental signatures of non-standard pre-BBN cosmologies

Graciela Gelmini - UCLA

GGI-Florence, Feb 20, 2009

If detected, DM particles will be the earliest relics we can study: they come from the pre-BBN era, from which we have no data so far.

The DM relic density and velocity distribution depend on cosmological parameters. Can we differentiate them from particle physics parameters? E.i. can we determine the pre-BBN history of the Universe through studying the DM particles? Can we discriminate between different pre-BBN cosmologies?

To start with, we need to know how large are the possible effects of different viable pre-BBN cosmologies on DM particle properties we could measure.

Outline:

- standard vs non-standard pre-Big Bang Nucleosynthesis cosmology
- WIMPs relic density
- WIMPs relic velocity (Ultra-Cold?, Warm?)
- “visible’ sterile neutrinos

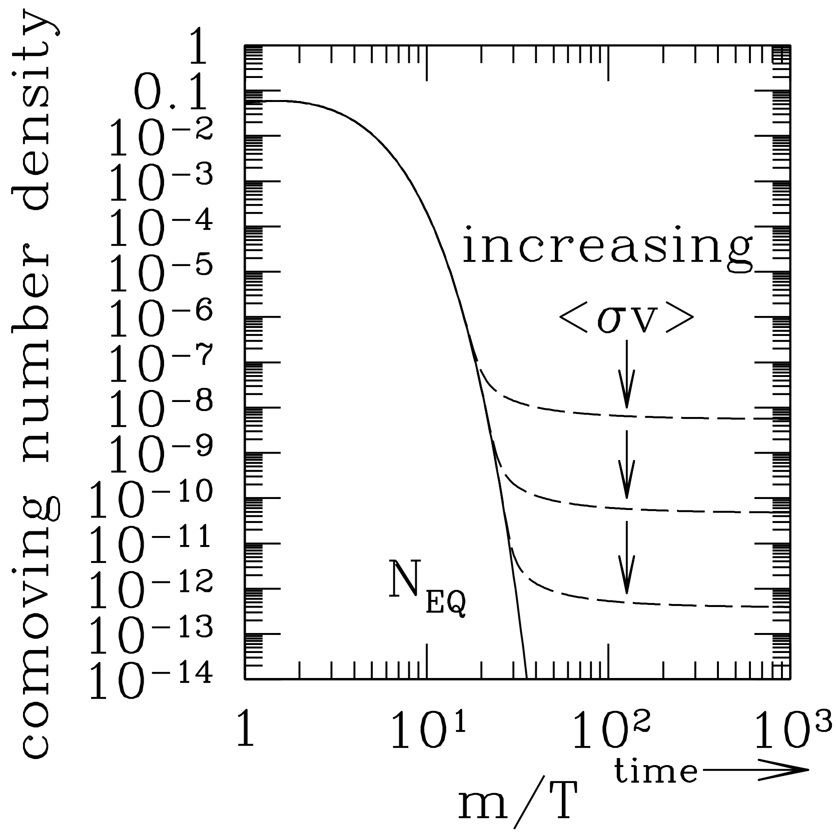
WIMPs as Dark Matter

Standard calculations: start at $T > T_{f.o.} \simeq m/20$

- WIMPs reach thermal equilibrium
- Chemical decoupling when $\Gamma_{\rm ann} = \langle \sigma v \rangle \, n \leq H$,
- No entropy change in matter+radiation

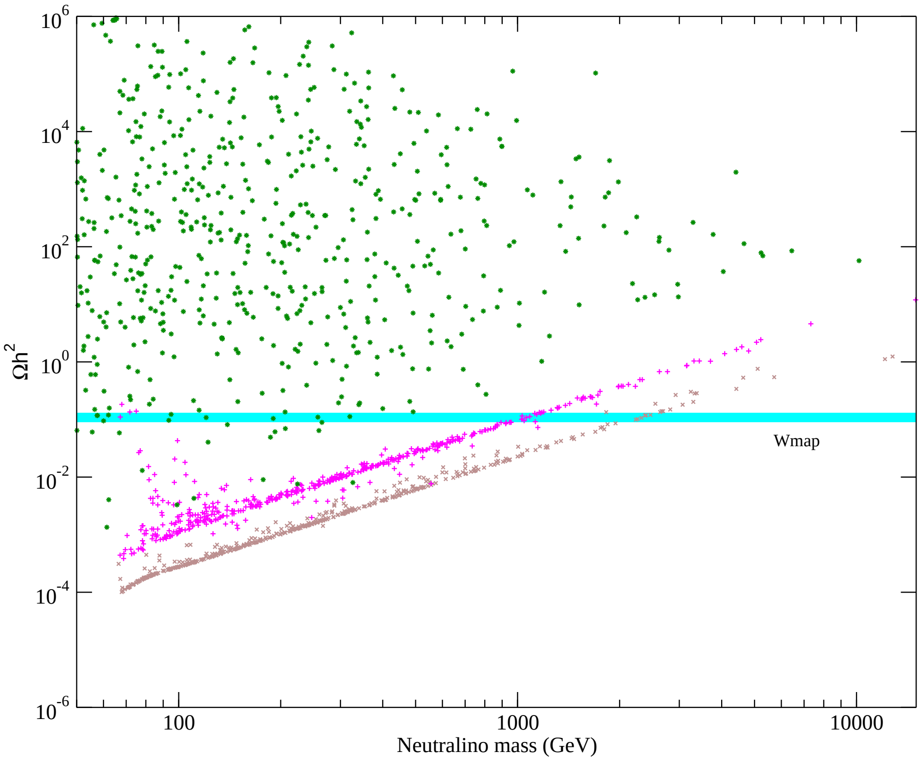
$$\Omega h^2 \approx \frac{2 \times 10^{-10} \mathrm{GeV}^{-2}}{\langle \sigma v \rangle}$$

Weak σ for $\Omega \sim 1$!



Dark Matter constraint, $\Omega_\chi^{\rm std} = \Omega_{\rm DM}$: Very constraining on models!

e.g. neutralinos in MSSM after LEP-II



- bino-like: OVERDENSE of fine-tuned
- higgsino-like: UNDERDENSE

(or $m \simeq 1$TeV-beyond LHC)

- wino-like: UNDERDENSE

(or $m \simeq 2$ TeV-beyond LHC)

.

Need "Well Tempered Neutralinos"

at boundary bino/higssino or bino/wino

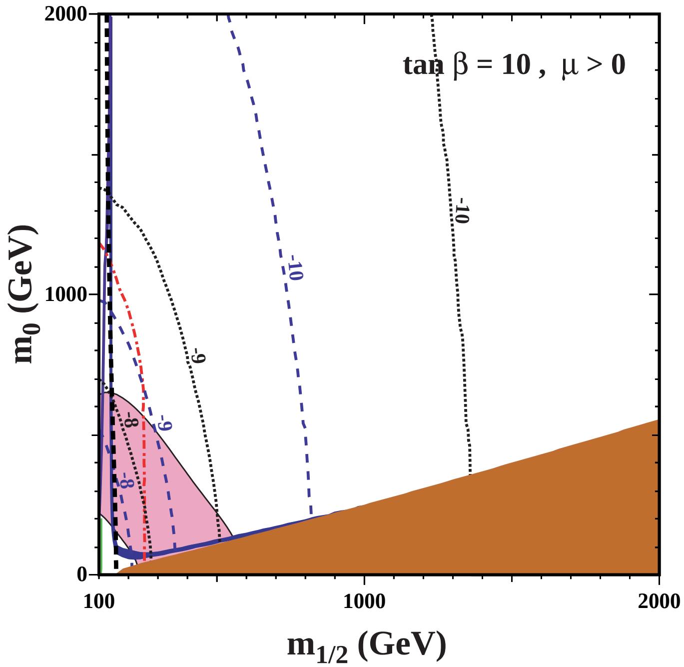
$M_1 = \pm\mu$ or $|M_1| = |M_2|$

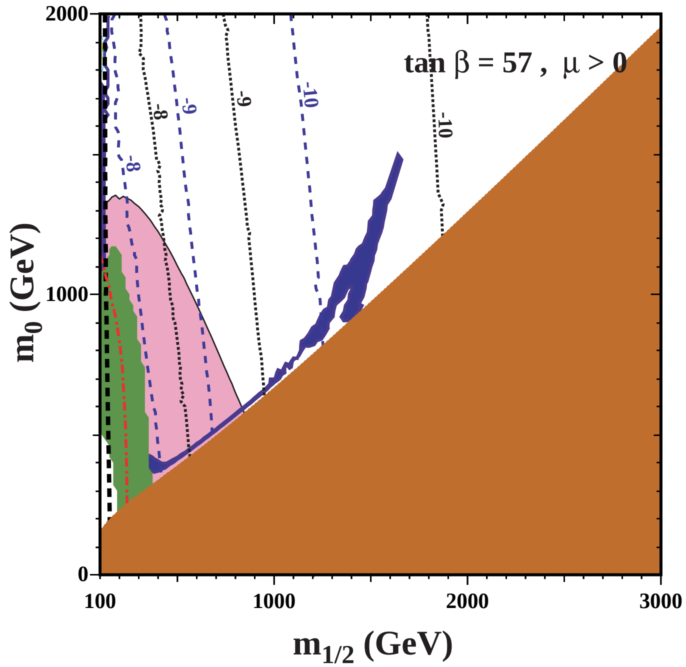
(Arkani-Hamed, Delgado, Giudice, 2006)

Dark Matter constraint: very constraining on models!

e.g. neutralinos in CMSSM are the DM only in the blue narrow bands

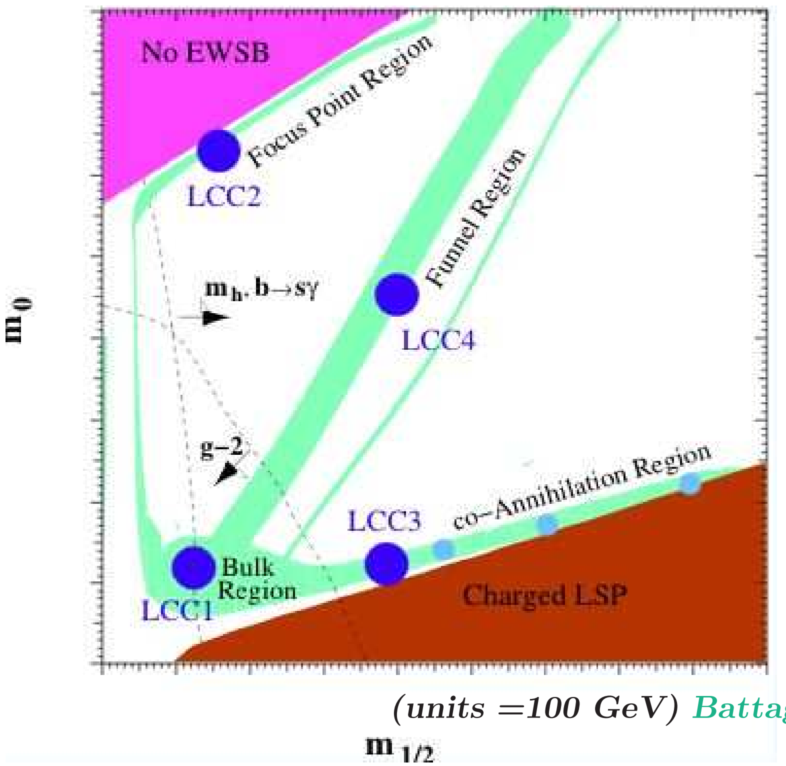
(e.g. J. Ellis et.al.2005)





In most of the parameter space WIMPs are overdense, thus models rejected?

Dark Matter constraint: narrow bands



(units =100 GeV) *Battaglia et al*

mSUGRA: bino-like neutralino has a helicity suppressed annihilation rate into $f\bar{f}$! Need: to be light (bulk), coannihilation with stau, $m = m_A/2$ resonance (funnel), Higgsino component (focus)

LHC-ILC benchmarks in DM bands:

A' to L'
(Battaglia, DeRoeck, Ellis, Gianotti, Olive, Pape 03)

SPS 1a',1b, 2, 3 ,4, 5
(Snowmass Points and Slopes)(Allanach etal. 02)

LCC 1, 2, 3, 4
(Linear Collider Cosmo)(White paper on ILC)

SPS1a', LCC2, D', LCC4 ...
(ILC World-wide study)(Battaglia et al 2006)

But bands depend on cosmology before BBN, an epoch from which we have no observations!!

We do not know the history of the Universe before BBN

- WIMPs decouple at $T_{f.o.} \simeq m_\chi/20 >$ MeV: earliest remnants

- BBN ($t_U \simeq$ 200 sec, $T \simeq$ 0.8 MeV) is the earliest episode from which we have a trace: the abundance of light elements D, ^{4}He, ^{7}Li.

- Next observable is CMB ($t_U \simeq 380$ kyr, $T \simeq$ eV)

- Next, the LSS of the Universe

To compute the WIMP relic density we must make assumptions about the pre -BBN epoch

our EP models allow us to get to $T \simeq 10^{16}$ GeV or even 10^{19} GeV!

But has the Universe achieved those large T ?

How high is T_{RH}, the highest temperature of the most recent radiation dominated epoch of the Universe?

We do not know, but we know how small it can be:

$$T_{RH} \geq 4\text{MeV}$$

To compute the WIMP relic density we must make assumptions about the pre -BBN epoch $T > 4$ MeV

Standard cosmological assumptions

- T_{RH}, highest temperature of the most recent radiation dominated epoch of the Universe, is large enough for WIMPs to reach thermal equilibrium
- WIMPs are produced thermally
- the entropy of matter and radiation is conserved

imply neutralinos can be the DM only in particular models

In non-standard cosmologies, can the neutralino be the cold dark matter in **any** supersymmetric model?

How to get a non-std abundance

- **Increase** the density by increasing the expansion rate at freese-out [e.g. quintessence-scalar-tensor models] or by creating neutralinos from particle (or topological defects) decays [non-thermal production].
- **Decrease** the density by reducing the expansion rate at freese-out [e.g. scalar-tensor models], by reducing the rate of thermal production [low reheating temperature] or by producing radiation after freeze out [entropy dilution].

Usually non-std scenarios contain additional parameters that can be adjusted to modify the WIMP relic density. However these are due to physics at a high scale, and do not change the model at the electroweak scale.

Non std pre-BBN cosmologies

- **Models that only change the pre-BBN Hubble parameter H**

  These models alter the thermal evolution of the Universe without an extra entropy production.

- **Low temperature reheating (LTR) models**

  A scalar field ϕ oscillating around its true minimum while decaying is the dominant component of the Universe.
  Entropy in matter and radiation is produced: not only the value of H but the dependence of the temperature T on the scale factor a is different.

Models that only change the pre-BBN H

The change in Ω_χ is more modest than in LTR models

- Extra contributions to ρ_U increase H (increases Ω_χ):

  -Brans-Dicke-Jordan cosmological model Kamionkowski, Turner-1990

  -models with anisotropic expansion Barrow-1982; Kamionkowski, Turner-1990; Profumo, Ullio-2003,

  - scalar-tensor models Santiago, Kalligas, Wagoner-1998, Damour, Pichon-1998, Catena, Fornengo, Masiero, Pietroni, Rosati; 2004; Catena, Fornengo, Masiero, Pietroni, Schelke-2007

  -kination models Salati-2002, Profumo, Ullio-2003

  -and other models Barenboim, Lykken-2006 and 2007; Arbey, Mahmoudi-2008

- H may be decreased (decreases Ω_χ) in some scalar-tensor models Catena, Fornengo, Masiero, Pietroni, Schelke-2007

Models that only change the pre-BBN H: Kination Salati-02; M. Joyce-01

Period in which the kinetic energy of a scalar field ϕ (quintessence?) dominates: $\rho_{\rm total} \simeq \dot{\phi}^2/2 \sim a^{-6}$
[Homogeneous field: $d\dot{\phi} + 3(da/a)\dot{\phi} = 0$ for $V = 0$ so $\dot{\phi} \sim a^{-3}$]

Parameter: $\eta_\phi = \rho_\phi/\rho_\gamma < 1$ at $T \simeq 1$ MeV

$T \sim a^{-1}$ as usual: $H_{\rm kination} \sim \sqrt{\rho_{\rm total}} \simeq \sqrt{\eta_\phi}(T/1{\rm MeV})H_{\rm standard} \sim T^3$

Thus decoupling happens earlier, when the density is larger and WIMPs underdense in the std. cosmology can be the whole of the DM:

$$\Omega_{\rm kination}/\Omega_{\rm std} \simeq \sqrt{\eta_\phi}10^3(m_\chi/100{\rm GeV})$$

Models that only change the pre-BBN Hubble parameter H: Scalar-tensor models of gravity

have a scalar field coupled only through the metric tensor to the matter fields. The expansion of the Universe drives the scalar field towards a state where the theory is indistinguishable from GR at a low T_ϕ, before BBN.

At $T > T_\phi$: $H \simeq A H_{\rm std} \sim T^{1.2}$, $A > 1$, when WIMPs freeze-out .
At T_ϕ: A drops sharply to 1, H becomes again smaller than Γ_χ ("reannihilation phase" - but net effect is increase in Ω_χ)

$$\Omega_\chi/\Omega_{\rm std} \sim 10 - 10^3$$

Catena, Fornengo, Masiero, Pietroni, Rosati; 04

With more than one matter sector (one "visible" and the other "hidden") H can be reduced by as much as 0.5! So

$$\Omega_\chi/\Omega_{\rm std} \sim 0.8 - 0.9 \ (0.1 - 0.2) \text{ for } m_\chi \simeq 10 \ (500)\text{GeV}$$

Catena, Fornengo, Masiero, Pietroni, Schelke-07

$H(T)$ for several pre-BBN cosmological models

"LTR": Low T_{RH}

.

"K": kination

.

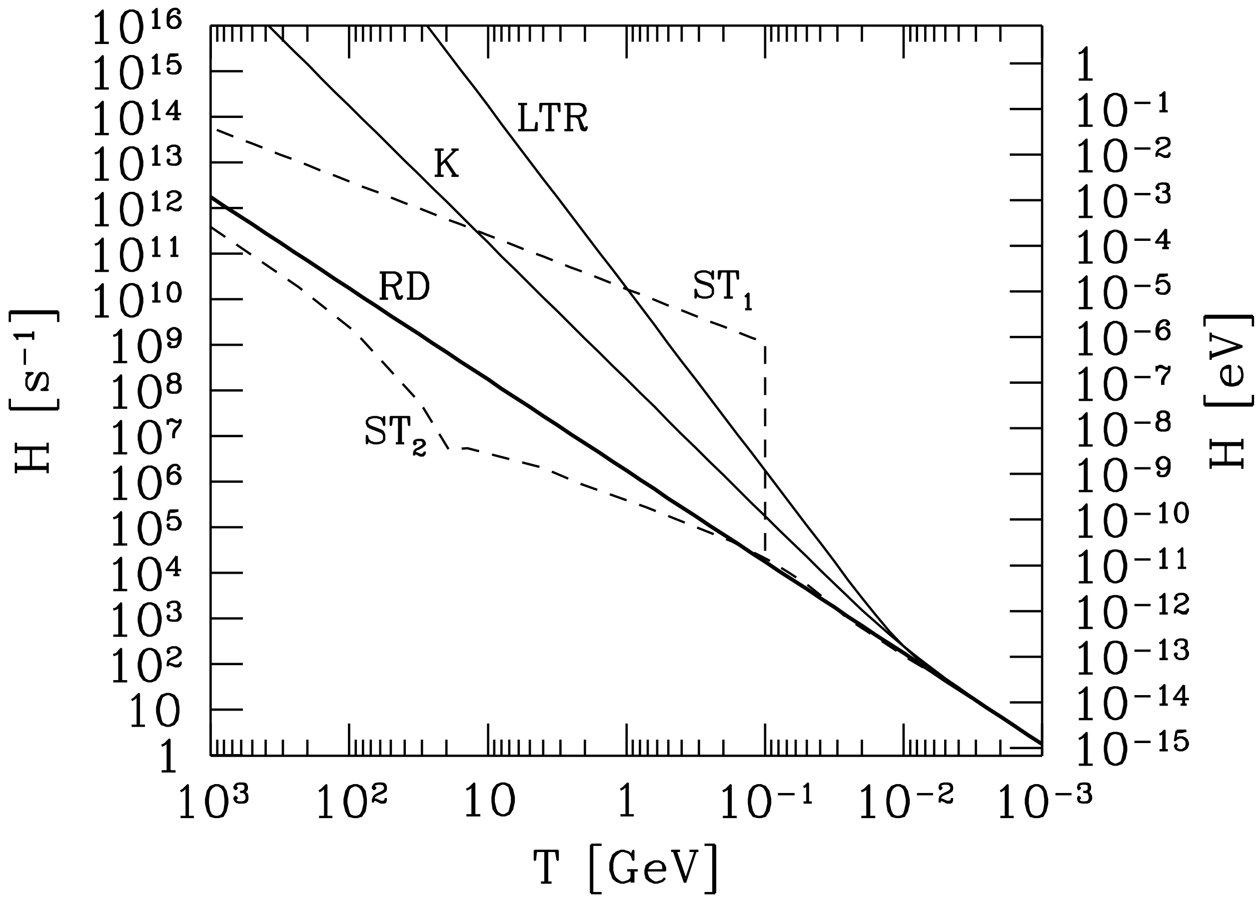
"ST1": scalar tensor with H increase

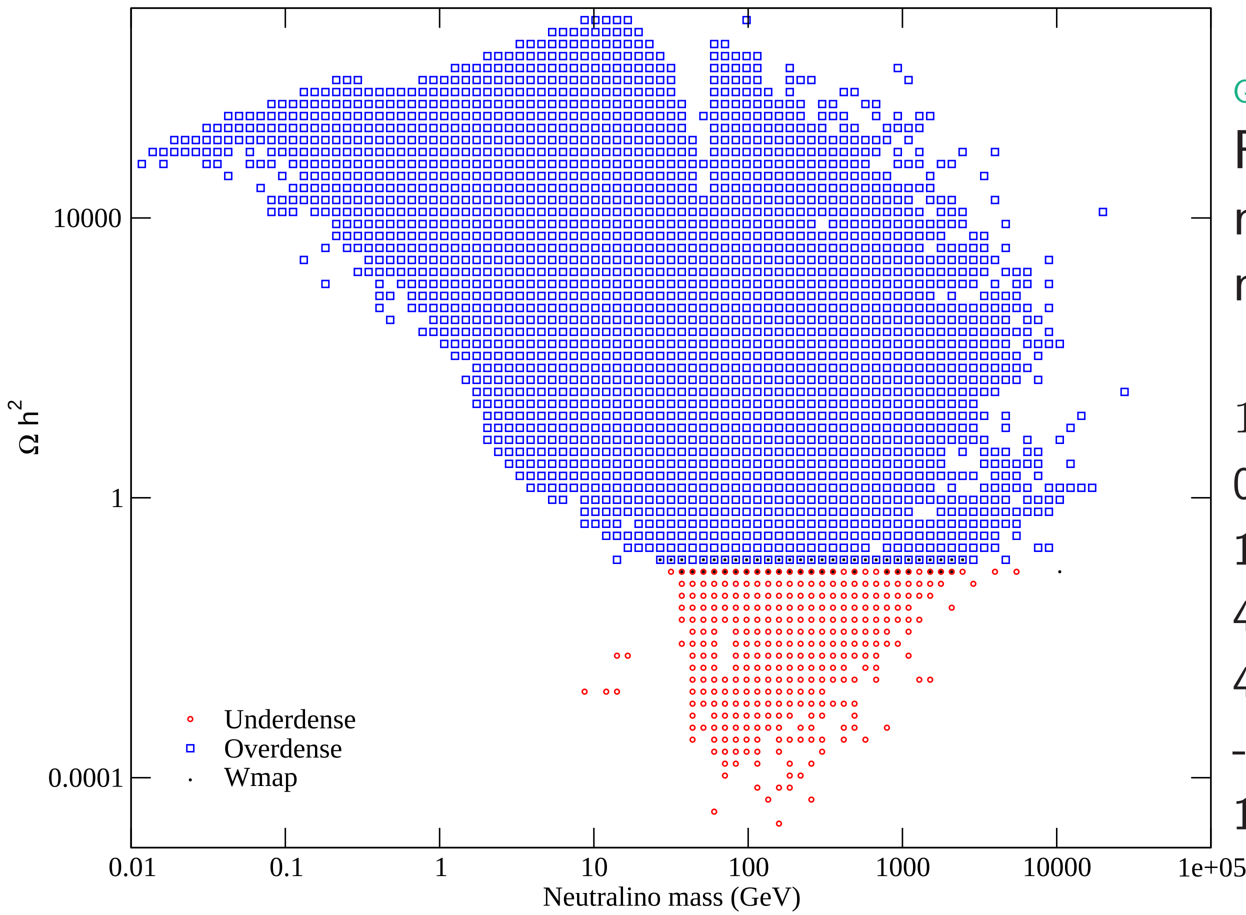
.

"RD": radiation-dom.

.

"ST2" : scalar tensor with H decrease





GG, Gondolo, Soldatenko, Yaguna, 07

Factors 10^3 to 0.1 are not enough for most neutralinos...

10^5 MSSM models:

0.1 GeV< M_1 <50TeV

10GeV< $M_{2,3}$ <50TeV

40GeV< $m_{\tilde{q}} m_{\tilde{\ell}}$ <50TeV

40GeV< μ, m_A <50TeV

-3m$_o$ < A_t, A_b <3m$_0$

1< $\tan\beta$ <60

Low temperature reheating (LTR) models

Models with a late episode of entropy creation or inflation, either with

- moduli fields, either the Polonyi field Moroi, Yamaguchi,Yanagida-95; Kawasaki, Moroi,Yanagida-96
  or others Moroi, Randall-00
- or an Affleck-Dine field and Q-ball decay Fujii, Hamaguchi-02; Fujii, Ibe-03
- or thermal inflation Lyth. Stewart-96.

Both thermal and non thermal production mechanisms have been discussed:

..... McDonald 1989; Moroi, Yamaguchi and Yanagida 1995; Kawasaki, Moroi and Yanagida 1996; Hashimoto, Izawa, Yamaguchi, Yanagida 1998; Chung, Kolb, Riotto 1999; Lin et al 2000; Moroi, Randall 2000; Giudice, Kolb, Riotto 2001; Fornengo, Riotto, Scopel 2002; Allahverdi, Drees 2002; Khalil, Muñoz, Torrente-Lujan 2002, Fujii, Hamaguchi 2002; Fujii, Ibe 03; Profumo, Ullio 2003; Pallis 2004; Kohri, Yamaguchi and Yokoyama, 2004, 2005; J. Kaplan 2006; Endo, Hamaguchi, Takahashi 06; Nakamura,Yamaguchi 2006; Gelmini, Gondolo 2006; Gelmini, Gondolo, Soldatenko, Yaguna 2006; Endo, Motoi, Takahashi 2006; Drees, Iminniyaz, Kakizaki 2006 and 2007; Profumo 2008.....

Late decaying scalar field ϕ

Moduli fields: pervasive in SUSY models, m_ϕ = O(10-100) TeV - gravitational strength couplings....thus,

$$T_{RH} \simeq 10 \text{ MeV} \left(\frac{m_\phi}{100 \text{ TeV}}\right)^{3/2} \left(\frac{M_P}{\Lambda_{\text{eff}}}\right)$$

- 4 MeV $< T_{RH} < T_{f.o.}$: thermal production suppressed
- ϕ-decays produce entropy, which dilutes the neutralino abundance
- ϕ can decay into SUSY particles producing b WIMPs per decay

G.G. and P. Gondolo, PRD74:023510, 2006

G.G., P. Gondolo, A. Soldatenko and C. E. Yaguna, PRD76,015010,2007

Only two extra parameters $T_{RH}(\Gamma_\phi)$ and $\eta \sim b/m_\phi$

Standard

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle\sigma v\rangle \left(n_\chi^2 - n_{\chi eq}^2\right), \quad (1)$$

$$\frac{ds}{dt} = -3Hs\,. \quad (2)$$

Late decaying scalar (WIMPs in kinetic but not necessarily chemical equilibrium)

$$\frac{d\rho_\phi}{dt} = -3H\rho_\phi - \Gamma_\phi\rho_\phi \quad (3)$$

$$\frac{dn_\chi}{dt} = -3Hn - \langle\sigma v\rangle \left(n_\chi^2 - n_{\chi eq}^2\right) + \frac{b}{m_\phi}\Gamma_\phi\rho_\phi \quad (4)$$

$$\frac{ds}{dt} = -3Hs + \frac{\Gamma_\phi\rho_\phi}{T} \quad (5)$$

With the right combination of T_{RH} and η any neutralino with standard density $\Omega_{\rm std} > 10^{-5}(100{\rm GeV}/m_\chi)$

Solutions

- $T < T_{RH}$ **radiation dominates**

- $T > T_{RH}$ **oscillating ϕ domination:** $H \simeq \rho_\phi^{1/2}/M_P \propto T^4$ (McDonald 1991)
  [use $\dot{\rho} = -3H(\rho + p) + \Gamma_\phi \rho_\phi$ and $p = \rho/3$, $\rho \simeq T^4$, $H \sim t^{-1}$ and $T \propto t^\alpha$]

  Since at $T = T_{RH}$, $H \simeq T_{RH}^2/M_P$ then

  $\rho_\phi \simeq T^8/T_{RH}^4 \quad \text{and } \rho_\phi a^3 = \text{const so } T \propto a^{-3/8}$ and $H \propto a^{-3/2}$

- $T_{RH} > T_{Std\ f.o.}$, **standard scenario recovered**

- $T_{RH} < T_{Std\ f.o.}$: **Four different solutions**

Late decaying scalar scenario

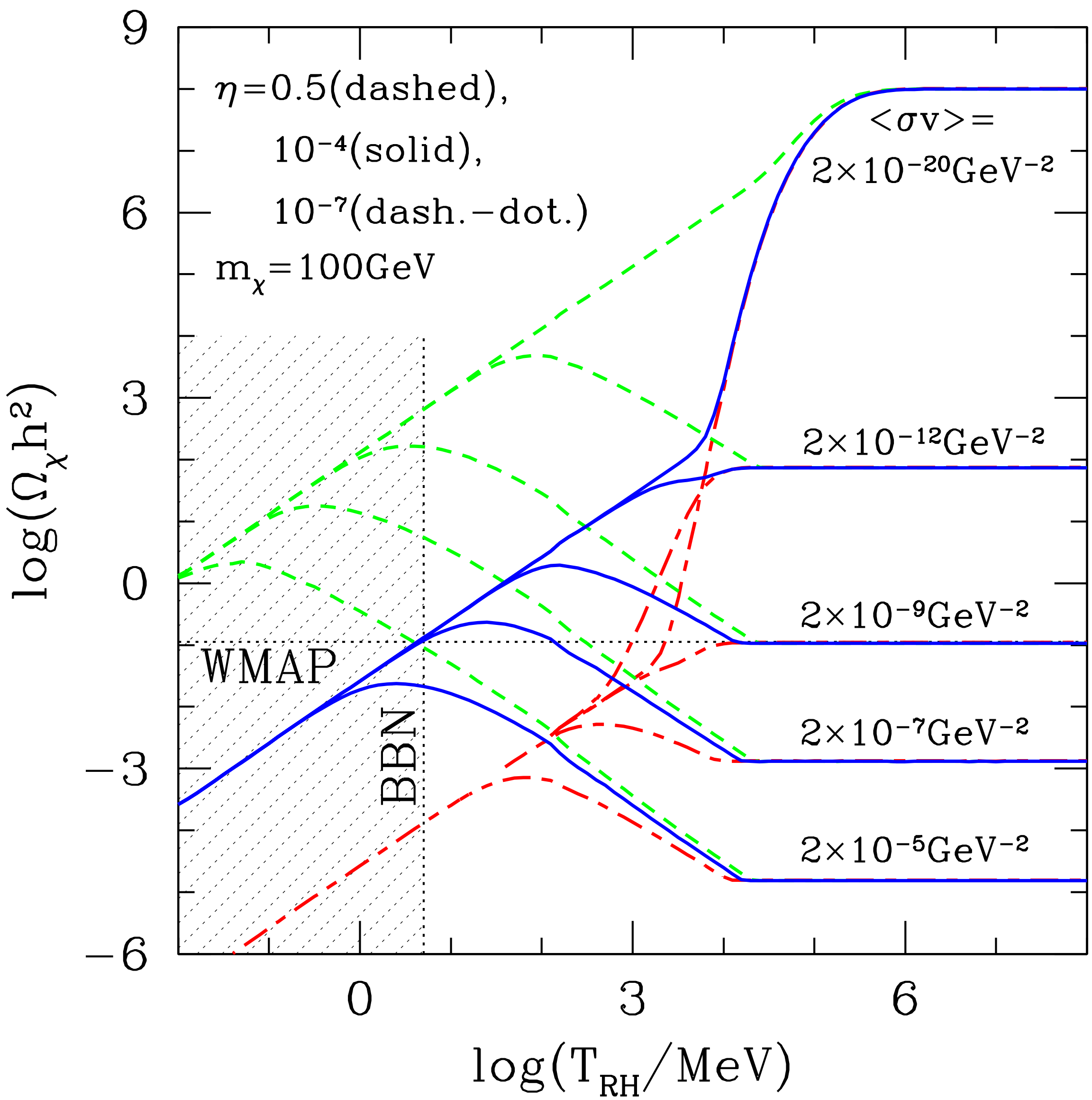
G.G. and Gondolo, 06

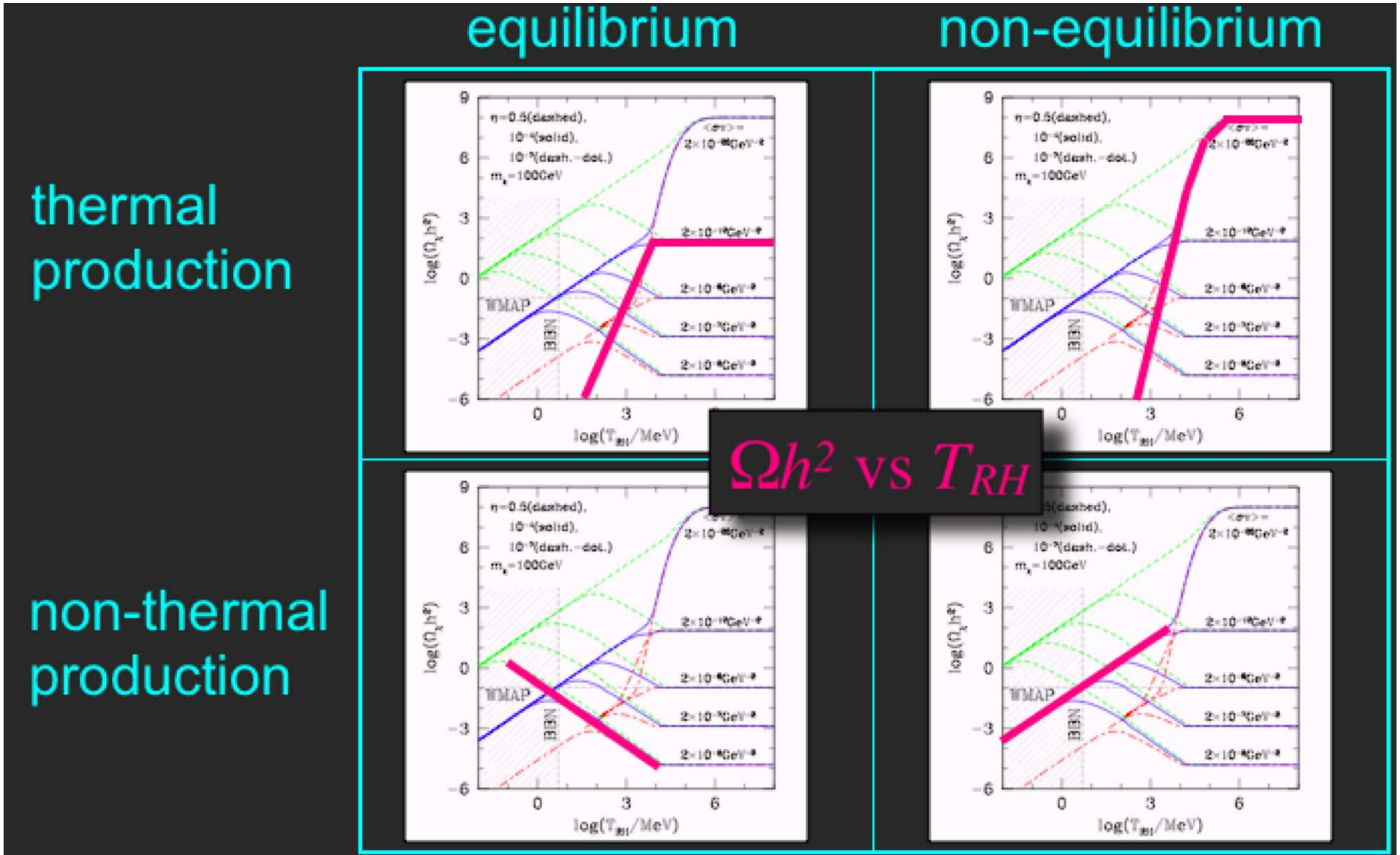
Two additional parameters:

T_{RH} and

$\eta = b\ \frac{100\mathrm{TeV}}{m_\phi}$

No solution for $\Omega_{\rm std} < 10^{-5}(\frac{100\mathrm{GeV}}{m_\chi})$




equilibrium
non-equilibrium
thermal production
non-thermal production
Ωh² vs T_RH
WMAP
BBN
m_χ=100GeV
log(Ω_χh²)
log(T_RH/MeV)

MSSM + Late decaying scalar field in Dark SUSY (G.G., Gondolo, Soldatenko and Yaguna, 2006)

We performed a random scan in 9 parameters in the ranges:

$$10 \text{ GeV} < M_i, m_A, \mu < 50 \text{ TeV}$$

$$10 \text{ GeV} < m_0 < 200 \text{ TeV}$$

$$-3m_0 < A_t, A_b < 3m_0$$

$$1 < \tan\beta < 60$$

The sign of μ was randomly chosen.

Accelerator constraints (as contained in DarkSUSY version 4.1)
1700 models (points) for each η, T_{RH} pair.

mSUGRA, mAMSB or split-SUSY are similar to - though not necessarily coincide with - particular examples of these models

MSSM

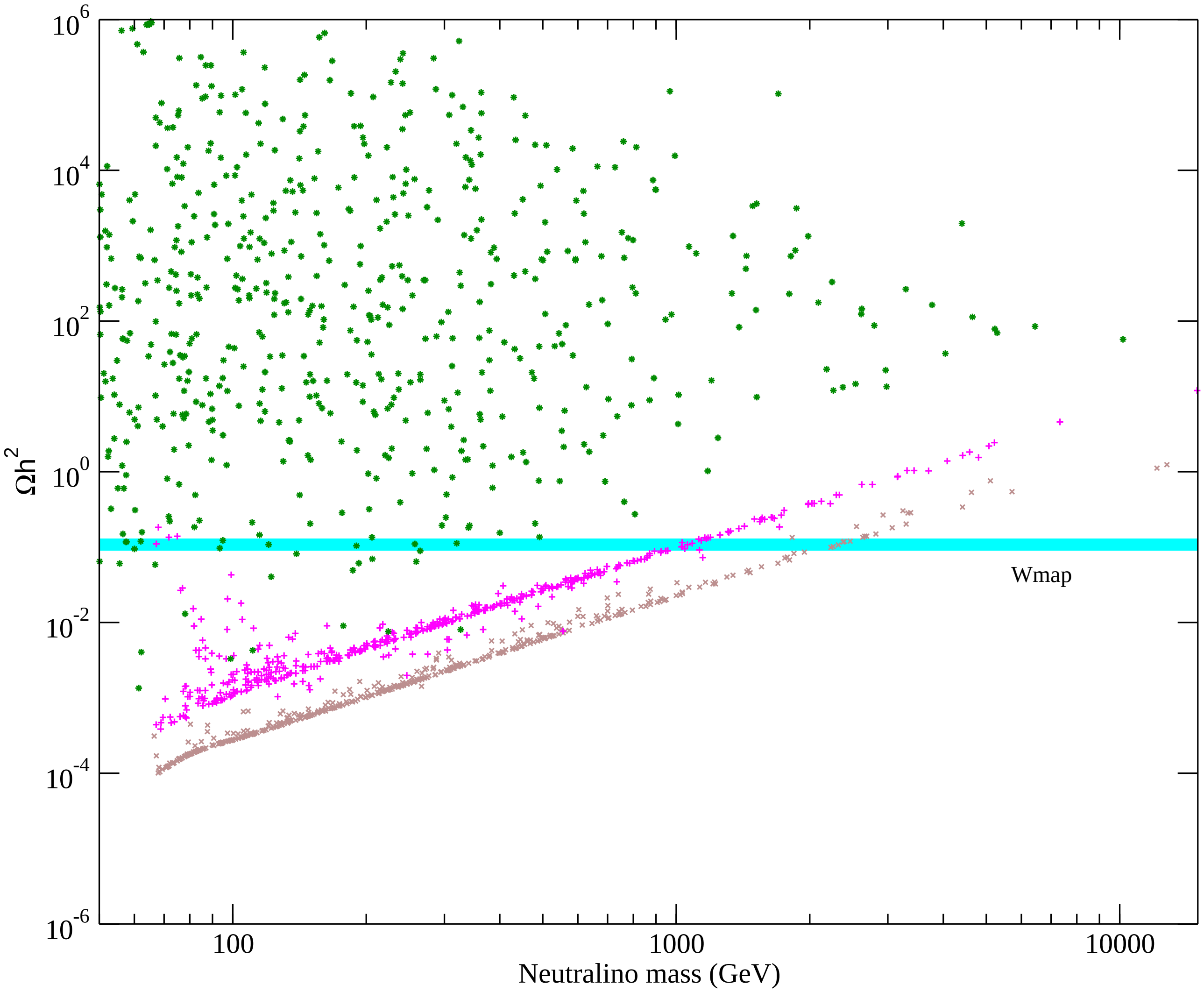
Standard cosmology

G.G., Gondolo, Soldatenko and Yaguna,PRD 74: 083514, 2006

bino-like

higgsino-like

wino-like



MSSM

1700 models (points)

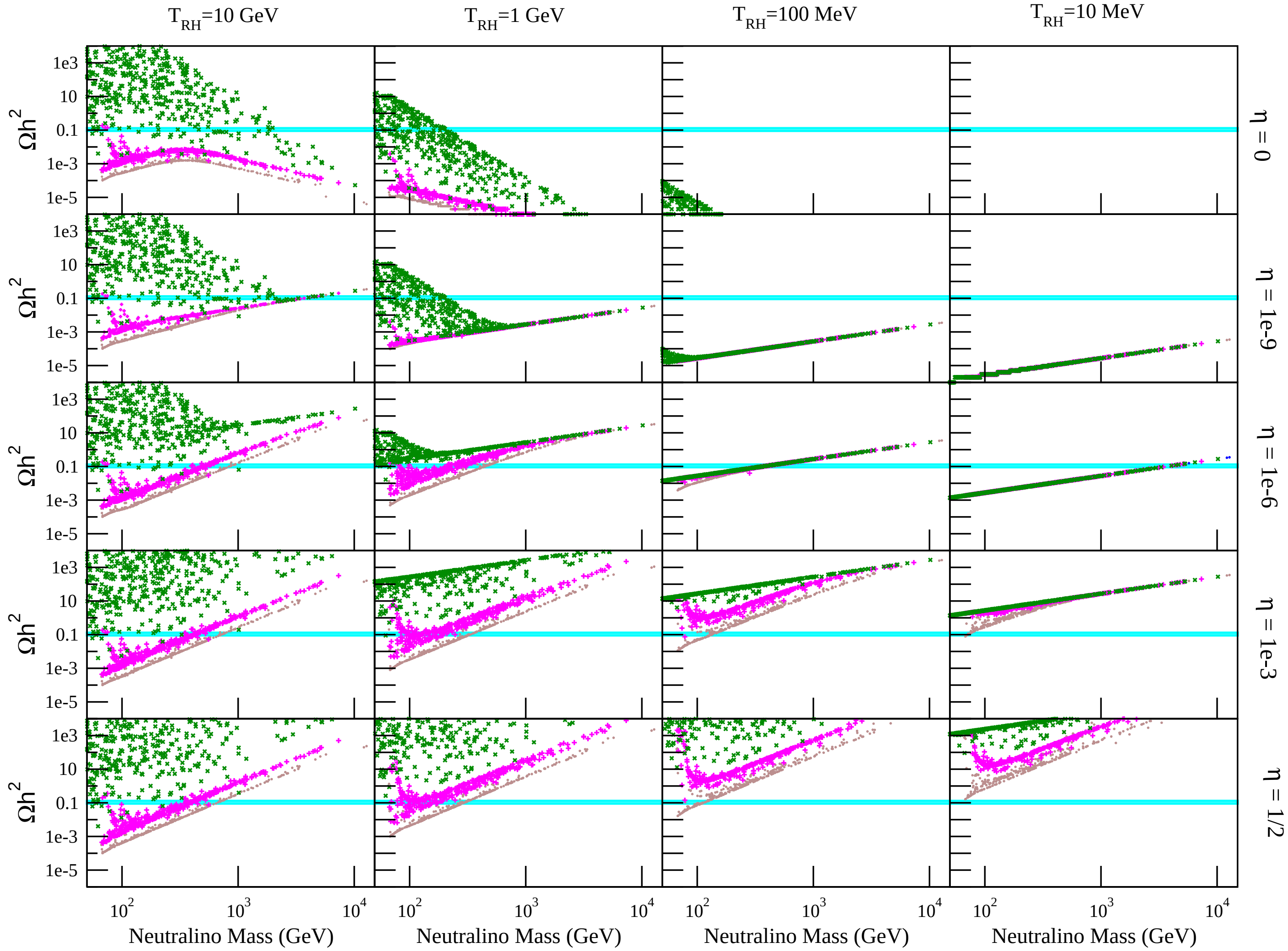
G.G., Gondolo, Soldatenko and Yaguna, 2006

All points can be brought to cross the DM cyan line with suited T_{RH}, η !

bino-like

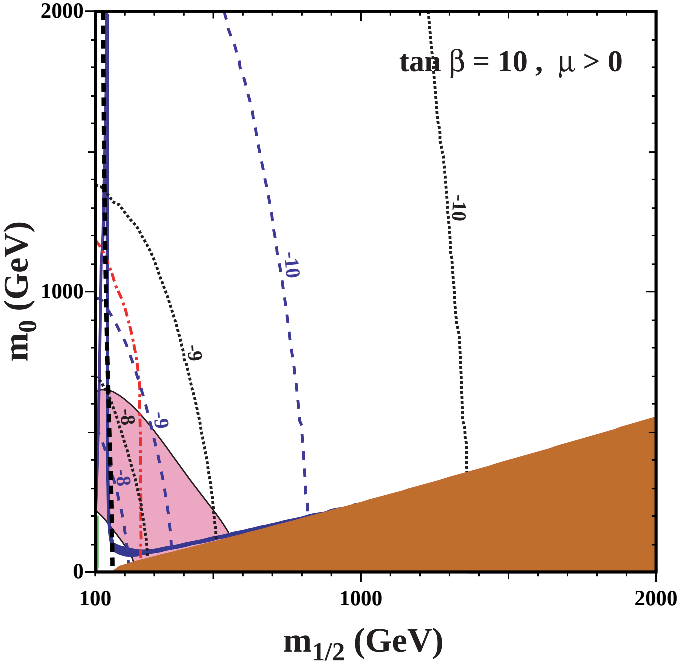
higgsino-like

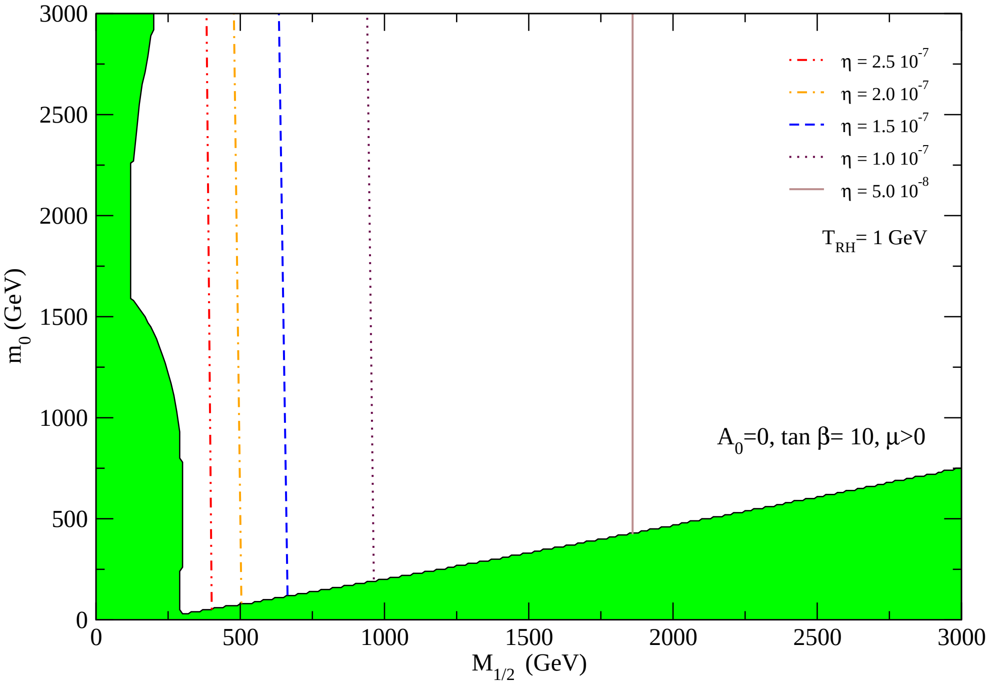
wino-like



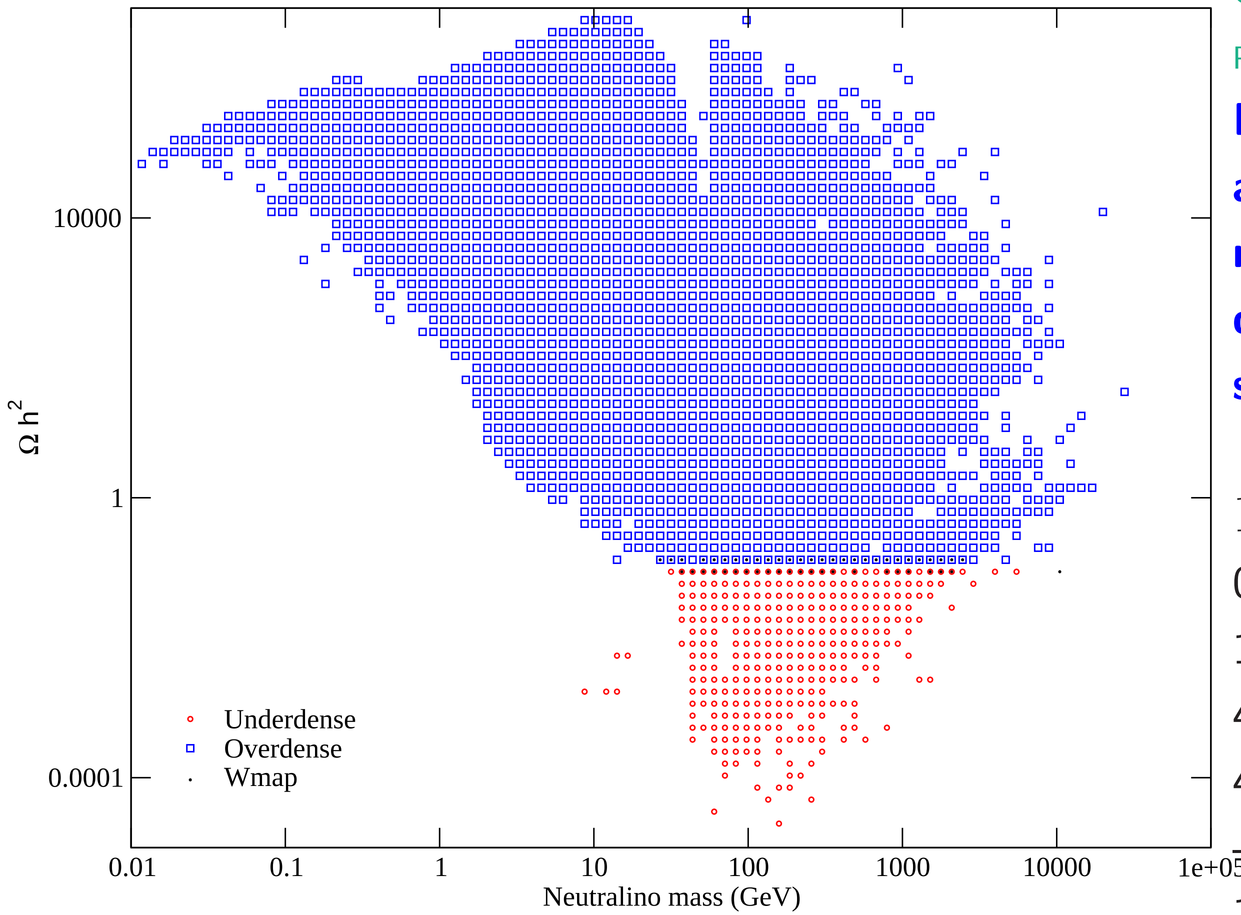
Non-std cosmology at the LHC

The narrow band can be anywhere in the parameter space, if right T_{RH}, η





Standard Ω: forbids blue region of neutralinos allowed otherwise



GG, Gondolo, Soldatenko, Yaguna, PRD76,015010,2007

If most of blue region allowed, many more models to find in direct and indirect DM searches too.

10^5 models with

0.1 GeV< M_1 <50TeV

10GeV< $M_{2,3}$ <50TeV

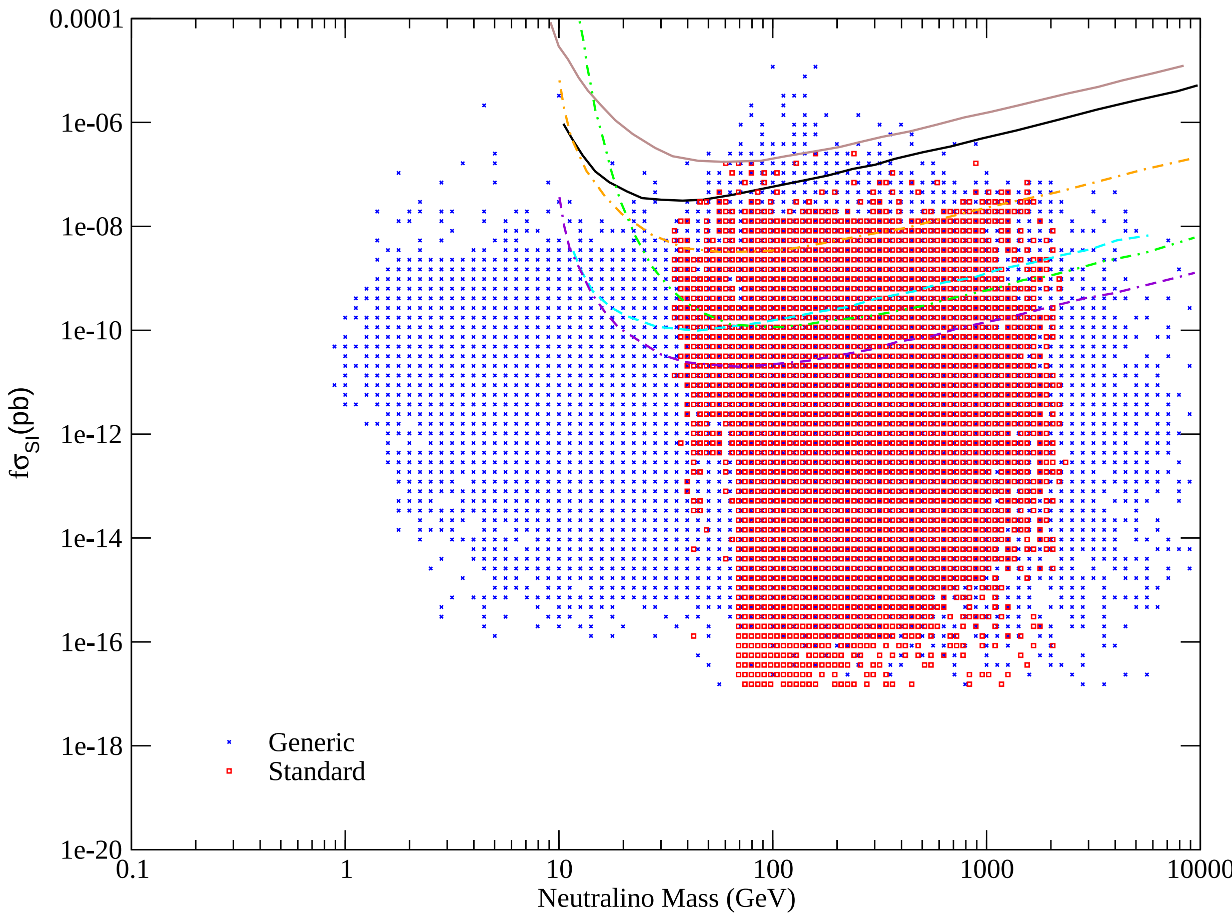
40GeV< $m_{\tilde{q}} m_{\tilde{\ell}}$ <50TeV

40GeV< μ, m_A <50TeV

-3m$_o$ $<A_t, A_b<$ 3m$_0$

1< $\tan\beta$ <60

Direct Detection: Std/Non-Std



GG, Gondolo, Soldatenko, Yaguna, PRD76,015010,2007

Many more light and heavy WIMPs to find in direct DM searches

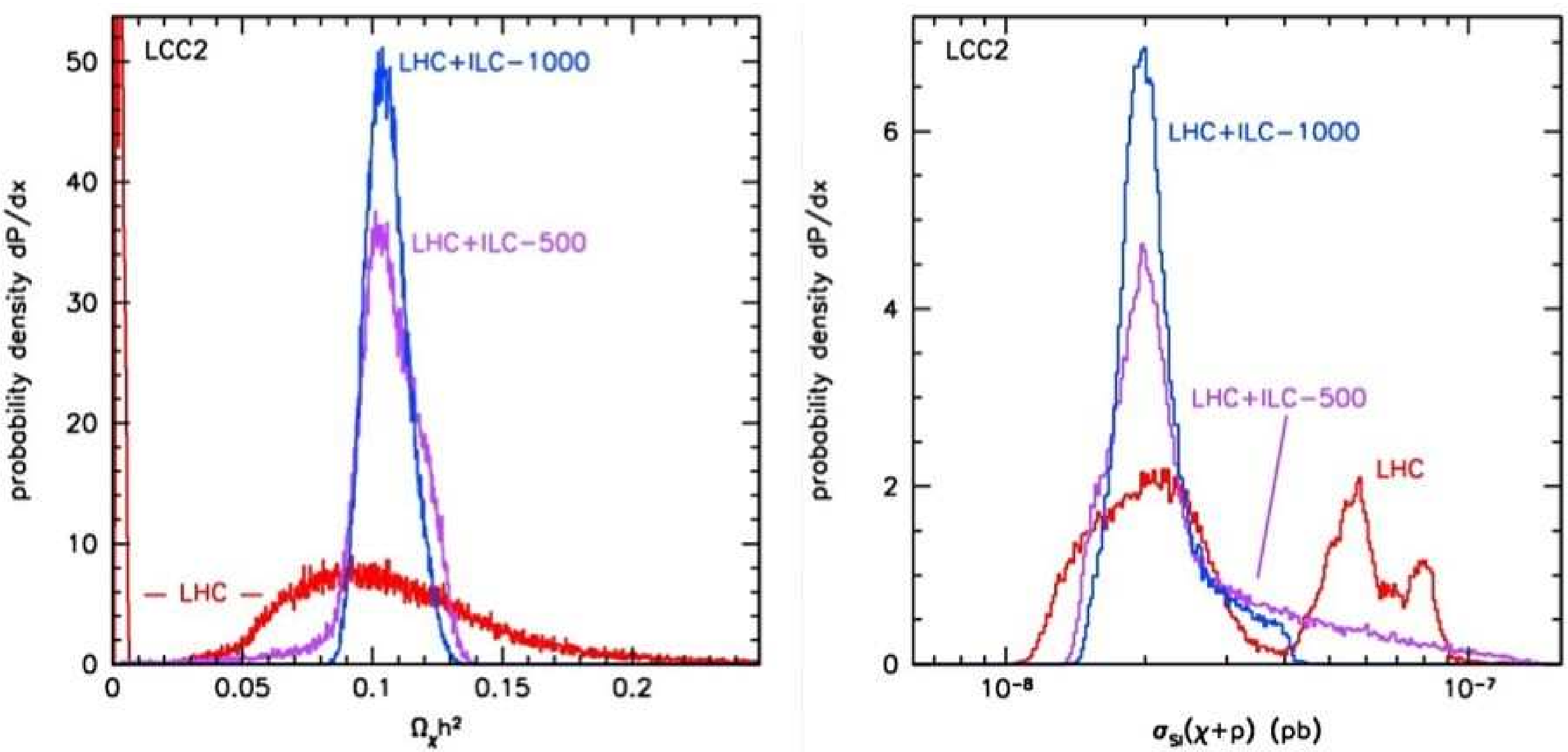
halo fraction

$f = \Omega_\chi / \Omega_{DM}$

$m_\chi < 30$GeV: bino-like

$m_\chi > 2$TeV: all types

Determination of $\Omega_\chi^{\rm std}$ for LCC2 (LCC2-Baltz, Battaglia, Peskin, Wisansky 2006)



$\Omega_\chi^{\rm std}$+ pre-BBN cosm. with the LHC and DM searches

-If $\Omega_\chi^{\rm std} >> \Omega_{DM}$

Two possibilities:1- this is the NLSP (SUSY spectrum could tell)

2- this is the DM (found also in DM searches)

and the pre-BBN cosmology is non standard

-If $\Omega_\chi^{\rm std} << \Omega_{DM}$

Two possibilities:1- this is the LSP and DM has other component(s)

2- this is the DM (found also in DM searches)

and the pre-BBN cosmology is non standard

-If $\Omega_\chi^{\rm std}$ compatible with Ω_{DM}

Two possibilities: 1- this is not the DM (NOT found in DM searches)

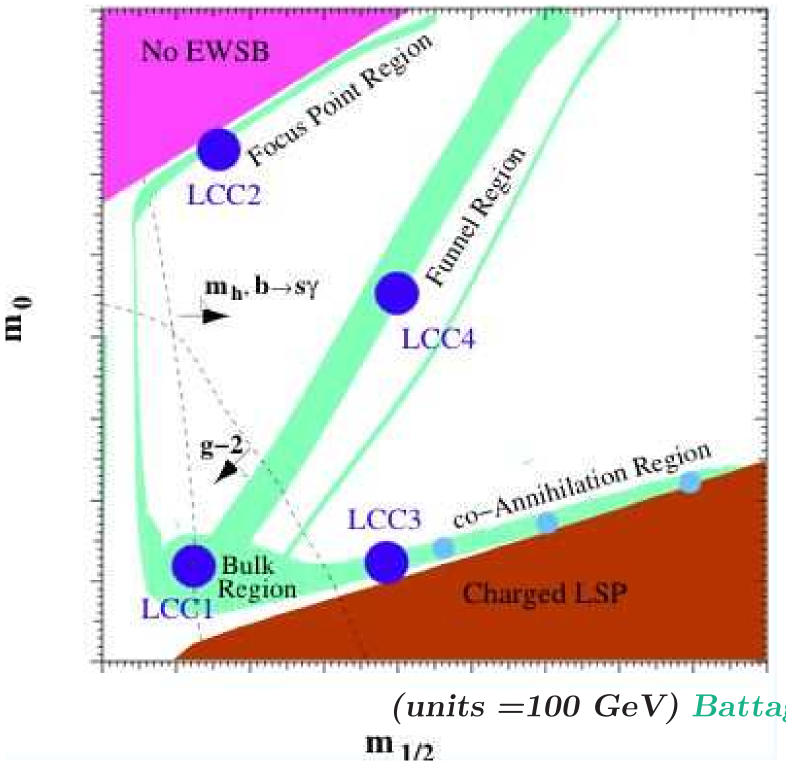
it decays or the pre-BBN cosmology is non standard

2- this is the DM (found also in DM searches)

We still would want to get bounds on the departure of the pre-BBN cosmology from standard! DM is the only remnant from that epoch! (Good argument for the ILC!)

Colliders as DM and pre-BBN cosmology probes

E.g. Chung, Everett, Kong, Matchev "Connecting LHC, ILC, and Quintessence," 07



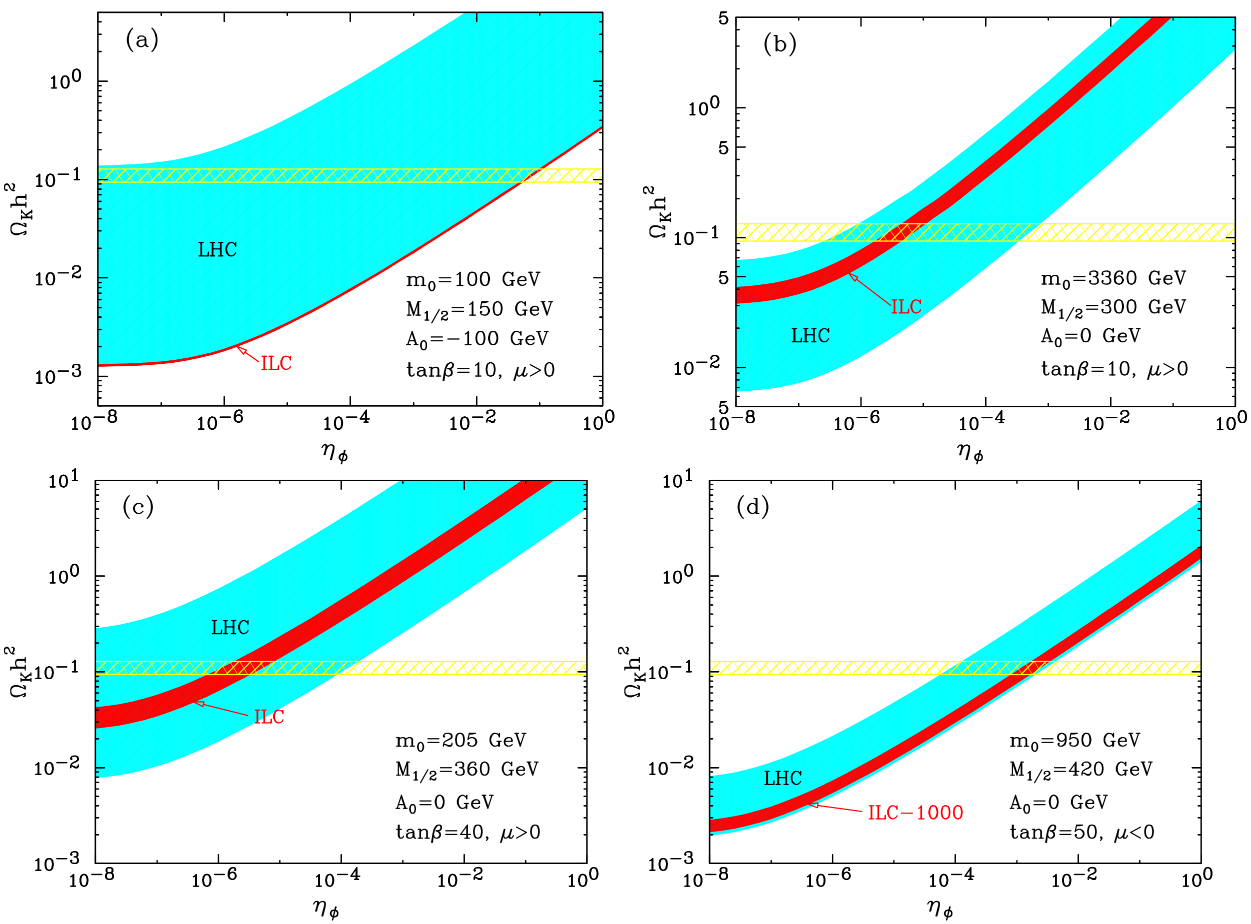
(units =100 GeV) *Battaglia et al*

mSUGRA benchmarks in DM regions: LCC 1, 2, 3, 4
(Linear Collider Cosmo)(White paper on ILC)

Simultaneous determination of
$\Omega_\chi h^2$ and quintessence parameter η_ϕ
at the LHC and the ILC for
LCC1′ 2′ 3′ 4′ study points shifted to
$\Omega^{\rm std} < \Omega_{DM}$ w.r.t unprimed points

Colliders as DM and pre-BBN cosmology probes

E.g. Chung, Everett, Kong, Matchev "Connecting LHC, ILC, and Quintessence," 07



Non-standard. relic velocities:

- **Neutralino Warm Dark Matter** Lin etal 01; Hisano,Kohri,Nojiri 01; GG,Yaguna 06

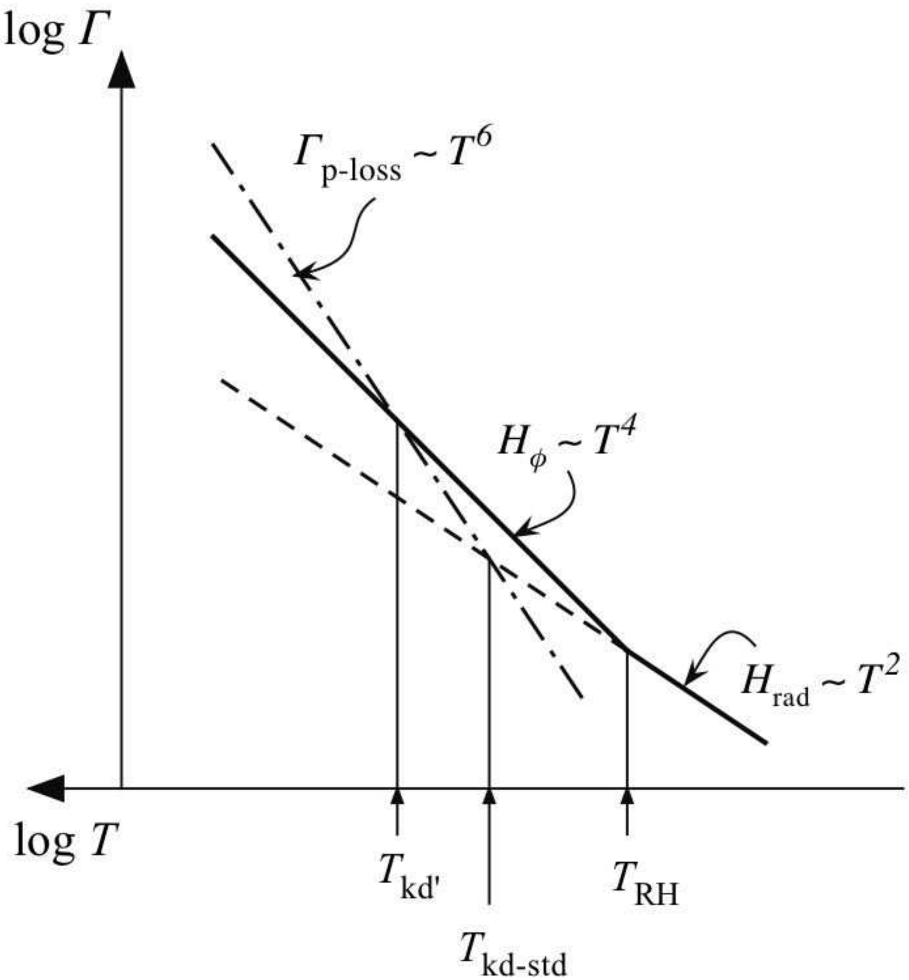
  If the elastic scattering cross section is so small that WIMPs produced in ϕ-decays never interact with the radiation bath: WIMPs are produced hot +late+ do not lose energy in interactions with thermal bath

  Split SUSY ($\mu(m_{\tilde{\nu}}) > 5(20)\mathrm{TeV}$) allow O(100GeV) mass Bino to be warm DM

- **Ultra-Cold WIMPs** GG, Gondolo, 2008

  WIMP relic speed depends on kinetic decoupling: $T_{kd-std} \simeq 10$ MeV - 1 GeV
  which may happen during a non-std cosmological period!
  ($v_{kd} \simeq \sqrt{\frac{T_{kd}}{m}}$ and then redshifts)

Ultra-Cold WIMPs in LTR $T_{RH} < T_{\mathrm{kd-std}}$, Gelmini, Gondolo- 08

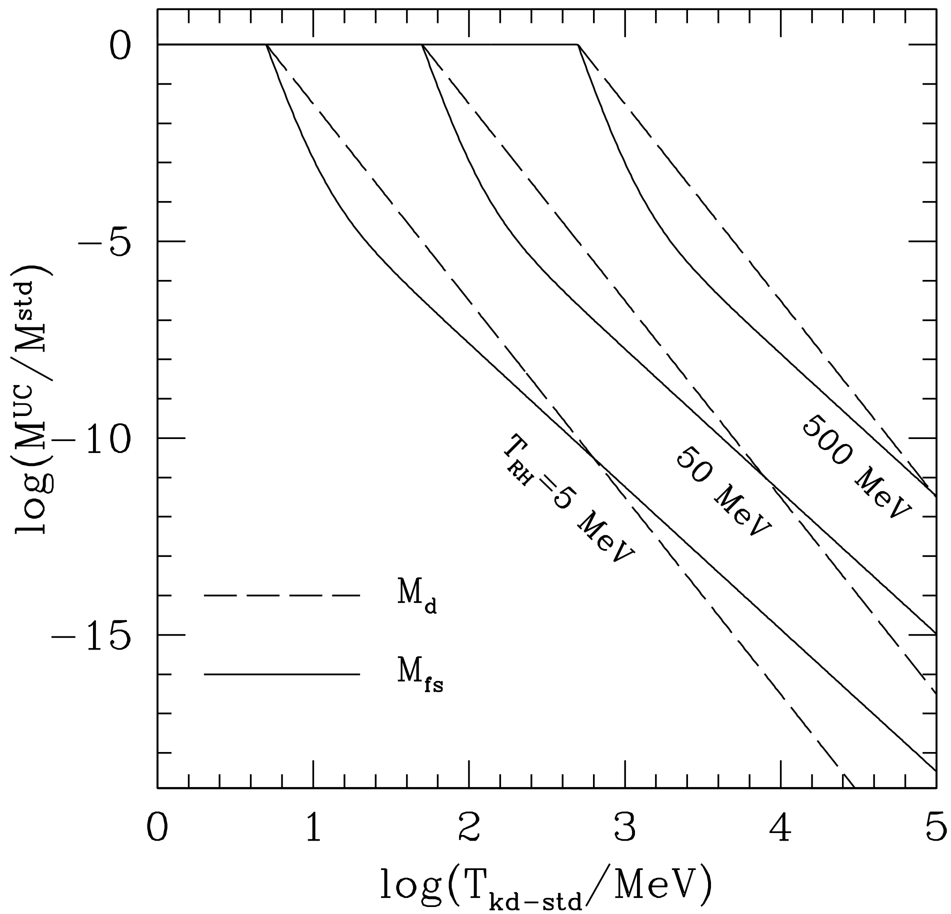


$$H \sim T^4$$

$$\Gamma \equiv \langle v\sigma_{\mathrm{el}}\rangle n_{\mathrm{rad}} \frac{T}{m_\chi}$$
$$\simeq \sigma_0^{\mathrm{el}} T^3 \left(\frac{T}{m_\chi}\right)^{2+l}$$

Horizon size at decoupling and free-streaming length are smaller!

Ultra-Cold WIMPs in LTR $T_{RH} = 5$ MeV$< T_{\rm kd-std}$ Gelmini, Gondolo- 08



M_d, M_{fs} = mass within the horizon and free-streaming volumes respectively

First DM structures formed could be much smaller!

This could only be seen if these persist within galactic halos and enhance WIMP annihilation rates.

Ultra-Cold WIMPs: large annihilation boost factor B?

Gelmini, Gondolo- 08

Oversimplified estimate using "Boost Factor": $B \simeq 0.1[(M/M_d)^{0.13} - 1]$

Strigari, Koushiappas, Bullock, Kaplinghat - 07

For a galaxy with $M \simeq 10^{12} M_\odot$ and with $M_d^{\rm std} \simeq 10^{-6} M_\odot$ to $10^{-12} M_\odot$:

Profumo, Sigurdson, Kamionkowski, 2006

$B^{\rm std} \simeq 20$ to 130 so with UCWIMPs, $B^{\rm UC} \simeq 10 - 100 B^{\rm std}$?

In reality it is not clear if the effect can be observed...

(In kination, effect is smaller $\frac{M_d^{\rm kim}}{M_d^{\rm std}} \simeq \frac{10^{-4}}{\eta_\phi^{5/2}} \left(\frac{100{\rm GeV}}{m_\chi}\right)^{5/4}$)

LRT and the "visible" sterile neutrino

G.G, Palomares-Ruiz, Pascoli, Phys. Rev. Lett. **93**, 081302 (2004); G.G,,Palomares-Ruiz, Pascoli, Osoba 2008

ν_s production through oscillations with active neutrinos has a sharp peak at

$$T_{\rm max} \simeq 130\,{\rm MeV}\left(\frac{m_s}{1\,{\rm keV}}\right)^{1/3} > \text{MeV}$$ (Dodelson, Widrow 1994)

Thus ν_s with $m_s > 10^{-3}$ eV are also relics from the pre-BBN era!

"visible": ν_s which could be found in laboratory experiments: all require large active-sterile mixings. **Standard cosmology rejects them as overabundant.**

A ν_s found in any lab. experiment would point towards a non-standard pre-BBN cosmology.

If $T_{RH} < T_{\rm max}$ production is suppressed.

e.g. for m_s <1 MeV: $n_s \simeq 10\,\sin^2 2\theta \left(\frac{T_{\rm RH}}{5\ {\rm MeV}}\right)^3 n_{\rm active}$

Cosmological bounds eliminated for $m_s < 1$eV and $m_s > 30$MeV

CONCLUSIONS-OPEN QUESTIONS

- DM particles, if ever discovered, will be the earliest relics of the Universe, from a moment from which we have no other data (this is true for sterile neutrinos too). With the LHC (and ILC) we are trying to measure a combination of both **the DM relic density and key parameters of the pre-BBN cosmology** since both aspects are tied up!

- It is essential to combine accelerator "measurements" of the std relic density (and std relic velocity) with DM direct and indirect searches which would tell us the actual relic density (astrophysical indications of the actual characteristic velocity.)

- We should figure out how to discriminate particle physics from pre-BBN cosmology.

- The best possible calculations of the WIMP relic density (and velocities) assuming a std cosmology are necessary to eventually discriminate between std. and non-std pre-BBN models (not to reject E.P. models at this time...i.e. no "dark matter constraint")