Dark Matter Theory 2

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Invisibles School, July 11, 2013

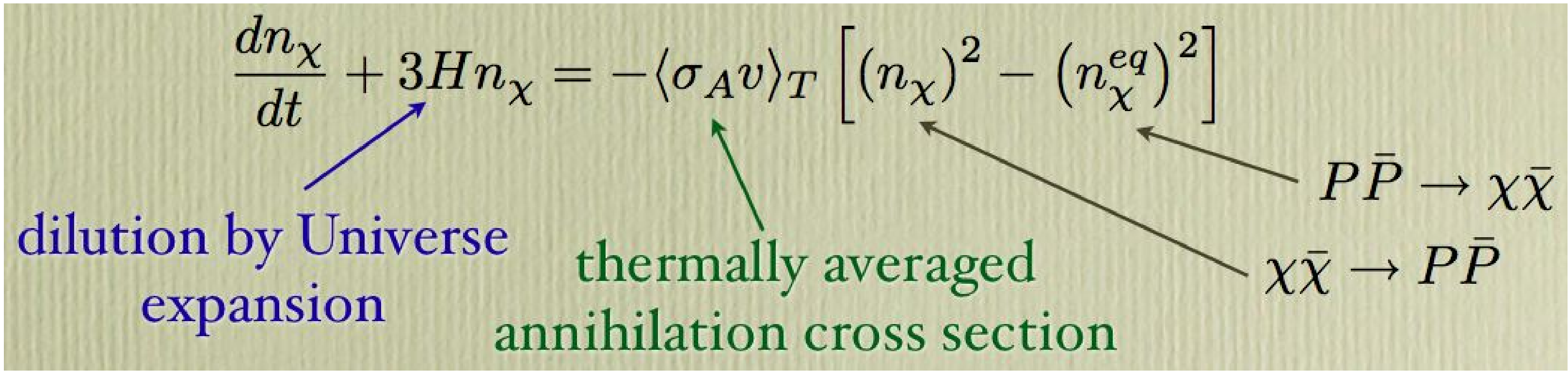
Content of Lecture 2

- Relic density of Non-Relativistic Relics- “Thermal WIMPs”
- Caveats to“Thermal WIMPs”
- Asymmetric DM
- Standard and non-standard pre-BBN cosmological assumptions
- Thermal and Non-Thermal WIMPs
- Paradigm of WIMPs: Supersymmetric candidates
- Sterile Neutrinos

- Axions

Actual calculation involves the Bolzmann Transport Equation:

Assuming no particle-antiparticle asymmetry, i.e. $n_\chi = n_{\bar\chi}$



$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_A v\rangle_T \left[(n_\chi)^2 - \left(n_\chi^{eq}\right)^2 \right]$$

dilution by Universe expansion

thermally averaged annihilation cross section

$P\bar{P} \to \chi\bar{\chi}$

$\chi\bar{\chi} \to P\bar{P}$

expansion: $n \sim a^{-3} \to \frac{dn}{dt} = -3\frac{\dot a}{a} n = -3Hn$

annihilation: $n \sim e^{-t/t_A}$ thus $\frac{dn}{dt} = -n/t_A$, $t_A \simeq \lambda_{M.F.P}/v = 1/\sigma_A n v$

creation: stop expansion at T, wait for equilibrium so $\frac{dn}{dt} = 0$

χ freeze-out when $\Gamma_A(T_{f.o.}) = \langle \sigma_A v \rangle_{T=T_{f.o.}} \, n^{eq}(T_{f.o.}) \simeq H$

Bolzmann Transport Equation and the conservation of entropy

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{ann} v \rangle \left(n^2 - n_{eq}^2\right) \qquad\qquad \frac{ds}{dt} = -3Hs$$

where $s = \frac{2\pi^2}{45} g_{s-eff}(T)\, T^3$ is the entropy density and$T$ the photon temperature

can be combined into a single equation for $Y = n/s$, and use $x = m/T$ (Kolb & Olive Phys Rev D33,1202,1986; Kolb&Turner book, Gelmini&Gondolo 1009.3690 and refs therein)

$$\frac{dY}{dx} = \frac{1}{3H}\frac{ds}{dx}\langle \sigma v \rangle \left(Y^2 - Y_{eq}^2\right)$$

When $g_{s-eff}(T)$ is approximately constant then we get,

$$\frac{x}{Y_{eq}}\frac{dY}{dx} = -\frac{\Gamma_A}{H}\left[\left(\frac{Y^2}{Y_{eq}^2}\right) - 1\right] \qquad\qquad \Gamma_A = n_{eq}\langle \sigma v \rangle$$

Thus when $\Gamma/H << 1$ the number per comoving volume $(Y \simeq n/a^3)$ becomes constant.
(Problem 1.a: cast the Boltzmann eq. in this form, 1.b: assume an asymmetry $Y_\chi - Y_{\bar{\chi}} = A$)

Decoupling of Relativistic Particles $m < T$ (active neutrinos)

Back-of-an-envelope calculation (litterary!) (This is Problem 2)

At decoupling

$$\Gamma \simeq n\sigma c \simeq G_F^2 T_{fo}^5 = H = \sqrt{\frac{8}{3}\pi G\rho} \simeq \frac{T_{fo}^2}{M_{Planck}}$$

putting numbers in, this emplies

$$T_{fo} \simeq MeV$$

Recall, the Fermi constant $G_F \simeq 10–5/$ GeV^2

Gravity const. $G \simeq 1/M_{Planck}^2$, $M_{Planck}^2 \simeq 10^{19}$GeV. RD Universe: $\rho = \rho_{rad} \sim T^4$.

This is when BBN is happening, and we have data on the Universe then.

(Since $n_{EQ} \sim T^3$ the frozen species still tracks the equilibrium density. Just after e^+e^- annihilate, heat-up γ's $T_\nu = (4/11)^{1/3}T$ and $n_{\nu_i} = (3/4)(T_\nu/T)^3 n_\gamma$)

Chemical Decoupling of Non-Relativistic particles $T < m$

Another back of an envelope calculation Until the moment of decoupling or freeze-out the DM is in equilibrium $n = n_{EQ}$

$\Gamma(T_{f.o.}) = \sigma v n_{EQ}(T_{f.o.}) = \sigma v \left(\frac{mT_{f.o.}}{2\pi}\right)^{3/2} e^{-m/T_{f.o.}} = H(T_{f.o.}) \simeq T^2_{f.o.}/M_{Planck}$

Where $e^{-m/T_{f.o.}}$ and $T^2_{f.o.}$ cross is determined by the exp., so

$T_{f.o.} \simeq m$ and thus $n_{EQ}(T_{f.o.}) \sim T^2_{f.o.}/\sigma v \simeq m^2/\sigma v$ (ignoring the exponential).

After decoupling the number density only decreases due to the expansion of the Universe: Volume $\sim a^3 \sim T^{-3}$. Thus, the DM density at $T < T_{f.o.}$

$$\rho = mn(T) = mn_{EQ}(T_{f.o.})\frac{T^3}{T^3_{f.o.}} \simeq \frac{m^3}{\sigma v}\frac{T^3}{m^3} = \frac{T^3}{\sigma v}$$

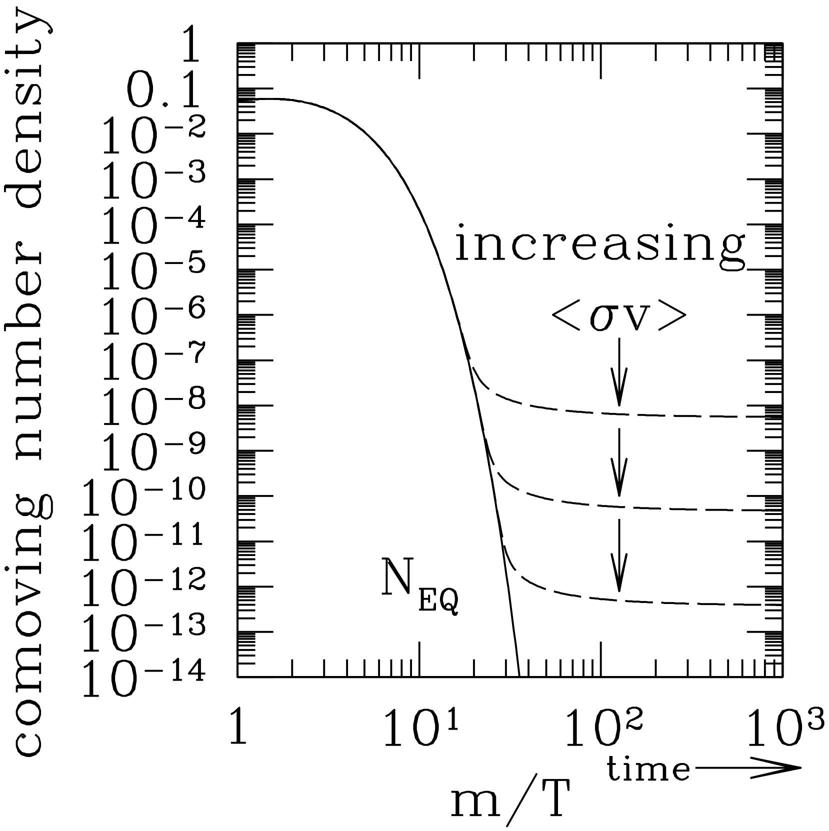
We got the crucial result that the relic density if inversely proportional to the cross section σ (with logarithmic corrections coming form the exponential factor)

"Thermal WIMPs" are Cold Dark Matter

Standard calculations: start at $T > T_{f.o.} \simeq m_\chi/20$ and assume that

- WIMPs reach equilibrium while Universe is radiation dominated
- No particle asymmetry
- Chemical decoupling (freeze-out) when $\Gamma_{ann} = \langle \sigma v \rangle \, n \leq H$,
- No entropy change in matter+radiation

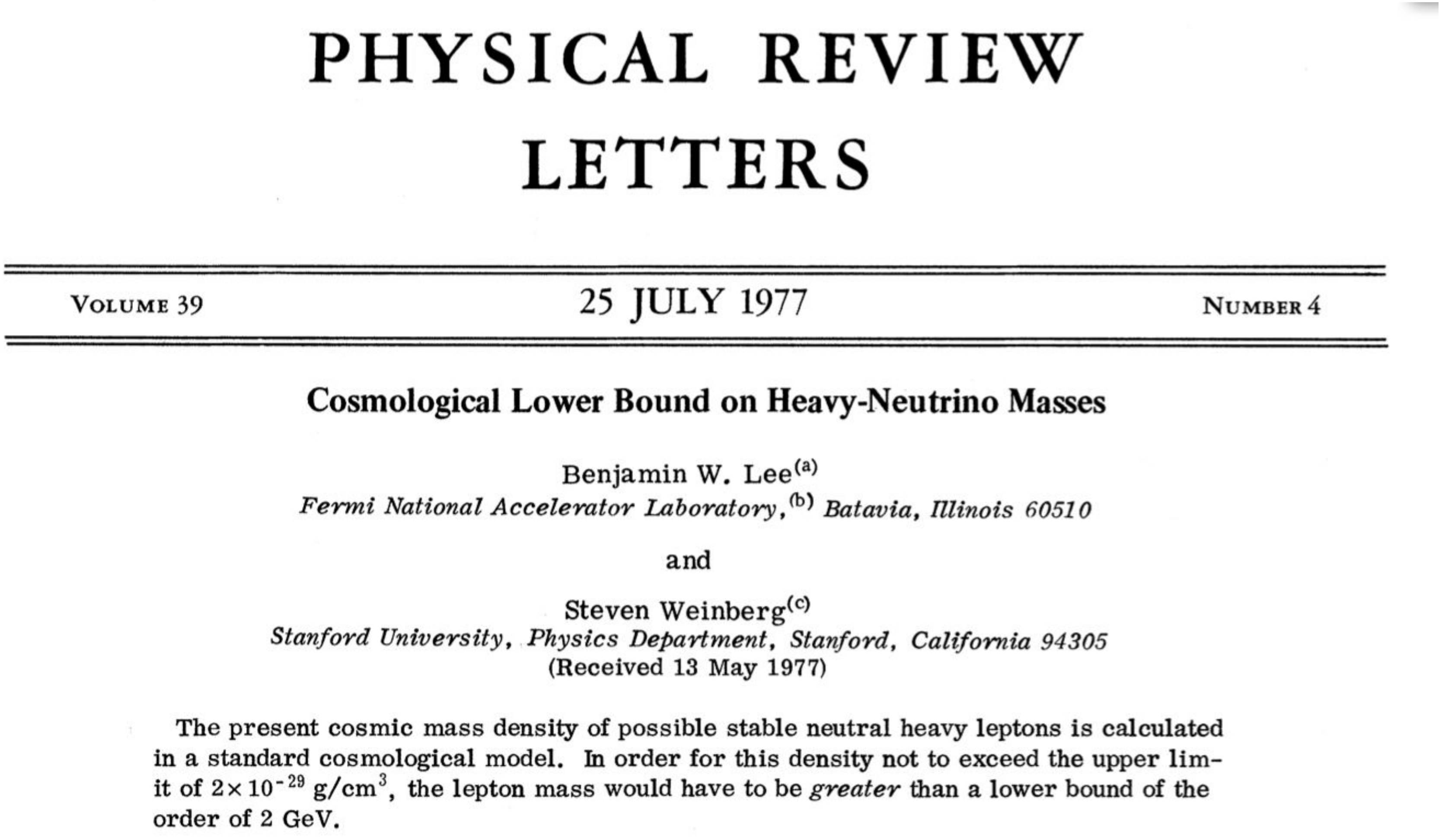
$$\Omega_{std} h^2 \approx 0.2 \, \frac{3 \times 10^{-26} cm^3/s}{\langle \sigma v \rangle}$$



Weak annihilation cross section
$\sigma_{annih} \simeq G_F^2 T^2 \simeq 3 \times 10^{-26} cm^3/s$
is enough to get $\Omega = \Omega_{DM} \simeq 0.2$!
"WIMP Miracle"

(Fermi-LAT limit on "WIMP Miracle" with s-wave scattering (σv independent of v) m>20 GeV)

The original WIMP Notice2 GeV for $\Omega_{DM} = 1$, now 4 GeV for 0.25



PHYSICAL REVIEW
LETTERS

VOLUME 39 25 JULY 1977 NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[(a)]
Fermi National Accelerator Laboratory,[(b)] *Batavia, Illinois 60510*

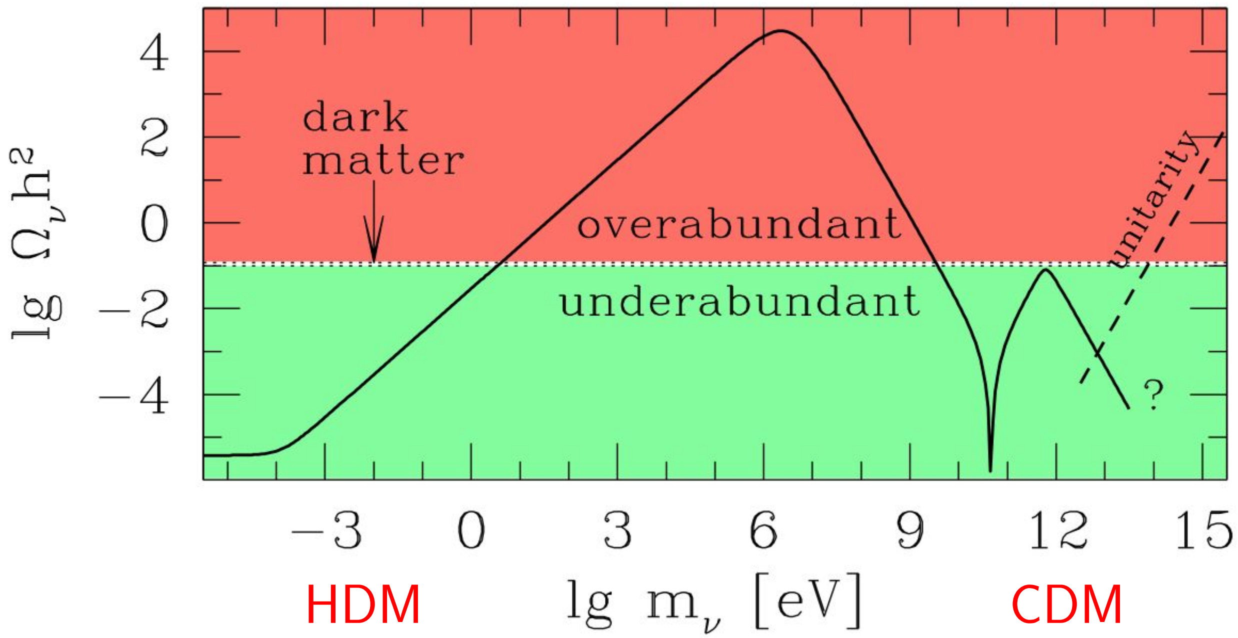
and

Steven Weinberg[(c)]
Stanford University, Physics Department, Stanford, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

The original WIMP Lee and Weinberg 1997 considered active neutrinos- now 4th gen- took Dirac neutrinos, $\chi \neq \bar{\chi}$ but without an asymmetry(Fig from P. Gondolo)



Two solutions, one on each side of the Z-resonance: $\Omega_\chi h^2 \simeq (GeV/m)^2$ and $\Omega_\chi h^2 \simeq (m_\chi/TeV)^2$

(See Problem 3.b and 3.c)

(For active neutrinos, $m < m_Z/2$ forbidden by LEP-but similar for other models)

Chemical Decoupling of Non-Relativistic particles $T < m$

happens for Waek Iteractions at

$$x_{f.o.} = \frac{m}{T_{f.o.}} \simeq 20$$

which is $T_{f.o.} > 4$MeV for $m > 80$ MeV! (For strong interactions $x_{f.o.} \simeq 45$)

Kinetic decoupling: happens after chemical decoupling:

the fraction of WIMP E lost per collision is small (T/M) thus

$$\Gamma_{E-loss} \simeq n\sigma_{scatt}(T/M) < \Gamma_{scatt}$$

$$T_{k.d.} \simeq 15\ MeV(m/100GeV)^{1/4} << T_{f.o.} \simeq 5\ GeV(m/100GeV)$$

Caveats to Thermal WIMPs as Dark Matter

- Asymmetric DM Only particles remain (no antiparticles). We owe our very existence to a particle-antiparticle asymmetry so why not also the DM? (Requires non-self conjugated DM candidates- neutralinos are Majorana particles instead) (Nussinov 85; Gelmini, Hall, Lin 87; Kaplan 92; Barr, Chivukula, Fahri 90; Enkvist, MacDonald 98; Gudnason, Kouvaris , Sannino 05; Kaplan, Luty, Zurek 09; Cohen et al 10; Frandsen, Sarkar, Sannino 10; Cheung, Zurek 11; Del Nobile, Kouvaris, Sannino 11....among others)
- Non-Standard Pre Big-Bang Nucleosynthesis (pre-BBN) cosmology
  BBN, at T$\simeq$ MeV, is the earliest episode in the Universe from which we have data. WIMP relic abundance is fixed at $T_{f.o.} \simeq m_\chi/20$, before BBN. If the standard pre BBN assumptions do not hold (i.e. in low reheating temperature models) relation between σ_{annih} and density can be very different.
- WIMPs can be produced in decays of other particles (Sigurdson, Kamionkowski 04; Kaplinghat 05)
- WIMPs may be unstable and decay into the present DM (Super-WIMP scenario) (Feng, Rayaraman, Takayama 03; Feng, Smith 04)

If DM is Warm, WIMP CDM could be a subdominant DM component or be created in decay and be WDM, but models very different from usual

Asymmetric DM (ADM) Idea almost as old as the "WIMP miracle"

For Baryons: if usual decoupling, $\sigma_{strong} \sim 1/m_\pi^2$ emplies $T_{f.o.} \simeq m_N/45$ (but eq. for Ω is very similar- it depends logarithmically on x=20 or x=45).

Predicted: $\Omega_B \simeq 10^{-10}$ and equal numbers of baryons and antibaryons (See Problem 3.a)

Observed: $\Omega_B \simeq 0.05$ and only baryons. Thus an early Baryon Asymmetry must exist

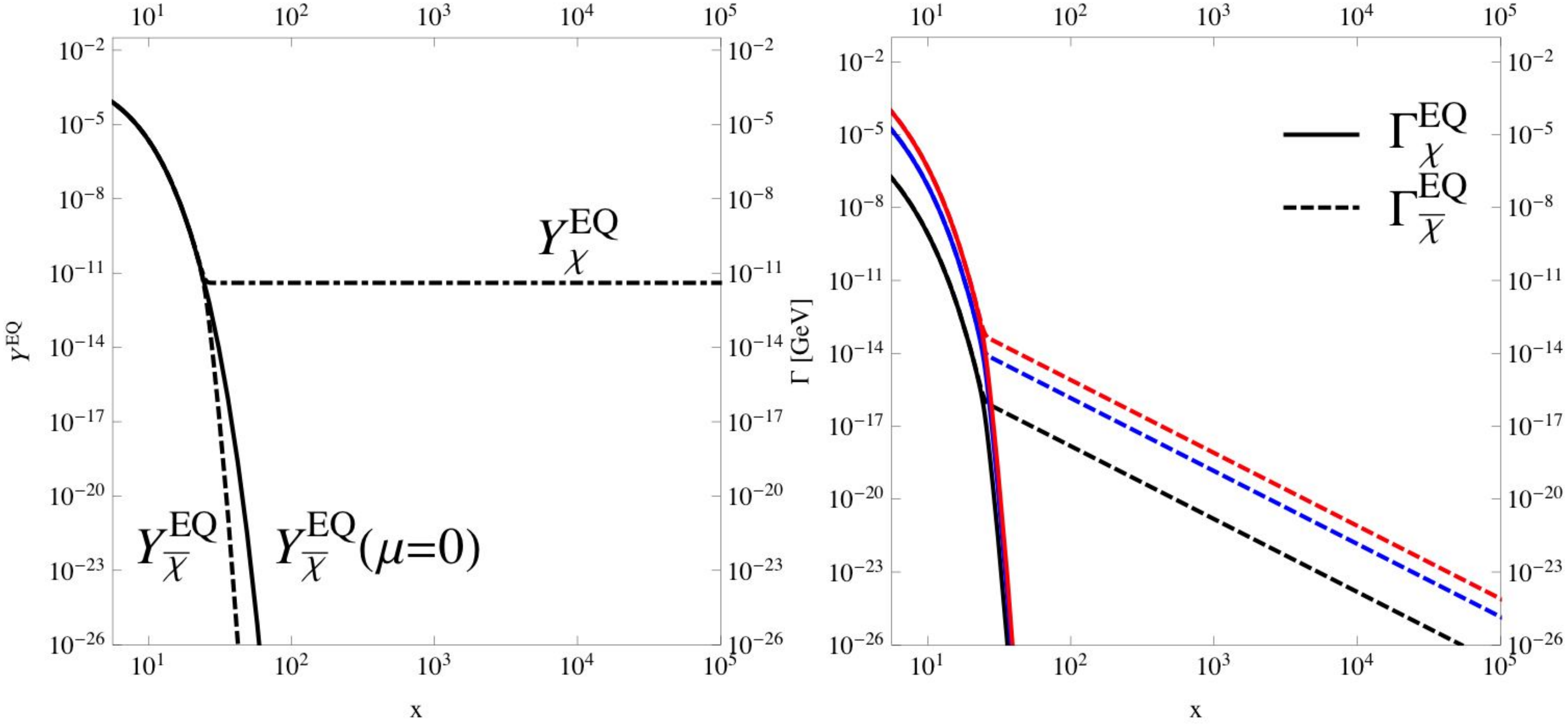
$A_B = n_B - n_{\bar{B}}/n_\gamma \simeq 10^{-9}$, and annihilation ceases when no $\bar{B}$ left.

For Dark Matter particles: assume A_{DM} and A_B generated by similar physics,

1985: Nussinov, if technibaryon and baryons have same number density then $\Omega_{DM}/\Omega_B = m_{TB}/1$ GeV (with $\Omega_{DM} \simeq 1$, $m_{TB} \simeq 100$GeV!)

1986: Gelmini, Hall and Lin, proposed model a for "cosmions" ($m_C = 5$ to 10 GeV) with $B - C$ number conserved and the same asymmetry is produced for both (when "cosmions" were abandoned to explain the solar-neutrino problem this paper was largely forgotten!- also we could account "only" for $\Omega_{DM} \simeq 0.2$)

Asymmetric DM relic density with majority χ and minority $\bar{\chi}$ components



If $Y - \bar{Y} = A$, when Y_{χ}^{EQ} becomes A, $\Gamma_{\bar{\chi}}^{EQ} \sim n_{\chi}^{EQ} \sim A/T^{3}$ while $n_{\bar{\chi}}^{EQ} \sim \Gamma_{\chi}^{EQ}$ decreases exponentially small until $\bar{\chi}$ freezes-out, when $\Gamma_{\bar{\chi}}^{EQ} \simeq H$. Γ_{χ}^{EQ} for $\langle \sigma_{\chi\bar{\chi}} v \rangle$, 9.5×10^{-9}GeV^{-2}, 9.0×10^{-7}GeV^{-2} and 5.0×10^{-6}GeV^{-2} (lower, middle, and higher) (Gelmini, Huh, Rehagen 1304.3697

Asymmetric DM (ADM) Idea almost as old as the “WIMP miracle”

assume A_{DM} and A_B generated by similar physics,

$A_{DM} \simeq A_B$ so $n_{DM} \simeq n_B$

$$\frac{\Omega_{DM}}{\Omega_B} \simeq \frac{n_{DM} m_{DM}}{n_B m_N} \simeq \frac{m_{DM}}{m_N}$$

$\Omega_{DM}/\Omega_B \simeq 5$ if $m_{DM} \simeq 5$ GeV. So ADM explains why $\Omega_{DM}/\Omega_B \simeq 5$

GeV scale ADM in hidden/mirror sector, or pNGB in Technicolor or low scale strong interactions....
Also possible TeV scale ADM in Technicolor: $A_{DM} \simeq A_B \exp\left(-m_{DM}/T_{weak}\right)$

(Nussinov 85; Gelmini, Hall, Lin 87; Barr, Chivukula, Fahri 90; Barr, 1991; Kaplan 92; Enkvist, MacDonald 98; Dodelson, Greene and Widrow, 1992; Fujii and Yanagida, 2002); Kitano and Low, 2005; Gudnason, Kouvaris , Sannino 05; Kitano, Murayama and Ratz, 2008; Kaplan, Luty, Zurek 09 [which now has 180 citations]; Cohen et al 10; Frandsen, Sarkar, Sannino 10; Cheung, Zurek 11; Del Nobile, Kouvaris, Sannino 11....among others)

Main characteristic: no annihilation rate after freeze-out.
But this is a pre-BBN cosmology dependent statement Gelmini, Huh, Rehagen 1304.3697

Problem to Compute DM Relic Densities

Big Bang Nucleosynthesis takes place when $T \simeq$ 1MeV and is the earliest epoch in the Universe from which we have data, the relic abundance of light nuclei.

DM candidates (and all sterile neutrinos too) are relics from before BBN. To compute relic abundances we must make assumptions about this epoch.

Standard pre-BBN era assumptions :

- T_{RH} is large,
  (T_{RH} is the highest temperature of the radiation dominated epoch of the Universe in which BBN occurs)

- particles of interest reach equilibrium before decoupling

- the entropy of matter and radiation is conserved, during/after decoupling.

Before BBN?

INFLATION?

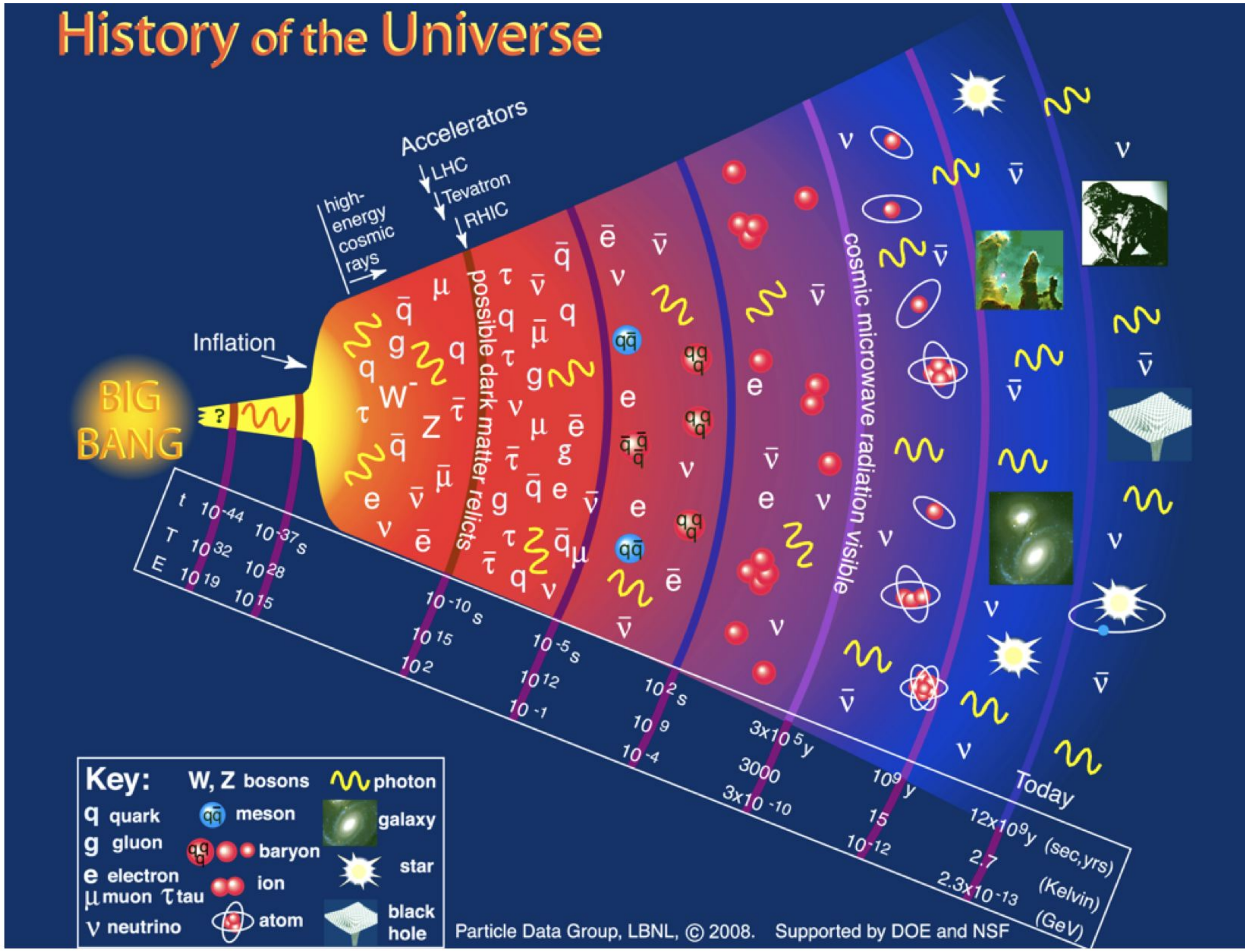
period of exponential expansion $a \sim e^{Ht}$

After "reheating", finishes in a Radiation Dominated Universe with temperature

$$T_{RH}$$

expanding adiabatically

$$a \sim 1/T \sim t^{1/2}$$



Particle Data Group, LBNL, © 2008. Supported by DOE and NSF.

INFLATION? could explain properties of the Universe not explained by the Big-Bang model such as

- Homogeneity and isotropy: why parts of the Universe at distances larger than ct$_U$, never in physical contact otherwise, are very similar.
- The origin of the inhomogeneities observed in CMB (as quantum fluctuations).

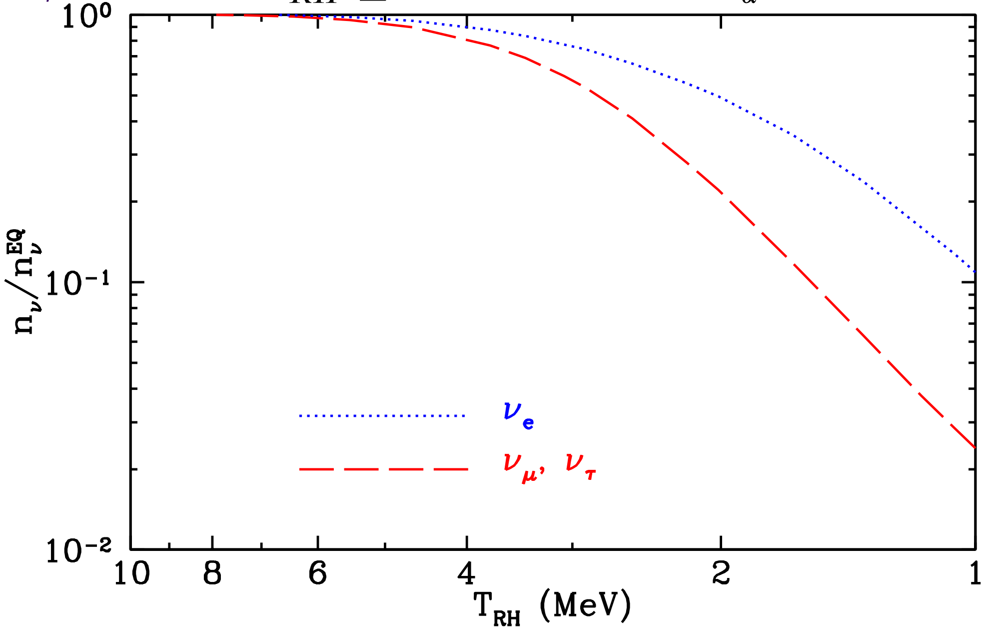
Not possible to determine which is T_{RH} if before BBN!

QCD allows us to compute what would be the content of the Universe at $T > 100$ MeV (this was not clear in the 70's- see the famous "The first three minutes" by Steve Weinberg) and 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 small T_{RH} can be? > BBN temperature:

- Giudice et al., 2000: For $T_{RH} \geq$ 5MeV number of ν_α within 10% of standard.



- Kawasaki, Kohri, Sugiyama, 2000 $T_{RH} > 0.7$ MeV (BBN)
- Ichikawai, Kawasaki, Tkahashi, 2005 $T_{RH} > 2$ MeV (with oscillations, BBN)
- Hannestad, 2004 $T_{RH} \geq 4$ MeV (BBN, CMB, LLS)
- De Bernardis, Pagano, Melchiorri 2008 $T_{RH} \geq 3.2$ MeV (95%CL, WMAP5, SDSS, H(z))

How to get non-std DM relic abundance

- **Increase** the density by increasing the expansion rate at freese-out [e.g. quintessence-scalar-tensor models] or by creating DM 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].

Non-std scenarios are more complicated (baryon number generation, for example). They contain additional parameters that can be adjusted to modify the DM relic density. However these are due to physics at a high energy 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

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

"LTR": Low T_{RH}

.

"K": kination

.

"ST1": scalar tensor with H increase

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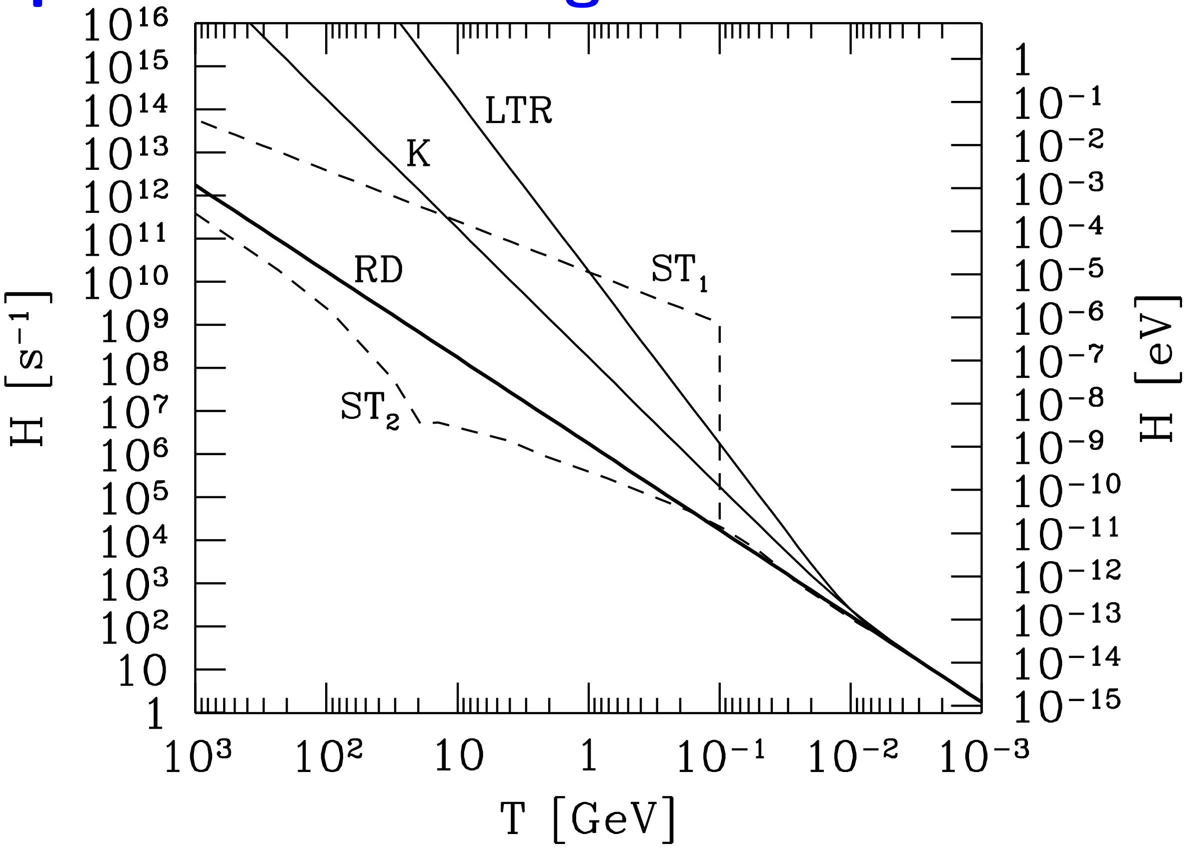
"RD": radiation-dom.

.

"ST2" : scalar tensor with H decrease



Low Reheating Temperature- Late decaying scalar field φ

Moduli fields: pervasive in SUSY models, $m_\varphi =$ O(10-100) TeV - gravitational strength couplings, but could be an inflation....thus,

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

- 4 MeV $< T_{RH} < T_{f.o.}$: thermal production suppressed
- φ-decays produce entropy, which dilutes the neutralino abundance
- φ can decay into DM 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} and $\eta \sim b/m_\varphi$

Standard

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

$$\frac{ds}{dt} = -3Hs\,. \tag{2}$$

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

$$\frac{d\rho_\varphi}{dt} = -3H\rho_\varphi - \Gamma_\varphi\rho_\varphi \tag{3}$$

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

$$\frac{ds}{dt} = -3Hs + \frac{\Gamma_\varphi\rho_\varphi}{T} \tag{5}$$

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

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

- $T > T_{RH}$ **oscillating φ domination:** $H \simeq \rho_\varphi^{1/2}/M_P \propto T^4$ (McDonald 1991)

  [use $\dot\rho = -3H(\rho + p) + \Gamma_\varphi \rho_\varphi$ 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

  $\rho_\varphi \simeq T^8/T_{RH}^4$ *and* $\rho_\varphi a^3 = const$ *so* $T \propto a^{-3/8}$ and $H \propto a^{-3/2}$ (as in matter domination) (see e.g. Giudice, Kolb, Riotto, 2001)

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

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

Late decaying scalar scenario

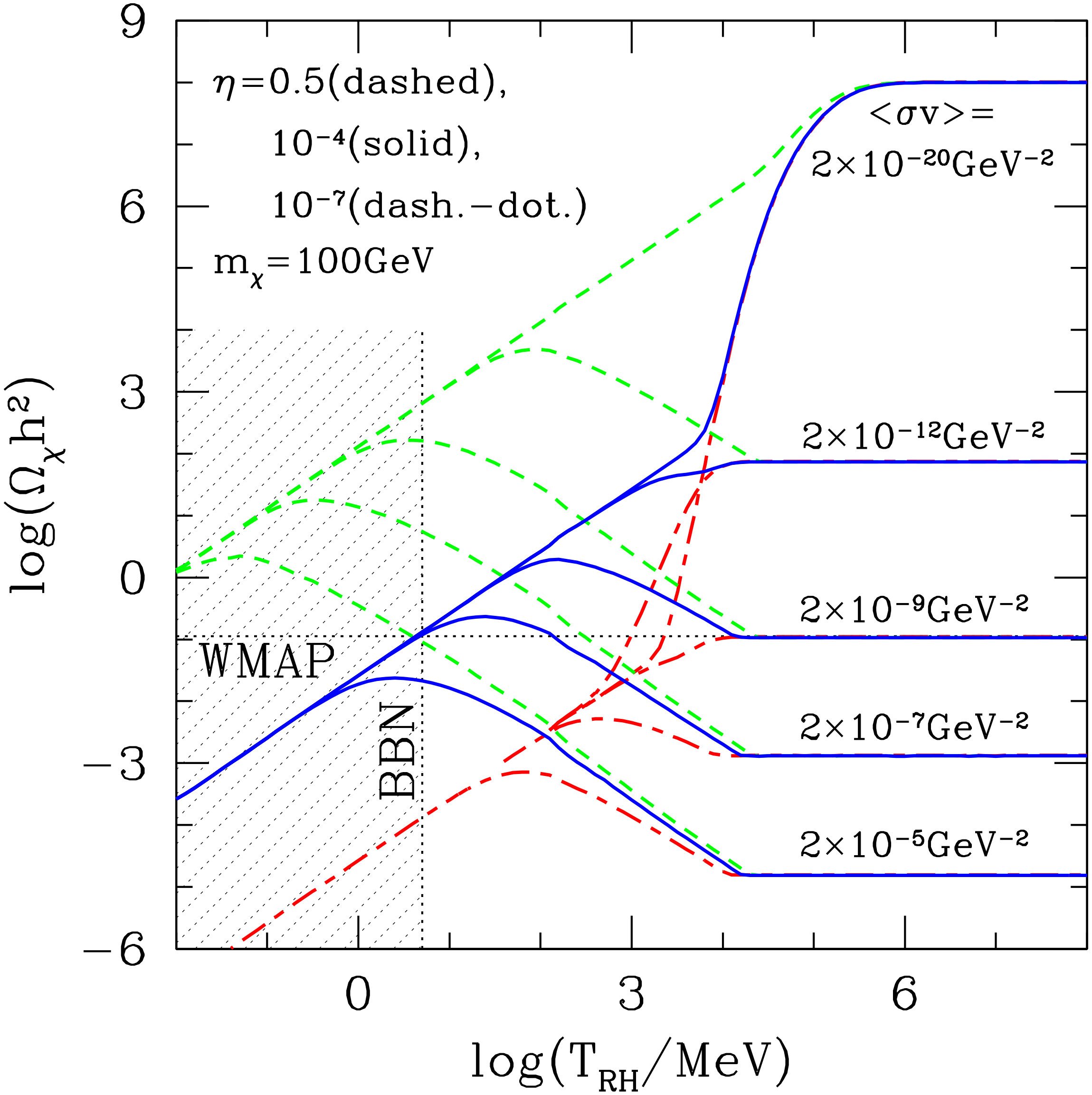
G.G. and Gondolo, 06

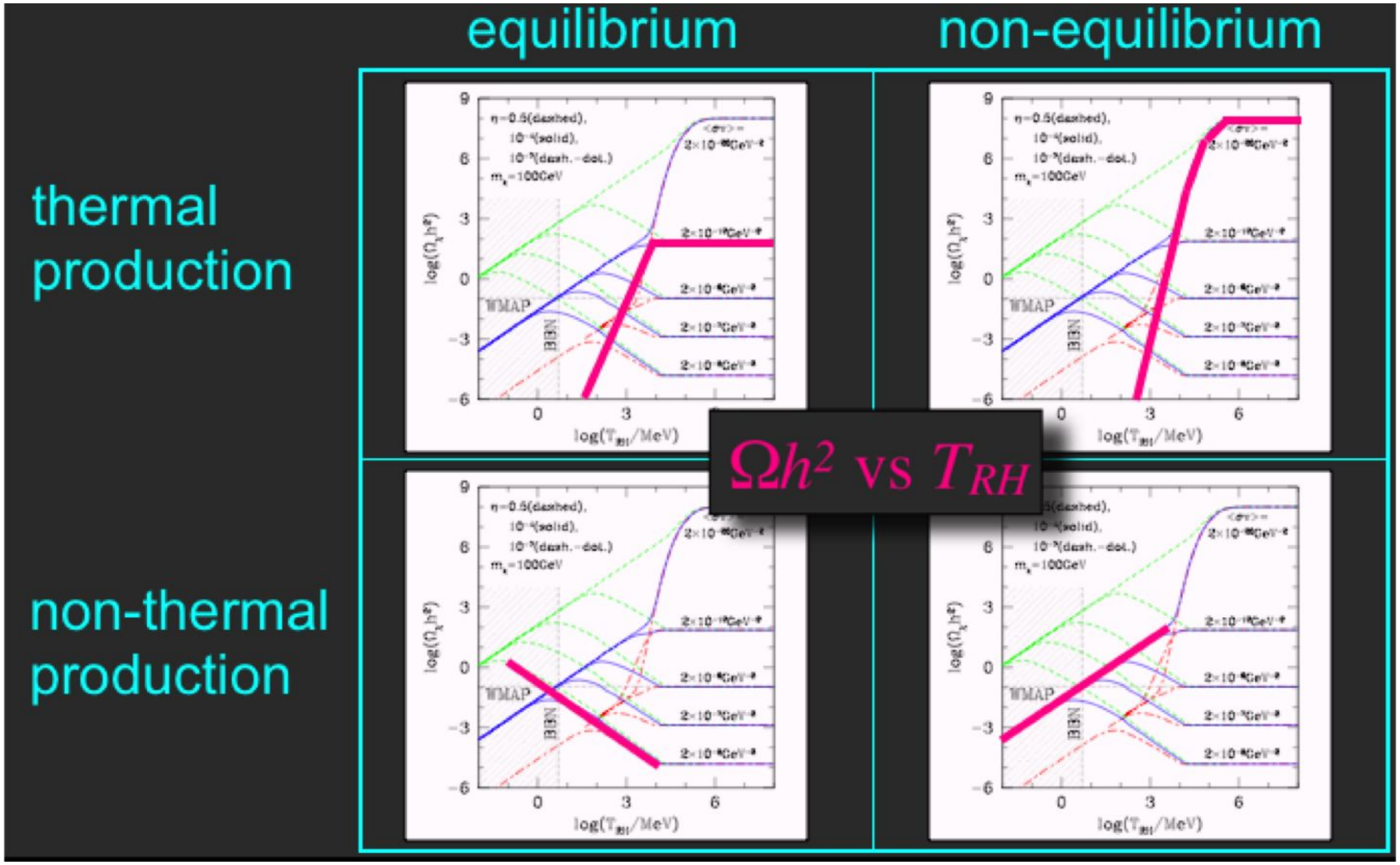
Two additional parameters:

T_{RH} and

$\eta = b\ \frac{100TeV}{m_{\varphi}}$

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





equilibrium | non-equilibrium

thermal production

non-thermal production

Ωh^2 vs T_{RH}

In the following we are going to discuss DM models and how they could be affected by a non-standard pre-BBN cosmology

Example: Supersymmetry (SUSY) Most studied model

- Symmetry between bosons and fermions.
- Models are completely calculable
- Hierarchy: maintains EW scale $\ll$ GUT scale (not so well now. . .)
- Requires two Higgs doublets minimum.
- Every known particle has supersymmetric partner(s)

Fermions:	**Bosons:**
SM fermions: ℓ, q	sfermions: $\widetilde{\ell}$, $\tilde{q}$
gauginos: $\widetilde{B}, \widetilde{W}, \tilde{g}$	SM gauge bosons: B, W, g
Gravitinos: $\widetilde{G}$	graviton
higssinos: $\widetilde{H}$	Higgs bosons

- R-parity= $(-1)^{3B+L+2S}$ is $P_{SM} = +1$, $P_{SUSY} = -1$
  Thus the Lightest SUSY Particle (LSP) is stable, thus a good WIMP DM candidate if neutral and colorless: neutralinos, sneutrinos, gravitinos...

MSSM

- If R-parity is conserved, the Lightest Supersymmetric Partner (LSP) is stable, thus a good WIMP dark matter candidate (if neutral):
  – $\tilde{\nu}$ sneutrino, $\widetilde{G}$ Gravitino (partner of graviton), $\tilde{a}$ axino (partner of the axion) or
  $\widetilde{\chi}^0$ neutralino (gaugino/ higgssino, partner of neutral gauge boson/Higgs boson)

- In most models the LSP is the lightest neutralino. In the basis $\widetilde{B}, \widetilde{W}_3, \widetilde{H}_1^0, \widetilde{H}_2^0$ the mass matrix is

$$\begin{bmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{bmatrix}$$

$\tan\beta = v_2/v_1$, M_1 : Bino mass, M_2 : Wino$_3$ mass, μ : mixes H_1 H_2

- One stage unification of fundamental forces: $M_2 = 2M_1$,
  if $M_1 < |\mu|$, LSP$=$ $\widetilde{B}$ typical cMSSM, if $M_1 \simeq |\mu|$, LSP $=$ mixed $\widetilde{B}$-$\widetilde{H}$ OK

“SuperWIMP” SUSY scenario (Feng, Rajaraman, Takayama 2003)

NLSP sleptons with weak annihilation cross section get close to the DM density...

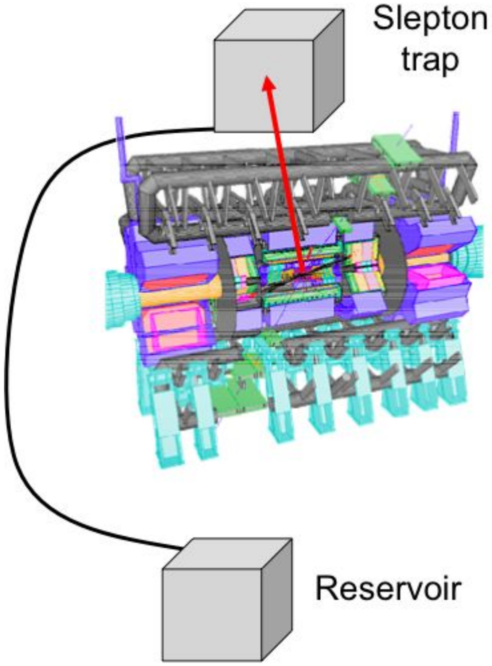
After one month decay into gravitinos $\widetilde{G}$ LSP! which inherit the right density (although interact only gravitationally, the DM is not a WIMP)

LSP can be WDM: it is produced late, hot and does not interact after(Cembranos et al 2006)

DM searches: NO HOPE
(couplings suppressed by 10^{-16})

In accelerators, NLSP could be trapped in kton water tanks and observed decay

(Feng, Smith 04, Hamaguchi et al. 04, Ellis et al 2005)



Many versions of SUSY- Many parameters

MSSM

- Minimum number of particles (SUSY partners+ two Higgs doublets)
- Number of parameters: 18 of the SM + 106!!!
- Parameter reduction:

  - p(phenomenological) MSSM with 19 free parameters

  – wMSSM: simplified weak-scale MSSM: 18 + 7 p.

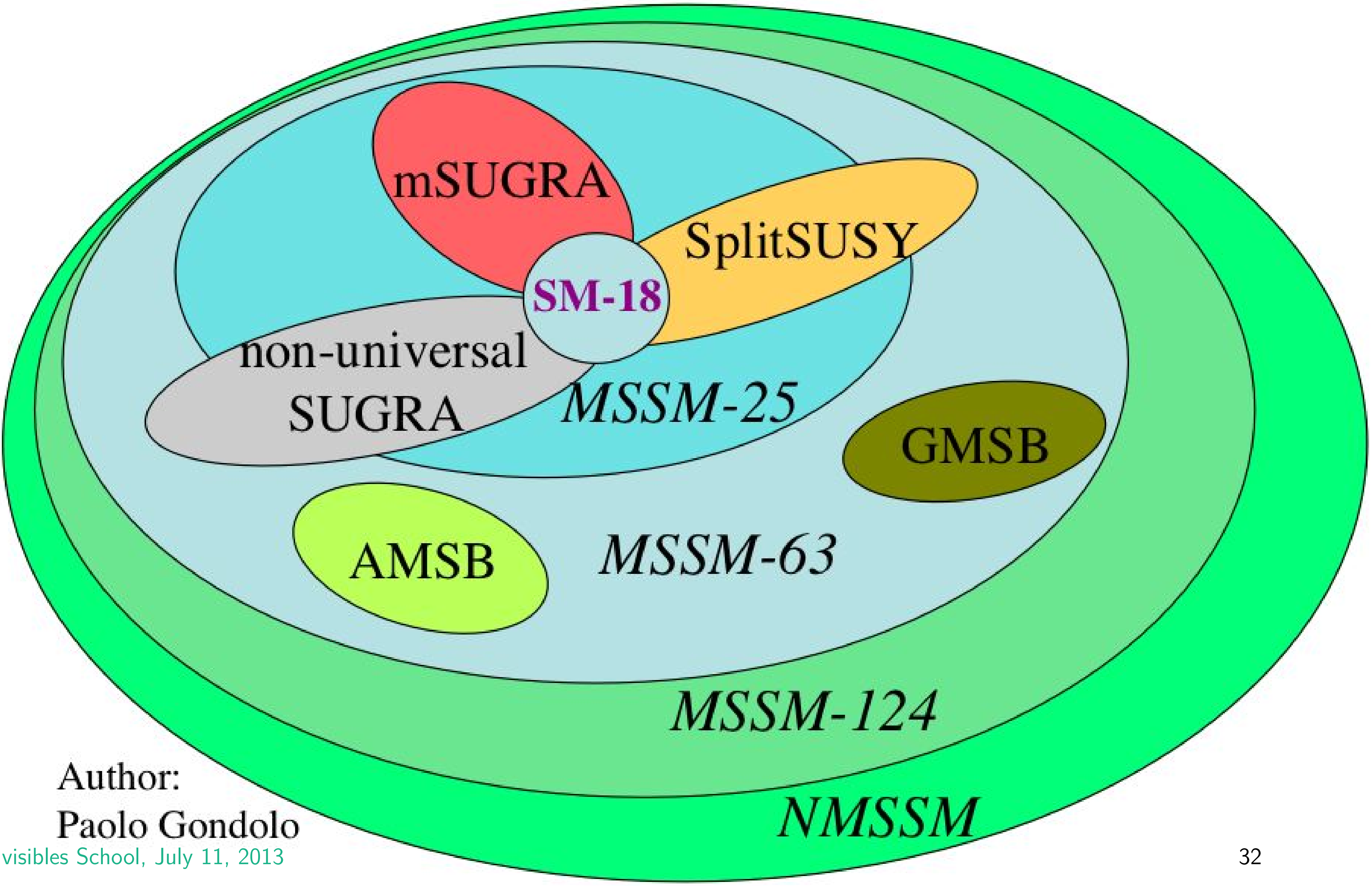
  $(M_2, \mu, \tan\beta, m_A, \widetilde{m}, A_b, A_t)$

  – CMSSM: constrained MSSM: 18+5 parameters $(m_0, A_0, m_{1/2}, \tan\beta, \mu)$

  – mSUGRA: minimal supergravity: 18+5 parameters $(m_0, A_0, m_{1/2}, \tan\beta, sign\ of\ \mu)$

NMSSM

- Non Minimum number of particles (extra singlet Higgs, etc)


mSUGRA
SplitSUSY
SM-18
non-universal
SUGRA
MSSM-25
GMSB
AMSB
MSSM-63
MSSM-124
NMSSM
Author:
Paolo Gondolo

Neutralino LSP relic abundance

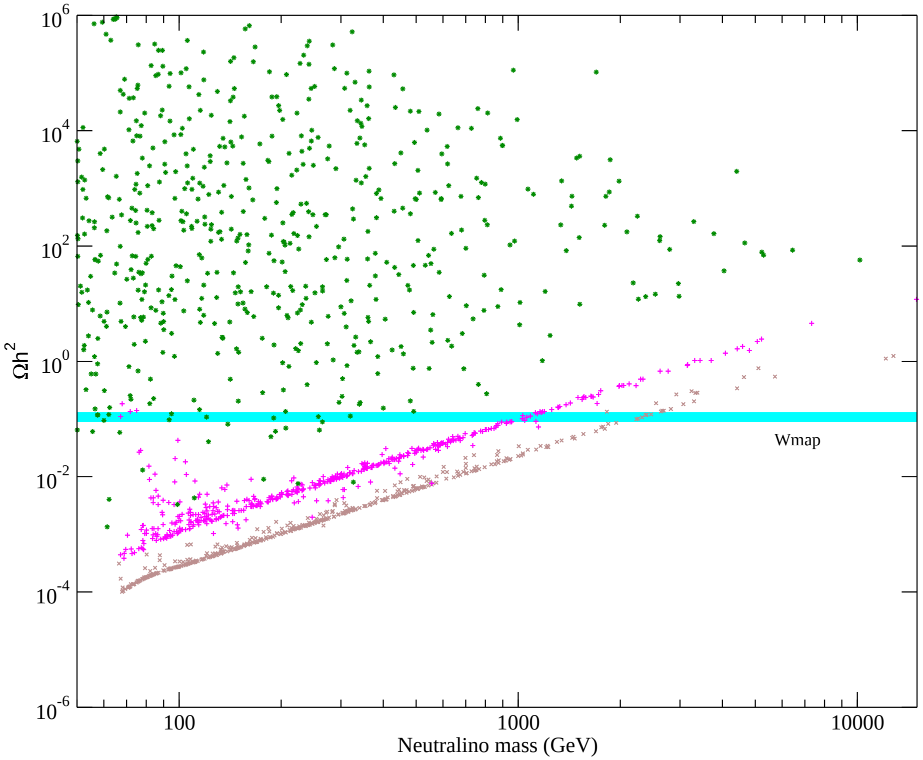
- LSP$= \widetilde{B}$ (typical in CMSSM) is OVERDENSE
  (σ_{annih} into $f\bar{f}$ through $\widetilde{f}$ exchange is helicity suppressed $\sim m_f$)

- LSP$= \widetilde{H}$ and $\widetilde{W}$ (not GU, AMSB) is UNDERDENSE
  unless $m \simeq TeV$ (large σ_{annih} into W^+W^-, ZZ, or $f\bar{f}$)

- RIGHT ABUNDANCE requires a special condition
  – Mixed composition (in CMSSM:"focus point"),
  – pole enhancement of σ_a ($m_\chi \simeq m_A/2$: "A-funnel region"- CP-odd Higgs A)
  –"coannihilation" between the LSP and the NLSP (Next to LSP)

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

e.g. neutralinos in MSSM after LEP-II (here, MSSM with 9 parameters)



1700 points

- 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)

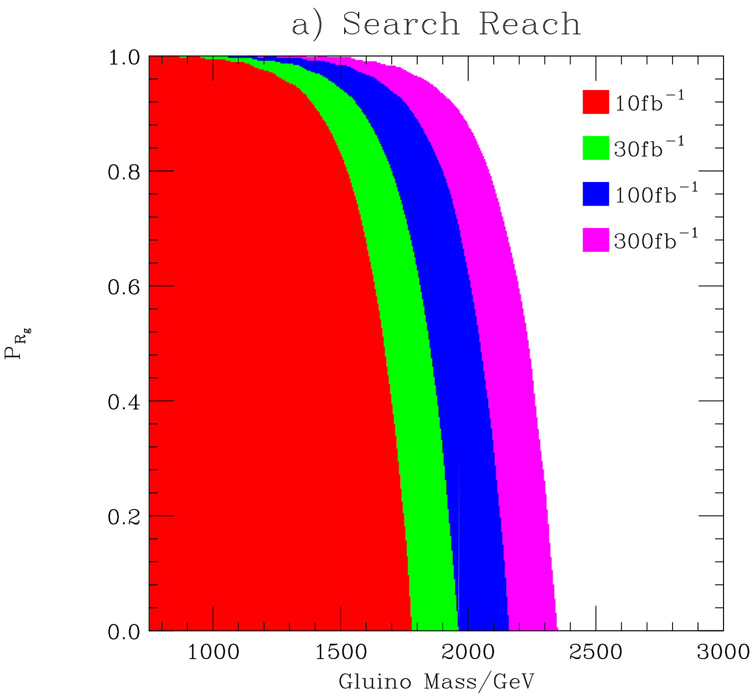
Split-SUSY

(Wells 2003, Arkani-Hamed Dimopoulos 2004, Giudice Romaninio 2004, Arkani-Hamed, Delgado, Guidice 2004, Dimopoulos, Arkani-Hamed; Giudice, Romanino 2004)

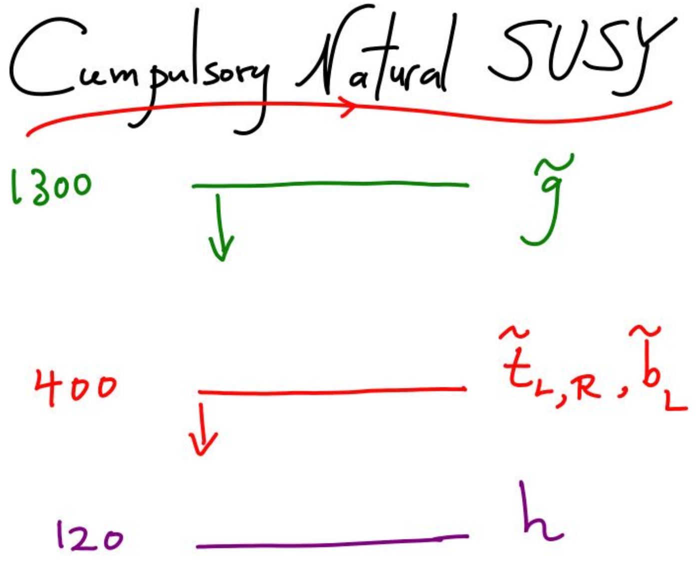
Forget fine tuning - think landscape of vacua
Keep DM and one stage GUT unification.
Scalars heavy, except
light SM-like higgs = 125 GeV
Neutralinos/charginos "light" but the best LHC background rejection is gone (no squarks, sleptons in cascades)

Long lived-hadronizing gluino,
R-hadron, is best LHC signal!

(Killian, Plehn,Richardson, Schmidt 2005)



Arkani-Hamed 2013: compulsory Natural SUSY after the Higgs discovery is SPLIT SUSY- Give up naturalness



Unavoidable tunings: $\left(\frac{400}{m_{\tilde{t}}}\right)^2, \left(\frac{4 m_{\tilde{t}}}{M_{\tilde{g}}}\right)^2$

And thermal WIMP at 1 - 3 TeV!

With non std. pre-BBN cosmology

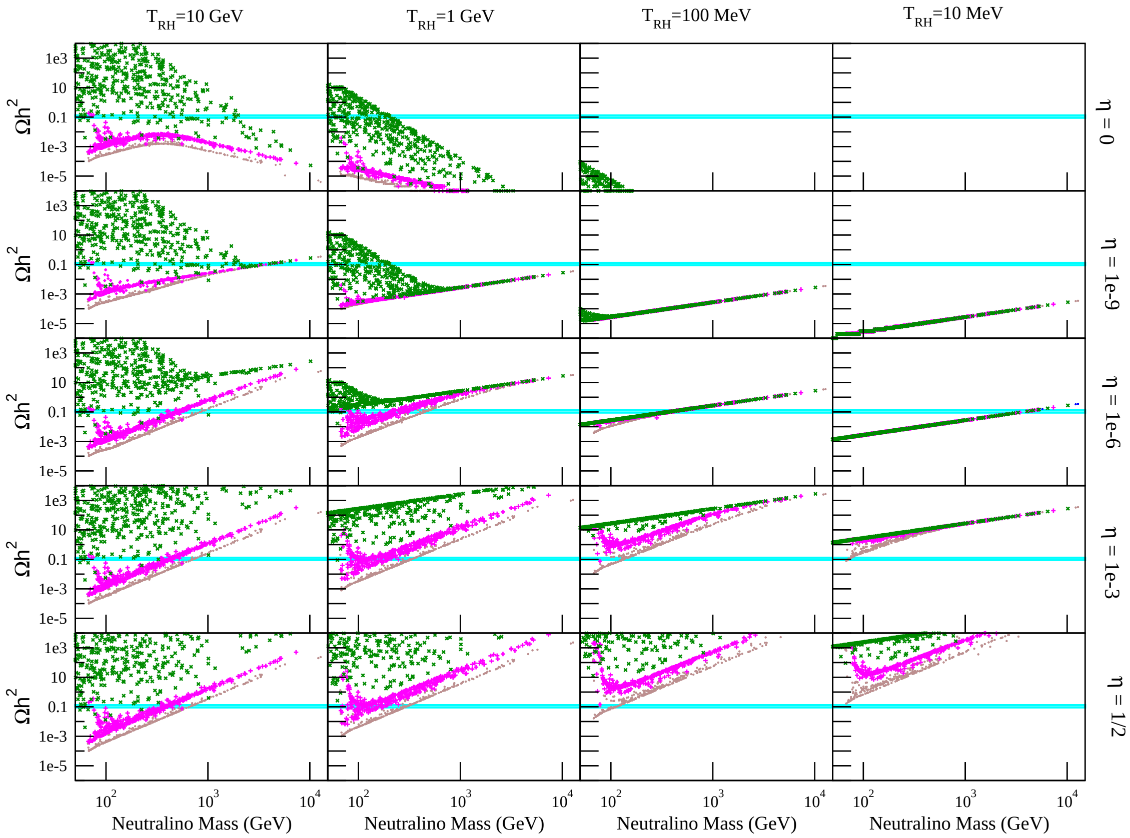
MSSM

1700 models (points)

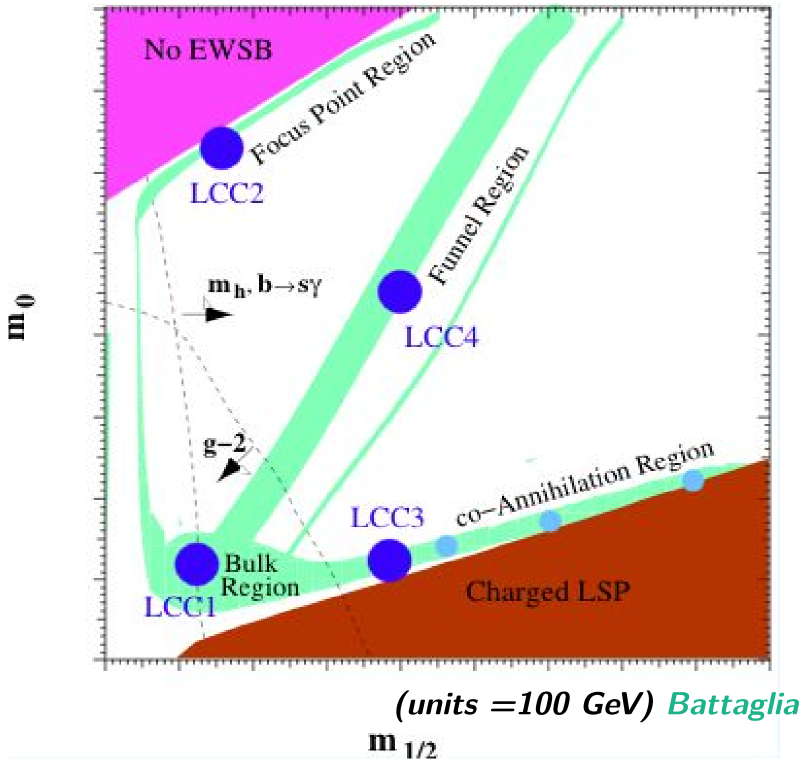
G.G. etal PRD 74: 083514, 2006

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

bino-like
higgsino-like
wino-like



Dark Matter constraint: narrow bands



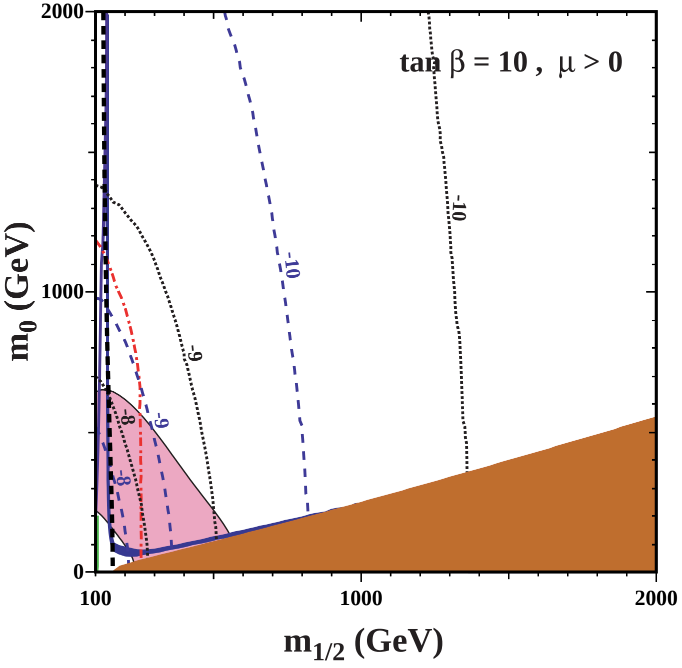
(units =100 GeV) *Battaglia et al*

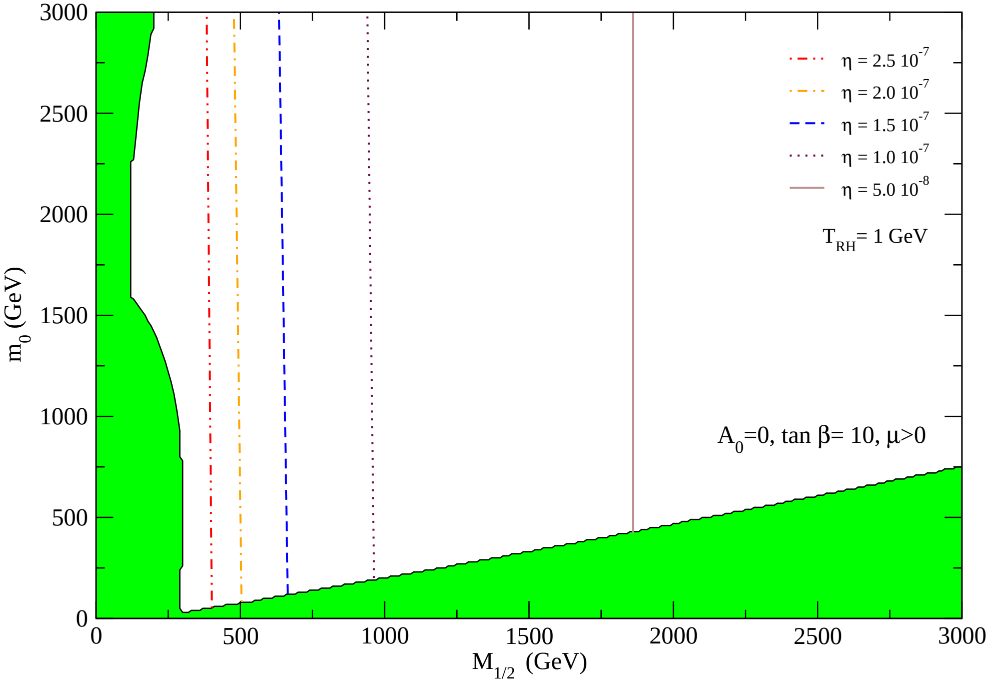
mSUGRA: bino-like neutralino has a helicity suppressed annihilation rate into $f\bar{f}$! Need: to be light (bulk), coannihilation with stau, $m = m_A/2$ resonance (funnel), Higgsino component (focus)

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

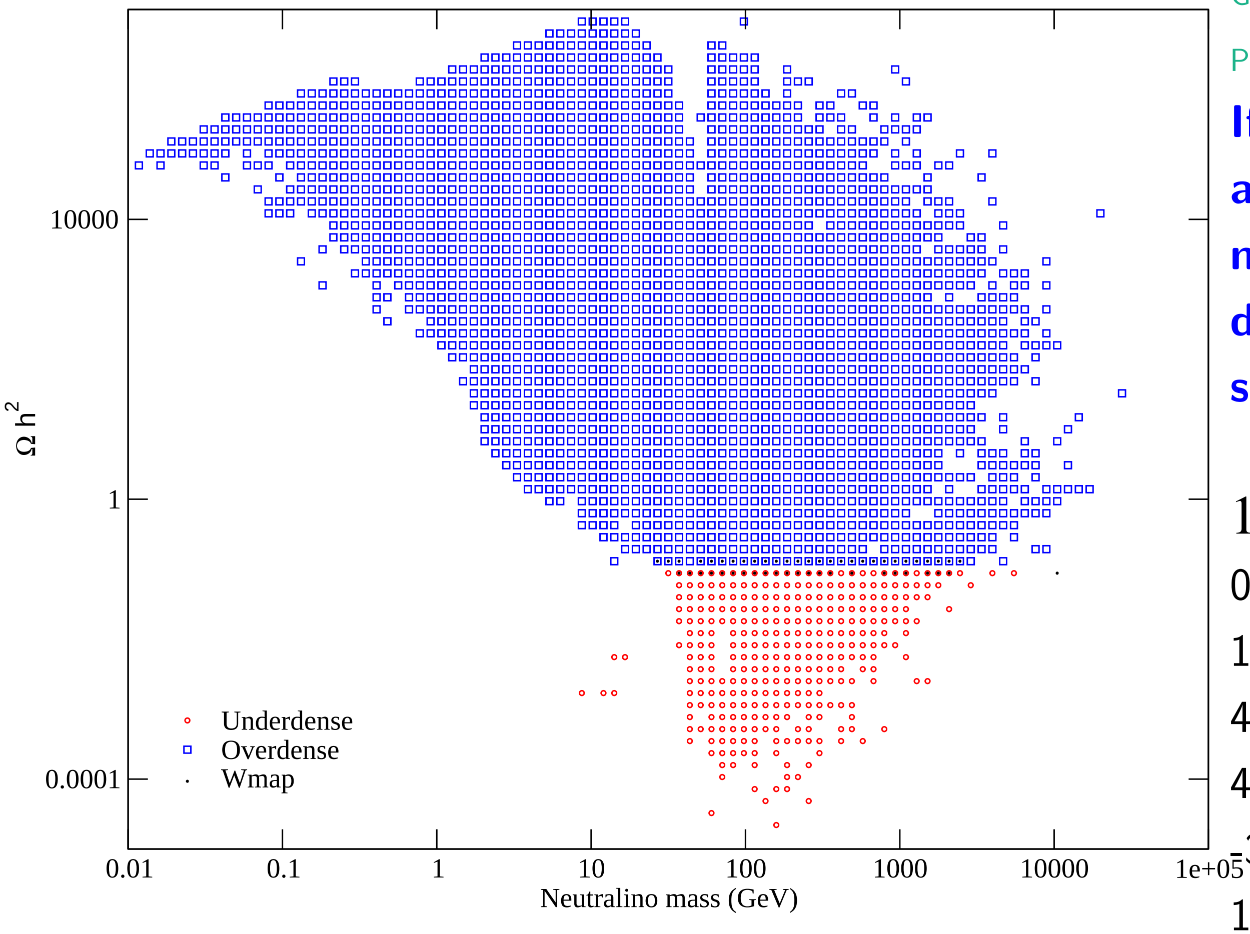
Non-std cosmology at the LHC

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

Non-standard relic WIMP 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 ($\mu(m_{\tilde{\nu}}) > 5(20) TeV$) allow O(100GeV) mass Bino to be warm DM

  Difficult for DM searches!

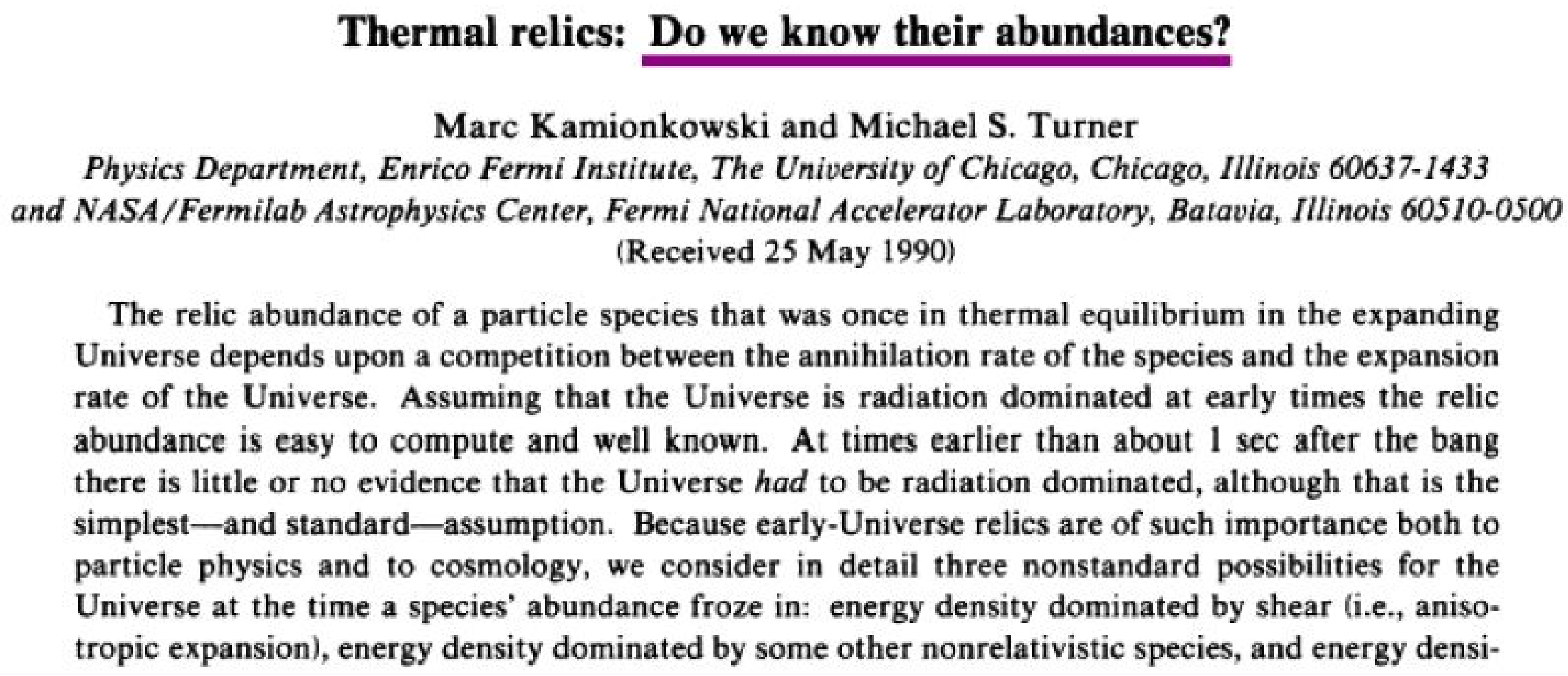
- **Ultra-Cold WIMPs** GG, Gondolo, 2008

  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)

WIMP's as cosmology probe

The neutralino density may be used to find out about the cosmology before BBN.

This is not a new idea



Thermal relics: Do we know their abundances?

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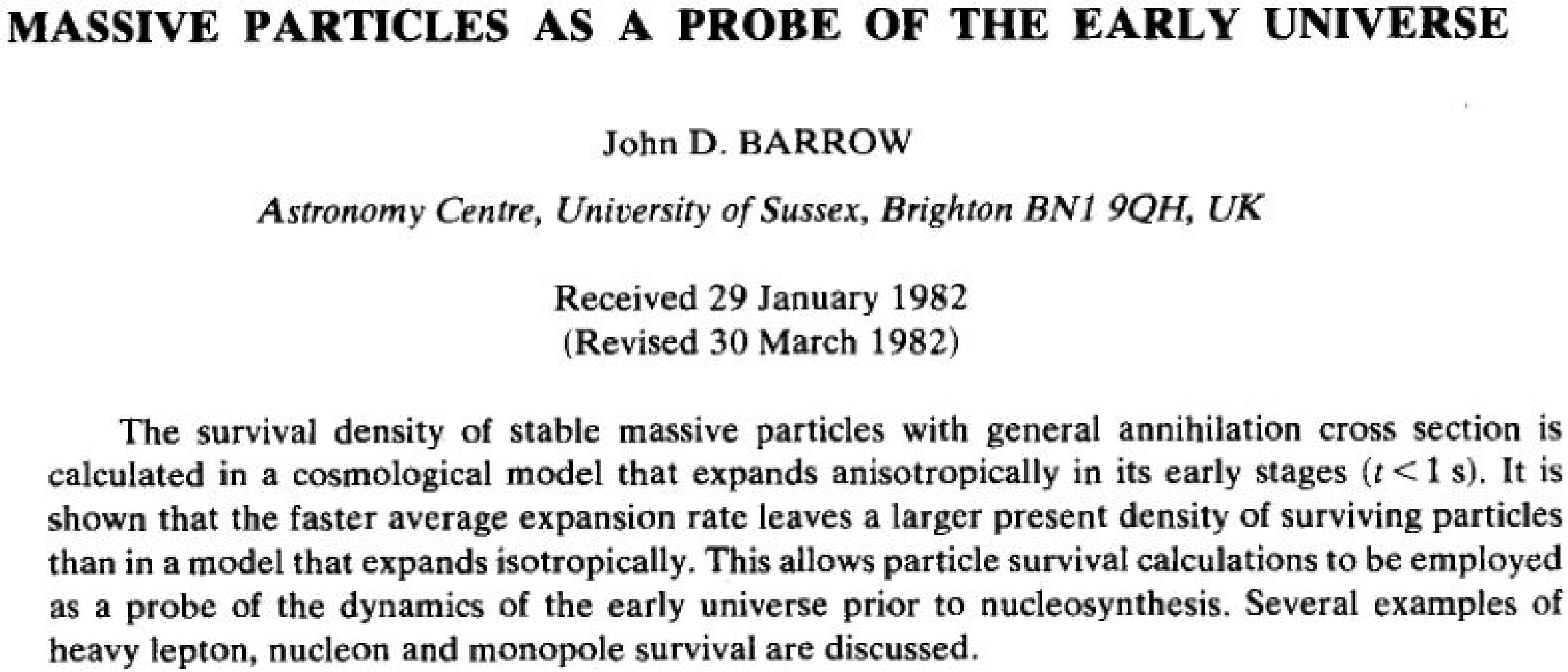
(Received 25 May 1990)

The relic abundance of a particle species that was once in thermal equilibrium in the expanding Universe depends upon a competition between the annihilation rate of the species and the expansion rate of the Universe. Assuming that the Universe is radiation dominated at early times the relic abundance is easy to compute and well known. At times earlier than about 1 sec after the bang there is little or no evidence that the Universe *had* to be radiation dominated, although that is the simplest—and standard—assumption. Because early-Universe relics are of such importance both to particle physics and to cosmology, we consider in detail three nonstandard possibilities for the Universe at the time a species' abundance froze in: energy density dominated by shear (i.e., anisotropic expansion), energy density dominated by some other nonrelativistic species, and energy densi-

WIMP’s as cosmology probe

The neutralino density may be used to find out about the cosmology before BBN..... This is not a new idea



MASSIVE PARTICLES AS A PROBE OF THE EARLY UNIVERSE

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Received 29 January 1982
(Revised 30 March 1982)

The survival density of stable massive particles with general annihilation cross section is calculated in a cosmological model that expands anisotropically in its early stages ($t < 1$ s). It is shown that the faster average expansion rate leaves a larger present density of surviving particles than in a model that expands isotropically. This allows particle survival calculations to be employed as a probe of the dynamics of the early universe prior to nucleosynthesis. Several examples of heavy lepton, nucleon and monopole survival are discussed.

Other particle candidates starting from those requiring the smallest modification of the Standard Model.

- Sterile neutrinos

- axions

- WIMPs appearing in EP models justified by reasons other than amounting for the DM

- "Boutique models" produced largely ad-hoc to try to explain DM hints

Sterile Neutrinos

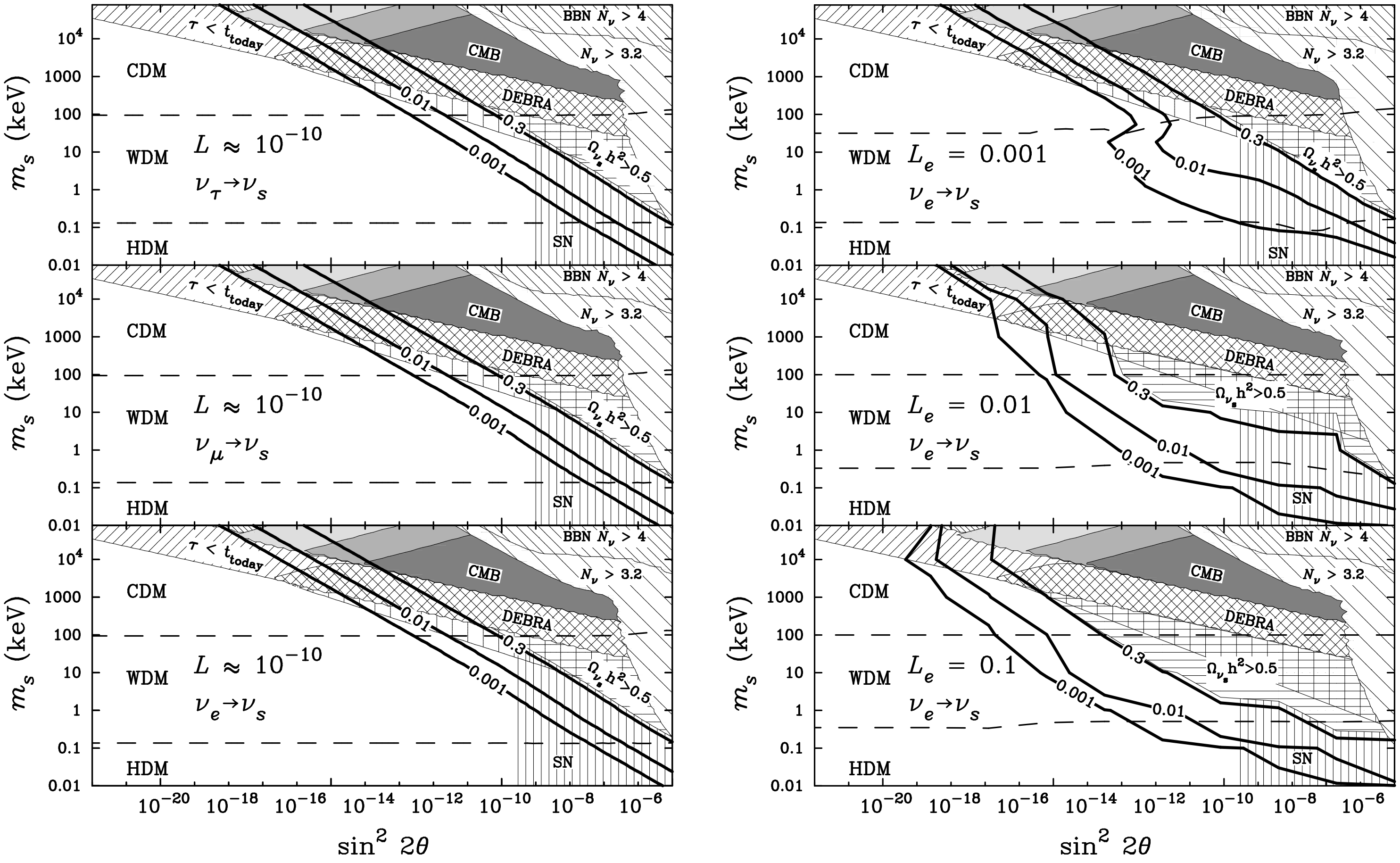
The SM has 3 “active neutrinos” ν_a with only weak interactions, but ν_s with no interactions can be easily added (one or more, of any mass)

Recall that for two-neutrino mixing:
$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$;
$|\nu_s\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$

-$|\nu_{\alpha,s}\rangle$: interaction eigenstates
-$|\nu_{1,2}\rangle$: mass eigenstates, $m_1 << m_2 \equiv m_s$

They can be created via active sterile oscillations, with or without a large lepton asymmetry, and can be Warm DM or Cool DM (with large Lepton Asymmetry L).

Sterile Neutrinos from Abazajian, Fuller, Pattel 2001



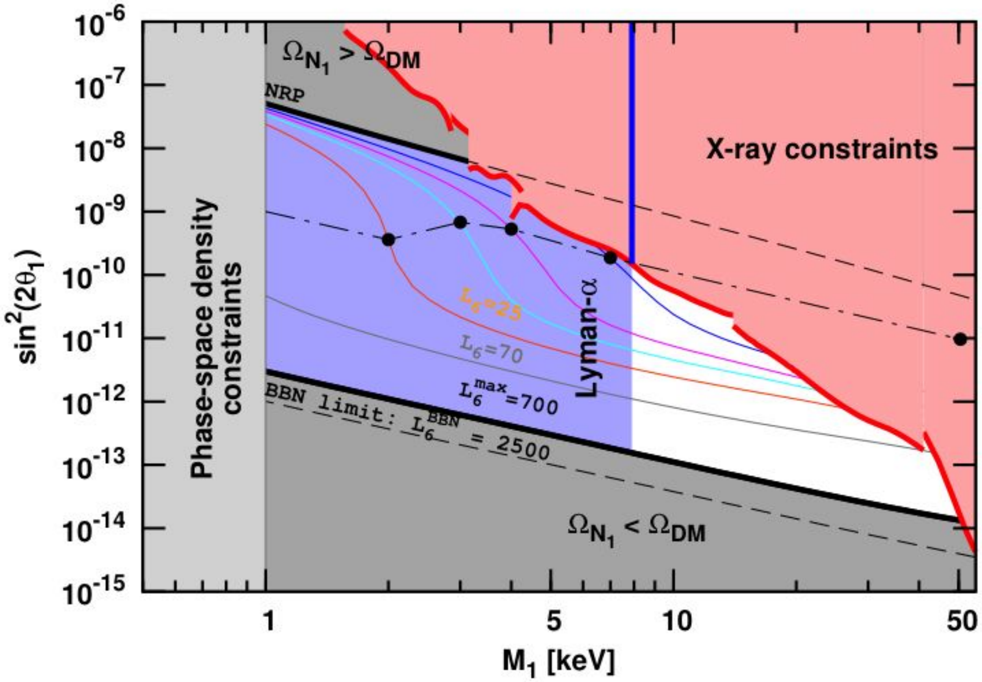
Sterile Neutrinos ("Light Sterile Neutrinos:A White Paper", Abazajian et al. hep-ph/1204.5379)

ν_s can be produced via a mixing $\sin\theta$ with ν_a and can be Warm DM or Cool DM (with large Lepton Asymmetry L).

$\nu_s \to \nu\gamma$ would produce X-rays in galaxies and galaxy clusters

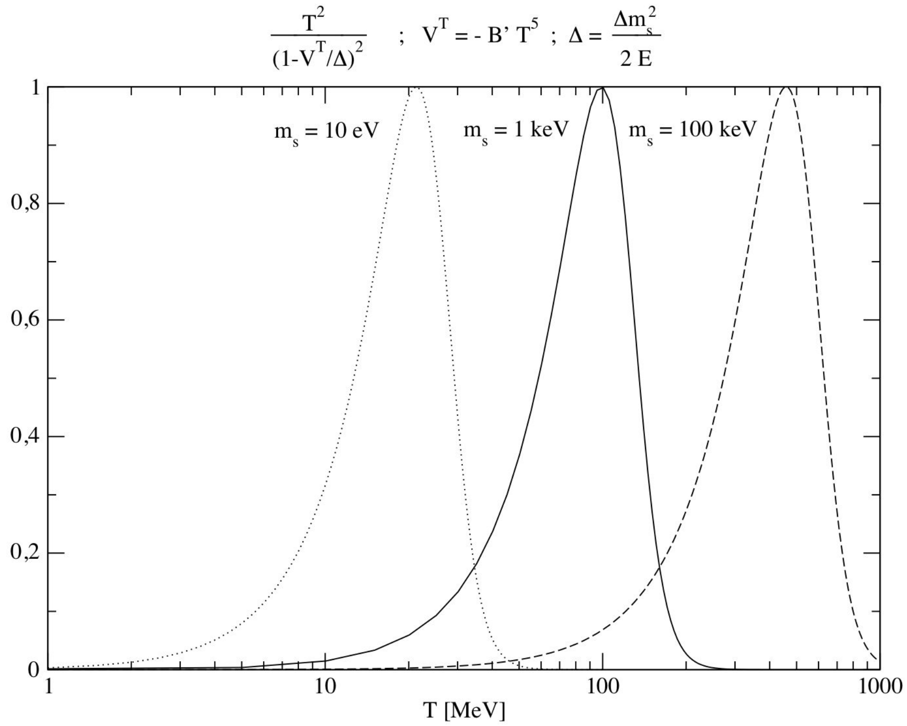
Dwarf-Spheroidal Galaxies phase space: $m_s > 1$ keV

Early structures (Ly-α clouds): $m_s > 8$ keV but not with large L



And ν_s can be produced in other ways (e.g. coupled to new scalar fields).

Sterile Neutrinos Through active-sterile oscillations ν_s production is max. at $T_{max} \simeq 133\ (m_s/keV)^{1/3}$ MeV; plot of $\frac{1}{f_\nu}\left(\frac{df_s}{dT}\right)_{E/T}$ vs T



Thus, ν_s produced while relativistic, i.e. $T_{max} > m_s/3$ for $m < 10$ GeV.

Sterile Neutrinos in Low Reheating Models Gelmini, Palomares-Ruiz, Pascoli 2004

Since we do not know the history of the Universe before about 4MeV. If we assume $T_R << T_{max}$, for $m_s < 1$MeV

$$\frac{n_{\nu_s}}{n_{\nu_\alpha}} \simeq 10 \ \sin^2 2\theta \left(\frac{T_R}{5\ MeV}\right)^3 .$$

so that $\Omega_s h^2 = (m_s\ n_{\nu_s}/\rho_c)h^2$ is

$$\Omega_s h^2 \simeq 0.1 \ \left(\frac{\sin^2 2\theta}{10^{-3}}\right) \left(\frac{m_s}{1\ keV}\right) \left(\frac{T_R}{5\ MeV}\right)^3$$

$$\left[Standard\ :\ \Omega_{\nu_s} h^2 \approx 0.1 \left(\frac{\sin^2 2\theta}{3\ 10^{-7}}\right) \left(\frac{m_s}{1\, keV}\right)^2\right]$$

So even very light ν_s evade cosmological abundance constraints for a low T_{RH}

(also for $m_s > 1$MeV see Gelmini, Osoba, Palomares-Ruiz, Pascoli 2008)