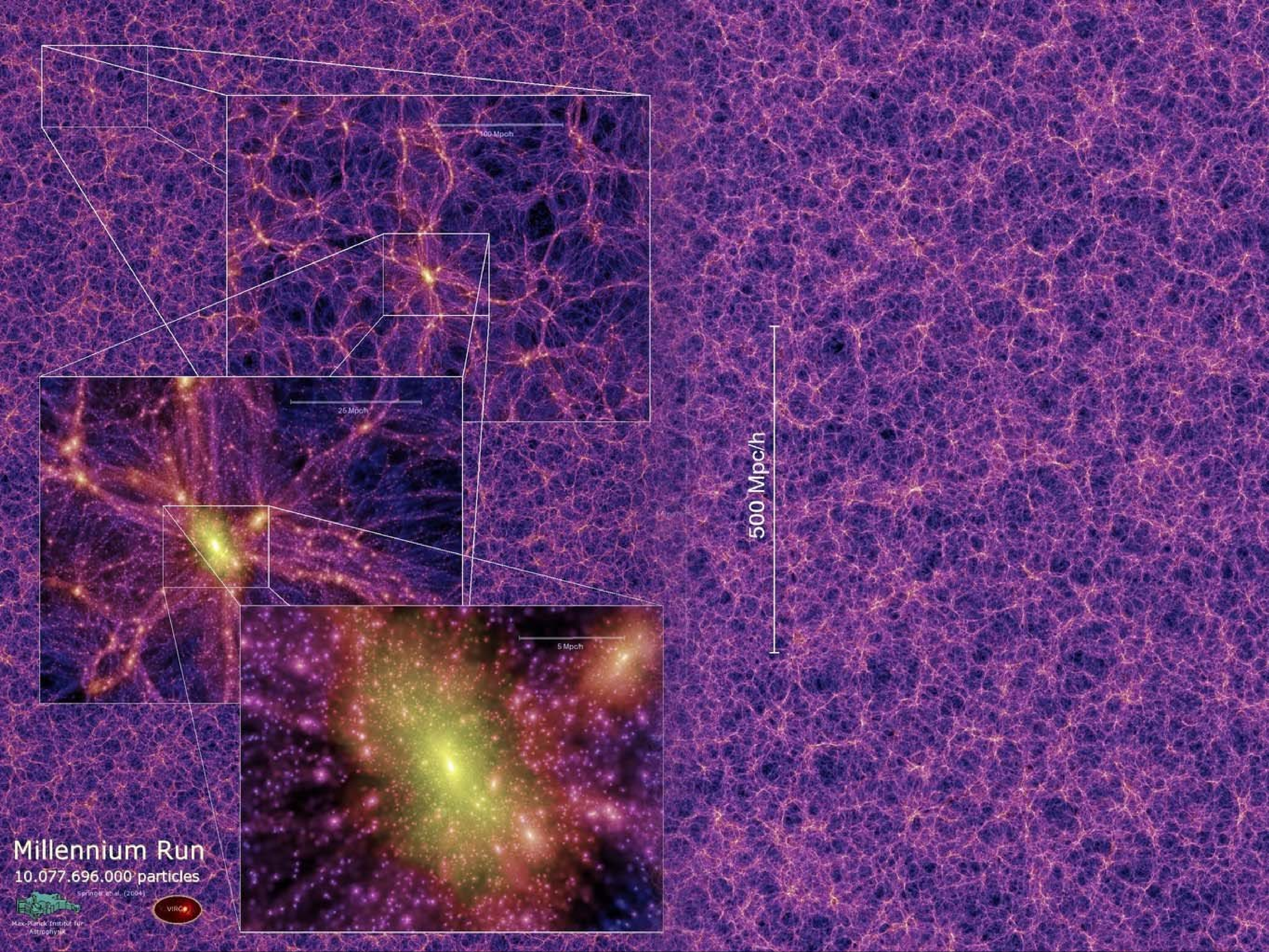
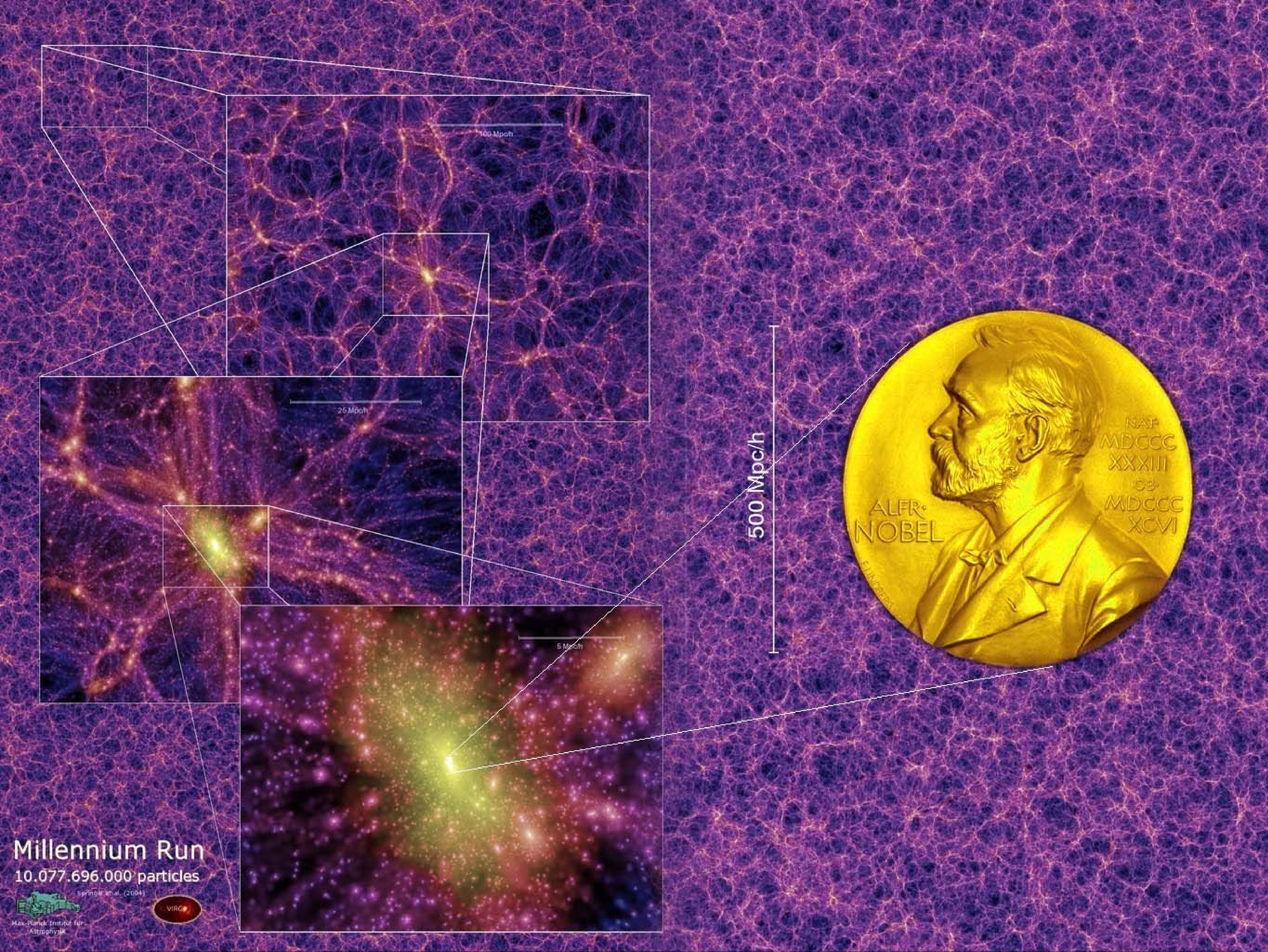

100 Mpc/h
25 Mpc/h
5 Mpc/h
500 Mpc/h
Millennium Run
10.077.696.000 particles
VIRGO


100 Mpc/h
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ALFR· NOBEL
NAT· MDCCC XXXIII
·OB· MDCCC XCVI
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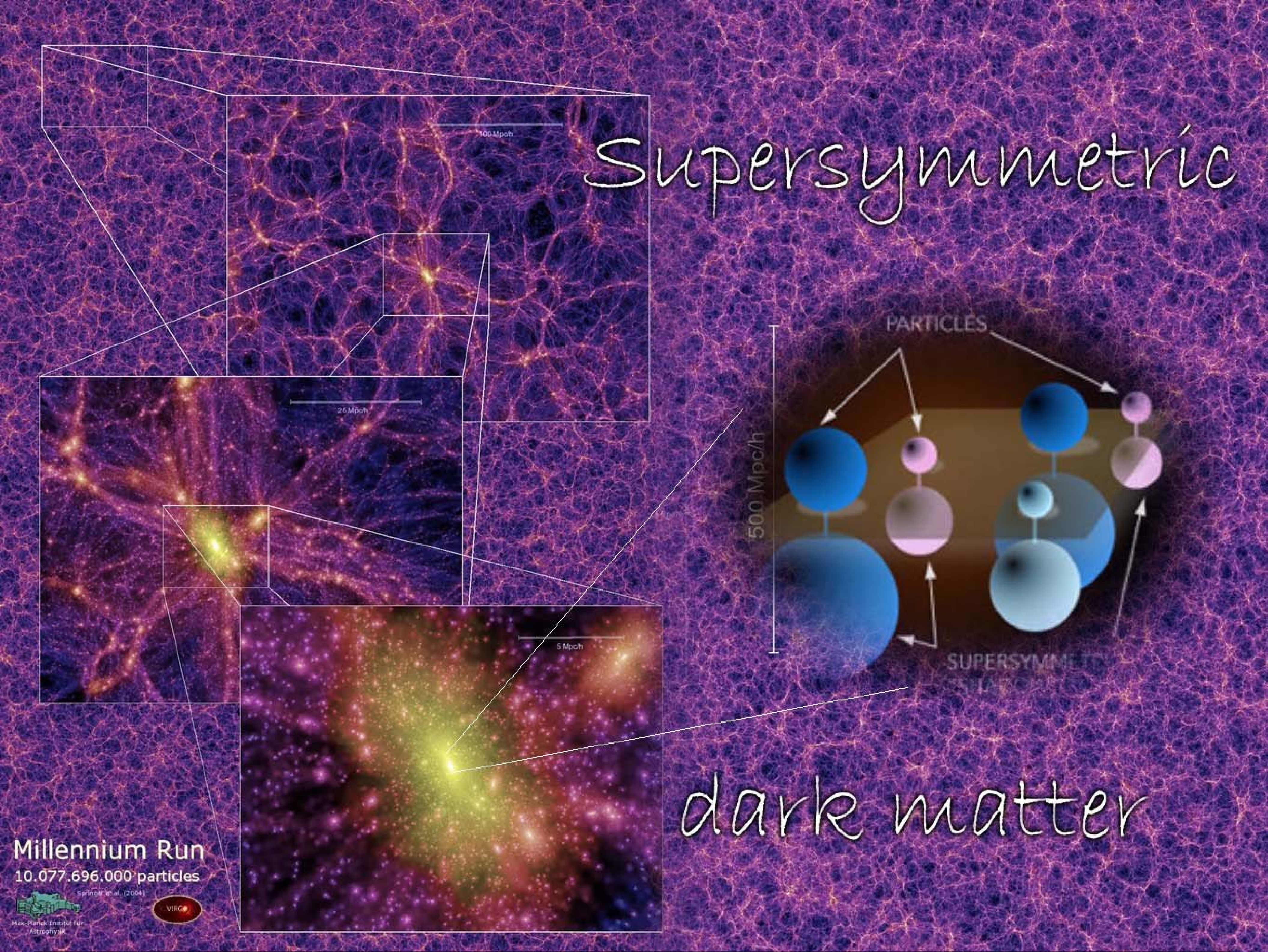
Springel et al. (2004)
Max-Planck-Institut für Astrophysik
VIRGO


Supersymmetric
dark matter
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25 Mpc/h
5 Mpc/h
500 Mpc/h
PARTICLES
Millennium Run
10.077.696.000 particles
Springel et al. (2004)
Max-Planck Institut für Astrophysik
VIRGO

We know

Dark matter is ...

cold (non-relativistic)

22 % of the Universe

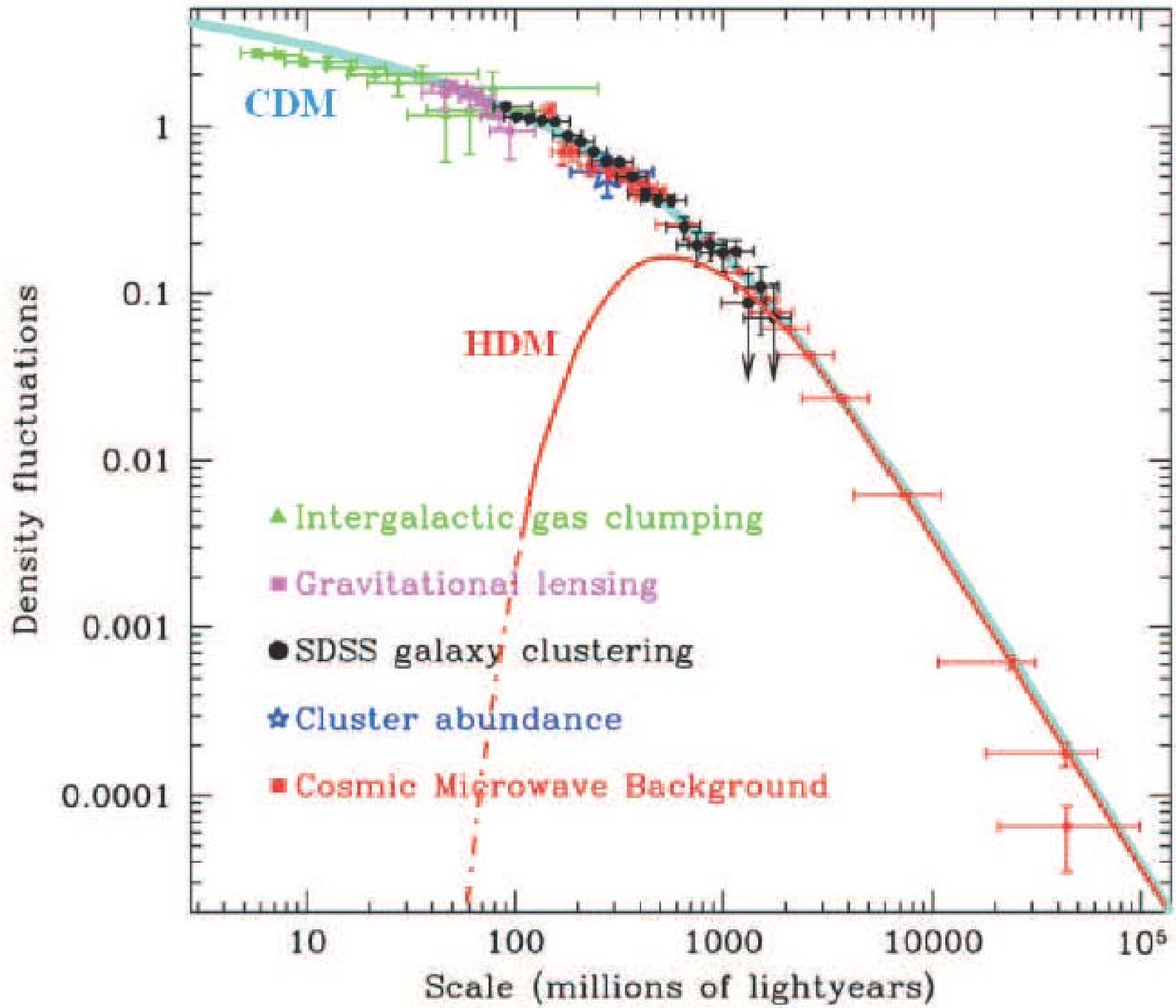
non-baryonic

weakly interacting (collisionless)

Cold

– Galactic structure requires cold dark matter

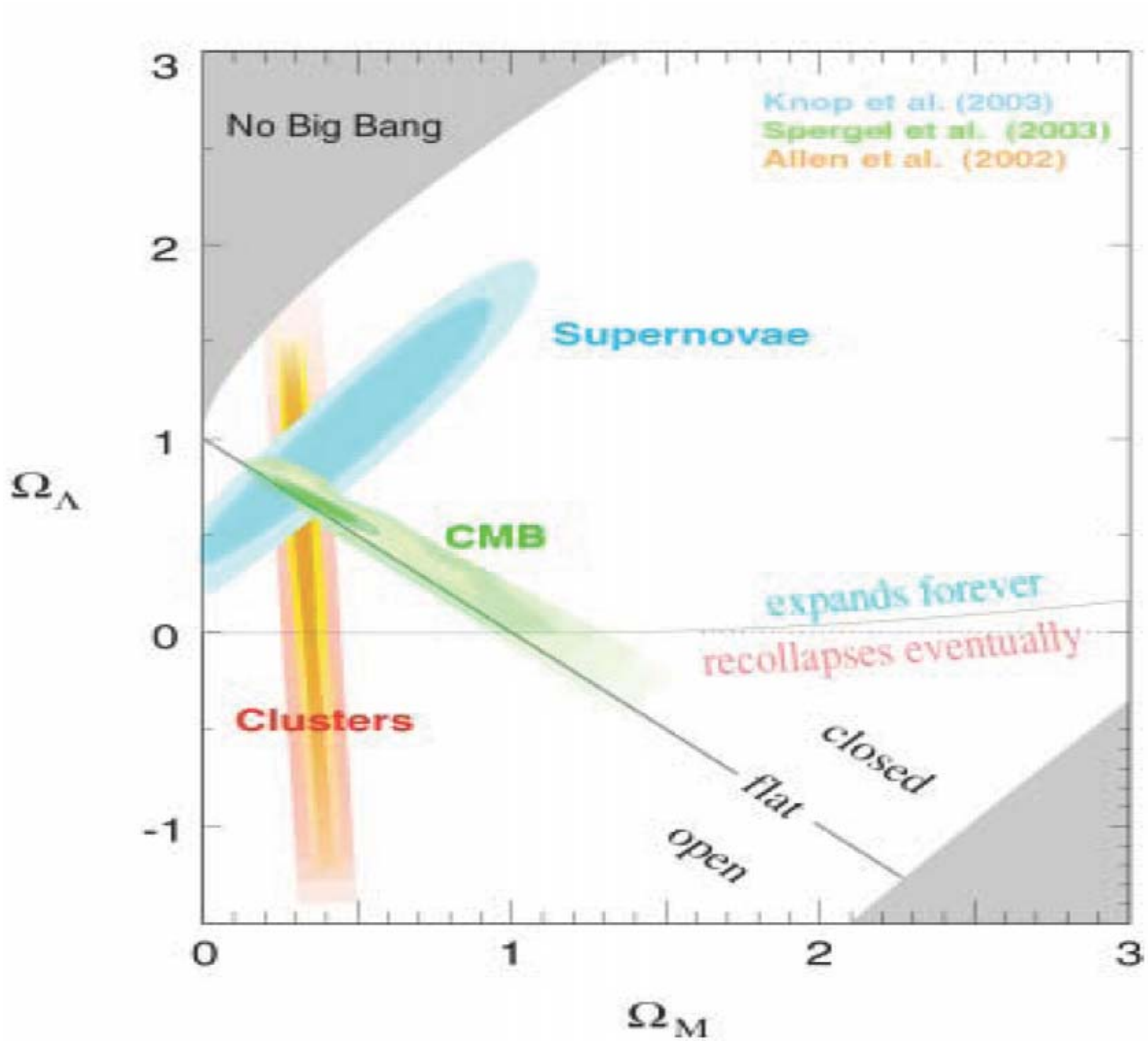
- CDM collapses first, attracting matter later



Maroto,Ramírez astro-ph/0409280

22 %

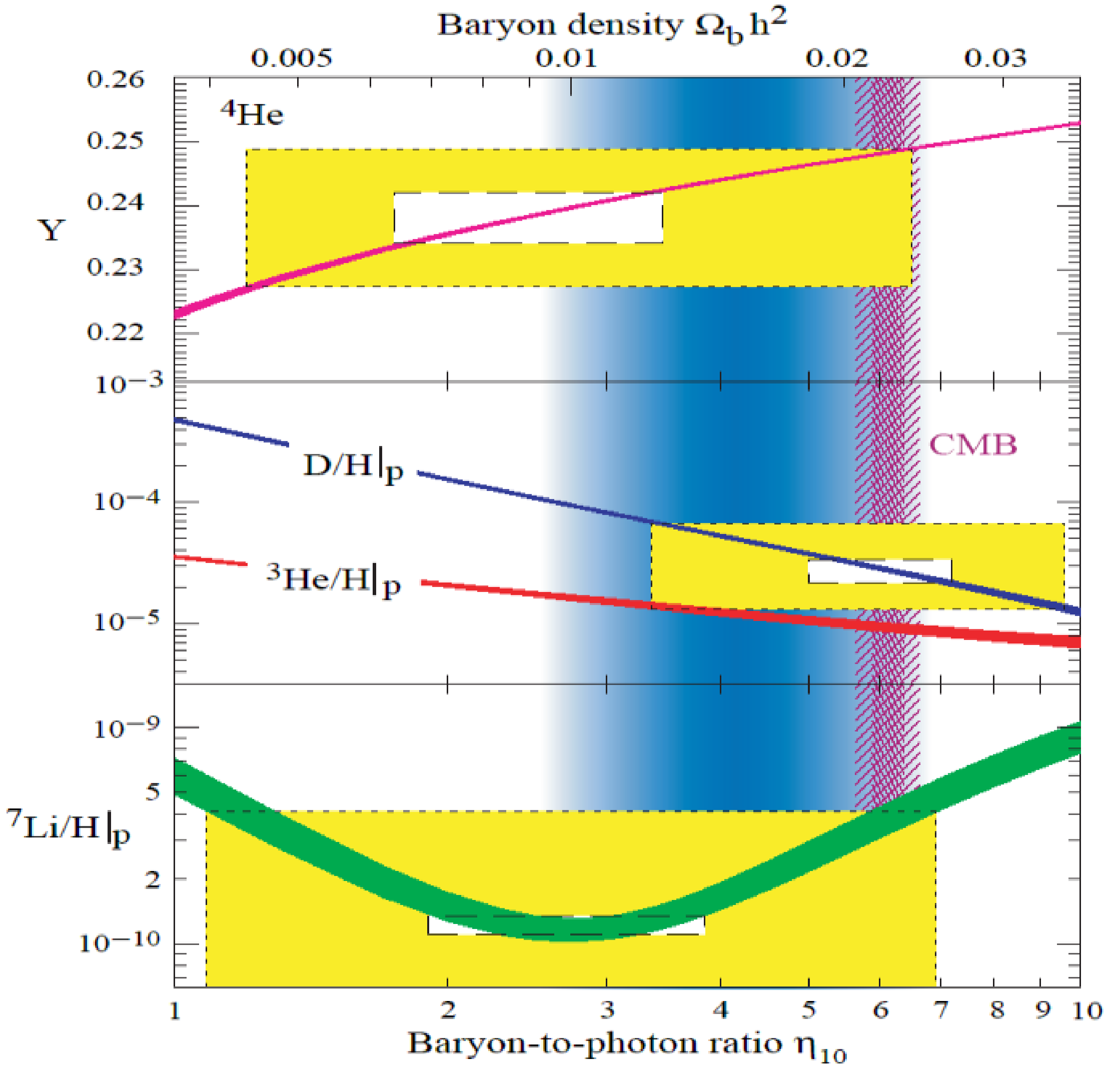
– E balance a 'la FRW: $\frac{\rho}{\rho_c} = \Omega_M + \Omega_\Lambda + \Omega_k$ $\rho_c = 3H_0^2/8\pi G_N$, $H_0 = 71 \pm 4$ km/s/Mpc



- SNe,WMAP,SDSS: $\Omega_M = 0.27 \pm 0.04$ $\Omega_\Lambda = 0.73 \pm 0.04$ $\Omega_{tot} = 1.02 \pm 0.02$
- direct, independent, precise, consistent observations → robust result

Non-baryonic

— Matter content: $\Omega_M = \Omega_{BM} + \Omega_R + \Omega_\nu + \Omega_{DM}$ with $\Omega_\nu, \Omega_r < 0.015$

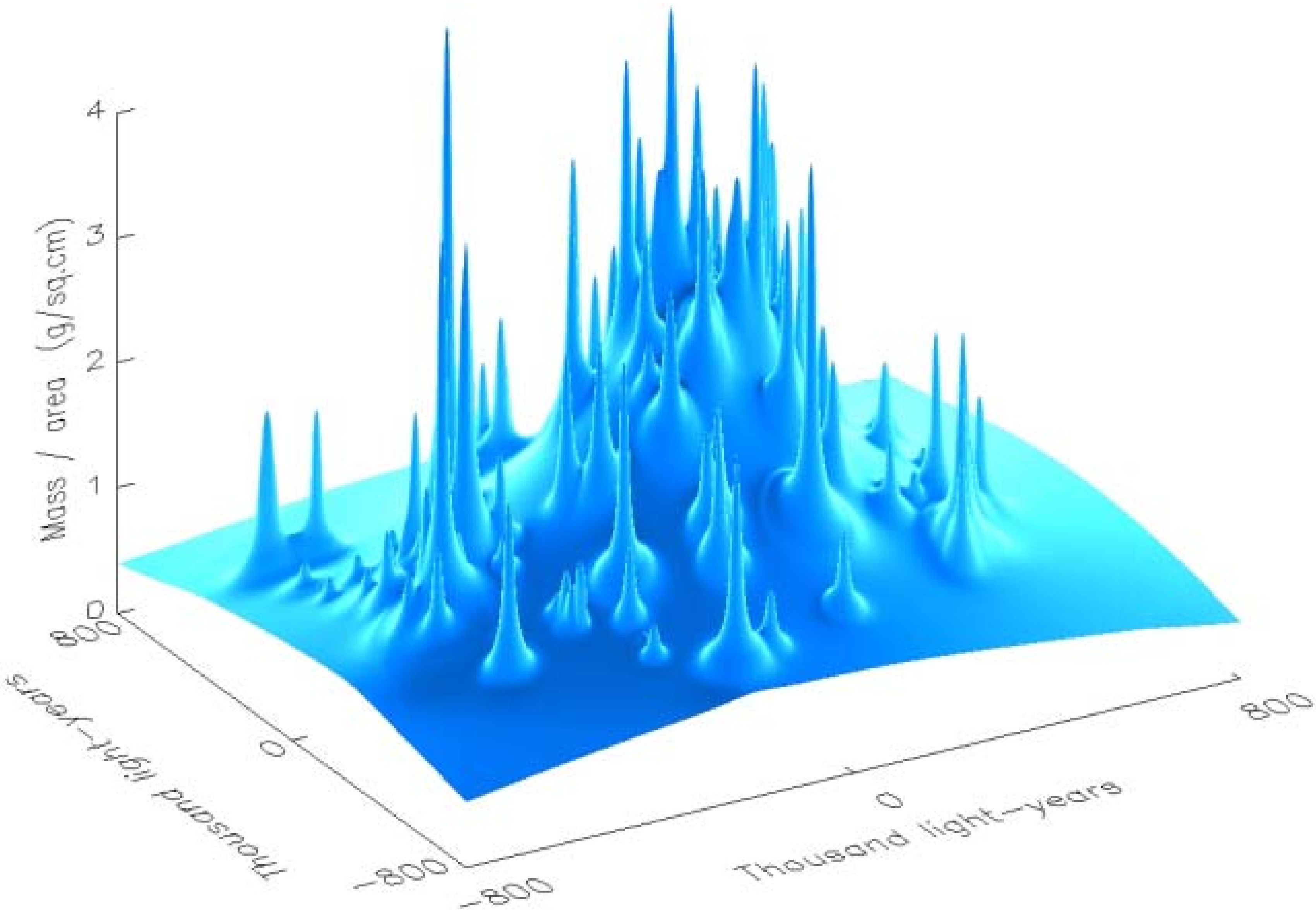


PDB 2005

- BBN&CMB, cosmic concordance: $\Omega_b = 0.044 \pm 0.004 \Rightarrow \Omega_{DM} = 0.22 \pm 0.04$
- new form of matter: non-baryonic, stable

Weakly interacting

– Gravitational lensing → mass dist'n of CL0024+1654 galaxy cluster



http://www.bell-labs.com/news/1997/january/15/1.html

We don't know

Does it exist?

How to directly detect/create it?

Why is it 22 % (now)?

What is it?

...

Dark matter - speculation (an incomplete list)

dark intergallactic gas, invisible nebulae; primordial black holes, intermediate mass black holes; MACHOs (massive compact halo objects): very faint stars, neu tron stars, brown stars, large or small planets, football size rocks; extra dimensional particles: bulk black holes, parallel branes, intersecting branes, branons (brane excitations), LKPs (lightest Kaluza-Klein particle), Kaluza-Klein neutrino, Kaluza-Klein partner of the photon (B_1) or neutrino (ν_1), LZP (lightest Z_3 charged Kaluza-Klein excitation), radion, extra dimensional SUSY particles; WIMPs (weakly interacting massive particles), superWIMPs, EWIMPs (extremely weakly interacting particles), WIMPZILLAs (extremely heavy weakly interacting massive particles); supersymmetric particles: neutralinos, cold gravitinos, warm gravitinos, scalar neutrinos, singlinos; LTP (lightest T-parity odd particle), SIMPs (strongly interacting massive particles), CHAMPs (charged massive particles), heavy double charged leptons, heavy neutrinos, right handed neutrinos, cryptons, cosmic strings, Q-balls, moduli fields, axions, axinos, self-interacting particles, self-annihilating particles, fuzzy dark matter, gauge singlet scalars, ultra light pseudo-Goldstone bosons, fourth generation baryonic matter, non-standard baryons, X particles, mirror matter; modified gravity: MOND (modified Newtonian dynamics), ...

Dark matter - speculation (an incomplete list)

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ELSEVIER Physics Reports 267 (1996) 195–373

Supersymmetric dark matter

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Contents

Supersymmetric dark matter - speculation

— Lot of interesting developments

- (left or right handed) sneutrino LSP de Gouvea et al.
- singlino LSP Suematsu et al.
- SU(5), SO(10) or other unified models Baer et al.
- Yukawa quasi-unification Lazarides et al.
- non-minimal SUGRA models Baer et al.
- split SUSY and it's variations Arkani-Hamed et al., ...
- supersymmetric little Higgs Shirman et al.
- string inspired models Dimopoulos et al, Allanach et al, Moretti et al., ...
- partly supersymmetric models Masip et al.
- loop contributions Nerzi et al., Barger et al.
- ...
- (in)direct detection, collider implications ... → next talk

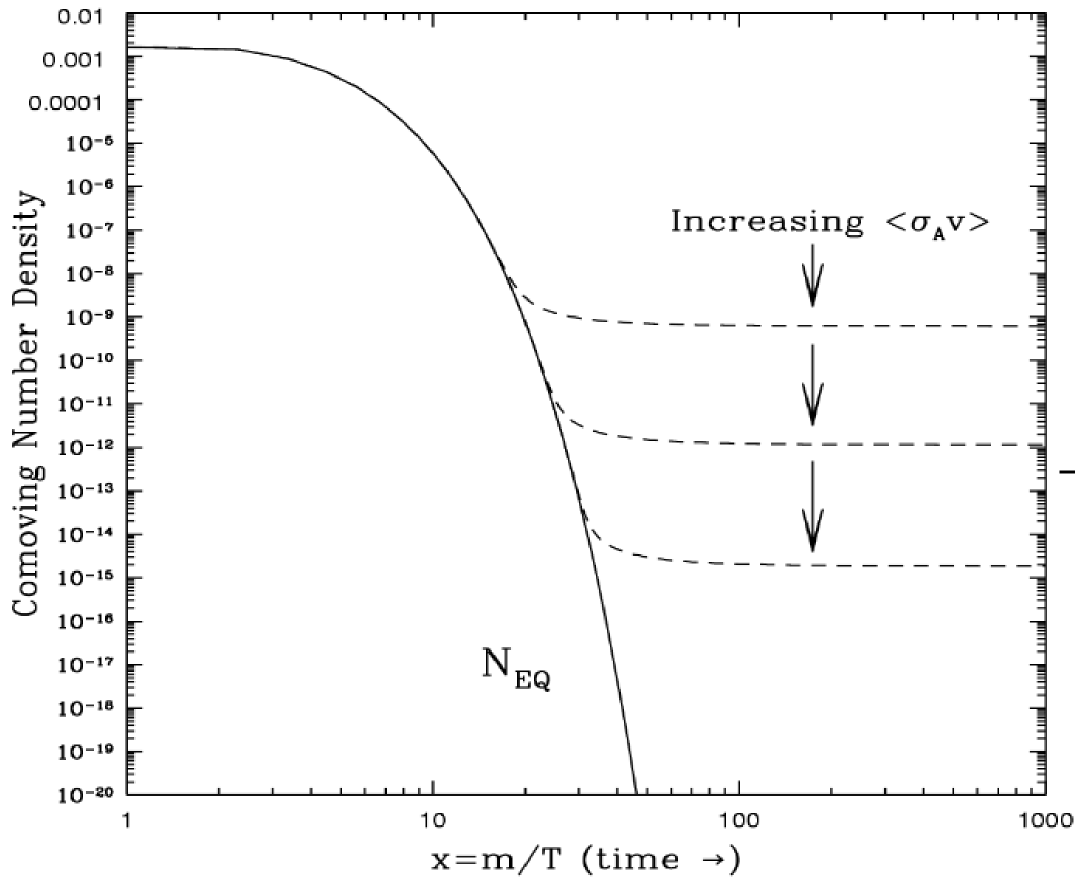
— I won't talk about dark matter in any of the above SUSY scenarios

Thermal relics

– Why would dark matter be made up by EW scale particles?

– WIMPs as dark matter

- $T \gg m_\chi$: equilibrium
  $\chi\chi \leftrightarrow SM$
- $T < m_\chi$: Boltzmann phase
  $\dot{N} \sim -\langle \sigma_{eff} v \rangle (N^2 - N_{eq}^2)$
  $N = N_{eq} \sim e^{-m/T}$
- $T \ll m_\chi \sim T_F$: freeze out
  $N \sim$ constant
- relic abundance :
  $N \sim \Omega_{CDM} \sim$
  $1 / \int_0^{x_F} \langle \sigma_{eff} v \rangle \, dx$
  $\sigma_{eff} = \sigma_{eff}(\alpha_\chi, m_\chi)$

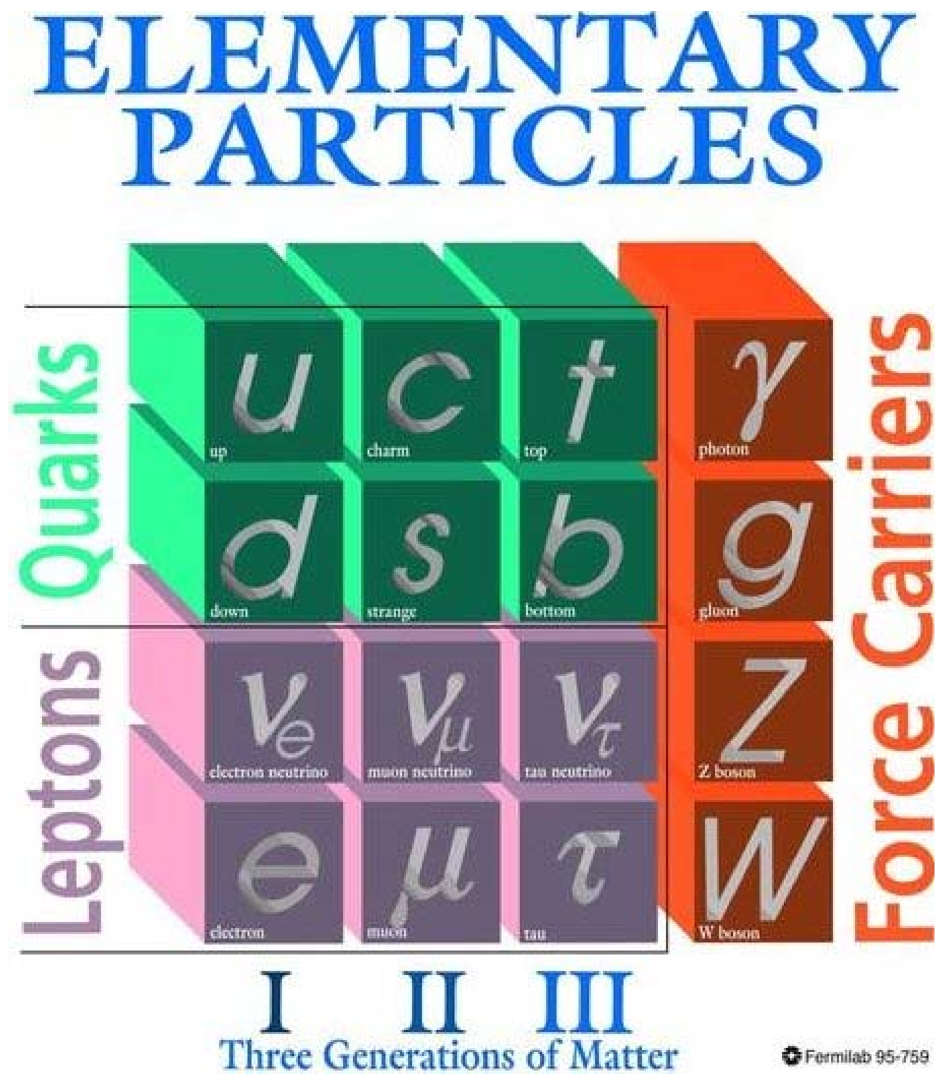


– WIMP great CDM candidate:

- neutral, stable (parity), non-baryonic, non-relativistic
- $\sigma_{eff} \sim \frac{\alpha_W}{M_W} \sim$ pb, $m_\chi \sim 0.1$ TeV $\rightarrow \Omega_{CDM} \sim 0.1$ 'remarkable coincidence' !

What is dark matter? (A particle theorist's view)

— WIMP properties



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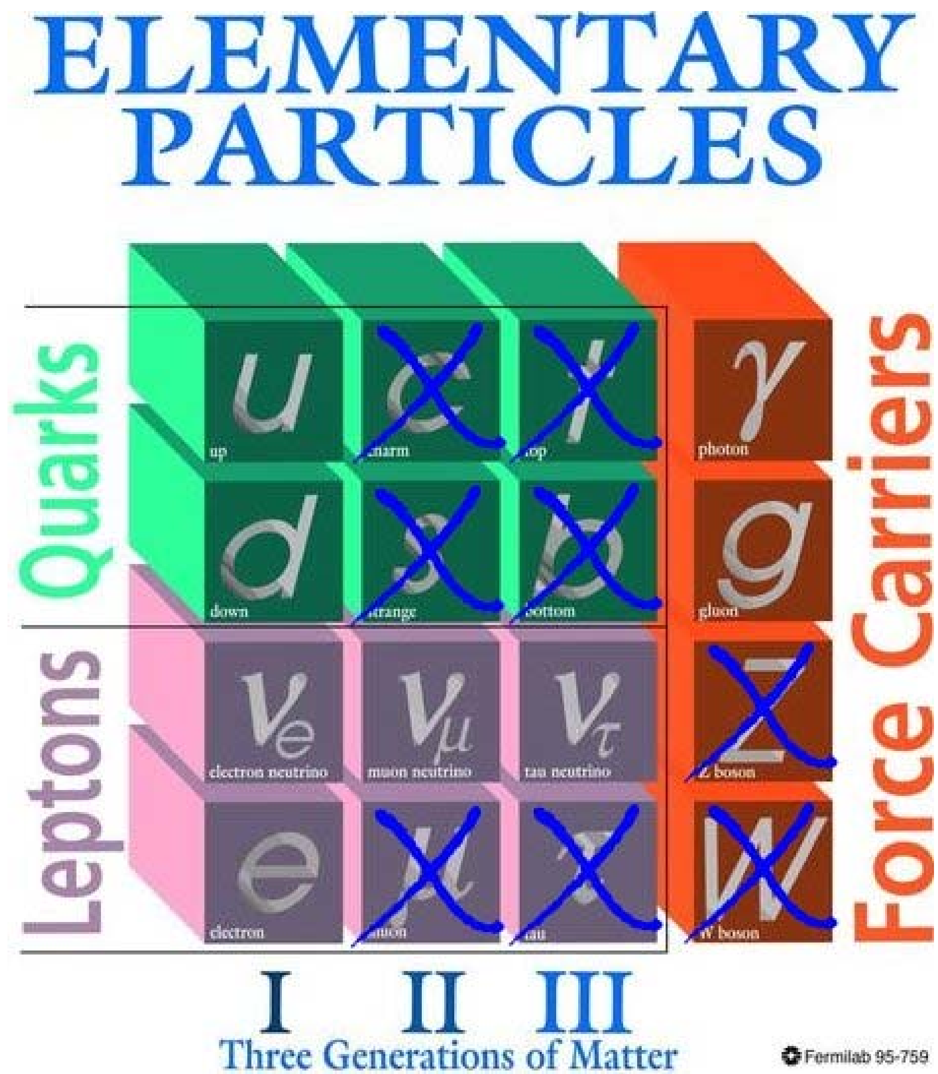
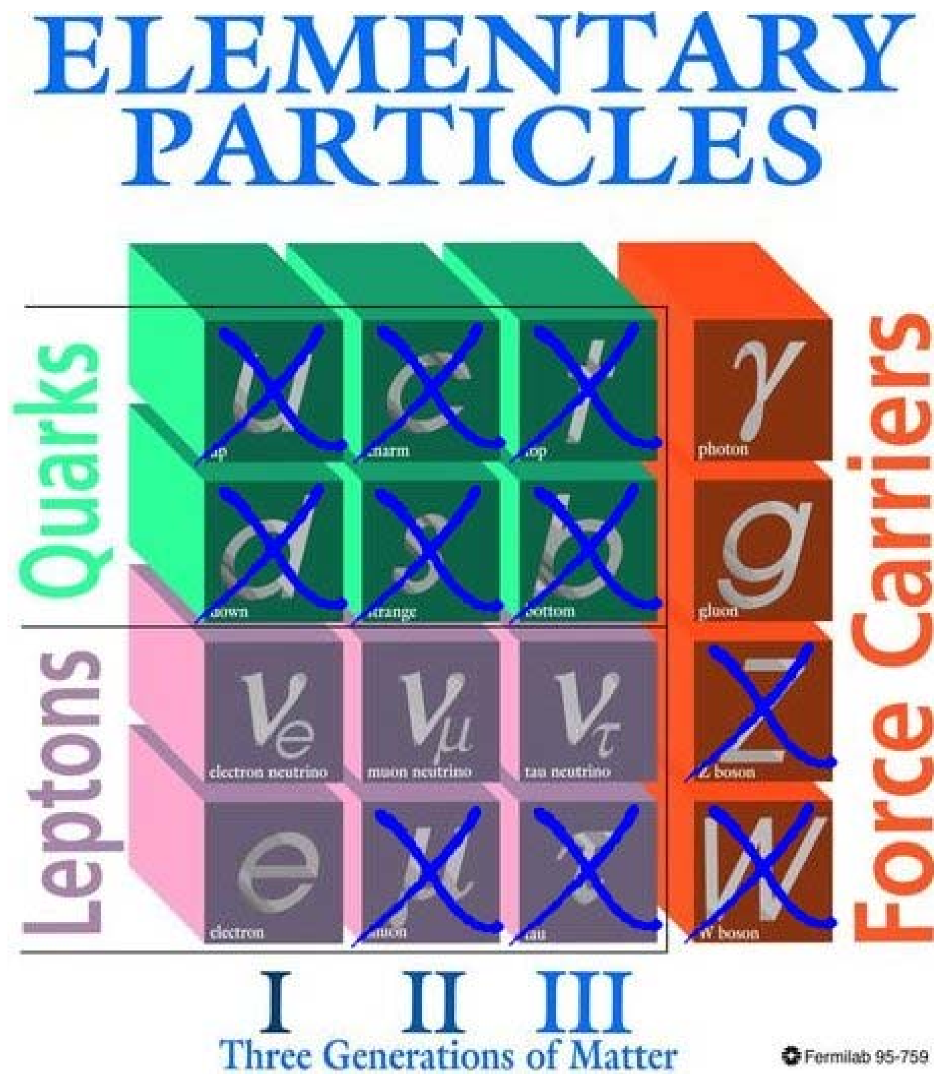
— WIMP properties

- stable



What is dark matter? (A particle theorist's view)

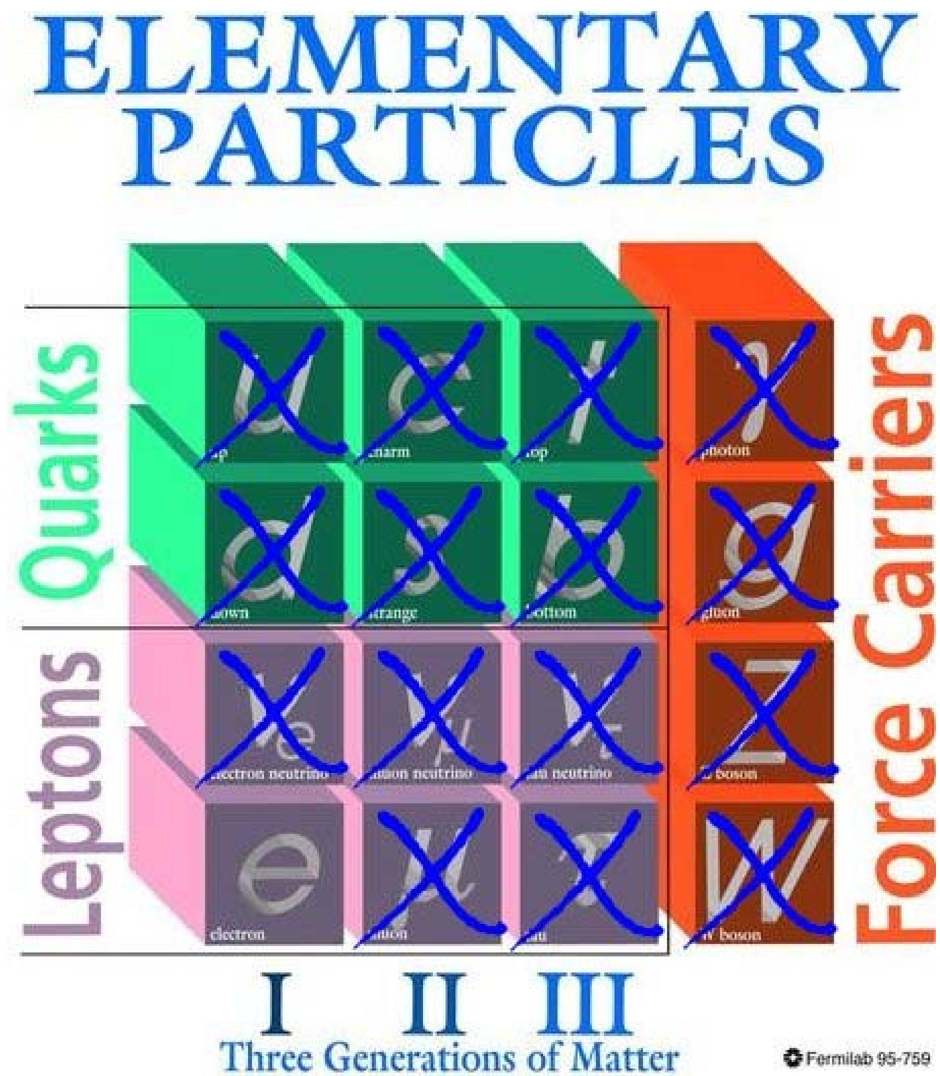
— WIMP properties
- stable
- non - baryonic



What is dark matter? (A particle theorist's view)

— WIMP properties

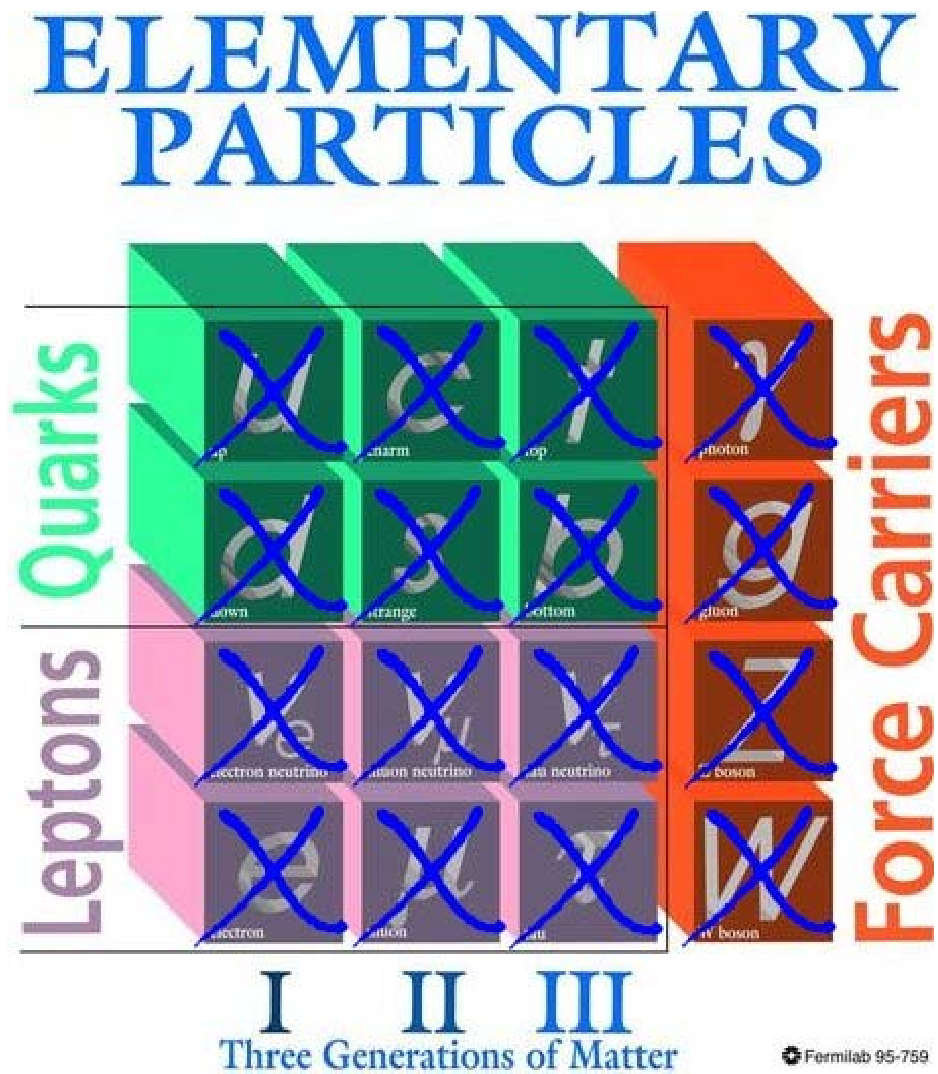
- stable
- non - baryonic
- non - relativistic



What is dark matter? (A particle theorist's view)

— WIMP properties

- stable
- non - baryonic
- non - relativistic
- weakly interacting



What is dark matter? (A particle theorist's view)

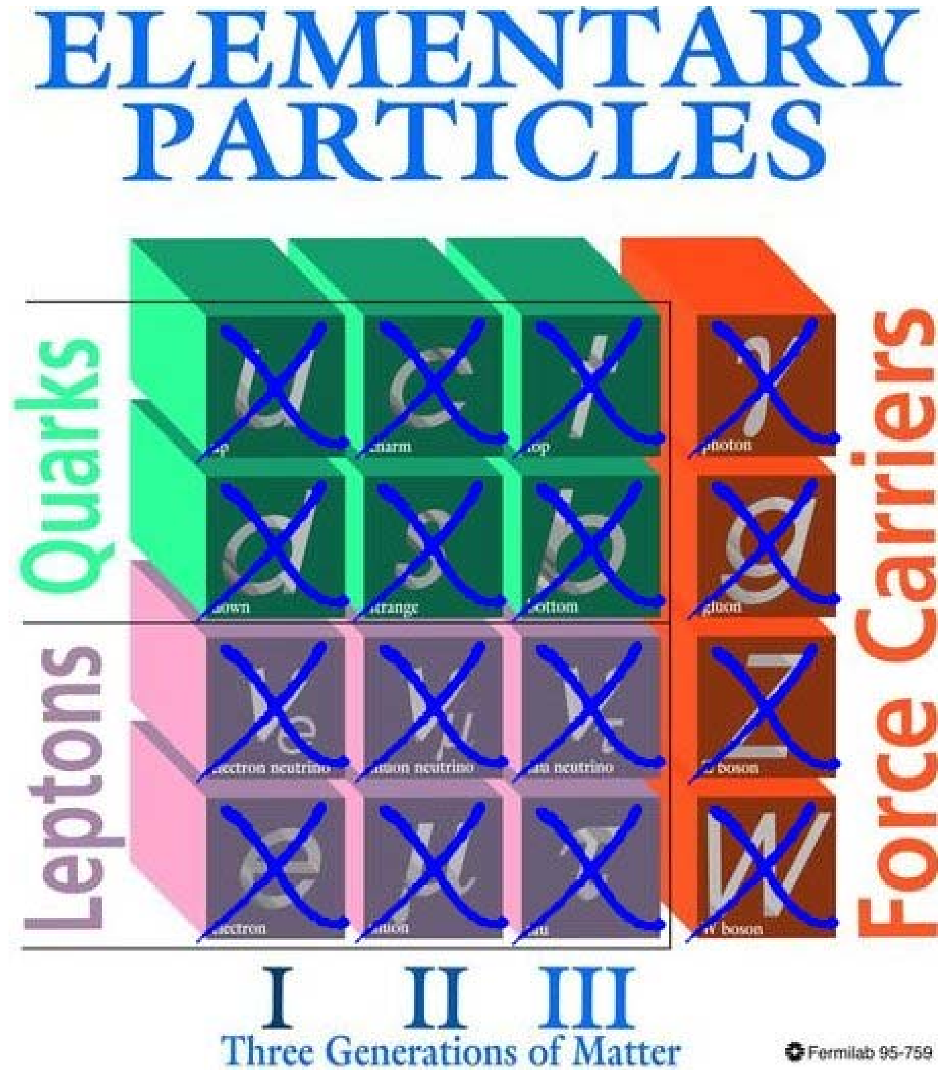
— WIMP properties

- stable
- non - baryonic
- non - relativistic
- weakly interacting

New physics !

— New matter originates from

- supersymmetry → LSP
- new space dimensions → LKP
- little Higgs + T parity → LTP
- ← ... your idea here ... → LXP



New physics? What new physics?

— WIMPs: LSP, LKP, LTP, LXP ...

— Quantum system: bosonic & fermionic harmonic oscillator

- Hamiltonian: $H = \sum_{i=1}^{2} (p_i^2 + \omega^2 x_i^2)/2 = \omega\,([b^+, b] + \{f^+, f\})/2$
- $[b, b^+] = \{f, f^+\} = 1,\ [b, b] = [b^+, b^+] = [b, f] = \ldots = \{f^+, f^+\} = \{f, f\} = 0$

— Generators of super-transformations

- $Q_- = \sqrt{2\omega}\, b^+ f,\ Q_+ = \sqrt{2\omega}\, b f^+$ transform bosons ↔ fermions
- easy to show: $[H, Q_\pm] = 0$ i.e.: H is supersymmetric

— MSSM: minimal supersymmetric version of the standard particle model

- SUSY: protects low Higgs mass from quantum corrections, generates dynamics of spontaneous EWSB, unifies gauge couplings, improves fits to EW data, predicts $\sin^2\theta$ (w GUTs), postpones proton decay, ...
- superpartners: fermionic/bosonic copies of standard particles ($\tilde{Z}$, $\tilde{e}\tilde{t}\tilde{c}$.)
- R-parity: $P_R = (-1)^{3(B-L)+2S}$ → particles even, superpartners odd
- LSP: lightest superpartner is stable

LSP candidates

— Neutral standard fields and their superpartners in the MSSM

spin \ mass	$M_{3/2}$	M_1	M_2	μ	μ	$m_{\tilde{a}}$	$m_{\tilde{\nu}}$
2	G						
3/2	$\tilde{G}$						
1		B	W^0				
1/2		$\tilde{B}$	$\tilde{W}^0$	$\tilde{H}_u$	$\tilde{H}_d$	$\tilde{a}$	ν_i
0				H_u	H_d	a	$\tilde{\nu}_i$

— Neutral superparticles

- sneutrino: $\Omega_{\tilde{\nu}} \lesssim 0.1$ if $m_{\tilde{\nu}} \gtrsim$ few hundred GeV
- neutralino: $\tilde{Z}_1 = n_{11}\tilde{B} + n_{10}\tilde{W}^0 + n_{1i}\tilde{H}_i$, 10 GeV $\lesssim m_{\tilde{Z}_1} \lesssim$ 1 TeV
- gravitino: spartner of graviton, m_G
- axino: spartner of axion
- singlino: massive, stable, neutral partner of Z' in gauge extensions
- gauge singlet scalars

What is the LSP? ← How is SUSY broken?

— Sparticle spectrum

← GUT scale BCs

← SUSY breaking

— Hidden sector models

~~SUSY~~ mediated by

- gravity : mSUGRA

  LSP = $\tilde{Z}_1$

- gravity : AMSB

  LSP = $\tilde{Z}_1$

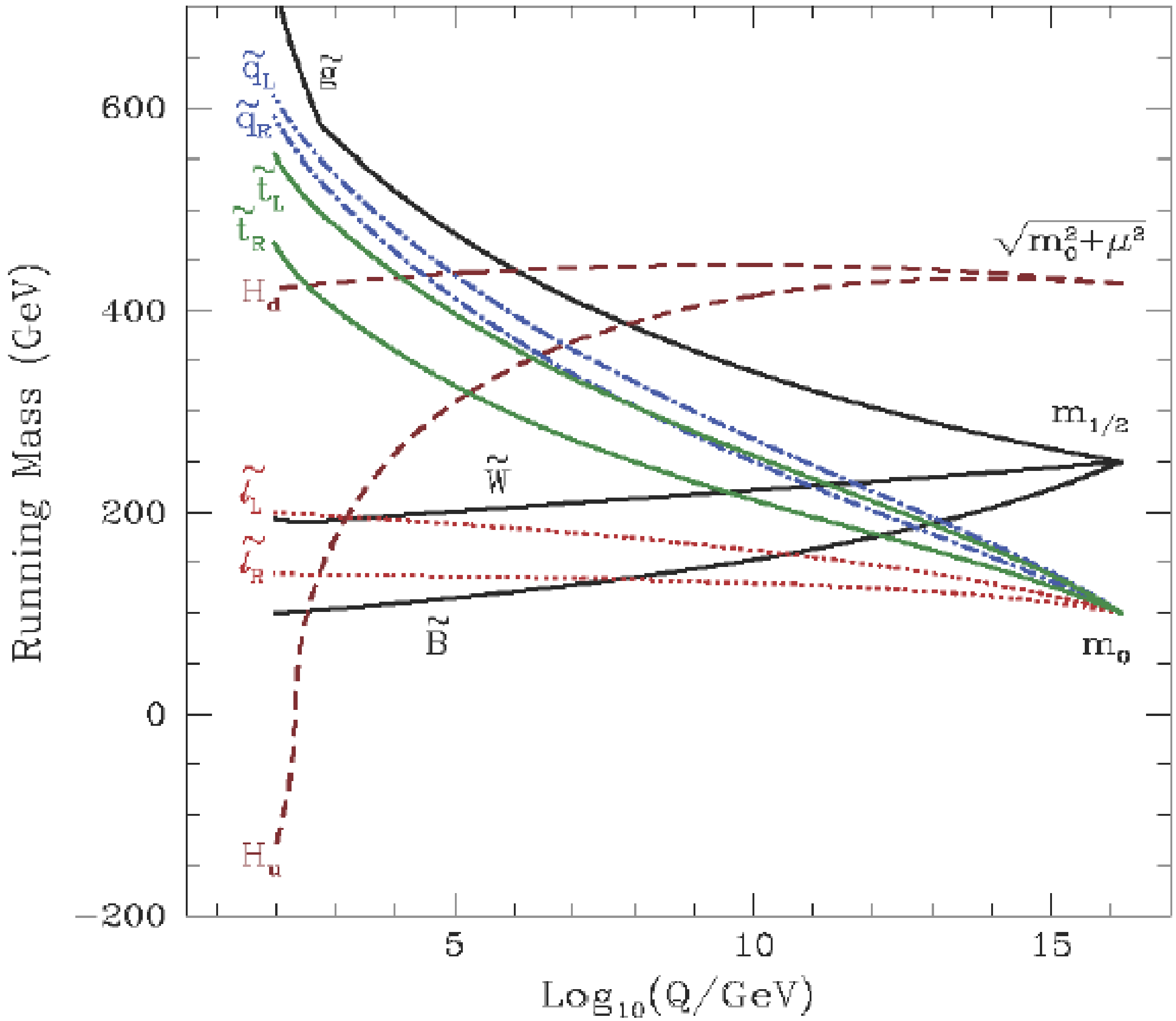
- gauge ia.s : GMSB

  LSP = $\tilde{G}$

- gauginos : $\tilde{g}$MSB

  LSP = $\tilde{Z}_1$

- brane/radion/... mediation



Olive 2003

Neutralino dark matter

— $\tilde{Z}_1$ properties

- stable (in models with R)
- non – baryonic, weakly ia
- mass ~ EW scale

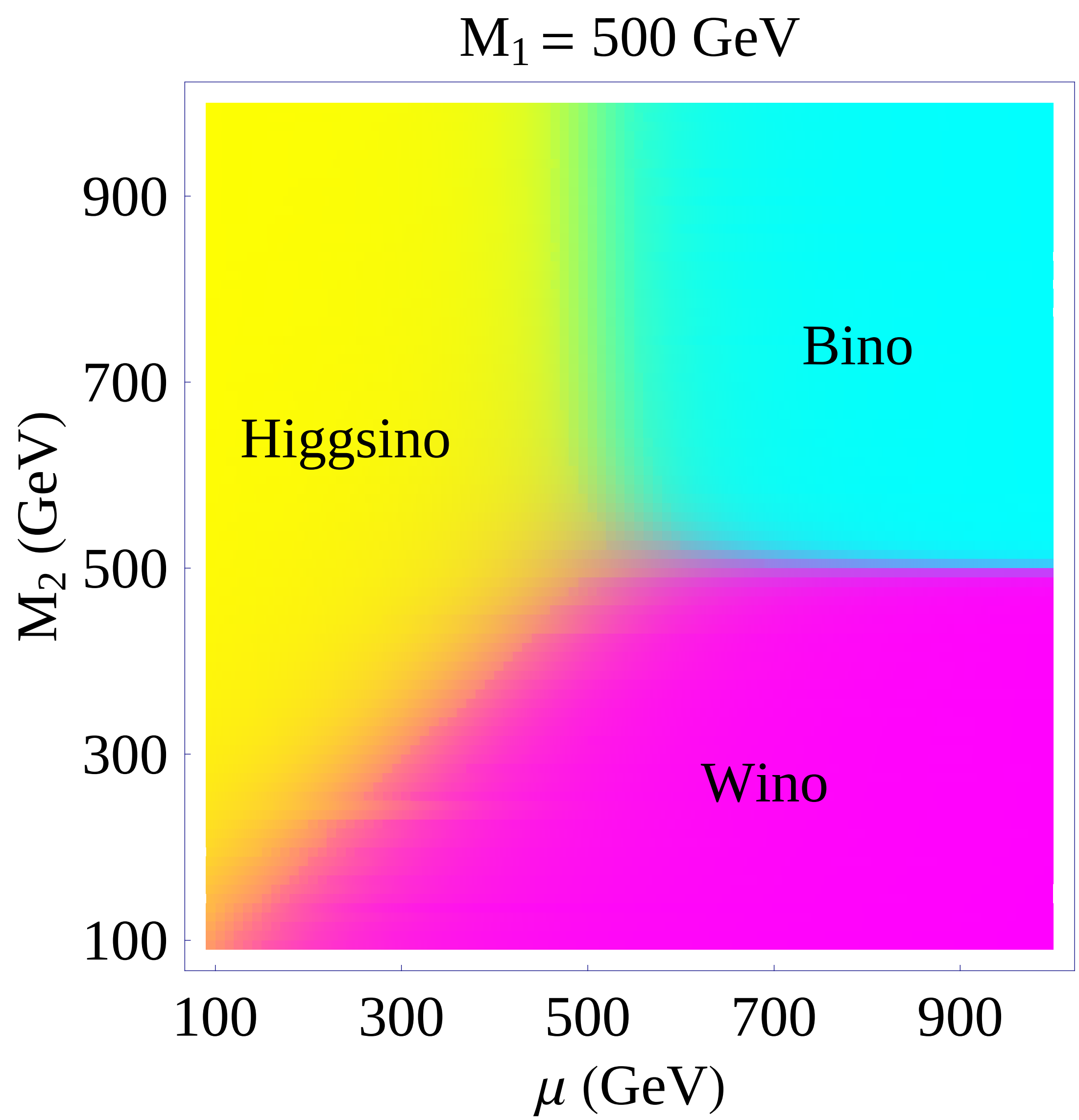
— $\tilde{Z}_1$ mass eigenstate =

$$n_{11}\,\tilde{B} + n_{1i}\,\tilde{H}_i + n_{13}\,\tilde{W}_3$$

— $\tilde{Z}_1$ relic abundance

$$\Omega_{\tilde{Z}_1} \sim \sigma_{eff}^{-1}$$

admixture	σ_{eff}	$\Omega_{\tilde{Z}_1}$
Bino	small	large
Higgsino	large	small
Wino	huge	tiny



Balázs 2005

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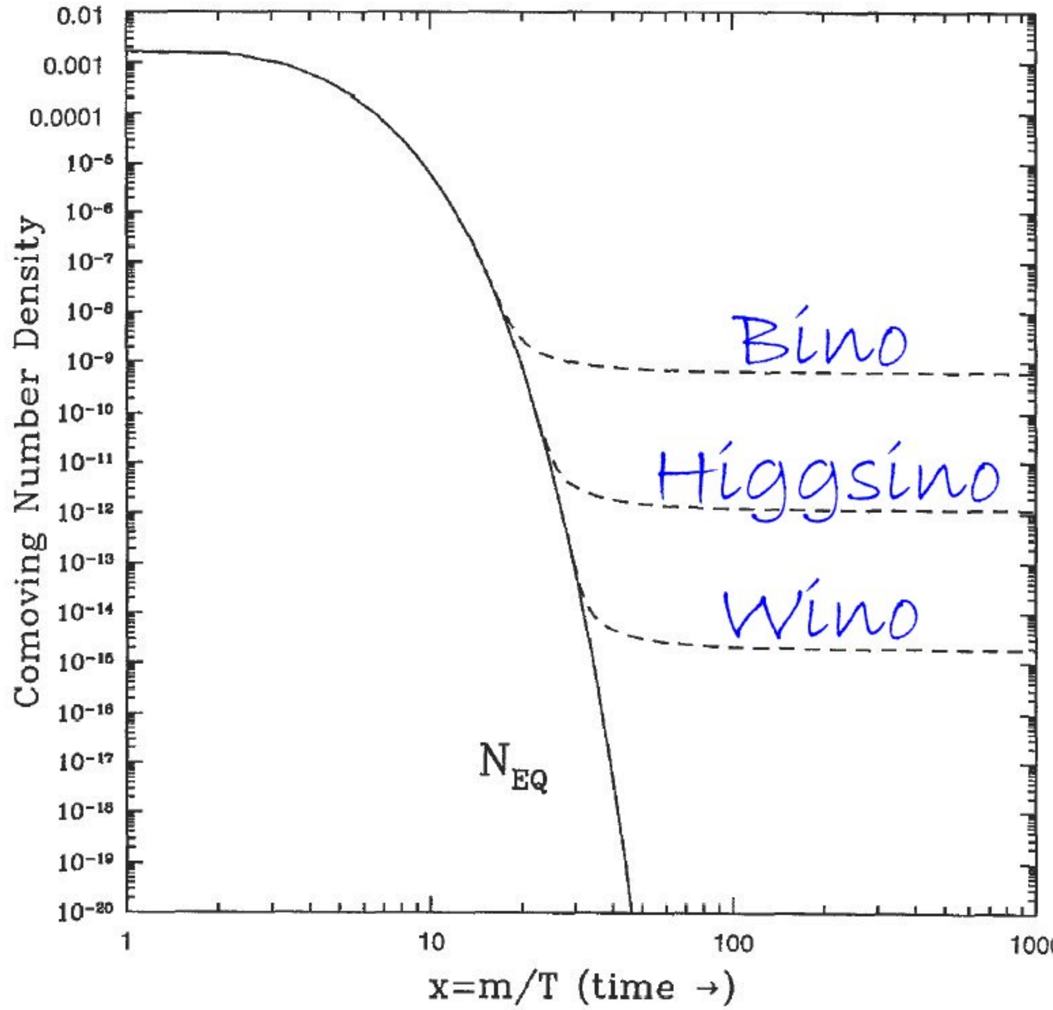


Kolb, Turner 1989

mSUGRA (CMSSM)

— The paradigm

$$\mathcal{L}_{soft} \sim m_{ij}^2 \phi_i^\dagger \phi_j + \frac{1}{2} m_a \overline{\lambda_a} \lambda_a + \frac{1}{3!} A_{ijk} \phi_i \phi_j \phi_k \supset \mu B H_u H_d$$

- universal BCs at $M_{GUT} \to m_0, m_{1/2}, A_0, B$ (legacy of old SUGRA models)
- B is traded to $v_u/v_d = \tan\beta$
- radiative electroweak symmetry breaking & $m_Z \Rightarrow \mu^2 \to \text{sign}(\mu)$ is free
- (SM–2+) 5 free parameters; MSSM valid from M_{GUT} to $M_{EW} \to$ (s)particle spectrum can be calculated at M_{EW} using RGE

— The bino

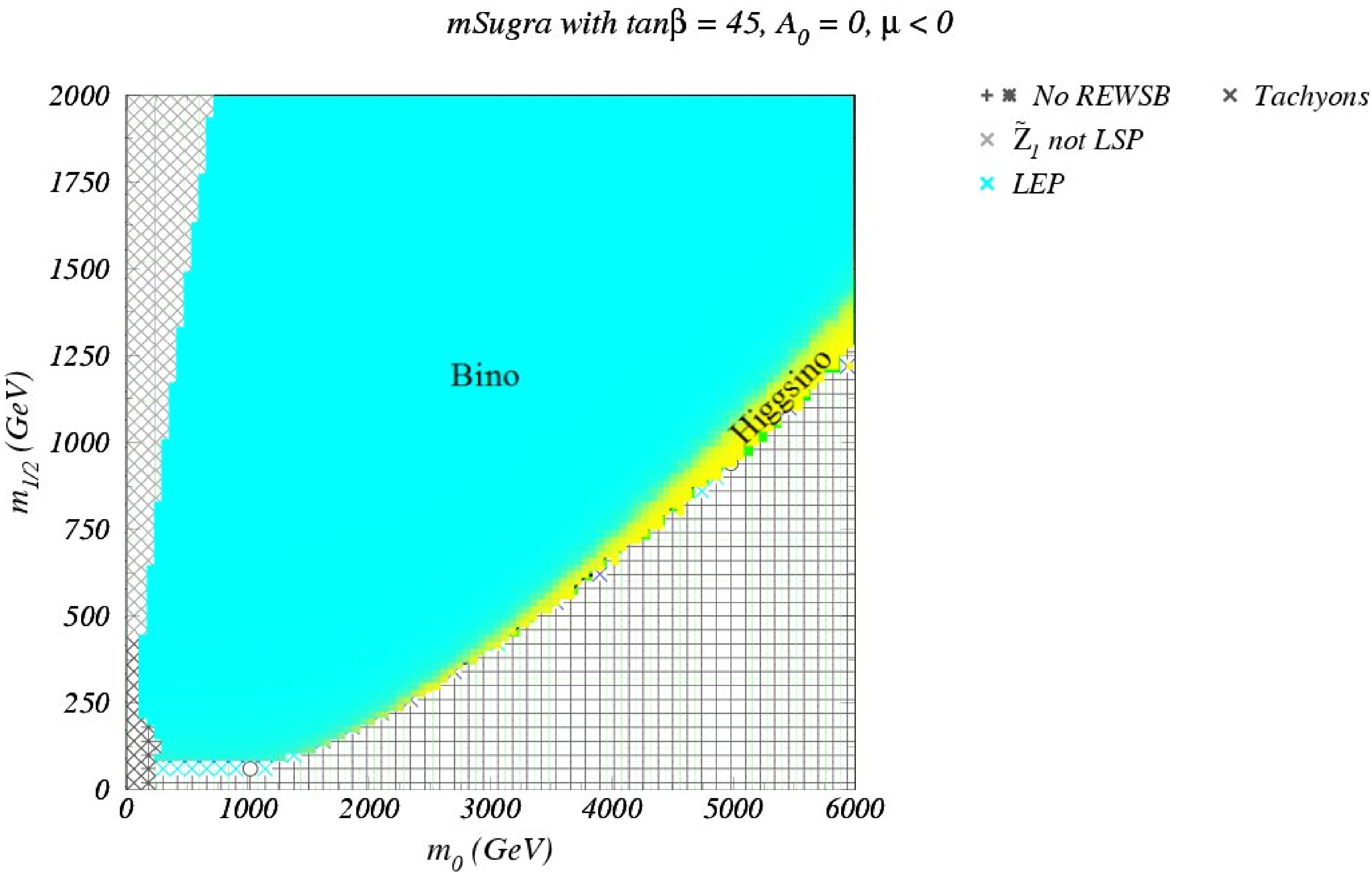
- $M_1/M_2 \sim 1/2 \leftarrow$ gauge unification
- $|\mu|$ fixed $\leftarrow$ radiative electroweak symmetry breaking

$\Rightarrow \tilde{Z}_1$ is bino in most of the mSUGRA parameter space

Many, many studies: Roszkowski,deAustri,Nihei; Djouadi,Drees,...;

deBoer,Huber,Sander,Kazakov; Ellis,Olive,...; Baer,Balázs,...

Dark matter = neutralino (An example)



Baer,Balázs JCAP0305(2003)

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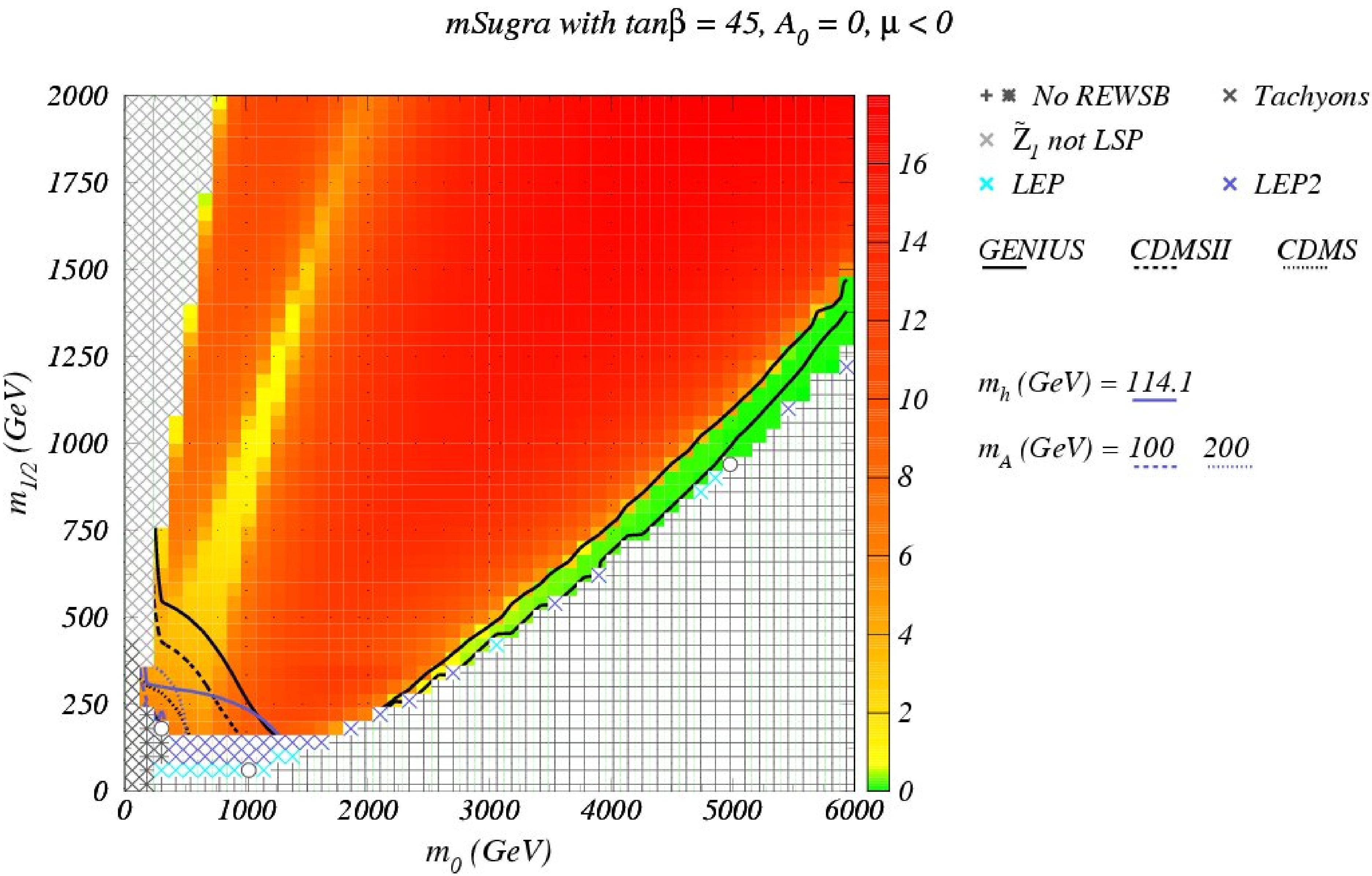

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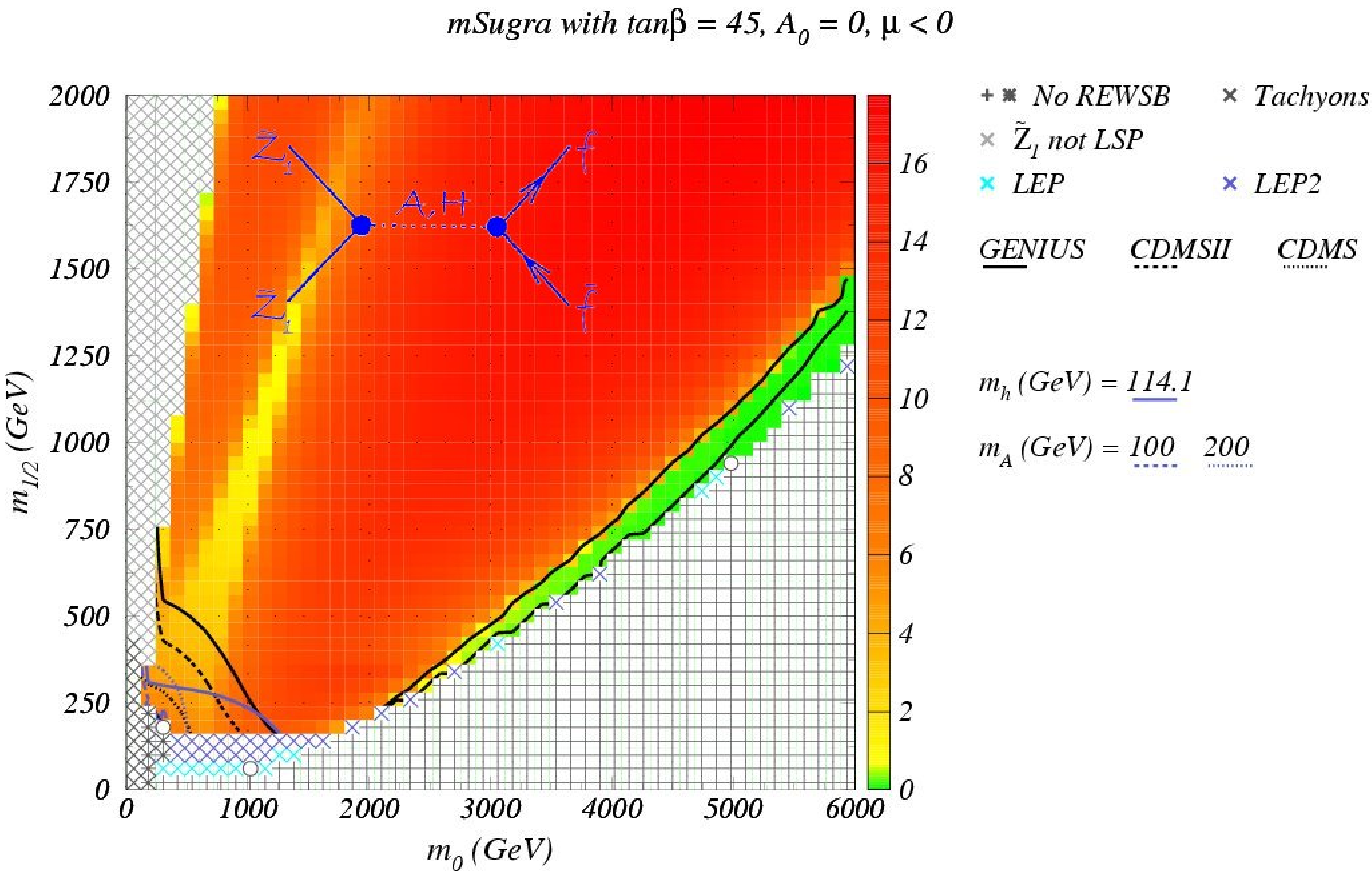

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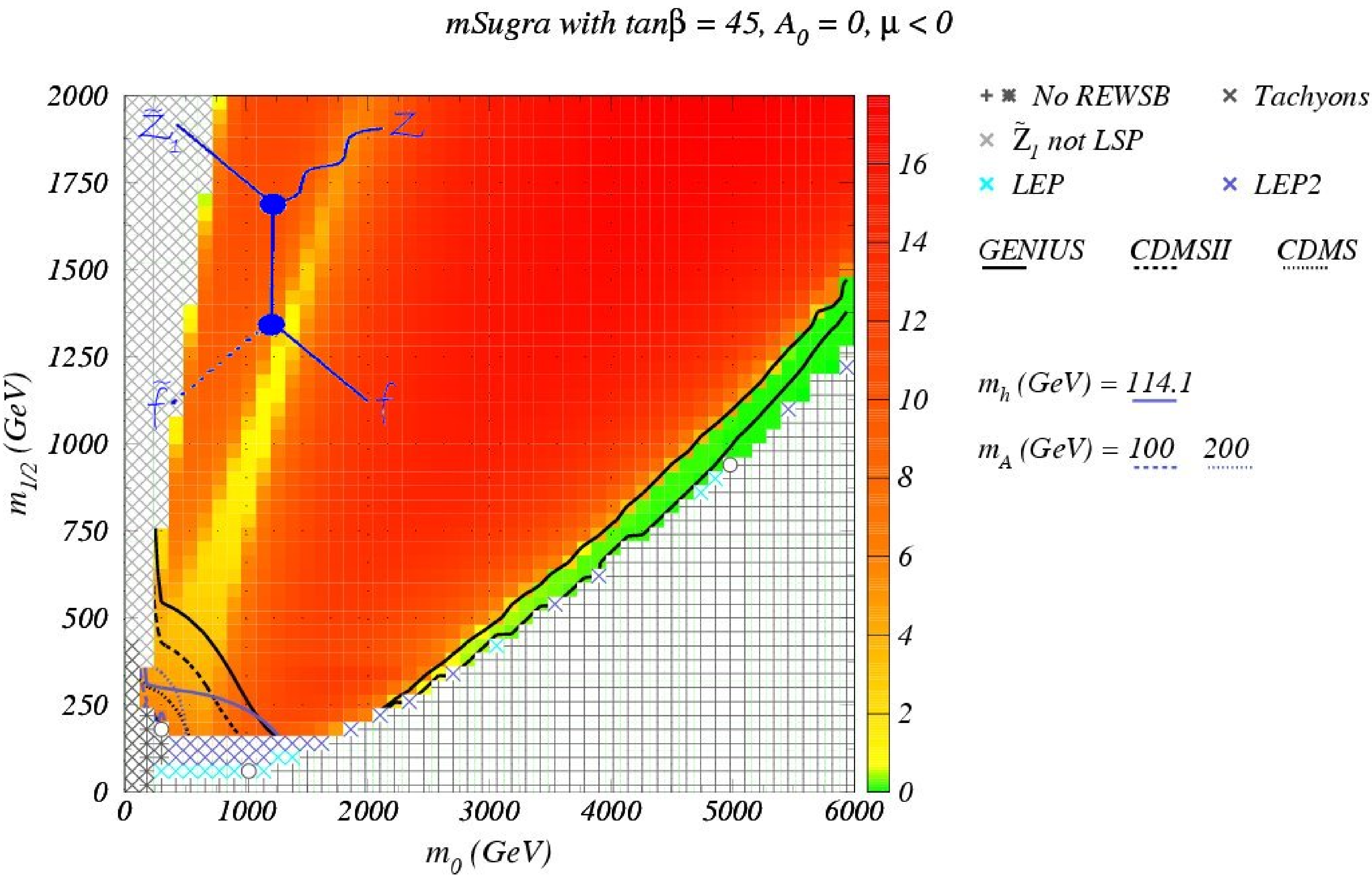

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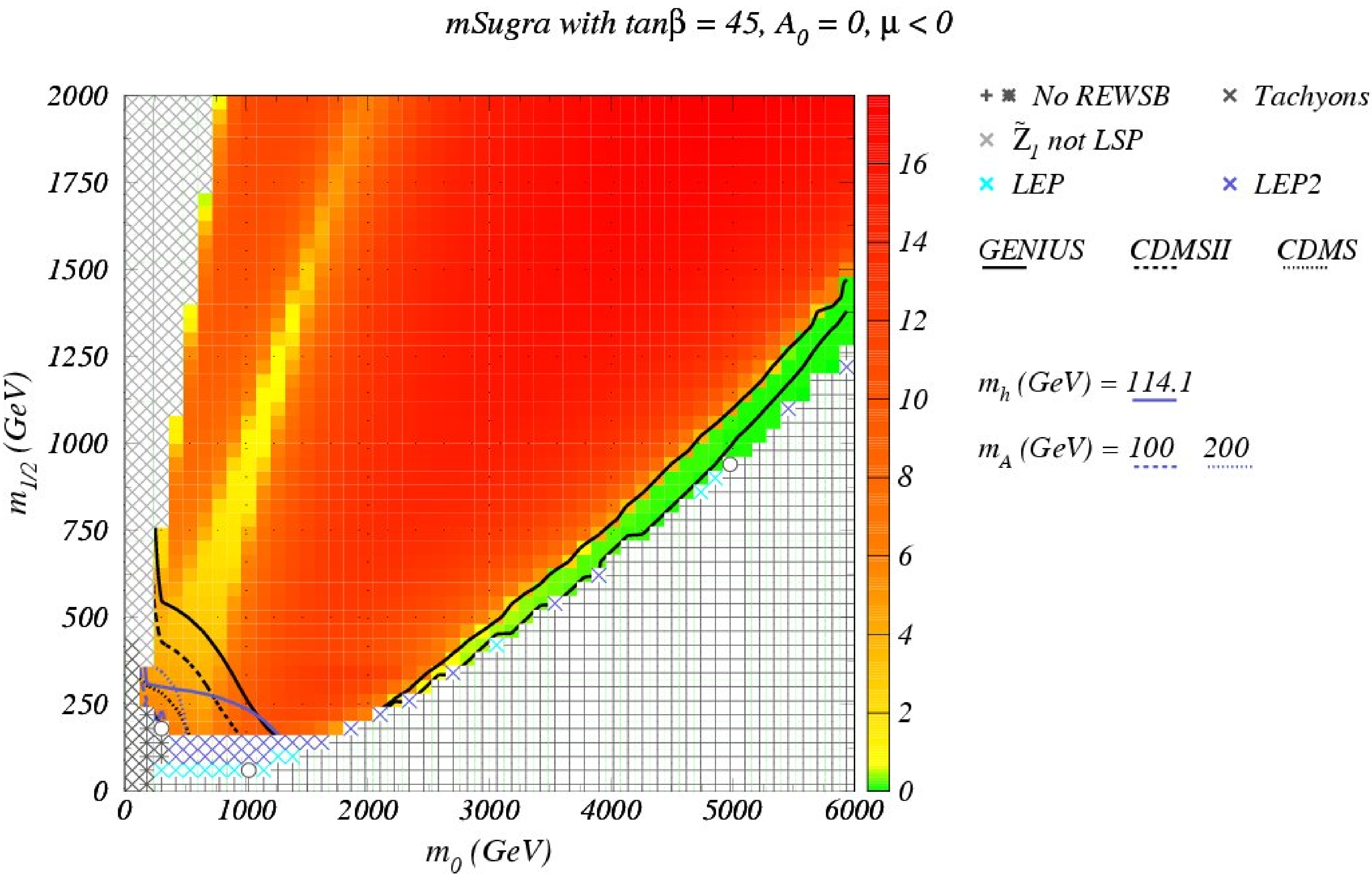
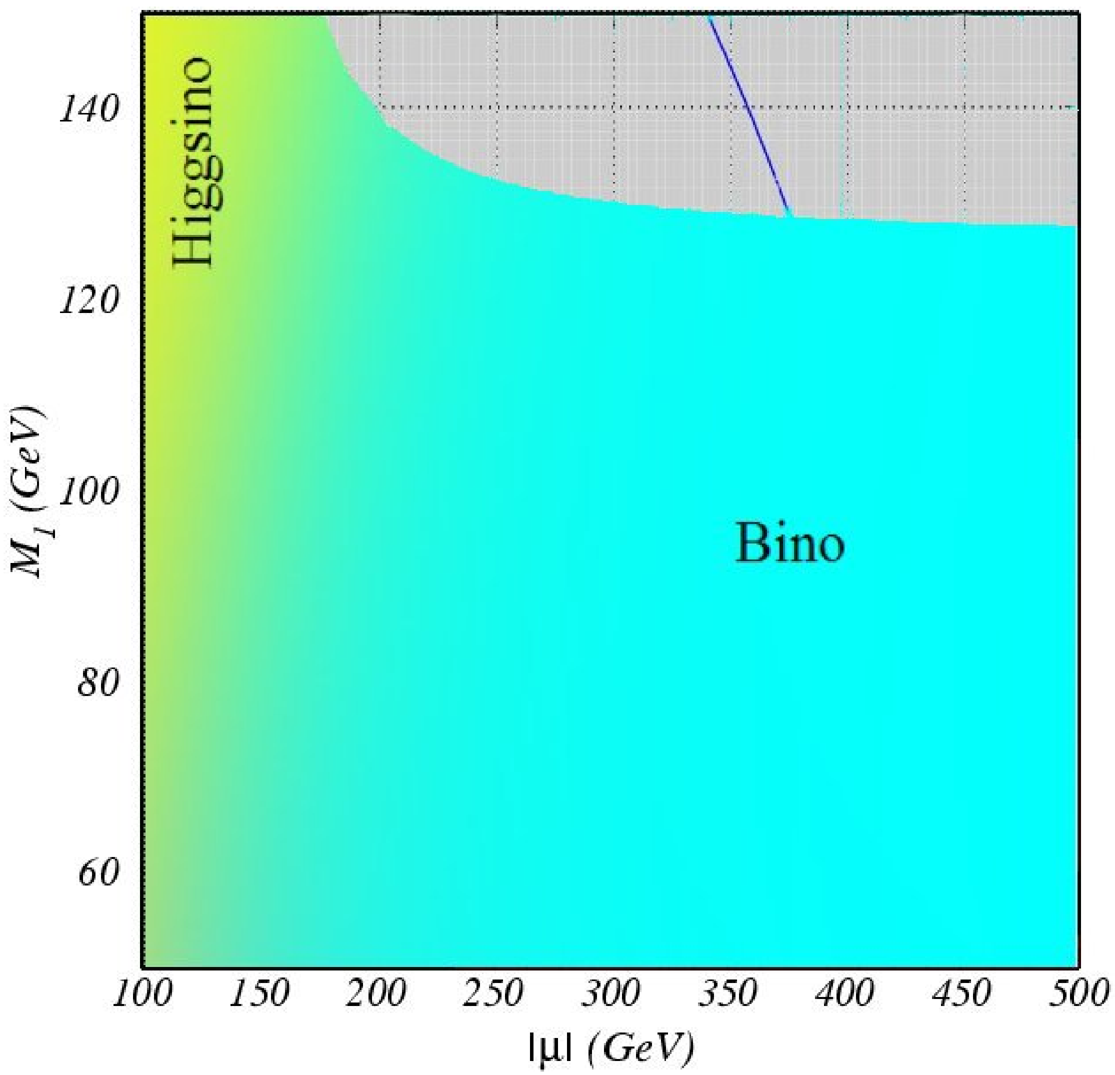


Baer, Balázs JCAP0305(2003)

Dark matter = neutralino (An another example)

– Can η_B & Ω_{CDM} be simultaneously generated in BMSSM?

- Can we predict all the matter content of the Universe correctly?



Input parameters:

$\tan\beta = 7$, $m_A = 1000$ GeV, $Arg(\mu) = 1.571$

$M_2 = M_1 g_2^2/g_1^2$, $Arg(M_1) = Arg(M_2) = 0$, $M_3 = 1$ TeV

$m_{U3} = 0$ GeV, $m_{Q3} = 1.5$ TeV, $X_t = 0.7$ TeV

$m_{L3}, m_{E3}, m_{D3} = 1$ TeV

$m_{L1,2}, m_{E1,2} = 10$ TeV

$m_{Q1,2}, m_{U1,2}, m_{D1,2} = 10$ TeV

Legend:

$m_{t1} > m_{Z1}$

Balázs, Carena, Menon, Morrissey, Wagner 2004

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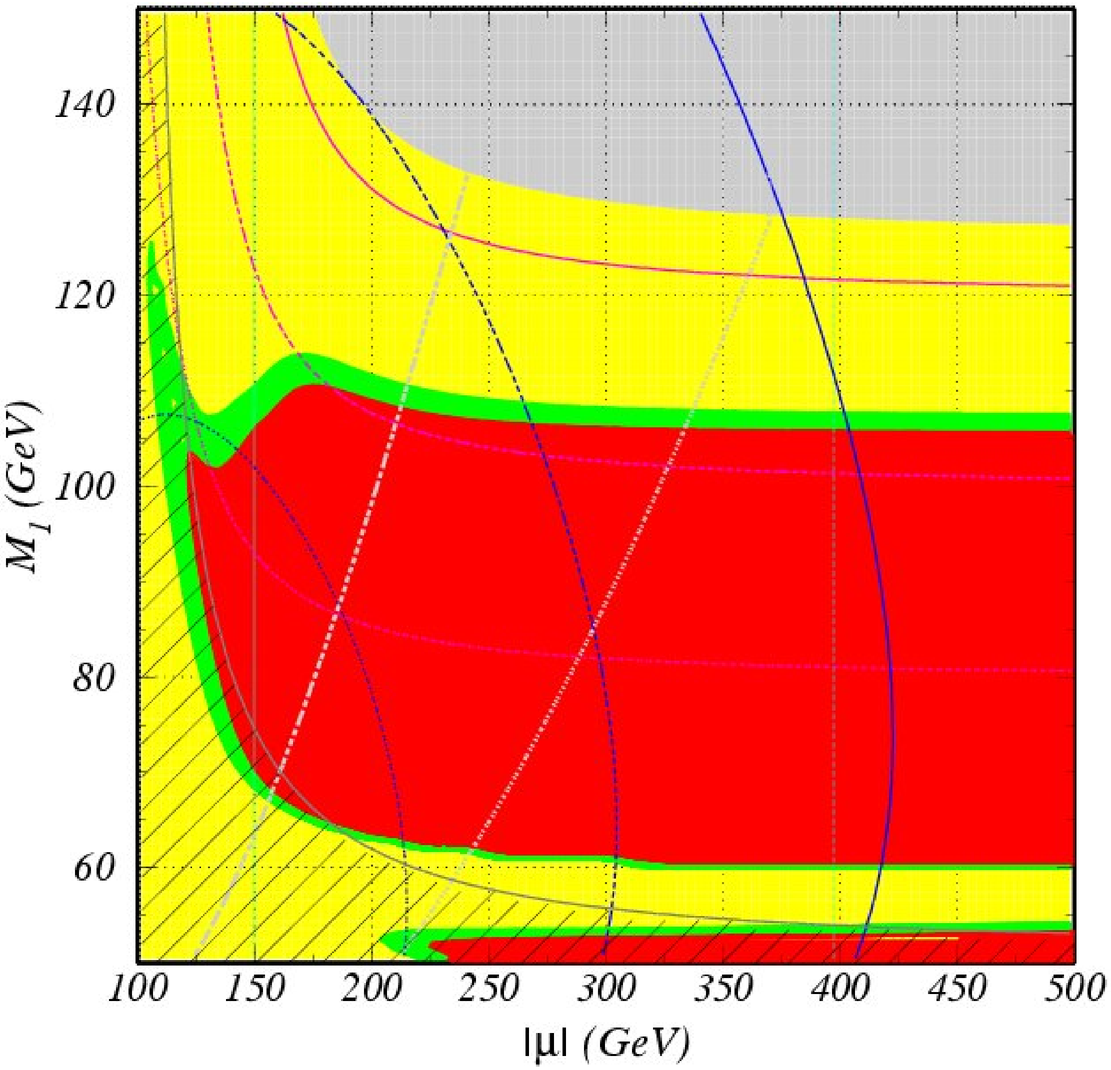

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Legend:

$m_{t1} > m_{Z1}$ | $m_{W1} < 103.5$ GeV

$\Omega h^2 > 0.129$ | $\Omega h^2 < 0.095$

$0.095 < \Omega h^2 < 0.129$

σ_{si} = 3E-08 3E-09 3E-10 pb

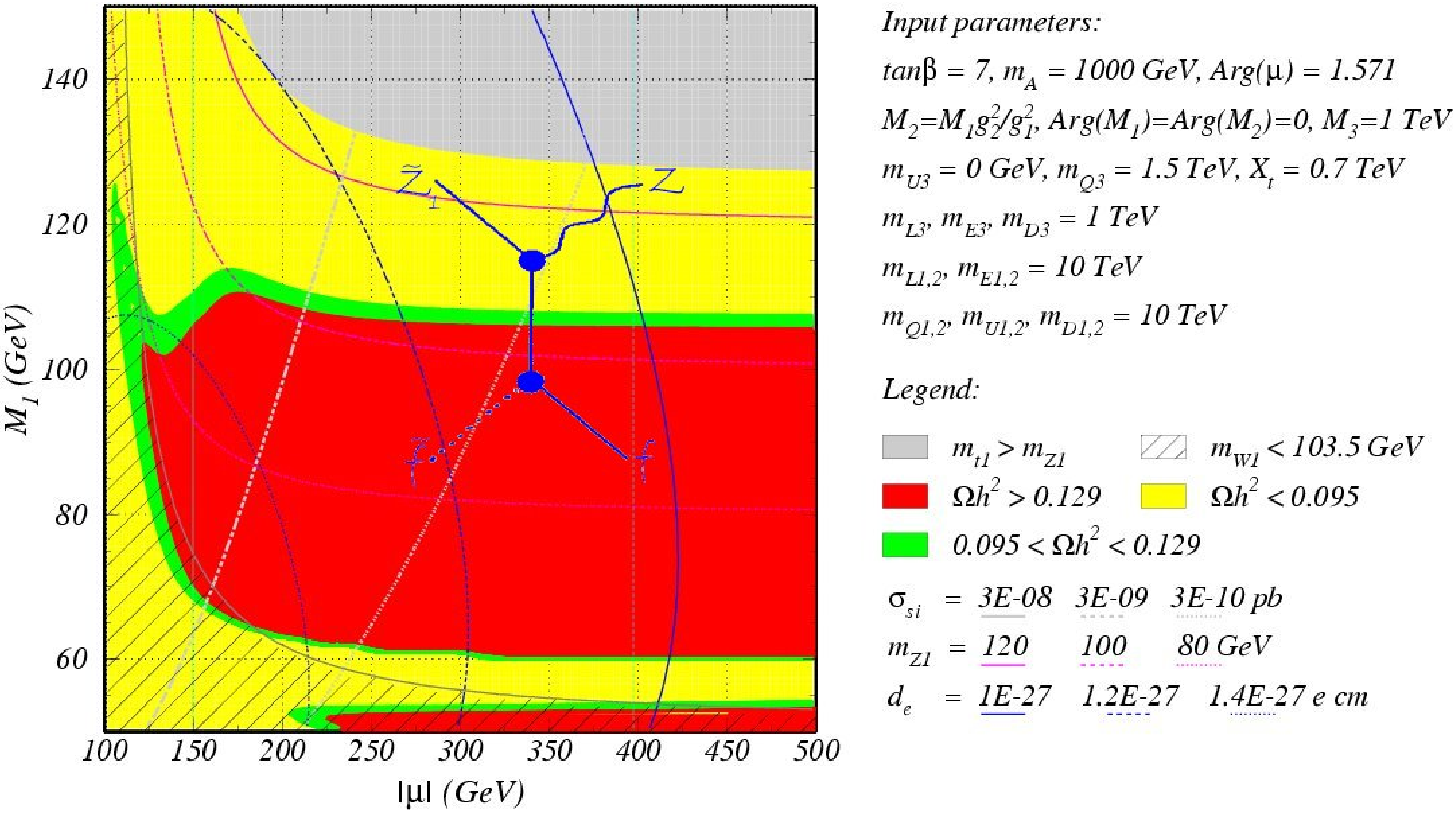
m_{Z1} = 120 100 80 GeV

d_e = 1E-27 1.2E-27 1.4E-27 e cm

Balázs, Carena, Menon, Morrissey, Wagner 2004

Dark matter = neutralino (An another example)

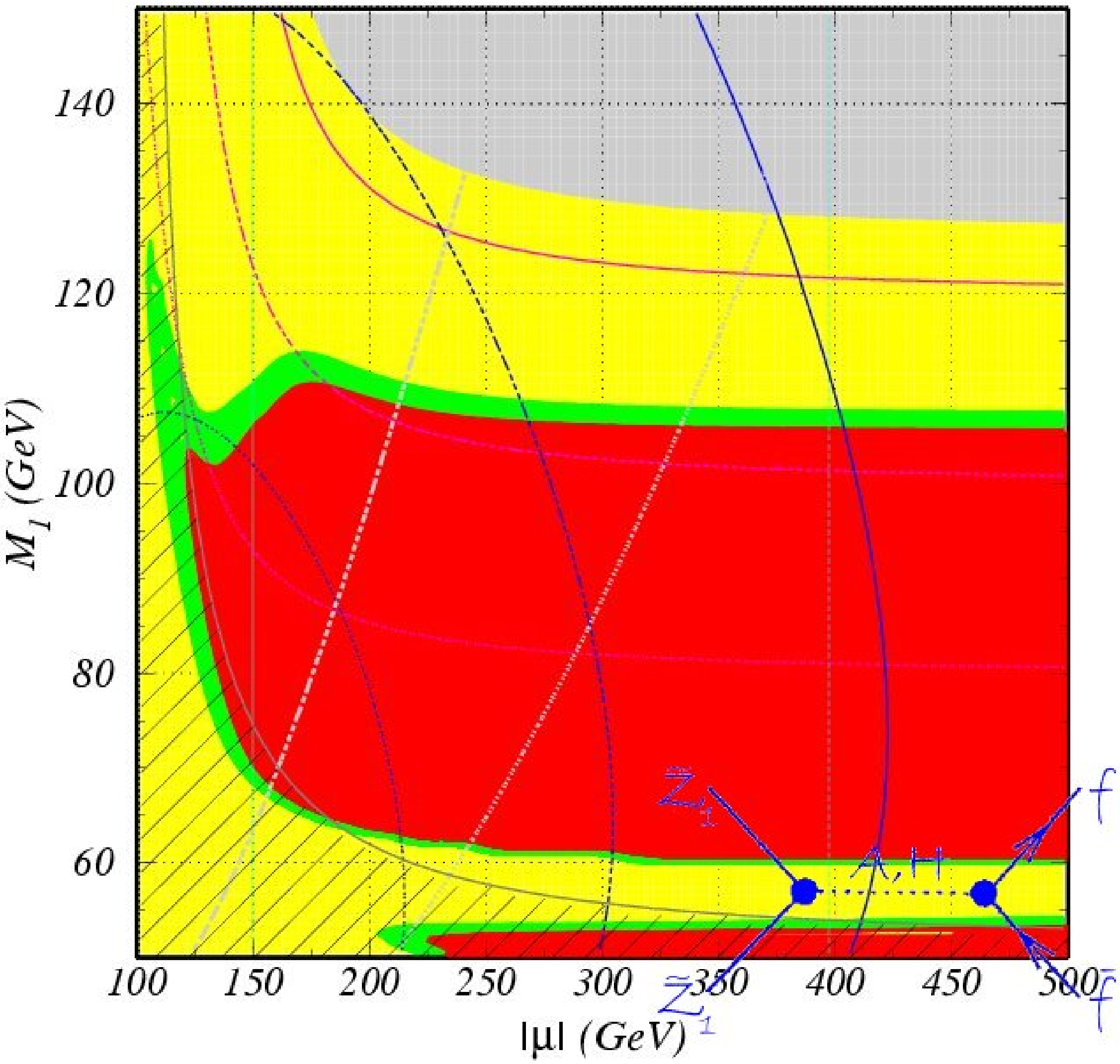
— $\tilde{t}_1$-$\tilde{Z}_1$ coannihilation lowers the neutralino relic density to agree with WMAP where $m_{\tilde{t}_1} \sim m_{\tilde{Z}_1}$



Balázs, Carena, Menon, Morrissey, Wagner 2004

Dark matter = neutralino (An another example)

— Annihilation via the h^0 (A^0) resonance also lowers the neutralino relic abundance to agree with WMAP where $2m_{\tilde{Z}_1} \sim m_{h^0(A^0)}$



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$m_{L1,2}$, $m_{E1,2} = 10$ TeV

$m_{Q1,2}$, $m_{U1,2}$, $m_{D1,2} = 10$ TeV

Legend:

- $m_{t1} > m_{Z1}$ (grey)
- $m_{W1} < 103.5$ GeV (hatched)
- $\Omega h^2 > 0.129$ (red)
- $\Omega h^2 < 0.095$ (yellow)
- $0.095 < \Omega h^2 < 0.129$ (green)

σ_{si}	=	3E-08	3E-09	3E-10 pb
m_{Z1}	=	120	100	80 GeV
d_e	=	1E-27	1.2E-27	1.4E-27 e cm

Balázs,Carena,Menon,Morrissey,Wagner 2004

Dark matter = neutralino (Another example)

E Hall, Nomura; Dermisek, Mafi (`01)

↑	visible brane		bulk		hidden brane
M_P	MSSM matter		MSSM gauge (Higgs)		3x2x1 singlets
M_{GUT}	SU(5)	$\xleftarrow{\text{Higgs}}$	SO(10)	$\xrightarrow{\text{orbifold}}$	G
M_C	4D N=0 $\xleftarrow{\text{inoMSB}}$ N=1	$\xleftarrow{\text{orbifold}}$	5D N=1 SUSY	$\xrightarrow{\text{orbifold}}$	4D N=0
	$M_i \neq M_j > 0,\ m_0 \approx A_0 \approx B_0 \approx 0$		closed		
M_{EW}	$m_{\tilde{q},\tilde{l}},\ A_i,\ B_\mu > 0$				

→ y

— G can be
- Pati-Salam: $SO(6)xSO(4) \sim SU(4)xSU(2)_L xSU(2)_R$
- Georgi-Glashow: (flipped) $SU(5)xU(1)$, or
- Weinberg-Salam-Glashow: $SU(3)_C xSU(2)_L xU(1)_Y$

— If $G = SU(3)_C xSU(2)_L xU(1)_Y \Rightarrow M_1 : M_2 : M_3$ arbitrary

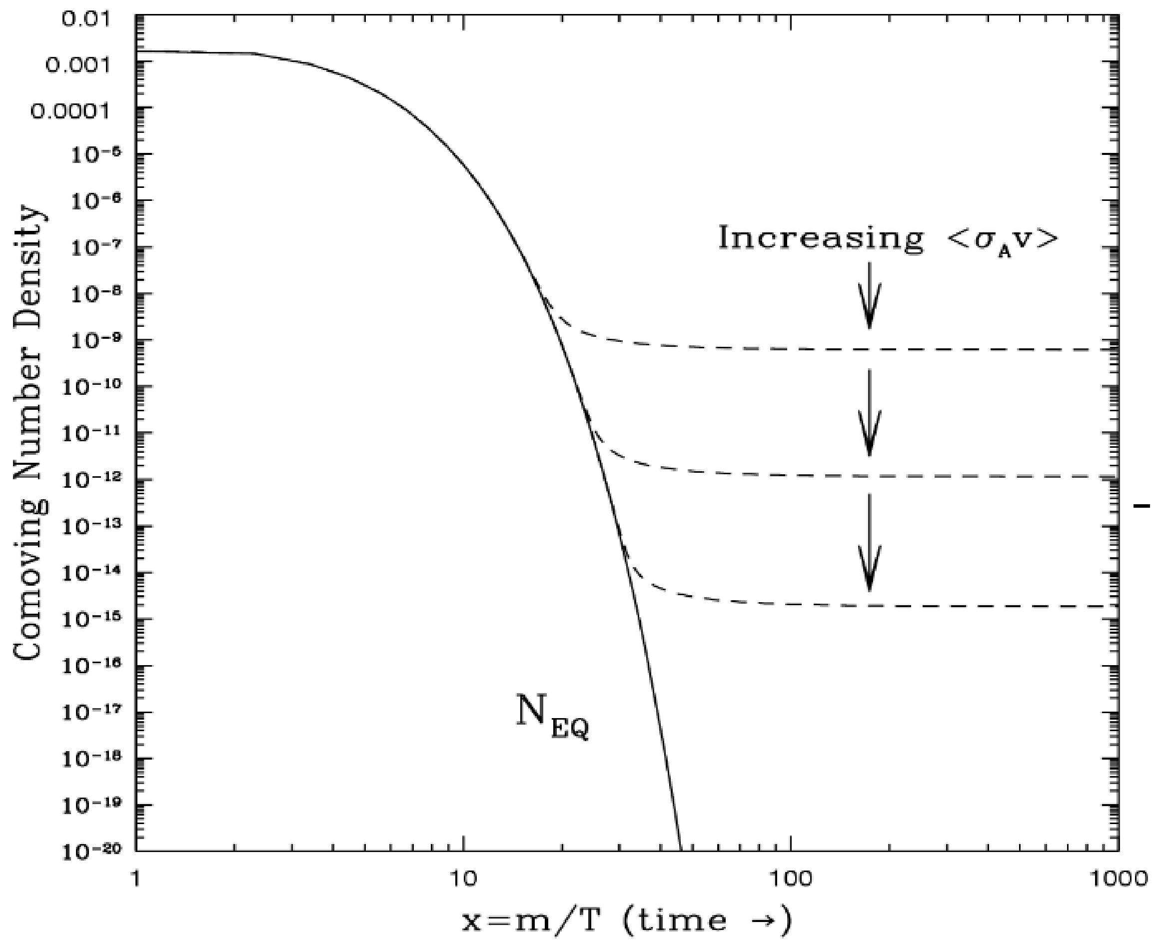
$\Rightarrow$ for $\forall\ \mu\ \exists\ \{M_1, M_2\}$ giving the right $\tilde{Z}_1$ admixture for WMAP!

Dark matter = gravitino

— Is it guaranteed that dark matter interacts with electroweak strength?

— If graviton LSP and WIMP NLSP with $\tau(\text{WIMP} \to \tilde{G}) \sim M_P^2 / M_W^3$ $\Rightarrow$ NO!

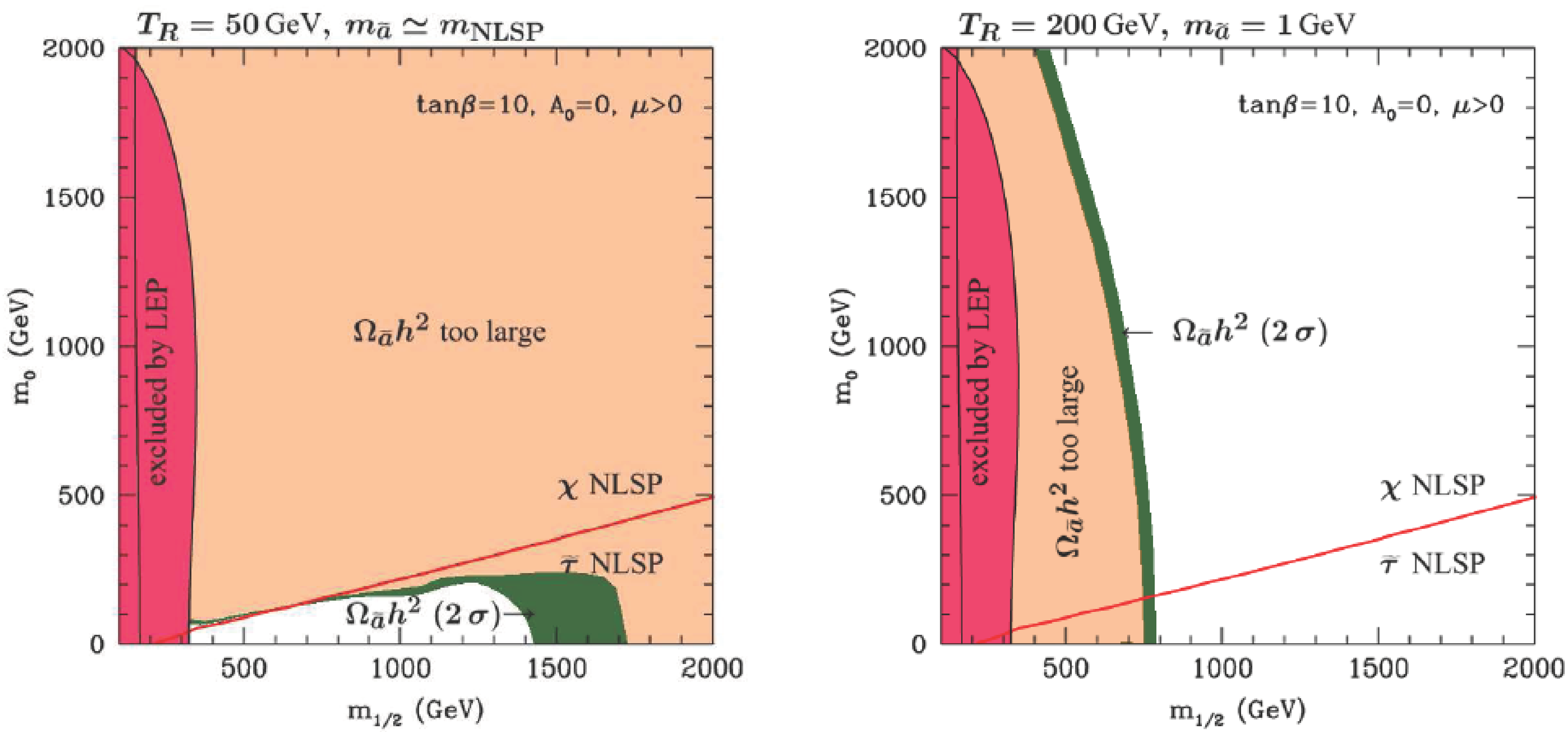
- after WIMP freezes it decays to $\tilde{G}$
- $\tilde{G}$ inherits WIMP relic density
- $\tilde{G}$ interacts only gravitationally
- only hope producing WIMP at colliders



Dark matter = axino

— Spartner of axion is viable DM candidate

- $m_{\tilde{a}} \sim$ eV - TeV a free parameter, couplings better known → relic density
- both thermal and non-thermal production is possible
- embedded in mSUGRA: axino complies with WMAP



Choi, Roszkowski 2005

Beyond the (MS)SM

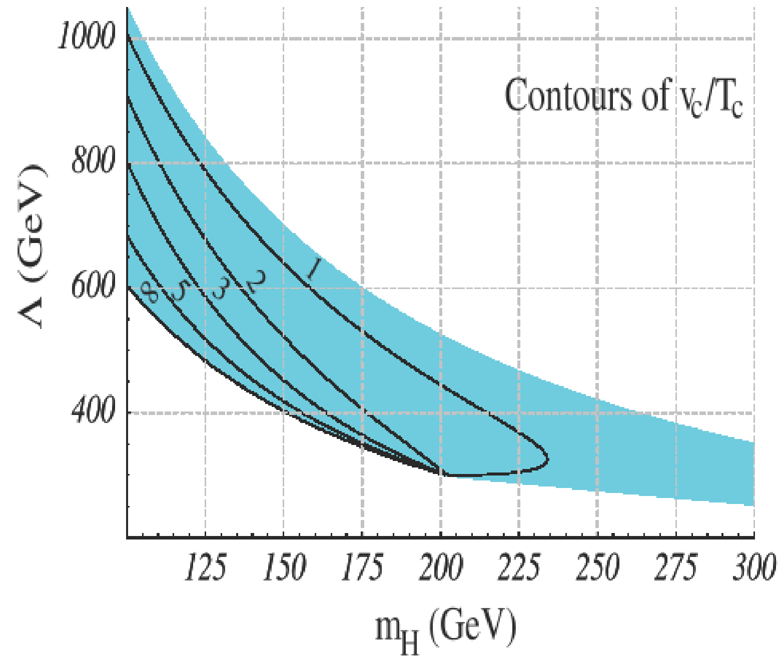
— Modifications of the Higgs potential

$V(\Phi) = \mu_H^2 |\Phi|^2 - \lambda |\Phi|^4 + \frac{1}{\Lambda} |\Phi|^6$,

- ease the upper Higgs mass limit from EWBG, opening up more para. space

  Grojean, Servant, Wells 2004

- this potential can be derived by decoupling a heavy scalar that couples to the Higgs sector



— Singlet extensions of the MSSM, like

- nMSSM

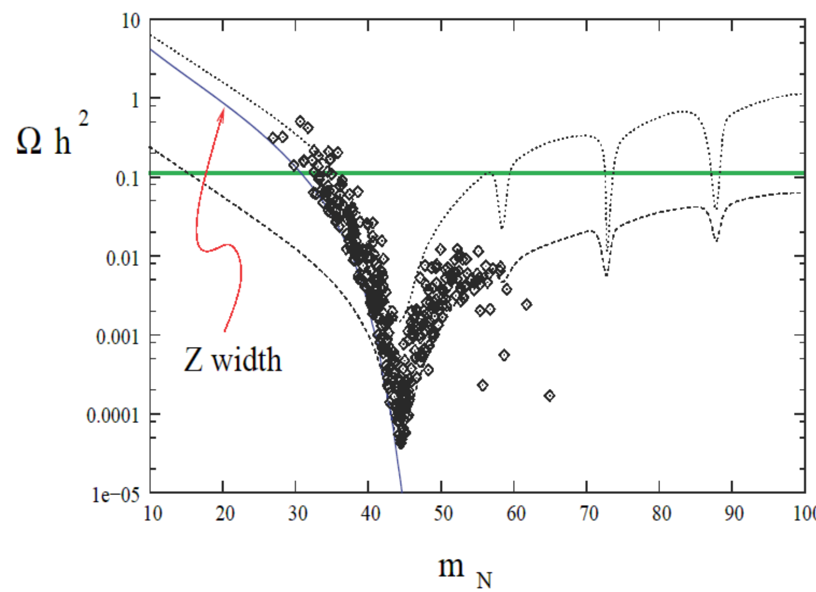
  $W = W_{MSSM} + \lambda \hat{S} H_1.H_2 + \frac{m_{12}^2}{\lambda^2} \hat{S}$

- NMSSM

  $W = W_{MSSM} + \lambda \hat{S} H_1.H_2 + \kappa \hat{S}^3$

offer more flexibility and easyly satisfy WMAP

Menon, Morrissey, Wagner 2004



Summary

— (Too) many dark matter candidates

— (Too) many supersymmetric scenarios

> A glance at SPIRES reveals that there are in excess of 3,000 papers discussing extra dimensions models which fit into the above categorization. I can summarize the current status of these extra dimensions models in two bullets:
>
> – There are too many models.
>
> – None of them are any good.

Lykken hep-ph/0503148

- (too) many of them are good (contrary to extra dimensional ones:)
- extensive experimental input from cosmology, astrophysics, direct and indirect dark matter searches, Tevatron, LHC, ILC, low energy experiments ($g-2$, $b \to s\gamma$, e^- EDM, ...), etc. is vital to figure out:

what dark matter is made of