DARK MATTER I

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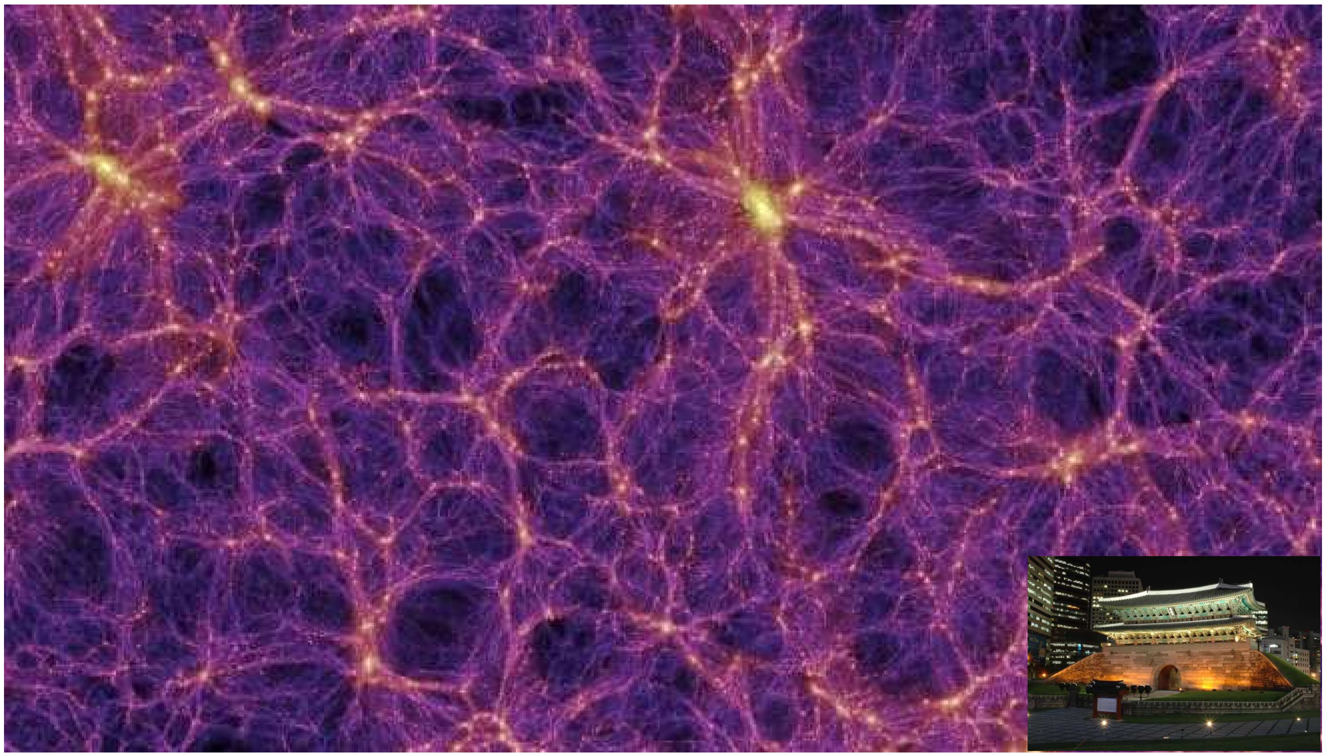


PRE-SUSY ’08, Seoul, Korea

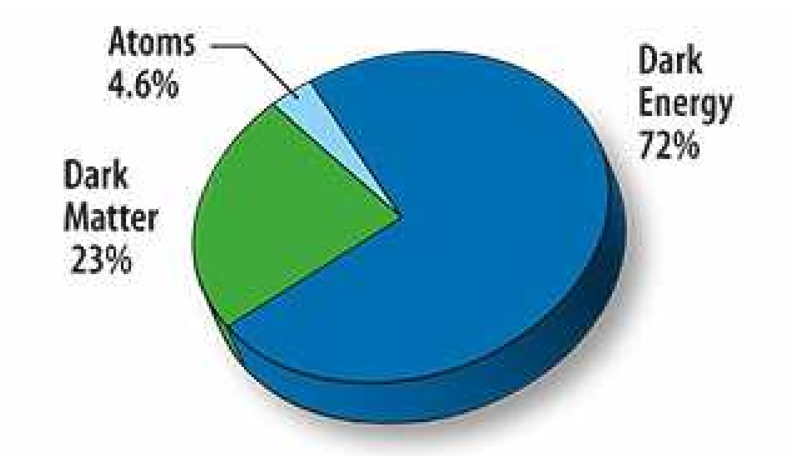
Plan of the 2 lectures on Dark Matter (theory):

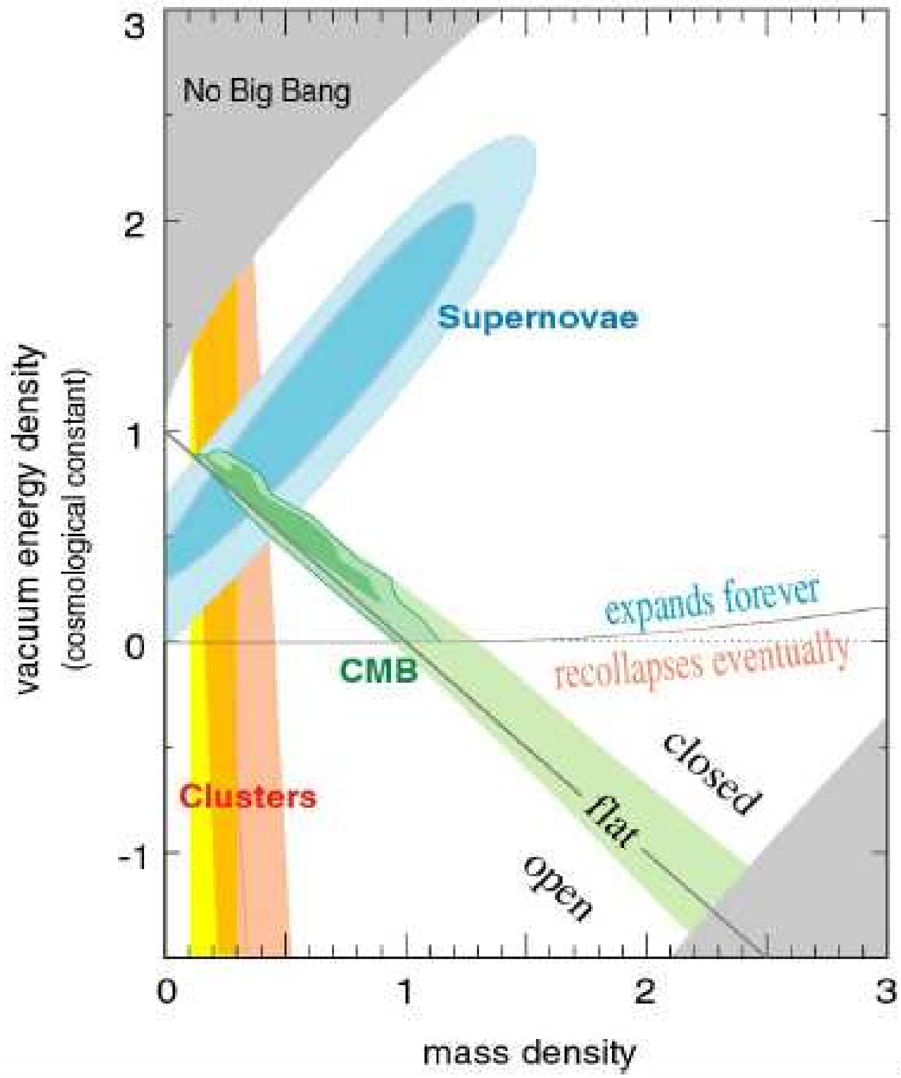
- Lecture 1
  - WIMP (Weakly Interacting Massive Particle) relic density
  - Particle WIMP candidates: neutralino and others (hints)
- Lecture 2
  - Direct and indirect detection of WIMPs
  (experiments covered by Youngduk Kim’s lecture)

N.B. I will not cover superWIMPS (gravitino, axino) which have interactions much below the weak scale
Viable candidates, can solve the Dark Matter problem but invisible to DM searches and hard (sometimes impossible!) to detect at accelerators

The concordance model

(more on that in D. Chung's lectures)

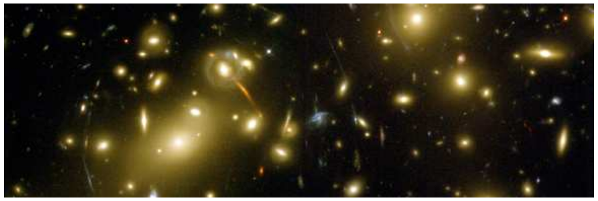


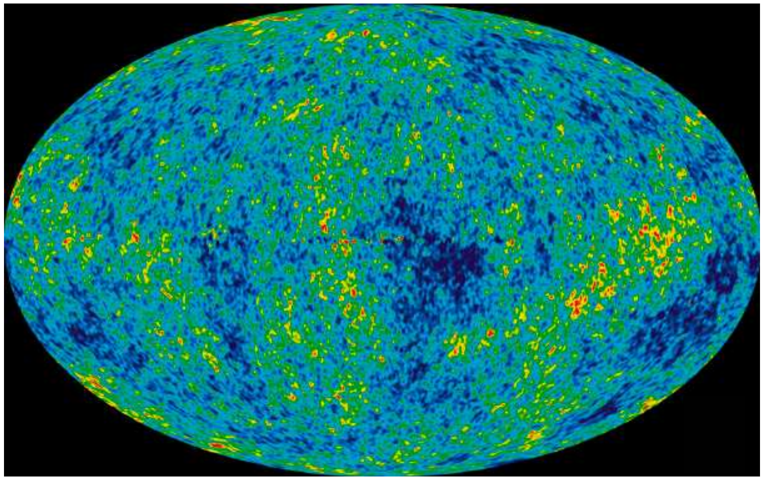


Evidence for Dark Matter

- Spiral galaxies
  - rotation curves
- Clusters & Superclusters
  - Weak gravitational lensing
  - Strong gravitational lensing
  - Galaxy velocities
  - X rays
- Large scale structure
  - Structure formation
- CMB anisotropy: WMAP
  - $\Omega_{tot}=1$
  - $\Omega_{dark\ energy}\sim 0.7$
  - $\Omega_{matter}\sim 0.27$
  - $\Omega_{baryons}\sim 0.05$
  - $\Omega_{visible}\sim 0.005$

$$\boxed{\Omega_{dark\ matter}\sim 0.22}$$





Apart from being unable to drive galaxy formation (they decouple too late from photons, not enough time for gravitational instabilites to grow) baryons are too few in the Universe in order to explain the dark matter because of nucleosynthesis

Observations give $0.6 < h < 0.8$

Big Bang nucleosynthesis (deuterium abundance) and cosmic microwave background (WMAP) determine baryon contribution $\Omega_B h^2 \approx 0.023$, so $\Omega_B \approx 0.04$

$\Omega_{lum} \approx (4 \pm 2) \cdot 10^{-3}$ (stars, gas, dust) => baryonic dark matter has to exist (maybe as warm intergalactic gas?)

But, now we know that $\Omega_M > 0.2$, so there has to exist non-baryonic dark matter

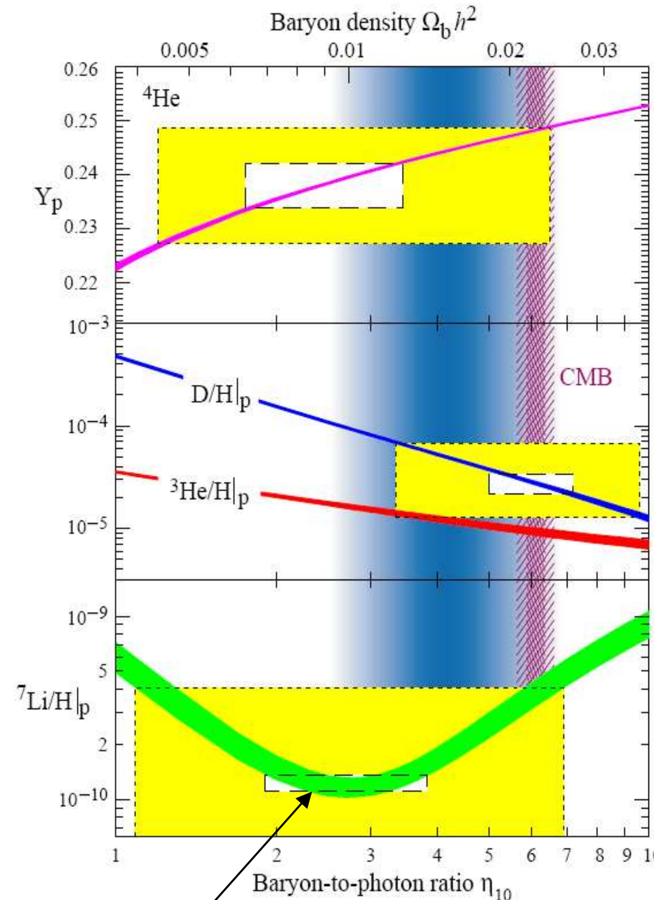


Figure 20.1: The abundances of ^{4}He, D, ^{3}He and ^{7}Li as predicted by the standard model of big-bang nucleosynthesis. Boxes indicate the observed light element abundances (smaller boxes: 2σ statistical errors; larger boxes: $\pm 2\sigma$ statistical and systematic errors added in quadrature). The narrow vertical band indicates the CMB measure of the cosmic baryon density. See full-color version on color pages at end of book.

Lithium underabundant?

Fields & Sarkar, 2004

A lot of matter in the Universe is dark and non-baryonic

The properties of a good Dark Matter candidate:

- ✓ stable (protected by a conserved quantum number)
- ✓ no charge, no colour (weakly interacting)
- ✓ cold, non dissipative
- ✓ relic abundance compatible to observation*
- ✓ motivated by theory (vs. “ad hoc”)

subdominant candidates – variety is common in Nature
→may be easier to detect

The first place to look for a DM candidate…

The Standard Model

GAUGE	Gauge bosons	$(SU(3)_c, SU(2)_L)_Y$
B-boson	$A_\mu^{(1)} = B_\mu$	$(\mathbf{1}, \mathbf{1})_0$
W-bosons	$A_\mu^{(2)\,a} = W_\mu^a$	$(\mathbf{1}, \mathbf{3})_0$
gluon	$A_\mu^{(3)\,a} = G_\mu^a$	$(\mathbf{8}, \mathbf{1})_0$

MATTER	Fermions	$(SU(3)_c, SU(2)_L)_Y$
leptons $I = 1, 2, 3$	$L^I = \begin{pmatrix} \nu_L^I \\ e_L^I \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{-1}$
	$E^{c\,I} = e_R^{-\,c\,I}$	$(\mathbf{1}, \mathbf{1})_{+2}$
quarks $I = 1, 2, 3$ ($\times$ 3 colors)	$Q^I = \begin{pmatrix} u_L^I \\ d_L^I \end{pmatrix}$	$(\mathbf{3}, \mathbf{2})_{+\frac{1}{3}}$
	$U^{c\,I} = u_R^{c\,I}$	$(\bar{\mathbf{3}}, \mathbf{1})_{-\frac{4}{3}}$
	$D^{c\,I} = d_R^{c\,I}$	$(\bar{\mathbf{3}}, \mathbf{1})_{+\frac{2}{3}}$

HIGGS	Higgs Boson	$(SU(3)_c, SU(2)_L)_Y$
Higgs	$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{+1}$

Weakly Interacting Massive Particles (WIMPs)

Particles with mass between a few GeV and a few TeV with cross sections of aproximately weak strength

THE ASTROPHYSICAL JOURNAL, **180**: 7–10, 1973 February 15

GRAVITY OF NEUTRINOS OF NONZERO MASS IN ASTROPHYSICS

R. COWSIK* AND J. MCCLELLAND
Department of Physics, University of California, Berkeley
Received 1972 July 24

ABSTRACT

If neutrinos have a rest mass of a few eV/c^2, then they would dominate the gravitational dynamics of the large clusters of galaxies and of the Universe. A simple model to understand the virial mass discrepancy in the Coma cluster on this basis is outlined.

Subject headings: cosmology — galaxies, clusters of — neutrinos

The idea was introduced 35 years ago for massive neutrinos.Now neutrinos are ruled out, but there is no shortage of alternative WIMPs!

Neutrino

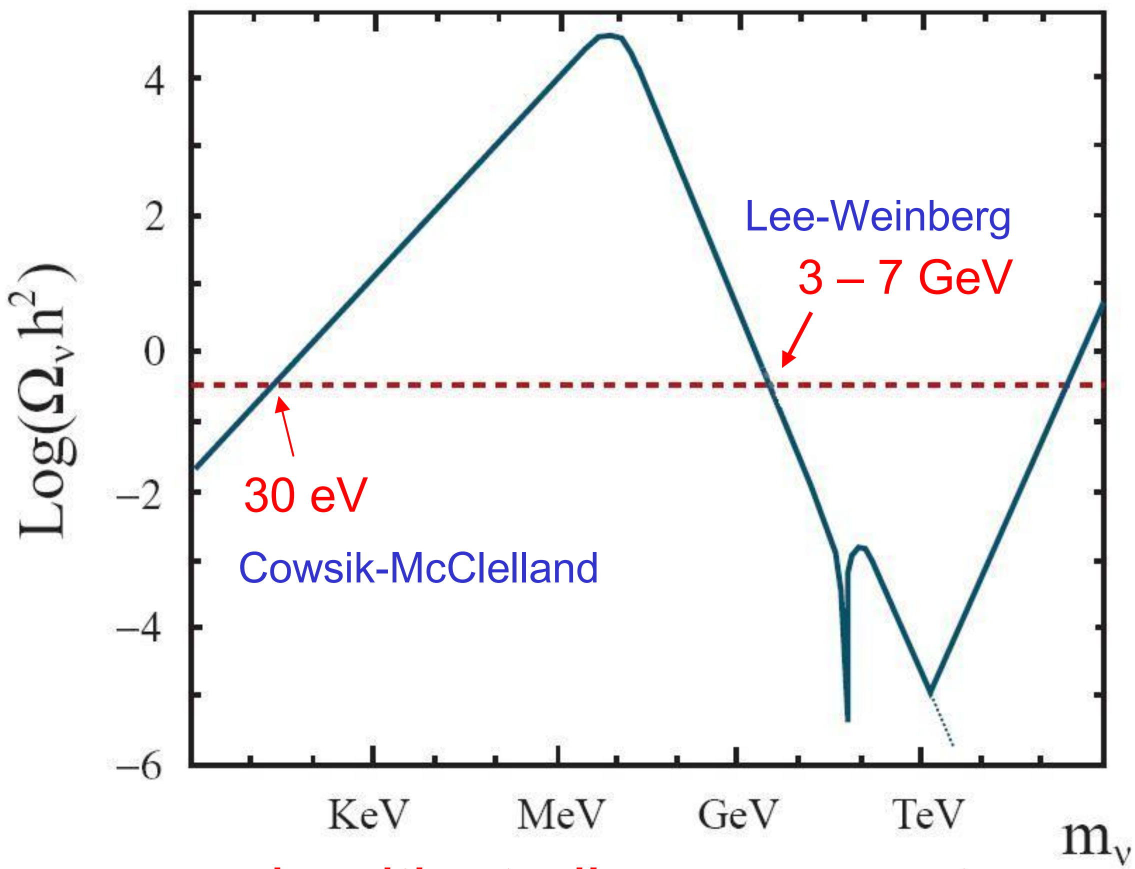
$$\Omega_\nu h^2 = \frac{\sum m_\nu}{91.5\,\mathrm{eV}}$$

HOT

$$\Omega_\nu h^2 \propto <\sigma_{ann} v>^{-1}$$

COLD

- $\Sigma m_\nu < 0.66$ eV (WMAP+LSS+SN)
- LEP: $N_\nu = 2.994 \pm 0.012$ $\rightarrow m_\nu \geq 45$ GeV $\rightarrow \Omega_\nu h^2 \leq 10^{-3}$
- DM searches exclude: 10 GeV ≤ mv≤ 4.7 TeV (similar constraints for sneutrinos and KK-neutrinos)



does not work

mix with sterile component (both for neutrinos and sneutrinos)

Limits on neutrino relic abundance date back to the 70s…

Cowsik-McClelland bound: m_ν< few eV

VOLUME 29, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 1972

An Upper Limit on the Neutrino Rest Mass*

R. Cowsik† and J. McClelland
Department of Physics, University of California, Berkeley, California 94720
(Received 17 July 1972)

In order that the effect of graviation of the thermal background neutrinos on the expansion of the universe not be too severe, their mass should be less than 8 eV/c^2.

Lee-Weinberg limit: m_ν>few GeV

PHYSICAL REVIEW LETTERS

VOLUME 39 25 JULY 1977 NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[(a)]
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and

Steven Weinberg[(c)]
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(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.

Pioneering work on direct DM searches @ Homestake mine in late ’80s:

Volume 195, number 4 PHYSICS LETTERS B 17 September 1987

LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

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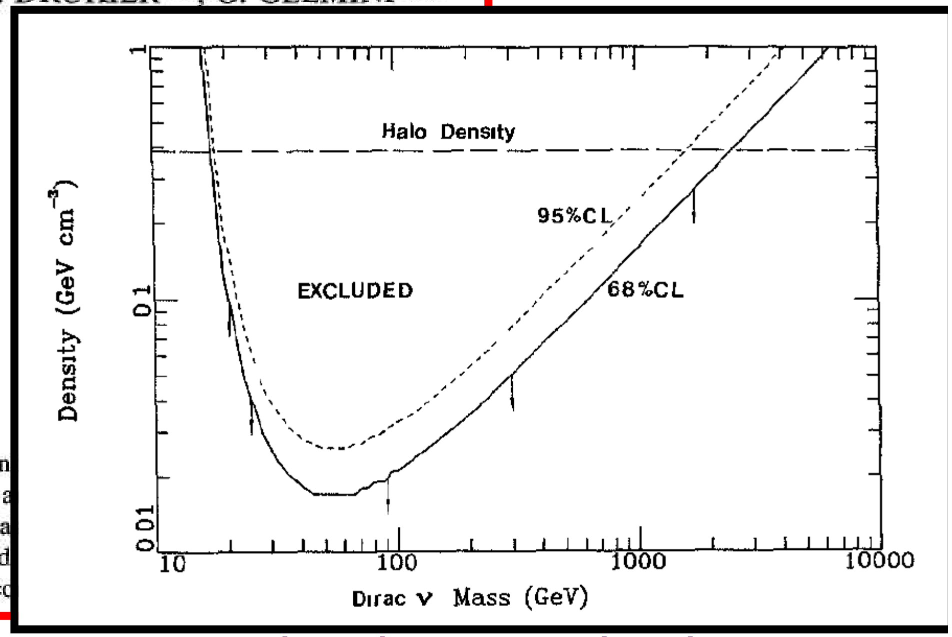
Received 5 May 1987

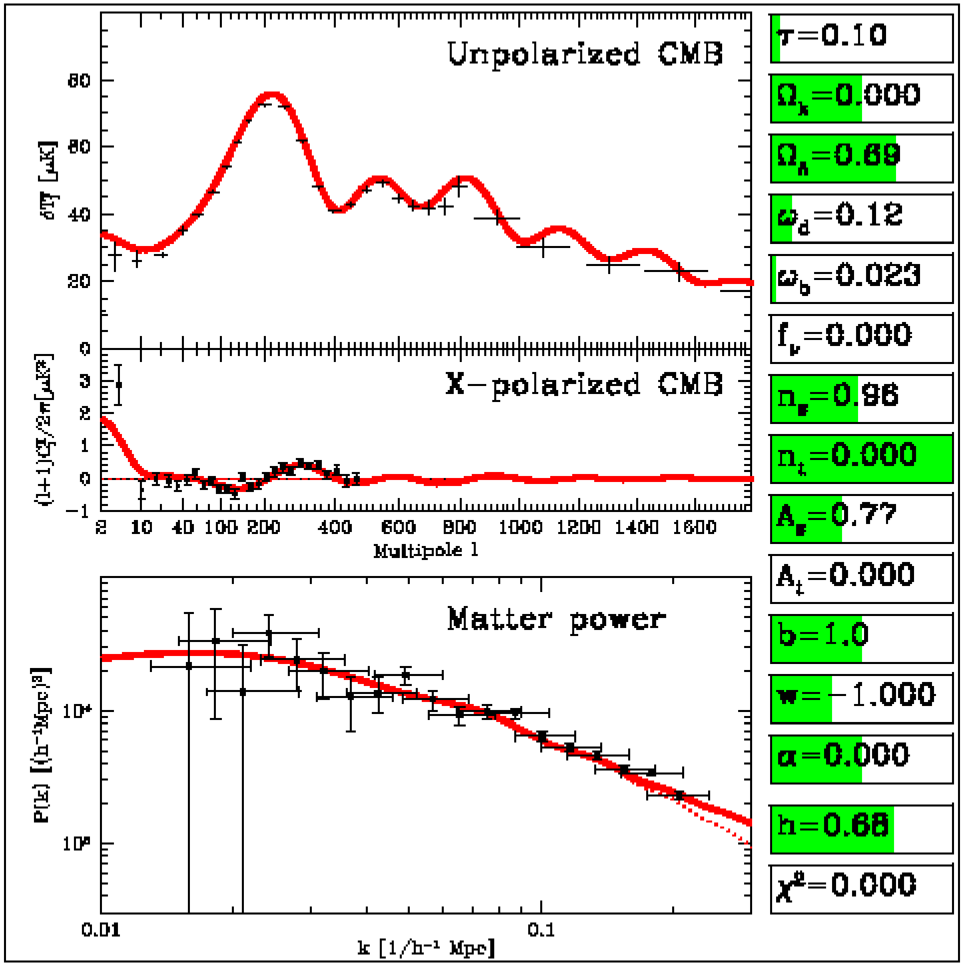
An ultralow background spectrometer is used as a detector of cold dark matter can
realistic model for the galactic halo, large regions of the mass–cross section space a
particles. In particular, a halo dominated by heavy standard Dirac neutrinos (taken a
dent Z^0 exchange interactions) with masses between 20 GeV and 1 TeV is excluded
neutrinos is <0.4 GeV/cm^3 for masses between 17.5 GeV and 2.5 TeV, at the 68% co



few GeV<M<few TeV excluded both for neutrinos ad sneutrinos*

however, today the sneutrino is not completely dead (rescaling due to relic density not applied to the signal at the time, see later)

Neutrinos don't's work also because they are hot dark matter (=relativistic at decoupling, erase density perturbation through free-streaming):



density fraction of light neutrinos

(from Mark Tegmark home page)

CLUSTERING IN A NEUTRINO-DOMINATED UNIVERSE

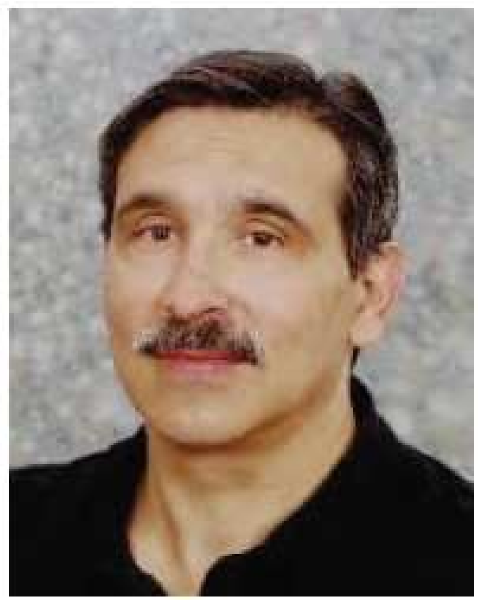
SIMON D. M. WHITE,[1,2] CARLOS S. FRENK,[1] AND MARC DAVIS[1,3]
University of California, Berkeley

Received 1983 June 17; accepted 1983 July 1

1983 ApJ 274, L1

ABSTRACT

We have simulated the nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution. Codes based on a direct *N*-body integrator and on a fast Fourier transform Poisson solver produce very similar results. The coherence length of the neutrino distribution at early times is directly related to the mass of the neutrino and thence to the present density of the universe. We find this length to be too large to be consistent with the observed clustering scale of galaxies if other cosmological parameters are to remain within their accepted ranges. The conventional neutrino-dominated picture appears to be ruled out.



Structure formation (i.e.: the very existence of galaxies) needs Cold Dark Matter and Cold Dark Matter implies physics beyond the Standard Model (light neutrinos don’t work)

Have to go non-baryonic and beyond the Standard Model

Two main guiding principles*:

1. simplicity
2. theoretical motivation

not always coinciding!

A recent example of a "minimal extensions" of the SM

Cirelli et al, NPB753(2006)

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + c \begin{cases} \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X} & \text{when } \mathcal{X} \text{ is a spin } 1/2 \text{ fermionic multiplet,} \\ |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2 & \text{when } \mathcal{X} \text{ is a spin } 0 \text{ bosonic multiplet,} \end{cases}$$

- add to SM extra **n-**tuplets of $SU(2)_L$ with minimal spin, isospin and hypercharge and search for assignements that provide most of all of the following properties:
  - lightest particle stable, no strong interactions,
  - only 1 parameter free: M
  - QC induce mass splitting ΔM, the lightest χ is neutral
  - DM candidate not excluded by DM searches

NB: in the SM the proton does not decay simply because decay modes consistent with renormalizability do not exist (accidental B-L symmetry)

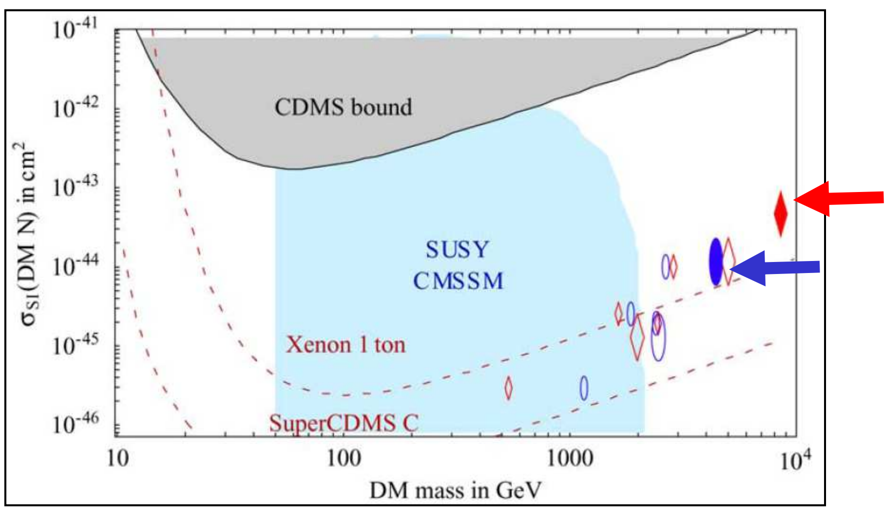
Minimal DM can be stable for the same reason.

The trick: choose **n** sufficiently high

Quantum numbers			DM can decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Events at LHC $\int \mathcal{L}\,dt = 100/\text{fb}$	σ_{SI} in 10^{-45} cm^2
$SU(2)_L$	$U(1)_Y$	Spin					
2	1/2	0	EL	0.54 ± 0.01	350	320–510	0.3
2	1/2	1/2	EH	1.2 ± 0.03	341	150–300	0.3
3	0	0	HH^*	2.0 ± 0.05	166	0.2–1.0	1.3
3	0	1/2	LH	2.5 ± 0.06	166	0.7–3.5	1.3
3	1	0	HH, LL	1.6 ± 0.04	540	3.0–10	2.5
3	1	1/2	LH	1.9 ± 0.05	526	25–80	2.5
4	1/2	0	HHH^*	2.4 ± 0.06	353	0.10–0.6	1.9
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	4.8–23	1.9
4	3/2	0	HHH	2.9 ± 0.07	729	0.01–0.10	10
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	1.5–8.7	10
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12
5	0	1/2	–	4.4 ± 0.1	166	$\ll 1$	12
7	0	0	–	8.5 ± 0.2	166	$\ll 1$	46

n≥5 for fermions   n≥7 for scalars

M is the only free parameter
fixed by relic abundance!



also direct detection is fixed

more candidates if stabilization mechanism added

[Cirelli et al, NPB753(2006)]

Note that DM candidates with the same quantum numbers of the previous table already exist in different contexts:

- scalar triplets in little Higgs models
- inert Higgs + Z_2 symmetry
- fermion or scalar triplet in see-saw models
- KK excitations of lepton doublets or of Higgses in extradimensions
- Higgsinos, sneutrinos, Winos in Supersymmetry

the above candidates are stable because of some symmetry
many free parameters with variable interaction rates
motivations from particle physics building

First attempts to explain Dark Matter with superparticles in the early ’80…

- “Massive photinos: unstable and interesting”,N. Cabibbo, G. R. Farrar, L. Maiani, PLB105(1981)155
- “Supersymmetry, Cosmology and New Physics at the Teraelectronvolt energies”, H. Pagels and J. R. Primack, PRL48(1981) 223
- “Cosmological Constraint on the Scale of Supersymmetry breaking”, S. Weinberg, PRL48(1982) 1303
- “Inflation can save the gravitino”, J. Ellis, A. D. Linde and D.V. Nanopoulos, PLB118(1982)59
- “Constraints on the photino mass from Cosmology”, H. Goldberg, PRL50(1983) 1419
- “The scalar neutrinos as the Lightest Supersymmetric Particles and Cosmology” L. E. Ibañez, PLB137(1984) 160
- “Supersymmetric Relics from the Big Bang”, J. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. Olive, M. Srednicki, NPB238(1984) 453
- …and many others following

…acronym “WIMP” eventually coined in mid ‘80

COSMOLOGICAL CONSTRAINTS ON THE PROPERTIES OF WEAKLY INTERACTING MASSIVE PARTICLES

Gary STEIGMAN

Bartol Research Foundation, University of Delaware, Newark, DE 19716, USA

Michael S. TURNER

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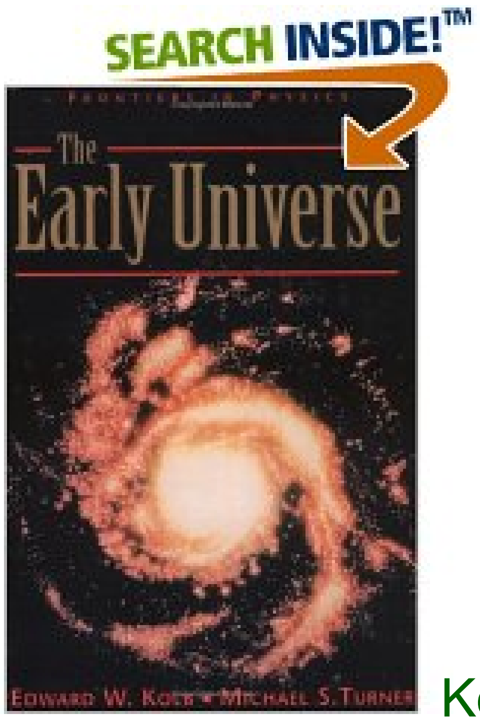
Received 9 October 1984

Considerations of the age and density of, as well as the evolution of structure in, the universe lead to constraints on the masses and lifetimes of weakly interacting massive particles (WIMPs). The requirement that the observed large-scale structure of the universe be permitted to develop, leads to much more restrictive bounds on the properties of WIMPs than those which follow from considerations of the age and density of the universe alone.



Kolb, Turner, The Early Universe

page 310

in which case one could conclude that $H_0 t_0 > 0.66$, in contradiction with the inflationary prediction.

Recalling that primordial nucleosynthesis restricts the baryonic contribution to be $\Omega_B \lesssim 0.15$, we see that inflation *requires* non-baryonic matter to be the dominant form of matter in the Universe. The simplest and most plausible form of such is relic WIMPs.[40] Prime candidates for the

---

[39] Since density perturbations correspond to fluctuations in the curvature, the density perturbations on the present Hubble scale imply that a very accurate measurement of Ω_0 would actually yield a value, $\Omega_0 = 1.0 \pm (\delta\rho/\rho)_{\rm HOR} = 1.0 \pm \mathcal{O}(10^{-5})$.

[40] WIMP© is a copyrighted trademark of the Chicago group, standing for Weakly Interacting Massive Particle.

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Updated Daily

Mar 26 - Obese man - video
Mar 26 - Sexy pole dancing - video
Mar 26 - Truth about firearms - video
Mar 26 - Amazing jumps - video

Mar 25 - Grandpa punched - video
Mar 25 - John Locke painting - video
Mar 25 - Cosby's joke stolen - video
Mar 25 - Men never change - video

Jun 2 - Painful jump - video
Jun 2 - Deadly car chase - video
Jun 2 - Crazy weather guy - video
Jun 2 - Hydrofoil board surfing - video
Jun 2 - Funny abortion interviews - video
Jun 2 - Playful cats compilation - video
Jun 2 - Three armed Chinese baby - video
Jun 2 - Mexican molester beat up - video
Jun 2 - Funny pong shots - video
Jun 2 - Orleans censorship - video

Why are WIMPs so popular?

The standard lore:

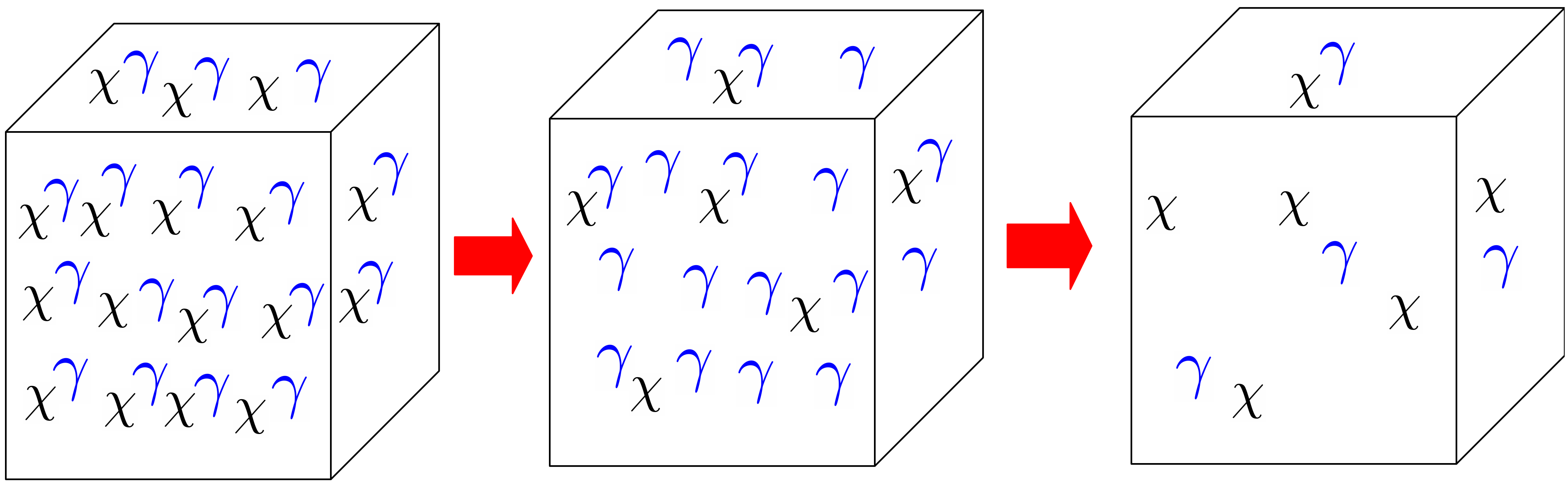
- the Cosmic Microwave Background Radiation (CMBR) is the remnant of the hot plasma that dominated the energy density in the early Universe
- from the measured temperature of the CMBR (T_0=2.7 K) we know the CMBR density today ($\rho_{\gamma,0}$~ 422 photons cm^{-3})
- Weak interactions kept WIMPs in thermal equilibrium with those photons in the early Universe <u>(THERMAL RELICS)</u>
- working out the decoupling between WIMPs and the plasma we can calculate the WIMP density normalizing it to $\rho_{\gamma,0}$ ~ 422 photons cm-3
- since WIMPs are COLD, they were non relativistic at decoupling, so their equilibrium density was exponentially suppressed compared to photons
- however, after decoupling (freeze-out) WIMPs density in a comoving volume stayed almost the same, while photons were deluted and redshifted away so that now they contribute $\Omega_\gamma \sim 10^{-3}$

Thermal equilibrium simplifies things!

$T \gg M_{WIMP}$

Decoupling: $T \ll M_{WIMP}$

now



$n_\chi \sim n_\gamma$

$n_{\chi,f} \ll n_{\gamma,f}$ (exponential suppression, $n_{\chi,f} \sim e^{-M/T}$)

$n_{\chi,now} \sim n_{\chi,f}$
$n_{\gamma,now} \ll n_{\gamma,f}$

CMB

normalize WIMP density to CMB

Decoupling is the key

the thermal cosmological density of a WIMP X

$\Omega_X h^2 \sim 1/\langle\sigma_{ann} v\rangle_{int}$

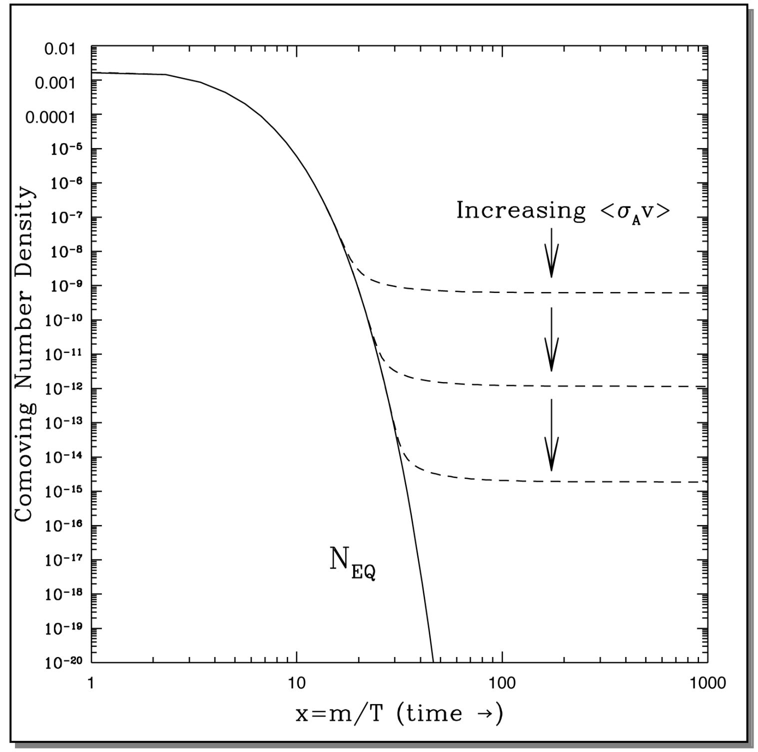
$\langle\sigma_{ann} v\rangle_{int} = \int_{x_f}^{x_0} \langle\sigma_{ann} v\rangle dx$

$x_0 = M/T_0$

T_0=present (CMB) temperature

$x_f = M/T_f$

T_f=freeze-out temperature



X_f>>1, X non relativistic at decoupling, low temp expansion for $\langle\sigma_{ann} v\rangle$: $\langle\sigma_{ann} v\rangle \sim a + b/x$

if σ_{ann} is given by weak-type interactions → $\Omega_X \sim 0.1\text{-}1$

…+ cohannihilations with other particle(s) close in mass + resonant annihilations

WIMP Boltzmann equations

Liouville operator $\longrightarrow$ $$\hat{L}[f] = C[f]$$ $\longleftarrow$ Collisional operator

$$f(x^\mu, p^\nu, t) = f(E, t)$$

phase-space density <u>depends on E only</u> (in FWR model spatially homogeneous and isotropic)

$$n(t) = \frac{g}{(2\pi)^3}\int d^3\vec{p} f(E, t)$$

WIMP number density

Liouville operator

momentum

background force

$$\hat{L} = \frac{d}{d\tau} = \frac{d}{dx^\mu}\frac{dx^\mu}{d\tau} + \frac{d}{dp^\mu}\frac{dp^\mu}{d\tau} = p^\mu \frac{d}{dx^\mu} - \Gamma^\mu_{\sigma\rho} p^\sigma p^\rho \frac{d}{dp^\mu}$$

$$\rightarrow E\frac{d}{dt} - \Gamma^0_{jk} p^j p^k \frac{d}{dE} = E\frac{d}{dt} - H|\vec{p}|^2 \frac{d}{dE}$$

$$d\tau \equiv \sqrt{-g^{\mu\nu} dx_\mu dx_\nu}$$ proper time

$$A = -\int d\tau = \int \mathcal{L} dt \rightarrow \mathcal{L} = -\dot{\tau}$$ action for free particle

$$p^\mu = \frac{d\mathcal{L}}{d\dot{x}_\mu} = -\frac{d\dot{\tau}}{dt} = \frac{dx^\mu}{d\tau}$$

$$\frac{d^2x^\mu}{d\tau^2} + \Gamma^\mu_{\sigma\rho}\frac{dx^\sigma}{d\tau}\frac{dx^\rho}{d\tau} = 0 \rightarrow \frac{dp^\mu}{d\tau} = -\Gamma^\mu_{\sigma\rho} p^\sigma p^\rho$$

(background-force term from geodesic equation)

affine connection

Dependence on gravitational background through affine connection

$$\Gamma^{\sigma}_{\lambda\mu} = \frac{1}{2}\left\{\frac{\partial g_{\mu\nu}}{\partial x^{\lambda}} + \frac{\partial g_{\lambda\nu}}{\partial x^{\mu}} - \frac{\partial g_{\mu\lambda}}{\partial x^{\nu}}\right\}$$

$$ds^2 = dt^2 - a^2(t)\left\{\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right\}$$

RW metric

only non-zero terms:

$$\Gamma^{i}_{jk} = \frac{1}{2}h^{il}\left(\frac{\partial g_{lj}}{\partial x^{k}} + \frac{\partial g_{lk}}{\partial x^{j}} - \frac{\partial g_{jk}}{\partial x^{l}}\right)$$

$$\Gamma^{0}_{ij} = \frac{\dot{a}}{a}h_{ij} = Hh_{ij}$$

$$\Gamma^{i}_{0j} = \frac{\dot{a}}{a}\delta^{i}_{j}$$

$$h_{ij} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Integration over phase-space of Liouville operator:

$$\frac{g}{(2\pi)^3}\int \frac{d^3\vec{p}}{E}\,\hat{L}[f] = \frac{g}{(2\pi)^3}\int \frac{d^3\vec{p}}{E}\left(\frac{df}{dt} - H\frac{|\vec{p}|^2}{E}\frac{df}{dE}\right) = \frac{dn}{dt} + 3Hn = s\frac{dY}{dt}$$

cosmological dilution

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

comoving density

$$s = \frac{\rho + p}{T} = g_s\frac{2\pi^2}{45}T^3$$

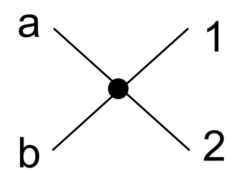
entropy density

$$a^3 s = constant$$

iso-entropic expansion

$$\frac{dY}{dt} = \frac{d}{dt}\left(\frac{Y}{s}\right) = \frac{d}{dt}\left(\frac{a^3Y}{a^3s}\right) = \frac{1}{a^3s}\frac{d}{dt}(a^3n) = \frac{1}{a^3s}\left(a^3\frac{dn}{dt} + 3a^2\dot{a}n\right) = \frac{1}{s}\left(\frac{dn}{dt} + 3Hn\right)$$

Collisional operator



a,b=WIMP
1,2=SM (light) particles

$$\frac{g}{(2\pi)^3}\int C[f]\frac{d^3\vec{p}}{E} =$$

$$-\int d\Pi_1\, d\Pi_2\, d\Pi_a\, d\Pi_b\, (2\pi)^4\delta^4(p_1+p_2-p_a-p_b)\,\left[|\mathcal{M}_{12\to ab}|^2 f_1 f_2 - |\mathcal{M}_{ab\to 12}|^2 f_a f_b\right] =$$

$$-\int d\Pi_1\, d\Pi_2\, d\Pi_a\, d\Pi_b\, (2\pi)^4\delta^4(p_1+p_2-p_a-p_b)|\mathcal{M}|^2[f_1 f_2 - f_a f_b] =$$

$$-\int d\Pi_1\, d\Pi_2\, d\Pi_a\, d\Pi_b\, (2\pi)^4\delta^4(p_1+p_2-p_a-p_b)|\mathcal{M}|^2[f_1 f_2 - f_1^{eq} f_2^{eq}] = -<\sigma v>\left(n^2 - n_{eq}^2\right)$$

$$f_{a,b} = f_{a.b}^{eq} = e^{-\frac{E_{a,b}}{T}}$$

SM particles assumed in thermal equilibrium

$$f_a^{eq} f_b^{eq} = e^{\frac{E_a+E_b}{T}} = e^{\frac{E_1+E_2}{T}} = f_1^{eq} f_2^{eq}$$

detailed balance

thermally averaged annihilation cross section:

$$<\sigma v>\equiv \frac{1}{n_{eq}^2}\int d\Pi_1\, d\Pi_2\, d\Pi_a\, d\Pi_b\, (2\pi)^4\delta^4(p_1+p_2-p_a-p_b)|\mathcal{M}|^2 f_1^{eq} f_2^{eq}$$

Boltzmann’s equation

$$\frac{dn}{dt} + 3Hn = - < \sigma v > \left(n^2 - n_{eq}^2\right)$$ (Lee-Weinberg)

$$\frac{dY}{dt} = -s < \sigma v > \left(Y^2 - Y_{eq}^2\right)$$

$$\frac{dY}{dx} = -\frac{xs}{H(T=m)} < \sigma v > \left(Y^2 - Y_{eq}^2\right) \qquad x = \frac{m}{T}$$

(t→x tranformation through iso-entropic expansion:

$$\frac{d}{dt}(a^3 s) = 0 \rightarrow \frac{d}{dt}(aT) = 0 \rightarrow \frac{d}{dt}\left(\frac{a}{x}\right) = \frac{\dot{a}}{x} - \frac{a}{x^2}\dot{x} = 0 \rightarrow \frac{dx}{dt} = Hx \quad)$$

$$\frac{dY}{dx} = -\frac{xs}{H(T=m)} < \sigma v > (Y^2 - Y_{eq}^2)$$

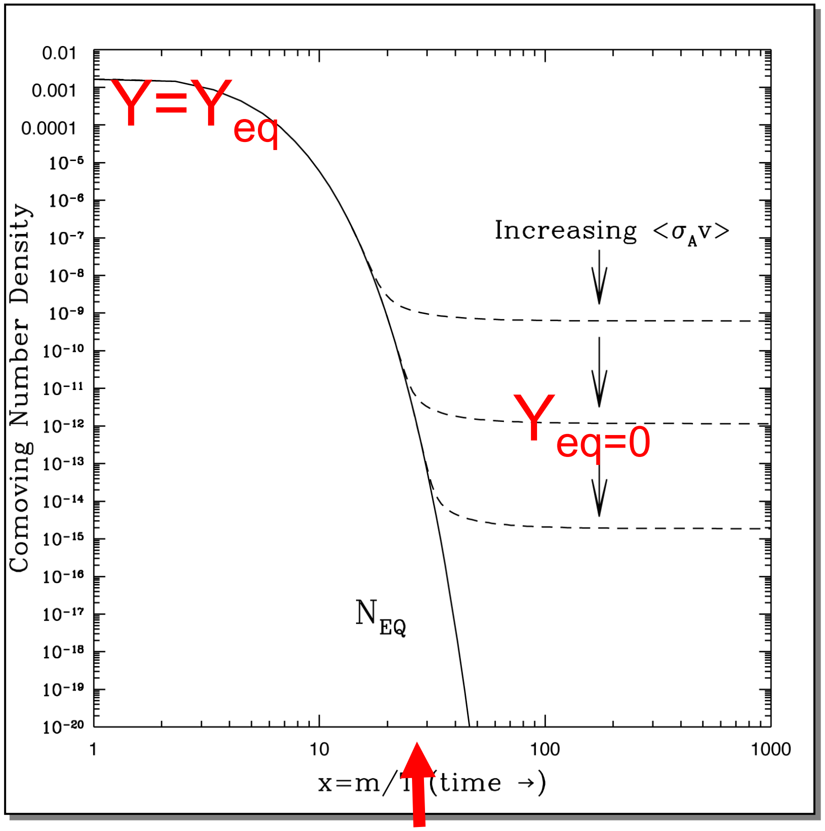
[Riccati equation, no closed-form solutions – can feed to computer]

approx solution when $x > x_f$:

$$\frac{dY}{dx} \simeq -\frac{xs}{H(T=m)} < \sigma v > Y^2$$

now separable and trivial to solve:

$$-\frac{dY}{Y^2} = \frac{xs}{H(T=m)} < \sigma v > \ dx$$



x_f ~20 (from numerical calculation)

$$\frac{1}{Y_0} - \frac{1}{Y_f} \simeq \frac{1}{Y_0} = \left(\frac{\pi}{45G}\right)^{\frac{1}{2}} m \int_{x_0}^{x_f} g_*^{\frac{1}{2}} < \sigma v > d\left(\frac{1}{x}\right)$$

$$\simeq \left(\frac{\pi}{45G}\right)^{\frac{1}{2}} g_*^{1/2}(T_f) \frac{m}{x_f} \left(a + \frac{b}{2x_f}\right) = \left(\frac{\pi}{45G}\right)^{\frac{1}{2}} g_*^{1/2}(T_f) \frac{m}{x_f} < \tilde{\sigma v} >$$

$$< \sigma v > \simeq a + \frac{b}{x}$$

$$< \tilde{\sigma v} > \equiv \frac{m}{T_f} \int_0^{T_f/m} < \sigma v > d\left(\frac{T}{m}\right) \simeq a + \frac{b}{2x_f}$$

Joining the pieces together: the WIMP relic abundance

$$\Omega_{WIMP} \equiv \frac{\rho_{WIMP}}{\rho_c} = \frac{m\, n_{WIMP}}{\rho_c} = \frac{m S_0 Y_0}{\rho_c}$$

$$S_0 = 2970 \text{ cm}^{-3}$$ today's entropy

$$\rho_c = 1.054 h^2 \times 10^{-5} \frac{\text{GeV}}{cm^3}$$ critical density

$$x_f \simeq 20$$ freeze-out temperature

$$g_*^{1/2} \simeq 10$$ # of degrees of freedom

m = WIMP mass

Y_0 : from Boltzmann equation

$$\Omega_{WIMP} h^2 = \frac{x_f}{g_*^{1/2}} \frac{3.45 \times 10^{-38}}{< \tilde{\sigma v} >} \simeq \frac{0.1 \text{ pbarn}}{< \tilde{\sigma v} >}$$

$$h \equiv H_0 / 100 \text{ km sec}^{-1} \text{Mpc}^{-1}$$

N.B. Very different scales conjure up to lead to the weak scale!

$$T_0 \simeq K \simeq 10^{-13}\ \mathrm{GeV}$$ CMB temp.

$$H_{100} = 100\ \mathrm{km\ sec}^{-1}\ \mathrm{Mpc} \simeq 10^{-42}\ \mathrm{GeV}$$ Hubble par.

$$m_{Planck} = 1/G^{1/2} = 10^{19}\ \mathrm{GeV}$$ Planck scale

$$\frac{x_f}{g_*^{1/2}}\left(\frac{45G}{\pi}\right)^{\frac{1}{2}}\frac{S_0}{\rho_c}G^{1/2} \simeq 10^2\,\frac{T_0^3}{H_{100}^2 m_{Plank}^3}$$

$$\simeq 10^2\,\frac{10^{-39}}{10^{-84}\times 10^{57}}\,\mathrm{GeV}^{-2} \simeq 10^{-9}\ \mathrm{GeV}^{-2} \simeq 1\ \mathrm{pbarn}$$

the WIMP “miracle”

on dimensional grounds:

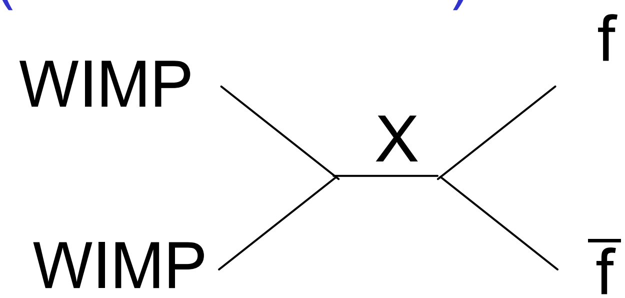
$$\sigma v \simeq \frac{\alpha^2}{M^2}$$

$$\alpha \simeq 0.1$$

$$\sigma v \simeq 1\ \mathrm{pbarn} \rightarrow M \simeq \mathrm{TeV}$$

WIMP are non relativistic, so typically (m=WIMP mass):

$$\sigma v \simeq \alpha^2 \frac{m^2}{M_X^4} = G_X^2 m^2$$



(cfr.: $\sigma v \simeq G_X^2 T^2$ for a relativistic particle)

$$\Omega \sim \frac{1}{\sigma v} \sim \frac{1}{m^2}$$

if m → 0 Ω → ∞

⇒ cosmological lower bound on m
(Lee-Weinberg limit and alike)

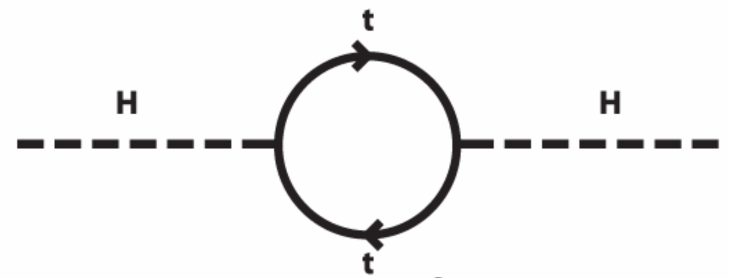
Dark Matter can be naturally related to New Physics at the TeV scale

Hierarchy problem:

Higgs mass expected to be below a few TeV (on general grounds, perturbativity of the theory)

radiative corrections to the Higgs boson of the Standard Model → loop of the type:

$$\int d^4P[1/(\not{P}-m_f)(\not{P}+\not{K}-m_f)]$$



for a Higgs of momentum K. Quadratically divergent for large P independently of K: $\delta m_H^2 \sim \lambda^2$, where λ is the scale beyond which the low-energy theory no longer applies (λ=cut-off of the SM)

N.B.: technically, not SM's business - the quadratic divergence is independent on the momentum of the Higgs and may be subtracted off

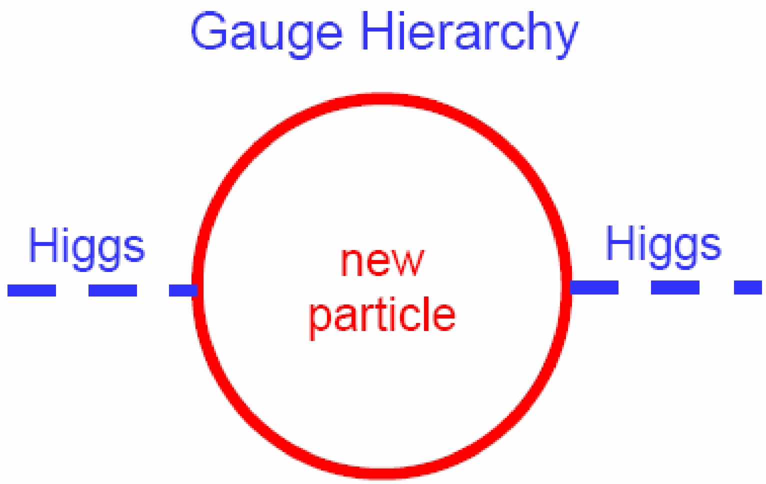
However the problem arises when embedding the SM in a more general theory: in this case $\delta m_H^2 \sim a\,\lambda^2$ is cancelled by new contribution $\delta m'^2_H \sim -b\,\lambda^2$ in such a way that $(a-b)\,\lambda^2 \sim$TeV scale – a huge cancellation unless $\lambda \sim$TeV itself

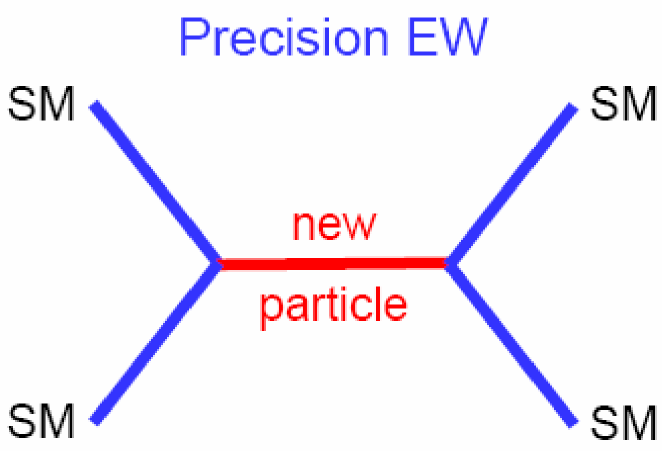
The bottom line

new physics at the TeV scale is cool because it kills two birds with one stone:

1. solves the hierarchy problem
2. explains the Dark Matter

LEP'S COSMOLOGICAL LEGACY





- Simple solution: impose a discrete parity, so all interactions require pairs of new particles. This also makes the lightest new particle stable.

Cheng, Low (2003); Wudka (2003)

- LEP's Cosmological Legacy:

  LEP constraints ↔ Discrete symmetry ↔ Stability

- Dark matter is easier to explain than no dark matter
- The WIMP paradigm is more natural than ever before, leading to a proliferation of candidates

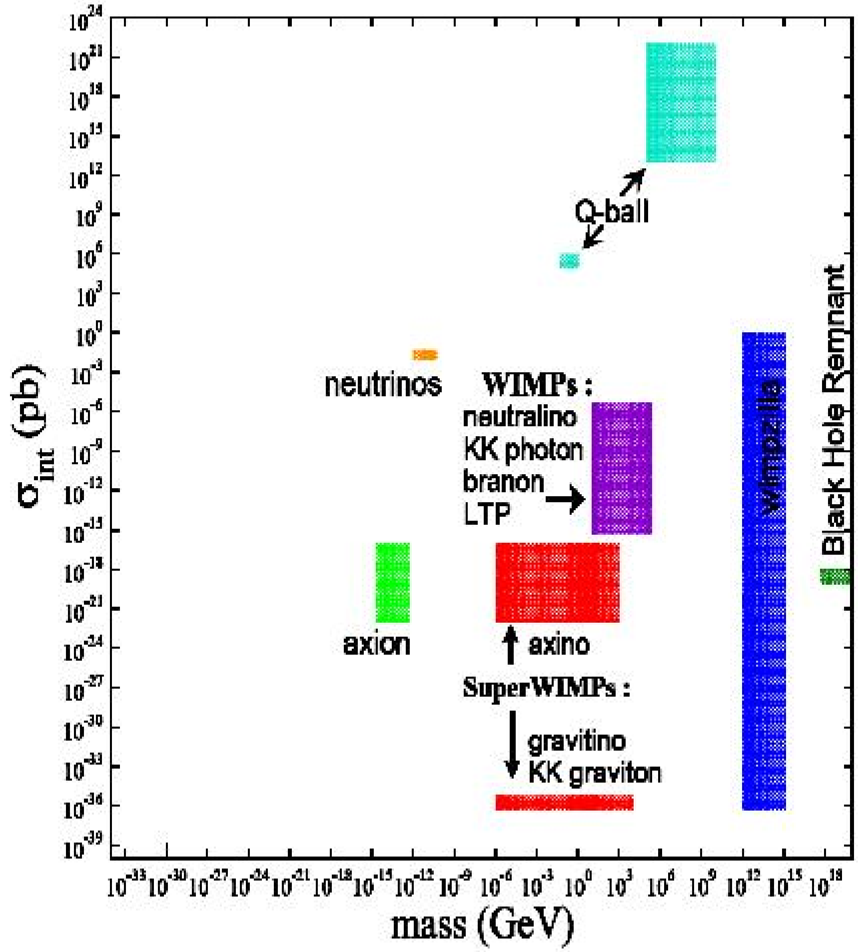
WIMP signal: missing energy+new particles produced in pairs

What WIMP?

Never run short of candidates…

(Incomplete) List of DM candidates

- Neutrinos
- Axions
- Lightest Supersymmetric particle (LSP) – neutralino, sneutrino, axino
- Lighest Kaluza-Klein Particle (LKP)
- Heavy photon in Little Higgs Models
- Solitons (Q-balls, B-balls)
- Black Hole remnants
- Hidden-sector tecnipions
- …



most popular thermal WIMP candidates from particle physics (solve hierarchy problem: $M_W/M_{Pl} \sim 10^{-16}$)

	conserved symmetry	DM candidate
•susy *	R-parity	χ (neutralino)
•extra dimensions	K-parity	$B^{(1)}$(KK photon)
•little Higgs	T-parity	B_H (heavy photon)

<u>all thermal candidates, massive, with weak-type interactions (WIMPs)</u>

* most popular candidate

SUSY is the most popular candidate. In fact:

!

experimentally SM works surprisingly fine after all
so sometimes you can hear people saying that
“Supersymmetry is a solution in search of a problem”

actually, physicists have found many “problems” susy can solve…
(more details in H. Murayama’s lectures)

- suggested by string theory
- renormalizable
- solves the hierarchy problem (why $m_W << m_{planck}$)
- compatible to GUT unification of gauge couplings
- $\boxed{\text{provides a DM candidate (if R-parity is introduced to prevent nucleon decay so that the LSP is stable)}}$

from Cosmology, not particle physics!

N.B. R-parity conservation is crucial → otherwise the Lightest Super Partner would decay!

most straightforward susy generalization of SM leads to the minimal (MSSM) superpotential:

$$W = \underbrace{\overset{\text{electron mass}}{f H_1 \tilde{L} \tilde{R}} + \overset{\text{d-type quark mass}}{h H_1 \tilde{Q} \tilde{D}} + \overset{\text{u-type quark mass}}{h' H_2 \tilde{Q} \tilde{U}}}_{\text{Yukawa couplings}} + \underset{\text{higgs mixing (at least 2 Higgs doublets required)}}{\mu H_1 H_2}$$

- in the SM accidental conservation of B and L
- the only scalar (Higgs) has no color – no lepton number → Yukawa couplings conserve L and B
- in SUSY many scalar hadrons and leptons (squaks and sleptons) → dangerous B- and L- violating Yukawa couplings!

an easy recipe of how to violate L & B at the tree level in susy:

L and H_1 have the same gauge quantum numbers!

take SM Yukawa coupling and make the substitutions $L \rightarrow H_1$, $H_1 \rightarrow L$

Field content of the MSSM as in Ref. [18]

Superfield	Component Fields	Quantum Numbers (SU(3), SU(2), U(1))	Name
	Matter fields		
Q_L	$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \equiv Q_L$ $\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix} \equiv \tilde{Q}_L$	$(3, 2, \frac{1}{3})$	left-handed quark doublet
$\hat{u}_R$	u^c_L $\tilde{u}^c_L$	$(3^*, 1, -\frac{4}{3})$	right-handed up-quark singlet
$\hat{d}_R$	d^c_L $\tilde{d}^c_L$	$(3^*, 1, +\frac{2}{3})$	right-handed down-quark singlet
$\hat{L}_L$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ $\begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}$	$(1, 2, -1)$	left-handed lepton doublet
$\hat{e}_R$	e^c_L $\tilde{e}^c_L$	$(1, 1, +2)$	right-handed lepton singlet
	Gauge fields		
$\hat{W}$	$\begin{pmatrix} W^{\pm} \\ W^3 \end{pmatrix}$ $\begin{pmatrix} \tilde{W}^{\pm} \\ \tilde{W}^3 \end{pmatrix}$	$(1, 0, 3)$	$SU(2)_L$ gauge fields
$\hat{B}$	B $\tilde{B}$	$(1, 1, +2)$	U(1) gauge field
	Higgs fields		
$\hat{H}_2$	$\begin{pmatrix} \phi^+_u \\ \phi^0_u \end{pmatrix}$ $\begin{pmatrix} \tilde{\phi}^+_u \\ \tilde{\phi}^0_u \end{pmatrix}$	$(1, 2, +1)$	up-type higgs doublet
$\hat{H}_1$	$\begin{pmatrix} \phi^+_d \\ \phi^0_d \end{pmatrix}$ $\begin{pmatrix} \tilde{\phi}^+_d \\ \tilde{\phi}^0_d \end{pmatrix}$	$(1, 2, -1)$	down-type higgs doublet

$$W_{R\!\!\!/} = f L\tilde{L}\tilde{R} + h L\tilde{Q}\tilde{D} + h' H_2\tilde{Q}\tilde{U} + \mu L H_2 + \lambda \tilde{u}\tilde{d}\tilde{d}$$

(then add the same "singlet" combination of the neutron)

- L and B violation at the tree lavel dangerous for proton decay
- when all dangerous Yukawa terms are removed the theory acquires a new symmetry, R parity:

$$R = (-1)^{2j+3B+L}$$

(j=spin, B=baryon number, L=lepton number)

by wich SM particles have R=1 and SUSY partners have R=-1

two main consequences of R parity conservation:

1. susy particles are created in pairs
2. the lightest susy particle (LSP) is stable and can be a Dark Matter candidate

N.B. direct constraints on R parity violating couplings are *orders of magnitude larger* than those required to allow stability of the LSP on a cosmological time scale (i.e. R-parity is *useful* and elegant but not garanteed); accelerators probe lifetime~10^{-8} s

however, can arise as an automatic symmetry in SO(10) GUT

Dark Matter Candidates

- light neutrino
- heavy neutrino
- axion
- Kaluza–Klein partners
- sneutrino
- GMSB messangers
- axino
- gravitino
- neutralino
- ...

SUSY

Supersymmetry and Dark Matter

Supersymmetry:

fermions $\Longleftrightarrow$ bosons

R=1		R=-1
leptons,quarks	$\Longleftrightarrow$	sleptons,squarks
gauge fields	$\Longleftrightarrow$	gauginos
Higgs fields	$\Longleftrightarrow$	higgsinos

R–parity conservation forbids
barion number violation
at the tree level

⇓

...and prevents the decay of the
Lightest Susy Particle (LSP)

THE LSP CAN BE THE DARK MATTER

Supersymmetry must be broken

Different ~~Susy~~ mechanisms
imply different DM candidates:

- ☑ Gravity Mediated
  → neutralino (Bino,Higgsino)
- ❐ Anomaly Mediated
  → neutralino(Wino),
  stau sneutrino
- ❐ Gauge Mediated
  → gravitino,
  GMSB messangers

GUT unification of gauge couplings

SUSY schemes (Gravity Mediated Susy breaking)

Universal SUGRA:unification of soft breaking terms at $M_{GUT} \simeq 10^{16}$ GeV + Radiative Electro–Weak Symmetry Breaking (REWSB)

Non–universal SUGRA:deviation from universality of soft breaking terms at M_{GUT} (Higgs sector, sfermions,gauginos)

Effective MSSM: effective model at the EW scale with a few MSSM parameters which set the most relevant scales

the sneutrino

Scalar lepton sector

$\tilde{L}^* = (\tilde{\nu}^* \ \tilde{e}^{*-})_L$ $\tilde{R} = \tilde{e}_R^-$	$L^T = (\nu^T \ e^{T-})_L$ $R = e_R^-$

$$W_{\rm MSSM} = \epsilon_{ij}(\mu \hat{H}_i^1 \hat{H}_j^2 - Y_l \hat{H}_i^1 \hat{L}_j \hat{R})$$

$$V_{\rm soft} = (M_L^2)\, \tilde{L}_i^* \tilde{L}_i + [\epsilon_{ij}(\Lambda_l H_i^1 \tilde{L}_j \tilde{R}) + h.c.]$$

$$\mathcal{M}_{\tilde{l}}^2 = \begin{pmatrix} m_L^2 - m_Z^2 \cos 2\beta (\frac{1}{2} + e_L \sin^2 \theta_W) & 0 \\ 0 & m_R^2 + e_R \sin^2 \theta_W \ m_Z^2 \cos 2\beta \end{pmatrix}$$

$$m_{\tilde{\nu}}^2 = m_L^2 + \tfrac{1}{2} m_Z^2 \cos 2\beta$$

- Mass parameter: $\boxed{m_L}$
- effMSSM at EW scale
- $m_L = m_R$

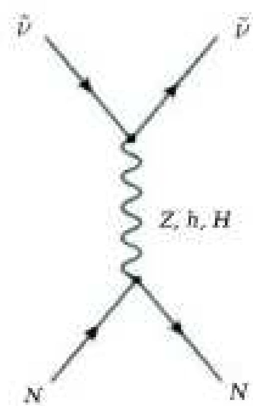
$\tilde{\nu}$ is neutral, stable, a WIMP $\Rightarrow$ may account for Cold Dark Matter

Experimental constraints on $\tilde{\nu}$ mass:

- Collider $\rightarrow$ relaxed in effMSSM
- Z–width bound:

$$\Delta\Gamma_Z = \frac{\Gamma_\nu}{2}\left[1 - \left(\frac{2m_{\tilde{\nu}}}{m_Z}\right)^2\right]^{3/2} \theta(m_Z - 2m_{\tilde{\nu}})$$

$$m_{\tilde{\nu}} \geq 45 - 50\,\mathrm{GeV}$$

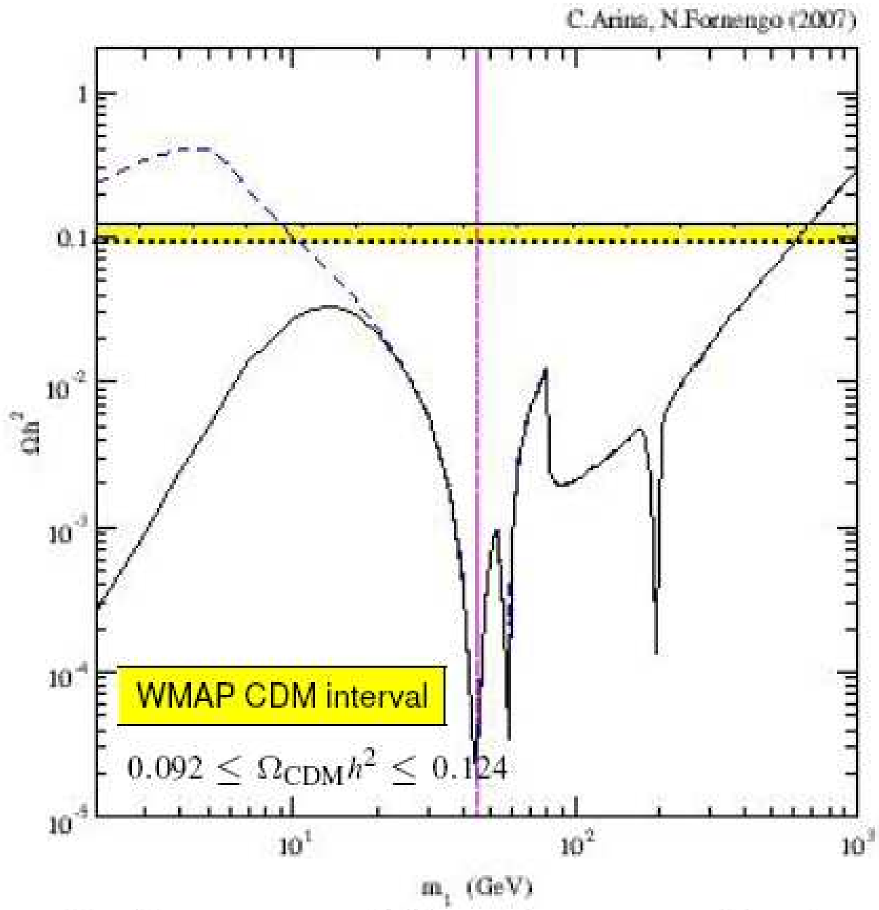


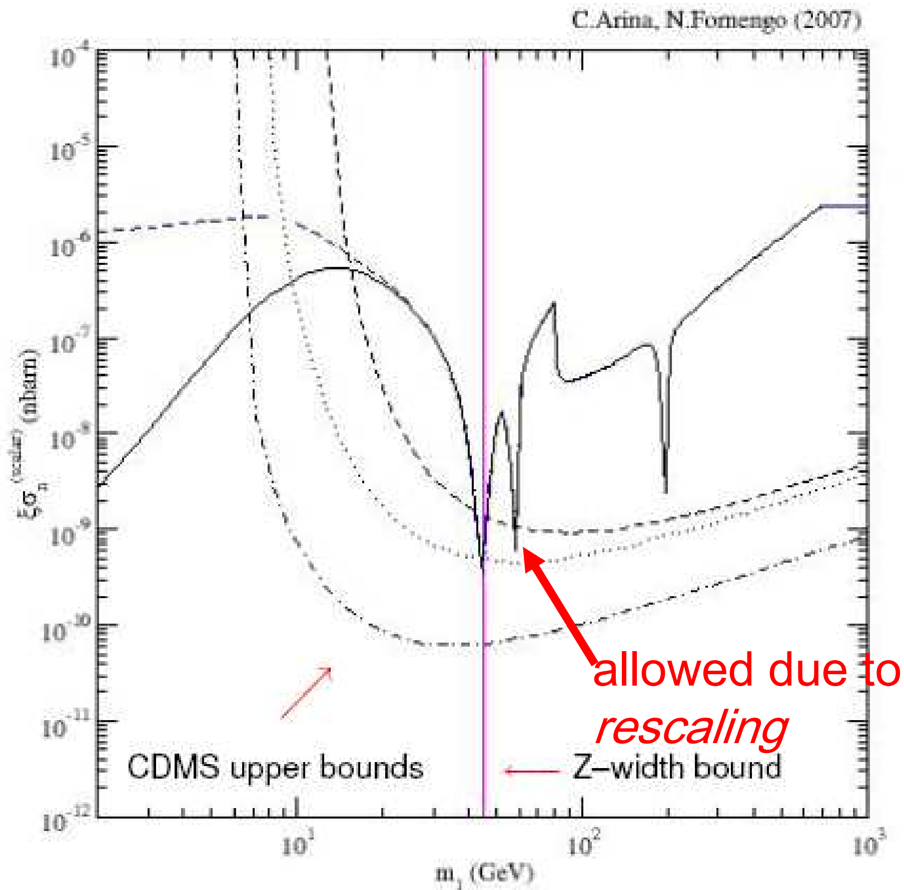
Direct detection

- elastic scattering on nuclei
- scalar interaction
- $\sigma_{\mathcal{N}} = \sigma_Z + \sigma_{h,H} \quad \longrightarrow$ Z and Higgs t-channel exchange
- $\boxed{\xi \sigma_{nucleon}^{(scalar)}}$ $\xi = \min(1, \frac{\Omega_{\tilde{\nu}} h^2}{\Omega_{CDM} h^2})$

[Arina, Fornengo, JHEP0711(2007)029]

the sneutrino





- dips → Z and Higgs $(h, H, A, H^{\pm})$ poles
- sharp drop → W^+W^- threshold

$\tilde{\nu}$-Z coupling huge:

⇒ low $\Omega h^2 \propto 1/ < \sigma_{ann} v >$

⇒ high detection rate $\xi\sigma^{(scalar)}_{nucleon}$

Sneutrinos excluded as CDM except in fine-tuned conditions

[Arina, Fornengo, JHEP0711(2007)029

rescaling

$$\rho_{WIMP} = \rho_{loc} \times \xi$$

local density of WIMPS

fraction of DM due to WIMPS

local density of matter as measured gravitationally (i.e.:total)

when the *calculated* relic density $\Omega_{WIMP}h^2$ is below the minimum value compatible to observation $(\Omega_{CDM}h^2)_{\rm min}$ one has ξ<1. Rescaling recipe:

$$\xi \equiv \min\left[1, \frac{\Omega_{WIMP}h^2}{(\Omega_{CDM}h^2)_{\rm min}}\right]$$

$$(\Omega_{CDM}h^2)_{min} = 0.095$$ (WMAP)

mixing with a right-handed component makes thing easier

MSSM+right handed neutrino superfield+Majorana mass term

$$\begin{aligned} W_{Maj} &= \epsilon_{ij}(\mu \hat{H}_i^1 \hat{H}_j^2 - Y_l \hat{H}_i^1 \hat{L}_j \hat{R} + Y_\nu \hat{H}_i^2 \hat{L}_j \hat{N}) + \tfrac{1}{2} M \hat{N}\hat{N} \\ V_{\text{soft}} &= (M_L^2)\tilde{L}_i^* \tilde{L}_i + (M_N^2)\tilde{N}^*\tilde{N} - [(m_B^2)\tilde{N}\tilde{N} + \epsilon_{ij}(\Lambda_l H_i^1 \tilde{L}_j \tilde{R} + \Lambda_\nu H_i^2 \tilde{L}_j \tilde{N}) + h.c.] \end{aligned}$$

Neutrino sector

$$-\mathcal{L}_\nu = \frac{1}{2}\begin{pmatrix}\nu_L^T & \nu_L^{cT}\end{pmatrix} \mathcal{M}_\nu \begin{pmatrix}\nu_L \\ \nu_L^c\end{pmatrix} + h.c.$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \qquad \begin{cases} m_D = v_2 Y_\nu \\ m_\nu \simeq m_D/M^2 \end{cases}$$

Sneutrino sector

$$\begin{cases} \tilde{\nu}_+ = \frac{1}{\sqrt{2}}(\tilde{\nu}_L + \tilde{\nu}_L^*) \\ \tilde{\nu}_- = \frac{-i}{\sqrt{2}}(\tilde{\nu}_L - \tilde{\nu}_L^*) \end{cases}$$

CP basis $\Phi_{\text{Maj}}^\dagger = (\tilde{\nu}_+^* \;\; \tilde{N}_+^* \;\; \tilde{\nu}_-^* \;\; \tilde{N}_-^*)$

$$\mathcal{M}_{\text{Maj}}^2 = \begin{pmatrix} m_L^2 + \frac{1}{2}m_Z^2\cos 2\beta + m_D^2 & F^2 + m_D M & 0 & 0 \\ F^2 + m_D M & m_N^2 + M^2 + m_D^2 + m_B^2 & 0 & 0 \\ 0 & 0 & m_L^2 + \frac{1}{2}m_Z^2\cos 2\beta + m_D^2 & F^2 - m_D M \\ 0 & 0 & F^2 - m_D M & m_N^2 + M^2 + m_D^2 - m_B^2 \end{pmatrix}$$

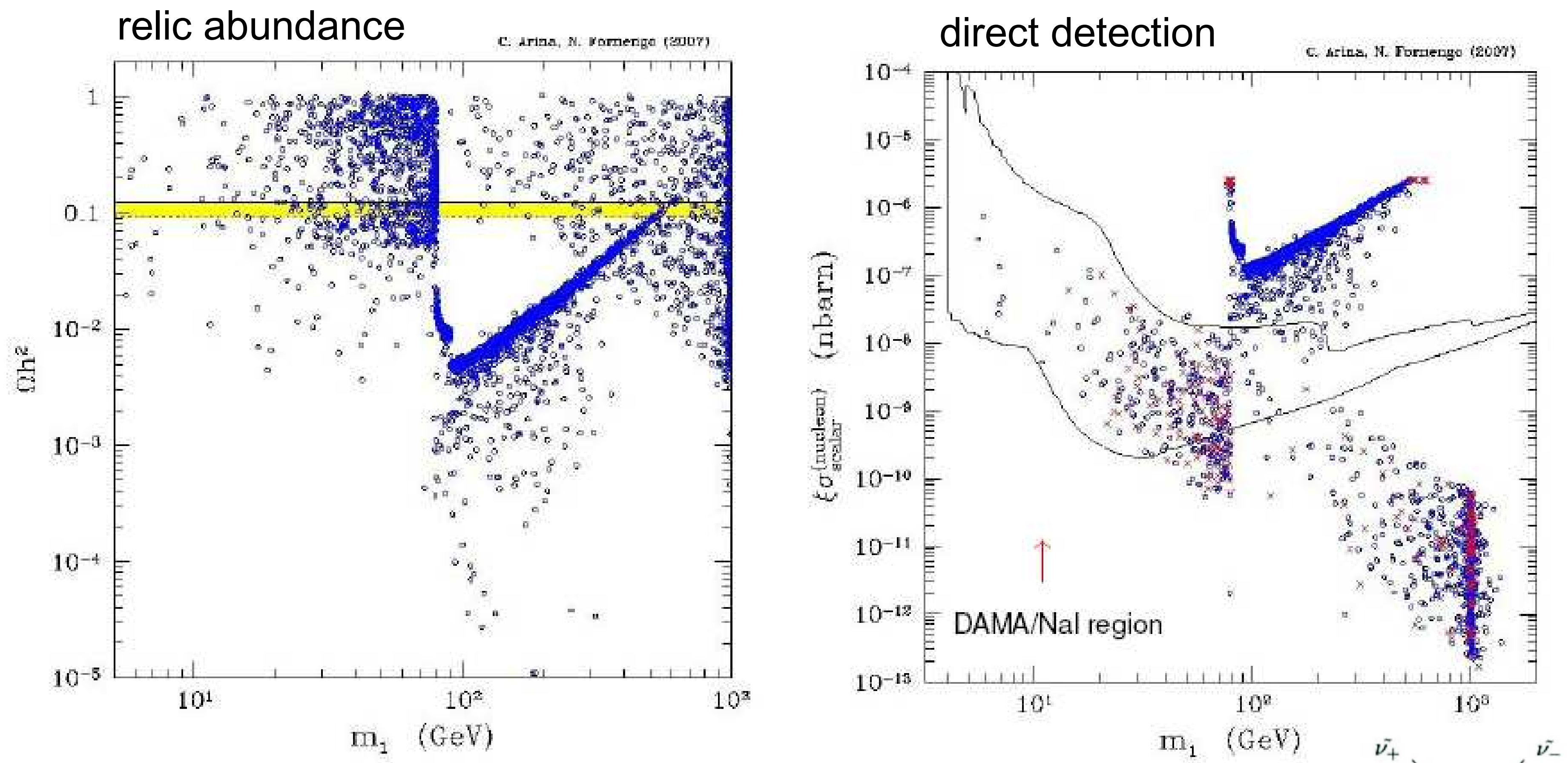
$$F^2 = v\Lambda_\nu \sin\beta - \mu m_D \text{cotg}\beta$$

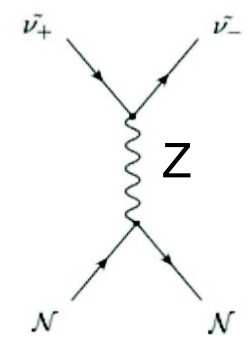
$$\boxed{M = 1\,\text{TeV}}$$

Typically $M = 10^{14}\,\text{GeV}$: less interesting for $\tilde{\nu}$ sector since the $m_{\tilde{N}}$ is driven by M, the $\tilde{N}$ decouple and do not mix with the left-handed component $\tilde{\nu}_L$

[Arina, Fornengo, JHEP0711(2007)029]

mixing with a right-handed component makes thing easier





- low see-saw scale M=1 TeV needed
- inelastic scattering in direct detection!

[Arina, Fornengo, JHEP0711(2007)029]

The neutralino

- The neutralino is defined as the lowest-mass linear superposition of bino $\widetilde{B}$, wino $\widetilde{W}^{(3)}$ and the two higgsino states $\widetilde{H}_1^0$, $\widetilde{H}_2^0$:

$$\chi \equiv a_1 \widetilde{B} + a_2 \widetilde{W}^{(3)} + a_3 \widetilde{H}_1^0 + a_4 \widetilde{H}_2^0$$

- neutral, colourless, only weak-type interactions
- stable if R-parity is conserved, thermal relic
- non relativistic at decoupling $\rightarrow$ Cold Dark Matter (required by CMB data + structure formation models)
- relic density can be compatible with cosmological observations: $0.095 \leq \Omega_\chi h^2 \leq 0.131$

  $\rightarrow$IDEAL CANDIDATE FOR COLD DARK MATTER

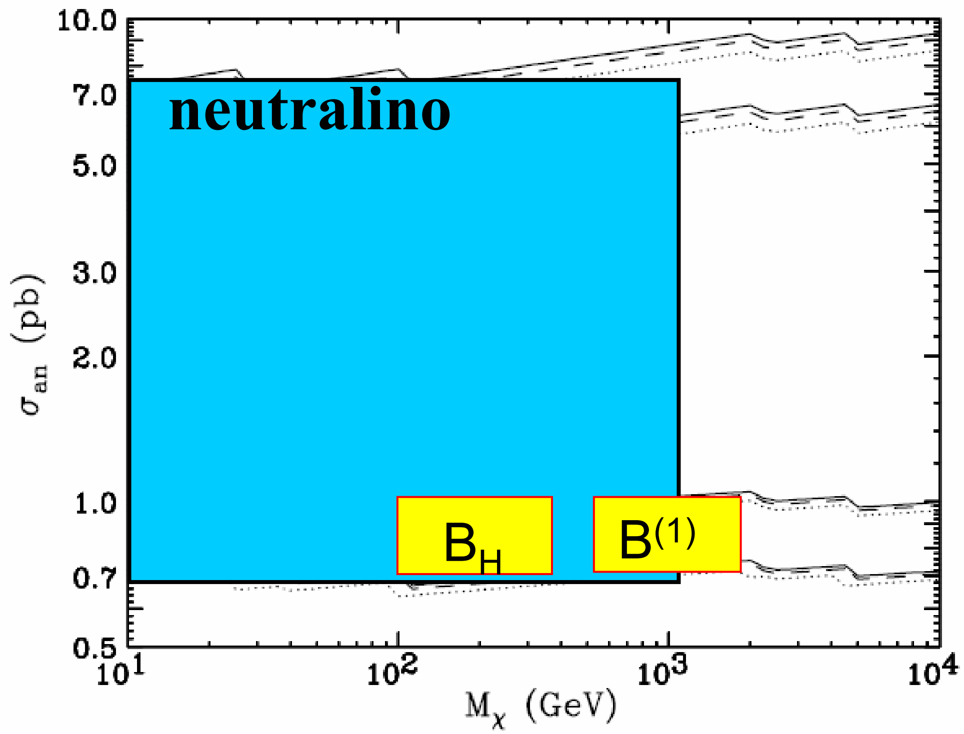
Neutralissimo?

$<\sigma_{ann}v>\sim a+b/x$:

$a\neq 0$: "s-wave" annihilator

$a=0$: "p-wave" annihilator

ranges of σ_{ann} that can provide the correct thermal relic density



neutralino=Majorana → s-wave suppression $(m_f/M_w)^2$ for $\chi\chi\to ff$

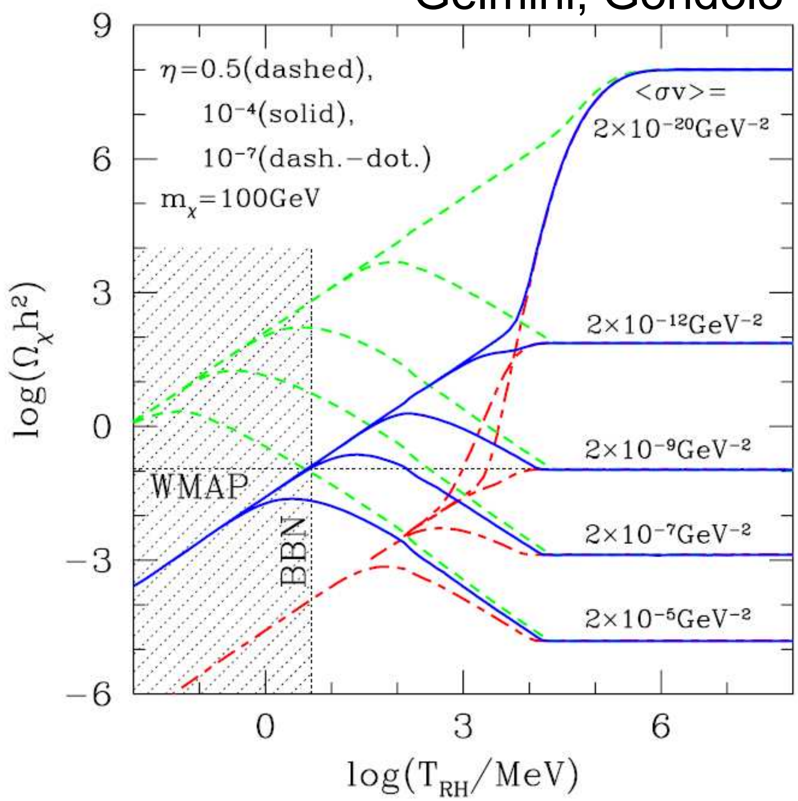
…+ cohannihilations with other particle(s) close in mass + resonant annihilations

Caveat: non-standard cosmological scenarios may change the usual picture!

- low reheating temperature

[Fornengo, Riotto, Scopel, PRD67,023514; Gelmini, Gondolo, PRD74,023510]

Gelmini, Gondolo



- inflaton φ reheats the Universe with $T_{RH}<T_f$
- $n=\eta\ (m_\varphi/100\ TeV)$ DM particles per φ decay are produced
- as long as $\Omega_X^{standard}>10^{-5}\ (100\ GeV/m_X)$ appropriate choice of T_{RH} and η provides the correct relic density

- different expansion history (kination)

[Kamionkowski, Turner, PRD42,3310; Salati, PLB571,121]

Supergravity–inspired models (SUGRA)

GUT–scale ($M_{GUT} \simeq 10^{16}$ GeV) relations:

- Unification of gaugino masses:
  $M_i(M_{GUT}) \equiv m_{1/2}$
- Unification of scalar masses:
  $m_i(M_{GUT}) \equiv m_0$
- Universality of trilinear couplings:
  $A^u(M_{GUT}) = A^d(M_{GUT}) =$
  $A^l(M_{GUT}) \equiv A_0 m_0$
- Other parameters: $sign(\mu), \tan\beta$

✔ RGE evolution of parameters down to the EW scale

✔ Radiative Electro Weak Symmetry Breaking (REWSB):

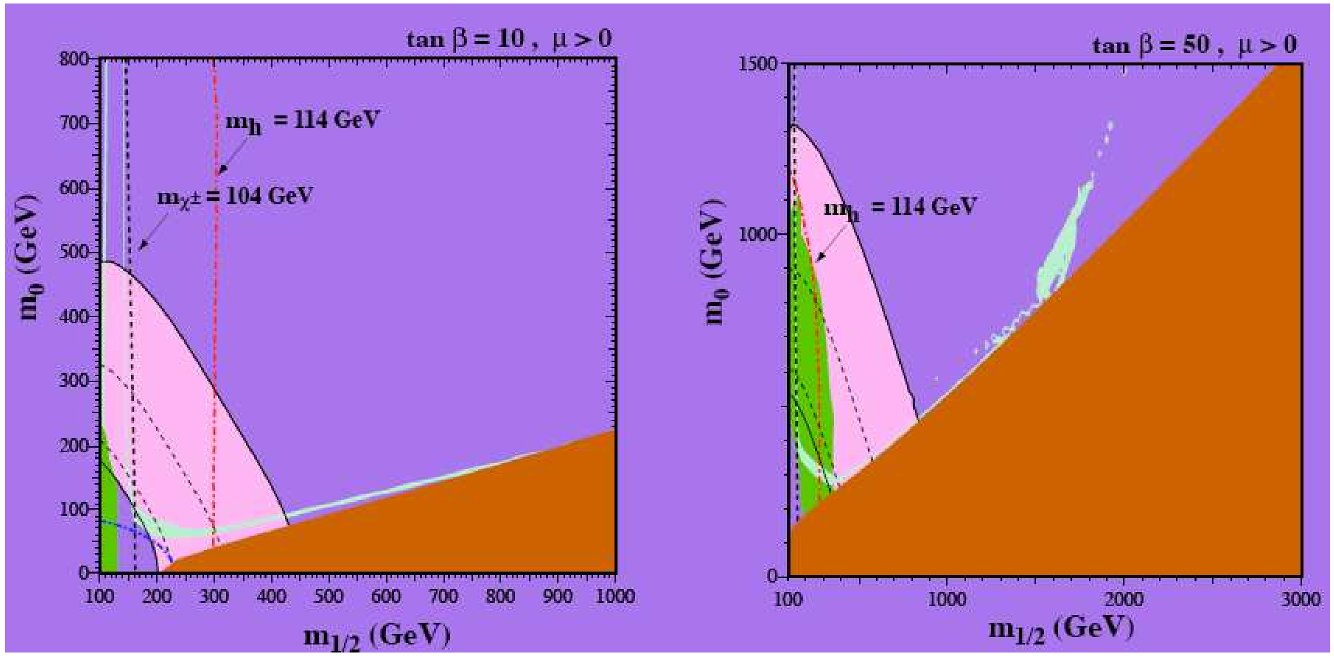
Typical predictions:

- $\chi \to$ gaugino (except "focus point region", $m_0 \gg m_{1/2}$)
- $m_A \gg O(m_Z)$ unless $\tan\beta \gtrsim 50$
- μ–M_2 correlation
- $m_{\rm quark} > m_{\rm slepton}$

Deviations from universality at M_{GUT} or a different unification scale imply significant modifications of these properties

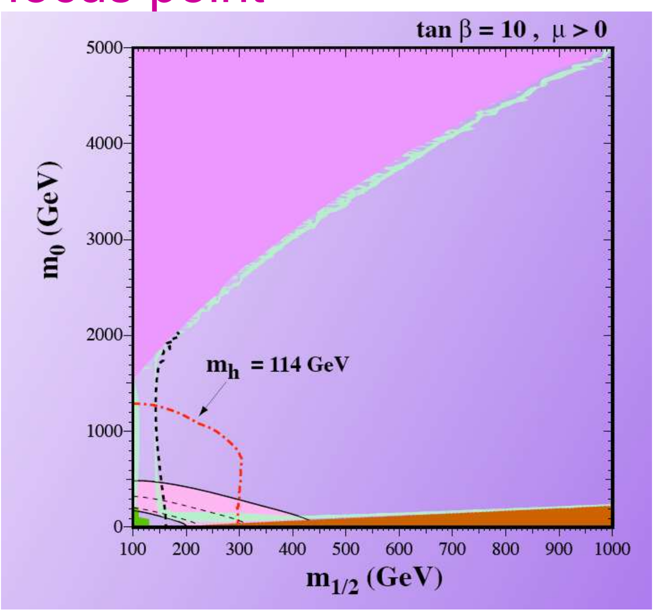
SUGRA
(a.k.a. CMSSM)

stau coannihilation   Higgs funnel



[Ellis, Olive, Santoso, Spanos]

focus point



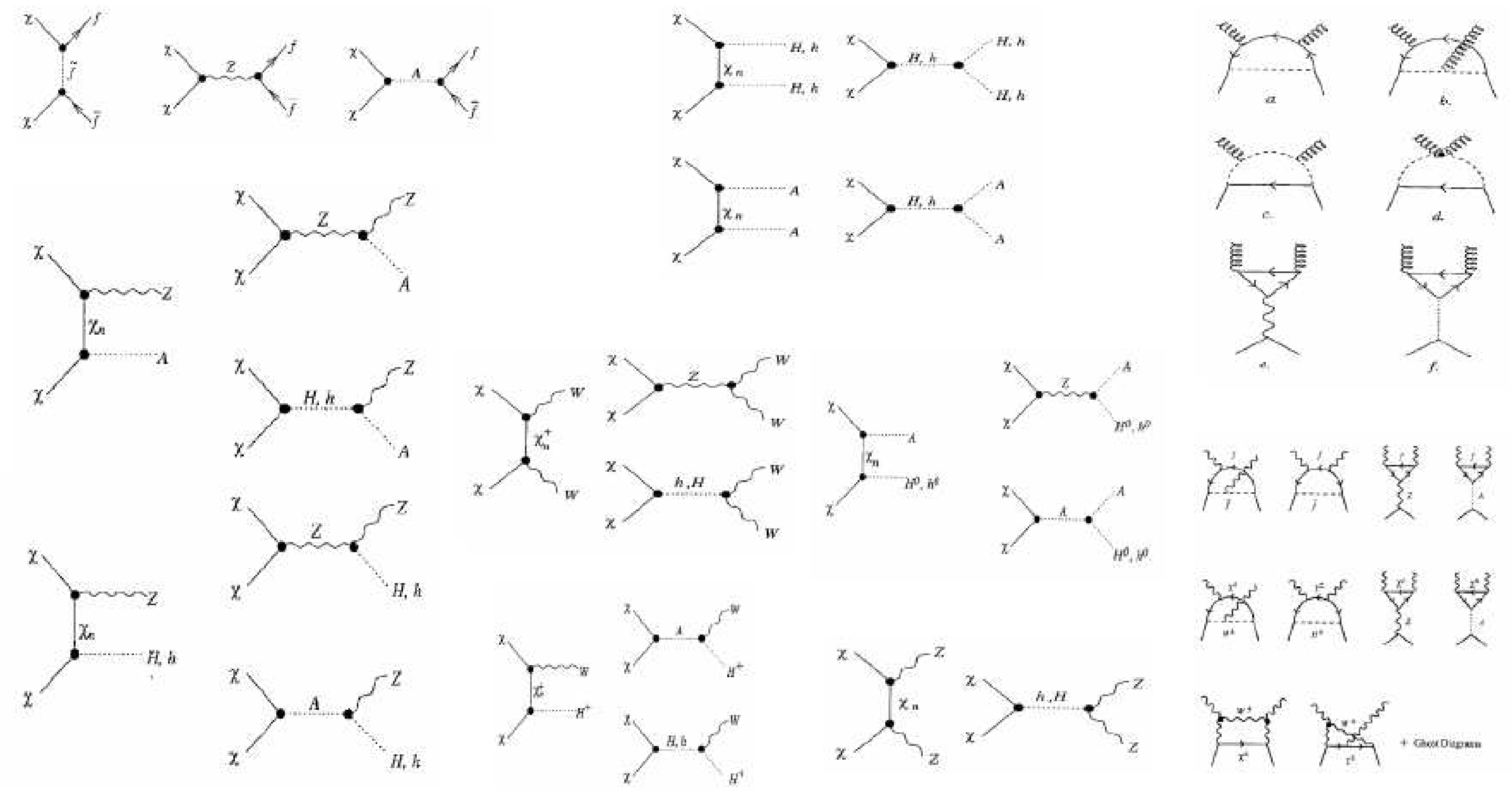
[Feng, Machev, Moroi, Wilczek]

- only few regions cosmologically allowed
- variants (e.g. non-universality of soft masses at the GUT scale or lower unification scale) that increase Higgsino content of the neutralino → lower relic abundance and higher signals

anyway, in general in SUGRA neutralino density tends to be too large

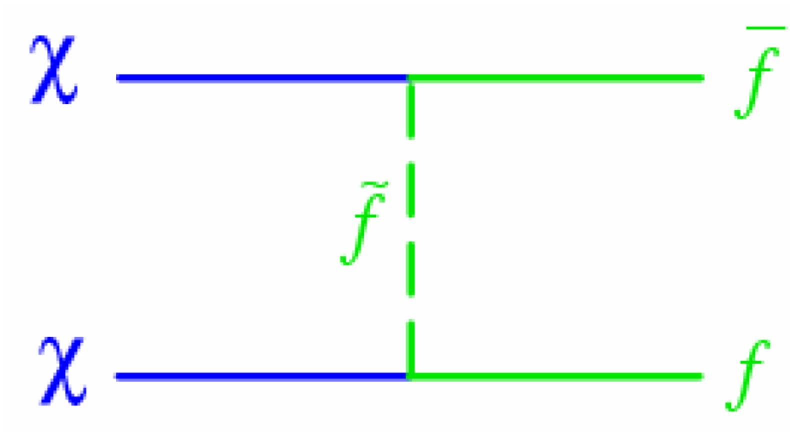
is the WIMP “miracle” *failing* ?

Many contributions to neutralino annihilation…

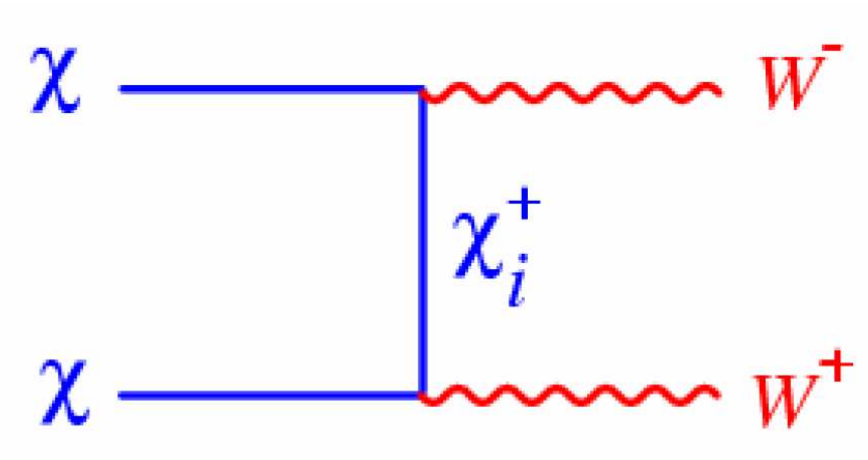


Jungman, Kamionkowski, Griest (1995)

…but two main classes:

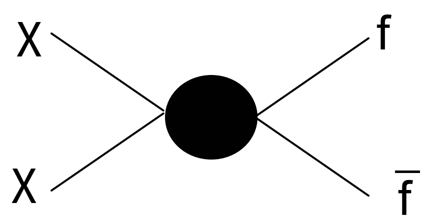


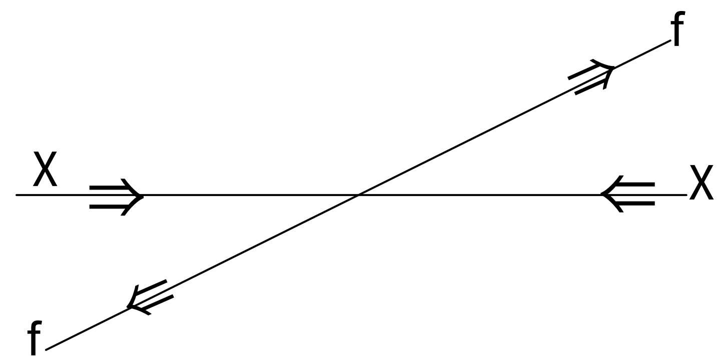
• fermion diagrams: m_f/M_W helicity suppression due to Majorana nature of neutralino
⇒ see next slide



• Gauge boson diagrams: suppressed if neutralino~Bino (this is usually the case when Radiative ElectroWeak Symmetry Breaking is implemented, $|\mu|>>M_1,M_2$)

m_f/M_W suppression of Majorana particles s-wave annihilation to fermions – a detailed explanation





1. intrinsic parity of Majorana particles is purely imaginary ($\pm$ i) so in s-wave CP(χχ)=-1 and when v→0 only non vanishing currents are $\chi\Gamma\chi$ $f\,\Gamma\,f$ with $\Gamma = \gamma_5, \gamma^\mu\gamma_5$ (pseudoscalar and axial coupling)
2. when v→0 the two annihilating Majorana particles need to have <u>opposite</u> spins due to Fermi blocking ($\chi = \chi^c$) so outgoing fermions have <u>same</u> helicities
3. however in the limit $m_f \to 0$ helicity flip required in outgoing fermions ($f_{L(R)}\,\gamma_5\,f_{L(R)} = f_{L(R)}\,\gamma^\mu\gamma_5\,f_{L(R)} = 0$)

<u>suppression</u> of annihilation cross section & dominance of <u>heavier</u> kinematically allowed final state fermion (b, τ)

Examples of less constrained SUSY scenarios

The Next-to-Minimal MSSM (NMSSM)

solves the μ problem, i.e. why $\mu \sim M_{EW}$

superpotential:

$$\boldsymbol{W} = \epsilon_{ij}\left(Y_u\, H_2^j\, Q^i\, u + Y_d\, H_1^i\, Q^j\, d + Y_e\, H_1^i\, L^j\, e\right) - \epsilon_{ij}\boldsymbol{\lambda}\, S\, H_1^i H_2^j + \frac{1}{3}\boldsymbol{\kappa} S^3$$

Higgs soft terms in the NMSSM:

$$-\boldsymbol{L}_{soft}^{Higgs} = m_{H_i}^2 H_i^* H_i + \boldsymbol{m_S^2}\, S^* S + (-\epsilon_{ij}\boldsymbol{\lambda}\, \boldsymbol{A_\lambda} S H_1^i H_2^j + \tfrac{1}{3}\boldsymbol{\kappa}\, \boldsymbol{A_\kappa}\, S^3 + \text{H.c.})$$

NMSSM particle content: MSSM+ $\left\{\begin{array}{l}\text{2 Higgs (CP-even, CP-odd)}\\ \text{1 neutralino dof}\end{array}\right.$

The lightest neutralino:

$$\tilde{\boldsymbol{\chi}}_{\boldsymbol{1}}^{\boldsymbol{0}} = N_{11}\tilde{B}^0 + N_{12}\tilde{W}_3^0 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0 + N_{\boldsymbol{15}}\tilde{\boldsymbol{S}}$$

CP-even Higgs:

$$\boldsymbol{h_1^0} = S_{11}H_1^0 + S_{12}H_2^0 + S_{\boldsymbol{13}}\boldsymbol{S}$$

SUSY schemes (Gravity Mediated Susy breaking)

- Universal SUGRA: unification of soft breaking terms at $M_{GUT} \simeq 10^{16}$ GeV + Radiative Electro–Weak Symmetry Breaking (REWSB)
- Non–universal SUGRA: deviation from universality of soft breaking terms at M_{GUT} (Higgs sector, sfermions, gauginos)
- Effective MSSM: effective model at the EW scale with a few MSSM parameters which set the most relevant scales

Effective MSSM: effective model at the EW scale with a few MSSM parameters which set the most relevant scales

- M_1 U(1) gaugino soft breaking term
- M_2 SU(2) gaugino soft breaking term
- μ Higgs mixing mass parameter
- $\tan\beta$ ratio of two Higgs v.e.v.'s
- m_A mass of CP odd neutral Higgs boson (the extended Higgs sector of MSSM includes also the neutral scalars h, H, and the charged scalars $H^{\pm}$)
- $m_{\tilde{q}}$ soft mass common to all squarks
- $m_{\tilde{l}}$ soft mass common to all sleptons
- A common dimensionless trilinear parameter for the third family ($A_{\tilde{b}} = A_{\tilde{t}} \equiv A m_{\tilde{q}}$; $A_{\tilde{\tau}} \equiv A m_{\tilde{l}}$)
- $R \equiv M_1 / M_2$

SUGRA$\rightarrow R=0.5$

Can the neutralino be *light*?

Lower limits on the neutralino mass from accelerators

- Indirect limits from chargino production ($e^+e^- \to \chi^+\chi^-$):

$$m_{\chi^\pm} \gtrsim 100 \text{ GeV} \Rightarrow m_\chi \gtrsim 50 \text{ GeV} \quad \text{if} \quad R \equiv \frac{M_1}{M_2} = \frac{5}{3}\tan^2\theta_w$$

- Direct limits from $e^+e^- \to \chi_0^i \chi_0^j$ $\quad (\chi_0^1 \equiv \chi,\, m_{\chi_0^1} < m_{\chi_0^2} < m_{\chi_0^3} < m_{\chi_0^4})$ †:
  - Invisible width of the Z boson (upper limit on number N_ν of neutrino families)
  - Missing energy + photon(s) or $f\bar{f}$ from $\chi_0^{i>1} \to \chi_0^1$ decay

- Direct limits from $\tilde{t} \to c\,\chi$ and $\tilde{b} \to b\,\chi$ at Tevatron ‡

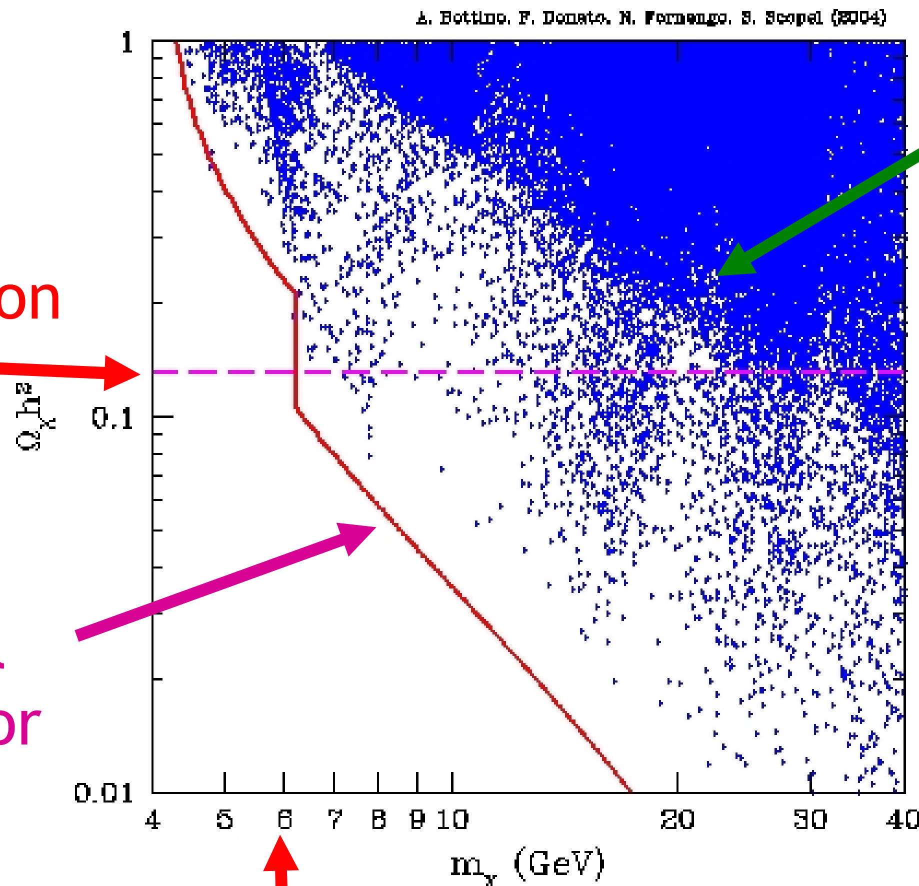
† small production cross sections

‡ light squark masses ($\lesssim 100$ GeV) required

➠ No absolute direct lower bounds on m_χ

Cosmological lower bound on m_χ (low m_A)

A. Bottino, F. Donato, N. Fornengo, S. Scopel, Phys. Rev. D 68, 043506 (2003)



scatter plot: full calculation

upper bound on $\Omega_{CDM}h^2$

curve: analytical approximation for minimal $\Omega_{CDM}h^2$

$$m_\chi\,[1 - m_b^2/m_\chi^2]^{1/4} \gtrsim 5.3\ \mathrm{GeV}\left(\frac{m_A}{90\ \mathrm{GeV}}\right)^2$$

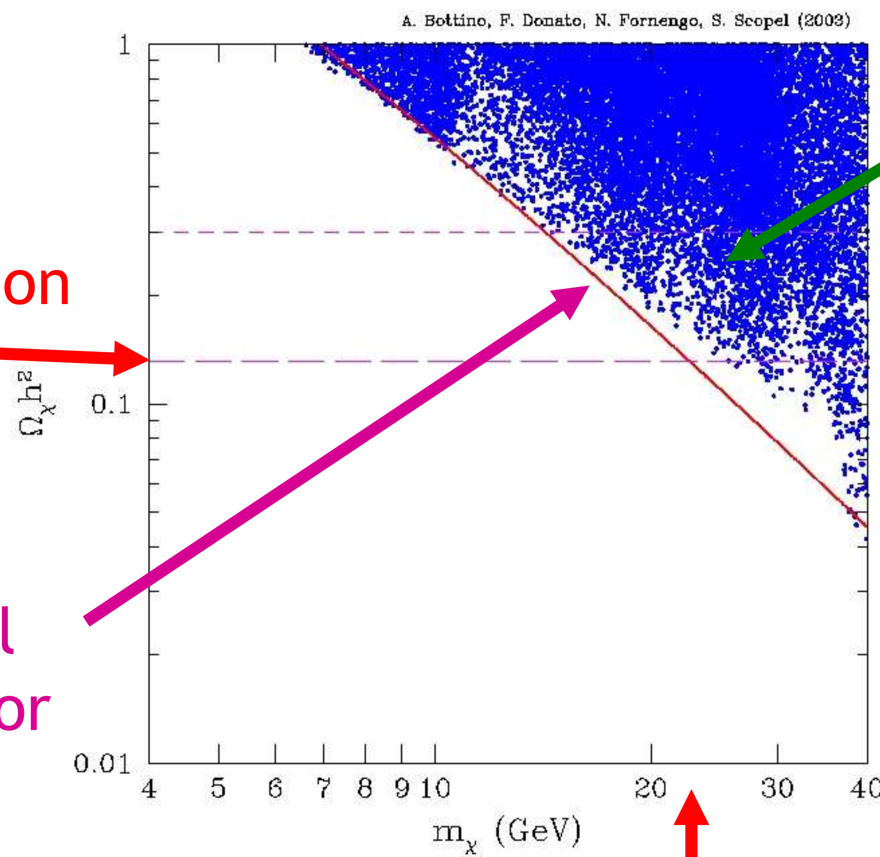
constraint “à la Lee-Weinberg”

Cosmological lower bound on m_χ ($m_A > 200$ GeV)

A. Bottino, F. Donato, N. Fornengo, S. Scopel, Phys. Rev. D 68, 043506 (2003)

scatter plot: full calculation

upper bound on $\Omega_{CDM}h^2$

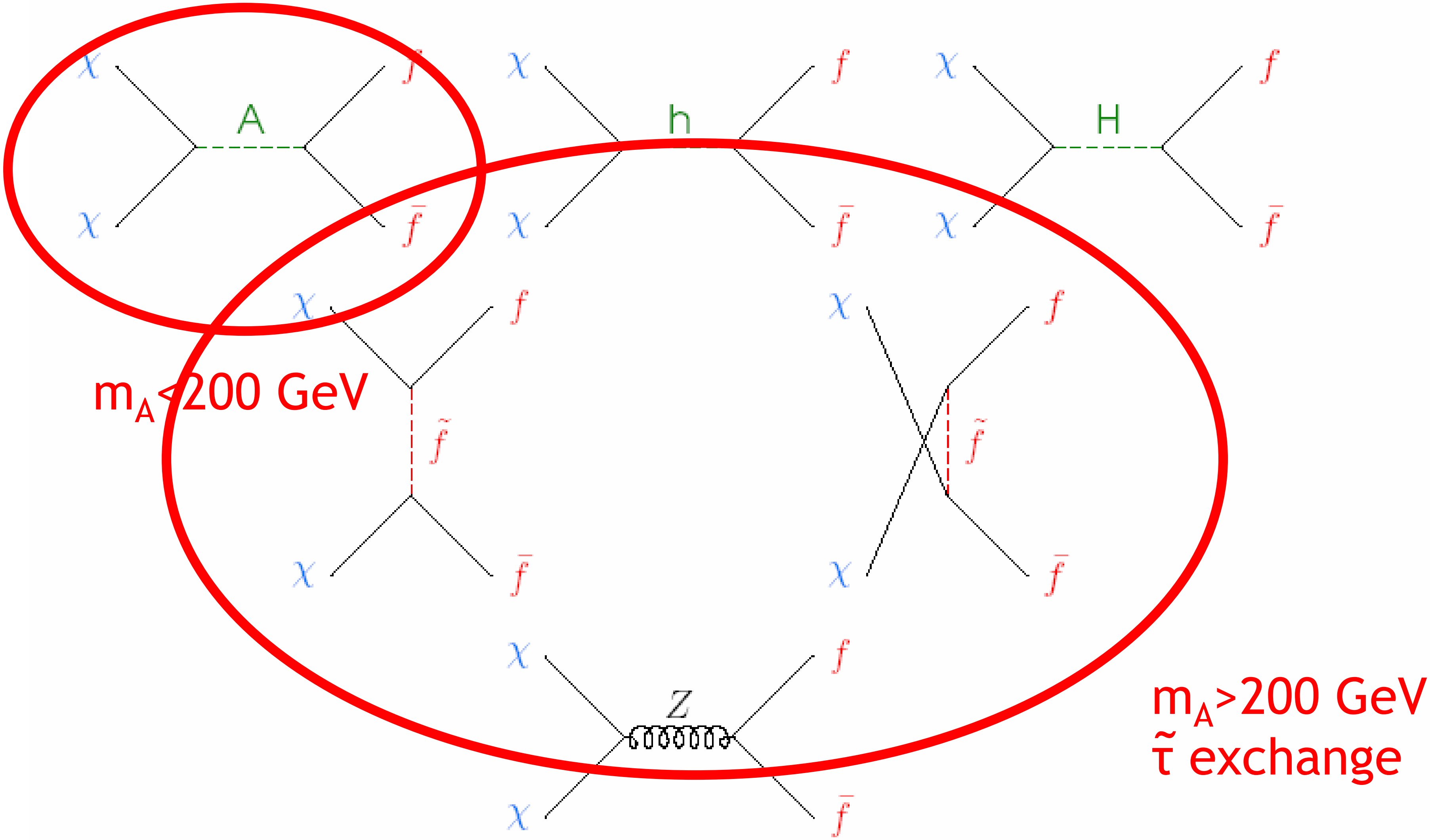


curve: analytical approximation for minimal $\Omega_{CDM}h^2$

$$m_\chi \left[1 - m_\tau^2/m_\chi^2\right]^{1/4} \gtrsim 22 \text{ GeV} \left(\frac{m_{\tilde{\tau}}}{90 \text{ GeV}}\right)^2$$

constraint “à la Lee-Weinberg”

χ–$\chi \rightarrow f\bar{f}$ annihilation cross section - Diagrams (low m_χ)



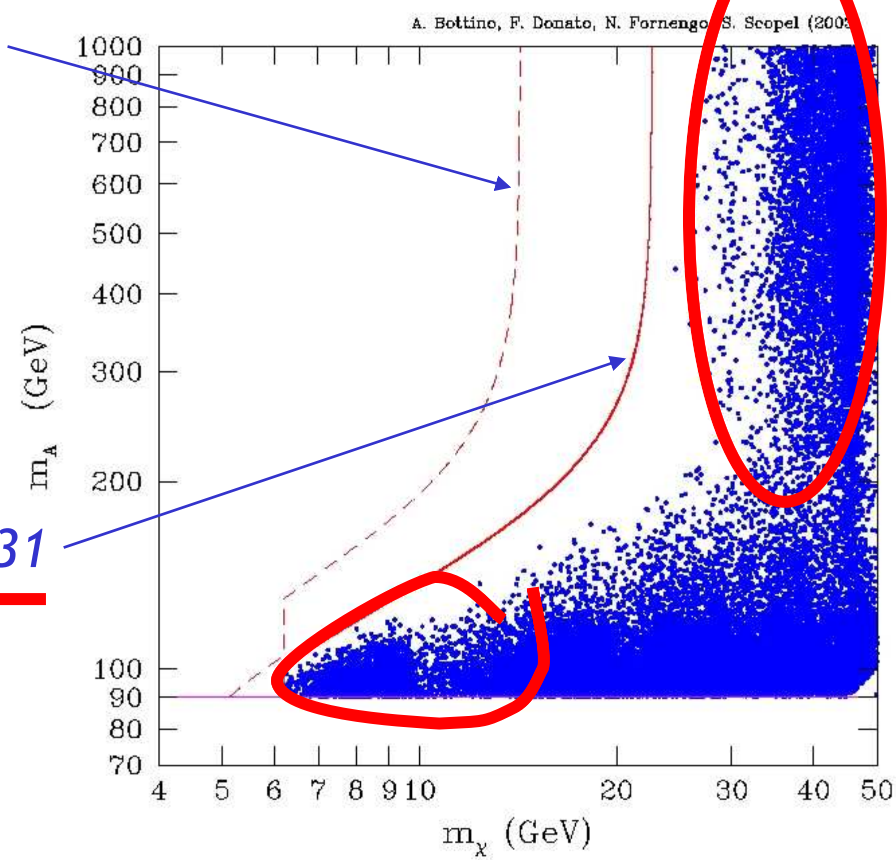
The bottom line: the cosmological lower bound on m_χ depends on the value of m_A:

✓ $m_\chi > 7$ GeV for light m_A

✓ $m_\chi > 22$ GeV for heavy m_A

$(\Omega_{CDM}h^2)_{max} = 0.3$

$(\Omega_{CDM}h^2)_{max} = 0.131$



Conclusions / part 1

- the WIMP “miracle”: combination of physical scales in a range of 60 orders of magnitude points to DM at the TeV scale → same cut-off expected in the SM
- can be realized in different well-motivated scenarios (KK photon in UED, Heavy photon in Little Higgs, sneutrino and neutralino in SUSY)+”Minimal” extensions of SM
- neutralino in susy is the most popular! Today available in different flavours: SUGRA, nuSUGRA, sub-GUT, Mirage mediation, NMSSM, effMSSM (light neutralinos), CPV,…
- neutralinos can be light

…to be continued