Dark Matter Candidates

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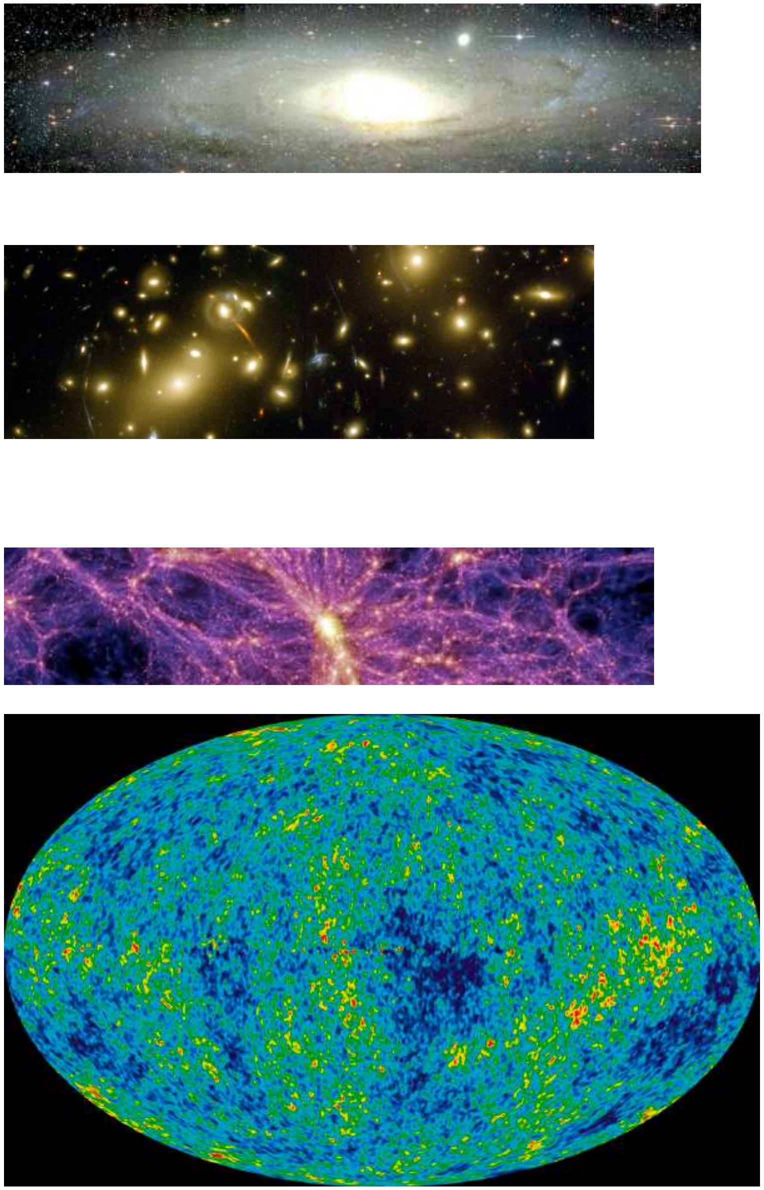
Outline

- Evidence for Dark Matter
- Dark Matter properties
- neutrinos
- axions
- WIMP candidates from UED, Little Higgs, SUSY
- The neutralino
    - Relic abundance
    - Direct detection
- Conclusions
- Topics covered by other talks:
    - Experimental direct searches (Pierluigi Belli, Dan Bauer)
    - Indirect detection – theory (Lars Bergström)
    - Indirect detection – experiment (Piergiorgio Picozza)

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
  - $\Omega_{tot}=1$
  - $\Omega_{\text{dark energy}} \sim 0.7$
  - $\Omega_{matter} \sim 0.27$
  - $\Omega_{baryons} \sim 0.05$

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

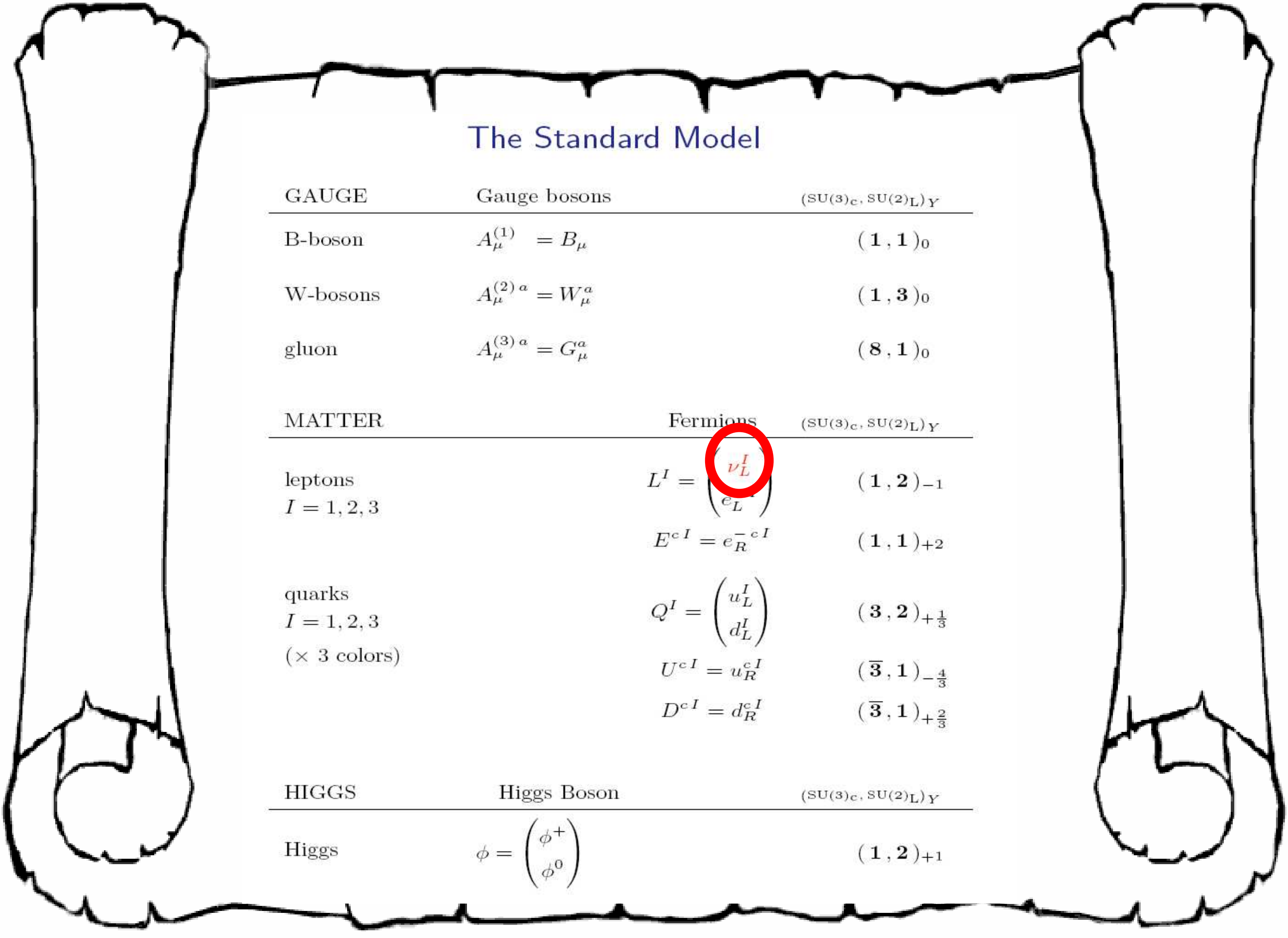


The properties of a good Dark Matter candidate:

- ✓ 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	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
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	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
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 $I = 1, 2, 3$ (× 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	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
Higgs	$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{+1}$

Neutrino

- $\Sigma m_\nu < 0.66$ eV (WMAP+LSS+SN)
- LEP: $N_\nu = 2.994 \pm 0.012$
  → $m_\nu \geq 45$ GeV
  → $\Omega_\nu h^2 \leq 10^{-3}$
- DM searches exclude:
  $10 \text{ GeV} \leq m_\nu \leq 5 \text{ TeV}$
  (similar constraints for sneutrinos and KK-neutrinos)

does not work

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

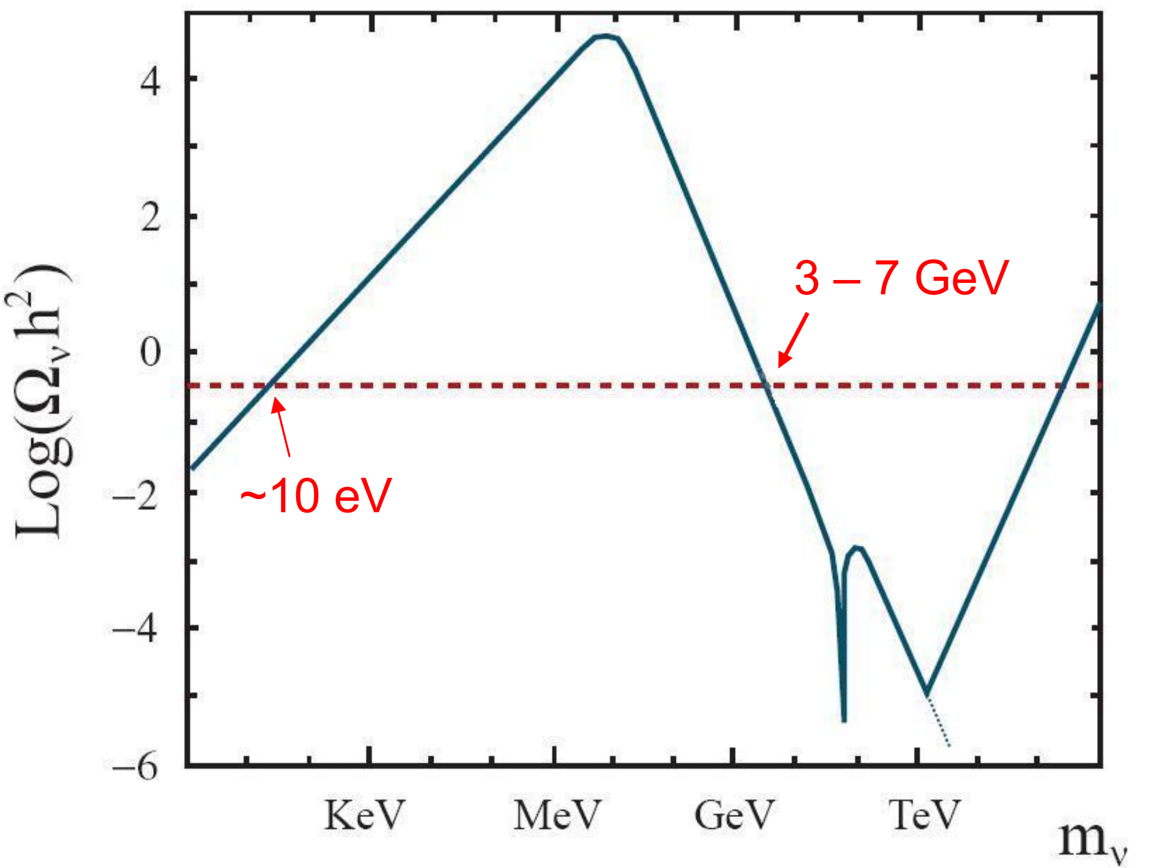
↓

HOT

$$\Omega_\nu h^2 \propto \langle \sigma_{ann} v \rangle^{-1}$$

↓

COLD

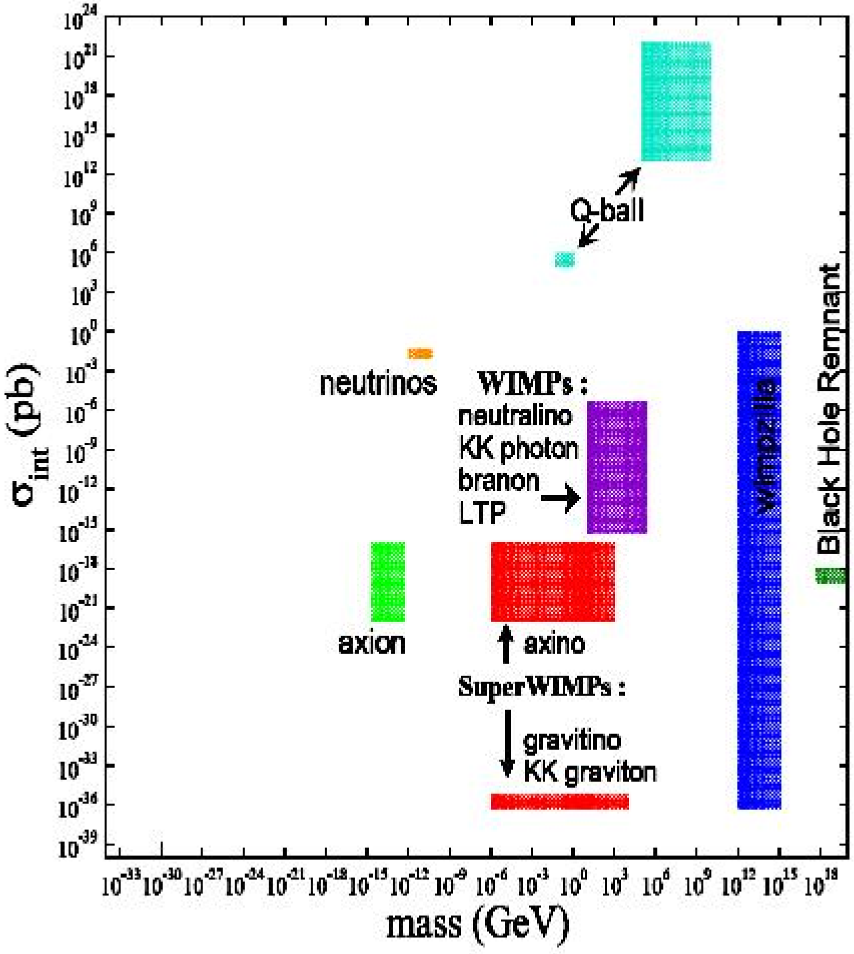


mix with sterile component (both for neutrinos and sneutrinos)

➡ beyond the standard model

(Incomplete) List of DM candidates

- RH 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
- …



The axion

- Pseudo Goldstone boson of Peccei-Quinn symmetry introduced to explain CP conservation in QCD: $\varphi = F\, e^{i\theta}$
- $$m_a \simeq 0.62\ \mathrm{eV}\left(\frac{10^7\mathrm{GeV}}{f_a}\right)$$
- 3 productions mechanisms in the early Universe:

1) misalignment ($T>\Lambda_{QCD}$) +coherent oscillations around minimum ($T< \Lambda_{QCD}$) :

$$\Omega_a h^2 = k_a \left(\frac{m_a}{10^{-5}\mathrm{eV}}\right)^{-1.175} \langle\theta_i^2\rangle$$

($0.3 < k_a <$a few)

if no inflation after PQ phase trans.: **average** (flat dist.→$\langle\Theta^2\rangle=\pi^2/3$)→$\mathbf{m_a \sim 10^{-5}}$ **eV**

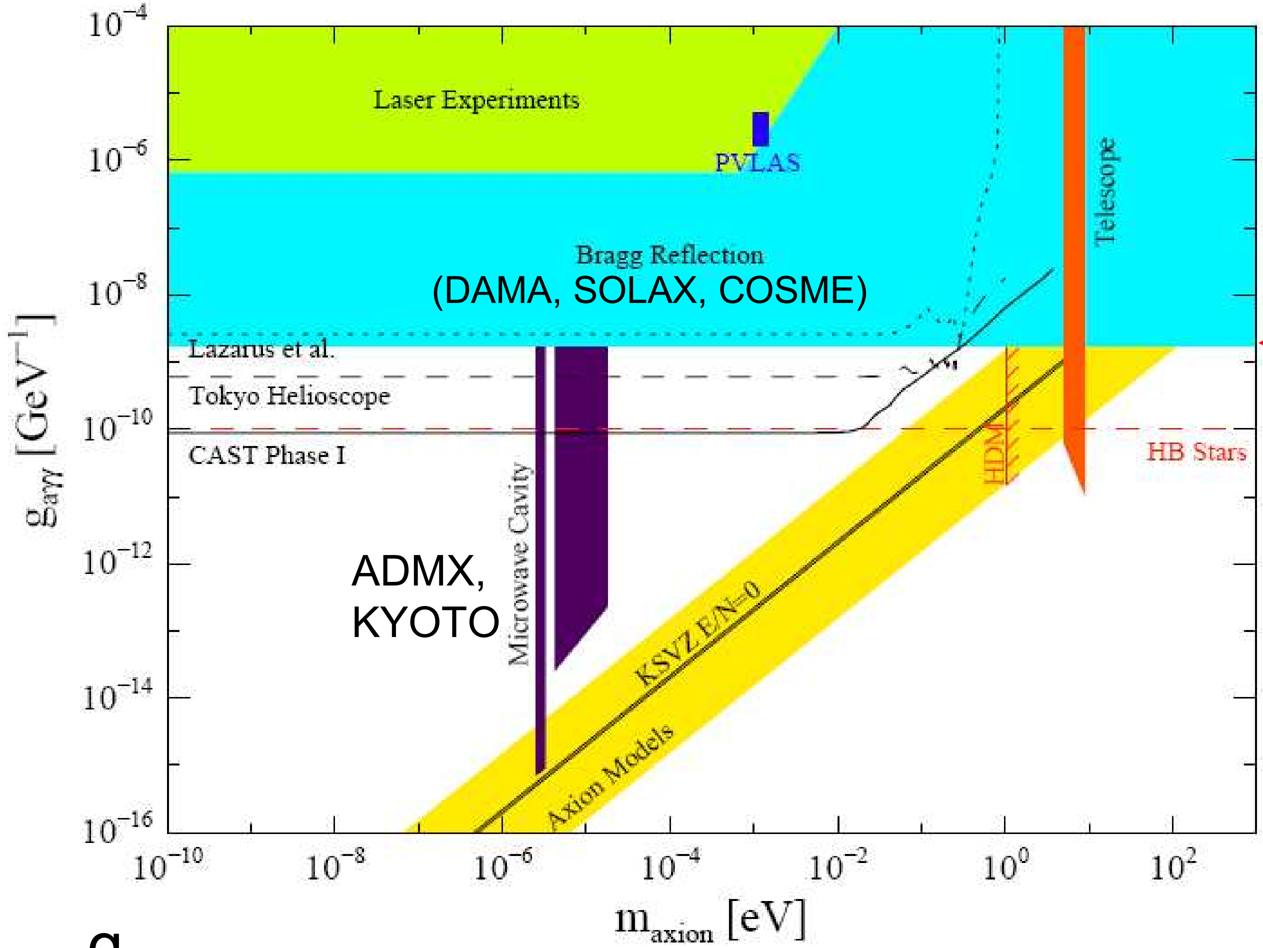
otherwise: smaller m_a possible

[Tegmark,Aguirre, Rees. Wilczek]

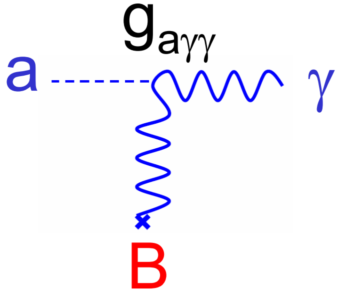
2) axion strings ($T_R>f_a$)

3) thermal ($m_a>10^{-3}$ eV, subdominant)

Experimental limits:



use data from WIMP searches! (but sensitivity improves as $(MT)^{1/8}$)



$g_{a\gamma\gamma}$ from theory & uncertainty in the masses of light quarks, (Buckley,Murayama, arXiv:0705.0542)

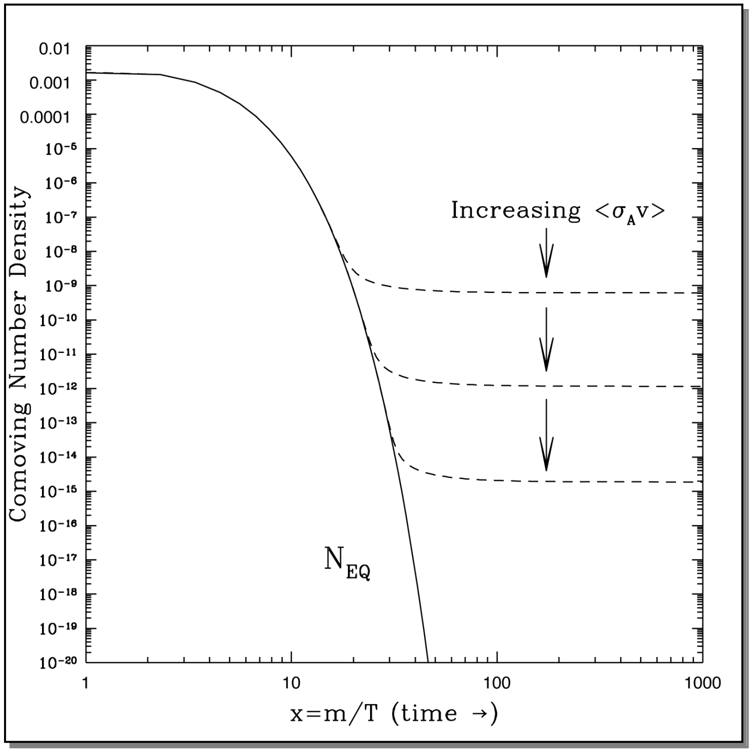
most popular DM candidates from particle physics

(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>

the thermal cosmological density of a WIMP X



$$\Omega_X h^2 \sim 1/<\sigma_{ann} v>_{int}$$

$$<\sigma_{ann} v>_{int} = \int_{x_f}^{x_0} <\sigma_{ann} v> dx$$

$x_0 = M/T_0$

T_0=present (CMB) temperature

$x_f = M/T_f$

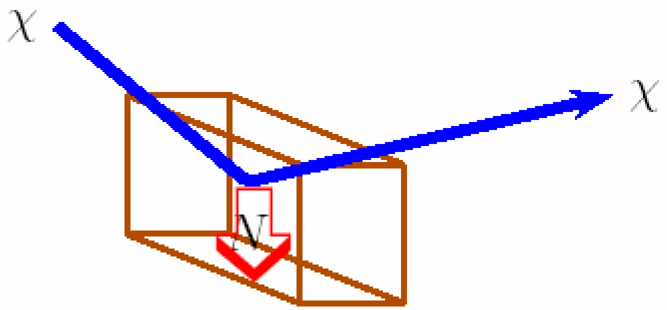
T_f=freeze-out temperature

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

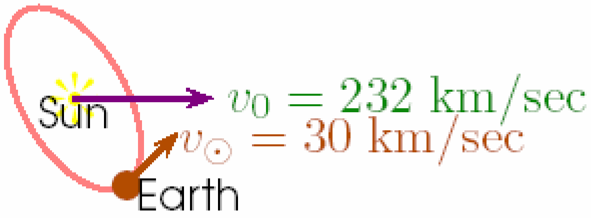
if σ_{ann} is given by weak-type interactions → $\Omega_X \sim 0.1-1$

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

WIMP direct detection



- Elastic recoil of non relativistic halo WIMPs off the nuclei of an underground detector
- Recoil energy of the nucleus in the keV range
- Yearly modulation effect due to the rotation of the Earth around the Sun (the relative velocity between the halo, usually assumed at rest in the Galactic system, and the detector changes during the year)



WIMP differential detection rate

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{vmin}^{v_{max}} d\vec{v}\, f(\vec{v}) |\vec{v}| \frac{d\sigma(\vec{v}, E_R)}{dE_R}$$

E_R=nuclear energy
N_T=# of nuclear targets
v=WIMP velocity in the Earth's rest frame

Astrophysics

- ρ_χ=WIMP local density
- f(v)= WIMP velocity distribution function

Particle and nuclear physics

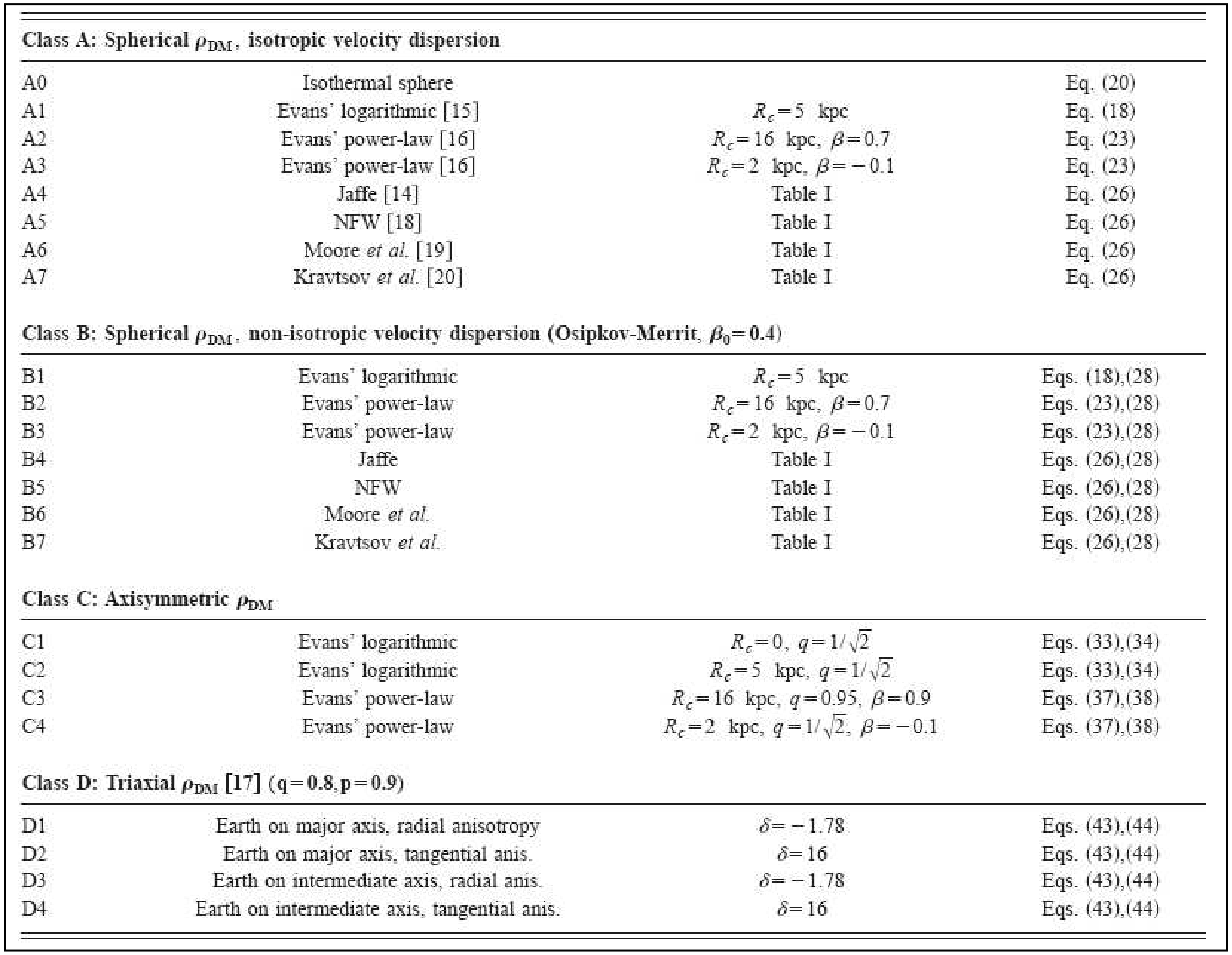
- $\frac{d\sigma(\vec{v}, E_R)}{dE_R}$ =WIMP-nucleus elastic cross section

$$\frac{d\sigma(\vec{v}, E_R)}{dE_R} = \left(\frac{d\sigma(\vec{v}, E_R)}{dE_R}\right)_{\text{coherent}} + \left(\frac{d\sigma(\vec{v}, E_R)}{dE_R}\right)_{\text{spin-dependent}}$$

usually dominates, α (atomic number)^2

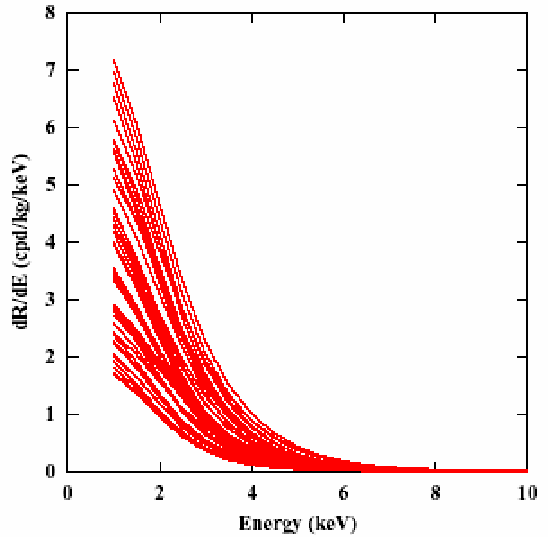
Different halo models are possible

[Belli, Cerulli, Fornengo, Scopel]

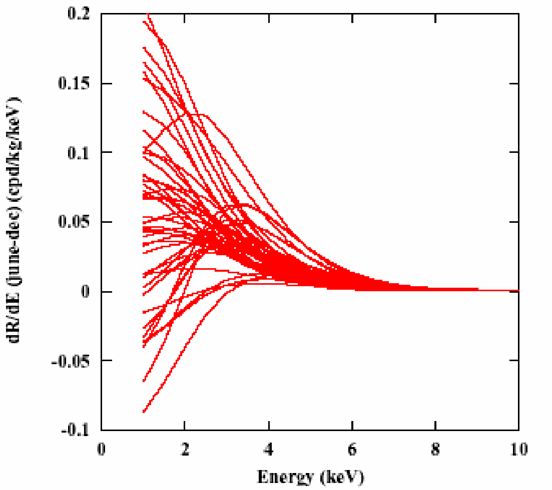


Class A: Spherical ρ_{DM}, isotropic velocity dispersion			
A0	Isothermal sphere		Eq. (20)
A1	Evans' logarithmic [15]	$R_c = 5$ kpc	Eq. (18)
A2	Evans' power-law [16]	$R_c = 16$ kpc, $\beta = 0.7$	Eq. (23)
A3	Evans' power-law [16]	$R_c = 2$ kpc, $\beta = -0.1$	Eq. (23)
A4	Jaffe [14]	Table I	Eq. (26)
A5	NFW [18]	Table I	Eq. (26)
A6	Moore *et al.* [19]	Table I	Eq. (26)
A7	Kravtsov *et al.* [20]	Table I	Eq. (26)
Class B: Spherical ρ_{DM}, non-isotropic velocity dispersion (Osipkov-Merrit, $\beta_0 = 0.4$)			
B1	Evans' logarithmic	$R_c = 5$ kpc	Eqs. (18),(28)
B2	Evans' power-law	$R_c = 16$ kpc, $\beta = 0.7$	Eqs. (23),(28)
B3	Evans' power-law	$R_c = 2$ kpc, $\beta = -0.1$	Eqs. (23),(28)
B4	Jaffe	Table I	Eqs. (26),(28)
B5	NFW	Table I	Eqs. (26),(28)
B6	Moore *et al.*	Table I	Eqs. (26),(28)
B7	Kravtsov *et al.*	Table I	Eqs. (26),(28)
Class C: Axisymmetric ρ_{DM}			
C1	Evans' logarithmic	$R_c = 0$, $q = 1/\sqrt{2}$	Eqs. (33),(34)
C2	Evans' logarithmic	$R_c = 5$ kpc, $q = 1/\sqrt{2}$	Eqs. (33),(34)
C3	Evans' power-law	$R_c = 16$ kpc, $q = 0.95$, $\beta = 0.9$	Eqs. (37),(38)
C4	Evans' power-law	$R_c = 2$ kpc, $q = 1/\sqrt{2}$, $\beta = -0.1$	Eqs. (37),(38)
Class D: Triaxial ρ_{DM} [17] (q=0.8,p=0.9)			
D1	Earth on major axis, radial anisotropy	$\delta = -1.78$	Eqs. (43),(44)
D2	Earth on major axis, tangential anis.	$\delta = 16$	Eqs. (43),(44)
D3	Earth on intermediate axis, radial anis.	$\delta = -1.78$	Eqs. (43),(44)
D4	Earth on intermediate axis, tangential anis.	$\delta = 16$	Eqs. (43),(44)

Interaction on NaI



time-independent part

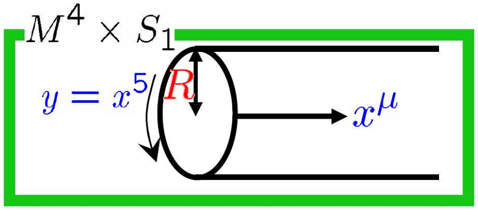


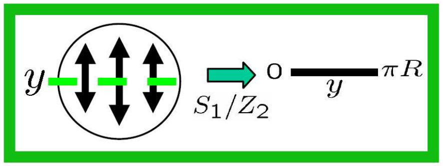
modulation amplitude

sizeable variation of the local density: $0.17 < \rho < 1.7$

The KK photon in Universal Extra Dimensions (UED)

[Appelquist, Cheng, Dobrescu, PRD67 (2000) 035002]





- all SM fields propagate in the 5th dimension
- dispersion relation in 5 dim:

$$E^2 = \vec{p}^2 + (p_5^2 + M^2)$$

implies an infinite tower of KK massive states in the effective 4-dim theory, since $p_5 = n/R$ ($R^{-1} > 300$ GeV from EW tests, n=0,1,2,3…)

- compactification on S_1/Z_2: $\mathcal{P}_{Z_2}\phi(x,y) = \eta\ \phi(x,-y)$ allows to get rid of unwanted dof at zero level → translational invariance broken in 5th dim
- residual invariance under discrete πR translations → KK parity $(-1)^n$ is conserved → LKP (Lightest KK particle) is stable
- 1-loop corrections (Cheng &al, 2002):
  LKP=1st excitation of weak hypercharge boson $B^{(1)}$

$B^{(1)}$ relic abundance

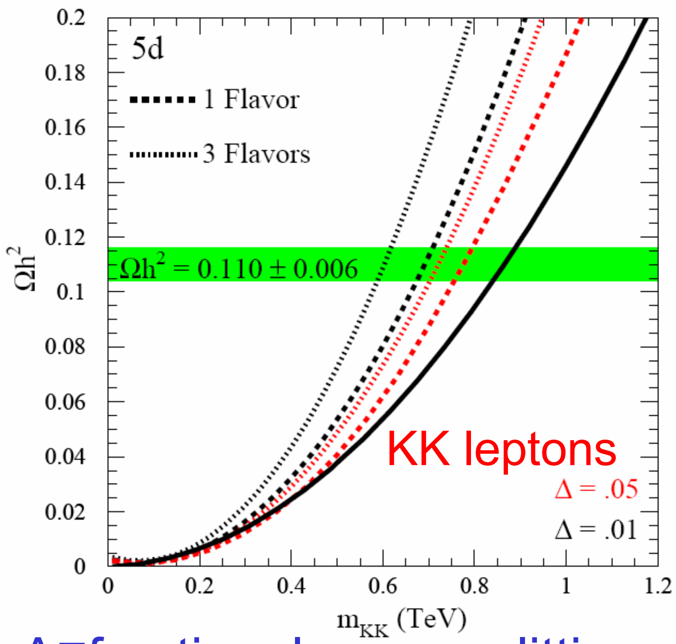
[Servant,Tait, NPB650,391;New J. Phys. 4,99; Kakizai & al., PRD71,123522; Kong, Matchev, JHEP0601,038]

- coannihilations (many modes with similar masses)
- resonances ($M_{NLKP} \sim 2 \times M_{LKP}$)

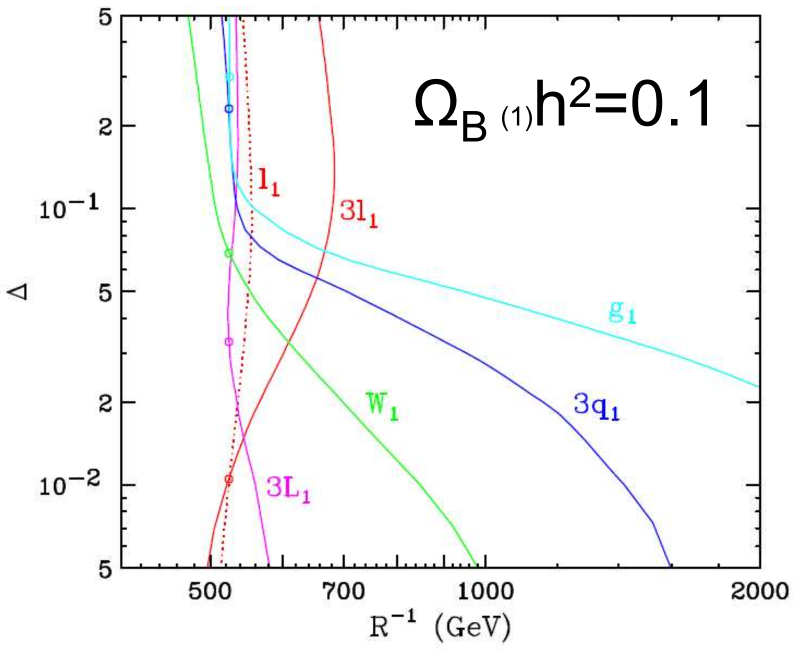
  - general rule of coannihilation:

if cohannihilating particle annihilates faster / slower than LKP→ smaller / larger relic abundance

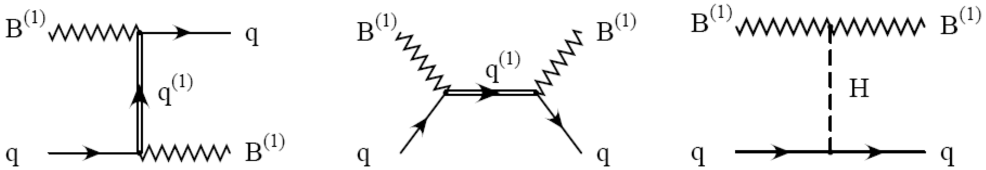
both cases are possible : KK quarks and gluons vs. KK leptons

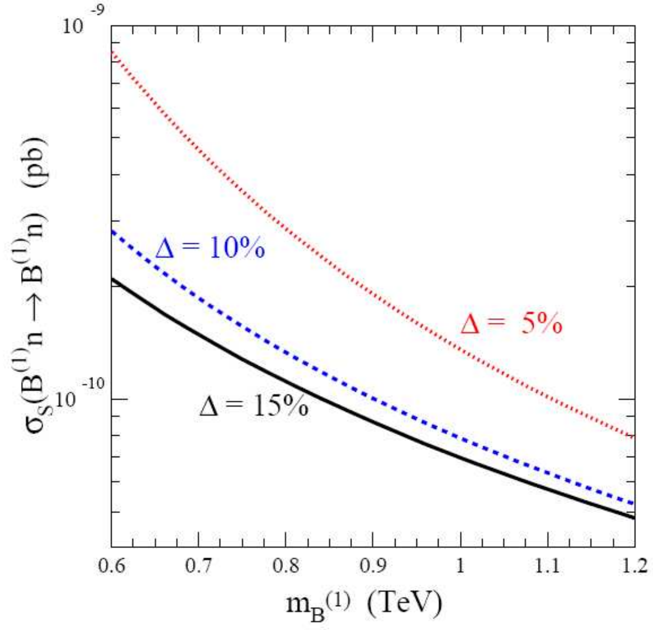


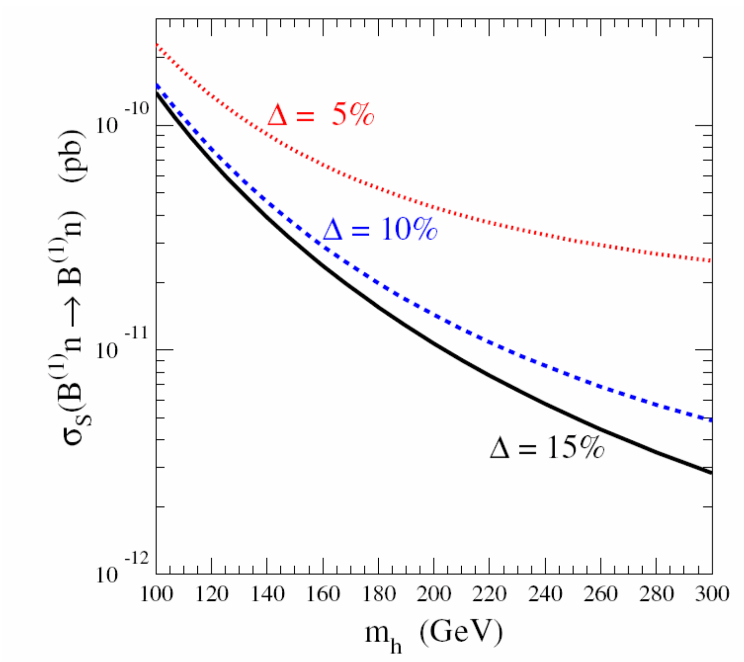
Δ≡fractional mass splitting



- low direct detection signals:

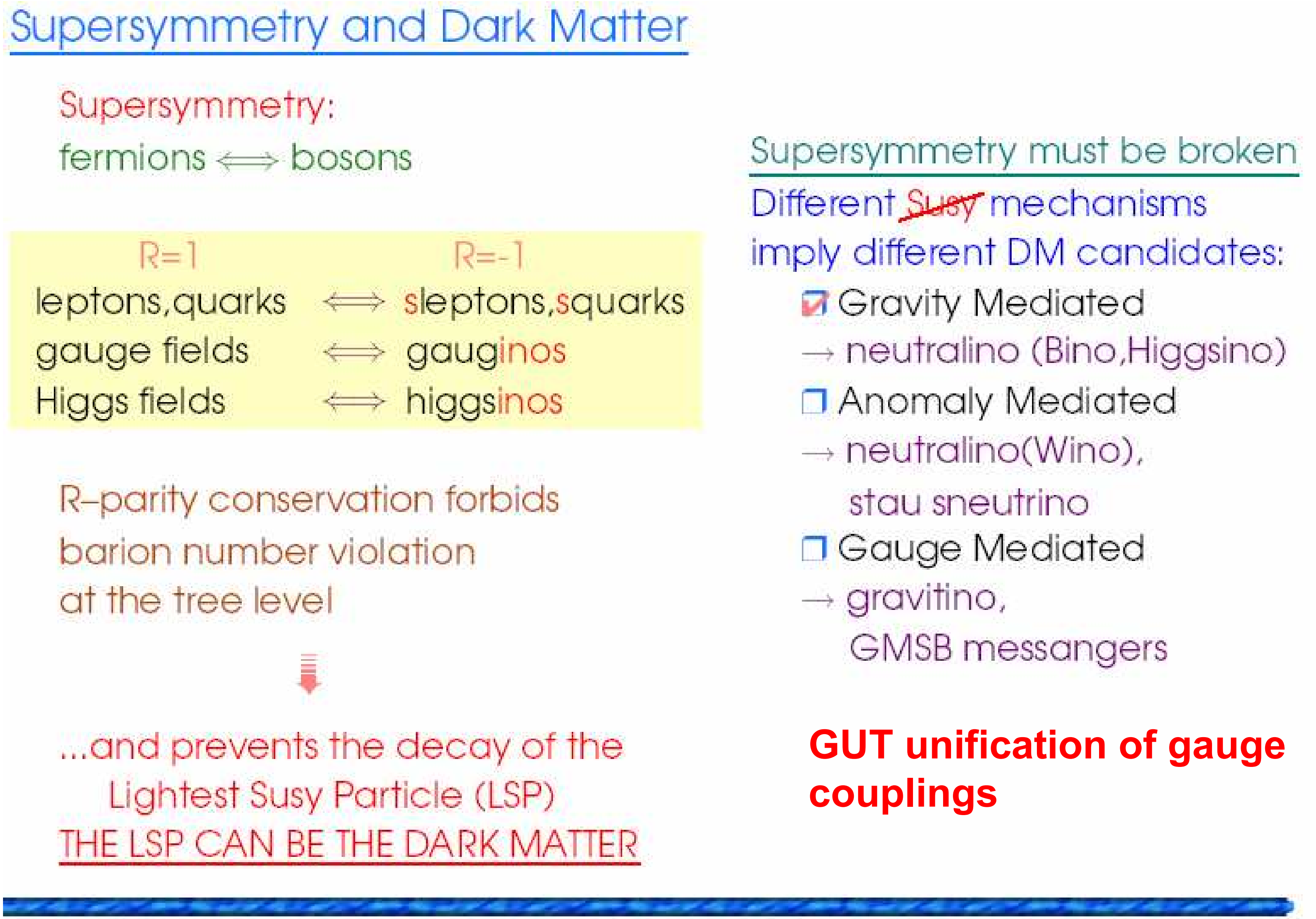






$$\Delta \equiv (m_{q1} - m_{B1})/m_{B1}$$

Right-handed KK-neutrino Dark Matter:
see talk by M.Yamanaka in parallel session



Supersymmetry and Dark Matter

Supersymmetry:

fermions ⟺ bosons

R=1		R=-1
leptons,quarks	⟺	sleptons,squarks
gauge fields	⟺	gauginos
Higgs fields	⟺	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

The neutralino

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

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

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

→IDEAL CANDIDATE FOR COLD DARK MATTER

Right-handed sneutrino Dark Matter:
see talk by T. Asaka in parallel session

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:

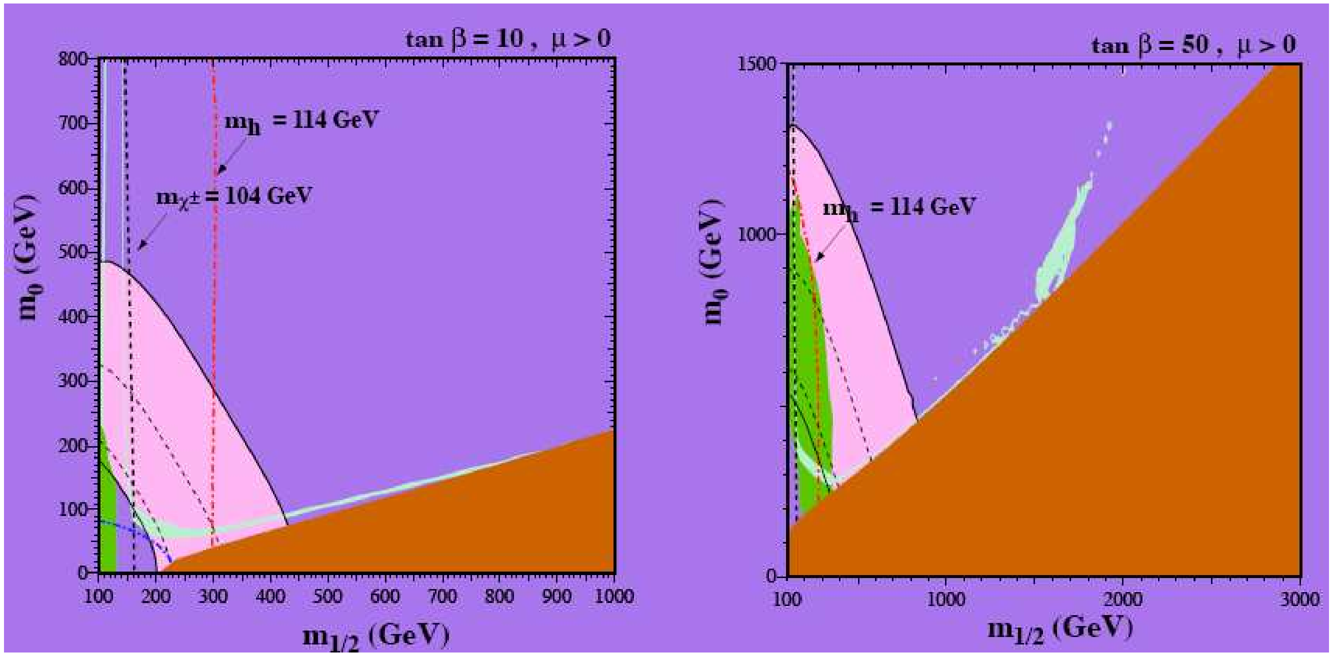
- ○ $\chi \rightarrow$ gaugino (except "focus point region", $m_0 \gg m_{1/2}$)
- ○ $m_A \gg O(m_Z)$ unless $\tan\beta \gtrsim 50$
- ○ μ–M_2 correlation
- ○ $m_{\rm quark} > m_{\rm slepton}$

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

SUGRA
(a.k.a. CMSSM)

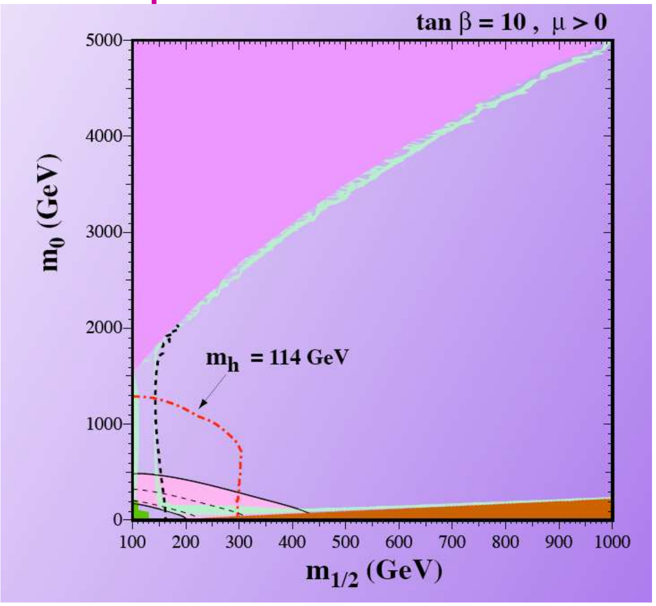
stau coannihilation

Higgs funnel



[Ellis, Olive, Santoso, Spanos]

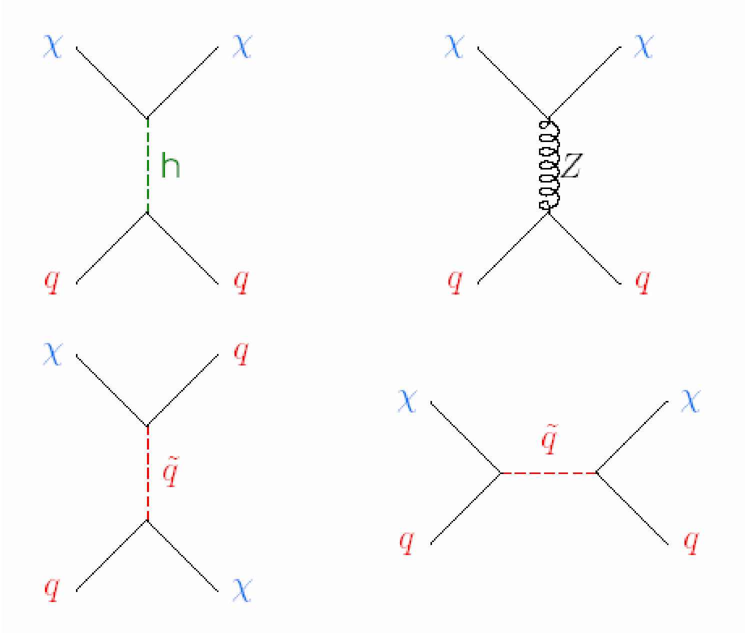
focus point

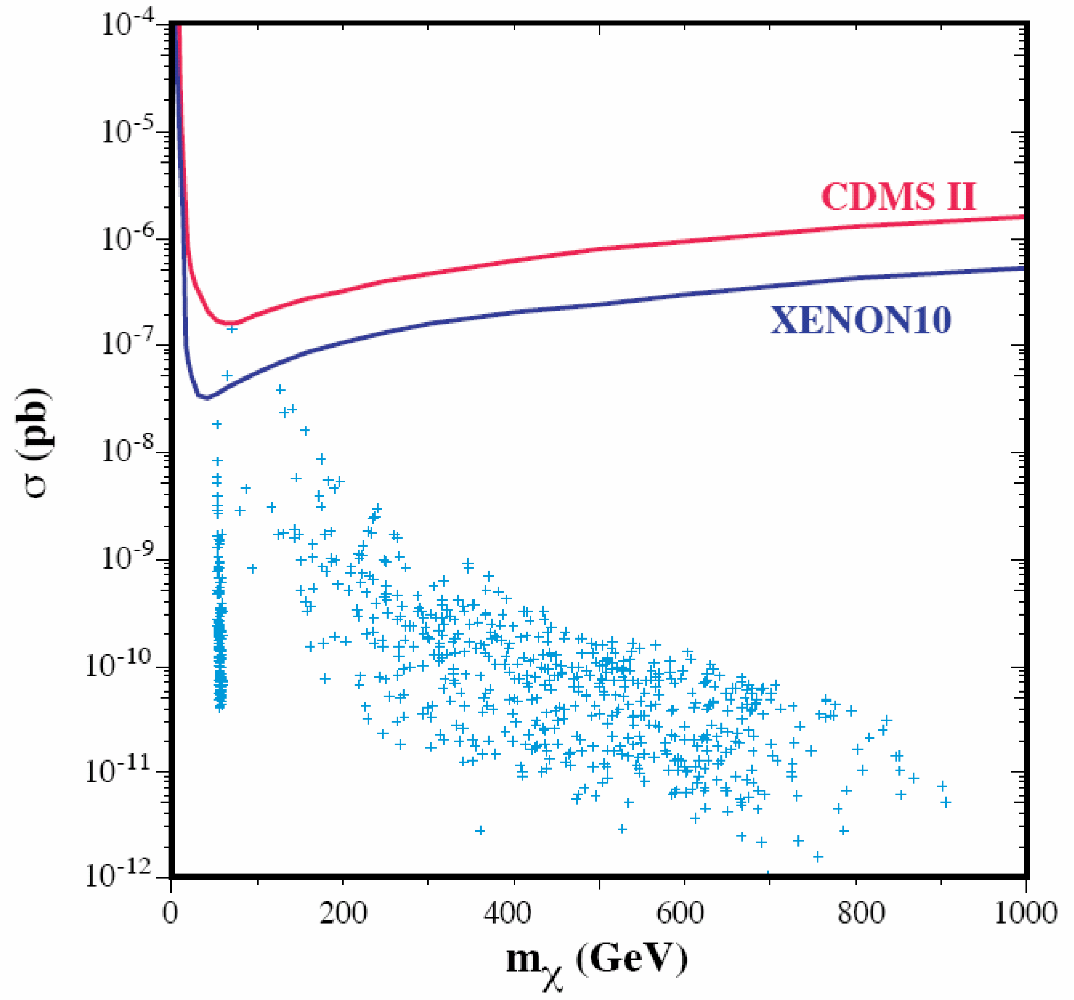


[Feng, Machev, Moroi, Wilczek]

- 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

Direct detection in SUGRA





[Ellis, Olive, Santoso, Spanos]

The Next-to-Minimal MSSM (NMSSM)

solves the μ problem, i.e. why μ~M_{EW} in: $\mu H_1 H_2$

superpotential:

μ=λ<S>

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

Higgs soft terms in the NMSSM:

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

NMSSM particle content:

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

The lightest neutralino:

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

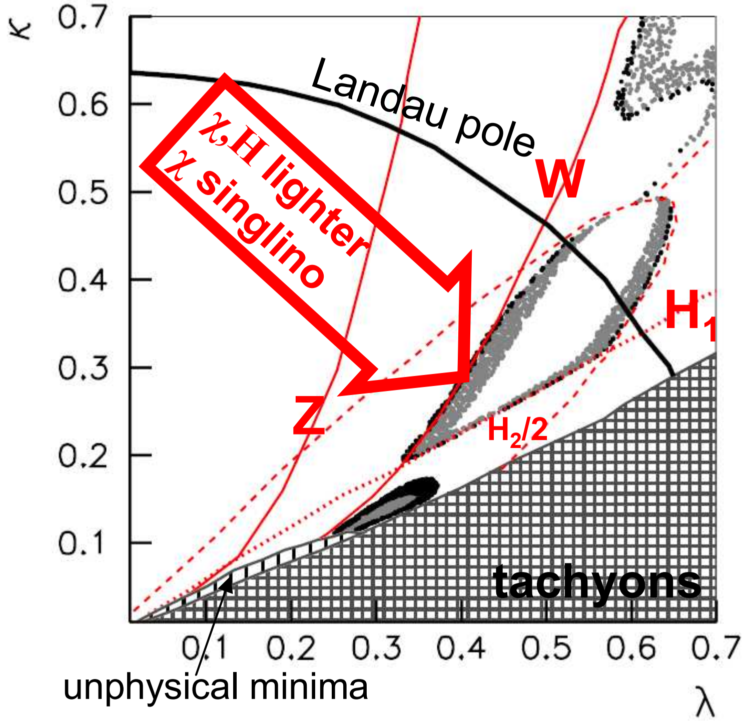
CP-even Higgs:

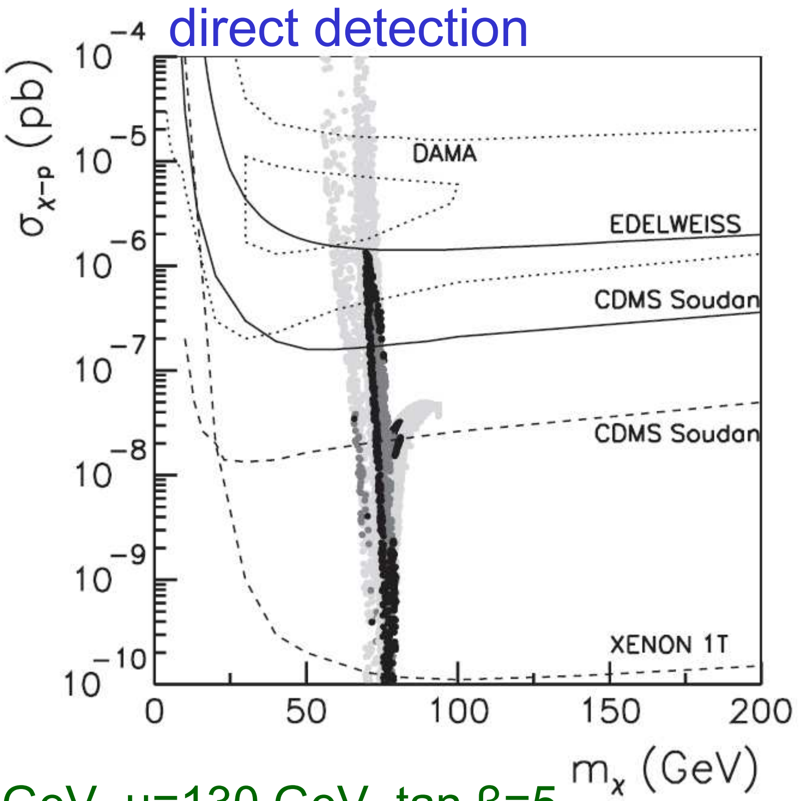
$$h_1^0 = S_{11}H_1^0 + S_{12}H_2^0 + S_{13}S$$

Relic density and direct detection rate in NMSSM

[Cerdeño, Hugonie, López-Fogliani, Muñoz, Teixeira]

relic abundance





M_1=160 GeV, M_2=320, A_λ=400 GeV, A_k=-200 GeV, μ=130 GeV, tan β=5

(sizeable direct detection)

- very light neutral Higgs (mainly singlet)
- light scalars imply more decay channels and resonant decays
- neutralino relatively light (< decay thresholds) and mostly singlino
- high direct detection cross sections (even better for lower M_1)

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→$R=0.5$

Can the neutralino be *light*?

Lower limits on the neutralino mass from accelerators

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

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

- ❒ 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 ‡

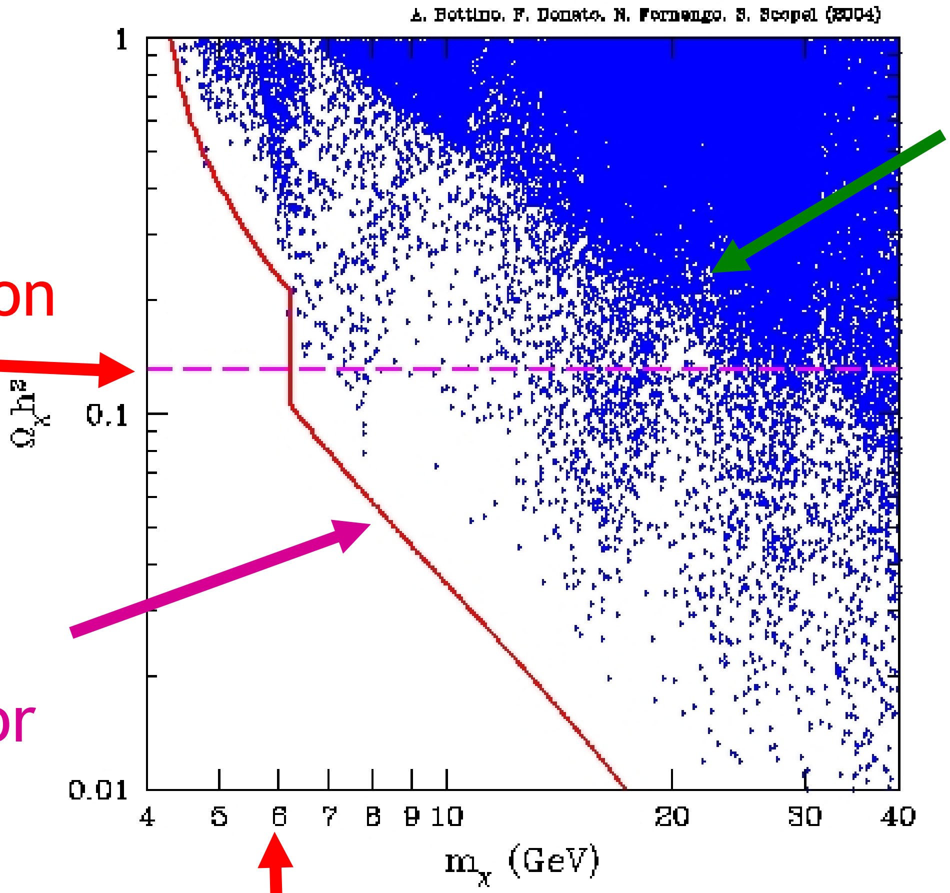
† small production cross sections

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

➠ No absolute direct lower bounds on m_χ

Cosmological lower bound on m_χ

[Bottino, Fornengo, Scopel, PRD68,043506]



scatter plot:
full calculation

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

$M_1 << M_2, \mu$

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

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

Neutralino – nucleon cross section

Color code:

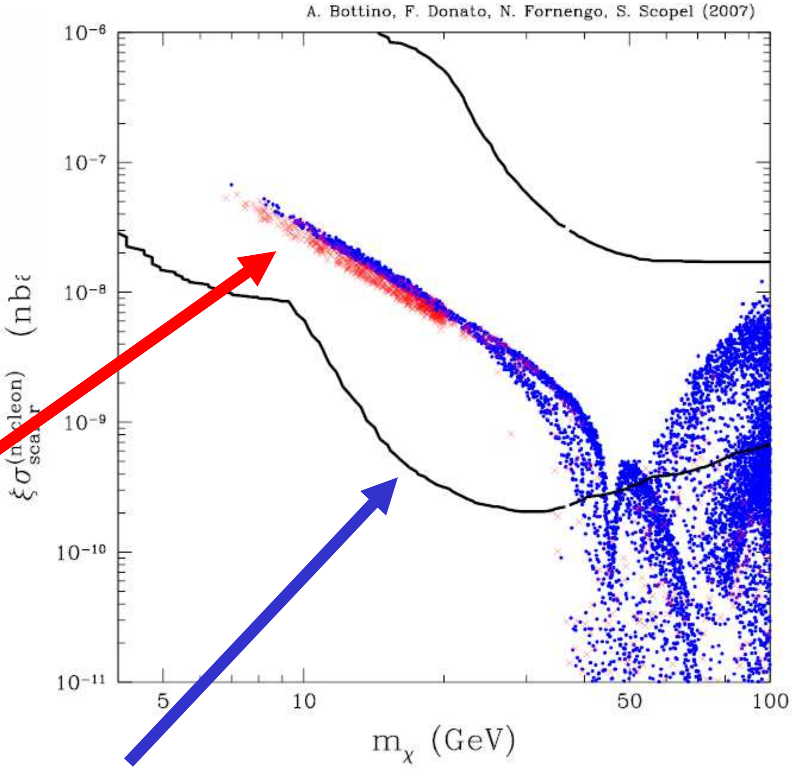
- ● $\Omega_\chi h^2 < 0.095$
- × $\Omega_\chi h^2 > 0.095$

tight correlation between relic abundance and χ-nucleon cross section:

$$\Omega_\chi h^2 \le (\Omega_{CDM} h^2)_{max}$$

$$\Downarrow$$

$$\sigma^{(\mathrm{nucleon})}_{\mathrm{scalar}} \gtrsim \frac{10^{-40} cm^2}{(\Omega_{CDM} h^2)_{max}} \; \frac{\mathrm{GeV}^2}{m_\chi^2 \, [1 - m_b^2/m_\chi^2]^{1/2}} \quad \text{for } m_\chi \lesssim 20 \text{ GeV}$$

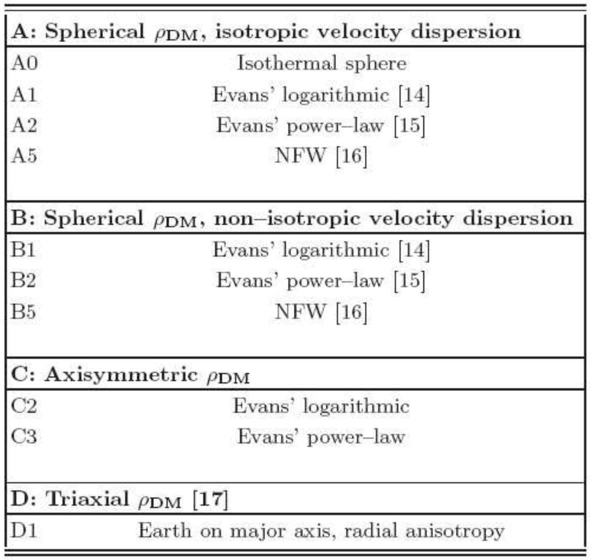


The elastic cross section is bounded from below

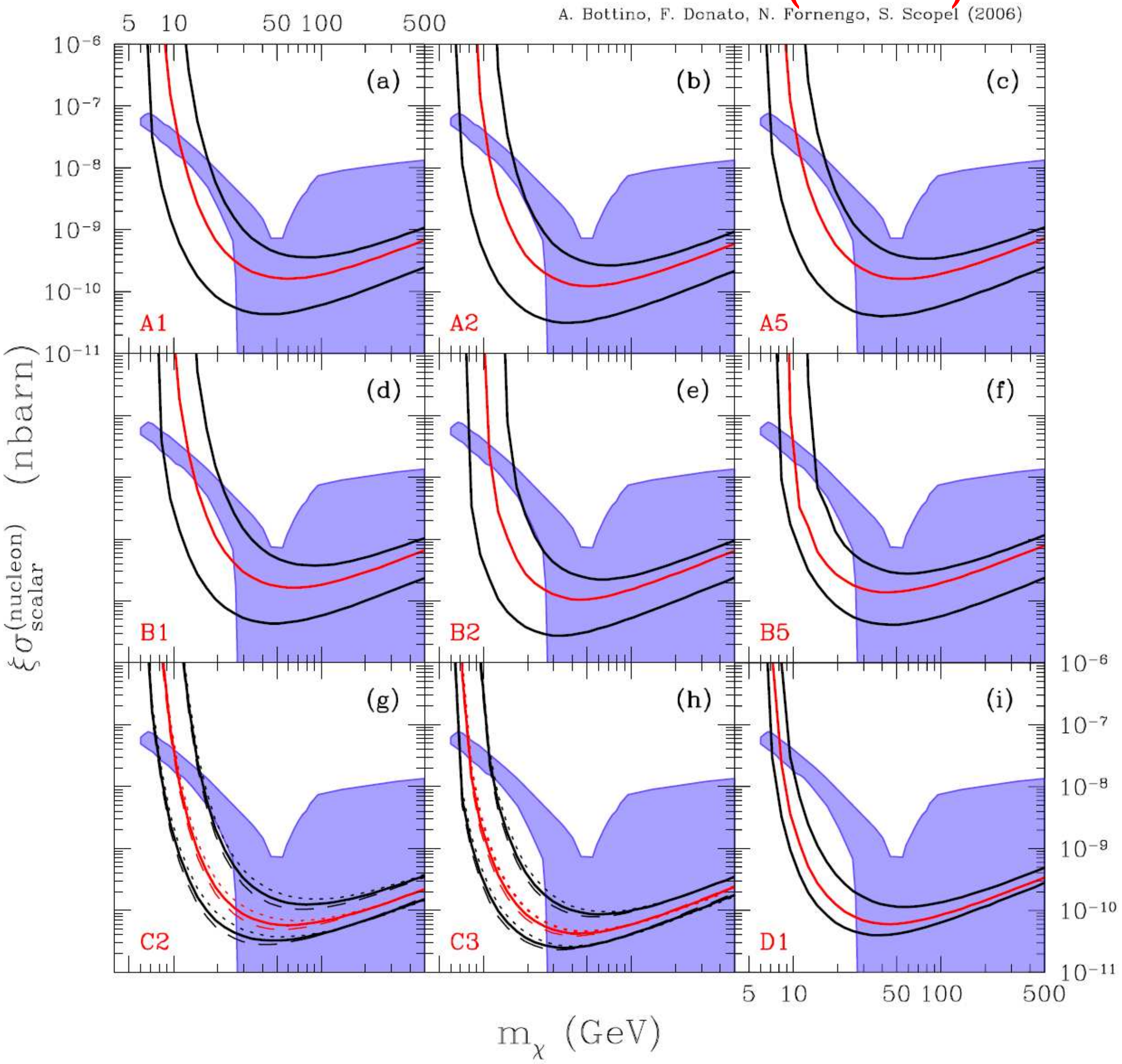
→ "funnel" at low mass

DAMA modulation region, likelyhood function values distant more than 4 σ from the null result (absence on modulation) hypothesis, Riv. N. Cim. 26 n. 1 (2003) 1-73, astro-ph/0307403

How exp. limit change with different halo models (CDMS):



A: Spherical $\rho_{\rm DM}$, isotropic velocity dispersion	
A0	Isothermal sphere
A1	Evans' logarithmic [14]
A2	Evans' power–law [15]
A5	NFW [16]
B: Spherical $\rho_{\rm DM}$, non–isotropic velocity dispersion	
B1	Evans' logarithmic [14]
B2	Evans' power–law [15]
B5	NFW [16]
C: Axisymmetric $\rho_{\rm DM}$	
C2	Evans' logarithmic
C3	Evans' power–law
D: Triaxial $\rho_{\rm DM}$ [17]	
D1	Earth on major axis, radial anisotropy



largest uncertainty at low masses from high velocity tail of the the distribution

A. Bottino, F. Donato, N. Fornengo and S. Scopel Phys.Rev.D72, 083521 (2005)

Conclusions

- WIMPs at the TeV scale can be realized in different well-motivated scenarios (KK photon in UED, Heavy photon in Little Higgs, neutralino in SUSY)
+"Minimal" extensions of SM (talk by Tytgat in parallel session)
- they can all provide the Cold Dark Matter with the correct abundance
- neutralino is still the most popular. Today available in different flavours: SUGRA, nuSUGRA, sub-GUT, Mirage mediation, NMSSM, effMSSM, CPV,…
- neutralinos can be light
- astrophysical uncertainties in signal predictions
- direct searches are already exploring some SUSY scenarios