Indirect Detection of Neutralino Dark Matter with Neutrino Telescopes.

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Centre de Physique des Particules de Marseille : Antares
Laboratoire de Physique Corpusculaire de Clermont-Ferrand : Theory

Contributions to this conference :

⇒ hep-ph/0204135, V.Bertin, E.N., J.Orloff

⇒ V. Barger, F. Halzen, D. Hooper, C. Kao, Phys. Rev. D 65 075022 (2002)

⇒ V.Bertin, E.N., on behalf of the Antares Collaboration

Previous similar works :

⇒ J.L. Feng, K.T. Matchev, F. Wilczek, Phys. Rev. D 63 045024 (2001)

⇒ L. Bergstrom, J. Edsjo, P. Gondolo, Phys. Rev. D 58 103519 (1998)

⇒ G. Jungman, M. Kamionkowski, K. Griest, Phys. Rept 267 (1996)

Contents

Cold Dark Matter

Universe composition : $\Omega = \Omega_\Lambda + \Omega_{mat} + \Omega_r$

$\star$ total density : $\Omega \sim 1$

$\star$ cosmological constant : $\Omega_\Lambda = 0.7 \pm 0.1$

$\star$matter : $\Omega_{mat} = 0.3 \pm 0.1$

baryonic matter : $\Omega_B = 0.04 \pm 0.01$; including $\Omega_{vis} \leq 0.01$

cold dark matter : $\Omega_{DM} = 0.26 \pm 0.1$

$\star$ relativistic components : $0.01 \leq \Omega_{rel} \leq 0.05$

neutrinos : $0.01 \leq \Omega_\nu \leq 0.05$

photons : $\Omega_\gamma = 4.8^{+1.3}_{-0.9} \times 10^{-5}$

$\star$ Hubble's constant :

$h \equiv H_0/100\,\mathrm{km}^{-1} \cdot \mathrm{s}^{-1} \cdot \mathrm{Mpc}^{-1} = 0.72 \pm 0.08$

$$0.1 \leq \Omega_{DM} h^2 \leq 0.2 \Longrightarrow \Omega_{DM} h^2 \leq 0.3 \text{ (conservative value)}$$

Focus only on cold dark matter : WIMPS

$\star$ dark halo of WIMPS ; best candidate = χ the lightest neutralino

$\star$ collisions with nuclei of massive astrophysical bodies $\Rightarrow$ capture (C)

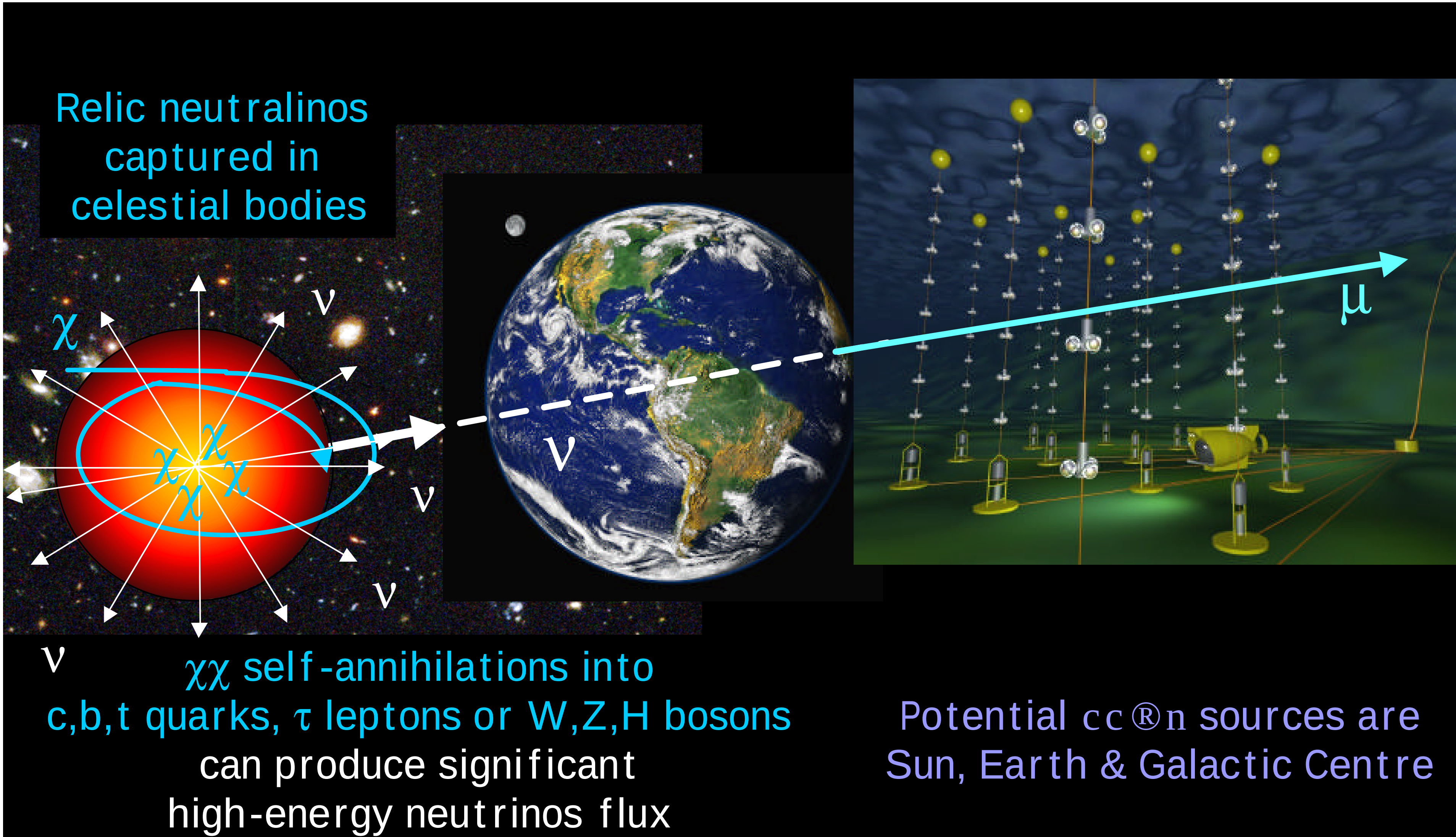
$\star$ WIMP population (N_χ) at the center of the Sun, the Earth ...

$\star$ χ = Majorana particle ; $\chi\chi$ annihilation (Γ_A) $\Rightarrow$

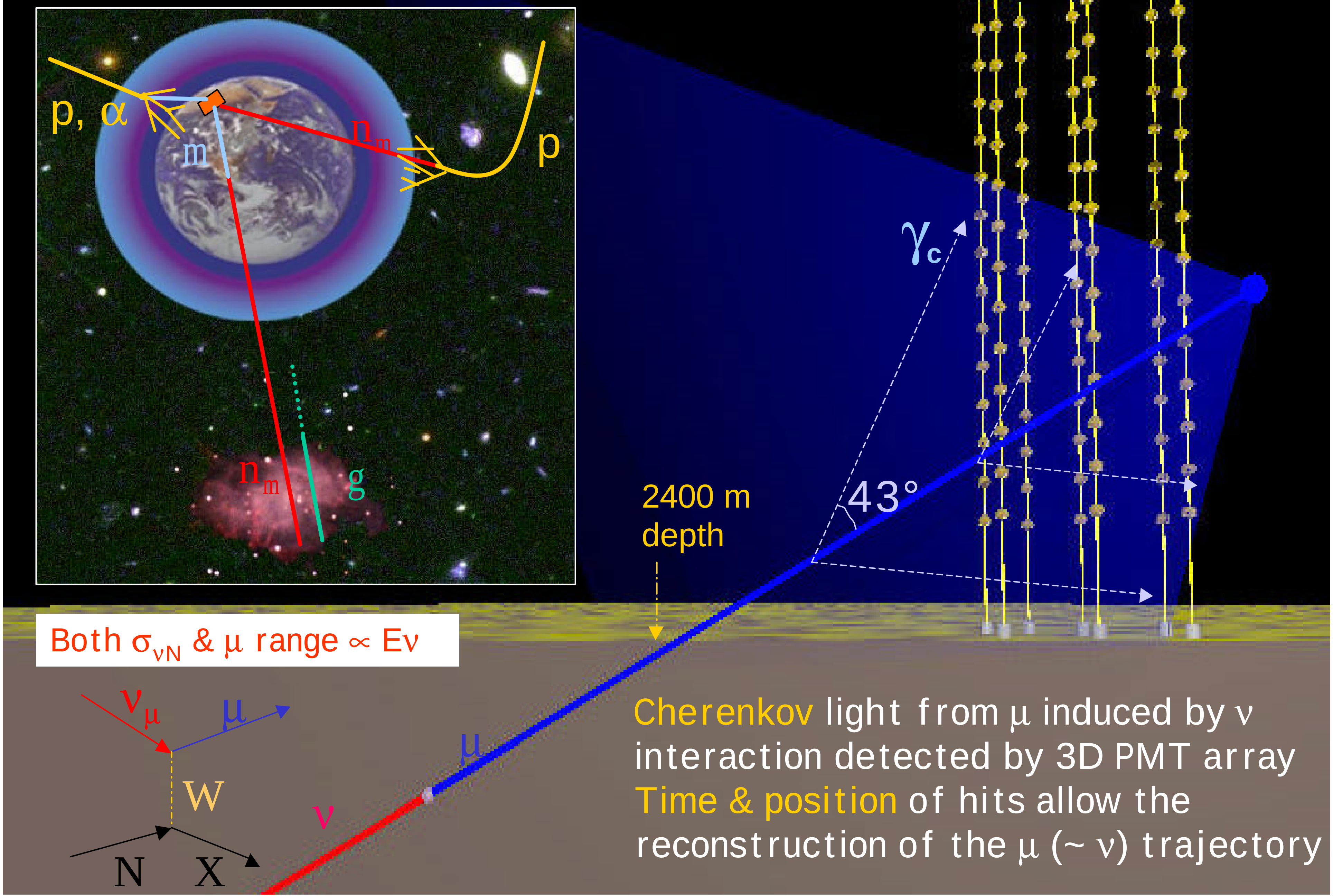
$$\chi\chi \Rightarrow b\bar{b}, t\bar{t}, WW, ZZ \Rightarrow \nu \text{ fluxes}$$

$$\dot{N}_\chi = C - C_A N_\chi^2 \quad ; \quad \Gamma_A = \frac{1}{2} C_A N_\chi^2 = \frac{C}{2} \tanh^2 \sqrt{CC_A}\, t \overset{eq}{\sim} \frac{C}{2}$$

Indirect detection of Dark Matter
neutralinos in a neutrino telescope



Detecting neutrinos



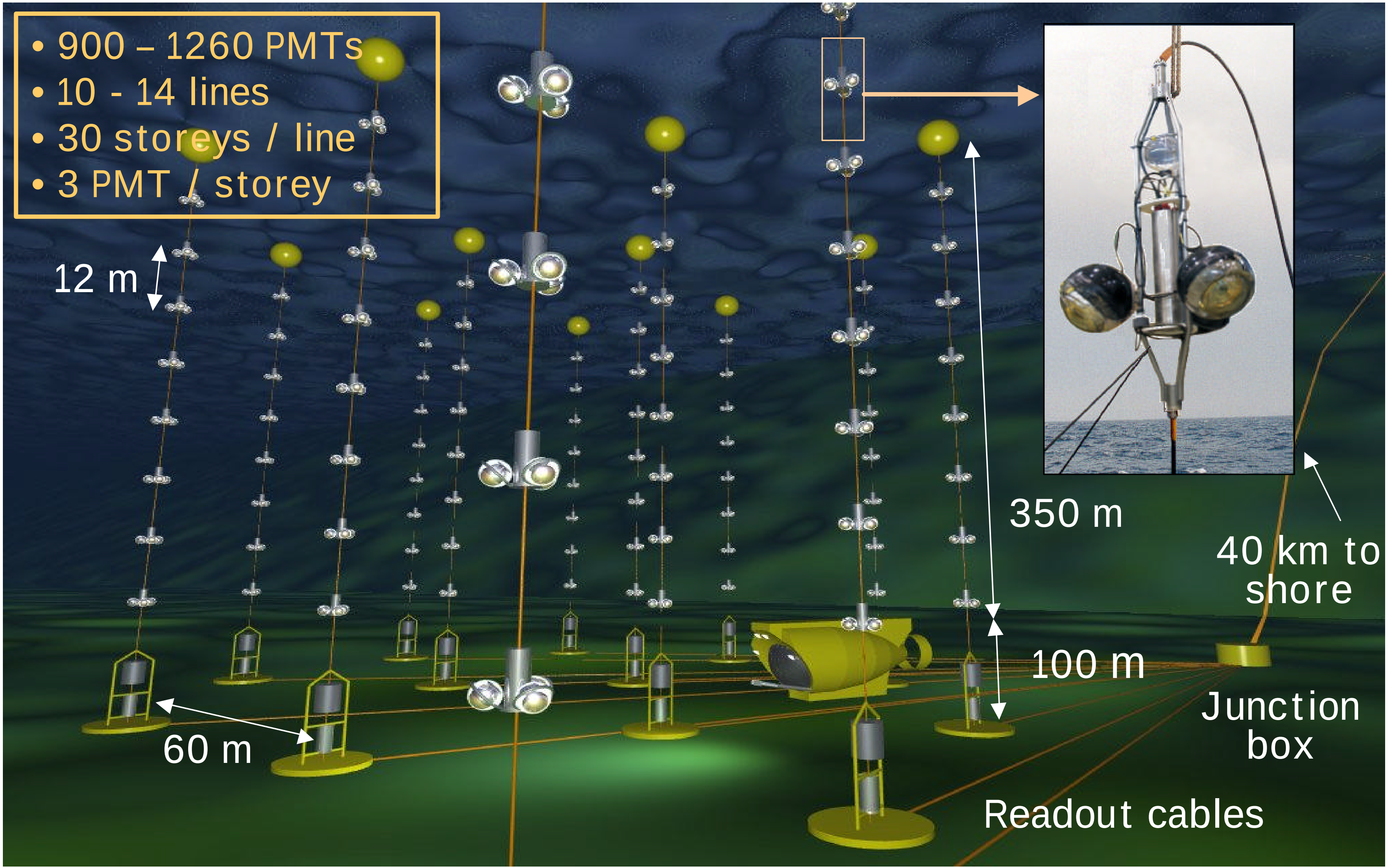
Both $\sigma_{\nu N}$ & μ range ∝ Eν

Cherenkov light from μ induced by ν interaction detected by 3D PMT array

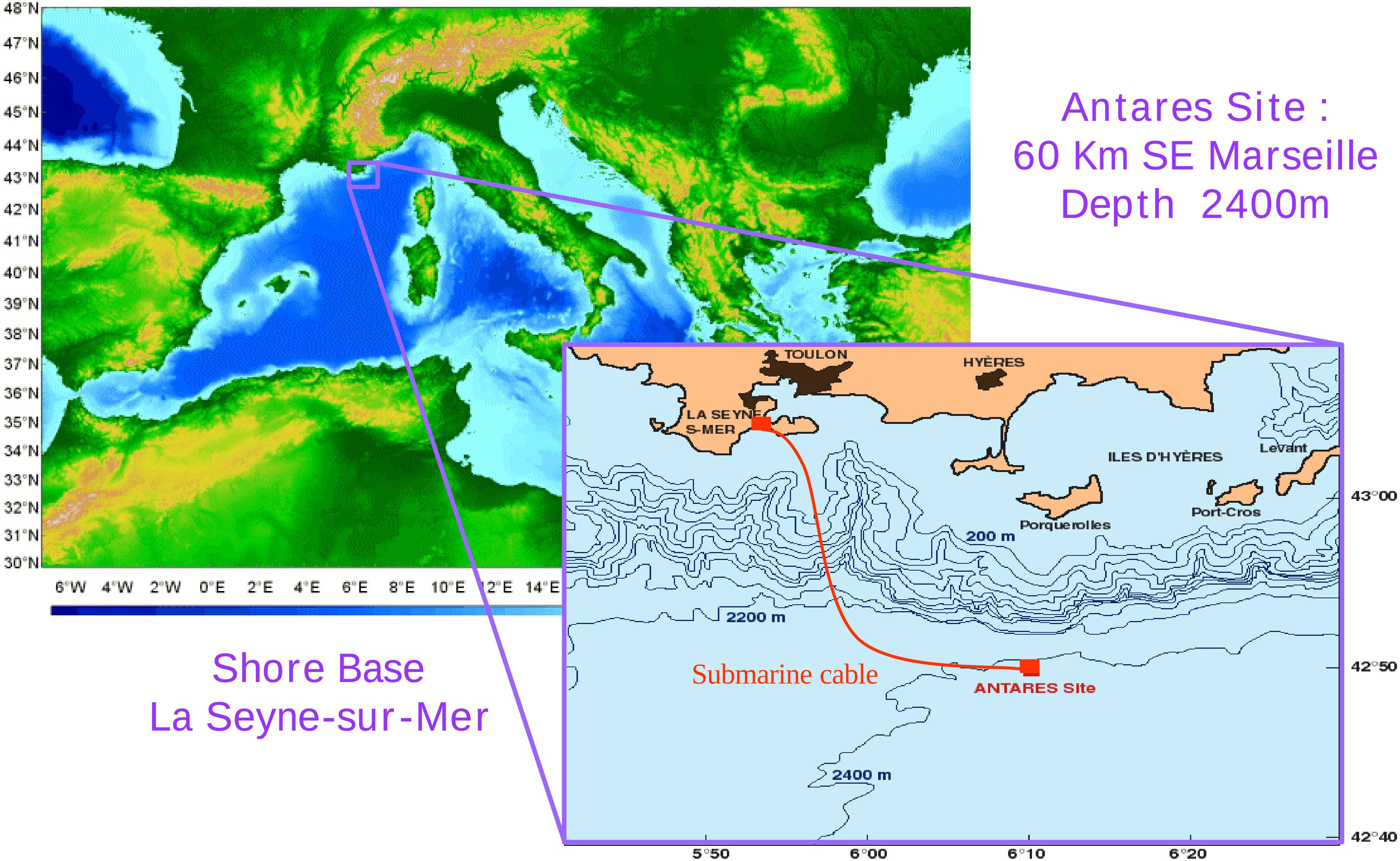
Time & position of hits allow the reconstruction of the μ (~ ν) trajectory

The Antares 0.1 km² detector

to be deployed by 2003-2005



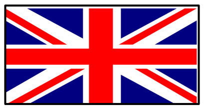
The Antares site



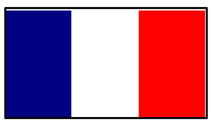
Antares Site :
60 Km SE Marseille
Depth 2400m

Shore Base
La Seyne-sur-Mer

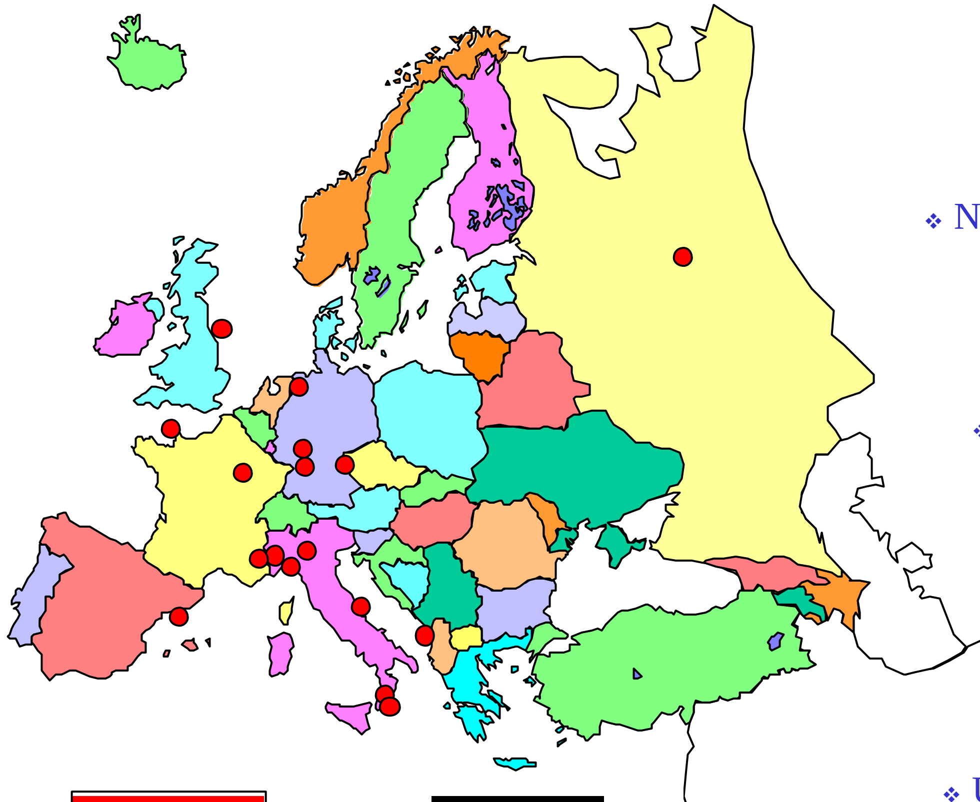
The ANTARES collaboration



- University of Sheffield



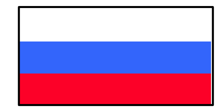
- CPPM, Marseille
- DSM/DAPNIA/CEA, Saclay
- C.O.M. Marseille
- IFREMER, Toulon/Brest
- LAM, Marseille
- IReS, Strasbourg
- Univ. de H.-A., Mulhouse
- ISITV, Toulon
- Observatoire de la Côte d’Azur



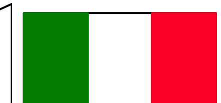
- IFIC, Valencia

- Universitat, Erlangen

- NIKHEF, Amsterdam



- ITEP, Moscou



- University of Bari
- University of Bologna
- University of Catania
- LNS – Catania
- University of Rome
- University of Genova

Neutralino

SM $\xrightarrow{SUSY}$ MSSM

- group $SU(3) \times SU(2) \times U(1)$
- 2 Higgs doublets : $\tan\beta = \frac{v_u}{v_d}$, 5 scalars : h, A, H, $H^{\pm}$
- R-parity conservation $\rightarrow$ stable LSP
- $m_p \neq m_{\tilde{p}} \Rightarrow$ Soft breaking terms $\mathcal{L}_{\rm soft}$

In the basis $(-i\tilde{B}, -i\tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0)$:

$$M_\chi = \begin{pmatrix} M_1 & 0 & -m_Z c\beta sW & m_Z s\beta sW \\ 0 & M_2 & m_Z c\beta cW & -m_Z s\beta cW \\ -m_Z c\beta sW & m_Z c\beta cW & 0 & -\mu \\ m_Z s\beta sW & -m_Z s\beta cW & -\mu & 0 \end{pmatrix}$$

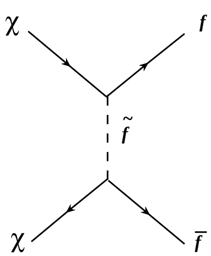
$$\chi = N_1 \tilde{b} + N_2 \tilde{W}^3 + N_3 \tilde{H}_d^0 + N_4 \tilde{H}_u^0$$

gaugino fraction : $g_{frac} = N_1^2 + N_2^2$

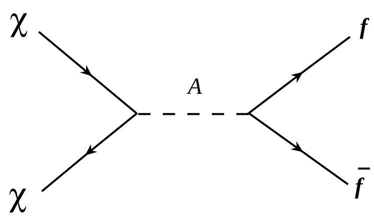
higgsino fraction : $h_{frac} = N_3^2 + N_4^2$

Leading channels in neutralino annihilation

Annihilation $\Rightarrow$ Relic density and indirect detection

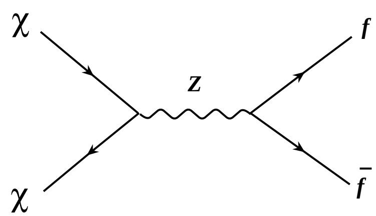


$\propto (\frac{m_\chi}{m_{\tilde f}})^2$

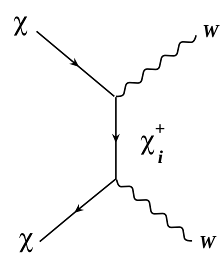


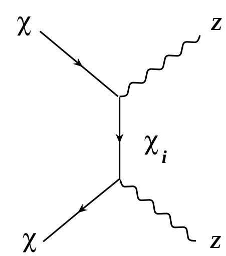
$\propto \frac{\tan\beta\, m_{f_d}}{m_W} (\frac{m_\chi}{m_A})^2 N_1 N_{3(4)}$

$\tan\beta\, m_{f_d} \leftrightarrow \frac{m_{f_u}}{\tan\beta}$



$\propto (\frac{m_f m_\chi}{m_Z^2}) N^2_{3(4)}$





$\propto \frac{1}{1+(m_{\chi_i^+}/m_\chi)^2-(m_W/m_\chi)^2}$

$(m_{\chi_i^+}, m_W) \leftrightarrow (m_{\chi_i}, m_Z)$

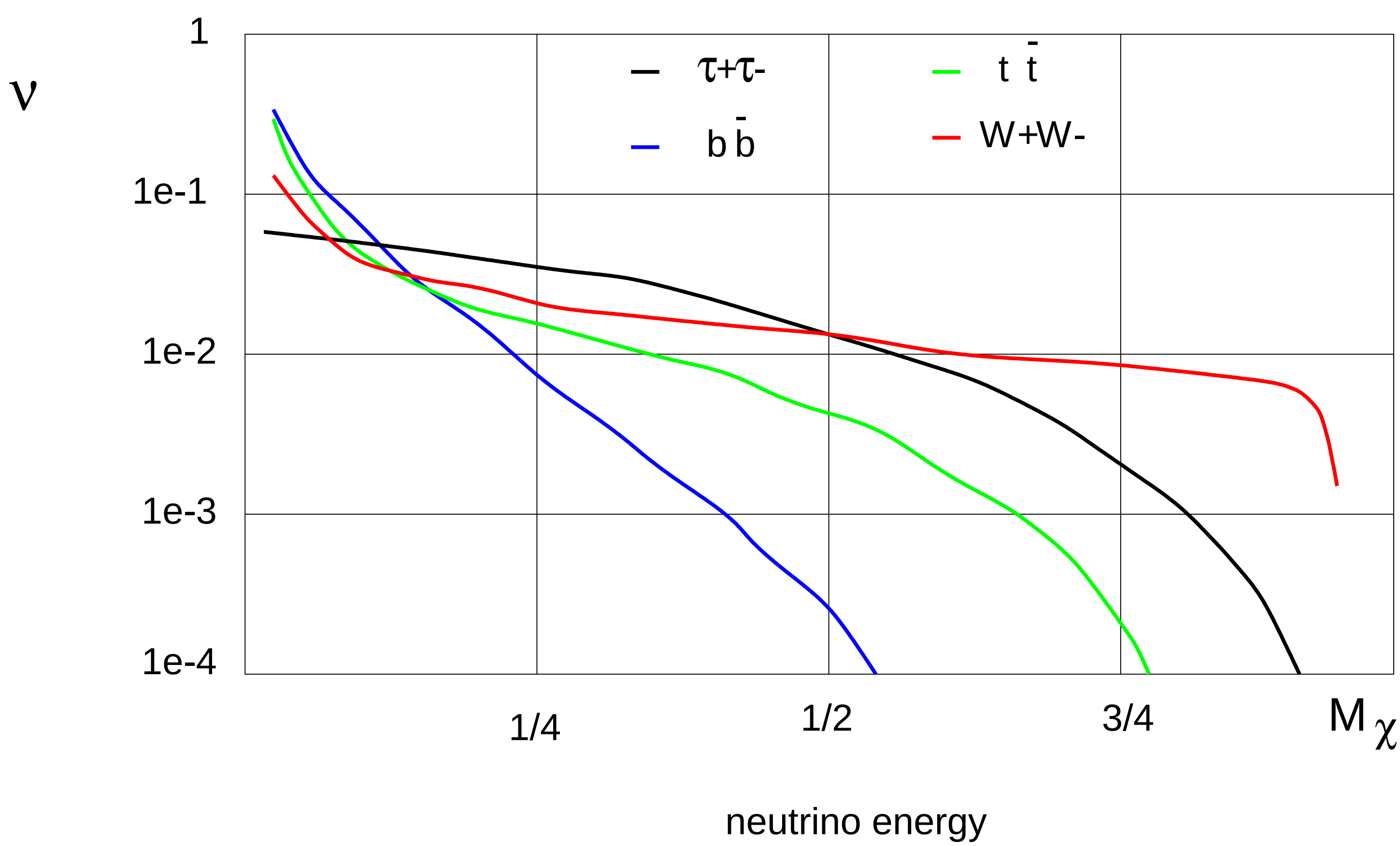
Differential Neutrino Flux

$$\left(\frac{d\Phi}{dE}\right)_i = \frac{\Gamma_A}{4\pi R^2} \sum_F B_F \frac{dN}{dE}_{F,i}(E_{\nu,E})$$

Γ_A annihilation rate

B_F branching ratio of F channel

Differential neutrino spectra

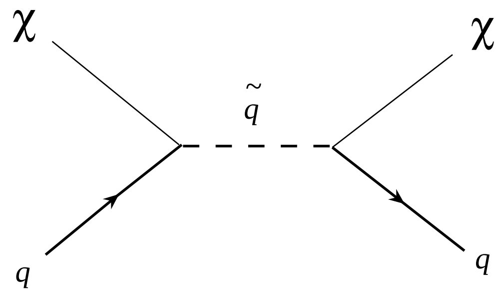


⇒ neutrino from $\chi\chi \rightarrow W^+W^-$ (hard spectrum) are more energetic and easier to detect

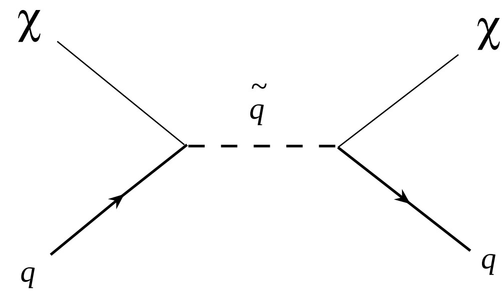
Neutralino Nucleon cross section

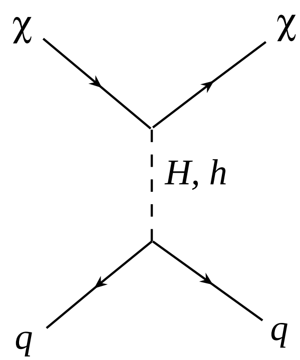
$\sigma_{\chi-p}^{spin/scal} \Rightarrow$ Indirect detection (capture) and direct detection

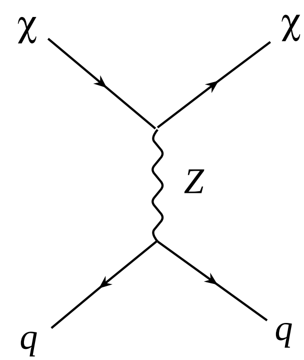
$\sigma_{\chi-p}^{scal}$



$\sigma_{\chi-p}^{spin}$







Capture : $C \sim \frac{\rho_\chi}{v_\chi} \sum_N M_b f_N \frac{\sigma_{\chi-N}^{spin/scal}}{m_\chi m_N} < v_{esc}^2 >_N \ F(v_\chi, v_{esc}, m_\chi, m_N)$

Prospect in MSSM

Parametrization :

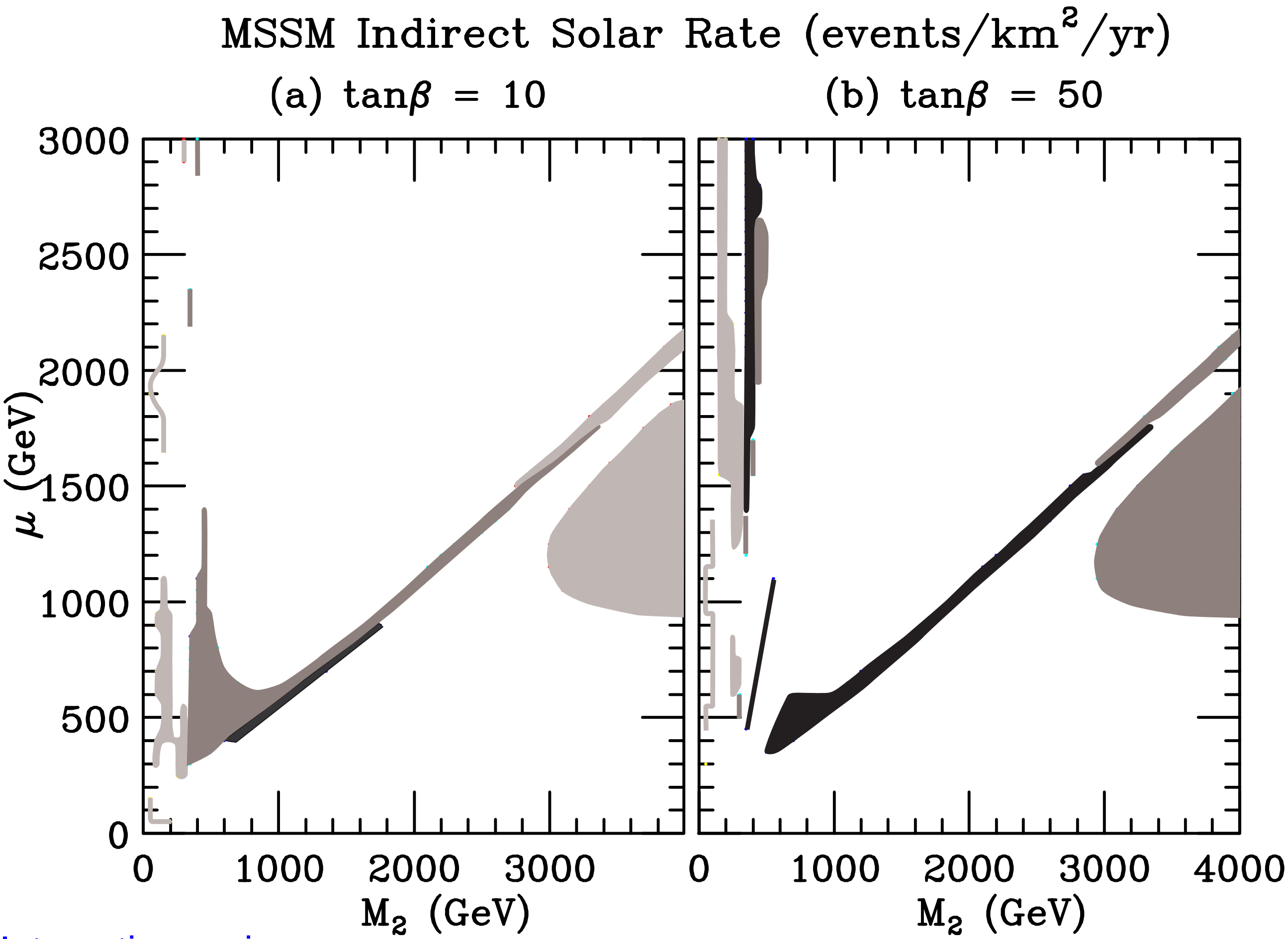
⋆ common value for the masses of scalar fermions and the trilinear couplings :
$m_{SUSY} = m_{\tilde{f}} = A_f = MAX(300\ GeV, 1.5\ m_\chi)$

⋆ $SU(2)$ gaugino mass : M_2

⋆ the Higgs mixing parameter : μ

⋆ the ratio of vevs: $\tan\beta = \frac{v_u}{v_d}$

⋆ the CP-odd Higgs boson mass : m_A



Interesting regions :

(i) in the neighborhood of $M_2 \sim 500$ GeV and $\mu \sim 500$ GeV

(ii) in the neighborhood of $M_2 \sim 4000$ GeV and $\mu \sim 1200$ GeV

(iii) in a narrow band with $M_2 \geq 1200$ GeV and $M_2 \sim 2\mu$

(iv) in a narrow band with $M_2 \sim 400$ GeV and $\mu \geq 1200$ GeV for $\tan\beta \sim 50$.

⇒ V. Barger, F. Halzen, D. Hooper, C. Kao, Phys. Rev. D 65 075022 (2002)

mSugra/CMSSM models

Parameters at GUT scale $\sim 2.\ 10^{16}$ GeV:

⋆ a common gaugino mass $m_{1/2}$
⋆ a common scalar mass m_0
⋆ a common trilinear coupling A_0
⋆ a common bilinear coupling B_0
⋆ Higgs parameter μ_0

+ Renormalization group equation and Radiative Electroweak Symmetry Breaking
$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2|_{Q_{EWSB}} - m_{H_u}^2|_{Q_{EWSB}} \tan^2\beta}{\tan^2\beta - 1} - \mu^2|_{Q_{EWSB}}$ achieved at $Q_{EWSB} \sim \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$

$\Rightarrow$ Input parameters : $m_0, m_{1/2}, A_0, \tan\beta, sgn(\mu)$
More consistency (CCB, Landau Poles, REWSB, less free parameters)

We used Suspect program available on
http://www.lpm.univ-montp2.fr:7082/ kneur/suspect.html

(study of the CMSSM with Suspect : hep-ph/0107316, A. Djouadi, M. Drees,J.L. Kneur)

Composition of the lightest neutralino :

⋆ bino χ : for low m_0
RGE drive $M_1|_{Q_{EWSB}} = \frac{M_2|_{Q_{EWSB}}}{2} = 0.41 m_{1/2} << |\mu|_{Q_{EWSB}}$

⋆ mixed bino-higgsino χ : EWSB

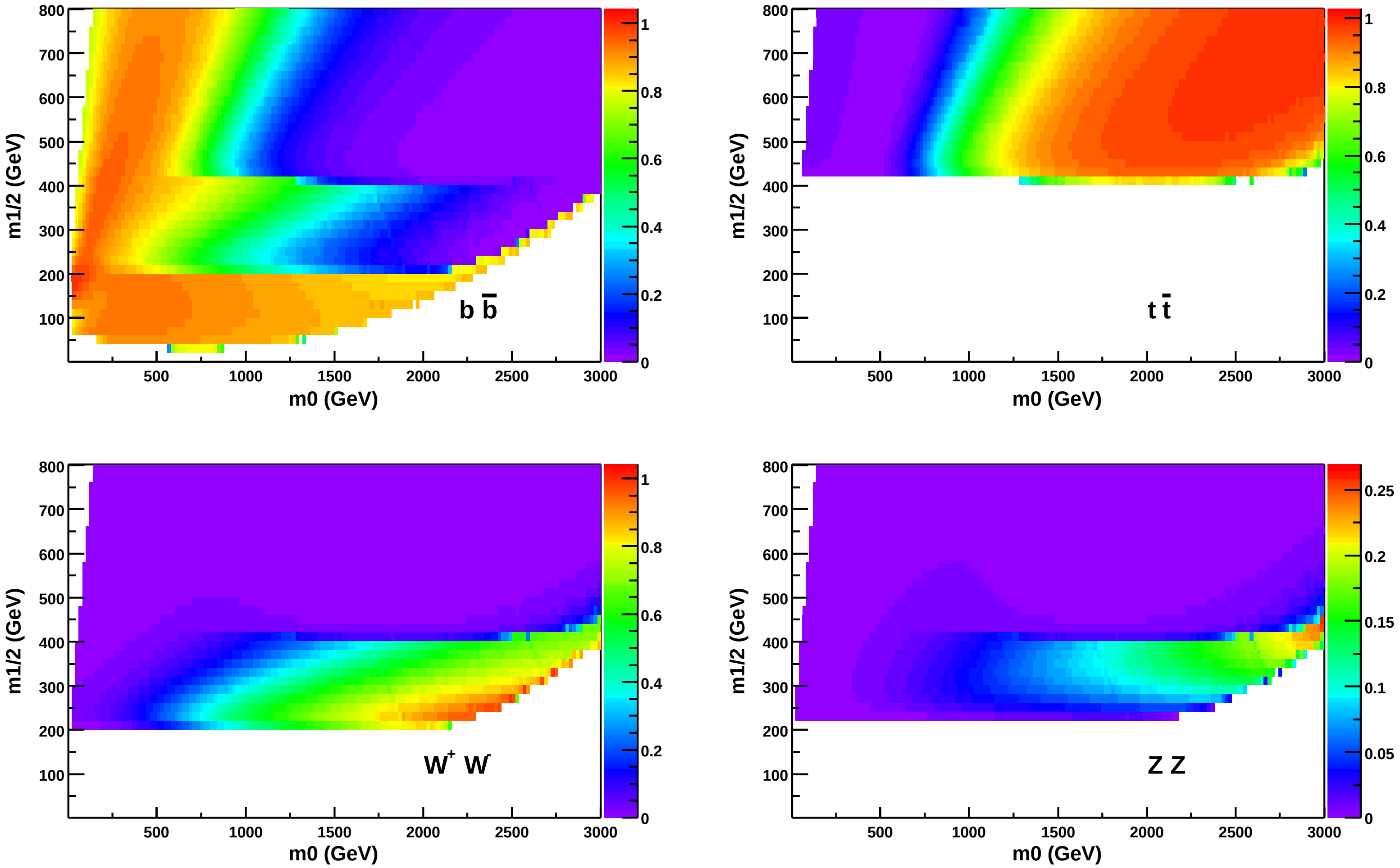
$$\sim -m_{H_u}^2|_{Q_{EWSB}} - \mu^2|_{Q_{EWSB}} \text{ if } \tan\beta \geq 5$$

for m_0 large (> 1000),

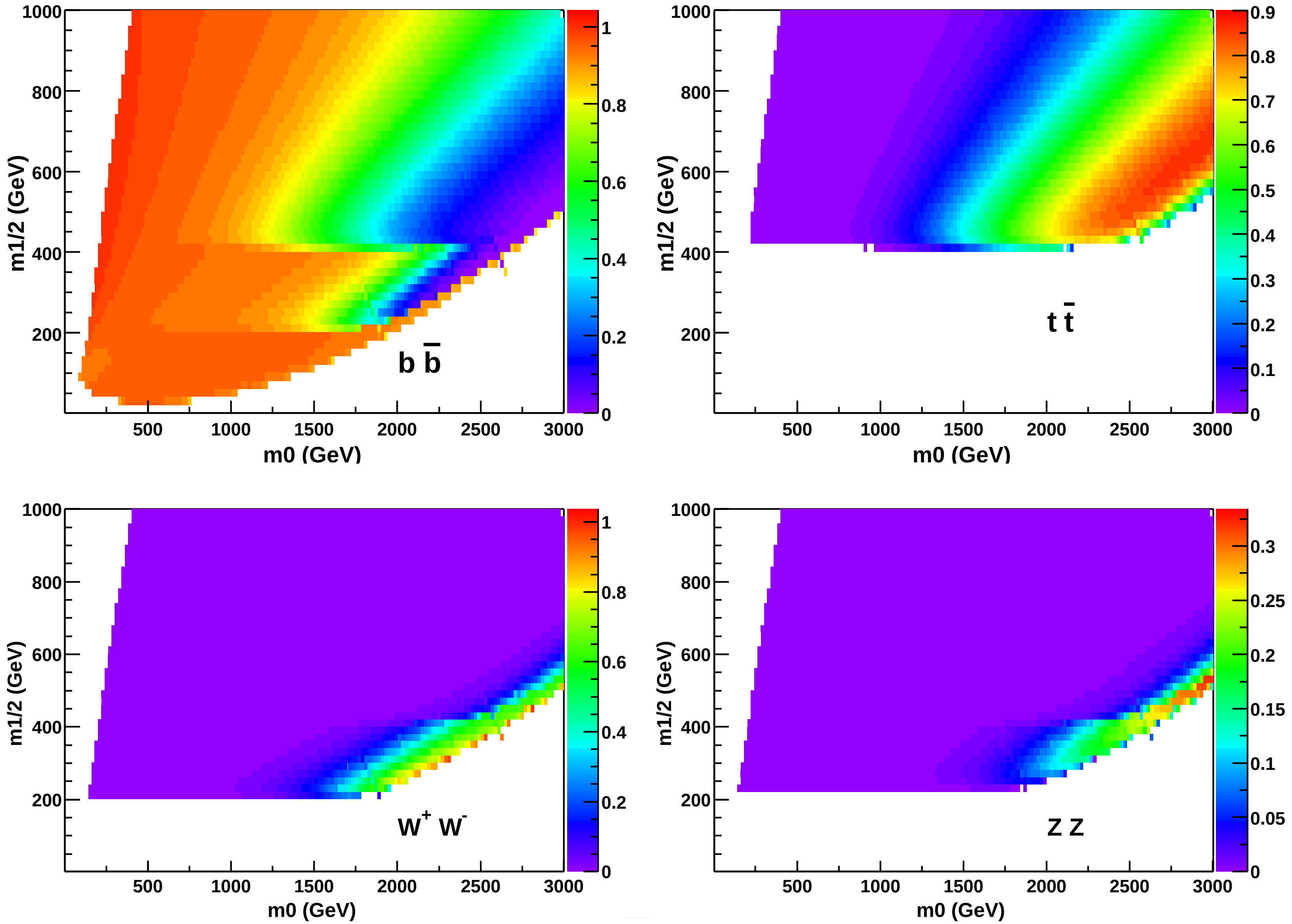
increasing $m_0 \Rightarrow m_{H_u}^2$ less negative $\Rightarrow \mu$ decreases $\Rightarrow \mu \sim M_1$

hep-ph/9909334 Feng, Matchev, Moroi “Focus point region”

A0=0 ; tan(β)=10 ; μ >0



A0=0 ; tan (β)=45 ; μ >0



Relic density

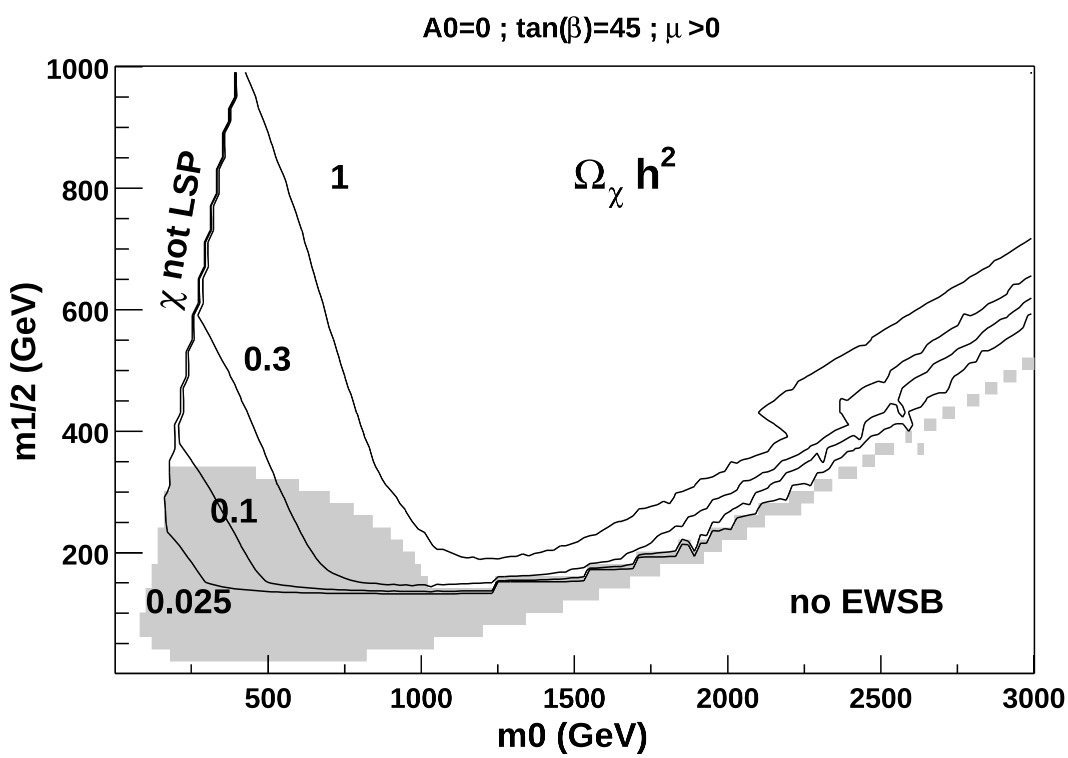
Boltzman equation :

$$
\left.\begin{aligned}
\frac{dn}{dt} = \quad & -3Hn - \sum_{j=1}^{N} < \sigma_{ij} v_{ij} > (n_i n_j - n_i^{eq} n_j^{eq}) \\
& - \sum_{j \neq i} [< \sigma'_{Xij} v_{ij} > (n_i n_X - n_i^{eq} n_X^{eq}) \\
& - < \sigma'_{Xij} v_{ij} > (n_j n_X - n_j^{eq} n_X^{eq})] \\
& - \sum_{j \neq i} [\Gamma_{ij}(n_i - n_i^{eq}) - \Gamma_{ji}(n_j - n_j^{eq})] \\
\\
\Omega_\chi = \quad & \frac{m_\chi n^0}{\rho_{crit}} \; ; \; \rho_{crit} = \frac{3H^2}{8\pi G}
\end{aligned}\right\} \Rightarrow \Omega_\chi h^2
$$

$$\chi\chi \xrightarrow{Z} t\bar{t}$$

$$\chi\chi \xrightarrow{A} b\bar{b} \qquad \chi\chi \xrightarrow{\chi_i^+} W^- W^+$$

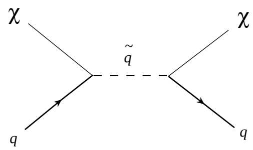
$$\chi\chi \xrightarrow{\chi_i} ZZ$$

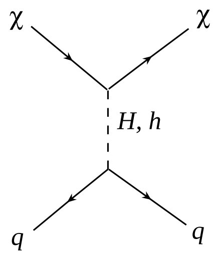


- grey region is excluded by experiments (LEP, $b->s\gamma$, ...)
- $\chi\tilde{\tau}$ and $\chi\tilde{t}$ coannihilations not included.

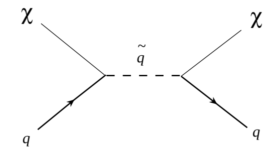
They happend in regions that ν telescopes cannot test.

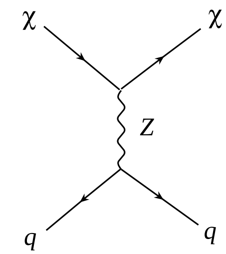
We used DarkSusy : http://www.physto.se/ edsjo/darksusy/





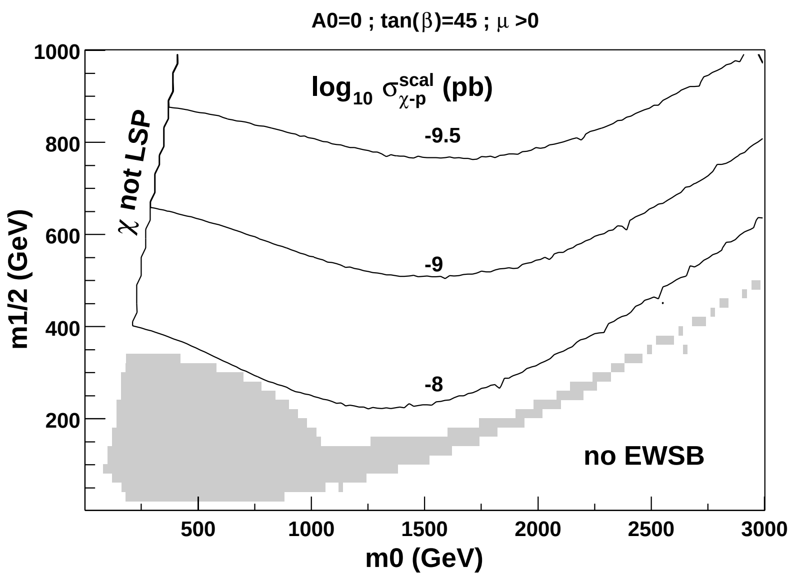
$\sigma_{\chi-p}$: Capture and Direct Detection



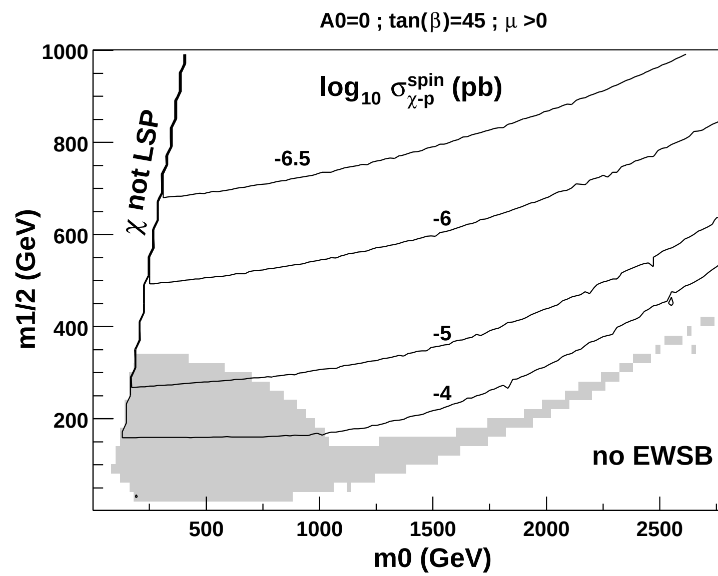


$$C \sim \frac{\rho_\chi}{v_\chi} \sum_N M_b f_N \frac{\sigma_N}{m_\chi m_N} < v_{esc}^2 >_N F(v_\chi, v_{esc}, m_\chi, m_N)$$

$\sigma_{\chi-p}^{scal}$



$\sigma_{\chi-p}^{spin}$



decrease when m_0 increase and reincrease with higgsino fraction

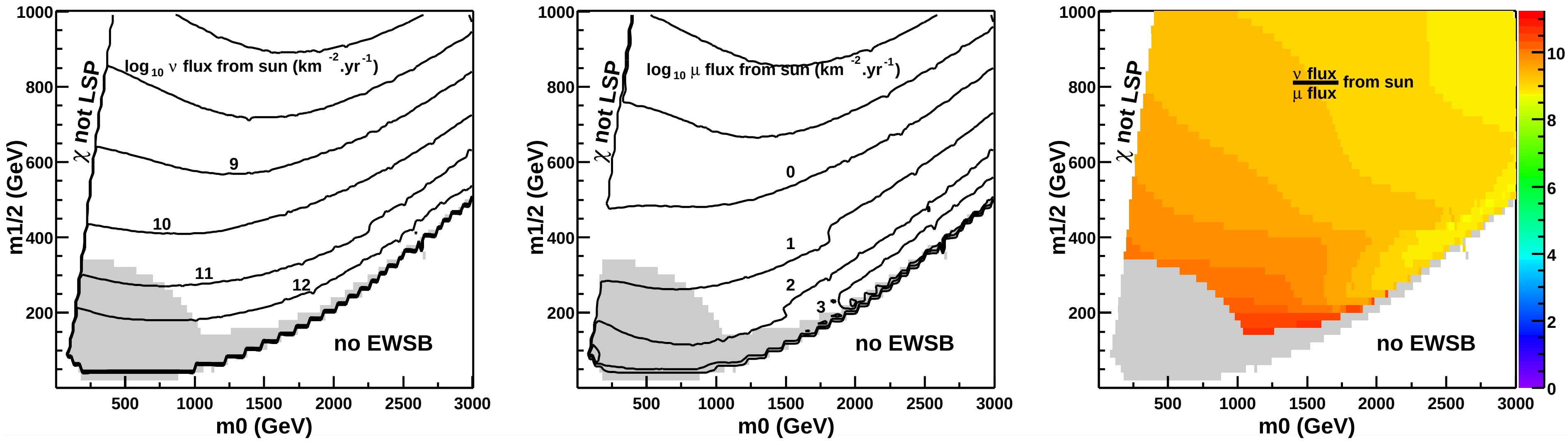
Z exchange, follow higgsino fractio

ν and μ fluxes from the Sun

when neutralinos are in equilibrium : $\mu_\odot\ flux \sim C_\odot \propto \sigma^{spin}_{\chi-p}$

ν flux | μ flux | conversion : $\frac{\nu}{\mu}$

A0=0 ; tan(β)=45 ; μ>0



follow $\sigma^{spin}_{\chi-p}$ and decrease with higgsino fraction

enhancement in $\chi\chi \xrightarrow{\chi_i^+} W^+W^-$ region

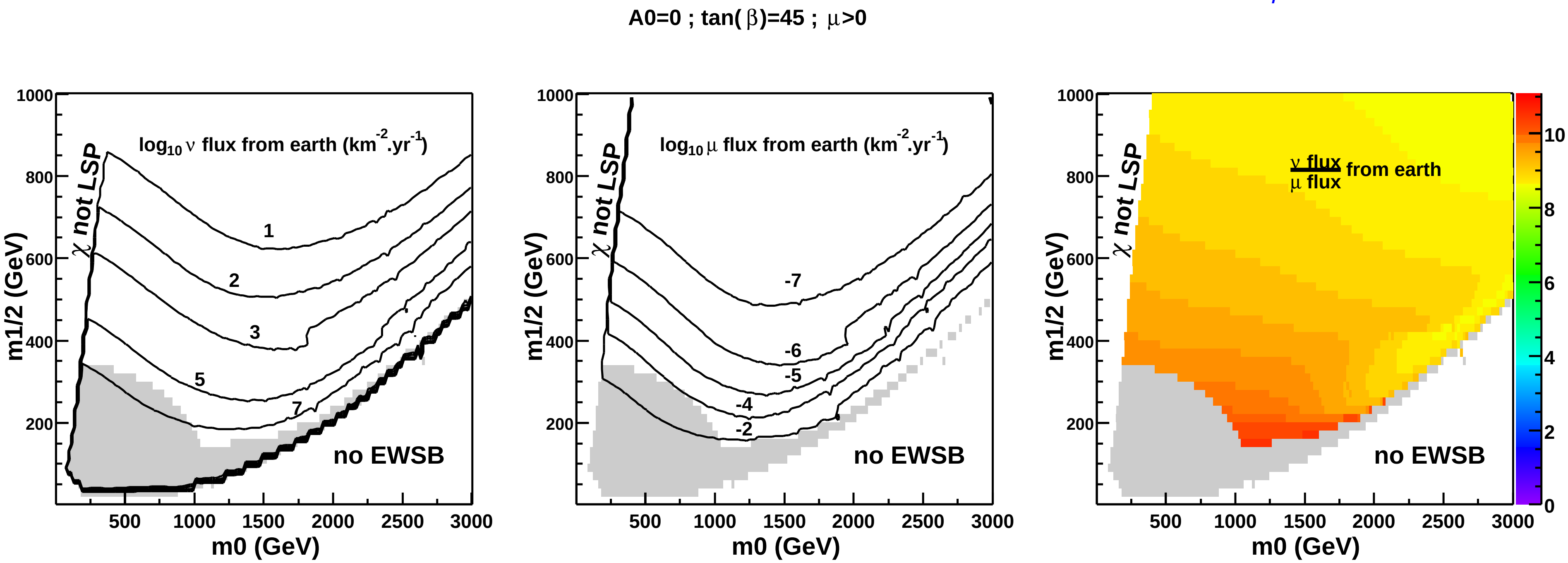
follow iso m_χ and annihilation BR regions

$\Rightarrow$ fluxes are max in mixed region

ν and μ fluxes from the Earth

$\sigma^{scal}_{\chi-p} \ll \sigma^{spin}_{\chi-p}$ and $M_\oplus \ll M_\odot \Rightarrow C_\oplus \ll C_\odot \Rightarrow$ so neutralinos not in equilibrium and $\Gamma_A^\oplus \ll \Gamma_A^\odot$

ν flux μ flux conversion : $\frac{\nu}{\mu}$

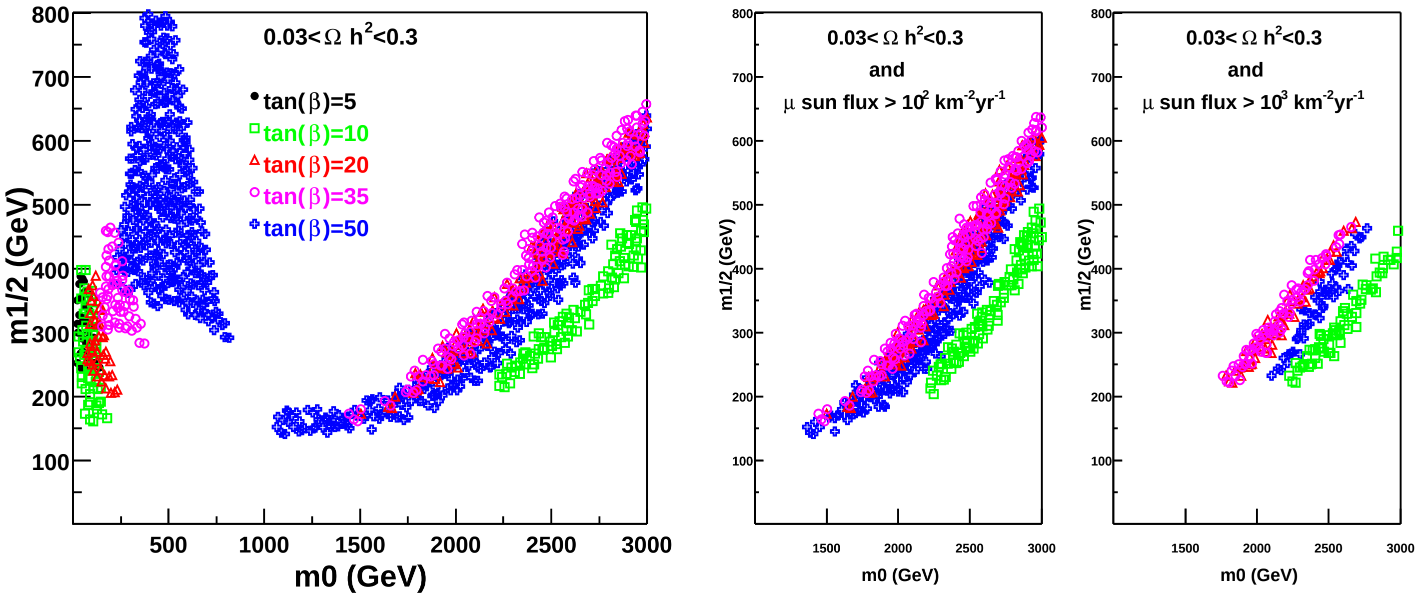


$\Rightarrow$ fluxes from the Earth depends on $\sigma^{scal}_{\chi-p}$ and annihilation cross section and are too low to be detected

Dependance on parameters

$0.03 < \Omega_\chi h^2 < 0.3$; Varying $\tan\beta$

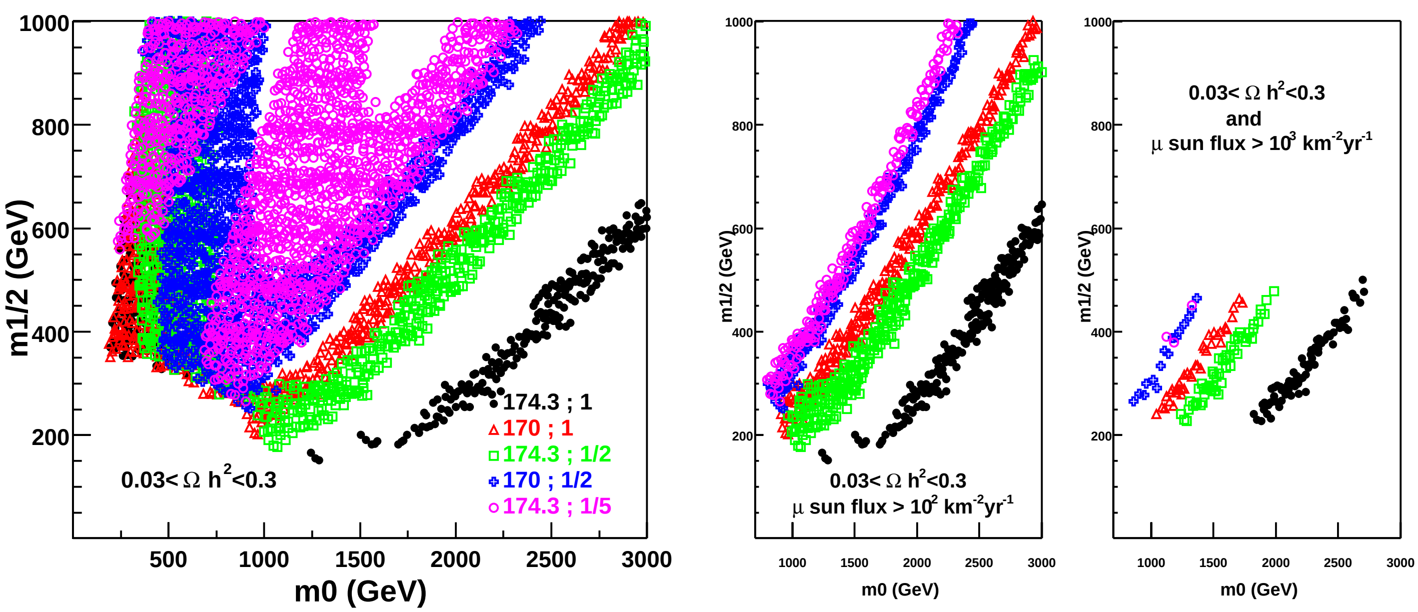
A_0=0 ; μ >0



$\sim km^3$ size $\sim Antares$

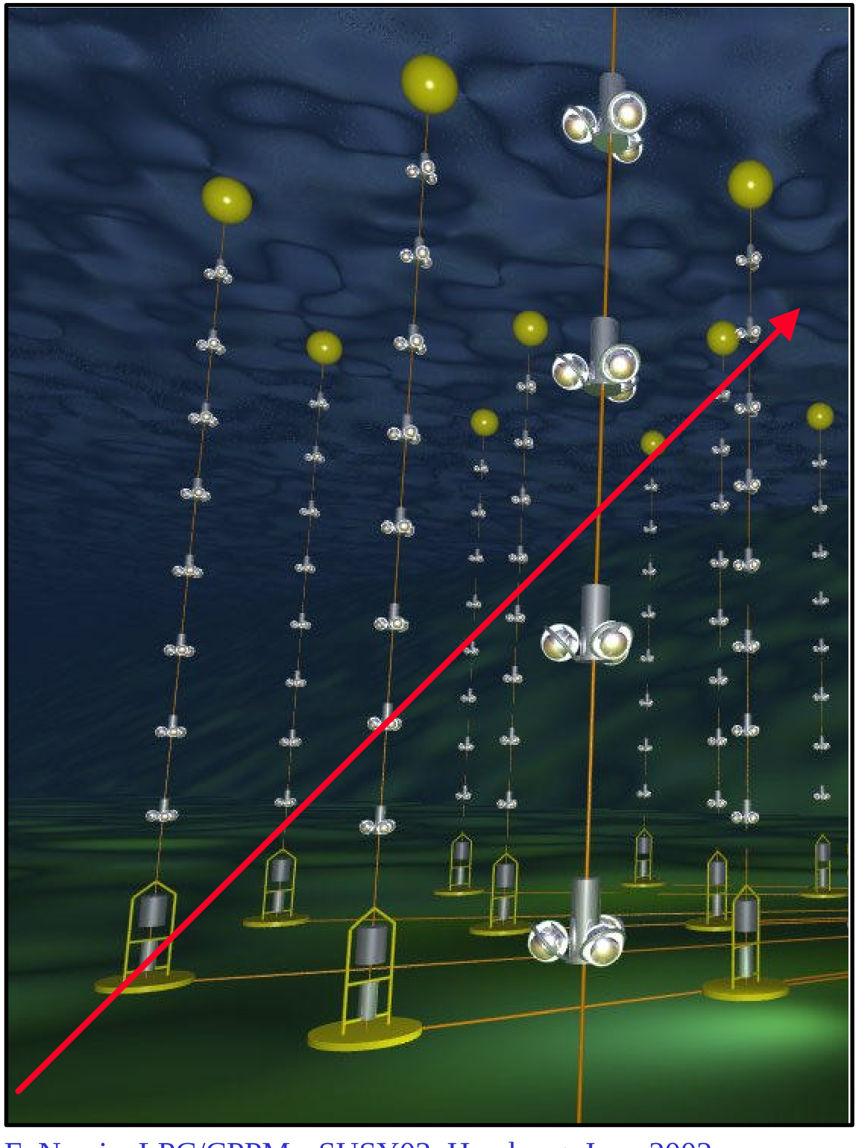
$0.03 < \Omega_\chi h^2 < 0.3$; Varying m_{top} and Q_{EWSB}

A0=0 ; tan(β)=45 ; μ >0



$\sim km^3$ size $\sim Antares$

Antares search for ν flux from χχ annihilations



- So-called "3D" analysis requiring Cerenkov photon hits on more than one string
- Apply a 2-3 degree cone around known position of Sun or Galactic Centre (cone size optimised with Mχ)
- Background from atmospheric neutrinos in cone is ~2 events/year
- Consider 2 extremes of neutrino spectrum:

  "hard" : $\chi\chi \rightarrow WW$

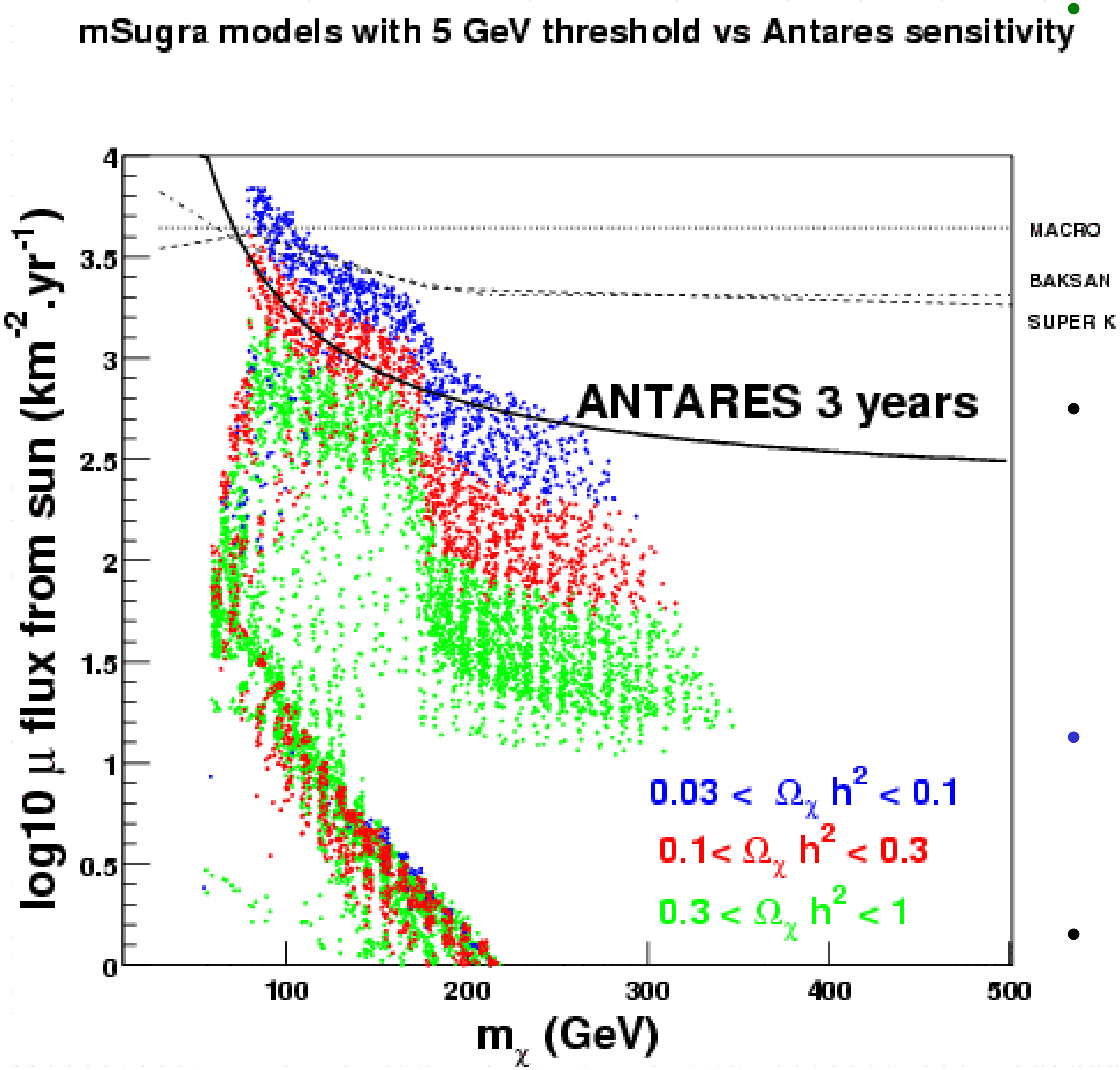
  (or $\tau\tau$ when $M\chi < M_W$)

  "soft" : $\chi\chi \rightarrow bb$

  (or tt when $M\chi > M_t$)

- (Separate procedure under development for flux from terrestrial neutralinos)

ANTARES Muon Flux Limit



- ANTARES sensitivity to neutralinos annihilating in the Sun :

  Results for 3 year's data taking with 10 strings ANTARES detector (90% CL sensitivity assuming no signal & hard spectrum neutrinos from neutralino annihilations)

- Comparison to latest (ICRC 2001) results from

  MACRO (6 years)

  Baksan (14.8 years)

  Super-K (3.5 years)

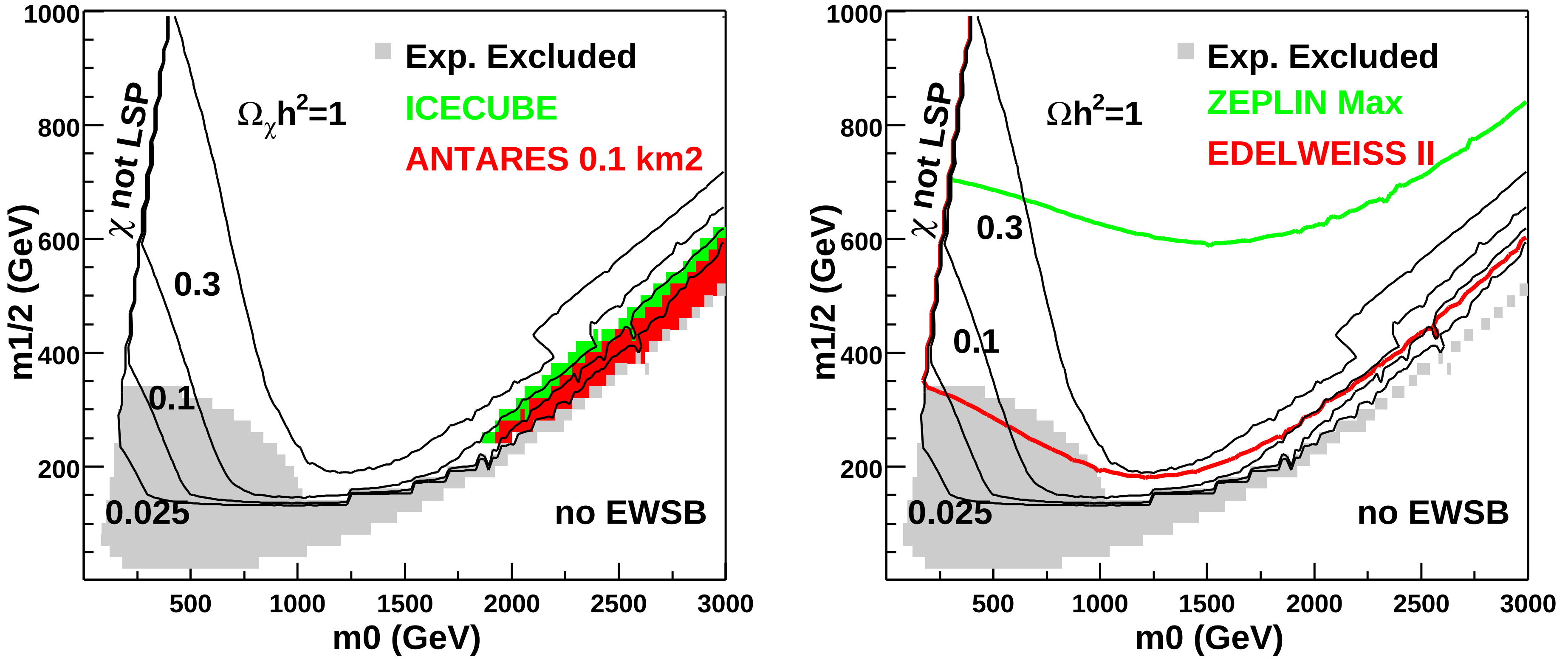
- Comparison to mSugra predictions (E.N., V.Bertin, J.Orloff, hep-ph/0204135)

- Similar sensitivity for neutralinos from the Galactic Centre

- Dedicated 1D analysis will improve sensitivity at low Mχ

Experiment sensitivities in the $(m_0, m_{1/2})$ plane

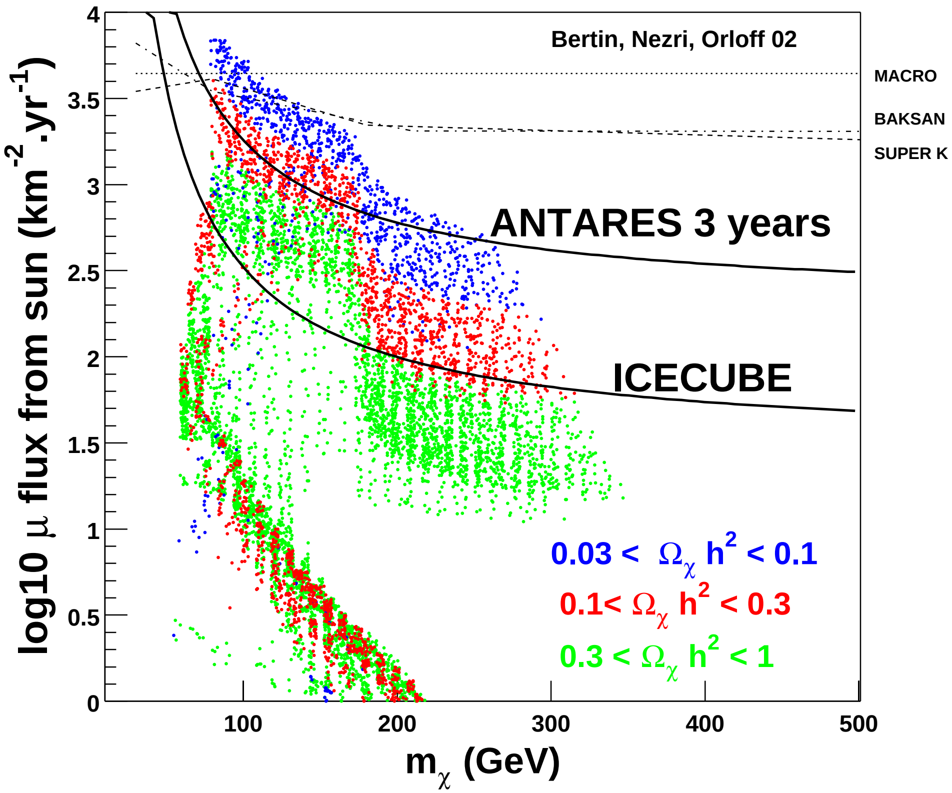
A0=0 ; tan(β)=45 ; μ >0



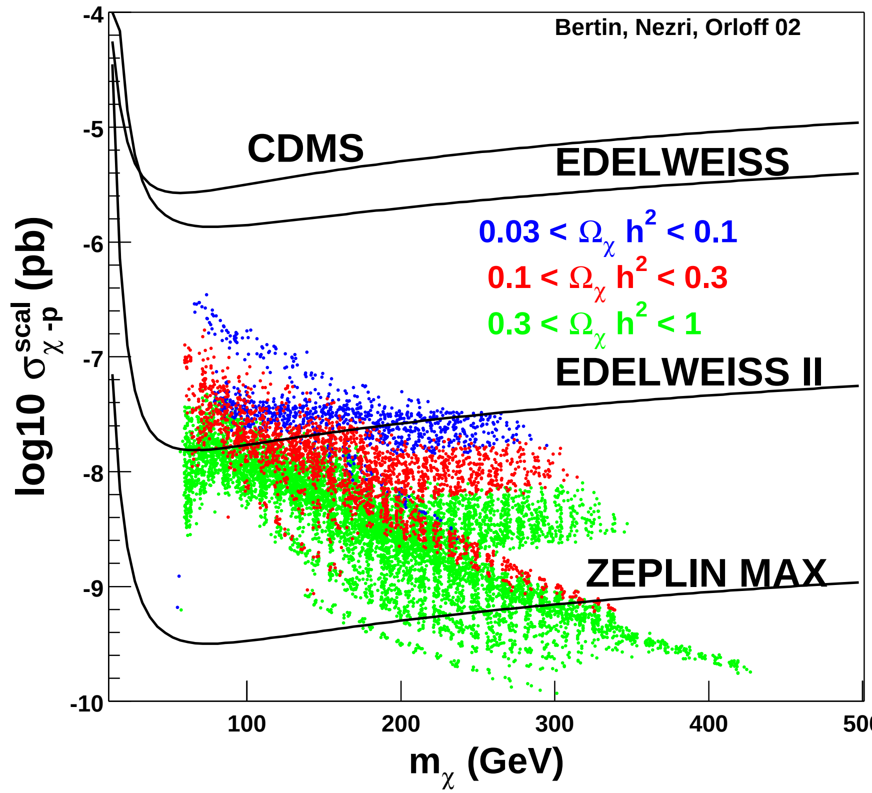
hep-ph/0204135 V. Bertin, E.N. J. Orloff

mSugra vs ν telescopes and direct detection experiments

mSugra models with 5 GeV threshold vs Antares sensitivity



mSugra models vs Direct Detection



hep-ph/0204135 V. Bertin, E.N. J. Orloff

Sugra models with non universal Higgs-boson masses at the GUT scale

Parametrization :

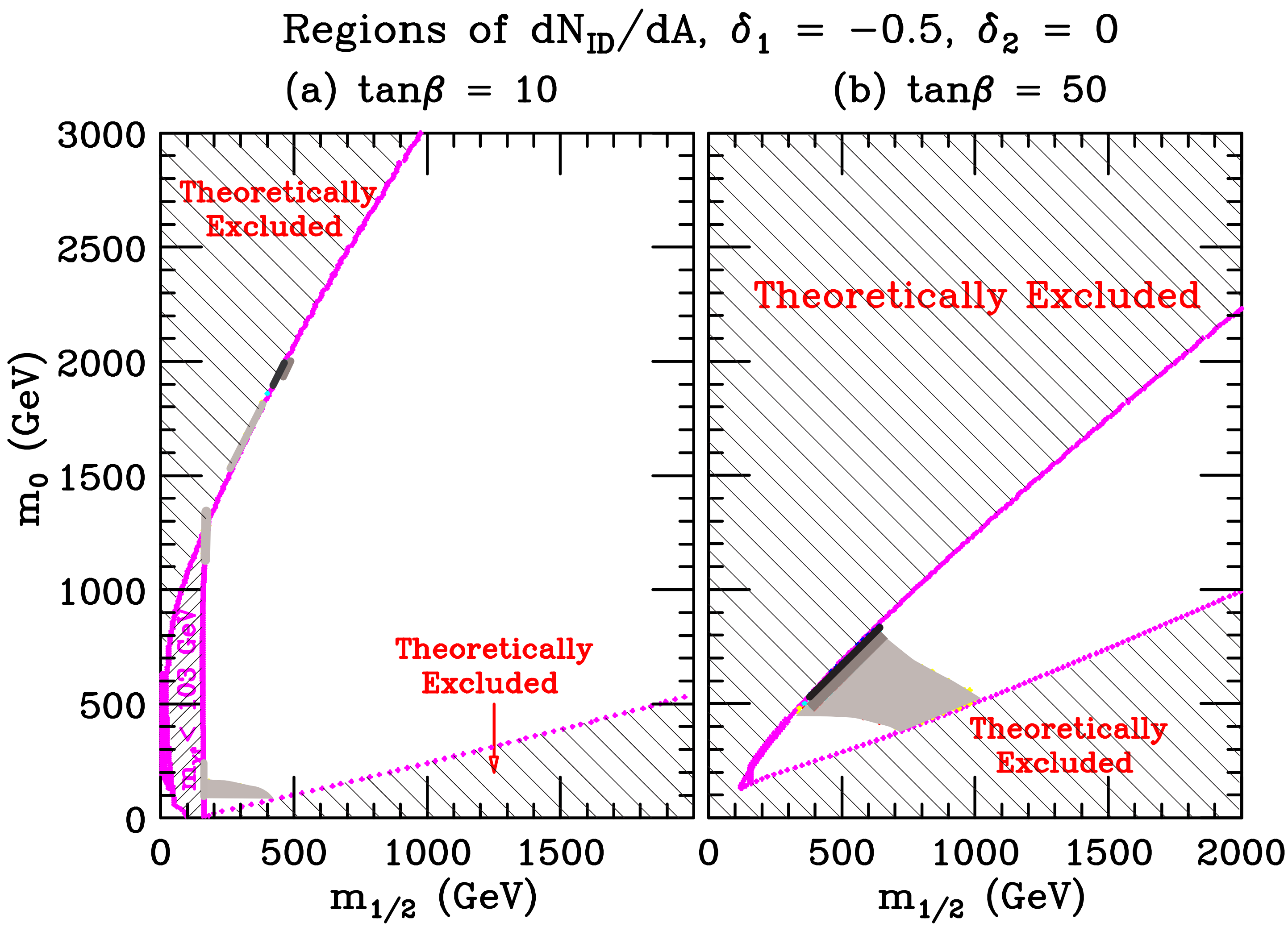
⋆ $m_0, m_{1/2}, A_0, \tan\beta, sgn(\mu)$

⋆ $m_{H_i}|_{GUT} = (1+\delta_i)m_0 = \rho_i m_0 \; i = 1, 2$

⋆ Universal mSugra corresponds to $\delta_1 = \delta_2 = 0$

⋆ $\delta_i = -1$ and $\delta_i = 1$ correspond to $m_{H_i}(\mathrm{GUT}) = 0$ and $m_{H_i}(\mathrm{GUT}) = 2m_0$.

$\Rightarrow$ change EWSB and μ



$\Rightarrow$ V. Barger, F. Halzen, D. Hooper, C. Kao, Phys. Rev. D 65 075022 (2002)

Conclusion

mSugra :

⋆ generically mSugra models in mixed region give a good relic density and high $\nu(\mu)$ fluxes from the Sun.

Only models with $\chi\chi \xrightarrow{\chi_i^+} W^+W^-$ or $\chi\chi \xrightarrow{\chi_i} ZZ$ as dominant annihilation processes could be test by current telescope sensitivities ($10^3\ \mu\ km^{-2} \cdot yr^{-1}$).

The next generation (km^3 size) will be much more efficient, especially for $m_\chi > m_{top}$.

But ∃ differences in fluxes between authors (RGE codes ?? differences between Neutdriver and Darksusy ??)

⋆ a neutrino signal in mixed region implies a quite light chargino : $m_{\chi^+} < 300 - 350\ GeV$ which should be discovered in accelerators.

⋆ A neutrino signal from the centre of the Earth is beyond reach of neutrino telescopes (flux from the Earth $\ll 1\ \mu\ km^{-2}.yr^{-1}$) except for the Iron resonance (m_χ already excluded ?).

Other models :

⋆ MSSM or mSugra with non universality of Higgs masses ($\Rightarrow \mu$ less constrained) can give higher fluxes.