Neutralino Dark Matter in light of DAMA, Pamela and Fermi/LAT

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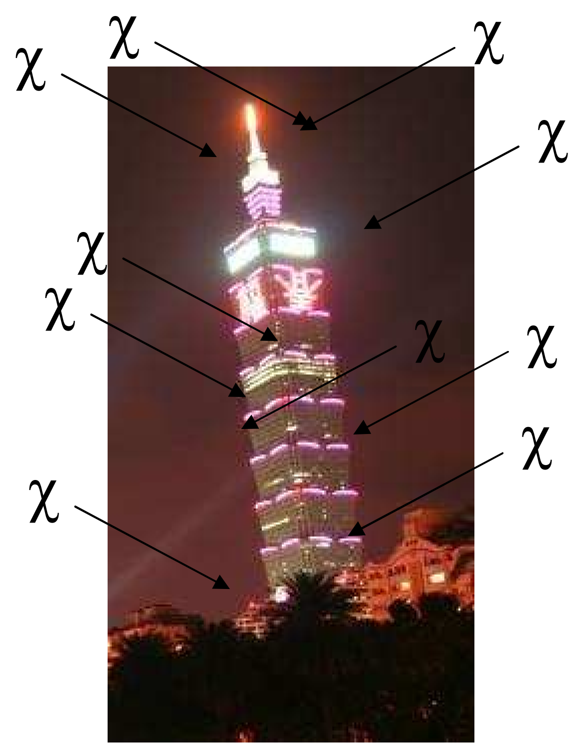


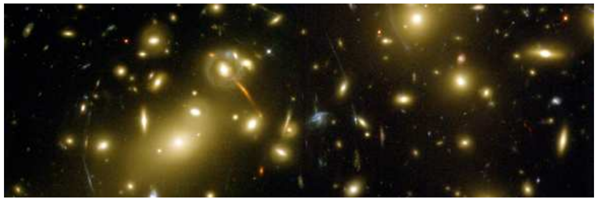
4th International Symposium on Symmetries in Subatomic Physics

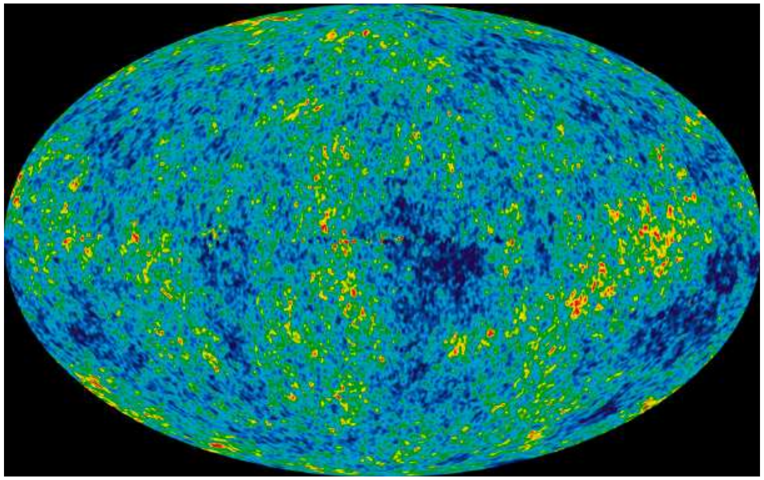
June 2~5, 2009 Department of Physics, National Taiwan University, Taipei, Taiwan

Evidence for Dark Matter

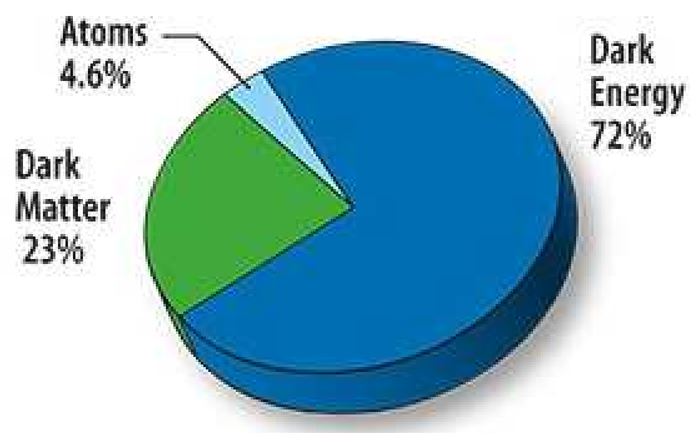
- Spiral galaxies
  - rotation curves
- Clusters & Superclusters
  - Weak gravitational lensing
  - Strong gravitational lensing
  - Galaxy velocities
  - X rays
- Large scale structure
  - Structure formation
- CMB anisotropy: WMAP
  - $\Omega_{tot}=1$
  - $\Omega_{dark\ energy}\sim 0.7$
  - $\Omega_{matter}\sim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

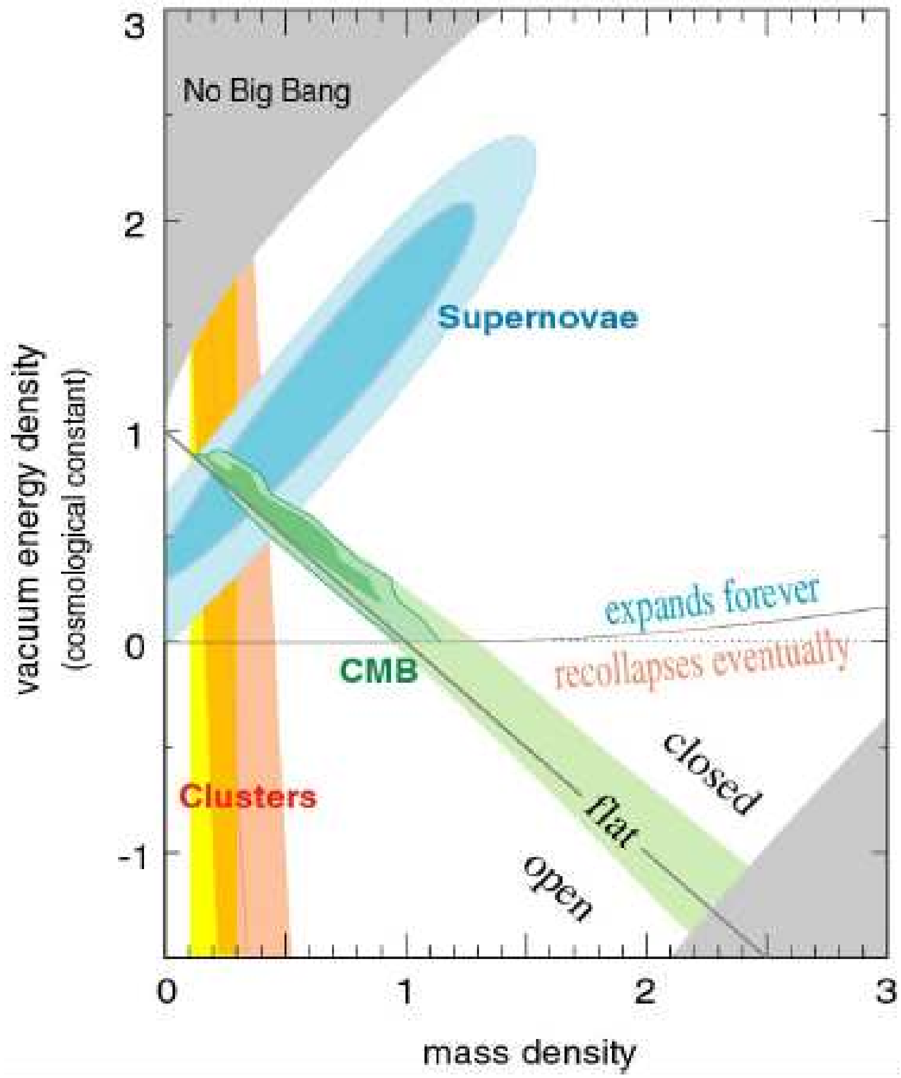
$$\boxed{\Omega_{dark\ matter}\sim 0.22}$$





The concordance model





Searches for relic WIMPs

- Direct searches. Elastic scattering of χ off nuclei ($\propto$ WIMP local density)

$$\chi + N \rightarrow \chi + N$$

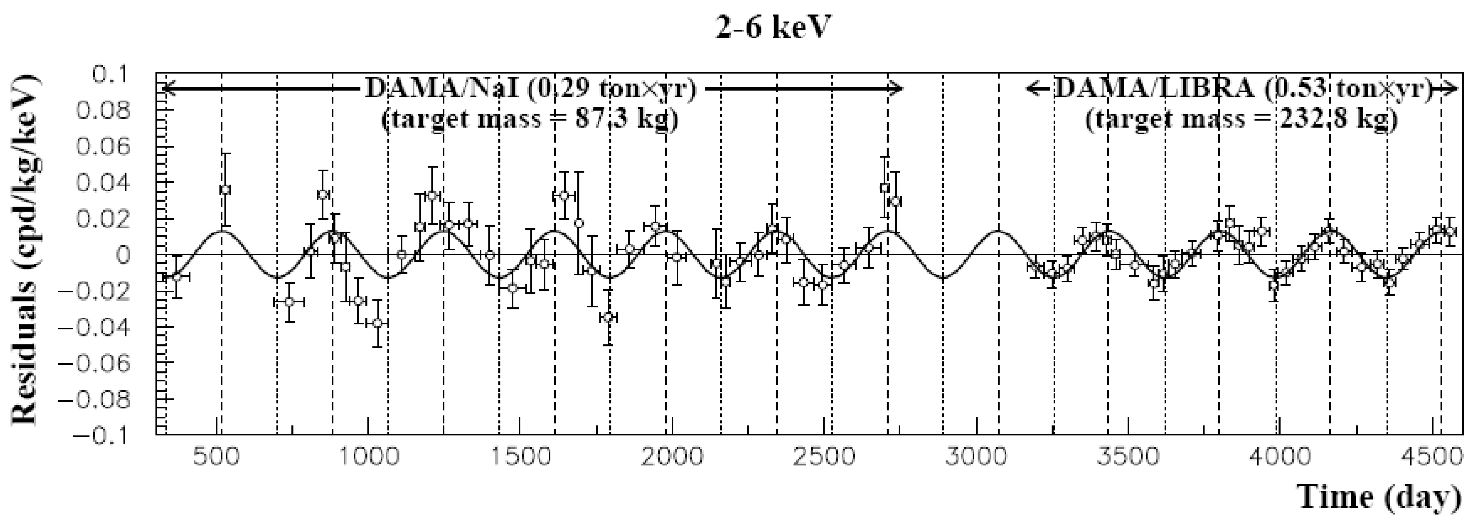
- Indirect searches. Signals due to χ - χ annihilations

$$\chi + \chi \quad \rightarrow \quad \begin{matrix} g\,\underline{g} \\ f\,\bar{f} \\ W^+W^- \\ ZZ \\ HH,\ hh,\ AA,\ hH,\ hA,\ HA,\ H^+H^- \\ W^+H^-,\ W^-H^+ \\ Zh,\ ZH,\ ZA \end{matrix} \quad \rightarrow \quad \nu,\ \bar{\nu},\ \gamma,\ \bar{p},\ e^+,\ \bar{d}$$

- ➢ Annihilations taking place in celestial bodies where χ's have been accumulated: ν's $\rightarrow$ up-going μ's from Earth and Sun
- ➢ Annihilations taking place in the Halo of the Milky Way or that of external galaxies: enhanced in high density regions ($\propto$ (WIMP density)^2) $\Rightarrow$ Galactic center, clumpiness

DAMA/Libra result (Bernabei et al., Eur.Phys.J.C56:333-355,2008, arXiv:0804.2741)

0.53 ton x year (0.82 ton x year combining previous data
8.2 σ C.L. effect

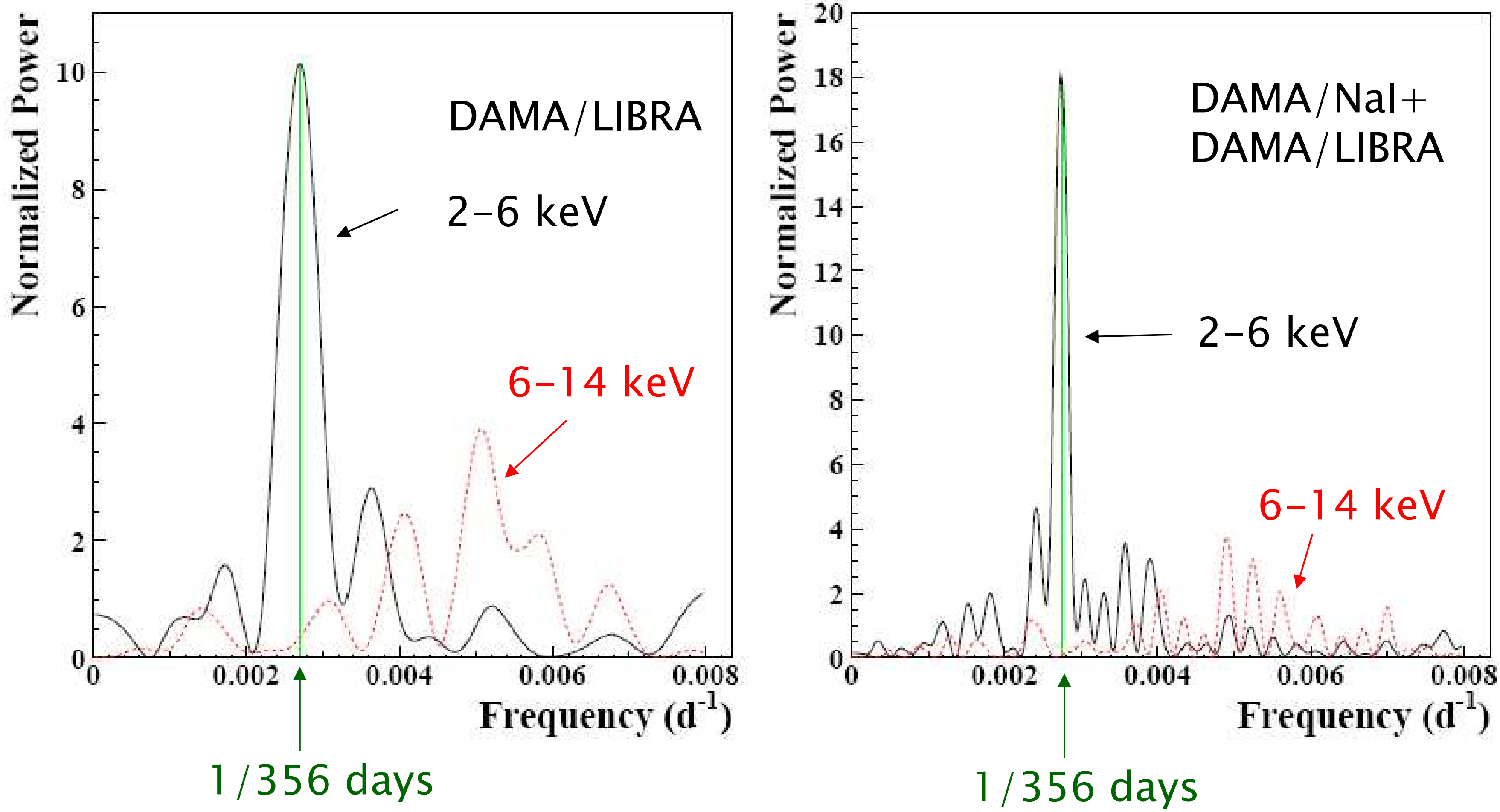


	A (cpd/kg/keV)	$T = \frac{2\pi}{\omega}$ (yr)	t_0 (day)	C.L.
DAMA/NaI				
(2–4) keV	0.0252 ± 0.0050	1.01 ± 0.02	125 ± 30	5.0σ
(2–5) keV	0.0215 ± 0.0039	1.01 ± 0.02	140 ± 30	5.5σ
(2–6) keV	0.0200 ± 0.0032	1.00 ± 0.01	140 ± 22	6.3σ
DAMA/LIBRA				
(2–4) keV	0.0213 ± 0.0032	0.997 ± 0.002	139 ± 10	6.7σ
(2–5) keV	0.0165 ± 0.0024	0.998 ± 0.002	143 ± 9	6.9σ
(2–6) keV	0.0107 ± 0.0019	0.998 ± 0.003	144 ± 11	5.6σ
DAMA/NaI+ DAMA/LIBRA				
(2–4) keV	0.0223 ± 0.0027	0.996 ± 0.002	138 ± 7	8.3σ
(2–5) keV	0.0178 ± 0.0020	0.998 ± 0.002	145 ± 7	8.9σ
(2–6) keV	0.0131 ± 0.0016	0.998 ± 0.003	144 ± 8	8.2σ

$$A \cos[\omega\,(t - t_0)]$$

$$\omega = 2\pi / T_0$$

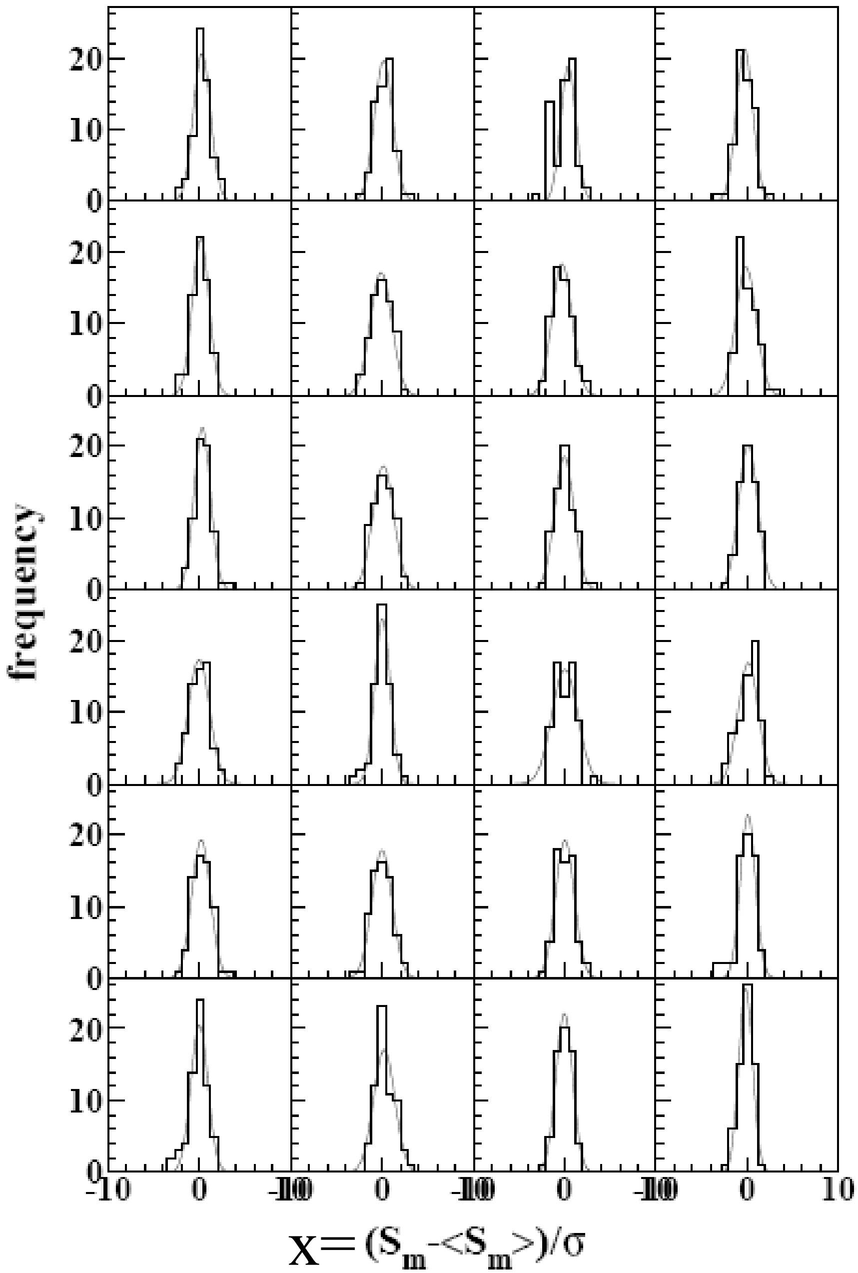
Power spectrum



the peak is only in the 2-6 keV energy interval
absent in the 6-14 keV interval just above

The WIMP signal decays exponentially with energy and is expected near threshold

$x=(S_m-\langle S_m\rangle)/\sigma$ distribution

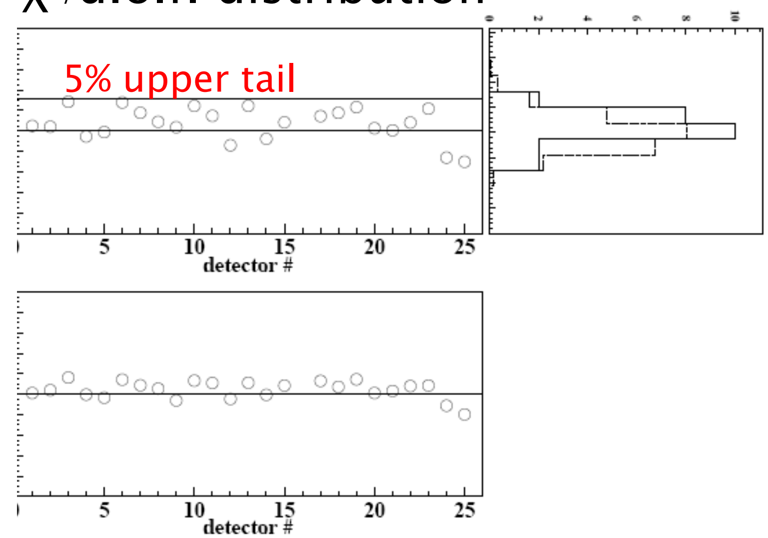


Effect is “spread out” on all 24 detectors (and affects only “single hits”)

each panel: distribution of $x=(S_m-\langle S_m\rangle)/\sigma$ in one DAMA/LIBRA detector over 4 years

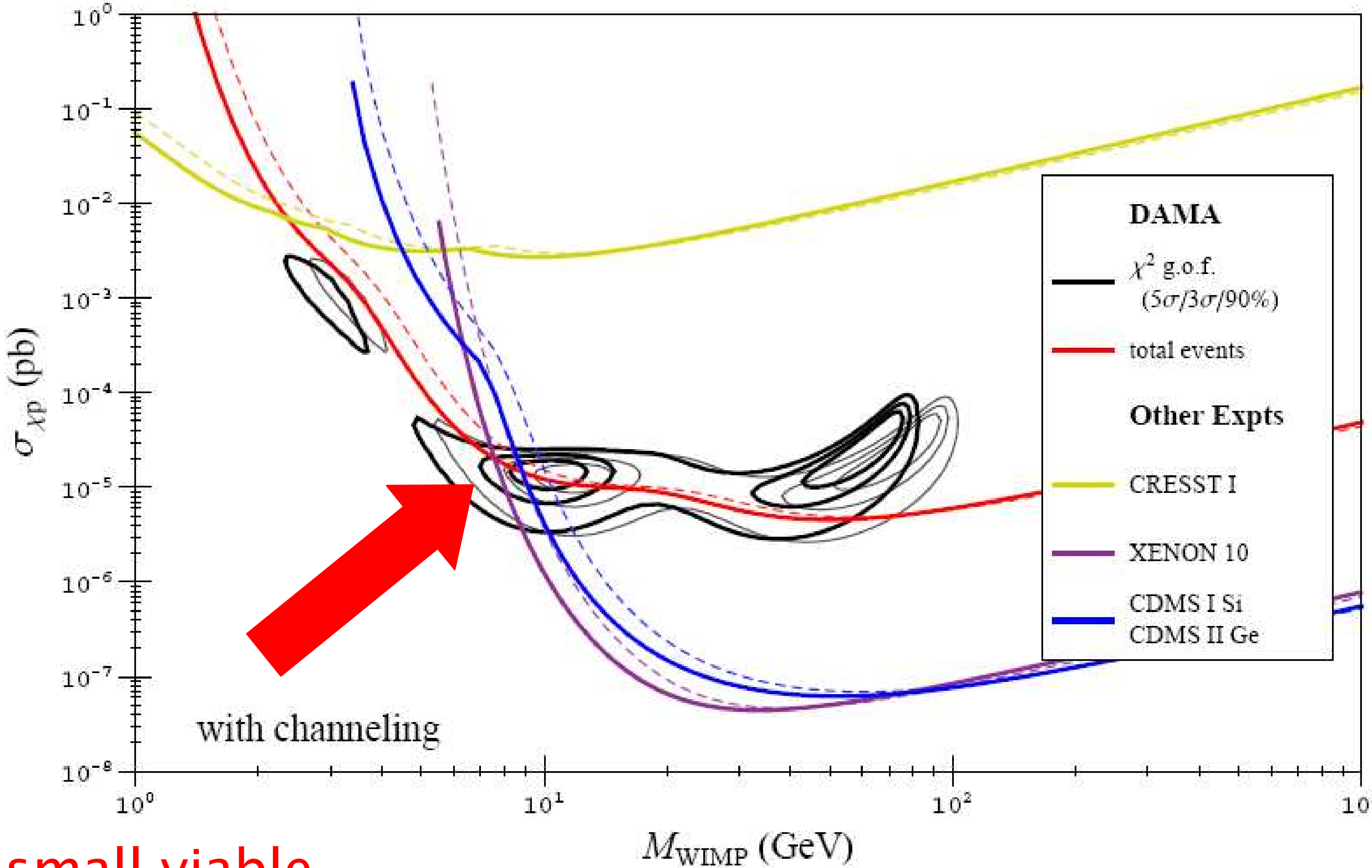
$\chi^2=\Sigma\ x^2$ (64 d.o.f:16 x 0.5 keV energy bins x 4 years)

χ^2/d.o.f. distribution



$\langle\chi^2/\text{d.o.f.}\rangle=1.072$

DAMA disfavoured by other direct searches



small viable window with $M_{WIMP} \lesssim 10$

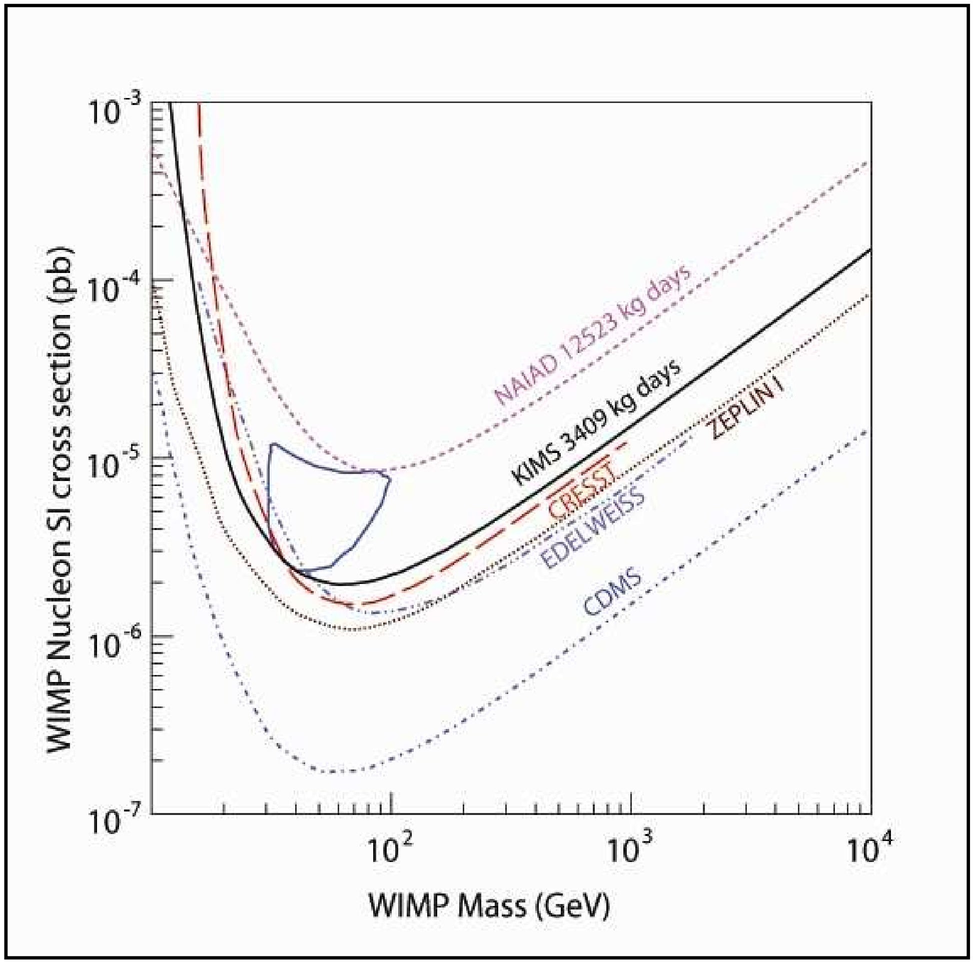
From Savage et al., arXiv:0901.271

existing constraints almost rule out the explanation of DAMA in terms of a WIMP with a coherent coupling, with the exception of a small window at $m_{WIMP} \lesssim 10$ GeV

however, a few words of caution are in order:

- most experiments excluding DAMA exploit techniques which are far less established than scintillation in NaI
- don't have the sensitivity to detect the signature of WIMPS (modulation, directionality)
(actually, more than "WIMP detectors" they are "WIMP constrainers"…)
- "background wall" met (background from the shielding material itself): need to exploit delicate background subtractions through double read-out to lower the count rate (efficiencies?)

KIMS spin independent limits (CsI)



ρ_D=0.3 GeV/c²/cm³

v_o=220km/s

v_{esc}=650km/s

Systematic uncertainty
Fitting, Quenching factor
energy resolution…
combined in quadrature
~ 15% higher than w/o syst.

Nuclear recoil of ^{127}I of DAMA signal region ruled out

PRL 99, 091301 (2007)

no light target in CsI → in principle Na in DAMA more sensitive for $m_{wimp} \lesssim$ 20 GeV (but maybe not, see later)

for $m_{wimpo} \gtrsim$ 20 GeV KIMS limit does not depend on scaling law for cross sections

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

Neutralino – nucleon cross section

Color code:

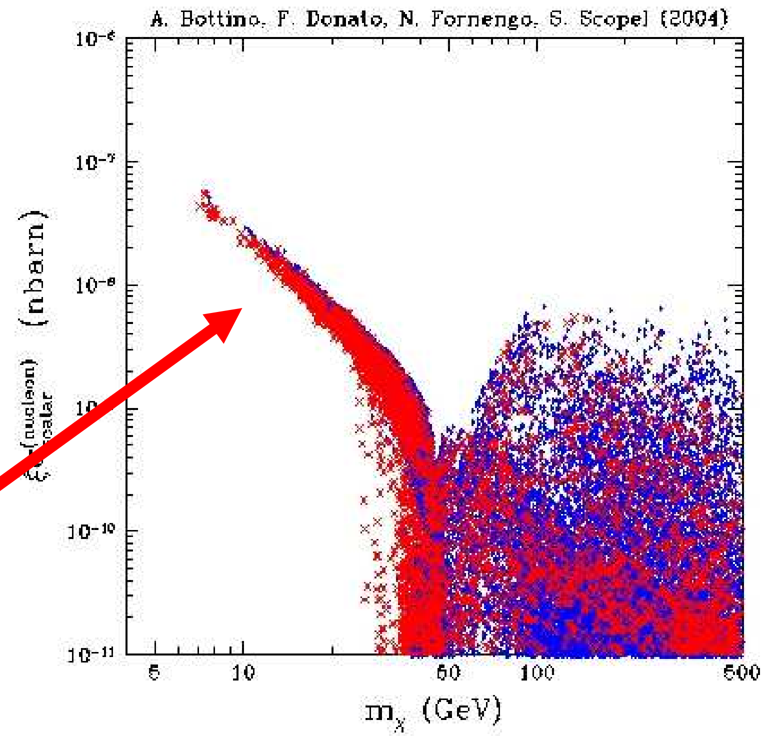
- • $\Omega_\chi h^2 < 0.095$
- × $\Omega_\chi h^2 > 0.095$

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

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

The elastic cross section is bounded from below:

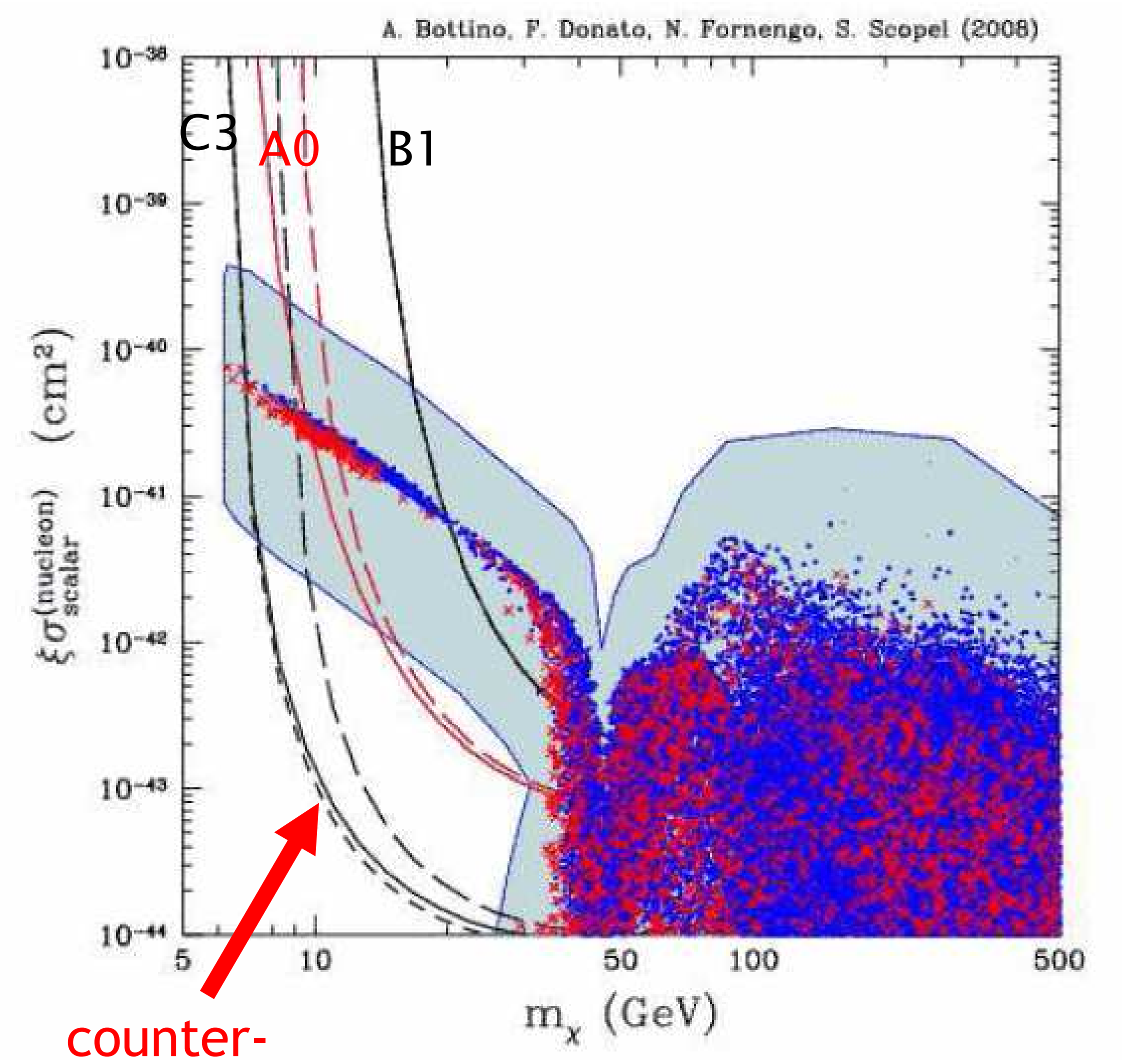
→ "funnel" at low mass



allowed in an effective MSSM scenario where gaugino masses are not universal at the GUT scale

Neutralino–nucleon cross section & CDMS limit (including astrophysical uncertainties)

[exp. data: Ahmed et al., arXiv:0802.3530]



counter-rotation

solid: v_{esc}=650 km/sec

long dashes: v_{esc}=450 km/sec

eff–MSSM

(including uncertainties due to hadronic matrix elements)

smaller values of hadronic matrix elements discussed in this conference by Thomas & Ross, 0901.3310[hep-lat]

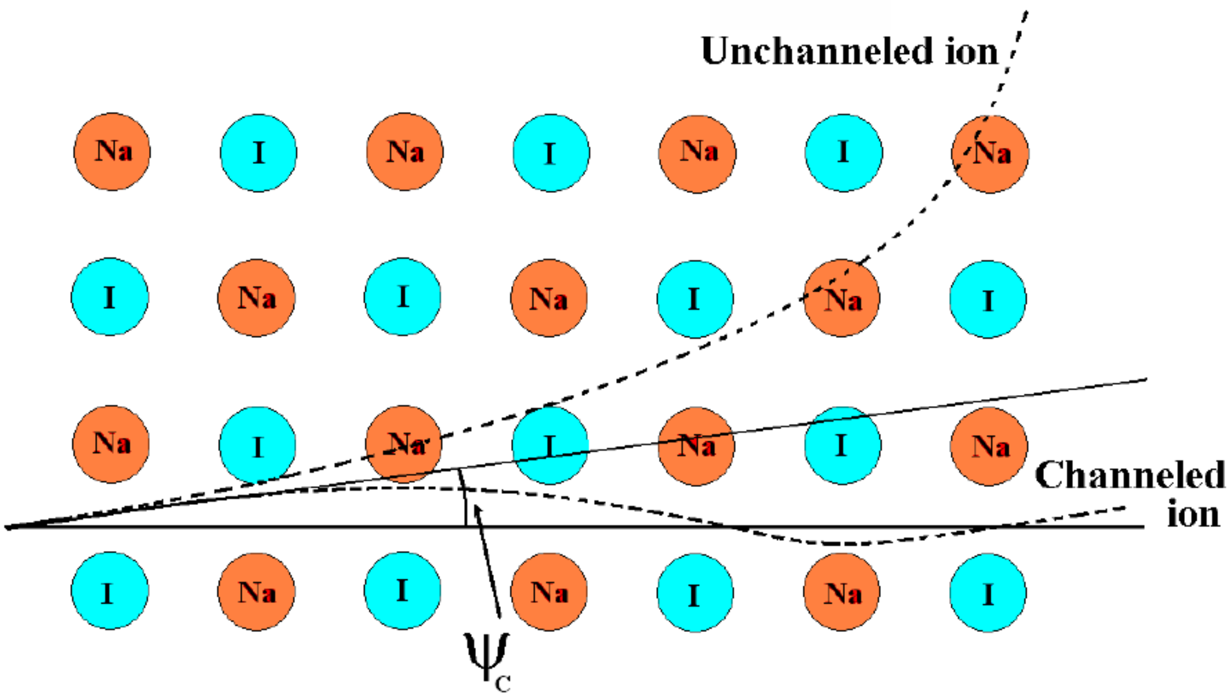
models for WIMP velocity distribution (Belli et al., PRD66,043503)

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)

shown in the previous slide

One possible exception: channeling effect in crystals

(Dobryshevsky, arXiv:0706.3095, Bernabei et al., arxiv:07100288)



critical angle:

$$\Psi_c = \sqrt{\frac{C a_{TF}}{d\sqrt{2}}\Psi_1}$$

$$\Psi_1 = \sqrt{\frac{2Z_1 Z_2 e^2}{Ed}}$$

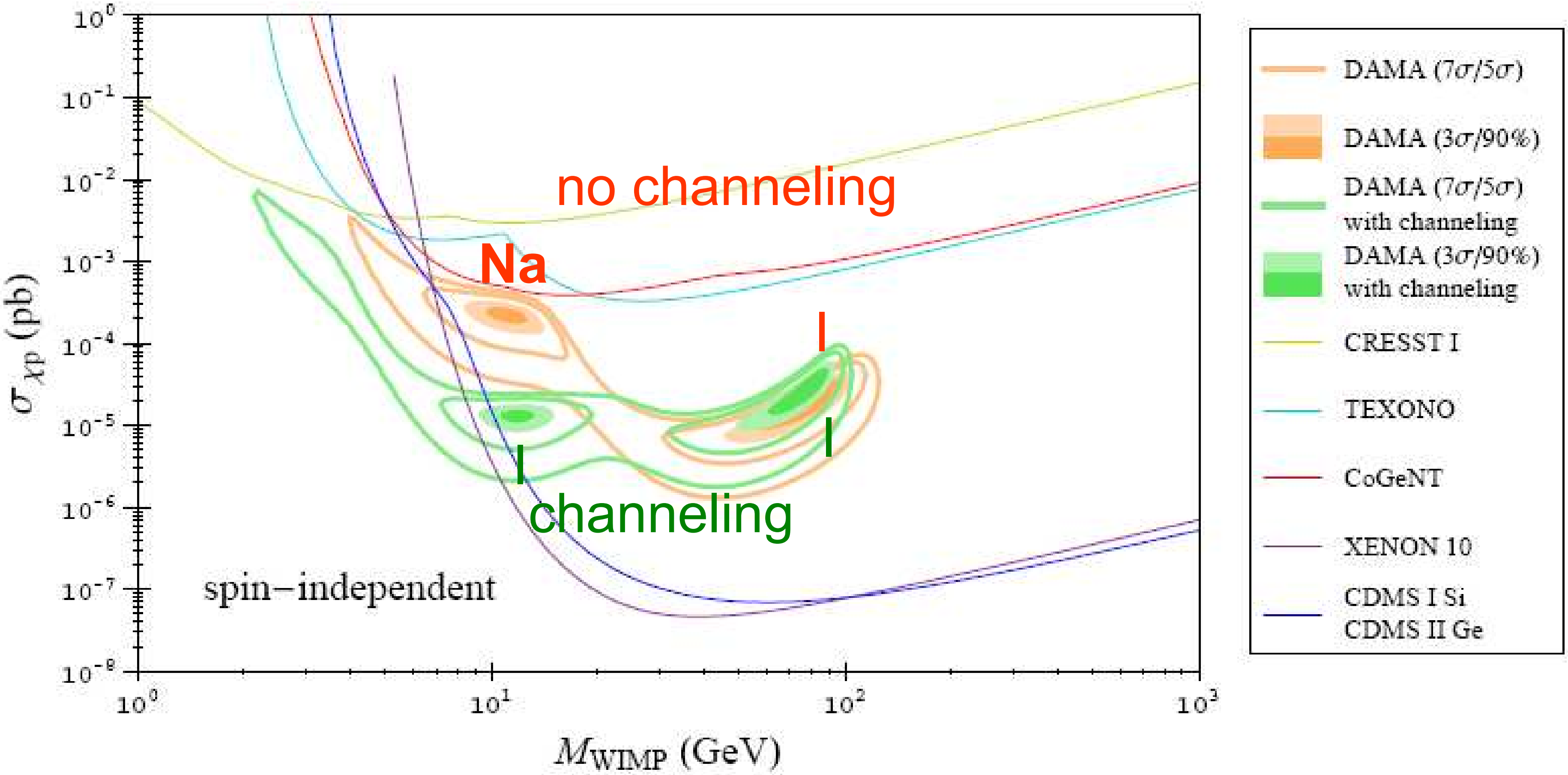
$C^2 \sim 3$, d=interatomic spacing

$$a_{TF} = \frac{0.8853 a_0}{\left(\sqrt{Z_1}+\sqrt{Z_2}\right)^{2/3}}$$

a_0=0.529 Å (Bohr radius)

- anomalous deep penetration of ions into crystalline targets discovered a long time ago (1957, 4 keV $^{134}CS^+$ observed to penetrate λ~ 1000 Å in Ge, according to Lindhard theory λ~ 44 Å)
- when the ion recoils along one crystallographic axis it only encounters electrons → long penetration depth and quenching~1

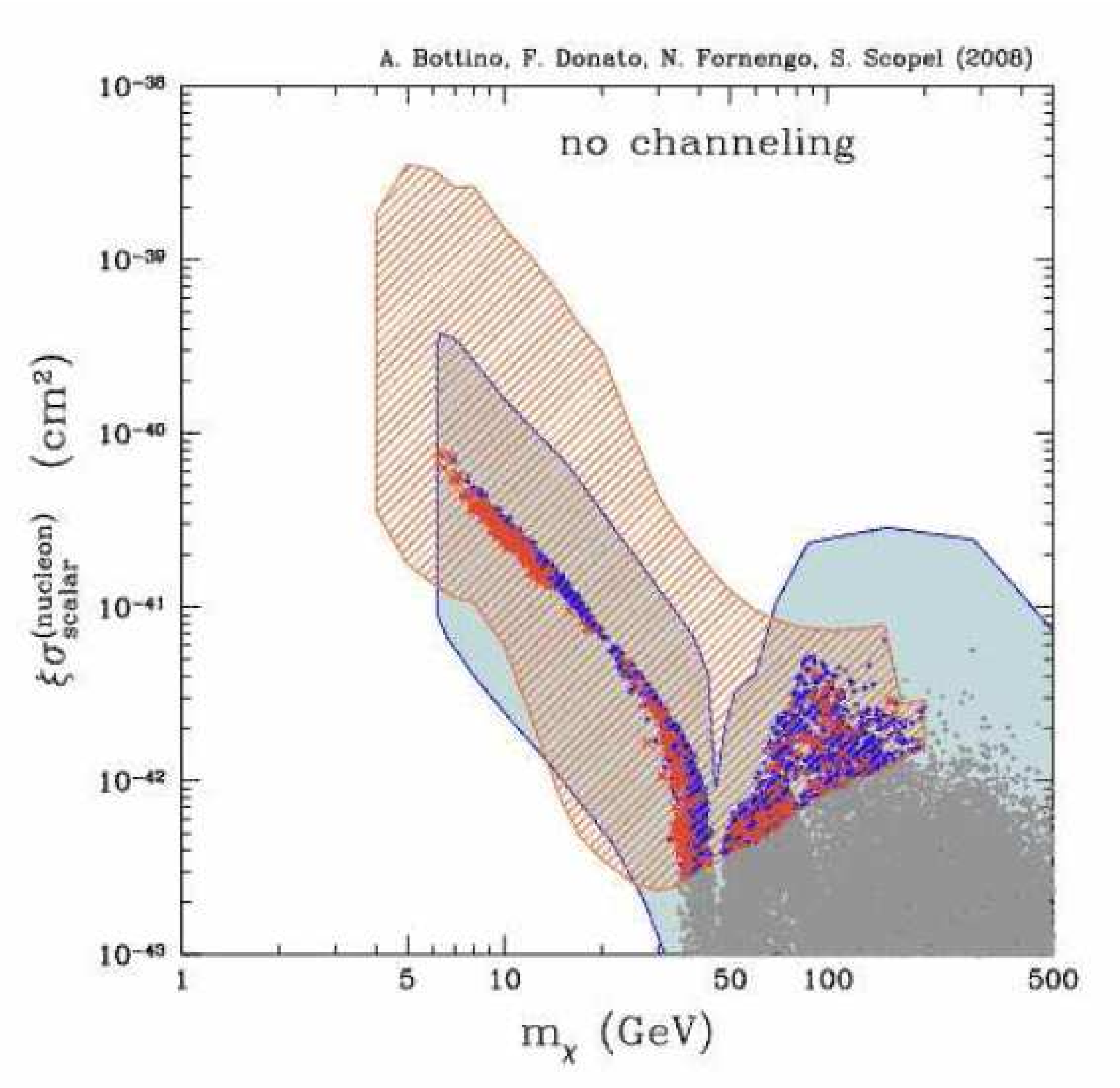
Savage et al., arXiv:0808.3607v3

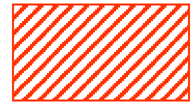


Channeling

- DAMA region moves to lower masses and cross sections → less tension between DAMA and other experiments
- In the DAMA region at low mass scattering dominated by Iodine, not Sodium → <u>KIMS might be sensitive also to the light WIMP window ($m_{WIMP} \lesssim 10$ GeV)</u>

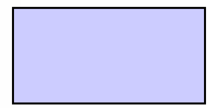
Comparing the model with latest DAMA/Libra data





DAMA/Libra

6.5 σ away from null ipothesis, convoluted on different halo models



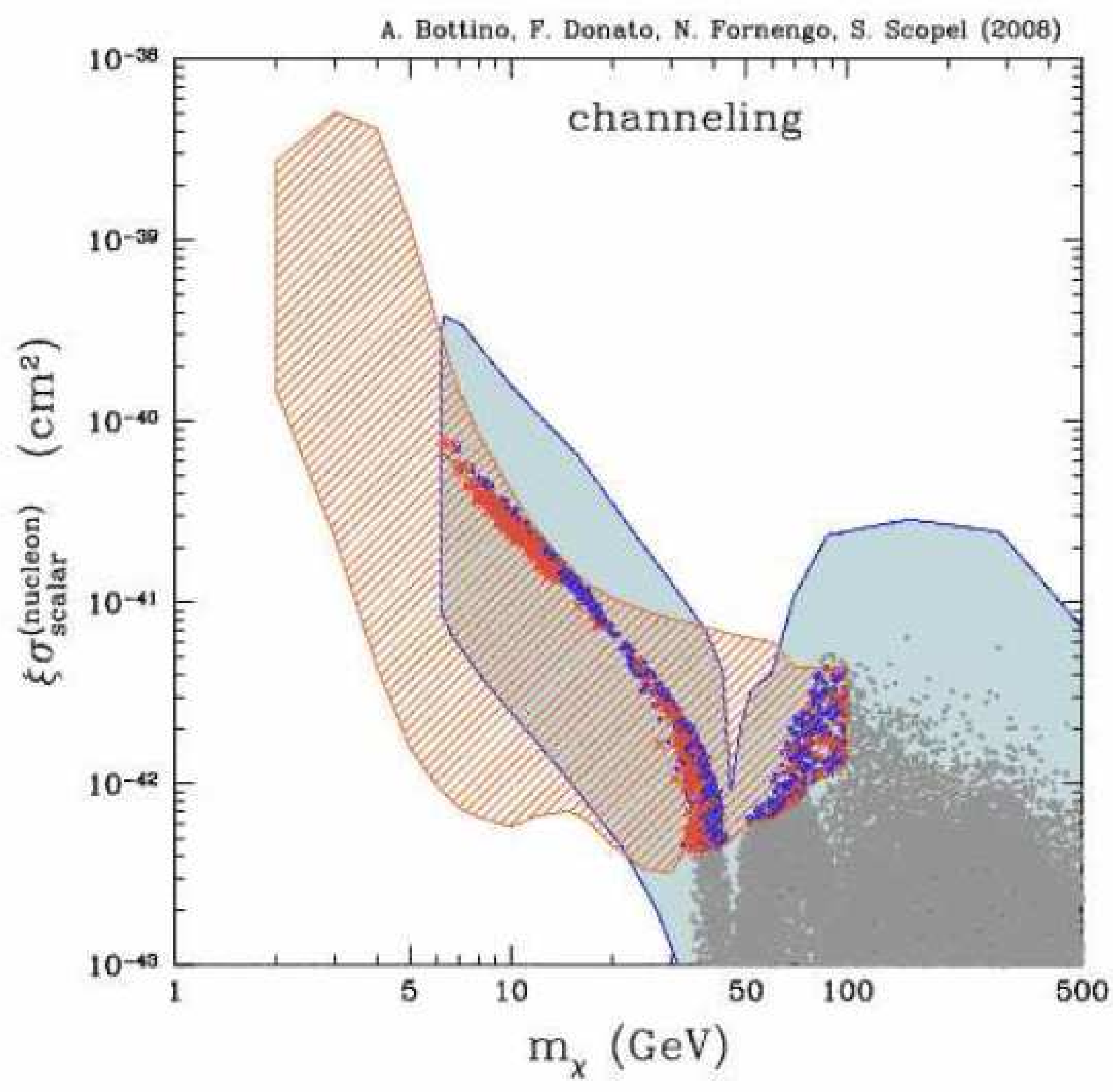
eff-MSSM

(including uncertainties due to hadronic matrix elements)

scatter plot: reference choice of hadronic matrix elements

channeling not included

Comparing the model with latest DAMA/Libra data



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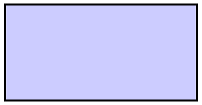


eff–MSSM

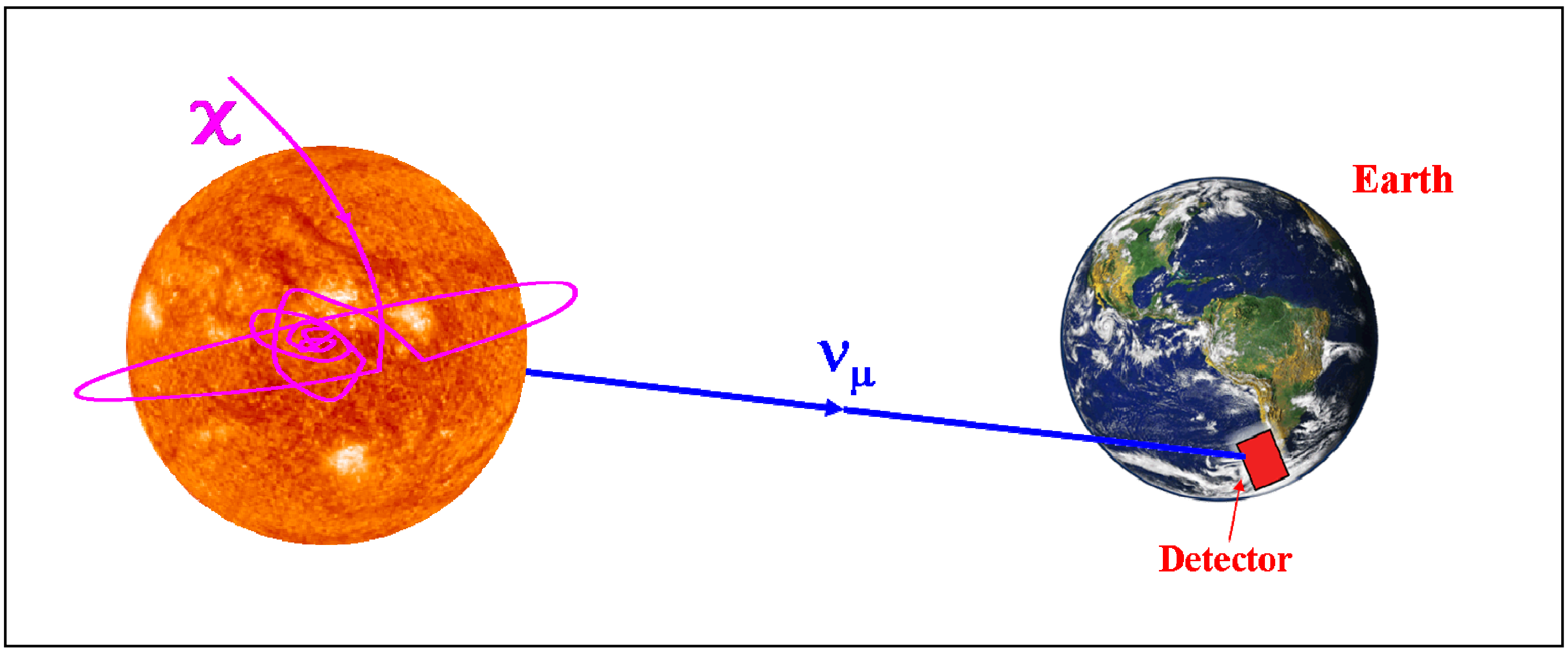
(including uncertainties due to hadronic matrix elements)

scatter plot: reference choice of hadronic matrix elements

channeling included

Neutrino telescopes

- ✓ WIMPs elastically scatter and are captured by massive bodies (Sun)
- ✓ Over billions of years, annihilation/capture rates equilibrate
- ✓ Annihilation products are absorbed, except for neutrinos



Capture rate in a celestial body (Sun)

when a WIMP is scattered off a nucleus below the escape velocity it is trapped inside the celestial body. The # of WIMPs captured per unit time is given by:

$$C = \frac{\rho_\chi}{v_\chi} \sum_i \frac{\sigma_{\mathrm{el},i}}{m_\chi m_i} (M_B f_i) \langle v_{esc}^2 \rangle_i X_i$$

v_χ=WIMP mean velocity
$\sigma_{el,i}$=cross section of WIMP elastic scattering off the nucleus i of m_i
M_B=mass of celestial body
f_i=fraction of M_B in element I
$\langle v^2_{esc} \rangle_i$ =square escape velocity averaged over the distribution of element i
X_i=kinematic factor of order 1 taking into account the relative velocity between the celestial body and the WIMP gas

Annihilation rate

$$\Gamma_A = \frac{C}{2}\tanh^2\left(\frac{t}{\tau_A}\right)$$

C=capture rate

t=age of celestial body (t=4.5 Gyr for Sun and Earth)

$$\tau_A = (CC_A)^{-1/2}$$ equilibrium time scale

$$C_A = \frac{<\sigma v>}{V_0}\left(\frac{m}{20\ \mathrm{GeV}}\right)^{3/2}$$ annihilation rate per effective volume

$$V_0 = \left(\frac{3m_{Pl}^2 T}{2\rho \times 10\ \mathrm{GeV}}\right)^{3/2}$$

T=central temperature

ρ=central density

for the Sun typically $t \gg \tau_A$ and capture and annihilation are in equilibrium, so that:

$$\Gamma_A \simeq \frac{C}{2}$$

flux from the Sun does not depend on the annihilation rate σv the Sun and the Earth are sensitive to the WIMP-nucleon scattering cross section

Sun: mostly hydrogen, sensitive to spin-dependent interaction or light WIMPs
Equilibrium between capture and annihilation always reached ($v_{esc} \lesssim 600$ km/sec)

Earth: rich of Iron and other metals, particularly sensitive to $M_{WIMP} \sim 50$ GeV
Equilibrium between capture and annihilation not always reached ($v_{esc} \lesssim 15$ km/sec)

Over a time of the same order of the age of the solar system the captured WIMPs eventually thermalize at the center of the celestial body with distribution:

$$n(r) = n_0 \mathrm{e}^{-\alpha m_\chi r^2}$$

with:

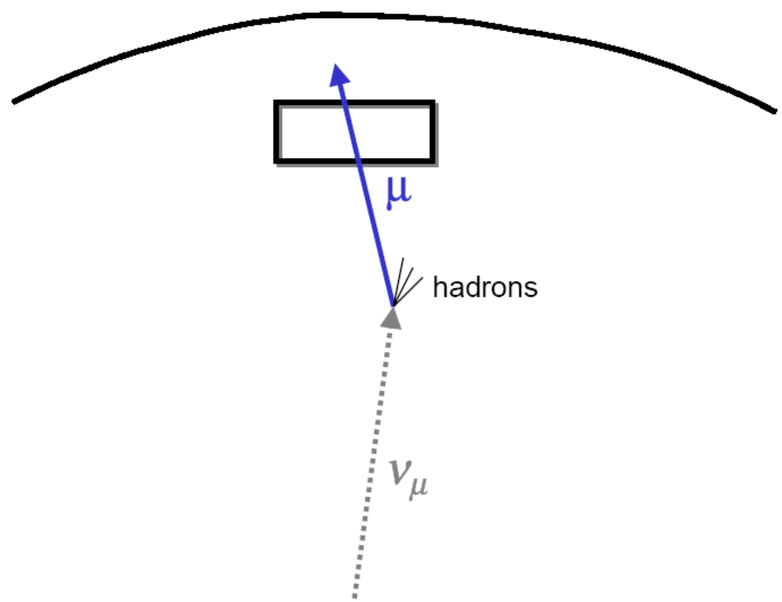
$$\alpha = \frac{2\pi G \rho}{3T}$$

(lighter WIMPs more “spread out”)

Rule of thumb: annihilation of WIMPs with mass m_{wimp} produce neutrinos with energies $m_{WIMP}/3 \lesssim E_\nu \lesssim m_{WIMP}/2$

Up-going muons flux

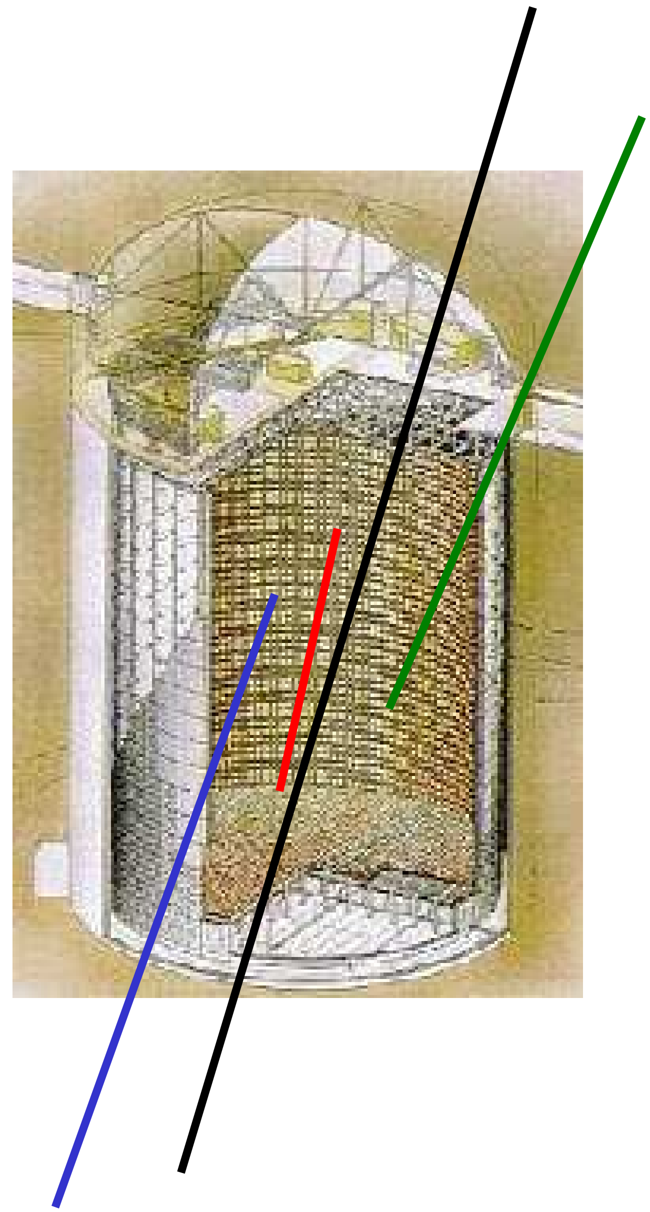
- both neutrino-nucleon cross section and muon range proportional to neutrino energy→μ flux depends on the second moment of the neutrino energy spectrum $\langle E^2 dN/dE \rangle$
- energy loss and multiple scattering of the muon in the rock included
- from MC simulation



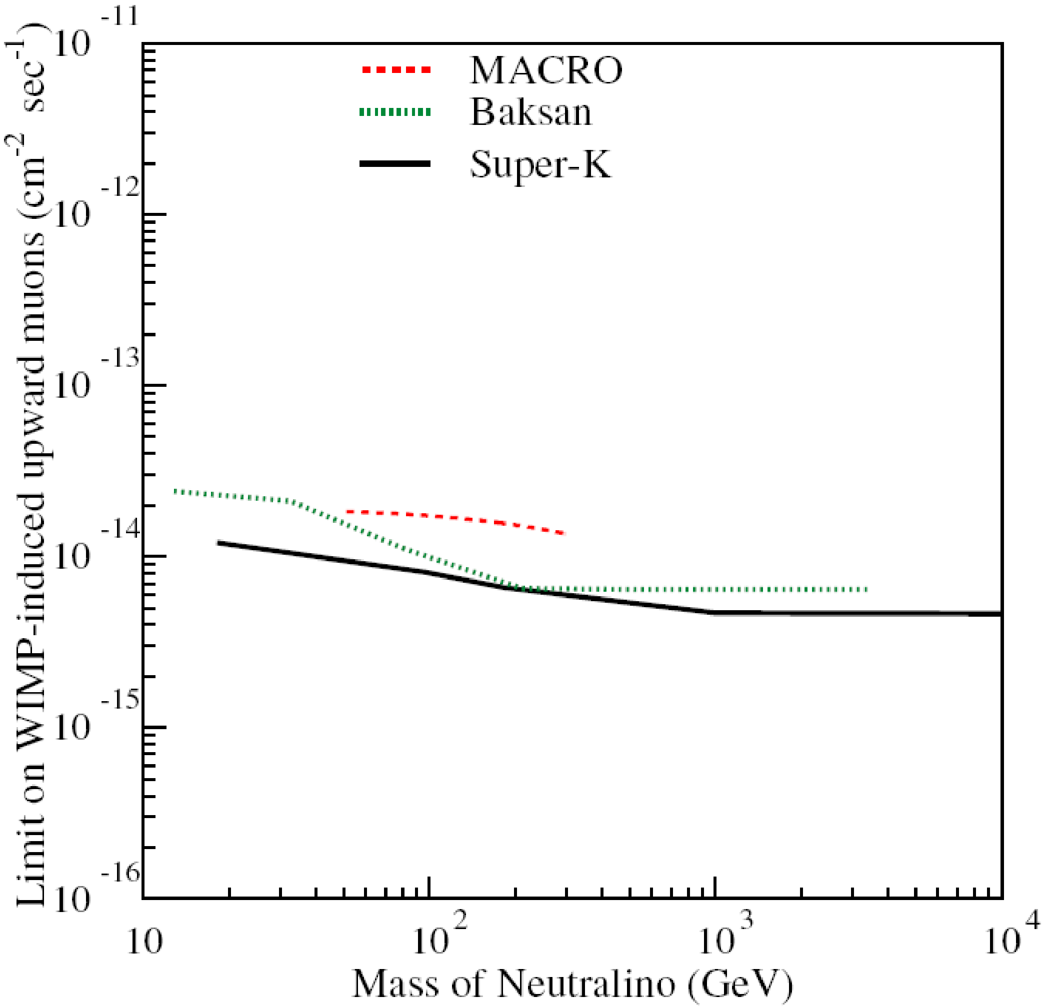
Glossary

muon events in SK are categorized as:

- stopping
- partially contained
- fully contained
- through-going

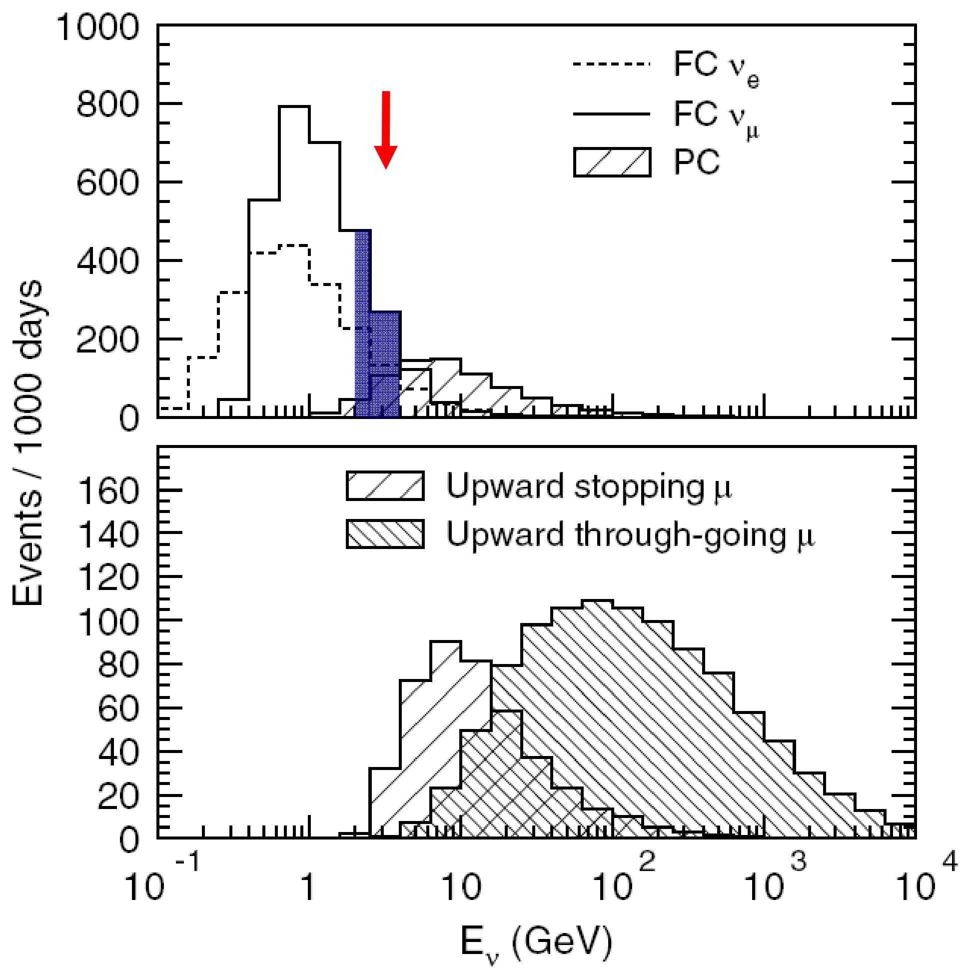


Using through-going events SK published a limit valid for $m_{WIMP} \gtrsim 18$ GeV (Desai et al., PRD70(2004)083523)



however, for m_{WIMP}~5 - 10 GeV, neutrinos with energies between 2 GeV and 4 GeV must be considered (Feng, Kumar, Learned, Strigari, JCAP01(2009)032)

Ashie et al., PRD71(2005)112005



in this range of energies most expected events are fully contained

N_{solar}=168 events/1000 days FC events for 2 GeV<E_ν<4 GeV and $m_{WIMP} \lesssim 10$ GeV

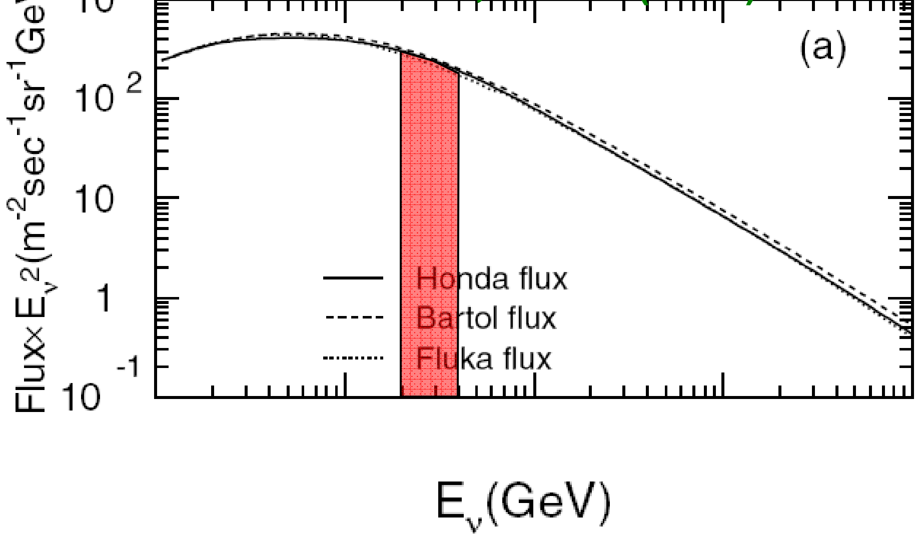
$$N_{\rm solar} = N\frac{1-\cos\theta}{2}$$

$$\theta \simeq 20^\circ\sqrt{10\,{\rm GeV}/E_\nu}$$

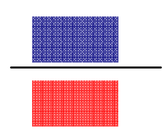
In order to convert this into a number of expected neutrinos one needs the exclusive "effective cross section" of SK for neutrinos with 2 GeV<E_ν< 4 GeV into fully contained muon events. This can be obtained by dividing the expected FC events by the corresponding atmospheric neutrino flux:

expected atm neutrino flux for 2 GeV<Ev<4 GeV

Ashie et al., PRD71(2005)112005



estimate of the effective cross section:

 ~ 2.1 X 10^{-8} m^2

To make a (rough) estimate of the future projected sensitivity from SK one can assume that the measured neutrino spectrum matches the predicted atmospheric background, so that, in any given bin with N neutrino events the bound on neutrinos from Dark Matter annihilation is $\sqrt{N}$

assuming that light WIMps mainly produce fully contained events it is then possible to set the following 2 σ upper bound on the neutrino flux (Feng et al., JCAP01(2009)032):

$$\Phi_{\mathrm{FC}}^{\max} = \frac{2\sqrt{N_{\mathrm{FC}}}}{2.1 \times 10^{-8}\ \mathrm{m}^2} \sim 1.6 \times 10^9\ \mathrm{m}^{-2} \sqrt{\frac{N_{\mathrm{days}}}{1679}}$$

with

$$N_{FC} = 168 \left(\frac{N_{days}}{1000} \right)$$

branching ratios for light relic neutralinos

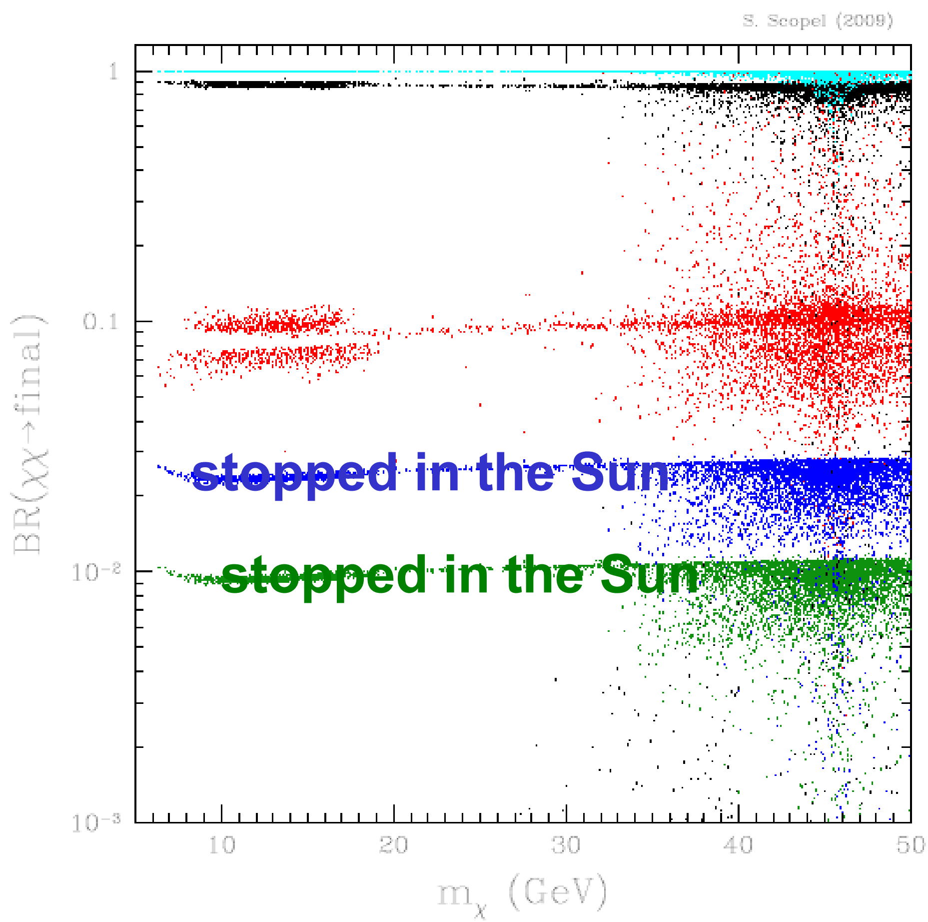
$$\frac{dN_\nu}{dE_\nu} = \frac{\Gamma_A}{4\pi d^2} \sum_{F,f} \underline{B^{(F)}_{\chi f}} \frac{dN_{f\nu}}{dE_\nu}$$

$BR(\chi\chi \to b\bar{b})$

$BR(\chi\chi \to \tau\bar{\tau})$

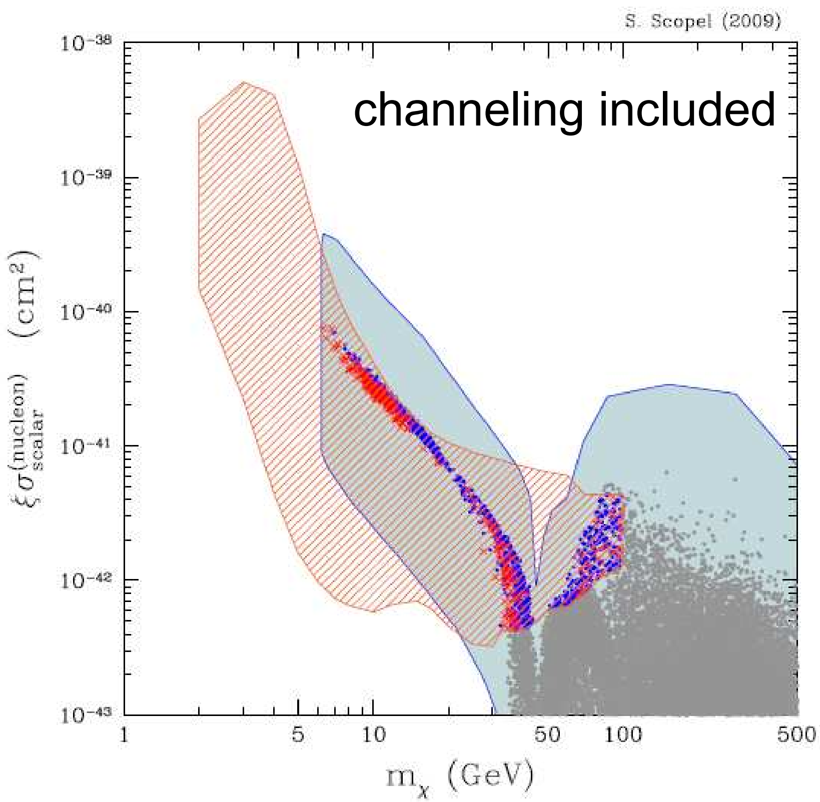
$BR(\chi\chi \to s\bar{s})$

$BR(\chi\chi \to d\bar{d})$

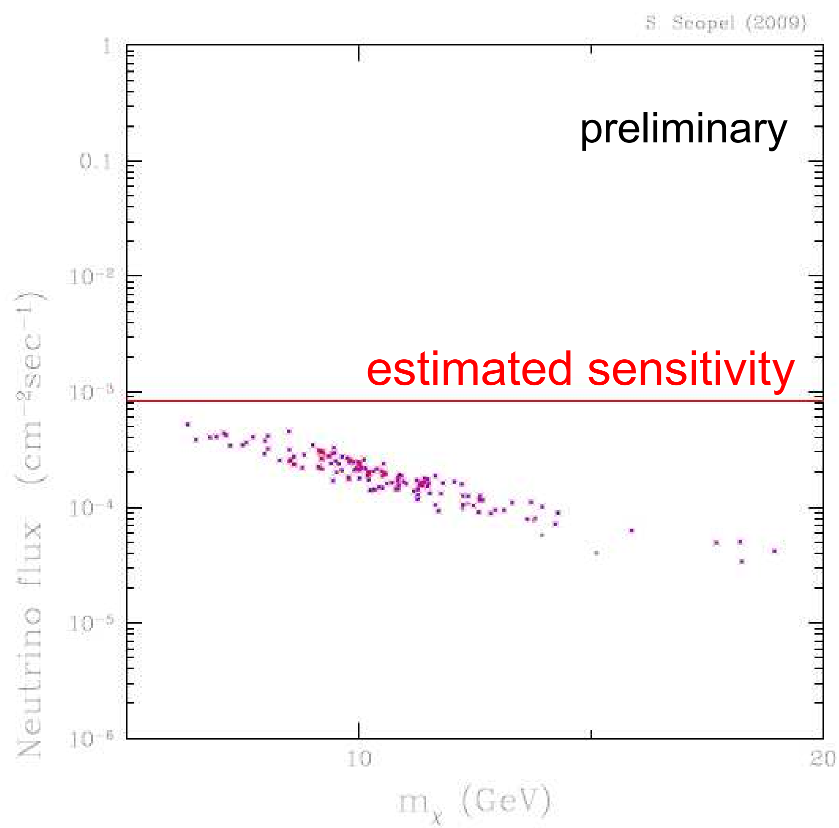


Comparison between direct detection and estimated future SK sensitivity to neutrinos from the Sun

direct detection

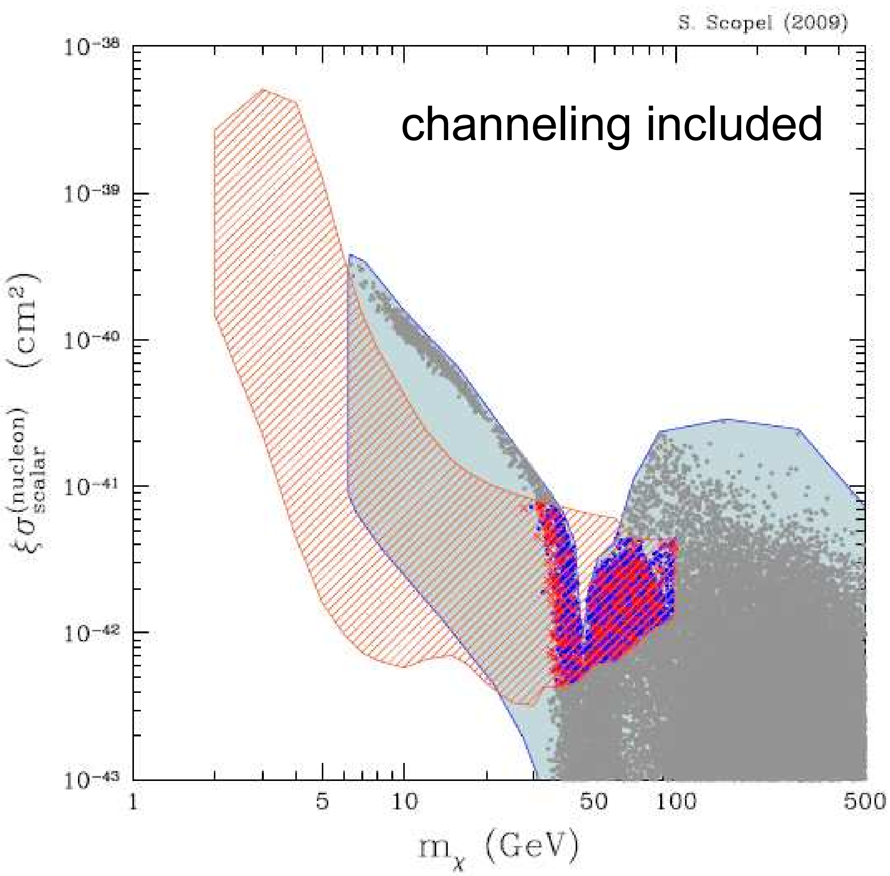


neutrino flux

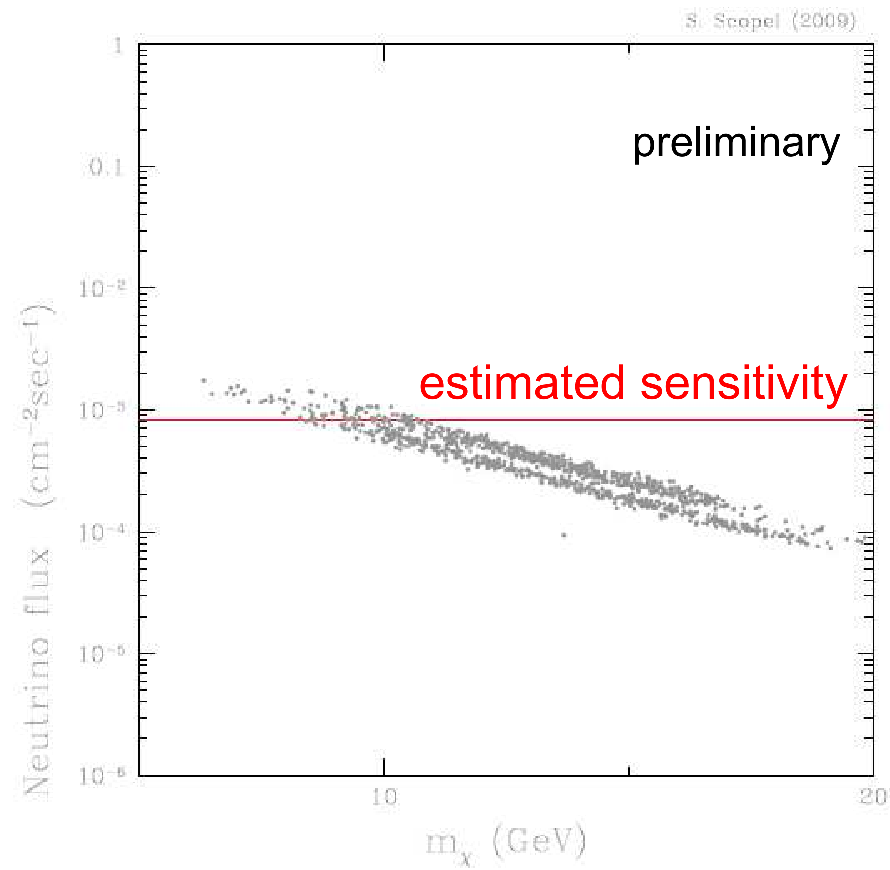


Comparison between direct detection and estimated future SK sensitivity to neutrinos from the Sun

direct detection



neutrino flux



maximal hadronic matrix elements

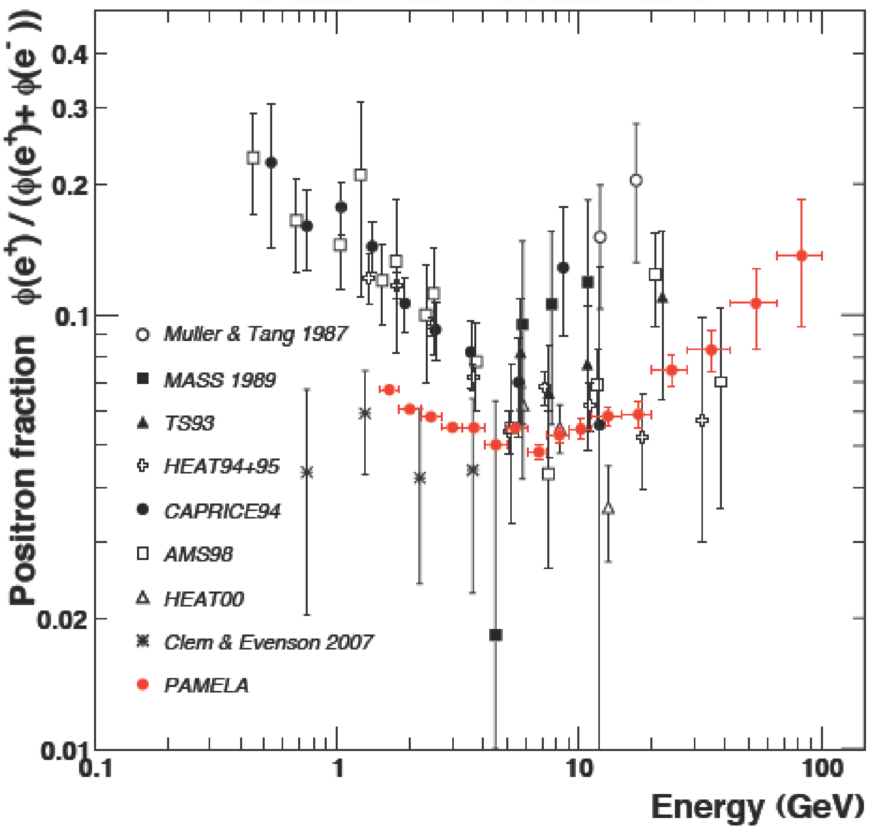
N.B. sensitivity to up-going muons does not weakens at low m_{WIMP}

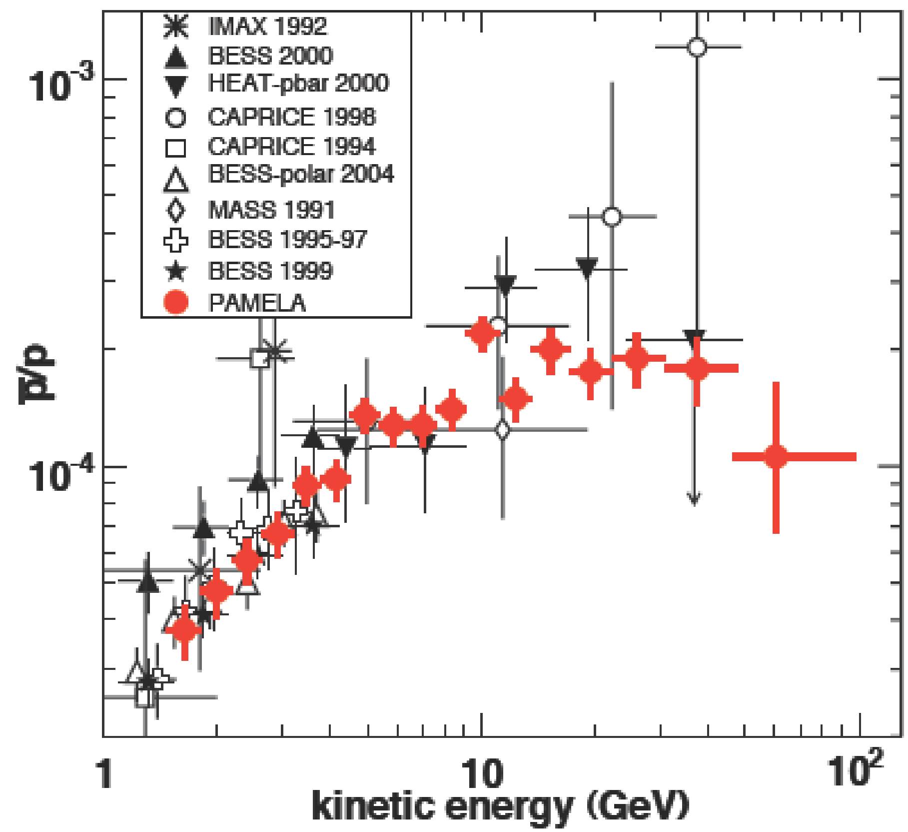
exotic component in cosmic rays

PaMeLa

a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

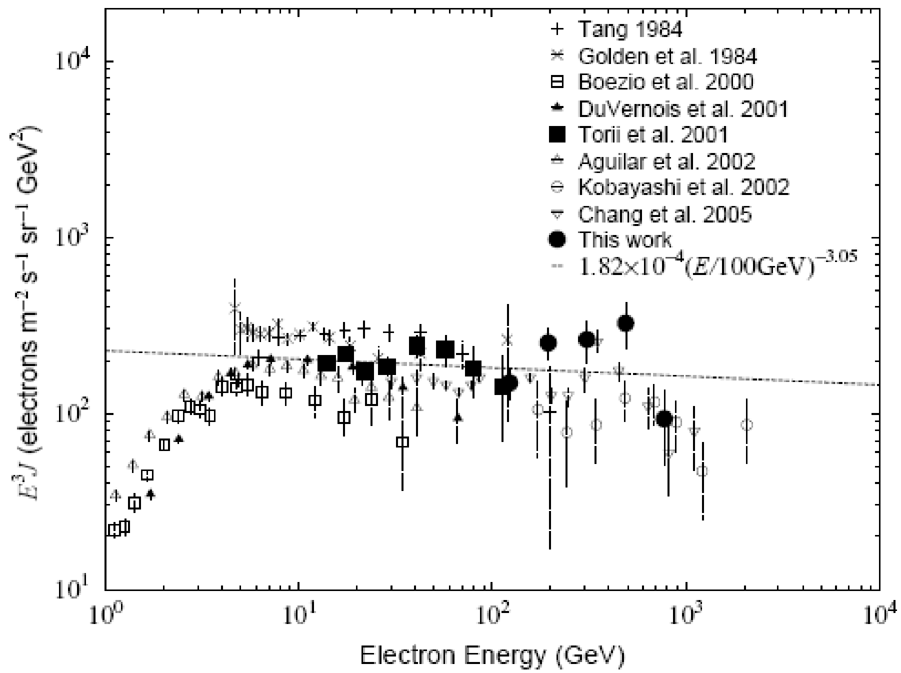
$e^+/(e^+ + e^-)$ arXiv:0810.4995, 4994 [astro-ph] $\bar{p}/p$





positron excess above 10 GeV. but no excess in antiprotons

- Balloon experiments measured the spectrum of $e^+ + e^-$ at energies higher than PAMELA
- if PAMELA excess keeps rising with energy positron fraction becomes of order unity at a few hundreds GeV
- data from ATIC-2 and PPB-BETS show a hint of an excess at those energies, and can anyway put constraints

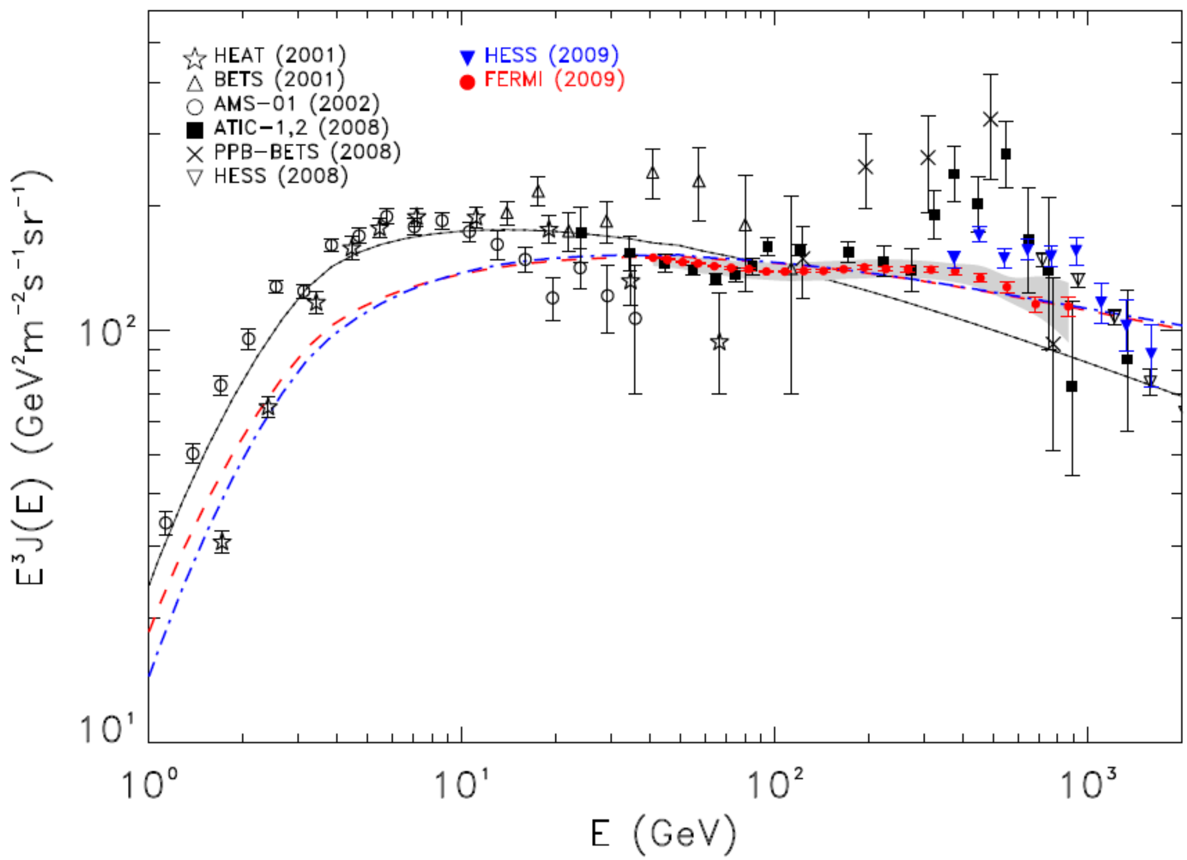


(arXiv:0809.0760)

Fig. 12. Electron energy spectrum observed with PPB-BETS (solid circles) in comparison with the energy spectra of BETS (solid squares) ant the other observations. The dash line shows the best fit power-law function of the combined spectrum of PPB-BETS and BETS with an index of -3.05 ± 0.05.

Electrons+positrons from Fermi/LAT (Abdo et al., PRL102,181101)

- ATIC peak not confirmed
- gamma detector! (former name: Gamma Large Area Telescope , GLAST)
- can get data on electrons too but not optimized for this ("thin" calorimeter, events are not fully contained)
- spectrum compatible to E^{-3} with **mild** excess @ same energy of ATIC



- Flatness of spectrum disfavours interpretations of PAMELA in terms of a light Dark Matter particle (m≲450 GeV)

Do we *really* need exotic physics to explain PAMELA/ATIC/Fermi?

CR Positron measurements are challenging

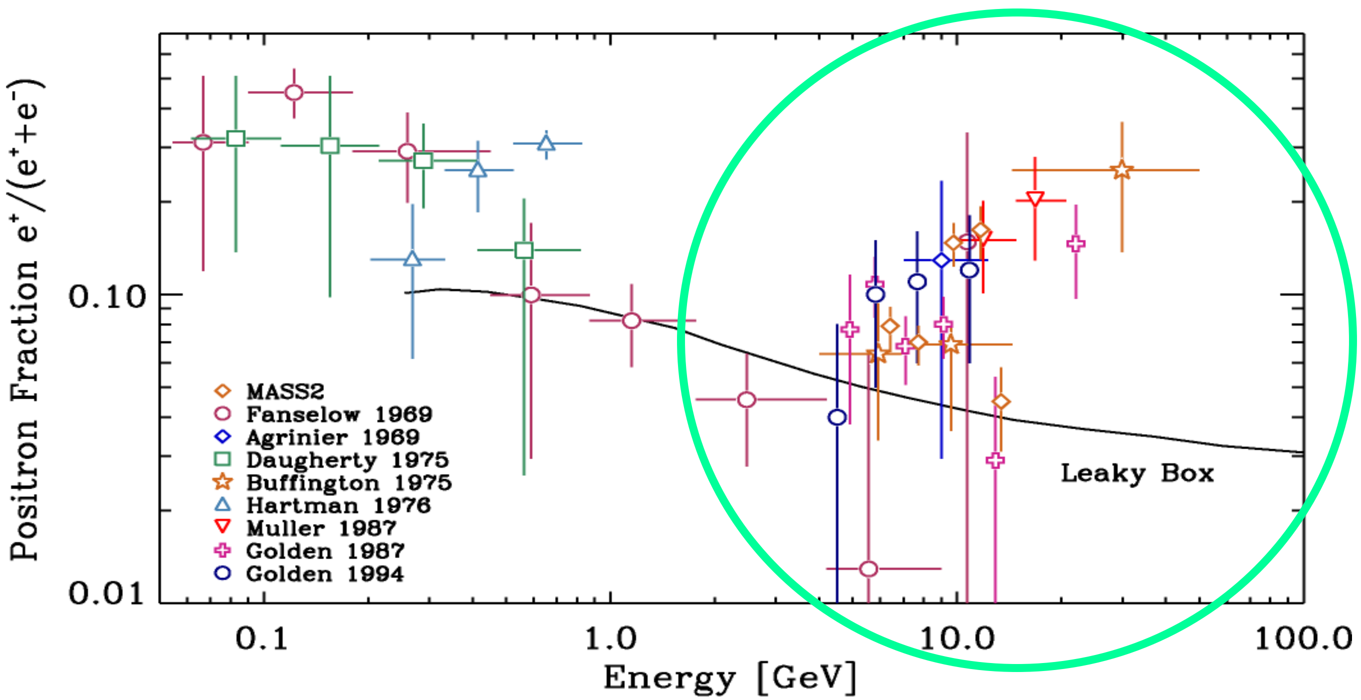
- Flux of CR protons in the energy range 1 – 50 GeV exceeds that of positrons by a factor of $>10^4$
- Proton rejection of 10^6 is required for a positron sample with less than 1% proton contamination.

The single largest challenge in measuring CR positrons is the discrimination against the vast proton background!

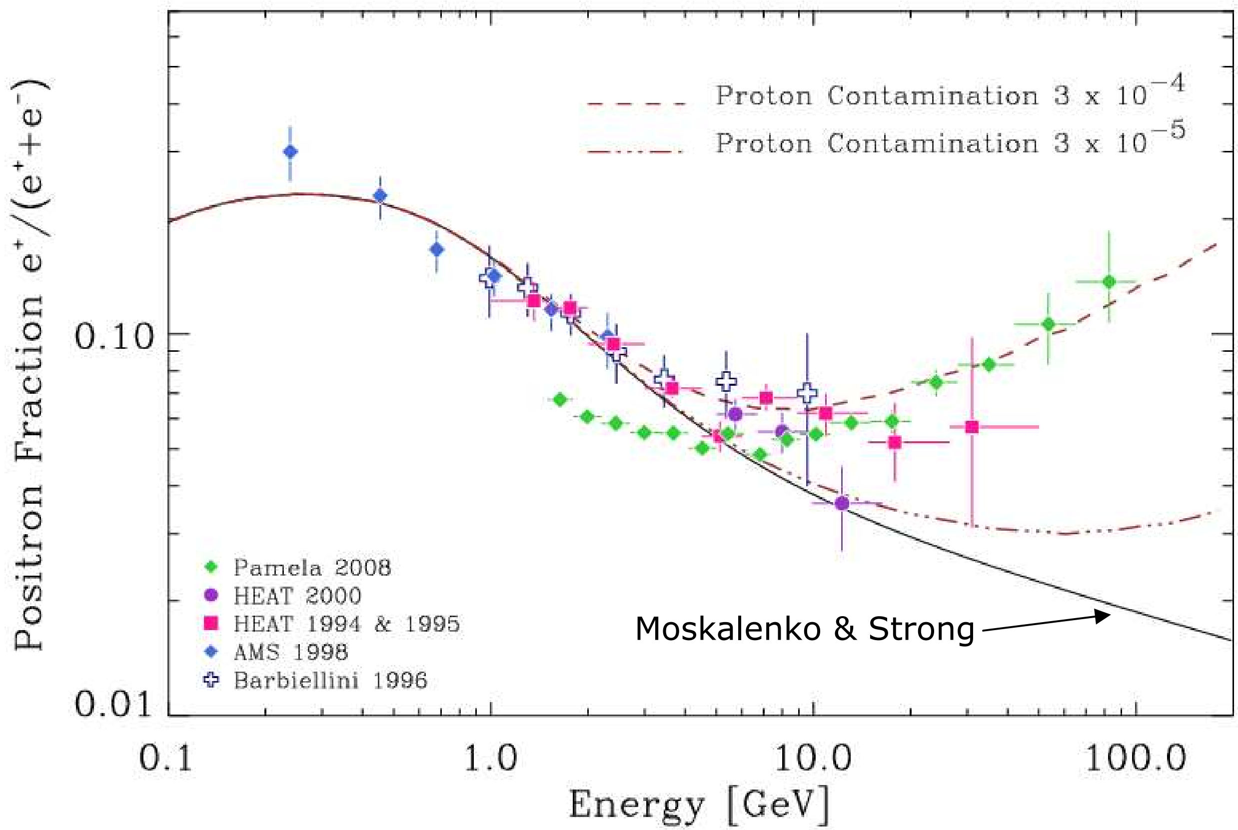
CR positron measurements
The early years: 1965 - 1984

What caused the dramatic rise at high energies at that time?

proton misidentification!



What a *little* dash of protons can do!



PAMELA claims p rejection of 10^{-5}. CAUTION! This is not verified using independent technique in flight.

•secondary to primary ratios expected to decrease with increasing energy - high energy particles escape more rapidly and thus traverse less material in the Galaxy than particles of lower energy

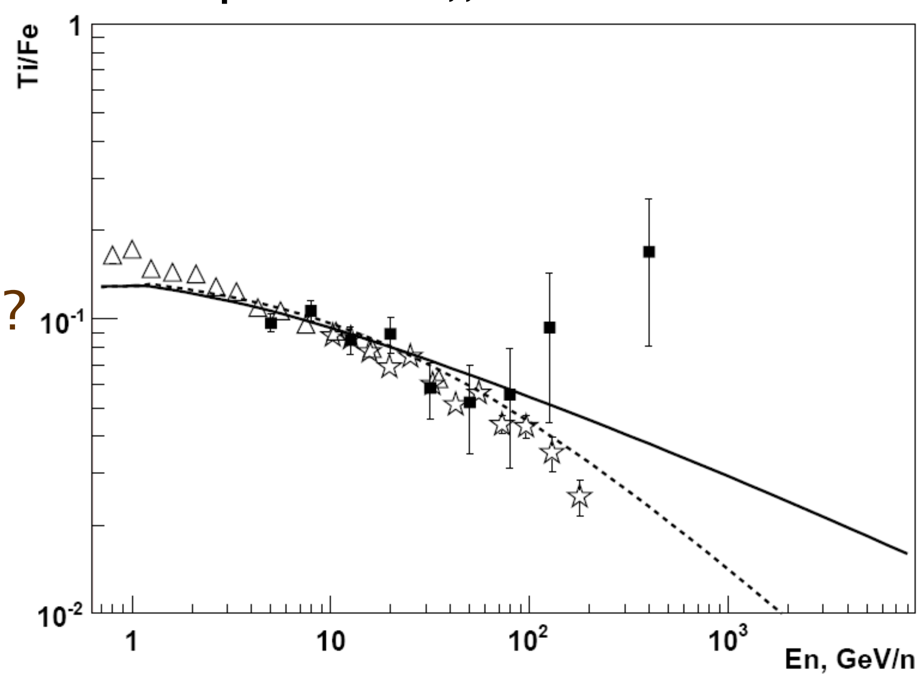
•this also means that the acceleration of the cosmic ray particles occurs <u>before</u> they begin to propagate

• conversely, if the acceleration process requires more time to reach higher energy, we would expect secondary to primary ratios to be constant, or even <u>increase</u> with energy

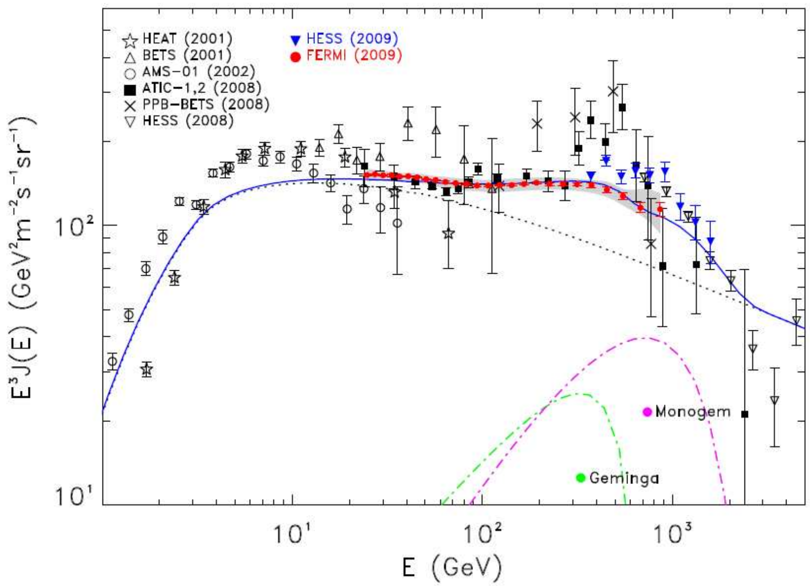
Ti/Fe ratio increasing with energy recently measured by ATIC-2

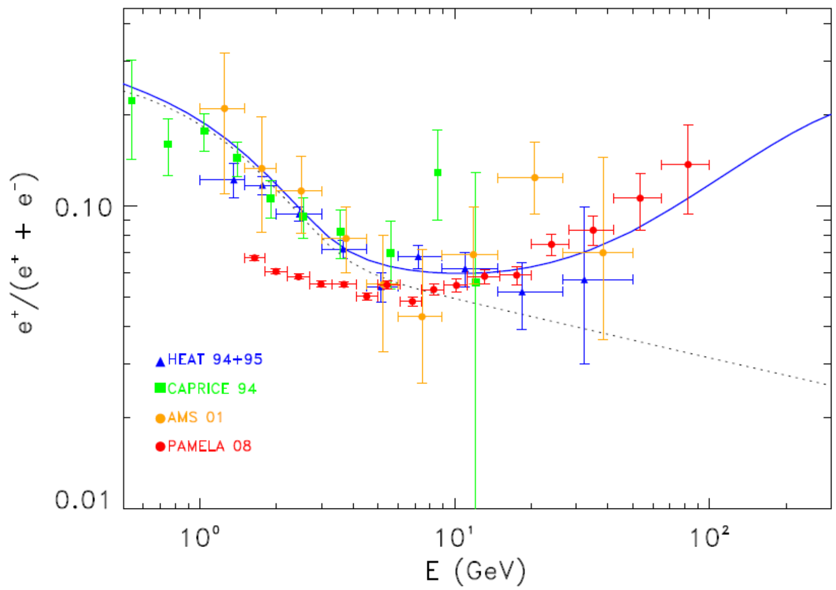
Secondaries produced in the source?
(P. Blasi, 0903.2794)

V.I.Zatsepin et al.,, arXiv:0905.0049



Pulsars as an explanation of PAMELA+Fermi (D. Grasso et al., arXiv:0905.0636 [astro-ph])





Fall-off at high energy crucial to discriminate from DM

More data expected!

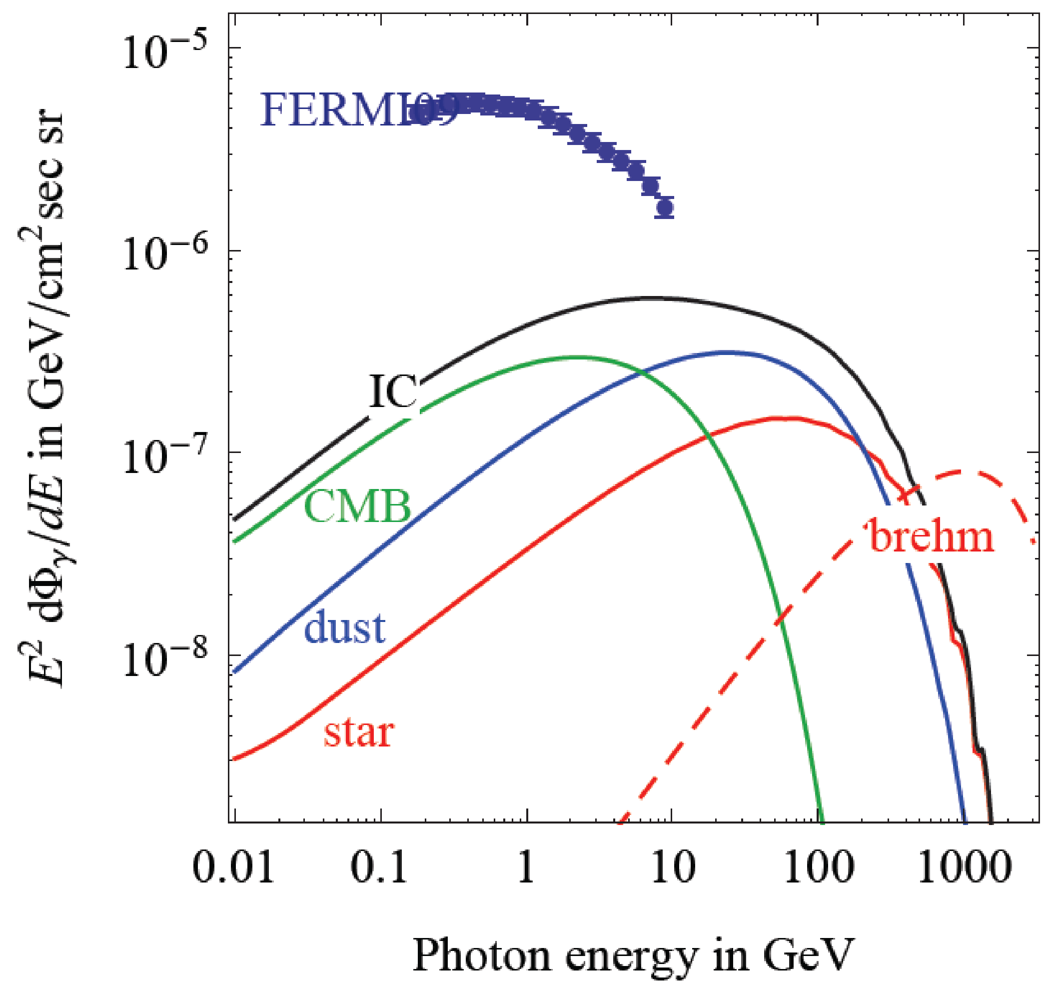
- ATIC and CREAM
  - Elemental abundances up to ~10^{15} eV
- PAMELA
  - Absolute positron flux
  - More on absolute antiproton flux
  - Electrons
  - Light nuclei
- Fermi Large Area Telescope
  - Electrons up to ~1 TeV
  - Diffuse emission (Galactic and extragalactic)

  Keep tuned:
  - A probe of electron spectrum from the solar surface to Saturn's orbit
  - A probe of CR proton spectrum beyond the heliospheric boundary
- AMS – will it fly?

An important cross check: gammas from Inverse Compton Scattering of electrons on ambient light (no matter where electrons/positrons come from they must produce it!)

Meade et al., 0905.0480

In the 10^0–20^0 region observed by Fermi it should be visible! Data on diffuse radiation expected to come soon.



Puzzles for DM interpretation

- Excesses in e^+/e^-; not in $\bar{p}$.
- Observed fluxes=(100-1000) x predicted flux for thermal DM:

$$\text{Observed Flux} = \left(\frac{\rho_{DM}}{0.3GeV/cm^3}\right)^2 \left(\frac{\langle\sigma v\rangle_{GAL}}{10^{-6}\text{GeV}^{-2}}\right)$$

$$\langle\sigma v\rangle_{FO} \sim 10^{-9}\text{GeV}^{-2}$$

Local clumpiness in DM distribution: 'Boost Factor'< 10

Lavalle et.al., 0709.3634 [astro-ph]

enhancement of <σv> at small velocities?

The Standard Lore about a steep rise in positrons from DM annihilation:

• most likely from direct annihilation to leptons. In this case neutralino disfavored – due to chirality flip Born cross section suppressed by m_e^2/m_{susy}^2 – but spin-1 DM particles from UED or little Higgs models are OK, as well as Dirac fermions from mirror DM

• production and decay of heavy bosons marginally OK (play with uncertainties). Compatible to a neutralino. Constraints from antiprotons?

• Instead, b quarks and tau leptons spectra too soft

• anyway, typically large boost factors required (clumpiness? – maybe unreasonably too large according to recent numerical simulations)

• otherwise large $\langle\sigma v\rangle$ → (1) non-thermal DM; (2) constraints from other indirect searches (gammas, antiprotons) – however astrophysical uncertainties are larger for the latter (positrons usually come from nearby)

New DM ideas

- Leptophilic property:

  1) DM couplings to leptons only.

  2) DM annihilates to sub-GeV particles that is forbidden kinematically to decay to proton/anti-p.

- Boosted annihilation in galaxy:

  1) Non-thermal DM.

  2) Assumed local clumpiness.

  3) Breit-Wigner resonance.

  4) Sommerfeld enhancement.

  5) Dirac gauginos

Large thoretical activity triggered by PAMELA

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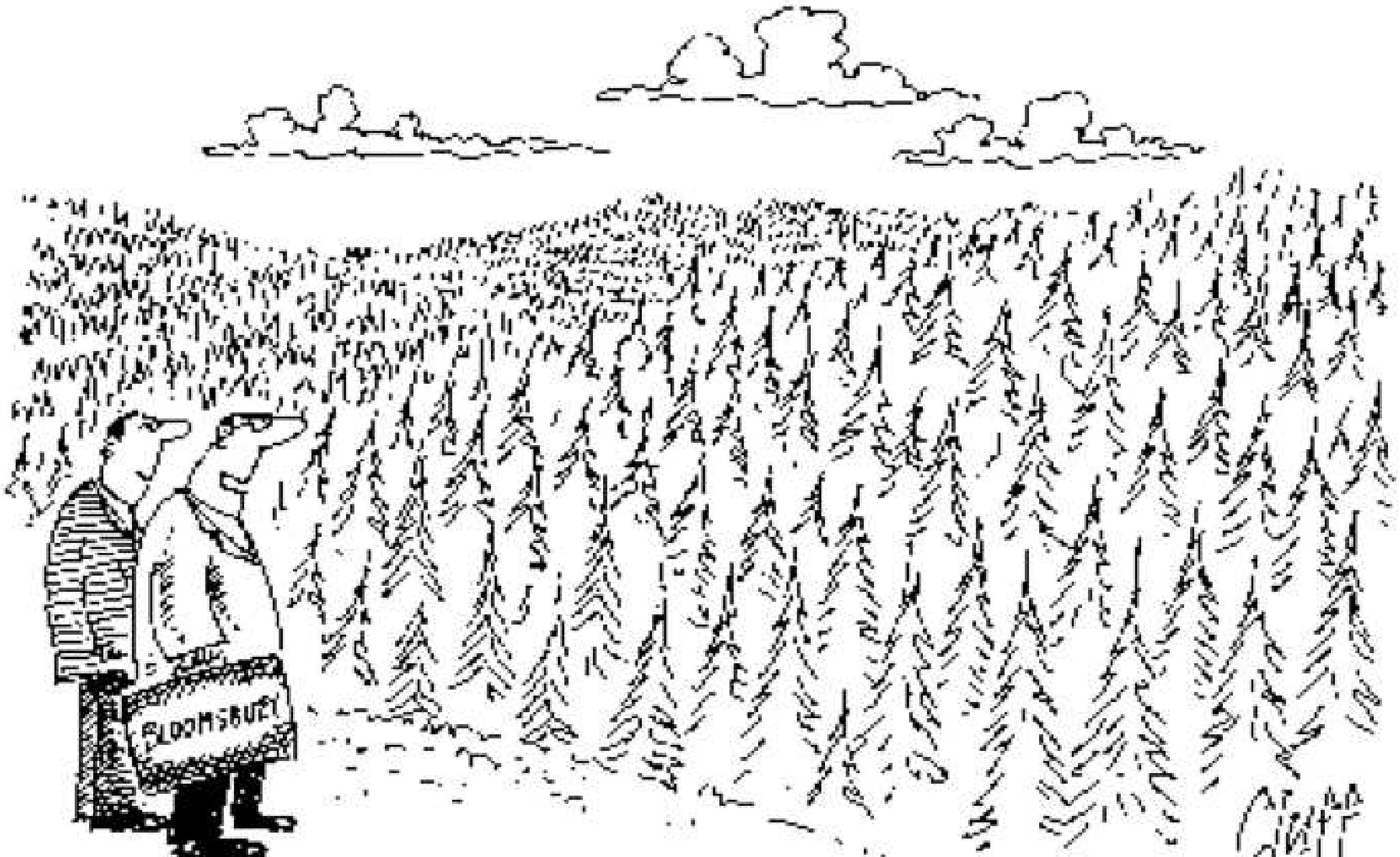
and more….

a small appetizer of the (near!) future awaiting us?

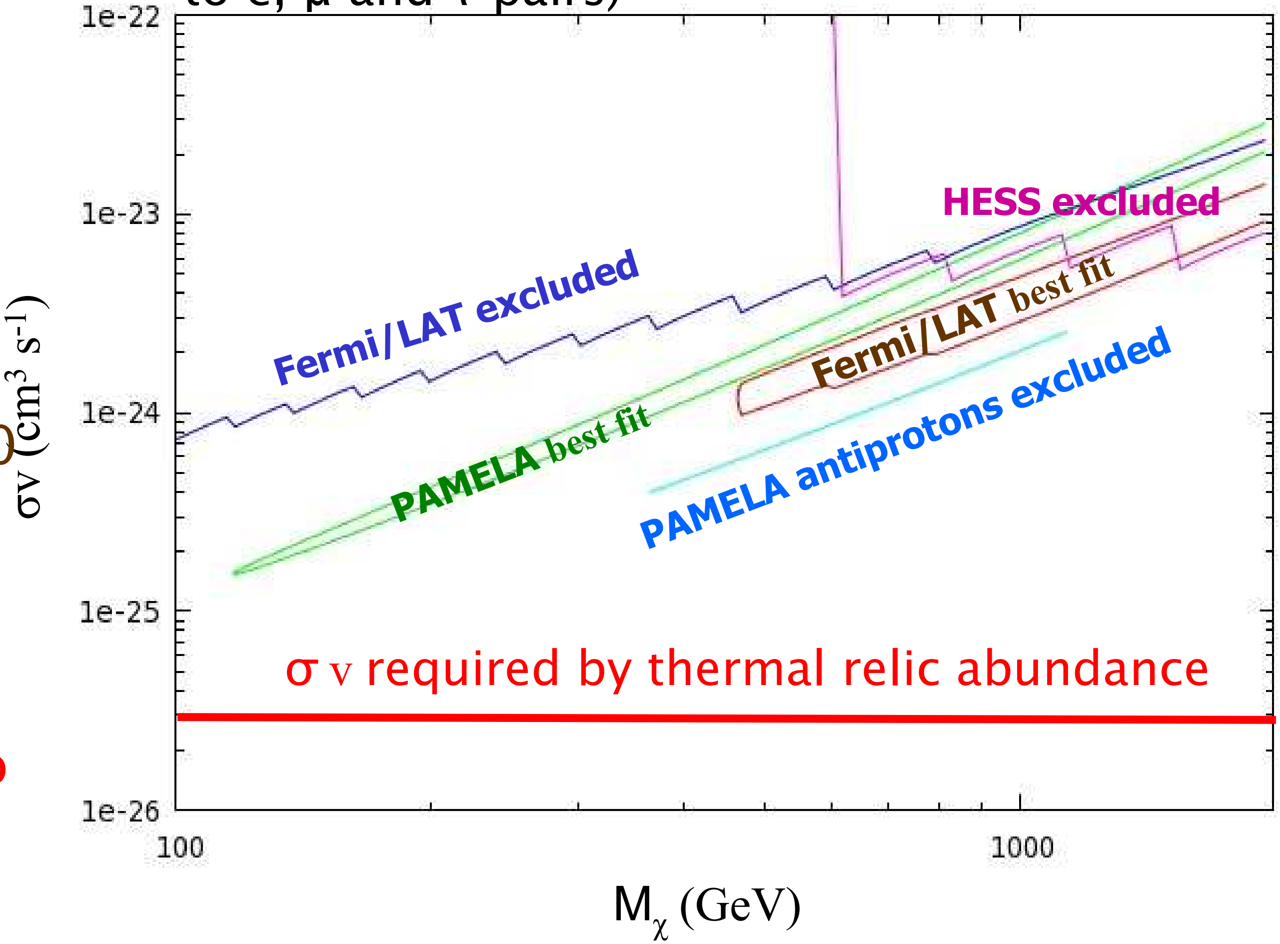


“One day, all these will be LHC phenomenology papers”

Positrons, electrons and antiprotons from space

- PAMELA positron excess fitted by large DM mass range
- Fermi/LAT data disfavor lower masses (m_{DM}<450 GeV)
- PAMELA antiprotons constraint the branching ratio to hadrons

Leptophilic dark matter (democratic annihilation to e, μ and τ pairs)



The values of σ v needed to explain PAMELA are almost two orders of magnitude larger compared to those required by a thermal relic abundance → non-thermal candidate? non-standard cosmology? Sommerfeld enhancement at low temperatures? boost factor from halo clumpiness?

Determining the Majorana/Dirac nature of gauginos will be an interesting task for future experiments looking for supeserymmtric CP and flavor violation, collider signatures and dark matter properties
(Choi, Drees, Freitas, Zerwas, PRD78(2008)095007)

Paul Dirac

Ettore Majorana

important distinctions between Majorana and Dirac gauginos:

1. Annihilation of a Dirac gaugino into a fermion-antifermion pair, $\chi\chi \rightarrow ff$, has a non-vanishing s-wave contribution even in the limit of vanishing fermion masses, and thus the leptonic final states are not suppressed
2. Dirac gauginos can have a vector coupling with the Z gauge boson, $\chi\gamma^{\mu}\chi Z$, leading to a potentially sizable <u>spin-independent</u> coherent scattering with nuclei (proportional to A^2)

- In the minimal supersymmetric standard model (MSSM) gauge supermultiplets are built up by two components, bosonic gauge fields and fermionic gaugino fields. Since neutral vector fields are self-conjugate, the corresponding supersymmetric partners are Majorana fields.

- fermionic components can be paired with two additional fermionic fields in N=2 supersymmetric theories – if the fields are mixed maximally the four fermionic degrees of freedom can join to a Dirac field and its charge-conjugate companion

In order to ensure such Dirac nature of dark matter, Majorana mass terms, which give mass splitting between Dirac components, have to be highly suppressed.

Otherwise, the heavier component of two quasi-degenerate Majorana gauginos will decay to the lighter one and the galactic dark matter will consist of pure Majorana gauginos.

If one assumes the N=2 structure in the Higgs sector, that is, the two Higgses H_u and H_d form a N=2 hypermultiplet, the Dirac structure imposed at the tree level is spoiled by a large amount due to the radiative corrections with the Higgs-Higgsino and fermion-sfermion in the loop.

$$\tilde{B}_2 \rightarrow \tilde{B}_1 \gamma \quad : \quad \Gamma \approx \frac{\alpha}{4\pi}\left(\frac{\alpha'}{4\pi}\frac{m_{\tilde{B}}^2}{\tilde{m}^2}\right)^2 \delta m_M$$

δm_M = splitting between two Majorana gauginos needs to be $\lesssim 10^{-33}$ GeV to ensure stability of Dirac state on cosmological scales

$$\Rightarrow \quad \delta m_M \ll \frac{m_{3/2}^3}{M_P^2}$$

large fine-tuning required

A way to enforce this property is to assume a continuous R symmetry which forbids the usual term for the Higgs bilinear $H_u H_d$ and the A-term soft breaking (Kribbs, Poppitz and Weiner, PRD78(2008)055010)

For the MSSM, writing all operators consistent with the SM gauge symmetries and the extended R-symmetry:

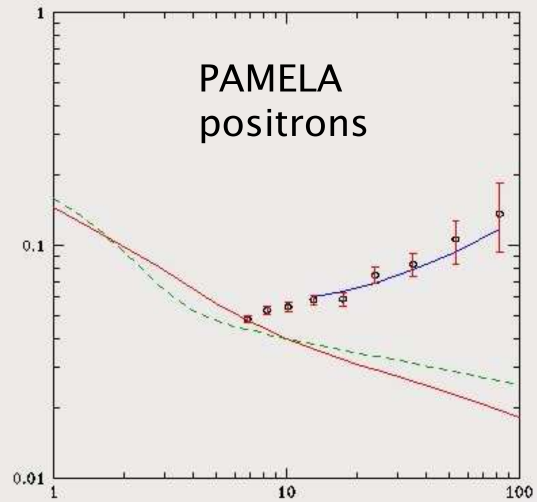
1. Majorana gaugino masses are forbidden.
2. The -term, and hence Higgsino mass, is forbidden.
3. A-terms are forbidden.
4. Left-right squark and slepton mass mixing is absent (no -term and no A-terms)

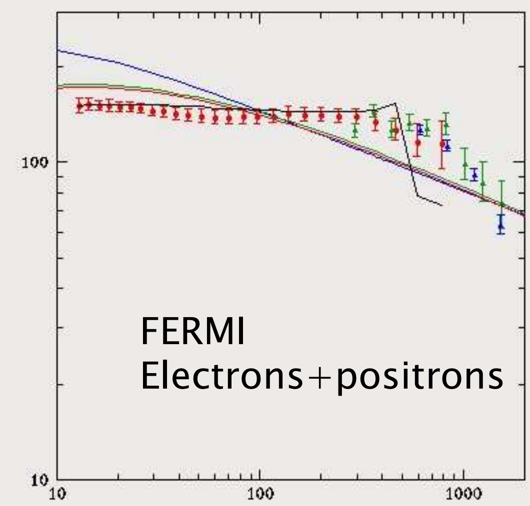
Absence of μ term → extended Higgs sector:

$$W_\mu = \mu_u H_u R_u + \mu_d H_d R_d$$

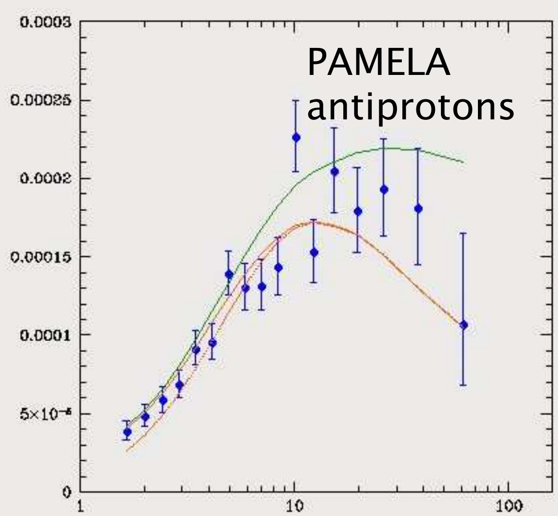
Dirac gaugino – work in progress (E.J. Chun, C.C. Park, S.S.)

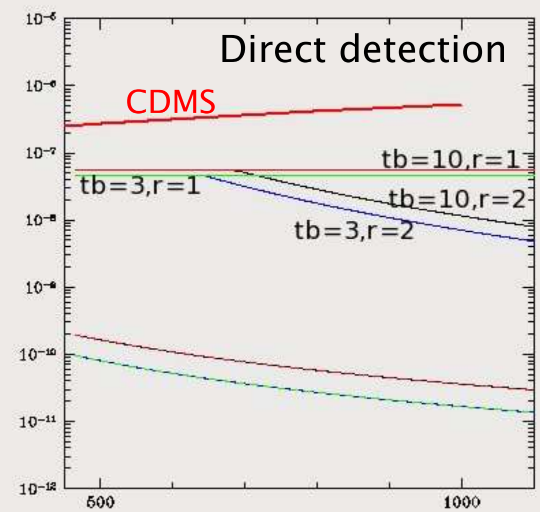
m_χ=450 GeV
σv=1.47 x 10^{-24} $cm^3 s^{-1}$





- sizeable direct detection cross section through Z exchange are possible for non-zero Higgsino component
- compatible to PAMELA antiprotons





Conclusions

1. DAMA result challenged by other searches
2. Light relic neutralinos $\lesssim$ 10 GeV compatible with present constraints
3. Light relic neutralinos compatible with DAMA effect
4. Hard to verify 2 & 3 at the same time, but not impossible
5. Light neutralinos might show up in fully contained up-going-muon events from the Sun at SK
6. Do we really need exotics to explain PAMELA?
7. If yes, PAMELA and Fermi/LAT at odds with "standard" neutralino, new ideas put forward
8. Dirac gauginos can explain the positron excess, direct detection cross section through Z exchange can be sizeable