Seminarium Fizyki Wysokich Energii, 9.IV.2010, Warszawa

Poszukiwania Ciemnej Materii

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PLAN

- Wstęp - Ciemna Materia
- Metody poszukiwania cząstek Ciemnej Materii
- Wyniki eksperymentalne
  - DAMA/LIBRA
  - CDMS
  - CoGeNT

  } detekcja bezpośrednia

  - PAMELA
  - ATIC
  - FERMI/GLAST
  - Super-Kamiokande

  } detekcja pośrednia
- Podsumowanie

Wstęp – Ciemna Materia

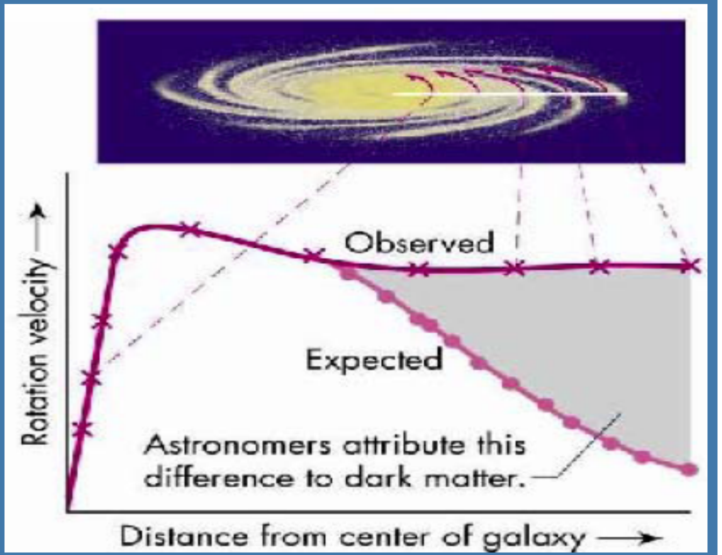
Dark Matter in the Universe

Universe – dominant mass contribution from unknown matter component. It manifests only through gravitational interactions with surrounding baryonic matter. Its presence determines evolution of Universe and can be observed through:

» *Velocity distribution in galaxy clusters (F.Zwicky in 1933)*

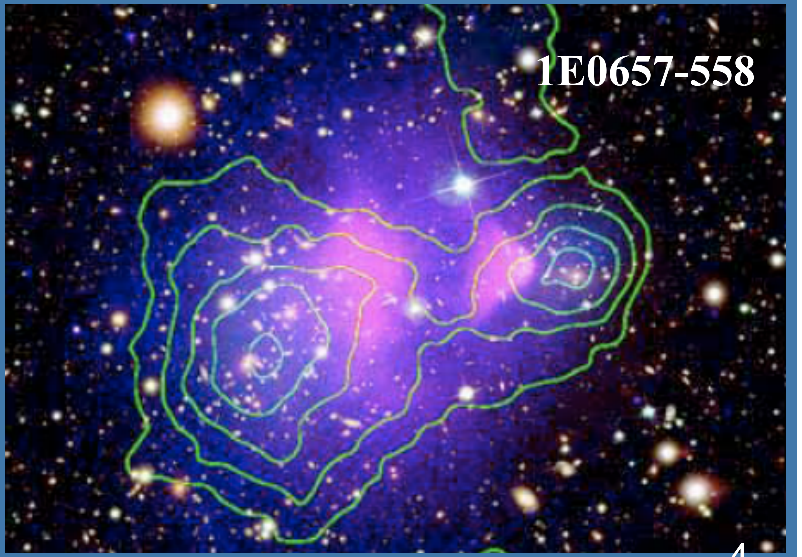
» *Galaxies rotation curves*

Dark Matter: ~95% mass of Galaxies



» *Gravitational lensing*

example: Bullet Cluster



» *Cosmic Microwave Backround (CMB)*

» *Evolution of large cosmic structures*

ΛCDM model

ΛCDM – standard model of a Big Bang cosmology, based on recent observations: CMB, large scale structures, accelerating expansion of the Universe

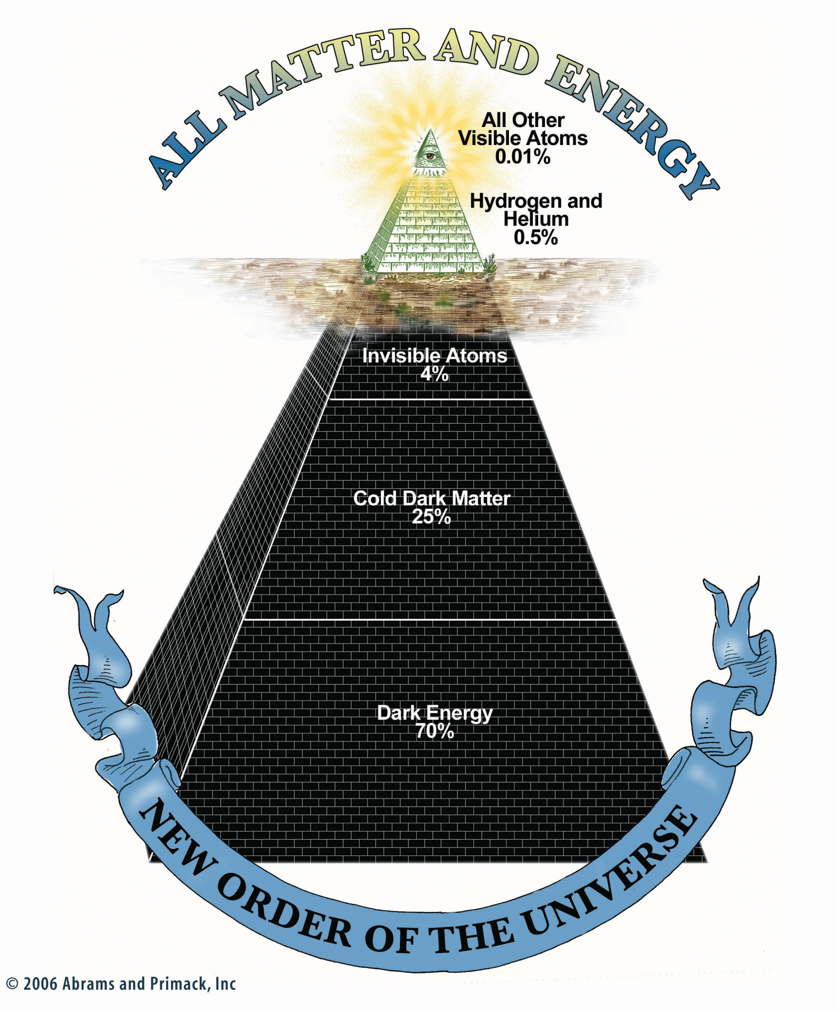
Cosmological parameters

- Ω_{tot} $\Omega_{tot} = 1.02 \pm 0.02$
- Ω_m $\Omega_m = 0.27 \pm 0.02$
- Ω_b $\Omega_b \sim 0.044 \pm 0.002$
- Ω_Λ $\Omega_\Lambda = 0.73 \pm 0.02$

Conclusions:

$\Omega_m >> \Omega_b$ => Dark Matter

$\Omega_m < 1$ => Dark Energy



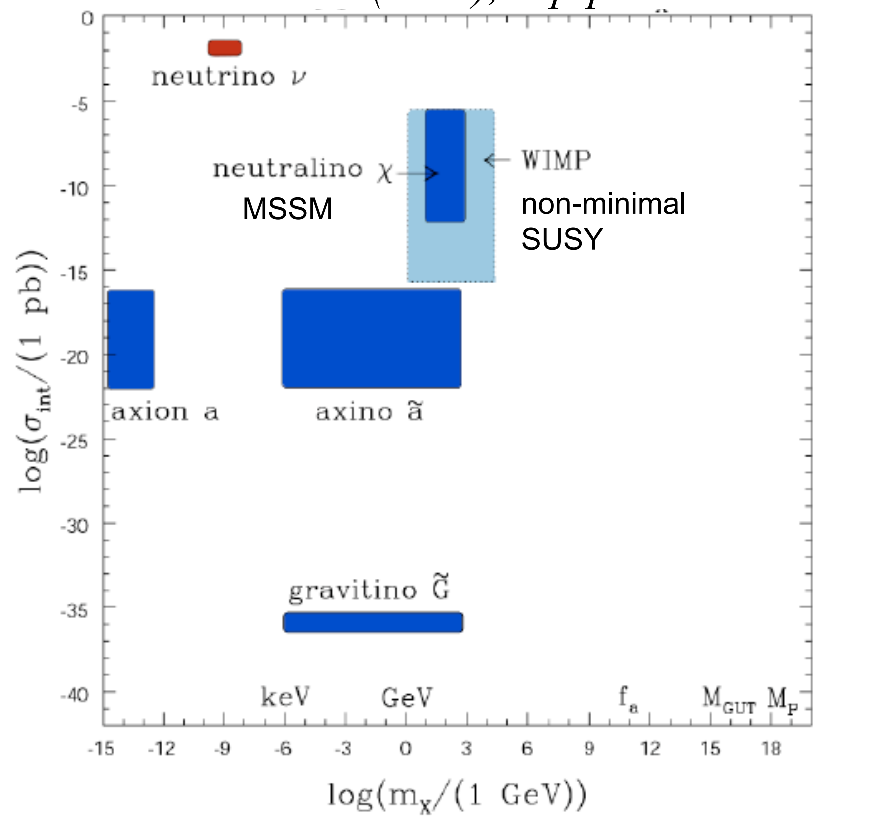
Dark Matter - candidates

well motivated candidates:

- ~~neutrino~~ – hot DM
- neutralino χ
- "generic" WIMP
- axion a
- axino ã
- gravitino $\tilde{G}$

(neutralino χ and "generic" WIMP:) **PRIME SUSPECT**

L.Roszkowski (2004), hep-ph/0404052



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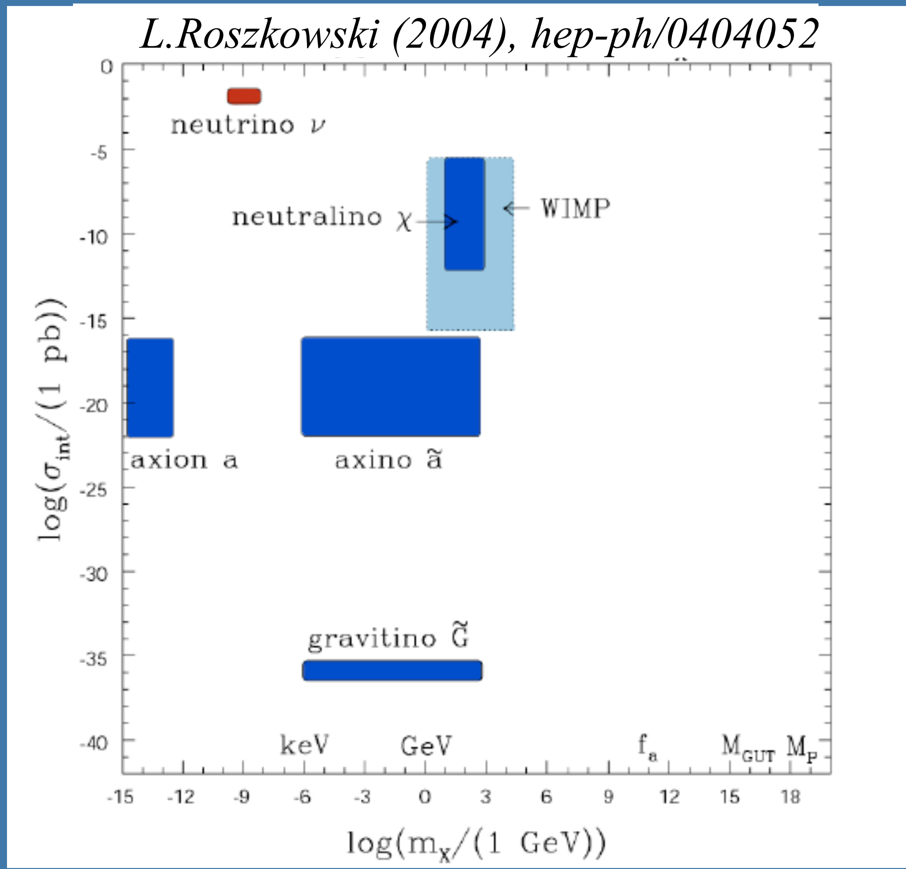


WIMPs naturally comes with SUSY:
(Weakly Interacting Massive Particle)

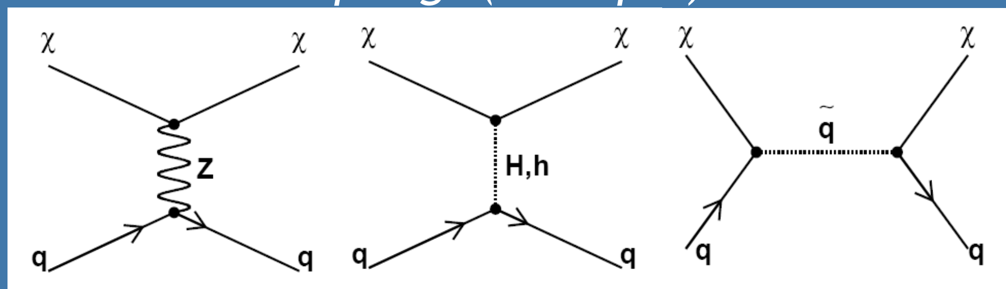
◆ **neutralino χ** - Lightest Supersymmetric Particle (LSP), **stable (R-parity conservation)**

$$\tilde{\chi} = a_1\tilde{\gamma} + a_2\tilde{Z} + a_3\tilde{H}_1 + a_4\tilde{H}_2$$

(6GeV) < 50 GeV < M_χ < ~10 TeV

↓ **LEP2** **cosmology**

neutralino couplings (example):

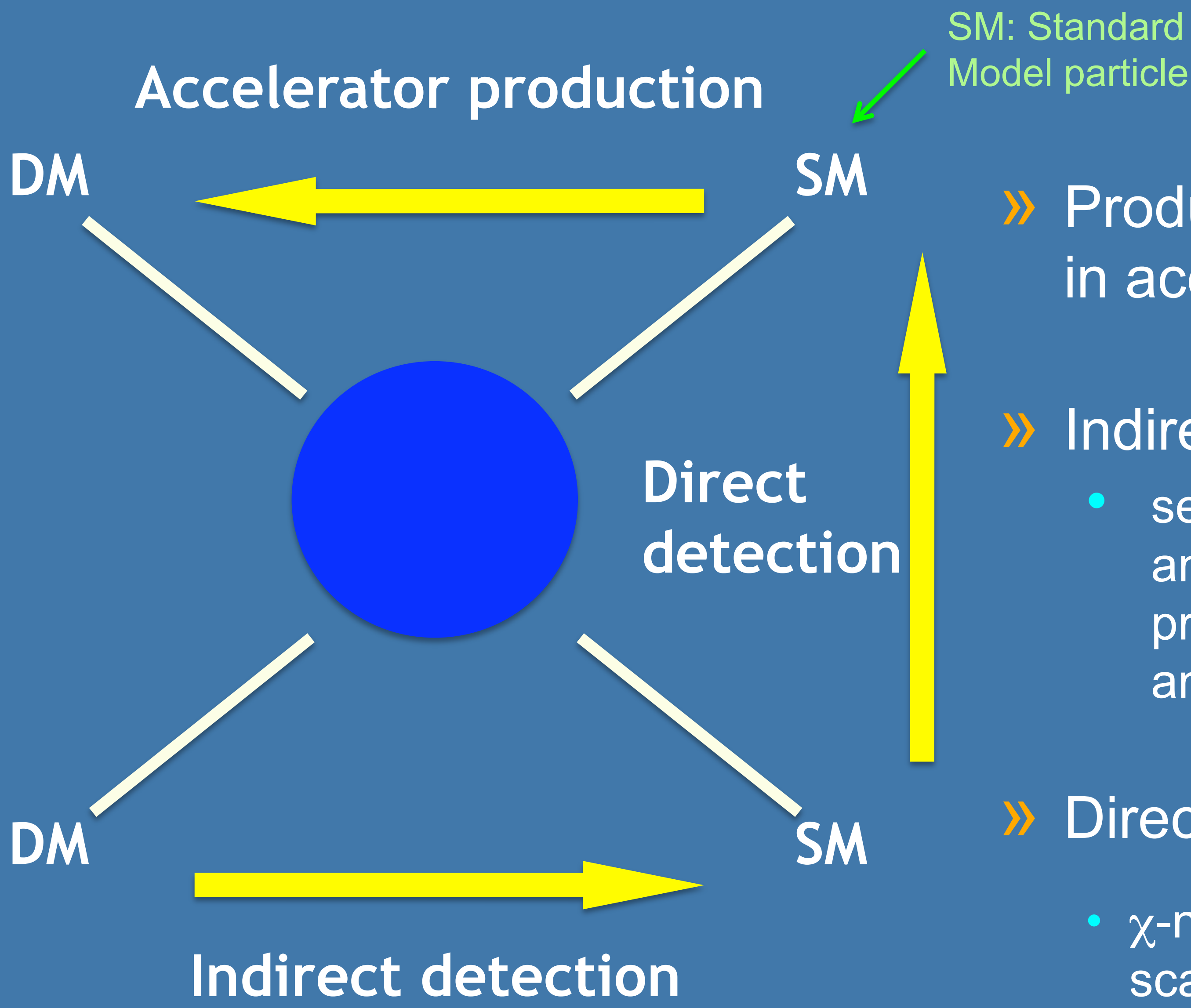


Bottino et al., Phys.Rev.D69:037302 (2004)

Jungman, Kamionkowski, Griest, Phys. Rep., 267, 195 (1996)

Metody poszukiwania cząstek Ciemnej Materii

Strategies: search for Dark Matter

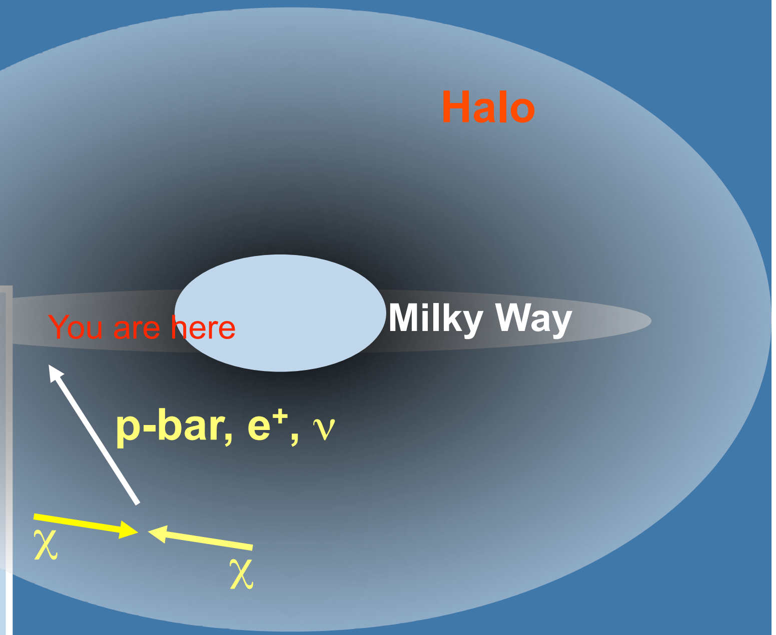


- Production
  in accelarators (LHC)
- Indirect detection:
  - search for annihilation/decay products of χ's (self-antiparticle)
- Direct detection:
  - χ-nucleus elastic scattering

Indirect search for WIMPs

» Indirect search = search for annihilation products of χ's (self-antiparticle)

$$\chi\chi \rightarrow \begin{cases} q\bar{q}\left(c\bar{c}, b\bar{b}, t\bar{t}, \ldots\right) \\ l\bar{l} \\ W^{\pm}, Z, H \end{cases} \rightarrow \ldots.. \rightarrow \nu, \gamma, \bar{e}, \bar{p}, \bar{H}_2,$$



- gammas *(HESS, MAGIC, EGRET, GLAST/FERMI)*

  insensitive to magnetic fields, E spectra not attenuated over galactic scales, produced in most DM annihilation modes in π^0 decays

- anti-matter: positrons, anti-deuteron, anti-proton *(PAMELA, HEAT, BESS, ATIC, AMS-02 …)*

  satellite or balloon-born expriments – go up to probe primary CR component

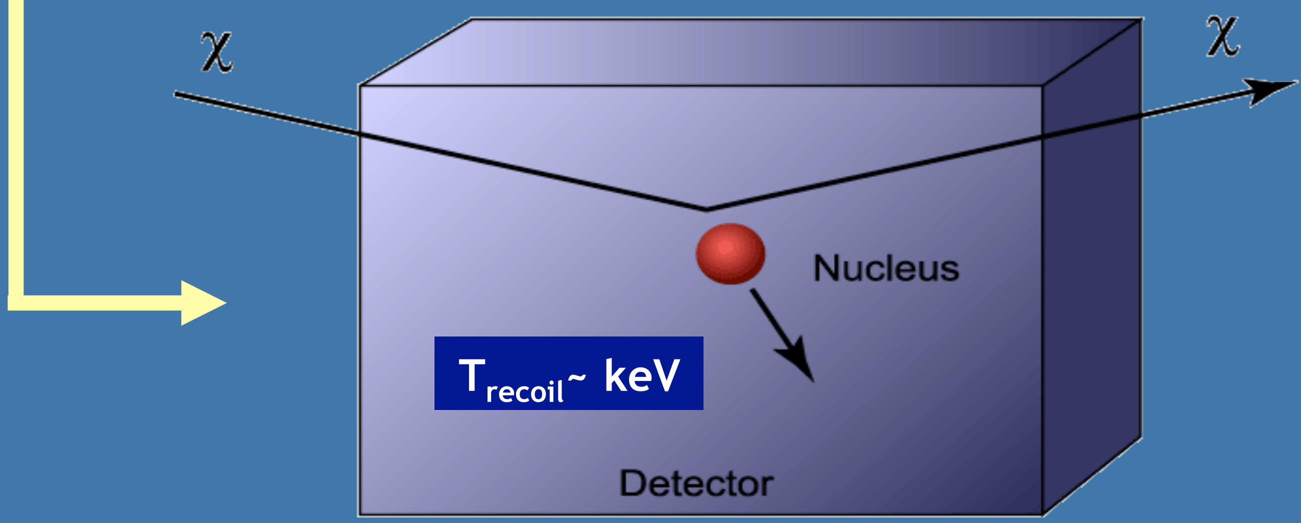
- neutrinos *(Super-Kamiokande, Ice-Cube)*

  χ get trapped in massive celestial objects (Sun, core of Earth, Galactic Center), start annihilating, only ν's escape

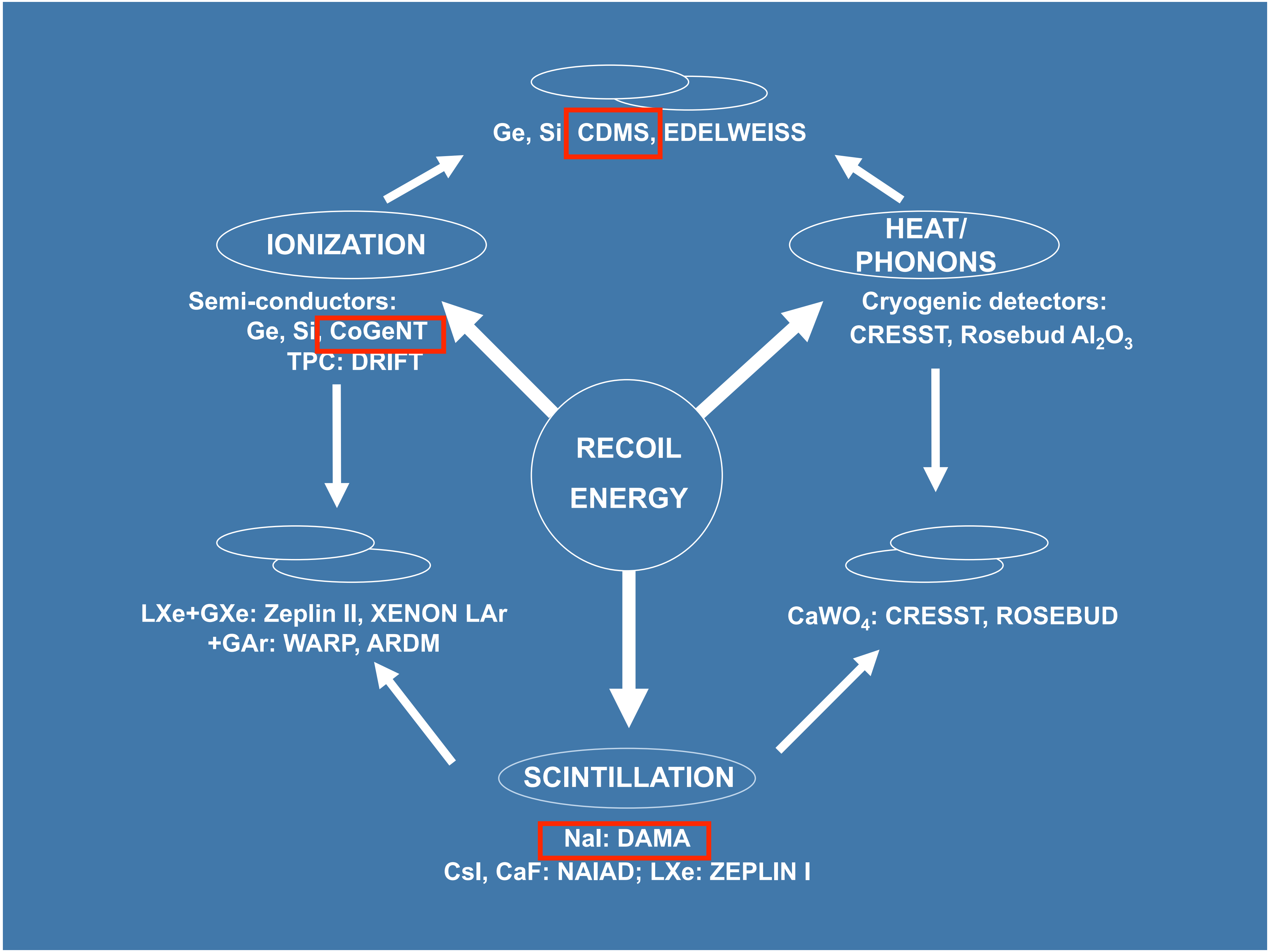
Direct search for WIMPs (χ's)

» WIMP-nucleus elastic scattering

$$\chi + (A,Z)_{\text{in rest}} \rightarrow \chi + (A,Z)_{\text{recoil}}$$



- » Terrestrial experiments: search for χ's in Galactic Halo
- » Need to go underground to suppress cosmic ray BKG
- » Recoil energy meas. with different techniques:
  - e/γ bkg discrimination vs. heavy nuclear recoils


Ge, Si CDMS, EDELWEISS
IONIZATION
HEAT/ PHONONS
Semi-conductors:
Ge, Si, CoGeNT
TPC: DRIFT
Cryogenic detectors:
CRESST, Rosebud Al_2O_3
RECOIL ENERGY
LXe+GXe: Zeplin II, XENON LAr
+GAr: WARP, ARDM
$CaWO_4$: CRESST, ROSEBUD
SCINTILLATION
NaI: DAMA
CsI, CaF: NAIAD; LXe: ZEPLIN I

Energia odrzutu

» Energia odrzutu zależy od:

- masy χ oraz masy jądra tarczy
- Energii kinetycznej WIMP-ów $T\chi$ **(model halo)**

przykładowy model halo

- **prędkość WIMP-ów w halo: rozkład *Maxwella-Bolzmanna* ze średnią prędkością względem centrum Galaktyki = 0, jej dyspersją ≈ 230 km/s, V_{esc} ≈ 600 km/s**
- **$V_{układu\ słon.}$ ≈ 230 km/s (względem halo) -> określa śred. $T\chi$**
- **ρ - gęstość WIMP-ów w halo galaktycznym (~ 0.3 GeV/c^2 ·1/cm^3)**

» Np. (rozpraszanie w fali S):

» Widmo energii jąder odrzutu dla ustalonej m_χ jest ciągłe i ma charakter eksponencjalny

Ar (Z=40)

- **$M\chi$ = 50 GeV/c^2 $\langle T_{odrzutu} \rangle$ = 14 keV**
- **$M\chi$ = 100 GeV/c^2 $\langle T_{odrzutu} \rangle$ = 24 keV**

Częstość zdarzeń

Liczba rejestrowanych przypadków (Rate):

$$R \sim \rho \cdot V \cdot \sigma$$

ρ - gęstość WIMP-ów w halo galaktycznym

σ - elastyczny przekrój czynny zależny od materiału tarczy - rodzaju sprzężenia WIMP-nukleon (spinu), czynnika postaci F(q^2) … dla WIMP-ów spodziewamy się $\sigma_{\chi\text{-nukleon}} \sim \sigma_{EW} < 10^{-38}\ \mathrm{cm}^2$

» Strumień WIMP-ów (ϕ_χ): $$\phi_\chi = \frac{\rho_x}{M_\chi} \cdot V_x$$

Przy założeniach: $\rho_\chi = 0.3\ \mathrm{GeV}/(c^2 \cdot \mathrm{cm}^3)$ $\upsilon_\chi = 230\ \mathrm{km/s}$ $M_\chi = 100\ \mathrm{GeV}/c^2$

dla dektora Ar oznacza to rejestrację

Strumień WIMP-ów: $\phi_\chi \approx 7 \times 10^4 \mathrm{cm}^{-2}\mathrm{s}^{-1}$

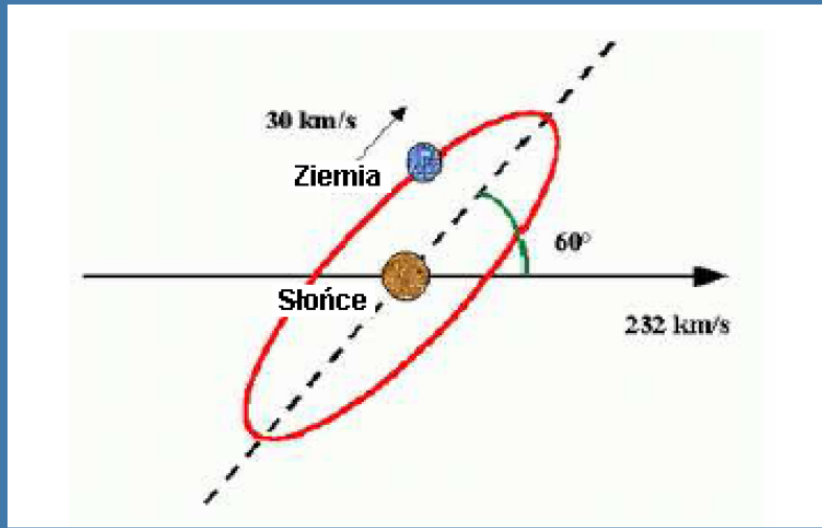
1000 przyp./ kg /dzień

przy $\sigma_{\chi\text{-nukleon}} = 10^{-38}\ \mathrm{cm}^2$

Aktualne wyniki eksperymentalne sugerują jednak iż $\sigma_{\chi\text{-nukleon}} < 10^{-42}$

Efekt modulacji sezonowej

» *V* – **średnia prędkość cząstki WIMP względem nukleonu (tarczy) – ZALEŻY OD PORY ROKU!**



Sumaryczna prędkość Ziemi i Słońca względem centrum Galaktyki:

Maksimum - 2 czerwiec - $V \approx 248$ km/h

Minimum - 2 grudzień - $V \approx 219$ km/h

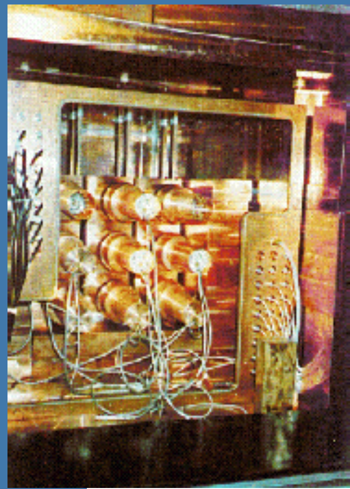
Wyniki – detekcja bezpośrednia

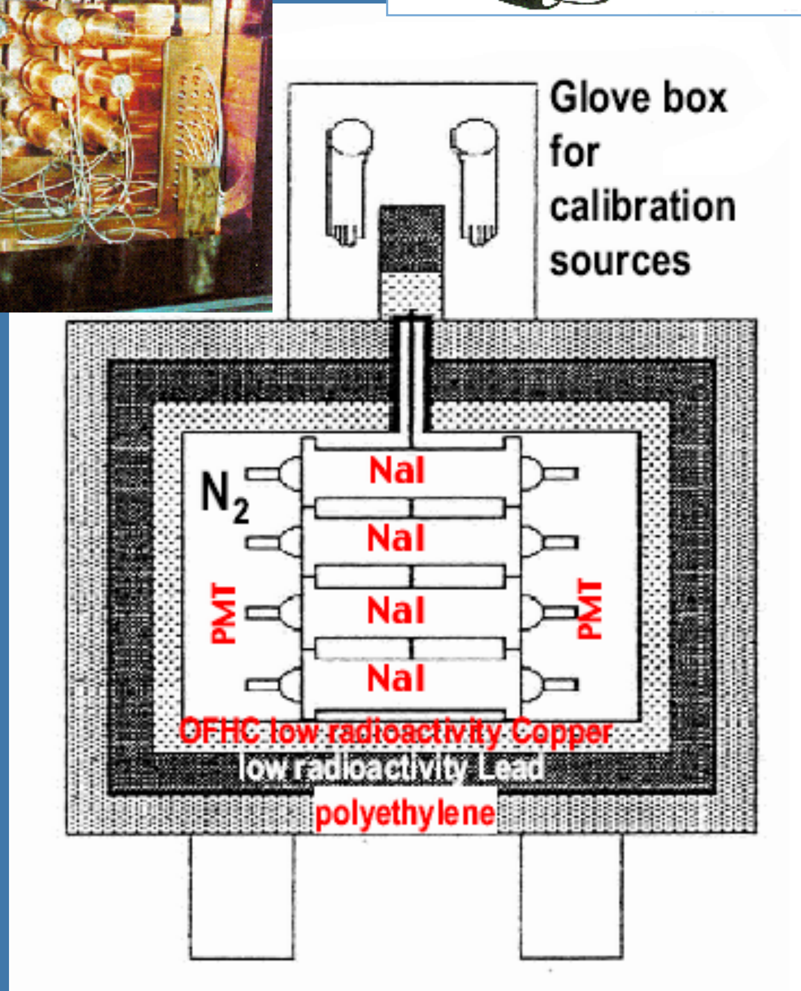
DAMA/LIBRA (~250kg NaI)

DArk MAtter/Large sodium Iodide Bulk for RAre processes

χ scatter on Na/I → scintillation

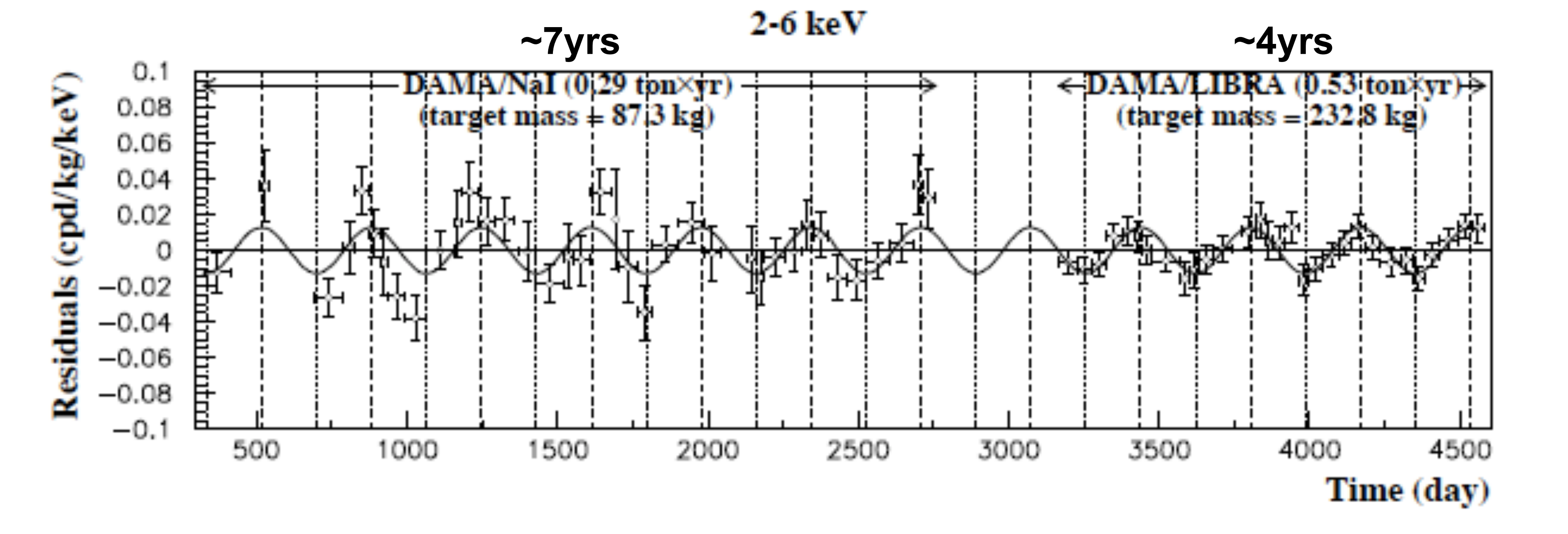
- Gran Sasso in Italy (4000 m w.e.)
- DAMA/NaI in operation since 1996
- NaI(Tl) scintillation crystals – 25 x 9.7 kg ≈ 250 kg; signal detected by two PMTs
- No active electron/gamma bkg determination technique
- Energy > 2 keV
- Exposition – 0.82 tonne·years
- Latest results: May 2008





source: EPJ C56 (2008), 333, arXiv:0804.2741

DAMA – annual signal modulation



$A\cos[\omega(t-t_0)]$: **A = (0.0129±0.0016) counts per day/kg/keV, t_0 = (144 ± 8) day, T = (0.998 ± 0.003) year** @ 8.2 σ CL

Characteristics

- cos(t)
- 1 year period ($T=2\pi/\omega$)
- phase (t_0) – summer/winter
- low energy signal
- single detector hit

„What other physical effect could satisfy all these criteria?"

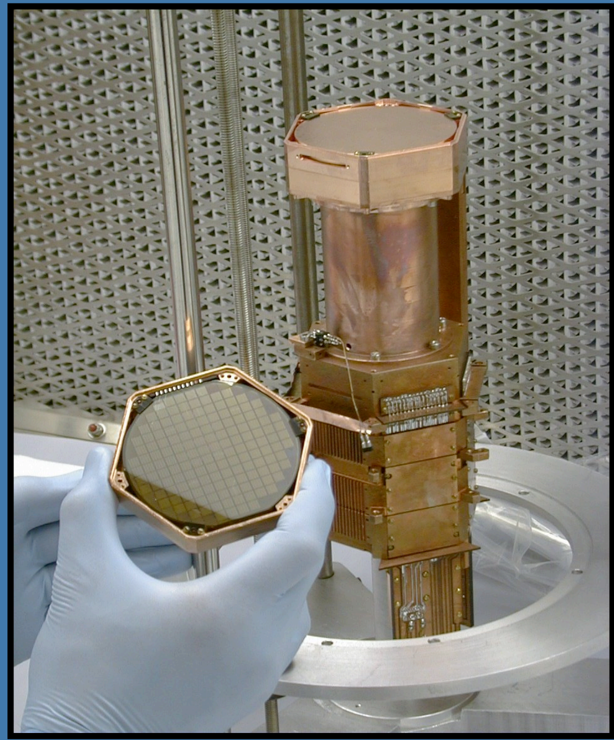
» model independent evidence

» no signal modulation > 6 keV and in „multiple hits events"

CDMS

(Cryogenic Dark Matter Search)

χ scatter on Ge/Si → ionization, phonons

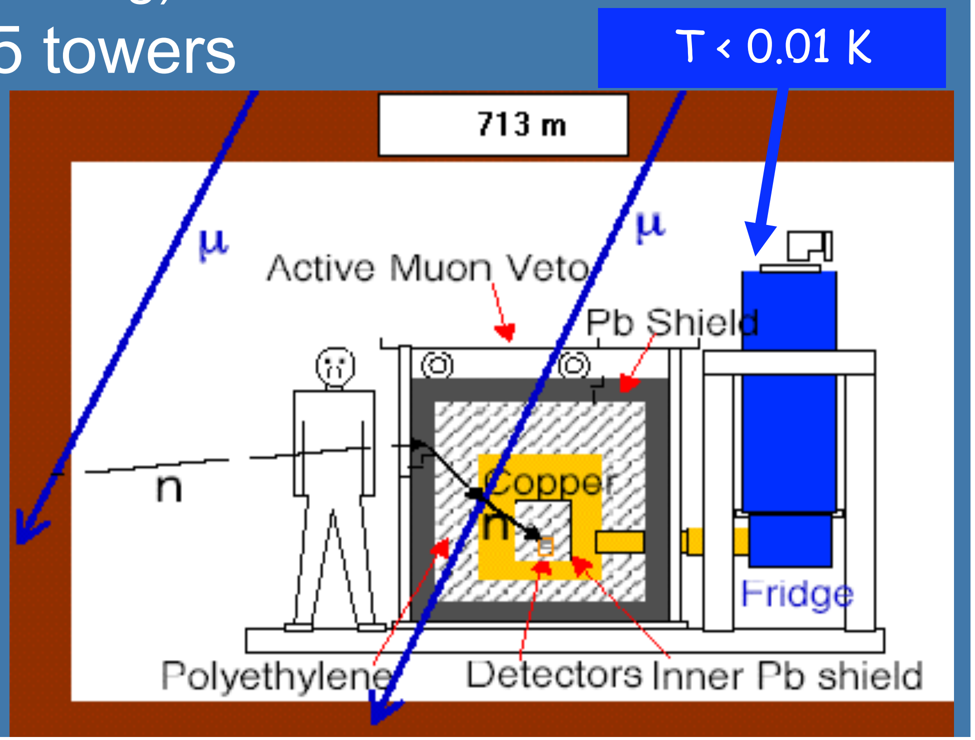


» CDMS II @ Soudan Lab (2004-2009) depth 2090 m w.e.

» 19 Ge (~4.75kg in total) & 11 Si (~1.1kg) particle detectors arranged in 5 towers

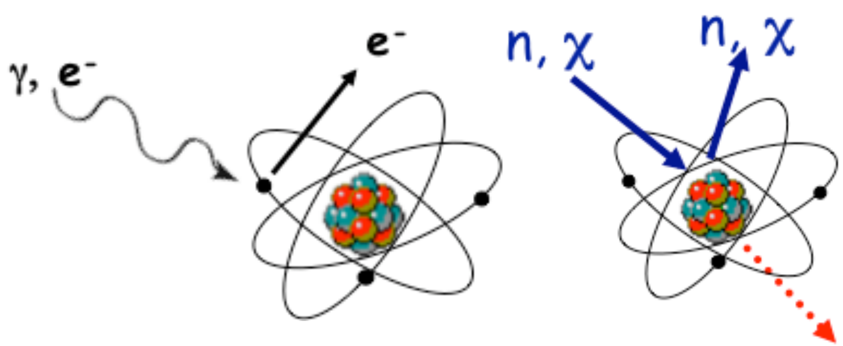
» Two independent signal detection methods: ionization and phonons

- 10-100 keV analysis energy range



CDMS – results (Dec. 2009)

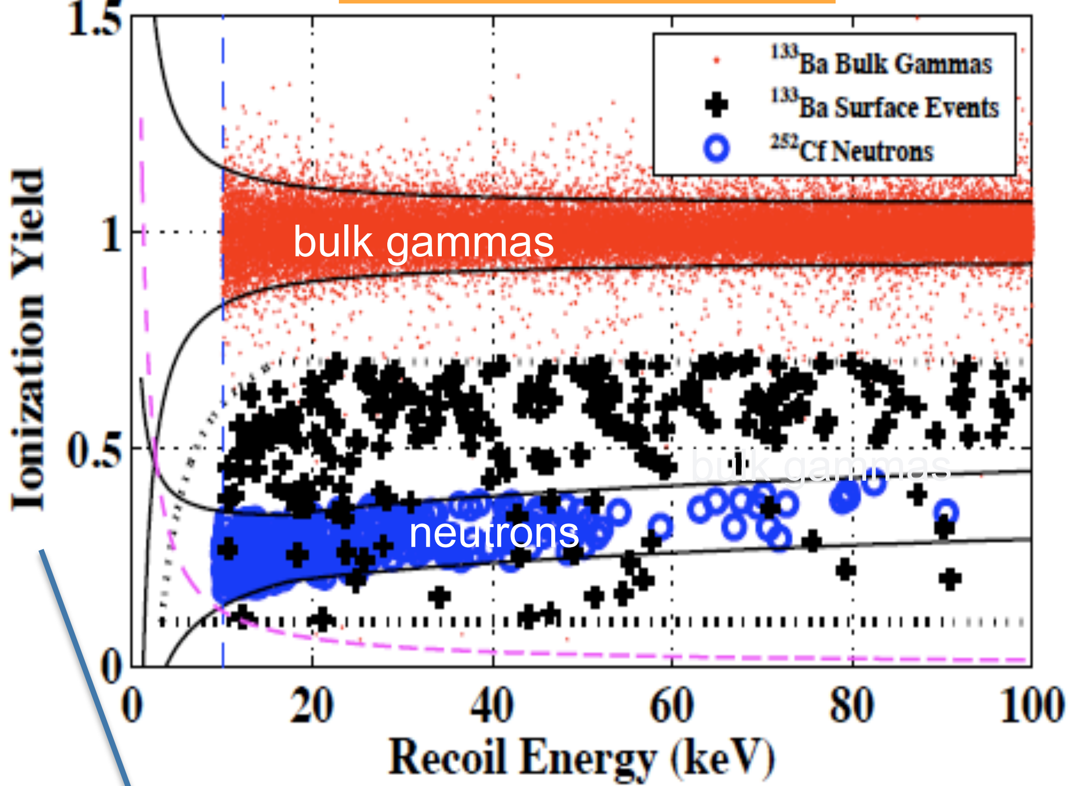
(*) J.Cooley @ SLAC Dec/17/2009 &
(*) Z. Ahmed et al., arXiv.org:0912.3592



- Most backgrounds (e,γ) produce electron recoils
- WIMPs, neutrons, alphas produce nuclear recoils
- "Ionization yield" depends on particle type

- Particles that interact in the „surface dead layer" result in reduced ionization yield (can mimic WIMP signal) -> However could be rejected based on timing of phonon signal

calibration data



„ionization yield" – ratio of energy deposited as ionization to phonons

CDMS – results (Dec. 2009)

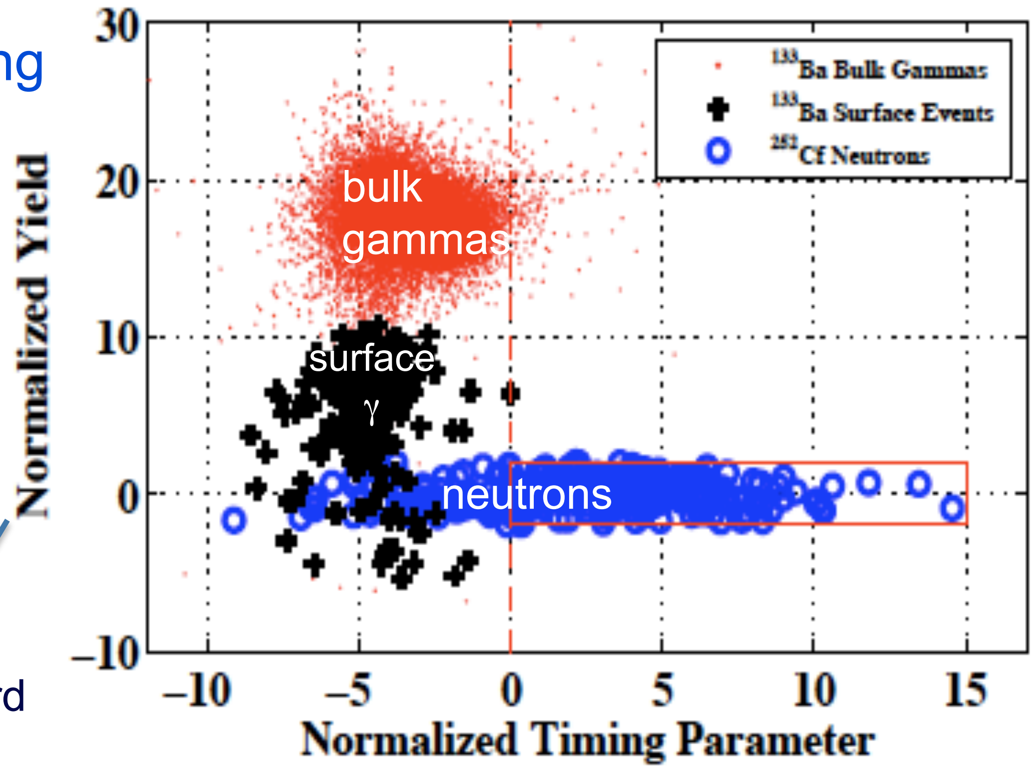
(*) Z. Ahmed et al., arXiv.org:0912.3592 (*) J.Cooley @ SLAC Dec/17/2009

- Gamma events have faster-rising phonon pulses than nuclear recoil events

- Yield + Timing criteria gives 10^{-6} misidentification probab. for electron events to be nuclear recoils

„normalization yield" – number of standard deviations from mean of nuclear recoil band

calibration data



Arbitrary units based on phonon rising time + its delay relative to ionization signal

CDMS – results (Dec. 2009)

(*) J.Cooley @ SLAC Dec/17/2009

(*) Z. Ahmed et al., arXiv.org:0912.3592

„Blind analysis" - estimate bkg, apply cuts,not look at the region where signal is expected... after opening the box:

data (from 2 detectors only)

2 events in signal region

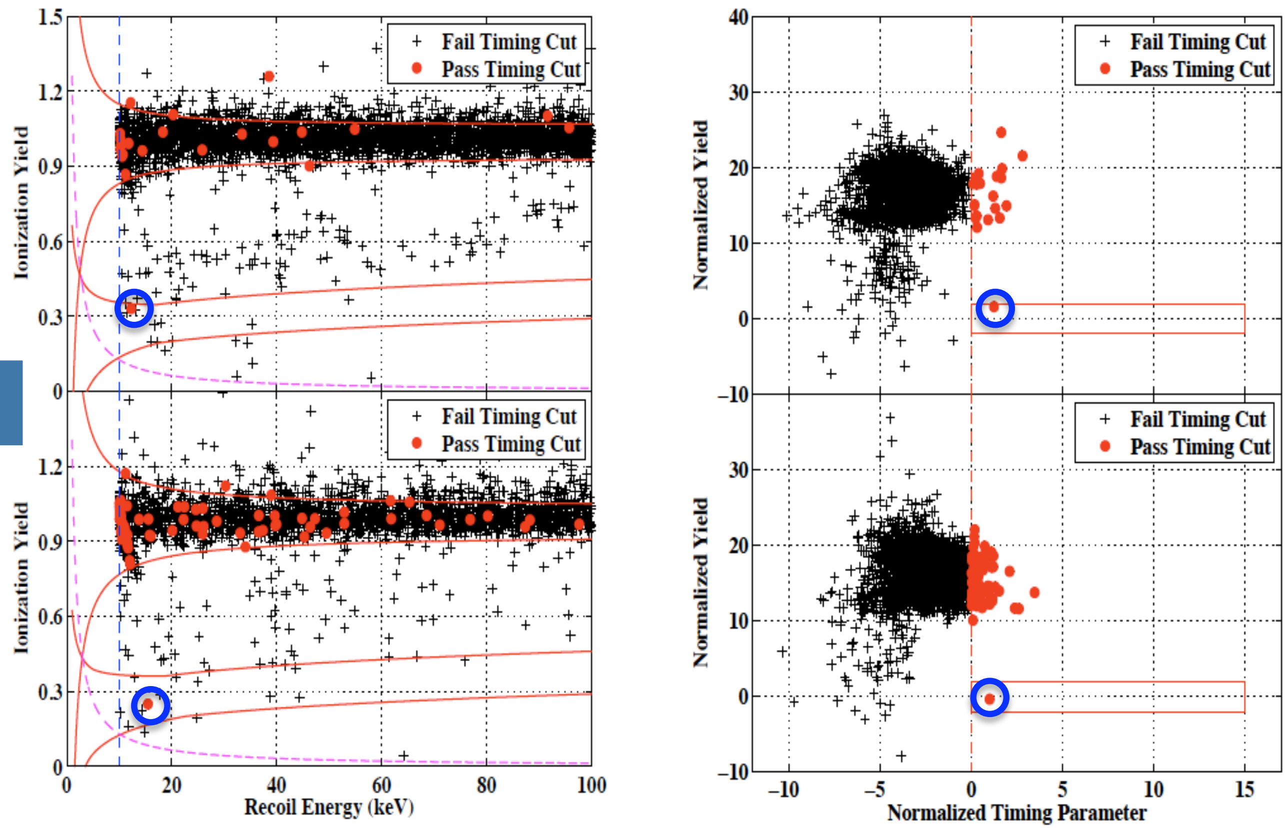
Expected background

- „surface" events:

0.80 ± 0.1(stat) ± 0.2(syst)

- μ-induced neutrons: 0.04 evts

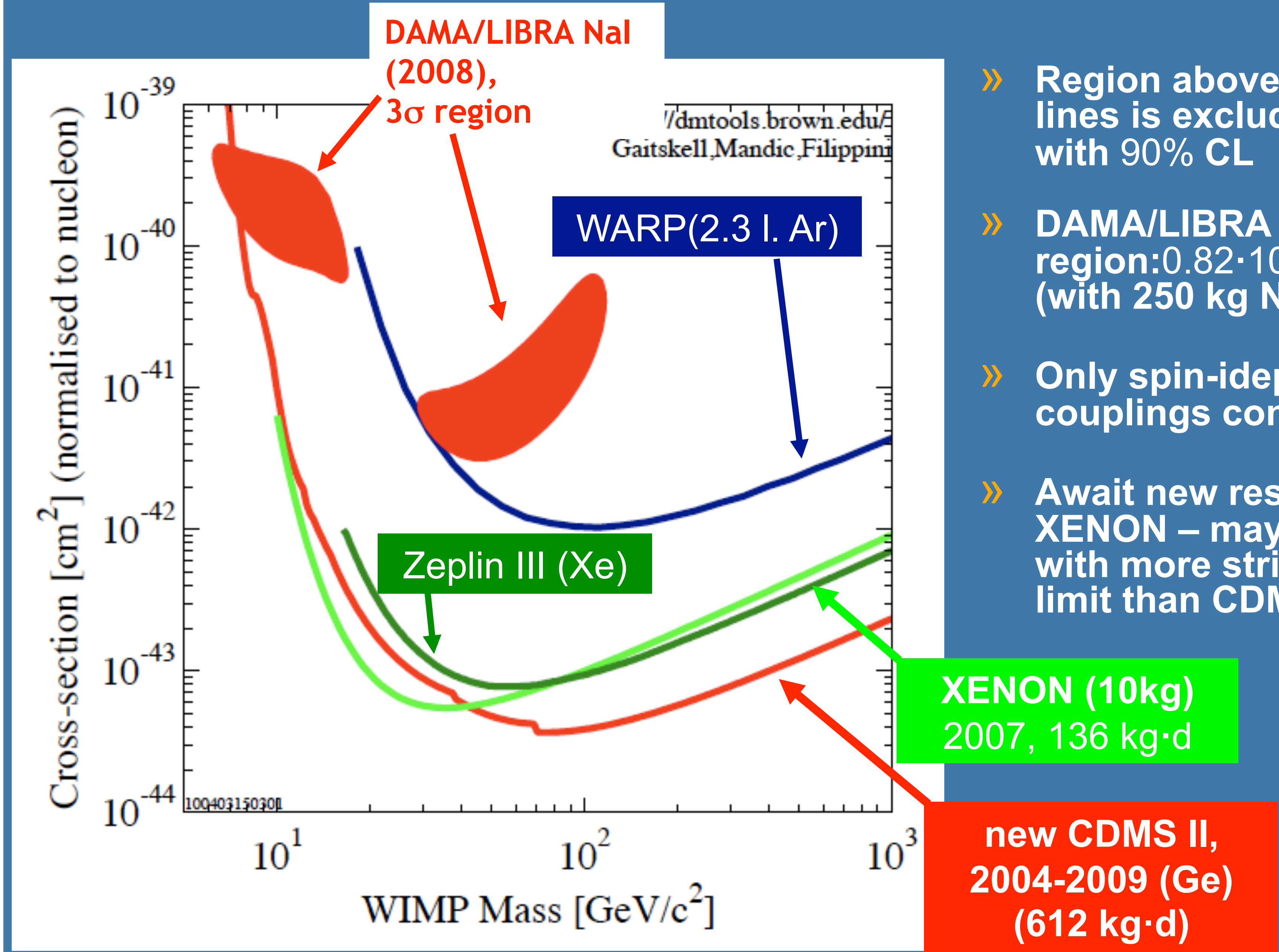
- radioactivity neutrons: 0.03-0.06 evts



Probability of observing 2 or more background events is 23%

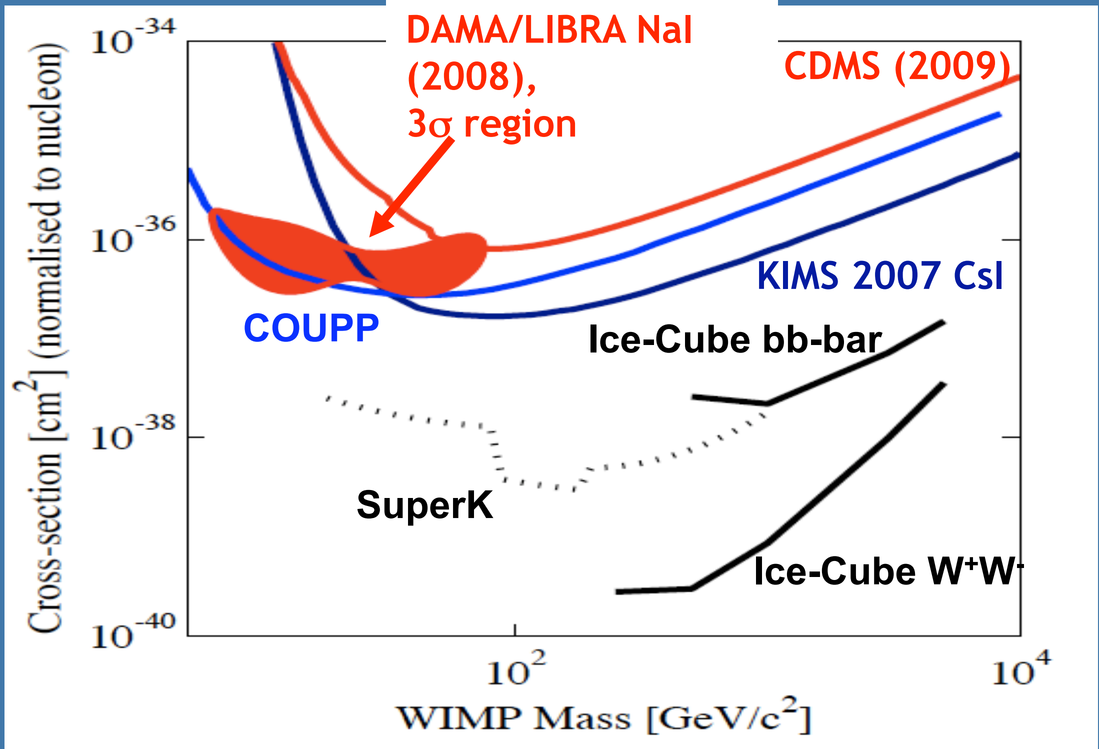
"Our results cannot be interpreted as significant evidence for WIMP interactions. However, we cannot reject either event as signal." (*)

Limits – direct detection (spin-independent)



- Region above lines is excluded with 90% CL
- DAMA/LIBRA allowed region: $0.82 \cdot 10^3$ kg·year (with 250 kg NaI)
- Only spin-idependent couplings constrained
- Await new results from XENON – may come with more stringent limit than CDMS

Limits – direct detection (spin-dependent)

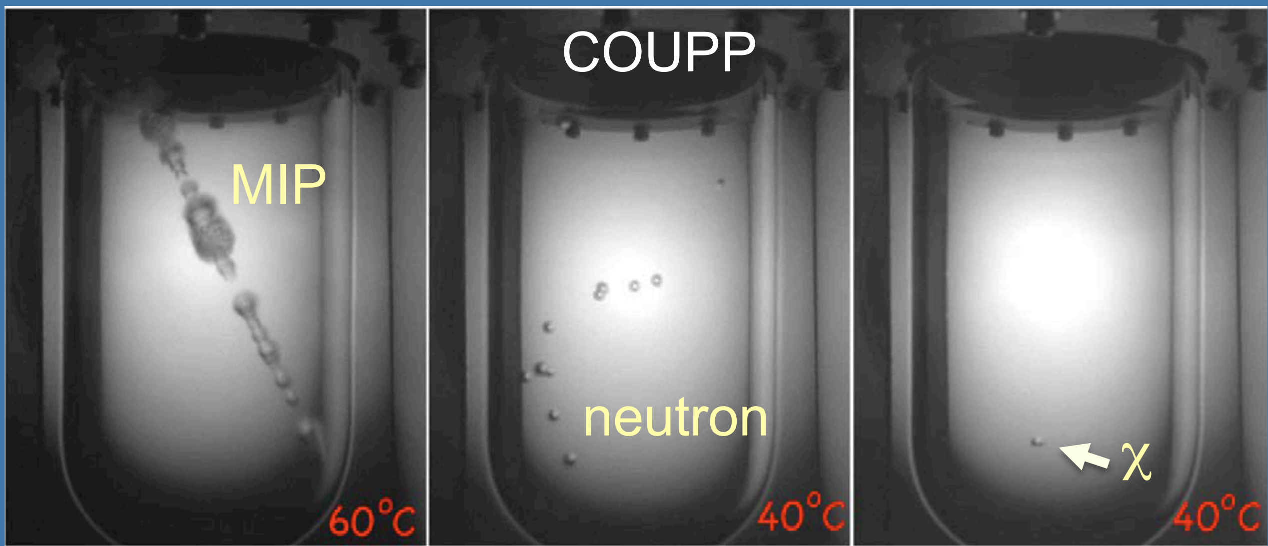


- DAMA/LIBRA results excluded also in SD phase space region
- Low energy region constrained by COUPP

COUPP

Chicagoland Observatory for Underground Particle Physics

- CF_3I 1.5 kg bubble chamber
- 250 kg•days exposure @ NuMI tunnel in FERMILab



- At moderate temp. & pressure chamber is sensitive only to high dE/dx radiation such as nuclear recoils
- 10^{-10} discrimination power against gamma/ electron events
- neutrons – may scatter (several/few bubbles)
- WIMPs – single bubbles

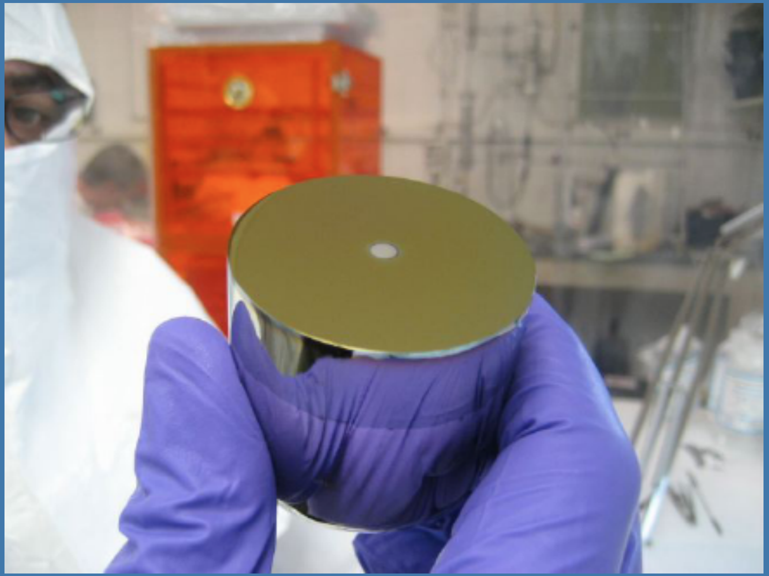
CoGeNT

(Coherent Germanium Neutrino Technology)

χ scatter on Ge → ionization

results published 25 Feb. 2010

- One 440g Ge detector; low noise technology = low energy treshold 0.4 keV electron equivalent
- Measures ionization energy; cannot distinguish e/γ from nuclear recoils
- Applications: neutrino elastic scattering (anti-ν from reactors), $\beta\beta$ decay, DM search
- Soudan Lab, ~20m from CDMS
- Setup with neutron/gamma shieldings and muon veto
- Data: Dec. 2009, 56 days (first trial run@Soudan)



- Prospects:
  Majorana detector 60 kg

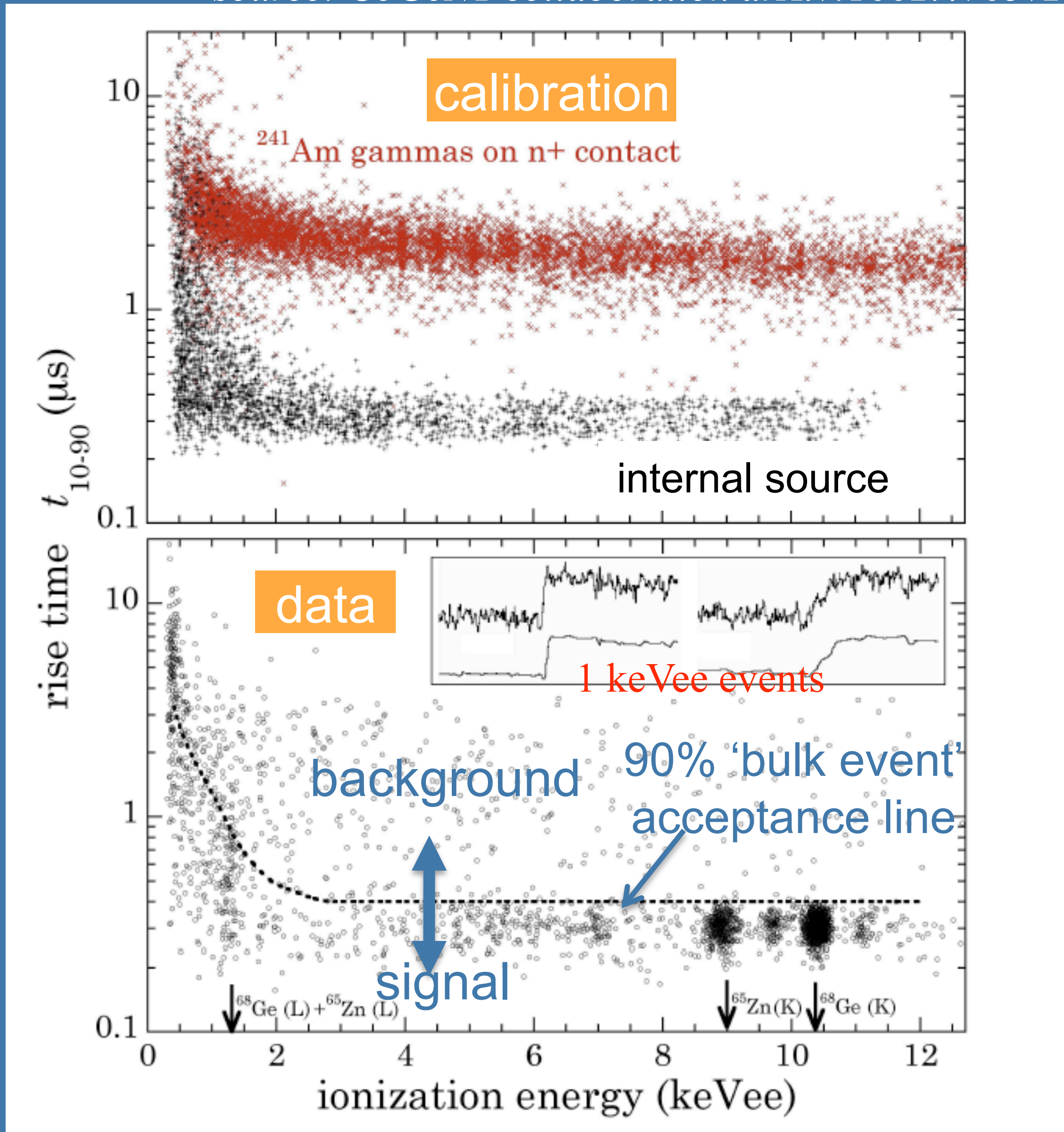
CoGeNT – results (Feb 2010)

source: CoGeNT collaboration arXiv:1002.4703v2

- Detector cannot distinguish e/γ events from nuclear recoils
- 'surface' – 'bulk' event rejection due to signal rise time in preamplifier
- Ge activation by CR neutrons/protons → unstable intrinsic isotopes, delayed decay emmiting X-ray

keVee = keV electron equivalent

1 keVee = 1 keV recoil x quenching factor



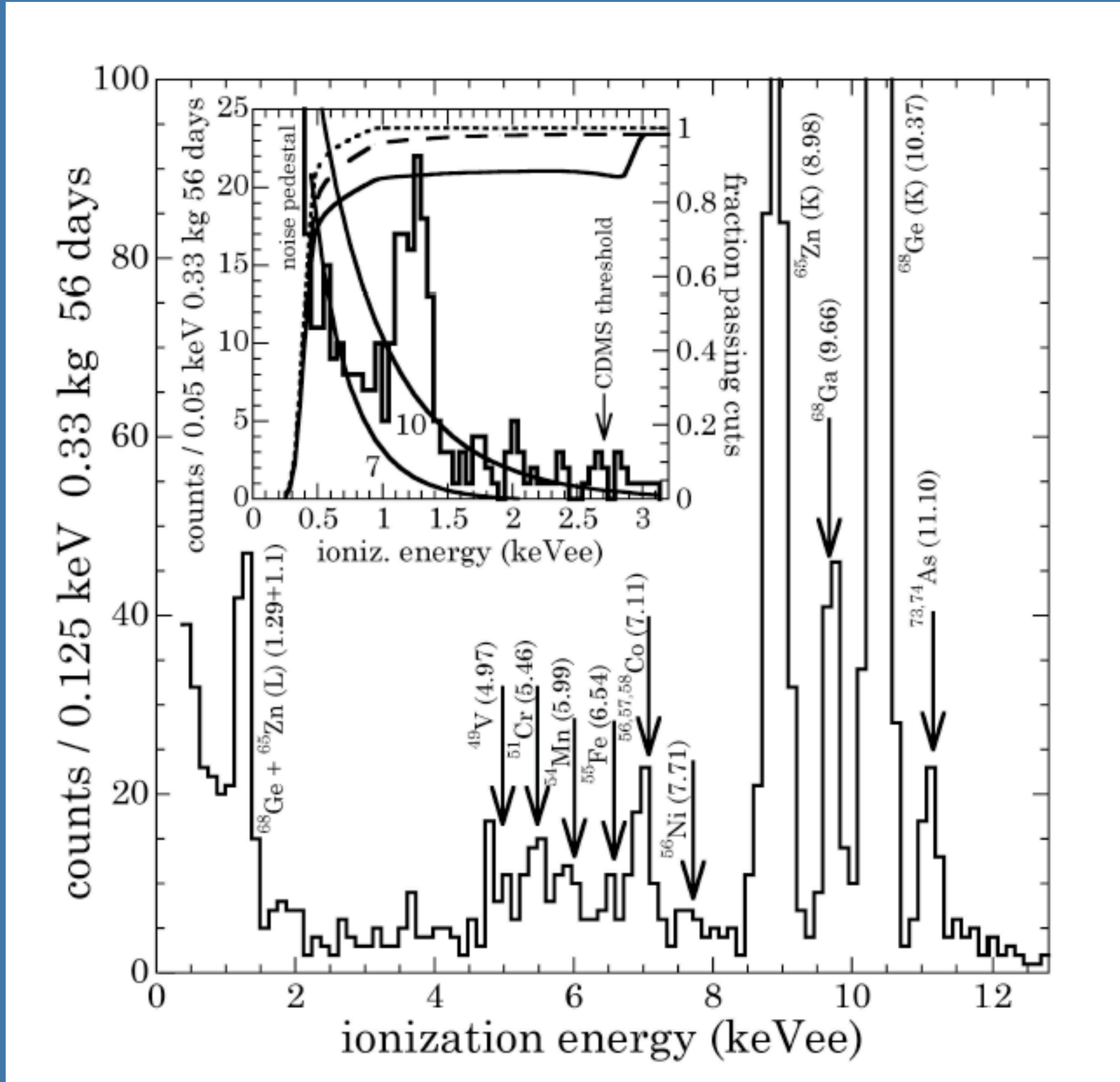
CoGeNT – results (Feb 2010)

source: CoGeNT collaboration arXiv:1002.4703v2

» All cosmogenic peaks due to Ge crystal activation identified

» Exponential event excess in 0.4-3.2 keVee range. Claim that not due to noise, external or internal radioactive bkg or semiconductor physics

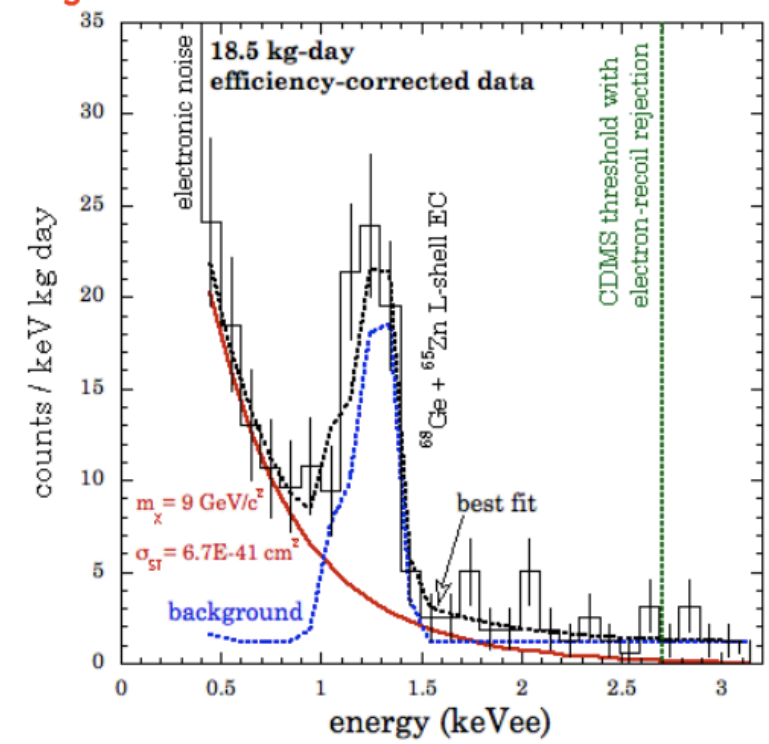
» FIT:
- Background: expo + constant + 2 Guassians to account for ^{65}Zn, ^{68}Ge peak
- WIMP signal: expo with shape defined by χ mass & normalization prop. to SI cross-section



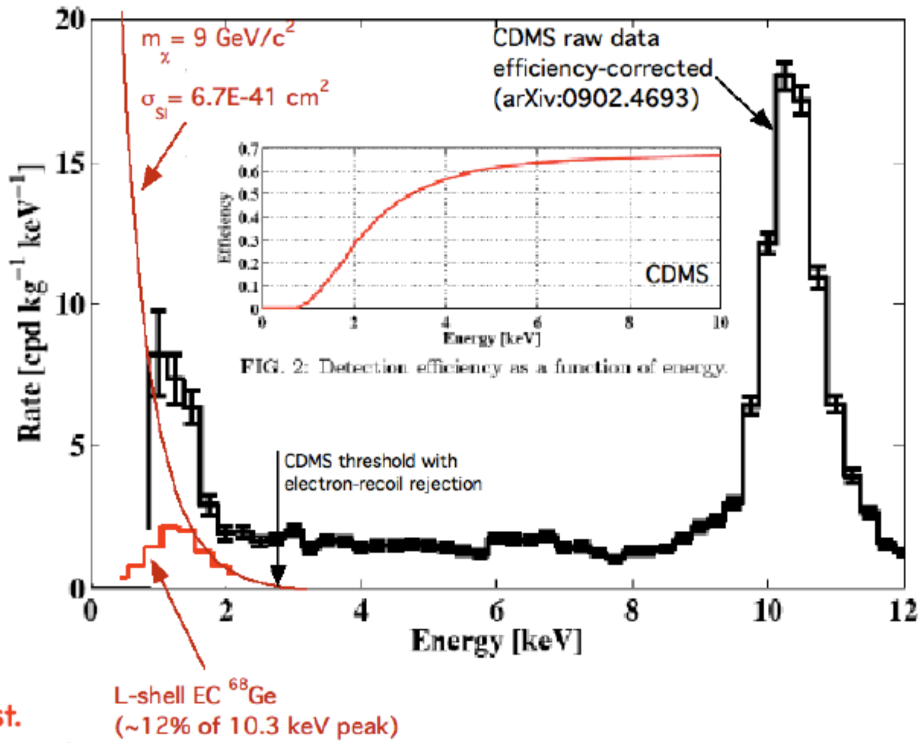
FIT results

- no WIMPs, only BKG: $\chi^2/dof = 20.4/20\ (=1.02)$
- m_χ=9GeV, σ_{SI}= 6.7×10^{-41}cm^{-2}+BKG: $\chi^2/dof = 20.1/18\ (=1.12)$

An example WIMP mass in the region:



Where is CDMS in all this?



Quotable: The excess of irreducible bulk-like events in CoGeNT is compatible with the WIMP hypothesis in a region where CDMS, DAMA and (several) phenomenological models (good thermal relics) can coexist. It is also equally compatible with any exponential background.

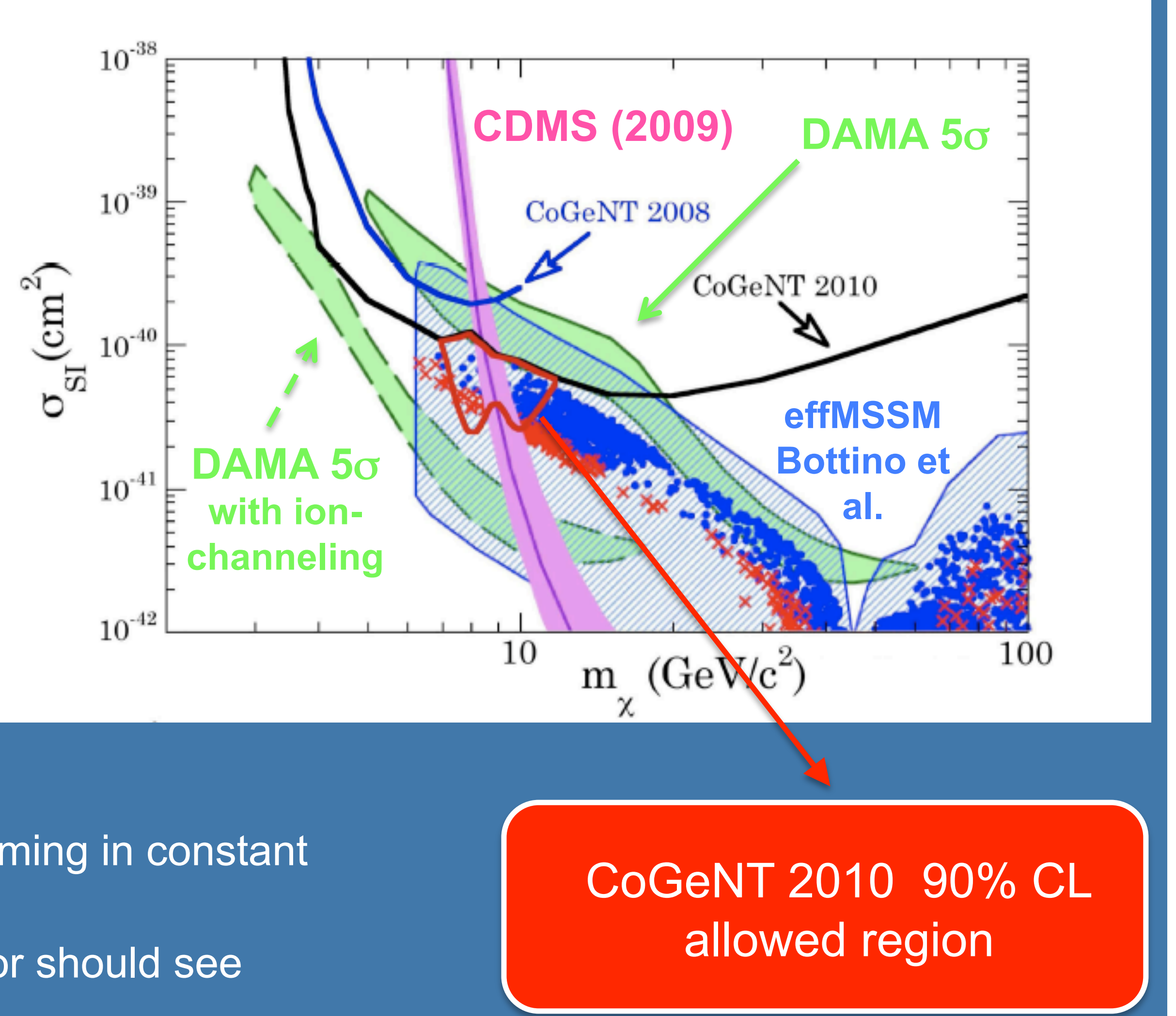
source: J.Collar @ UCLA DM 2010, Feb/26

CoGeNT – results (Feb 2010)

source: CoGeNT collaboration arXiv:1002.4703v2

» CoGeNT claim

- m_χ ~7-11 GeV WIMP fits the data nicely
- compatible with CDMS 2 evts, also with DAMA region
- excess not due to neutrons (MC simulation)
- no evidence of detector contamination
- very different from electronic noise (?)



» If genuine:

- already see >70 DM events coming in constant rate
- MAJORANA 60kg demonstrator should see annual modulation

Direct detection – summary

DAMA – annual modulation signal, positive signal not confirmed by other experiments

Spin Independent

DAMA region excluded with 3σ CL by other exp. for Mχ > ~10GeV

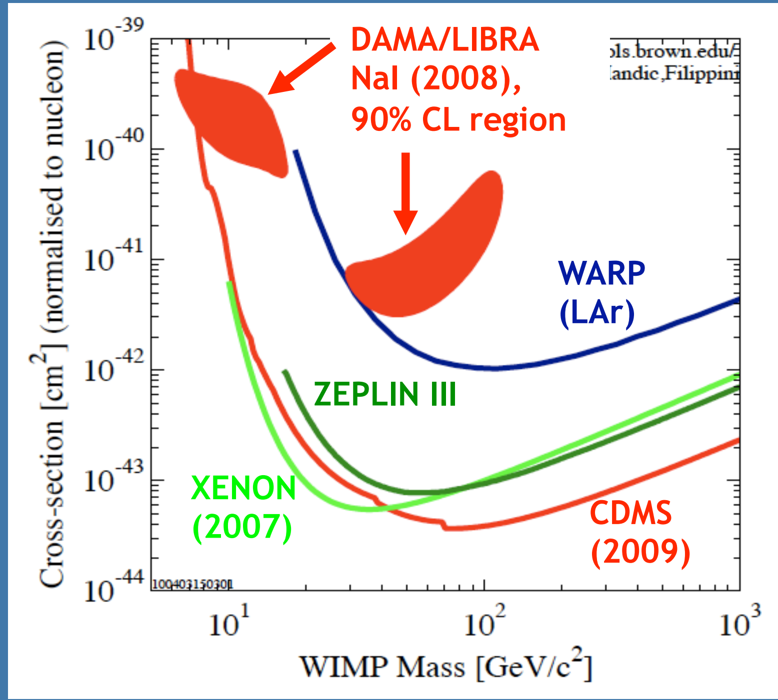
Spin Dependent

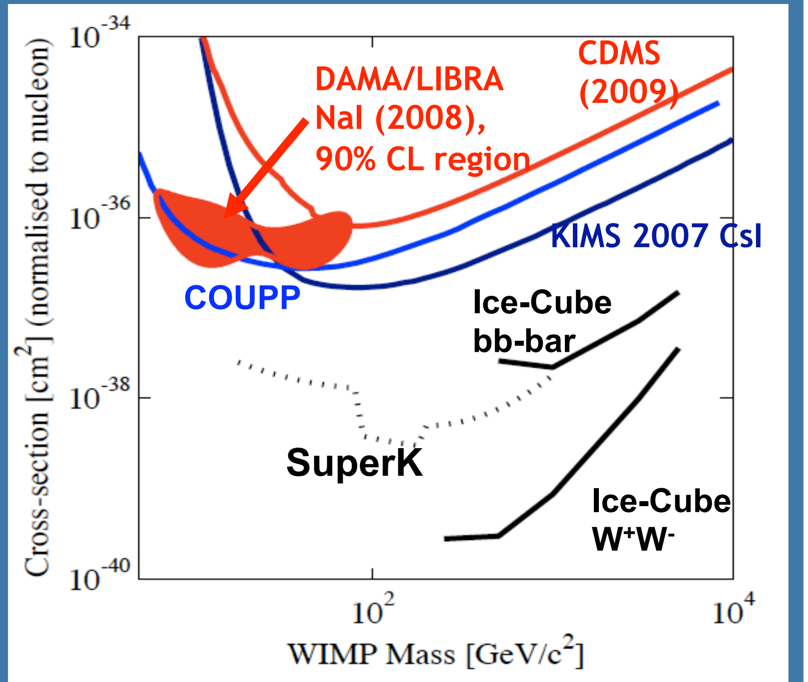
DAMA region excluded for Mχ > ~10 GeV (strong constrains from Indirect searches)

DAMA region for Mχ < ~10 GeV constrained partially by COUPP

CDMS-II – 2 events in signal region, not statistically significant for discovery
→ the most stringent SI limit

CoGeNT – exploring low WIMP mass range in SI, signal not convincing





Wyniki – detekcja pośrednia

DM self-annihilation cross section

$< \sigma_a v >$ - cross section averaged over the relative velocity distribution

» Sets the obs. DM mass density

$\Omega_M = 0.27 \pm 0.02$ *WMAP*

-> *in thermal relic scenarios:*

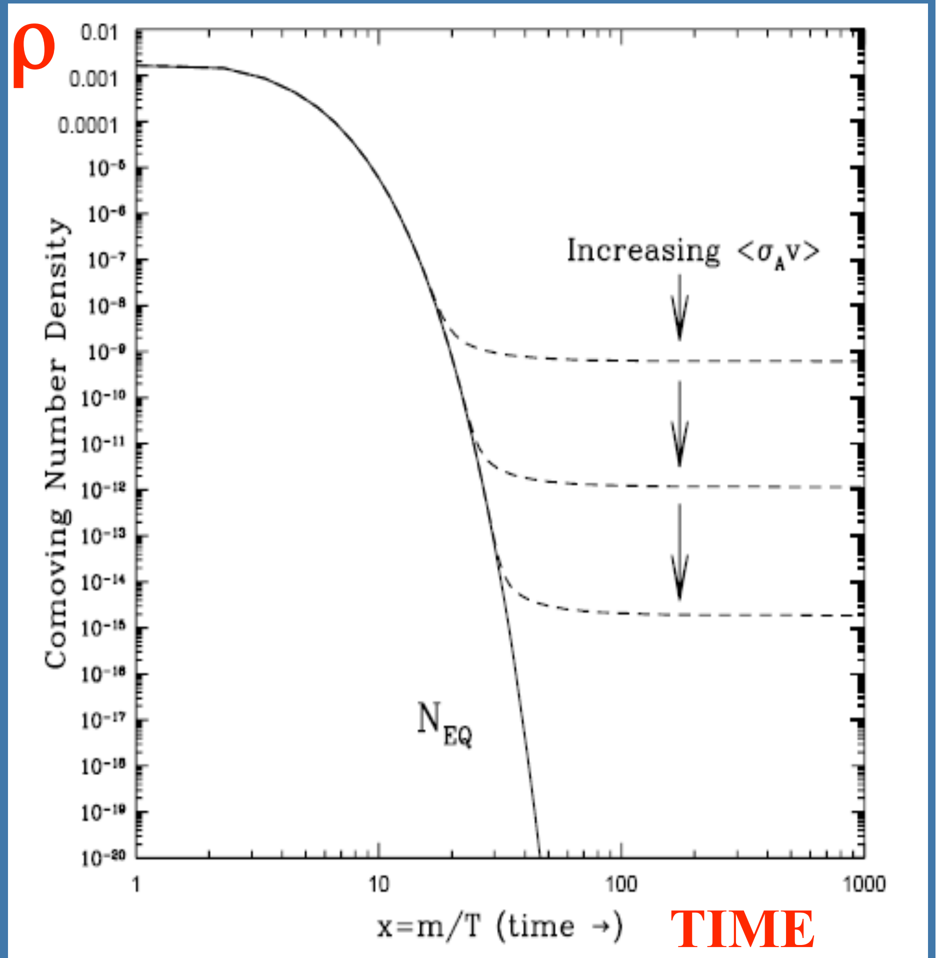
$\langle \sigma_a V \rangle$ ~ 3 x 10^{-26} cm^3/s

» Sets the annihilation rate in DM halos

$$\Gamma_A \propto \langle \sigma_a V \rangle \frac{\rho_\chi^2}{m_\chi^2}$$

Numerical density squared

„freeze out" of the relic particle

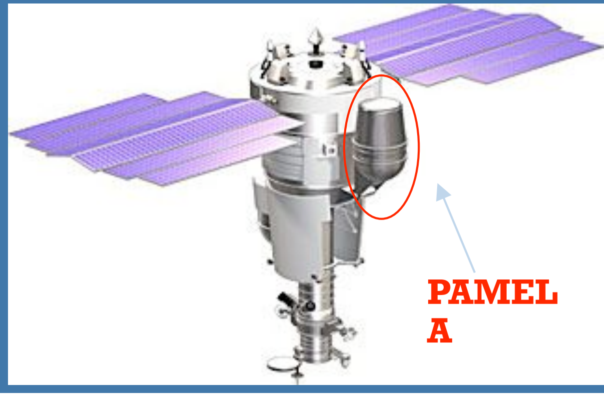


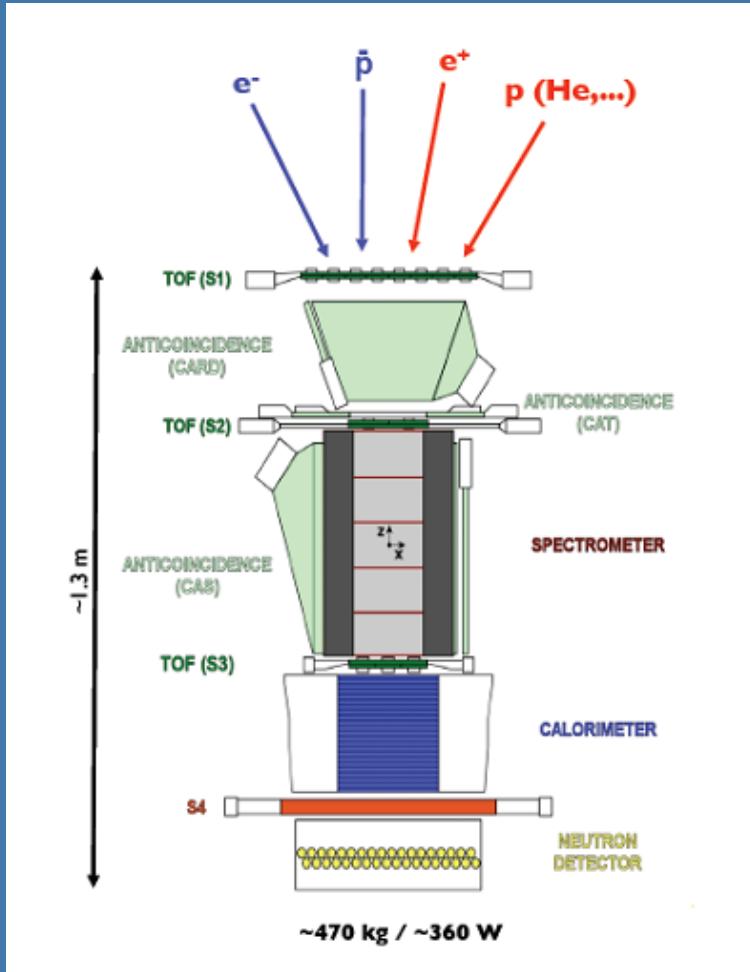
PAMELA

a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

» PAMELA is mounted on satellite Resurs-DK1, inside a pressurized container
» launched June 2006
» minimum lifetime 3 years
» Detector: spectrometer (B-field, dE/dx), calorimeter, neutron detector

» Simultaneous measurement of many cosmic-ray species
» New energy range (e.g. contemporary antiproton & positron maximum energy ~ 40 GeV)
» Unprecedented statistics

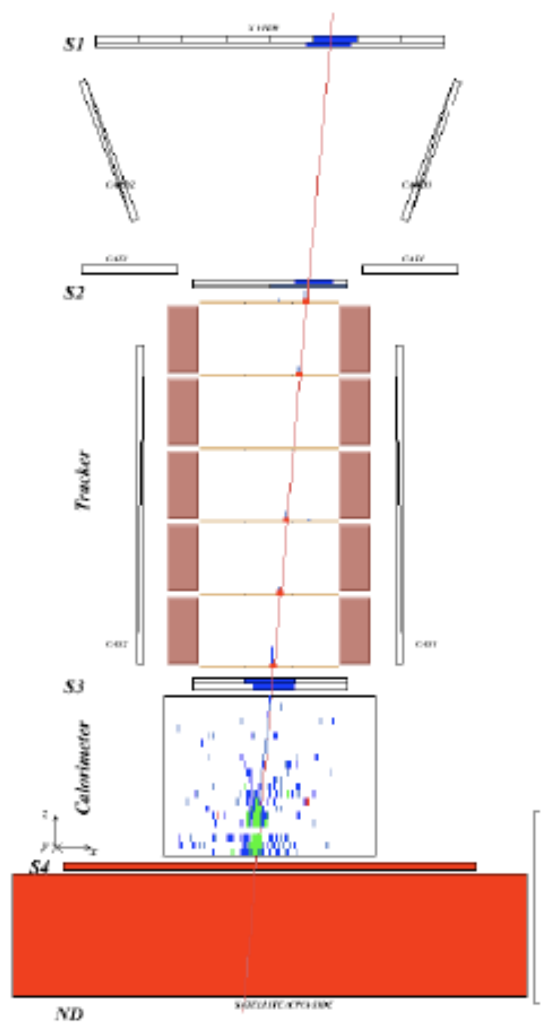




- Antiprotons: **80 MeV ÷190 GeV**
- Positrons: **50 MeV ÷ 300GeV**
- Electrons: **up to 400 GeV**
- Protons: **up to 700 GeV**
- Electrons+positrons: **up to 2 TeV**(from alorimeter)

PAMELA – antiproton/positron identification

- Positron measurement could be a tricky bussiness,
- ... especially that expected p/e^+=10^3-10^4

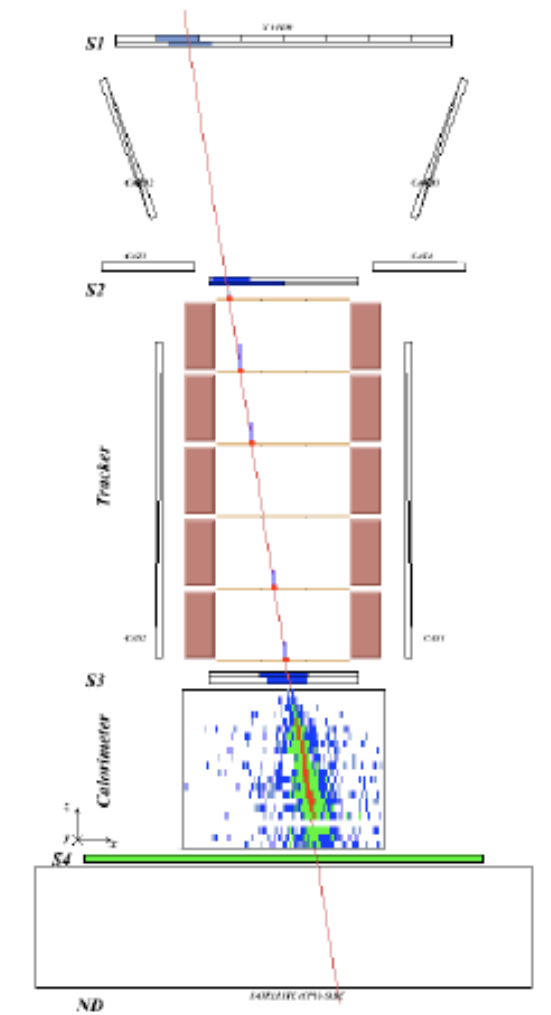


Antiproton

Bending in spectrometer: sign of charge

Ionisation energy loss (dE/dx): magnitude of charge

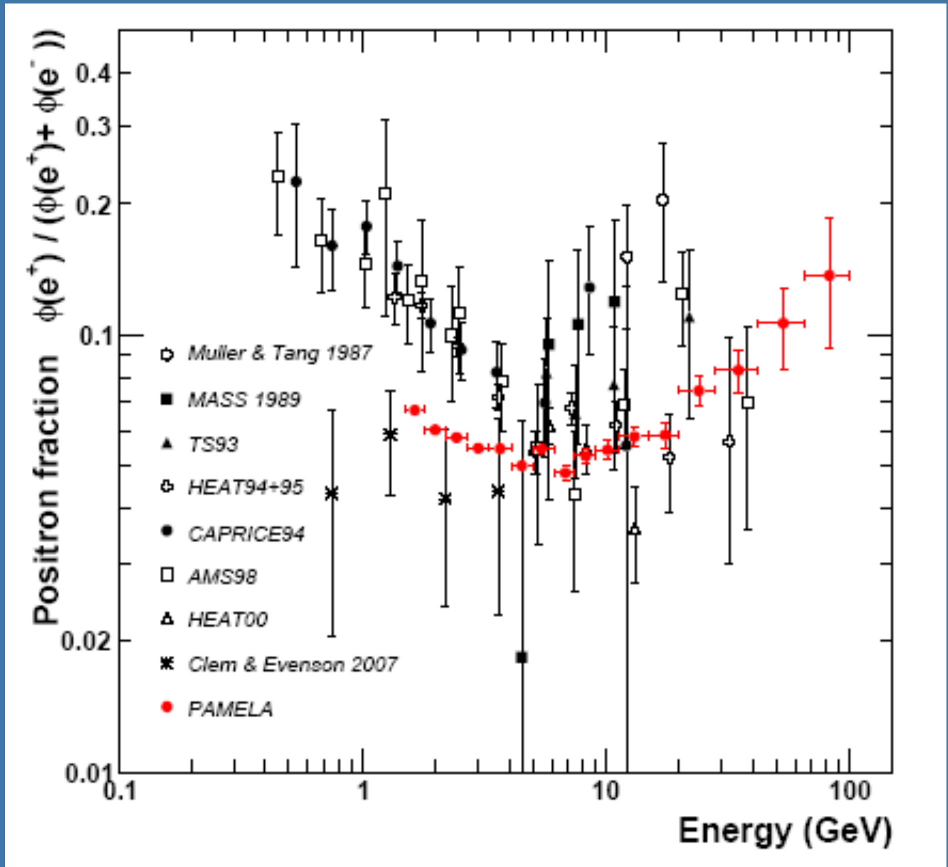
Interaction pattern in calorimeter: electron-like or proton-like, electron energy

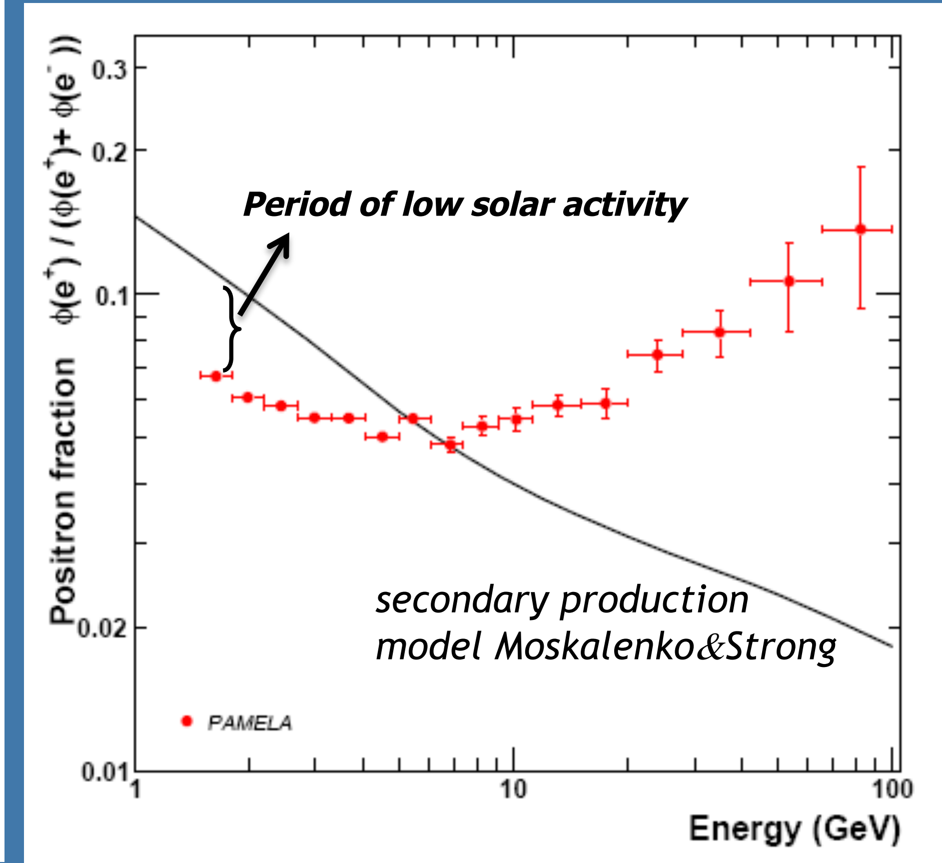


Positron

PAMELA results (positrons)

O.Adriani et al. [PAMELA Collaboration], Nature, 458,607-609(2009)





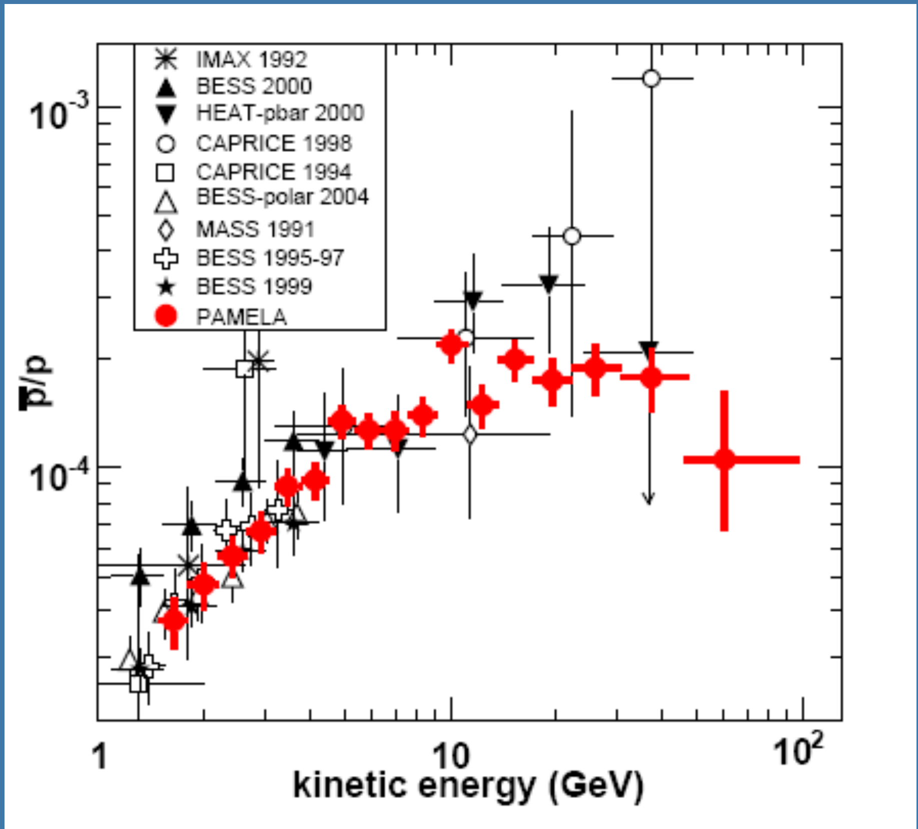
positrons from secondary production

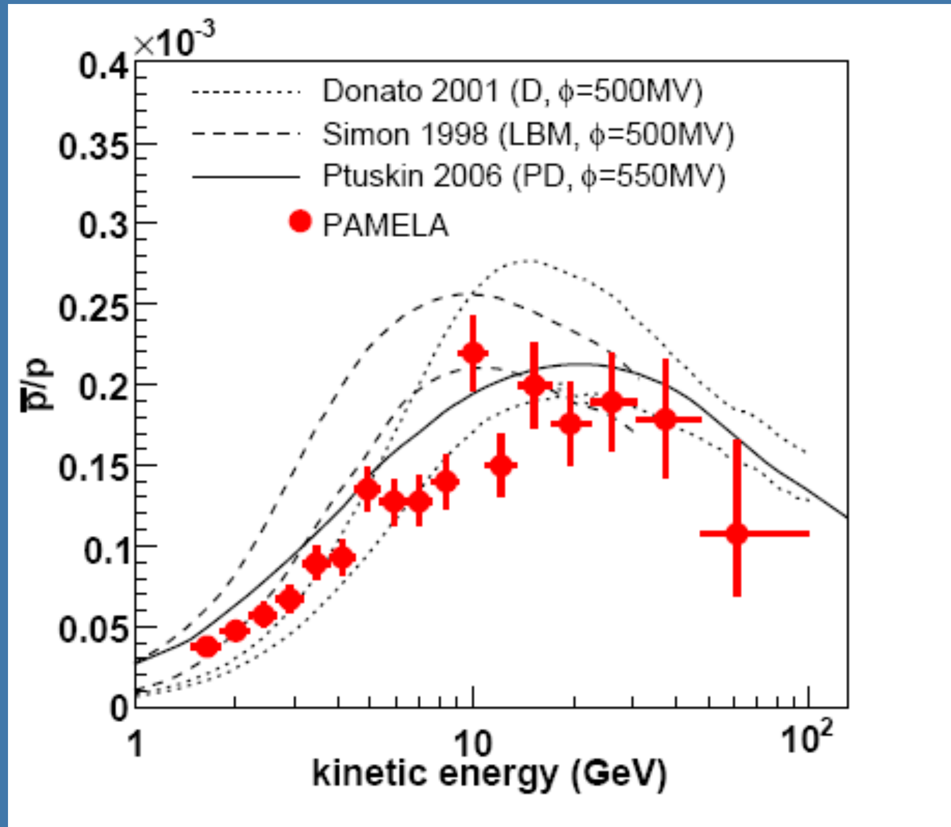
$$\mathrm{CR} + \mathrm{ISM} \rightarrow \pi^{\pm} + \ldots \rightarrow \mu^{\pm} + \ldots \rightarrow e^{\pm} + \ldots$$
$$\mathrm{CR} + \mathrm{ISM} \rightarrow \pi^{0} + \ldots \rightarrow \gamma\gamma \rightarrow e^{\pm}$$

» Cosmic-ray positrons are a sensitive probe of the local astrophysical environment (few kpc) → energy loose due to Inverse Compton and Synchrotron Radiation

PAMELA results (antiprotons)

(*) O.Adriani et al. [PAMELA Collaboration], arXiv.0810.4994(Oct 2008)



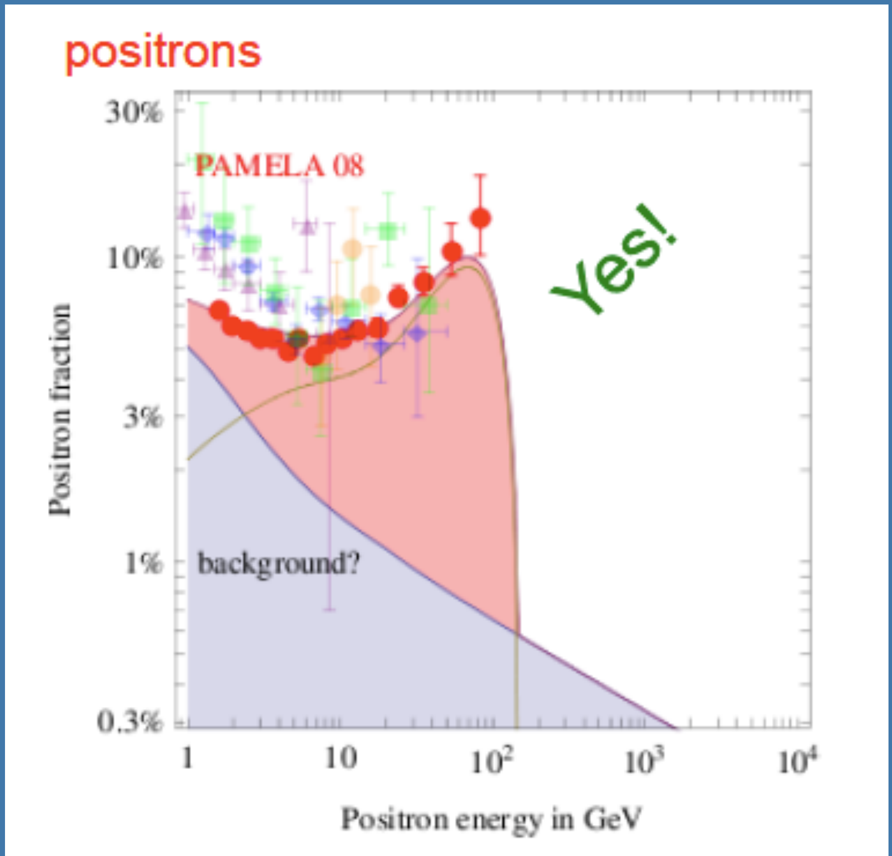


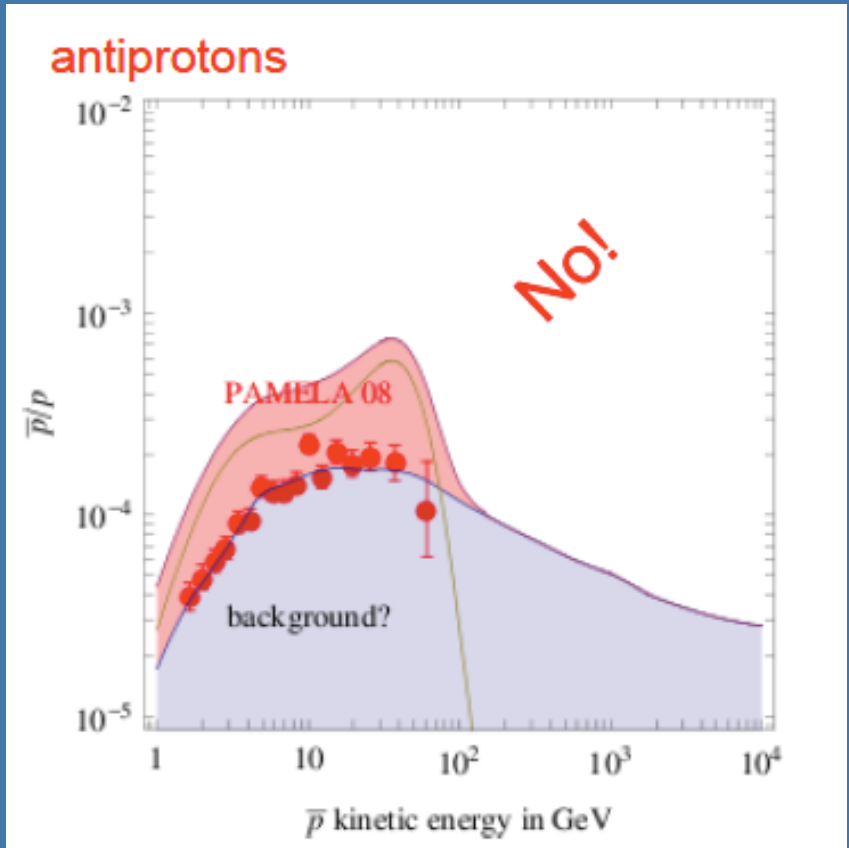
- Agreement with other experiments and „secondary" production models
- If DM ann. is responsible for positron excess -> observed antiproton flux should be also higher: 5-10 times for 1 TeV neutralino ann. to W^+W^-!!! (assuming typical thermal relic DM smoothly distributed in our Galaxy – NFW model)

M.Cirelli et al., Nucl. Phys. B 813 (2009) 1; arXiv: 0809.2409v3

PAMELA results fit with annihilating DM

DM with m_χ = *150* GeV and W^+W^- dominant annihilation channel

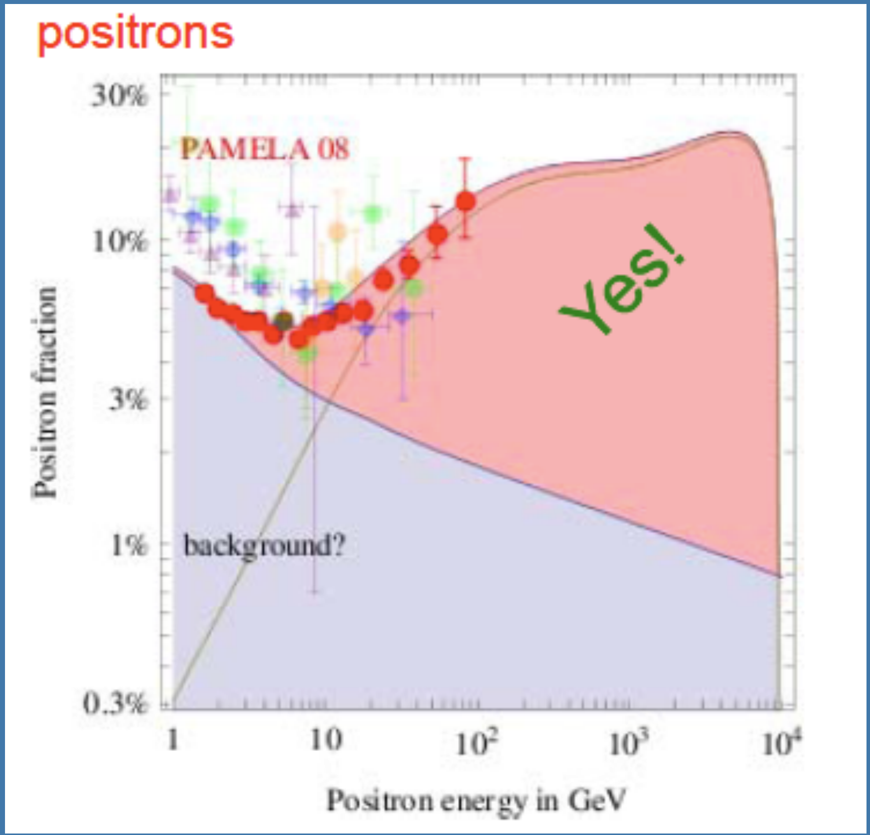


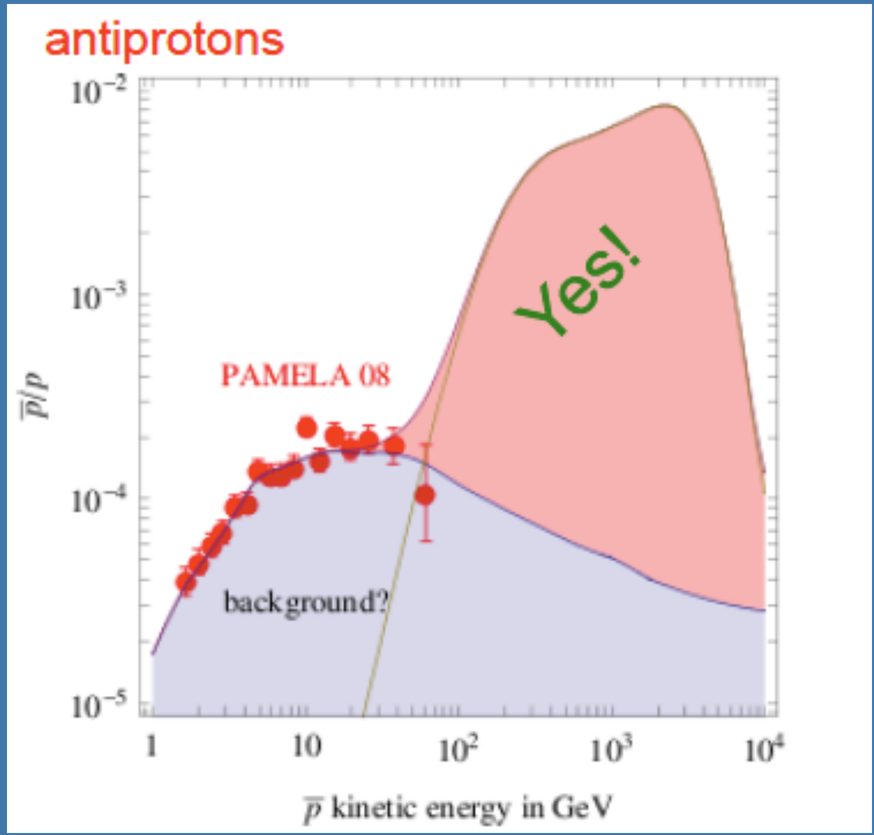


M.Cirelli et al., Nucl. Phys. B 813 (2009) 1; arXiv: 0809.2409v3

PAMELA results fit with annihilating DM

DM with m_χ = *10* TeV and W^+W^- dominant annihilation channel: unnaturally high mass for most SUSY models

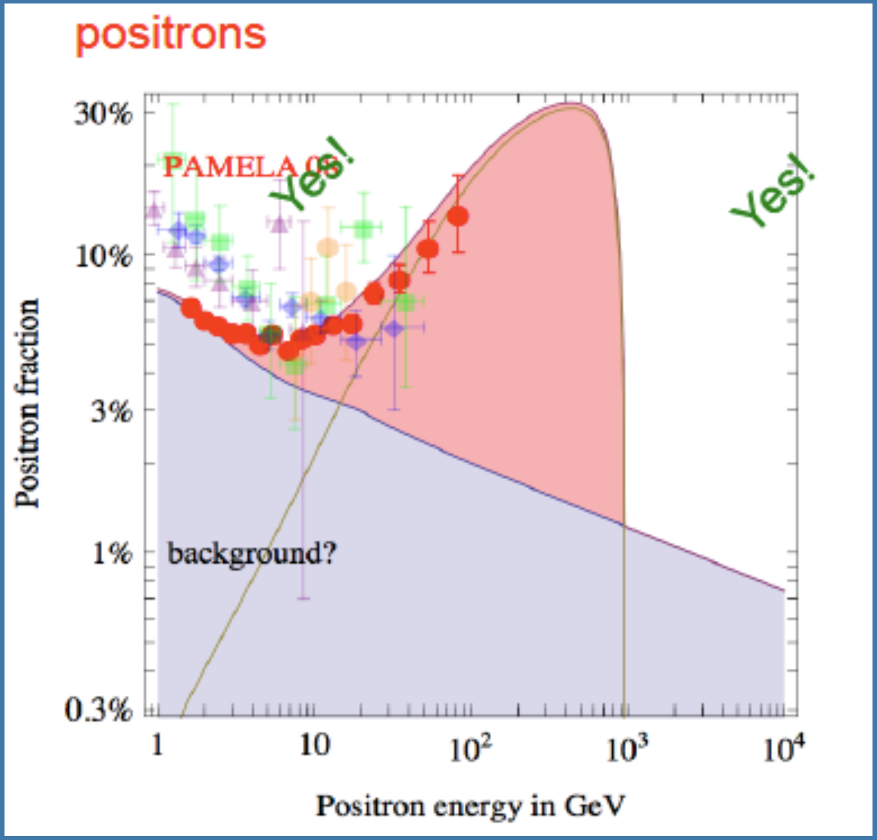


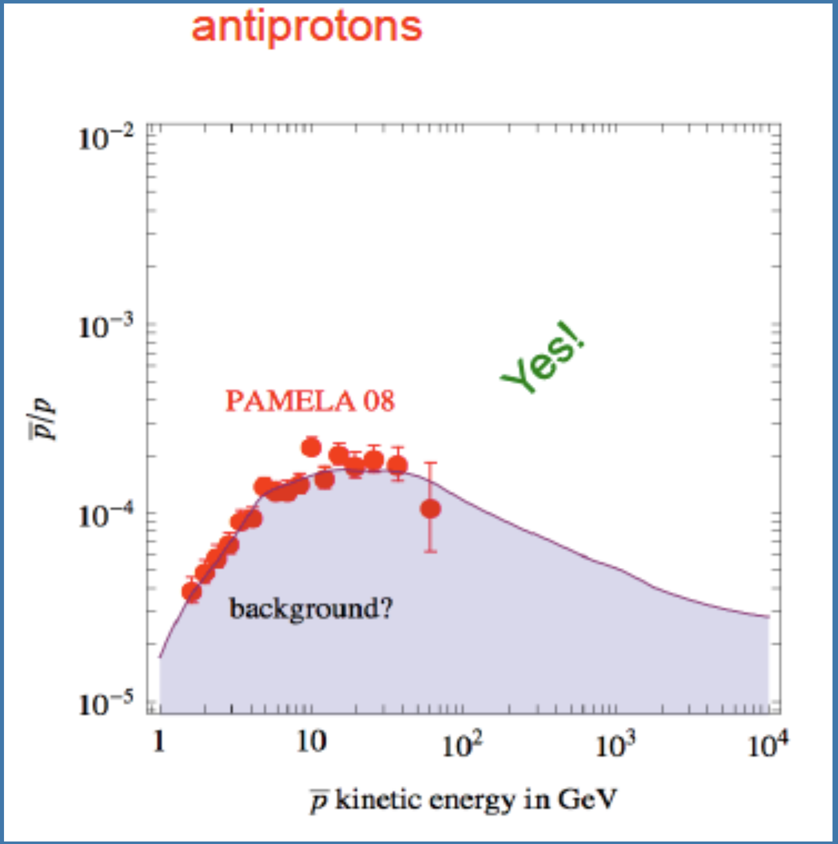


M.Cirelli *et al.*, Nucl. Phys. B 813 (2009) 1; arXiv: 0809.2409v3

PAMELA results fit with annihilating DM

DM with $m_\chi = 1$ TeV and $\mu^+\mu^-$ dominant annihilation channel

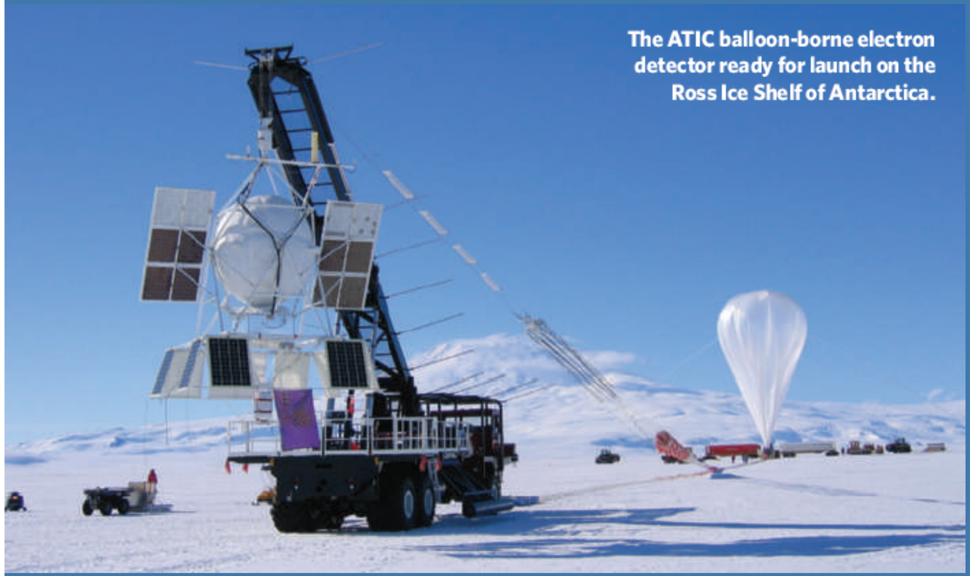




ATIC

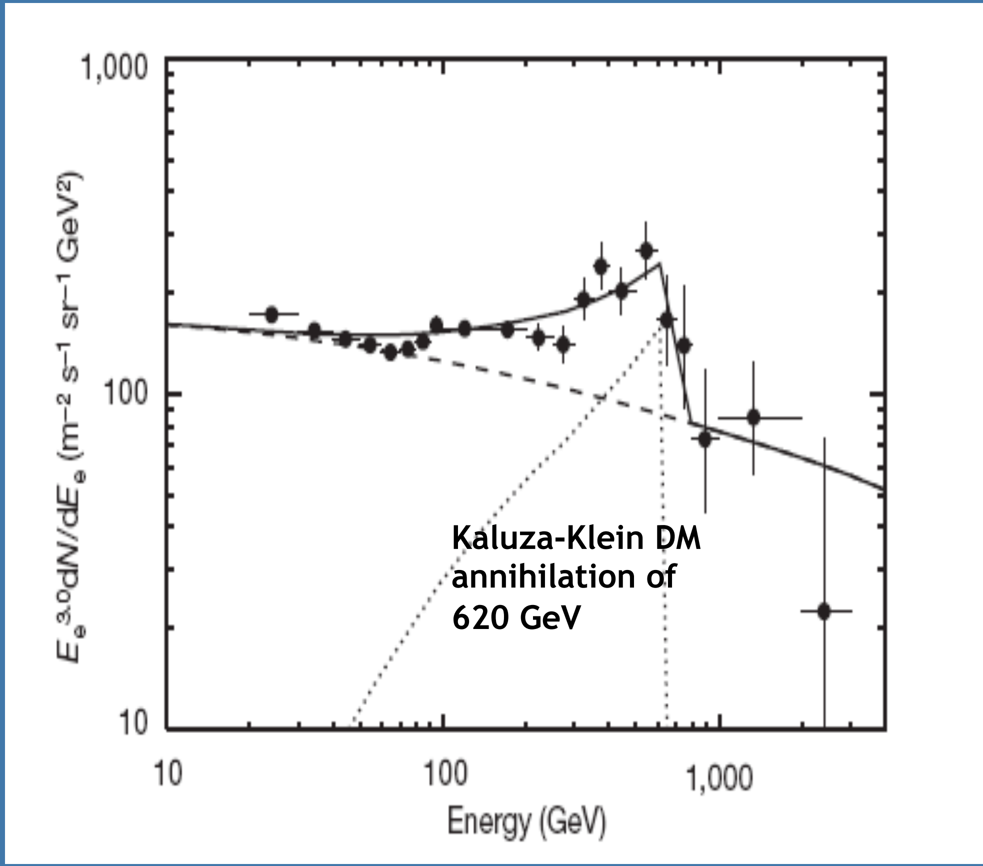
Advanced Thin Ionization Calorimeter

- Baloon born experiment for C.R. measurement
- Operated from McMurdo, Antarctica
- ATIC-1 15 days (2000/2001)
- ATIC-2 17 days (2002/2003)
- flights @ 36km



ATIC: $e^{+}+e^{-}$ flux in cosmic rays

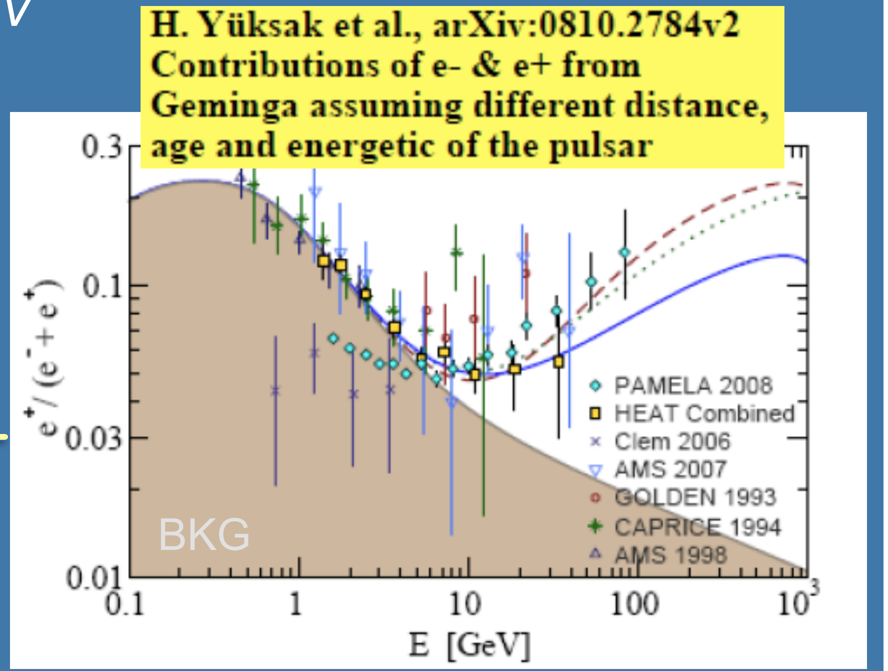
J. Chang, et al. [ATIC Collaboration], Nature, 456, 362-365 (2008)



PAMELA & ATIC positron excess – discussion

- *PAMELA excess of HE positrons > 10GeV (p-bar flux agrees with expectation)*
- *ATIC excess of e^+ + e^- at about 300-600 GeV*

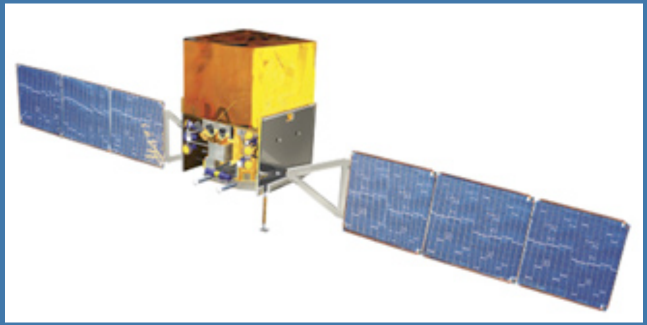
If genuine, possible explanations:



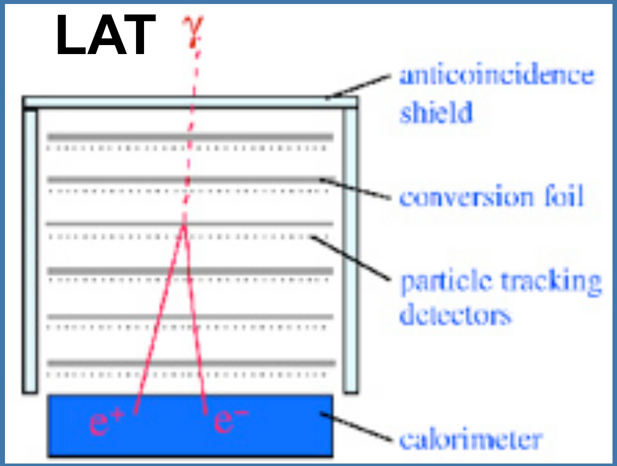
- Insufficient BKG estimation model
- Nearby pulsar ...
  - good explanation
  - could be a source of e+e- pairs ... their escape probability not clear
- DM annihilation ... some problems:
  - Hard energy spectrum (with a cut off) observed by ATIC → then χ should mostly ann. to charged leptons (unlikely in most SUSY models)
  - Also should be overproduction in p-bar and γ's
  - High ann. rate required -> 'boost factor' of 10^2-10^3 ... could be related to DM clumps in local halo ρ or enhanced annihilation cross section $<\sigma V>$

DM origin of positron excess seems weak

- await more data: FERMI (PLANCK and AMS in future)

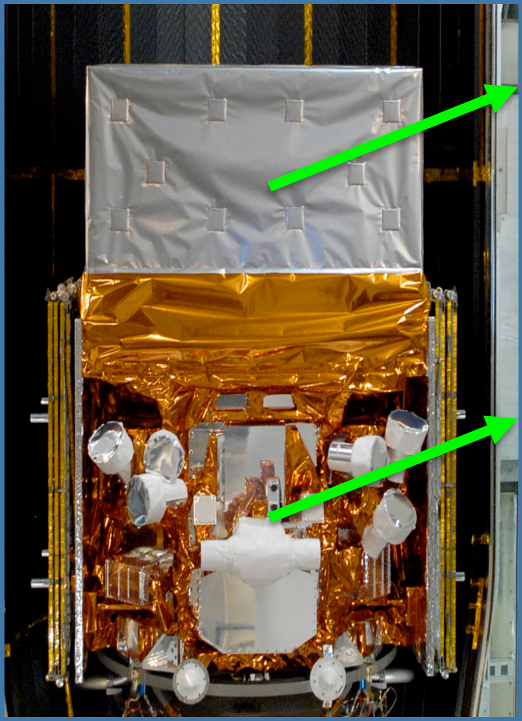


FERMI (GLAST)



Observatory:

- Launched by NASA in June 2008
- Design life 5 yrs (min), goal: 10 yrs
- Astroparticle mission exploring mainly high energy gamma-ray sky
- Results from its first year of operation
- Two instruments:
  - Large Area Telescope
  - Gamma Burst Monitor



LAT (Large Area Telescope)

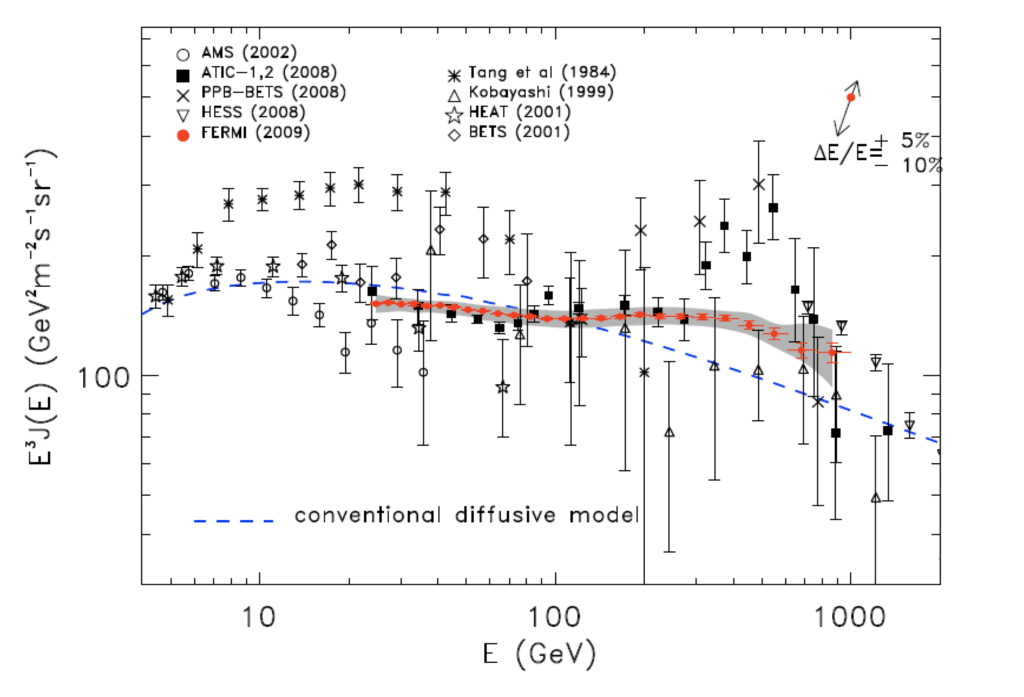
- 20 MeV - >300 GeV
- Anticoincidence detector; Tracker; Calorimeter
- No magnetic field

GBM (Gamma Burst Monitor)

- 8 keV - >20 GeV
- 12 NaI + 2 BGO detectors
- Search for GRBs

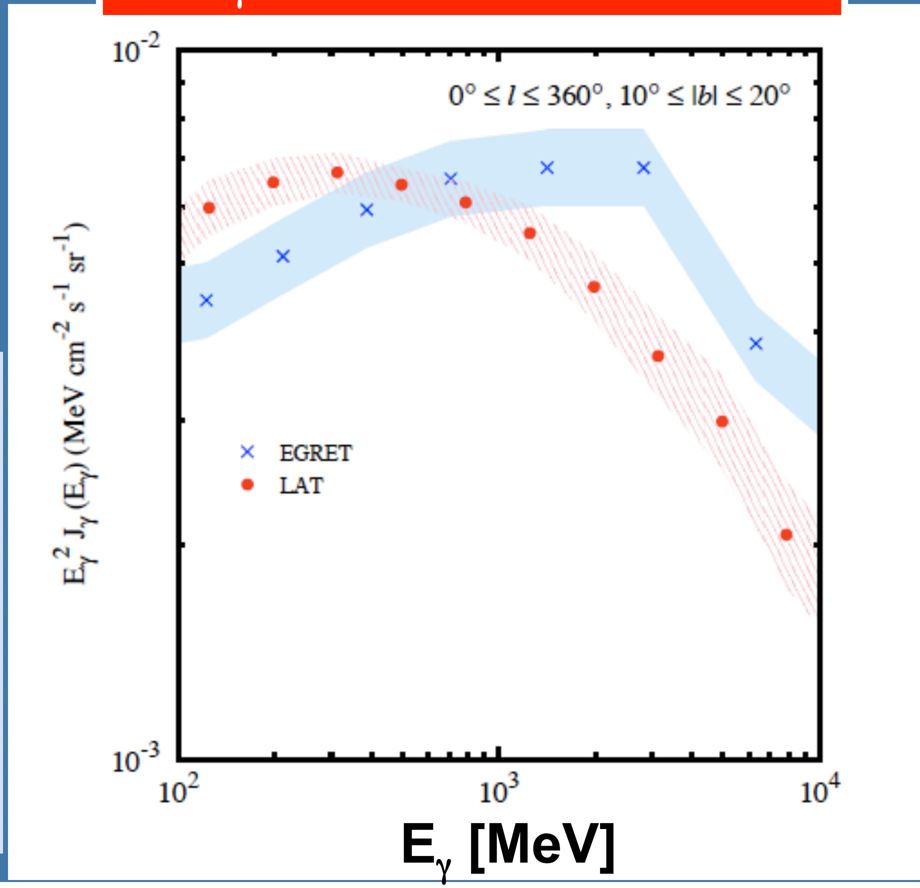
FERMI results

$e^+ + e^-$

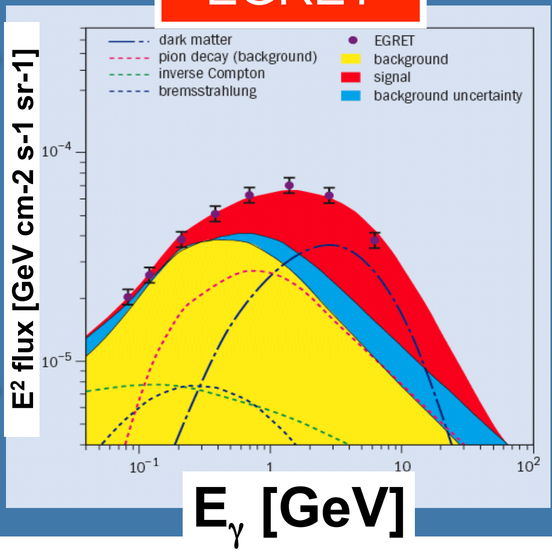


FERMI only slightly confirm the excess seen by ATIC(PAMELA)

HE γ's: FERMI-LAT + EGRET



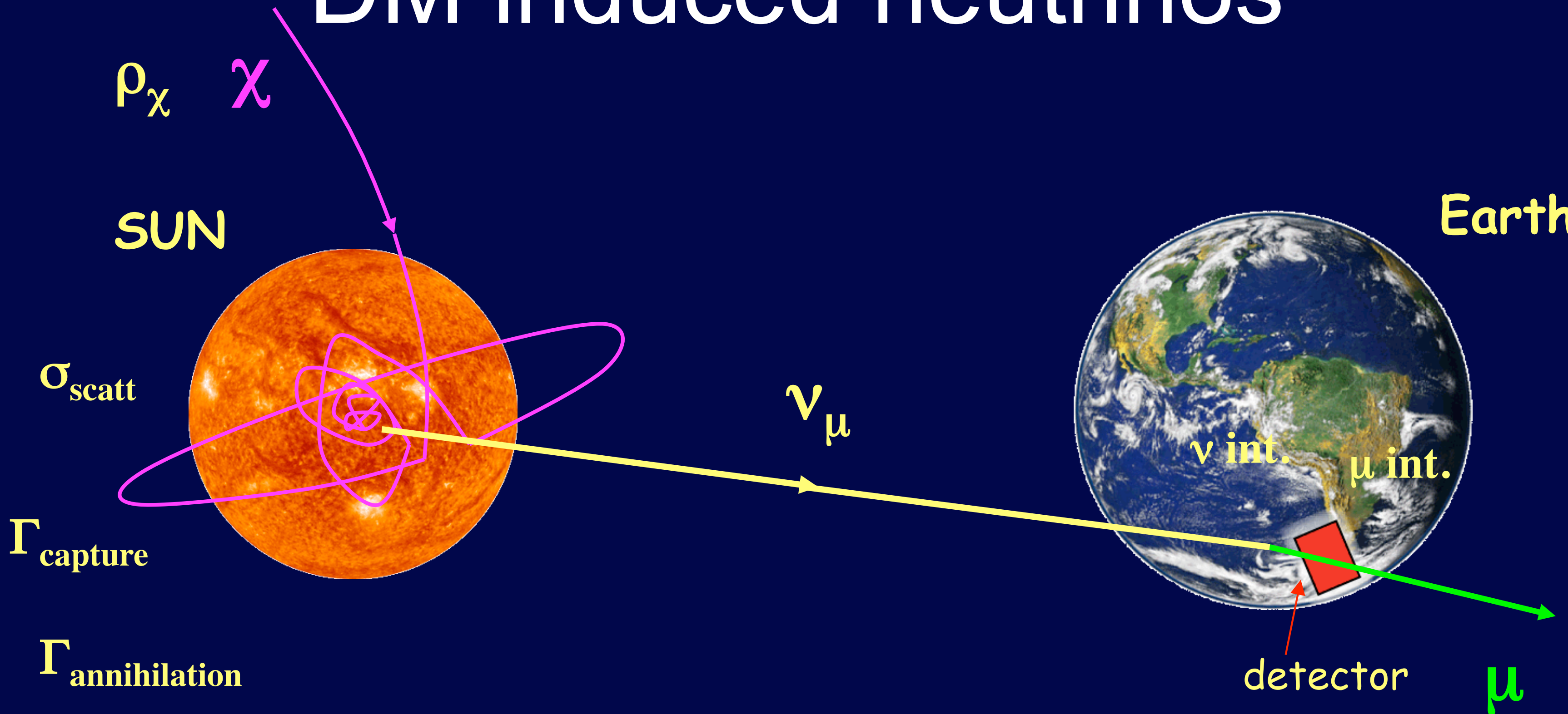
EGRET



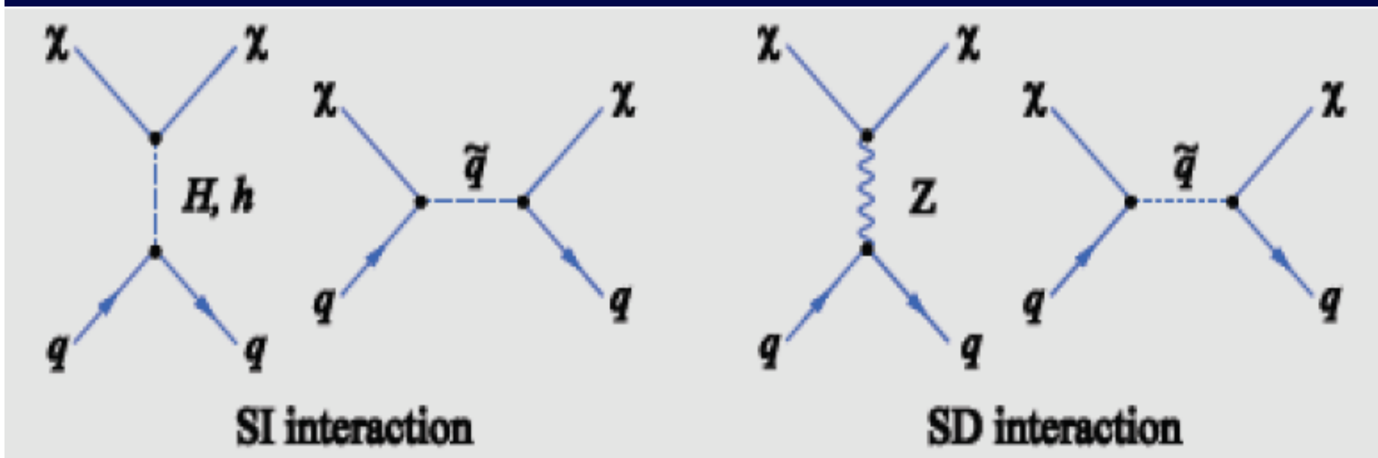
FERMI does not confirm HE gamma excess seen by EGRET

P.Mijakowski

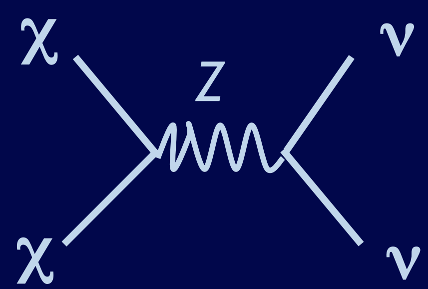
DM induced neutrinos



χ scattering in the Sun

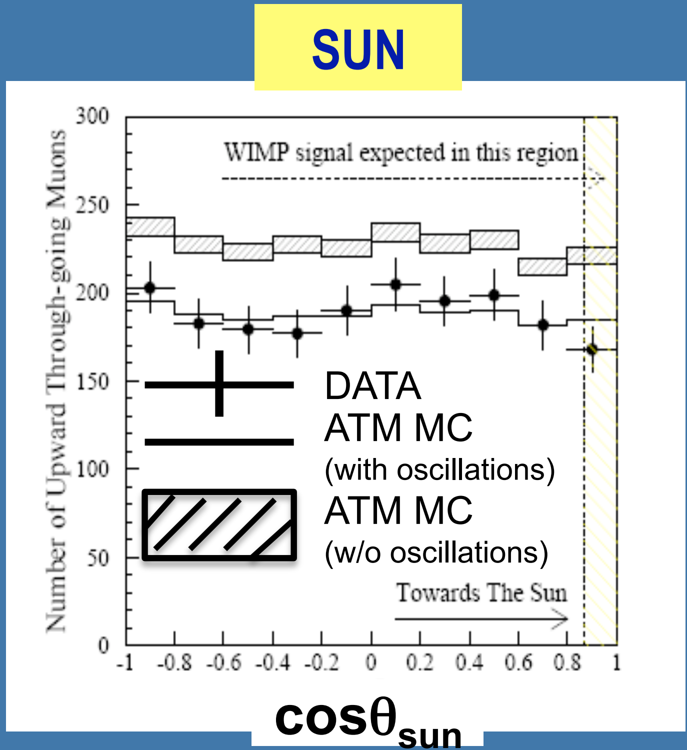


χ annihilation

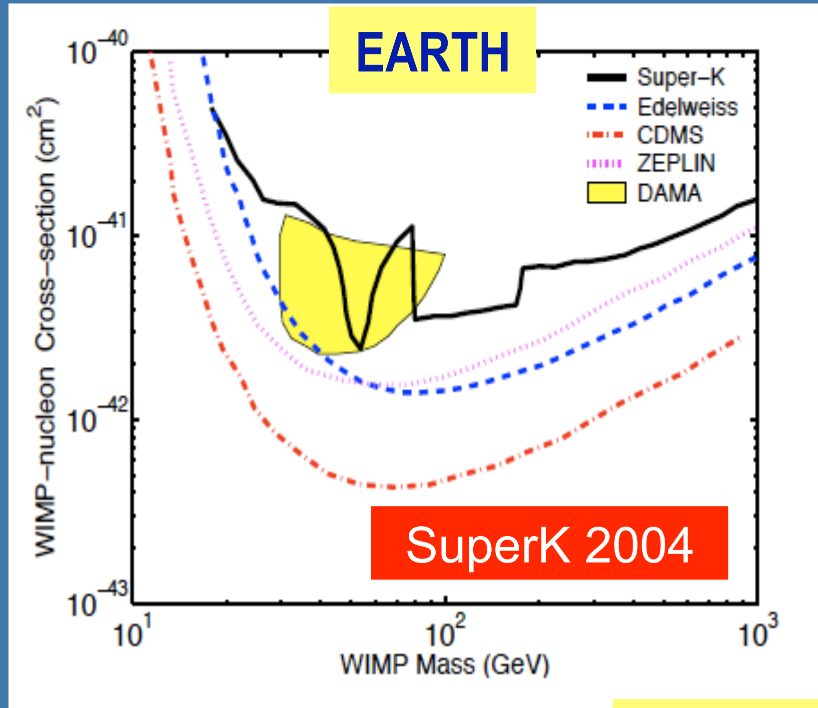


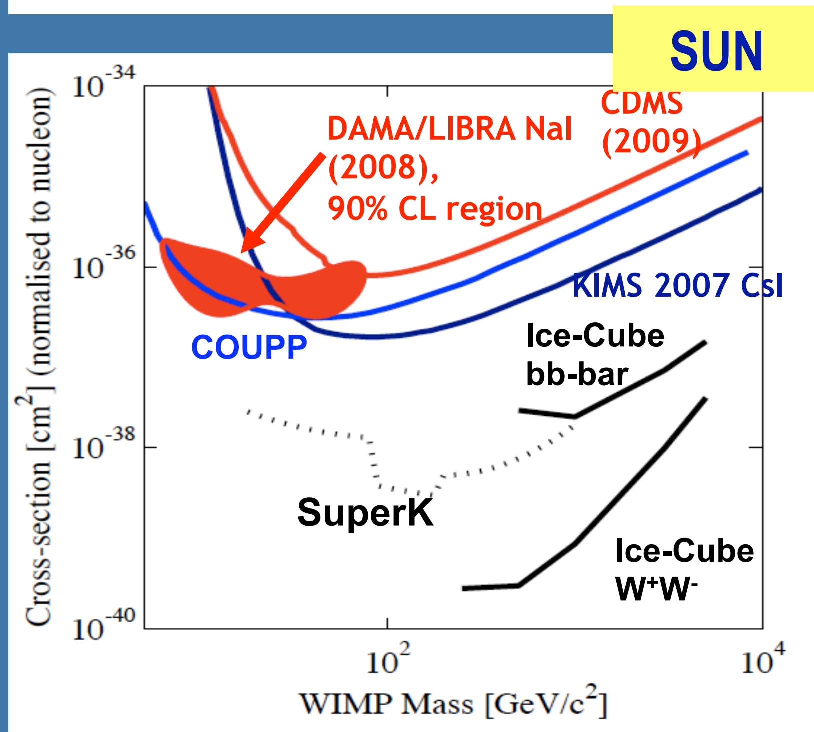
Search for WIMPs in SuperK (directional flux)

(*) S.Desai et al., Phys.Rev. D70 (2004) 083523



- Search for excess of neutrinos from direction of Sun, core of Earth, Galactic Center
- WIMP mass range 18GeV-10TeV -> neutrino energy: ~5 GeV – 5 TeV
- Result: no excess over the expected atmospheric ν flux
- Limit: DM-induced ν flux, limit on χ-nucleon cross section based on equilibrium assumption – capture rate ($\sim\sigma_{\chi\text{-nucl}}$) = annihilation rate ($\sim<\sigma V>$)





Search for ν's from diffuse DM annihilation @ SuperK (my PhD)

» Investigation is limited to „most optimistic" WIMP annihilation channel:

$$\chi + \chi \longrightarrow \nu + \overline{\nu}$$

neutrino energy = WIMP mass

signal is isotropic

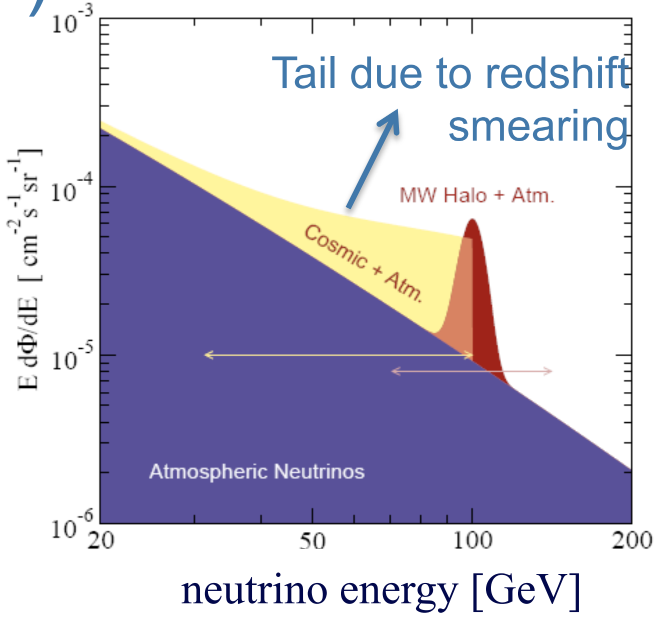
» Due to distinctive energy spectra of WIMP-induced neutrinos coming from that „golden channel" it is possible to test data against characteristic distortions in energy and cos spectra

» Use method of min χ^2 to find best allowed WIMP contribution

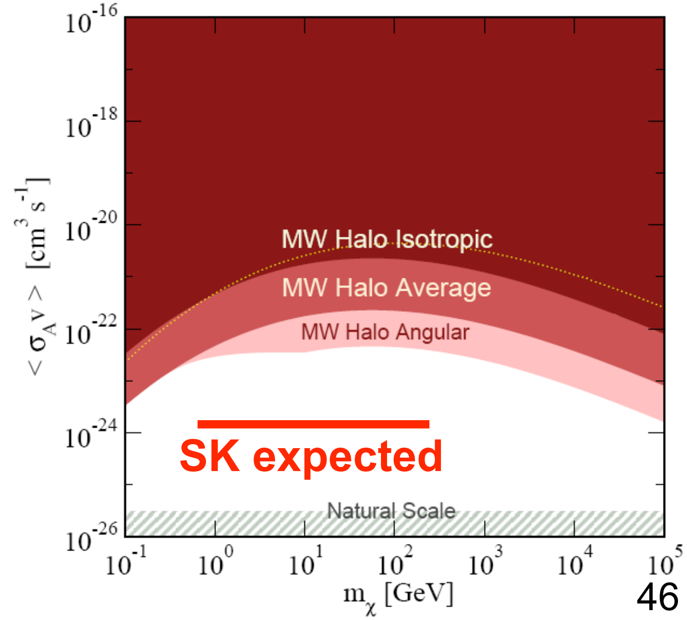
» Derive conservative upper limit on WIMP total self-annihilation cross section $<\sigma V>$,

SuperK analysis would improve ν based world limit by 1-2 orders of magnitude

Illustration of 100 GeV DM annihilation signal



(*) J.F.Beacom et al., Phys. Rev. D76, 123506 (2007)



Podsumowanie

» Ciemna Materia – czas nowych, wielce obiecujących wyników...

Detekcja bezpośrednia

- DAMA – twierdzi że odkryła CM już przeszło 10 lat temu
- Pozostałe eksperymenty (kilkanaście) nie potwierdzają tych wyników
- CDMS (2009) – 2 przypadki w obszarze spodziewanym dla sygnału (tło 0.8 przyp.); weryfikacja niedługo przez XENON
- CoGeNT – wskazuje na model CM o masach 7-10 GeV

Detekcja pośrednia

- PAMELA/ATIC – nadmiar pozytonów (oraz $e^+ + e^-$) ponad spodziewane tło, przy energiach > 10 GeV (ATIC: 300-600 GeV) ... sytuacja trudna do wytłumaczenia anihilacją CM w ramach standardowych modeli i założeń
- FERMI – nie potwierdza tak znaczącego efektu nadmiaru $e^+ + e^-$; rozproszony strumień fotonów z obszaru Galaktyki nie większy niż przewidywany

» Czy w roku 2010 odkryjemy Ciemną Materię?

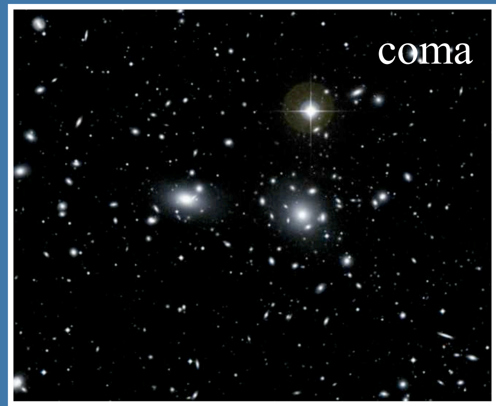
- Co raz więcej wyników potwierdzających... niestety niespójnych.
- Obserwacja wymaga potwierdzenia przez kilka eksperymentów bezpośrednich (różne materiały), przez eksperymenty pośrednie w zakresie różnych kanałów produkcji (antymateria, γ,ν) oraz w LHC

Dziękuję za uwagę

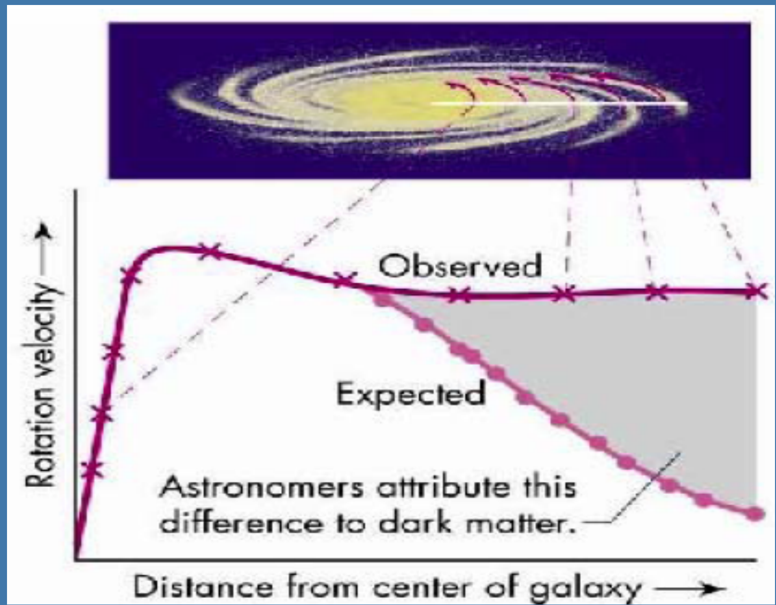
BACKUP

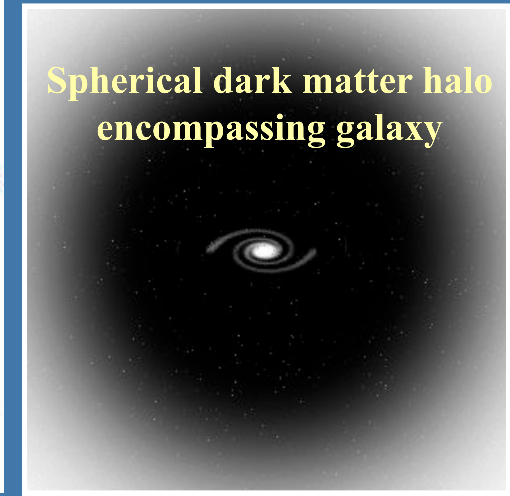
Dark Matter in the Universe

» 1933 r. - Fritz Zwicky, COMA cluster. Velocity of galaxies too high to form bound system (if total mass was related only to luminous part of the system)



» 1970,80s – rotation curves of galaxies; halo of unseen matter component (?)





CONCLUSIONS

- unseen matter component, manifests through gravitational interactions
*- modification of gravity on large scales / MOND (**MOdified Newtonian Dynamics**)*

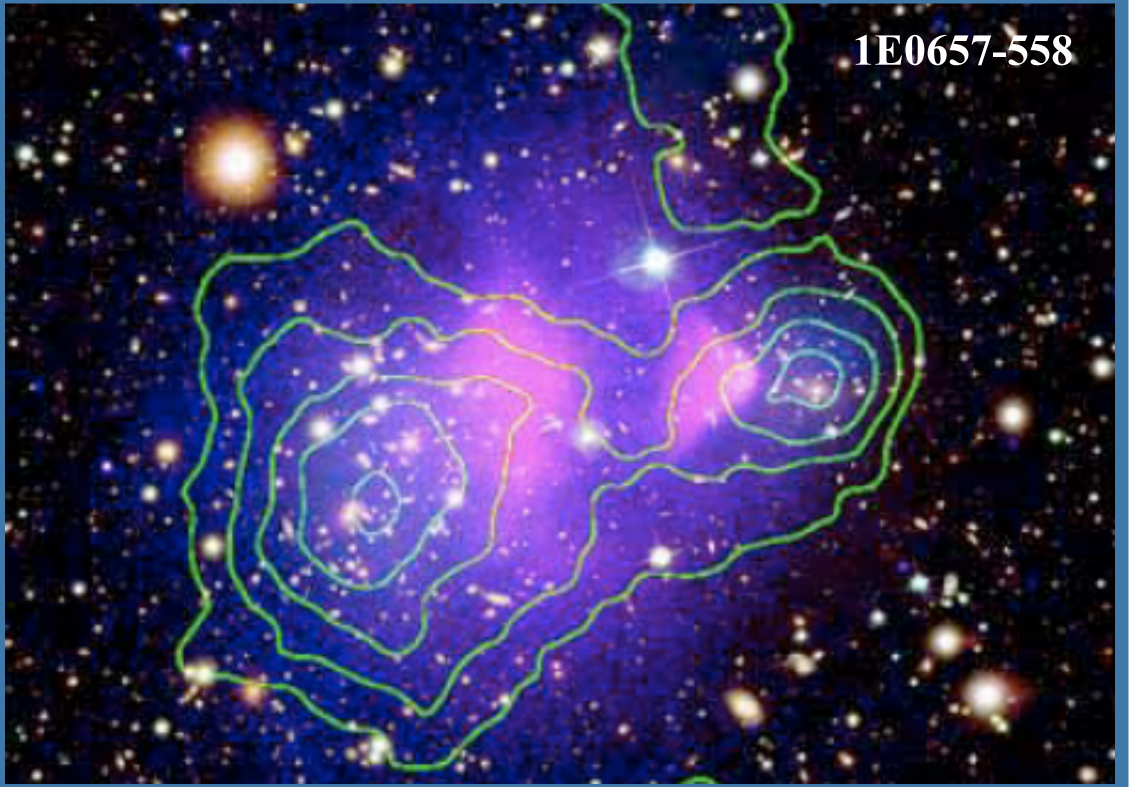
Bullet Cluster

direct empirical proof of existence of dark matter

- » Distribution of mass in colliding clusters of galaxies (1E 0657-56)
- » Gravitational lensing – total gravitational potential (Hubble Space Telescope, European Southern Observatory VLT, Magellan) / violet
- » X-rays – Chandra X-ray Observatory (NASA) / pink

- » Typically, gas represents most of the mass of ordinary (baryonic) matter in clusters (2 times more than luminous matter). It interacts e-m and slows down during collision.
- » Result: mass concentration related to luminous matter
- » X-rays regions: only 10% of the mass of cluster pair

- DARK MATTER
- ~~MOND~~



(*) D.Clowe et al. 2006 Ap. J. 648 L109

ΛCDM model

- ΛCDM – cosmological model based on recent observations: CMB, large scale structures, accelerating expansion of Universe

Cosmological parameters

- Ω_{tot} $\Omega_{tot} = 1.02 \pm 0.02$ **„flat" Universe!**
  cosmic microwave background (***WMAP - 2003 r.***)
- Ω_m $\Omega_m = 0.27 \pm 0.02$
  WMAP (2006 r.)
  $\Omega_m \sim 0.3$
  gravitational interactions (i.e. rotation curves)
- Ω_b $\Omega_b \sim 0.040 \pm 0.005$ (astro-ph/0001318)
  Big Bang Nucleosynthezis (BBN) + abundance of ligh elements (H,D,He,Li)
  $\Omega_b \sim 0.044 \pm 0.002$
  WMAP (2006 r.)
- Ω_{lumni} $\Omega_{lumni} \sim 0.006$
  Luminescence of stars and interstellar medium

ΛCDM model

Cosmological parameters

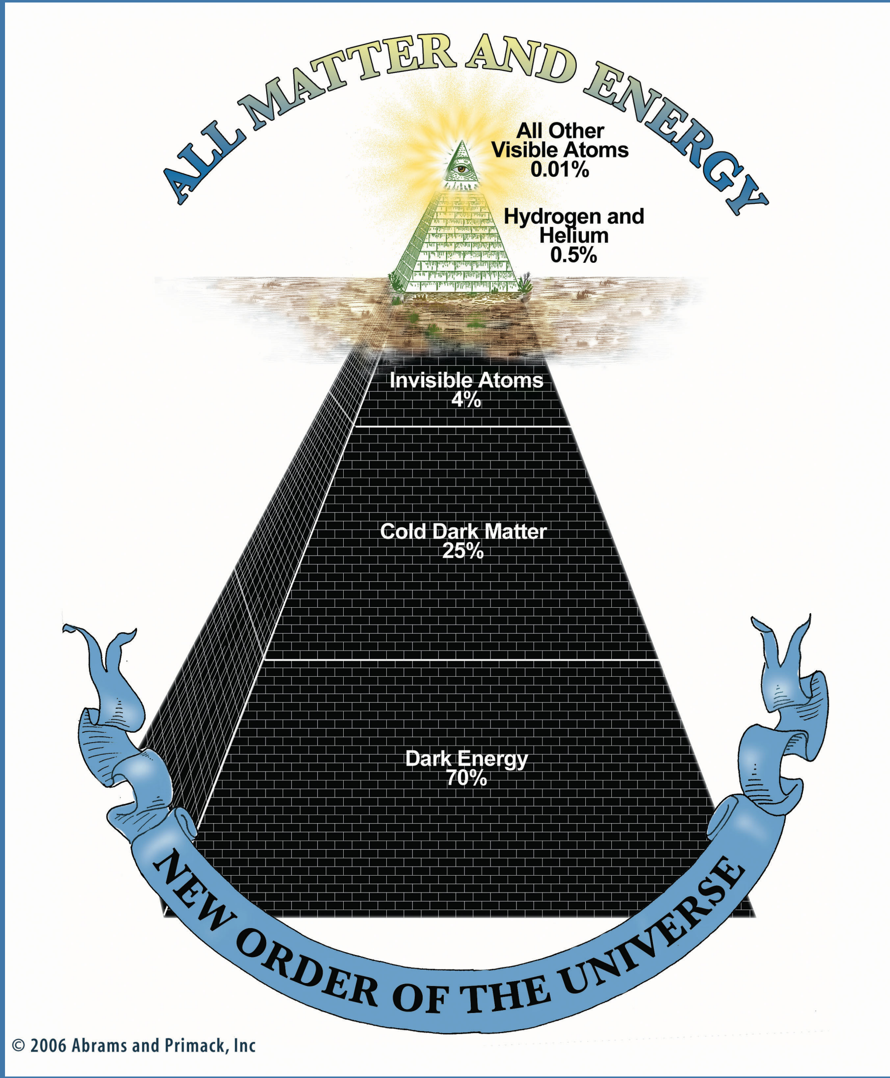
» Ω_Λ $\Omega_\Lambda = 0.73 \pm 0.02$

WMAP (2006 r.) + SN Ia

Conclusions:

$\Omega_m >> \Omega_b$ => Dark Matter

$\Omega_m < 1$ => Dark Energy



Dark Matter candidate: WIMP

It seems that DM consists of some sort of particles which interacts via gravity and/or weak force. MOND (Modified Newtonian Dynamics) are rather excluded.

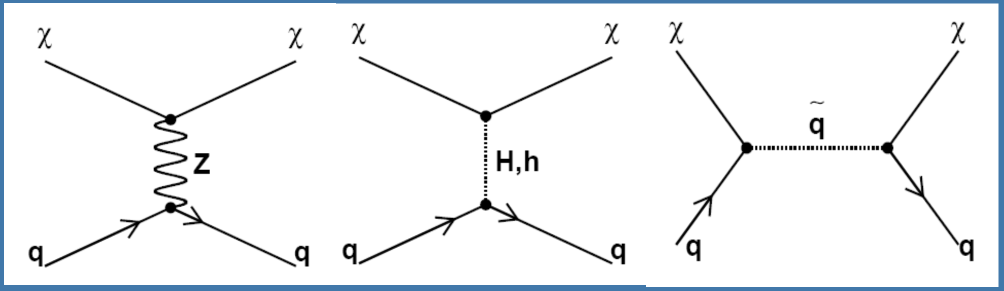
WIMP (Weakly Interacting Massive Particle)

one of very well motivated candidates for DM particle:

- **neutral**
- **long lived**
  (with τ ~ age of Universe)
- **massive** (M_χ ~ 100 GeV)
- **weakly scale couplings**

$$\sigma \leq 10^{-2}\text{pb } (10^{-38}\text{ cm}^2)$$

neutralino couplings (example):



Jungman, Kamionkowski, Griest, Phys. Rep., 267, 195 (1996)

WIMPs naturally come with SUSY:

- **neutralino χ (SUSY)** - Lightest Supersymmetric Particle (LSP), **stable (R-parity conservation in SUSY)**

neutralino(χ) $18\text{ GeV} < M_\chi < 7\text{ TeV}$

LEP **cosmology**

MOND

$$\vec{F} = m \cdot \mu\left(\frac{a}{a_0}\right)\ \vec{a}$$

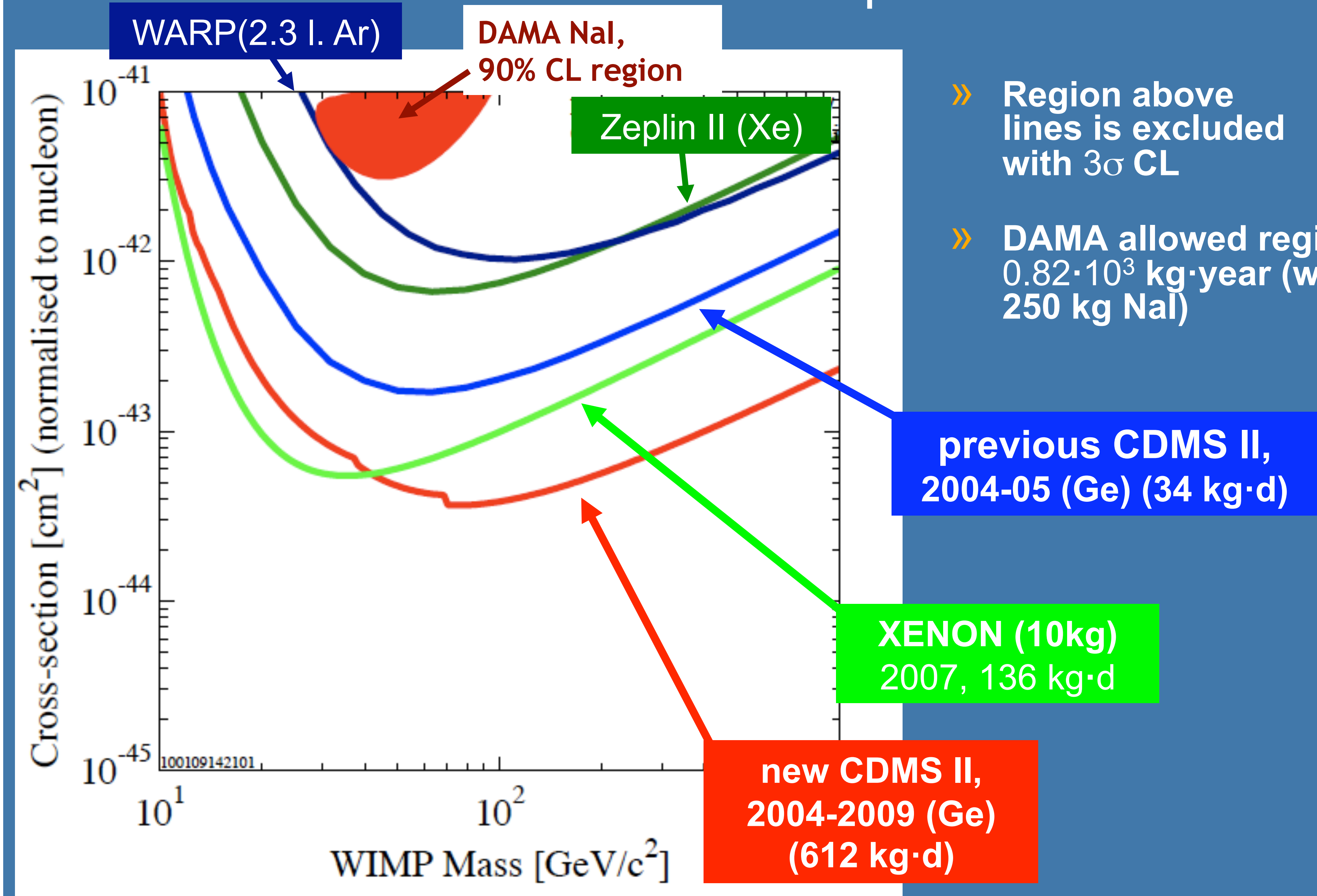
$\mu(x)=1$ for $x>>1$

$\mu(x)=x$ for $x<<1$

$a_0 \sim 10^{-8}\ cm/s^2$

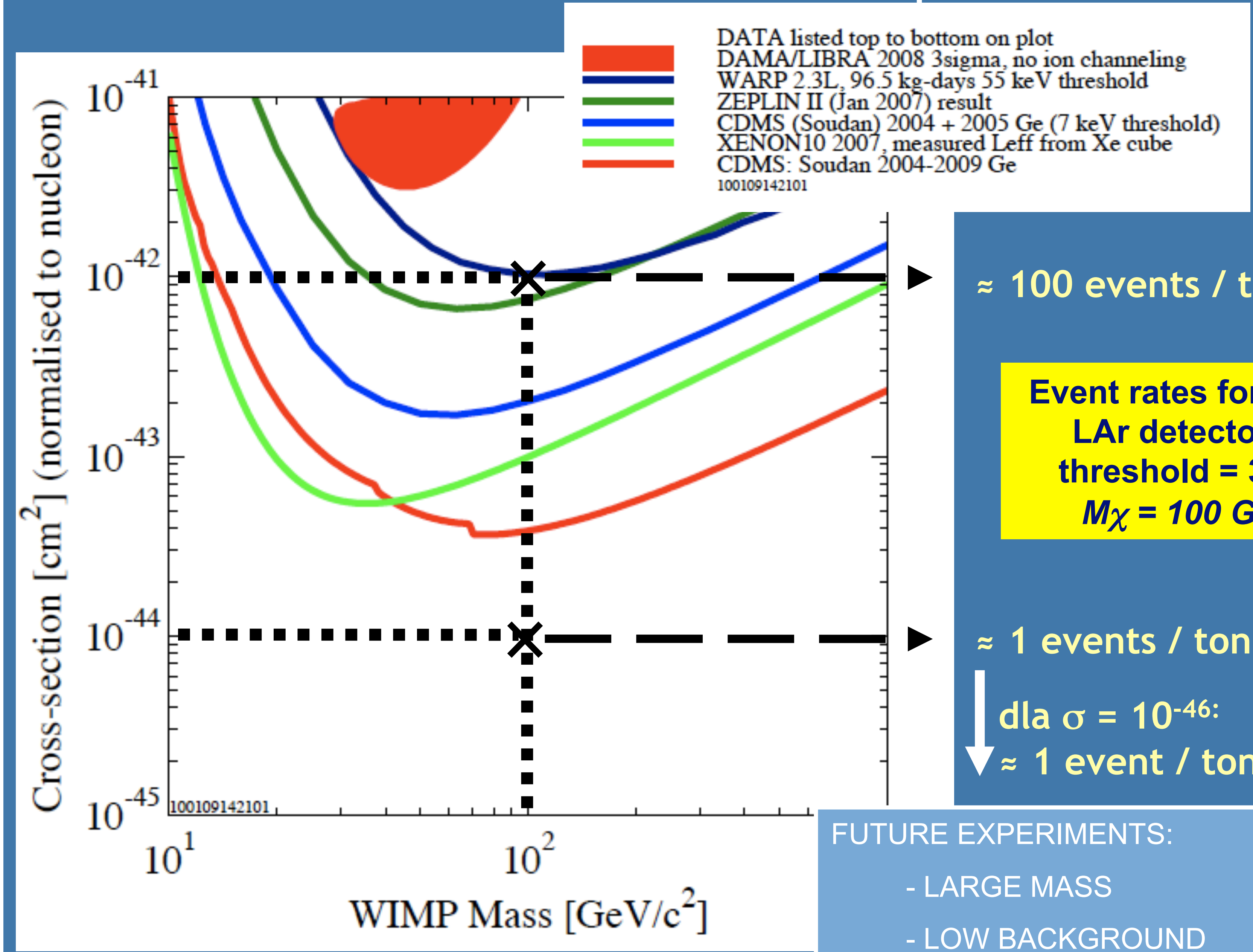
Propozycja M.Milgroma – 1981r.

Direct detection – current experimental limits



- **Region above lines is excluded with 3σ CL**
- **DAMA allowed region:** $0.82 \cdot 10^3$ **kg·year (with 250 kg NaI)**

Direct detection – current experimental limits



≈ 100 events / tonne / day

Event rates for 1 tonne LAr detector with threshold = 30 keV, *M_χ = 100 GeV/c²*

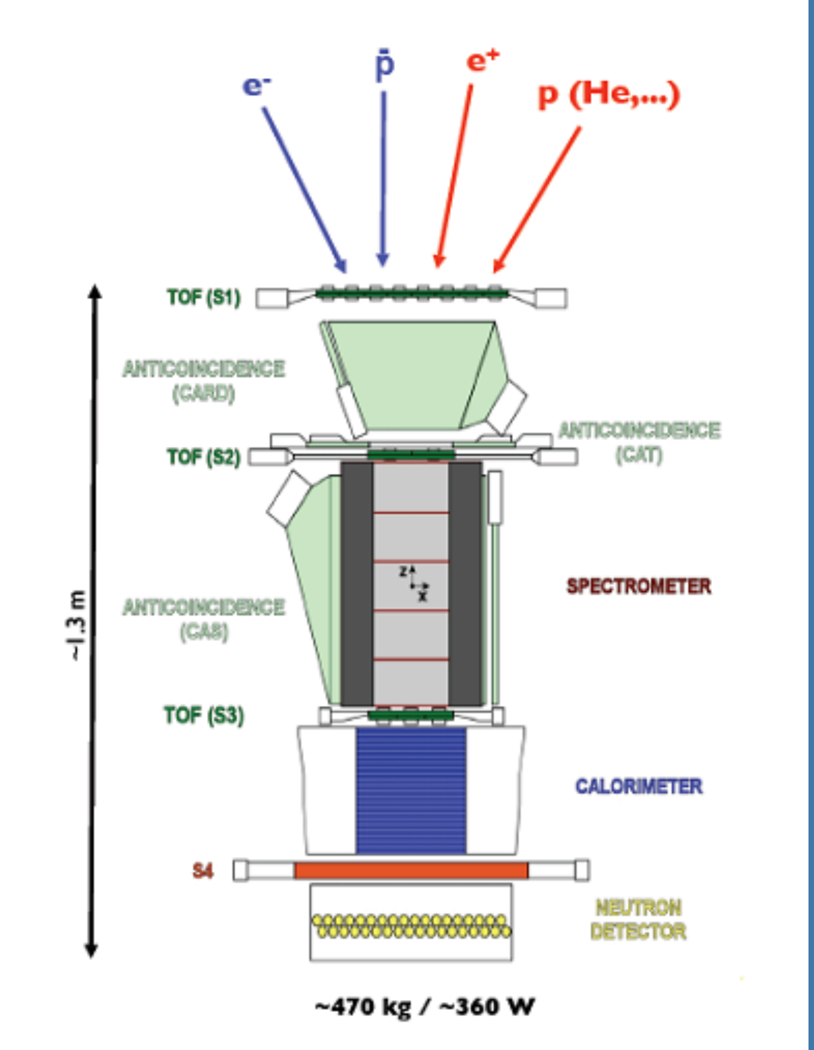
≈ 1 events / tonne / day

dla $\sigma = 10^{-46}$:
≈ 1 event / tonne /100 days

FUTURE EXPERIMENTS:

- LARGE MASS
- LOW BACKGROUND
- LONG EXPOSITION

PAMELA detector principle



Time-of-flight: trigger, albedo rejection, mass determination (up to 1 GeV)

Bending in spectrometer: sign of charge

Ionisation energy loss (dE/dx): magnitude of charge

Interaction pattern in calorimeter: electron-like or proton-like, electron energy

Trigger, ToF, dE/dx

- S1, S2, S3; double layers, x-y
- plastic scintillator (8 mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

Sign of charge, rigidity, dE/dx

- Permanent magnet, 0.43 T
- 21.5 cm^2sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view ⇒ MDR ~ 1000 GV (6 plane) ~600 GV (5 plane)

Electron energy, dE/dx, lepton-hadron separation

- 44 'Si-x / W / Si-y' planes (380 μm)
- 16.3 X_0 / 0.6 λ_L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm^2sr

- 36 ^{3}He counters
- $^3He(n,p)T$; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 μs collection time

Lepton-hadron separation

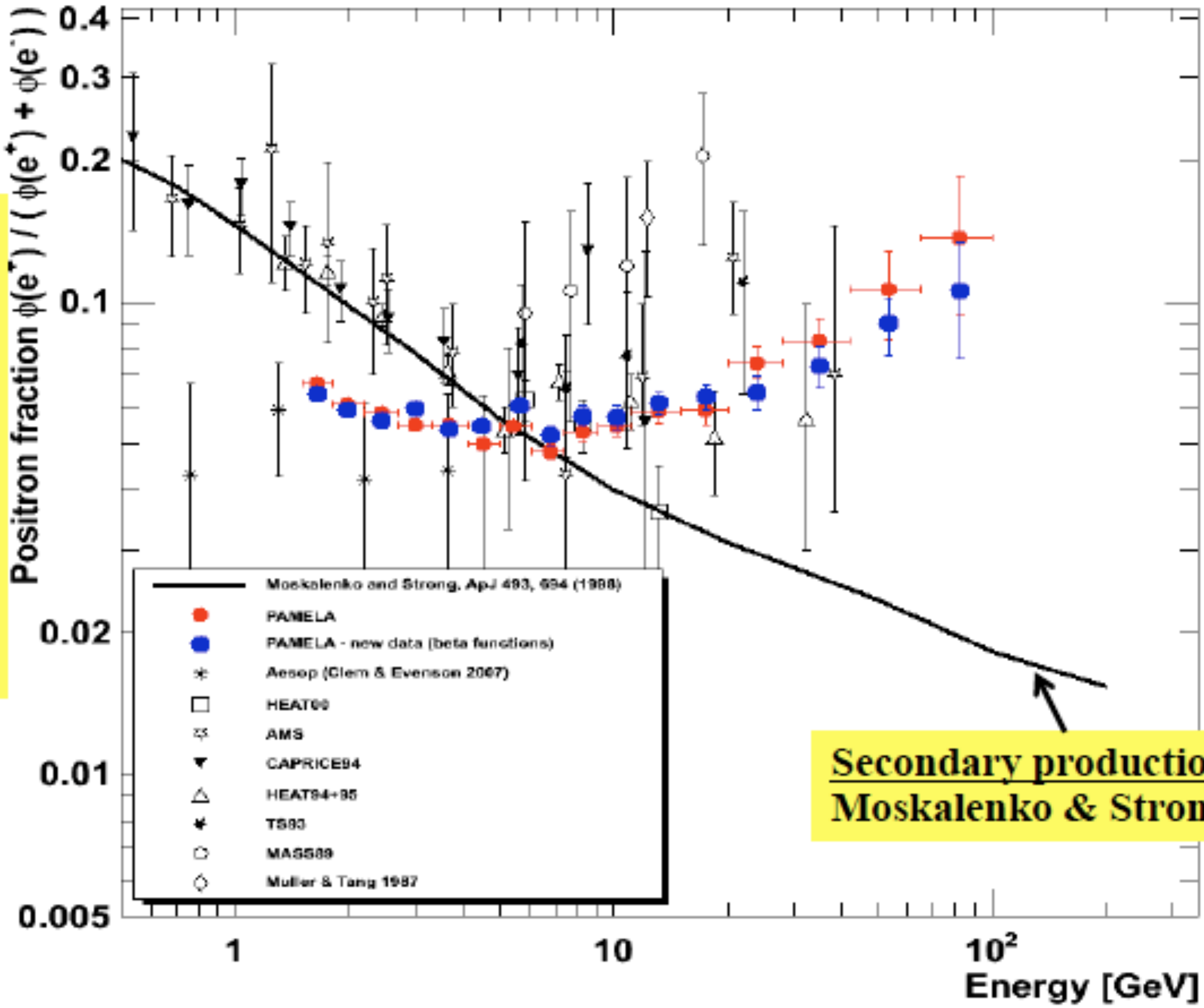
M. Pearce 2009

PAMELA results (positrons)

new results
published Jan 2010

In Nature article published data acquired till February 2008

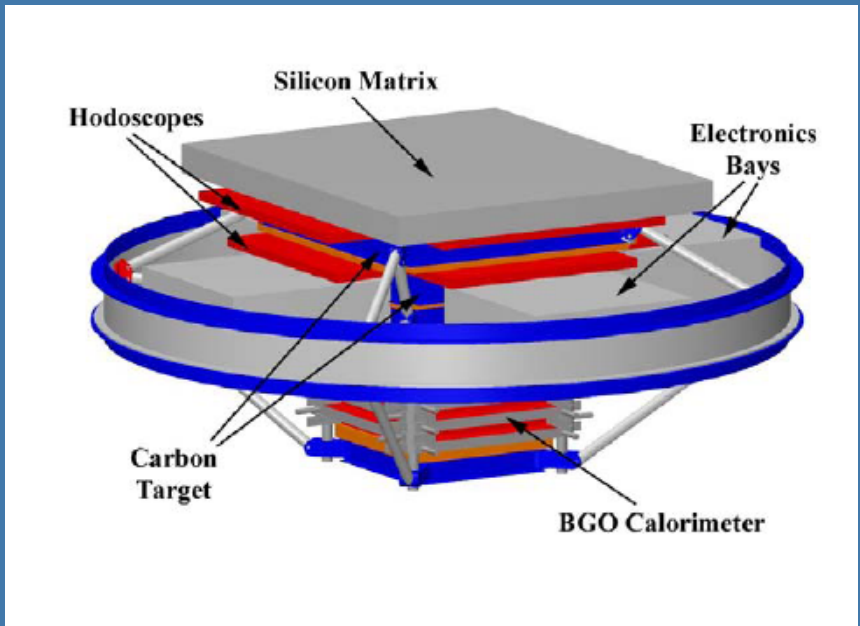
New data reduction: data till end of 2008. With same approach of Nature paper ~30% increase in statistics better understanding of systematics.



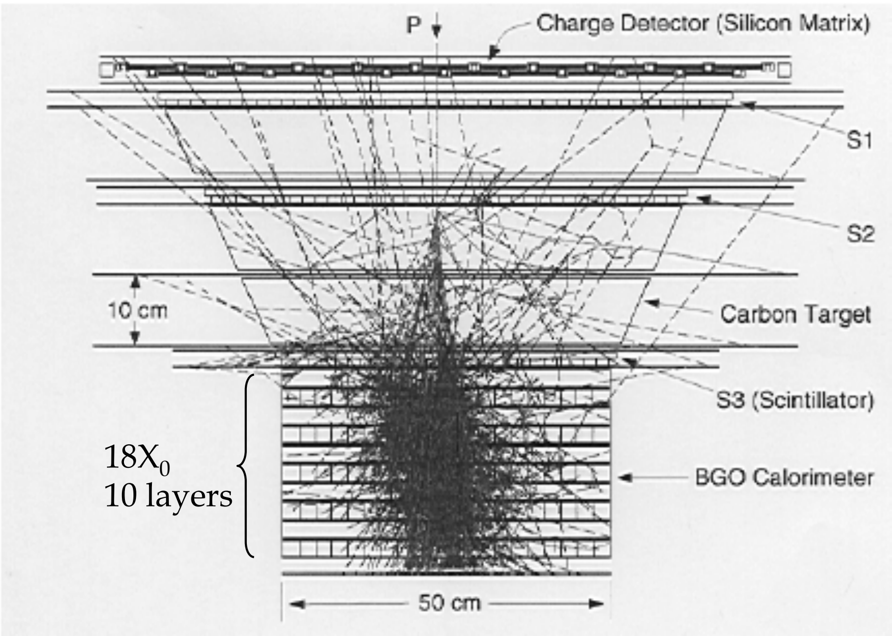
Secondary production
Moskalenko & Strong 98

ATIC
Advanced Thin Ionization Calorimeter

» Baloon born experiment for C.R measurement
» Operated from McMurdo, Antarctica
» ATIC-1 15 days (2000/2001)
» ATIC-2 17 days (2002/2003)
» flights @ 36km

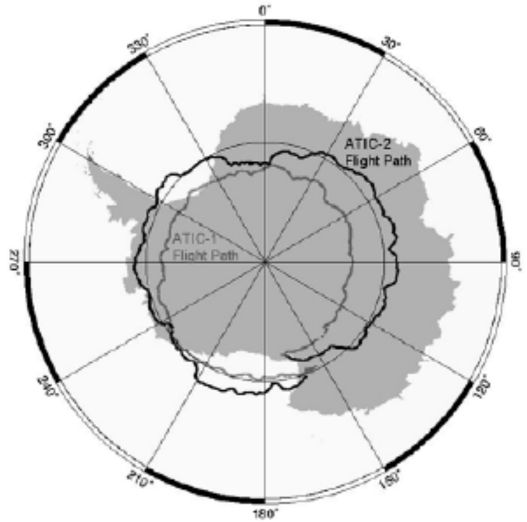


ATIC Instrument Summary



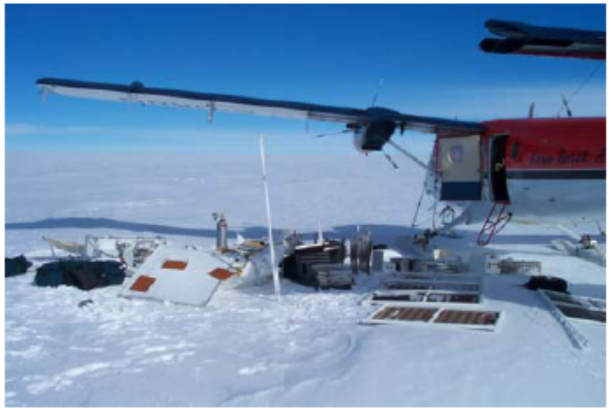
- Measure charge, energy and number
- Ionization Calorimetry only practical method to measure high energy light elements
- Silicon Matrix (Si) has 4,480 pixels to measure GCR charge in presence of shower backscatter
- Graphite Target to interact the primary particle and generate fragments that, in turn, will start an electromagnetic cascade. Also provides some backscatter shielding
- Plastic scintillator hodoscopes (S1, S2, S3) , embedded in Carbon target, provides event trigger plus charge & trajectory information
- Fully active calorimeter includes 400 Bismuth Germinate (BGO) crystals to foster and measure the nuclear - electromagnetic cascade showers

Flight and Recovery

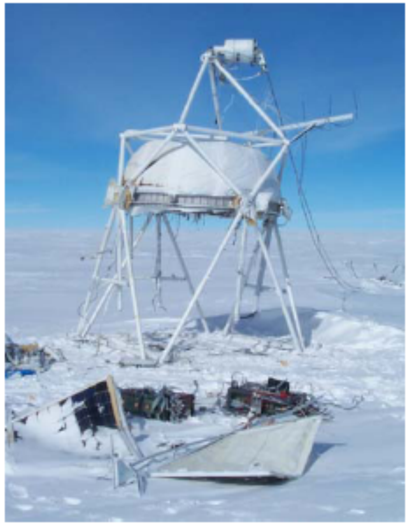


Flight path for ATIC-1 (2000)
and ATIC-2 (2002)

The good ATIC-1 landing on 1/13/01 (left) and the not so good landing of ATIC-2 on 1/18/03 (right)



ATIC is designed to be disassembled in the field and recovered with Twin Otters. Two recovery flights are necessary to return all the ATIC components. Pictures show 1st recovery flight of ATIC-1



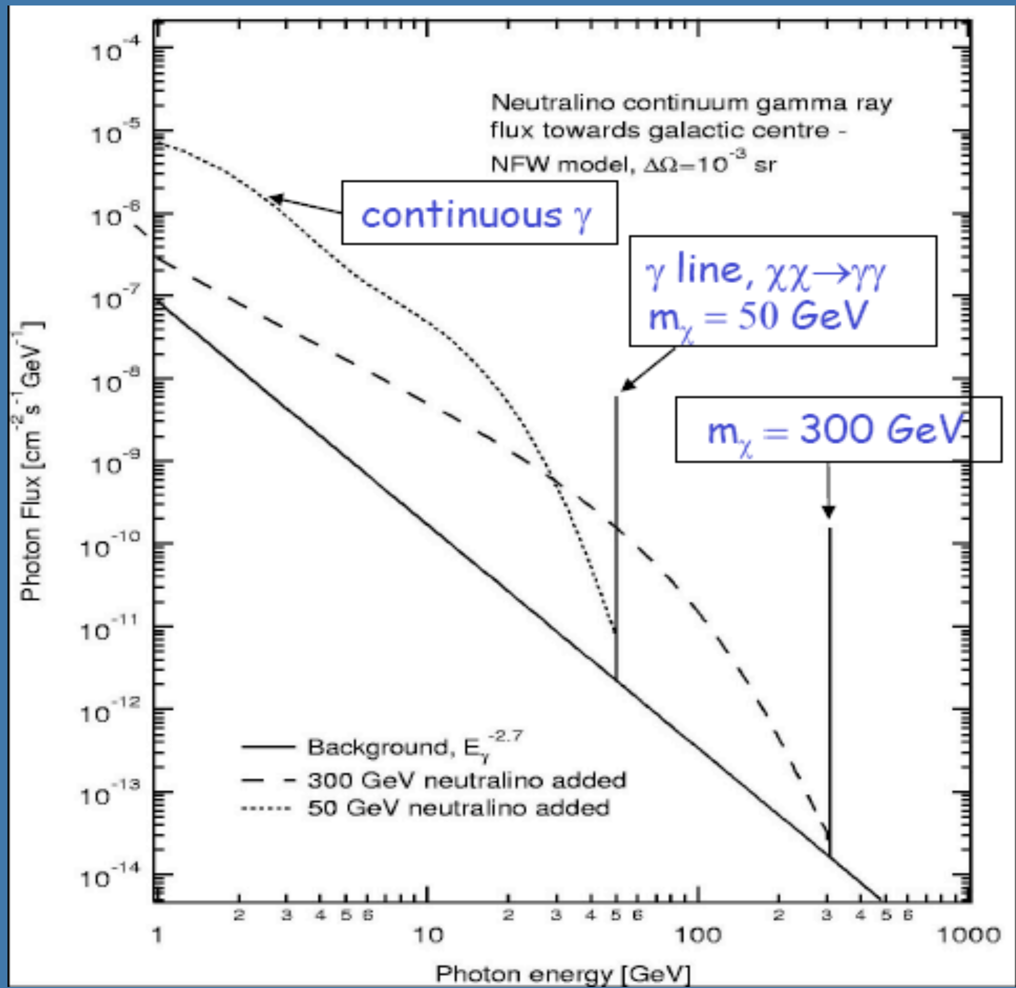
DM annihilation to gammas

Advantages

- insensitive to magnetic fields (source information)
- not attenuated over galactic scales – energy spectrum
- produced in the most of WIMP annihilation modes, π^0 decays (abundant ann. product)

Uncertainities:

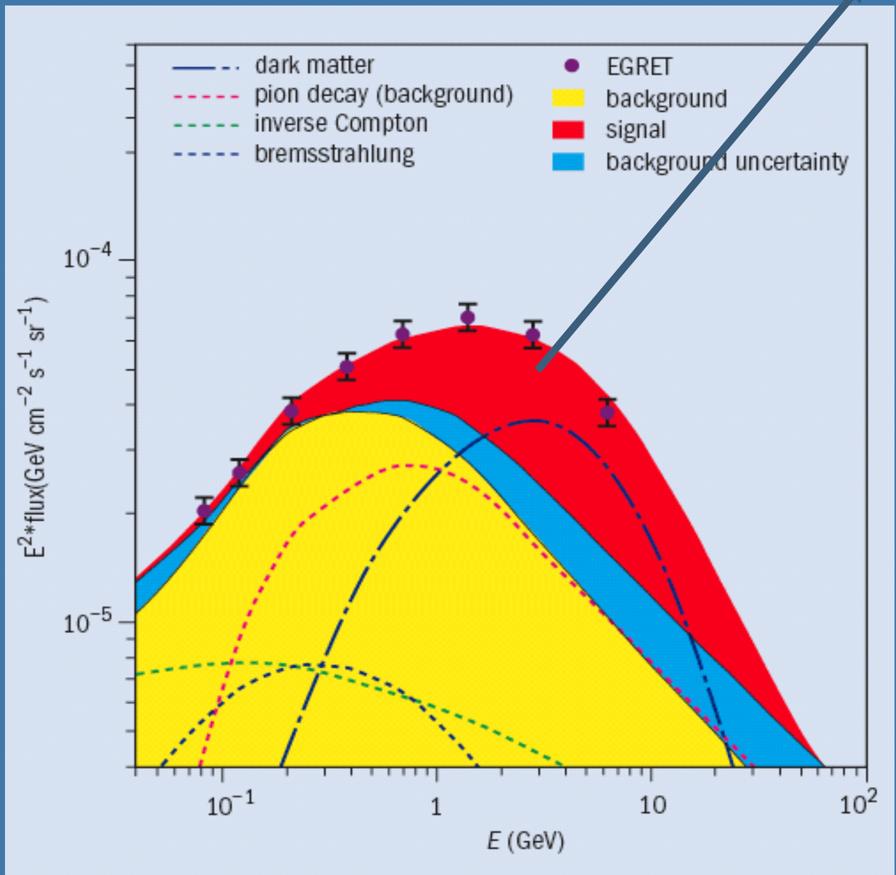
- Astrophysical background rate
  - distribution around Galactic Center

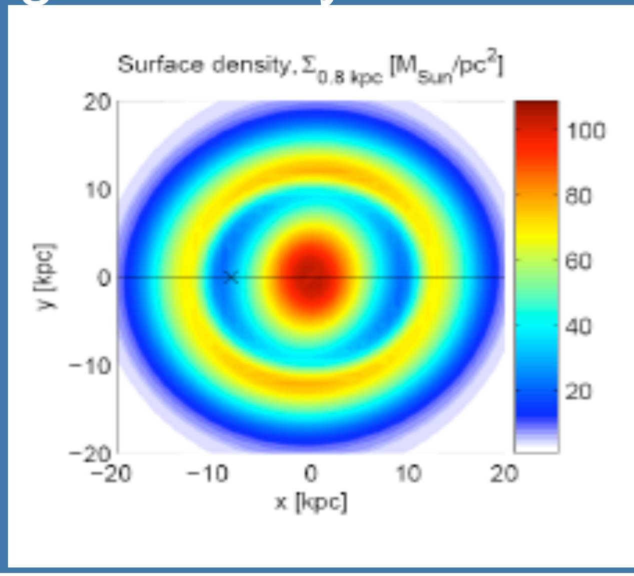


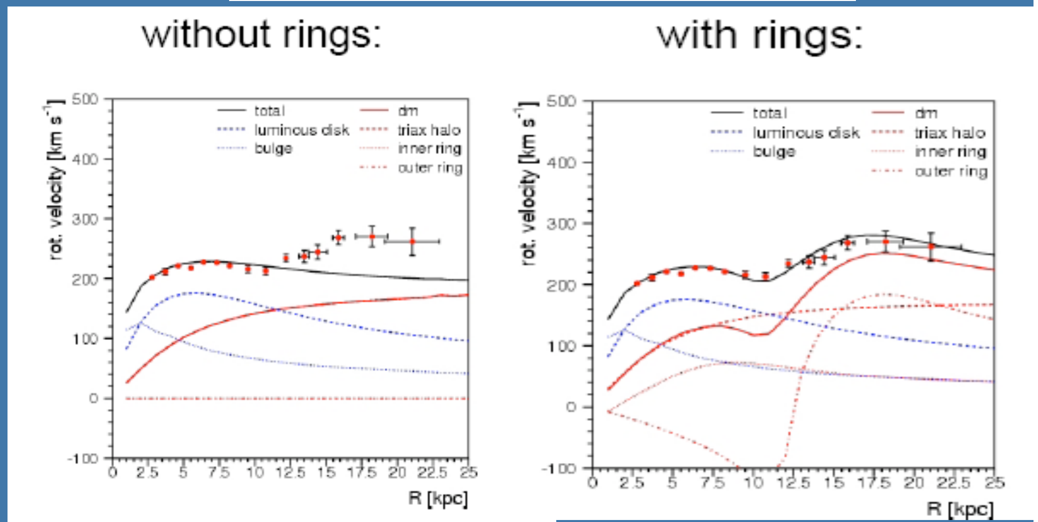
DM annihilation to gammas - EGRET

» EGRET excess in diffuse galactic gamma ray flux

50-100 GeV neutralino annihilation?

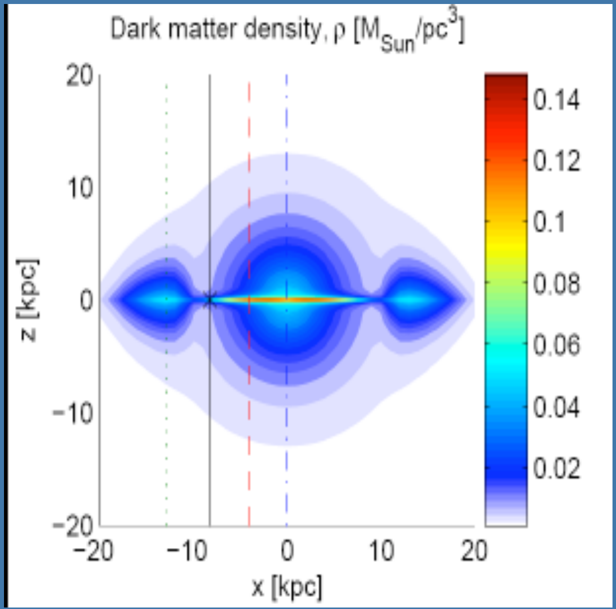






DM annihilation to gammas - EGRET

Objections to EGRET interpretation

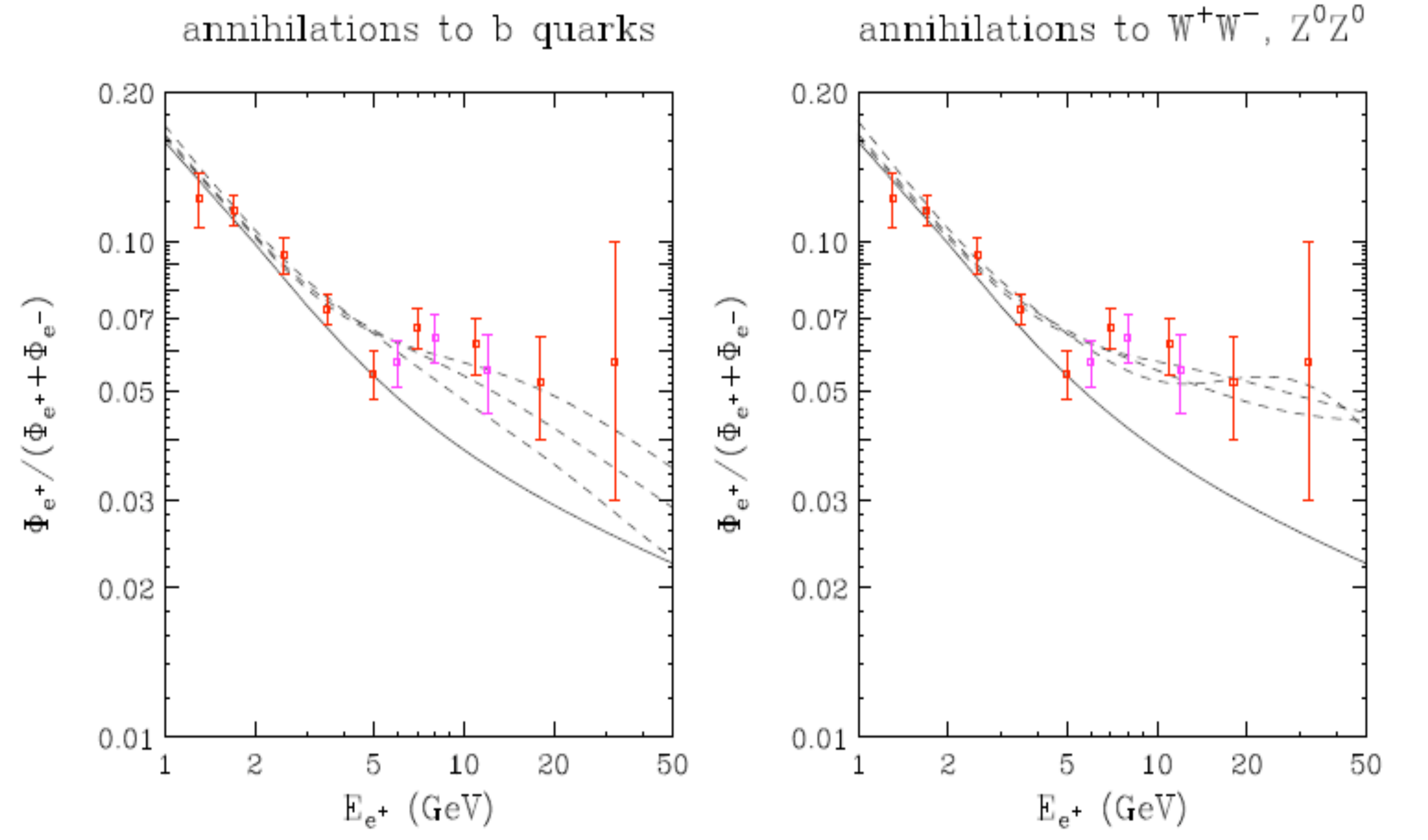


- DM density concentrated to the galactic plane. This is not what one expects from CDM!
- Excess in anti-protons data – NOT observed (correlation: fragmentation of quark jets)
- Instrumental problem with EGRET?
- Too simple conventional model for galactic gamma-ray emission?

await GLAST

DM annihilation to positrons (HEAT)

(*) D. Hooper., Annu. Rev. Nucl. Part. Sci. (2008), Vol. 58



- DATA: HEAT exp.
- solid line: Galactic cosmic ray model (Moskalenko & Strong)
- Dotted lines – WIMP masses 100, 300, 600GeV

» *for* $\langle \sigma_A v \rangle = 3\times 10^{-26} cm^3/s$, $\rho_\chi = 0.3 GeV/cm^3$ *ann. rate should be boosted ~50 to normalize the HEAT data*

» *Consequence: DM clumps in local halo (but expected only ~5-10); different cross section (then should be observed by others)*

Dark Matter annihilation to neutrinos

… where they may come from?

Search for neutrinos from DM annihilation (strategies)

Directional flux
related to regions of increased DM density:

- core of Sun, Earth, Galaxy Center
- constrain SD/SI $\sigma_{\chi n}$

Diffuse flux:

- flux averaged over large cosmic volumes (many galactic halos) or over Milky Way
- constrain DM self-annihilation cross section $\langle \sigma \cdot v \rangle$

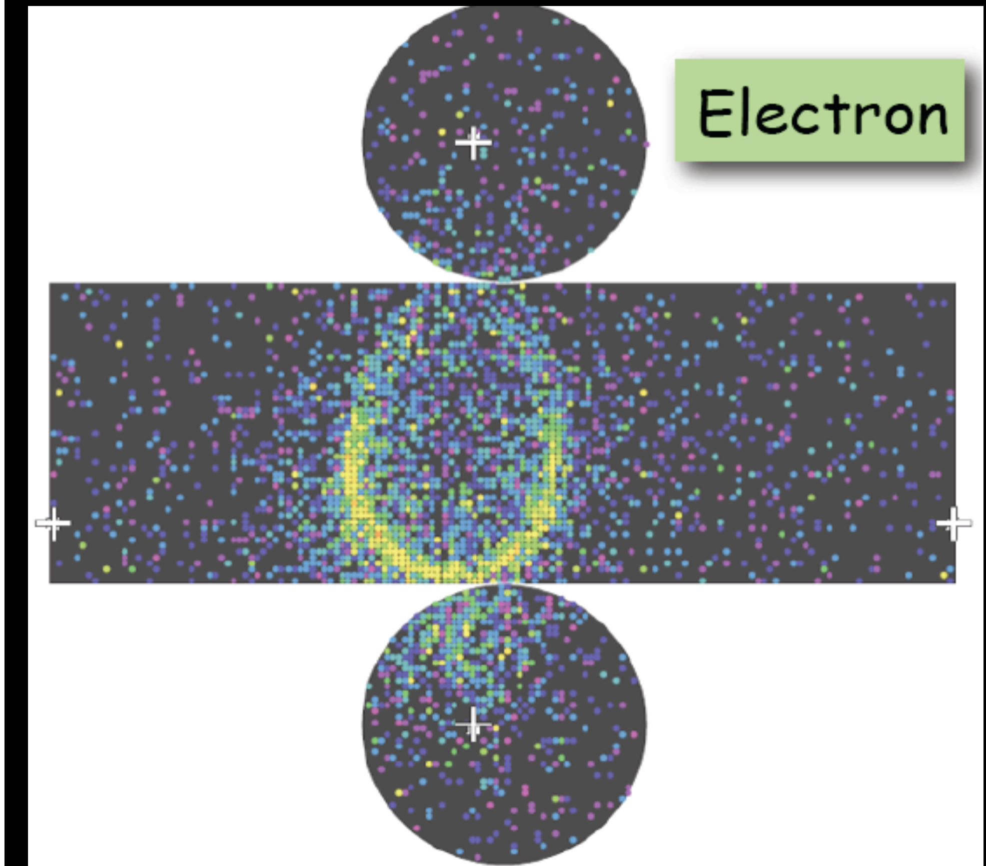
Cerenkov ring categories

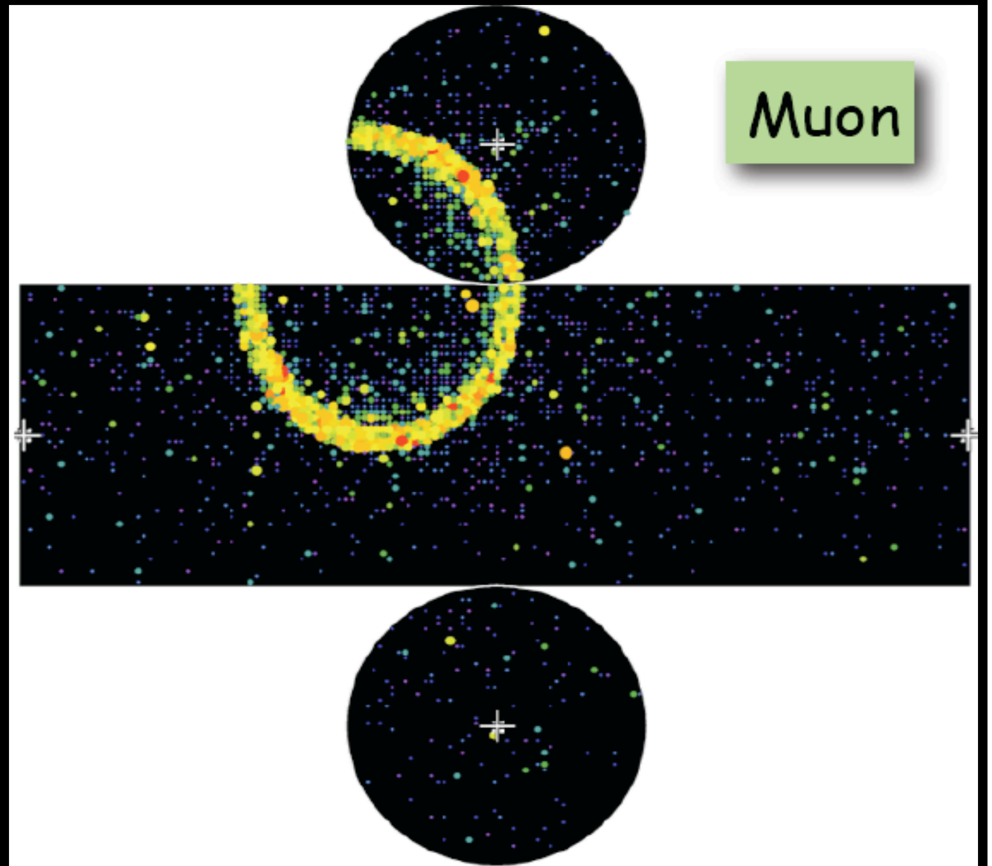
How can we distinguish interacting neutrino flavor?

- » e-like
- » μ-like

fuzzy rings (due to E-M showers)

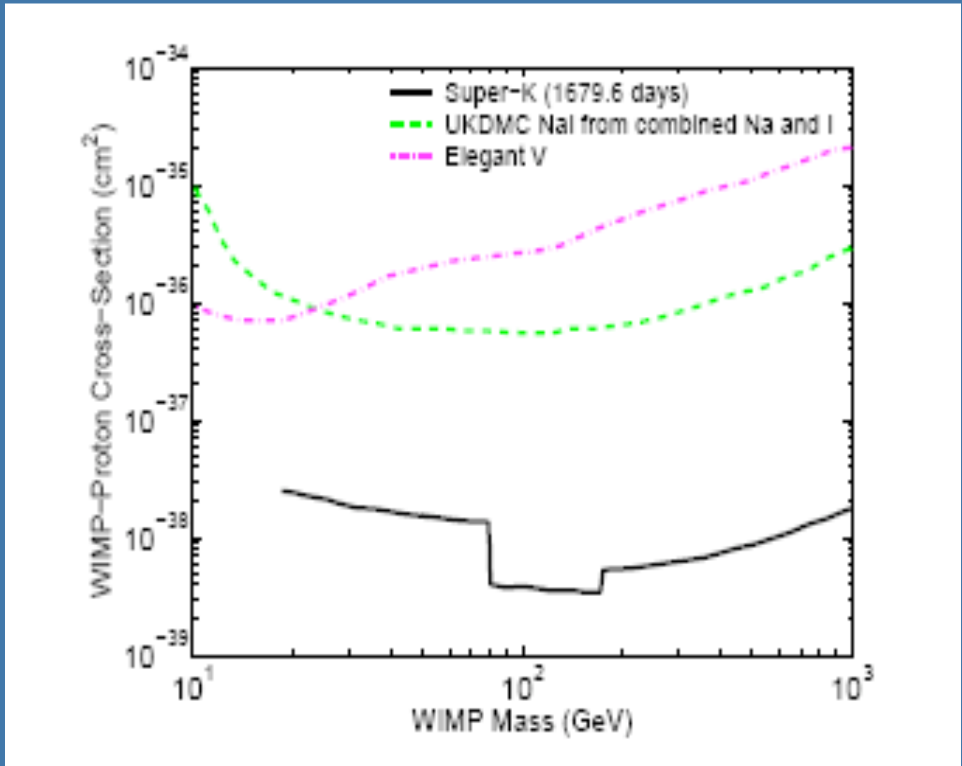
solid rings

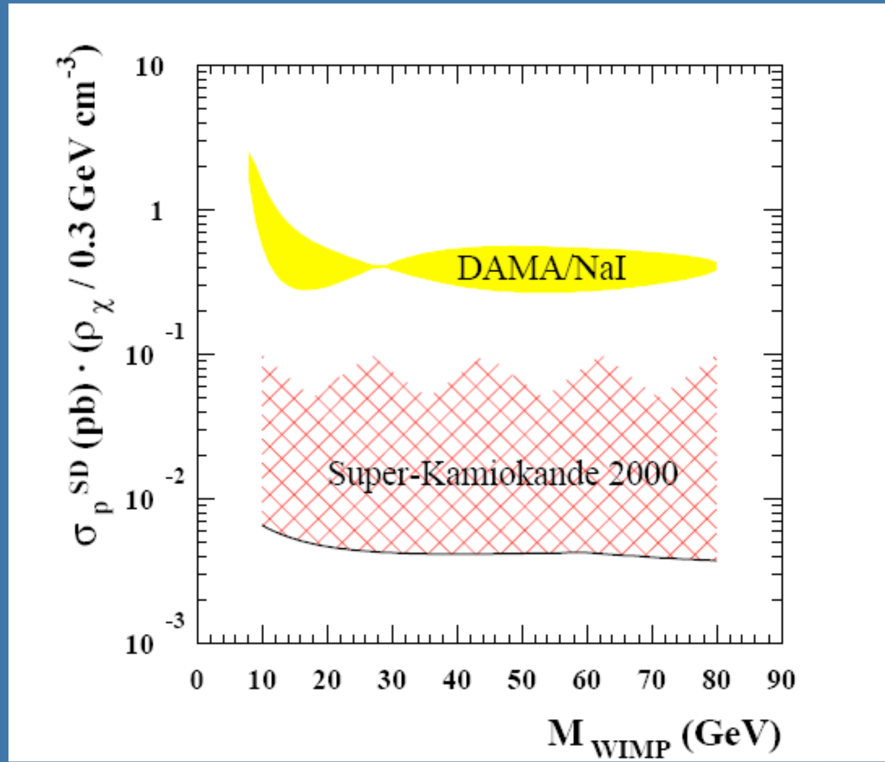




SuperK limit for neutrialino elastic cross section (spin dependent)

(*) S.Desai et al., Phys.Rev. D70 (2004) 083523; Erratum-ibid. D70 (2004) 109901





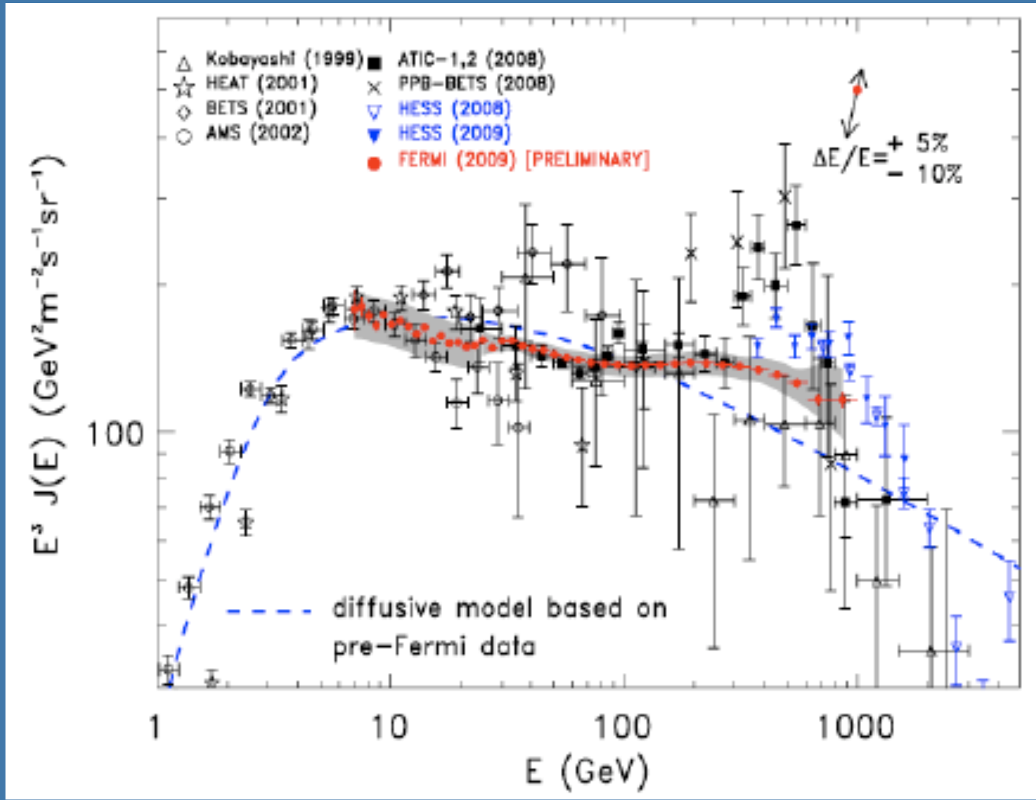
(*) Kamionkowski, Ullio, Vogel JHEP 0107 (2001) 044

- Limit 100 times lower than from direct search experiments
- DAMA annual modulation due to axial vector couplings ruled out by this result *(Kamionkowski et al.)*

» EGRET – excess of gammas (not confirmed by preliminary FERMI data)

» FERMI, HESS – also observe excess of $e^+ + e^-$

» HEAT – excess of e^+



» The indirect experiments seem to see some effect above expected background:
- nearby pulsar (?)
- wrong bkg estimation (propagation) (?)
- DM annihilation (?)

» DM signal would be difficult to concile with standard WIMP model:
- *requires „boost factors" ~ 50-1000*
- *... which could related to DM clumps in local halo (ρ) or different annihilation cross section (but then some excess should likely be observed in more experiments)*

» await more data: PAMELA, FERMI (PLANCK and AMS in future)