Neutrino Group Seminar, 11.I.2010, Wrocław

Search for neutrinos from Dark Matter annihilation in Super-Kamiokande

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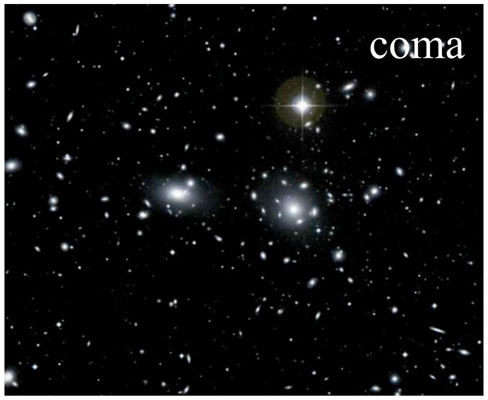
OUTLINE

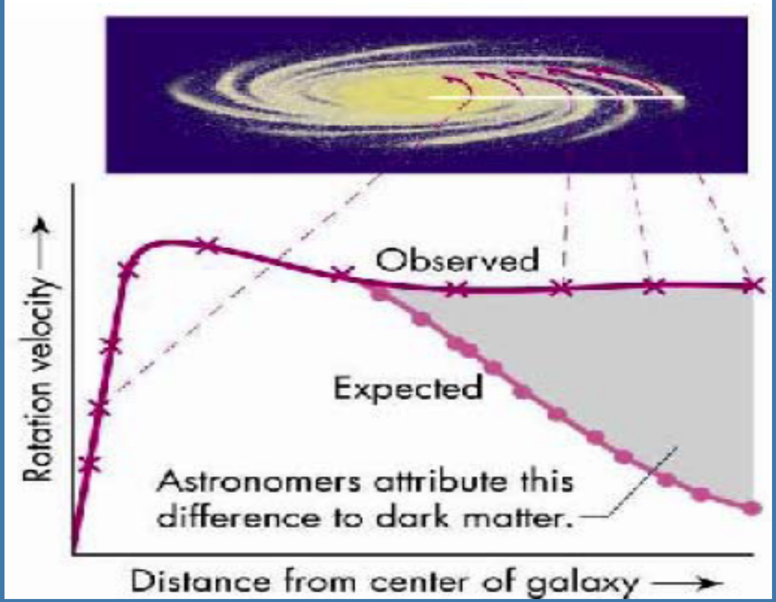
- Dark matter
- Status of experimental searches
  - direct search
  - indirect search
- Search for dark matter with Super-Kamiokande

Dark Matter in the Universe

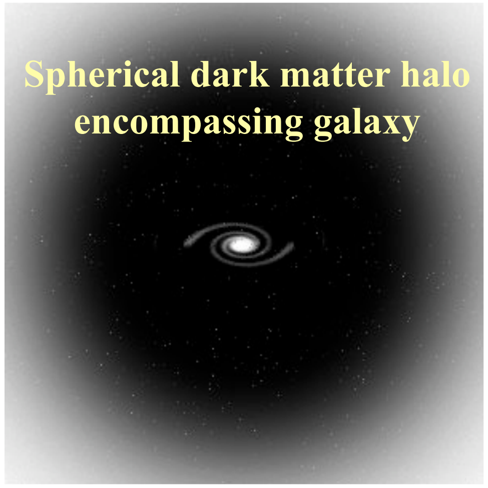
- 1933 r. - Fritz Zwicky, COMA cluster. Velocity of galaxies too high to form bound system (if total mass was related only to luminous part of the system)



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



Astronomers attribute this difference to dark matter.



CONCLUSIONS

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

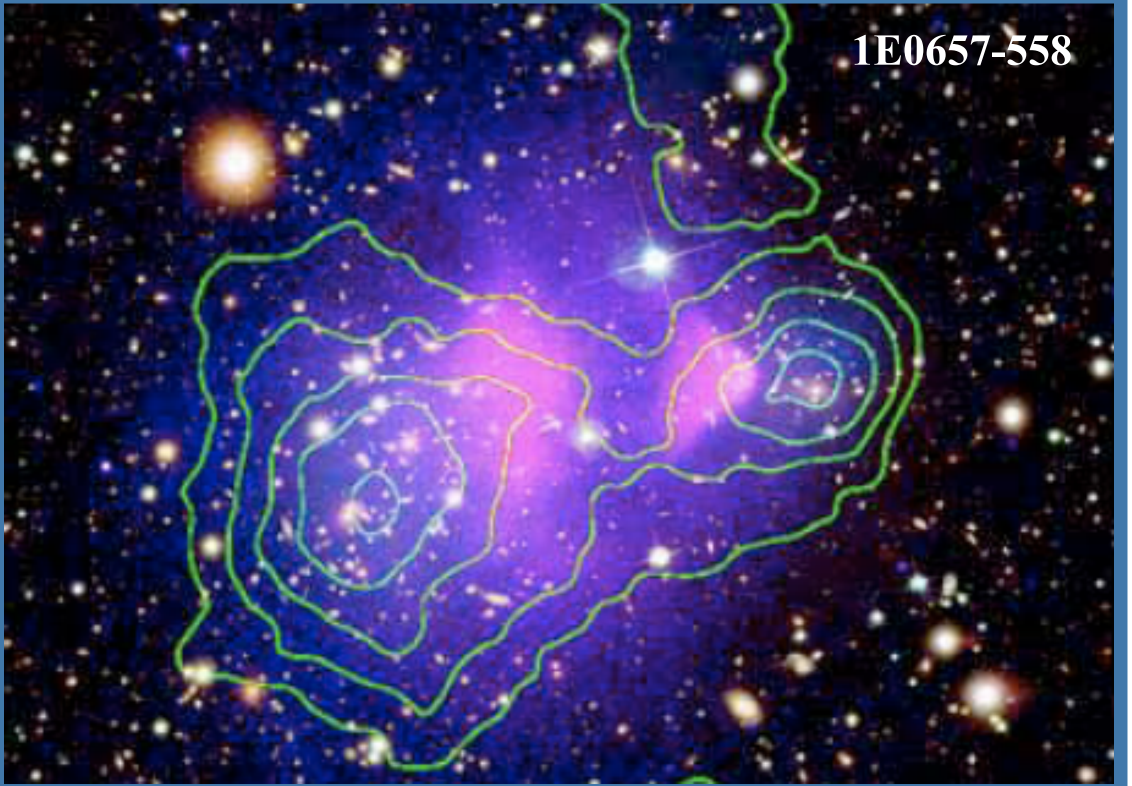
Bullet Cluster

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

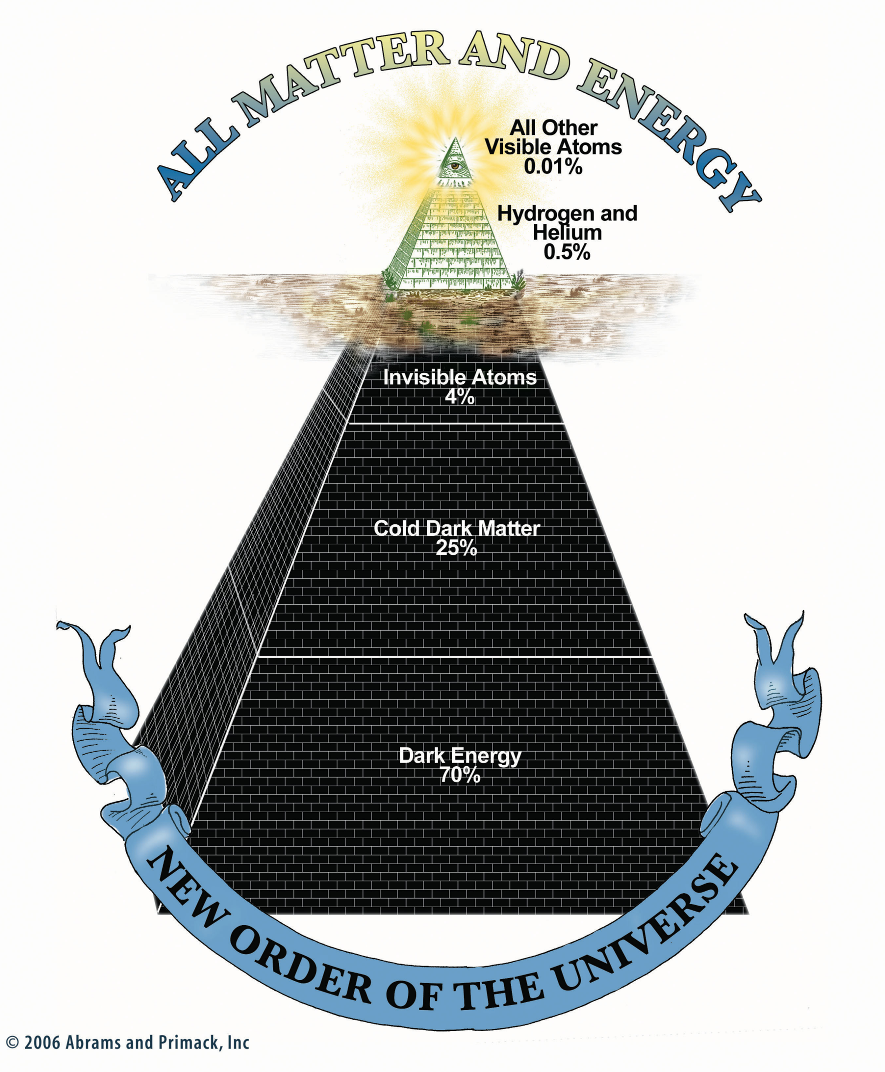
Cosmological parameters

- » 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

< 7% Galactic Halo mass (exp. EROS)

» Existing particles
  - ~~MACHO's~~ (**M**assive **A**stronomical **C**ompact **H**alo **O**bjects), **i.e. neutron stars, black holes, brown dwarfves ...**
  - ~~**neutrinos**~~ **- H**ot **D**ark **M**atter (**HDM**)

cosmic structure formation requires CDM

» Predicted:
  - **Axions**
  - **WIMPs** (**W**eakly **I**nteracting **M**assive **P**articles) - **C**old **D**ark **M**atter (**CDM**)

» Exotic:
  - WIMPzillas, LIMPs, Kaluza-Klein DM, monopoles, sterile neutrinos…

WIMP

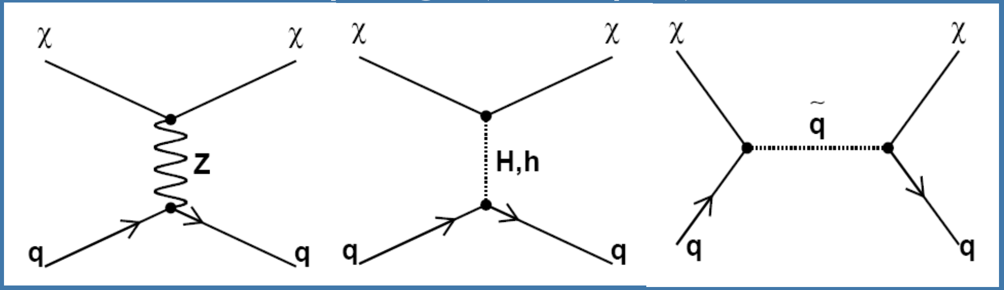
Weakly Interacting Massive Particle

Search for particles:

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

  $\sigma \leq 10^{-2}$pb (10^{-38} 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 GeV < M_χ < ~10 TeV

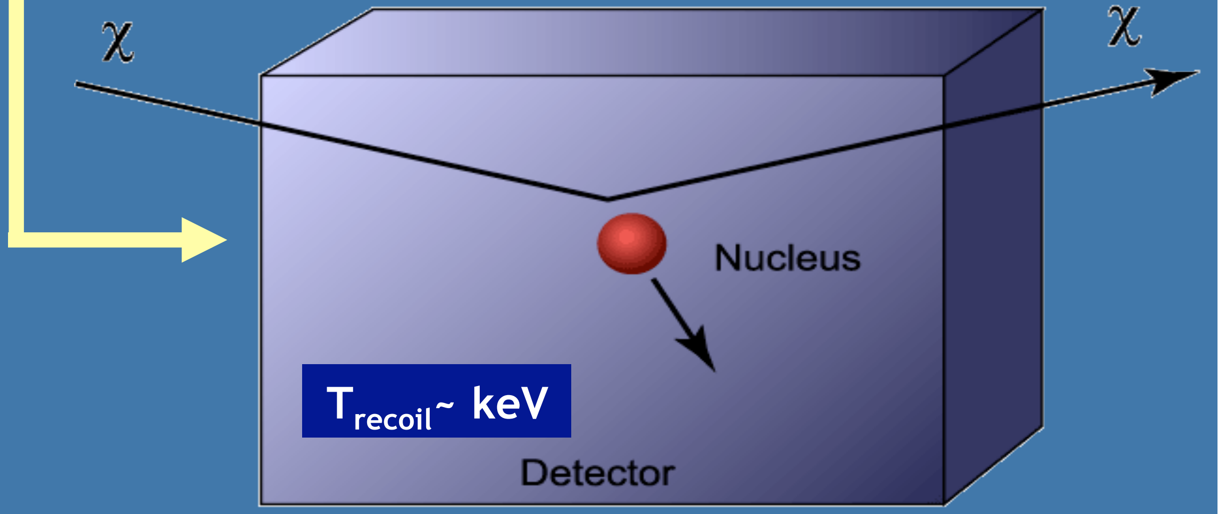
LEP **cosmology**

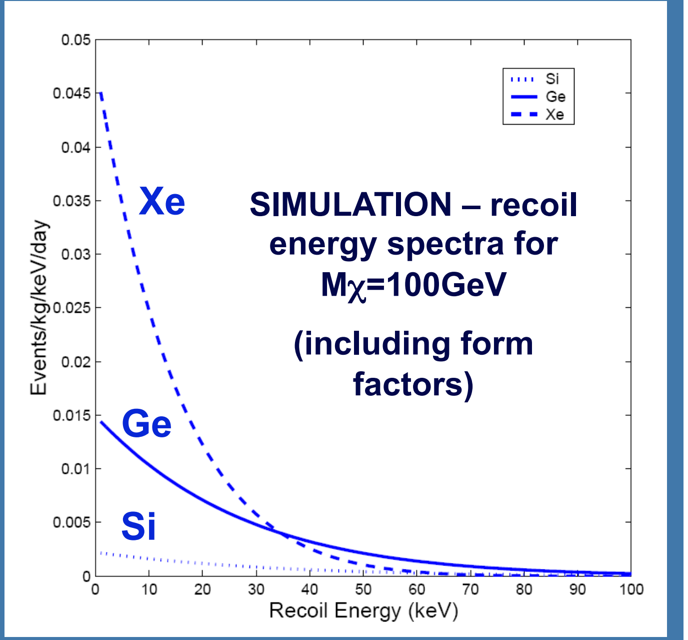
Direct search for WIMPs (χ's)

» Direct detection experiments:

  - production in accelerators (LHC)
  - WIMP-nucleus elastic scattering

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

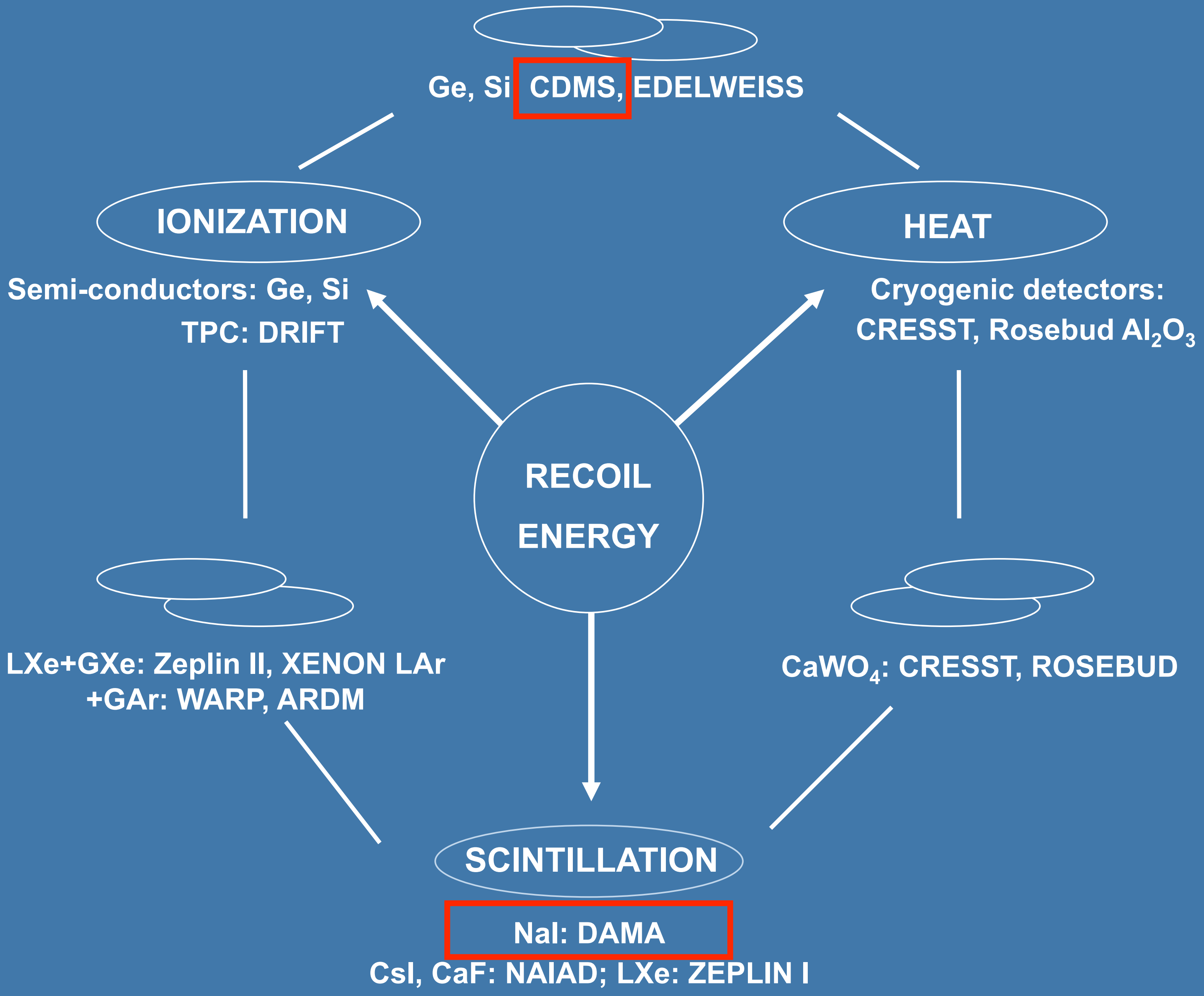




SIMULATION – recoil energy spectra for Mχ=100GeV

(including form factors)

» Terrestrial experiments (χ's in Galactic Halo)



Ge, Si CDMS, EDELWEISS

IONIZATION

Semi-conductors: Ge, Si

TPC: DRIFT

HEAT

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

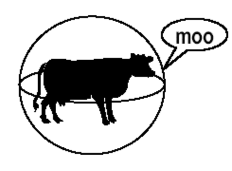
CsI, CaF: NAIAD; LXe: ZEPLIN I

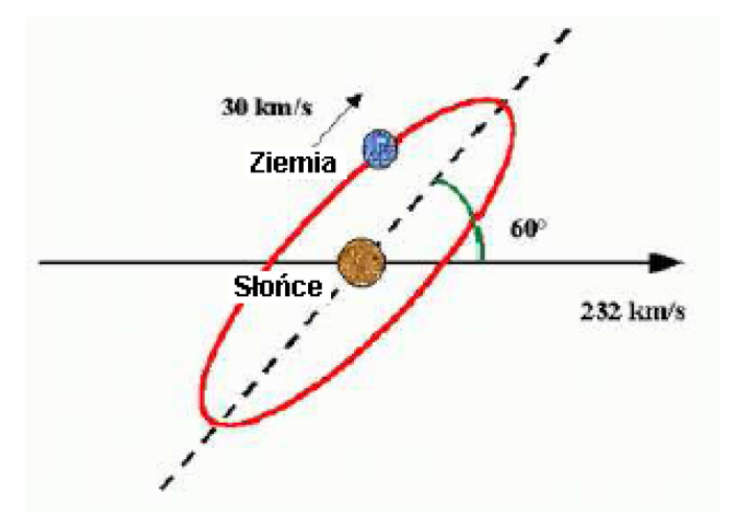
Annual modulation effect

$$\text{event Rate} \sim \rho \cdot V \cdot \sigma$$

halo model

- WIMP velocity distribution in Halo: *Maxwell-Bolzmann* with mean velocity with respect to Galactic Center $<V> = 0$, dispersion $V_0 = 220$ km/s
- $V_{\text{solar system}} \approx 230$ km/s -> **depends on time of the year**
- ρ - WIMP density in halo (~ 0.3 $\text{GeV/c}^2 \cdot 1/\text{cm}^3$ @ Solar System position)





Effective Earth velocity with respect to the Galactic Center:

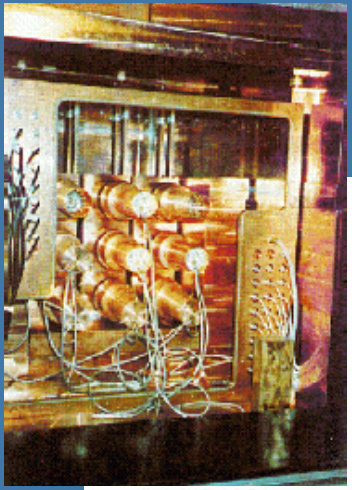
Maximum - June/2 - $V \approx 248$ km/h

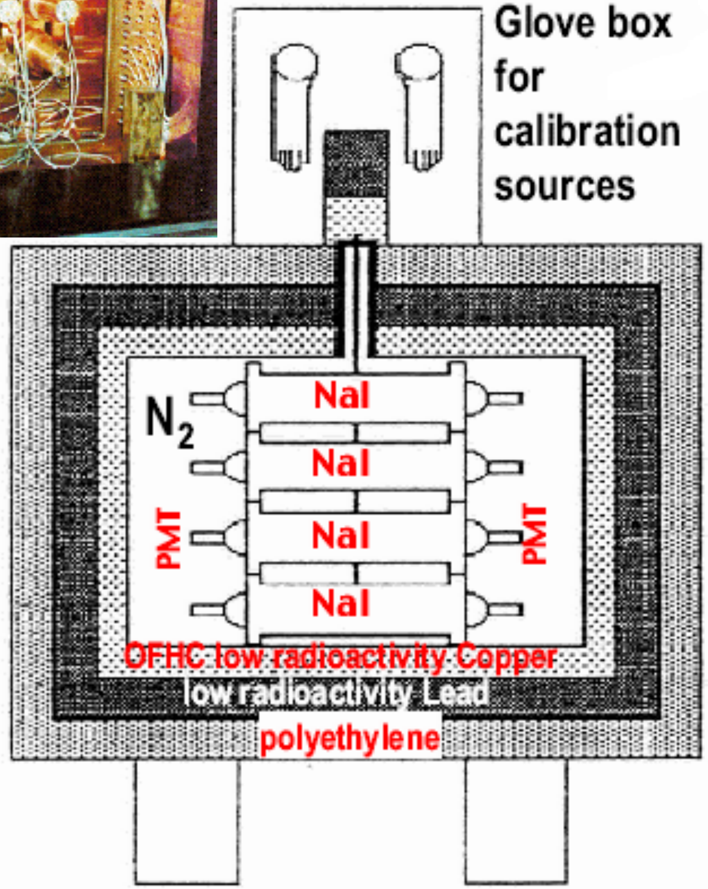
Minimum - Dec/2 - $V \approx 219$ km/h

DAMA/LIBRA (~250kg NaI)

DArk Matter/Large sodium Iodide Bulk for RAre processes

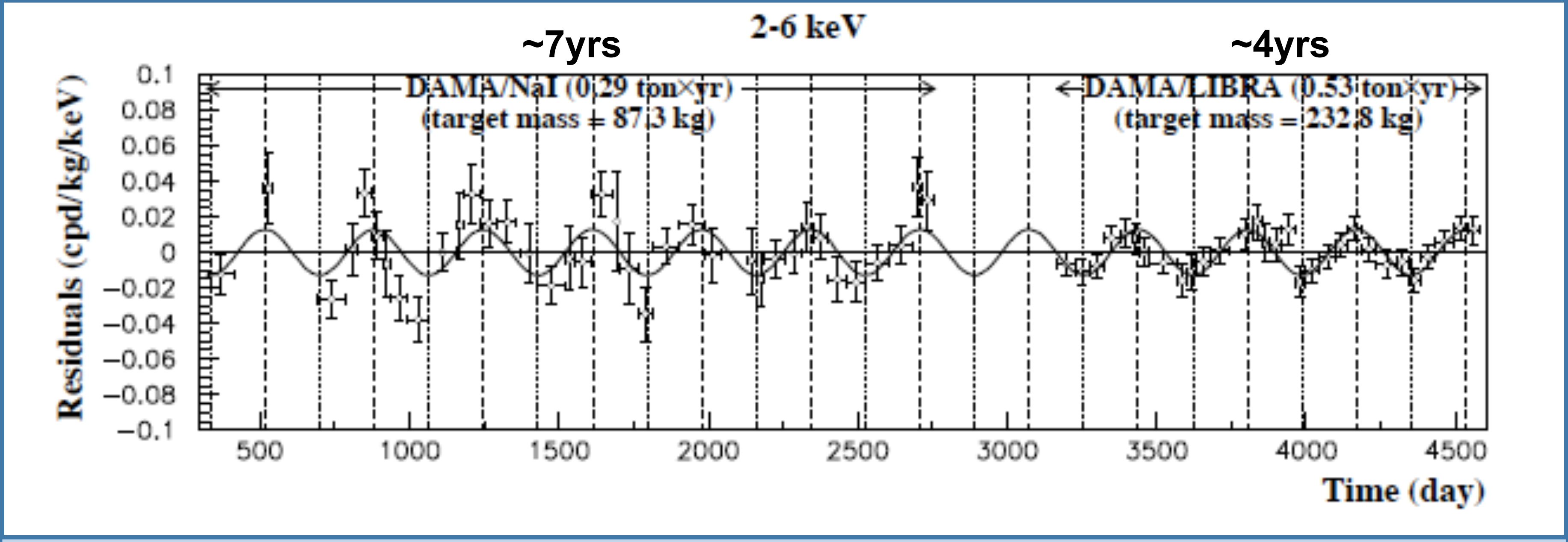
- Gran Sasso in Italy (4000 m w.e.)
- DAMA/NaI in operation from 1996
- NaI(Tl) scintillation crystals – 25 x 9.7 kg ≈ 250 kg; signal detected by two PMTs
- No active electron/gamma bkg determination technique
- Energy > 2 keV
- Exposition – 0.82 tonne·years





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
- only in one detector

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

» model independent evidence

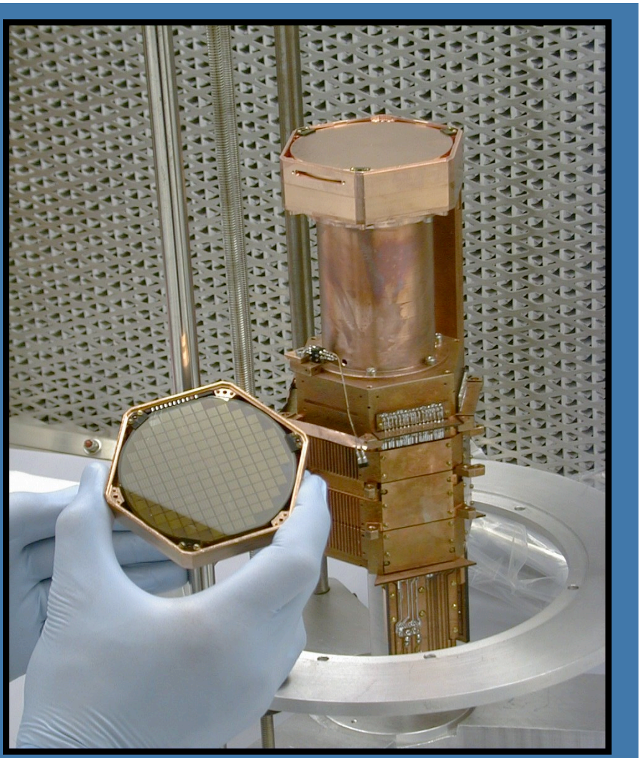
» no signal modulation > 6 keV and in „multiple hits events"

CDMS

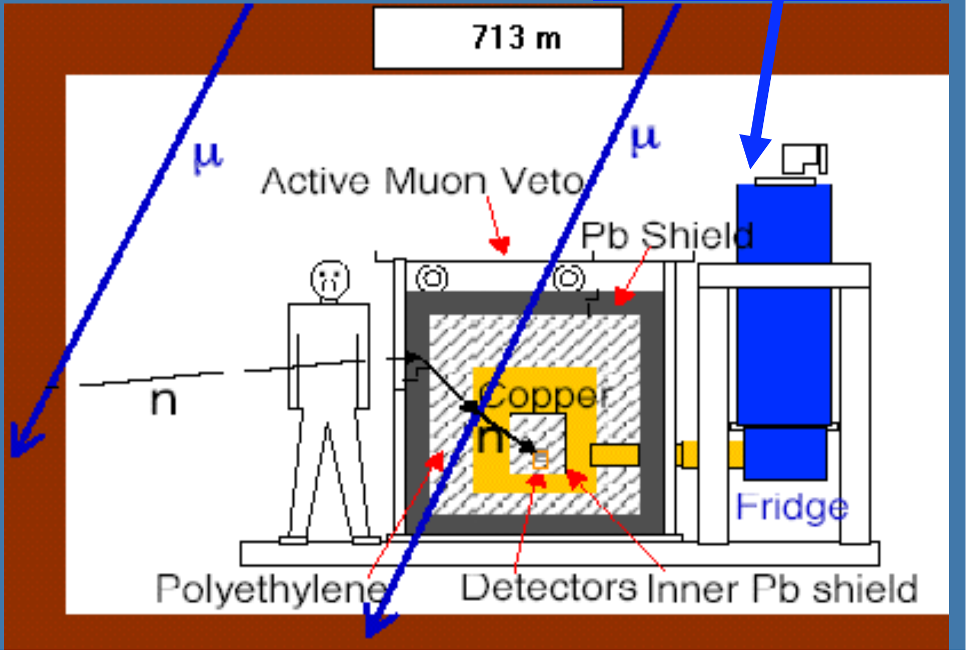
(Cryogenic Dark Matter Search)

new results published 17 Dec. 2009

- CDMS II @ Soudan Lab (2004-2009) depth 713 m (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
  - xy-position imaging
  - surface (z) event rejection from pulse shape and timing



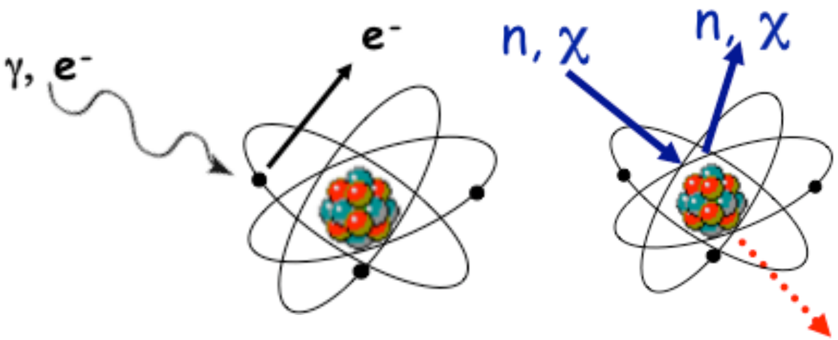
T < 0.01 K



CDMS – results (Dec. 2009)

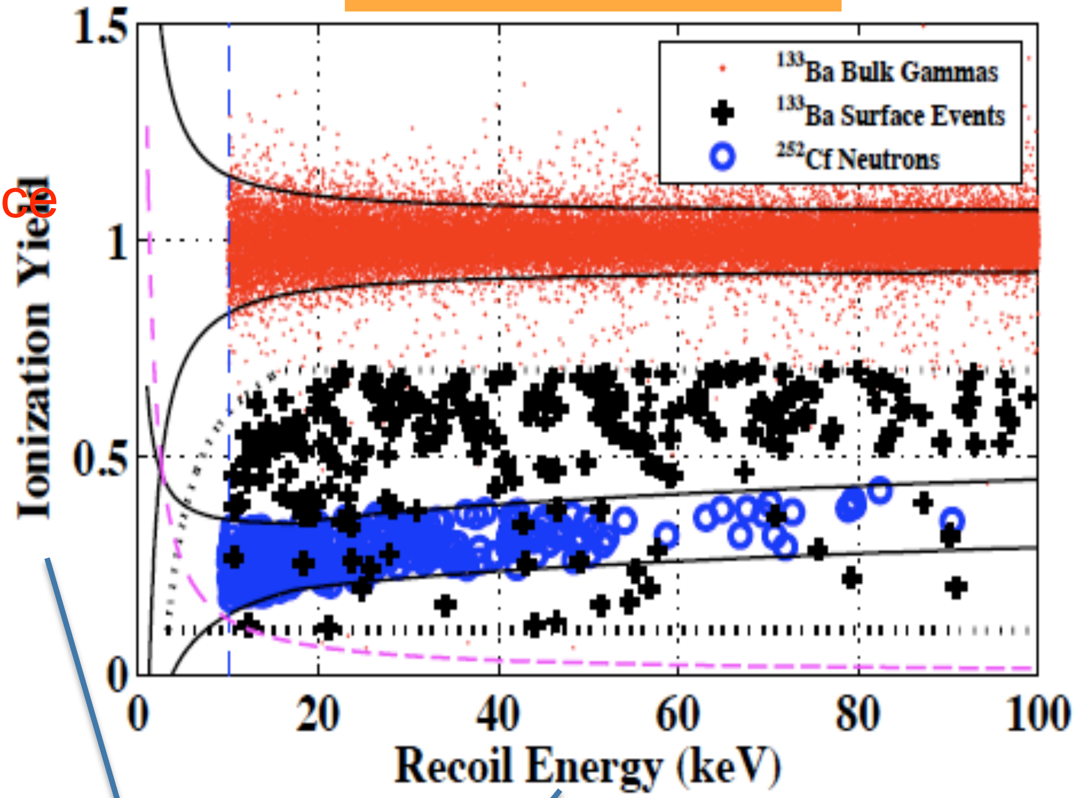
(*) J.Cooley @ SLAC Dec/17/2009

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



- Most backgrounds (e,γ) produce electron recoils
- WIMPs and neutrons 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 and pluse shape of the signal

calibration data



„recoil energy” – phonon energy

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

CDMS – results (Dec. 2009)

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

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

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

2 events in signal region

Expected background

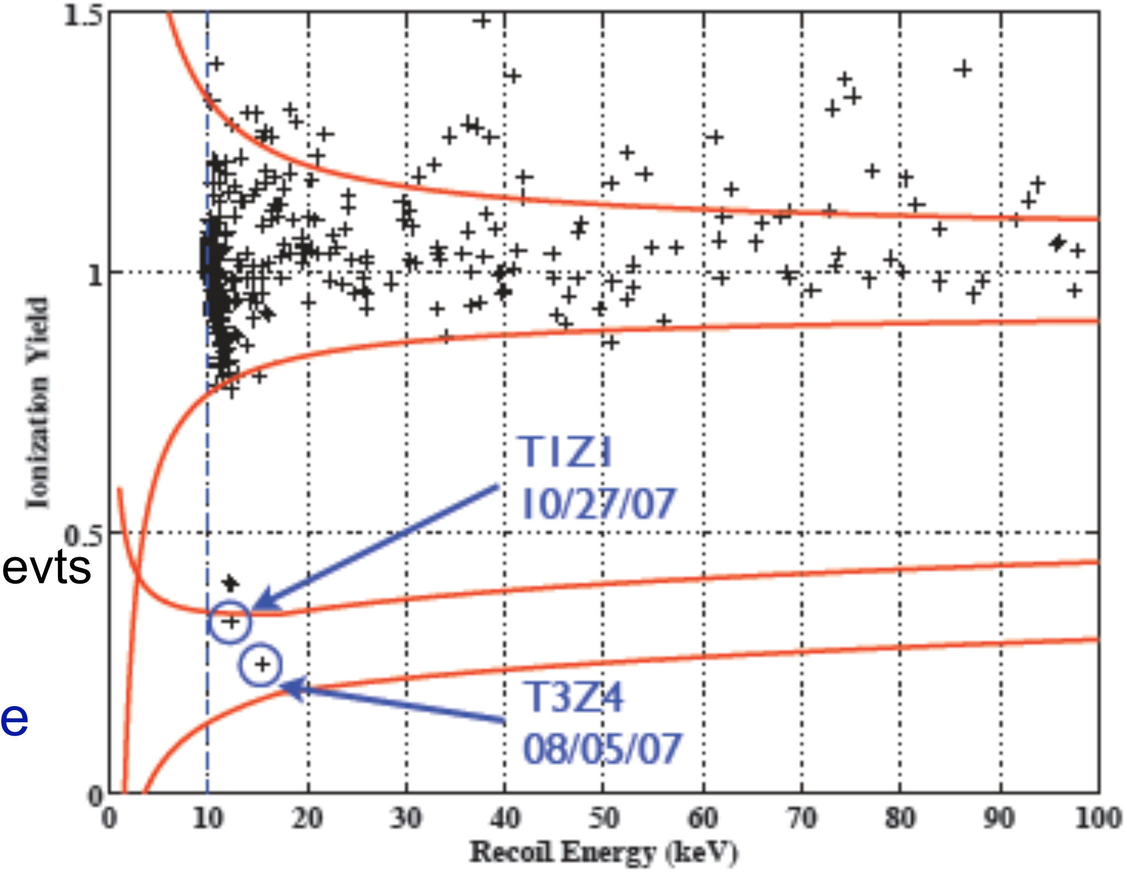
- „surface" events:

0.80 ± 0.1(stat) ± 0.2(syst)

- cosmogenic neutrons: 0.04 evts
- radioactivity neutrons: 0.03-0.06 evts

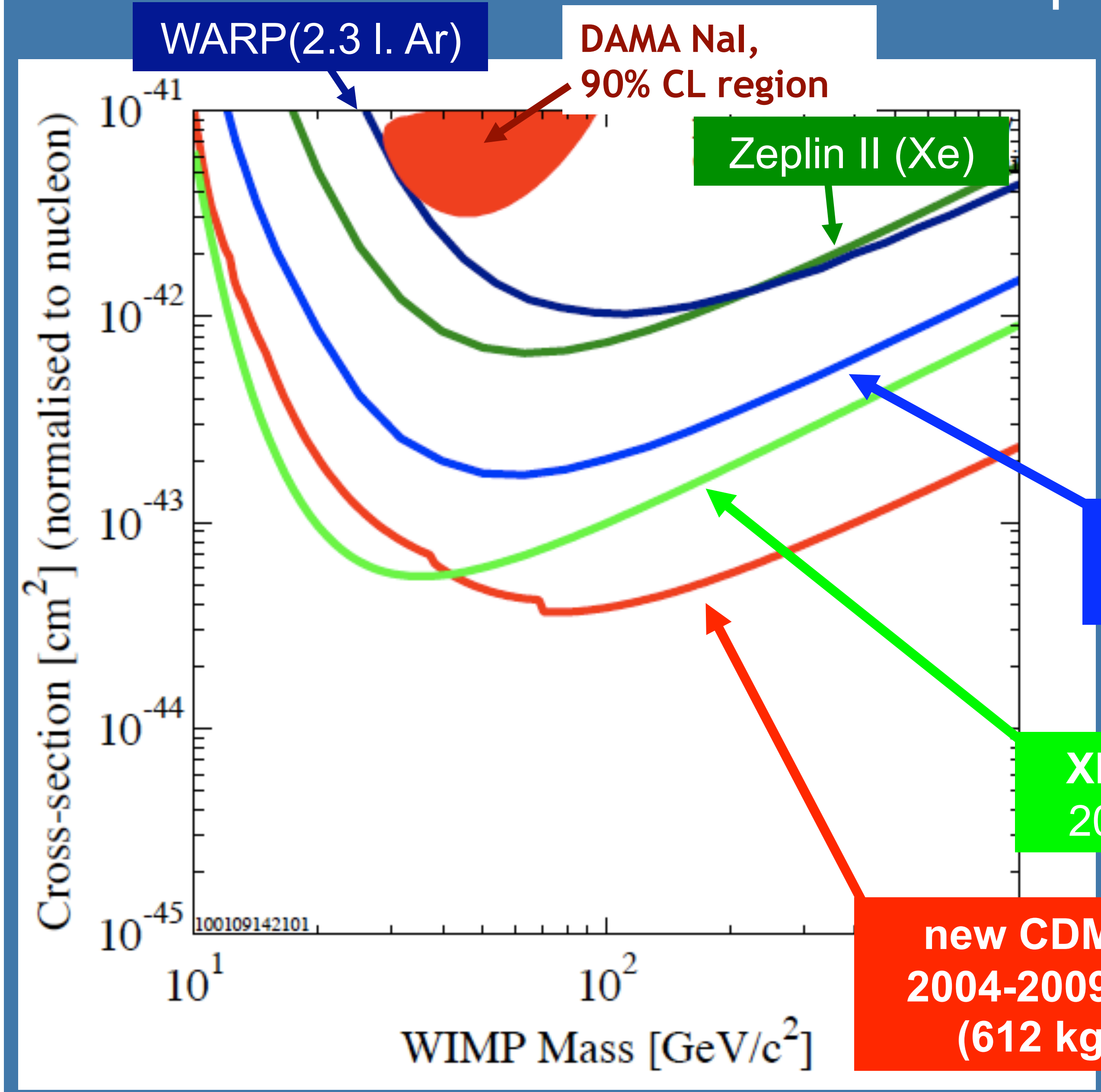
Probability of observing 2 or more background events is 23%

data (from 2 detectors only)



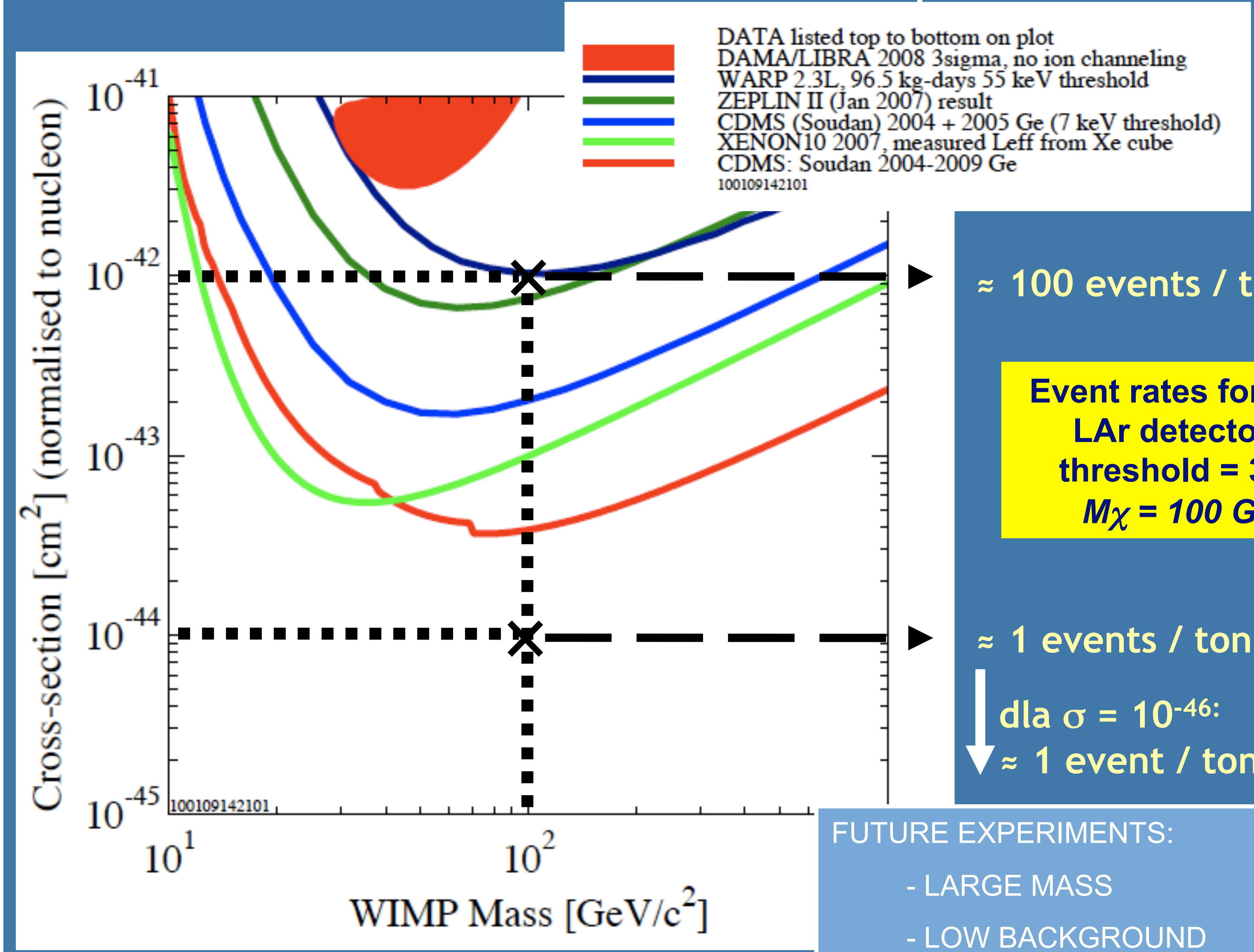
"Our results cannot be interpreted as significant evidence for WIMP interactions. However, we cannot reject either event as signal." (*)

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, *Mχ = 100 GeV/c^2*

≈ 1 events / tonne / day

dla σ = 10^{-46}:

≈ 1 event / tonne /100 days

FUTURE EXPERIMENTS:

- LARGE MASS
- LOW BACKGROUND
- LONG EXPOSITION

P.Mijakowski

Indirect search for WIMPs

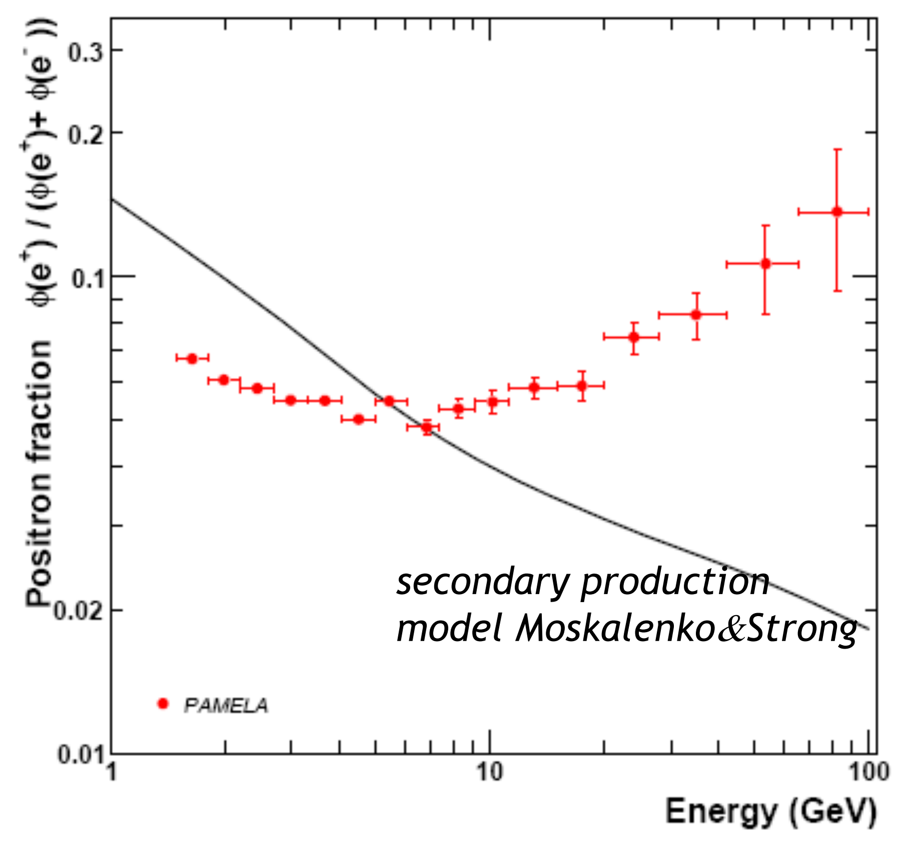
- Indirect search = search for annihilation products of χ's (self-antiparticle):
  - gammas *(HESS, MAGIC, EGRET, GLAST/FERMI)*
  - anti-matter: positrons, anti-deuteron, anti-proton *(PAMELA, HEAT, BESS, ATIC, AMS-02 …)*
  - neutrinos *(Super-Kamiokande, Ice-Cube, ANTARES)*

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

Positron/electron excess observed in primary cosmic rays by PAMELA & ATIC

PAMELA: positron ratio in cosmic rays

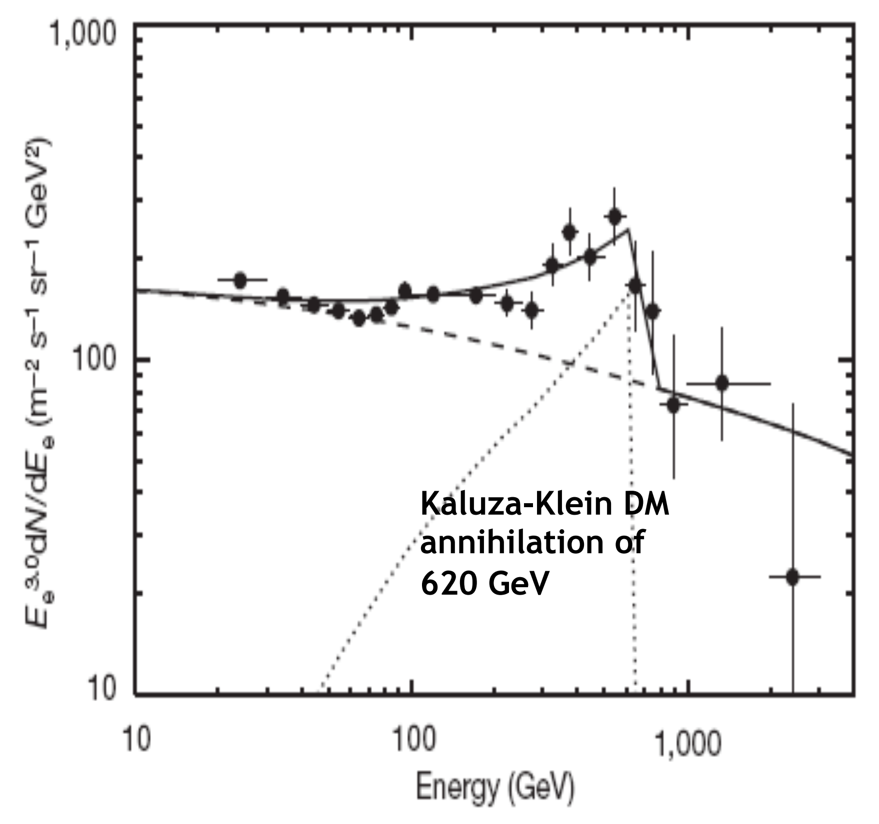
O.Adriani et al. [PAMELA Collaboration],
Nature, 458,607-609(2009)



secondary production
model Moskalenko&Strong

ATIC: e^++e^- flux in cosmic rays

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

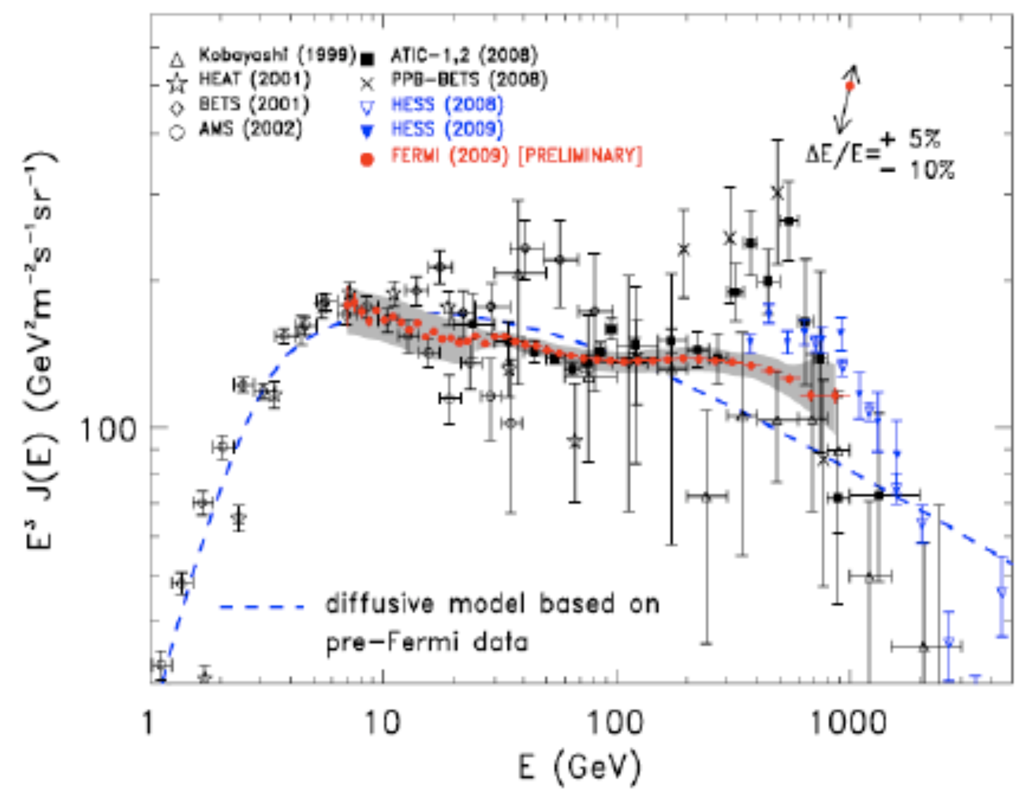


Kaluza-Klein DM
annihilation of
620 GeV

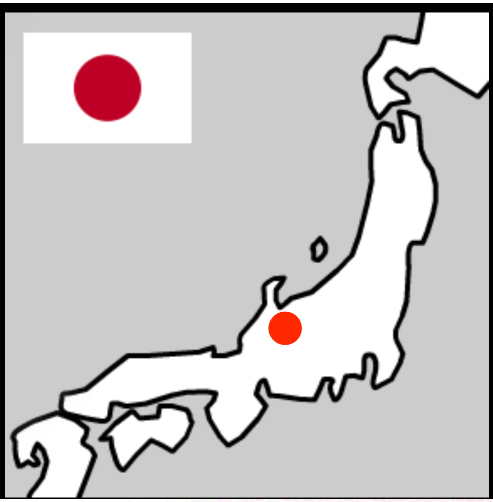
positrons from secondary production

$$\left\{\begin{array}{l}\mathrm{CR} + \mathrm{ISM} \to \pi^\pm + \ldots \to \mu^\pm + \ldots \to e^\pm + \ldots \\ \mathrm{CR} + \mathrm{ISM} \to \pi^0 + \ldots \to \gamma\gamma \to e^\pm\end{array}\right.$$

- 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 (?)



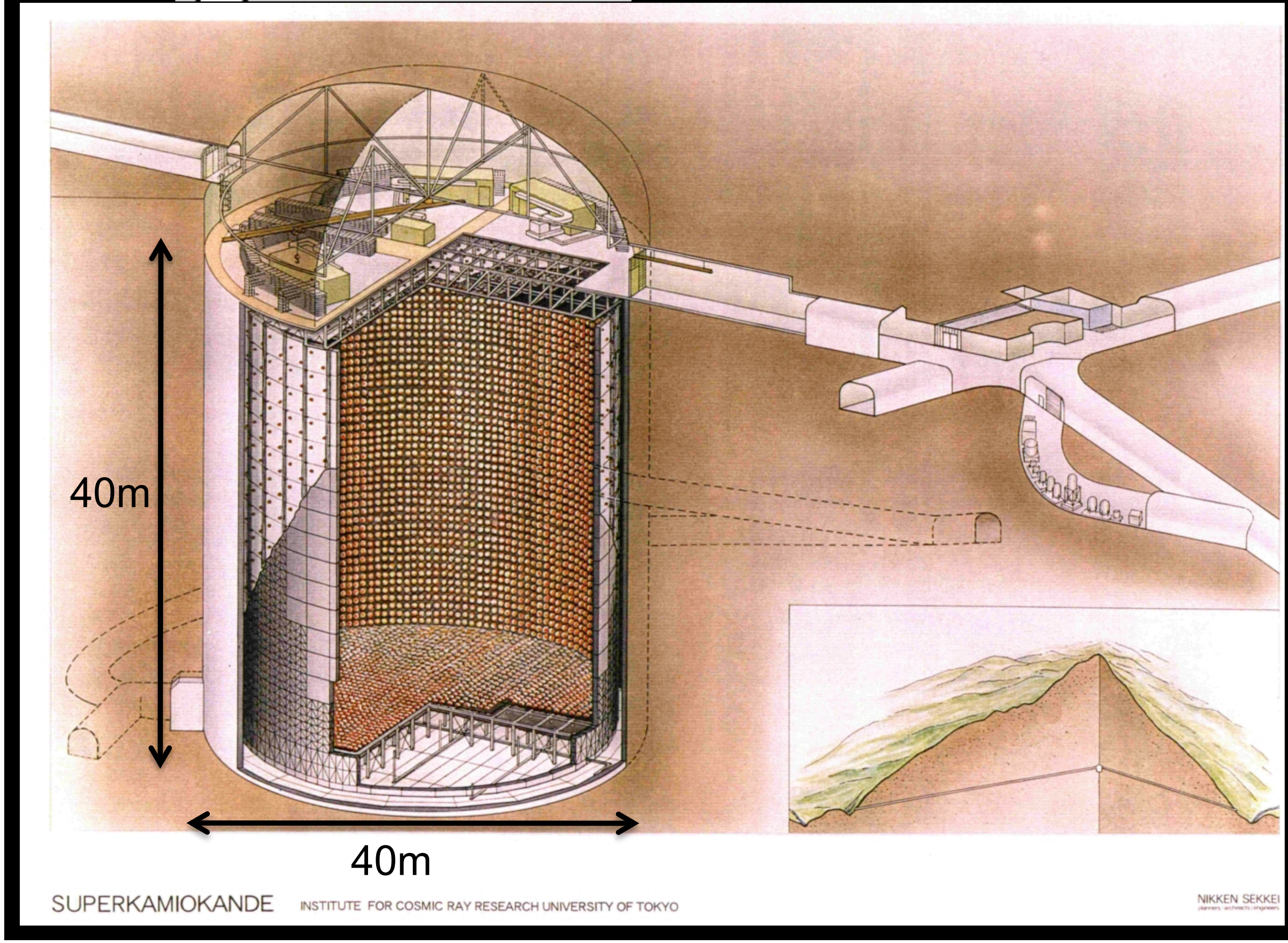
- DM signal would be difficult to concile with standard WIMP model:
  - *requires „boost factors" ~ 50-1000*
  - *... which could related to DM clumps in local halo (ρ) or different annihilation cross section (but then some excess should likely be observed in more experiments)*
- await more data: PAMELA,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



Super-Kamiokande

Water Cerenkov detector in Kamioka, Japan

- in operation since 1996



- 50kton water, 22.5kton fiducial volume
- 12k inner PMTs /2k outer PMTs

detect light; possible reconstruction of energy and direction of neutrinos

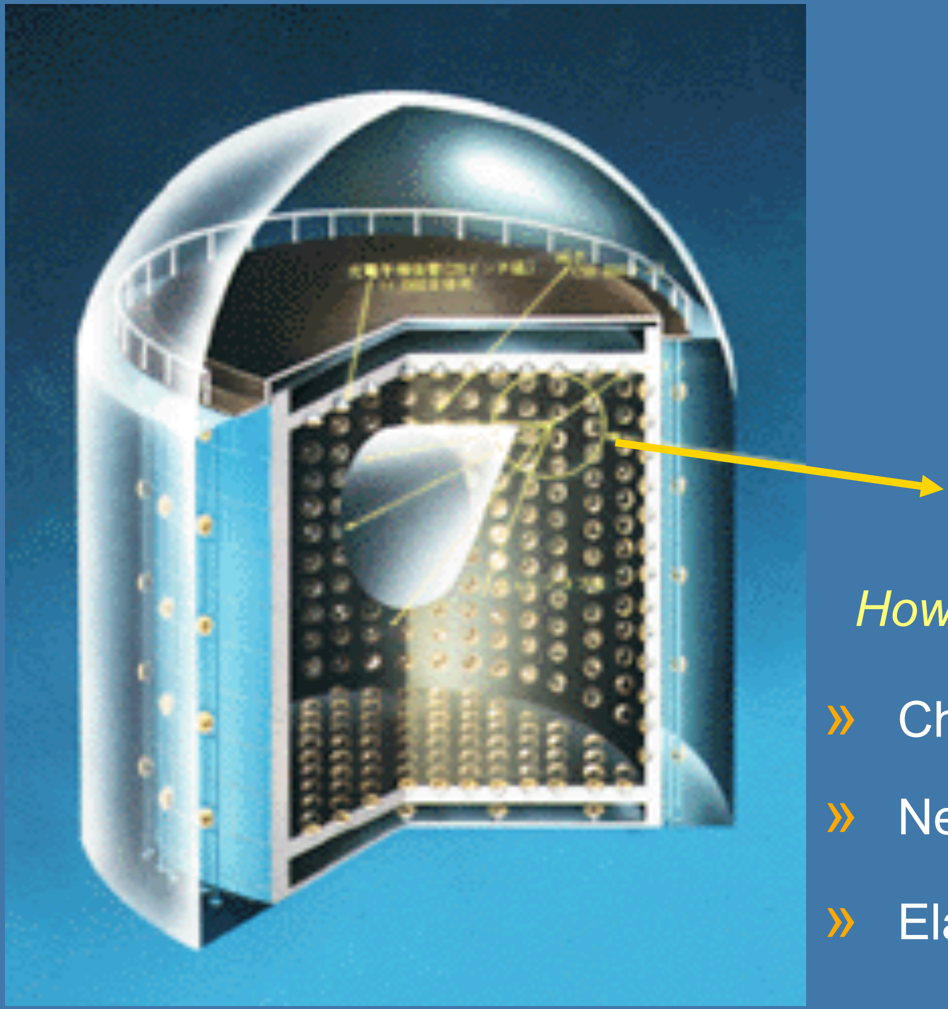
- SK investigates atmopsheric/cosmic,

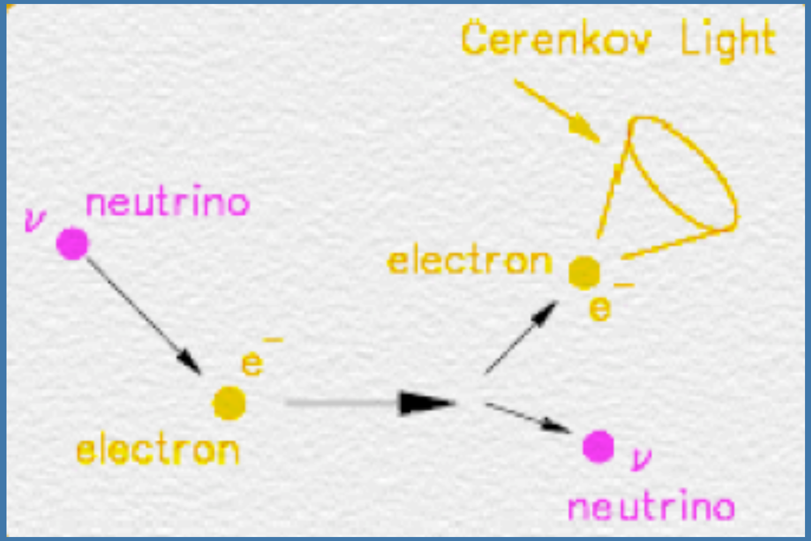
solar & accelerator ν

- detect SN1987 ν's
- neutrino oscillation discovery (1998)

Water Cerenkov detector principle

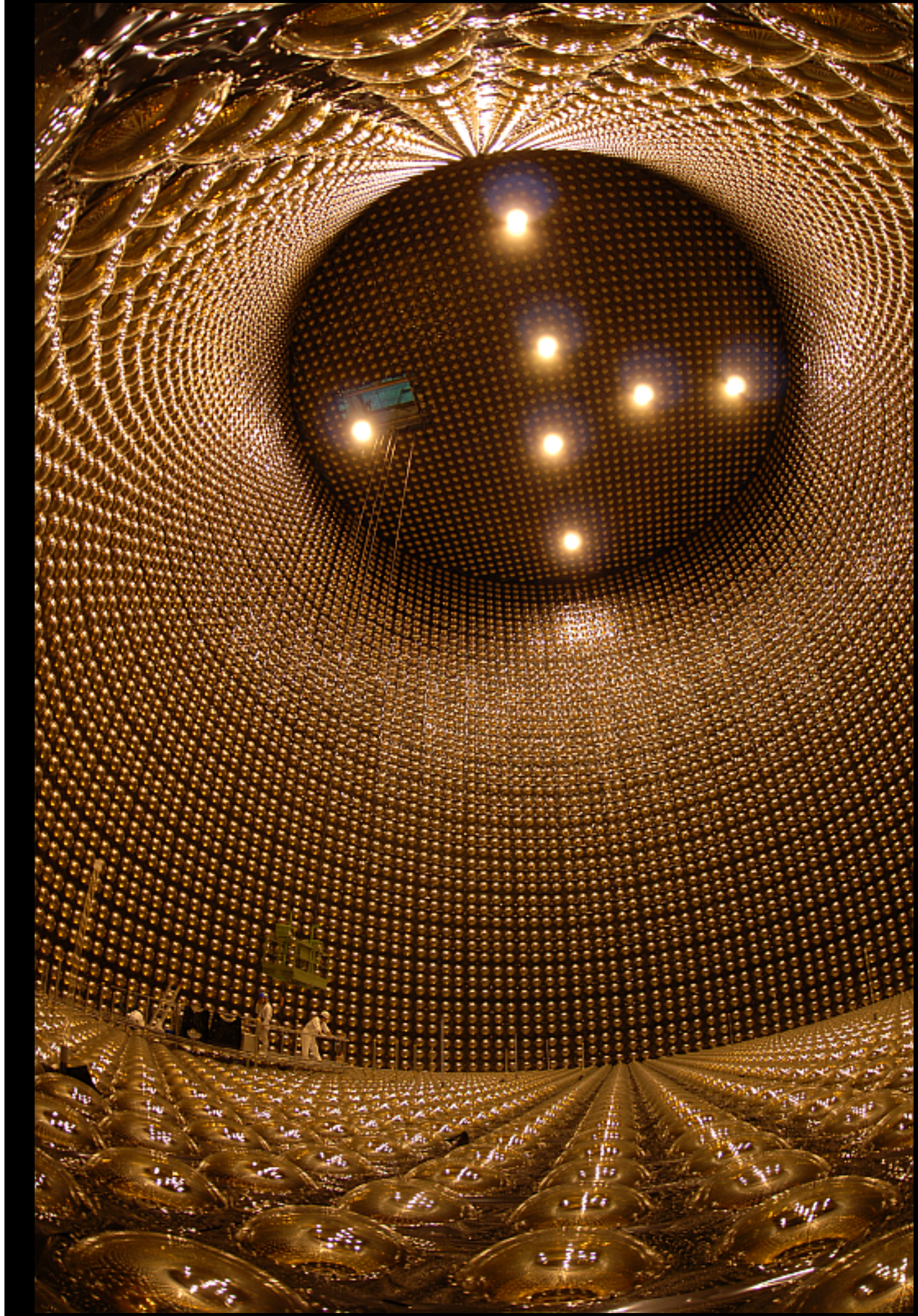
- Charged particles propagating in water with v > c in water emit e-m radiation

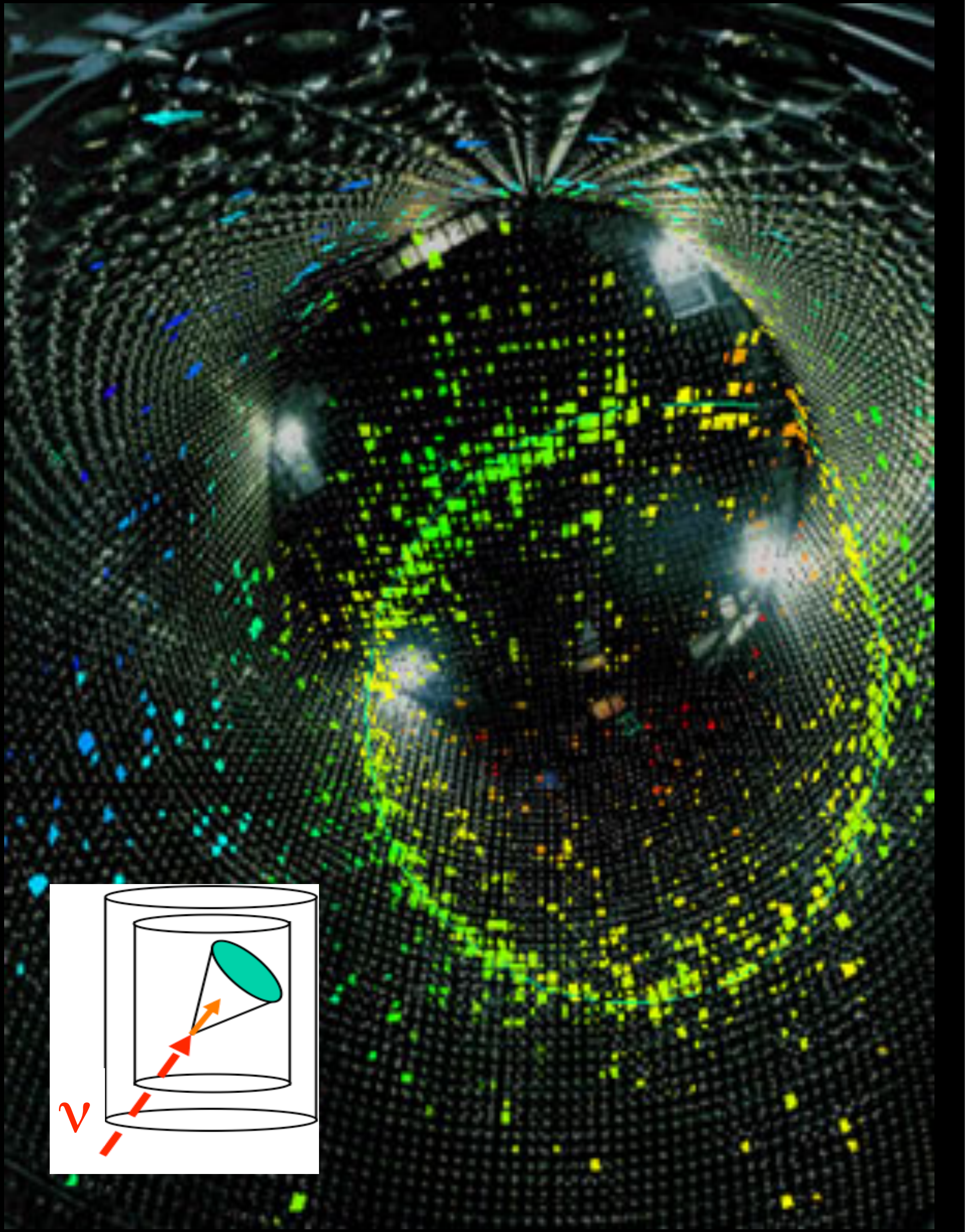




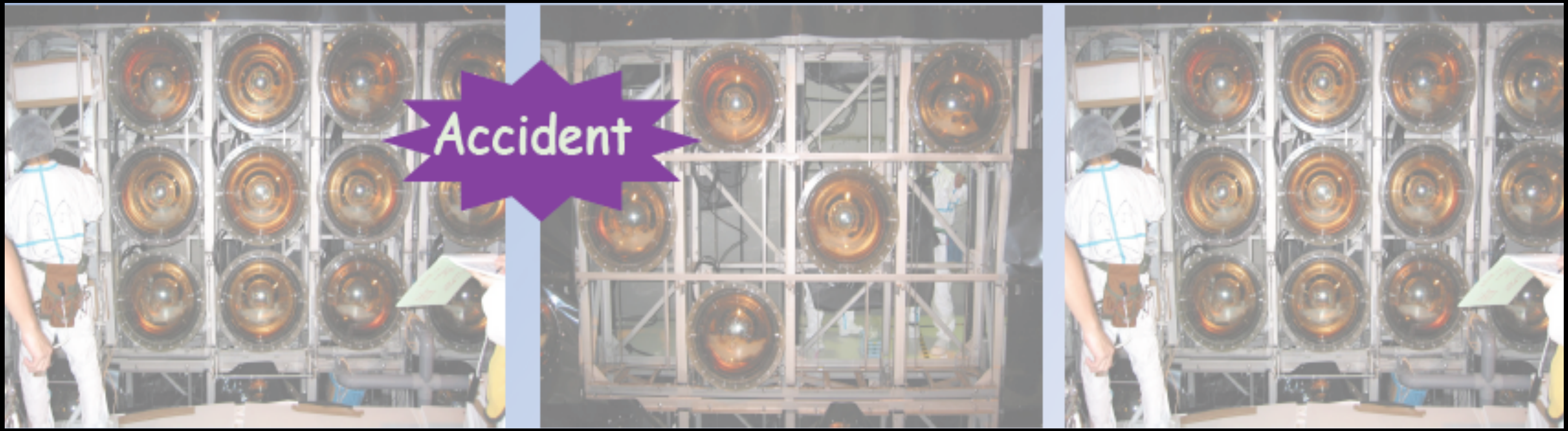
How neutrinos interact?

- Charged Current ν + N->μ/τ/e+p+...
- Neutral Current ν + N->ν+n+...
- Elastic Scattering ν + e^-->ν+e^-




ν

Super-K phases



SK-I

runs 1996-2001

accident in 2001

SK-II

runs 2002-2005

~50% PMTs

SK-III

runs Sep/2006-sep/2008

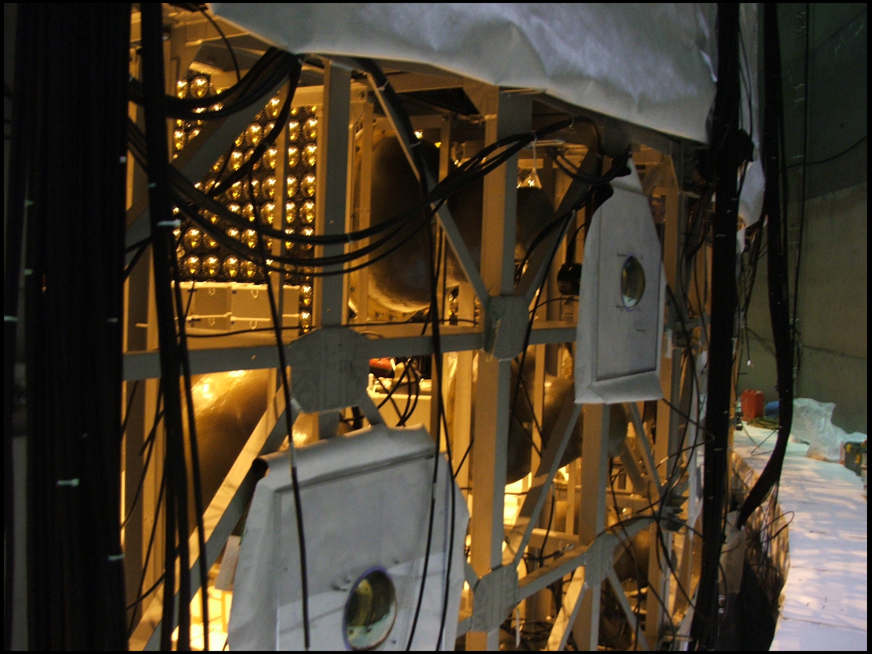
fully reconstructed

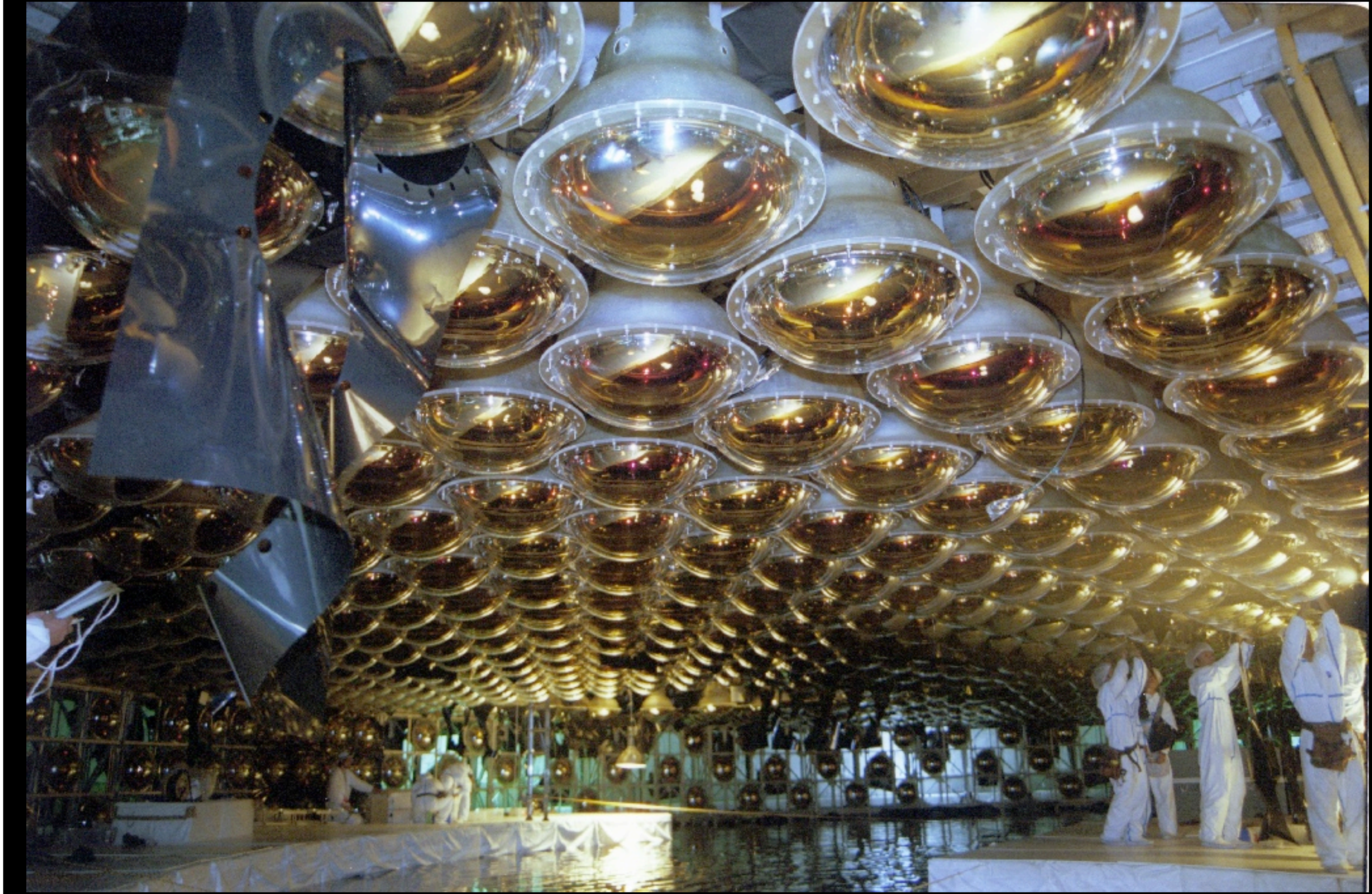
added acrylic shells for PMTs

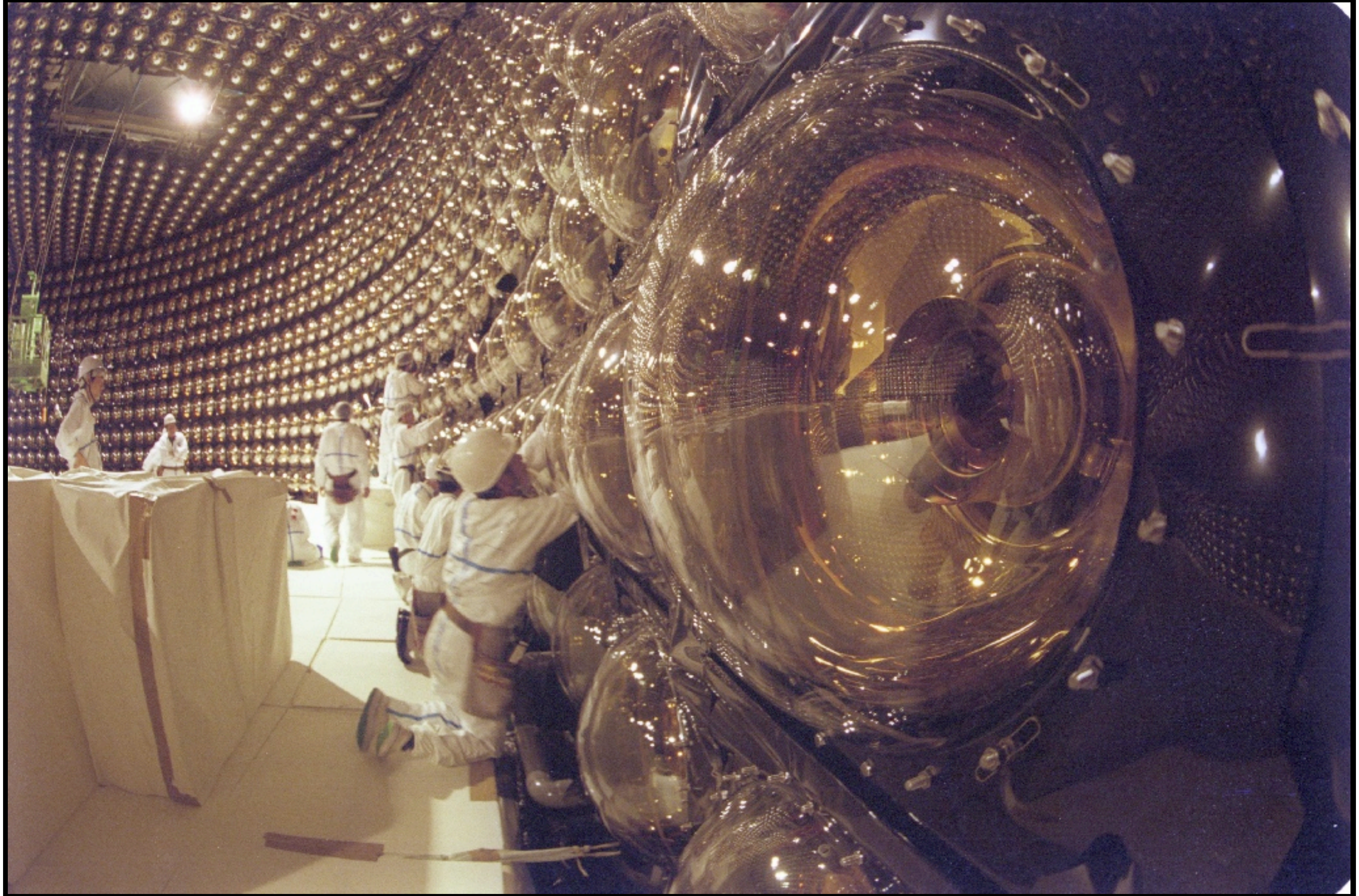
SK-IV from 6/Sep 2008

- new electronics/DAQ/online software
- ready for T2K beam

SK-III reconstruction in 2006





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雪崩注意


立入禁止

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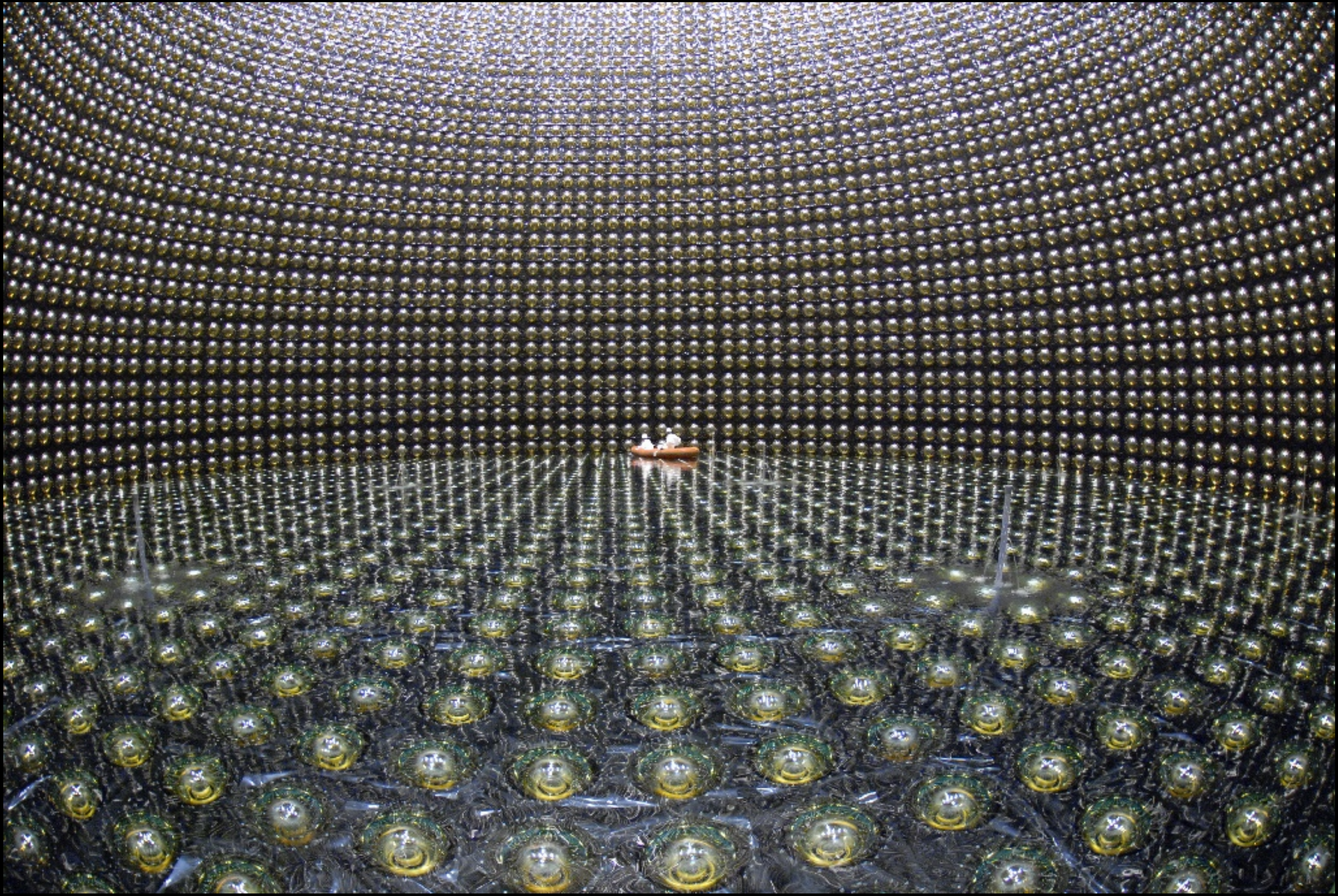
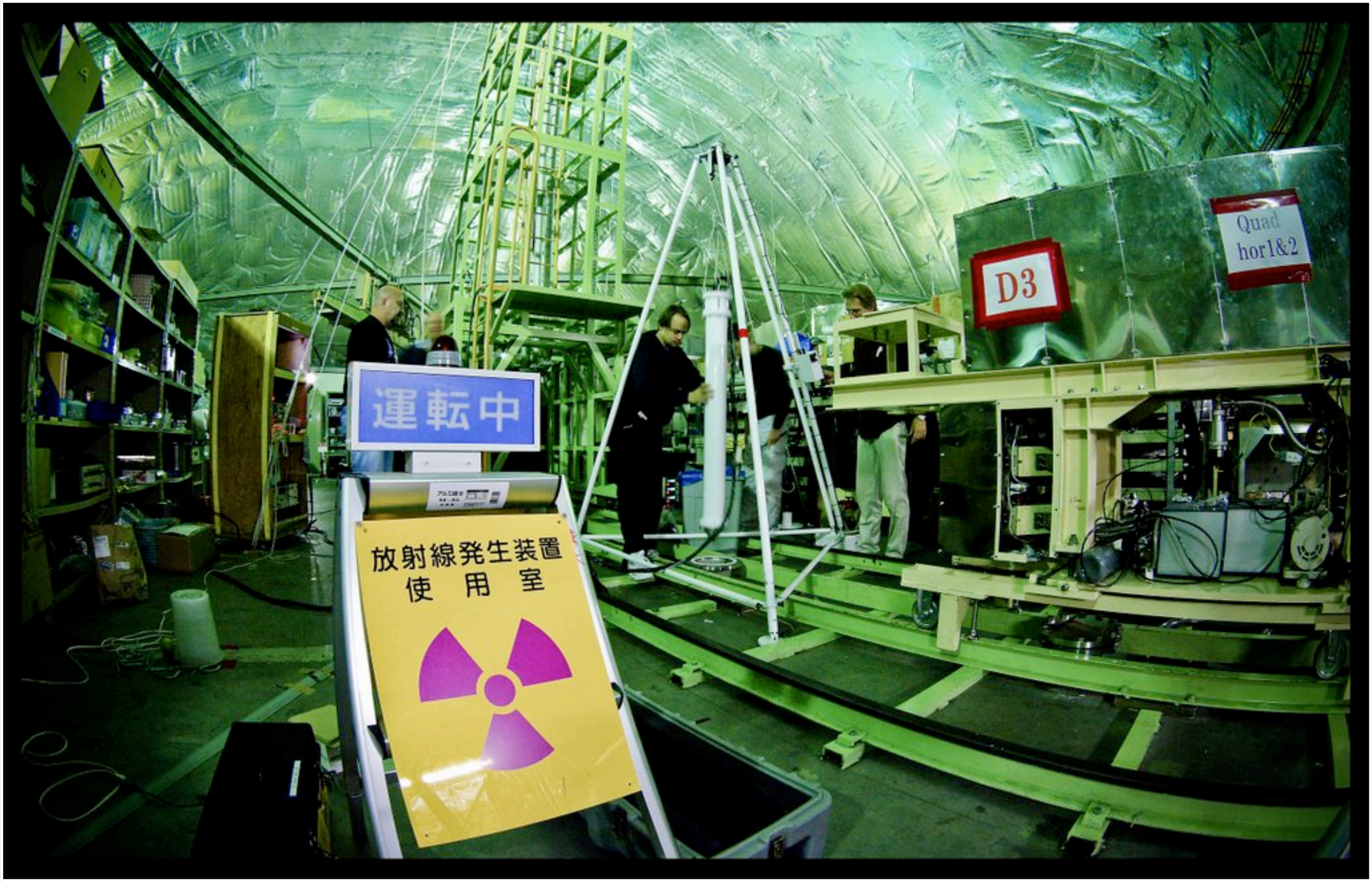


© Kamioka Observatory, ICRR, Univ, of Tokyo

Super-Kamiokande: ~100 people

60% 🇯🇵, 40% 🇺🇸, small groups from 🇰🇷, 🇨🇳, 🇪🇸

2 pers. 🇵🇱 : prof. Danuta Kiełczewska, Piotr Mijakowski



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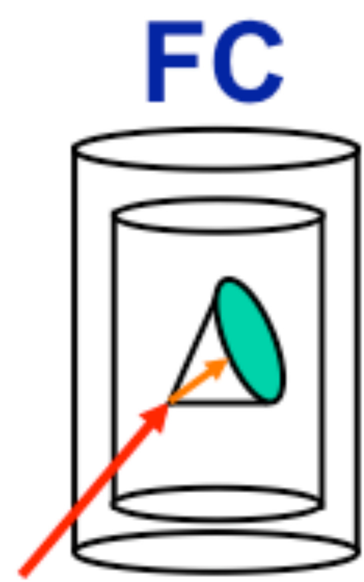
Super-K data sample

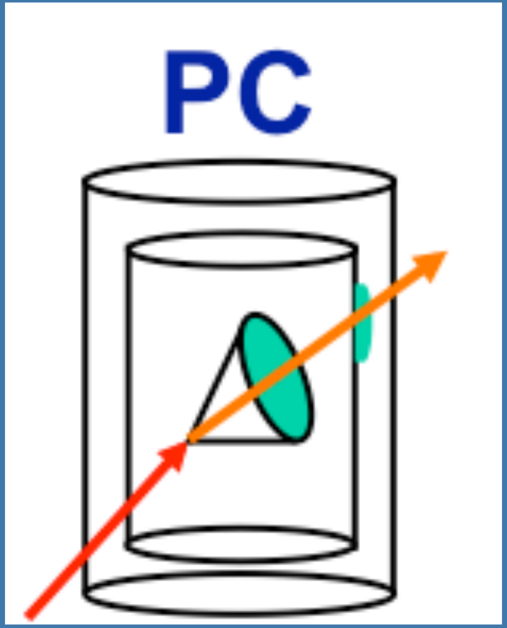
(event classification)

Fully contained



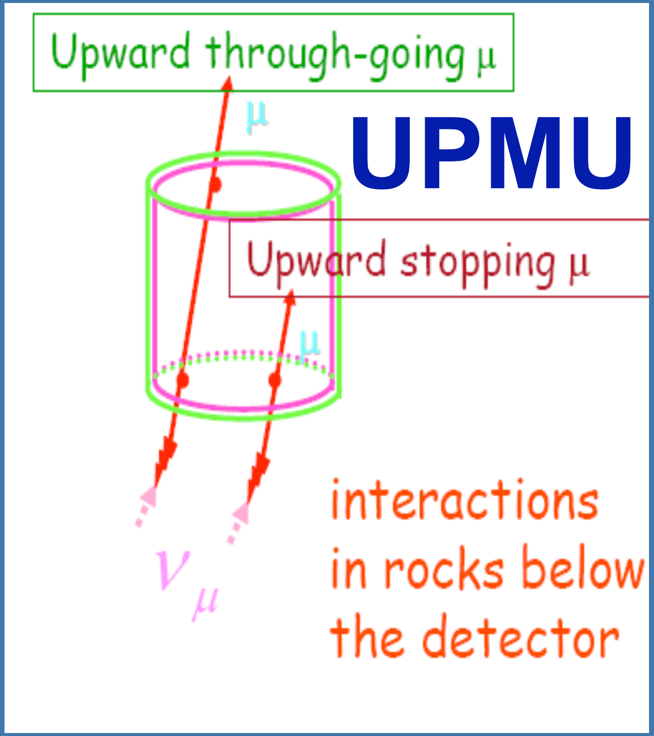
- total ν energy information
- E>30MeV
- not good ν direction reconstr. (for low energy)
- e/μ identification

Partially contained



- only partial energy deposited
- E_{vis} > 300MeV

Upward-going muons



- downward going muons are neglected (mainly BKG atm μ)
- no ν energy information
- good ν direction info

Super-K data sample

Depending on true neutrino energy
different event categories
(samples) are populated

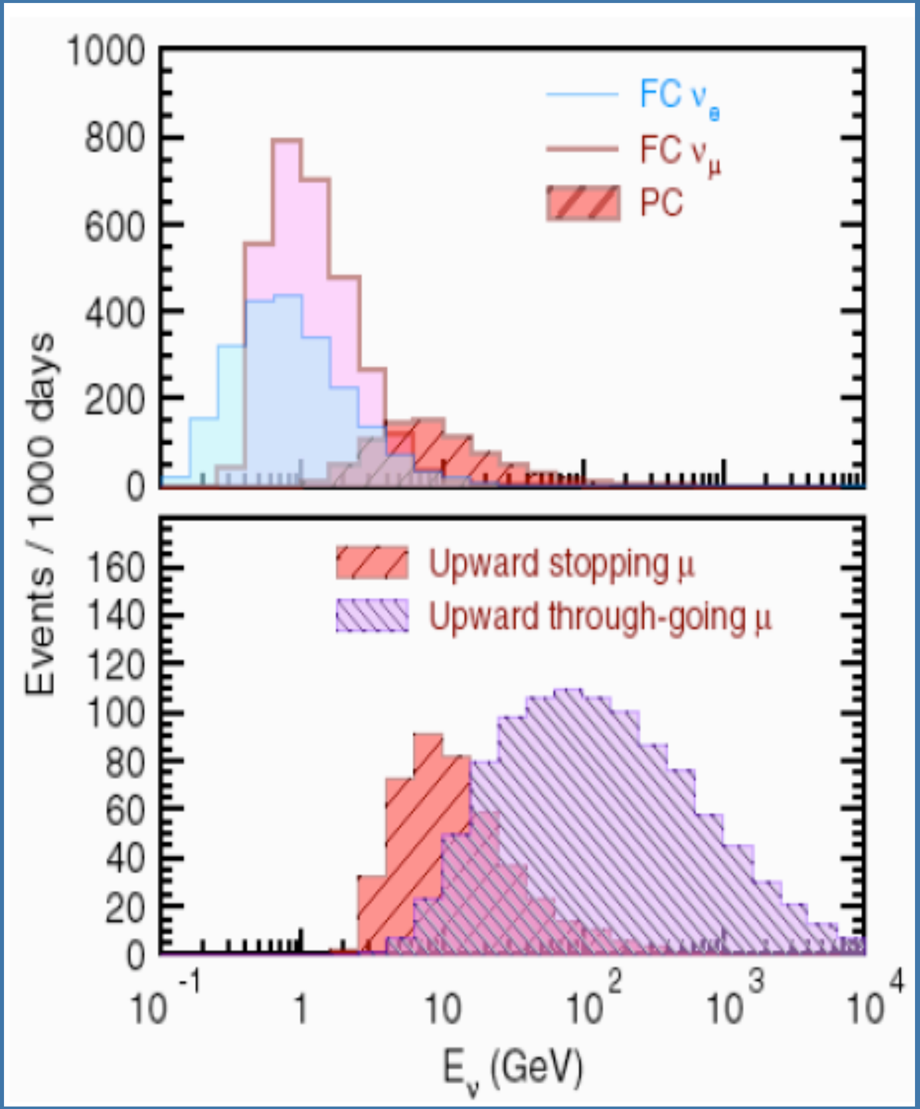
Atmospheric neutrinos interaction rate:

FC = ~8.3 events/day

PC = ~0.7 events/day

UPMU = 1.5 events/day

expected number of atm. ν events in
each event category as a function of ν energy



Monte Carlo for atmospheric ν's

Dark Matter annihilation to neutrinos

… where they may come from?

Search for neutrinos
from DM annihilation (approaches)

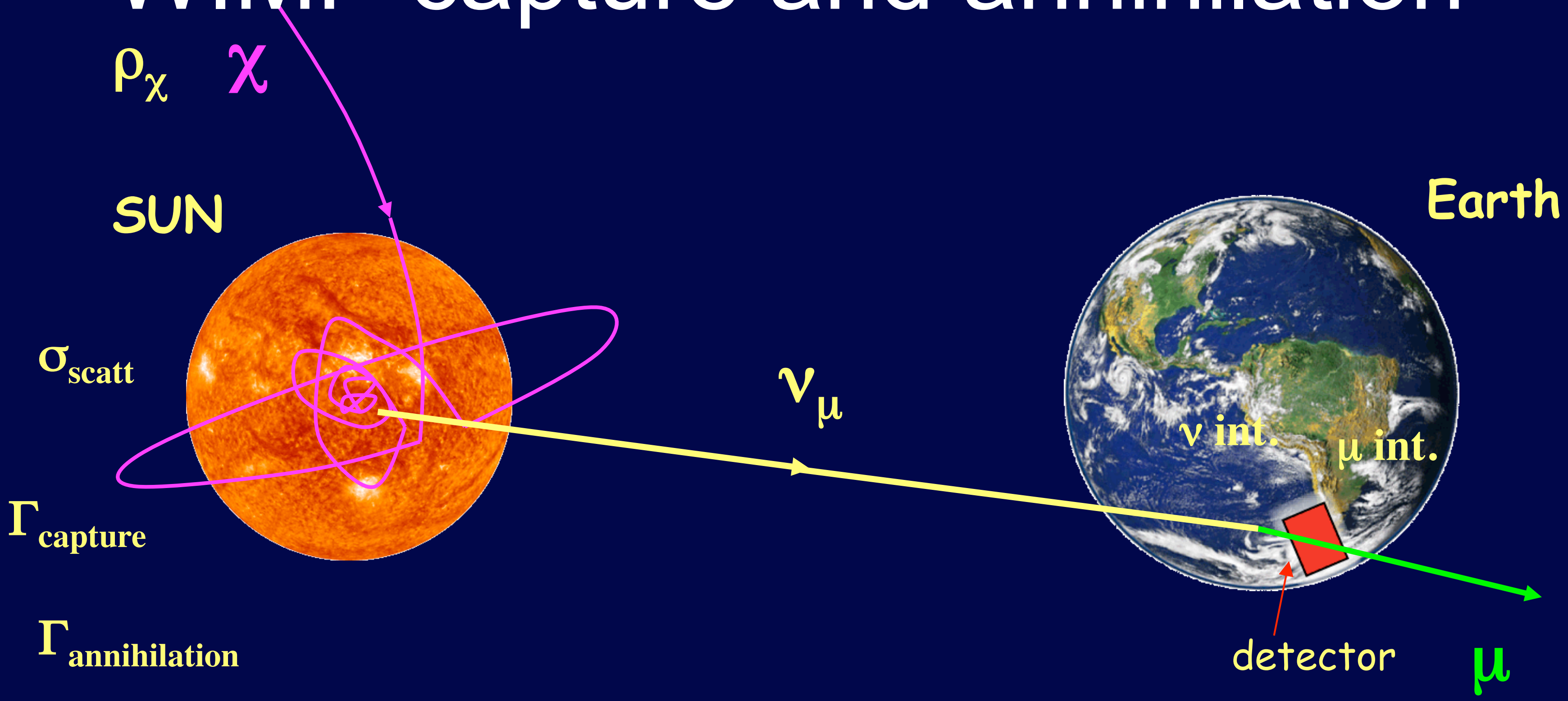
Directional flux
related to regions of increased DM density:

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

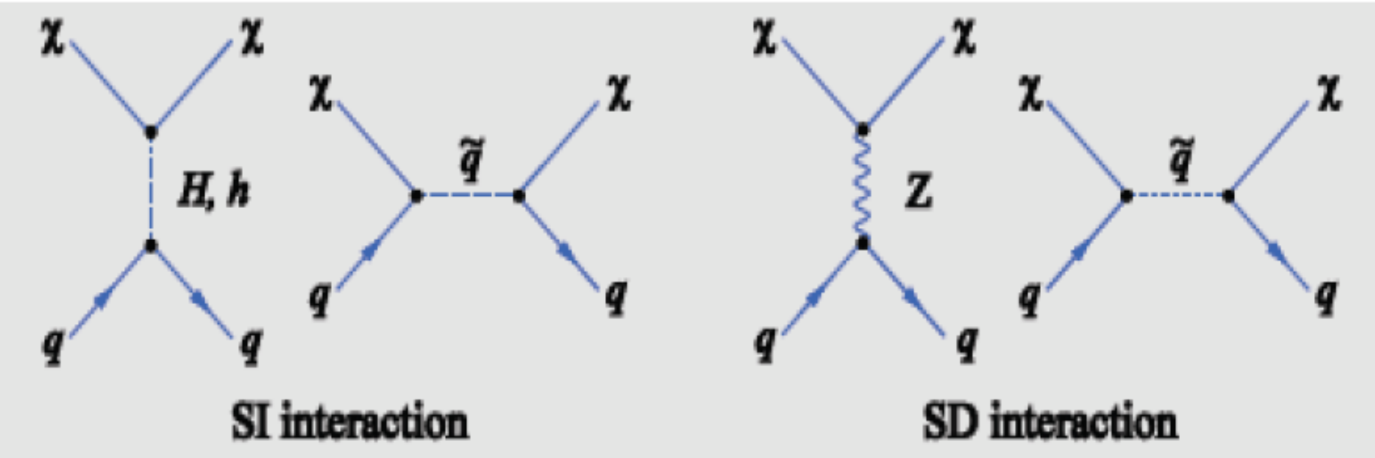
Diffuse flux:

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

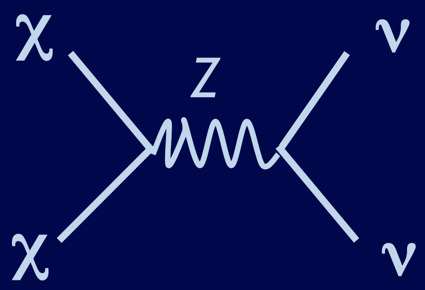
WIMP capture and annihilation



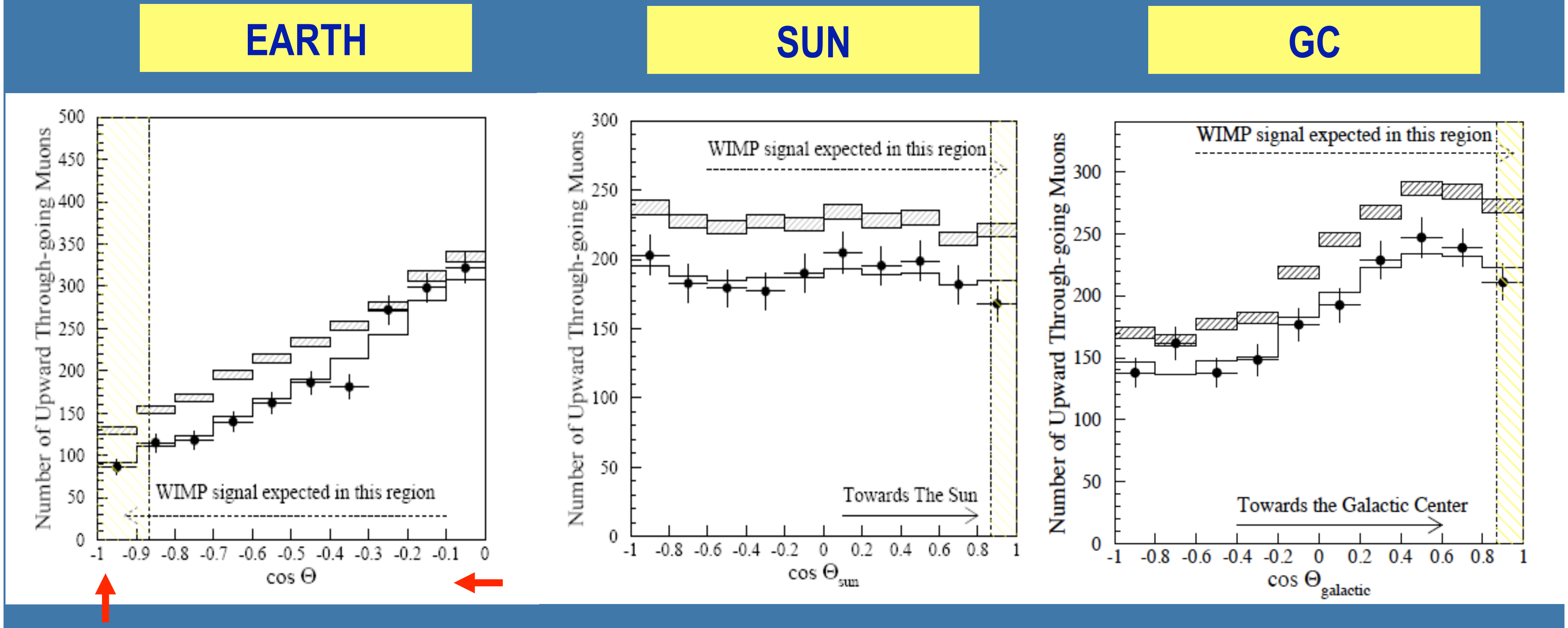
χ scattering in the Sun



χ annihilation



Search for WIMPs in SuperK (directional flux)

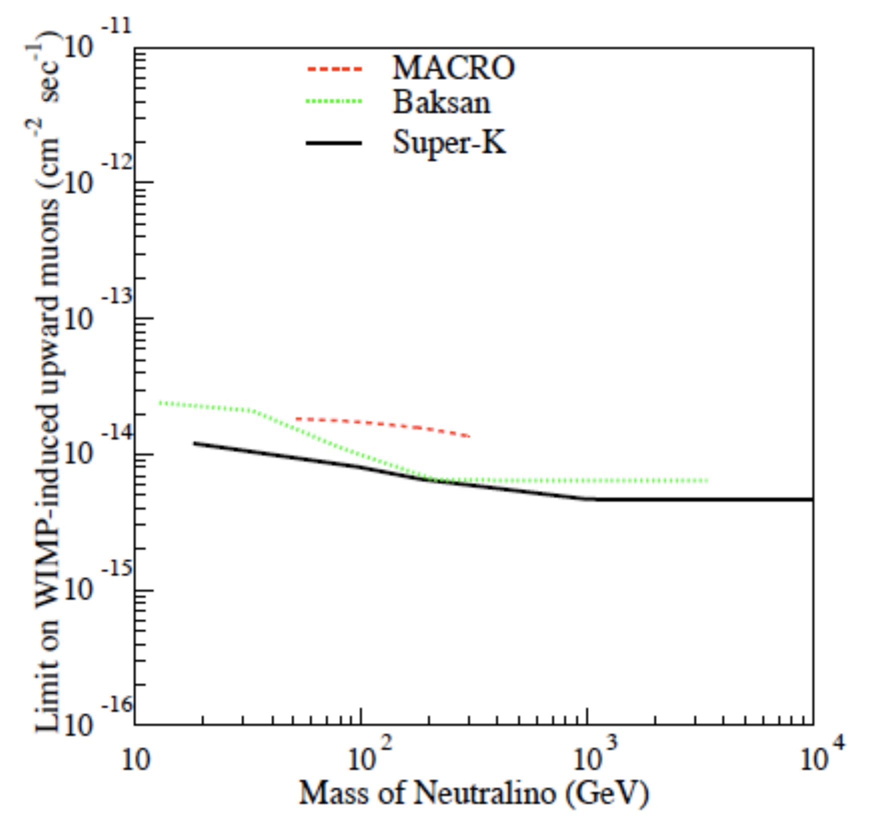


(*) S.Desai et al., Phys.Rev. D70 (2004) 083523

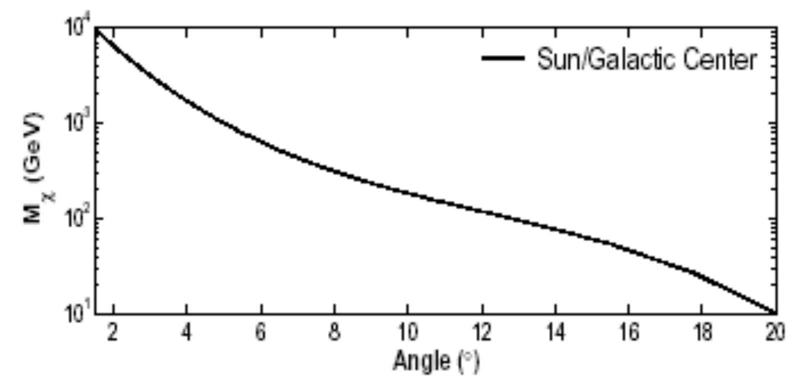
- Search for excess of neutrinos in SK1 data (1679.6 live days)
- WIMP mass range 18GeV-10TeV **->** neutrino energy: ~5 GeV – 5 TeV
- Data sample: upward through-going muons
- Currently new analysis: more data, lower energy neutrinos also included (T.Tanaka)

SuperK – WIMP-induced neutrino flux limit from Sun

Limit: WIMP-induced upward muons (SUN)



simulation

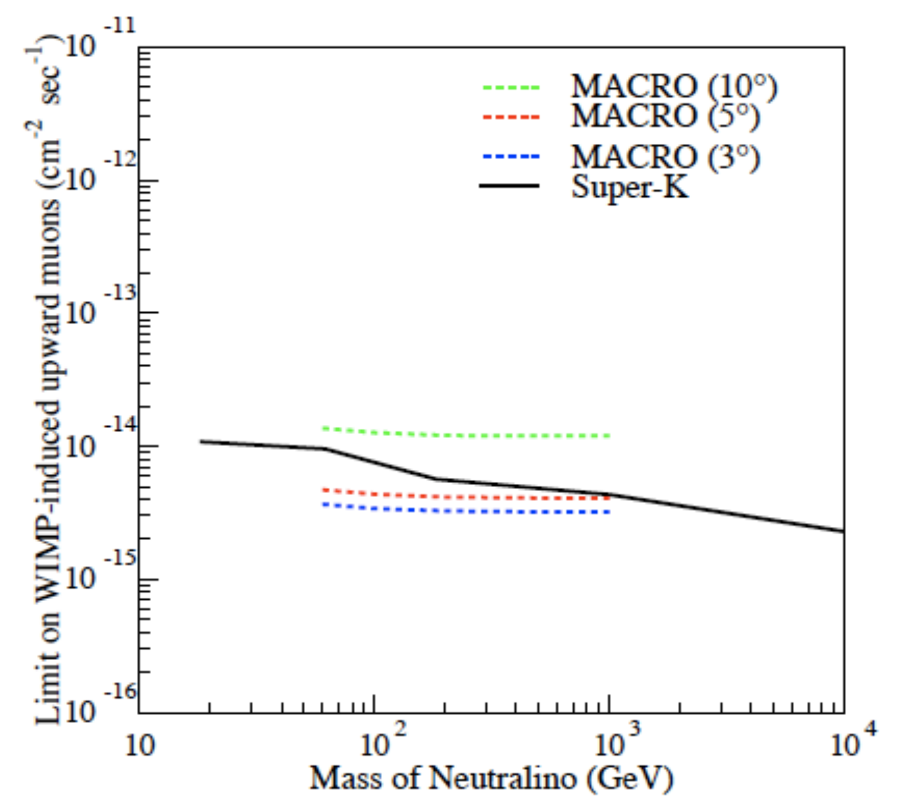


Cone which contains 90% of neutrino flux form WIMP annihilation in Sun

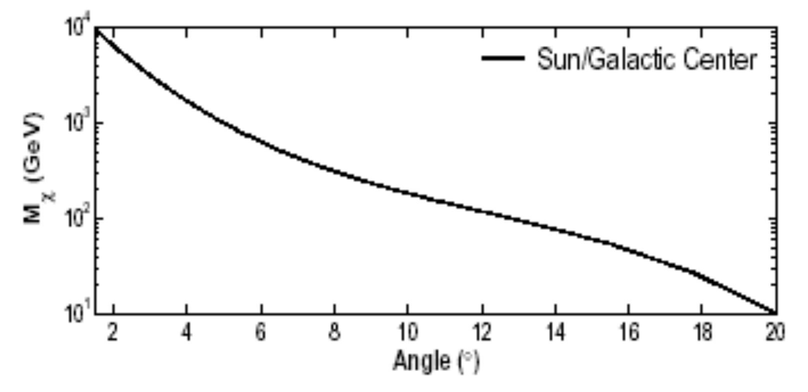
(*) S.Desai et al., Phys.Rev. D70 (2004) 083523

SuperK – WIMP-induced neutrino flux limit from Galactic Center

Limit: WIMP-induced upward muons (GC)



simulation



Cone which contains 90% of neutrino flux form WIMP annihilation in GC

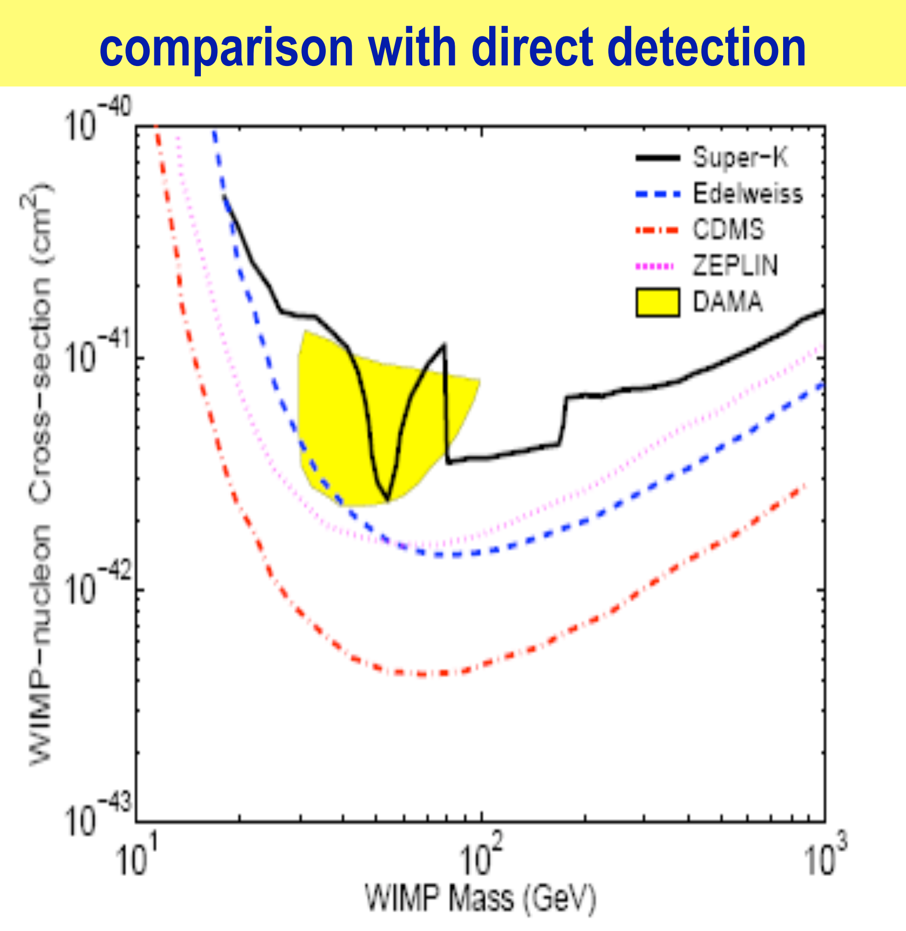
(*) S.Desai et al., Phys.Rev. D70 (2004) 083523

SuperK limit for neutralino elastic cross section (spin independent)

- Comparison with direct detection: assuming only spin-independent interactions in Earth/Sun & equilibrium between annihilation and capture rate

$$\text{Max Ratio (M)} = \frac{\text{Direct Detection Rate (M, } \sigma \text{)}}{\text{Super-K limit (M)}}$$

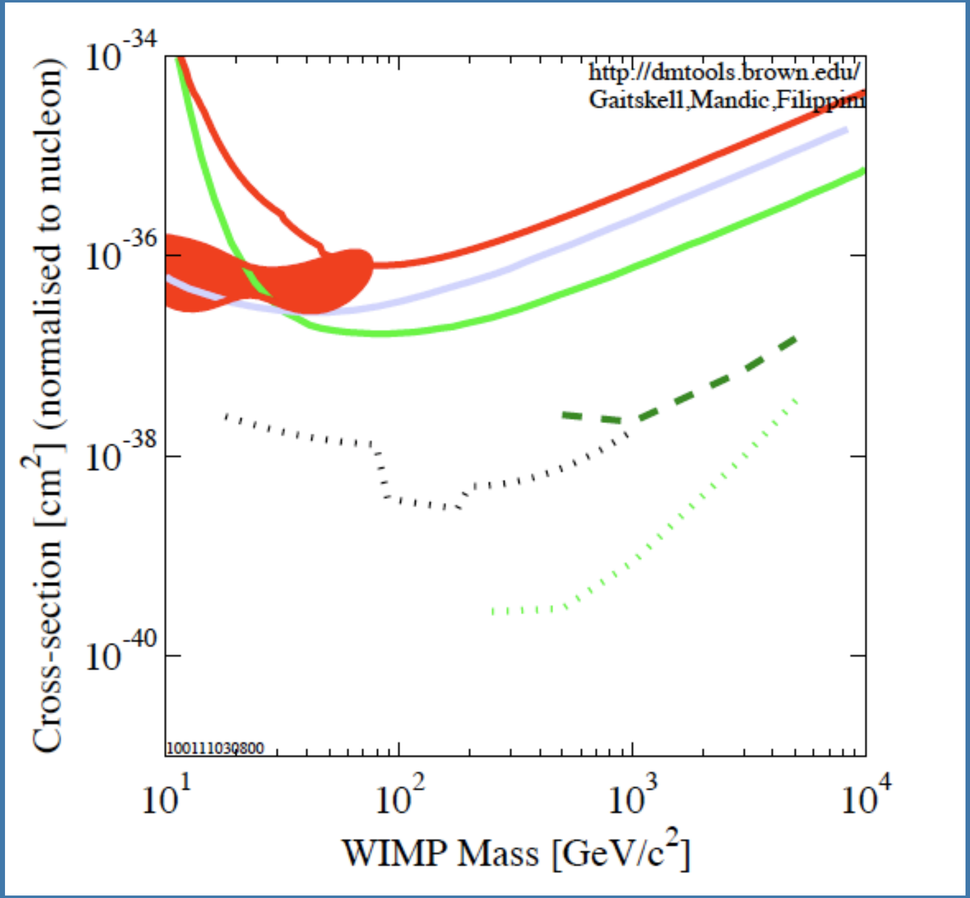
- *Currently:* lowest limit in direct detection -> CDMS II: $3.8 \cdot 10^{-44}$ cm^2 for 70 GeV WIMP

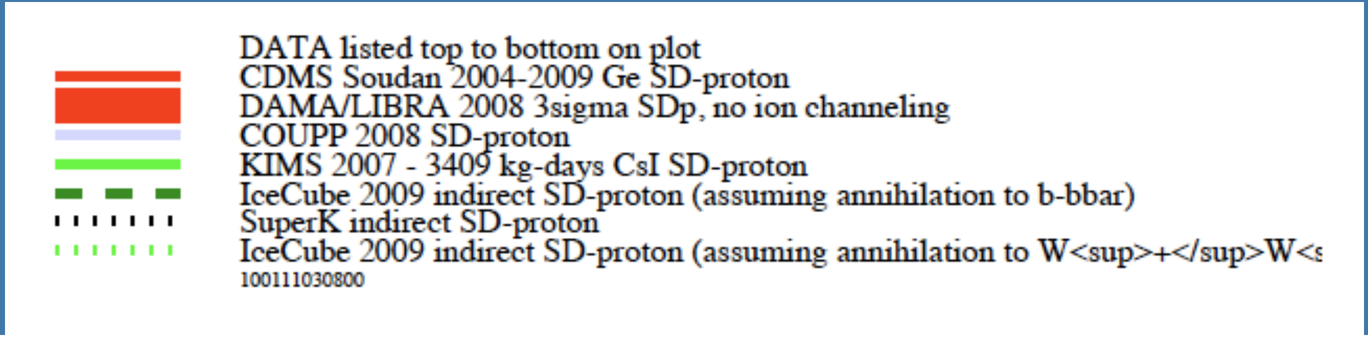

comparison with direct detection

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

SuperK limit for neutralino elastic cross section (spin dependent)

- Limit 100 times lower than from direct search experiments
- DAMA annual modulation due to axial vector couplings ruled out by this SK result




DATA listed top to bottom on plot
CDMS Soudan 2004-2009 Ge SD-proton
DAMA/LIBRA 2008 3sigma SDp, no ion channeling
COUPP 2008 SD-proton
KIMS 2007 - 3409 kg-days CsI SD-proton
IceCube 2009 indirect SD-proton (assuming annihilation to b-bbar)
SuperK indirect SD-proton
IceCube 2009 indirect SD-proton (assuming annihilation to W⁺W<s
100111030800

Diffuse search idea

- Investigation is limited to „most optimistic” but model independent WIMP annihilation channel

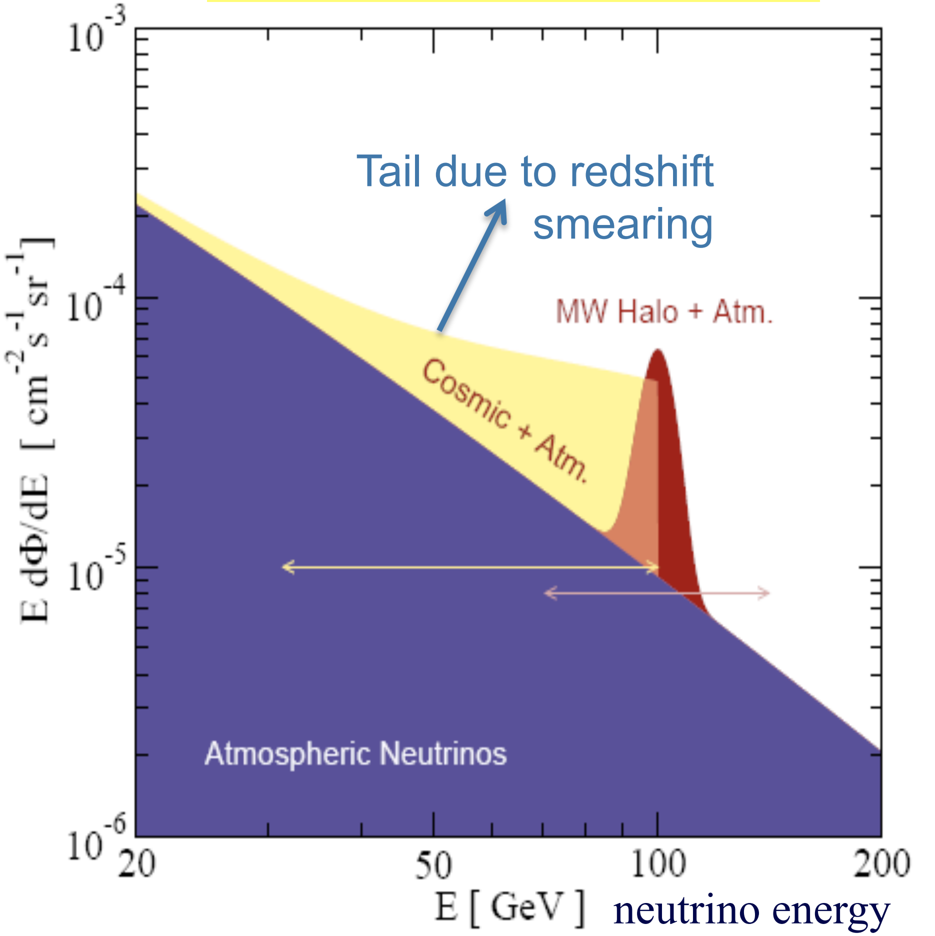
$$\chi + \chi \longrightarrow \nu + \overline{\nu}$$

neutrino energy = WIMP mass

signal is isotropic

- Relevant for DM diffuse annihilation and also for DM decay modes
- 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 $<\sigma V>$, lifetime τ_{DM}

Illustration of 100 GeV DM annihilation signal



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

DM self-annihilation cross section

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

- Sets the obs. DM mass density

  Ω_M = 0.27 ± 0.02 *WMAP (2006 r.)*

-> in thermal relic scenarios:

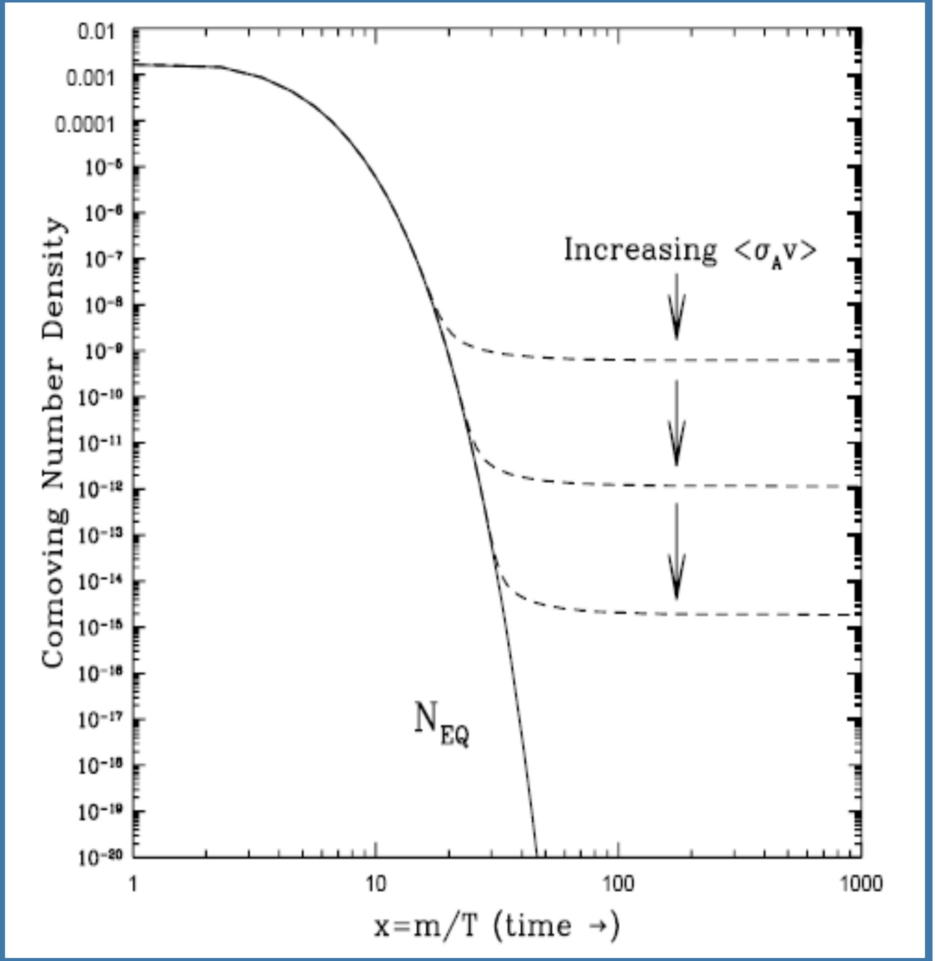
$< \sigma_a v >$ ~ 3 x 10^{-26} cm^3/s

- Sets the annihilation rate in DM halos

2

n_χ - DM number density

„freeze out" of the relic particle



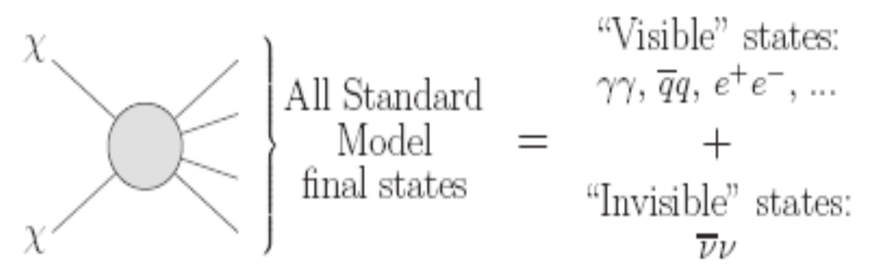
Upper bound on DM total annihilation cross section

MOTIVATION

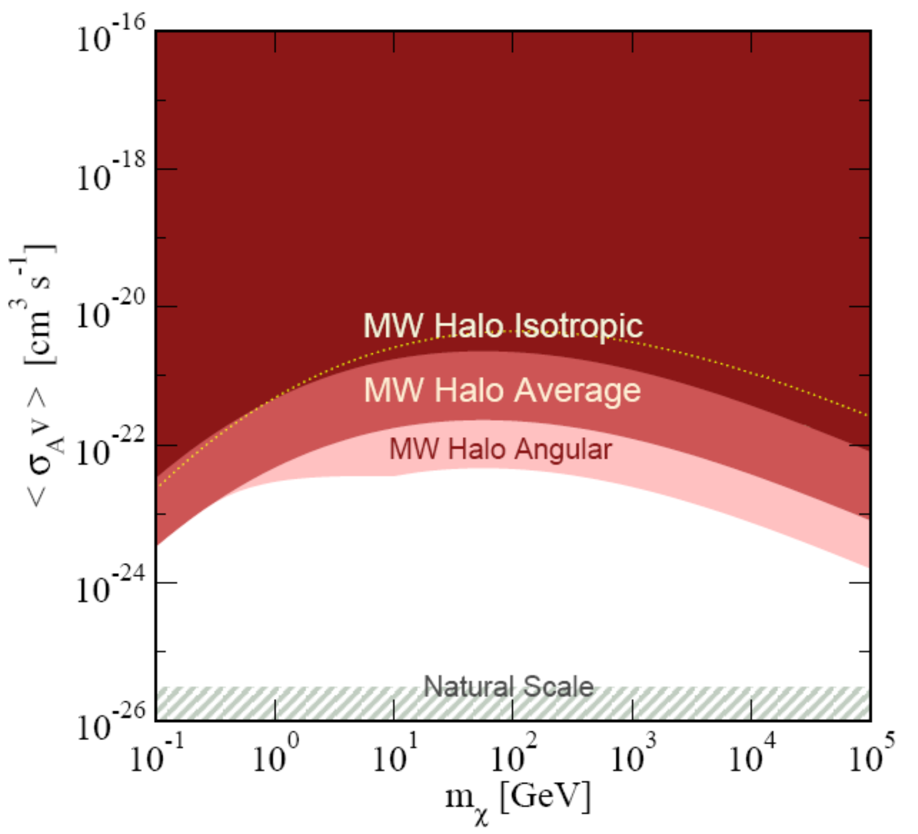
- Existing limit based only on data available for general public (made by J.F Beacom et all.)
- No dedicated anylysis from experiments

- No upward fluctuations in available data
- Limit on DM-induced neutrino diffuse flux and DM annihilation cross section (constrains on DM evolution and distribution)

- combining with γ searches -> provide conservative upper limit on **total** $<\sigma_A V>$



χ, χ All Standard Model final states = "Visible" states: $\gamma\gamma$, $\bar{q}q$, e^+e^-, ... + "Invisible" states: $\bar{\nu}\nu$



Assumption: **BR = 100% for** $\chi\chi \rightarrow \bar{\nu}\nu$

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

Consequence:

General upper limit on the **total** DM self annihilation cross section. Why?

Least detectable particles bounds total cross section most conservatively -> all other limits (derived from other ann. products, like γ's) would be more stringent than that; limit on cross section derived that way cannot be overreached (with only SM final states)

SuperK dedicated analysis

Dedicated SK/Ice-Cube analysis could improve limit on total self-annihilation cross section

by 1-2 orders of magn.

What can be improved comparing to Beacom analysis?

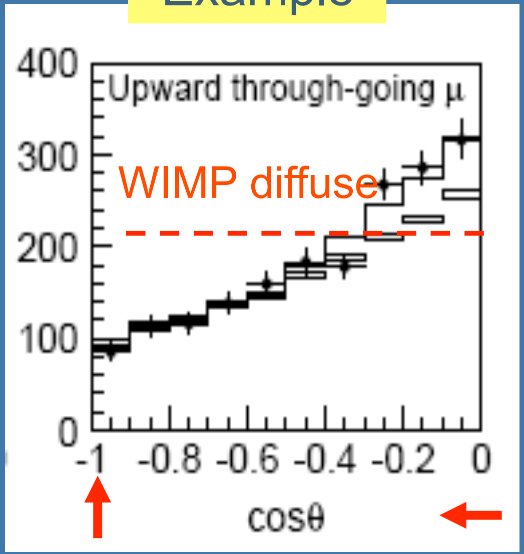
- **use angular feature of WIMP signal:**

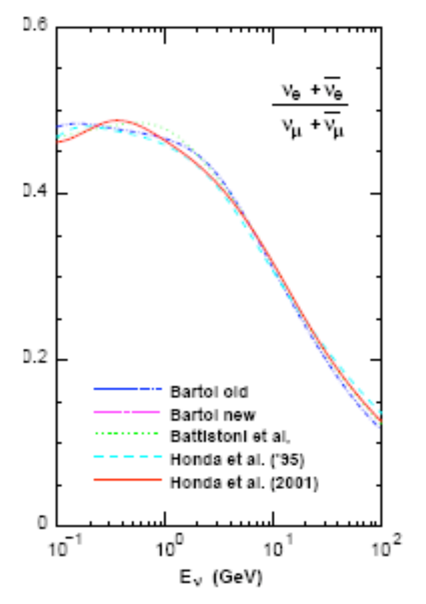
  DM signal isotropic, atm. neutrino bkg is often peaked at horizon

- **use precise energy information**

- **use also** $(\nu_e, \bar{\nu}_e)$ **:**
  - same ν_e, ν_τ, ν_μ ratio is assumed in

Example





FIT idea

PROCEDURE OUTLINE:

FC: fully contained
PC: partially contained
UPMU: upward going muons

- Use $(\nu_e, \bar{\nu}_e), (\nu_\mu, \bar{\nu}_\mu)$
- Investigate energy (FC, PC) & cosθ (UPMU, FC, PC) distributions
- Simulate DM annihilation diffuse signal
- Test DM annihilation singal hypothesis in atmospheric neutrino data by minimazing χ^2 distributions / fit the best ATM MC model and WIMP contribution:

depends on ν oscillation parameters

secret knowledge

fitted

$$\chi^2 = \sum_{i=1}^{nbins} \frac{\left(N_i^{obs} - \left(N_i^{atm\nu} + \beta \cdot N_i^{WIMP}\right) \cdot \left(1 + \sum_{j=1}^{Nsyserr} f_j^i \cdot \varepsilon_j\right)\right)^2}{\sigma_i^2} + \sum_{j=1}^{Nsyserr} \left(\frac{\varepsilon_j}{\sigma_j}\right)^2 \Bigg|$$

for every WIMP mass

β – WIMP signal normalization parameter

$\beta, \Delta m_{23}, \theta_{23}$+ 122 ε_j are fitted

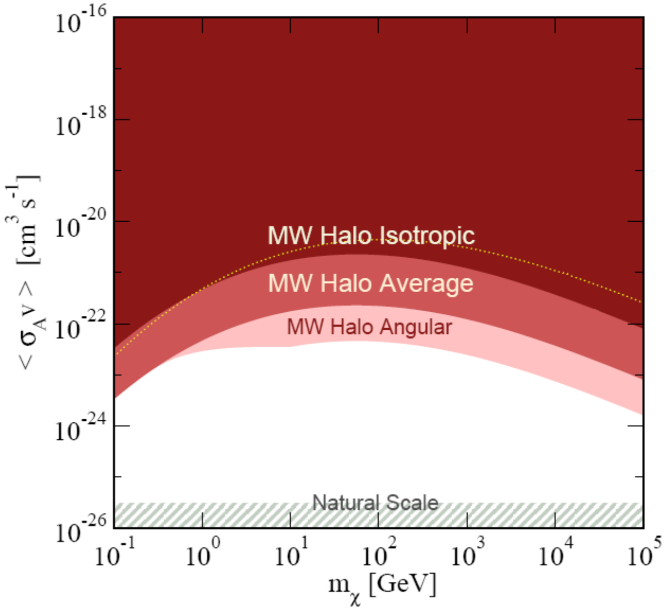
sys. error

Hands on the results of diffuse search

- None or very low (less < 2σ) WIMP contribution allowed over the entire energy range in SuperK data → No evidence for WIMP induced signal

- Could derive limit on DM-induced neutrino diffuse flux and total **self-annihilation cross section <σv>** (and **DM decay lifetime**) under a few DM galactic halo distribution models

- Preliminary calculations show that this analysis can improve the existng world limit by 1-2 orders of magnitude



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

SUMMARY

- » DARK MATTER – new interesting results to be confirmed or rejeceted soon by the next generation of direct and indirect experiments + LHC
  - CDMS – 2 events in the signal region (0.8 bkg expected)
  - postrion/electron excess in primary cosmic rays (PAMELA/ATIC/FERMI)
- » Super-Kamiokande - search for neutrinos from DM annihilation

DIRECTIONAL

- No excess of neutrinos from core of the Sun/Earth/Galaxy
- Limit on DM induced ν flux; comparison with direct experiments (DAMA region ruled out)

DIFFUSE

- Preliminary checked over wide energy range that no statistically significant DM annihilation signal can be accomodated by SK data
- In this dedicated analysis we expect to improve the existing world neutrino limit on $<\sigma v>$ by 1-2 orders of magnitude (especially in low energy)

--> complementary approach in DM searches, verification of theoretical models

... DM still not discovered but we keep looking for it

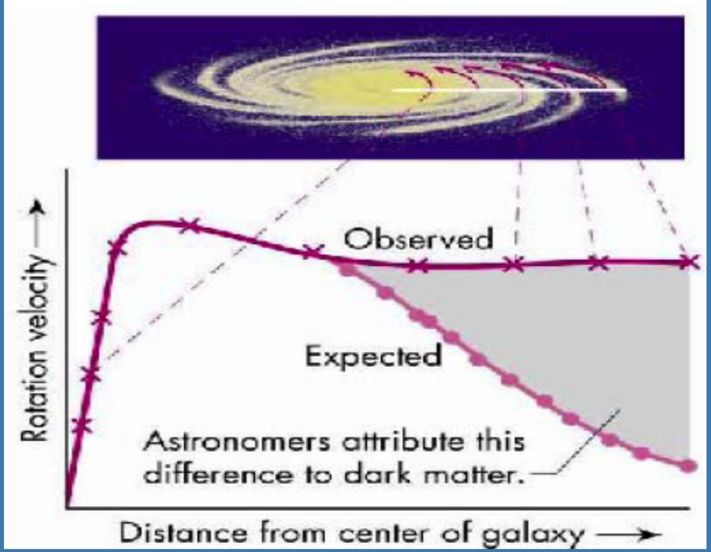
Thank you for your attention

BACKUP

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 derived from:

- *Velocity distribution in galaxy clusters (F.Zwicky in 1933)*
- *Galaxies rotation curves*
- *Gravitational lensing*
- *Cosmic Microwave Backround (CMB)*
- *Abundance of light elements in Universe, nucleosynthezis*
- *Evolution of large cosmic structures*



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

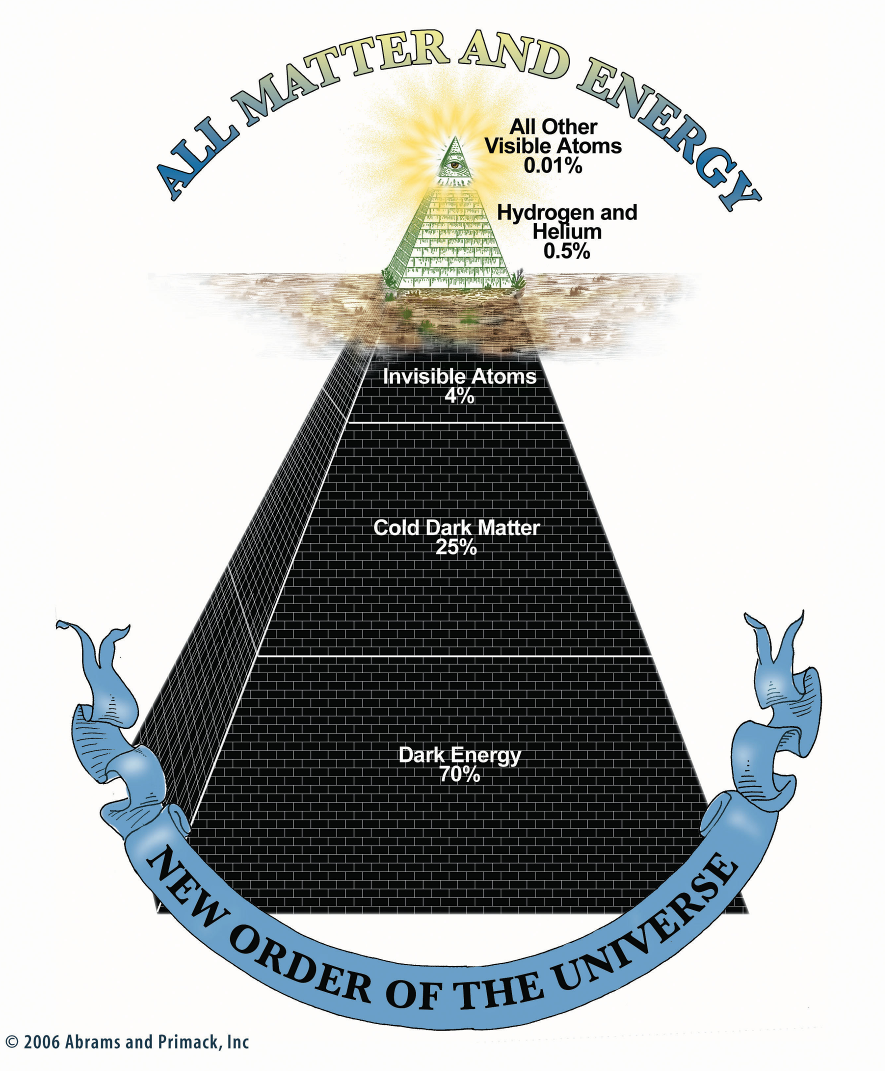
» Ω_Λ Ω_Λ = 0.73 ± 0.02

WMAP (2006 r.) + SN Ia

Conclusions:

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

$\Omega_m < 1$ => Dark Energy



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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.

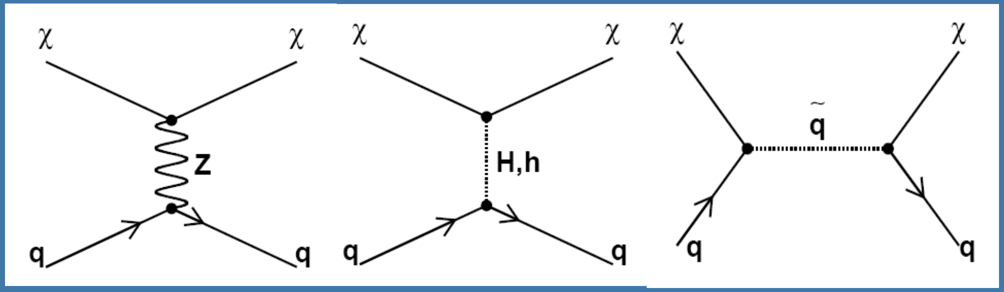
WIMP (Weakly Interacting Massive Particle)

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**

Energia odrzutu

» Energia odrzutu zależy:

- masy χ oraz masy jądra tarczy
- Energii kinetycznej WIMP-ów T_χ **(model halo)**

model halo

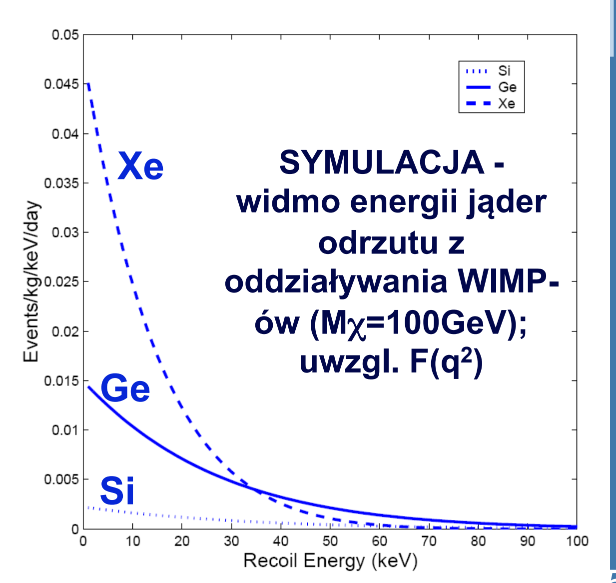
- **prędkość WIMP-ów w halo: rozkład *Maxwella-Bolzmanna* ze średnią prędkością względem centrum Galaktyki = 0**
- **$V_{\text{układu słon.}} \approx 230$ km/s (względem halo) -> określa śred. T_χ**
- **ρ - gęstość WIMP-ów w halo galaktycznym (~ 0.3 GeV/c² ·1/cm³)**

» Np. (rozpraszanie w fali S):

Ar
(Z=40)

$M_\chi = 50$ GeV/c² $\langle T_{\text{odrzutu}} \rangle = 14$ keV

$M_\chi = 100$ GeV/c² $\langle T_{\text{odrzutu}} \rangle = 24$ keV



SYMULACJA - widmo energii jąder odrzutu z oddziaływania WIMP-ów (M_χ=100GeV); uwzgl. F(q²)

Częstość zdarzeń

Liczba rejestrowanych przypadków (Rate):

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

ρ - **gęstość WIMP-ów w halo galaktycznym (~ 0.3 GeV/c^2 ·1/cm^3)**

σ - **elastyczny przekrój czynny zależny od materiału tarczy - rodzaju sprzężenia WIMP-nukleon (spinu), czynnika postaci F(q^2) … $\leq 10^{-38}$ cm^2**

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

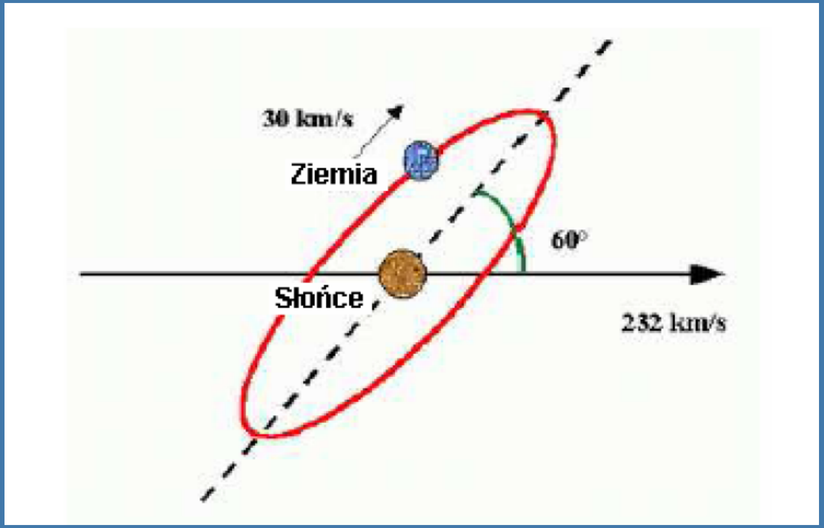
Przy założeniach: $\rho_\chi = 0.3\ \mathrm{GeV}/(c^2 \cdot \mathrm{cm}^3)$ $M_\chi = 100\ \mathrm{GeV}/c^2$ $v_\chi = 230\ \mathrm{km/s}$

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

(por. np. strumień neutrin p-p ze Słońca: $6 \times 10^{10} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ *, gdzie* $\sigma_{\nu N} \sim 10^{-44}\ \mathrm{cm}^2$

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

MOND

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

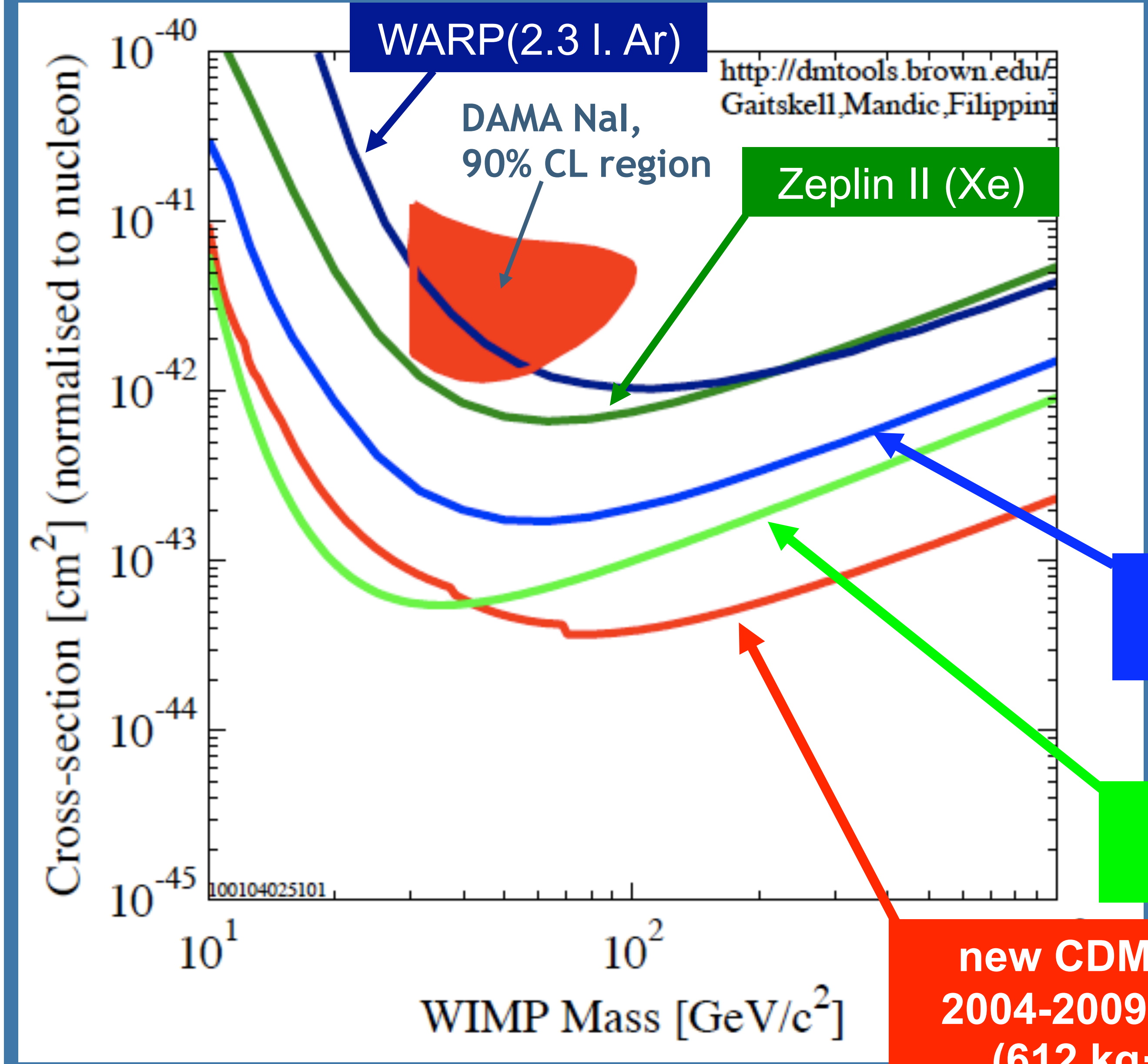
$\mu(x)=1$ for $x>>1$

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

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

Propozycja M.Milgroma – 1981r.

Direct detection – current experimental limits

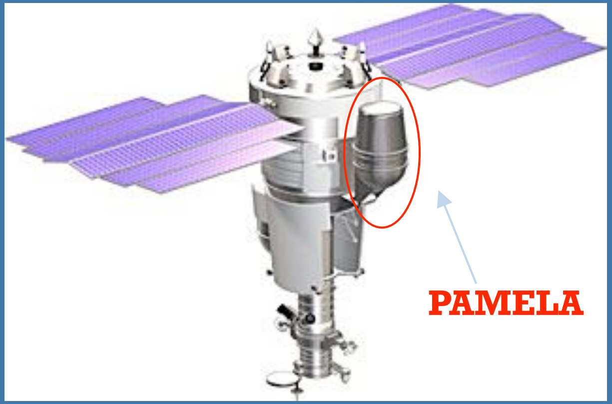


- **Region above lines is excluded with 3σ CL**
- **DAMA allowed region:** $5.8 \cdot 10^3$ **kg·d (100 kg NaI)**

PAMELA

a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

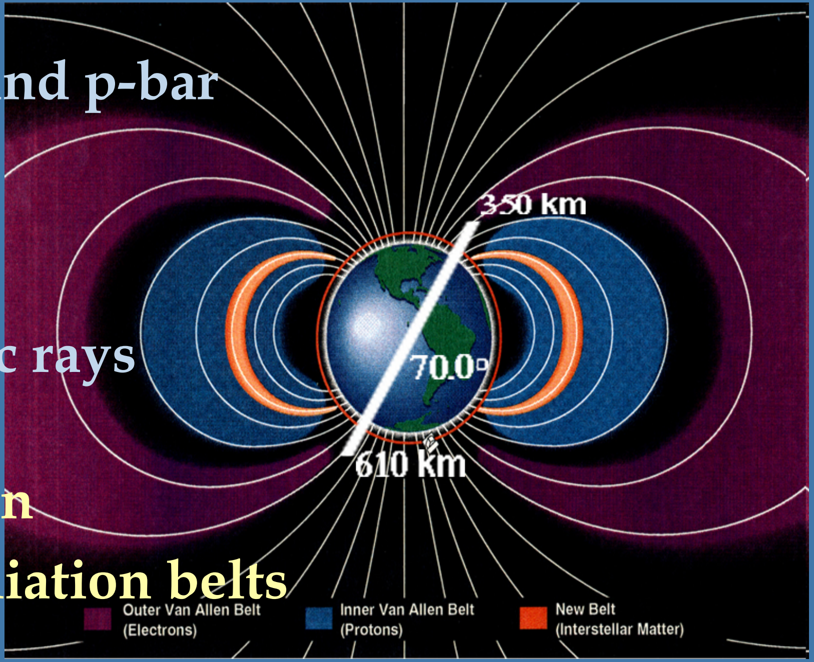
- PAMELA is mounted on satellite Resurs-DK1, inside a pressurized container
- launched June 2006
- minimum lifetime 3 years
- data transmitted via Very high-speed Radio Link (VRL)



scientific objectives:

- Search for **dark matter annihilation** (e^+ and p-bar spectra)
- Search for **anti-He** (primordial antimatter)

- Study **composition and spectra** of cosmic rays (including light nuclei)
- Study **solar physics** and **solar modulation**
- Study **terrestrial magnetosphere** and **radiation belts**



PAMELA **nominal capabilities**

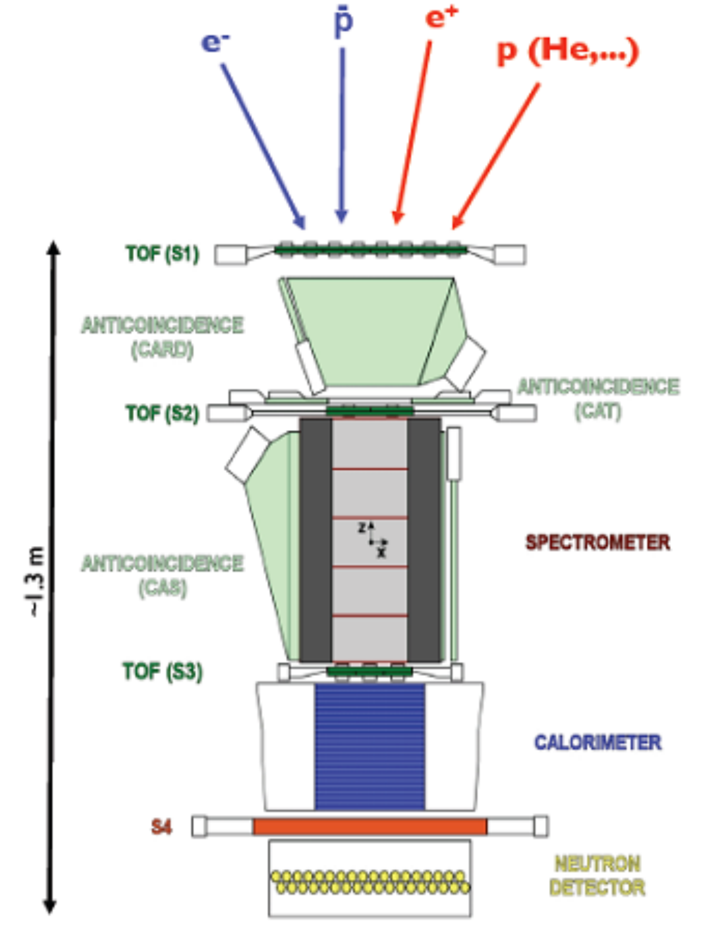
	energy range	particles in 3 years
» Antiprotons	**80 MeV ÷190 GeV**	$O(10^{4})$
» Positrons	**50 MeV ÷ 270 GeV**	$O(10^{5})$
» Electrons	up to 400 GeV	$O(10^{6})$
» Protons	up to 700 GeV	$O(10^{8})$
» Electrons+positrons	up to 2 TeV	(from calorimeter)
» Light Nuclei	up to 200 GeV/n	He/Be/C: $O(10^{7}/^{4}/^{5})$
» Anti-Nuclei search	sensitivity of $3\text{x}10^{-8}$ in anti-He/He	

- **Simultaneous measurement of many cosmic-ray species**
- **New energy range**

  (e.g. contemporary antiproton & positron maximum energy ~ 40 GeV)
- **Unprecedented statistics**

  e.g. 1 HEAT flight ~ 25 days of PAMELA data
  1 CAPRICE98 flight ~ 5 days PAMELA data

PAMELA detector principle



~470 kg / ~360 W

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^{2}sr
- 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^{2}sr

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

Lepton-hadron separation

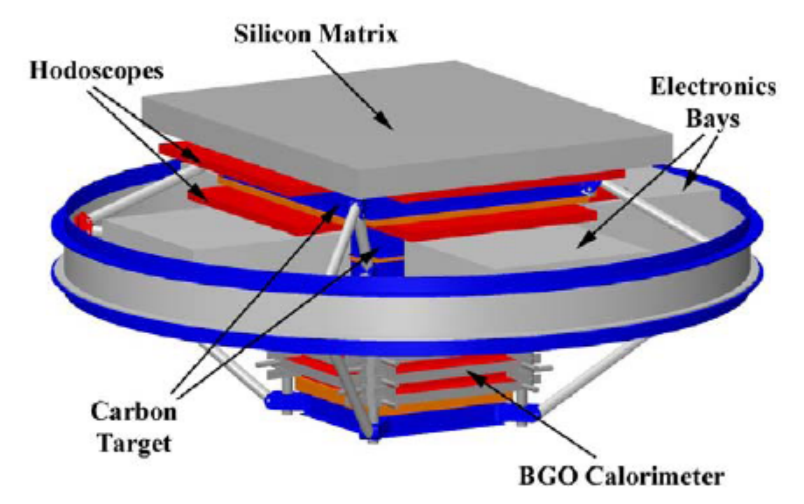
M. Pearce 2009

ATIC

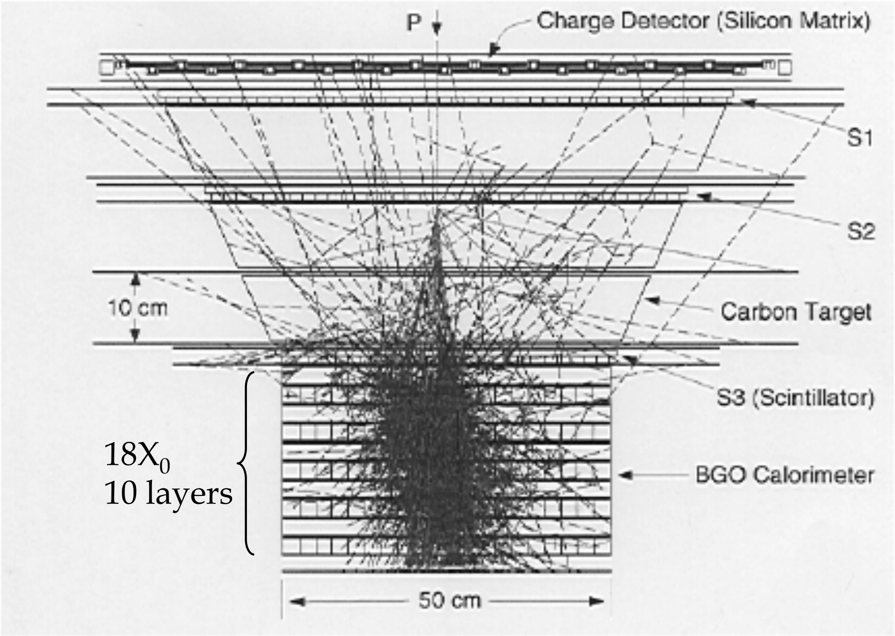
Advanced Thin Ionization Calorimeter

- 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

The ATIC balloon-borne electron detector ready for launch on the Ross Ice Shelf of Antarctica.

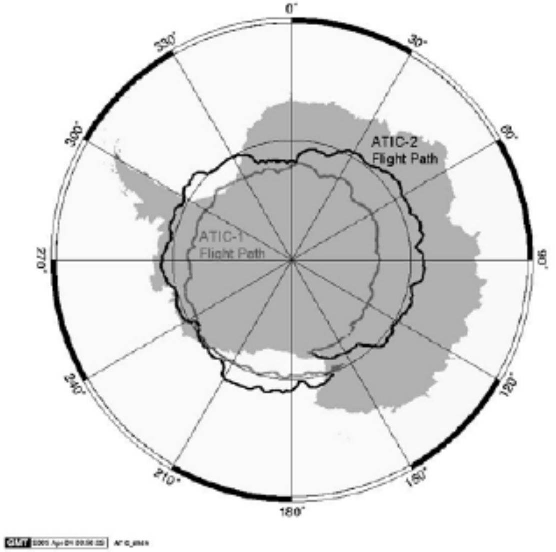


ATIC Instrument Summary

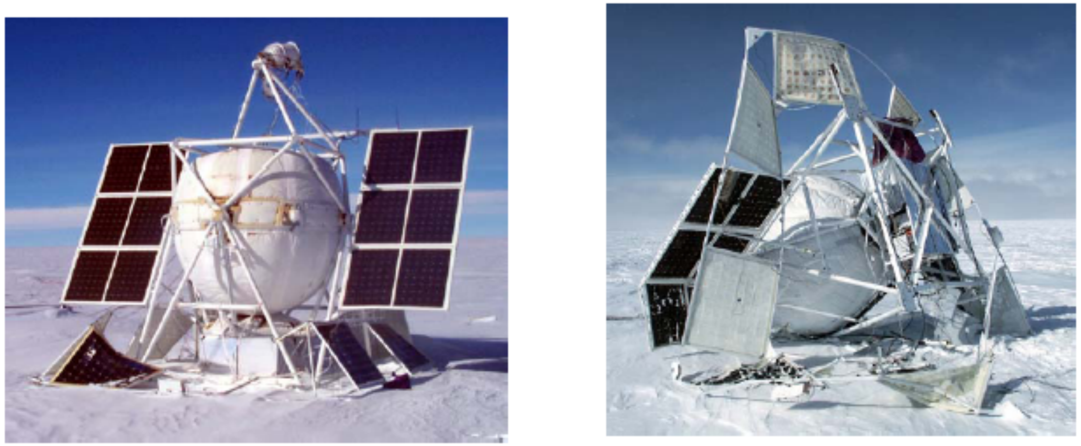


- Measure charge, energy and number
- Ionization Calorimetry only practical method to measure high energy light elements
- Silicon Matrix (Si) has 4,480 pixels to measure GCR charge in presence of shower backscatter
- Graphite Target to interact the primary particle and generate fragments that, in turn, 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

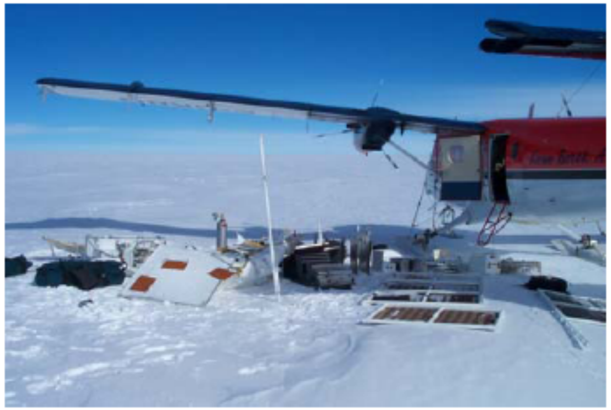
Flight and Recovery



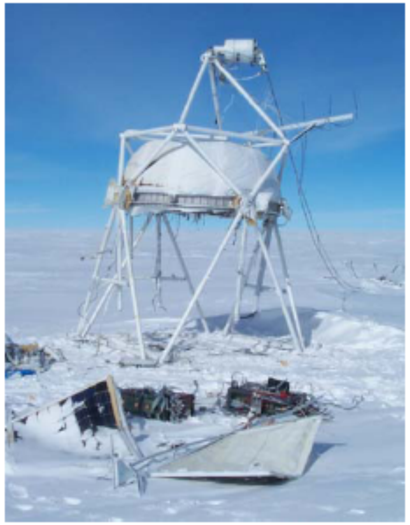
Flight path for ATIC-1 (2000)
and ATIC-2 (2002)



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



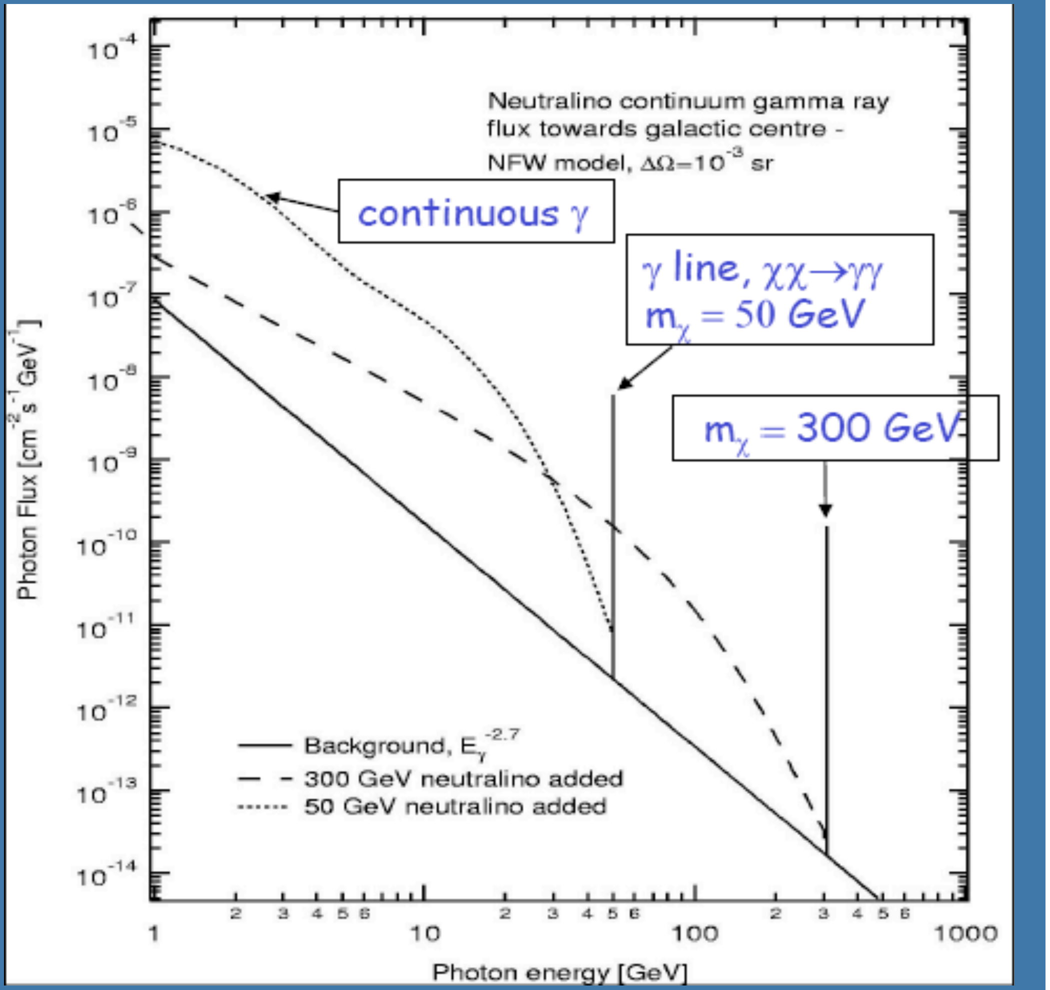
DM annihilation to gammas

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:

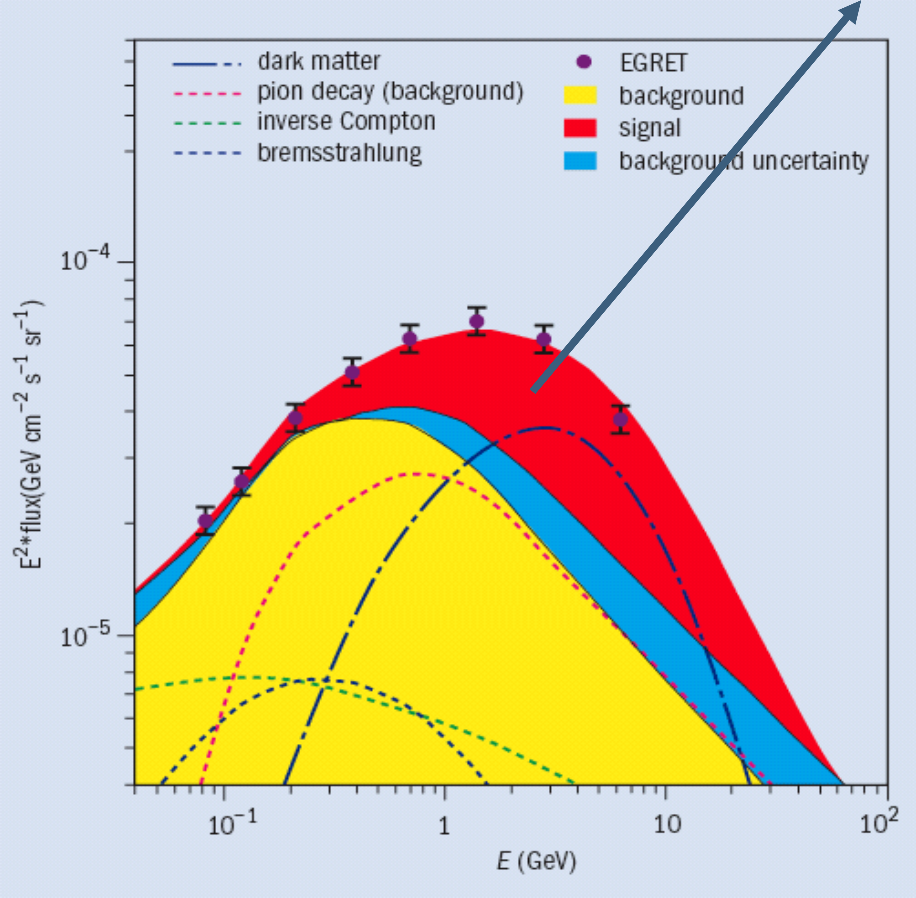
- » *Astrophysical background rate*
  - *distribution around Galactic Center*

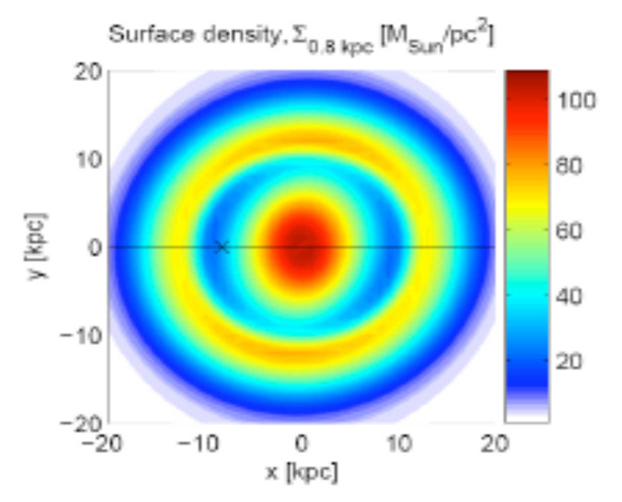


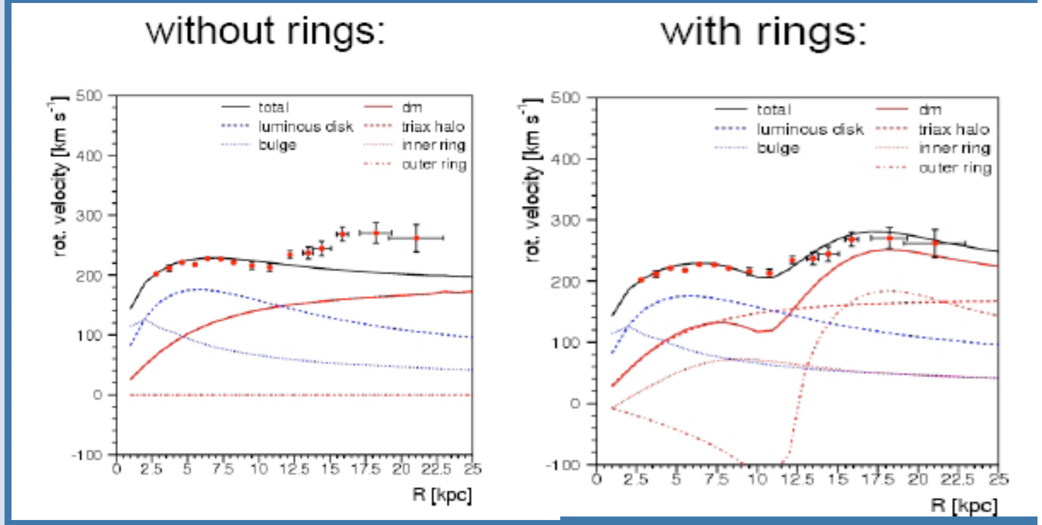
DM annihilation to gammas - EGRET

- EGRET excess in diffuse galactic gamma ray flux

50-100 GeV neutralino annihilation?

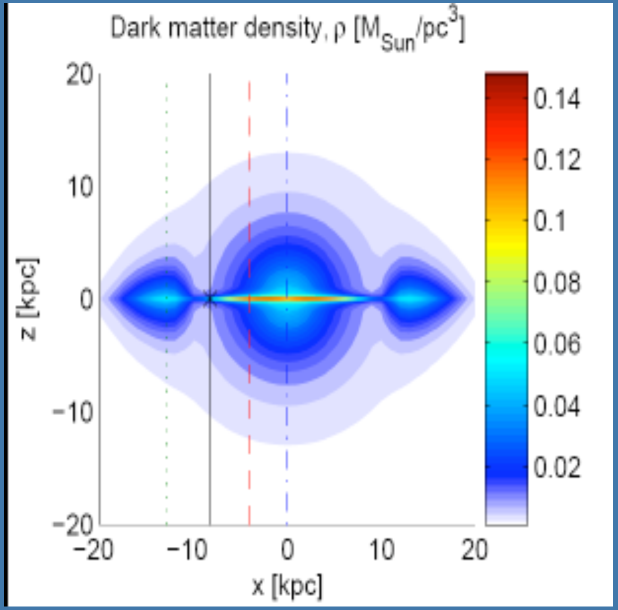






DM annihilation to gammas - EGRET

Objections to EGRET interpretation



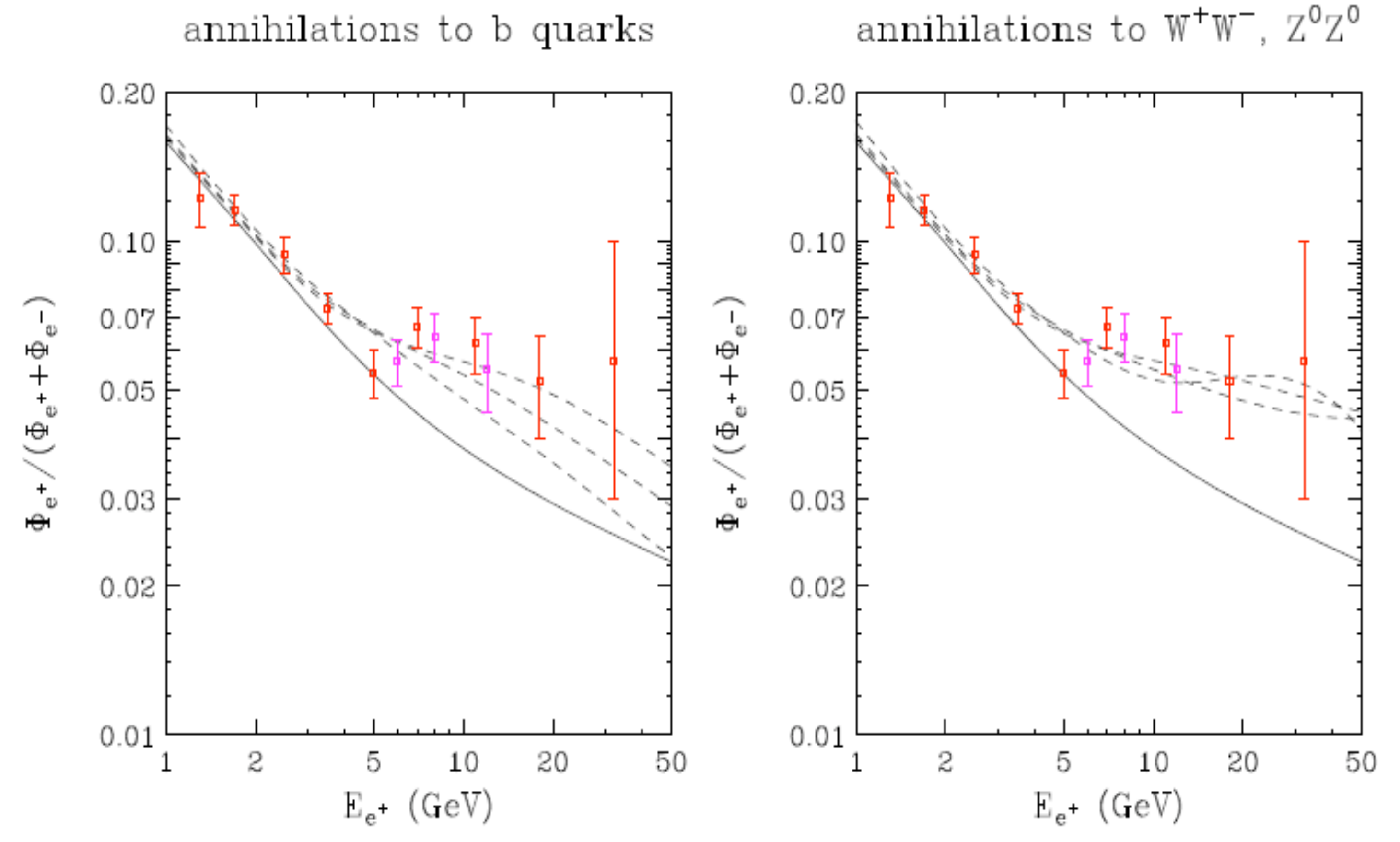
- » DM density concentrated to the galactic plane. This is not what one expects from CDM!
- » Excess in anti-protons data – NOT observed (correlation: fragmentation of quark jets)

- » 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* $\langle \sigma_A v \rangle = 3\times10^{-26} cm^3/s$, $\rho_\chi = 0.3 GeV/cm^3$ *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)*

DM annihilation to anti-matter

- *Charged anti-particles (positrons, anti-protons, anti-deuterons)*
  -> diffuse spectrum at Earth

- *positrons -> lose energy over typical length scales (few kpc), probe the local DM distribution, less uncertainty*

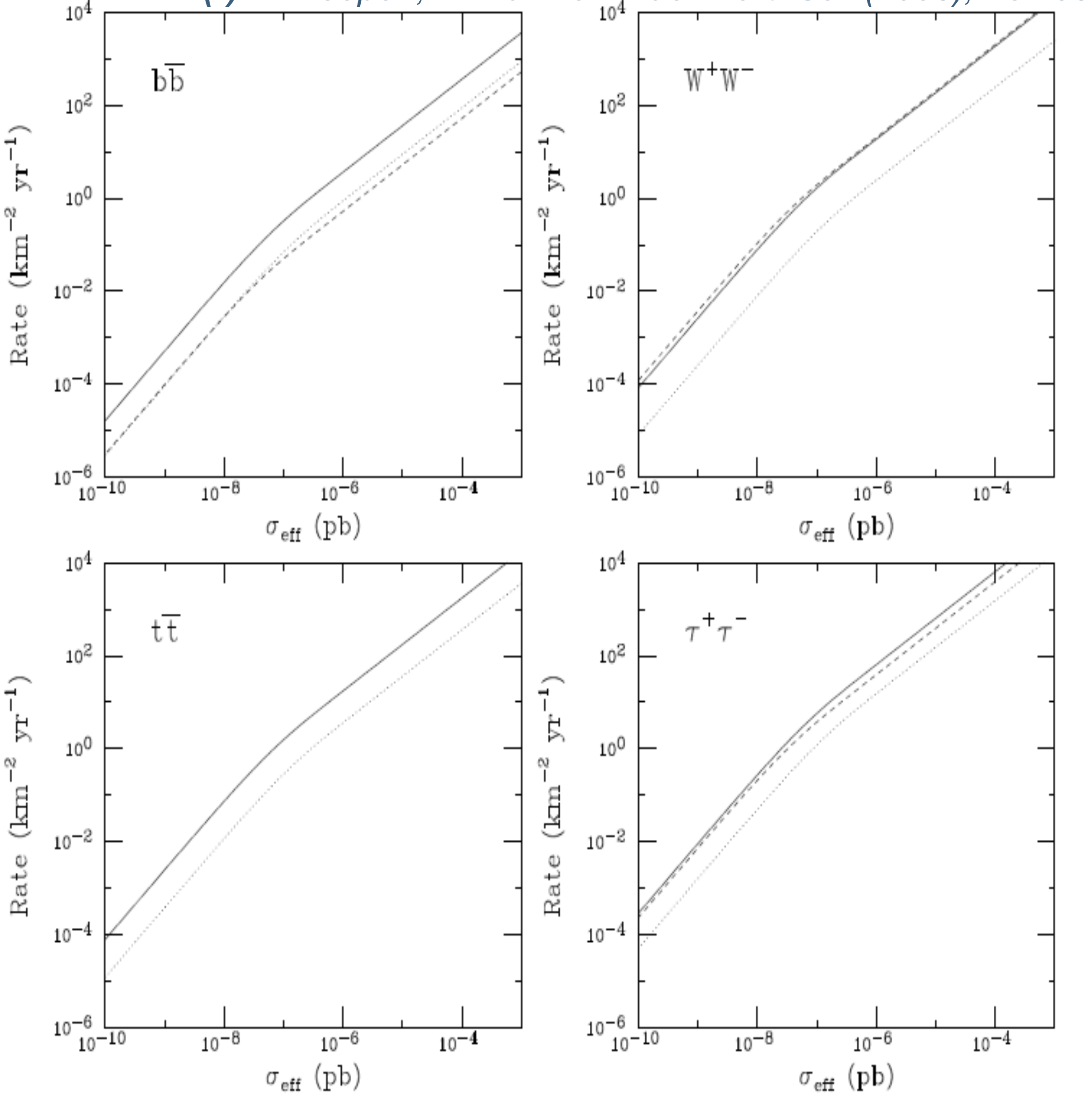
- *Satellite-based exp.*
  -> HEAT, AMS-01, Pamela, AMS-02 (planned)…

- ***WIMP's effective elastic scattering cross section in the Sun for a variety of annihilation modes. The effective elastic scattering cross section is defined as***

  $\sigma eff = \sigma H,SD+\sigma H,SI +0.07\sigma He,SI$

  The dashes, solid and dotted lines correspond to WIMPs of mass 100, 300 and 1000 GeV, respectively.

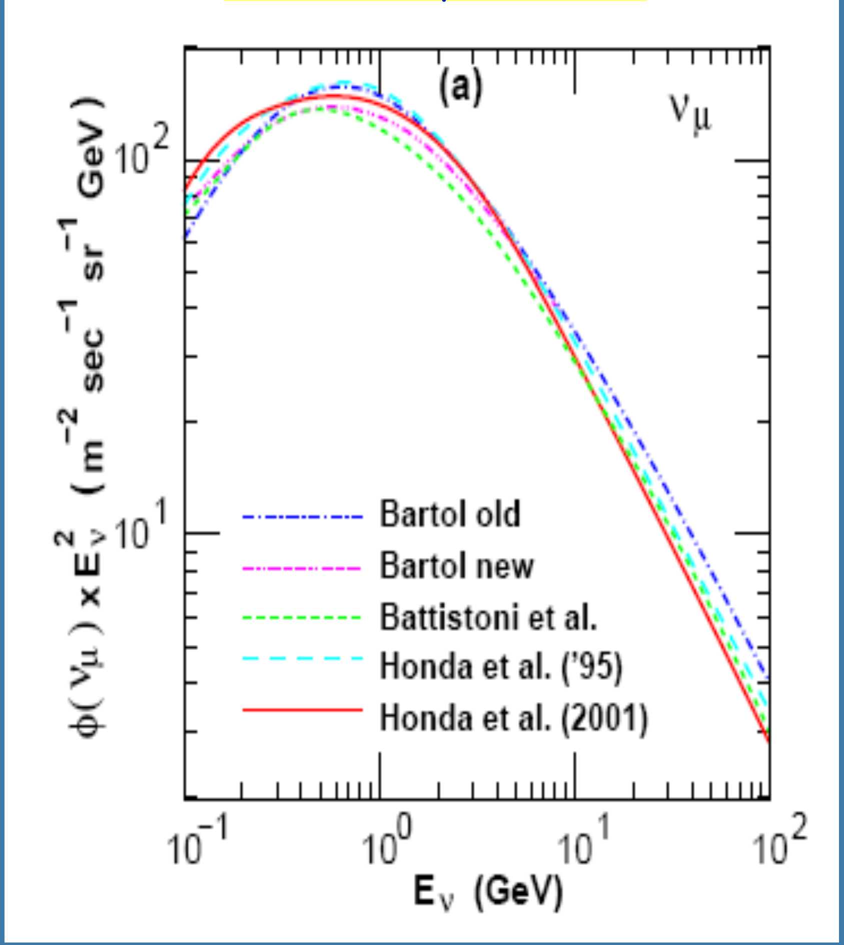
(*) D. Hooper., Annu. Rev. Nucl. Part. Sci. (2008), Vol. 58

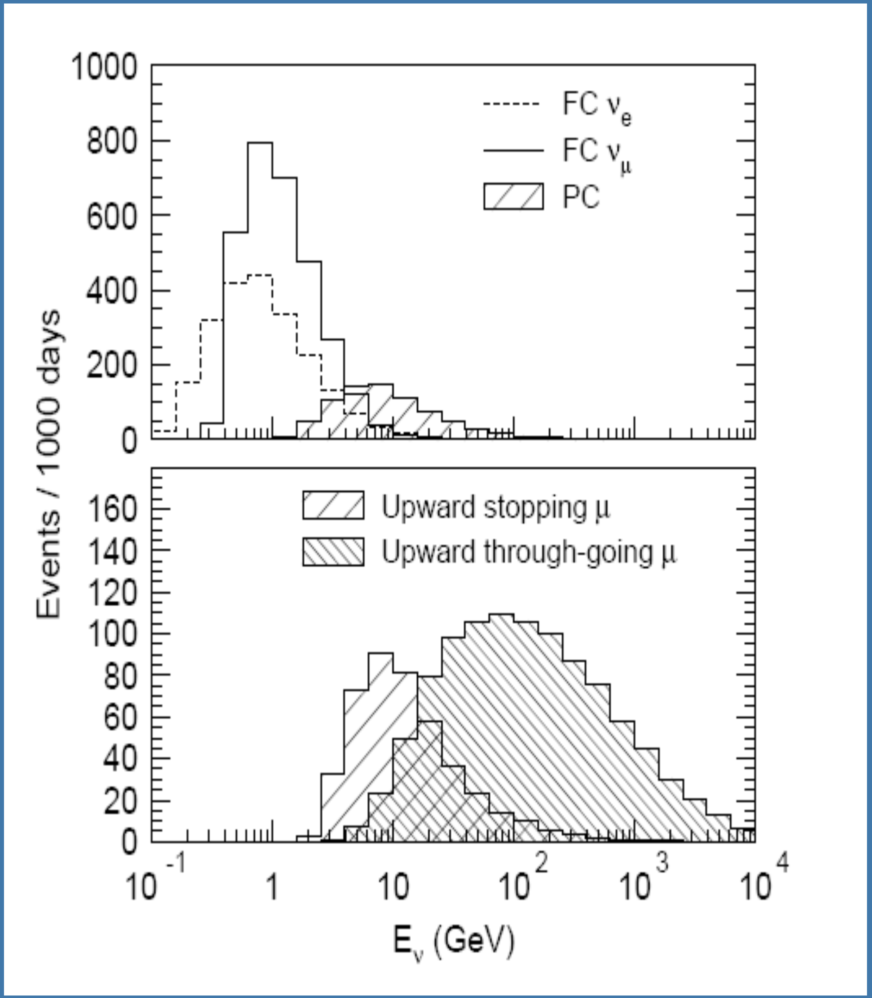


- ***„To detect neutrinos from WIMP annihilations in the Sun over the background of atmospheric neutrinos, a rate in the range of 10-100 events per square-kilometer, per year is required"***

Atmospheric neurinos in SK

Atm. ν_μ (MC)





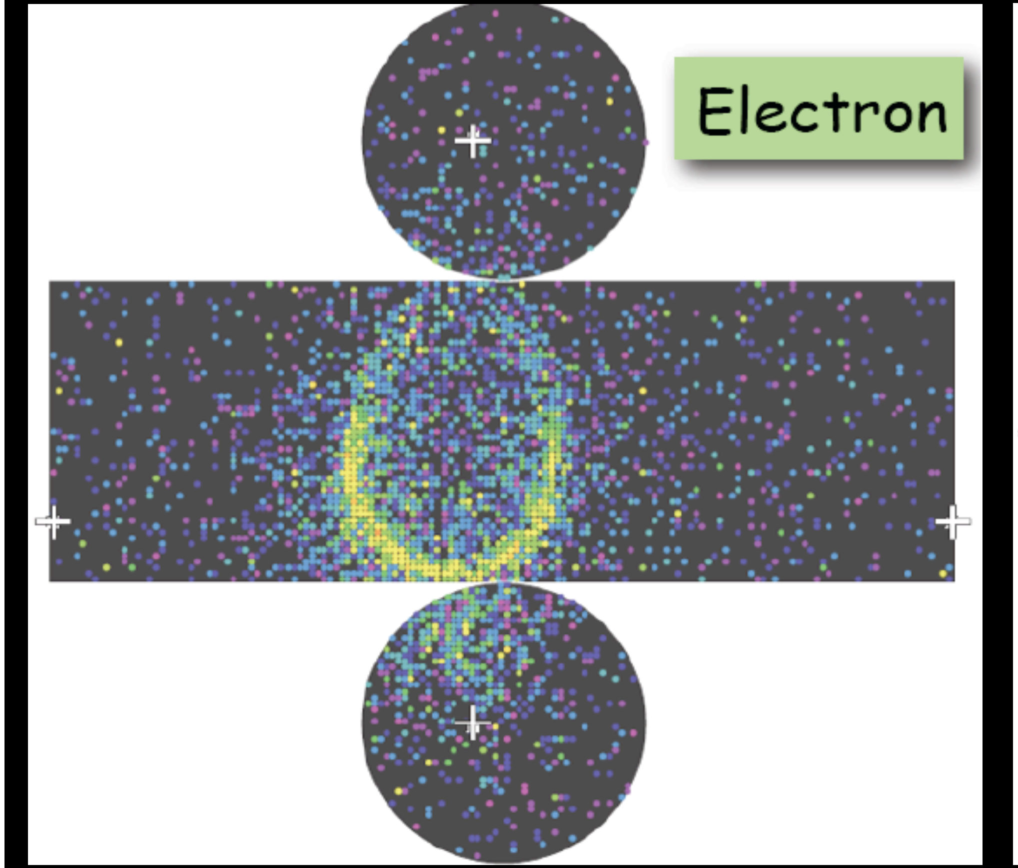
expected number of neutrino events in
each event category as a function of neutrino energy

Cerenkov ring categories

How can we distinguish interacting neutrino flavor?

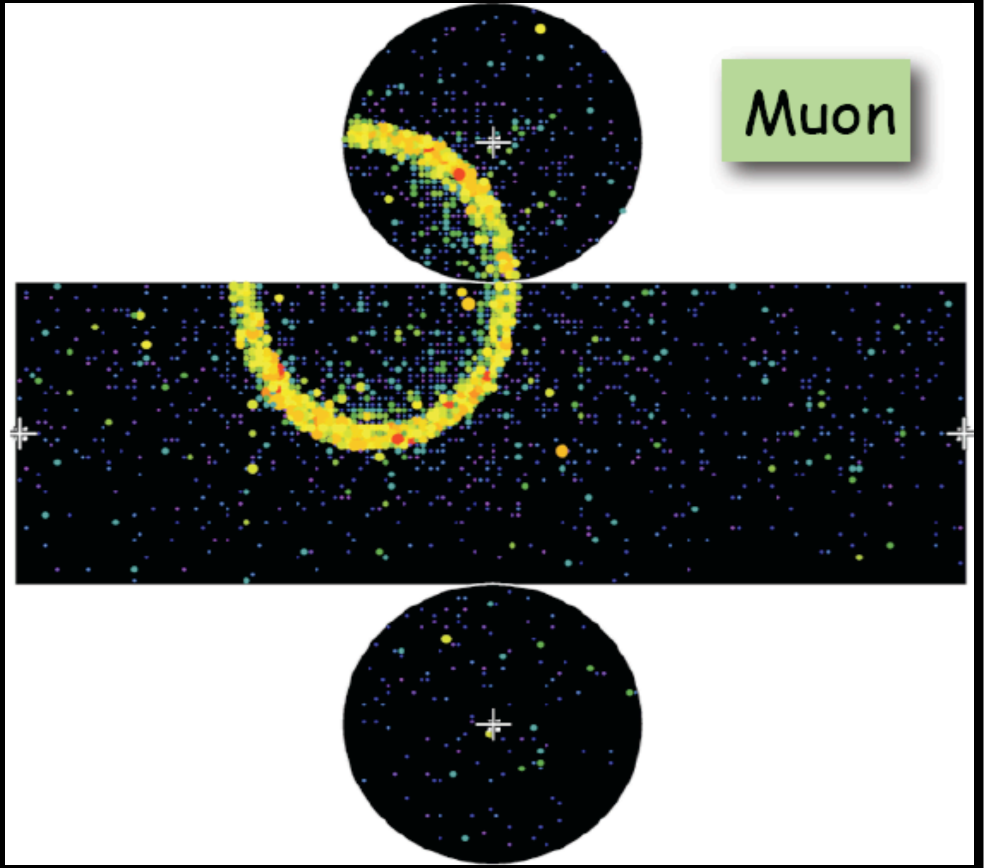
- e-like

fuzzy rings (due to E-M showers)



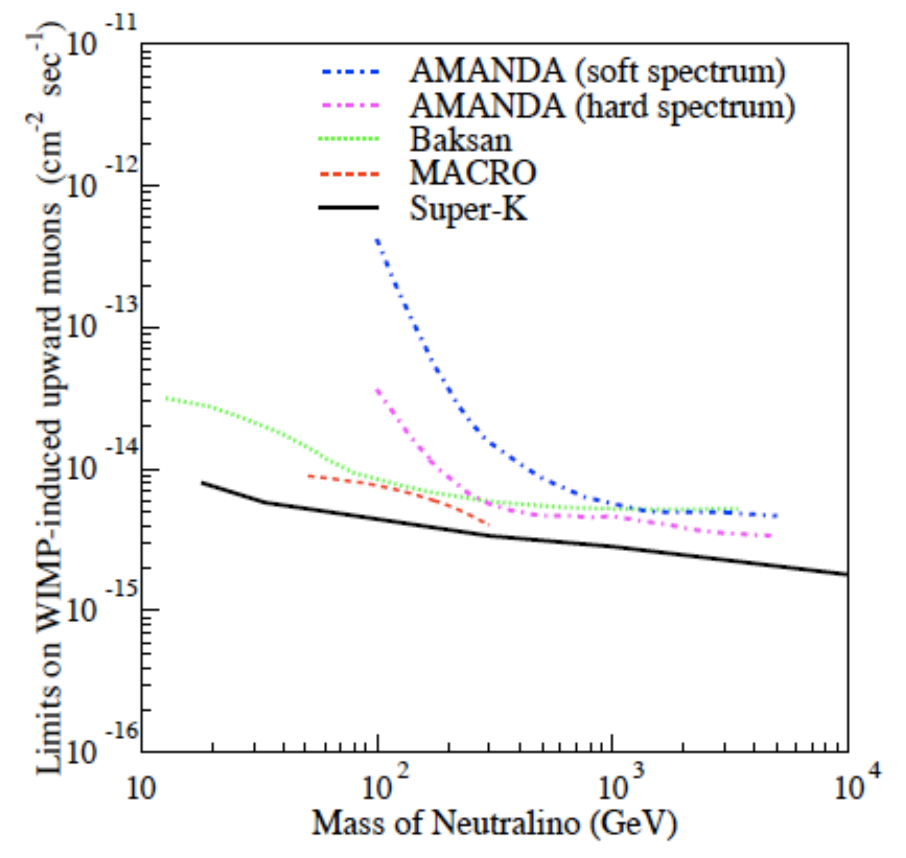
- μ-like

solid rings

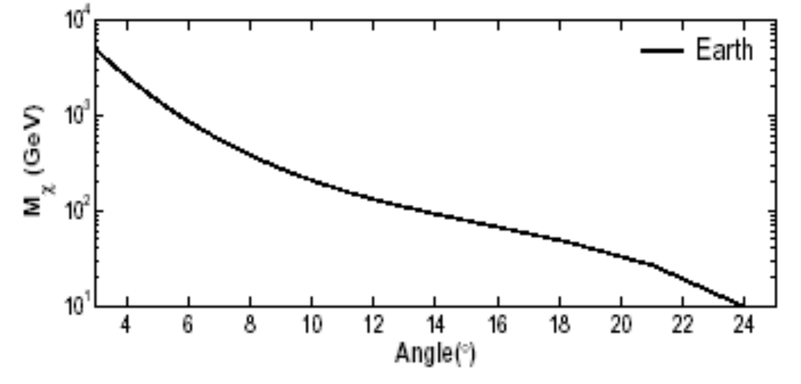


SuperK – WIMP-induced neutrino flux limit from Earth

Limit: WIMP-induced upward muons (EARTH)



simulation

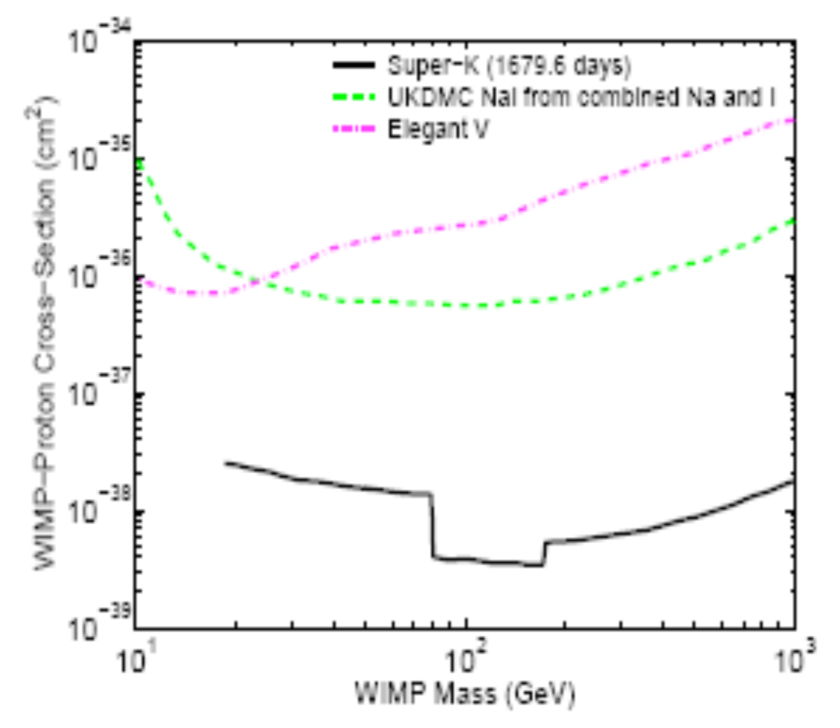


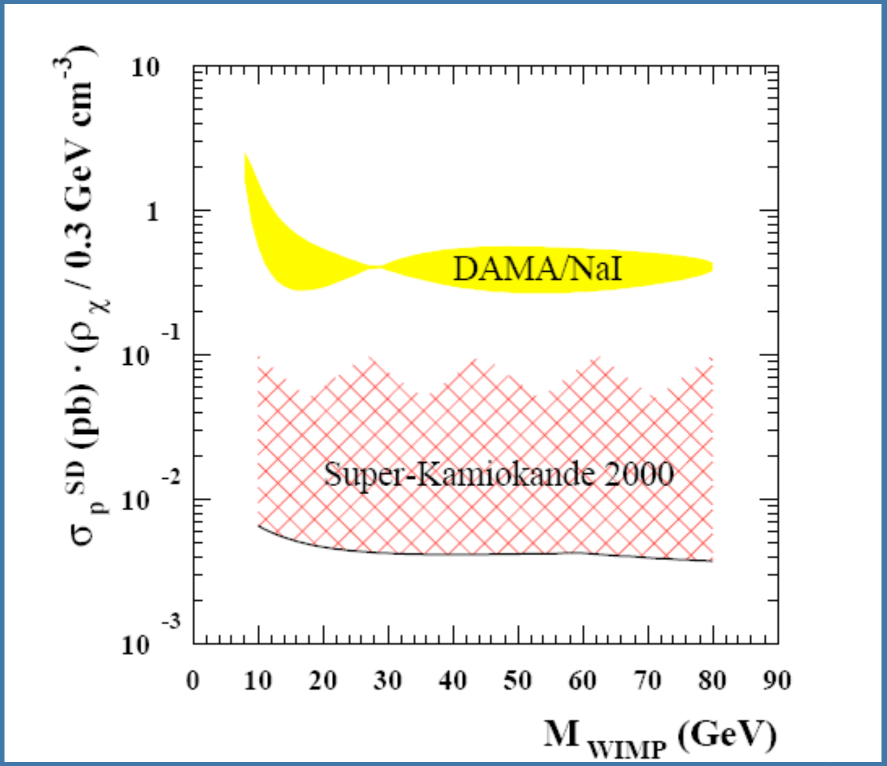
cone half-angle which contains 90% of neutrino flux form WIMP annihilation in Earth

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

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.)*

„full approach” fit

- How to include systematic uncertainties in χ^2 calculation ? Add „pull terms”...

depends on ν oscillation parameters

secret knowledge

fitted

$$\chi^2 = \sum_{i=1}^{nbins} \frac{\left(N_i^{obs} - \left(N_i^{atm\nu} + \beta \cdot N_i^{WIMP}\right)\cdot\left(1 + \sum_{j=1}^{Nsyserr} f_j^i \cdot \varepsilon_j\right)\right)^2}{\sigma_i^2} + \sum_{j=1}^{Nsyserr}\left(\frac{\varepsilon_j}{\sigma_j}\right)^2$$

sys. error

- In case of „poissonian” χ^2:
  (better to use when bins may ocassionally contain small # events)

$$\chi^2 = 2\sum_{i=1}^{nbins}\left(\left(N_i^{atm\nu} + \beta \cdot N_i^{WIMP}\right)\cdot\left(1 + \sum_{j=1}^{Nsyserr} f_j^i \cdot \varepsilon_j\right) - N_i^{obs} + N_i^{obs}\ln\frac{N_i^{obs}}{\left(N_i^{atm\nu} + \beta \cdot N_i^{WIMP}\right)\cdot\left(1 + \sum_{j=1}^{Nsyserr} f_j^i \cdot \varepsilon_j\right)}\right) + \sum_{j=1}^{Nsyserr}\left(\frac{\varepsilon_j}{\sigma_j}\right)^2$$