7. Indirect Search Experiments

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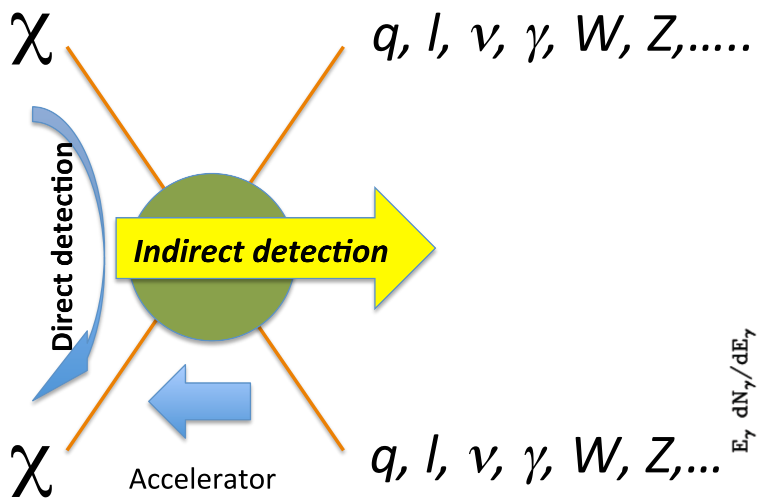
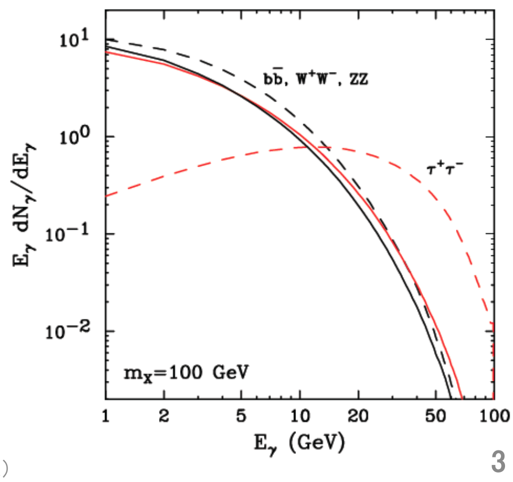
Overviews



- Spectrum shape can be predicted



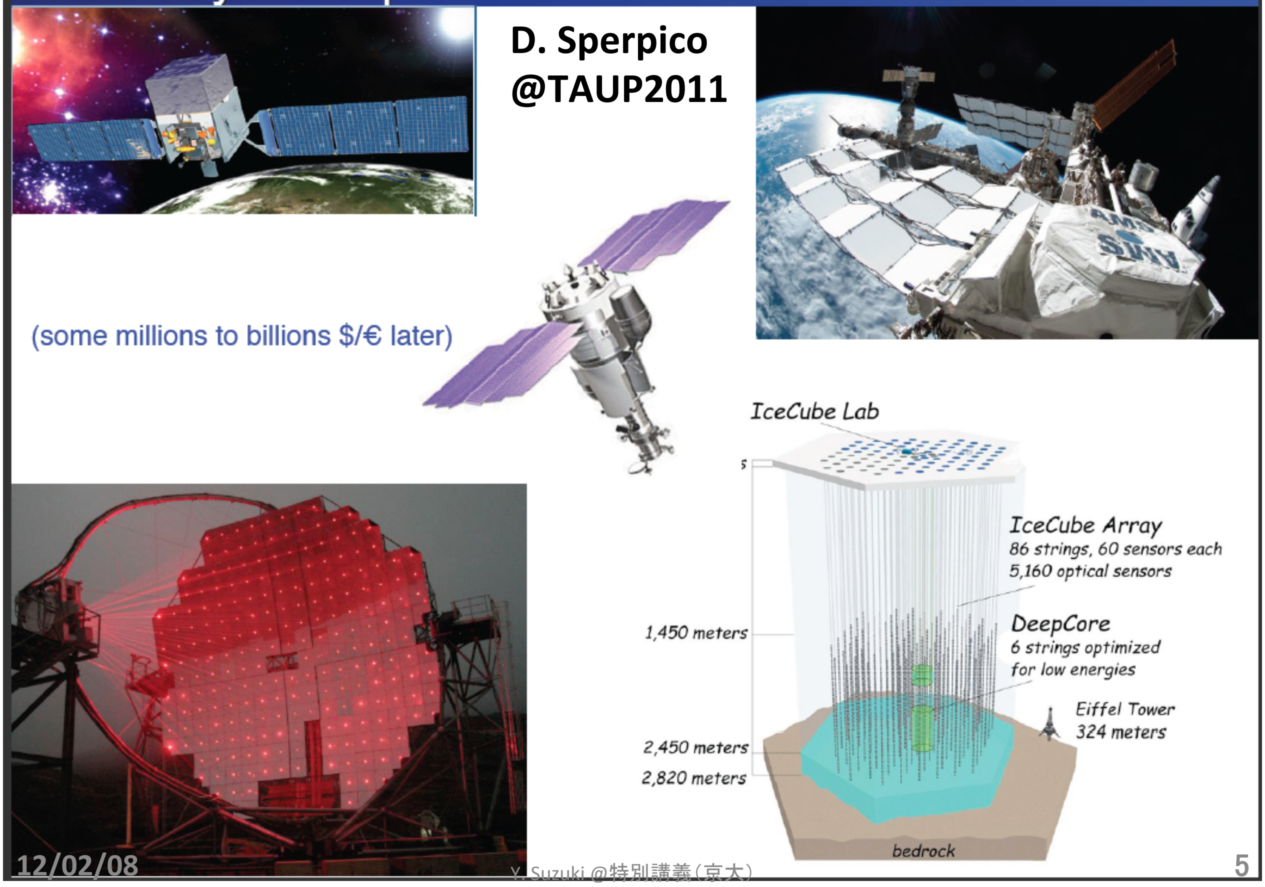
Detection Methods

- Neutrinos (from Core of the sun and/or earth, Galactic Center,)
  – Underground/underwater Neutrino Detector
  – Super-K, IceCUBE, ANTARES etc.
- Charged Particles (Halo)
  – Balloon, Satellite, Space Station, Cherenkov Telescope
- Gamma (Galactic Center, Dwarf, Halo)
  – Satellite, Space station, etc

Go to your exper. friends and tell them to find DM

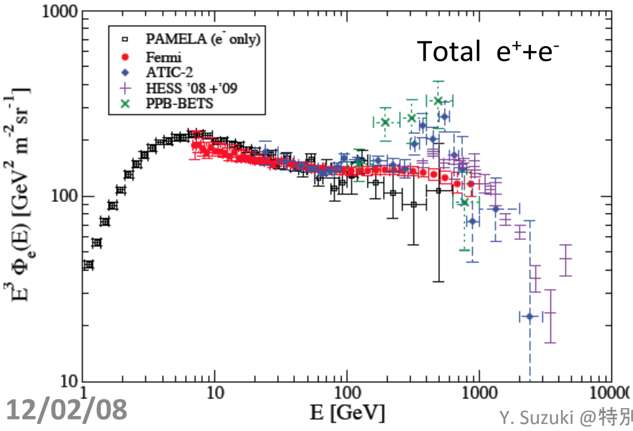
D. Sperpico @TAUP2011

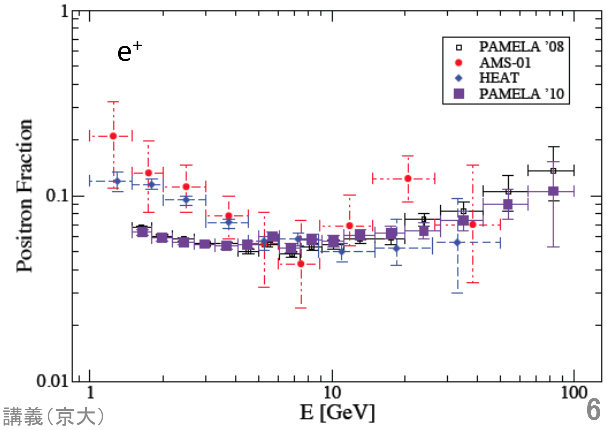
(some millions to billions $/€ later)



Situation

- No positive convincing results in neutrinos, charged particles and γ's
- But,
  - PAMERA and other experiments: see excesses in $e^{+}+e^{-}$ and in e^{+}





Neutrinos

From the sun and the earth and from the Galactic center

- IceCUBE South pole (under ice)
- ANTARES Mediterranean (under water)
- Super-K Japan (underground)

Neutrinos from the sun

- Ref) G. Wikstrom and J. Edsjo, JCAP 04,009(2009)
- Ref) K. Greist and D. Sedkel, NPB283, 681 (1987)
- Detection through the upgoing muons
- Muon flux measurements (limits)

  → Elastic scattering cross section (SI, SD)

Solar WIMPs (SK)

- SD interactions
  - Below escape velocity → Accumulation in the sun
  - Annihilation

$$\chi\chi \longrightarrow b\bar{b} \quad \text{Soft channel}$$
$$WW^{+} \quad \text{Hard channel}$$
$$ZZ, HH etc.$$

  - Decay to produce neutrinos

Capture and Annihilation

- WIMPs capture and annihilation in the sun

$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N$$

- C_C, C_A, C_E: capture, annihilation and evaporation rates (constants)
- M_χ > 5 GeV → Evaporation can be neglected.

  Ref) see Griest and Seckel, NPB, 283,681(87)

<解>

$$N^2 = \frac{C_C}{C_A} \tanh^2(t/\tau)$$

Hyperbolic functionのおさらい

- $X^2 - y^2 = 1$ を満たす

$$\begin{cases} x=\cosh^2\theta \\ Y=\sinh^2\theta \end{cases}$$

$$\cosh x = \frac{e^x + e^{-x}}{2} = \frac{e^{2x}+1}{2e^x}$$

$$\sinh x = \frac{e^x - e^{-x}}{2} = \frac{e^{2x}-1}{2e^x}$$

$$\tanh x = \frac{e^x - e^{-x}}{e^x + e^{-x}} = \frac{e^{2x}-1}{e^{2x}+1}$$

$$\frac{d\tanh ax}{dx} = a(1-\tanh^2 ax)$$

← 証明

Capture and Annihilation

$$\frac{dN}{dt} = C_C - C_A N^2$$ ← $$N^2 = \frac{C_C}{C_A}\tanh^2(t/\tau)$$ $$\frac{d\tanh ax}{dx} = a(1-\tanh^2 ax)$$

逆証明

$$N = \sqrt{\frac{C_C}{C_A}}\tanh(t/\tau)$$ であるから

$$\frac{dN}{dt} = \frac{1}{\tau}\sqrt{\frac{C_C}{C_A}}(1-\tanh^2(t/\tau))$$

$$\frac{dN}{dt} = \frac{1}{\tau}\sqrt{\frac{C_C}{C_A}}(1-\frac{C_A}{C_C}N^2)$$

$$= \frac{1}{\tau}\frac{1}{\sqrt{C_A C_C}}(C_C - C_A N^2)$$

$$\tau \equiv 1/\sqrt{C_A C_C}$$

Capture and Annihilation

- Annihilation rate:

$$\Gamma_A \equiv \frac{1}{2} C_A N^2 = \frac{1}{2} C_C \tanh^2(t/\tau)$$

$$r = 1/\sqrt{C_C C_A}$$

- 現在の太陽の年齢　t= $t_\odot$= 4.5x10^9 yr: $t_\odot/\tau$ >>1
- Annihilation and capture ➔ in equilibrium: Γ_A=(1/2)C_C
- Annihilation rateは、scattering cross sectionだけによる。。。

- μ-rate → scattering cross section (Home Work) $\kappa_f^{SD}(m_\chi)$

  ➔ ref) K. Greist and D. Sedkel, NPB283, 681 (1987)

Scattering Cross Section

$$\sigma^{SD} = \kappa_f^{SD}(m_\chi) \cdot \Phi_\mu^f$$

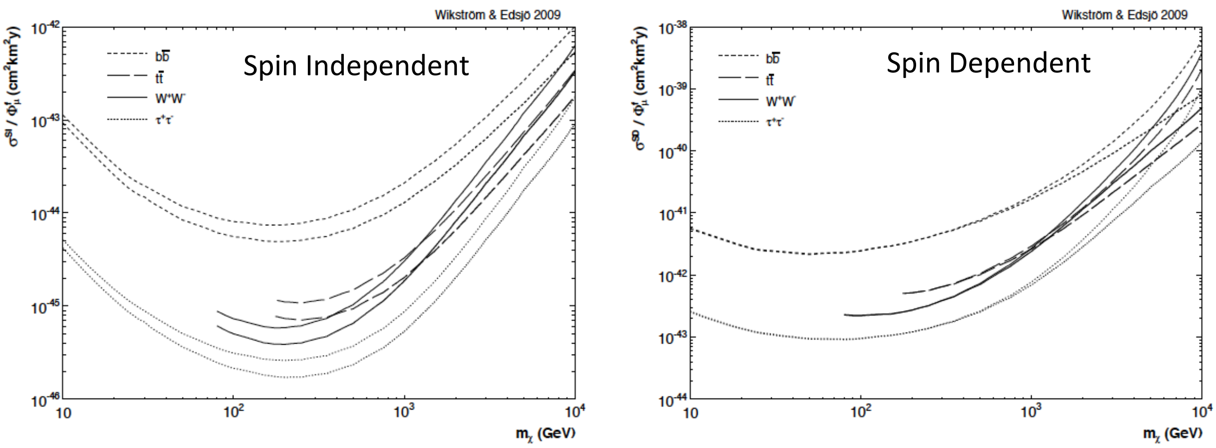


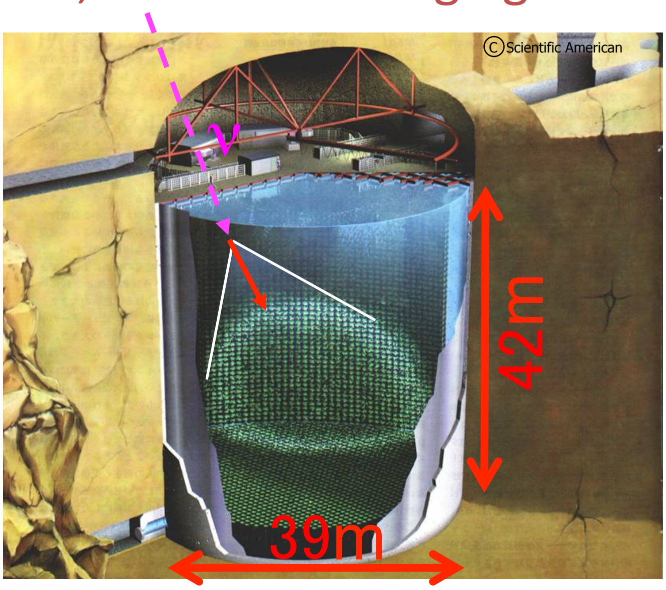
FIG. 3: The conversion factors $\kappa_f^{SI} = \frac{\sigma^{SI}/\text{cm}^2}{\Phi_\mu^f/\text{km}^{-2}y^{-1}}$ (left panel) and $\kappa_f^{SD} = \frac{\sigma^{SD}/\text{cm}^2}{\Phi_\mu^f/\text{km}^{-2}y^{-1}}$ (right panel) as a function of m_χ, for annihilation channels $f = W^+W^-$, $\tau^+\tau^-$, $t\bar{t}$, and $b\bar{b}$. Lower lines for each channel are from the standard calculation and upper lines are from the conservative calculation. For the muon flux we have used a threshold of 1 GeV.

Super-K results

- Super-K I, II, III (3109.6 days)
  - Ref): Tanaka et al., Astrop. J. 742, 78 (2011).
  - Look for neutrinos from WIMPs annihilation in the Sun
  - Upward going muons ← Very high energy neutrinos@SK: 4351 events
    - Stopping: 919 events
    - Through going non-showering: 2901 events
    - Through going showering: 531 events

Super-Kamiokande

50,000 tons of Imaging Water Cherenkov Detector



- Inner: 32,000 tons
  (Outer Vol: ~2.5 m thick)
- Fid. Vol: 22,500 tons
- 11,146 PMTs (ID)
  - 50 cm in diameter
  - 40% coverage
- 1,885 PMTs (OD)
  - 20 cm in diameter
- 1,000 m underground

~130 Collaborators from 36 inst. (5 countries)

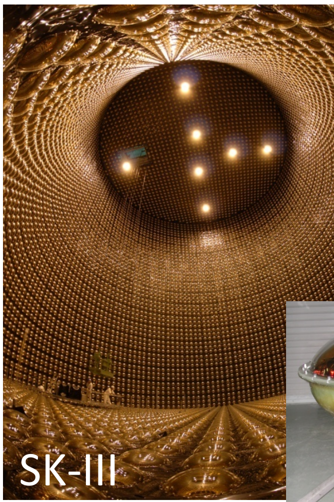
Brief history of Super-K

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10

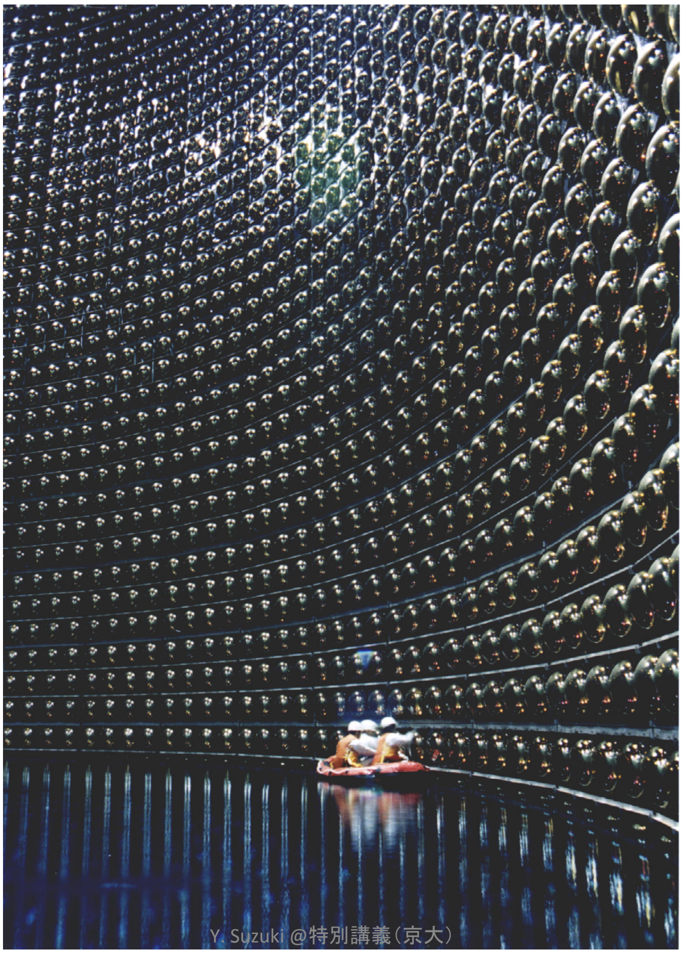
SK-I | SK-II | SK-III | SK-IV

K2K | T2K

- **SK started on April, 1996 (SK-I)**
  - **12th Anniversary**
- **4 phases: SK-I, SK-II, SK-III, SK-IV**
  - **Accident (lost more than half of PMTs)**
    - **Nov-12, 2001**
  - **SK-II (5,182 PMTs (19% cov.))**
    - **Dec-2002 → Nov-2005**
  - **SK-III (11,129 PMTs (40% cov.))**
    - **July-2006 →**
  - **SK-IV w/new front end electronics**
    - **Sept-6, 2008 →**
- **K2K: March-1999 → Nov-2004**
- **T2K: 2009 →**

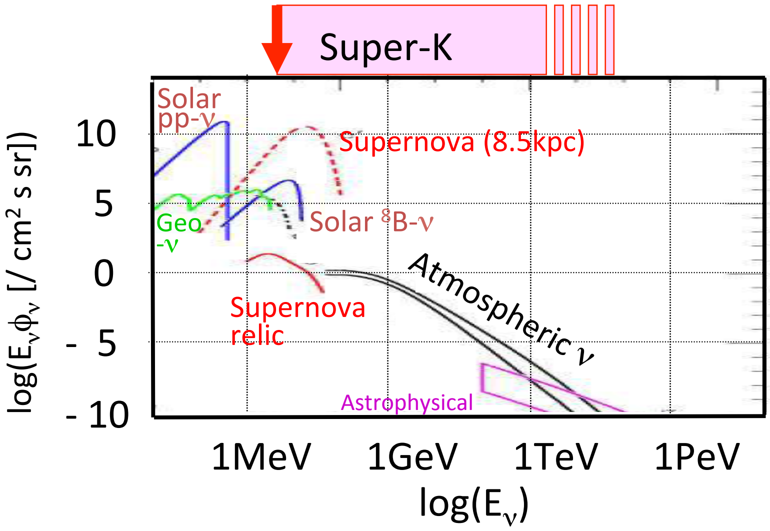


Protection case



Energy Range *(data from SK-I)*

- Trigger: 100% eff. for E_{obs} > **4.5 MeV**
  (50% efficiency @ 3.7MeV)
- Trigger Rate: 1,700Hz → 15 Hz (recorded)

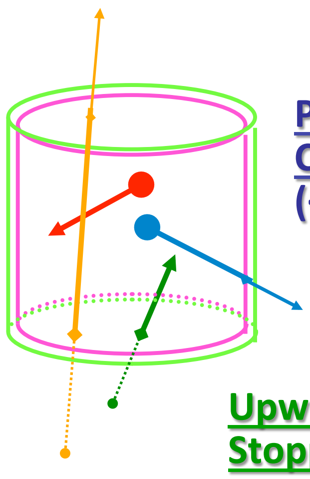


- 6 p.e. / MeV
- Resolution
  (solar/supernova ν)
  14.2% @10MeV
  (atmospheric ν)
  $1.7+0.7/\sqrt{E(\mathrm{GeV})}$ %
  (single ring μ)

Atmospheric Neutrino Events in Super-K

- ***Event category***

Fully Contained (FC)
($\langle E_\nu \rangle$ ~ 1GeV)
subGeV: Evis<1.33GeV
Multi-GeV: >1.33GeV



Partially Contained (PC)
($\langle E_\nu \rangle$ ~ 10GeV)

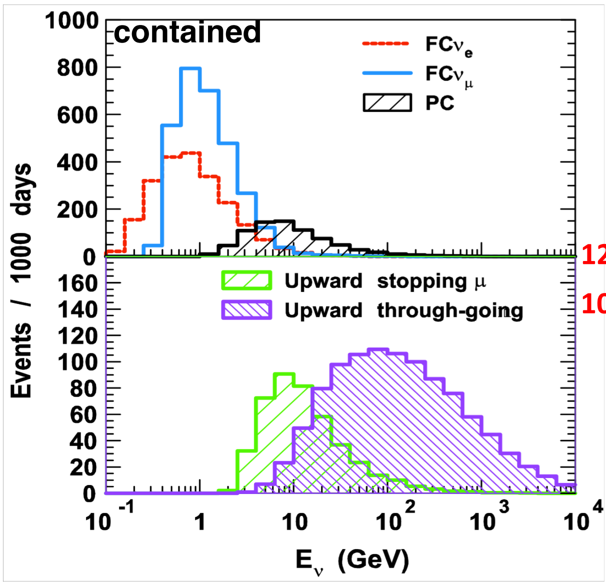
Upward Through-going μ
($\langle E_\nu \rangle$ ~ 100GeV)

Interaction in the rock

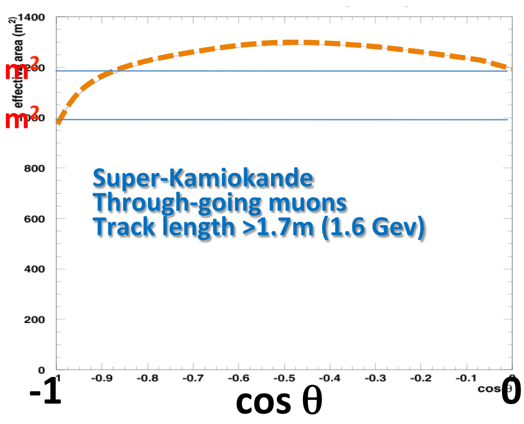
Upward Stopping μ
($\langle E_\nu \rangle$ ~ 10GeV)

Atmospheric Neutrino Events in Super-K

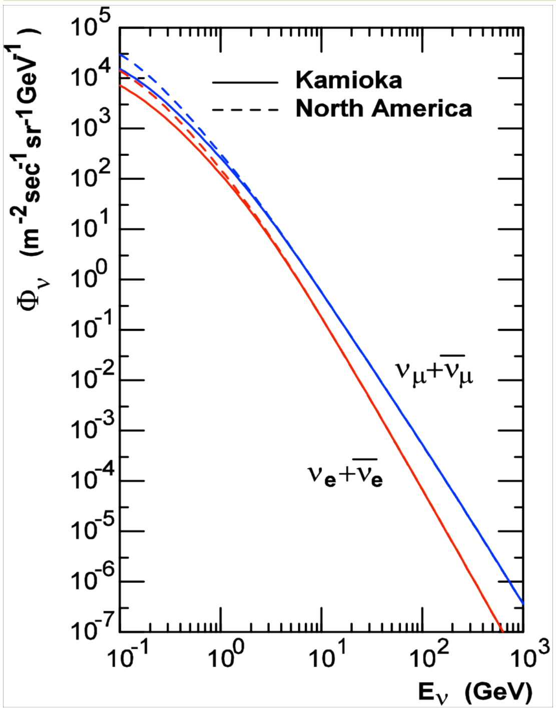
Parent neutrino Energy



- **Fiducial volune: 22.5 kton**
- **Effective area: ~1,200m²**

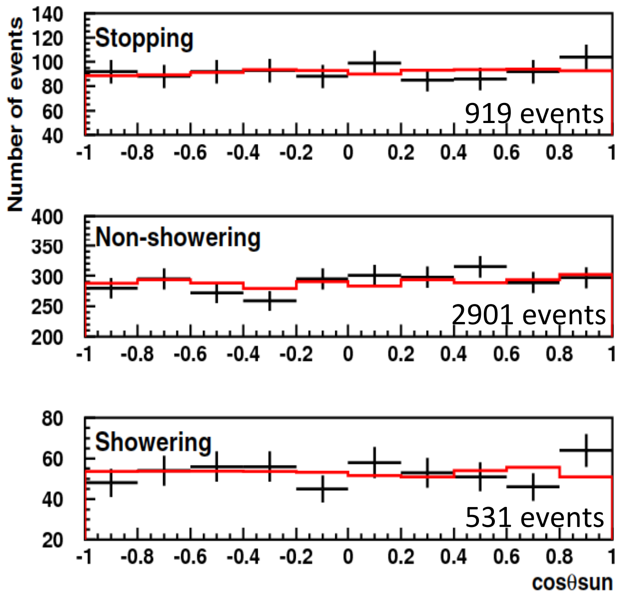


Upward going muons



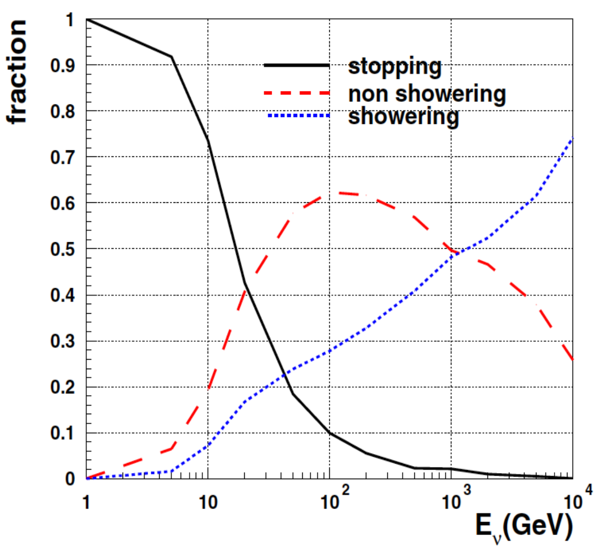
- Sensitivity towards high energy neutrinos
- Cross sections
  - – $\sigma(\nu N) \sim E_\nu$
- Muon Range
  - – ~Proportional to E_μ

Results (directional plots)



- 3109.6 days
- Total 4351 events.
- Red lines are contributions from the atmospheric neutrinos
- No obvious excess by eye

Three Categories



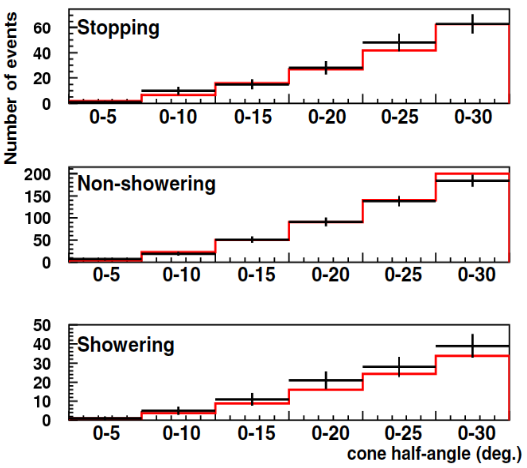
Parent neutrino energy

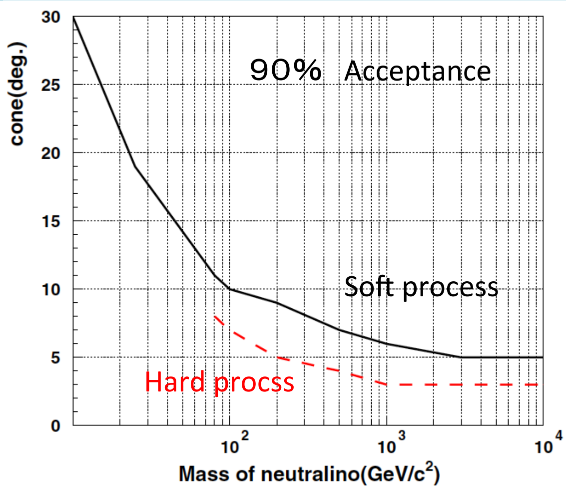
- Fractions of parent neutrinos as a function of energy
- Three categories are normalized to 1 at each neutrino energy

Process to be considered

- Soft process (softest spectrum)
  - Annihilation into bb
- Hard process
  - Annihilation into W^+W^- (hardest neutrino spectrum)

Cone Half-Angle





- As a function of the cone half-angle (acceptance for individual WIMP mass)
- Red line: atmospheric neutrino BG

Flux limit

- Flux limit

$$\phi(90\%C.L.) = \frac{N_{90}(n^1_{obs}, n^1_{BG}, F^1, n^2_{obs}, n^2_{BG}, F^2, n^3_{obs}, n^3_{BG}, F^3,)}{\epsilon \times A \times T}$$

  - ε: efficiency, T= live time
  - A: detector cross sectional area (depends upon sun's position)

- ← N_{90} (90% C.L.)

$$L(n^i_{obs}|n_s) = \prod_{i=1}^{3} \frac{(n_s F^i + n^i_{BG})^{n_obs^i}}{n^i_{obs}!} e^{-(n_s F^i + n^i_{BG})}$$

$$C.L. = \frac{\int_{n_s=0}^{N_{limit}} L(n^i_{obs}|n_s) dn_s}{\int_{n_s=0}^{\infty} L(n^i_{obs}|n_s) dn_s}$$

Numerical Results

Table 1
Event Summary to Calculate the Flux Limit (ϕ) Assuming the Soft Annihilation Channel is Dominant

		Stopping			Non-showering			Showering				
m_χ (GeV)	θ (deg)	n_{obs}	n_{BG}	F (%)	n_{obs}	n_{BG}	F (%)	n_{obs}	n_{BG}	F (%)	N_{90}	$\phi(\times 10^{-15})$ (cm^{-2} s^{-1})
10	30	63	62.5	98	184	200.3	2	39	33.7	0	14.8	8.9
100	10	10	6.7	78	19	22.5	16	5	3.8	6	10.9	6.5
1000	6	3	2.7	59	8	7.2	29	1	1.4	12	6.41	3.8
10000	5	1	1.9	28	7	4.6	52	1	0.9	20	6.99	4.2

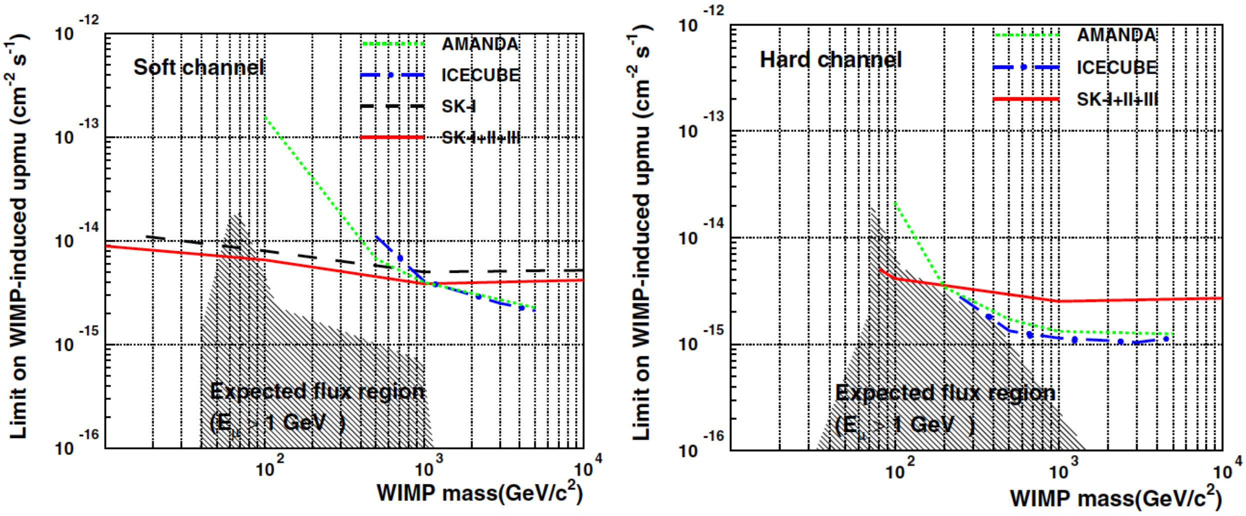
Notes. The numbers of events (n_{obs}) and estimated background (n_{BG}) for each cone half-angle (θ) which corresponds to a certain WIMP mass (m_χ) are shown for all categories of upmu. This cone half-angle is defined by the criterion that more than 90% of the WIMP-induced upmus are contained for the assumed WIMP masses. We also show the estimated fraction (F) of each upmu category for the given WIMP mass. The calculated result of N_{90} and the flux limit for each WIMP mass are shown in the last two columns.

Table 2
Event Summary and Upmu Flux Limit Assuming the Hard Annihilation Channel is Dominant

		Stopping			Non-showering			Showering				
m_χ (GeV)	θ (deg)	n_{obs}	n_{BG}	F (%)	n_{obs}	n_{BG}	F (%)	n_{obs}	n_{BG}	F (%)	N_{90}	$\phi(\times 10^{-15})$ (cm^{-2} s^{-1})
80.3	8	4	4.2	44	14	13.4	40	3	2.5	16	8.4	5.0
100	7	3	3.3	42	10	9.9	41	2	2.2	17	6.9	4.1
1000	3	0	0.5	40	2	2.1	41	1	0.3	19	4.2	2.5
10000	3	0	0.5	24	2	2.1	54	1	0.3	22	4.5	2.7

Note. The meaning of each column is the same as in Table 1.

Flux limit



Flux limit to SD cross section

- Flux limit <-> SD cross section limit
  - Ref: G.Wikstrom, J.Edsjo JCAP 090;009, 2009
- Assumption
  - One annihilation channel dominates
  - Accumulation & escape : equilibrium
  - SD interactions only
  - DM density and velocity is constant

Conversion factor

$$\sigma^{SD} = \kappa_f^{SD}(m_\chi) \cdot \Phi_\mu^f$$

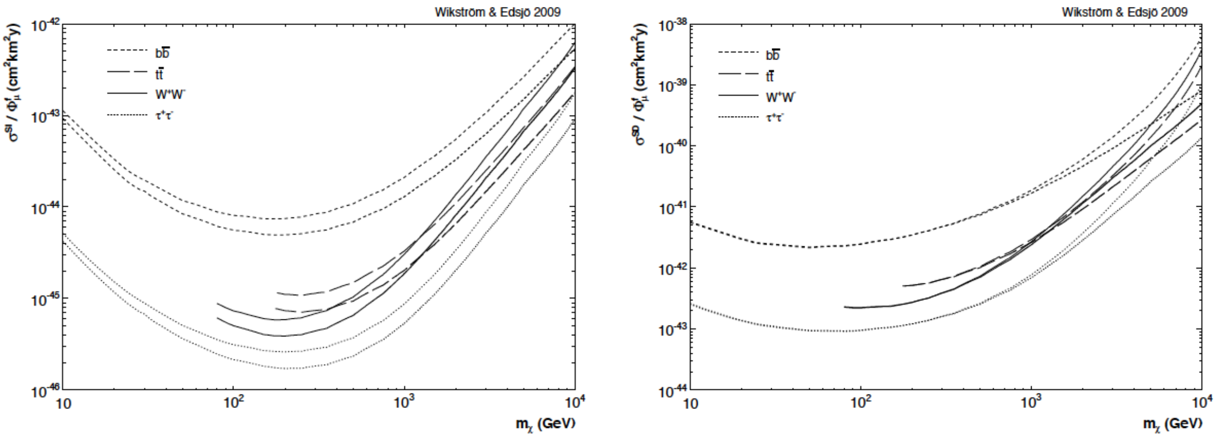
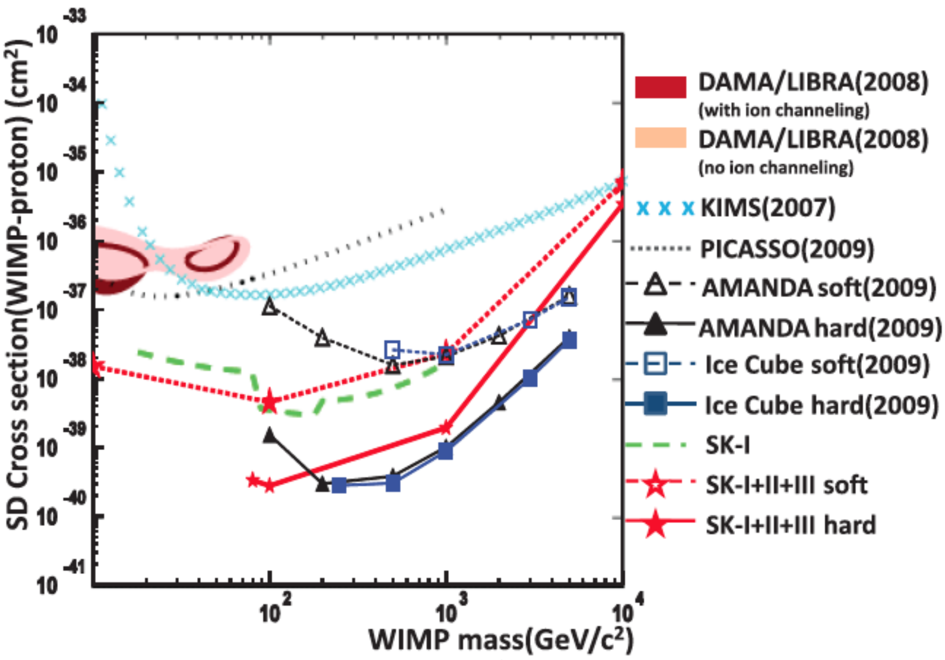


FIG. 3: The conversion factors $\kappa_f^{SI} = \frac{\sigma^{SI}/\mathrm{cm}^2}{\Phi_\mu^f/\mathrm{km}^{-2}y^{-1}}$ (left panel) and $\kappa_f^{SD} = \frac{\sigma^{SD}/\mathrm{cm}^2}{\Phi_\mu^f/\mathrm{km}^{-2}y^{-1}}$ (right panel) as a function of m_χ, for annihilation channels $f = W^+W^-$, $\tau^+\tau^-$, $t\bar{t}$, and $b\bar{b}$. Lower lines for each channel are from the standard calculation and upper lines are from the conservative calculation. For the muon flux we have used a threshold of 1 GeV.

SD cross section limit (SK)



Charged Particles

Annihilation signal from Halo

- PAMERA Satellite
- Fermi-LAT Satellite

Cosmic Ray positron

- 1928, P.M.A.Dirac: Dirac equation, invention of positron
- 1932, K.D. Anderson: discovery of positron
- 1964, J.A.De Shong, R.Hildebrand and P. Meyer: $e^+/(e^++e^-)$ in CR
  - Ref) Phys. Rev. Lett. 12, 3 (1964)
- Fraction decreases up to ~10 GeV and increases above ~10 GeV (HEAT, CAPRICE, AMS01, PAMERA)

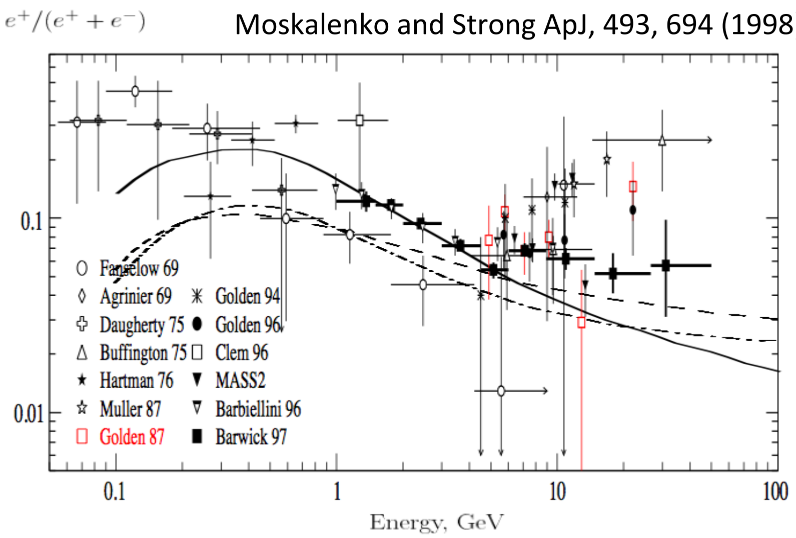
Cosmic Ray positron

CR positron production

- Mostly secondary production:
  - CR + Inter stellar gas (ISG) → $\pi^{\pm}$ → $e^{\pm}$, ν
  - Fraction decreases with energy
    - Ref) R.J. Protheroe, ApJ, 254, 391 (1982)
    - Ref) I.V.Moskalenko and A.W. Strong, 493, 694 (1998)
- Effects of Rising spectrum:
  - Pulsars
  - CRs interacting with giant molecular clouds
  - Dark Matter

Cosmic Ray positron

Moskalenko and Strong ApJ, 493, 694 (1998)



- Positron fraction (no reacceleration): Solid line: Protheroe (1982), leaky-box (dashed-dot), diffusion (dashed).
- (Divided by the electron spectrum used by Protheroe (1982))

PAMELA

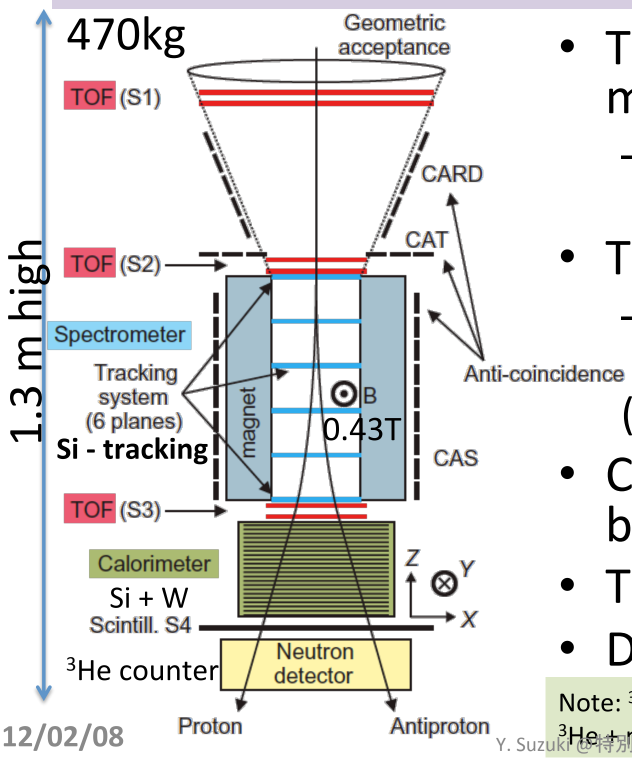
a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

- Antiparticle study: hundreds of GeV
- Antiparticles ← dark matter particle
- If WIMPs are Majorana → can annihilate → particle and antiparticles in the halo of the Galaxy ➔ signature of DM
- BG ← secondary particle production by CR interactions with the inter stellar medium.
  - CR transports
  - Solar activities
  - Additional astrophysical sources

Launched by a Soyuz-U rocket on 15 June 2006
Data from 11 July 2006

Ref) M. Boezio et al.,
New Journal of Physics 11, 105023 (2009)

PAMELA



- TOF: ~300ps res. and dE/dx measurement
  - e^-(e^+) and p($\bar{p}$) separation up to 1 GeV/c
- Tracking: sp. res. ~3μm
  - Maximum detectable rigidity (MDR) > 1 TV

  (Rigidity: momentum/charge)
- Calorimeter: for same sign backgrounds
- Trigger: ~25 Hz
- Data: 14GB/day

Note: ^{3}He counter
$^3He + n \rightarrow p + t$ + 764 keV

Design PAMELA performance

Table 1. Design PAMELA performance.

Particle	Energy range
Antiprotons	80 MeV–190 GeV
Positrons	50 MeV–300 GeV
Electrons	up to 500 GeV
Protons	up to 700 GeV
Electrons + positrons	up to ~1 TeV (from calorimeter)
Light nuclei (He/Be/C)	up to 200 GeV nucleon $^{-1}$
Antinuclei search	sensitivity of 3×10^{-8} in anti-He/He

Ref) M. Boezio et al.,
New Journal of Physics 11, 105023 (2009)

Particle identification

- Particle Identification
  - Rigidity (spectrometer)
  - Energy deposits
  - Interaction topology (Calorimeter)
- Spill over:
  - protons in anti-proton sample
  - electrons in positron sample

  ← mis-assignment of charge (deflection uncertainty: spectrometer)
- Mis-identification of like charge particles:
  - Protons in positron sample
  - Electrons in anti-proton sample

  ← Electron hadron mi-identification (calorimeter)

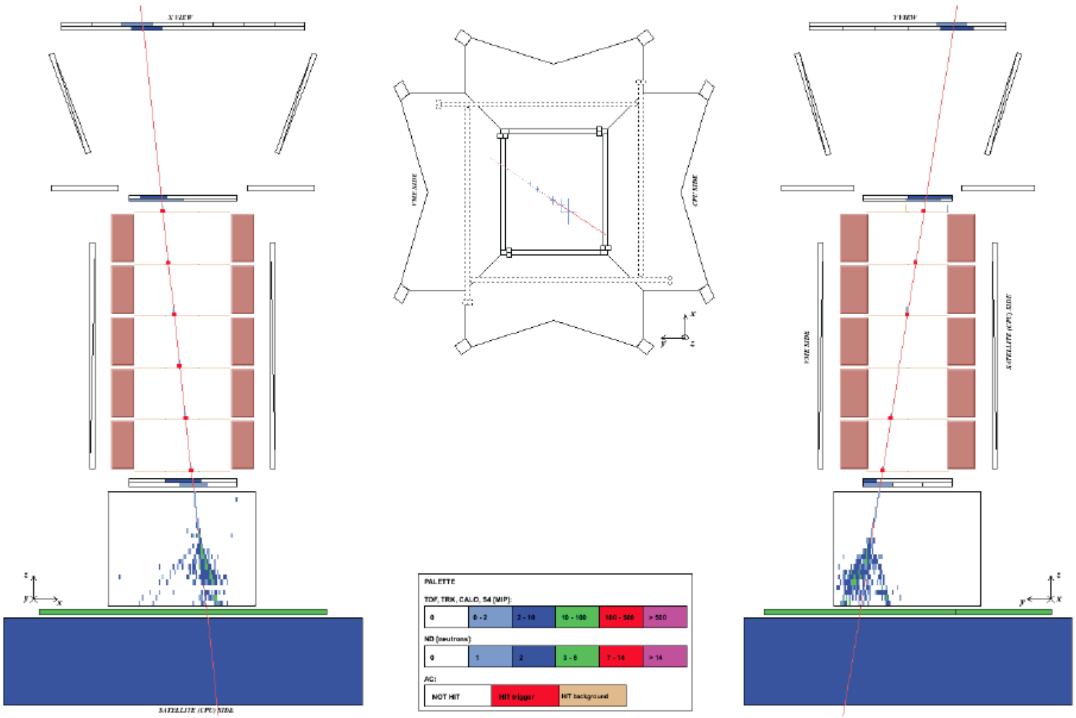


Figure 2. The event display an ∼29 GV antiproton interacting in the calorimeter. The bending (x) and non-bending (y) views are shown on the left and on the right, respectively. A plan view of PAMELA is shown in the center. The signal as detected by PAMELA detectors is shown along with the particle trajectory (solid line) reconstructed by the fitting procedure of the tracking system.

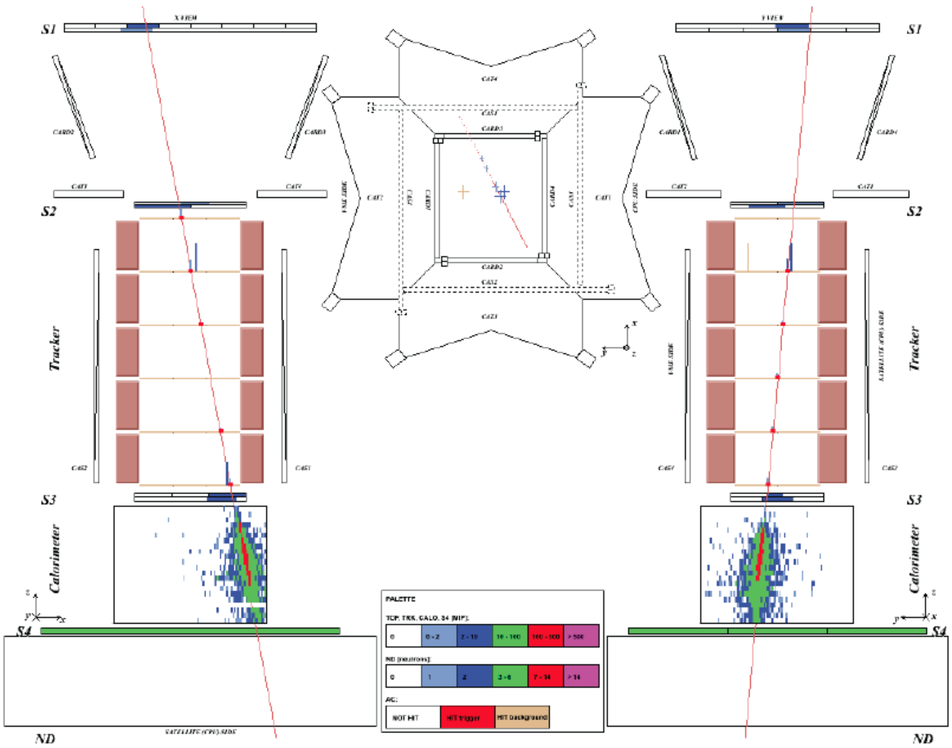
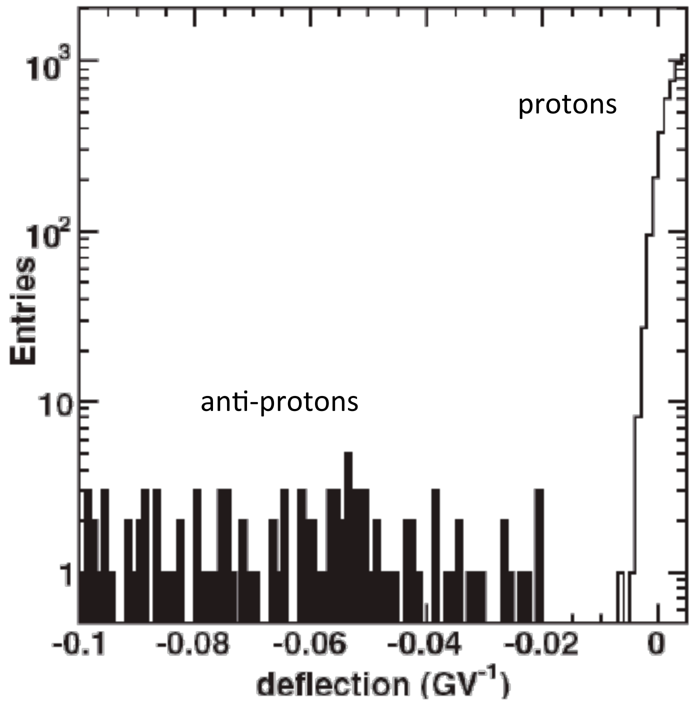


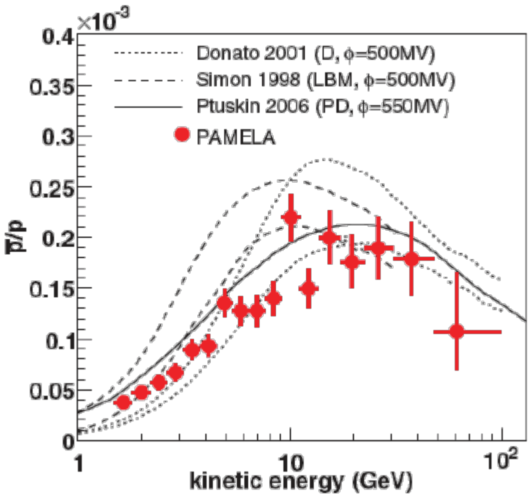
Figure 3. The event display a ∼92 GV positron. The bending (x) and non-bending (y) views are shown on the left and on the right, respectively. A plan view of PAMELA is shown in the center. The signal as detected by PAMELA detectors is shown along with the particle trajectory (solid line) reconstructed by the fitting procedure of the tracking system.



Spill over

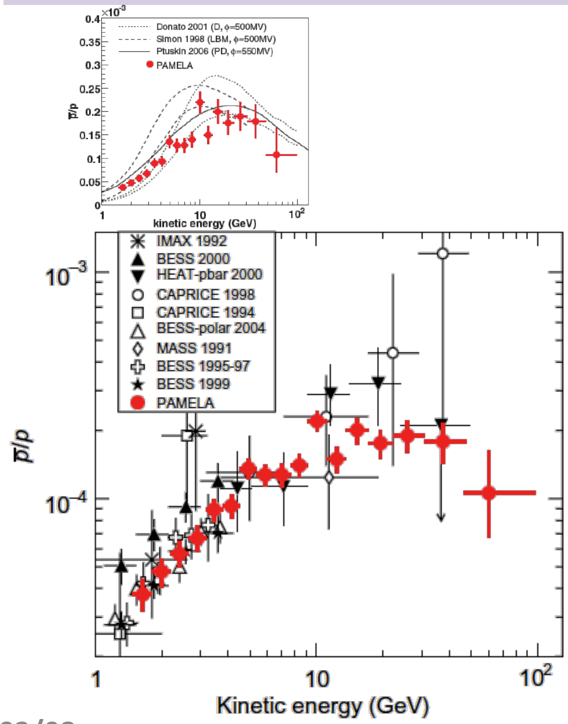
Figure 4. The deflection reconstructed by the track fitting procedure for negatively and positively charged down-going particles that did not produce an electromagnetic shower in the calorimeter. The shaded histogram corresponds to the selected antiprotons.

Anti-proton proton ratio



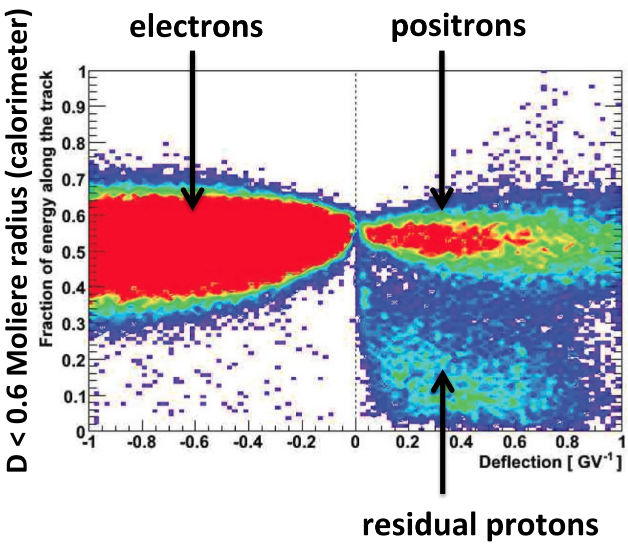
- Agree with the pure secondary production of anti-protons
- Theoretical prediction
  - LBM: Leaky Box Model
    (ref) M. Simon et al., ApJ, 499,250(98)
  - D: Diffusion model with reacceleration
    (ref) F.Donato et al, ApJ, 563, 172(01)
  - PD: Plain diffusion model
    (ref) A.S.Ptuskin et al, ApJ, 642,902(06)

Anti-proton proton ratio



- No excess of $\bar{p}/p$ was found
- 4×10^{-5} @2GeV
- $(1.5\sim2)\times10^{-4}$@10GeV then level off
- Agree with other experiments

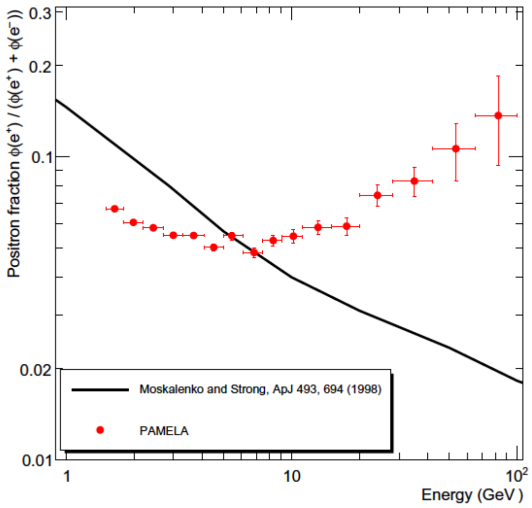
Positron signal



BG reduction

- e: spill over
  - 300 GeV maximum
- P: mis-identification
  - by calorimeter ($16.3X_0$)
    - $p/e^+ = 10^3$ @1 GeV
    - $p/e^+ = 10^4$ @100 GeV
  - Additional information from neutron counter and dE/dx measurements

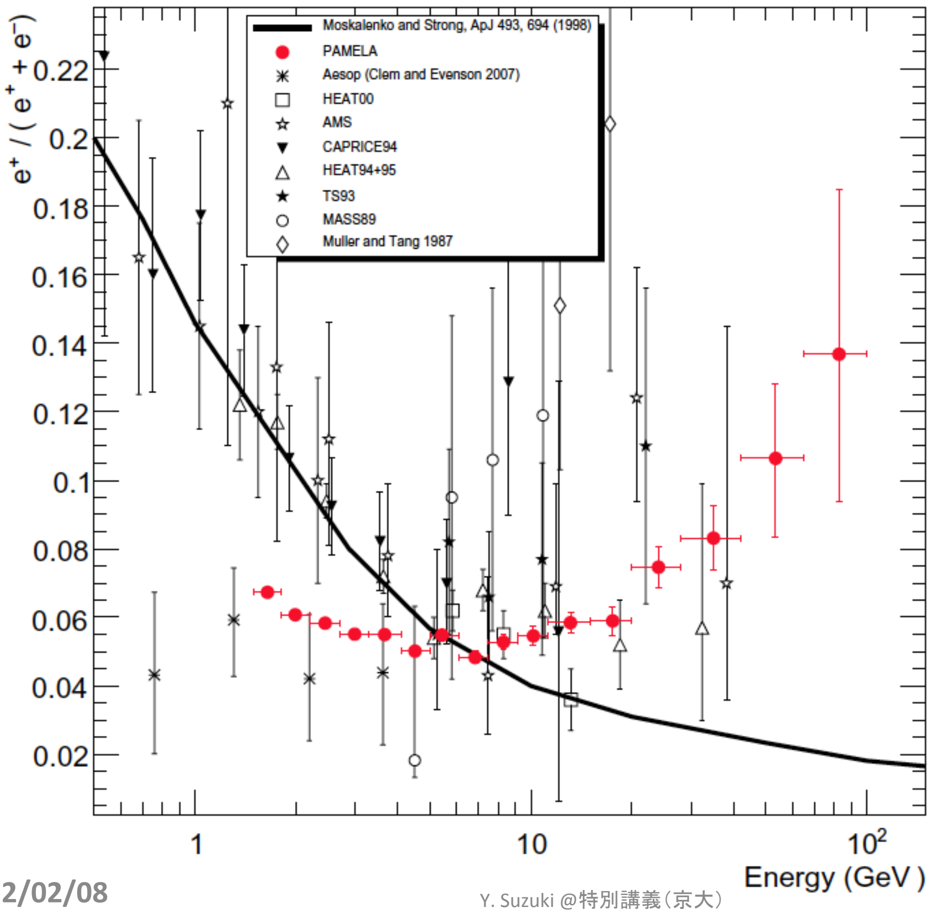
Positron fraction



- Line: theoretical prediction (pure secondary positron production)

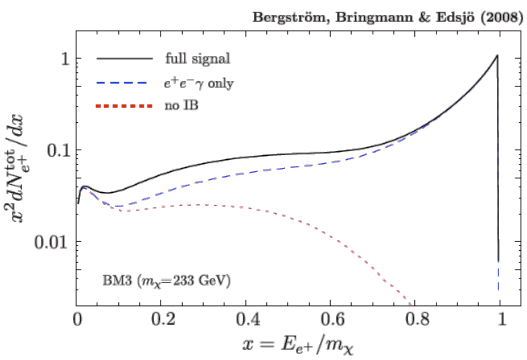
  (ref) I.V.Moskalendo et al., ApJ, 493,694.
- Discrepancy in low energy < a few GeV

  ← Solar modulation
- Disagreement above ~10 GeV

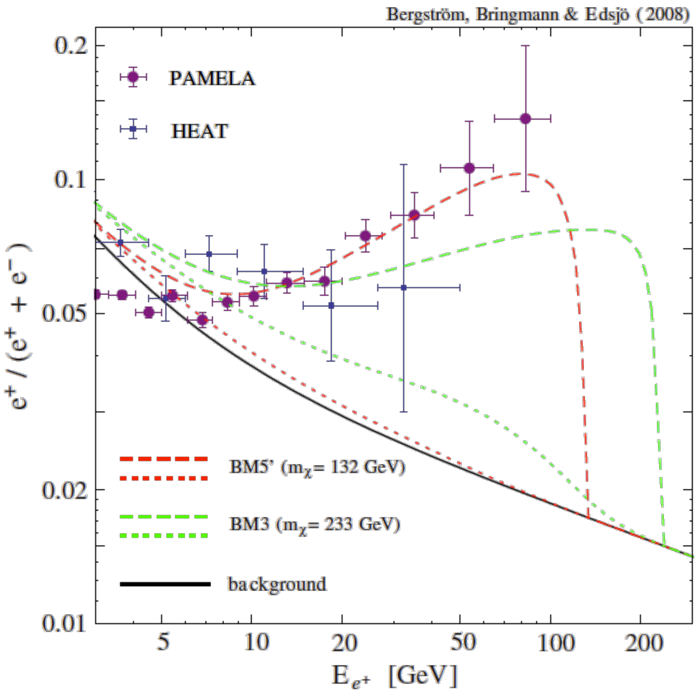


Comparison with other experiments

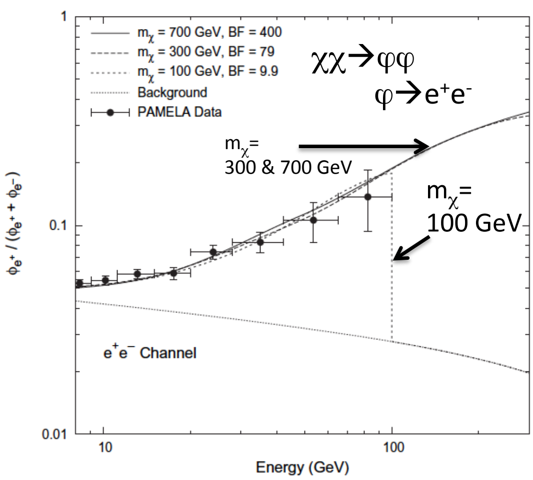
Dark Matter Signal ?



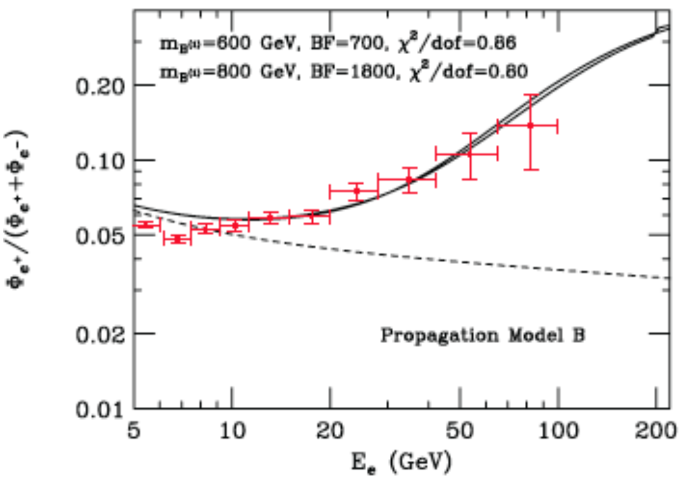
- Pronounce spectral signature
  w/ radiative corrections
- BUT, Need boost factor of 1×10^4
- (ref) L. Bergstrom et al., Phys. Rev. F78, 103520(08)



Dark Matter Signal ?

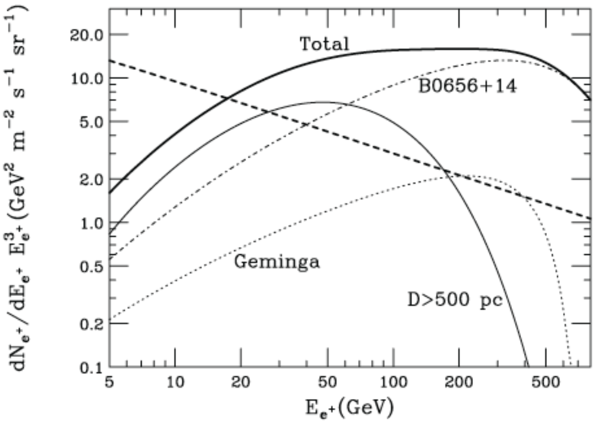


- φ: light boson interact only in dark sector
- Need large boost factors

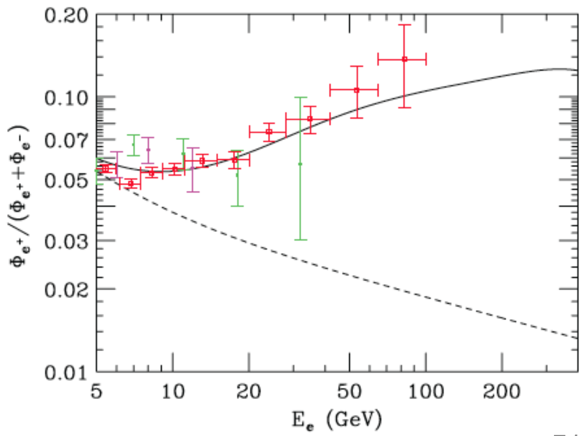


- KK dark matter of the mass of 600 and 800 GeV.
- Need large boost factors

Pulsars ?



Contribution from Geminga, B0656+14 and matured pulsars > 500 pc

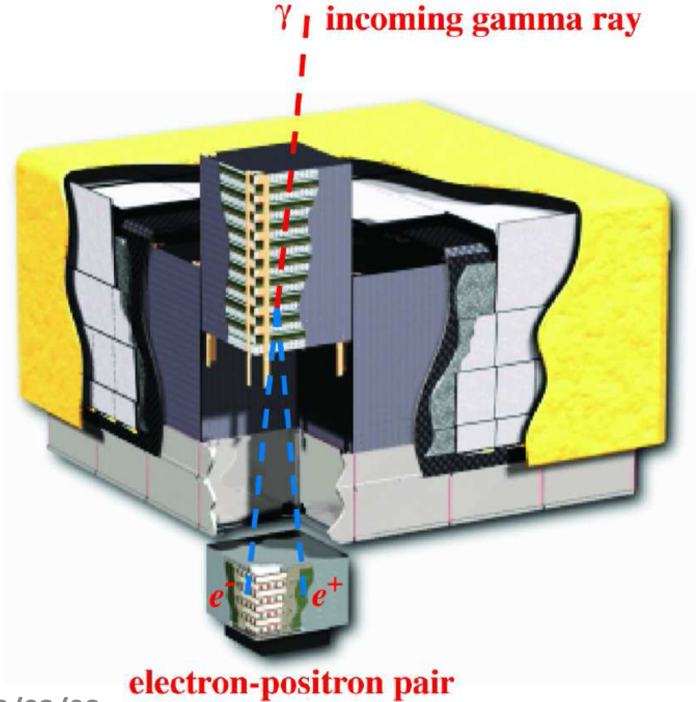


Fermi for electron and positron

– Ref) arXiv: 1109.0521V1(astro-ph.HE.)

- Fermi LAT
  - Detector ref) arXiv: 0902.1089

Fermi Large Area Telescope



- 1.8 m x 1.8 m x 0.72m
- 650W
- 2,789kg
- A pair conversion telescope
- Tracker and calorimeter, each 4x4 = 16 modules
- 20MeV~ 300 GeV
- Field of view; 2.4 sr
- Sky exposure is almost uniform in 2 turn, 3 hours (35)

Tracker

- Vertical 18 x,y staking planes
- Silicon strip
- Tungsten converter

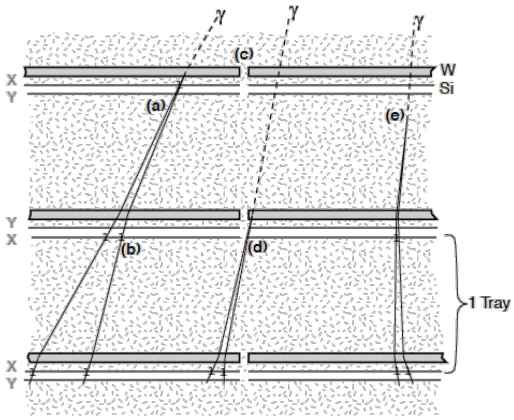


FIG. 5.— Illustration of tracker design principles. The first two points dominate the measurement of the photon direction, especially at low energy. (Note that in this projection only the x hits can be displayed.) (a) Ideal conversion in W: Si detectors are located as close as possible to the W foils, to minimize the lever arm for multiple scattering. Therefore, scattering in the 2nd W layer has very little impact on the measurement. (b) Fine detector segmentation can separately detect the two particles in many cases, enhancing both the PSF and the background rejection. (c) Converter foils cover only the active area of the Si, to minimize conversions for which a close-by measurement is not possible. (d) A missed hit in the 1st or 2nd layer can degrade the PSF by up to a factor of two, so it is important to have such inefficiencies well localized and identifiable, rather than spread across the active area. (e) A conversion in the structural material or Si can give long lever arms for multiple scattering, so such material is minimized. Good 2-hit resolution can help identify such conversions.

Calorimeter

- 96 CsI(Tl) crystals, arranged in 8 layer hodoscope
- Total depth 8.6 radiation length

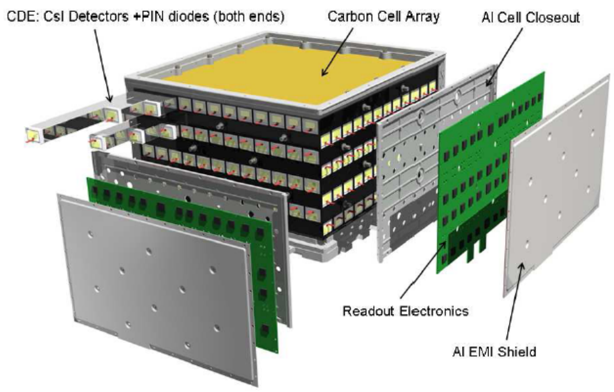


FIG. 6.— LAT calorimeter module. The 96 CsI(Tl) scintillator crystal detector elements are arranged in 8 layers, with the orientation of the crystals in adjacent layers rotated by 90°. The total calorimeter depth (at normal incidence) is 8.6 radiation lengths.

Detector Photos

28 Atwood et al.

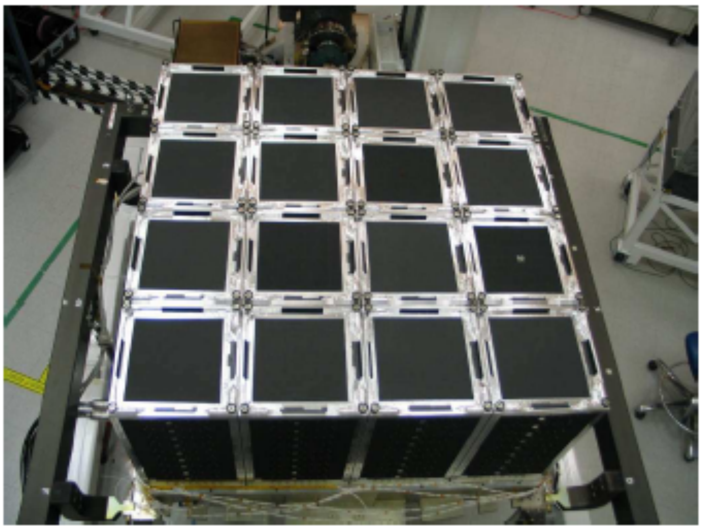


FIG. 3.— Completed tracker array before integration with the ACD.

Detector Photos

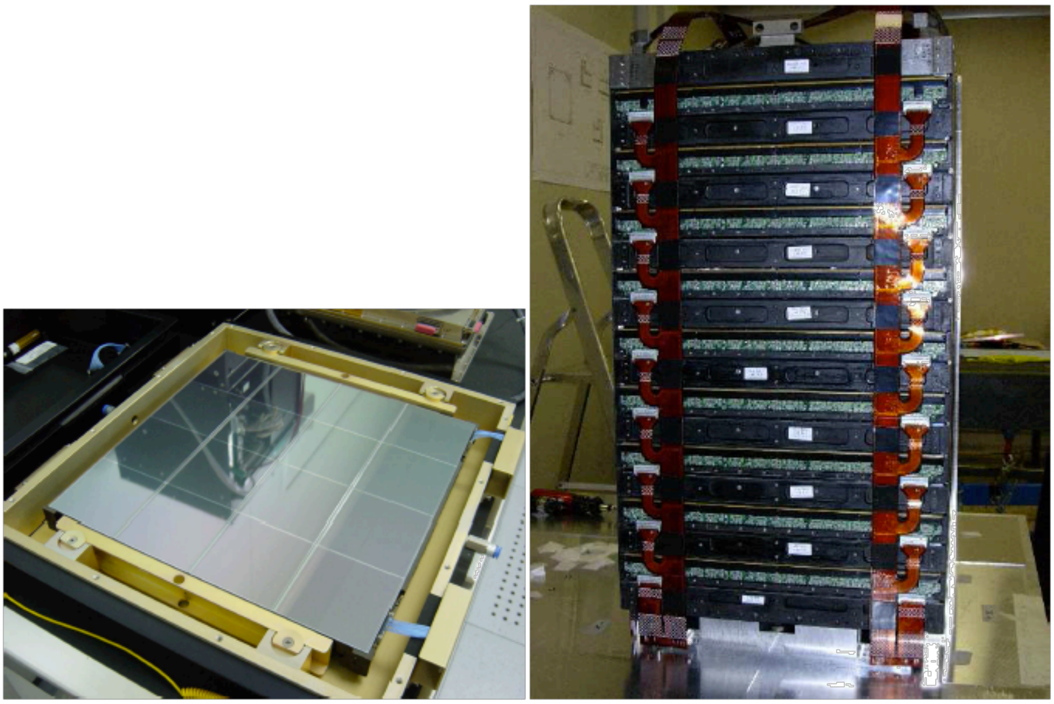
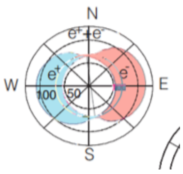
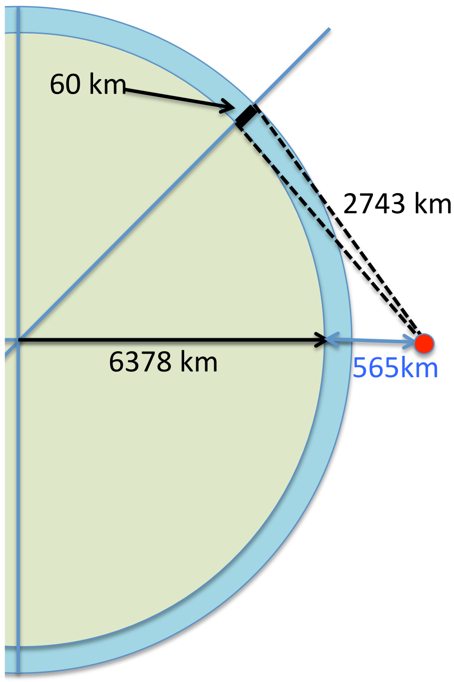


Fig. 4.— (a) A flight tracker tray and (b) a completed tracker module with one sidewall removed.



Earth's Horizon

- Earth's (atmospheric) horizon:
  - R=6378 (赤道半径）
  - 大気の厚さ～60km
  - Fermiの高度~565km
  - Nadir angle
    - arcsin 6438/(6378+565)= 68°
  - Dist. to the horizon=2743 km
  - View width of the horizon from the satellite:
    - arctan(60/2743) = 1.3°



Electrons and Positrons Separation

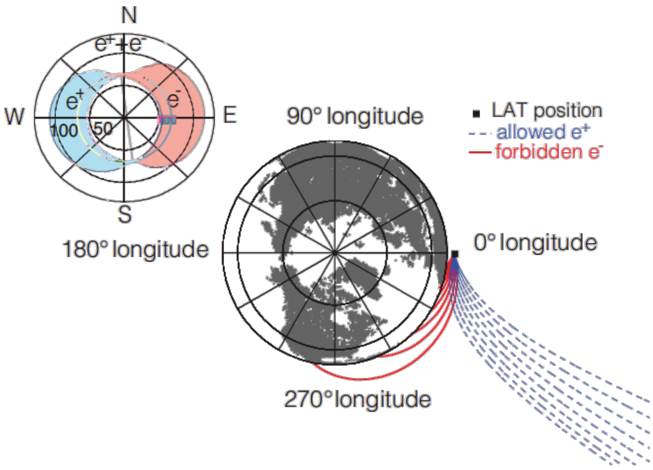


FIG. 1: Examples of calculated electron (red) and positron (blue) trajectories arriving at the detector, for 28 GeV particles arriving within the Equatorial plane (viewed from the North pole). Forbidden trajectories are solid and allowed trajectories are dashed. Inset: the three selection regions (electron-only, positron-only, and both-allowed) for the same particle energy and spacecraft position as the trajectory traces (viewed from the instrument position in the Equatorial plane).

- No magnet

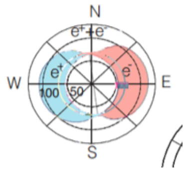
➔Make use of earth's magnetic field

- West (blue in fig):
  - Positrons only allowed
  - Electrons forbidden
- East (red in fig):
  - Positrons forbidden
  - Electrons only allowed
- Every 30 second at the instantaneous latitude and longitude (altitude 565 km)

➔ the regions for every energy bins were set

Deflection Horizon

- Deflection Horizon:
  - the curve that separates the allowed and forbidden regions
  - Depends on a particular energy, charge, and spacecraft position.
- Low energy: differ significantly from the actual Earth horizon.
- High energy: asymptotically approach to the un-deflected horizon.



Earth’s Horizon

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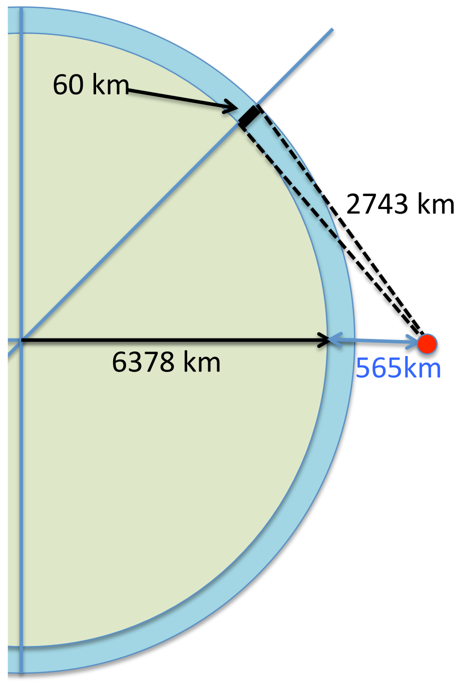
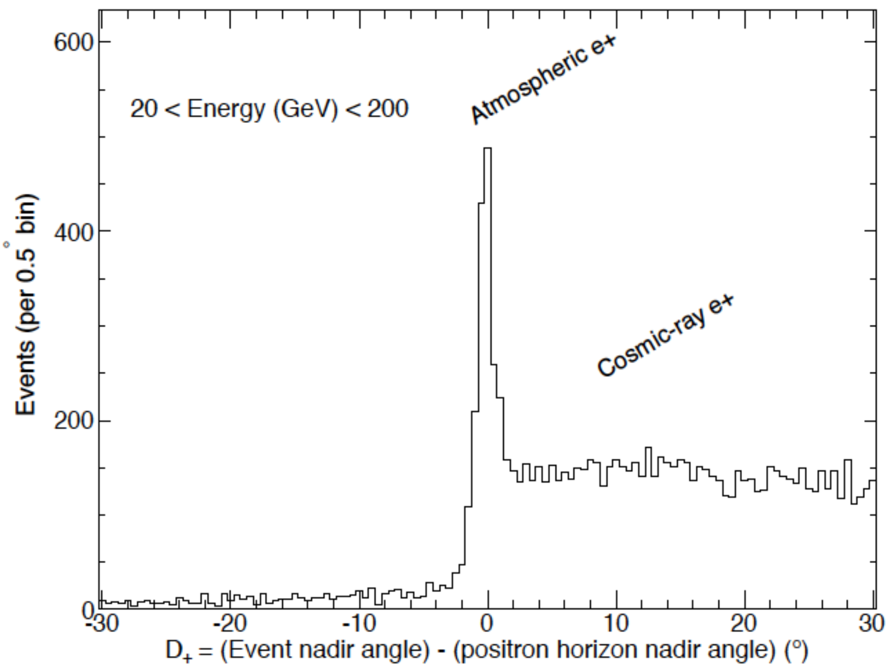


Selection of $e^{\pm}$



Positron Fraction

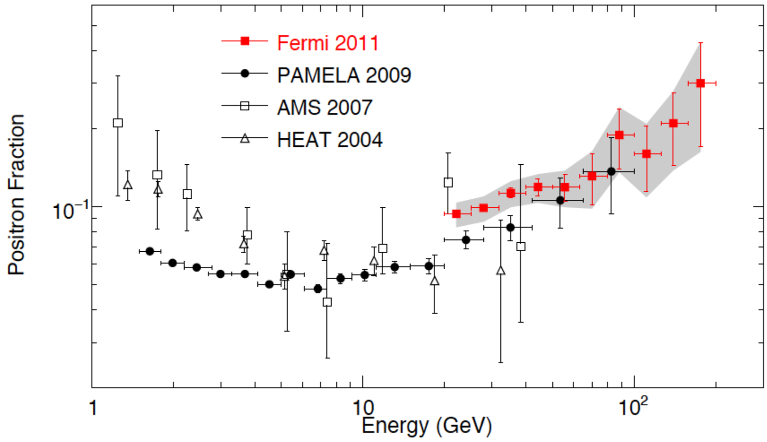


FIG. 5: Positron fraction measured by the Fermi LAT and by other experiments [10, 14, 35]. The Fermi statistical uncertainty is shown with error bars and the total (statistical plus systematic uncertainty) is shown as a shaded band.

- Positron fraction beyond 100 GeV up to 200GeV
- It continuously rises as energy increases

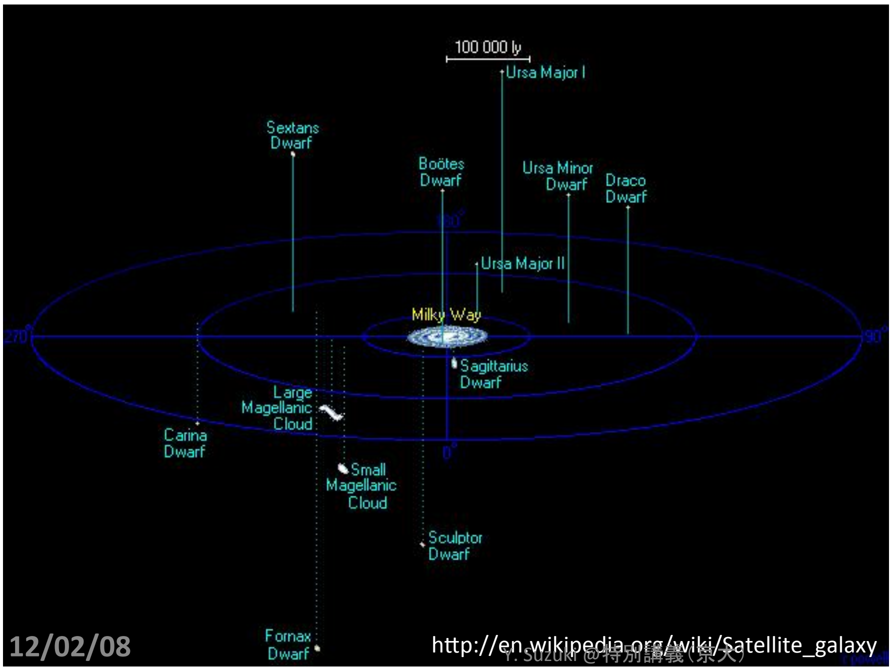
Boost問題が何らかで解決して、これがDark Matterの信号だとすると、質量は200GeV以上

Gamma

- Galactic Center
  - Point like w/diffuse BG
- Halo
  - High statistic
- Clusters
  - Semi-point like
  - Low statistic
  - Low BG
- Extragalactic

Dwarf spheroidal satellite galaxies (dSphs) Fermi

- Ref) Fermi-LAT M. Ackermann et al. astro/ph1108.3546v3



dSphs Fermi measured

- Bootes I
- Carina
- Coma Berenices
- Draco
- Fornax
- Sculptor
- Segue I
- Sextans
- Ursa Major II
- Ursa Minor

Dwarf spheroidal satellite galaxies (dSphs) Fermi

- dSphs: Dark Matter dominant
  - w/o active star formation
  - w/o detected gas content
  - Good signal to noise ratio
  - But small signal rate

$$\phi(E,\psi) = \frac{<\sigma_{ann} v>}{(8\pi m_\chi^2)} \times N_\chi(E) \times J(\psi)$$

$N_\chi(E)$: γ energy distribution

$$J(\psi) = \int_{l.o.s\Delta\Omega} \mathrm{d}l\Delta\Omega\rho^2[l(\psi)]$$

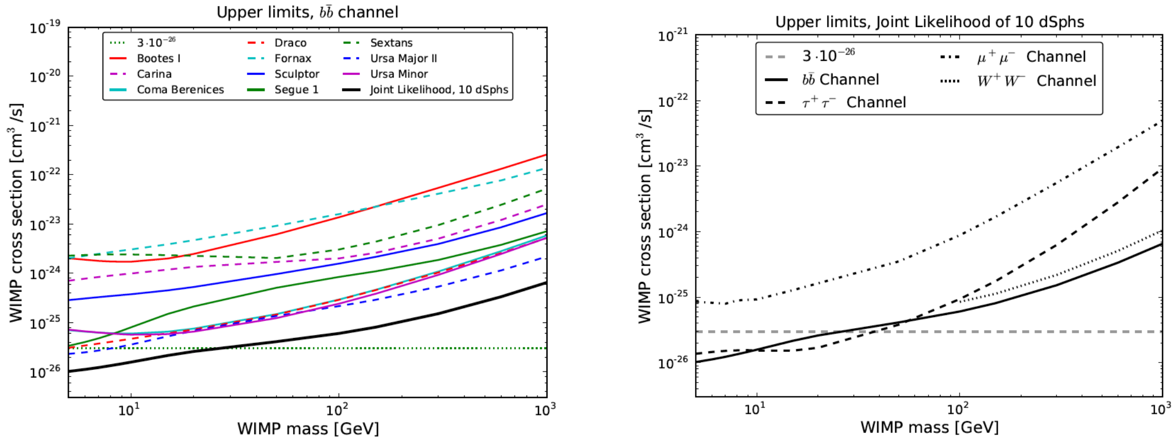
→ line of sight integral of squared DM density, ρ

ψ: direction of sight

$\Delta\Omega$: solid angle

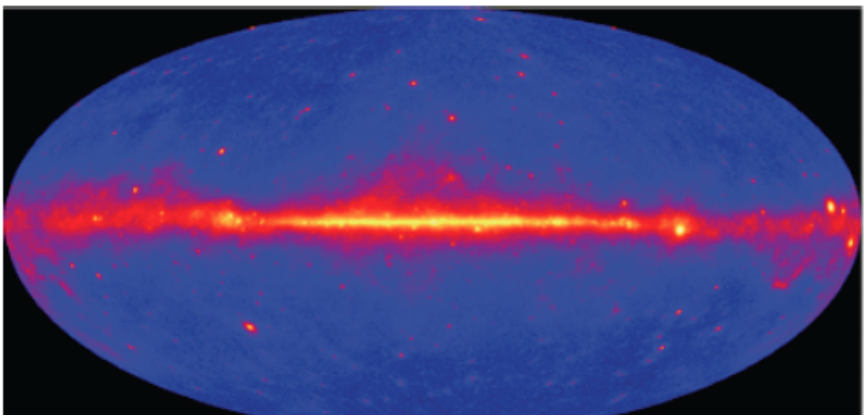
Dwarf spheroidal satellite galaxies (dSphs) Fermi

- 24 months data: Limits range $10^{-26}cm^3/s$ @ 5 GeV~ $5x10^{-23}cm^3/s$ @ 1 TeV
- Ruled out some region of $3x10^{-26}cm^3/s$



WIMP annihilation cross section for all selected dSphs and for the joint likelihood analysis

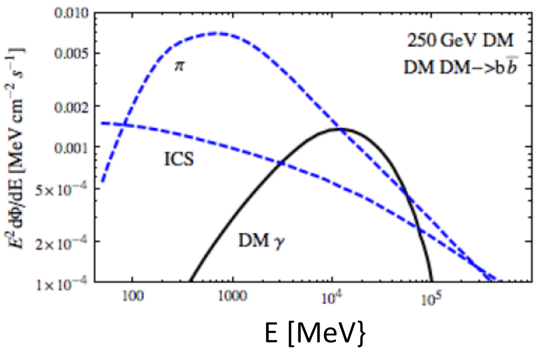
Diffuse galactic γ-rays Fermi

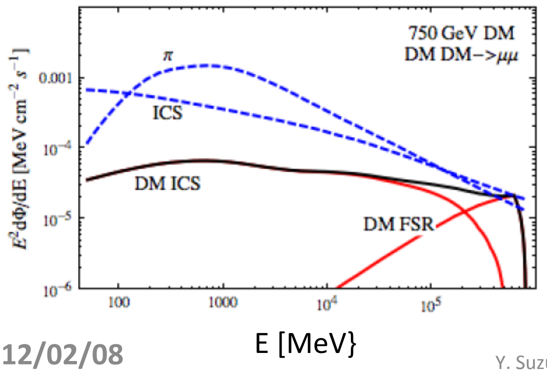


- Inner Galaxy: Extending 10~20 deg away from the Galactic Plane
- Mask the plane
- Avoid astrophysical BG

- 21 months of Fermi-LAT data
- DM signal vs BG:
  - substantially different signature

Diffuse galactic γ-rays Fermi





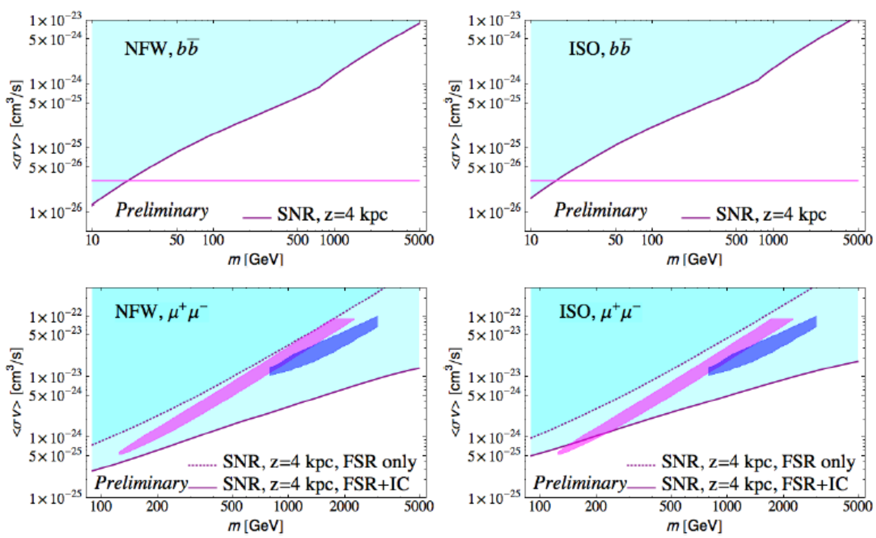
Back Grounds

- CR protons on Interstellar gas
  - $p \rightarrow \pi^0 \rightarrow 2\gamma$
- CR electrons
  - Bremsstrahlung
  - Inverse Compton Scattering (ICS)

Signal

- $b\bar{b}$-channel (similar for other quark and gauge boson productions)
  - Hadronization, $\pi^0 \rightarrow 2\gamma$
- $\mu+\mu-$ channel
  - Inverse Compton
  - Final State Radiation (FSR)

Diffuse galactic γ-rays Fermi



Those allowed regions:

- Purple: PAMERA DM interpretation
- Blue: Fermi-LAT DM interpretation

- For masses around 20 GeV the thermal relic value of the annihilation cross section is reached, irrespectively of the DM Halo profile.
- The DM interpretation of the PAMELA/Fermi CR features is ruled out.

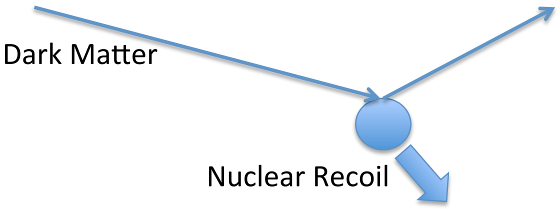
END

8. Direct Search Experiments

8. Direct Search Experiments

- Technology
- Backgrounds
- DAMA
- CoGeNT
- CRESST-II
- CDMS-II
- XENON
- Other experiments
- Low Mass Dark Matter?

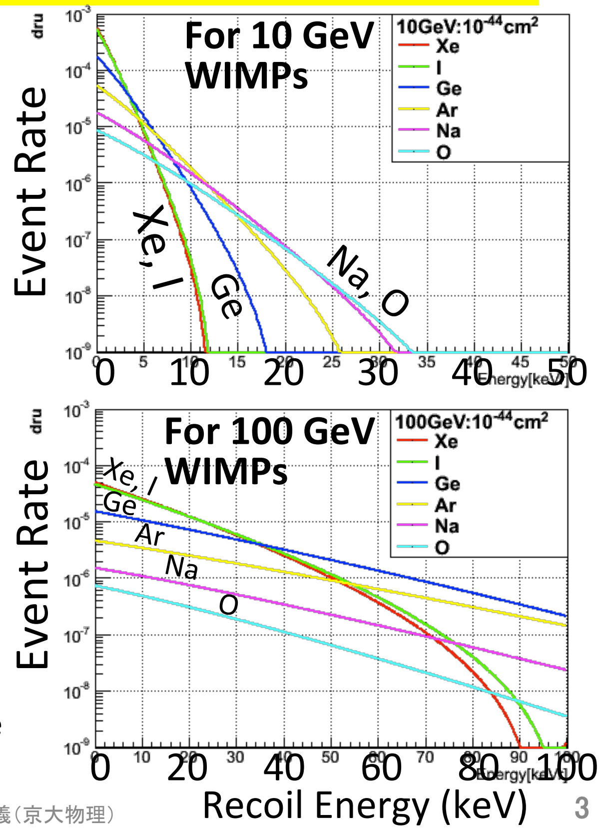
Direct Detection



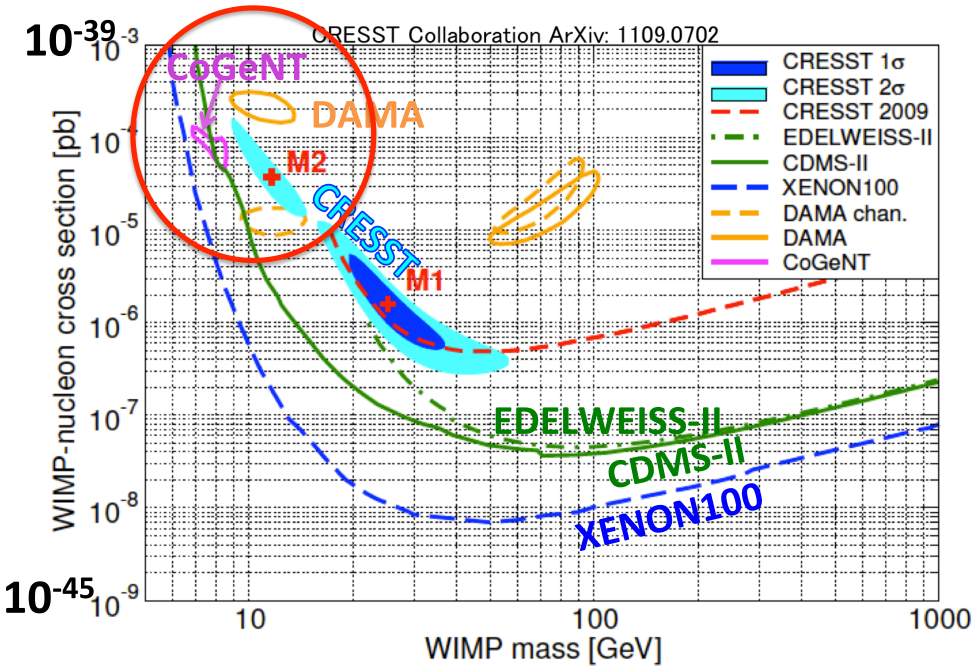
- Direct searches : Observe Nuclear Recoils
  - χ + N ➔ χ + N
- Recoil Energy:
  - 🡐Kinetic energy of DM

$$E_R = \frac{M_\chi v^2}{2}\frac{4M_\chi M_A}{(M_\chi + M_A)^2}\frac{(1-cos\theta)}{2}$$

  - 1~100 keV
  - For low mass DM, sp. become very soft for large target masses like Xe, Ge,,
    - Loose efficiency unless lowering the threshold
- **dru : ev/kg/keV/day**



Current Experimental Situation



Current players of the game

Positive Indication

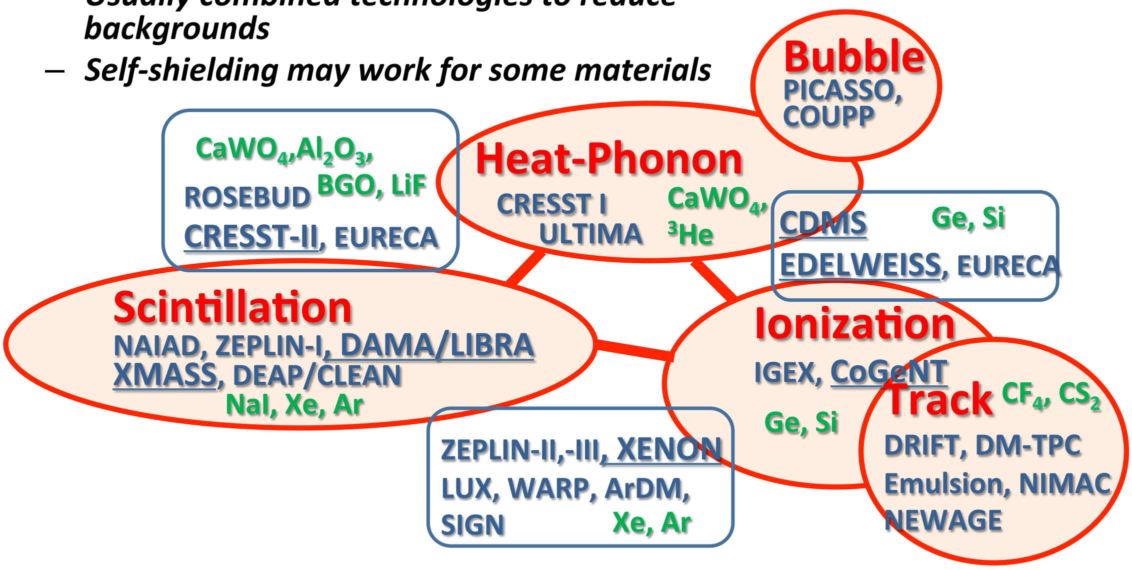
Experiment∂	Target	Threshold	Total Exposure	Recoil Identification	Main body of Signal ?	Modulation
DAMA/LIBRA	NaI	2.0 keV_{ee}	427,000 kg-days	(NR+EM)	—	O
CoGeNT	Ge	0.5 keV_{ee}	140 kg-days	(NR+EM)	O by fit w/BG	O
CRESST	$CaWO_4$	10.0 keV	>700 kg-days	NR	O by fit w/BG	—

Negative and set limit

Experiment∂	Target	Threshold	Total Exposure	Recoil Identification	Main body of Signal ?	Modulation
CDMS-II	Ge/Si	10.0 keV	612 kg-days	NR		
CDMS-II (LE)	Ge	2.0 keV_{NR}	241 kg-days	(NR+reducedEM)		
EDELWEISS	Ge	20.0 keV	384 kg-days	NR		
XENON100	Xe	8.4 keV_{NR}	1471 kg-days	NR		
XENON10 (LE)	Xe	1.4 keV_{NR}	15 kg-days	(NR+reducedEM)		

Technologies for Direct Search Experiments

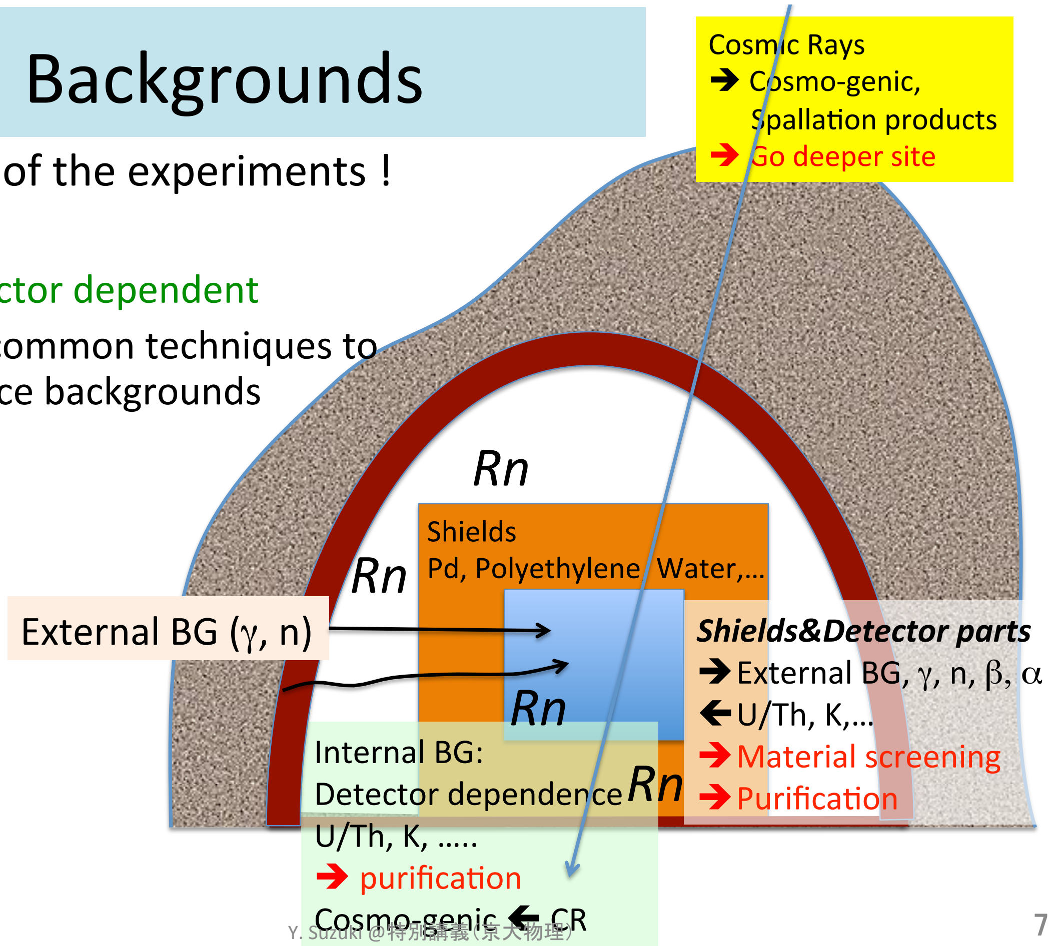
- *Various Detection Technology*
  - *Scintillation, Heat-Phonon and Ionization*
  - *Usually combined technologies to reduce backgrounds*
  - *Self-shielding may work for some materials*



Backgrounds

Key Issue of the experiments !

- Many:
  - detector dependent
  - but common techniques to reduce backgrounds



Natural Radio-Activities

- **U/Th decay chain (Internal / External)**
  - α: a few MeV
  - Maximum β/γ energy ~ 5MeV
  - Serious for experiments detecting energy < 5MeV
  - Contamination: usual material O(1~10ppm)
  - ➔ ~20 Bq/kg (for 1ppm ^{238}U (τ = 4.47 x 10^9 yr))

    [assume radiation equilibrium ➔ O(200) Bq/kg,

    depending on kinds of radiation $\alpha/\beta/\gamma$ to detect and acceptance]

Radiation Equilibrium

- $N_1(\tau_1^{1/2} = 1/\lambda_1) \rightarrow N_2(\tau_2^{1/2}=1/\lambda_2) \rightarrow$ と崩壊してゆく核を考える

$$\frac{dN_1}{dt} = -\lambda_1 N_1 \quad (\Rightarrow N_1 = N_1^0 e^{-\lambda_1 t})$$
$$\frac{dN_2}{dt} = -\lambda_2 N_2 + \lambda_1 N_1 = -\lambda_2 N_2 + \lambda_1 N_1^0 e^{-\lambda_1 t}$$

$$e^{\lambda_2 t}\frac{dN_2}{dt} = -\lambda_2 N_2 e^{\lambda_2 t} + \lambda_1 N_1^0 e^{-(\lambda_1-\lambda_2)t}$$
$$\frac{d(N_2 e^{\lambda_2 t})}{dt} = \lambda_1 N_1^0 e^{-(\lambda_1-\lambda_2)t}$$
$$N_2 e^{\lambda_2 t} = \frac{\lambda_1 N_1^0}{\lambda_2-\lambda_1} e^{-(\lambda_1-\lambda_2)t} + C$$
$$N_2 = \frac{\lambda_1 N_1^0}{\lambda_2-\lambda_1} e^{-\lambda_1 t} + C e^{-\lambda_2 t}$$

t=0で、$N_2=N_2^0$となるように C を決める

$$N_2 = \frac{\lambda_1 N_1^0}{\lambda_2-\lambda_1}(e^{-\lambda_1 t} - e^{-\lambda_2 t}) + N_2^0 e^{-\lambda_2 t}$$

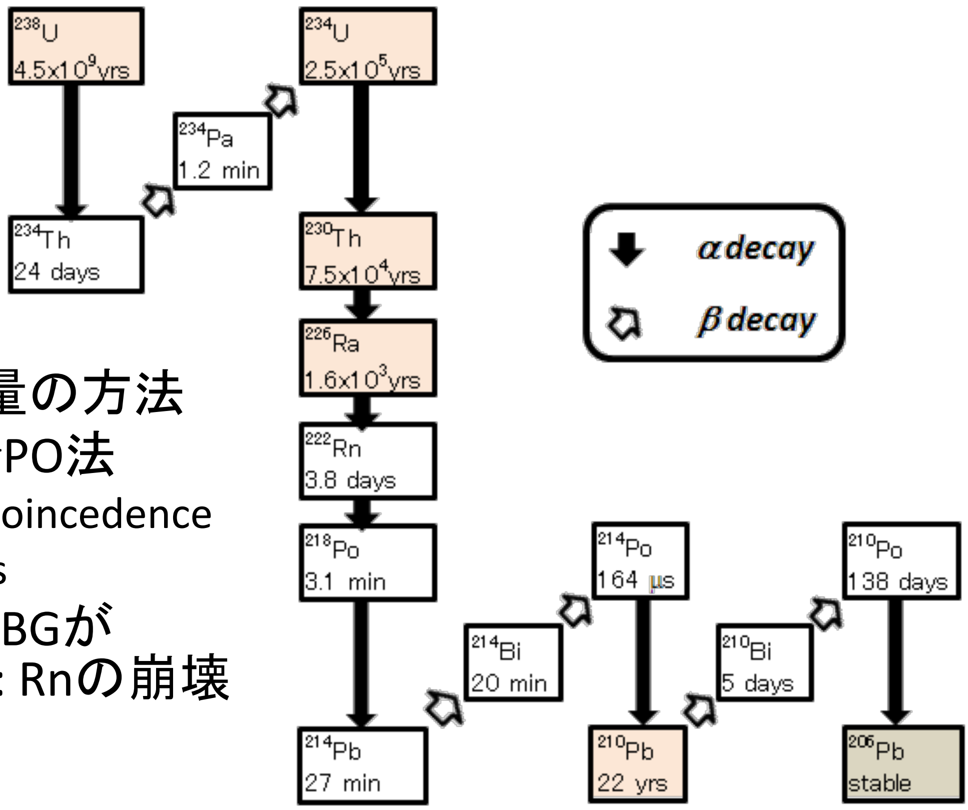
Radiation Equilibrium

- $\tau_1^{1/2} >> \tau_2^{1/2}$ ($\lambda_1 << \lambda_2$) の時、

$$N_2 = \frac{\lambda_1 N_1^0}{\lambda_2} e^{-\lambda_1 t}$$

➔ $N_2\lambda_2 = \lambda_1 N_1$ となり、崩壊数が同じになる。

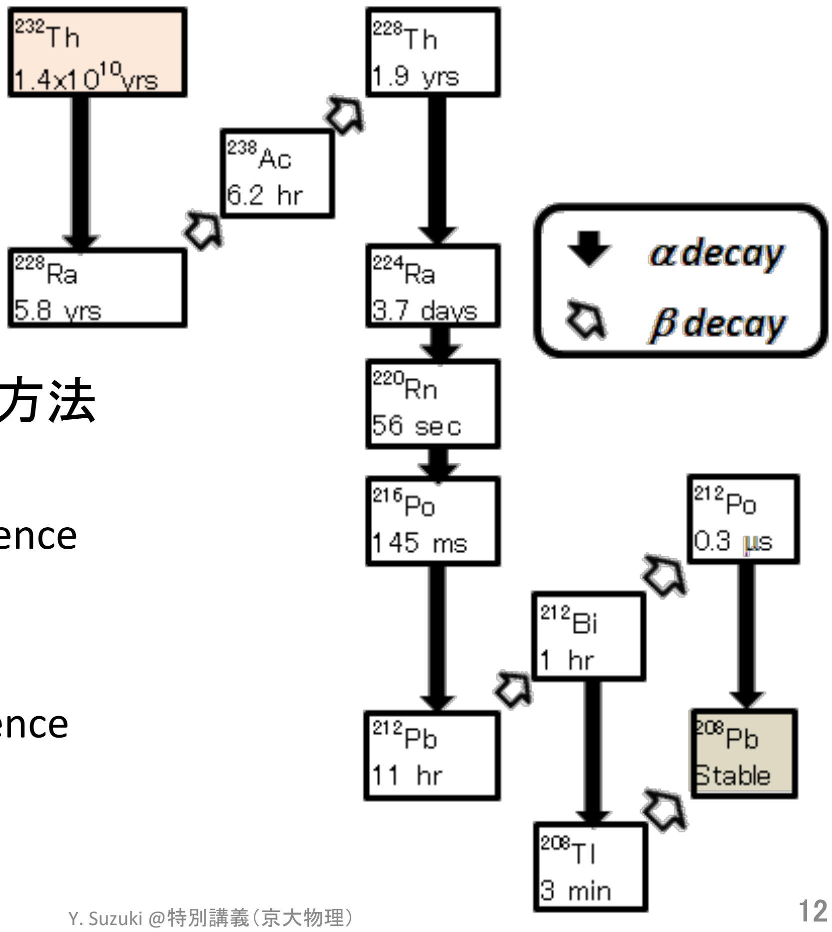
^{238}U



同定・定量の方法

- ^{214}Bi-^{214}PO法
  - β−α coincidence
  - 164μs
- ^{210}PbのBGがserious: Rnの崩壊で蓄積

^{232}Th



- 同定・定量の方法
- ^{212}Bi-^{212}PO法
  - β−α coincidence
  - 0.3 μs
- ^{220}Rn-^{216}Po法
  - α−α coincidence
  - 145ms

BG の Level

- たとえばXMASSの目標BGは、10^{-4} dru (ev/kg/keV/day)
- 100keVのenergy spanを考えると、1.2×10^{-7} Bq/kgになる。0.12 μBq/kg
- 10-100 Bq/kg　からは10^{-8}~10^{-9}低い。

1ppm 238U

Rn

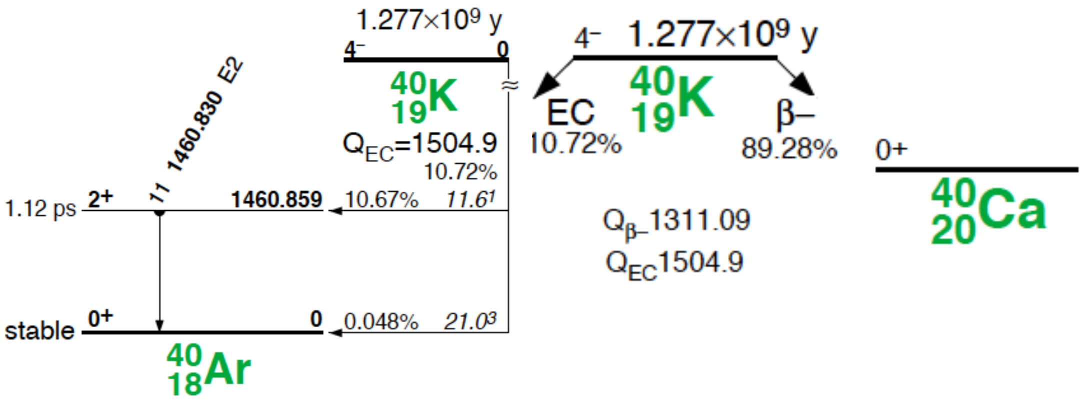
Rn (Gas) : $\tau_{1/2}$= 3.82 days, E_{α} = 5.59 MeV

- most problem for many cases
  - 10~1000 Bq/m^3
  - SKのタンク水：　3 mBq/m^3
  - XMASSの液体キセノン中：数mBq/m^3
- さらに、^{210}Pbの源
- 活性炭で除去可能
- 液体からは、ガス抜き

^{40}K

^{40}K(0.0117%): $\tau_{1/2}$=1.25x10^{9}yr

➔ Problem for PMT glass



K-Shell (X) ~ 3 keV

Secondary Radio-Activities

- ***Example:***

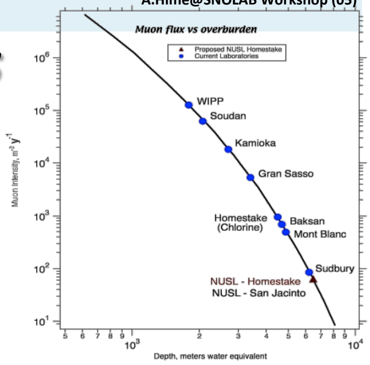
(n, α), (n, p), (p, n),,,,,,,,, ← Cosmogenics, Nuclear Reactors, A-Bomb

- **^{85}Kr (U-fission): $\tau_{1/2}$=10.8yr, 0.687MeV(β^-)**
  ➔ problem for Xe and Ar detectors
- **^{42}Ar: $\tau_{1/2}$=32.9yr, 0.600MeV(β^-), ^{39}Ar: $\tau_{1/2}$=269yr, 0.565MeV(β^-)**
  ➔ problem for Ar detectors
- **^{14}C:$\tau_{1/2}$=5730yr, 0.156MeV(β^-)**
  ➔ cannot use organic scintillator < a few 100 keV
- **^{60}Co:(5.3yr, 1.33, 1.17MeVγ) ← cosmogenics in Cu**
  270 days exposure on the ground → 2.1 mBq/kg
  ➔ ***produce Cu underground factory, if this level is a problem***

Radio-activities: the source of Internal BGs
➔ need PURIFICATION
Cosmogenics ➔ go underground

Undergrounds

A.Hime@SNOLAB Workshop (05)



Clean radioactive environments

- Small flux of cosmic muons

  2 km w.e. (Kamioka) → 0.8×10^{-5}

  6 km w.e. (SNO) → 1.9×10^{-8}

  - Reduced production of radio-activities
  - small neutron flux
  - small gamma flux (mostly high energy)
- But, U/Th in rocks
  - β/γ
  - Neutrons through (α, n) reactions
- **Need Shields: Pb, Cu, CH_2, H_2O, etc**
  - But, Pb: ^{210}Pb (22.3yr, 47keVγ) ← U-decay chain
  - Cu: ^{60}Co (5.3yr, 1.33, 1.17MeVγ) ← cosmogenics
  - Water may be best for both γ and neutron
    - Many experiments have proposed to use water

➔ Self-shielding may be effective

no extra vessel or extra structure for shields

» Ex. Xenon single phase detector

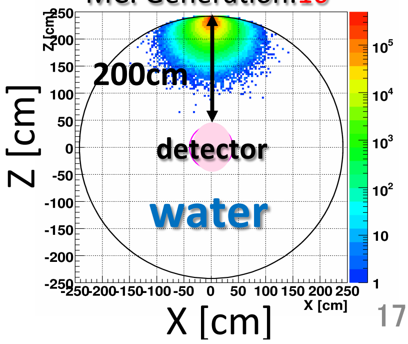
Typical neutron flux at Kamioka

$8.26\pm0.58\times10^{-6}$/cm^2/s (thermal)

$1.15\pm0.12\times10^{-5}$/cm^2/s (non-thermal)

10MeV neutrons

MC: Generation:10^7



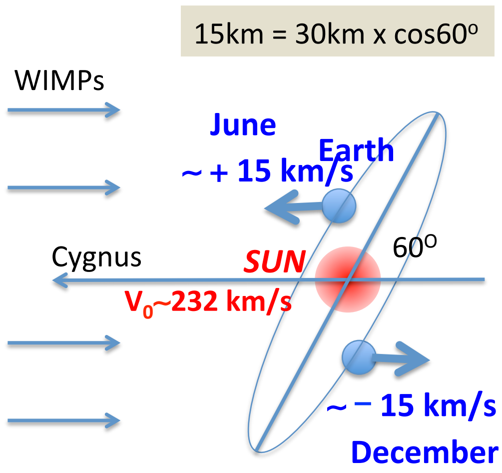
DAMA/LIBRA

Annual modulation

- Sun's velocity in the halo: ~ 232 km/s
- Earth's velocity around the Sun x cos60°: ±15 km/s

Evidence for the annual modulation

1) Modulated rate according cos(t) w/ a proper time period (1 year)
2) A proper phase (Max @ about 2 June)
3) Modulation amplitude <7%
4) Define to be in a low energy range
5) Single hit events in a multi-detector set-up

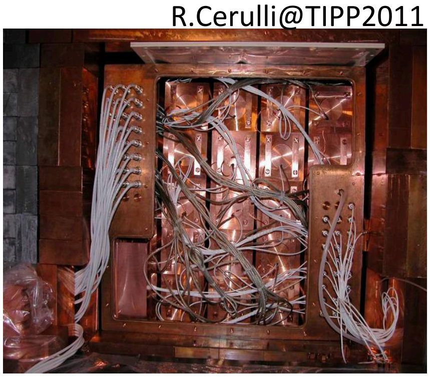


Detector

DAMA/LIBRA:

- High purity low BG NaI(Tl)
  - 5x5=25 modules, (10.3x10.3x25.4)cm^3
  - Each module: 9.70 kg
  - ~250kg NaI(Tl) for DAMA/LIBRA
- 10 cm light guide at both end and equipped with 2 low BG PMTs
  - Coincidence at 1 pe level
- Shields: Cu/Pb/Cd-foils/ polyethylene/paraffin + 1 m concrete

R.Cerulli@TIPP2011



View at the end of DAMA/LIBRA

- 5.5 ~ 7.5 pe /keV

Radioactive impurities in NaI(Tl) crystal

- α: (7 ~ a few 10) /kg/day
- ^{232}Th (if equilibrium): 0.5 ppt ~ 7.5 ppt
- ^{238}U (if equilibrium): 0.7 ppt ~ 10 ppt
- ^{nat}K < 20 ppb
- ^{210}Pb: (5 ~ 30) mBq/kg

Operation

- Total exposure: 1.17 ton-yr (13 cycles)
  - 427,000 kg-days
    - DAMA/LIBRA (Setp 9, 2003 → Sept 1, 2009) 0.87 ton･yr exposure
    - DAMA/NaI 0.29 ton･yr exposure

Analysis

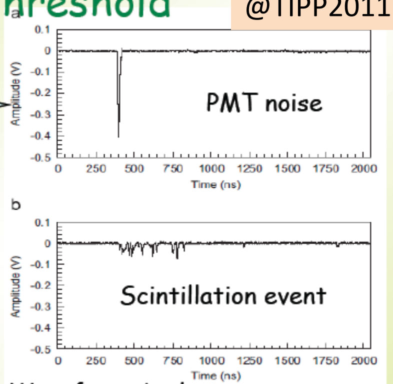
- Calibration by γ and X-ray sources
- Software energy threshold ~2keV$_{ee}$
- both *single-hit* events (one module fired) and *multiple-hit* events (more than one module fired) are acquired
- Data selection
  - Noise cuts: remove noise pulses (mainly PMT noise, Cherenkov light in the light guides and in the PMT windows, and afterglows) near the energy threshold in the *single-hit* events
  - Single hit selection

Noise rejection near the energy threshold

R. Cerulli @TIPP2011

Typical pulse profiles of PMT noise and of scintillation event with the same area, just above the energy threshold of 2 keV

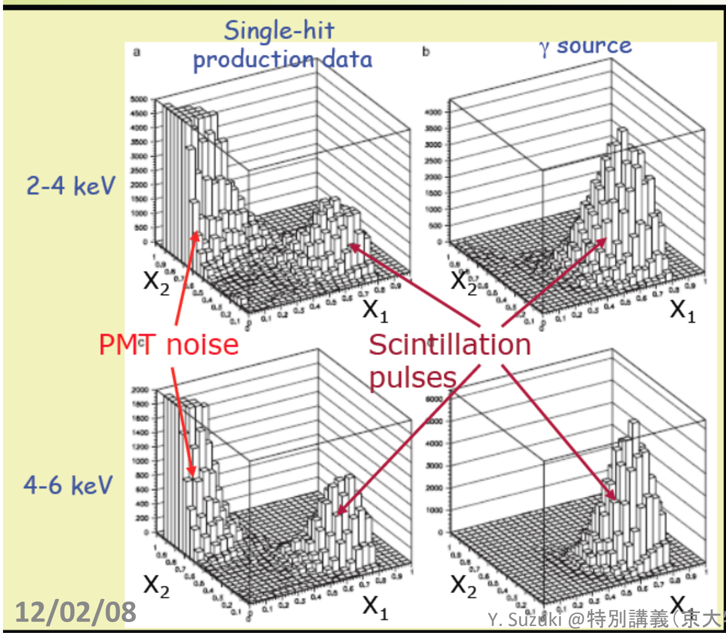
The different time characteristics of PMT noise (decay time of order of tens of ns) and of scintillation event (decay time about 240 ns) can be investigated building several variables



From the Waveform Analyser 2048 ns time window:

$$X_1 = \frac{\text{Area (from 100 ns to 600 ns)}}{\text{Area (from 0 ns to 600 ns)}};$$

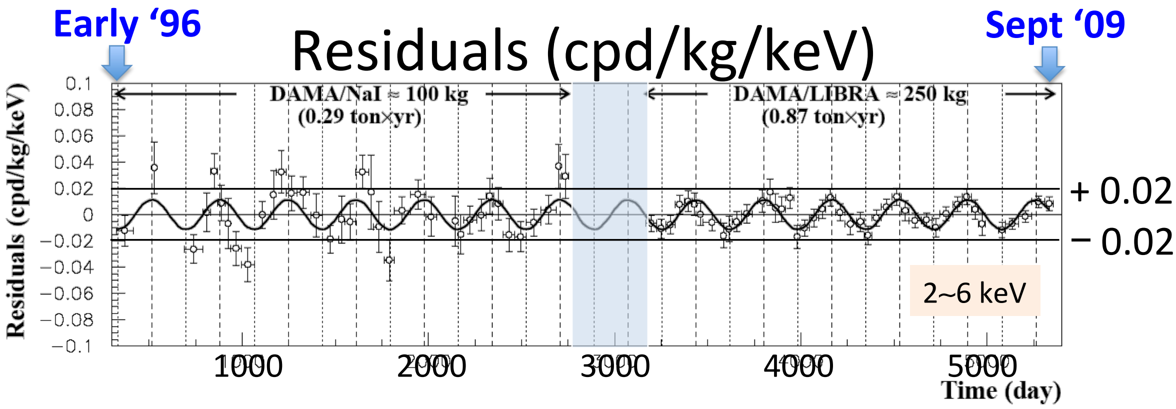
$$X_2 = \frac{\text{Area (from 0 ns to 50 ns)}}{\text{Area (from 0 ns to 600 ns)}}$$



- The separation between noise and scintillation pulses is very good.
- Very clean samples of scintillation events selected by stringent acceptance windows.
- The related efficiencies evaluated by calibrations with ^{241}Am sources of suitable activity in the same experimental conditions and energy range as the production data (efficiency measurements performed each ~10 days; typically 10^4–10^5 events per keV collected)

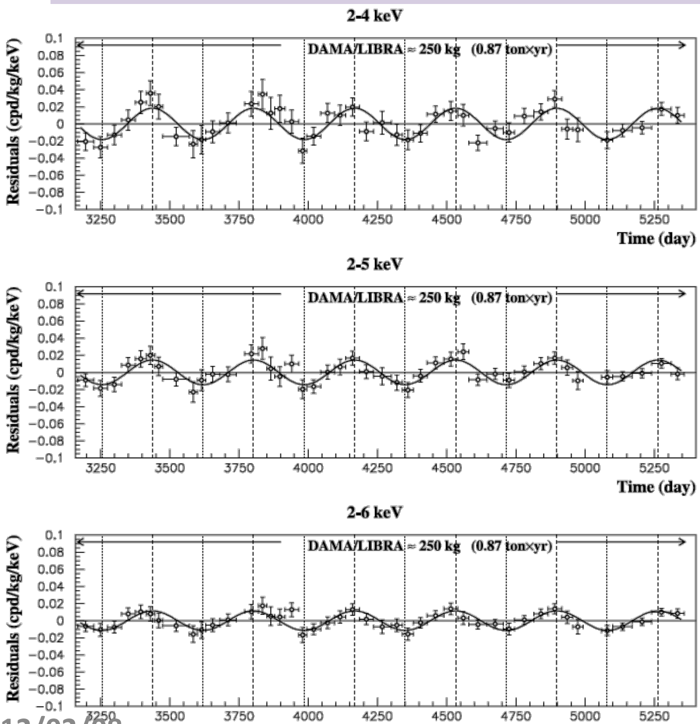
This is the only procedure applied to the analysed data

Results



- Annual modulation (13 annual cycles)
  - $S_k=S_0+S_m\cos\omega(t-t_0)$
  - 8.9 σ for Single-hit events in (2~6)keV
- Amplitude: 0.0116±0.0013 cpd /kg /keV
- Phase (peak): 146±7 days
  - DM_{peak}:June-2: 152.5 days
- Period: 0.999±0.002 yr

Residuals for DAMA/LIBRA



- different energy intervals

Residuals over six years

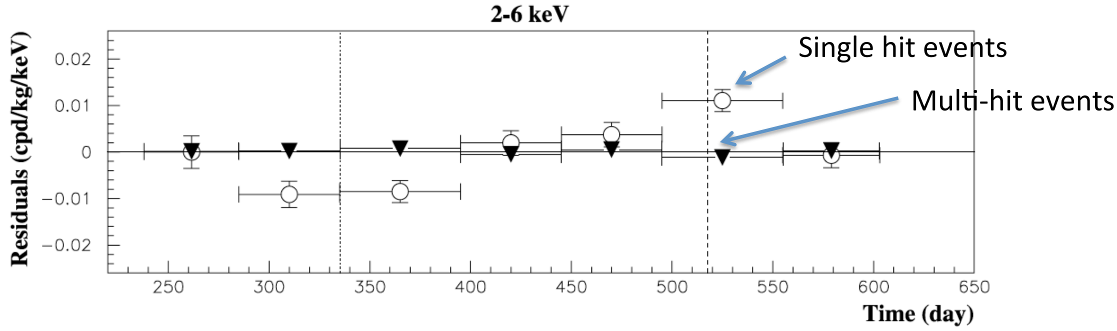


Fig. 5 Experimental residual rates over the six DAMA/LIBRA annual cycles for *single-hit* events (*open circles*) (class of events to which DM events belong) and for *multiple-hit* events (*filled triangles*) (class of events to which DM events do not belong). They have been obtained by considering for each class of events the data as collected in a single annual cycle and by using in both cases the same identical hardware and the same identical software procedures. The initial time of the figure is taken on August 7th. The experimental points present the errors as vertical bars and the associated time bin width as *horizontal bars*. See text and Ref. [31]. Analogous results were obtained for the DAMA/NaI data [13]

Residuals in higher energy region

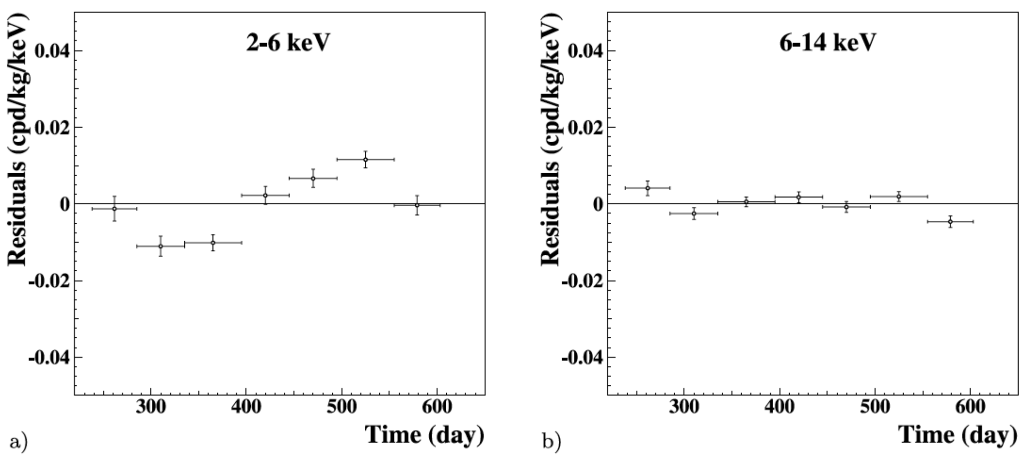


Fig. 4 Experimental residuals in the (2–6) keV region and those in the (6–14) keV energy region just above for the cumulative 1.17 ton × yr, considered as collected in a single annual cycle. The experimental points present the errors as *vertical bars* and the associated time bin width as *horizontal bars*. The initial time of the figure is taken at August 7th. The clear modulation satisfying all the peculiarities of the DM annual modulation signature is present in the lowest energy interval, while it is absent just above; in fact, in the latter case the best fitted modulation amplitude is: (0.00007 ± 0.00077) cpd/kg/keV

Modulation Amplitude (differential)

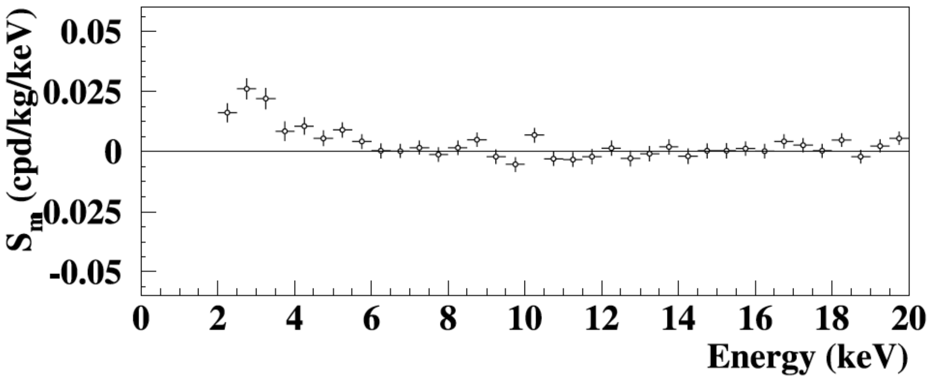


Fig. 6 Energy distribution of the S_m variable for the total cumulative exposure 1.17 ton×yr. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. In fact, the S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 27.5 for 28 degrees of freedom

Energy spectrum of total events

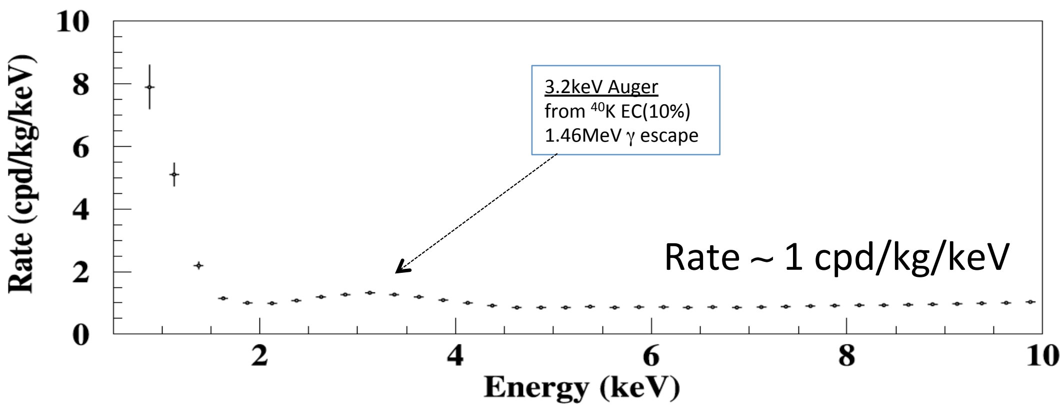
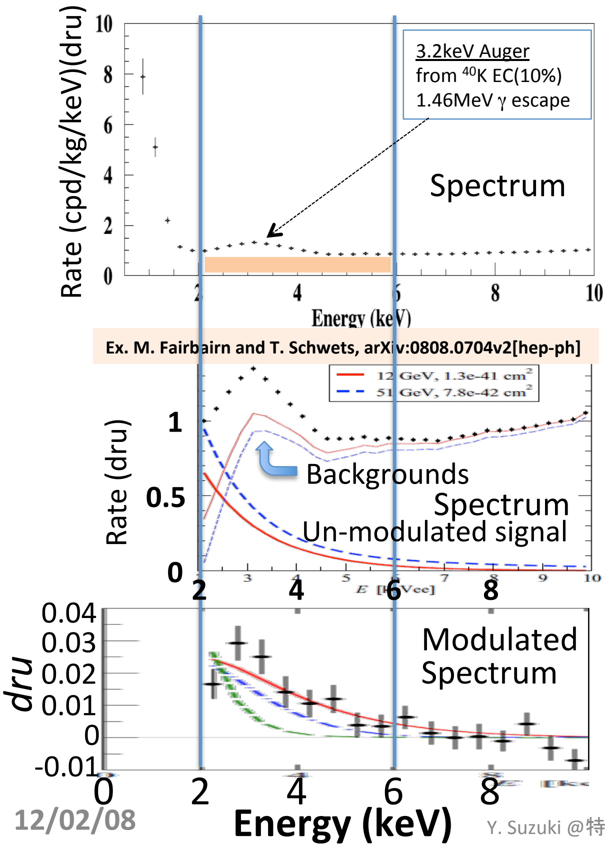


Fig. 1 Cumulative low-energy distribution of the *single-hit* scintillation events (that is each detector has all the others as veto), as measured by the DAMA/LIBRA detectors in an exposure of 0.53 ton × yr. The energy threshold of the experiment is 2 keV and corrections for efficiencies are already applied

Question: Where is the un-modulated part of signal, S_0 ?



- ***Must be in somewhere underneath of the spectrum !***
- In most of the elastic scattering cases, $S_0(E)$ monotonically goes down as energy increase, then backgrounds must sharply goes down below 3~4 keV.

➔This may not be natural

➔Simple Elastic Scattering interpretation may have a internal inconsistency?

Inelastic ? → also strong tension

→ Other scenarios ???

Also similar study: V. A. Kudryavtsev et al. J. Of Phys. Conf. Ser. 203(2009)012039

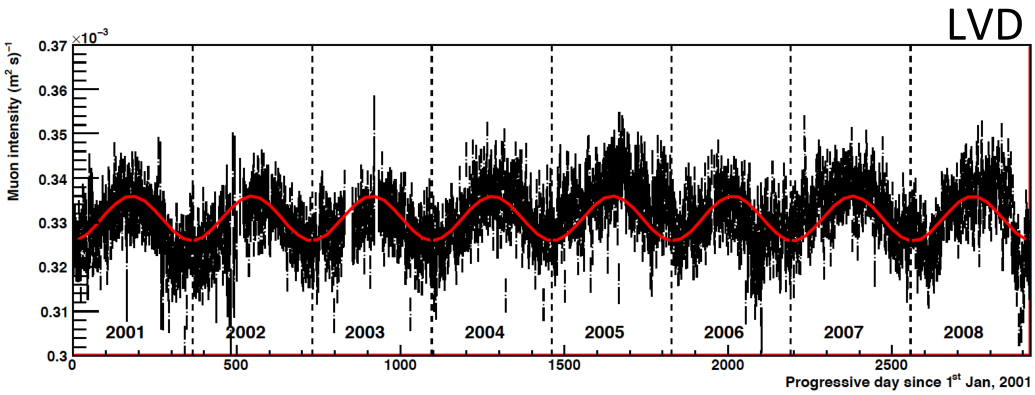
Effect to mimic modulation

- Effects to mimic modulation ?

  (~1.2×10^{-2} dru)

Temperature: < 10^{-4} dru	No!
Rn: < 2.4×10^{-6} dru	No!
Noise: < 10^{-4} dru	No!
Energy scale < 2 x 10^{-4} dru	No!
Efficiency: < 10^{-4} dru	No!
Backgrounds	No!
← > 6keV & multi-hits: <10^{-4} dru	
μon flux variation: < 3×10^{-5} dru	No!

Muon flux variation



- Muon flux variation in LVD @Gran Sasso,
  - Eμ > 1.3 TeV,
  - Amplitude; 1.5±0.6%
  - Maximum: Beginning of July

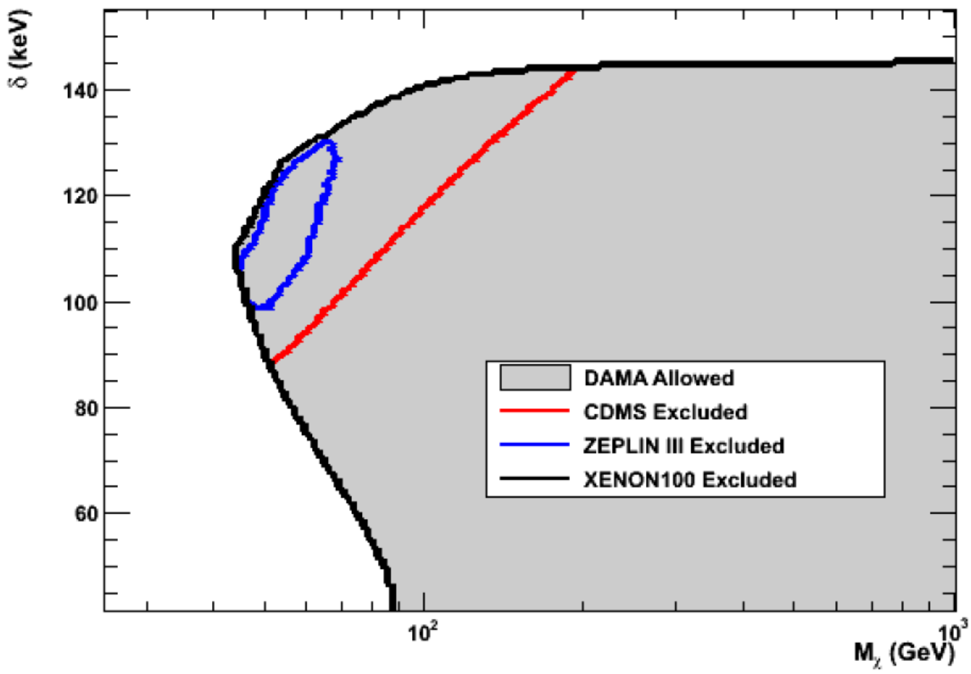
Questions

- What are the remaining (un-modulated) backgrounds
- Where is the main un-modulated fraction of DM signals?
- More information of the multi-hit events
- Inner 9 module vs outer 16 modules

Incompatibility with other negative experiments

- Inelastic DM: χ + N → χ^* +N
  - δ: mass splitting
  - $v_{thr} = (2\delta/\mu)^{1/2}$
    - Higher target atomic number is better (Ge → I)
    - Enhanced annual modulation: higher energy side is effective
    - Escape velocity becomes important factor
- Processes w/ e-m radiations are lost in other experiments

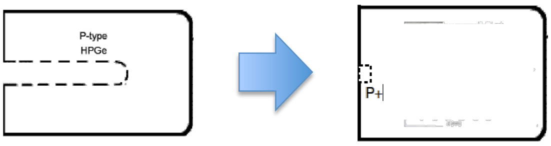
Inelastic scattering



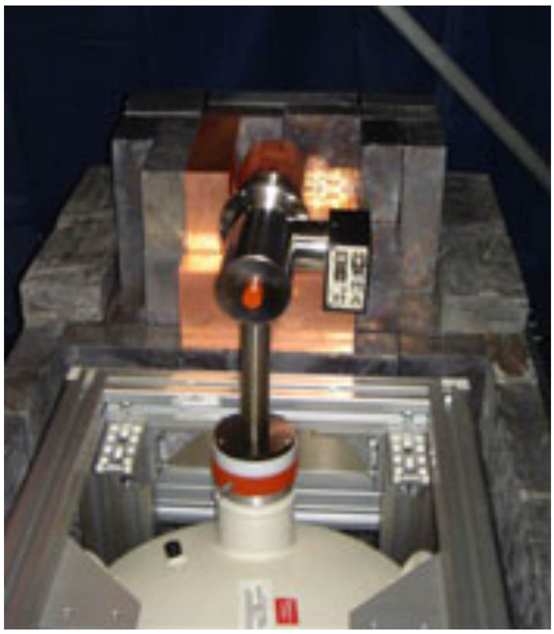
CoGeNT

Coherent Germanium Neutrino Telescope

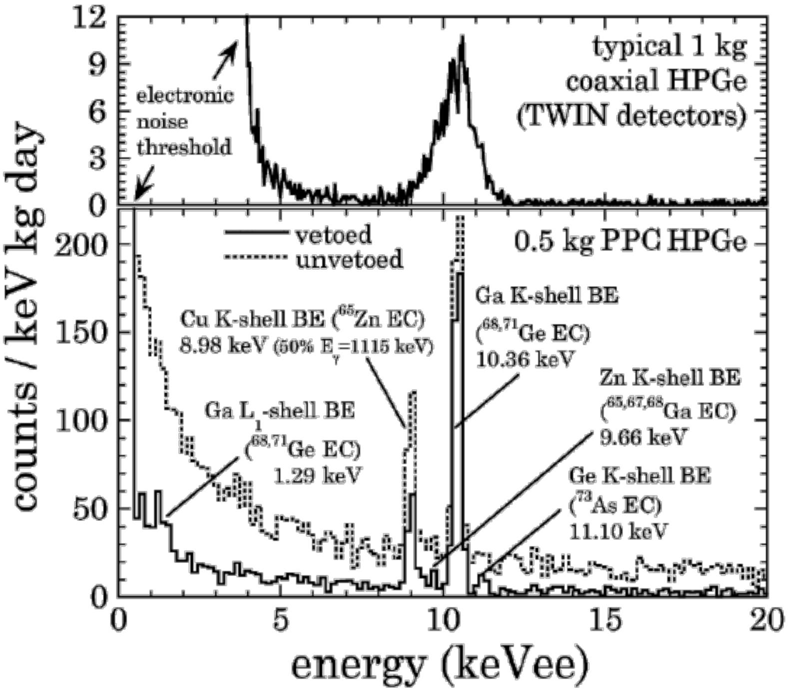
Detector



- P-type Point Contact (PPC) germanium detectors:
  – 440g
  – High resolution (low C)
  – Obs. Cosmogenic peaks



Cosmogenic peaks



Detector

- Threshold ~ 0.4 keVee (lowest)
- No Nuclear Recoil separation
- 330 m w.e. → Soudan (2100m w.e.)
  - Order reduction of BG

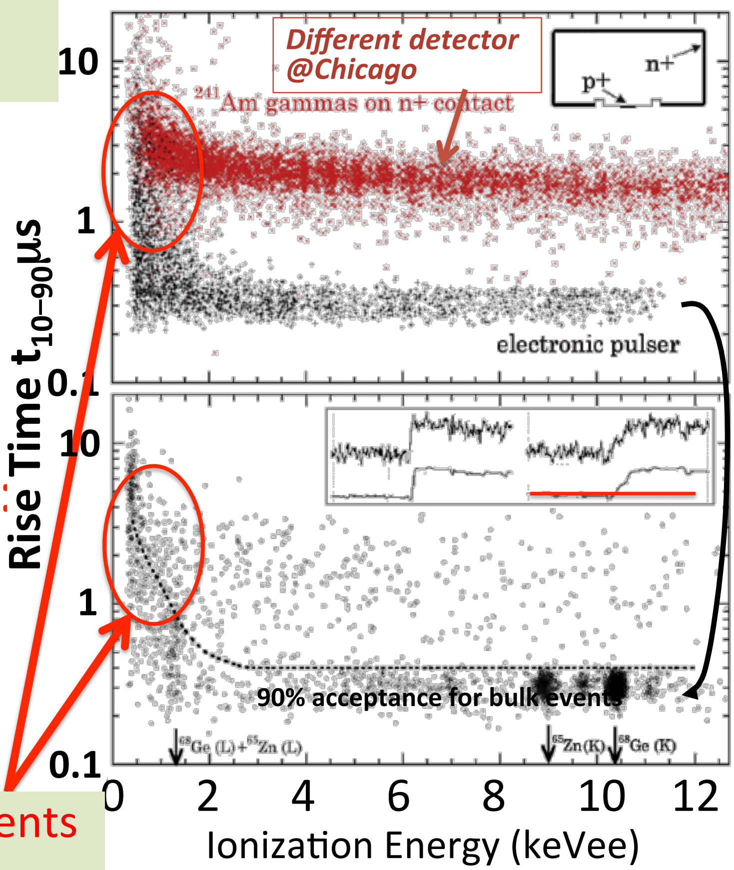
Surface BG

- Must reject surface events (~external γ's)
  - (n+) 1mm dead, 1mm transition

Rise time difference:

Bulk (0.3 μs ~ 2 μs @low energy)

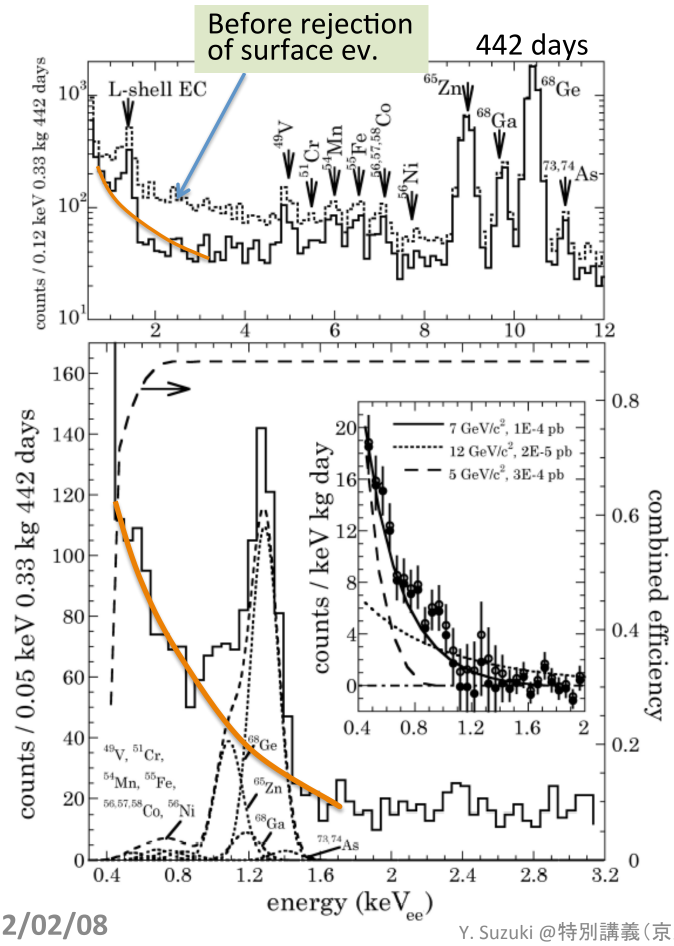
Surface (2 μs ~ 4μs @low energy)



Leakage from surface events should be evaluated

Analysis

- Surface events: Partially collected
  - 1mm dead region
  - 1mm transition region
- 440g → 330g fid. (2mm cuts)
- After the timing cut (surface BG cut)
  - found irreducible excess below 3 keV (unknown BG or….)
  - Observed cosmogenic peaks.
- Either electron events or NR



Spectrum

- BG level:Read from figure
- Top: 40 counts
  → 2.3 dru
- Bottom: 20 counts
  → 2.7 dru

Remaining Backgrounds

- Known Backgrounds
  – L-shell EC below ^{65}Zn (<10%)
  – Neutron(~0.1%)
  – Leakage of the surface events:

  no evaluation

  They said that any such contamination should be modest (PRL106,131301)

  ➔ Need clear and quantitative evaluation of the leakage from the surface events

Results

- Fit
  - Free spin independent cross section, free exponential and constant terms and two gaussian for the L-shell EC (^{65}Zn and ^{68}Ge)

region

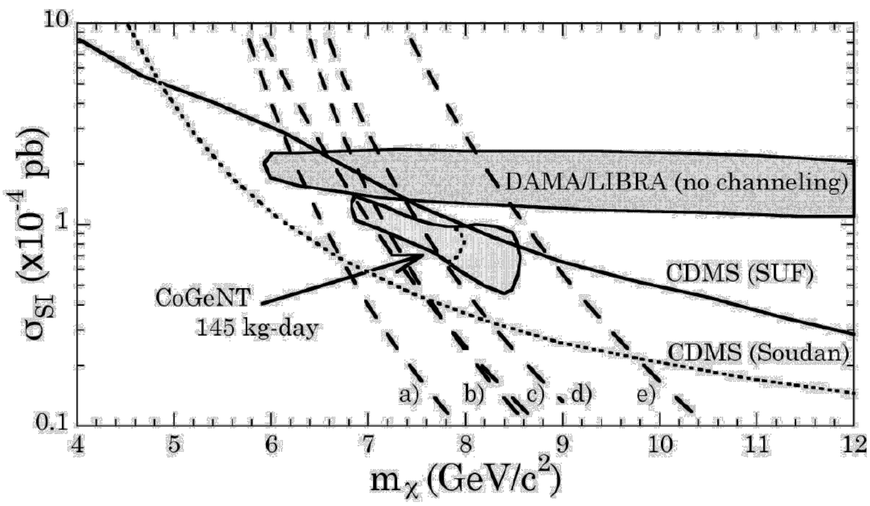
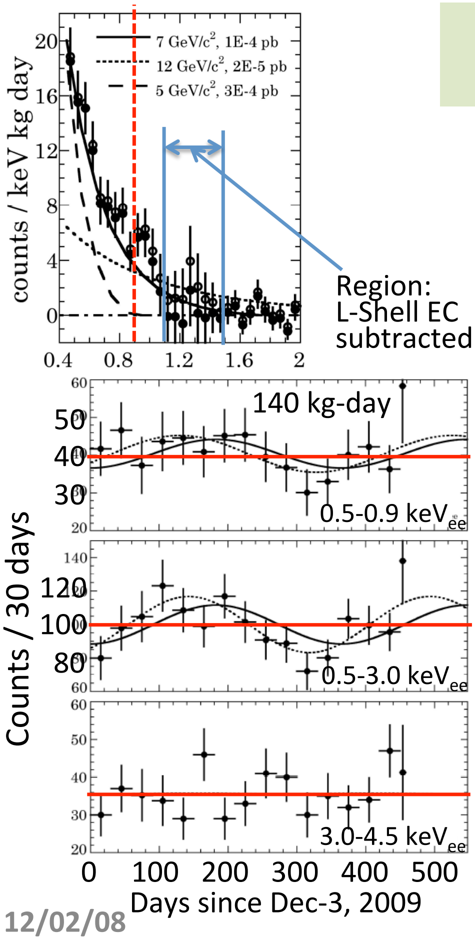


FIG. 2: ROI extracted from the irreducible spectra in Fig. 1 (inset) under consideration of a light-WIMP hypothesis. A small dotted line bisects it, separating the domains favored by the black dot (left) or white circle (right) spectra in Fig. 1. Additional uncertainties and ROI definition are mentioned in the text. The DAMA/LIBRA ROI includes present uncertainties in its position [11], with the exception of ion channeling [14], conservatively assumed to be entirely absent. A solid line indicates limits from CDMS [15]. The dotted line corresponds to CDMS limits [7] disputed in [16]. Dashed lines correspond to most recent XENON100 results [8], under a number of cases described in [17] (trace a) corresponds to the sensitivity claimed in [8]). Recent exclusions by XENON10 [18] are examined in [17].



CoGeNT modulation

- Data: Dec-4th 2009 ~ March-6th 2011 (442 effective days)
- Assume: all the unknown excess is 'signal'
- Modulation (0.5 – 3.0 keVee)
  - χ^2/d.o.f. = 7.8 /12 (80% C.L. Accept.)
  - χ^2/d.o.f. = 20.3 /15 (85% C.L. Reject.) for null hypothesis
  - 99.4% C.L. (2.8 σ)
- Amplitude: 16.6±3.8% (347±29 days periods)
  - Minimum: Oct 16±12 d
- Modulation between 0.5 -3.0 keV may be too strong

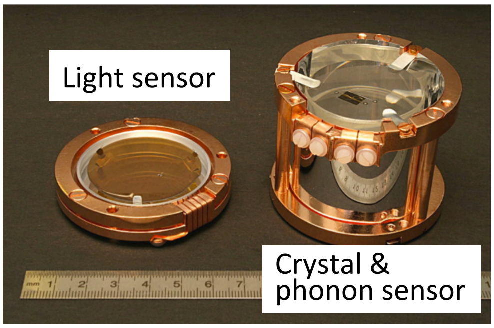
➔ Wait more data

- CoGeNT Next:
  ➔ 4 crystals (C4)

CRESST-II

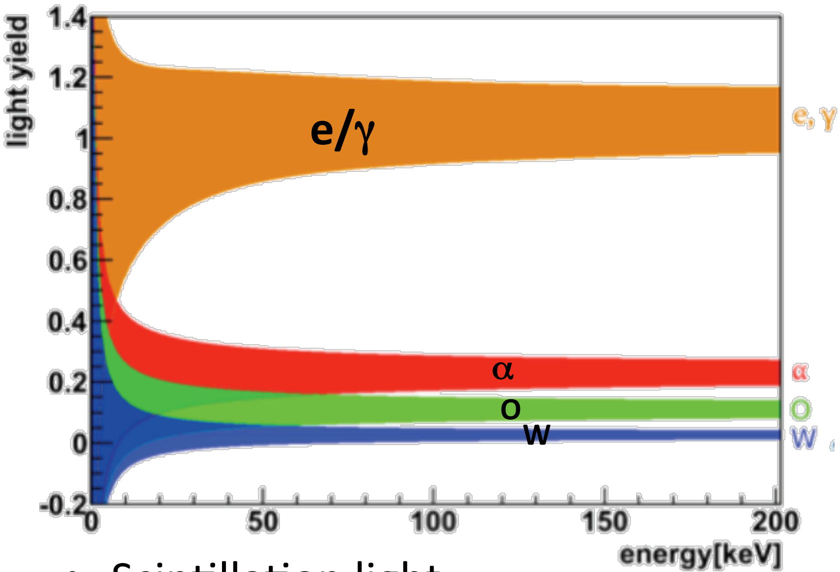
CRESST-II

- $CaWO_4$(Multi-material target)
  - 40 mm in diameter and height
  - 33 crystals, (0.3kg each)
  - up to 10 kg
  - phonon (~10 mK)
  - Scintillation
- Cross section → A^2 dependence, but heavy nuclei → small nuclear recoil energy
- Energy interval: 12 to 40 keV



- 10mK
- Phonon → Transition Edge Sensor
- Scintillation light → TES

Scintillation light



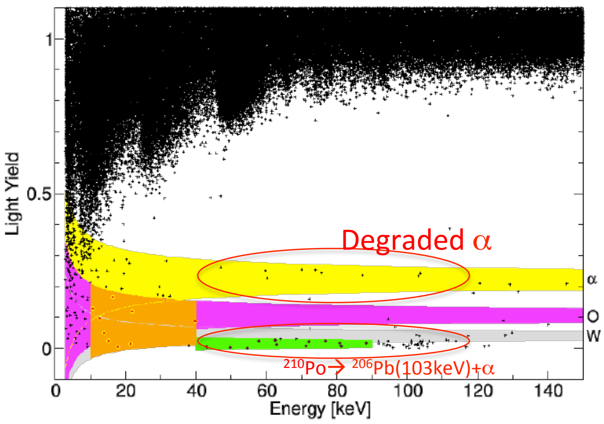
Ca: 6.38+0.62-0.65%
Lead: 1.4%

- Scintillation light:
  → Reduced light output for nuclear recoils
  → Light output decreases with increasing mass number of recoiling nucleus

Operation

- Data used (July 2009 – March 2011)
  - 730kg*days
  - 8 detector modules

Results

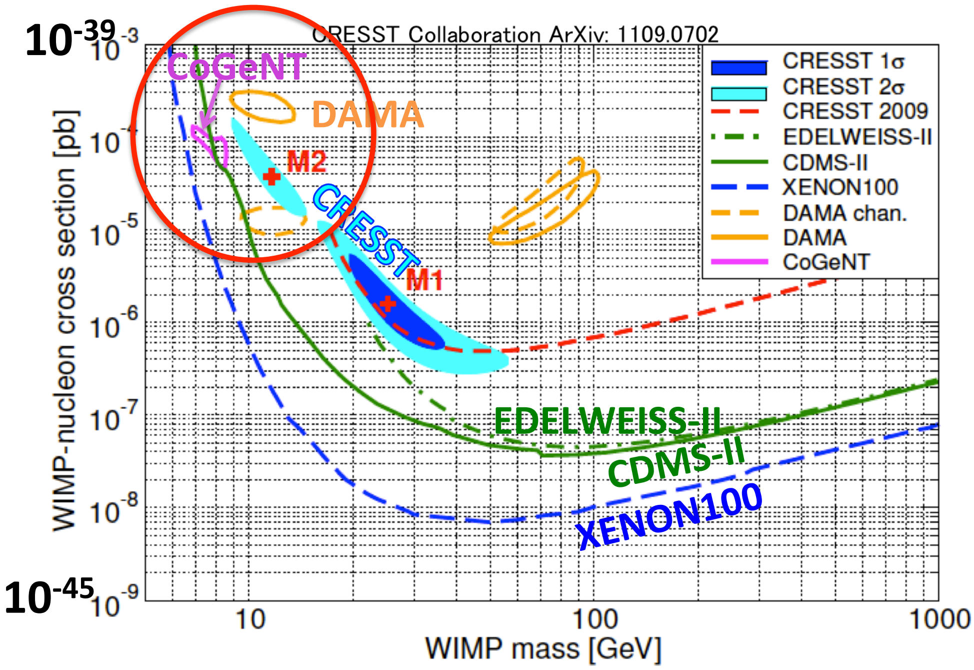


	M1	M2
e/γ-events	8.00 ± 0.05	8.00 ± 0.05
α-events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
$\sigma_{\chi N}$ [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$

- O-band events
  - 67 events
- 4 source of BG
  - Leakage from e/γ band
  - Leakage from α related
    - Degraded α events
  - Neutron events (O)
  - Pb recoils:

    ^{210}Po→ ^{206}Pb(103keV) +α(out)
- "room for signal"
  - 36～44 %

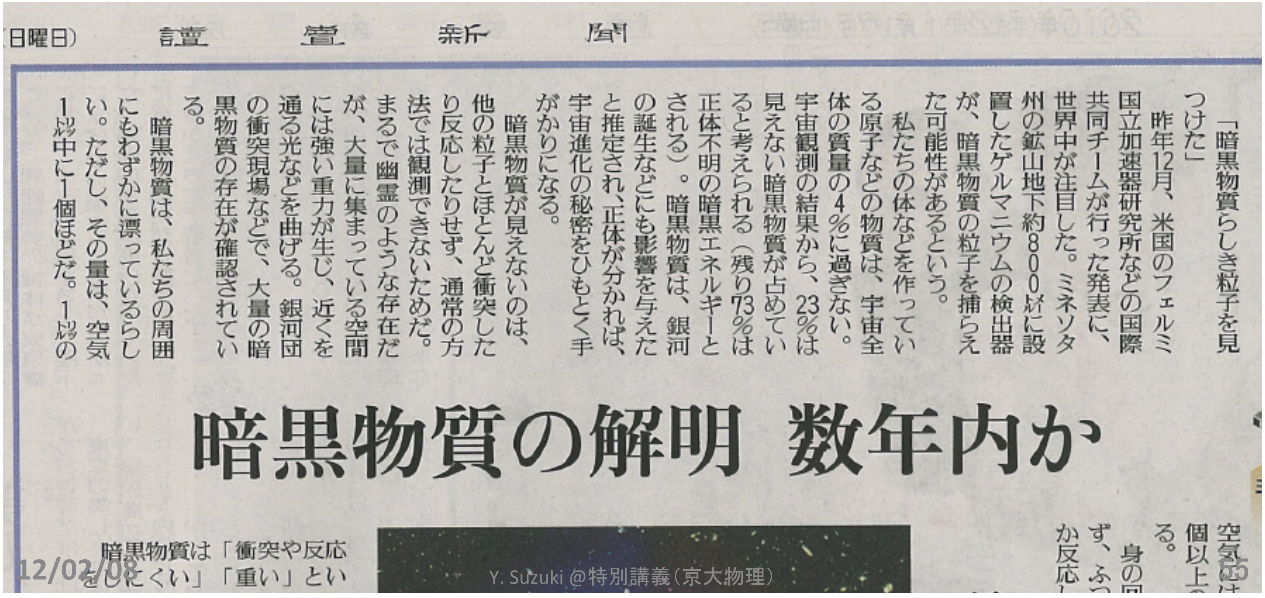
Current Experimental Situation



CDMS-II

2009年１２月

- ニュースが走る：
  CDMS（**C**ryogenic **D**ark **M**atter **S**earch） II 実験（アメリカ、ミネソタ州）が、ダークマター（DM)らしき候補を２事象（２例）観測か？



（日曜日）　読売新聞

「暗黒物質らしき粒子を見つけた」

昨年12月、米国のフェルミ国立加速器研究所などの国際共同チームが行った発表に、世界中が注目した。ミネソタ州の鉱山地下約800メートルに設置したゲルマニウムの検出器が、暗黒物質の粒子を捕らえた可能性があるという。

私たちの体などを作っている原子などの物質は、宇宙全体の質量の4%に過ぎない。宇宙観測の結果から、23%は見えない暗黒物質が占めていると考えられる（残り73%は正体不明の暗黒エネルギーとされる）。暗黒物質は、銀河の誕生などにも影響を与えたと推定され、正体が分かれば、宇宙進化の秘密をひもとく手がかりになる。

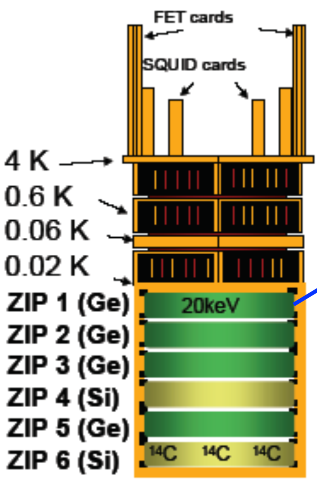
暗黒物質が見えないのは、他の粒子とほとんど衝突したり反応したりせず、通常の方法では観測できないためだ。まるで幽霊のような存在だが、大量に集まっている空間には強い重力が生じ、近くを通る光などを曲げる。銀河団の衝突現場などで、大量の暗黒物質の存在が確認されている。

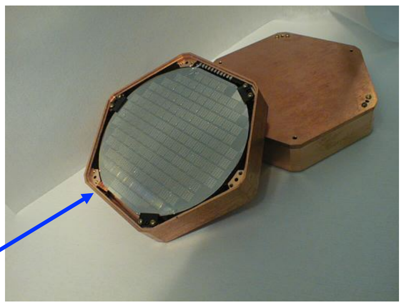
暗黒物質は、私たちの周囲にもわずかに漂っているらしい。ただし、その量は、空気1リットル中に1個ほどだ。1リットルの

暗黒物質の解明　数年内か

暗黒物質は「衝突や反応をしにくい」「重い」とい

CDMS-II 実験





アメリカ Soudan鉱山

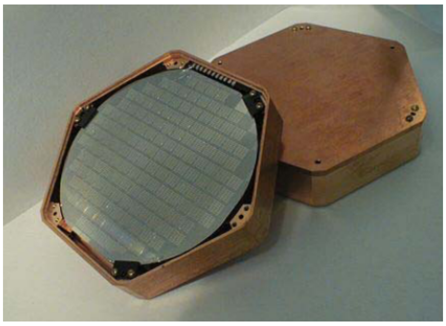
発熱測定
と
電離電荷測定

4個の250gゲルマニウム
2個の100gシリコン
50mKに冷却

利点：
　高いバックグラウンドの峻別能力
　高いエネルギー分解能
欠点：
　大きくするのが難しい。高価である。

Detector

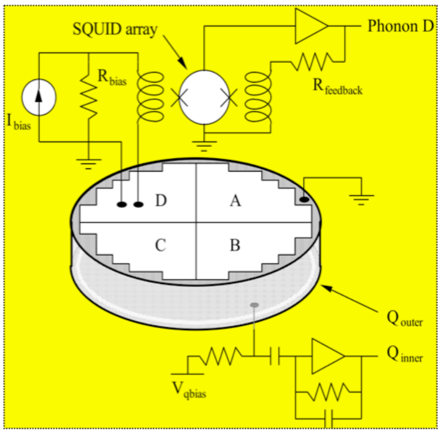
- Ge(&Si) detector (~10mm thick and ϕ=76mm)
- 230g x19 (Ge) ~ 4 kg
  (11 Si detector: not used)
- Lead and polyethylene shields, surrounded by plastic scintillators
- Soudan Underground Laboratory, USA: 713 m depth

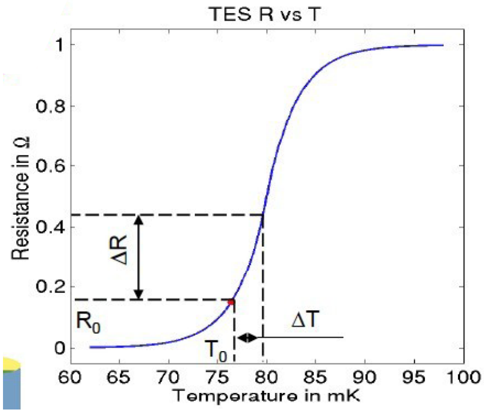


Detector

- 5 towers (T1-T5) and 6 positions (Z1-Z6)
- Ionization and phonon (<50mK)
- Top surface: 4 phonon read out channel
  - Each: 1036 tungsten transition edge sensors
  - Ground reference for ionization
- Bottom surface: Ionization electrode
  - Two concentric grids

CDMS Collaboration





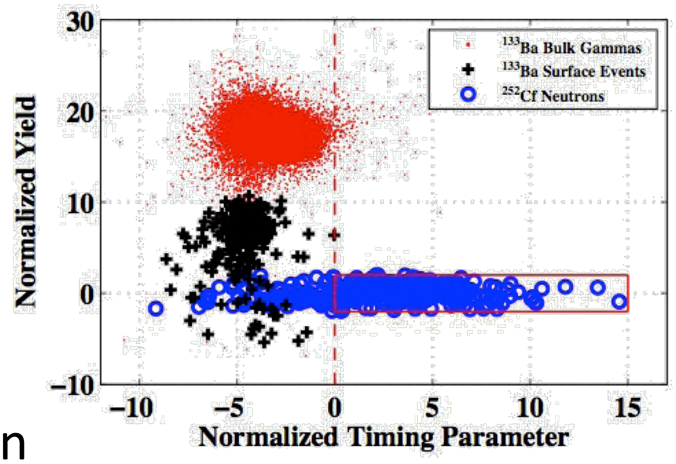
Operation

- July 2007 → Sept 2008
- Only Ge detector: aiming for SI interaction (A^2)
- Data: 612kg-days

Analysis

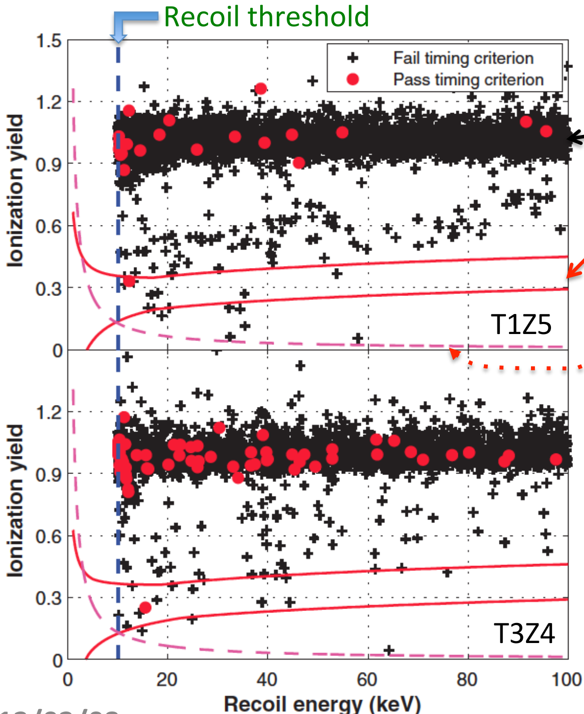
- 10 keV ~ 100keV in a single detector
- No deposit in other detectors
- No activity in Scintillation veto
- Acceptance calibration: Nuclear recoils induced by a ^{252}Cf neutron source

BG reduction



- Ionization and phonon
  - Nuclear recoils: less ionization yield
    - ➔ 1 in 10^4 raj. for γ's
  - Surface electron events (<μm): reduced ionization collection
    - → first arrival of phonon
    - ➔ Timing cut ➔ surface events
- Over all $>10^6$ rajection

Ionization Yield



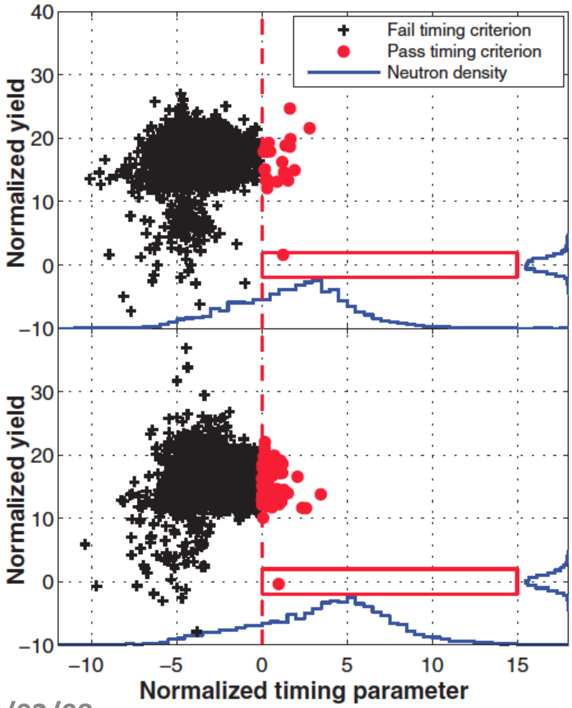
γ-ray band

Acceptance region: Nuclear Recoils

Ionizaton threshold

- Round red marked events: to satisfy the timing criteria for the bulk events
- Two events remained

Timing Parameter

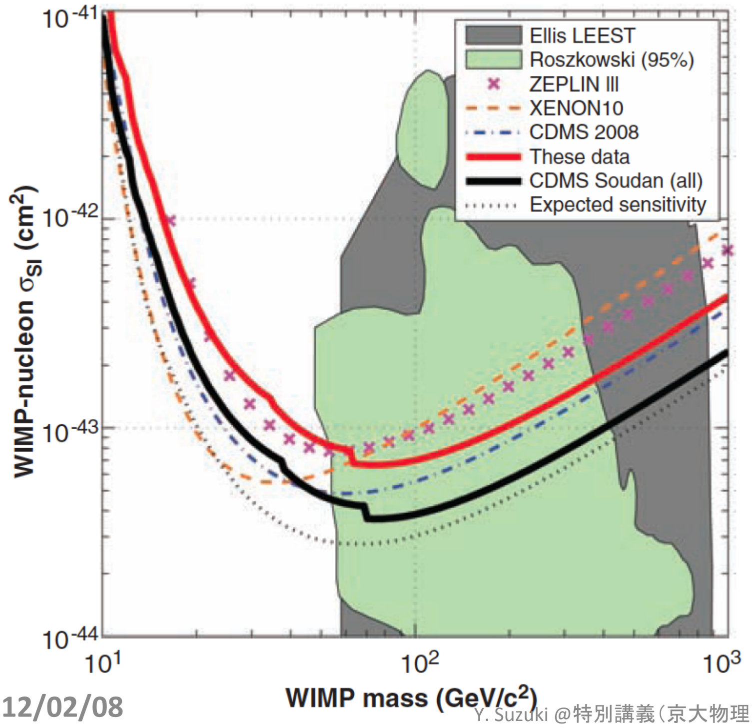


- Normalized yield: number of standard deviations from the mean nuclear recoil yield
- normalized timing parameter: timing relative to acceptance region
- The solid red boxes: the signal regions.
- The blue histograms: calibration neutrons

Results

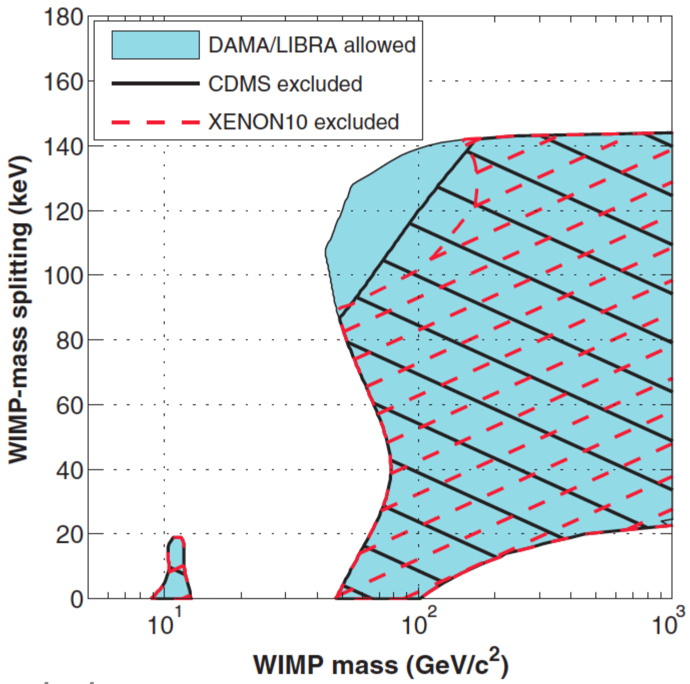
- 2 events found
  - 12.3 keV, 15.5 keV
- Backgrounds: 0.9±0.2 events
  - 0.8±0.1±0.2 surface events
  - 0.1 neutron events
    - 23% probability to have : more than 2 BG events
- LIMIT (for 70 GeV/c^2)
- $\sigma_{SI} < 7.0 \times 10^{-44}$ cm^2
- $\sigma_{SI} < 3.8 \times 10^{-44}$ cm^2 for combined with prev. results

Spin Independent cross section



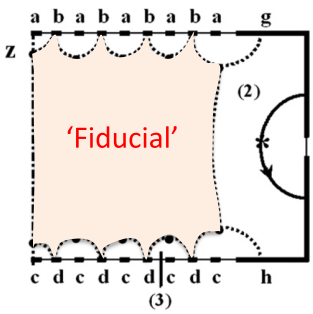
- WIMP-nucleon spin-independent cross section as a function of WIMP mass.

Inelastic Dark Matter



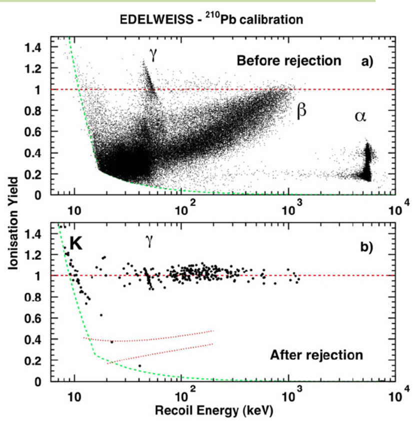
- Inelastic Dark Matter

EDELWEISS-II

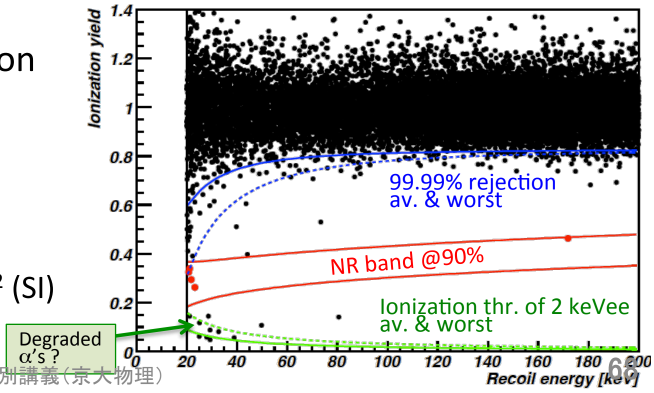


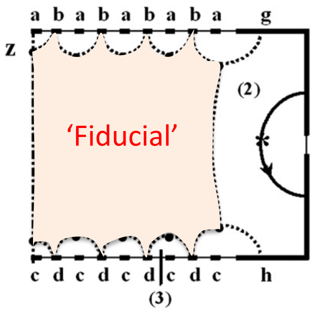
EDELWEISS-II

400g x 10 Ge= 4 kg (1.6kg:fid.)
Phonon+ *charge collection electrodes w/ interleaved geometry (Ge-ID)*
➔ reject of near surface events
Rej, Rate: 6x10^{-5}



- Threshold: E_{NR} < 20keV
- ~14 months of running: 384kg*day
- Found: 5 Nuclear Recoil events
- < 3.0 BG events
  γ-BG leak (<0.9), surface (0.3), muon induced(0.4), neutron(1.4)
- Combined Analysis w/ CDMS-II
- Next Step:
  - Next EDELWEISS-III
    - 26kg (40 x 800g) aiming 10^{-45}cm^2 (SI)
    - Start installation in 2012





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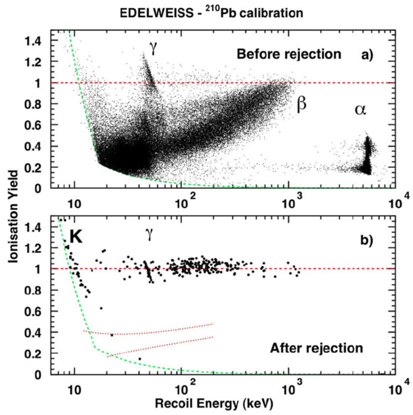

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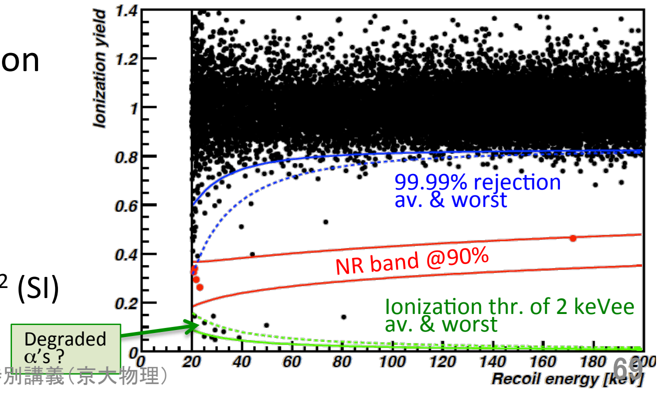
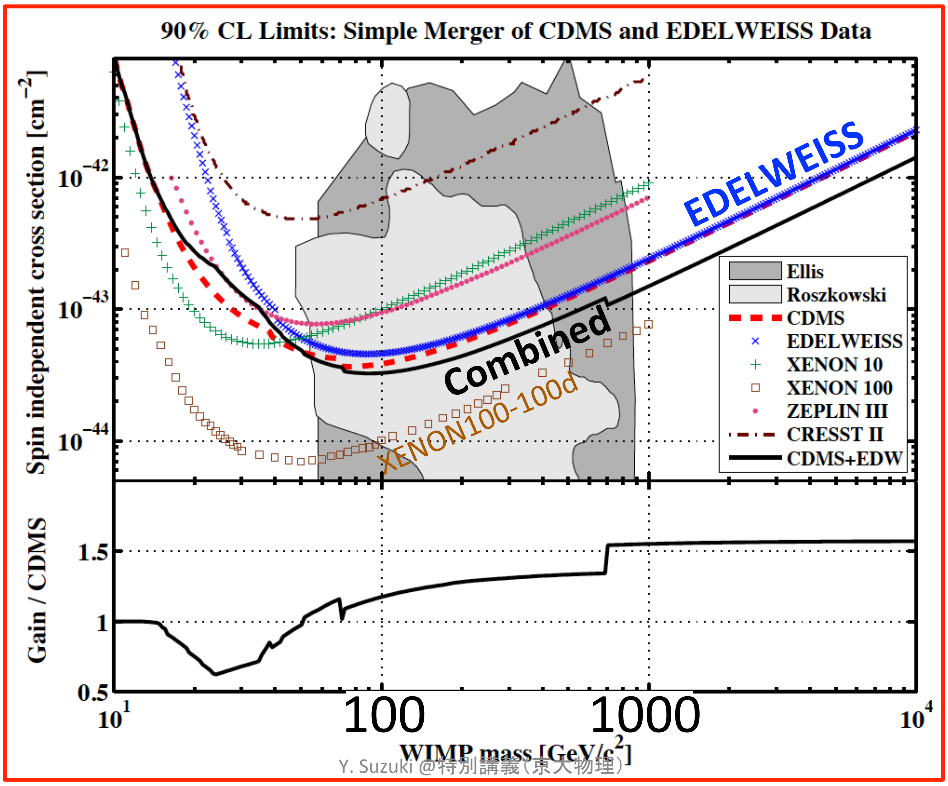


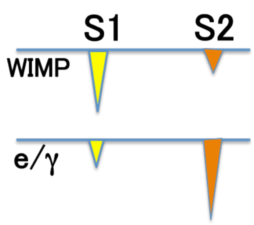
EDELWEISS II



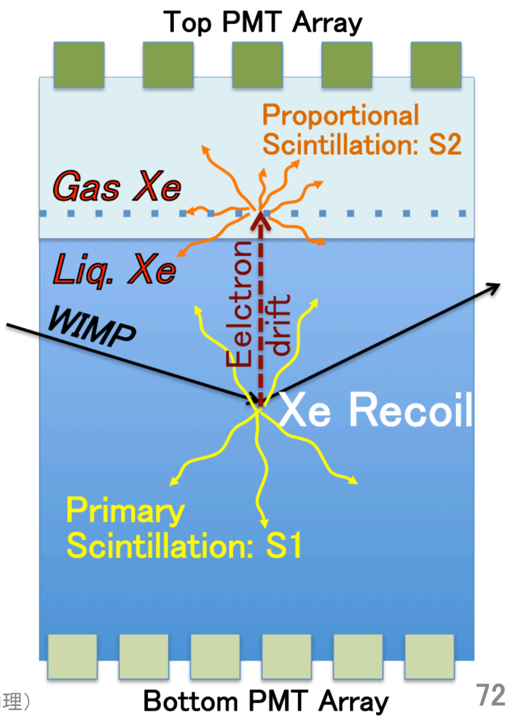
XENON

Detector

- 2 phase
- liquid Xenon detector
- Simultaneous detection of light (S1) and charge (as S2)
  – Ionization e's → S2 (prop. Scinti.)
- S2/S1 →NR and EM discri: ~1/1000



$(S2/S1)_{\mathbf{WIMP}} < (S2/S1)_{\gamma}$



Detector

- ~30cm height and ~30cm diameter
- 161 kg: 99 kg active veto, 62 kg target
- 48 kg fiducial mass
- 100.9 live days (Jan and June 2010)
- Pos. Res.:
  - (x,y):<3mm (1σ) (hit pattern of the top PMT array)
  - z: 0.3mm (1σ) (drift time)

Operation

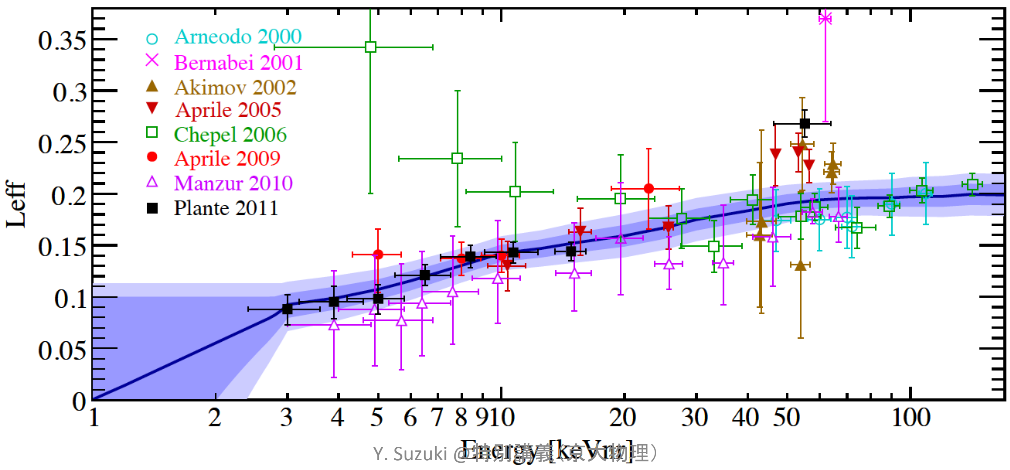
- 100.9 live days (till June in 2010) w/ 48 kg fiducial mass (62kg) ➔ 1471kg-day
- BG <5x10^{-3} ev/keV$_{ee}$/kg/day before signal discrimination
- 242 PMTs: Hamamatsu R8520-AL

Characteristics

- Rn in passive shields < 1 Bq/m^3
- Event Trigger: by S2
- Trig eff: >99% at 300pe in S2
- Continuous xenon purification 🡐 a hot getter
- Mean electron life time τ_e: 230μs to 380μs
  - Weekly ^{137}Cs calibration
  - Time evolution →S2 z-correction : syst < 2.5%
- S2 (x,y) corrections by a map obtained with ^{137}Cs

Scintillation Efficiency

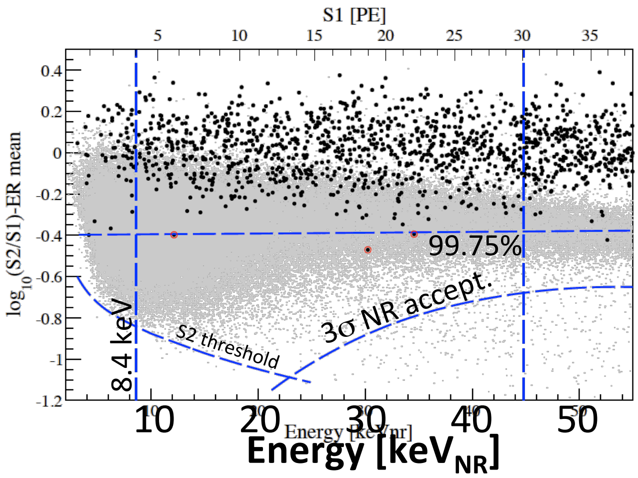
- $L_y(122keV_{ee})=(2.20\pm0.09)pe/keV_{ee}$
- $E_{NR} = ((S1/S_{NR})/(L_y/S_{ee}))(1/\mathcal{L}_{eff})$
  - $S_{NR}=0.95$, $S_{ee}=0.58$: electric field QF
  - $\mathcal{L}_{eff}$: Scintillation efficiency
- Mean 🡐 by Gaussian assumption of the data
- 1σ and 2σ bands
- < $3keV_{nr}$: logarithmically extrapolated to $\mathcal{L}_{eff}=0$ at $1keV_{nr}$
- G. Plante et al. (2011), arXiv: 1104.2587



Energy Calibration

- Spatial dependence of the light correction for S1, by maps from:
  - 40 keV_{ee} line from neutron on ^{129}Xe
  - 662keV_{ee} line (w/in 3% agreement)
  - 164keV_{ee} line ^{131m}Xe (neutron activated)
- $L_y(122keV_{ee})=(2.20\pm0.09)pe/keV_{ee}$
  - at 530V/cm

Event Selection

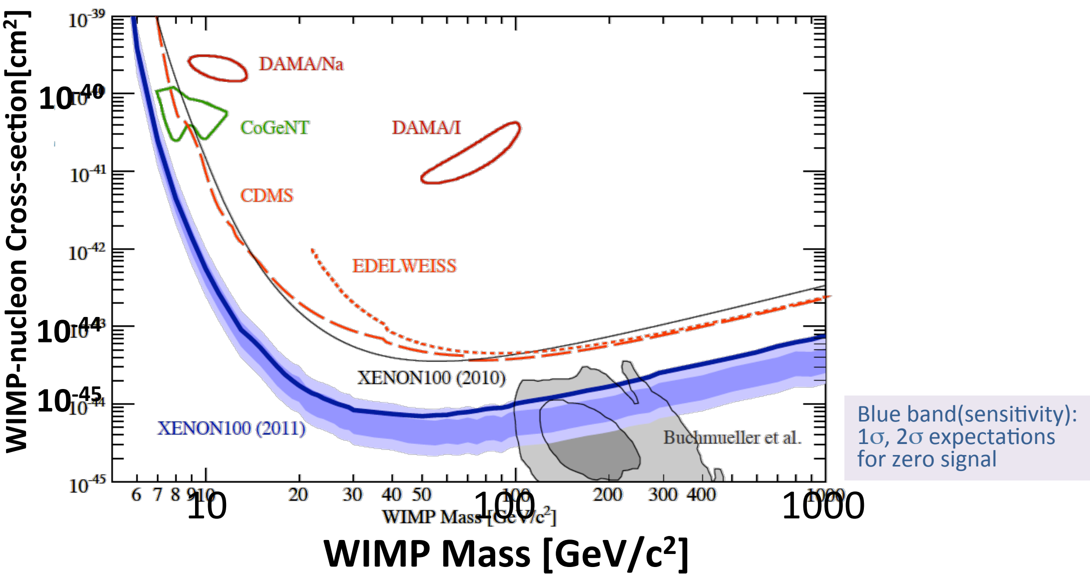


- 3 events remain after S2/S1 selection (99.75% EM rejection)

Results

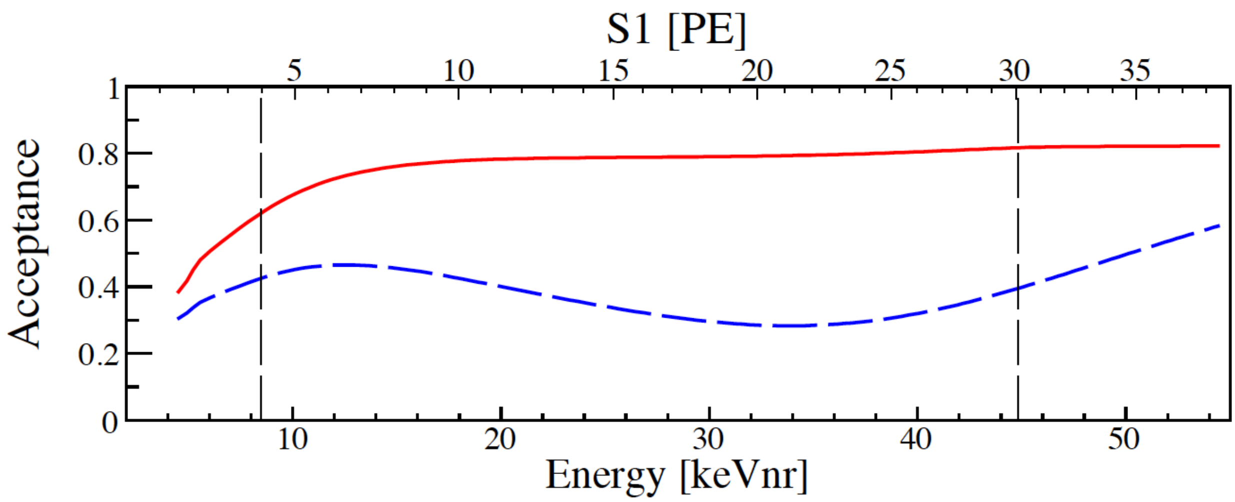
- Expected BG: 1.8±0.6
  - ^{85}KR: 1.14±0.48
  - Others: 0.56(+0.21/-0.27)
- >7.0x10^{-45} cm^2 for 50GeV/c^2 @90% C.L.

Spin independent cross section

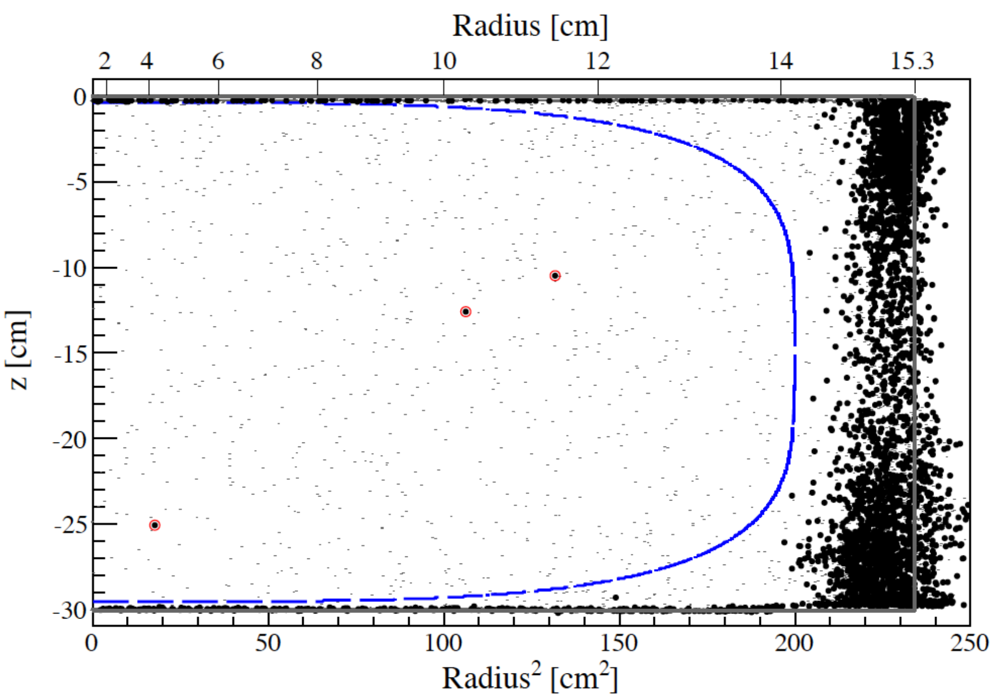


- XENON is moving to XENON1T in preparation

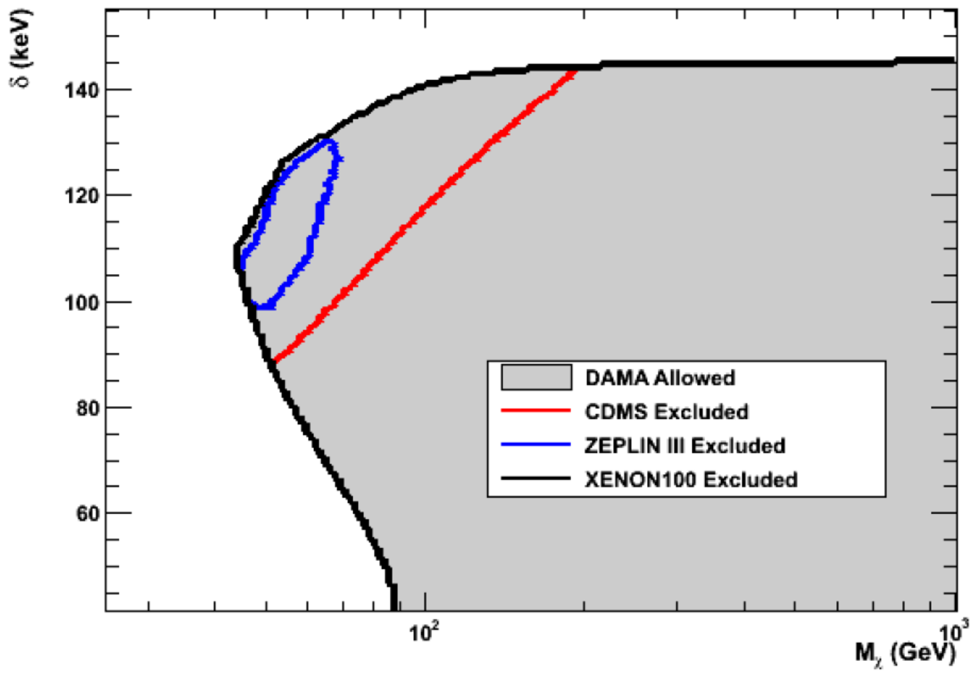
Acceptance



Vertex Distribution



Inelastic



Current players of the game

Experimentð	Target	Threshold	Total Exposure	Recoil Identification	Main body of Signal ?	Modulation
DAMA/LIBRA	NaI	2.0 keV_{ee}	427,000 kg-days	(NR+EM)	Not identified	O
CoGeNT	Ge	0.5 keV_{ee}	140 kg-days	(NR+EM)	O?	O
CRESST	$WCaO_4$	10.0 keV	>700 kg-days	NR	O? (not official)	
CDMS-II	Ge/Si	10.0 keV	612 kg-days	NR		
CDMS-II (LE)	Ge	2.0 keV_{NR}	241 kg-days	(NR+reducedEM)		
EDELWEISS	Ge	20.0 keV	384 kg-days	NR		
XENON100	Xe	8.4 keV_{NR}	1471 kg-days	NR		
XENON10 (LE)	Xe	1.4 keV_{NR}	15 kg-days	(NR+reducedEM)		

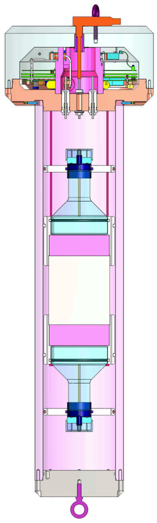
Current and Future direct WIMP Search experiments

35 programs (not complete list : sorry for those projects I have missed)

Experiment s	site	Target & mass	technology	Achieved (cm^2)	Sensitivity (cm^2)	Status & comments	Year to start
Xenon							
ZEPLIN-III	Boulby	Xe: 8kg	two phase		SI: 10^{-43}	Stop in 5- 2011	results soon
XENON100	LNGS	Xe: 48kg	two phase		SI: $7x10^{-45}$		On going
XENON1T	LNGS	Xe: 1t	two phase		SI: 10^{-47}		2015
XMASS	Kamioka	Xe: 100kg	single phase		SI: 10^{-45}	commissioning	On going
XMASS-1.5	Kamioka	Xe: 1ton	single phase		SI: 10^{-46}		2013
XMASS-II	Kamioka	Xe: 10ton	single phase		SI: 10^{-47}		2016
PANDA-X	Jing Ping	Xe: 25kg	two phase		SI: 10^{-45}		> 2013
LUX	SUSEL	Xe: 100kg	two phase		SI: $<10^{-45}$	Surface lab	2012
LZS	SUSEL/ SNO	Xe: 1ton	two phase		SI: 10^{-47}		2015
Ar							
WARP	LNGS	Ar:140kg	two phase		SI: $5x10^{-45}$	commissioning	
DarkSide50	LNGS	DAr: 50kg	two phase		SI: 10^{-45}	prototype	
ArDM	Canfranc	Ar: 850kg	two phase			Prototype	2011
DEEP3600	SNOLAB	Ar: 1ton	Single phase		SI: 10^{-45}		2012
MiniCLEAN	SNOLAB	Ar: 150kg	Single phase		SI: 10^{-44}		2011
DARWIN	Europe	Ar or Xe: tons	two phase		SI: $<10^{-47}$		
MAX	DUSEL	Ar and Xe			SI:$<10^{-47}$	R&D	

Experiments	site	Target & mass	technology	Sensitivity (cm^2)	Achieve (cm^2)	Status & comments	Year to start
Ge							
Super-CDMS	SOUDAN	Ge: 15kg	char+phonon	SI: $5x10^{-45}$			2011
Super-CDMS	SNOLAB	Ge: 100kg	char+phonon	SI: $3x10^{-46}$			2015
CoGeNT-C4	SOUDAN	Ge: 4kg	charge			installation	2011
CDEX	Jing Ping L	PC-Ge:10 kg	charge	SI: 10^{-43}		1kg test	
Bubble Chamber							
PICASSO	SNOLAB	C_4F_{10}: 2.6kg	BC	SD: $2x10^{-37}$			On going
SIMPLE	Rustrel	C_2ClF_5: 26 kg	BC			Test 0.2kg	Install 2012
COUPP	SNOLAB	60kg	BC			4kg test	2011
Scintillation (+phonon)							
DAMA	LNGS,	NaI: 250kg	Scintillation	SI: 10^{-40}			On going
KIMS	Yang Yang	CsI: 104.4kg	Scintillation	SD:10^{-38}			On going
CINDMS	Jing Ping L	CsI(Na)	Scintillation			R&D	
CRESST-II			Sintill+phonon				On going
ROSEBUD	Canfranc	Al_2O_3 etc.	Scintill+phonon			R&D	
DM-Ice	South pole	NaI:>250kg	Scintillation	Test DAMA		Prototype: 17kg	?
EURECA	LSM	Multi-T: 1ton	many	SI: 10^{-46}		Phase-I: 150kg	2015
Tracking							
Drift-III	Boulby	CS2:4kg,24m^3	TPC	SD: 10^{-40}			?
DM-TPC		CF4	PMT+TPC			Prototype test	
NewAGE	Kamioka	CF4	microTPC			Prototype test	
MiMac	LSM	CF4	microTPC			Prototype	2011 1m^3
Cygnus	World?		Tracking			White paper	

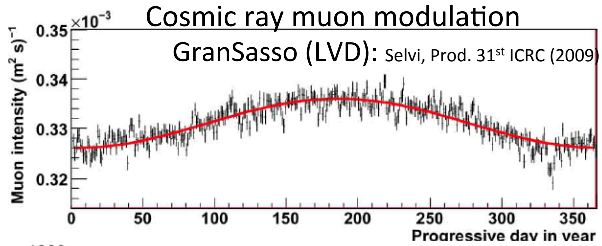
Test directly DAMA and GoGeNT

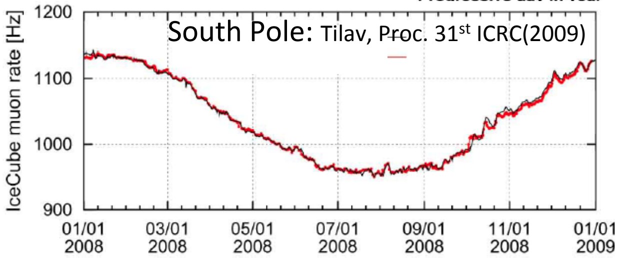


DM-Ice

- Test directly DAMA
- NaI detector
  @South pole:
- **Cosmic modulation is opposite**
- Dec-2010 ~ :
  - Feasibility test
  - 8.5kgx2 NaI from NAIAD
- Inside BG: 5~10 times higher than DAMA
- ICE is clean:
  - U/Th: ppt
  - K: ppb

Cosmic ray muon modulation

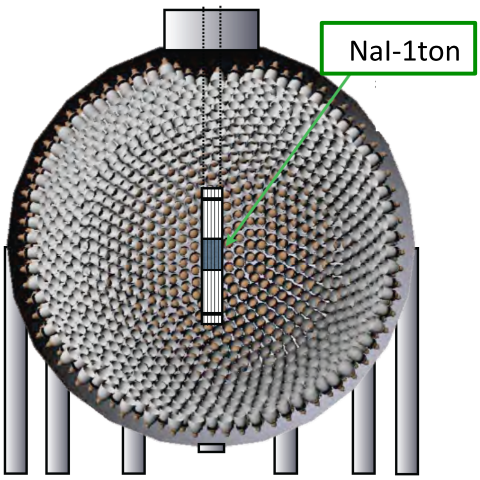




- Need to make low BG crystal
  - ✓ U/Th may be ok, but
  - ✓ K is more serious: need <ppt?
- R&D for low BG PMT

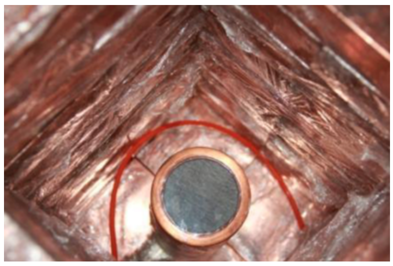
- Place NaI in KamLAND (or Borexino)

KamLAND-NaI



CEDX: Point Contact Ge detector

- Jing Ping Lab. in China



- 20g is running
- 1kg is testing !
- Aim to check GoGeNT results

'Standard' WIMPs search experiments should go on

100kg ➔ 1tons ➔ multi-tons ; sensitivity down to 10^{-47} cm^2 (SI)

XENON, XMASS, EURECA, Darwin, MAX, LZD, ………

Experimental Incompatibility ?

- DAMA ⇔ CoGeNT
  – Na vs Ge
  – Isospin dependence ?
- CDMS-II ⇔ CoGeNT
  – Both Ge: really in trouble
- Xenon ⇔ (DAMA/CoGeNT)
  – Isospin dependent
  – Inelastic interaction
- Many thought to reconcile the results

END