暗黒物質（ダークマター）の探し方

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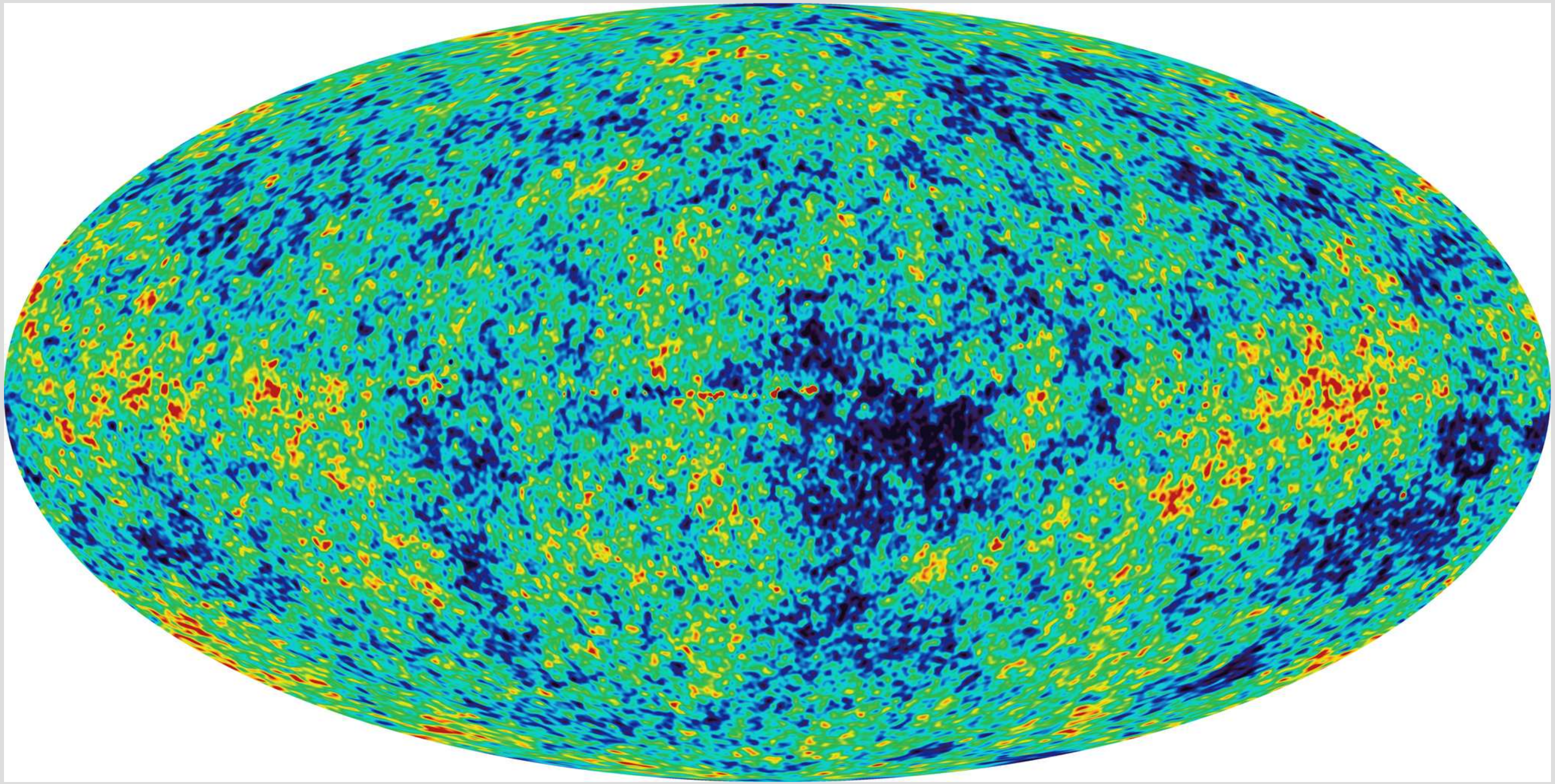
物理学教室

蓑輪　眞

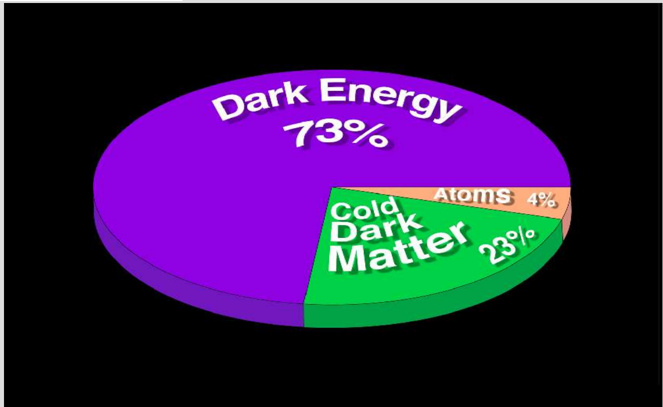
暗黒物質の“歴史”

- 1933　F. Zwicky　かみのけ座銀河団の速度分散　Helv. Phys. Acta. 6 (1933) 110
  Virial 定理　≪　赤方偏移の光学観測 → Dark Matter の存在
- 1965　A. Penzias & R. Wilson 宇宙マイクロ波背景輻射 (CMB) の発見
  電波観測の発達
- 1973　J. Ostriker & P. Peebles　ApJ. 186 (1973) 467
  多体系のシミュレーションによる回転銀河の安定条件
  ≪　我々の銀河の回転速度 220km/s → Dark Matter の存在
- 1970 年代後半　電波（HI ガス 21cm 輝線）による銀河回転曲線の観測
  → Dark Matter の存在の立証
- 1992 COBE　宇宙マイクロ波背景輻射のゆらぎの発見
  → インフレーションモデル、$\Omega_{tot} = 1$ を示唆
- 1998 Super Kamiokande　ニュートリノ質量の発見
  → ~~HDM~~　CDM

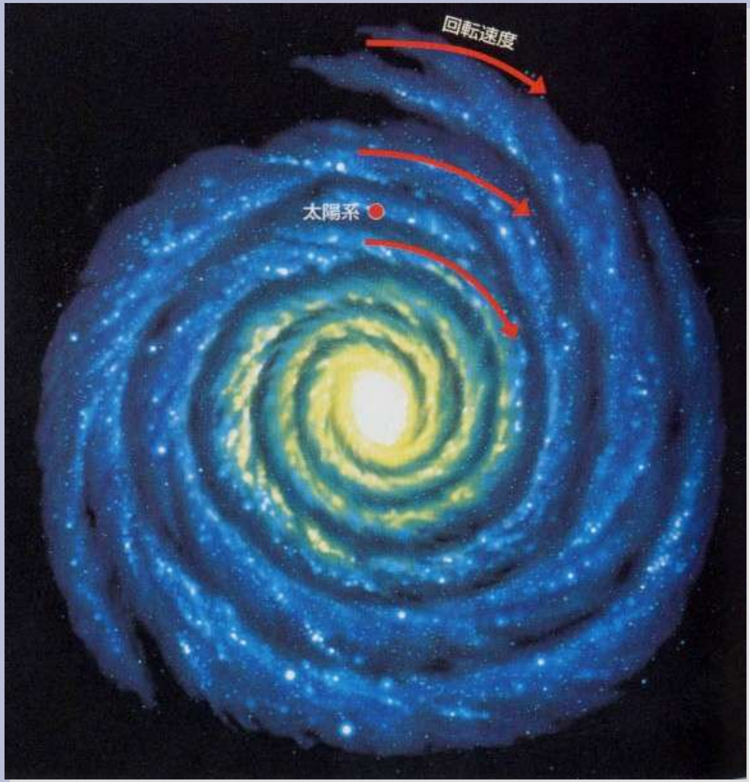
WMAP の援護射撃

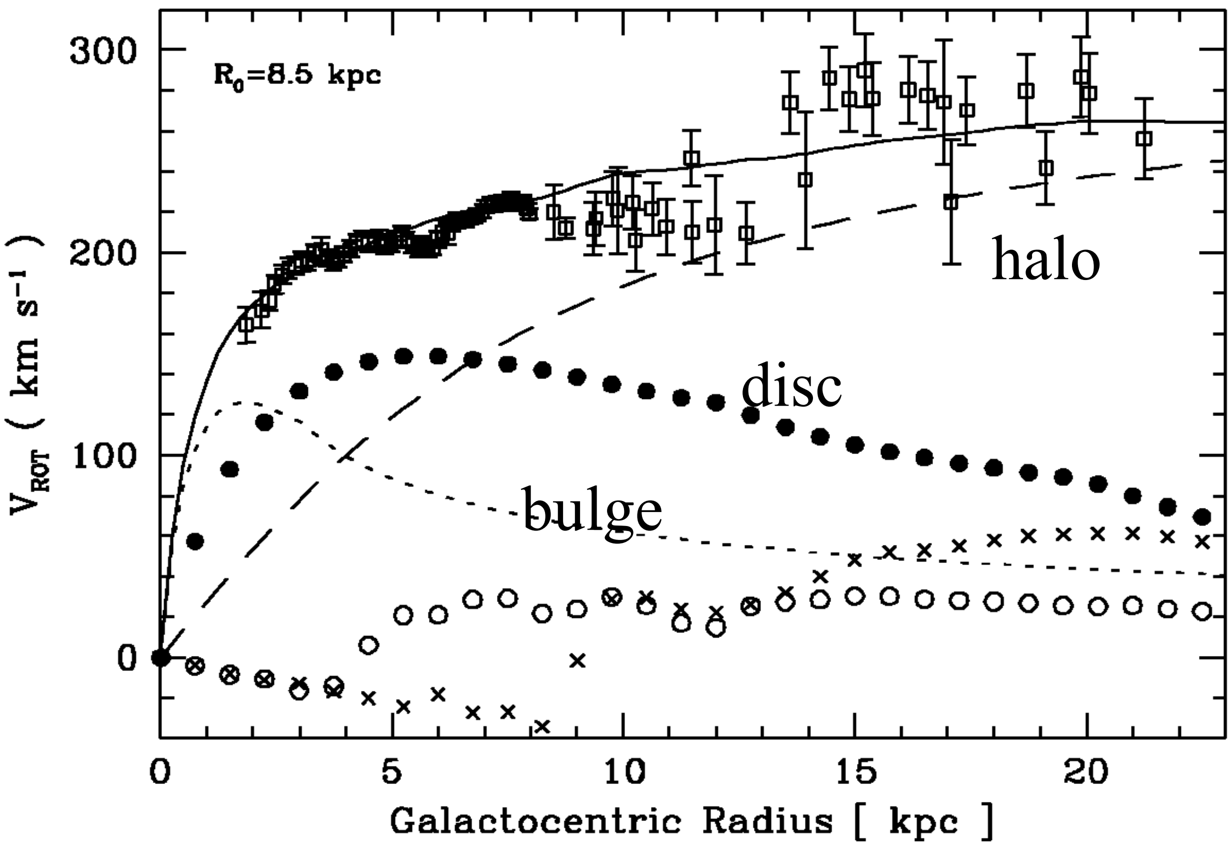


Pictures: NASA/WMAP Science Team;
http://map.gsfc.nasa.gov/



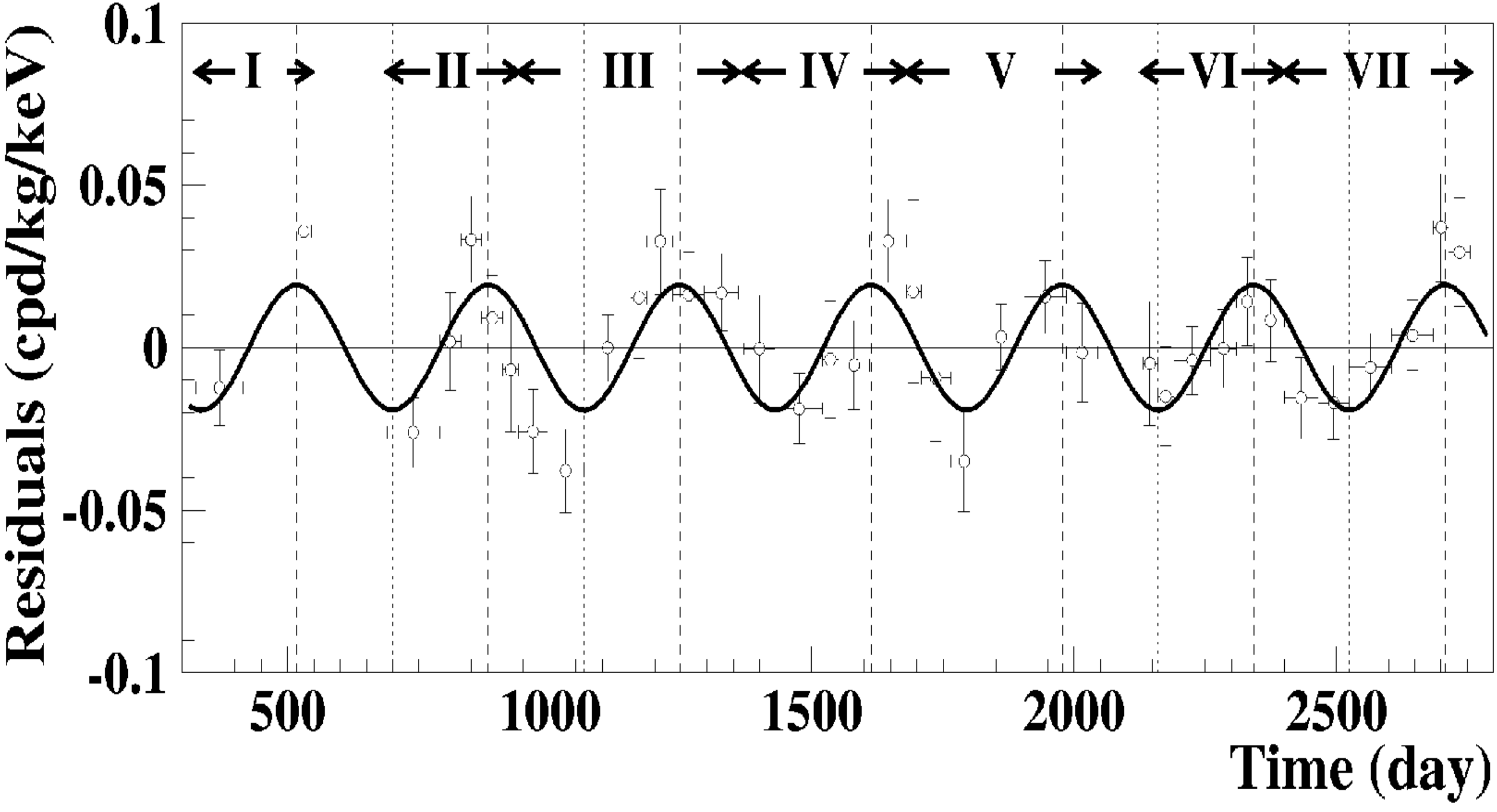
近傍にある証拠


回転速度
太陽系


R₀=8.5 kpc
halo
disc
bulge
V_ROT (km s⁻¹)
0
100
200
300
0
5
10
15
20
Galactocentric Radius [kpc]

DAMA's <discovery> by annual modulation

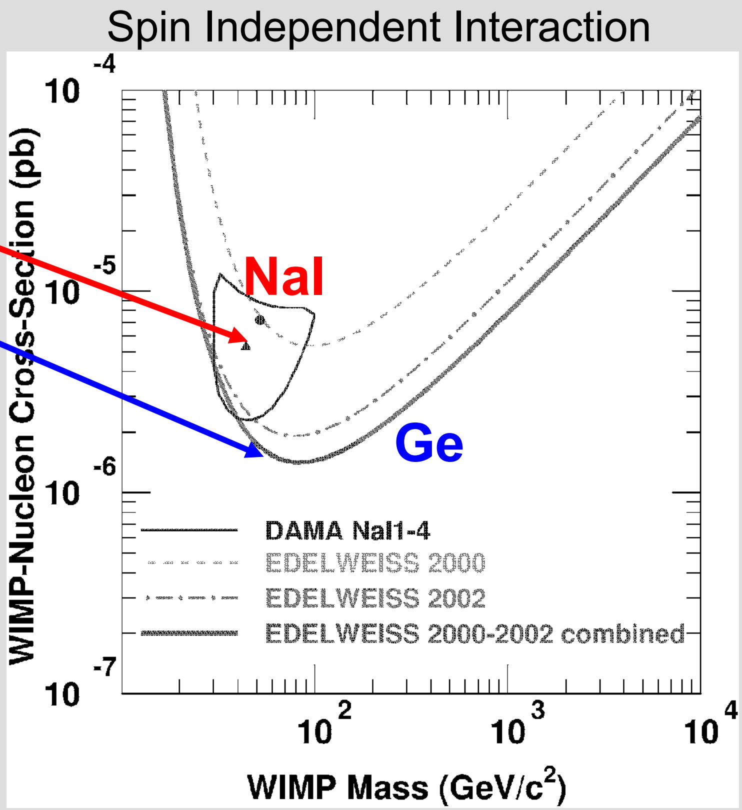
R. Bernabei et al., Riv. Nuovo Cim. 26(2003)1.)



The story

- 1998　イタリア　DAMA
  “Annual Modulation を確認”

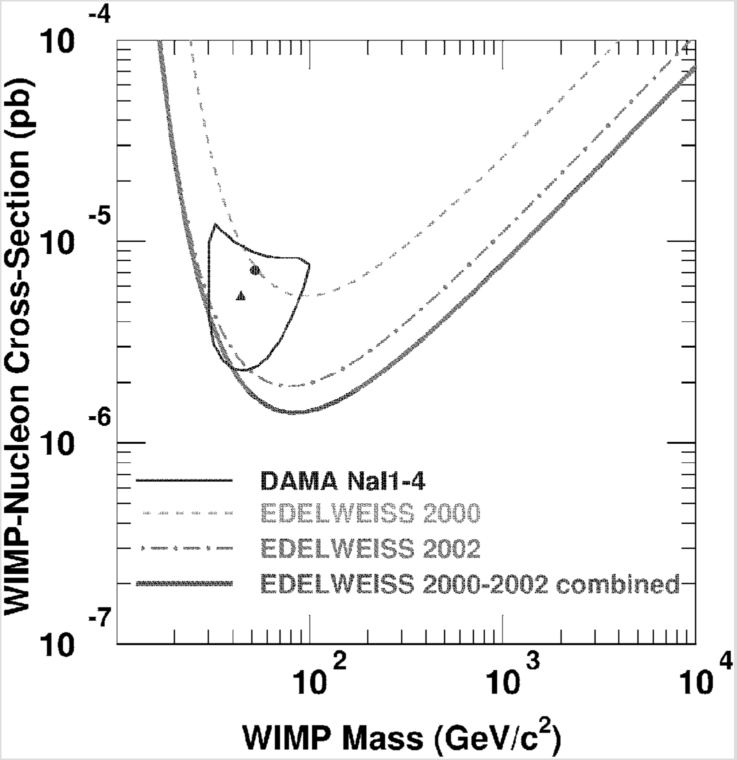
- 2000　アメリカ　CDMS
- 2002　フランス　EDELWEISS
  “すべてのイベントを暗黒物質”
  とする conventional な方法で
  DAMA region をExclude



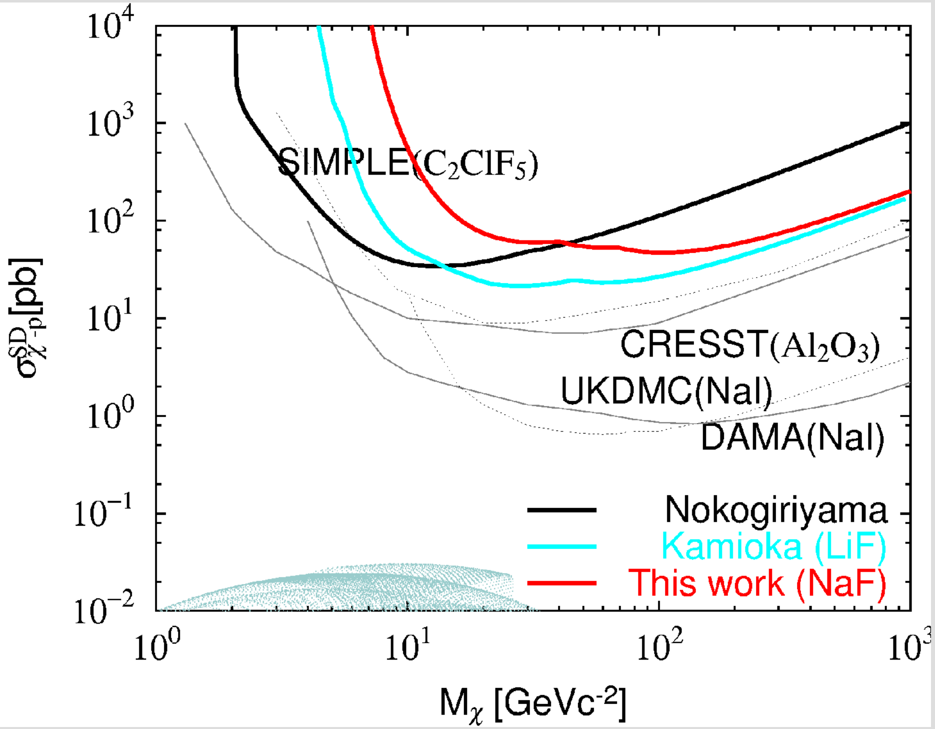
(Phys. Lett. B **545** (2002) 43)

Current exclusion limits in $\sigma^{\mathrm{SI}}_{\chi-\mathrm{n}}$ and $\sigma^{\mathrm{SD}}_{\chi-\mathrm{p}}$

SI



SD



Dark Matter Candidates

- Axion （KSVZ, DFSZ）

$$m_a \propto \frac{1}{f_{PQ}} \qquad 10^{-6}\mathrm{eV} \leq m_a \leq 10^{-2}\mathrm{eV}$$

- Neutralino
  - ➢Lightest Supersymmetric Particle
  - ➢R-parity の保存から安定

→ 宇宙初期に生成され現在まで存在し続ける

$$\chi = a_1\tilde{B} + a_2\tilde{W}_3 + a_3\tilde{H}_1 + a_4\tilde{H}_2$$

- gauginos と higgsinos の線形結合の基底状態
- coupling　SUSY モデル依存
- $39\mathrm{GeV} < m_\chi$

Searches, direct and indirect

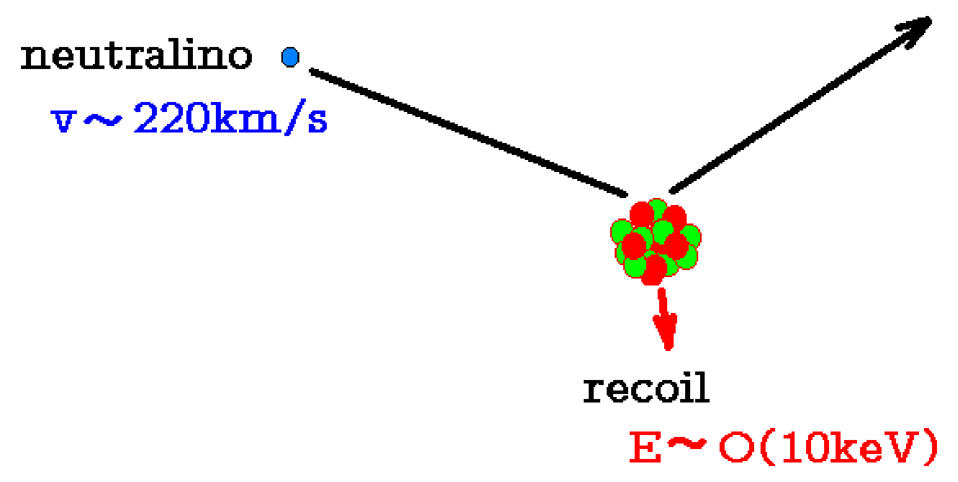
INDIRECT searches

$$\chi\chi \rightarrow WW, ZZ, \gamma\gamma \rightarrow e^{-}, p^{-}, d^{-}, \gamma, \upsilon, \ldots$$

BESS, GLAST, AMS, SK, AMANDA, MACRO, . . .

DIRECT searches

Nuclear recoil detection



Direct detection, relevant parameters

- Event rate

SUSY

$$R \sim \sigma_{\chi-\mathrm{N}} \times n\langle v\rangle \propto \sigma_{\chi-\mathrm{N}} \times \left(\frac{\rho}{M_\chi}\right) \times \int v\, f(v)\, dv$$

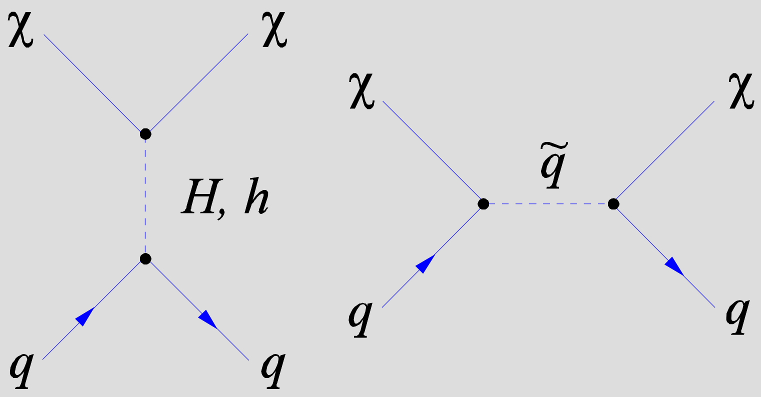
$$\rho(r) = \frac{\rho_0}{1 + r^2/r_0^2}$$

Isothermal Halo Model

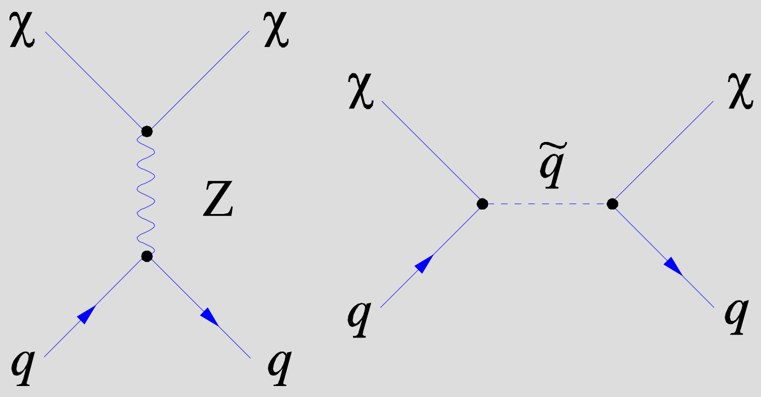
$$f(\vec{v}) = \frac{1}{\pi^{3/2} v_0^3} e^{-|\vec{v}|^2/v_0^2}$$

Cross section

- $\sigma_{\chi-N}$ depends fundamentally on the χ–quark interaction strength.
  - Spin–independent (SI): H, h, squark exchange
  - Spin–dependent (SD): Z, squark exchange



SI interaction



SD interaction

Spin Independent and Spin Dependent cross sections

- Cross Section

$$\sigma_{\chi-\mathrm{N}} = \sigma^{\mathrm{SI}}_{\chi-\mathrm{N}} + \sigma^{\mathrm{SD}}_{\chi-\mathrm{N}}$$

  - SI interaction

$$\sigma^{\mathrm{SI}}_{\chi-\mathrm{N}} \simeq A^2 \frac{\mu^2_{\chi-\mathrm{N}}}{\mu^2_{\chi-\mathrm{p}}} \sigma^{\mathrm{SI}}_{\chi-\mathrm{n}}$$

A : mass number

μ : reduced mass

  - SD interaction

$$\sigma^{\mathrm{SD}}_{\chi-\mathrm{N}} = \frac{\lambda^2 J(J+1)}{0.75} \frac{\mu^2_{\chi-\mathrm{N}}}{\mu^2_{\chi-\mathrm{p}}} \sigma^{\mathrm{SD}}_{\chi-\mathrm{p}}$$

λ : Landé factor

J : total spin of the nucleus

• SD Cross Section

- conventional approximation
  using the odd-group model in which
  the contribution of either proton or neutron is considered.

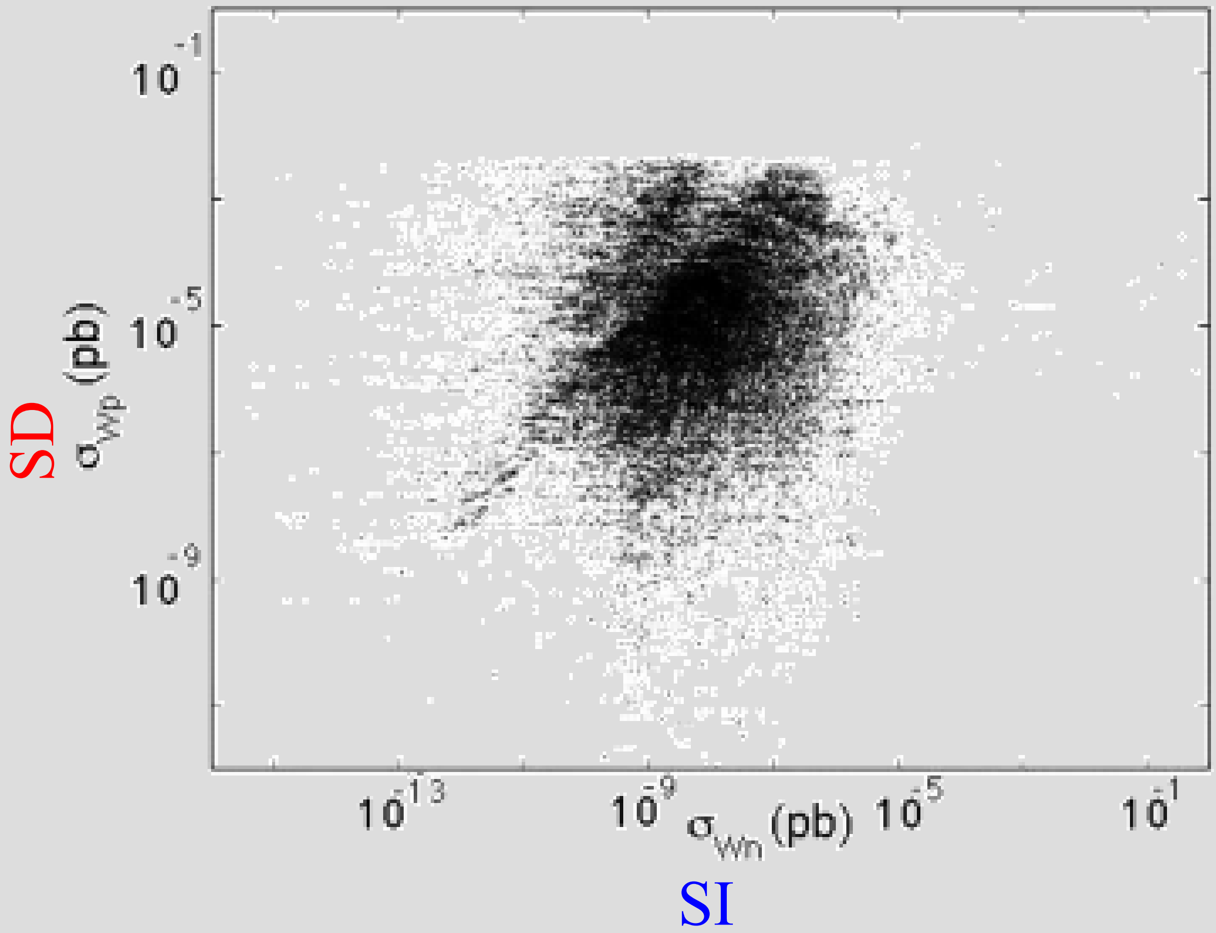
$$\sigma^{\mathrm{SD}}_{\chi-\mathrm{N}} = \frac{\lambda^2 J(J+1)}{0.75} \frac{\mu^2_{\chi-\mathrm{N}}}{\mu^2_{\chi-\mathrm{p}}} \sigma^{\mathrm{SD}}_{\chi-\mathrm{p}}$$

Isotope	unpaired	abundance	$\lambda^2 J(J+1)$
^{7}Li	p	92.5%	0.411
^{19}F	p	100%	0.647
^{23}Na	p	100%	0.041
^{73}Ge	n	7.8%	0.065
^{127}I	p	100%	0.023

→ LiF for SD

(odd-group model)

Spin Dependent (SD)
and
Spin Independent (SI)



$$\frac{\sigma^{\mathrm{SD}}_{\chi-p}}{\sigma^{\mathrm{SI}}_{\chi-n}}$$

can be as large as

$$10^3 \sim 10^4$$

Fig. 10 of J. I. Collar et al, New J. of Phys. 2 (2000) 14.1

- Expected energy spectra

$$\frac{dR}{dE_R} = c_1 \frac{R_0}{E_0 r} e^{-c_2 E_R / E_0 r} \quad \text{[count/keV/kg/day]}$$

$$R_0 = \frac{361}{M_\chi M_N} \left(\frac{\sigma_{\chi-N}}{1\text{pb}} \right) \left(\frac{\rho_D}{0.3\text{GeVcm}^{-3}} \right) \left(\frac{v_0}{230\text{km/s}} \right) \quad \text{[count/kg/day]}$$

R : countrate

E_R : recoil energy

c_1, c_2 : const

E_0 : kinetic energy of DM

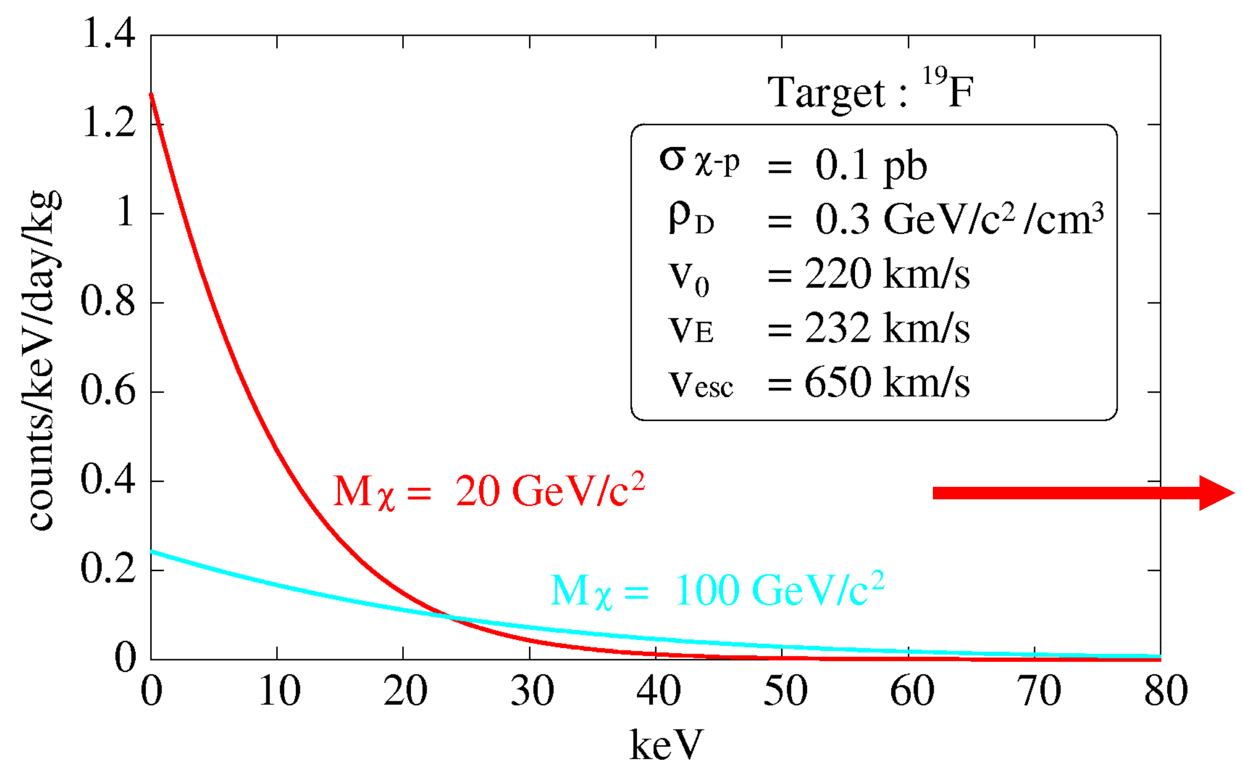
v_0 : DM velocity

M_χ : DM mass

M_N : target mass

$$r = \frac{4 M_\chi M_N}{(M_\chi + M_N)^2}$$

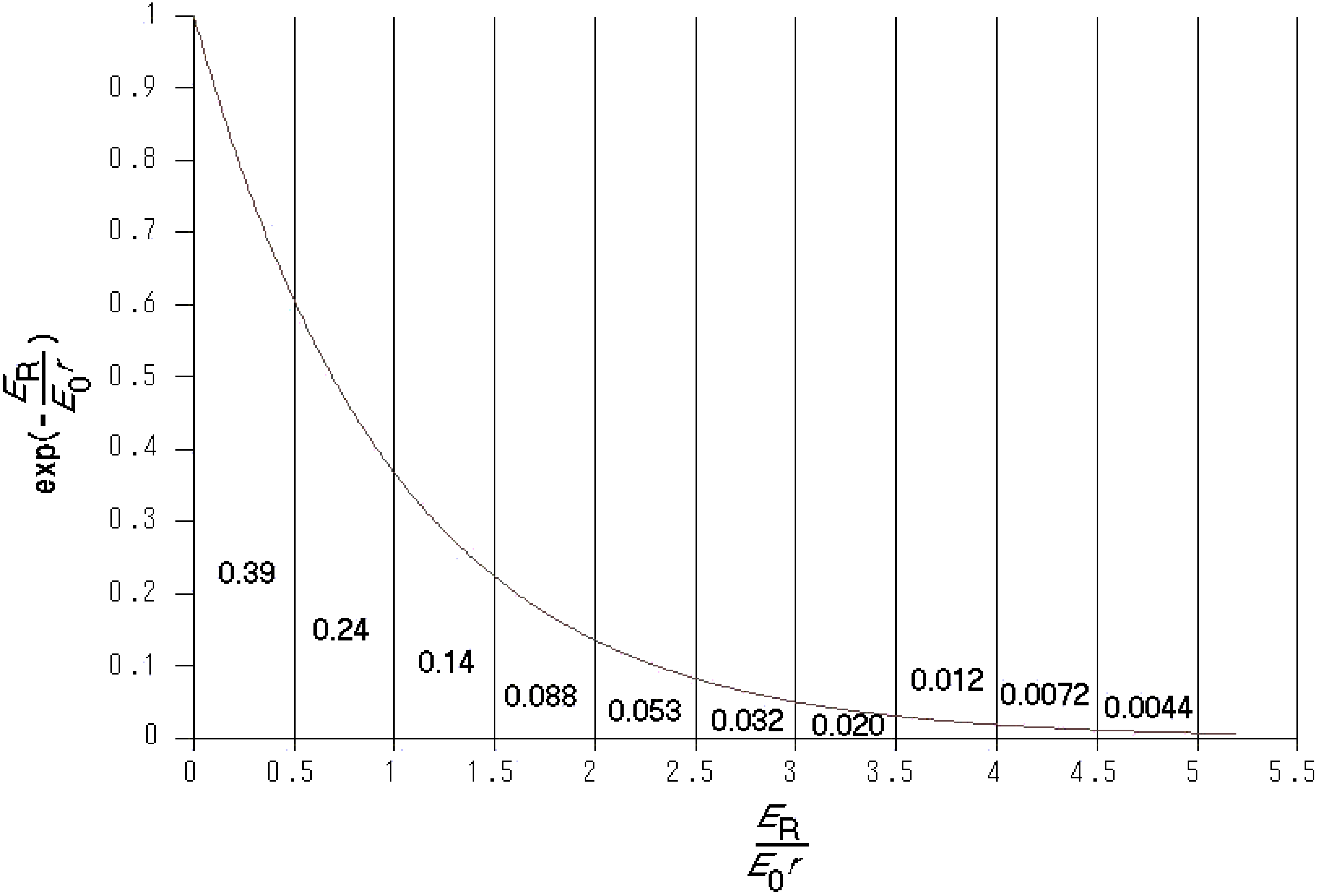
ρ_D : DM density



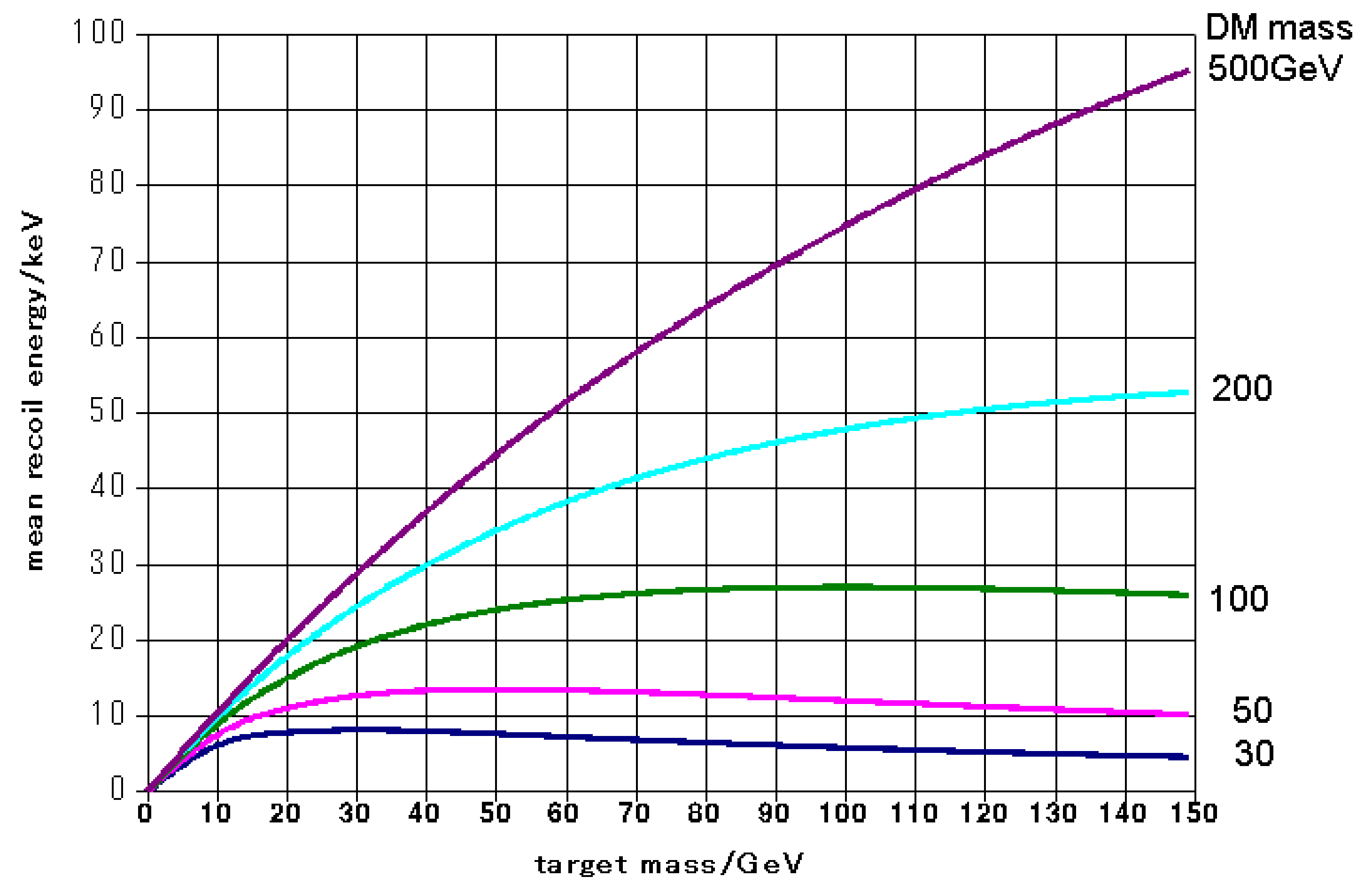
low threshold and low BG are required

$$E_0 = \frac{1}{2} M_\chi v_0^2 \qquad r = \frac{(4MM_{\mathrm{N}})}{(M+M_{\mathrm{N}})^2} \qquad E_0 r = 10 \text{ keV}$$

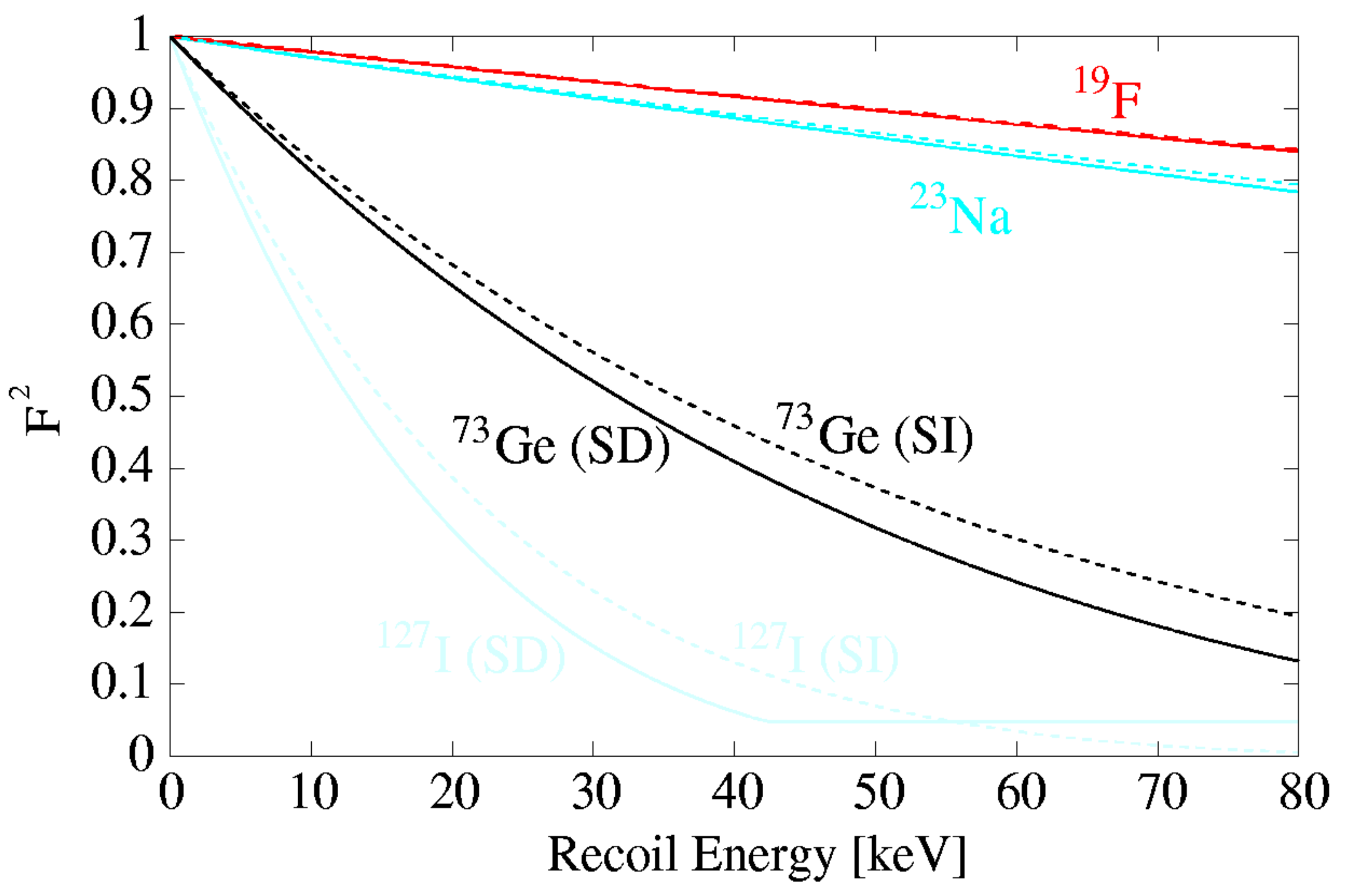
for M=50GeV and A=19



Mean recoil energy $E_o r$ vs target mass



Nuclear form factor



Running experiments and projects (not complete)

Bolometers

- CDMS(Ge/Si)
- Tokyo(LiF/NaF)
- CRESST(Al_2O_3)

Scintillators/semiconductors

- DAMA(NaI, CaF_2, LXe)
- UK(NaI)
- HDMS(Ge), GENIUS(Ge)
- Osaka(CaF_2)
- XMASS(LXe)

Quenching factor

$$q = \frac{E_{\text{visible}}}{E_{\text{R}}}$$

- q < 1 for scintillators and semiconductors

  0.3 (Na), 0.09 (I)
  0.25 (Ge)
  0.46 (LXe)

  → low effective threshold

- q = 1 for bolometers

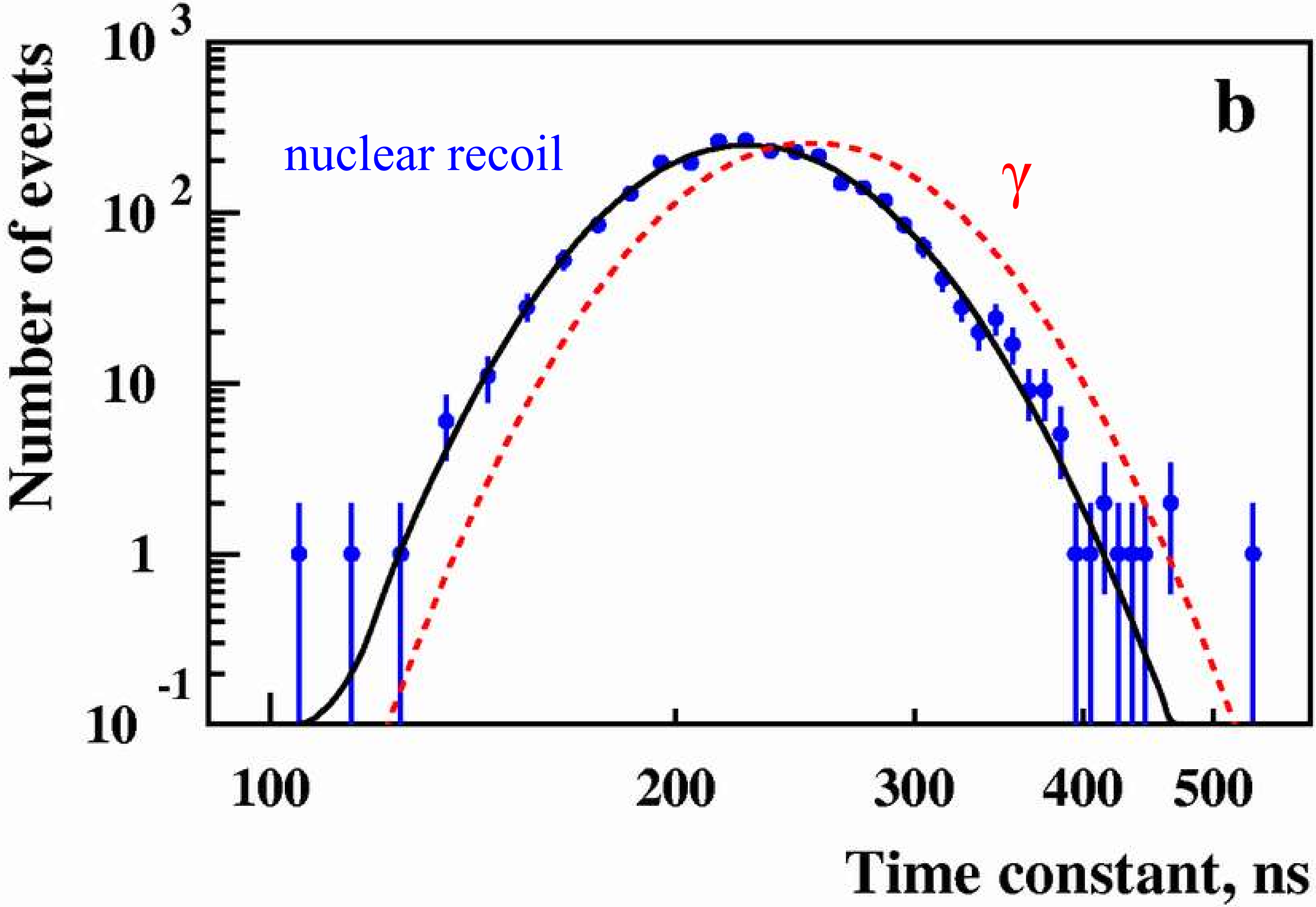
Techniques for **DM** detection

- Pulse shape discrimination/analysis PSD/PSA (e/γ - nuclear recoil separation)
- Bolometry (q = 1)
- Phonon–ionization simultaneous measurement (e/γ – nuclear recoil separation)

- Annual modulation
- Direction sensitive detection
- Bubble chamber (!)
- Background shields

PSD/PSA (NaI(Tl))

B. Ahmed, et al., Astropart. Phys. 19 (2003) 691.



6-8 keV

Statistical subtraction

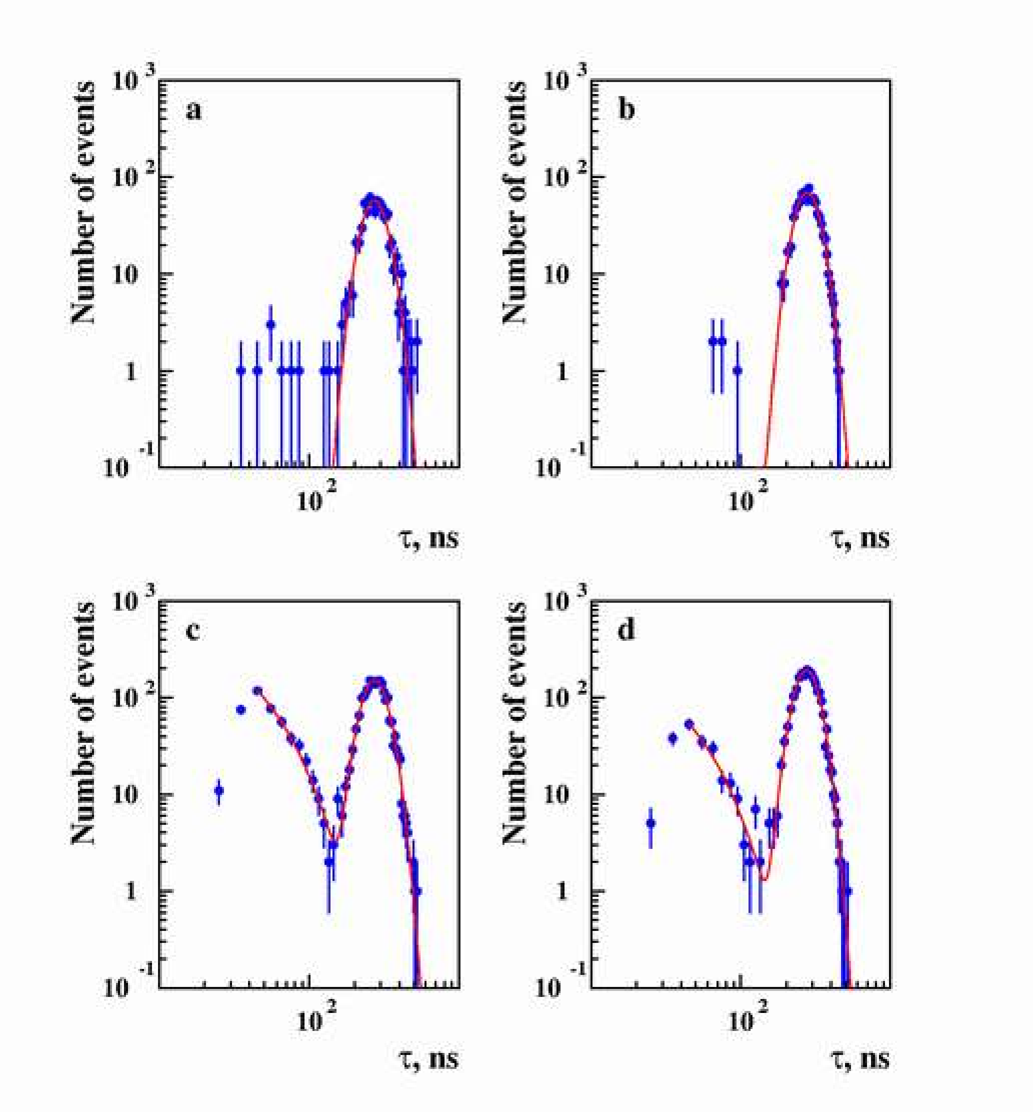
B. Ahmed, et al., Astropart. Phys. 19 (2003) 691.

6 – 7 keV

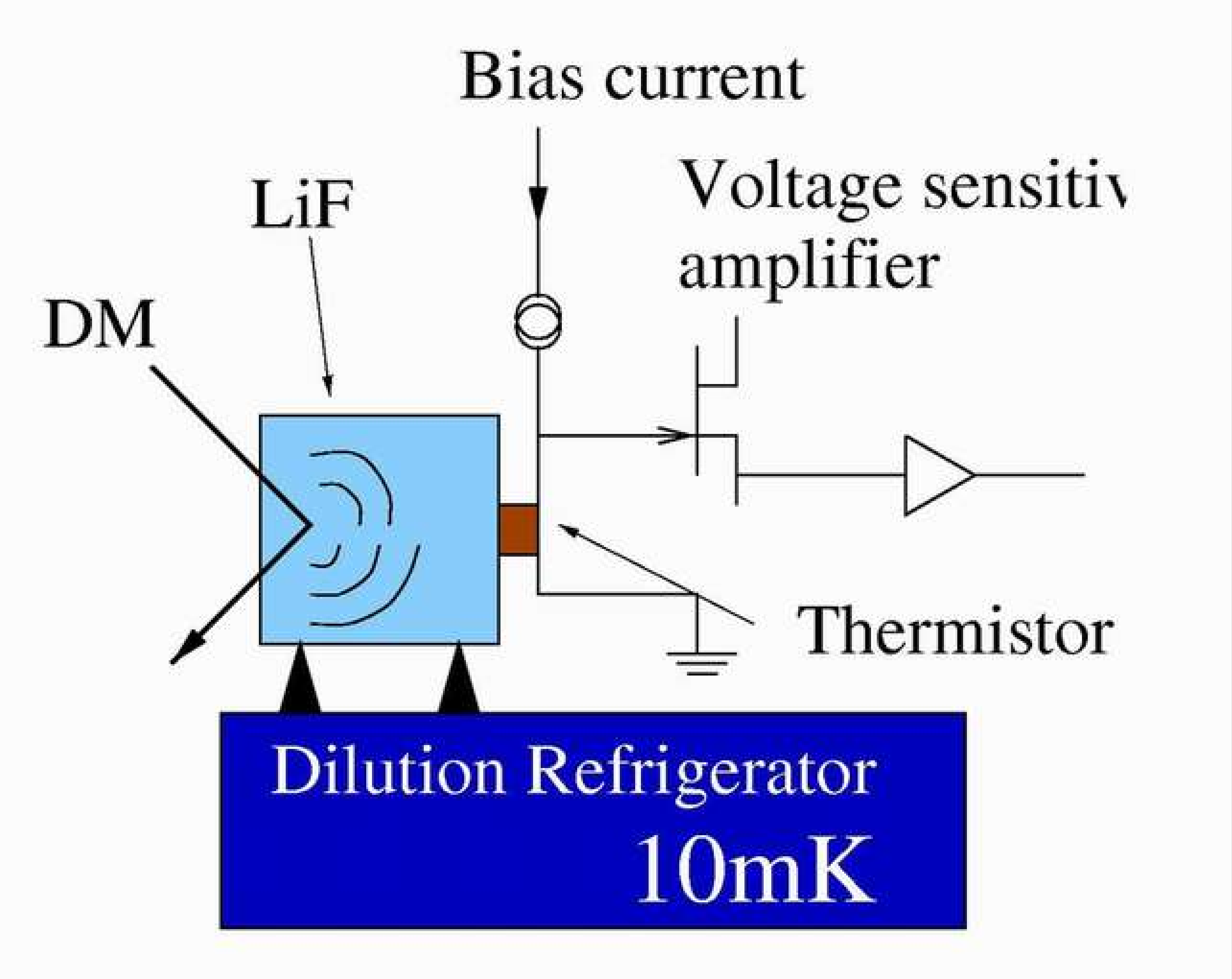
7 – 8 kev

γ-calibration

real data



Bolometer

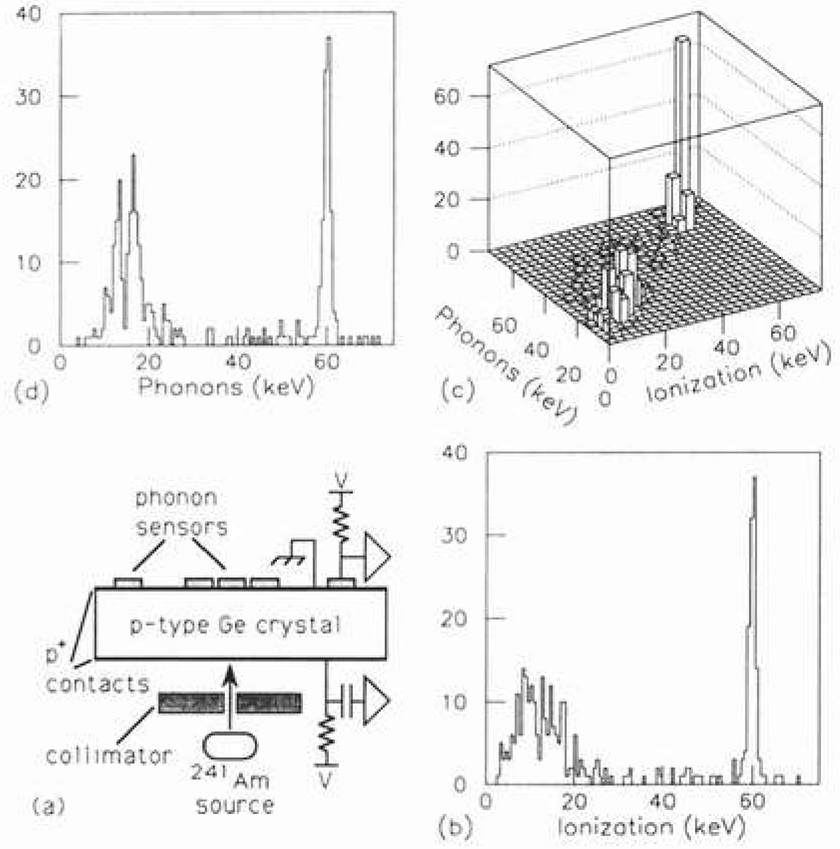


Specific heat:

$$C \propto \left(\frac{T}{\Theta_D} \right)^3$$

Θ_D : Debye temperature

Phonon – ionization simultaneous measurement



T. Shutt et. al.,
Phys. Rev. Lett. 69 (1992) 3531

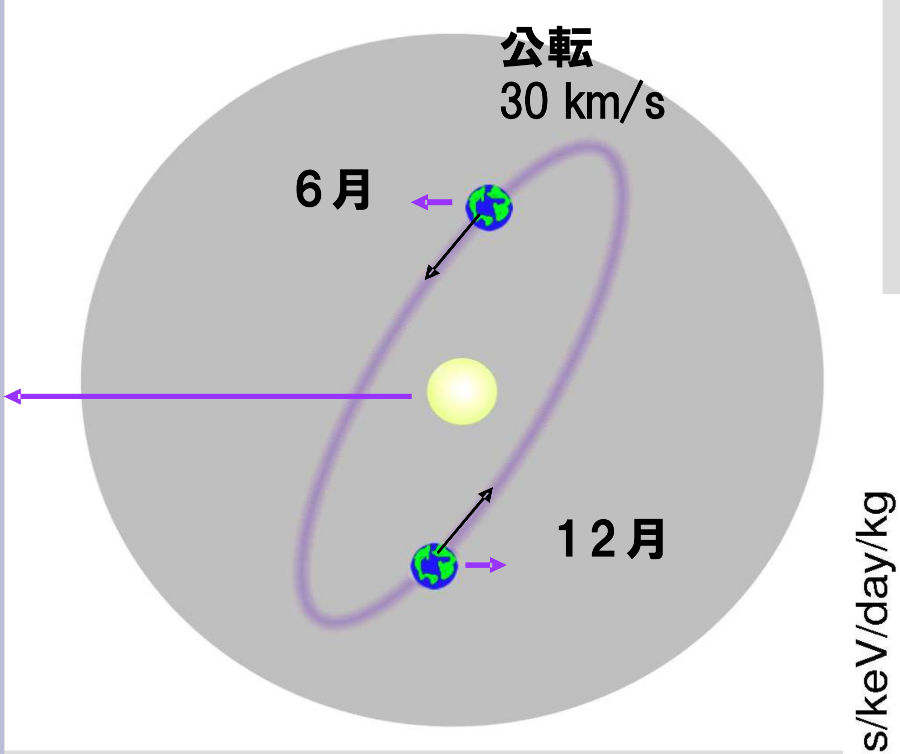
Same response to e/γ

but

to nuclear recoil,
$q = 1$ for phonon
$q = 0.25$ for ioninzation

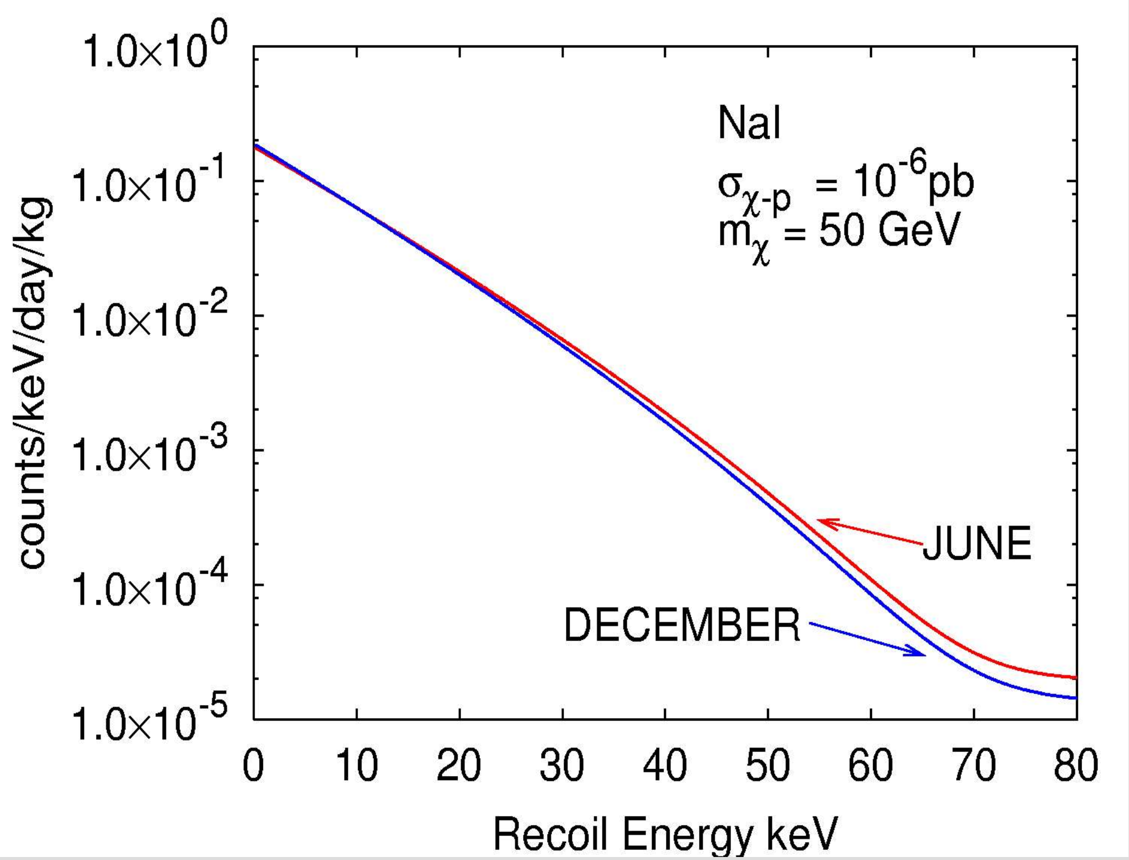
e/ γ - nuclear recoil separation

Annual modulation

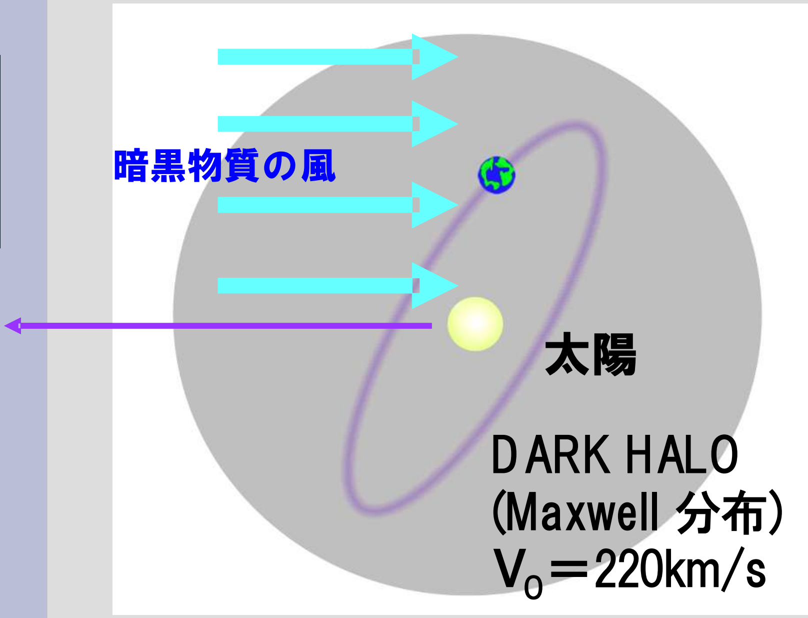


$$\vec{v}_{\mathrm{E}} = \vec{v}_{\mathrm{SUN}} + \vec{v}_{\mathrm{ES}}$$

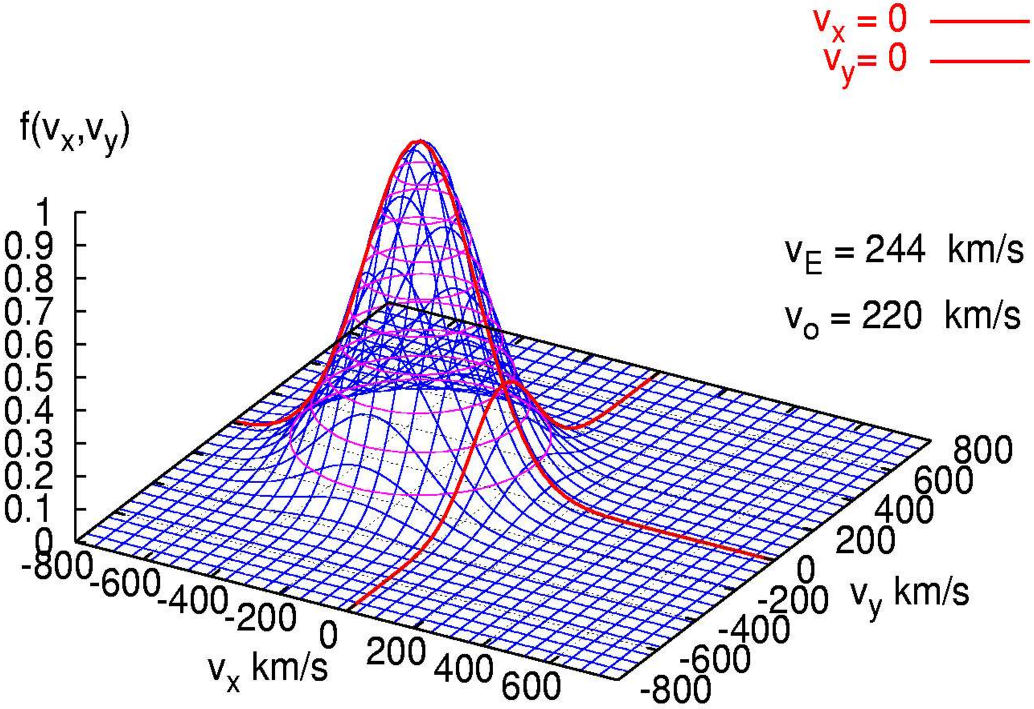
Only a few % effect

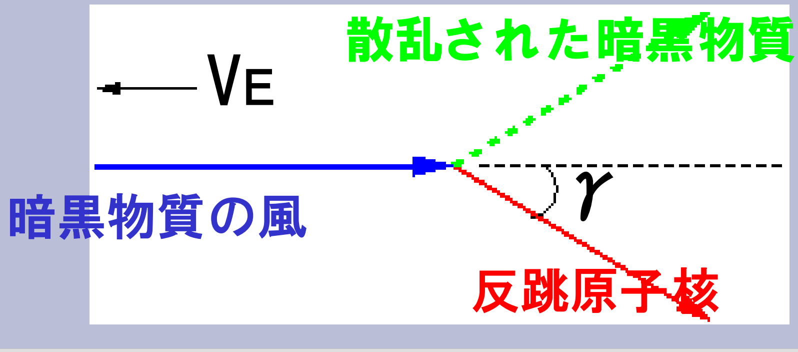


Direction sensitive detection



Strong DM wind





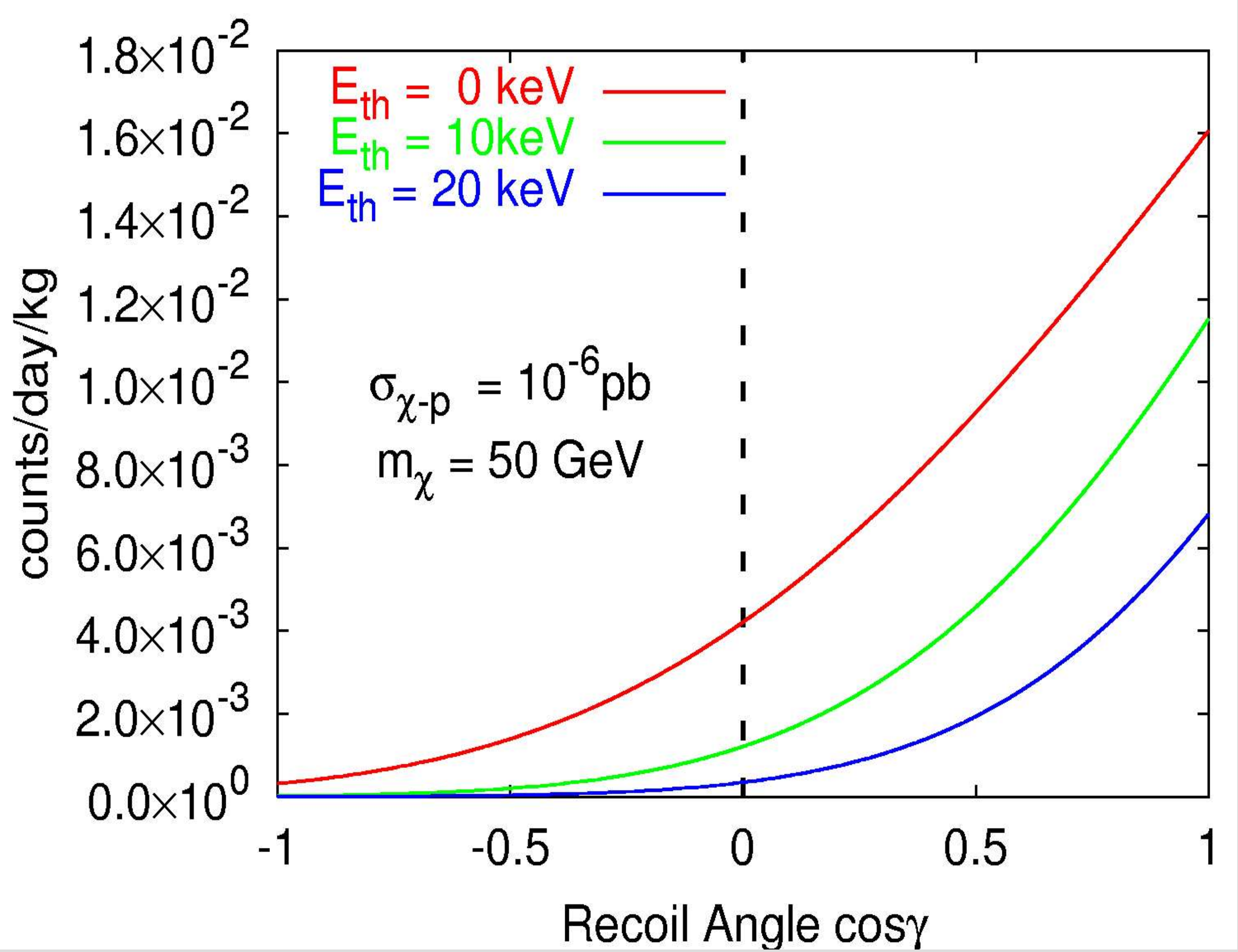
VE

散乱された暗黒物質

暗黒物質の風

γ

反跳原子核

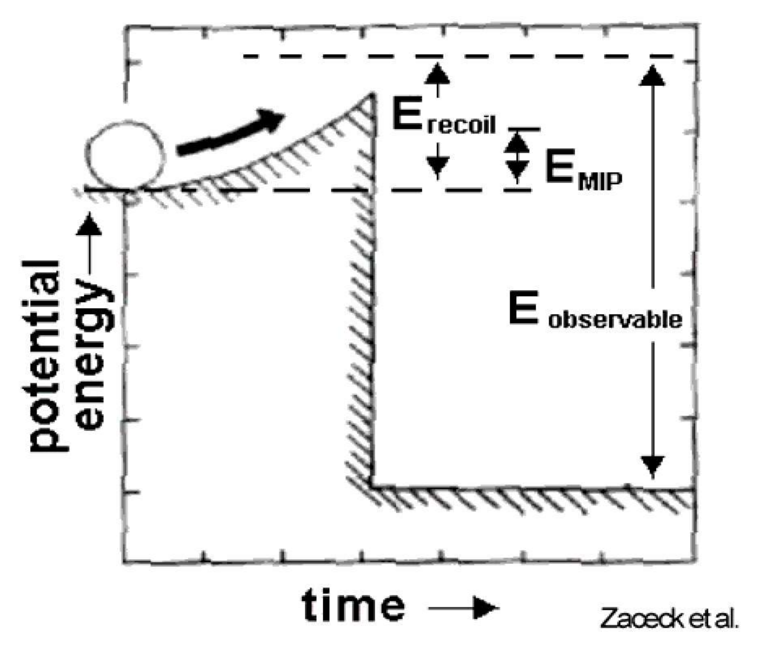


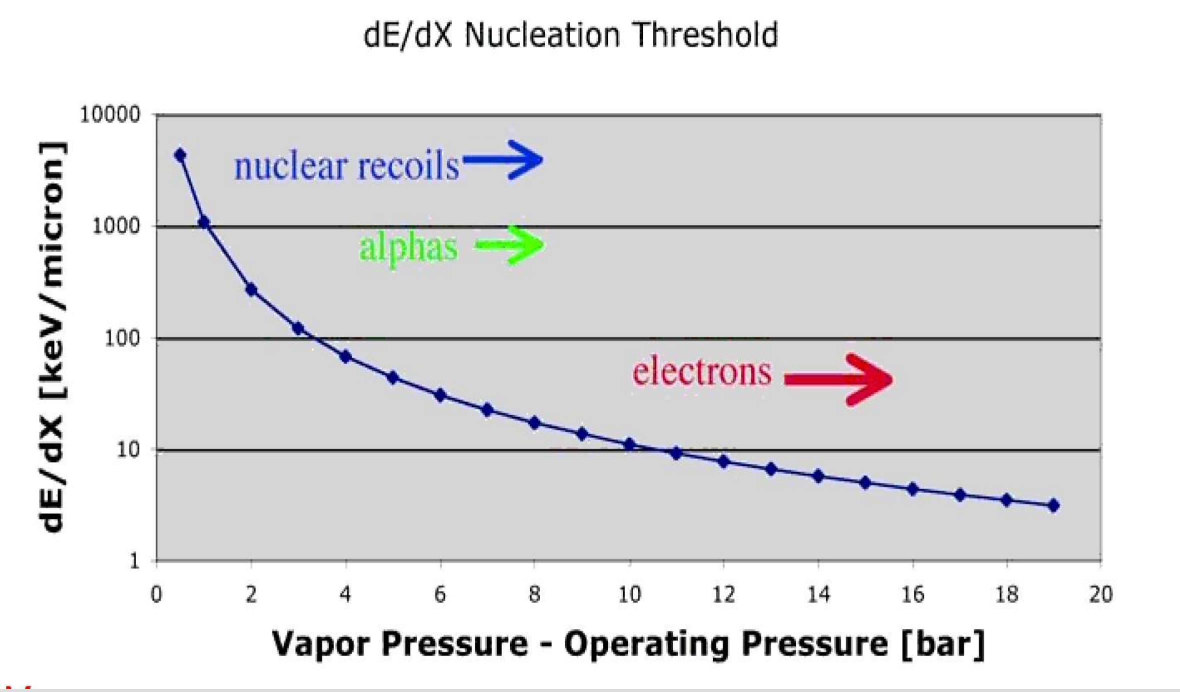
Heavy liquid bubble chamber

J. I. Collar/U. Chicago

CF_3Br / CF_3I heavy liquid bubble chamber

Total insensitivity to Minimum Ionizing Particles, yet sensitive to low-energy nuclear recoils (tunable dE/dx and E-threshold)





Background shields

- Oxygen Free High Conductivity Copper (OFHC)
- Old-age(archaeological) lead

$$T_{1/2}(^{210}\mathrm{Pb}) \sim 20\ \mathrm{years}$$

- Pure water
- Active self shielding → fiducial volume
- Radon purge

Tokyo Group (Minowa)

- Bolometer experiments (SD-sensitive)
  - Pilot run LiF Nokogiriyama(~15m.w.e.) ~1999
  - Results LiF/NaF Kamioka(~2700m.w.e.) ~2003
- R&D, direction sensitive scintillators 2003~
  - Pilot run stilbene Kamioka

Bolombeter SD limits in a_p and a_n

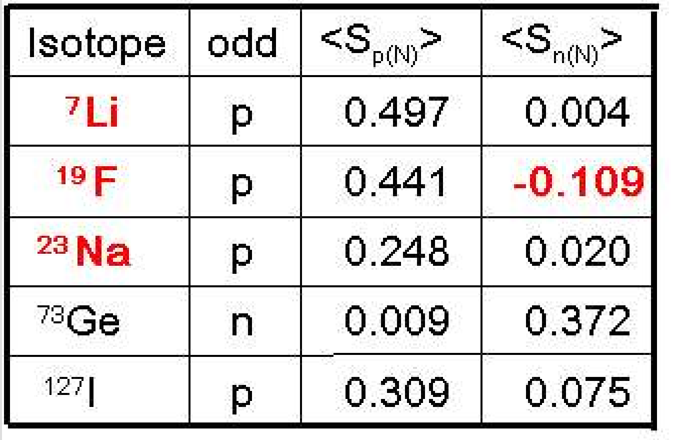
$$\sigma^{\mathrm{SD}}_{\chi-\mathrm{N}} = \frac{\lambda^2 J(J+1)}{0.75} \frac{\mu^2_{\chi-\mathrm{N}}}{\mu^2_{\chi-\mathrm{p}}} \sigma^{\mathrm{SD}}_{\chi-\mathrm{p}} = 4 G_{\mathrm{F}}^2 \mu^2_{\chi-\mathrm{N}} C^{\mathrm{SD}}_{\mathrm{N}}$$

$$C^{\mathrm{SD}}_{\mathrm{N}} \propto \left(a_{\mathrm{p}} \langle S_{\mathrm{p(N)}} \rangle + a_{\mathrm{n}} \langle S_{\mathrm{n(N)}} \rangle\right)^2 \frac{J+1}{J}$$

$a_{\mathrm{p}},\ a_{\mathrm{n}}$: χ - nucleon couplings

$\langle S_{\mathrm{p(N)}} \rangle,\ \langle S_{\mathrm{n(N)}} \rangle$: expectation values of p, n spin in N

$\langle S_{p(N)} \rangle$ and $\langle S_{n(N)} \rangle$



Isotope	odd	$\langle S_{p(N)} \rangle$	$\langle S_{n(N)} \rangle$
^{7}Li	p	0.497	0.004
^{19}F	p	0.441	**-0.109**
^{23}Na	p	0.248	0.020
^{73}Ge	n	0.009	0.372
^{127}I	p	0.309	0.075

For a_p , a_n determination,

- ^{19}F is complementary to ^{23}Na, ^{73}Ge, ^{127}I due to opposite sign of $\langle S_{p(N)} \rangle / \langle S_{n(N)} \rangle$

- NaF is more sensitive to a_n than LiF.

SD limits in a_p and a_n

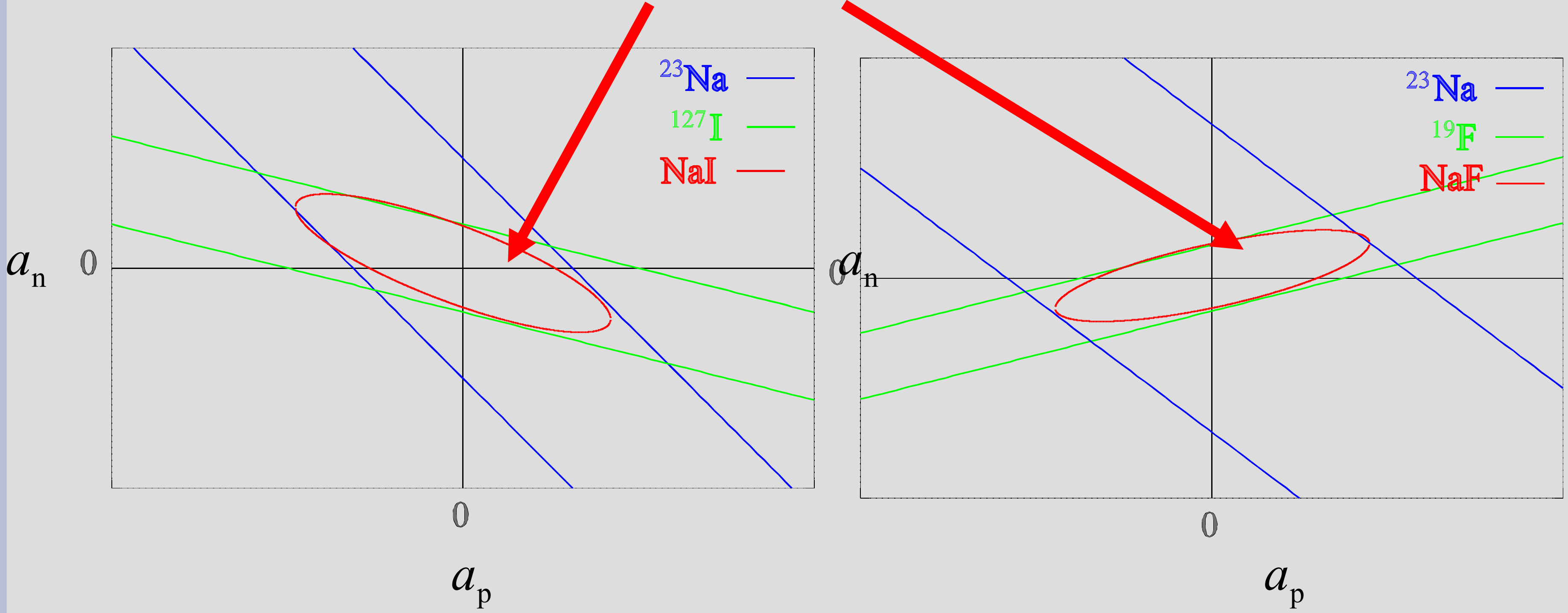
- $\langle S_{p(N)} \rangle / \langle S_{n(N)} \rangle > 0$

e.g. $N_i = {}^{23}\mathrm{Na},\ {}^{127}\mathrm{I}$

COMPLEMENTARY

- $\langle S_{p(N)} \rangle / \langle S_{n(N)} \rangle < 0$

e.g. $N_i = {}^{19}\mathrm{F}$

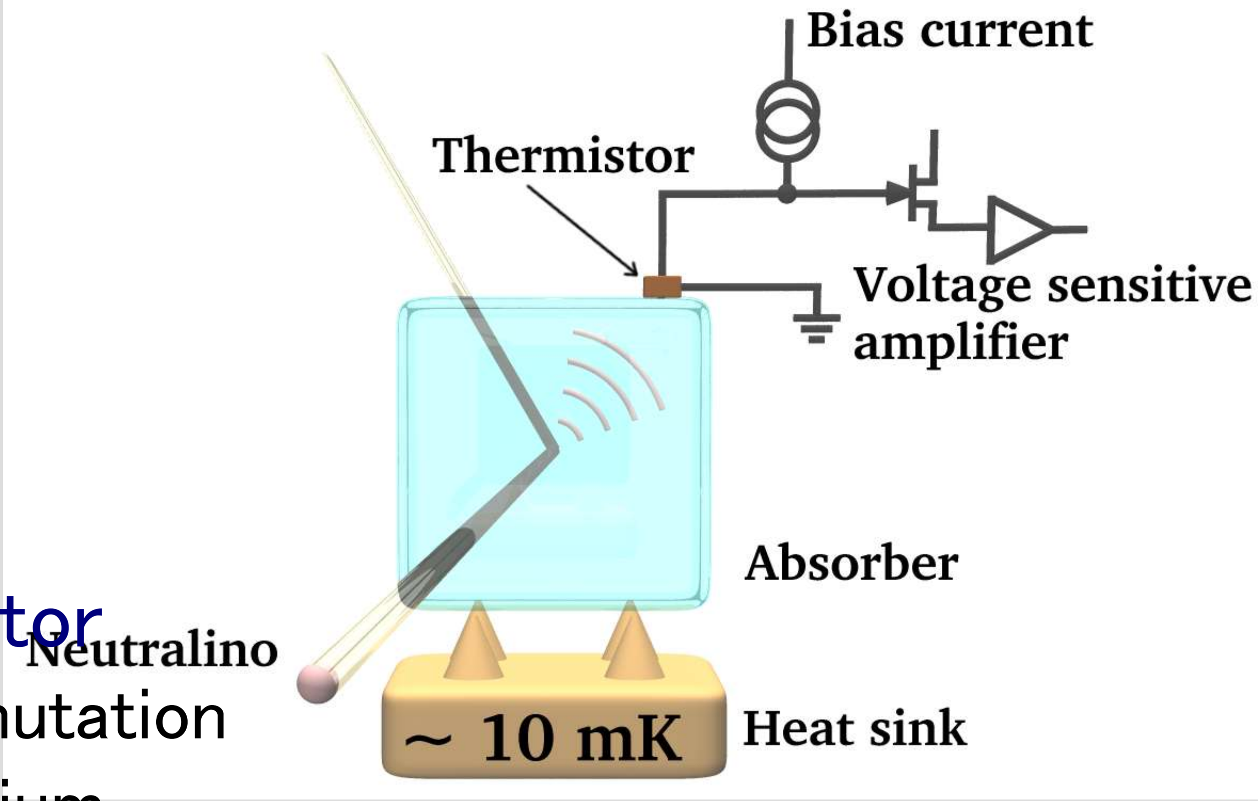


Detector

- Bolometer
  - Wide choice of target
  - High resolution
  - Low threshold
  - No quenching

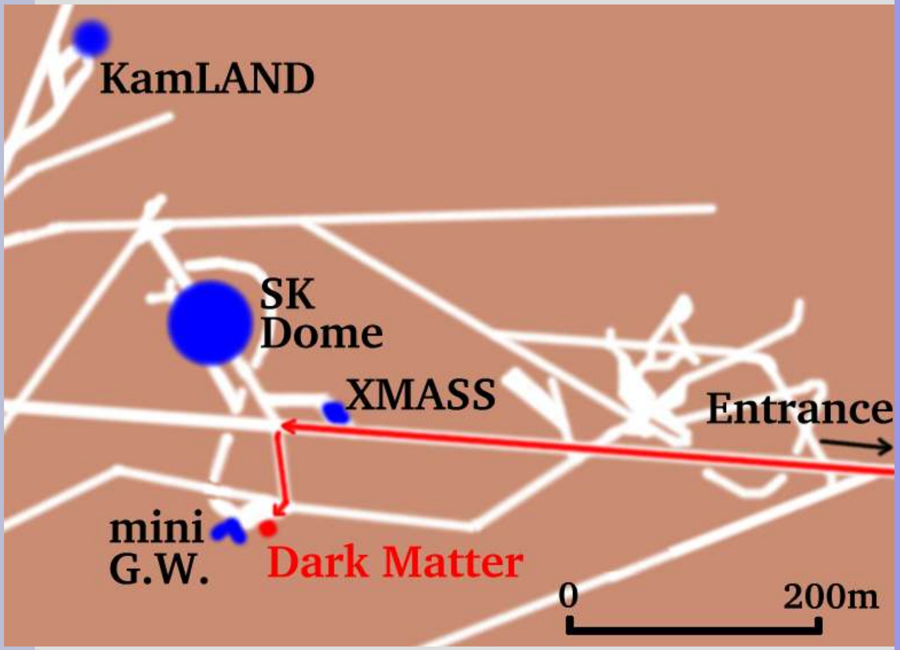
$(E_{\text{visible}} = E_{\text{recoil}})$

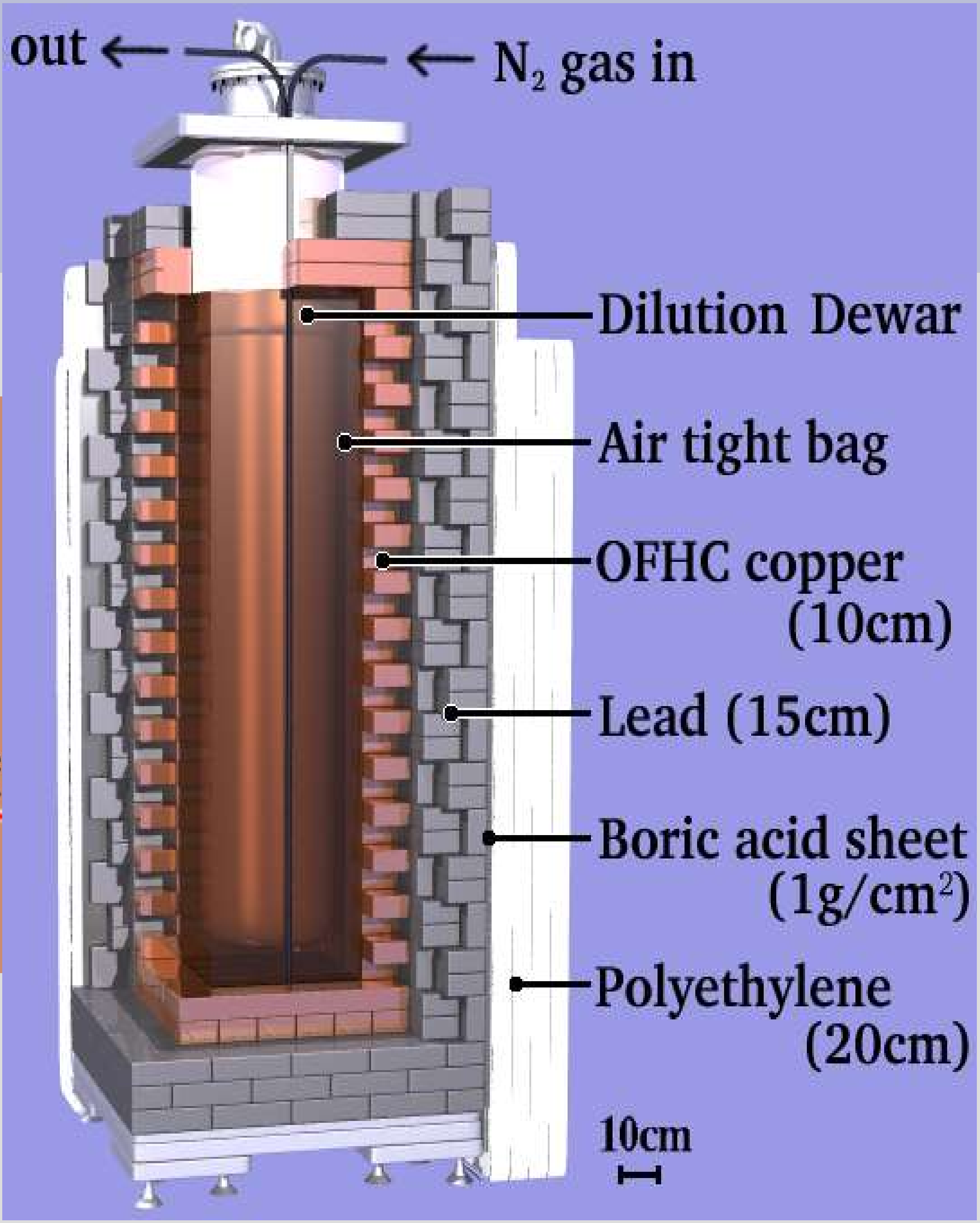
- NTD Ge thermistor
  - Neutron Transmutation Doped Germanium



Schematic drawing of a bolometer

- Set Up
  - Outer Shields





- set at **Kamioka Observatory** (~2700m.w.e.)

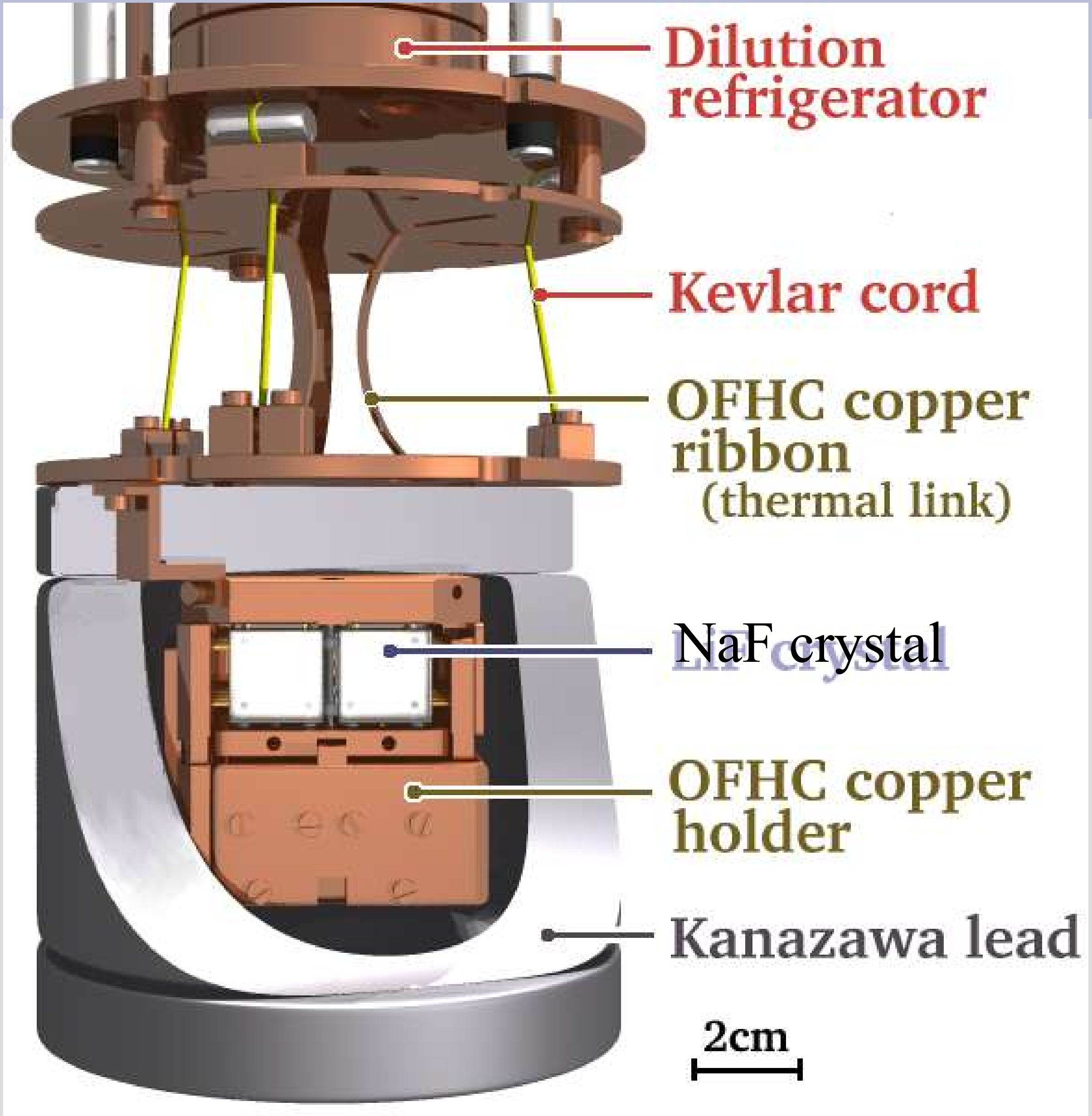
- Inner Shield
-

old lead (>400yrs.)
from a wrecked ship.

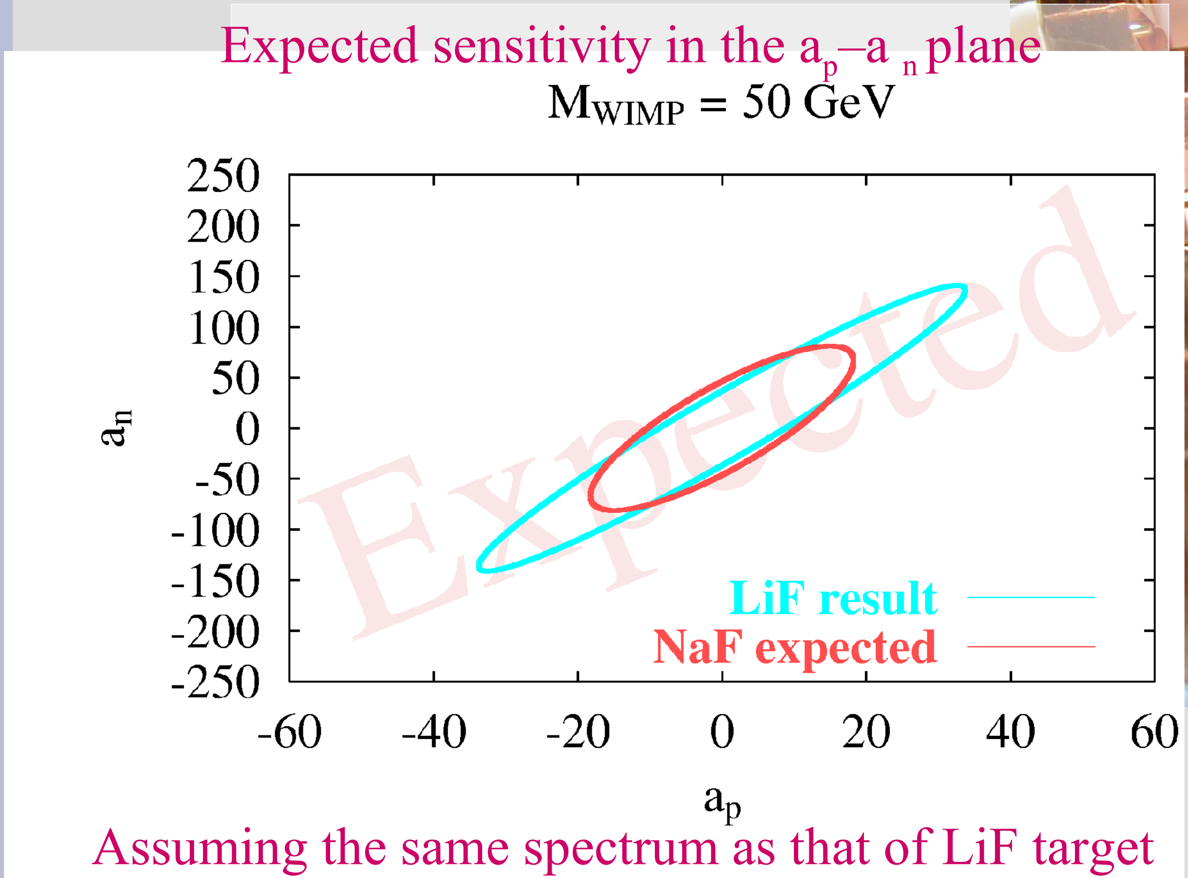
21 Pb < 2.0 Bq/kg
0

suspending it
with kevlar cords.

→ vibration noise reduction



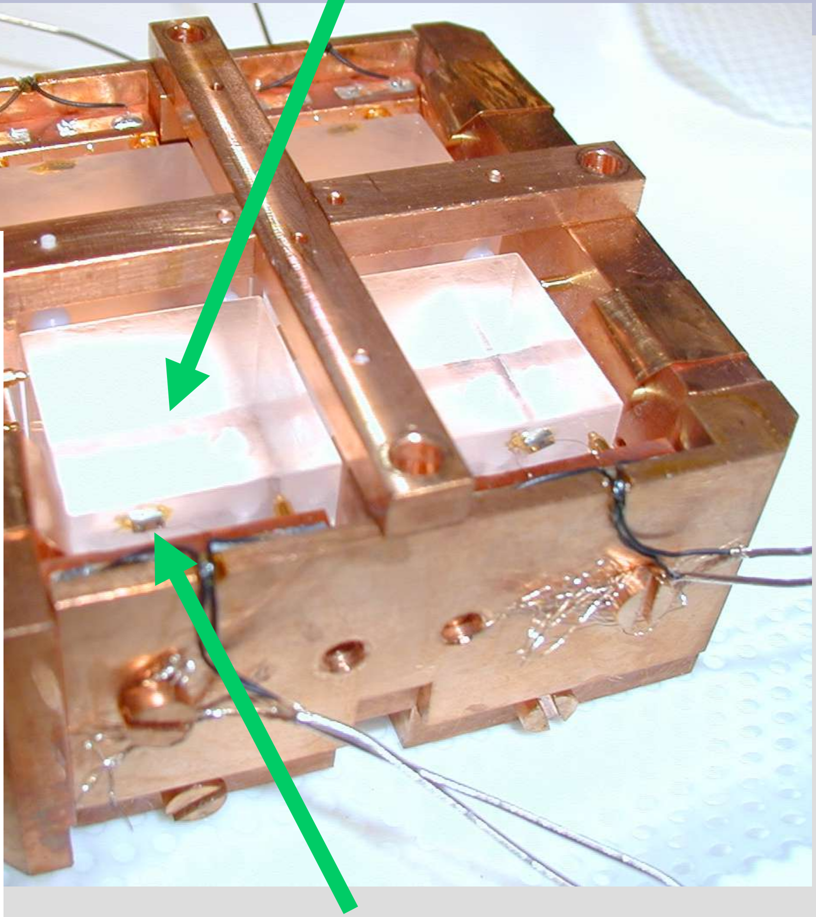
- NaF Bolometer Array
  - 8pcs × 22g NaF crystals ($2 \times 2 \times 2$ cm^3)



Expected sensitivity in the a_p–a_n plane

M_{WIMP} = 50 GeV

Assuming the same spectrum as that of LiF target



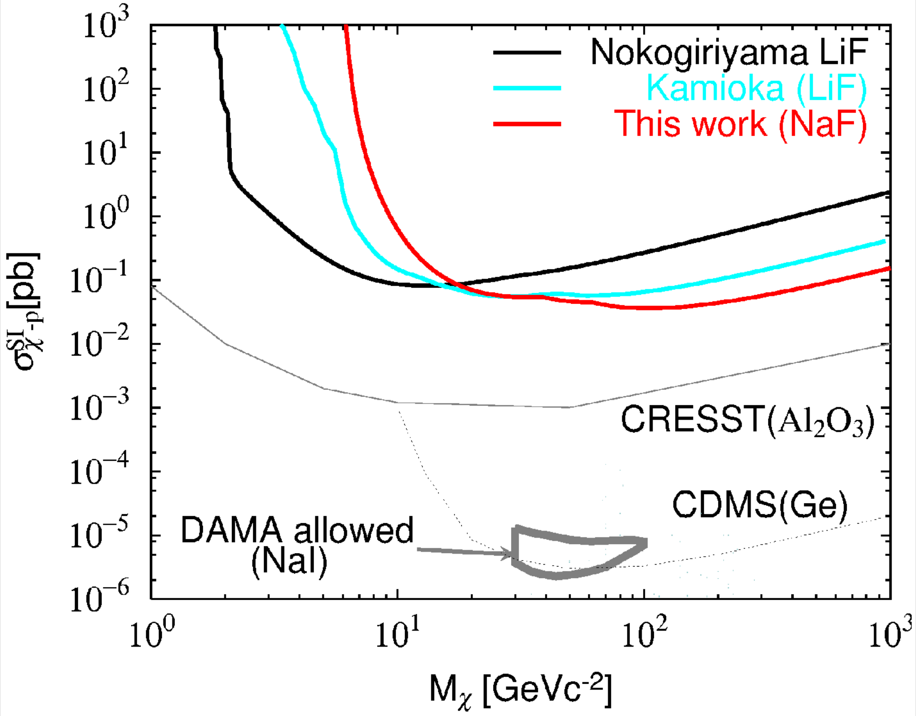
NaF crystal

NTD Ge thermistor

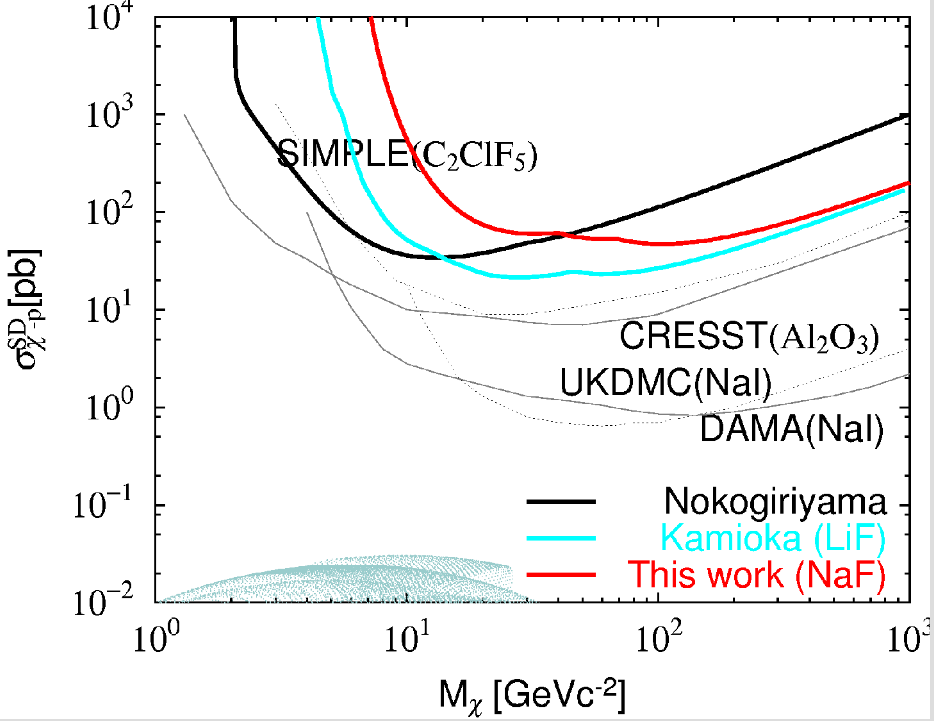
Result (SI and SD $\sigma_{\chi-p}$ limit)

- Assumption : All events are dark matter events

SI



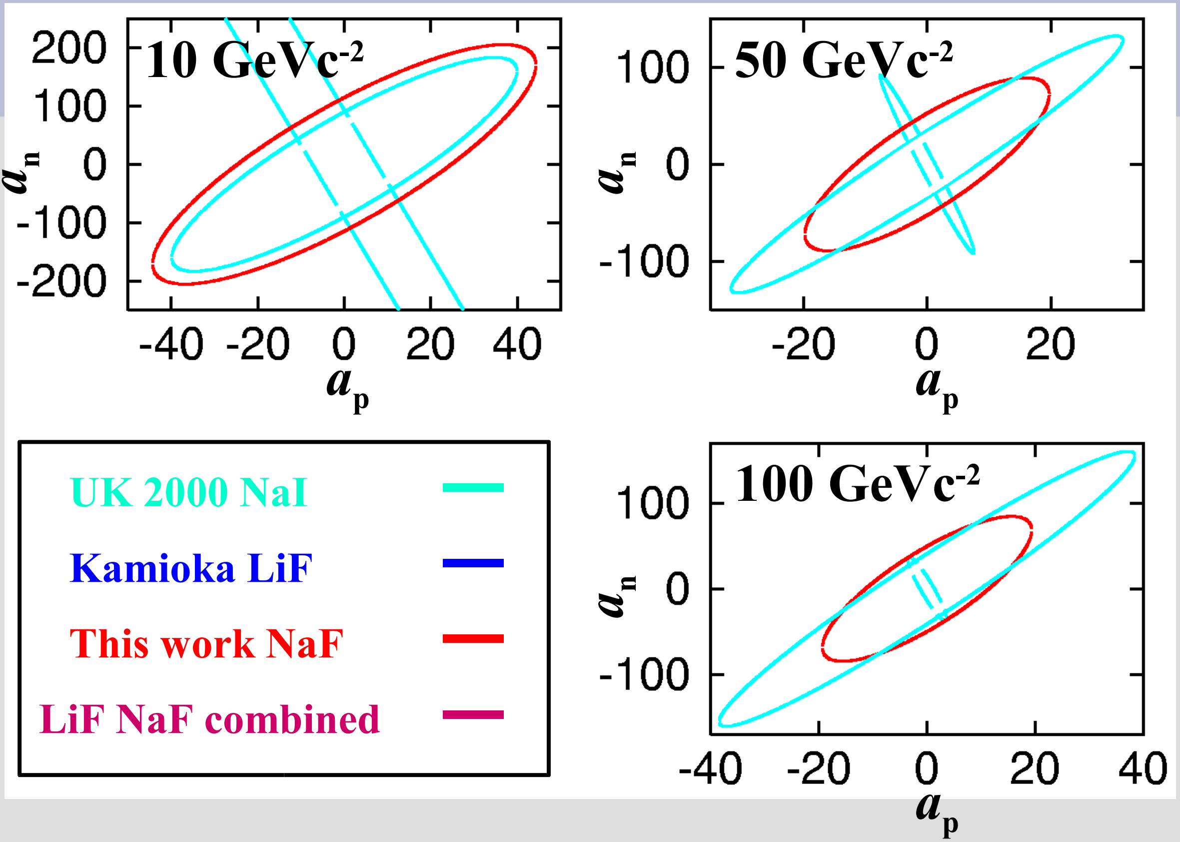
SD

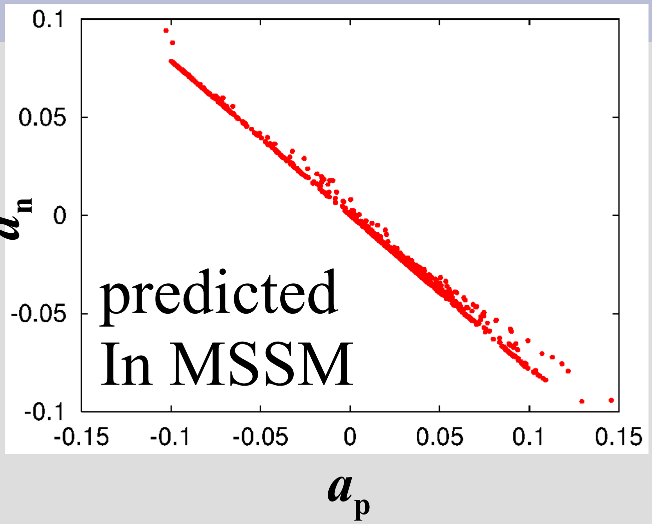


- Best limits (for 103 GeV)

SI : 0.036 pb
SD : 47 pb

Result (SD limits in the a_p–a_n plane)





$\tan\beta = 2, 8$

$10\,\mathrm{GeV} \le M_2 \le 1\,\mathrm{TeV}$

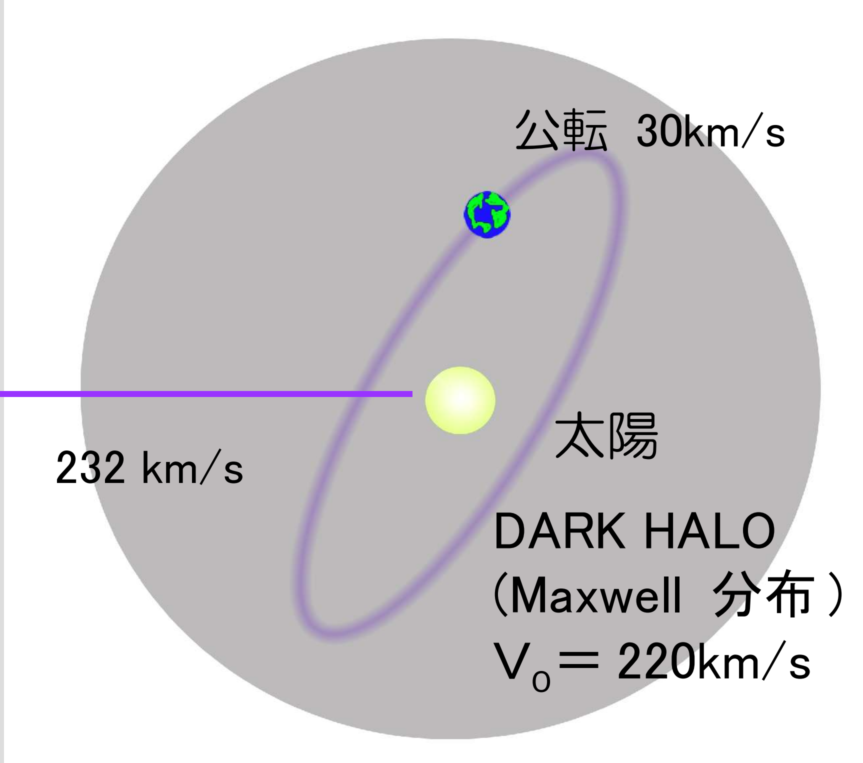
$10\,\mathrm{GeV} \le |\mu| \le 1\,\mathrm{TeV}$

- We **improved LiF limits** in a part of the parameter space.
- Combined limits with the results of LiF are **more stringent than UK2000 limits** for 10, 50 and 100 GeV^{-2}.

Direction sensitive scintillators R&D

銀河中での地球の動き

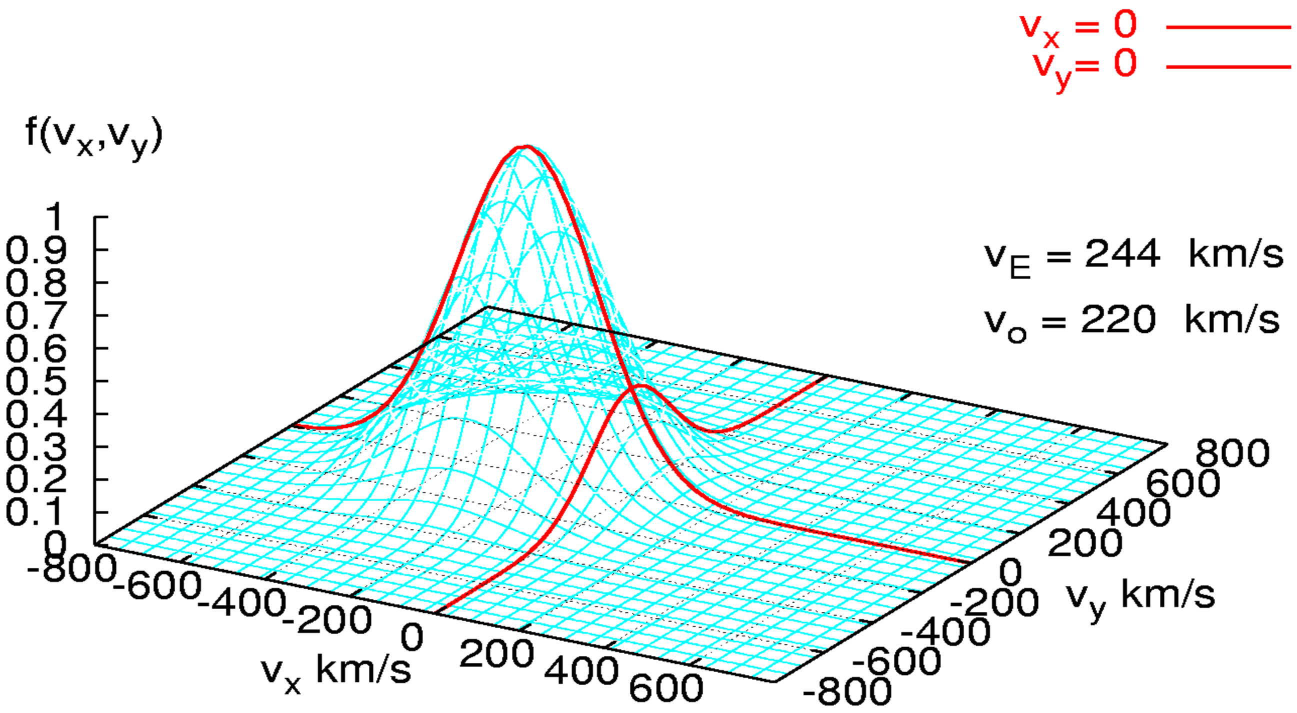
Cygnus



地球の自転 → DMの入射方向の日変化

地球の自転動きが暗黒物質のシグナルを生む

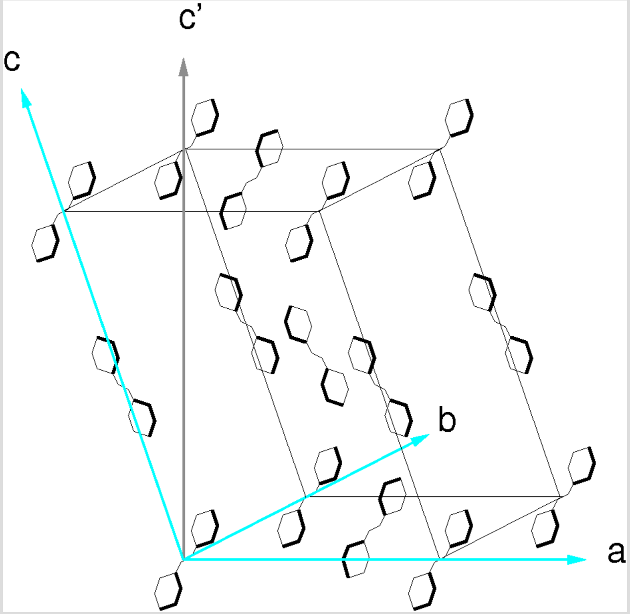
DM wind is fairy strong



スチルベンシンチレーター

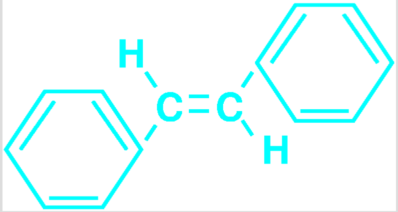
重荷電粒子の入射方向によって発光量が異なる　Z. Phys. 162 (1961) 122

→ 反跳原子核の方向に対する感度が期待される



単斜晶系　単結晶

trans-stilbene

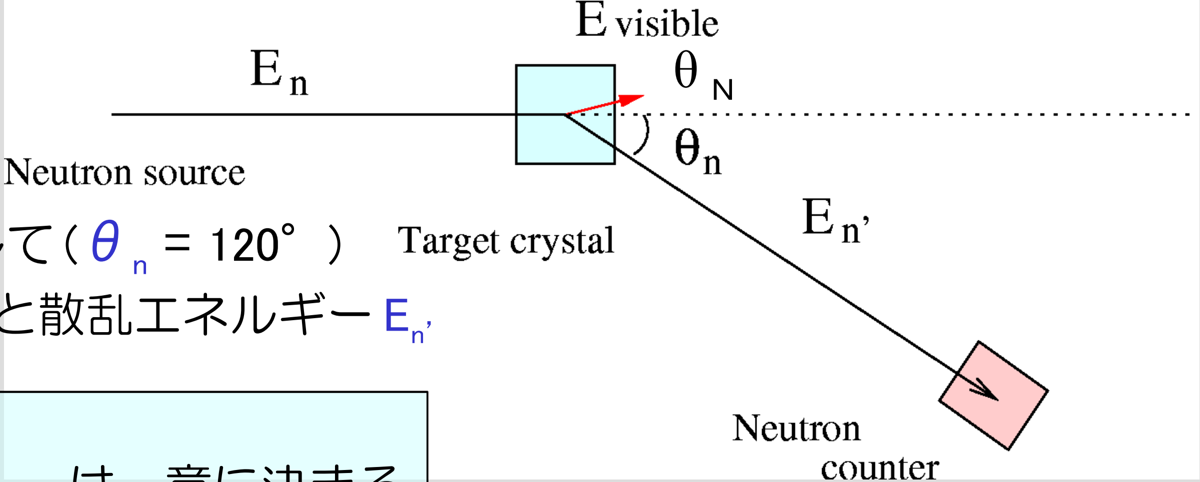


- 発光量　：30% of NaI
- 発光波長：410 nm
- 減衰時間：即発成分 5 ns
- 結晶軸 c' に対する角度により光量異なる

m_χ o(10GeV) の暗黒物質に感度のある低エネルギー（100keV 以下）の炭素反跳について測定を行った

中性子による発光効率測定

炭素反跳測定の原理



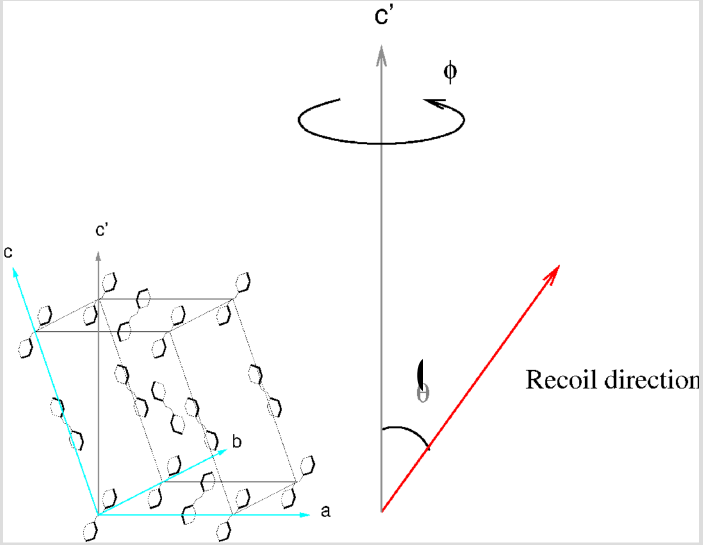
中性子散乱角 θ_n を固定して（$\theta_n = 120°$）
TOF で入射エネルギー E_n と散乱エネルギー $E_{n'}$ を測定

→ 反跳原子核
反跳エネルギー E_R
反跳角 θ_N
は一意に決まる

kinematics
中性子↔ＷＩＭＰ

求めるべきもの

発光効率の c’ 軸に対する反跳角 θ 依存性

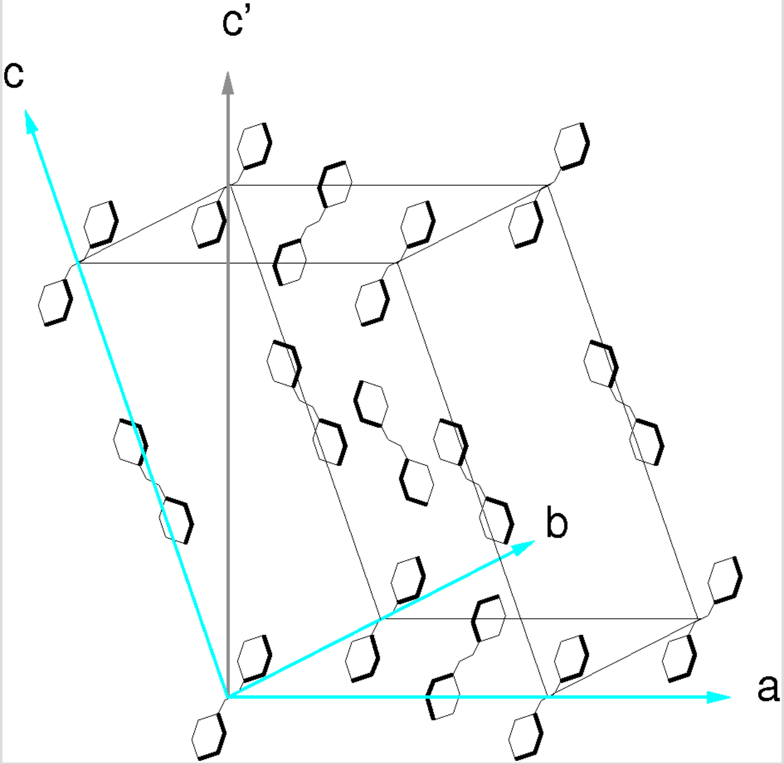


$$\text{Relative efficiency}\quad q(E_R,\theta) = \frac{E_{\text{visible}}}{E_R}$$

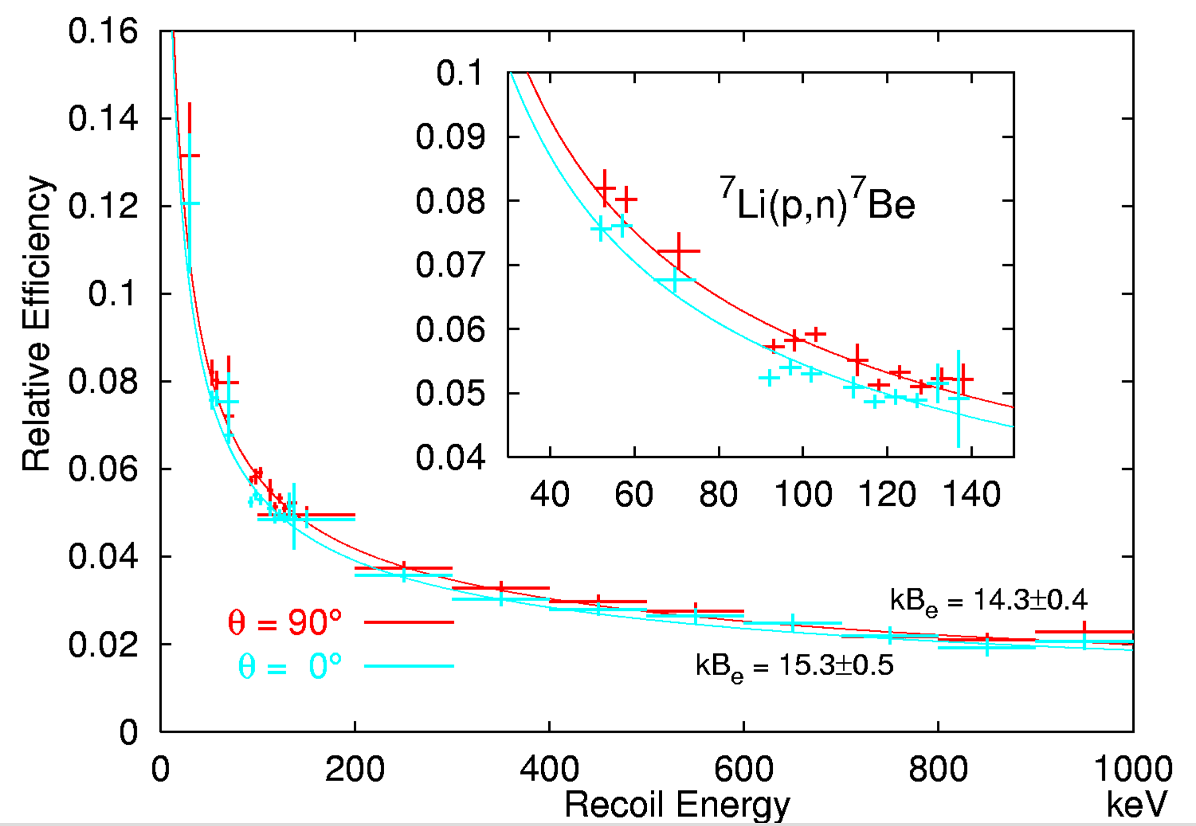
スチルベン結晶

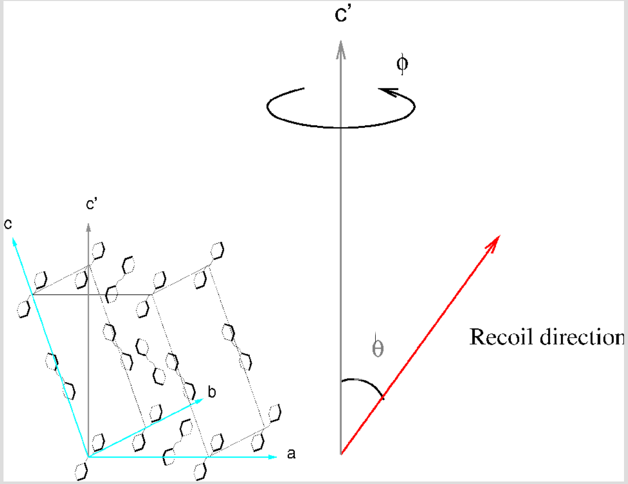
●5cm φ × 5cm　116g

Cryos Beta Ltd.,　Ukraine



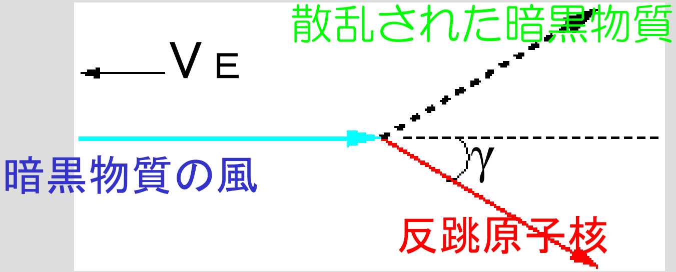
結果

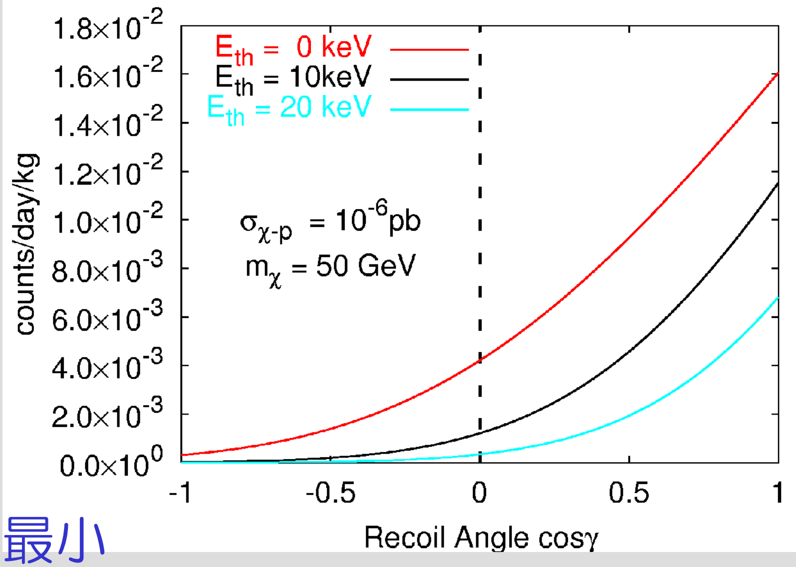




- 炭素反跳の発光効率は c’ axis に関して７％変化
- ほかの軸に対する（ϕ）依存性は見られなかった

暗黒物質探索への利用





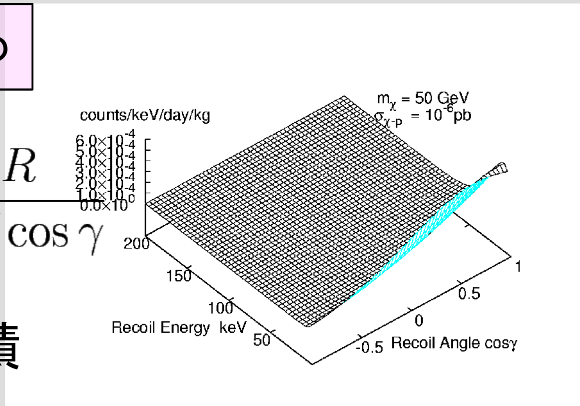
スチルベンの発光量は

- c’ // VE のとき最小
- c’ ⊥ VE のとき最大

暗黒物質にシグナルは光出力スペクトルに現れる

$$\frac{dR'}{dE_{\rm vis}} = \int dE_R\, d\cos\gamma\, \delta\left(E_{\rm vis} - q(E_R, \cos\gamma)E_R\right) \frac{d^2R}{dE_R\, d\cos\gamma}$$

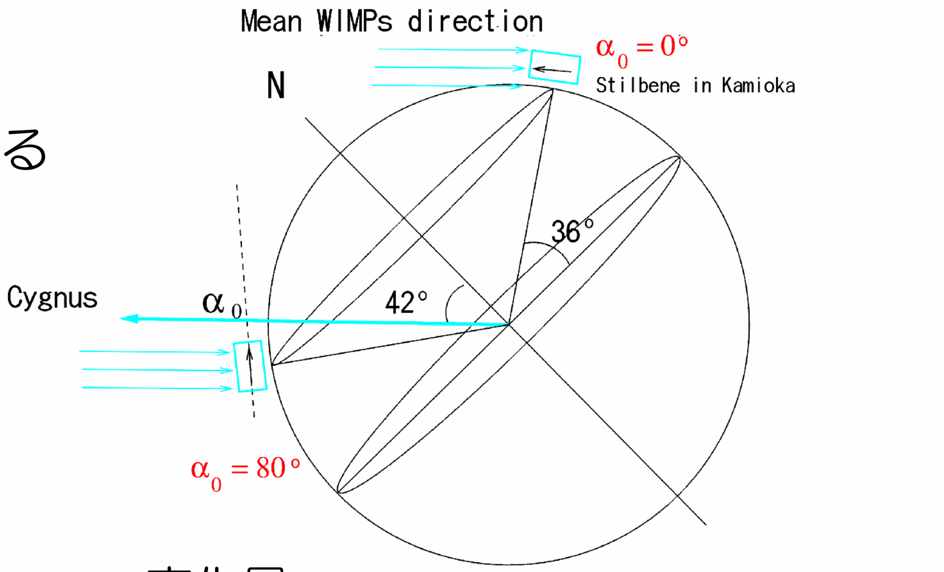
$\cos\theta$ = c’ の方向と反跳方向の内積



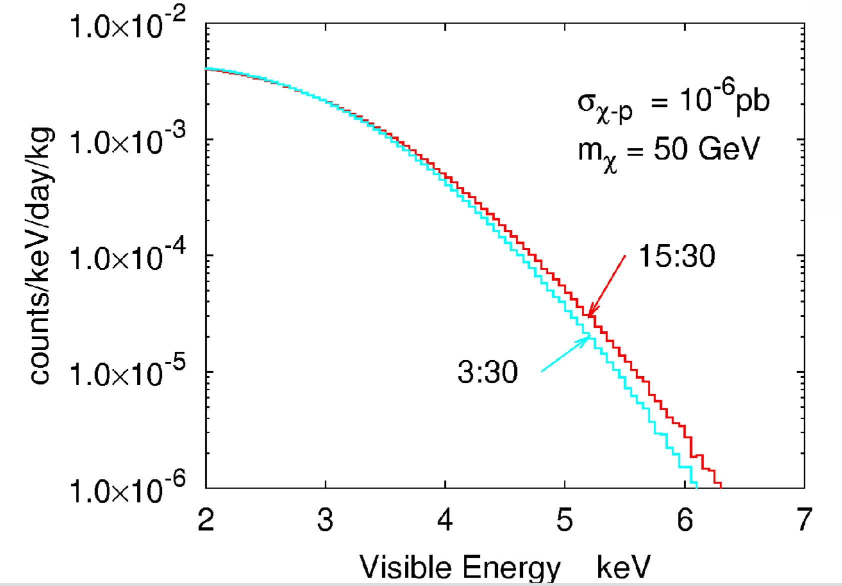
暗黒物質探索への利用

- Cygnus. の方向
  RA21 h 12 m，
  dec.+48.19°
- 神岡（北緯36度25分）で実験する

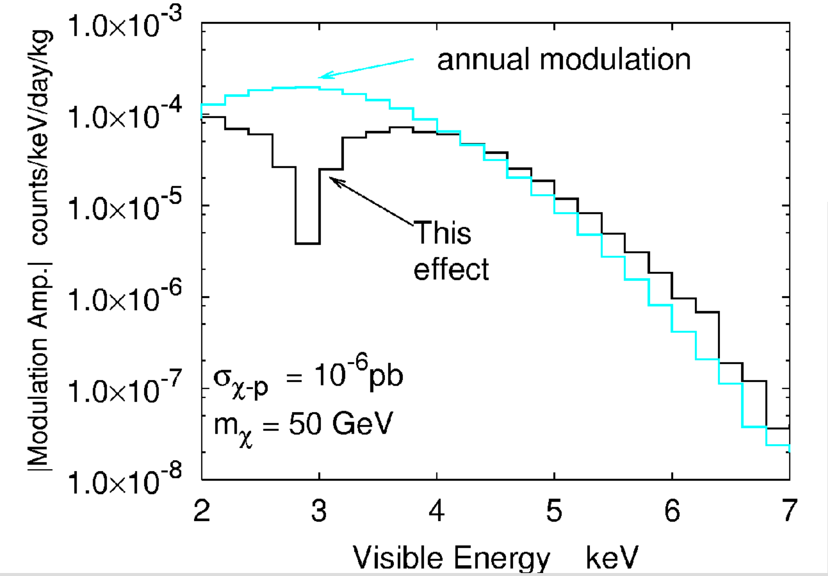
c’ 軸を北極に向けておけば
地球の自転により風向きとc’ 軸
の角度が約80° 変化する。



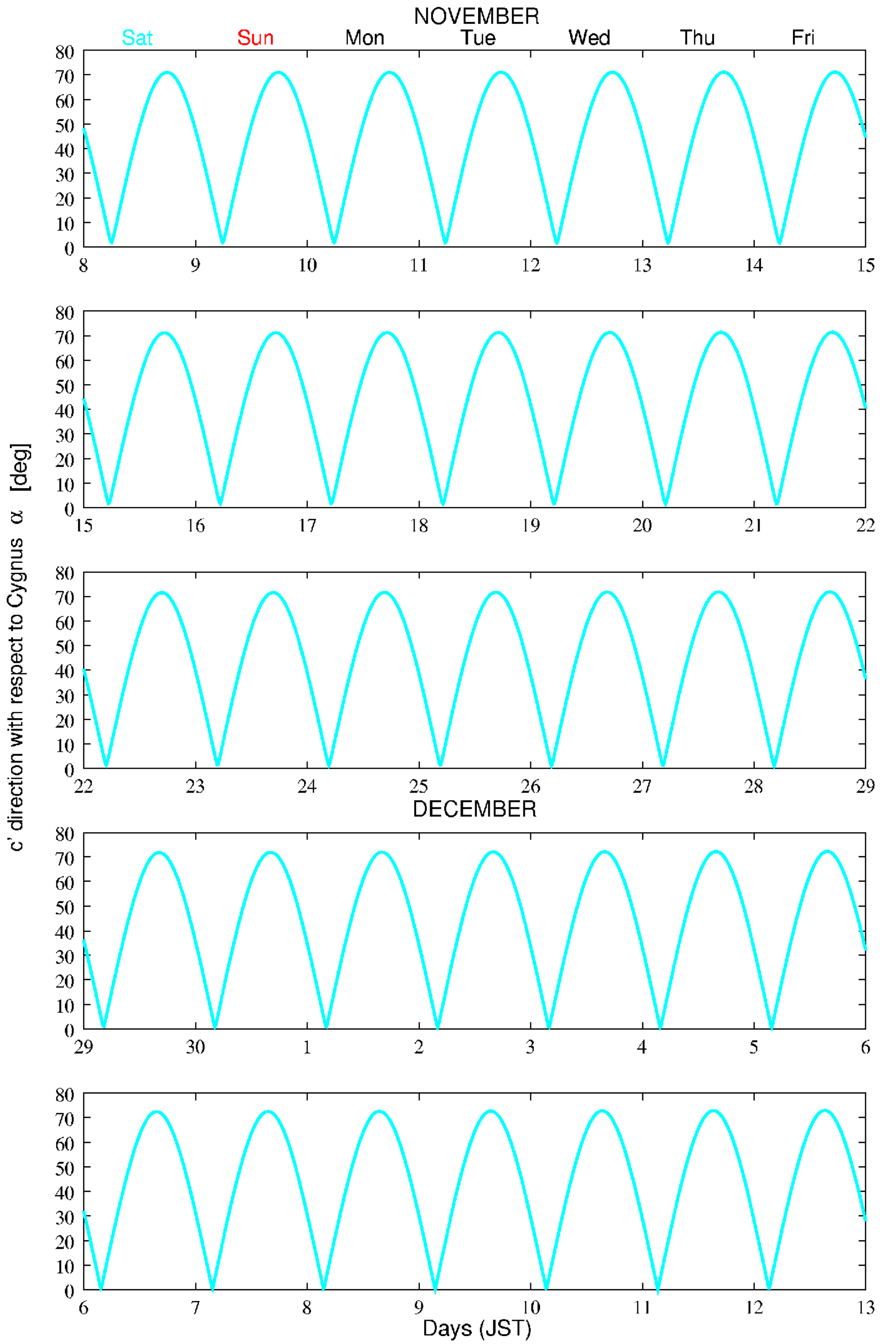
スペクトルの変化　2003. 12. 1



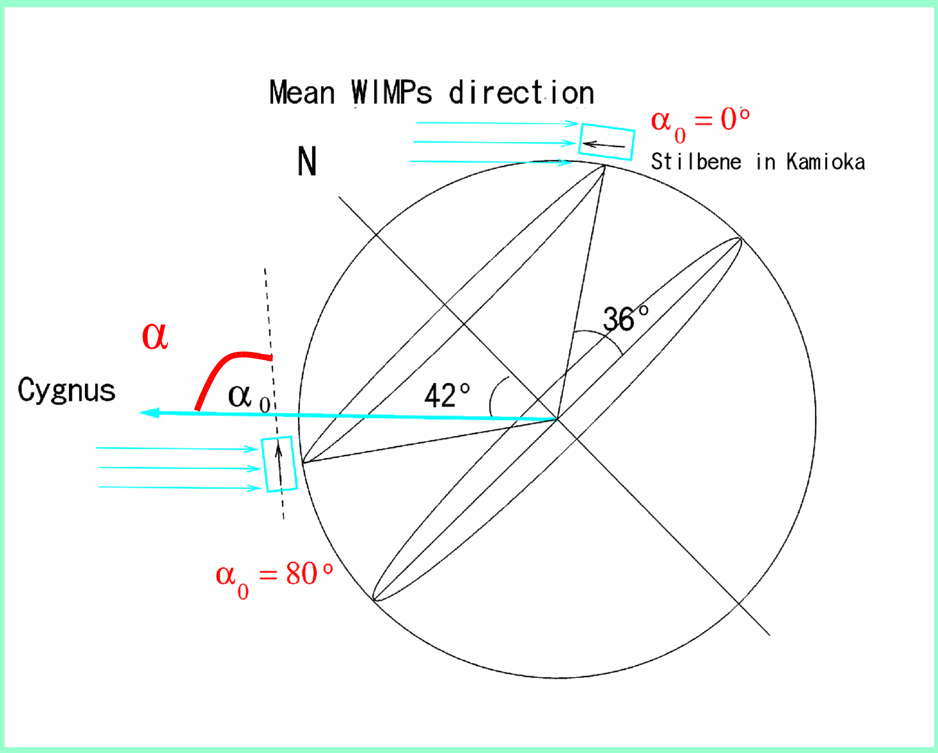
変化量



風向きの変化



測定期間中の
地球の進行方向と結晶軸ｃ’
のなす角 α の変化



問題点

実験を制限しているもの

1. バックグラウンドレート

PMT 中の放射性不純物
（ダイノード構造のセラミック、ステム部分のガラス）

→
- 結晶の周りを古い鉛で囲う
- 光検出器の改善（量子効率の意味でも）
  Avalanche Photodiode，Prism PMT など

2. スチルベン結晶

Anisotropy not sufficient

A=12 is not large enough for SI detection $\left(\sigma^{\mathrm{SI}}_{\chi-\mathrm{N}} \propto A^2\right)$

→
- より異方性のある、アントラセン・ナフタレンの使用
- Spin に依存した相互作用に有利な ^{19}F を含む結晶の製造
  Octafluoronaphtalene, dodecafluoroanthracene

END
Tokyo Group Results

Publications

**H. Sekiya, M. Minowa, Y. Shimizu, Y. Inoue, W. Suganuma:
Measurements of anisotropic scintillation efficiency for carbon recoils in a stilbene crystal for dark matter detection,
astro-ph/0307384, Physics Letters B571 (2003) 132-138.**

**A.Takeda, M.Minowa, K.Miuchi, H.Sekiya, Y.Shimizu, Y.Inoue, W.Ootani, Y.Ootuka:
Limits on the WIMP-Nucleon Coupling Coefficients from Dark Matter Search Experiment with NaF Bolometer,
astro-ph/0306365, Physics Letters B572 (2003) 145-151.**

**Y. Shimizu, M. Minowa, H. Sekiya, Y. Inoue:
Directional scintillation detector for the detection of the wind of WIMPs,
astro-ph/0207529, Nuclear Instruments and Methods in Physics Research Section A 496 (2003) 347-352.**

**K. Miuchi, M. Minowa, A. Takeda, H. Sekiya, Y. Shimizu, Y. Inoue, W. Ootani, and Y. Ootuka:
First results from dark matter search experiment with LiF bolometer at Kamioka Underground Laboratory,
astro-ph/0204411, Astroparticle Physics 19 (2003) 135-144.**

Another challenging DM search XMASS experiment

- Goals

☆ Direct detection of Dark Matter
→ Discovery of Dark Matter

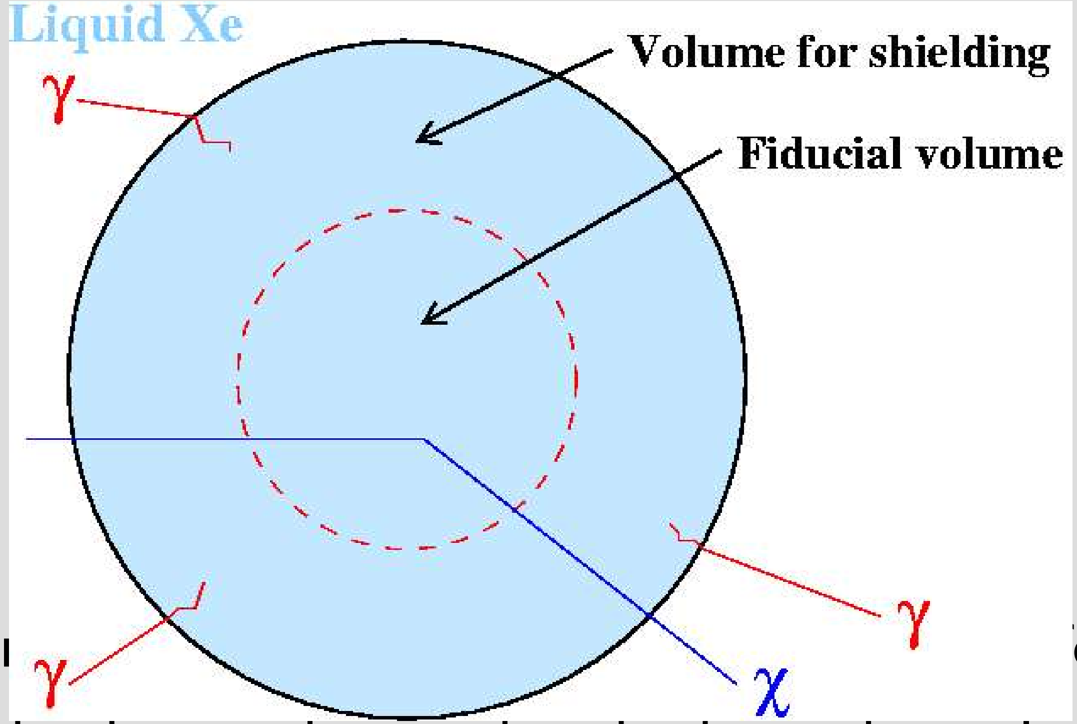
☆ Real time observation of low energy solar ν (pp, ^{7}Be)
→ Precise determination of ν oscillation parameters

☆ Observation of 0νββ decay
→ Majorana property and absolute mass of ν

XMASS = Multipurpose Ultra low-background detector
with liquid Xe

- Key idea

Self shielding for γ ray background by liquid Xe (Z=54)



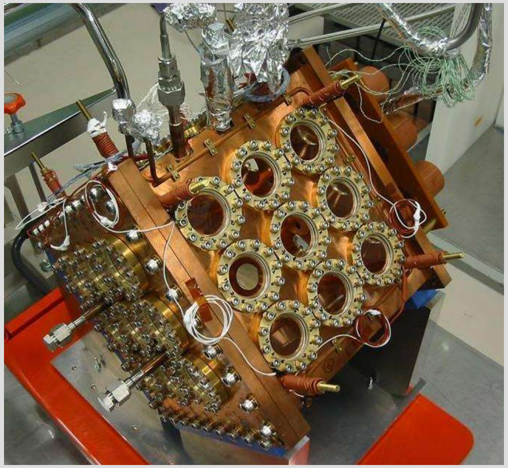
Reconst ormation

→ γ ray backgrounds are absorbed in outer volume

→ Dark matter can go into fiducial volume

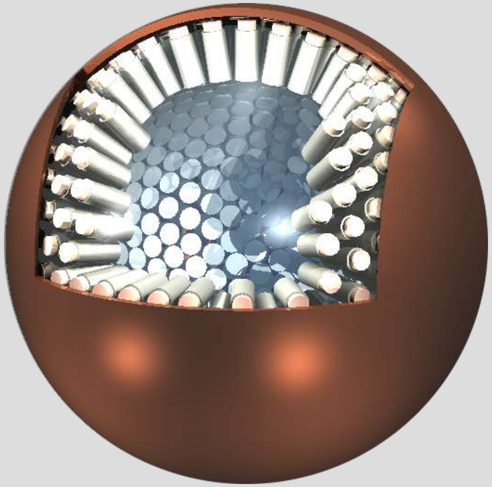
- Strategy of the scale-up

100kg prototype



~ 30cm

800kg detector



~ 80cm

~ 10ton detector

~ 2.5m

R&D

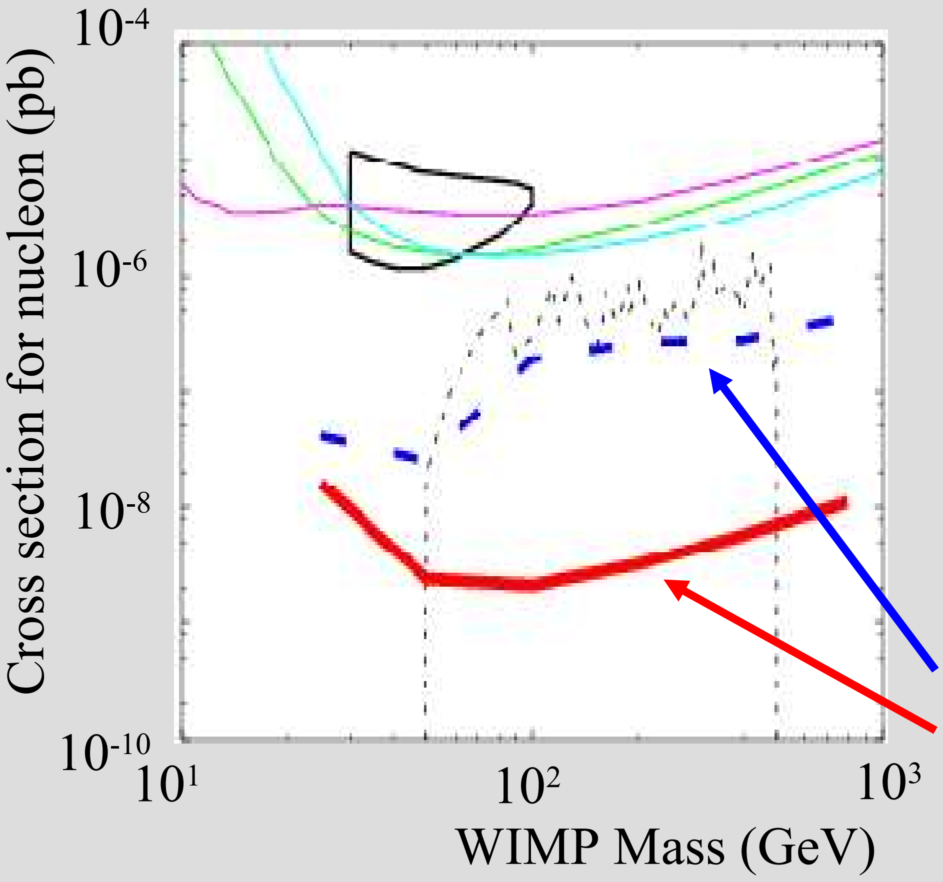
Now

Dark matter search

Multipurpose detector

- Sensitivity of 800kg detector for DM (SI)

Spin independent interaction



Discover!

▭ DAMA (NaI)

Exclude

— Edelweiss (Ge)

— ZEPLIN (Xe)

— CDMS (Ge)

XMASS 800kg detector (Xe)
(5keV threshold, 5year)

Annual modulation (3σ discovery)

Raw spectrum (3σ discovery)

$>10^2$ improvement of sensitivity for existing experiments

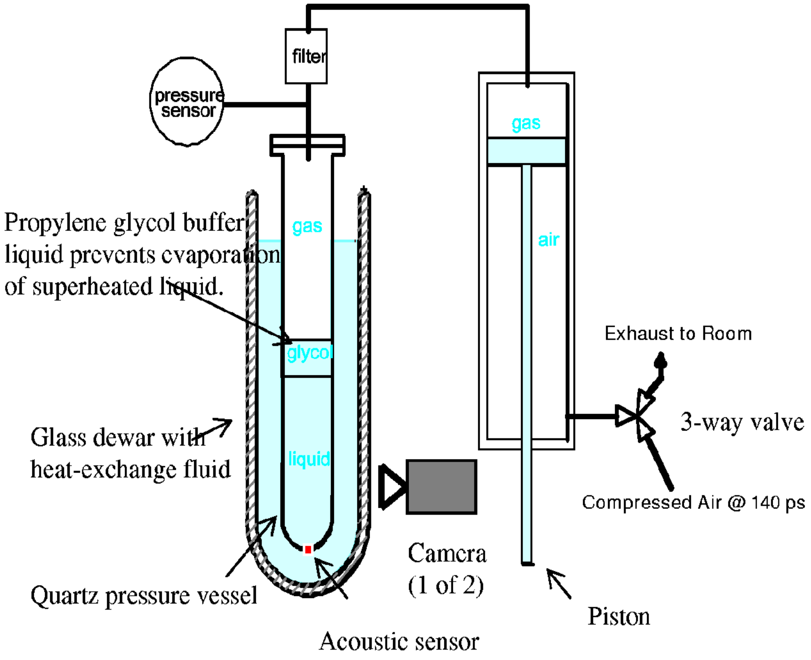
END
XMASS Project

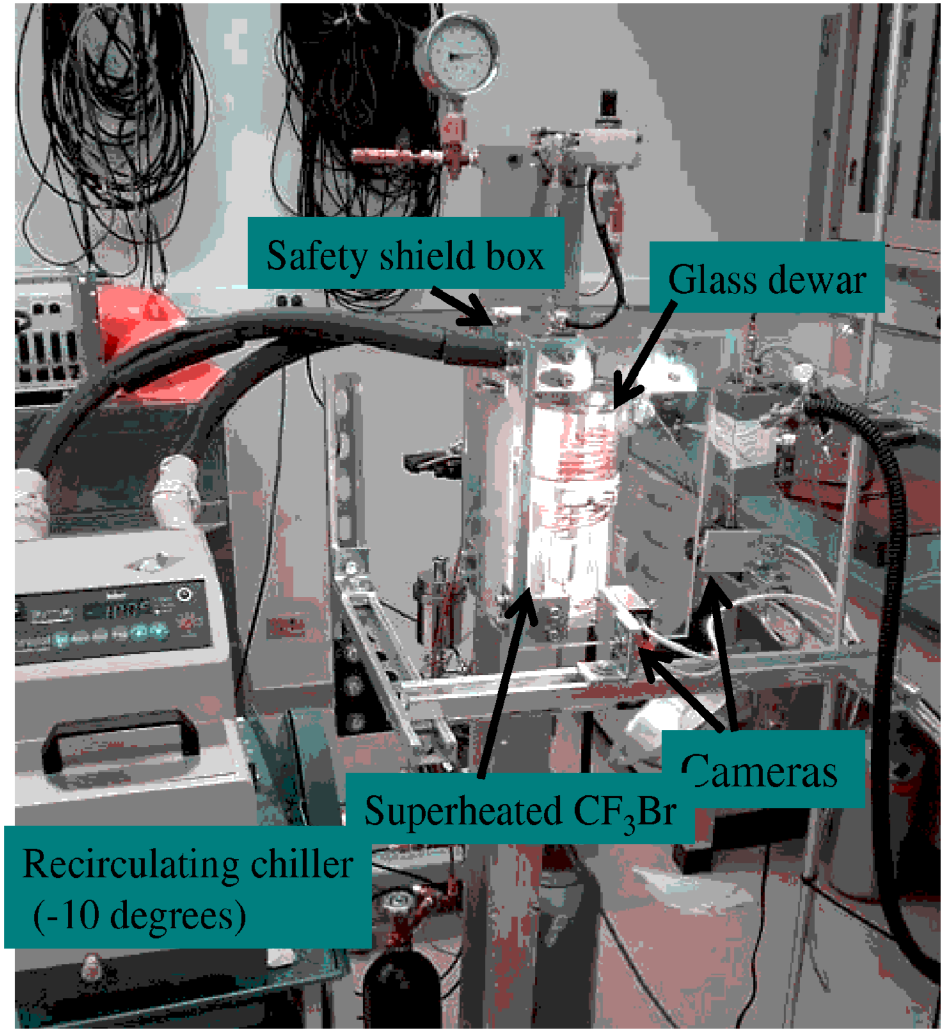
Kavli Institute
for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO

First prototypes:
~20 ml active volume
Pressure: 0-150 psi
Temp: -80 to + 40 degrees C

Stereo photography of bubbles

Three triggers: acoustic, pressure and video





⇒ Old Bubble Chambers radiation-ready for only few ms at a time (coincident with beam spill)

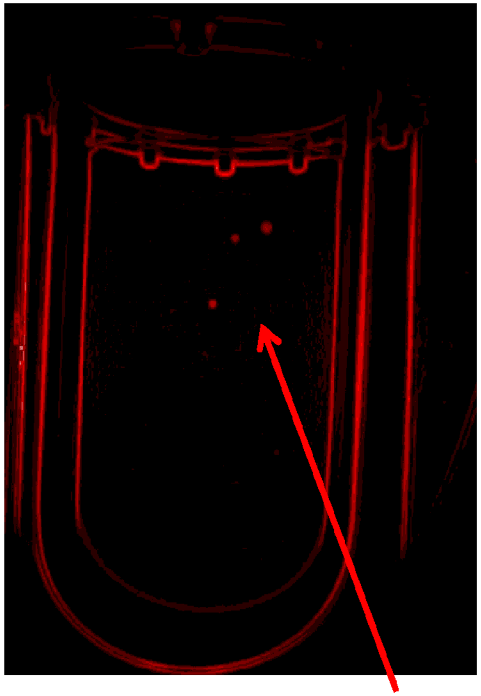
⇒ Gas pockets in surface imperfections and motes can act as inhomogeneous nucleation centers.

⇒ A BC dedicated to WIMP searches must remain superheated indefinitely, except for radiation-induced events. Low degree of superheat helps, but is not enough.

⇒ *Recent* progress in neutralization of inhomogeneous nucleation sites (from work unrelated to bubble chambers!). E.g. use of liquid "lid", outgassing in presence of buffer liquid, cleaning techniques and wetting improvement via vapor deposition.

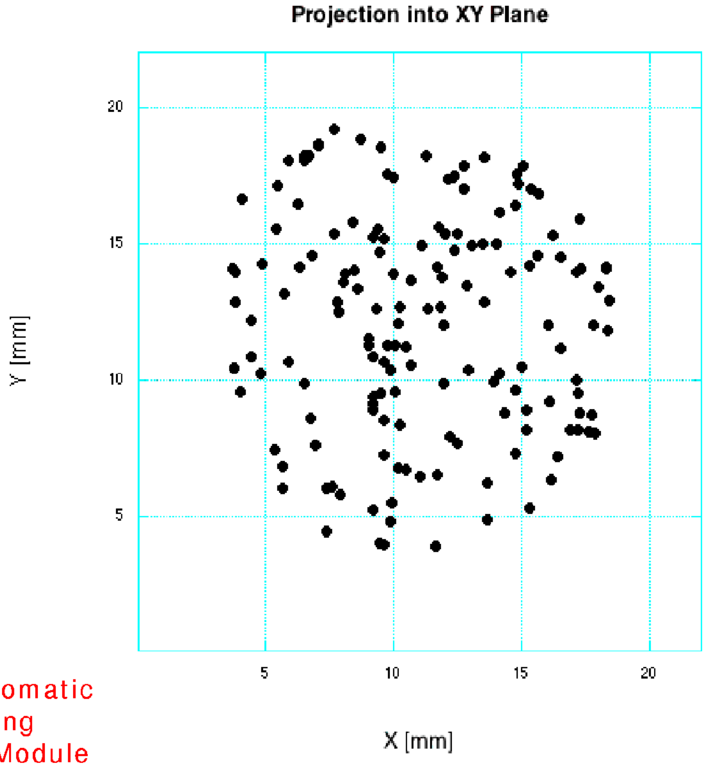
Fancy: Position Reconstruction

- Bubble positions can be reconstructed in 3 dimensions by scanning images taken by two cameras offset by 90 degrees.
- Position resolution is currently 530 microns r.m.s. (approximately 1/4 bubble diameter)
- Uniform spatial distribution of background events, consistent with background neutrons.

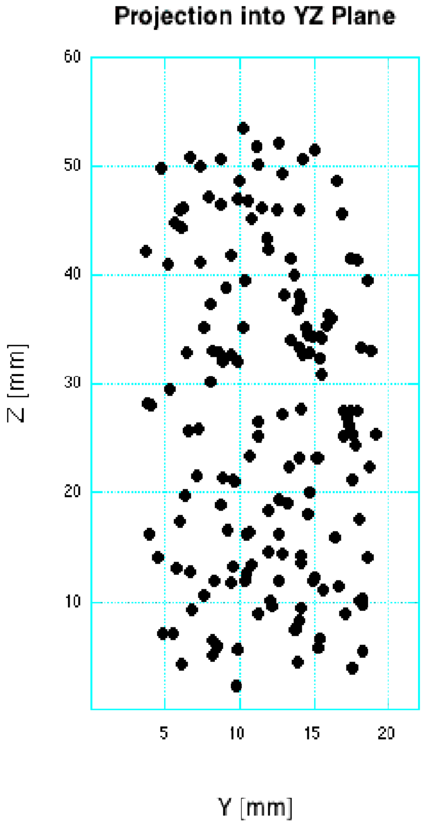


intermediate step in automatic
inspection algorithm using
NI Vision Development Module
(2 kg chamber)

163 background events (1.5 live days)



Projection into XY Plane



Projection into YZ Plane

Sensitivity necessary for the discovery of DM (SI)

- How can one reach $\boxed{\sigma^{\mathrm{SI}}_{\chi-\mathrm{n}} \geq 2\times10^{-12}\,\mathrm{pb}}$?

- Current typical limit with NaI(Tl) – PSA by UK group is:

$$\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{visible}}} \leq 4\times10^{-1}\,\mathrm{events/kg/day/keV}\,(@\,4-5\,\mathrm{keV})$$

$$\longrightarrow \quad \sigma^{\mathrm{SI}}_{\chi-\mathrm{n}} \leq 2\times10^{-5}\,\mathrm{pb}\,(@\,M_{\chi}\sim100\,\mathrm{GeV})$$

Well experienced experimentalist would not say that

- One has to go down to

$$\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{visible}}} \leq \boxed{4\times 10^{-8}}\,\mathrm{events/kg/day/keV}\,(@\,4-5\,\mathrm{keV})$$

- with 6 p.e. /keV (NaI(Tl))
  5 p.e. /keV (LXe)
- even lower p.e.'s for larger volume detectors

To go further,

- Huge mass conventional detectors never help even with PSA.
- → exposure[kg・days] more than
  several × {background rate[/kg/day]} $^{-1}$
  is not necessary
- Bolometr background rate is too high.
- Annual modulation effect is too small.
- Innovation needed
- → Direction sensitive (and, hopefully, SD-sensitive) detector
- → Self-shielding ultra pure material(e.g. LXe)
- → Even cleverer detection technique to be discovered (e. g. Bubble chamber)