The XMASS Dark Matter Experiment in Kamioka, Japan:

Status and Results

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Kavli IPMU
The University of Tokyo

Outline

- **Kavli IPMU:** introducing the institute

- **Dark Matter:** setting the stage

- **Kamioka Observatory:** the preeminent underground science laboratory in Japan

- **XMASS Experiment:**
  - design
  - status
  - first results
  - future plans

(if time allows: - Liquid noble gas cleanup...)

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

one of the 5 original WPI centers:

- **founded Oct. 1, 2007**
- **first institute in Todias Jan. 11, 2011**
- **first Kavli institute in Japan May 10, 2012**

best evaluations among WPI centers...

wpi World Premier International Research Center Initiative

Mandates:

(Solicitation 2007/03):

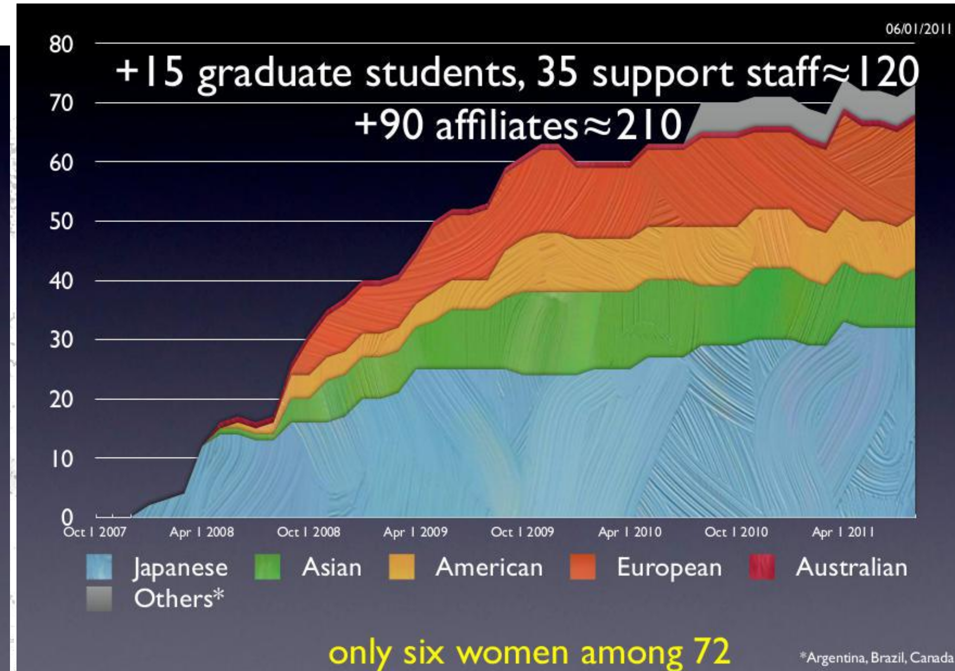
- secure research funding matching WPI funding ✓
- > 30% non-Japanese ✓
- > 200 staff members ✓
- globally visible like Max-Planck, IAS, IHES with their long traditions

ministerial funding: 10(+5) years... Todai:

TODIAS

review criteria: science, globalization, interdisciplinary research, organizational reform

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE



members have to be outside of Japan for 1-3 month/year

- We of course are aware this is not a true indicator of the "impact" of an institution, but in the absence of any better alternative:

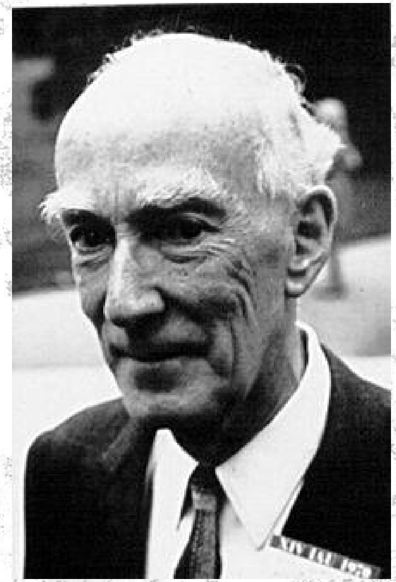
institute	IPMU	IAS	KITP	YITP	Perimeter	ICTP
citation/ paper	7.6	7.3	8.1	6.5	9.6	4.5
#papers >50 citations	8	18	8	3	13	4

- We have provided an additional report on mathematics for more detailed review

Thomson Reuters, excluding reviews
fields: astronomy, astrophysics, particle and fields, multidisciplinary physics, mathematics, applied mathematics

@ 3rd anniversary (Oct. 2010)

Early Observations: Oort & Zwicky

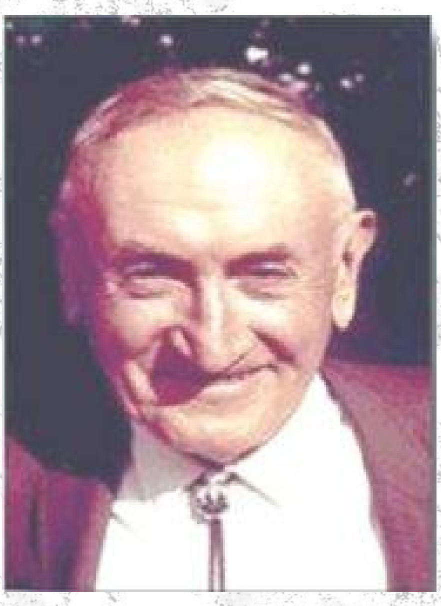


1932: Jan Oort (Leiden, Netherlands):

"measures" matter in galactic disk near sun from motion of nearby stars: $1M_{\odot}/375ly^3 > 2m_{stars}$

→ dark matter

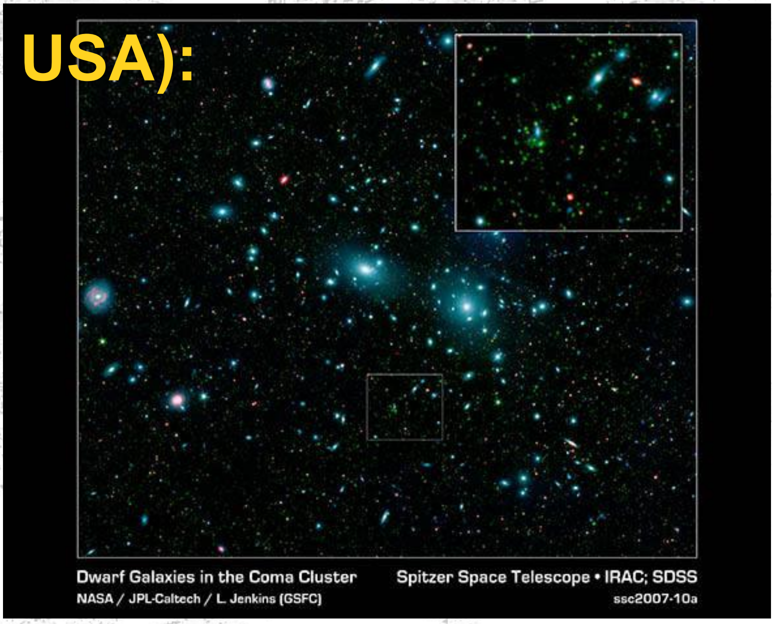
Vera Rubin @ Carnegie Institution of Washington:
rotation curves of galaxies
1975 AAS meeting
1980 paper



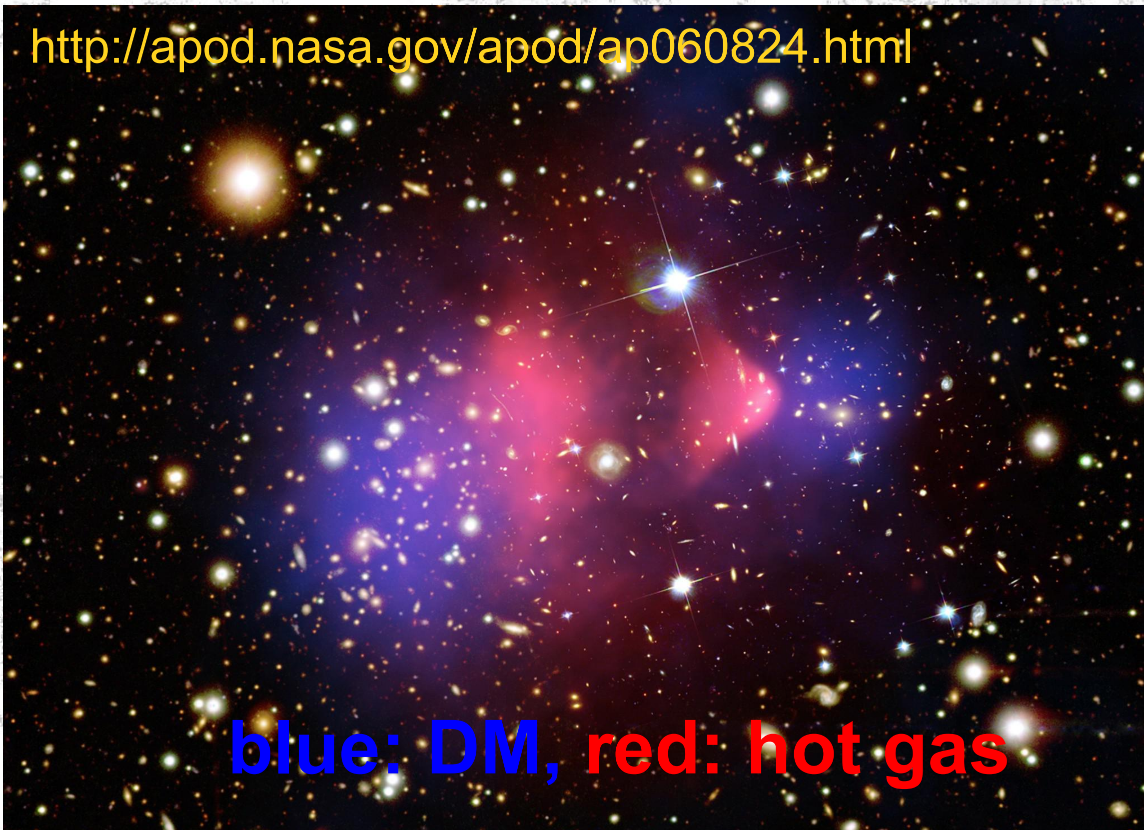
1933: Fritz Zwicky (Caltech, USA):

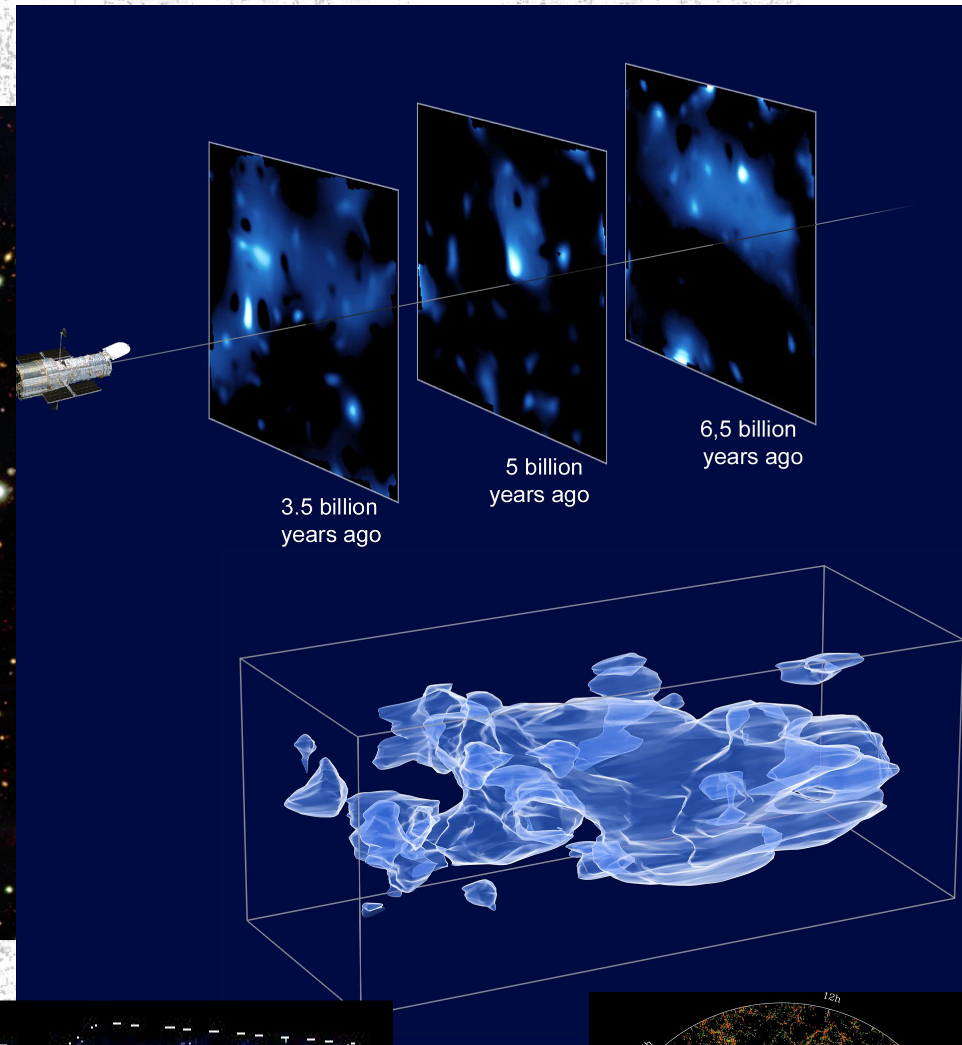
virial theorem: $\Sigma T = \frac{1}{2} \Sigma U$
→ galaxies in Coma cluster too fast for cluster's gravitational potential

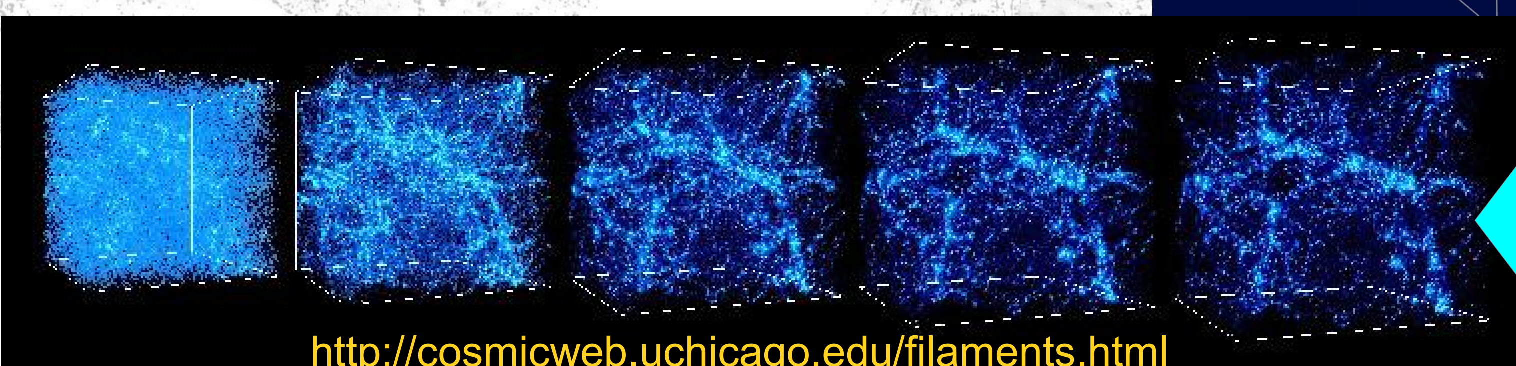
→ dark matter



Dark Matter: It's out there ...







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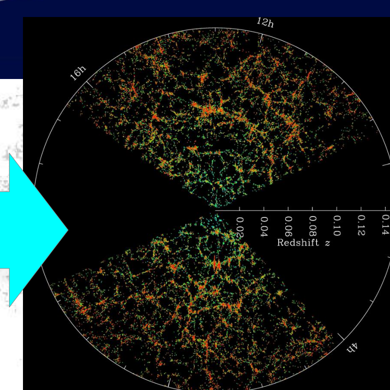


So What Are We Looking For?

- gravitating: …
- cold: → massive ← if particle …
- collisionless: → no E/M interaction
  → no strong interaction
  at most: weakly interacting ???

New Scientist (2005/03/19): Michael Brooks: 13 things that do not make sense:

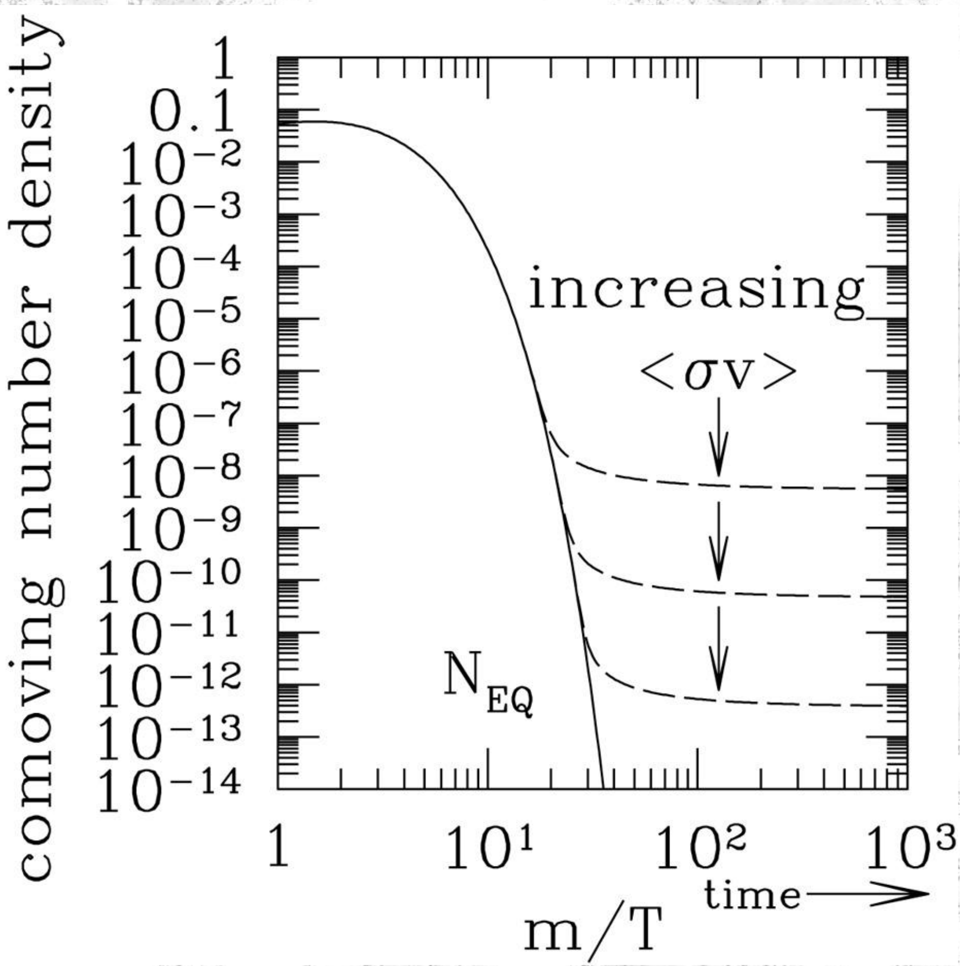
Maybe we can't work out what dark matter is because it doesn't actually exist. That's certainly the way Rubin would like it to turn out. "If I could have my pick, I would like to learn that Newton's laws must be modified in order to correctly describe gravitational interactions at large distances," she says. "**That's more appealing than a universe filled with a new kind of sub-nuclear particle.**"

(Rubin as in: Vera Rubin)

favorites are: neutralino, axion, Kaluza-Klein, gravitino

Dark Matter and the WIMP Miracle

WIMP denomination → weak interaction ...



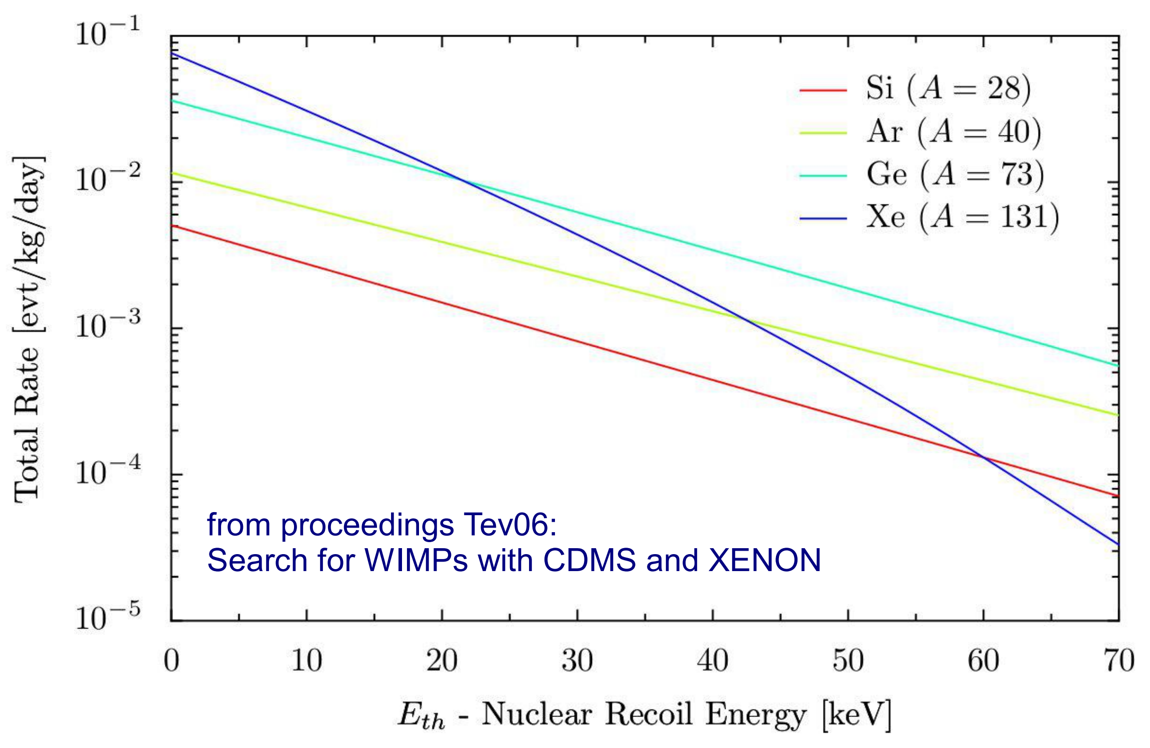
WIMP decoupling after BB:

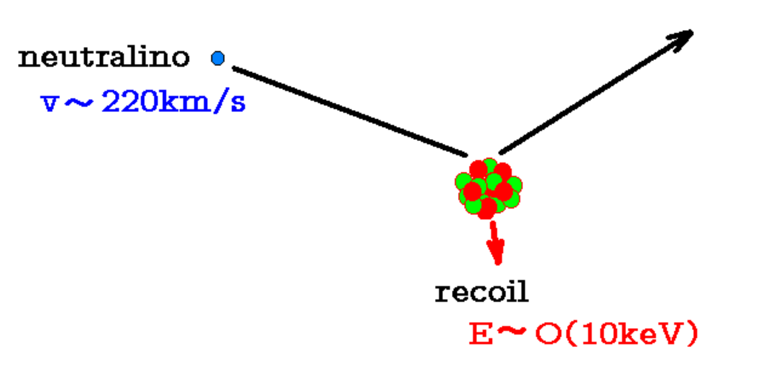
velocity averaged annihilation cross-section for **GeV-TeV mass WIMPs**:

$\langle\sigma v\rangle = 3\times10^{-26}cm^3/s$
→ **correct DM density**

TeV ~ SUSY partners ?!?
→ miracle …

WIMP Dark Matter Searches: Direct Detection





important for verification:
different target materials
→ consistency!

two types of interaction:

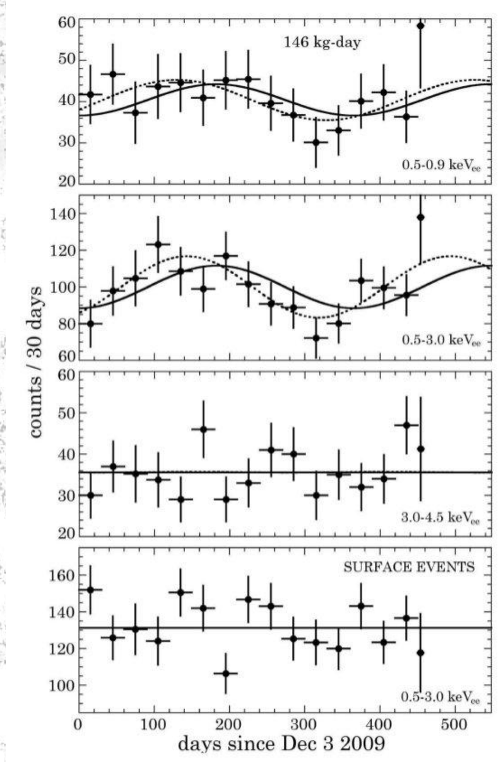
- **spin dependent (odd isotopes), smaller cross section**
- **spin independent; σ ~ A² (coherent: whole nucleus)**

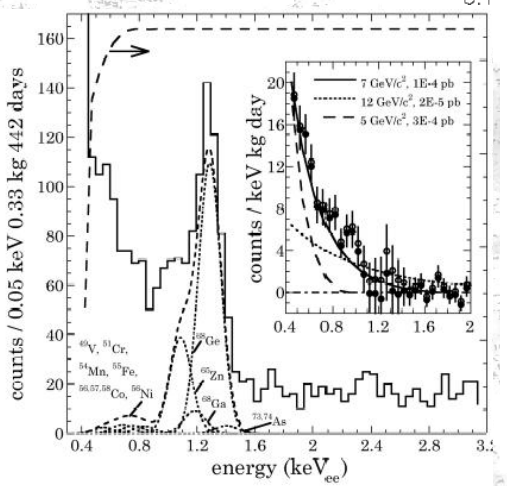
Hints of Low Mass WIMPs

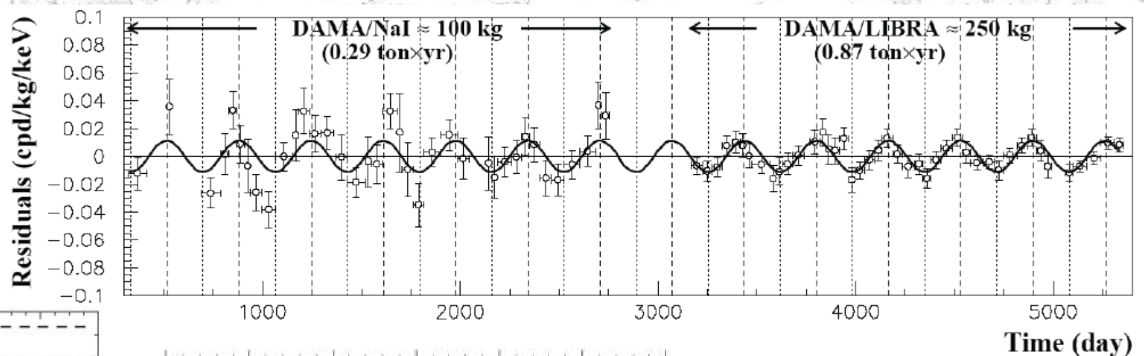
DAMA/Libra: 250kg NaI(Tl), scintillation
13 years of measurement

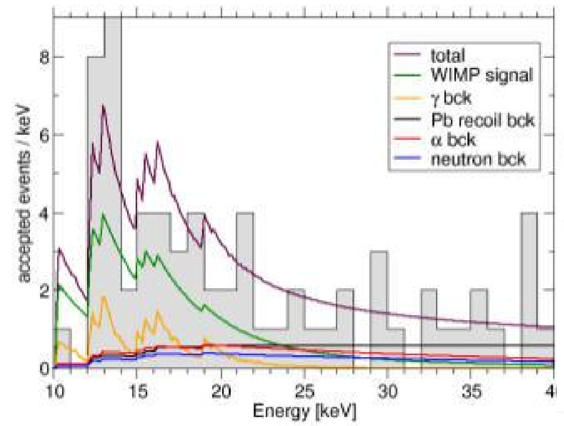
CoGeNT: 440g p-type Ge detector, ionization
442 live days

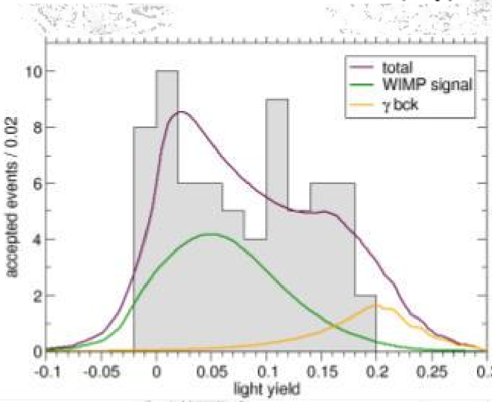
CRESST-II: 8x300g CaWO4, scintillation + phonon
730kg/d



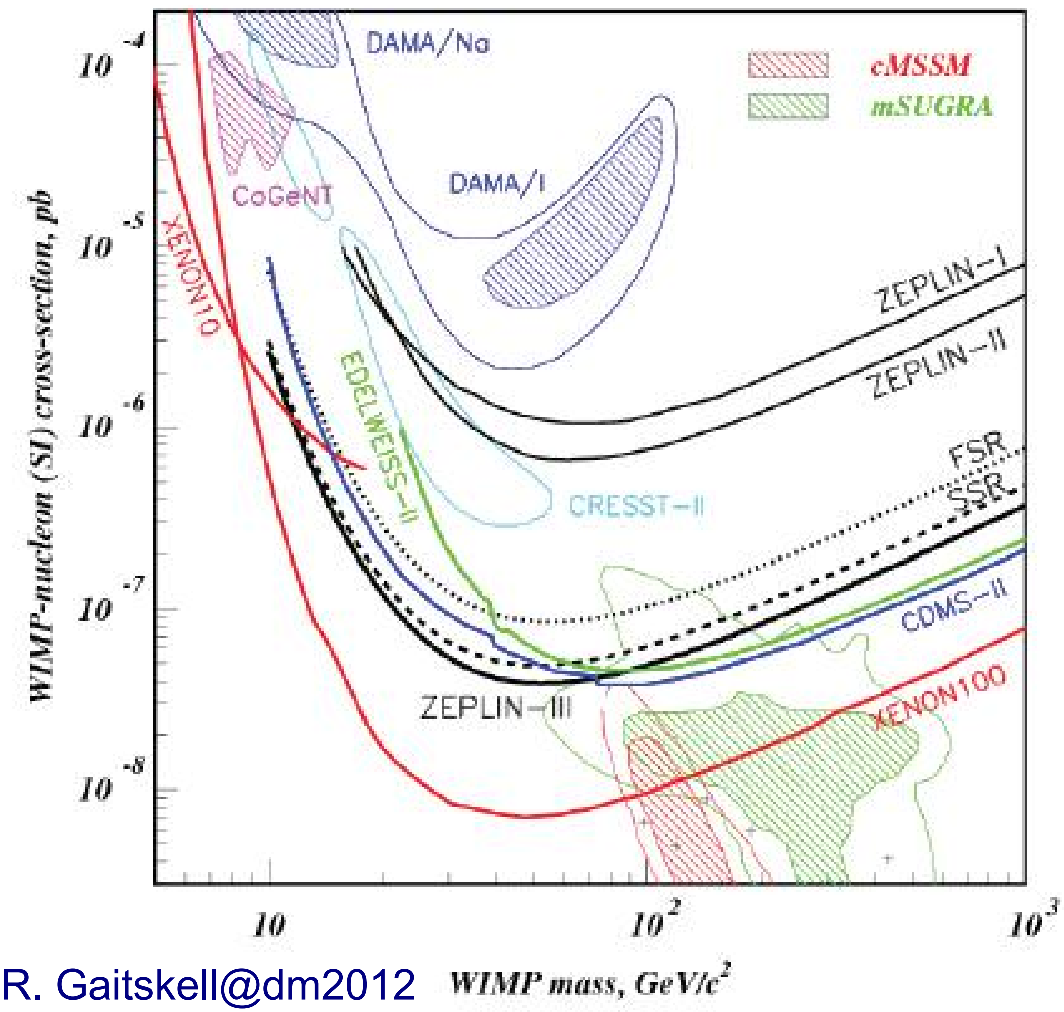








The Current Situation:



R. Gaitskell@dm2012

(WIMP hypothesis:)

compatible:
- **spectra:** **CoGeNT/CRESST-II**
- **modulations:** **DAMA/CoGeNT**

tension:
- **Xe/all of the above**
- **modulation amplitude** **(halo assumptions...)**

The Kamioka Observatory: new: KAGRA

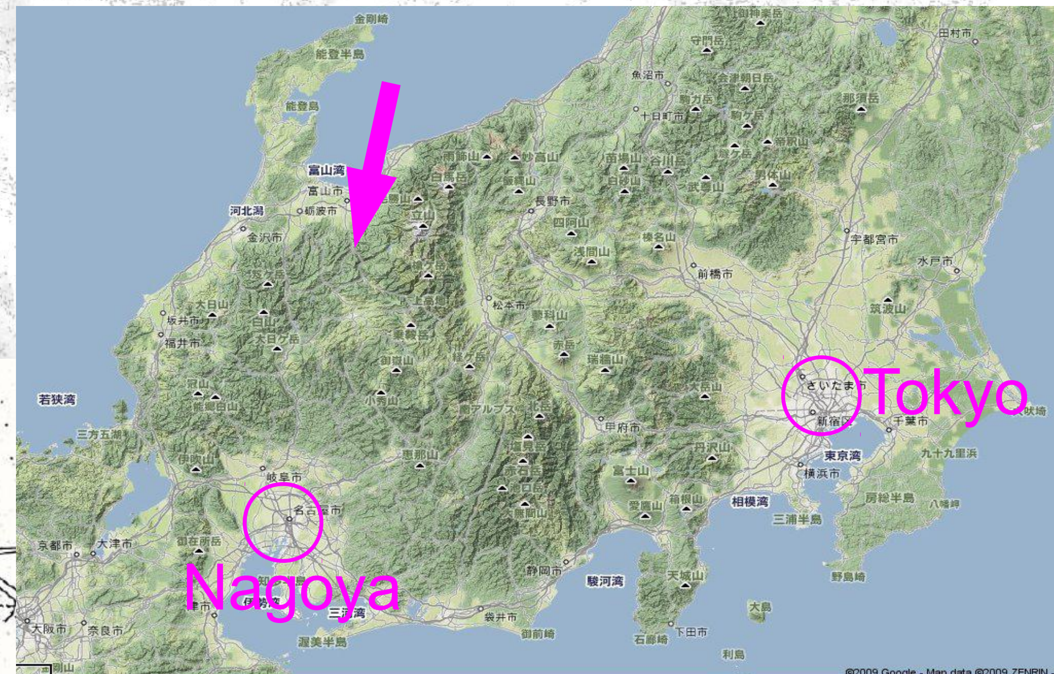
Super-Kamiokande, (T2K)

KamLAND (Xe)

CANDLES

XMASS

IPMU Lab



IPMU Lab:
U, Th → HP-Ge ← few 100ppt
→ ICP-MS ← 1ppq*
Kr → API-MS ← 1ppt*
* after concentration

EGADS

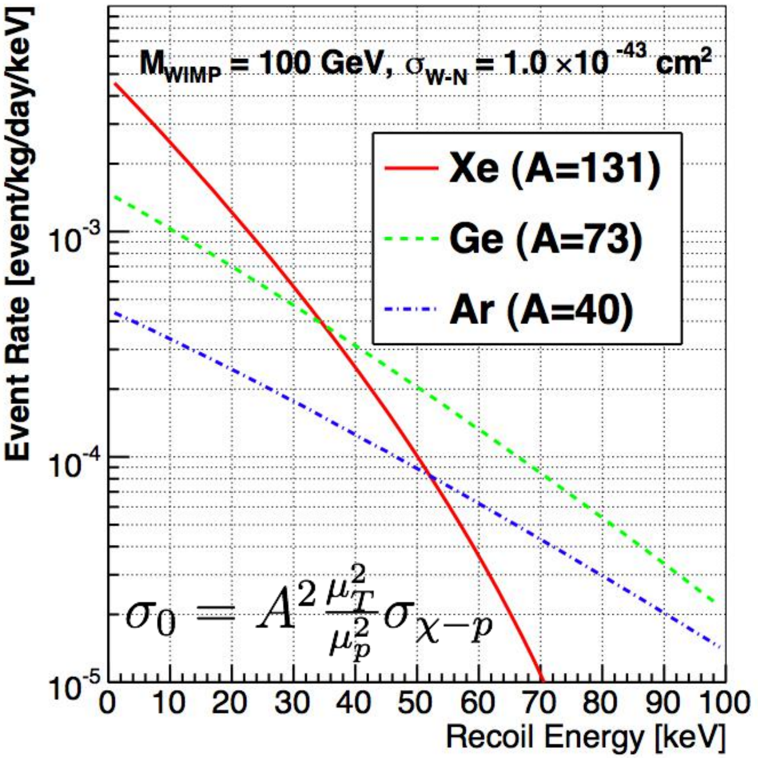
NEWAGE

CLIO

Legend:
DM, ν, ββ, GW

The XMASS Experiment

Xe detector for weakly
interacting **MASS**ive particles
Xe ν-**MASS** detector
Xe **MASS**ive ν-detector



Exploiting Xenon:

- **high mass number $\rightarrow$ SI cross section**
- **no long-lived radioactive isotope**
- **good scintillation yield: ~ 46ph/keV**
- **high density (liquid): 3g/cm^3**
- **48% odd isotopes (natural) $\rightarrow$ SD cross section**
- **$\beta\beta$ candidate: ^{136}Xe $\rightarrow$ ^{136}Ba+2e+2.48MeV**

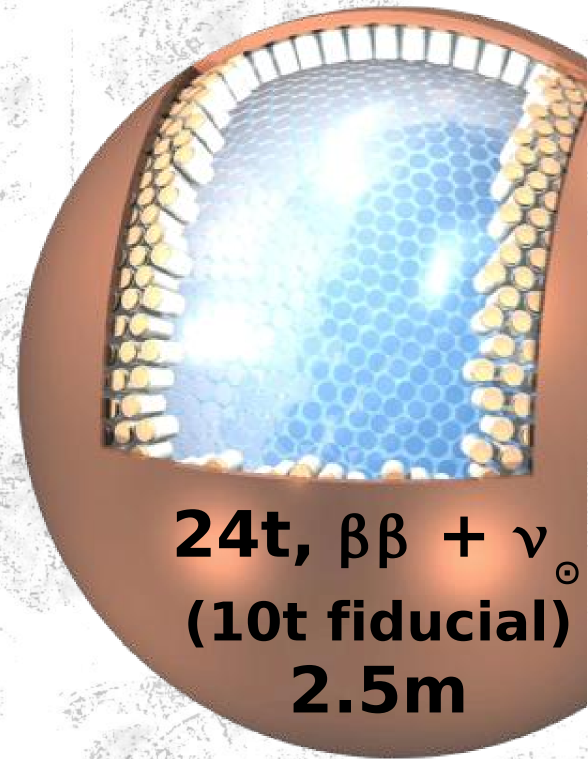
Ultimately: 10t fiducial volume multi-purpose detector:

- neutrino mass:	$\beta\beta$
- Dark Matter:	WIMP limited by:
- solar neutrinos:	pp, ^{7}Be

(water tank in Hall C designed to hold this...)

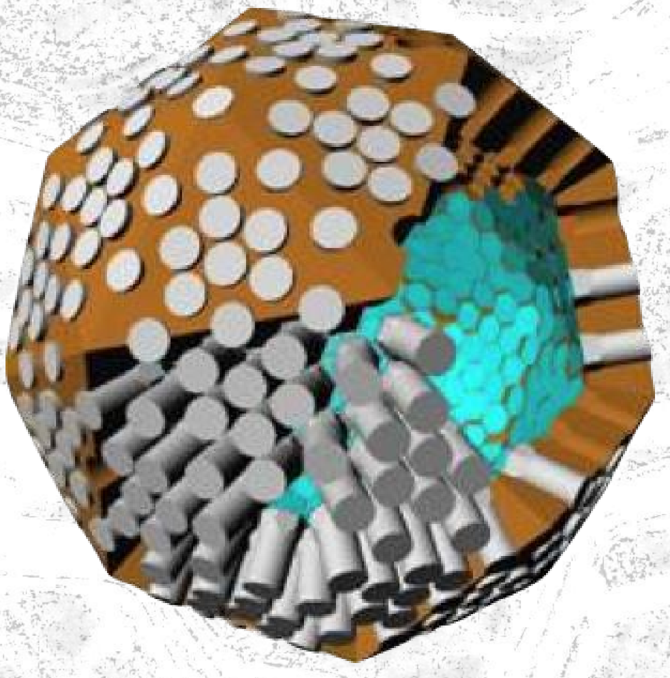
XMASS Progression:

the far future:

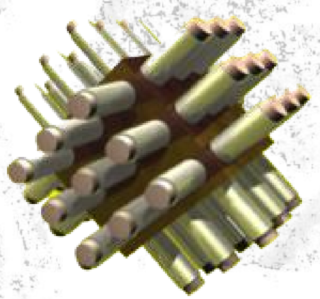


24t, $\beta\beta$ + $\nu_\odot$
(10t fiducial)
2.5m

the current incarnation:
800kg WIMP detector
(100kg fiducial), 80cm



the PAST:
100kg **prototype**,
(3kg fiducial), 30cm
proof of principle



100kg reference:
arXiv:0912.2405

detector technology
advantages:

- simple
- scalable
- self-shielding

ultimately: 24t (10t fid.) 2.5m ???

the next step:
5 ton total, > 1.5ton fiducial

The XMASS Collaboration

Kamioka Observatory, ICRR, University of Tokyo:

Y. Suzuki, M. Nakahata, S. Moriyama, M. Yamashita, Y. Kishimoto, A. Takeda, K. Abe, H. Sekiya, H. Ogawa, K. Kobayashi, K. Hiraide, B. Yang, A. Shinozaki, K. Hieda, O. Takachio, D. Umemoto, N. Oka, K. Nakagawa

IPMU, University of Tokyo: K. Martens, J.Liu

Kobe University: Y. Takeuchi, K. Miuchi, K. Hosokawa, A. Murata, Y.Ohnishi

Tokai University: K. Nishijima, F. Kusaba

Gifu University: S. Tasaka

Yokohama National University: S. Nakamura, I. Murayama, K. Fujii

Miyagi University of Education: Y. Fukuda

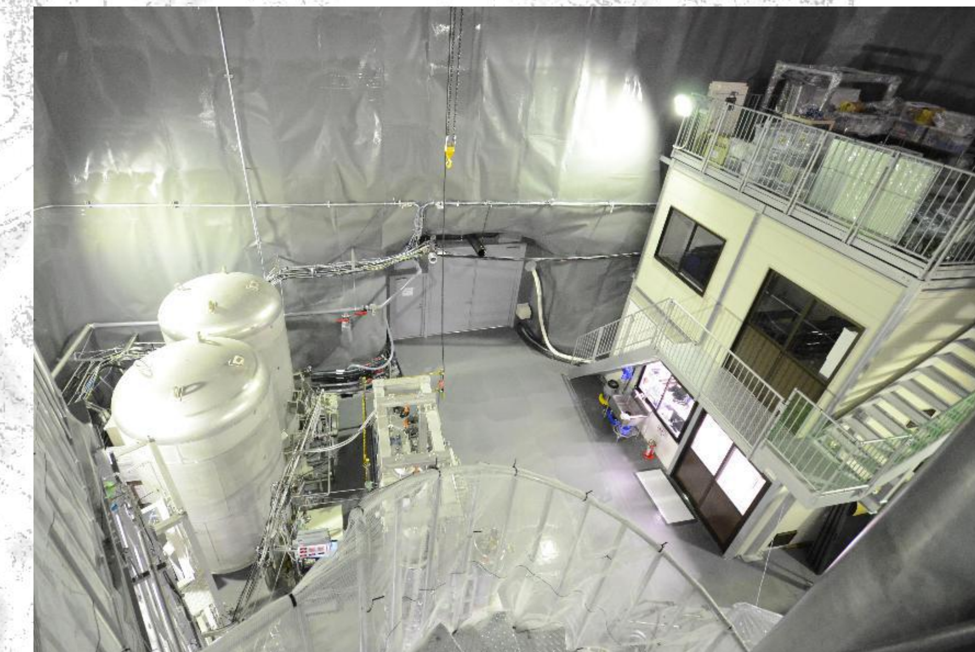
STEL, Nagoya University: Y. Itow, K. Masuda, H. Uchida, H. Takiya

Sejong University: Y.D. Kim, N.Y. Kim

KRISS: Y.H. Kim, M.K. Lee, K.B. Lee, J.S. Lee

42 collaborators, 10 institutions, 2 countries

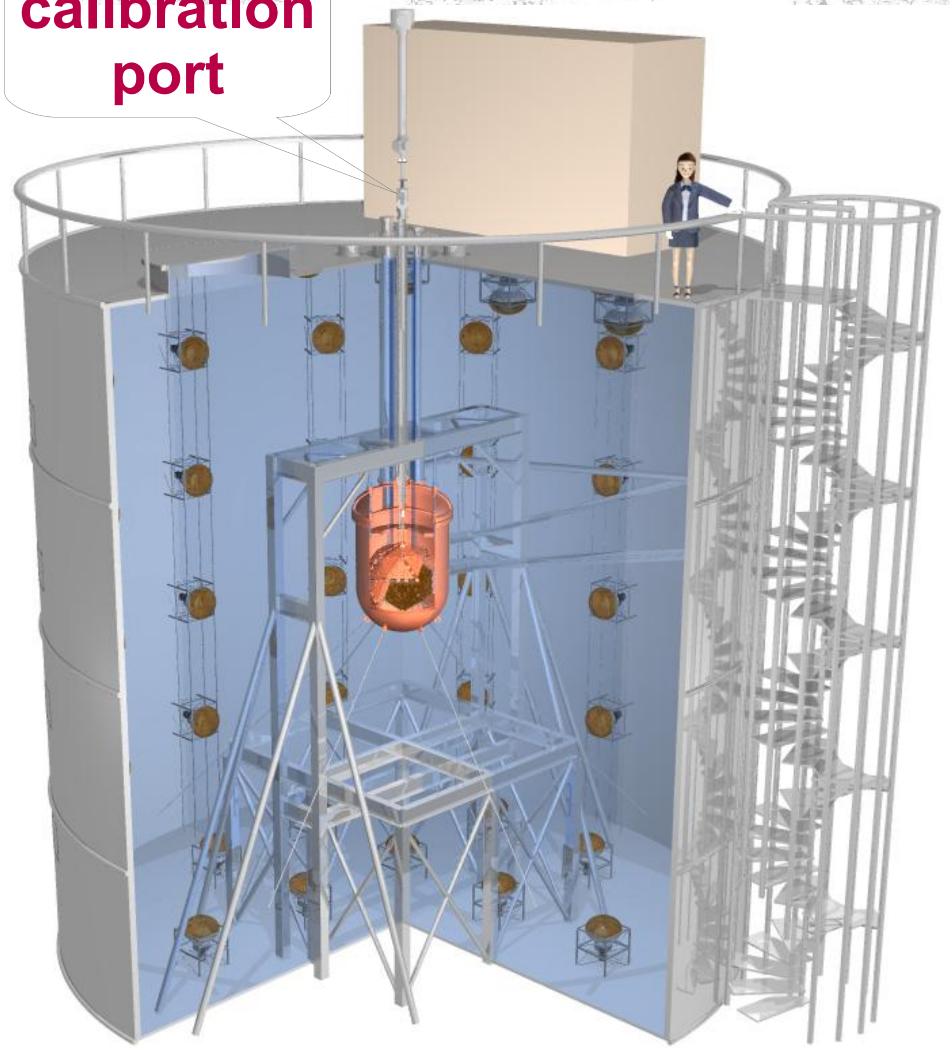
Hall C in Kamioka: XMASS



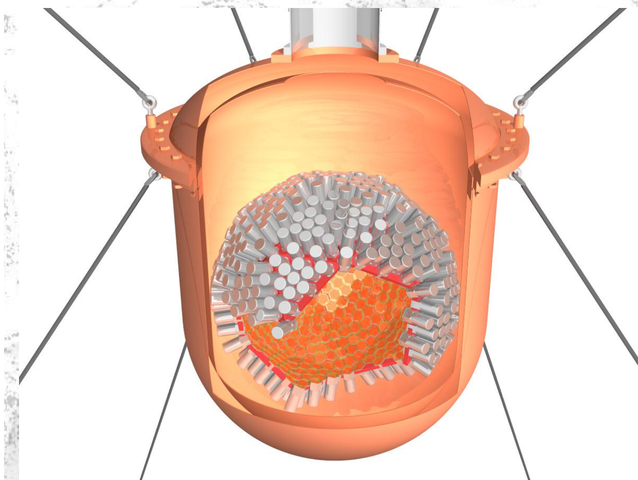
Hall C:
15m,21m,15m (h,d,w)

XMASS from the Outside In:

calibration port



Inner Detector(ID): 642 PMTs

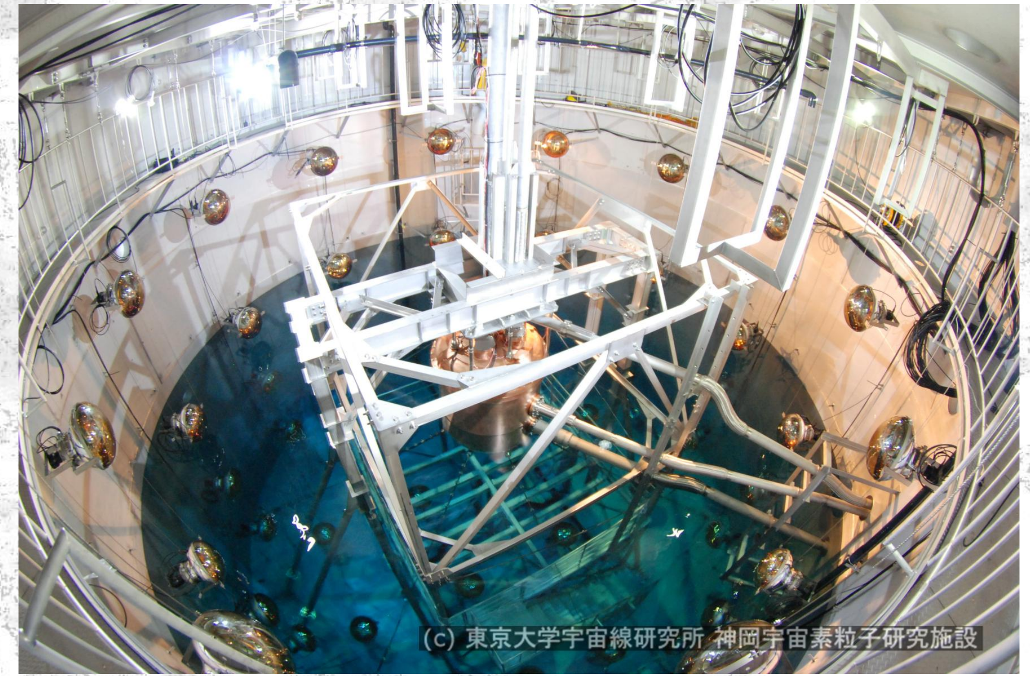


1100 kg LXe (total)

835 kg (inside PMTs)

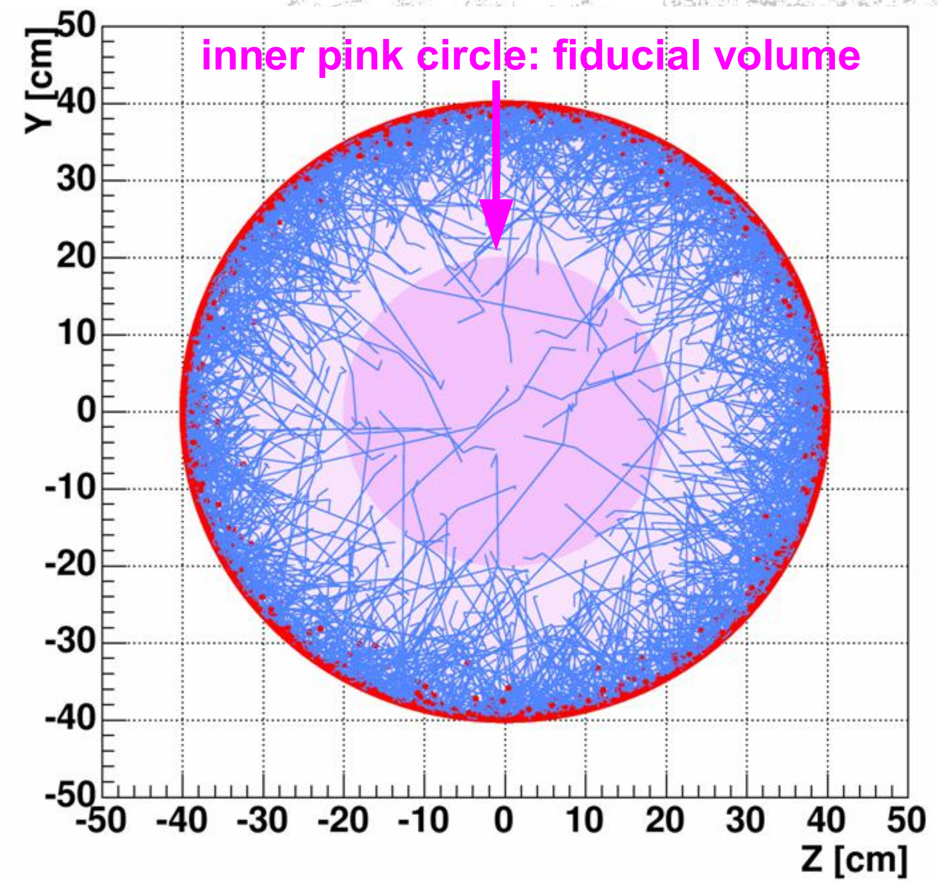
100 kg (fiducial)

Outer Detector (OD): 72 x 20inch PMTs (=SK)



Shielding Against External Radiation

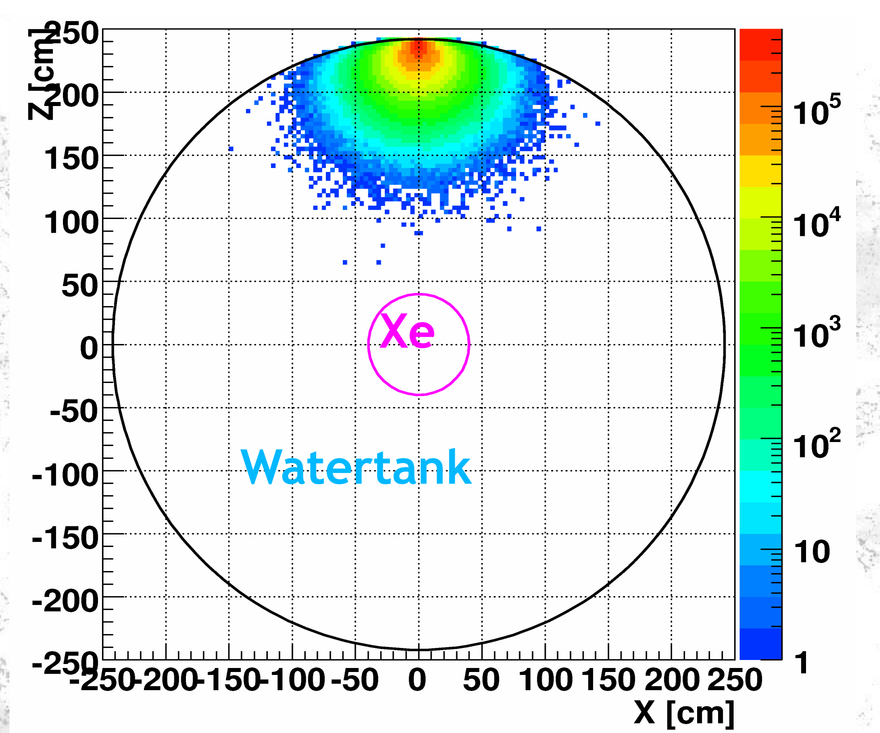
gamma radiation:
xenon →
self-shielding:



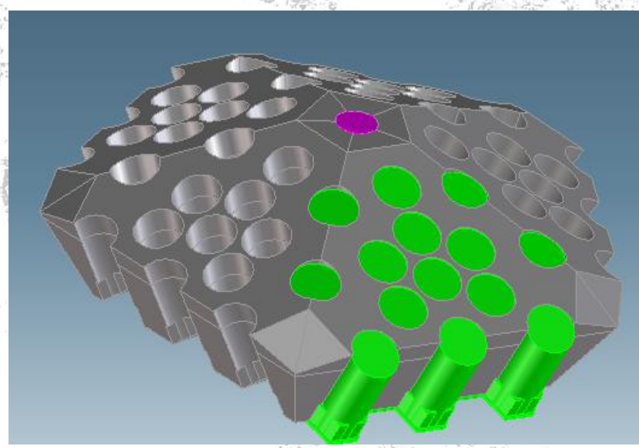
also: hall lining Rn retarding
Rn-"poor" outside air supply

fast neutrons:
water tank
11m high (10m water)
10m ∅
active: μ-veto

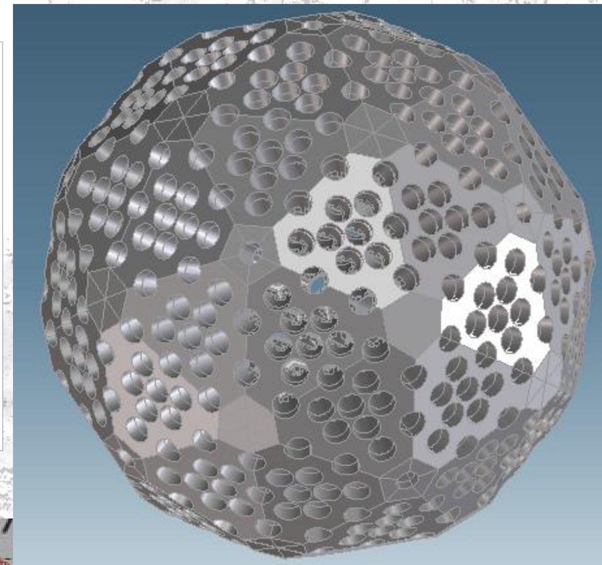
fast Neutron MC:



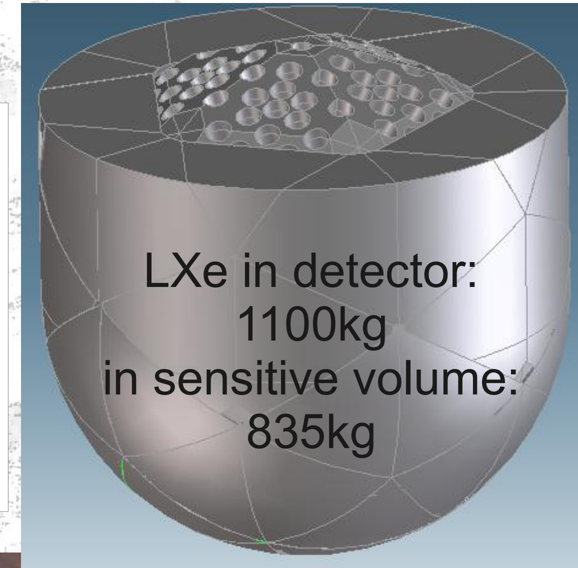
Inner Detector Structure:

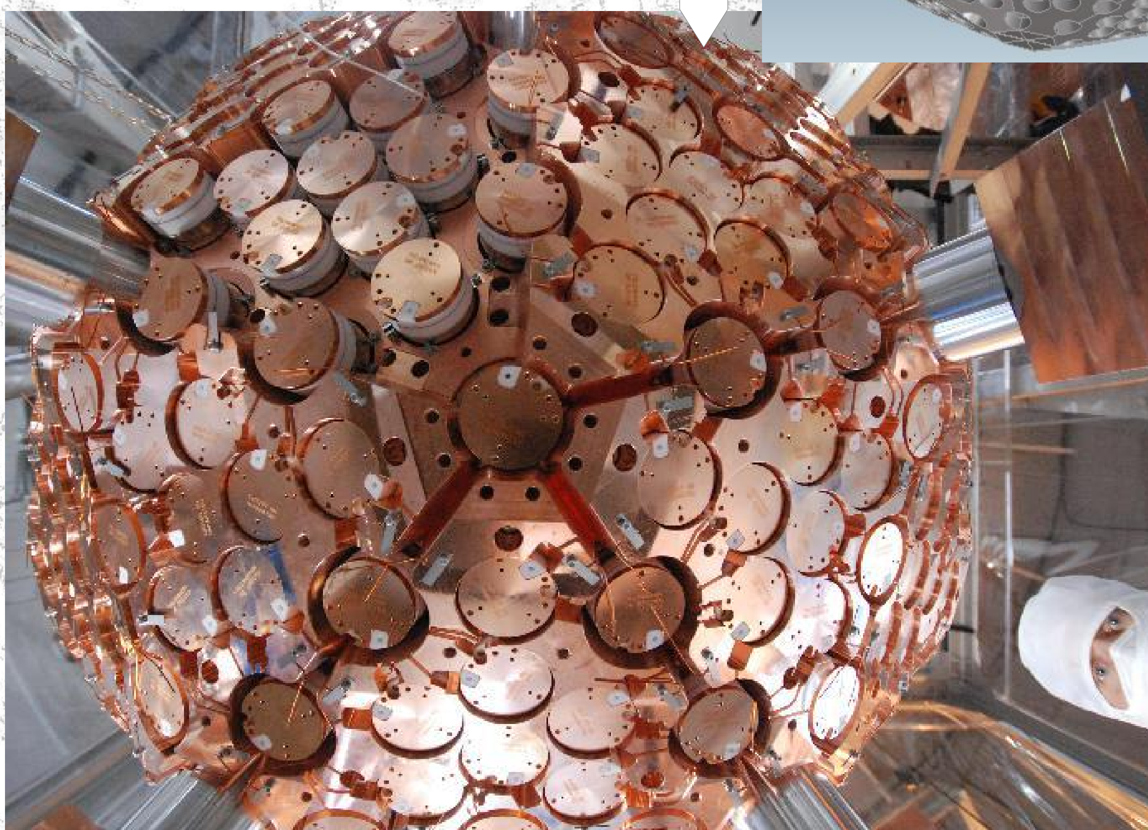


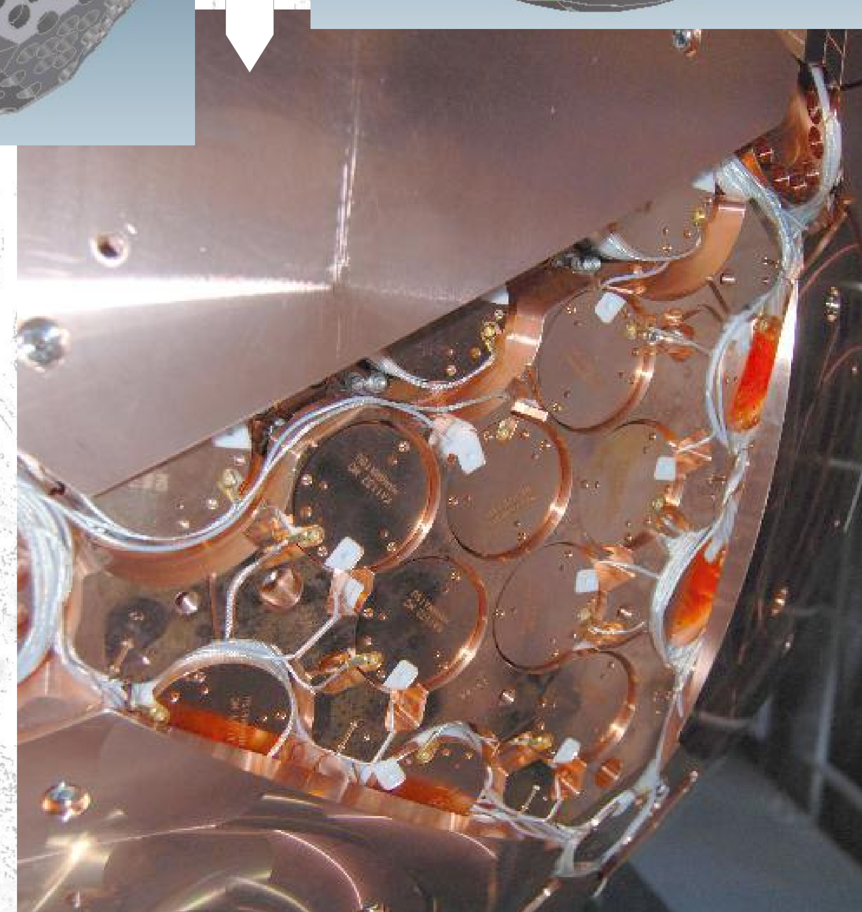
2nd LAYER



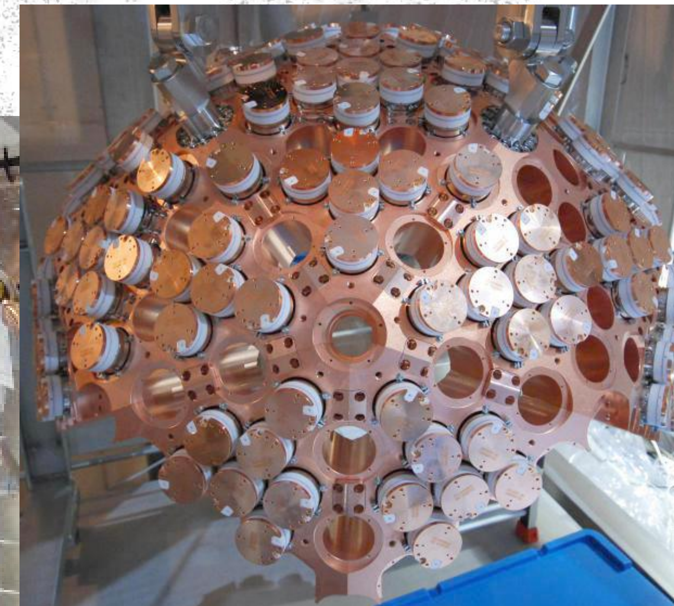
FILLER



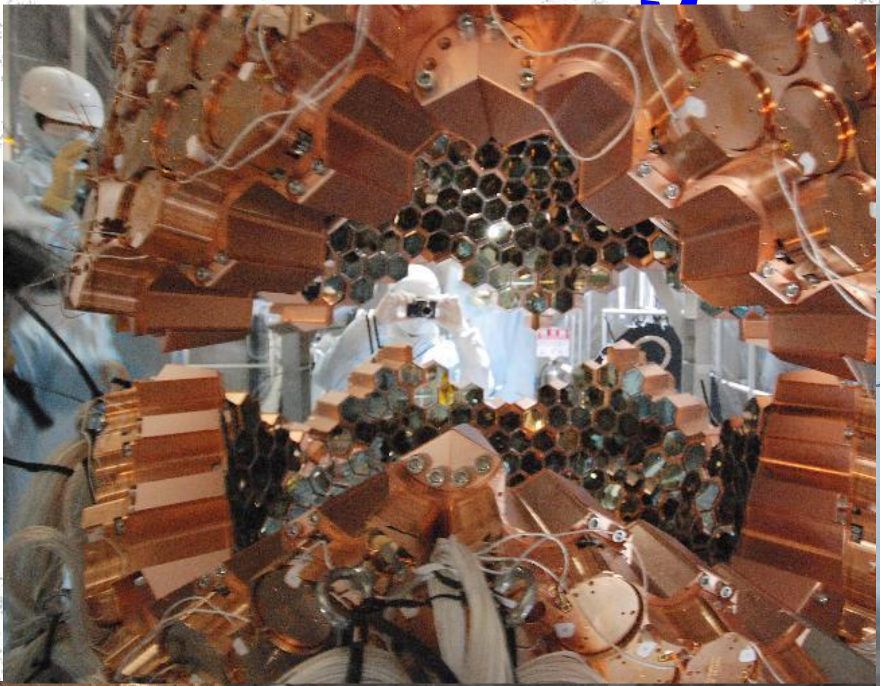


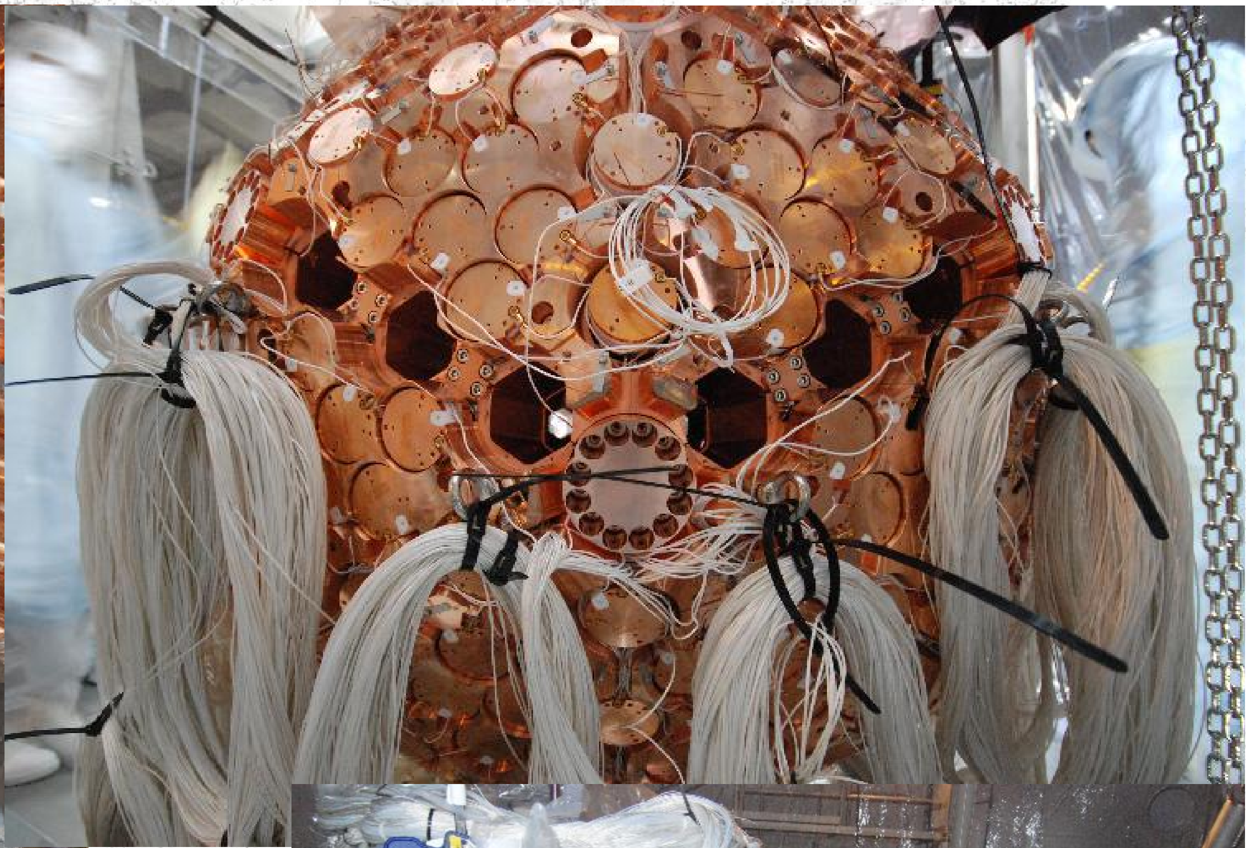


Building the Inner Detector 1:



Building the Inner Detector 2:



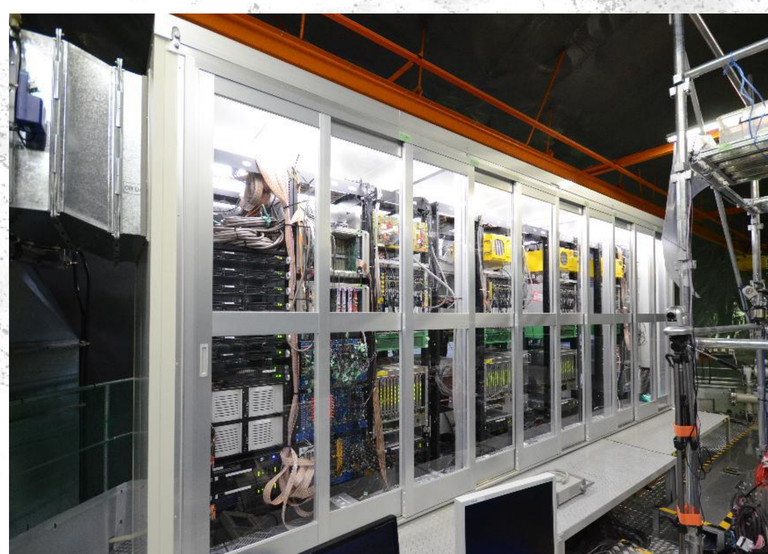


Feb ⇔ 2010

Electronics:

Super-Kamiokande ATM:

12 bit ADC/TDC
integration: -100ns – +300ns
1.2 μs window



new: FADCs

CAEN V1751
8 ch/board
bandwidth 500MHz,
sampling rate 1GS/s
resolution 10bit
1.2 μs window

Low BG PMT Development:

BG: biggest worry → PMT

great development:

U < 1.0
Th< 0.94
K < 9.68
Co = 4.47±0.34

630 hexagonal + 12 round) PMTs:

Hamamatsu R10789: QE 28-39%
+
XMASS photocathode coverage: 62.4%

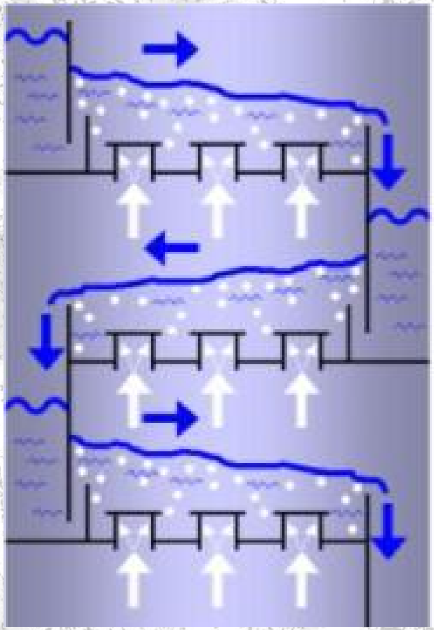
Xe Distillation: $^{(85)}$Kr Removal

otherwise:
extensive materials validation before construction:

IPMU Lab:
U, Th → HP-Ge ← few 100ppt
→ ICP-MS ← 1ppq*
Kr → API-MS ← 1ppt*
* after concentration

experience:
detector stable w/o:
- routine getter operation
- active Rn removal

hall C distillation system:
(used before filling detector)



K.Abe et al, Astroparticle Physics 31(2009), p290

capacity of XMASS Xe distillation system:
6kg/h; did 1 ton in ~ 1 week → (3.3±1.1)ppt

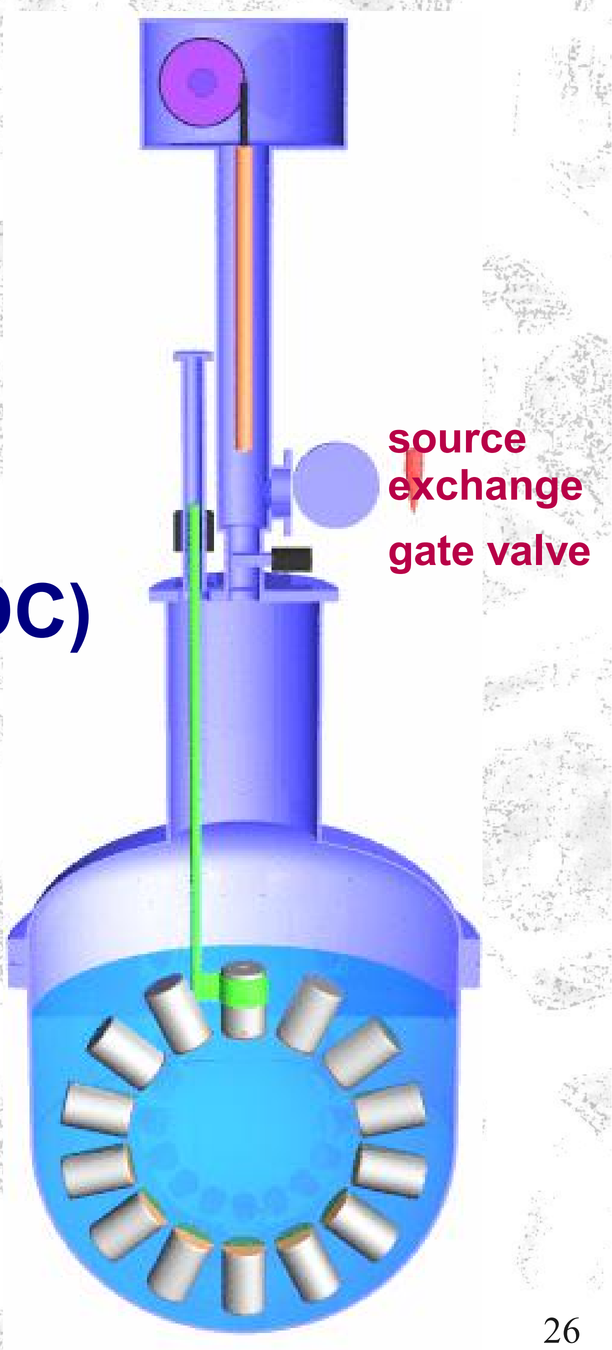
XMASS Calibration System:

"internal" γ calibration for XMASS:

- ^{57}Co (122keV) ← main anchor of energy scale
- ^{241}Am (59.5keV), ^{109}Cd (88keV), ^{55}Fe (5.9keV)

"external" (hose)

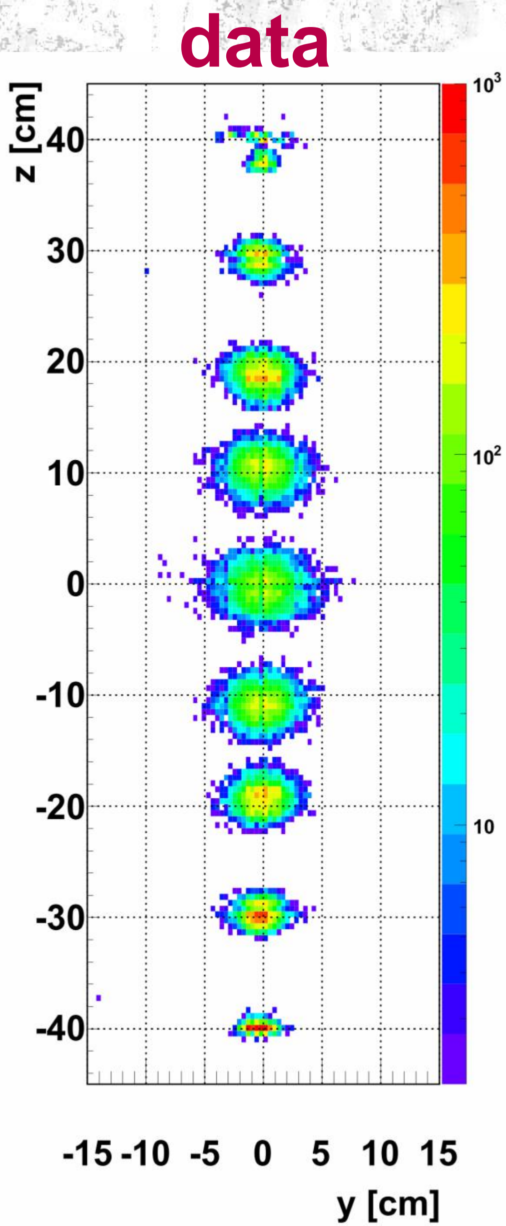
- ^{60}Co, ^{137}Cs
- ^{252}Cf neutron calibration (needs FADC)

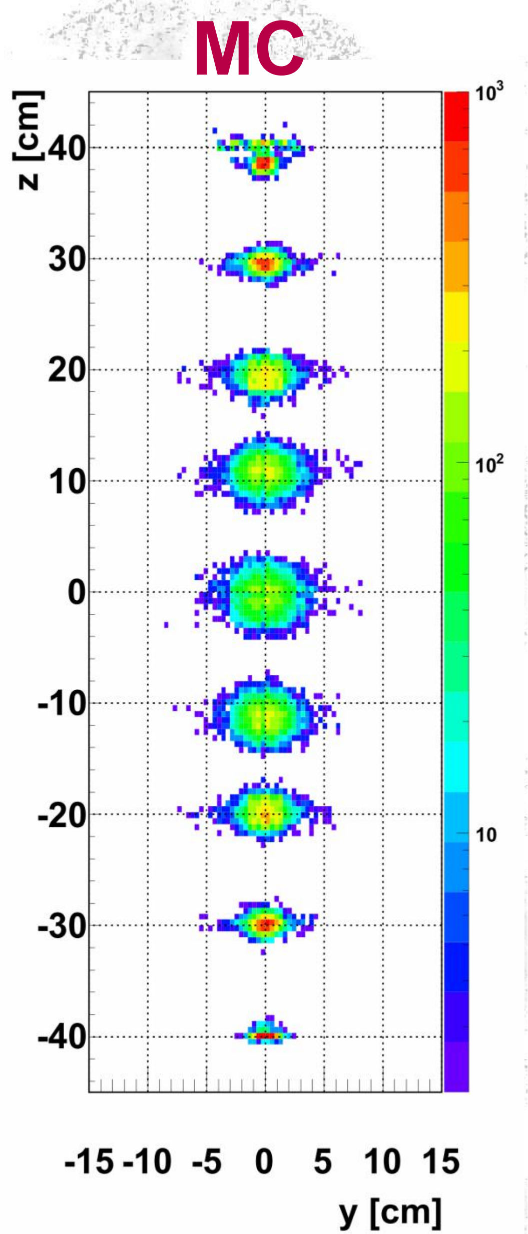


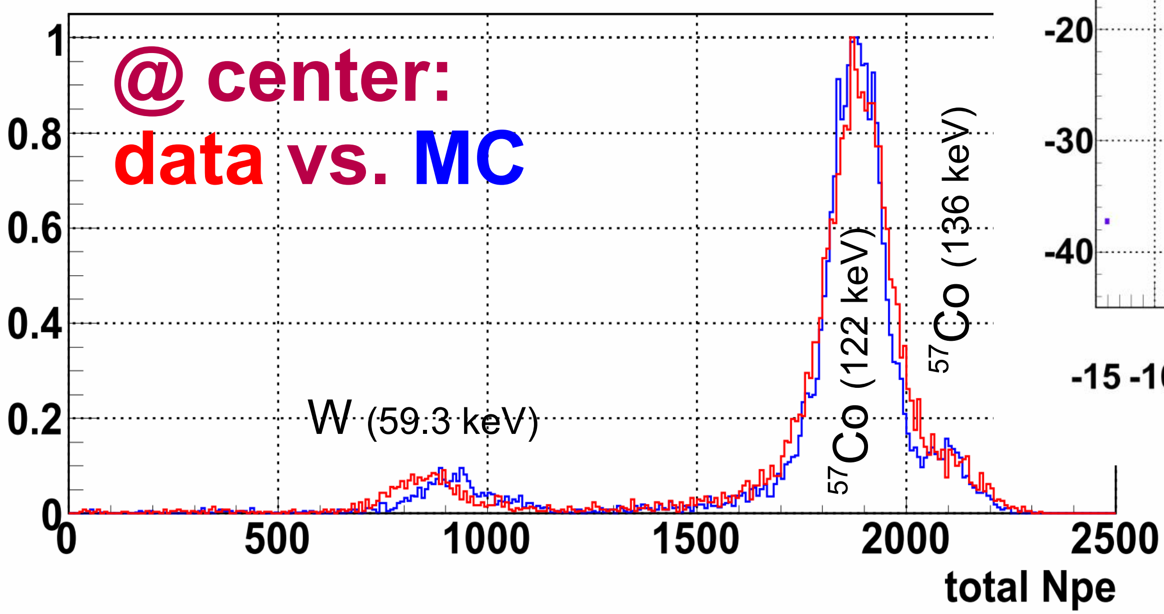
^{57}Co Calibration:

center position sets energy scale:
$\rightarrow$ 14.7 p.e./keV$_{ee}$
resolution 4% rms

reconstruction:



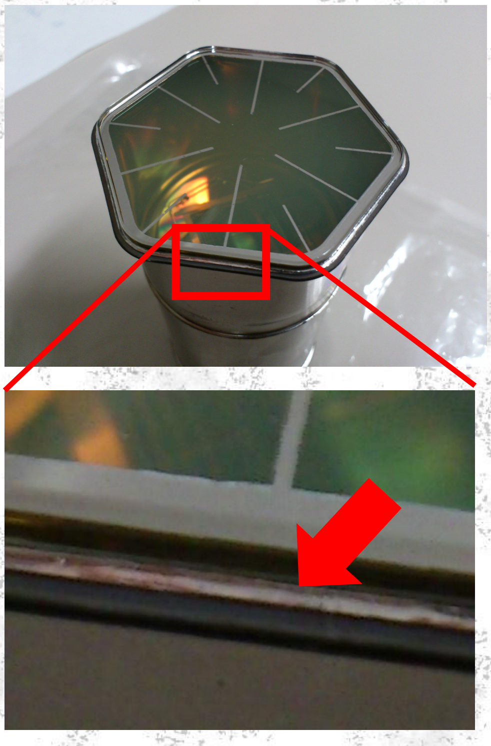




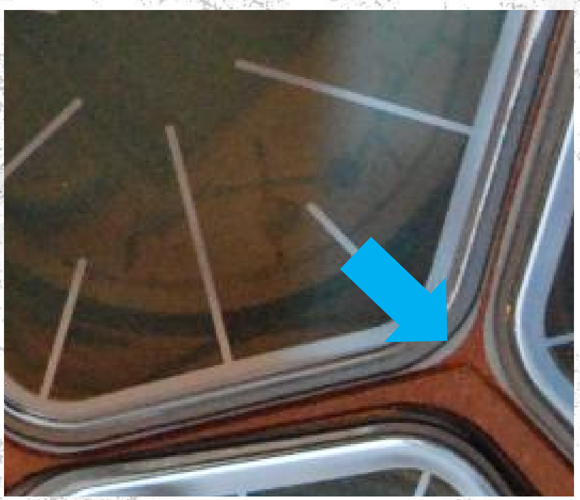
BG: The Likely Culprits:

unexpected BG observed
from “surface between” PMTs:

α,β from “local” materials ?!



Al seal for PMT window:
^{238}U and ^{210}Pb (not in secular equilibrium)

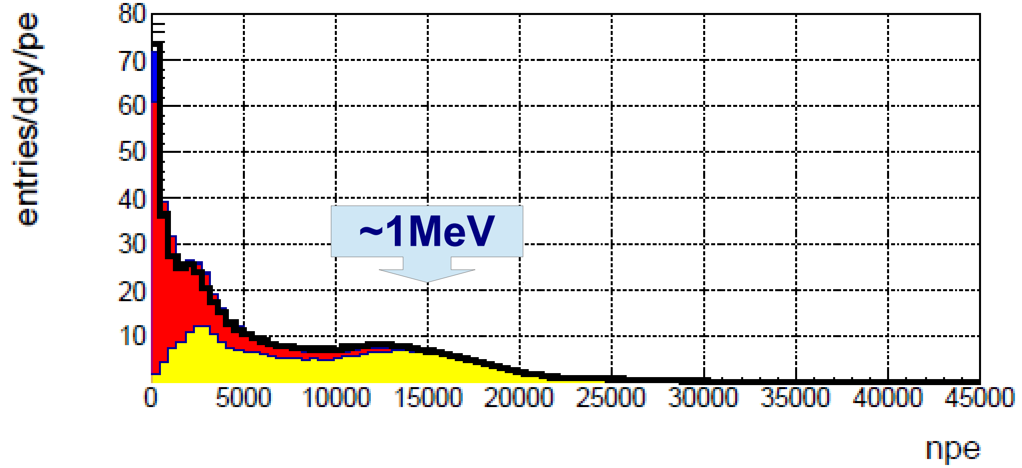


Gore-Tex (light barrier) under PMT rim:
may contain up to
6% modern carbon

Background and Its Sources 1:

higher energies (0.1-3MeV):

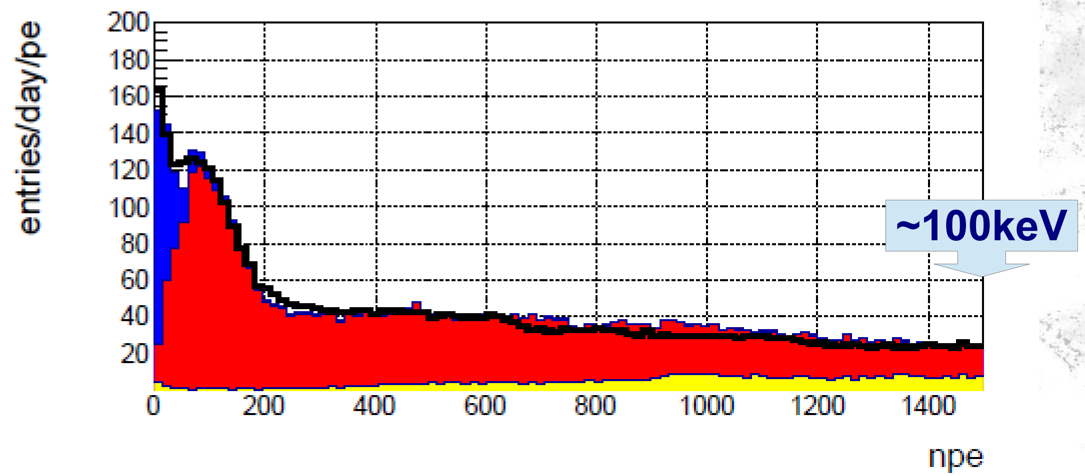
understood: γ from PMTs consistent w/Ge



histogram: data
MC: ^{210}Pb on Al
MC: PMT gammas

mid energies (5keV-1MeV):

understood: α,β on surface consistent w/Ge



Background < 5keV (XMASS design thres.)

under study …

<u>one</u> hypothesis:

some ^{14}C in Gore-Tex???
(modern carbon)

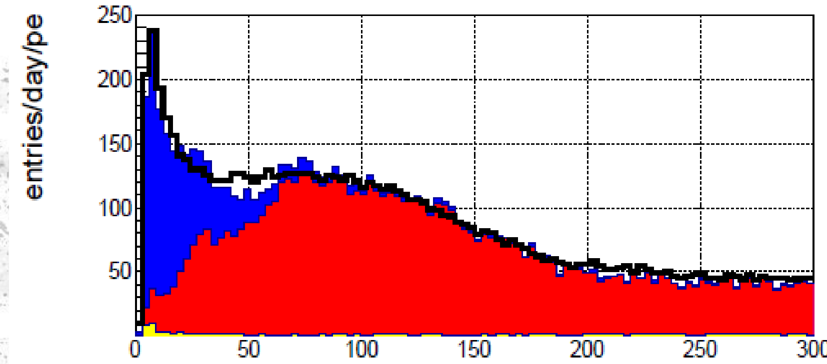
<u>if so:</u>

what assumption about light propagation and generation INSIDE the Gore-Tex material???

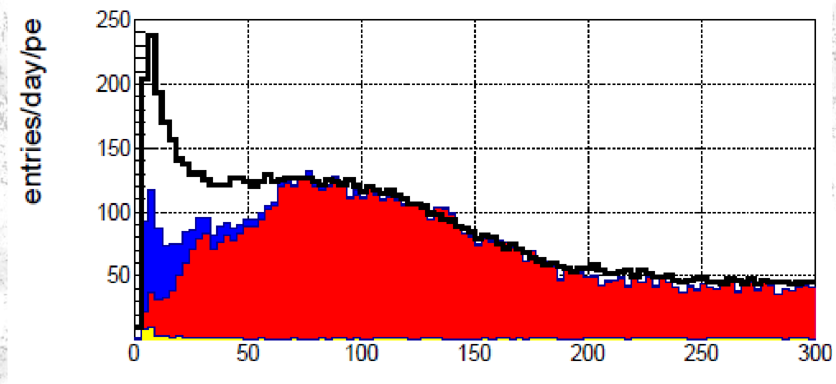
<u>shown:</u> two assumptions:

both:	**generation: LXe**
top:	**0.3mm att. length**
bot:	**0.1mm att. length**

wrong tree? (as in: barking up the …)



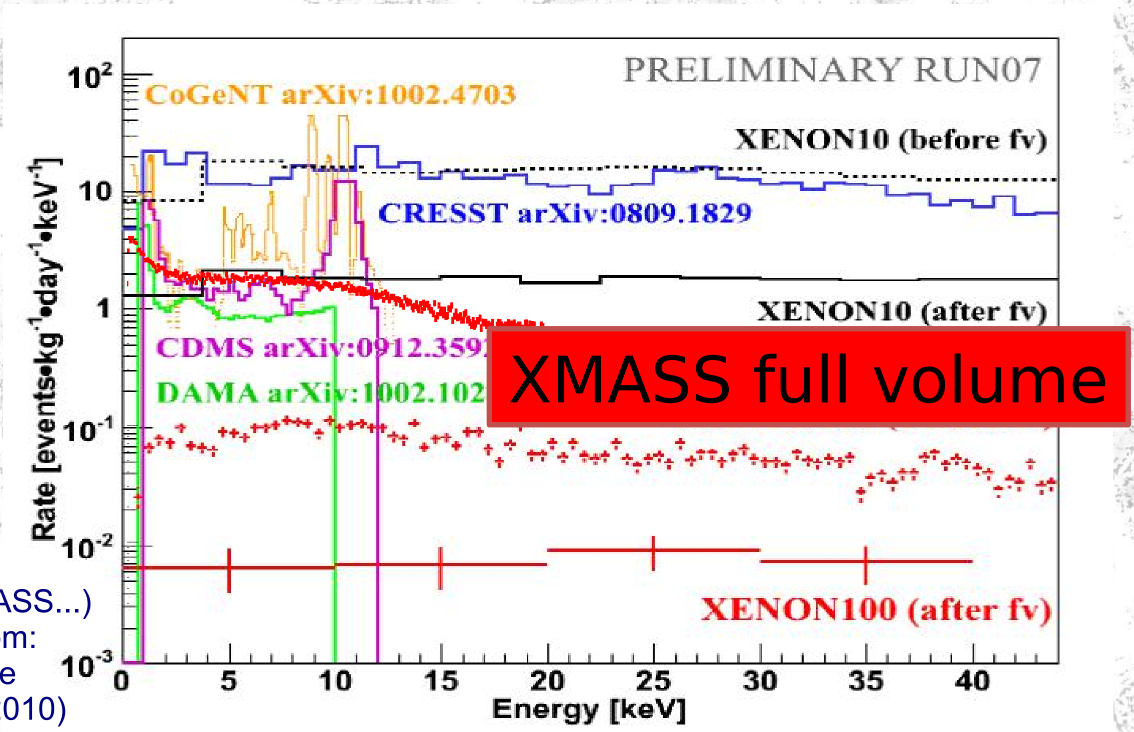
histogram: data
MC: ^{210}Pb on Al
MC: ^{14}C in Gore-Tex



The Good News: BG (Low), <u>LY high</u>

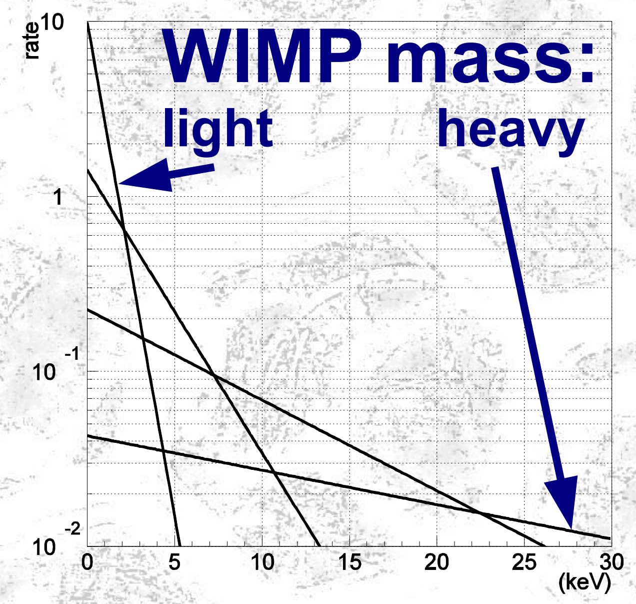
(still optimizing: reduce leakage of surface events into FV)

but:



graph (- XMASS...) taken from: E. Aprile (Princton 2010)

cum grano salis:



high light yield (LY) → low threshold → <u>go for light WIMPs</u>

(heavy WIMPs → large A → large cross section → to come)

Light WIMPs: Full Volume, Low Threshold

playing to our strength:

full volume = 835kg
4 hit threshold = 6.8 days

our limit: maximally allowed cross section: MC prediction < data

backgrounds considered: **cuts applied:**

backgrounds considered		cuts applied
- no OD activity	→	ID trigger only
- no afterpulse activity	→	timing RMS < 100ns
- Cherenkov (^{40}K in photocathode)	→	q(20ns)/q(total) < 0.6
- ringing, radioactivity	→	$\pm\,\Delta t > 10$ms

systematics accounted for:

L_{eff}, energy resolution & scale, trigger efficiency, cuts

Cherenkov Cut

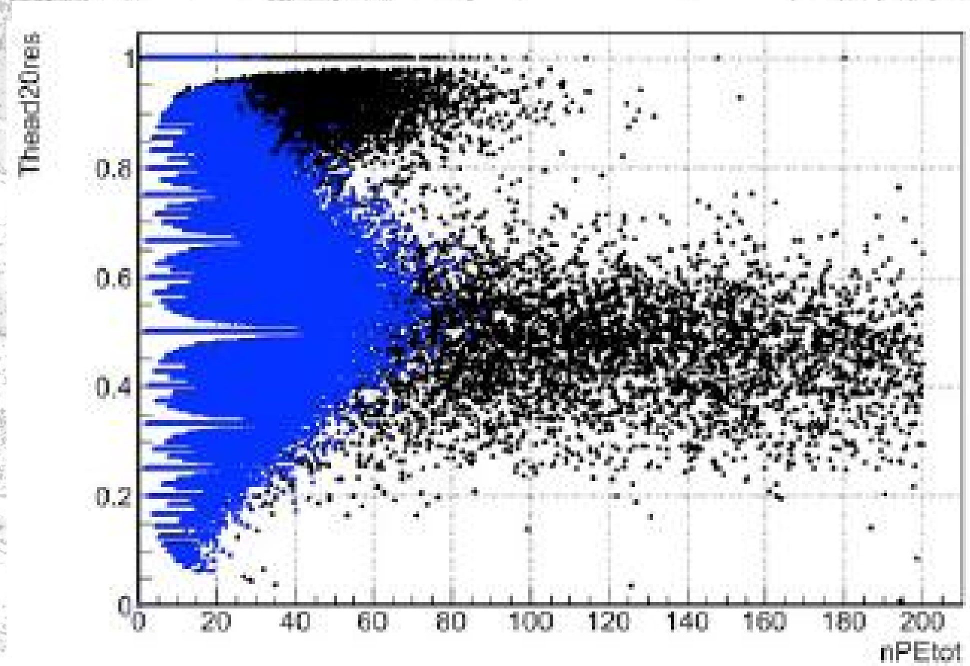
Cherenkov light emission in PMT glass (^{40}K, …)

Cherenkov photons emitted "immediately":
→ timing structure by PMT timing resolution (~3.5ns)
scintillation events:
→ time constant τ ~ 25ns (low energy γ and nucl. recoil)

cut parameter:

$$\frac{\text{charge(first 20ns)}}{\text{charge(total)}}$$

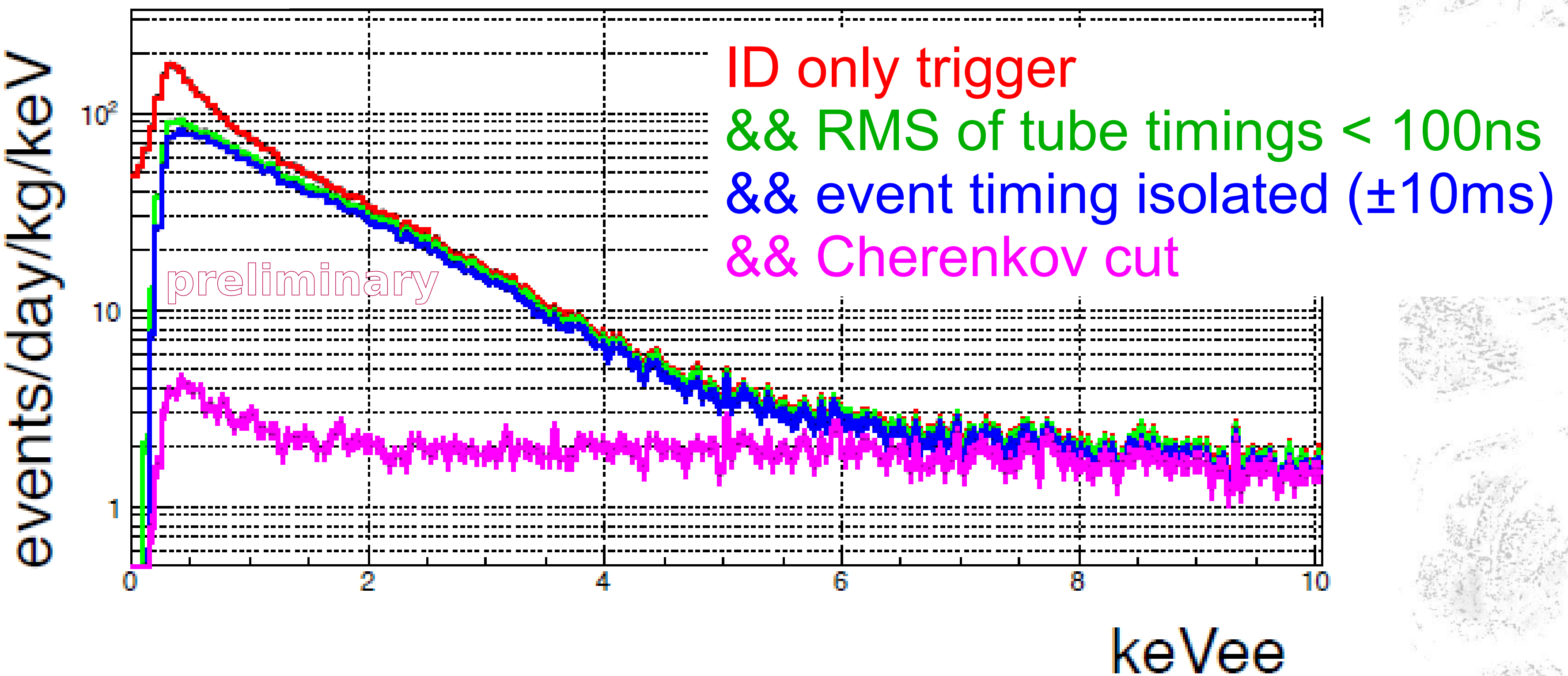
keep < 0.6



efficiency varies with p.e. range: 40% – 70%

XMASS Full Volume (835kg): Low Mass WIMPs

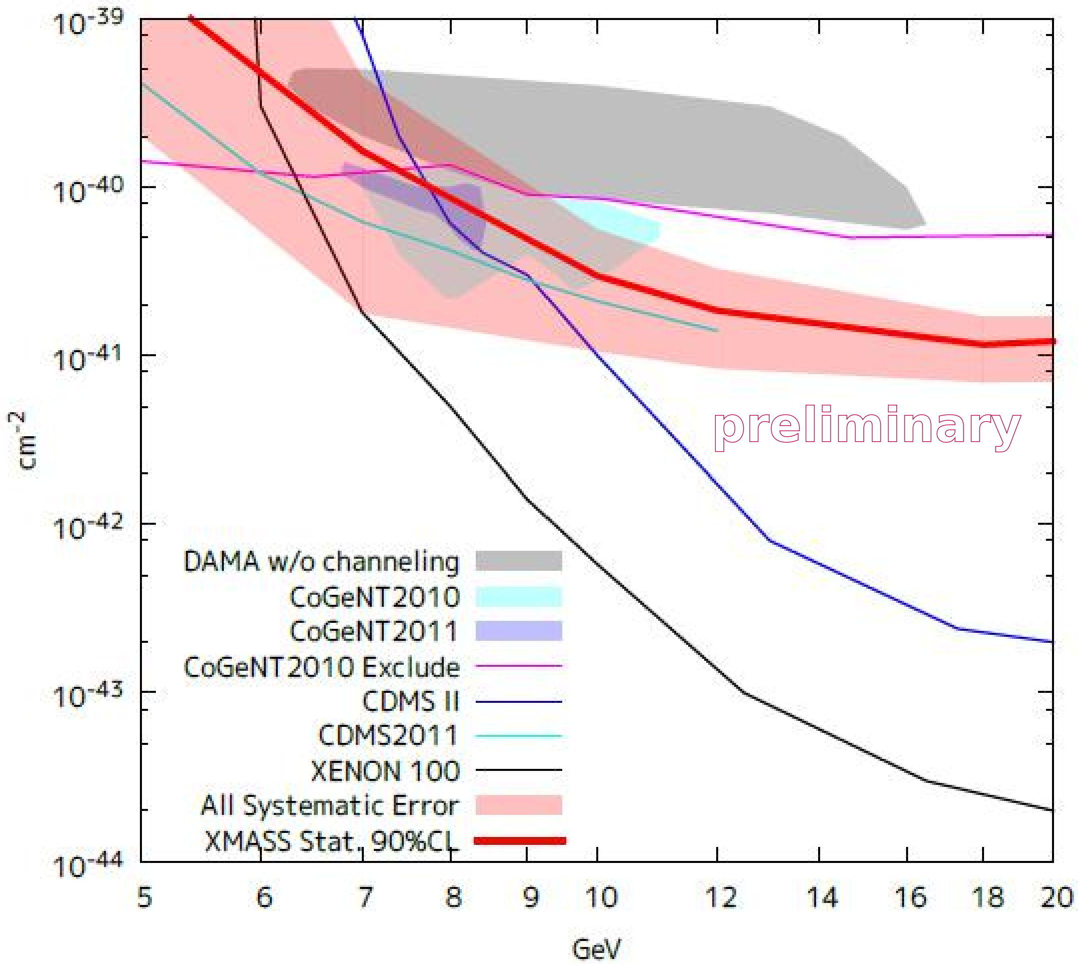
data set: 6.8 days of low threshold data



XMASS Result 1:

systematic contributions:
(in order of importance)

- L_{eff} uncertainty *
- energy resolution
- trigger efficiency
- energy scale
- Cherenkov cut



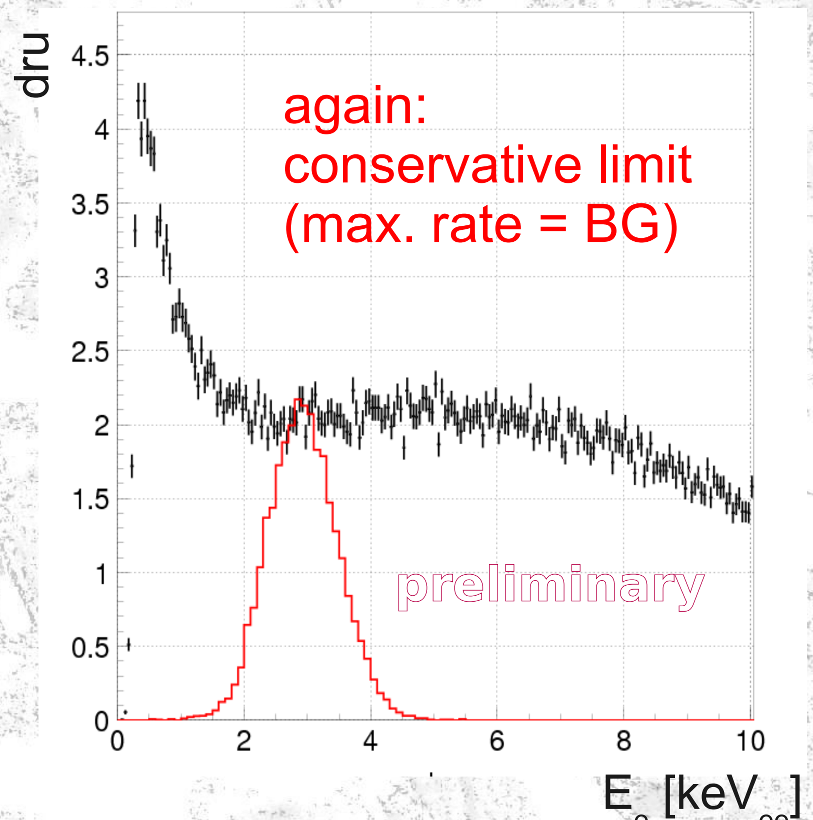
* following arXiv 1203.1589 (Xe100)

XMASS Full Volume (835kg): Pseudoscalar by Axioelectric Effect

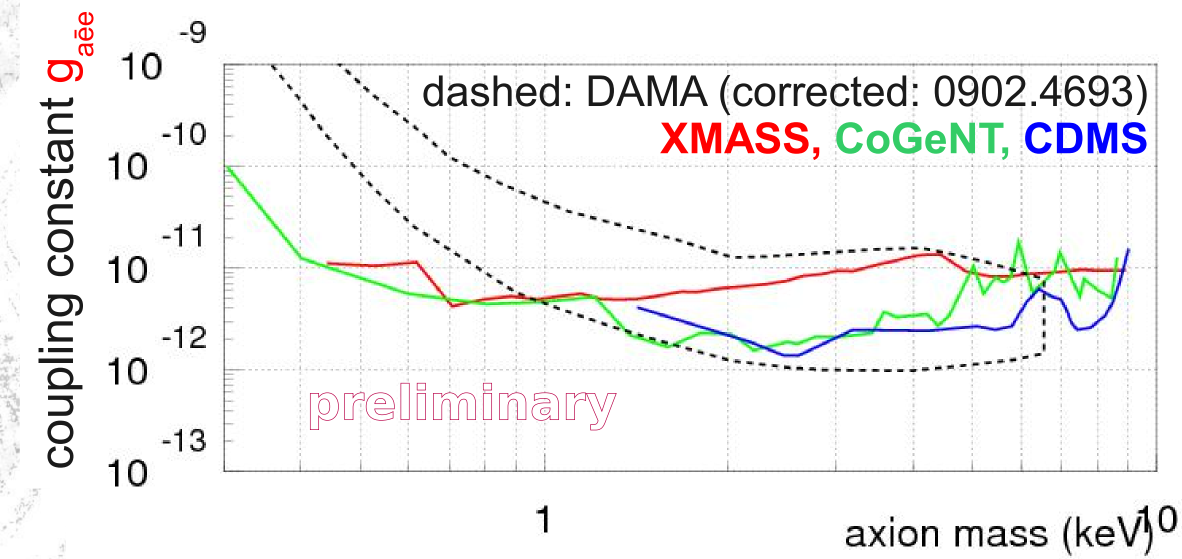
originally pursued to explain DAMA vs. nucl. recoil;

rate: $R[kg^{-1}d^{-1}] = 1.2\times10^{19}A^{-1}g^2_{a\bar{e}e}\,m_a p\sigma_{pe}$

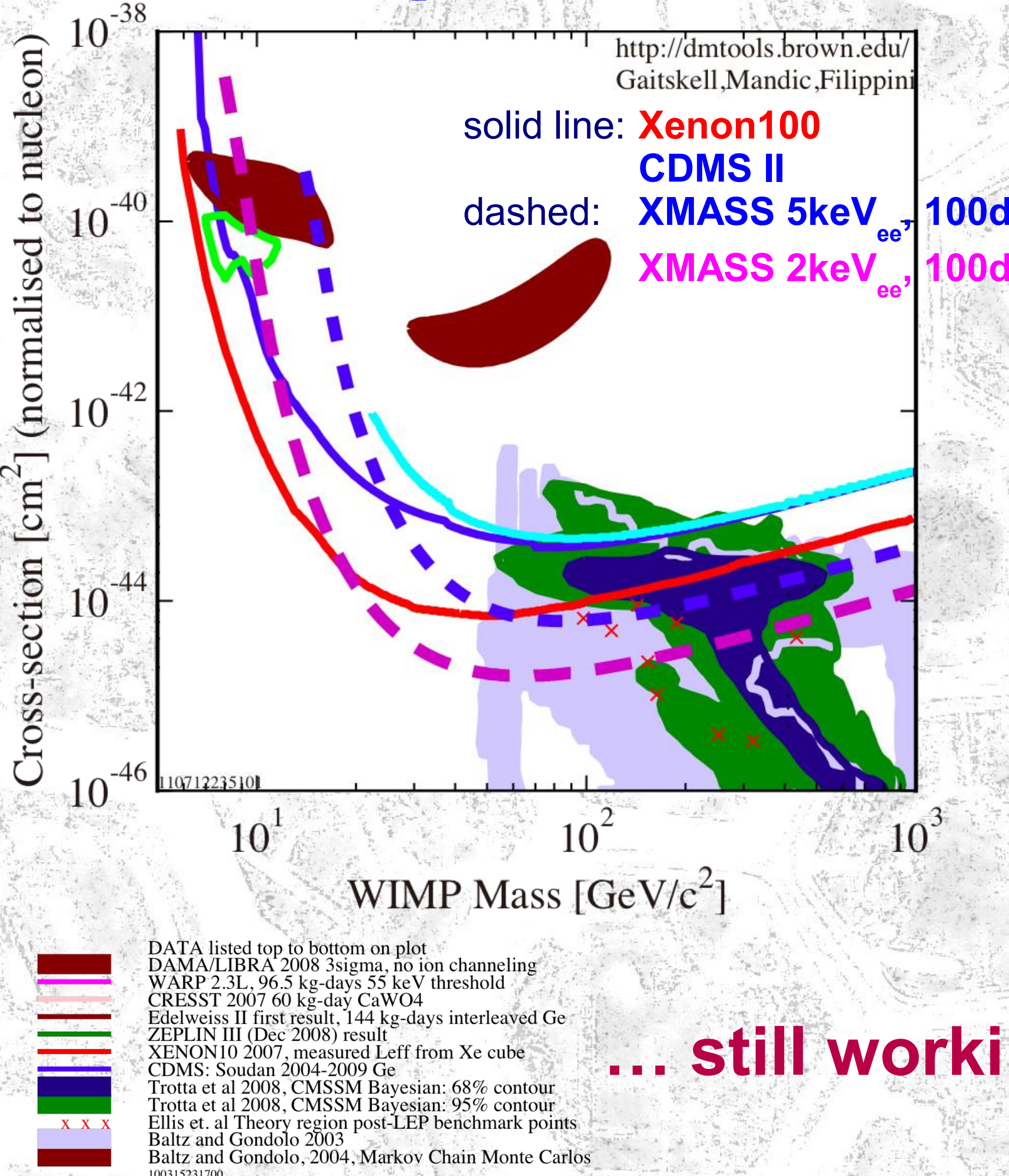
but: **photoelectric cross section σ_{pe} ~ 1/v …**



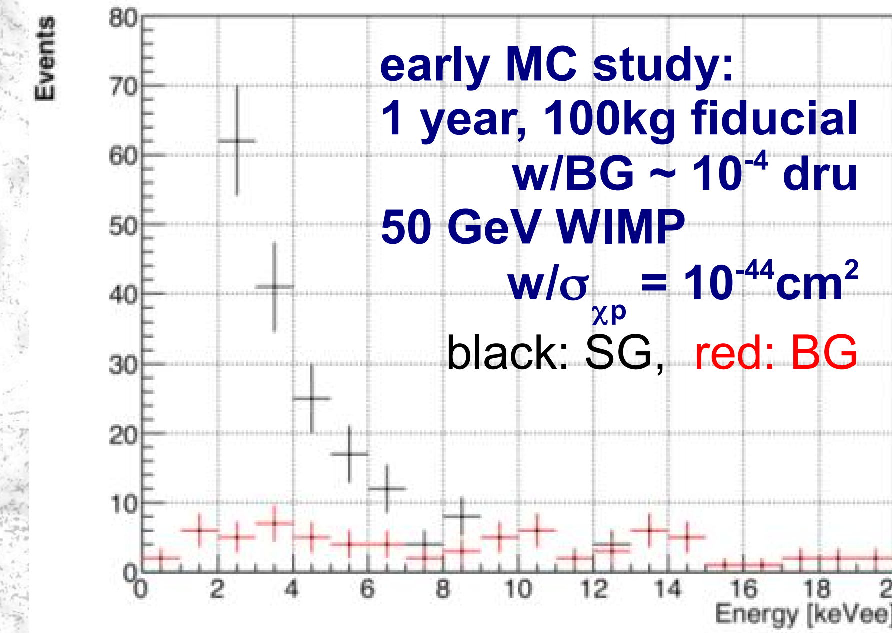
(from astro-ph/0511252)



Prospects with Fiducialization:

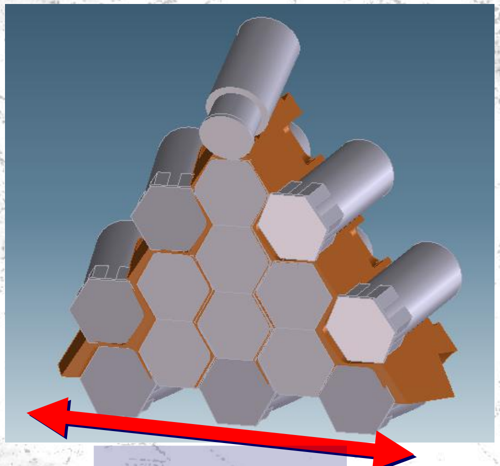


high light yield allows lower threshold



… still working on "surface leakage" …

Refurbishment:



in preparation:

- latter half of this year

lines of attack:

- Cu surface cleanup → electropolish to “rm -r U* Th*”
- light barrier (Cu cover) for PMT Al seal ← MC study
- remove Gore-Tex (presumed guilty until proven innocent …)

Conclusions

XMASS 800kg completed first commissioning phase:

- exceptional light yield: 14.7 PE/keV$_{ee}$
- still analyzing data (stay tuned...)
- backgrounds largely understood

preparing for detector refurbishment:

- surface cleaning
- modification of inter-PMT spaces

→ resume data taking with reduced surface BG & FADC - early next year.

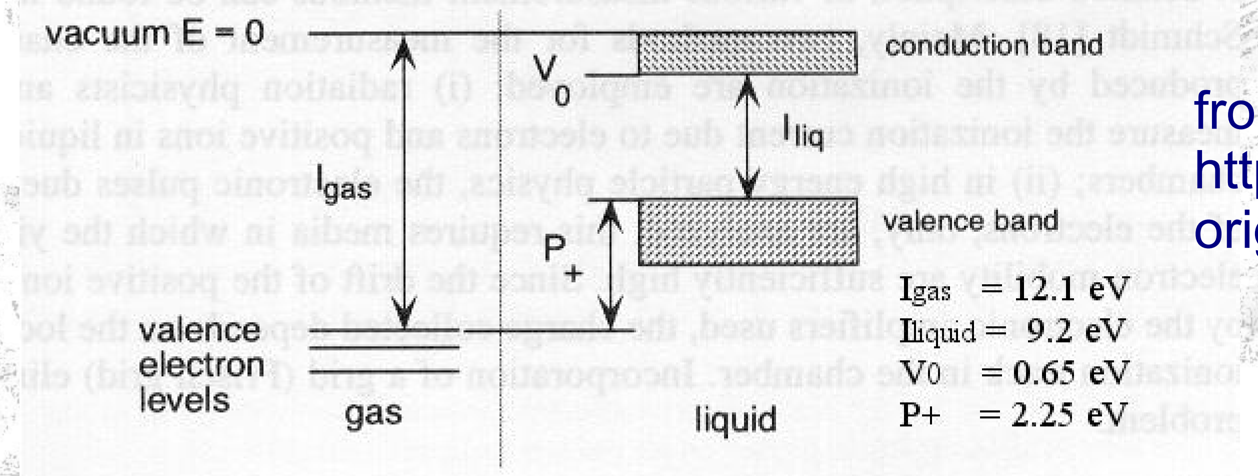
Results (so far): light WIMP limit, axio-electric cross section limit
more to come → stay tuned...

also:
Starting to plan for 5 ton version of XMASS: XMASS 1.5

On Rn Removal from Liquid Phase

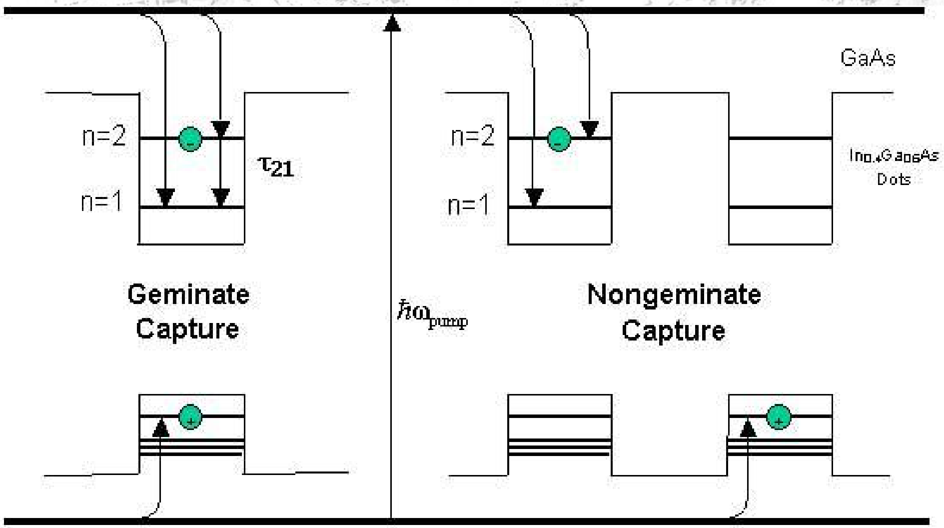
tested: **charcoal trap** (NIM A 661 (2012) p. 50-57)

new idea: **charge sweep**



from:
http://www.pd.infn.it/~conti/LXe.html
original Werner F. Schmidt

in solids: atoms in lattice
→ electron/hole trapped
in fluids: atoms moving
→ “ions” drifting



Info from Relevant Literature:

Radiation Phys&Chem 74 (2005) 152: The mobility of positive and negative ions in liquid xenon (W.F. Schmidt, O. Hilt et al.)
→ TMSi+: 8cm/s @ 40kV/cm , O2- 10cm/s @ 15kV/cm

NIM A 555 (2005) 205: Mobility of thorium ions in liquid xenon (K. Wamba et al.) → ion drift 1cm/s @ 4kV/cm

thesis Oliver Hilt:
Electronische und ionische Leitungsprozesse in flüssigem Xenon

Hole Drift and LXe Flow:

(holes would likely be relevant for Rn removal...)

hole mobility @ 170K: 3.7e-3 cm2V-1s-1
electric field strength: 3kV/cm → v_{h+} = 11cm/s

positive ion mobility: ~ 0.1e-3 – 0.2e-3 cm2/V/s → v_{I+} ~ 0.5 cm/s

cleaning volume: 1cm x 4cm cross section,
1l/min = 1000cm^3/min; 4cm^2 cross section → flow ~ 4cm/s

maximal drift time for positive ions: 2s → flow carries 8cm....

total length ~ 10cm → collision time constant ~ 0.5 sec (2cm)

Hole Attachment Kinematics:

k_+: reaction constant for charge transfer from hole to molecule/atom;
change in number n_{Rn} of Rn atoms in a hole concentration n_h:

$$dn_{Rn} = n_h k_+ n_{Rn} dt$$

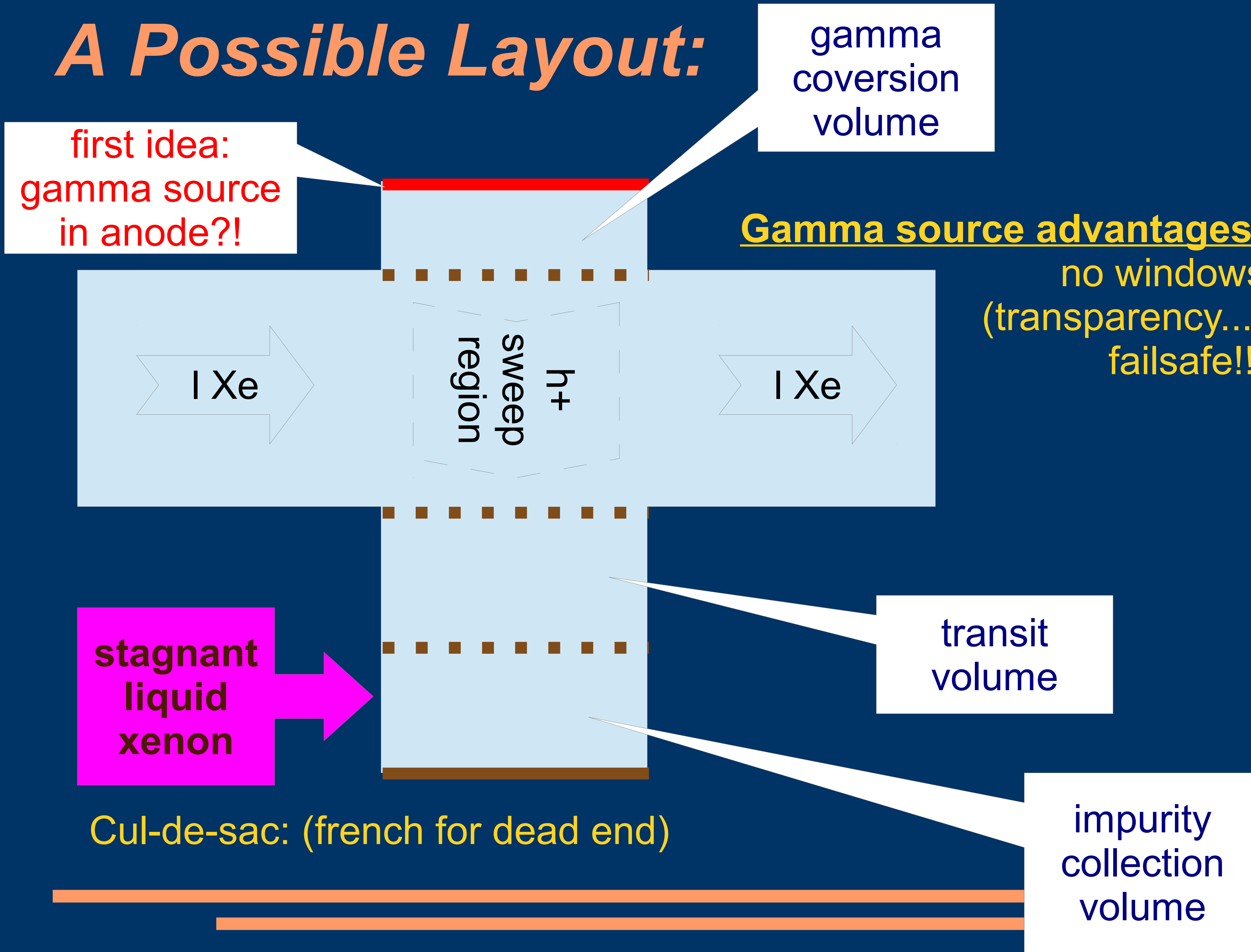
solution: $n_{Rn}(t) = n_0 \exp(-k_+ n_h t)$ $\longrightarrow$ time constant: $\tau = 1/(k_+ n_h)$

little known in lXe; guidance from measurements in other materials ($CCl_4^+ \longrightarrow C_nH_m^+$ in different liquid alkanes...):

$\longrightarrow$ $k_+ \sim 1e\text{-}11 cm^3/s$ from before: $\tau < 0.5s$ (2cm flow)

$\longrightarrow$ $n_h > 1/(k_+ \tau) = 2e11/cm^3$

A Possible Layout:



Gamma source advantages:

no windows
(transparency...)
failsafe!!!

Cul-de-sac: (french for dead end)

Creating e^-/h^+ Pairs in Liquid Xenon

Hole drift: ~10cm/s @ 3kV/cm; we need $2e11h^+/cm^3$
$\rightarrow$ need to produce $2e12h^+/s/cm^2$

mean energy required to produce e-/h+ pair: W = 15.4eV

^{55}Fe: 6keV / 15eV = 400 h^+
$\rightarrow$ ~ 5 GBq
^{207}Bi: 1.6MeV/15eV = 110,000 h^+
$\rightarrow$ ~ 18MBq

IF all go into 1cm2 ...

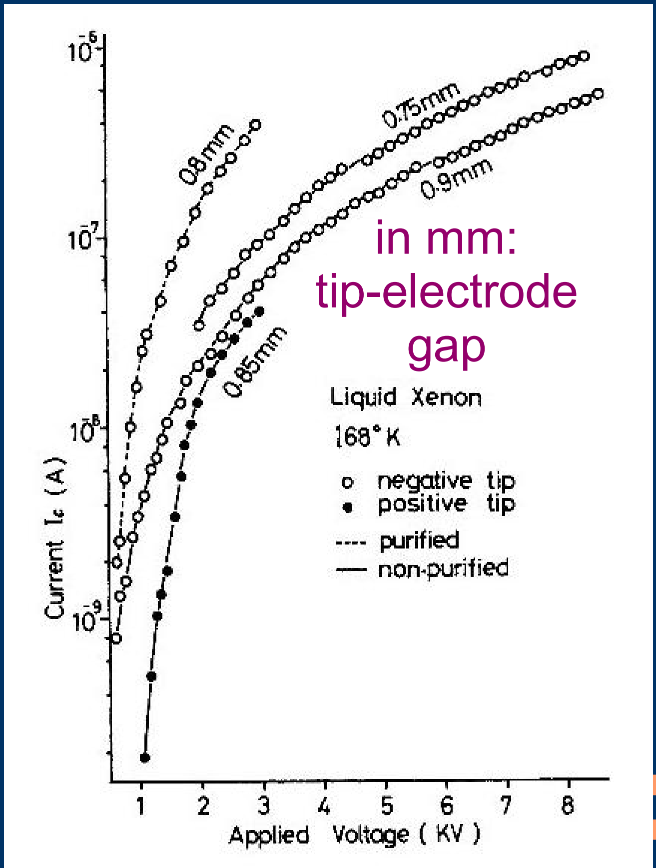
Conclusion: not workable!

Solution: Hole injection by field emission; done in lAr & lXe:
IEEE Transactions Vol. EI-19, Feb. 1984; Arii + Schmidt

Hole Injection in lXe:

From: IEEE Transactions on Electrical Insulation Vol. EI-19, Feb 1984
K. Arii & W.F. Schmidt: Current Injection and Light Emission in Liquid Argon and Xenon in a Divergent Electric Field

problem with article above: "... A quantitative evaluation of our data is not possible since no control existed over the geometry of the tip and its change during the injection process."

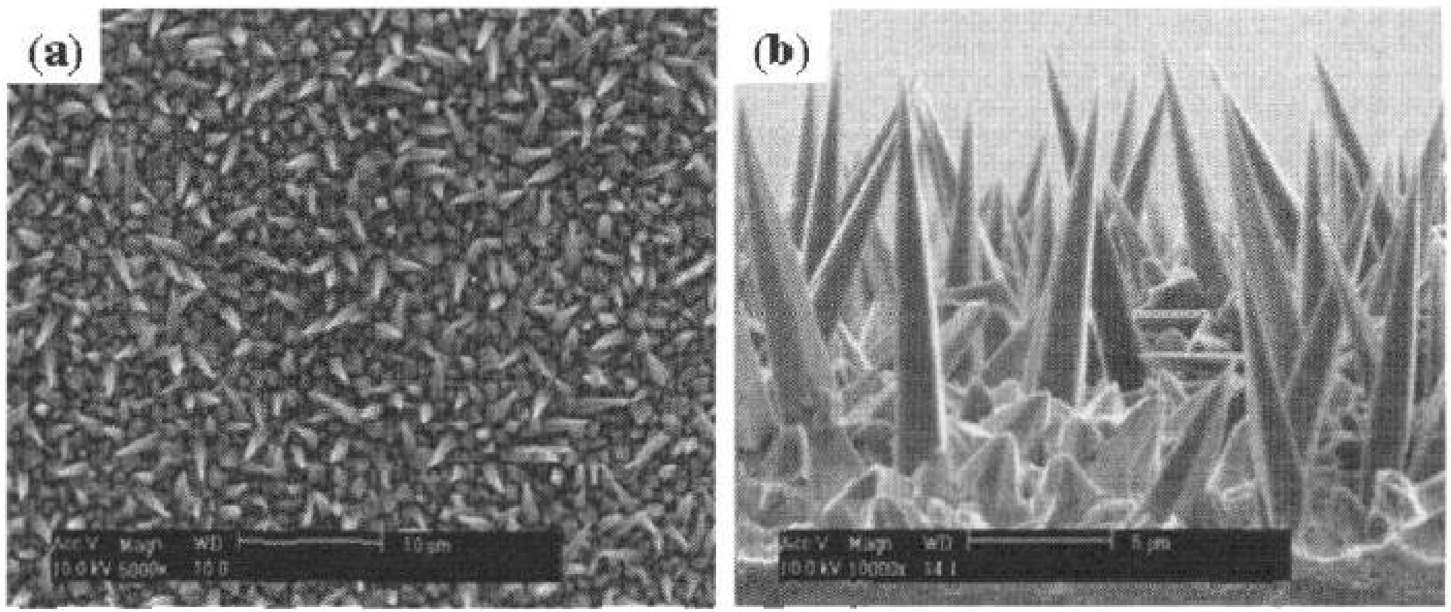


but: the principle is okay !!!
→ hole injection by field emission from tip,
→ resulting current stable.

last time: need 2e12h^+/cm^2/s; 40cm^2 (later)
→ ~ $10^{14}h^+$/s = 16μA; 1.6e-9A/tip → 10000tips

Q: uniform hole current over all volume ???

Pics from SNU, Seoul, Korea:

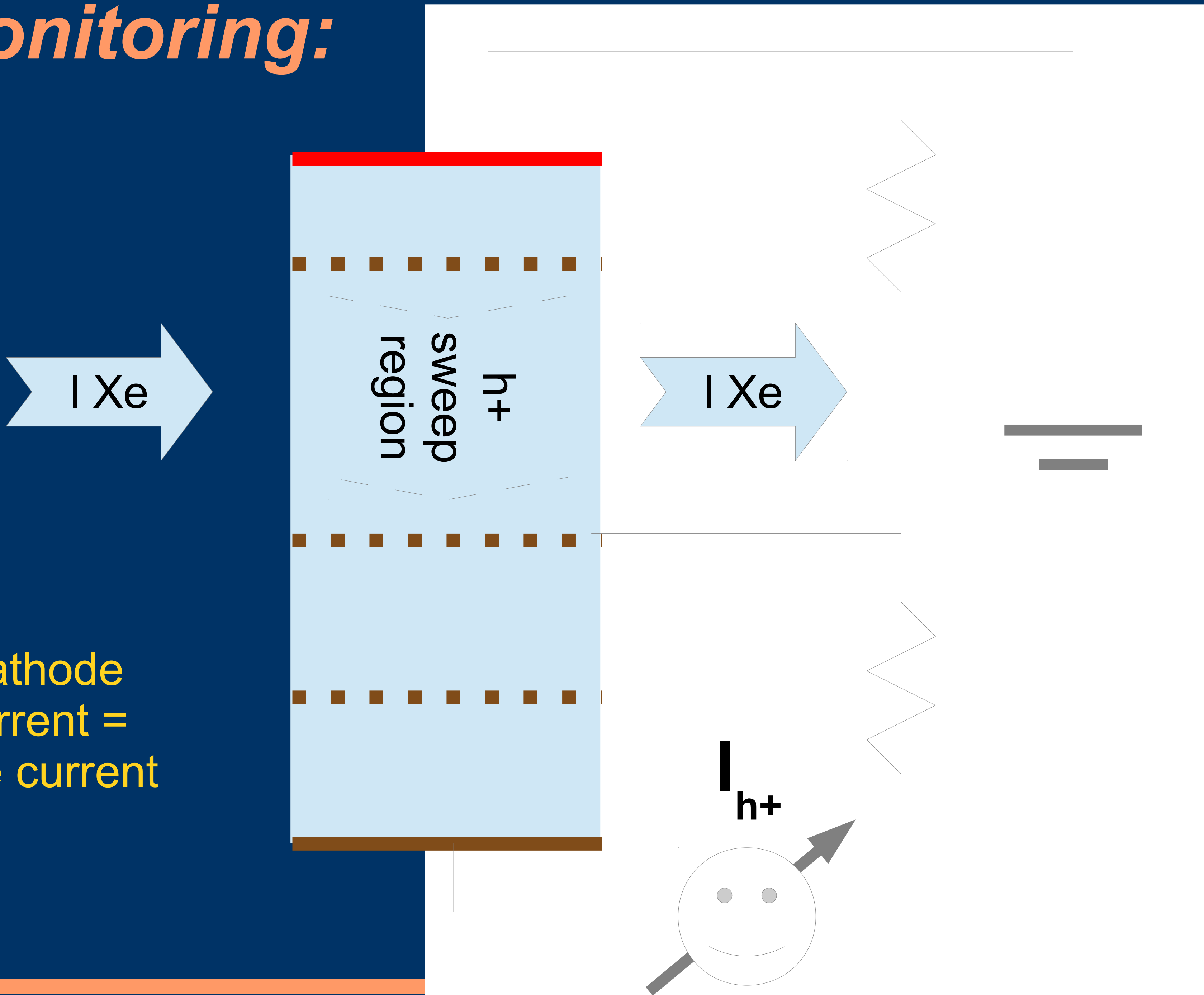


10µm 5µm

Figure 1 Copper micro-tips formed by high current pulse electroplating. (a) Top view, (b) Cross view

from: IEEE, Vacuum Nanoelectronics Conference 2006, p101+102:
Field Emission Characteristics of Carbon Nanocoils Grown on Copper Micro-tips
W.Y. Sung, W.J. Kim, S.C. Yeon, S.M. Lee, H.Y.lee, Y.H. Kim ← **in contact**

Monitoring:



Cathode current = hole current

Summary:

- drifting complicated molecules and simple atoms in both
  LXe and LAr proven and measured

- injecting both holes (positive charges) and electrons into both
  LXe and LAr proven and measured

conclusion:

- method to “move” impurities (electronegative = very easy...)
  from main liquid(!) circulation stream to smaller secondary
  stream for further treatment (e.g. evaporation and hot getter)

- questions: - can Korean Cu micro-tips be replicated?
  - are they stable over time under operating conditions

note: electrons can be generated by shining UV on metal...
that alone could take care of electronegative impurities