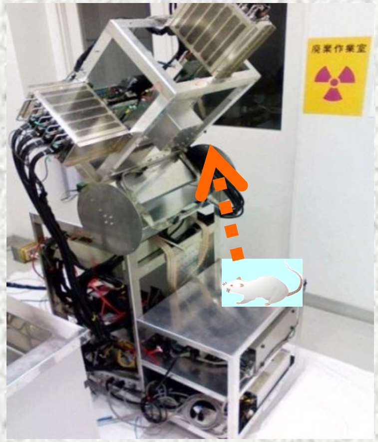
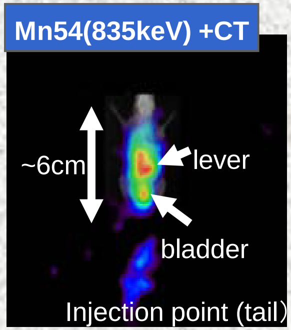
Development of electron tracking Compton camera for both balloon and future satellite experiments of MeV gamma-ray astronomy





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08/2/2012 GRB Meeting @ Extreme Universe Lab.

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- Research Institute for Sustainable Humanosphere, Kyoto Univ. A.Takada
- KEK, Ibaraki, Japan ; M.Ikeno, M.Tanaka, and T.Uchida[b]
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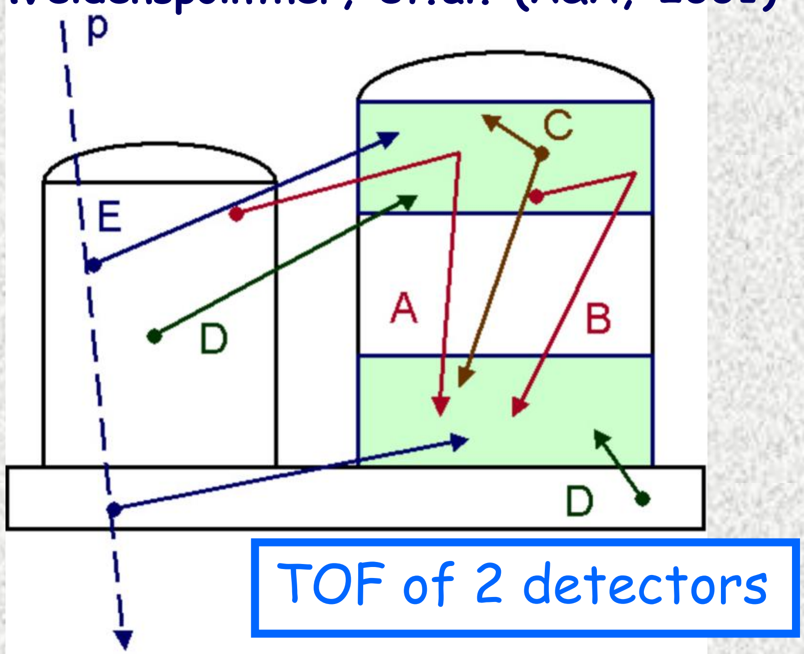
- Swedish Institute of Space Physics (IRF) :M.Yamauchi
- EISCAT : E. Turunen

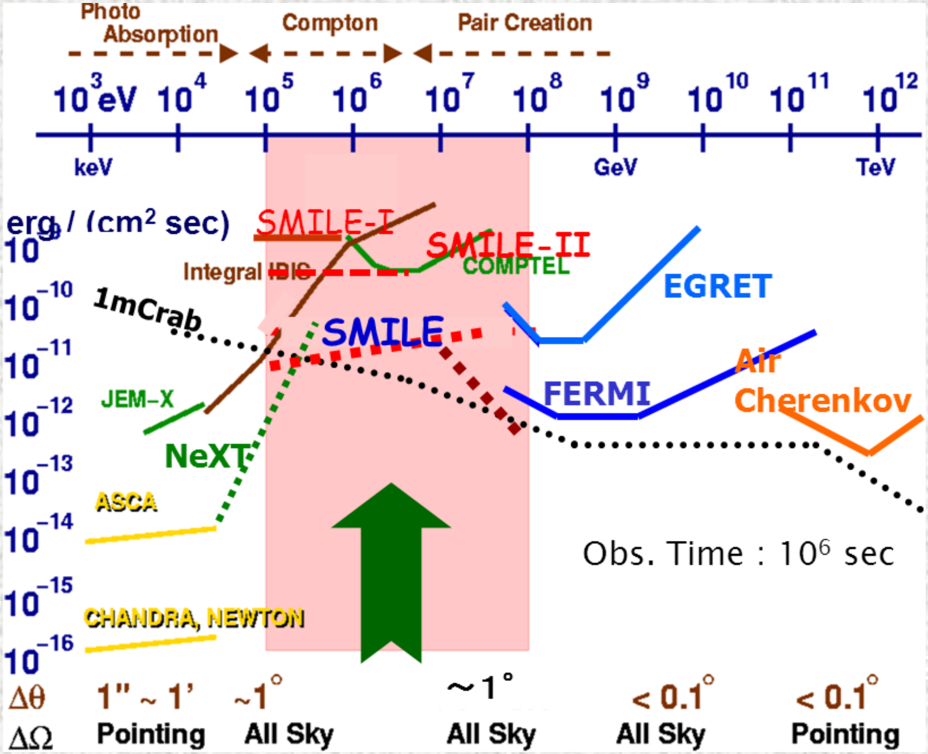
CONTENS

1. Review of Electron Tracking Camera & SMILE-I experiment
2. SIMLE-II balloon-Experiment around the North Pole
3. What can ETCC do to detect high-z GRB?
4. Terrestrial Gamma ray bursts
5. Summary

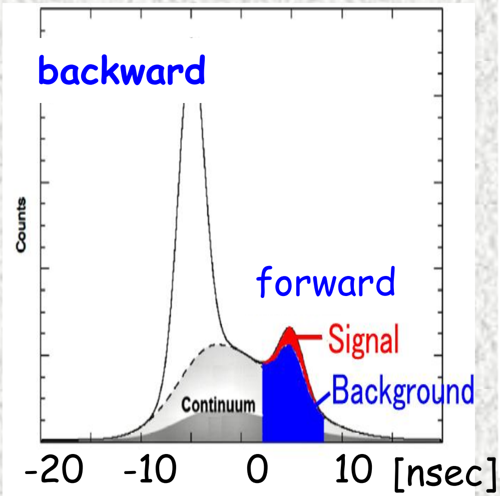
MeV Astronomy

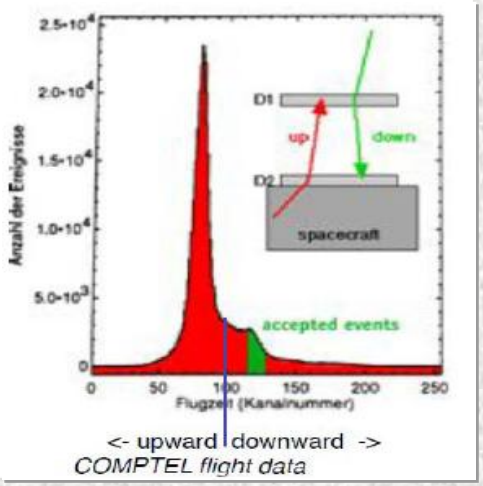
G.Weidenspointner, et.al. (A&A, 2001)





Effective Area =13cm²@1MeV





Line γ

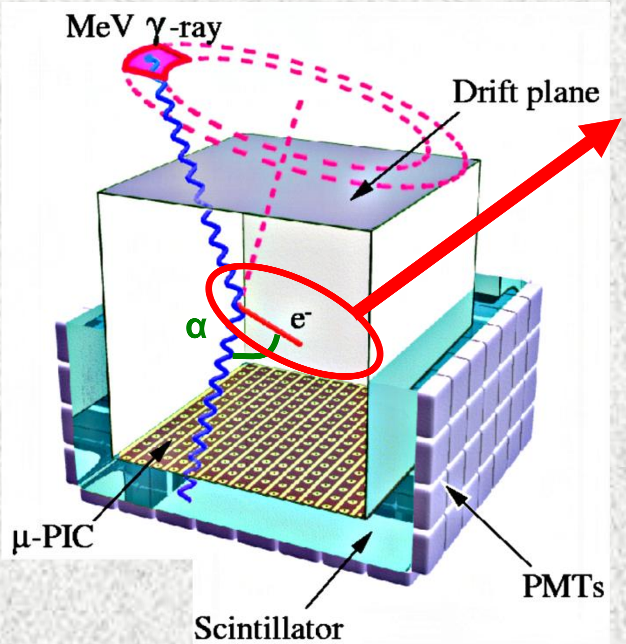
- Nucleosynthesis

  ^{26}Al・^{60}Fe, 511 keV

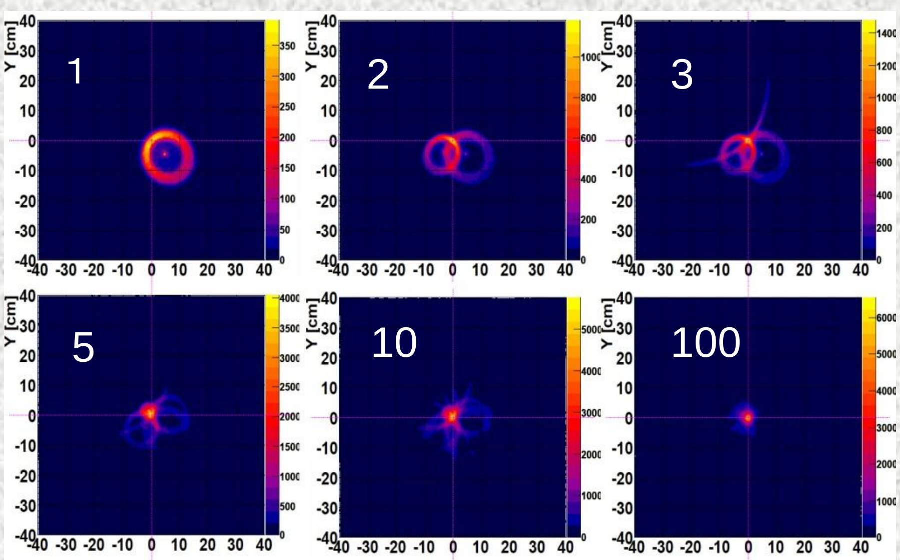
Continuum γ

- Strong Gravitational Potential (BH)
- Cosmic ray ; particle acceleration
- High-z **GRB**
- Terrestrial Gamma bursts

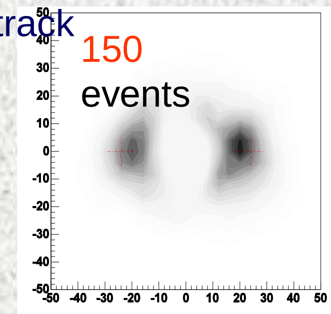
Electron Tracking Compton Camera(ETCC)



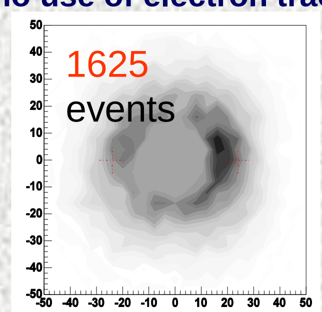
1. Determination of the direction of each gamma ray
2. Noise Reduction by Kinematics(α)
3. Large FoV. ~3str
4. For All Sky MeV-γ Survey with >10 better than COMPTEL

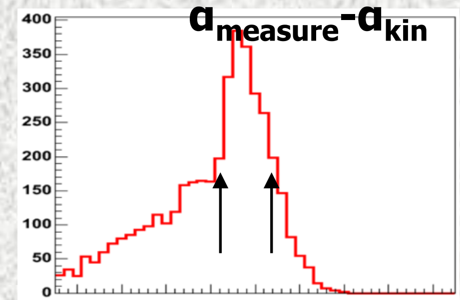


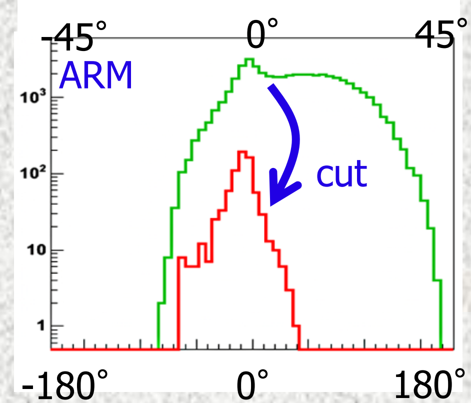
In use of electron track



no use of electron track

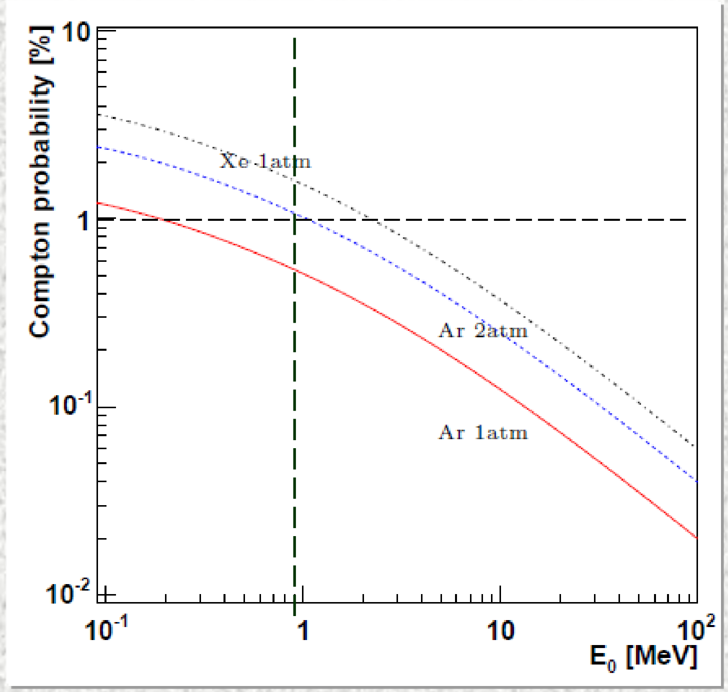


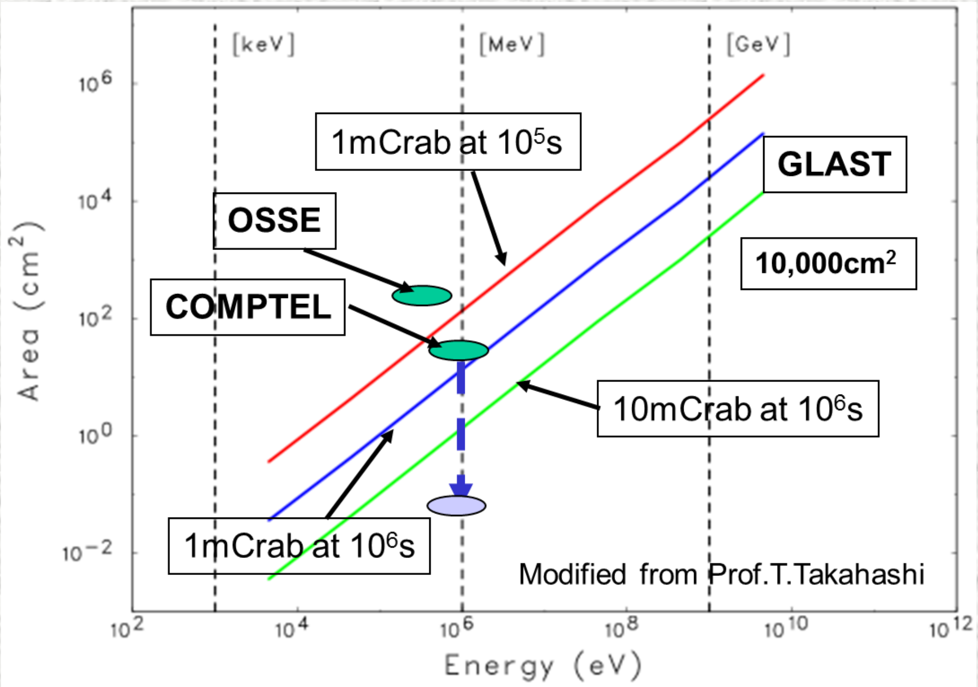




Simulated Efficiency for 50cm cube TPC

Compton probability (50cm thick)





50cm cubic Xe (or CF_4)2atm 0.5% eff.
13 cm^2 @1MeV, 50cm^2@0.5MeV

COMPTEL(2m×3m)
~13cm^2@1MeV

FOV〜3str(FWHM)@1MeV ⟺ 1str @1MeV

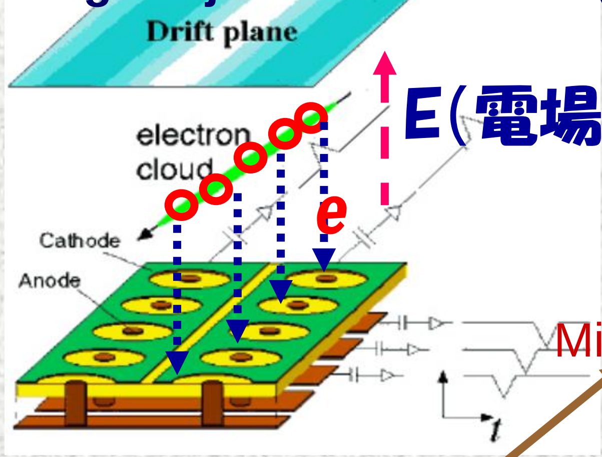
Energy Band 0.1~100MeV (e+ e- tracking >20MeV) ⟺ 1~20MeV

B.G. cut ; Directional & Kinetic, ⟺ TOF

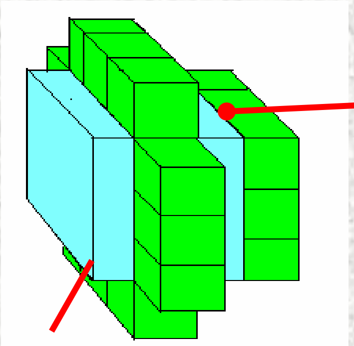
Particle Identification (e, p n)

10cm-cube μ-TPC & ETCC

Timing Projection Chamber (TPC)

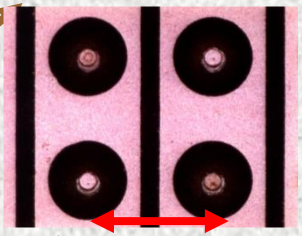


TPC

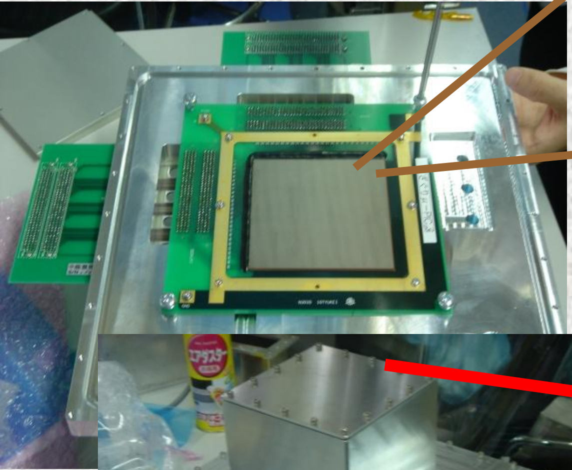


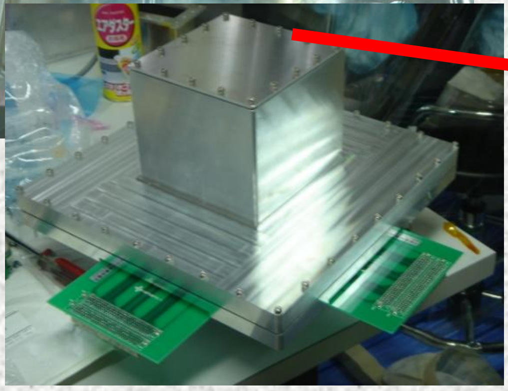
GSO Pixel

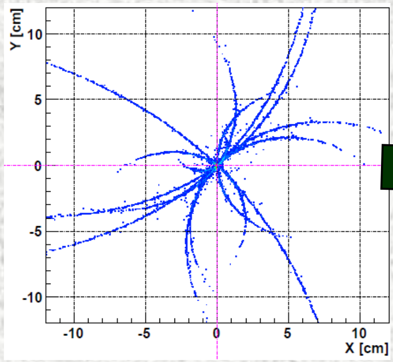
μ−PIC
Micro Pixel Chamber

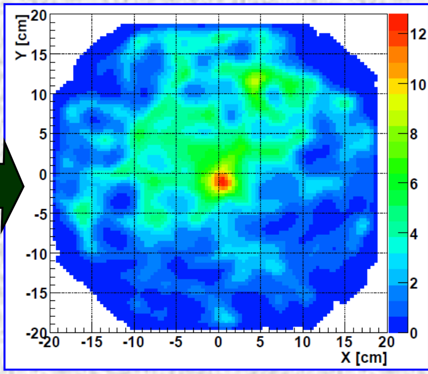


400μm

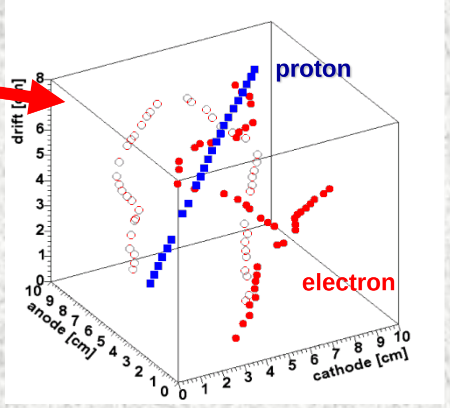


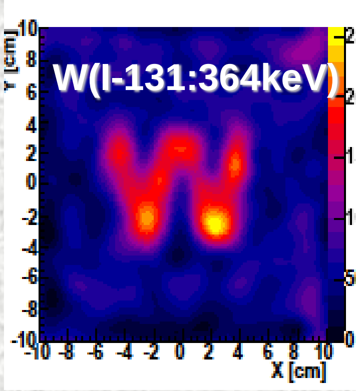


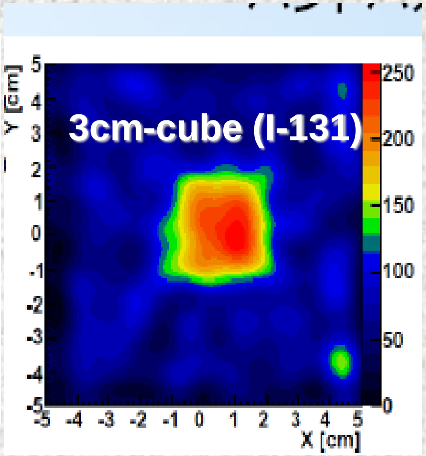




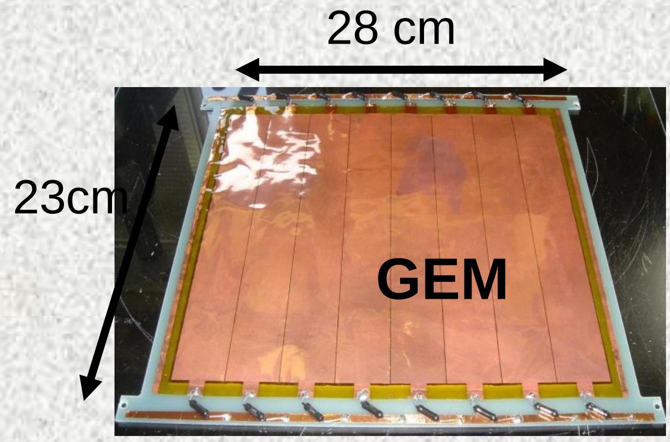
Imaging of 3D tracks



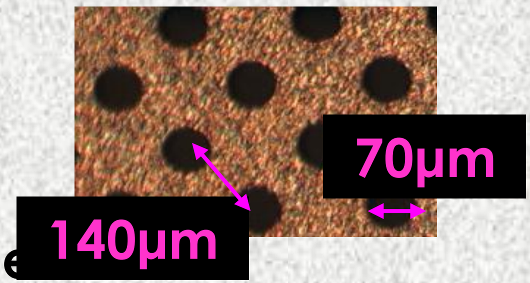


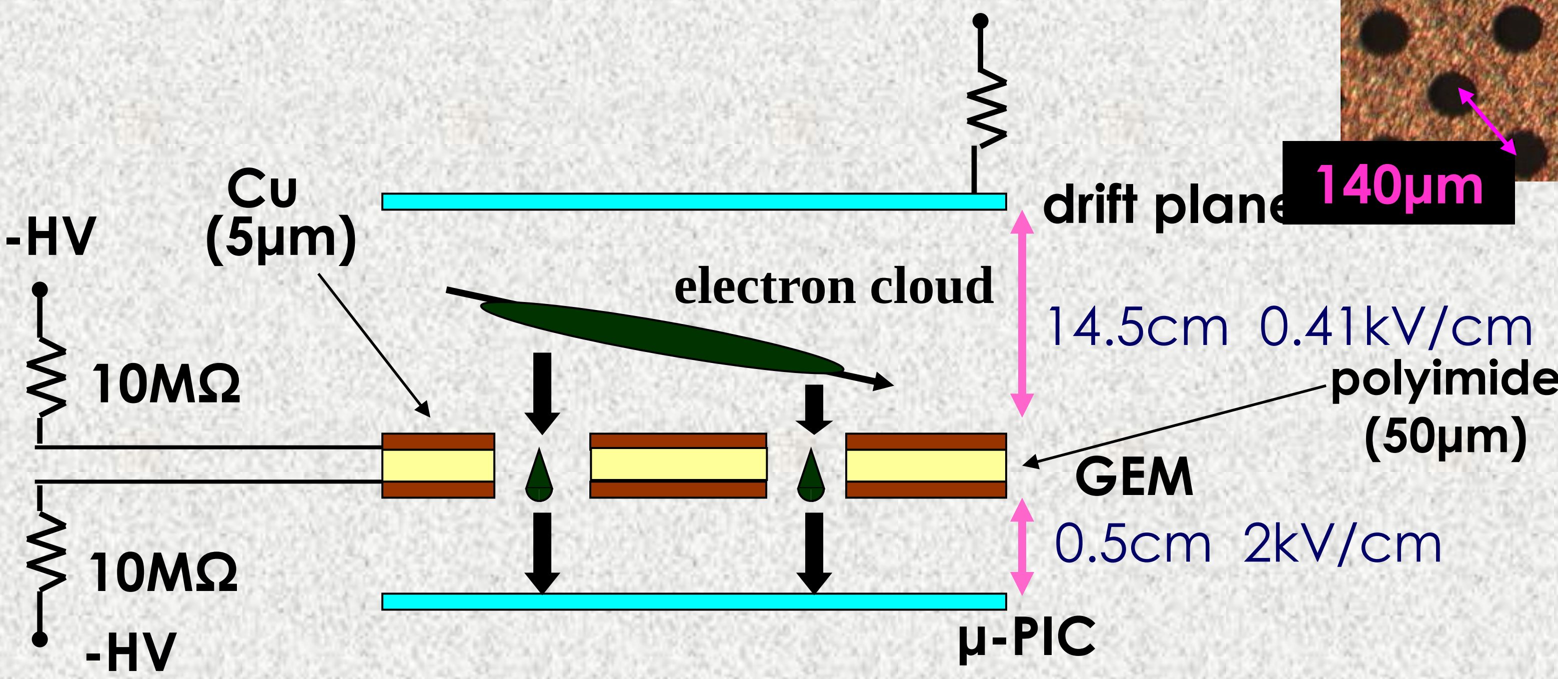


Hybrid µPIC(+GEM)



segmented GEM (8 segments)
to reduce capacitance and thus damage caused by discharge
23 cm x28cm size

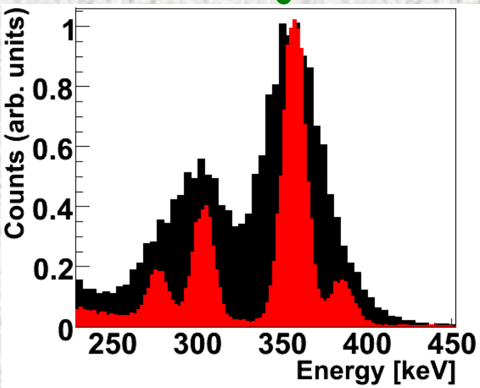




Electorns (~2 in one pixel)bare amplified by the GEM and the µ-PIC with a gain of $>2x10^4$

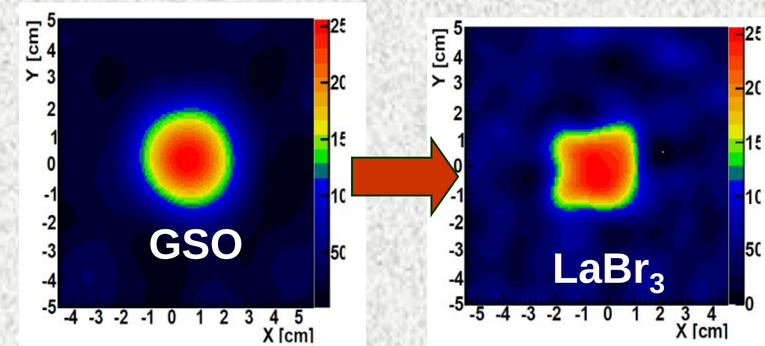
Position Resolution

Improvement of Scintillator
GSO-> $LaBr_3$

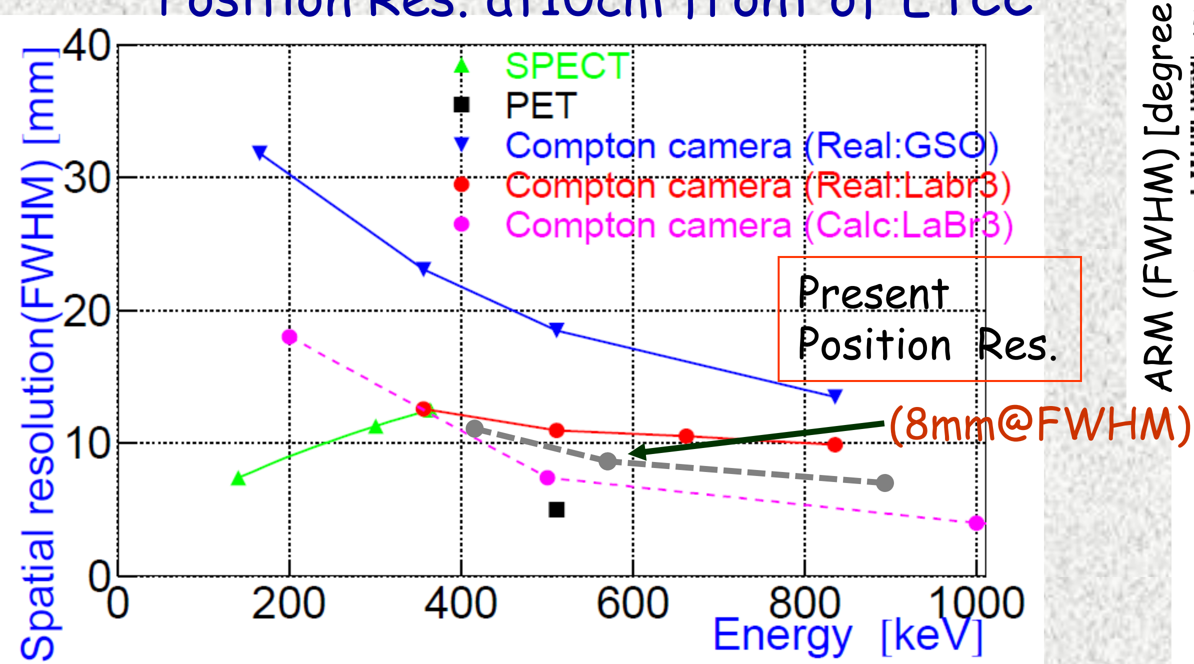


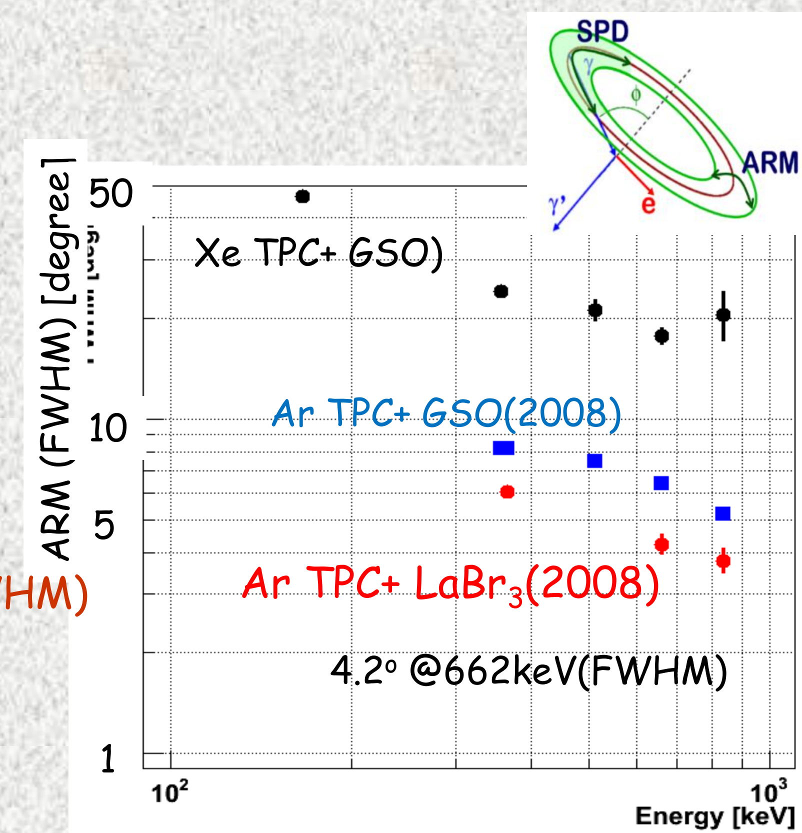
^{131}I (364keV)

3cm cube



Position Res. at10cm front of ETCC



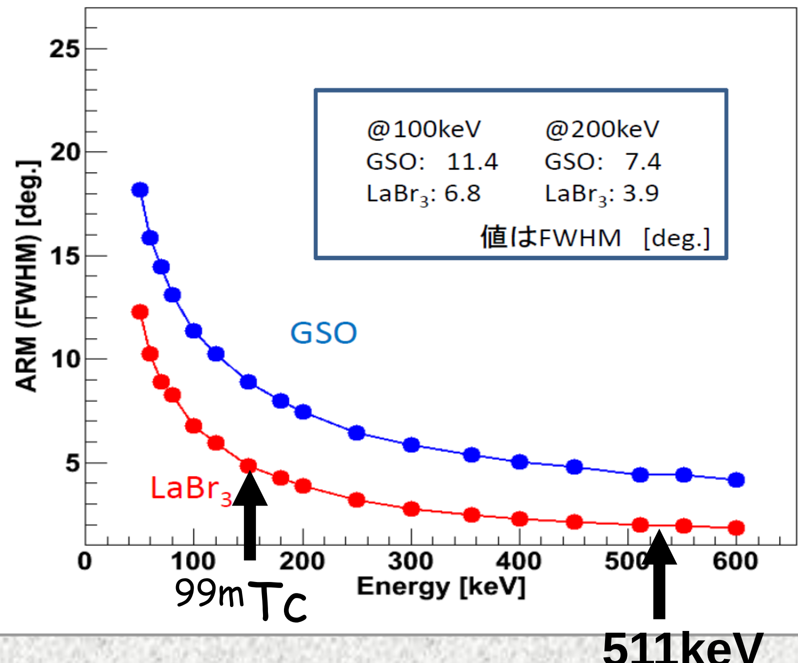


Future Angular Resolution of ETCC

	Angular Res. Observed (degree)	Angular Res. (Estimation) degree	ΔE/E	ΔX/X	Doppler
GSO	5º.0 ± 0.2	5º.2	4º.3	2º.8	0º.9
$LaBr_3$	4º.2 ± 0.3	4º.3	2º.7	3º.2	0º.9

Due to Error of Compton Scattering Point in TPC

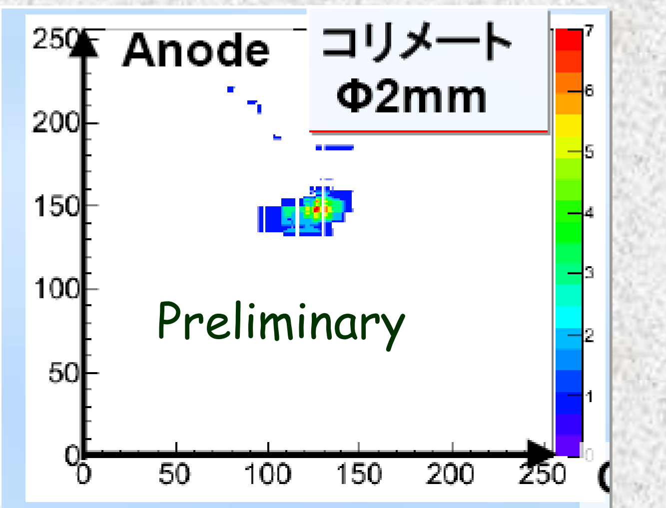
simulation :(TPC ΔE/E=10%@22keV)



30cm TPC (Ar 1atm)

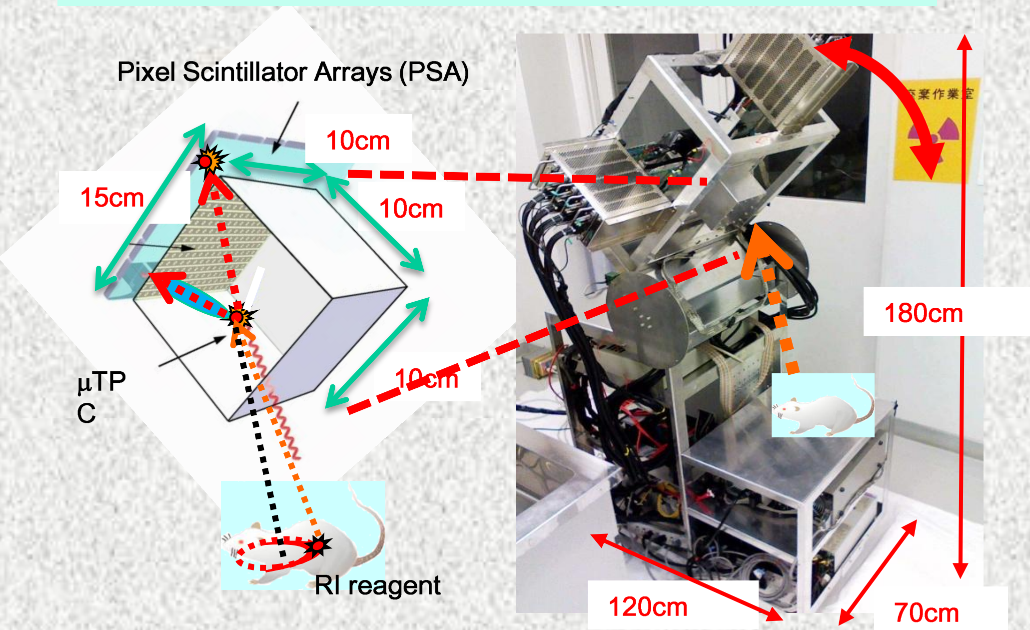
GSO 10%, $LaBr_3$ 3%@662keV

with Doppler broadening

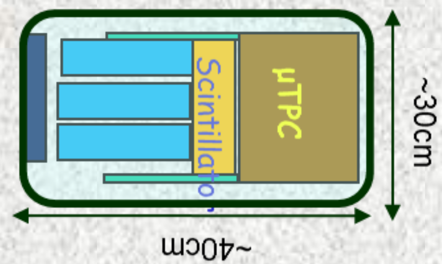


ETCC for Molecular Imaging based on first balloon detector technology

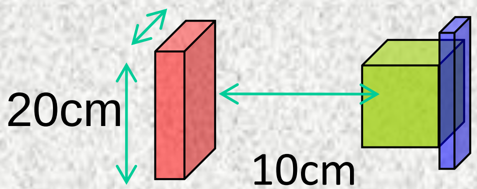
Mobile ETCC for small and middle animals

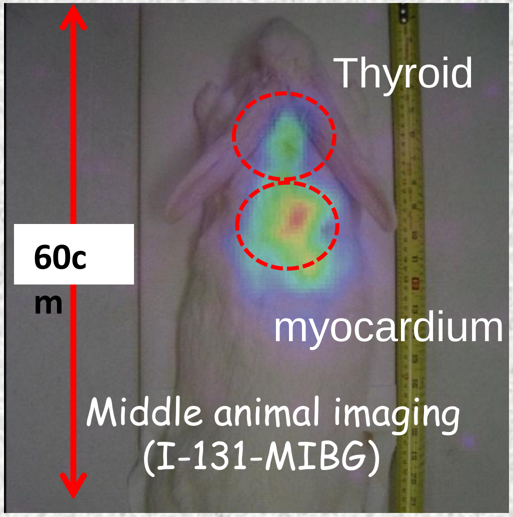


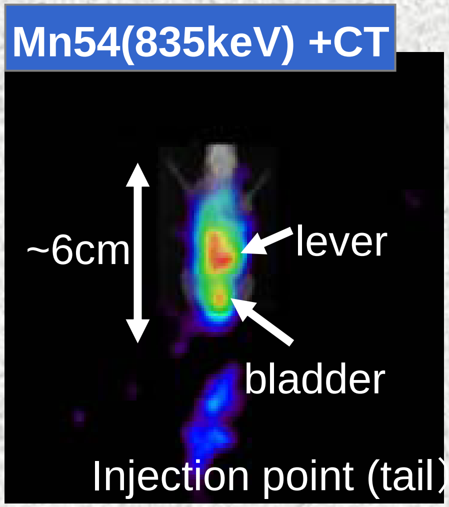
Compact ETCC

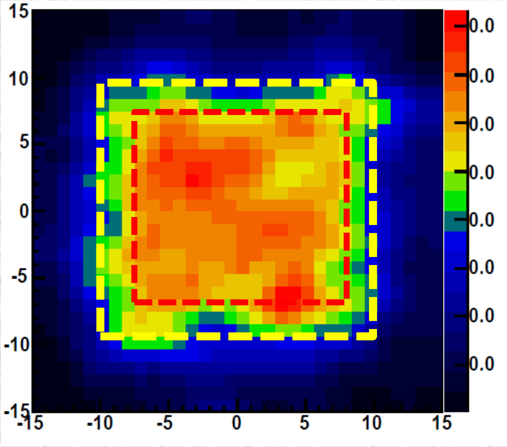


364keV panel phantom









Uniformity： 11% (1σ)

Variety of RI applications in ETCC

	Ce-139	Cr-51	Ba-133	I-131	Au-198	Na-22	F-18	Cu-64	Cs-137	Mn-54	Fe-59	Zn-65	Co- 60
Energy [keV]	167	320	354	364	410	511, 1275	511	511	662	835	1095, 1292	1116	1173, 1333
Life	137.6 day	27.7 day	10.52year	8.01 day	2.6 day	2.609 Year	109.8 min	12.70 hour	30.04 year	312.1 day	44.5 day	244 day	5.271 year

SPECT

PET

Energy dynamic range : 167 – 1333 keV.

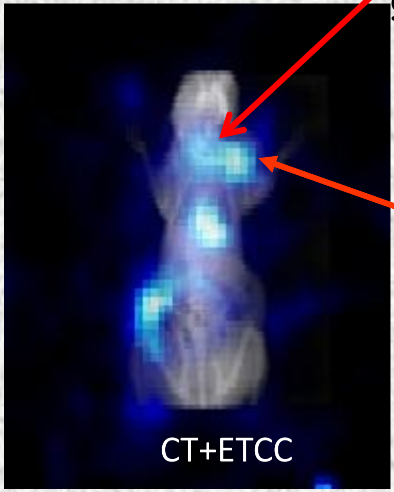
F18-FDG

ETCC

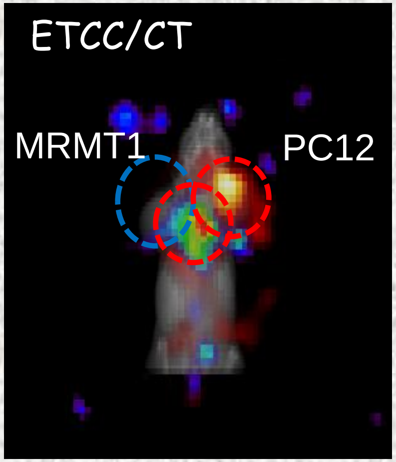
Zn-65-Porphyrin

Thyroid grant

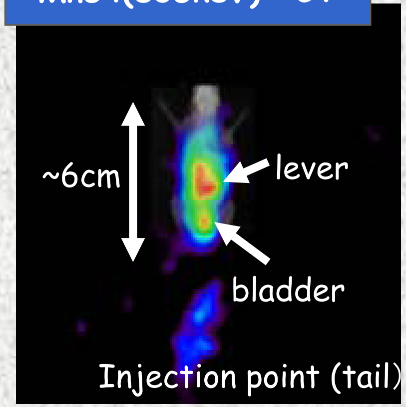
PC12

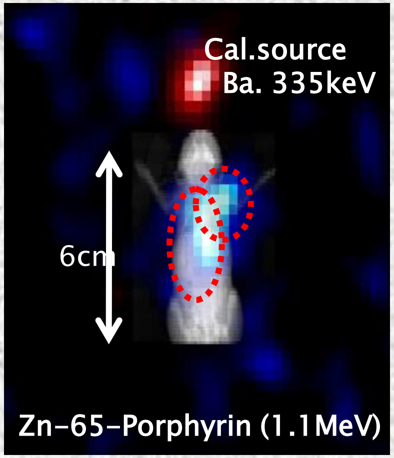


Rainbow : 511keV
Orange : 365keV



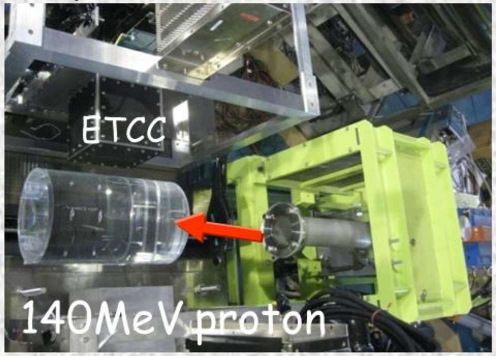
Mn54(835keV) +CT



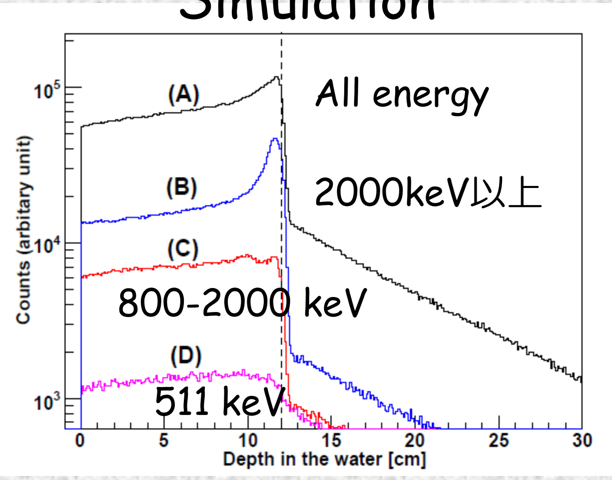


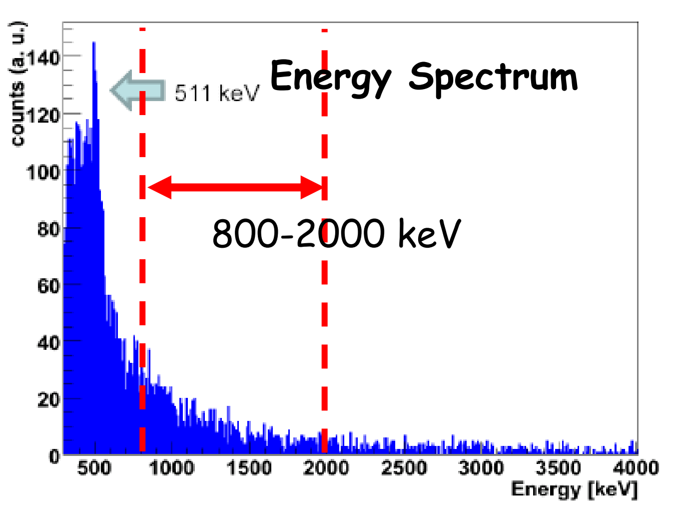
On-time imaging approach for beam therapy

Experiment @ RCNP

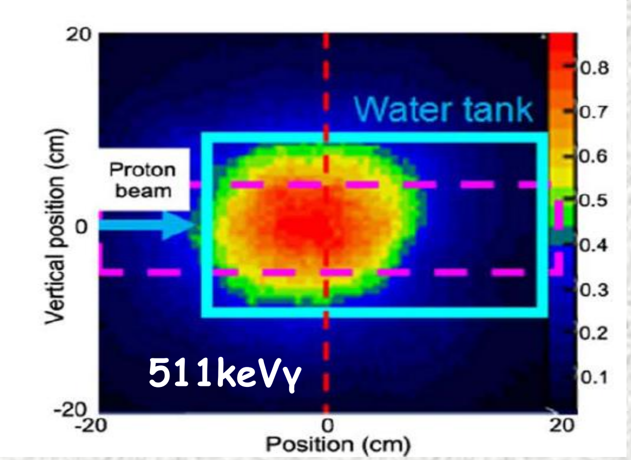


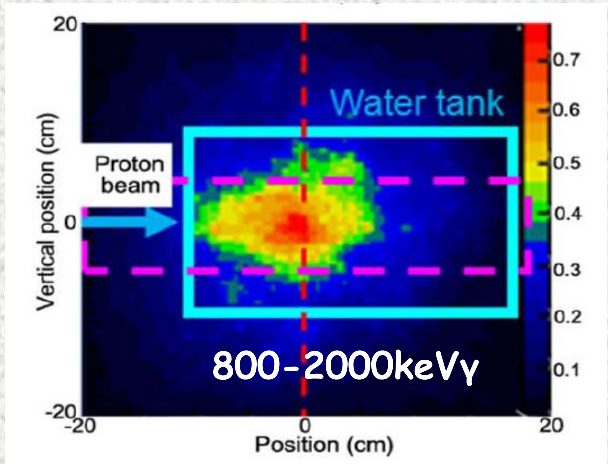
Simulation



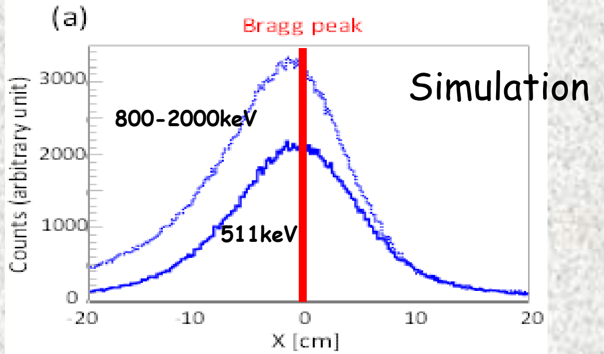


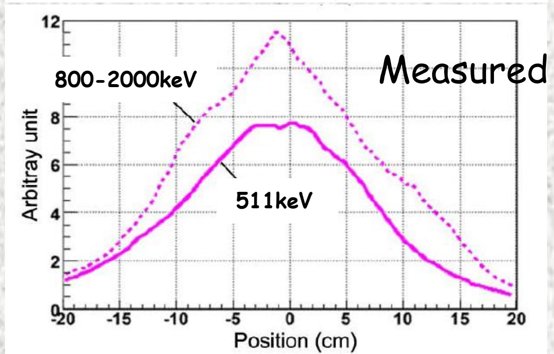
First Imaging at Beam-on !





Bragg Peak





SMILE Road Map

10cm cube camera @ Japan (Sep. 1st 2006)

- Observation of diffuse cosmic/atmospheric γ
  ~400 photons during 3 hours (100 keV~1MeV)

30cm cube camera with Domestic balloon (@Kiruna

- Observation of Crab/Crg X-1 + REP-γ

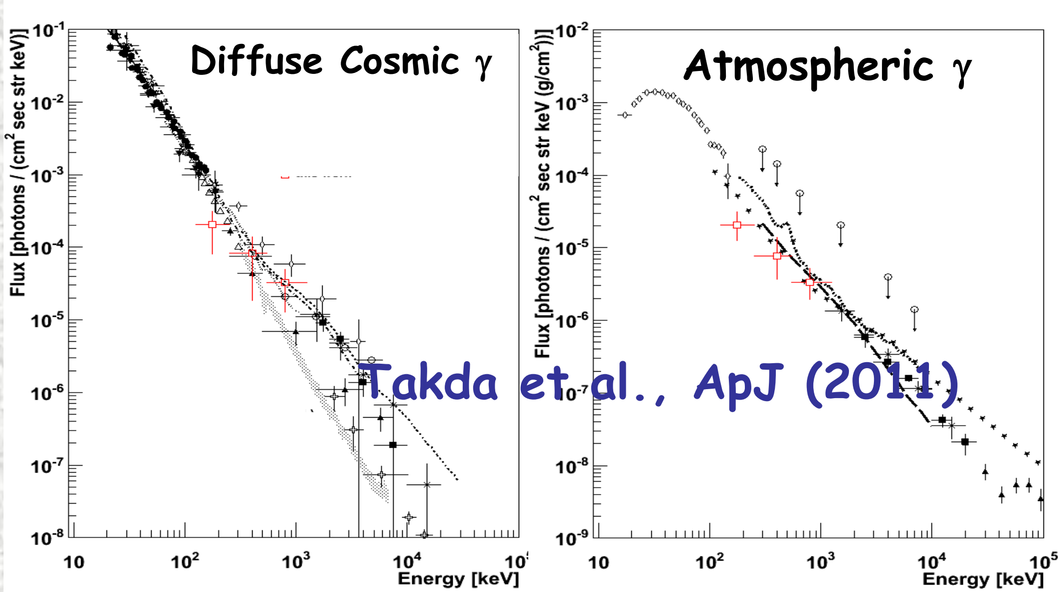
40cm cube camra with long duration observation

- Galactic survy & Gamma-Ray Burst Detection

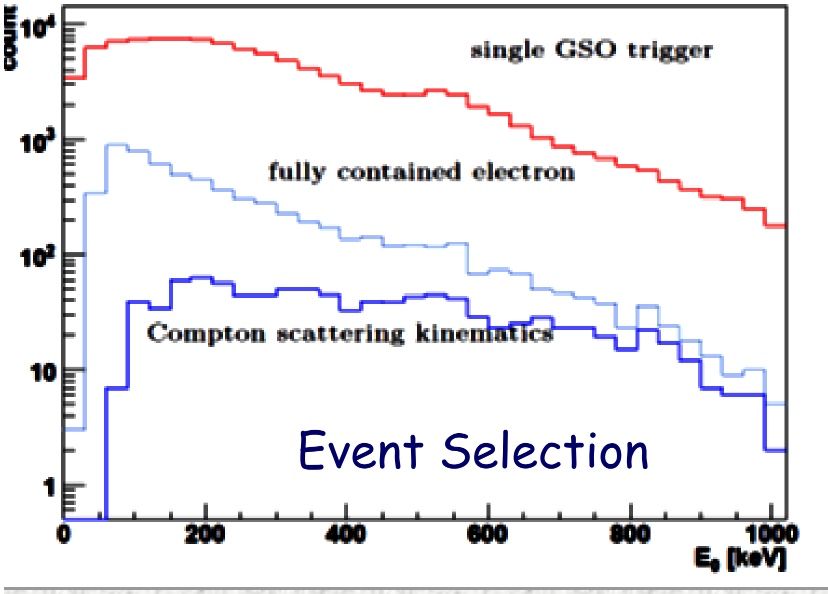
50cm or 1m cube camera with satellite

- All sky survey, detection of highest-z GRB

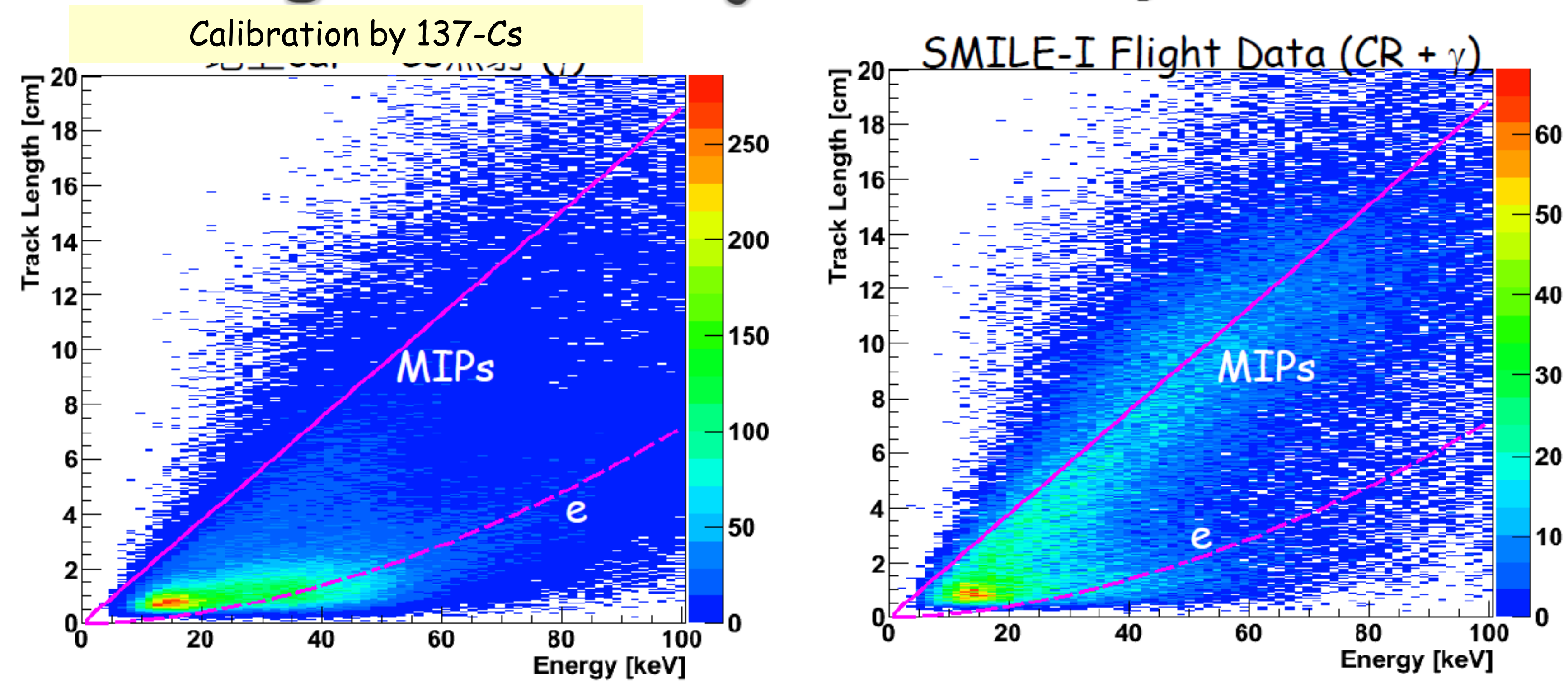
All Trigger # 2.3x10^5 (3hours)
Signal ⇒ ~420(down going) +500(up)
Simulation ⇒ ~400 (diffuse cosmic)



Takda et al., ApJ (2011)



Background rejection by TPC

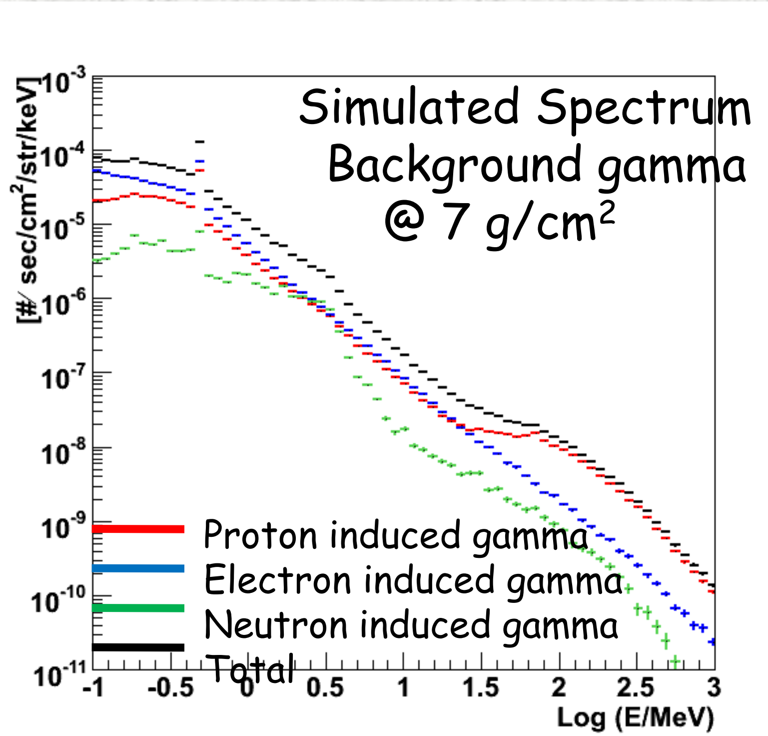


Good Particle ID using dE/dx

We can clearly separate Stopping e in TPC, Minimum ionizing particle & Neutron

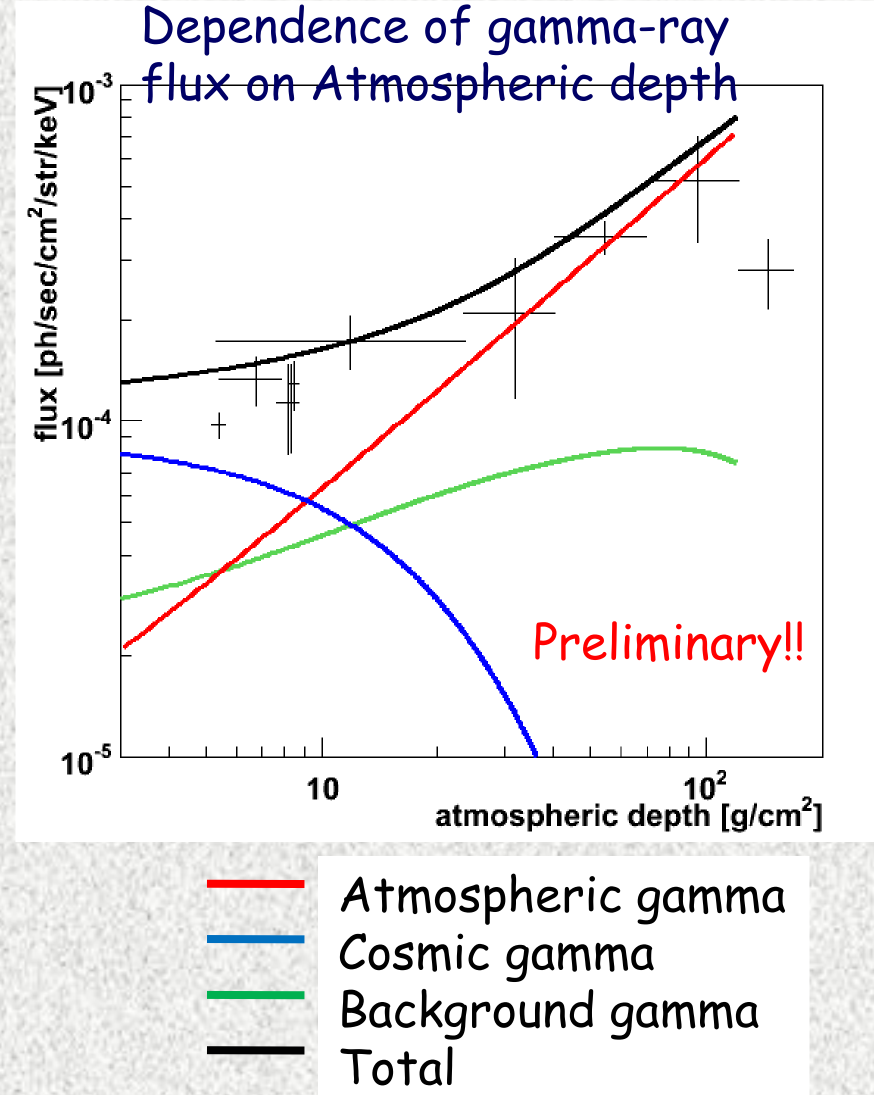
Only Gamma-Compton events in TPC remained !

B.G. Simulation & Growth Curve



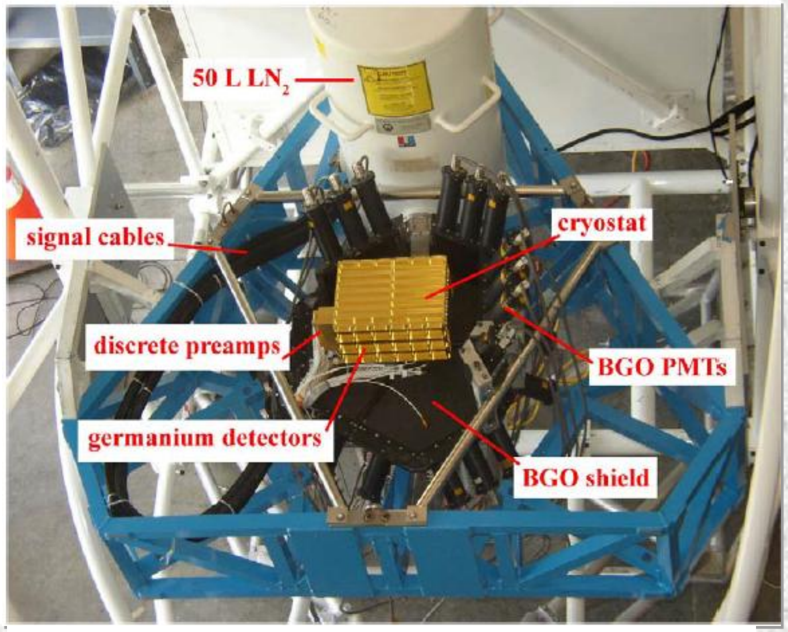
Simulator expected :
obtained Compton events at level flight

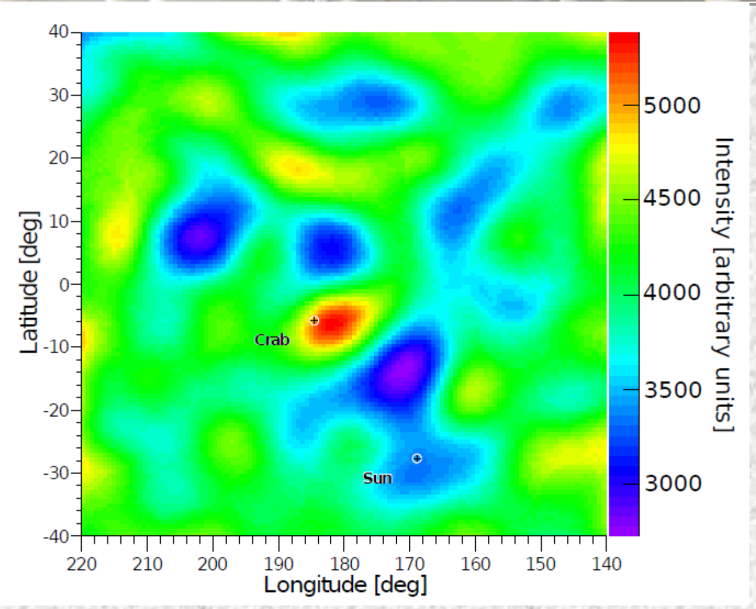
signal gamma-rays	~78%
BG-gamma from detector	~20 %
neutron	1.5%
charged particle	< 0.25%



Good Consistency between Simulation and Data

Berkeley NCT Experiment





M. S. Bandstra et al. ApJ 2011

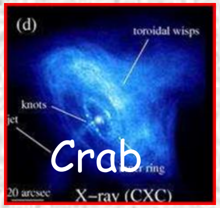
- Crab 4s detection with 29ks (8hrs)
- Ge strip Detector with BGO Veto
- FoV 3.2 str (BGO veto ~8str)
- Simple Simulation ~3800 gamma
- 65.8% remaining after data selection
  ~290k events -> 667 Crab gamma
- MLEM method needed
- Background 29141 events

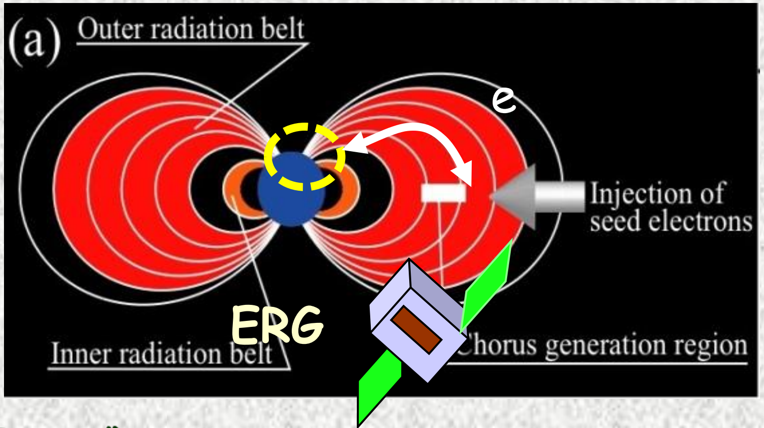
SMILE-II in the North Pole

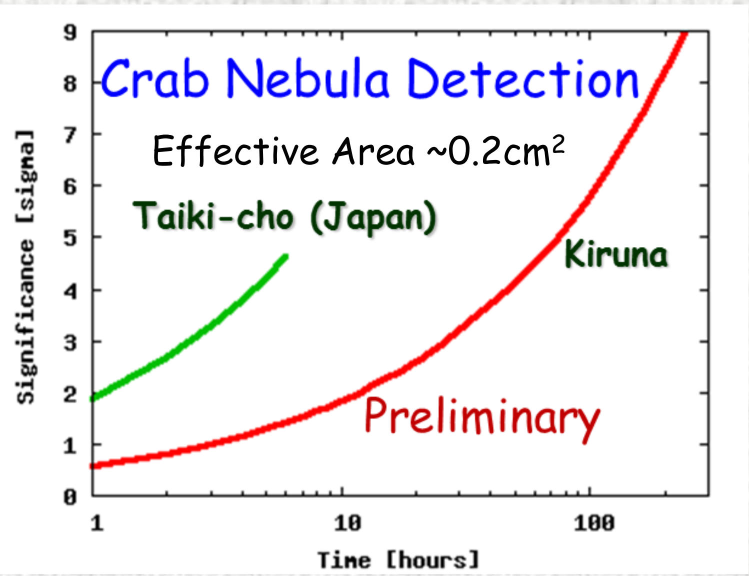
Terrestrial γ-ray bursts due to Relativistic Electron Precipitation (REP)

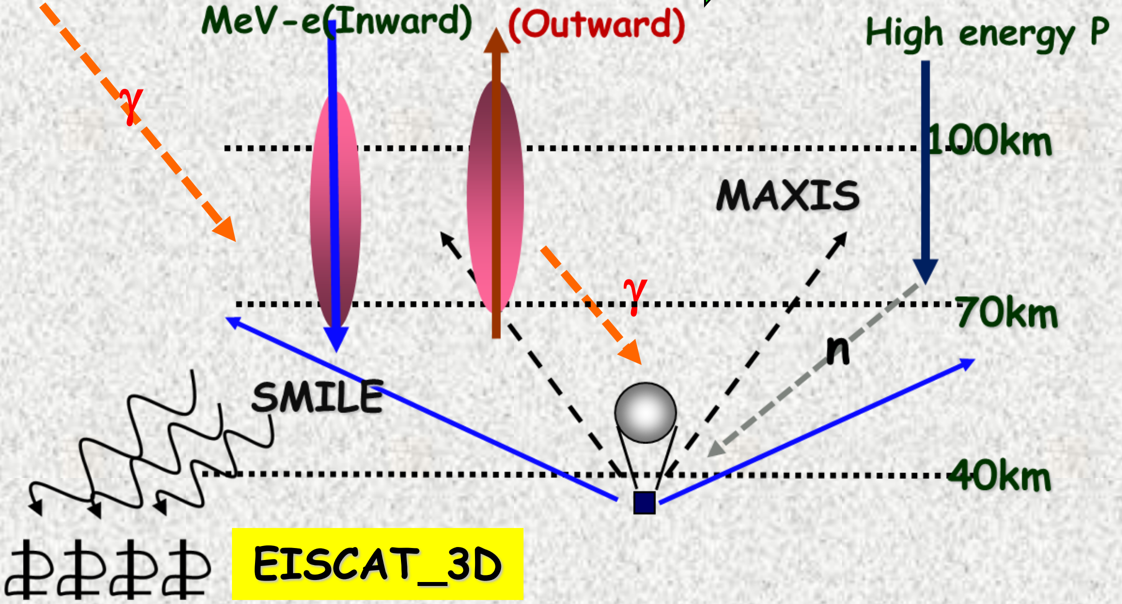
Collaboration:
Kyoto、NiPR, Nagoya STE-lab, JAXA, Hokkaido, Kanazawa, IRF, Lu lea Tech. Univ., EISCAT, BARREL(UC Santa Cruz, Dartmouth)

MeV γ from Compact stars, AGN & GRB

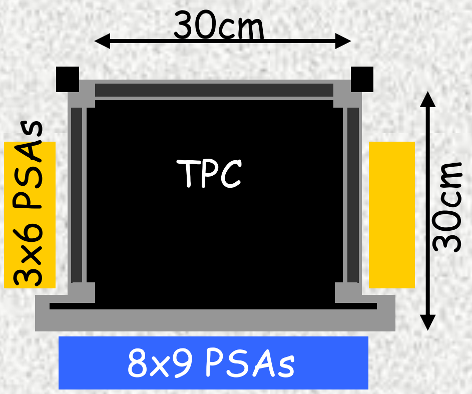


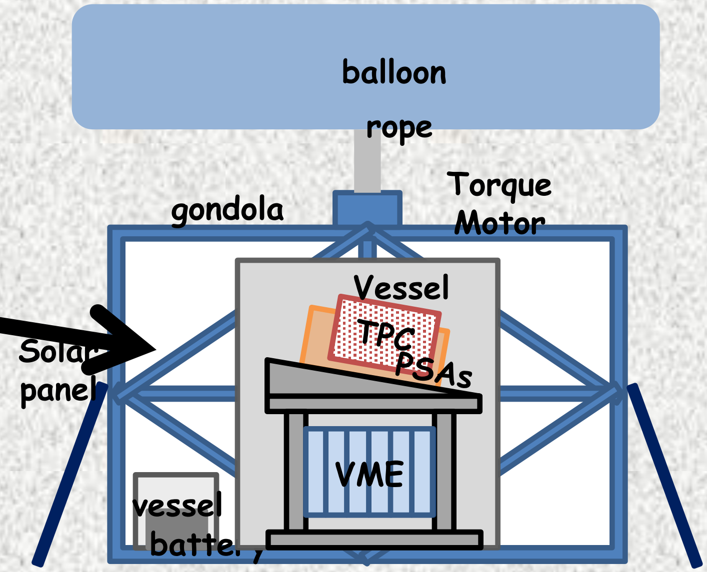




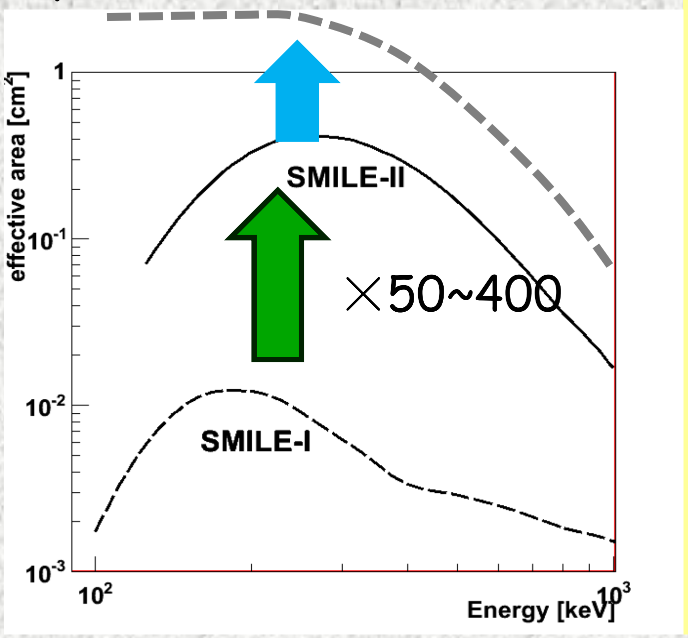


Simulation of SMILE-II flight model





Improvement of Effective area



Sensitivity for the Crab Observation (Japan)

SMILE-I

- ~400 gamma from upper hemisphere /3hours (SMILE-I)

Case of 0.5cm² SMILE-II (39km altitude)

20000 gamma from upper hemisphere /3h

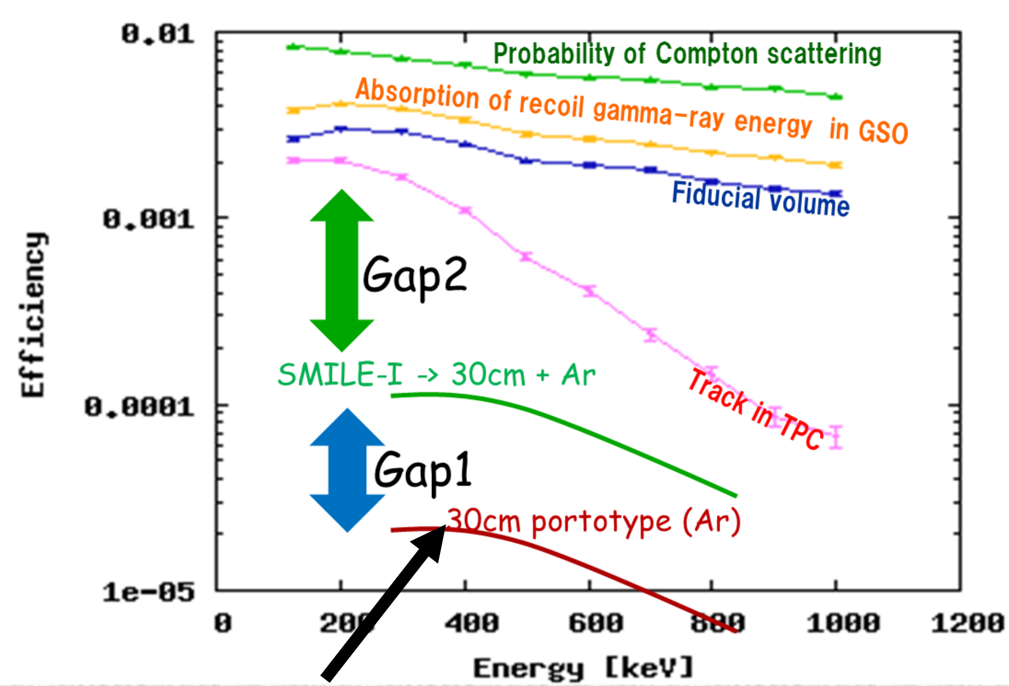
Crab (>100keV) 200 gamma expected

$d\theta$ =10 degree

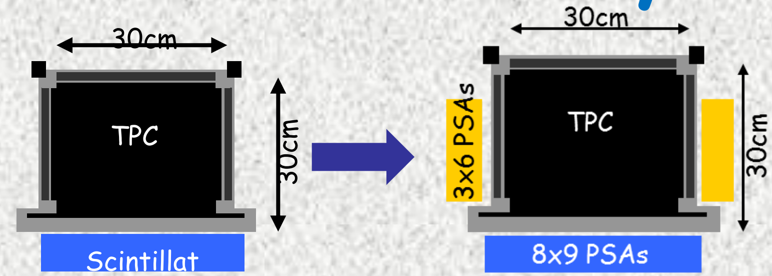
Background 700-1200 events

- Significance 5.5-8σ level /3hours

Improvement of SMILE-II Efficiency



30cm Prototype : 2.5×10^{-5}@340keV



SMILE-I

- Absorber: 35GSO-PSAs
- 10x10x15cm TPC gas: Xe+Ar 1atm

Flight Model

- Absorber: 216 GSO-PSAs
- 30x30x30cm TPC gas: Ar 1.5atm
- Azimuthal Tracking of target
- New Reconstruction method

Improvement of Efficiency (sure parts)

Side Scintillator wall x2
thin vessel x 1.5
Tracking for target x 1.5
Choice of gas (CF4) or Ar 1. 5atm x1.5
800um pitch -> noise reduction

obtained eff. $3.3\text{-}6\times10^{-4}$
effective are 0,26-0.5cm^2

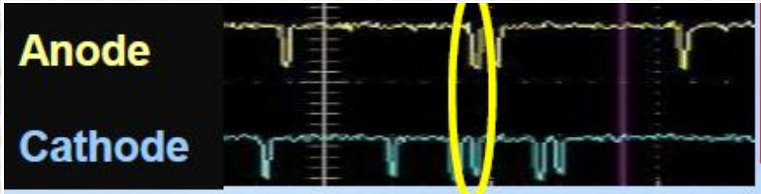
More challenge for Gap2

New electronics of Scinti, x >1.5
New electron tracking+dE/dx > x4
ARM 10°-> ~8° x1,5
SPD ~100°-> <50° X 4

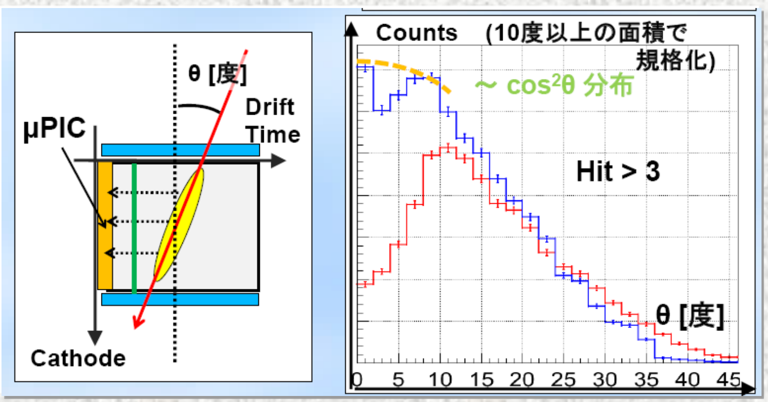
Total improvements x5-20?

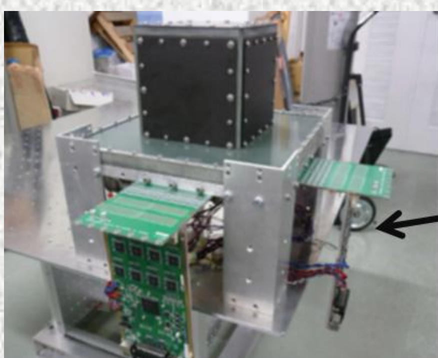
Effect by electron tracking improvement

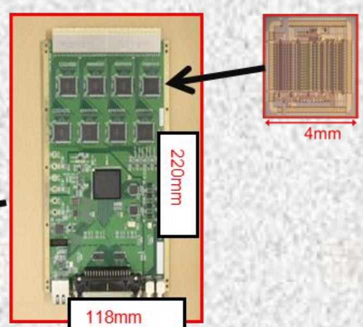
Recording of all hit points on X and Y strips



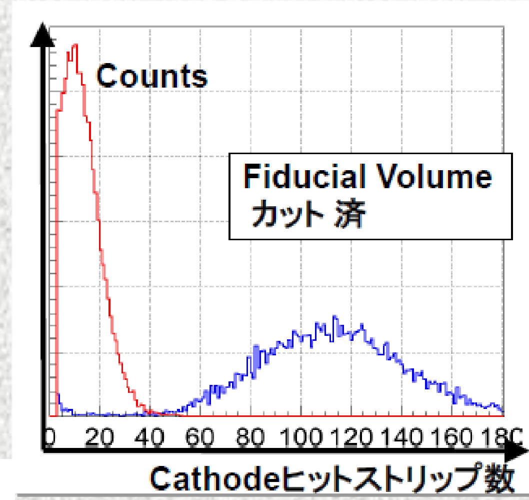
Remove of inefficient region

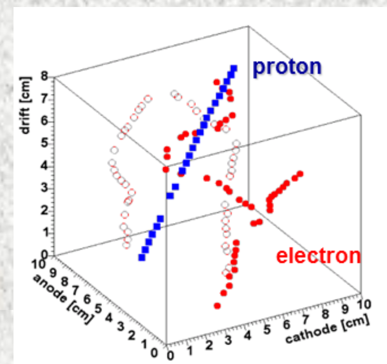




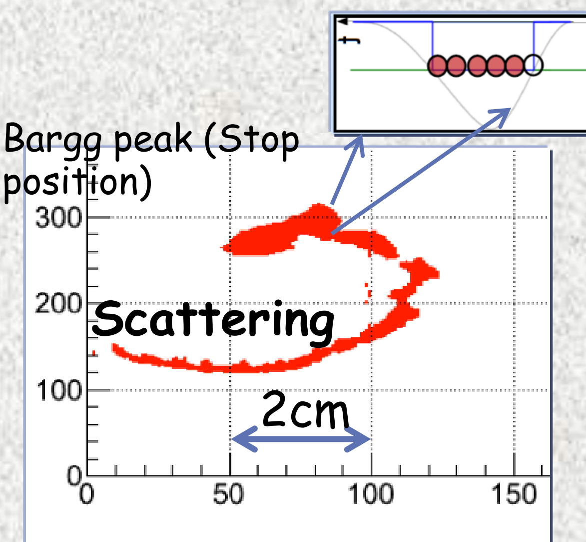


Increase of hit points on track





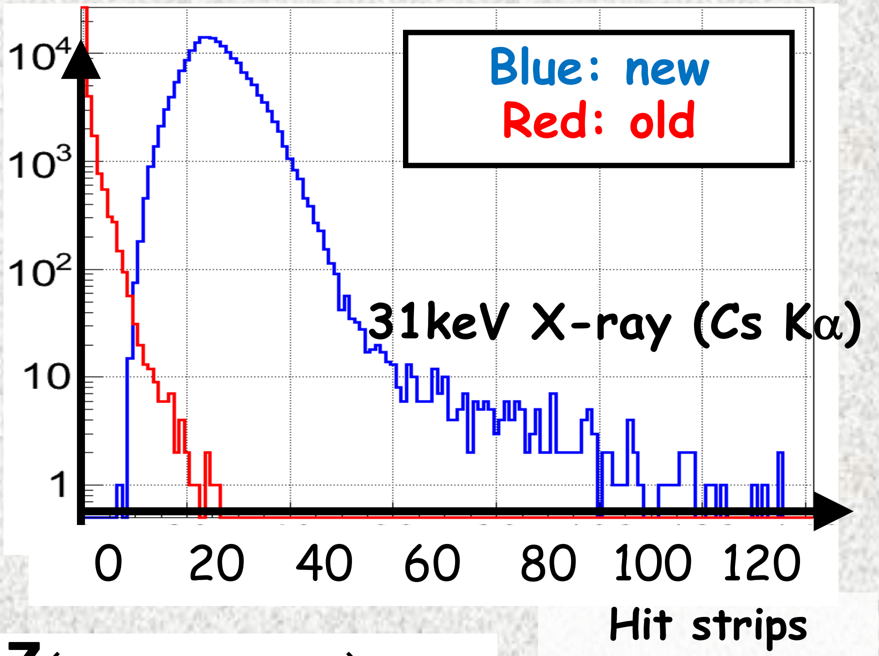
Bargg peak (Stop position)

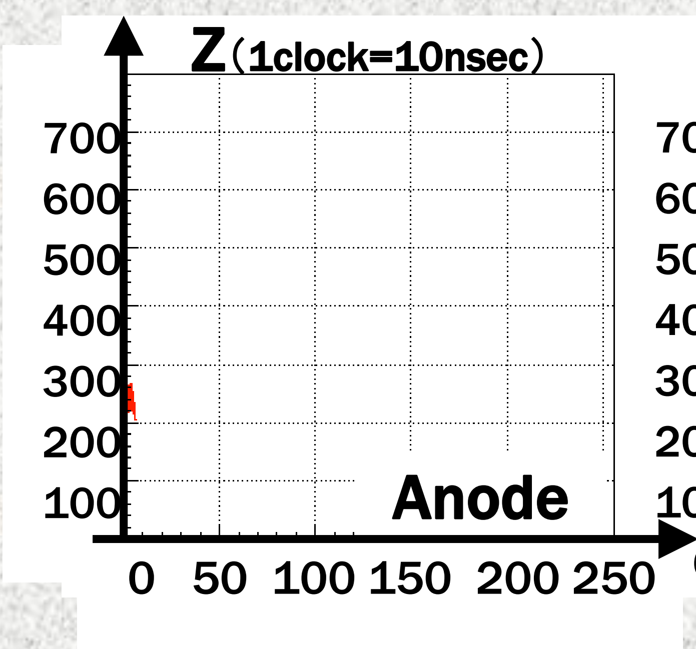


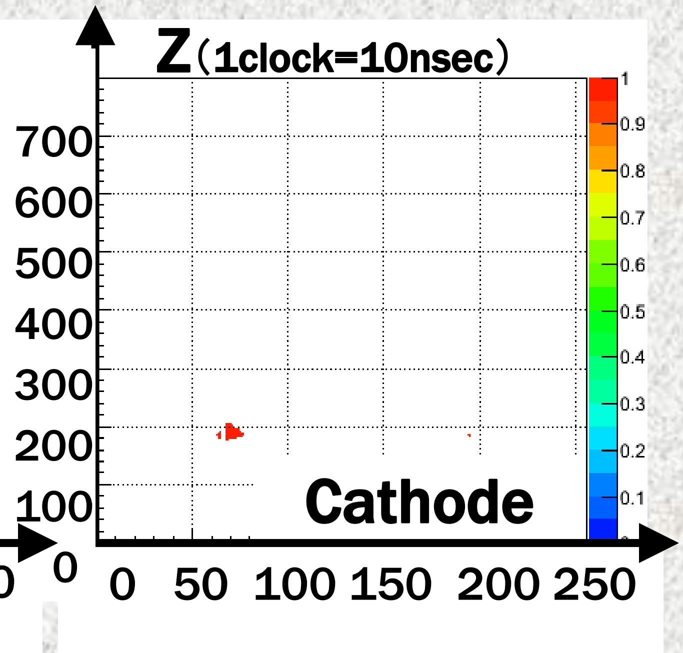
Direction determination

- All events are satisfied with >5hits in New method for 31 keV X-ray
- Old only ~2%
- TPC independent trigger

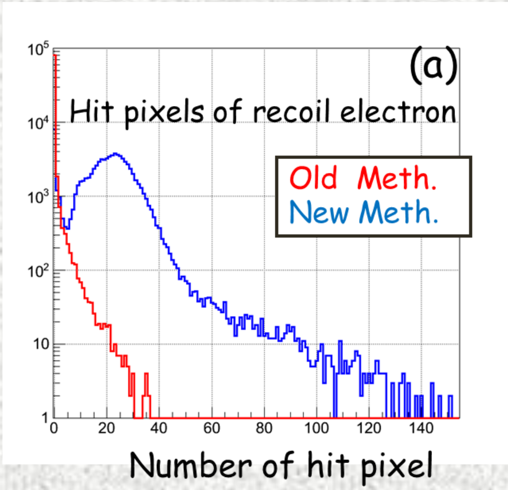
good X-ray polarization detector

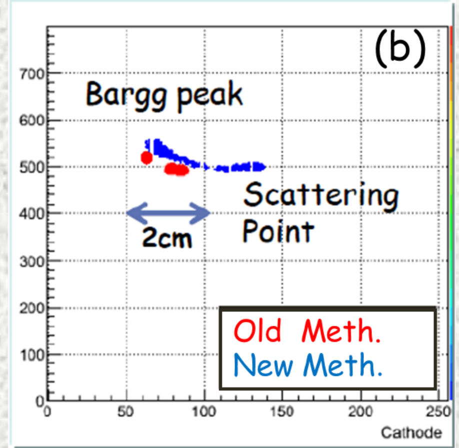




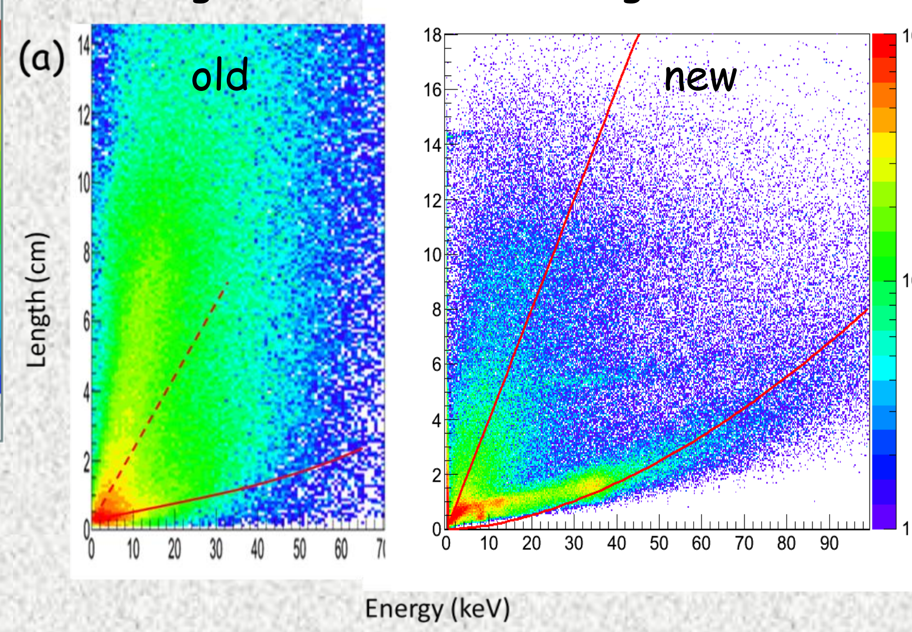


Electron tracks of Compton events (662keV)



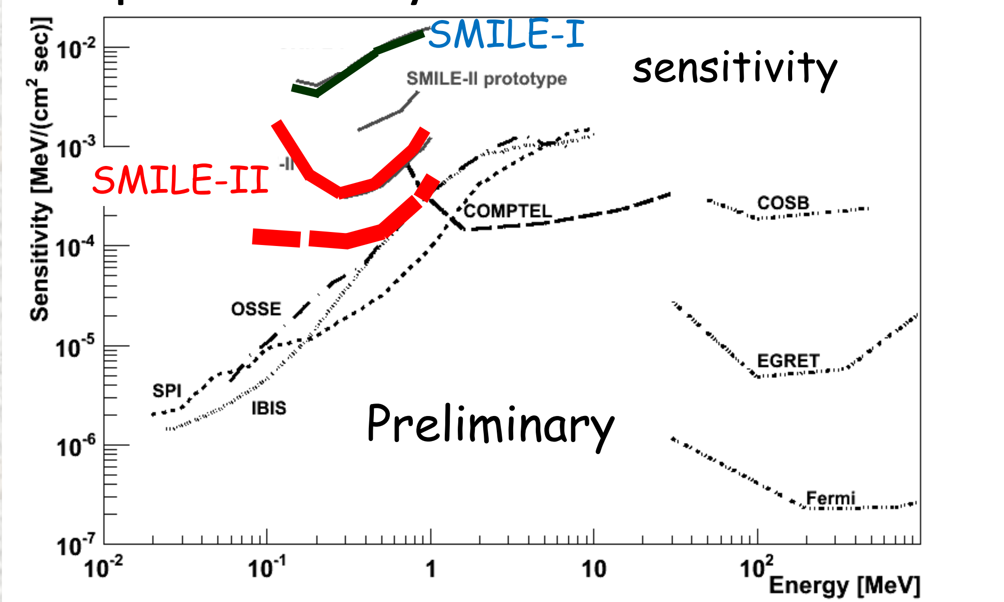


Ar gas old & New tracking in 10cm TPC



1. Sampling points in a track x~10 times
2. Efficiency of detection electron in 662keV γ x ~20times
3. All Tracks in 30keV X-ray more 5hits
4. Almost all recoil electron will be detected in TPC with more 4hits
5. Now Imaging test is on-going

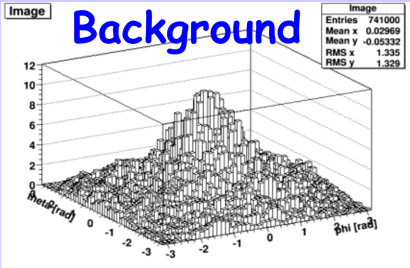
Expected sensitivity of SMILE-II with 10^6 s at a 3σ.

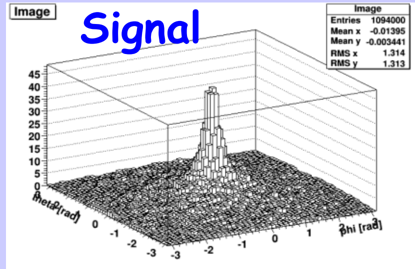


SMILE-II with 0 .5cm^2 eff. area

SMILE-II with the improvement of the tracking

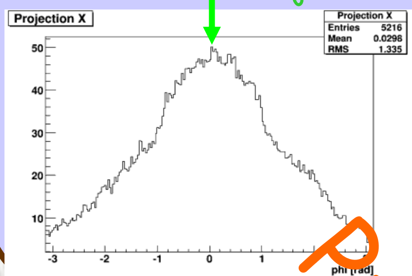
Conventional Compton in SMILE-II

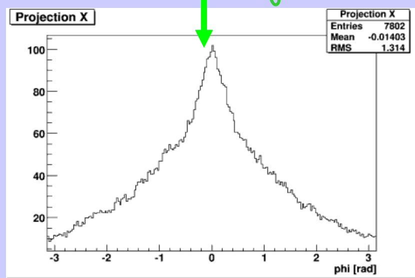




Projection

Projection





PSF = ARM

Signal Rate

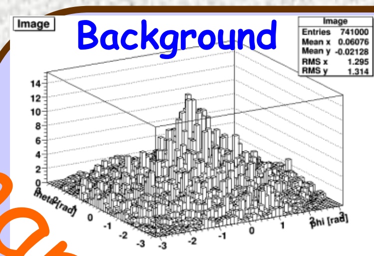
1.1[points/sec]

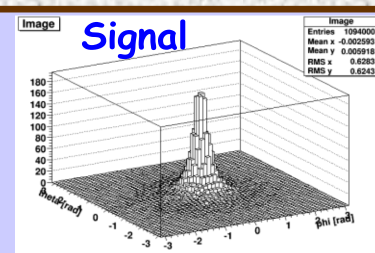
BG rate

4.1[points/sec]

S;N=1:3.7

Preliminary!





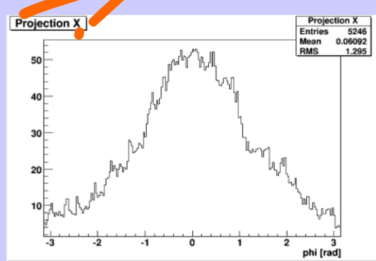
PSF = ARM

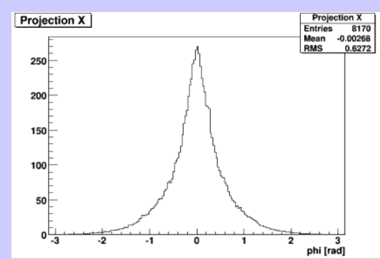
Signal rate

4.7[points/sec]

BG rate

3.1[points/sec]





S:N=1:0.7

Advanced Compton (SPD = 80deg)

Imaging Method

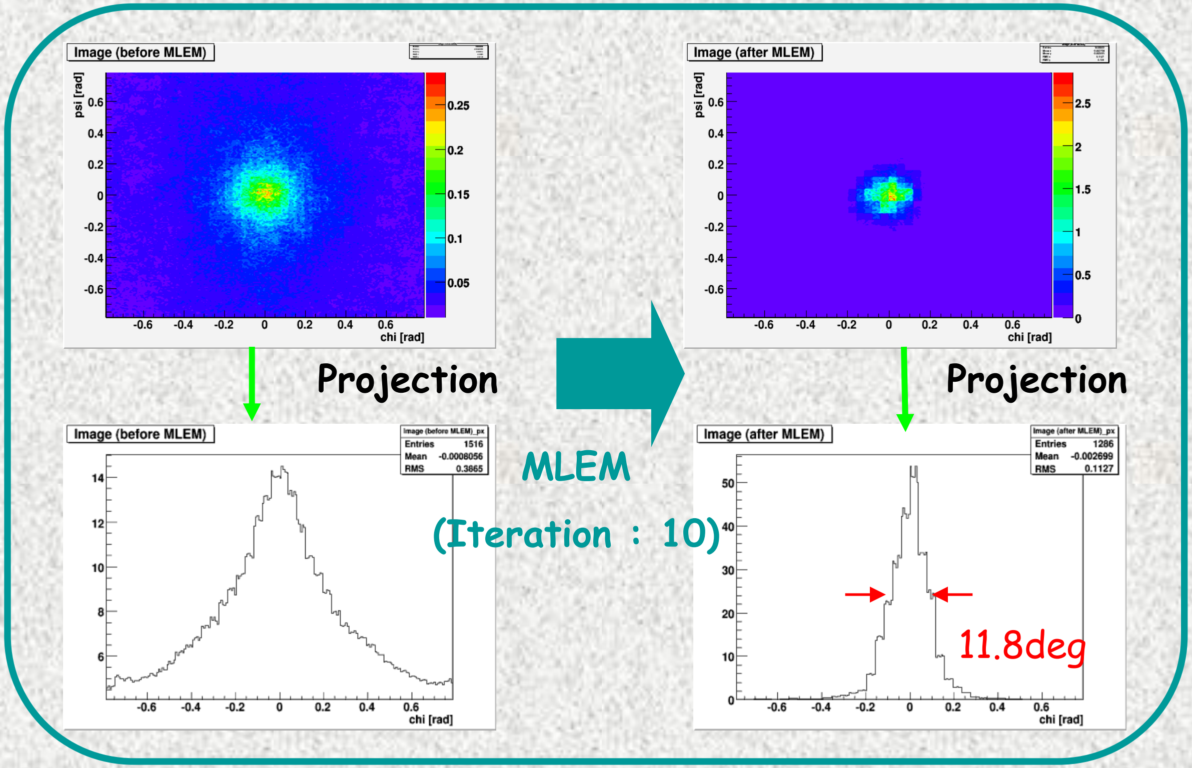
Maximum likelihood Expectation Maximization (MLEM)

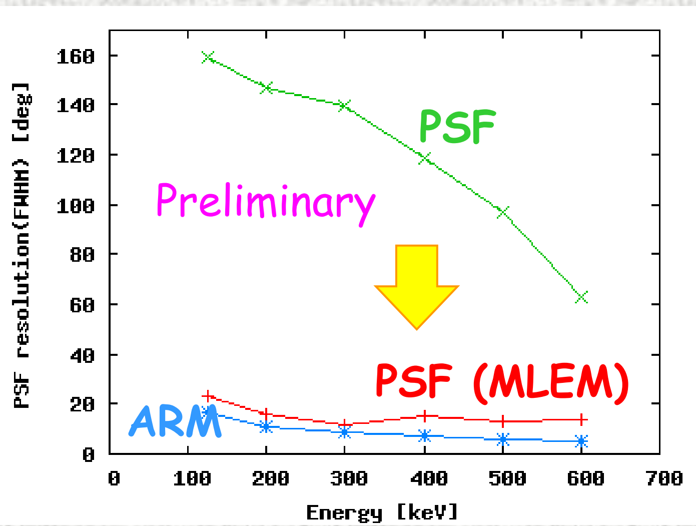
Remove known background effects such as detector acceptance or random noise

Signal -> ARM resolution, BG-> Flat distribution

Signal (3000keV)

Conventional Compton

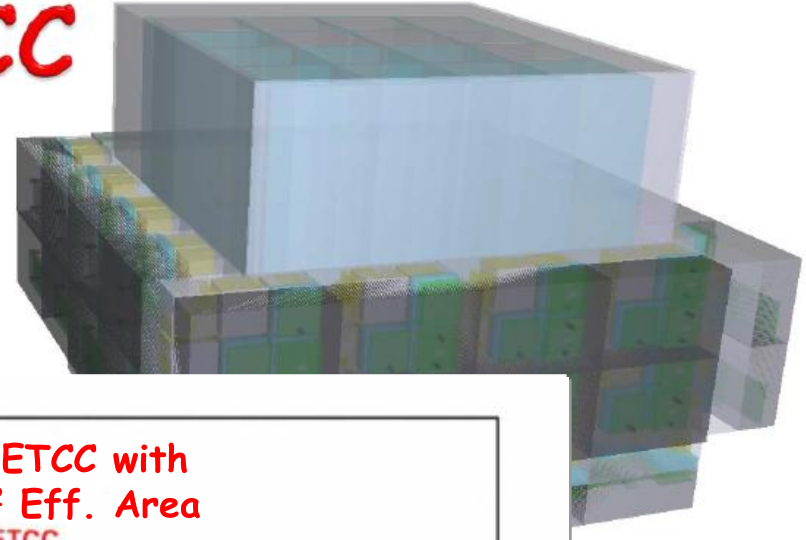


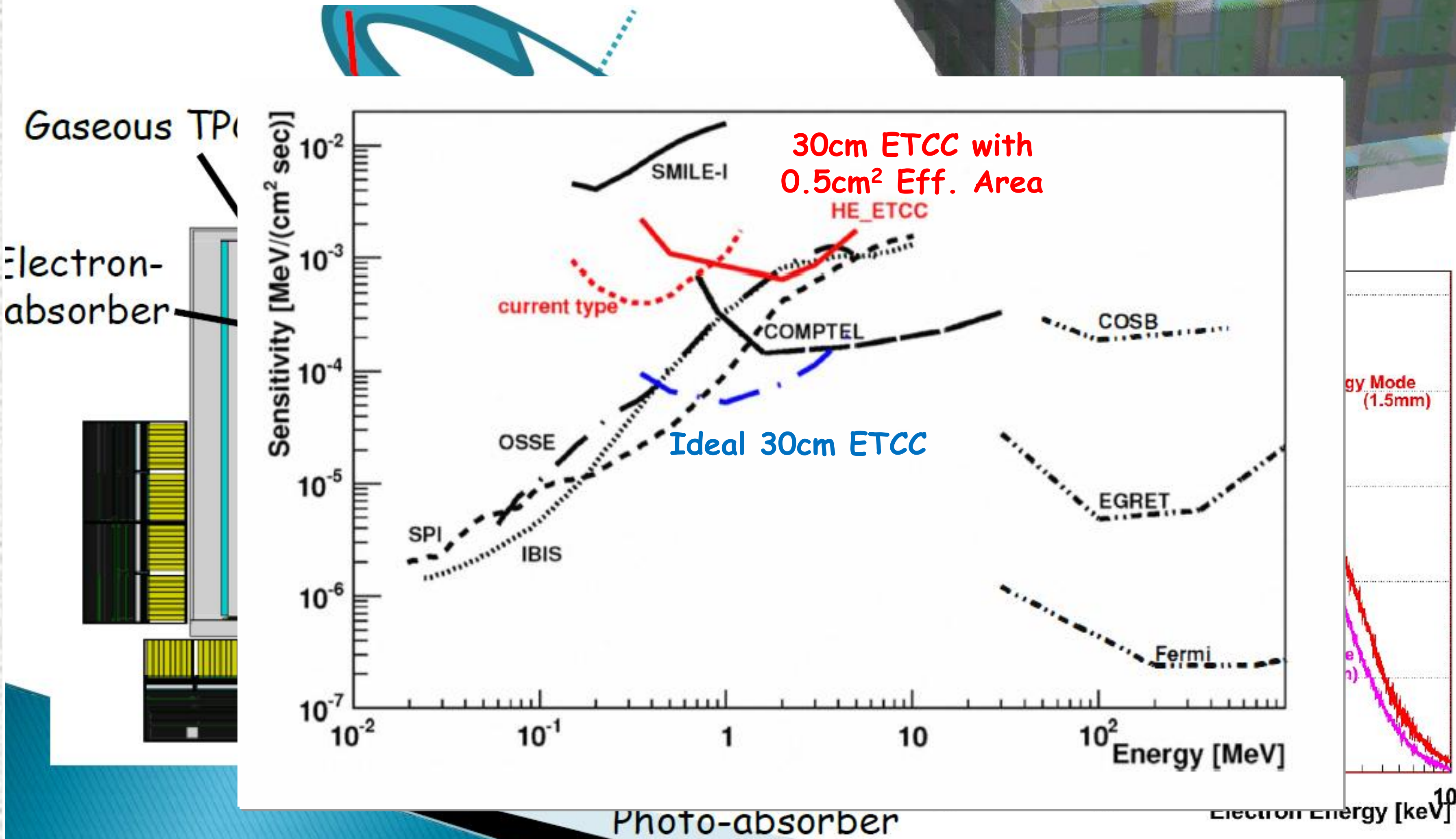


Advanced C.C. more improvement expected

High Energy mode ETCC

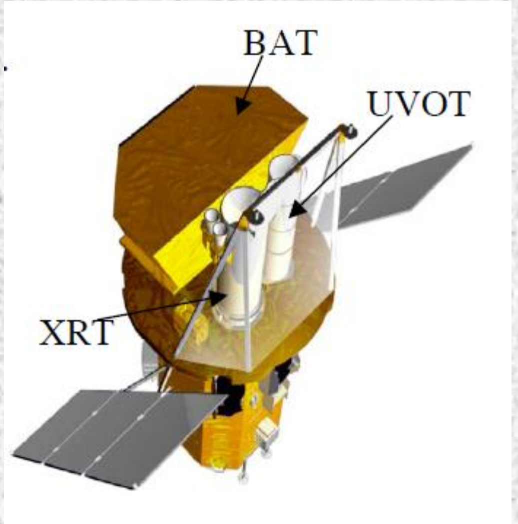
Plastic Scintillation walls (~1cm thick) set in the TPC for detecting recoil electron



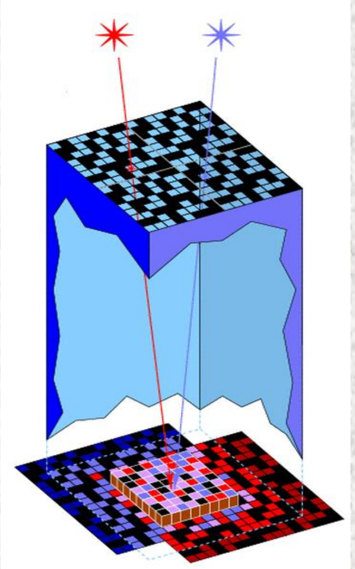


GRB Detection with Swift

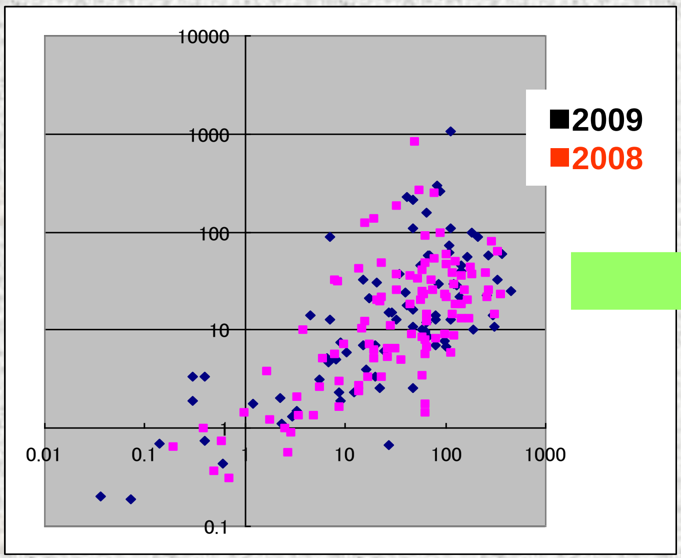
BAT 15-100keV X-rays

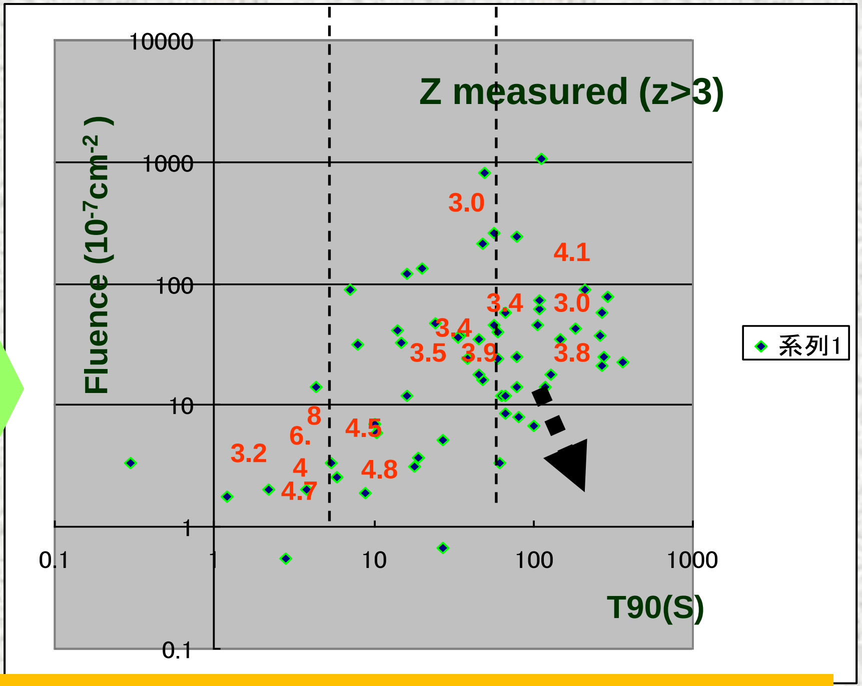


Coded Mask
- Large FoV Imaging possible in X and γ-rays
- But need much photons
- No rejection for B.G. photon



Swift GRB(08-09)





Trigger bias looks to appear above for long GRB with z>4

Sensitivity of X-ray Burst Trigger

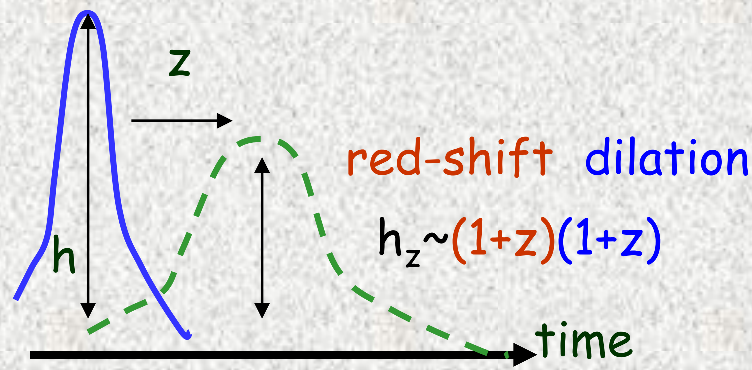
- Diffuse X-ray BG:~10ph./$cm^{-2}s^{-1}str^{-1}$ >5keV
- $Ph._{lim} \propto \sqrt{(A\text{: Detection Area})}$

  A($10^4 cm^2$ >5kev)->10^5counts s-1 in A

  -> 0.20Ph./$cm^{-2}s^{-1}$ at 8σ
- $Ph._{lim} \propto hz \sim (1+z)^2$

  $z+1 \propto (A)^{1/4}$

  If z_{lim}(Swift)~7 -> z_{lim}(Swiftx10)~12



Salvaterra et al. 2008

Instrument	Band (keV)	Field of view (sr)	P_{lim} (photon s^{-1} cm^{-2})	z_{max}	GRBs per year at $z \geqslant 6$	GRBs per year at $z \geqslant 10$
Swift	15–150	1.4	0.4	6.3–7.5	1.3–4	0.09–0.1
			0.25	7.0–8.3	2–7	0.16–0.25
			0.1	7.5–9.9	3-16	0.3–0.9
INTEGRAL/IBIS	20–200	0.1	0.2	3.8–5.2	0.1-0.5	<0.01
GLAST/GBM (on-board)	50–300	9	0.7	6.2–6.3	1.2–1.5	<0.1
GLAST/GBM (ground)			0.47	6.8–6.9	1.8–2.4	0.05–0.12
SVOM	4–50	2	1.0	6.7–7.4	2–4	0.1–0.13
EDGE	8–200	2.5	0.6	6.9–8	2–6	0.18–0.23
EXIST	10–600	5	0.16	9.7–11.3	11–56	0.9–2.8

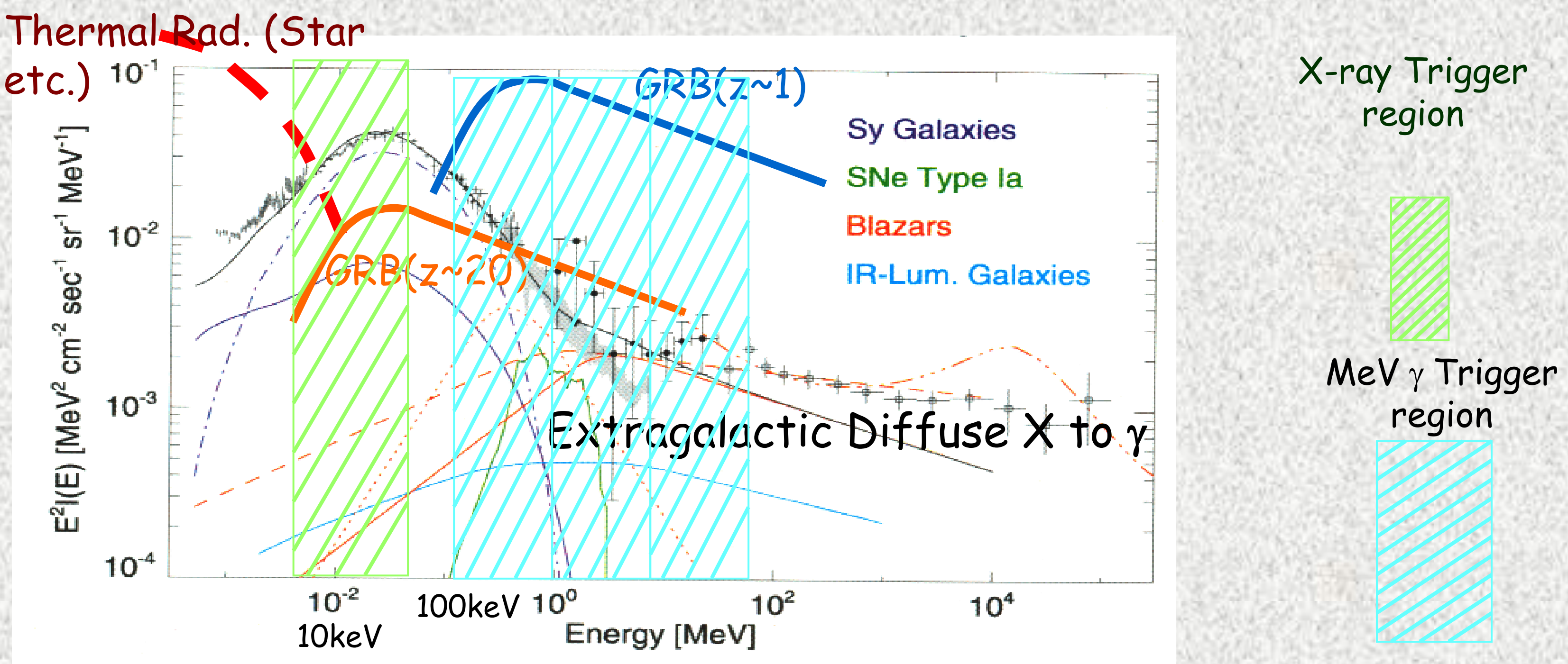
New Trigger Strategy

- B.G.high —> peak Trigger; sensitivity $\propto$ $(1+z)^{-2}$
- B.G.low —> Integrated Trigger; sensitivity $\propto$ $(1+z)^{-1}$

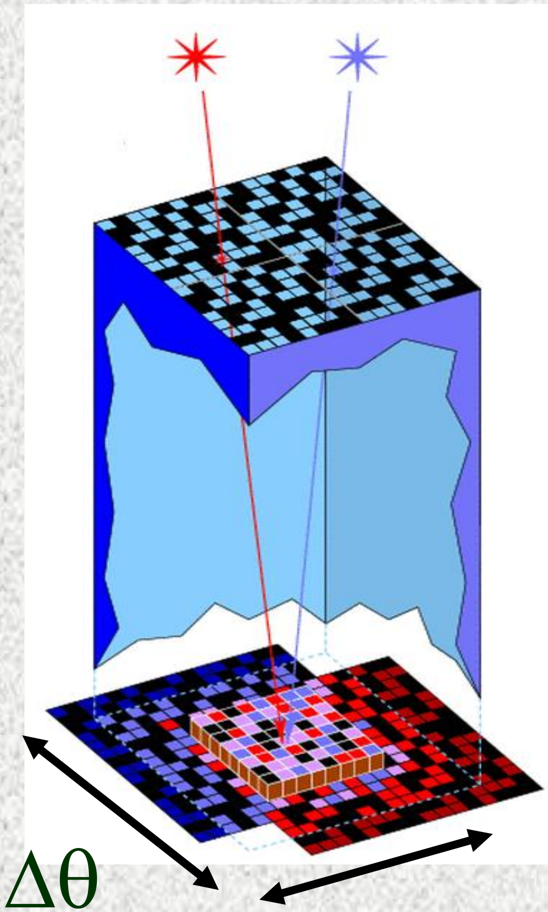
Imaging ability for each photon

Even 10° resolution -> 1/100 B.G. of 1 str Detector

->Imaging Trigger photon by photon in ETCC

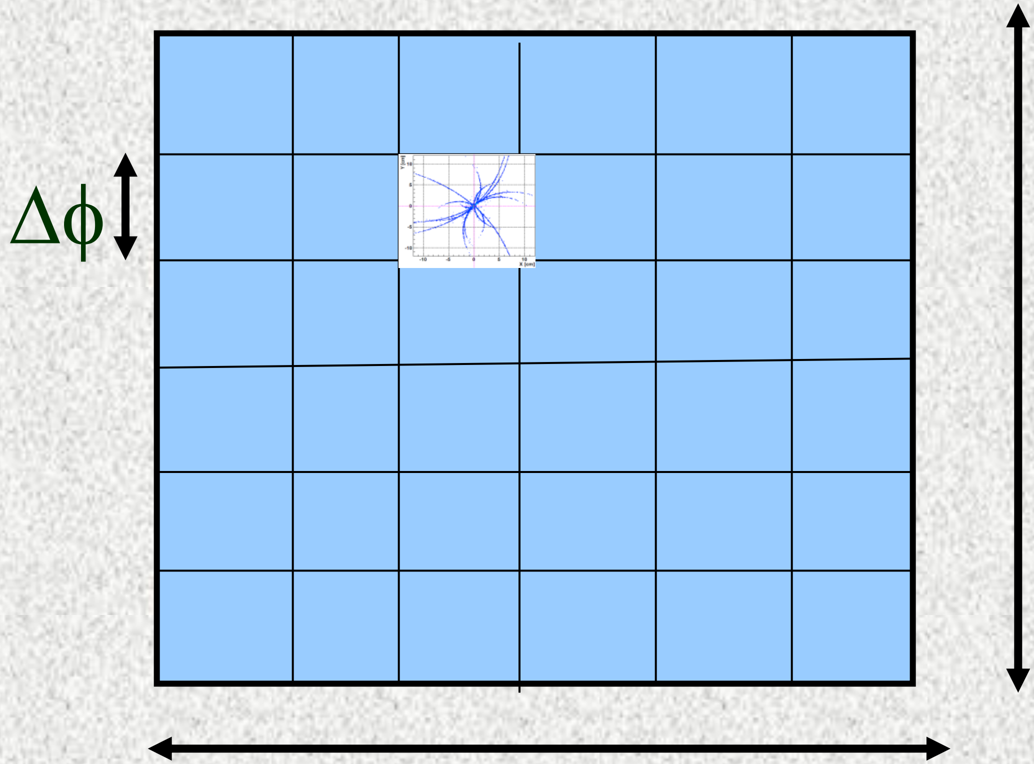


Modified from Weidenspointner & Varendorff 2001



Noise area = Δθ x Δθ

ETCC Field of View



Δθ ~120degree

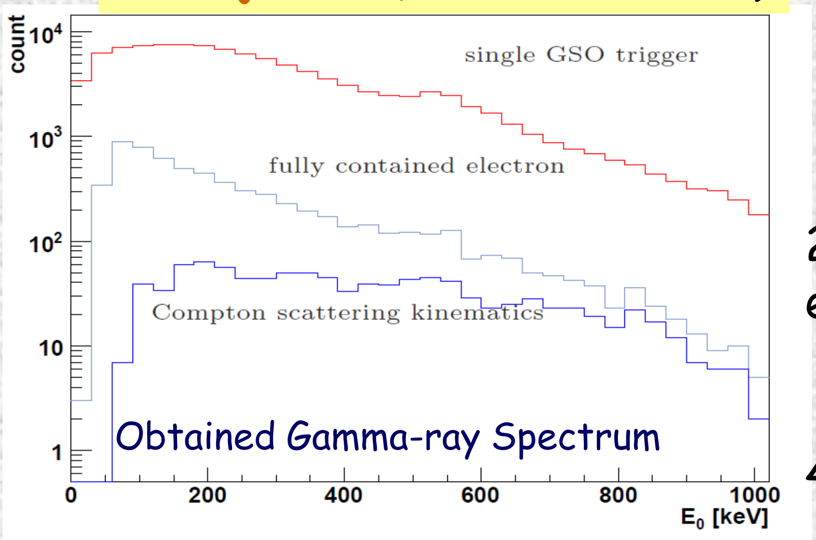
Noise area = (Δφ x Δφ)

Δφ/Δθ =10 Noise reduction -> 1/100

Imaging GRB Trigger in Sub-MeV

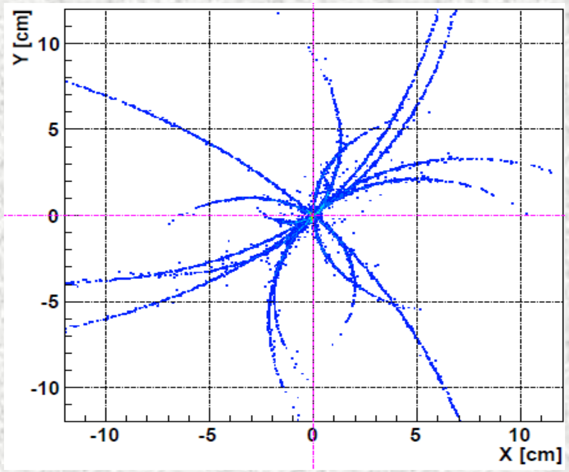
- ETCC measure the each photon direction >100keV
- Cosmic BG >100keV; ~80ph./10^3s >100keV in 4°x4° @100cm^2 area
- BG; several 10 x of Diffuse γ but rejected by Kinematical cut

BG Rejection (SMILE-I off-line)



2.23×10^5 events

420 γ



Several γ Mapping in Lab.

- P_{lim} ~70 ph. >100keV in 4°x4° @~100cm^2 in 10^3 sec (8σ)
- Point Accuracy for GRBs <0.2° for 300γ, 0.5° for 30γ
- With a wide field of view infra red or X-ray telescope (~0°.5)

Expected Flux >100keV for GRB@z~20

Fluence(>100keV)-> #of Photon @100cm^{2}ETCC Position Accuracy.

Fluence (>100keV)	# of Photon @100cm^2 ETCC	Position Accuracy
10^{-6} erg/cm^2	~10^3 photon	<0.1°
10^{-7} erg/cm^2	~ 10^2 photon	<0.3°
10^{-8} erg/cm^2	~10 photon	~1°

For Radio observation for long GRB ~ 1° resolution is enough

Expected Photon #(>100keV) for GRB @z=20 & $E_{iso}=10^{52}$ erg ->**1000 ph**.

two Fermi-LAT GRB (080916, 090902B) events=> @z=20 >1000 ph.(>100keV)

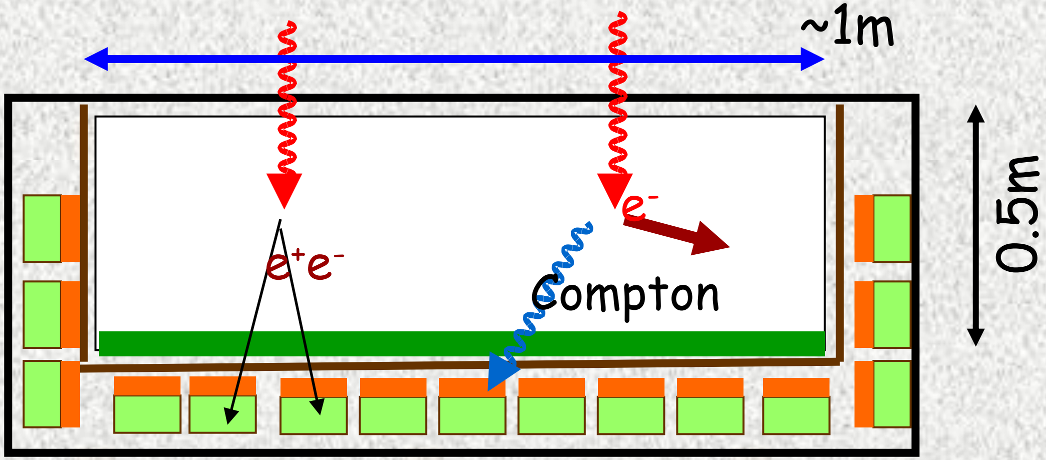
*Fluence(100keV-10MeV) ~ 10xFluence(5-50keV) for typical GRB

GRB	z	Epeak (keV)	Fluence (5- 50 keV) (erg/cm2)	Peak Flux (ph/cm2/s)
090423A	20	36 +/- 7	(2.6 +/- 0.2) x 10-7 ☑	0.3 +/- 0.1 ☑
080913	20	48 (+83, -18)	(2.1 +/- 0.2) x 10-7 ☑	0.2 +/- 0.1 ☑
050904	20	152 (+116, -52) !?	(1.7 +/- 0.1) x 10-6 ☑	0.1 +/- 0.1 ▲
060927	20	23 (+8, -3)	(0.3 +/- 0.1) x 10-6 ☑	0.3 +/- 0.1 ☑
060510B	20	27 +/- 17	(1.2 +/- 0.1) x 10-6 ☑	0.1 +/- 0.1 ▲
060223A	20	18 (+26, -3)	(1.7 +/- 0.1) x 10-7 ☑	0.1 +/- 0.1 ▲
060206	20	18 +/- 5	(2.0 +/- 0.1) x 10-7 ☑	0.2 +/- 0.1 ☑

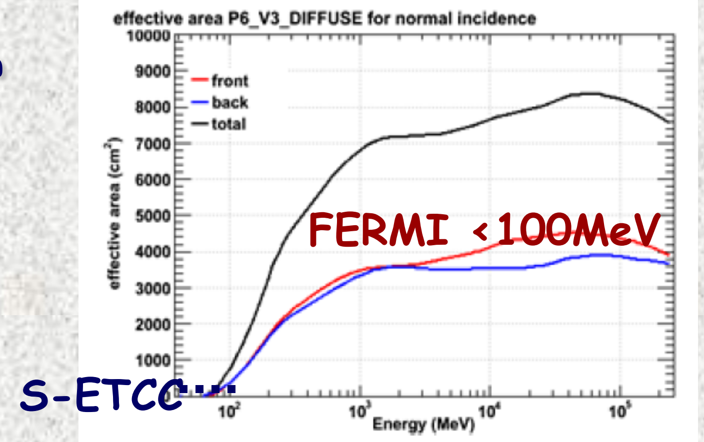
Eiso (10^{52}erg)	Expected γ (>100keV)
89	2.6×10^3
7	2×10^3
38	1.7×10^4
	3×10^3
20	1.2×10^4
3	1.7×10^3
5	2×10^3

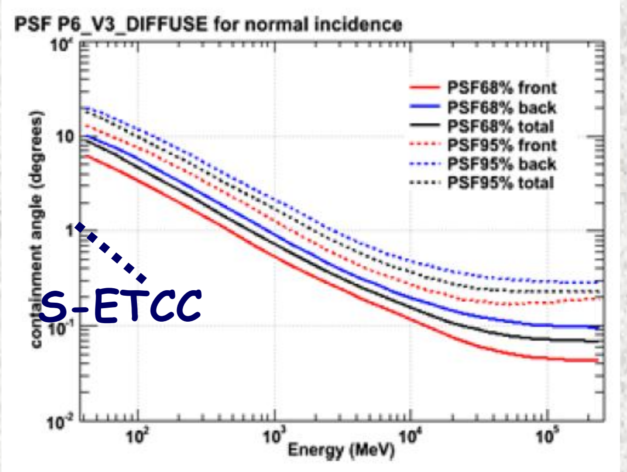
using Dr. Yonetokus' table

Satellite ETCC Detector



Double Scintillator
(laBr3+GSO)





Requirements

Detection Area 100-30cm^2 from 0.1-100MeV

Angular Res. ~4^o - ~0.3^o <0.1-100MeV

-> Position Resolution 0.2^o for ~300 photons

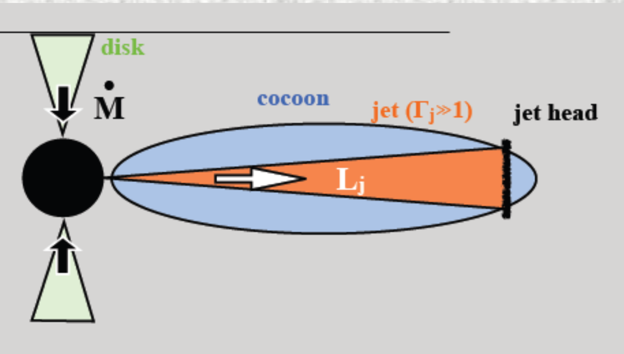
Expected Sensitivity ~1/50 of COMPTEL

Small Satellite ETCC 40x40x40cm ETCC

Detection Area ~10cm^2

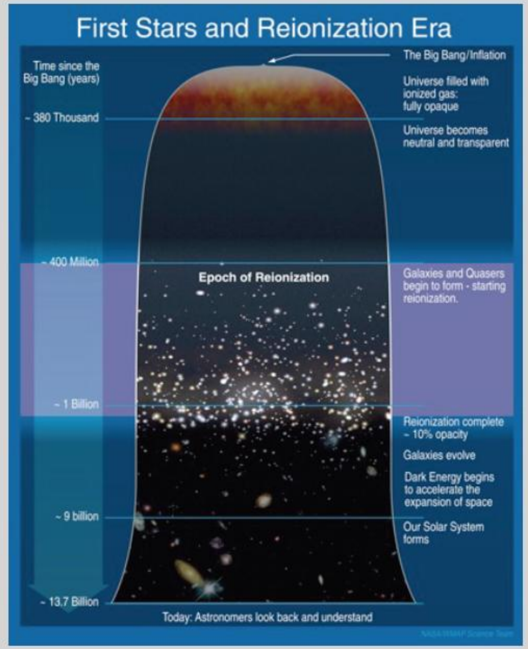
Sensitivity ~1/15 of COMPTEL

Detection of GRB from POP-III



The First Stars

From Dr. Suwa

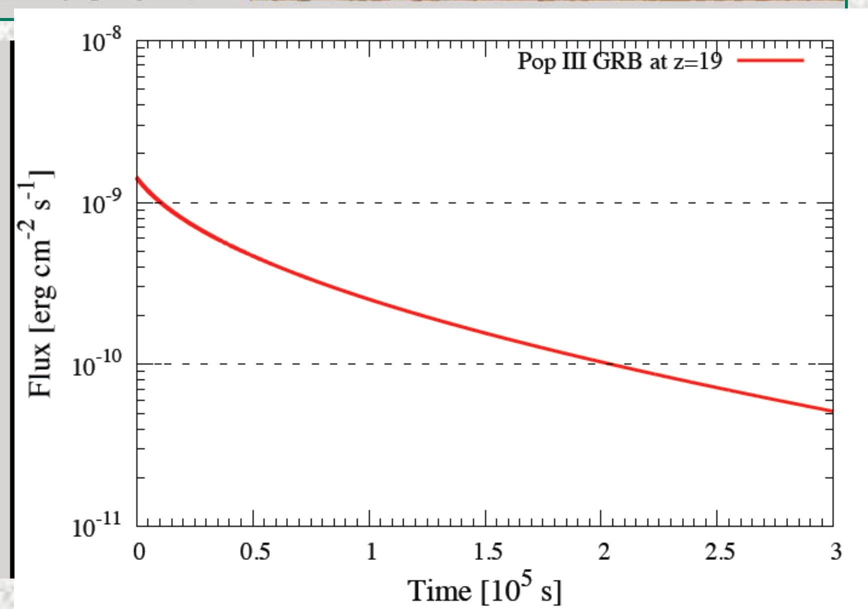


http://imagine.gsfc.nasa.gov/docs/sats_n_data/satellites/jwst_darkages.html

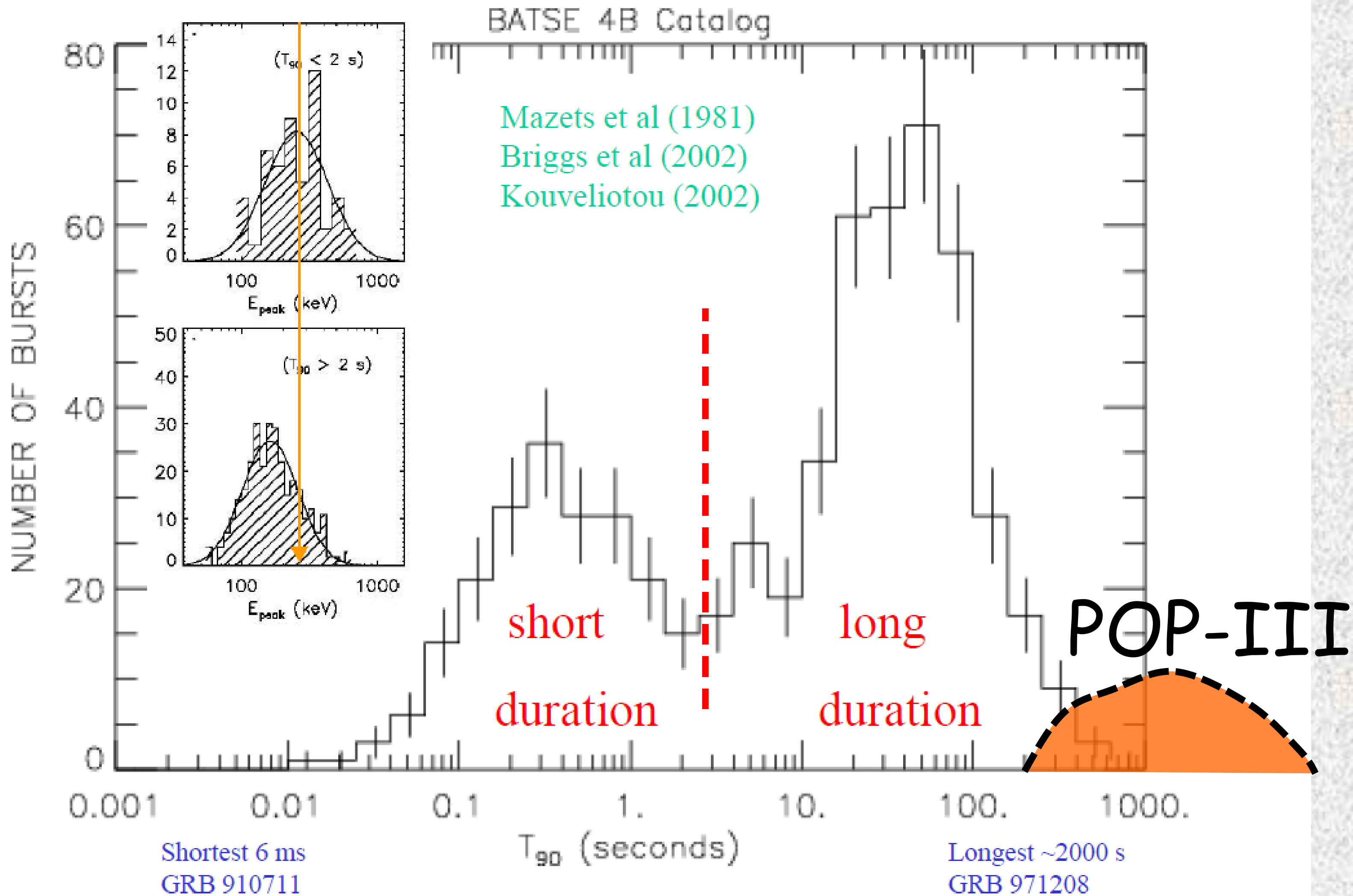
- Metal free (zero metal)
- Predicted to have been very massive(>~100M☉)
- The end of the cosmic "dark age"
- Related to reionization
- Difficult to observe

Can we observe the first stars using the "FIRST GRB"??

Model	Mass [M☉]	Radius [10^{11}cm]	Mechanism	break time [s]	E_{GRB} [10^{52} erg]	E_{cocoon} [10^{52} erg]	T_{90}	E_{iso} [10^{54} erg]
Pop III	915	90	MHD	690	45	57	1500	120
			Neutrino	failed GRB				
GRB	16	0.4	MHD	4.7	1.0	0.23	49	2.6
			Neutrino	2.8		0.42	10	



Bi-modal duration distribution of GRBs

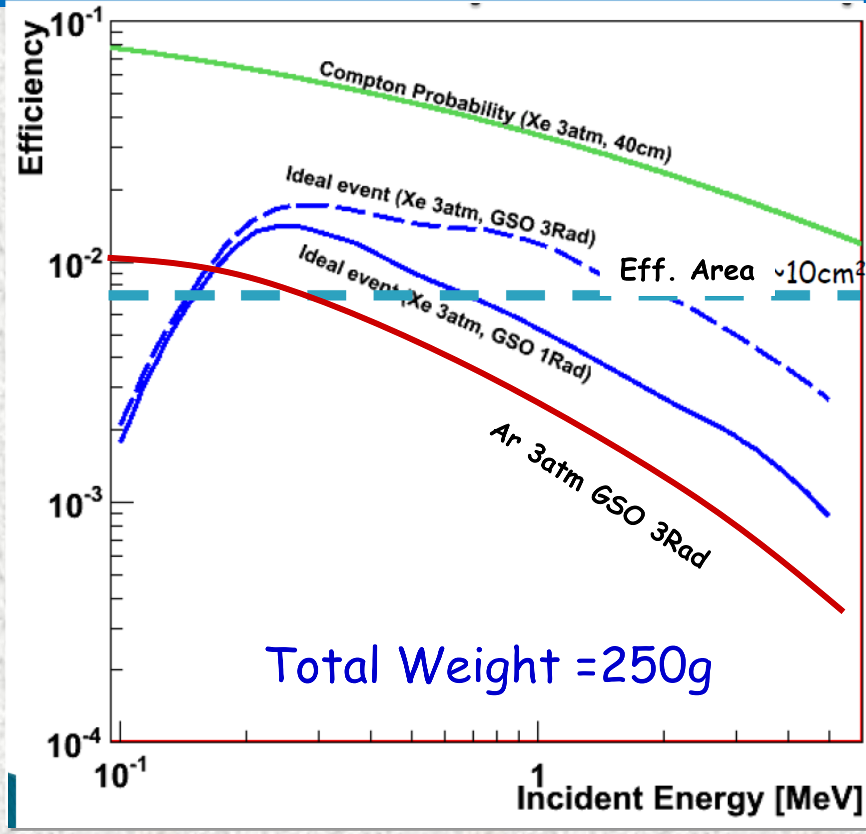


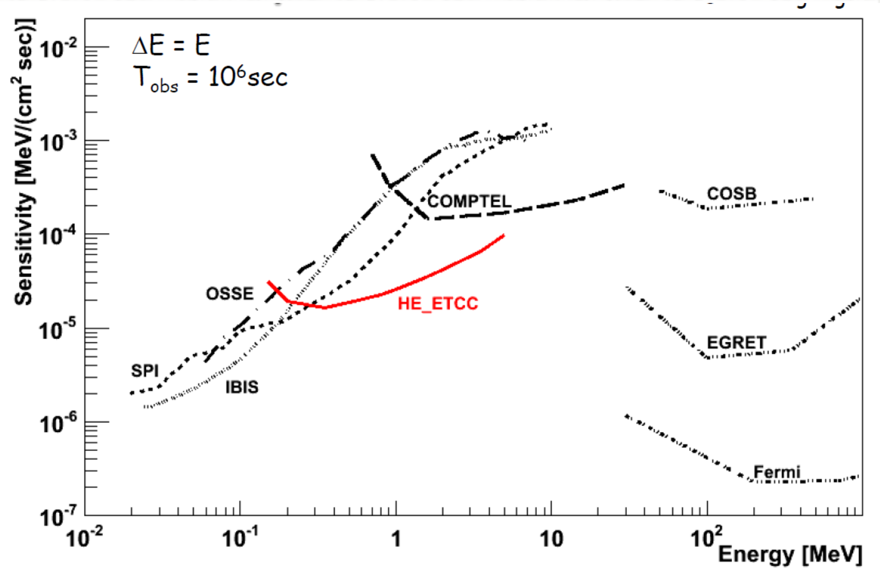
Unique method to detect and identify POP-III

Detection of long GRB by 40x40x40cm ETCC($10cm^2$ eff. Area)

- 10^{-8}erg/cm^2s 1γ(>100keV)@$10cm^2$
  for GRB of 10^{-9}erg/cm^2s (900M_{solar})
- 10^3s 100γ B.G. 8γ in 4x4° S/N =10σ
- 10^5s 10^4γ B.G> 800γ S/N =300σ
- 5σ detection during 10^5s -> 140γ

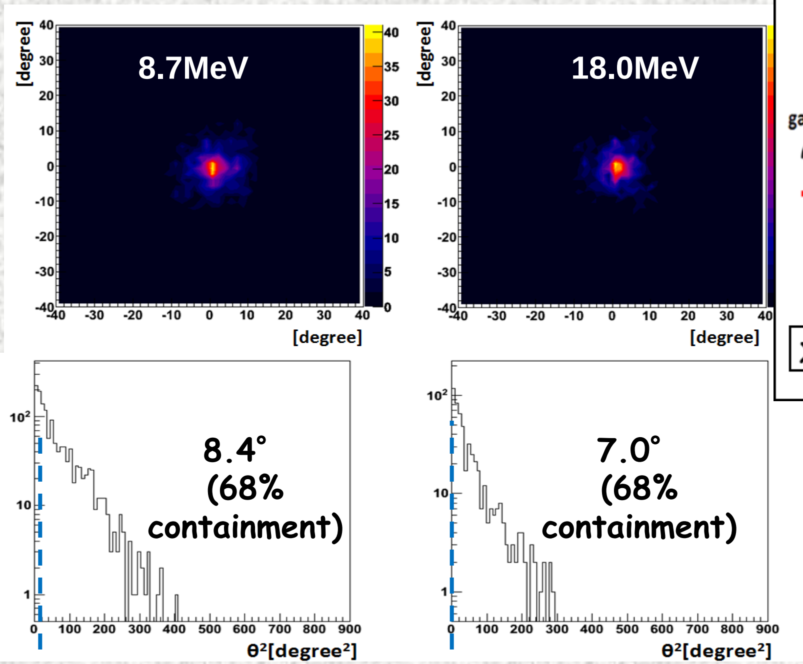
for infra red telescope 300γ needed
detection limit ~30 M_{solar}
for radio telescope ~100γ needed
detection limit ~10M_{solar}

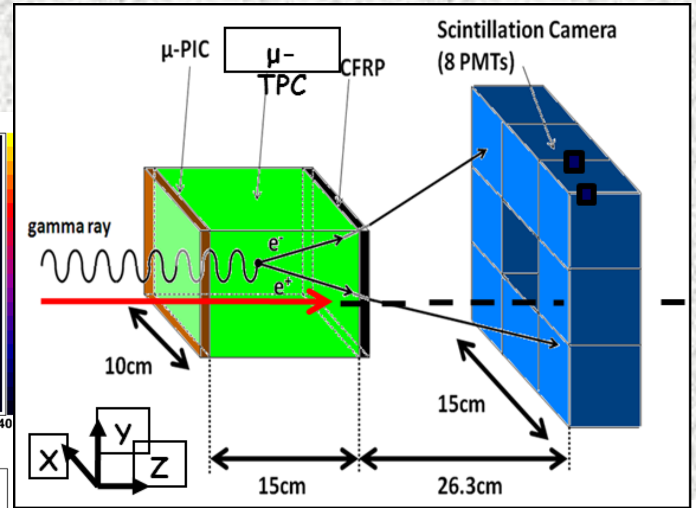


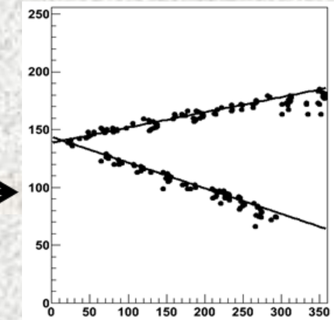


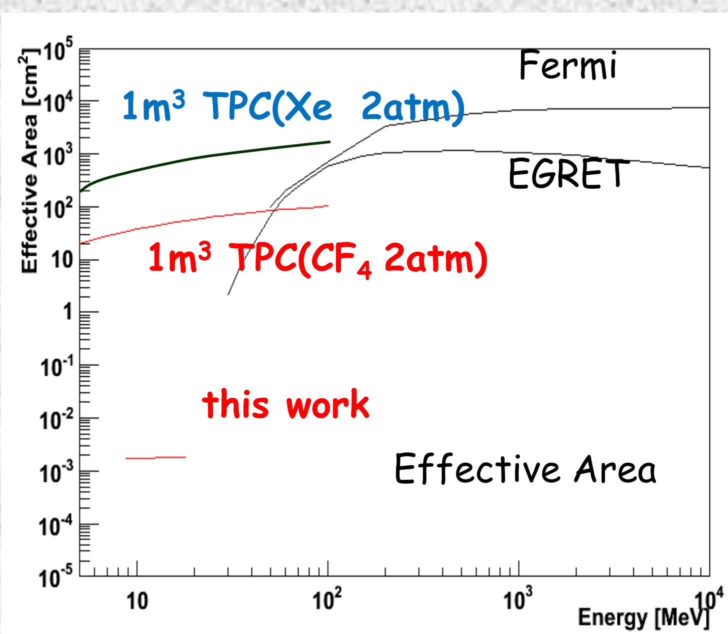
Gas : Xe 3atm
TPC size : ($10x10x40\ cm^3$) x (4x4)
Electron-absorber:
plastic scinti. (1.02 g/cm^3)
GSO pixel : 6x6x(13 or 40)mm^3
Bottom : 96x96 pixel
Side : (96x32 pixel) x 4

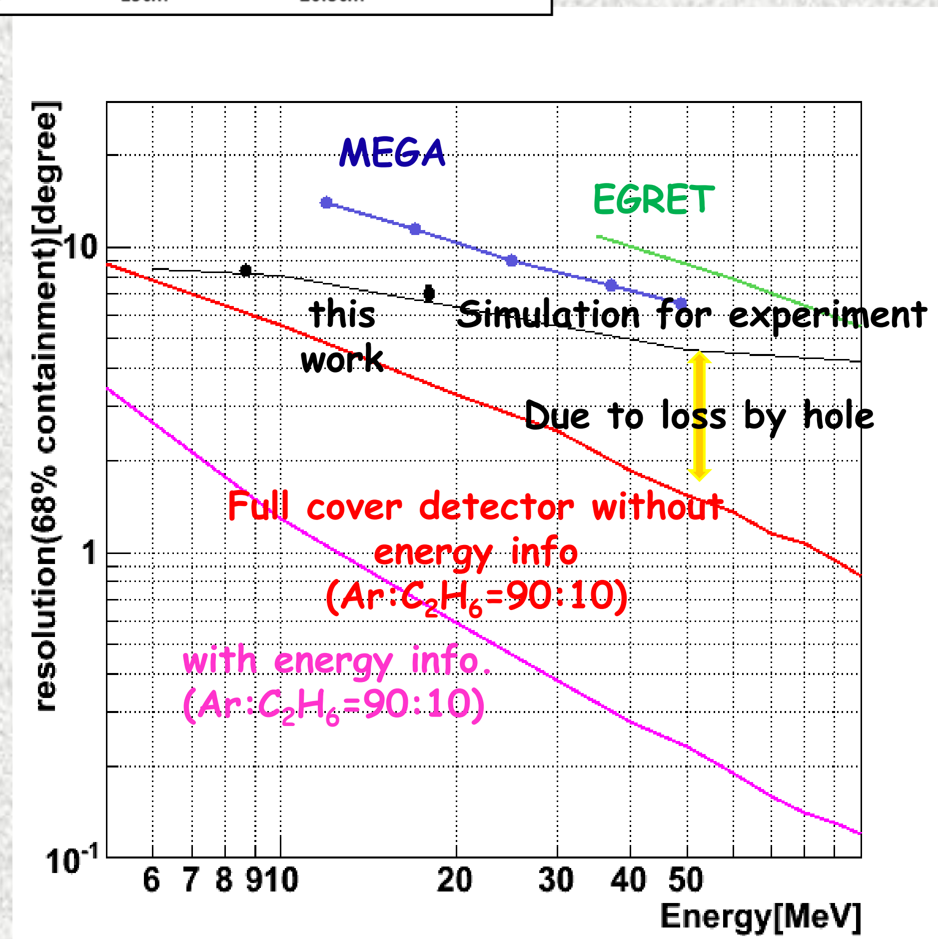
Pair creation











γ-ray burst due to Relativistic Electron Precipitation in 1996 @Kiruna for SMILE-II

K.R.Lorentzen et al.,(2000)

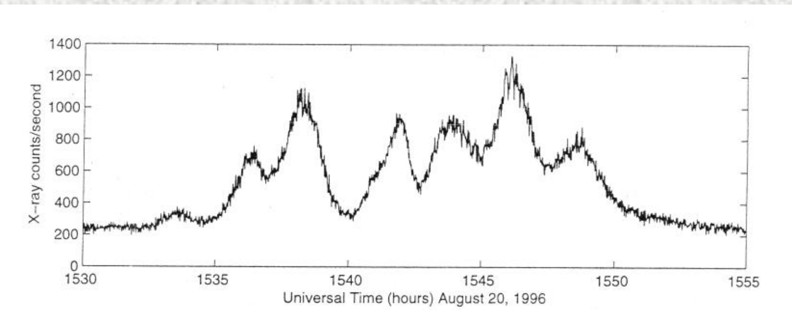
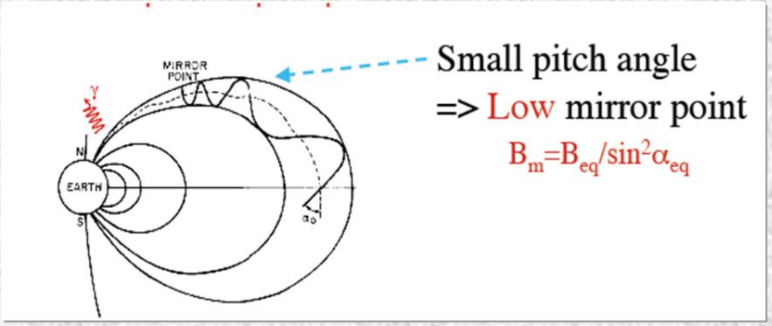


Figure 1. X-ray imager data taken during the relativistic electron precipitation event of August 20, 1996. The X-ray count rate between 20 and 120 keV is averaged over 1 s. The 10–20 s modulation is most clearly visible superposed on the peak starting near 1545 UT.



- Next MAXIS (2000) 9 REP events in dusk side

-> >10 times efficient imaging observation with balloon

- SIMILE-II balloon Exp. 100kev-2MeV

~20σ detection for imaging Δθ 5°

Wide field of View with ~3str

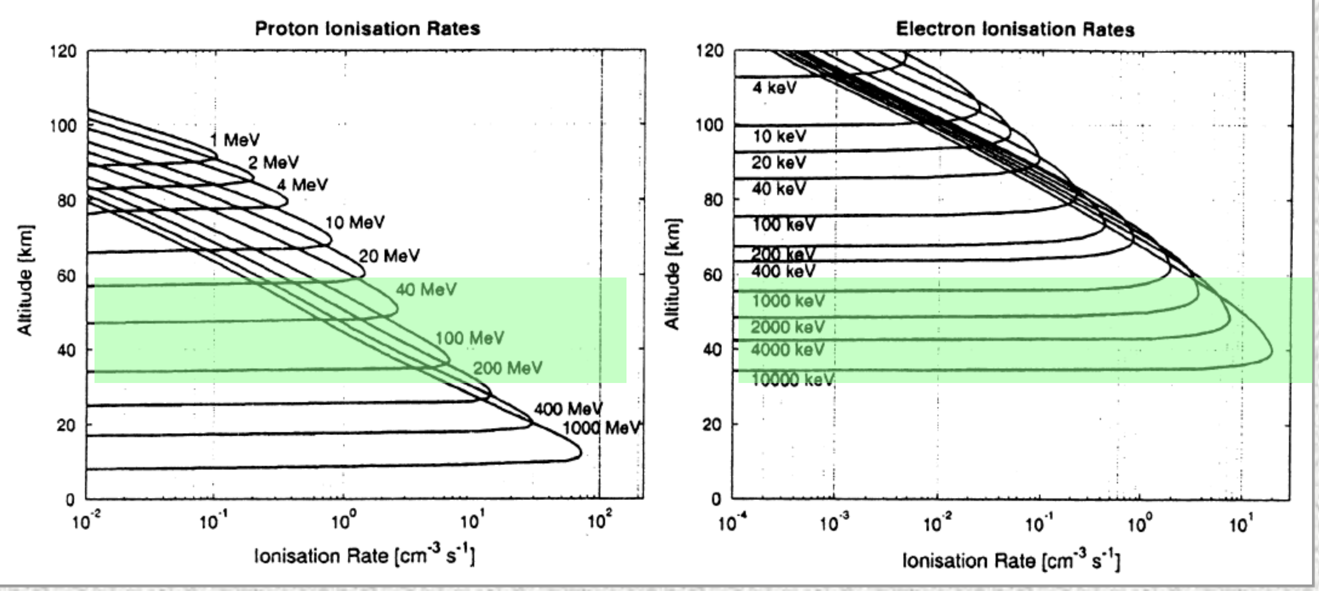
- Polar circle flight

Collaboration with EISCAT-3D (LOFRA)

Ion chemistry in Stratosphere due to high energy particles precipitation

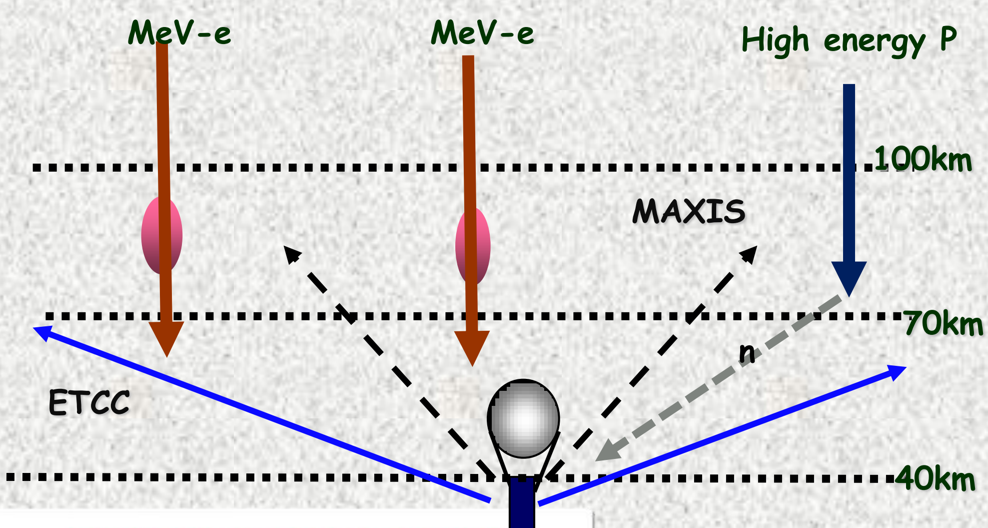
- particle precipitations (electron and proton) affect on O_3, NO_x in stratosphere.
- In particular, High energy particle precipitation like REP may be dominant for ionization system in stratosphere.
- Precise data of High energy Precipitation rate, position, time, flux, lateral & vertical spread are necessary.

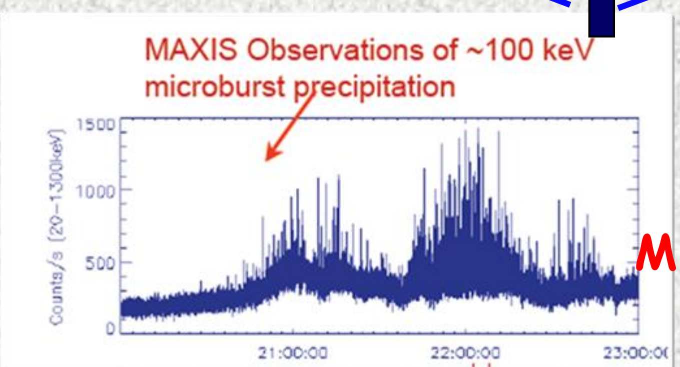
E. Turunen et al. / Journal of Atmospheric and Solar-Terrestrial Physics 71 (2009) 1176–1189



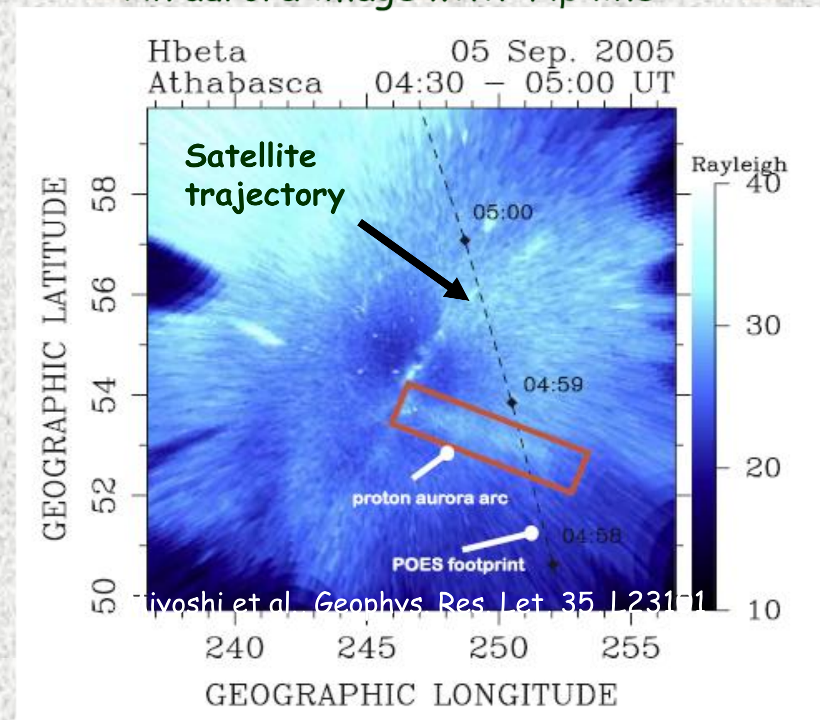
Feature of ETCC for REP bursts

- ETCC ~4str >500km radius far from balloon
- detecting weak & far distant REP less than Atmospheric BG x ~10
- Measurement of position and spectrum of REP
- Imaging a vertical and lateral spreads of far distant REP & **Micro bursts**
- Detecting a Proton precipitation (>10MeV) by detecting secondary neutron





An aurora image with Hβ line



Summary

- SMILE-II is planned to begin since 2013@Kiruna one-day test flight and since 2014 long duration flight for observations of celestial and terrestrial gamma-rays during this solar maximum (~2018)
- Improvement of tracking performance will increase the sensitivity of SMILE-II dramatically.
- This improvement would enable to develop compact satellite ETCC with multi ten cm^2 effective area in the MeV region.
- ETCC may enable us to detect longer duration GRB than 10^3 sec, and we will check it by the long duration flight (2 week flight , about 10 GRBs in the FoV. For typical GRBs with $>10^{-6}$erg/cm^2, >10 γ are expected)