Performance of a nanosatellite MeV telescope

R. Rando
F. <u>Berlato</u>, G. <u>Lucchetta</u>
D. Bastieri, F. Urso
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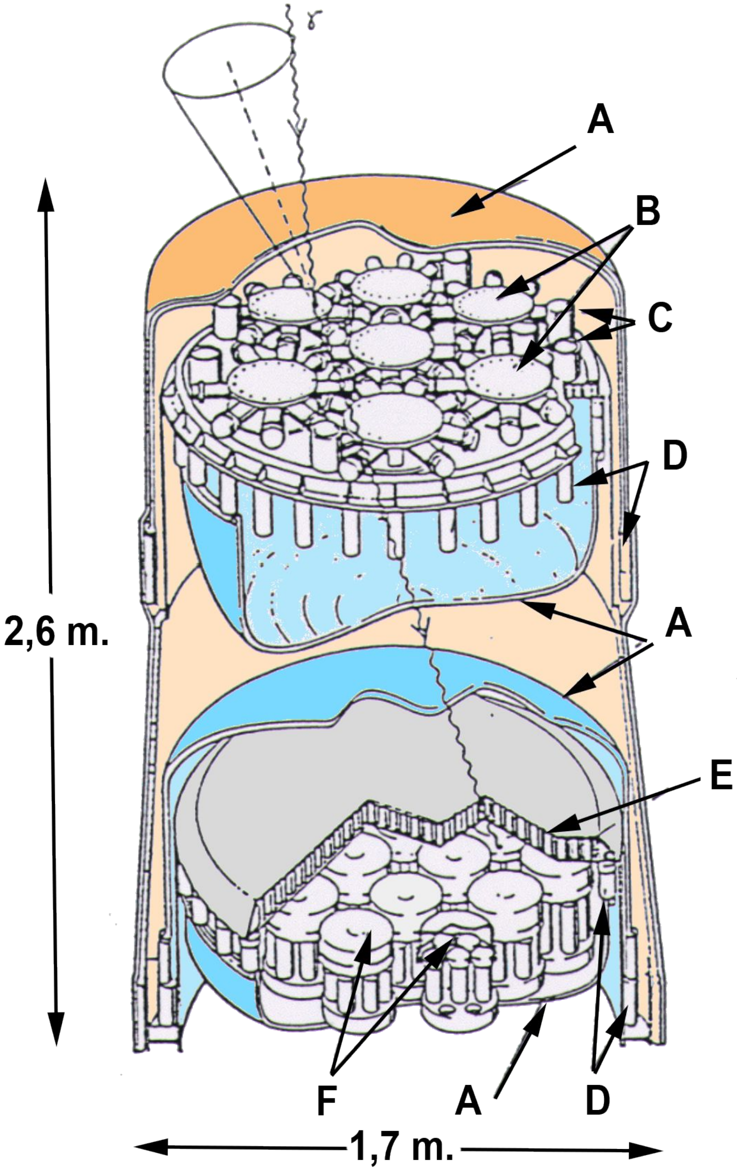
Dept. of Physics and Astronomy
University of Padova



(paper submitted to AJ)

E-Astrogam 1st workshop – Feb 28 / Mar 2, 2017 - Padova

Outline

- Why?
- Design
- Instrument performance
- Scientific performance
- Improvements
- conclusion

Why?

Is there an opportunity for a nano-scaled MeV mission based on a silicon tracker?

- “cheap”
- Rapid development
- Low background due to activation (5 kg versus 12 tons for CGRO) ←
- Easy to deploy
- Can test hw/sw in view of future larger missions (e-Astrogam)

What are the issues we will face?

- Small section → effective area?
- Small height → small lever arm → angular resolution?
- Small perimeter/surface : proportionally more readout channels (power?)

Need to carefully evaluate the ratio of performance to costs

Designing the payload

Based on the extremely successful "CubeSat"
Scientific payload is 2U : 20x10x10 cm^3
Another 2 to 4 U for the rest (power/transmission/attitude/...)

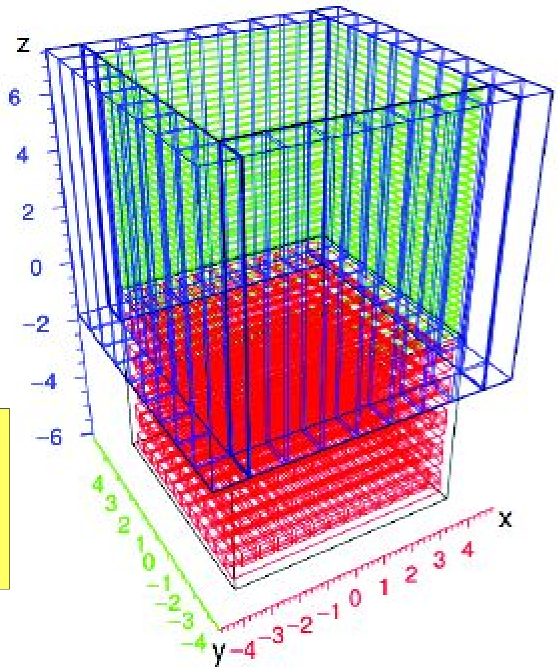
TRACKER

Parameter	Value or range
Tracker size	$7.7 \times 7.7 \times 7.5$ cm^3
Number of layers	30
Layer thickness	500 μm
Strip pitch	150 μm
Guard ring	1 mm
Read-out electronics	VATA460
Electronic noise	1200 e$^-$
Bit digitization	10

CALORIMETER

Parameter	Value or range
Bottom crystals size	$0.5 \times 0.5 \times 7.5$ cm^3
Lateral crystals size	$1.0 \times 1.0 \times 8.5$ cm^3
Depth resolution (1 σ)	1 cm
Photodiode read-out	Hamamatsu S3590
Read-out electronics	VATA460
Crystals per bottom plane	12
Bottom planes	10

Cost ~500k€
Power ~5W
Weight ~3.5 kg



Plastic scintillator ACD is not shown
Design is relatively conservative (esp. CAL):

- Photodiode could be SiPM
- Separate CAL and TKR ASICs?
- CAL depth resolution could be better (0.5 cm?)

But:

- no passive materials (e.g. structural)
- no space for readout electronics!!!

Tuning the parameters

Previous slide is a summary of a lengthy process
Originally design was much different... e.g. no lateral CAL
The impact of the design choices for TKR and CAL were evaluated
Detailed in the 2 master theses:

Berlato, F. 2016,
"Design and optimization around 1 MeV of a calorimeter for a CubeSat mission"
http://tesi.cab.unipd.it/53502

Luccehtta, G. 2016,
"Design and optimization around 1 MeV of a tracker for a CubeSat mission"
http://tesi.cab.unipd.it/53541

Checked Aeff,ARM,Eres, sensitivity varying e.g.:

- DSSD thickness, strip pitch
- TRK ASIC charge resolution
- CAL crystal dimensions
- CAL depth resolution
- ...

Simulations

Simulations and event recon: **MEGAlib**

Isotropic gamma rays (power law spectrum, same no per decade)

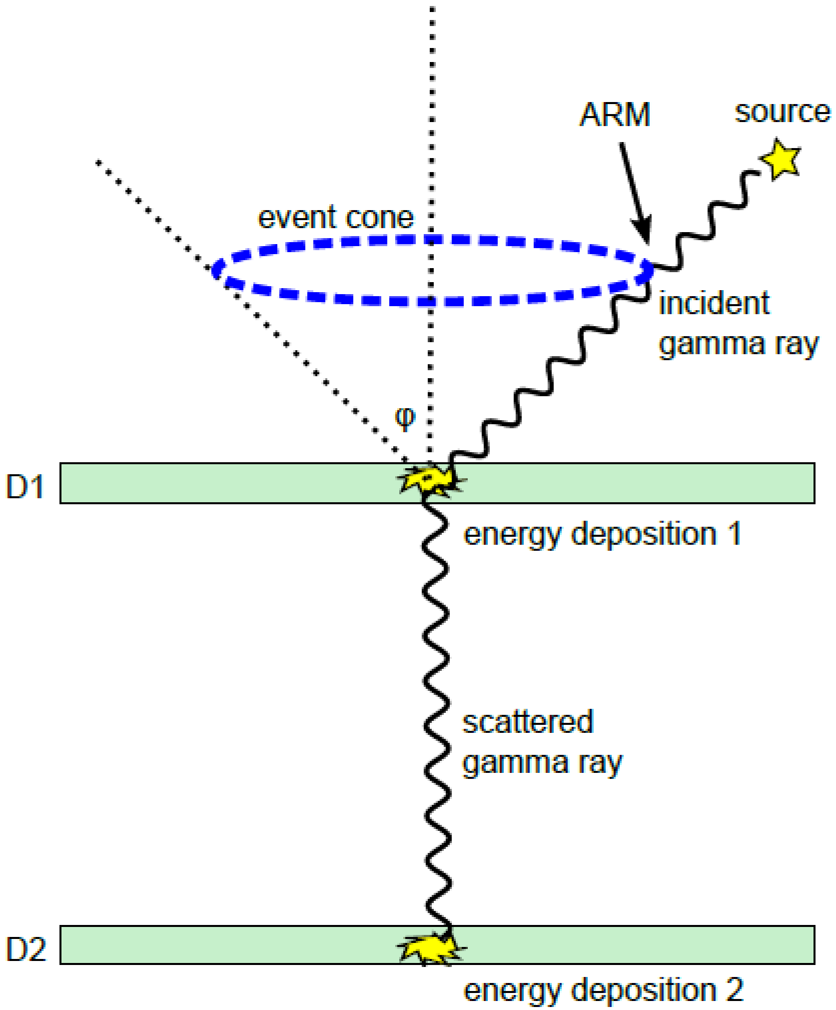
Backgrounds:

- "**Albedo**" similar to estimate for e-Astrogam
- **EGB** from COMPTEL (depends on resolved srcs)
- No activation (should be negligible wrt albedo, also missing too many elements in model): set to 0
- No charged particles yet (should be negligible wrt albedo): set as 2*EGB in all estimates

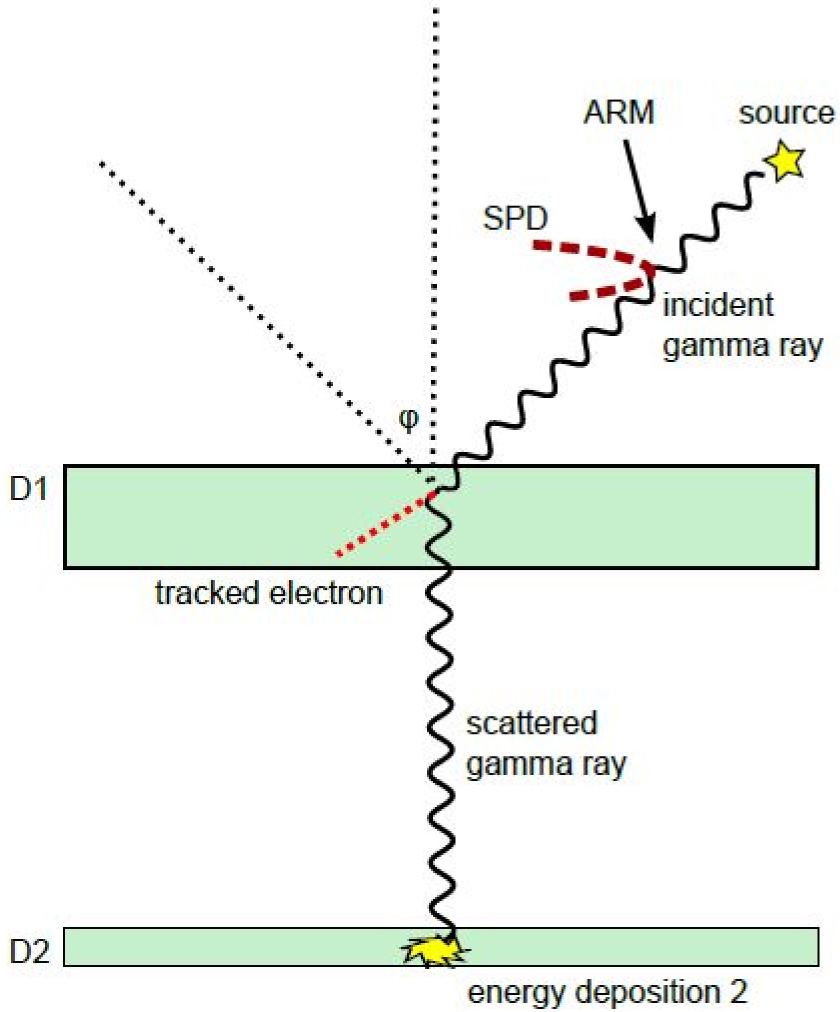
Trigger: one hit in TKR, one in CAL*
Events are reconstructed, divided into event classes and analyzed
Focus on "compton" / some basic work only for "pair"
Divide into sub-classes : CAL hit in lateral/bottom calorimeter

Tweak Megalib/revan to save all event variables in ROOT tuple
Check distributions, apply cuts
Evaluate instrumental performance

Unnecessary slide

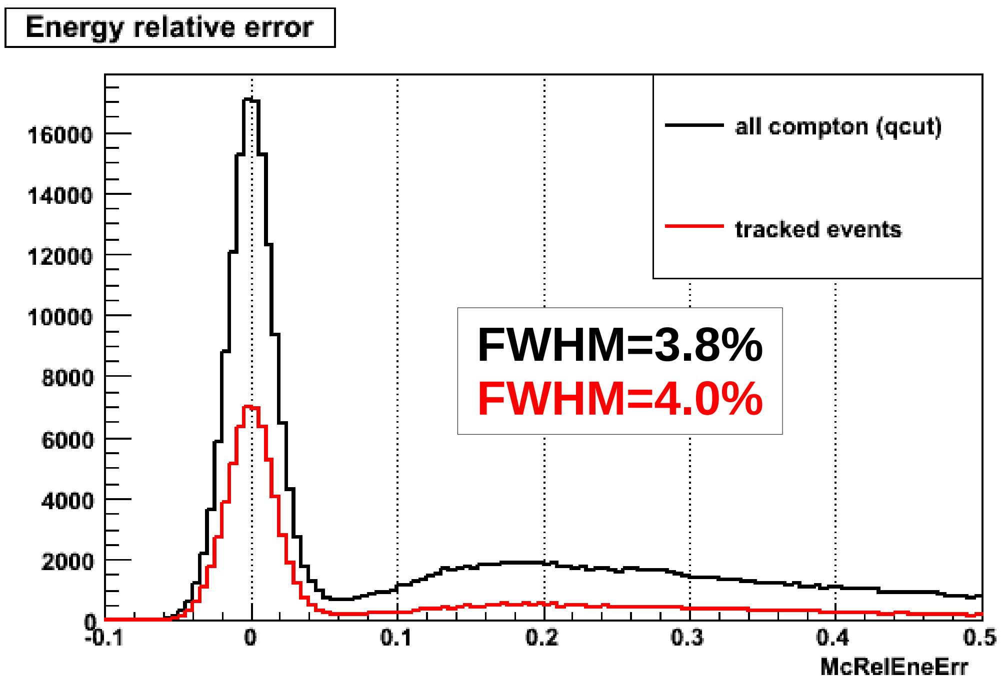


ARM: error on cone aperture



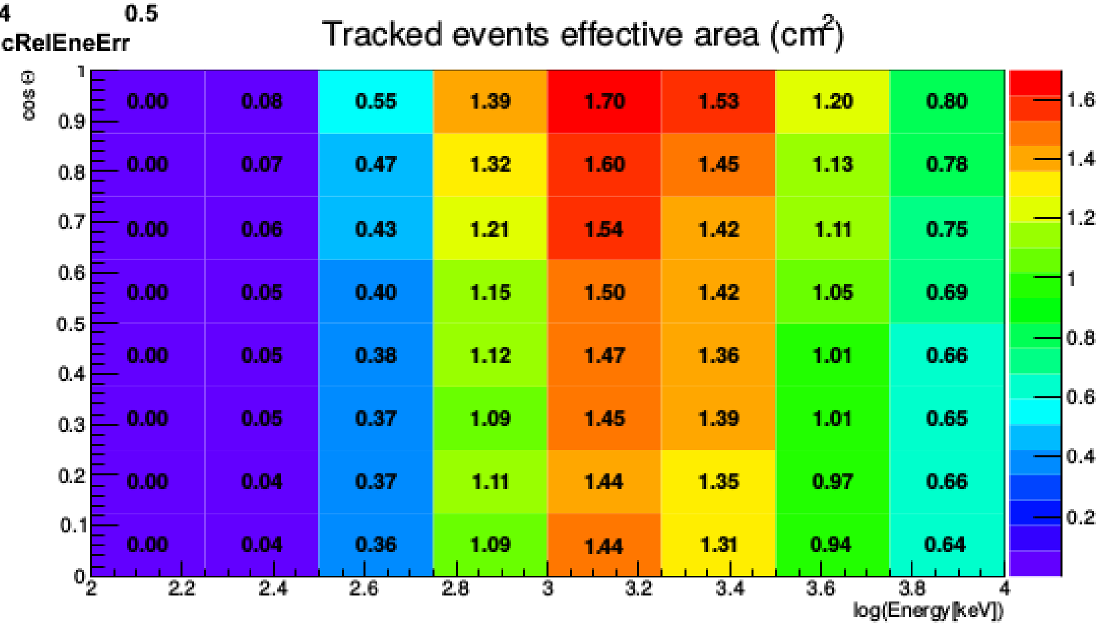
SPD: error on scatter plane

Energy resolution and effective area



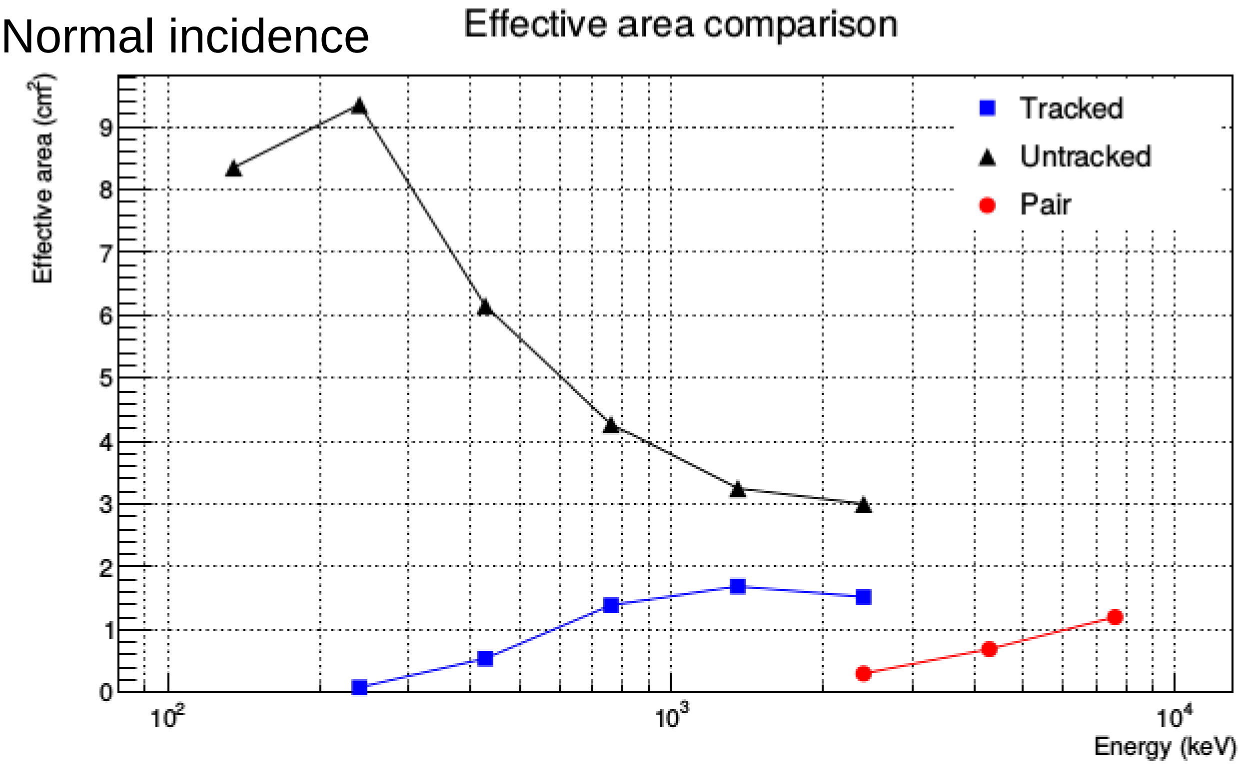
Energy resolution does not depend strongly on event class / energy
Here: 1 MeV < McE < 2 MeV

Effective area is ~ cm^2
Even for tracked, ~1 cm^2 at 1 MeV
For untracked, ~3-4 cm^2 at 1 MeV
Wide field of view!

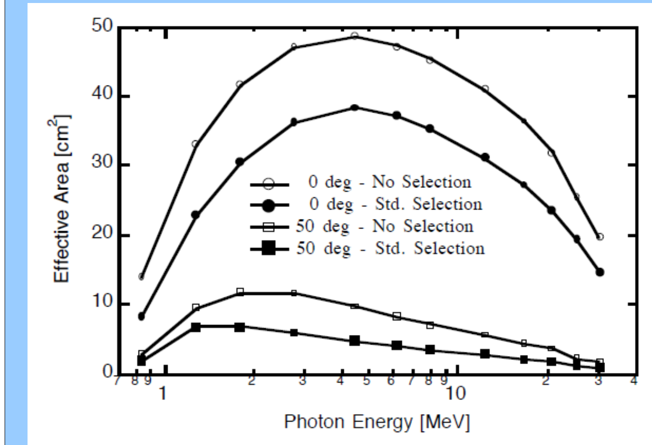


Effective area

Normal incidence



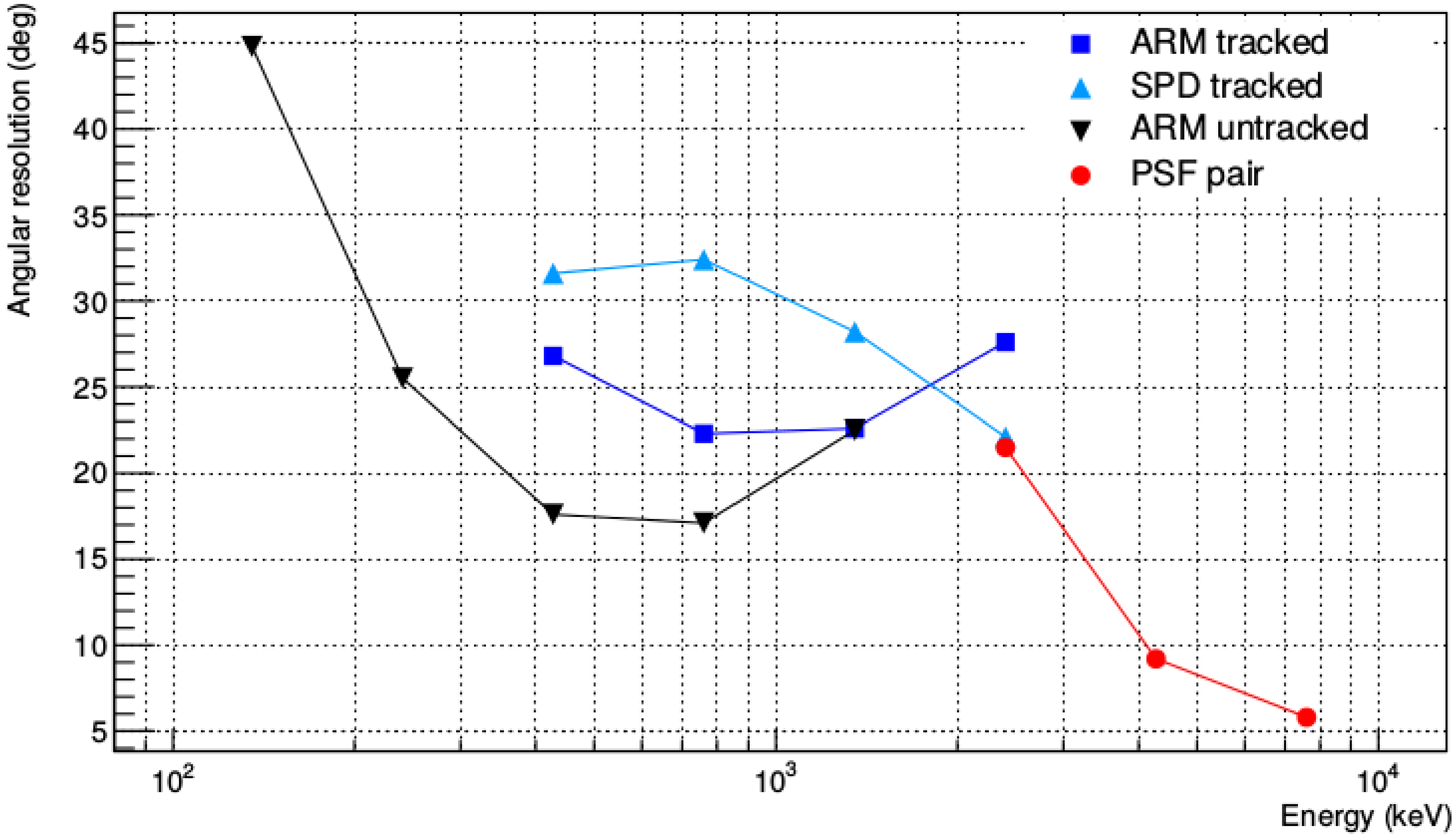
COMPTEL



AEFF at 1 MeV:
~15 cm^2 normal
~ 3.5 cm^2 at 50°
(incl. ev. selections)
(Diehl '96)

At 1 MeV: several cm^2 for untracked, ~1 cm^2 for tracked
Rough estimate for pair, rather small

Angular resolution



NB:
FWHM for ARM
HWHM for SPD

SPD=180° for untracked events

COMPTEL:
ARM~5.4° FWHM
At 1 MeV
(den Herder '92)

Resolution proves to be not exceptional (15-30°)
Lever arm is really unfavorable
Improving position resolution in CAL will help!
Reminder: here **1 cm**, could be **0.5 cm**
→ correspondingly ARM improves by **~40%**

Evaluating sensitivity

At this stage, **continuum sensitivity for point sources** only
Semi-analytical calculation, bin by bin

Simulate bkg sources: get bkg flux inside the resolution element → Analytically **calculate** minimum flux to have 3σ sensitivity on top of that

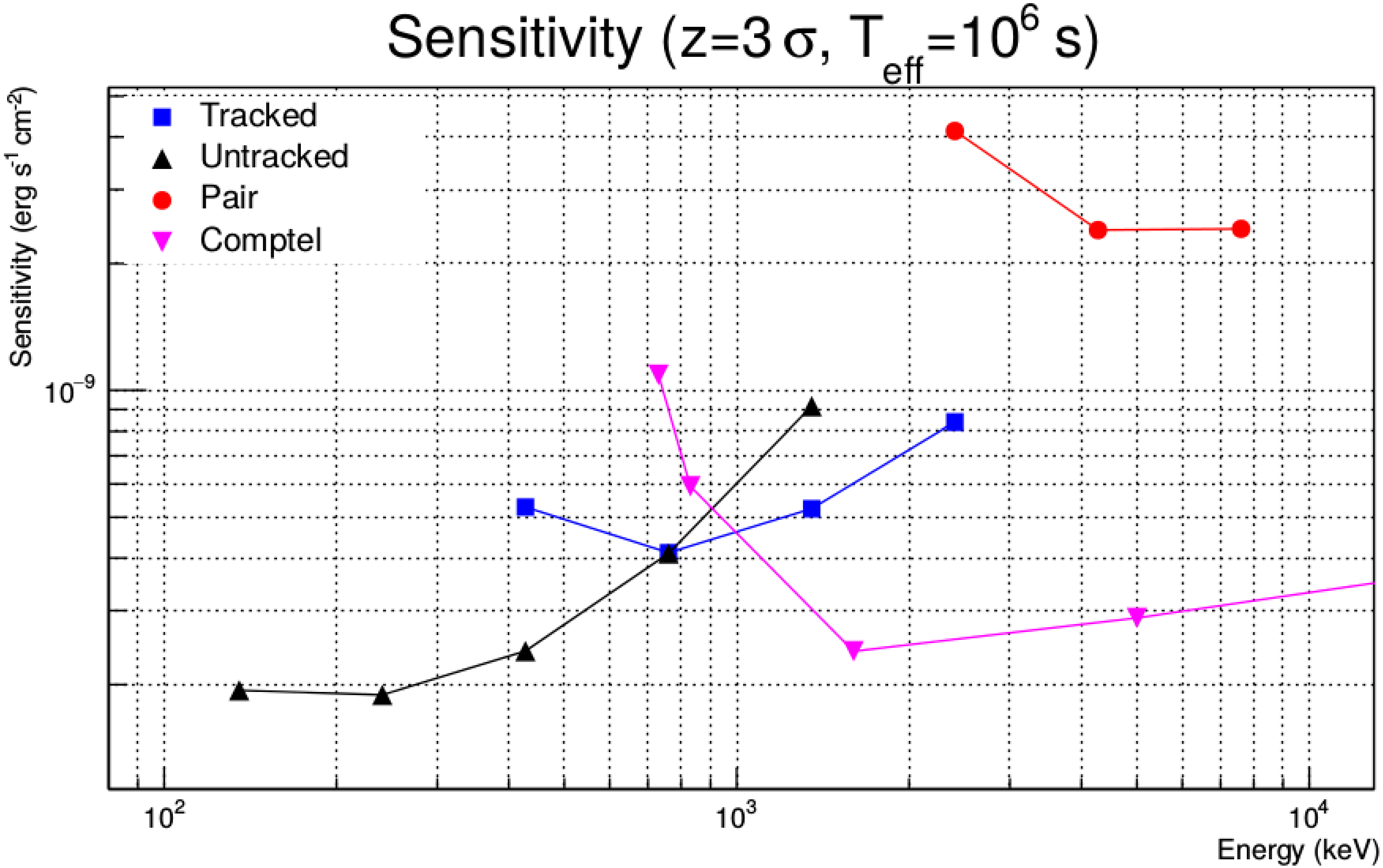
Assuming **10^6 s observation** (2 weeks)
Assuming point source "**at zenith**" (so scale time accordingly)
For each energy bin:

- From simulated EGB, measure F_{EGB}
- From simulated albedo, measure F_{ALB}
- Charged particles: assume $N_{CP}=2*F_{EGB}$
- Activation assumed negligible: $F_{ACT}=0$
- Determine number of BKG in the resolution element (determined by **ARM & SPD**)
- Determine minimum flux of a point source to have 3sigma detection

Main contribution to bkg is Albedo: ~15×EGB at 1 MeV normal, tracked events

Overall background event rate: 10 Hz untracked, 1.2 Hz tracked

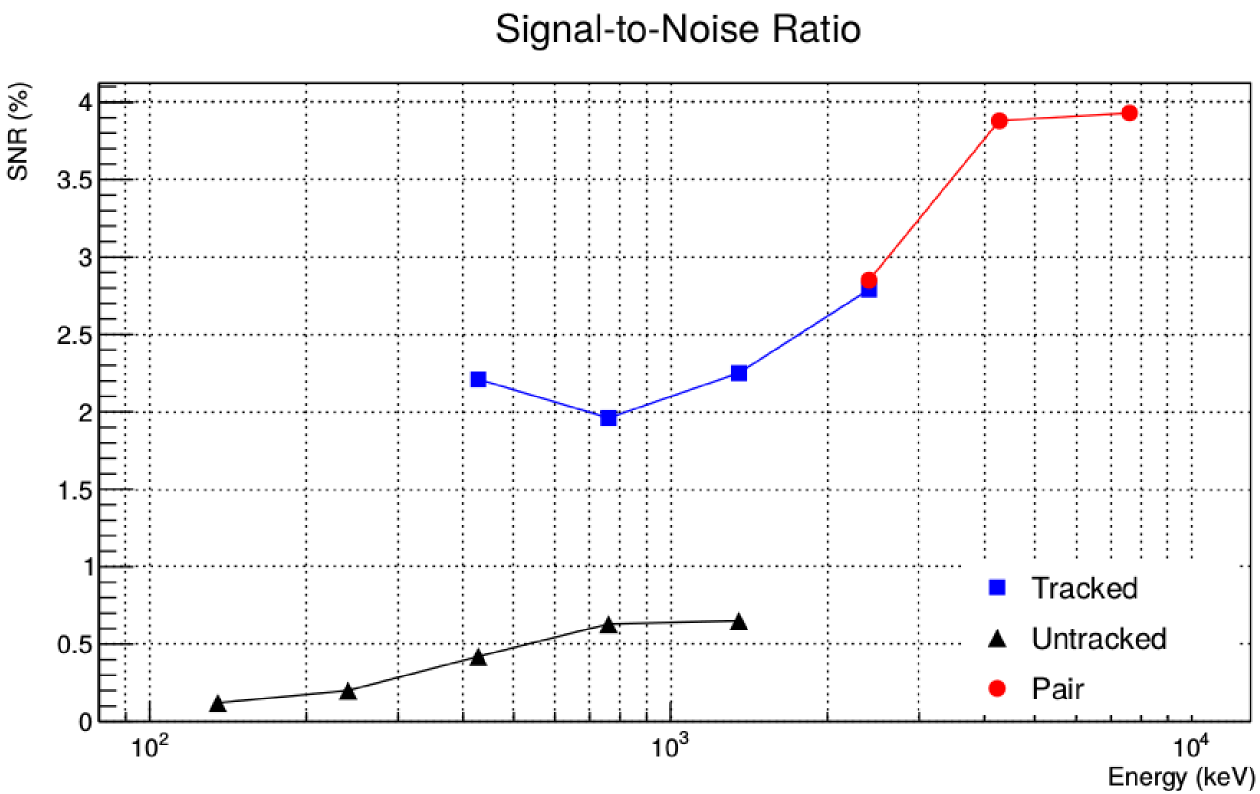
Point source continuum sensitivity



COMPTEL from Schoenfelder 2004

Not so fast: SNR

Main issue is SNR (signal to background ratio within the resolution element)



SNR is at a few % level

This implies control of systematics at the % level

Really need to improve this

Main culprits for high background rate:

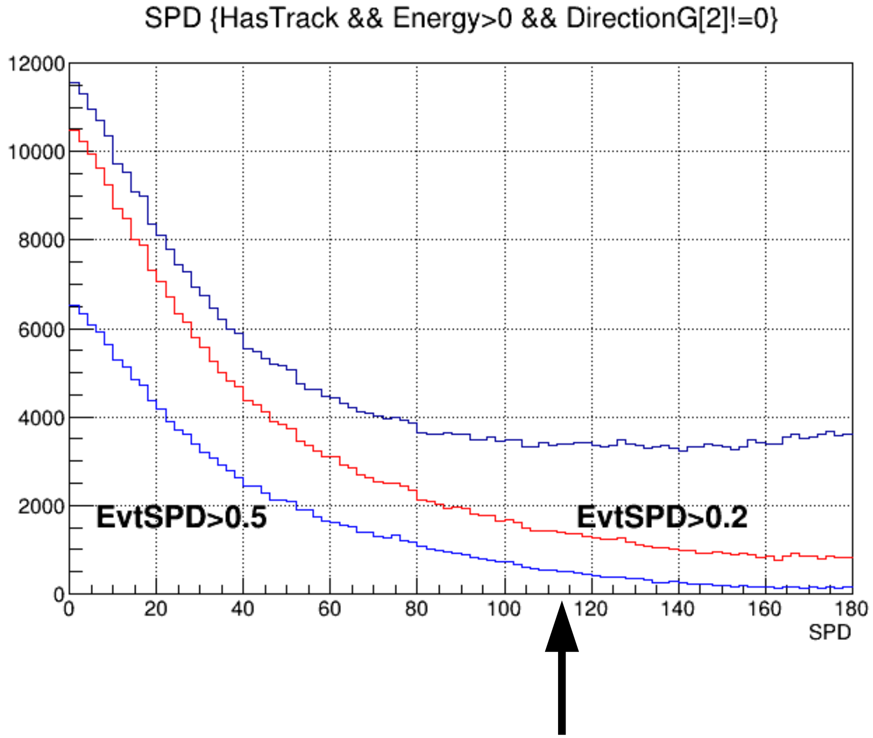
- **high albedo** contamination even at zenith
- **large resolution element**

Tracked events: SPD is still quite large
Improving SPD would help the most, but it is hard (determined by scattering in Si)
Improving ARM also reduces the resolution element (e.g. improving CAL depth resolution)

Trying to improve SPD with event analysis on ground

Changing the TKR to improve this is hard, effect not so large (e.g. DSSD thickness)
Try quality cuts:

- By hand, not much success
- Simple NN test, some improvement



Distance of point source from Albedo max (113°)

SPD → tracked events
On the left:
SPD distribution, "signal" set (all E all °)
Effect of cut on NN (using CNTK toolkit)

Moderate cut is good, some improvement in sensitivity:

- x2 at 500 keV
- Negligible at 1 MeV

Change in SNR is small

Energy bin	SNR (std)	SNR (+NN)
316-562	2.2%	2.8%
0.56-1	2.0%	2.3%
1-1.8	2.2%	2.7%
1.8-3.2	2.8%	3.4%

Conclusion

Evaluated the performance of a nano-sat Compton satellite
Reasonably conservative design, some major simplifications though (no passive mat.'s)
Results:

- Sensitivity reaches COMPTEL's at 1 MeV, better below
- But SNR is low, **this is the main issue** to be solved
- **Improving angular resolution would improve all parameters**

Some machine learning attempted to improve this "on ground": sensitivity improves, SNR does not
Improve design of CAL, less conservative

Cost of a micro-sat would be comparable with that of a technological demonstrator for an M-class payload (~500k€, 1/1,000 of M5 budget)
Launch is not prohibitive ("easy" if within cubesat specs)

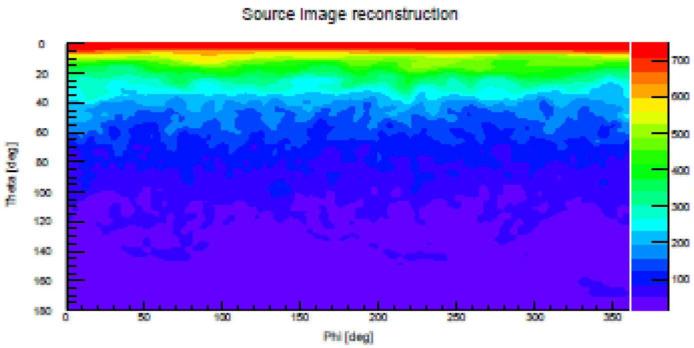
(If issues can be solved) this could be a pathfinder / placeholder before large scale instruments are (hopefully) deployed

Lots of work to be done, but gain useful knowledge in preparation for the future instruments

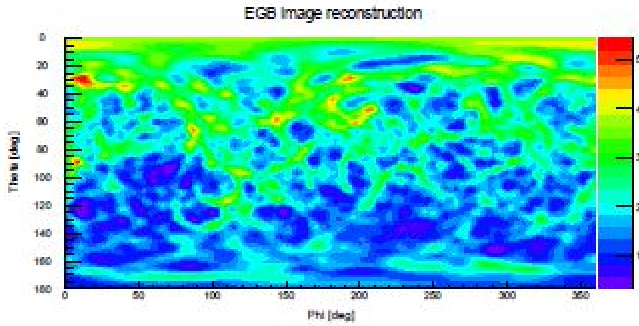
Lots of work still to do: line sensitivity, polarization, ...

spares

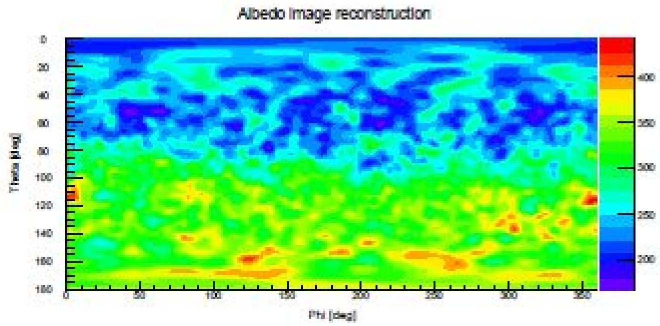
Sensitivity estimate (with revan)



Point src at zenith



EGB



“Albedo”

Obtain ratio of Albedo and EGB within the resolution element

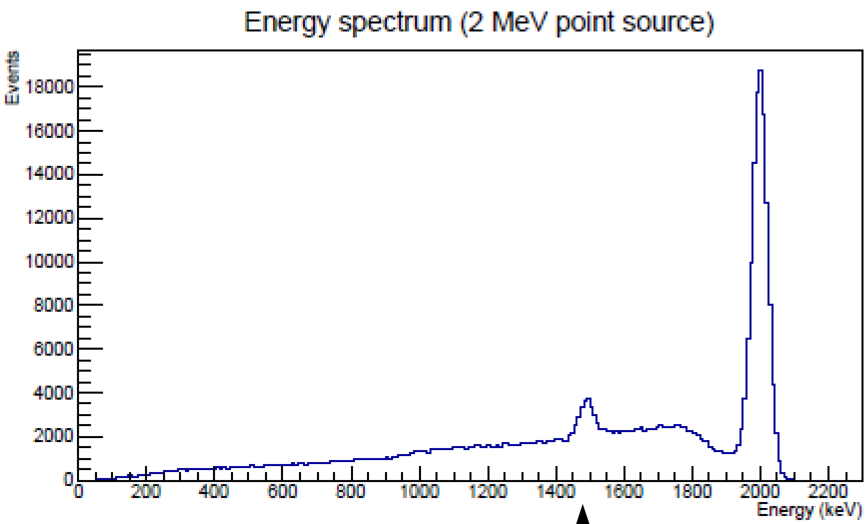
ϕ-average & t-scale:
Signal-to-noise ratio

Scale EGB flux up (analytic) to account for Albedo and (estimated) charged flux

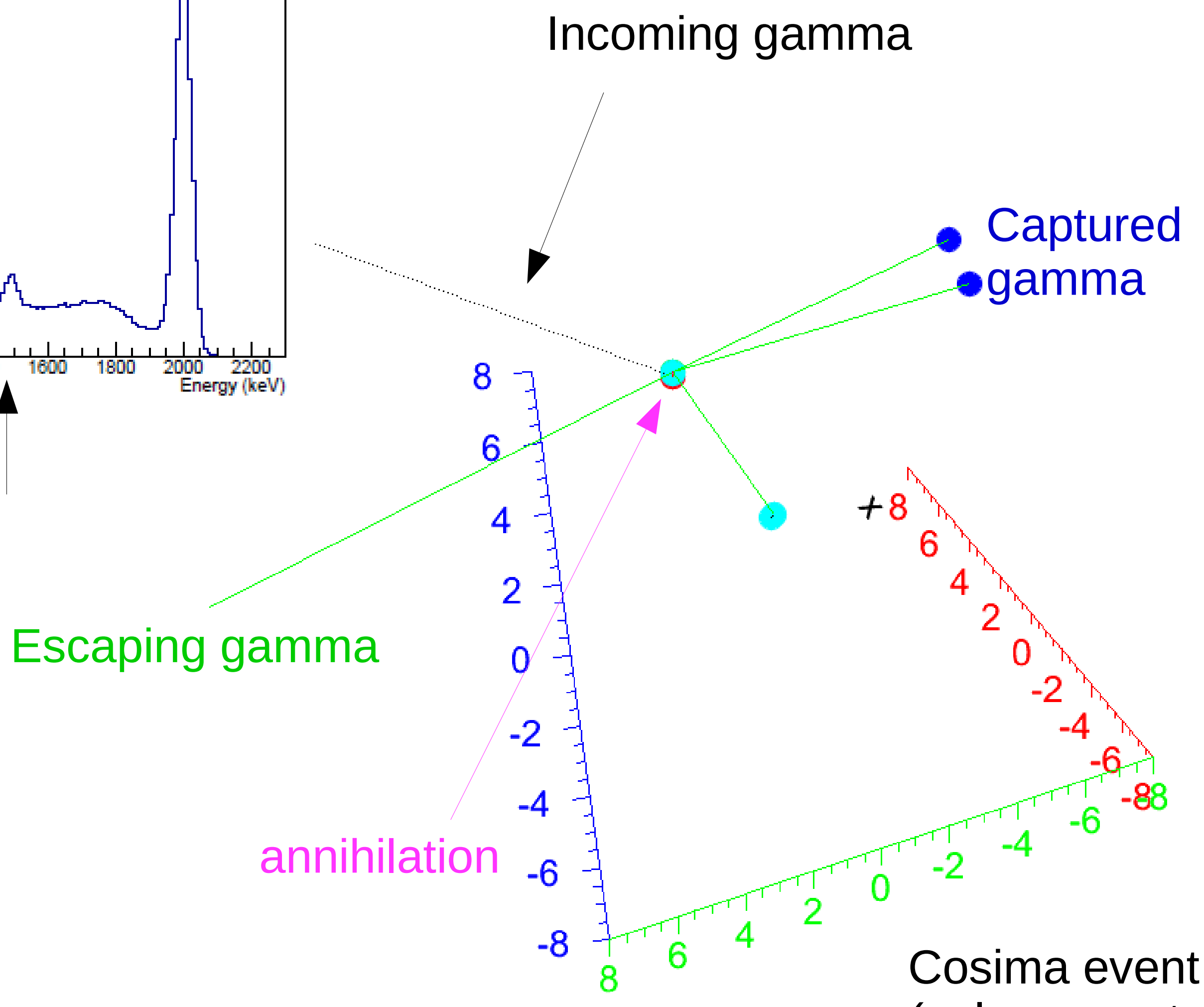
$$N_B = F_B A_{eff} T_{eff} \Delta\Omega$$

$$F_z = \frac{z^2 + z\sqrt{z^2 + 4N_B}}{2T_{eff} A_{eff}}$$

Pair contamination in the “Compton” set

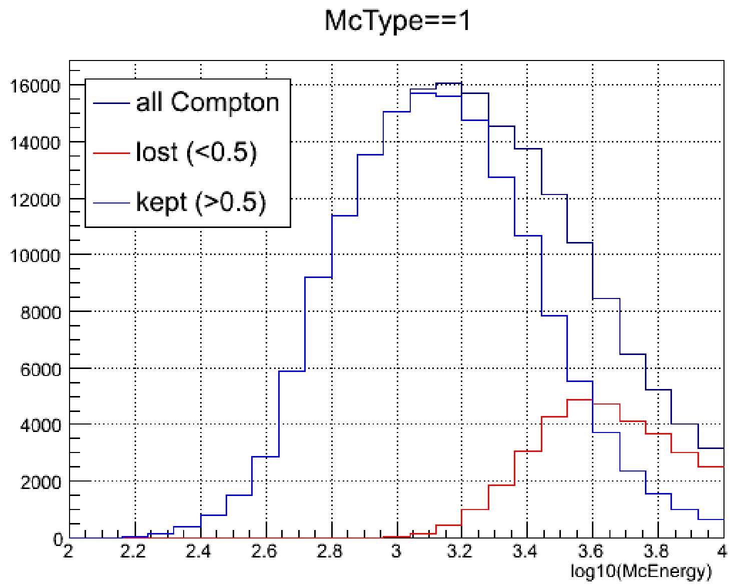


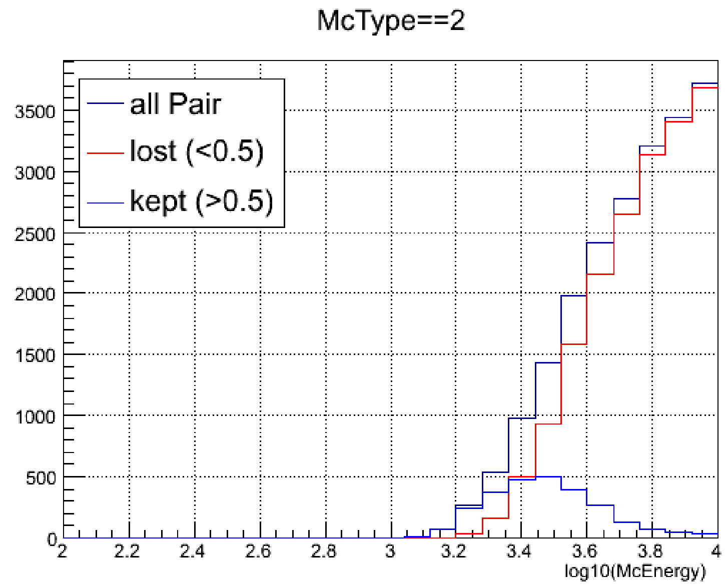
$Er_{ec}=E_{MC}-511$ keV

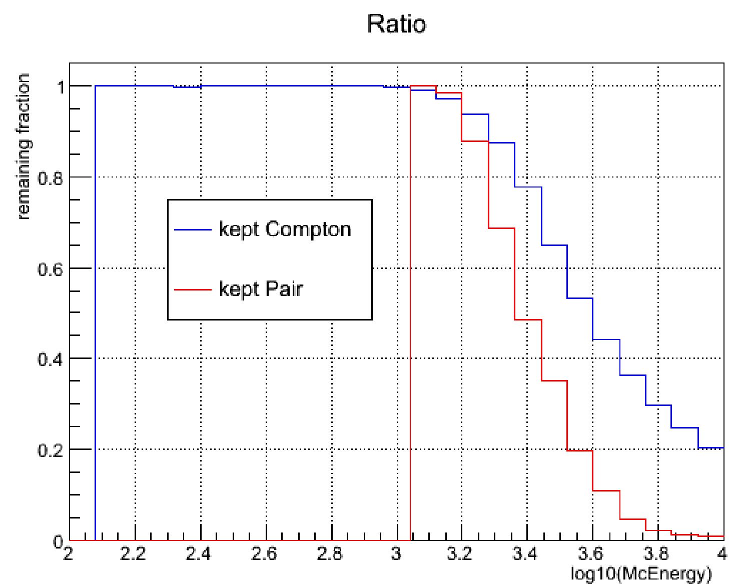


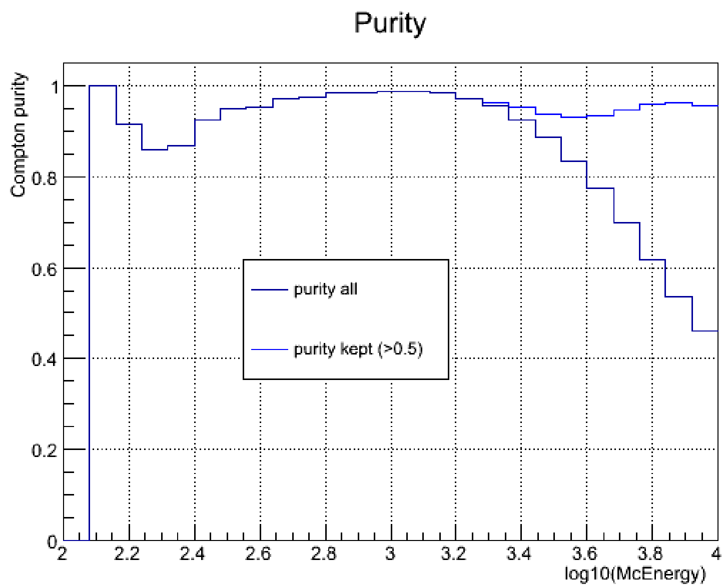
Cosima event
(volumes not shown)

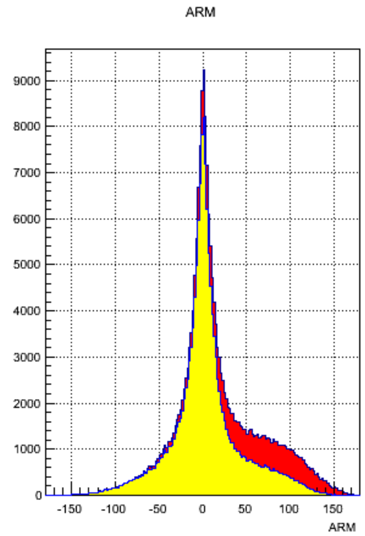
Other NN tests: pair contamination in “Compton”





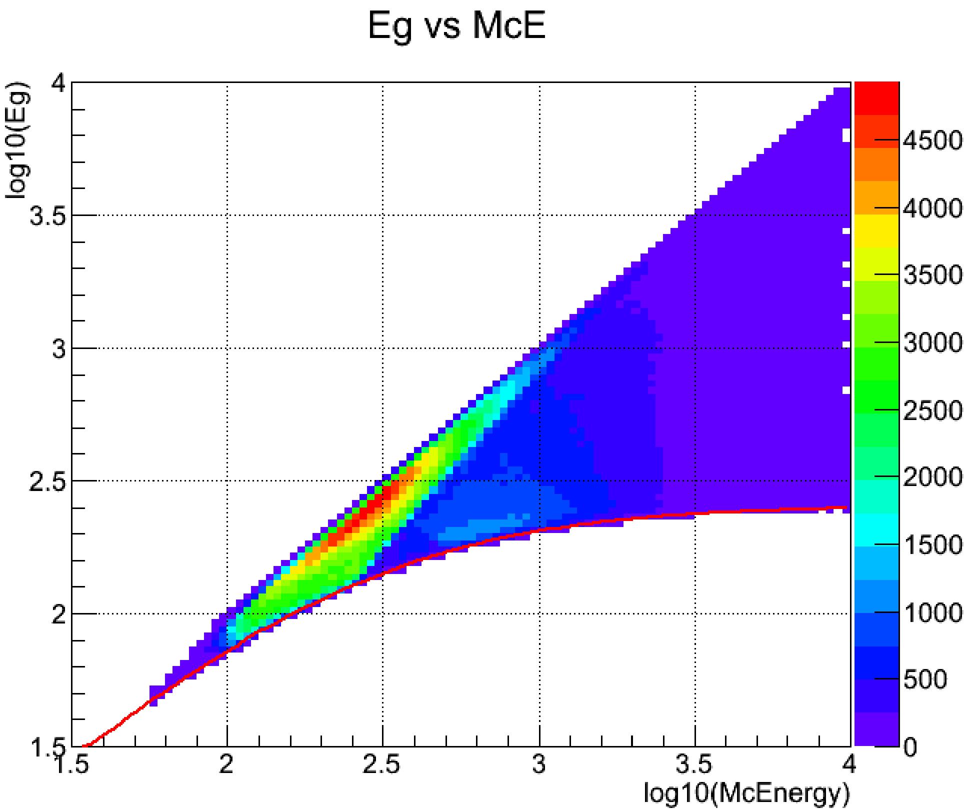




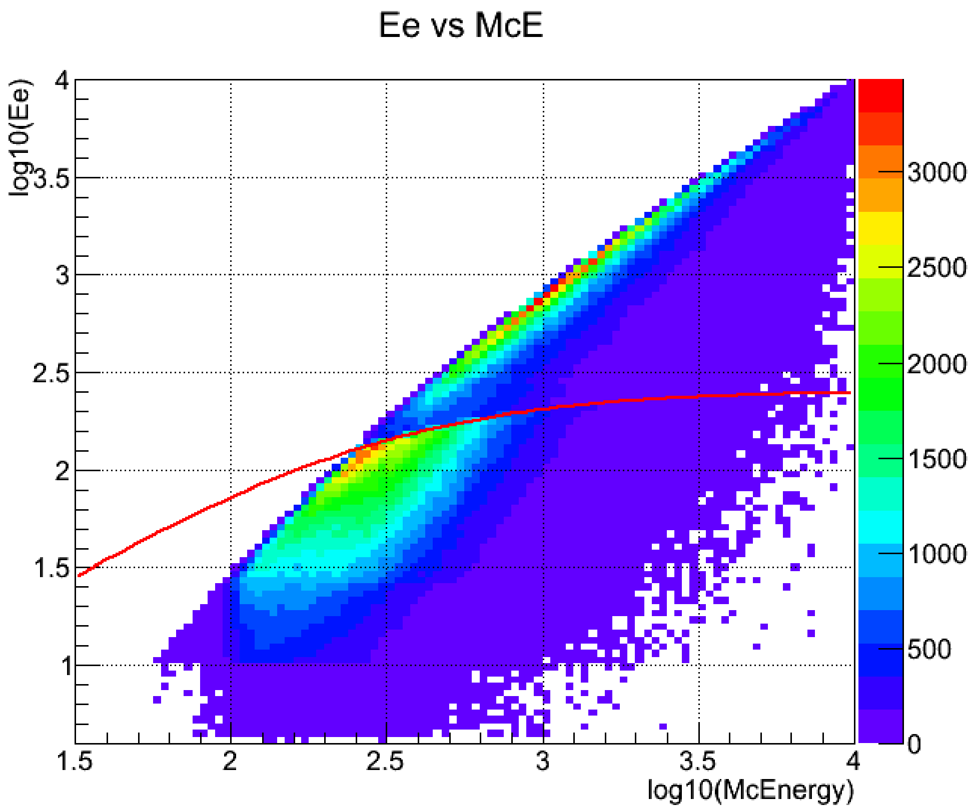


ARM before and after cut

Untracked partially absorbed

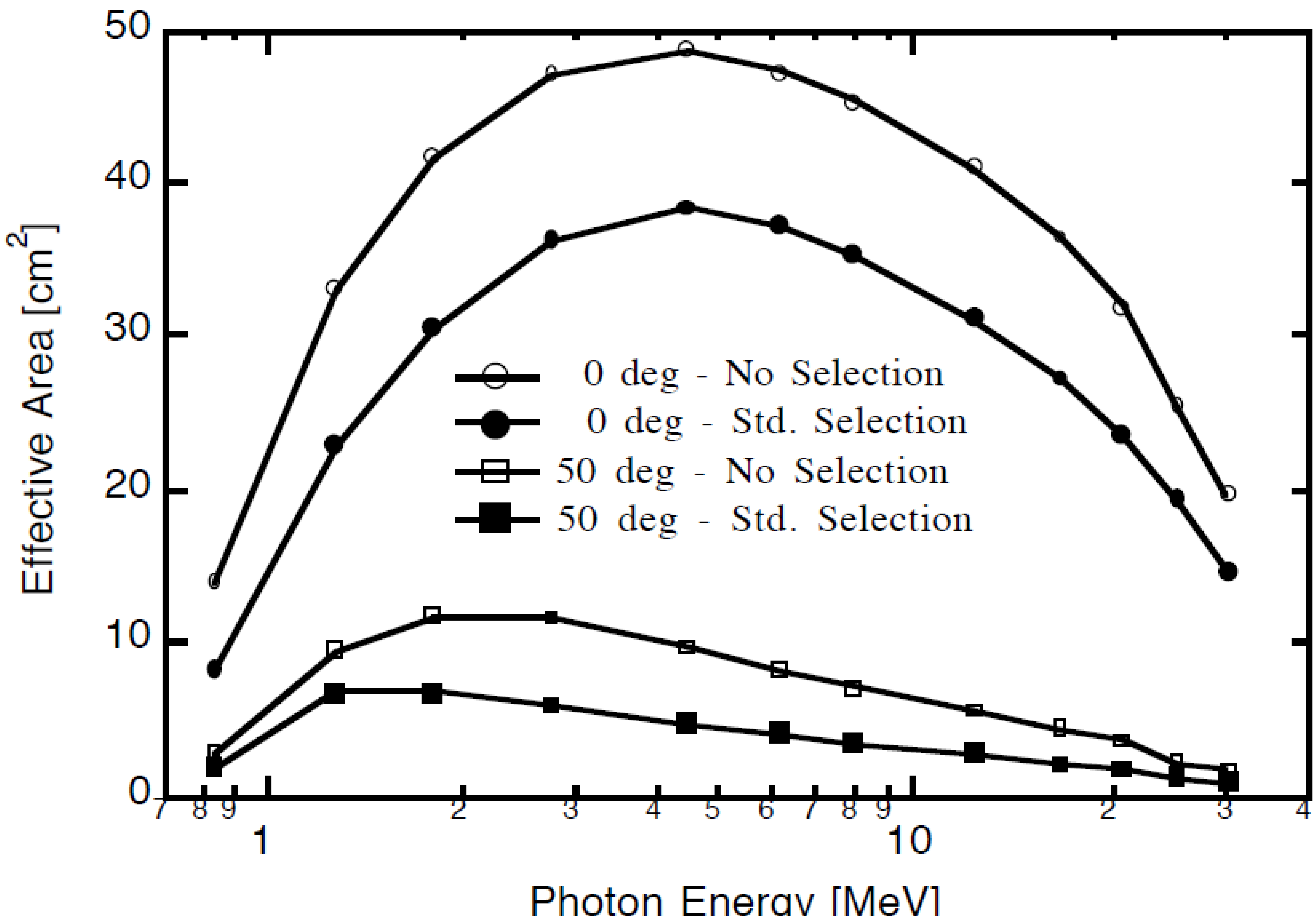


Gamma ray energies vs Mc E
Red: gamma kinematic lower limit

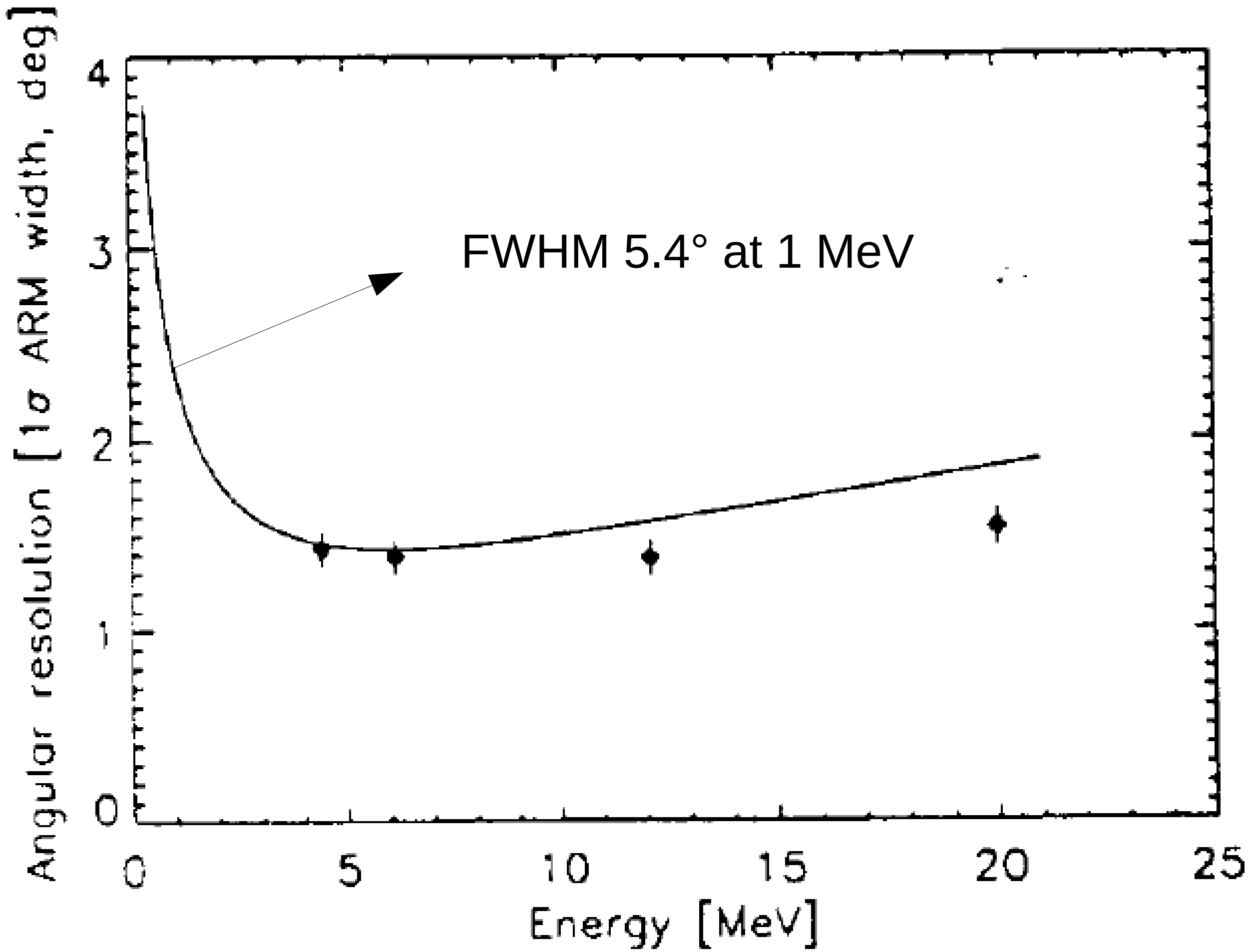


Electron energies vs Mc E
Red: gamma kinematic lower limit
Overpopulation below comes from partially absorbed gammas mis-tagged as electrons

COMPTEL Aeff

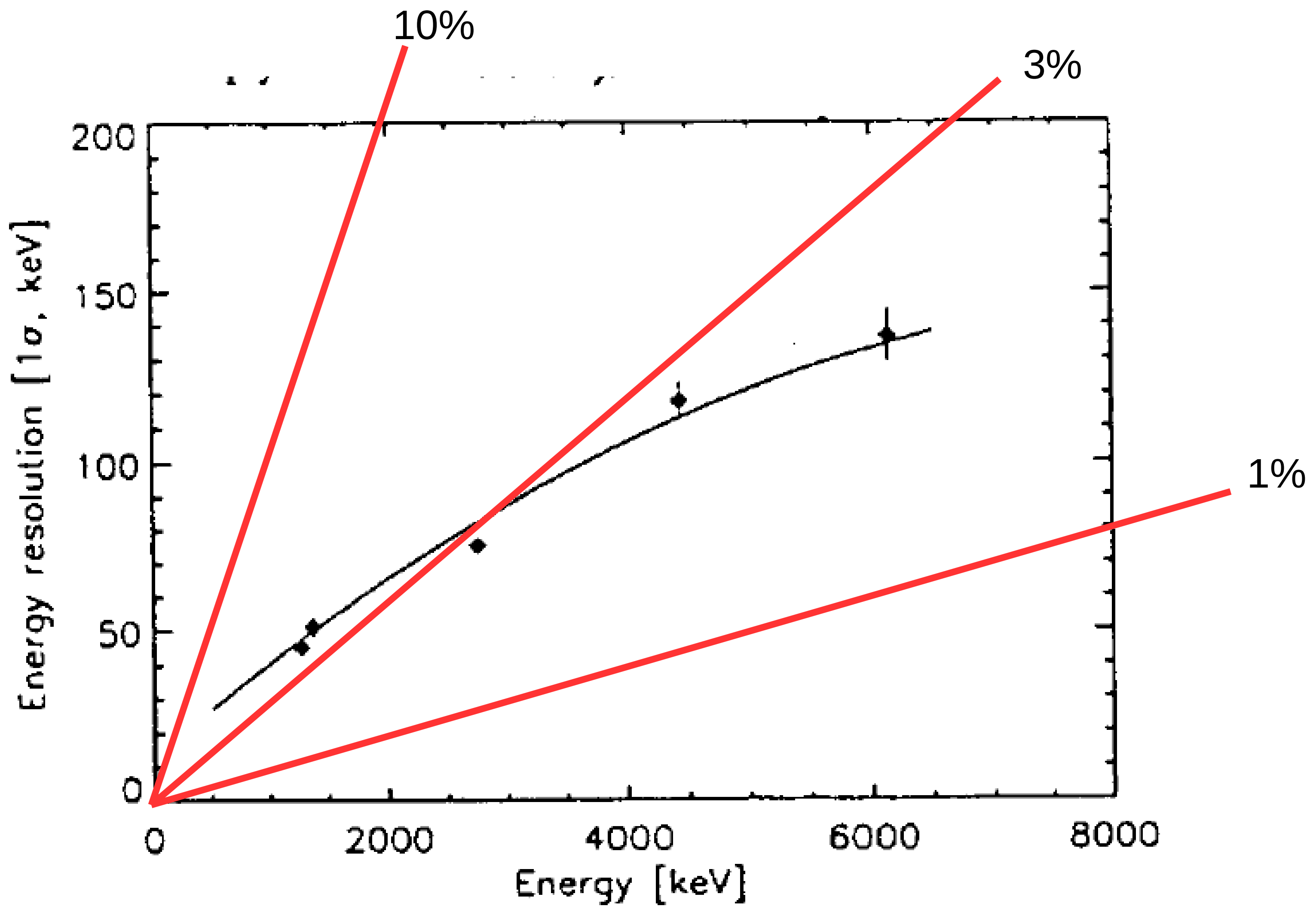


COMPTEL ARM

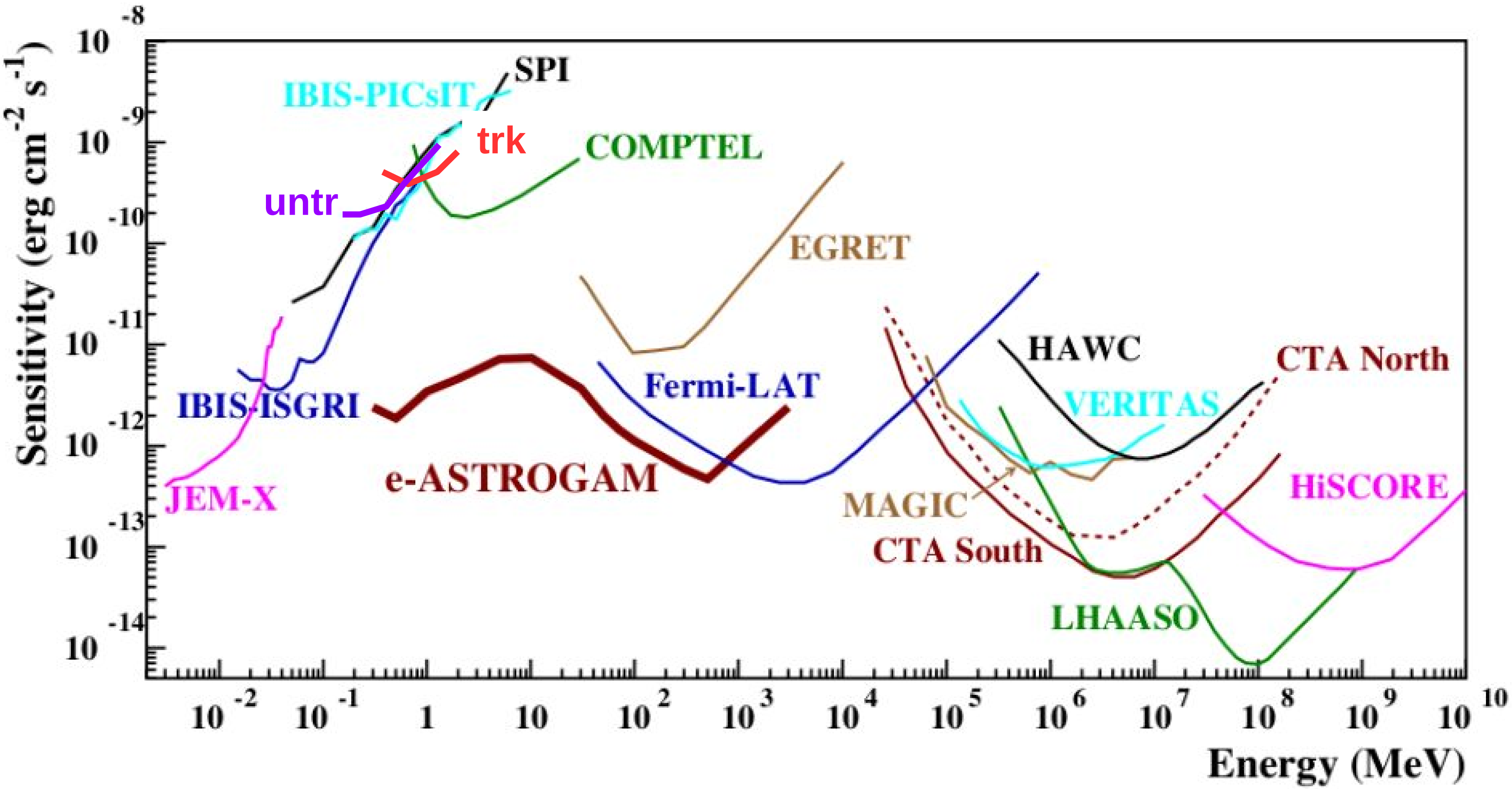


FWHM 5.4° at 1 MeV
Angular resolution [1σ ARM width, deg]
4
3
2
1
0
0
5
10
15
20
25
Energy [MeV]

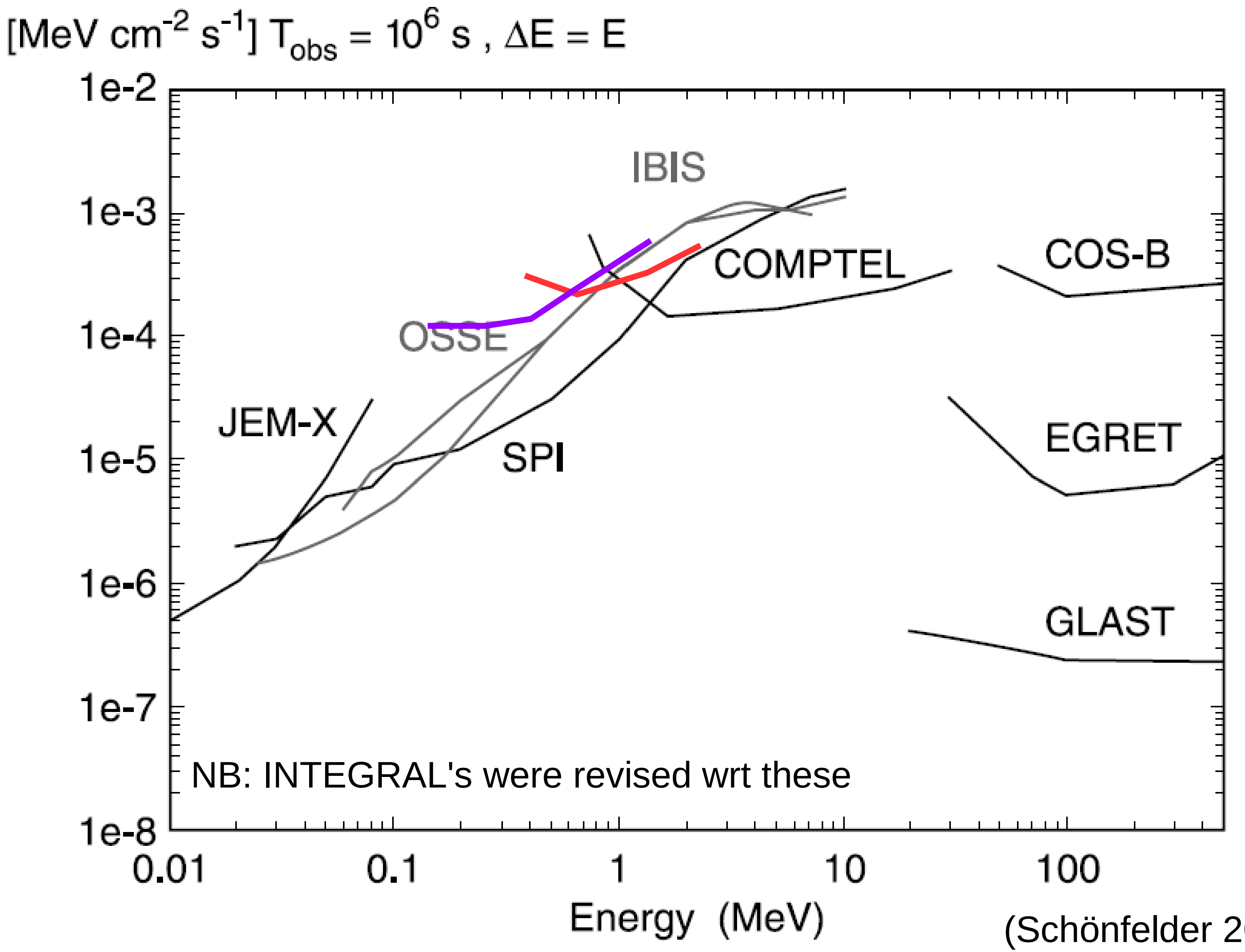
COMPTEL Eres



Full sensitivity plot

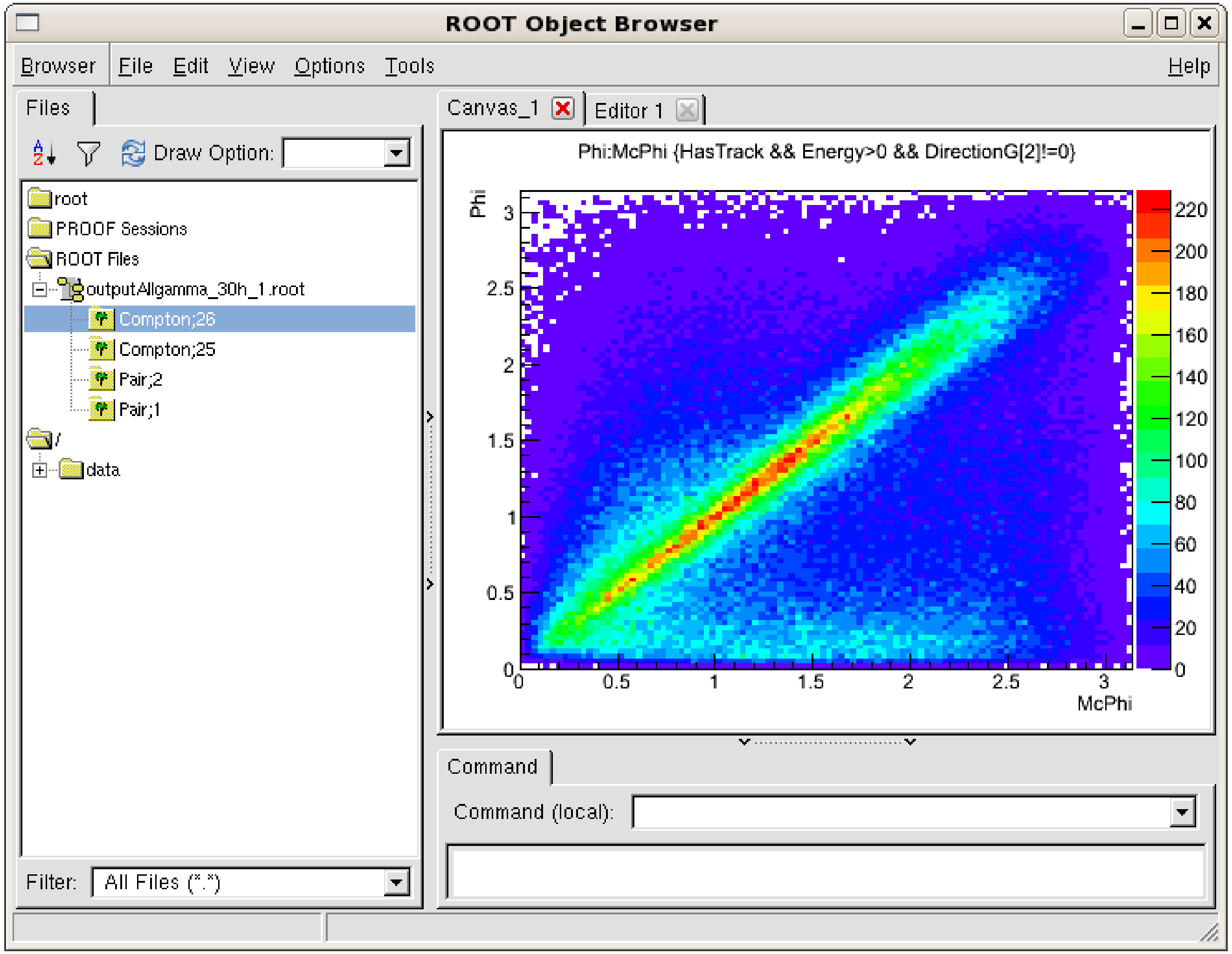


Full sensitivity plot 2



(Schönfelder 2004)

tuple1


ROOT Object Browser
Browser
File
Edit
View
Options
Tools
Help
Files
Draw Option:
root
PROOF Sessions
ROOT Files
outputAllgamma_30h_1.root
Compton;26
Compton;25
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data
Filter:
All Files (*.*)
Canvas_1
Editor 1
Phi:McPhi {HasTrack && Energy>0 && DirectionG[2]!=0}
Phi
McPhi
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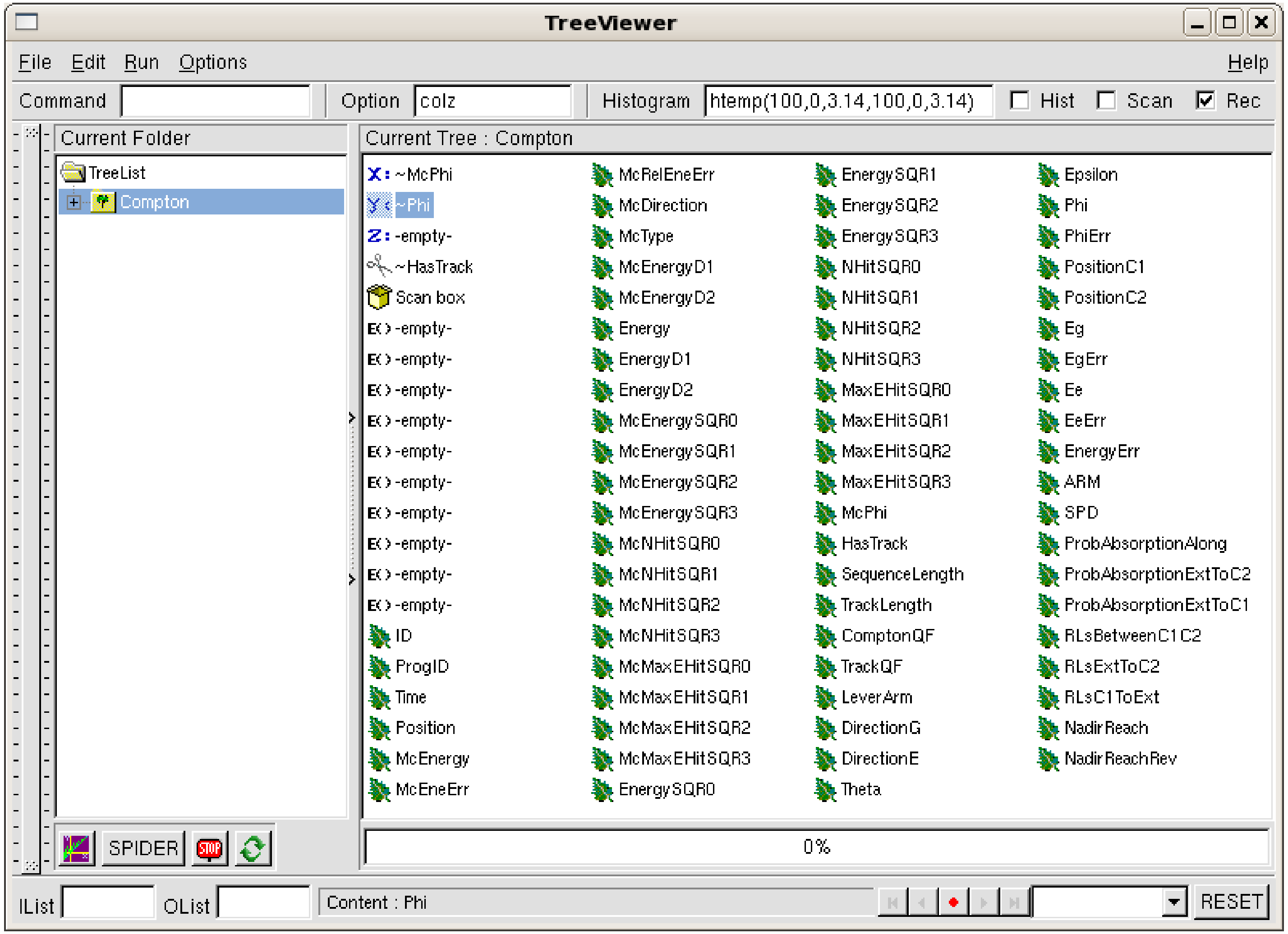
Command
Command (local):

tuple2


TreeViewer
File Edit Run Options
Help
Command
Option colz
Histogram htemp(100,0,3.14,100,0,3.14)
Hist Scan Rec
Current Folder
TreeList
Compton
Current Tree : Compton
X: ~McPhi
Y: ~Phi
Z: -empty-
~HasTrack
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E() -empty-
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ProgID
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McDirection
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McEnergyD1
McEnergyD2
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McEnergySQR1
McEnergySQR2
McEnergySQR3
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McNHitSQR1
McNHitSQR2
McNHitSQR3
McMaxEHitSQR0
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EnergySQR0
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MaxEHitSQR0
MaxEHitSQR1
MaxEHitSQR2
MaxEHitSQR3
McPhi
HasTrack
SequenceLength
TrackLength
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TrackQF
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DirectionG
DirectionE
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Phi
PhiErr
PositionC1
PositionC2
Eg
EgErr
Ee
EeErr
EnergyErr
ARM
SPD
ProbAbsorptionAlong
ProbAbsorptionExtToC2
ProbAbsorptionExtToC1
RLsBetweenC1C2
RLsExtToC2
RLsC1ToExt
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SPIDER
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IList
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RESET