Developing Detector Responses for Swift's Burst Alert Telescope using GEANT4

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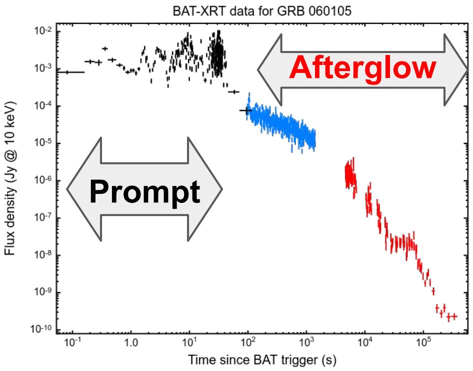
Outline

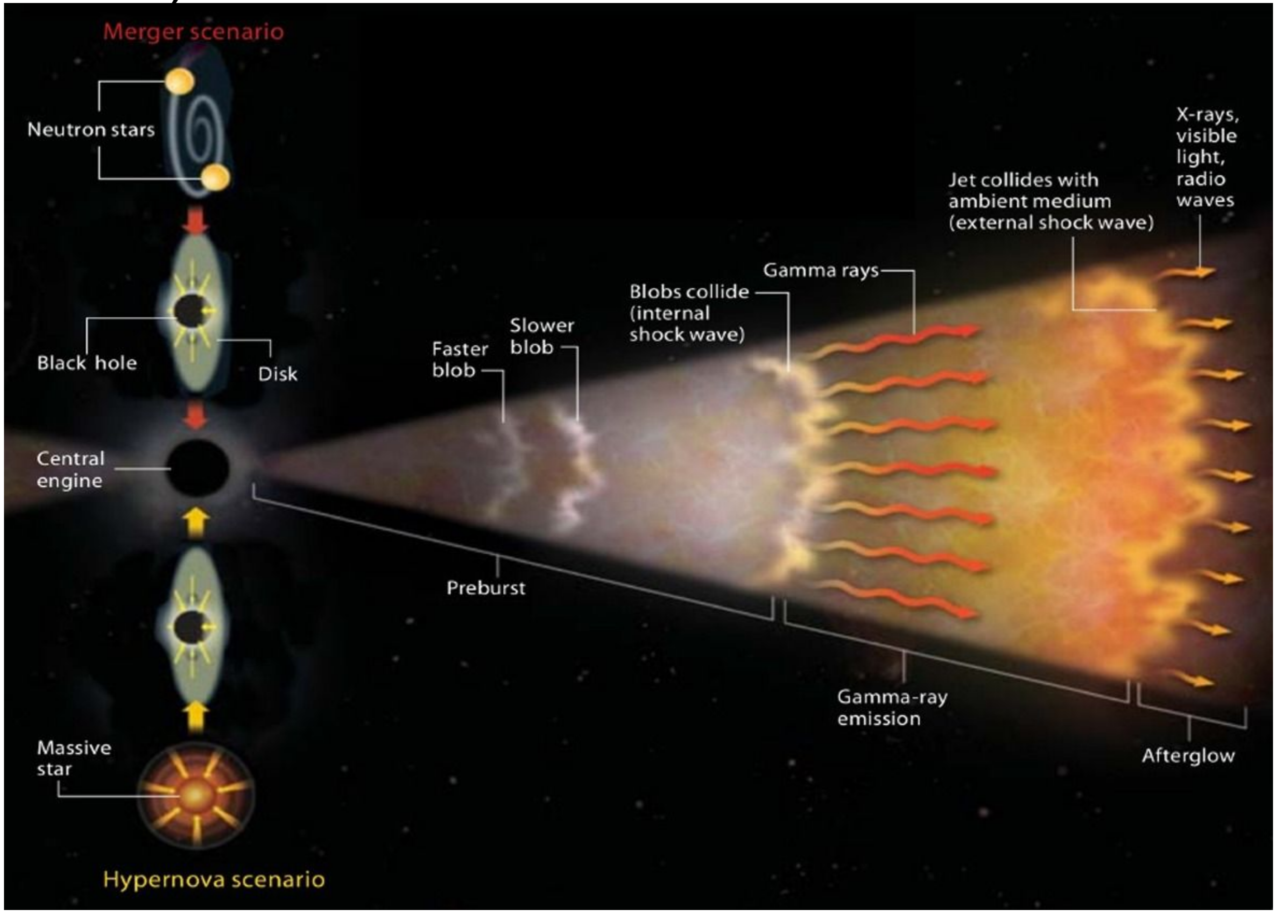
- A little about GRBs and Swift
- An overview of constructing the standard analysis’ responses and calibration
  - No GEANT here, and stuff well before my time
- Constructing an outside the FoV response using GEANT4 and an overview of the Swift Mass Model
  - GEANT starts here
- Constructing responses for a new analysis and GRB search using GEANT4

Lots of credit to Derek Hullinger and Goro Sato for figures from their Theses

Gamma-Ray Bursts (GRBs)

Short GRBs



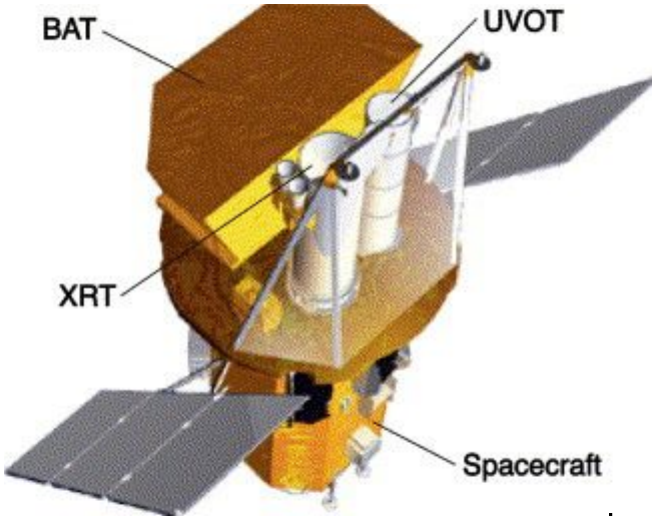


Long GRBs

Image credit: NASA

The Neil Gehrels Swift Observatory

- Designed to detect GRBs and observe the early afterglow
- Can re-point “swiftly”, ~ 1 minute
  - Previously hours



Gehrels 2004

Instruments

Burst Alert Telescope (BAT)

- Coded mask imager (15 - 150 keV)
- Detects and localizes GRBs (a few arcmins)
- Large FoV, ~ 2 st

X-Ray Telescope (XRT)

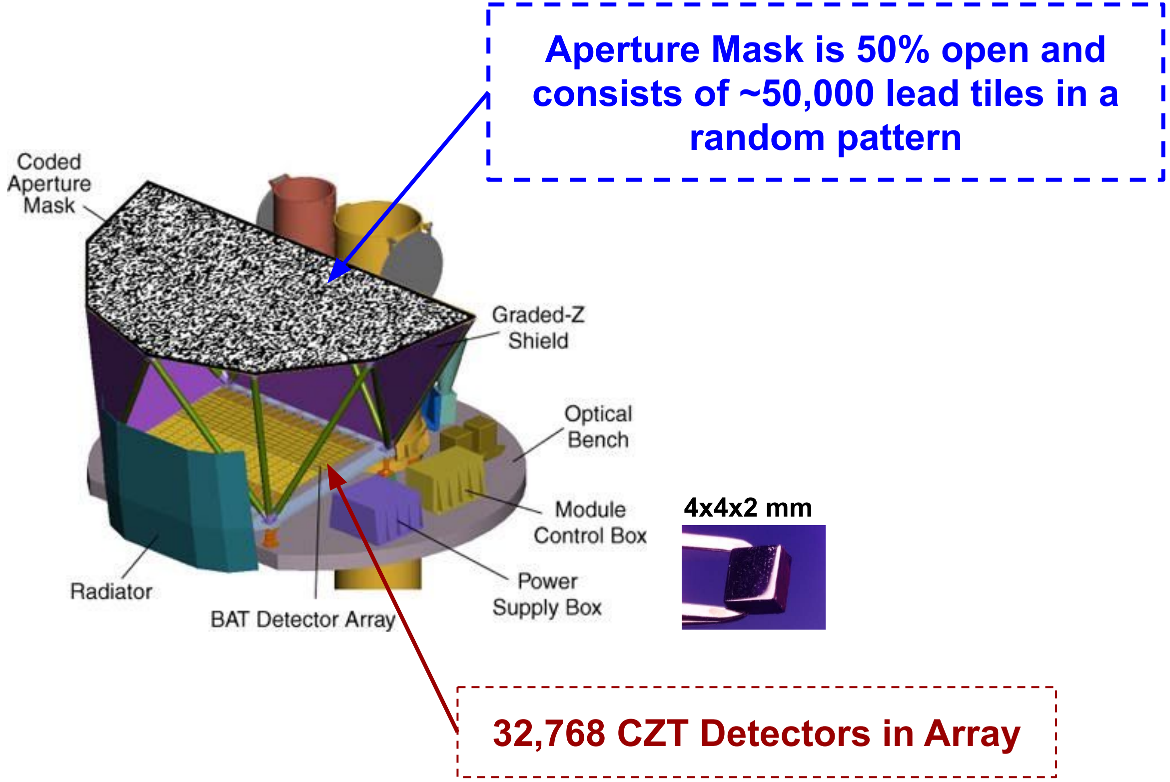
- 0.3 - 10 keV
- CCD spectroscopy
- Localizations of a few arcseconds

UV/Optical Telescope (UVOT)

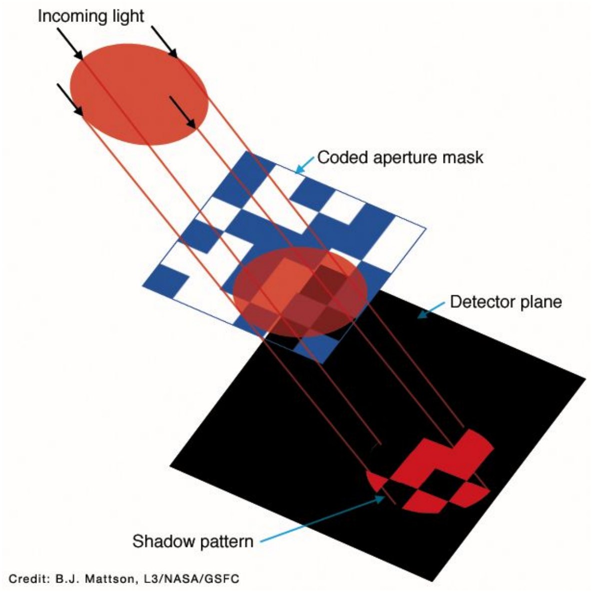
- 170 - 650 nm
- 7 band filters
- Capable of sub-arcsecond localization

- Launched Nov. 2004
- >1000 GRBs detected
- Swift Mission Operations Center at Penn State

How BAT Works



Basic Concept



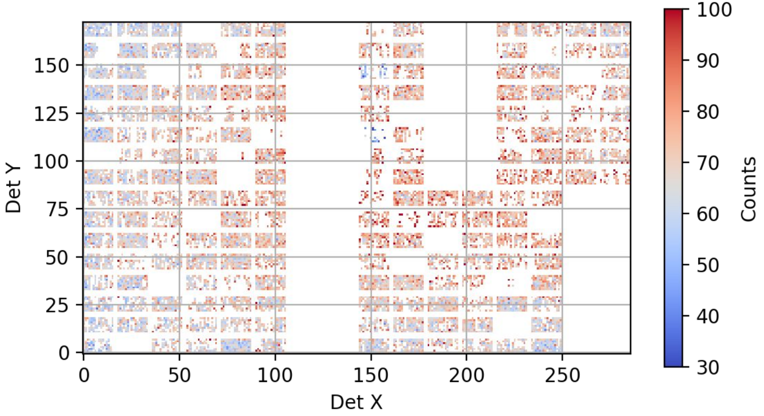
Energy Resolution of CZT Detectors: ~5 keV @ 60 keV

How BAT Works

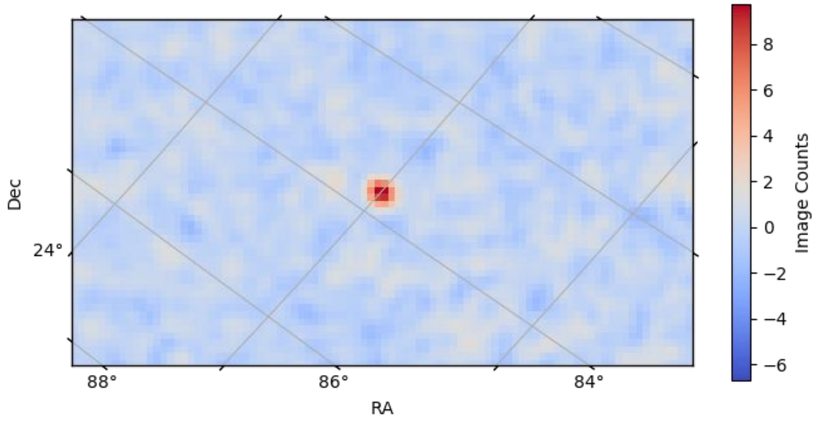
Cross-correlate with Mask Pattern

Crab in Detector Space

Detector Plane Image (DPI)



Crab in Sky Space



Mask-Weighted Counts
Gaussian noise centered around 0 where there's no source
Automatic Bkg subtraction

Zoomed in
Full FoV is ~2 sr

Mask-Weighted Counts - Used for imaging and spectra

The expected counts in each detector is a combination of background and the signal flux that makes it through to the detector

$$R_i = S * f_{trans} * (f_i + (1 - f_i)*f_{pb}) * A_{eff} + S_{scat} * A_{eff} + B$$

Where: f_{trans} and f_{pb} are transparency through lead mask tiles and passive materials respectively

f_i is the fraction of the detector that's not shadowed by the mask

S_{scat} is the signal scattered off elsewhere on the craft

Mask weighted counts are the sum of the counts in each detector multiplied by their mask weight, $w_i = 2f_i - 1$

$$R_{mkwts} = \sum R_i * w_i$$

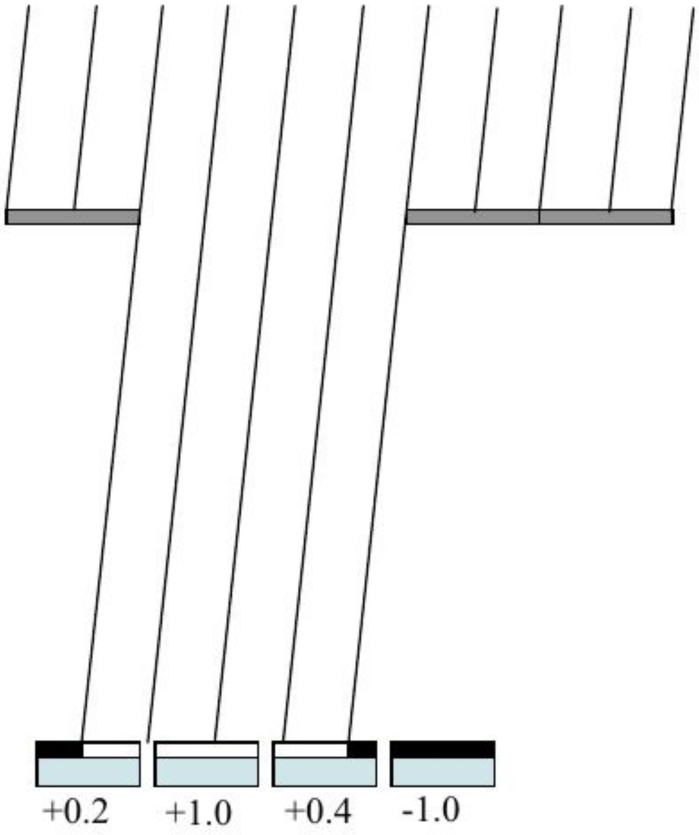
assuming $\sum w_i = 0$

$$R_{mkwts} = S * f_{trans} * A_{eff} * (1-f_{pb}) \sum w_i^2/2$$

$$\sum S_{scat} * A_{eff} * w_i = 0$$

$$\sum B * w_i = 0$$

Anything that's not correlated with w_i will go to 0.



w_i

Detector Response Matrix (DRM)

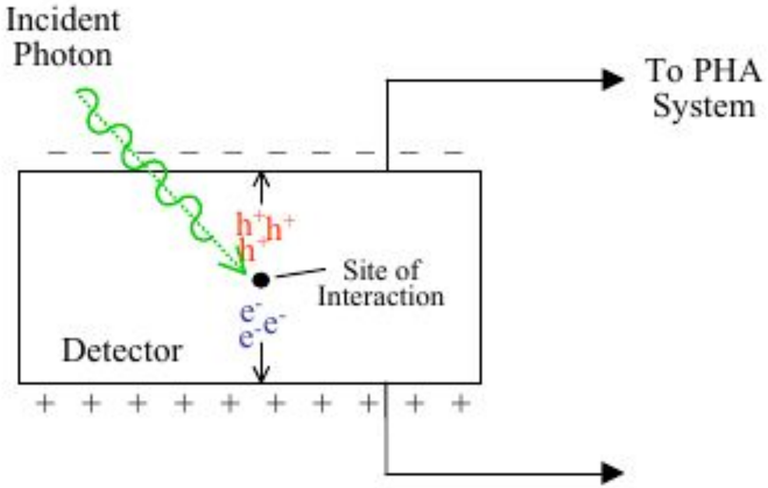
DRM x Photon Fluxes = Counts per measured energy bin

$$\begin{pmatrix} R_{11} & R_{12} & \cdots & R_{1m} \\ R_{21} & R_{22} & \cdots & R_{2m} \\ \vdots & \vdots & & \vdots \\ R_{n1} & R_{n2} & \cdots & R_{nm} \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \\ \vdots \\ P_m \end{pmatrix} = \begin{pmatrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{pmatrix}$$

$\sum_m R_{1m} = A_{eff} (E = E_1)$

R_{11} = (Probability count falls in energy bin 1) x $A_{eff} (E = E_1)$

CZT Detectors



$$\frac{Q}{Q_0} = \left(\frac{\lambda_e}{D}\right)\left[1 - \exp\left(-\frac{D-z}{\lambda_e}\right)\right] + \left(\frac{\lambda_h}{D}\right)\left[1 - \exp\left(-\frac{z}{\lambda_h}\right)\right]$$

$$\lambda = \mu\,\tau\,E.$$

Hect relation gives readout efficiency due to charge trapping as a function of depth and electron and hole mobility inside detector

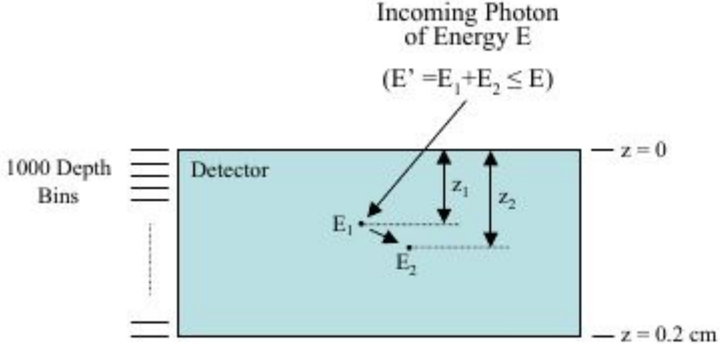
Mobility needs to be found for each detector, but first “depth distribution” needs to be found

The deeper the energy is deposited in the detector the less efficient. Higher energy photons travel further into detector

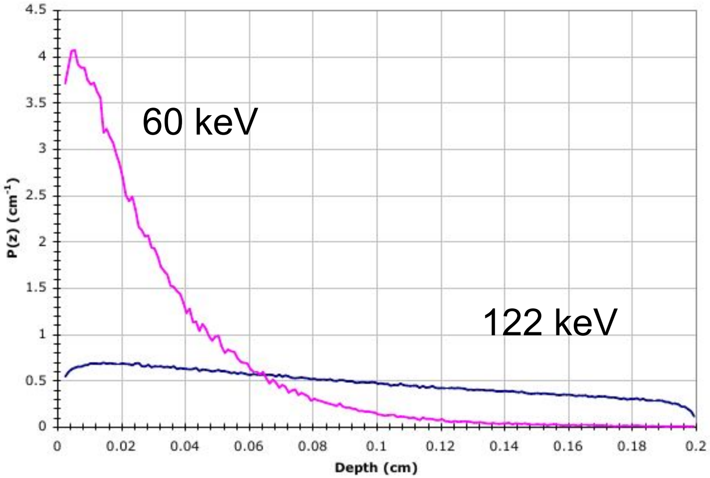
Depth distribution

Simulation ran to find distribution of where energy is deposited (could be done in GEANT but wasn't)

- Ran at many photon energies and source angles
- Interactions where all energy is deposited are tracked along with Cd and Te "escapes"
- Compton interactions with escapes are ignored



$$z_{ave} = \frac{z_1 E_1 + z_2 E_2}{E_1 + E_2}$$



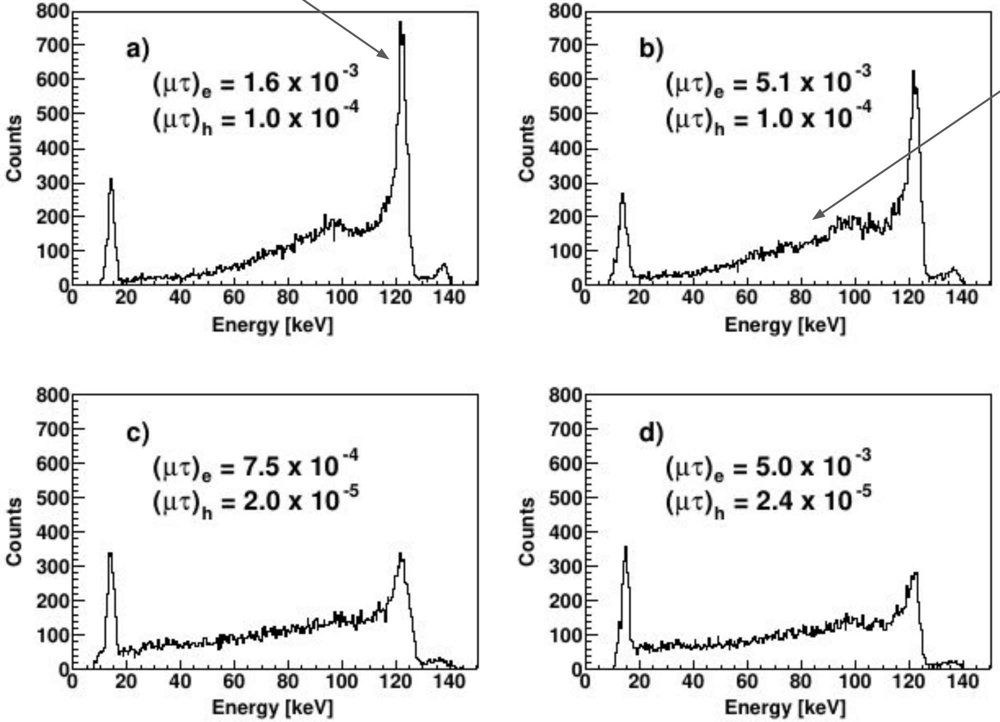
Depth distribution for full energy deposited line at 60 and 122 keV.
Higher energies penetrate deeper into detector

Calibration

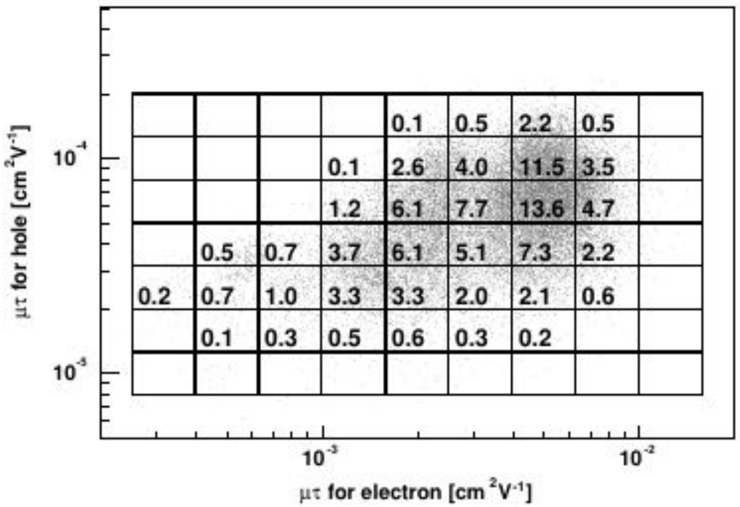
Using depth distributions, $(\mu\tau)_e$ and $(\mu\tau)_h$ were found for each detector using calibration measurements of Cobalt lines (14.4, 122, 136 keV)

Main peak

Tail from charge trapping

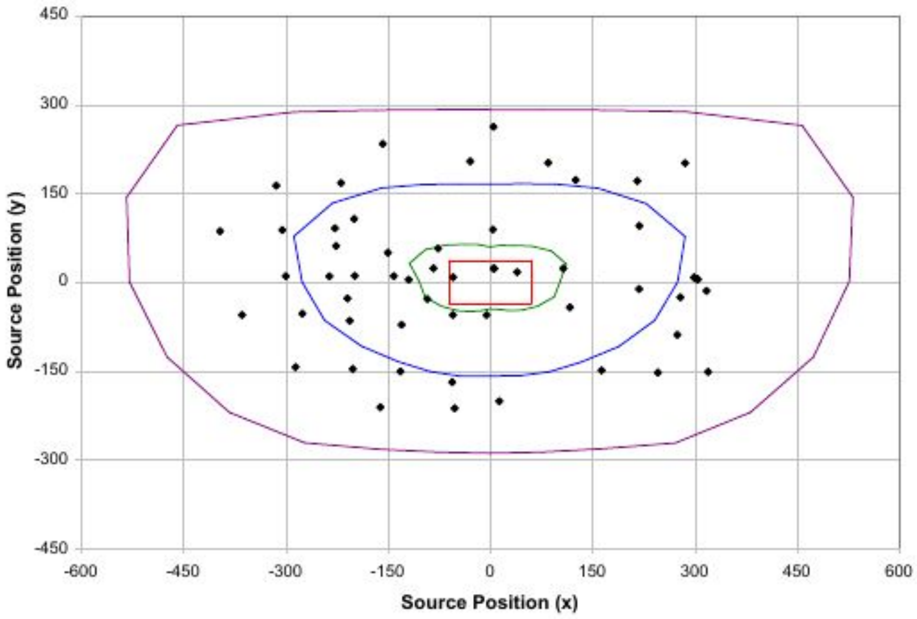


For the full array DRM, uses weighted average of (μτ) bin centers



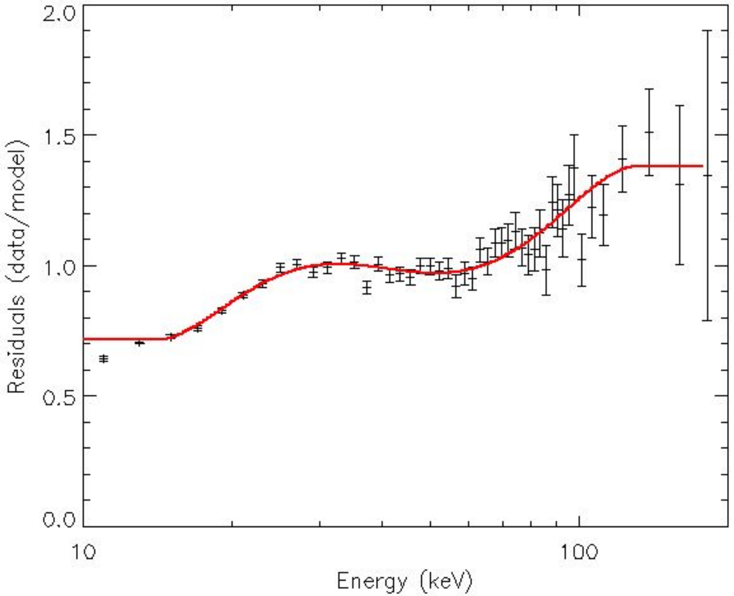
Full Array Calibration

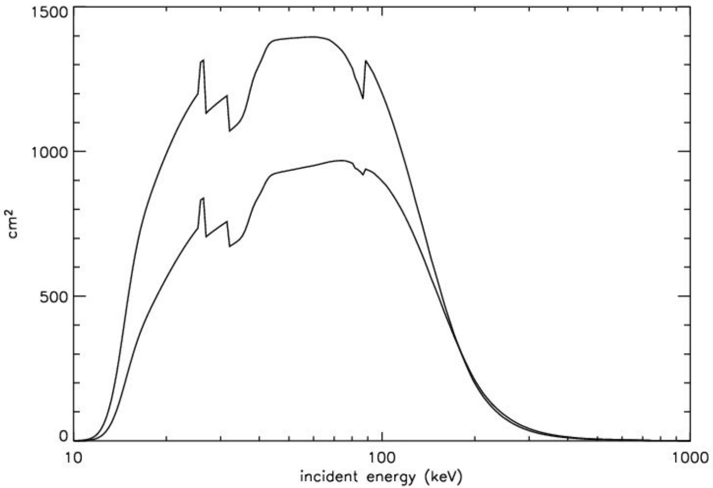
- Calibration of the summed mask-weighted response
- All dets at once, with mask in place
- Ba placed at several positions
  - Lines 31, 35, 53, 81 keV
- Used averaged response from all dets, with mask shadow and absorption from passive materials (mask supports, air, etc.) taken into account
- Fit small corrections to overall normalization and energy resolution



Post Launch Calibration

- Calibration observations of the Crab revealed the Aeff being too high at low energies and too low and high energies
- To fix this:
  - Extra absorption added by silver and lead tile edges
  - Polynomial fit to force correct response to Crab spectra

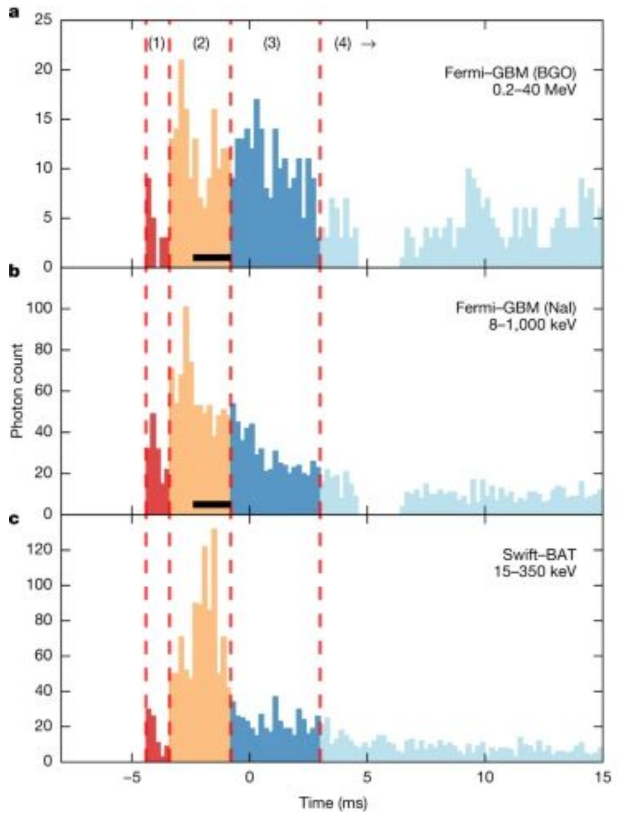




Final Aeff for on axis and 45 deg off axis

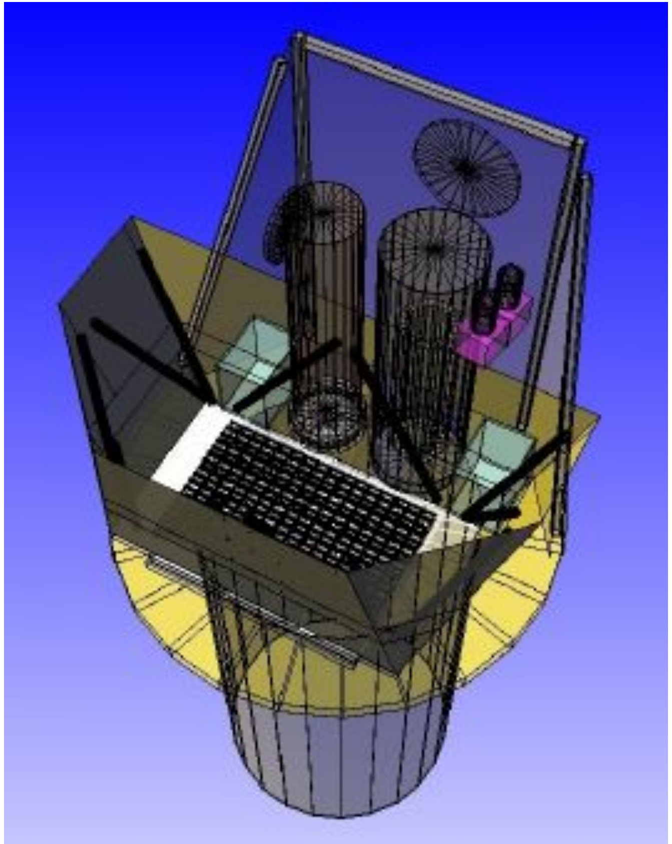
A Response With No Mask Weights

- A magnetar giant flare (MGF) happened in a nearby galaxy, bright enough to saturated Fermi GBM
- Was outside the coded FoV of BAT, but still detected by photons that traveled through the shield
- Wanted to make a response to this event
  - No mask weights means we need to account for the photons that travel through or scatter off parts of the craft
  - Used GEANT with a mass model made by the BAT team



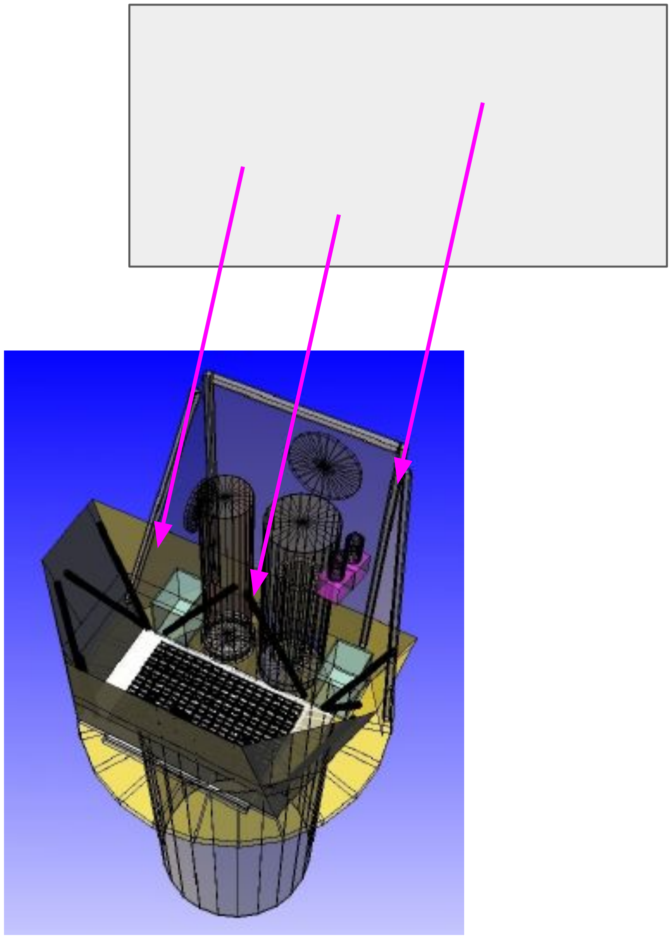
https://www.nature.com/articles/s41586-020-03077-8

The Swift Mass Model (SwiMM)



- Very detailed, but not perfect
- Contains the majority of the craft components, represented as well as they can as Geometries
    - Hard to do electronics and the flexible sheet-like shield
- All 32,768 CZT detectors are individual sensitive detectors
    - Able to track the E_{dep} and position (which detector and the depth) of each hit
- Contains exact mask pattern (hidden in figure)
- Some components are missing, especially in the bottom half

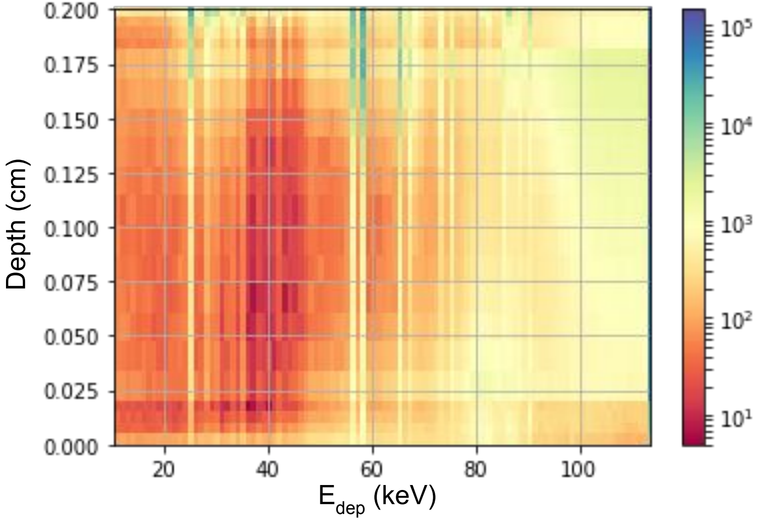
GEANT4 Runs to Make Construct Response



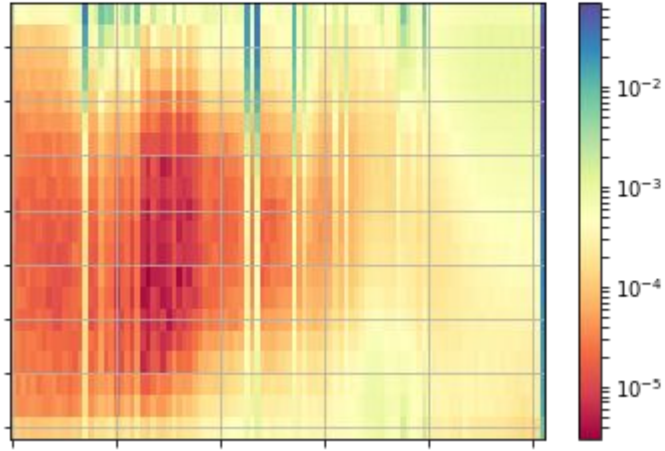
- Need to make a summed detector DRM for one specific sky position
- For a set of photon energies, run a photon beam coming from MGF's position relative to BAT (θ, ϕ = 48.5°, -98.4°)
- For each photon that generates a hit, get E_{dep} and the average depth in the detector (z).
- For each photon beam make 2D hist of E_{dep} and z

From 113 keV photon beam

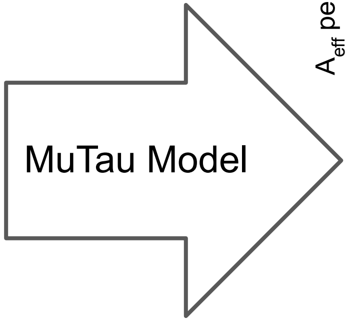
GEANT Results to DRM

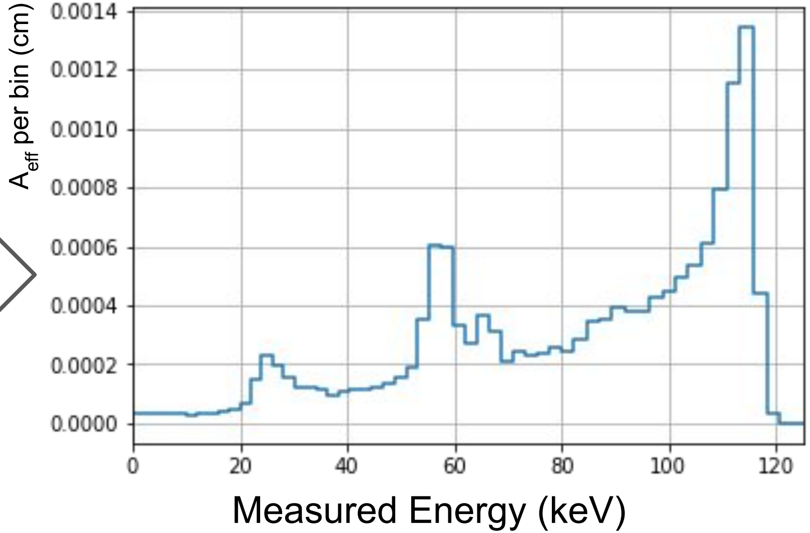


Counts from Sim



Aeff / dz / det

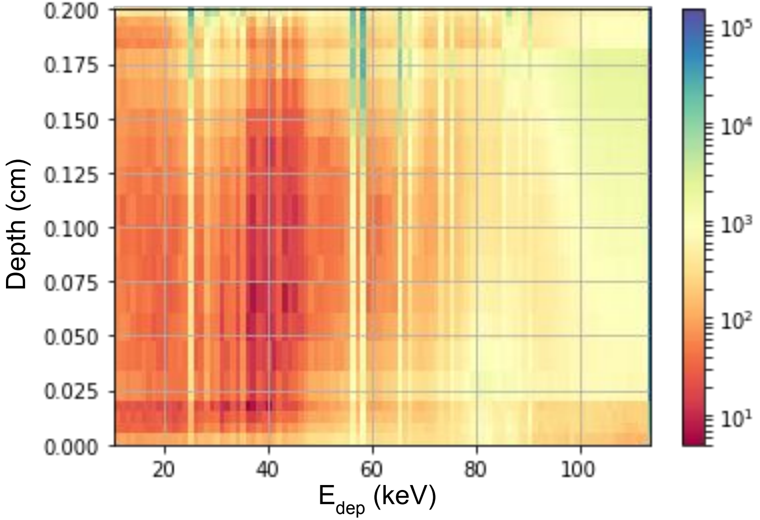




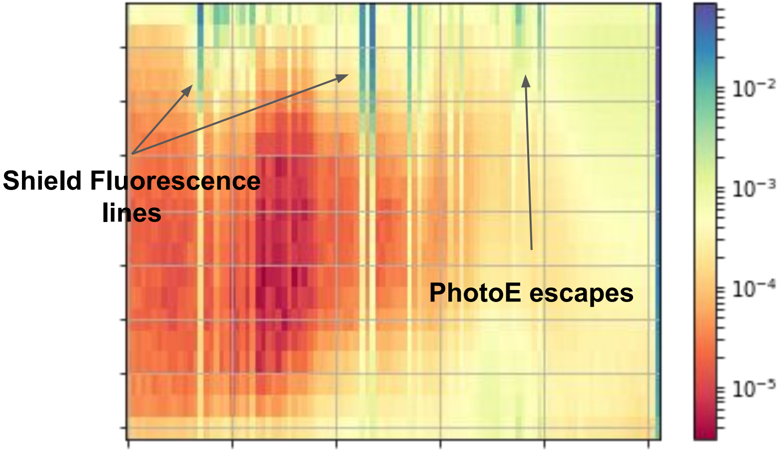
MuTau Model = Using Hect relation to get measured energy from depth distribution for each E_{dep} and applying Gauss Conv for energy resolution

GEANT Results to DRM

From 113 keV photon beam

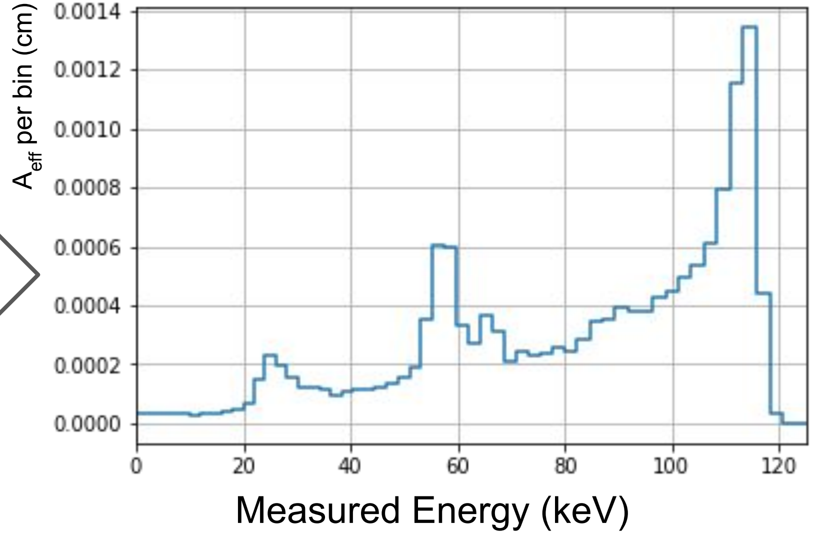


Counts from Sim



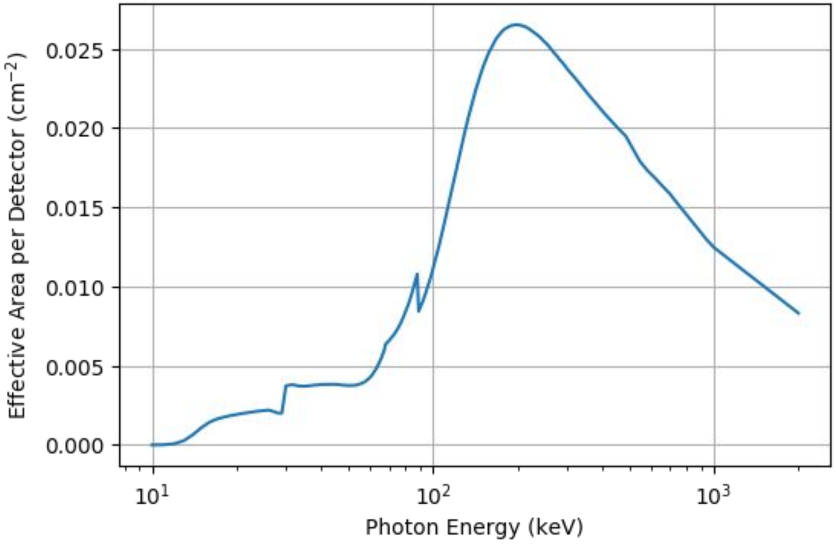
Aeff / dz / det

MuTau Model

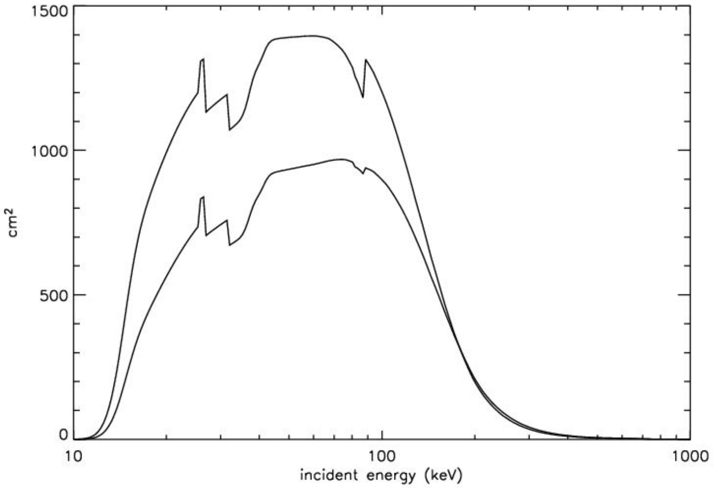


MuTau Model = Using Hect relation to get measured energy from depth distribution for each E_{dep} and applying Gauss Conv for energy resolution

Final effective area curve for MGF



Effective area curve for mask-weighting in FoV



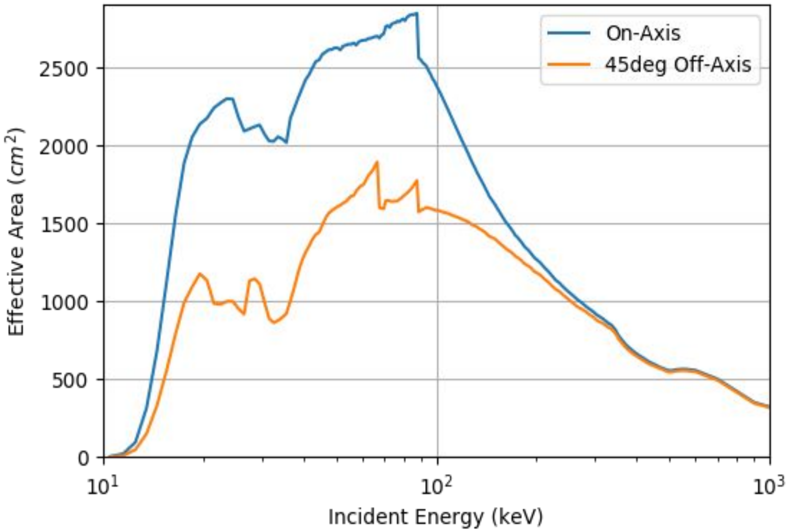
Scale doesn’t match (per det vs total), but difference in shape is apparent

A New Analysis Method - searching for dimmer GRBs

The imaging analysis is very computationally efficient and is automatically background subtracted, but the mask-weighted technique

- Has a 56% efficiency
- Its A_{eff} reduces as transmission through mask tiles increase (higher energy)
- Ignores uncoded dets

Total A_{eff} for detector counts



Assumes all detectors are active

A_{eff} for mask weighted counts

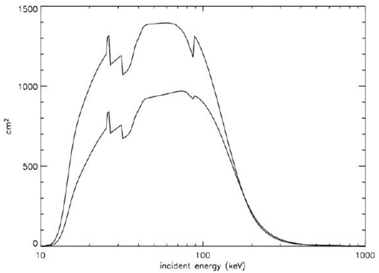


Figure 8. Effective area of the BAT for on- and off-axis (45 deg.) sources.

Swift BAT Calibration Document

To have a higher A_{eff} , avoid mask-weighted counts and instead keep the data as detector counts

NITRATES (Non-Imaging Transient Reconstruction And TEmporal Search)

- Use the max LLH technique, with a binned Poissonian likelihood
  - Data binned by detector and ~9 energy bins
- Search for GRBs, using a LLHR comparing a bkg-only model to a bkg + signal model

N_{ij} = number of counts in detector, i and energy bin, j

$\lambda_{ij}(\mathbf{\Theta})$ = number of expected counts from model(s), given model parameters $\mathbf{\Theta}$

$$l_{ij}(\mathbf{\Theta}|N_{ij}) = \text{Poisson}(N_{ij}\, ;\, \lambda_{ij}(\mathbf{\Theta}))$$

$$\text{LLH}(\mathbf{\Theta}|\mathbf{N}) = \sum_i \sum_j \ln[\, l_{ij}(\mathbf{\Theta}|N_{ij})\,]$$

- To do this, need responses that includes all possible source counts (including scattering and transmission through the craft, mask, lead tiles, etc.)
- Need a DRM for each detector and for the whole sky
  - (9 Ebins)x(200 PhotonEs)x(3.2E5 dets)x(~5E5 sky positions) = ~3E13 floats = ~ 1 PB !!!
- Need a right mix of pre-computed parts and parts calculated on the fly

https://arxiv.org/abs/2111.01769 NITRATES paper

Constructing The Response

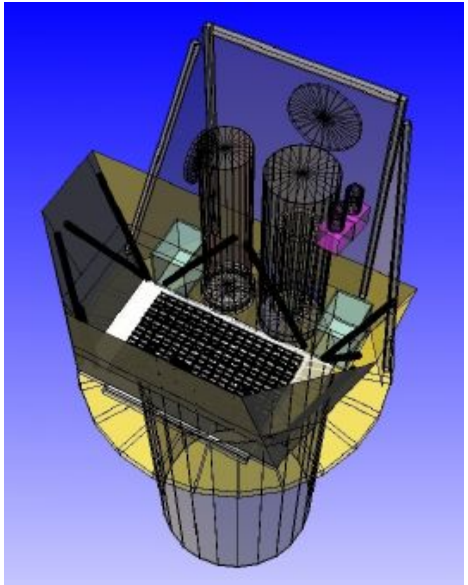
Want a per detector response that supports the whole sky and photon energies ~10 keV - ~5 MeV

Separate into 2 parts

- Indirect response
  - Photon first interacts with another part of the craft
  - Mostly Compton scattering and fluorescence lines from the shield
- Direct response
  - Photon makes it to detector unimpeded

Direct response changes more quickly with sky position, especially in the coded FoV.

Swift Mass Model (SwiMM)



Use SwiMM and Geant4 to simulate photon fluxes at a set of photon energies and sky positions. Use results to build responses with MuTau model.

Do simulations with whole mass model to make the indirect responses (ignore direct hits)

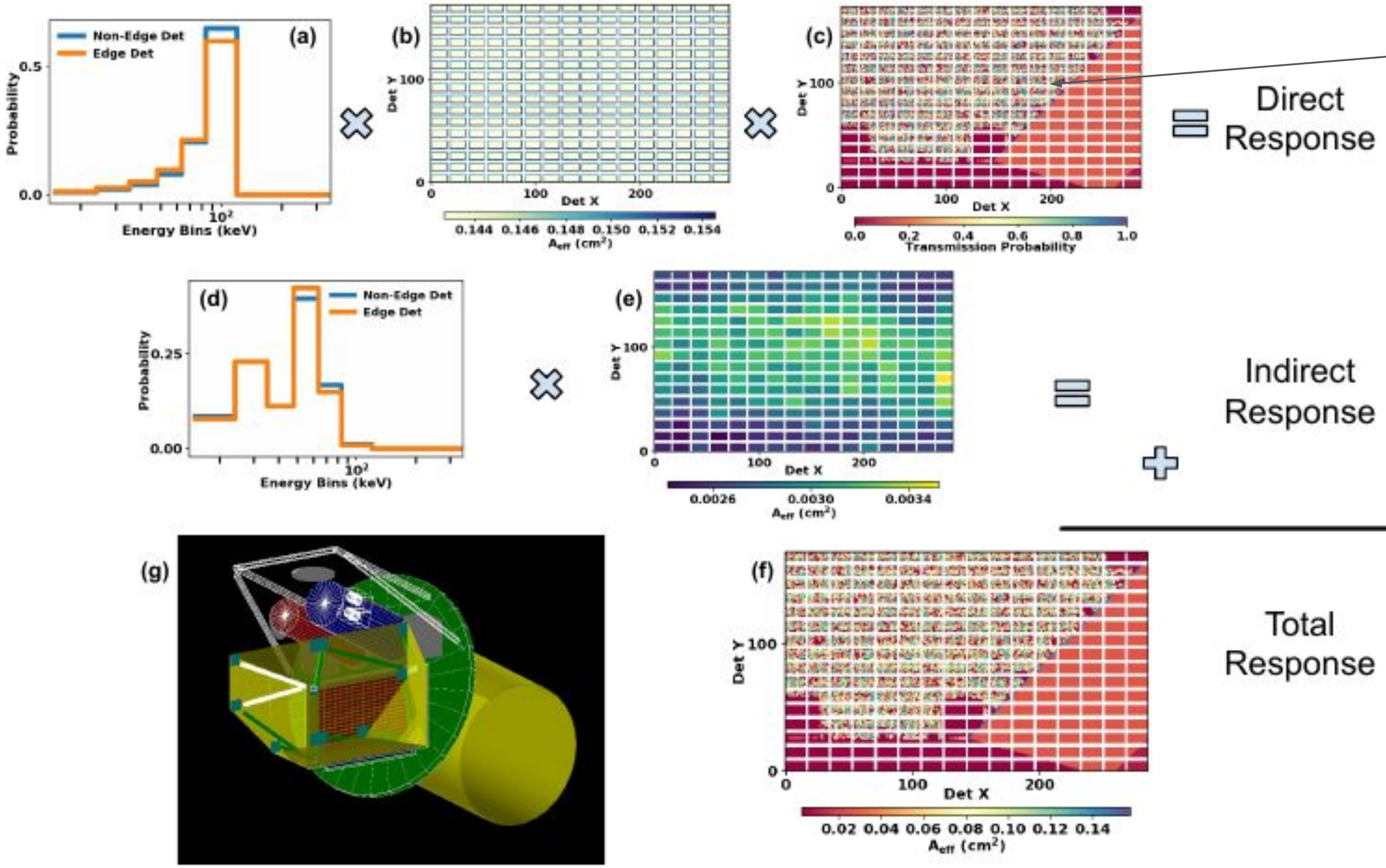
For direct response, remove all elements of the mass model besides the detectors and nearby elements.
Will need to adjust this response by the transmission probability.

$$R_{ij}(\theta, \phi, E_\gamma) = R_{ij}^{indirect}(\theta, \phi, E_\gamma) + t_i(\theta, \phi, E_\gamma) \times R_{ij}^{direct'}(\theta, \phi, E_\gamma)$$

Where: t_i = transmission probability to detector i

Indirect and direct responses made every few degrees, saved and interpolated between. t_i recalculated every new position

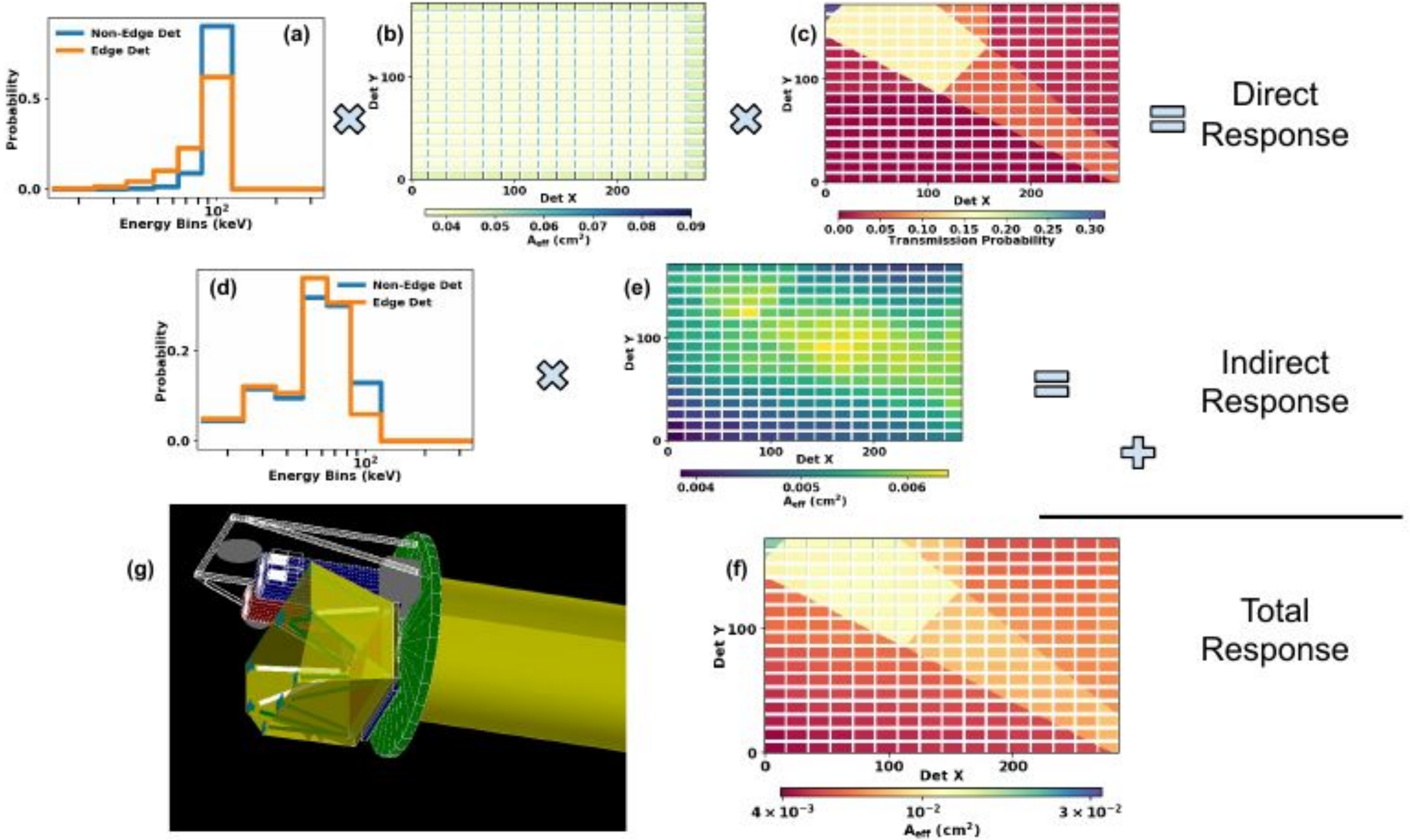
Construction of 100.5 keV Photon Response, Theta 35°



t_i in coded region includes shadowded fraction of each det, which is precomputed and stored.

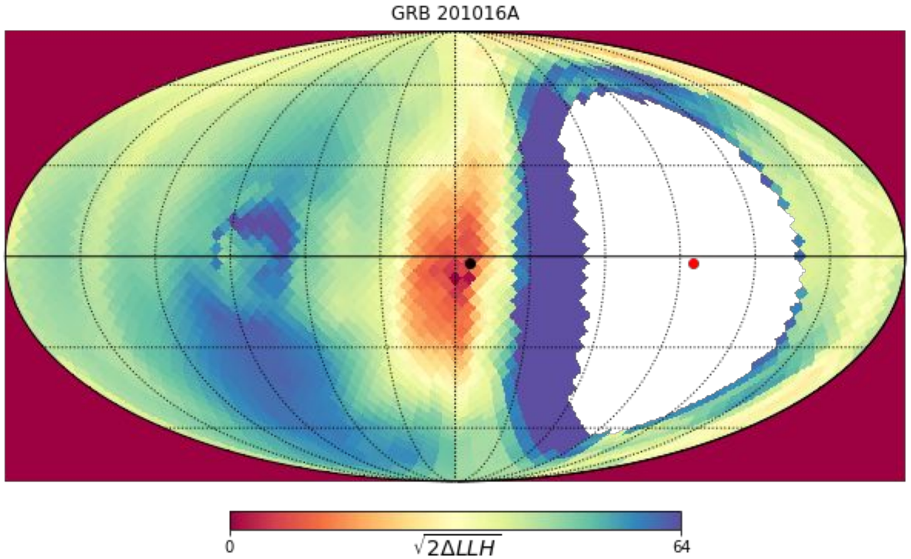
Similar dets are grouped together when going from depth dists. to responses with charge trapping and other effects included.

Construction of 100.5 keV Photon Response, Theta 75°



Results

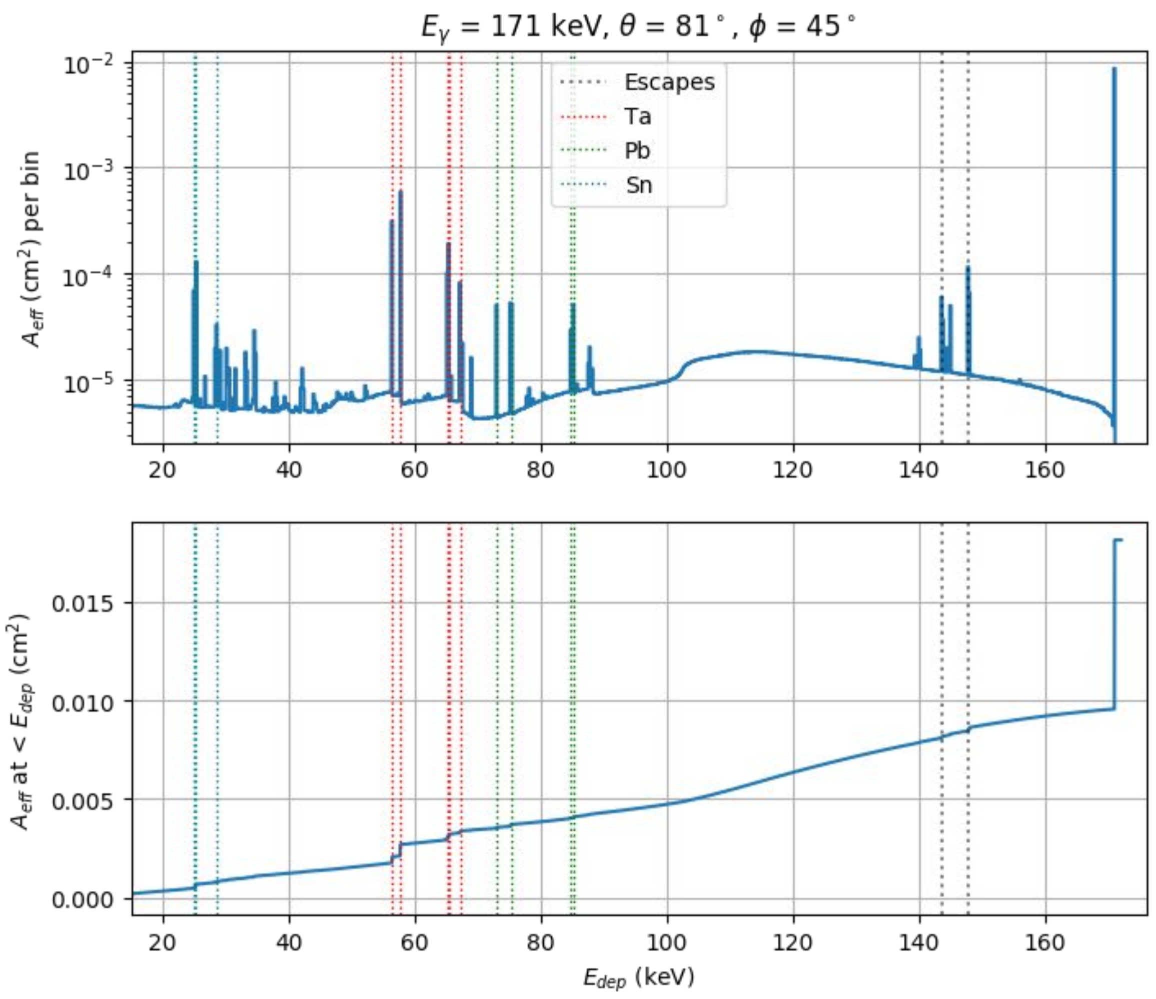
- The NITRATES search is capable of localizing (to a few arcminutes) inside the coded FoV GRBs
  - Has localized ~20 GRBs that were too weak to be found via imaging
- Also capable of determining if a GRB is outside the coded FoV
  - Impossible with imaging
- Rough localizations outside the coded FoV are also possible
- There has been no large effort to calibrate responses yet
  - Mostly a search so far, not used for spectral measurements
  - Results so far generally agree with measurements by other detectors
  - Some known issue spots
- Effort underway to use OFOV bursts also detected by GBM to calibrate responses



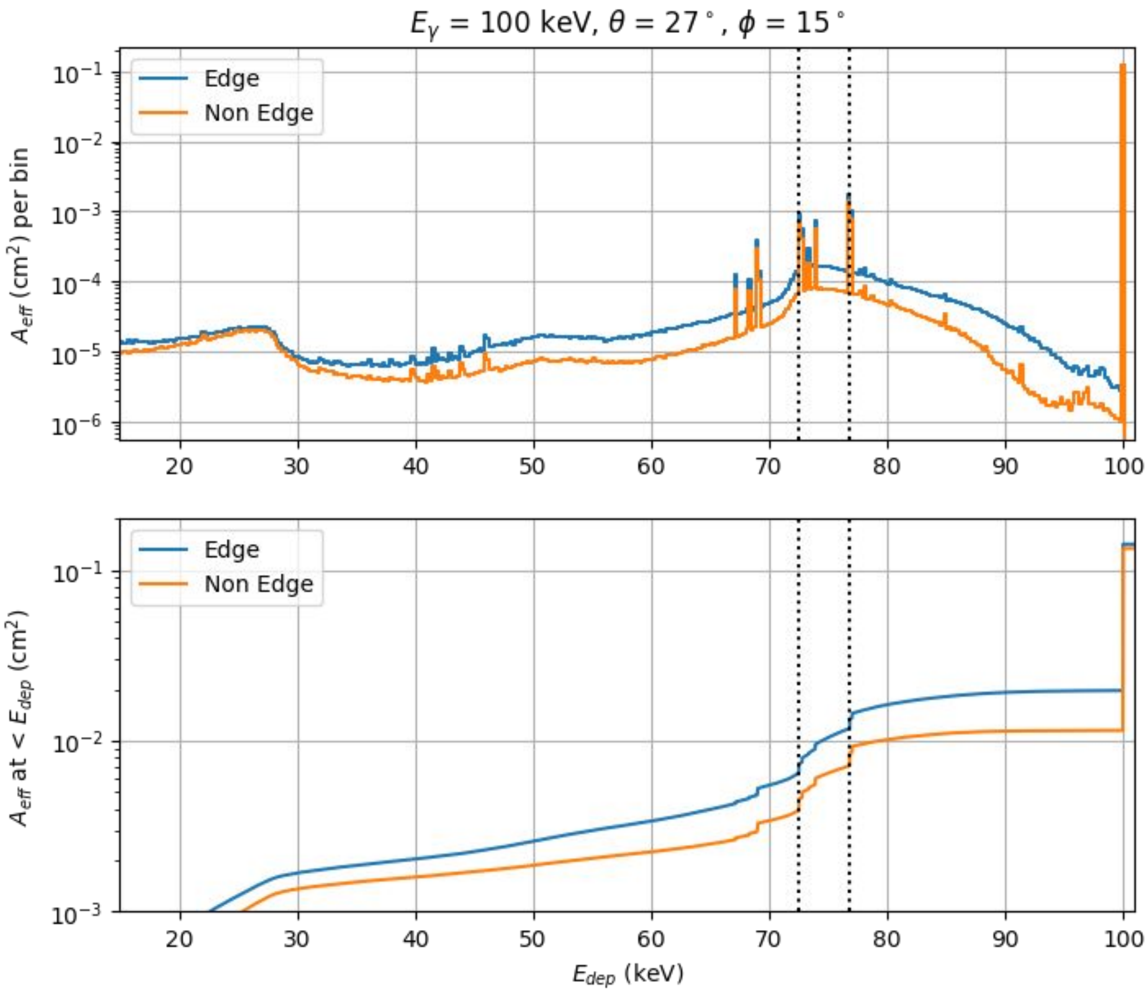
If I could go back to the calibration stage

- Larger energy range of lab calibration
  - Full response was only validated with lines between 31 keV and 81 keV
- Having a complete mass model at this stage would be great (was not used for calibration at all before launch)
  - Could check for agreement between GEANT4 results and lab results
  - If there's not agreement can more easily fix mass model or do more calibration
- More thought about data analysis at this stage
  - What might we be able to do past the main analysis and what calibration date would be necessary for it

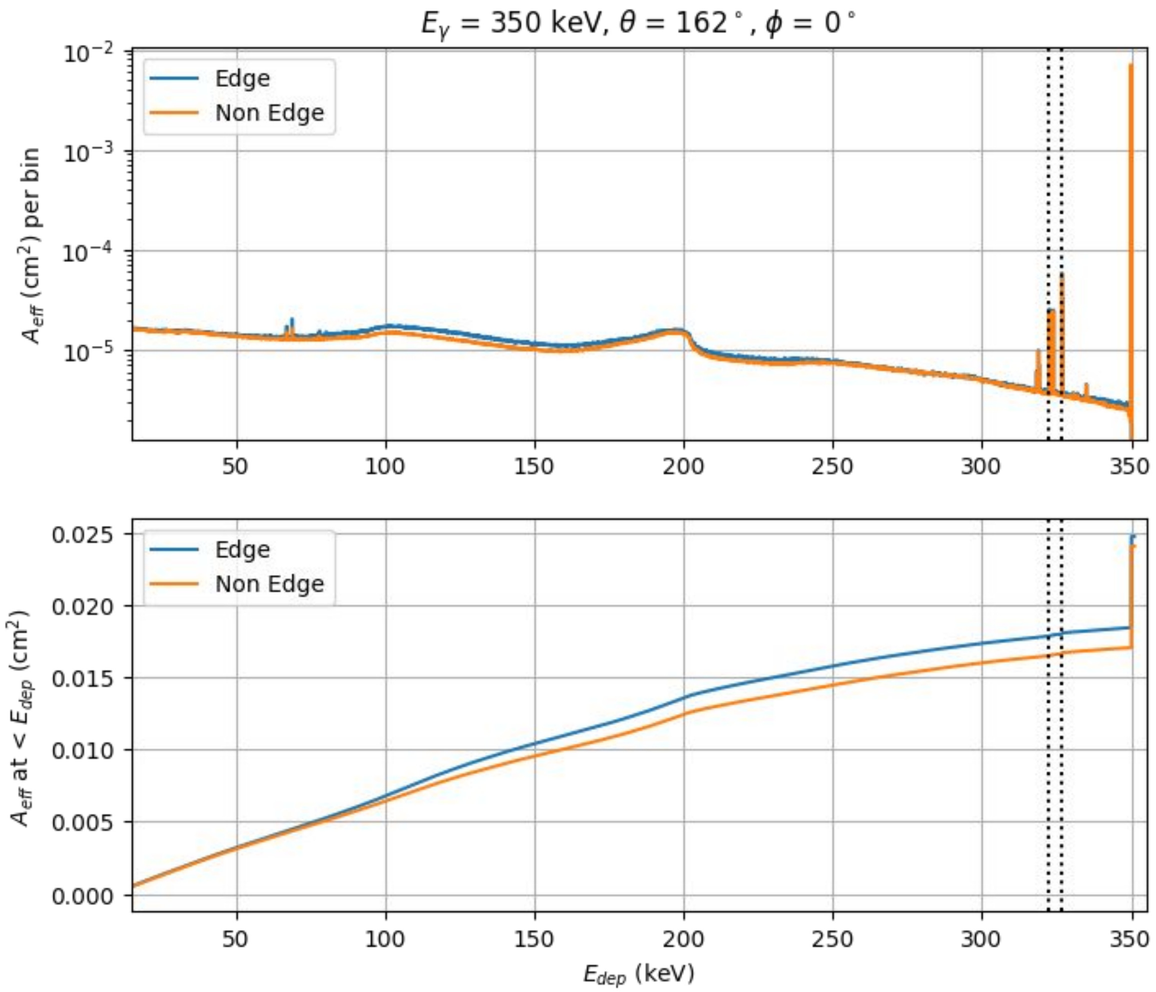
Backup Slides



Full craft Sim



Dets only Sim



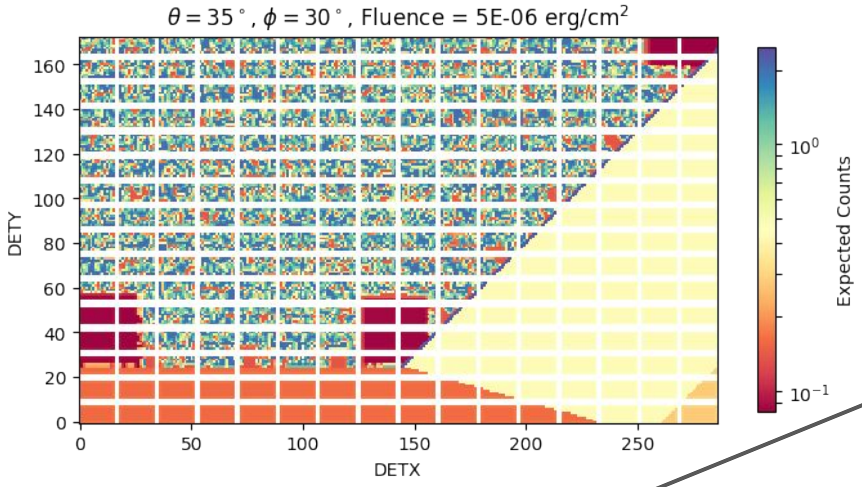
Dets only Sim

The total A_{eff} over all detectors and split between the direct and indirect components

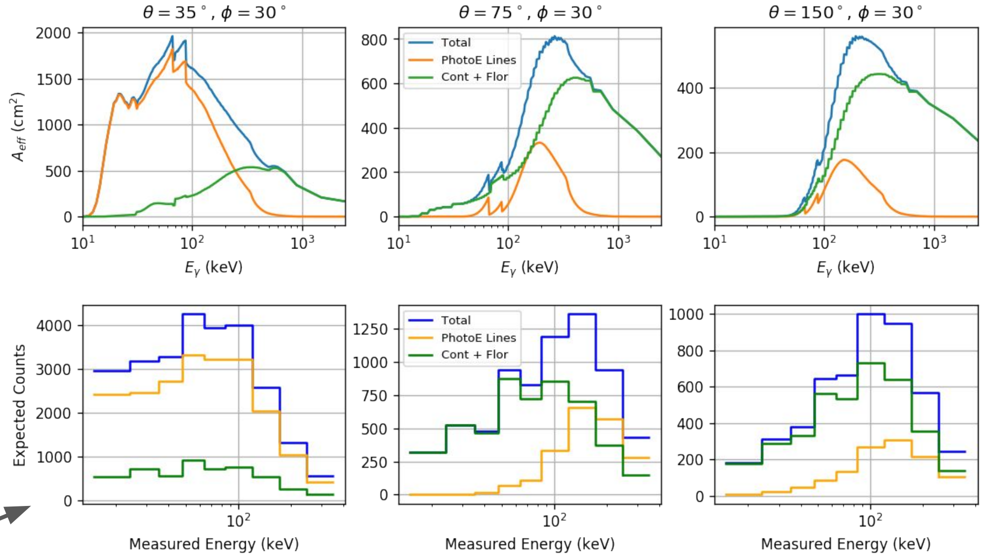
Partially Coded

Out of Coded FoV

Out of Coded FoV
Coming from below



Same flux and position as

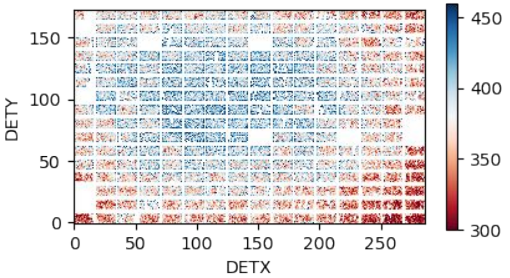


Expected counts from the PS model with a cutoff power-law spectra with γ = 0.5, E_{peak} = 350 keV, and a 10 keV - 1000 keV fluence of 5×10^{-6} erg cm^{-2} .

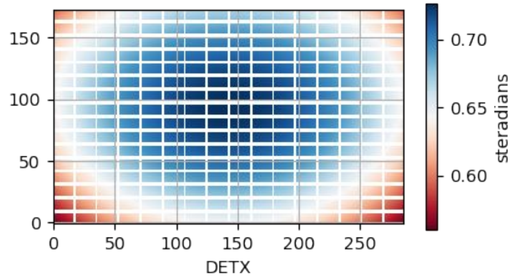
Diffuse Model

- CXB shining through mask openings creates spatial pattern across detector plane
- CXB photons that travel through mask tiles or shield and cosmic ray induced photons do not create any particular spatial pattern
- Two parameters per Ebin

≈1300 s of exposure with no bright sources



Ω_i



$$\lambda_{ij}^{diff} = (\Omega_i \, \phi_j^b + r_j^b) T$$

ϕ_j^b = rate per det. per Ω_i
r_j^b = rate per det.

Ω_i = unblocked solid angle for detector i
T = duration

Point Source Model

Sky Position: (θ, ϕ)
Spectra: Norm (A) and shape parameters

For a cutoff power-law spectrum
$\boldsymbol{\Theta}^{PS} = \{\theta, \phi, A, E_{peak}, \gamma\}$

Detector Response

$$R_j(E_\gamma) = w_j A_{eff}(E_\gamma)$$

w_j is the probability of count falling in Ebin j, $\sum w_j = 1$

For a photon spectra, $f(E_\gamma)$

$$\lambda_{ij}^{PS} = T \int f(E_\gamma) \, R_{ij}(E_\gamma) \, dE_\gamma$$