Simulation Studies of CTA Reconstruction Performance

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cta cherenkov telescope array

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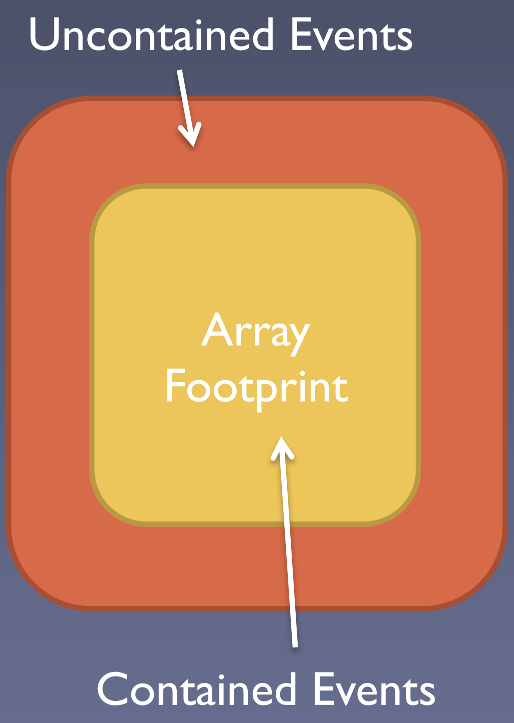
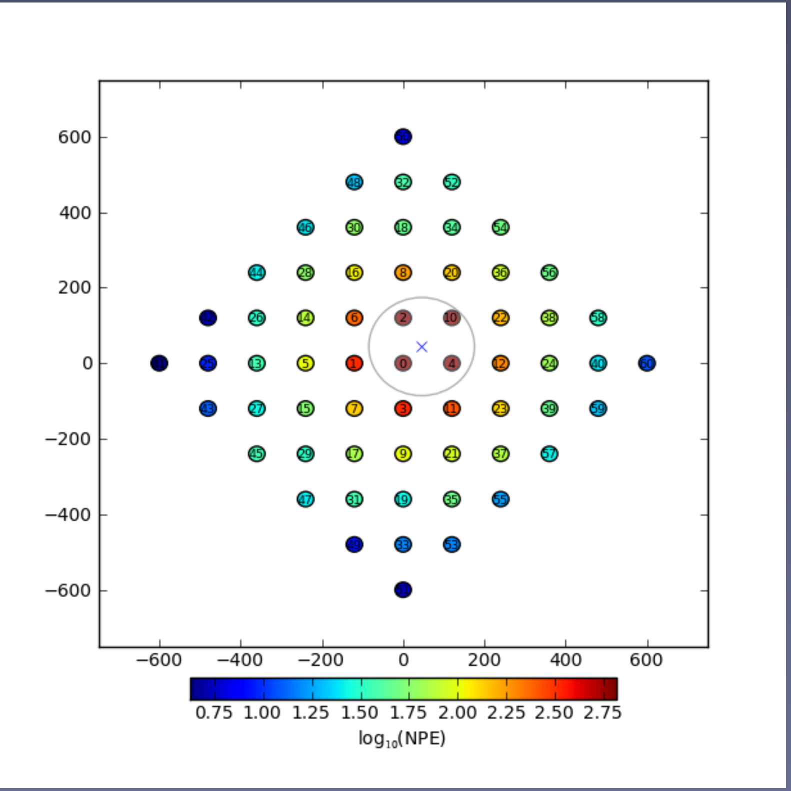
Scope of Study

- Evaluate performance of a CTA-like instrument using CORSIKA-generated gamma-ray showers (30 GeV - 3 TeV)
- Idealized Detector Model – allows telescope characteristics influencing array performance to be more easily disentangled
- Focus on ‘contained’ events and configurations that most closely correspond to the proposed designs for the Medium-Sized Telescope (MST)
  - Schwarzschild-Couder (SC-MST)
  - Davies-Cotton (DC-MST)
- Performance Metrics
  - Gamma-ray Angular Resolution – 68% Containment Radius (R_{68})
  - Energy Resolution
  - Point-Source Sensitivity (relative signal-to-noise) in background-dominated regime



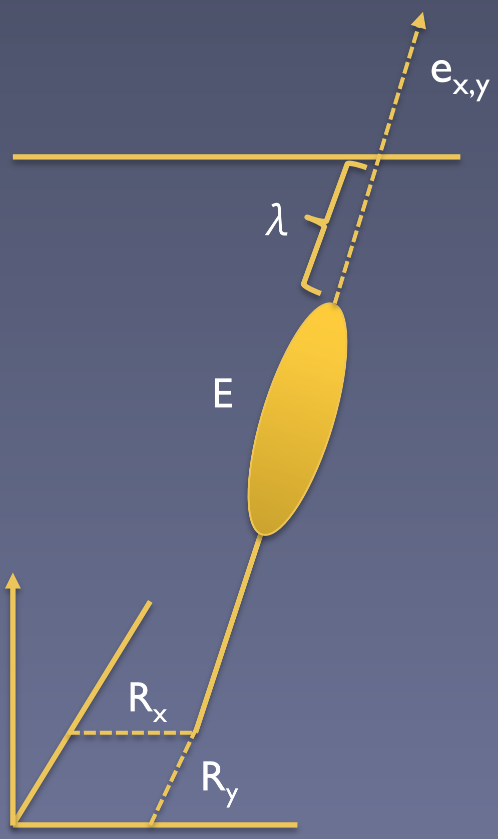
Idealized Detector Model

- Array of 61 MSTs (10 m aperture)
- Constant Gaussian Optical PSF across FoV (no ray-tracing)
- Light losses modeled with standard QE and reflectivity
- Simplified Electronics Model
  - Infinite integration gate
  - Single PE Charge Resolution: σ_q= 0.4
  - Electronics Noise: σ_b = 0.1
- Night-sky background photons with constant density across the FoV (100 PE/deg^2)
- Trigger simulated with a threshold on true image amplitude (60 PE)



Gamma-ray Reconstruction

- Reconstruction Parameters
  - Trajectory – Direction/Core Position
  - Energy
  - Interaction Depth
- Likelihood-based Reconstruction
  - Find the trajectory, energy, and interaction depth that maximize the likelihood for the image intensity in each pixel as computed from an image template model
  - Computationally slow but better performance than standard geometric reconstruction (Naurois et al. 2009)



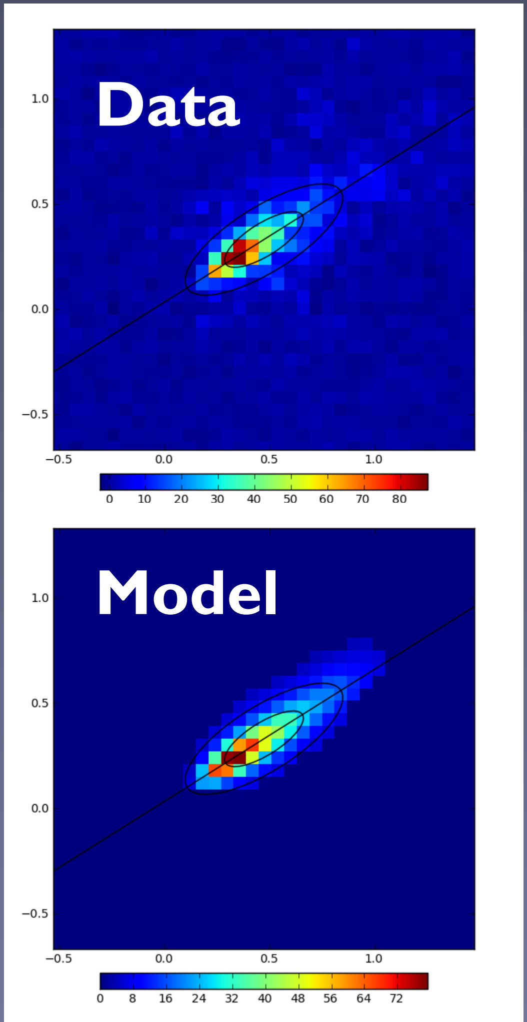
Likelihood Reconstruction

- Library of image templates accumulated by averaging over many simulated showers
- Array log-likelihood computed by summation over image pixel log-likelihoods in each telescope

$$L_{\rm pix}(s,n|\mu(\boldsymbol{\theta}),\mu_b,\sigma_b,\sigma_\gamma) = \frac{(\mu+\mu_b)^n e^{-(\mu+\mu_b)}}{n!} g(s,n)$$

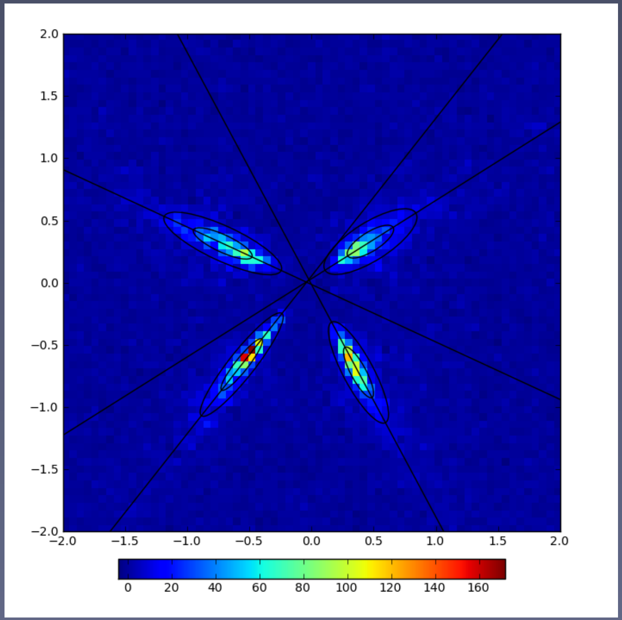
$$g(s,n) = \frac{1}{\sqrt{2\pi\left(\sigma_b^2 + n\sigma_\gamma^2\right)}} \exp\left[-\frac{(s-n)^2}{2\left(\sigma_b^2+n\sigma_\gamma^2\right)}\right].$$

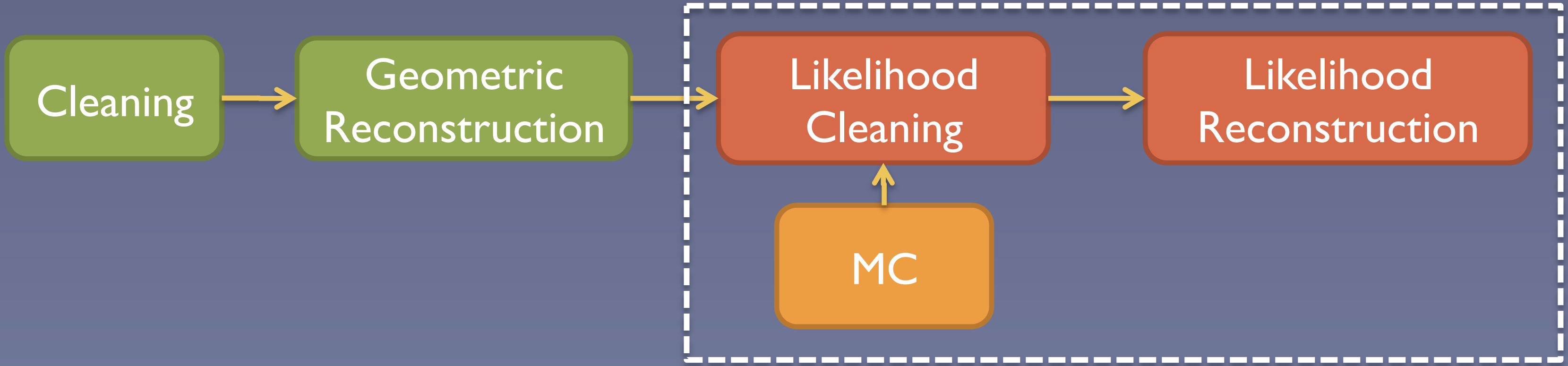
- Maximize array likelihood in 6D space of reconstruction variables



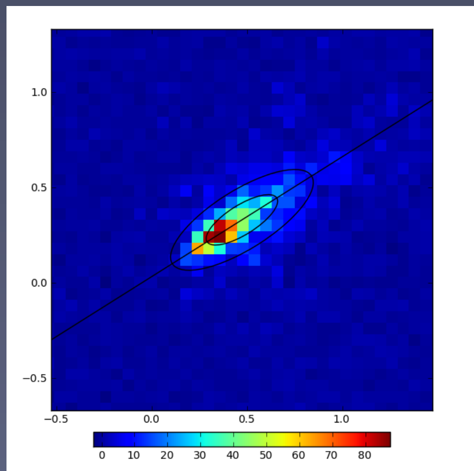
Likelihood Reconstruction: Seeding

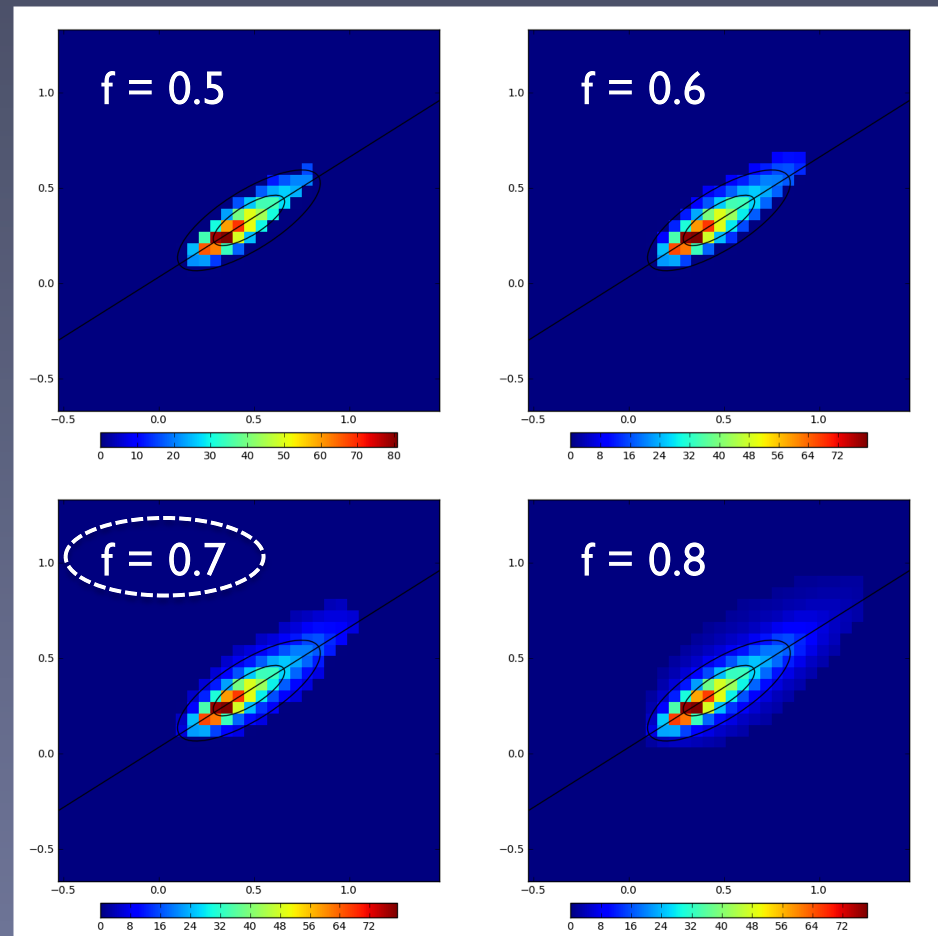
- Reconstruction seeded with MC values
- Insensitivity of likelihood reconstruction to parameter seeds was verified by randomizing seed values





Likelihood Reconstruction: Cleaning

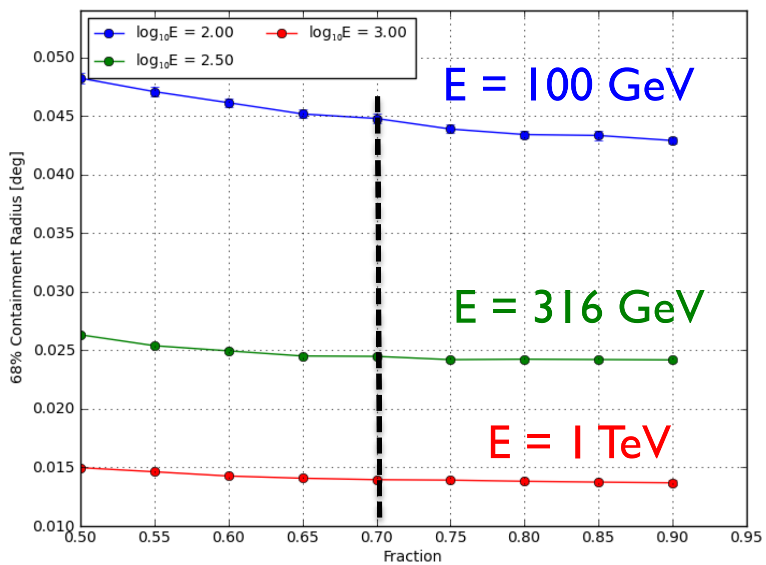




- Use seed parameters to compute list of pixels encompassing a fraction f of the model image intensity
- Likelihood reconstruction is only weakly dependent on f for f >0.6

Likelihood Reconstruction: Cleaning

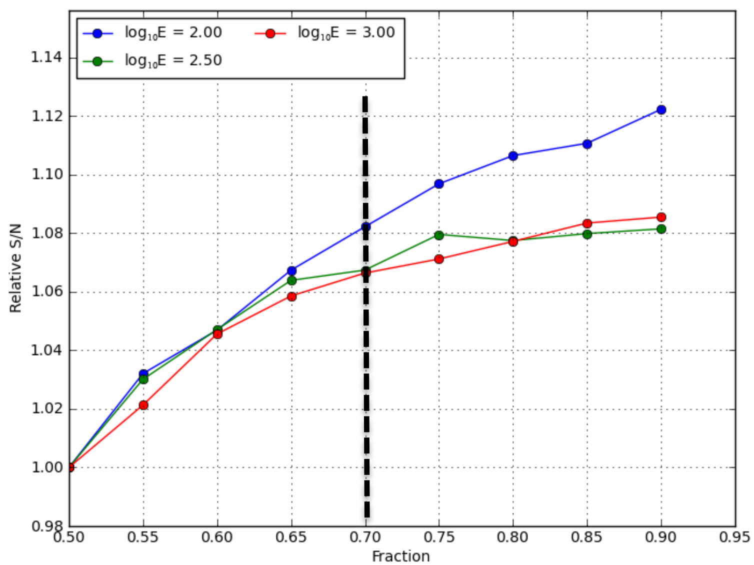
Angular Resolution



0.5 → 0.9

Fraction (f)

Signal-to-Noise

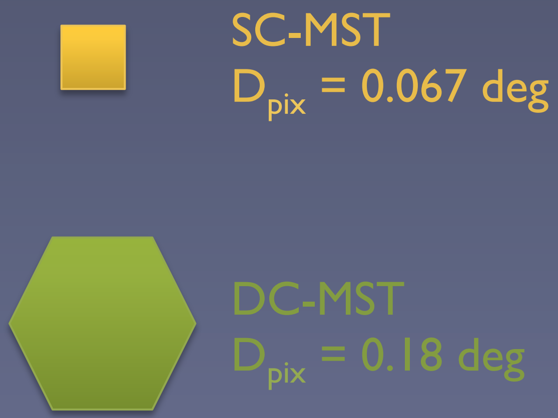


0.5 → 0.9

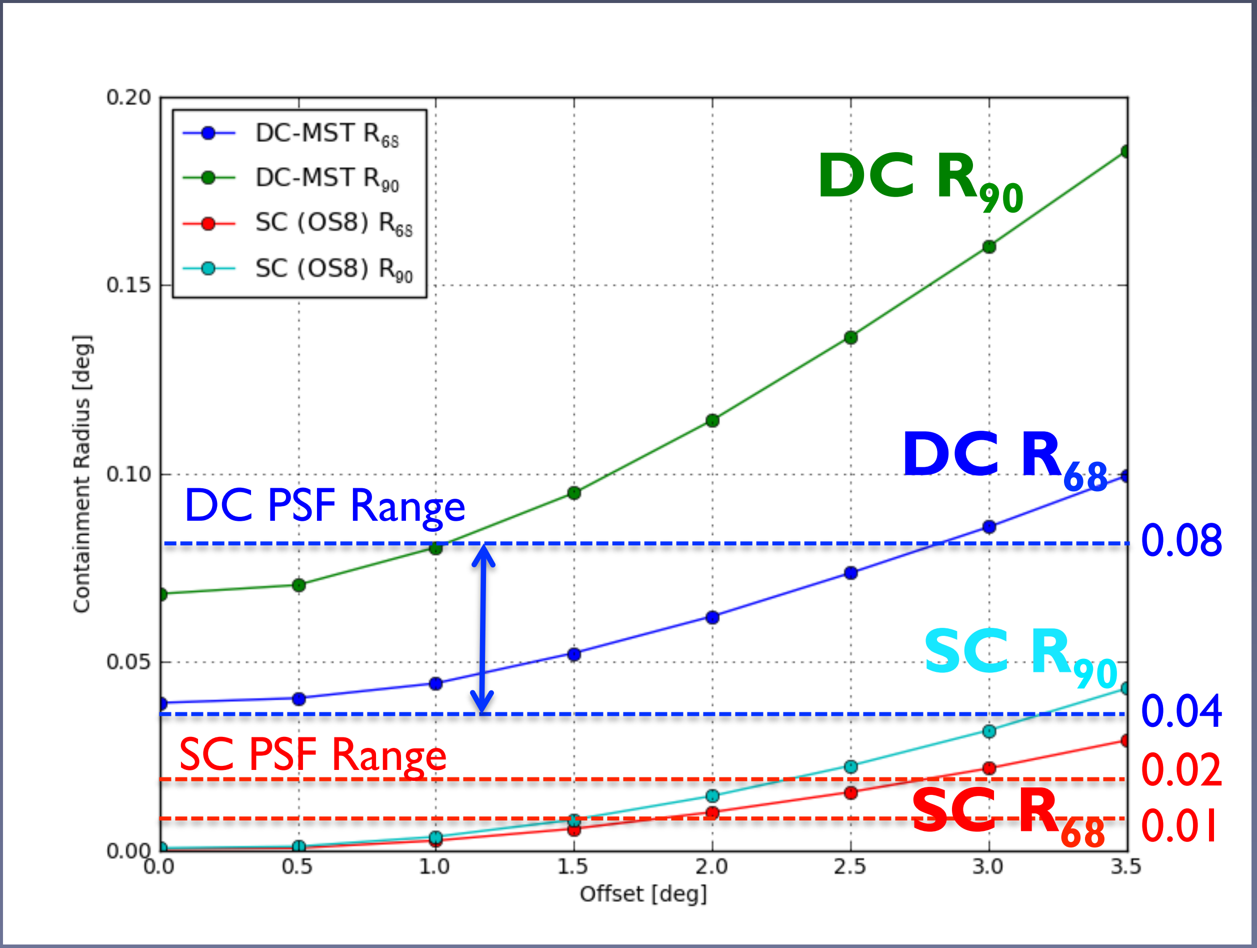
Fraction (f)

Pixel Size/Optical PSF Studies

- Intrinsic transverse angular size of a Cherenkov shower is ~1 arcminute – imaging resolution on this scale is needed for best reconstruction performance
- Need good PSF to realize full benefit of small pixels – ideally $R_{pix} < R_{psf}$
- Range of simulated pixel sizes and optical PSFs
  - D_{pix} = 0.02-0.18 deg
  - R_{68} = 0.01-0.08 deg



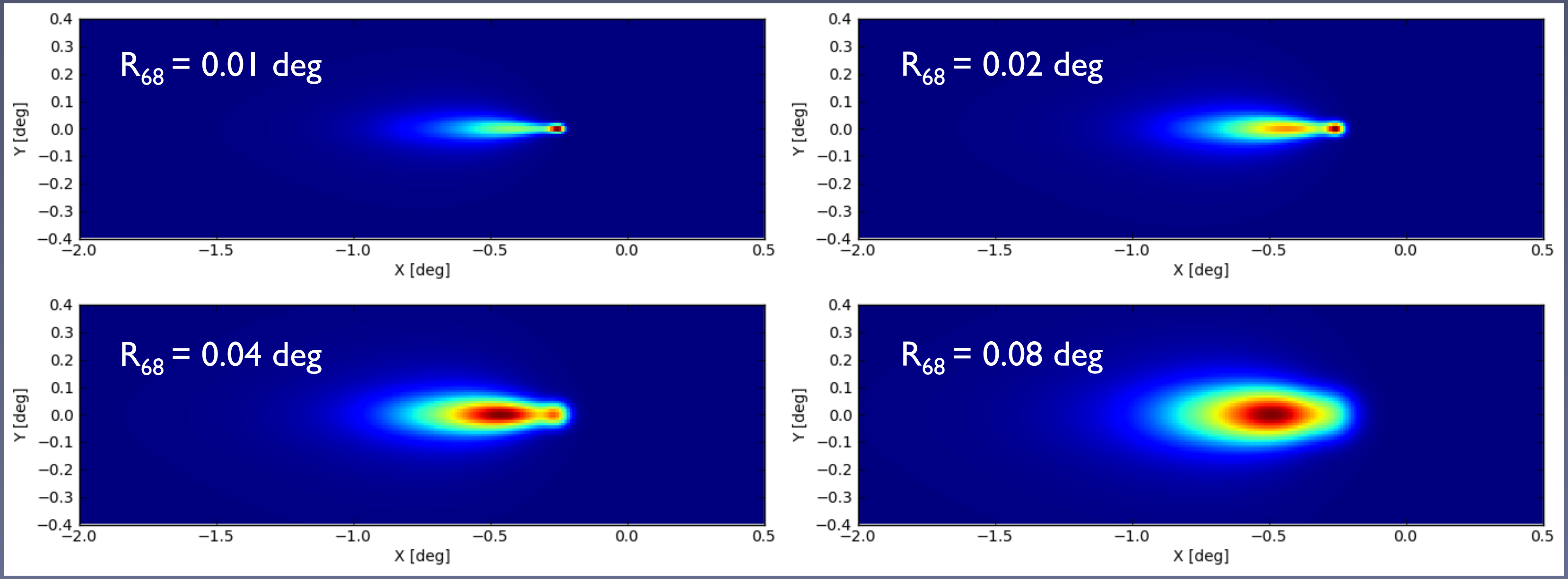
Optical PSF



0.0 Field Angle [deg] 3.5

Optical PSF

E = 100 GeV $\lambda = 0.5$

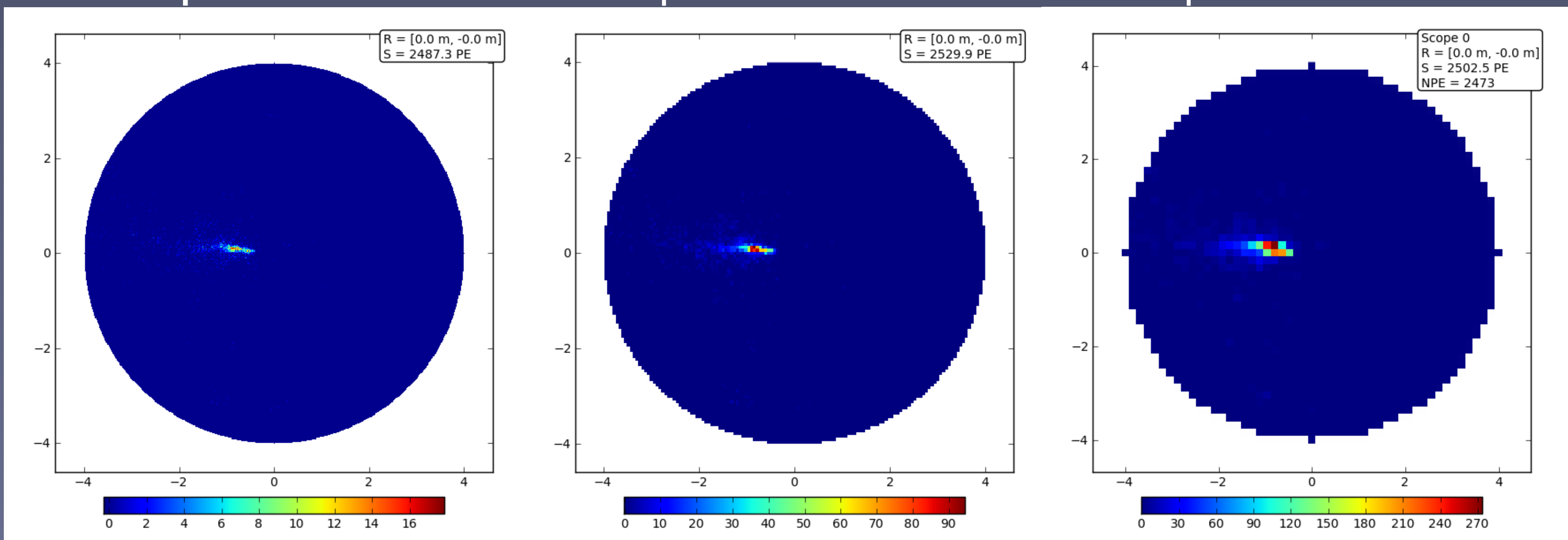


Pixel Size

$\mathbf{D_{pix}}$ = 0.02 deg
$\mathbf{N_{pix}}$ = ~100k

$\mathbf{D_{pix}}$ = 0.06 deg
$\mathbf{N_{pix}}$ = ~10k

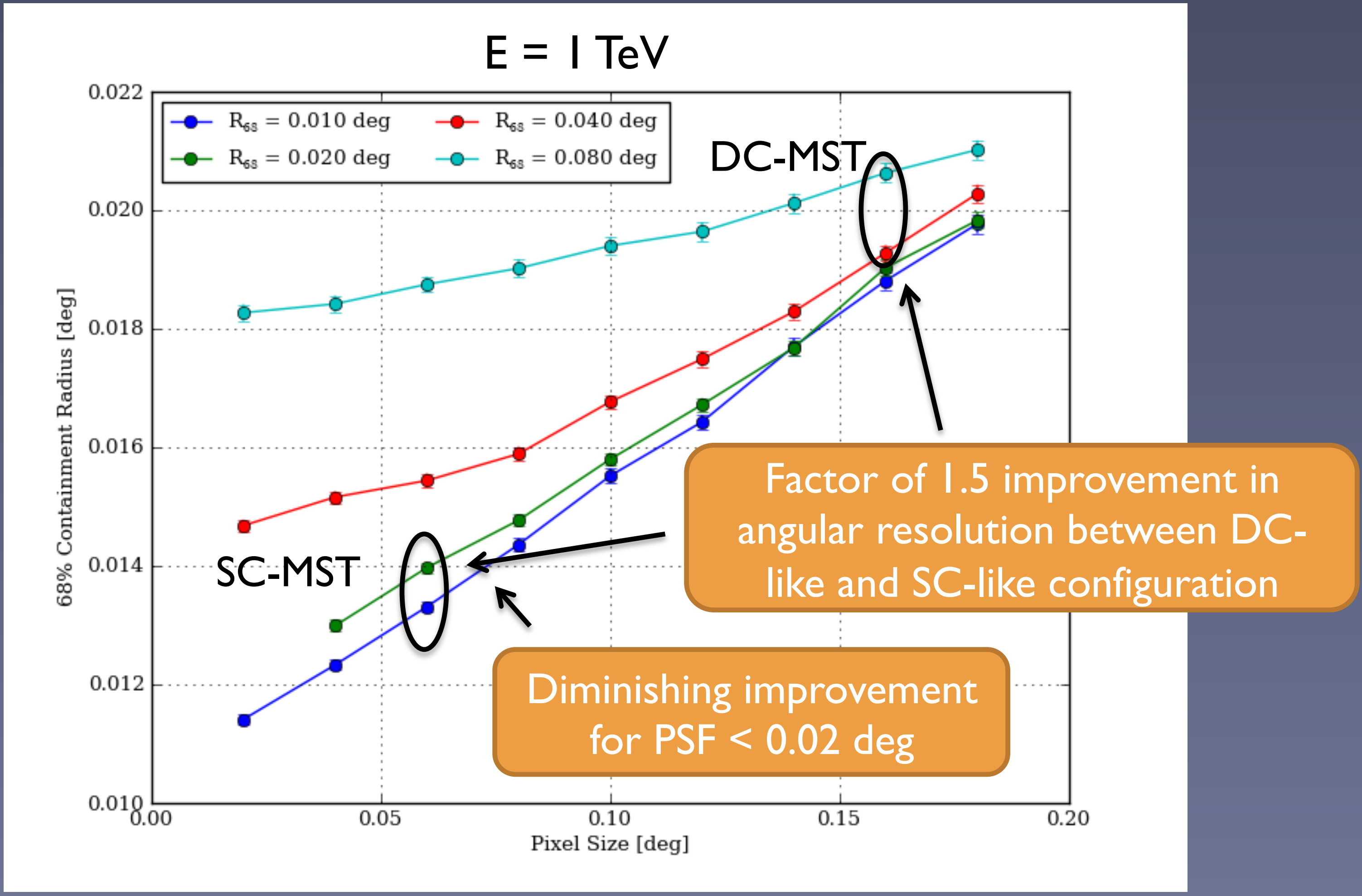
$\mathbf{D_{pix}}$ = 0.16 deg
$\mathbf{N_{pix}}$ = ~2k



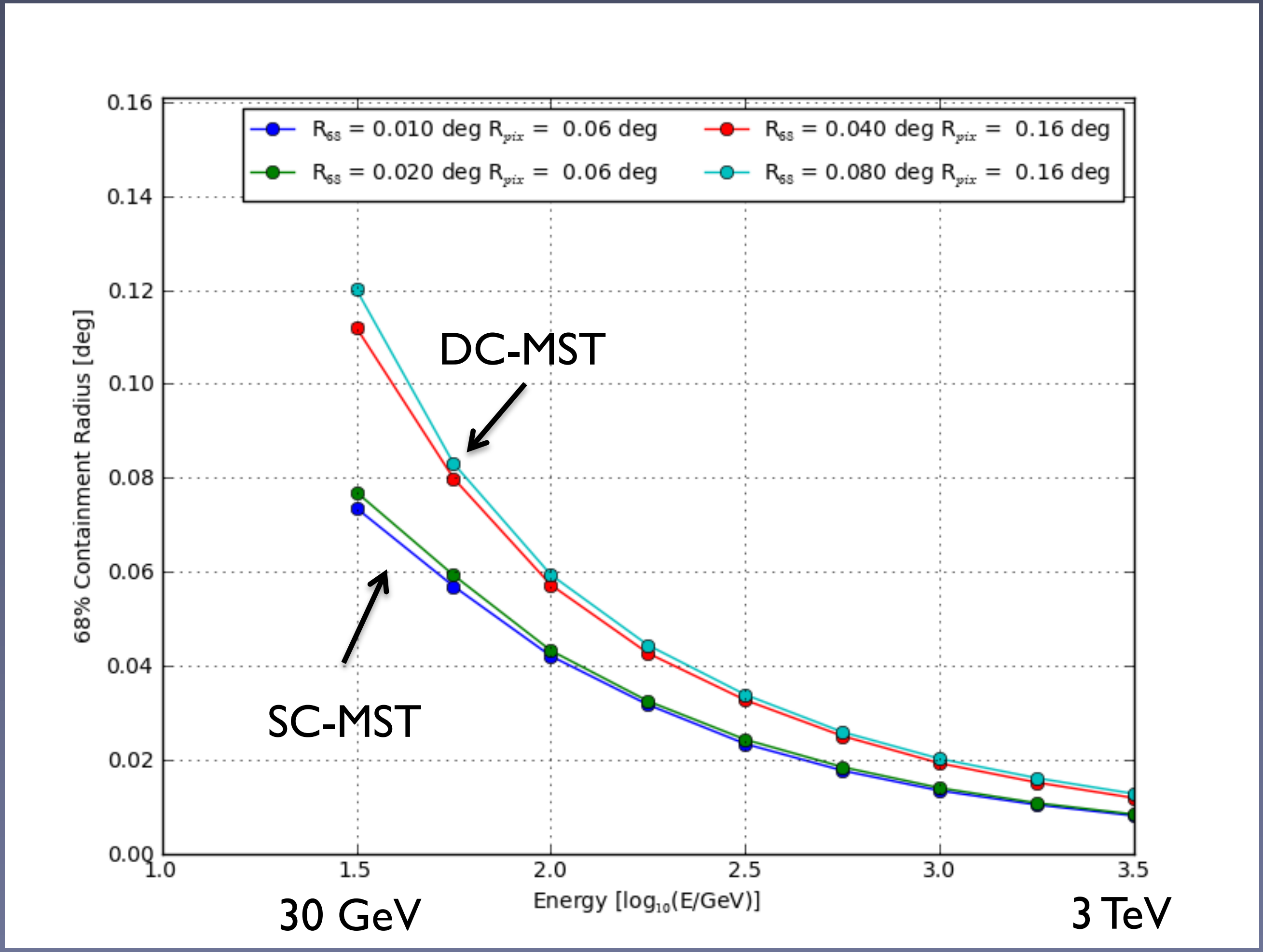
SC-MST

DC-MST

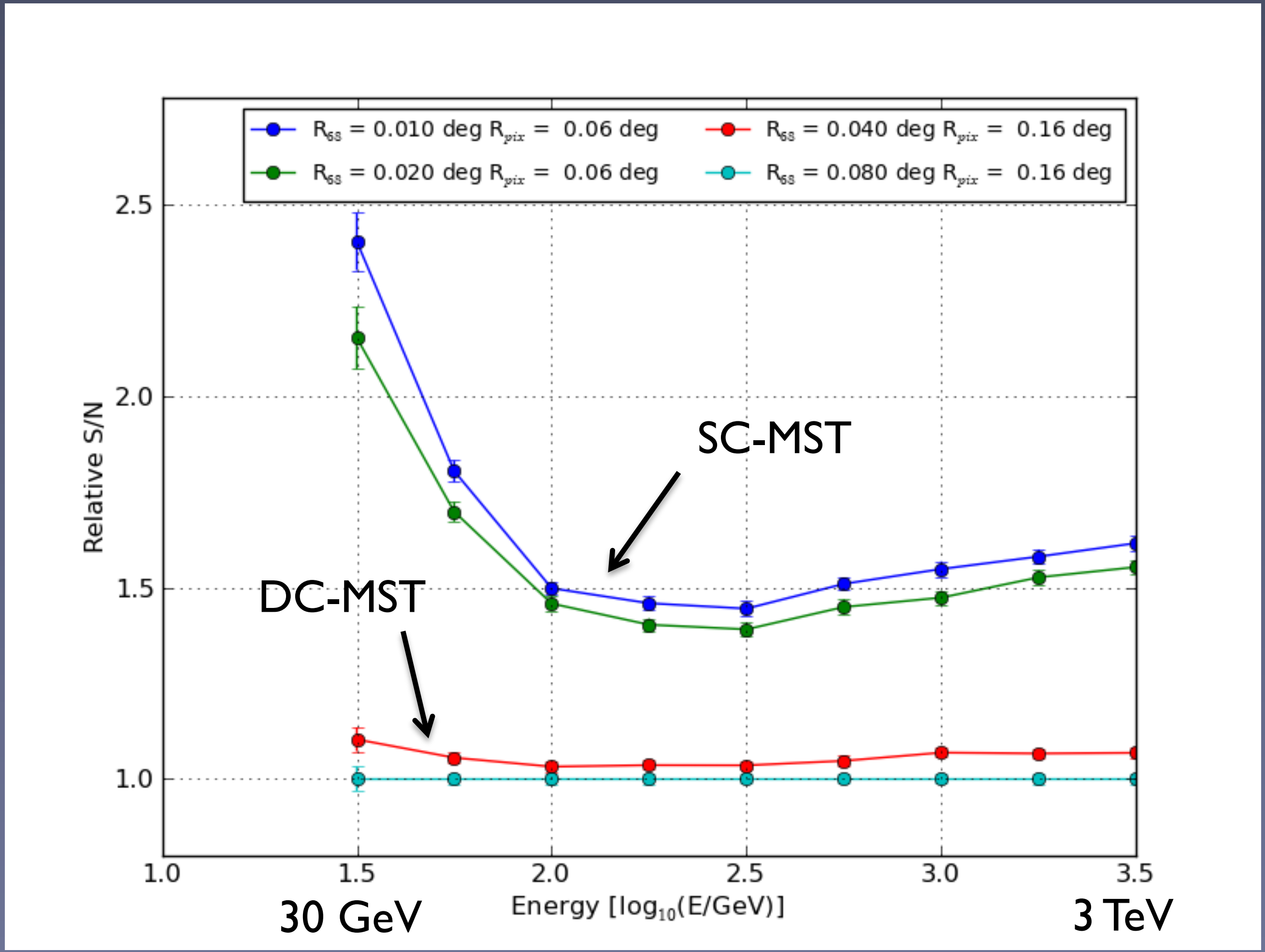
Pixel Size/PSF: Angular Resolution



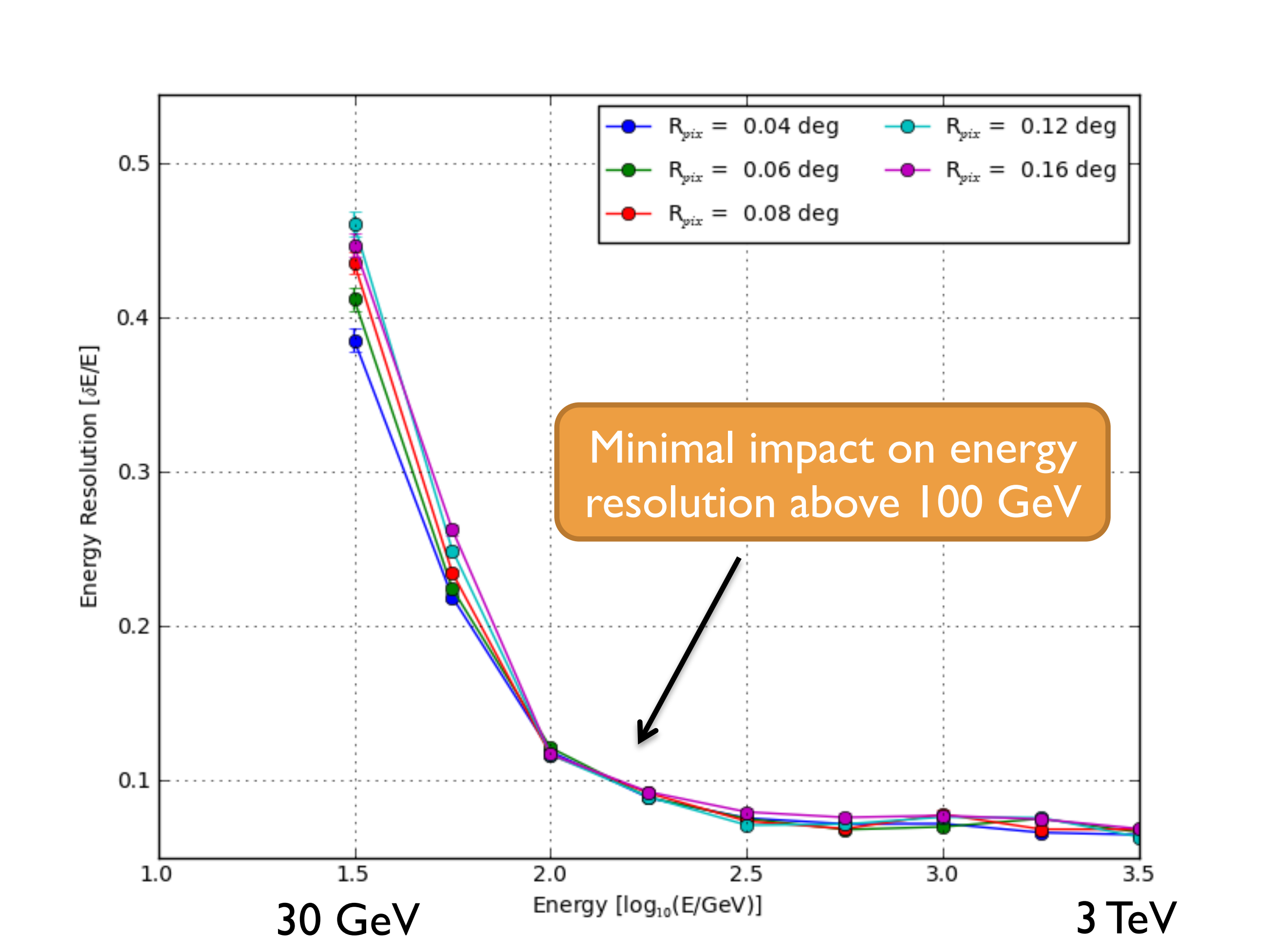
Pixel Size/PSF: Angular Resolution



Pixel Size/PSF: Sensitivity

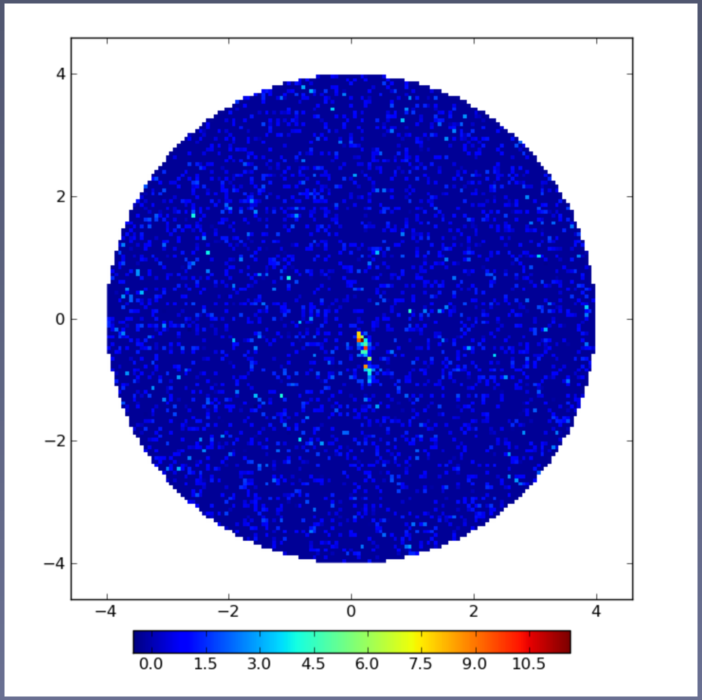


Pixel Size/PSF: Energy Resolution

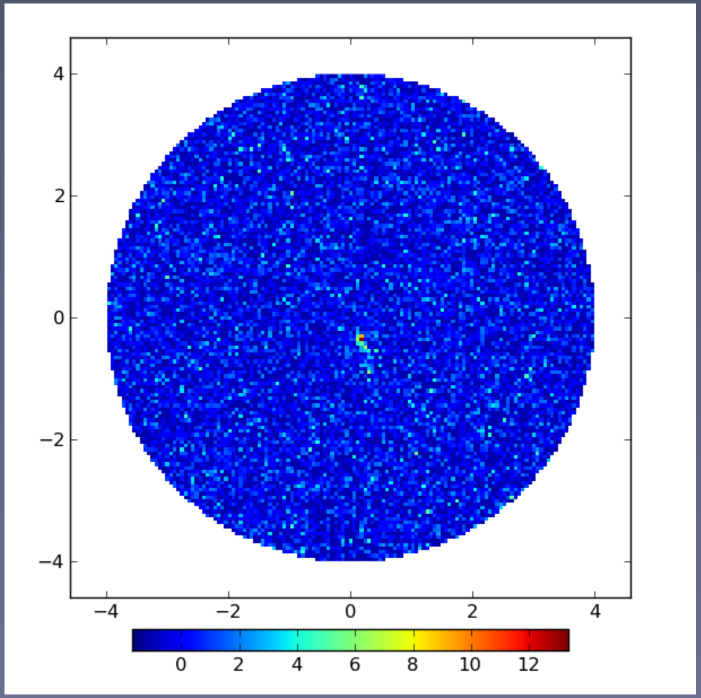


Pixel Size/PSF: NSB

Extragalactic Field
NSB = 100 PE/deg^2



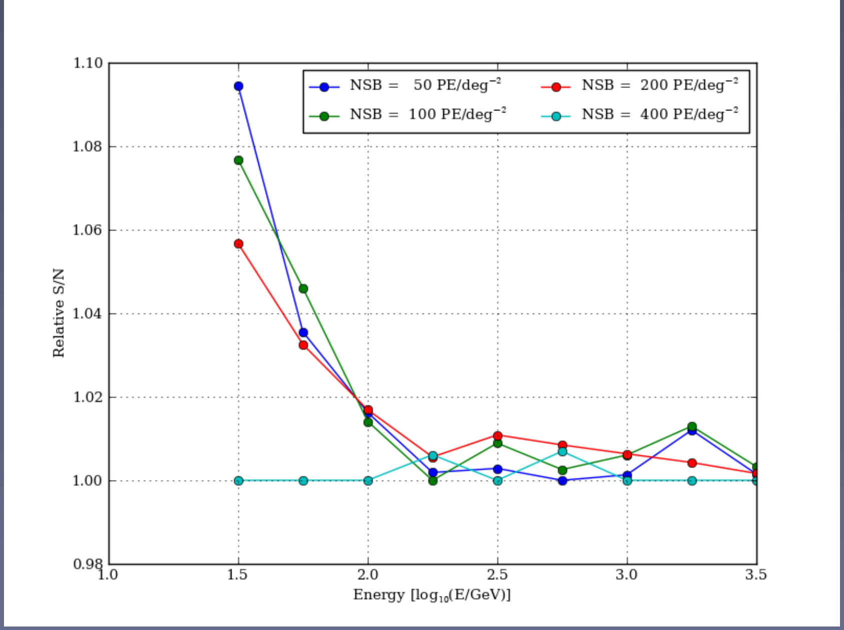
Galactic Field
NSB = 300 PE/deg^2



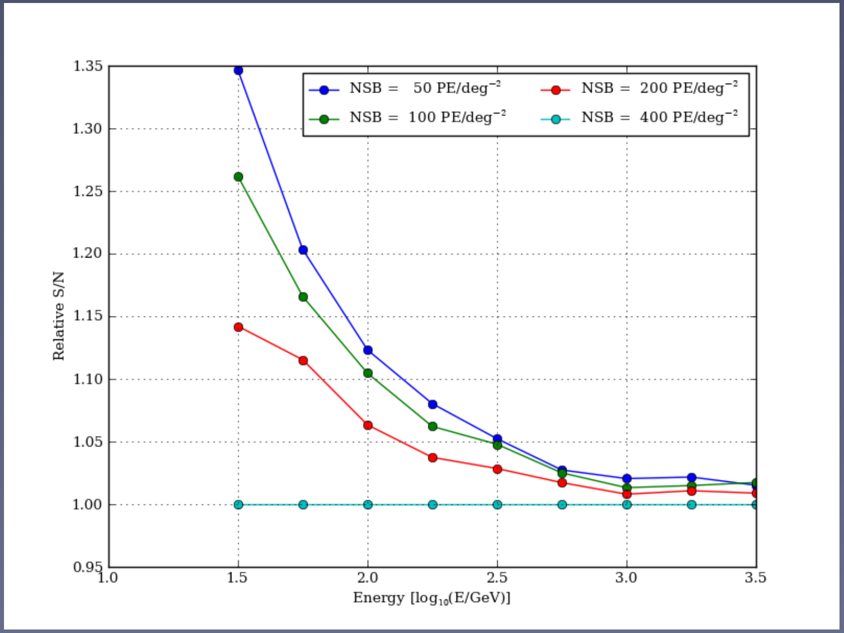
E =100 GeV Shower Image

Pixel Size/PSF: NSB

SC-MST
(R_{pix} = 0.06 deg R_{68} = 0.02 deg)



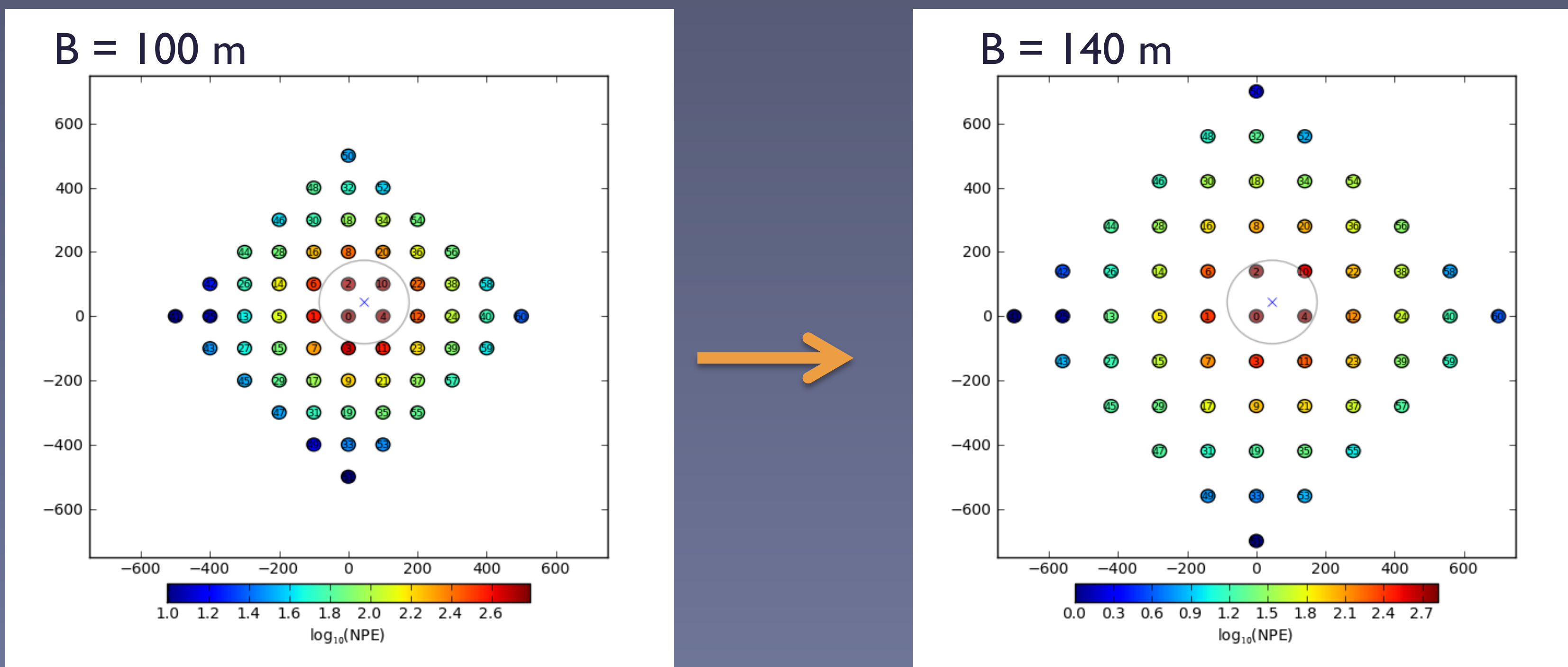
DC-MST
(R_{pix} = 0.16 deg R_{68} = 0.08 deg)



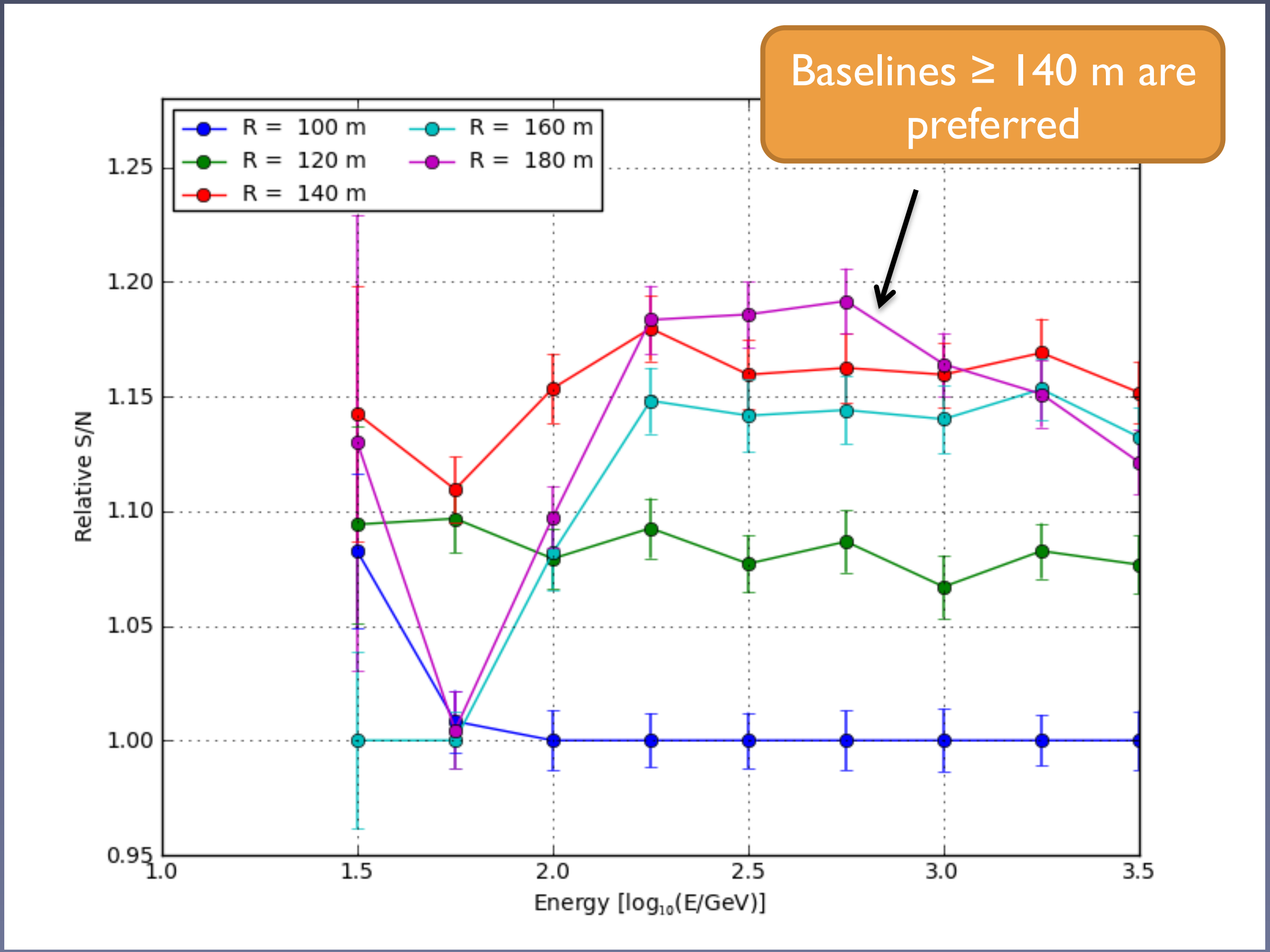
Smaller pixel size/PSF mitigates impact of NSB on reconstruction performance

Telescope Baseline

- A more densely packed array will generally have better reconstruction performance at the expense of collection area
- A natural scale for the baseline is ~120-140 m (~4 telescopes in Cherenkov light pool)



Telescope Baseline

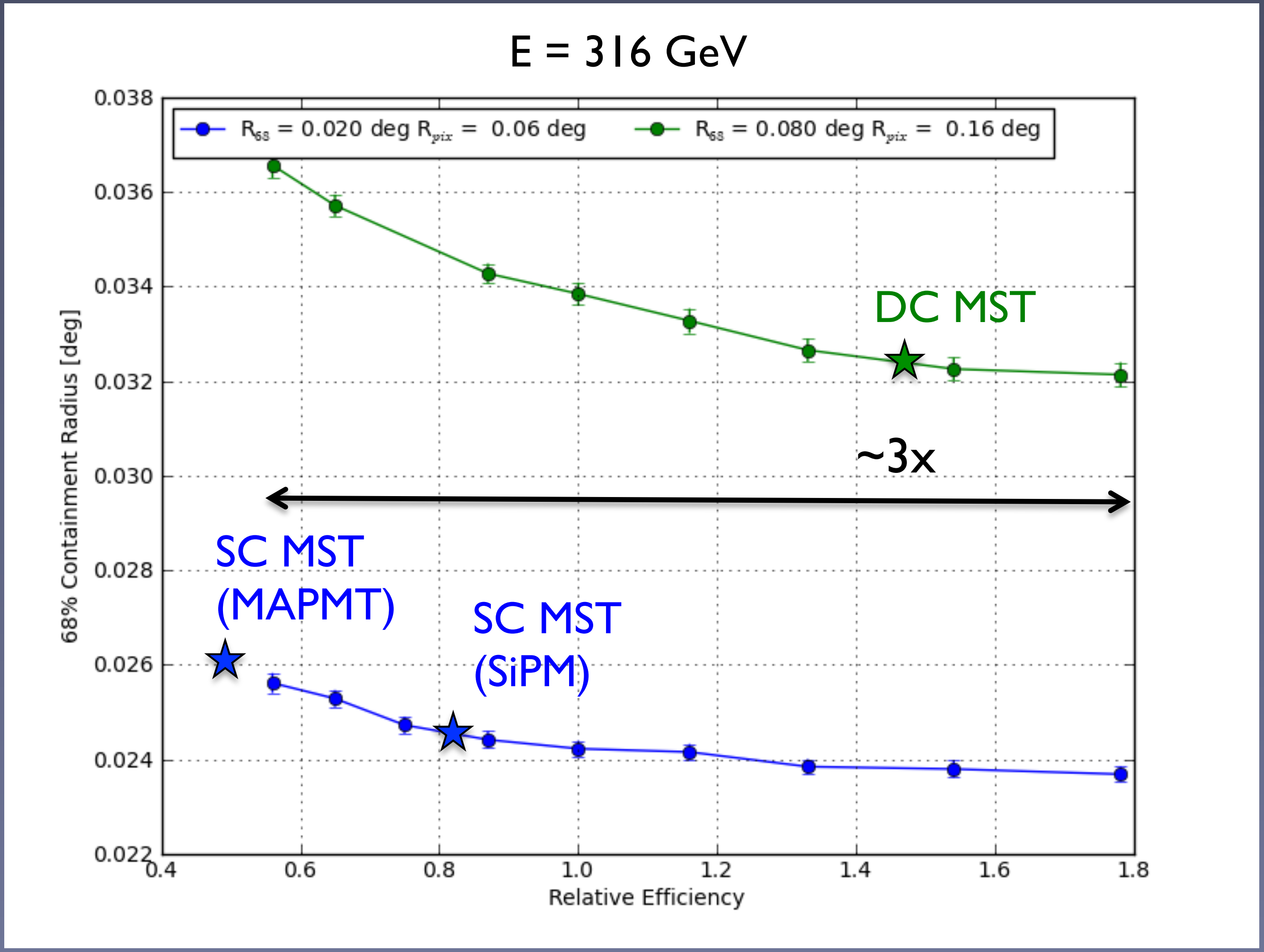


Light Collection Area

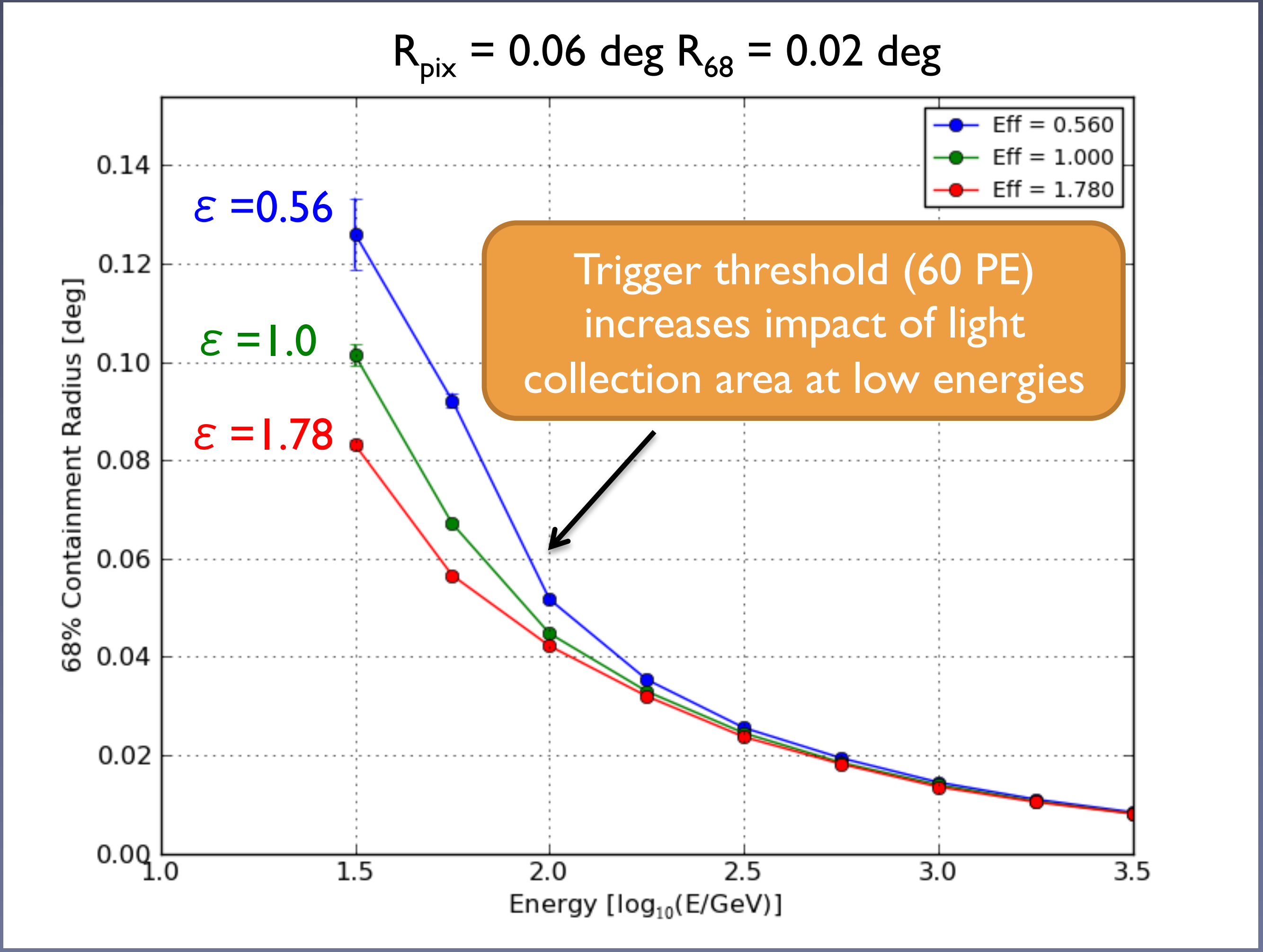
- Effective Light Collection Area
  - Mirror Area
  - Focal Plane Efficiency (deadspace, lightcones, etc.)
  - Photosensor PDE
- All factors contributing to light collection are folded into a single efficiency scaling (1.0 = canonical 78.5 m^2 MST)

	Effective Area (250-700 nm) [m^2]	**Scale Factor**
DC-MST	16.2	1.45
Reference MST	11.2	1.0
SC-MST (ASTRI SiPM)	9.2	0.82
SC-MST (Hamamatsu MPPC)	8.3	0.74
SC-MST (MAPMT)	5.0	0.45

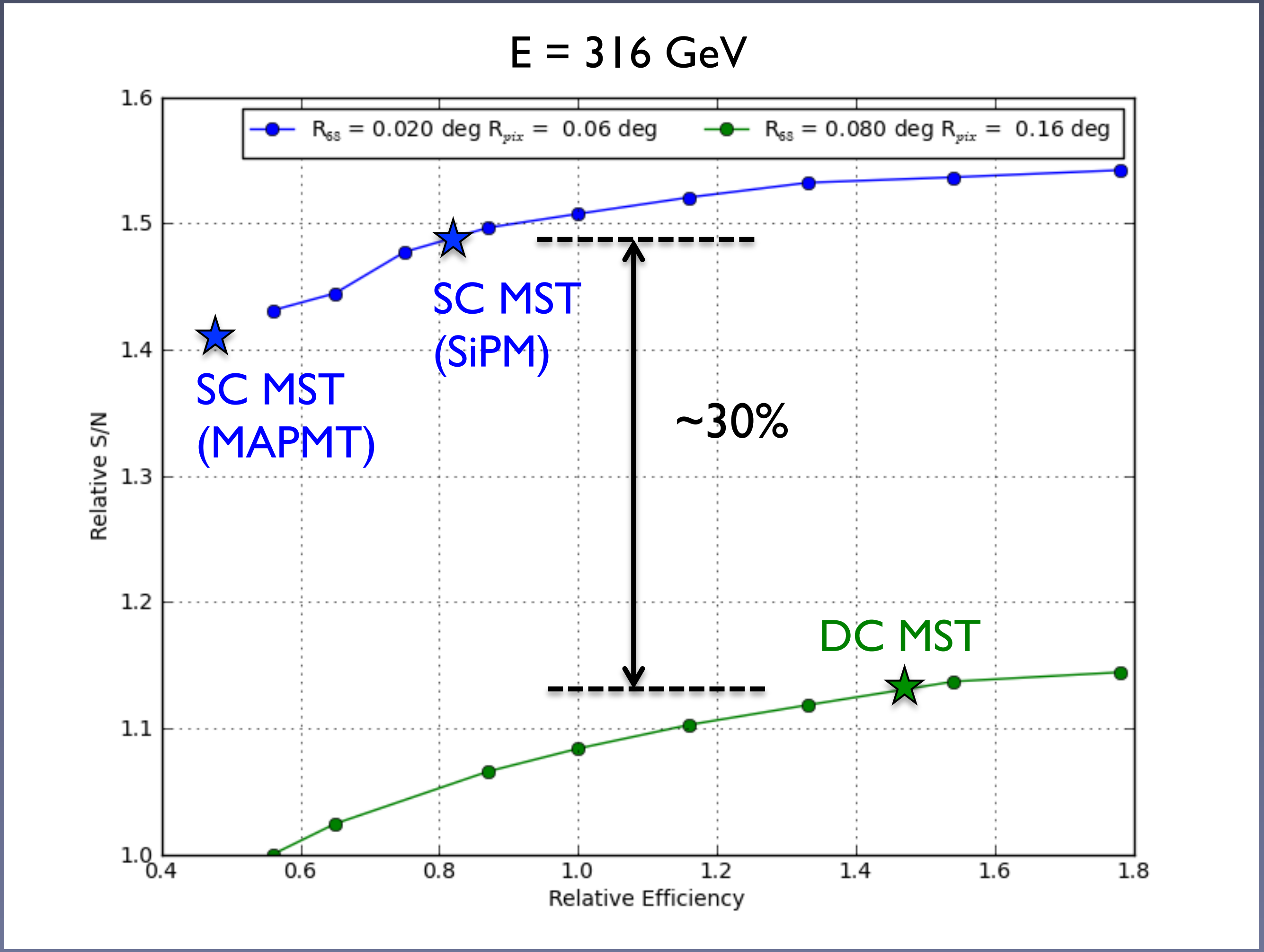
Light Collection Area: Angular Resolution



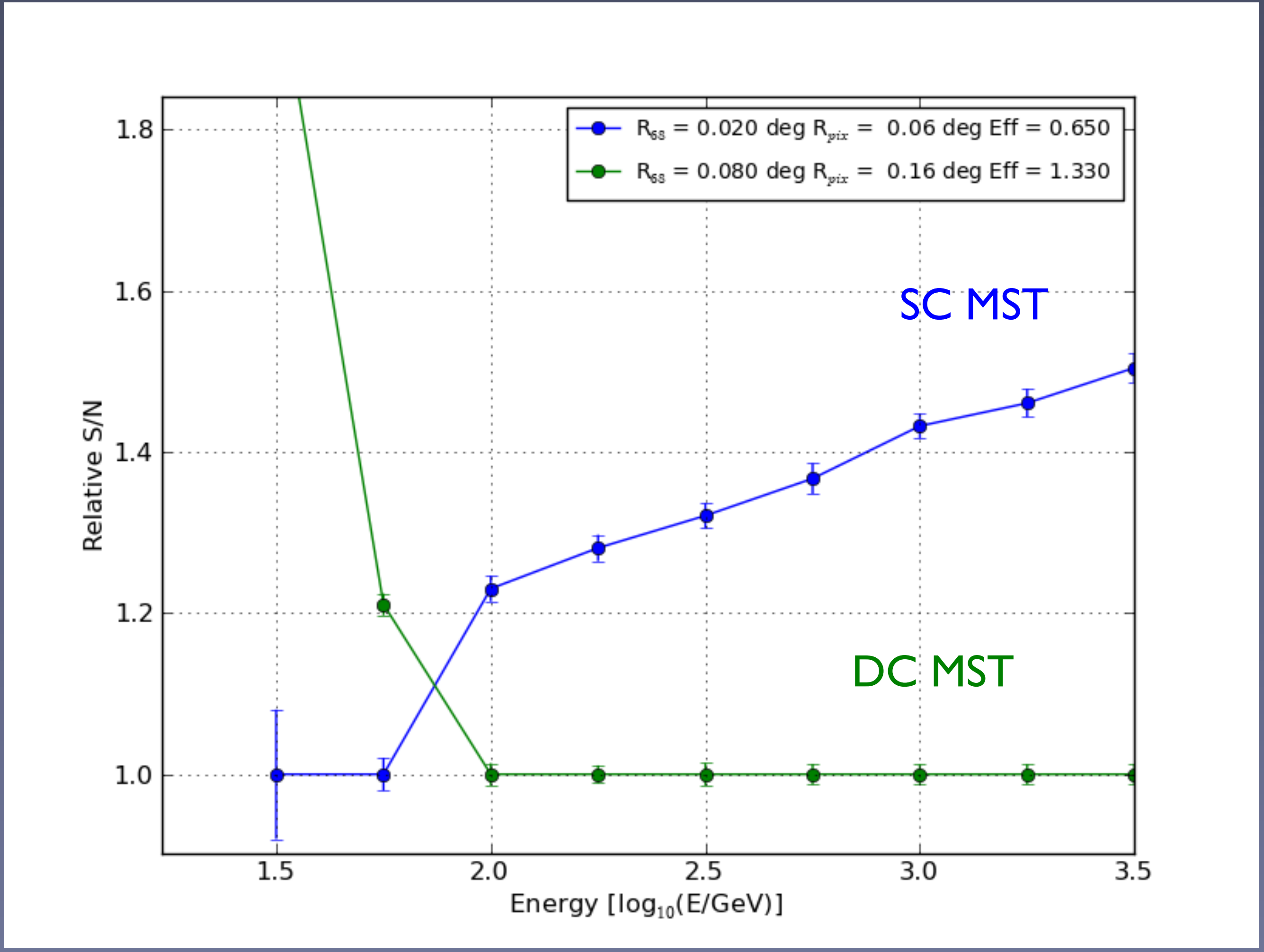
Light Collection Area: Angular Resolution



Light Collection Area: Sensitivity



Light Collection Area: Sensitivity



Geomagnetic Field

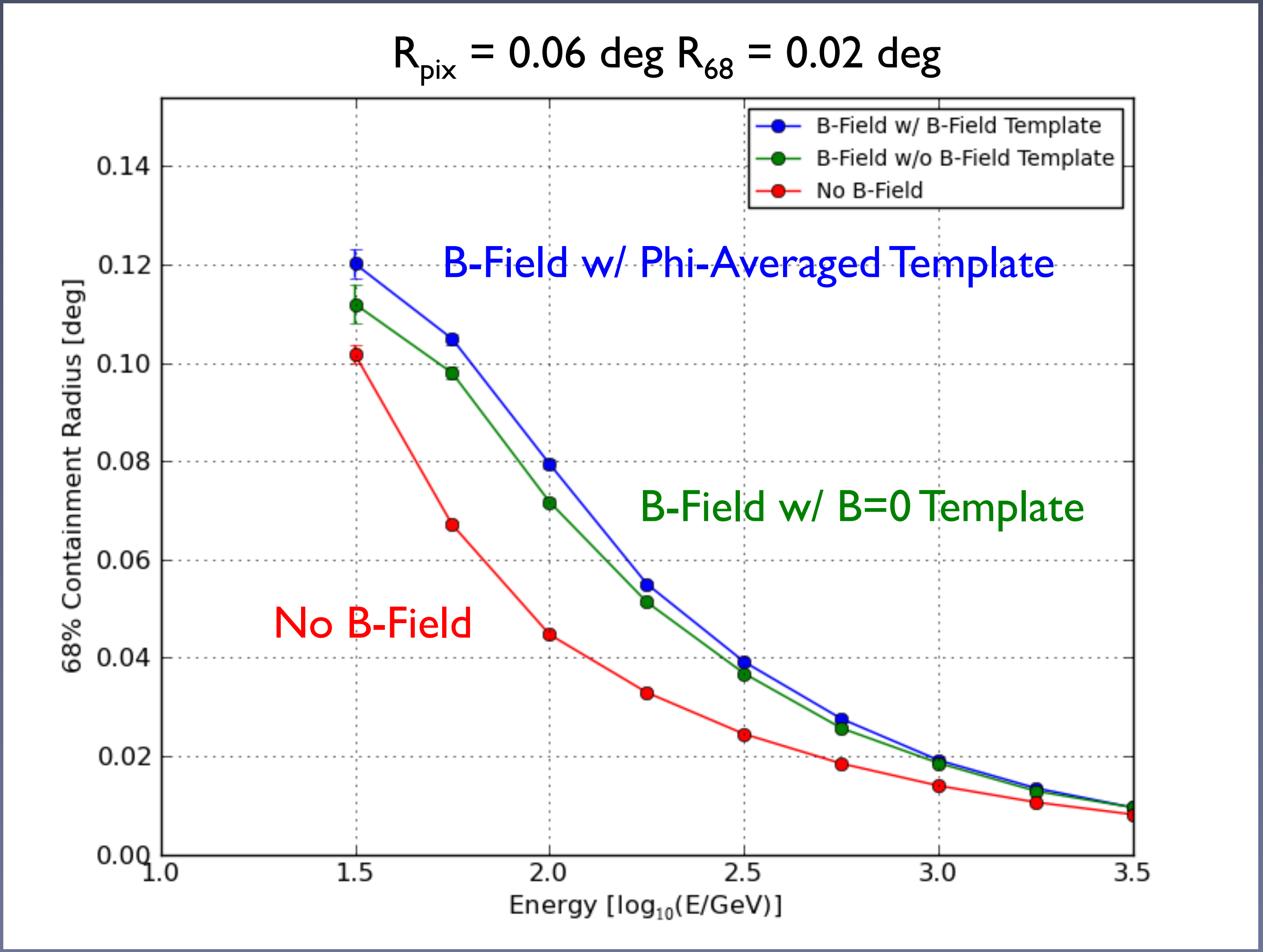
- All simulated performance shown thus far generated with B-Field switched off
- Influence of geomagnetic field is expected to degrade reconstruction performance for low energy showers
- Compare reconstruction performance for showers simulated with and without B-Field
  - Equatorial B-field configuration $|B| = 31.3\ \mu T$
  - Analyze with image templates generated with and without B-Field

Geomagnetic Field

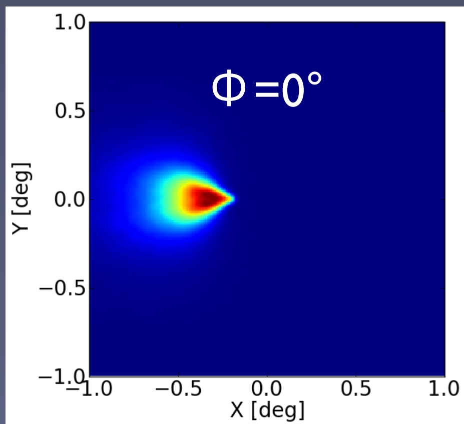
B-Field used for these studies:
$|B| = 31.3\ \mu T$ ($B_x = 27.5\ \mu T$, $B_z = -15.5\ \mu T$)

Site	Latitude	Longitude	Altitude [m]	Declination	Inclination	Horizontal Intensity [μ T]	Vertical Intensity [μ T]	Total Field [μ T]
ALMA	22°59'56"S	67°45'39"W	5000	- 4.7°	-20.22°	21.697	-7.991	23.121
H.E.S.S.	23°16'18"S	16°30'00"E	1800	-13.62°	-64.62°	12.190	-25.684	28.429
Salar de Pocitos (Argentina)	24°26'40"S	67°06'10"W	3650	-4.72°	-22.37°	21.266	-8.860	23.038
El Leoncito (Argentina)	31°44'11"S	69°16'39"W	2600	0.7°	-31.83°	20.179	-12.529	23.753
La Silla (Chile)	29°15'00"S	70°43'48"W	2400	0.7°	-28.57°	20.815	-11.336	23.702
Beaufort West (South Africa)	32°28'48"S	22°14'60"E	1750	-24.07°	-65.38°	11.023	-24.065	26.469
La Palma	28°45'42"N	17°53'26"W	2230	-6.55°	38.28°	30.388	23.987	38.714
VERITAS	31°41'18"N	110°53'00"W	1270	10.42°	58.27°	24.915	40.299	47.379
San Pedro Martir (Mexico)	31°02'00"N	115°25'00"W	2800	11.5°	56.07°	25.385	38.596	46.196
Sierra Negra (Mexico)	18°59'00"N	97°18'00"W	4000	4.75°	47.08°	27.768	29.868	40.782
Hanle (India)	32°45'36"N	78°57'36"E	4515	1.55°	50.47°	31.853	38.604	50.049
Oman A	23°6'00"N	57°31'5"E	2000	1.08°	35.37°	35.029	24.869	42.959

Geomagnetic Field: Angular Resolution

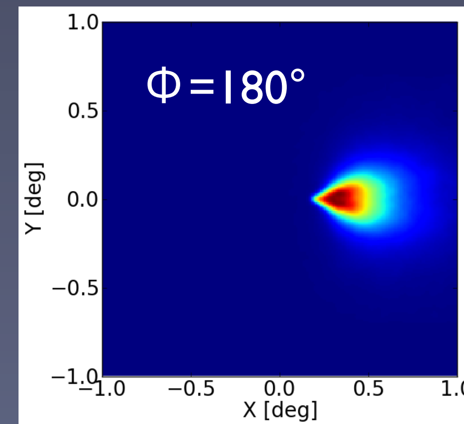


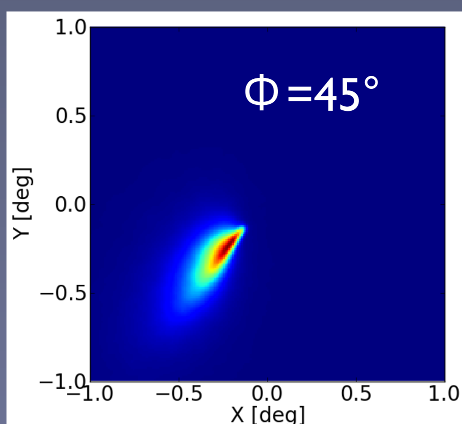
Geomagnetic Field

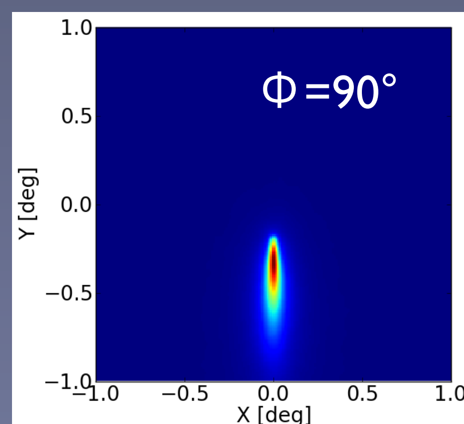


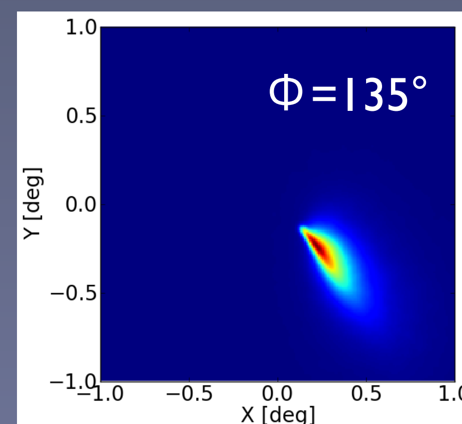
Φ:Viewing angle relative to magnetic field

E = 100 GeV
R = 80 m
λ =0.5



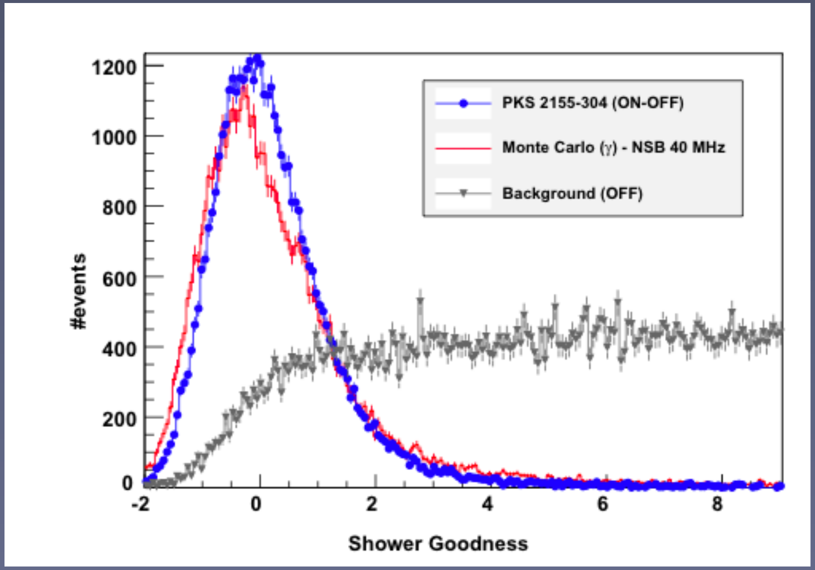






Background Rejection

- Likelihood model can also be used for background rejection by comparing log-likelihood with its expected value – "goodness of fit"
- Work currently underway to study background rejection as a function of pixel size, light collection, etc.



Naurois et al. 2009

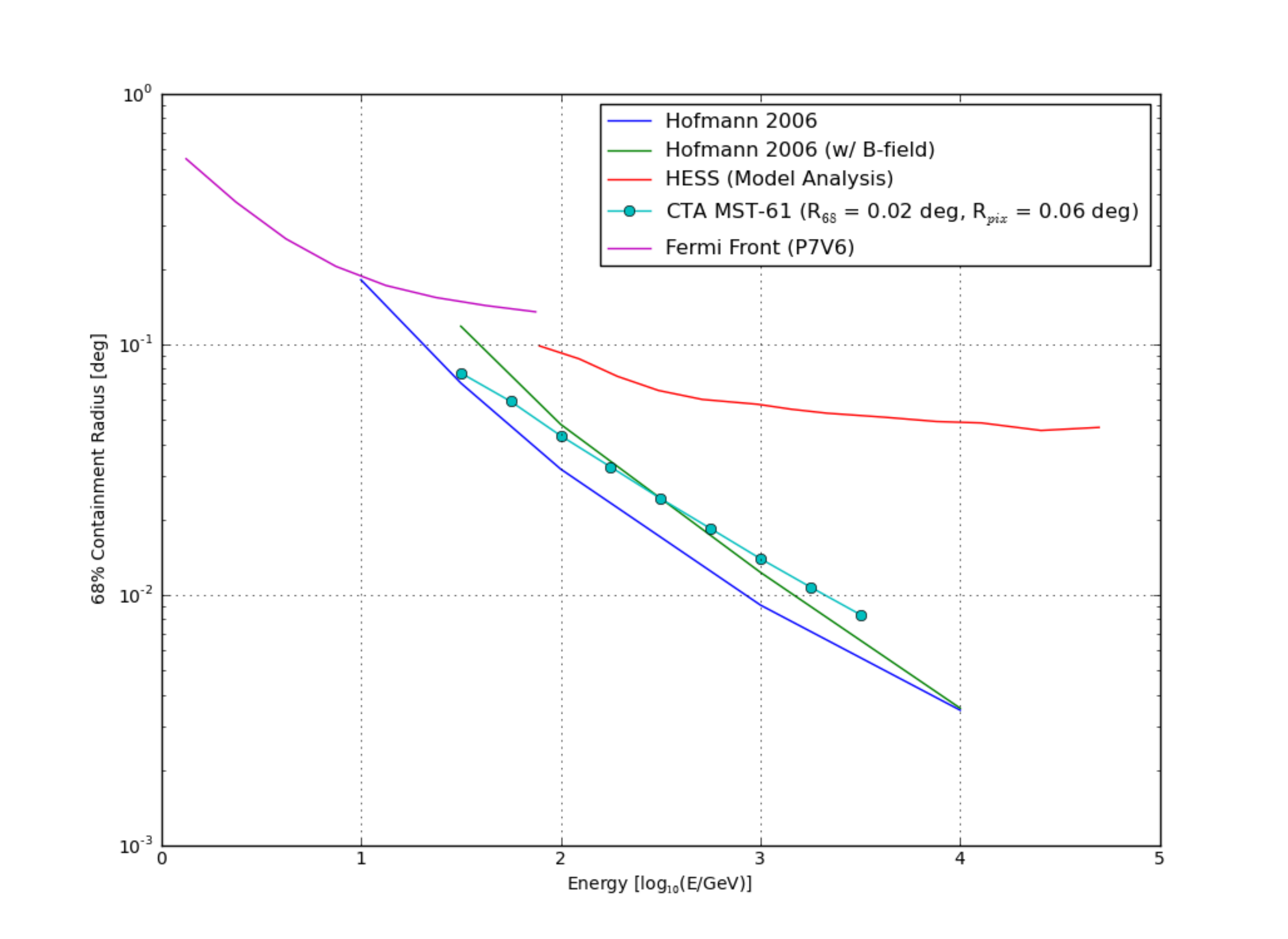
Conclusions

- Image Resolution
  - A small pixel size in conjunction with good optical PSF ($R_{68} \leq 0.02$ deg) can improve angular resolution/point-source sensitivity of a CTA-like array by as much as ~40-60%
  - An optical PSF of $R_{68} = 0.02$ deg (SC-MST PSF at ~3 deg) is sufficient to gain most of the improvement in angular resolution for $R_{pix} \sim 0.06$ deg
  - Improved image resolution reduces impact of NSB on reconstruction performance
  - Image resolution has minimal impact on energy resolution
- Light Collection Area
  - Imaging resolution is more important for angular resolution than light collection area at high energies (> 100 GeV) – SC-like configuration will have superior angular resolution to MST-like configuration regardless of light collection area of the respective telescopes
  - Light collection area becomes relevant below 100-200 GeV due to impact on trigger threshold
- Geomagnetic field
  - Strong influence on reconstruction performance below 1 TeV
  - Critical consideration for evaluating sites and studying array performance at low to intermediate energy

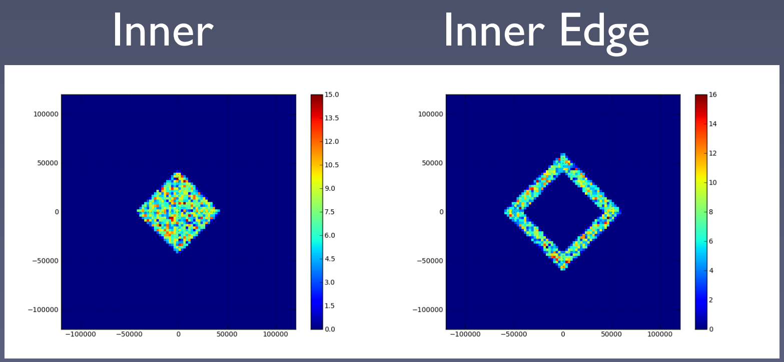
Future Work

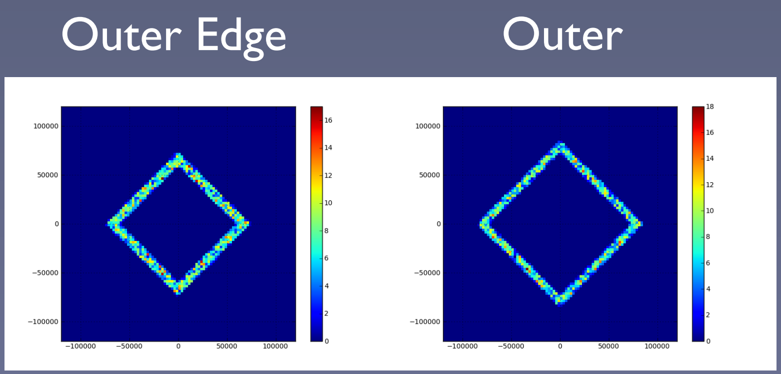
- Study performance of likelihood analysis using image templates with viewing angle dependence
- Develop simplified version of read_hess (slim_read_cta) incorporating likelihood reconstruction and density-based image cleaners
- Explore background rejection and generate differential sensitivity curves for the configurations under study using both idealized detector and sim_telarray (i.e. Hybrid sims) simulation frameworks

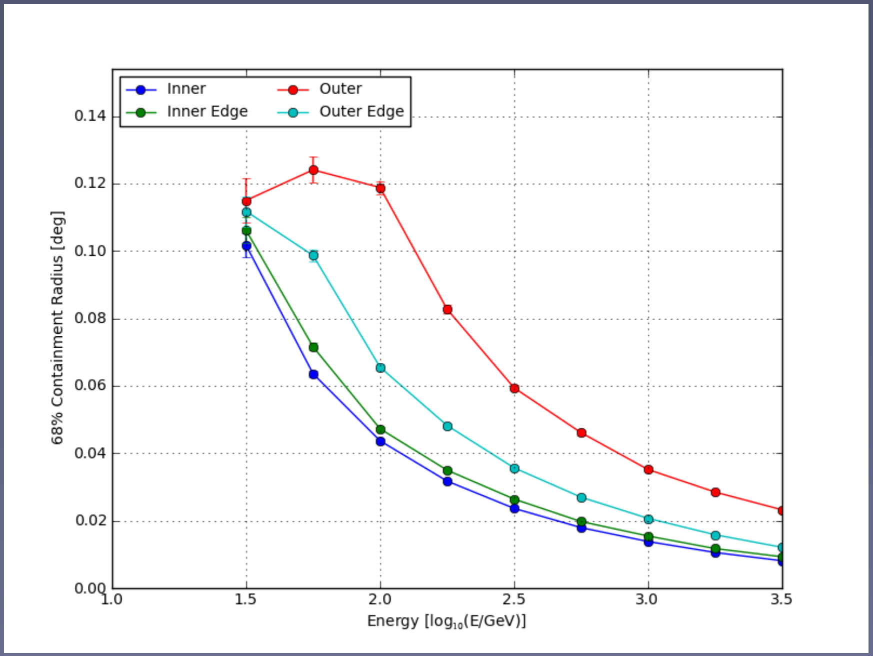
Conclusions/Next Steps



Event Containment







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