Towards precision VHE gamma-ray astronomy in the CTA-LST era

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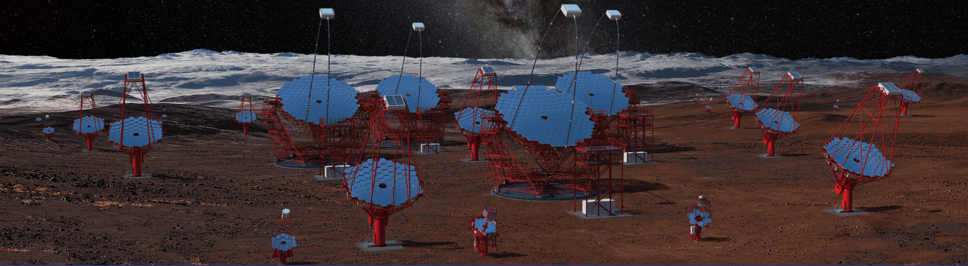
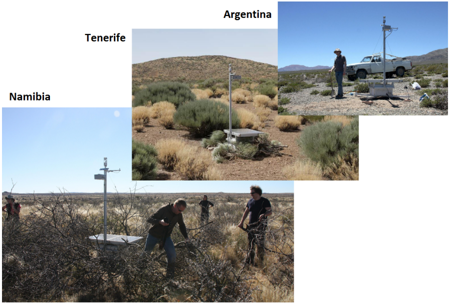
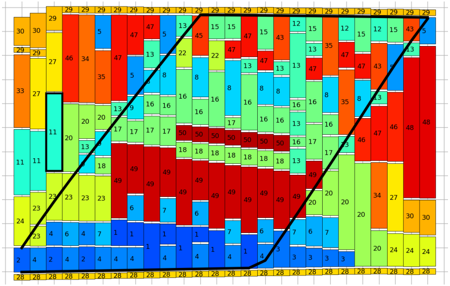
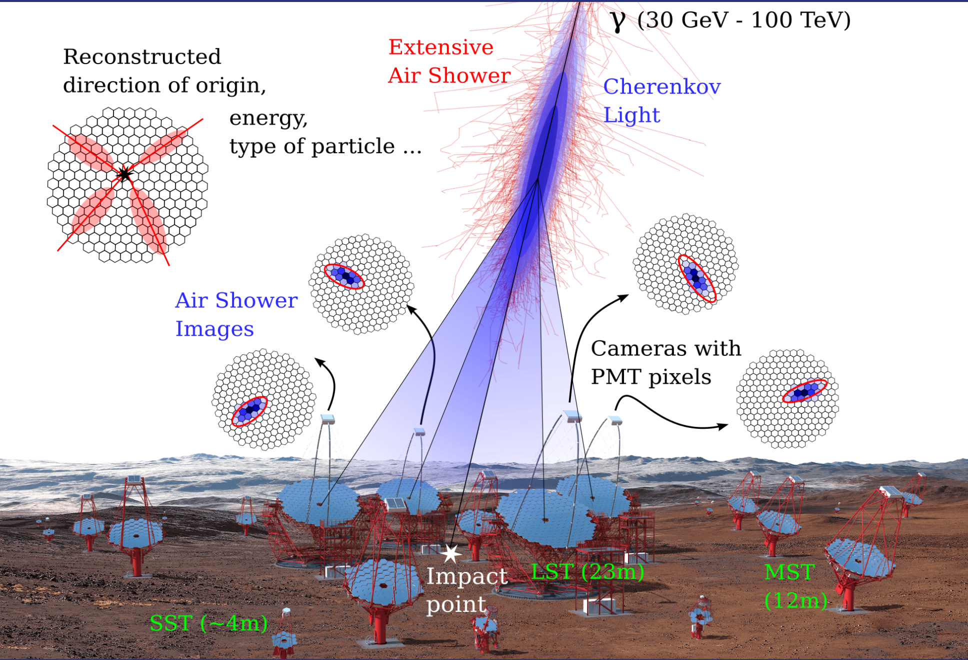


- ATMOSCOPE (CTA site evaluation, 9 candidate sites, 6 countries)
- ▸ MAGIC LIDAR system
- ▸ Atmospheric calibration method for MAGIC
- ▸ multi-year obs. campaign of Galactic Center
- ▸ Analysis software for extended sources
- Observation scheduler for MAGIC
- Convener of ATCA and Galactic WG

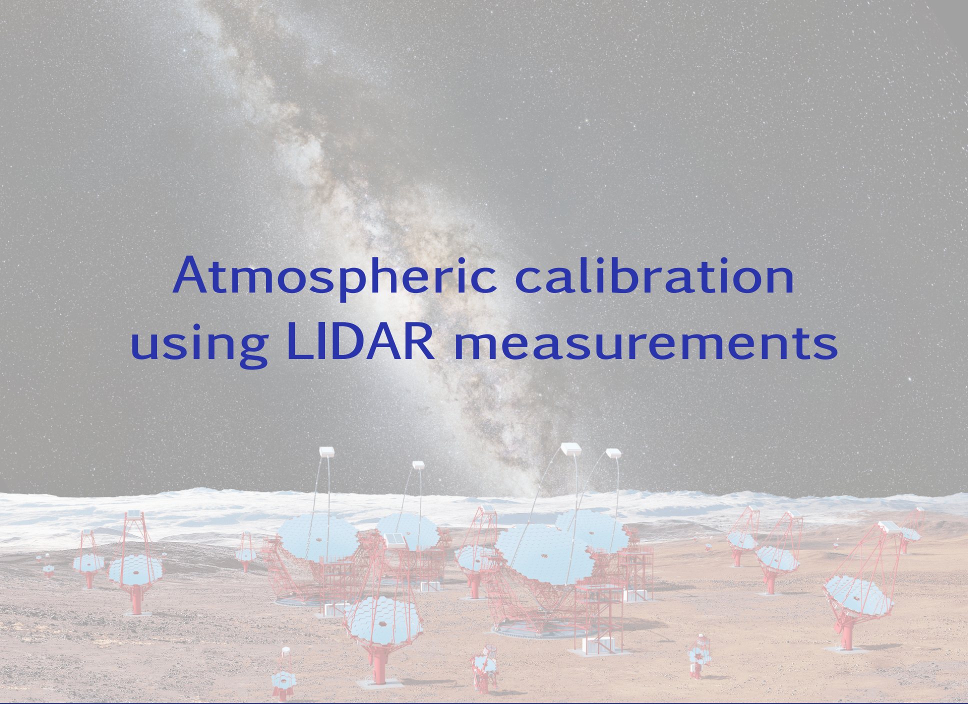


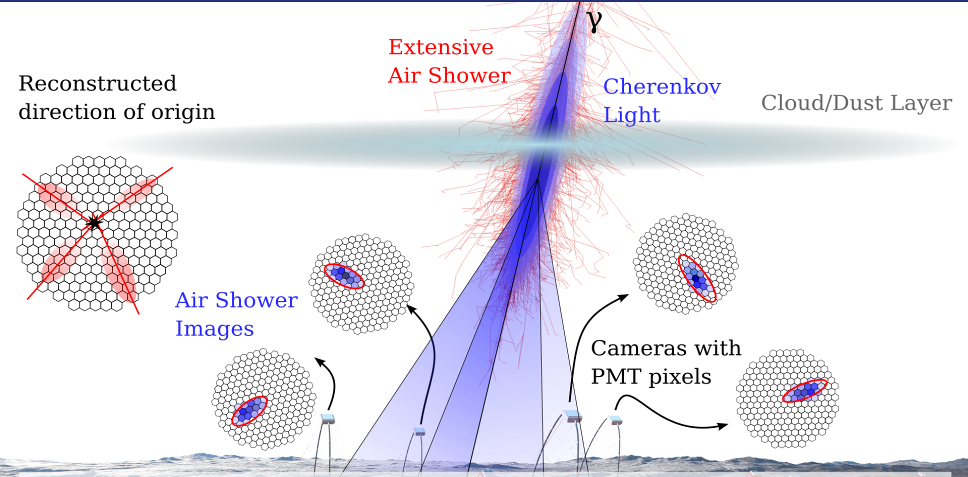


Imaging Air Cherenkov Telescopes and CTA in a nutshell



Atmospheric calibration using LIDAR measurements





Consequences for the reconstruction:

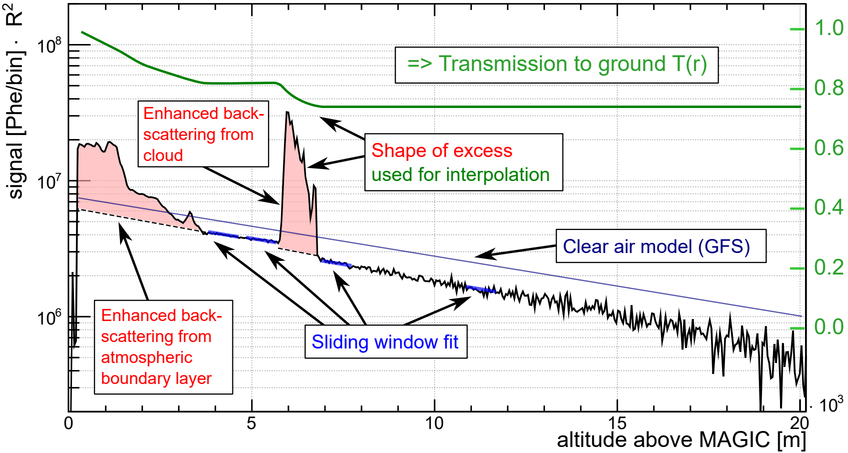
- 0^{th} order: energy threshold increased
- 1^{st} order: energy bias proportional to transmission for Cherenkov light and instrument response (trigger efficiency, A_{eff}) changed
- 2^{nd} order: shower reconstruction biased (classification, direction, ...)

The MAGIC LIDAR system (measuring transmission)

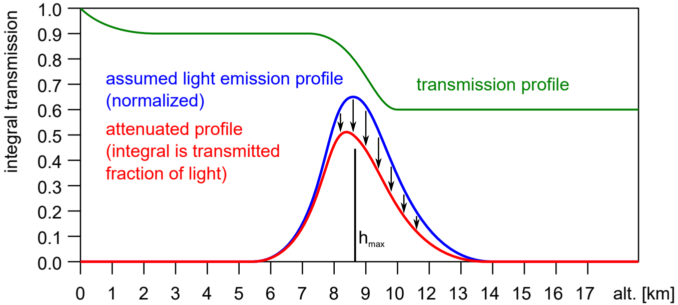
- LIght Detection And Ranging (LIDAR) system operating alongside with MAGIC
- Using 25 μJ pulse energy, 532 nm pulsed laser ('micro'-LIDAR)
- Hybrid Photo Detector (HPD) for single photon counting
- GAsP photocathode for high QE (> 50%)
- Automatically slave-tracking MAGIC coordinates on robotic mount

image credit: Robert Wagner, Matthias Bergmann

- Plot: solid angle corrected back-scattered **ph.e. counts** v.s. **altitude**
- Example: **real data** with **cloud** and **aerosol layer** (small zenith distance)
- Assumption: clear air regions with **dominant Rayleigh scattering** (532 nm)
- Method: **fitting/comparing** Rayleigh **model** to LIDAR data in sliding window
- Final result: integral **transmission** to ground



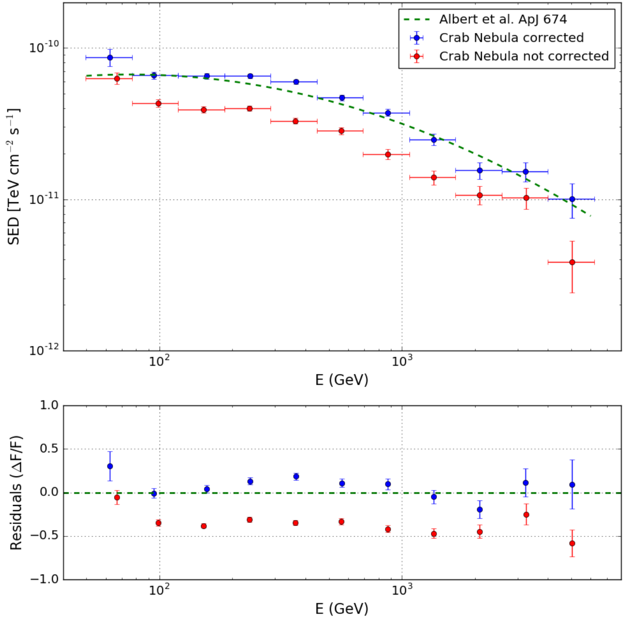
Event wise energy correction strategy:



$$\overline{\tau} = \int_0^{h_{max}} \epsilon(h) \cdot T_{aer}(h)\, \mathrm{d}h, \quad (1)$$

$$E_{true} = \frac{E_{obs.}}{\overline{\tau}} \quad (2)$$

1st order: instrument response is function of *observed* energy $A(E_{obs.})$

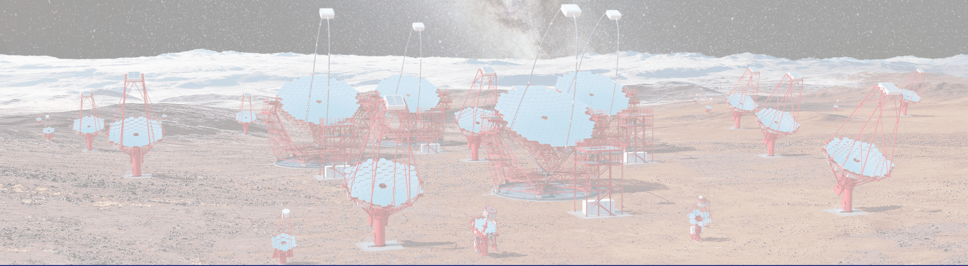


- Crab Nebula spectrum (standard candle, ApJ 674, not a fit!)
- Before correction: flux underestimated by $\sim 40\%$
- After correction: good match, considering the bad quality of the data

Conclusions and perspective for LIDAR/atmospheric corrections

- First successful atmospheric correction method for IACTs based on LIDAR
  - Presented at several conferences:
    arXiv:1403.3591, EPJ Web of Conferences 89, 02003 (2015)
  - Paper currently being finalized (together with Markus Gaug)
- First papers applying the method to scientific data:
  - Mrk501 MWL campaign (Furniss et al, ApJ, 812 (2015) 65)
    only 5h of 22h surviving standard cuts, 10 more h recovered using this method
  - V339 Del nova outburst (Ahnen et al. A&A, (2015), 582, A67)
    adjustment of upper limits
- Plans for future (CTA):
  - Implement for use with first (LST) science data
  - Adapt/improve (new instruments, Raman LIDAR, better calibration)
  - Explore more sophisticated methods (tailored Monte Carlo)

Studying the VHE emission from the Galactic Center



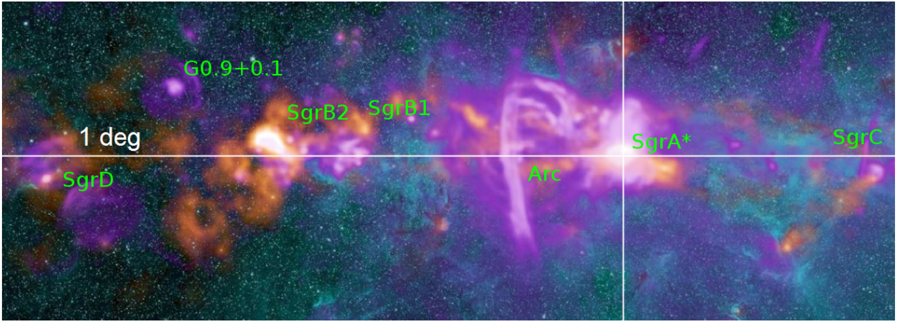


image source: http://images.nrao.edu

- GC hosts Super Massive Black Hole (SMBH) $(4 \cdot 10^6\,\mathrm{M}_\odot)$
- very dense and active astrophysical environment
- considered good place to search for DM annihilation/decay

G2 gas cloud falling onto the Galactic Center

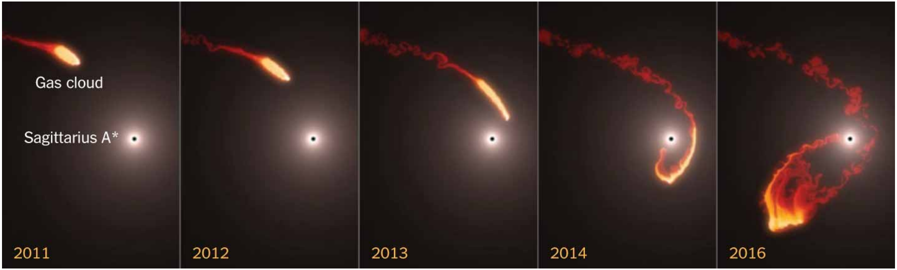


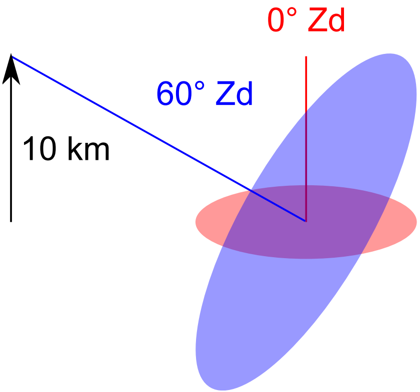
image source: ESO

- Gas cloud of $3\,m_{\odot}$ on its way towards SgrA* (S. Gillessen et al. 2012)
- Pericentre passage 2013-2014, at $\sim 2000\ r_g$ (S. Gillessen et al. 2013)
- Possible interaction with the SMBH

⇒ Monitoring campaigns triggered in nearly all wavelengths (radio to γ rays)

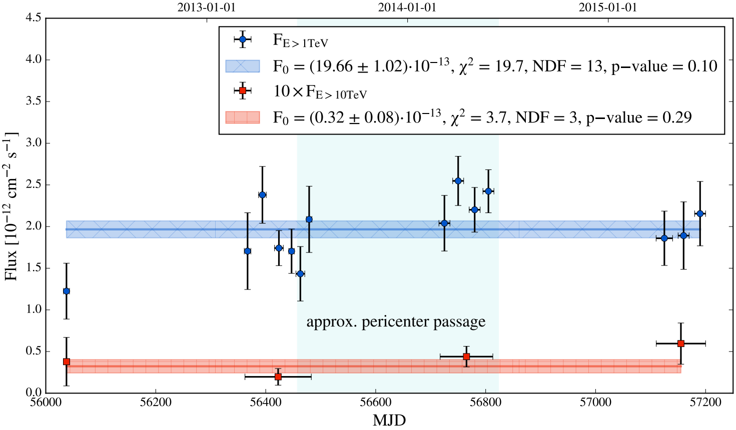
- Observations by MAGIC in 2012 - 2015 (and also 2016)
- Publishing paper in A&A (accepted for publication, arXiv:1611.07095)

- Culmination: ~58° Zd
- Observation between 58° and 70°
- Larger light pool size
- Cherenkov light diluted
- Enhanced absorption
- Energy threshold × 4 to 10
- Collection area × 4 to 10



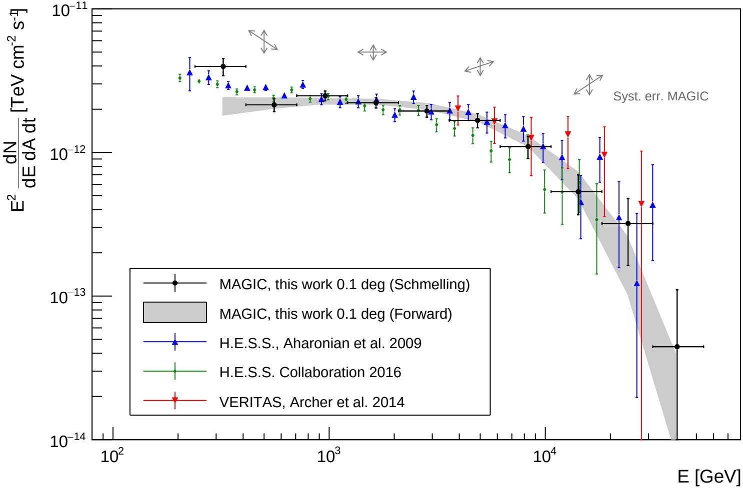
Light curve during G2 pericentre passage

- MAGIC light curve for the central point-like (SgrA*) source: $E > 1$ TeV, $E > 10$ TeV
- Integration radius 0.1° around SgrA*
- Only very good quality 2012/13/14/15 data (~67h)
- Flux compatible with constant in all energy bands
- Also no reports about unusual flux variability in other wavebands



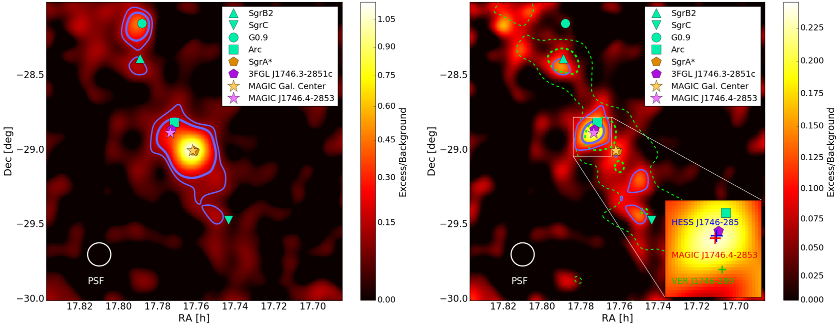
- MAGIC SED compared to other previous measurements
- Integration radius 0.1° around SgrA*, ~67h of very good quality 2012/13/14/15 data
- Power law with exponential cutoff fit (forward folding):

$$\frac{dF}{dE} = (7.26 \pm 0.89)\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}\left(\frac{E}{2\,\mathrm{TeV}}\right)^{(-1.85\pm0.13)} \exp - \frac{E}{(7.57\pm2.29)\,\mathrm{TeV}}$$



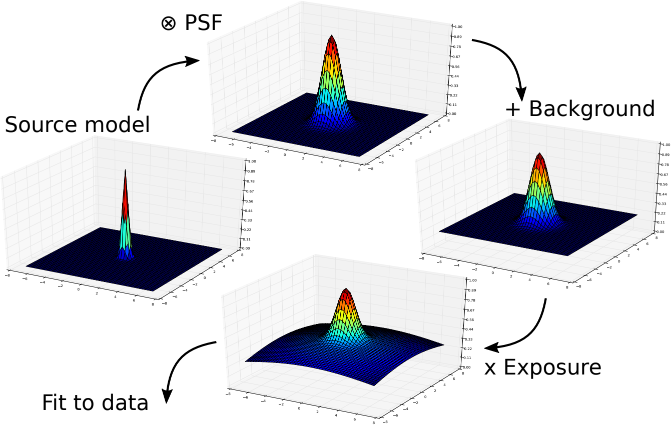
Sky Map of the GC region – fitting/subtracting known sources

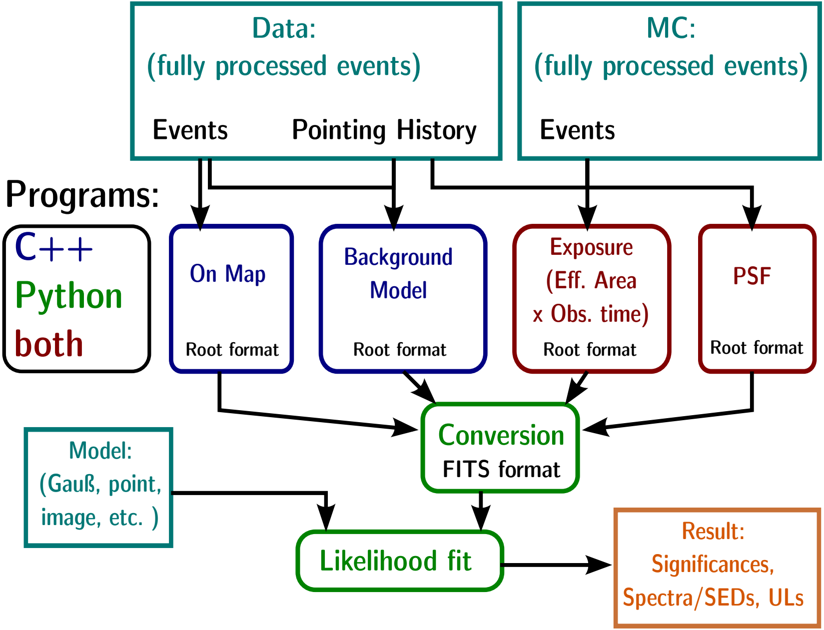
- Excess in units of background $(N_{on} - N_{off})/N_{off}$ with TS significance contours
- Point-like emission from the locations of SgrA* and G0.9+0.1 (left: fitted/subtracted)
- Diffuse emission from along the Gal. plane (ridge seen by H.E.S.S.)
- New source MAGIC J1746.4-2853 at location of radio Arc
- Possible coincidence with 3FGL J1746.3-2851c, HESS J1746-285 and VER J1746-289
- Possible counterparts/scenarios:
  - Bremsstrahlung from cosmic electrons in MCs? (Yusef-Zadeh et al., 2013)
  - CRs (past activity of SgrA* or Supernovae) interacting with MC (Oka et al. 2001)?
  - PWN candidate at location of the source (Lemiere et al. 2015)
- Complex morphology, difficult to analyze with available software (opt. for point srcs.)!



New software tools for extended sources

- Energy spectra from arbitrary morphology and sky pos.
- Spatially overlapping components ⇒ simultaneous fit required!
- Developing software tools with Ievgen Vovk and Marcel Strzys
- Energy bin-wise Poissonian likelihood fit
- Similar to Fermi analysis

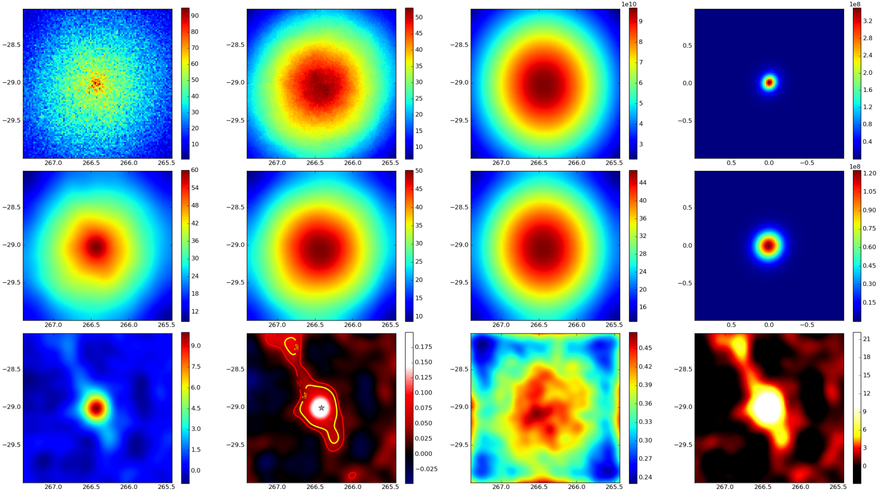



Data:
(fully processed events)
Events
Pointing History
MC:
(fully processed events)
Events
Programs:
C++
Python
both
On Map
Root format
Background Model
Root format
Exposure (Eff. Area x Obs. time)
Root format
PSF
Root format
Conversion
FITS format
Model:
(Gauß, point, image, etc.)
Likelihood fit
Result:
Significances, Spectra/SEDs, ULs

The ingredients for the fit

On-events | Background model | γ-Exposure (MC) | PSF (MC)

$500\,\text{GeV} < E < 1\,250\,\text{GeV}$

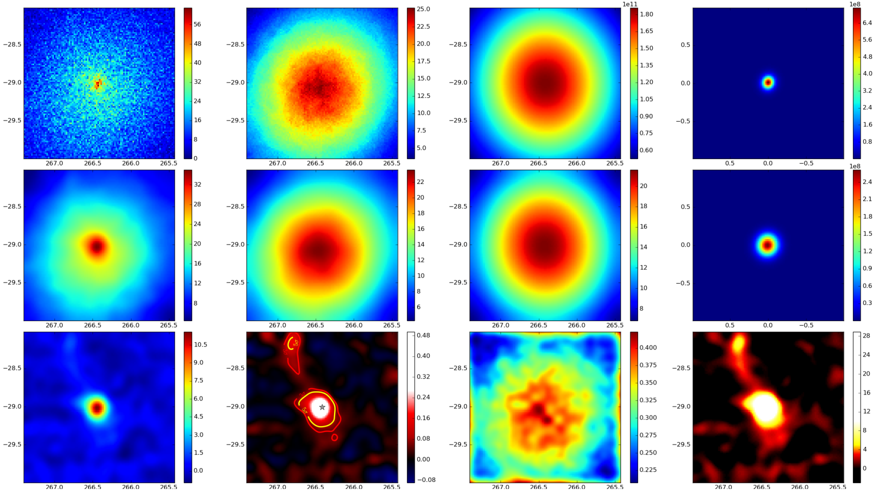


Excess-events | Rel. Flux and sign. cont. | Test statistic std. | TS value map

The ingredients for the fit

On-events | Background model | γ-Exposure (MC) | PSF (MC)

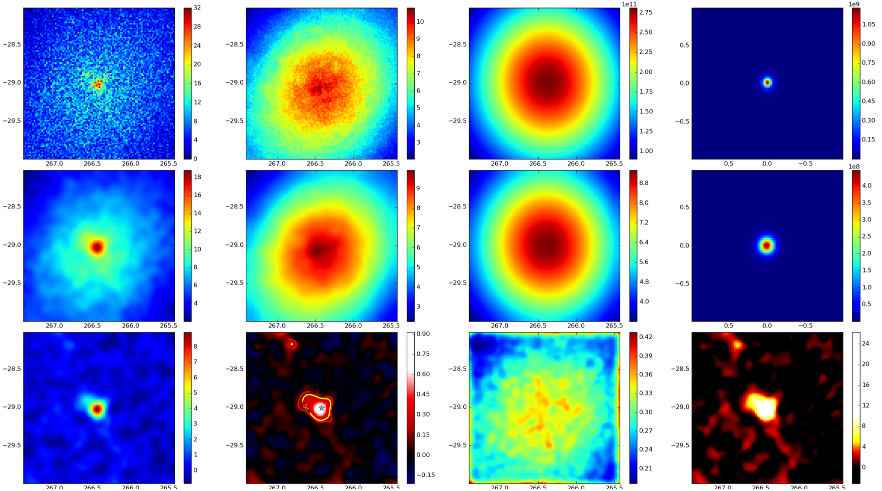
$$1\,250\,\mathrm{GeV} < E < 3\,150\,\mathrm{GeV}$$



Excess-events | Rel. Flux and sign. cont. | Test statistic std. | TS value map

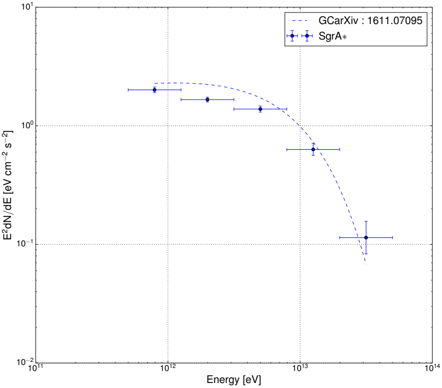
On-events | Background model | γ-Exposure (MC) | PSF (MC)

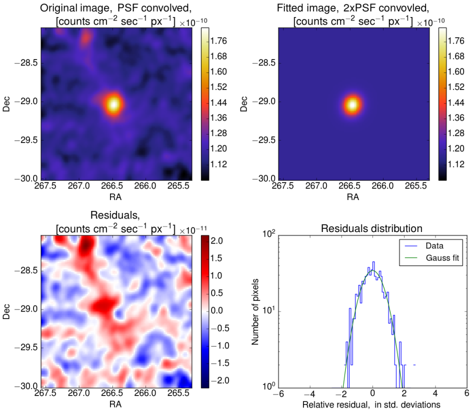
$$3150\,\mathrm{GeV} < E < 7900\,\mathrm{GeV}$$



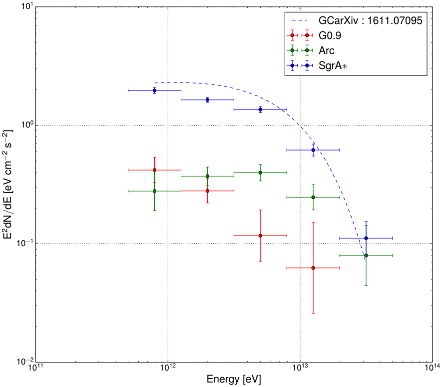
Excess-events | Rel. Flux and sign. cont. | Test statistic std. | TS value map

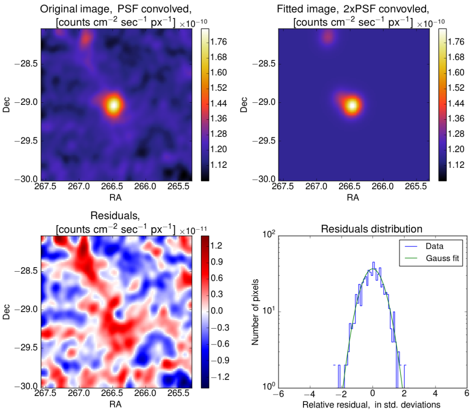
- Fitting single point source at position of SgrA*
  (left: SED, right: observation/model/residuals for 2^{nd} E bin)
- All results are still preliminary!



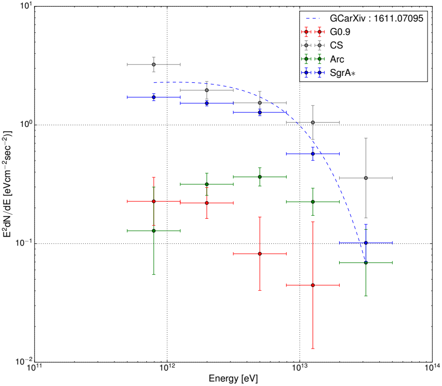


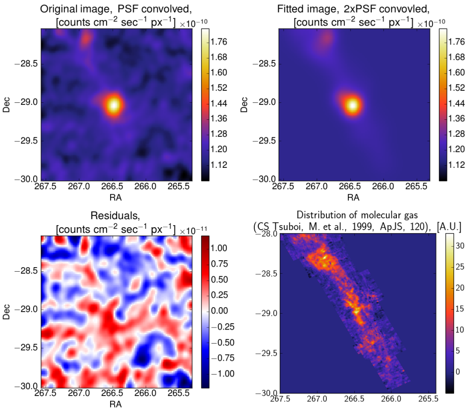
- Including point sources at position of radio Arc and G0.9
- All results are still preliminary!





- Including also CS dist. (tracer for dense molecular material → CR target)
- All results are still preliminary!





Summary and Outlook

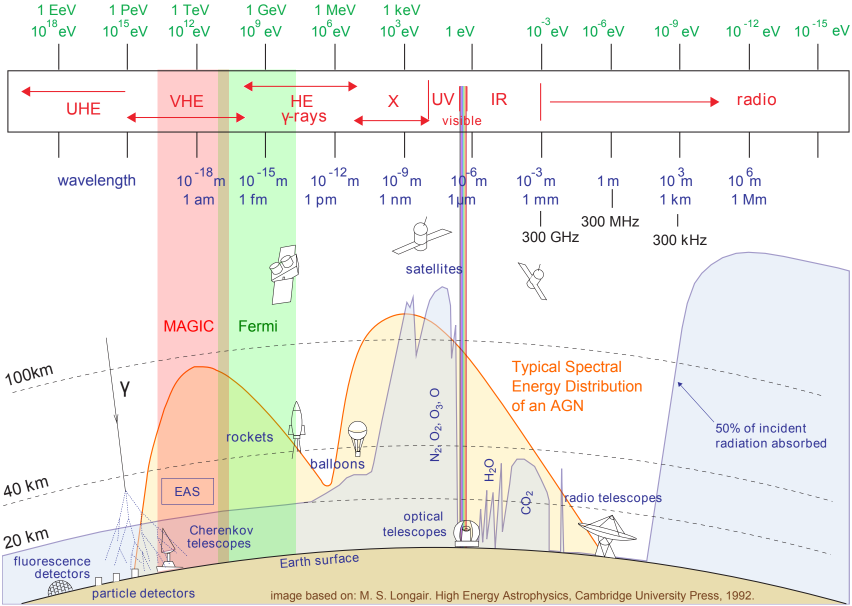
- Developed new LIDAR based technique for calibrating IACT data
  - Method performs well and reduces systematic errors
  - Can be implemented for CTA-LSTs, especially for first science data
  - Plans for CTA: implementation, improvements, new instruments, new techniques
- Observing GC with MAGIC during G2 fly-by (since 2012)
  - Paper accepted by A&A (arXiv:1611.07095)
  - Detailed study of spectrum and light curve (no variability)
  - New emission region close to radio Arc of unknown nature
  - Complex morphology needs new analysis tools
  - Plans for CTA: GC is important target, LSTs can continue HZD study from LP
- Developing new analysis software with Ievgen Vovk and Marcel Strzys
  - Likelihood fit of spatial model to sky maps in spectral bins
  - First results look promising, final release within few months
  - Second publication on GC diffuse emission in the pipeline
  - Plans for CTA: mandatory for Gal. science, already collaborating with DL3 WG
- Other activities for MAGIC and CTA:
  - ATMOSCOPEs for site selection (Fruck et al., J. Inst. 10, P04012 (2015))
  - Scheduler for MAGIC observations (in team of 3)
  - Convener of the Gal. physics WG (4) and ATCA WG (2)
- Plan for MAGIC: investigate possibility of making operation (semi)-robotic

Thanks for your attention!

Backup

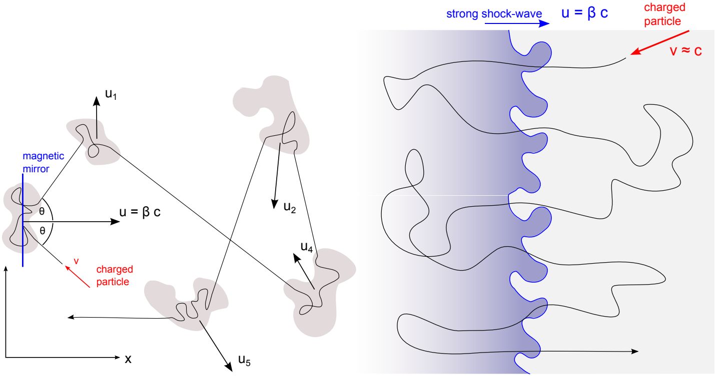
General Background

IACTs in context of other Instruments

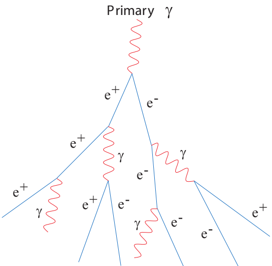


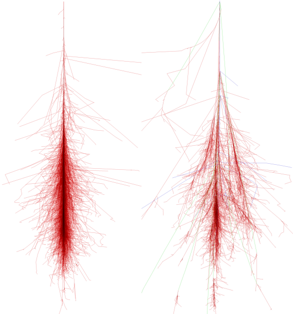
Short excursion: How are VHE γ-rays produced?

- γ-rays in the TeV regime are exclusively of non-thermal origin.
- They are always produced as a by-product of the acceleration of charged particles to VHE
- The favored acceleration scenarios are: Diffusive shock acceleration and acceleration in rotating magnetic fields (Pulsars, BH plerions)
- Leptonic γ prod.: Bremsstrahlung, Curvature radiation, Inverse Compton scattering (IC) – mostly on synchrotron radiation produced by the same population (SSC)
- Hadronic γ prod.: decay of π^0 form pp interaction



EM (left) and hadronic (right) shower and Atmospheric MC simulations (center)





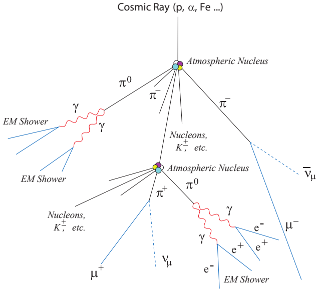
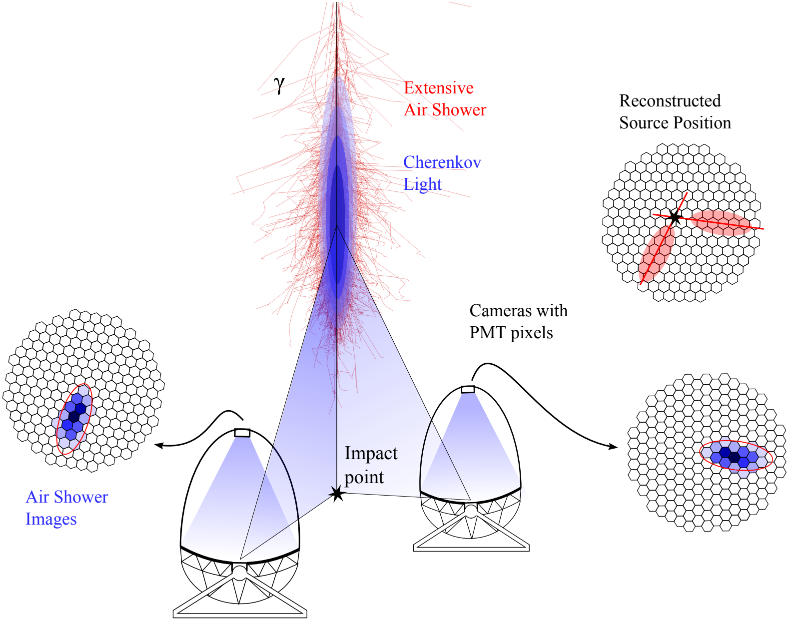


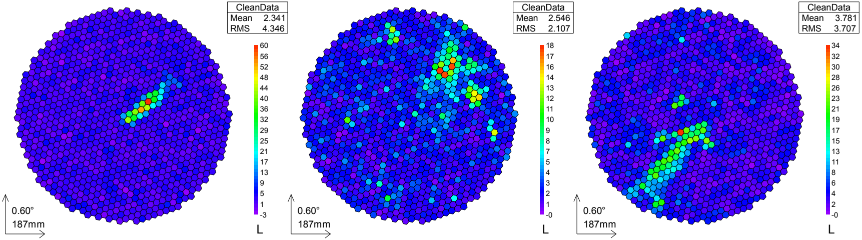
image credit: Robert Wagner / CORSIKA

Detection technique – Imaging Air Cherenkov Telescopes



Images recorded by the cameras of the MAGIC telescopes

- The two cameras consist of 1039 photomultiplier pixels each (3.5° FoV)
- Events last only a few ns
- Different coincidence criteria (charge concentration in small region of camera in one and simultaneous such events in both telescopes) required for the events to be recorded
- Typical CR event rate 300 Hz
- Event classification offline via Random Forests

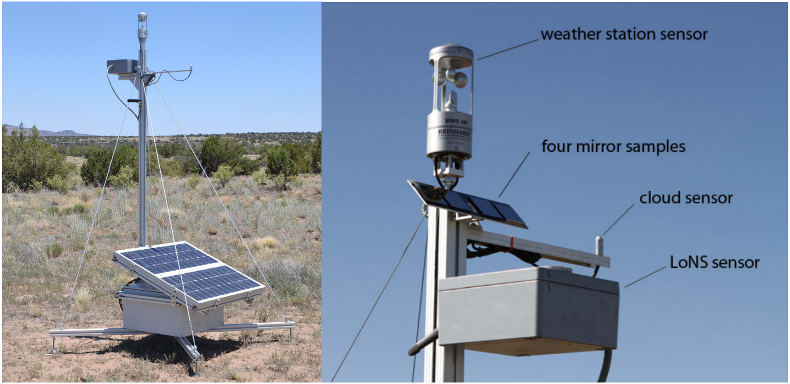


The MAGIC telescopes

- Imaging Air-shower Cherenkov Telescopes for observing γ-rays from 80 GeV to 30 TeV
- located on the Roque de los Muchachos (at 2200 m a.s.l.) on the Canary island La Palma
- two 17m diameter parabolic dish, $f/D = 1$, telescopes
- photomultiplier (PMT) cameras with 1039 pixels recording at 2GS/s
- support structure from carbon fiber

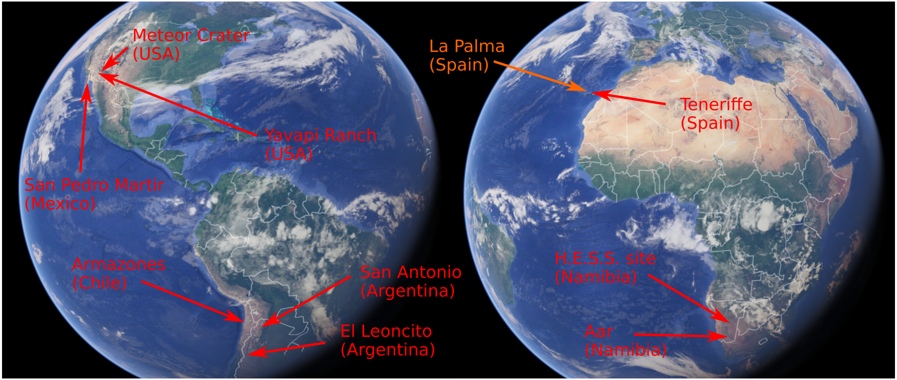
image credit: Robert Wagner

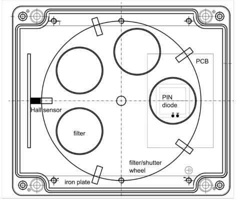
ATMOSCOPE

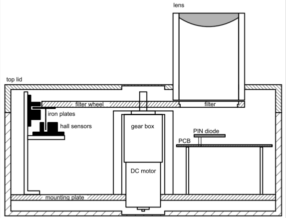


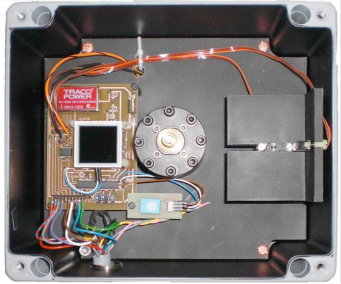
- Autonomous Tool for Measuring Observatory Site COnditions PrEcisely
- deployed at several CTA site candidates and taking data since ∼ 2 years
- paper published in JINST (Instrumentation for comparing night sky quality and atmospheric conditions of CTA site candidates, Fruck et al. 2015)

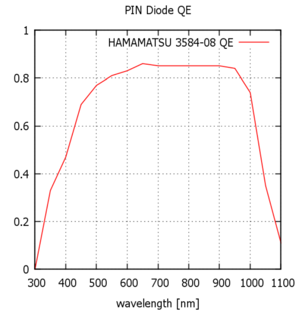
- Total of 9 ATMOSCOPES deployed in 6 countries
- One LONS-only in La Palma

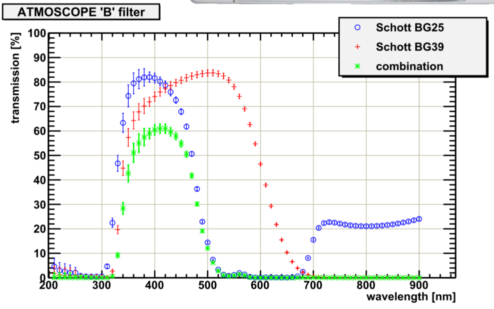



PCB
PIN
diode
Hall sensor
filter
filter/shutter
wheel
iron plate


lens
top lid
filter wheel
filter
iron plates
hall sensors
gear box
PIN diode
PCB
DC motor
mounting plate

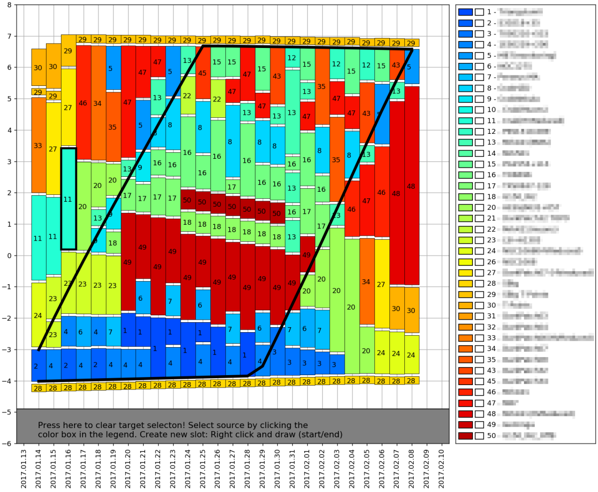

TRACO
POWER

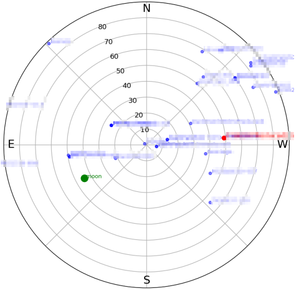

PIN Diode QE
HAMAMATSU 3584-08 QE
0
0.2
0.4
0.6
0.8
1
300
400
500
600
700
800
900
1000
1100
wavelength [nm]


ATMOSCOPE 'B' filter
Schott BG25
Schott BG39
combination
transmission [%]
0
10
20
30
40
50
60
70
80
90
100
200
300
400
500
600
700
800
900
wavelength [nm]

Scheduling

Scheduling GUI program





---> Mouse position: Zd = 14.7, Az = 276.9

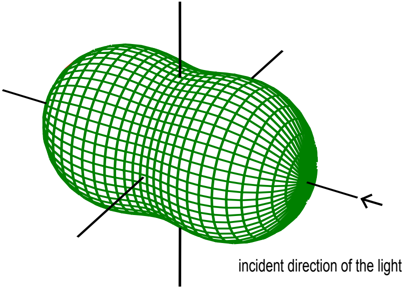
(19.1) .... : 0.839 - 1.837 (1.00 h dark)

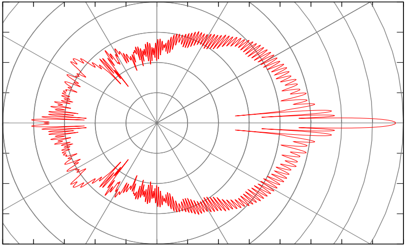
---> Mouse position: Zd = 31.0, Az = 265.2

(16.1) .... : 0.190 - 3.423 (3.23 h moon)

---> Mouse position: Zd = 48.9, Az = 275.1

LIDAR



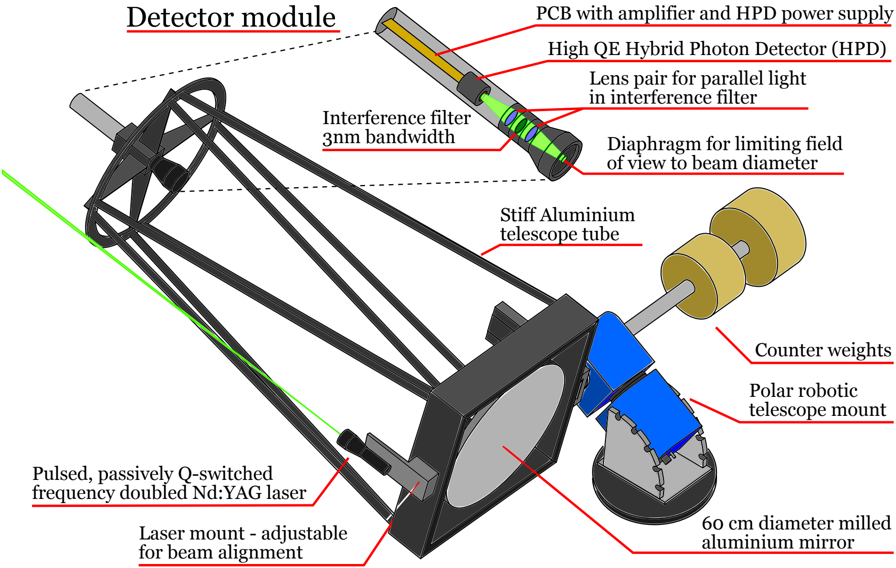


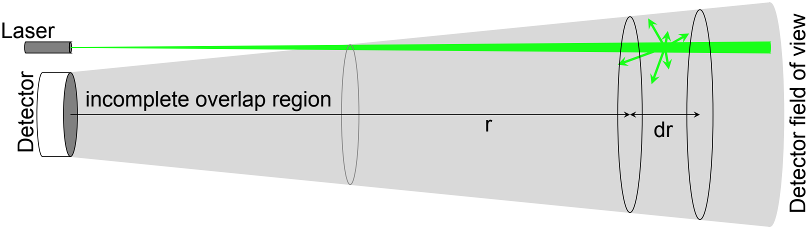
Rayleigh scattering

- always present
- scattering on molecular dipoles
- λ^{-4} dependency

Mie/aerosol scattering

- only important in boundary layer and inside clouds
- scattering on water droplets or aerosol/ice particles
- (comparably) weak wavelength dependency
- enhanced cross-section for forward scattering
- plot: example for a dielectric water sphere of $d = 10\lambda$

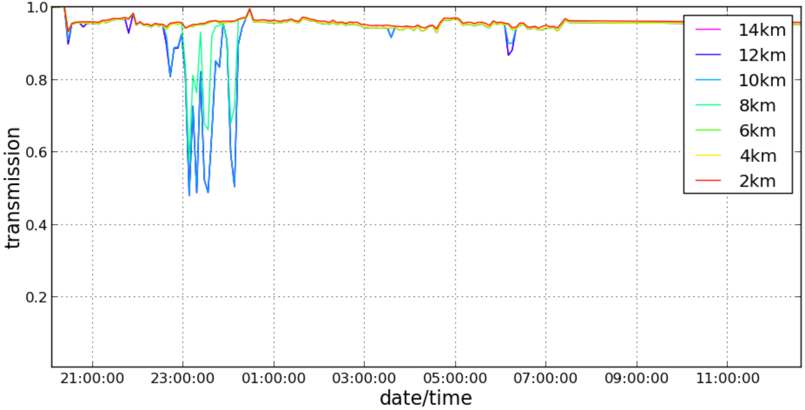

Detector module
PCB with amplifier and HPD power supply
High QE Hybrid Photon Detector (HPD)
Lens pair for parallel light in interference filter
Interference filter 3nm bandwidth
Diaphragm for limiting field of view to beam diameter
Stiff Aluminium telescope tube
Counter weights
Polar robotic telescope mount
Pulsed, passively Q-switched frequency doubled Nd:YAG laser
Laser mount - adjustable for beam alignment
60 cm diameter milled aluminium mirror



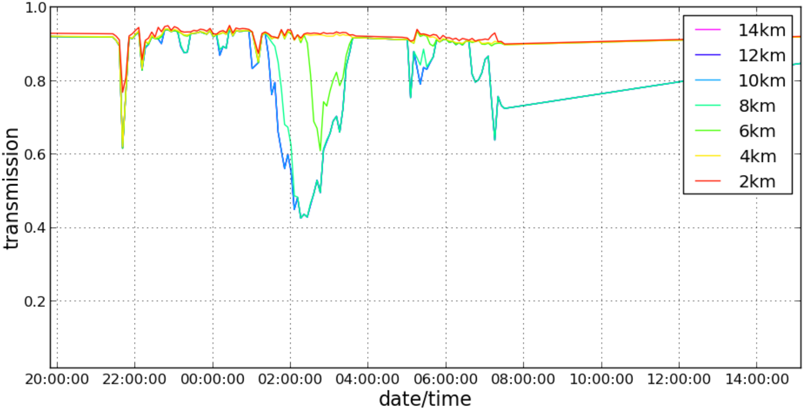
$$\mathrm{d}N(r) = N_0\ C\ G(r)\ \frac{A}{r^2}\ \beta(r)\mathrm{d}r\ \exp\left(-2\int_0^r \sigma(r')\mathrm{d}r'\right)$$

- N_0,$\mathrm{d}N(r)$: photons: in laser pulse, in range bin
- C,$G(r)$: overall efficiency, overlap (laser-FOV) and focus effects
- $\frac{A}{r^2}$: solid angle (detector seen from location of scattering)
- $\beta(r)\mathrm{d}r$: volume backscattering coefficient times range bin length
- $\exp\left(-2\int_0^r \sigma(r')\mathrm{d}r'\right)$ total attenuation on the way
- two unknown functions: $\beta(r)$ and $\sigma(r)$
- $\frac{1}{r^2}$ dependency demands for high dynamic range

Examples:
Few high altitude clouds

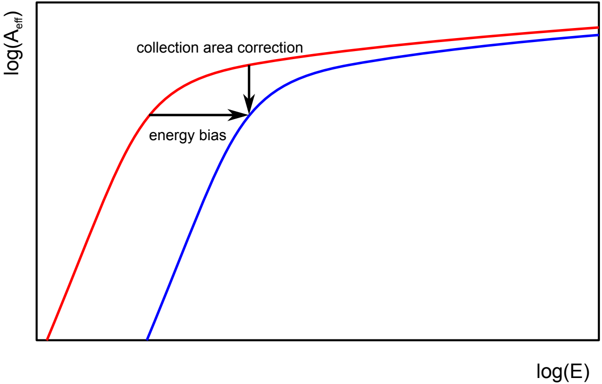


Examples:
Mid altitude clouds



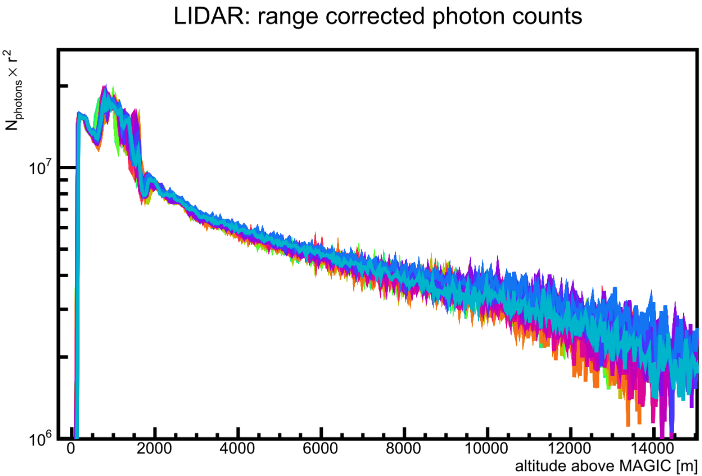
Examples:
Thick low and mid altitude clouds

Collection area correction strategy:



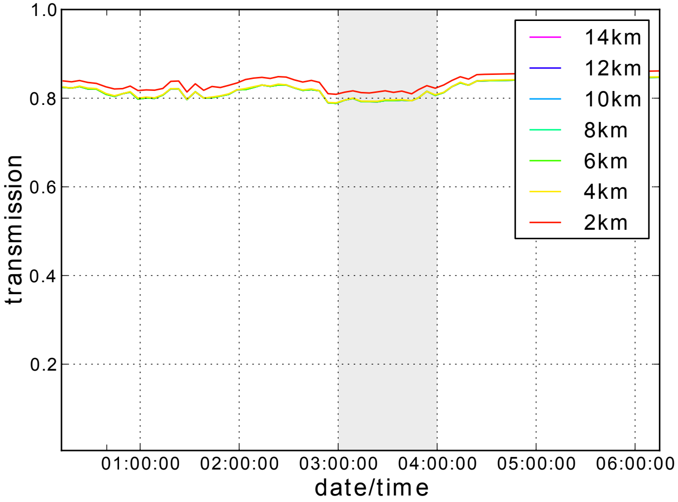
- only correcting the energy is not sufficient: A_{eff} (from MC) is still wrong
- $A_{eff} = A_{sim} \cdot N_{rec}/N_{sim}$ is estimated using MC assuming optimal conditions
- events affected by atmospheric extinction "mimic an events of lower energy"
- energy correction + binning → migration matrix
- recalculating A_{eff} by applying matrix to vector of inverse A_{eff} from MC

Some corr. examples:

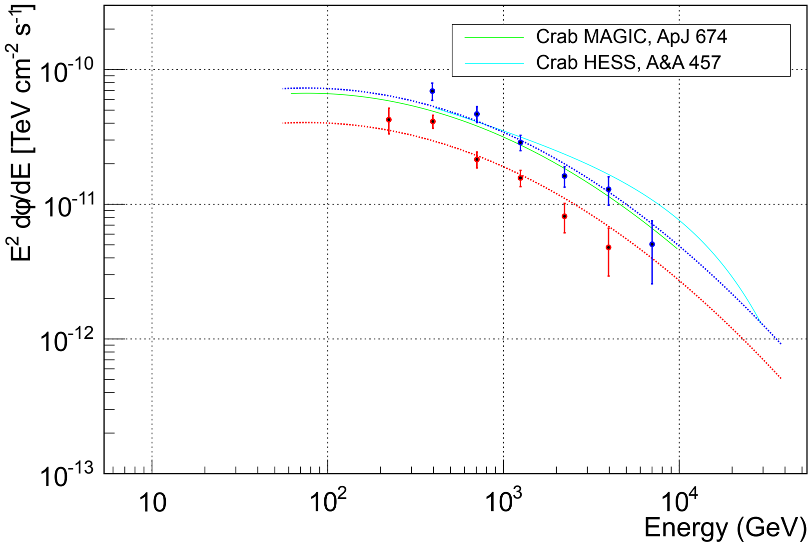


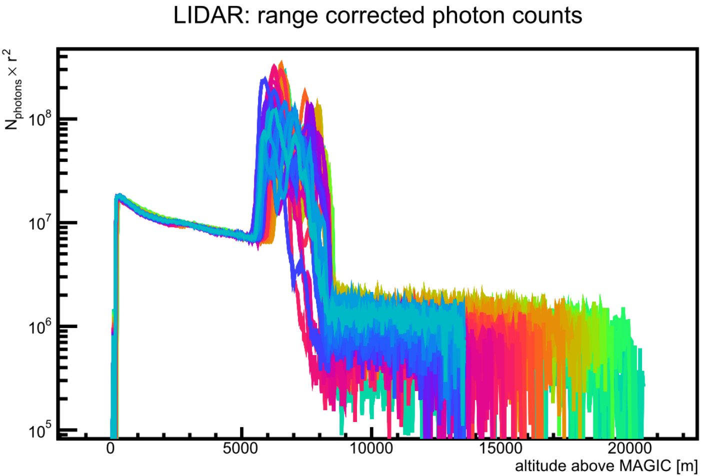
- last days with “Calima” (Sahara dust intrusion) in beginning of September 2013
- should be easy to correct since shower is not “deformed” by aerosol layer

Correcting Crab Nebula data

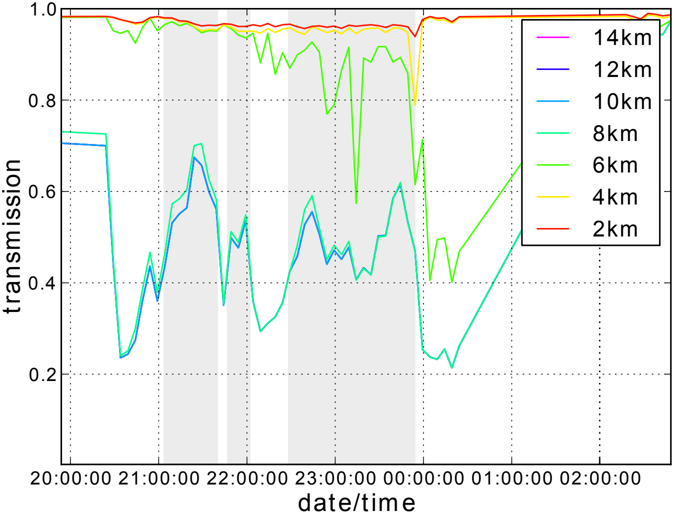


- transmission is at constantly $\sim 80\%$
- about 20% upscaling of the energy will be needed ...


Crab MAGIC, ApJ 674
Crab HESS, A&A 457
E2 dφ/dE [TeV cm-2 s-1]
10-10
10-11
10-12
10-13
10
102
103
104
Energy (GeV)

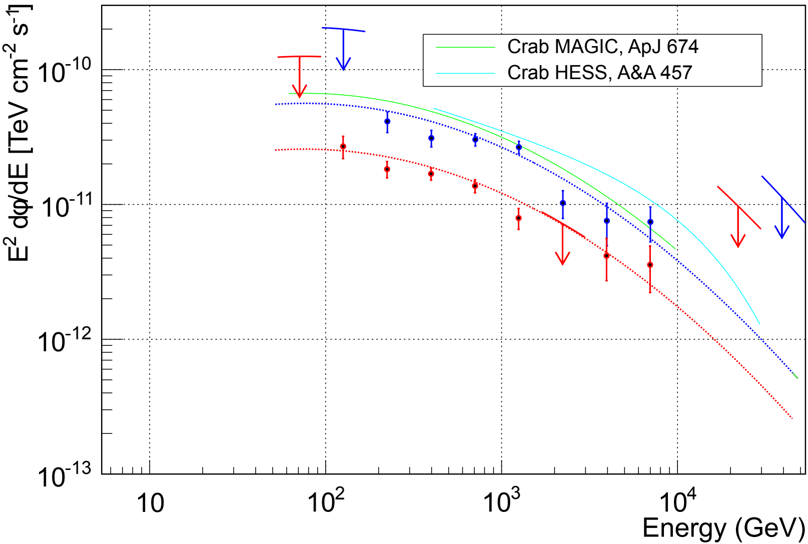


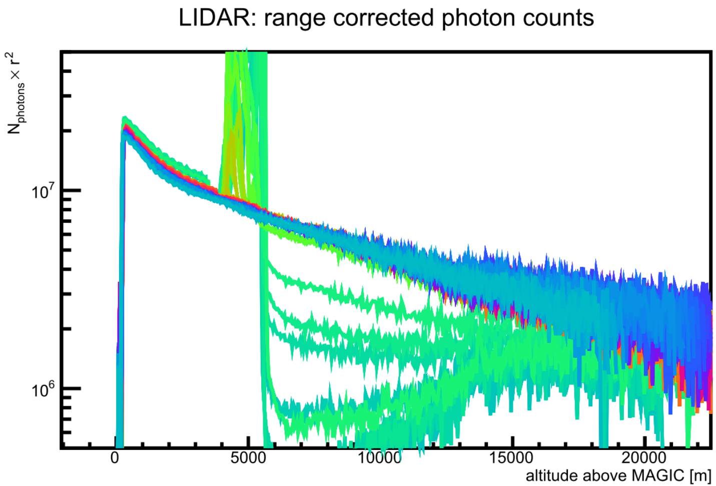
- this is a “horrible” example of cloudy sky conditions that can occur on La Palma from time to time
- it is hard to believe that IACTs can work properly under such conditions



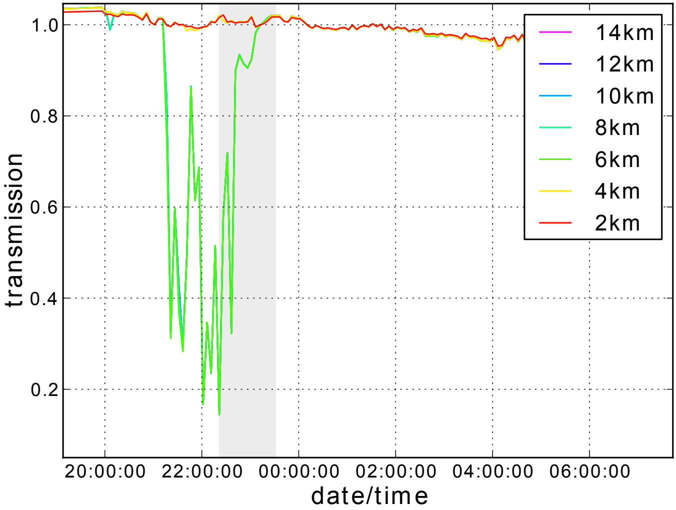
- actually part of the data (>50%) had to be removed because the transmission was below 40% for the given sample
- here air-showers get "truncated" and therefore the "hadronnes"

Correcting Crab Nebula data

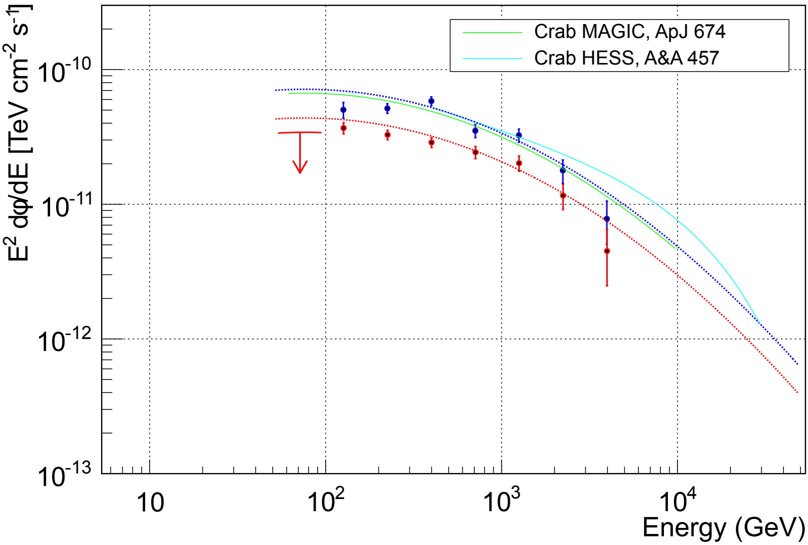




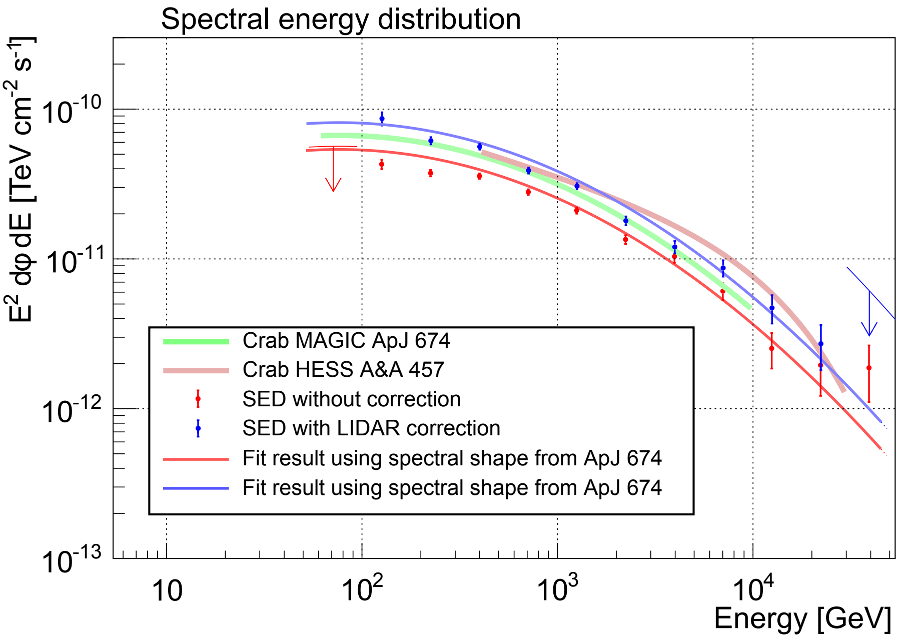
- another quite cloudy example from Dec 24th 2013
- this time medium level clouds of quite high opacity



- another quite cloudy example from Dec 24th 2013
- this time medium level clouds of quite high opacity

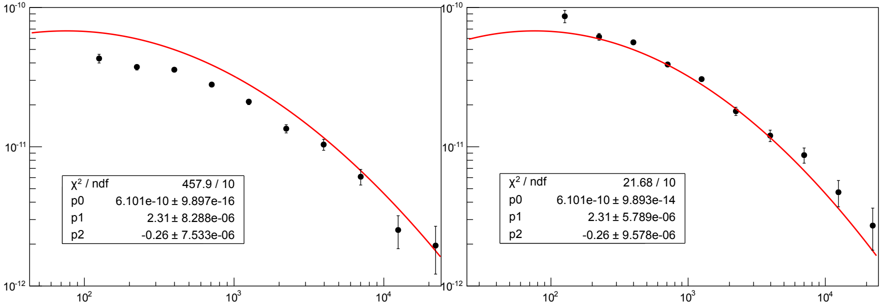

Crab MAGIC, ApJ 674
Crab HESS, A&A 457
$E^2\, d\phi/dE$ [TeV cm^{-2} s^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10
10^2
10^3
10^4
Energy (GeV)

Larger data sample:



Spectral energy distribution
E2 dφ dE [TeV cm-2 s-1]
10-10
10-11
10-12
10-13
10
10^2
10^3
10^4
Energy [GeV]
Crab MAGIC ApJ 674
Crab HESS A&A 457
SED without correction
SED with LIDAR correction
Fit result using spectral shape from ApJ 674
Fit result using spectral shape from ApJ 674

Correcting Crab Nebula data



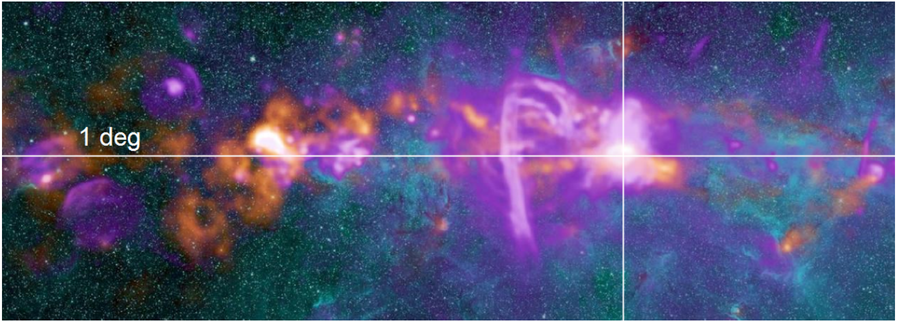
- Degree of improvement becomes clear only when comparing the χ^2 values in respect to the spectrum published in ApJ 674
- Before correction: 458 with 7 degrees of freedom
- After correction: 22 with 7 degrees of freedom

Galactic Center

Milky Way galaxy:

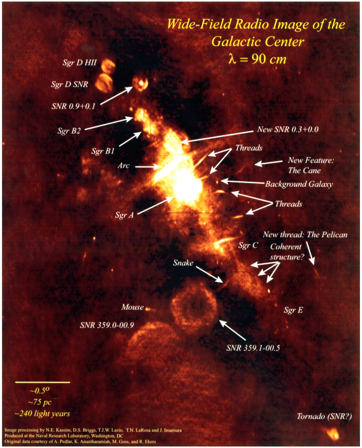
- disk (30 kpc x 0.3 kpc): young stars, gas, molecular clouds, dust
- bar (4.5 kpc) and bulge (1.5 kpc): old stars low star formation
- Galactic Center (250 pc): dense molecular clouds high star formation rate

image source: ESO/S. Brunier



- VLA (20cm): H II regions that are illuminated by hot, massive stars, supernova remnants, and synchrotron emission
- Caltech Submillimeter Observatory (1.1mm): cold (20-30 K) dust associated with molecular gas
- Spitzer (IR): primarily emission from stars and from polycyclic aromatic hydrocarbons

image source: http://images.nrao.edu



- bright point-like radio source
- at the center of SgrA-West (Mini-Spiral)
- at the edge of SNR SgrA-East
- thought to be SMBH
- from stelar motions: $\approx 4 \cdot 10^6\ M_\odot$

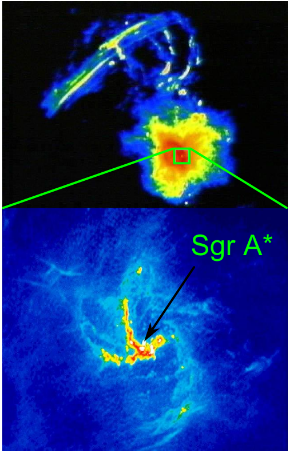
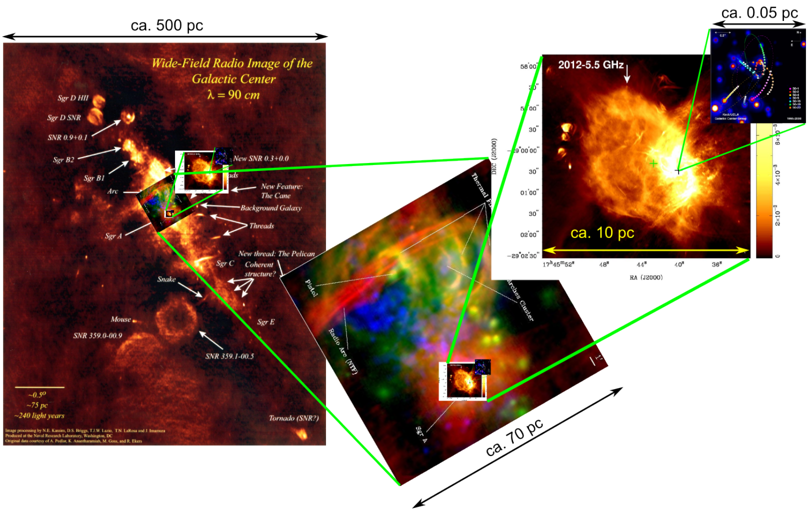
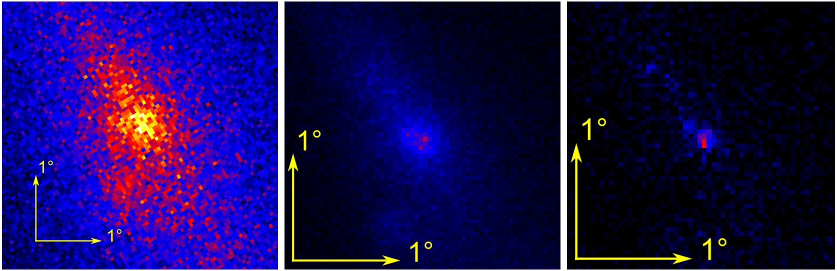


image source (left): N. E. Kassim, D. S. Briggs, T. J. W. Lazio, T. N. LaRosa, J. Imamura (NRL/RSD)
image source (right): astro.ucla.edu

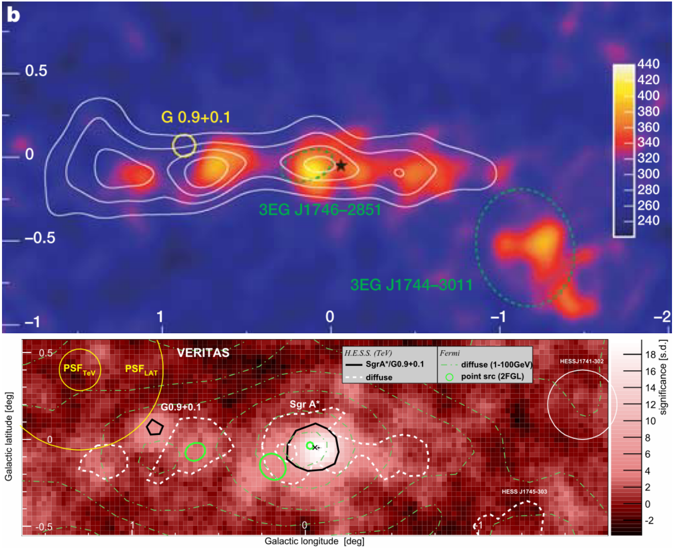


- few 10 OB stars confined inside the central arc-sec around SgrA*
- star S2 periastron: 120 AU, period: 15.6 y

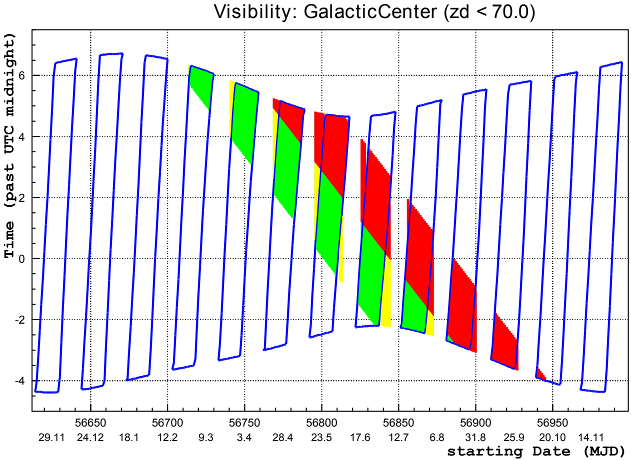
refer to for example: Ghez, A. M., et al. The Astrophysical Journal 509.2 (1998): 678.



- resolution only reasonable for $E > 1\,\mathrm{GeV}$
- hint for G0.9+01, Arc?


b
G 0.9+0.1
3EG J1746–2851
3EG J1744–3011
0.5
0
–0.5
–1
1
0
–1
–2
440
420
400
380
360
340
320
300
280
260
240
VERITAS
PSF$_{TeV}$
PSF$_{LAT}$
H.E.S.S. (TeV)
SgrA*/G0.9+0.1
diffuse
Fermi
diffuse (1-100GeV)
point src (2FGL)
HESSJ1741-302
HESS J1745-303
G0.9+0.1
Sgr A*
Galactic latitude [deg]
Galactic longitude [deg]
significance [s.d.]
18
16
14
12
10
8
6
4
2
0
-2

- Total observability throughout the year (only about 1/3 of the year available for monitoring)

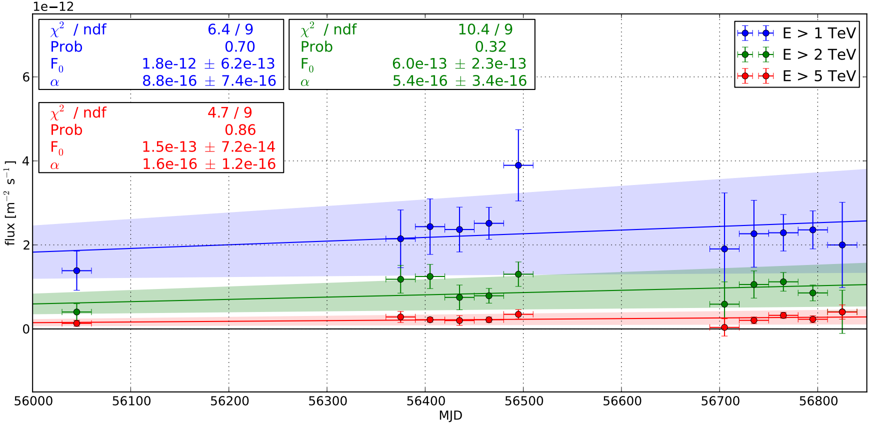


- Due to limited trigger delay between both telescopes, part of the observable window is lost

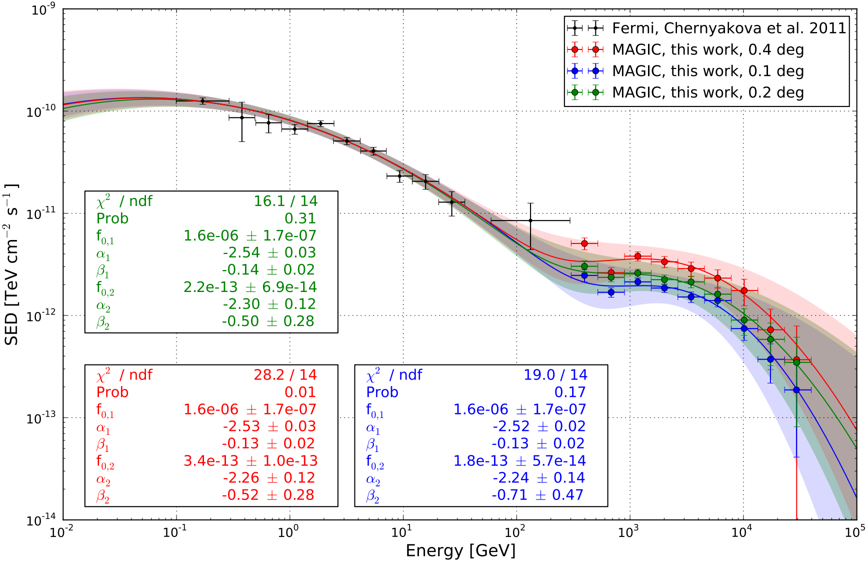
- Collection area increases with $1/cos(Zd)^2$
  $A_{col,60^{\circ}Zd}/A_{col,0^{\circ}Zd} \approx 4$
  $A_{col,70^{\circ}Zd}/A_{col,0^{\circ}Zd} \approx 9$
- Influence of the Atmosphere is increasing $\rightarrow$ need good weather conditions
- Need dark conditions for reasonable energy threshold
- Stereo power is decreasing?
- Focusing?
- MAGIC standard analysis is not optimized for HZD? However, the analysis seems to work quite well!

Lightcurve fitted with:

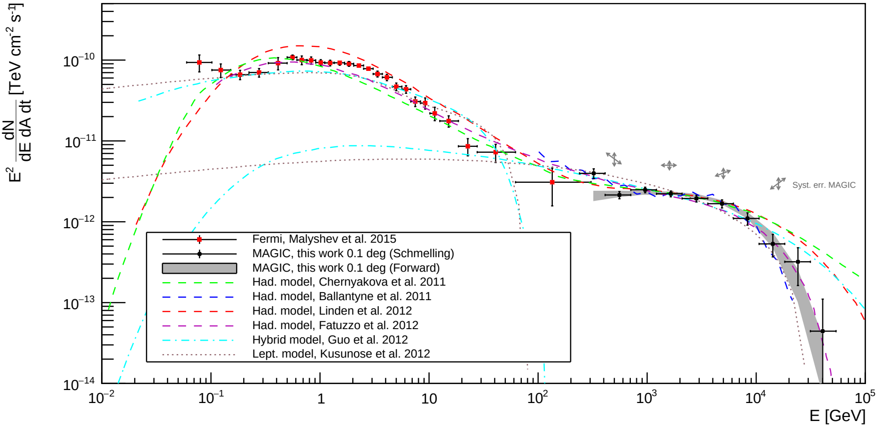
$$F(t) = F_0 + \alpha\,(t[\mathrm{MJD}] - 56000)$$



- Correlated fit: $\frac{dF}{dE} = f_{0,1}\left(\frac{E}{5\,\mathrm{GeV}}\right)^{\alpha_1+\beta_1 \log\left(\frac{E}{5\,\mathrm{GeV}}\right)} + f_{0,2}\left(\frac{E}{3\,\mathrm{TeV}}\right)^{\alpha_2+\beta_2 \log\left(\frac{E}{3\,\mathrm{TeV}}\right)}$



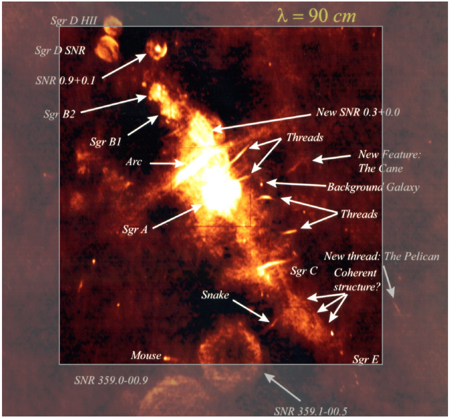
SED including 2015 Fermi data and models

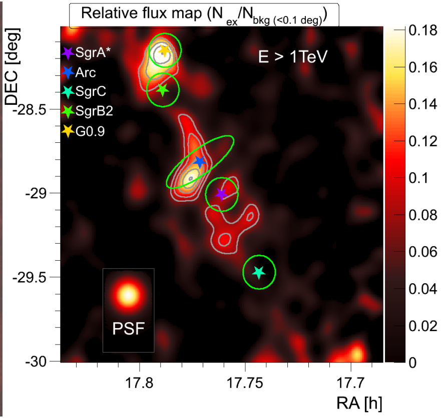


- peculiar 2-bump structure – none-trivial for modeling
- hadronic scenarios are exploiting morphology (target) and time variability (source)
- leptonic models have problems explaining the spectral shape with single source
- the available data does not yet allow discrimination of models

- good correlation between 90 cm radio image and TeV skymap
- G0.9 is known TeV source (Aharonian et al., 2005)
- radio Arc has TeV counterpart (not previously studied in TeV, Fermi GeV data available)

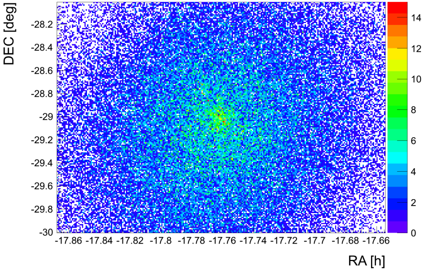
⇒ developed method for calculating spectrum from the elliptical region defined by the radio image



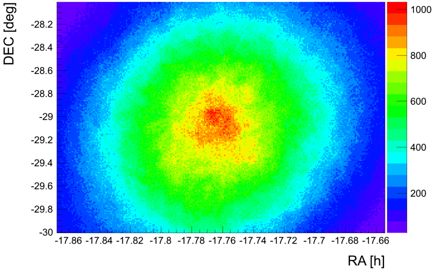


radio image: N. E. Kassim, D. S. Briggs, T. J. W. Lazio, T. N. LaRosa, J. Imamura (NRL/RSD)

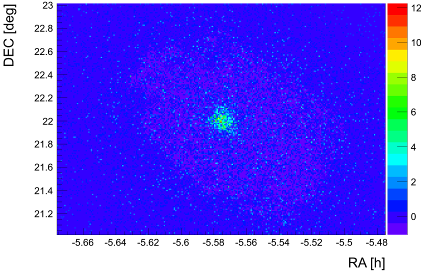
On-Skymap



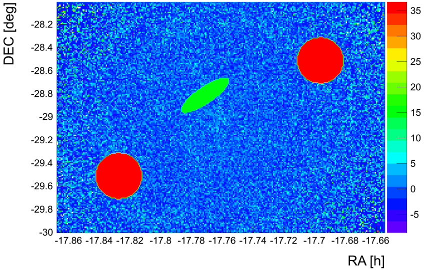
Background estimate (oversampled)

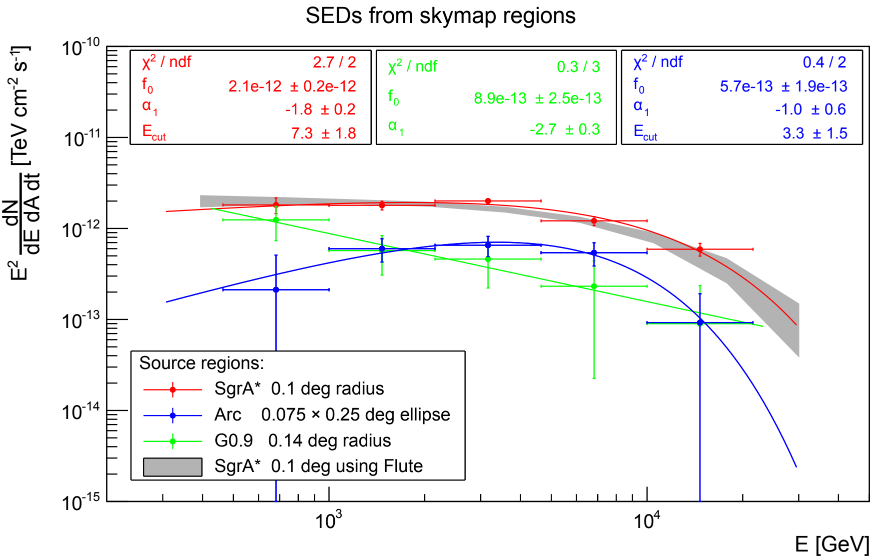


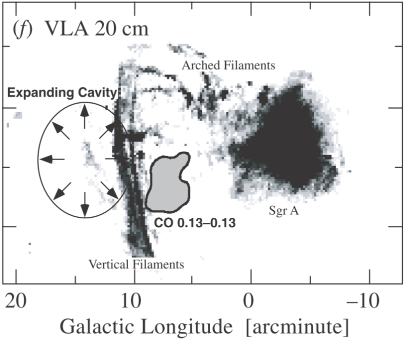
Background subtracted skymap (Crab-Nebula)

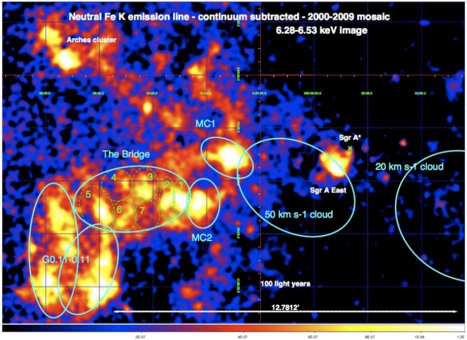


Skymap (bg-subtracted and normalized)




SEDs from skymap regions
$E^2 \frac{dN}{dE\,dA\,dt}$ [TeV cm^{-2} s^{-1}]
E [GeV]
χ^2 / ndf 2.7 / 2
f_0 2.1e-12 ± 0.2e-12
α_1 -1.8 ± 0.2
E_{cut} 7.3 ± 1.8
χ^2 / ndf 0.3 / 3
f_0 8.9e-13 ± 2.5e-13
α_1 -2.7 ± 0.3
χ^2 / ndf 0.4 / 2
f_0 5.7e-13 ± 1.9e-13
α_1 -1.0 ± 0.6
E_{cut} 3.3 ± 1.5
Source regions:
SgrA* 0.1 deg radius
Arc 0.075 × 0.25 deg ellipse
G0.9 0.14 deg radius
SgrA* 0.1 deg using Flute

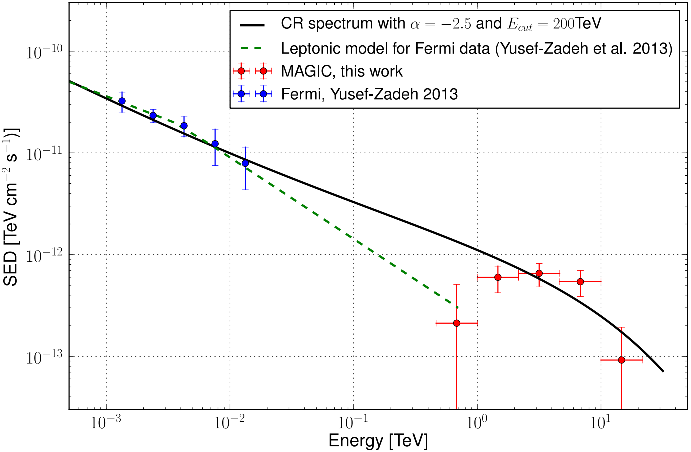




- Expanding giant molecular cloud G0.11-0.11 exactly matching the coordinates of MAGIC excess (M. Tsuboi et al. 1997) — possible origin: 10 - 100 SNE
- Possible origin of Arc γ-radiation from GMC G0.11-0.11 - maybe interaction of linear filaments and expanding GMC?
- Fe K_α emission either X-ray echo of SgrA* (M. Clavel et al. 2013) flare or excited by CRs (F. Yusef-Zadeh et al. 2013)
- Are same CRs also producing the TeV emission?

Simple hadronic model for GeV-TeV emission from the Arc

- Yusef-Zadeh et al., 2013 modeling Fermi data with e^--Bremsstrahlung
- are γ rays from π_0 decay also possible? (formul.: Aharonian et al., 2013)
- assuming CR interaction with G0.11-0.11 ($6.3 \cdot 10^5\,M_\odot$) (Handa et al. 2006)
- single power-law spectrum with exponential cut-off (for protons)



- Flux for the central object (GC/SgrA*):
  $F_{E>1\,\mathrm{TeV}} \approx 2 \cdot 10^{-12}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$,
  $F_{E>2\,\mathrm{TeV}} \approx 1 \cdot 10^{-12}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$,
  $F_{E>5\,\mathrm{TeV}} \approx 2 \cdot 10^{-13}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- This corresponds to ≈20 evts/h, ≈15 evts/h, ≈7 evts/h in case of MAGIC taking into account the average effective collection areas
- The observations are of course not background free

⇒ We are quite statistics limited, especially at high energies

- Also, because of the detection technique the angular resolution is always worse than 0.05°

Systematics

Systematics

- What changes when going to large Zd?

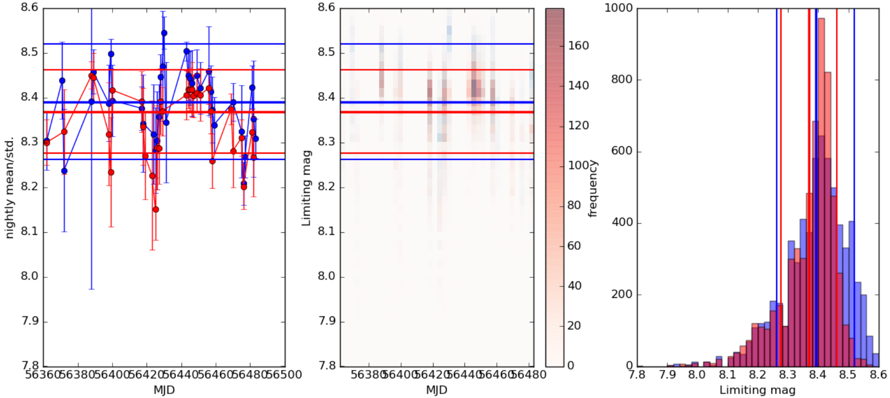
Systematic effect	Uncertainty
F-Factor	10% ES
atmospheric transmission	$\lesssim$10% ES
mirror reflectivity	8% ES
PMT electron collection efficiency	5% ES
light collection in a Winston Cone	5% ES
PMT quantum efficiency	4% ES
signal extraction	3% ES
temperature dependence of gains	2% ES
charge flat-fielding	2-8% ES FN
analysis and MC discrepancies	$\lesssim$10-15% FN
background subtraction	1-8% FN
broken channels/pixels	3% FN
mispointing	1-4% FN
NSB	1-4% FN
trigger	1% FN
unfolding of energy spectra	0.1 SL
non-linearity of readout	0.04 SL

⇨ 15% (atmospheric transmission)

⇨ ? (analysis and MC discrepancies)

Table: J. Aleksic et al. 2012, Astroparticle Physics 35, 2012, 435448

- LIDAR cannot be used at large Zd.
- Starguider as alternative?
- Limiting magnitude of identified stars as indicator for changes in atm. trans.
- The std. of relative spread within one year is between 11% and 14%.
- Nearly ($> 90\%$) of the daily averages lie in this range.
- Zd ranges: < 64 deg, > 64 deg



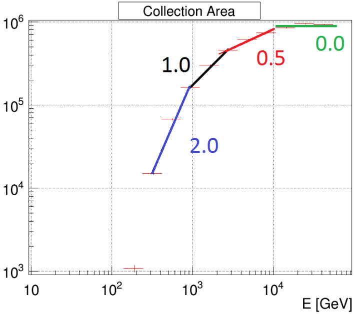
- How do errors propagate into $d\phi/dE$ or SED?
- Error in flux normalization: Easy, allways linearly in Y-Axis direction.
- Error in energy scale: Not that easy ...

$$\left(\frac{d\phi}{dE}\right)_{assumed} = \frac{N}{\Delta E \cdot A_{eff}(E) \cdot T_{eff}}$$

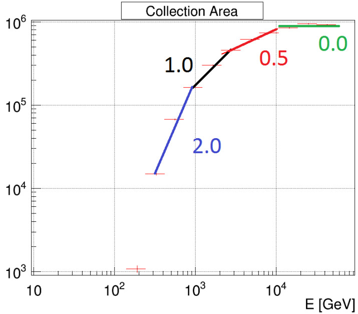
Energy scale wrong by factor α ($E \to \alpha E$)

$$\left(\frac{d\phi}{dE}\right)_{true} = \frac{N}{(\alpha \cdot \Delta E) \cdot A_{eff}(\alpha \cdot E) \cdot T_{eff}}$$

Approximate A_{eff} as power law, locally



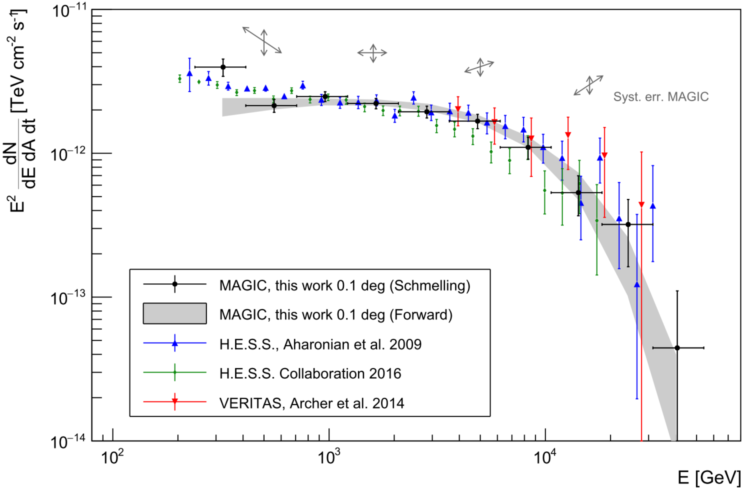
Approximate A_{eff} as power law with index β, locally



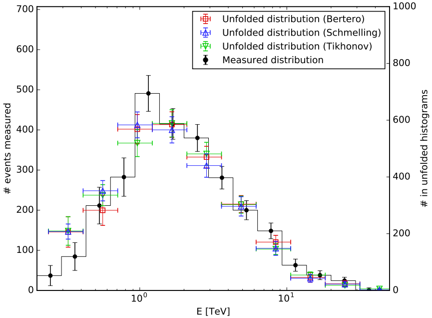
$$\left(\frac{d\phi}{dE}\right)_{true} = \frac{N}{(\alpha \cdot \Delta E) \cdot A_{eff}(\alpha \cdot E) \cdot T_{eff}} = \alpha^{-1-\beta} \cdot \left(\frac{d\phi}{dE}\right)_{assumed}$$

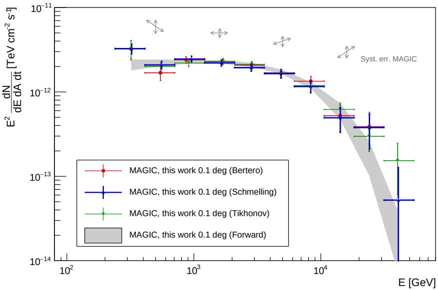
$$SED_{true} = \frac{(\alpha \cdot E)^2 \cdot N}{(\alpha \cdot \Delta E) \cdot A_{eff}(\alpha \cdot E) \cdot T_{eff}} = \alpha^{1-\beta} \cdot SED_{assumed}$$

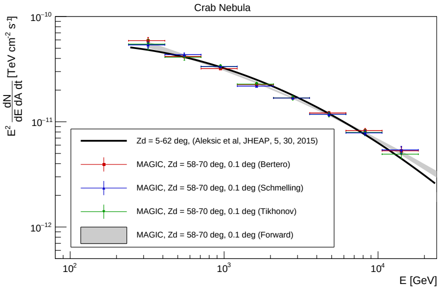
And this is how it would looks like for the GC ...

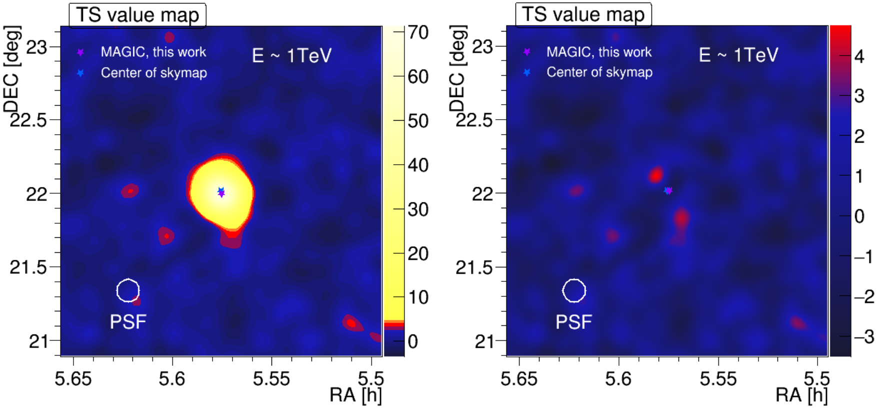


Systematics – unfolding methods (spectral deconvolution)

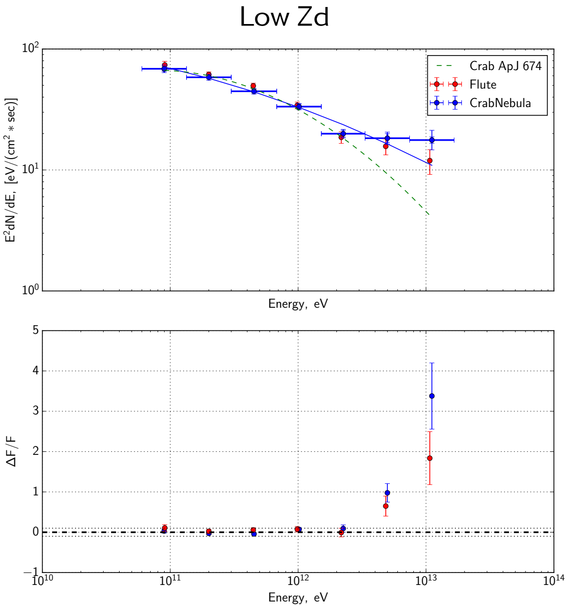


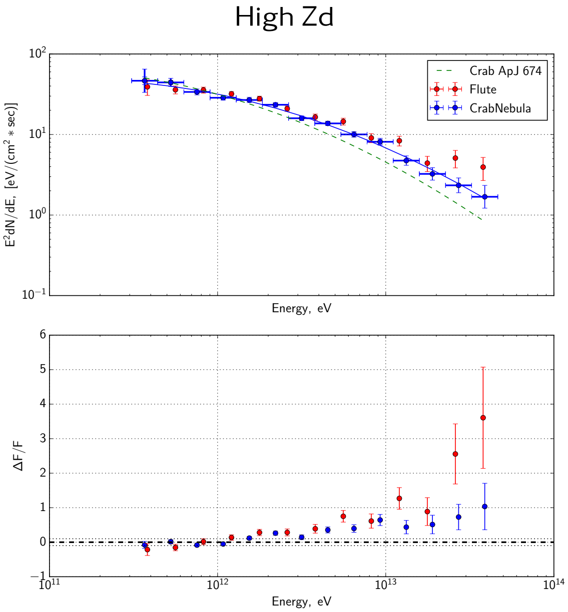





TS value map
MAGIC, this work
Center of skymap
E ~ 1TeV
PSF
DEC [deg]
RA [h]
23
22.5
22
21.5
21
5.65
5.6
5.55
5.5
70
60
50
40
30
20
10
0
TS value map
MAGIC, this work
Center of skymap
E ~ 1TeV
PSF
DEC [deg]
RA [h]
4
3
2
1
0
−1
−2
−3

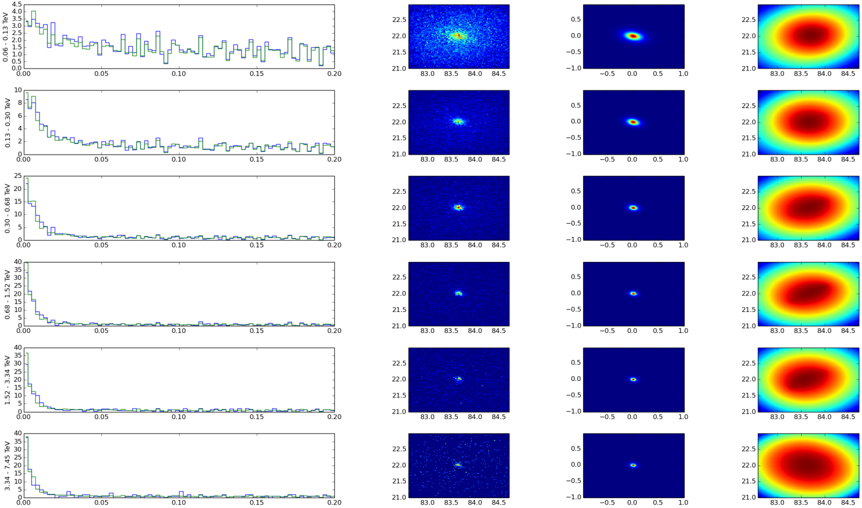
SkyPrism
(Likelihood code)


Low Zd
Crab ApJ 674
Flute
CrabNebula
E²dN/dE, [eV/(cm² * sec)]
Energy, eV
ΔF/F
Energy, eV

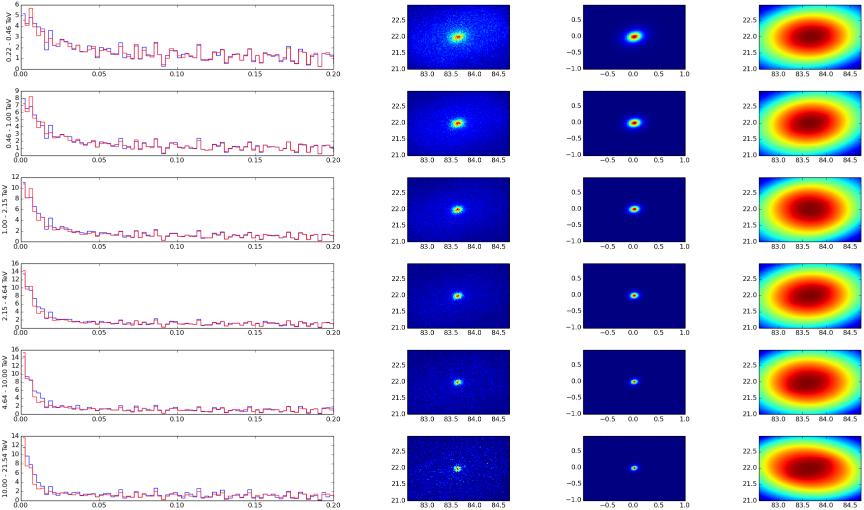

High Zd
10^2
10^1
10^0
10^{-1}
E^2dN/dE, [eV/(cm^2 * sec)]
Crab ApJ 674
Flute
CrabNebula
Energy, eV
6
5
4
3
2
1
0
−1
ΔF/F
10^{11}
10^{12}
10^{13}
10^{14}
Energy, eV

PSF Model vs. Crab Nebula

Low Zd

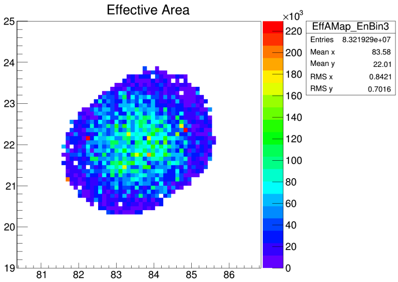


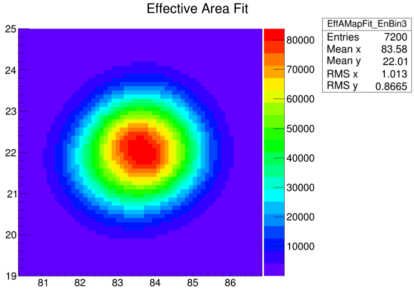
High Zd



0.22 - 0.46 TeV
0.46 - 1.00 TeV
1.00 - 2.15 TeV
2.15 - 4.64 TeV
4.64 - 10.00 TeV
10.00 - 21.54 TeV

- MC statistics require special strategy for coll. area map
- Applying multi-component fit using binomial statistics
- Error is propagated by creating 100 random maps based on fit parameters and errors





MCMC

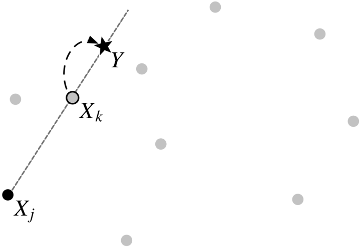
Select new position in parameter space according to:

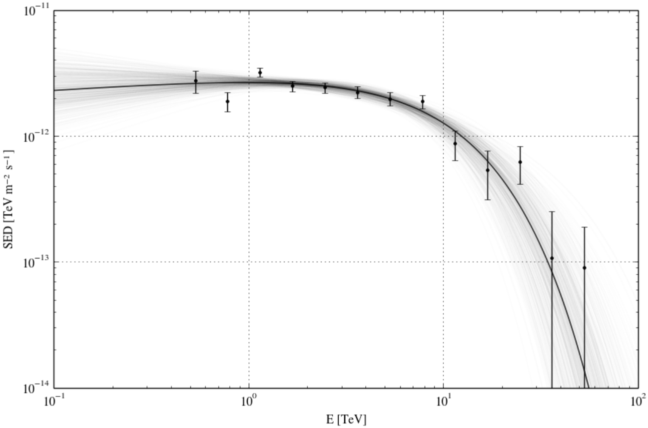
$$X_k(t) \rightarrow Y = X_j + Z(X_k(t) - X_j),\ j \neq k$$

Z is a random scaling factor which is distributed like:

$$g(Z) \propto \begin{cases} \frac{1}{\sqrt{Z}} & , Z \in [\frac{1}{a}, a] \\ 0 & , \text{else} \end{cases}$$

a is the only parameter, on which to tune (eventually)

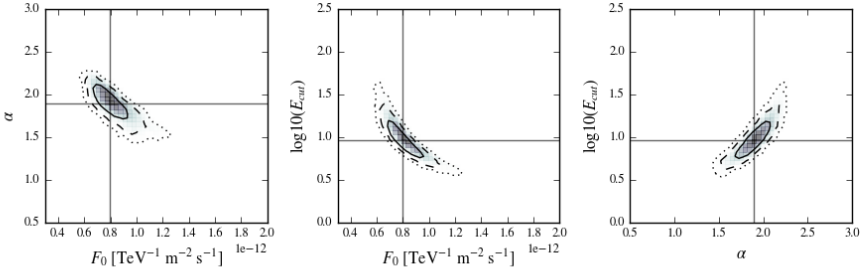




Model:

$$\frac{\mathrm{d}F}{\mathrm{d}E} = f_0 \left(\frac{E}{E_0}\right)^{-\alpha} \exp\left(-\frac{E}{E_{cut}}\right)$$

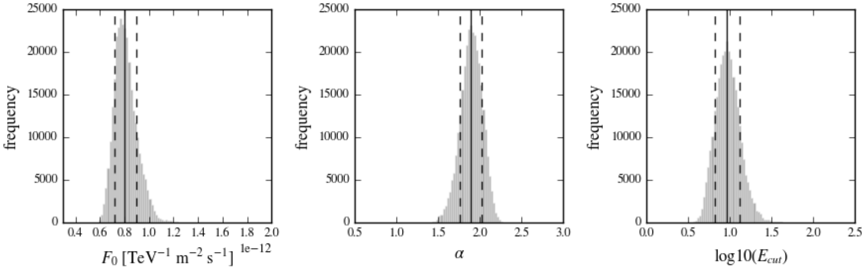
Parameter covariance using emcee:



Model:

$$\frac{\mathrm{d}F}{\mathrm{d}E} = f_0 \left(\frac{E}{E_0} \right)^{-\alpha} \exp\left(-\frac{E}{E_{cut}} \right)$$

"All very nice, but I want to state numbers and errors in my paper!"

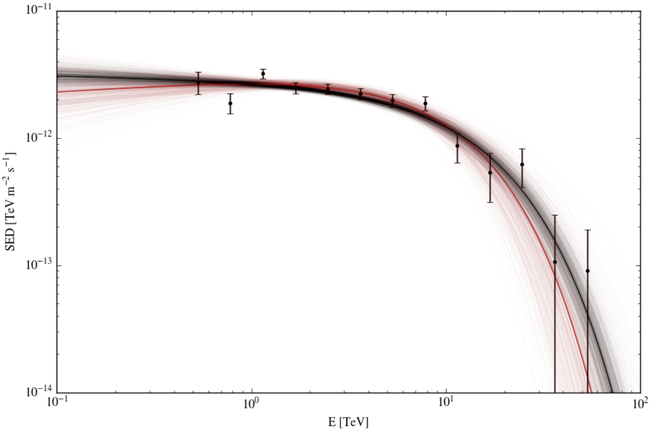


These histograms are literally showing you how likely a parameter value is to appear in the posterior distribution!

Parameters:

$$F_0 = 7.95^{+1.022}_{-0.766} \times 10^{-13}, \alpha = 1.89^{+0.126}_{-1.31}, \log 10(E_{cut}) = 0.962^{+0.150}_{-0.140}$$

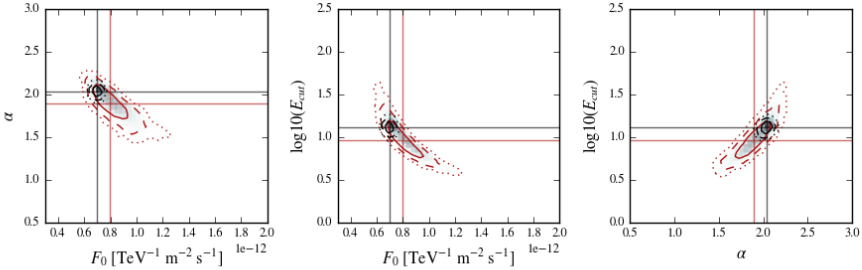
SED sampled with emcee using HESS+VERITAS spectrum as prior Archer et al. 2016



Model:

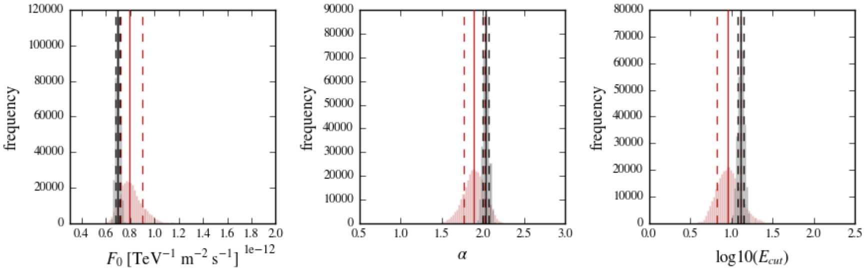
$$\frac{dF}{dE} = f_0 \left(\frac{E}{E_0} \right)^{-\alpha} \exp\left(-\frac{E}{E_{cut}} \right)$$

Parameter covariance using HESS+VERITAS spectrum as prior Archer et al. 2016:



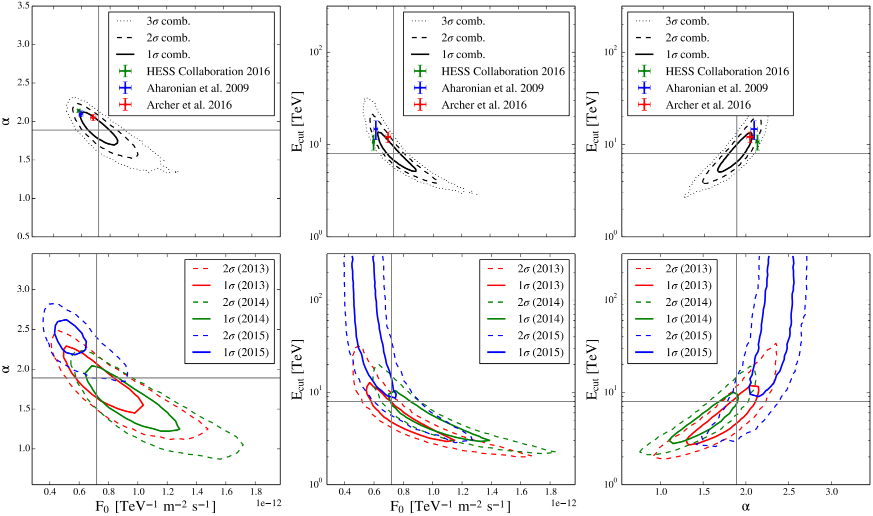
Model:

$$\frac{\mathrm{d}F}{\mathrm{d}E} = f_0\left(\frac{E}{E_0}\right)^{-\alpha}\exp\left(-\frac{E}{E_{cut}}\right)$$



Parameters:

$$F_0 = 6.97^{+0.168}_{-0.169} \times 10^{-13}, \alpha = 2.03^{+0.033}_{-0.033}, \log 10(E_{cut}) = 1.12^{+0.038}_{-0.042}$$


3σ comb.
2σ comb.
1σ comb.
HESS Collaboration 2016
Aharonian et al. 2009
Archer et al. 2016
2σ (2013)
1σ (2013)
2σ (2014)
1σ (2014)
2σ (2015)
1σ (2015)
α
E_cut [TeV]
F_0 [TeV^-1 m^-2 s^-1]
1e−12