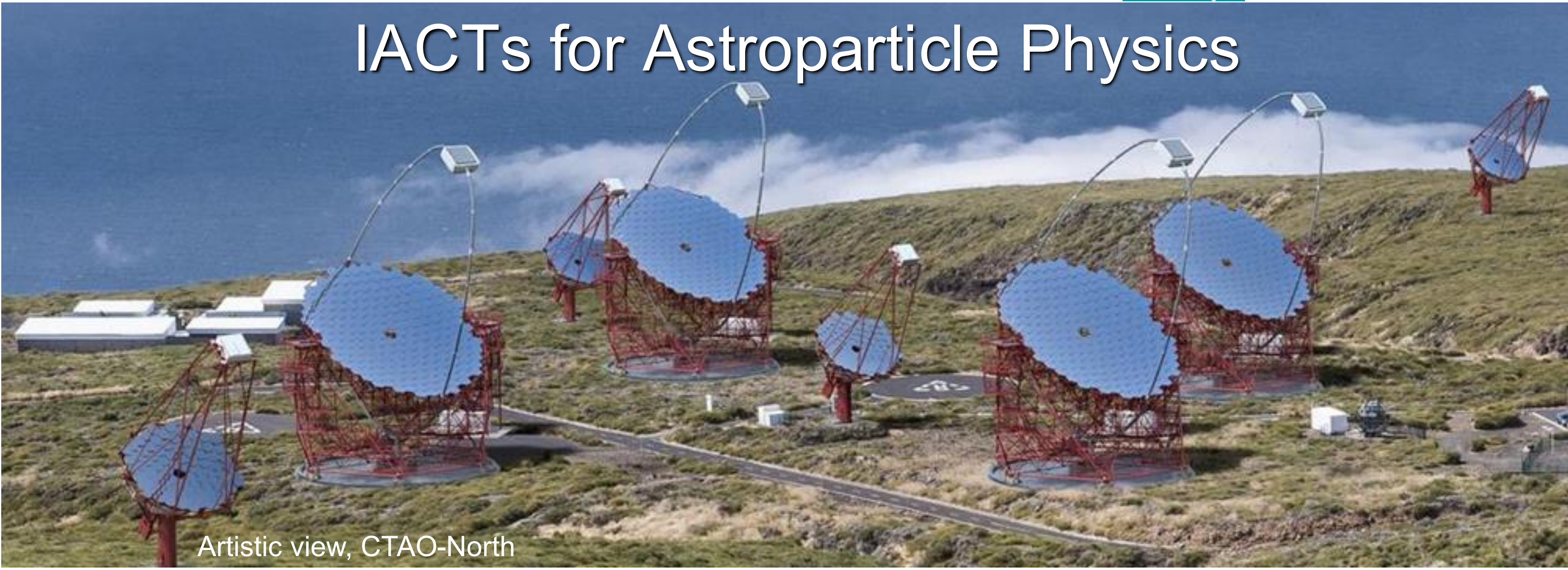
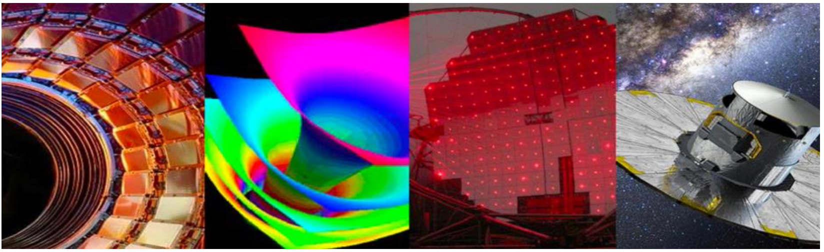
IACTs for Astroparticle Physics



Artistic view, CTAO-North



CPAN Network on Instrumentation and Detectors

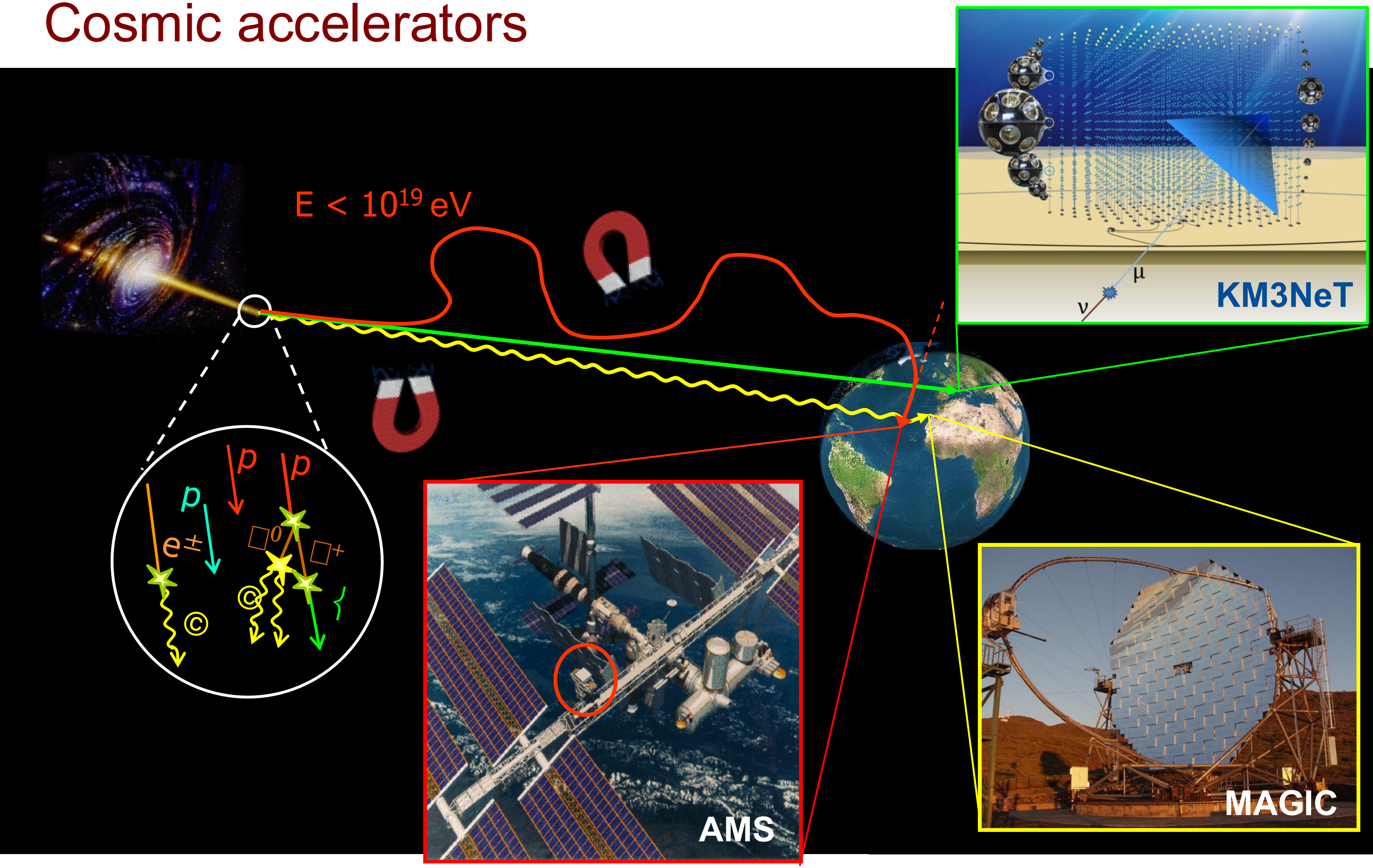
TIDPAN 2026 - Valencia

Juan Abel Barrio (IPARCOS)

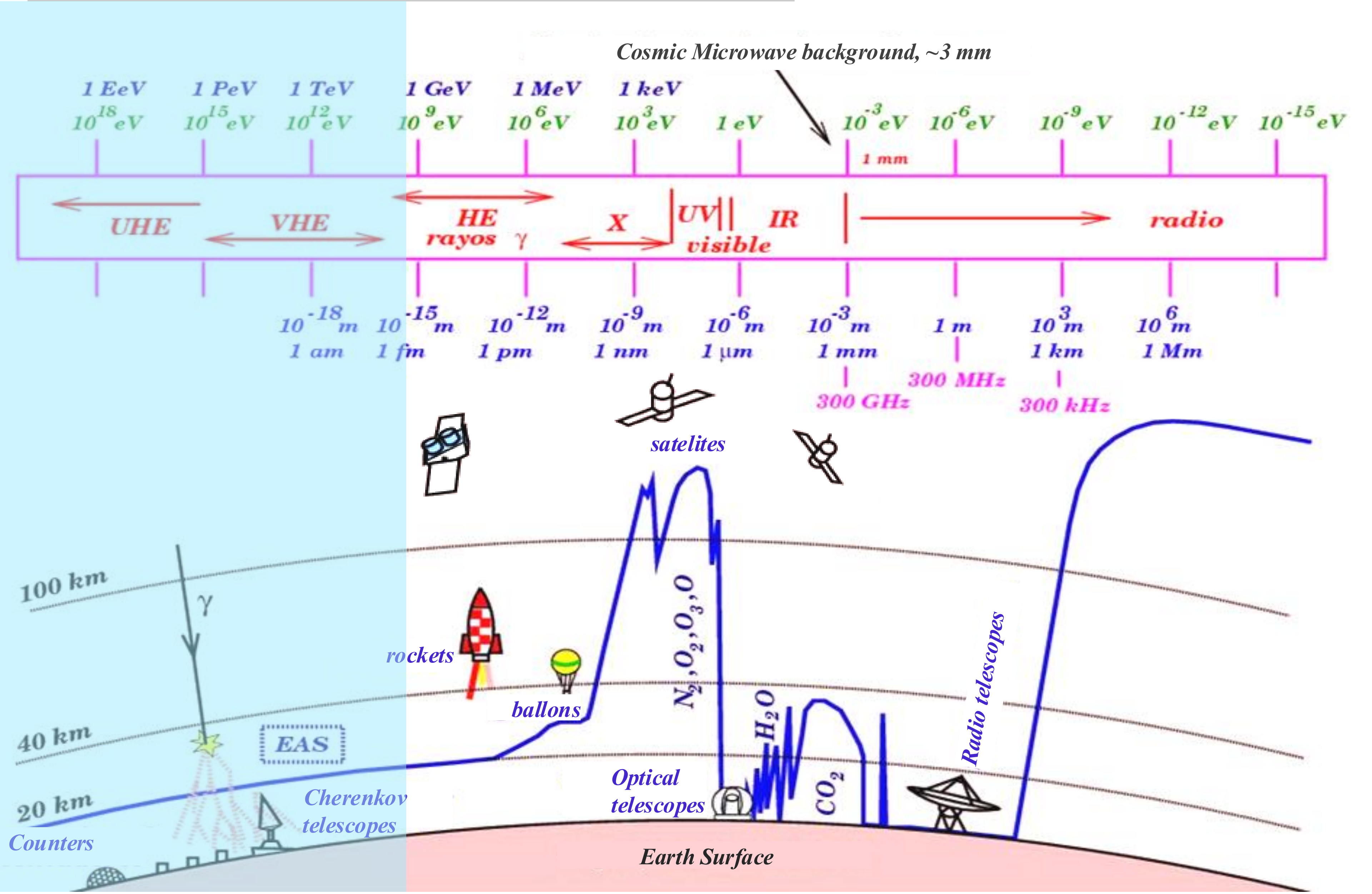
High Energy Physic Group – Institute of Particles and Cosmos Physics – University Complutense of Madrid

Astroparticle Physics

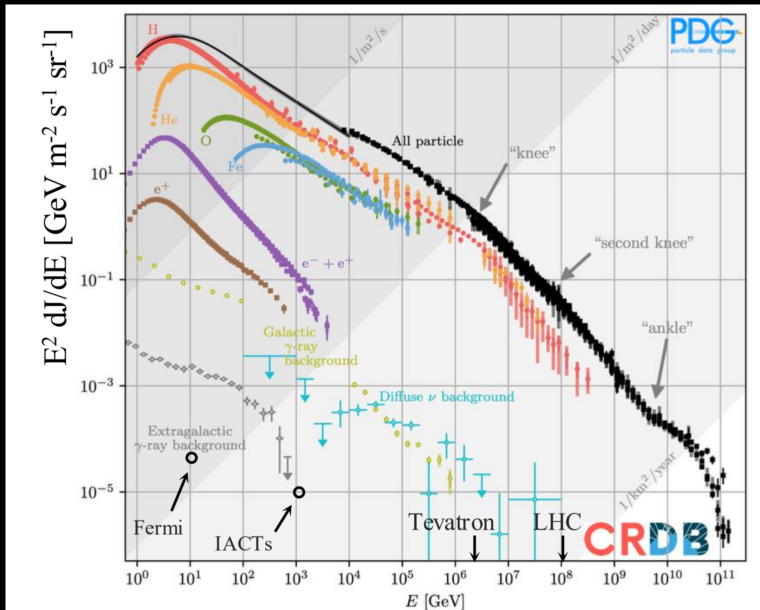
Cosmic accelerators

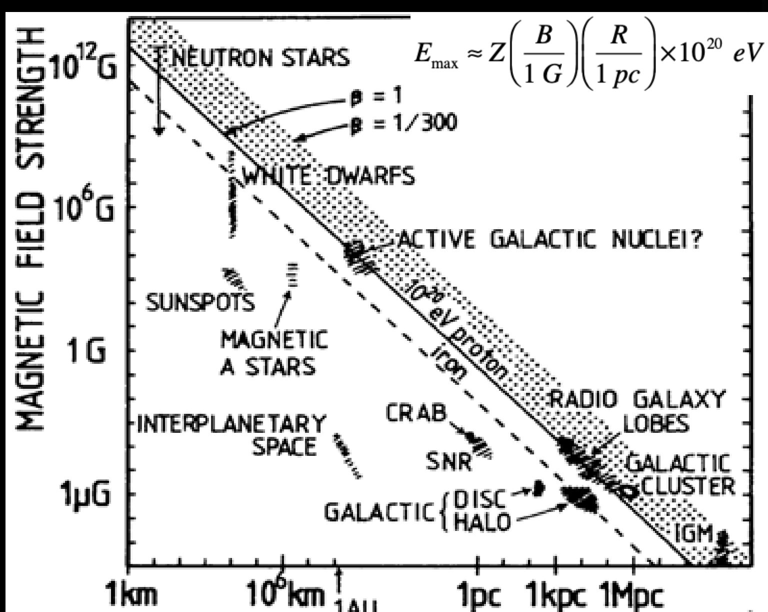


Gamma ray astrophysics

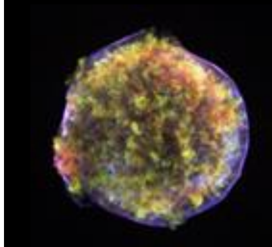


Scientific case



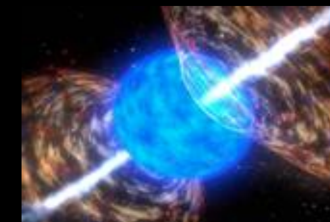


Hillas, 1984

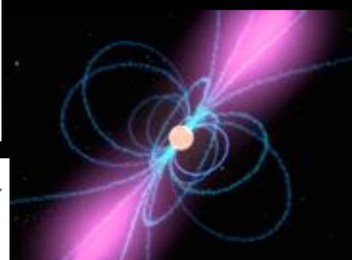


Supernova Remnants

Pulsar Wind Nebulae **(e.g. Crab)**



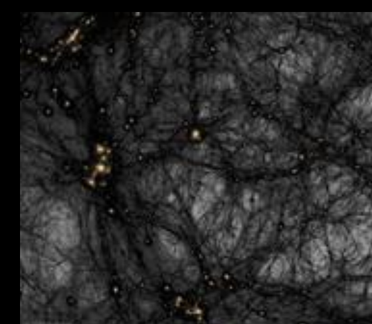
Gamma-ray Bursts



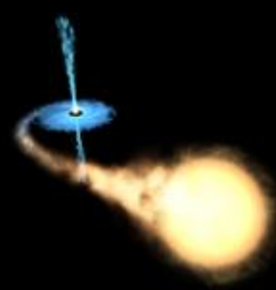
Pulsars

Compact-object mergers

Fundamental physics



Dark Matter
Lorentz Invariance
Cosmology



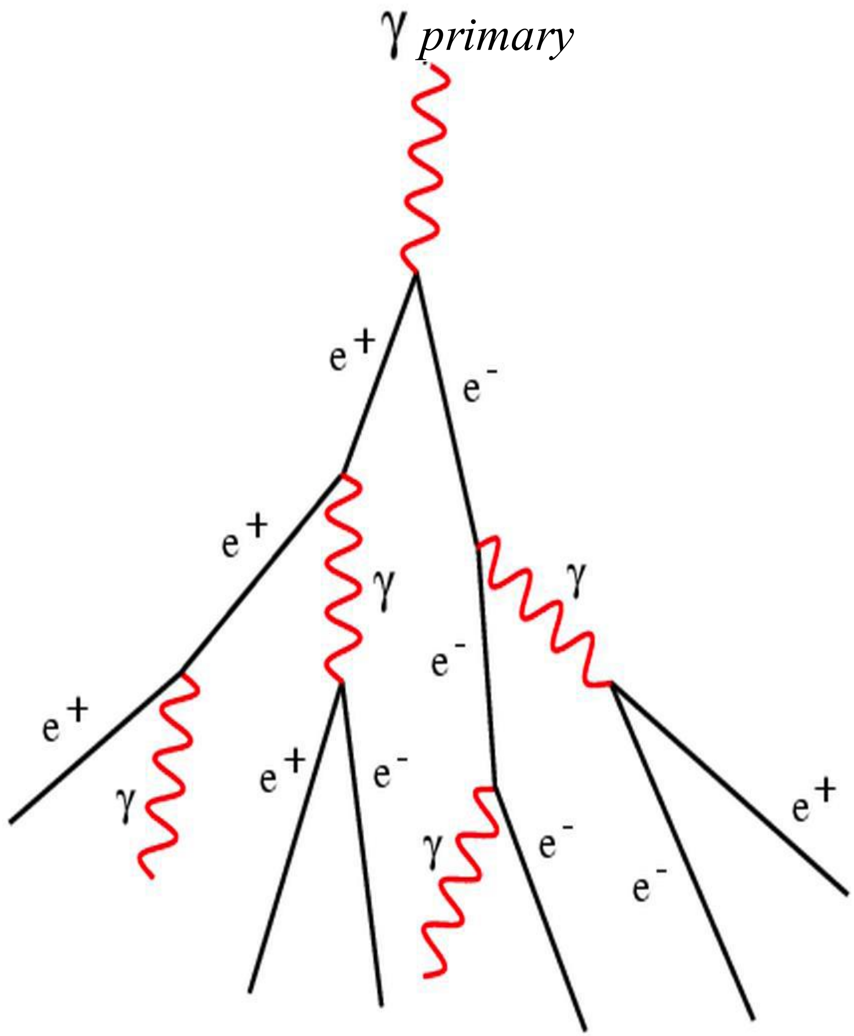
Gamma-ray Binaries

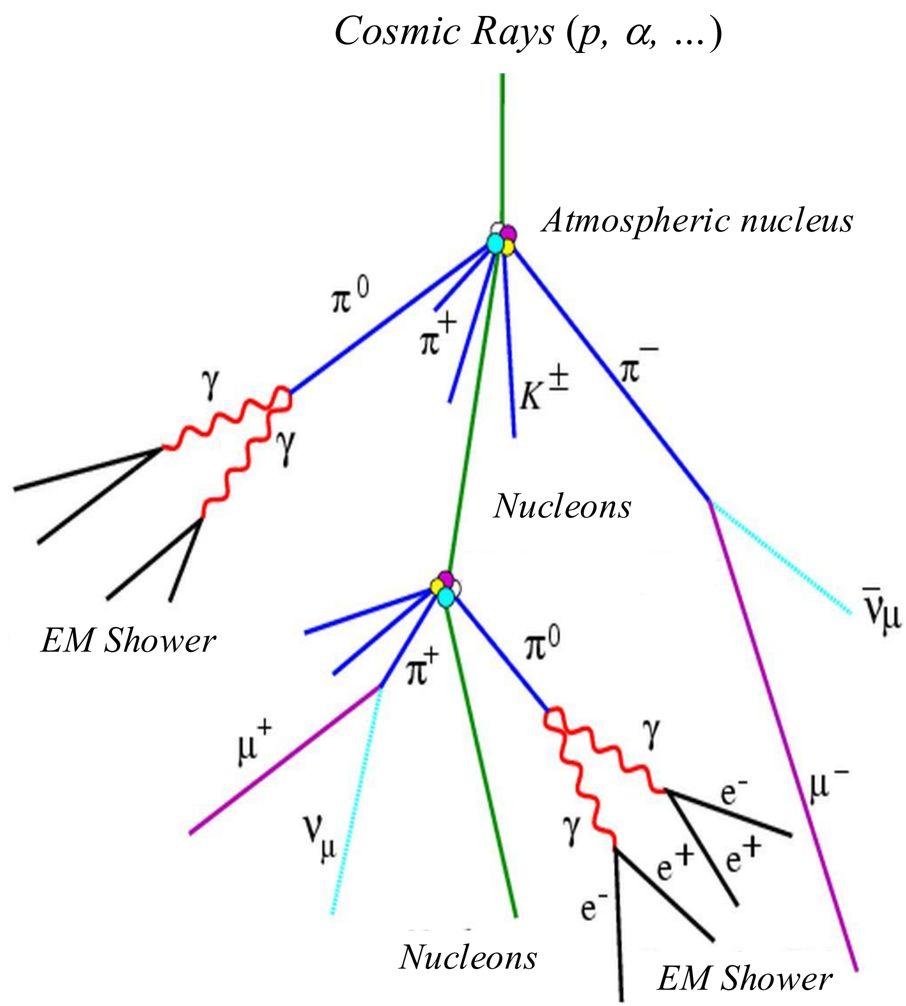
Active Galactic Nuclei

Contents

- Detection technique
  - Atmospheric Showers
  - Cherenkov Telescopes
- Telescopes
  - Building blocks
  - CTA
- All-sky monitors

Extended Air Showers (EAS)

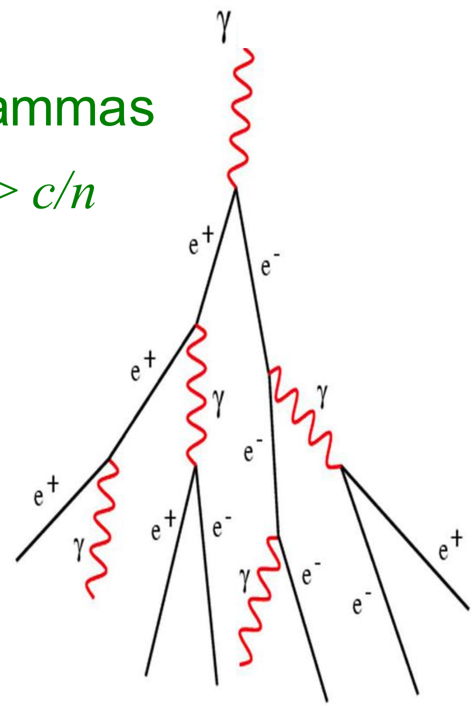




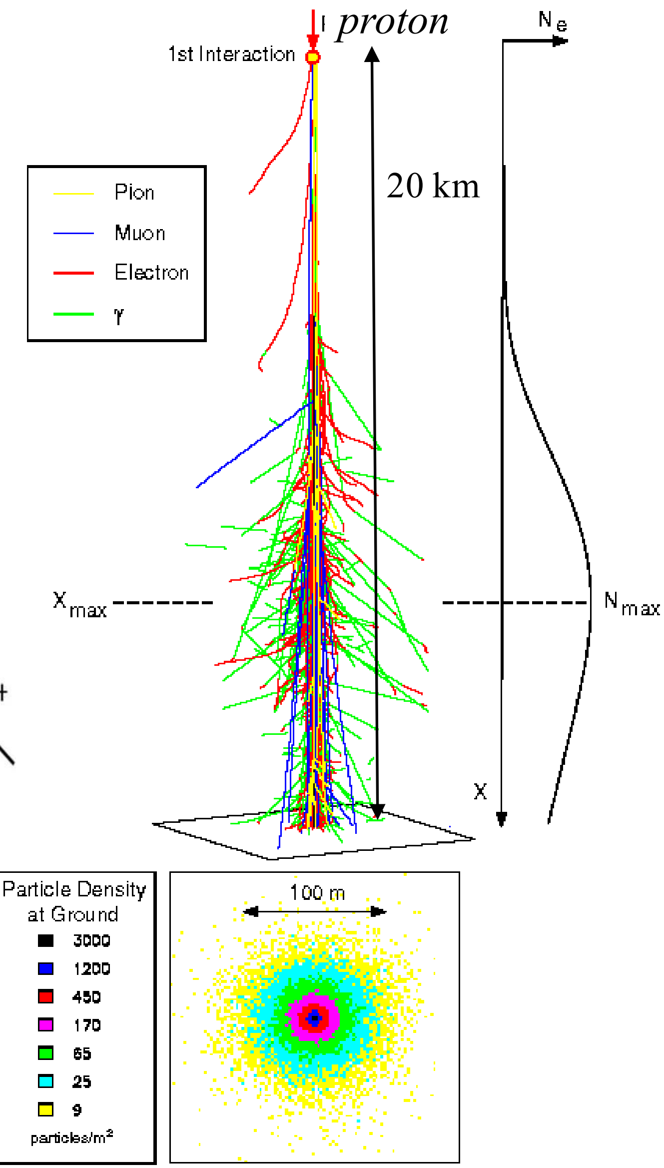
Extended Air Showers

Shower secondaries

- EM shower:
  - Electrons, positrons, gammas
  - Cherenkov ($\check{C}$) light: $v_{e-} > c/n$
  - Fluorescence light
  - Radio waves



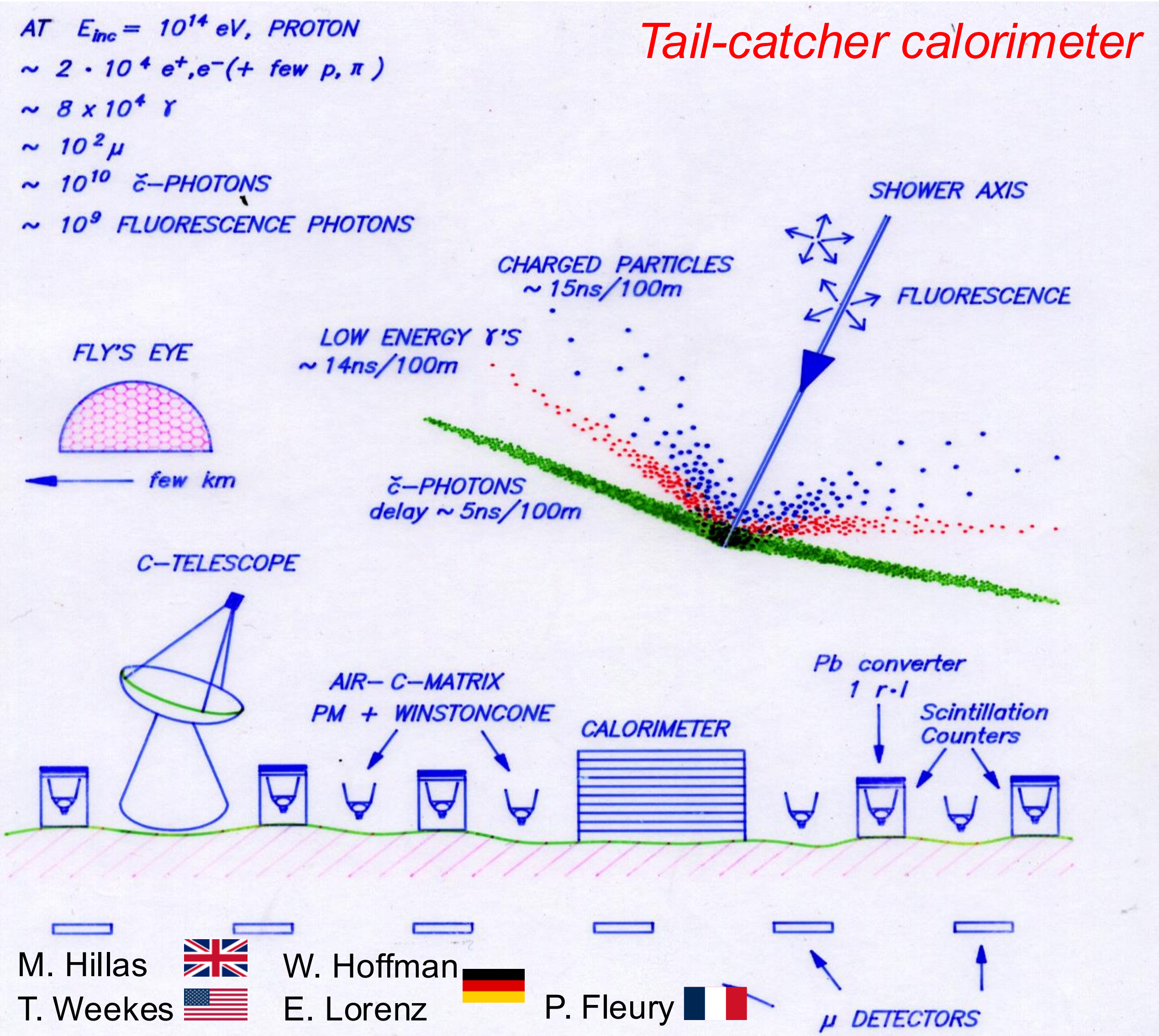
- Hadronic showers:
  - *Same as EM-EAS*
  - Muons, neutrinos
  - Other hadrons



Extended Air Showers

Shower secondaries: ballpark numbers

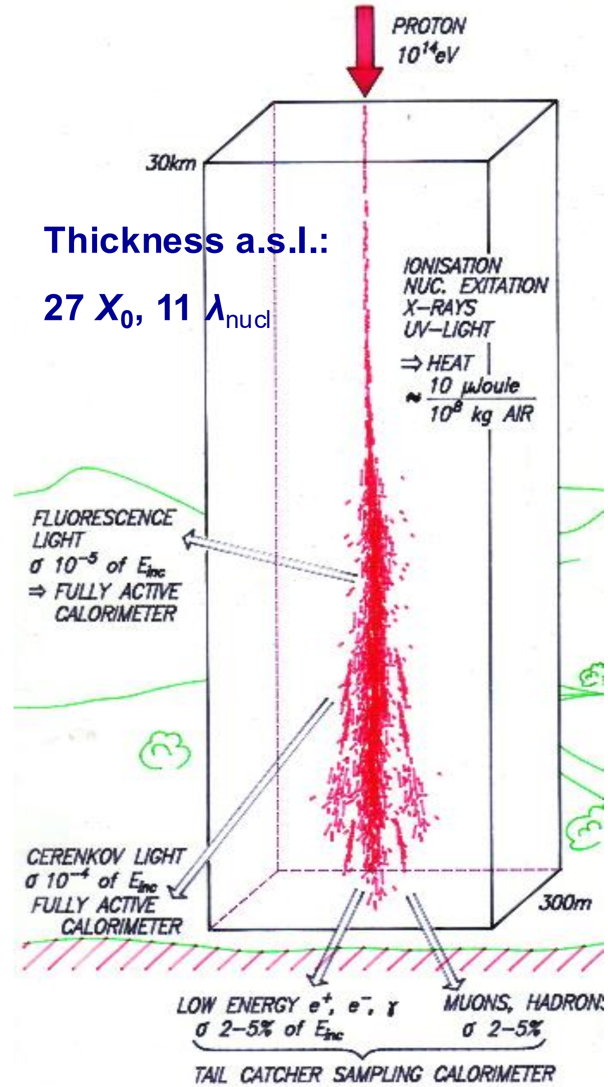
Tail-catcher calorimeter



M. Hillas
T. Weekes
W. Hoffman
E. Lorenz
P. Fleury

Thickness a.s.l.:

27 X_0, 11 λ_{nucl}



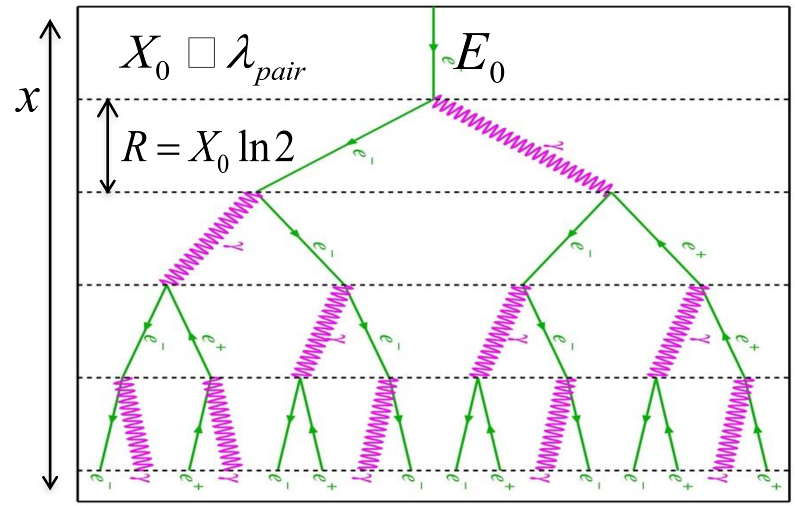
Simplified model (Heitler, 1944)

- Model parameters
  - Radiation Length (bremsstrahlung):

$$E = E_0 e^{-\frac{x}{X_0}};\ X_0\left(g/cm^2\right) \square 180\frac{A}{Z^2};\ t = \frac{x}{X_0}$$

  - Mean free path (pair creation):

$$\lambda_{pair} = (9/7)X_0$$



- Energy and nº secondaries *N* after *n* steps, thickness *t* and depth *x:*

$$E = E_0 e^{-t} = E_0/N;\ N = 2^n;\left(2/3\,e^{\pm}, 1/3\,\gamma\right) \qquad N(t) = e^t = 2^n \square \frac{x}{X_0} = n\ln 2 \square \quad R = \frac{x}{n} = X_0 \ln 2$$

- Shower maximum:

$$\left(\frac{dE}{dx}\right)_i = \left(\frac{dE}{dx}\right)_r \Rightarrow E = E_c \qquad x_{\max} = X_0 \ln\left(N_{\max}\right);\ N_{\max} = N\left(x_{\max}\right) = \frac{E_0}{E_c}$$

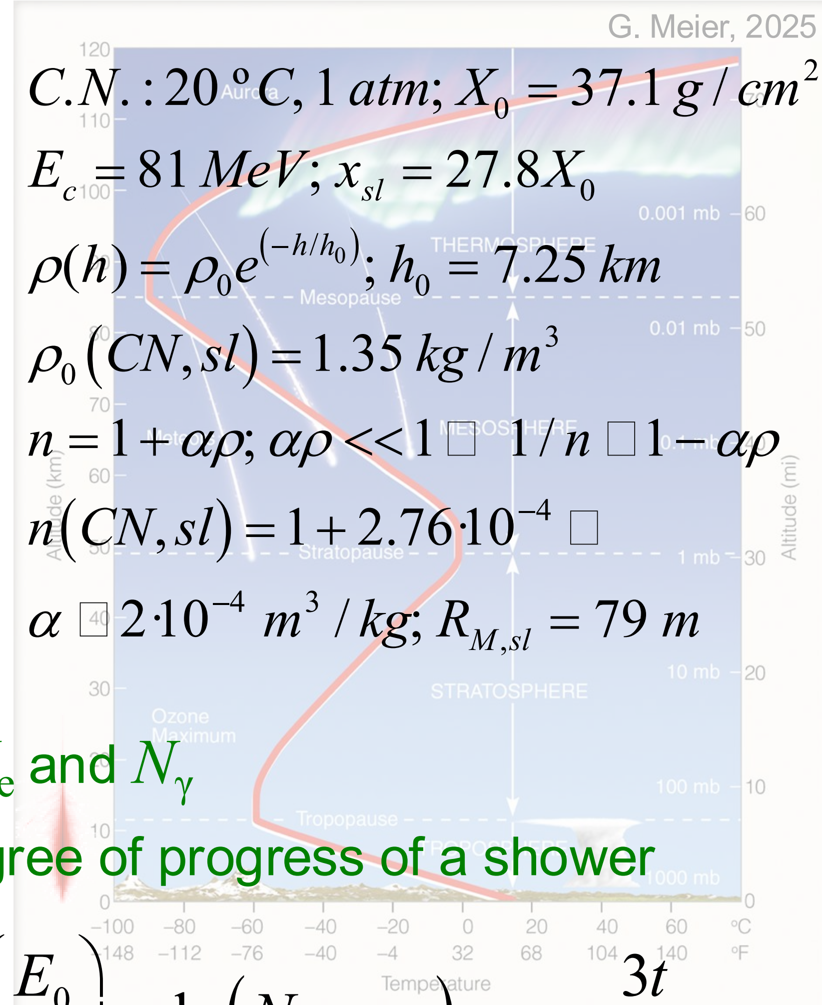
- Track length of charged secondaries:

$$L = \frac{2}{3}\int_0^{x_{\max}} N(x)dx = \int_0^{x_{\max}} e^{\frac{x}{X_0}} dx = \frac{2}{3}X_0\left(\frac{E_0}{E_c} - 1\right) \propto E_0$$

Quantitative model (Greisen, 1956)

- Features:
  - Passive low-Z medium
  - Tail-catcher calorimeter
  - Exponencial density profile → x_{max} more compressed than in a man-made calorimeter
  - Bremsstrahlung + pair creation + dE/dx ionization + Coulomb Scat.

G. Meier, 2025



$C.N.: 20\,^{\circ}C, 1\,atm; X_0 = 37.1\,g/cm^2$

$E_c = 81\,MeV; x_{sl} = 27.8 X_0$

$\rho(h) = \rho_0 e^{(-h/h_0)}; h_0 = 7.25\,km$

$\rho_0(CN, sl) = 1.35\,kg/m^3$

$n = 1 + \alpha\rho; \alpha\rho << 1 \square\ 1/n \square 1 - \alpha\rho$

$n(CN, sl) = 1 + 2.76 \cdot 10^{-4} \square$

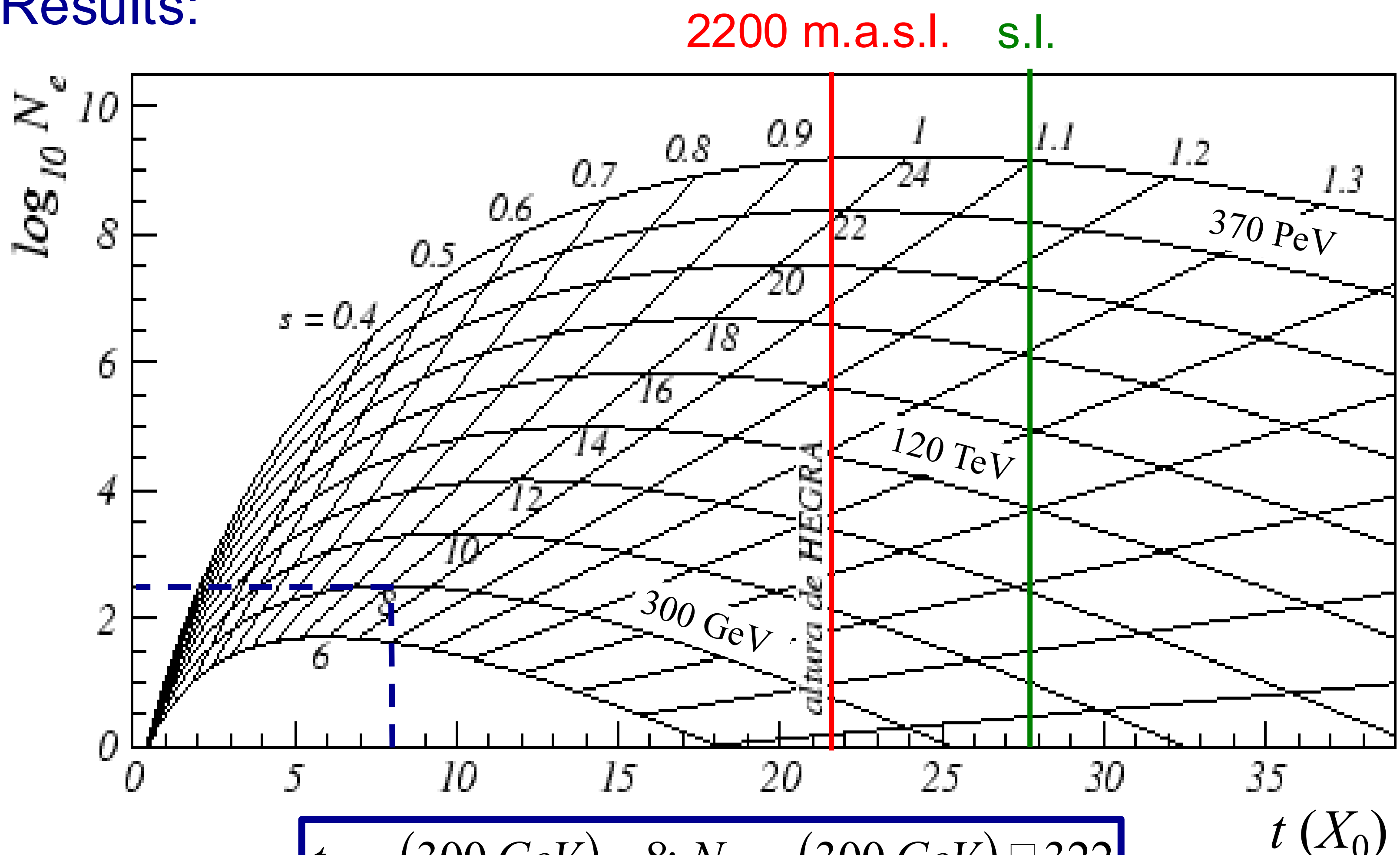
$\alpha \square 2 \cdot 10^{-4}\ m^3/kg; R_{M,sl} = 79\,m$

- Outcome
  - Coupled differential equations for N_e and N_γ
  - *Age parameter* s measuring the degree of progress of a shower

$$N_{e^\pm}(t) \approx \frac{0.15}{\sqrt{y}} e^{[t(1-1.5\ln s)]};\ y = t_{\max,Heit} = \ln\left(\frac{E_0}{E_c}\right) = \ln\left(N_{\max,Heit}\right);\ s = \frac{3t}{t+2y}$$

Quantitative model (Greisen, 1956)

- Results:



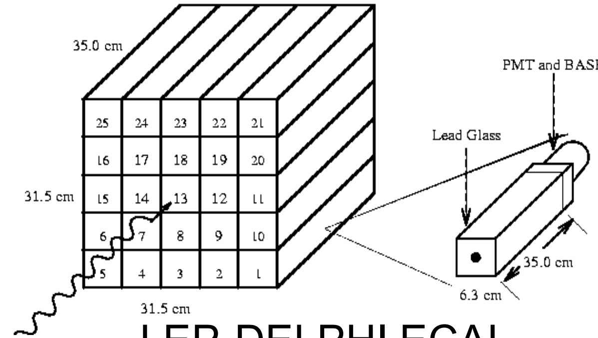
$$t_{e,\max}\left(300\ GeV\right)=8;\ N_{e,\max}\left(300\ GeV\right)\square 322$$

Electromagnetic Showers

Quantitative model (Greisen, 1956)

- Caveats & extras:
  - Calorimeter with no test-beam available
  - $e^+ e^-$ atmospheric absorption limiting E_0
  - $\check{c}$ light less absorbed by atmosphere → smaller E_0 allowed → lead-glass-like ECAL
- Cherenkov light as secondary:
  - Subtle changes in light transmission: clouds, ozone, aerosols
  - $\check{c}$ light not exactly proportional to $\mathrm{dE/dx}$
  - Dark-night-alone observations
  - No *walls* → Night Sky Background (NSB)

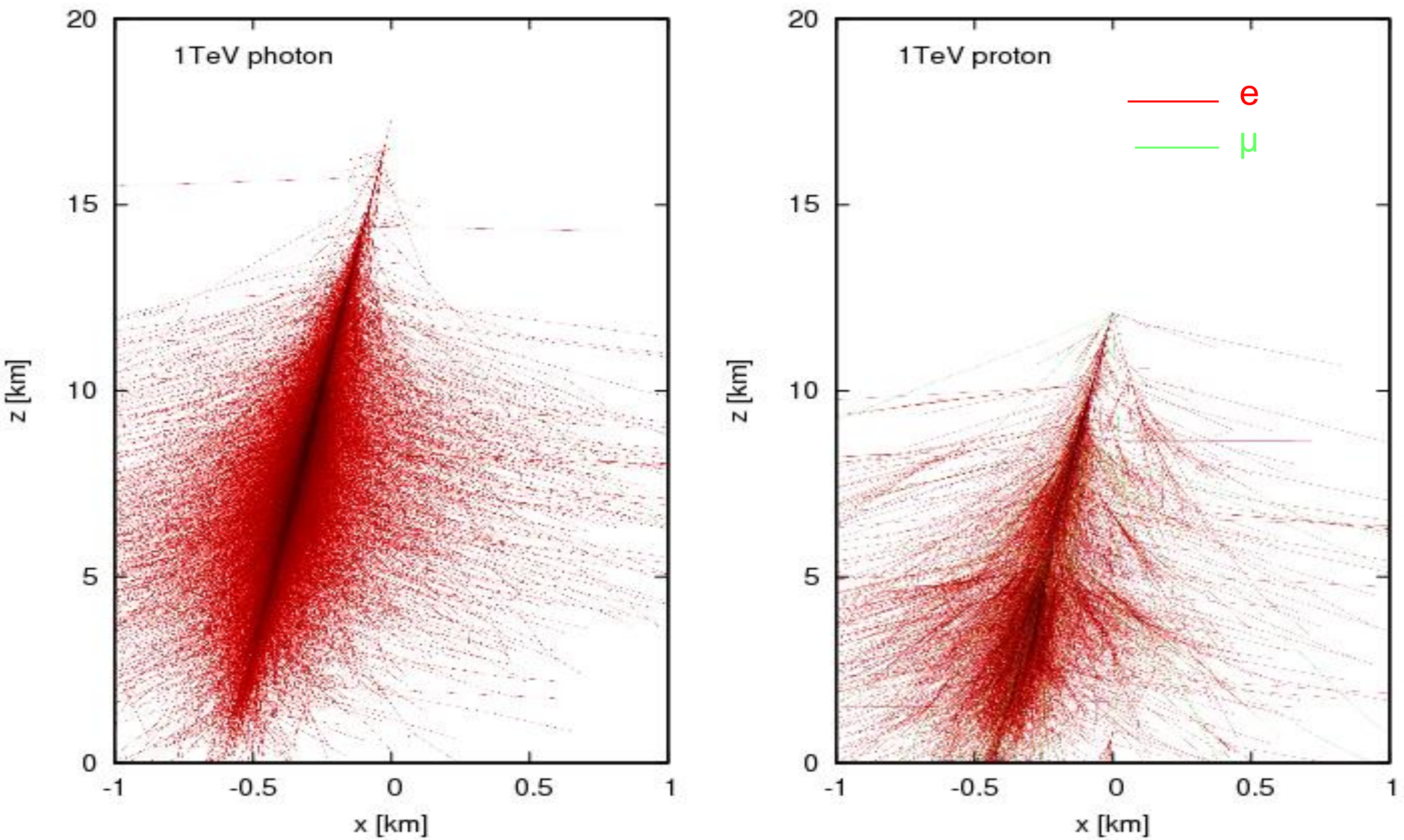
→ MC simulation is essential



LEP-DELPHI ECAL

Extended Air Showers

MC simulation of EAS



Contents

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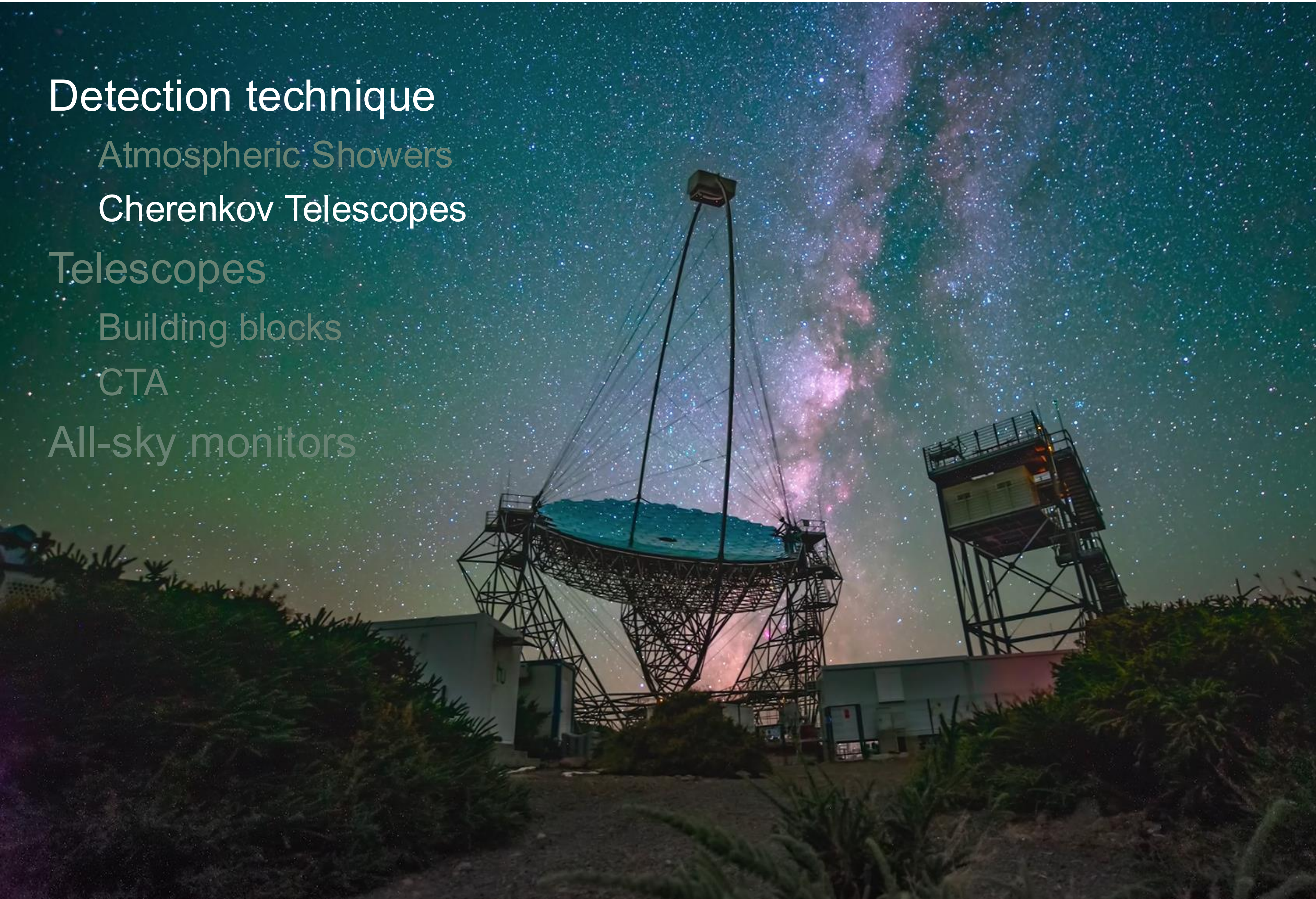
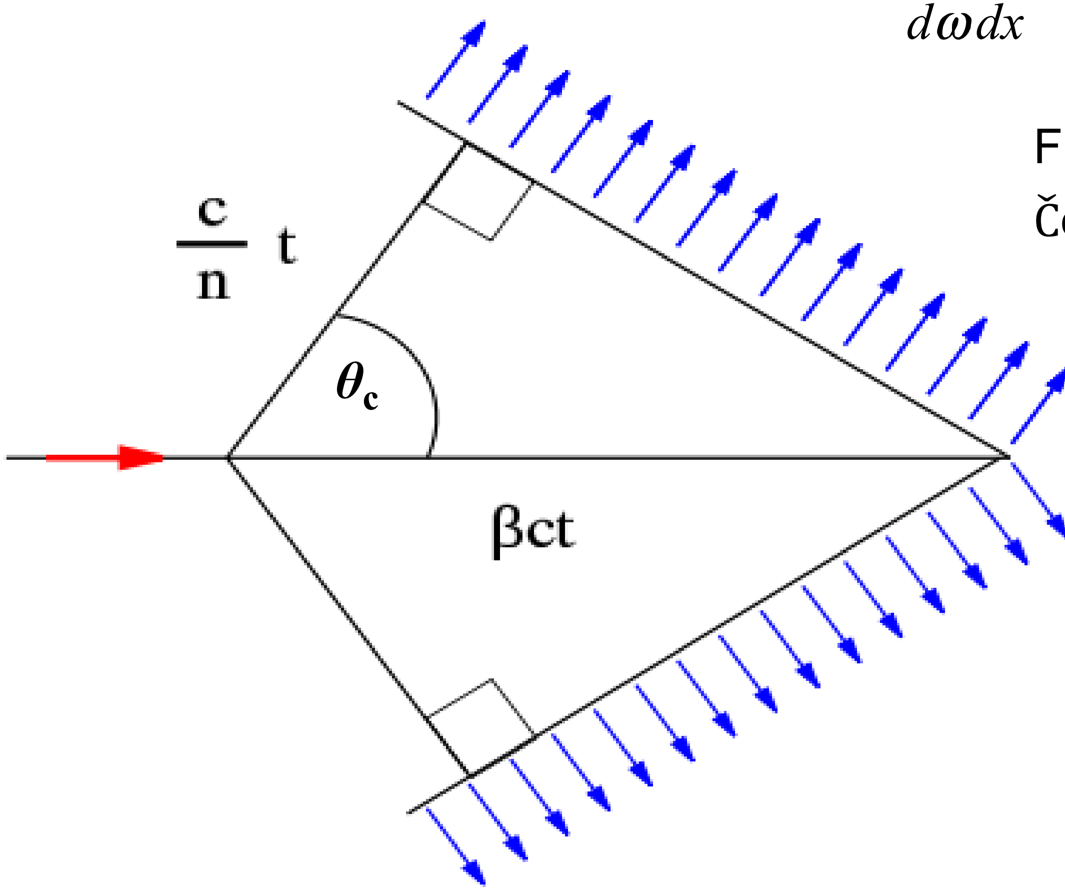


Cherenkov Radiation emitted by EAS

– Cherenkov light by a charged particle

$$\beta > \beta_{th} = \frac{1}{n}; \quad \cos\theta_c = \frac{1}{\beta n} \;\square\; \frac{1}{n}$$

$$\frac{d^2E}{d\omega dx} = \frac{z^2\alpha\hbar\omega}{c}\left(1 - \frac{1}{\beta^2 n^2(\lambda,\rho)}\right)$$



Frank, Tamm
Čerenkov

Cherenkov Telescopes

Cherenkov Radiation emitted by EAS

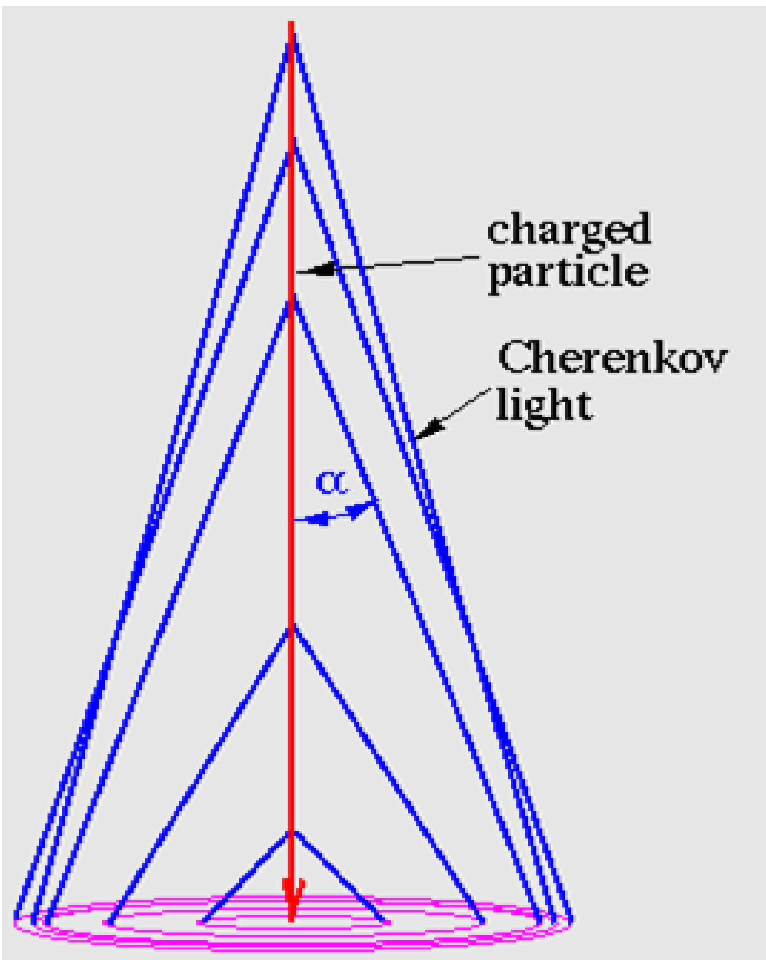
- Cherenkov light by a charged particle
- Cherenkov light by a charged part. on ground

$$\beta > \beta_{th} = \frac{1}{n}; \quad \cos\theta_c = \frac{1}{\beta n} \approx \frac{1}{n}$$

$$\frac{d^2E}{d\omega dx} = \frac{z^2\alpha\hbar\omega}{c}\left(1 - \frac{1}{\beta^2 n^2(\lambda,\rho)}\right)$$

$$x = \int_h^{\infty} \rho(h')\,dh' = \rho_0 h_0 e^{(-h/h_0)} = h_0\rho$$

$$n = 1 + \alpha\rho;\ \alpha\rho << 1 \Rightarrow\ 1/n \approx 1 - \alpha\rho$$



Cherenkov Telescopes

Cherenkov Radiation emitted by EAS

- Cherenkov light by a charged particle
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$$\beta > \beta_{th} = \frac{1}{n}; \quad \cos\theta_c = \frac{1}{\beta n} \approx \frac{1}{n}$$

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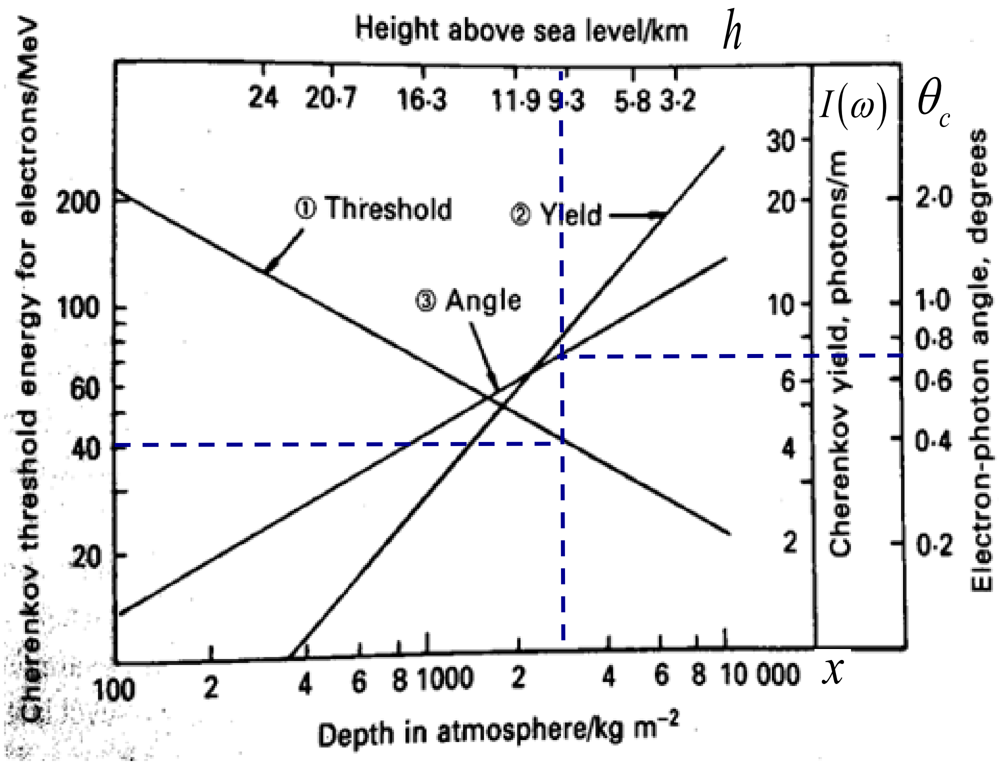


$$x = \int_h^{\infty} \rho(h')dh' = \rho_0 h_0 e^{(-h/h_0)} = h_0\rho$$

$$n = 1 + \alpha\rho;\ \alpha\rho << 1 \approx\ 1/n \approx 1 - \alpha\rho$$

$$\gamma_{th} = \left(1 - \beta_{th}^2\right)^{-1/2} \approx \left(2\alpha\rho\right)^{-1/2} \propto x^{-1/2}$$

$$1 - \theta_c^2/2 \approx \cos\theta_c \approx 1 - \alpha\rho \approx\ \theta_c \propto x^{1/2}$$

$$I(\omega) = \frac{d^2E}{d\omega dx} \propto \sin^2\theta_c \approx \theta_c^2 \propto x$$

$$E_{th,e}(10\ km) \approx \gamma_{th} m_e c^2 = 40\ MeV \qquad x_{\max}(300\ GeV) = t_{\max} X_0 \approx 3000\ kg/m^2$$

$$E_{th,\mu}(10\ km) \approx \gamma_{th} m_\mu c^2 = 8\ GeV \qquad h_{\max}(300\ GeV) \approx 8.6\ km;\ \theta_{c,\max} \approx 0.7^{\circ}$$

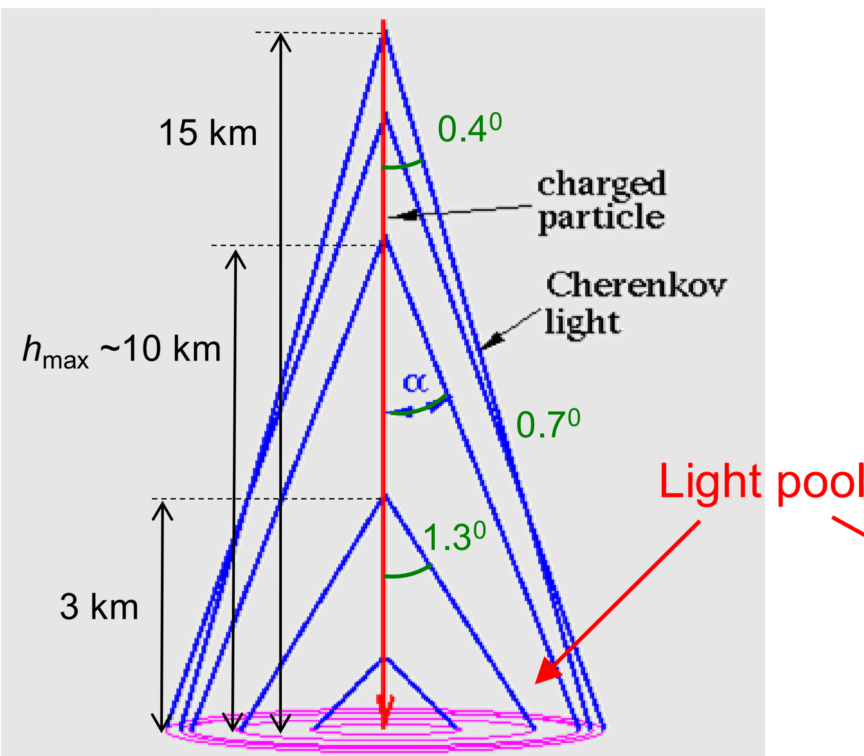
Cherenkov Radiation emitted by EAS

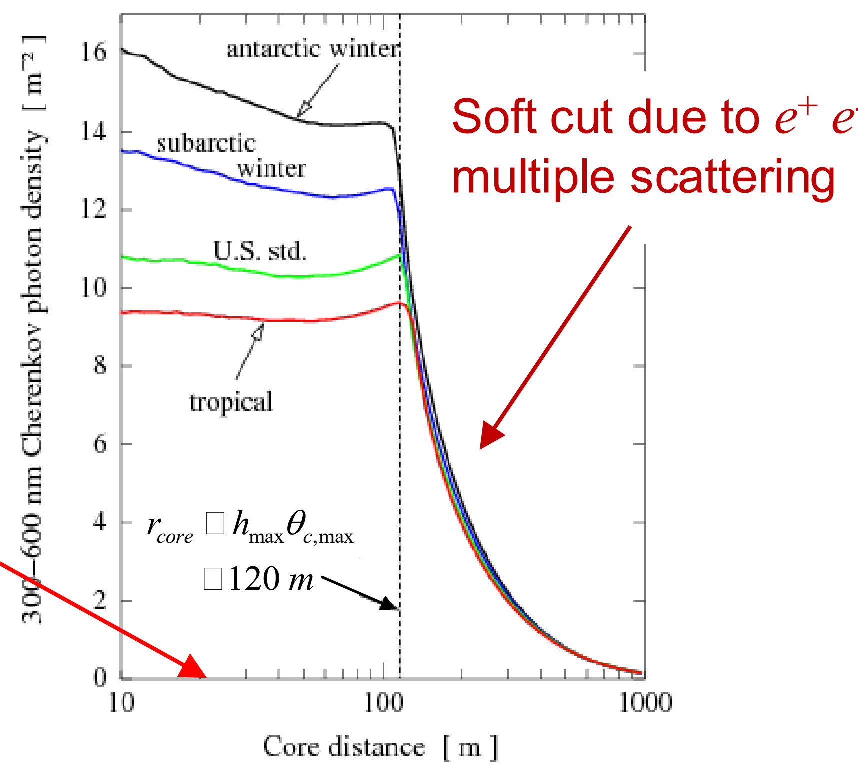
- Cherenkov light by a charged particle
- Cherenkov light by a charged part. on ground
- Cherenkov light by a shower on ground (MC)

$$\beta > \beta_{th} = \frac{1}{n}; \quad \cos\theta_c = \frac{1}{\beta n} \approx \frac{1}{n}$$

$$\frac{d^2E}{d\omega dx} = \frac{z^2 \alpha \hbar \omega}{c}\left(1 - \frac{1}{\beta^2 n^2(\lambda,\rho)}\right)$$

$$x_{\max}(300\ GeV) = t_{\max} X_0 \approx 3000\ kg/m^2;\ h_{\max}(300\ GeV) \approx 8.6\ km;\ \theta_{c,\max} \approx 0.7^{o}$$





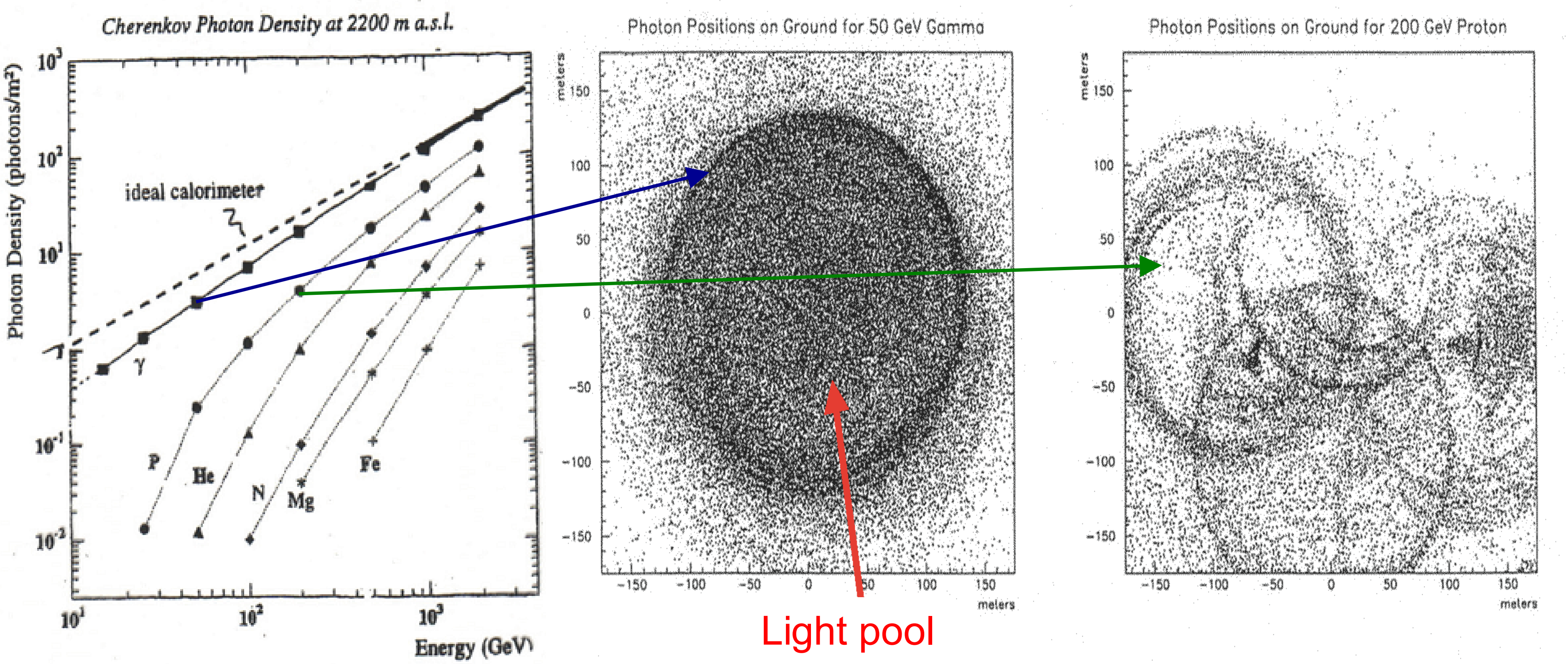
Cherenkov Telescopes

Cherenkov Radiation emitted by EAS

- Cherenkov light by a charged particle
- Cherenkov light by a charged part. on ground
- Cherenkov light by a shower on ground (MC)
  - → *tail-catcher or full-active calorimeter*

$$\beta > \beta_{th} = \frac{1}{n}; \quad \cos\theta_c = \frac{1}{\beta n} \; \square \; \frac{1}{n}$$

$$\frac{d^2E}{d\omega dx} = \frac{z^2\alpha\hbar\omega}{c}\left(1 - \frac{1}{\beta^2 n^2(\lambda,\rho)}\right)$$



Cherenkov Telescopes

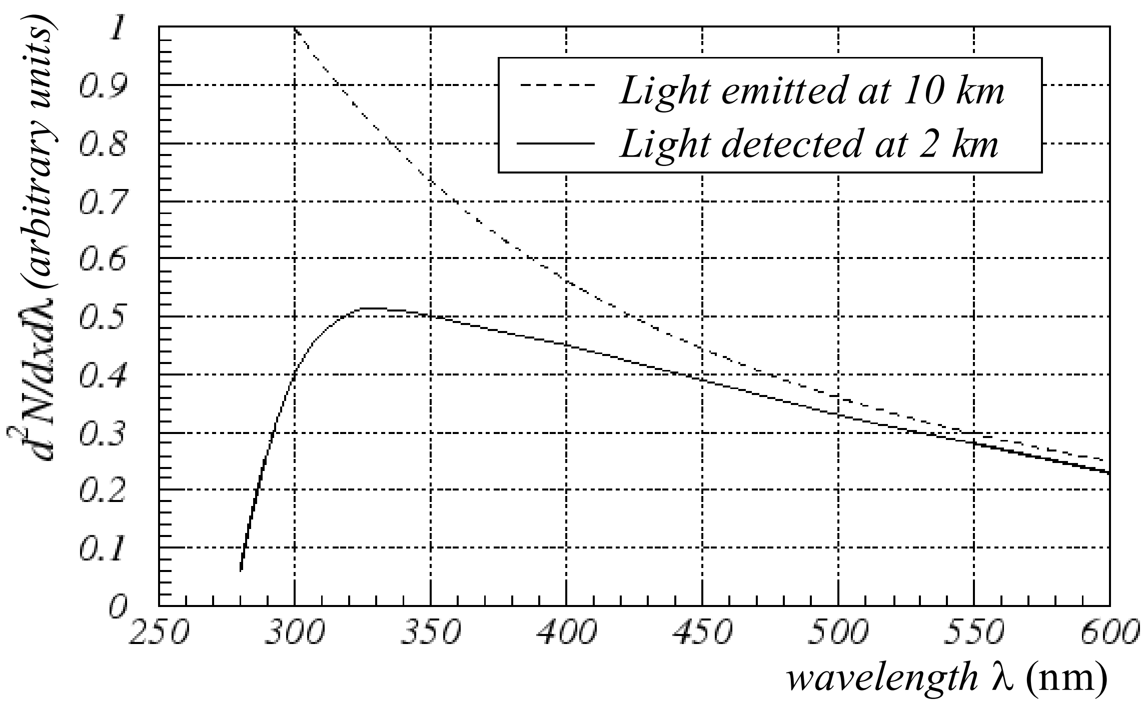
Cherenkov Radiation emitted by EAS

- Cherenkov light by a charged particle
- Cherenkov light by a charged part. on ground
- Cherenkov light by a shower on ground (MC)
- Chernkov spectrum on ground

  (incl. ozone+Rayleigh+aerosol absorbtion)

$$\beta > \beta_{th} = \frac{1}{n}; \quad \cos\theta_c = \frac{1}{\beta n} \;\square\; \frac{1}{n}$$

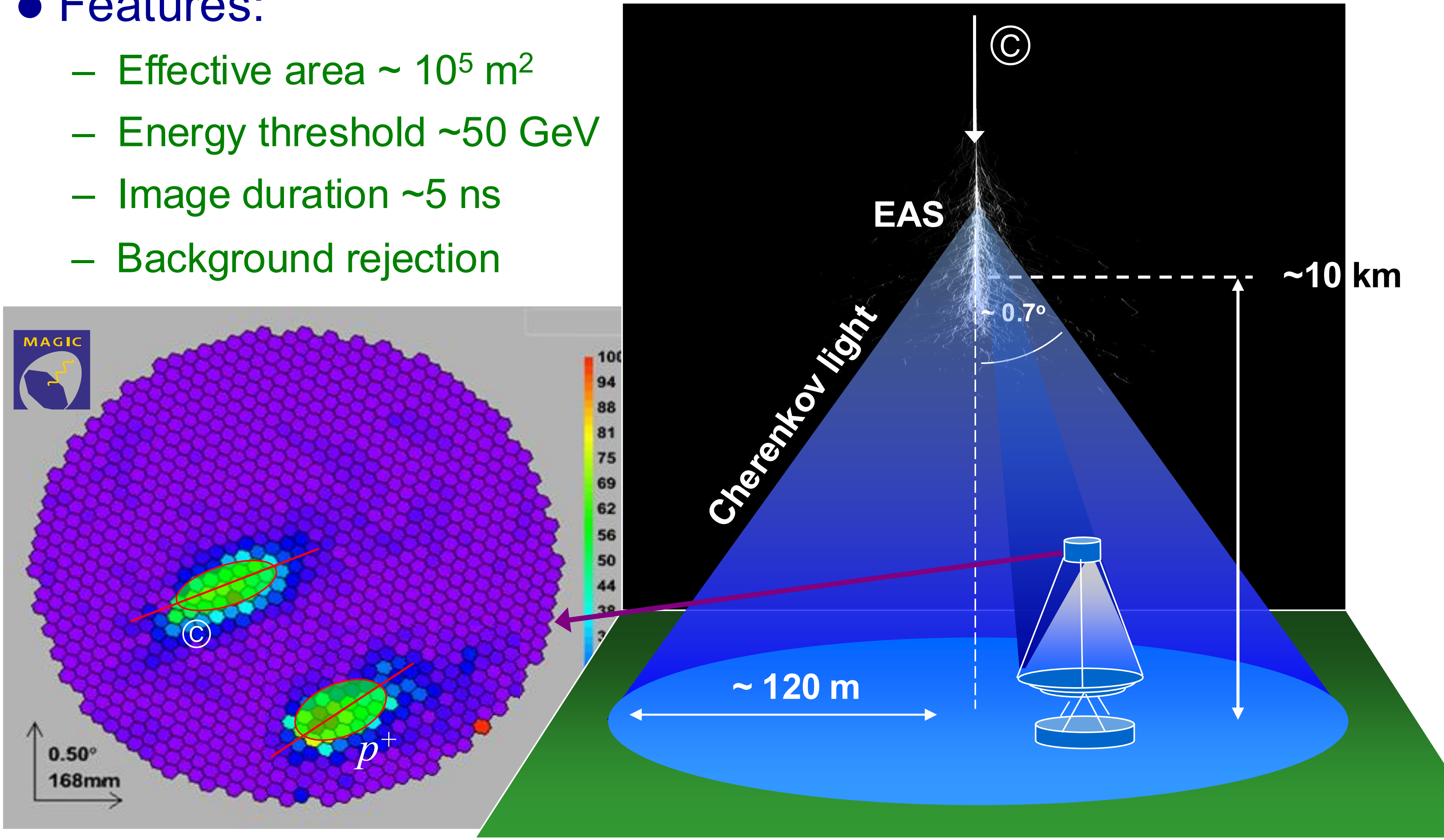
$$\frac{d^2E}{d\omega dx} = \frac{z^2\alpha\hbar\omega}{c}\left(1 - \frac{1}{\beta^2 n^2(\lambda,\rho)}\right)$$



$$\frac{d^2N}{d\lambda dx} = \frac{z^2\alpha}{c}\sin^2\theta_c \frac{1}{\lambda^2}$$

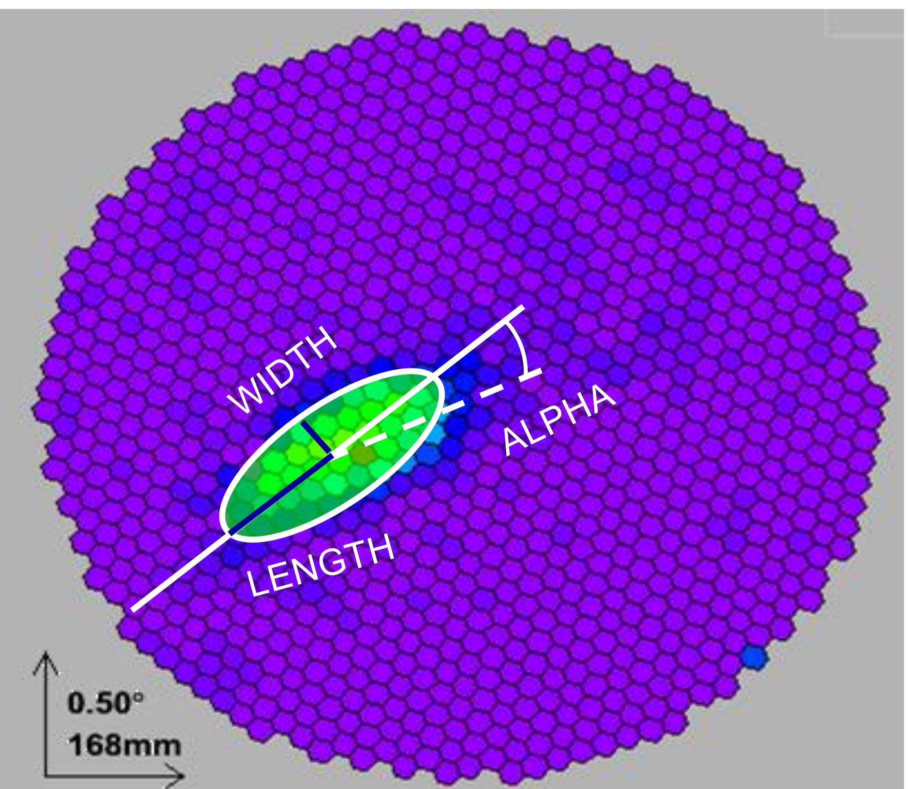
Operation principle

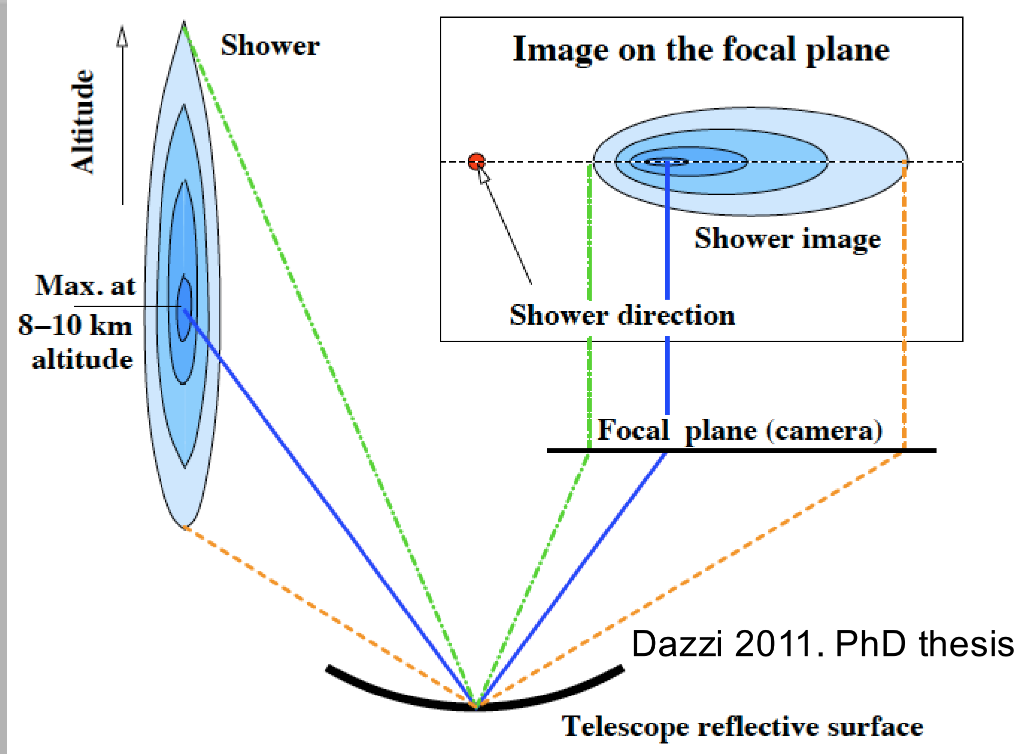
- Features:
  - Effective area ~ 10^5 m^2
  - Energy threshold ~50 GeV
  - Image duration ~5 ns
  - Background rejection



Operation principle

- Imaging Atmospheric Cherenkov Telescope (IACT):
  - Shower develop. *imaged* at the telescope camera (*full-active calorimeter*)
  - 2nd moments of Cherenkov light distribition at camera: Hillas parameters
  - Background rejection, Energy, Direction of arrival and Impact parameter

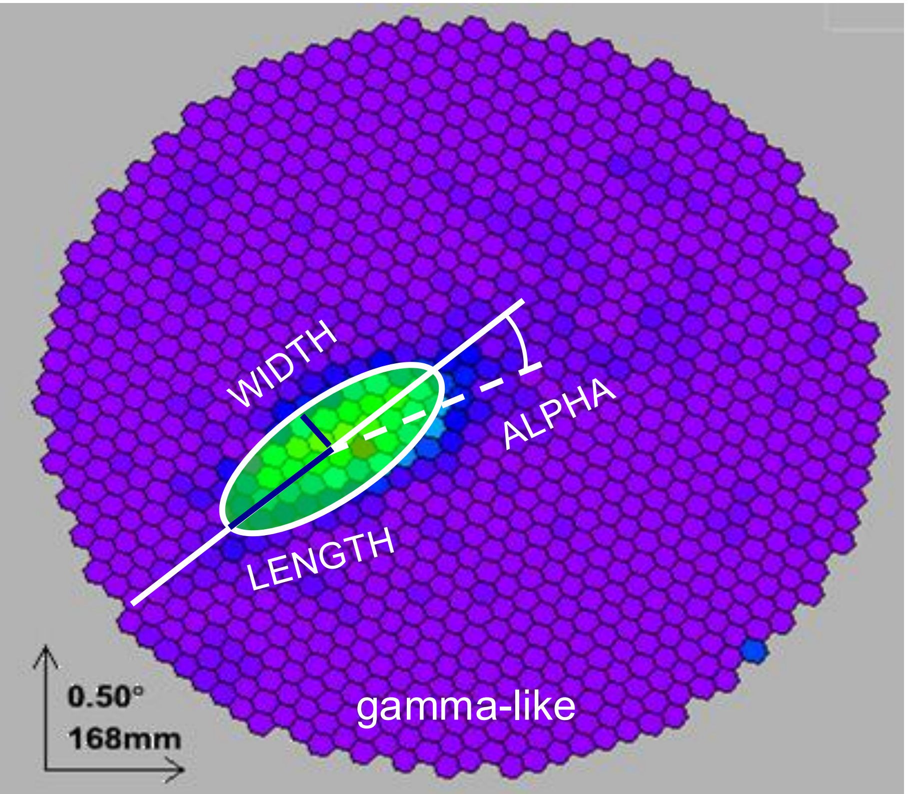


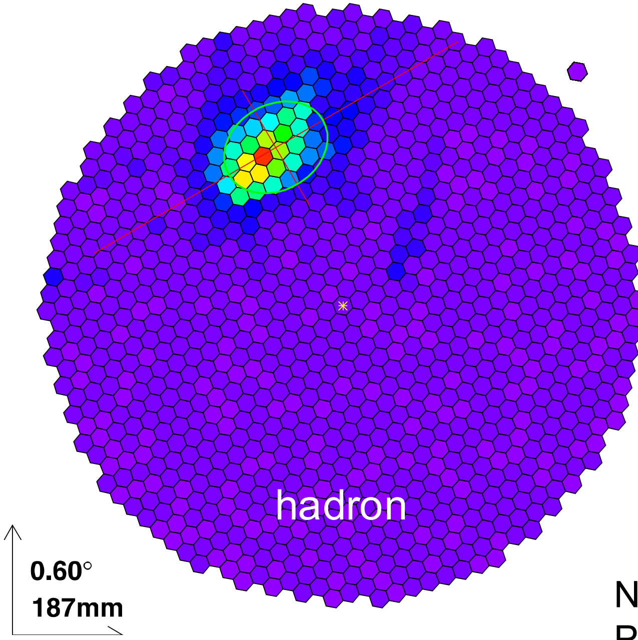


Cherenkov Telescopes

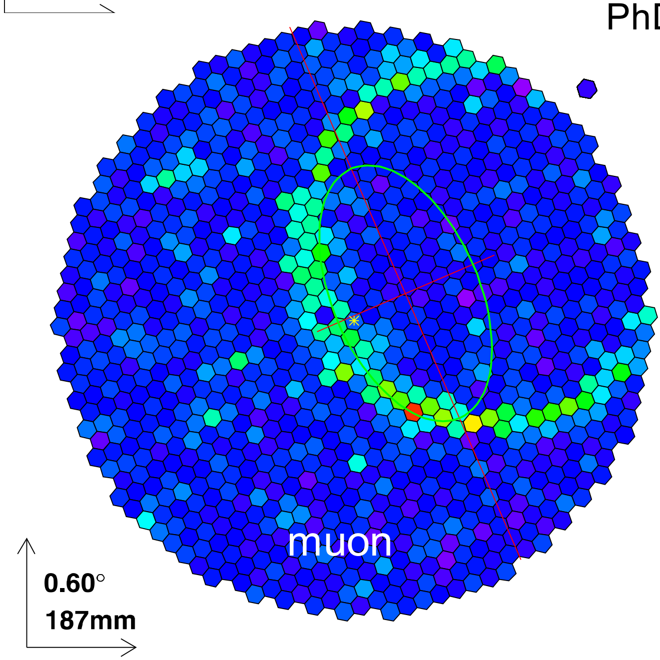
Operation principle

- IACT:
  - EAS develop. *imaged* at camera
  - Hillas parameters
  - Background rejection





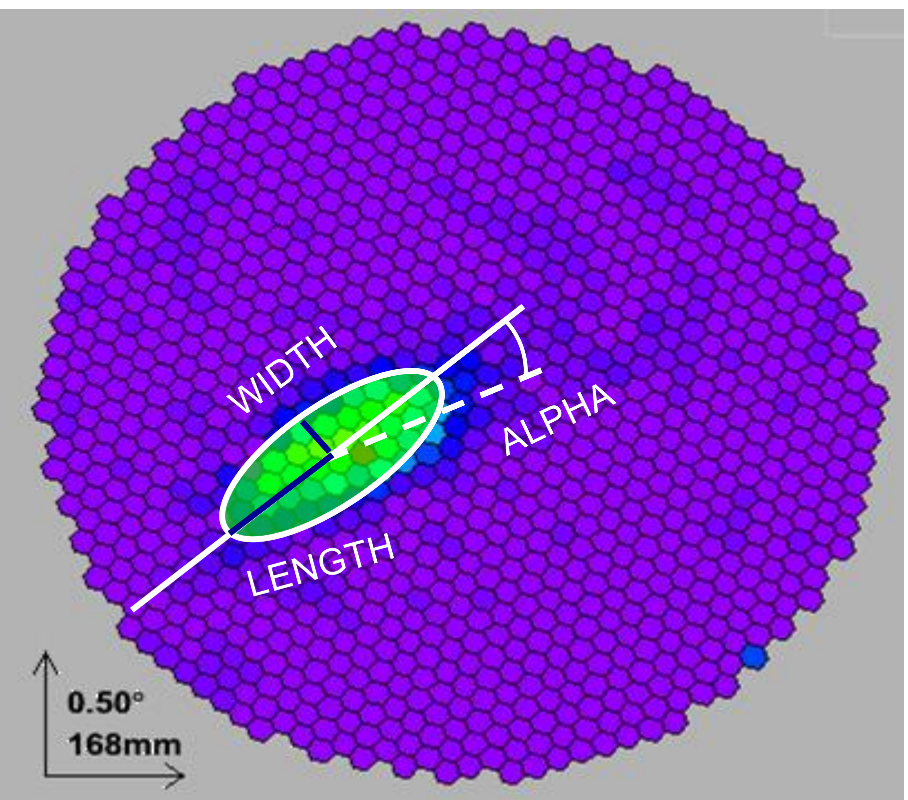
Nieto 2012, PhD thesis



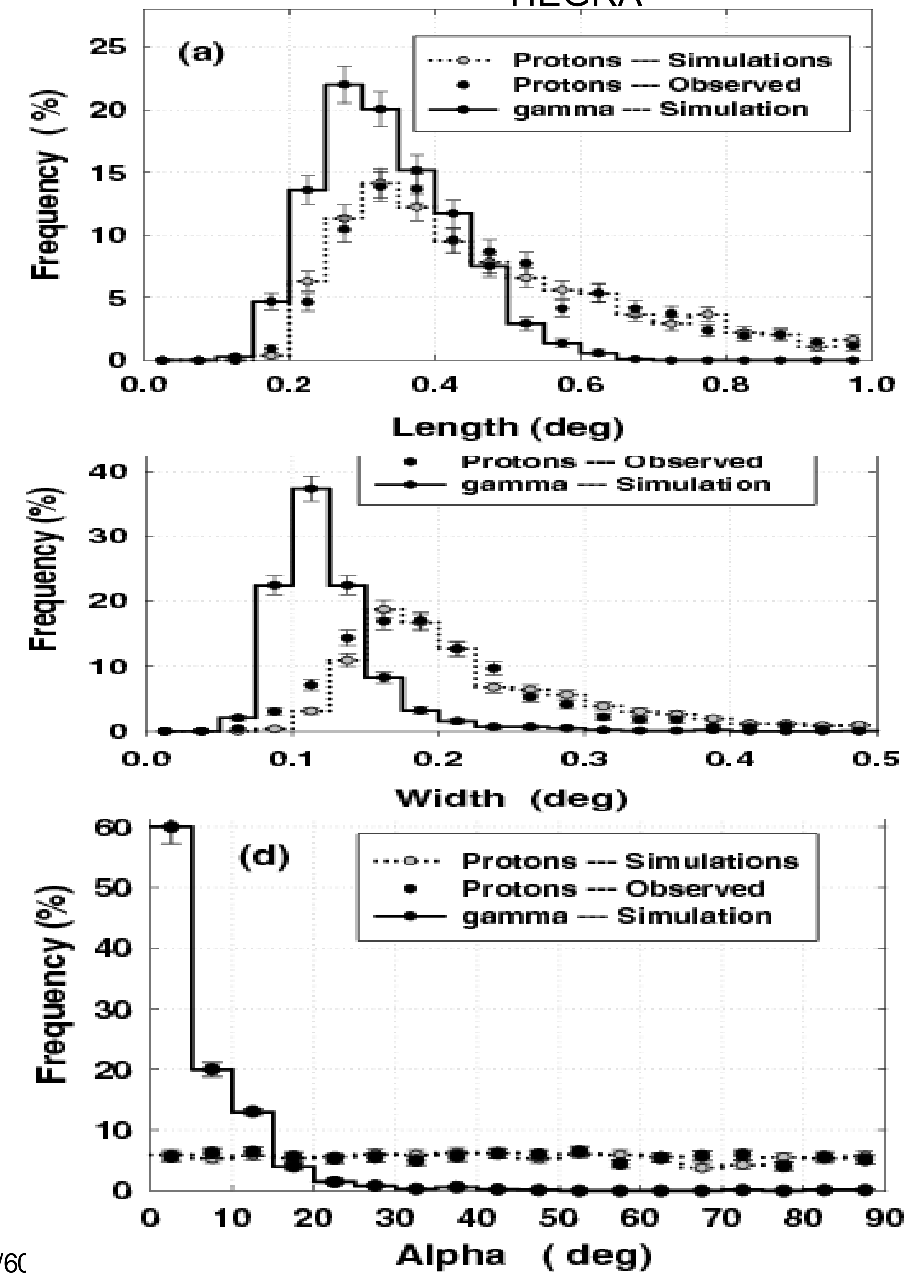
Cherenkov Telescopes

Operation principle

- IACT:
  - EAS develop. *imaged* at camera
  - Hillas parameters
  - Background rejection



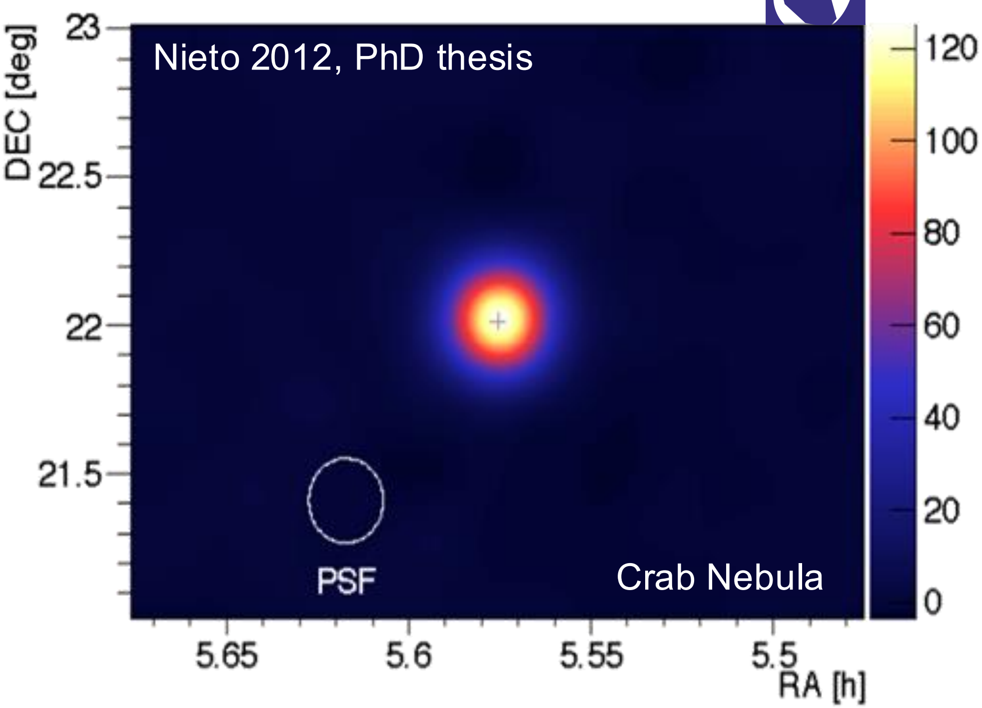
HEGRA



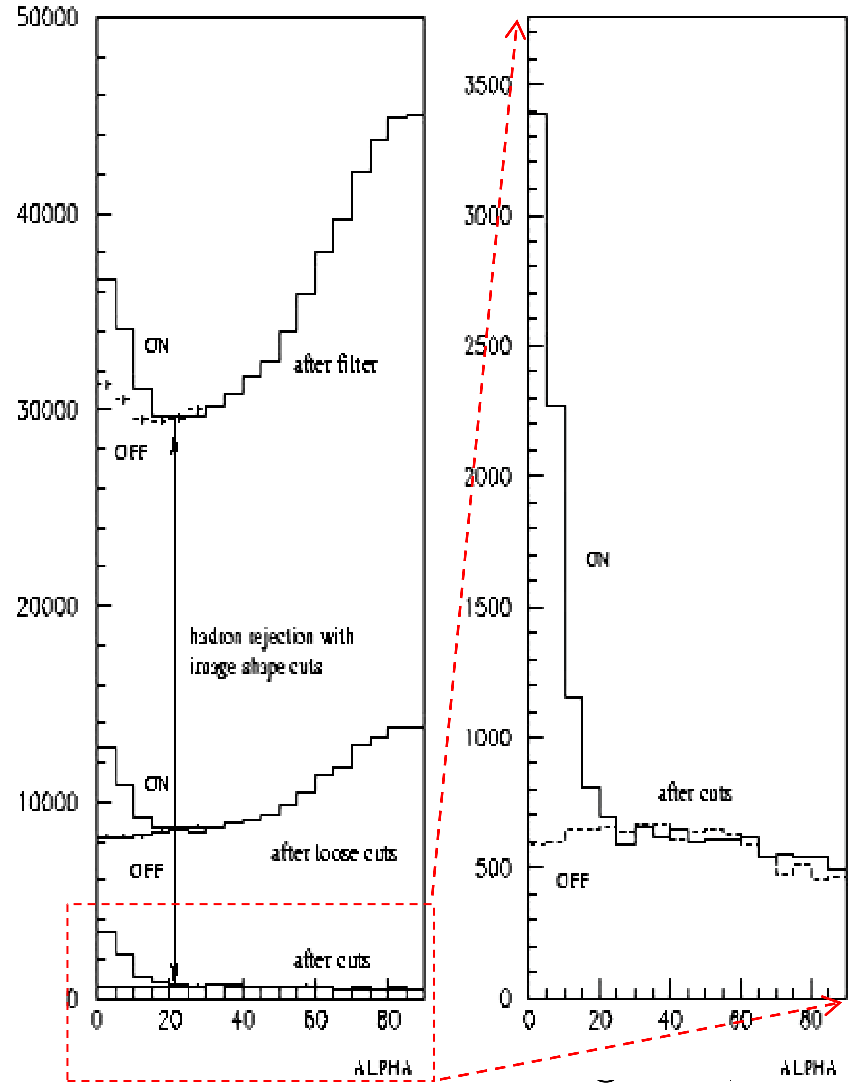
Cherenkov Telescopes

Operation principle

- IACT:
  - EAS develop. *imaged* at camera
  - Hillas parameters
  - Hadron rejection factor ~200, angular resolution ~0.1°



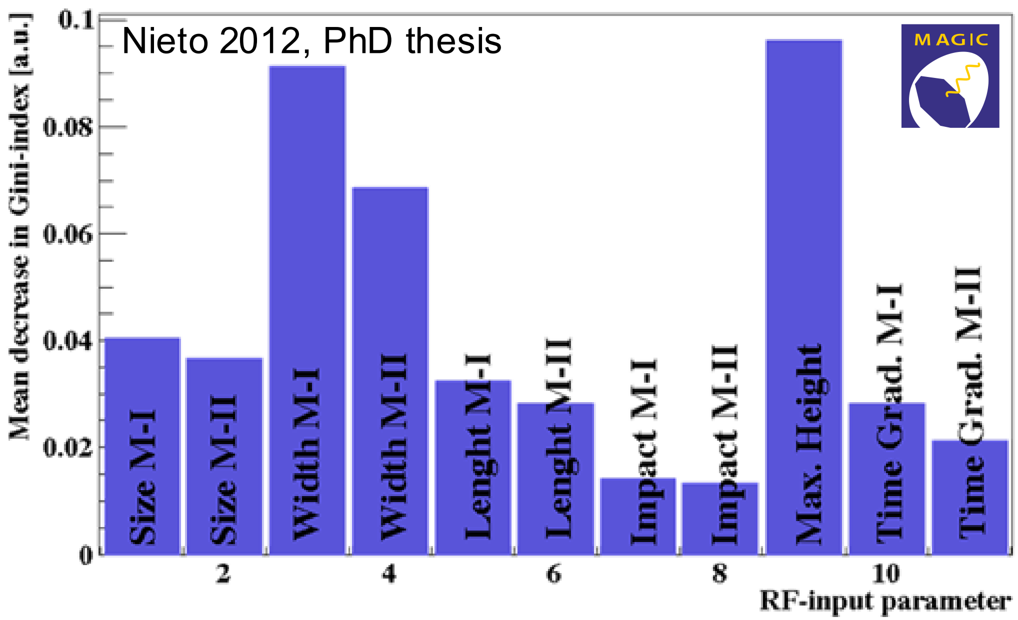
HEGRA CT1: Mkn 501, 1997

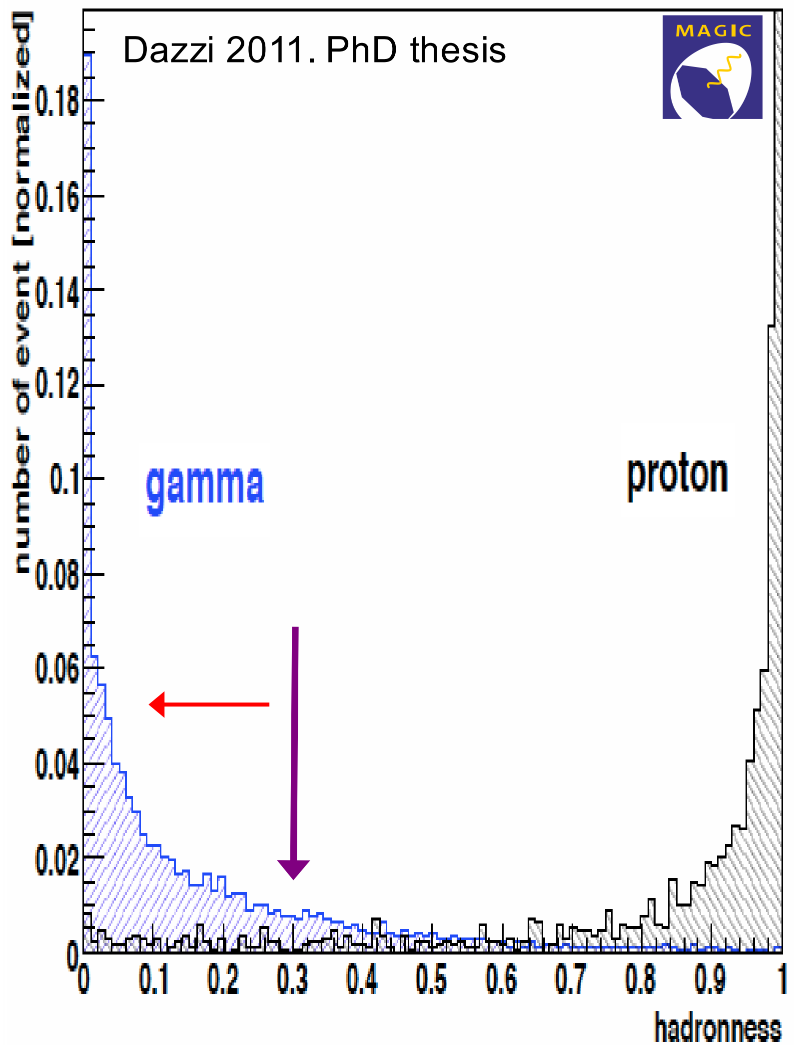


Operation principle

- IACT:
  - EAS develop. *imaged* at camera
  - Hillas parameters → Machine Learning
  - Hadron rejection factor ~200, angular resolution ~0.1º

Bagging Decision Trees (aka *Random Forest)*

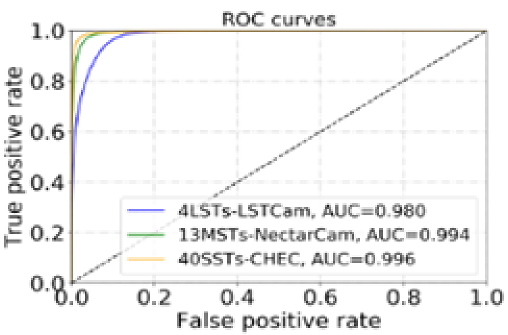


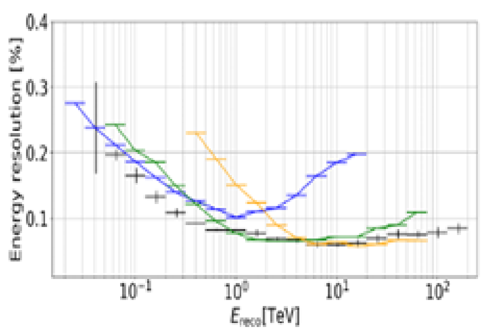


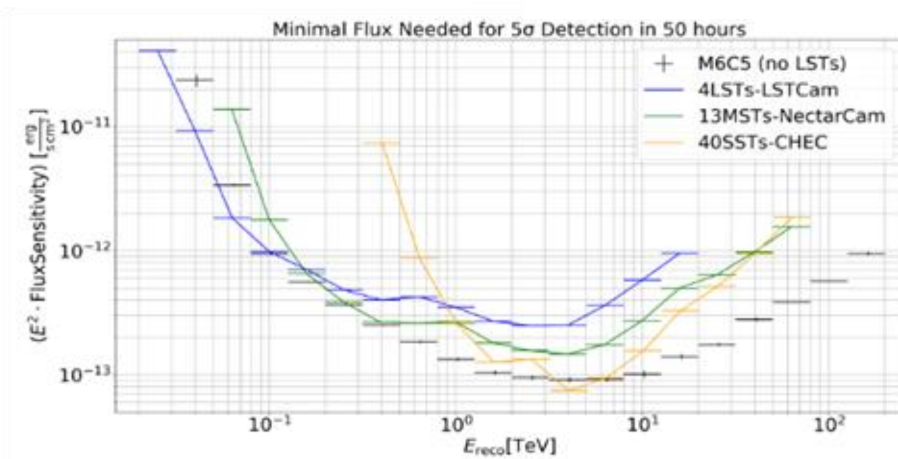
Cherenkov Telescopes

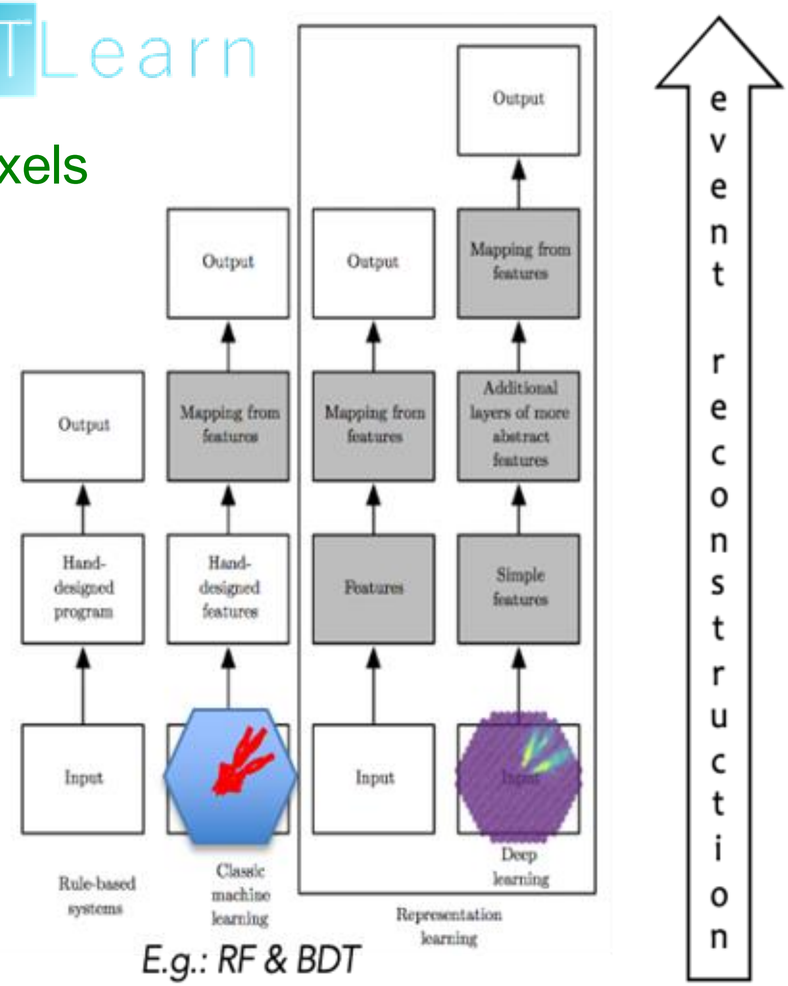
Operation principle

- IACT:
  - EAS develop. *imaged* at camera
  - CNN-based reconstruction based of pixels
  - Demonstrated on MAGIC real data









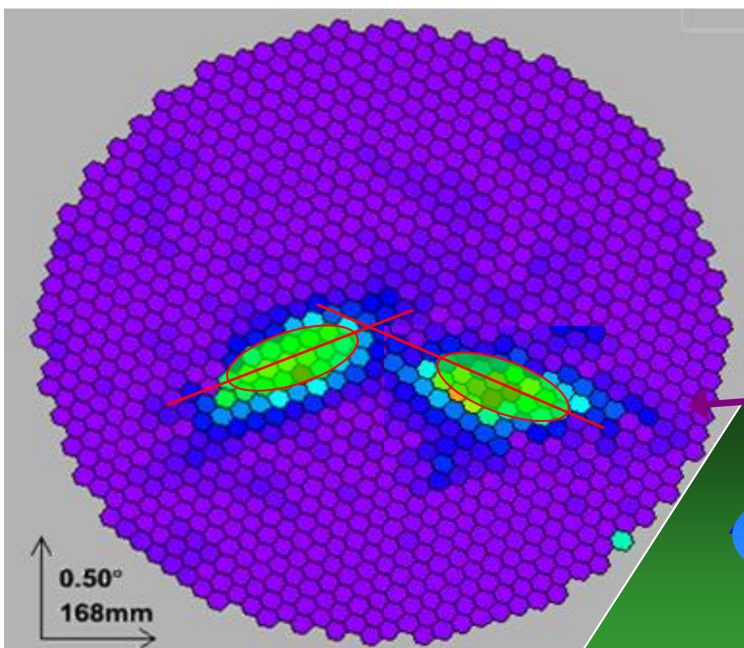
DOI 10.5281/zenodo.3342952

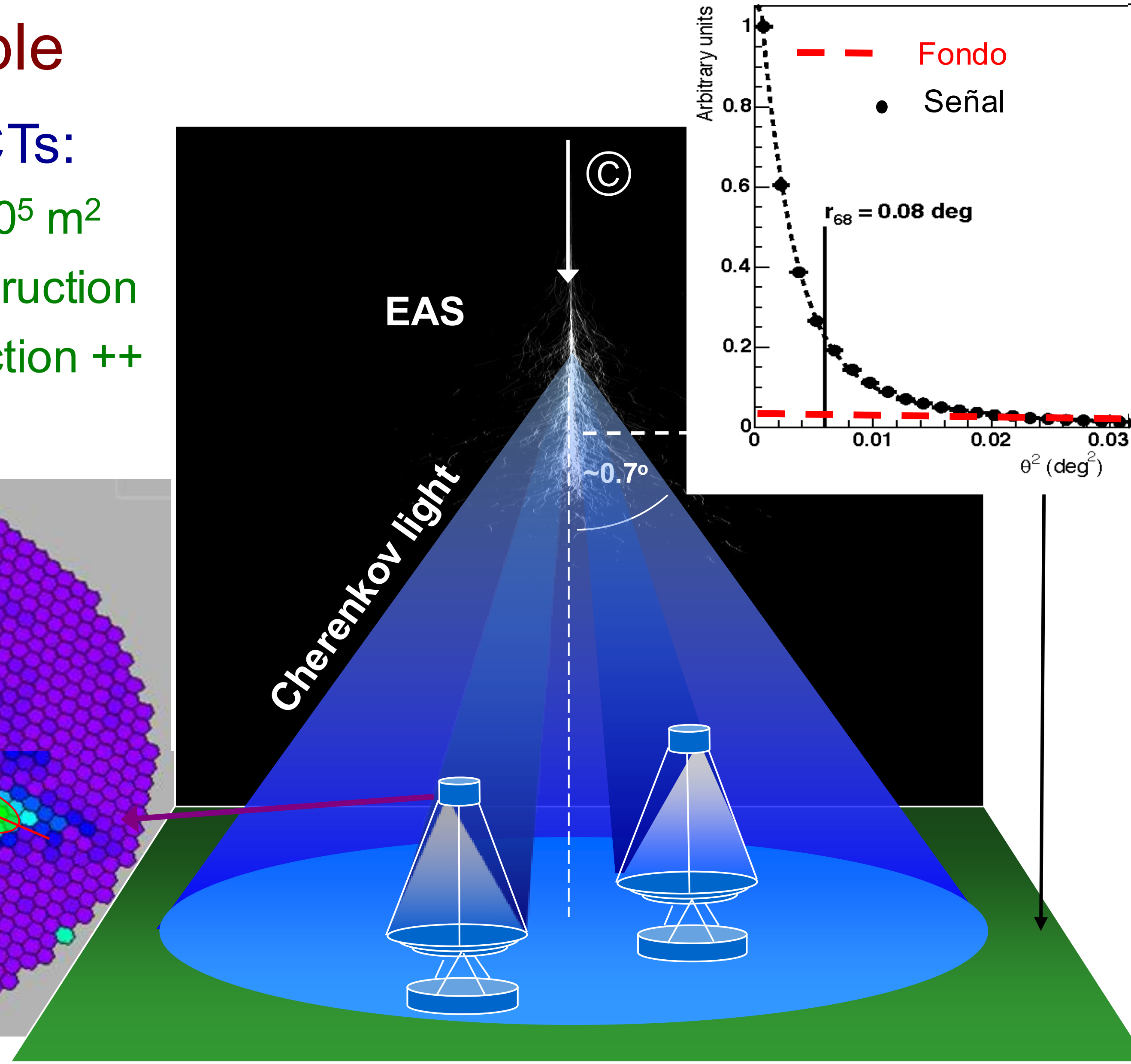
T. Miener et al., PoS(ICRC2025)757

Cherenkov Telescopes

Operation principle

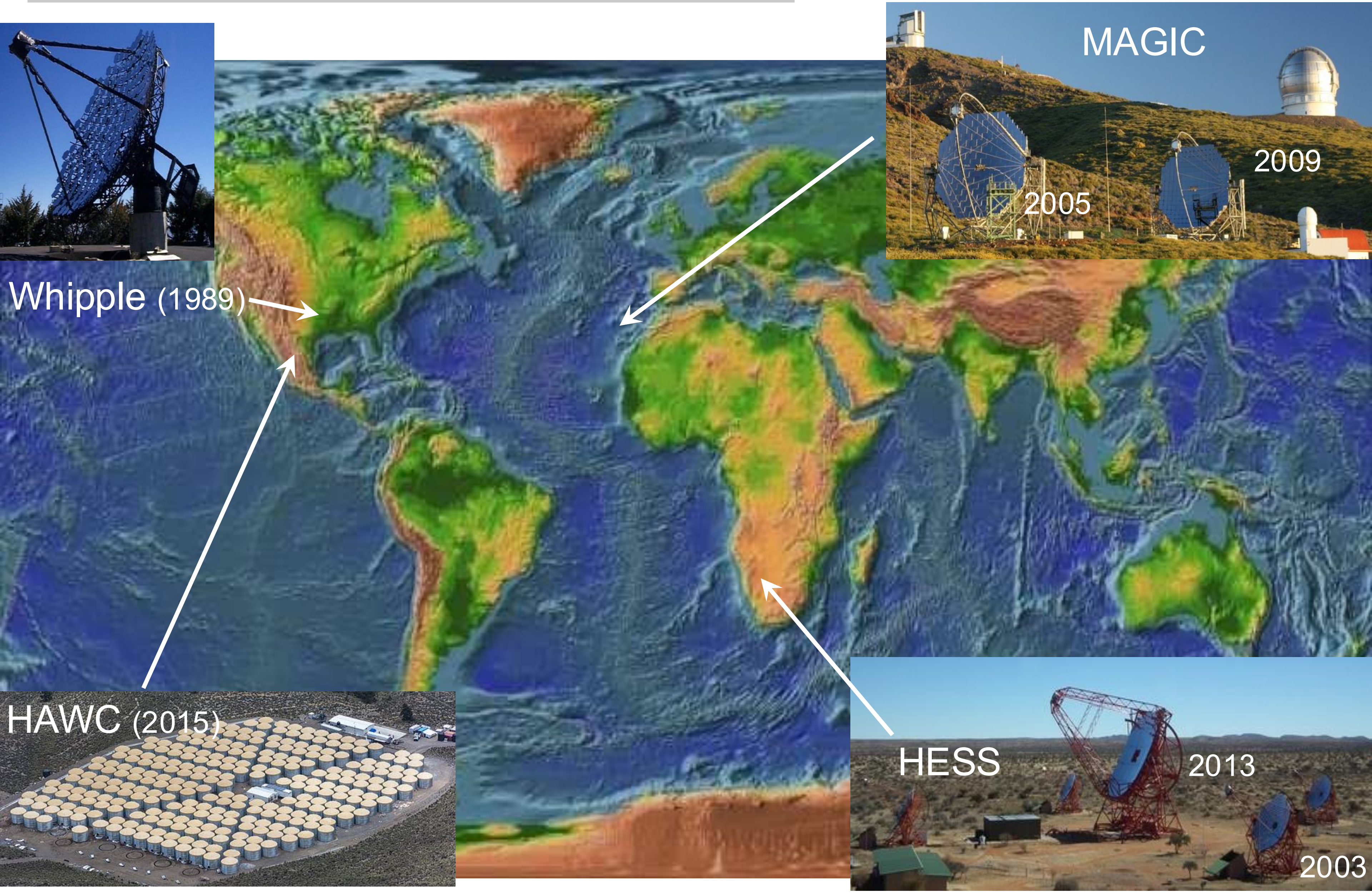
- **Stereoscopic IACTs:**
  - Effective area ~10^5 m^2
  - Improved reconstruction
  - Background rejection ++





Contents

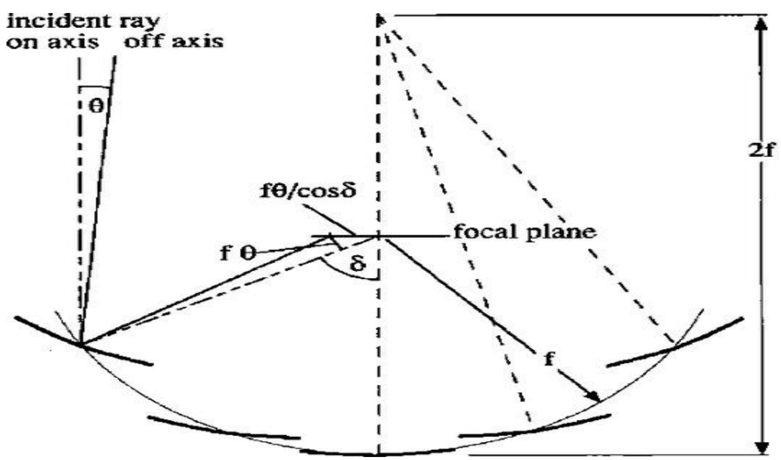
Instruments

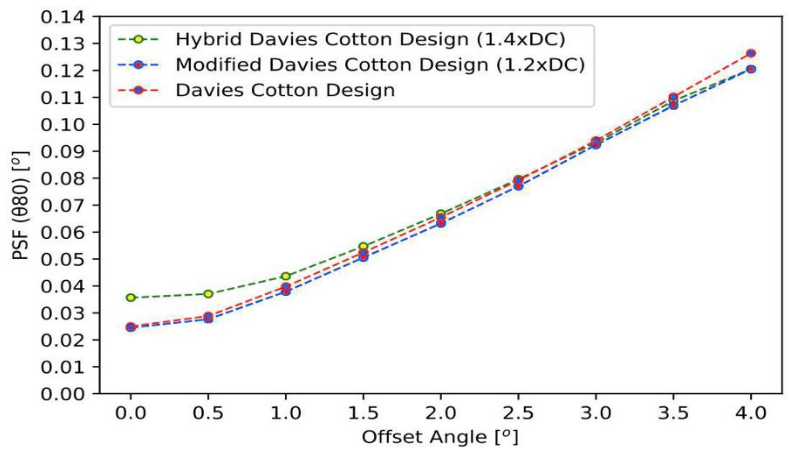


Telescope Building Blocks

Structure

- Layout:
  - Aimed pointing accuracy ~0.004º
  - Modified-Davies-Cotton for off-axis

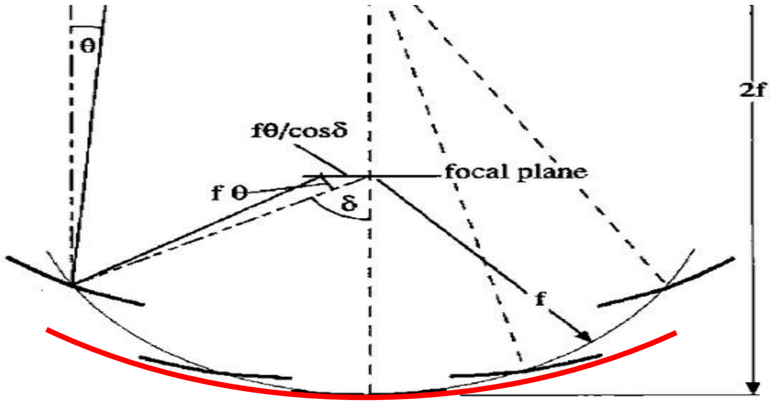


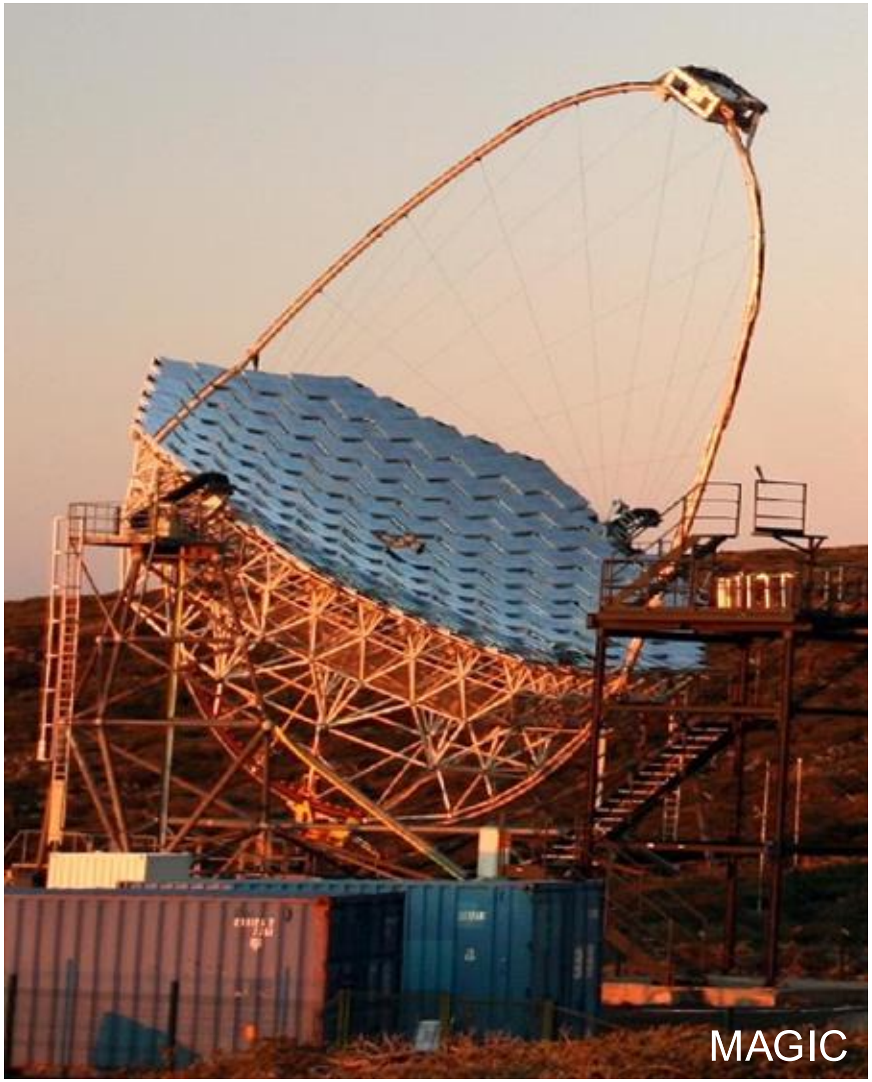


Telescope Building Blocks

Structure

- Layout:
  - Aimed pointing accuracy ~0.004º
  - Modified-Davies-Cotton for off-axis
  - Parabolic for isocronous photons





Telescope Building Blocks

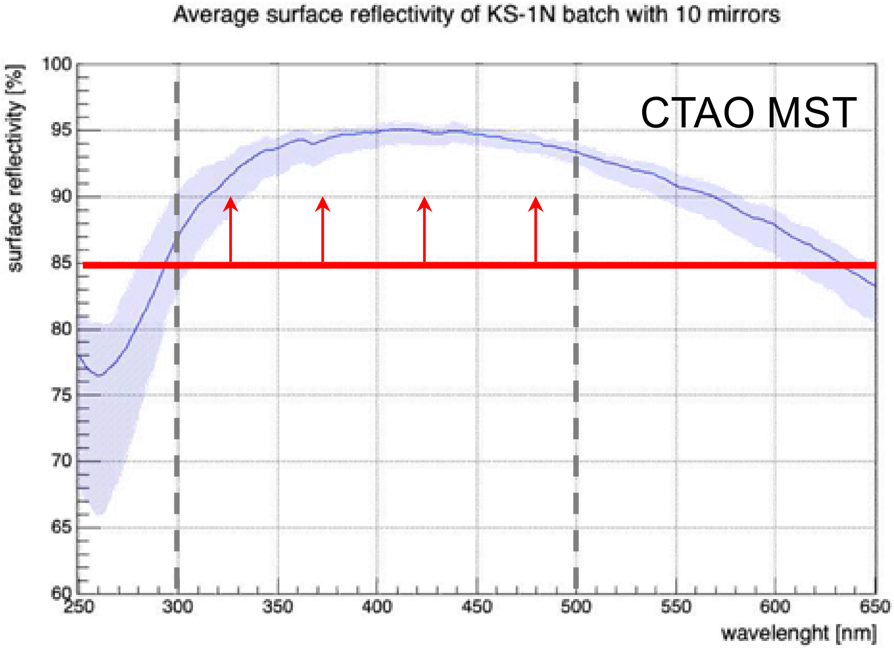
Structure

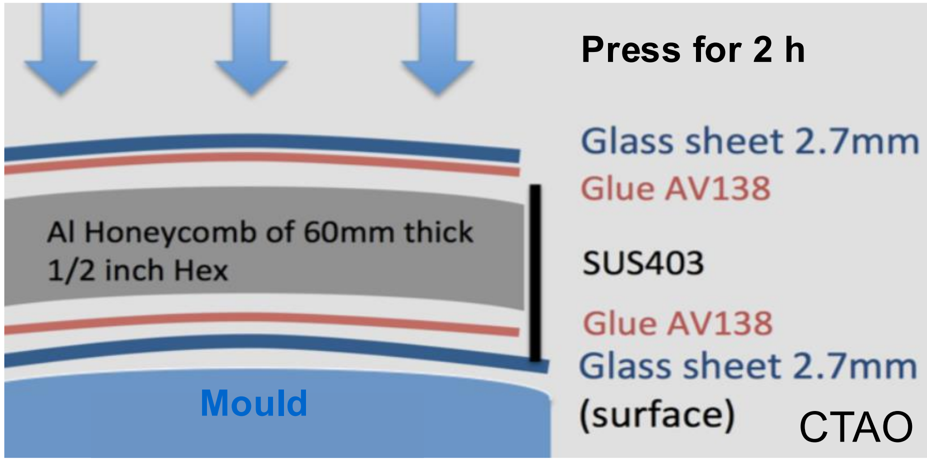
- Layout:
  - Aimed pointing accuracy ~0.004º
  - Modified-Davies-Cotton for off-axis
  - Parabolic for isocronous photons
  - Alt-Azimuth mount
- Light-weight structure (CFRP tubes)

Telescope Building Blocks

Optics

- Reflecting surface
  - Teselated light-weight mirrors
  - Multilayer spherical cold-slumped
  - Reflectivity >~90%

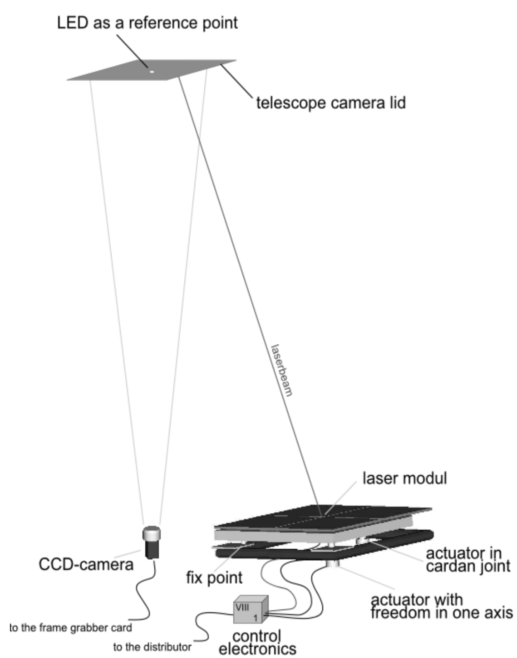


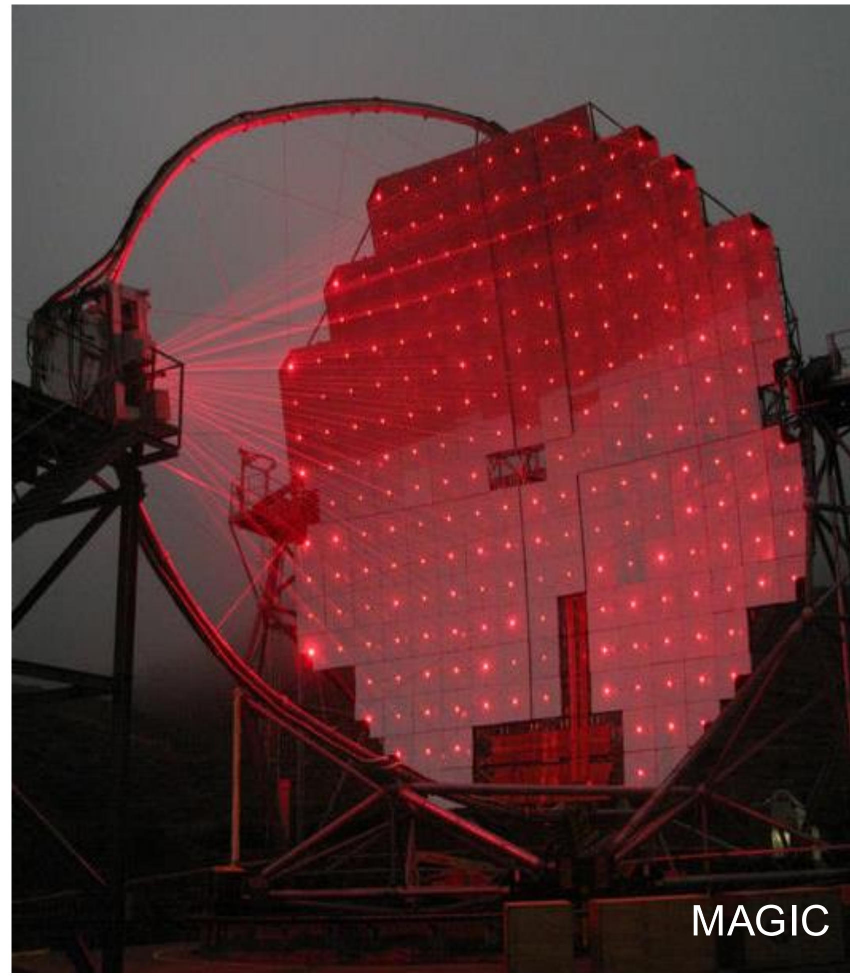


Telescope Building Blocks

Optics

- Reflecting surface
  - Teselated light-weight mirrors
  - Multilayer spherical cold-slumped
  - Reflectivity >~90%
- Active Mirror Control
  - Laser-spot+CCD+actuators

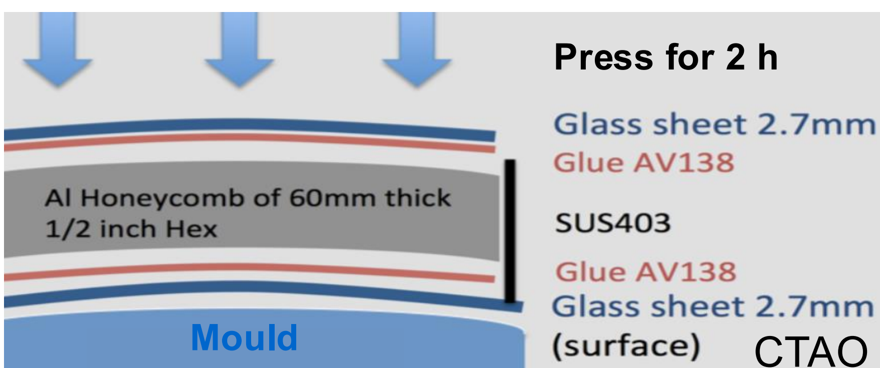




Telescope Building Blocks

Optics

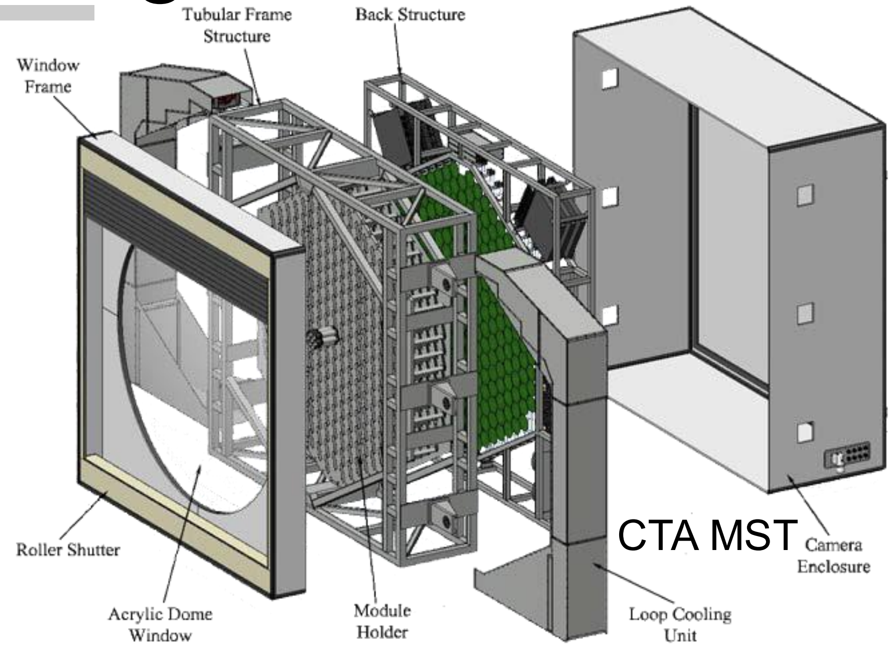
- Reflecting surface:
  - Teselated light-weight mirrors
  - Multilayer spherical cold-slumped
  - Reflectivity >~90%
- Active Mirror Control
  - Laser-spot+CCD+actuators
- Outdoor operation
  - No dome → mirror protection
  - Evaporated *Al/xx* + *SiO_2/yyO_2*
  - Harsh conditions

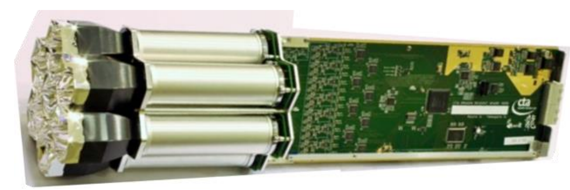


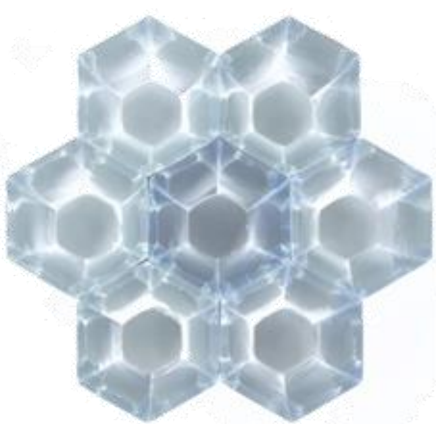
Telescope Building Blocks

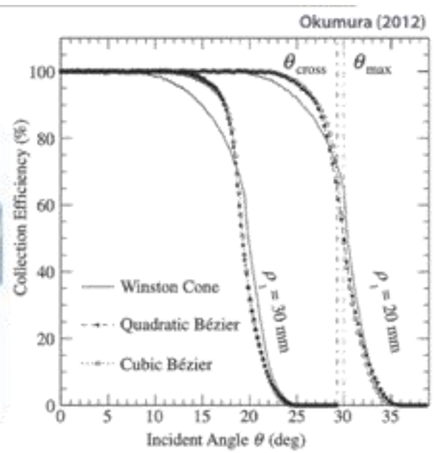
Camera

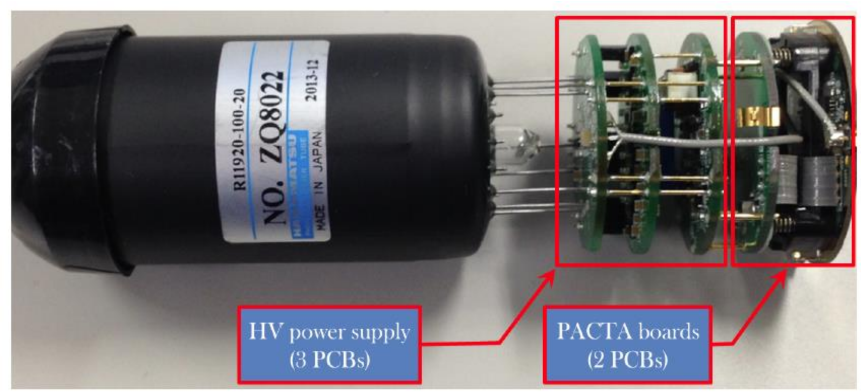
- Mechanics & cooling
  - Sealed, ~1000 pixel ~5º FoV (3 m)
  - Water/air cooling
  - Modular structure: ~10-pix + FEBs
- Focal Plane Instrumentation
  - Light concentrators
  - 40% QE PMTs
  - Preamp with dual gain (0.5 - 1000 pe)





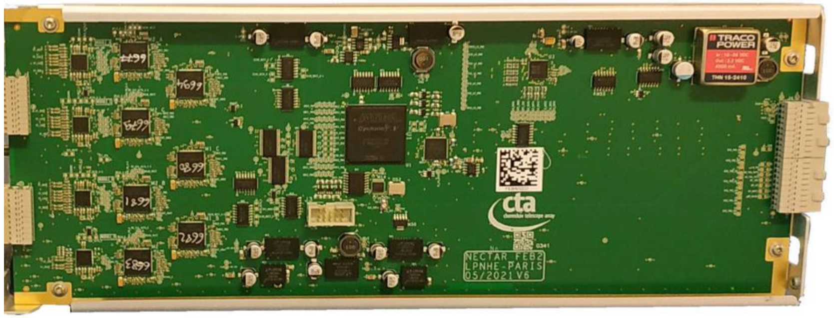






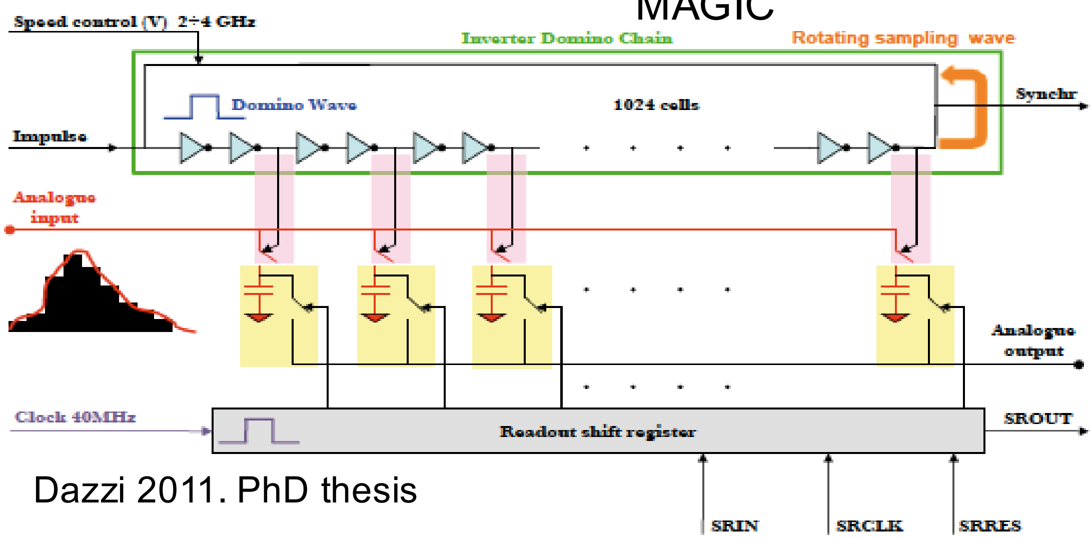
Camera

- Read-out & DAQ
  - FEBs based on Switched Capacitor Array ASICs
  - 1 GS/s sampling, ~500 MHz BW & 12-bit ADC @ 40 MHz
  - FEB buffers delivered (TCP/UDP) to Event Builder multi-core PC on ground at ~10 kHz trigger rate via Ethernet Switches

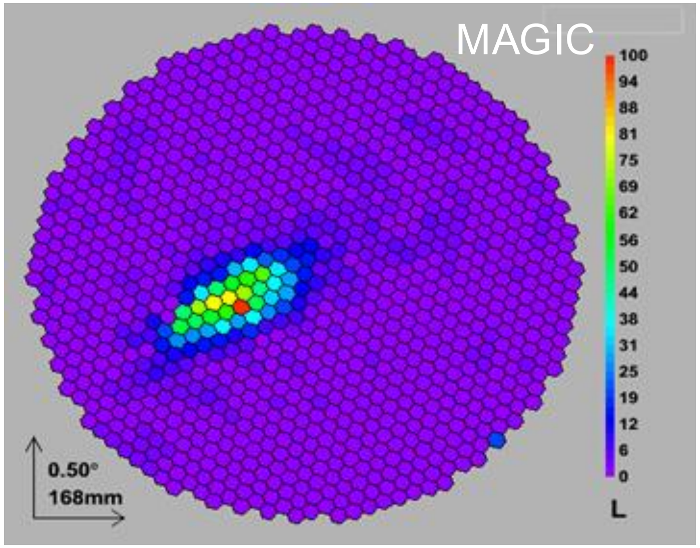


CTA MST

MAGIC

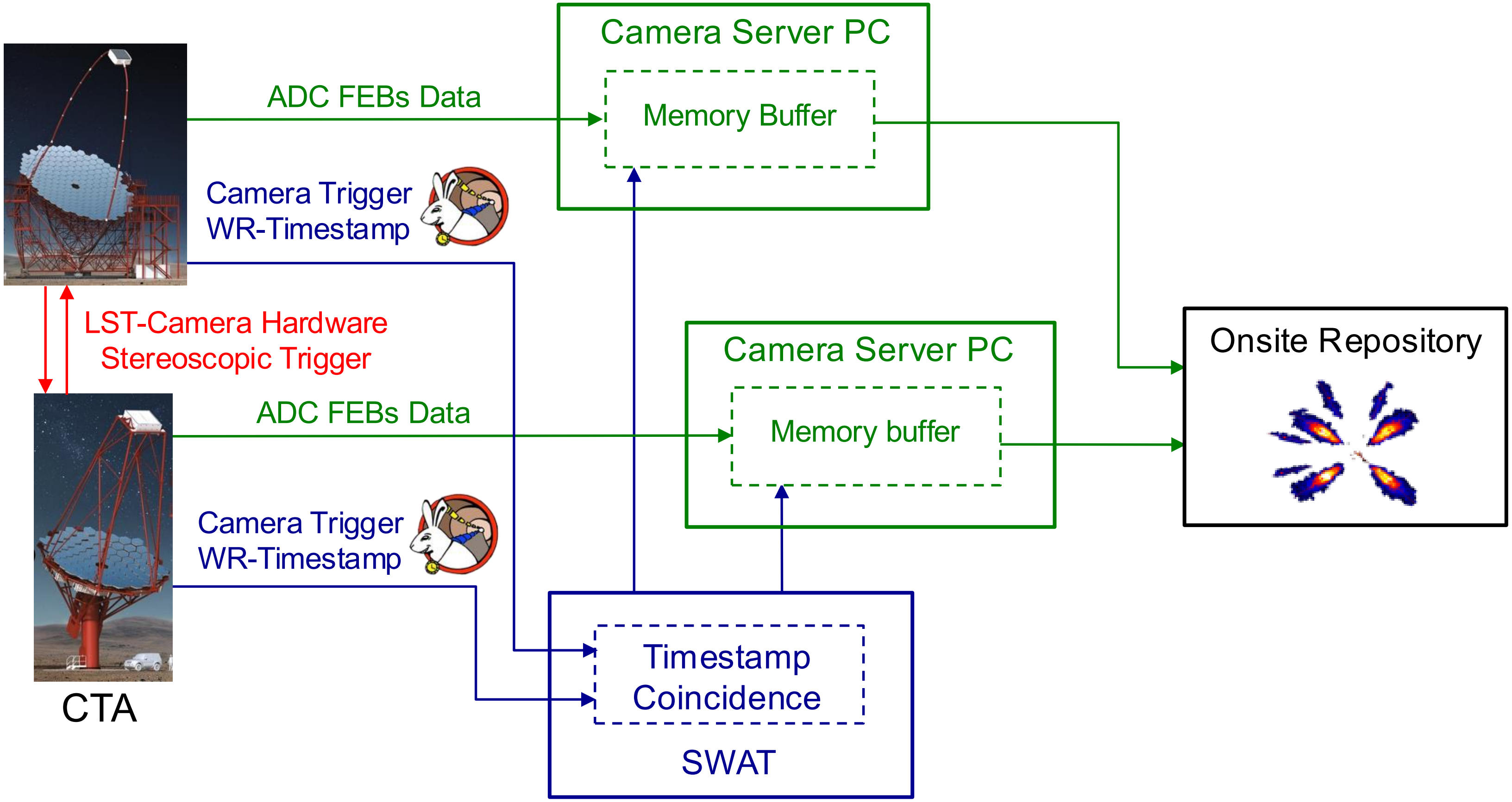


Dazzi 2011. PhD thesis



Camera: multi-level trigger

- Array Trigger
  - Stereoscopic SoftWare Array Trigger, with ~1 s latency,
  - Based on White-Rabbit-timestamped Camera Triggers

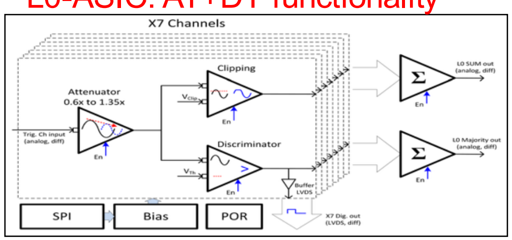


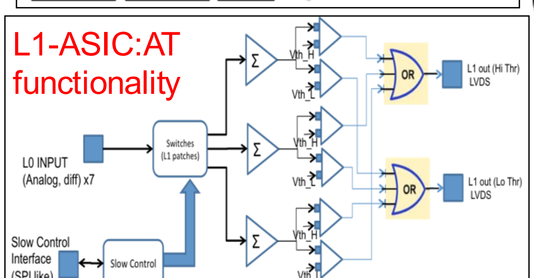
Telescope Building Blocks

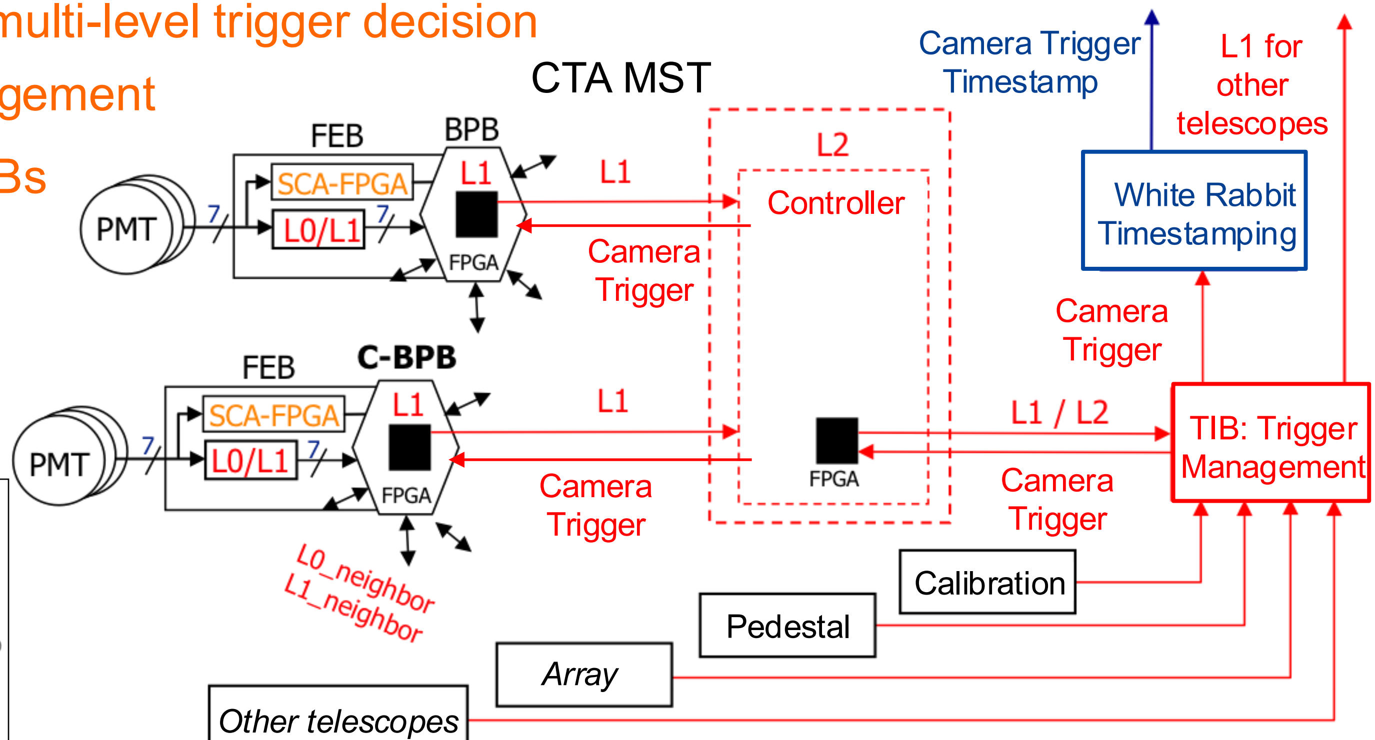
Camera: multi-level trigger

- Array Trigger
- Camera Trigger
  - Separate gamma-ray-like from NSB-induced events
  - Triggers the readout of the FEB SCA buffers (1 – 4 μs depth)
  - Hardware trigger (latency ~250 ns, precision ~1 ns), in stages:
    - ASIC-based multi-level trigger decision
    - Trigger management
    - Trigger to FEBs

L0-ASIC: AT+DT functionality



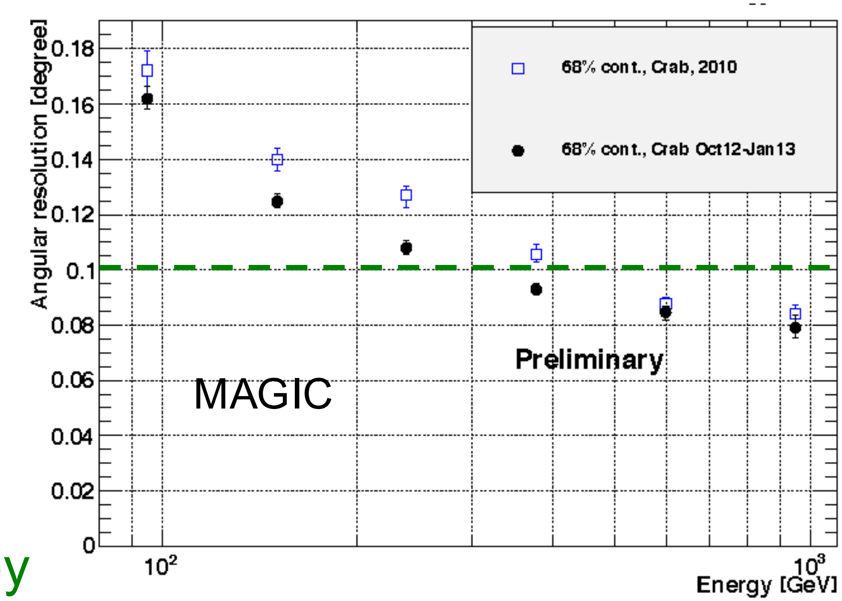


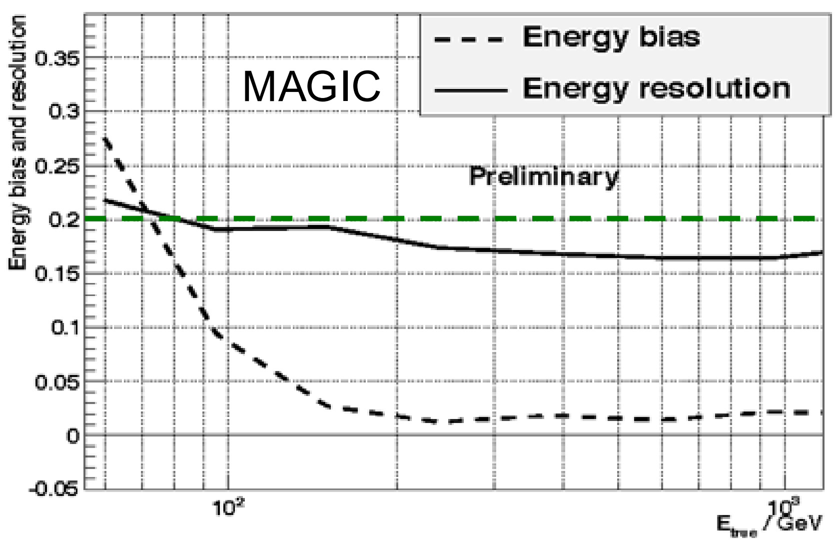


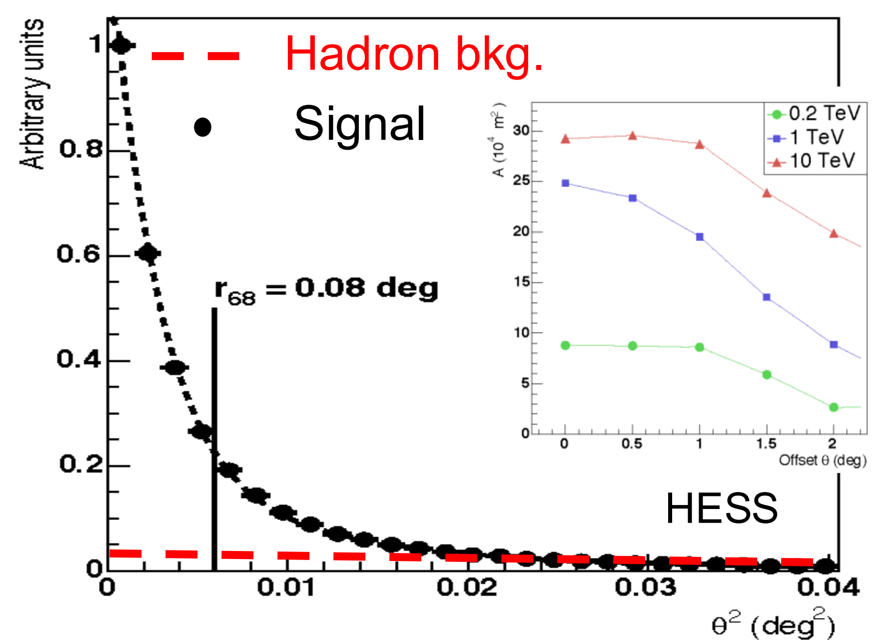
Telescope Building Blocks

Telescope performance

- Aim
  - E_{th} ~50 GeV (match satellites)
  - Fast repositioning (20 s, for GRBs)
  - $\Delta E/E$ <20%, $\Delta\theta$ ~ 0.1º @ 300 GeV
- Results
  - Improved sensitivity from stereoscopy
  - Extended-source analysis







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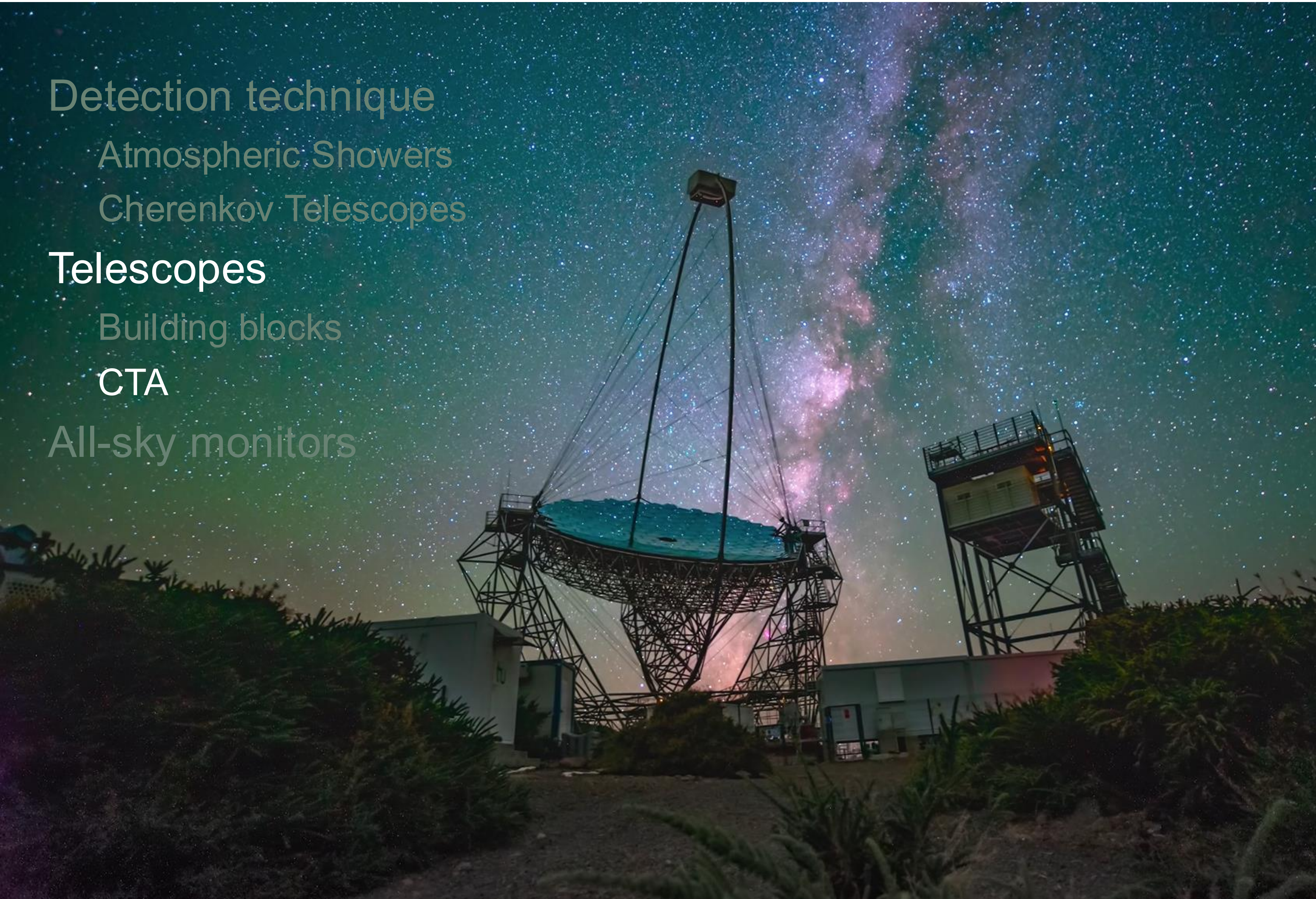
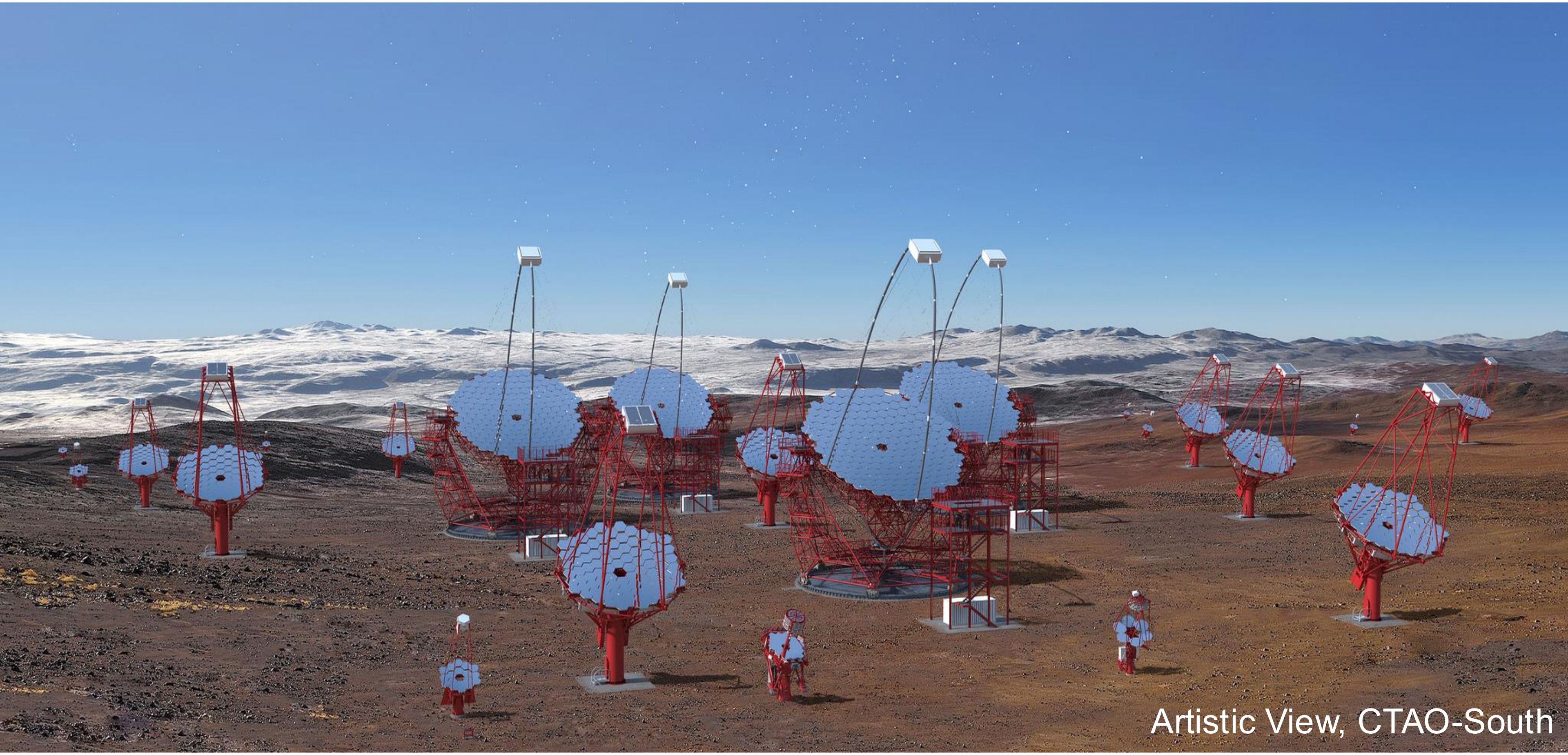


Cherenkov Telescope Array



Improved Sensitivity x10
Extended Energy Coverage x10
Improved Angular Resolution

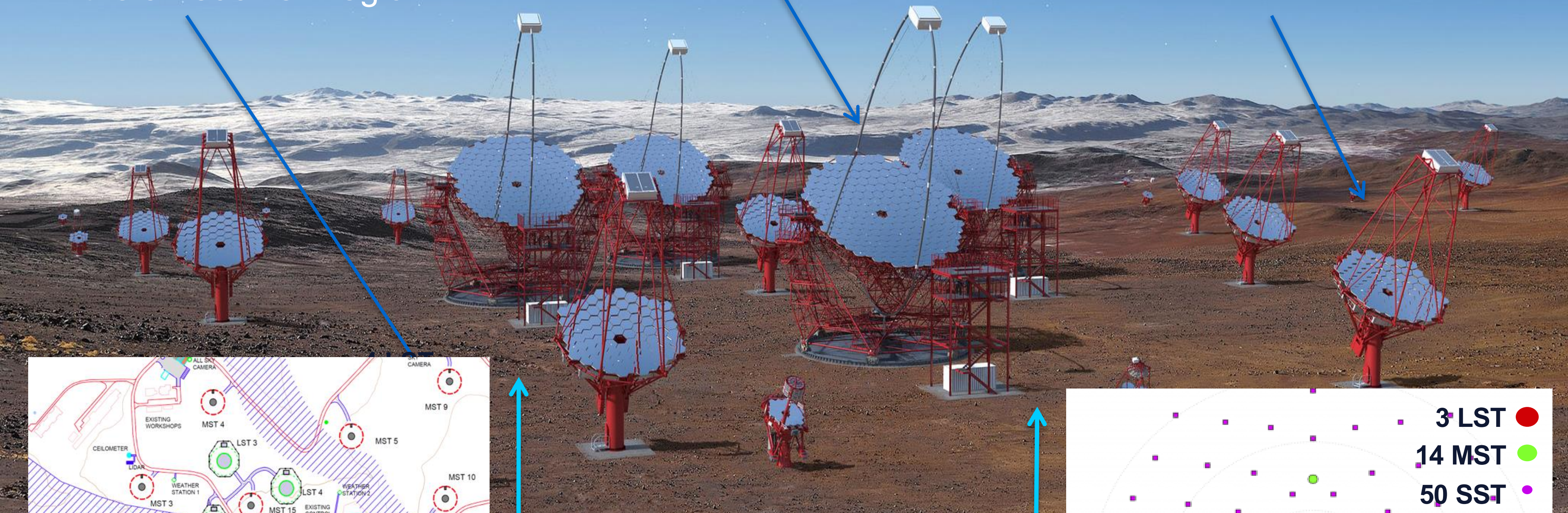
Two Sites (North/South)
~100 telescopios

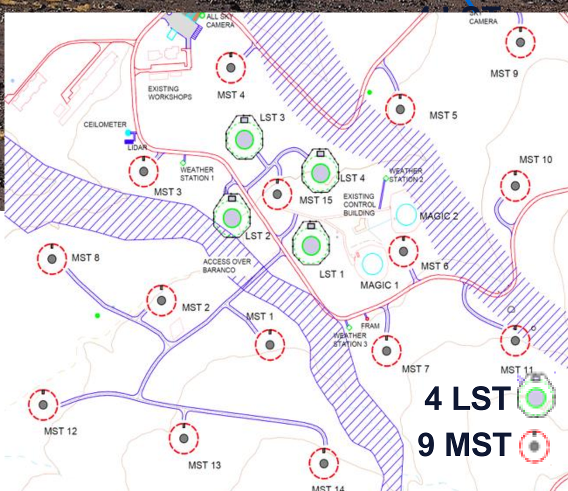
Cherenkov Telescope Array

SSTs, 4 m ø dual mirror,
spanning for ~4.5 km^2,
in the 5 - 300 TeV region

LSTs, 23 m ø parabolic
at the center of the array,
for the 20 - 150 GeV range

MSTs, 12 m ø Davies-Cotton
in a ~1 km^2 area,
for the 0.15 - 5 TeV domain

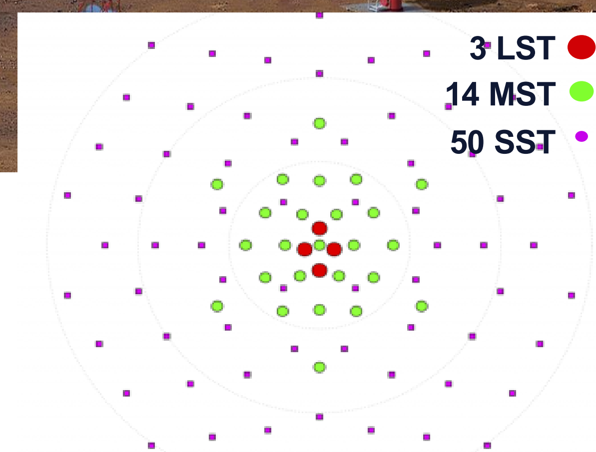




1 km

CTAO-North @ ORM Canary Island

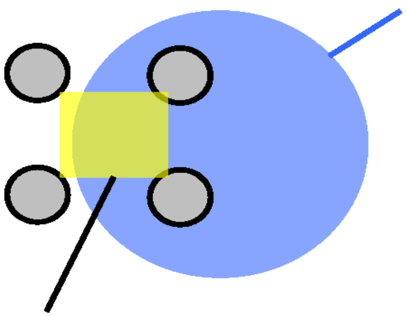
2 km



CTAO-South @ Paranal Chile

Cherenkov Telescope Array

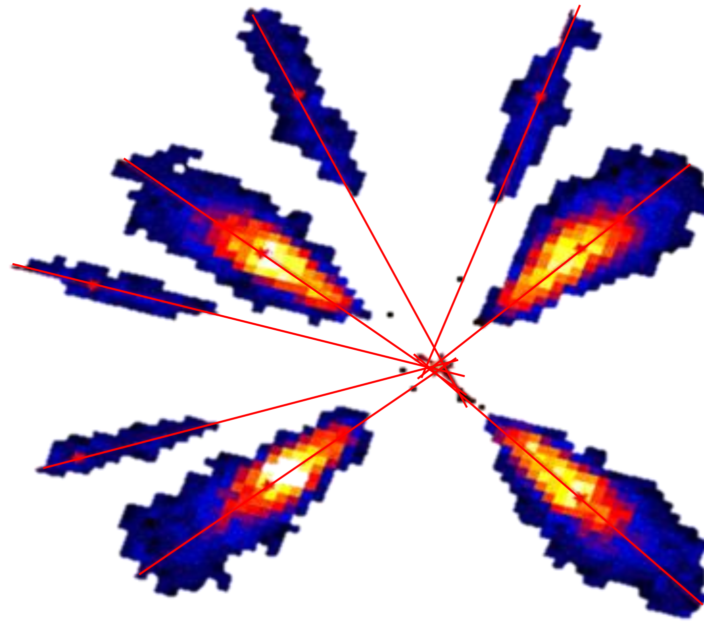
Deep stereoscopic observations



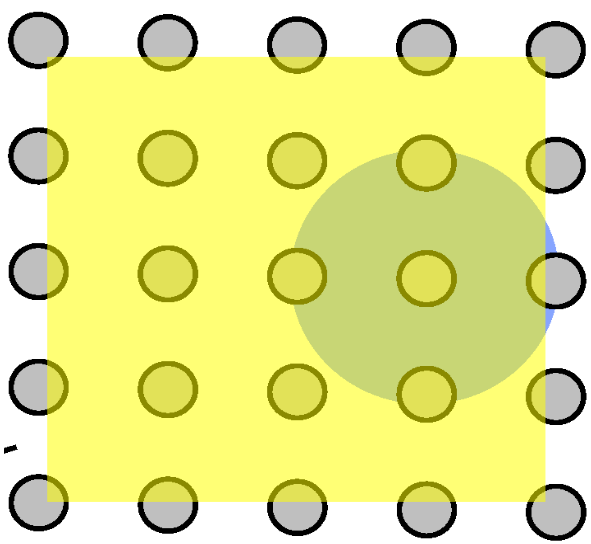
Light radius ~100-150 m

→ Typical telescope spacing

Optimum Trigger & Reco región → many EAS lost

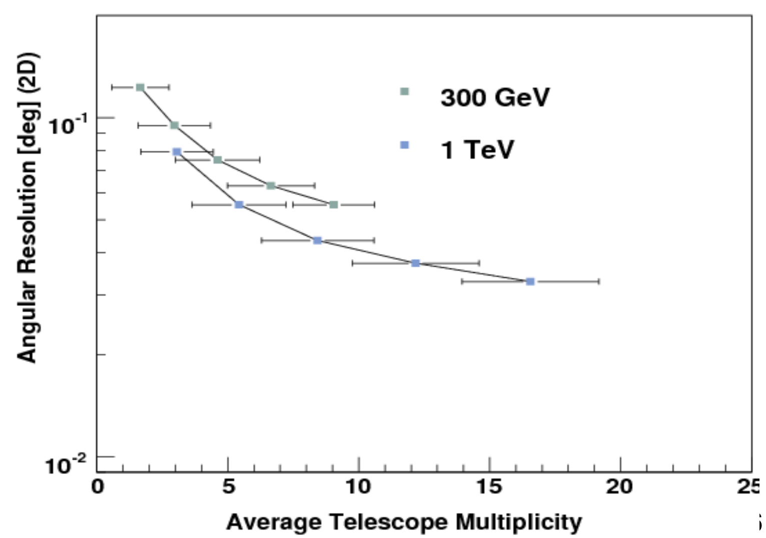


Funk & Hinton 2009



Larger collection area

More images → better reconstruction



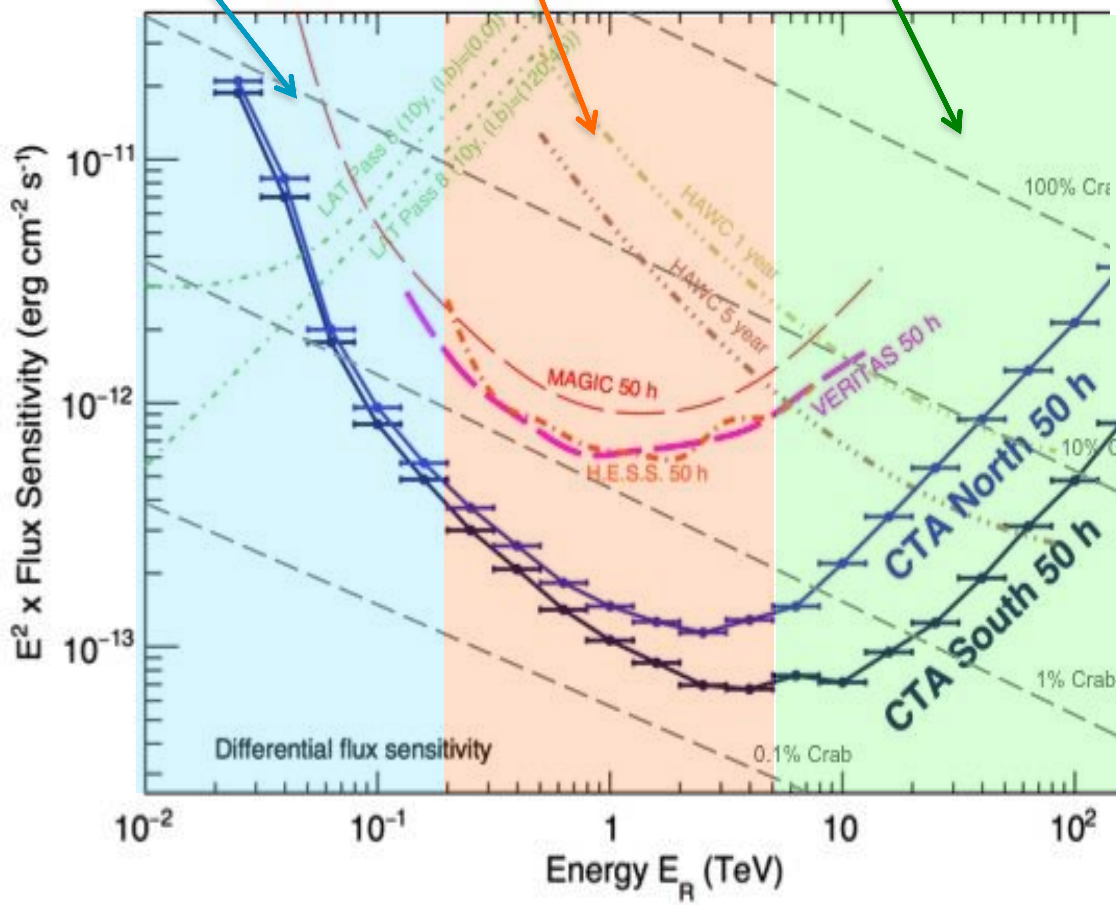
Cherenkov Telescope Array

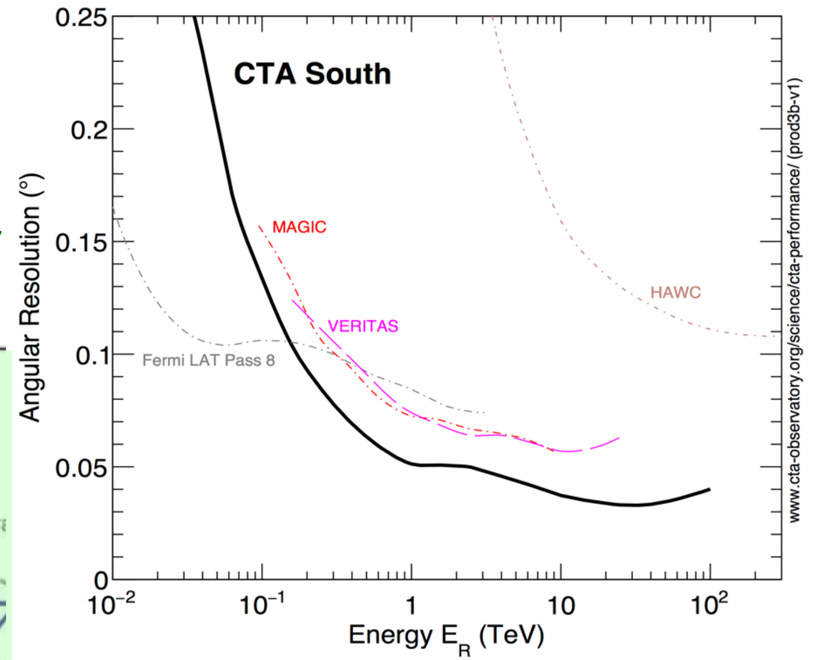
Expected performance

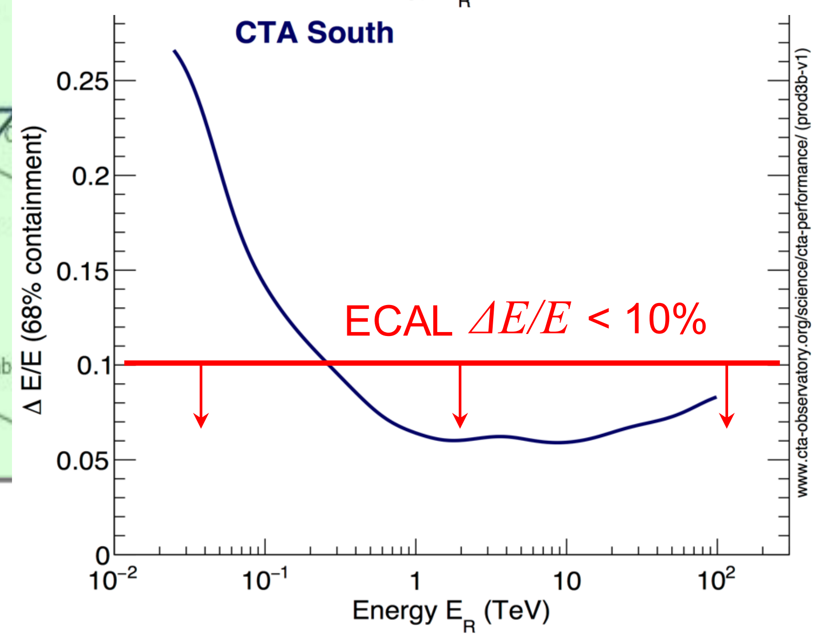
High-z AGNs
Pulsars
GRBs

Population studies
Extended sources
Precision studies

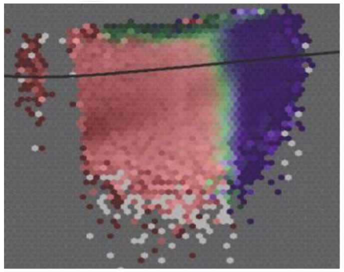
Pevatrons
Cosmic Accelerator cut-off



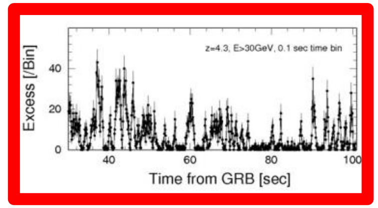




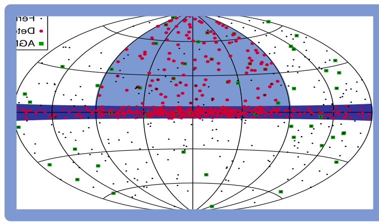
Key Science Projects



Dark Matter Programme

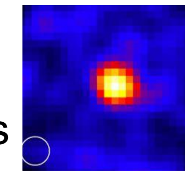


Transients



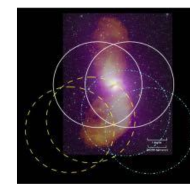
ExGal Survey

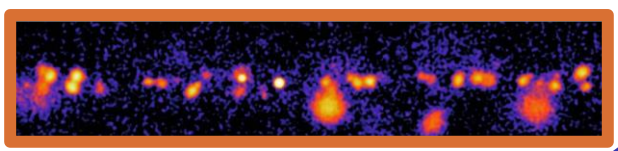
Galaxy Clusters



Star Forming Systems

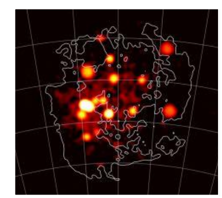
AGN



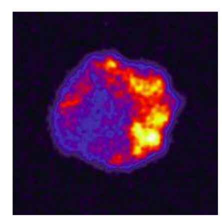


Galactic Plane Survey

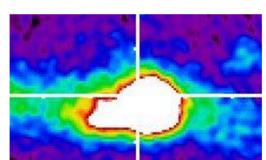
LMC Survey



PeVatrons



Galactic Centre



Galactic

Extragalactic

Science with the Cherenkov Telescope Array arXiv:1709.07997 ~20 pp

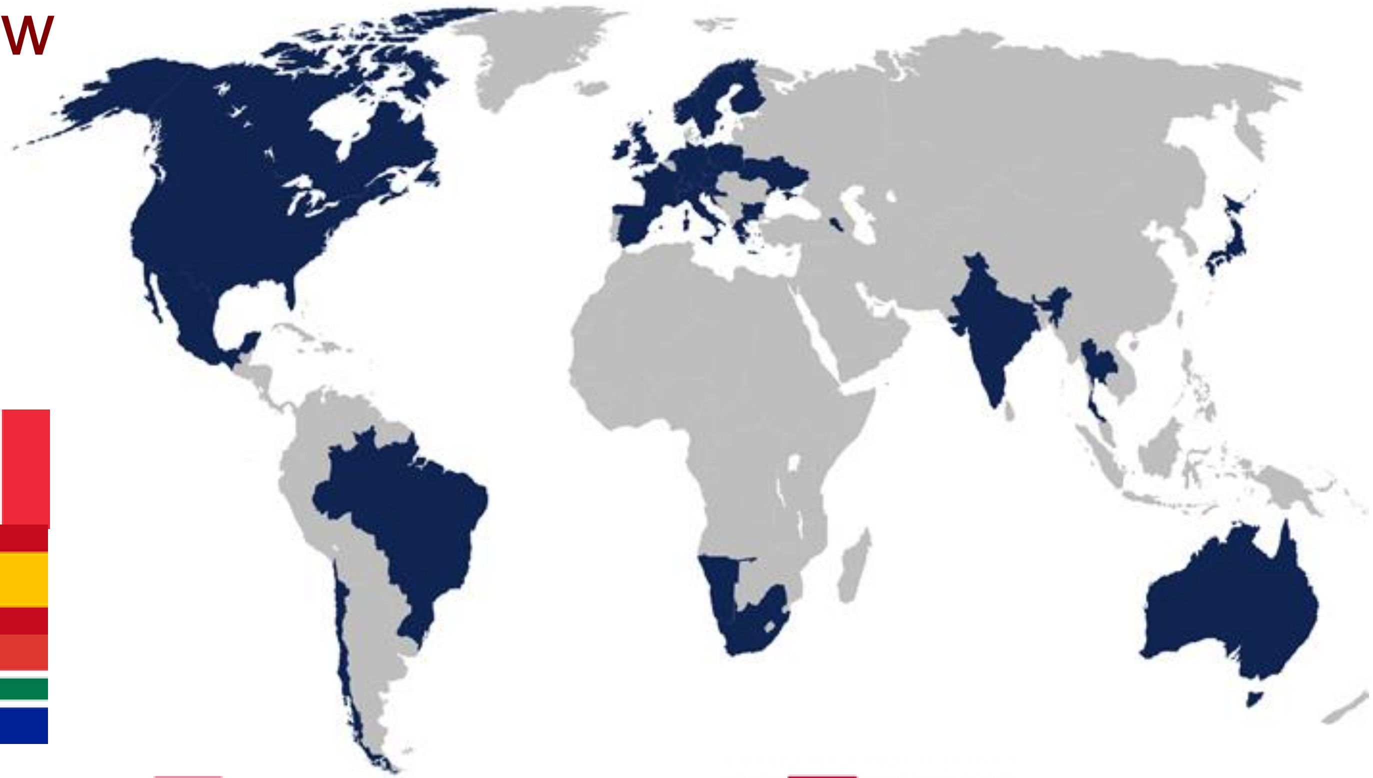
Cherenkov Telescope Array

Project overview

~15 countries
~200 institutes
~1500 members

CTAO Council

CTAO ERIC



CTAO Office opens at Bologna in 2017

ERIC Established in 2025

Design	Prototyping	Pre-production (2019 – 2026)	Production (2027 – 2030?)
2008 - 2012	2012 - 2018	Early LST Science	Early CTAO Science

First Pre-production LST-1 on CTAO-North 2019

First Pre-production MSTs on CTAO-South 2026

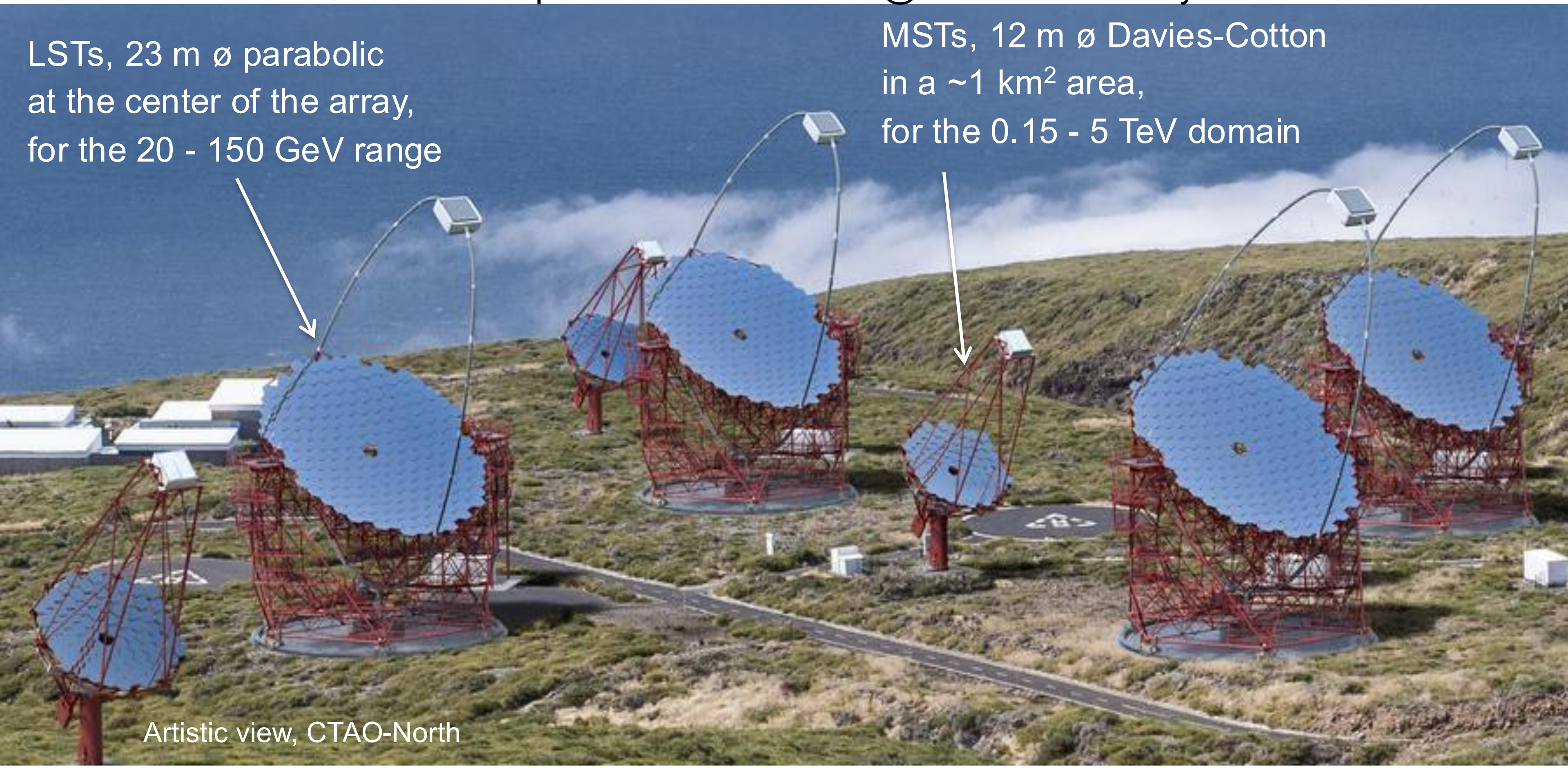
Cherenkov Telescope Array

Large Size Telescope

- Design ← MAGIC
  - Sensitibity in the 20-150 GeV range
  - Fast slewing: 180º in 20 s
  - Tesselated parabolic reflector 23m Ø
  - Fast 4.5º *FoV* camera
  - Pointing error 14'' (0.07 mrad)
- Structure
  - Azimuth rail, bogies and central pin
  - 4 motors for fast azimuth slewing
  - Two elevation bearings & 1 motor
  - Reflector frame & arc with CFRP tubes & headstays
- Optics
  - 28 m focal distance, 0.1° pixels
  - ~200 1.5 m spherical mirrors, 6 radii
  - Active Mirror Controls
- Camera
  - 1855 Light-Concentrator + PMT
  - 0.5 – 2000 pe dynamic range
  - FEB based on DRS4 SCA @ 1 GS/s with 300 MHz BW & 12-bit ADC

LSTs @ CTAO-North

Observatorio Roque de los Muchachos @ La Palma Canary Island



LSTs @ CTAO-North

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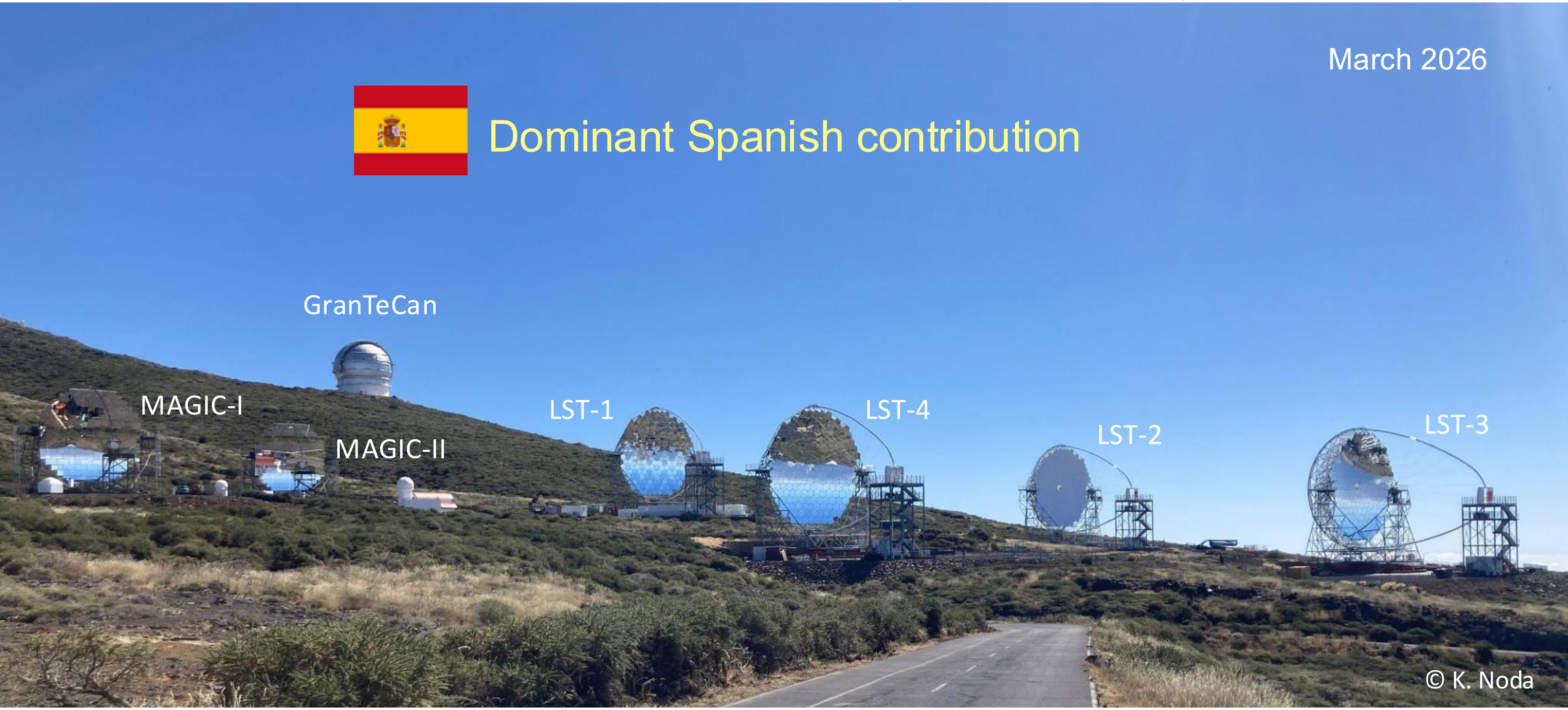
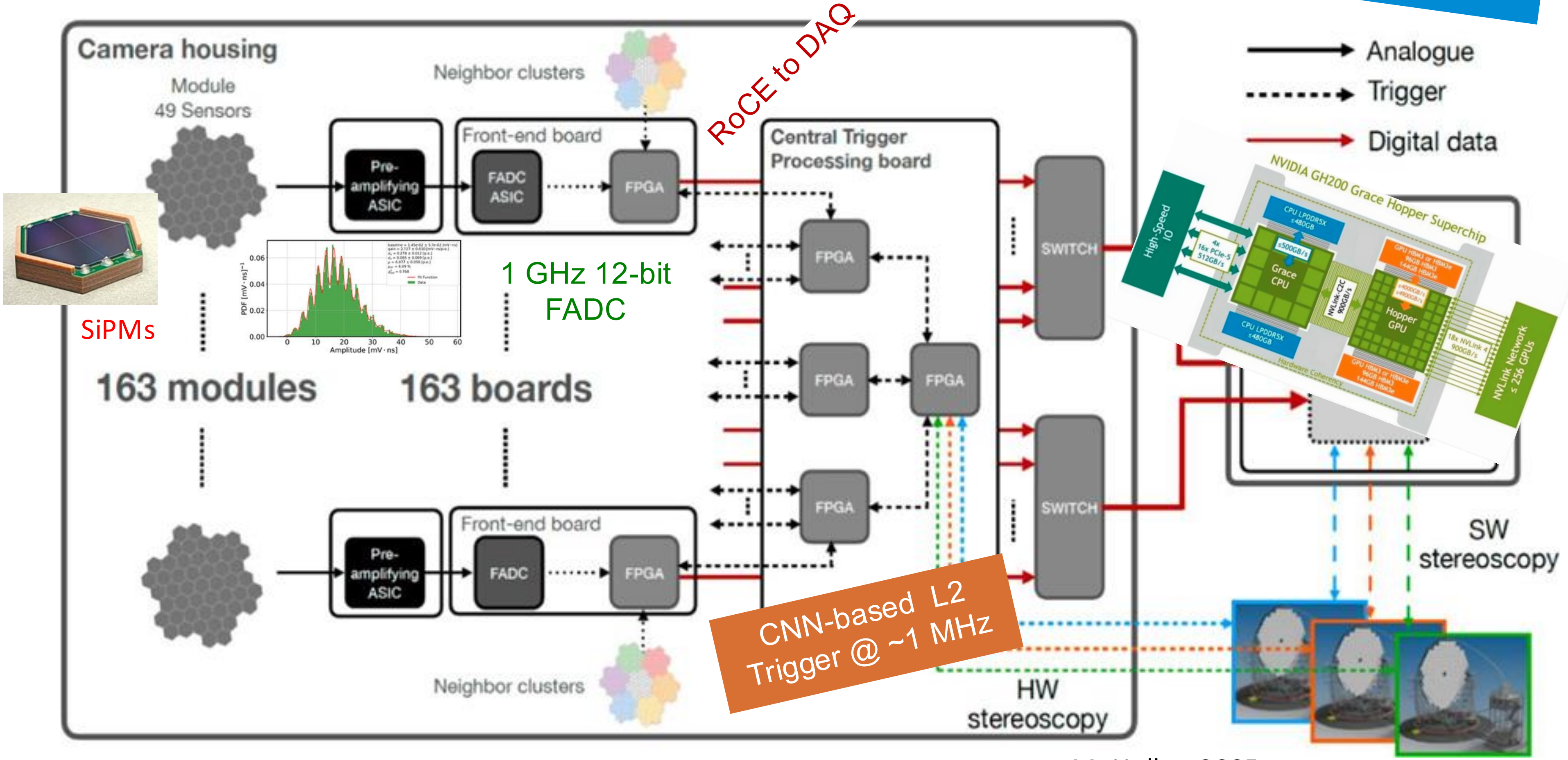


LST Advanced Camera

Candidate for mid-term upgrade of CTAO telescope cameras

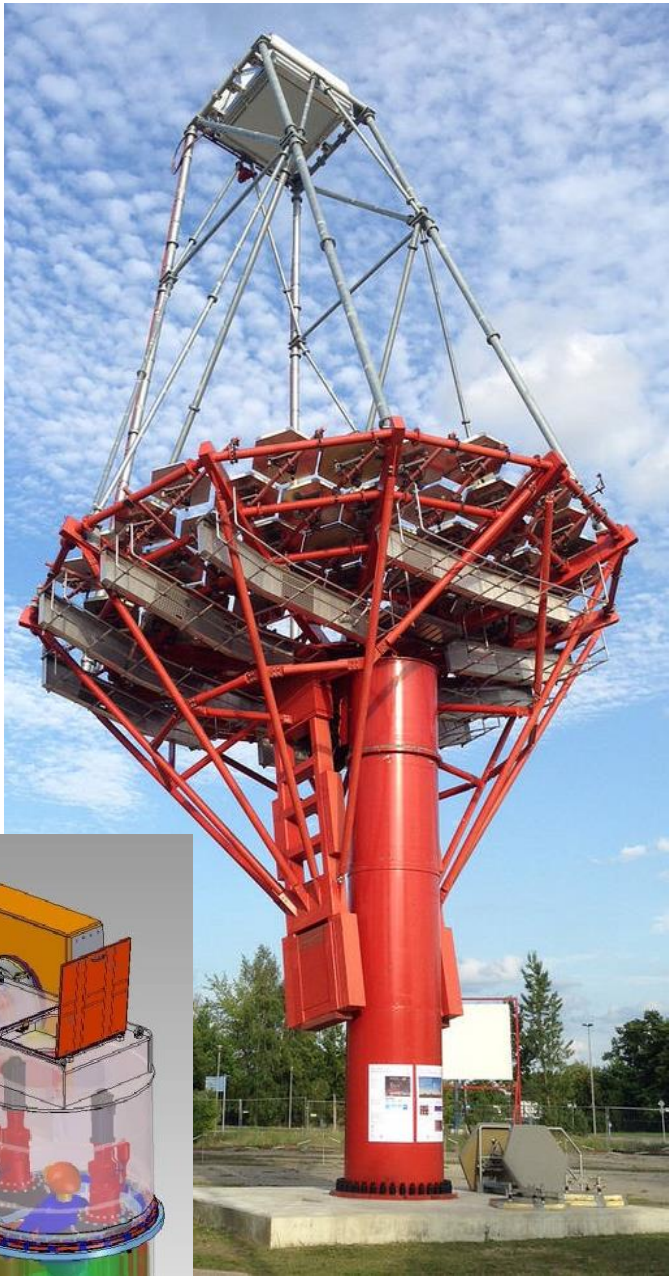


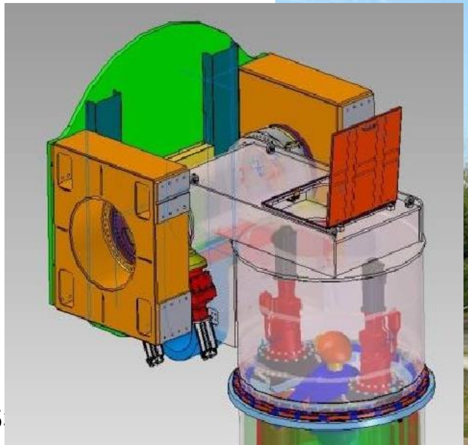
M. Heller, 2025

Cherenkov Telescope Array

Medium Size Telescope

- Robust design ← HESS
  - Max. sensitivity in core range 0.15 – 5 TeV
  - Tesselated 12 m Ø reflector, mod. Davies-Cotton
  - Fast ~8º FOV ~3 m wide camera, in two flavours: FlashCam (South) and NectarCAM (North)
  - Pointing error 7'' (0.04 mrad)
- Positioner + structure
  - Tower + head + yokes, with azimuth drive rotating head and elevation drives rotating yokes
  - Steel beams and tubes for mirror and camera support
- Optics
  - 16 m focal distance, 0.18° pixels
  - ~86 1.2 m spherical mirrors
  - Active Mirror Control





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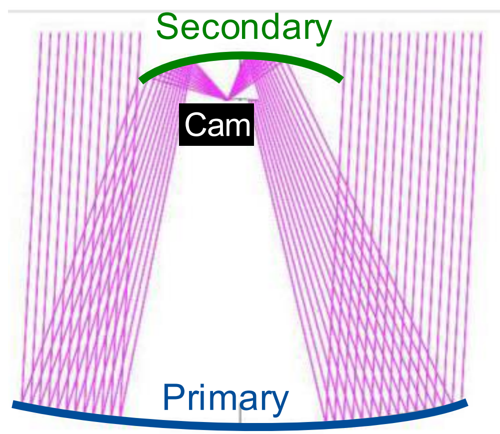
  - Pointing error 7” (0.04 mrad)
- Positioner + structure
  - Tower + head + yokes, with azimuth drive rotating head and elevation drives rotating yokes
  - Steel beams and tubes for mirror and camera support
- Optics
  - 16 m focal distance, 0.18° pixels
  - ~86 1.2 m spherical mirrors
  - Active Mirror Control
- Cameras
  - FlashCam based on 250 MS/s 12-bit FADCs
  - NectarCAM based on NECTAr SCA @ 1 GS/s with 500 MHz BW & 12-bit ADC

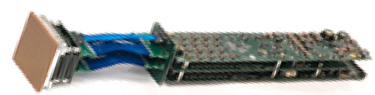
Cherenkov Telescope Array

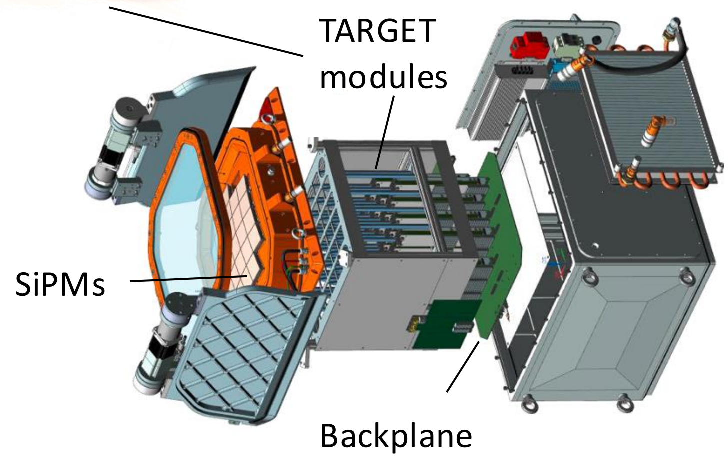
Small Size Telescope

- New IACT design
  - Sensitibity in the 5-300 TeV range
  - Schwartschild-Coude 4 m Ø
  - Fast 9º *FoV* camera
  - Pointing error 7’’ (0.04 mrad)

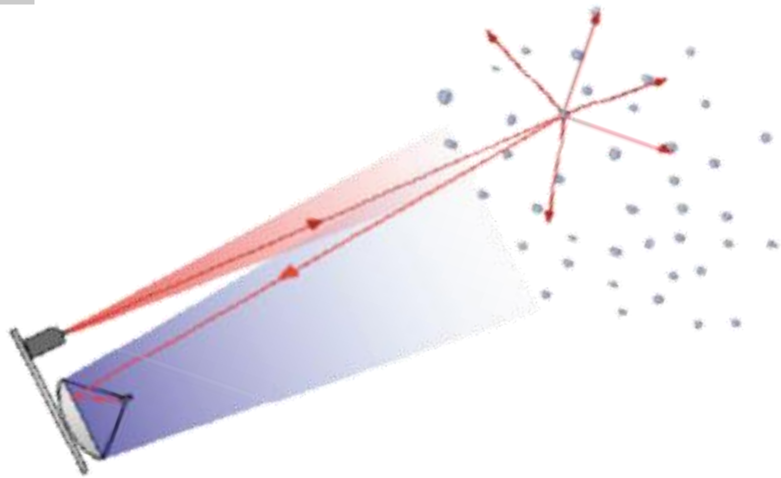


- Structure
  - Alt-azimuth steel mount with counter-weights
  - Two elevation bearings and the camera support on the primary mirror structure
- Optics
  - Segmented primary mirror and monolithic secondary one, with aspheric facets & AMC
- Camera
  - 2048 SiPMs as photosensors
  - FEB TARGET modules based on TARGET SCA @ 1 GS/s with 500 MHz BW & 12-bit ADC

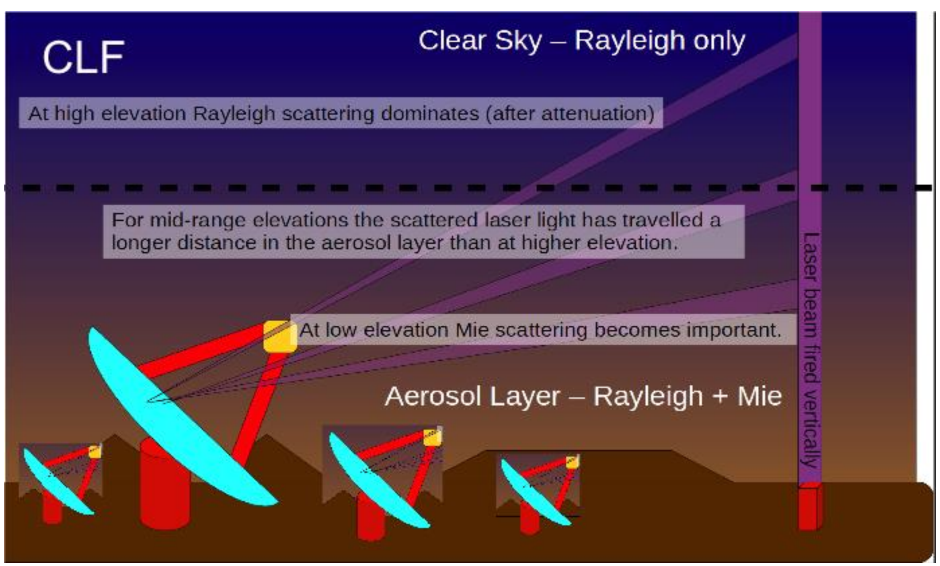




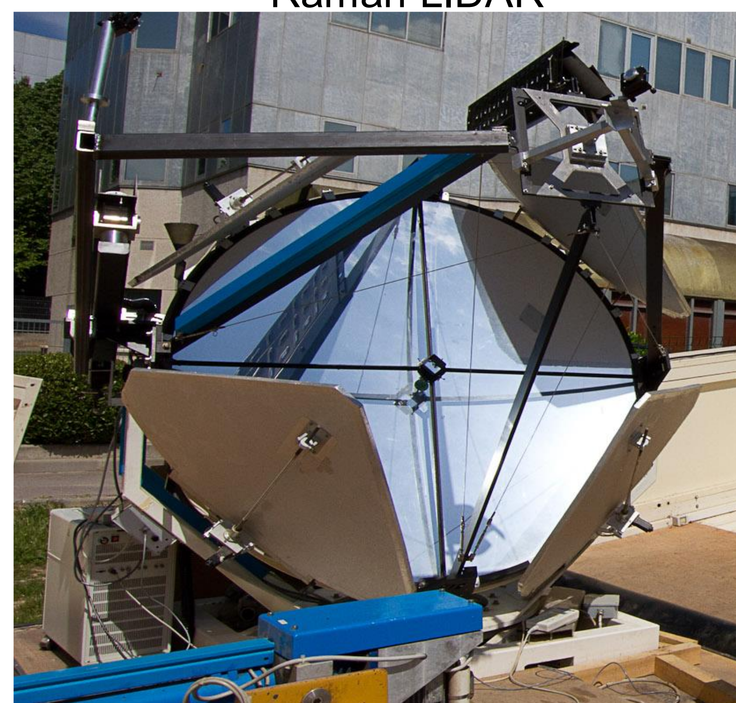
Calibration



- Atmospheric monitoring:
  - Extinción por aerosoles y moléculas
  - Elastic/Raman LIDAR
  - Monitorización adicional de nubes, etc
- Telescope calibration
  - Overall optical telescope characterization by means of a *Central Laser Facility* (CLF)
  - Camera Calibration light sources in each IACT

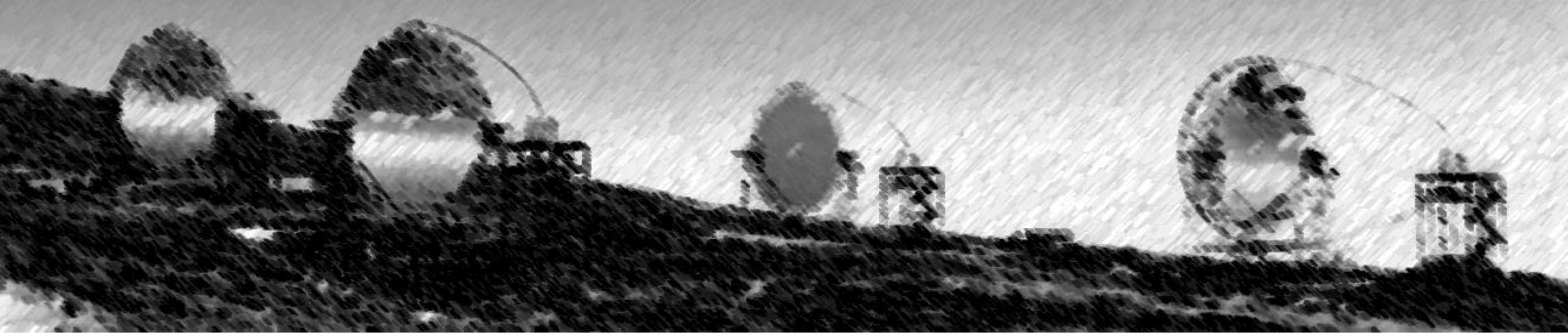


Raman LIDAR



Summary

- Astroparticle Physics unveils cosmic accelerators in compact objects
- IACT operating since 40 years recording photon messengers from cosmic accelerators
- IACT working as fully-active calorimeter using the Atmosphere
- Current generation (MAGIC, HESS, VERITAS) fully succesfull
- Next generation (CTAO) ready to start



Acknowledgements

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AGENCIA ESTATAL DE INVESTIGACIÓN

Comunidad de Madrid

Astrofísica y Física de Altas Energías

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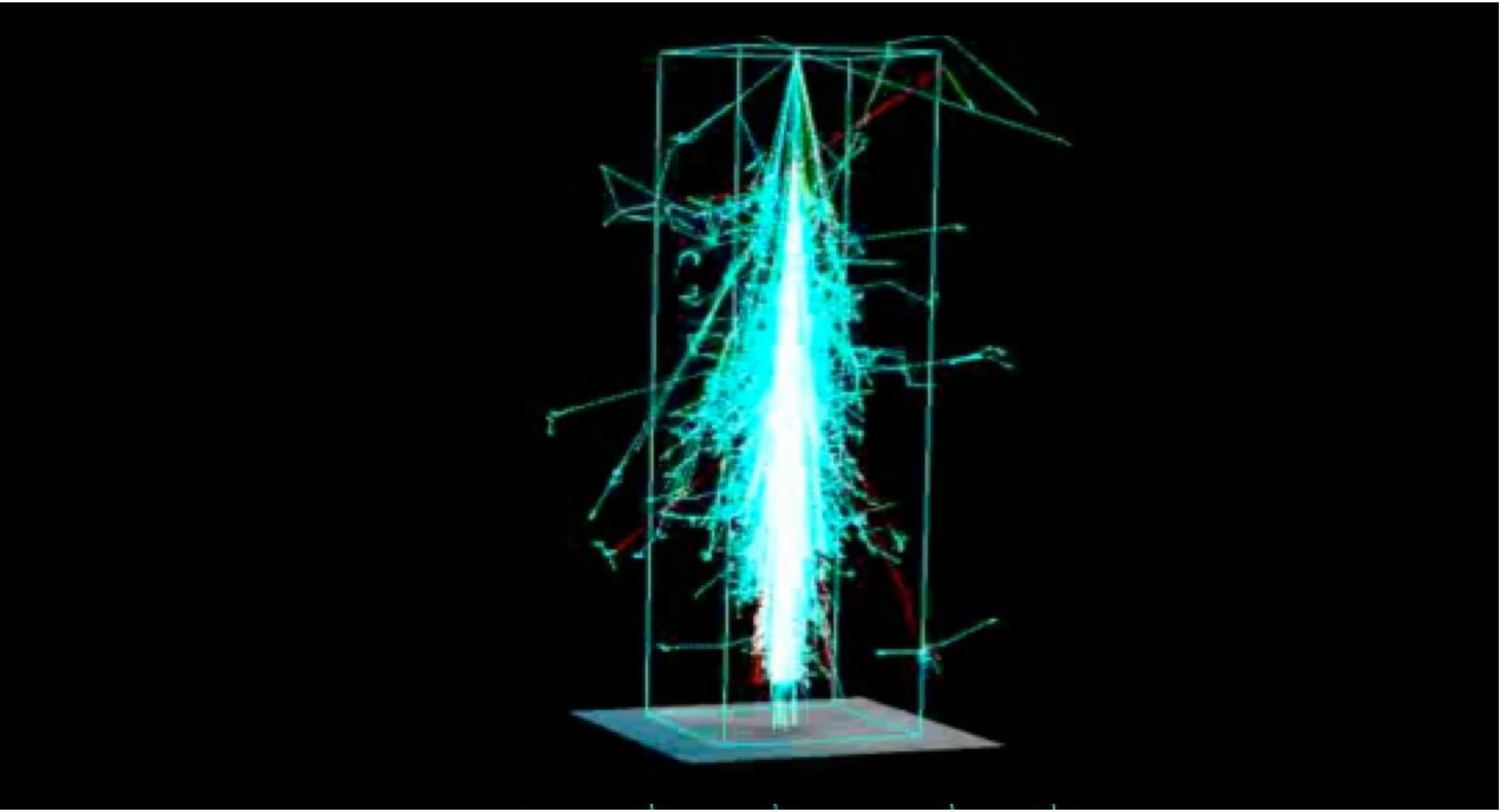
IPARCOS

UNIVERSIDAD COMPLUTENSE MADRID

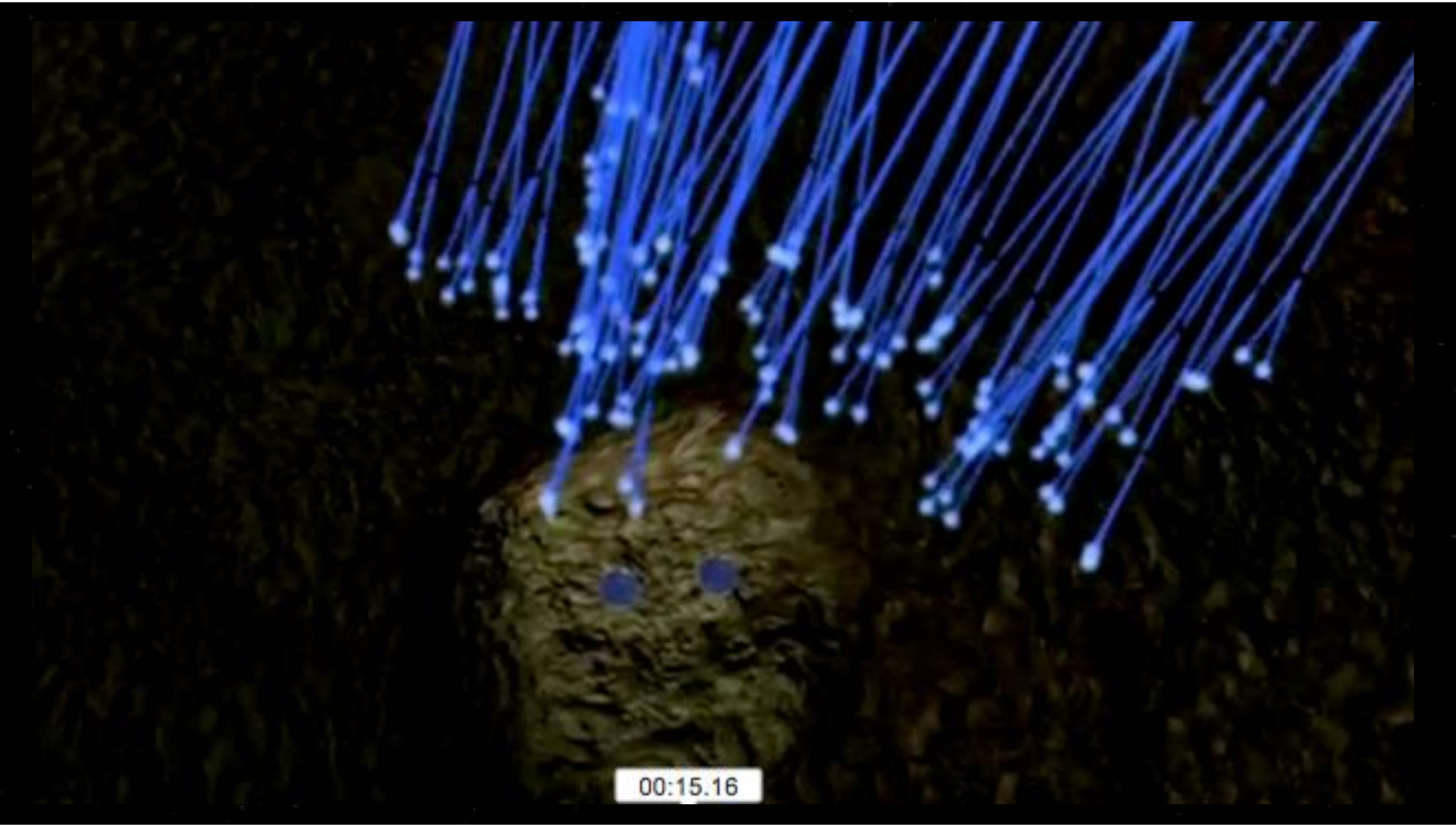
Backup

MC simulation of EAS



Cherenkov Telescopes

Steroscopic Observation

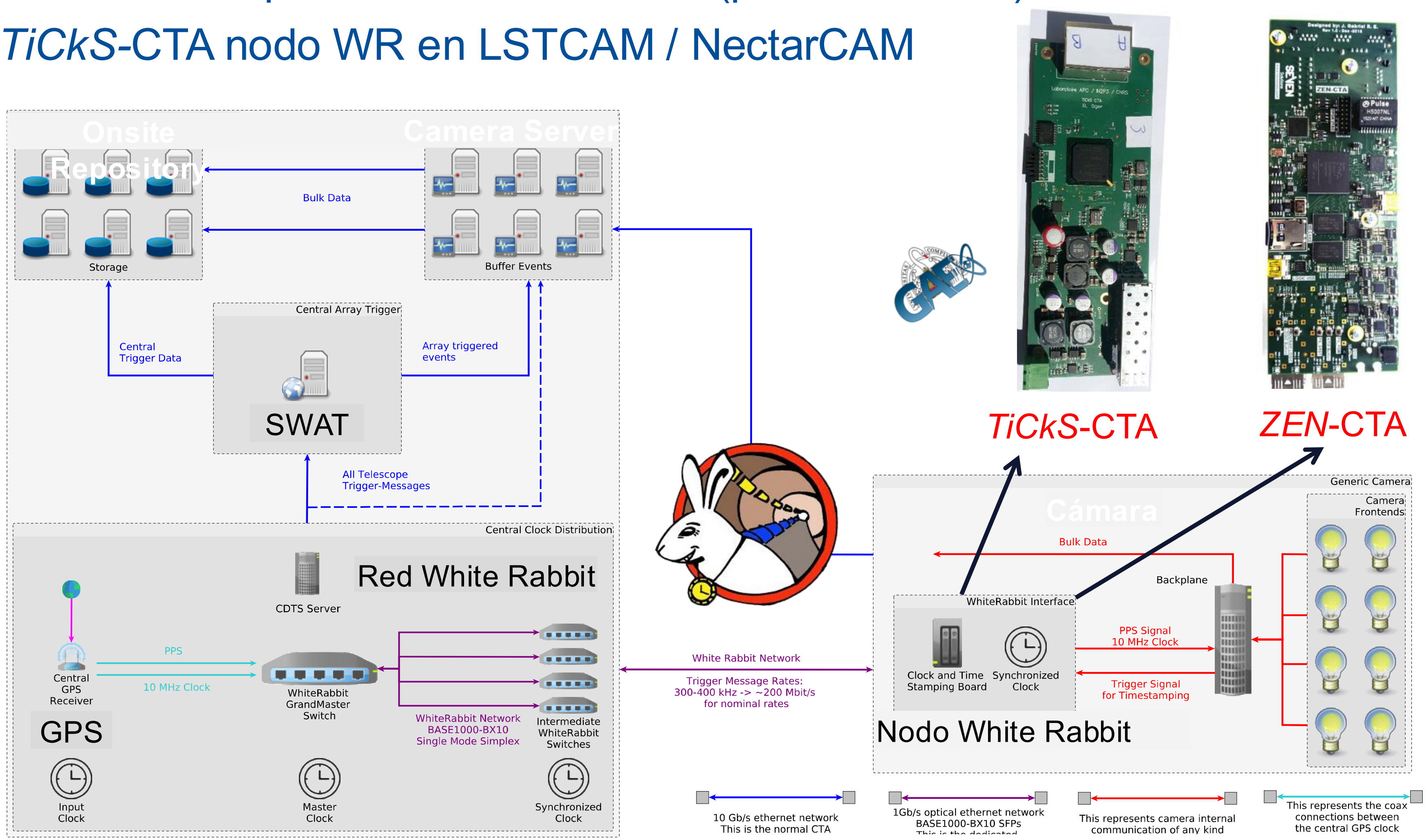


Trigger de array

Clock Distribution and Trigger timeStamping (CDTS)

- Basado en el protocolo *White Rabbit* (precisión~1 ns)
- *TiCkS*-CTA nodo WR en LSTCAM / NectarCAM

Seven Solutions ©

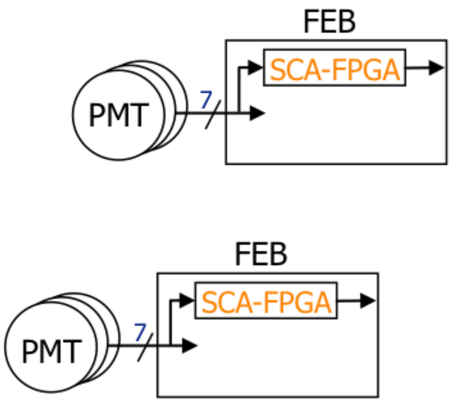


EXTRA

Camera: multi-level trigger

- Array Trigger
- Camera Trigger
  - Separate gamma-ray-like from NSB-induced events
  - Triggers the readout of the FEB SCA buffers (1 – 4 μs depth)

CTA MST



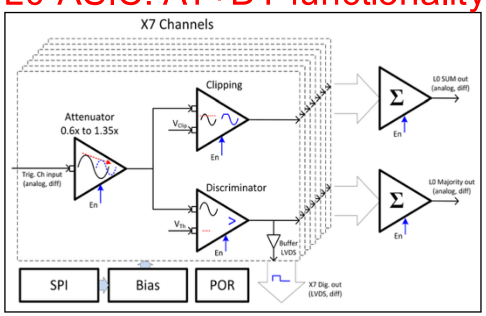
Telescope Building Blocks

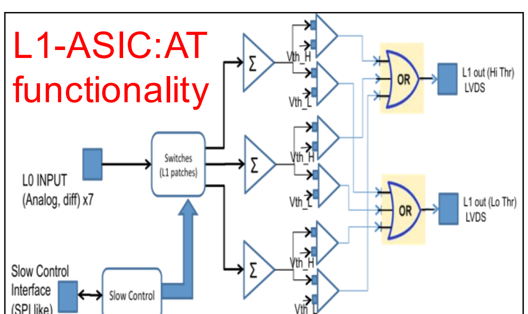
EXTRA

Camera: multi-level trigger

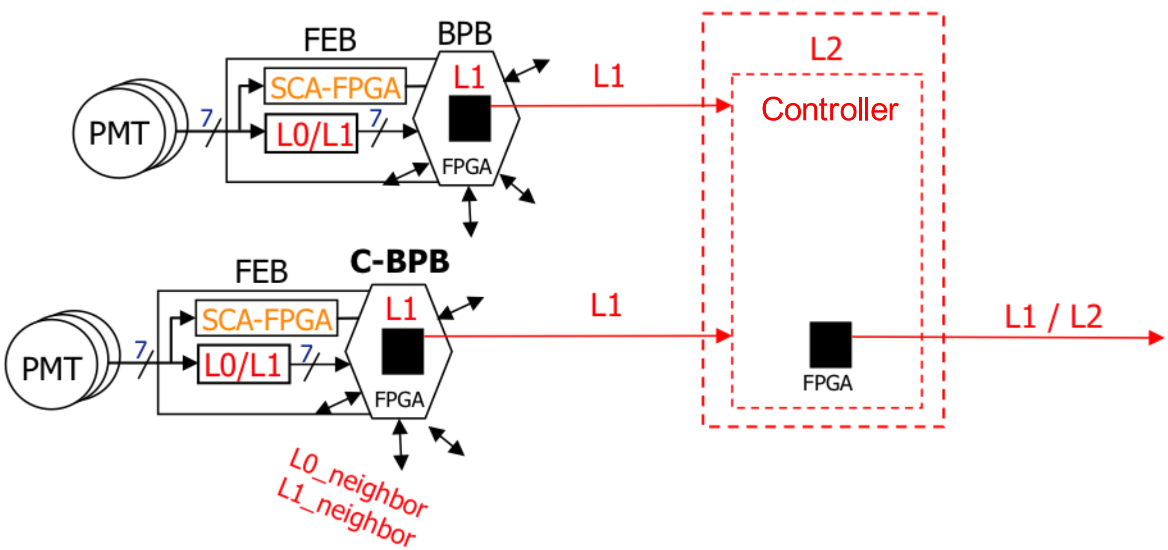
- Array Trigger
- Camera Trigger
  - Separate gamma-ray-like from NSB-induced events
  - Triggers the readout of the FEB SCA buffers (1 – 4 μs depth)
  - Hardware trigger (latency ~250 ns, precision ~1 ns), in stages:
    - ASIC-based multi-level trigger decision

L0-ASIC: AT+DT functionality





CTA MST

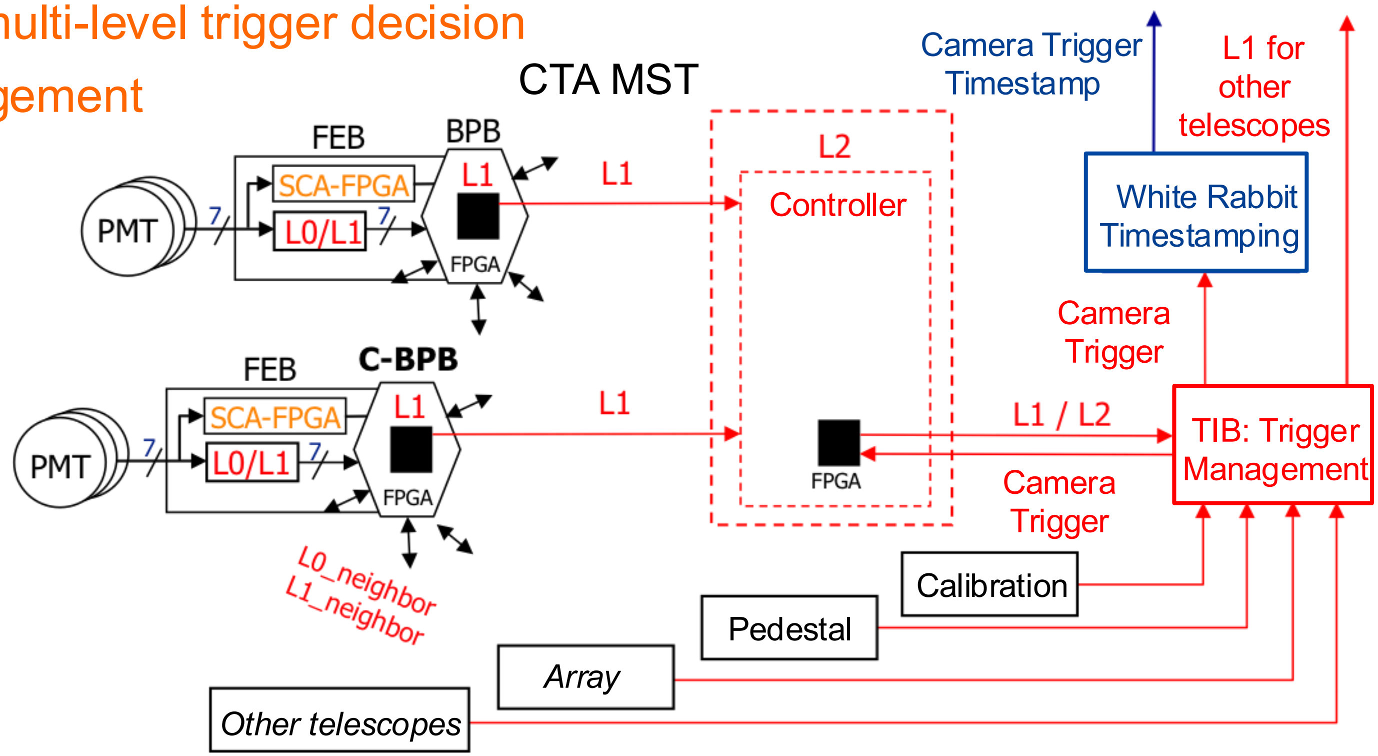


Telescope Building Blocks

EXTRA

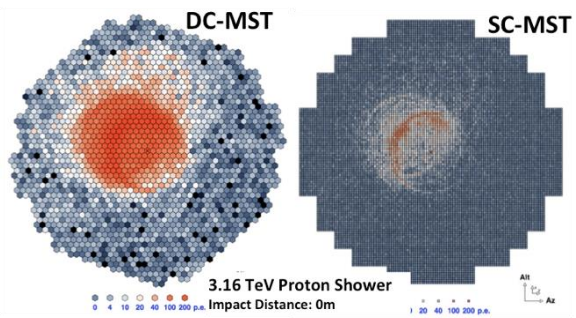
Camera: multi-level trigger

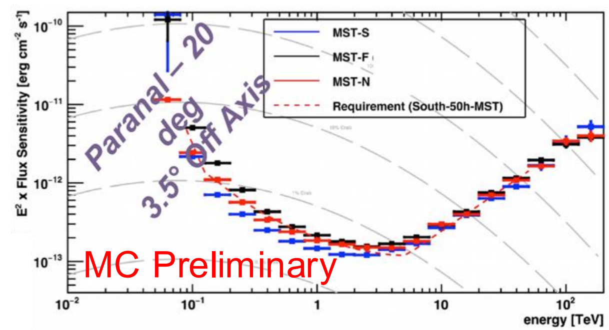
- Array Trigger
- Camera Trigger
  - Separate gamma-ray-like from NSB-induced events
  - Triggers the readout of the FEB SCA buffers (1 – 4 μs depth)
  - Hardware trigger (latency ~250 ns, precision ~1 ns), in stages:
    - ASIC-based multi-level trigger decision
    - Trigger management



Schwarzschild-Couder MST

- Aim
  - Max. sensitivity in core range 0.15 – 5 TeV
  - Enhanced γ–ray angular resolution

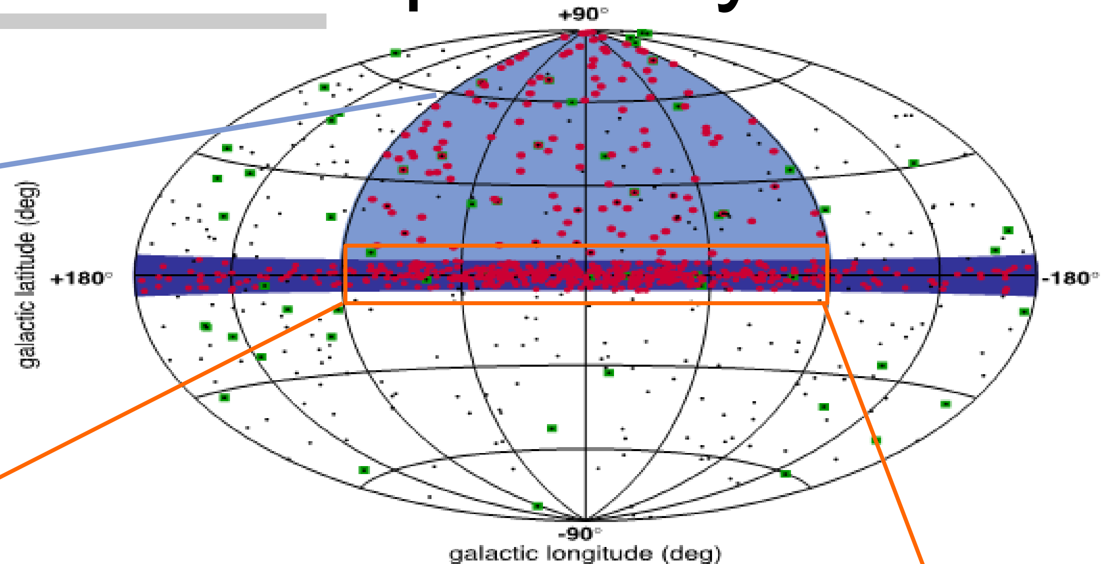




- Main specs
  - Dual-mirror Schwarzschild-Couder optics with 10 m Ø primary mirror
  - 8º FOV camera, with 0.07º pixels
- US teams with international contributions
- Status and plans
  - Prototype SC-MST (pSCT) finished by Aug. 2018 at VERITAS site → 1-year commissioning
  - Live: http://cta-psct.physics.ucla.edu/

Cherenkov Telescope Array

Surveys



Extragalactic survey:

¼ of sky with ~ 6 mCrab sensitivity during ~1000 h

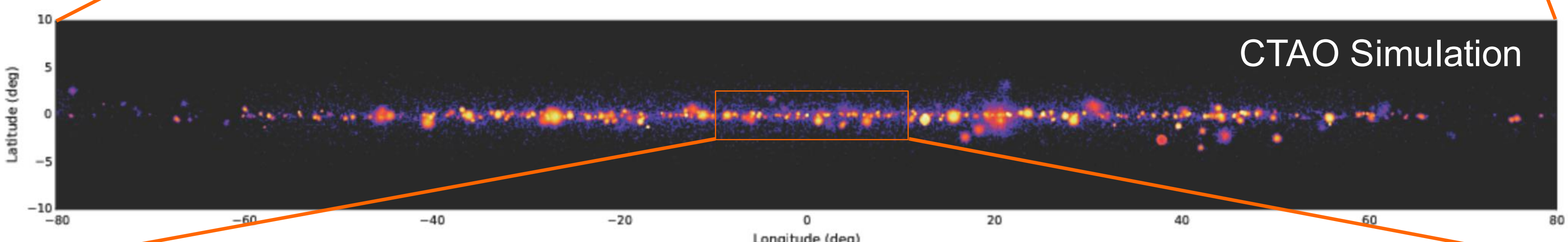
Population studies, unknown sources

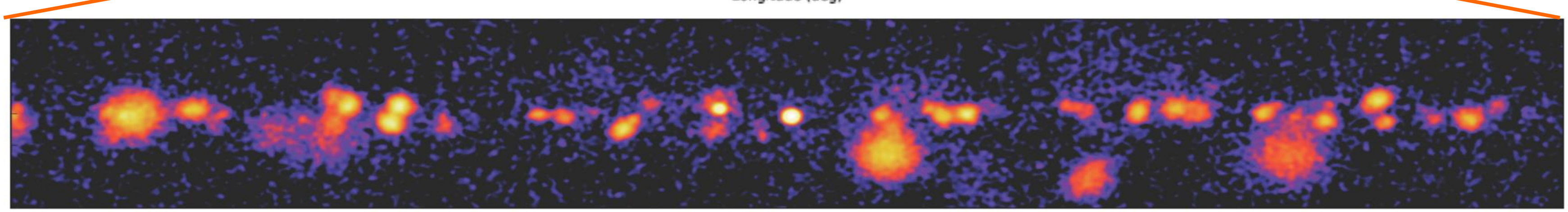
- Fermi/LAT 2FHL catalog
- Detectable sources within CTA surveys
- AGNs detected by IACTs

Galactic Plane survey:

Full GP with ~2-4 mCrab sensitivity during ~1600 h

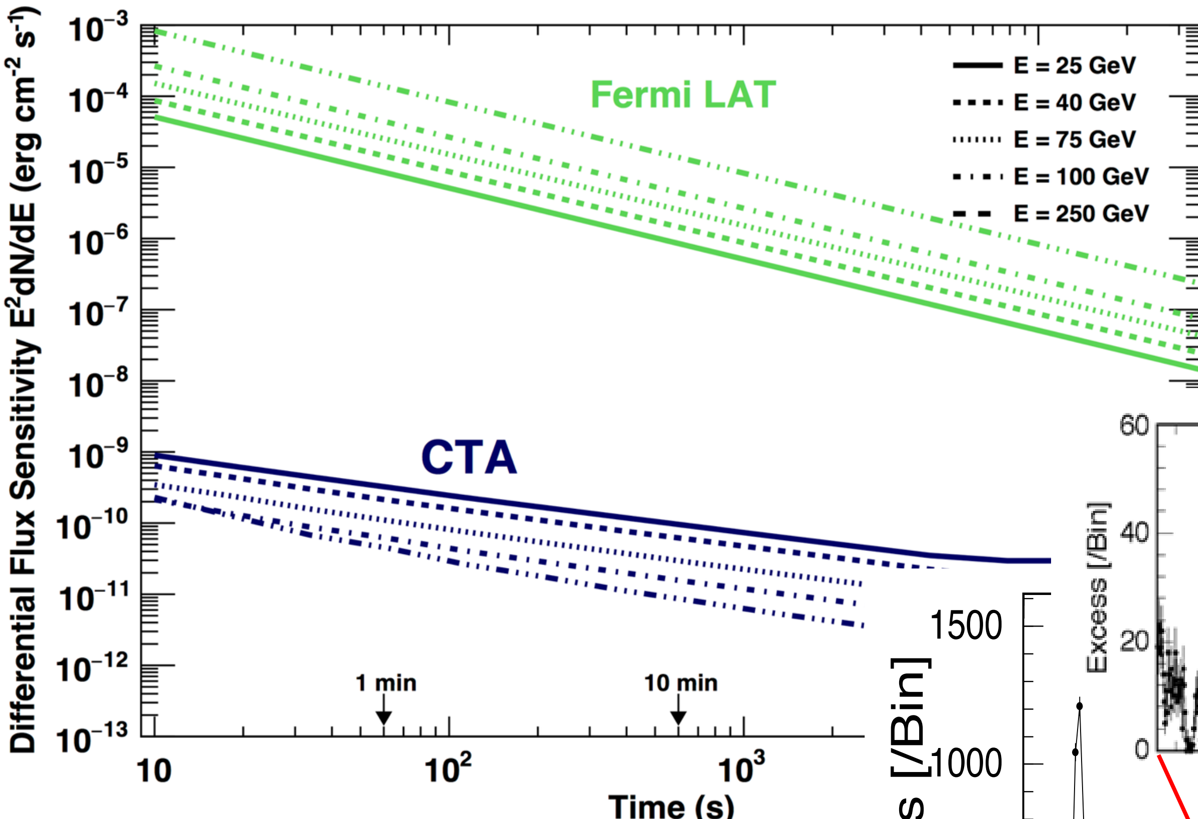
~400 new VHE sources: SNR, PWN, PeV candidates





Cherenkov Telescope Array

Transients

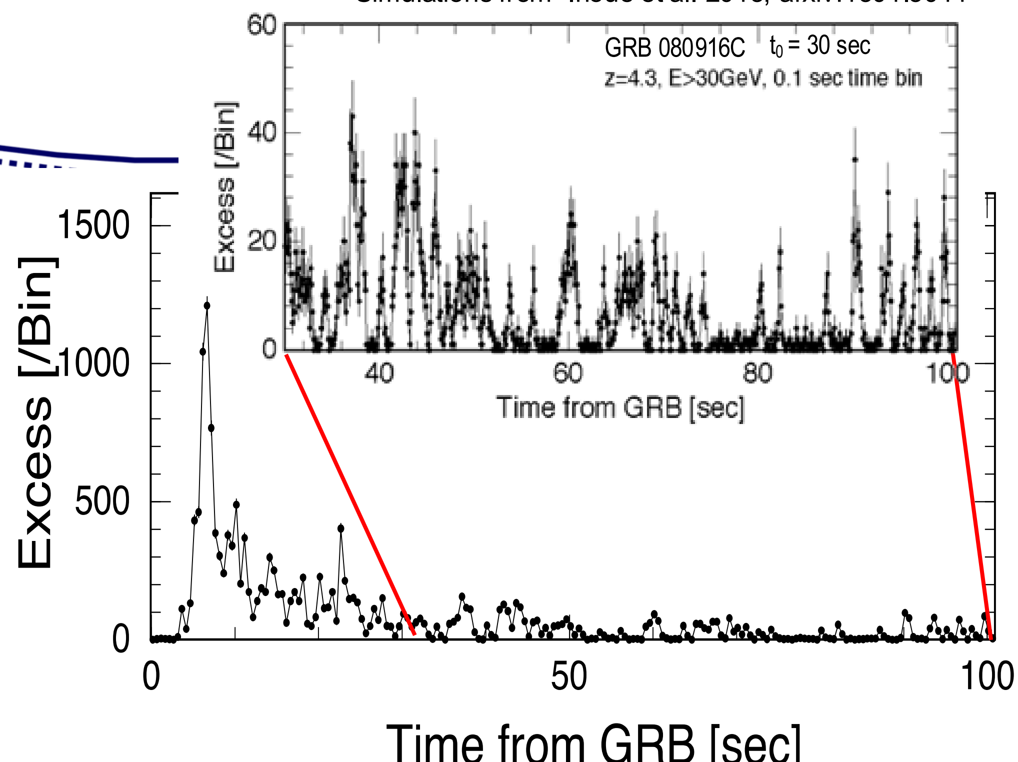


CTA transient targets:

Sensitivity to ~minute to ~day transients

GRBs, AGN flares, γ-ray binaries, GWs, etc

Simulations from Inoue et al. 2013, arxiv:1301.3014



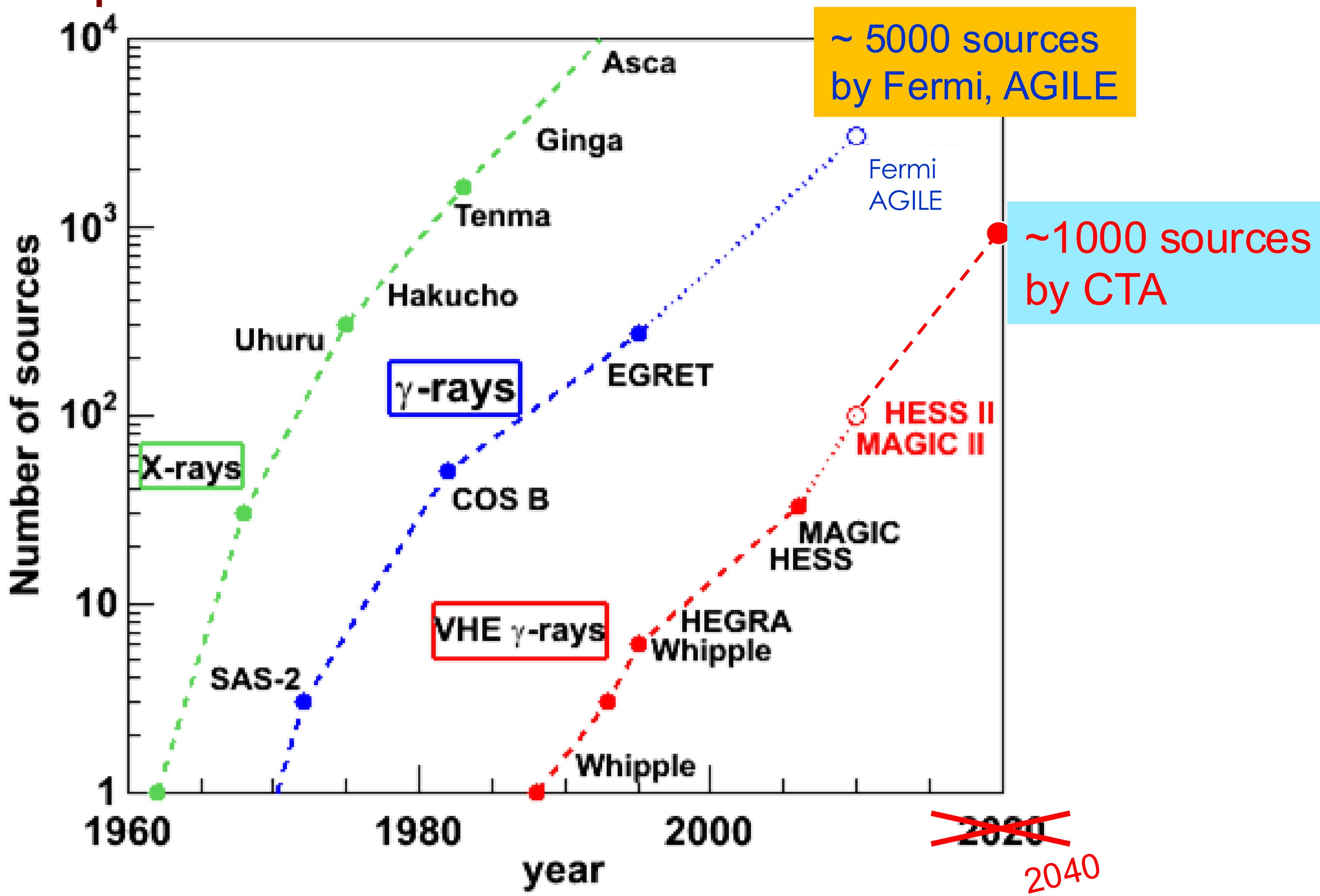
GRB detection requirements:

Low energy threshold

Fast repositioning

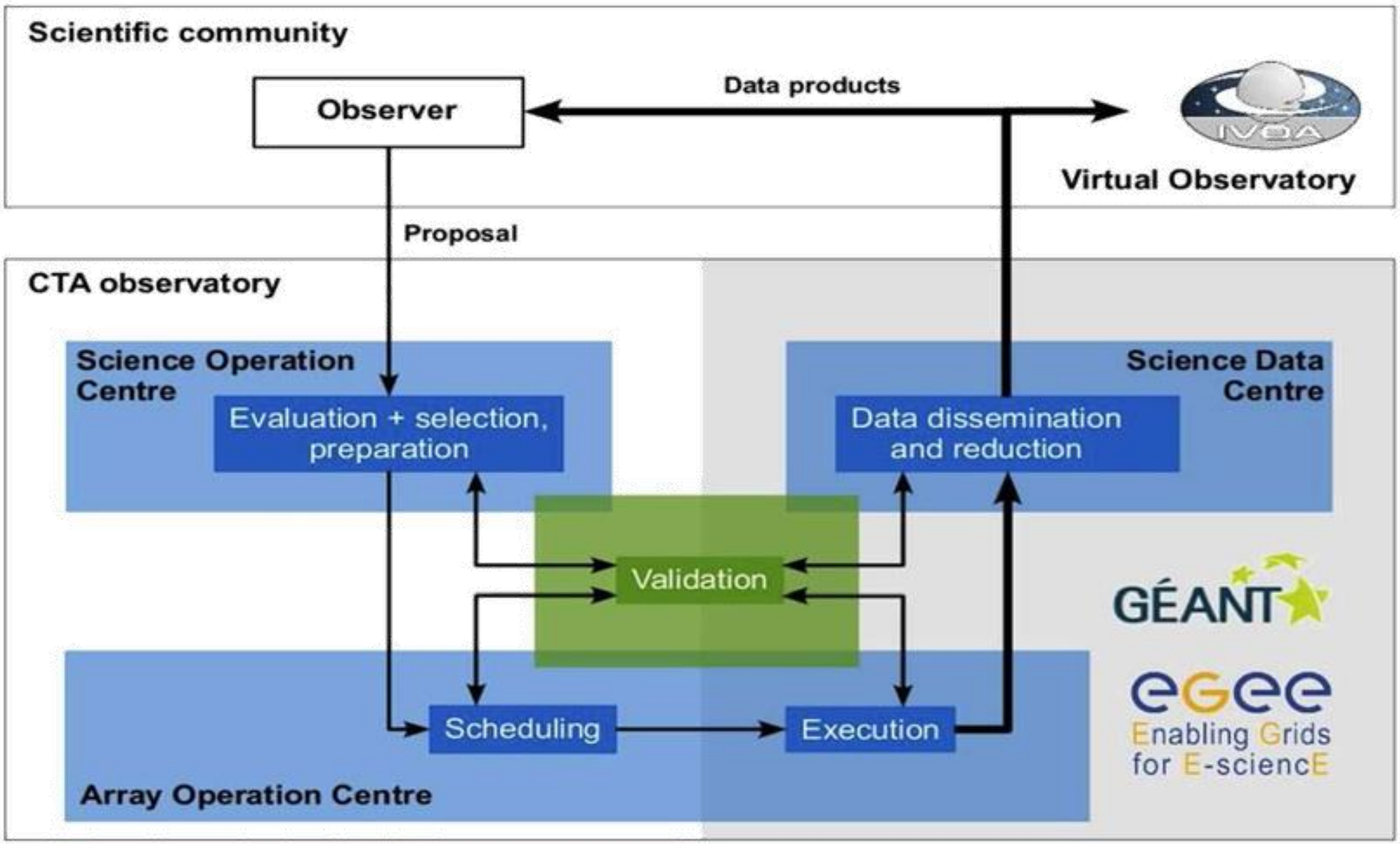
Cherenkov Telescope Array

Kifune's plot



CTAO control/operation

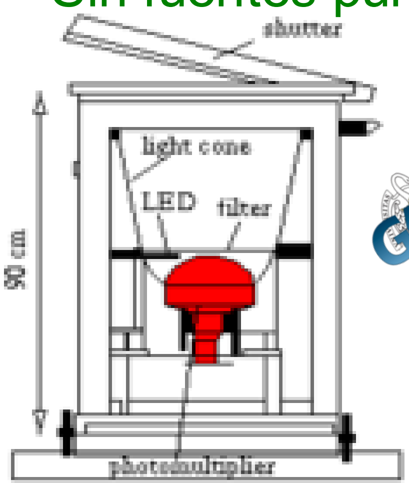
- Telescope Control
  - Cameras, motors, etc
  - *Alma Common Software & OPC-UA standard*
- Array operation
  - Observing proposals
  - Scheduling
- Data management
  - Reduction
  - Dissemination

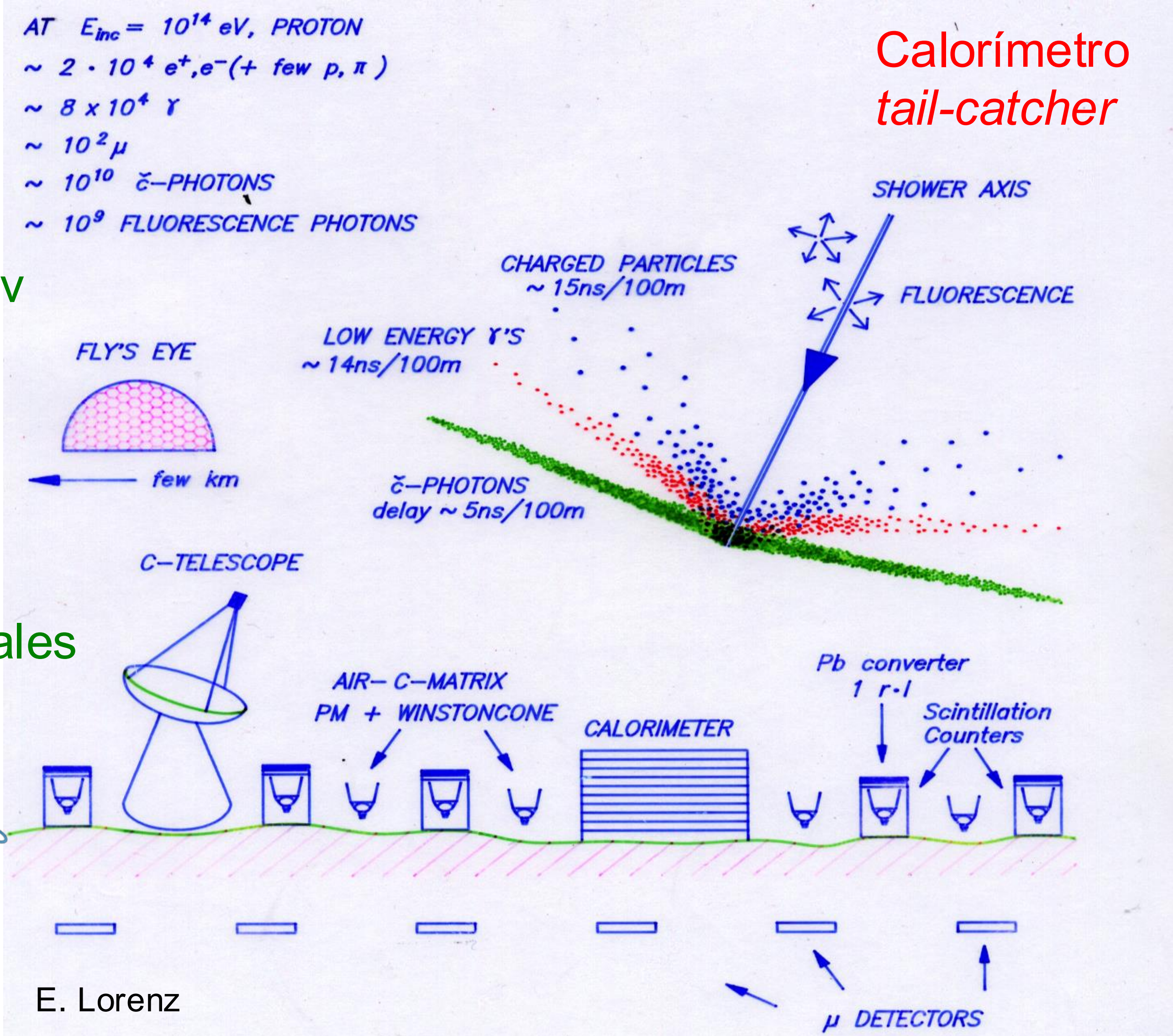


Primeros detectores

AIROBICC

- Instrumento
  - PMTs + conos Winston
  - Medida Cherenkov
  - PMTs 20 cm Ø
- Resultados
  - FOV ~ 45º
  - E > ~10 TeV
  - Sin fuentes puntuales



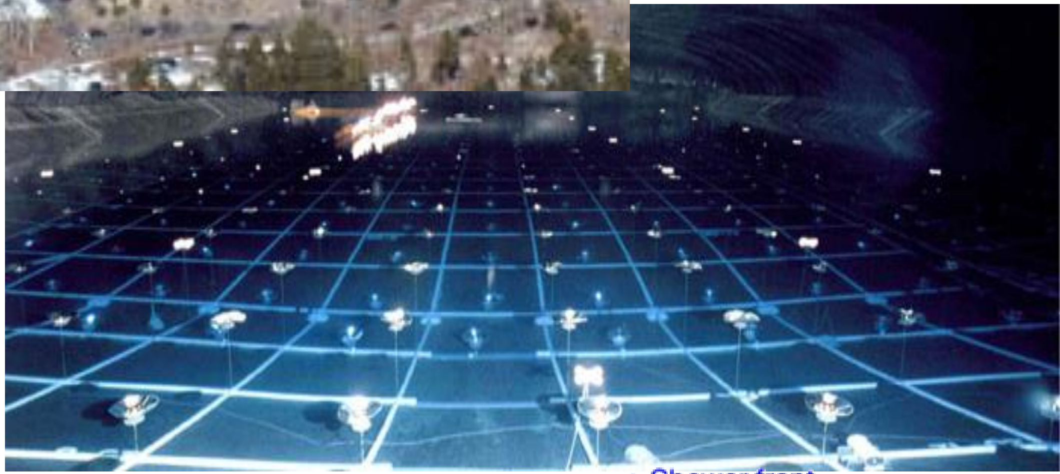


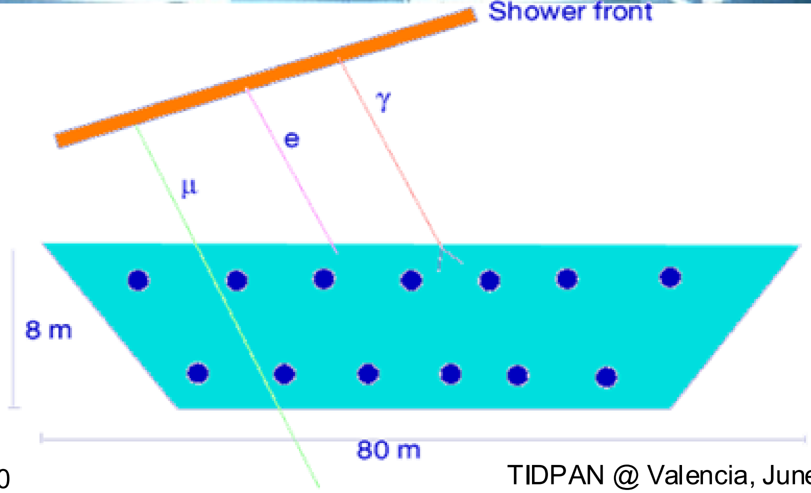
E. Lorenz

Milagro

Instrumento

- Piscina
  - Agua en 60 x 80 x 8 m
  - 750 PMTs en dos filas
  - Luz Cherenkov de partículas cargadas
  - Dirección de la cascada con la fila superior
  - Identificación de hadrones y energía con la fila inferior
- Tanques externos
  - 175 tanques para localizar el *core*
- Rendimiento
  - E > 2 TeV
  - FOV ~ 2 sr, $\Delta\theta$ ~ 0.5º
  - Sensibilidad: 0.5 CU





Milagro

Instrumento

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  - 175 tanques para localizar el *core*
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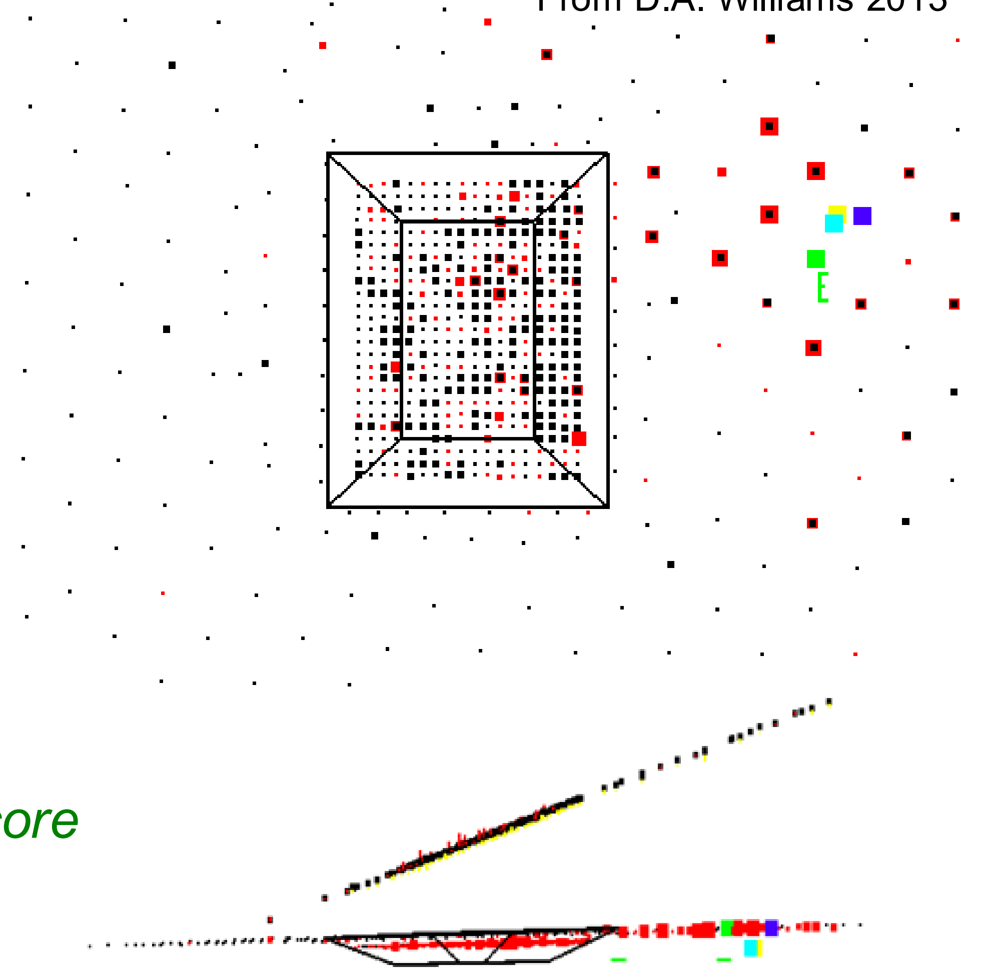
  - E > 2 TeV
  - FOV ~ 2 sr, $\Delta\theta$ ~ 0.5º
  - Sensibilidad: 0.5 CU

From D.A. Williams 2013



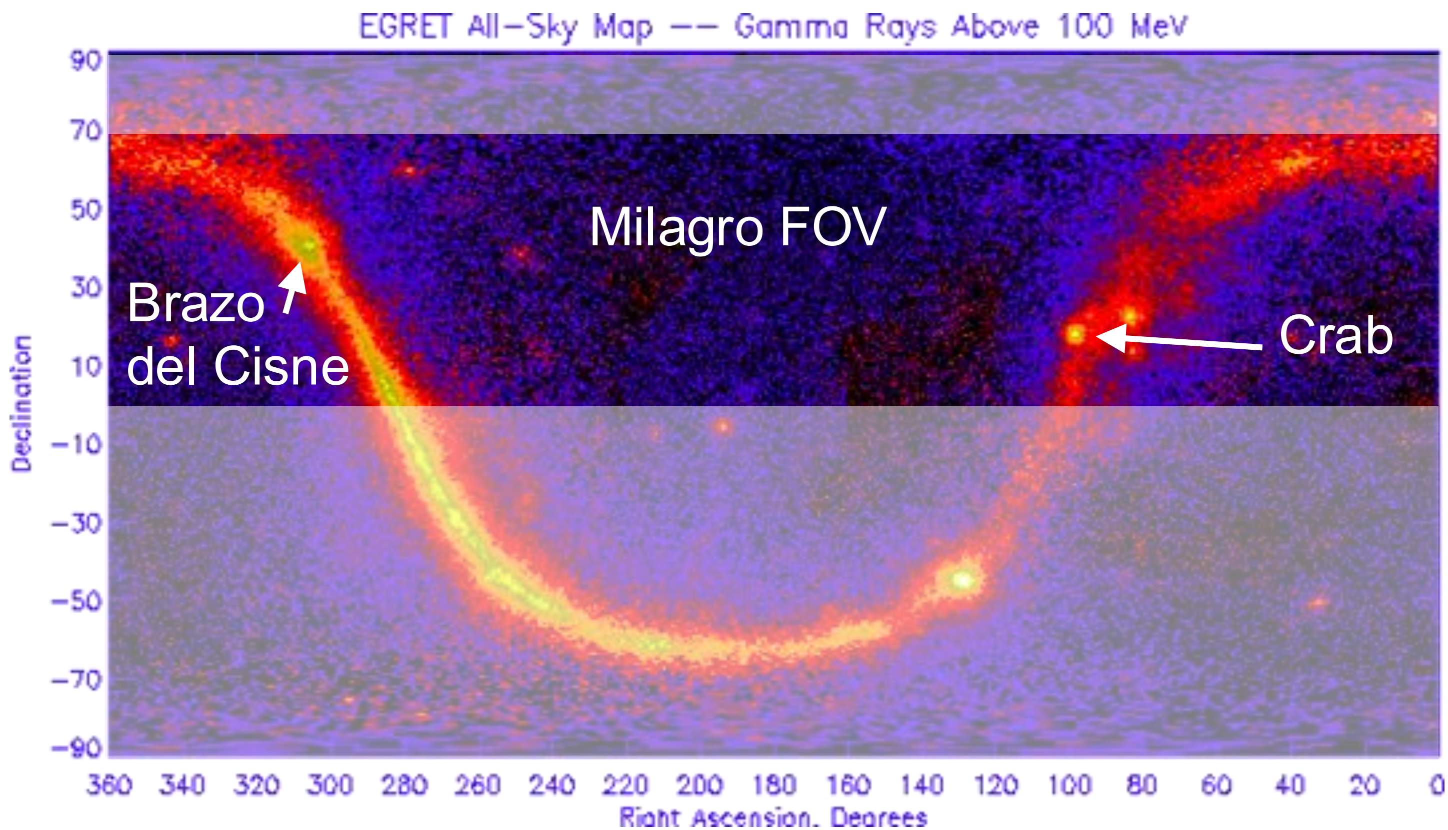
Rayo γ simulado

EXTRA

Milagro

Resultados

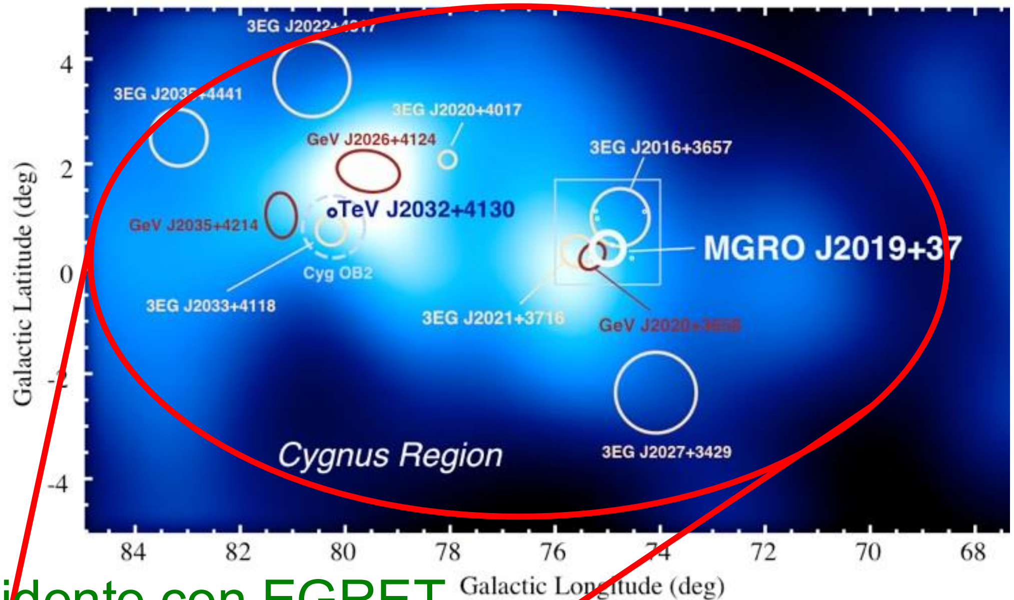
- Mapa del cielo
- Fuentes puntuales
  - Nebulosa del Cangrejo
  - Mrk 421

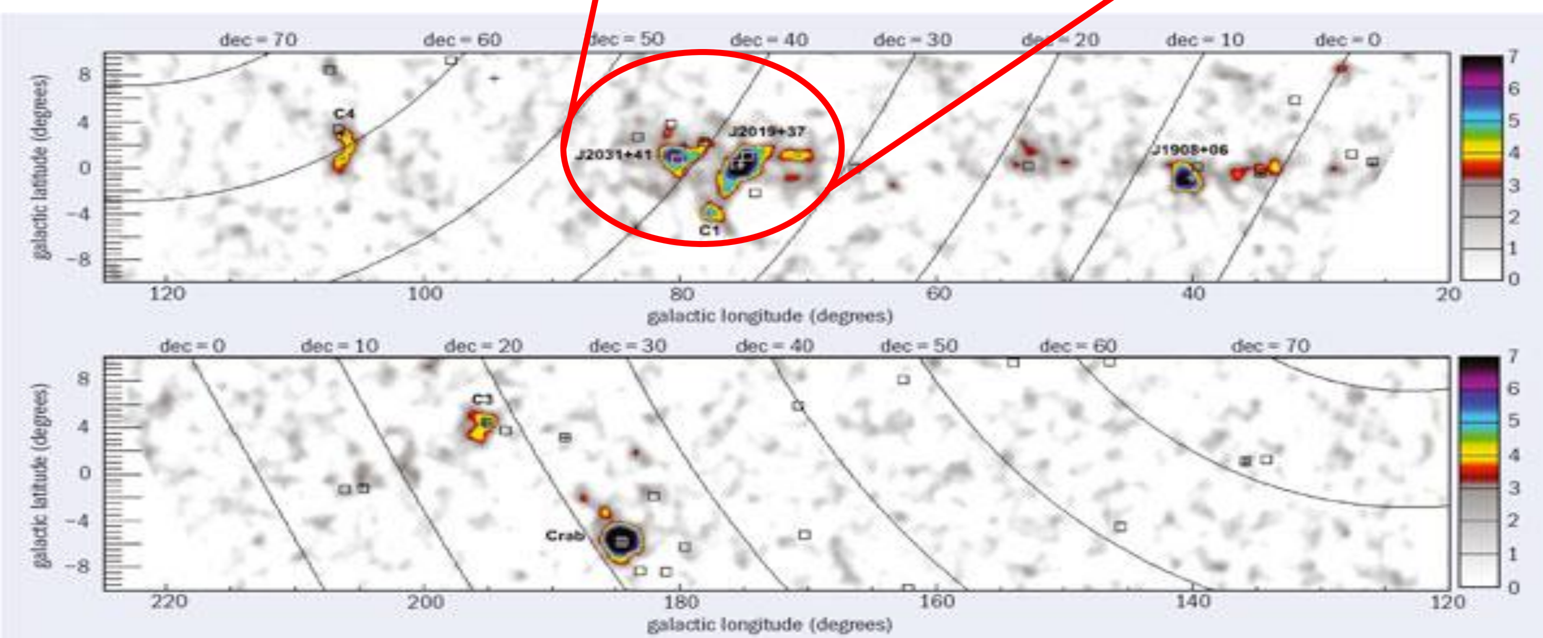


Milagro

Resultados

- Mapa del cielo
- Fuentes puntuales
  - Nebulosa del Cangrejo
  - Mrk 421
- Fuentes extensas
  - Región del Cisne, coincidente con EGRET





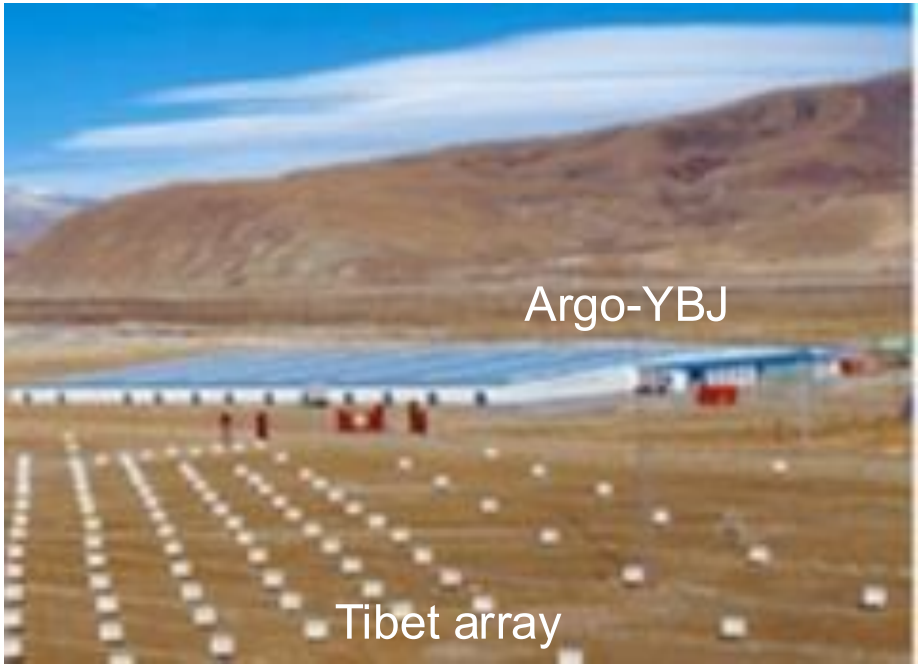
Índice

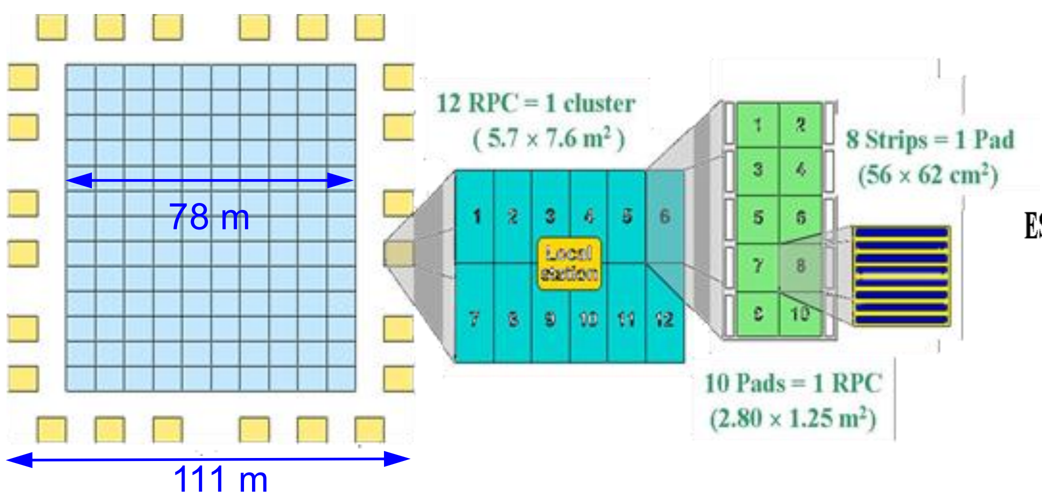
- Técnicas de detección
  - Cascadas atmosféricas
  - Telescopios Cherenkov
- Telescopios
  - Historia
  - Detectores actuales: MAGIC/HESS
  - Detectores futuros: CTA
- Monitores de cielo
  - Historia
  - Detectores actuales: HAWC

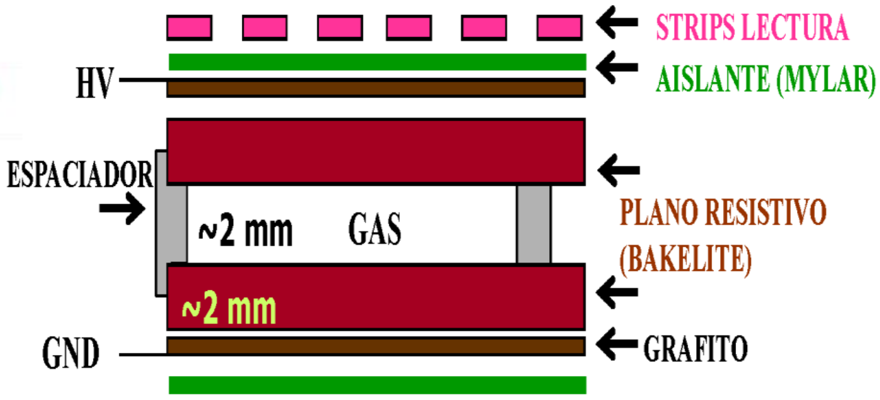
Argo

Instrumento

- Mosaico de RPCs
  - Observatorio 4300 m.a.s.l (Tibet)
  - Resistive Plate Chamber + Pb
- Rendimiento
  - E > 500 GeV
  - $\Delta\theta \sim 0.2^{\circ}$
  - Sensitivity 0.3 CU



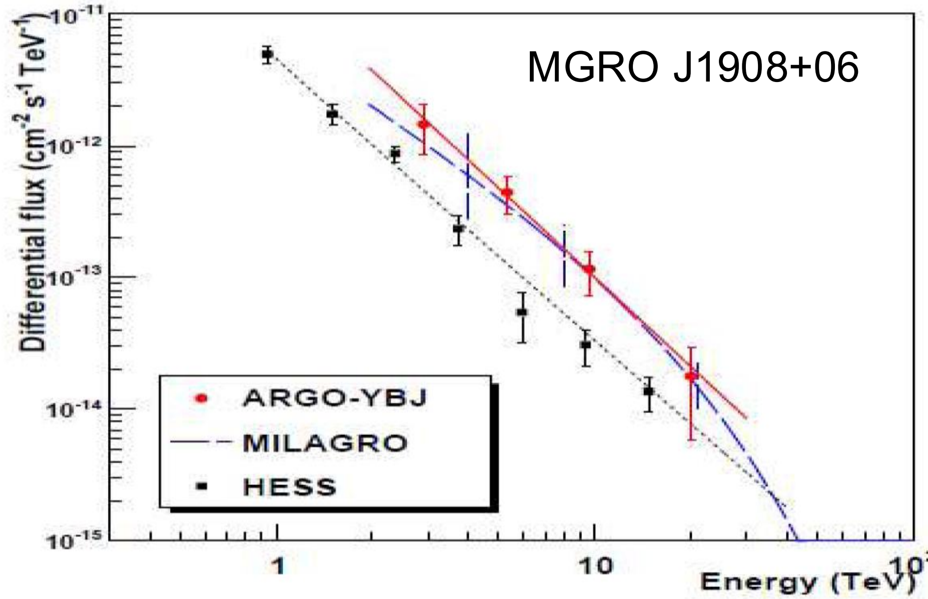


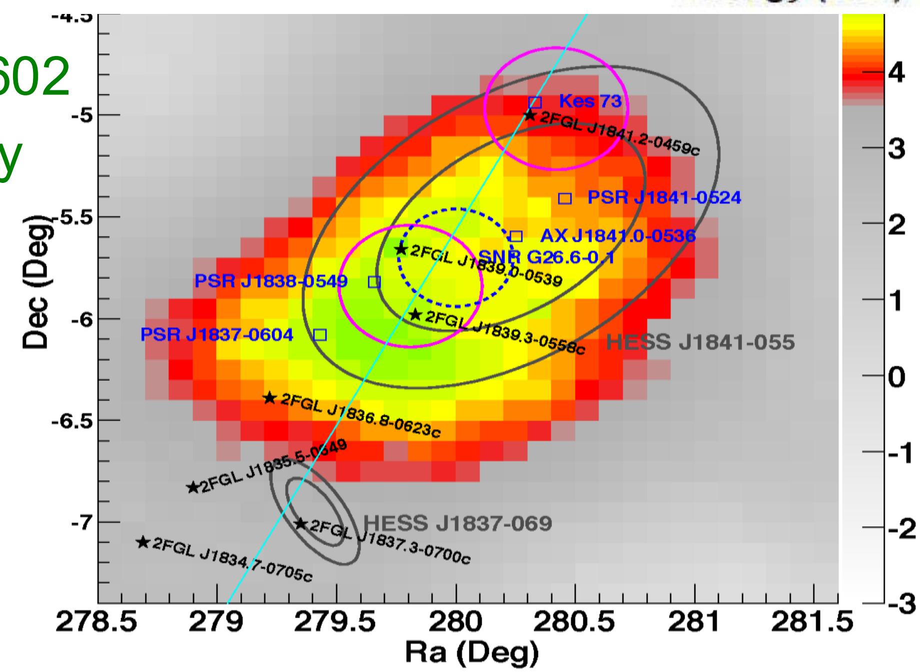


Argo

Resultados

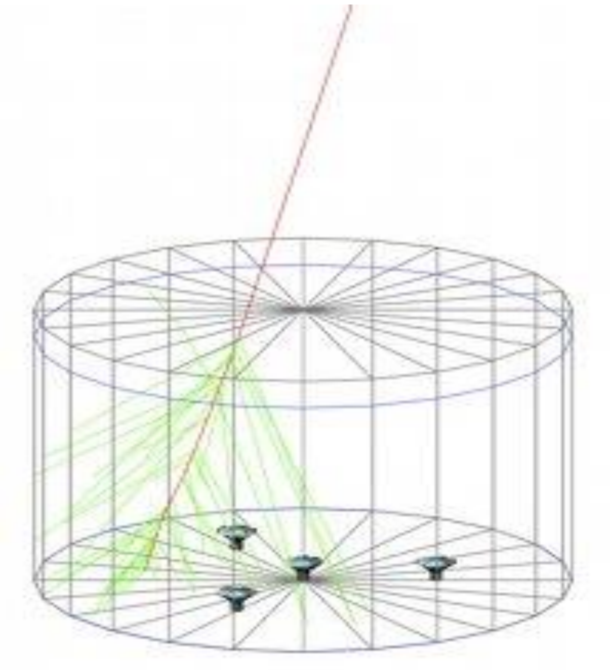
- Mapa del cielo
- Fuentes puntuales
  - Crab, Mrk 421
- Fuentes extensas:
  - MGRO J2031+41
  - MGRO J1908+06 → Posible asociación Fermi PSR J1907+0602
  - HESS J1841-055 → entorno muy concurrido para la identificación





Instrumento

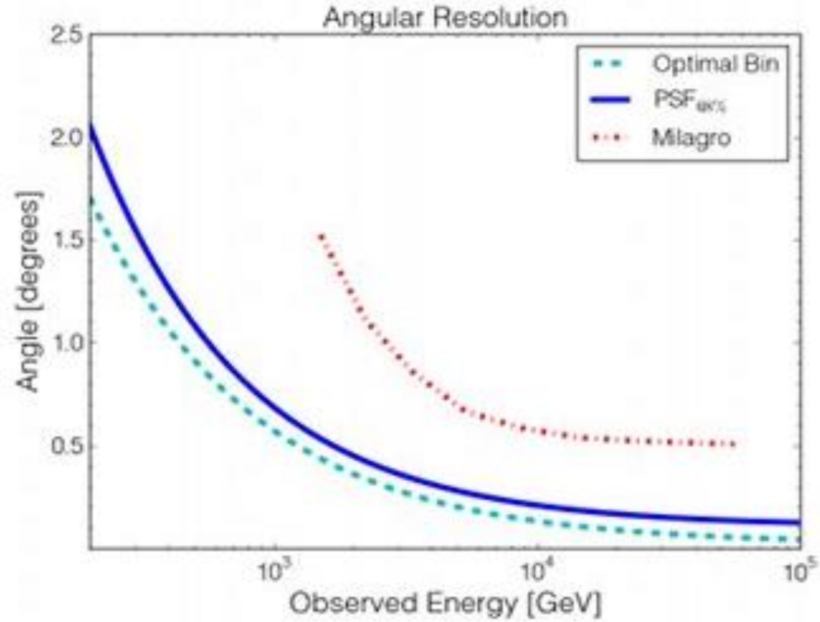
- Matriz de tanques
  - 111 tanques de agua ~ 4000 m.a.s.l.
  - 4 PMT en cada tanque
  - Luz Cherenkov de partículas cargadas
  - Dirección de la cascada con los tiempos de llegada en los PMTs
  - Identificación de hadrones por hits aislados

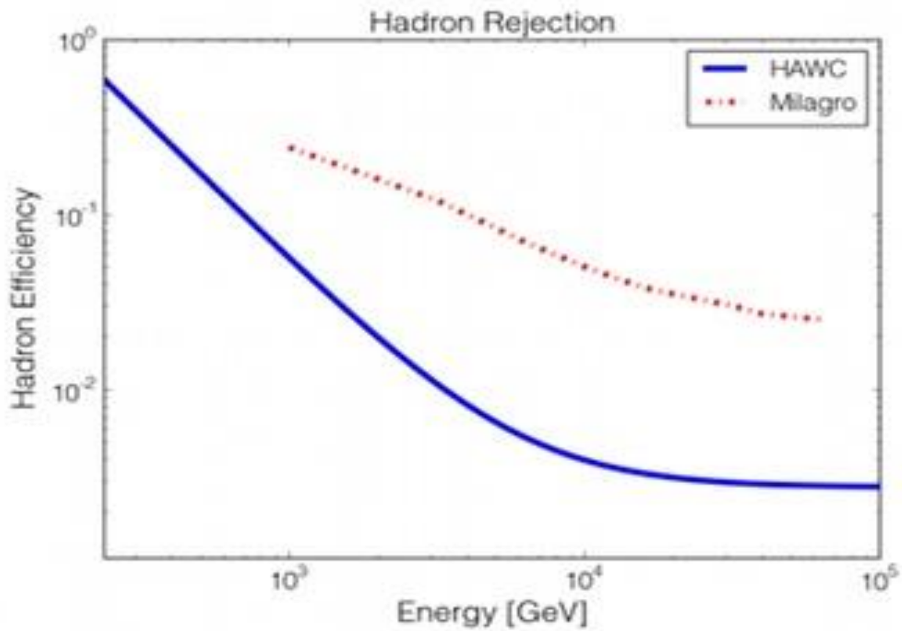


HAWC

Instrumento

- Matriz de tanques
  - 111 tanques de agua ~ 4000 m.a.s.l.
  - 4 PMT en cada tanque
  - Luz Cherenkov de partículas cargadas
  - Dirección de la cascada con los tiempos de llegada en los PMTs
  - Identificación de hadrones por hits aislados
- Rendimiento
  - 1 TeV < E < 100 TeV
  - FOV ~ 2 sr, $\Delta\theta$ ~ 0.5º @ 1 TeV





HAWC

1^{er} mapa del cielo E > 1 TeV