The Cherenkov Telescope Array

an advance facility for the ground-based high energy gamma-ray astronomy

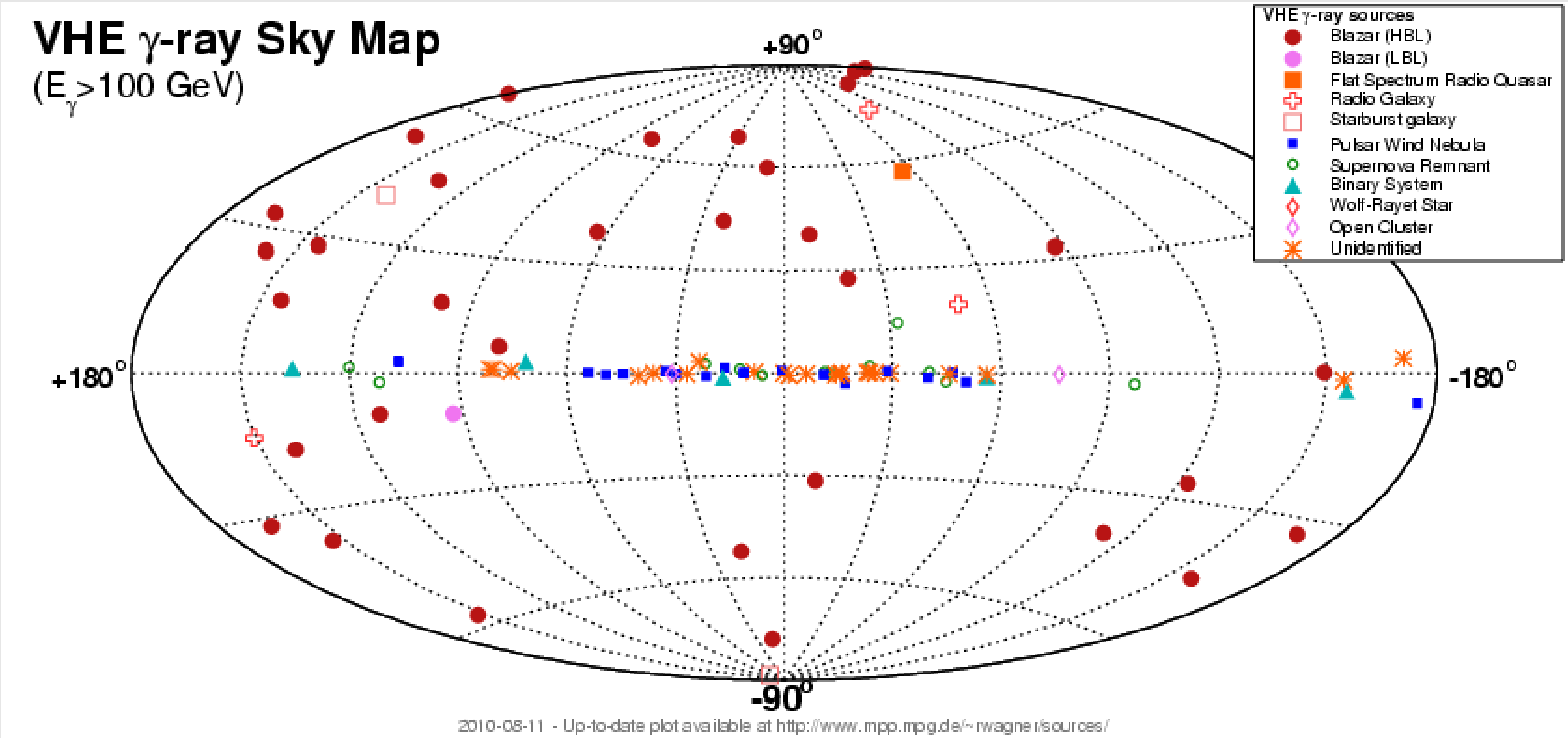
M. Clementina Medina
IRFU – CEA - France

SciNeGHE 2010

Outline

- State of art of the Gamma-Rays Astronomy
- CTA: a new science infrastructure
- Realizing CTA
- Summary

State of the VHE gamma-rays astronomy



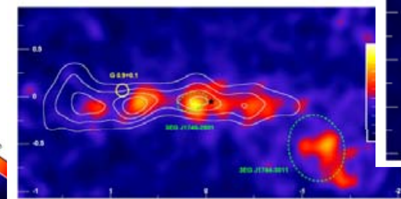
July 2010:
103 TeV sources
61 Gal. / 42 EG

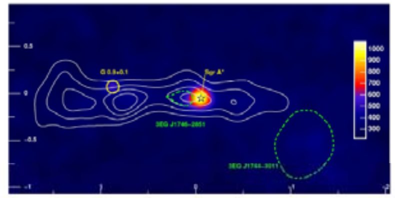
Highligths

- **Microquasars**: Science, 309, 746 (2005), Science 312,1771 (2006)
- **Pulsars**: Science, 322, 1221 (2008)
- **Supernova remnants**: Nature, 432, 75 (2004)
- **Galactic Centre**: Nature, 439, 695 (2006)
- **Galactic Survey**: Science, 307,1839 (2005)
- **Starbursts**: Nature, 462, 770 (2009), Science, 326, 1080(2009)
- **AGN**: Science, 314, 1424 (2006), Science, 325, 444 (2009)
- **EBL**: Nature, 440, 1018 (2006), Science, 320, 752 (2008)
- **DM**: Phys Rev Letters, 96, 221102 (2006)
- **LIV**: Phys Rev Letters, 101, 170402 (2008)
- **Cosmic Ray Electrons**: Phys Rev Letters (2009)

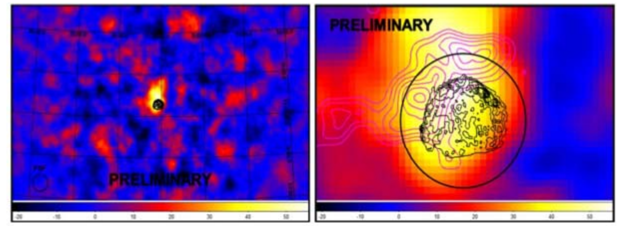
RESULTS FROM HESS, MAGIC & VERITAS

From J. Hint, TeVPa 2010

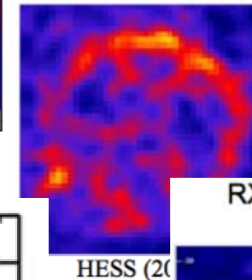




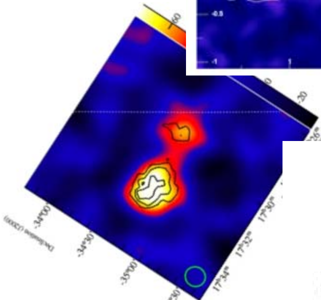
TYCHO



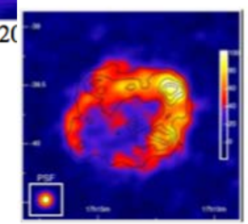
Vela Junior

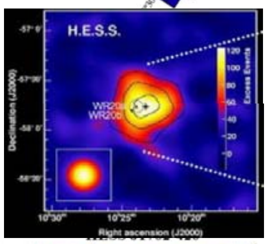


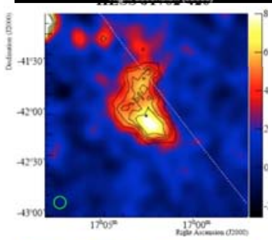
Galactic Sources Population

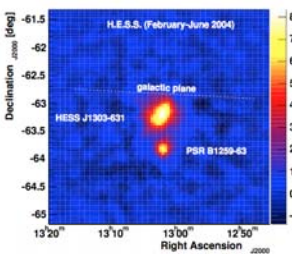


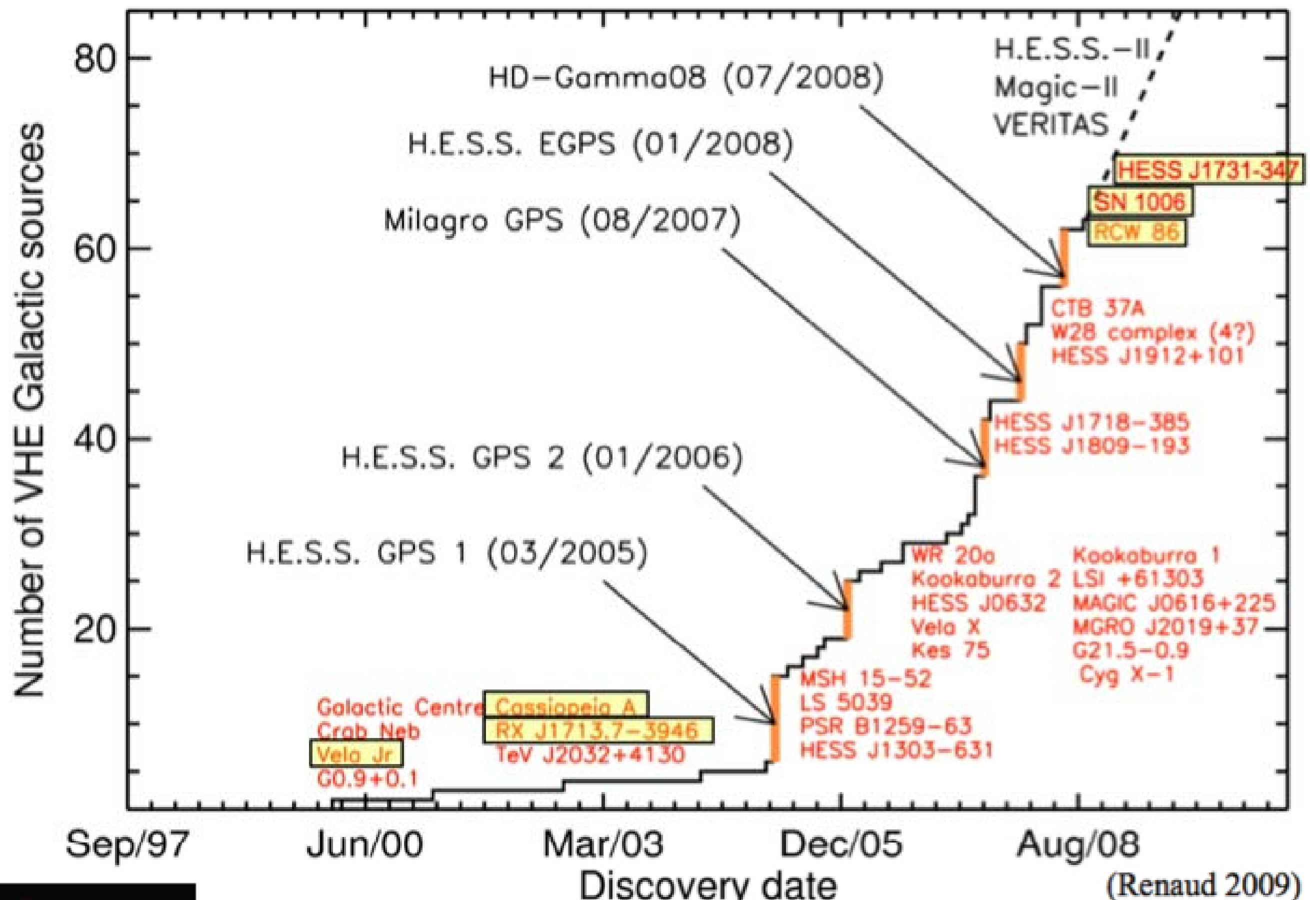
RX J1713

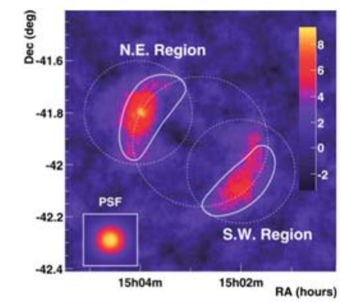


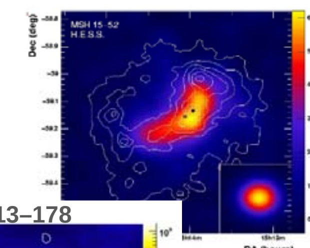




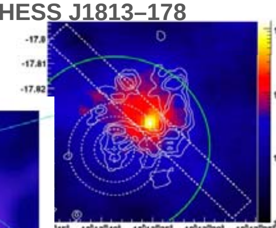


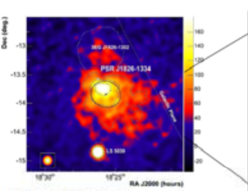




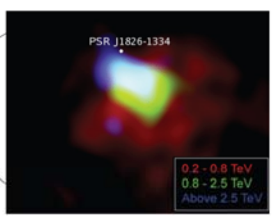


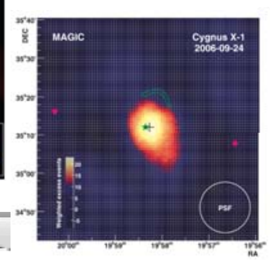
HESS J1813–178

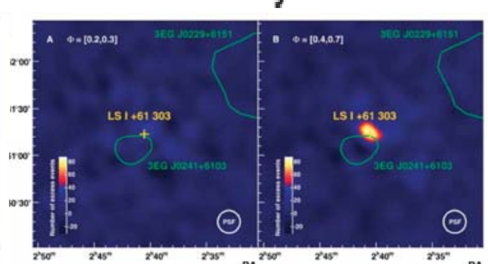


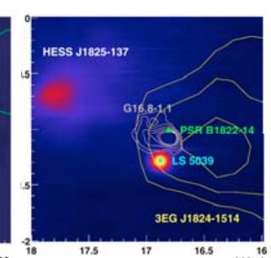


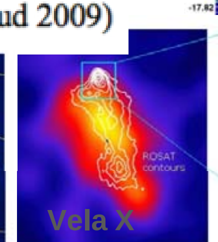
HESS J1823-137



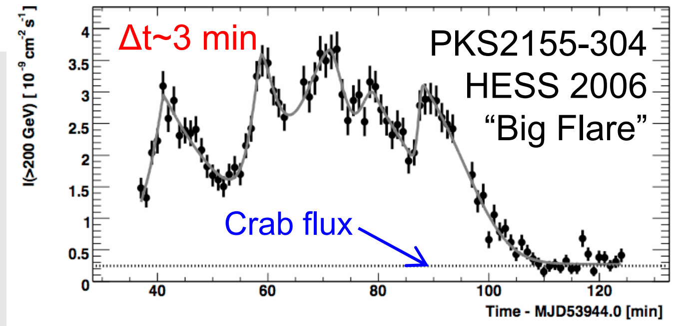




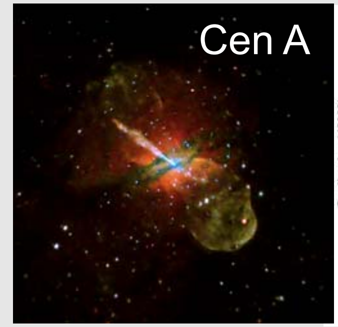


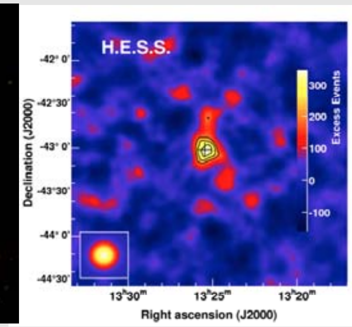


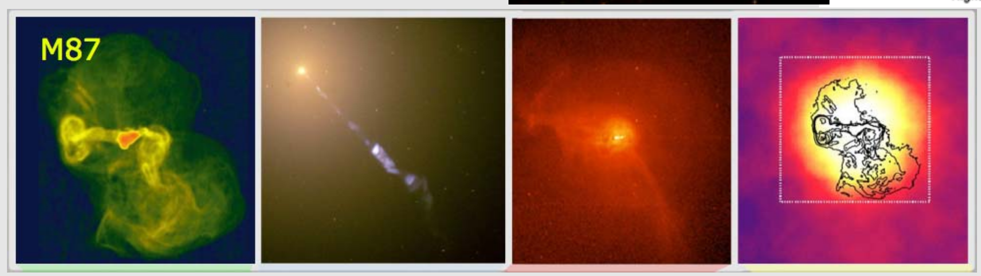
Extragalactic sources



- **Active Galaxies**
  - 33 BL Lacs (mostly HBL)
    - High Flux variability
  - FSRQ (3C279; PKS 1222+21; PKS 1510-089)
  - Radio galaxies
    - Cen A (core emission)
    - M 87 (days scale variability,) Flare 2008.
    - IC 310 (recently detected by MAGIC & Fermi)



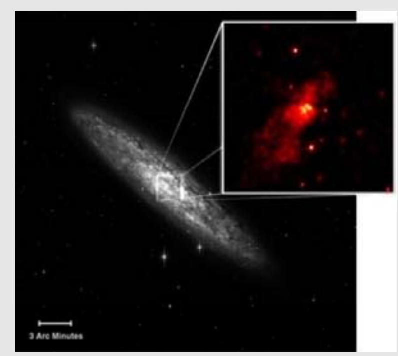




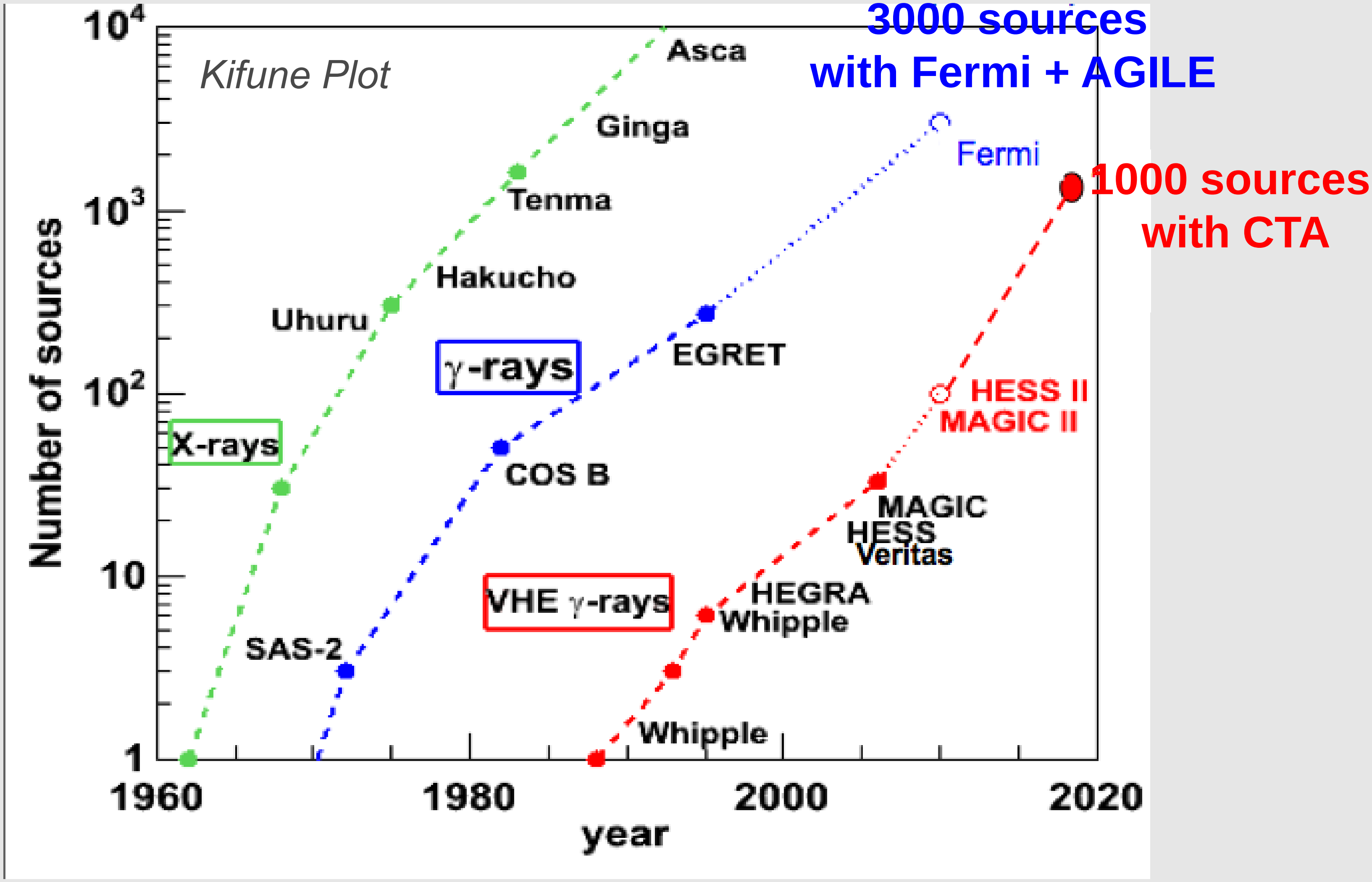
- **Starburst galaxies**

M82 VERITAS
z = 0.0008
Discovery 2009

NGC 253 HESS
z = 0.0008
Discovery 2009



Source demographic grow



The next generation of IACT arrays needs to function like a true observatory:
Observation time for astro-physical/particle community
Open access data at different levels

CTA: a new science infrastructure

The Concept
The Scientific Motivation
& Potential

CTA as a revolutionary concept

- Advancing VHE Gamma-Ray Astronomy
- Unprecedented performance as an IACT instrument.
- European and international integration (Consortium)
- Operation as an open observatory
- New technical implementation, operation, and data access

Advancing VHE Gamma-Ray Astronomy

guaranteed high-energy astrophysics results & large discovery potential

Cosmic rays origin and interaction

- Origin and propagation of Galactic cosmic rays (only SNR?)
- Understanding of processes around pulsars, binary systems, PWN structure
- Starburst galaxies
- Signatures of UHECR acceleration sites ?

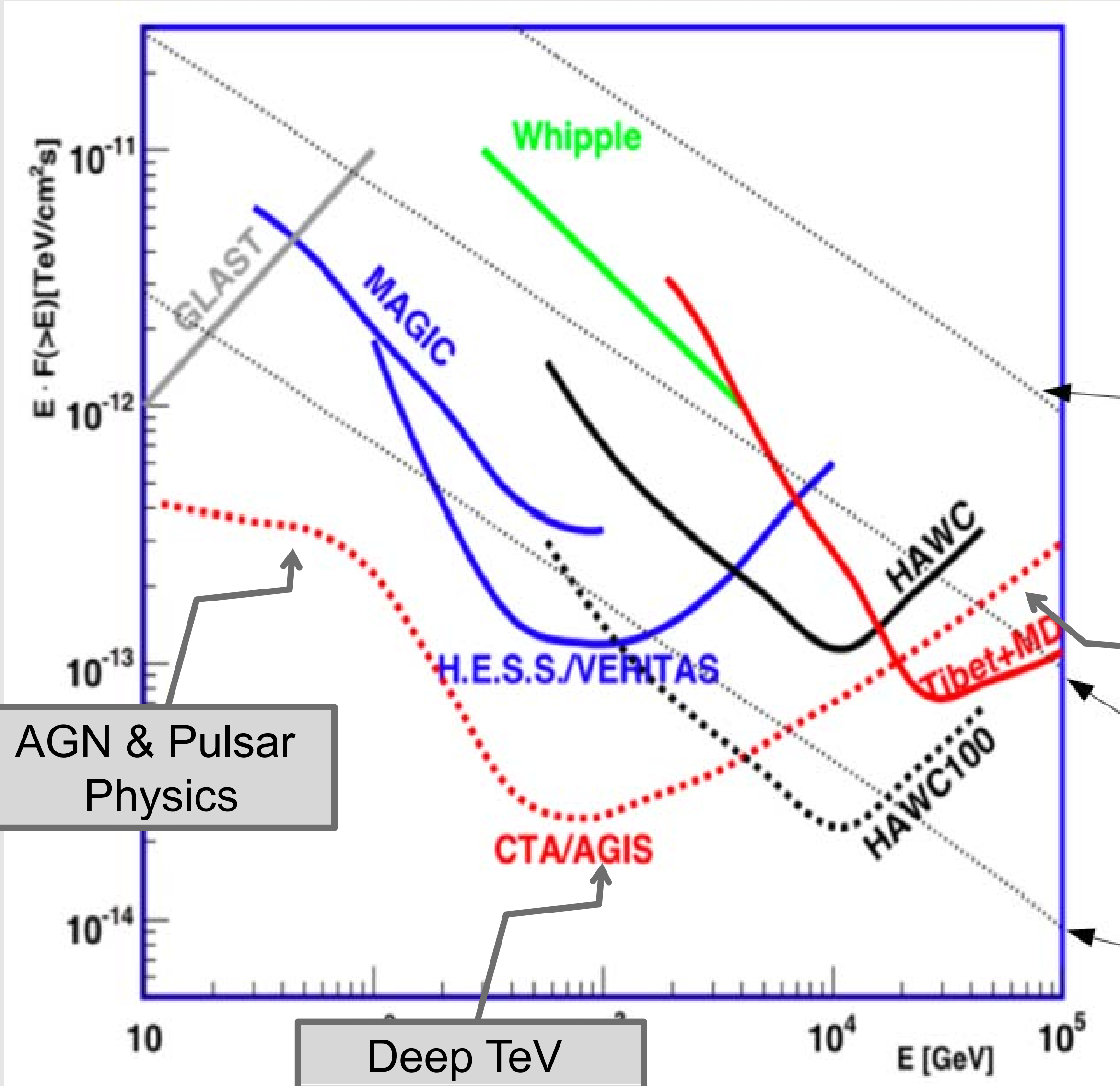
Nature of the different types of black hole particle accelerators

- Detailed understanding of acceleration & emission processes in different classes of AGN
- Detection of VHE gamma rays from GRBs ?

Beyond the Standard Model Physics

- Cosmology with VHE gamma rays (probing the EBL)
- Fundamental physics
  - Detection of Dark Matter?
  - Test Lorentz Invariance Violation

Unprecedented performance as an IACT instrument.



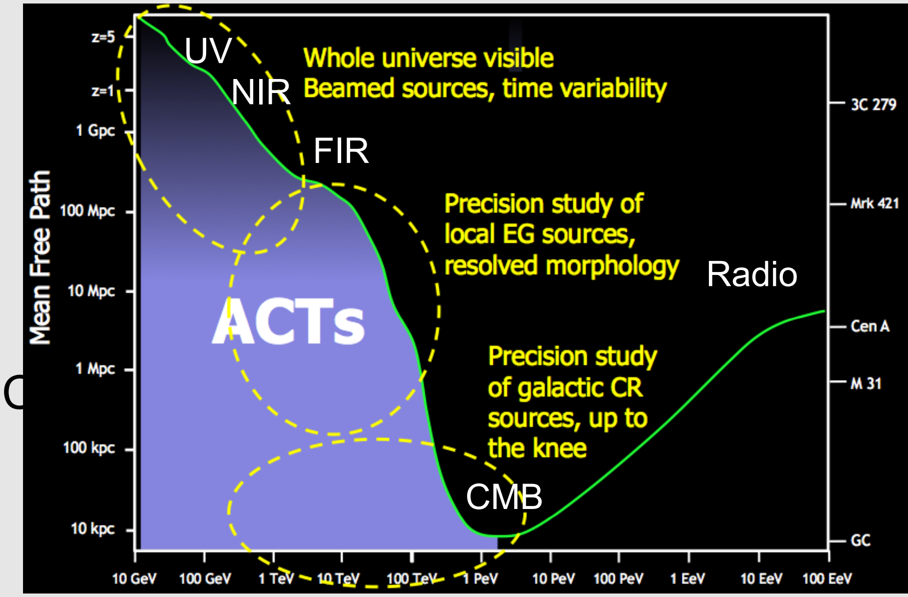
AGN & Pulsar Physics

Deep TeV Sky survey

10% Crab

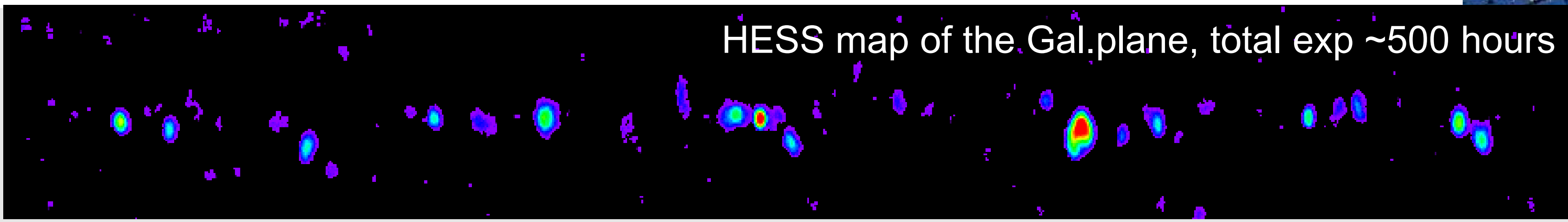
1% Crab

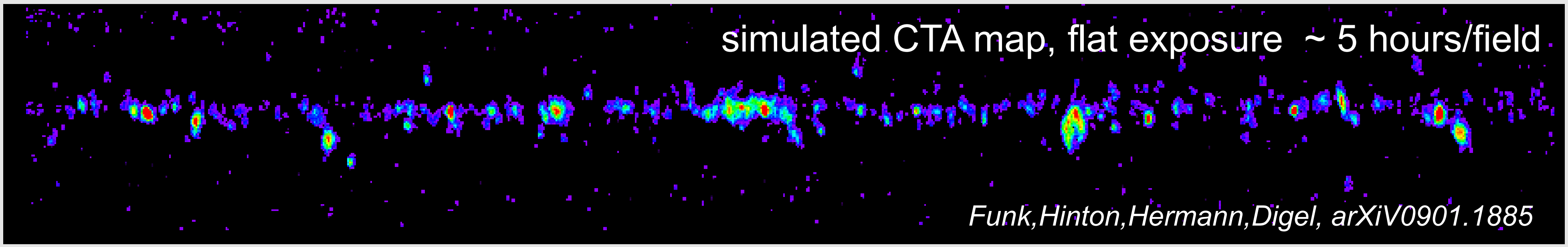
Exploration of the EHE regime of galactic sources



Expectations for galatic survey

~ 300 sources in -30° ≤ l ≤ 30°





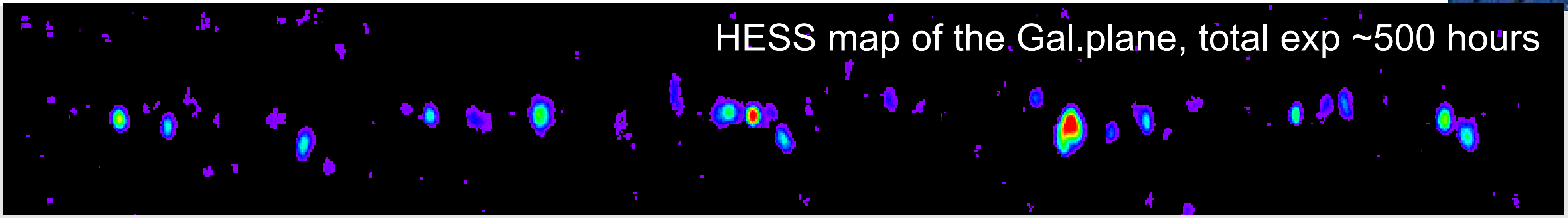
SNRS:

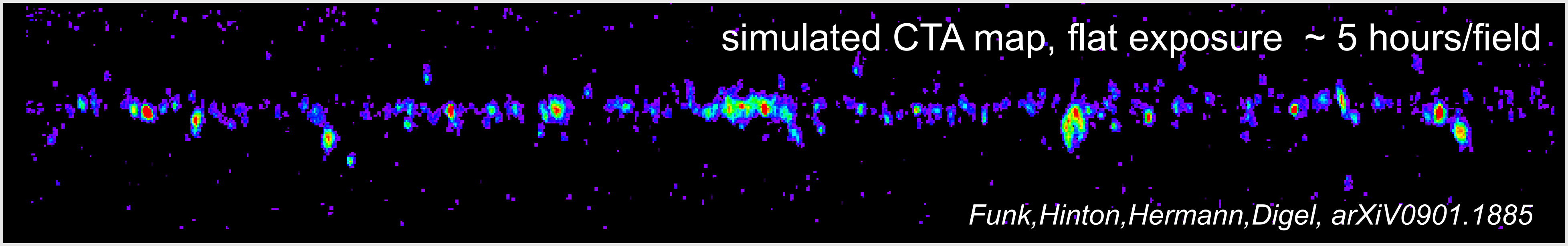
- CTA Galactic plane survey, currently known shell SNRs detectable to 10–15 kpc (i.e. throughout most of the Galaxy)
- If shells shine 2000 yr in TeV, ~40 TeV shells in Galaxy; ~25 detectable (vs 6 currently known)
- Gamma-Ray shell directly resolvable by CTA to 5–7 kpc
- More distant SNR shells identifiable through follow-up multi-wavelength observations (e.g. radio)

Y. Gallant, TevPa 2010

Expectations for galatic survey

~ 300 sources in -30° ≤ l ≤ 30°



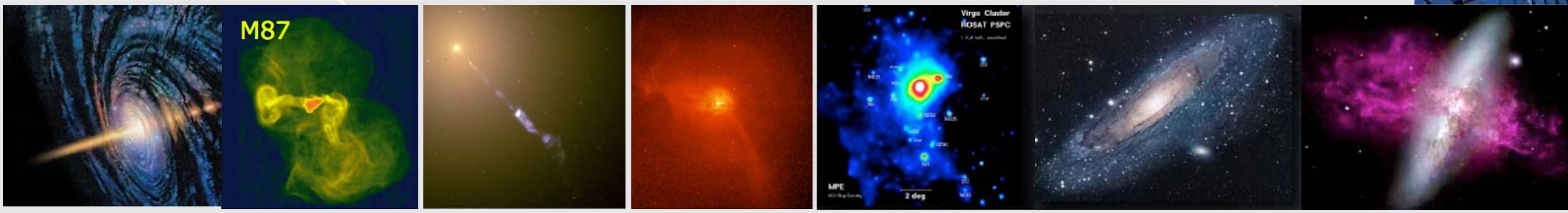


Pulsar Wind Nebulae

- CTA will detect luminous PWNe like the Crab to the distance of the Large Magellanic Cloud
  luminosity-limited survey
- If PWNe shine 10 000 yr in TeV, ∼200 TeV PWNe in Galaxy (75% detectable by CTA)
- In a CTA Galactic plane survey, weaker PWNe like Kes 75 detectable to ∼13–15 kpc
  (i.e. in large fraction of Galaxy)
- Identifiable through follow-up MWL observations (non-thermalX-ray nebulae, pulsar search)

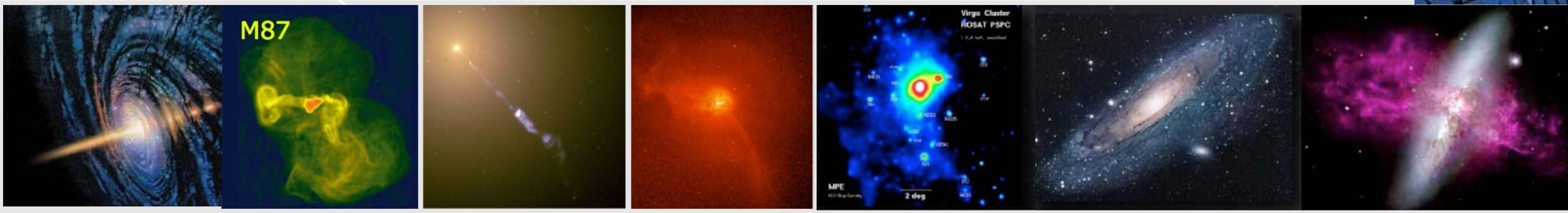
Similar for other Galactic TeV γ-ray sources : *Y. Gallant, TevPa 2010*
binaries, SNRs interacting with molecular clouds, star forming regions. . .

Extragalactic studies with CTA:
Active Galaxies, Cosmic Radiation Fields and Cosmology

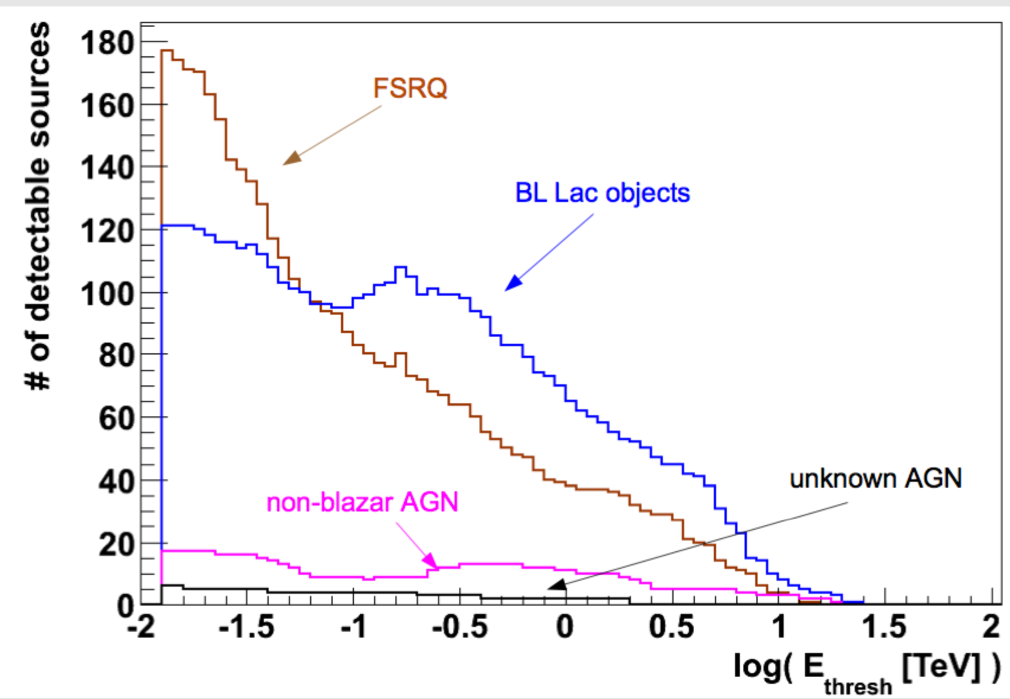


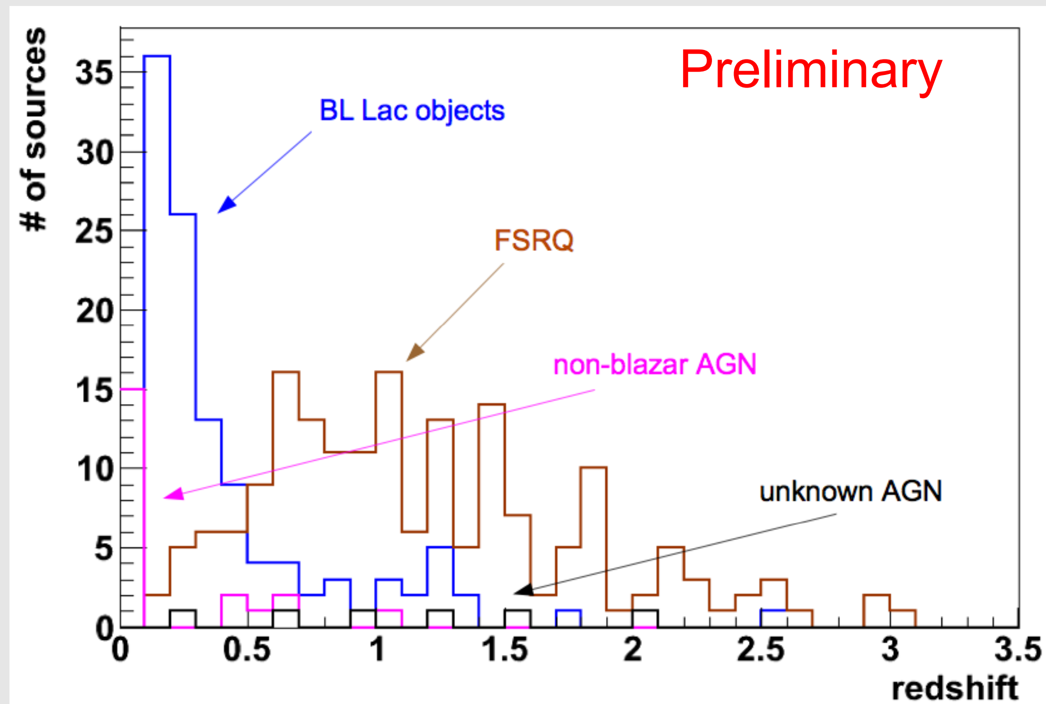
- **Study of different AGN classes at VHE (unification, "blazar sequence")**
  - today: ~30 BL Lacs, 3 FSRQ, 3 radio galaxies,
  - Population studies, luminosity function today:
    - largely biased in redshift,
    - small statistics
  - Spectral features and variability
    - information on acceleration & cooling processes
    - hadronic vs. leptonic scenarios
    - constraints on emission region
  - Mapping of radio galaxies
  - Probing the EBL and the extragal. magnetic field

Extragalactic studies with CTA: Active Galaxies, Cosmic Radiation Fields and Cosmology



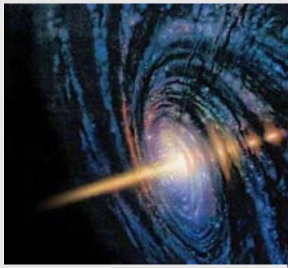
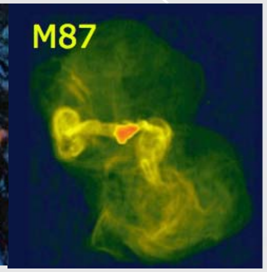
- **Predicted AGN detectability using Fermi**

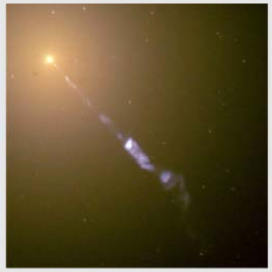
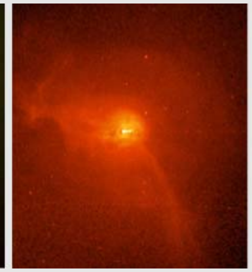
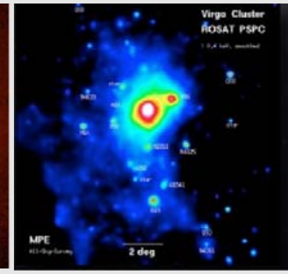




A. Zech Snowpac 2010

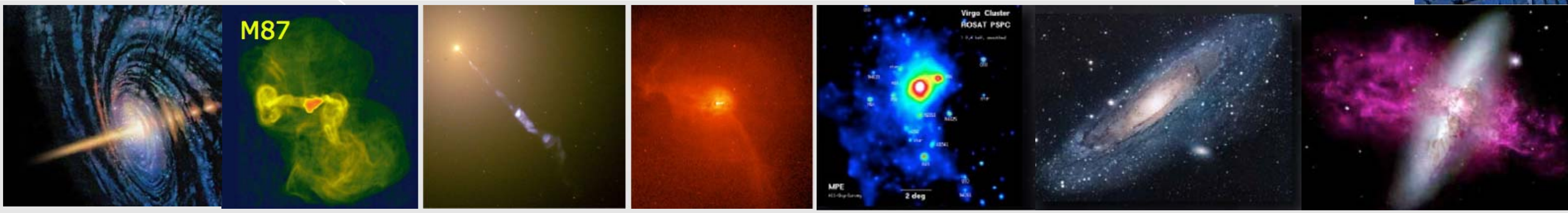
Extragalactic studies with CTA:
Starbursts Galaxies, GRBs, Dark matter searches


- **Starburst Galaxies**
  - VERITAS and H.E.S.S. have observed TeV gamma-rays from the nearest starburst galaxies.
  - Improved CTA sensitivity at higher and lower energies implies
    - understand the spectra, constrains on physical emission scenarios,
    - study the relationship star formation processes and gamma-ray emission
- **GRBs**
  - Fermi LAT → emission above 10 GeV (30 GeV) from 4 (2) GRBs
  - A good fraction observables by CTA:
    - Rapid observations (1’ reaction time) and a wide energy range
      - “capture” the SED

Extragalactic studies with CTA:
Starbursts Galaxies, GRBs, Dark matter searches



- **Dark matter search**
  - DM can annihilate or decay to detectable gamma-rays. Large dark matter densities → detectable fluxes, (i.e. annihilation rate $\propto$ square of the density).
  - Galactic Centre
    - the most promising candidate to look for DM annihilation radiation.
      - Identification of dark matter complicated.
      - Angular and energy resolution of CTA + enhanced sensitivity → disentangle the different contributions to the radiation from the GC.
  - Other individual targets: dwarf spheroidals and dwarf galaxies.
    - Large mass-to-light ratios + low astrophysical backgrounds.
  - CTA will provide coverage for the highest-energy part of the multi-wavelength spectrum necessary to pinpoint, discriminate and study dark matter indirectly.

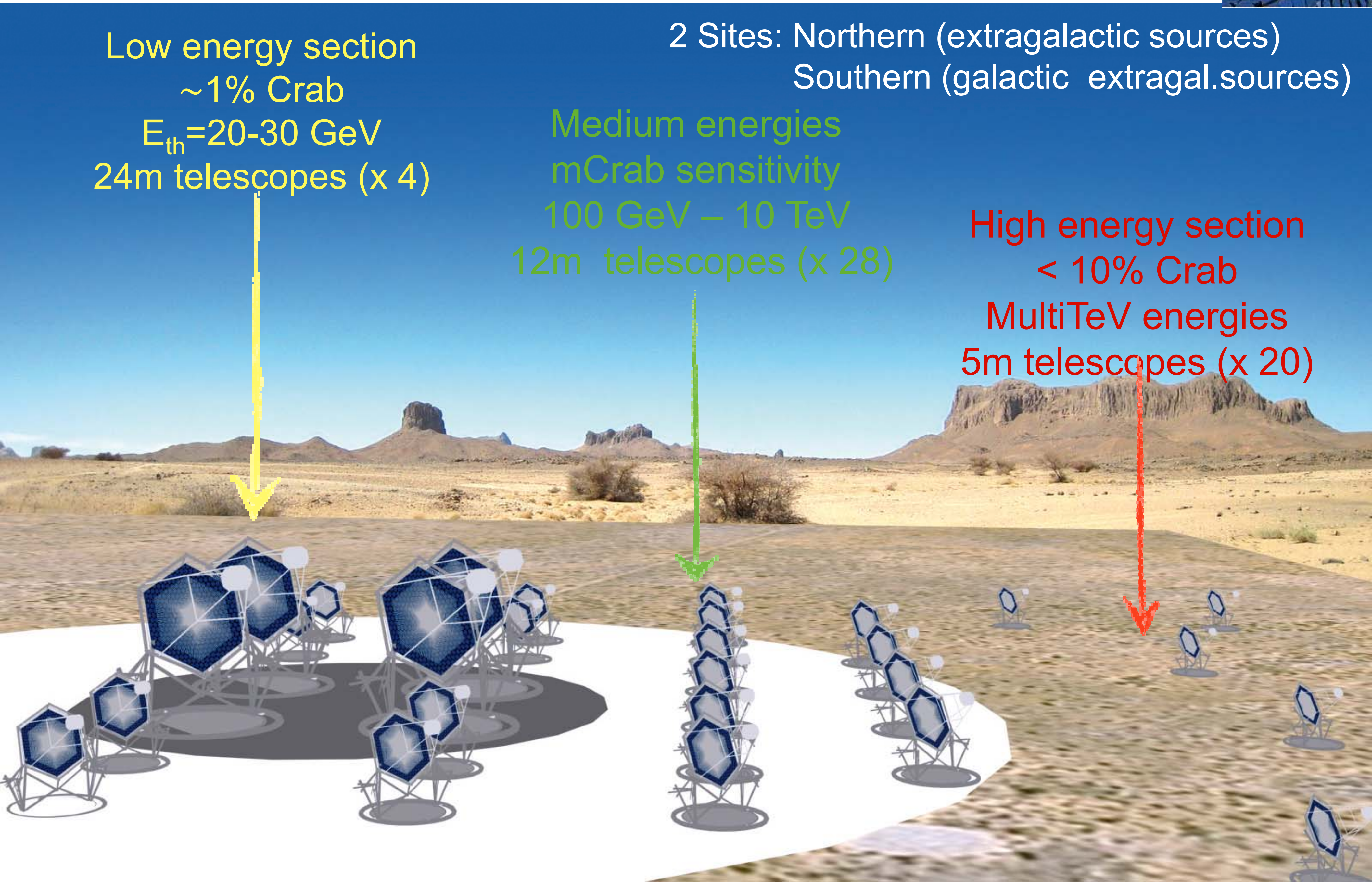
European and international integration

- Consortium formed by 22 countries
  - 16 European countries
  - Argentina, Armenia, Japan, Namibia, South Africa, United States
  - 100 institutions
  - 200 physicists and engineers
  - Regular general CTA meetings since 2006
  - spokesperson: W. Hofmann (MPIK Heidelberg)
  - co-spokesperson: M. Martinez (IFAE Barcelona)

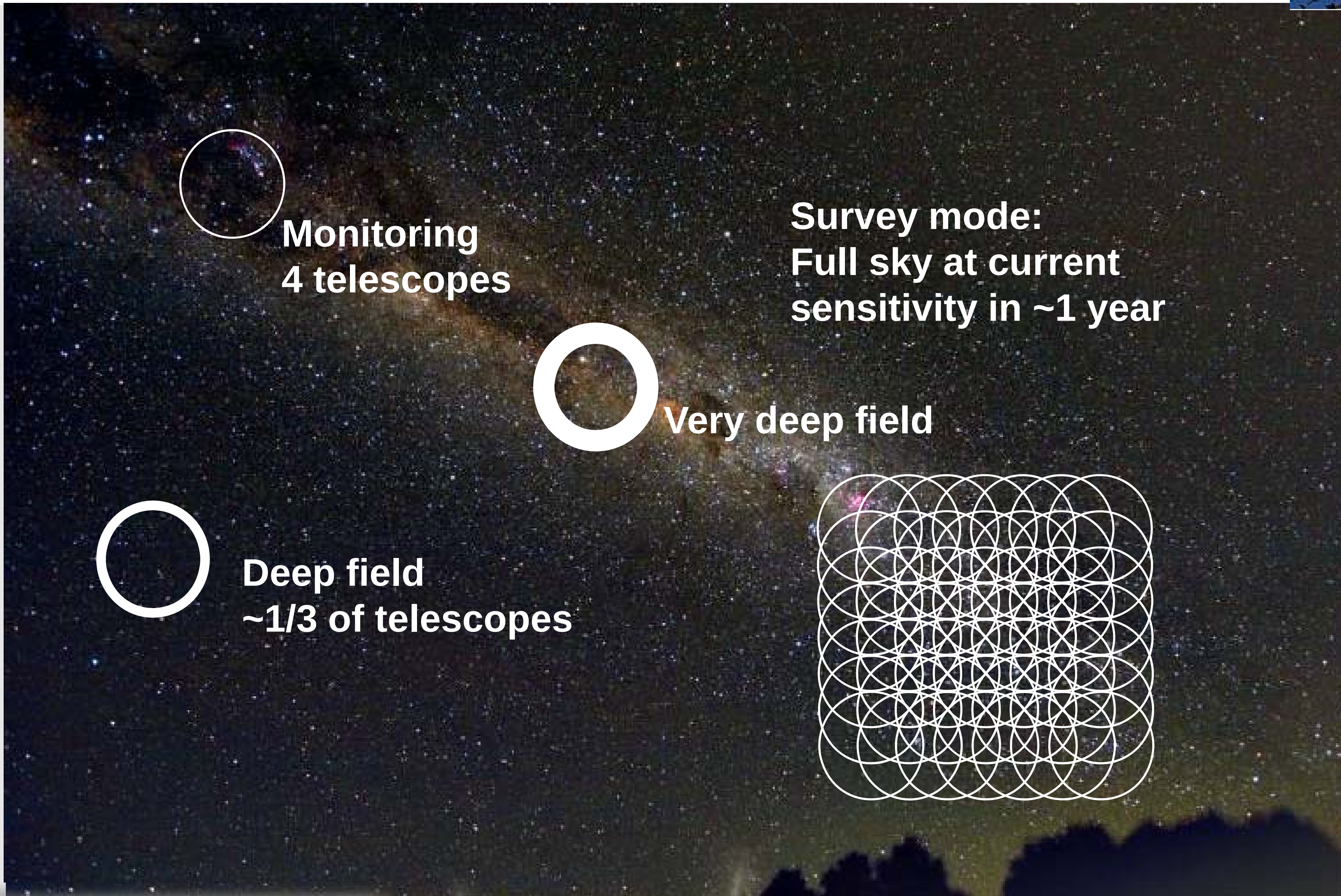
CTA unprecedented scientific performance

- **Sensitivity**
  - A factor 10 more sensitive than current instruments
- **Spectral coverage**
  - A single facility covering three to four orders of magnitude in energy range.
- **Angular resolution**
  - A factor 5 better than what is typical for current instruments (arc-minute range)
- **Temporal resolution**
  - On sub-minute time scales.
- **Flexible operation modes**
  - Wide range of configurations (in-depth study of individual objects + monitoring tens of flaring candidates)
- **Survey capability**
  - Increase of sky area surveyed per unit time + full-sky survey at high sensitivity.
- **Global coverage and integration**
  - Two sites (North + South)

CTA basic layout



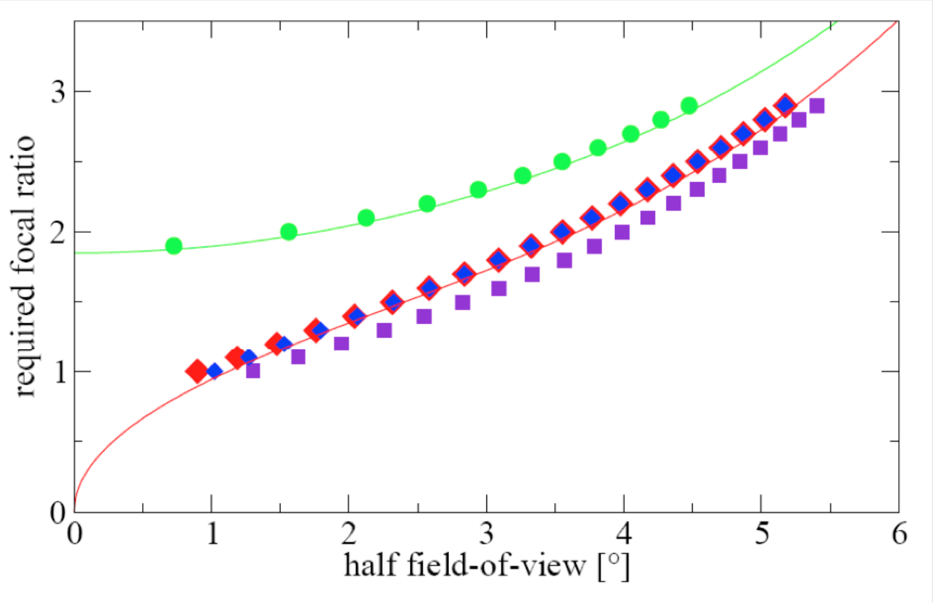
Several operation modes



CTA TELESCOPE layout

- **Field of view**
  - High energy array → large FoV mandatory
  - Low & intermediate array → not so trivial:
    - Detection of high energy showers at large impact distance without truncation
    - Efficient study of extended sources and diffuse emission regions
    - Large-scale surveys and parallel study of many clustered source
    - Larger FoV → growing number of photosensors and electronics channels.

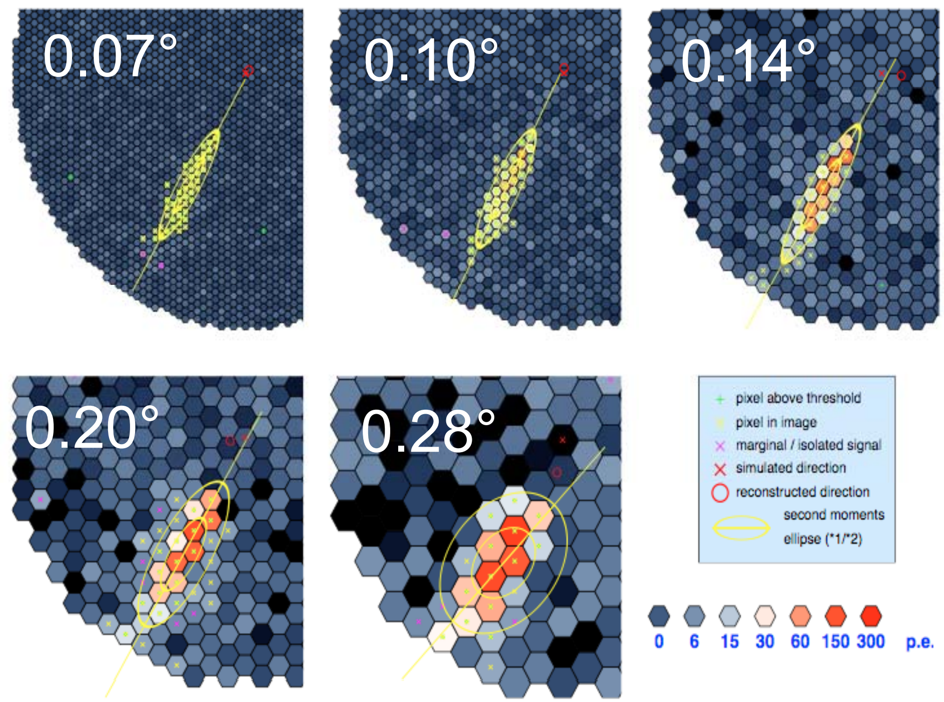
      → Optically challenging



Focal ratio required
as a function of the half angle of the FoV
Spherical design
Parabolic design with constant radii
Davies-Cotton design
Parabolic design with adjusted radii

CTA TELESCOPE layout

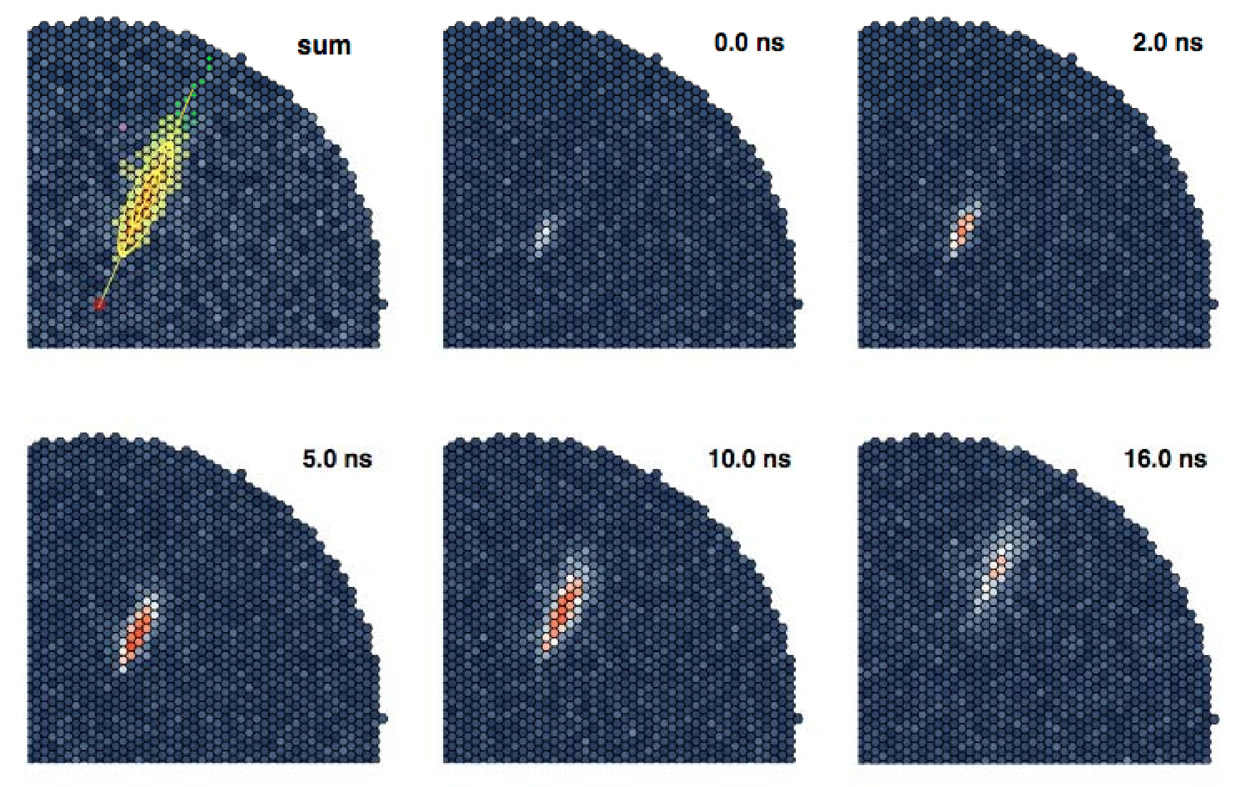
- **Pixel size**
  - The gain of small pixels depends strongly on the analysis technique
    - classical second-moment analysis: 0.2° − 0.15°
    - full image distribution: 0.06°− 0.03°
  - Pixel size → influence on trigger strategies.
  - ***Current simulations***:
    - 0.07° for large size telescopes
    - 0.15° for medium size telescopes
    - 0.25° for small size telescopes



Identical field-of-view
γ-ray shower of 460 GeV

CTA TELESCOPE layout

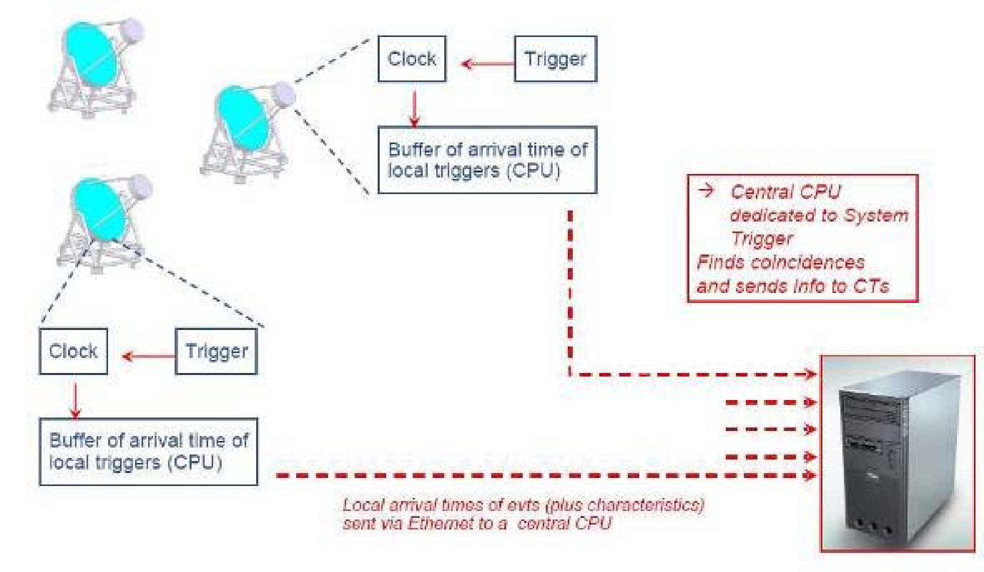
- **Signal shape and timing recording**
  - to reject backgrounds
  - to reduce the signal integration windows → reduce amount of NSB noise
- Variable and matched integration windows across the image
- Under study with the current MAGIC and VERITAS systems,



1 ns samples
10 TeV gamma shower
250 m core distance
Optics and pixels H.E.S.S.1
FoV of 10°.
25 ns total

CTA TELESCOPE layout

- **Trigger strategy**
  - Multi-telescope trigger coincidence
  - Signals from different telescopes combined at the pixel level
  - Intermediate solutions:
    - trigger pre-processors extract image features
    - the system trigger decision includes this information.
- **Trigger topology**
  - Derived locally.
  - The central station take a global decision.
- **Trigger schemes**
  - multi-level hierarchy
    - first trigger level (pixels and pixel groups)
    - higher levels (image or telescopes morphology)



The Cherenkov Telescope Array

The Design Studies:
Performance
Telescope technology
Site selection

http://fr.arxiv.org/abs/1008.3703

CTA Design Studies

- **AIMS**
  - select the appropriate sites
  - reduce production costs of telescopes, sensors, electronics etc (technology already proven with HESS, MAGIC,VERITAS).
  - improve reliability of components and systems

Working Groups

Performance & Physics

- Monte Carlo simulations
- Physics

Instrumentation

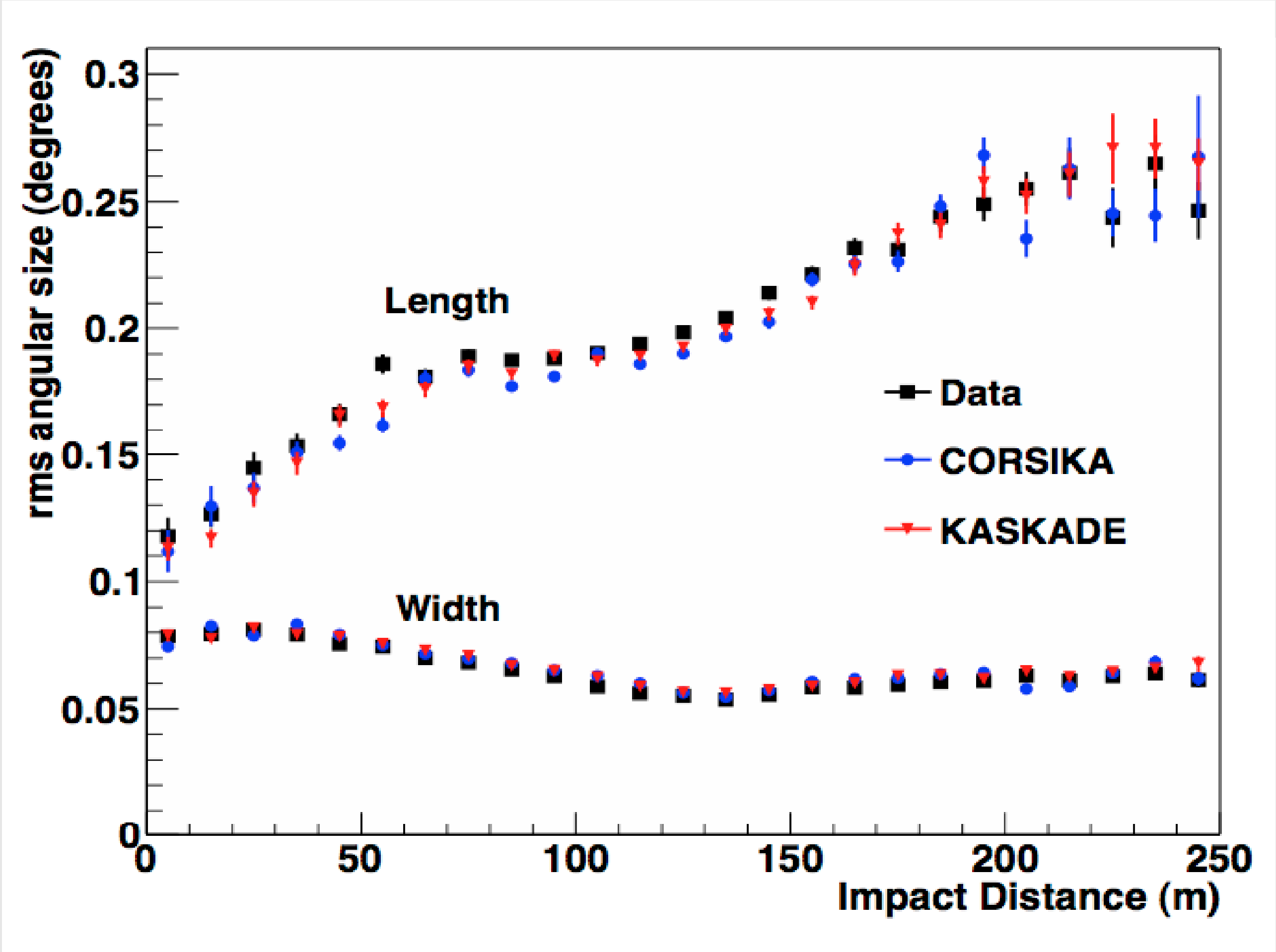
- Telescope
- Mirrors
- Focal Plane Instrumentation
- Electronics
- Quality assurance

Observatory Selection & Operation

- Site Selection
- ATAC
- Data
- Observatory

Monte Carlo Studies

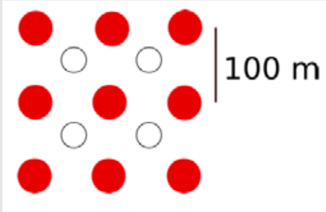
- **Development & validation of simulation tools**
  - Air showers simulators
    - Interaction models
    - Atmosphere treatment
    - Time consumed
  - Telescope simulators
    - Images reproduction
    - Accuracy on energy
    - Timing



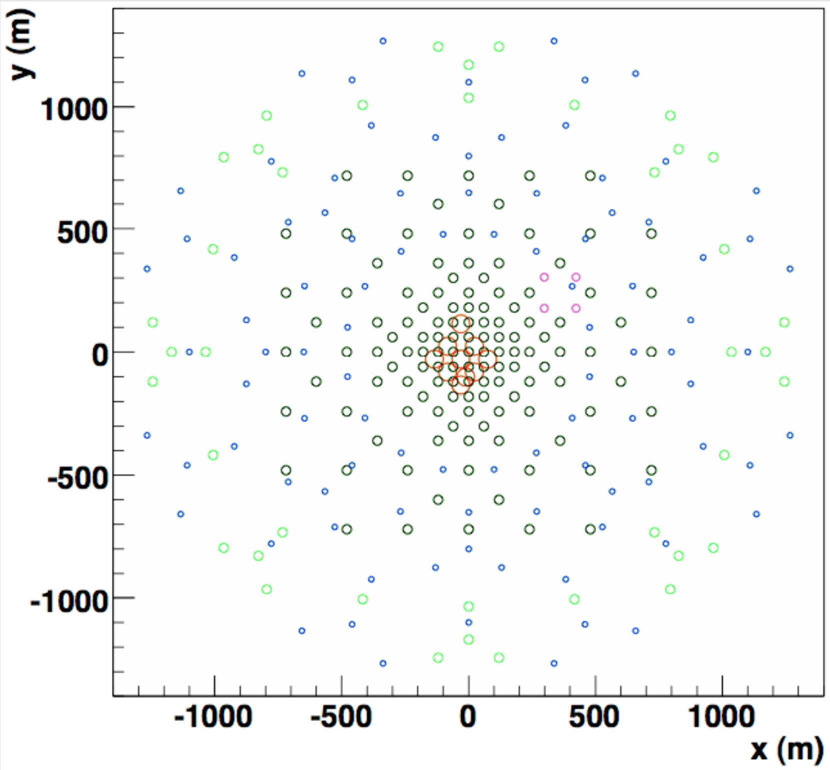
Blazar PKS2155-304
2006 HESS data
High S/N → almost not background
Inputs MC: measured spectrum, HESS optical efficiency, zenith angle

MonteCarlo Studies (Array configurations)

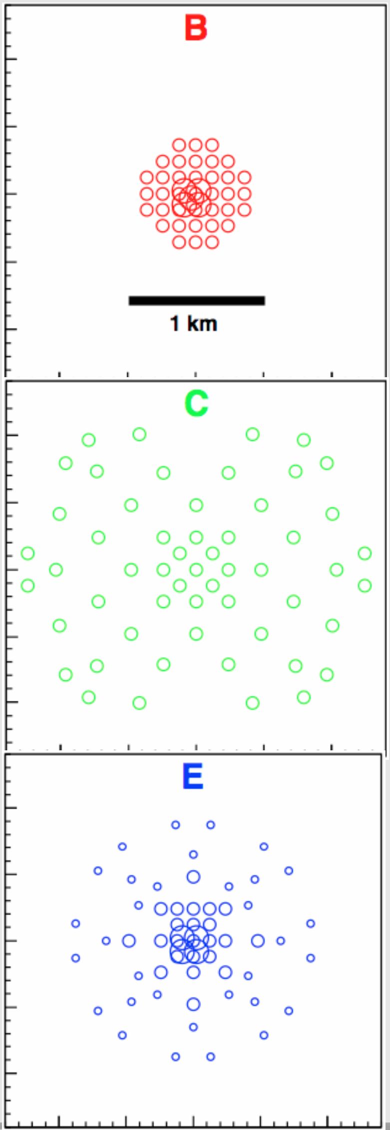
Benchmark array
9 telescopes



Hyper-array 275 telescopes



Sub arrays (under cost constraints)



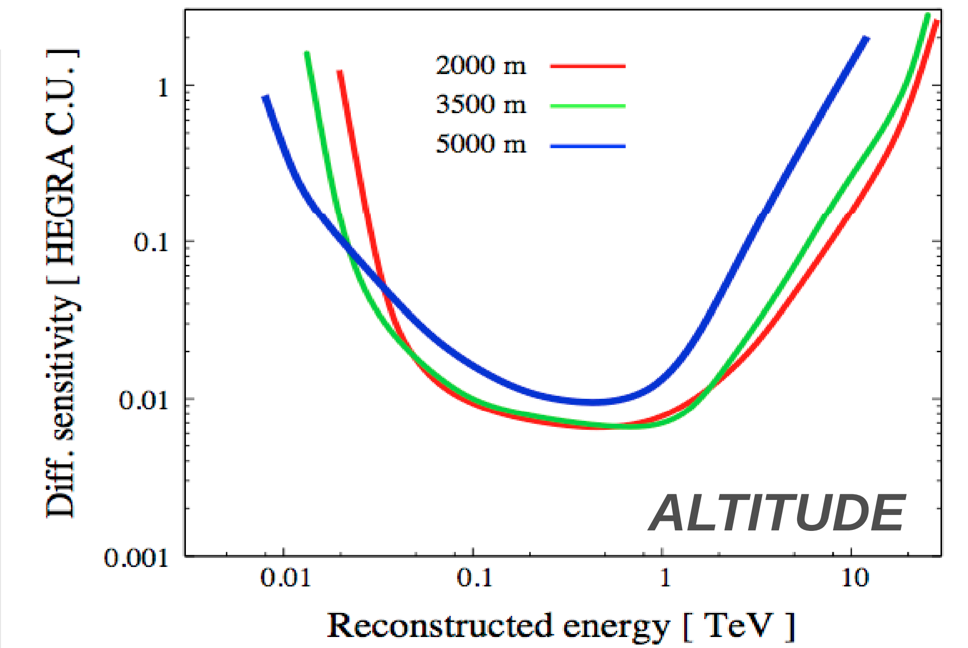
B: compact distribution with large telescopes Better performance at low energy

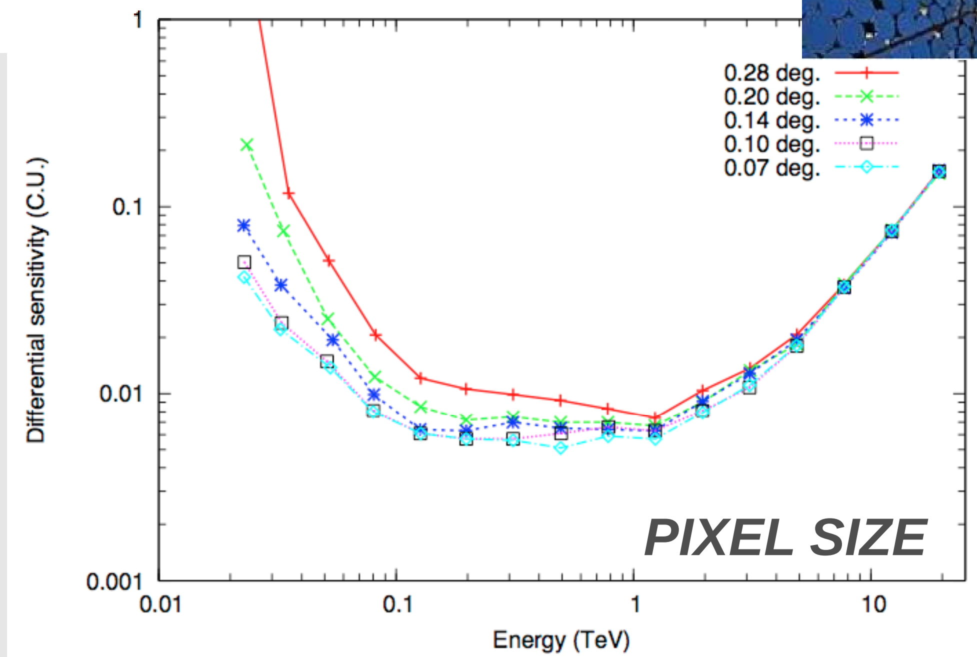
C: extended distribution with medium telescopes Better performance at high energy

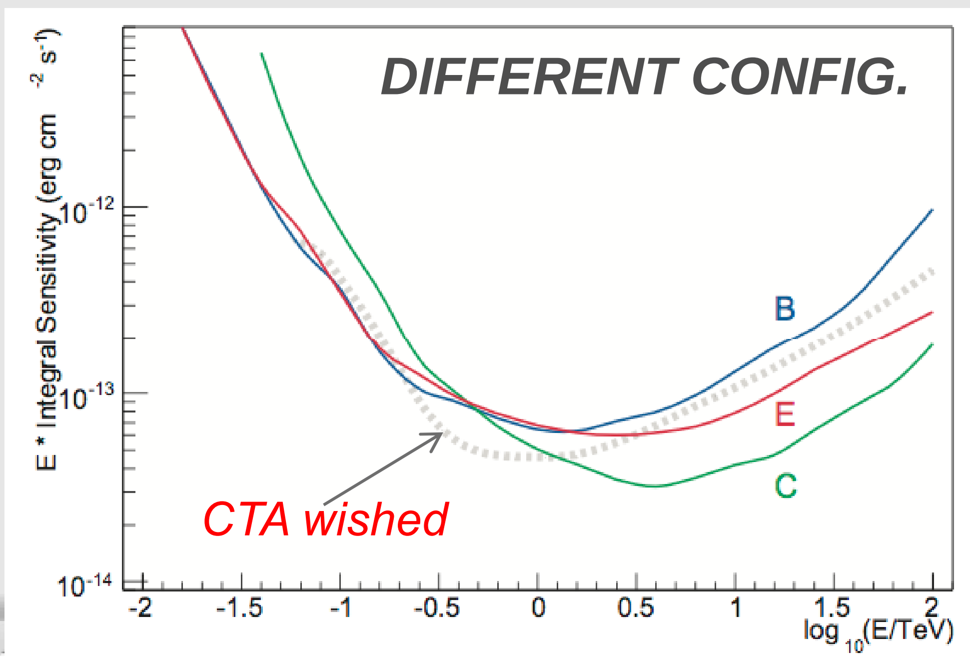
E: combination of both Better performance at all energies

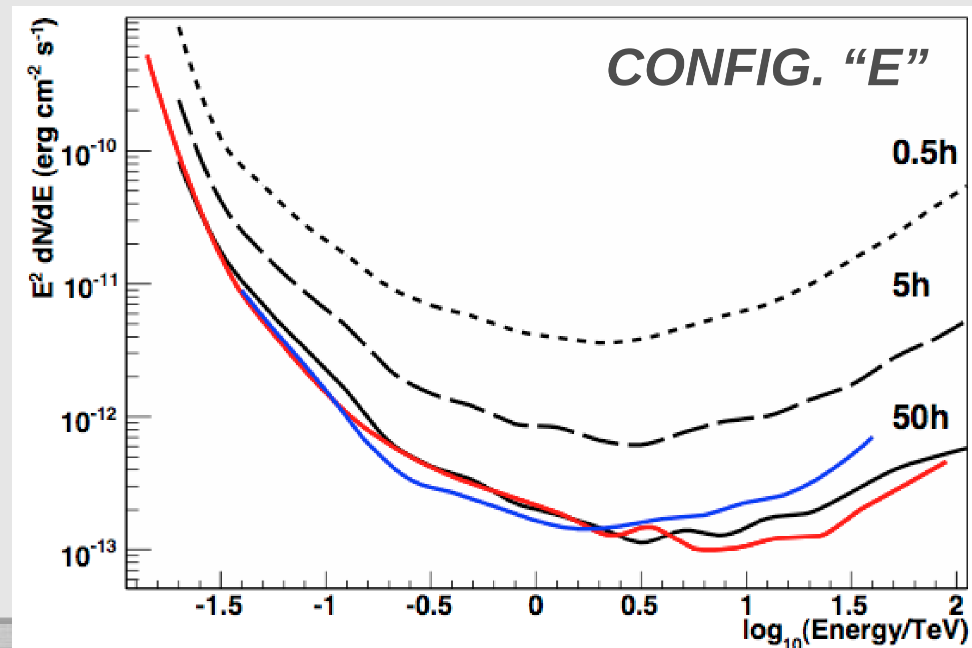
O(10^11) events generated: *O*(10^2) TB data stored

MonteCarlo Studies (Sensitivity)

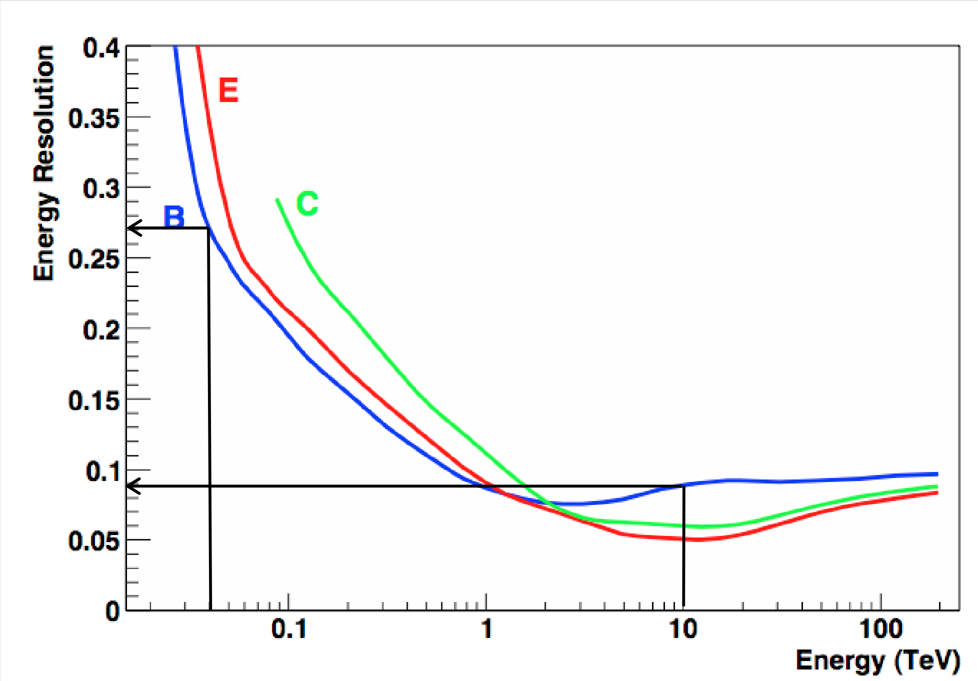






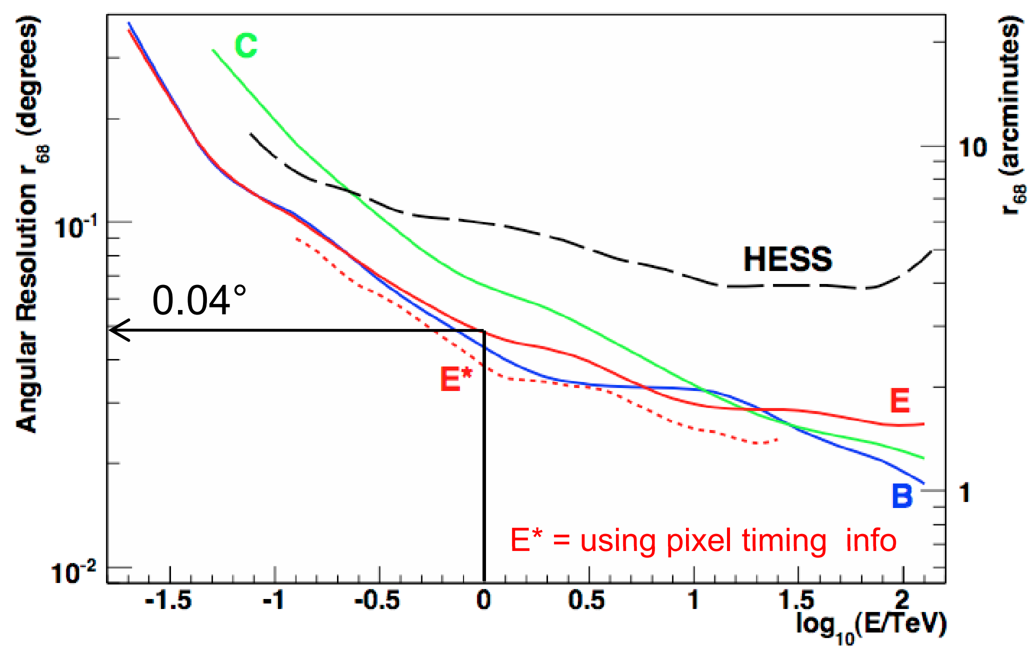


MonteCarlo Studies (Angular & Energy Resolution)



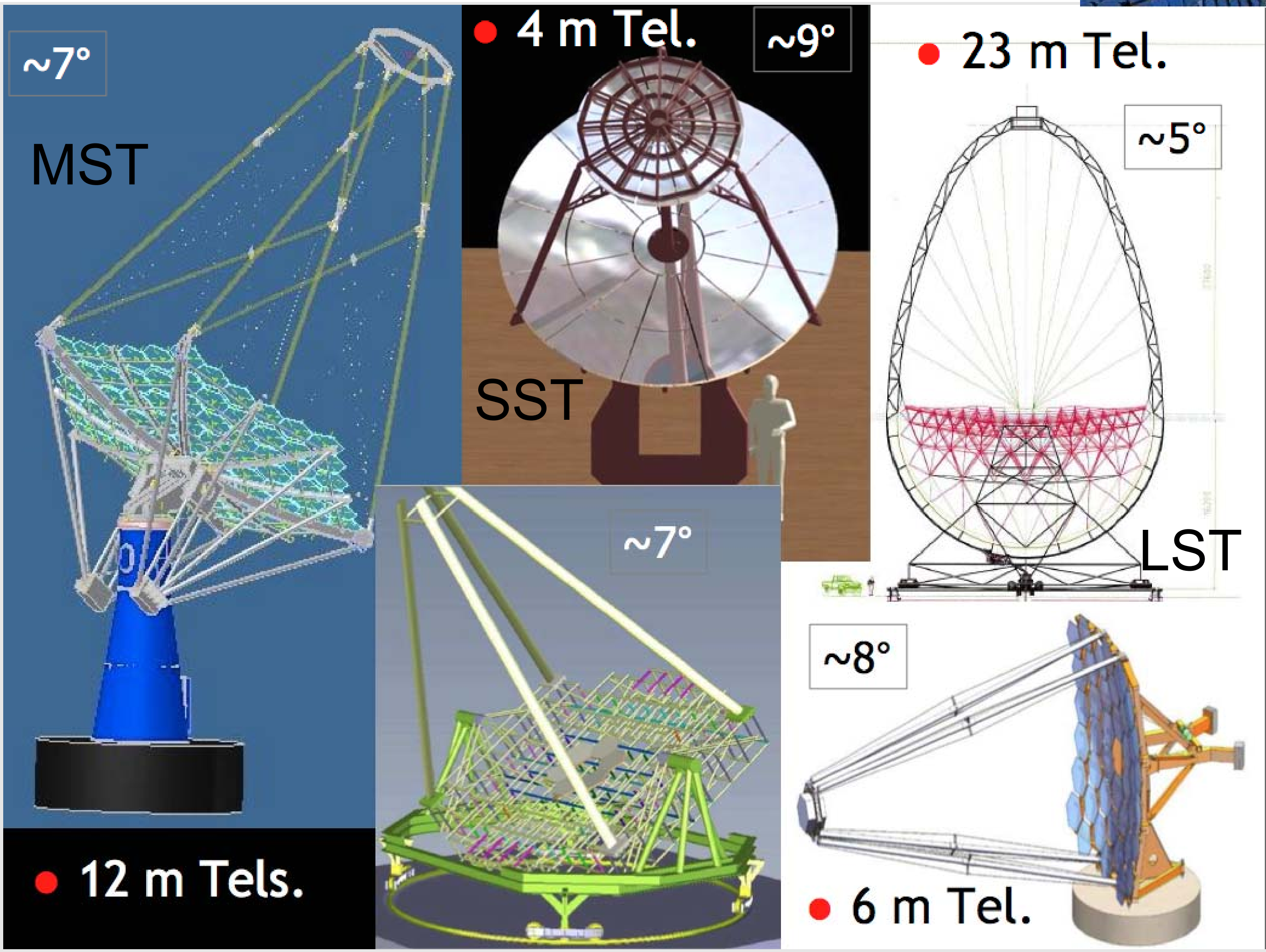
Energy resolution < 30% all CTA range
10% for 1 TeV

Angular resolution
for 1 TeV: 0.04°-0.05°



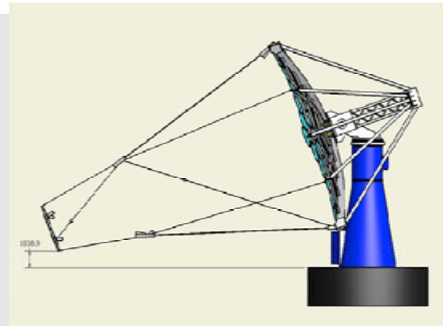
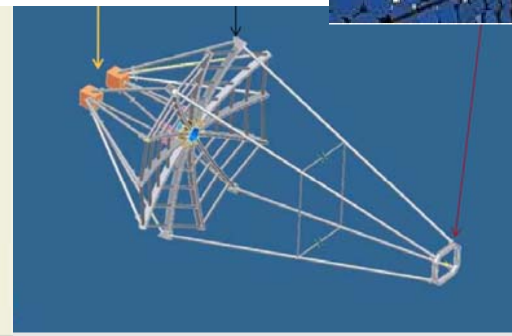
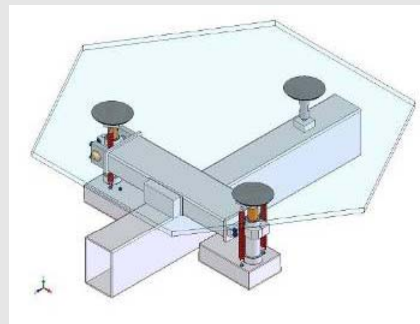
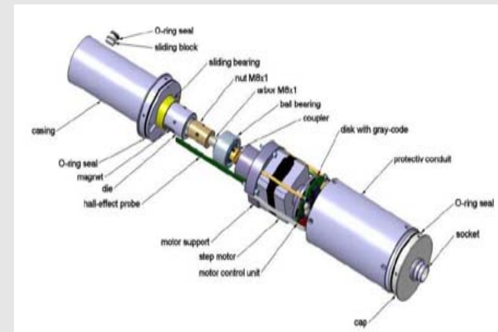
CTA Technology (Telescopes)

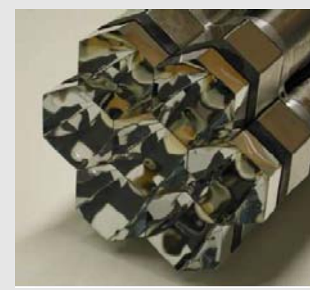
- MST
  - Middle Size
  - 1500 pixels
  - 2.5 ton camera
  - f/d ~ 1.4
- LST
  - Large Size
  - 2500 pixels
  - 2 ton camera
  - f/d ~1.2
- SST
  - Small Size
  - 1300 pixels

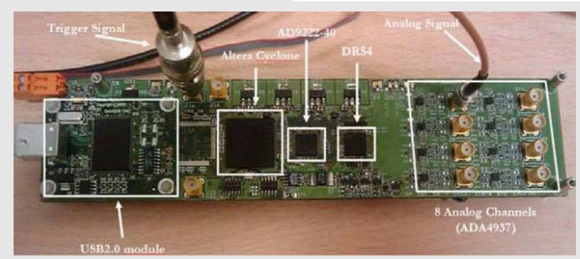


Telescope Technology

- Mount & Dish
  - Mounting system & drivers
  - Dish design and camera support
- Telescope optics
  - Mirrors
  - Alignment system
- Photon detection
  - Electronics
  - Triggering
  - Camera integration
- Calibration and monitoring

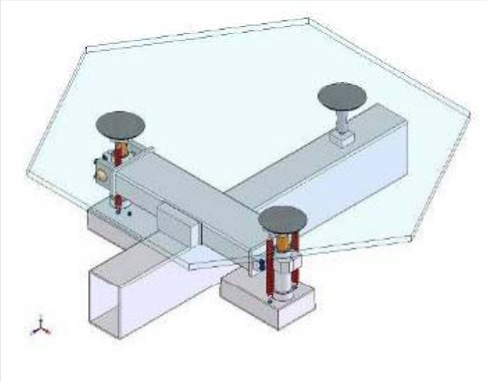




CTA mirror studies

Baseline

- 10000 m^2 of mirror area !!!
- Focusing worse than astronomical mirrors
- Hexagonal shape
- Size: 1200 mm ± 2 mm flat to flat (MST prototype)
- Weight < 35 kg/m^2 (including AMC and fixations)
- Reflectance > 80% (300-600 nm)
- Spot size < 1mrad (68% containment)
- Spherical with radius 30-40 m (MST), aspherical (LST)

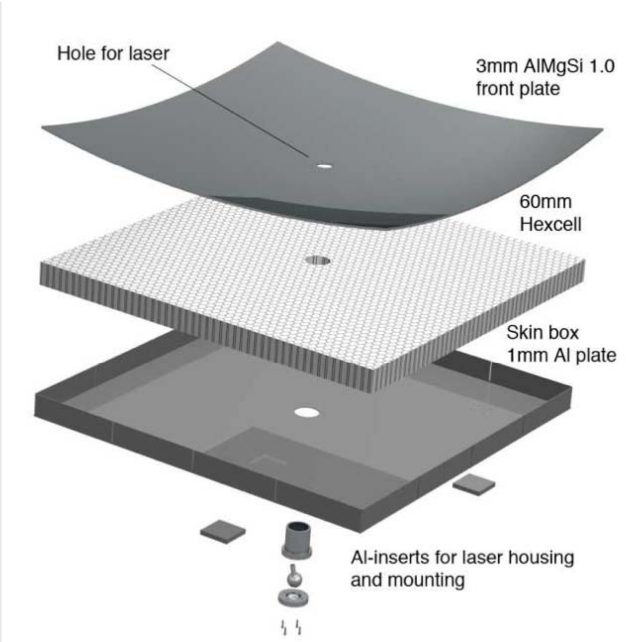


Mirror production technology → grinding/polishing or milling

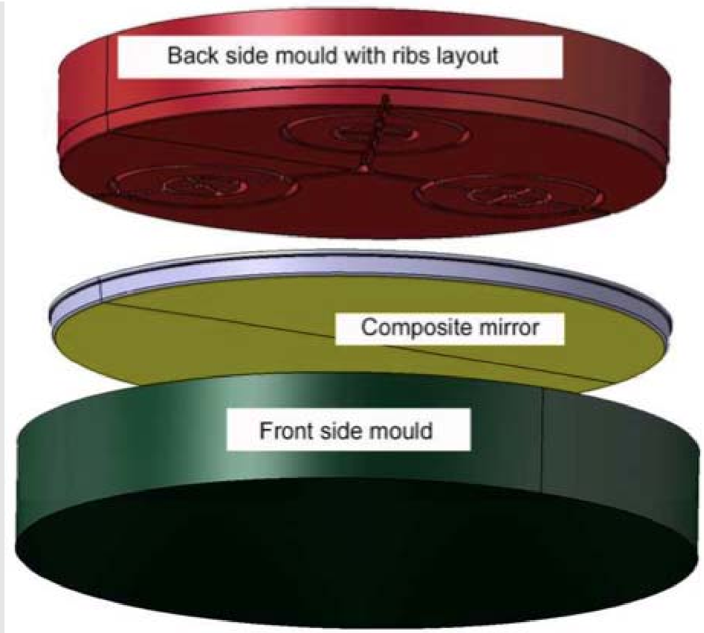
Mirror production technology → replica technique (mold)

CTA mirror deveopments

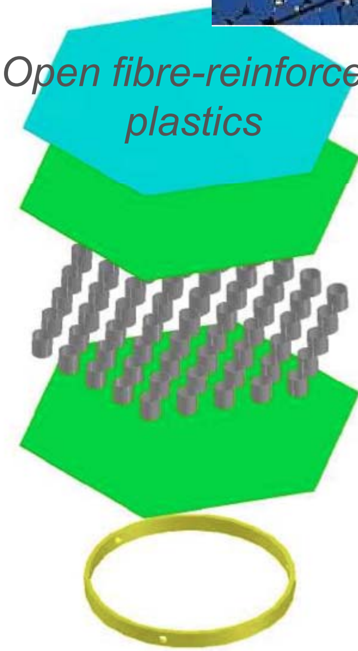
Diamond-milled aluminium

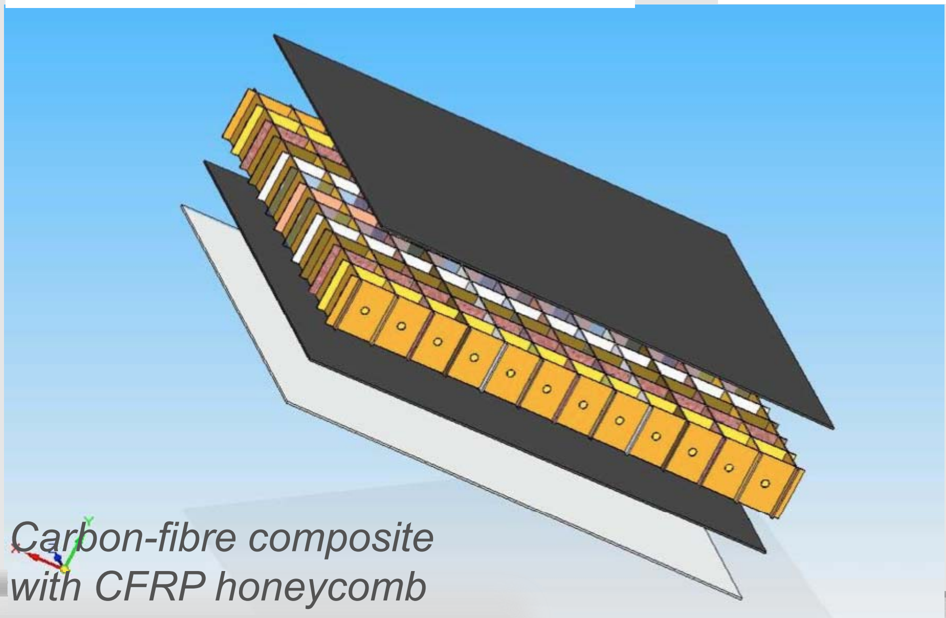


Carbon-fibre composite SMC technology



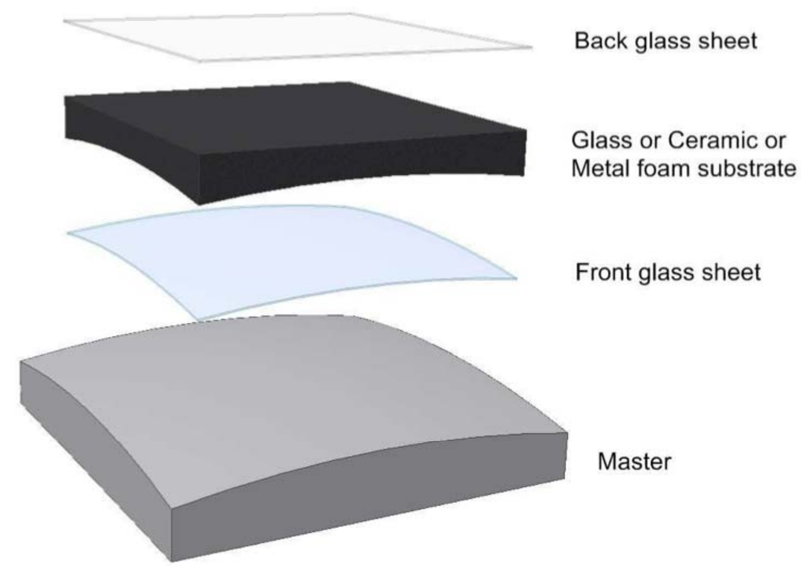
Open fibre-reinforced plastics



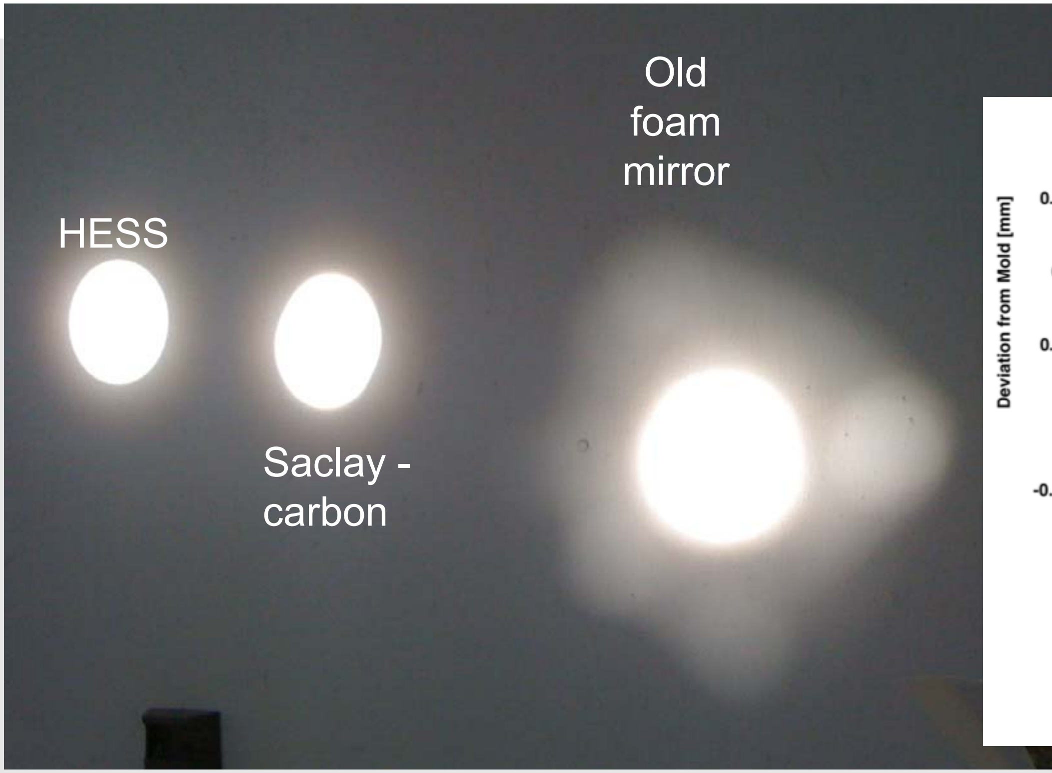


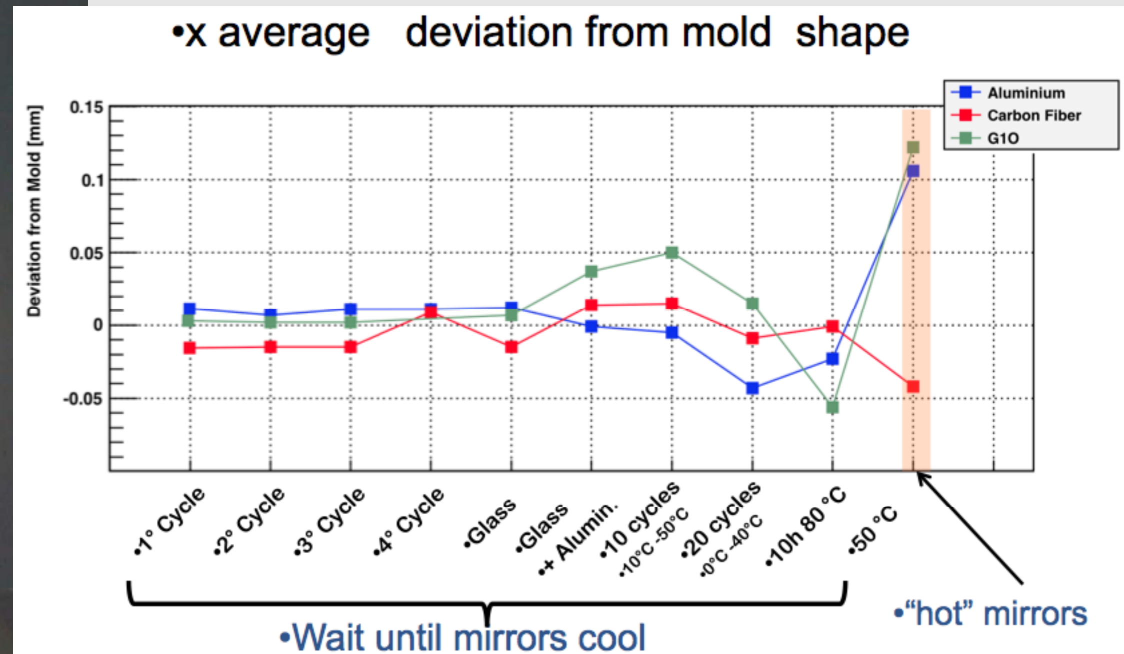
Carbon-fibre composite with CFRP honeycomb

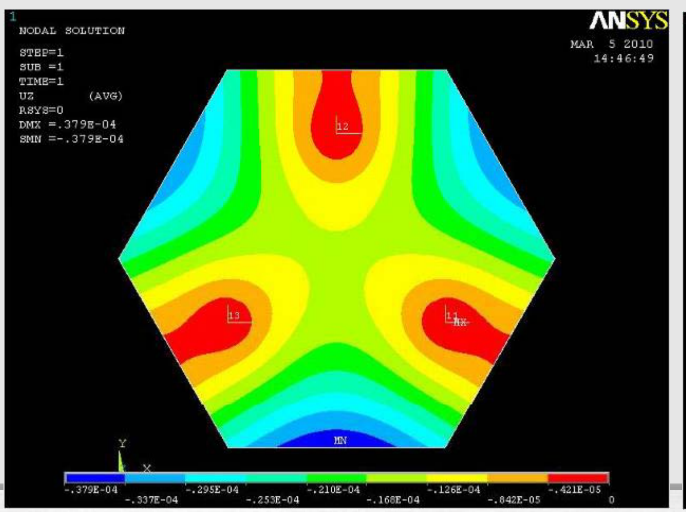
Cold slumped glass-foam sandwich

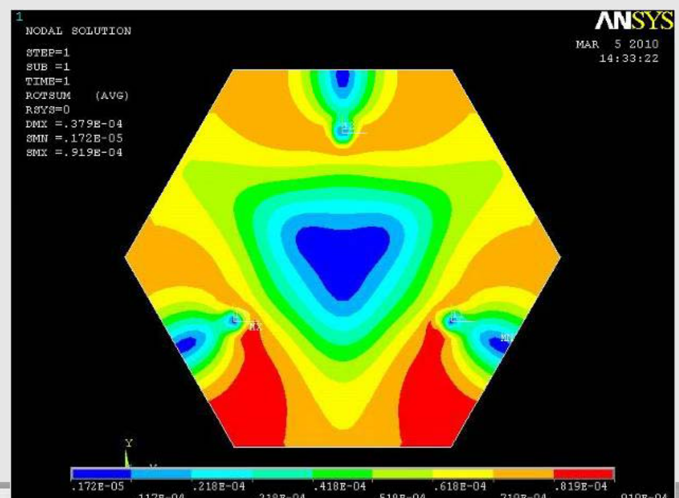


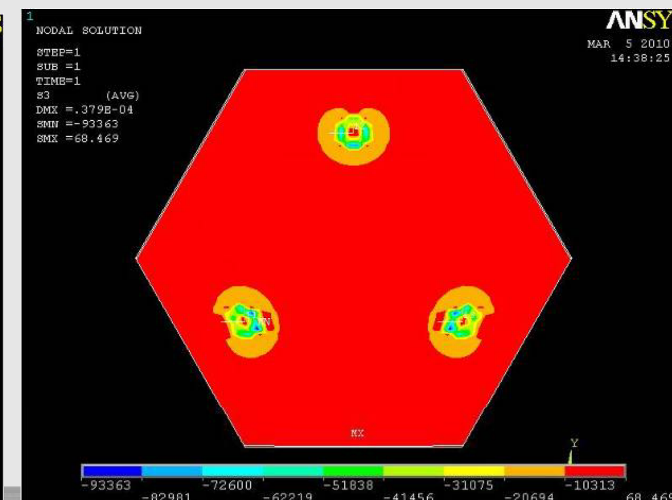
CTA Mirrors evaluation





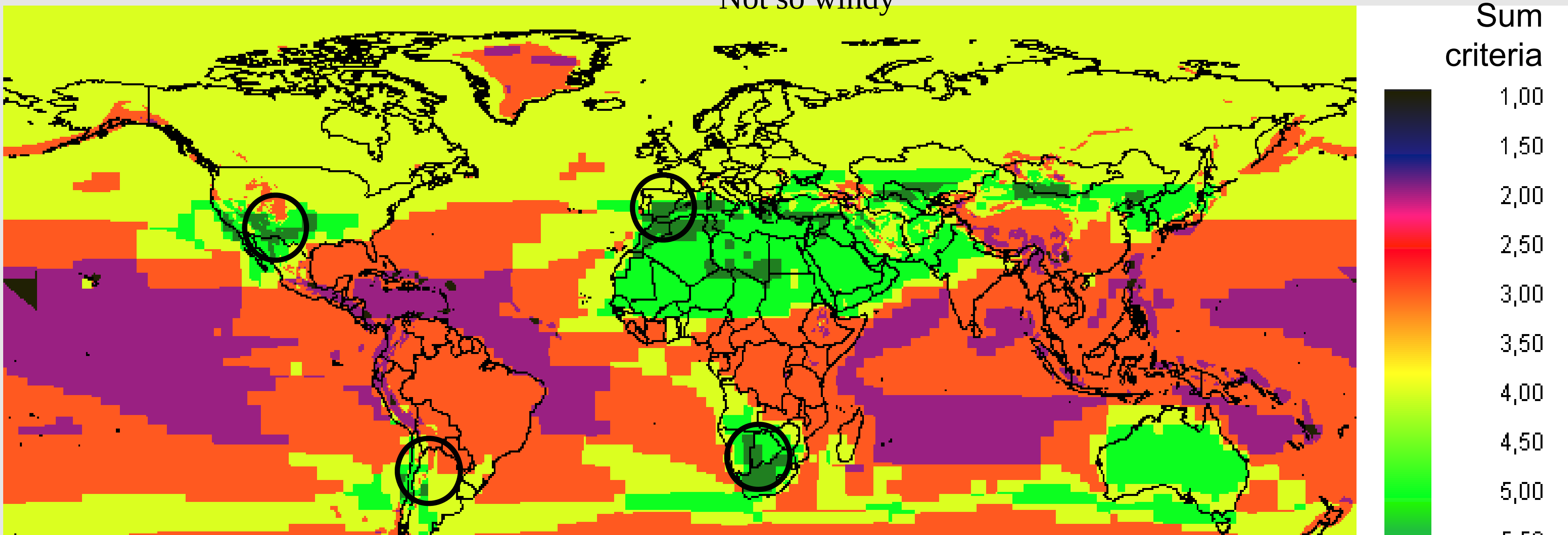






CTA Site Search

Not so high (<1500 m) / No sysmik risk / More than 60% of clear days (until 2025) / Nice aire temperatures (~20°C) / Not so windy



Reduced list of candidates

Good place to live?

Local measurements
Dedicated instruments

Realizing CTA : open observatory

Organisation
Operation
Time Schedule

Project Phases

- **Design Study**:
  - definition of the layout of the arrays,
  - telescope types,
  - design of the telescopes and small-scale prototyping.
- **Prototyping and Preparatory**:
  - prototyping and deployment of full-scale telescopes,
  - preparation of the construction and installation,
  - solving technical, organizational and legal issues,
  - site preparation.
- **Construction** :
  - construction,
  - deployment and commissioning of telescopes.
- **Operation** :
  - operation as an open observatory
  - calls for proposals and scheduling,
  - operation and maintenance of the facility,
  - processing of the data and provision of analysis tools.

Time Schedule and costs

design study

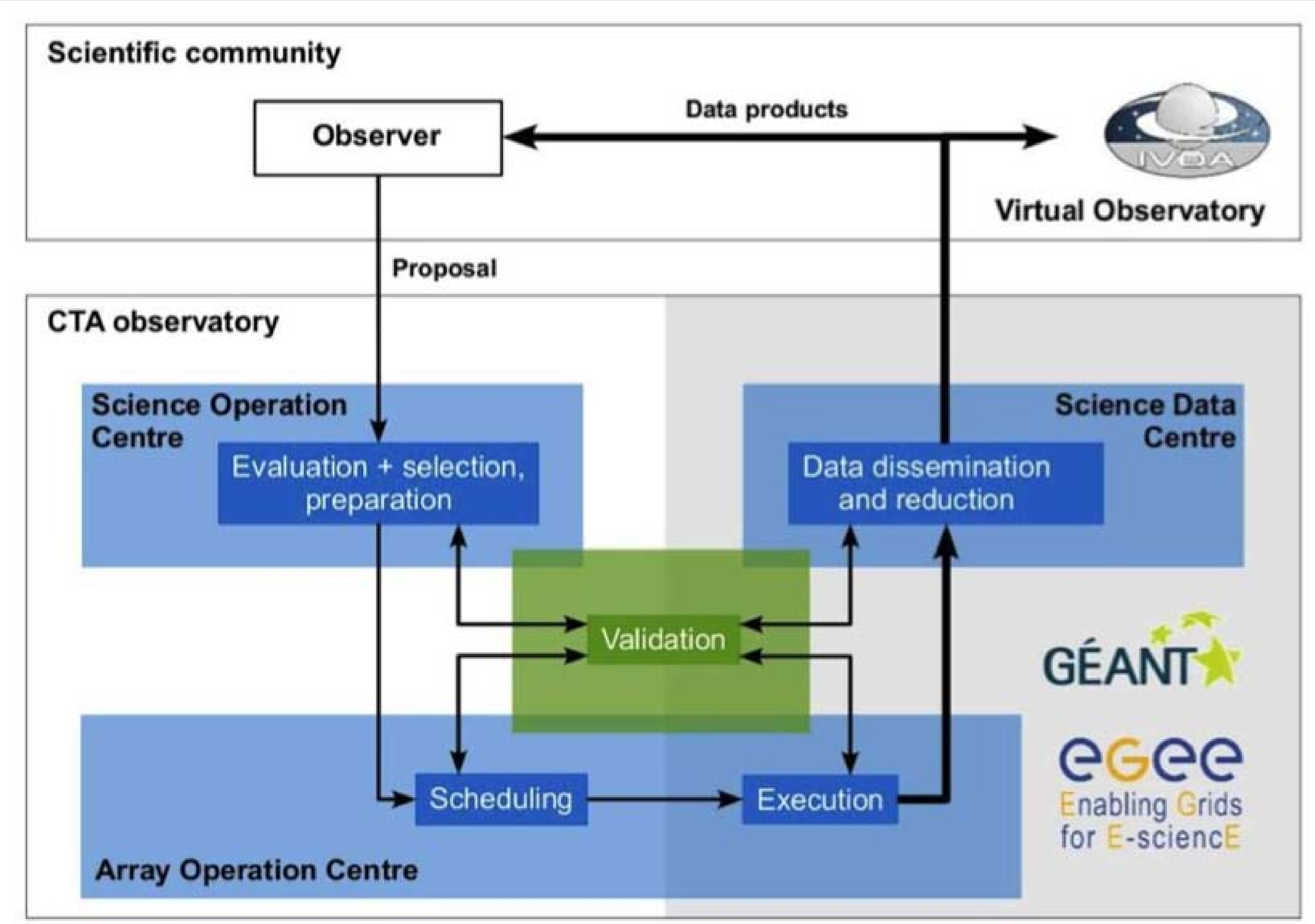
FP7 Prep. Phase
5.2 M€

	06	07	08	09	10	11	12	13
Site exploration								
Array layout								
Telescope design								
Component prototypes								
Array prototype								
Array construction								
Partial operation								

conceptual
design report

100M€ Southern Obs.
50M€ Northen Obs.

CTA Operation as an open observatory



Summary and outlook

☑ *CTA will be the major observatory in VHE gamma ray astronomy in the 2020s with both guaranteed astrophysics and a significant discovery potential.*

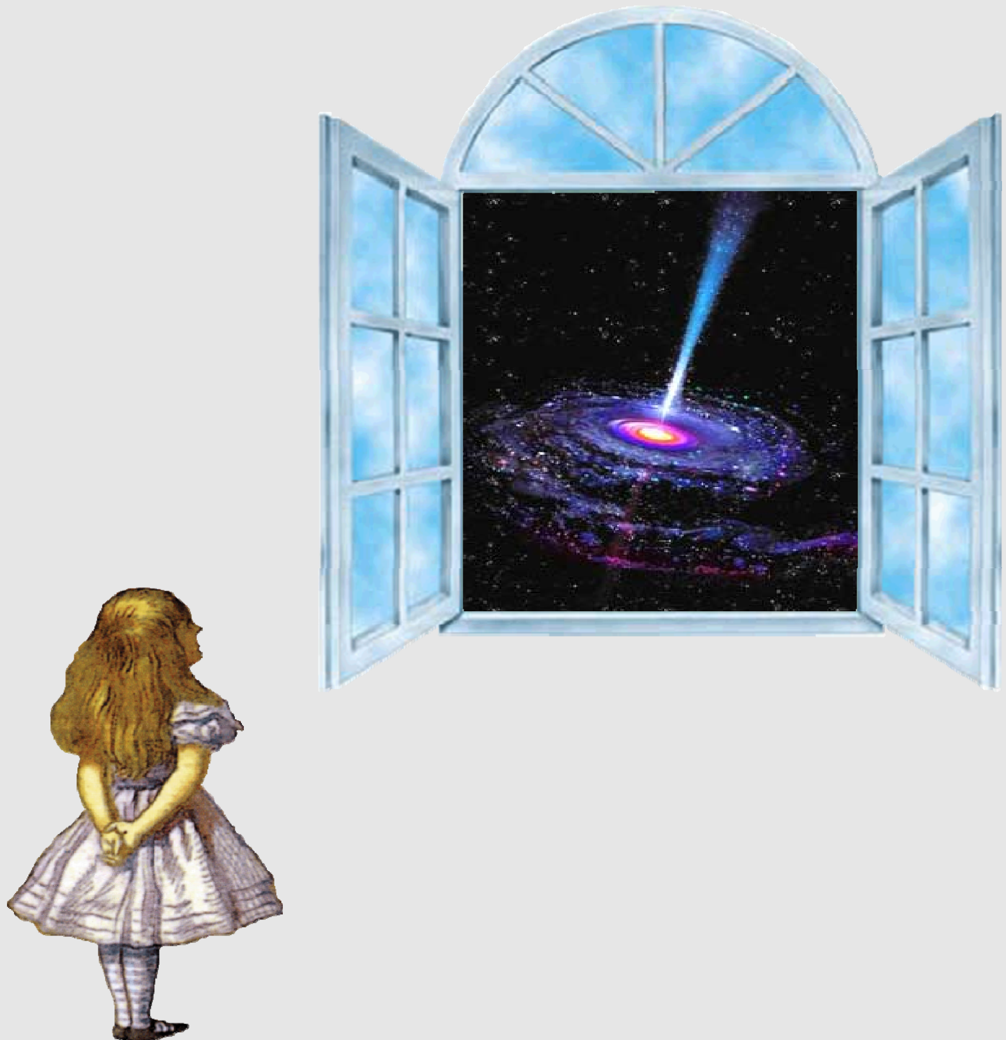
☑ *CTA received excellent reviews and high rankings in Science Roadmaps in Europe and across the world.*

☑ *CTA is an acknowledged ESFRI project & features high on roadmaps of future projects of ApPEC, ASPERA and ASTRONET.*

☑ *The CTA design study is aiming at reducing costs and improving reliability of instruments and systems.*

☑ *It is still on-going, with significant advances in mirror technology, telescope design (MST), electronics.*

☑ *The FP7 Prep. Phase for CTA should start in 2010 (duration 3 years).*



THANKS!

Backup slides

CTA operation as an open observatory

- Scientific program steered by proposals
  - measurements of specific objects
- Observations according to observing proposals selected for scientific excellence by peer-review
- Limited number of outstanding proposals from scientists working in institutions outside the CTA-supporting countries
- All data obtained by the CTA accessible to scientists outside the proposing team after a finite period.
- CTA observations conducted by a dedicated team of operators.

CTA mirror studies

Mirror production technology

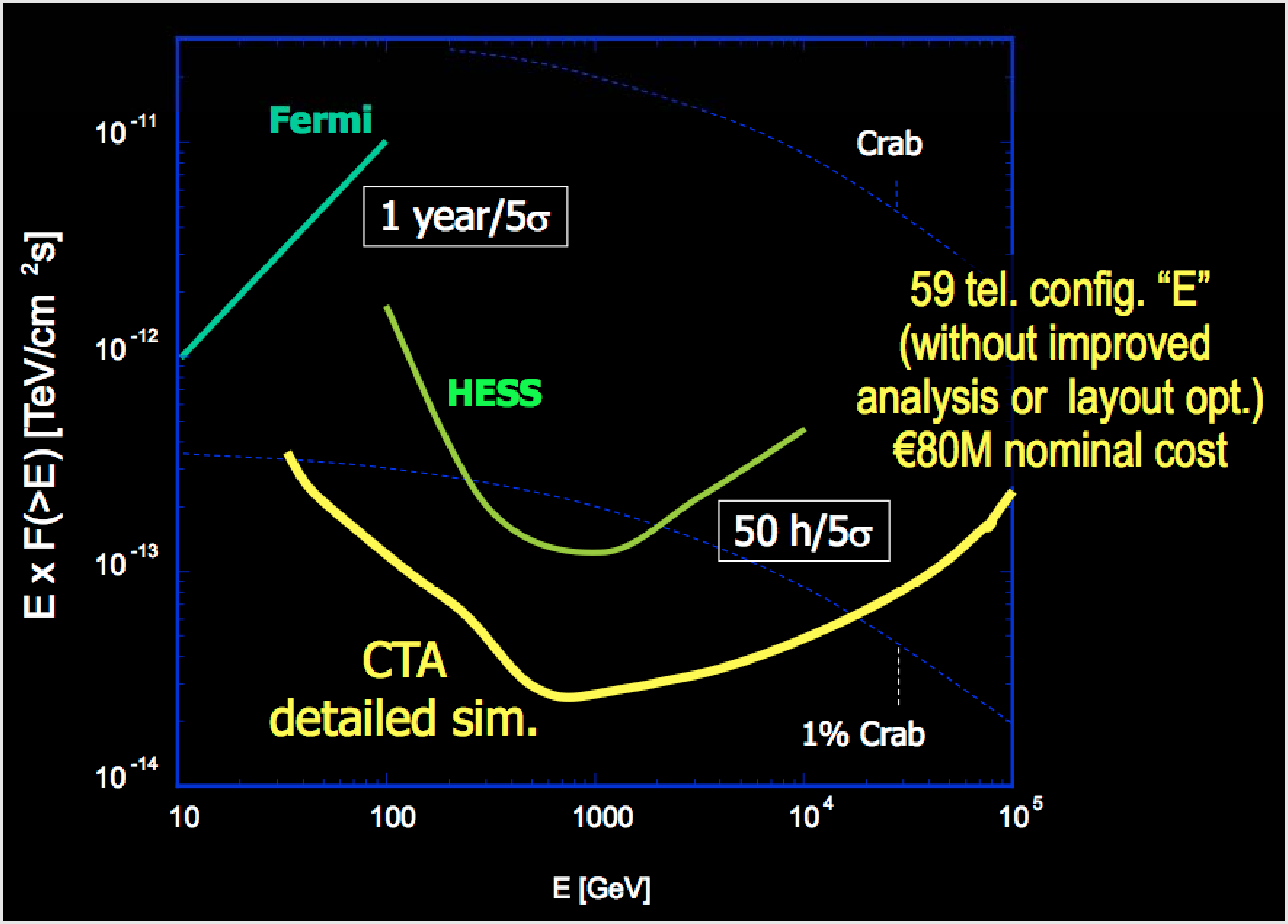
grinding/polishing or milling

- Glass mirror
  - HEGRA, CAT, H.E.S.S., VERITAS
  - machined and polished glass blanks
  - Aluminium coated
  - protection layer of SiO_2
  - high reflectivity
  - good PSF
  - Fragile, heavy
  - fast ageing and degradation
- Diamond-milled aluminium mirrors
  - MAGIC
  - Sandwich: 2 thin aluminium layers & an aluminium honeycomb
  - Rigid, light
  - high T conductivity
  - Slow degradation
  - Low reflectivity

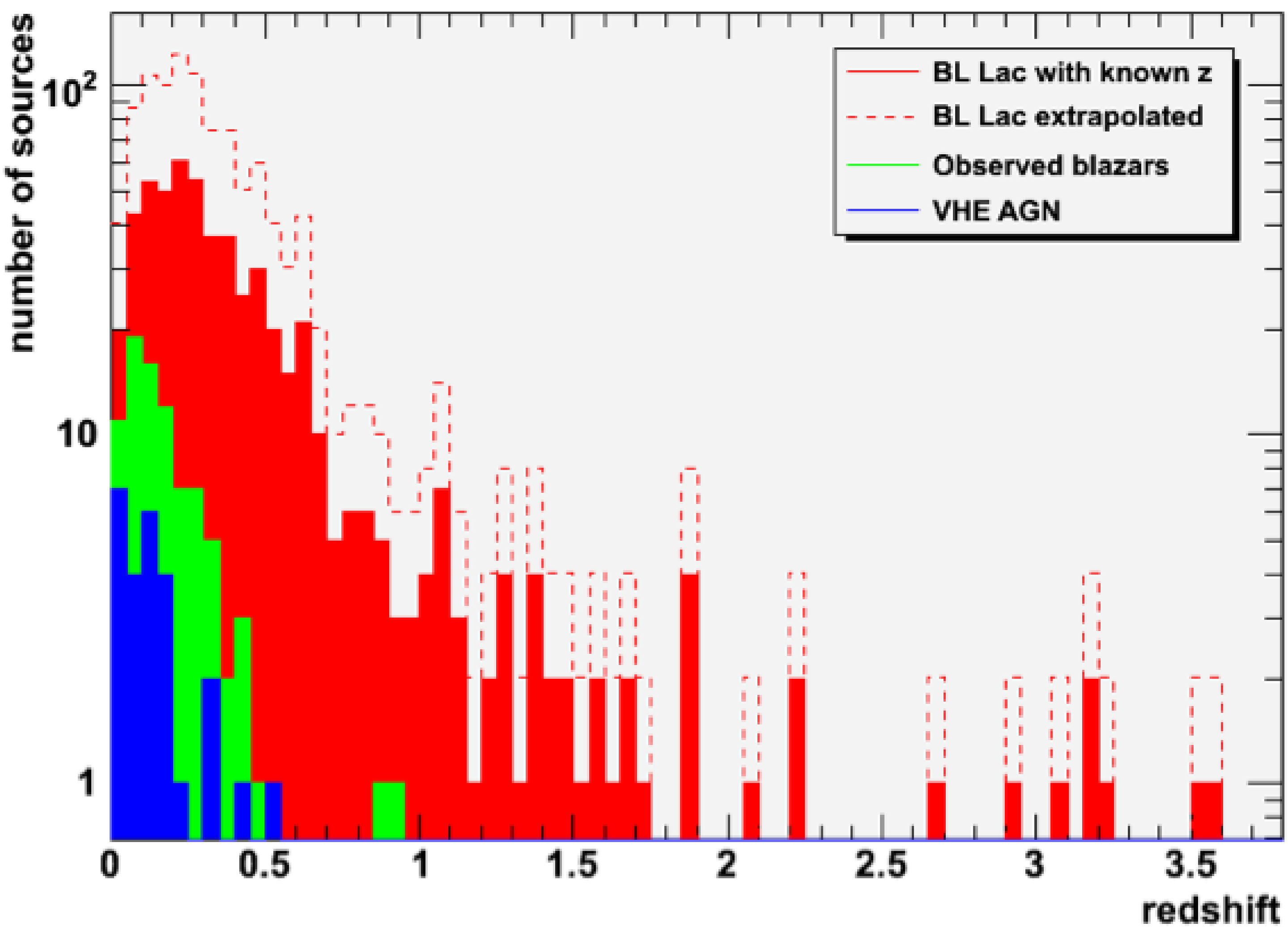
replica technique (mold)

- Cold slumped glass mirrors
  - two thin glass sheets glued on a suitable core material.
  - Front glass sheet formed on a master using vacuum suction
  - Thermal insulation
- Aluminium foil mirrors
  - Aluminium honeycomb sandwich
  - 2 thin Al sheets
  - Imperfect reflection properties
- Fibre reinforced plastics mirrors
  - Carbon or glass-fibre reinforced plastic
  - Sandwich structure:
  - Foam, honeycomb
  - Expensive
  - Low weigth

CTA wished sensibility and energy range



AGN population

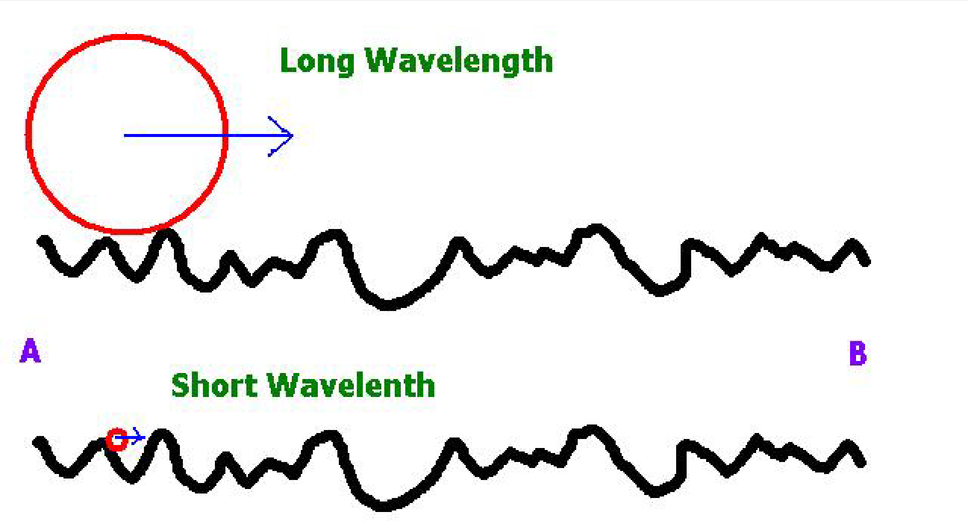


Veron-Cetty & Veron BLLAC catalog (12th edition)

=> still many blazars to discover at TeV energies !

=> and maybe other types of AGN ?

• Space-time at large distances is "smooth" but, if Gravity is a quantum theory, at very short distances it might show a very complex ("foamy") structure due to Quantum fluctuations.



• A consequence of these fluctuations is the fact that the speed of light in vacuum becomes energy dependent.

• The energy scale at which gravity is expected to behave as a quantum theory is the Planck Mass

$$E_{QG} = O(M_P) = O(10^{19})\ \text{GeV}$$

Blazars and Lorentz invariance

From a purely phenomenological point of view, the effect can be studied with a **perturbative expansion**. The arrival delay of γ-rays emitted simultaneously from a distant source should be proportional to the path L to the source and the difference of the power *n* of their energies:

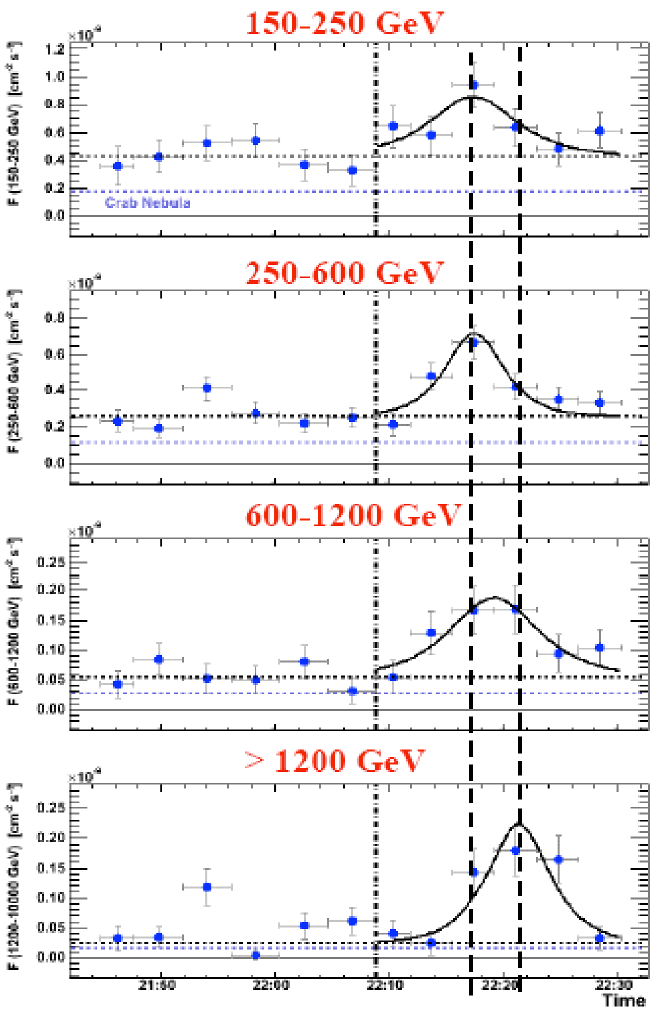
$$\Delta t \sim \frac{E^n - E_0^n}{E_{QG}^n} \frac{L}{c}$$

M82

The expected delay is very small and to make it measurable one needs to observe very high energy γ-rays coming from sources at cosmological distances.

Juan Cortina (IFAE)

Blazar Mrk 501, July 2005 (astro-ph/0702008)



LCs for different energy ranges (4 min bins)

July 9

Flare is seen in all energy ranges

Time delay of 4 +/- 1 minute between highest and lowest energy ranges

Blazars and Lorentz invariance

If that delay would be fully caused by propagation in the vacuum then:

- for first order (n=1) =>

  $E_{QG} \sim M_P/200$ +- 25%

- for second order (n=2) =>

  $E_{QG} \sim 8\ 10^{9}$ GeV $\sim 7\ 10^{-10}\ M_P$

M82

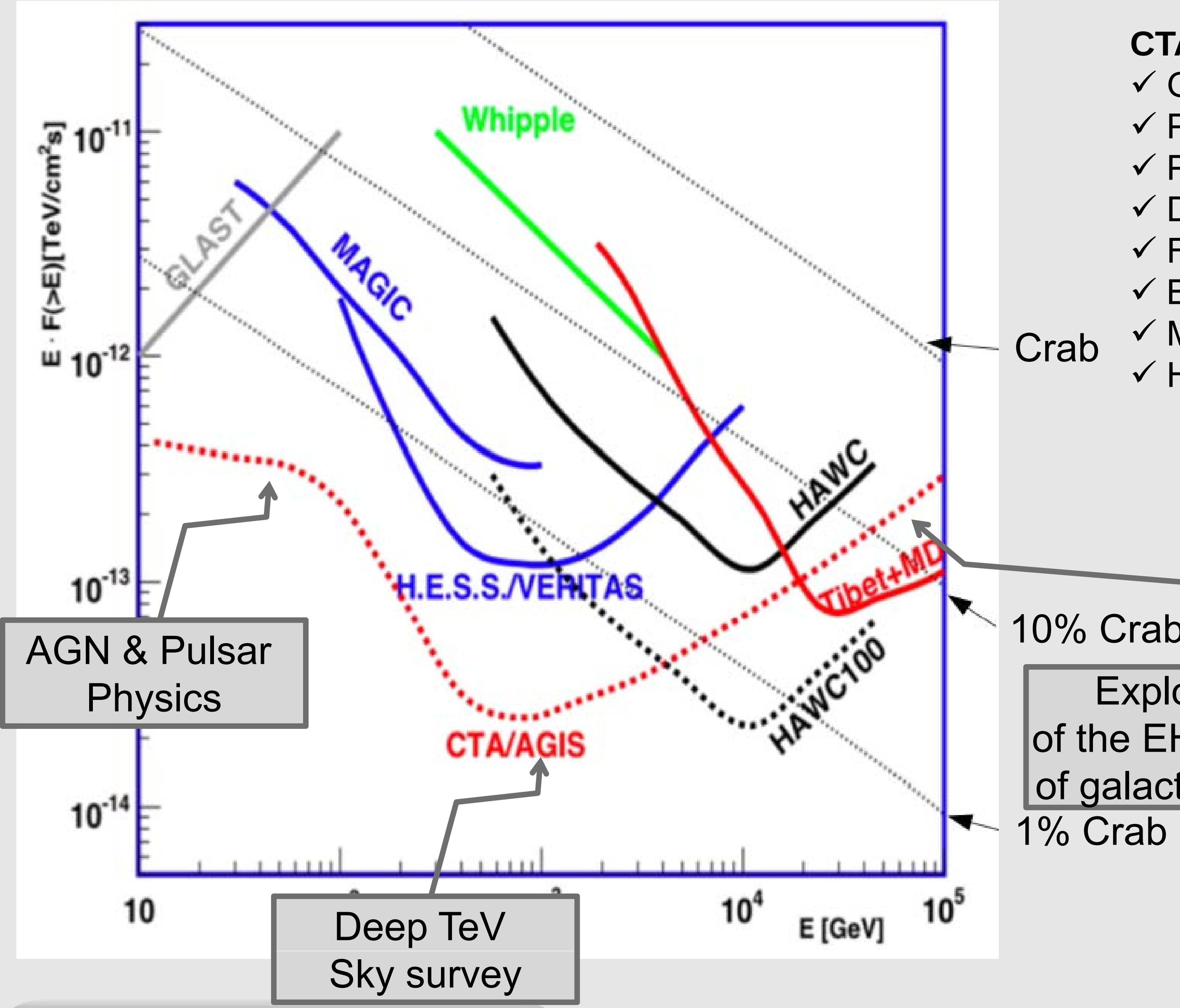
If delay had an astrophysical origin then the above numbers should be considered as lower bounds on the Quantum Gravity scale

Most relevant: we provide the most stringent limits to date on Lorentz Invariance.

<u>CTA: need larger sample for objects and higher sensitivity to access even faster variability.</u>

Juan Cortina (IFAE)

Unprecedented performance as an IACT instrument.

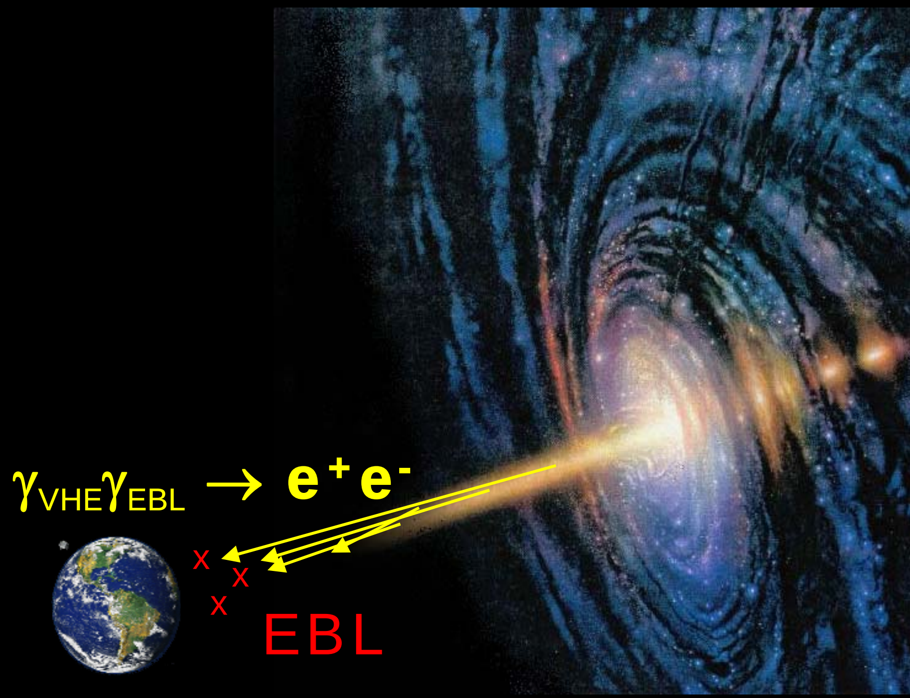


CTA High-energy phenomena

- ✓ Galactic and extragalactic astrophysics
- ✓ Plasma physics
- ✓ Particle physics
- ✓ Dark matter
- ✓ Fundamental physics of space-time.
- ✓ Birth and death of stars
- ✓ Matter circulation in the Galaxy
- ✓ History of the Universe.

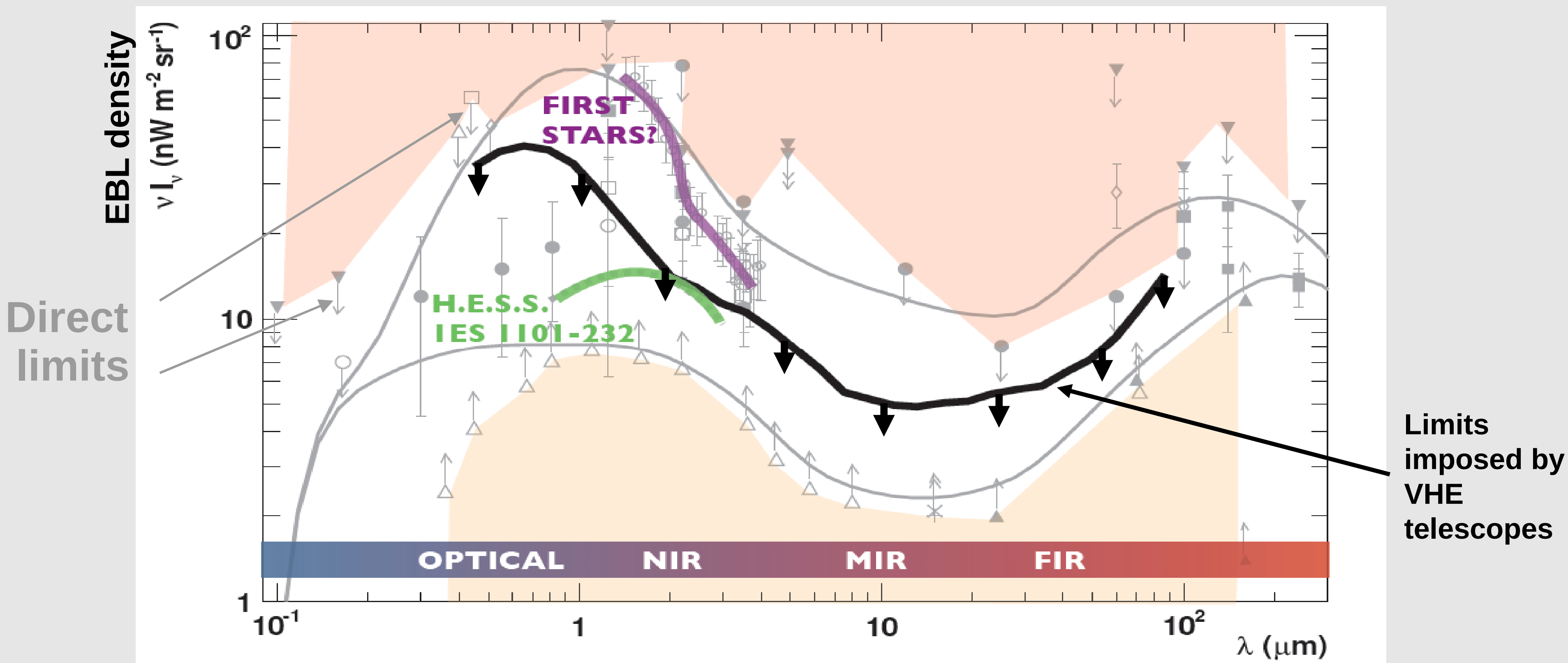
Blazars and EBL

- Extragalactic VHE γ-rays produce pairs when they interact with the **Extragalactic Background Light** (metagalactic field in the optical to far infrared range).



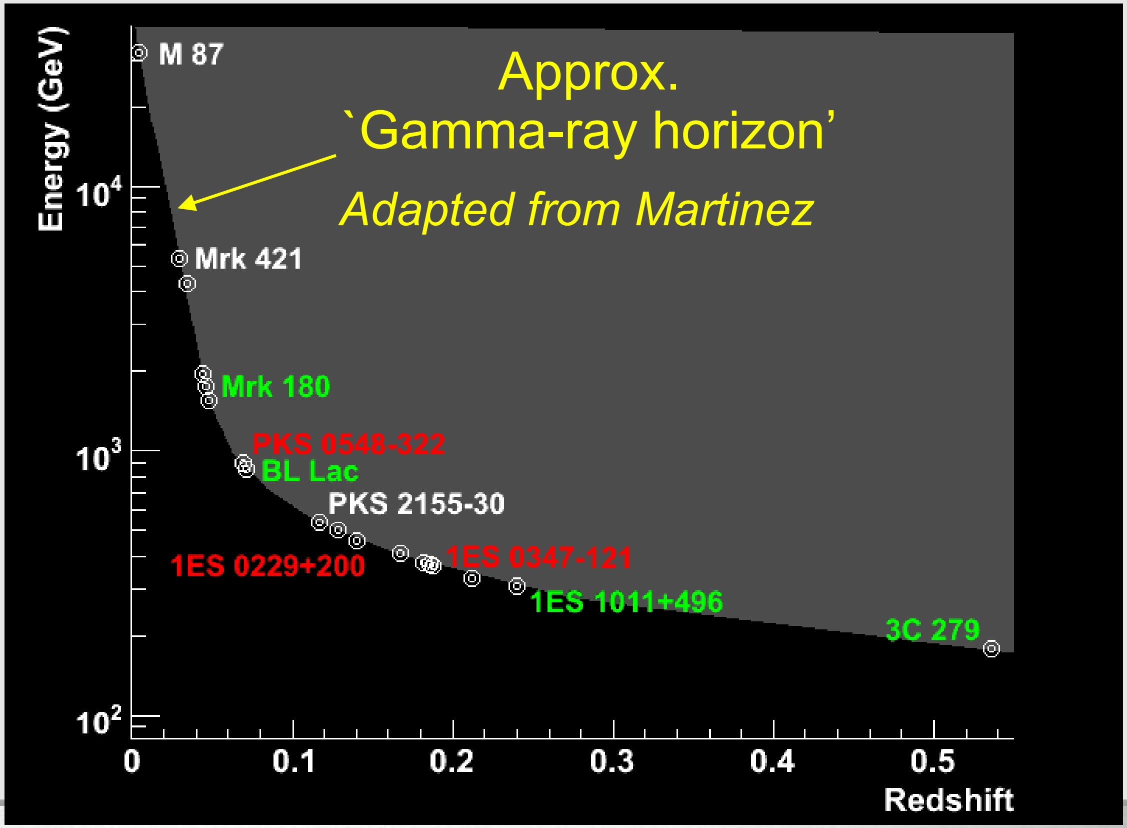
Blazars and EBL

- Absorption features in the spectra of blazars allow to determine the EBL in the mid IR range where no direct measurement is feasible.



Blazars and cosmology

- The EBL limits the maximum distance which a γ-ray of a given energy can travel, i.e., for each energy there is a "γ-ray horizon".
- Lower threshold instruments like MAGIC are expanding this horizon but CTA may bring it well beyond z=1, into the bulk of the cosmological AGNs.



Measuring the EBL as a function of redshift sets important constraints to **models of structure formation**.

And could be used to measure cosmological parameters. The cutoff energy provide an **independent estimate of the distance to the sources.**

Juan Cortina (IFAE)