Multimessenger astroparticle physics

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Lecture 8

A look to the future.

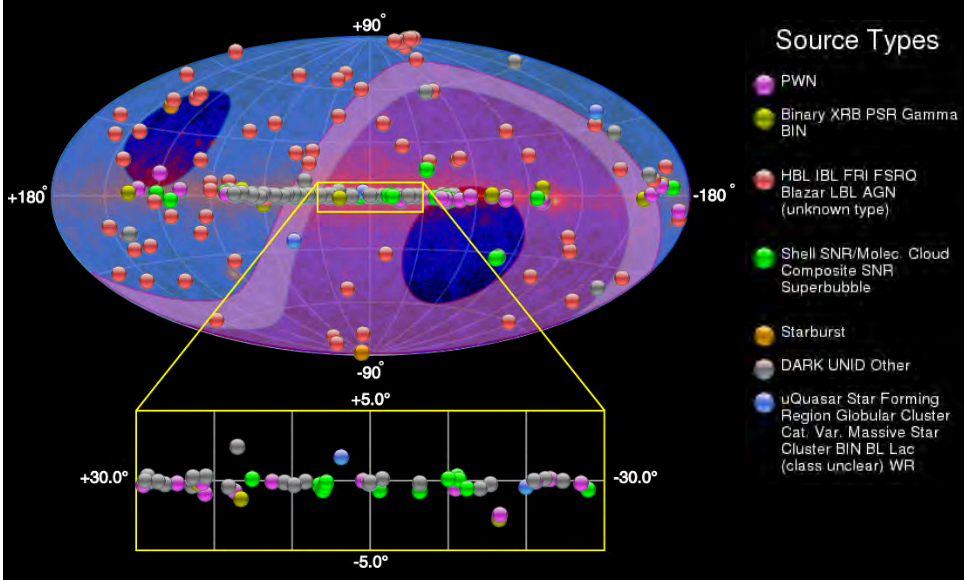
Summary^2 of previous 2 lectures

- HE astrophysics is today essentially gamma astrophysics. Thousands of astrophysical gamma-ray emitters in the HE region and >200 in the VHE region
  - New emitters and new classes of emitters
  - A diffuse background up to the TeV, maybe the sum of unresolved point-like emitters
  - We have seen both the leptonic and the hadronic gamma-ray mechanisms at work
  - We have identified mechanisms of emission explaining cosmic rays up to the PeV – also in action, but (by far) not enough to explain the full flux
  - The SED of many emitters can be modeled in an effective way
  - Interesting perspects for fundamental physics. DM:
    - A standard WIMP below 400 GeV is on reach for HE gamma detectors, if just one WIMP and the particle was in thermal equilibrium
    - Dwarf spheroidals (no need for background models) and the GC region (a mess from the point of view of astronomy) are the favorite targets
    - Can find indirect evidence for Axion-Like Particles
- Multimessenger astrophysics (just starting) will teach us more, both from the point of view of astrophysics and of fundamental physics
  - We just detected astrophysical neutrinos [signal of (7±2)/year with 1km^3 detector, s/b ~ 2/1), and we know that probably a several-km^3 detector is needed do to astronomy
  - Gravitational waves: first signals (~2/year with two large interferometers)
  - Protons cannot be used for astronomy (but they give us O(100 TeV) c.m. energies)

Summary of older lectures

- Detectors for charged cosmic rays: (1) need large effective area for the UHE, (2) smart instruments on satellite for particle identification. For (1) we are close to the limit (Auger) unless we change technology, for (2) we are close to the limit (AMS-02)
- Astrophysical neutrino detectors: we need several km^3; we are close to the limit (IceCube) but still improving (Antares -> km^3NeT)
- Photons:
  - In the MeV region, instruments did not reach the technological limit, yet (no new instrument since COMPTEL, 1991-2000)
  - In the GeV region, Fermi is close to the technological limit
  - In the TeV region, the Cherenkov technique reigns. HESS, MAGIC and VERITAS have still potential, and there is room for improvement by "brute force"
  - In the PeV region, only one detector presently active, and there is room for improvement by "brute force" – plus something

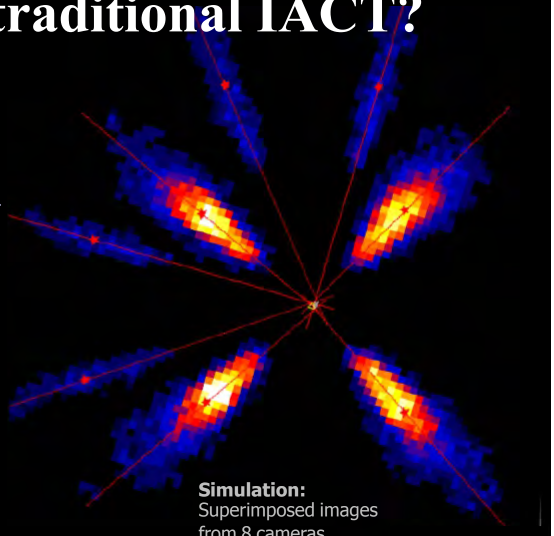
3k HE and >200 VHE photon emitters



The TeV gamma region: CTA

The 20 GeV- 100 TeV region: how to do better with traditional IACT?

- More events
  - More photons = better spectra, images, fainter sources
    - Larger collection area for gamma-rays
- Better events
  - More precise measurements of atmospheric cascades and hence primary gammas
    - Improved angular resolution
    - Improved background rejection power



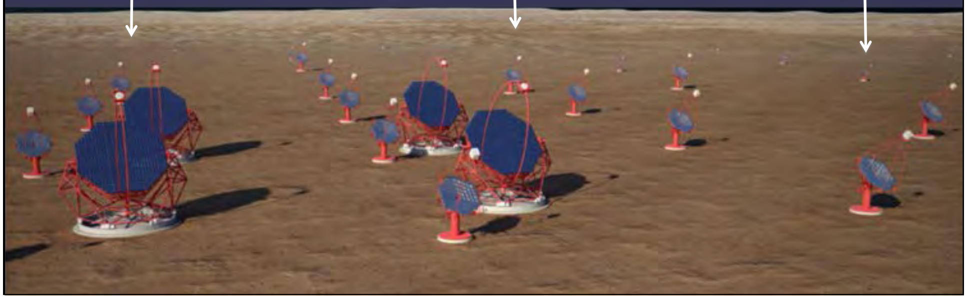
☛ The CTA solution: More telescopes !

What is CTA? A multi-telescope Cherenkov array

Low energies
Energy threshold 20 GeV
23 m diameter
4 telescopes
(LST)

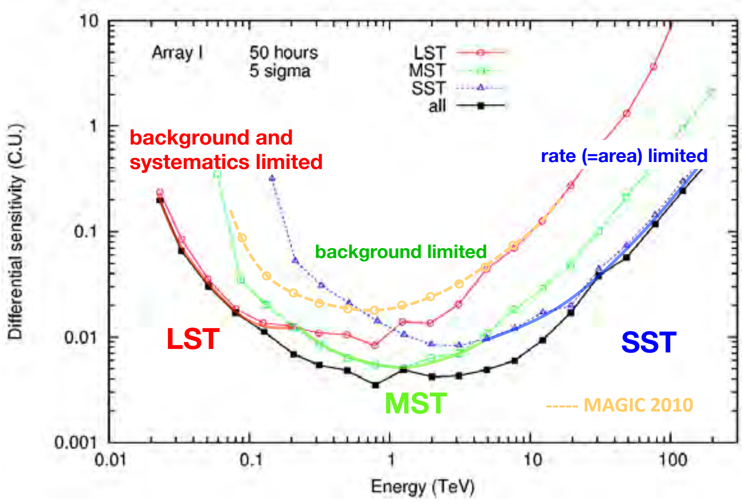
Medium energies (MST)
100 GeV – 10 TeV
9.5 to 12 m diameter
25 single-mirror telescopes
up to 24 dual-mirror telescopes
mCrab sensitivity in 50h at 0.1-10 TeV

High energies
10 km^2 area at few TeV
4 to 6 m diameter
70 telescopes
(SST)



CTA sensitivity in units of Crab flux

for 5 σ detection & $N_\gamma > 10$ in each 0.2-dex bin in E, in 50 h



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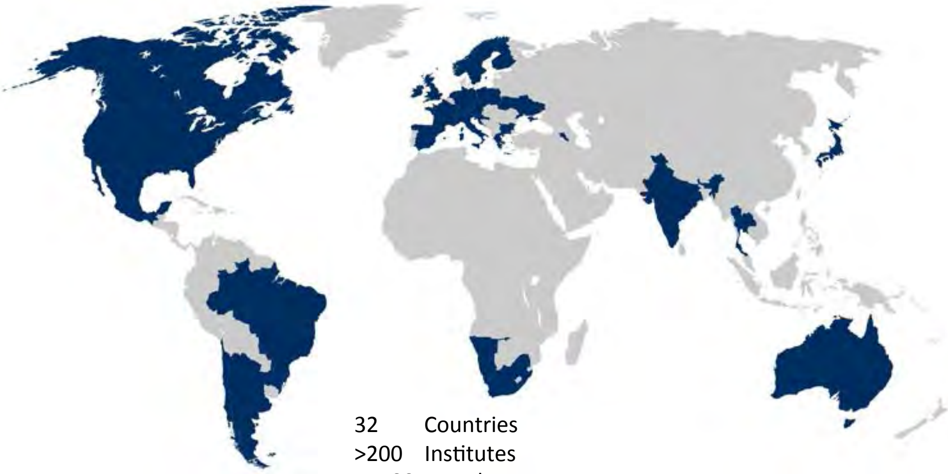
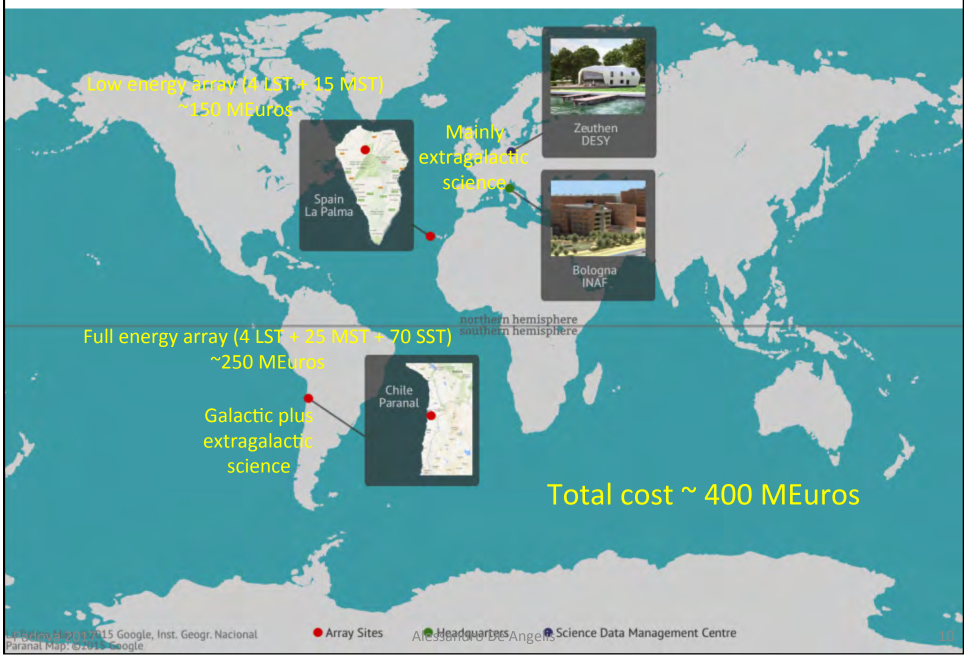
CTA consortium: a world-wide effort



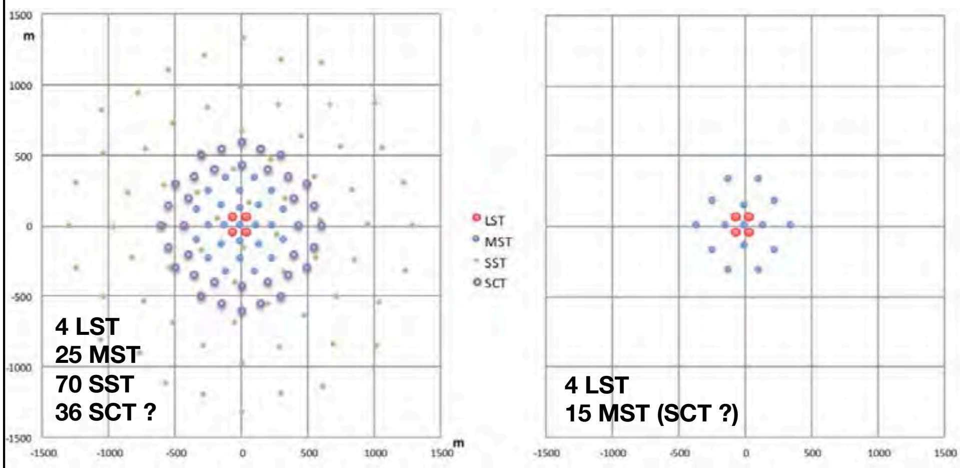
32 Countries
>200 Institutes
>1500 Members

All-sky coverage: two observatories



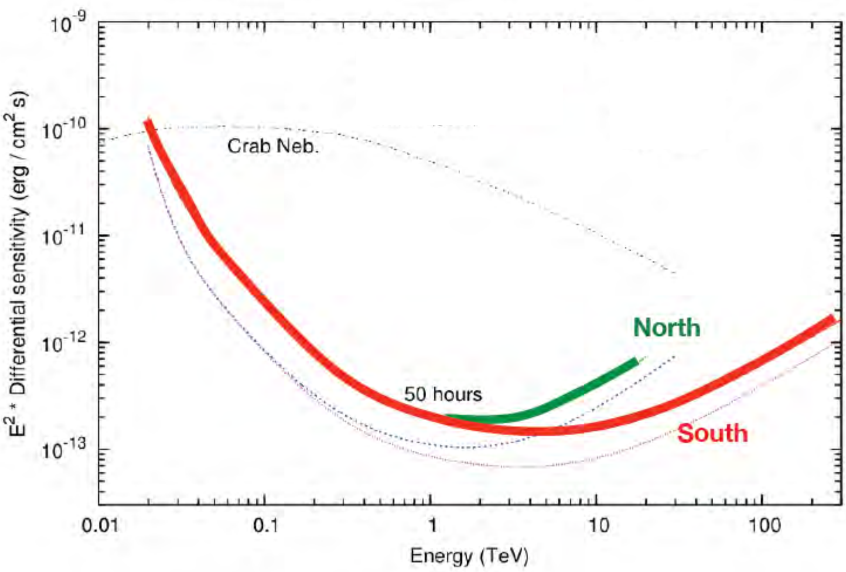
array layoutS

Reference (baseline) layouts



CTA-South CTA-North

Sensitivity for North and South



Telescope Specifications

SiPM Cameras (SCT and SST)

3 SST types

	LST "large"	MST "medium"	SCT "medium 2-M"	SST "small"
Number	**4 (S) 4 (N)**	**25 (S) 15 (N)**	**≤ 24 (S and N)**	**70 (S)**
Energy range	20 GeV to 1 TeV	200 GeV to 10 TeV	200 GeV to 10 TeV	> few TeV
Effective mirror area	> 330 m^2	> 90 m^2	> 50 m^2	> 5 m^2
Field of view	> 4.4°	> 7°	> 7°	> 8°
Pixel size ~PSF θ_{80}	< 0.12°	< 0.18°	< 0.07°	< 0.25°
Positioning time	50 s, 20 s goal	90 s, 60 s goal	90 s, 60 s goal	90 s, 60 s goal
Target capital cost	7.4 M€	1.6 M€	< 2.0 M€	500 k€

LST

(optimized for the 20 GeV-200 GeV range)

- 23 m diameter (400 m^2 dish area)
- 28 m focal length
- 200x2m^2 hexagonal mirrors
- 4.5 deg FoV
- 0.1° pixels, camera diam. 2m
- Light structure for 20 s positioning
- AMC
- 4 LSTs on North site, 4 LSTs on South site
- Prototype = 1st telescope at La Palma.
- Foundations finished end 2016
- Inauguration expected Nov 15, 2017
- Japan, Germany, INFN Italy, Spain, IN2P3 France, India, Brazil, Croatia, Sweden

LST1 construction (webcam live)

MEDIUM-SIZED 12 M TELESCOPE

OPTIMIZED FOR THE 100 GEV TO ~10 TEV RANGE

100 m² dish area
16 m focal length
1.2 m mirror facets

8° field of view
~2000 x 0.18° pixels

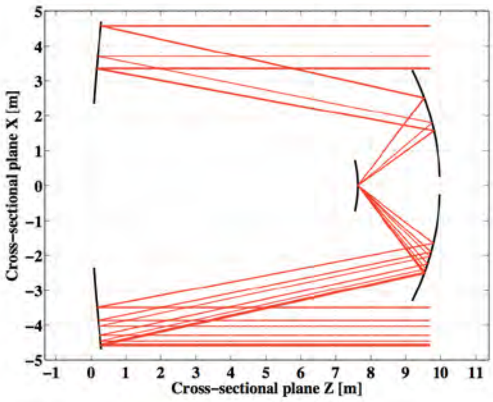
25 MSTs on South site
15 MSTs on North site

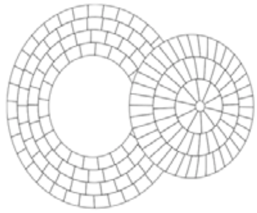
Berlin
MST prototype
operational

Two-Mirror Telescopes

Schwarzschild-Couder (SC) Design

Vassiliev, Fegan, Brousseau
Astropart.Phys.28:10-27,2007





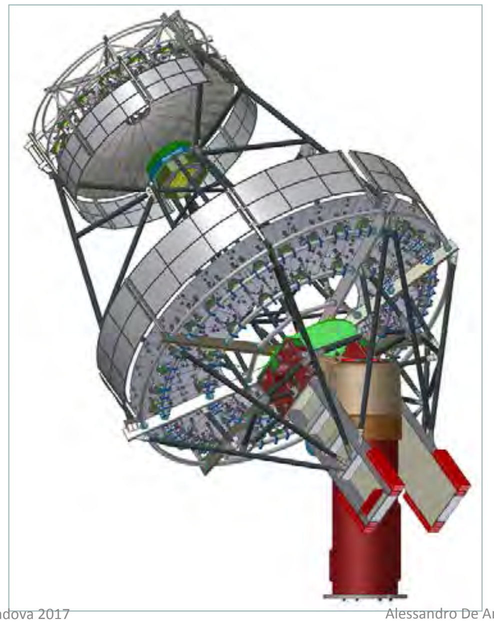
- Reduced plate scale
- **Improved PSF**
- **Uniform PSF across f.o.v.**

➜ Low-cost small telescopes with compact sensors (SST-2M)

➜ Higher-performance, cost-effective, medium telescope (MST-SCT)

3 telescope prototypes within CTA are using two mirror designs

Medium Telescope 2-mirror (SCT)



9.7 m primary
5.4 m secondary
5.6 m focal length, f/0.58
50 m^2 mirror dish area
PSF better than 4.5′
across 8° FOV

8° field of view
11328 x 0.07° SiPMT pixels
TARGET readout ASIC

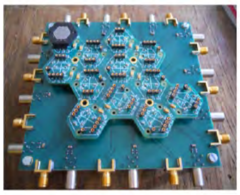
SCTs can augment / replace MSTs in either S or N
→ proposed US contribution

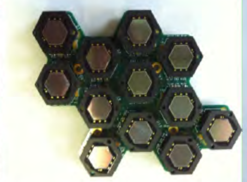
➜ Increased γ-ray collection area
➜ Improved γ-ray ang. resolution
➜ Improved DM sensitivity

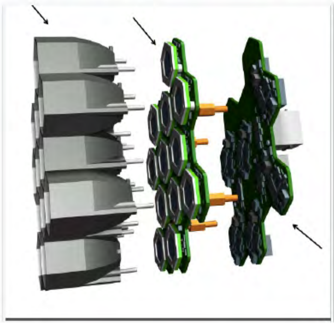
pSCT construction near Tucson (webcam live)

SST: HIGH THRESHOLD, OPTIMIZED FOR LOW COST
(SST-1M inauguration, Krakow June 2014)

CTA TELESCOPE DESIGN & PROTOTYPING: SST-1M

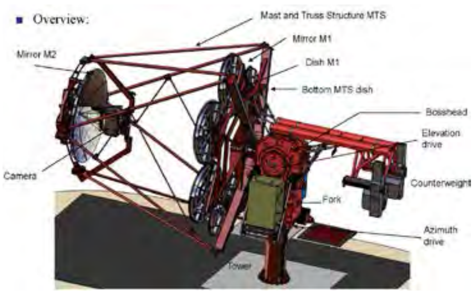






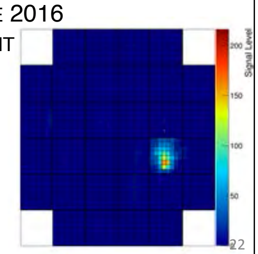
Small Telescope 2-mirror (SST-2M)

SST-2M –ASTRI MECHANICAL PROTOTYPE INAUGURATION, 24 SEPT 2014 (SERRA LA NAVE, SICILY)



SST-2M-GCT (GATE TELESCOPE) INAUGURATED IN JUNE 2016

SAW ALREADY 1ST LIGHT



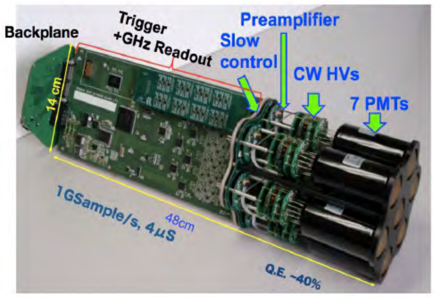
BOTH 2-MIRROR SST DESIGNS: COMPACT, SILICON-PM CAMERAS

CAMERAS

NectarCam
cooling studies

FlashCam
144 pixel
focal plane

LST camera
cluster

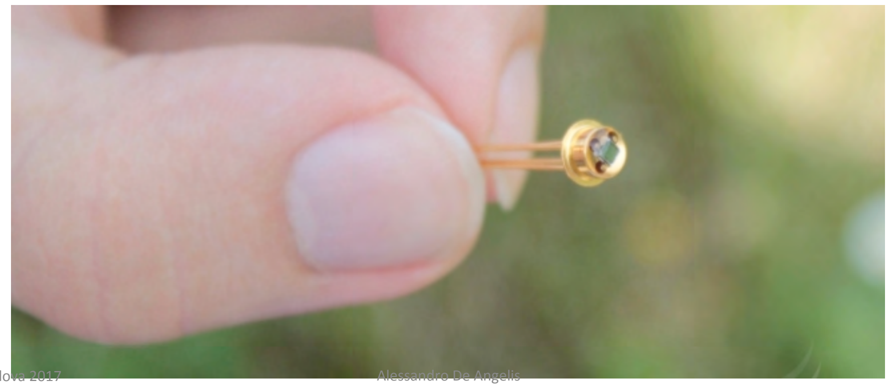


SiPM: the technological challenge for small cameras

Cameras need high granularity, and typical PMT size of 5-6 mm

Difficult to do with standard PMT

New detectors (SiPM) under development

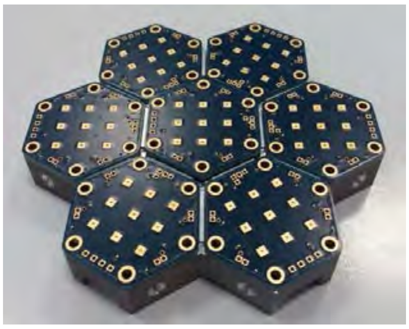


LST in the future: large surface SiPM?

Challenge: single sensor with large area (1 inch diameter)
Amplify-and-sum stage, one output per pixel

Prototype of analog sum scheme will be tested in MAGIC

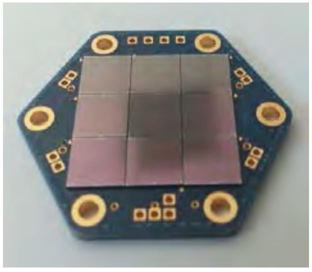
Prototype cluster using Hamamatsu and developed by MPI mounted on MAGIC Jun 15

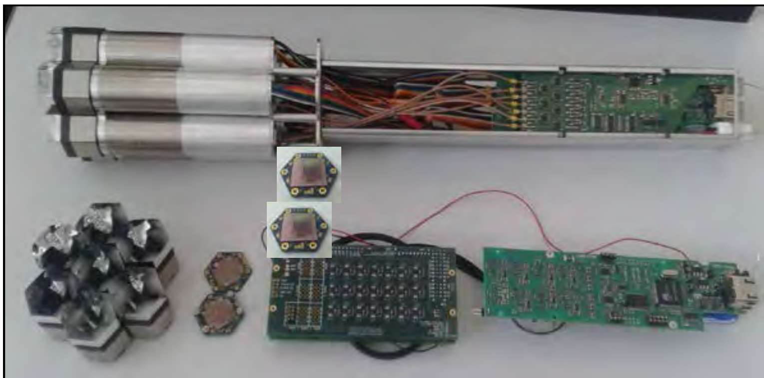


9 FBK 6x6 mm^2 sensors
Sensor electronics by INFN Padova
MAGIC cluster control electronics and

Signal: 2 mV per phe; noise: 0.5 mV rms
Linearity: ok to >200 phe

Assembly and test now,; installed in MAGIC October 2015 for comparison with the standard PMT clusters (and with the similar Max Planck SiPM cluster, just installed)



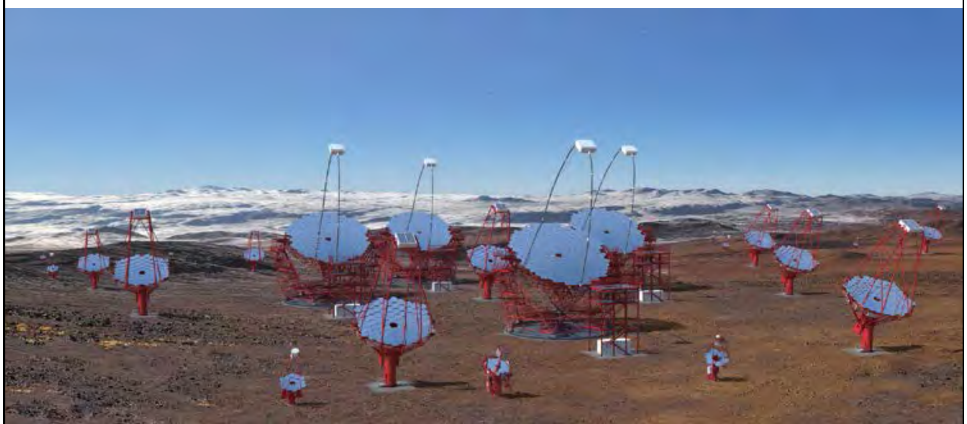


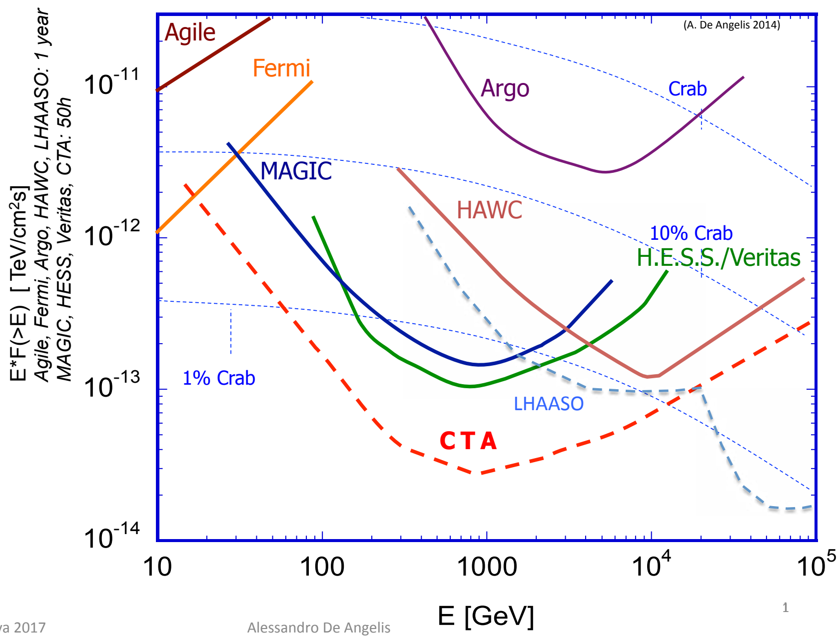
In picture:
Top: standard MAGIC PMT cluster
Bottom: components for SiPM cluster, mechanical structure removed

CTA-N: rendering

LST1 to commissioned in 2018 (inauguration end 2017?)
LST2-4 commissioned in 2020?
First 5 MST commissioned in 2022?

CTA-S in Paranal: rendering (works starting in 2018?)



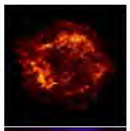


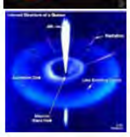
Guaranteed Science with CTA

An advanced Facility for ground-based gamma-ray Astronomy

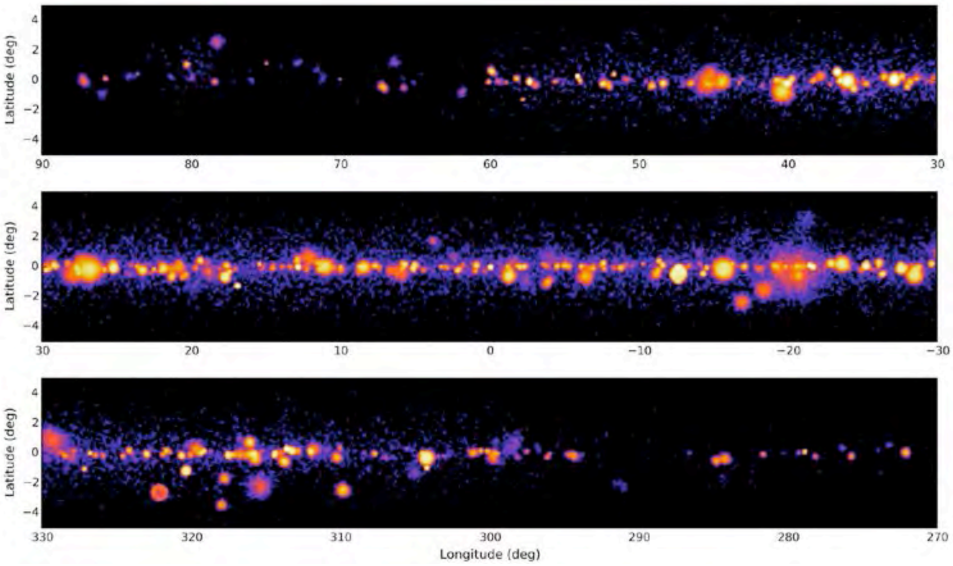
~200 -> ~2000 sources above 100 GeV

- Study of sources and propagation of high energy particles in the Cosmos, on scales ranging from compact objects to large scale structures
  - Pulsars
  - Pulsar wind nebulae
  - Stellar winds
  - Supernova remnants
  - Diffuse emission
  - Galactic center region
  - Starburst galaxies
  - Clusters of galaxies
- Black holes and their environment
  - Stellar-mass black holes
  - Supermassive black holes



Simulation of the visibility of the Galaxy



OTHER POSSIBLE DESIGNS FOR VHE GAMMA ASTROPHYSICS

An experimentalist's view of gamma rays: different energy regions

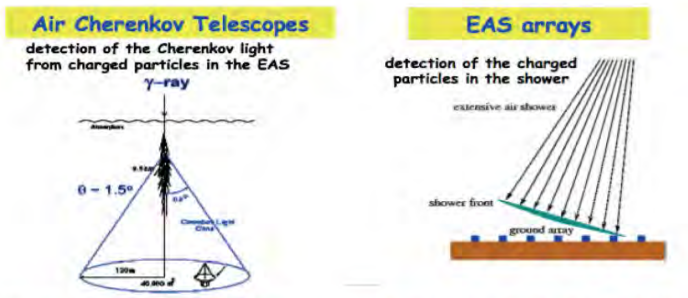
1. MeV: 30 keV to 30 MeV
2. GeV: 30 MeV to 30 GeV
3. TeV: 30 GeV to 30 TeV
4. PeV : 300- GeV - 30+ TeV

CTA

- (subjectively) chosen from the requirements of
  – (i) detection specifics and
  – (ii) principal scientific issues
- Can CTA be helped in regions 1., 2. and 4. ?

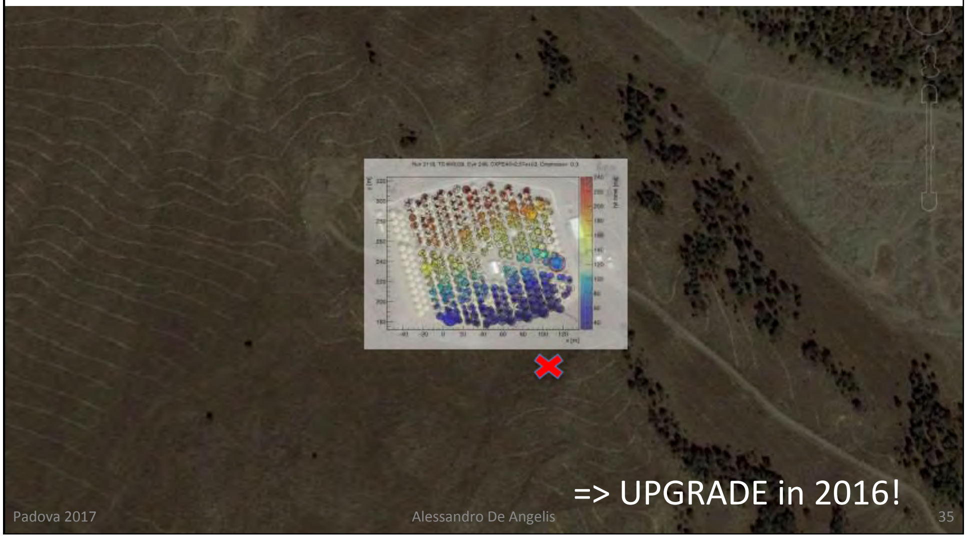
EAS-type designs (serendipity => GRB, unexpected…)

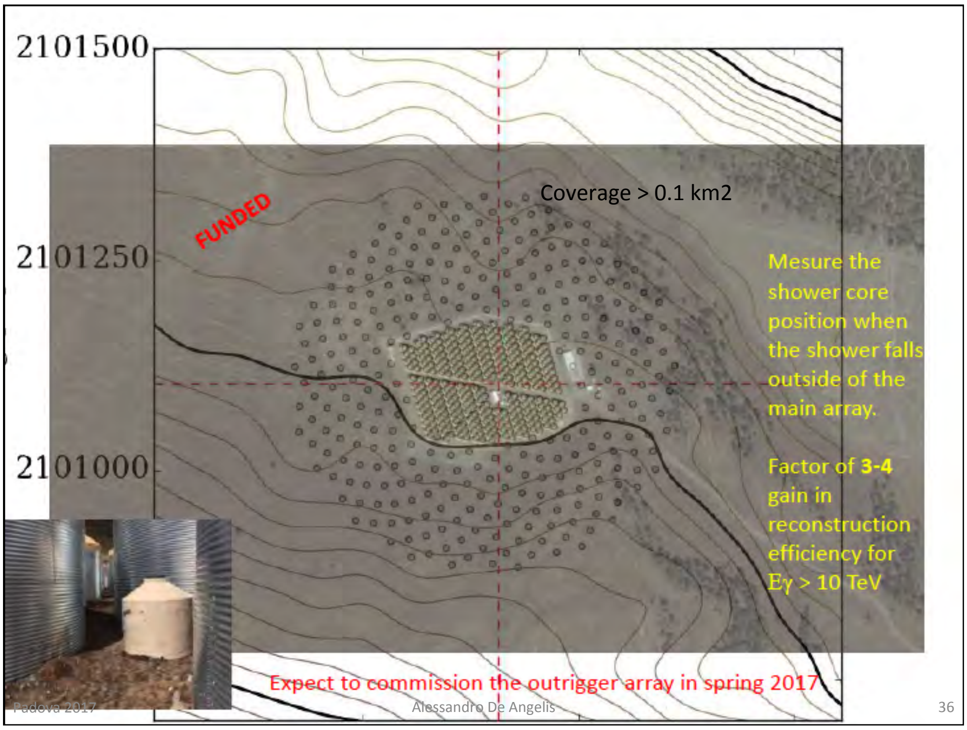
- CTA can be non optimal for PeV detection
- EAS can be the key for Pevatron studies



Air Cherenkov Telescopes	EAS arrays
Very low energy threshold (≈50 GeV)	Higher energy threshold (≈300 GeV)
Excellent bkg rejection (>99%)	Good bkg rejection (>80%)
Excellent angular resolution (≈0.05 deg)	Good angular resolution (0.2-0.8 deg)
Good energy resolution (≈15%)	Modest energy resolution (≈50%)
High Sensitivity (< % Crab flux)	Good Sensitivity (5-10% Crab flux)
Low duty-cycle (≈10%)	High duty-cycle (≈100%)
Small field of view (4-5 deg)	Large field of view (≈2 sr)

HAWC: most VHE triggered showers energy falls outside of the array





The LHAASO project

The Large High Altitude Air Shower Observatory (LHAASO) project is a new generation all-sky instrument to perform a combined study of cosmic rays and gamma-rays in the wide energy range 10^{11} -- 10^{17} eV.

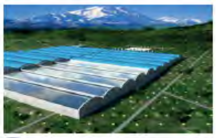
The experiment will be located at 4300m asl (606 g/cm^2) in the Sichuan province

1 KM2A:
5635 EDs
1221 MDs

WFCTA:
24 telescopes
1024 pixels each

WCDA:
3600 cells
90,000 m^2

SCDA:
452 detectors



Coverage area: 1.3 km^2

Francesco Simeone - The Future of Research on Cosmic Gamma Rays - 28/8/2015 3

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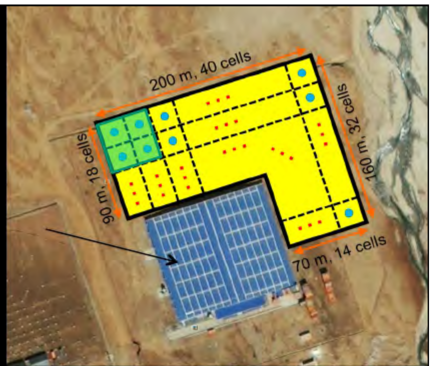
LHAASO

- Phase-0: Large Area Water Cherenkov Array (LAWCA)
  - YangBaJing, Tibet: around the ARGO detector
  - Completion end 2014
- Phase-1
  - Final site: Shangri-La
    - 4.3 km altitude
  - Sensitivity?
    - Will depend on background rejection power achieved in practice, but will be a **very** powerful instrument



Angular resolution:

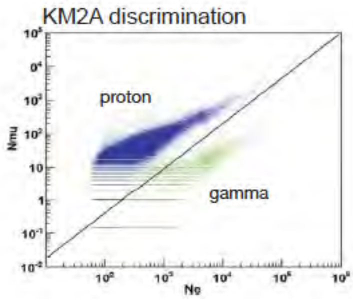
30 TeV ~0.4°

100TeV ~0.3 °

Energy relsolution:

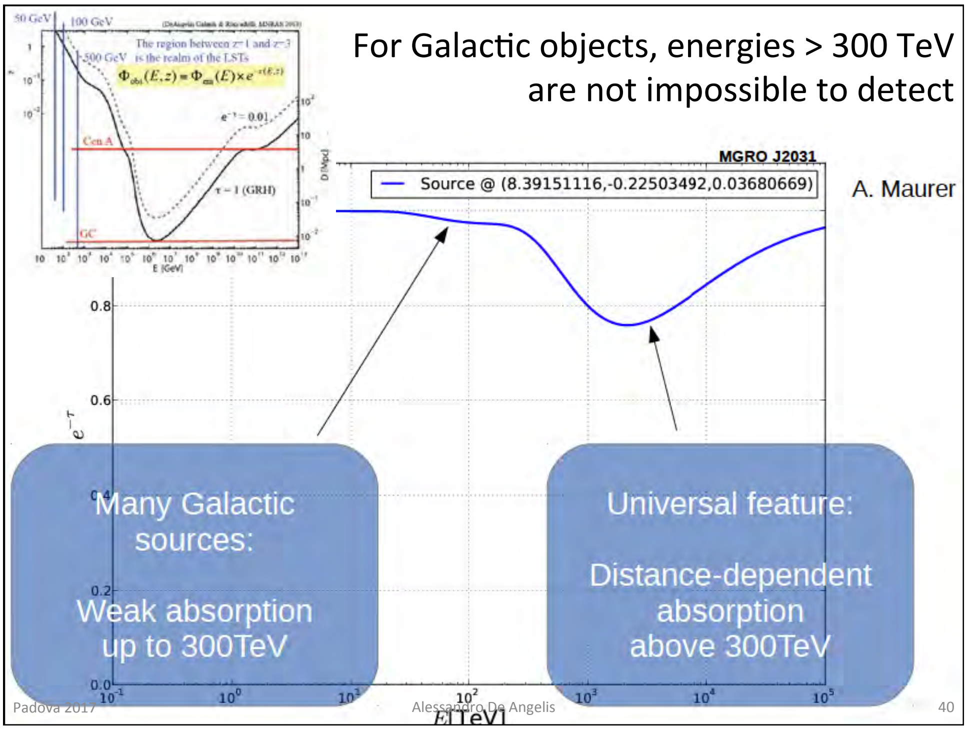
30 TeV ~30%

100 TeV ~20%

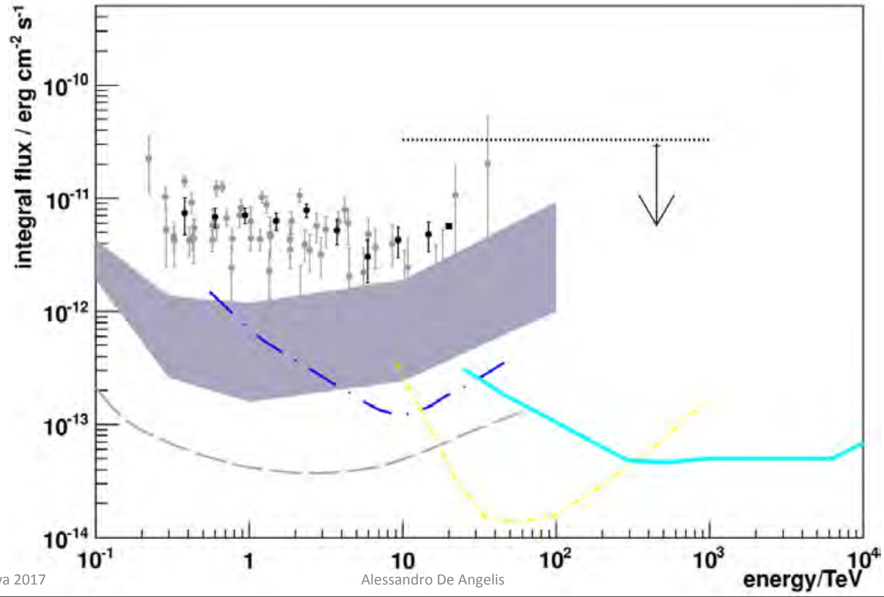


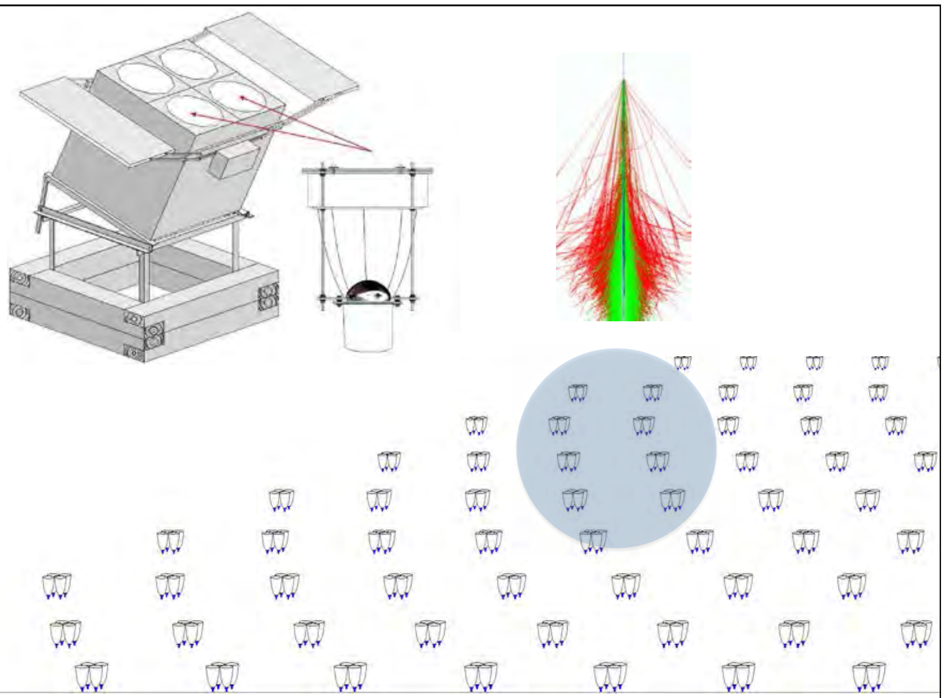
2018: start scientific operation of the first quarter of LHAASO.
2021: conclusion of the installation of all main components.

For Galactic objects, energies > 300 TeV are not impossible to detect



Flux limitations => large area is the key: HiSCORE





Tunka-HiSCORE → TAIGA

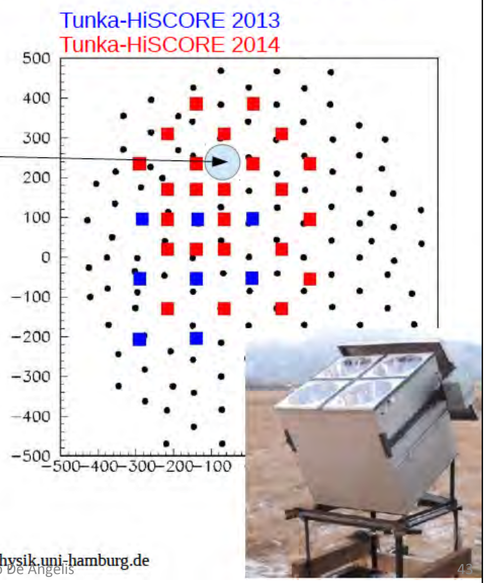
Tunka Advanced Instrument for Gamma ray and cosmic ray physics

10/2014: extension

- Total: 29 stations
- Tilting mode
- 0.25 km²

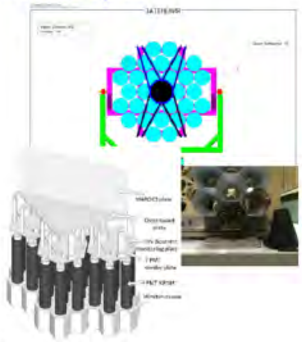
2015+:

- First telescope
- Hybrid timing+imaging
- In total 10 telescopes planned
- Muon detectors



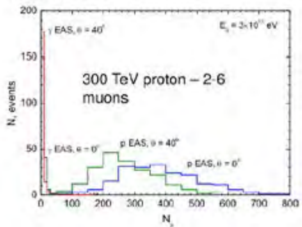
TAIGA Telescopes

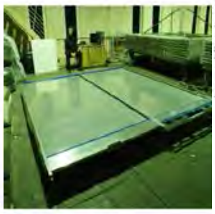
- Dish: Davies-cotton tesselated, 34 mirrors (60cm)
- 4.3 m dish diameter
- 4.75 m focal length
- F/D ~ 1.2
- 397 PMT camera foV 8° (0.38° / pixel)
- Proven design components

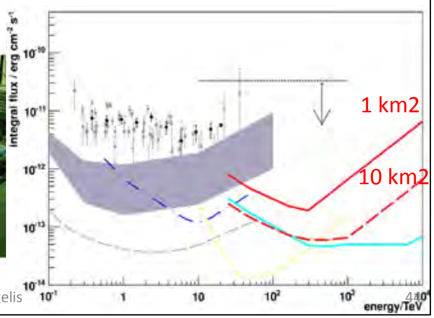


September 3, 2014 martin.tluczy

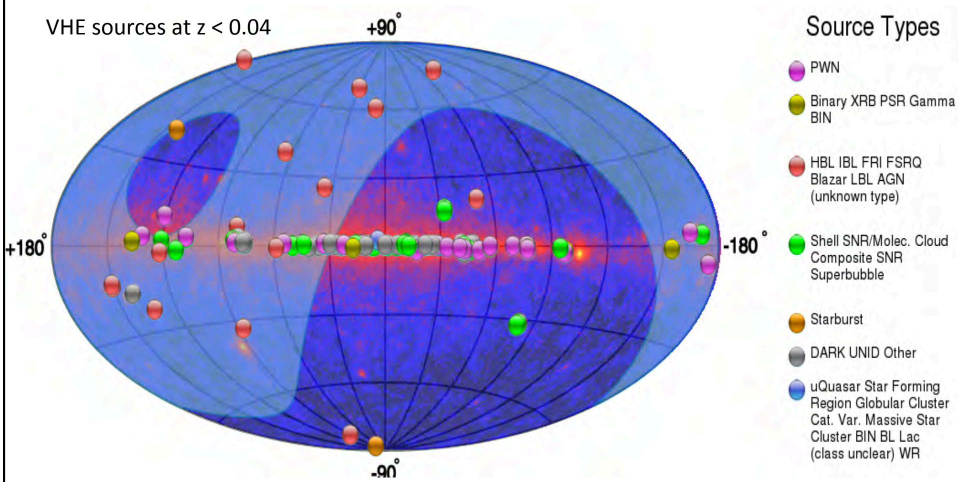
- Planned: equip 0.2% of array area with Muon detectors





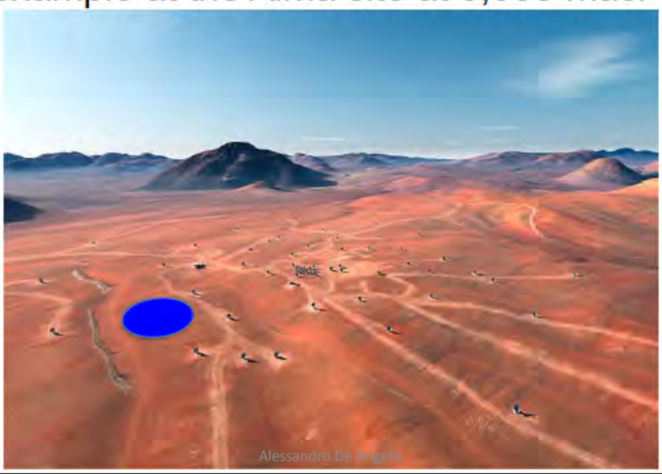


HAWC+, LHAASO, HiSCORE ~ funded, but there is a strong case for a sub-PeV experiment in the Southern hemisphere



HAWC South

- 3rd generation water Cherenkov detector
- higher altitude, more sensitive than HAWC
- for example at the Alma site at 5,000 masl



Large Array Telescope for Tracking Energetic Sources (LATTES)

- Instrument a large area with closed-loop RPCs
  - Under test (MARTA)
- and Cherenkov tanks
  - Cherenkov can be water or glass, under test (CESAR)
- Proposal by CBPF Rio, LIP Lisboa, Univ. Padova & Udine (2014; to be reiterated in 2017)
- Possible sites
  - Argentina
  - Bolivia (Chacaltaya site, latitude 16.3 S, altitude 5200 m asl)
  - Chile (Atacama destert, latitude 23.7 S, altitude 5060 m asl)

The qualities of LATTES

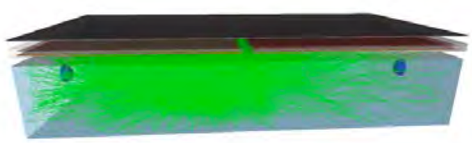
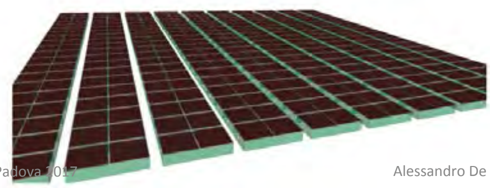
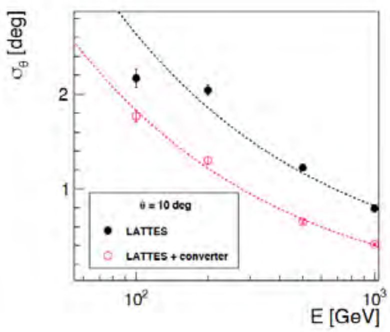


Figure 2: Basic detector station, with one WCD covered with RPCs and a thin slab of lead. The green lines show the tracks of the Cherenkov photons produced by the electron and positron from the conversion of a photon in the lead (for better visualisation the Tyvek's reflectivity was scaled by 1/10).



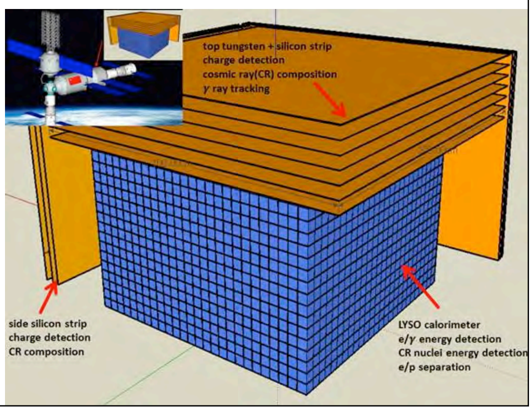


Goal: to reach sensitivity in the 100 GeV – 30 TeV region

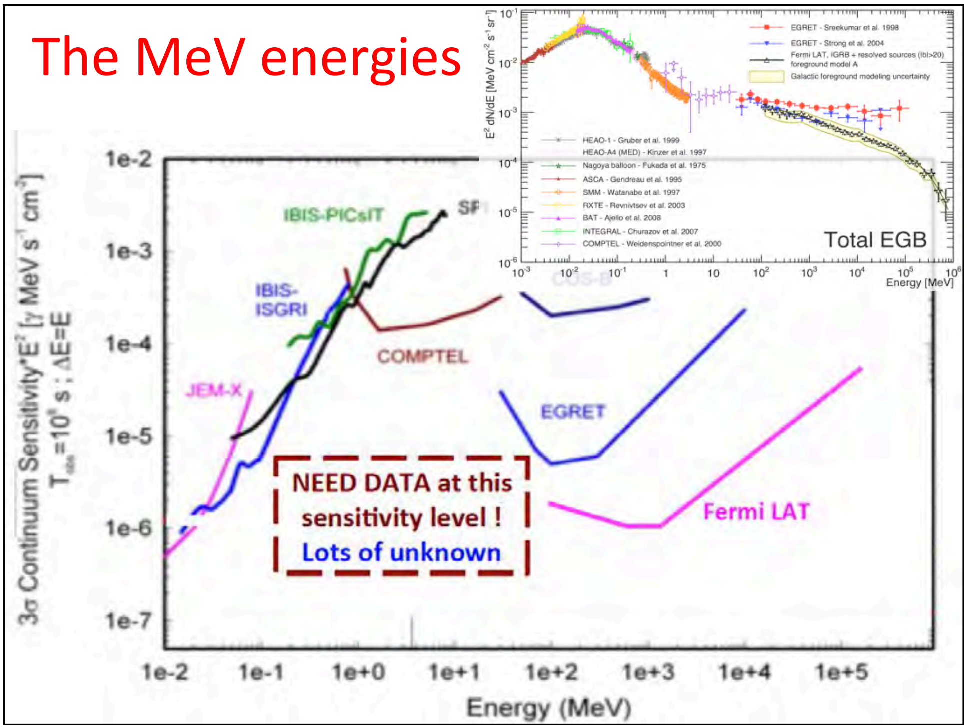
LOWER ENERGIES (GeV and MeV)

GeV region from space

- Fermi can fly till 2028 (granted till 2020)
- Difficult to find a successor…
- Only one super-Fermi project on the field: the Chinese-Italian HERD
  - A Fermi with better calorimetry
  - A few years after the CSS
  - Approved in 2017
- Also useful for observing charged cosmic rays up to ~ the knee

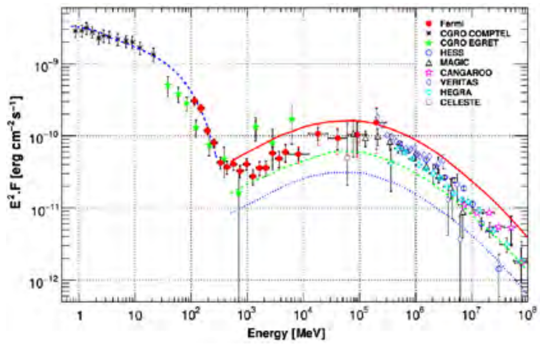


The MeV energies



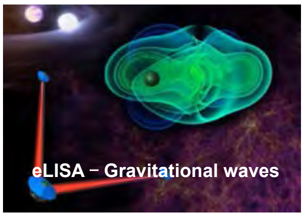
O(1 MeV)

- The MeV region is the less known, and its knowledge has large impact on the modeling of SEDs



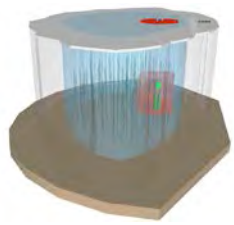
- As a bonus, Compton photons are naturally polarized

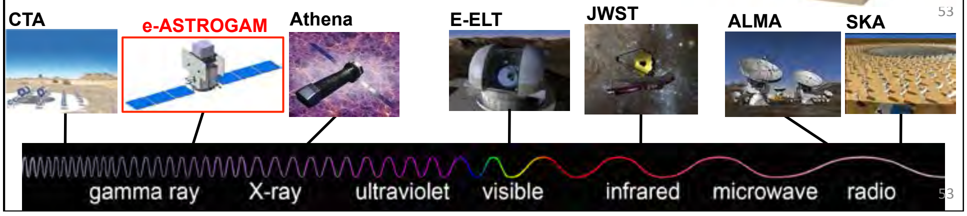
e-ASTROGAM (Europe, De Angelis et al.) and AMEGO (US, McEnery et al.) – 2028/29



1. Processes at the heart of the extreme Universe (AGNs, GRBs, microquasars): prospects for the Astronomy of the 2030s
   - Multi-wavelength, multi-messenger coverage of the sky (with CTA, SKA, eLISA, ν detectors...), with special focus on transient phenomena
2. The origin of high-energy particles and impact on galaxy evolution, from cosmic rays to antimatter
3. Nucleosynthesis and the chemical enrichment of our Galaxy

Km3Net/IceCube-Gen2 - ν





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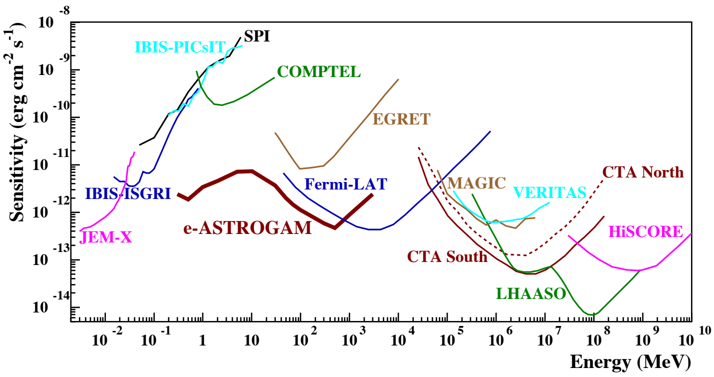
e-ASTROGAM scientific requirements

1. Achieve a sensitivity better than that of INTEGRAL/CGRO/COMPTEL by a factor of 20 - 50 – 100 in the range 0.2 – 30 MeV
2. Fully exploit gamma-ray polarization for both transient and steady sources
3. Improve significantly the angular resolution (to reach, e.g., ~ 10' at 1 GeV)
4. Achieve a very large field of view (~ 2.5 sr) ⇒ efficient monitoring of the γ-ray sky
5. Enable sub-millisecond trigger and alert capability for transients



A. De Angelis, 1st e-ASTROGAM Workshop, Padova

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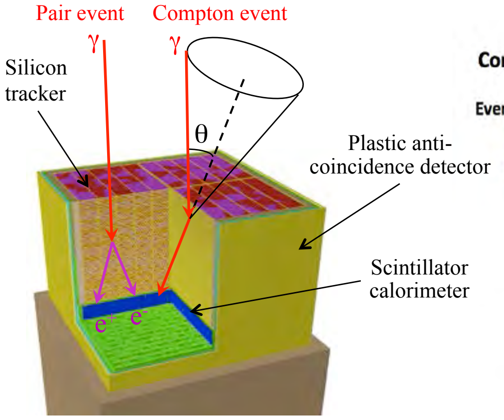
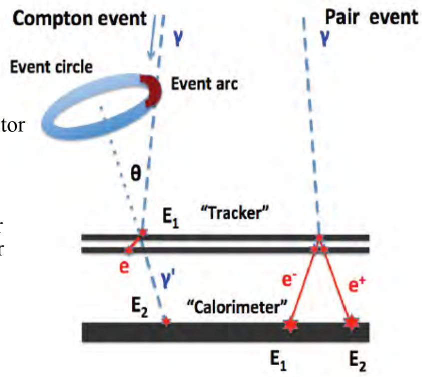
How to measure gamma rays in the MeV-GeV?

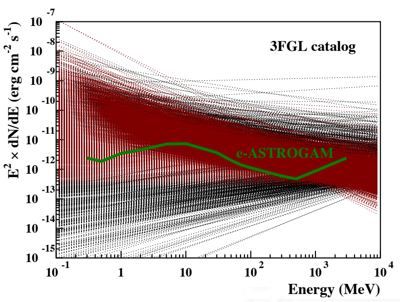




- **Tracker** – Double sided Si strip detectors (DSSDs) for excellent spectral resolution and fine 3-D position resolution (1m^2, 500 μm thick, 0.3 Xo in total)
- **Calorimeter** – High-Z material for an efficient absorption of the scattered photon ⇒ CsI(Tl) scintillation crystals readout by Si drift detectors or photomultipliers for best energy resolution. 8 cm (4.3 Xo)
- **Anticoincidence detector** to veto charged-particle induced background ⇒ plastic scintillators readout by Si photomultipliers

e-ASTROGAM discovery space

- Over 2/3 of the 3033 sources from the 3rd *Fermi* LAT Catalog (3FGL) have power-law spectra (E_γ > 100 MeV) steeper than E_γ^{-2}, implying that their peak energy output is below 100 MeV



- These includes about 1100 (candidate) blazars and more than **720 unassociated sources**
- Most of these sources will be detected by **e-ASTROGAM** ⇒ large discovery space for new sources and source classes

Type	3 yr	New sources
Total	3000 – 4000	~1800 (including GRBs)
Galactic	~ 1000	~400
MeV blazars	~ 350	~ 350
GeV blazars	1000 – 1500	~ 350
Other AGN (<10 MeV)	70 – 100	35 – 50
Supernovae	10 – 15	10 – 15
Novae	4 – 6	4 – 6
GRBs	~600	~600

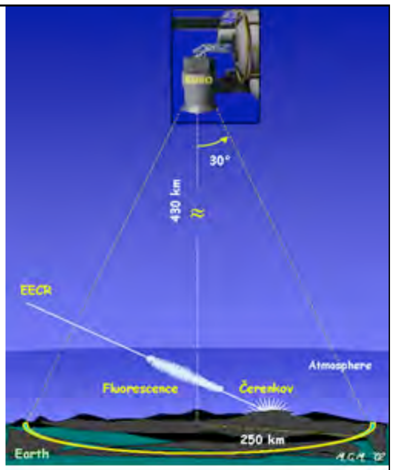
UHE COSMIC RAYS

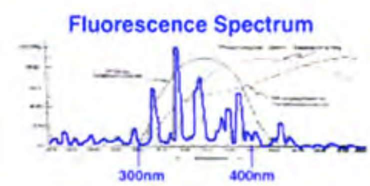
Upgrade of Auger (funded, to be completed in 2018)

- Auger's surface (3000 km2) unbeatable
- Upgrade in the next years: scintillators coupled to the tanks to improve the capability of hadron classification, presently based on the shower shape

New concepts: space

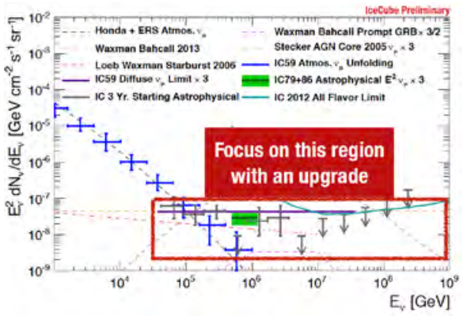
- Increase the effective area by looking from space
- Problem: lower threshold at some EeV
- The JEM-EUSO concept
- No clear schedule

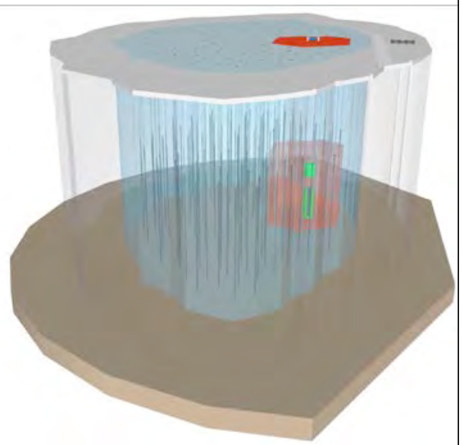




ASTROPHYSICAL NEUTRINOS

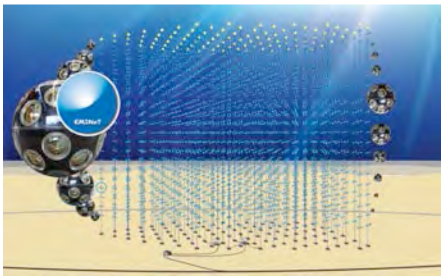
IceCube-Gen2, a ten-cubic-kilometer detector

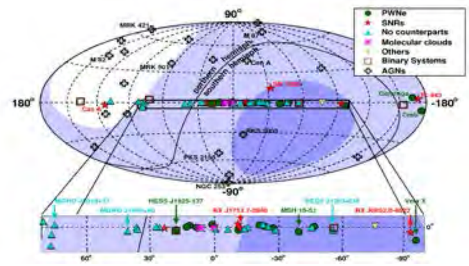




- Spacing between light sensors to exceed 250 meters, instead of the current 125 meters in IceCube. The IceCube-Gen2 instrumented volume might rapidly grow at modest costs.
- By roughly doubling the instrumentation already deployed, the telescope will achieve a tenfold increase in volume to about 10 cubic kilometers, aiming at an order of magnitude increase in neutrino detection rates.

Km3Net in the Mediterranean Sea





- Plan to reach ~5km^3
- Better angular resolution
- Better visibility of the GC region

Source Name	Source radius (°)	Visibility	Number of events per year For E_ν > 5 TeV	
			Signal ν	Atm ν
RX J1713.7–3946	0.7	0.74	4 – 11	6.4
RX J0852.0–4622	1.0	0.84	2 – 6	17
HESS J1745–303	0.2	0.66	0 – 22	1.4
HESS J1626–490	< 0.1	0.91	4 – 9	1.6
Vela X	0.4	0.81	4 – 15	3.5
Crab Nebula	< 0.1	0.39	1 – 3	0.8

CONCLUSIONS

- Gamma rays:
  - A rich panorama of gamma experiments at VHE gamma proposed for the future. CTA will lead the field.
    - Besides CTA, new techniques. Exploration of the PeV region is fundamental – and feasible. Northern projects approved, will produce nice science. Need to converge to a Southern 100 GeV-100 TeV EAS array.
  - In the longer term, need taking care of multiwavelength aspects: priorities are
    - A MeV mission (room for smart improvement; 2 missions proposed)
    - A successor of Fermi
- Multimessenger astronomy gamma/neutrinos can help our understanding of cosmic accelerators, of physics under extreme environments and of fundamental particle physics
  - Neutrino detectors will grow (at high price), and we know what we can get for astronomy
  - In a few years we'll know the impact of GW (cfr the dedicated lecture)
  - Auger to be upgraded, but new technologies look far away in time