Multimessenger Astroparticle Physics

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8. A Look to the Future

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Archeology

- HE astrophysics was until 2017 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 prospects 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 ~1/month with 1km^3 detector, s/b ~ 4/1), and we know that probably a several-km^3 detector is needed do to astronomy. One neutrino event associated with gamma rays.
  - Gravitational waves: first signals (~3/year, will soon become ~0.5-1/month). One associated with gamma rays.
  - Protons cannot be used for astronomy (but they give us O(100 TeV) c.m. energies)

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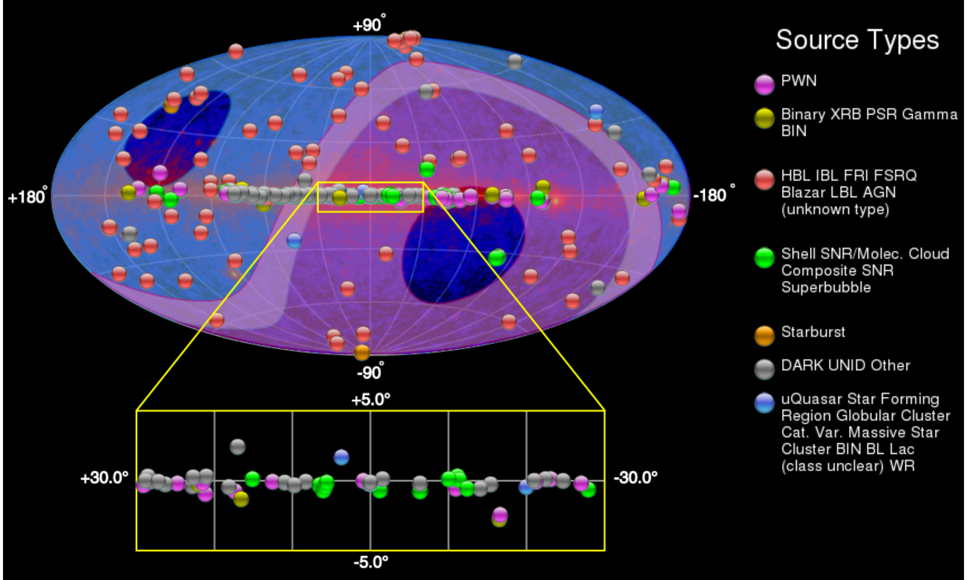
Instruments

- 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 at 1 km^3 (IceCube) and 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 in addition there is room for improvement by “brute force”
  - In the PeV region, only one detector (HAWC) presently active, and there is room for improvement − also by “brute force”, and by going South

3k HE and >200 VHE photon emitters



The TeV gamma-ray region: CTA

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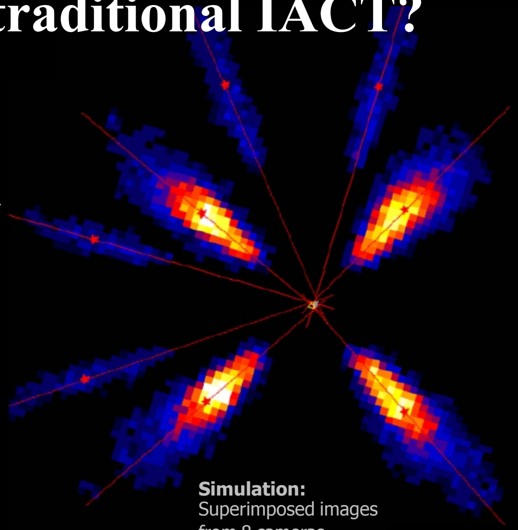
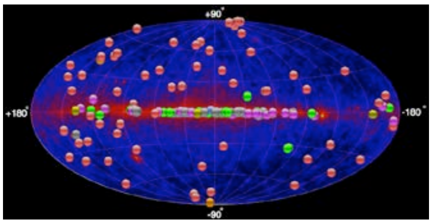
The 20 GeV- 100 TeV region: how to do better with traditional IACT?

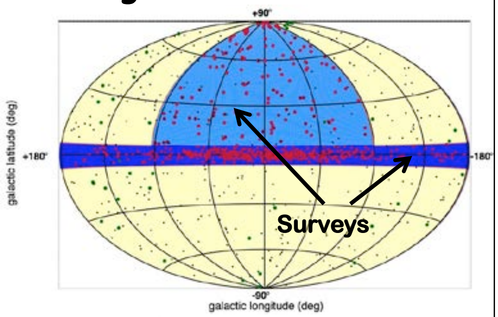
- More events
  - More photons = better spectra, images, fainter sources
    - Larger collection area for gamma-rays
- Better events
  - More precise measurements of atmospheric cascades and hence primary gammas
    - Improved angular resolution
    - Improved background rejection power

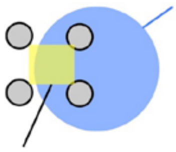


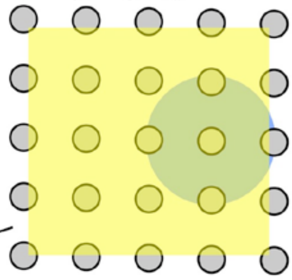
☛ The CTA solution: More telescopes !

From current arrays to CTA

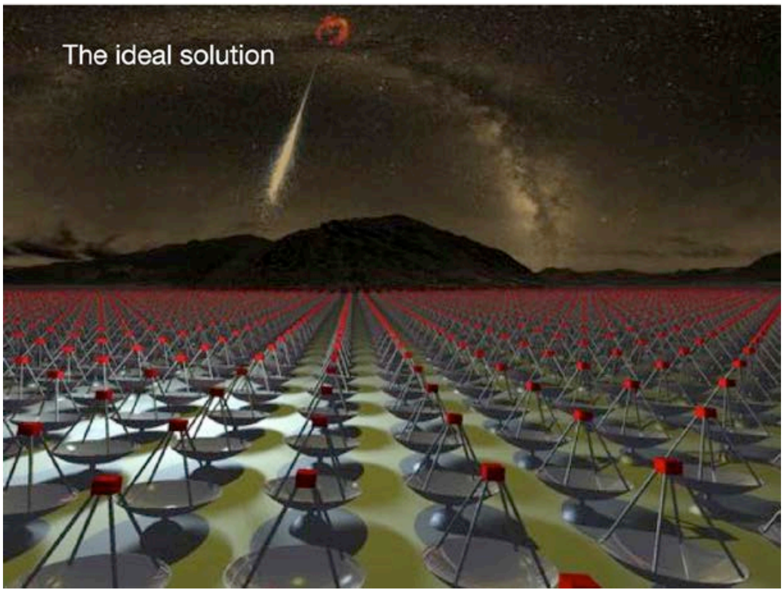






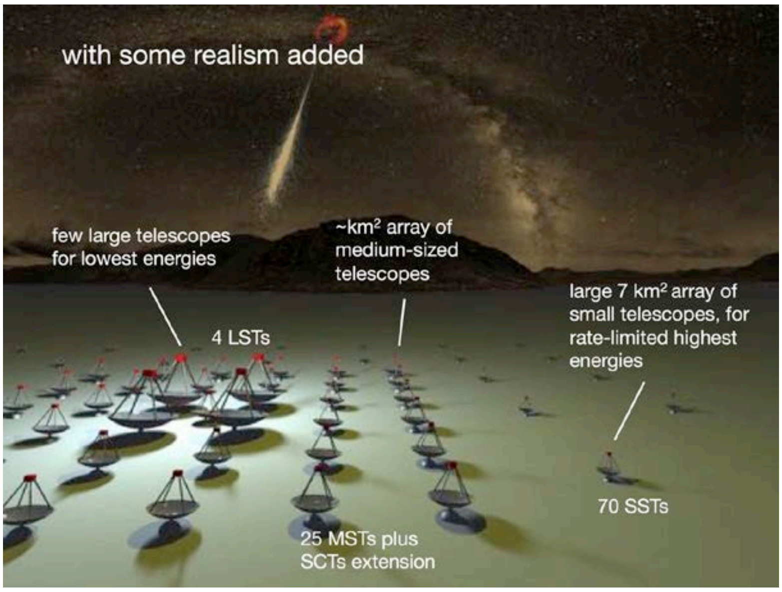


A next generation VHE facility



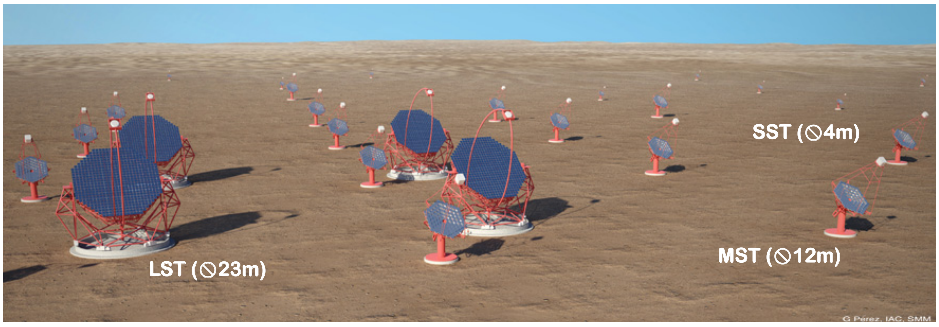
W. Hofmann

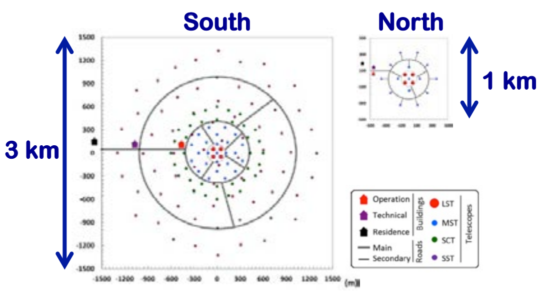
A next generation VHE facility



W. Hofmann

The CTA Observatory



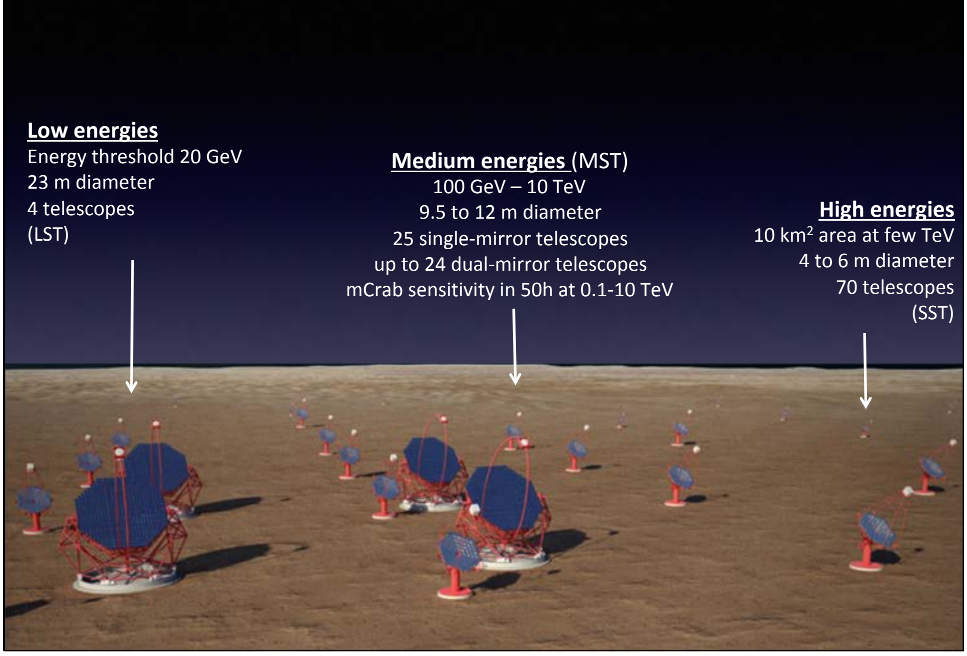


SCT (⦸10m)

Characteristics

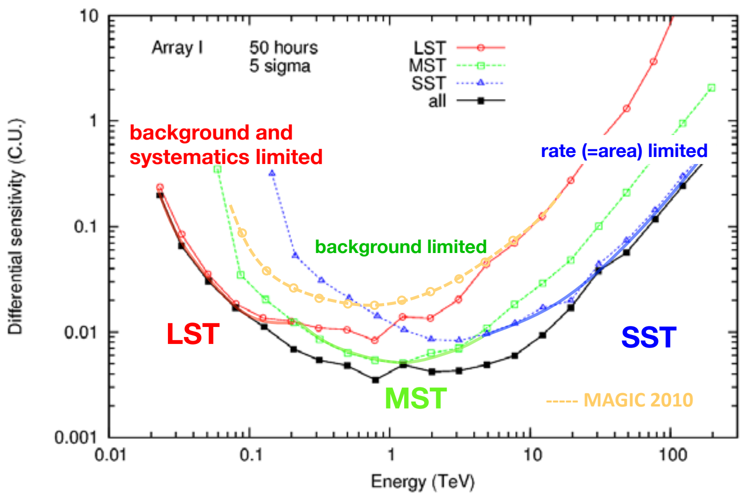
2 sites (north & south)
3 telescope size classes
About 120 telescopes in total
South U.S. extension with about 25 SCT telescopes

What is CTA? A multi-telescope Cherenkov array



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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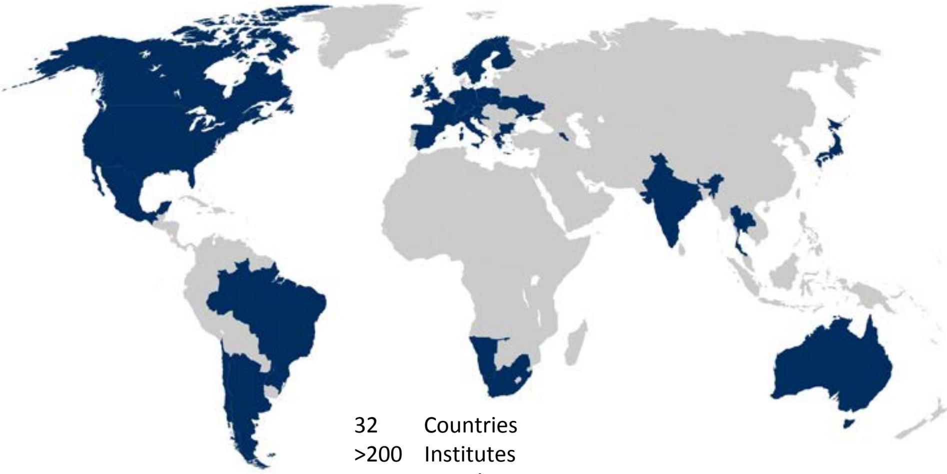
CTA consortium: a world-wide effort



32 Countries
>200 Institutes
>1500 Members

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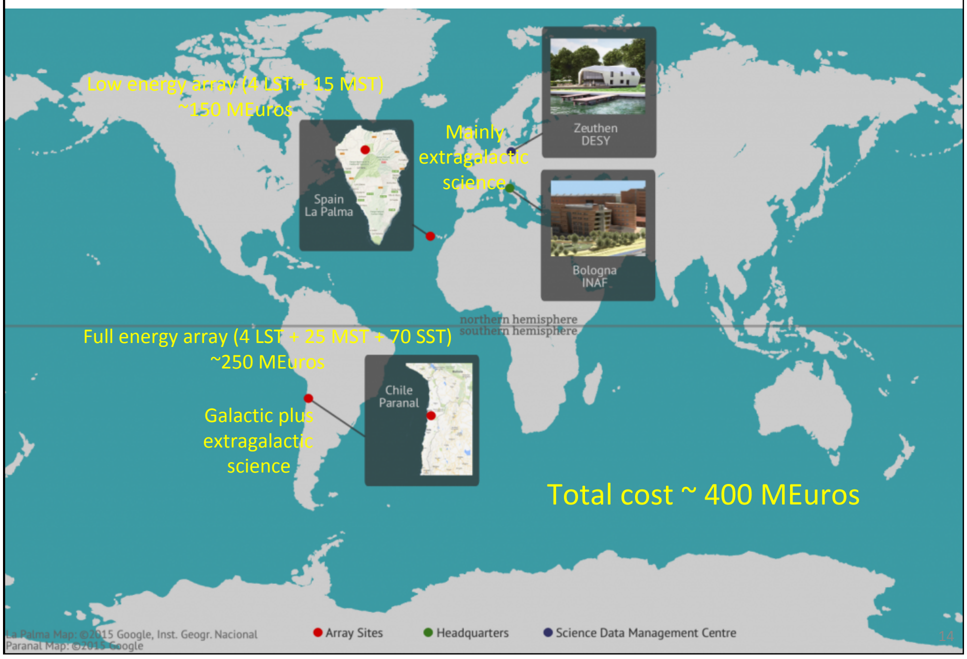
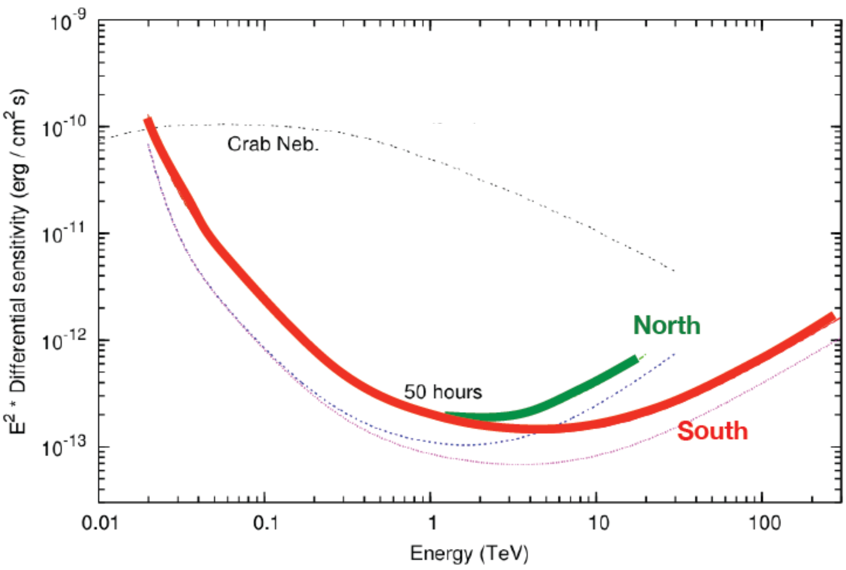
All-sky coverage: two observatories



Sensitivity for North and South



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Telescope Specifications

SiPM Cameras

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	400 m²	100 m²	> 50 m²	> 5 m²
Field of view	> 4.4°	> 7°	> 7°	> 8°
Pixel size θ_{80}	0.1°	< 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
Capital cost	10 M€	2 M€	2 M€	800 k€

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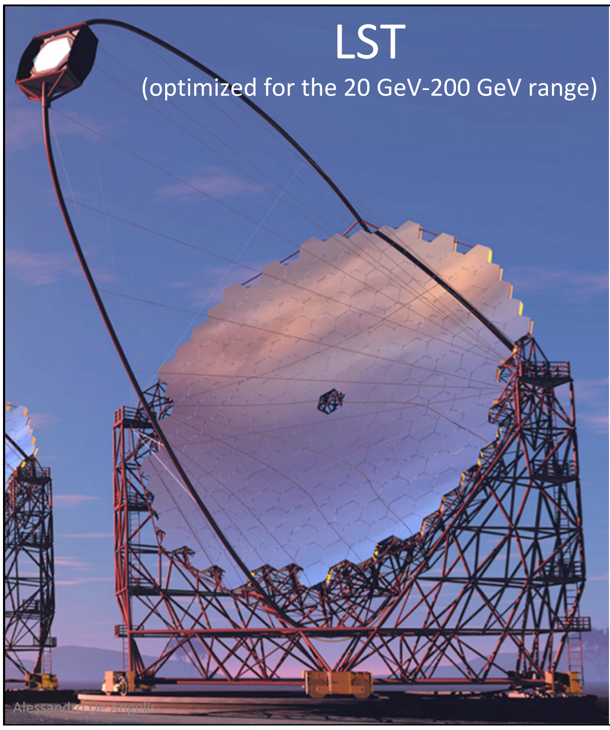
CTA-N: rendering

LST1 to be commissioned in 2018 (inauguration October 10, 2018)
LST2-4 commissioned in 2020?
First 5 MST commissioned in 2022?

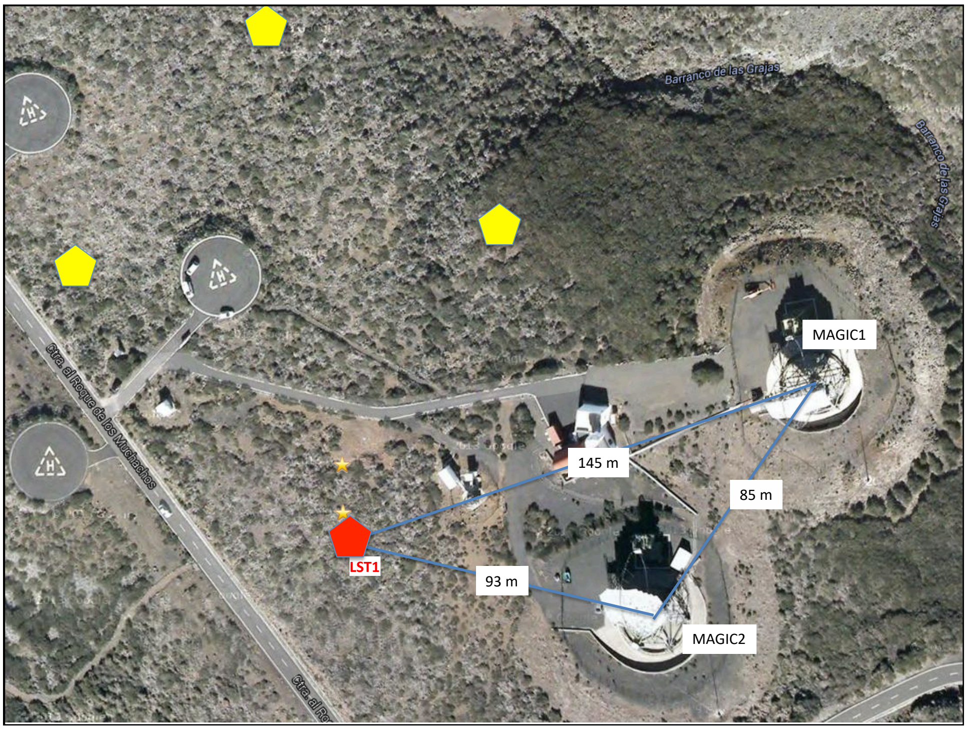
LST

(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 fixed Oct 10, 2018
- Japan, Germany, INFN Italy, Spain, IN2P3 France, India, Brazil, Croatia, Sweden

LST Webcam. Inauguration October 10, 2018



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

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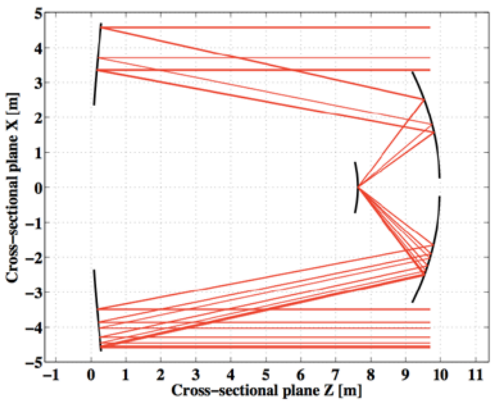
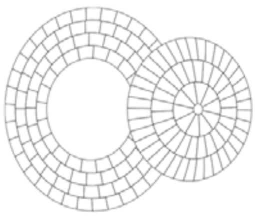
Two-Mirror Telescopes

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

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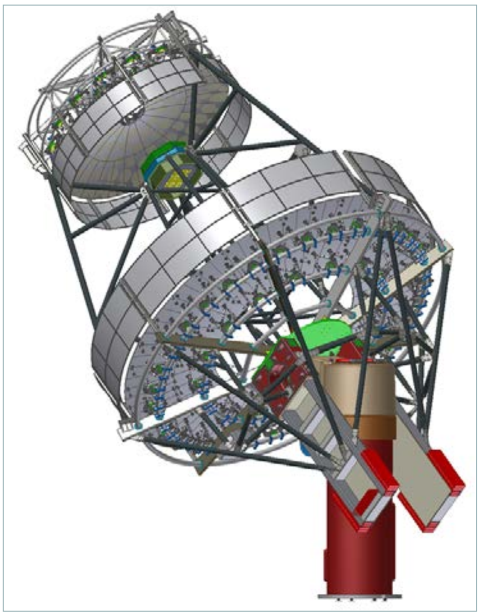
Medium Telescope 2-mirror (SCT)



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

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pSCT construction near Tucson (webcam live)

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

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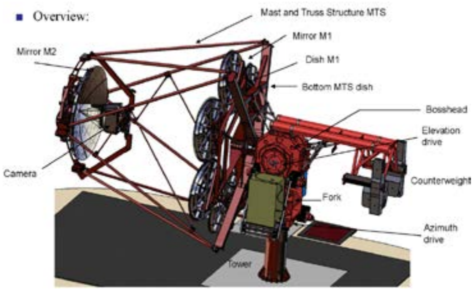
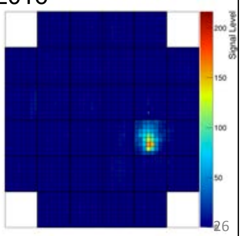
Small Telescope 2-mirror (SST-2M)

cta cherenkov telescope array

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

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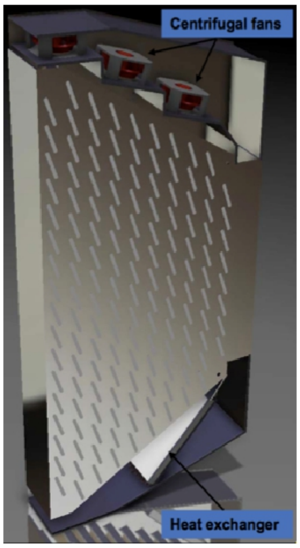
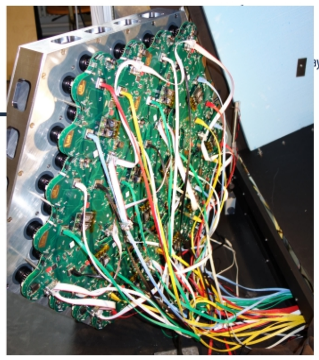
CAMERAS

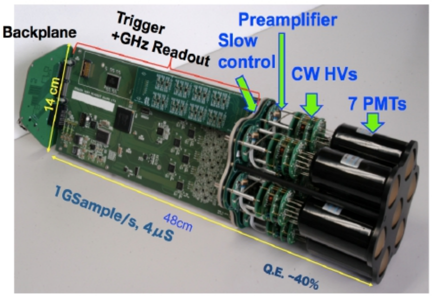


NectarCam
cooling studies

FlashCam
144 pixel
focal plane



LST camera
cluster

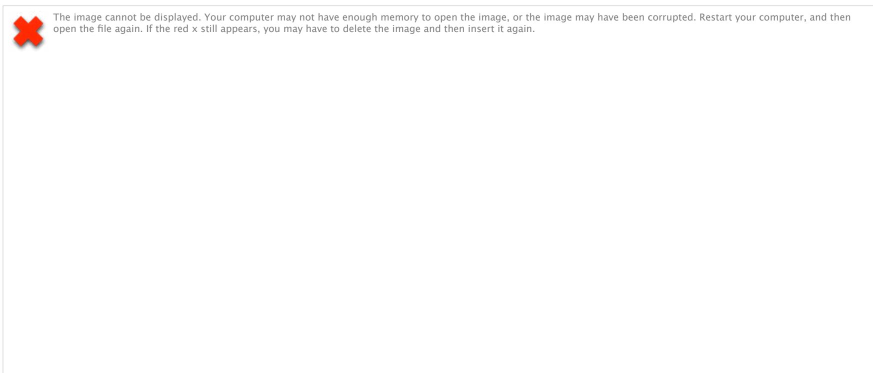


SiPM: the technological challenge for small cameras

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

Difficult to do with standard PMT

New detectors (SiPM) under development



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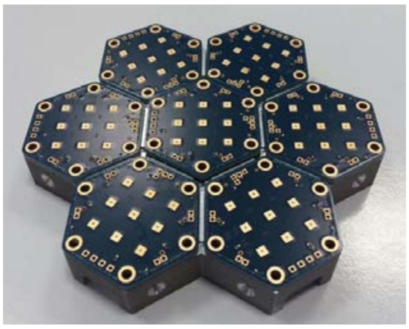
LST in the future: large surface SiPM?

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

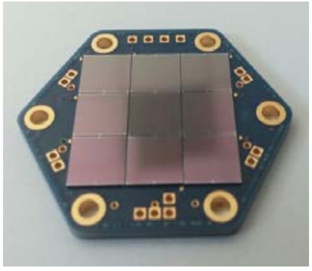
Prototype cluster using Hamamatsu and developed by MPI mounted on MAGIC Jun 15



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)



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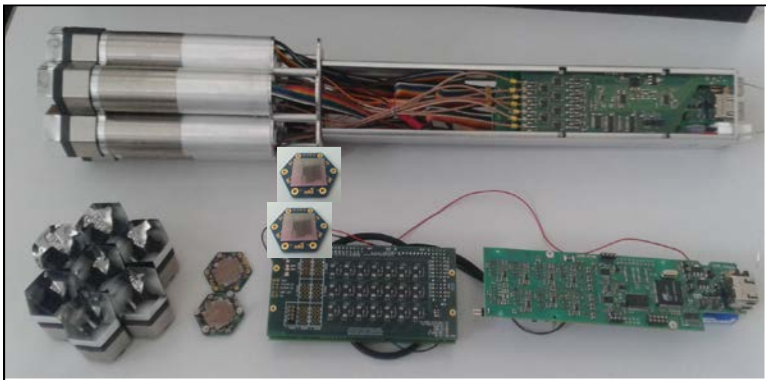

In picture:
Top: standard MAGIC PMT cluster
Bottom: components for SiPM cluster, mechanical structure removed

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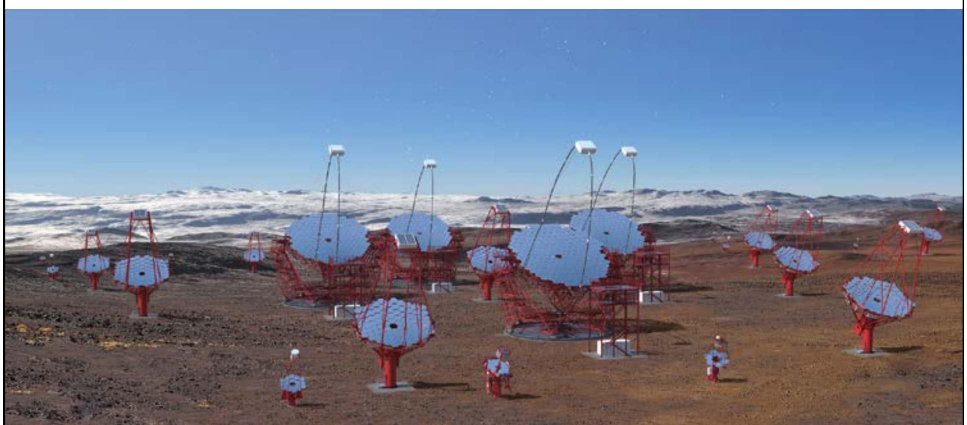
Several prototipes…

CTA-S in Paranal: rendering (works starting in 2019?)



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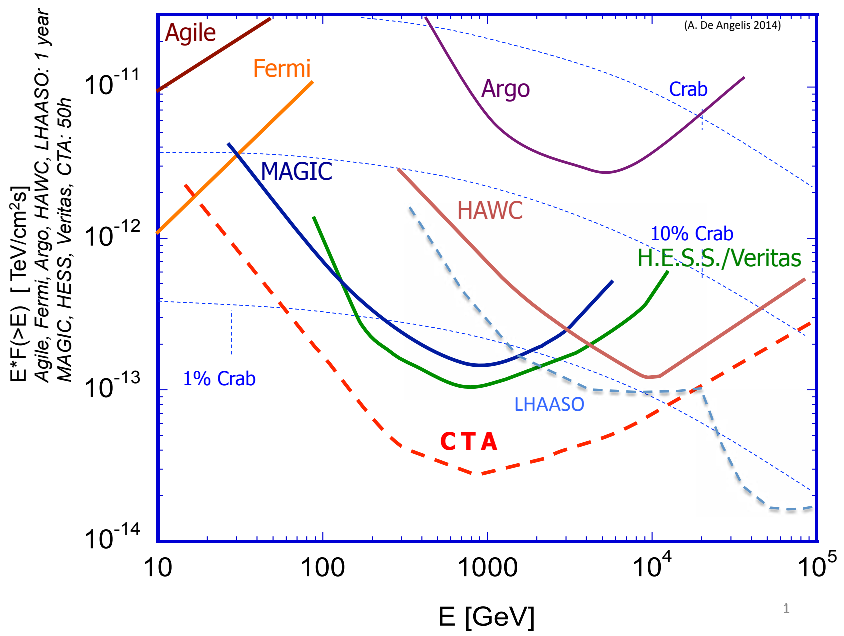
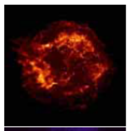
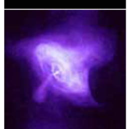
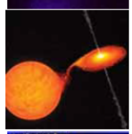
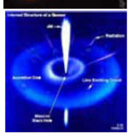


Guaranteed Science with CTA

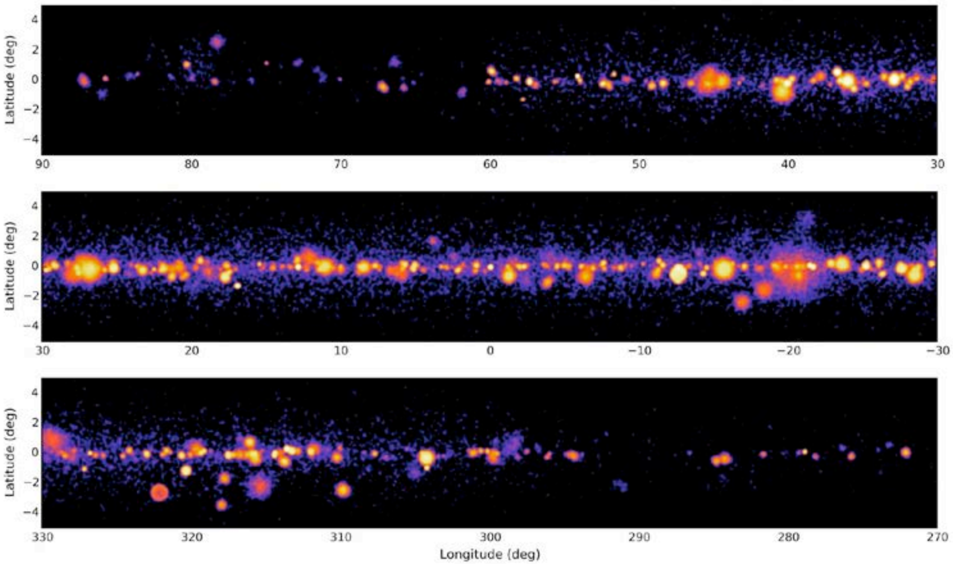
An advanced Facility for ground-based gamma-ray Astronomy

~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

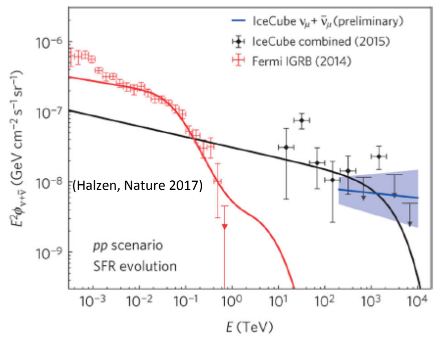





Sources of Galactic Cosmic Rays

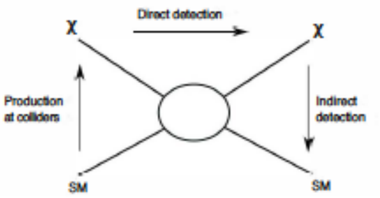


Gravity near compact objects (in particular through multimessenger astronomy)

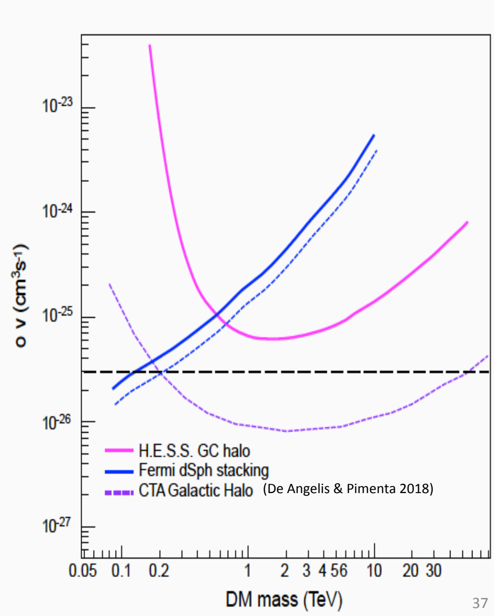
- Astrophysics has recently became multimessenger thanks to the simultaneous observations of GW/gamma rays and of neutrino/gamma ray events
- While the counterparts of GW events seem out of reach for IACTs (~MeV), IACTs are perfect for the counterparts of neutrino events



Dark Matter and New Particles



- Indirect detection of DM: CTA will reach the "thermal cross section" in 3 years
- Photon propagation: explore new regions in the axion m/coupling plane



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The unexpected

- A number 10x of sources detected
- Access to unexpected science (fast transients, new compact objects, etc.)
- Tests of fundamental symmetries of Nature in an unexplored regime

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OTHER POSSIBLE DESIGNS FOR VHE GAMMA ASTROPHYSICS

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

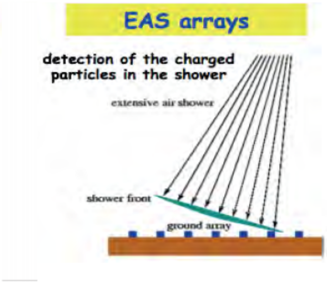
1. MeV: 30 keV to 30 MeV
2. GeV: 30 MeV to 30 GeV
3. TeV: 30 GeV to 30 TeV
4. PeV : 300- GeV - 30+ TeV


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



Very low energy threshold (≈50 GeV)
Excellent bkg rejection (>99%)
Excellent angular resolution (≈0.05 deg)
Good energy resolution (≈15%)
High Sensitivity (< % Crab flux)
Low duty-cycle (≈10%)
Small field of view (4-5 deg)

Higher energy threshold (≈300 GeV)
Good bkg rejection (>80%)
Good angular resolution (0.2-0.8 deg)
Modest energy resolution (≈50%)
Good Sensitivity (5-10% Crab flux)
High duty-cycle (≈100%)
Large field of view (≈2 sr)

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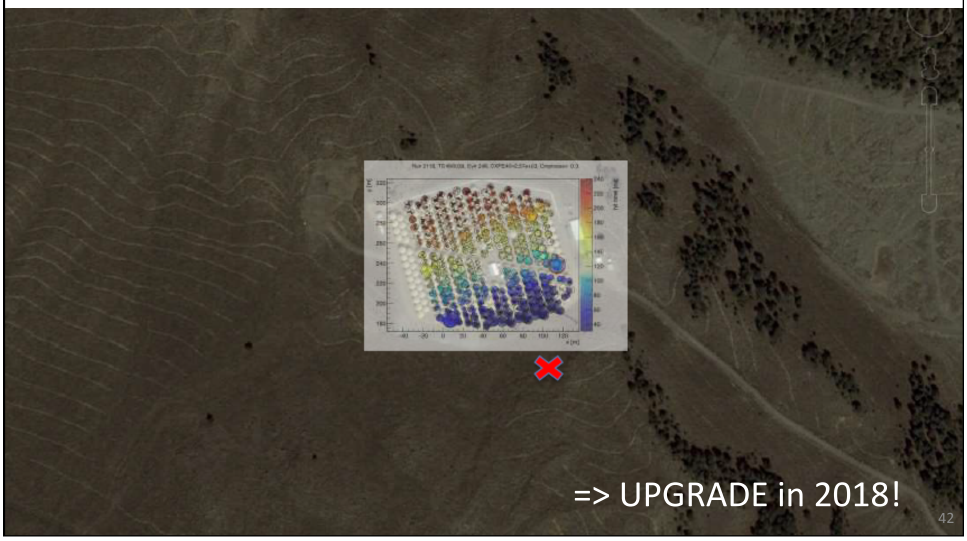
HAWC: most VHE triggered showers energy falls outside of the array



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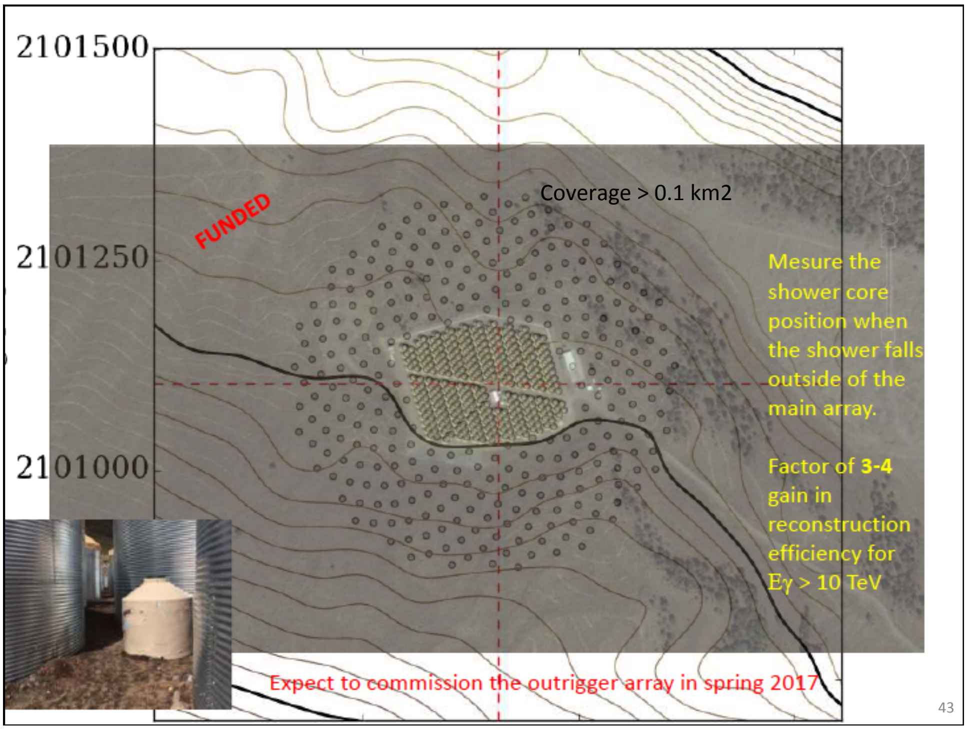
2101500
2101250
2101000
FUNDED
Coverage > 0.1 km2
Mesure the shower core position when the shower falls outside of the main array.
Factor of 3-4 gain in reconstruction efficiency for Eγ > 10 TeV
Expect to commission the outrigger array in spring 2017
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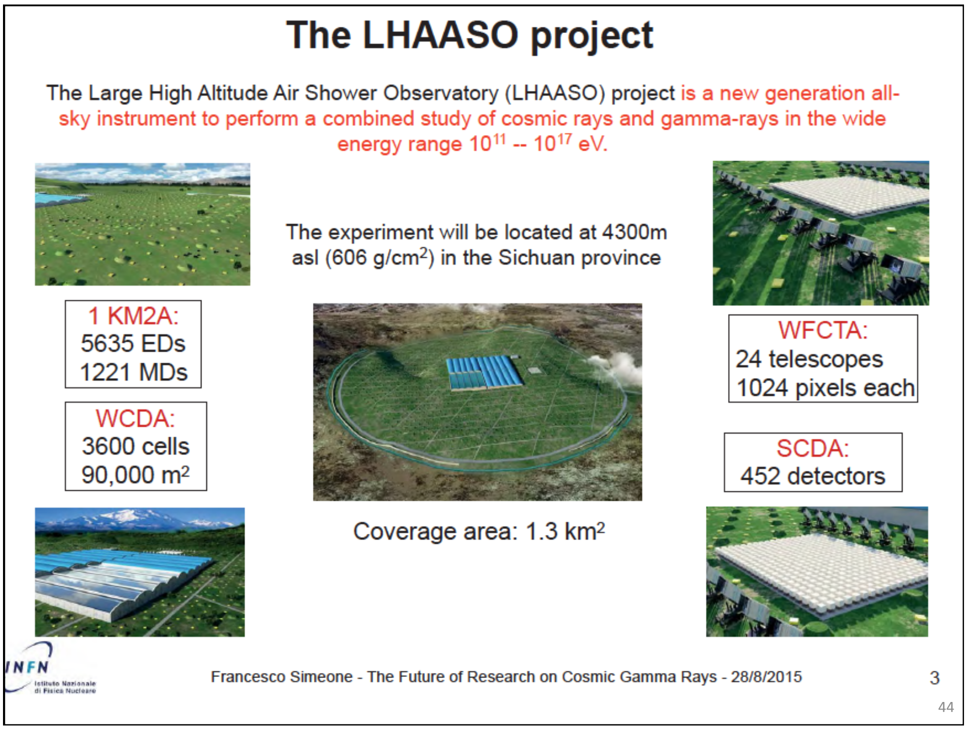
The LHAASO project
The Large High Altitude Air Shower Observatory (LHAASO) project is a new generation all-sky instrument to perform a combined study of cosmic rays and gamma-rays in the wide energy range 10^11 -- 10^17 eV.
The experiment will be located at 4300m asl (606 g/cm^2) in the Sichuan province
1 KM2A: 5635 EDs 1221 MDs
WCDA: 3600 cells 90,000 m^2
WFCTA: 24 telescopes 1024 pixels each
SCDA: 452 detectors
Coverage area: 1.3 km^2
Istituto Nazionale di Fisica Nucleare
Francesco Simeone - The Future of Research on Cosmic Gamma Rays - 28/8/2015
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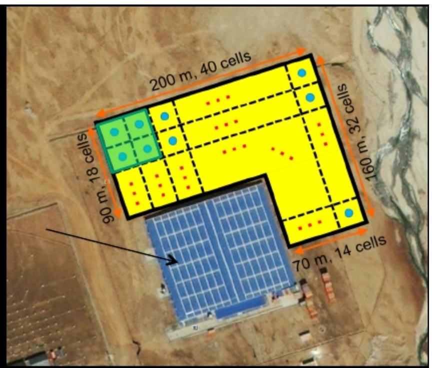
LHAASO

- 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:

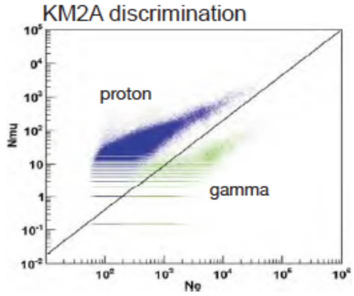
30 TeV ~0.4°

100TeV ~0.3 °

Energy relsolution:

30 TeV ~30%

100 TeV ~20%



2019: start scientific operation of the first quarter of LHAASO.
2022: conclusion of the installation of all main components.

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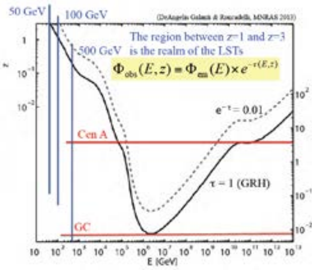
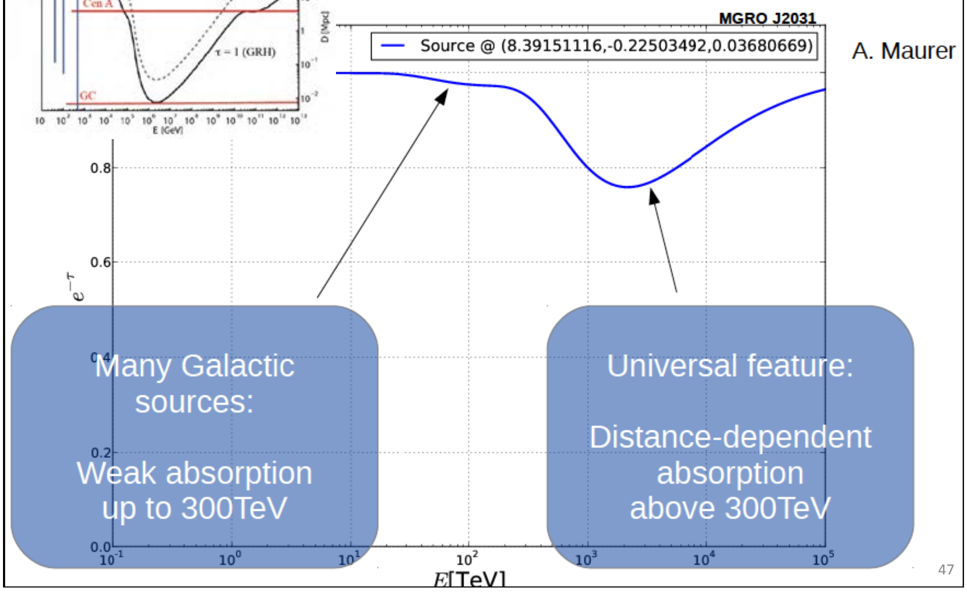
For Galactic objects, energies > 300 TeV are not impossible to detect





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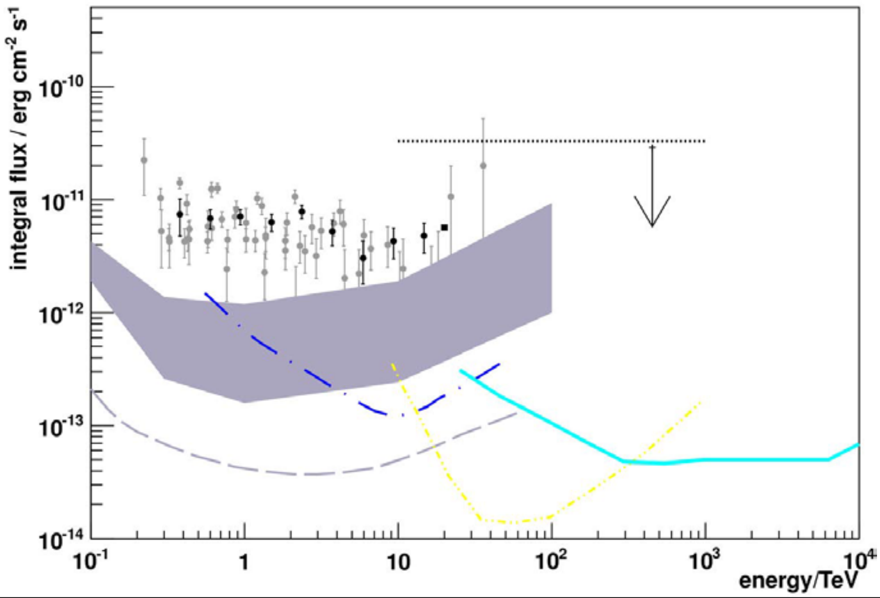
Flux limitations => large area is the key: HiSCORE



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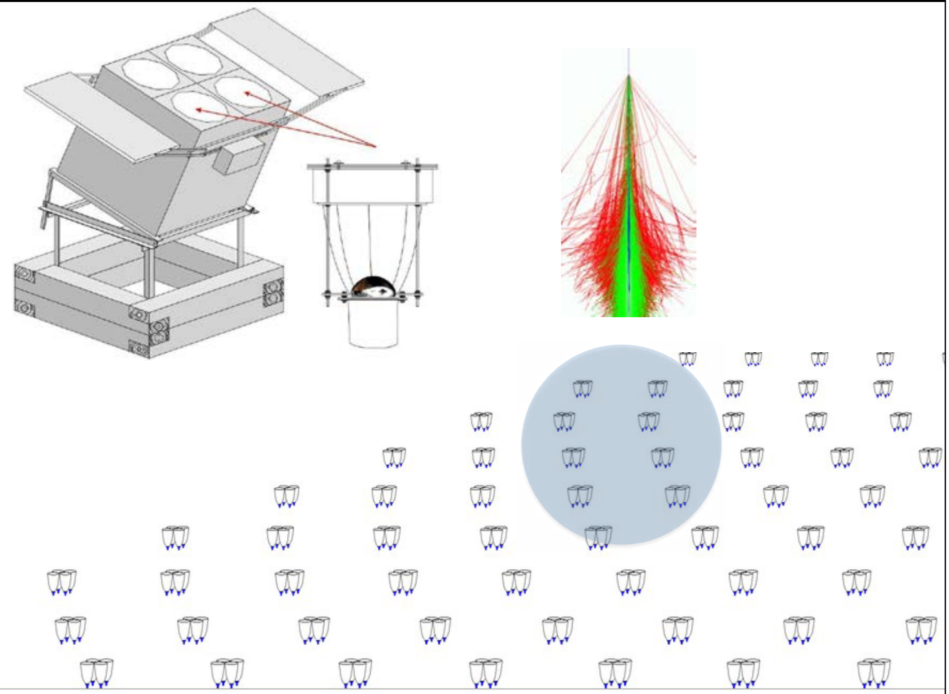

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Tunka-HiSCORE → TAIGA

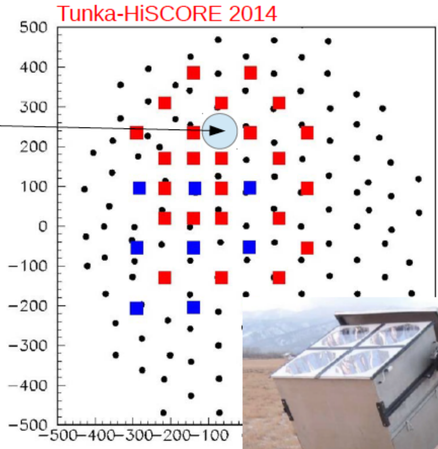
Tunka Advanced Instrument for Gamma ray and cosmic ray physics

10/2014: extension

- Total: 29 stations
- Tilting mode
- 0.25 km²

2015+:

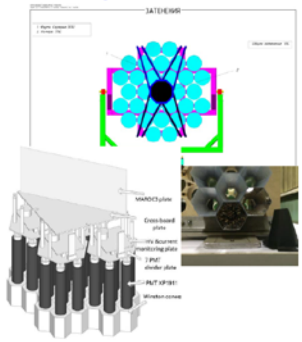
- First telescope
- Hybrid timing+imaging
- In total 10 telescopes planned
- Muon detectors



September 3, 2014 martin.tluczykont@physik.uni-hamburg.de

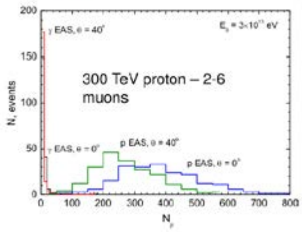
TAIGA Telescopes

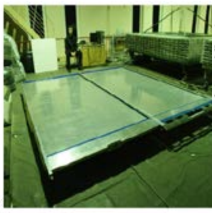
- Dish: Davies-cotton tesselated, 34 mirrors (60cm)
- 4.3 m dish diameter
- 4.75 m focal length
- F/D ~ 1.2
- 397 PMT camera foV 8° (0.38° / pixel)
- Proven design components

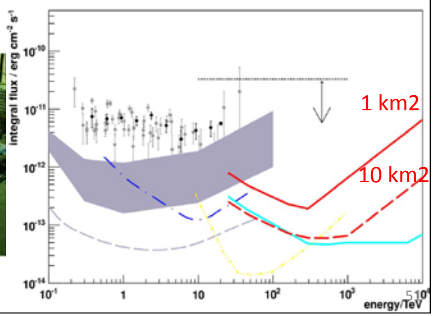


September 3, 2014 martin.tluczy

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

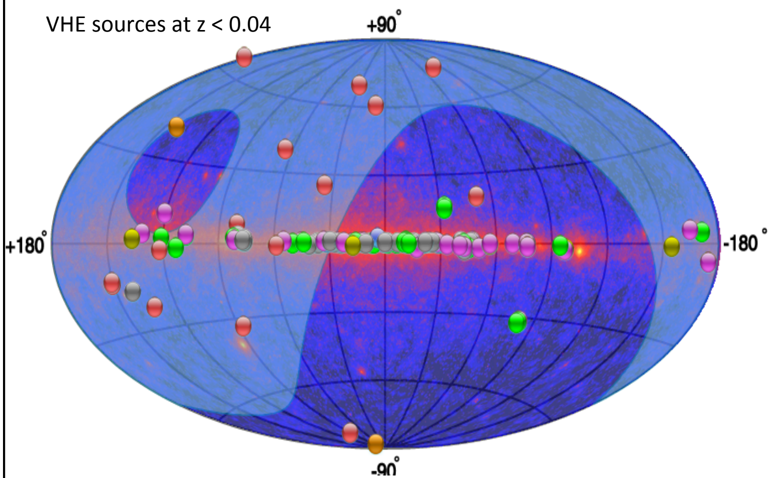






HAWC+, LHAASO, HiSCORE ~ funded, but there is a strong case for a sub-PeV experiment in the Southern hemisphere

VHE sources at z < 0.04



Source Types

- PWN
- Binary XRB PSR Gamma BIN
- HBL IBL FRI FSRQ Blazar LBL AGN (unknown type)
- Shell SNR/Molec. Cloud Composite SNR Superbubble
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR

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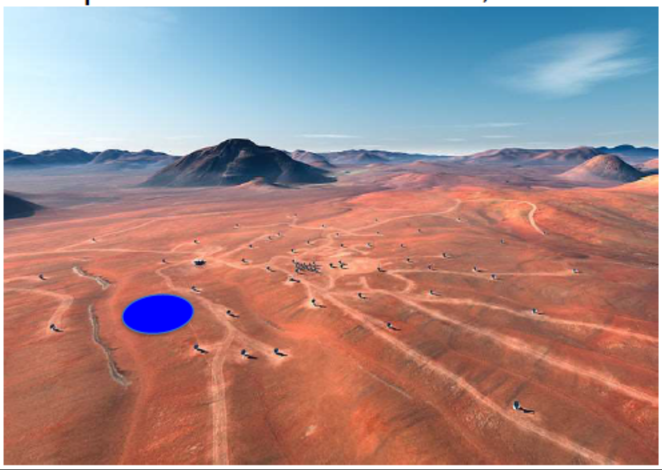
HAWC South

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



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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 desert, latitude 23.7 S, altitude 5060 m asl)

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The qualities of LATTES

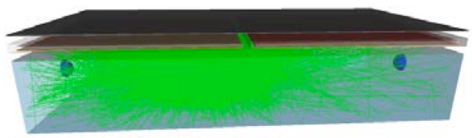
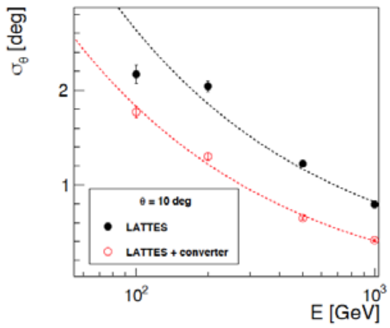
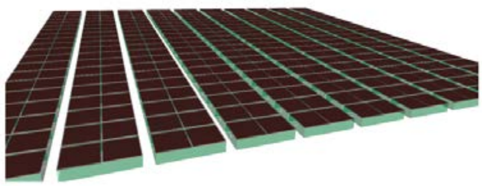


Figure 2: Basic detector station, with one WCD covered with RPCs and a thin slab of lead. The green lines show the tracks of the Cherenkov photons produced by the electron and positron from the conversion of a photon in the lead (for better visualisation the Tyvek's reflectivity was scaled by 1/10).



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



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LOWER ENERGIES (GeV and MeV)

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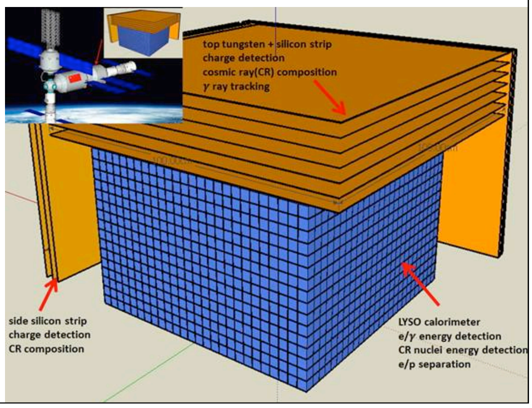
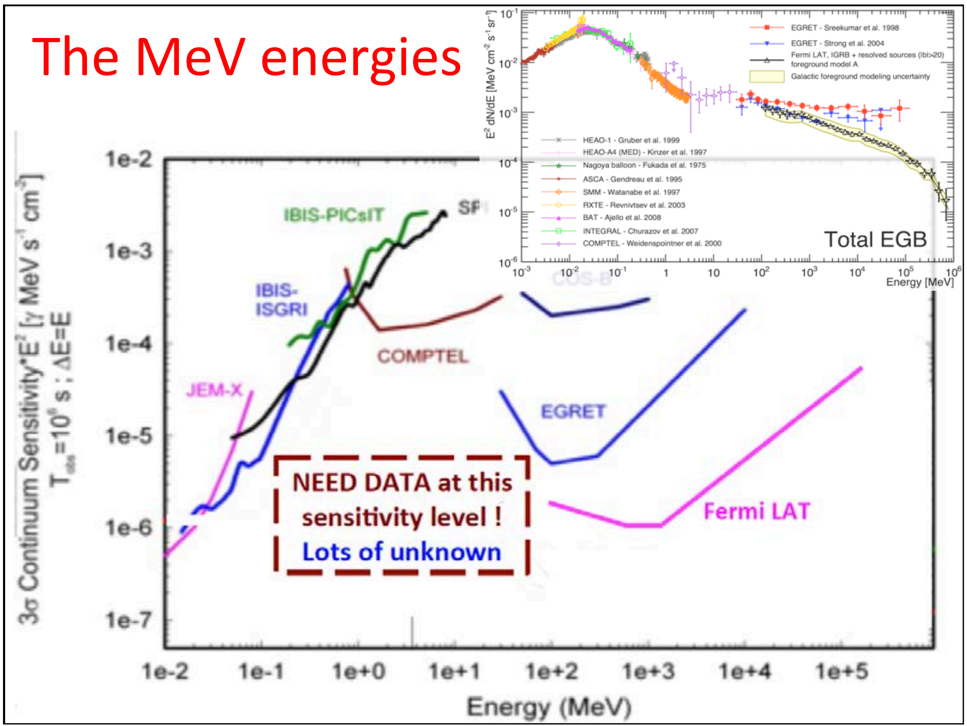
GeV region from space

- 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
  - Operational 2024?
- Also useful for observing charged cosmic rays up to ~ the knee

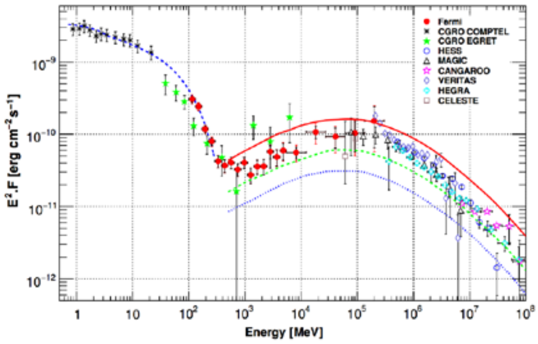


The MeV energies



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

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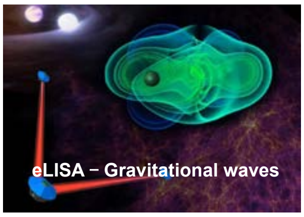
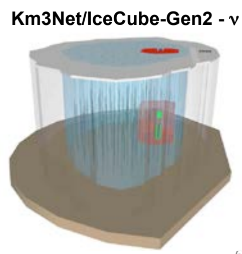
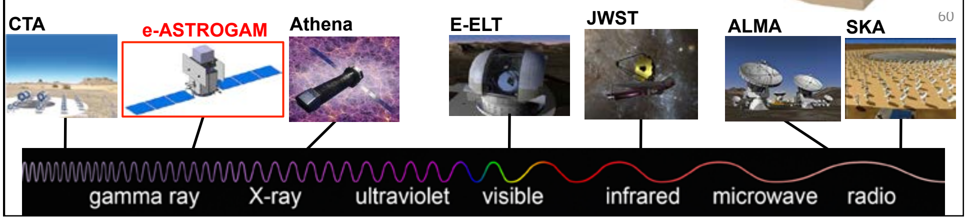
e-ASTROGAM (Europe, De Angelis et al.) and AMEGO (US, McEnery et al.) – 2028/29





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



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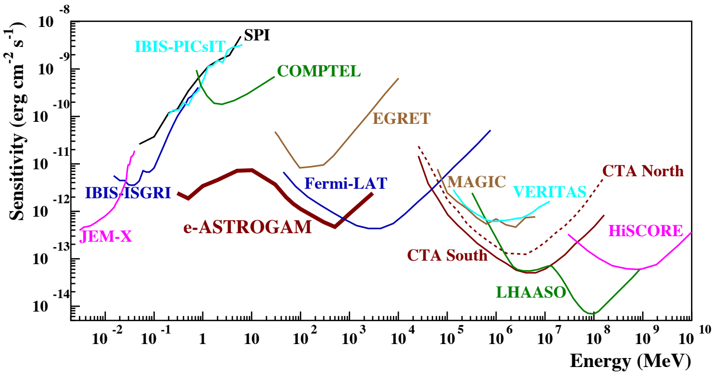
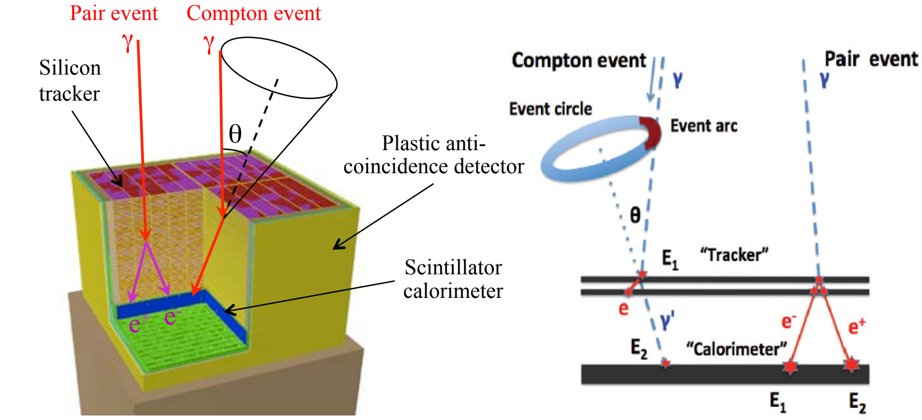
e-ASTROGAM scientific requirements

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



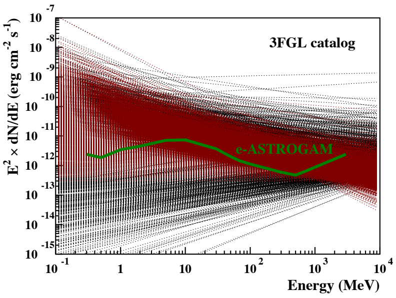
How to measure gamma rays in the MeV-GeV?



- **Tracker** – Double sided Si strip detectors (DSSDs) for excellent spectral resolution and fine 3-D position resolution ($1 m^2$, 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

NEUTRINOS

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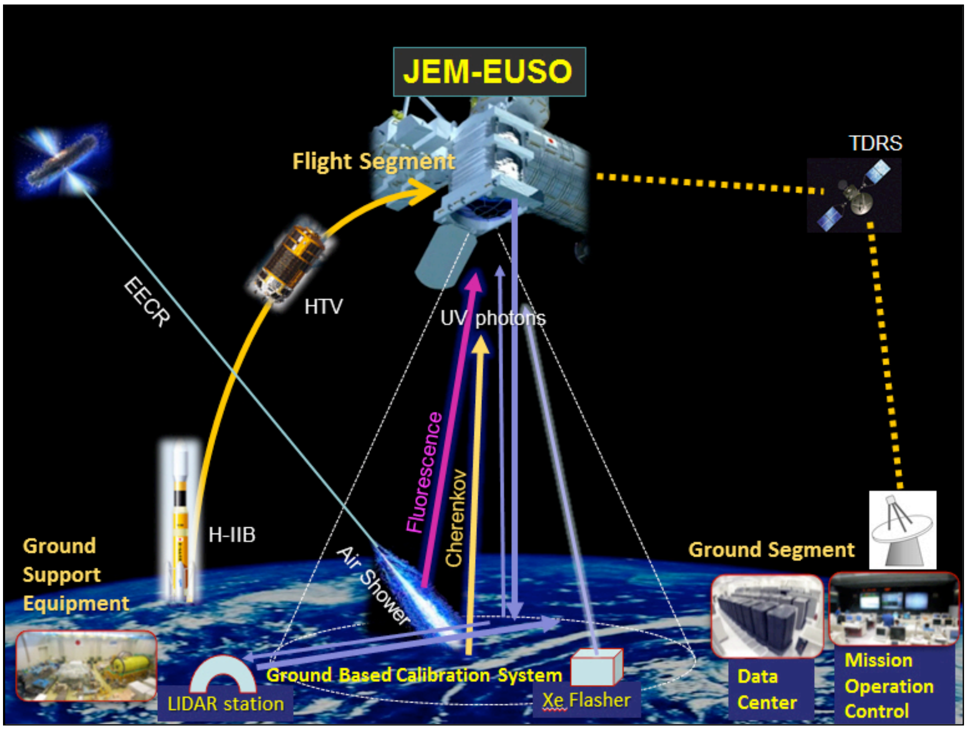
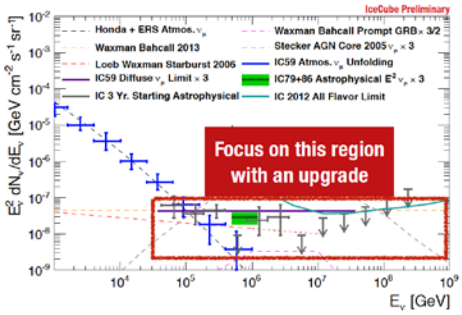
Astrophysical neutrinos: the future

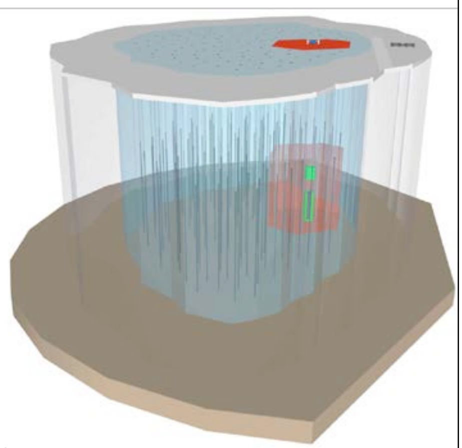
- Three lines of development:
  1. Large volume
  2. High precision
  3. New technologies
- At extremely high energies, above 100 PeV, a cosmogenic neutrino flux is expected from the interaction of highest energy cosmic-ray protons with the CMB. Predicted are in a range of approximately 1 event/year/km3 or lower. The idea to increase the effective volume of detectors to be sensitive to such rates seems feasible only:
  - Adopting the EUSO concept
  - Detecting coherent radio emission up to GHz originated by the ν interaction in dense, radio-transparent media (Askar'yan effect).

    Several prototype detectors are being developed.
- ν Astronomy has just started and a rich physics program is ahead of us. A global neutrino network (IceCube-Gen2 in the South Pole, Gigaton Volume Detector (GVD) in the lake Baikal and KM3NeT in the Mediterranean sea) will operate.



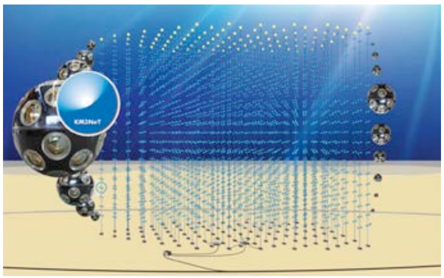
IceCube-Gen2, a 10-cubic-kilometer detector

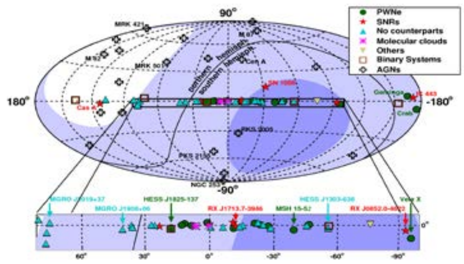




- Spacing between light sensors ~ 250 meters, instead of the current 125 meters in IceCube. The IceCube-Gen2 instrumented volume might rapidly grow at modest costs.
- By ~ doubling the instrumentation already deployed, the telescope will achieve a tenfold increase in volume to about 10 cubic kilometers,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

GRAVITATIONAL WAVES

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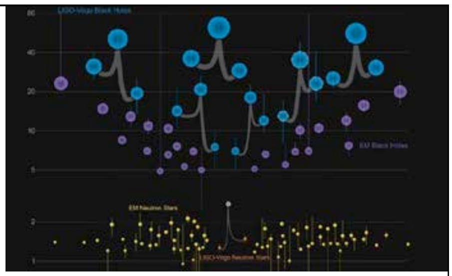
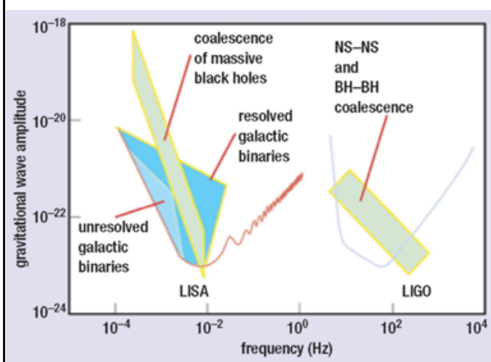
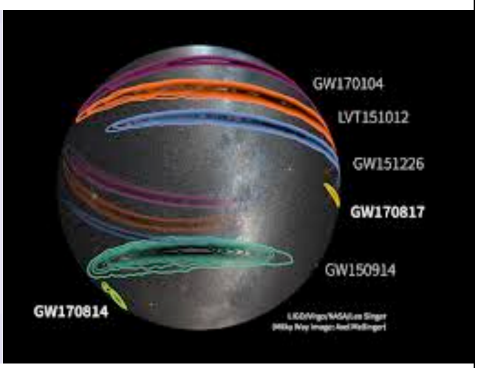
Lessons learned: how to improve from the few events detected



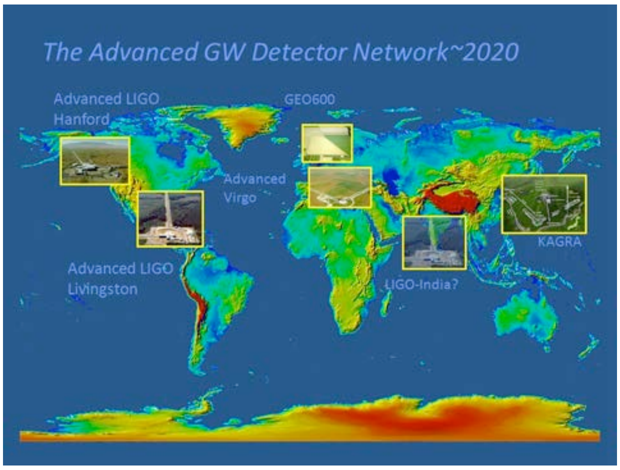
- Increase sensitivity
- Improve localization
- Open new frequency/strain ranges (observe new phenomena)





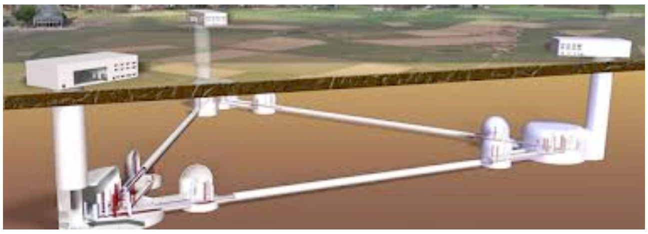
The future - 0

- The LIGO/VIRGO system will double its efficiency by ~2020-2024, incorporating KAGRA, INDICO, GEO600



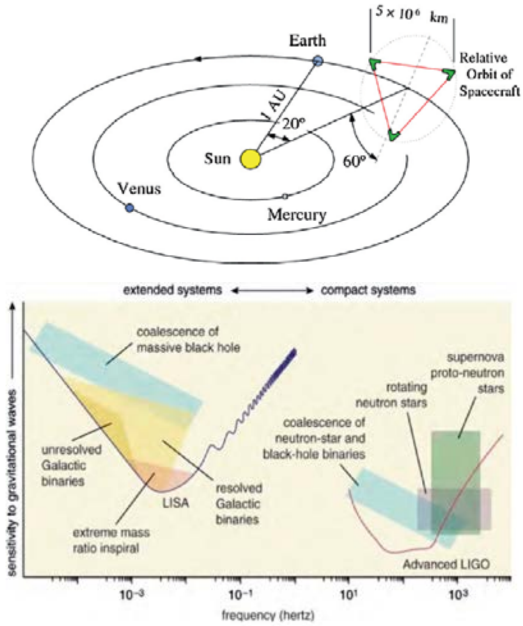
The future – I
Einstein Telescope and Cosmic Explorer (>2024)

- 3-arm interferometers allow standalone pointing
- A US equivalent also under evaluation



The future – II: LISA

- In a more distant future a space observatory will be built extending the detection sensitivity to a much lower frequency range (0.1 mHz − 100 mHz).
- The LISA project, comprising three satellite detectors spaced by more than 2.5 million km, has been approved by ESA; launch is scheduled in 2034



UHE COSMIC RAYS

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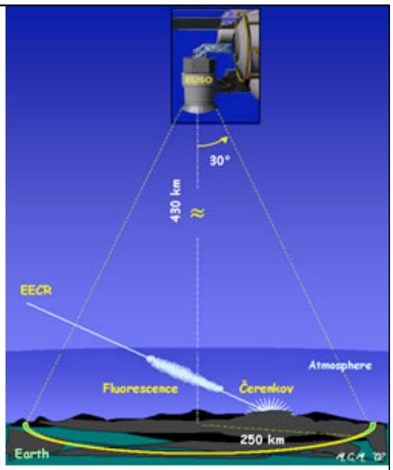
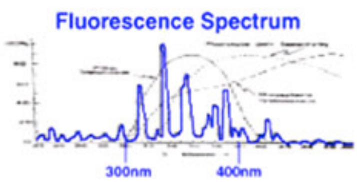
Upgrade of Auger (funded, to be completed in 2019)

- 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
- The EUSO concept
  - Problem: sensitivity starts oly at some EeV
  - No clear schedule





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: priority is
    - A MeV mission (room for smart improvement; 2 missions proposed)
- Neutrino detectors will grow (at high price), and we know what we can get for astronomy
- Auger to be upgraded, but new technologies look far away in time
- Multimessenger astronomy gamma/neutrinos can help our understanding of cosmic accelerators, of physics under extreme environments and of fundamental particle physics

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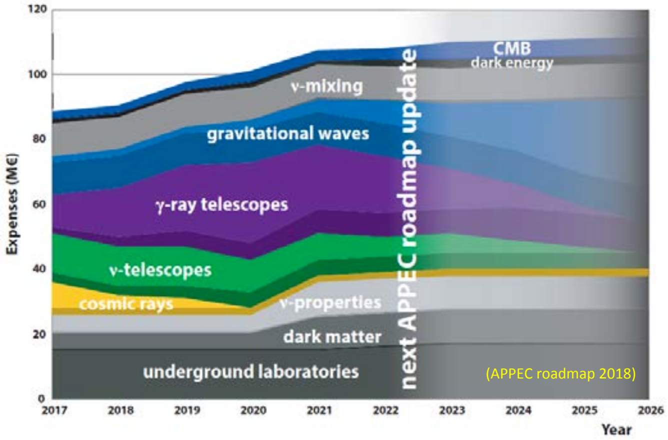
Planned investment in astroparticle physics for the next years

(budget excluding manpower, labs, regional funds, and competitive calls by NASA/ESA)

(M/L space missions approved can be ~50 MEUR/year on top of this)



Alessandro De Angelis

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Mar 7, 15h (Lab Paolotti, 3h)	Laboratory on Fermi-LAT data analysis I	Lab
Mar 8, 9h30 (Lab Paolotti, 3h)	Laboratory on Fermi-LAT data analysis II	Lab
Mar 22, 15h (Room 315)	Presentations by the students	