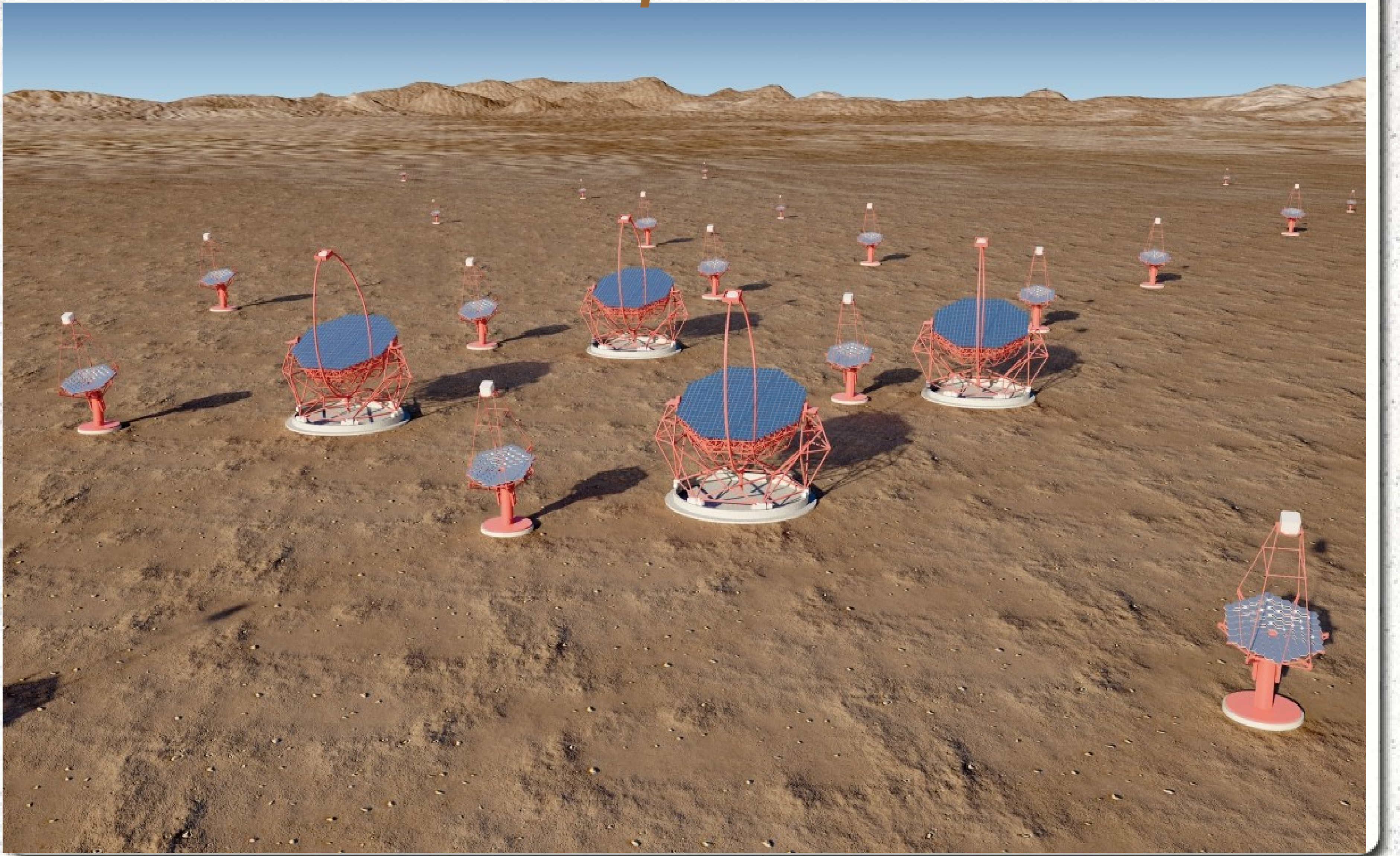
Cherenkov Telescope Array

-A Sensitive Probe of the Extreme Universe-



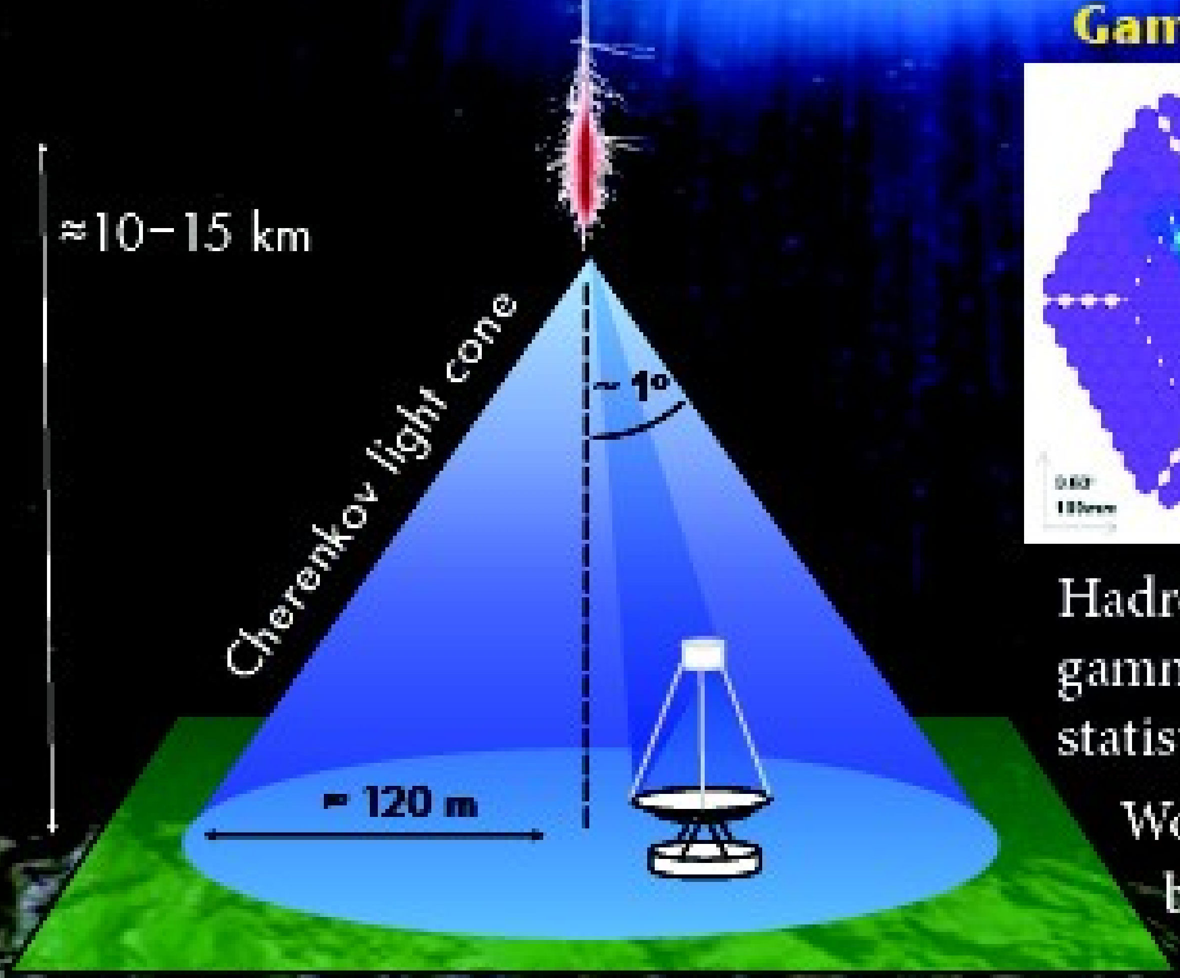
Elina Lindfors, Finnish Center for Astronomy with ESO, on behalf of the CTA consortium

Outline

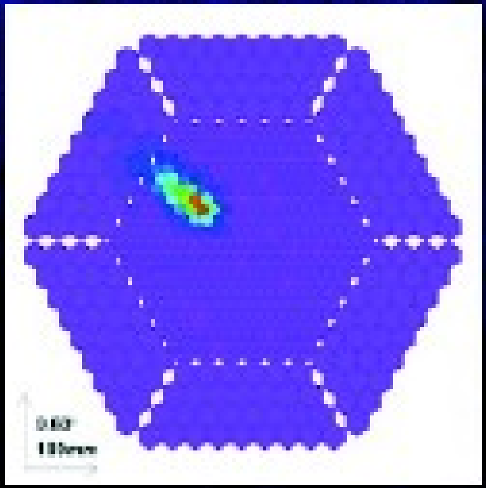
- Introduction
  - Imaging Air Cherenkov Telescopes
  - Very High Energy Gamma-Ray Universe
- Cherenkov Telescope Array
- Science with Cherenkov Telescope Array

The Imaging Air Cherenkov Technique

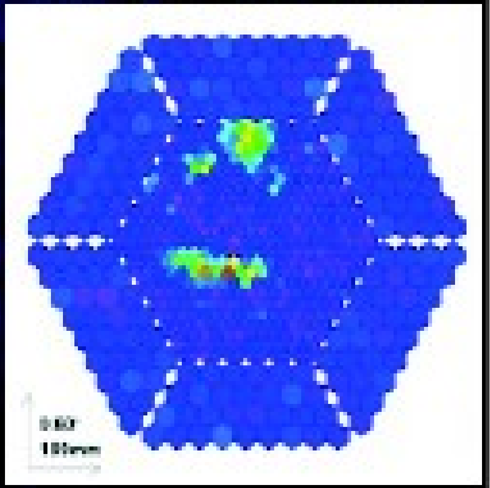
- Extended Air Shower initiated in atmosphere
- Detect the Cherenkov radiation from charged particles in EAS
- A mirror reflects and concentrates the light
- An image of the shower formed in a photomultiplier camera



Gamma event



Hadron event



Hadrons (background) dominate over gammas (signal). They must be rejected statistically in the analysis

Works excellent > 100 GeV
but challenging < 100 GeV

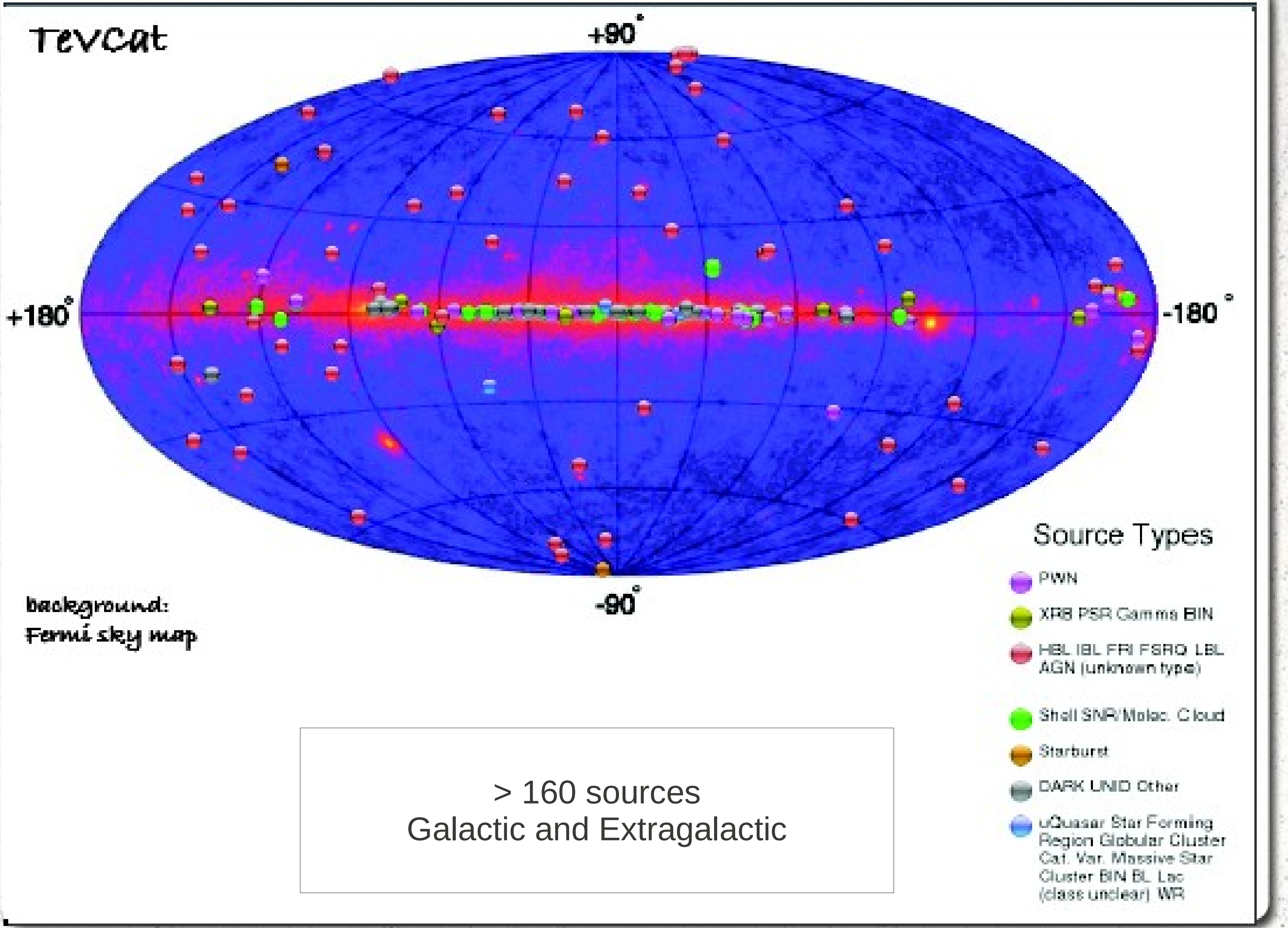
MAIN IACT OBSERVATORIES IN THE WORLD

MAGIC

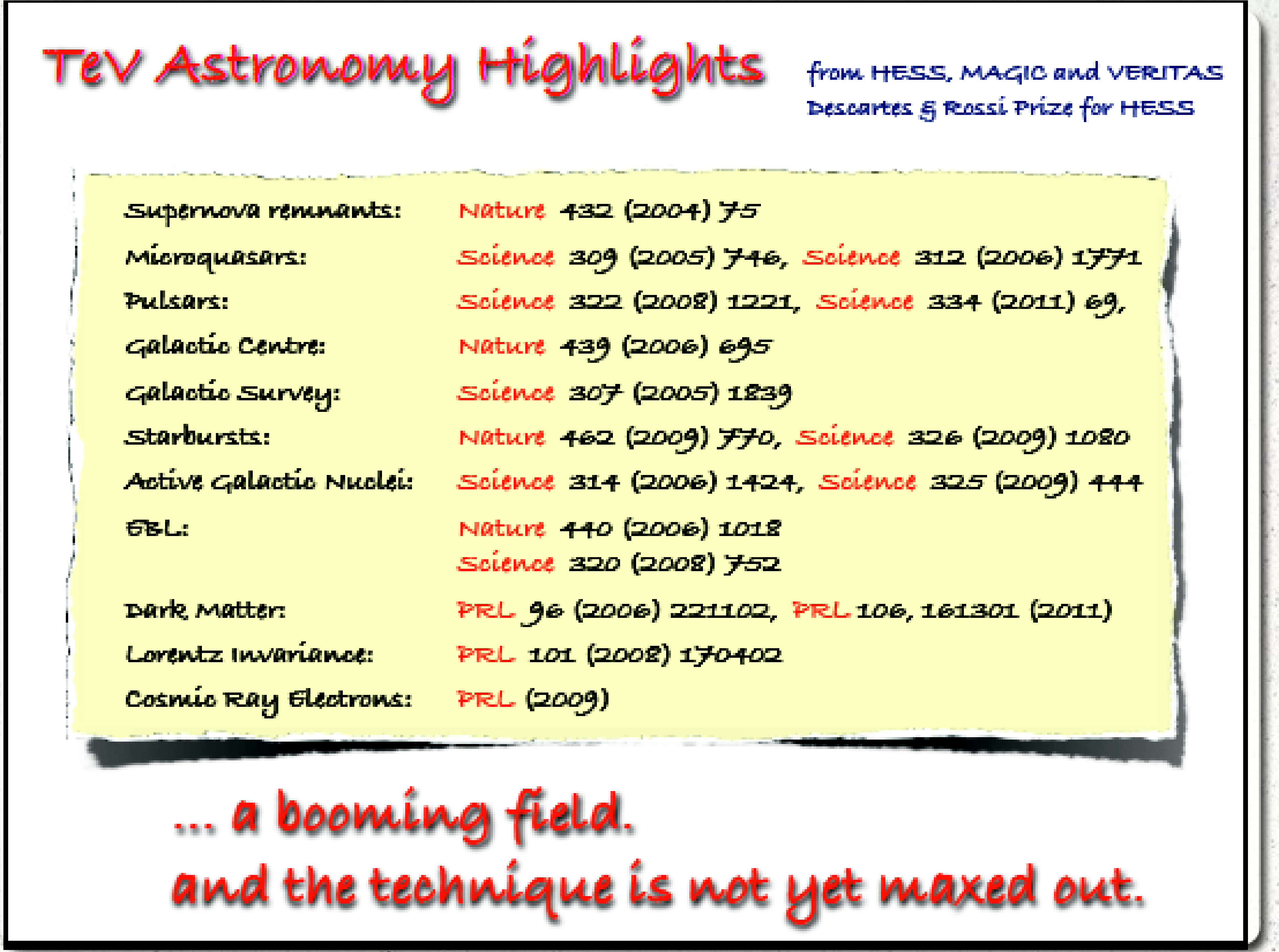
VERITAS

H.E.S.S.

Slide: E.Prandini



> 160 sources
Galactic and Extragalactic



TeV Astronomy Highlights

from HESS, MAGIC and VERITAS
Descartes & Rossi Prize for HESS

Supernova remnants:	Nature 432 (2004) 75
Microquasars:	Science 309 (2005) 746, Science 312 (2006) 1771
Pulsars:	Science 322 (2008) 1221, Science 334 (2011) 69,
Galactic Centre:	Nature 439 (2006) 695
Galactic Survey:	Science 307 (2005) 1839
Starbursts:	Nature 462 (2009) 770, Science 326 (2009) 1080
Active Galactic Nuclei:	Science 314 (2006) 1424, Science 325 (2009) 444
EBL:	Nature 440 (2006) 1018 Science 320 (2008) 752
Dark Matter:	PRL 96 (2006) 221102, PRL 106, 161301 (2011)
Lorentz Invariance:	PRL 101 (2008) 170402
Cosmic Ray Electrons:	PRL (2009)

... a booming field.
and the technique is not yet maxed out.

Slide: J. Knapp

CTA

10x more sensitive than current instruments

+ much wider energy coverage and field of view

substantially better angular and energy resolution

50-100 telescopes of three sizes

Design: 2008-12, Prototyping: 2011-14, Construction: 2015-19

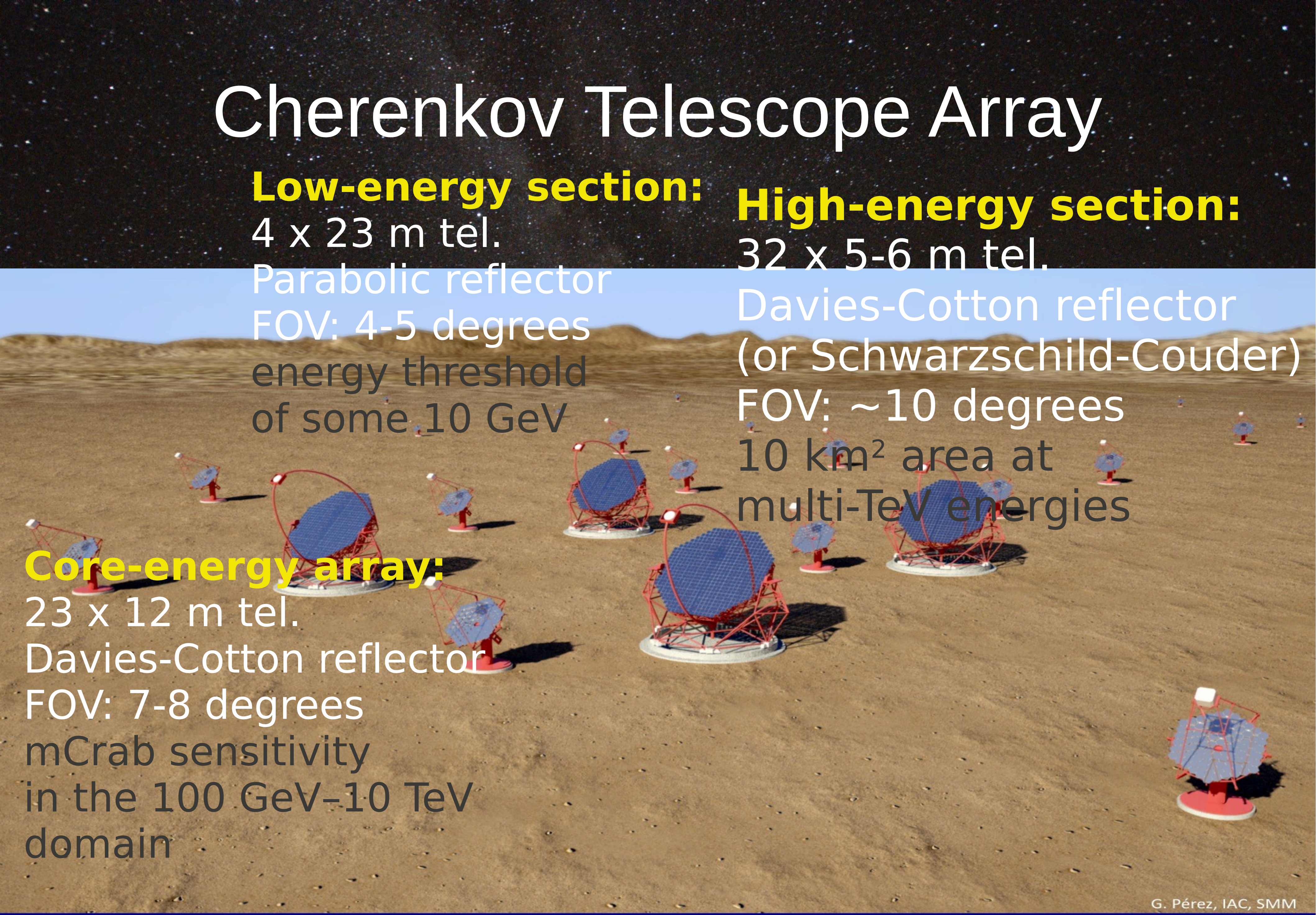
cta
cherenkov telescope array

... an advanced facility for
ground-based gamma-ray astronomy

CTA is the global next generation project.

A precise and sensitive probe of the extreme universe,
with huge potential for extreme astronomy and
fundamental physics with TeV photons

Cherenkov Telescope Array



G. Pérez, IAC, SMM

Low-energy section:

4 x 23 m tel.

Parabolic reflector

FOV: 4-5 degrees

energy threshold of some 10 GeV

High-energy section:

32 x 5-6 m tel.

Davies-Cotton reflector (or Schwarzschild-Couder)

FOV: ~10 degrees

10 km^2 area at multi-TeV energies

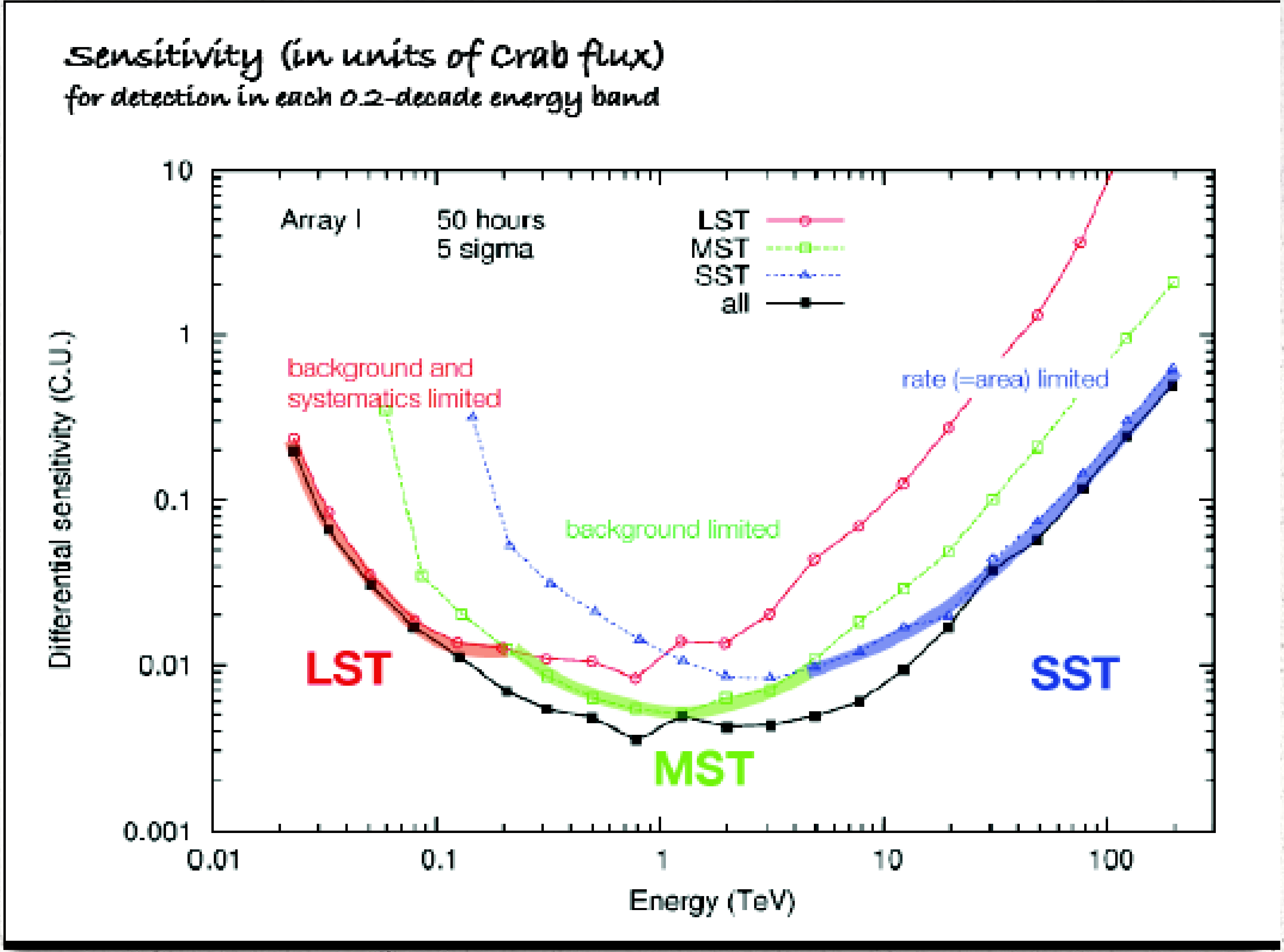
Core-energy array:

23 x 12 m tel.

Davies-Cotton reflector

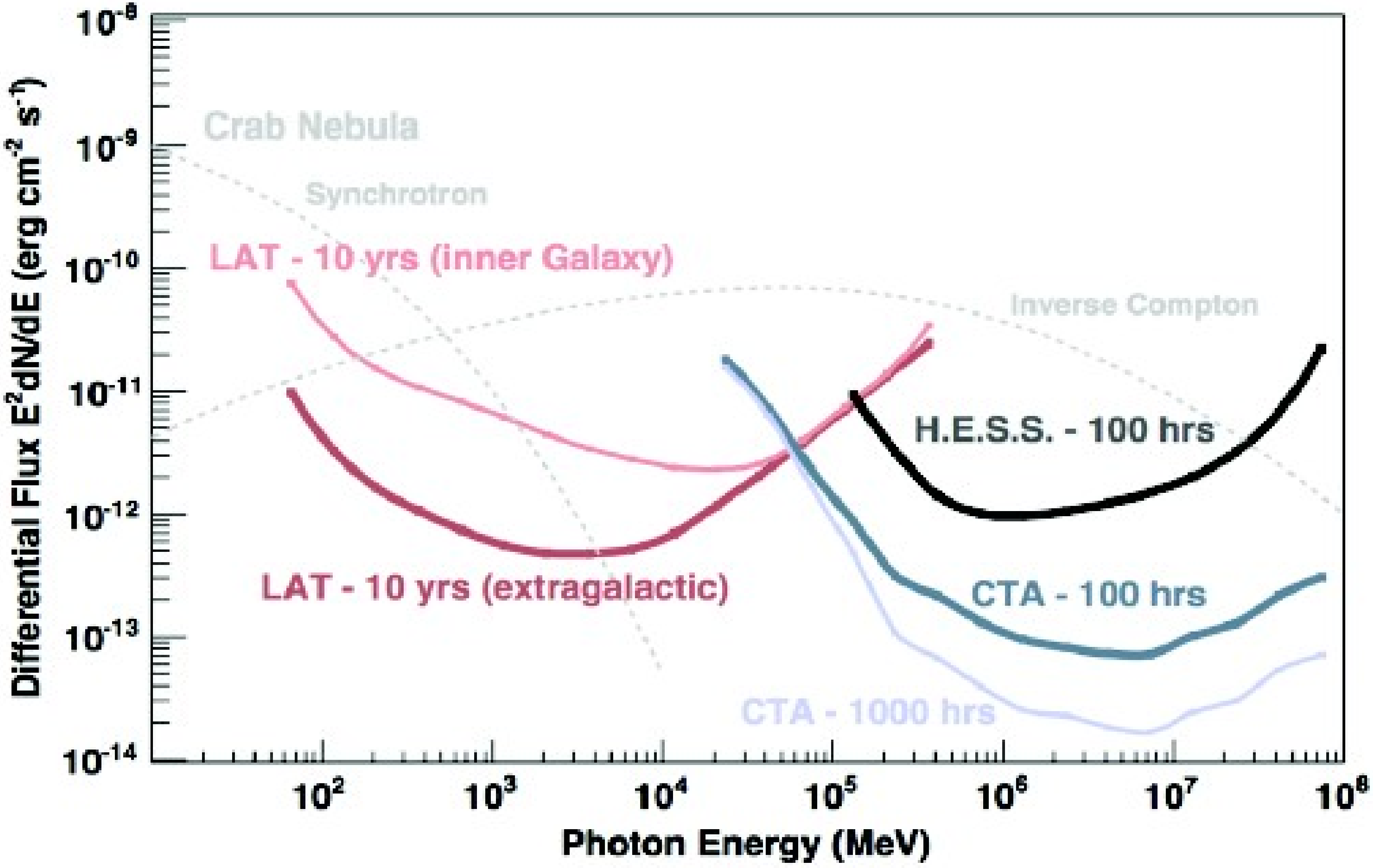
FOV: 7-8 degrees

mCrab sensitivity in the 100 GeV–10 TeV domain



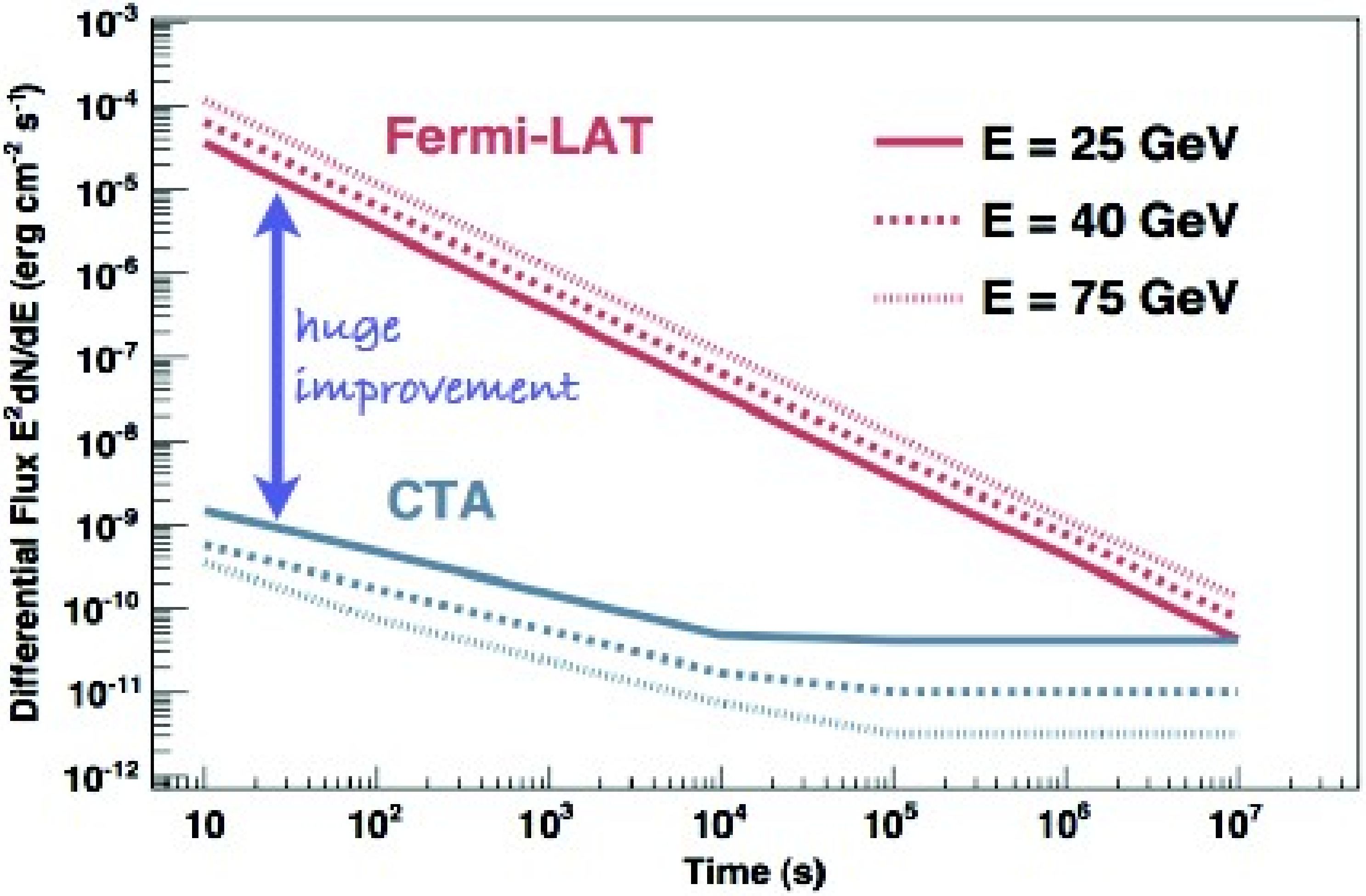
Bernlöhr et al. 2013, Astroparticle Physics, Special Issue

CTA versus Fermi – steady sources

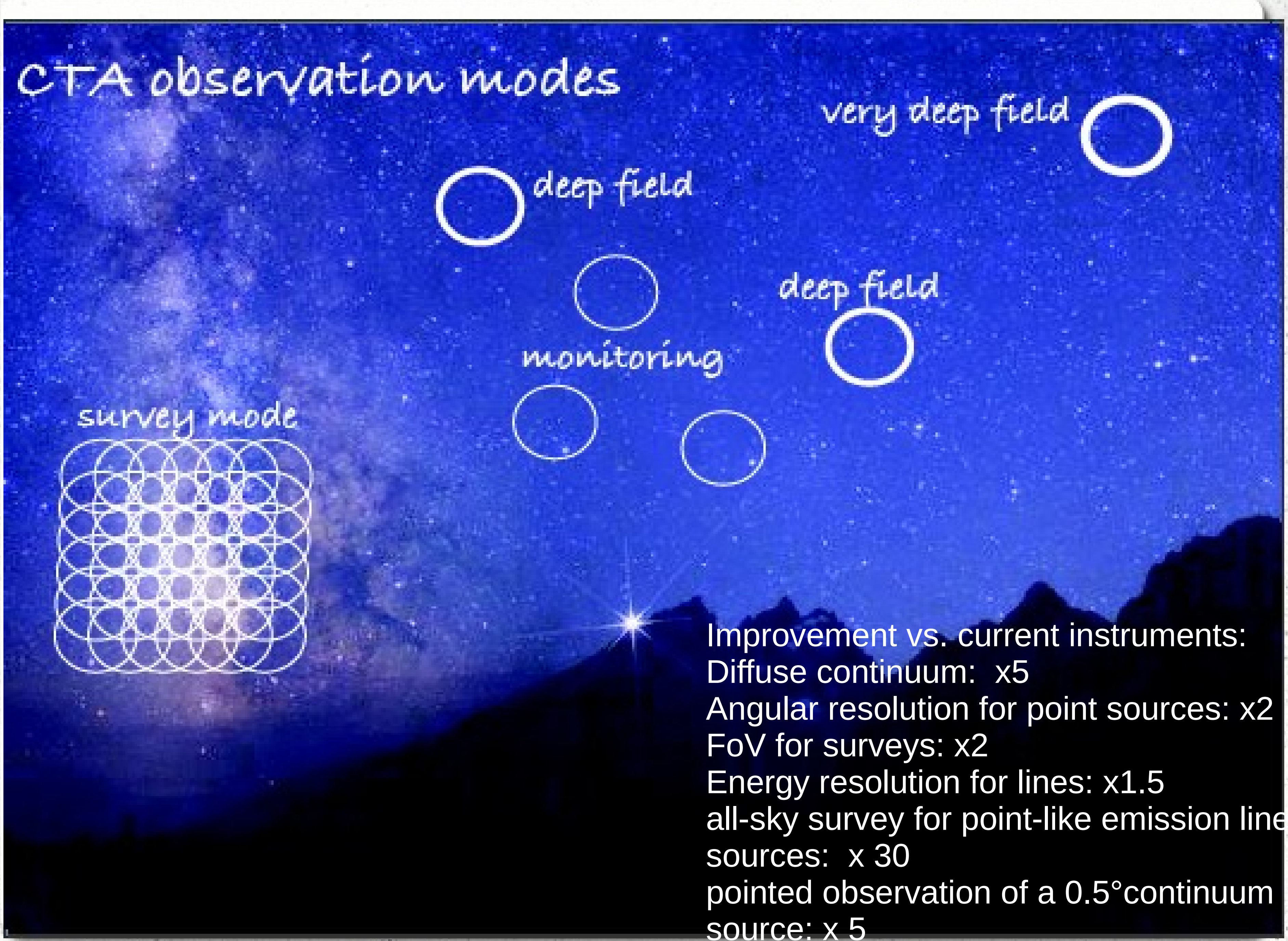


Variability and Short-Timescale Phenomena

(flares, GRBs, ...)



Funk, Hinton 2012



Improvement vs. current instruments:
Diffuse continuum: x5
Angular resolution for point sources: x2
FoV for surveys: x2
Energy resolution for lines: x1.5
all-sky survey for point-like emission line sources: x 30
pointed observation of a 0.5°continuum source: x 5

Scientific Objectives:

Cosmic energetic particles

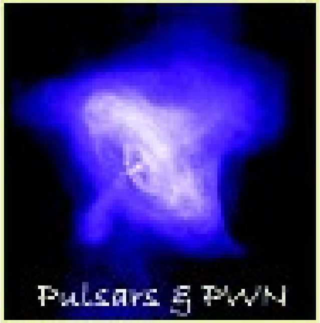
- Origin of the galactic cosmic rays
  - Also UHECR signatures
- Role of ultra-relativistic particles in in clusters of galaxies, AGN, Starbursts...
- The physics of (relativistic) jets and shocks

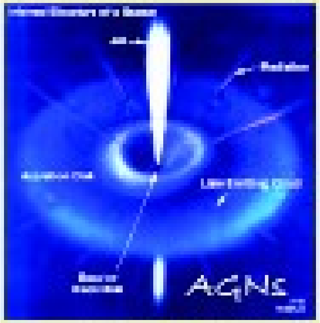
Fundamental Physics

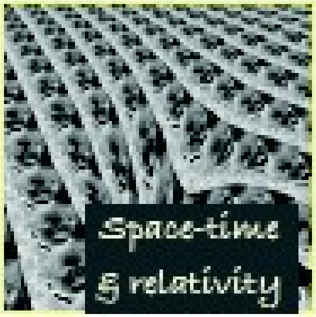
- Dark Matter annihilation / decay
- Lorentz Invariance Violation

Cosmology

- cosmic FIR-UV radiation,
- cosmic magnetism

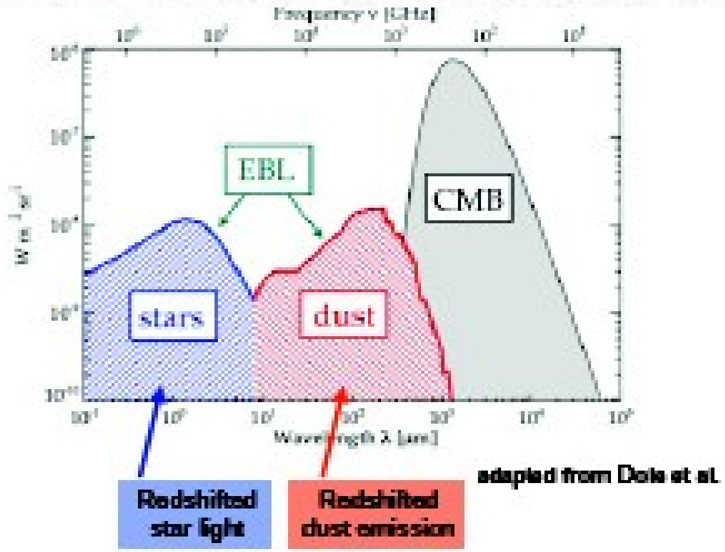




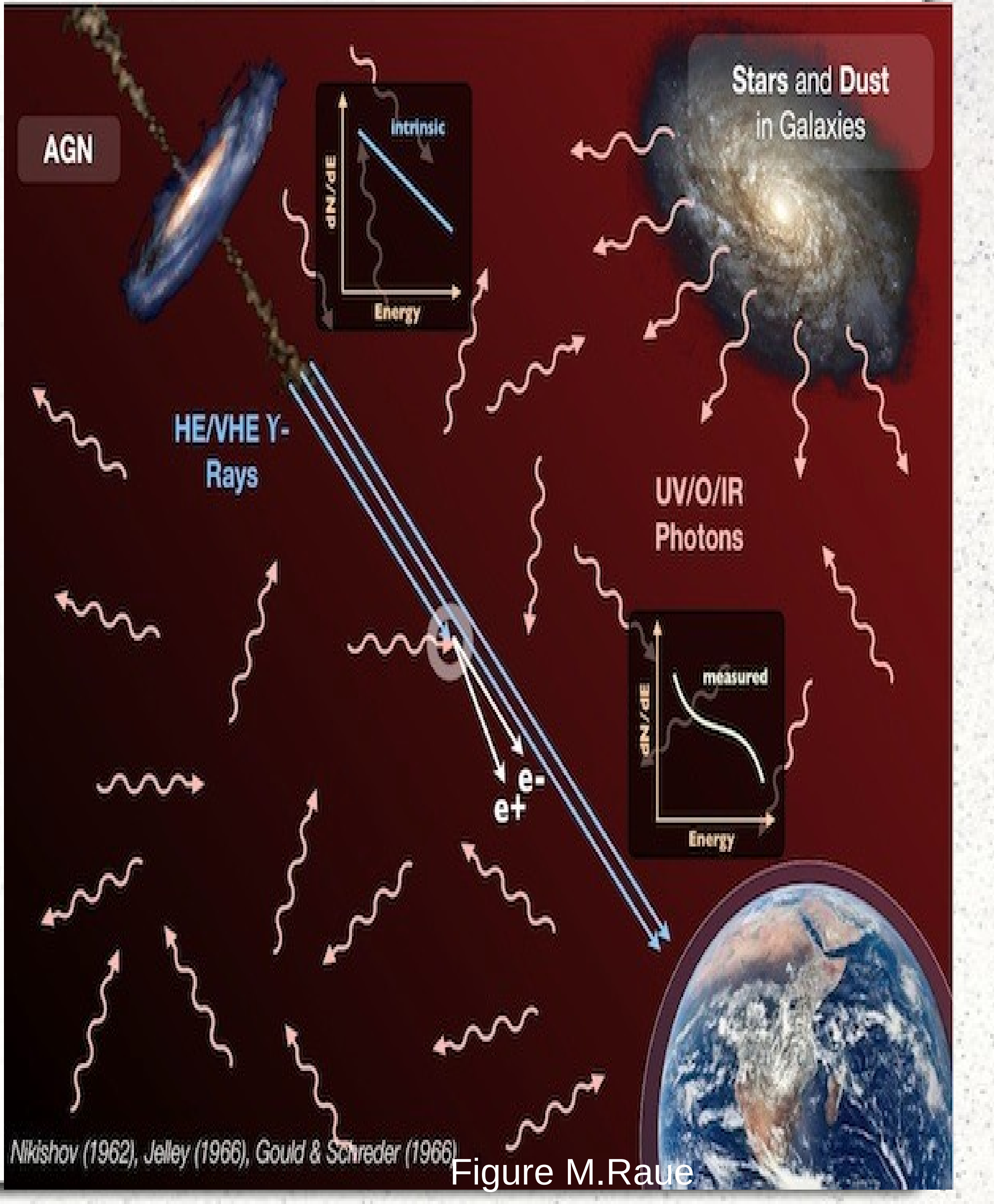


VHE gamma-rays as probes of Cosmology

Extragalactic background light and Intergalactic Magnetic field: History of Structure formation of the Universe



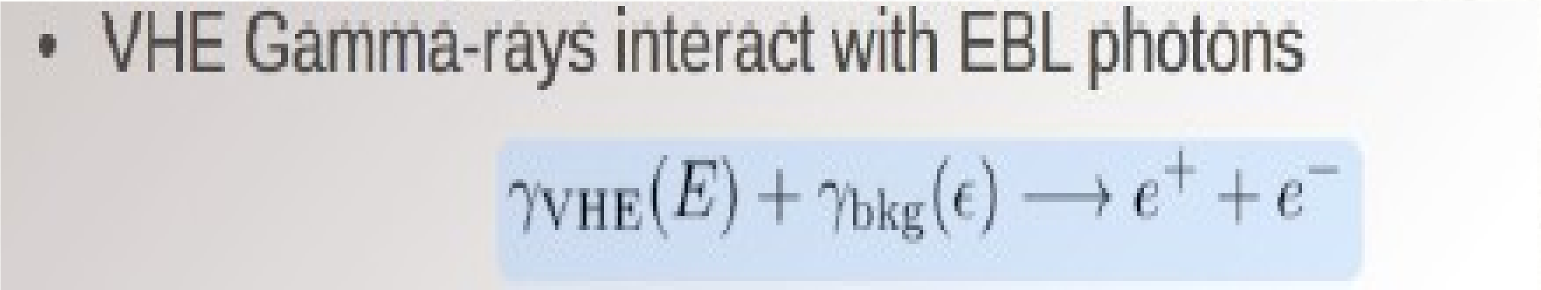
adapted from Dole et al.



Nikishov (1962), Jelley (1966), Gould & Schreder (1966)

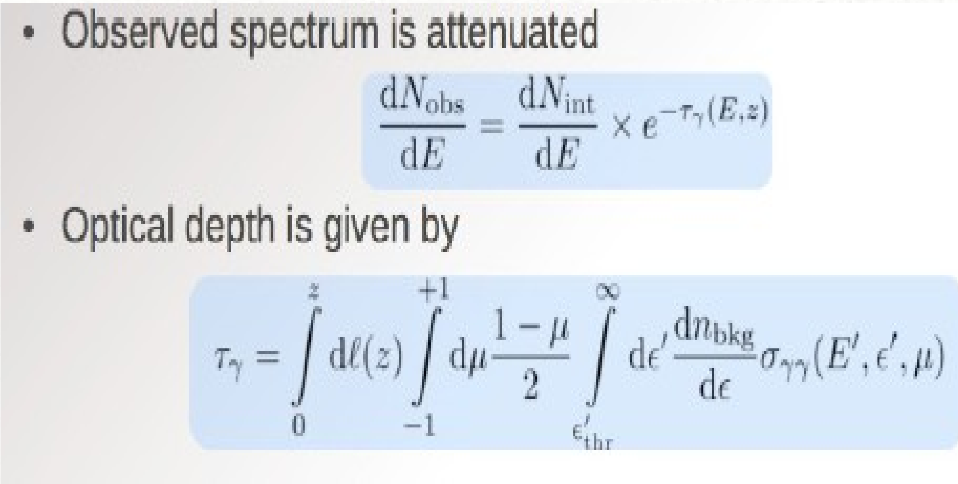
Figure M.Raue

VHE gamma-rays as probes of Cosmology



- VHE Gamma-rays interact with EBL photons

$$\gamma_{\mathrm{VHE}}(E) + \gamma_{\mathrm{bkg}}(\epsilon) \longrightarrow e^{+} + e^{-}$$

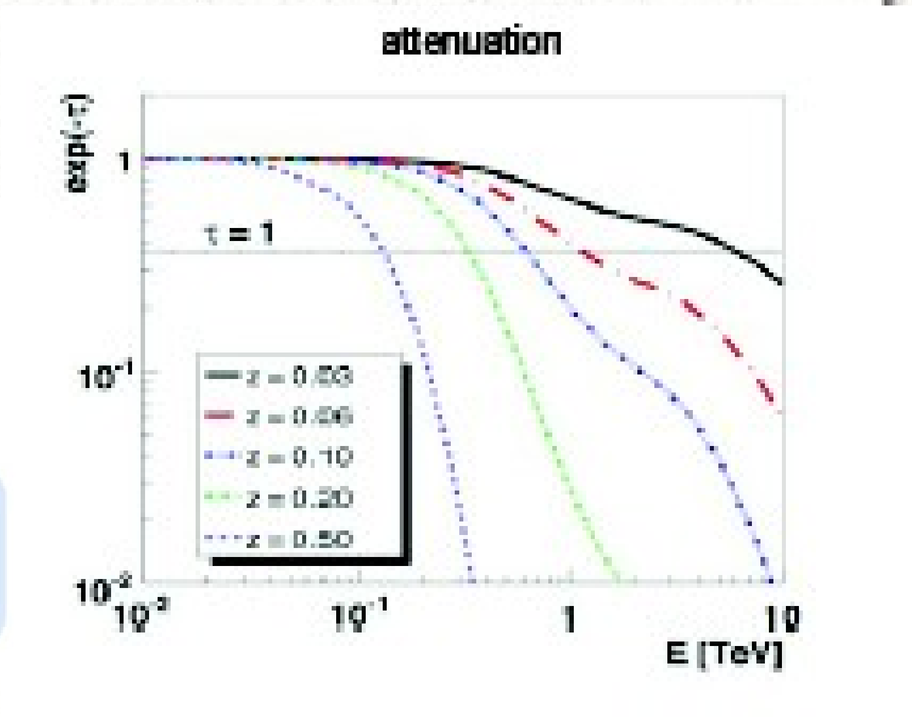


- Observed spectrum is attenuated

$$\frac{\mathrm{d}N_{\mathrm{obs}}}{\mathrm{d}E} = \frac{\mathrm{d}N_{\mathrm{int}}}{\mathrm{d}E} \times e^{-\tau_\gamma(E,z)}$$

- Optical depth is given by

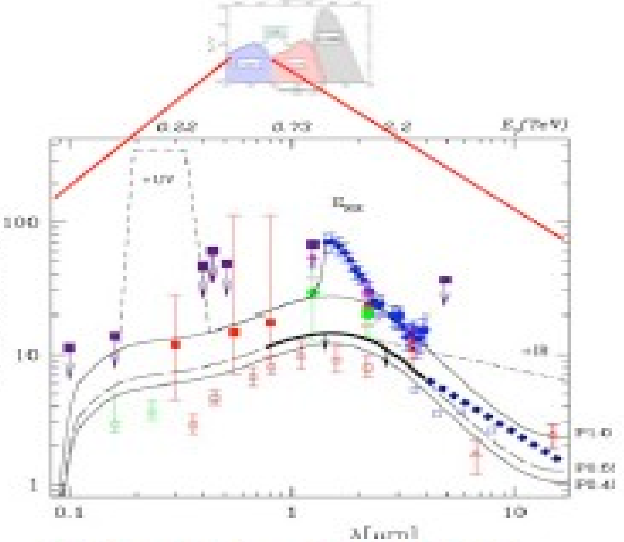
$$\tau_\gamma = \int_0^z \mathrm{d}\ell(z) \int_{-1}^{+1} \mathrm{d}\mu \frac{1-\mu}{2} \int_{\epsilon'_{\mathrm{thr}}}^{\infty} \mathrm{d}\epsilon' \frac{\mathrm{d}n_{\mathrm{bkg}}}{\mathrm{d}\epsilon} \sigma_{\gamma\gamma}(E', \epsilon', \mu)$$



Adapted from M. Meyer

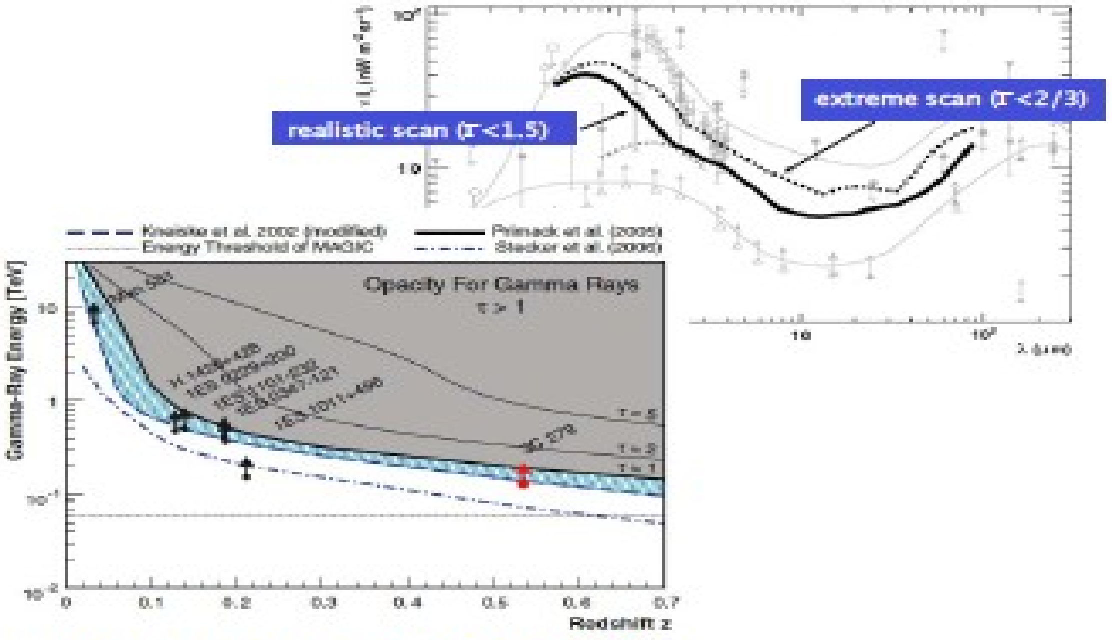
VHE gamma-rays as probe of Cosmology

- Constraints from the current instruments:



HESS, Nature 440 (2006) 1018-1021

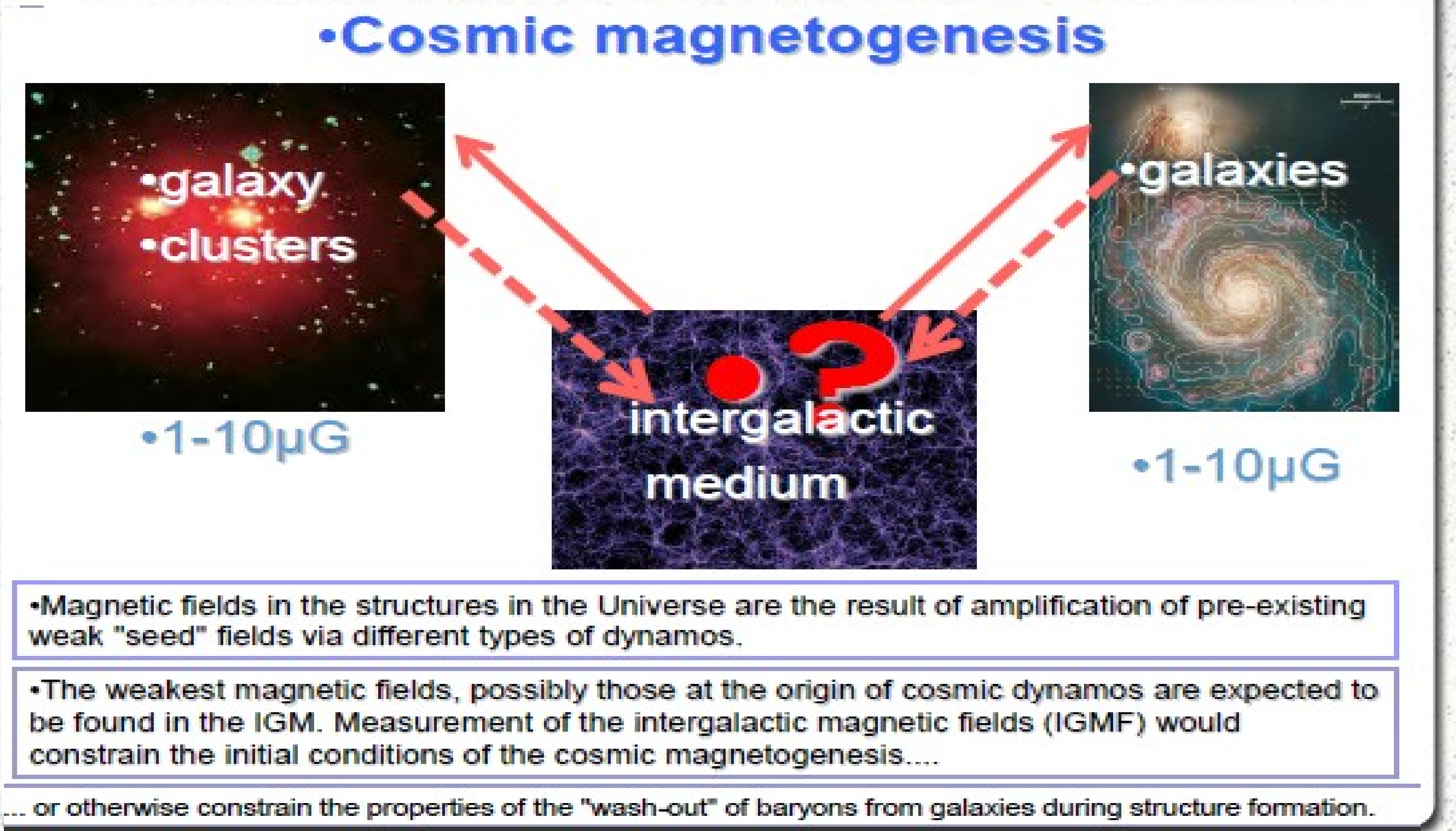
DM & Raue (2007)



MAGIC, Science 320 (2008) 1752

Adapted from D.Mazin

VHE gamma-rays as probe of Cosmology



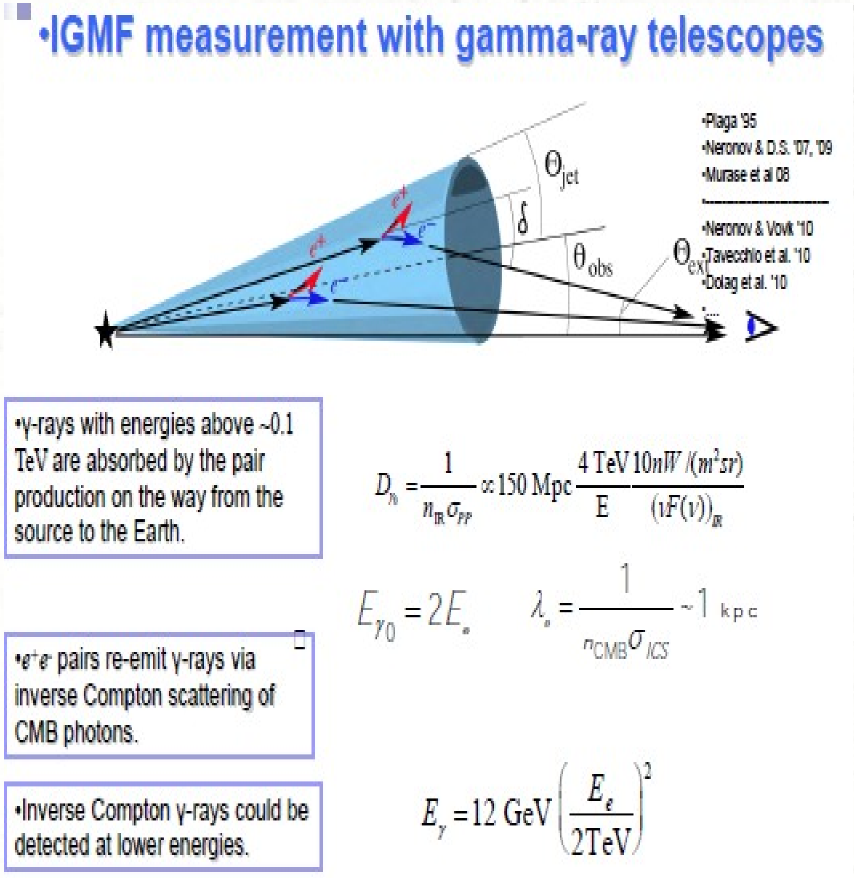
•Magnetic fields in the structures in the Universe are the result of amplification of pre-existing weak "seed" fields via different types of dynamos.

•The weakest magnetic fields, possibly those at the origin of cosmic dynamos are expected to be found in the IGM. Measurement of the intergalactic magnetic fields (IGMF) would constrain the initial conditions of the cosmic magnetogenesis....

... or otherwise constrain the properties of the "wash-out" of baryons from galaxies during structure formation.

Slide from: D. Semikoz

VHE gamma-rays as probe of Cosmology



•IGMF measurement with gamma-ray telescopes

- •Plaga '95
- •Neronov & D.S. '07, '09
- •Murase et al 08
- •Neronov & Vovk '10
- •Tavecchio et al. '10
- •Dolag et al. '10
- •....

•γ-rays with energies above ~0.1 TeV are absorbed by the pair production on the way from the source to the Earth.

$$D_{\gamma} = \frac{1}{n_{IR}\sigma_{\gamma\gamma}} \propto 150\,\mathrm{Mpc}\,\frac{4\,\mathrm{TeV}}{\mathrm{E}}\,\frac{10\,nW/(m^2 sr)}{(\nu F(\nu))_{IR}}$$

$$E_{\gamma_0} = 2E_e \qquad \lambda_e = \frac{1}{n_{CMB}\sigma_{ICS}} \sim 1\ \mathrm{kpc}$$

•e^+e^- pairs re-emit γ-rays via inverse Compton scattering of CMB photons.

•Inverse Compton γ-rays could be detected at lower energies.

$$E_{\gamma} = 12\,\mathrm{GeV}\left(\frac{E_e}{2\,\mathrm{TeV}}\right)^2$$

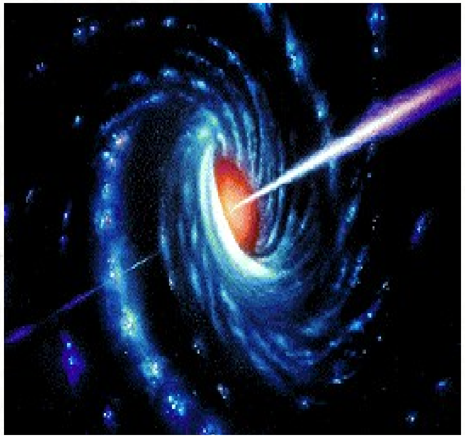
- Magnetic field produces:

  -Extended emission around the point source, detectability depends on the telescope sensitivity

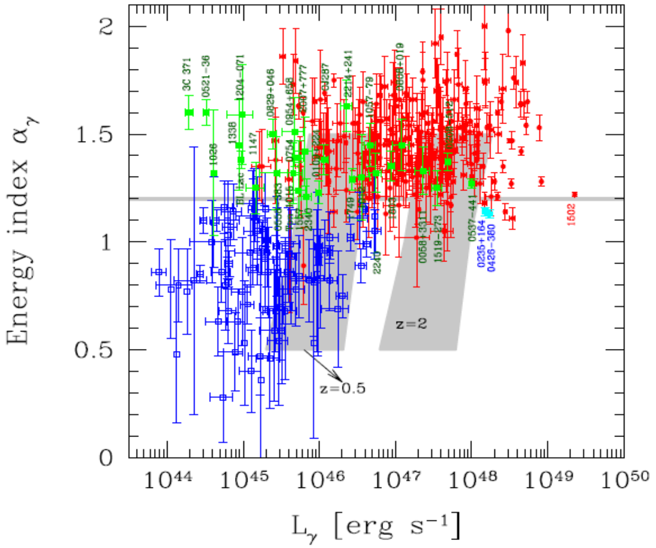
  -Time delay of the secondary emission: Blazars with hard spectra: bright in the VHE (0.1-10 TeV) energy band and preferentially be not-so-bright in the HE (0.1-10 GeV) band, to make the cascade emission visible on top of the direct primary source emission. Good examples are the brighest VHE blazars, like Mrk 421 and Mrk 501.

VHE gamma-rays as probe of Cosmology

The beacons: Blazars



- The most numerous objects in the gamma-ray sky
- VHE gamma-rays: ~60 blazars: X-ray selected BL Lacs (HBLs) are most numerous
- Highest redshift source 3C279 (FSRQ, z=0.536), but several (BL Lac) sources with unknown redshift (cannot be used as probes)
- Variability vs. sensitivity of experiments: Many sources can be detected only during flares.

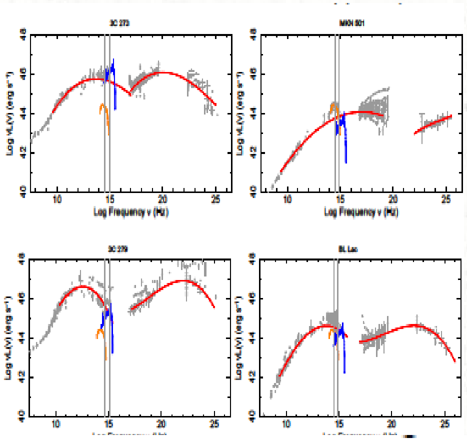


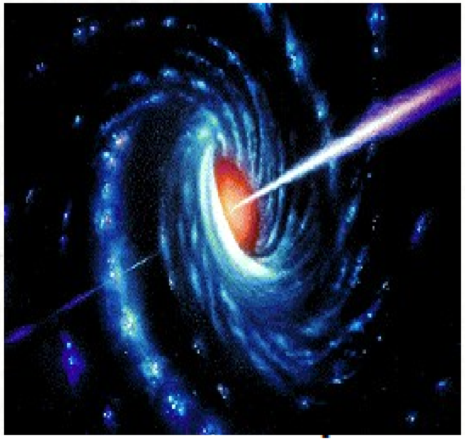
Red: FSRQs, Blue BL Lacs
Ghisellini et al. 2010

VHE gamma-rays as probe of Cosmology

Blazars

- Many open questions about the particle acceleration in the jets, emission sites and emission mechanisms
- One of the biggest mysteries is the very short time scale (<1 hour) scale variability: CTA will be ideal tool for studying it





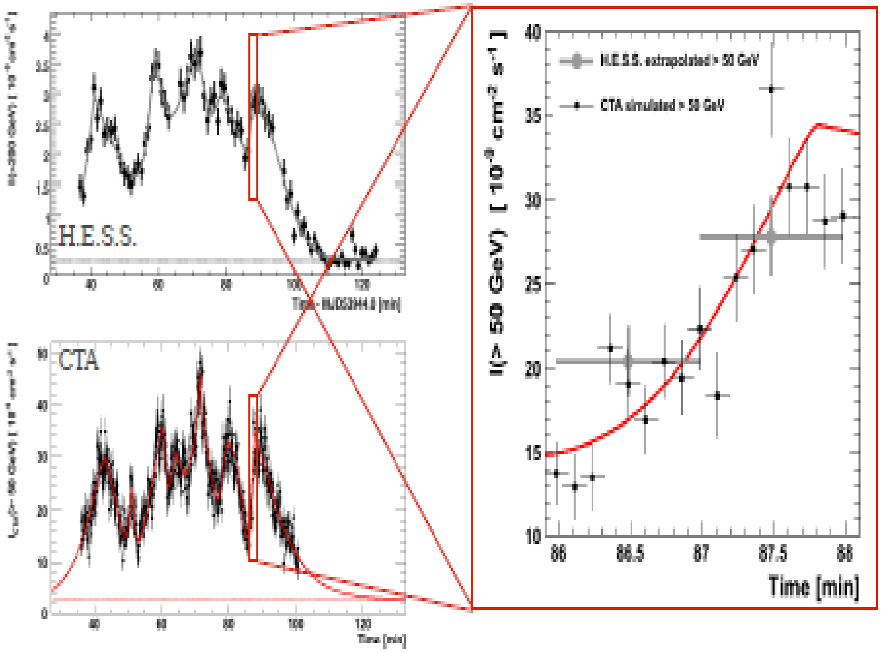


Figure: J. Biteau

VHE gamma-rays as probe of Cosmology

- CTA will:

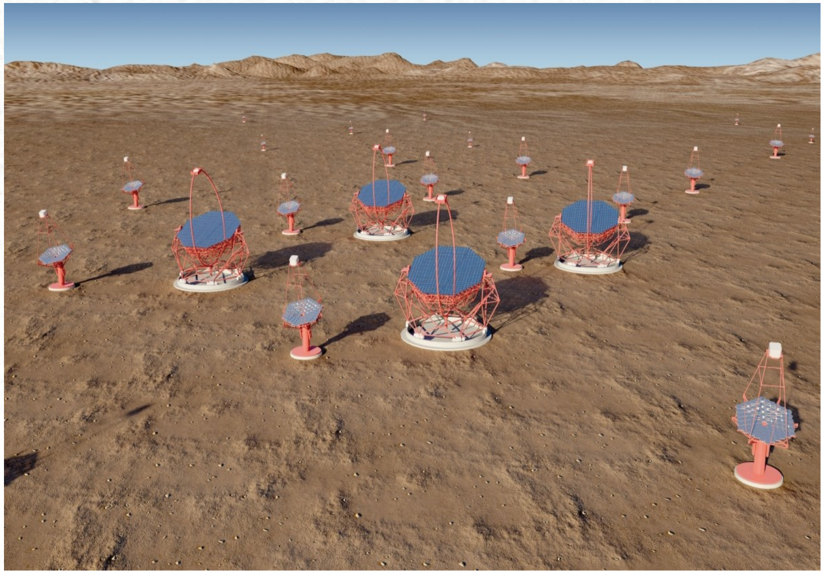
  -Provide insight to the blazar physics in the shortest timescales

  -Detect more distant blazars, detect more hard spectrum blazars and provide high quality (high photon statistics) spectra

- This will enable us to:

  -Study the evolution of the Extragalactic Background Light

  -Put strong constraints on the strength of the intergalactic magnetic field



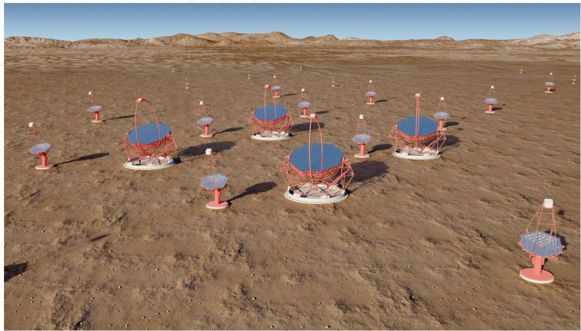
Indirect detection of Dark Matter

- WIMPs can annihilate to Standard Model Particles and have hadrons and leptons as final products of annihilation; neutrinos, cosmic rays, electromagnetic radiation from charged products and prompt gamma-rays =>indirect detection

- In context of gamma-ray astronomy, the differential flux of gamma-rays from within a solid angle ΔΩ around a given astronomical target where DM is expected, can be written as:

$d\Phi(\Delta\Omega, E)/dE = B_F * 1/4\pi * (\sigma v)/2m^2 \Sigma BR\, dN/dE * J(\Delta\Omega)$

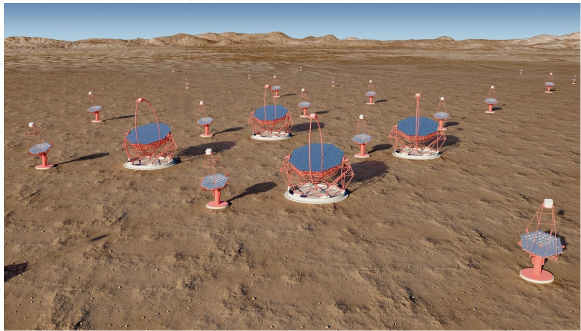
Boost factor, Particle Physics factor, astrophysics factor



Indirect detection of Dark Matter

- Current instruments have already presented some limits, but do not have required sensitivity to reach the thermal value of the annihilation cross section
- Where to look: **high M/L ratio**:
- **Dwarf Galaxies, Clusters of Galaxies, Galactic Halo**

  Anisotropies in the diffuse gamma-ray background
- CTA will be an excellent experiment for other fundamental physics searches as well, especially for Quantum Gravity (QG) and Axion-like particle (ALP) searches.



- Prospects for CTA discussed in Doro, Conrad et al. 2013, Astroparticle Physics, 43, 189

Indirect detection of Dark Matter

-CTA will have a much higher chance of DM detection compared to the current generation of IACT:

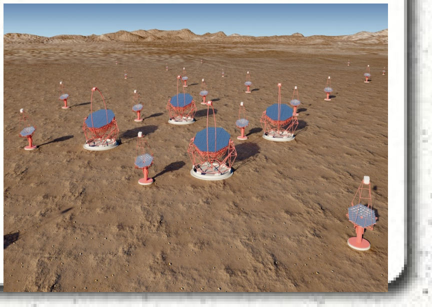
***an extended energy range** will allow characterizing WIMPs with lower masses, if they exist

***the improved sensitivity** in the entire energy range will improve the probability of detection or identification of DM through the observation of spectral features, if any

***the increased FOV** with a homogeneous sensitivity as well as the improved angular resolution will allow for much efficient searches for extended sources and spatial anisotropies.

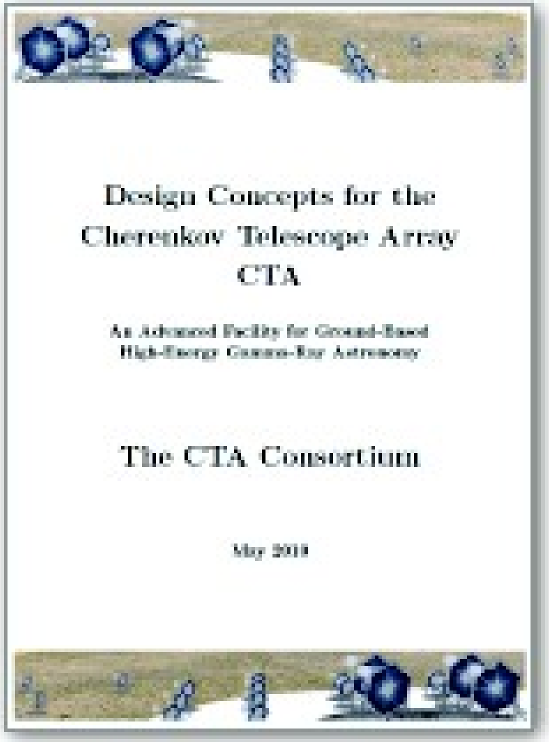
-If signatures of dark matter appear in direct detection experiments, gamma-ray observations may provide complementary approach to identify its properties and mass.

-Moreover, the heavy dark matter candidates would go undetected by the future experiments, while CTA could be the only experiment sensitive in this mass region.



More Details:

general info: www.cta-observatory.org

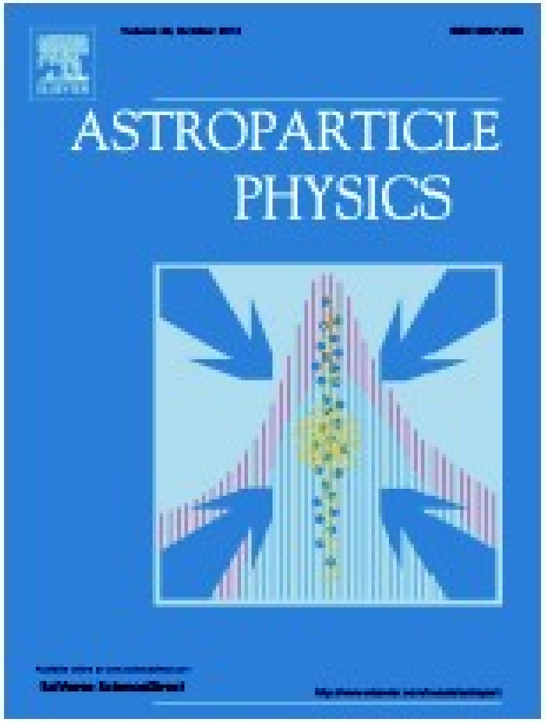


Design Concepts for the
Cherenkov Telescope Array
CTA

The CTA Consortium

"Design Concepts for the
Cherenkov Telescope Array"

120 pages
arXiv:1008.3703
Exp. Astronomy 32 (2011) 193-316



ASTROPARTICLE
PHYSICS

"Seeing the High-Energy Universe
with the Cherenkov Telescope Array"

368 pages
in press, December 2012

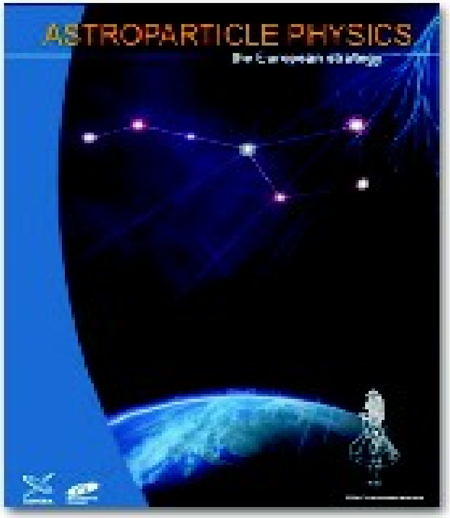
Conclusions:
Strong will and strong scientific motivation exists

European Strategy Forum on Research Infrastructures

ESFRI

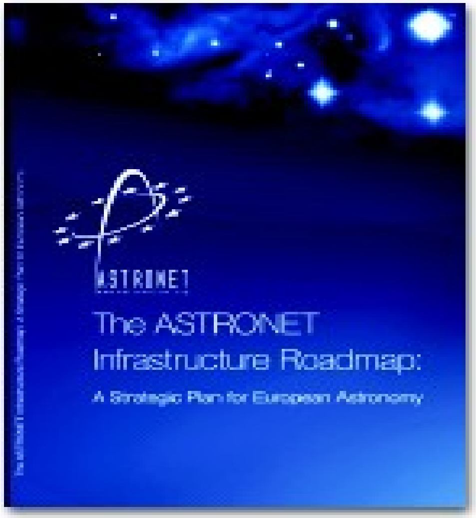
EUROPEAN ROADMAP FOR RESEARCH INFRASTRUCTURES

Roadmap 2008



ASTROPARTICLE PHYSICS

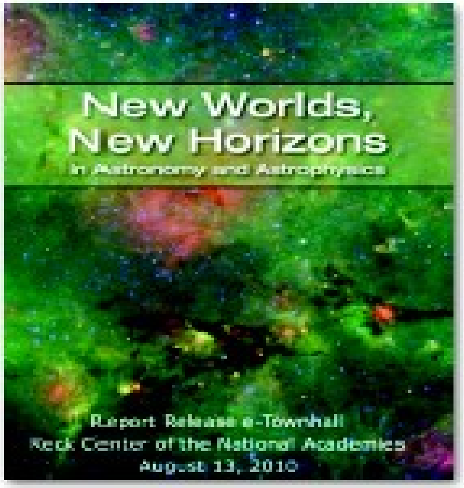
the European strategy



ASTRONET

The ASTRONET Infrastructure Roadmap:

A Strategic Plan for European Astronomy



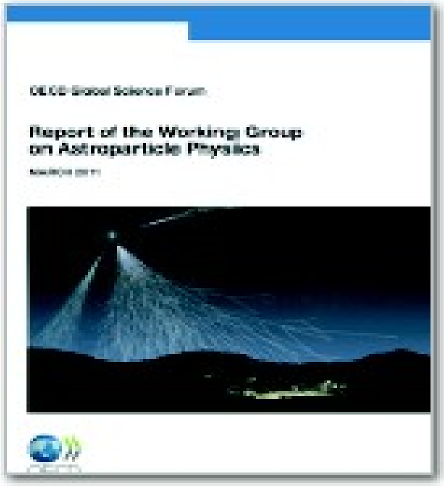
New Worlds, New Horizons

in Astronomy and Astrophysics

Report Release e-Townhall

Keck Center of the National Academies

August 13, 2010



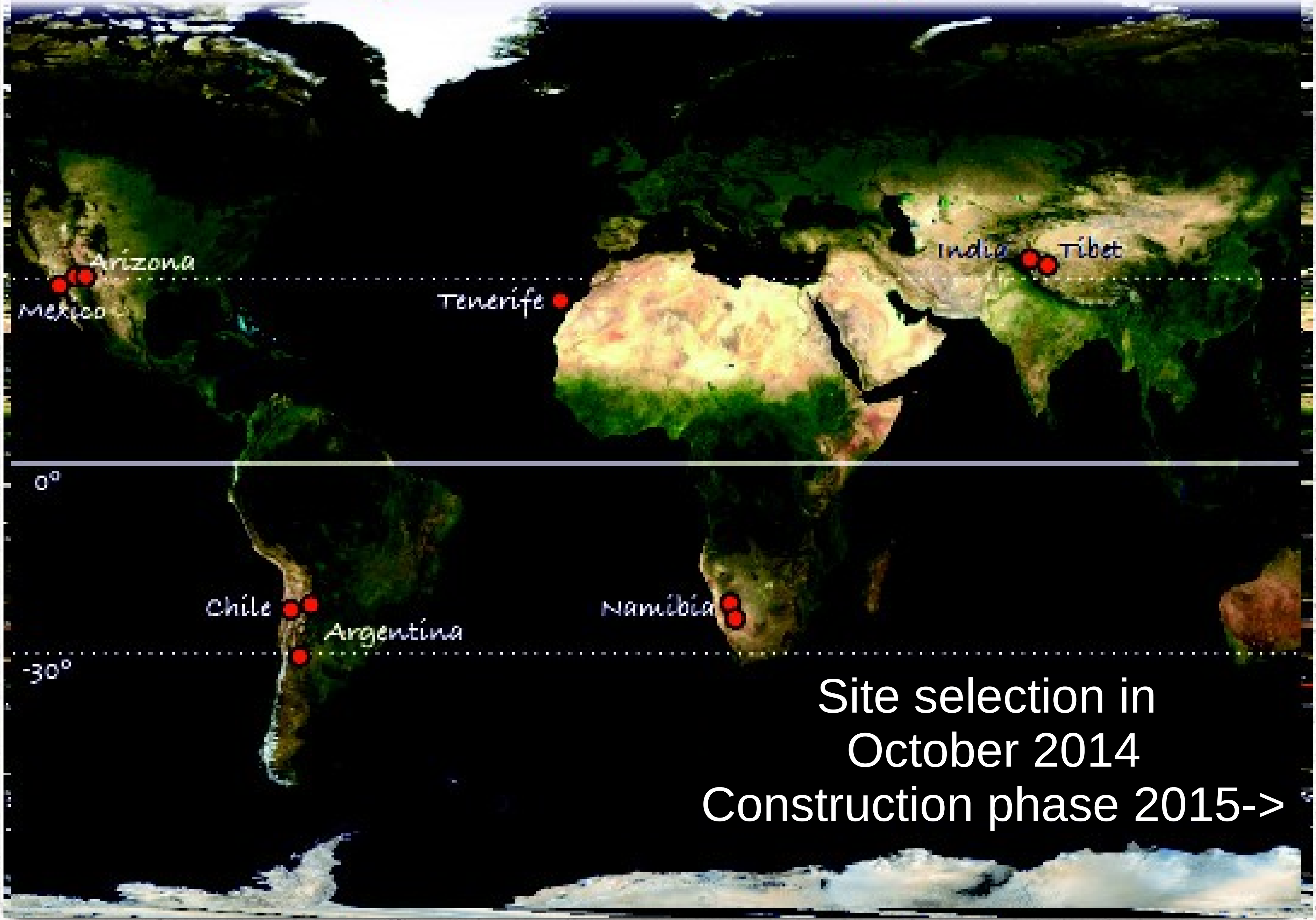
OECD Global Science Forum

Report of the Working Group on Astroparticle Physics

CTA:

highly ranked on national and international roadmaps

One observatory with two sites - operated by one consortium



Site selection in
October 2014
Construction phase 2015->

Thank You!

Back-up

Dwarf galaxies

- Bounds on the annihilation cross-section

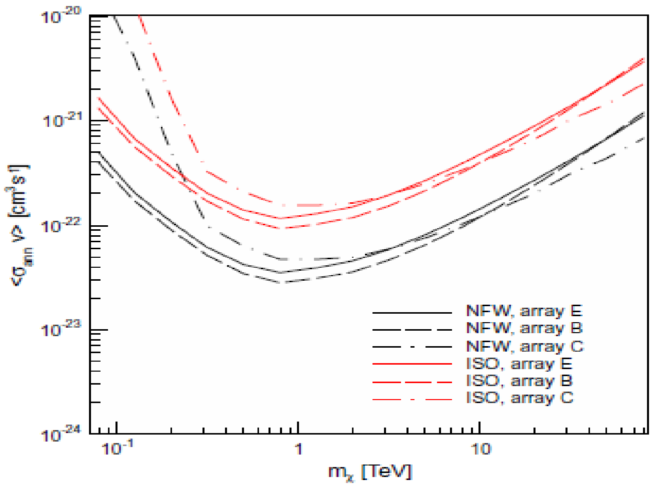


Fig. 1. CTA sensitivities on the velocity-averaged annihilation cross-section as a function of the WIMP mass for 100 h observation of Sculptor with the CTA array *E* (solid line), *B* (dashed line) and *C* (dashed-dotted line). Both the NFW (black line) and cored isothermal (ISO, red line) DM halo profiles are shown, for an integration solid angle $\Delta\Omega = 1 \times 10^{-5}$ sr. Annihilations are assumed to occur with 100% branching ratio into $b\bar{b}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Sculptor, DM profiles: cusped profile, cored isothermal

- Bounds on Boost factors
-

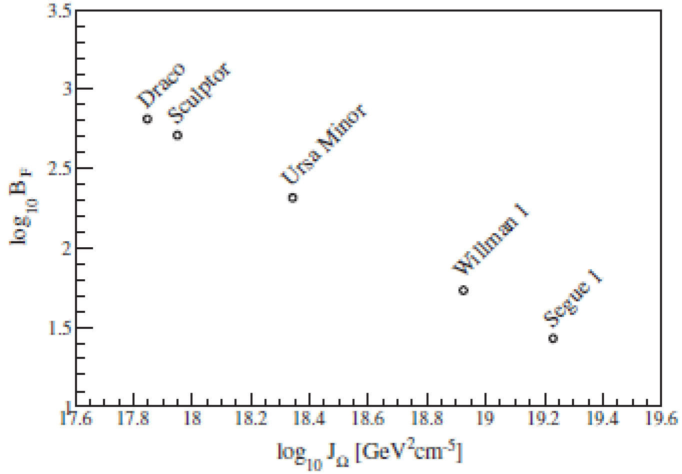


Fig. 4. Minimum boost factor required for a 5σ detection in 100 h by array *B*, for the dSphs in Table 1.1 and a 1 TeV WIMP annihilating into $\tau^+\tau^-$. The density profiles are taken to be NFW, except for Segue 1 where an Einasto profile has been assumed. The smallest boost required is $B_F = 25$ for Segue 1.

- 1TeV WIMP annihilation to tau+, tau-

Galaxy clusters

- Additional complication as the signal has to be distinguished from other gamma-ray contributions (in particular the gamma-ray signal from CR interactions should also be spatially extended). Different spectral shapes, different spatial extensions have to be used to distinguish.
- Exclusion limits assuming no significant CR gamma-ray signal

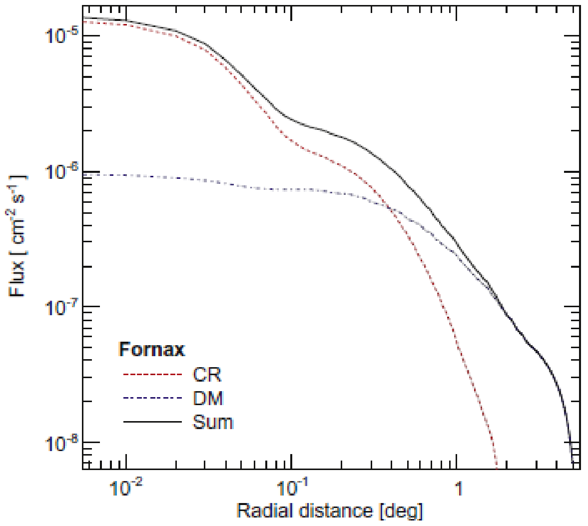


Fig. 7. The surface brightness (above 1 GeV) of the gamma-ray emission from the Fornax cluste from CRs (red), DM (blue) and the sum of the two contributions (black). The DM emission is calculated from the K' benchmark model of [112] which has mass of 570 GeV and a velocity-averaged cross-section of 4.4×10^{-26} cm^3 ss^{-1}. Adapted from Ref. [30]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

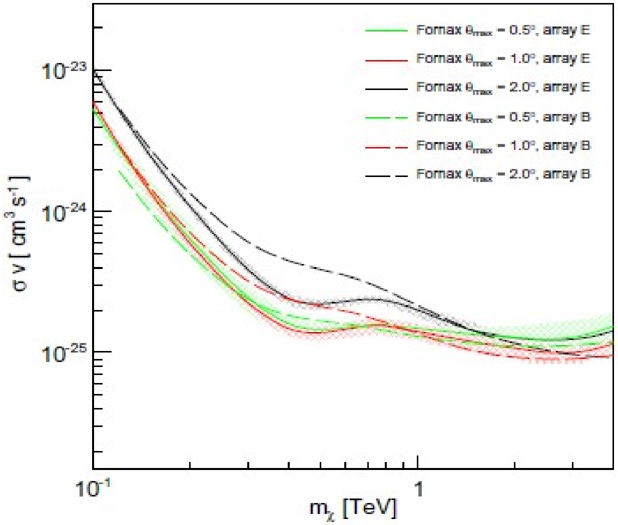


Fig. 6. Prospect of detection of DM-induced signal from Fornax for a DM particle annihilating into $b\bar{b}$ and 100 h integration time. The reference model is taken from Ref. [30] with subhalo boost factor $B_F = 580$. The shaded regions indicate the 1σ standard deviation among 10 different simulations.

Galactic Halo and Centre

- Galactic centre and plane sources of strong gamma-ray emission from astrophysical origin, target to regions outside galactic plane, but still close enough to GC to exhibit a sizeable gamma-ray flux from DM annihilation in the MW halo. (angular distance of 0.3pc from the GC)
- Using so called ring -method improves the sensitivity
- Galactic halo observations illustrate best sensitivity for the dark matter searches with CTA

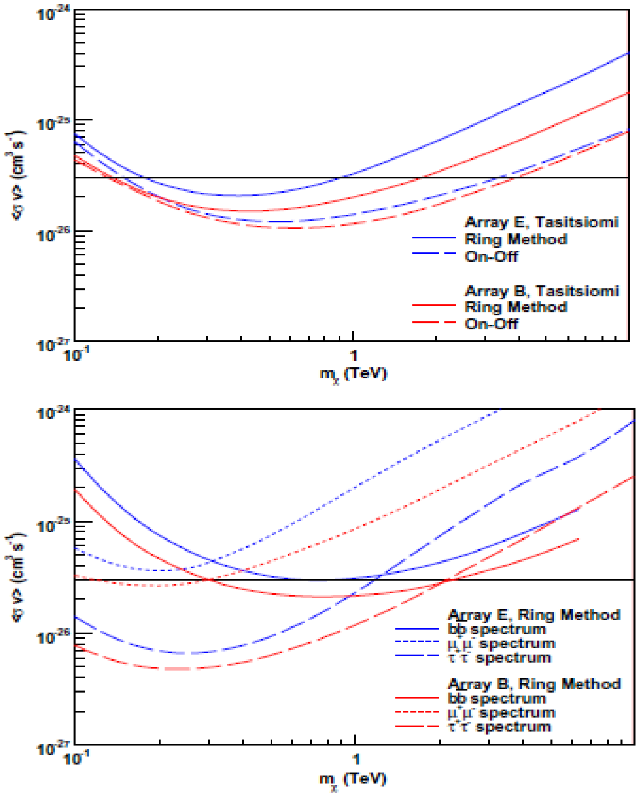


Fig. 9. CTA sensitivities on the velocity averaged annihilation cross-section as a function of the WIMP mass. Shown are curves for the candidate arrays *E* (blue) and *B* (red). **Top:** Comparison of the *Ring Method* (solid lines) and On–Off Method for background subtraction. Annihilation as in [60] was assumed. **Bottom:** Comparison of different WIMP spectra for the *Ring Method*. The solid line denotes the case of annihilation into $b\bar{b}$; $\mu^+\mu^-$ and $\tau^+\tau^-$ spectra are shown by the dotted and dashed lines, respectively. On both panels, the classical annihilation cross section for thermally produced WIMPs at 3×10^{-26} cm^3 s^{-1} is indicated by the black horizontal line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)