TeV Gamma-Ray Astronomy
H.E.S.S. and beyond

G.Hermann
MPIK Heidelberg

TeV Gamma-Ray Astronomy
H.E.S.S. and beyond

- Physics Motivation
- Imaging Cherenkov Technique
- H.E.S.S. Results
    - Galactic sources
    - Extragalactic sources
- The Future

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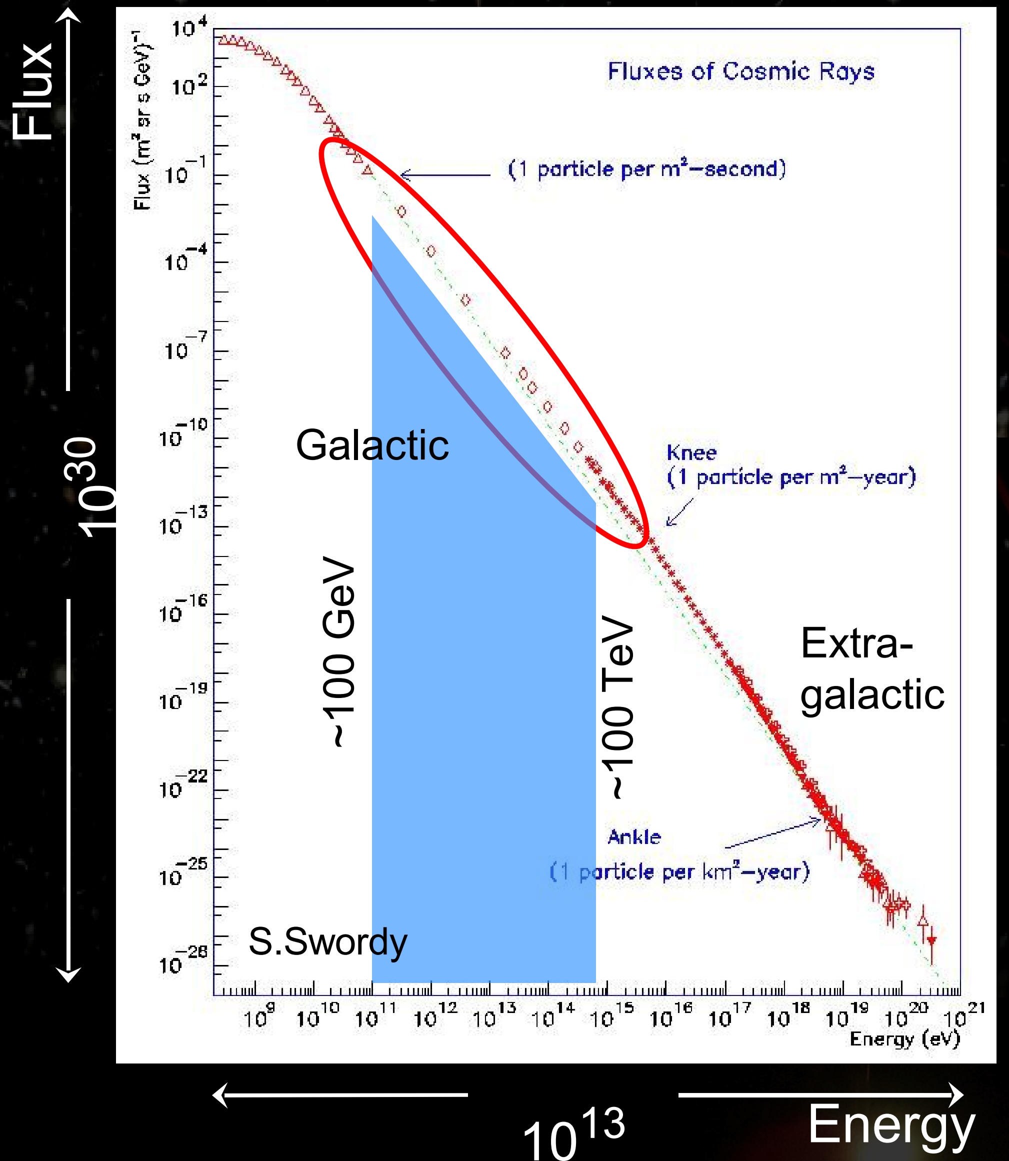
The Cosmic Ray Puzzle



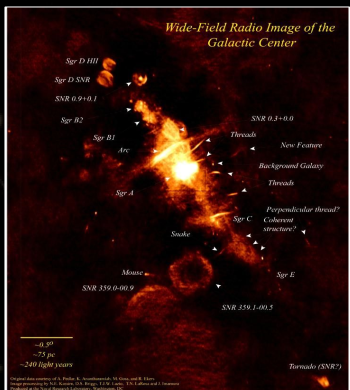
- Mostly nuclei p, He, … Fe
  also $e^{\pm}$
  few γ, ν
- Non thermal spectrum

  $dN/dE \sim E^{-\alpha}$
- Isotropic distribution

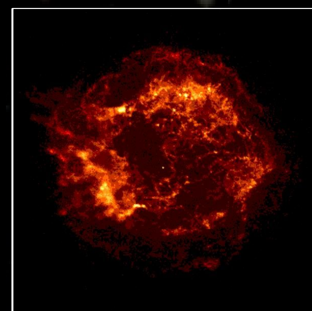
Discovery in 1912, but
- Cosmic ray origin ?
- Sources ?
- Processes ?

Potential Sources and Processes

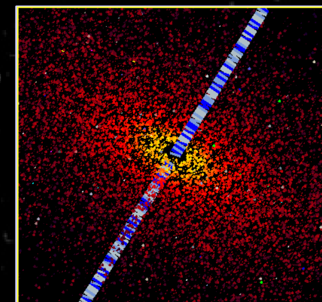
Dark Matter



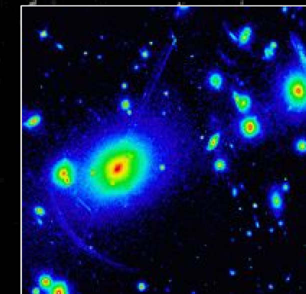
Super Nova Remnants (SNR)



Active Galactic Nuclei (AGN)



Clusters of Galaxies



- SNR as sources of CR
- Acceleration of relativistic particles
- Energy transfer in pulsars
- Environment of neutron stars and Black Holes
- Properties of relativistic jets

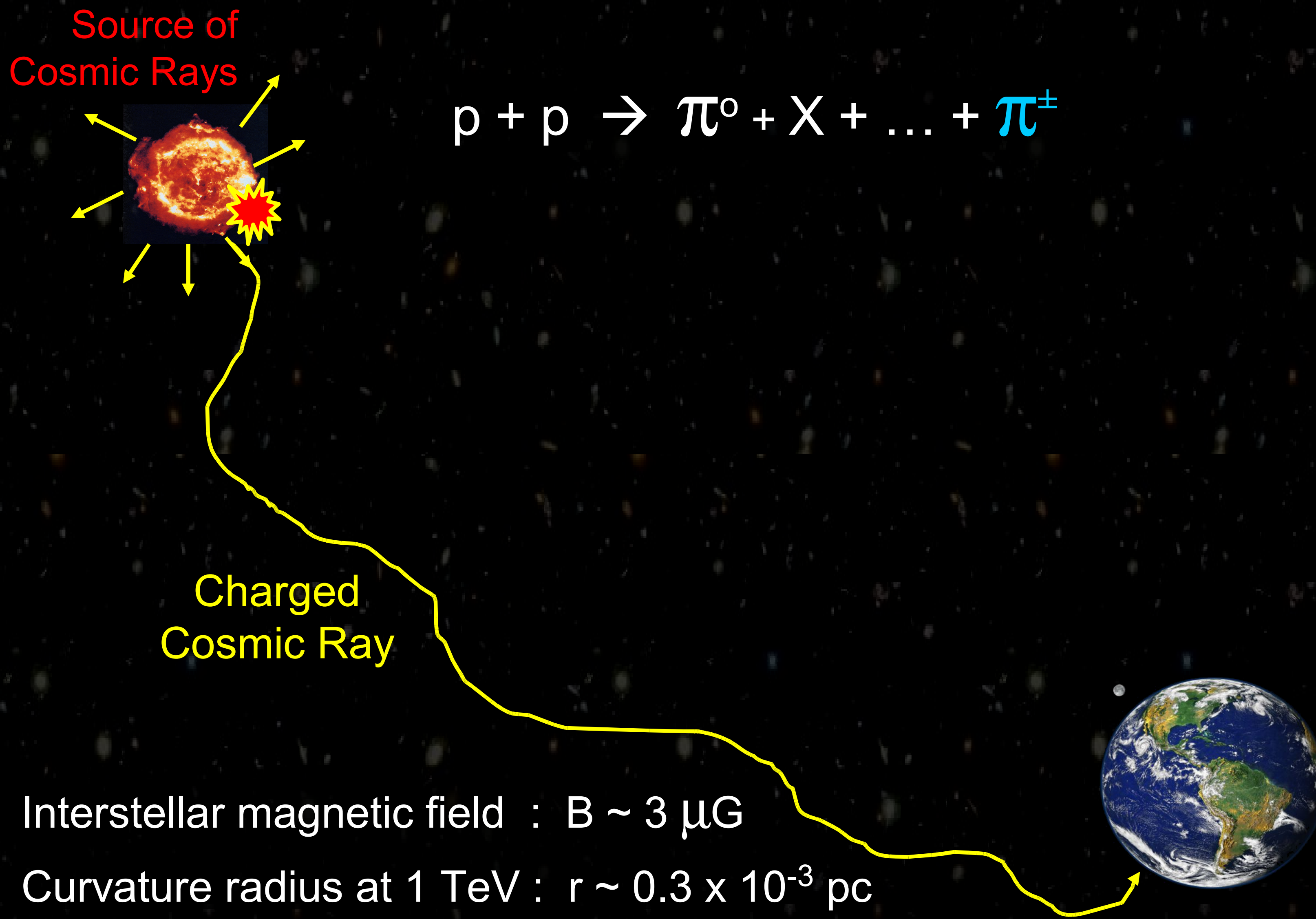
- Indirect search for DM
- Cosmology: diffuse EBL GRBs and GRBRs

Pulsar Nebula

Binary Systems

Tracers to Cosmic Ray Accelerators

$$p + p \rightarrow \pi^{o} + X + \ldots + \pi^{\pm}$$



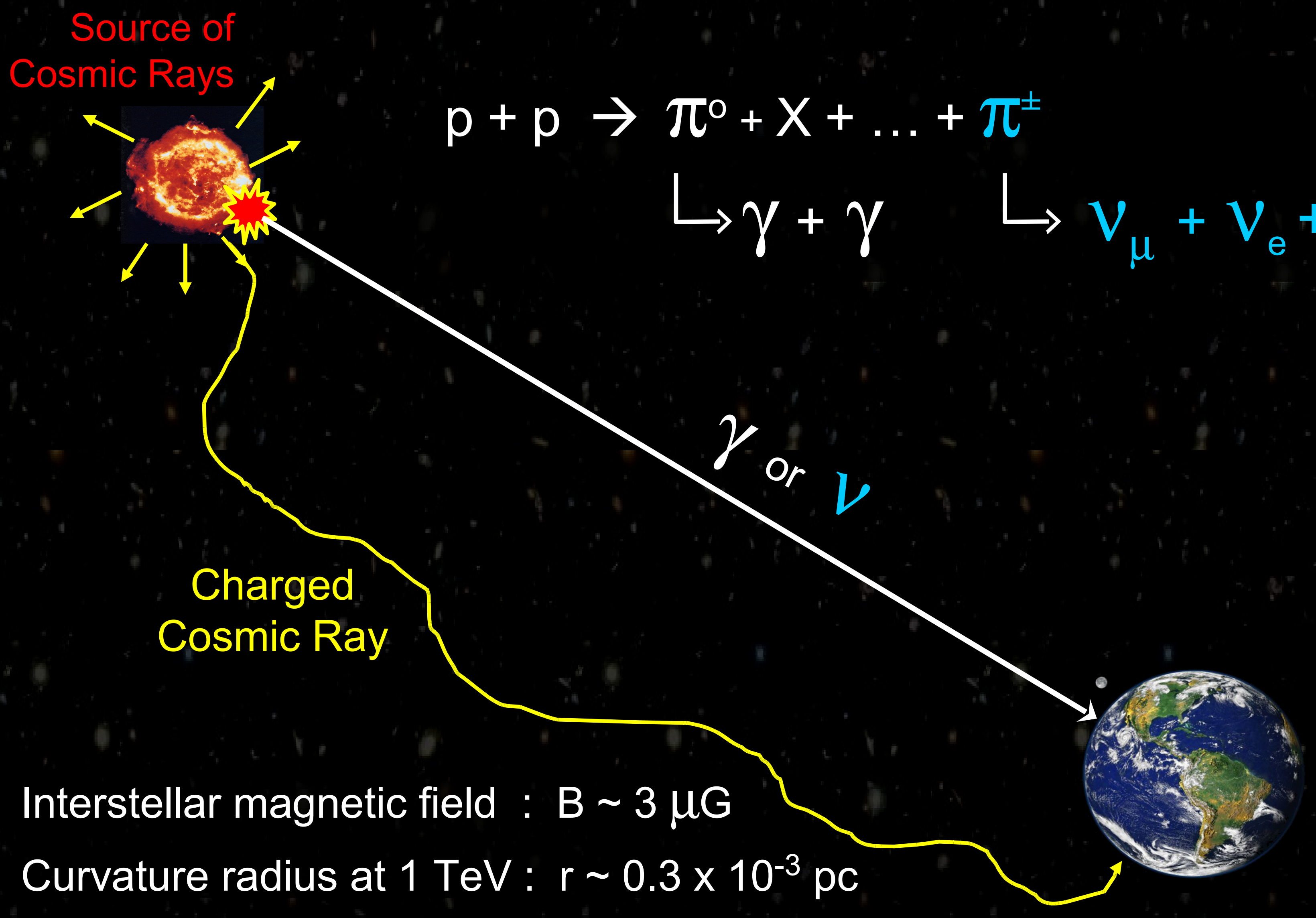
Interstellar magnetic field : $B \sim 3\ \mu G$

Curvature radius at 1 TeV : $r \sim 0.3 \times 10^{-3}$ pc

Tracers to Cosmic Ray Accelerators

$$p + p \rightarrow \pi^o + X + \ldots + \pi^{\pm}$$

$$\pi^o \rightarrow \gamma + \gamma \qquad \pi^{\pm} \rightarrow \nu_\mu + \nu_e + \ldots$$



Interstellar magnetic field : $B \sim 3\ \mu G$

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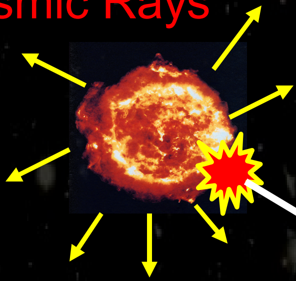
Tracers to Cosmic Ray Accelerators



$$p + p \rightarrow \pi^{o} + X + \ldots$$
$$\hookrightarrow \gamma + \gamma$$

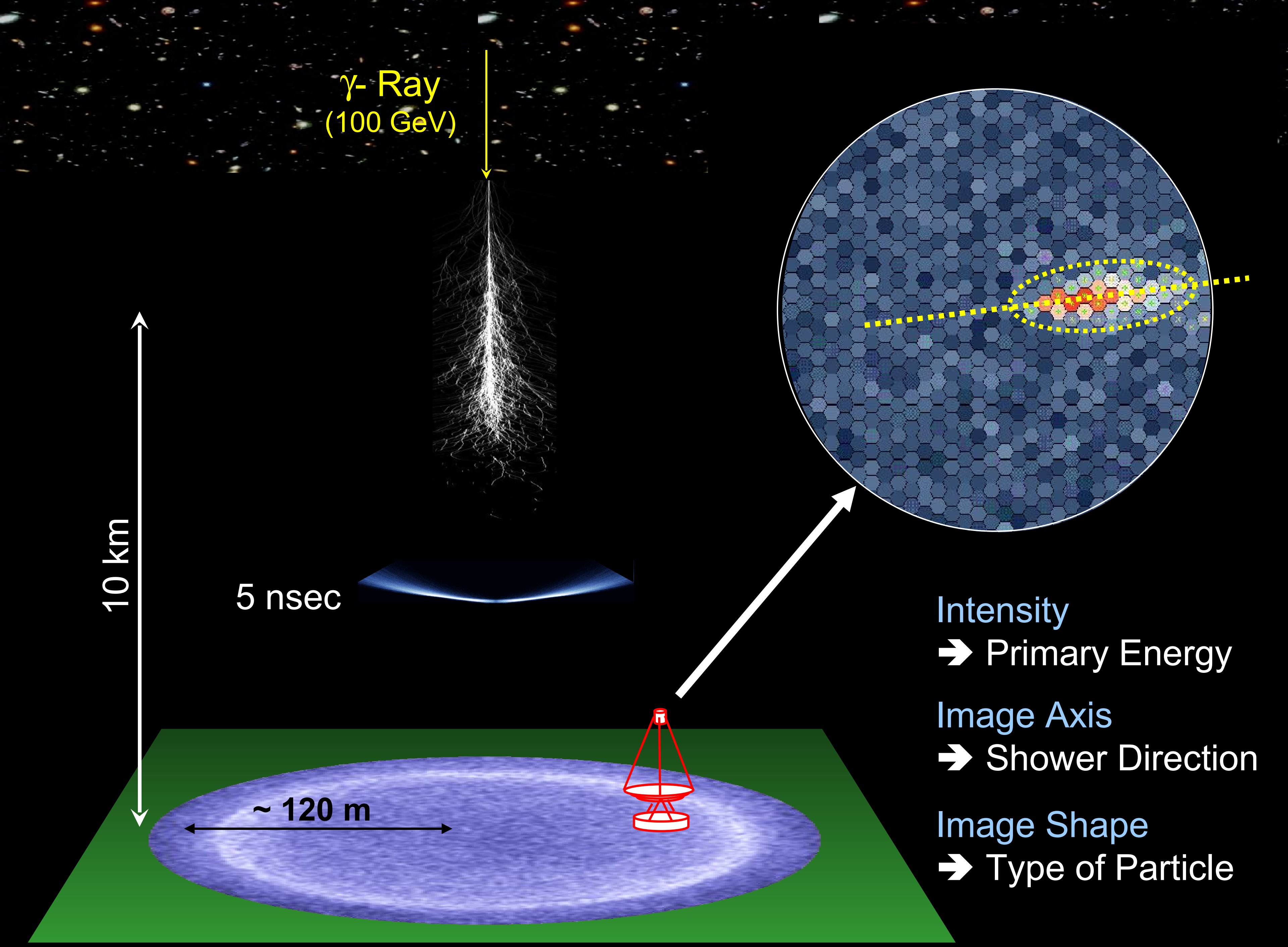
γ

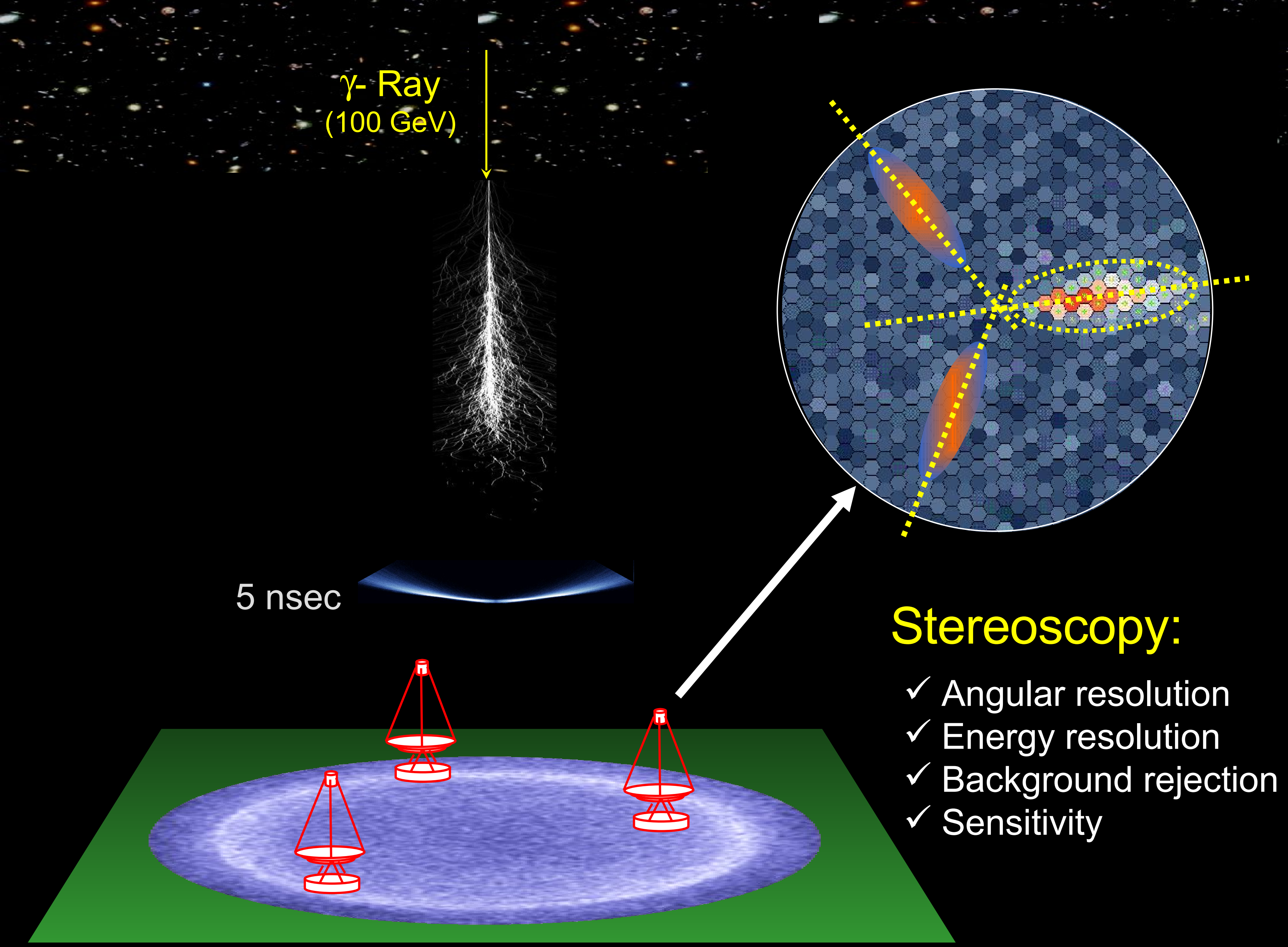
Infer properties of *primary particle distribution* in the sources and their *interactions*

Observables

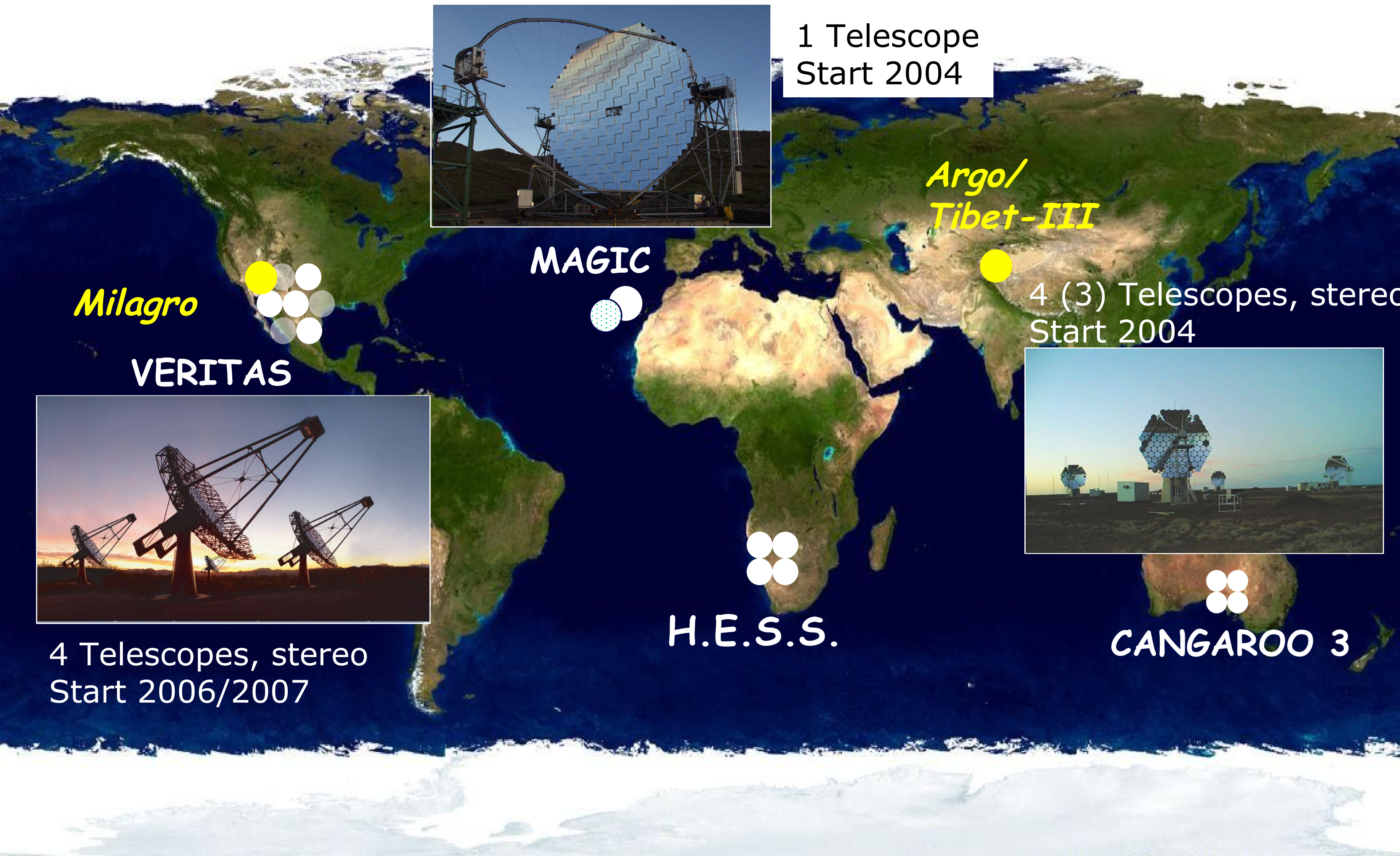
- Energy Spectra
  flux, range, shape
- Source Morphology
- Variability/Periodicity

+ Multi-Wavelength (radio, IR, optical, X-ray)

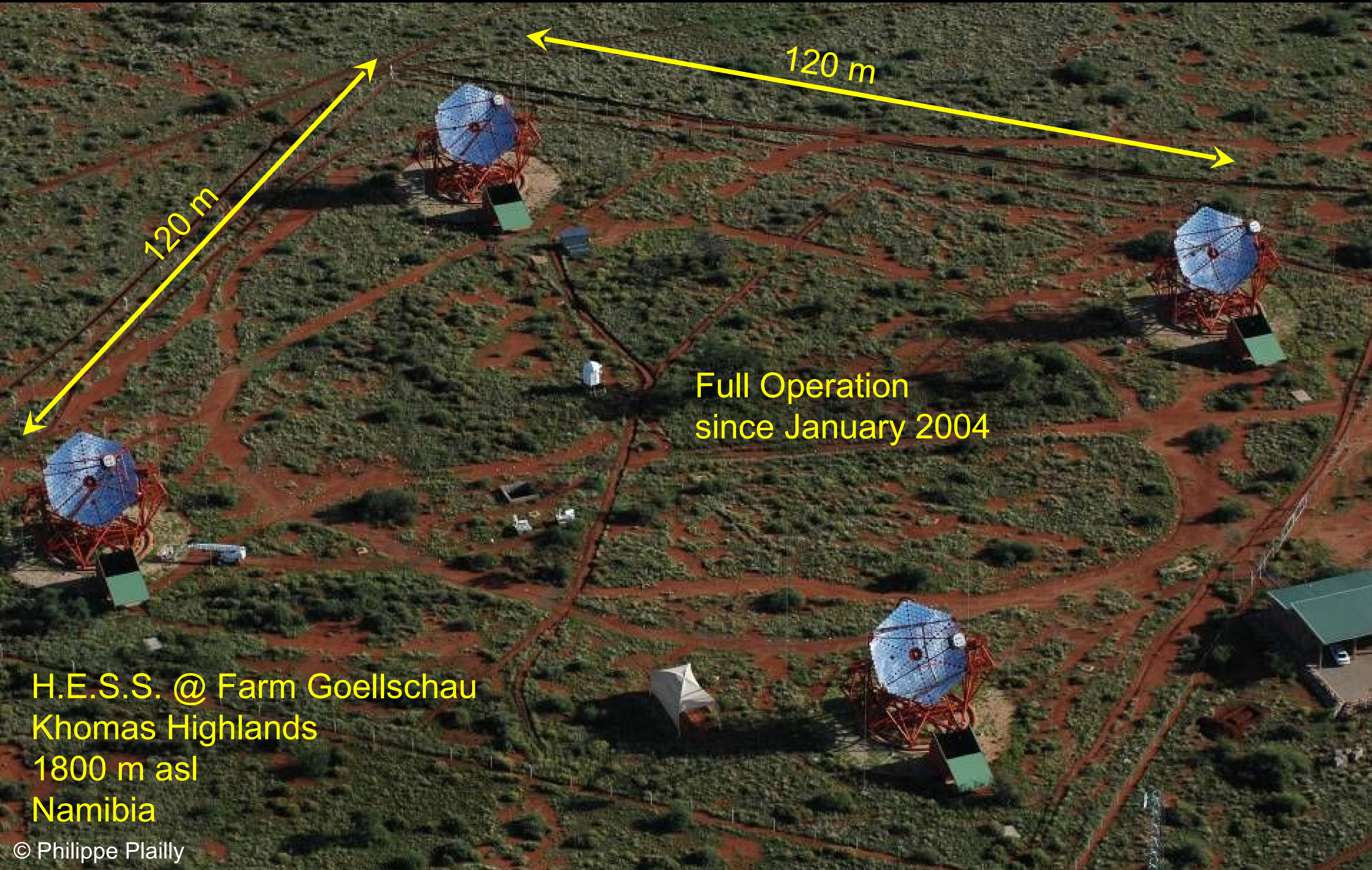

γ- Ray
(100 GeV)
10 km
5 nsec
~ 120 m
Intensity
➔ Primary Energy
Image Axis
➔ Shower Direction
Image Shape
➔ Type of Particle


γ- Ray
(100 GeV)
5 nsec
Stereoscopy:
✓ Angular resolution
✓ Energy resolution
✓ Background rejection
✓ Sensitivity

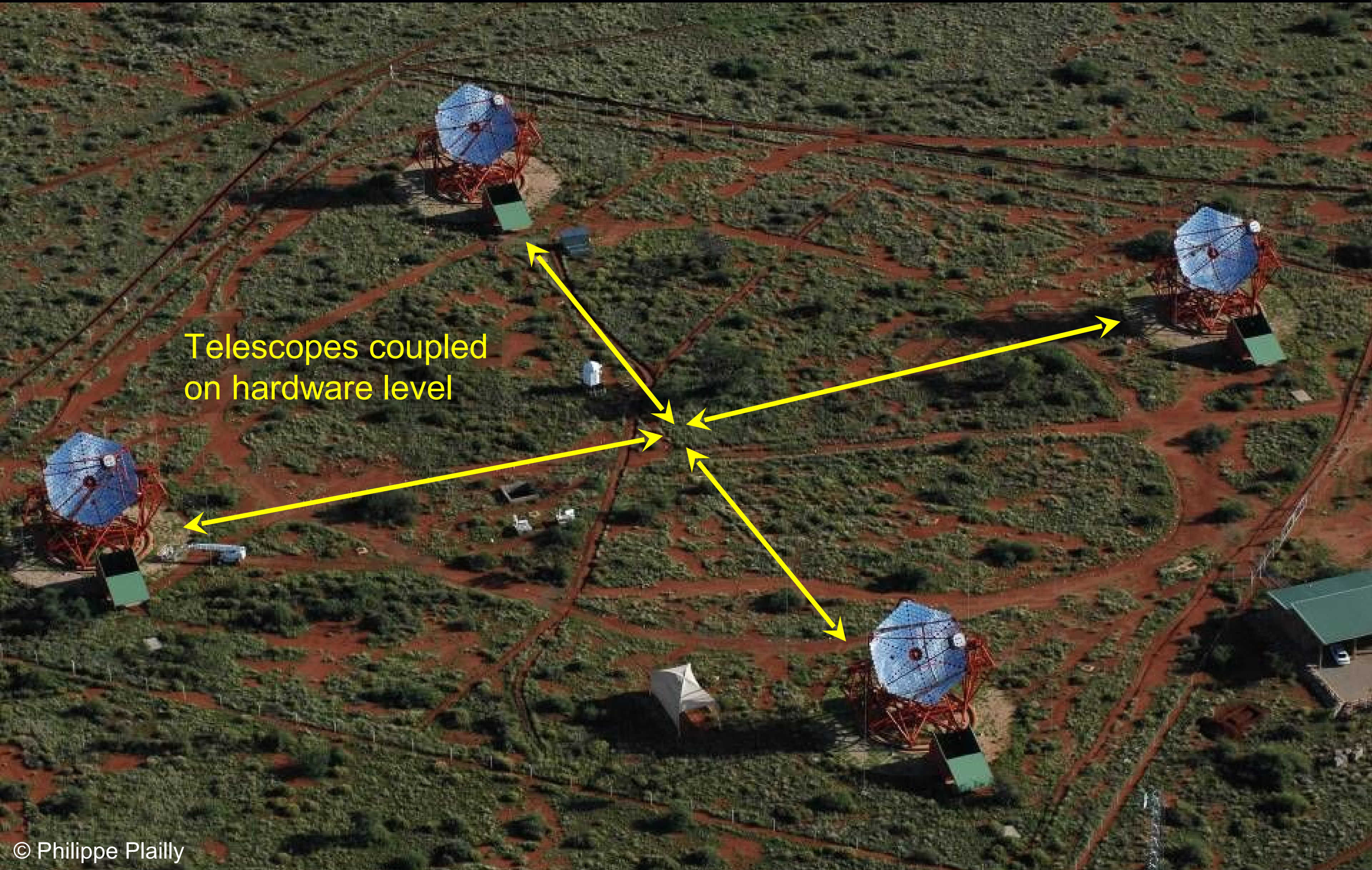
Major Ground-Based γ-Ray Installations

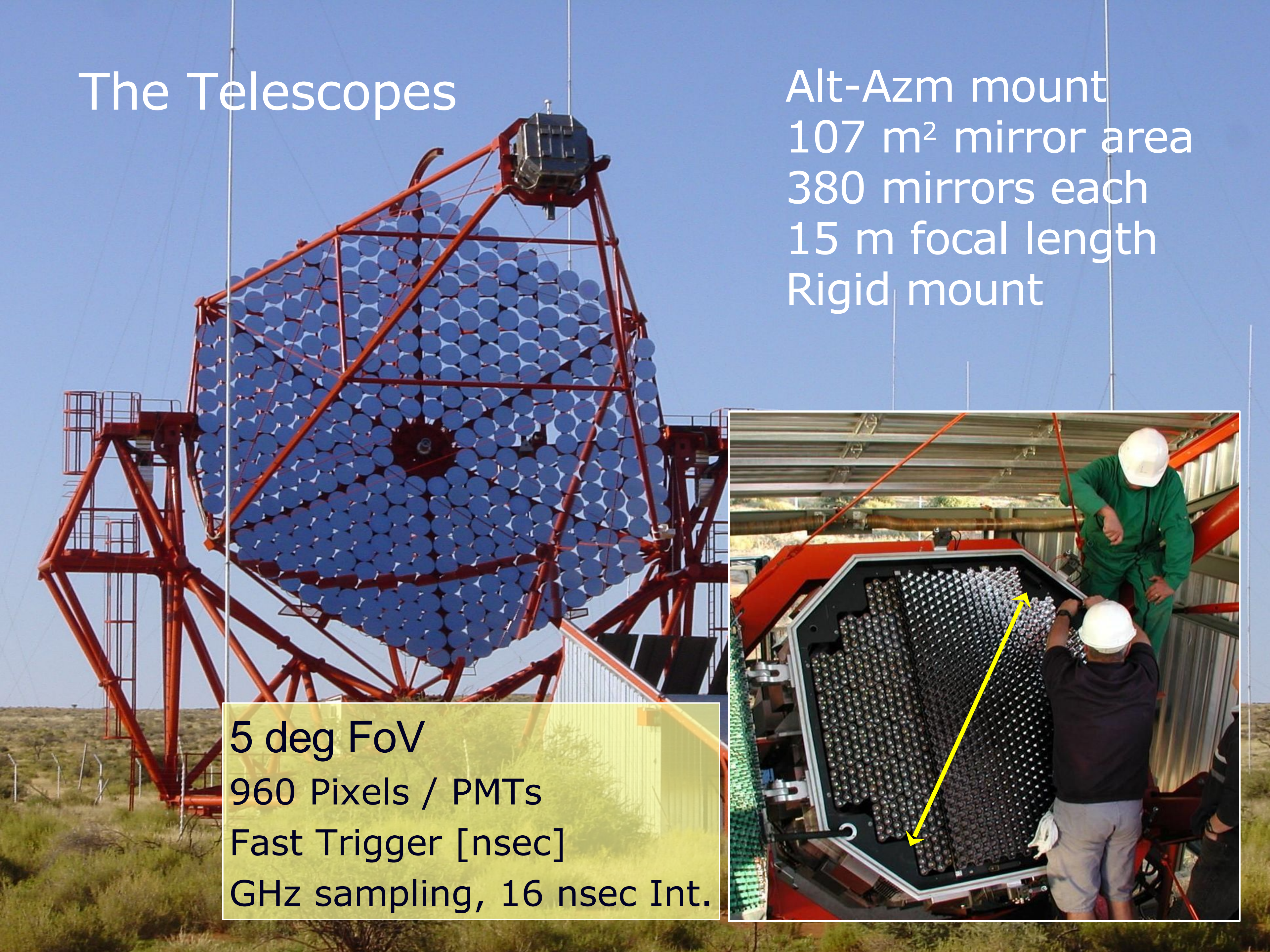


High Energy Stereoscopic System



High Energy Stereoscopic System

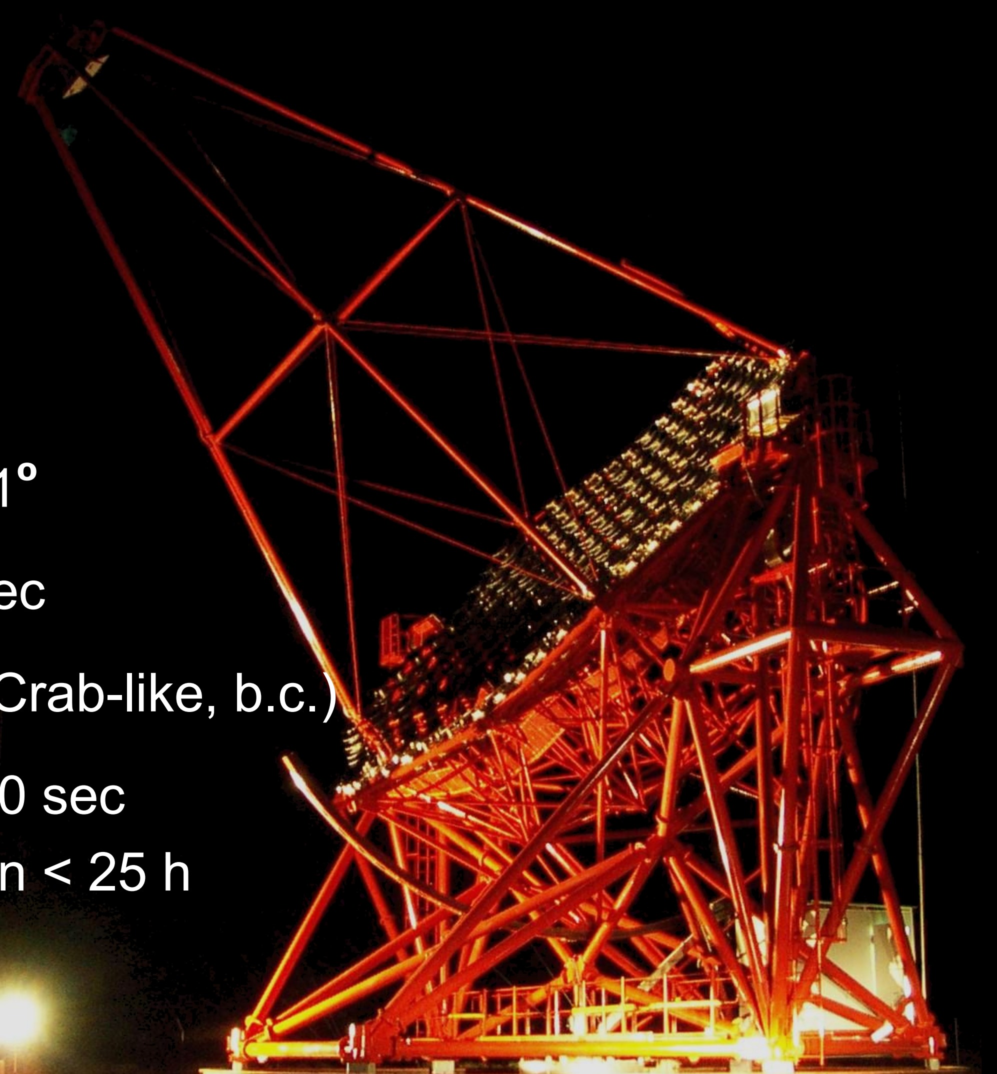



The Telescopes
Alt-Azm mount
107 m² mirror area
380 mirrors each
15 m focal length
Rigid mount
5 deg FoV
960 Pixels / PMTs
Fast Trigger [nsec]
GHz sampling, 16 nsec Int.

Stereo Performance Parameters

State of the Art

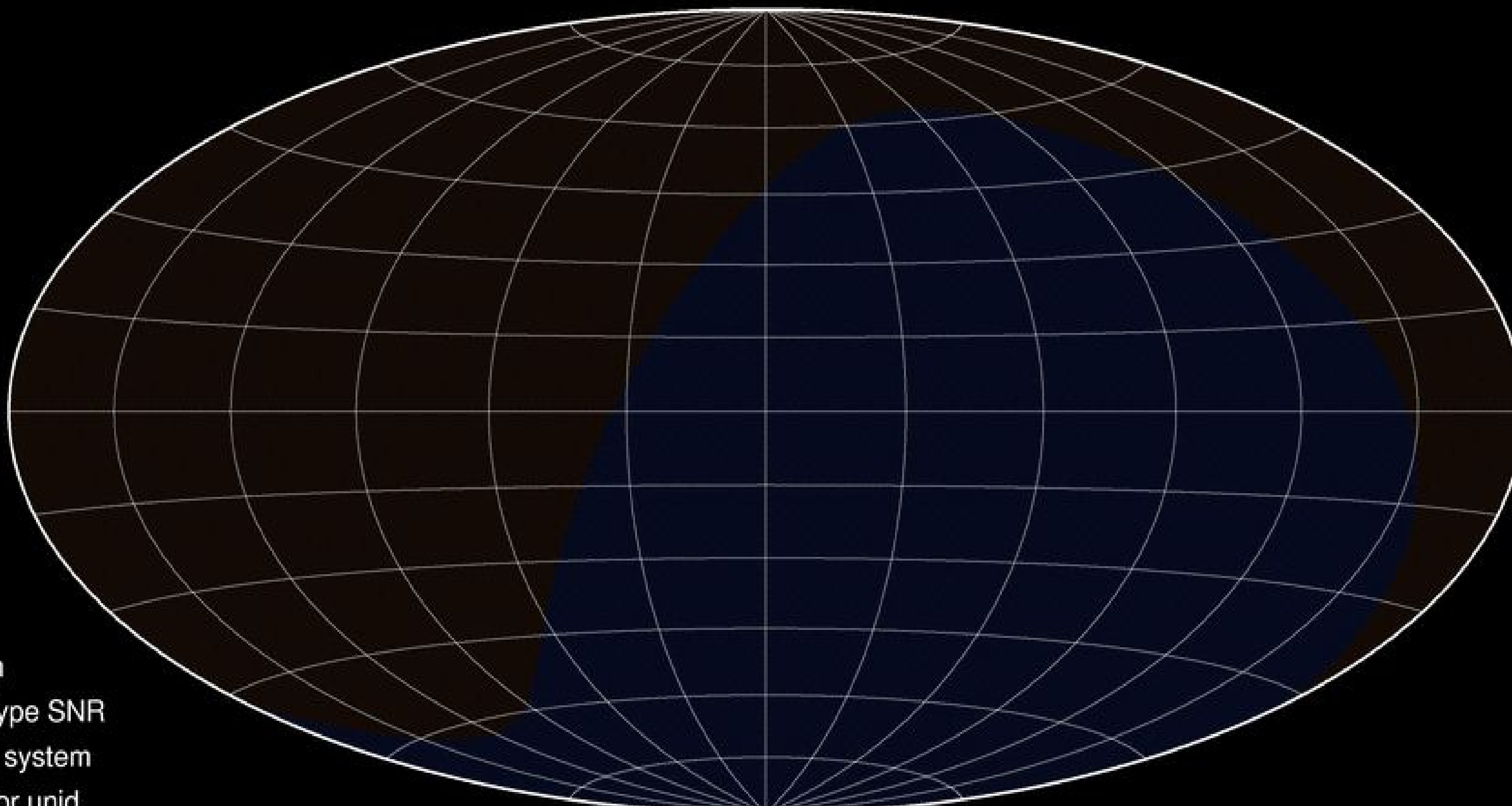
Energy Threshold:	100 GeV
Energy resolution:	15 %
Field of view:	~ 4 deg
Angular resolution:	0.05° - 0.1°
Pointing accuracy:	10-20 arcsec
Signal Rate:	~55 / min (Crab-like, b.c.)
Sensitivity:	1 Crab in 30 sec
	0.01 Crab in < 25 h



The High-Energy Gamma Ray Sky (1988)

E > 100 GeV

(Galactic coordinates)

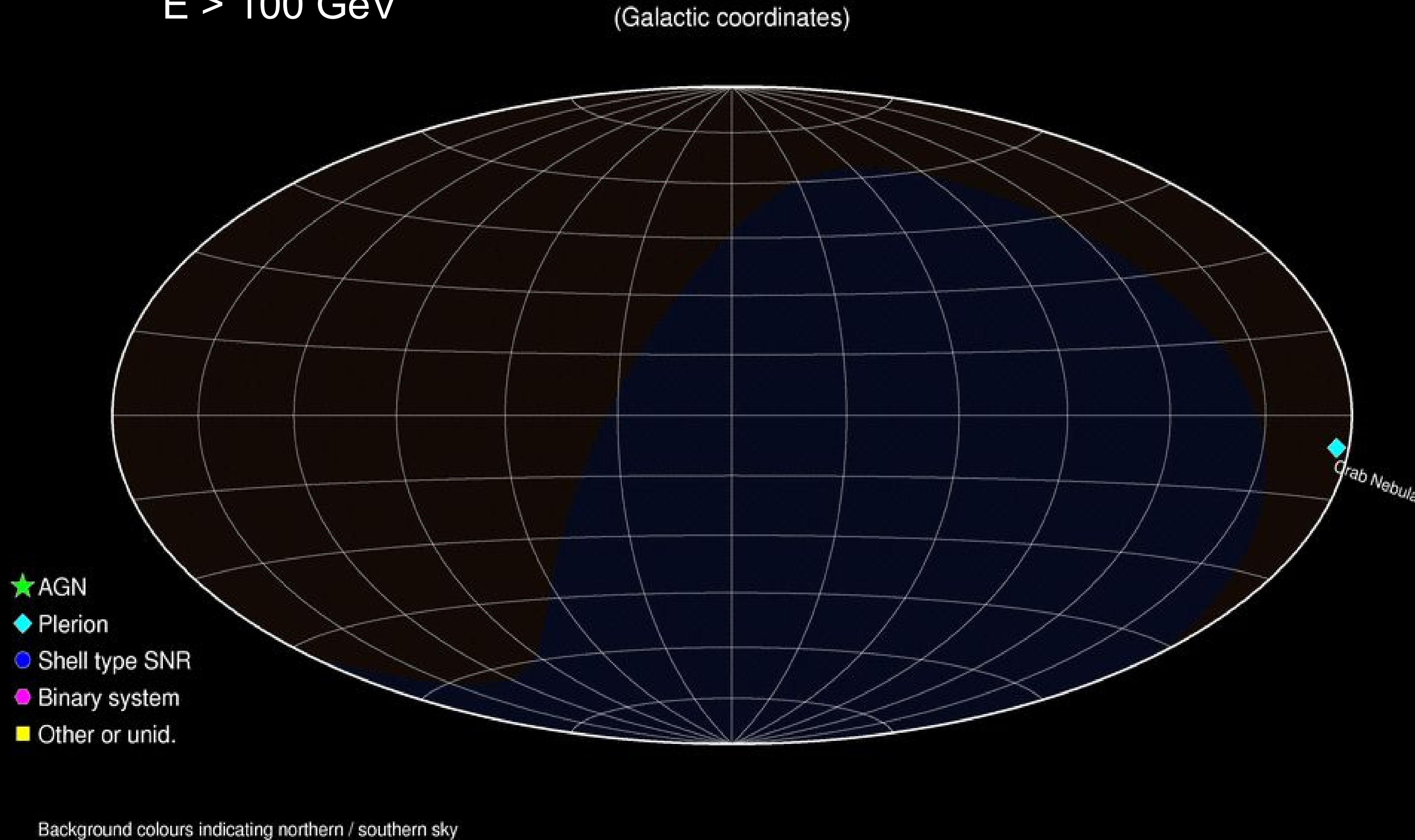


- AGN
- Plerion
- Shell type SNR
- Binary system
- Other or unid.

Background colours indicating northern / southern sky

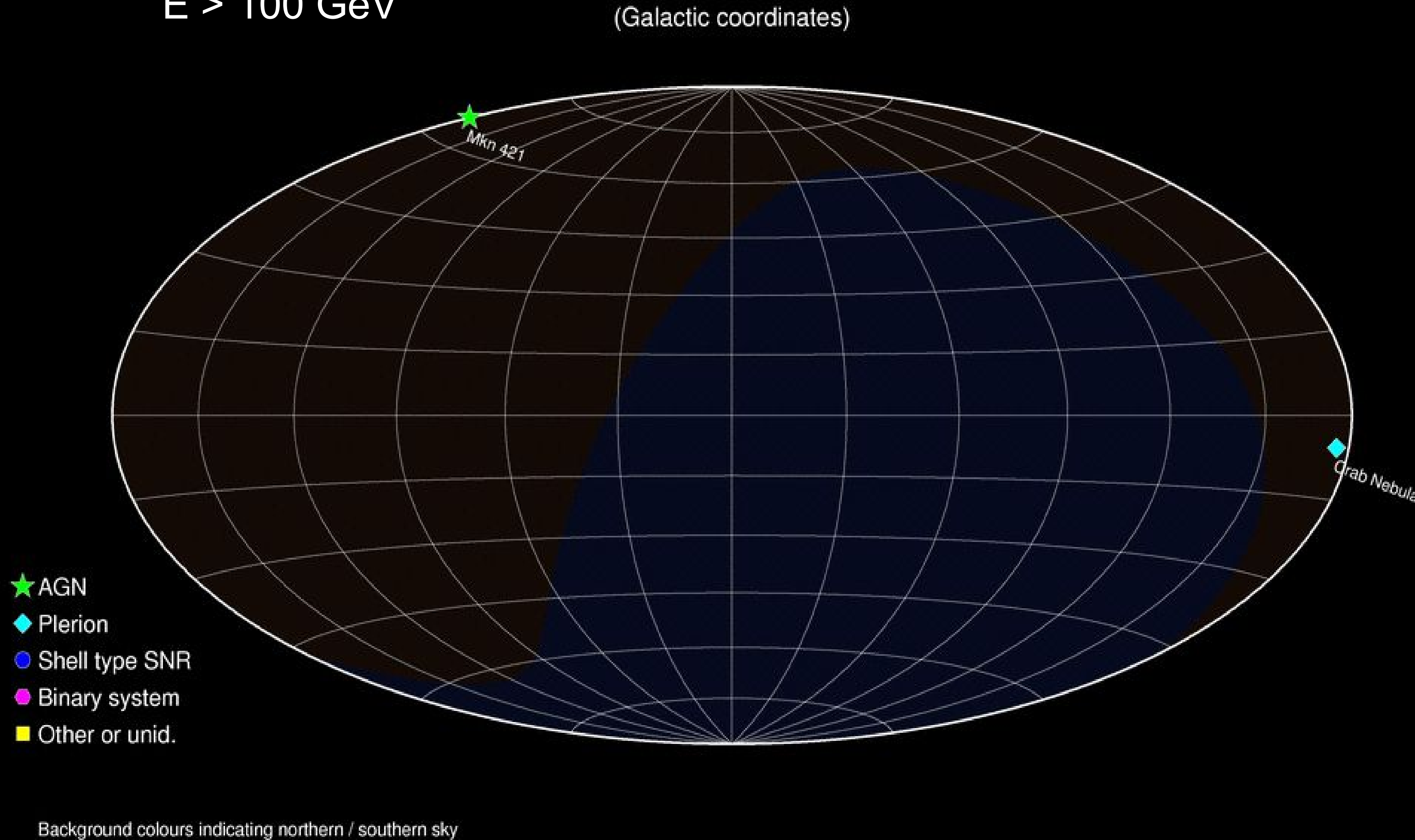
The High-Energy Gamma Ray Sky (1989)

E > 100 GeV



The High-Energy Gamma Ray Sky (1992)

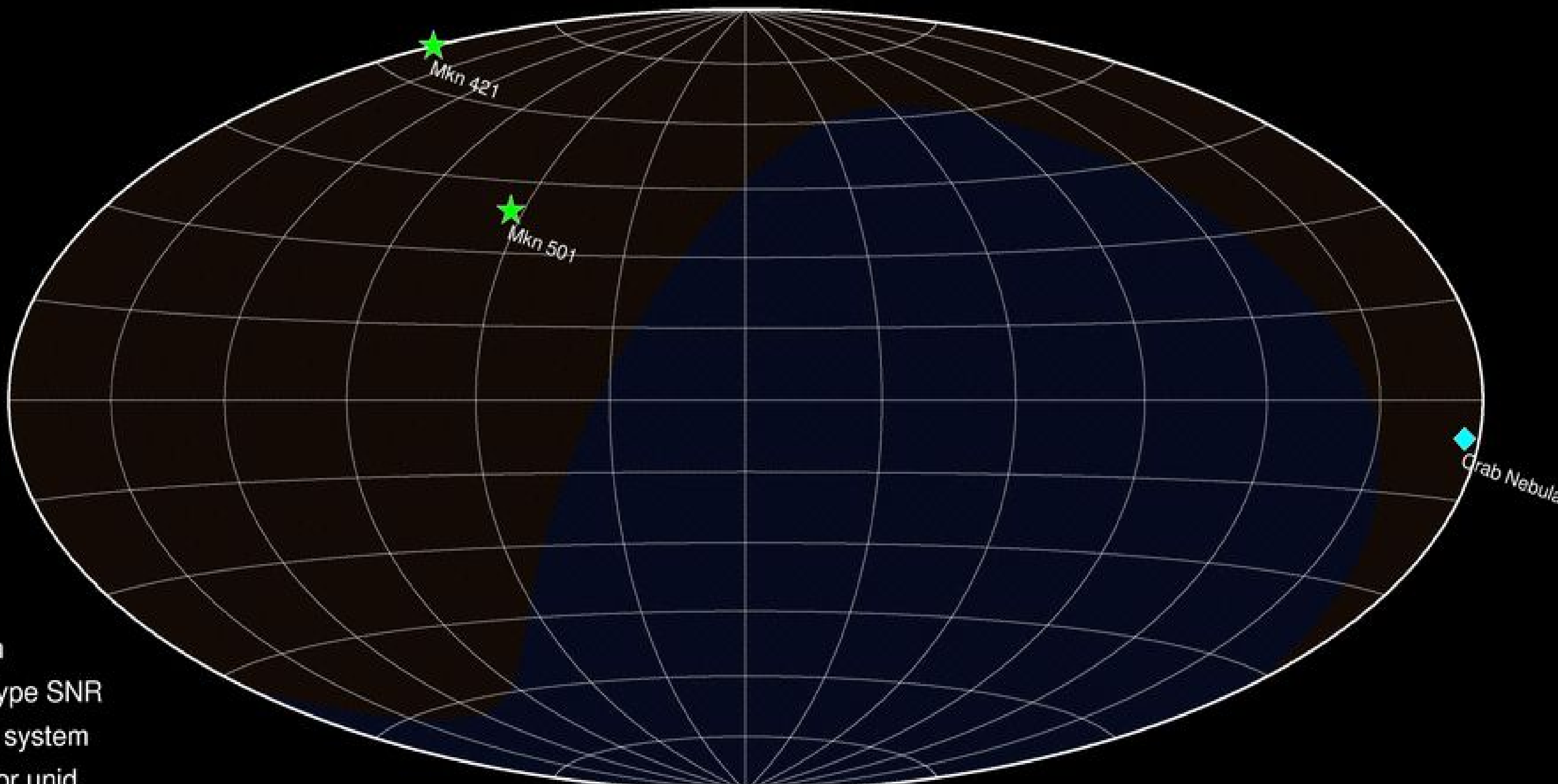
E > 100 GeV



The High-Energy Gamma Ray Sky (1996)

E > 100 GeV

(Galactic coordinates)

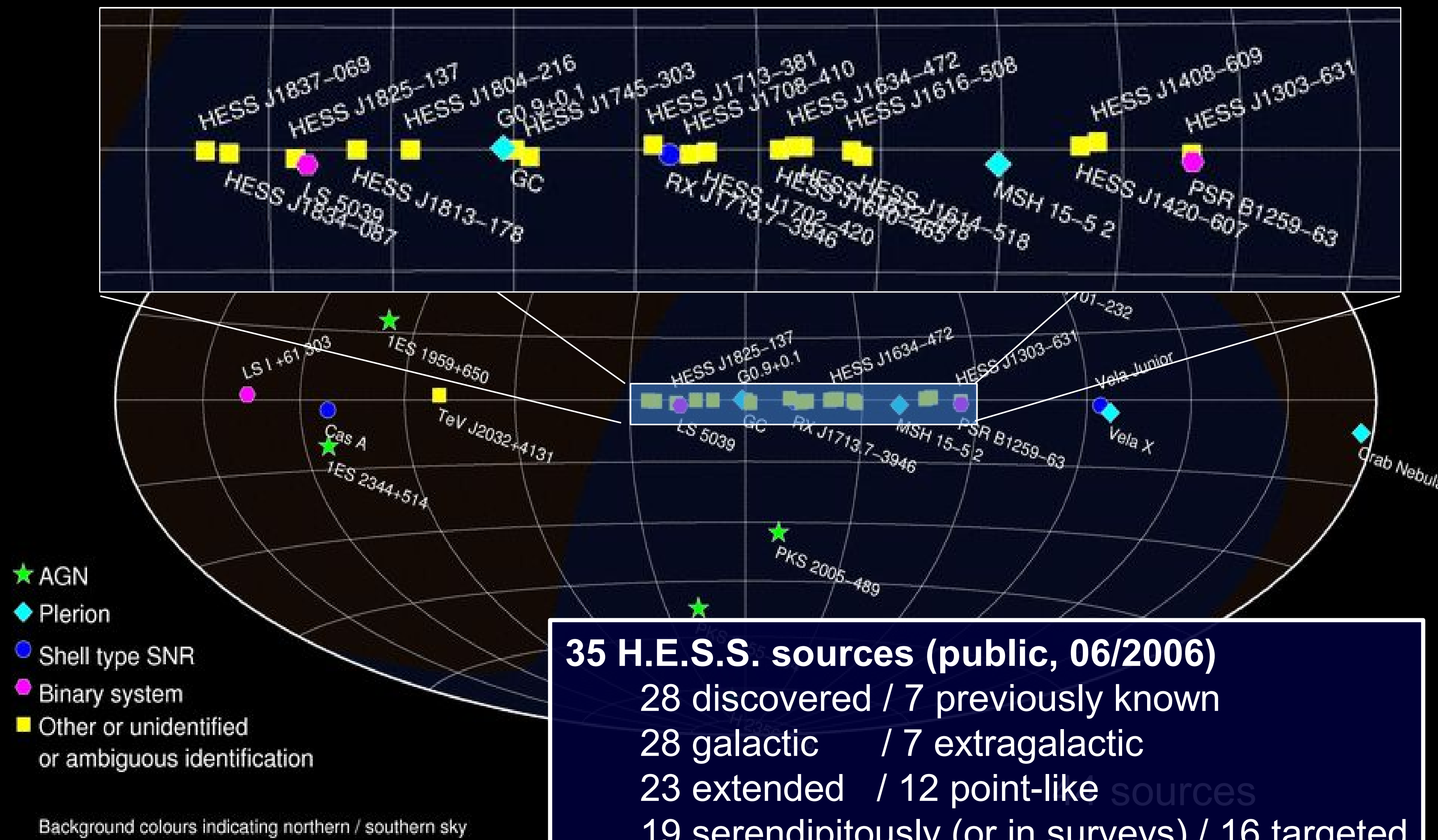


- AGN
- Plerion
- Shell type SNR
- Binary system
- Other or unid.

Background colours indicating northern / southern sky

The High–Energy Gamma Ray Sky (2007)

(Galactic coordinates)



35 H.E.S.S. sources (public, 06/2006)

28 discovered / 7 previously known

28 galactic / 7 extragalactic

23 extended / 12 point-like

19 serendipitously (or in surveys) / 16 targeted

Courtesy: K.Bernlöhr

TeV Gamma-Ray Astronomy
H.E.S.S. and beyond

- Physics Motivation
- Imaging Cherenkov Technique
- H.E.S.S. Results
  - Galactic sources
  - Extragalactic sources
- The future CTA

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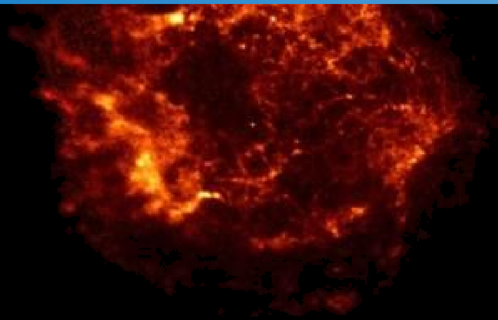
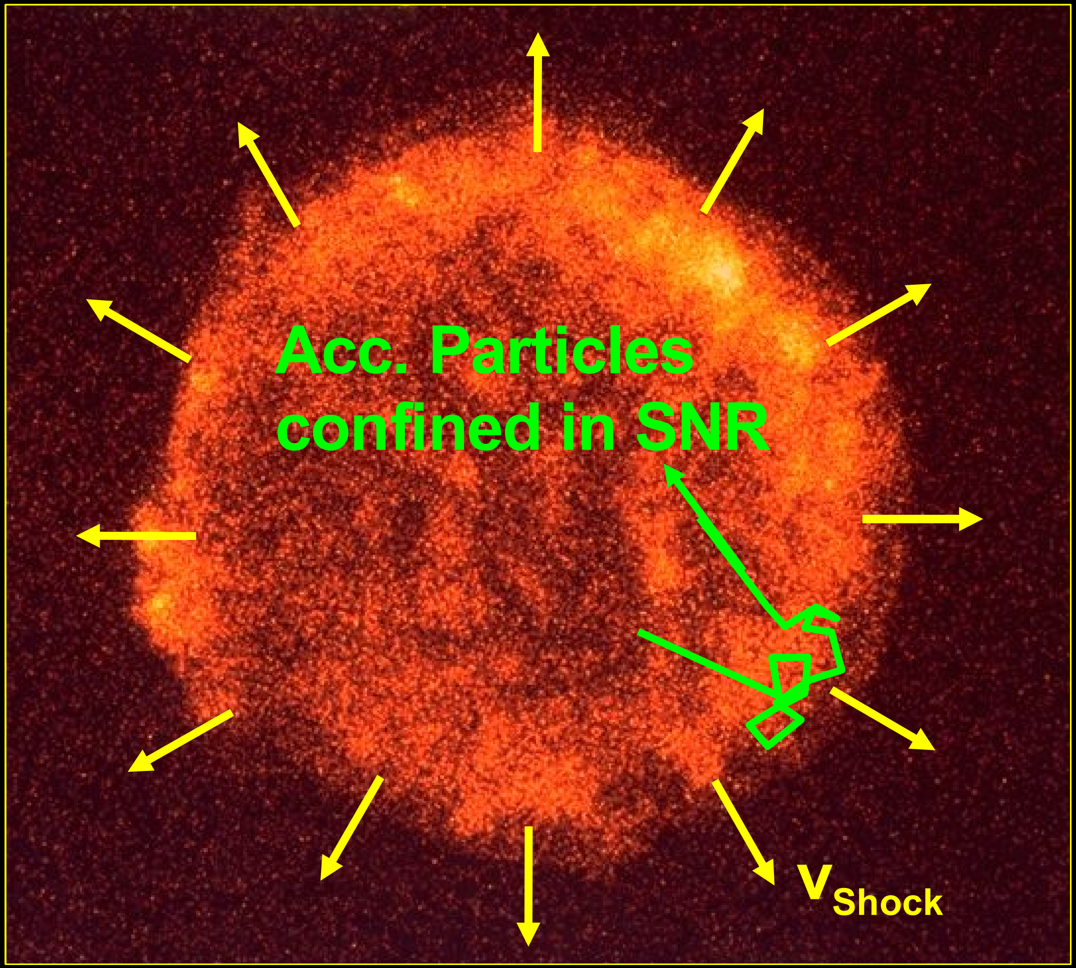
Classes of Galactic Sources



Related Physics:
- Shock acceleration
- Sources of Cosmic Rays
- Leptonic vs hadronic models

- ➢ Supernova remnants
- ➢ Pulsar wind nebulae
- ➢ Binary Systems
- ➢ Galactic center
- ➢ “Dark sources”

The Sources of Galactic Cosmic Rays ?



Elastic collisions of particles at the shock front
→ Fermi acceleration

Universal Law

dN/dE ~ $E^{-\alpha}$; α ~ 2.1

Gamma Ray Emission

from π^o Decay after collision

w/ ambient matter

Galactic CR budget

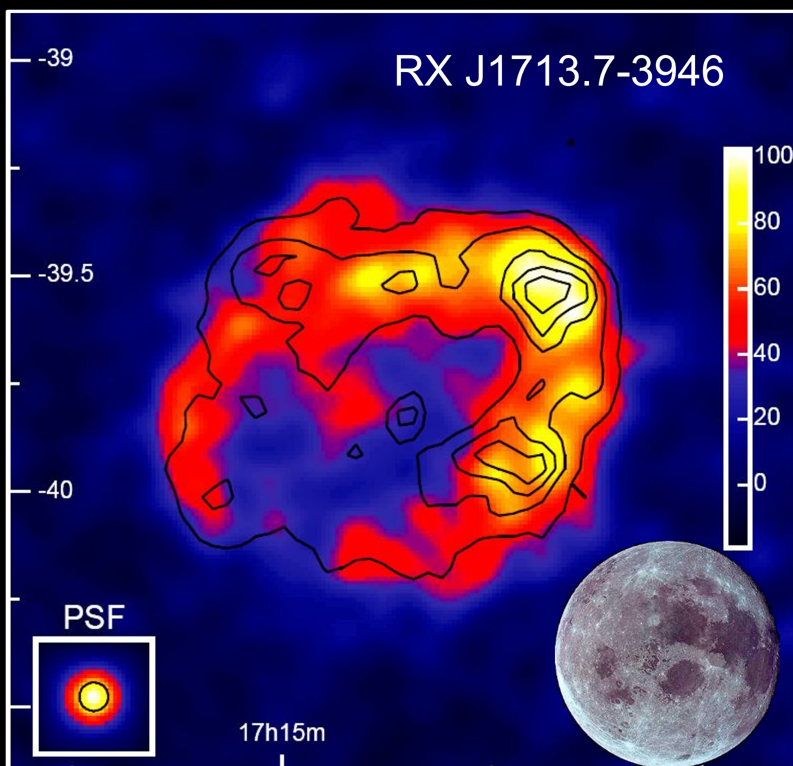
1 SNR / 30 yr

10^{51} erg each

→ 10 % efficiency into CR would be sufficient

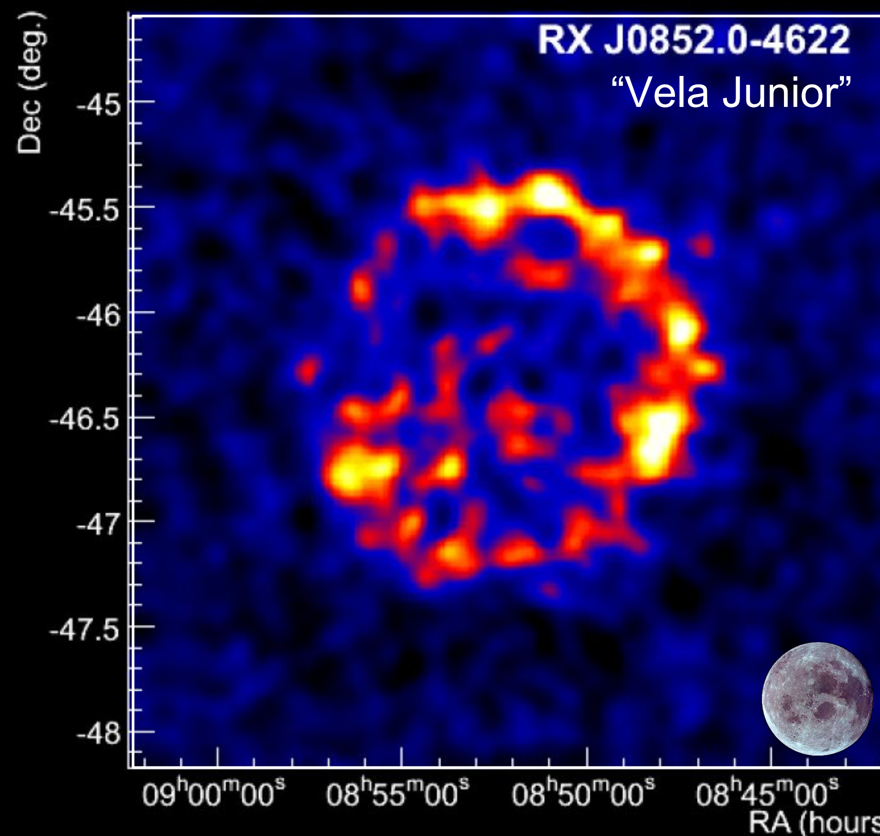
TeV Gamma-Rays from SNRs

See also: H.E.S.S., Nature (2004)



2004-2006 Data

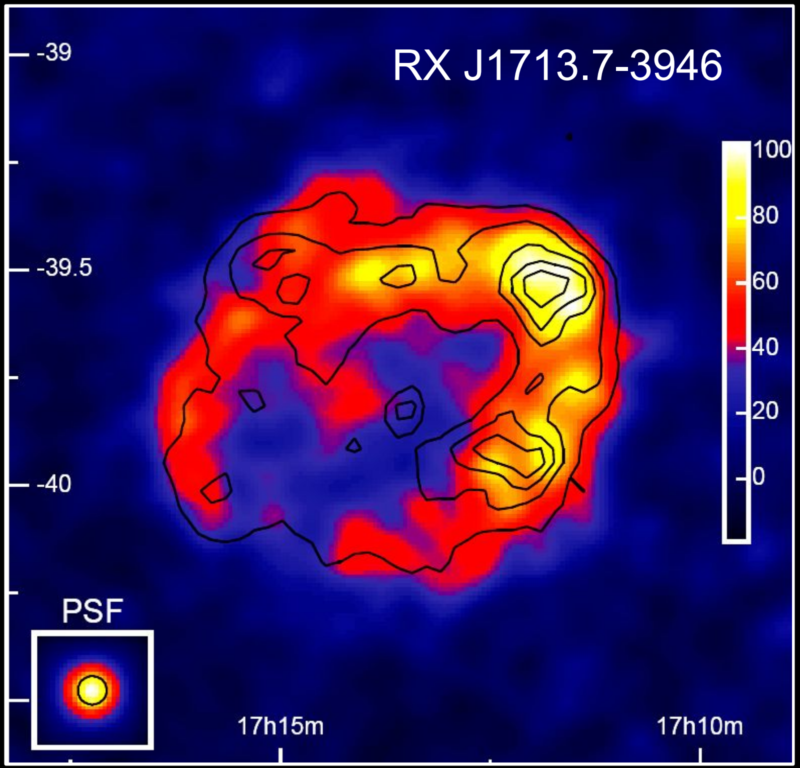
Largest TeV source: ~2 deg diameter



Proof of TeV emission from the shell of SNRs

TeV Gamma-Rays from SNRs

See also: H.E.S.S., Nature (2004)



2004-2006 Data

Energy of particles at least up to the “knee” ?

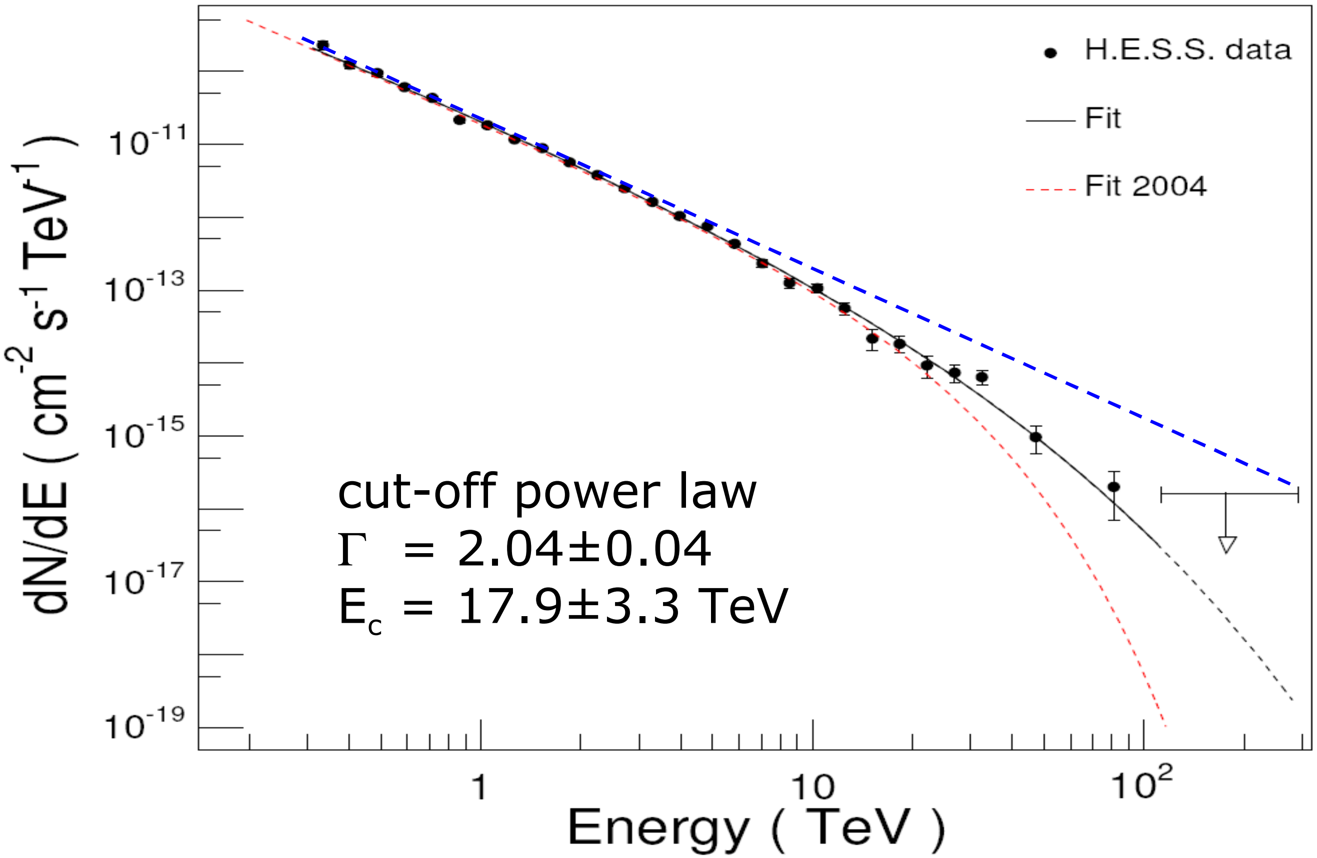
Are the accelerated particles the nucleonic cosmic rays ?

Is O(10 %) converted into Cosmic Rays ?

Proof of TeV emission from the shell of SNRs

Energy Spectrum of RX J1713.7

Particle acceleration to beyond 100 TeV



H.E.S.S., astroph 0611813

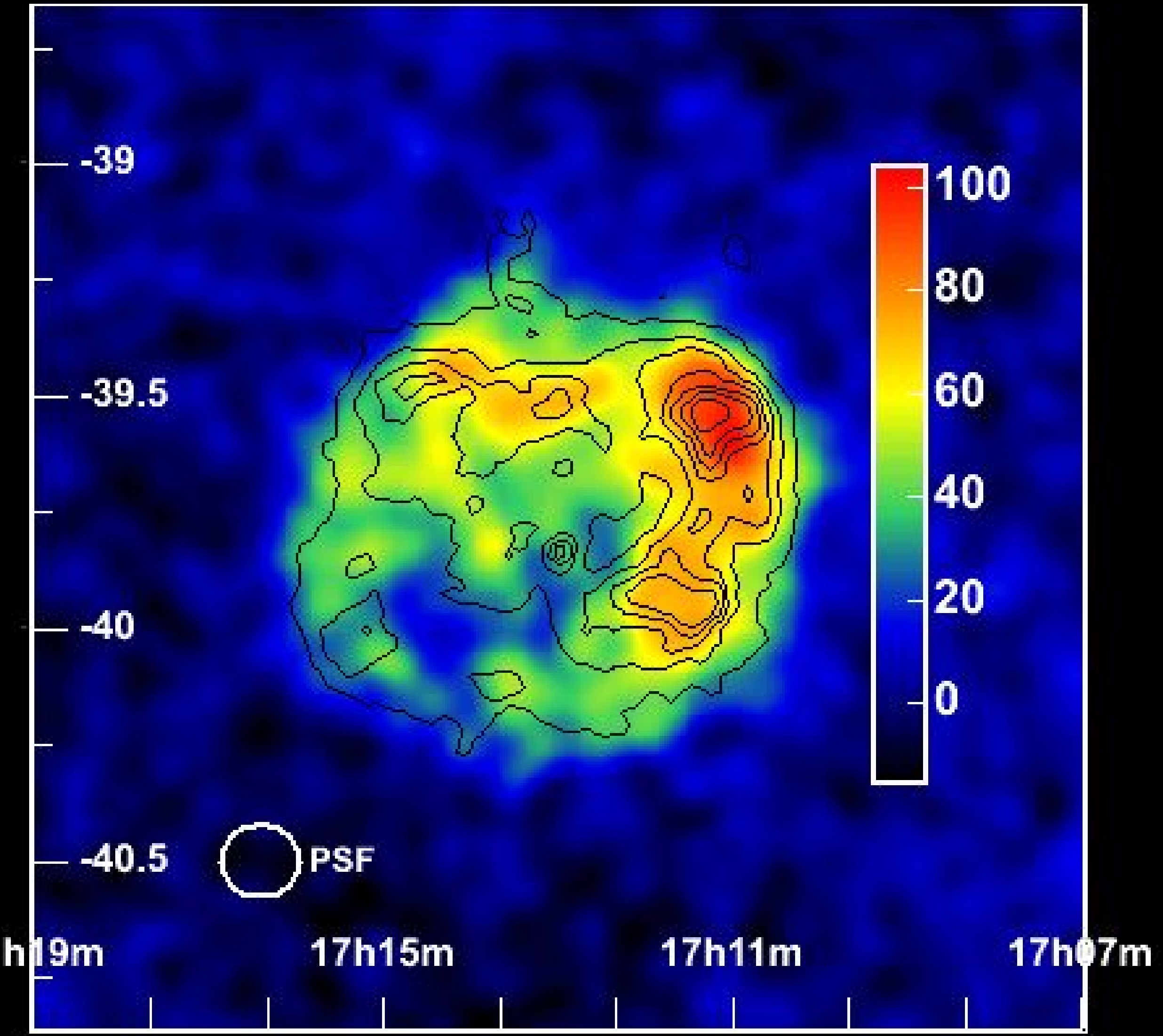
RX J1713.7: TeV / X-ray Correlation

What are the primary particles ?

Almost perfect
X-ray <–> gamma-ray correlation !

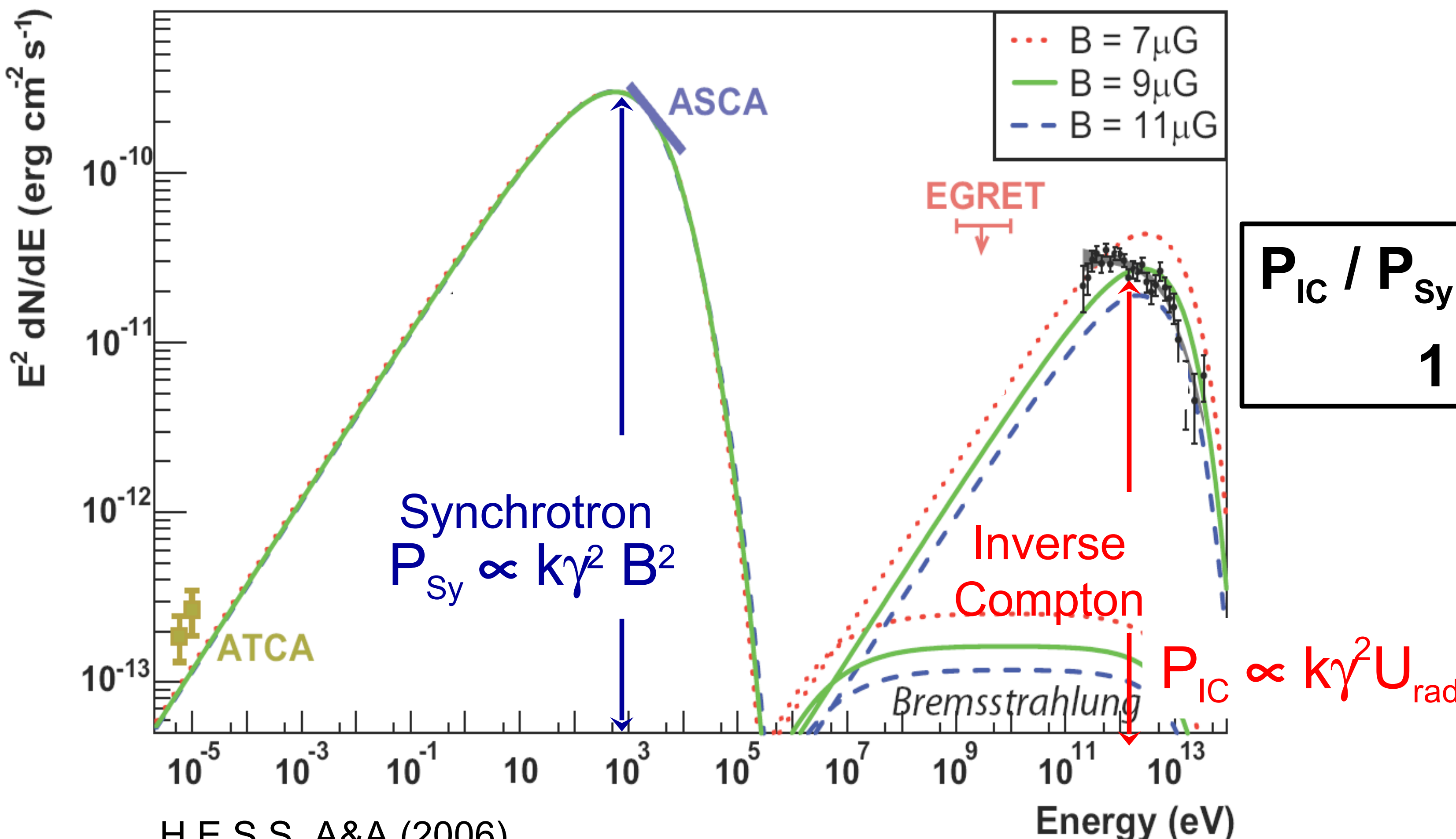
Are the primary particles electrons ?

X-ray contours: ASCA



Leptonic emission model for RXJ 1713

Assume Electrons: Synchrotron + Inverse Compton

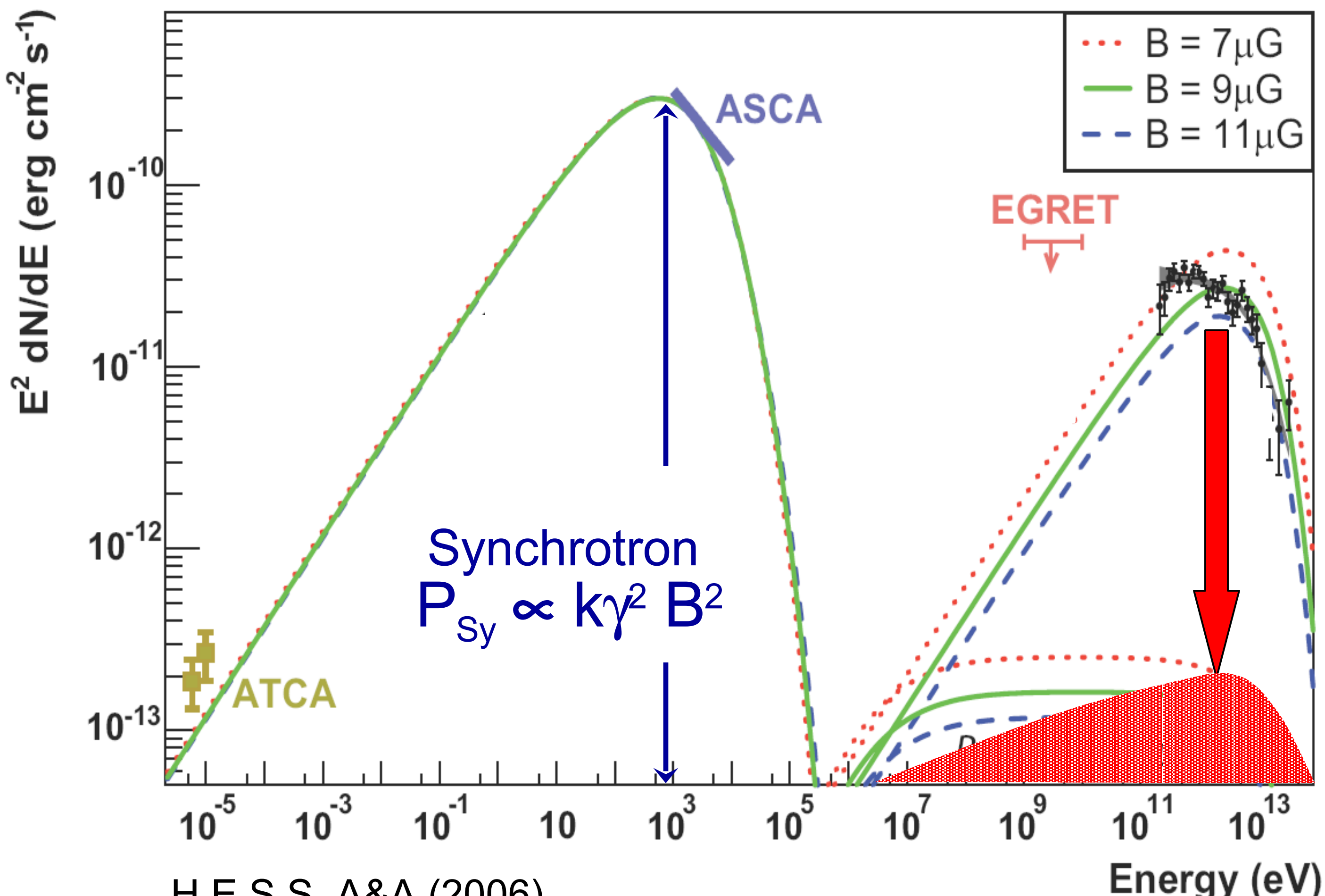


$P_{IC} / P_{Sy} \propto 1 / B^2$

H.E.S.S. A&A (2006)

Leptonic emission model for RXJ 1713

Assume Electrons: Synchrotron + Inverse Compton



H.E.S.S. A&A (2006)

$P_{IC} / P_{Sy} \propto 1 / B^2$

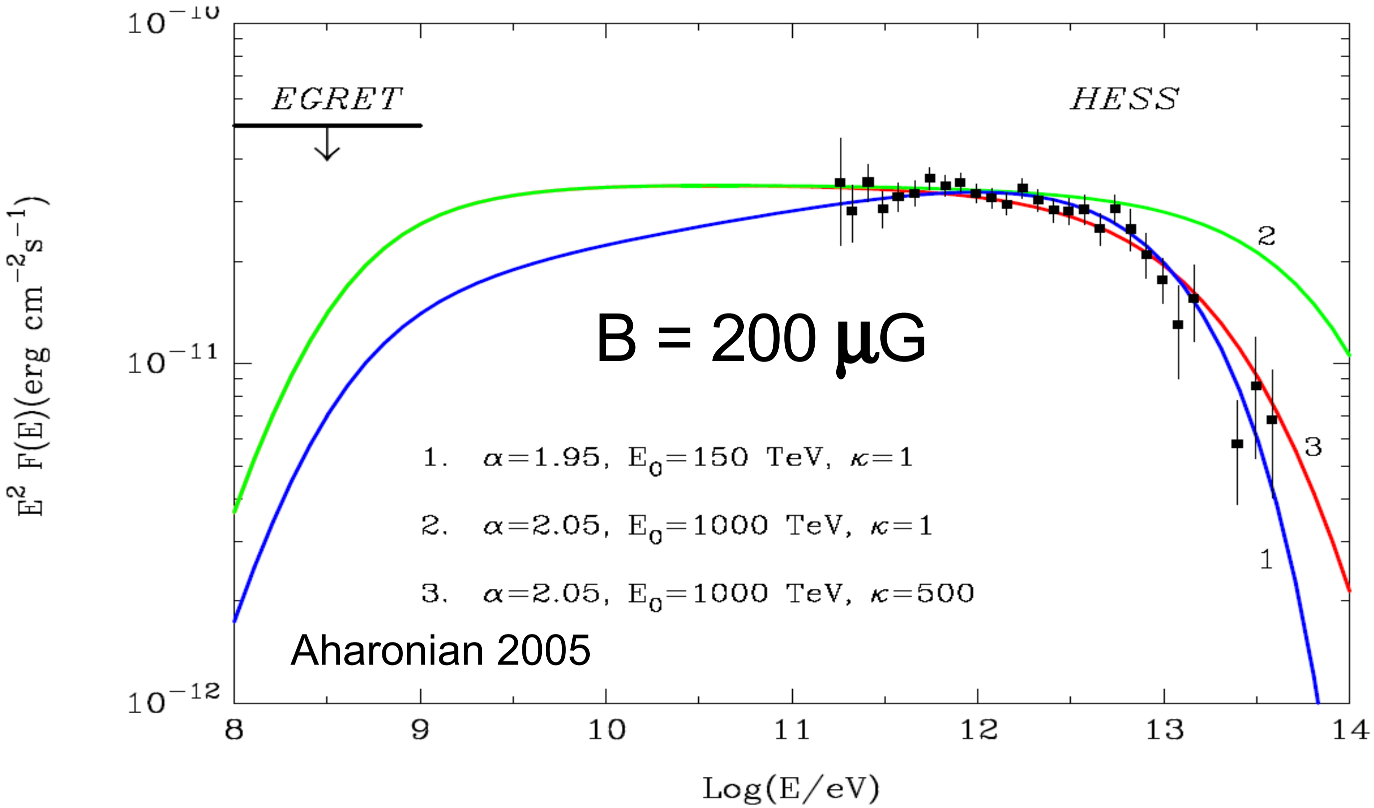
High B-Field

65…230 μG

Berezkho, Völk (2006)

Hadronic emission model for RXJ 1713

Collision of protons w/ ambient gas : $p + p \rightarrow \pi^o + X$



Hadronic models describe data reasonably well !

→ What's the efficiency of the cosmic accelerators ?

Classes of Galactic Sources

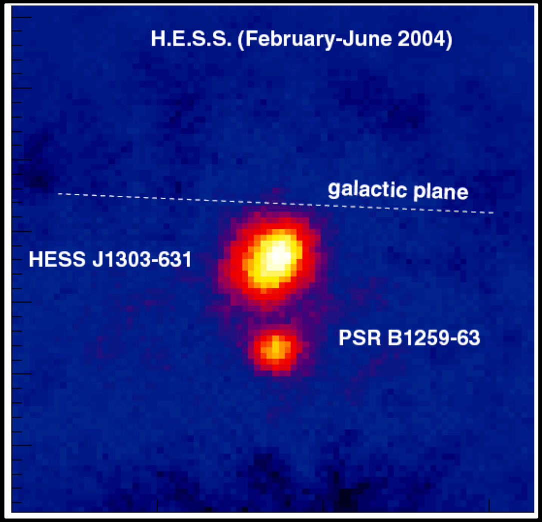
Related Physics :
Relativistic Jets
Accretion by Black Holes / NS

- Supernova remnants
- Pulsar wind nebulae
- Binary Systems
- Galactic center
- “Dark sources”

Binary Systems

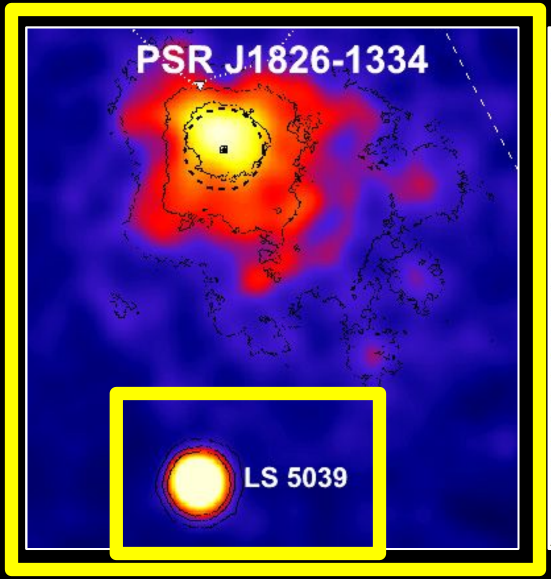
The first galactic TeV sources seen with variable emission

PSR B1259-63 (HESS)



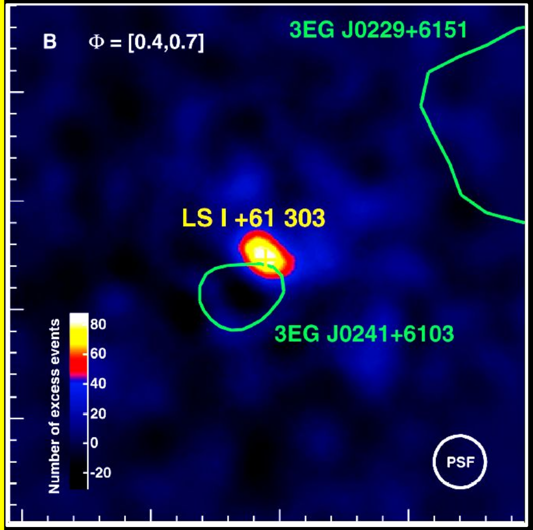
Binary Pulsar System

LS 5039 (HESS)



Microquasar

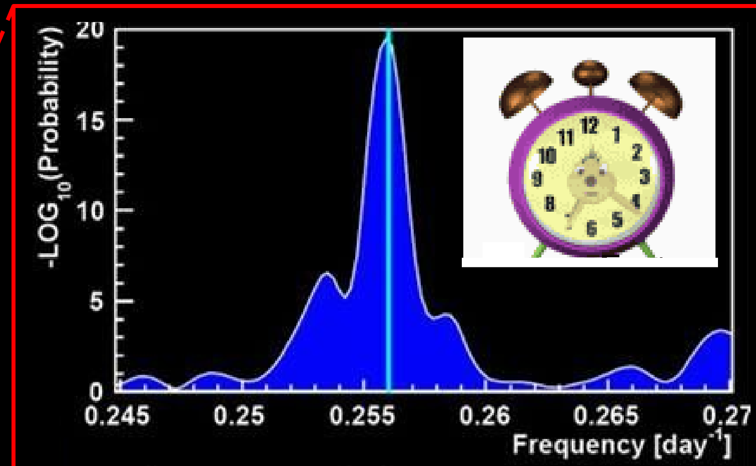
LS I+61 303 (MAGIC)

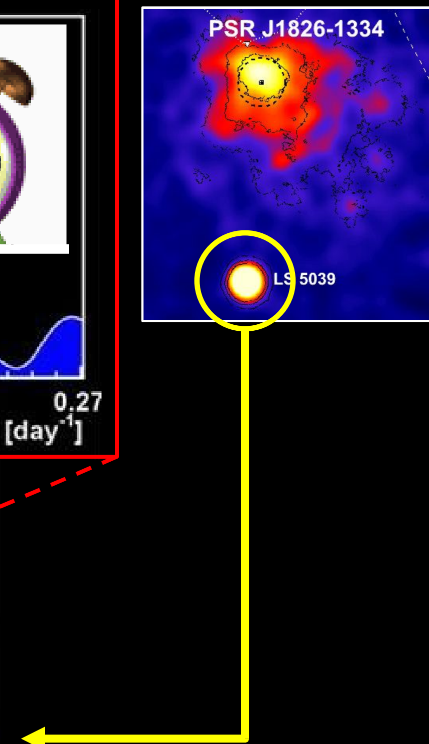


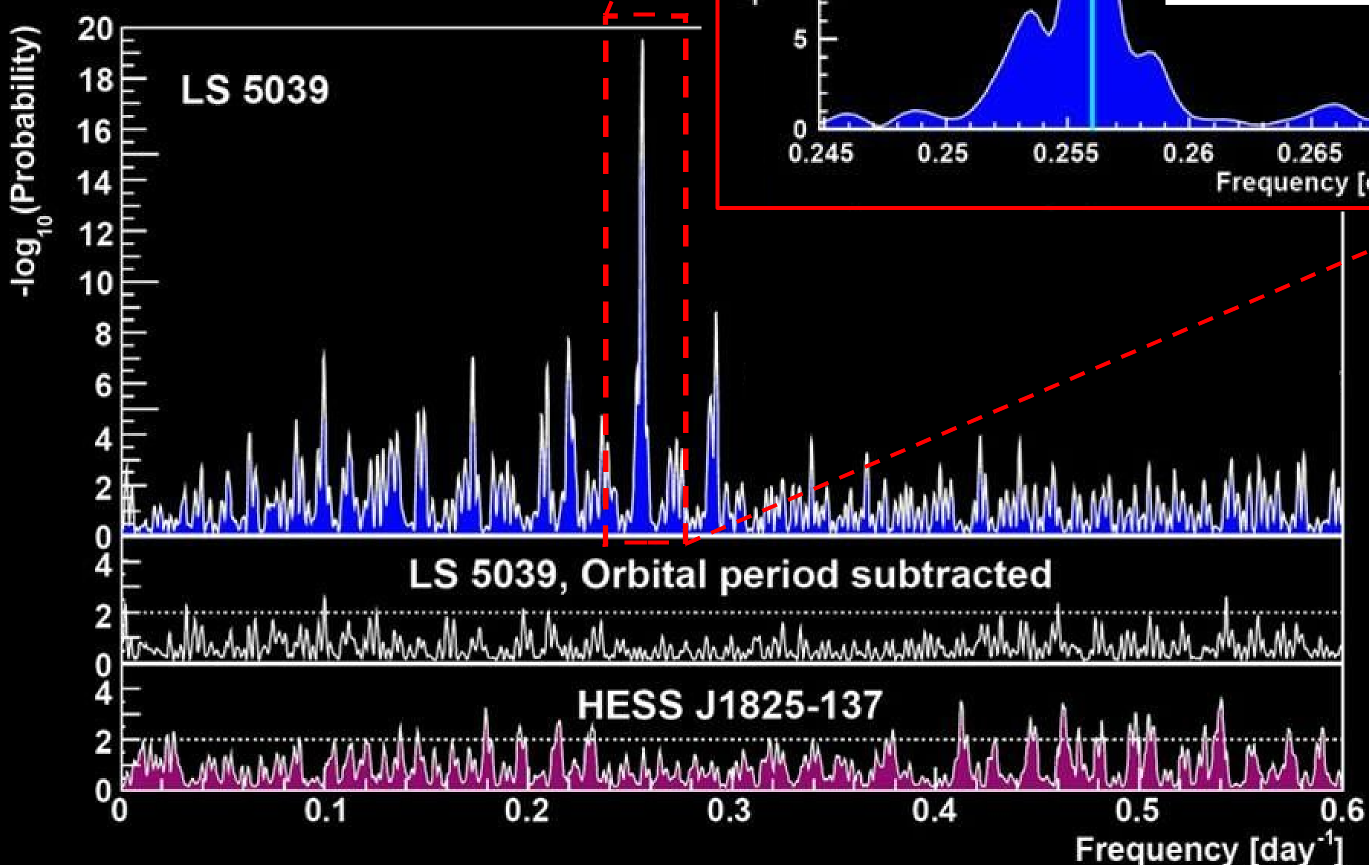
Microquasar

LS 5039: Periodicity Analysis

Period:
HESS: 3.908(2) d
Optical: 3.9060 d





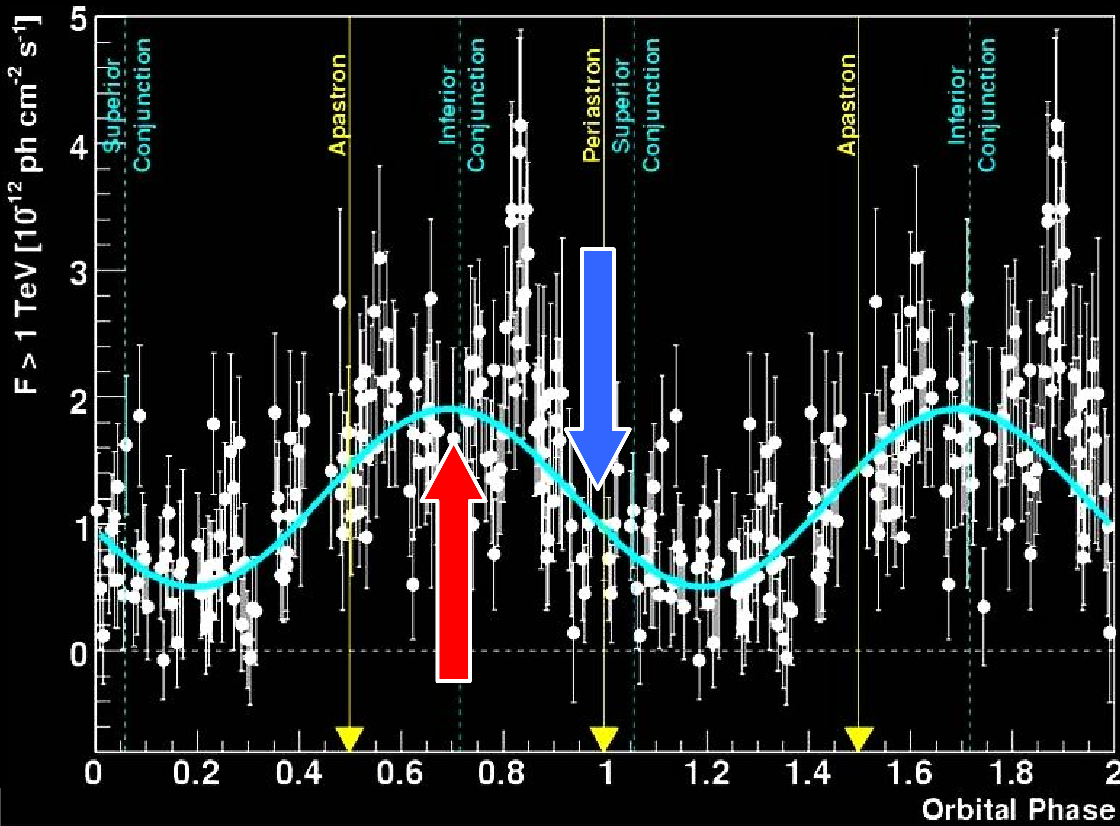


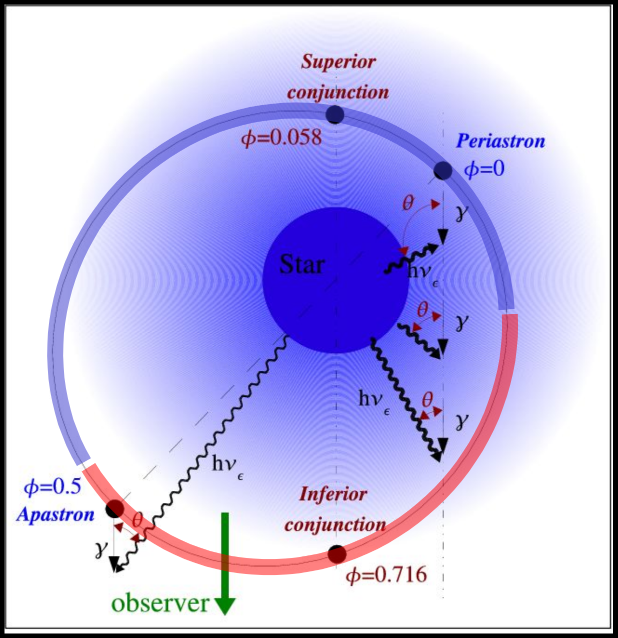
H.E.S.S. Science (2005)
H.E.S.S. A&A (2006)

LS 5039: Periodicity Analysis

First detection of periodic emission at energies above 100 GeV

Folded light curve (two periods)





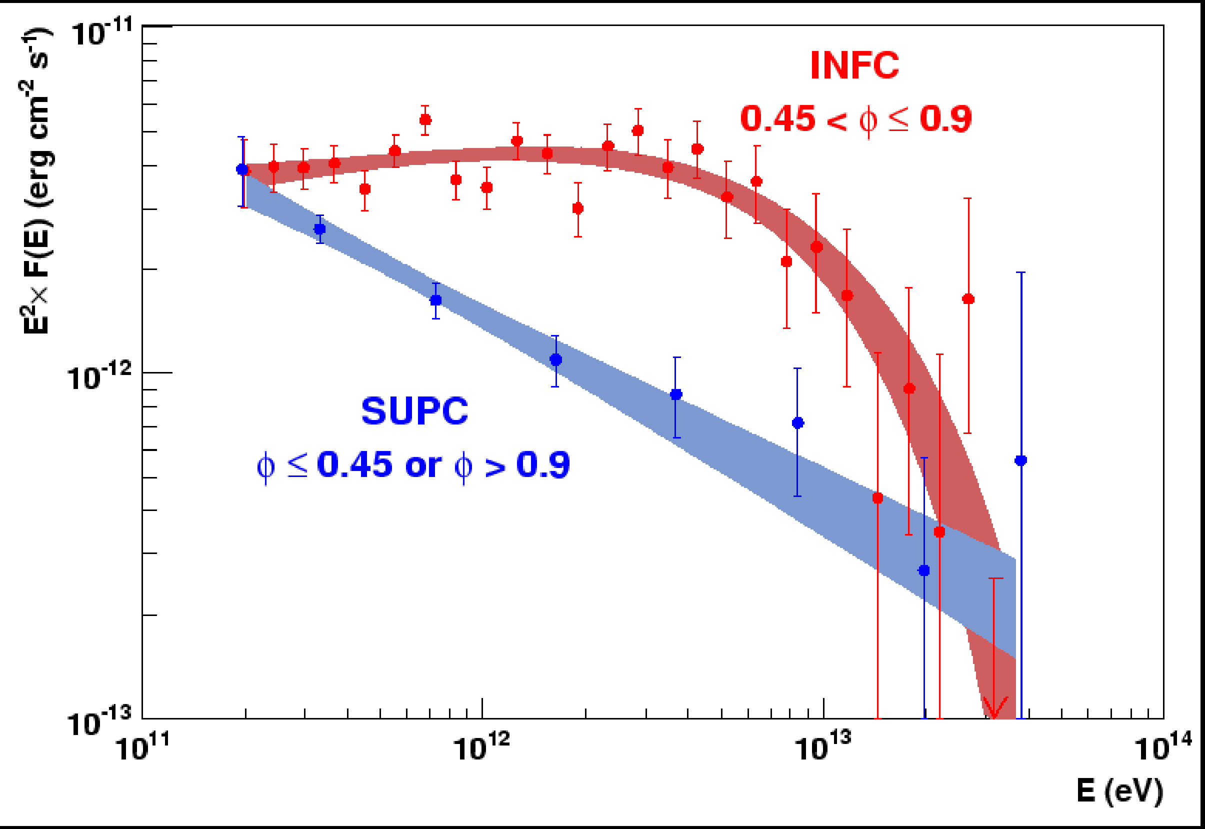
Observer

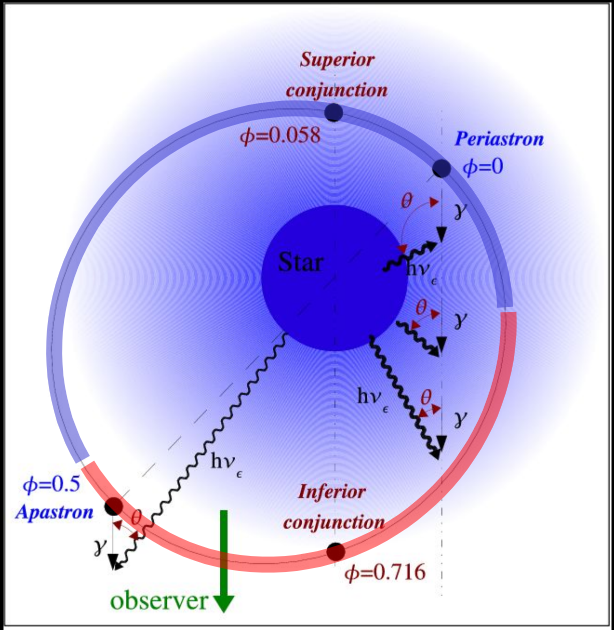
LS 5039: Energy Spectrum

Spectrum harder and flux higher at INFC than at SUPC

→ need to consider intrinsic absorption of γ-rays in photon field of the star (varies over orbit)

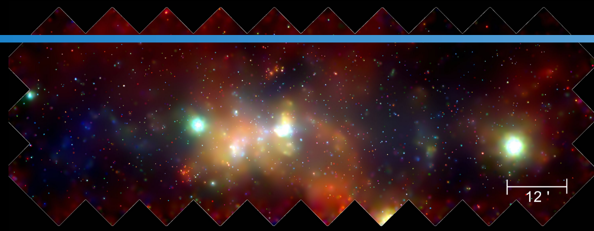
→ and changes in accretion/acceleration process





Observer

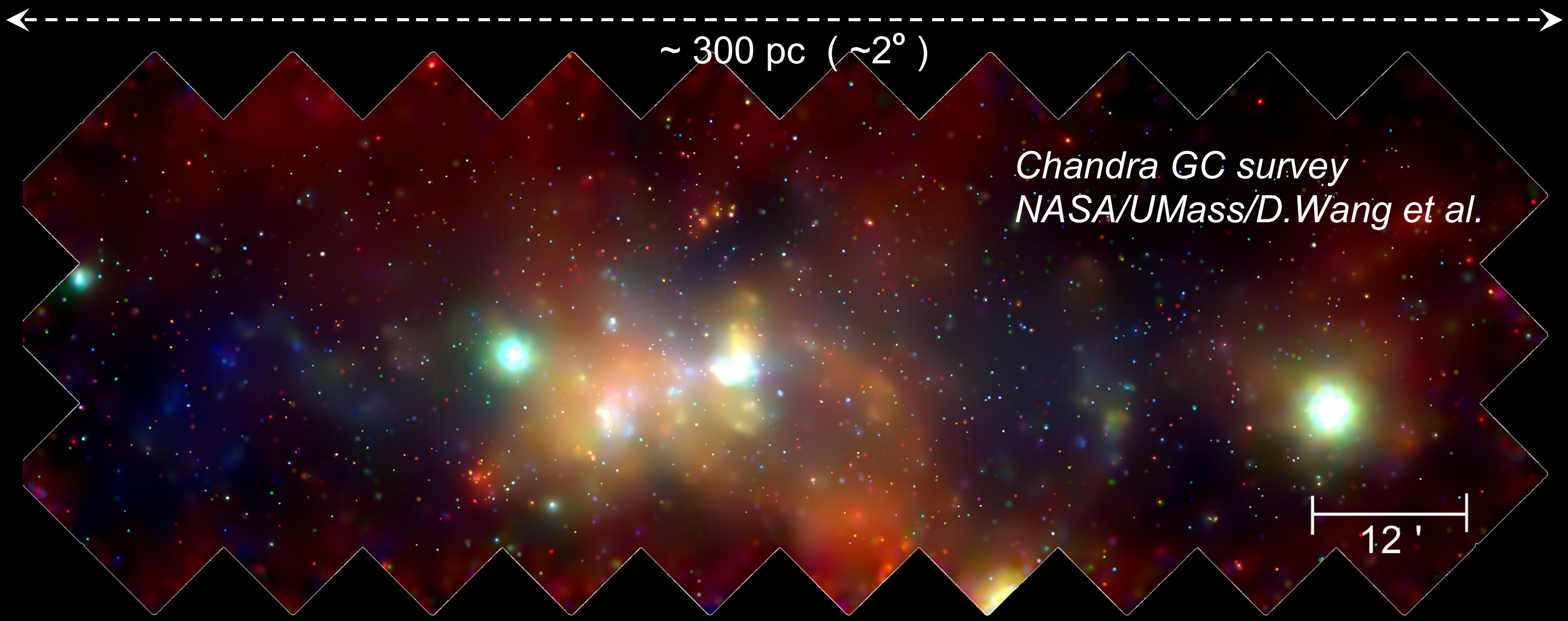
Classes of Galactic Sources



Related Physics :
- Accretion by SM Black Hole
- CR Propagation
- Dark Matter
- …

- Supernova remnants
- Pulsar wind nebulae
- Binary Systems
- **Galactic center**
- “Dark sources”

Galactic Center Region



Astrophysics:

full “zoo” of objects
Pulsars and PWN
Supernova remnants
X-Ray binaries
Molecular clouds

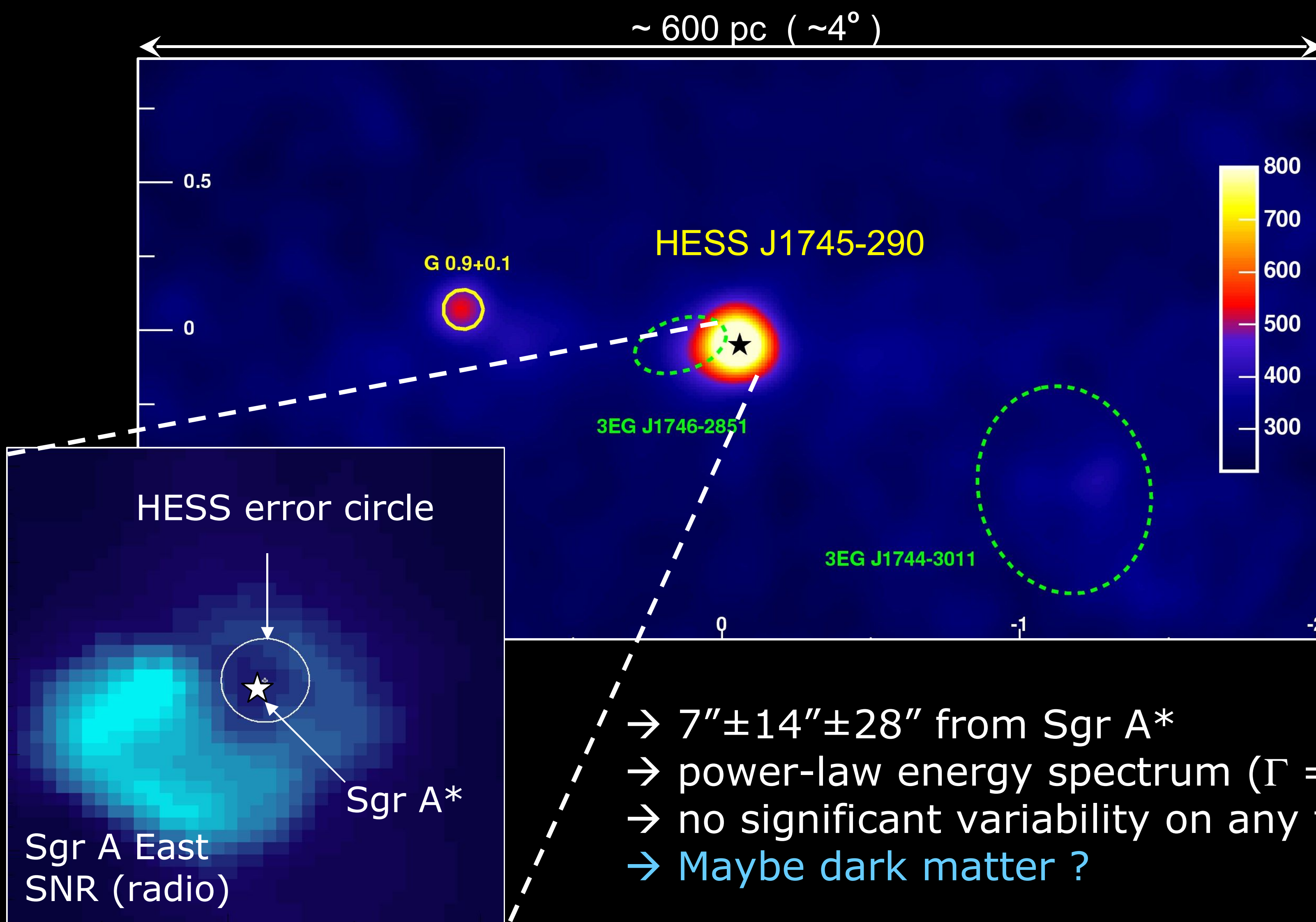
Bit more exotic:

Supermassive BH Sgr A*

Even more exotic:

Dark Matter accumulation
→ Neutralino annihilation

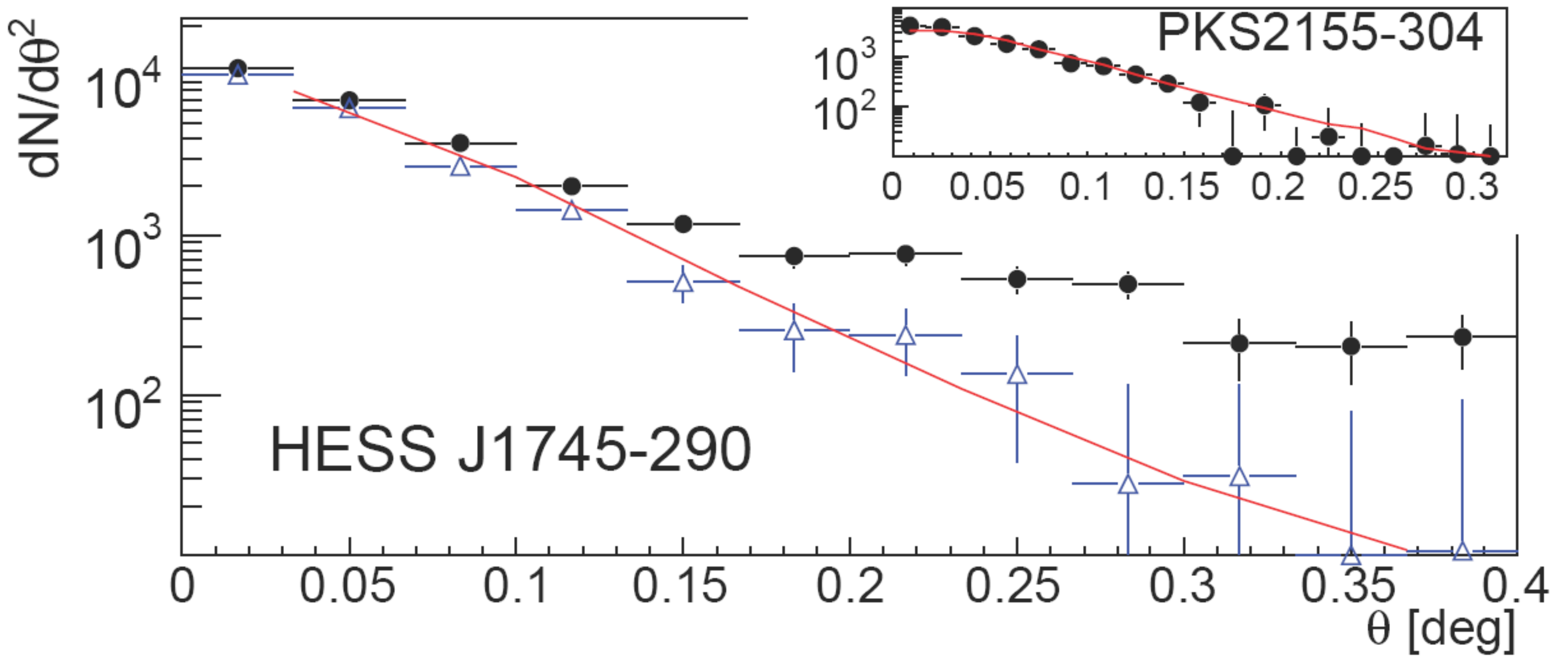
The Galactic Center Region



→ 7″±14″±28″ from Sgr A*
→ power-law energy spectrum ($\Gamma = 2.25$)
→ no significant variability on any time scale
→ Maybe dark matter ?

Dark Matter at the Galactic Center ?

Angular distribution

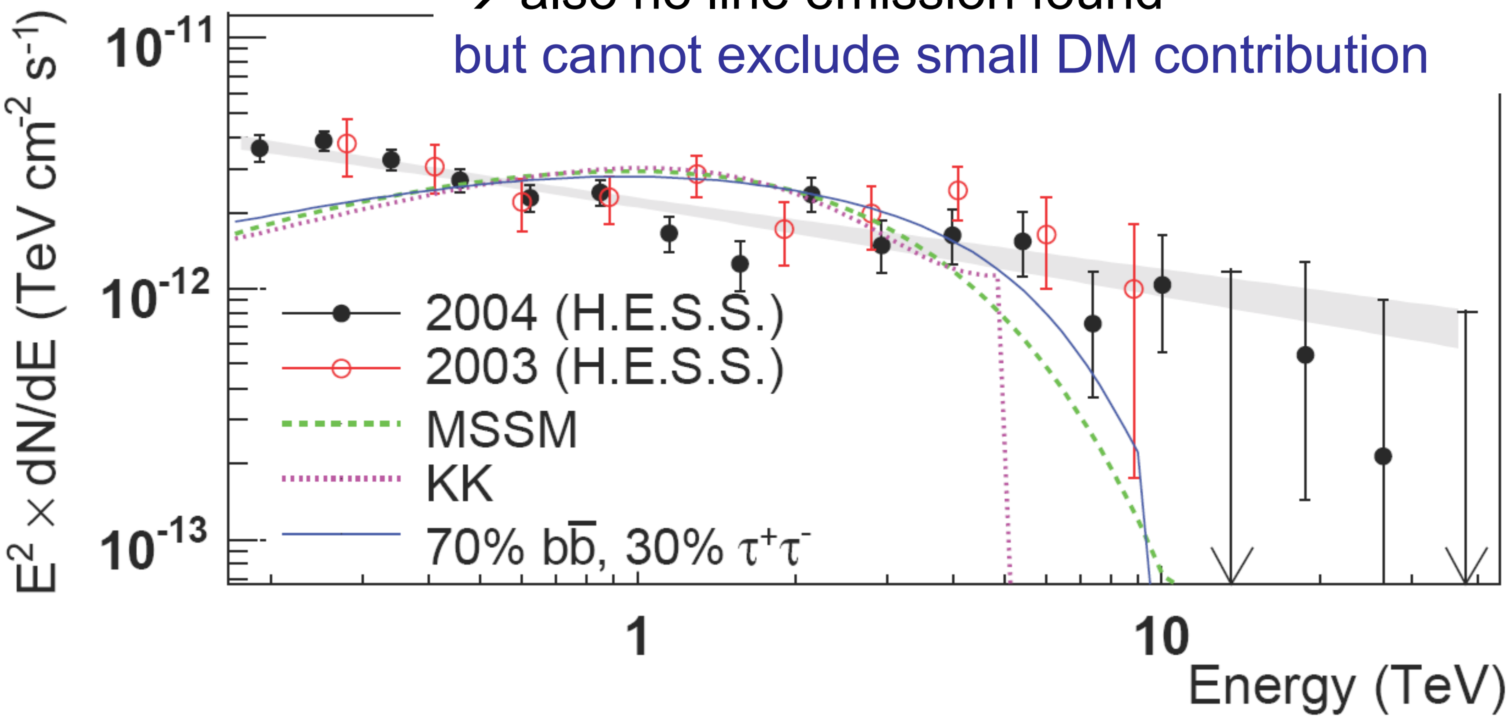


Well described by H.E.S.S. PSF for point like source

H.E.S.S., PRL 97 (2006)

Dark Matter at the Galactic Center ?

→ need uncomfortably high neutralino masses
→ spectrum incompatible with simple scenarios
→ also no line emission found
but cannot exclude small DM contribution



H.E.S.S., PRL 97 (2006)

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H.E.S.S. and beyond

- Physics Motivation
- Imaging Cherenkov Technique
- H.E.S.S. Results
  - Galactic sources
  - Extragalactic sources
- The future: CTA

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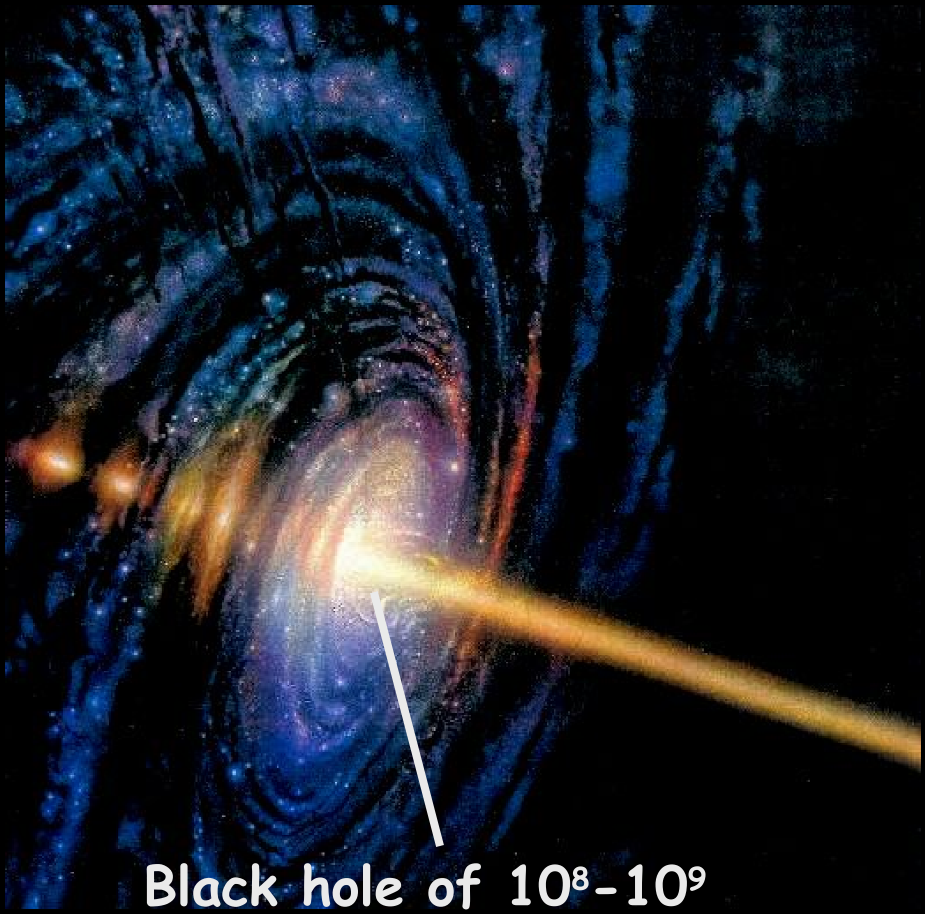
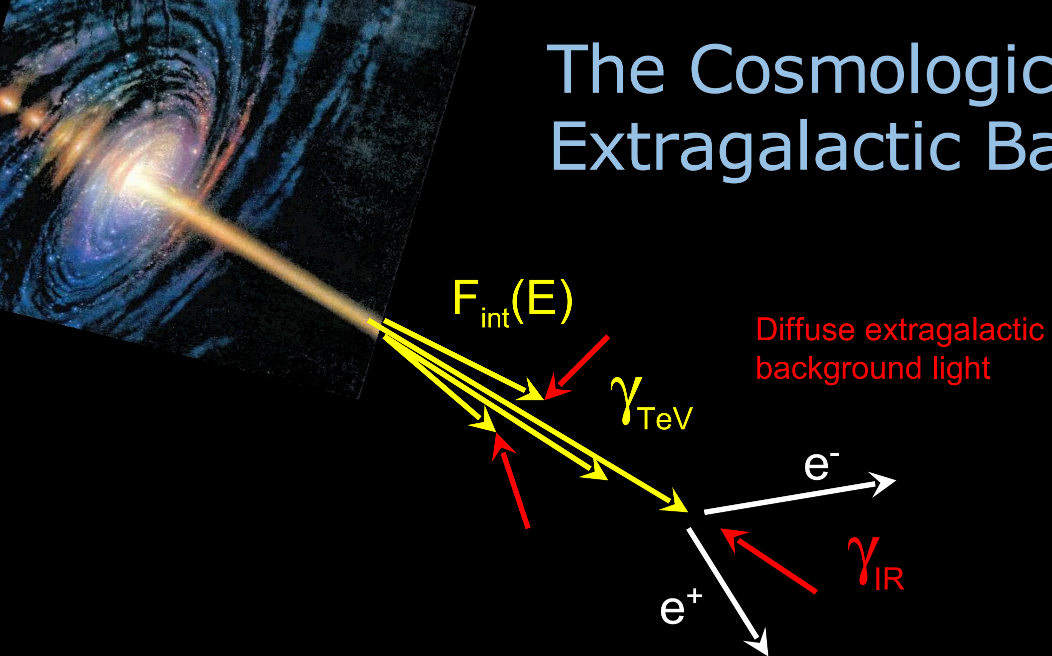
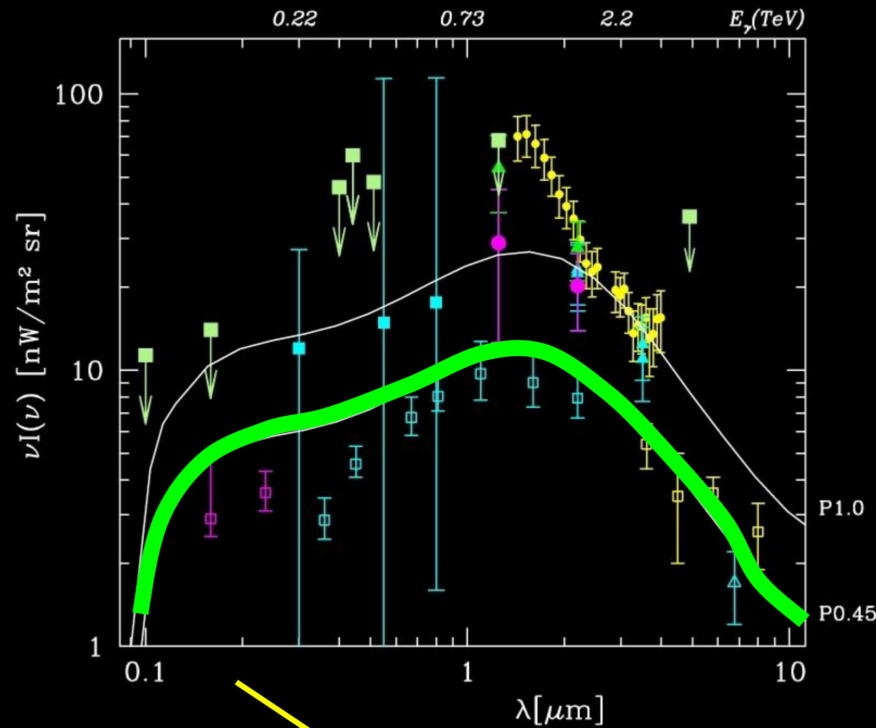
Active Galactic Nuclei & Cosmology

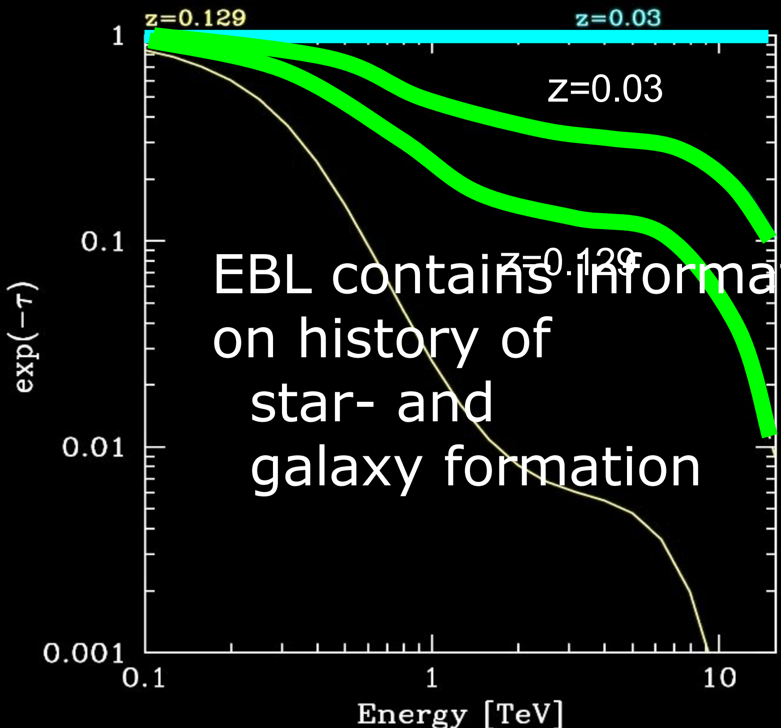


Object	Z
M87	0.0043
Mkn 421	0.031
Mkn 501	0.034
1ES2344+514	0.044
Mkn 180	0.045
1ES 1959+650	0.047
PKS 2005-489	0.071
PKS 2155-304	0.117
H1426+428	0.129
H2356-309	0.165
1ES 1218+304	0.182
1ES 1101-232	0.186
PG 1553+113	>0.25 ?

The Cosmological Extragalactic Background Light (EBL)

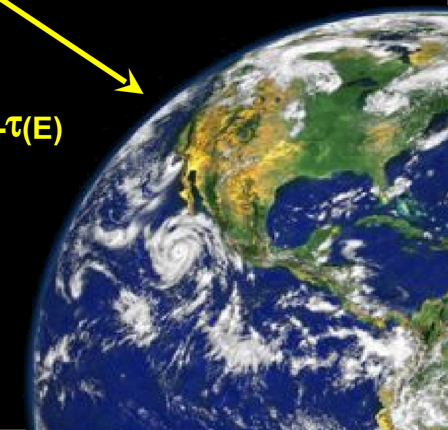




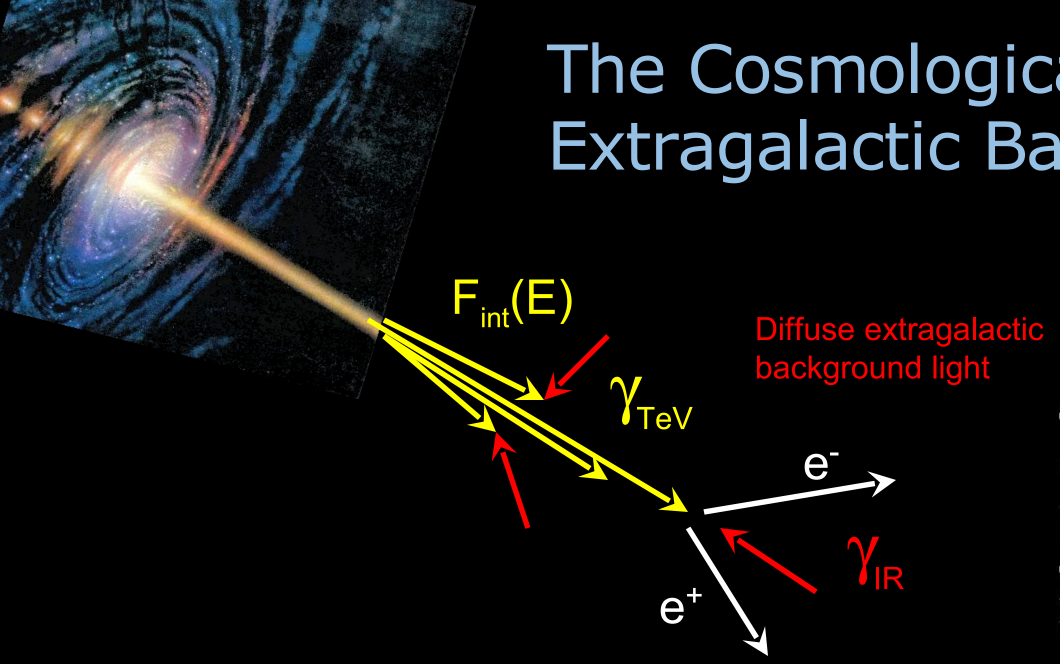


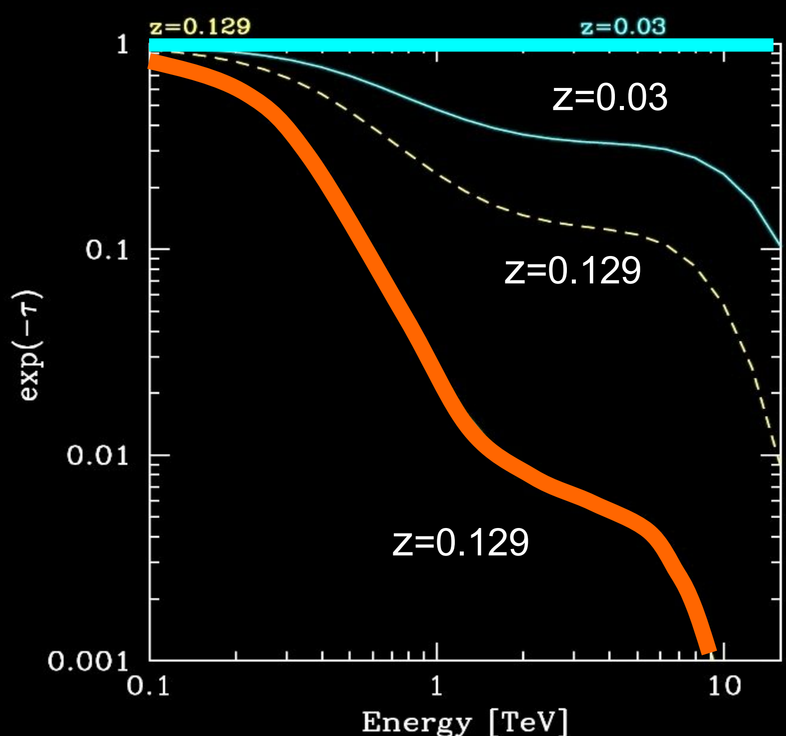
EBL contains information on history of star- and galaxy formation

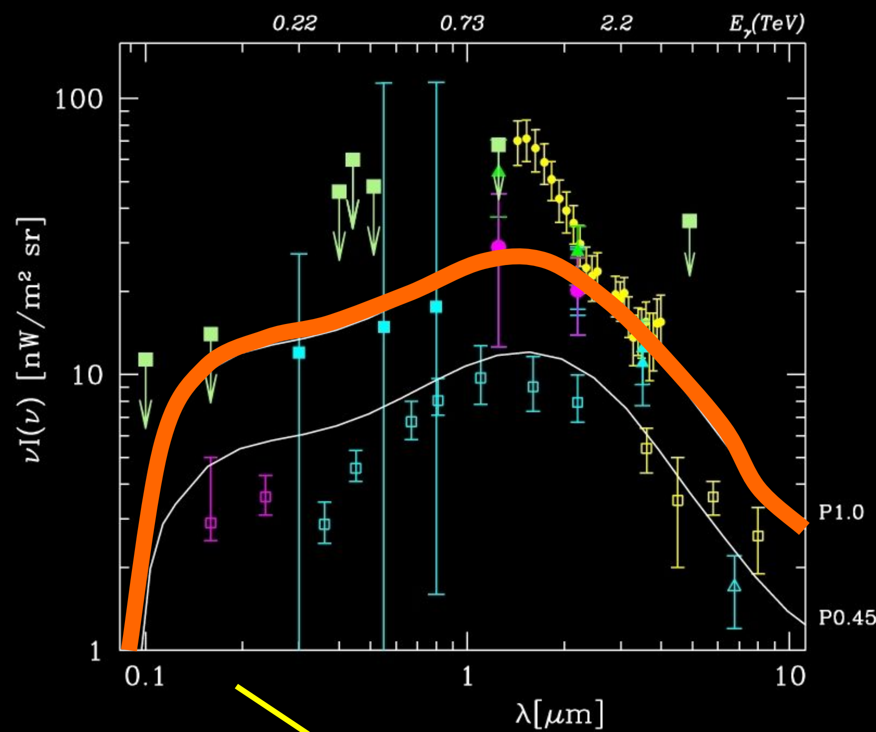
$F_{obs}(E) = F_{int}(E) \cdot e^{-\tau(E)}$



The Cosmological Extragalactic Background Light (EBL)

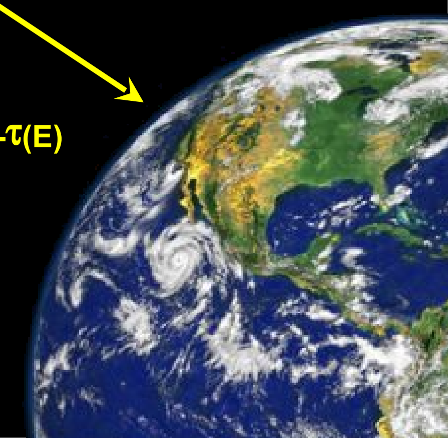






$F_{obs}(E) =$

$F_{int}(E) \cdot e^{-\tau(E)}$



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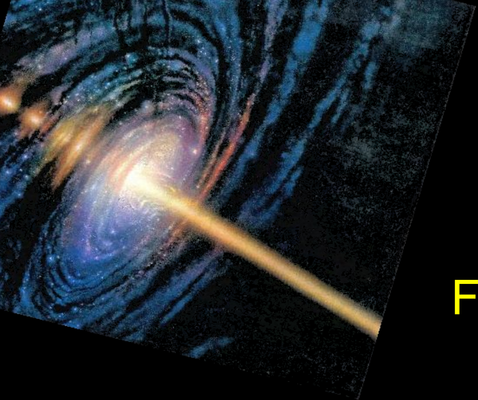
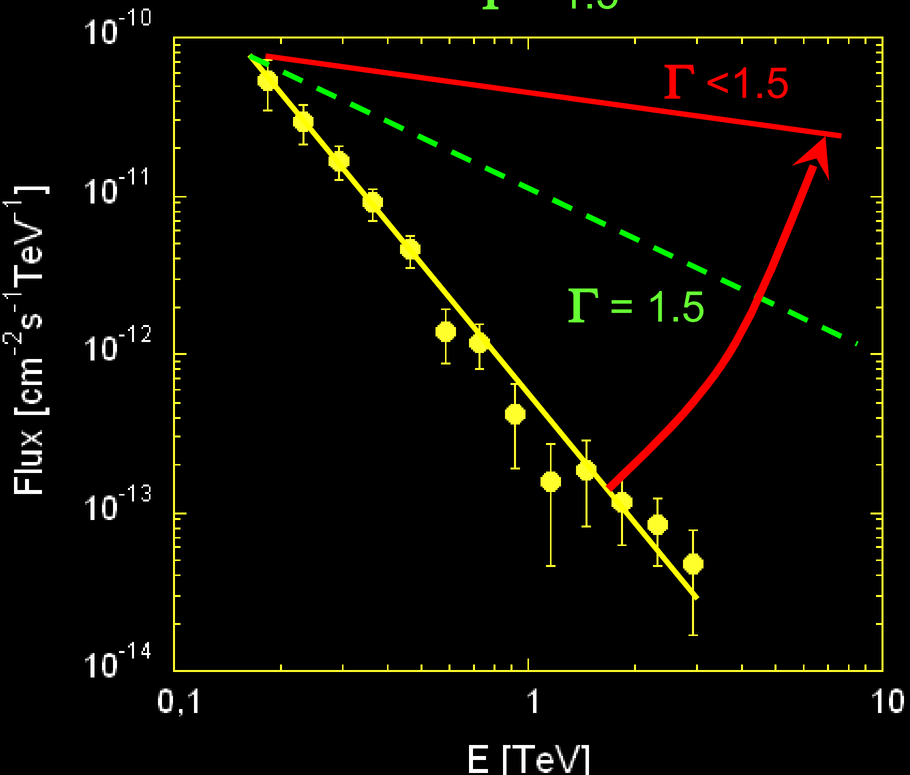
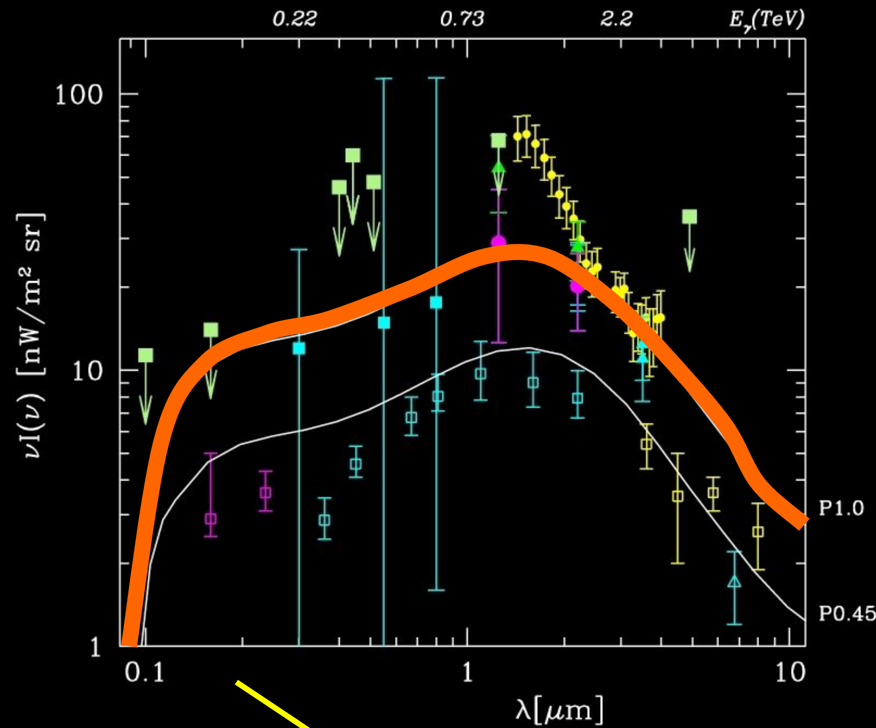


$F_{int}(E)$

Assumption:
intrinsic spectrum of blazars can't be harder than

$\Gamma = 1.5$





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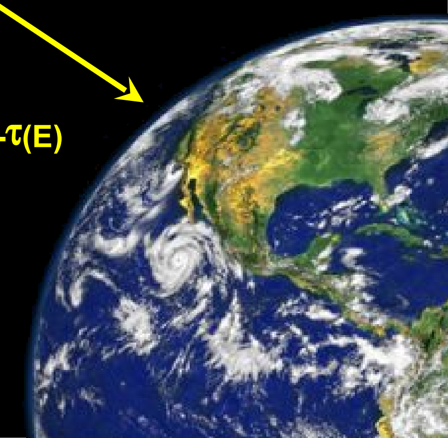

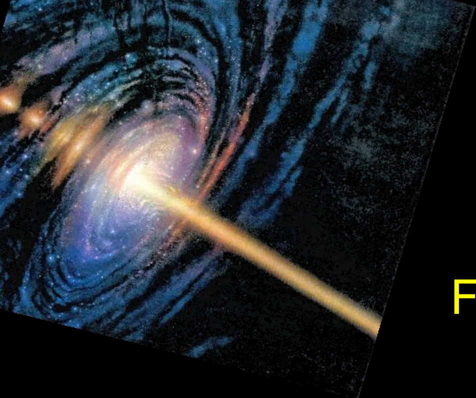

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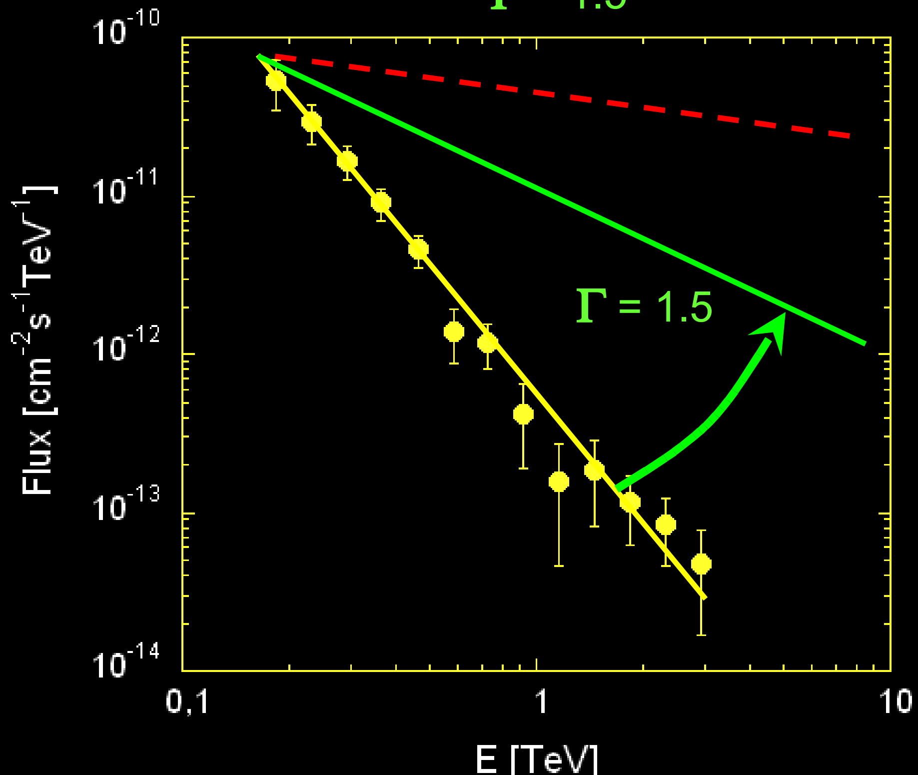
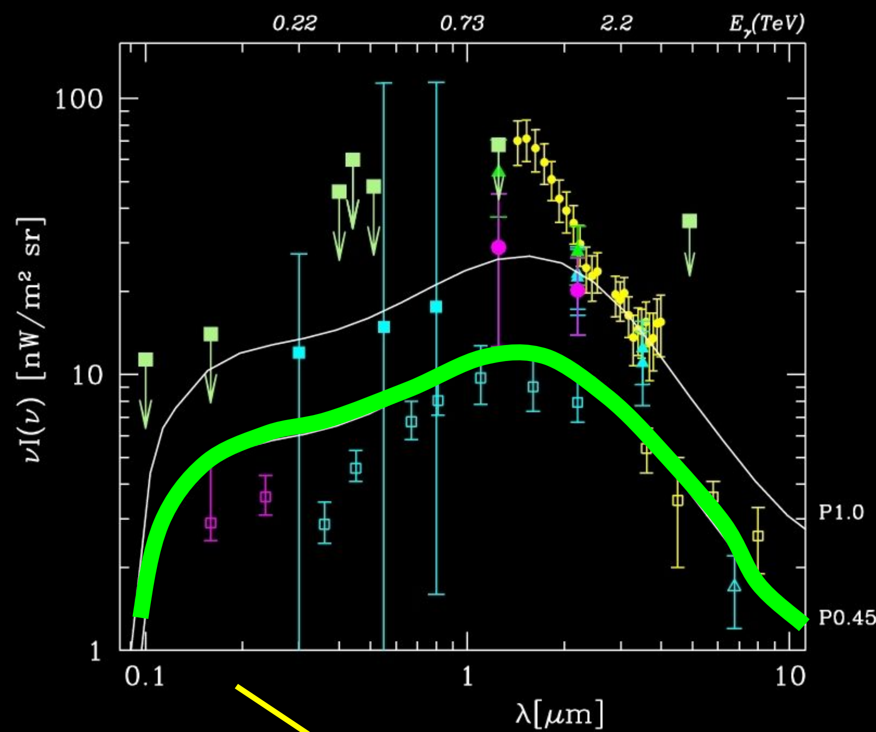
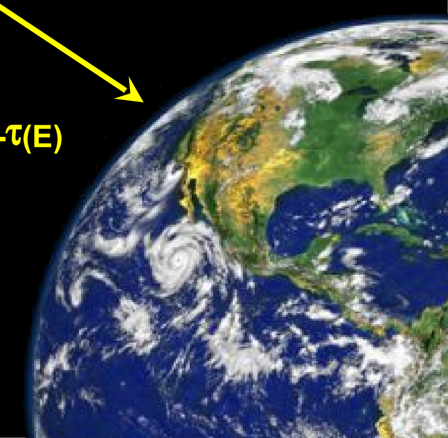
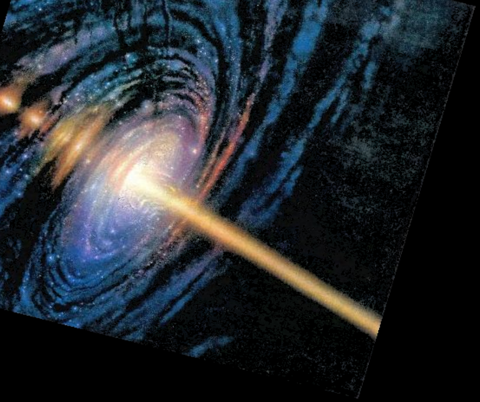




$$F_{obs}(E) = F_{int}(E) \cdot e^{-\tau(E)}$$





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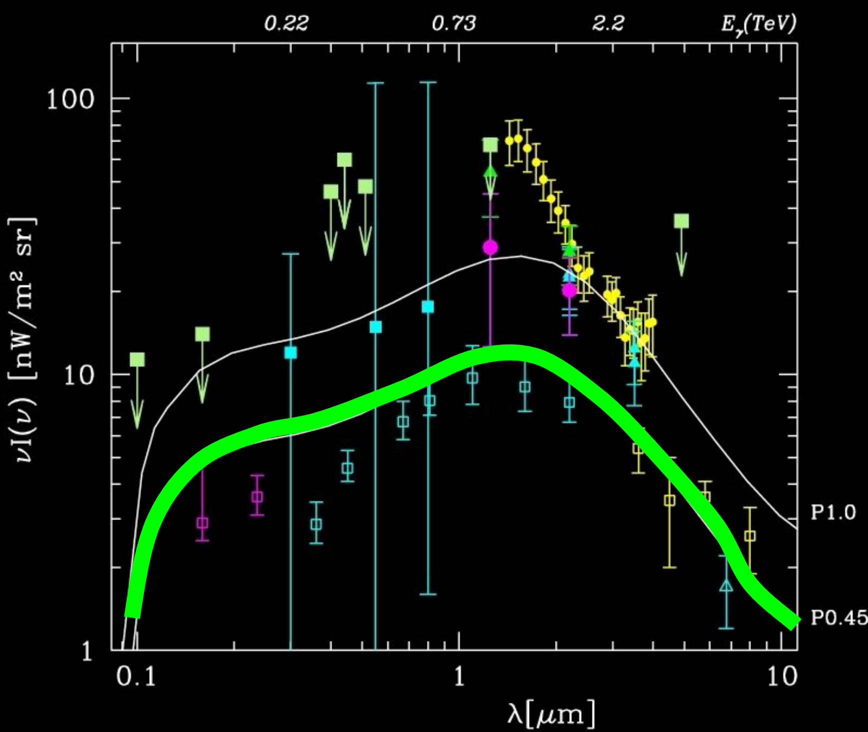


H.E.S.S. results:

→ The EBL is at the lower limit (given by the Hubble galaxy count)

→ No significant contribution of cosmological pop III stars (z ~ 7…15)

→ The Universe is more transparent to Gamma-Rays than expected

→ We can "see" further than expected, more sources accessible

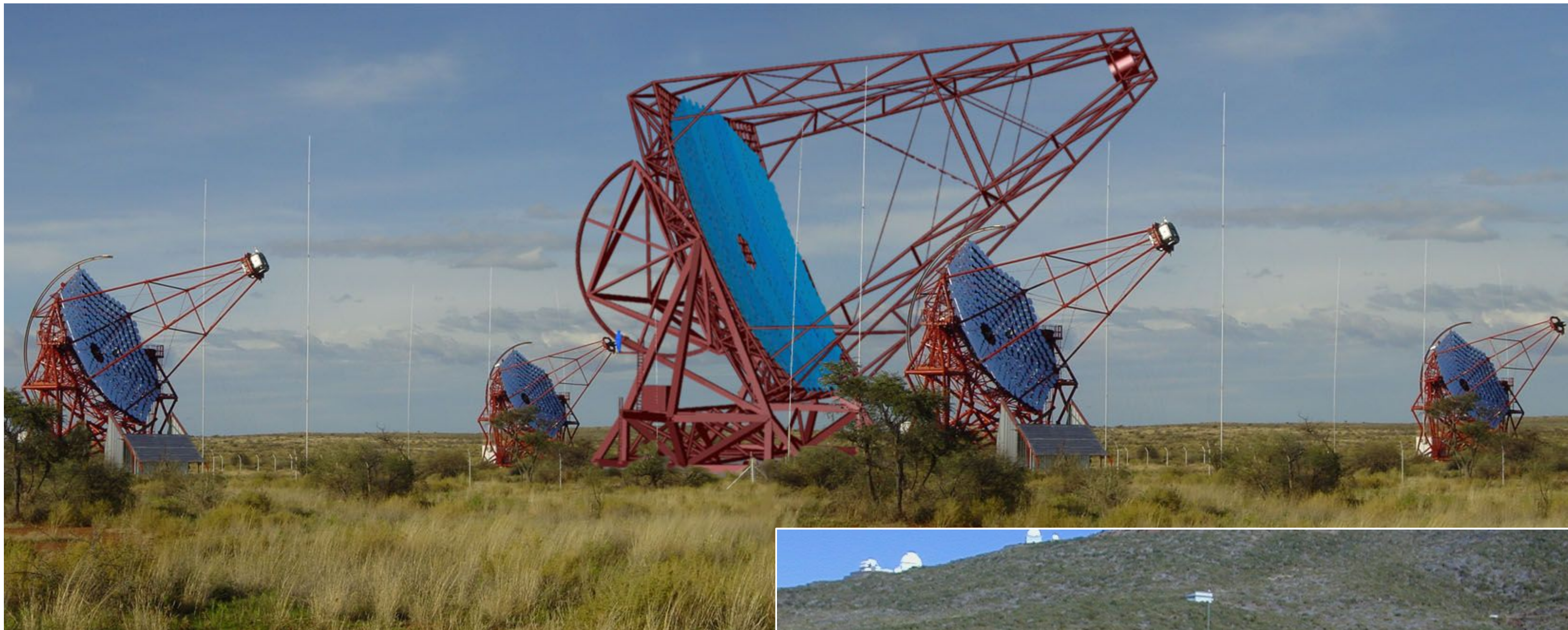
H.E.S.S. Nature (2006)

TeV Gamma-Ray Astronomy
H.E.S.S. and beyond

- Physics Motivation
- Imaging Cherenkov Technique
- H.E.S.S. Results
  - Galactic sources
  - Extragalactic sources
- The future

G.Hermann
MPIK Heidelberg

Near Future: H.E.S.S. Phase II, MAGIC 2



Improved sensitivity (x1.5 - 2) in current regime up to a few TeV

Energy range down to ~50 GeV will finally become accessible

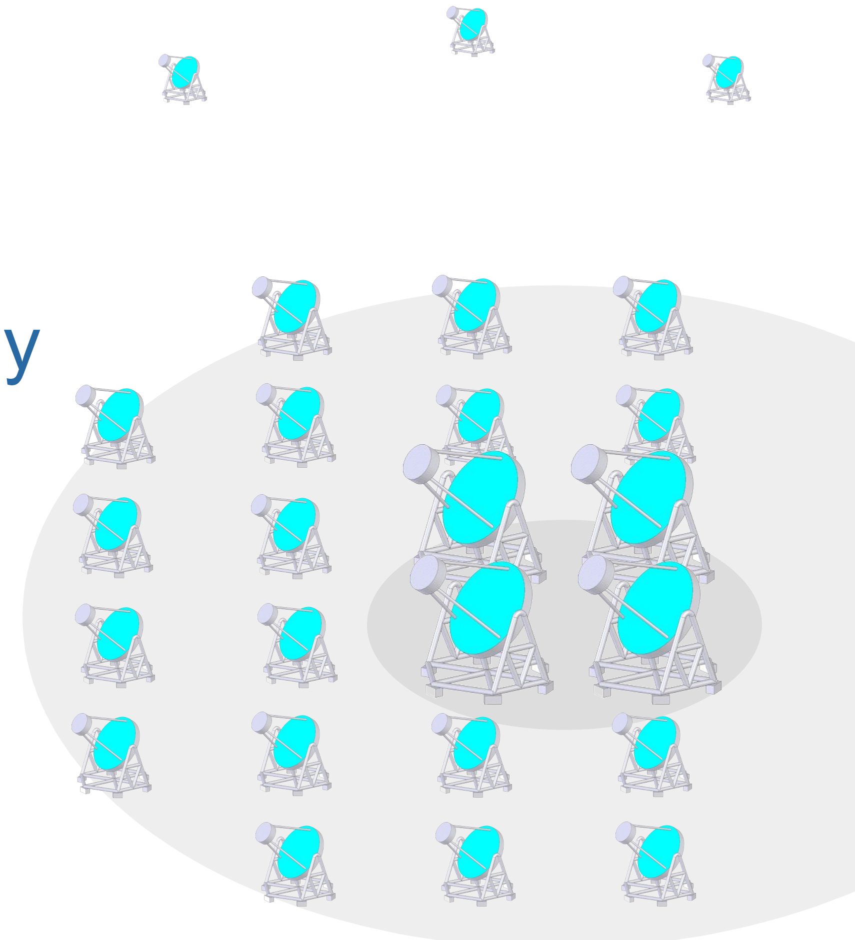
Cherenkov Telescope Array

An advanced Facility for ground-based gamma-ray Astronomy

A ground-based facility for

TeV Gamma-Ray Astronomy

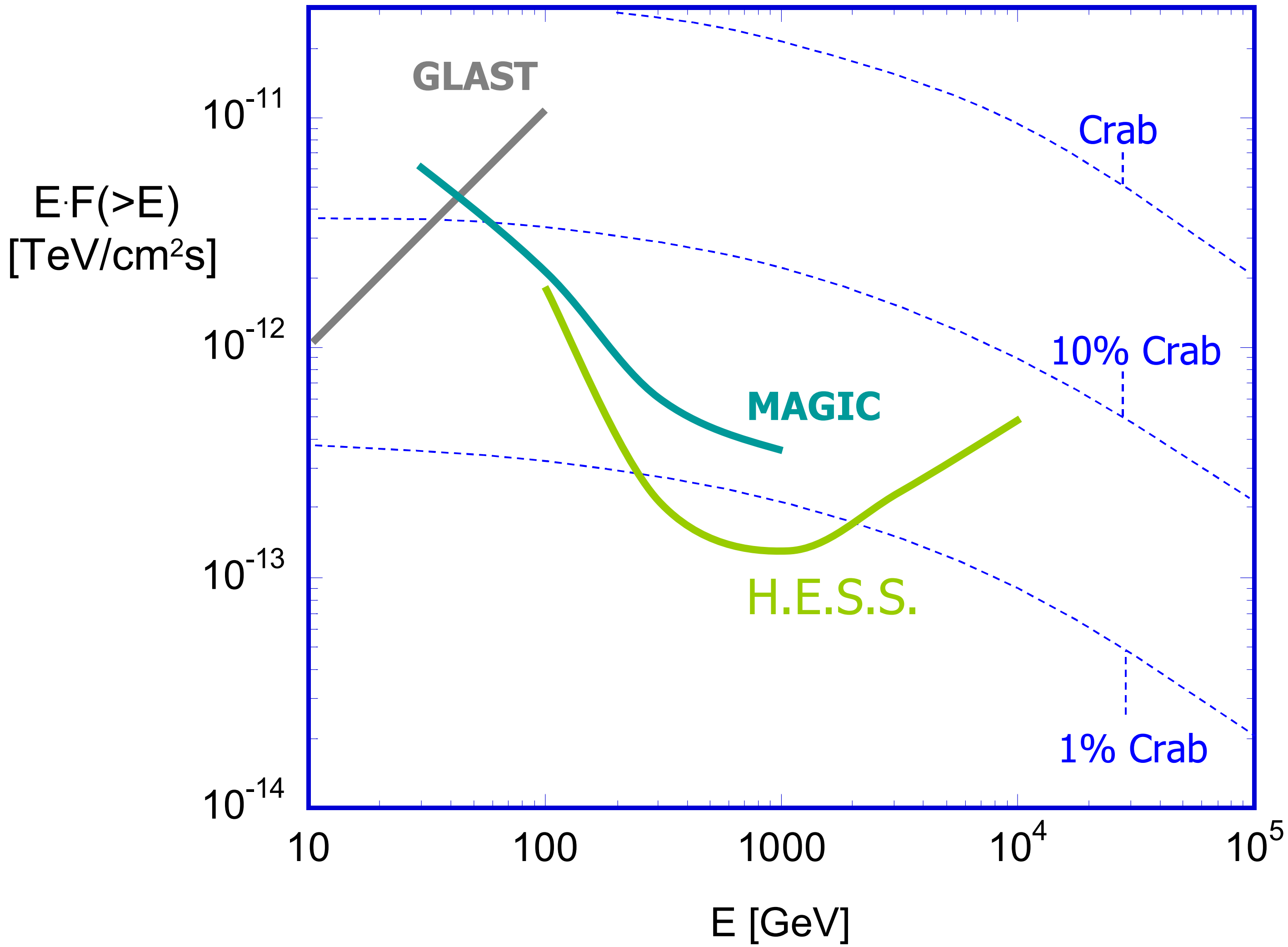
for the next decade



German Hermann, MPI Kernphysik, Heidelberg

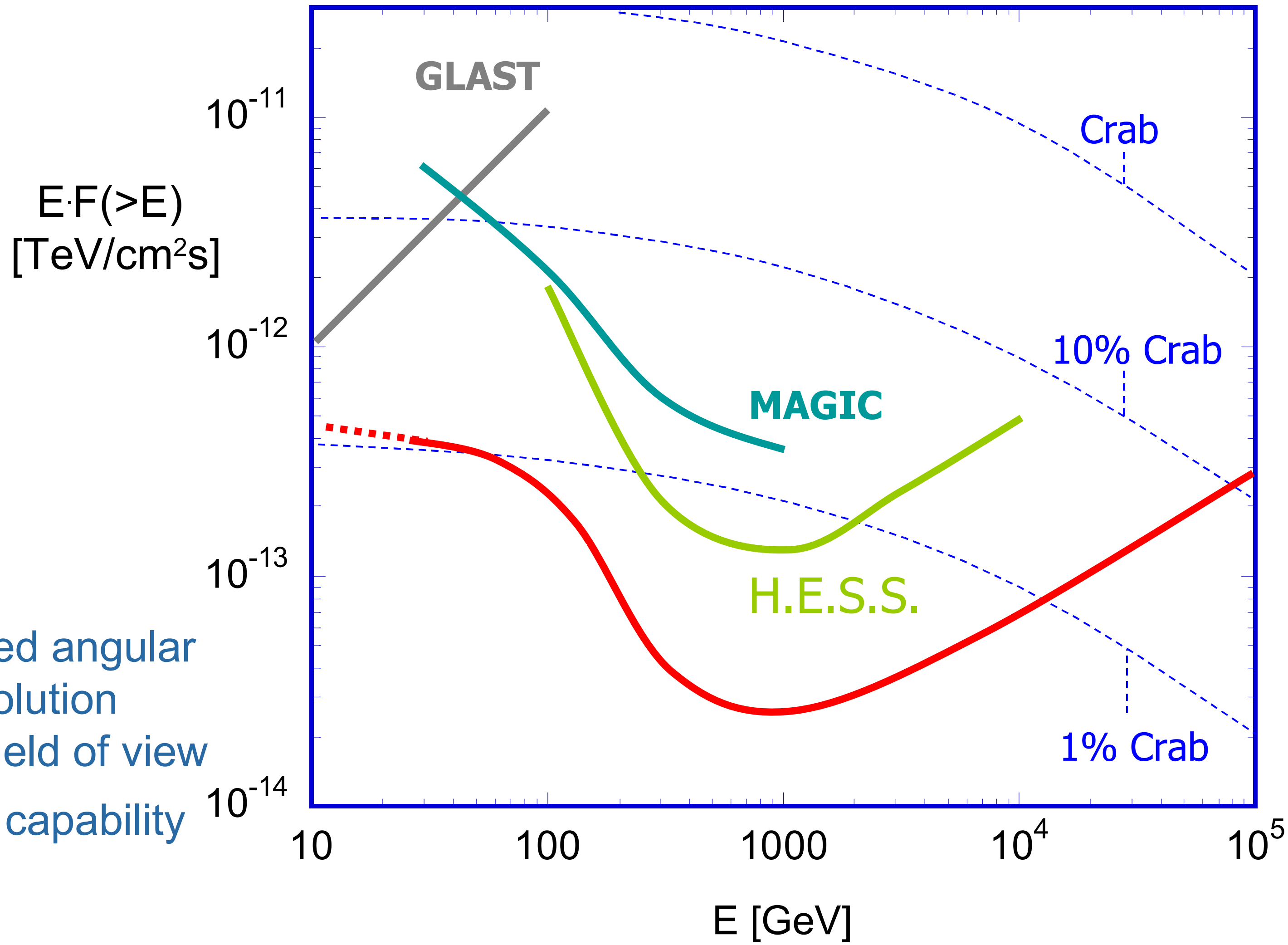
Sensitivity aimed for

An advanced Facility for ground-based gamma-ray Astronomy



Sensitivity aimed for

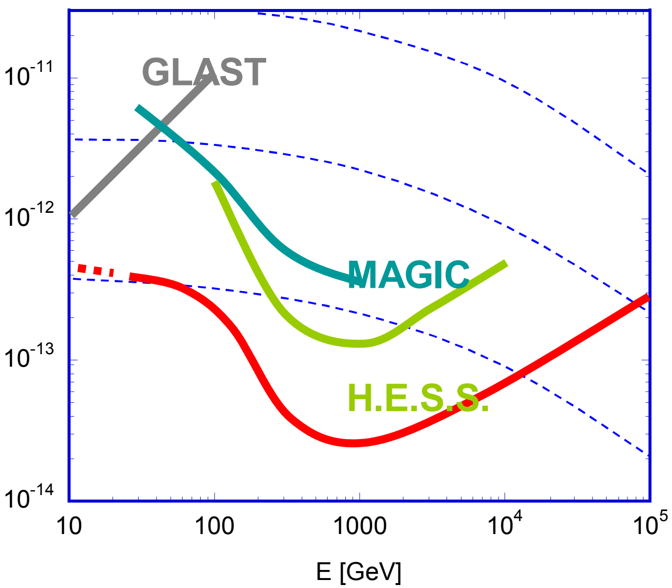
An advanced Facility for ground-based gamma-ray Astronomy



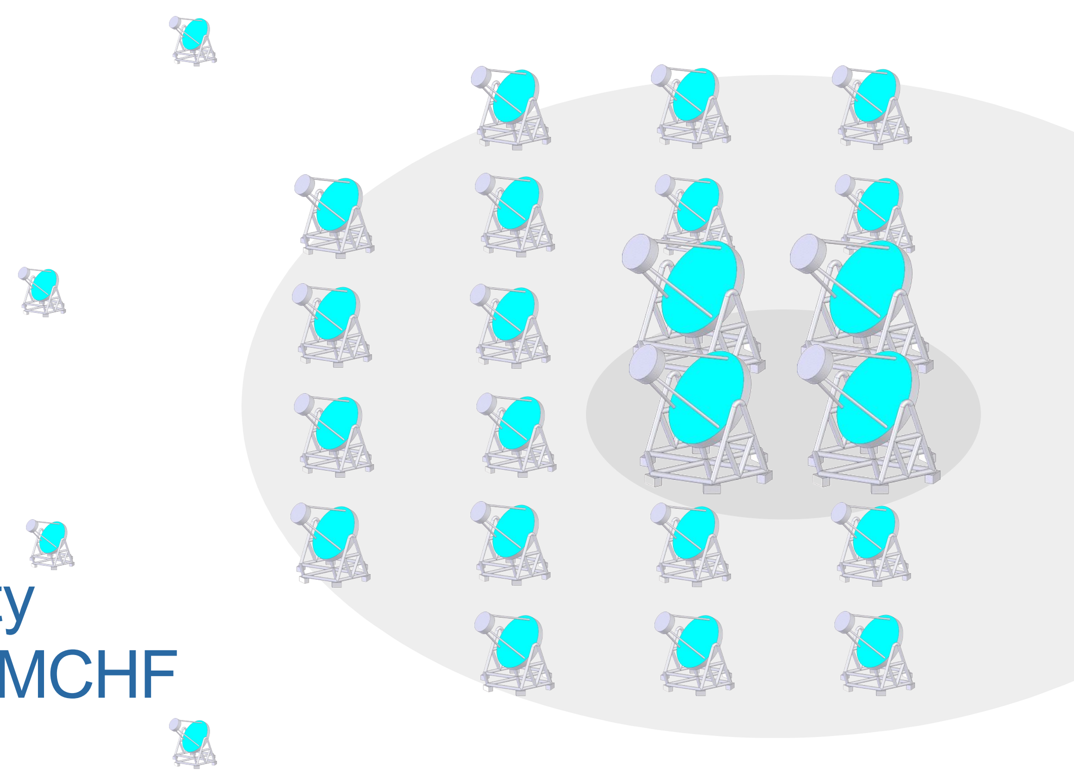
+ Improved angular resolution
+ Large field of view
+ all-sky capability

Technical Implementation

An advanced Facility for ground-based gamma-ray Astronomy



Possibly mix of telescopes:
e.g (5m), 14m, 28m
Large FoV



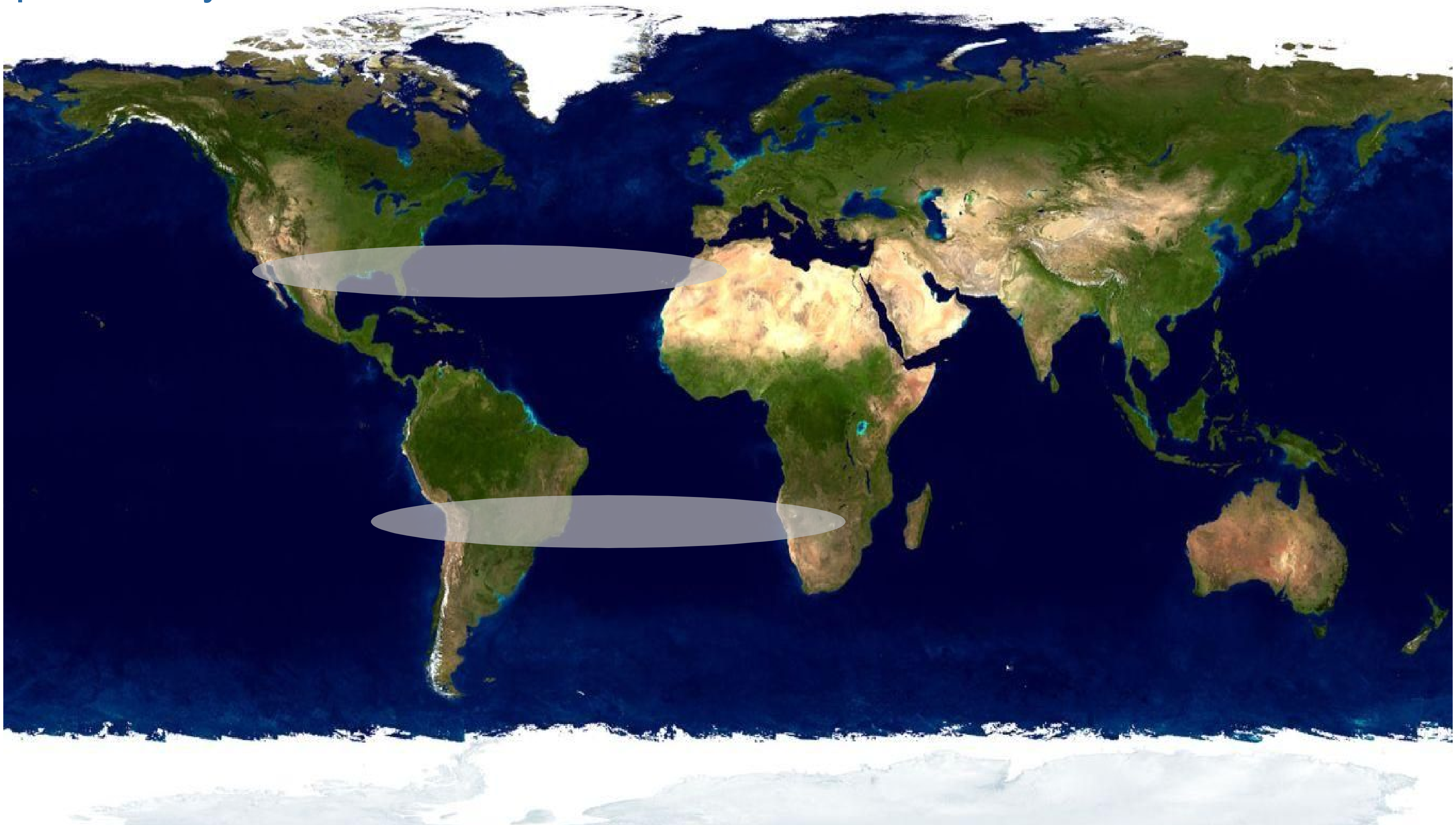
Will need
- O(30-50) telescopes
- O(10000) m^2 mirror area
- O(50) m^2 photo sensitive area
- O(50000-100k) electronics channels

→ Factor of 10 in sensitivity with only factor of 10 in MCHF

Cherenkov Telescope Array

An advanced Facility for ground-based gamma-ray Astronomy

One observatory with two site
operated by one consortium



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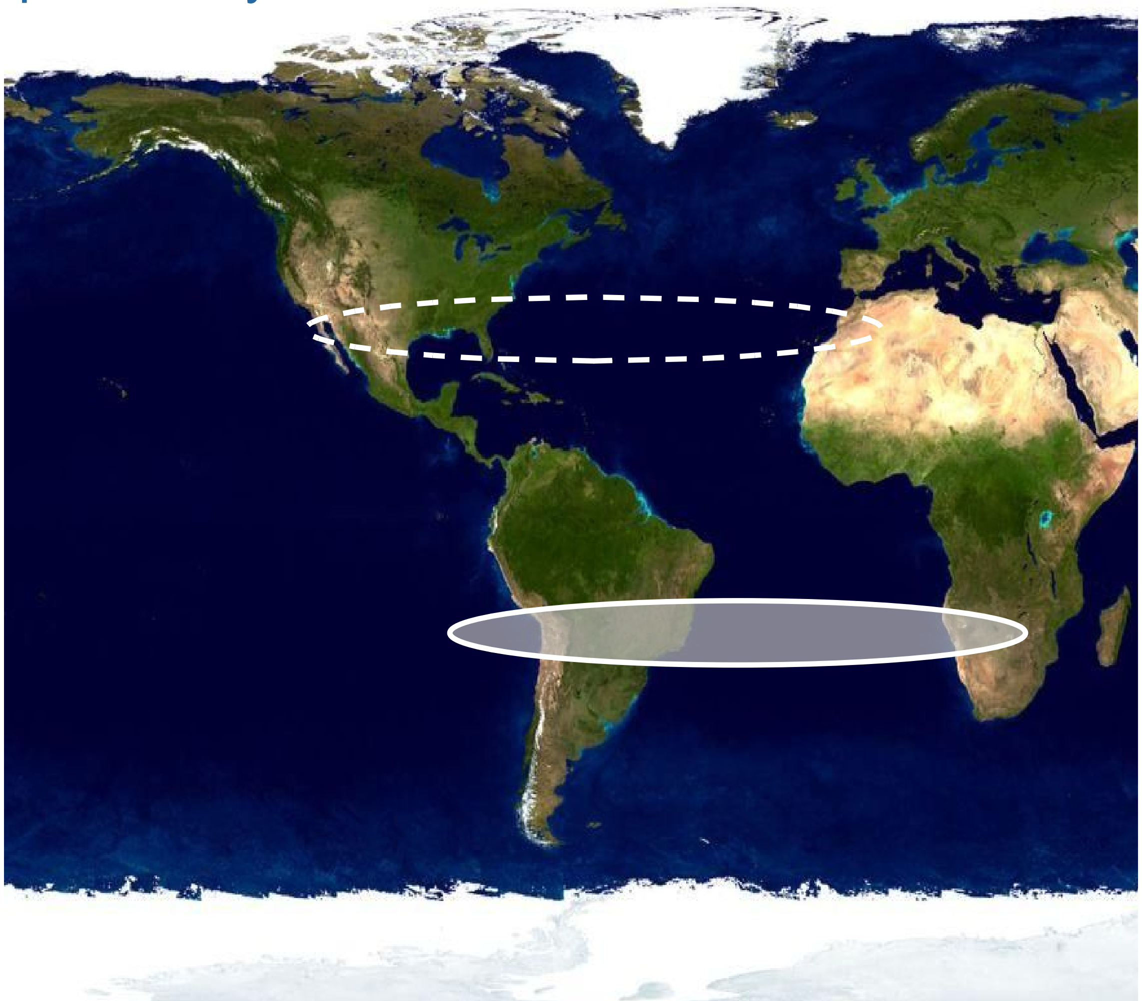


Southern Array (100 ME)

→ Full energy and sensitivity coverage
some 10 GeV …. 100 TeV

→ Angular resolution:
0.02 … 0.2 deg

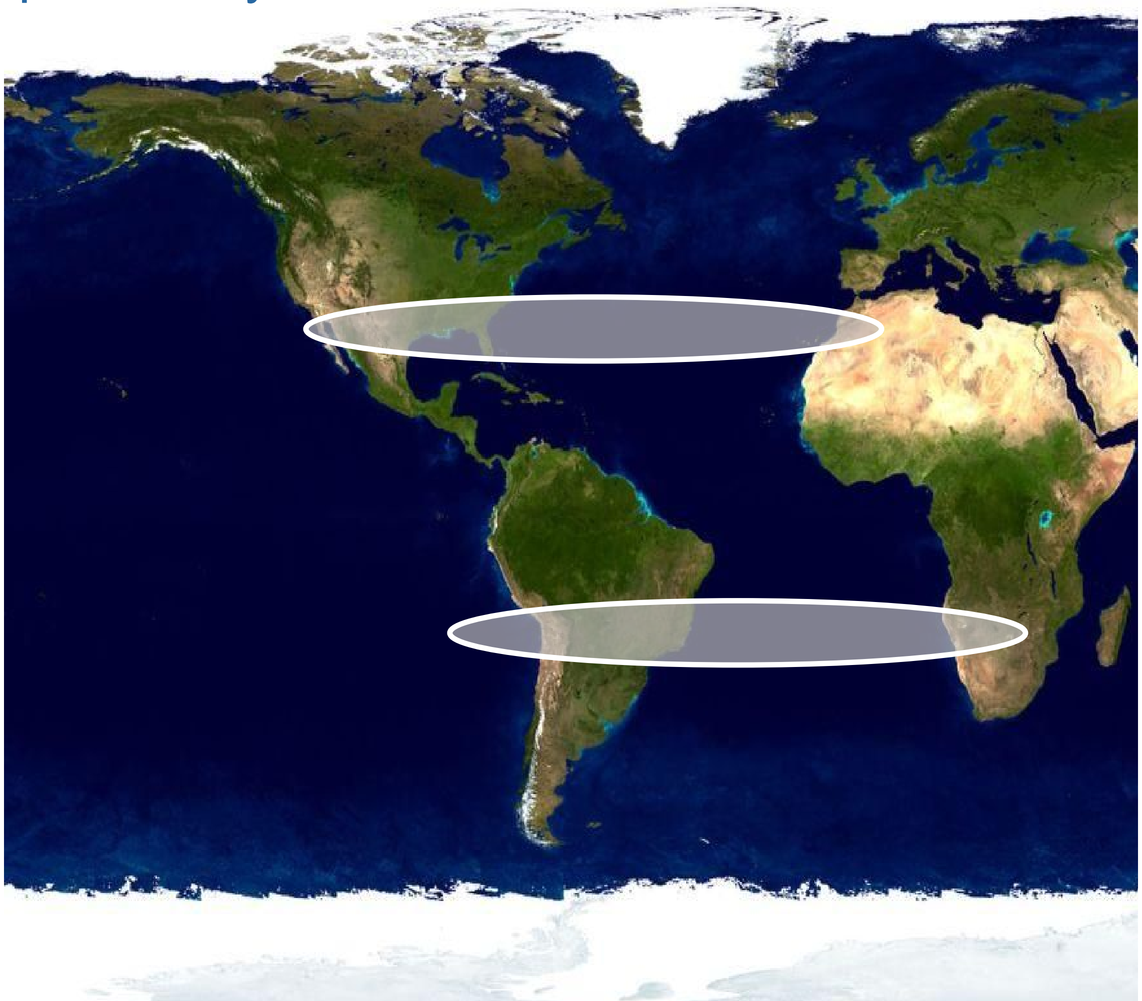
→ Large field of view
Galactic + Extragal. Sources

Cherenkov Telescope Array

An advanced Facility for ground-based gamma-ray Astronomy

One observatory with two site operated by one consortium

50 % open time !



Northern Array (50 ME)

→ complementary to SA for full sky coverage

→ Energy range some 10 GeV …. ~1 TeV

→ Small field of view Mainly extragal. Sources

Southern Array (100 ME)

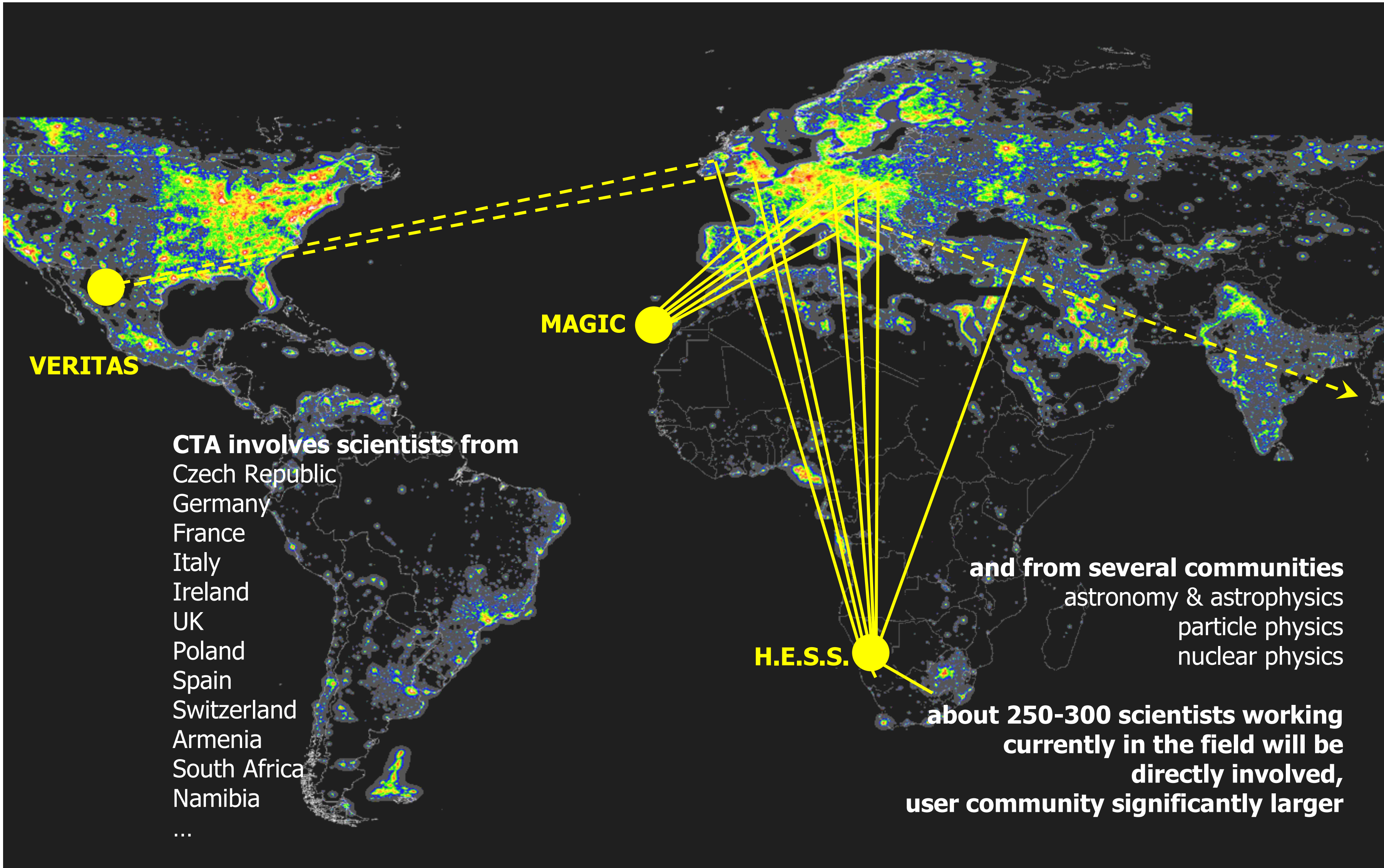
→ Full energy and sensitivity coverage some 10 GeV …. 100 TeV

→ Angular resolution: 0.02 … 0.2 deg

→ Large field of view Galactic + Extragal. Sources

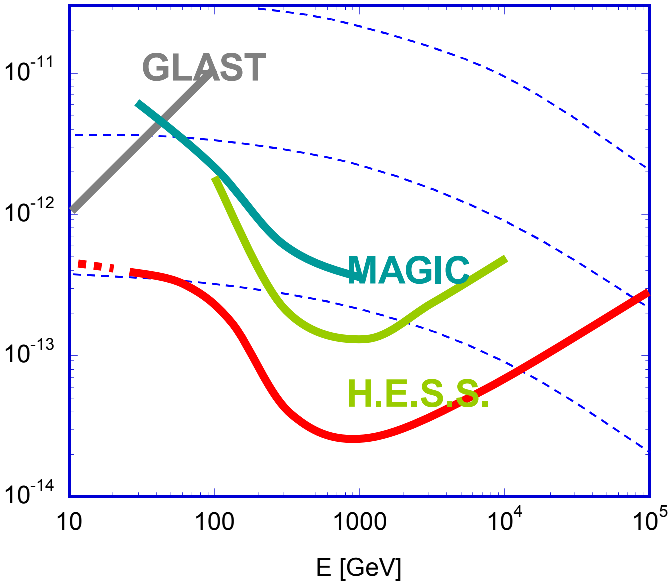
Who is the CTA Consortium ?

An advanced Facility for ground-based gamma-ray Astronomy



Technical Implementation

An advanced Facility for ground-based gamma-ray Astronomy



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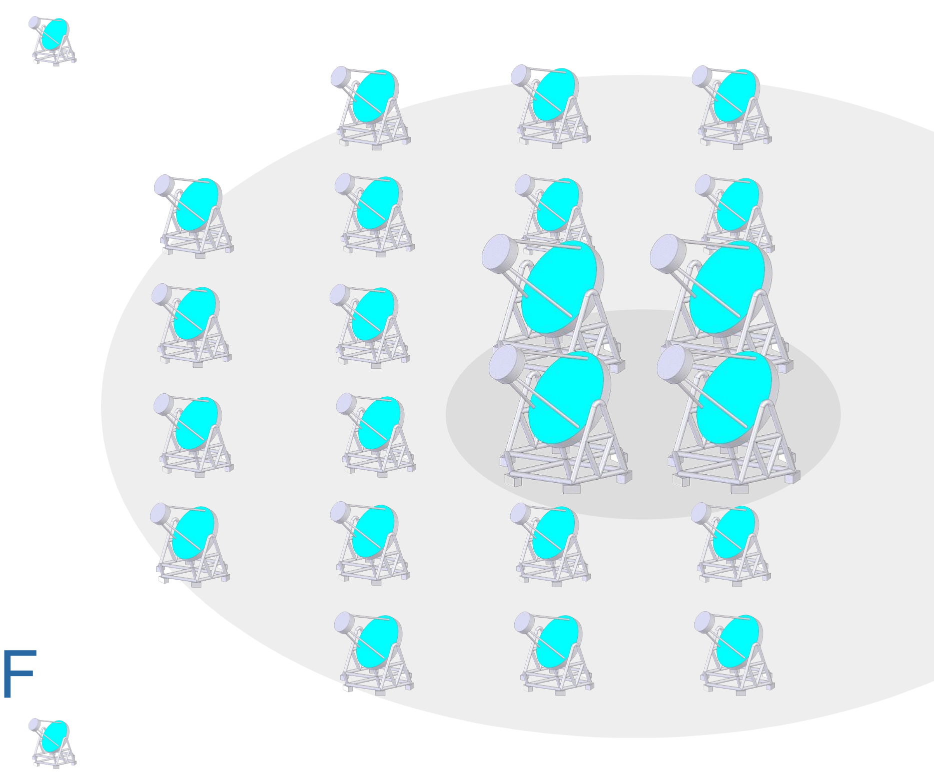

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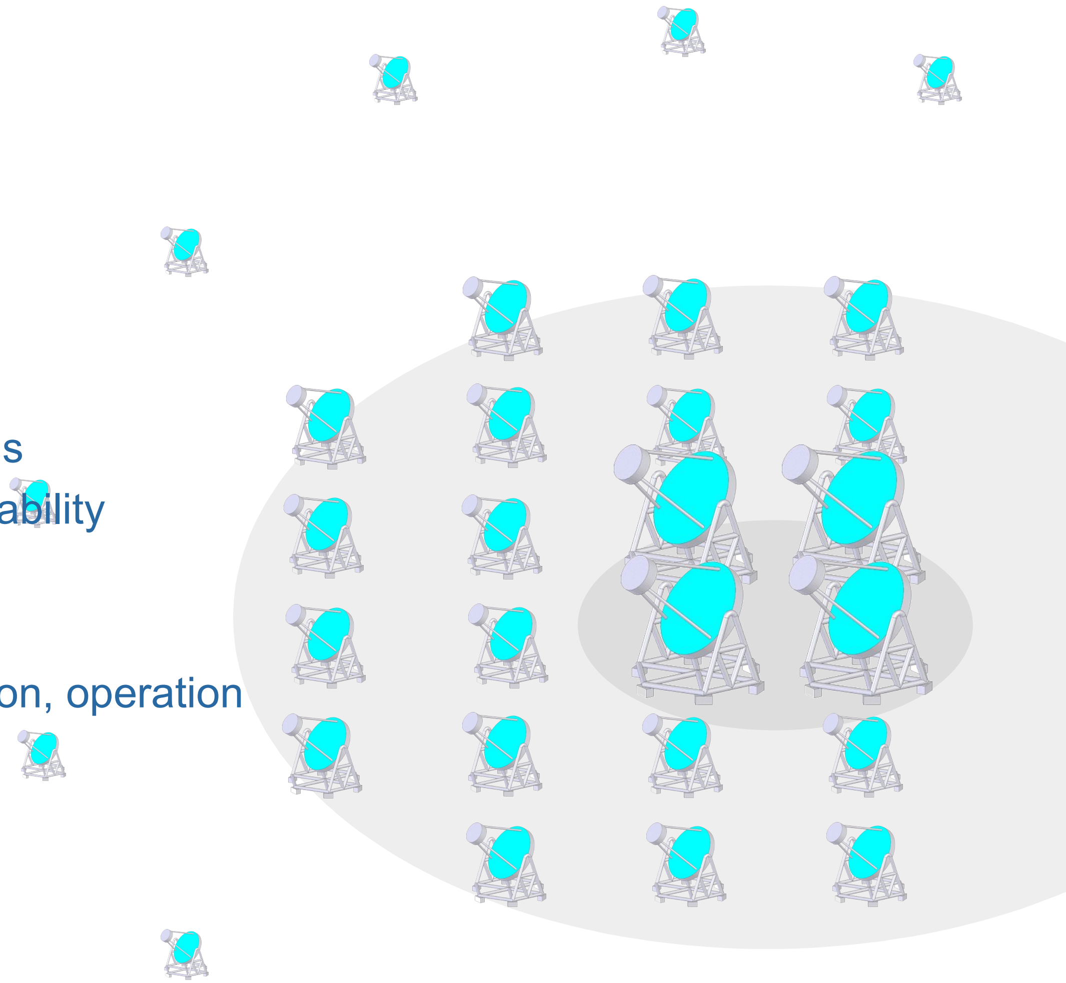
Technical Implementation

An advanced Facility for ground-based gamma-ray Astronomy

Needed: (Cost) Optimization of Design, Layout and Production

FP7 Design Study

- System Configuration
- Telescope and optics options
- Mirror Facets
- Photon detectors and readout options
- Industrial production studies and reliability
- …
- Site Studies
- Observatory construction, organization, operation
- …



Technical Implementation

An advanced Facility for ground-based gamma-ray Astronomy

Needed: (Cost) Optimization of Design, Layout and Production

O(50) m^2 photo sensitive area
→ PMT evaluation/ optimization

FP7 Design Study

- System Configuration
- Telescope and optics options
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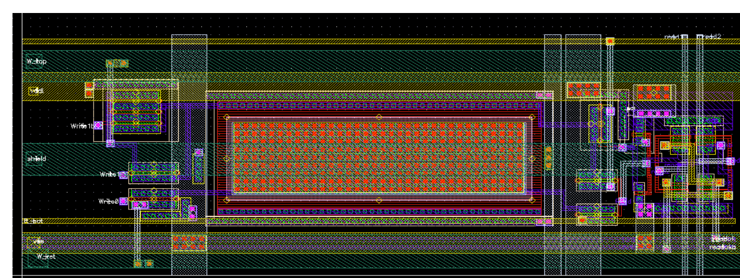
- …

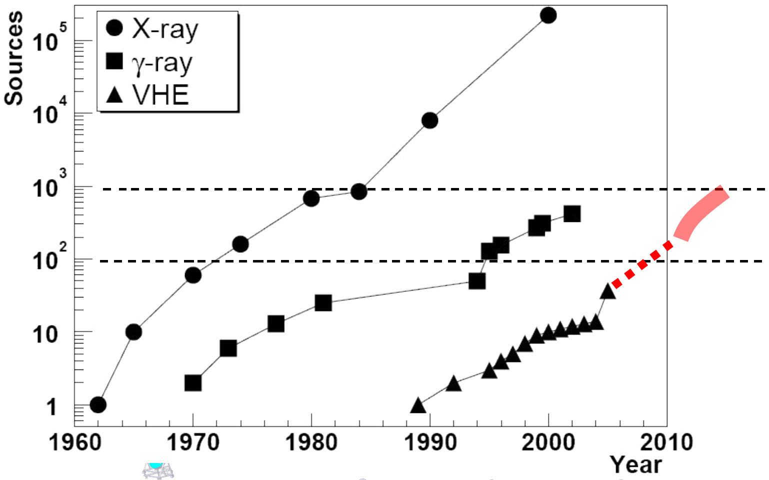
O(50000-100k) channels
Readout electronics

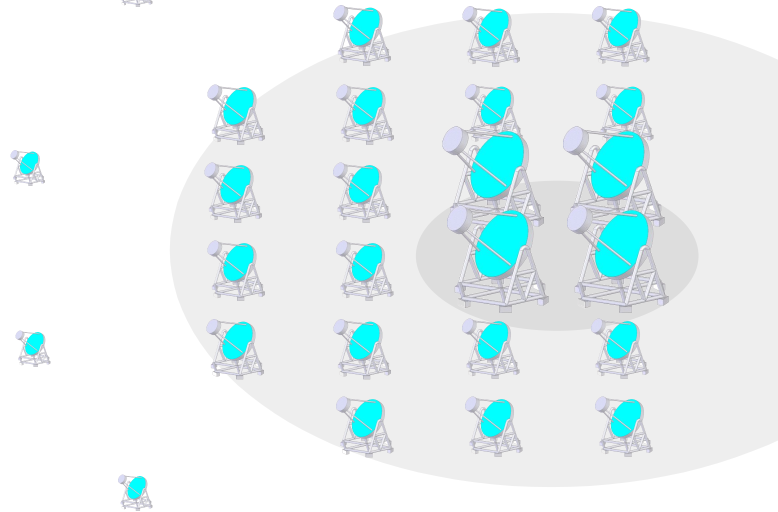


Timeline

An advanced Facility for ground-based gamma-ray Astronomy

Spring 2007	Letter of Intend
Spring 2007	FP7 DS application
2007-2010	Design Study
End 2008	Proposal (design options)
End of FP7:	TDR w/ implementation choices
2009/2010:	start production/installation





→ just about the right time to join *CTA*

CTA in a multi wavelength world

An advanced Facility for ground-based gamma-ray Astronomy