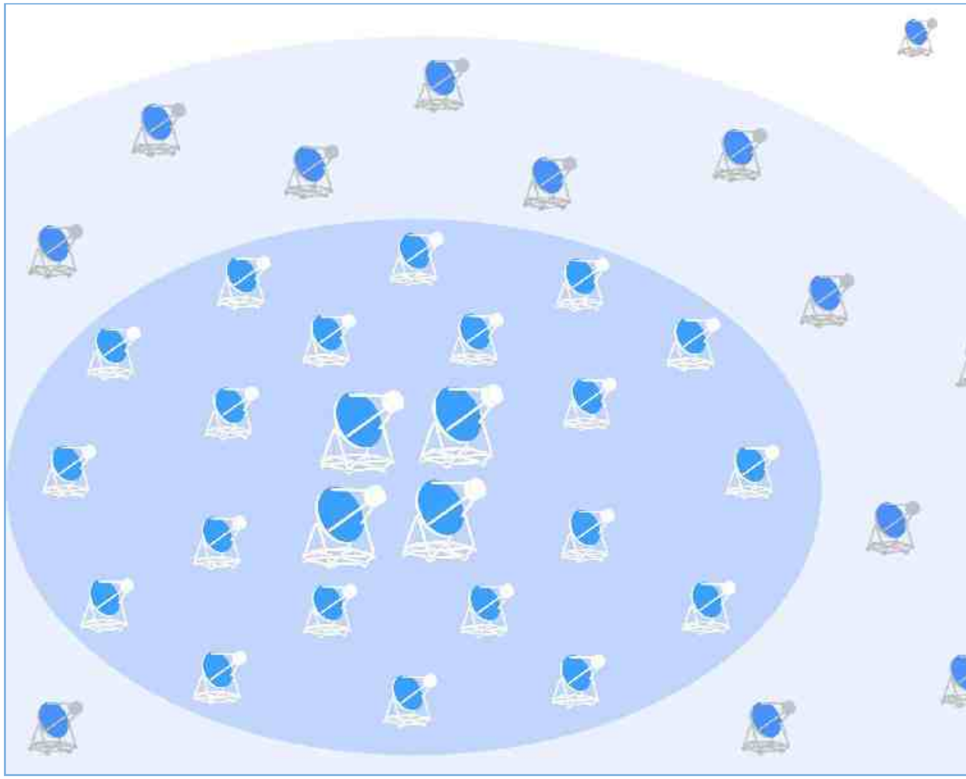
TeV gamma-ray astrophysics: today and tomorrow



German Hermann, MPI für Kernphysik

ICRR, March 17, 2009

Part I: Observations with the High Energy Stereoscopic System

- Introduction
- The H.E.S.S. experiment
- H.E.S.S. observations
  - Galactic sources
  - Extragalactic physics
  - Quantum Gravity
  - Dark Matter search
- A glance on H.E.S.S. phase 2

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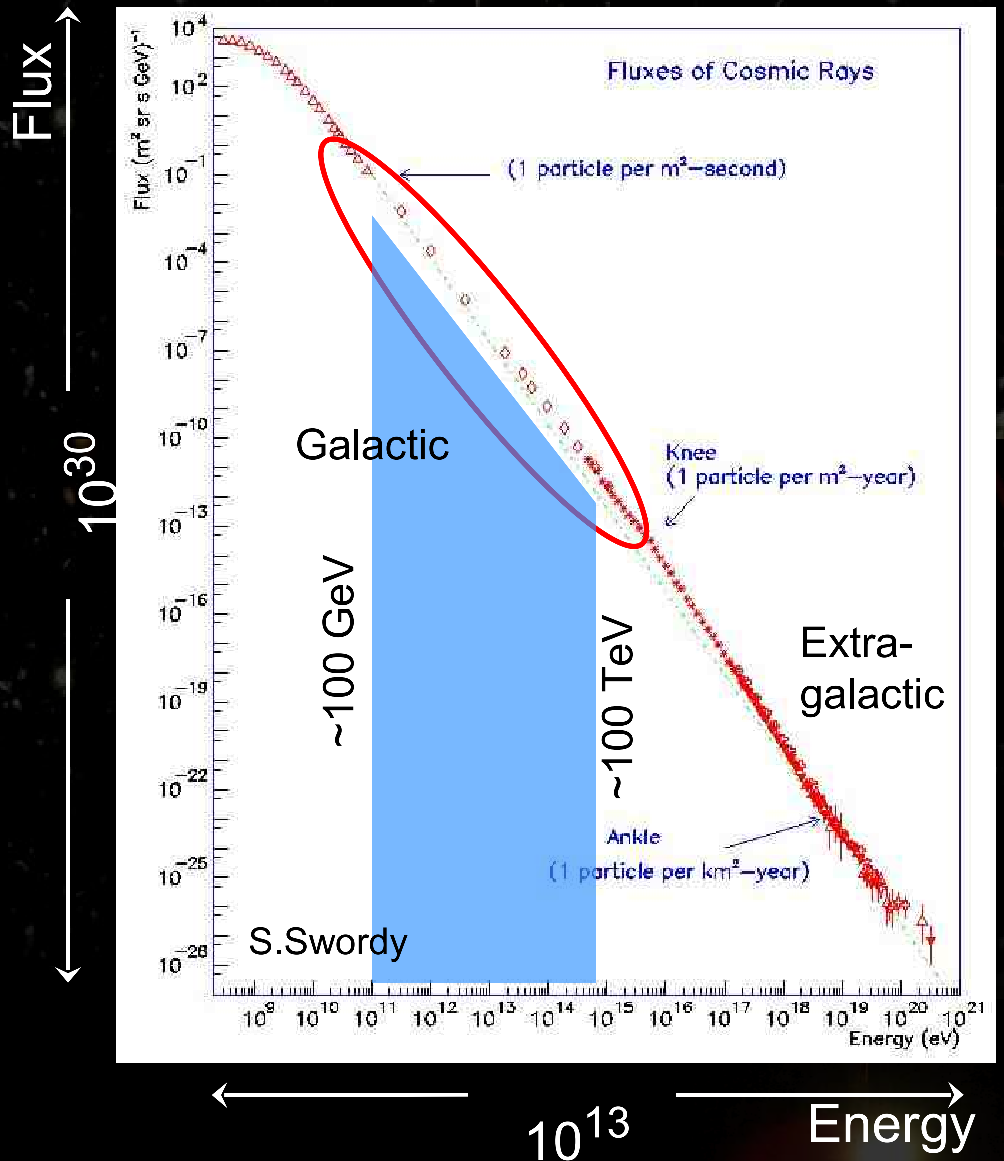
The Cosmic Ray Puzzle



- Mostly nuclei p, He, … Fe
  also $e^{\pm}$
  few γ, ν
- Non thermal spectrum
  $dN/dE \sim E^{-\alpha}$
- Isotropic distribution

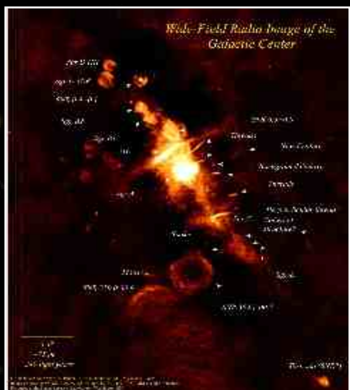
Discovery in 1912, but

- Cosmic ray origin ?
- Sources ?
- Processes ?

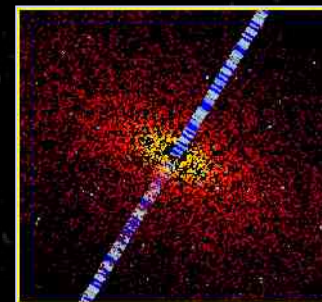
Potential Sources and Processes

Clusters of Galaxies

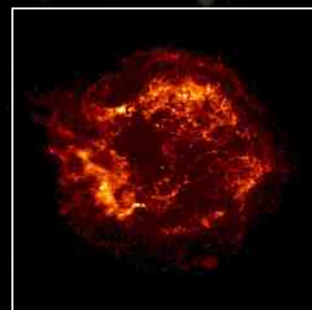
Dark Matter



Active Galactic Nuclei (AGN)

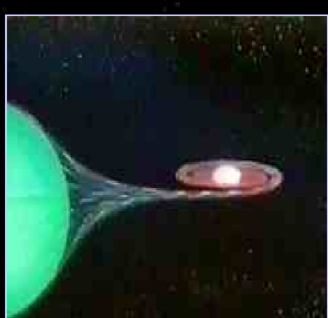


Super Nova Remnants (SNR)



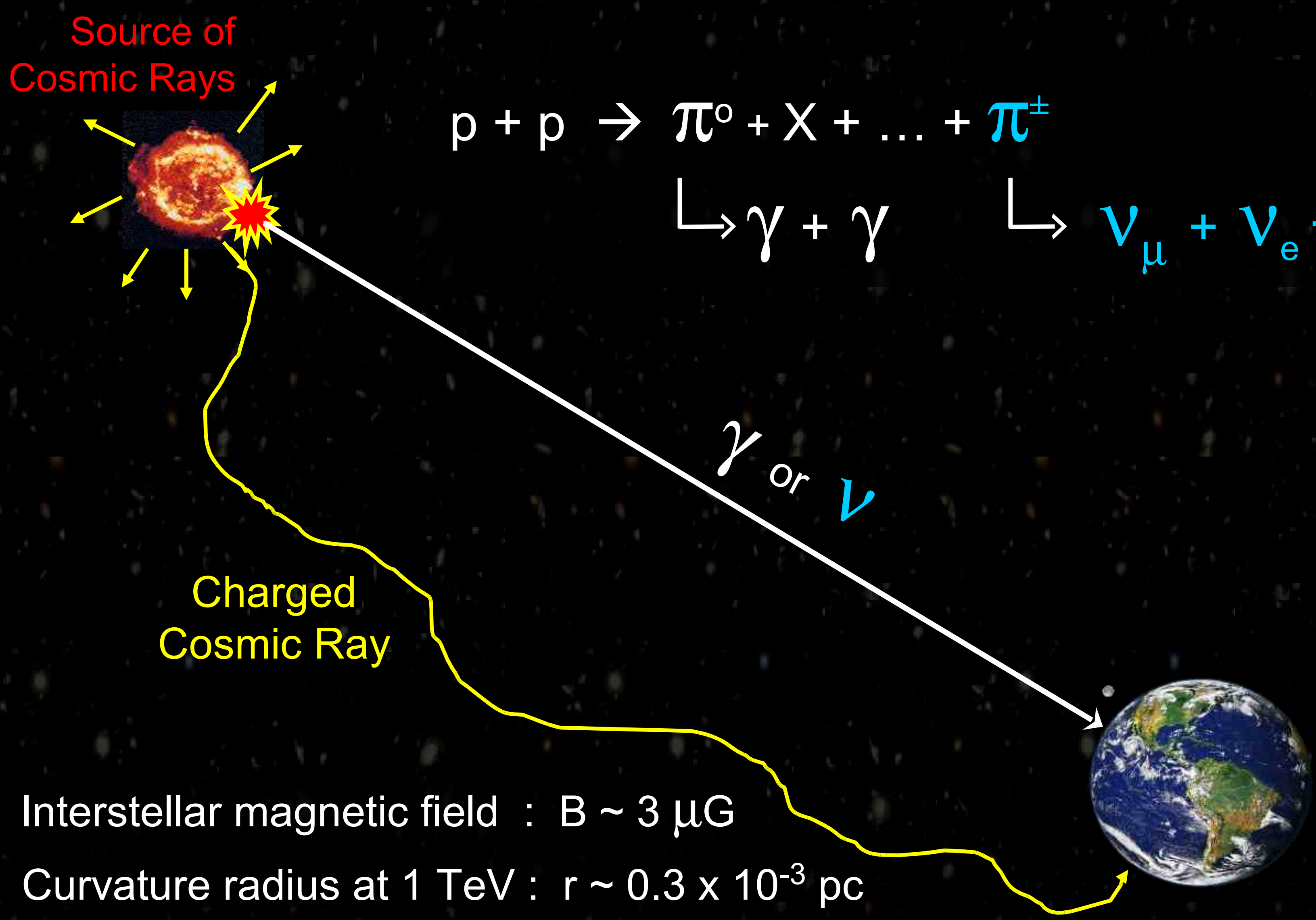
Pulsar Nebula

Binary Systems



- 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

Tracers to Cosmic Ray Accelerators



Tracers to Cosmic Ray Accelerators

Source of
Cosmic Rays

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

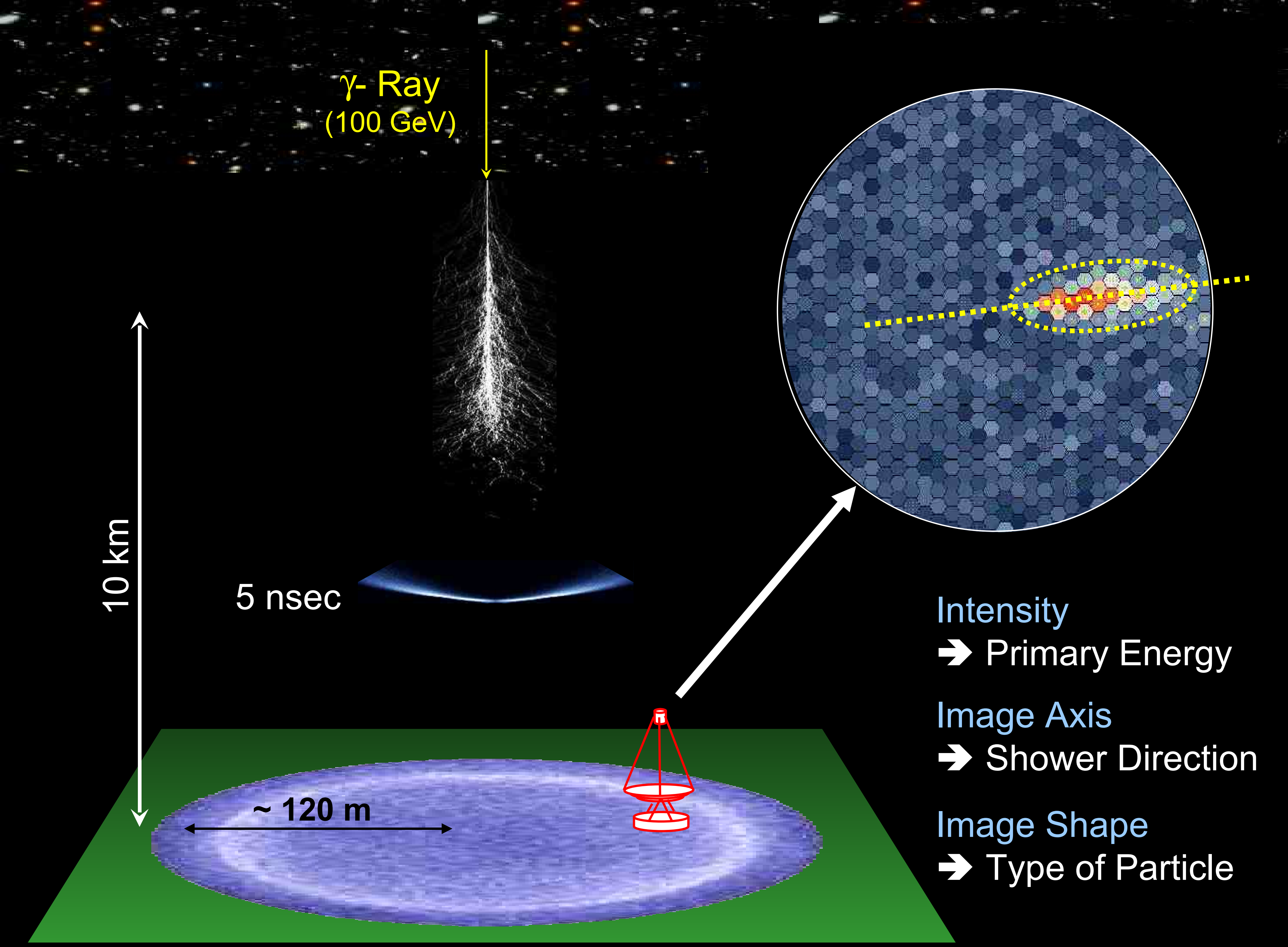
γ

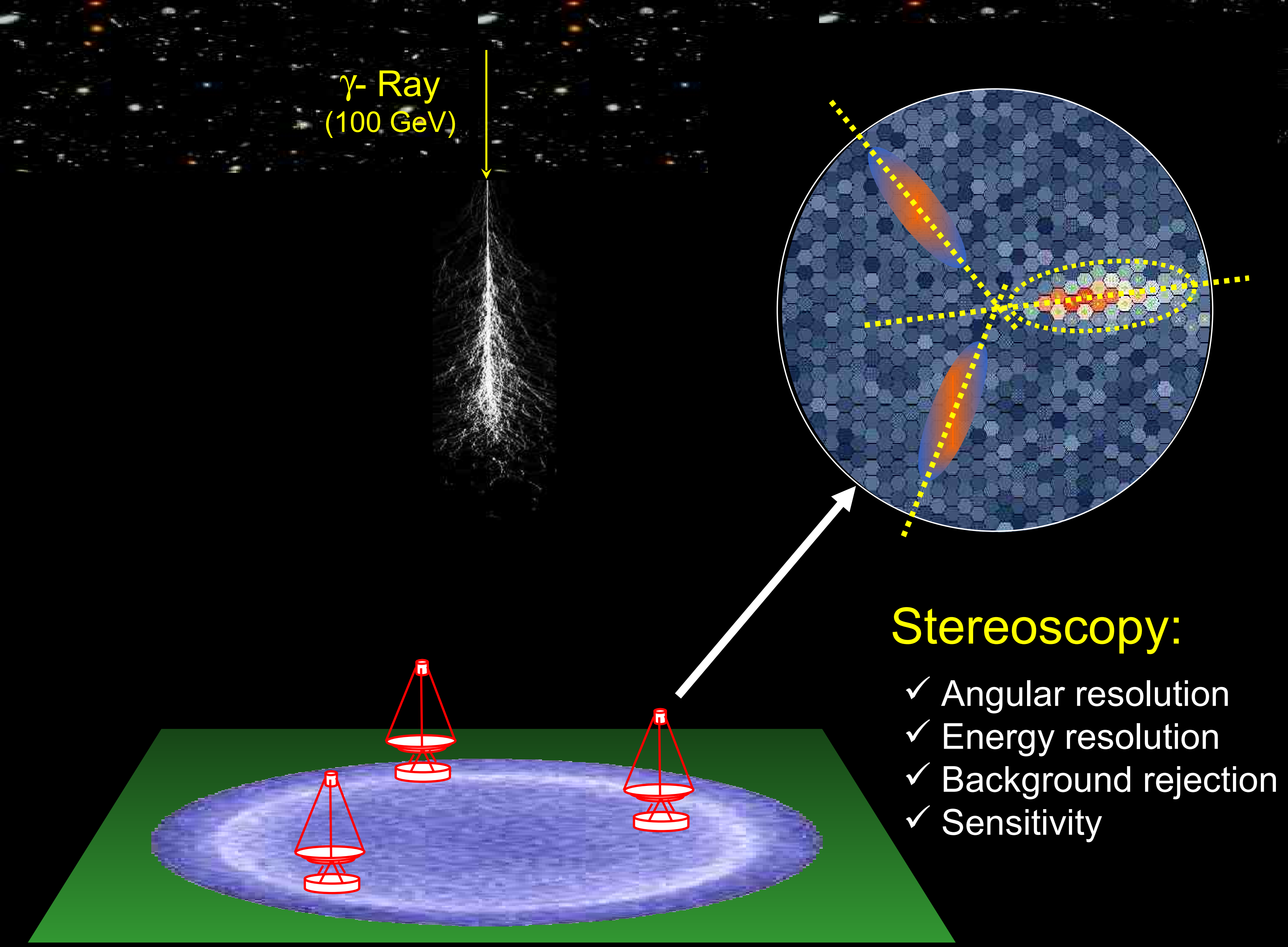
Infer properties of *primary particle distribution* in the sources and their *interactions*

Observables

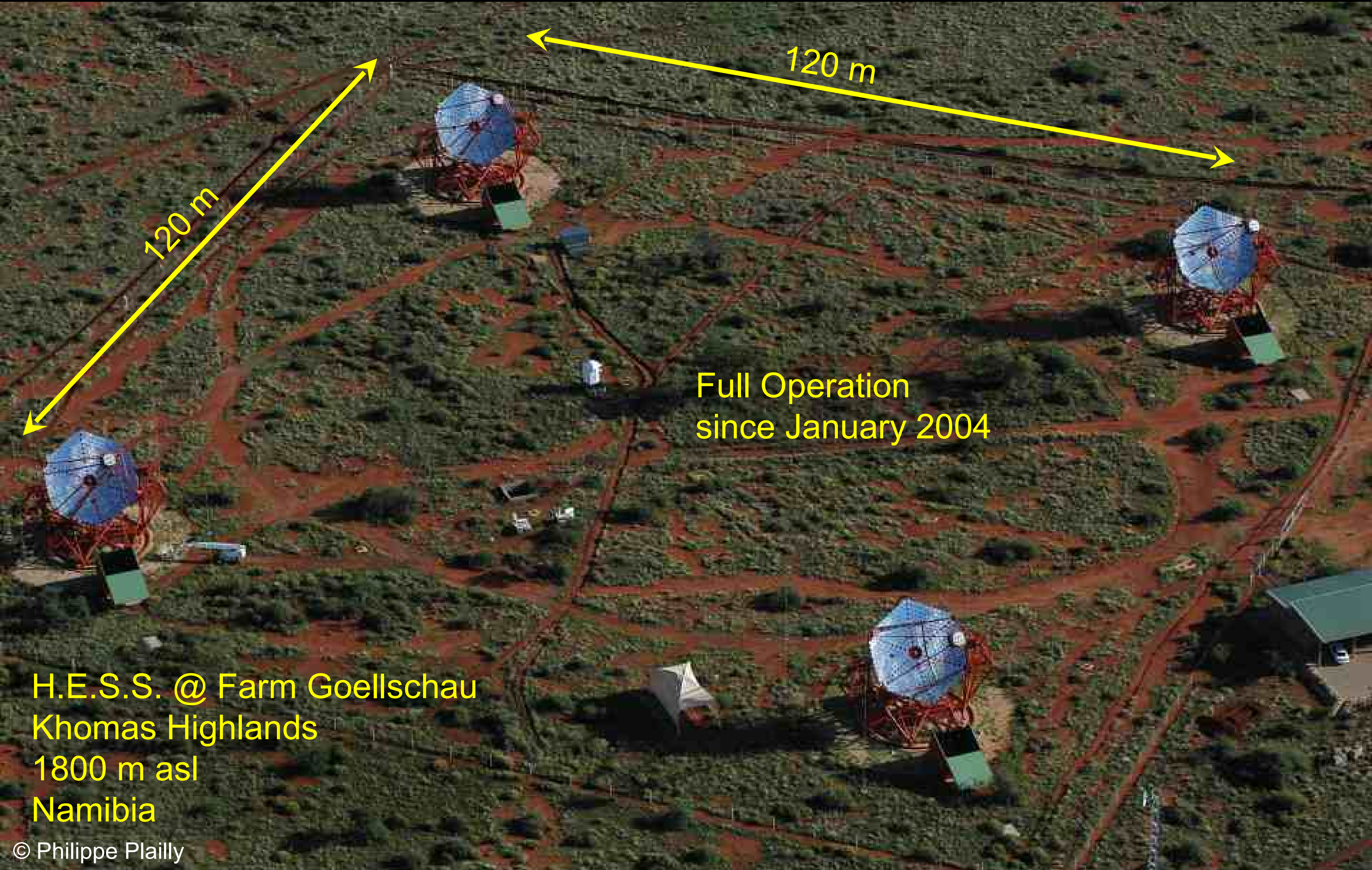
- Energy Spectra
  flux, range, shape
- Source Morphology
- Variability/Periodicity

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

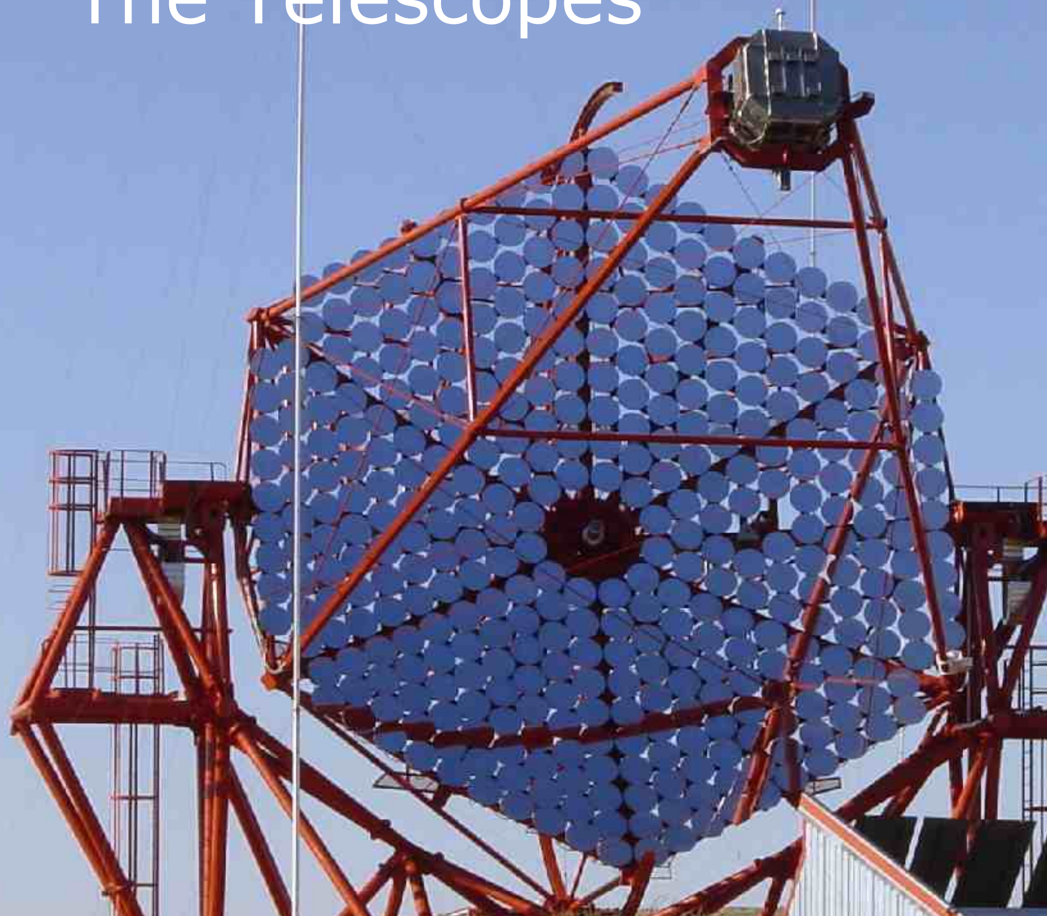

γ- Ray
(100 GeV)
10 km
5 nsec
~ 120 m
Intensity
➔ Primary Energy
Image Axis
➔ Shower Direction
Image Shape
➔ Type of Particle


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

High Energy Stereoscopic System



The Telescopes

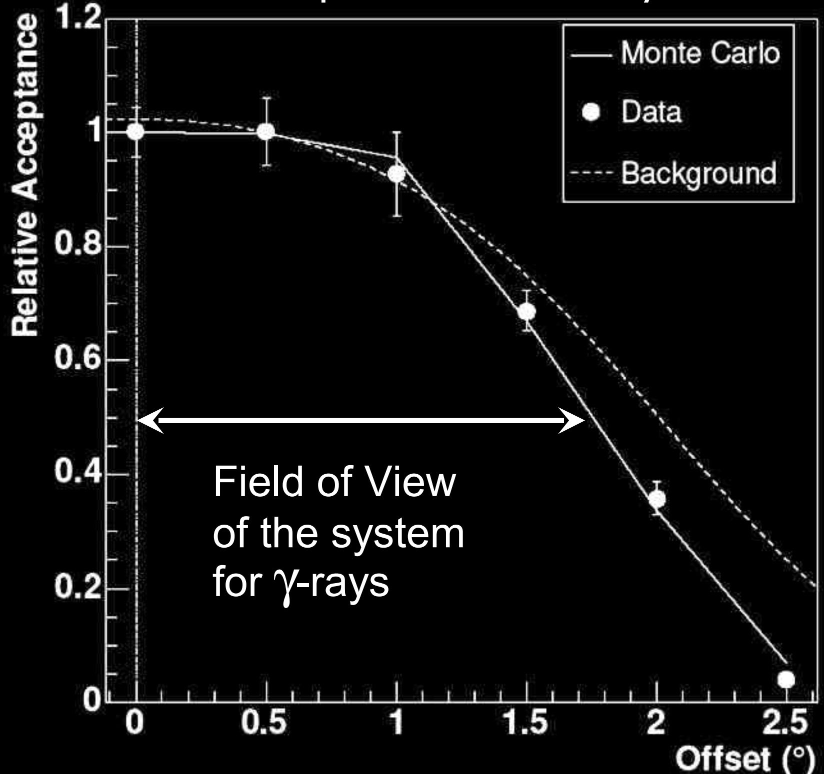


Alt-Azm mount
107 m^2 mirror area
380 mirrors each
15 m focal length
Rigid mount

5 deg FoV
960 Pixels / PMTs
Fast Trigger [nsec]
GHz sampling, 16 nsec Int.

Field of View on the Sky

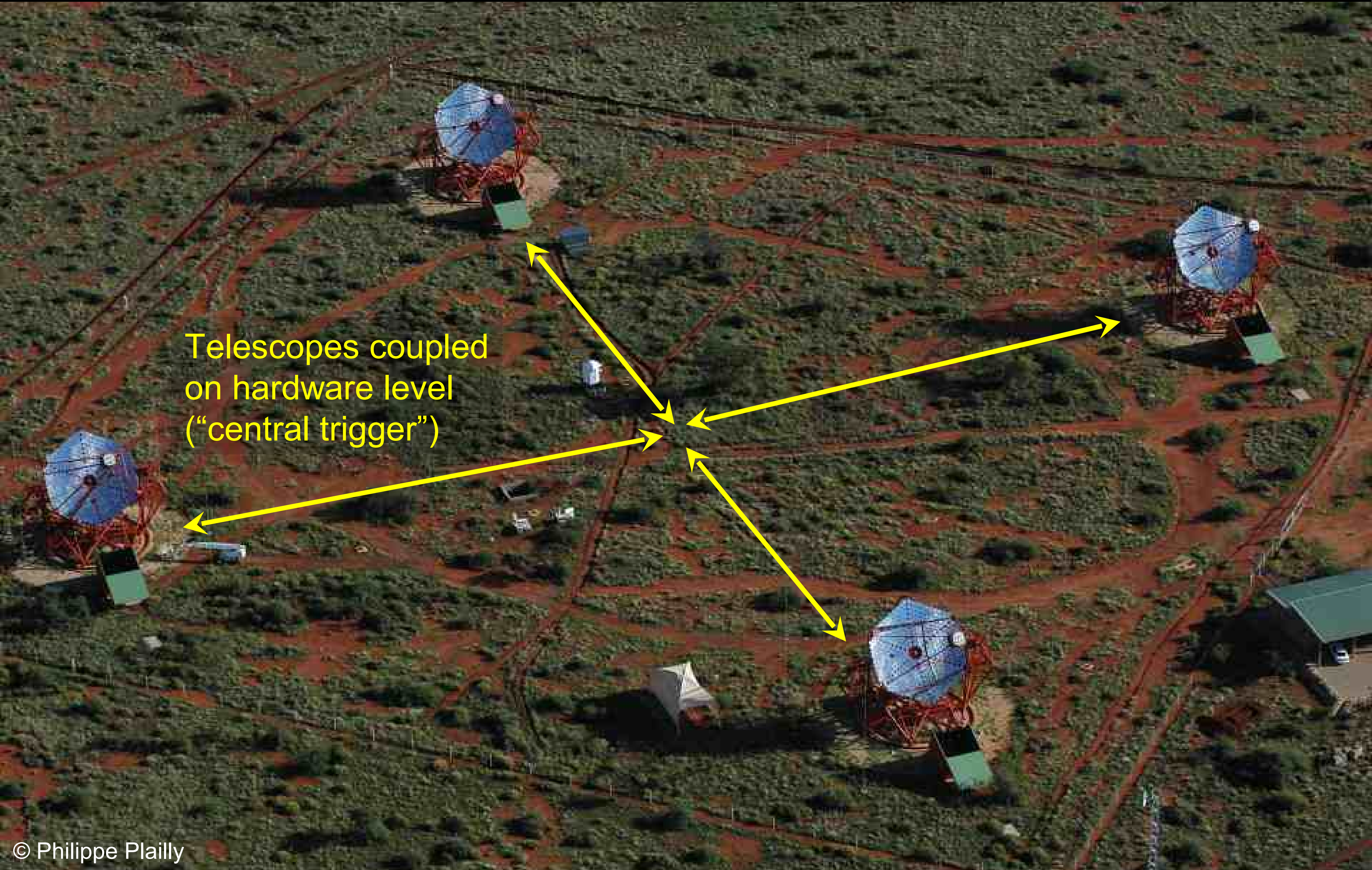
Rel. acceptance of the system



50 % acceptance : 3 deg
20 % acceptance : >4 deg

→ Sky Surveys
→ Extended sources
→ Serendipitous discoveries
→ High energy performance

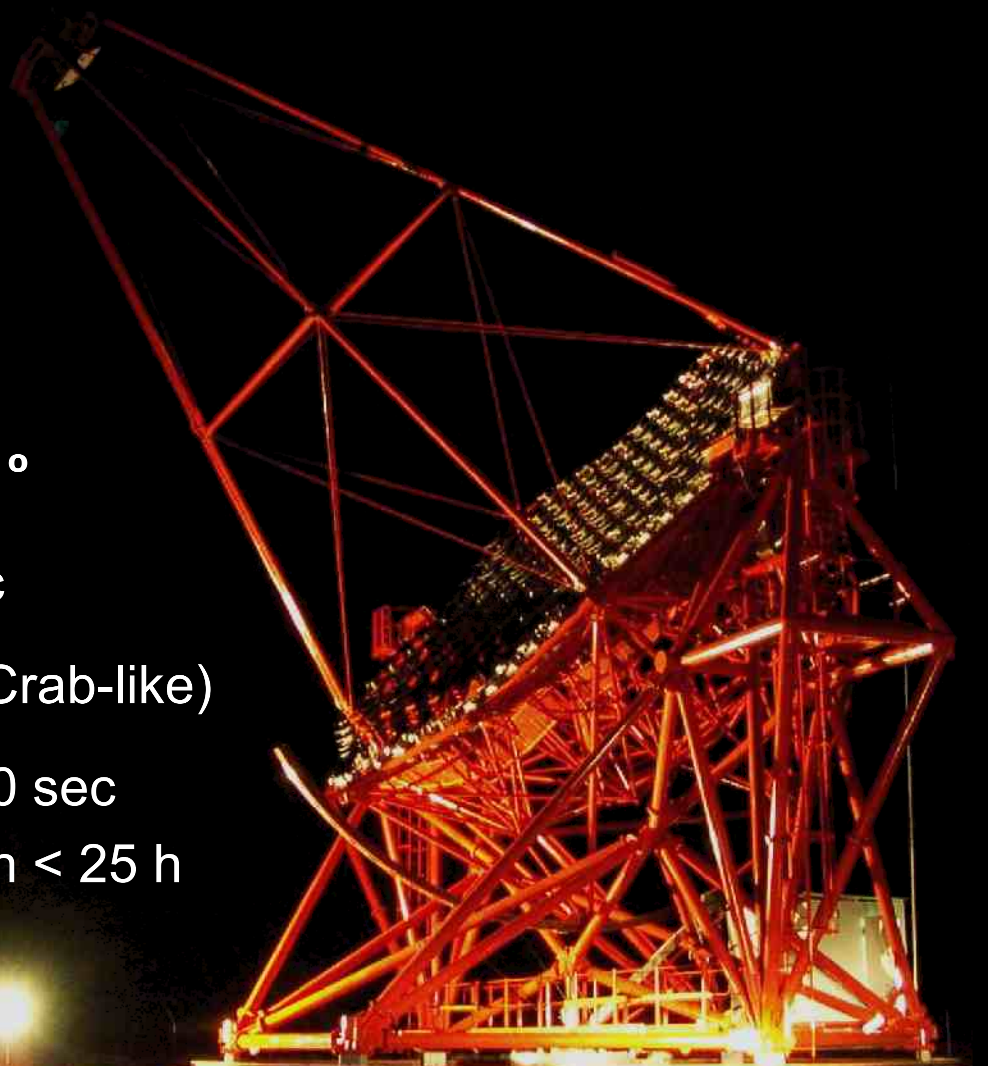
High Energy Stereoscopic System



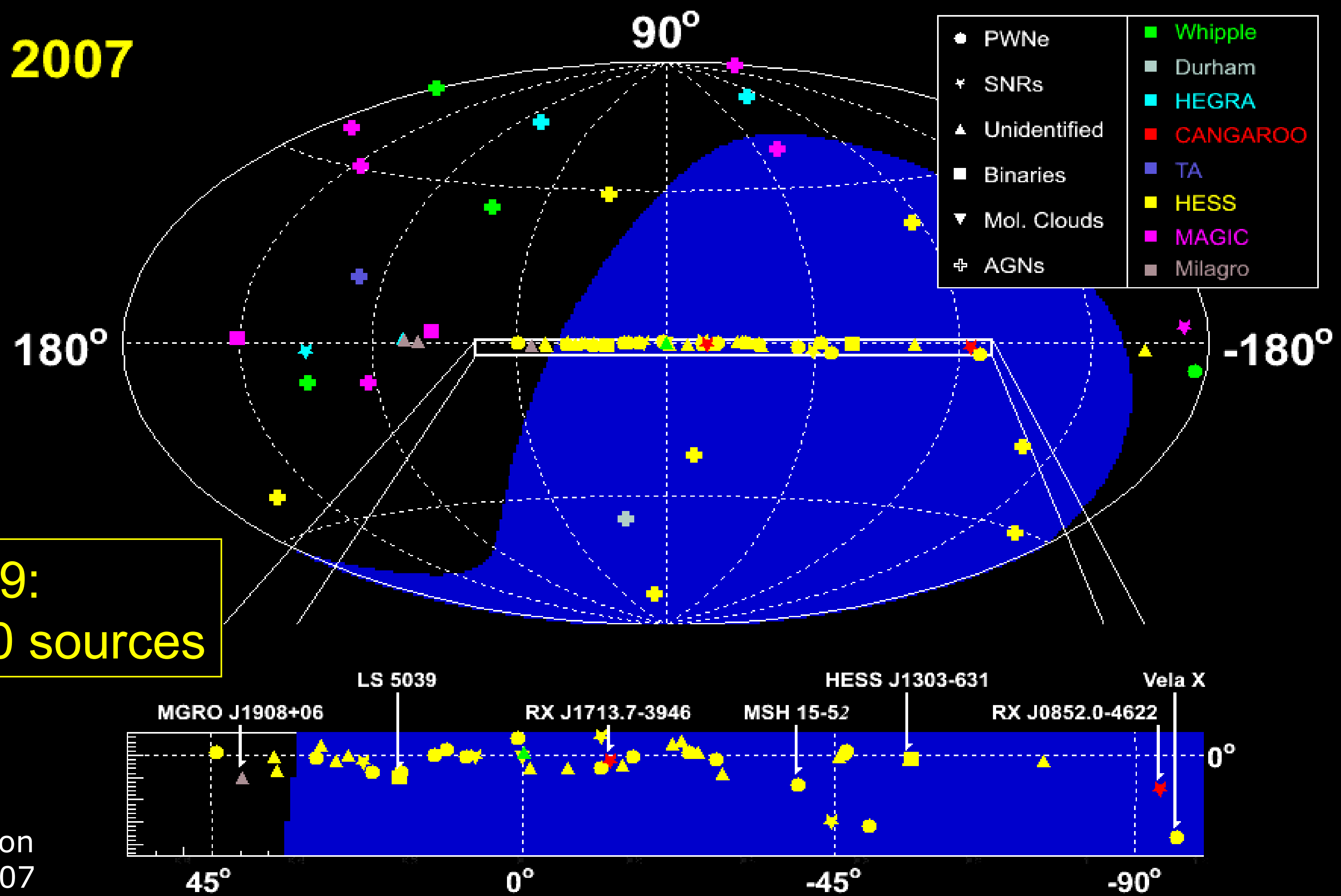
Stereo Performance Parameters

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 arcsec
Signal Rate:	~55 / min (Crab-like)
Sensitivity:	1 Crab in 30 sec 0.01 Crab in < 25 h



The sky in TeV gamma rays



2009:
> 80 sources

Jim Hinton
ICRC 2007

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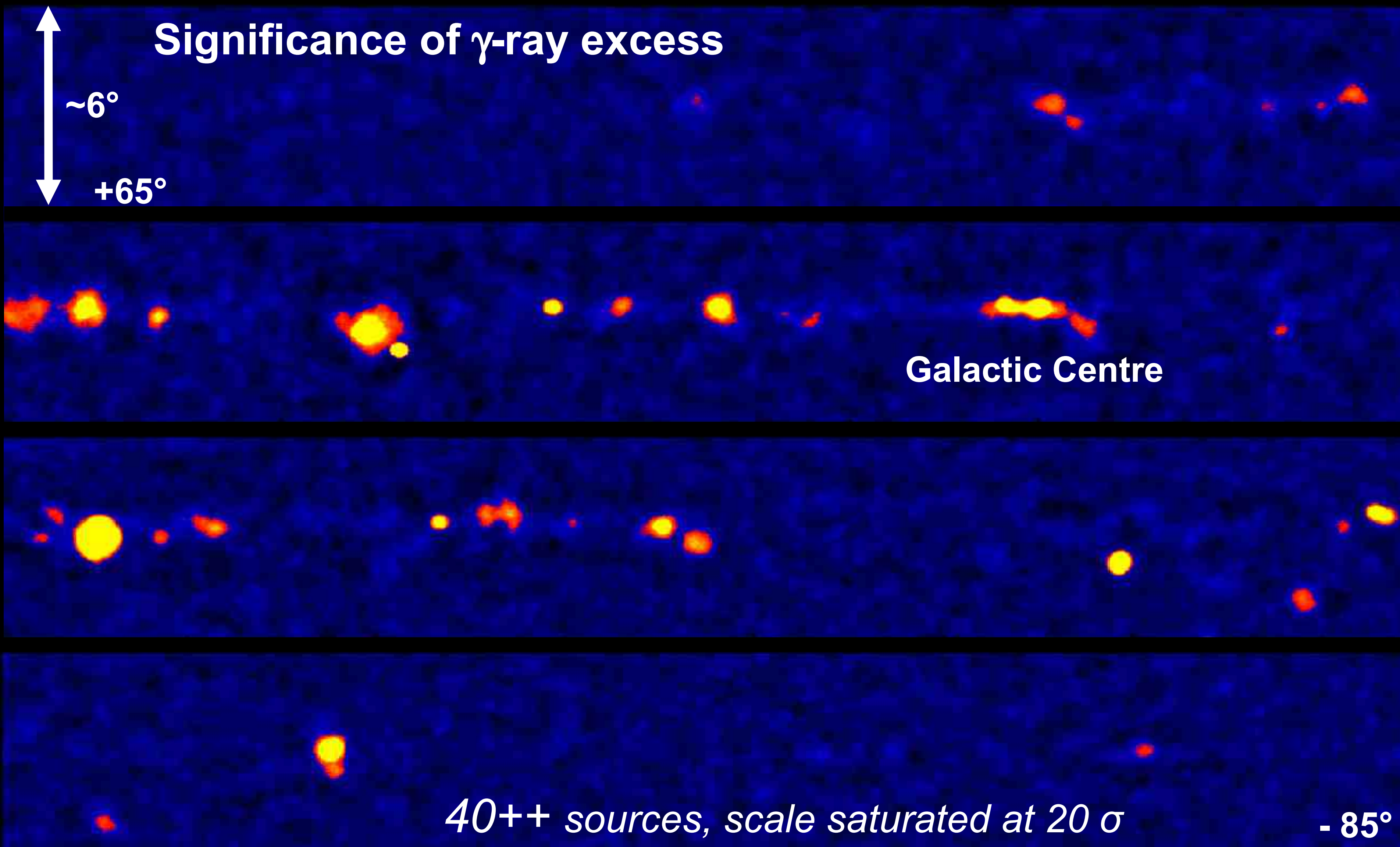
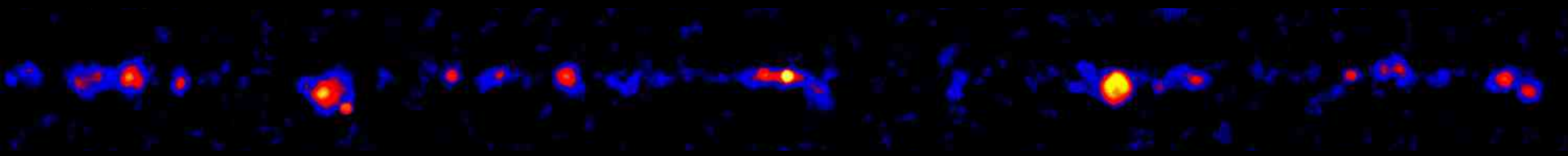
H.E.S.S. Galactic Plane Survey



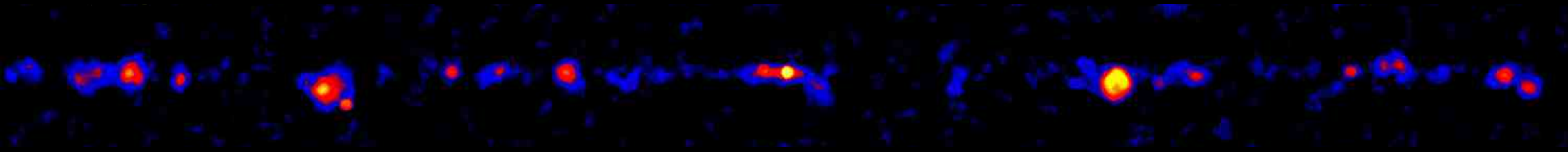
Classes of Galactic Sources



- Stellar winds
- Supernova remnants
- Pulsar wind nebulae
- Binary Systems
- Molecular Clouds

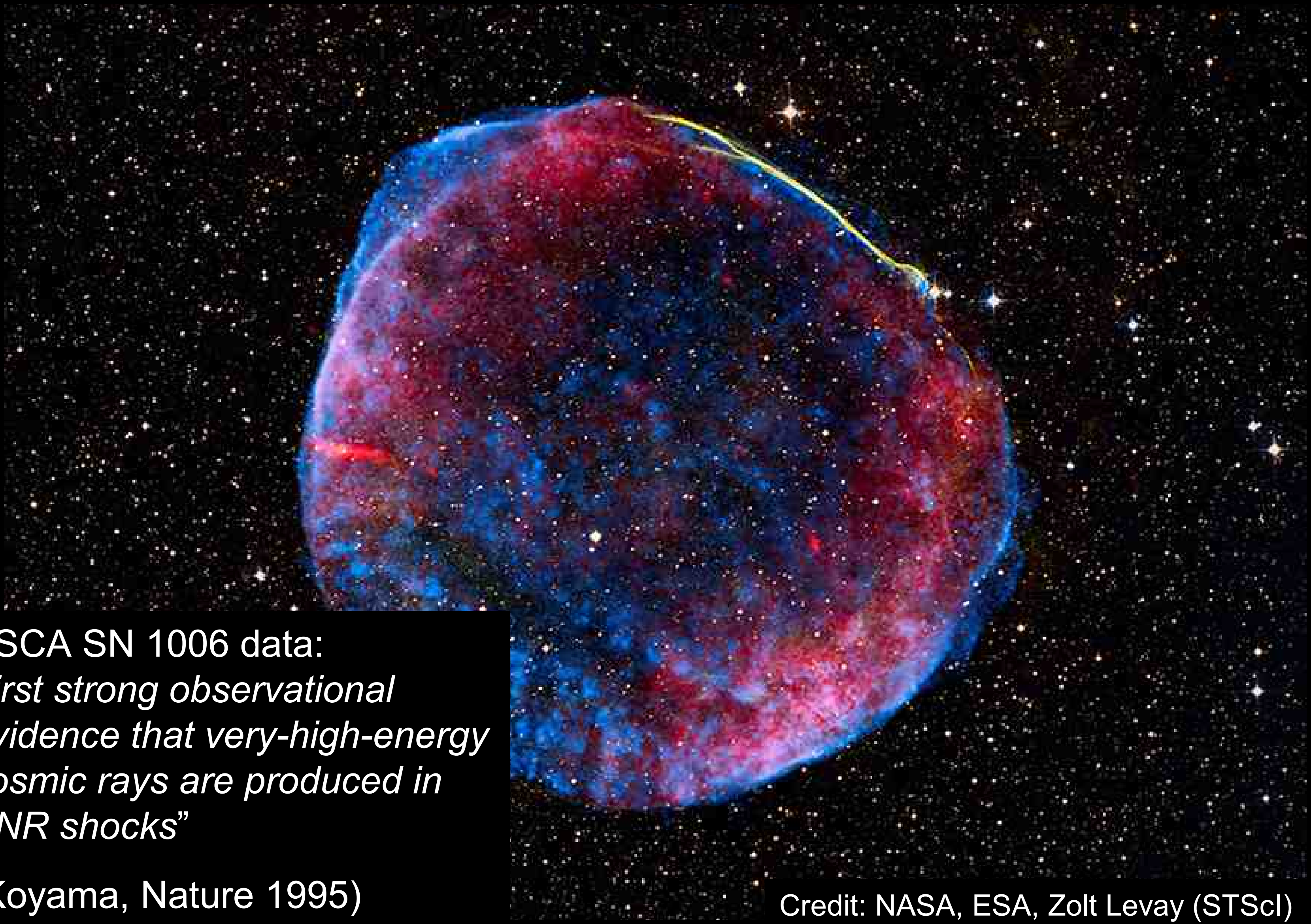
- Galactic center
- “Dark sources”

Classes of Galactic Sources



- Supernova remnants
- Molecular Clouds
- “Dark sources”

SNRs as Sources of Galactic Cosmic Rays



ASCA SN 1006 data:
"*first strong observational evidence that very-high-energy cosmic rays are produced in SNR shocks*"

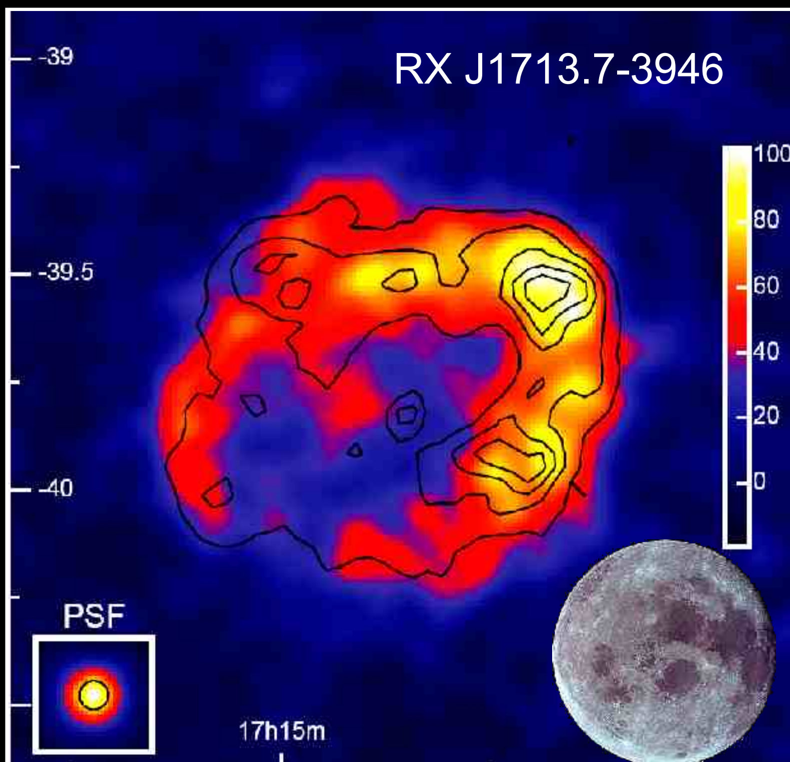
(Koyama, Nature 1995)

Credit: NASA, ESA, Zolt Levay (STScI)

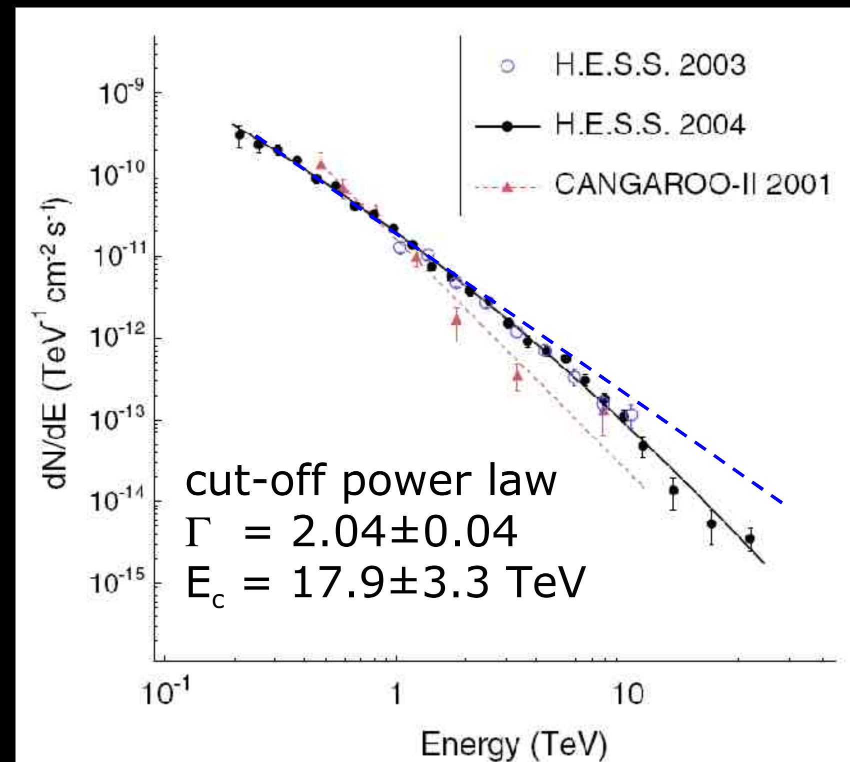
TeV Gamma-Rays from (young) SNRs

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

Particle acceleration to beyond 100 TeV



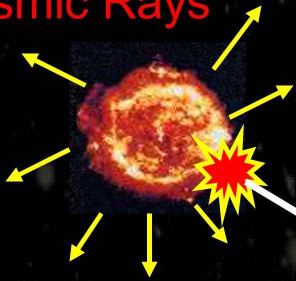
2004-2006 Data



Proof of TeV emission from the shell of SNRs

What particles are accelerated … ?

Source of
Cosmic Rays



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)

What particles are accelerated … ?

… protons ?

Source of Cosmic Rays

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

γ

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

Observables

- Energy Spectra
  flux, range, shape
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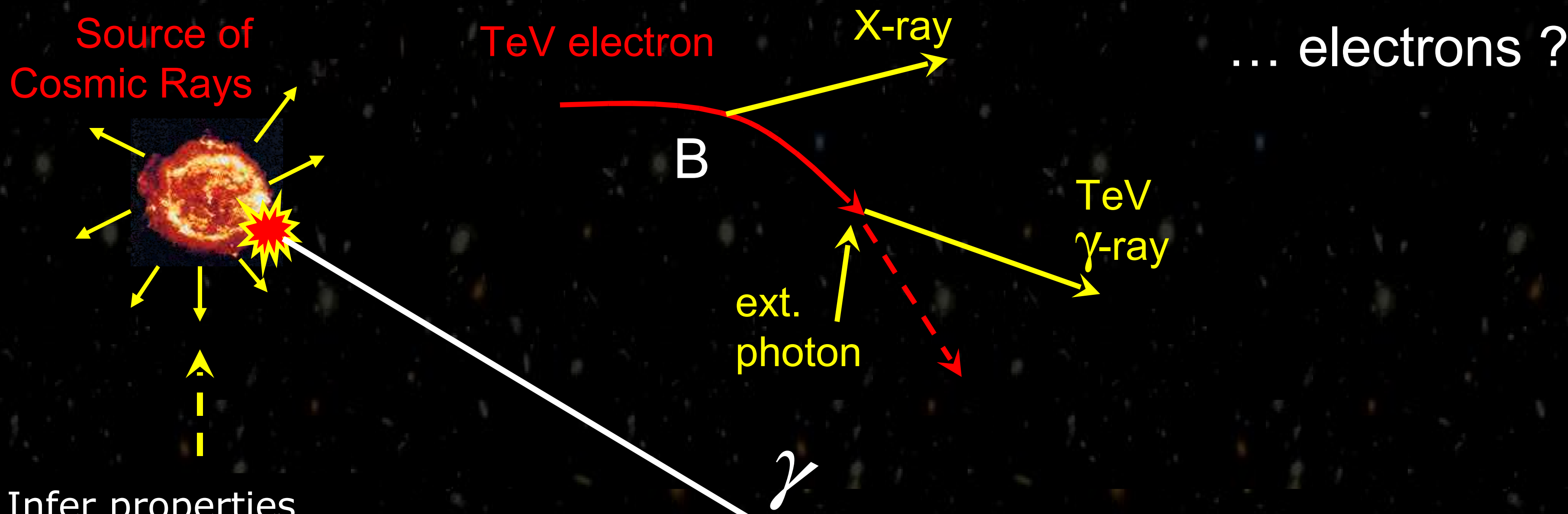
What particles are accelerated ?



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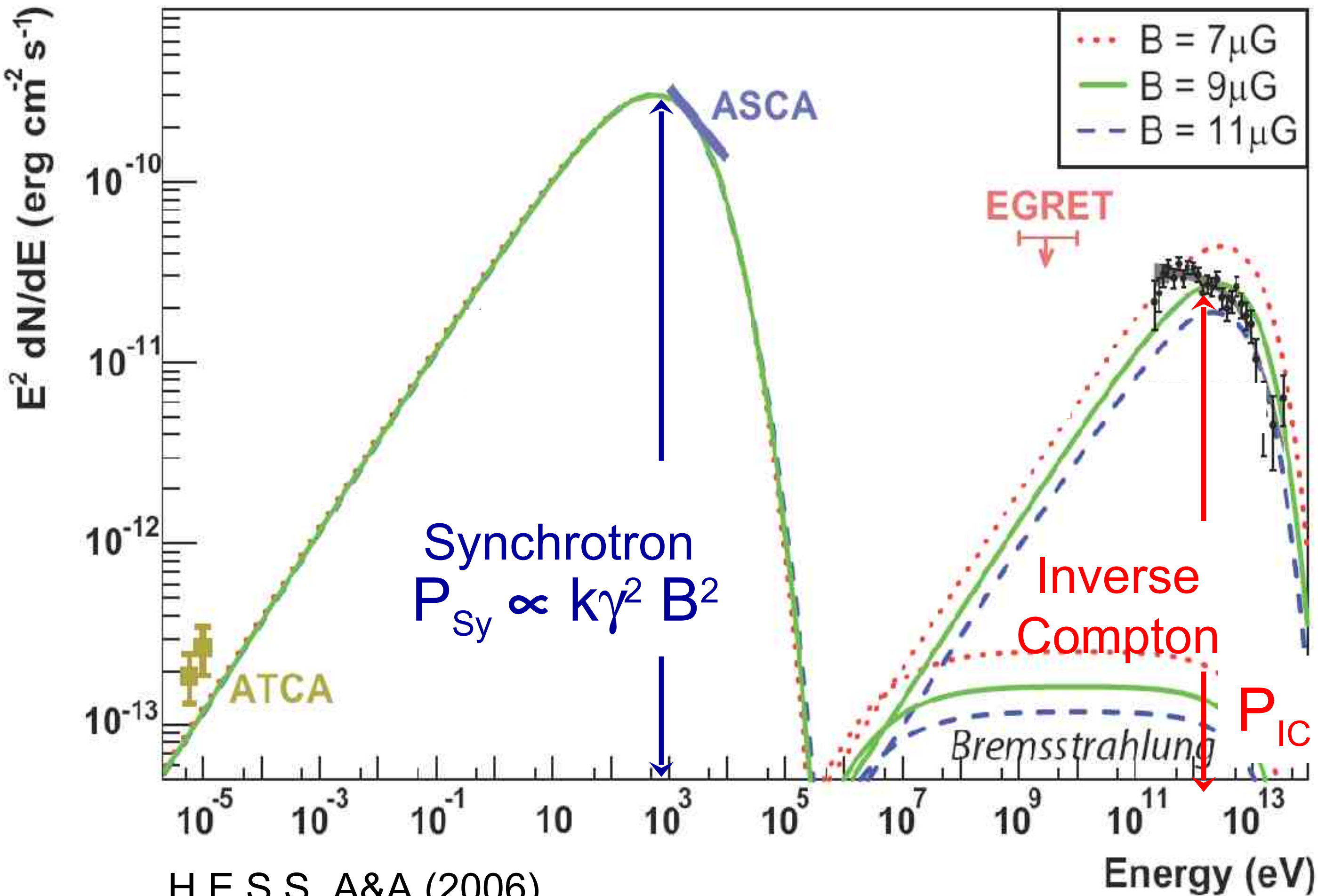
Leptonic emission model for RXJ 1713

Assume Electrons: Synchrotron + Inverse Compton

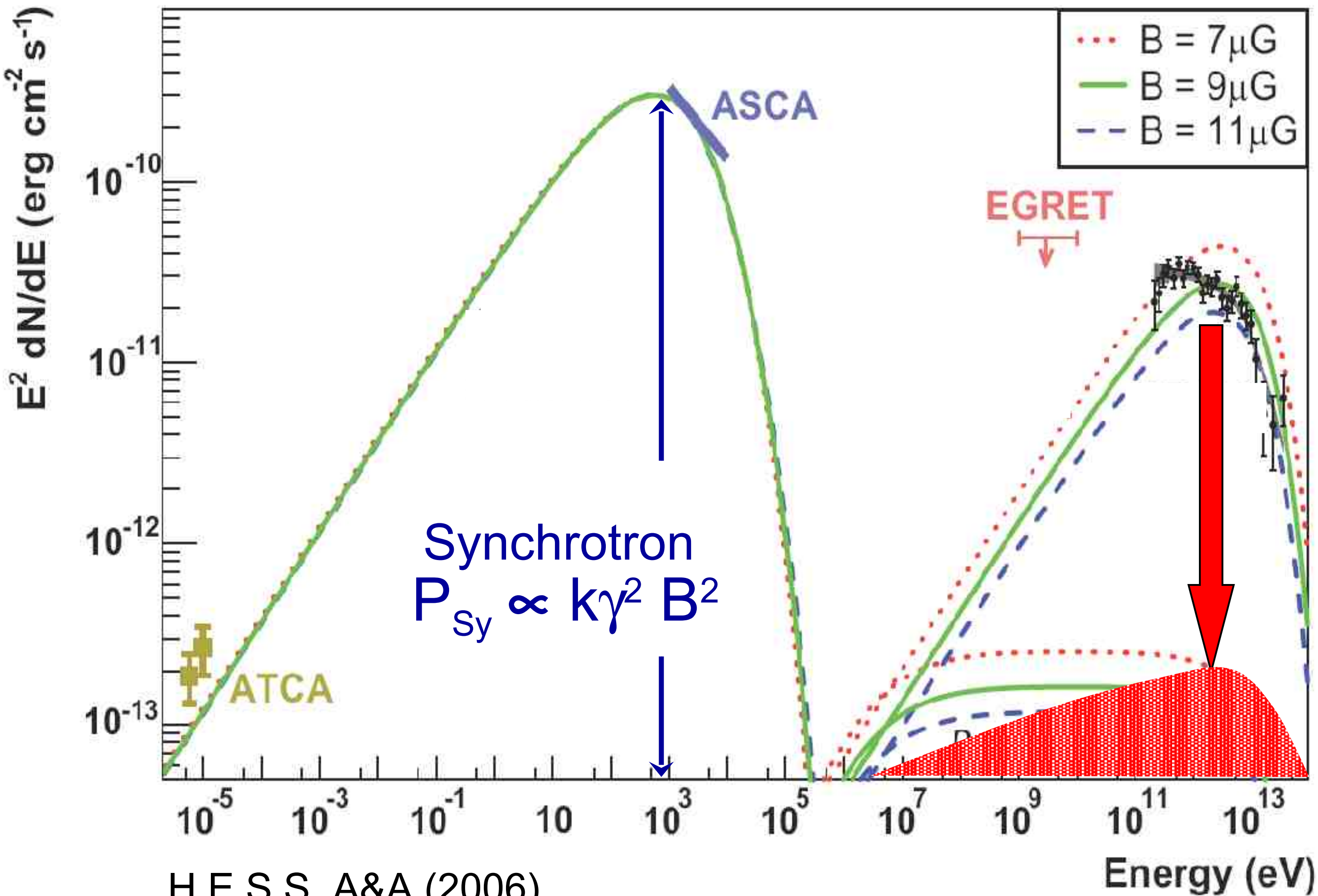


$P_{IC} / P_{Sy} \propto 1 / B^2$

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

Leptonic emission model for RXJ 1713

Assume Electrons: Synchrotron + Inverse Compton



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

High B-Field

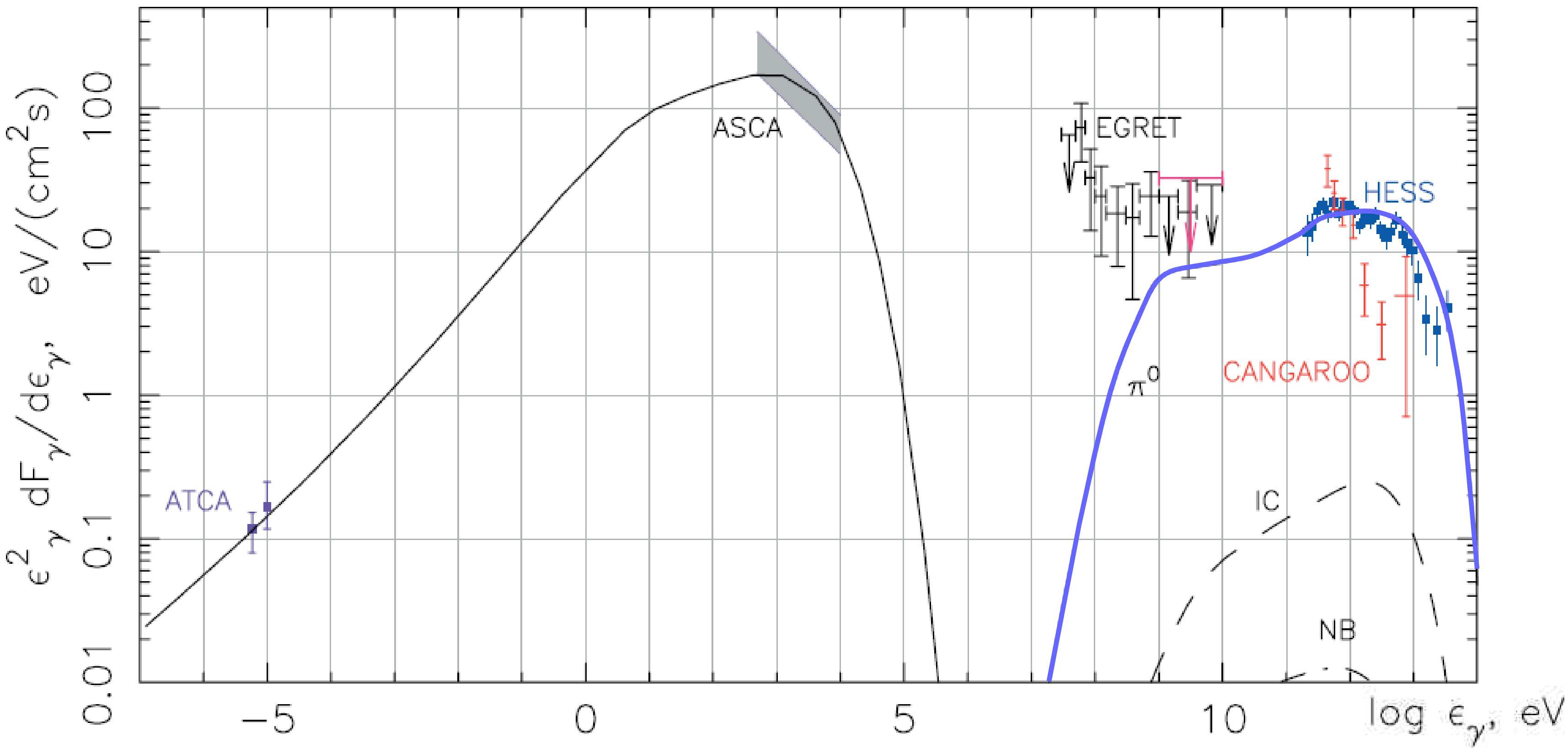
65…230 μG

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

Berezkho, Völk (2006)

Hadronic emission model for RXJ 1713

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

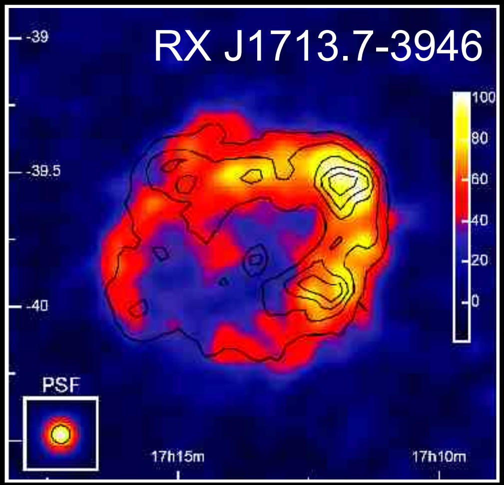


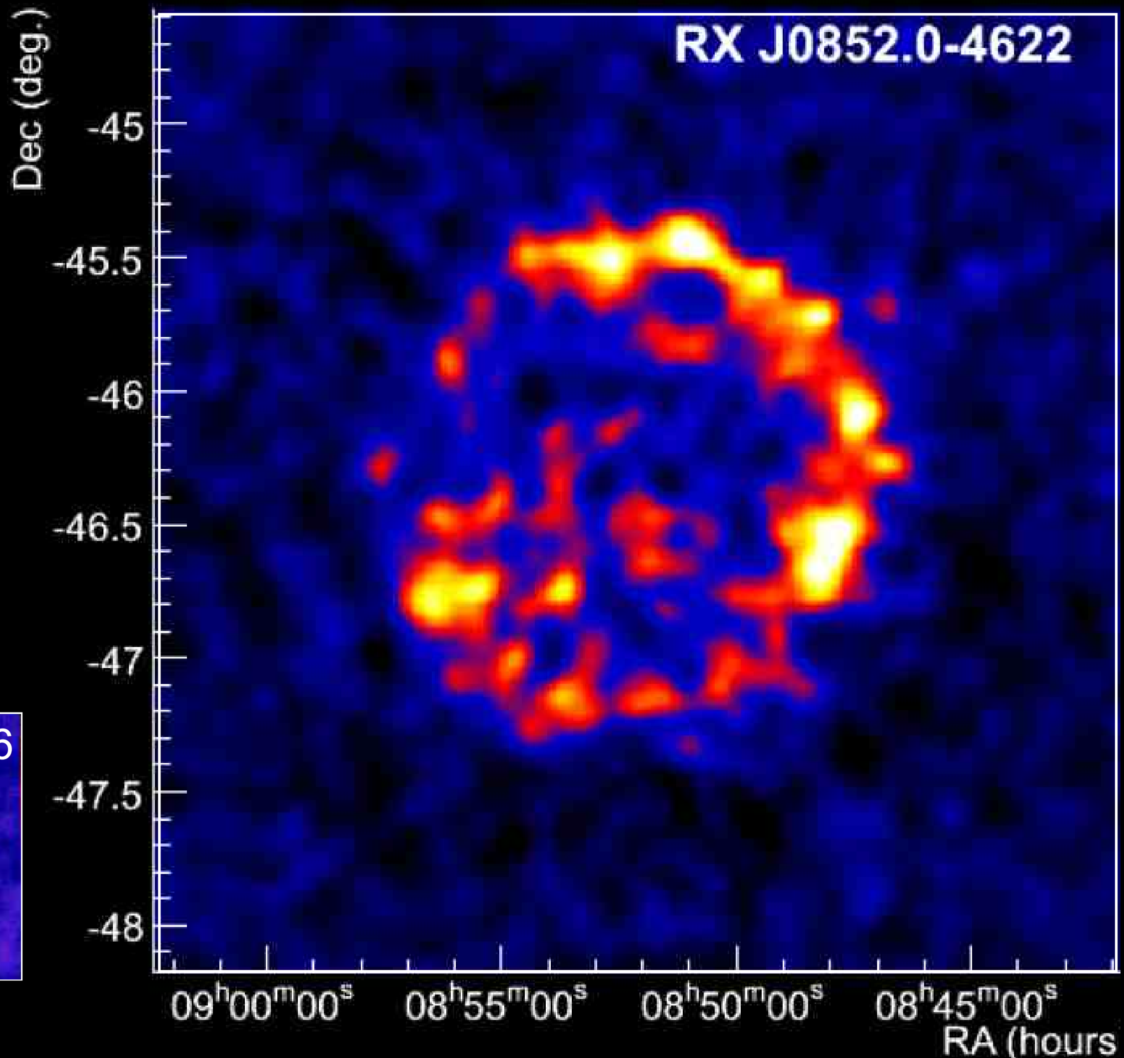
Berezkho, Völk (2006)

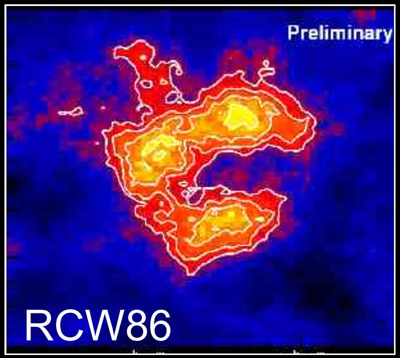
Hadronic models describe data reasonably well !

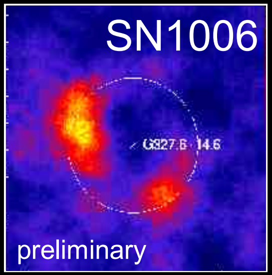
Are SNRs *the* sources of Galactic cosmic rays ???

Towards population studies of shell-type TeV SNRs …



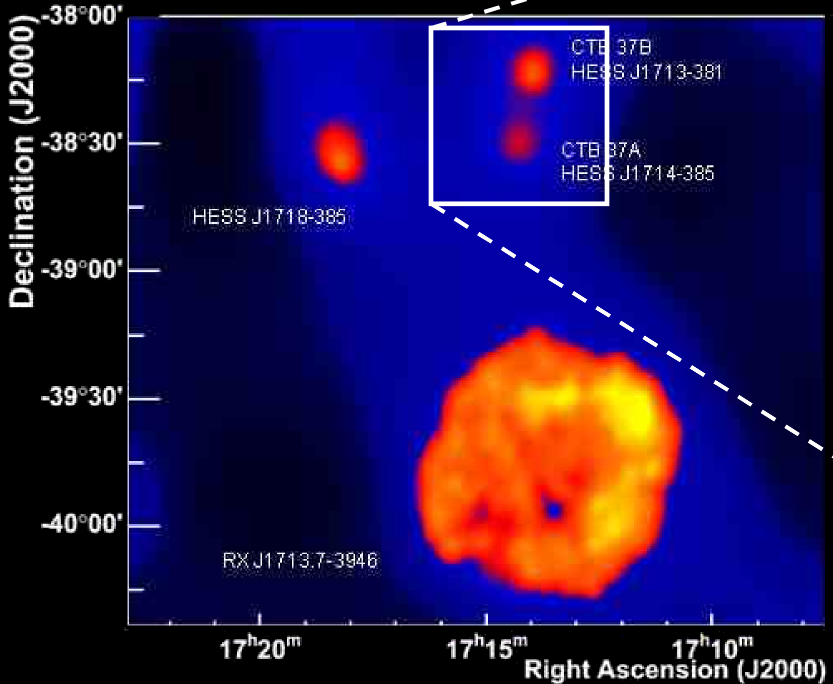


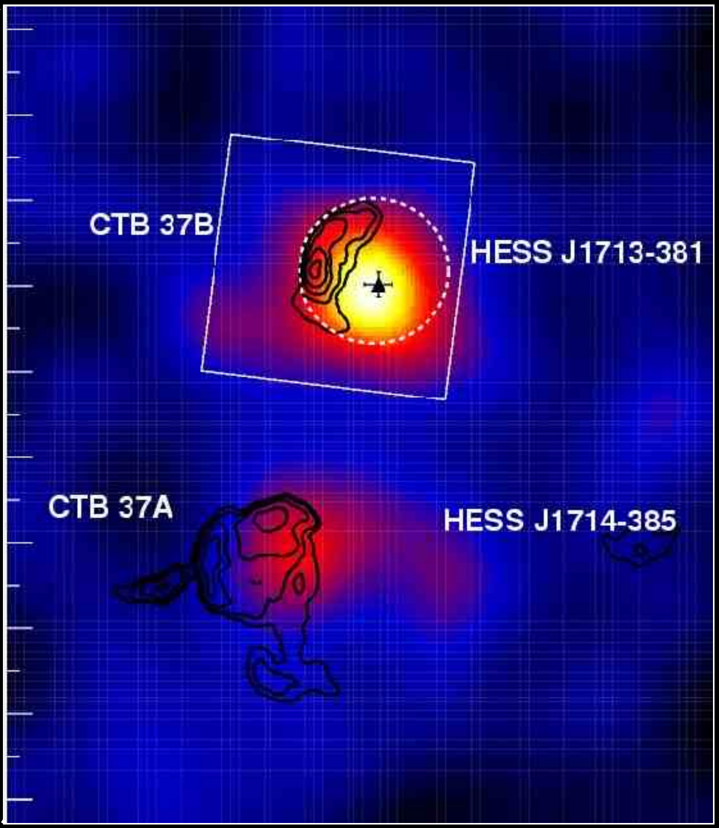




Maps ~ to scale

… and of TeV - SNR associations





→ Large FoV
→ Deep exposure @ RX J1713.7

→ CTB 37 A and CTB 37B both candidates for the support of hadronic scenario for TeV-γ-ray production
H.E.S.S. (2008)

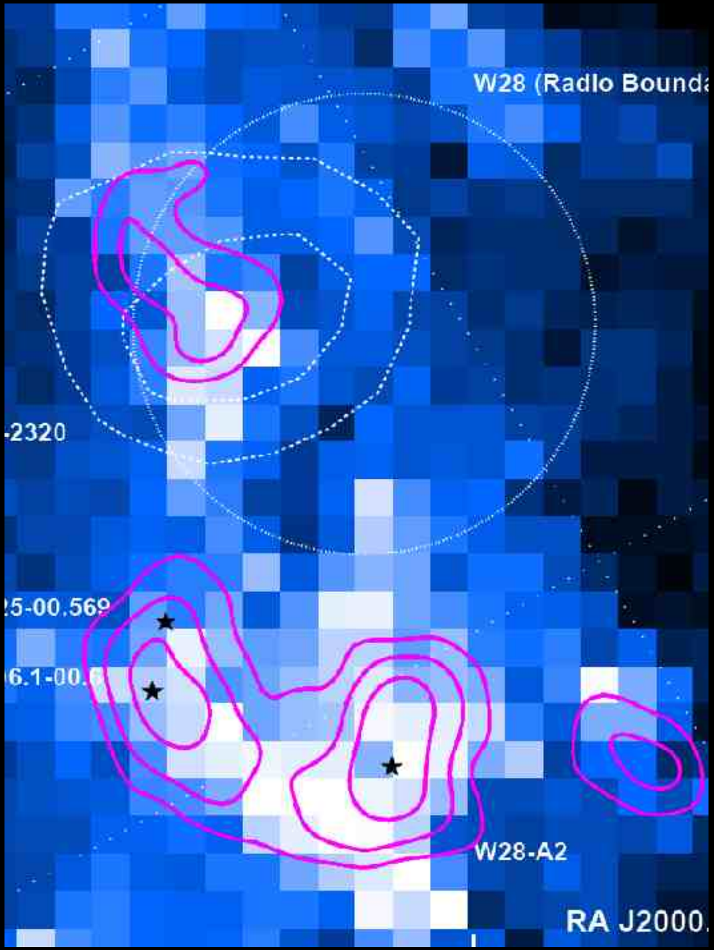
When cosmic rays meet targets …

Which fraction of
SNR energy goes into
cosmic-ray nuclei?

How/when are particles
Released ?

Interacting SNR probe
Nature of accelerated particles,
particle release, and
particle propagation in
our galaxy

NANTEN CO 10-20 km/s
Moriguchi, Y. YFukui



W28: ~35-150 kyrs old
Molec. clouds ~0.5 – 1 10E5 $M_\odot$

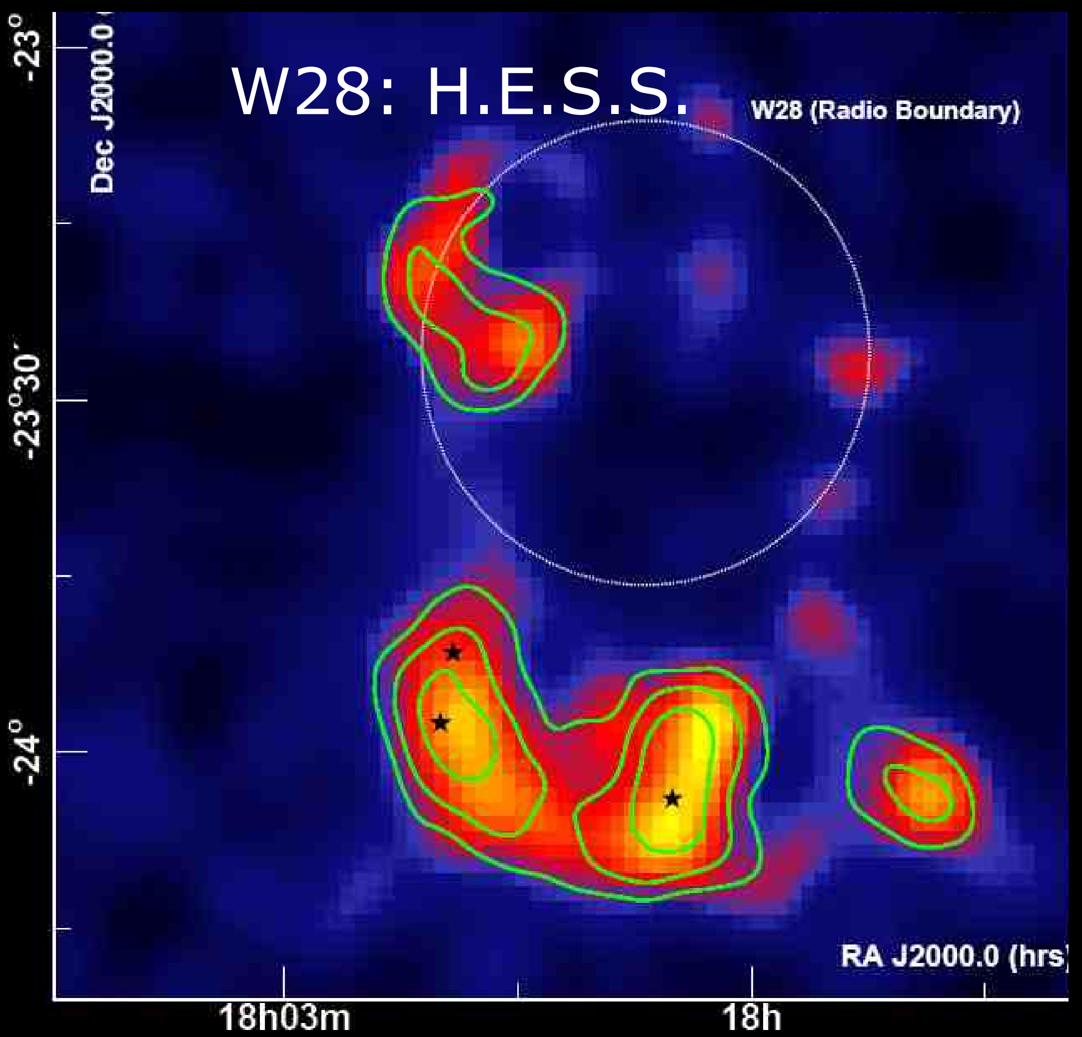
SNR interacting with molecular clouds

Which fraction of
SNR energy goes into
cosmic-ray nuclei?

How/when are particles
Released ?

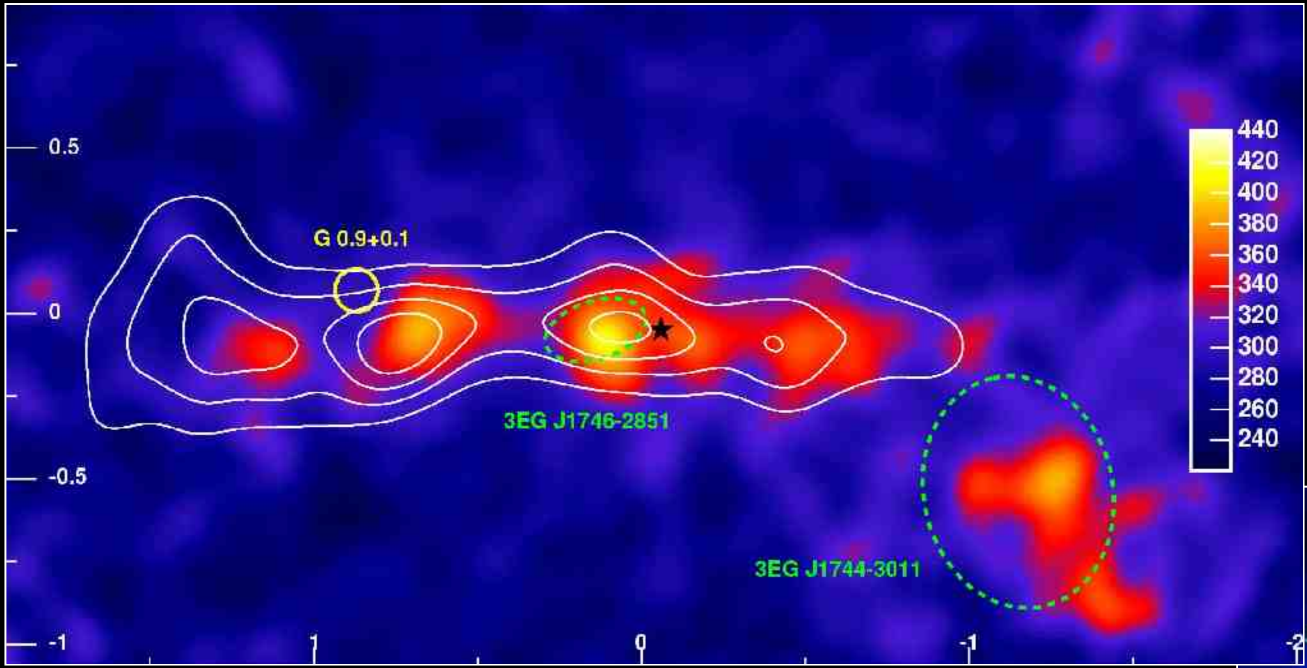
If hadronic emission and
association w/ clouds ok:

→ x 10-30 higher CR density
than in solar system



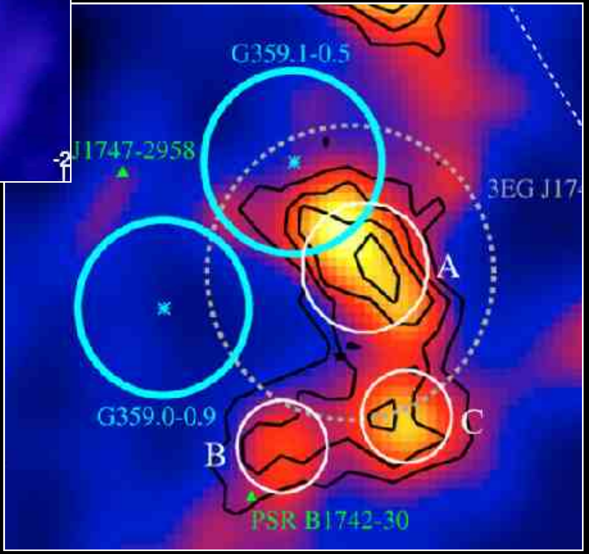
HESS, A&A (2008)

TeV-Emission from molecular clouds



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

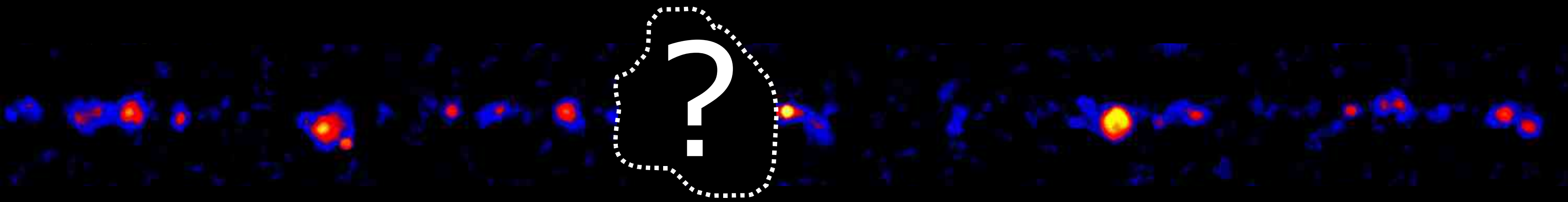
HESS J 1745-303



Aharonian (H.E.S.S.), A&A (2008)

Interaction of CR with molecular clouds:
→ Future: tracing of CR density in the Galaxy

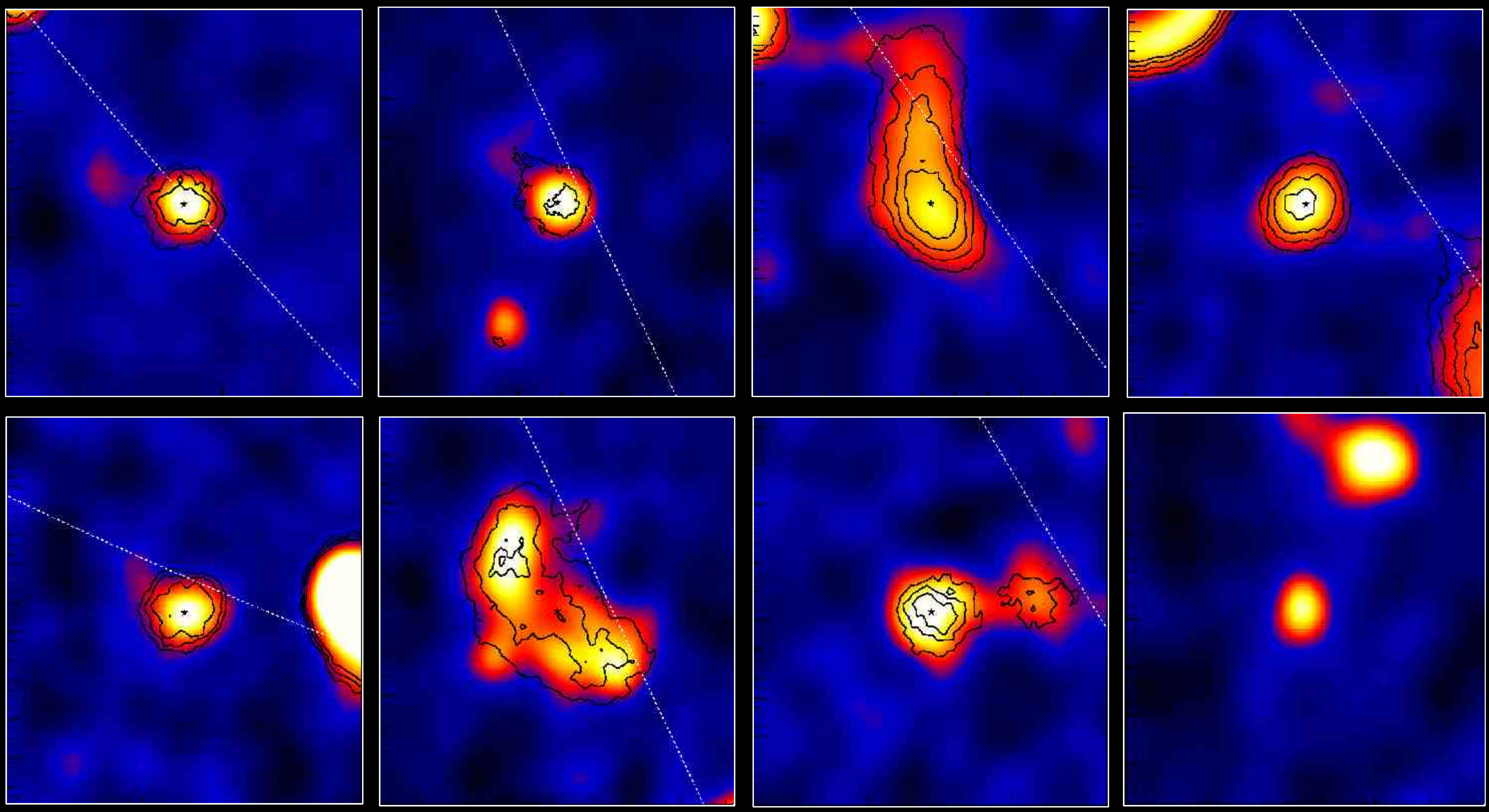
Classes of Galactic Sources



- “Dark sources”

Discovery Potential: “Dark Sources”

A bias free view on the sky: → new class of TeV sources



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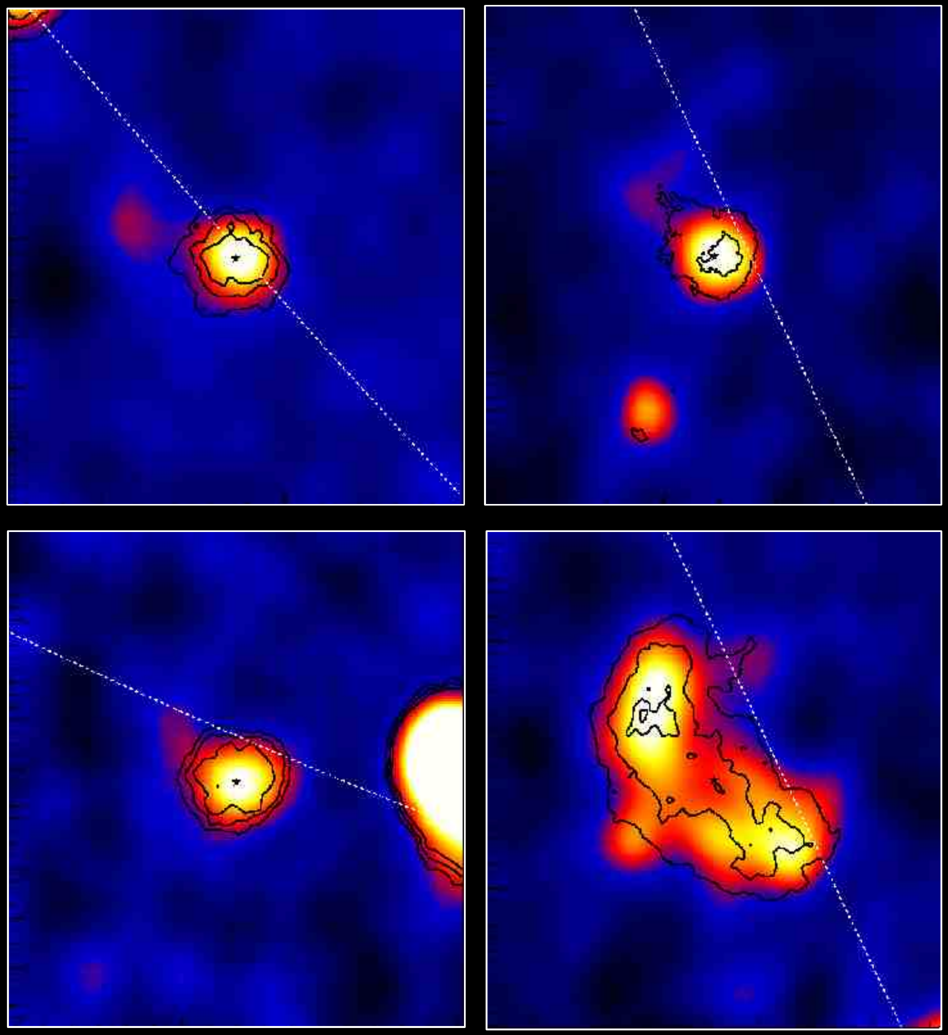


No counterparts in other energy bands seen (radio, IR, optical, X-ray, …)

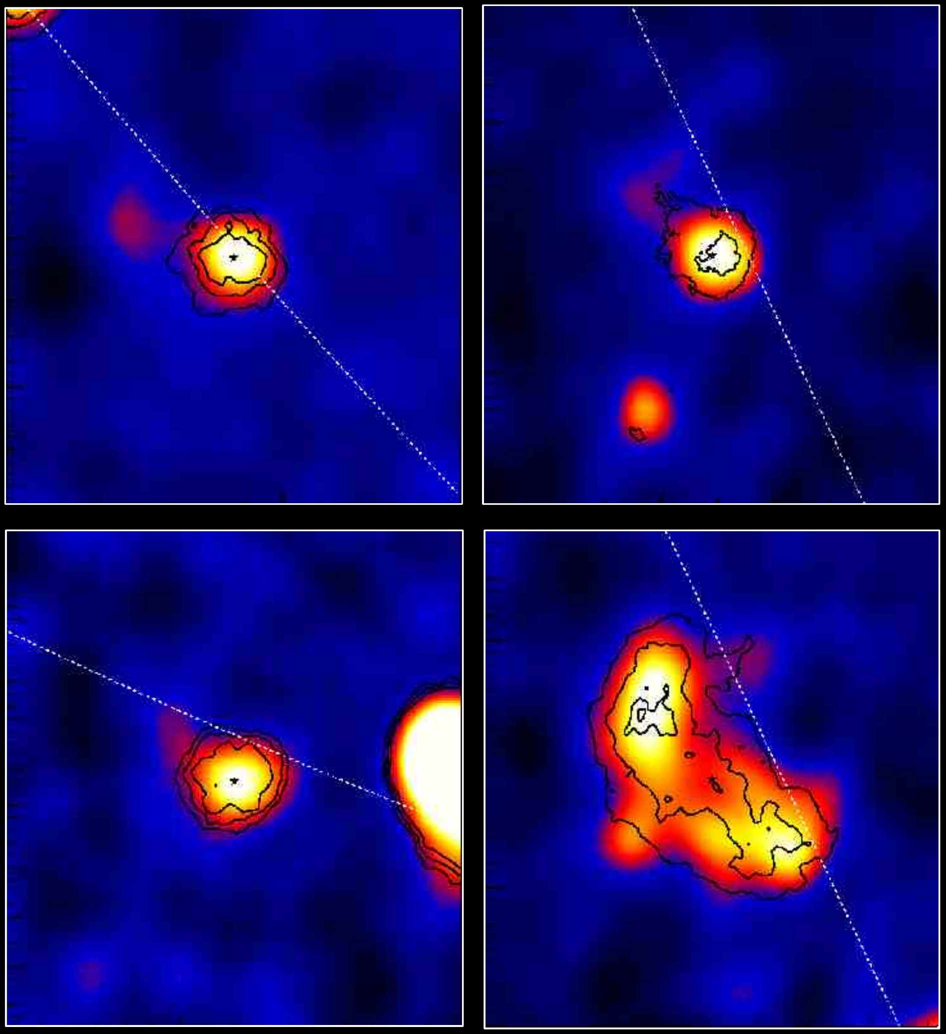
Aligned with Galactic plane
All are extended: O (10 arcmin)
Hard spectrum: $\Gamma \sim$ 2.1 … 2.5

→ Maximum energy output of these sources in TeV γ-rays
→ Hadron accelerator ?
→ Old PWN ?
→ GRB remnant ?
→ Dark Matter ?

HESS A&A 477 (2008)

Discovery Potential: "Dark Sources"

A bias free view on the sky: → new class of TeV sources

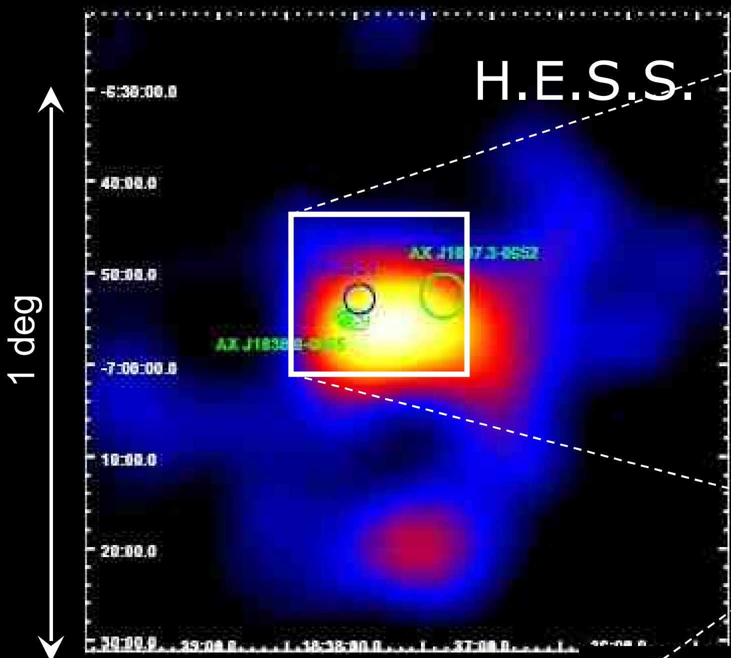


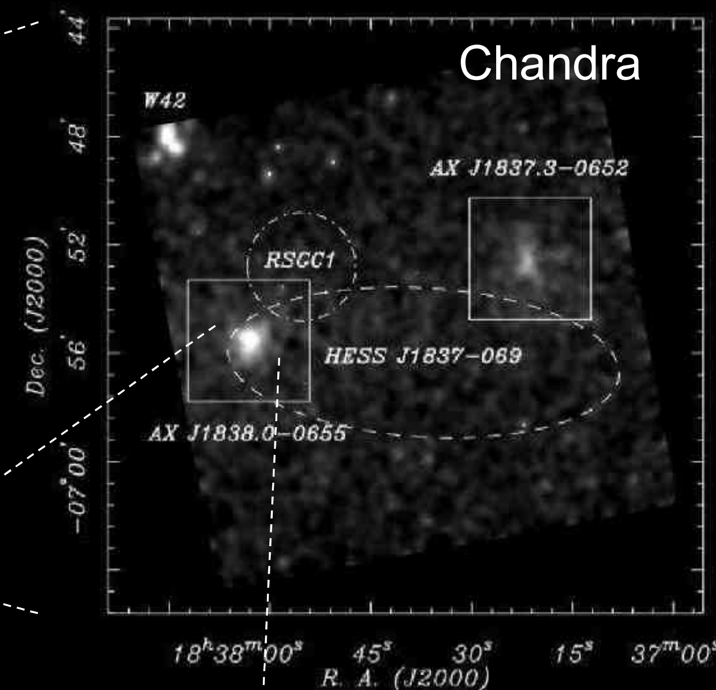
No counterparts in other energy bands seen (radio, IR, optical, X-ray, …)

→ More sensitive X-ray and radio observations following the TeV detection

HESS A&A 477 (2008)

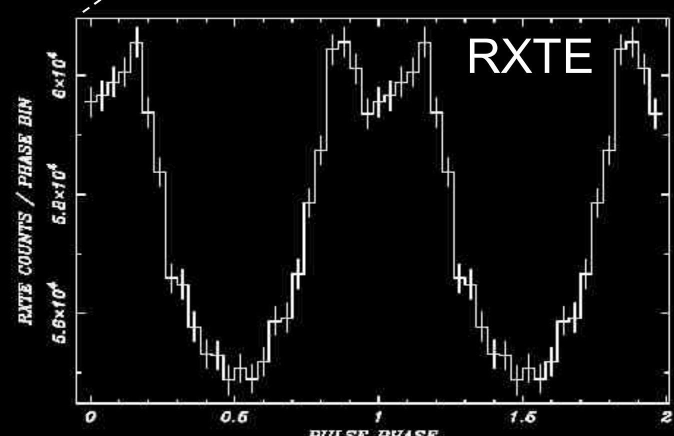
Pulsar discovery triggered by H.E.S.S.





HESS J1837:
7 ‘ x 3 ‘ extension
Flux ~ 0.13 Crab

2 % of dE/dt of Pulsar
needed to power
TeV flux !



Discovery of
PSR J1838−0655
Gotthelf & Halpern (2008)
period 70.5 ms,
spin-down energy loss
~5.5 x 10^{36} ergs/s

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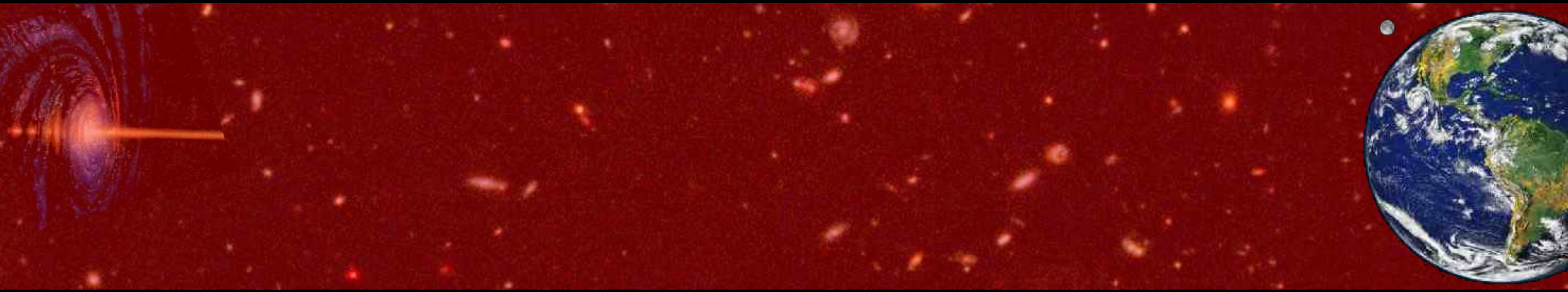
Extragalactic Physics with H.E.S.S.

Object	Z	Type
Cen A	0.001	AGN (FR I)
M87	0.004	AGN (FR I)
Mkn 421	0.030	BLLac (HBL)
PKS 0548-322	0.069	BLLac (HBL)
PKS 2005-489	0.071	BLLac (HBL)
RGB J0152+017	0.08	BLLac (HBL)
PKS 2155-304	0.116	BLLac (HBL)
1ES0229+200	0.139	BLLac (HBL)
H2356-309	0.165	BLLac (HBL)
1ES 1101-232	0.186	BLLac (HBL)
1ES 0347-121	0.188	BLLac (HBL)
PG 1553+113	>0.25 ?	BLLac (HBL)

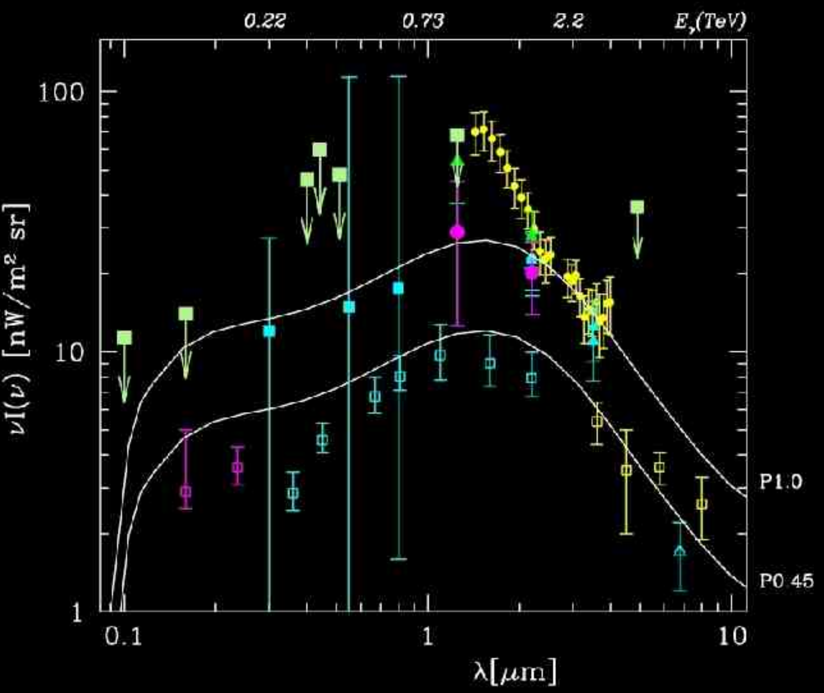
Detection of 12 AGN
Discovery of 9 AGN
Upper Limits on >20 Objects (< 0.01 … 0.05 Crab)

The Extragalactic Background Light



EBL contains information on history of star- and galaxy formation

→ Direct measurement very difficult due to foreground light



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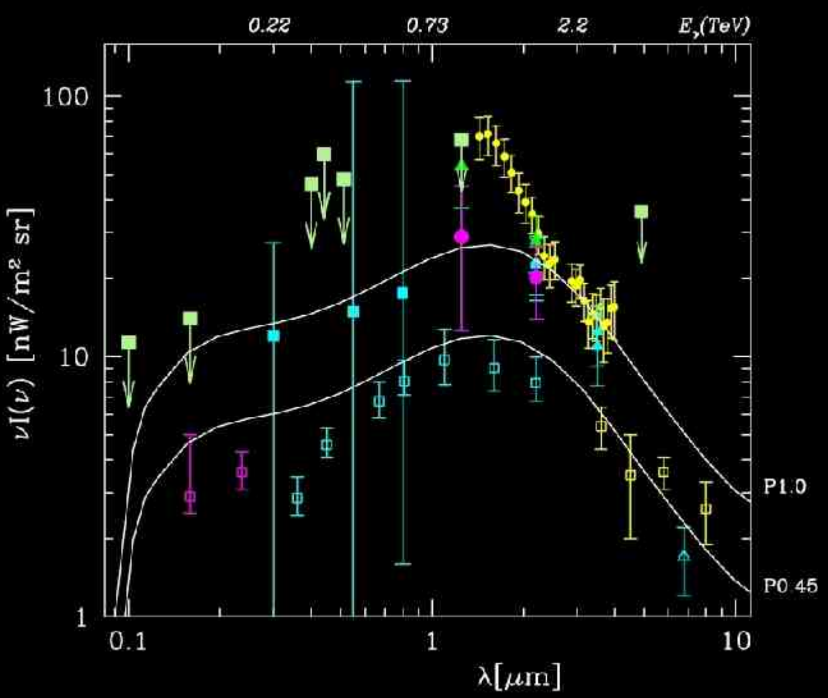
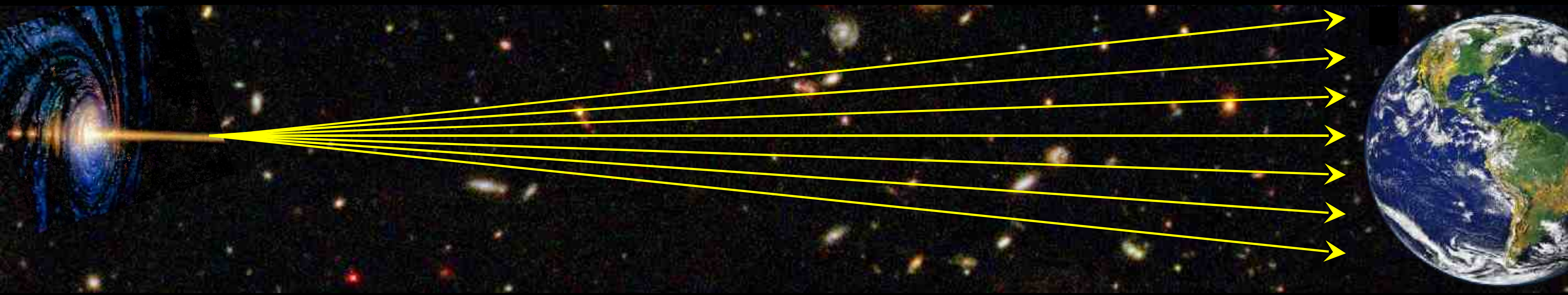
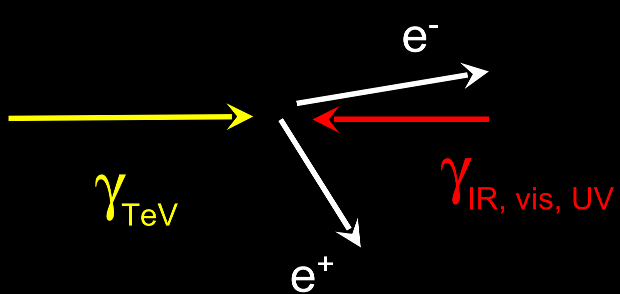
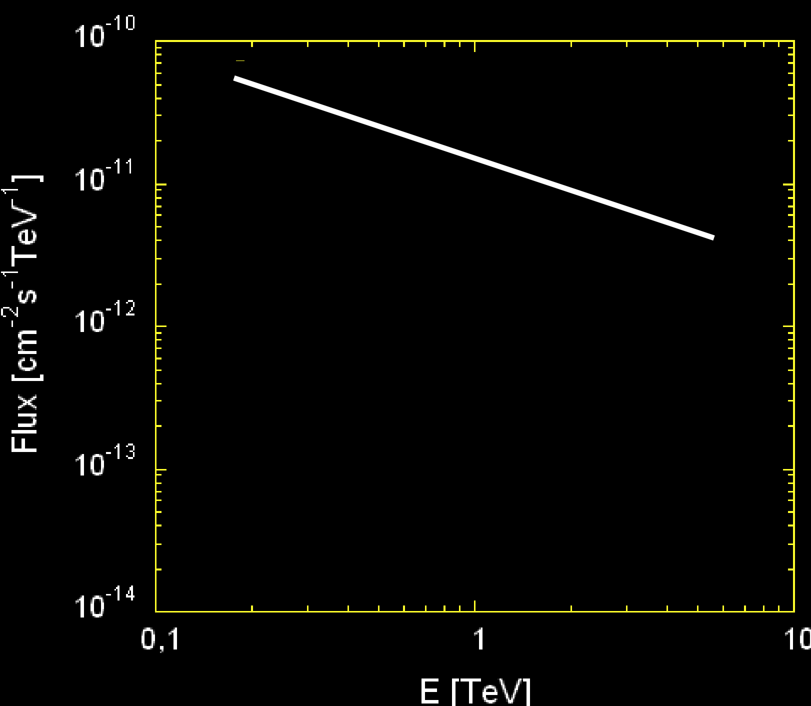


EBL absorption of TeV gamma rays

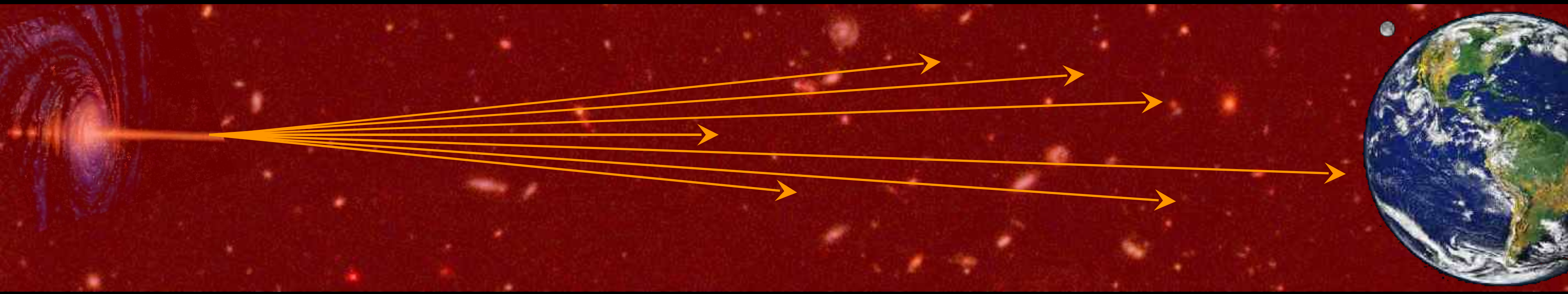


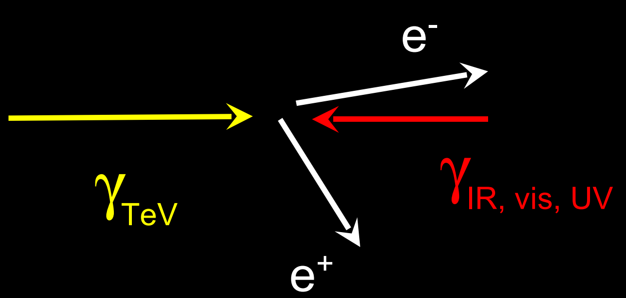


Absorption through pair production with diffuse EBL in FIR to UV (for TeV to GeV)

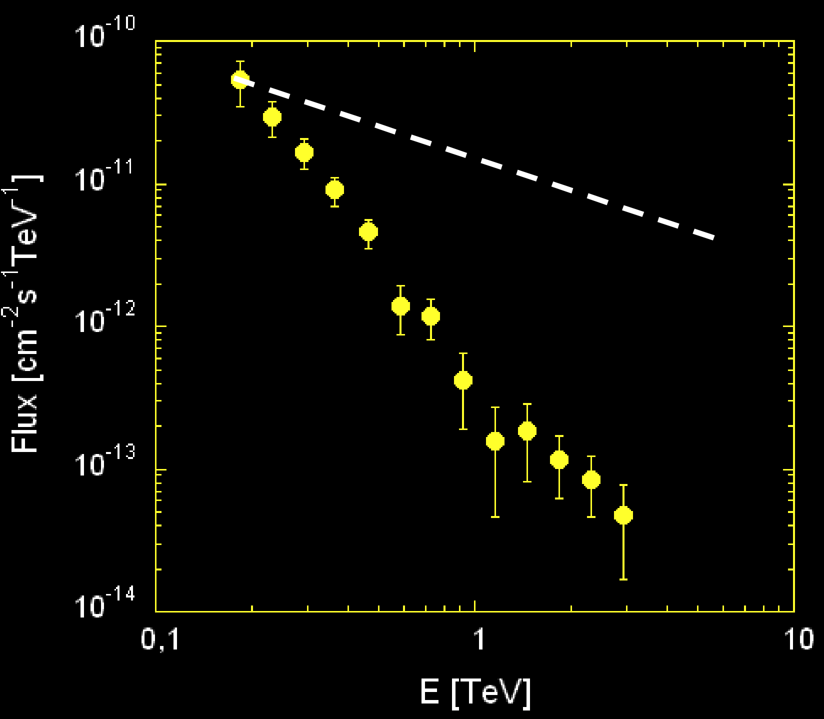


EBL absorption of TeV gamma rays

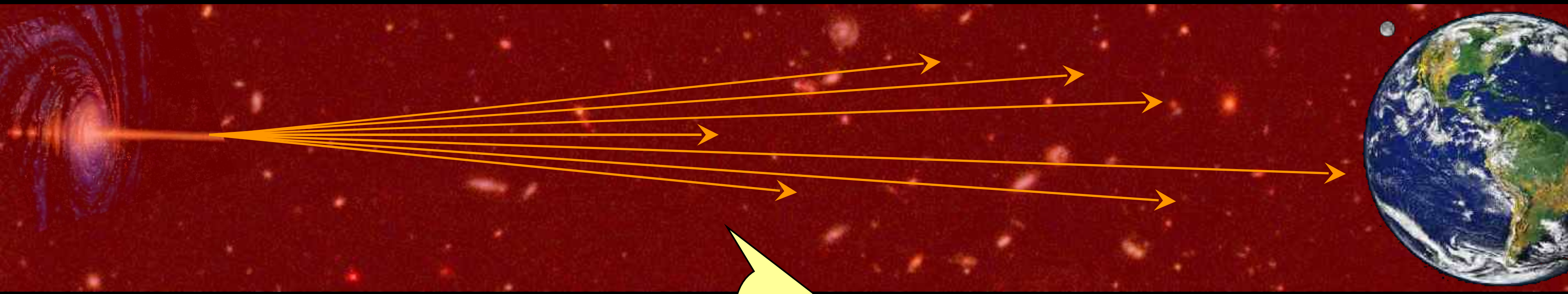


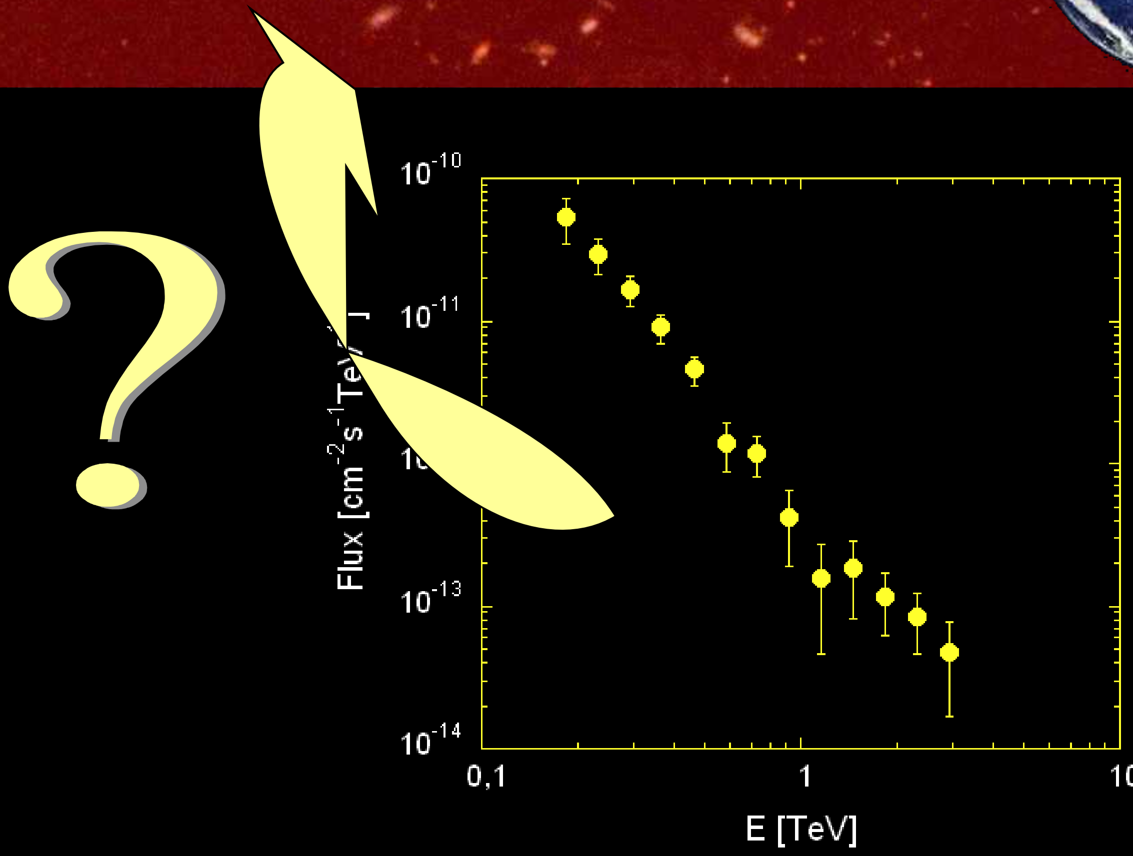


Absorption through pair production with diffuse EBL in FIR to UV (for TeV to GeV)

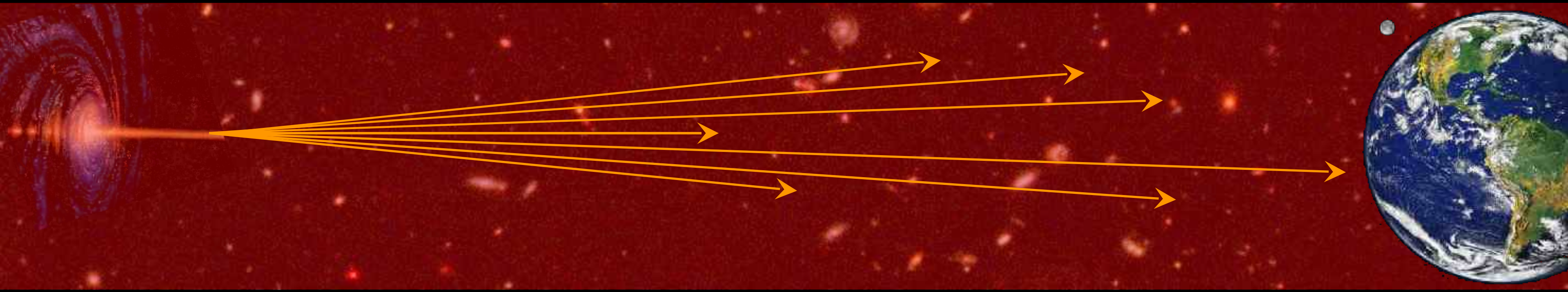


Reconstructing the EBL density





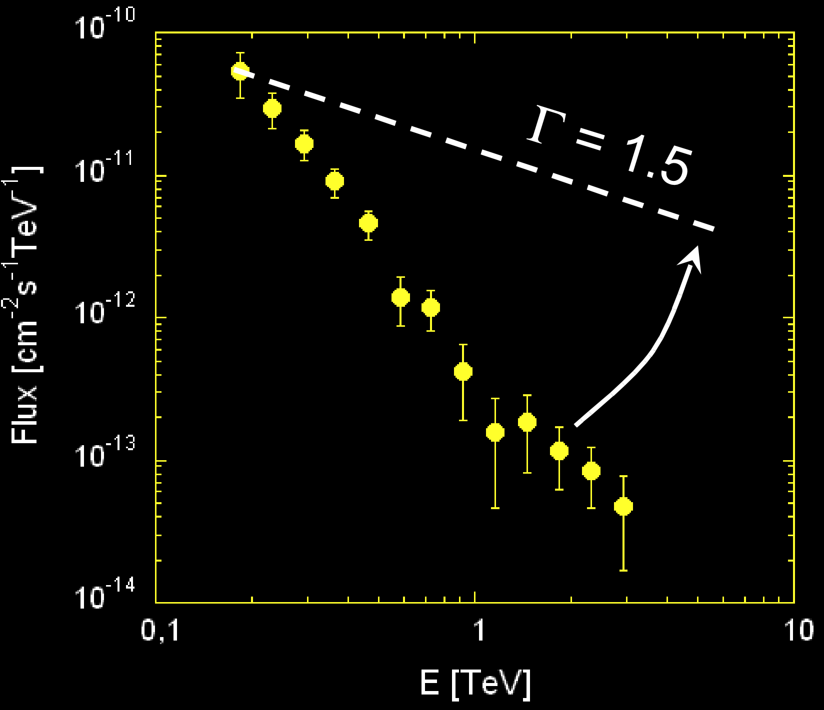
Reconstructing the EBL density



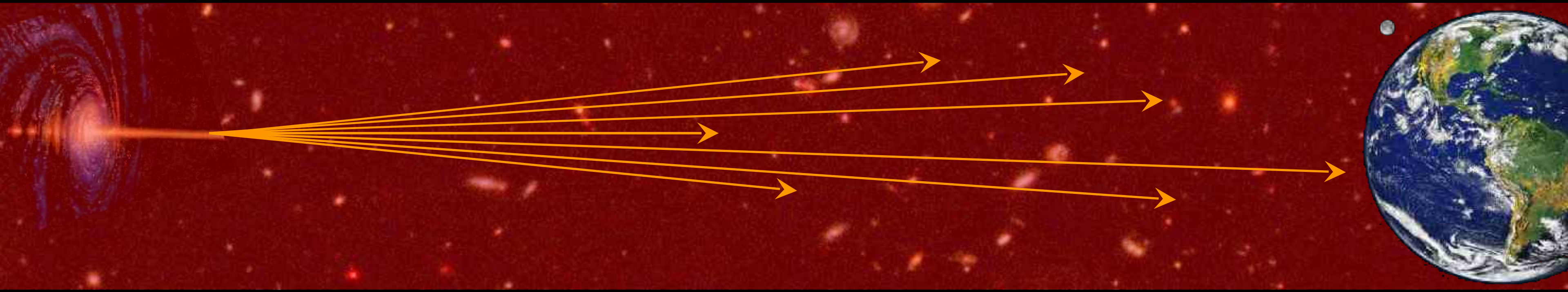
Assume minimum power law index Γ = 1.5 at source

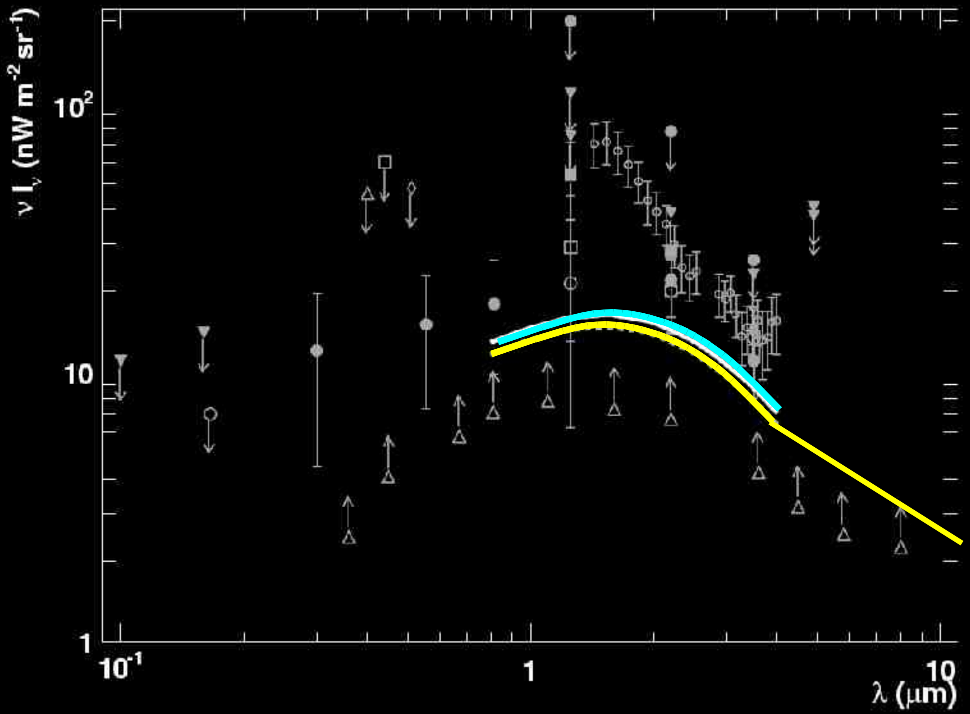
“Adjust” EBL such, that observed spectrum compatible with assumed source spectrum

→ EBL intensity



The Extragalactic Background Light





- EBL is at lower limit, as obtained from Hubble galaxy count

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

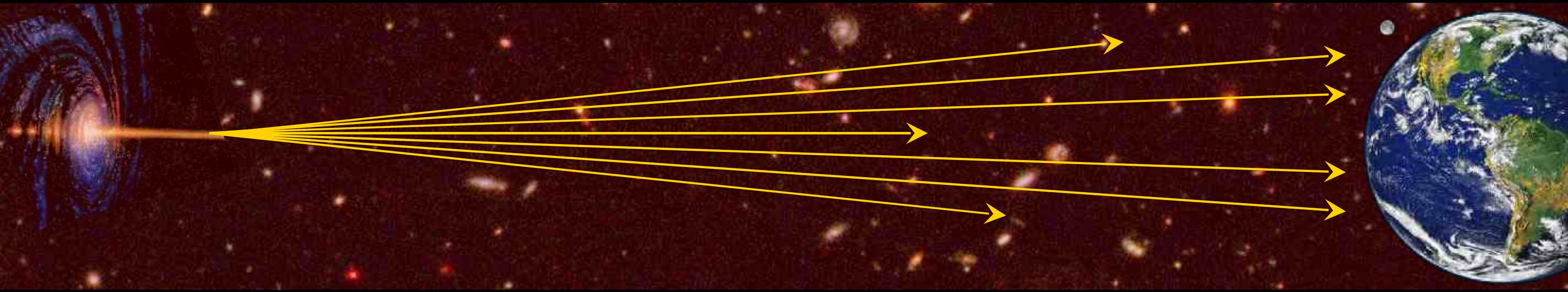
- Confirmed by 1ES0347, z = 0.188

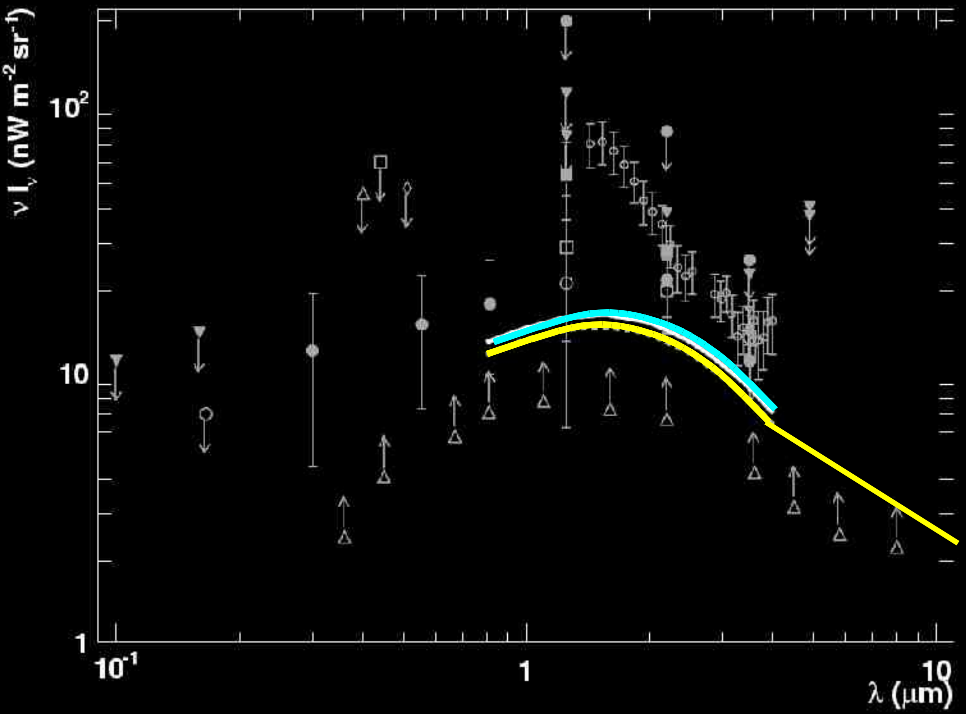
H.E.S.S., A&A 473 (2007)

- Additional constraints on Mid-IR by 1ES 0229 w/ hard spectrum :
  → EBL (2-10 μm) ~ λ^{-1}

H.E.S.S., A&A 475 (2007)

The Extragalactic Background Light





- EBL is at lower limit, as obtained from Hubble galaxy count
- No significant contribution of 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

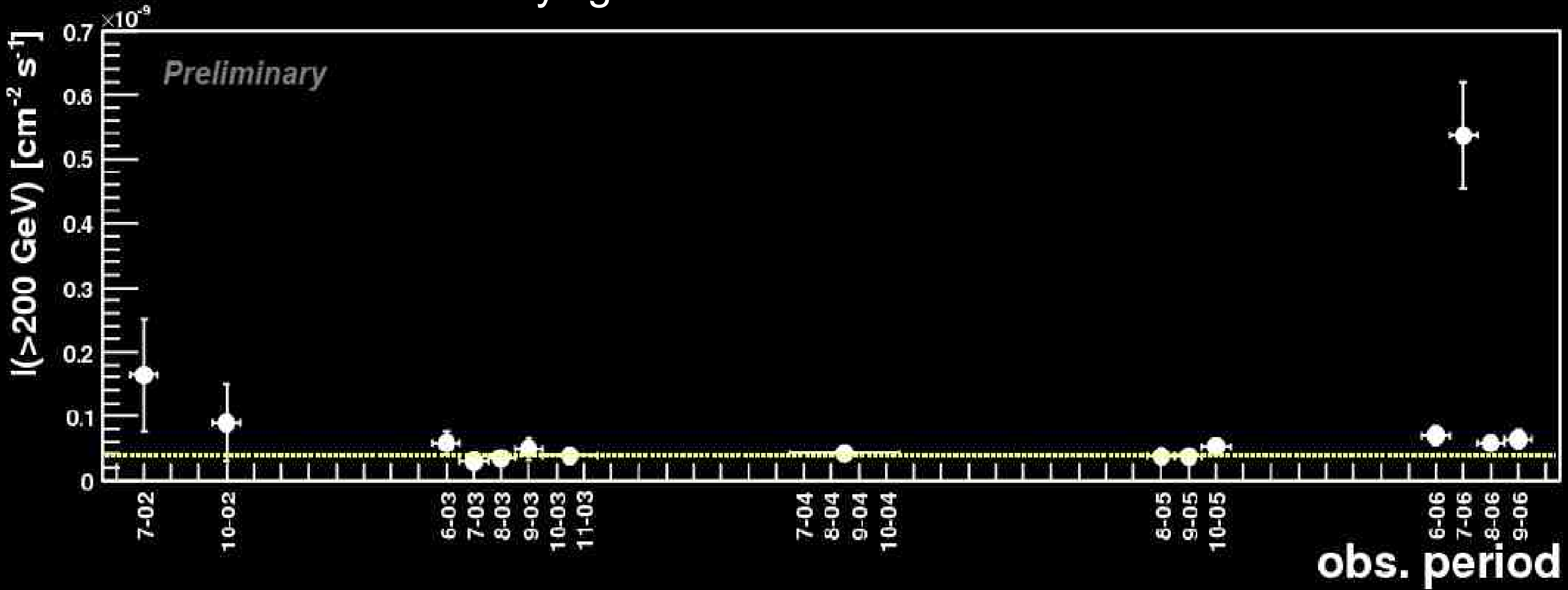
Part I: Observations with the High Energy Stereoscopic System

- The H.E.S.S. experiment
- Overview of observations
  - Classes of Galactic sources
  - Extragalactic physics
  - Quantum Gravity
  - Dark Matter search
- A glance on H.E.S.S. phase 2

skip

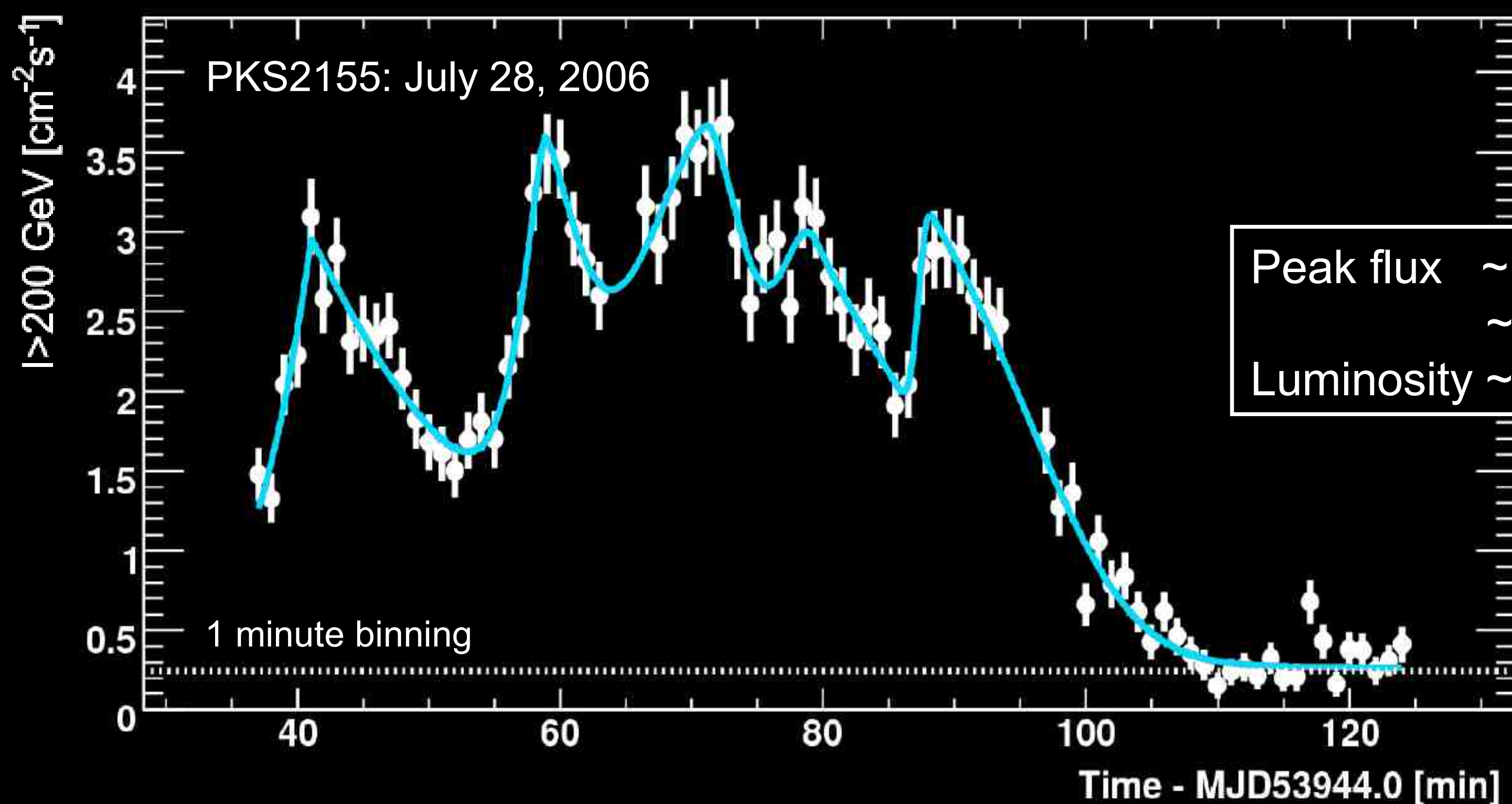
PKS 2155 Monitoring

Monthly light curve: 2002 … 2006



- Source monitored since 2002 (~240 h)
- Average flux : 3.95 +- 0.39 10^{-11} cm^{-2} s^{-1}
- Huge outburst in July 2006 - two main flares of 28 and 30 July

“Photons from hotter hell” (T.Weekes)

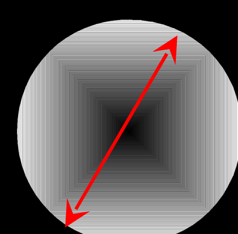


Peak flux ~15 x Crab
~50 x average
Luminosity ~10^{12} x Crab

→ Variability on timescales 2-3 minutes

→Characteristic length scale R_{BH}

→ R_{BH} / c ~ 1...2 · 10^4 s



Emission region region Doppler boosted w/
Γ ~ 100

HESS, A&A (2007)

Probing Quantum Gravity: $c(E) \neq c(E')$?

Postulate:

"…that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body''

A.Einstein (1905)

Probing Quantum Gravity: $c(E) \neq c(E')$?

Postulate:

"…that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body"

really ?

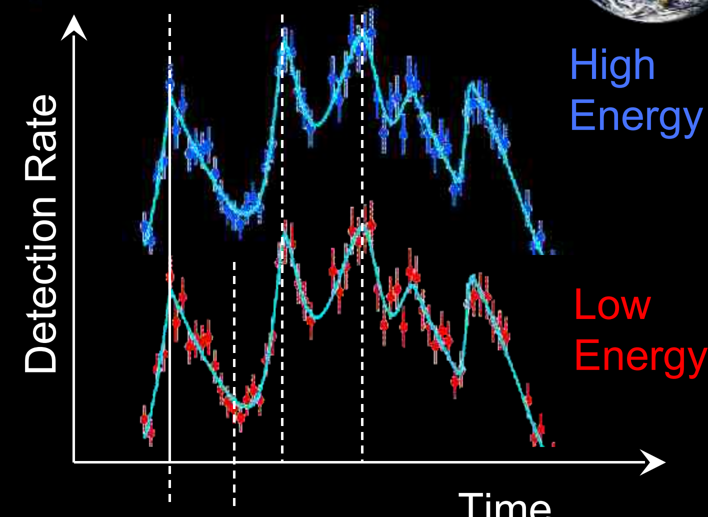
A.Einstein (1905)

Probing Quantum Gravity: c(E) ≠ c(E') ?

$$c' = c\,(1 \pm \frac{E}{k \cdot M_{\rm p}} \pm \frac{E^2}{p^2 \cdot M_{\rm p}^2})$$

$$M_{\rm p} = 1.22 \cdot 10^{19} GeV$$

$$\Delta t_{\rm QG} = L\,(\frac{1}{c_1} - \frac{1}{c_2}) \approx \frac{\Delta E \cdot L}{k \cdot M_{\rm p} \cdot c}$$



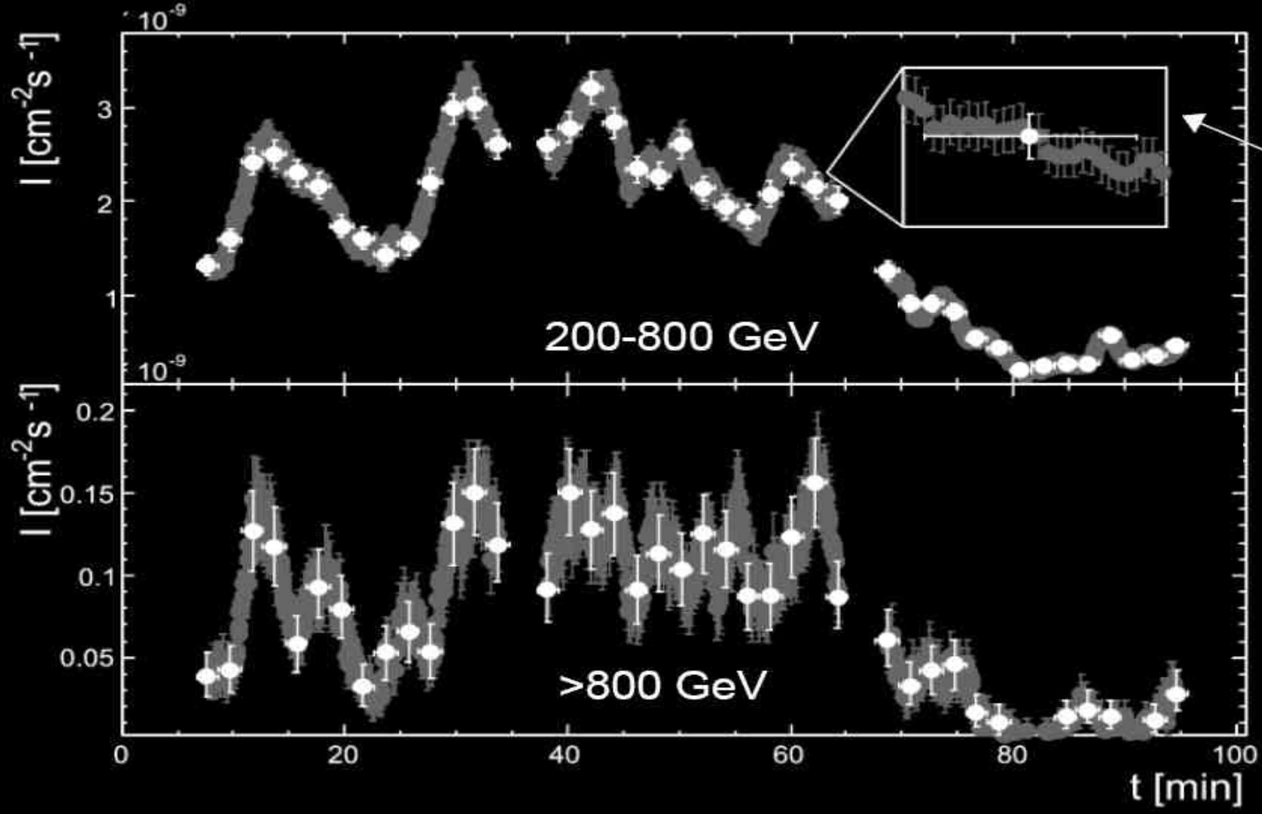
$\Delta t_{\rm QG}$?

→ Look a distant objects (O(100) Mpc)
→ Look at real high energies (TeV)

→ Be aware of *astrophysical* source effects (spectral changes)

Probing Quantum Gravity: c(E) ≠ c(E′) ?

(oversampled) light curves in 2 energy bands

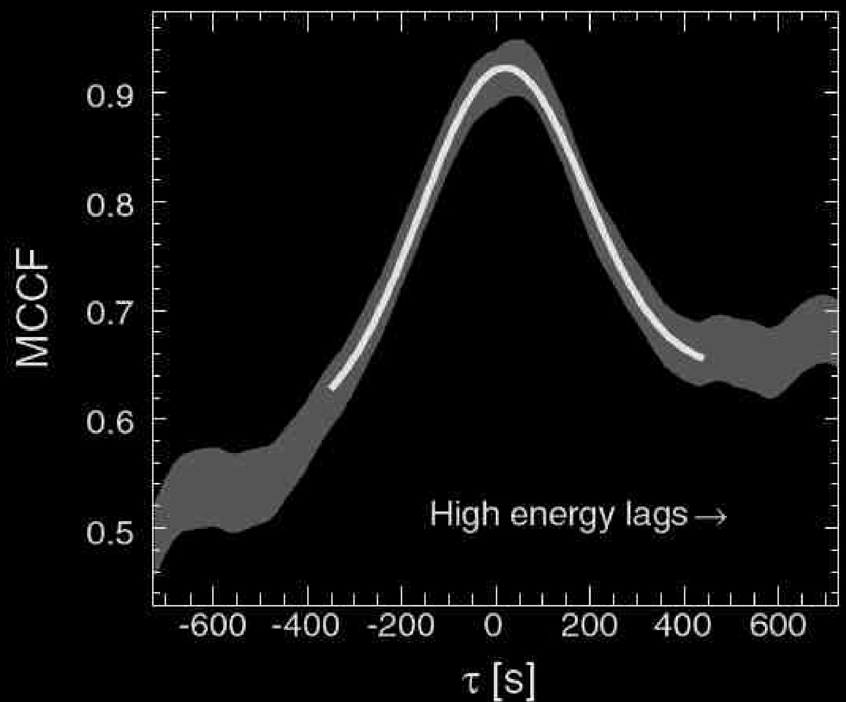


Oversampled 2-min bin

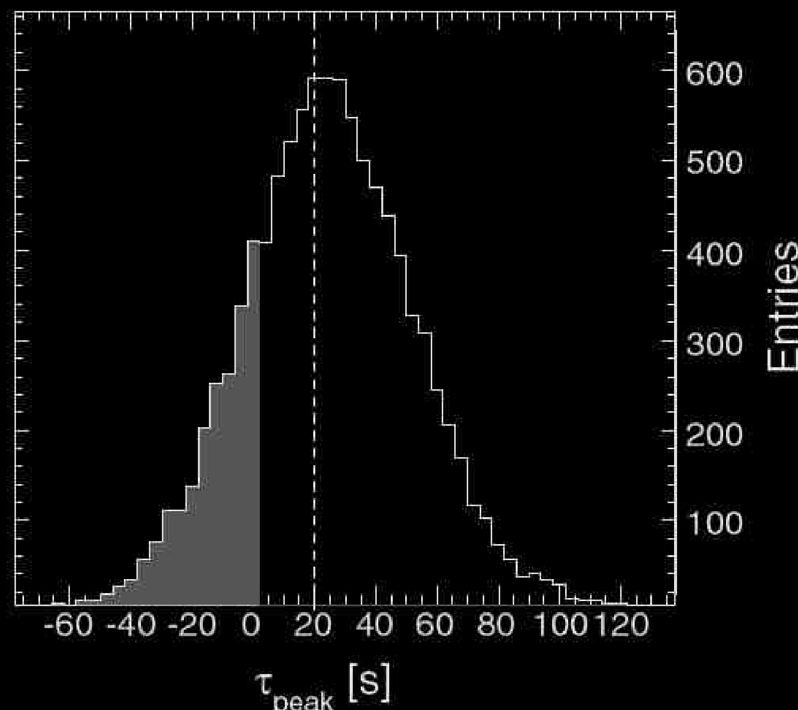
→ Look at modified cross correlation function (MCCF)

Probing Quantum Gravity: c(E) ≠ c(E') ?

Modified cross correlation function



MCCF peak distribution (MC)



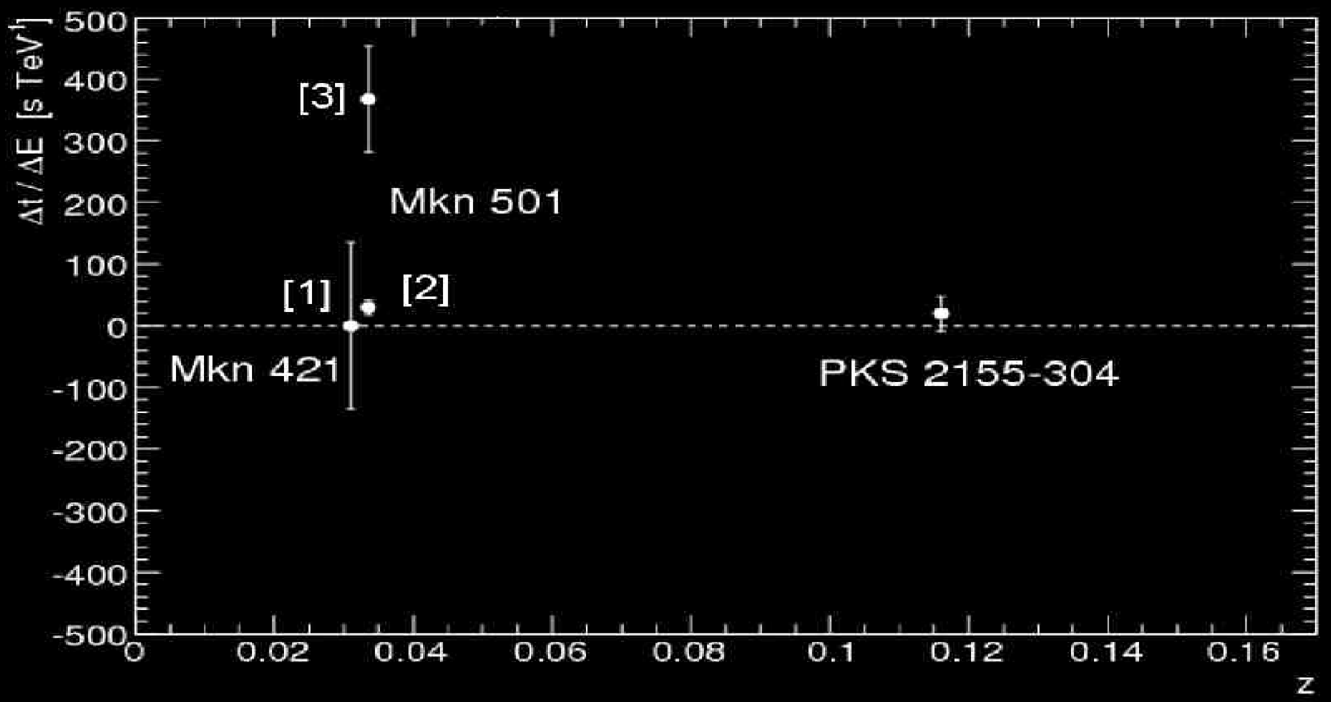
MCCF: peak at 20 sec, but ….

… MCCF peak distribution shows that delay is consistent with zero !!!

Probing Quantum Gravity: $c(E) \neq c(E')$?

Most constraining limit on speed of light modification to date:

$$E_{QG} > 5\ \%\ M_P$$



No trend with redshift observed

HESS, PRL 101 (2008)

Part I: Observations with the High Energy Stereoscopic System

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- A glance on H.E.S.S. phase 2

Near Future: H.E.S.S. Phase II

Improved sensitivity (x1.5 - 2) in current regime up to ~ 1 TeV

Energy range down to ~50 GeV will finally become accessible

Near Future: H.E.S.S. Phase II

Near Future: H.E.S.S. Phase II

Last fall in Annecy …

H.E.S.S. collaboration in front of camera mechanics test setup (09/2008)

Part I: Conclusions from H.E.S.S. observations

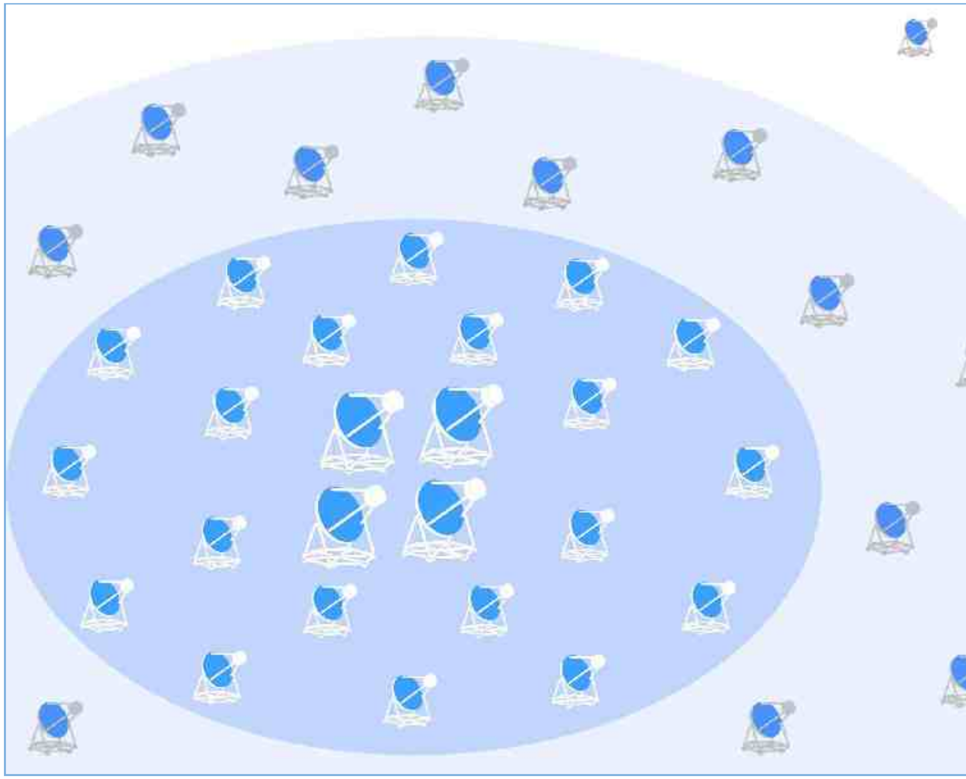
From source hunting to real astrophysics ….

- Many discoveries, population studies now possible
- ‘Precision’ measurements
- Cosmology and particle physics
- Composition ($e^{\pm}$, Fe)
- Still more in the pipeline

The path towards *CTA* is paved

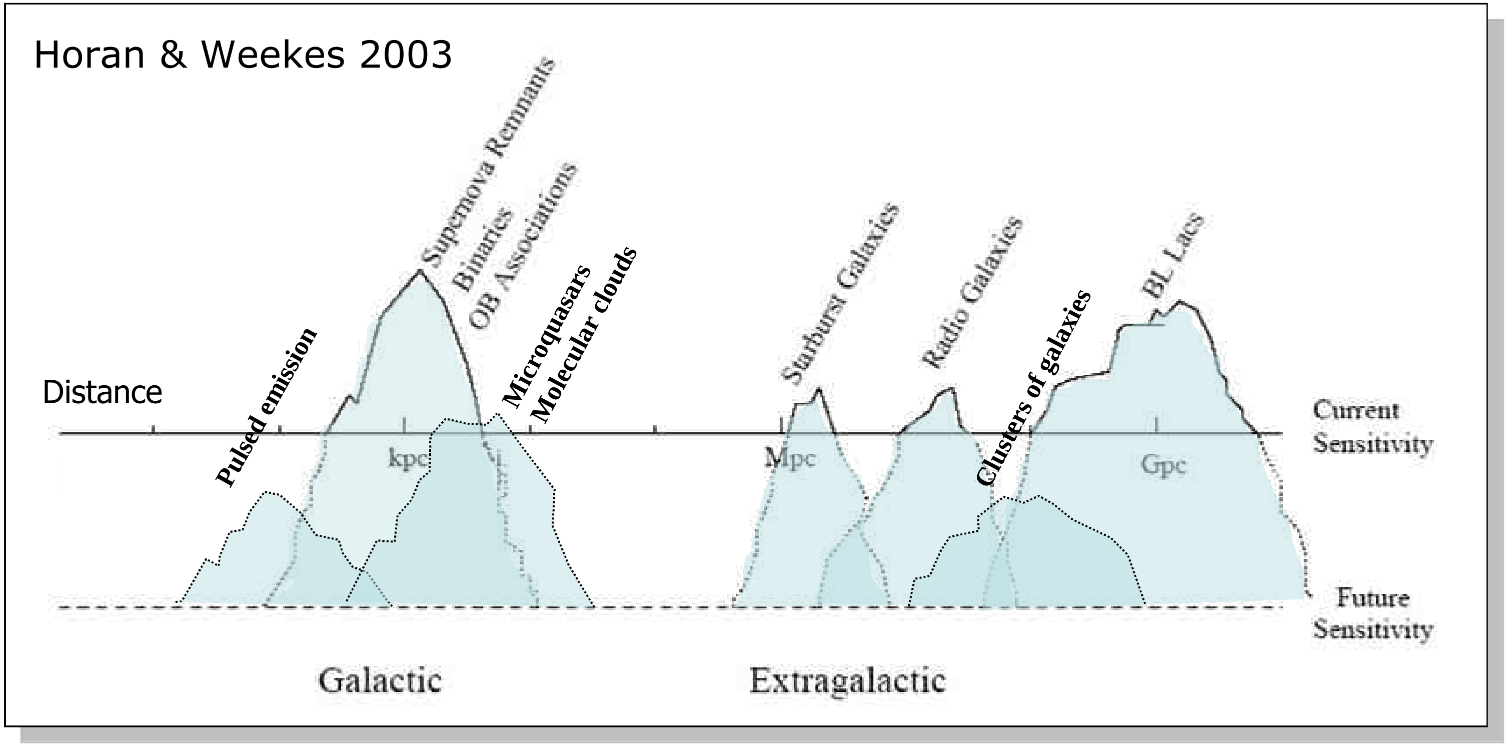
Part II: Design Study for the Cherenkov Telescope Array *CTA*

- The CTA Observatory
- Design Study for CTA
- Technical Developments
- Outlook



Science Potential

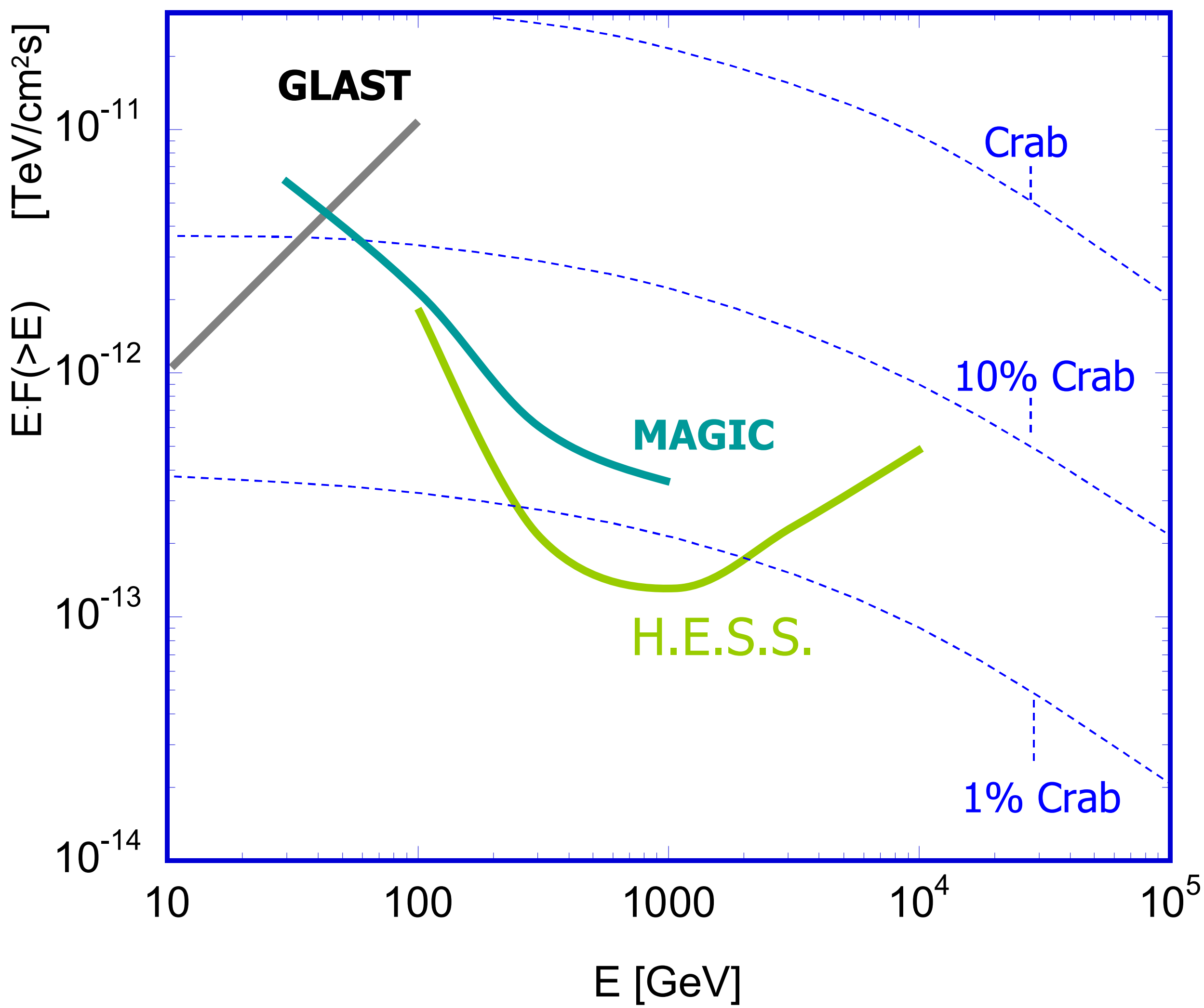
An advanced Facility for ground-based gamma-ray Astronomy



- Current instruments have passed the critical sensitivity threshold and reveal a rich panorama, but this is clearly only the tip of the iceberg.
- Many objects & object classes just below sensitivity limit
- Broad and diverse program ahead, combining guaranteed astrophysics with significant discovery potential

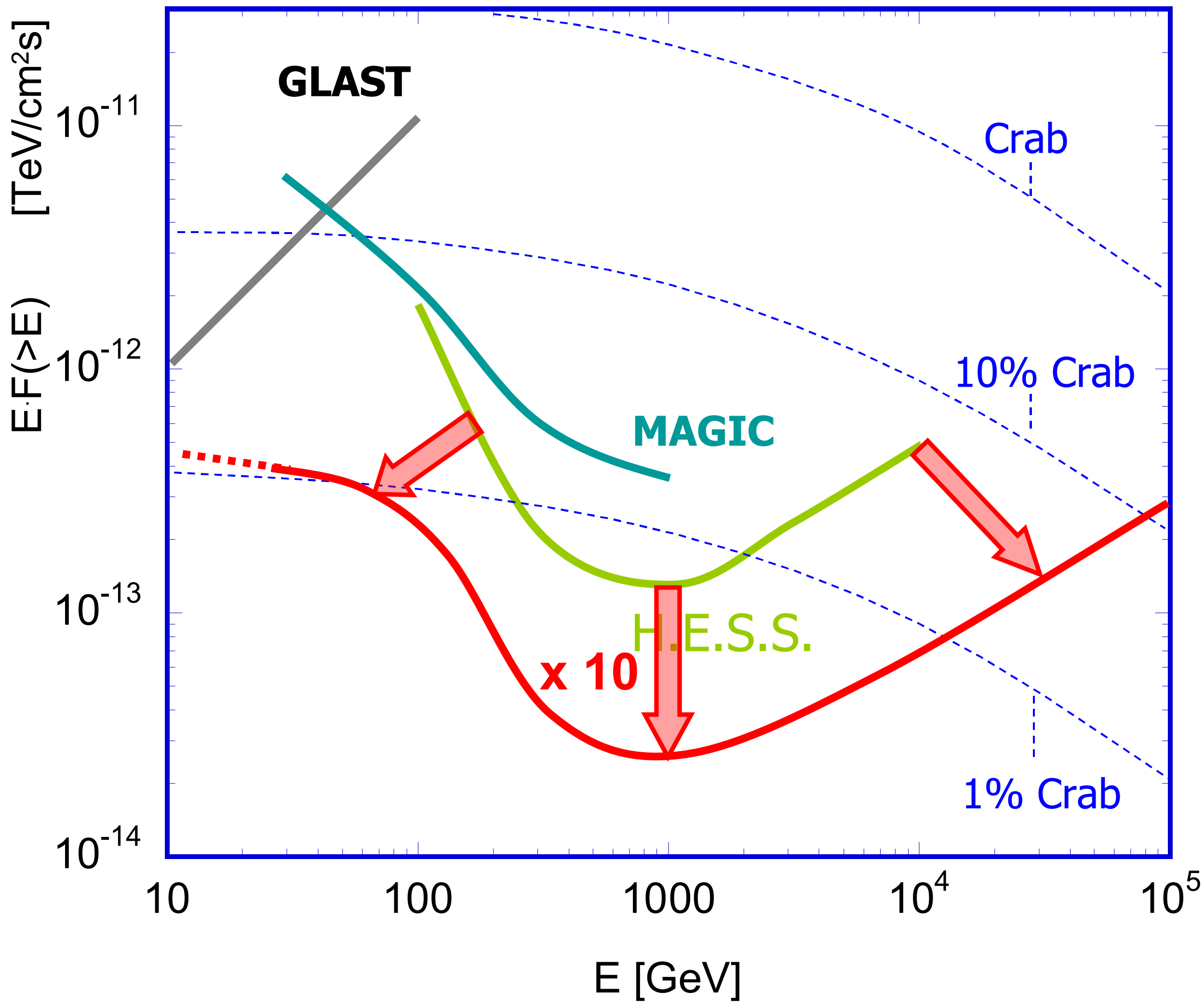
Next Generation: Wish list

An advanced Facility for ground-based gamma-ray Astronomy



Next Generation: Wish list

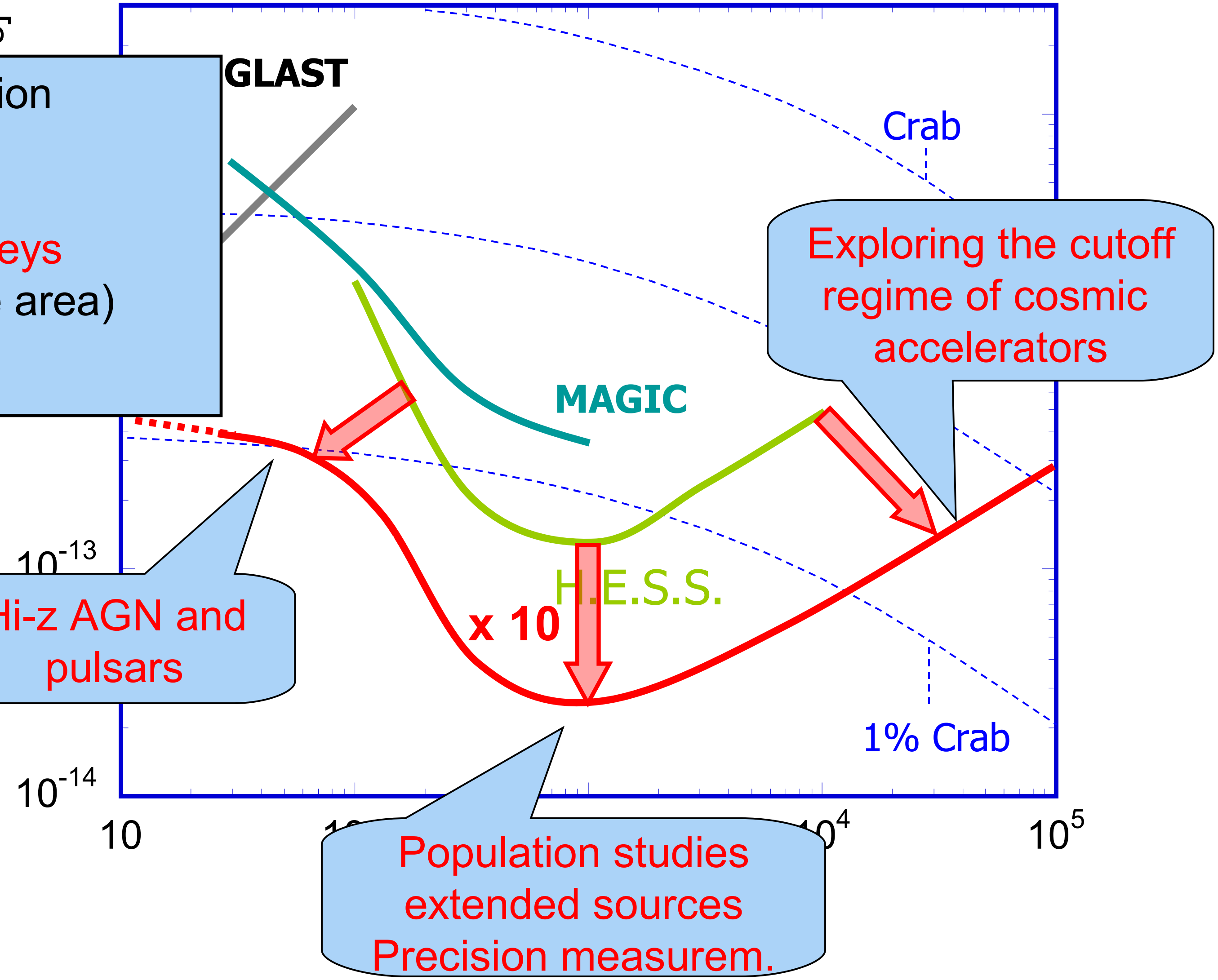
An advanced Facility for ground-based gamma-ray Astronomy



Next Generation: Wish list

An advanced Facility for ground-based gamma-ray Astronomy

- Improved angular resolution
  source morphology
- large FoV (6-8 deg)
  extended sources, surveys
- High detection rate (large area)
  transient sources



Goals for CTA

An advanced Facility for ground-based gamma-ray Astronomy

- provide a next-generation instrument for the user community, to address a wide range of topics in high-energy astrophysics and to explore the full sky

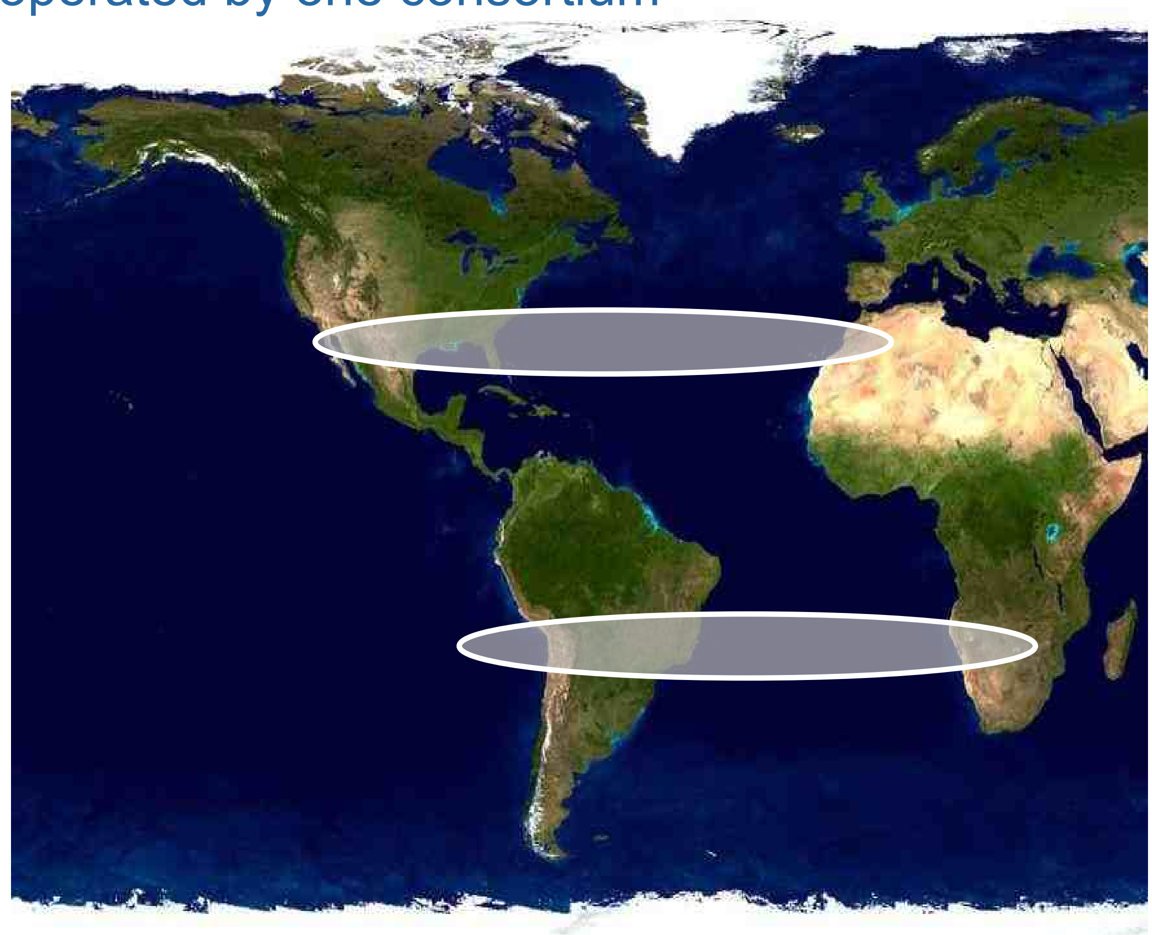
- CTA will allow population studies of TeV sources
- New quality of data: in depth studies on individual objects

- expected large number of detectable objects – O(1000) – implies operation as open observatory, with appropriate tools for data dissemination and data analysis
- expect (500+) users from astronomy, astroparticle physics, plasma physics, particle physics (DM), cosmology

The CTA Observatory

An advanced Facility for ground-based gamma-ray Astronomy

One observatory with two site
operated by one consortium



Northern Array (50 ME)

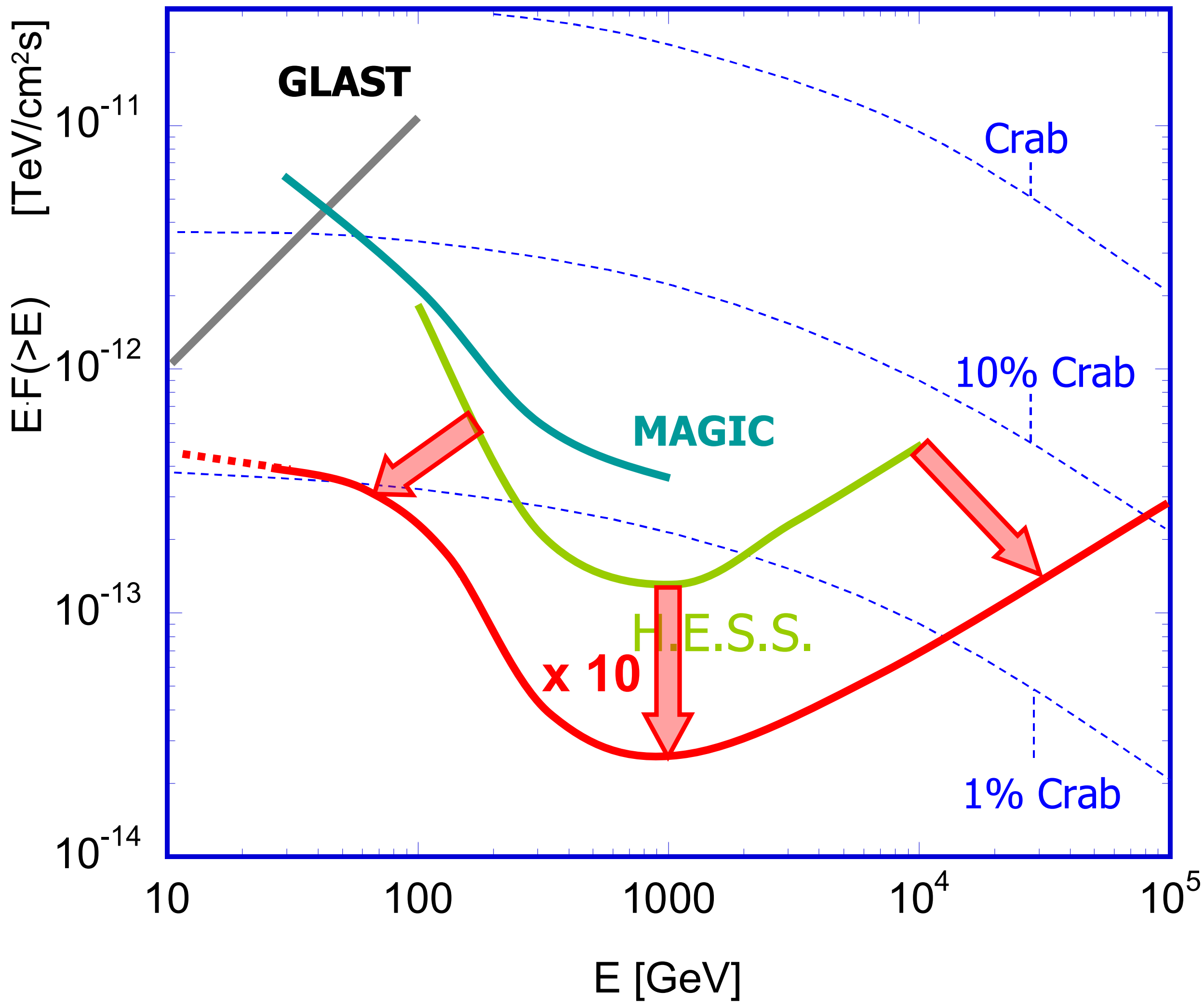
- → complementary to SA for full sky coverage
- → Energy range some 10 GeV …. ~1 TeV
- → Small field of view Mainly extragal. Sources

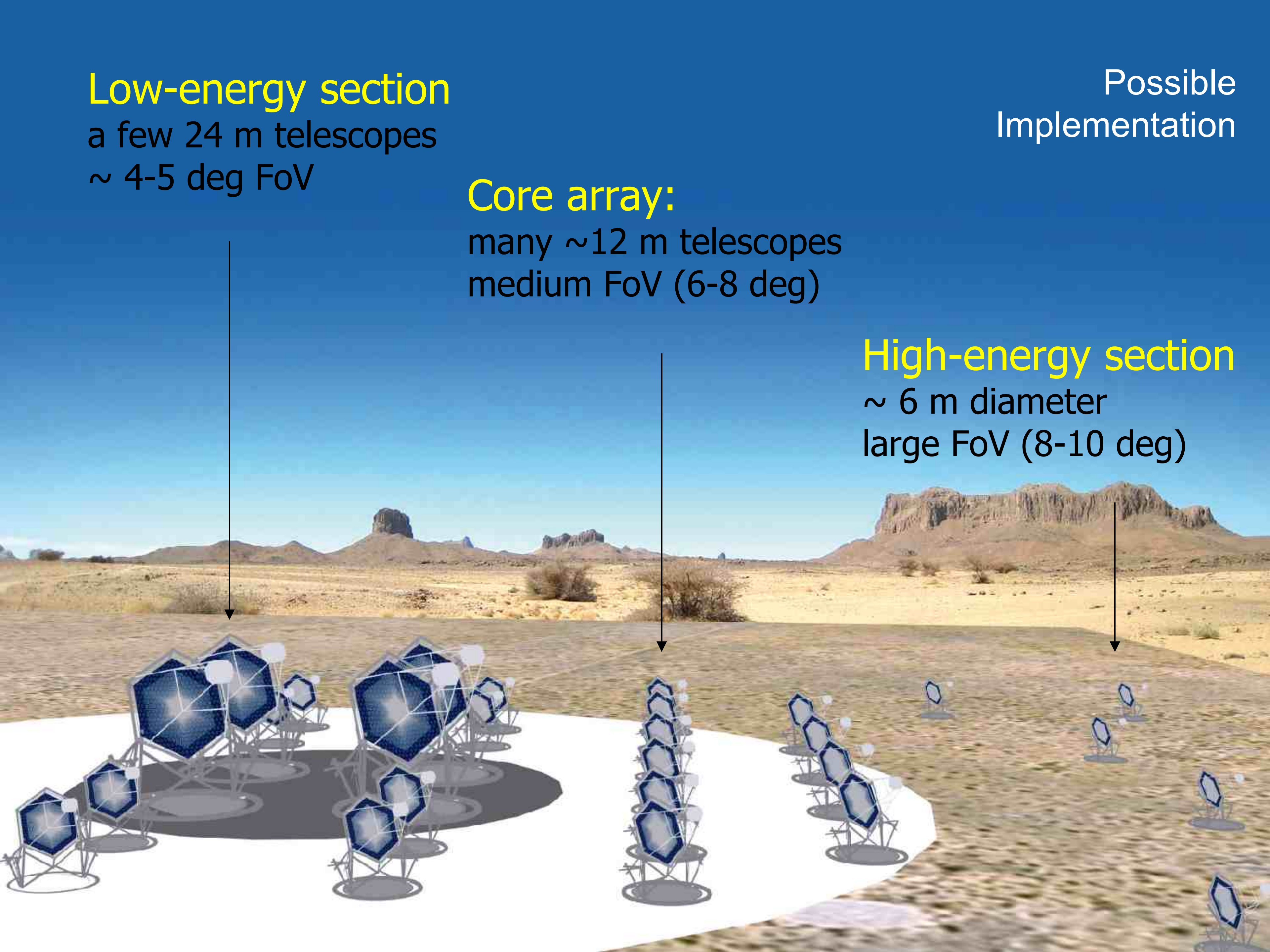
Southern Array (100 ME)

- → Full energy and sensitivity coverage some 10 GeV …. 100 TeV
- → Angular resolution: 0.02 … 0.2 deg
- → Large field of view Galactic + Extragal. Sources

How to get there ?

An advanced Facility for ground-based gamma-ray Astronomy





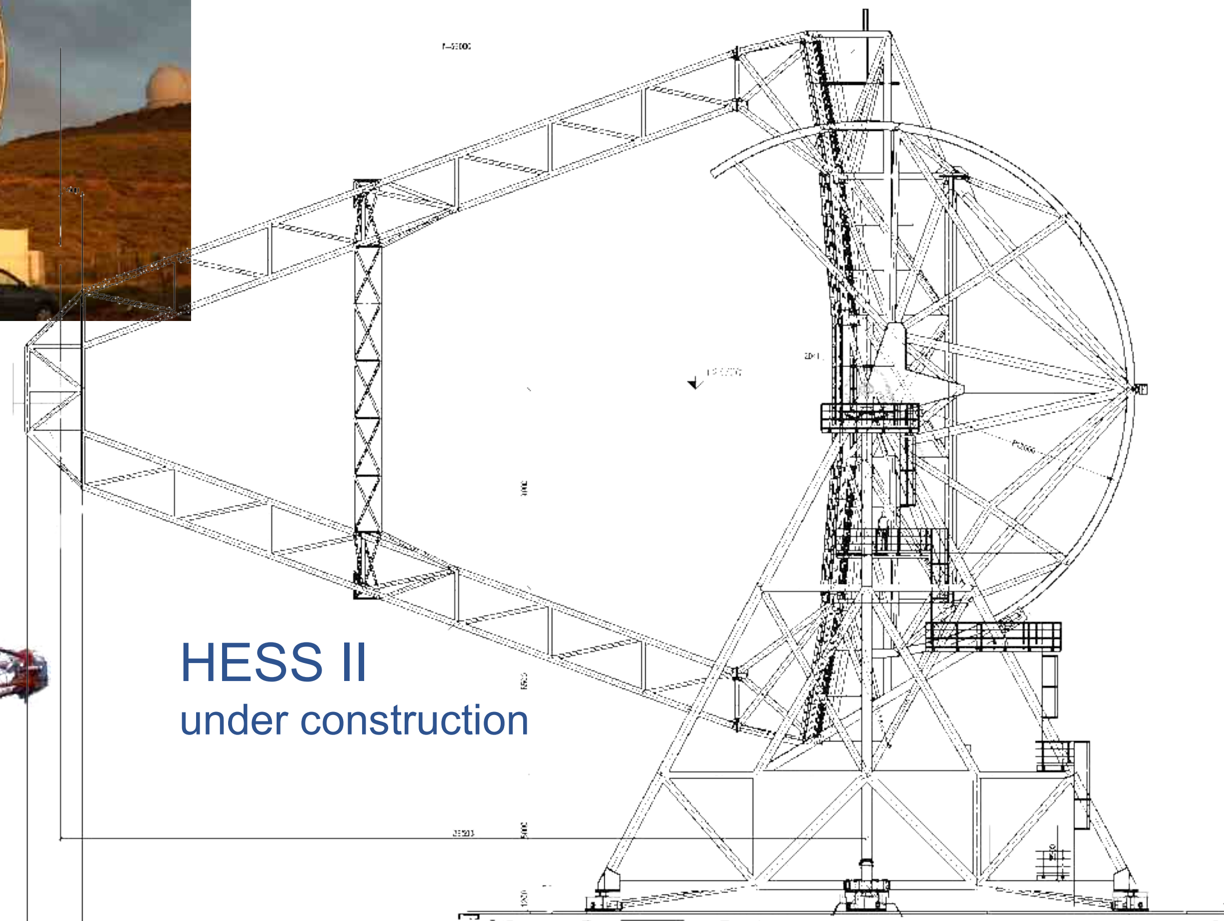
Low-energy section
a few 24 m telescopes
~ 4-5 deg FoV
Possible
Implementation
Core array:
many ~12 m telescopes
medium FoV (6-8 deg)
High-energy section
~ 6 m diameter
large FoV (8-10 deg)

Do we know, how to build telescopes ?
yes !!! **but** …

MAGIC

telescopes
to scale

HESS I



HESS II
under construction

… but …

- **Current telescopes not optimized for large-scale production**
  - Cost would exceed target cost (100 M€ for full site) by factor 1.5 to 2
  - Instrument reliability needs to be improved / built-in
- We believe **we can built even better / more efficient telescopes**
  - wider field of view
  - improved photo sensors
  - improved electronics signal recording
  - overall optimized array layout
- Need to develop tools to **operate a user facility** and to provide effective data access
  - Observation scheduling and system control
  - Science data center and data access tools

… and there are 'a few' challenges

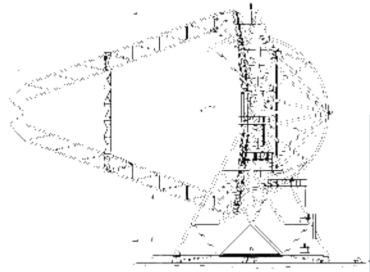
An advanced Facility for ground-based gamma-ray Astronomy

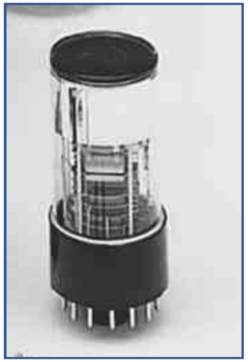
Will need
- O(50-100) telescopes, core array
- O(10000) m^2 mirror area
- O(70) m^2 photo sensitive area
- O(100k) electronics channels

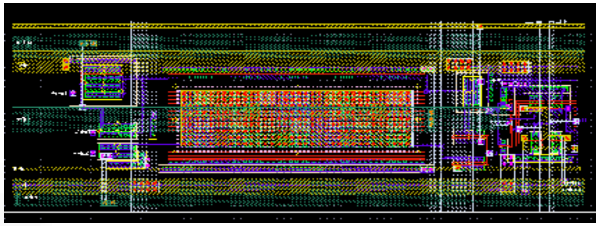
→ Factor of 10 in sensitivity
with only factor of 10 in M€

Find an optimized array layout
that has the required performance

Optimize design for effective production /
commissioning, and for
stability and high reliability







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Find an optimized array layout
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Optimize design for effective production /
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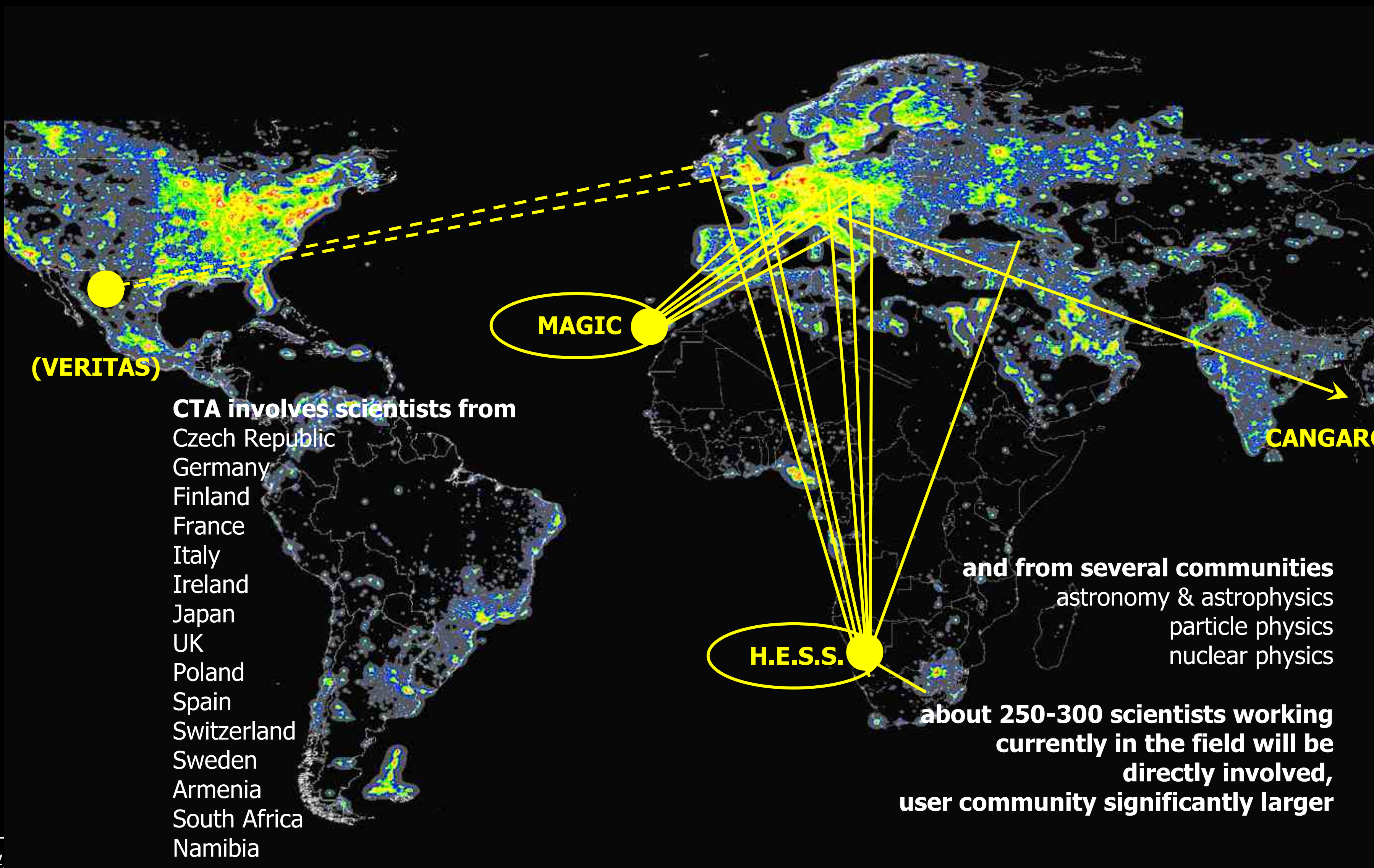
→ *Design Study*

CTA

Design Study in a joint effort !



CTA involves scientists from

Czech Republic
Germany
Finland
France
Italy
Ireland
Japan
UK
Poland
Spain
Switzerland
Sweden
Armenia
South Africa
Namibia
...

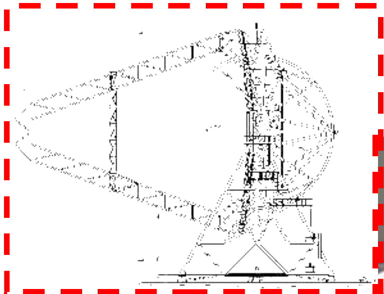
and from several communities

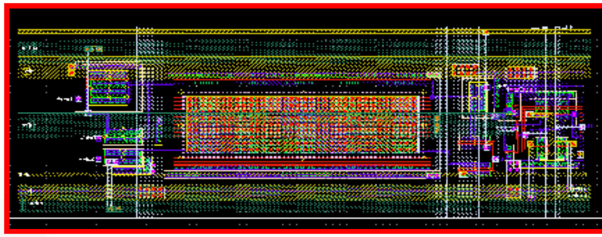
astronomy & astrophysics
particle physics
nuclear physics

about 250-300 scientists working currently in the field will be directly involved, user community significantly larger

Will need
- O(50-100) telescopes, core array
- O(10000) m^2 mirror area
- O(70) m^2 photo sensitive area
- O(100k) electronics channels

→ Factor of 10 in sensitivity
with only factor of 10 in M€





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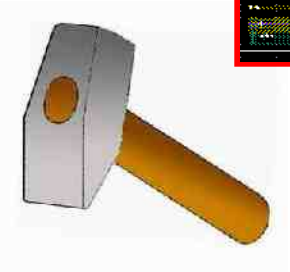
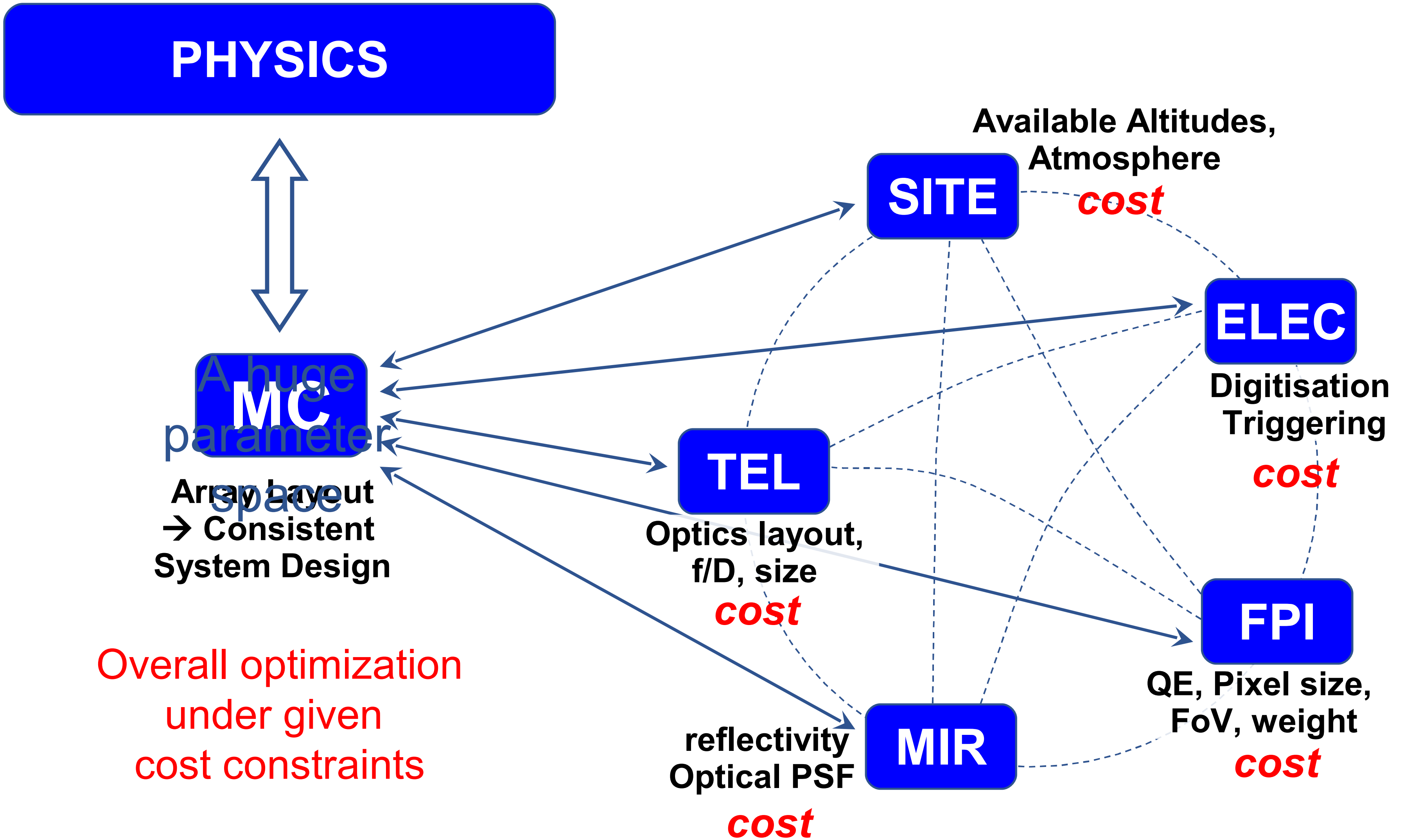


A complex optimization problem

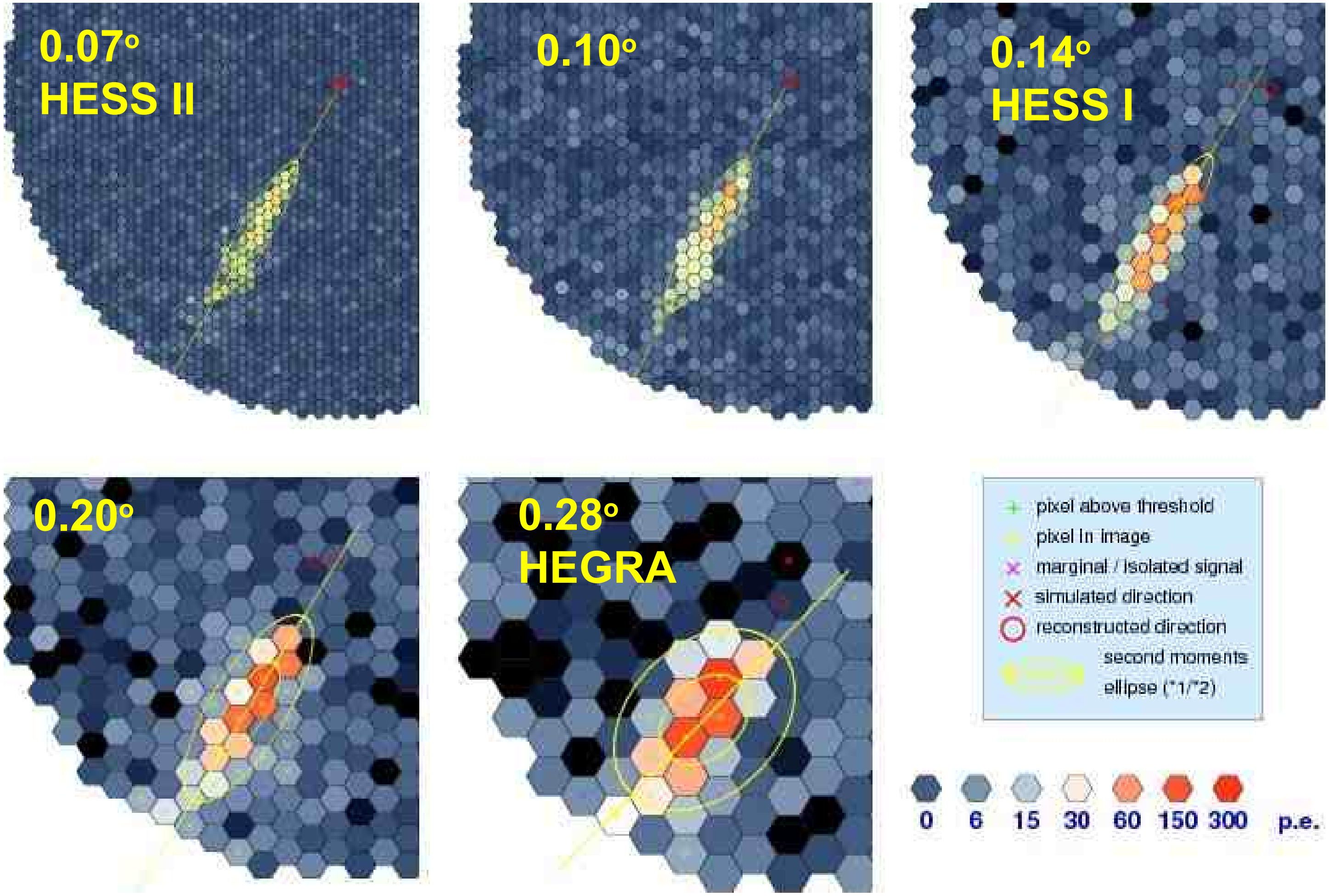
An advanced Facility for ground-based gamma-ray Astronomy



Overall optimization under given cost constraints

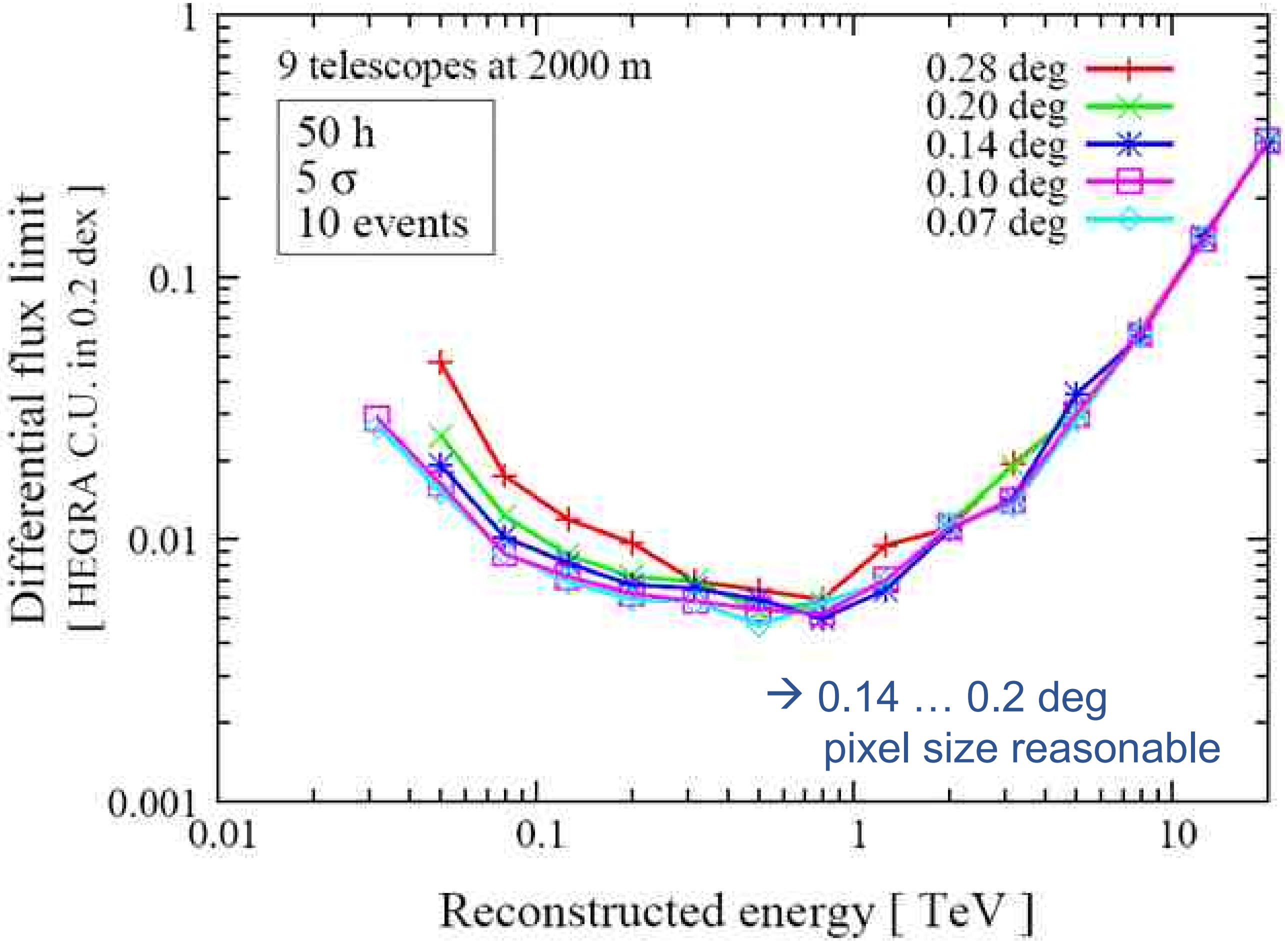
Camera: what Pixel Size is really needed ?

An advanced Facility for ground-based gamma-ray Astronomy



Example: Sensitivity vs Pixel Size

An advanced Facility for ground-based gamma-ray Astronomy

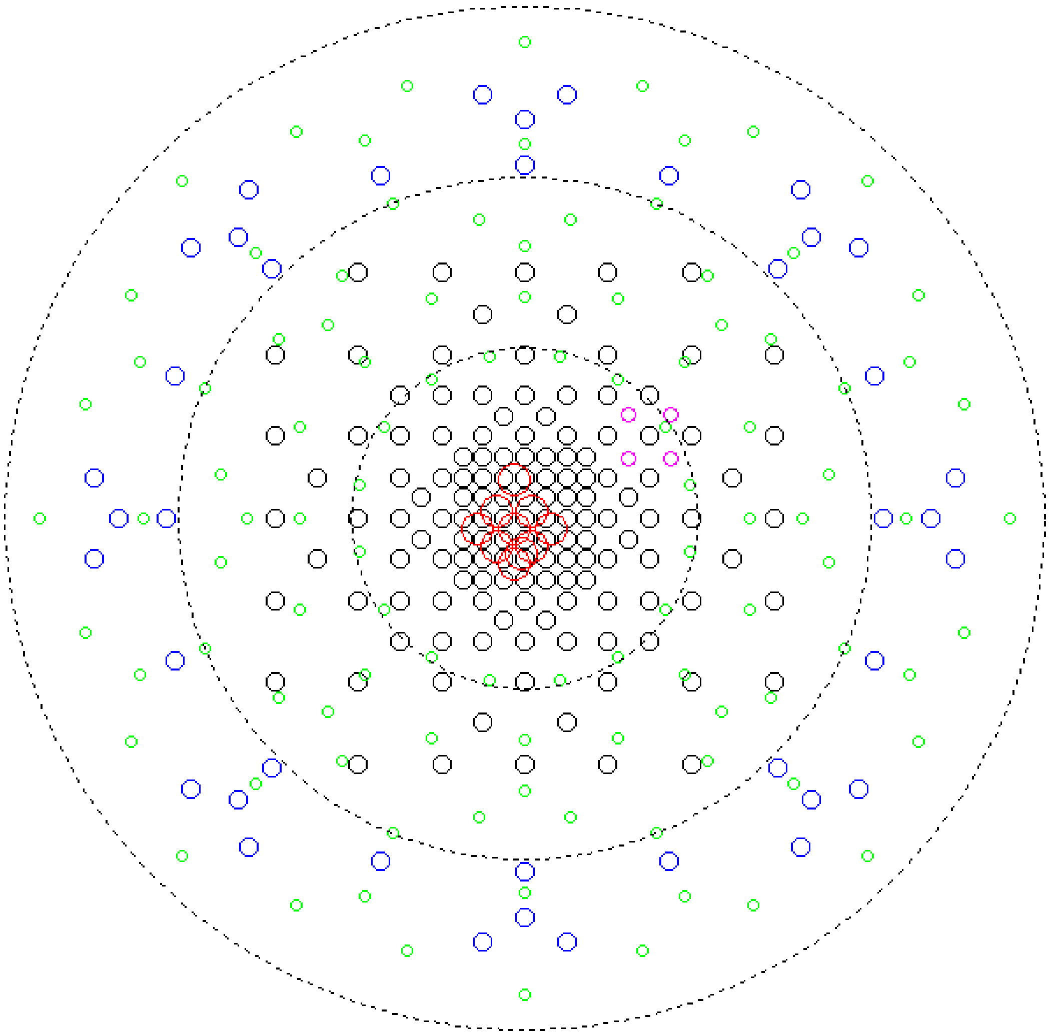


Factor 16 in no of pixels & camera cost

→ 0.14 … 0.2 deg pixel size reasonable

MC: Large Scale End-2-End Simulations

An advanced Facility for ground-based gamma-ray Astronomy



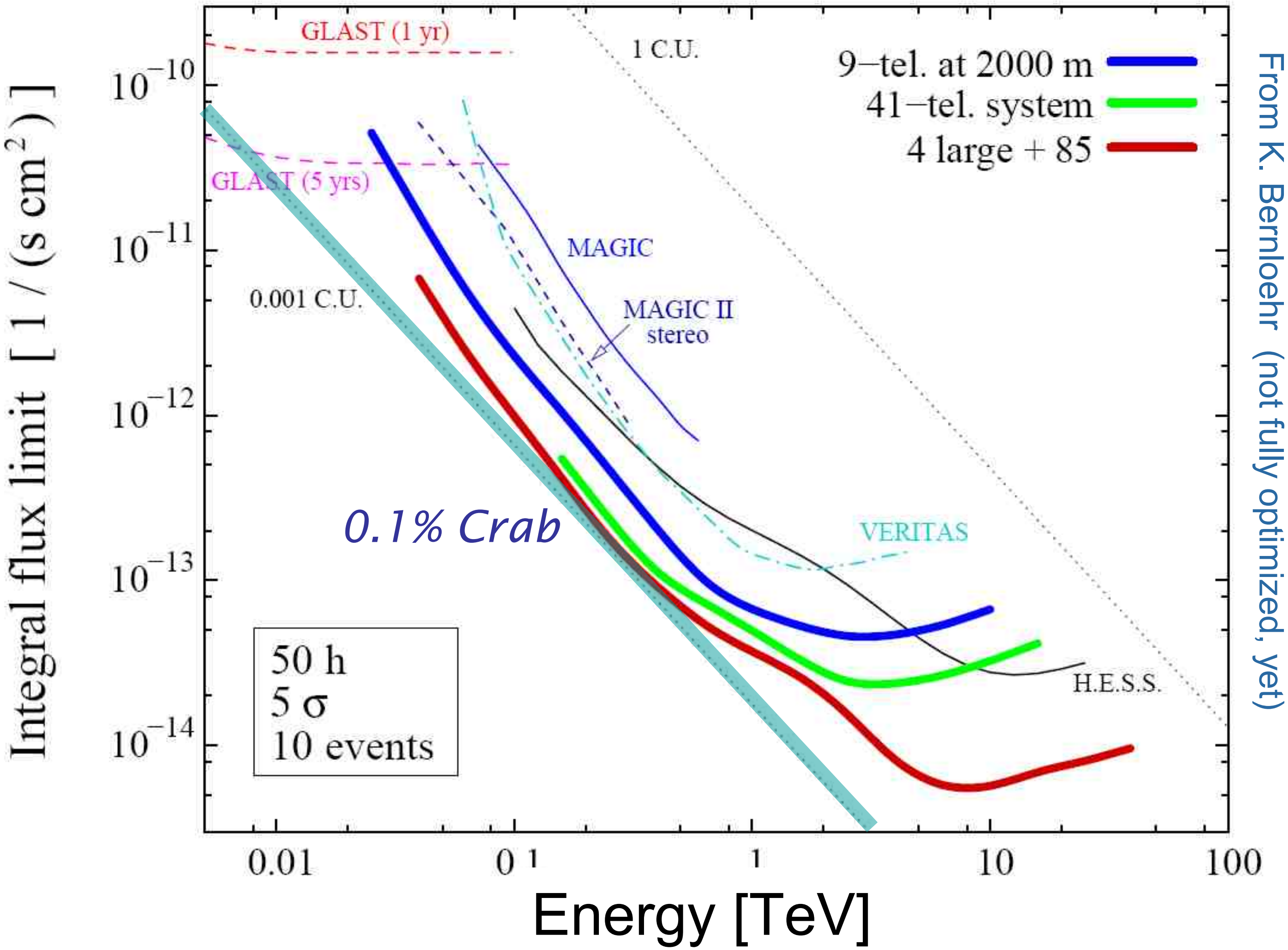
Large scale simulation of "Hyper-Array" with 275 telescopes of 5 different types, sizes, …

→ Selection of candidate arrays under cost constraints
→ Study of performance
→ Assessment of physics performance

~ 0.5 Billion events generated during last few months

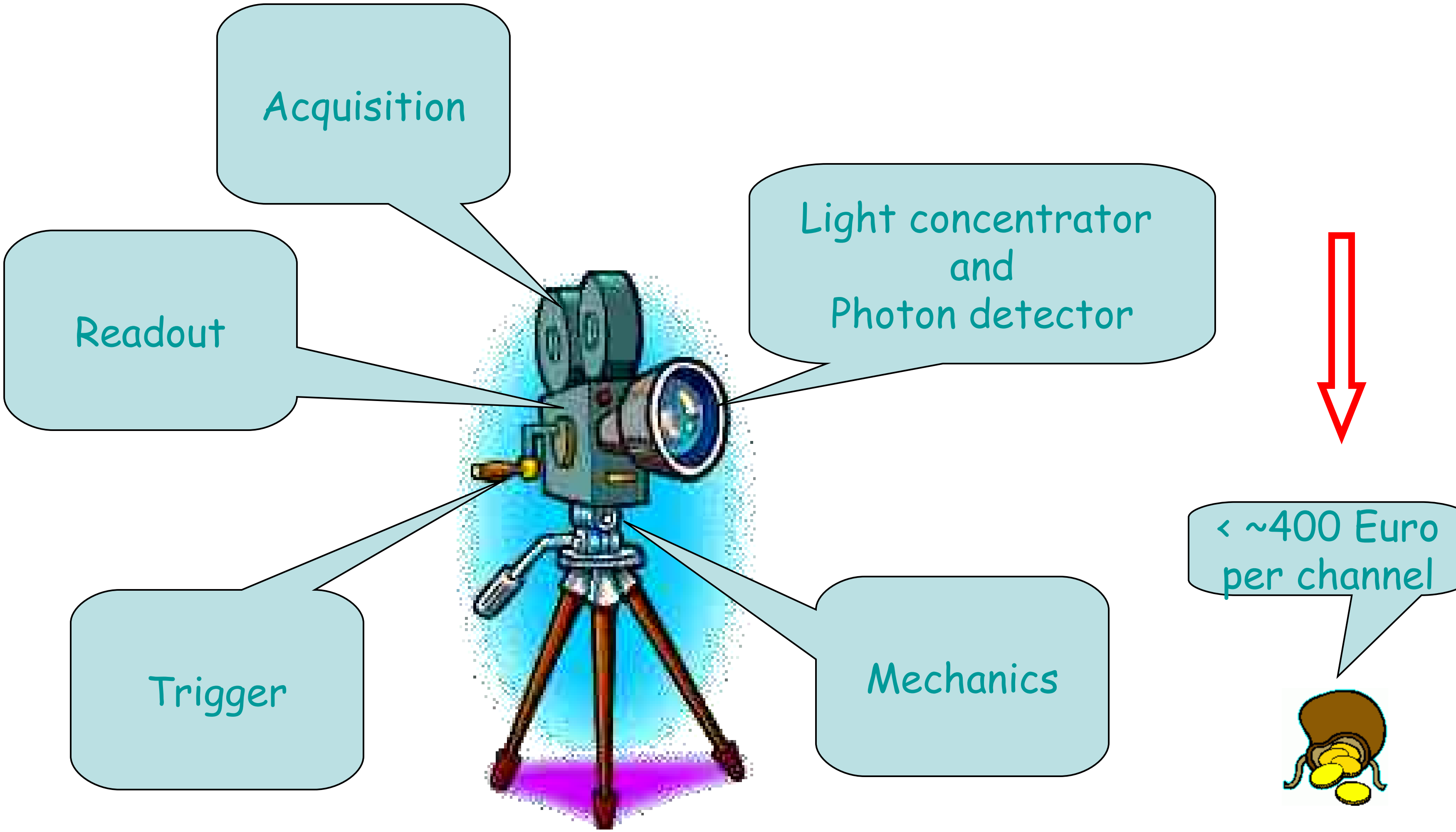
Preliminary MC Results: it's feasible !

An advanced Facility for ground-based gamma-ray Astronomy



Camera: Electronics and Photon Detectors

An advanced Facility for ground-based gamma-ray Astronomy



from P.Vincent

Cameras: large Quantity of Components

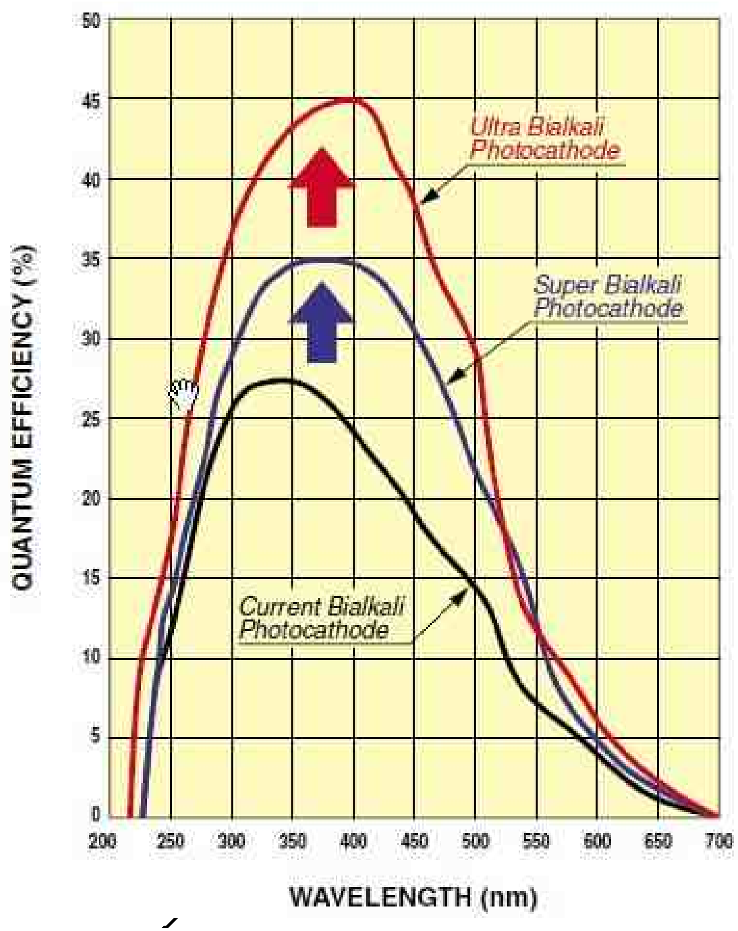
An advanced Facility for ground-based gamma-ray Astronomy

O (100 000) channels
photomultipliers, pre-amps
light concentrators
high voltage, …

Smart & cost effective design needed
(±10 E/channel ⇔ ± ~1 Telescope)

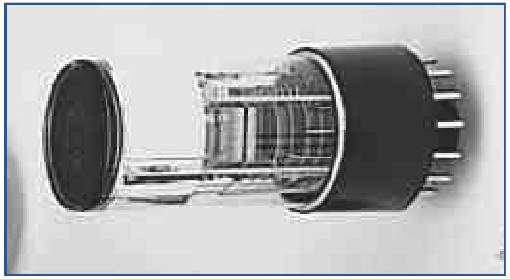
Current cameras: O(1000 € / chan) …

Improved PMTs

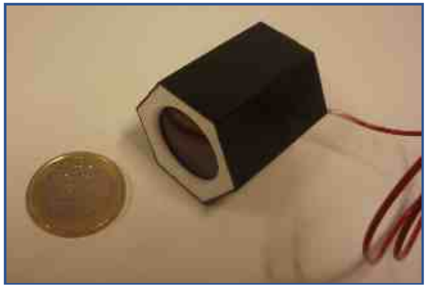


Cooperation with manufacturers to improve/adapt performance to CTA specific requirements
→ e.g. low afterpulsing, hi QE
cost, cost, cost ….

Baseline Design:
→ PMTs



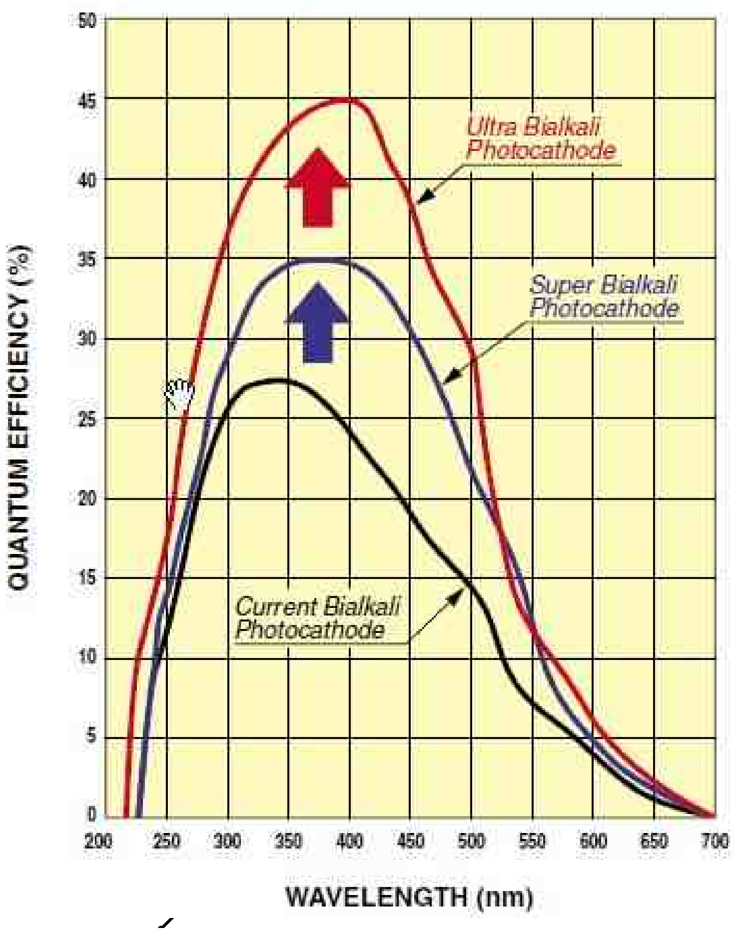
Keeping an eye on future developments e.g. HPDs (still way too expensive)



Photon Detectors: PMTs Baseline Design

An advanced Facility for ground-based gamma-ray Astronomy

Improved PMTs



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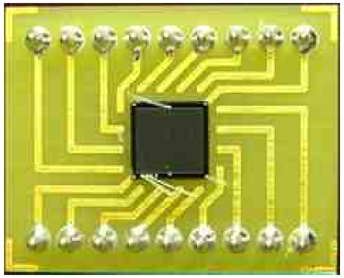
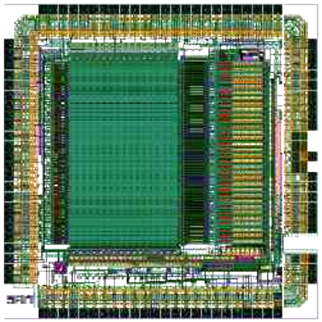


Silicon PMTs

- Under development in many labs and in industry
- Still a significant step to a large-area detector
- Cost and practical performance open
- Particularly interesting for low-energy section
- R&D path for possible upgrades

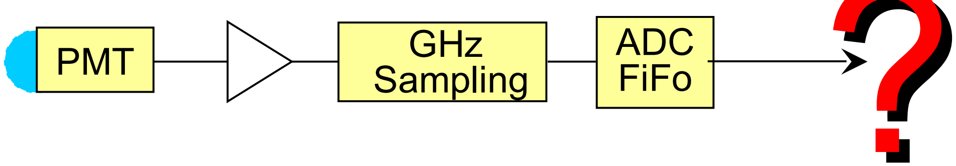
Camera Readout Options

An advanced Facility for ground-based gamma-ray Astronomy

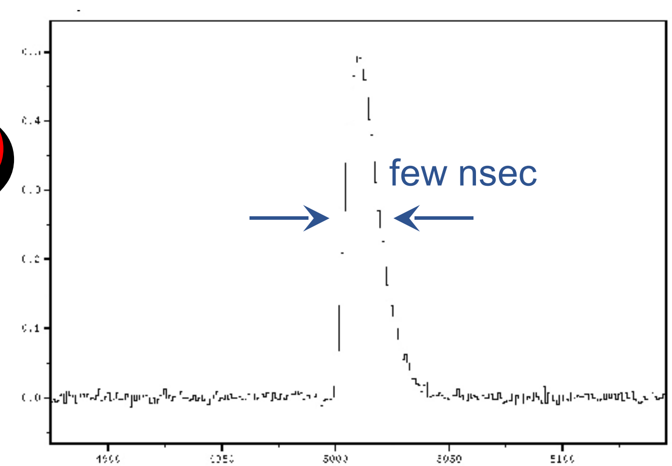


Existing pipeline chips:
e.g. SAM (H.E.S.S. 2),
DRS4 (MAGIC 2)
GHz sampling;
11-12 bit dynamic range
256 -1024 cells depth

1) Existing solutions
- Proven to work
- → Need to be adapted & integrated w/ RO-scheme
- → cost optimization
- low risk



2) NeCTAr project (2009-2011)
- highly integrated FE chip
- → Cost reduction



O(nsec) Cherenkov flashes
→ O(100 MHz - GHz) sampling

Front-end to back-end data transfer

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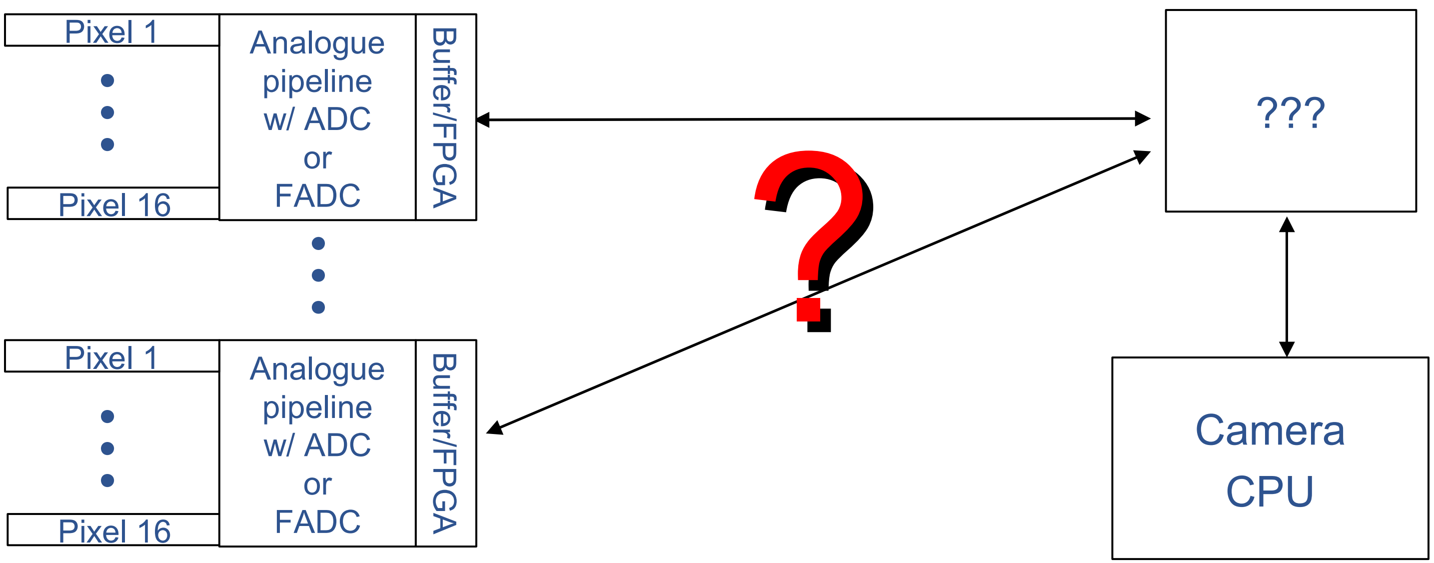
1 Byte / pixel / evt
(20 nsec @ ~ 800 MHz x 2 gain)
2000 channels
10 kHz camera triggers
→ ca. 600 MByte/sec

For optimum use of pulse shape, data needs to be analyzed by using info from all Pixels / correlations and not just per pixel

→ Bus – System into CPU ?



Ethernet-based front-end readout: tests

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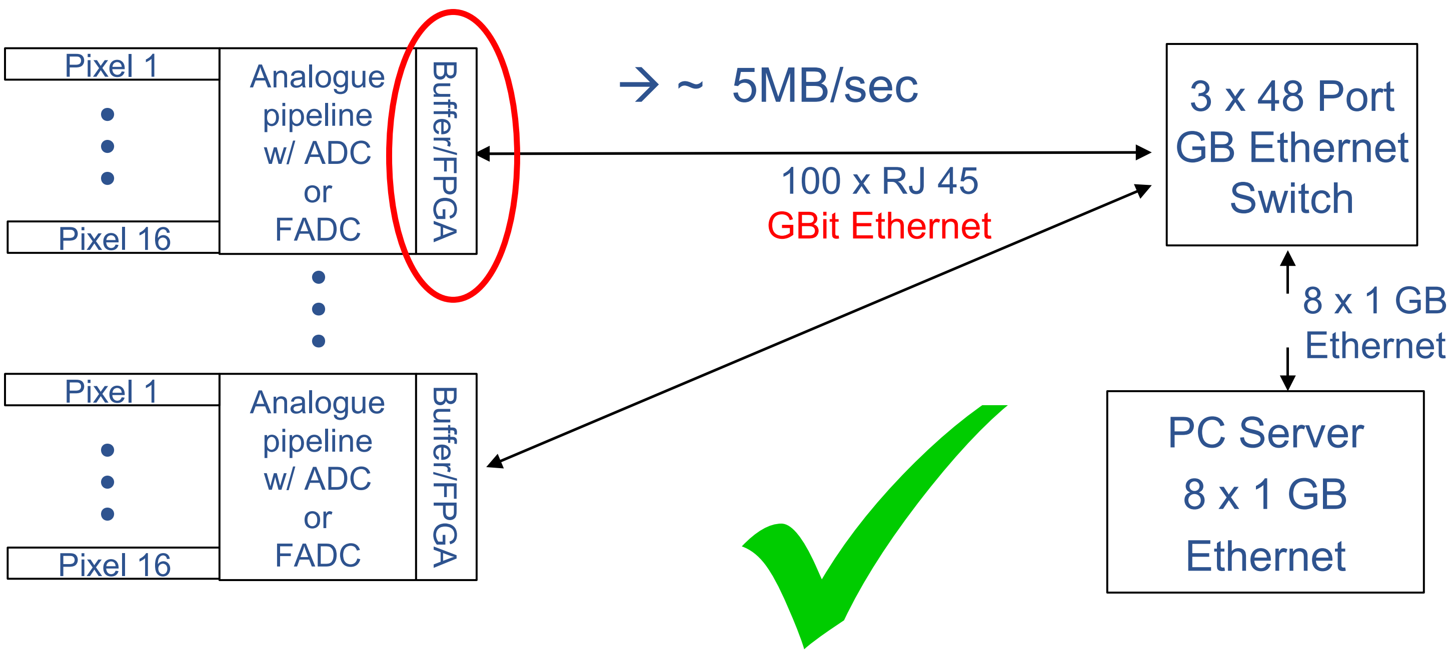
FPGA MAC sender:
100 MBit and GBit Eth interface successfully implemented (and used)

switch & server bandwidth:
48 groups (nodes) sending data transferred into one server
→ 700 MByte/sec (loss free)
(low cost solution, using standard commercial components)



Tentative Timeline

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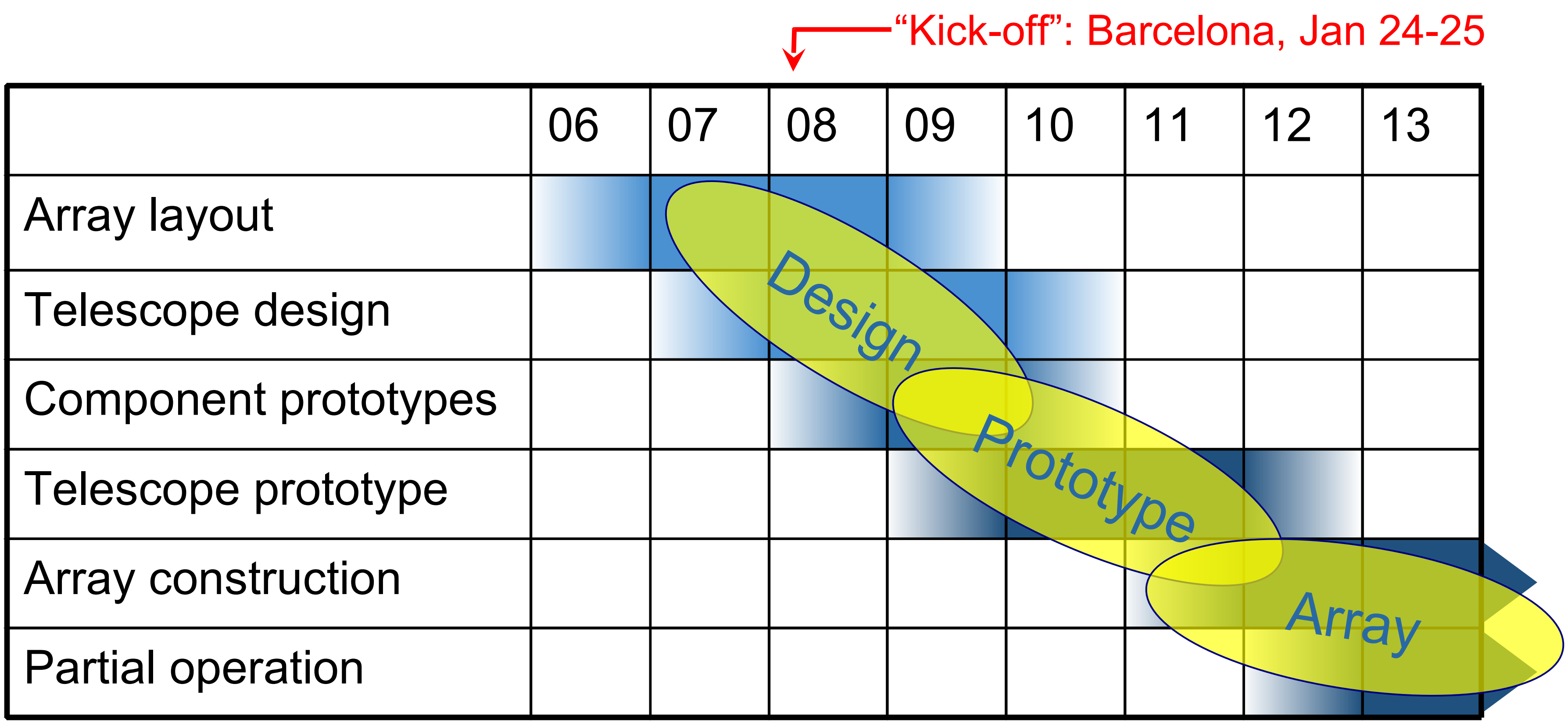

TeV gamma-ray astronomy: today and tomorrow

Thank you !!!