D. Mazin
MPI for physics, Munich

THE GAMMA-RAY BRIGHT FUTURE: THE CTA PERSPECTIVE

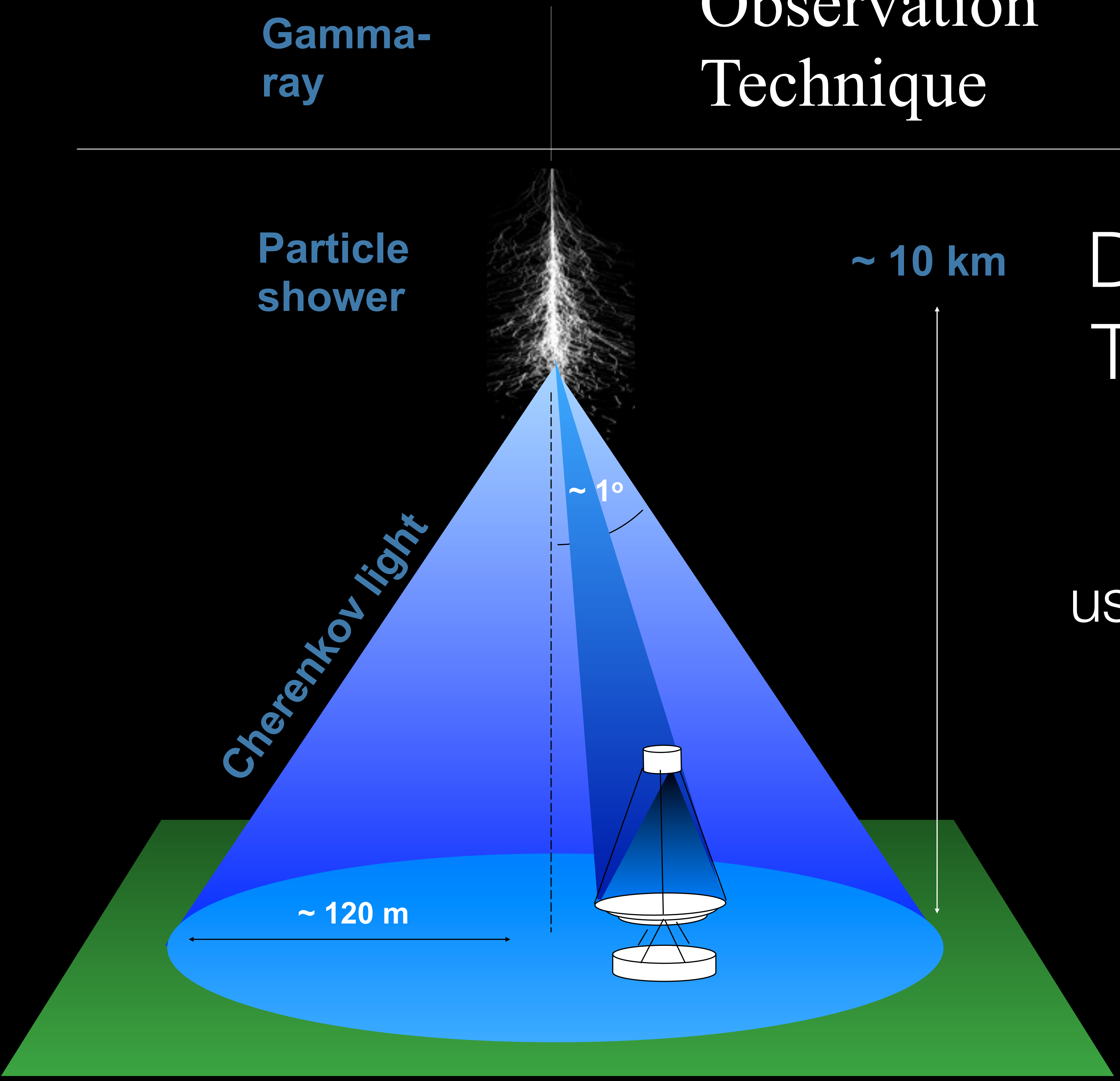
for the CTA consortium

Thanks for material from Werner Hofmann, Manel Martinez and Diego F. Torres

contents

- Very High Energy Gamma-Ray Astronomy
  - Observation technique
  - Major results
- CTA: concept
- Technical implementation
- Physics ahead
  - Major drivers
  - Selected physics cases
- Status of the project

Observation Technique



Detection of TeV gamma rays

using Cherenkov telescopes

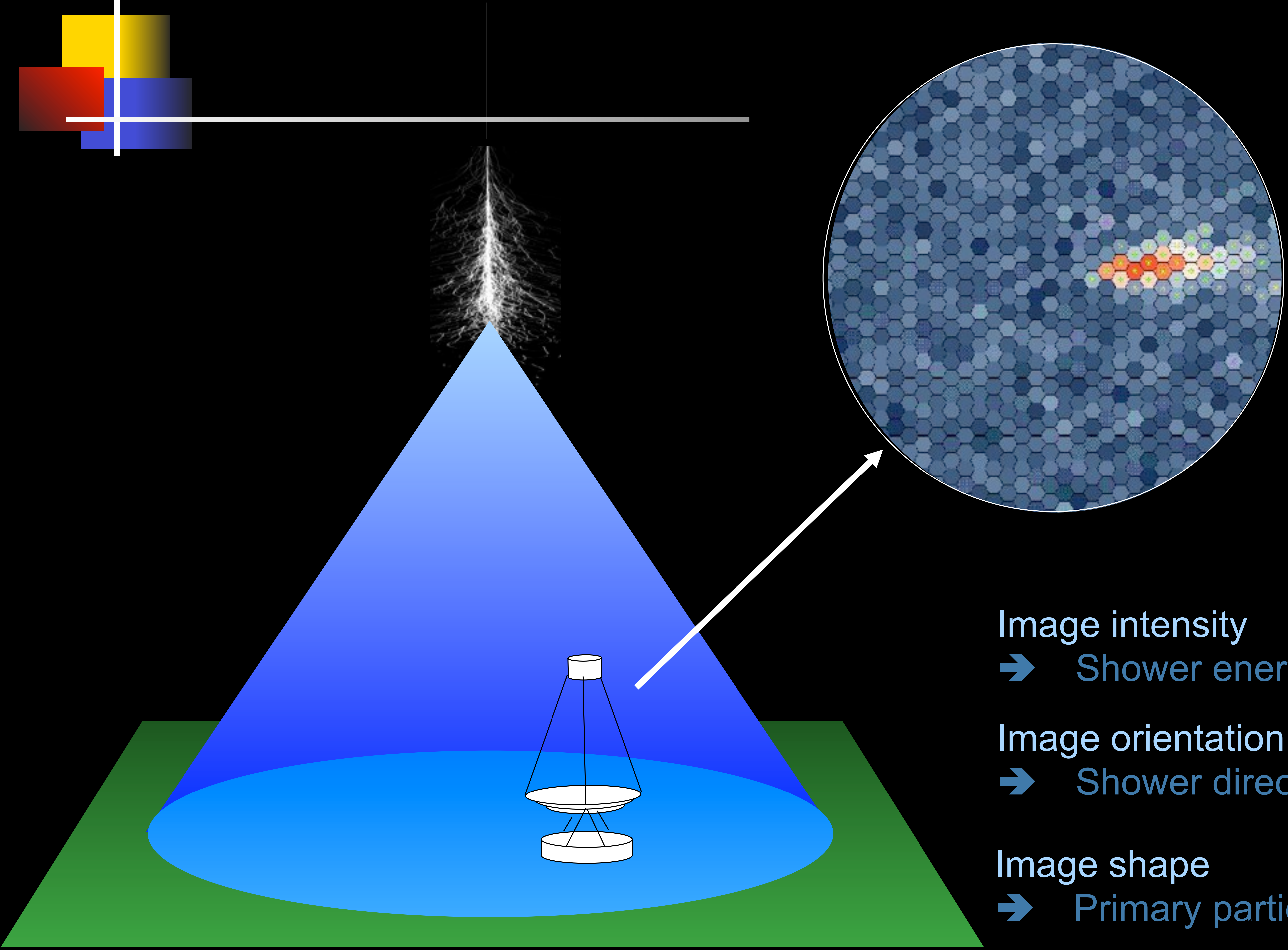
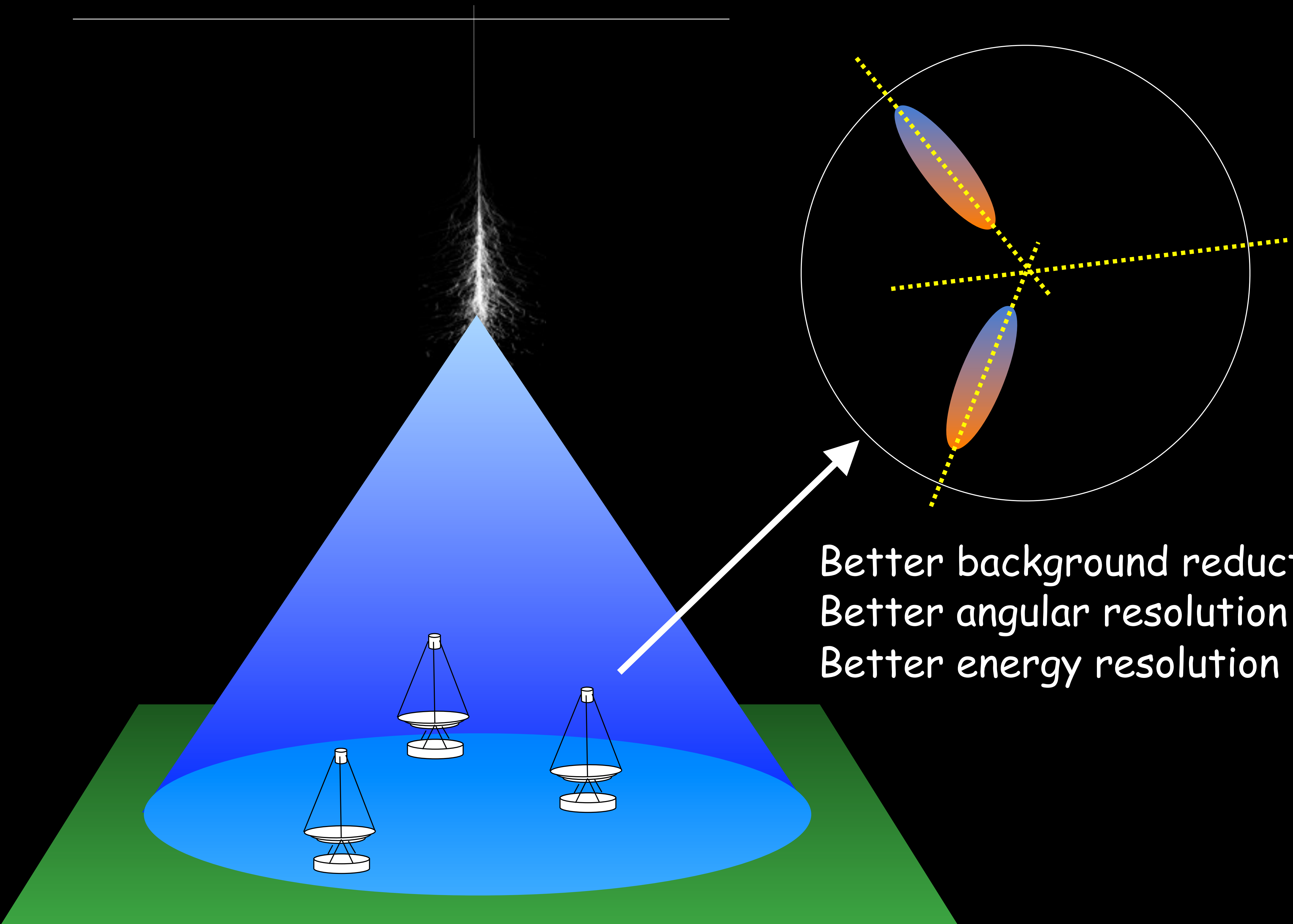


Image intensity
➔ Shower energy

Image orientation
➔ Shower direction

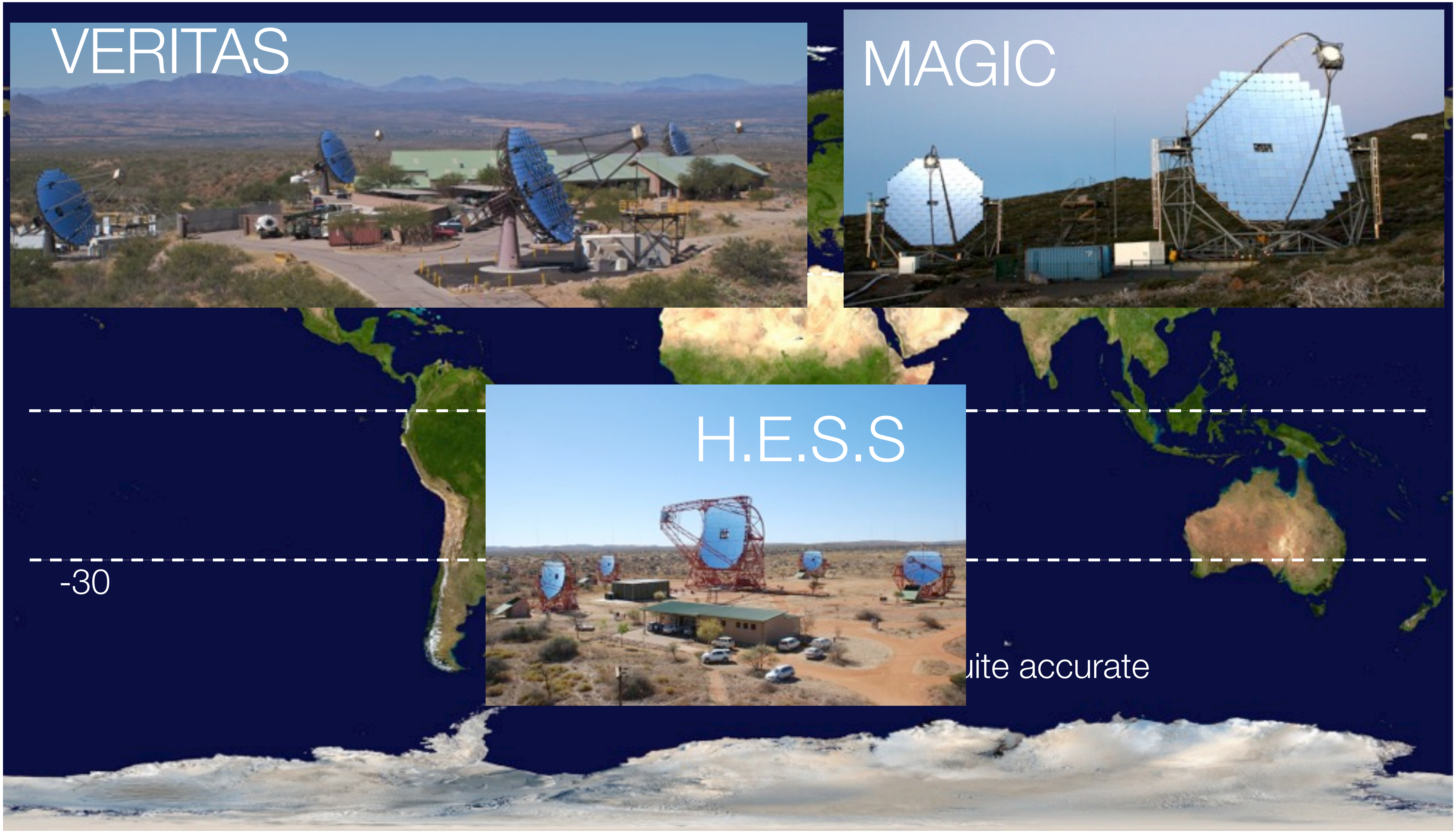
Image shape
➔ Primary particle

Systems of Cherenkov telescopes



Better background reduction
Better angular resolution
Better energy resolution

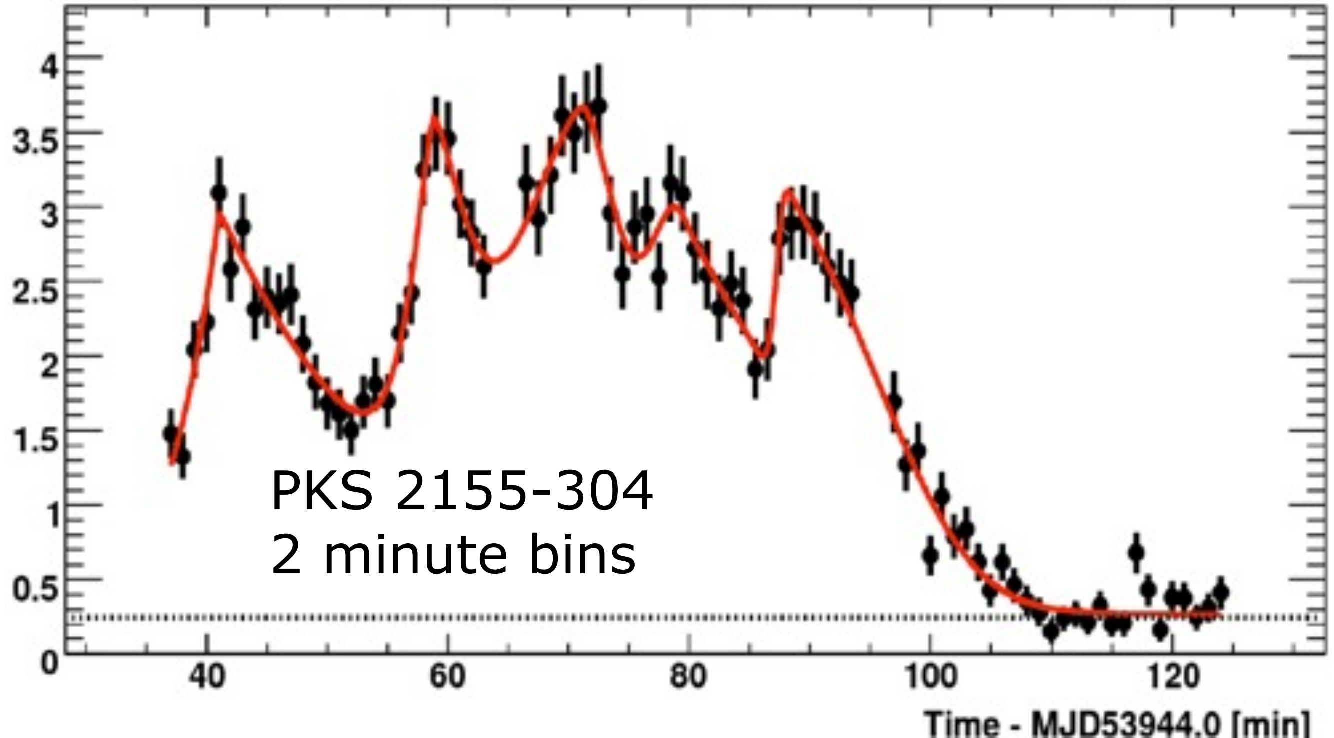
Current status: 3 major observatories



With instruments like H.E.S.S., MAGIC, VERITAS:

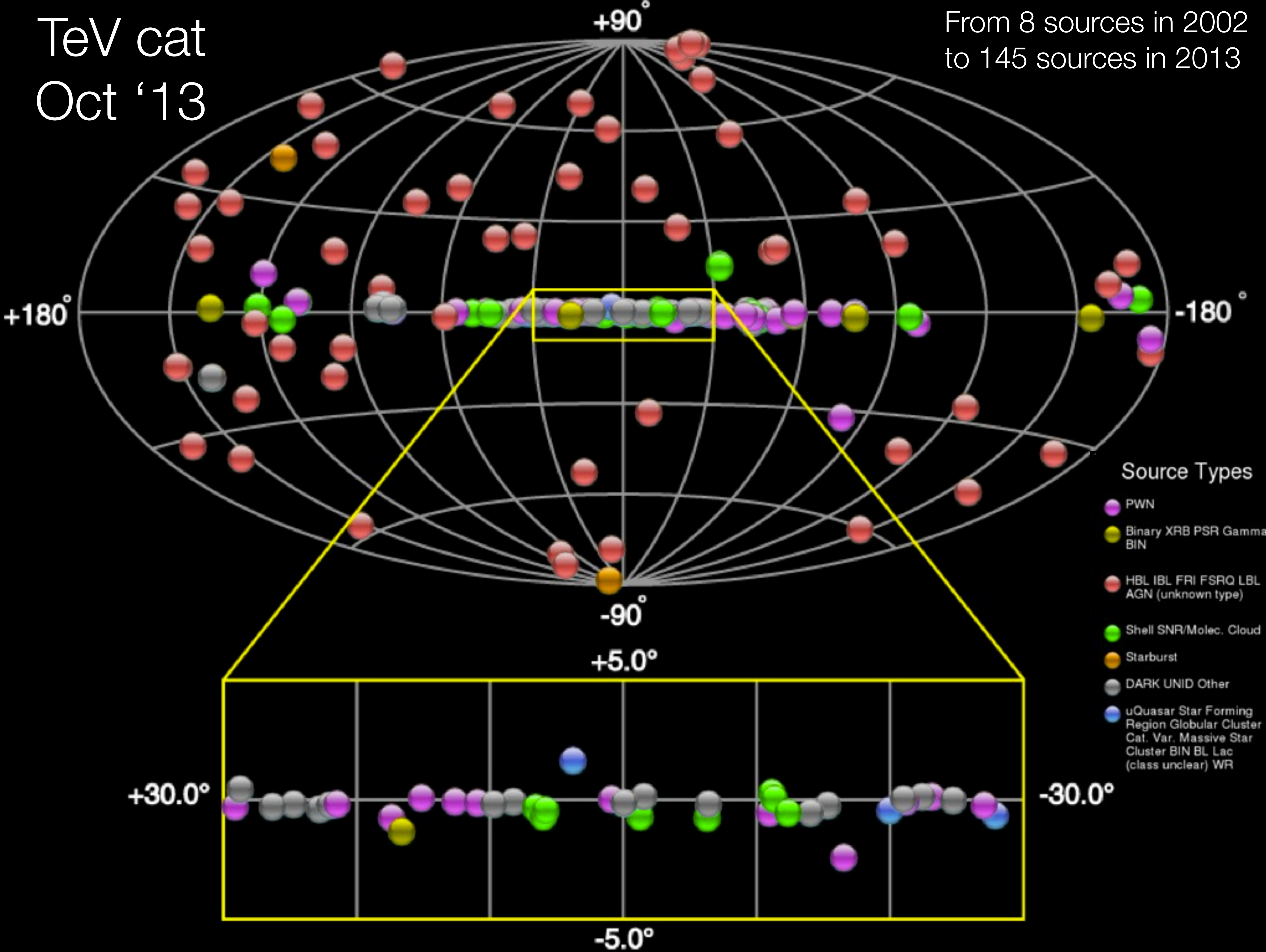
“Real astronomy”

- High sensitivity
  - 3 orders of magnitude dynamic range in flux between strongest and faintest sources
- Wide spectral range
  - >2 orders of magnitude coverage in energy, up to 10s of TeV
  - 10-15% energy resolution
- Resolved source morphology
  - ~5’ angular resolution
  - 10-20” source localization
- Survey capability
  - H.E.S.S. Galactic Plane Survey:
  - 2% Crab sensitivity
- Well-resolved light curves
  - Minute-scale variability of AGN

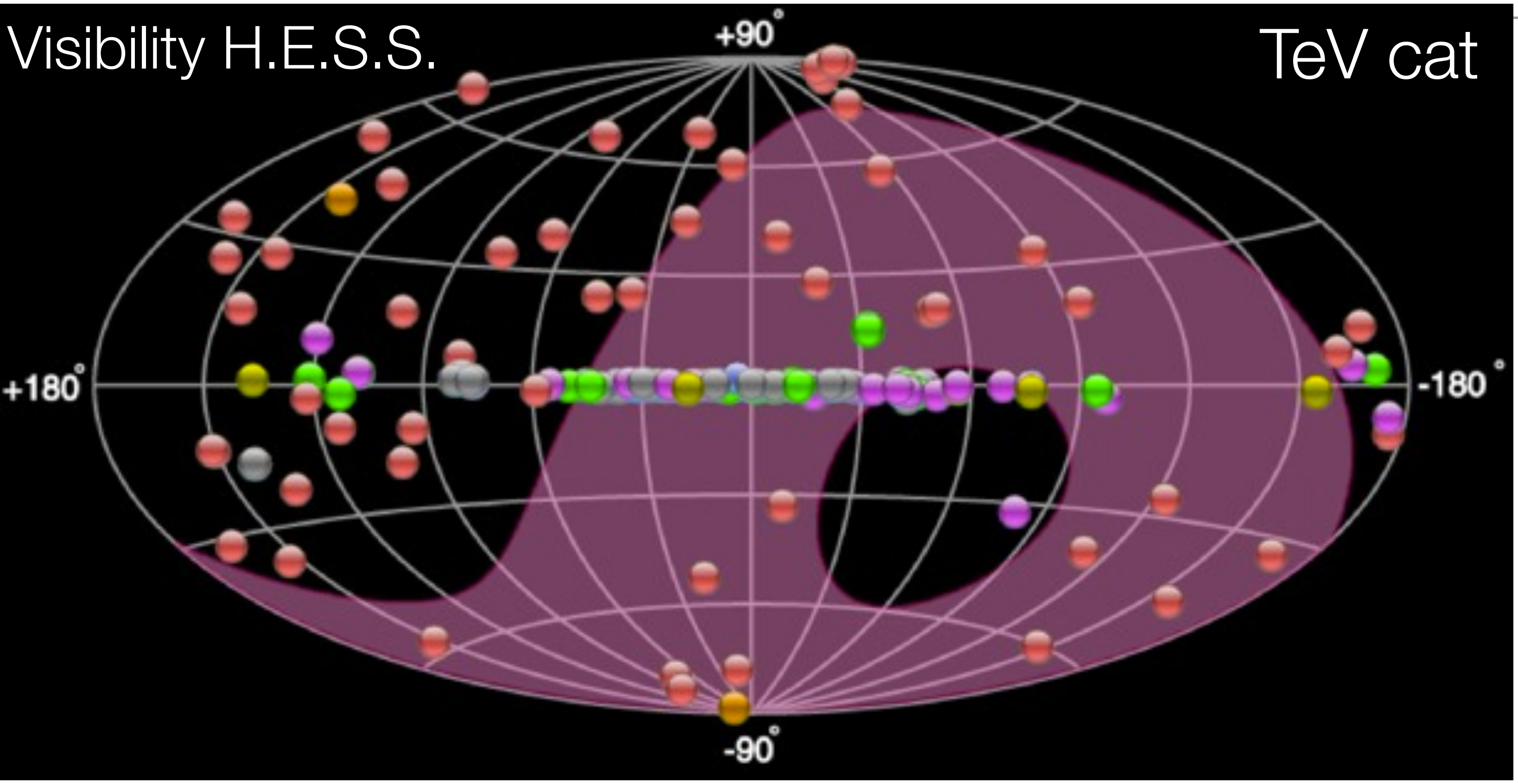

PKS 2155-304
2 minute bins

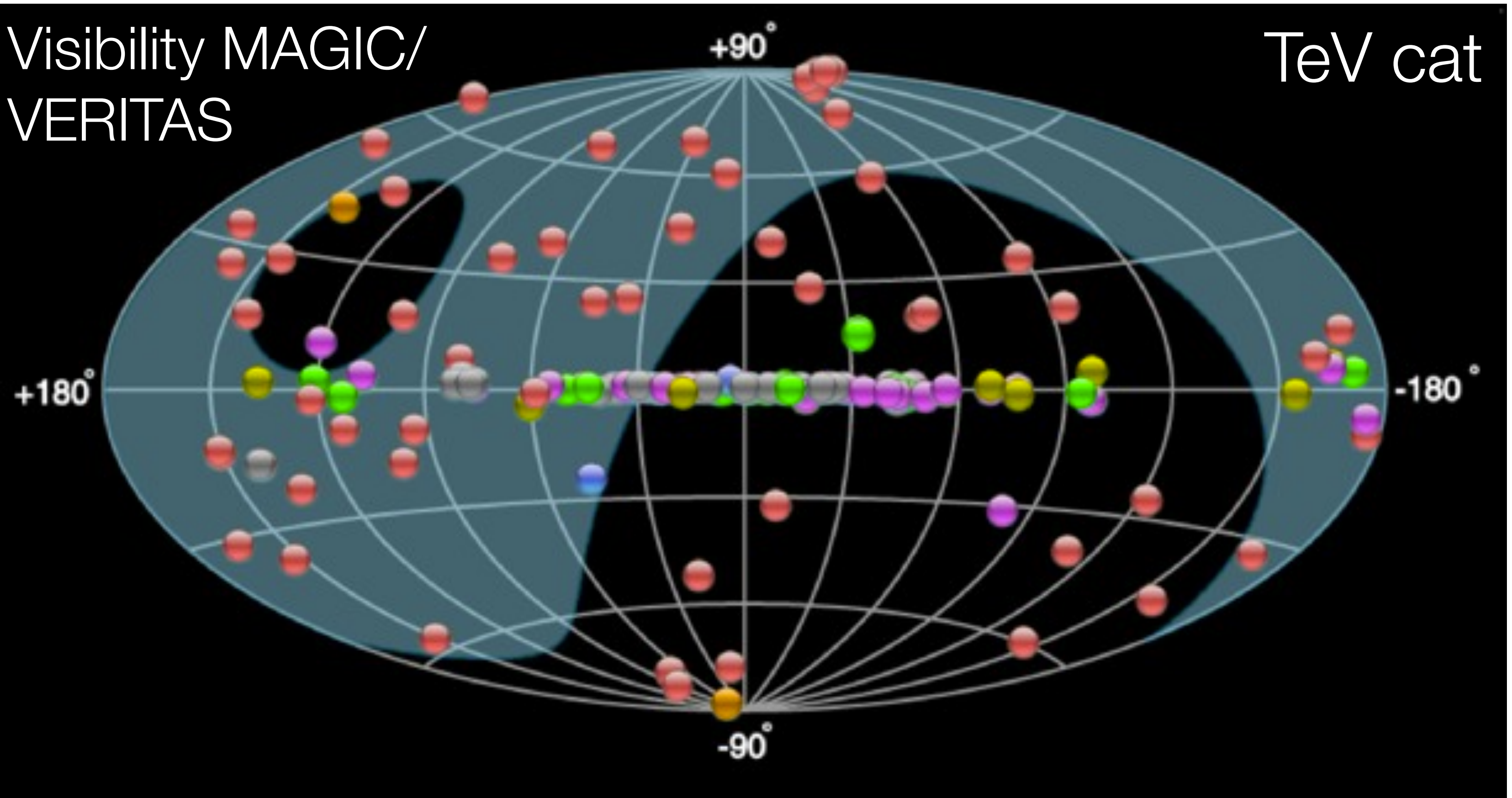
TeV cat
Oct ‘13

From 8 sources in 2002
to 145 sources in 2013



Observability of the sky



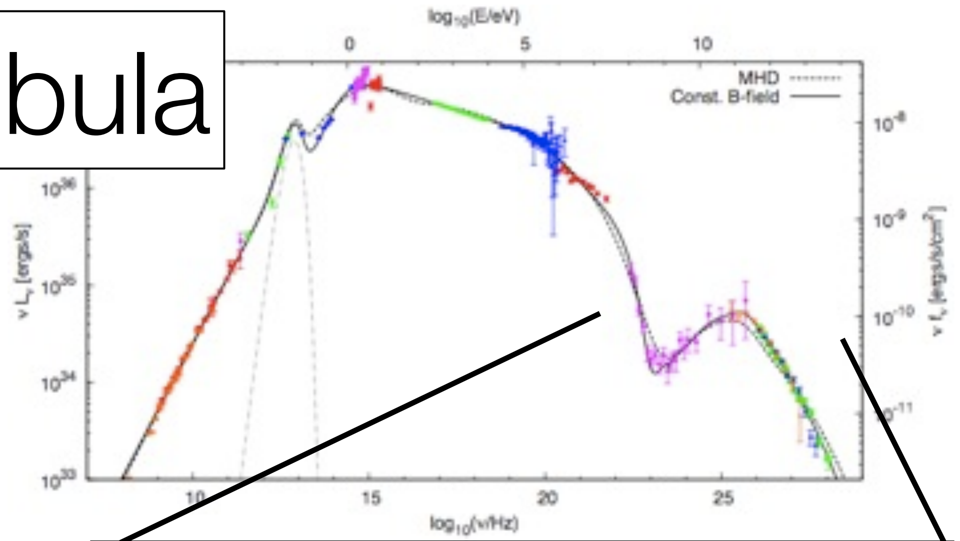


- Visibility is shown for culmination below zd=30deg
- One can see that sources with culmination up to zd=45 are also detected (but fewer)
- Good complementarity of the sites
- Number of useful hours: ~1200h per year, including moon time

Spectra and Phasograms

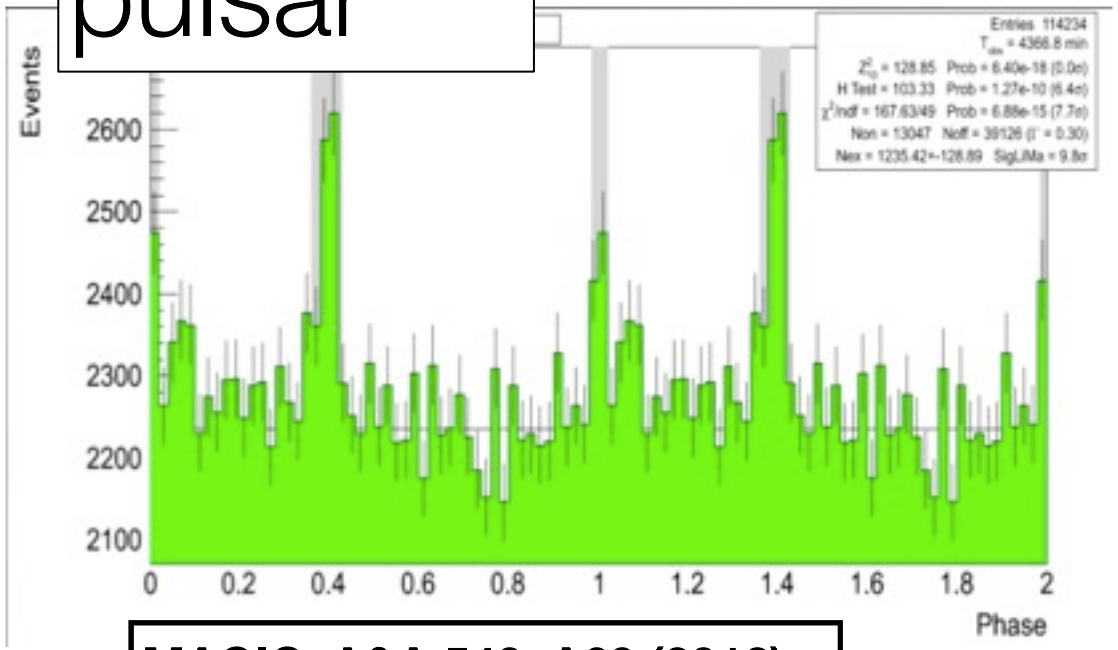
Crab Pulsar and Nebula is our **standard candle**:
- Left over after supernova 1054
- 2 kpc away
- Pulsar with 33.6 ms period
- Relativistic electrons (Γ up to ~10^9) extending up to a few pc -> Nebula

nebula

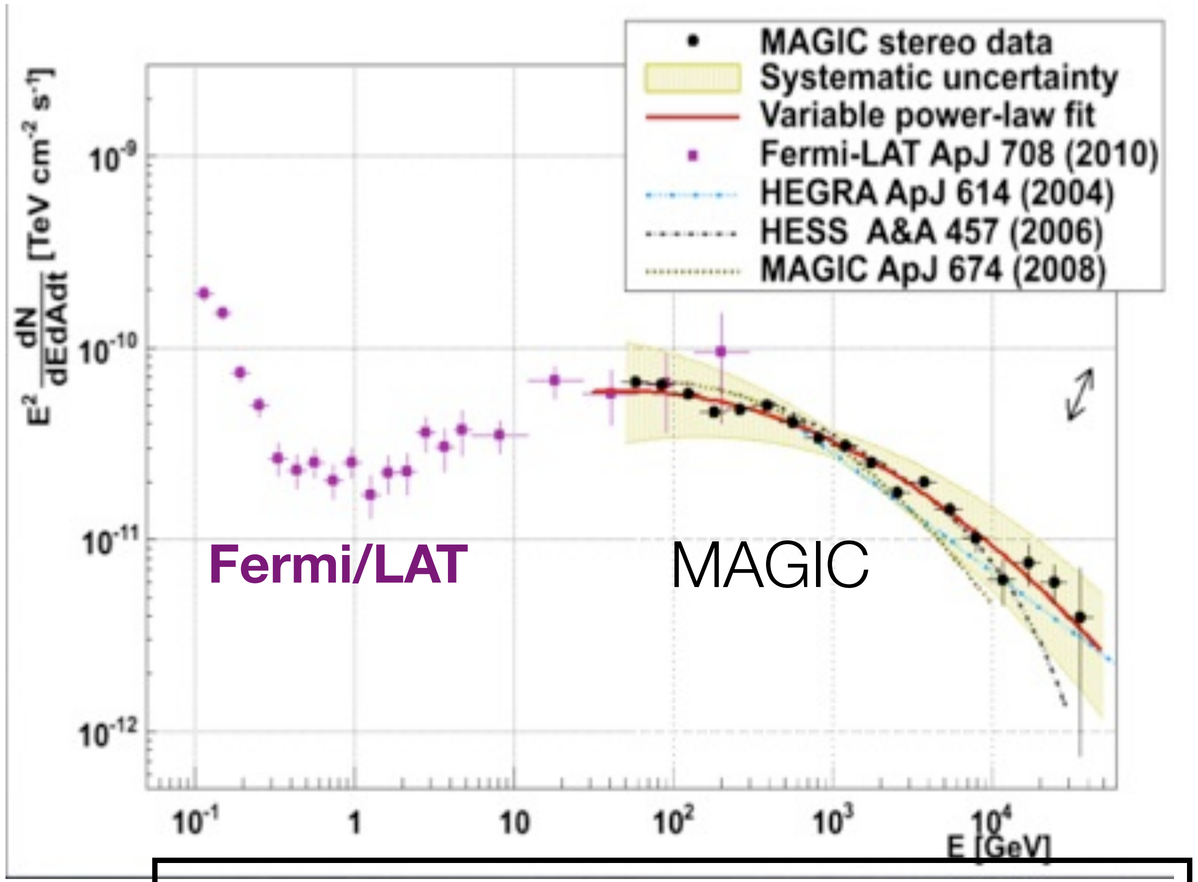


Meyer et al., A&A 523, A2 (2010)

pulsar



MAGIC, A&A 540, A69 (2012)



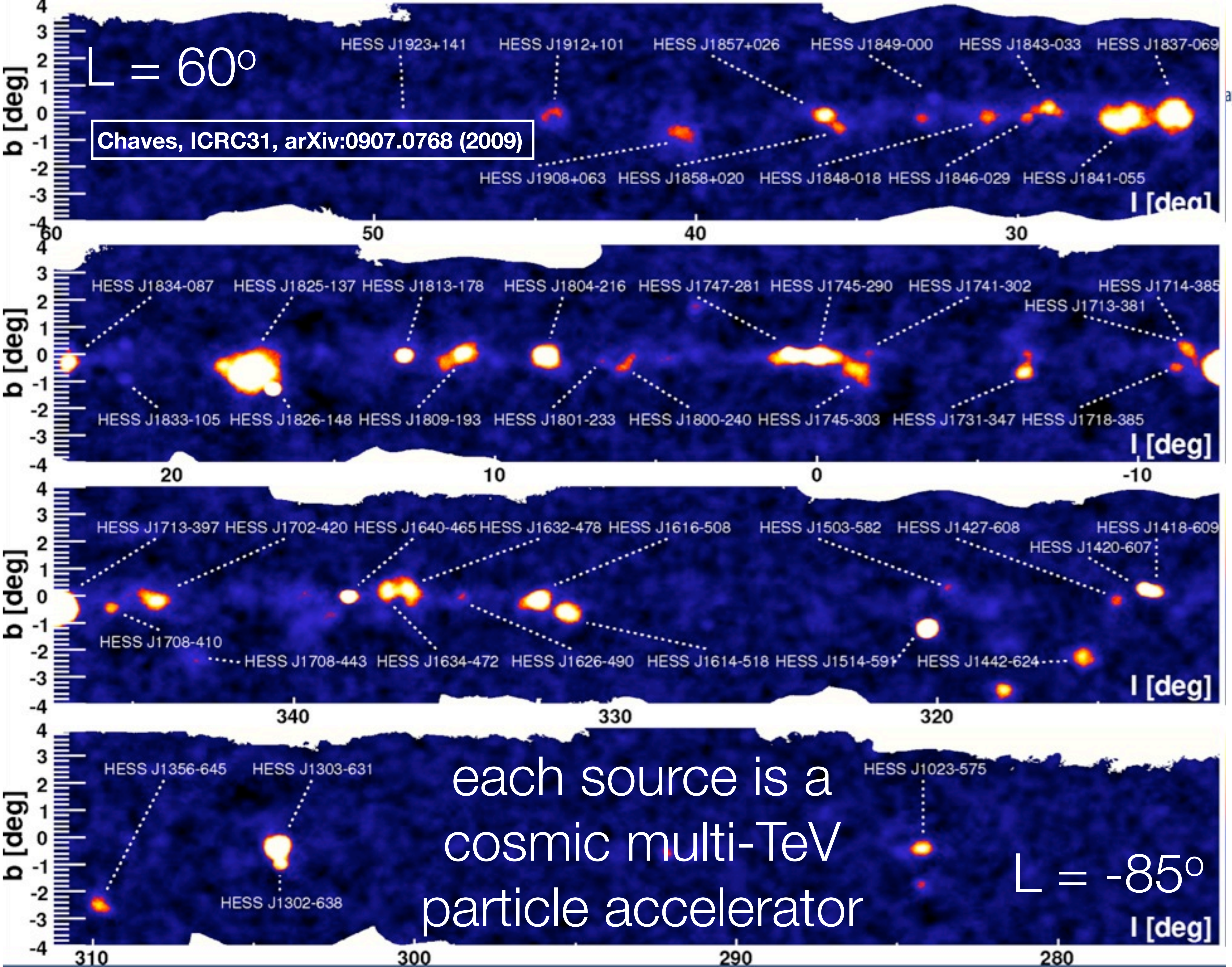
Fermi/LAT

MAGIC

Zanin et al., ICRC32, arXiv:1110.2987 (2011)

L = 60°

Chaves, ICRC31, arXiv:0907.0768 (2009)



each source is a cosmic multi-TeV particle accelerator

L = -85°

Propagation of Gamma-rays

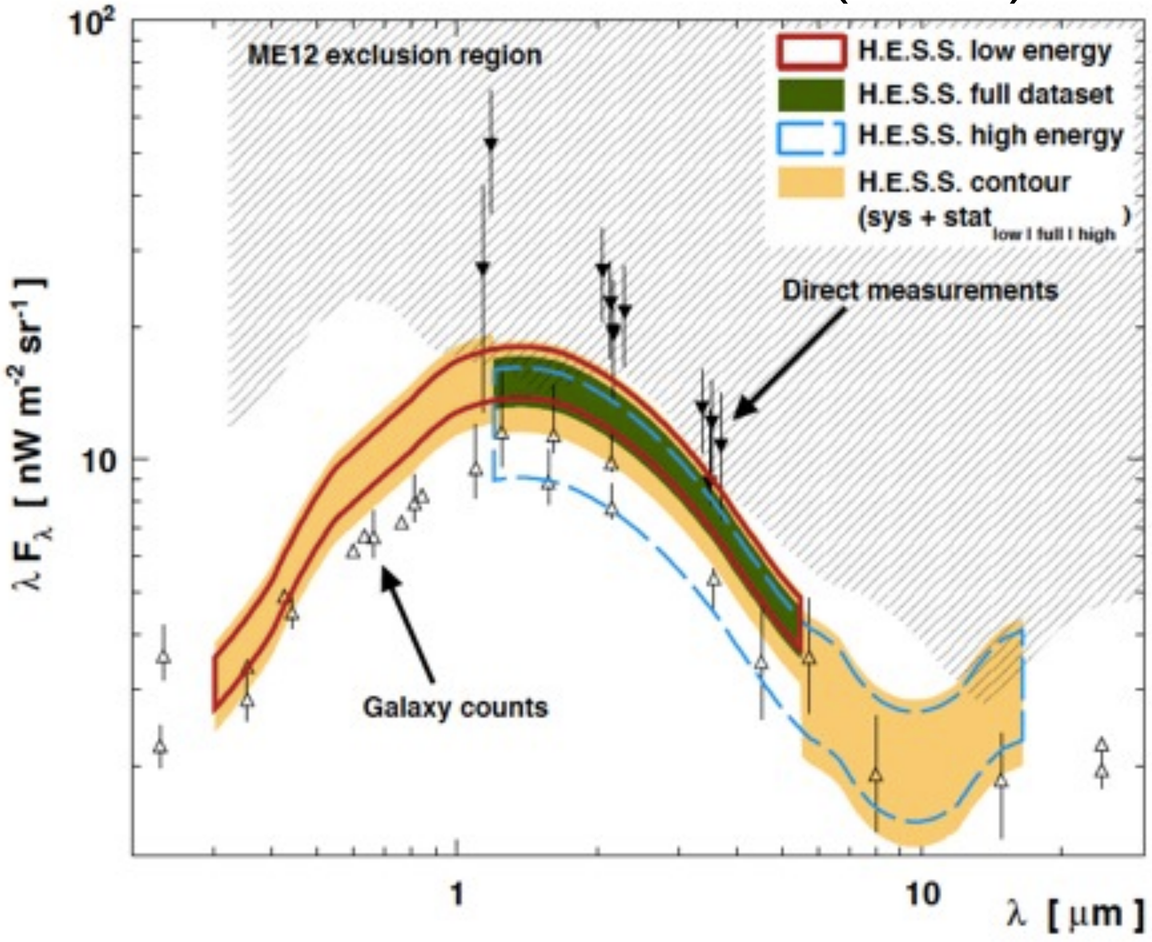
- TeV gammas are partially absorbed on the way to the Earth:

$$\gamma_{\mathrm{TeV}} + \gamma_{\mathrm{EBL}} \rightarrow e^+ e^-$$

- This effect can be used to infer EBL density from measured AGN spectra

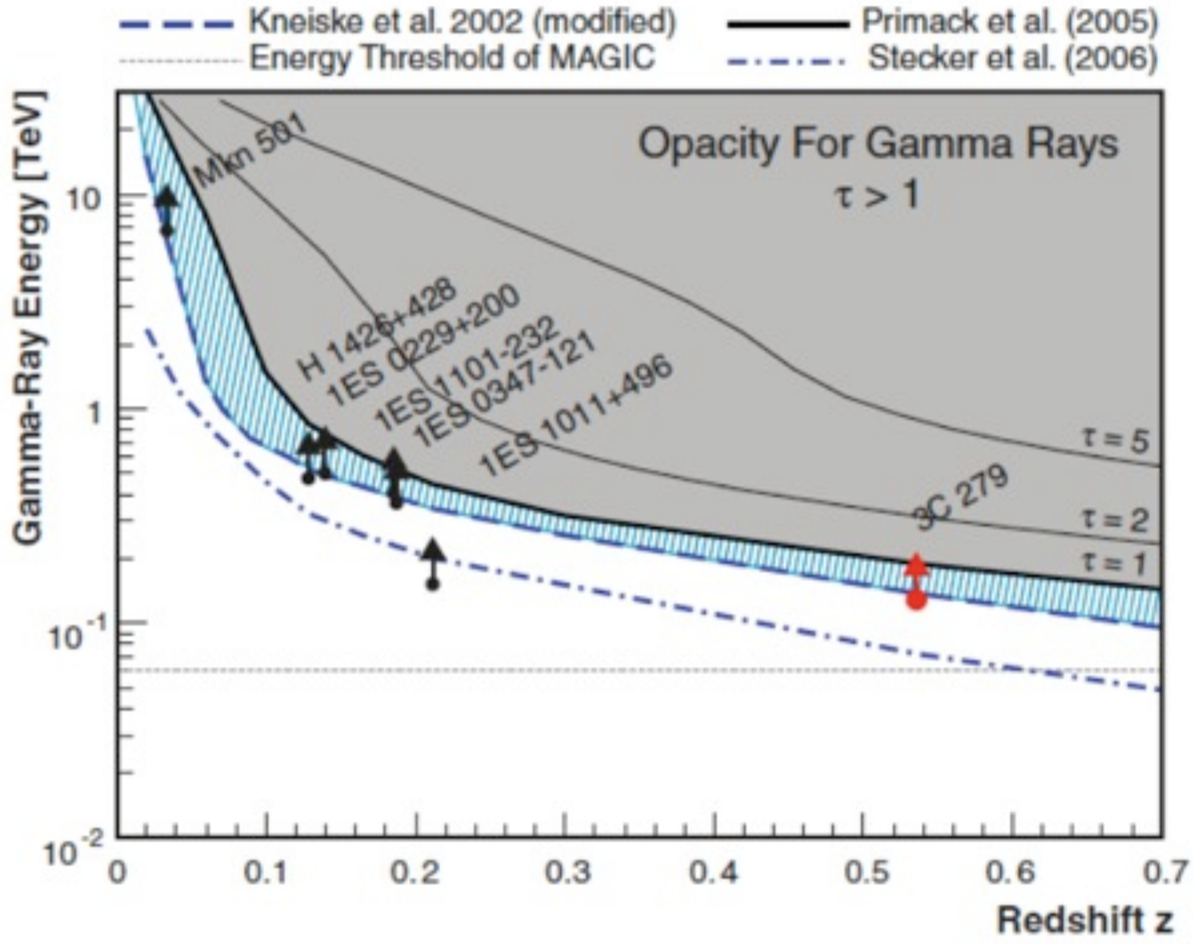
Extragalactic background light

H.E.S.S., A&A 550, 11 (2013)



Optical depth of Gamma-rays

MAGIC, Science 320, 1752 (2008)



Highly successful, but …

Some key object classes still elusive, e.g.

- Galaxy clusters as cosmological storehouses of CRs
- Very high energy emission from GRB
- Dark Matter annihilation signatures

Some key mechanisms remain to be understood, e.g.

- Supernovae as sources of cosmic rays: do they provide sufficient peak energy & energy output?
- Cosmic ray escape from accelerators and propagation
- Energy conversion in pulsars

Energy range & angular resolution of current instruments insufficient to probe details

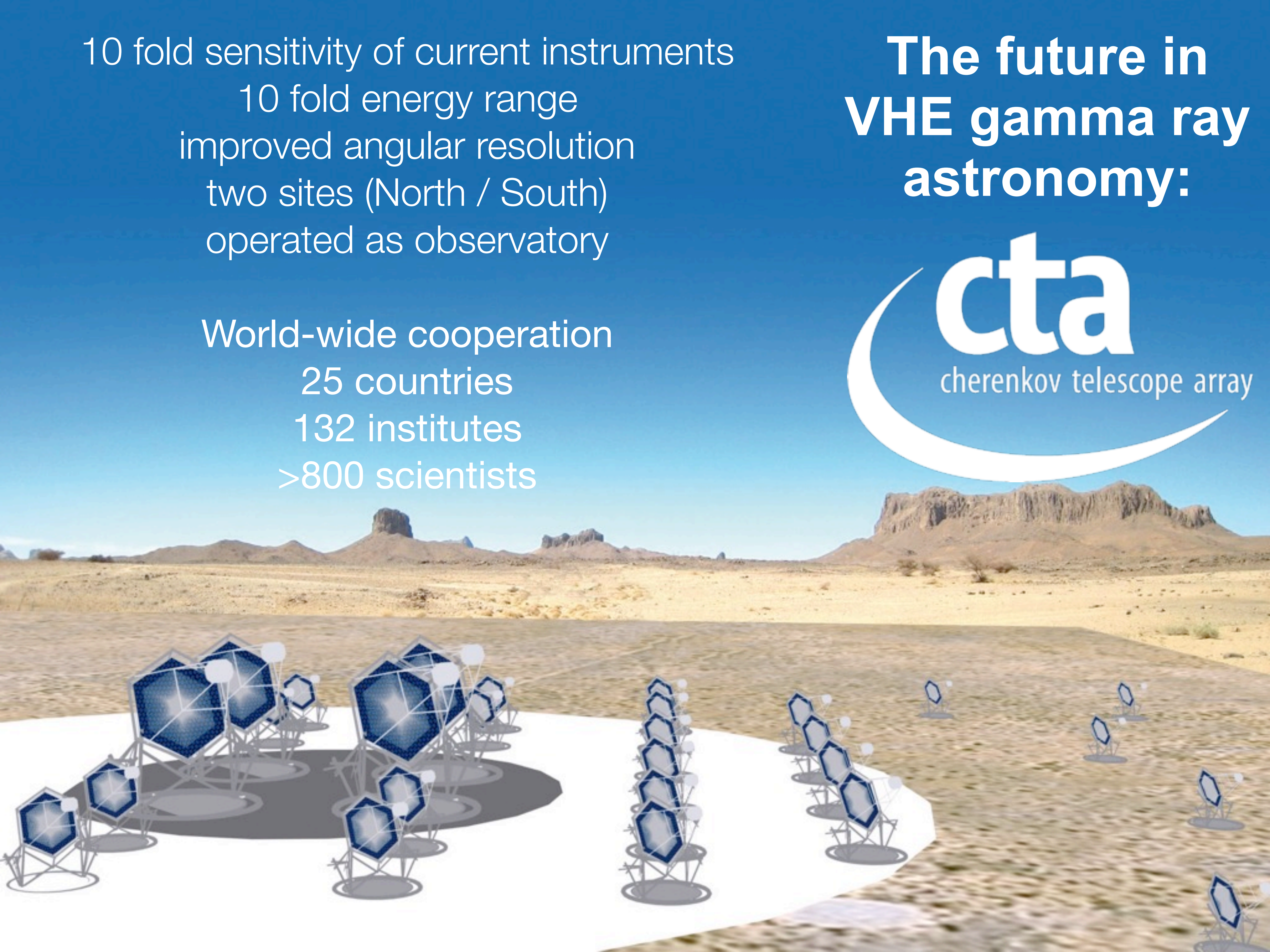
CTA concept

The future in VHE gamma ray astronomy:

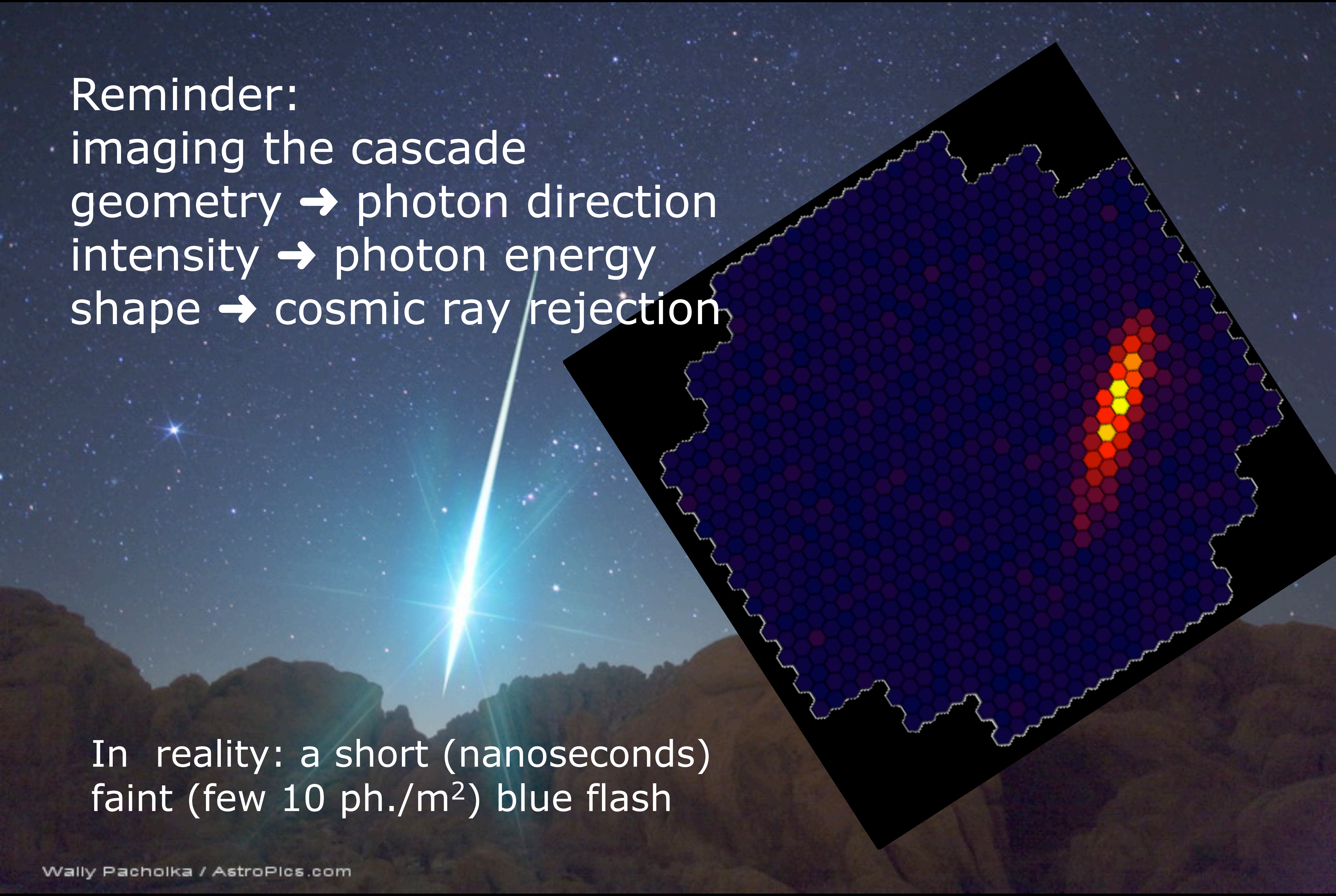
cta
cherenkov telescope array

10 fold sensitivity of current instruments
10 fold energy range
improved angular resolution
two sites (North / South)
operated as observatory

World-wide cooperation
25 countries
132 institutes
>800 scientists

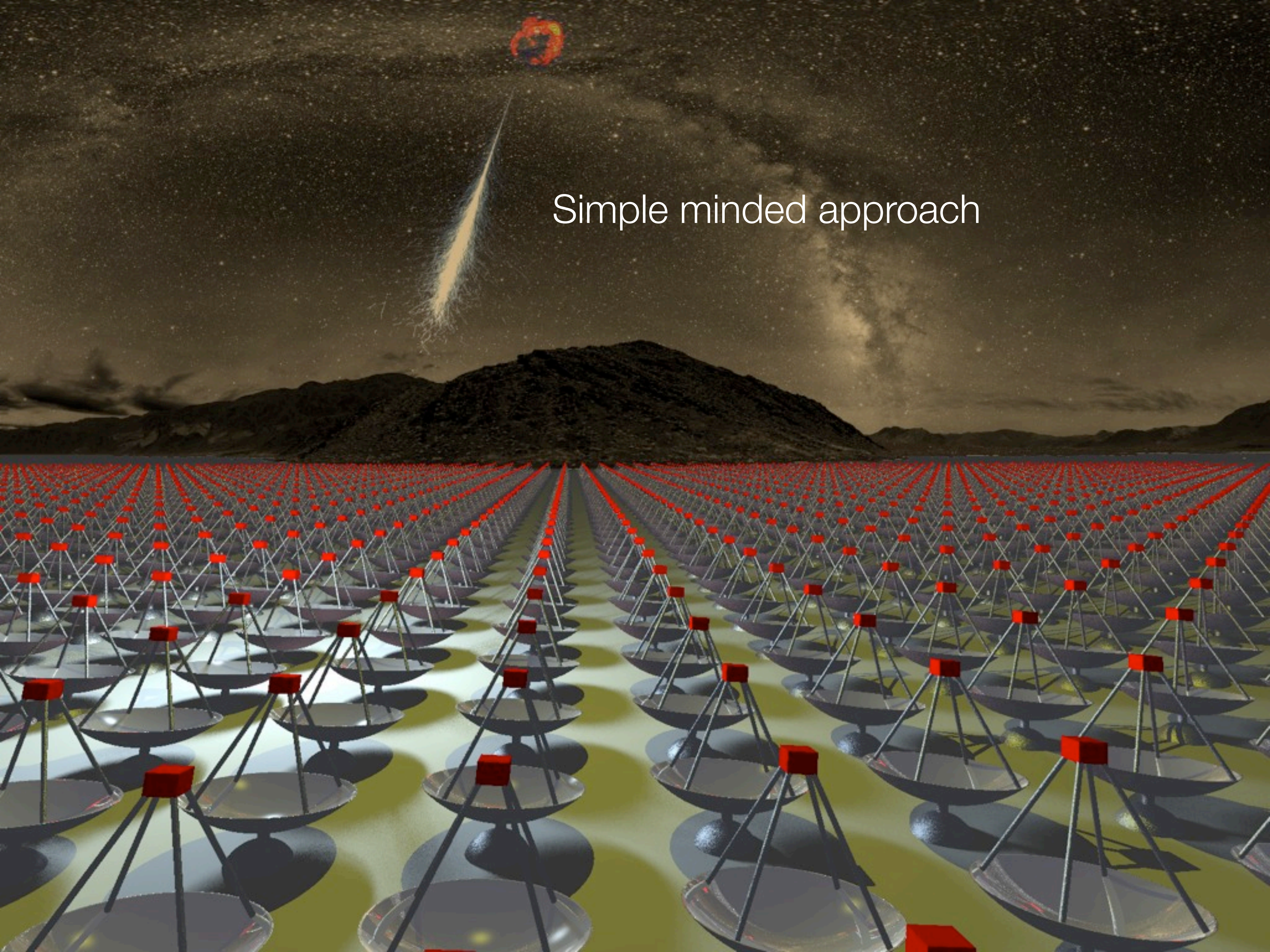


Reminder:
imaging the cascade
geometry ➜ photon direction
intensity ➜ photon energy
shape ➜ cosmic ray rejection

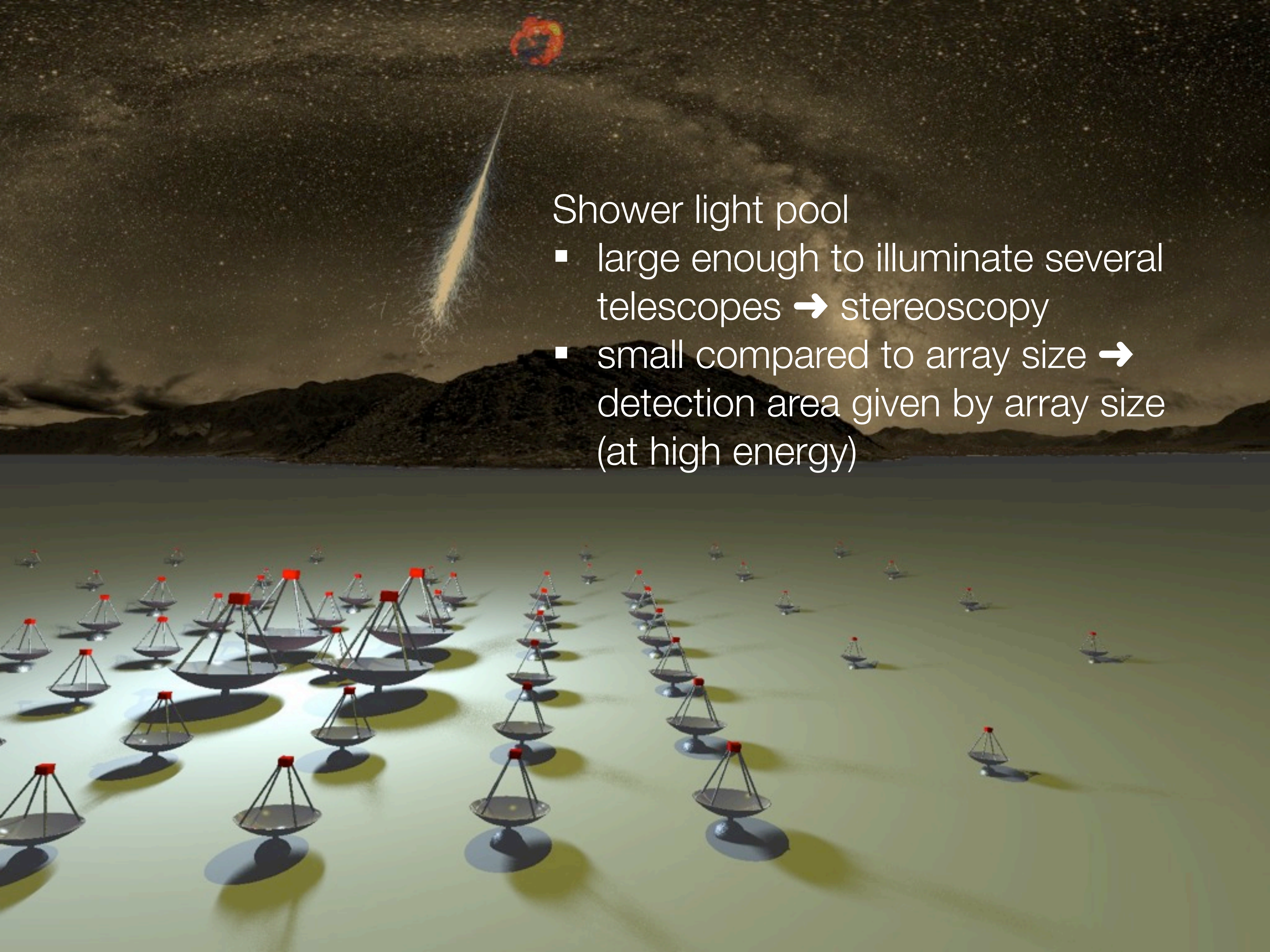


In reality: a short (nanoseconds) faint (few 10 ph./m^2) blue flash

Wally Pacholka / AstroPics.com



Simple minded approach



Shower light pool

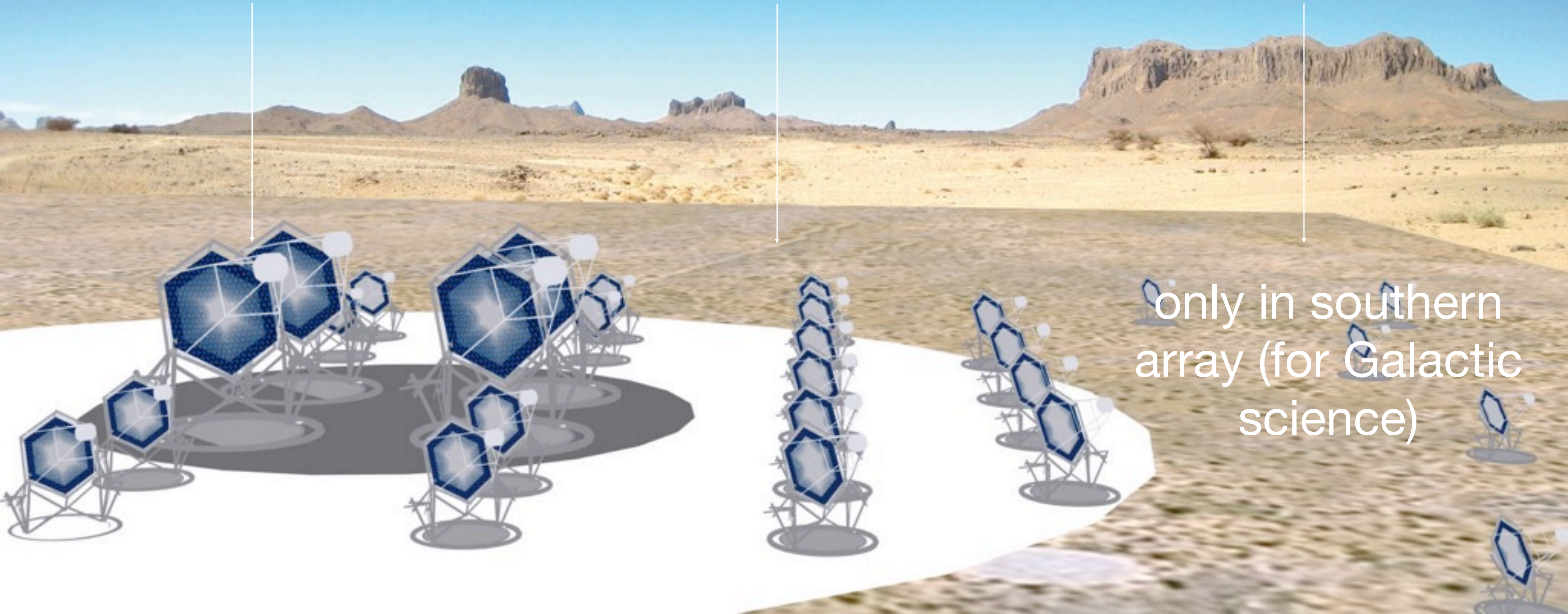
- large enough to illuminate several telescopes ➜ stereoscopy
- small compared to array size ➜ detection area given by array size (at high energy)

The Cherenkov Telescope Array concept

Low energy
Few 23 m
telescopes
4…5° FoV
~2500 pixels
~ 0.1°

Medium energy
About twenty 12 m
telescopes
6…8° FoV
~1500 pixels
~ 0.18°

High energy
Fifty + 4…7 m
telescopes
8…10° FoV
~1500…2000 pixels
~ 0.2°…0.3°



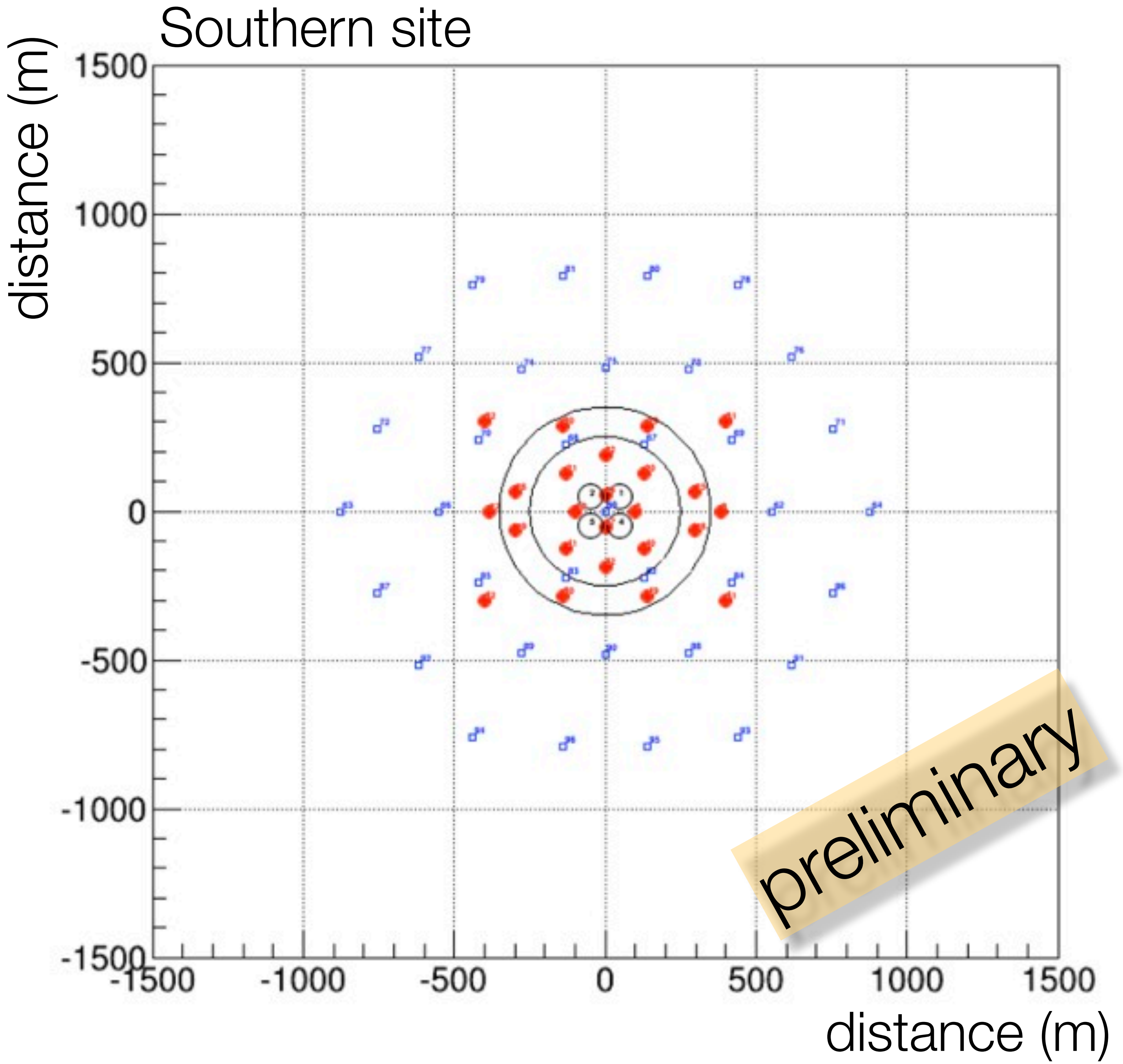
only in southern array (for Galactic science)

Technical implementation

Possible CTA configuration (under discussion)

- Balanced array (low, mid and high energies)

- Consists of
  - **4 large** size telescopes
  - **24 mid** size telescopes
  - **35 small** size telescopes

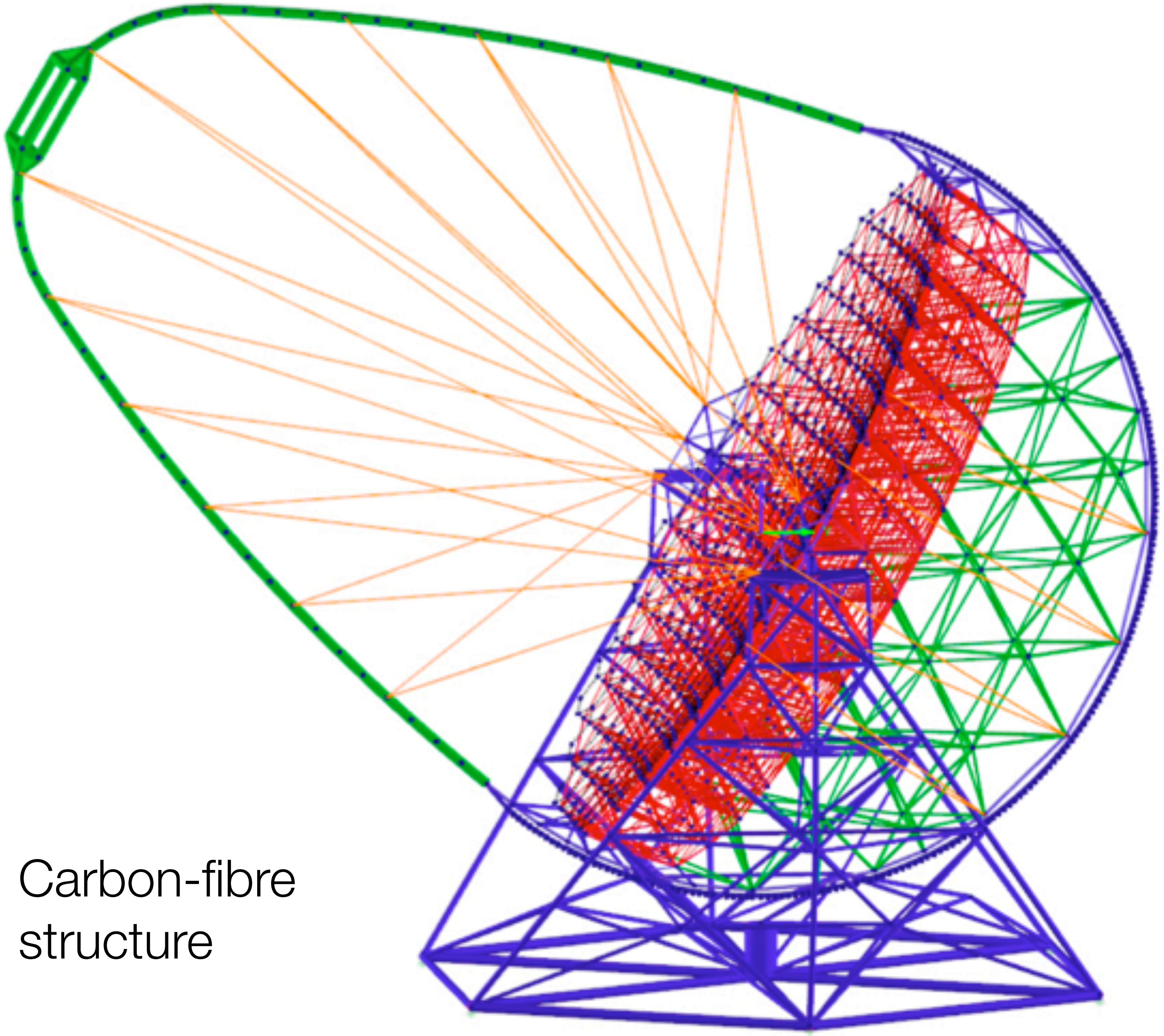


smaller size in the North (less or no SSTs)

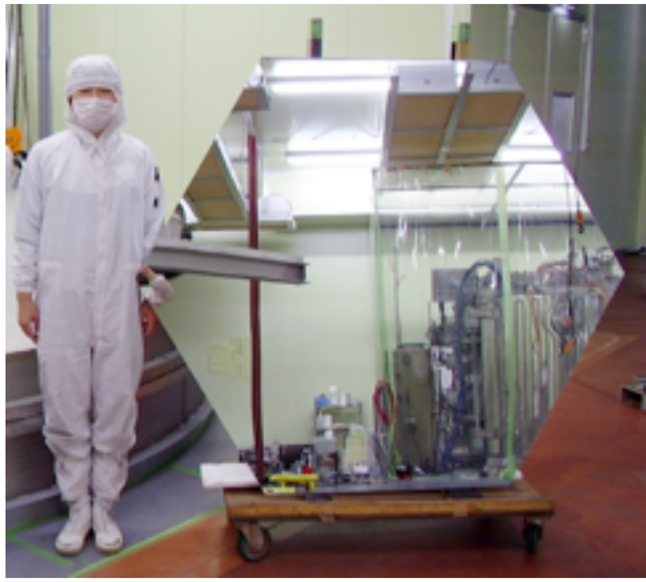
Design: 23 m Large Telescopes

optimized for the range below 200 GeV

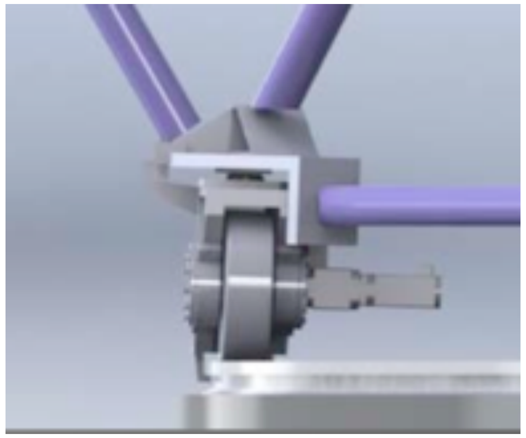
27.8 m focal length
4.5° field of view
0.1° pixels

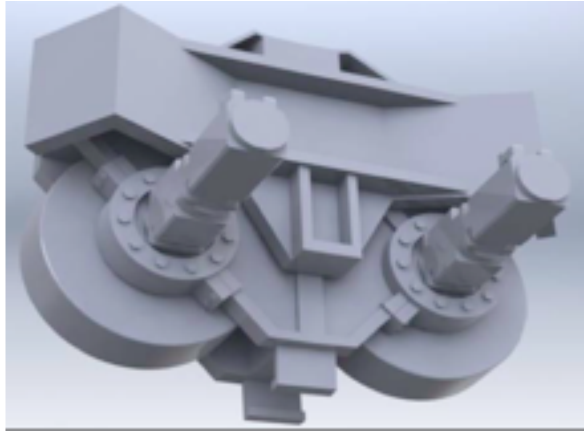


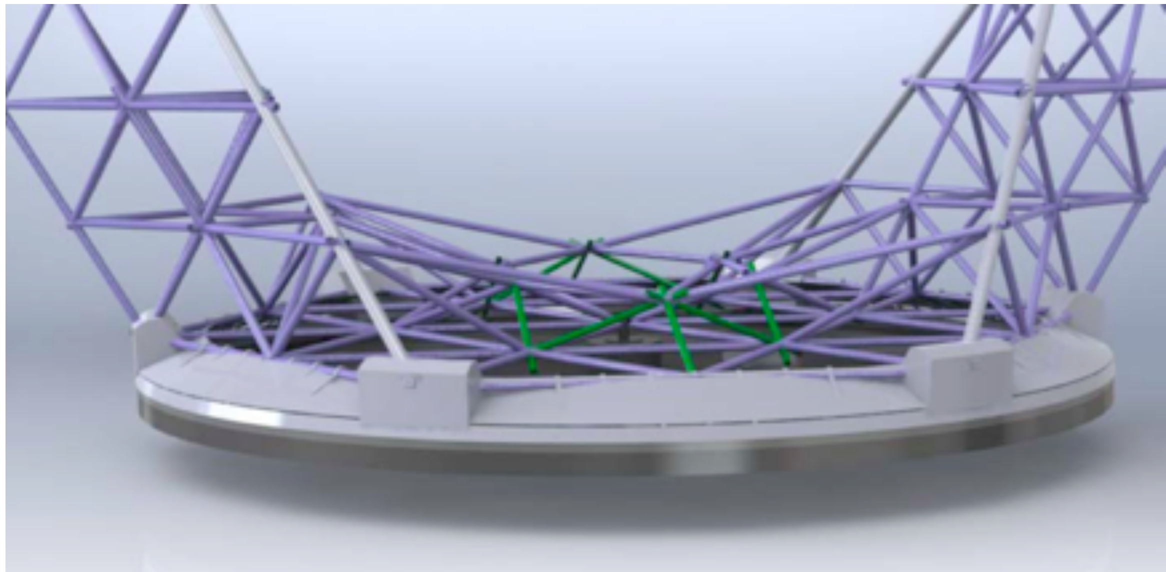
400 m^2 dish area
1.5 m sandwich
mirror facets



On (GRB) target
in < 20 sec.





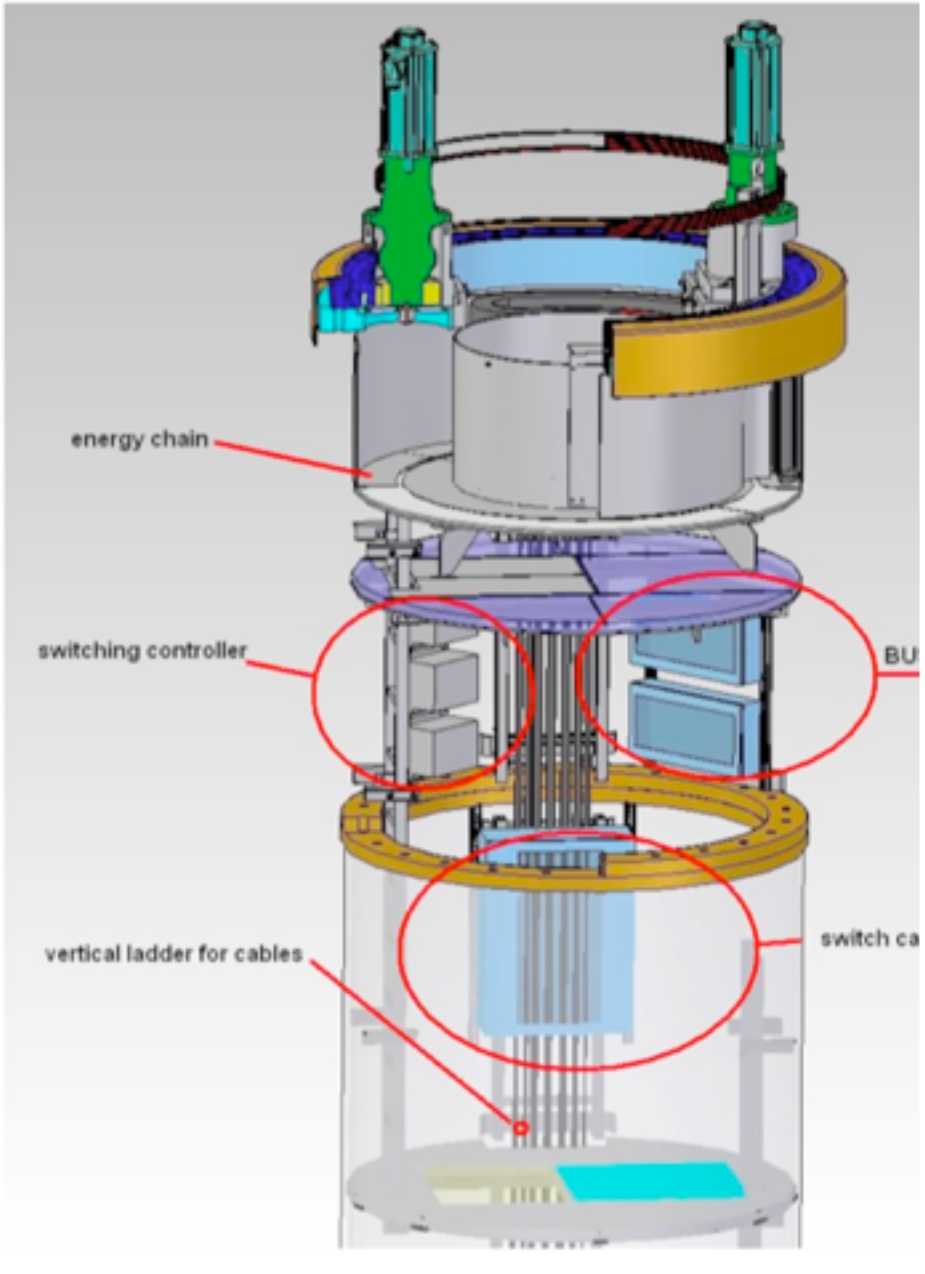


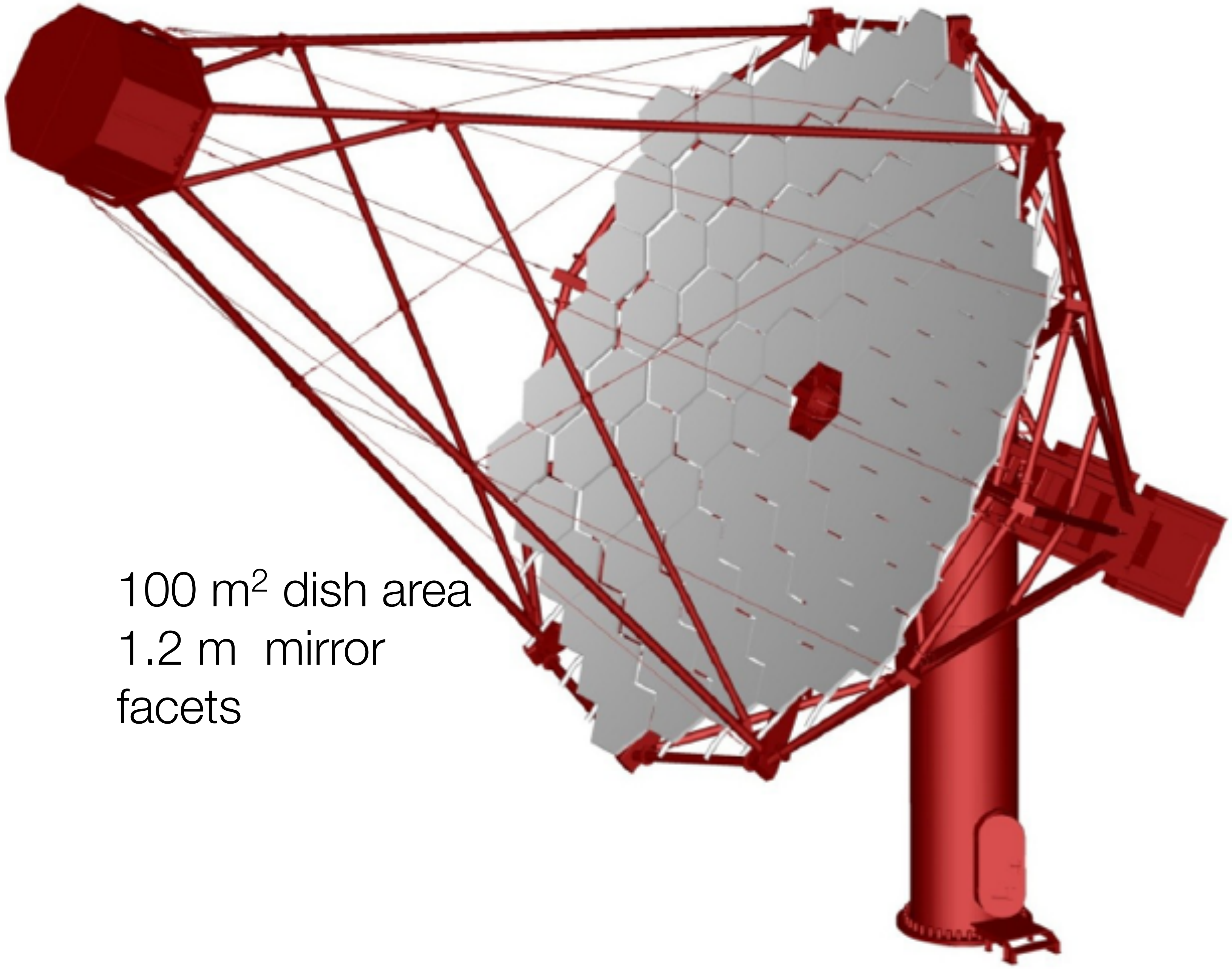
Carbon-fibre
structure

Design: Medium-Sized 12 m Telescope

optimized for the 100 GeV to ~10 TeV range

16 m focal length
7-8° field of view
0.18° pixels



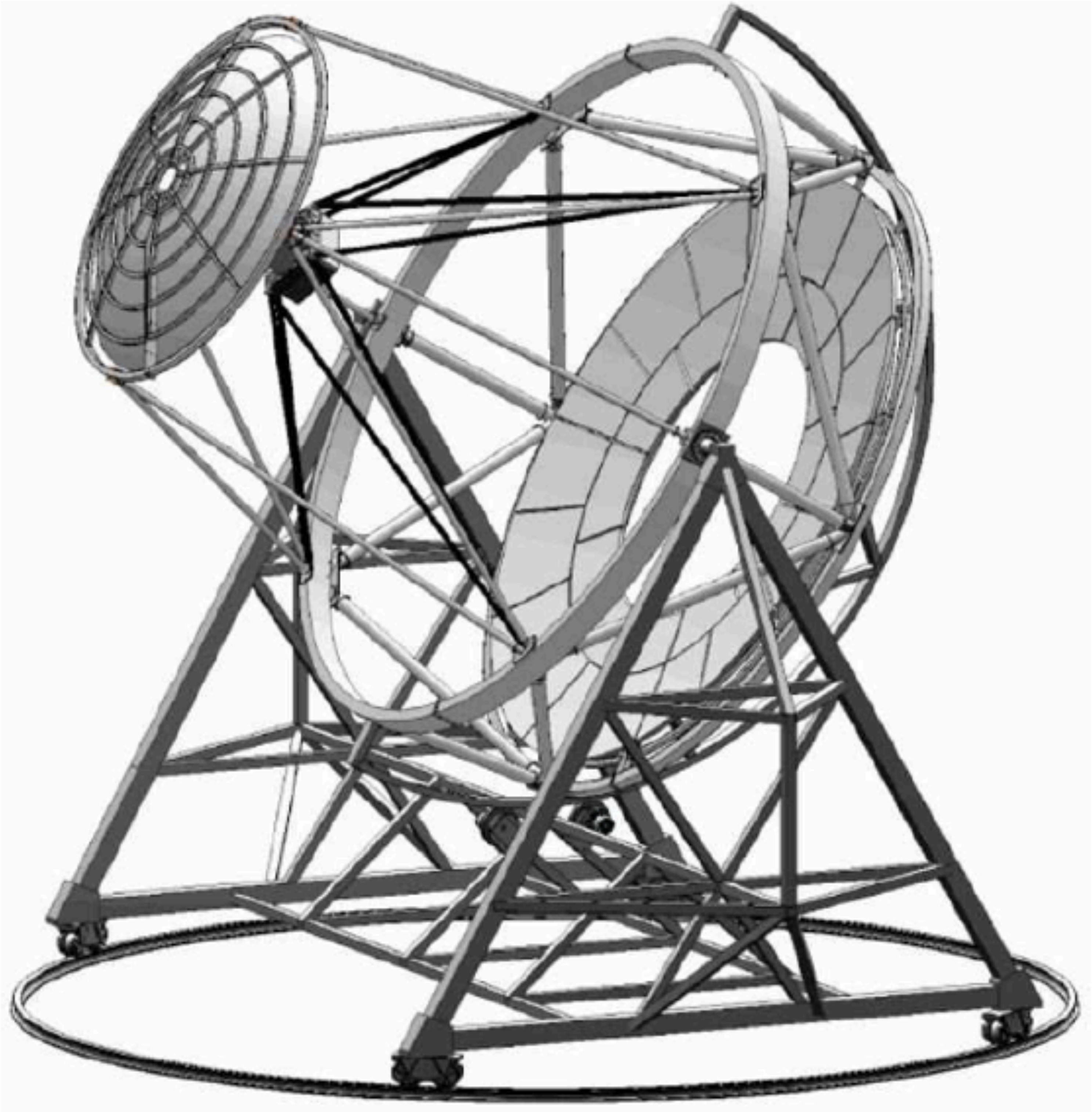


100 m^2 dish area
1.2 m mirror
facets

Dual Mirror Option for medium telescope

Improved imaging
Small plate scale

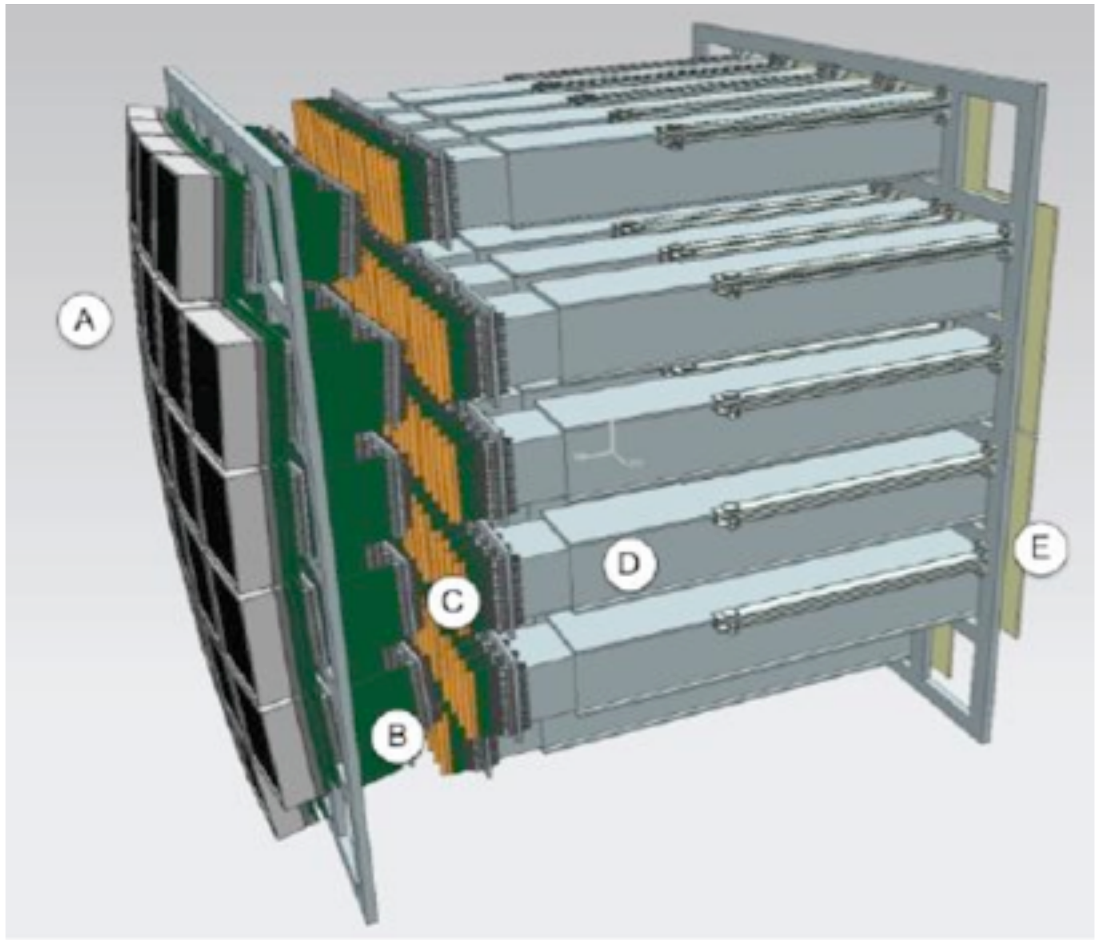
Discussed for
US-driven expansion
of MST array



Design: Small 4-6 m Telescopes

cover the range above few TeV across 10 km^2

Multi-Anode PMT camera option



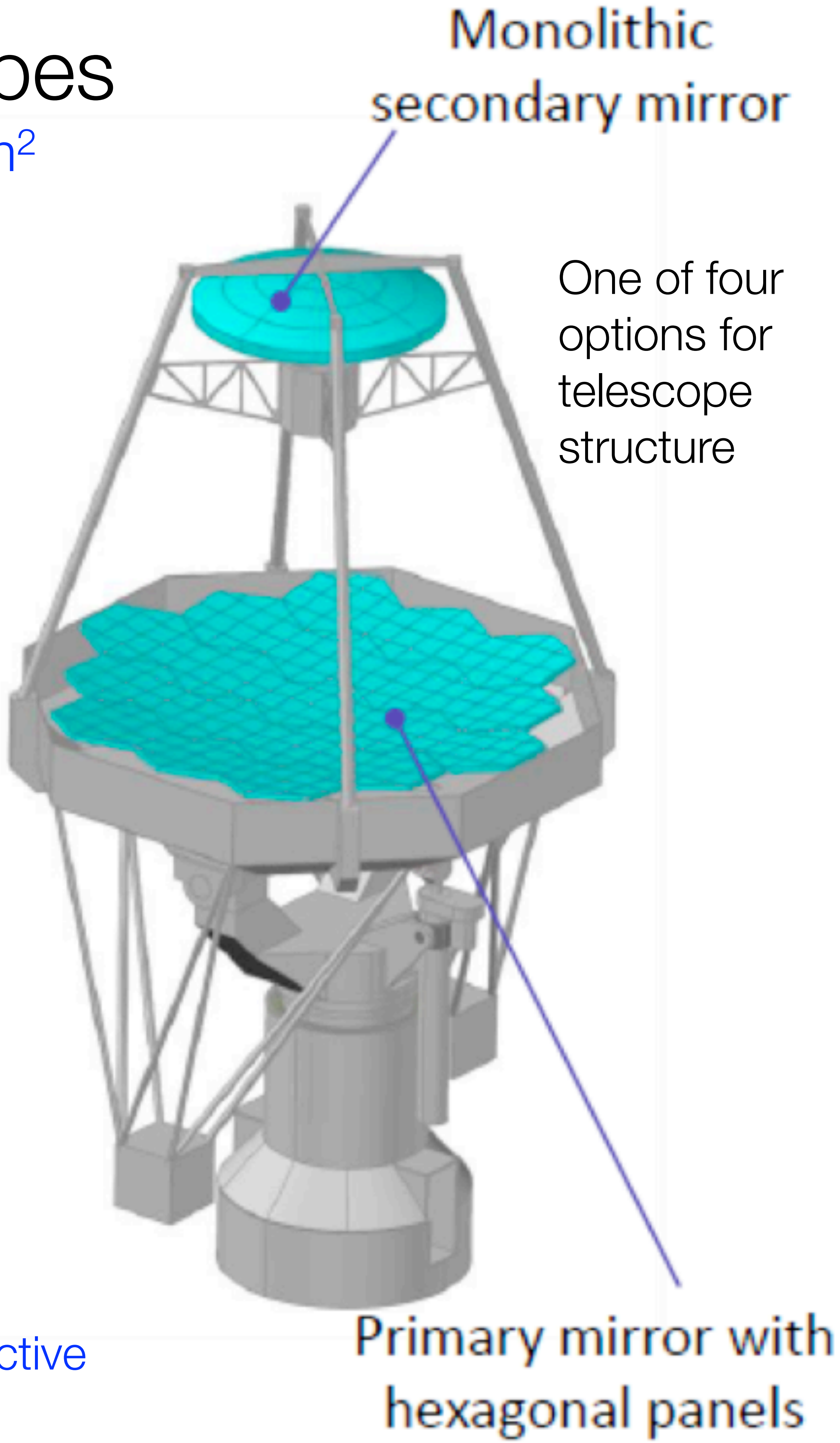
Under study:

dual-mirror optics with compact photo sensor arrays

single-mirror optics

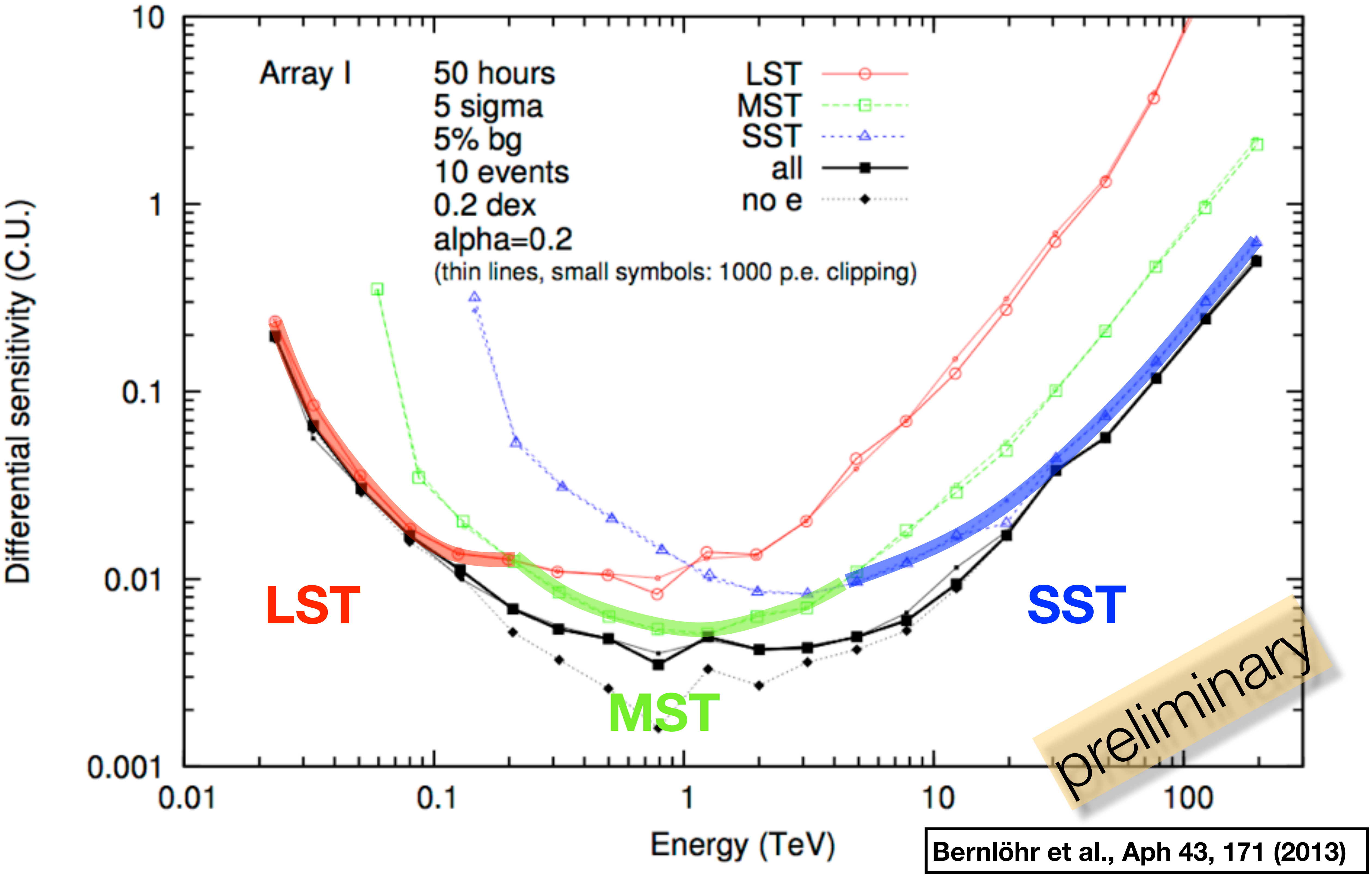
PMT-based and silicon-based sensors

➜ Not yet conclusive which solution is most cost-effective



One of four options for telescope structure

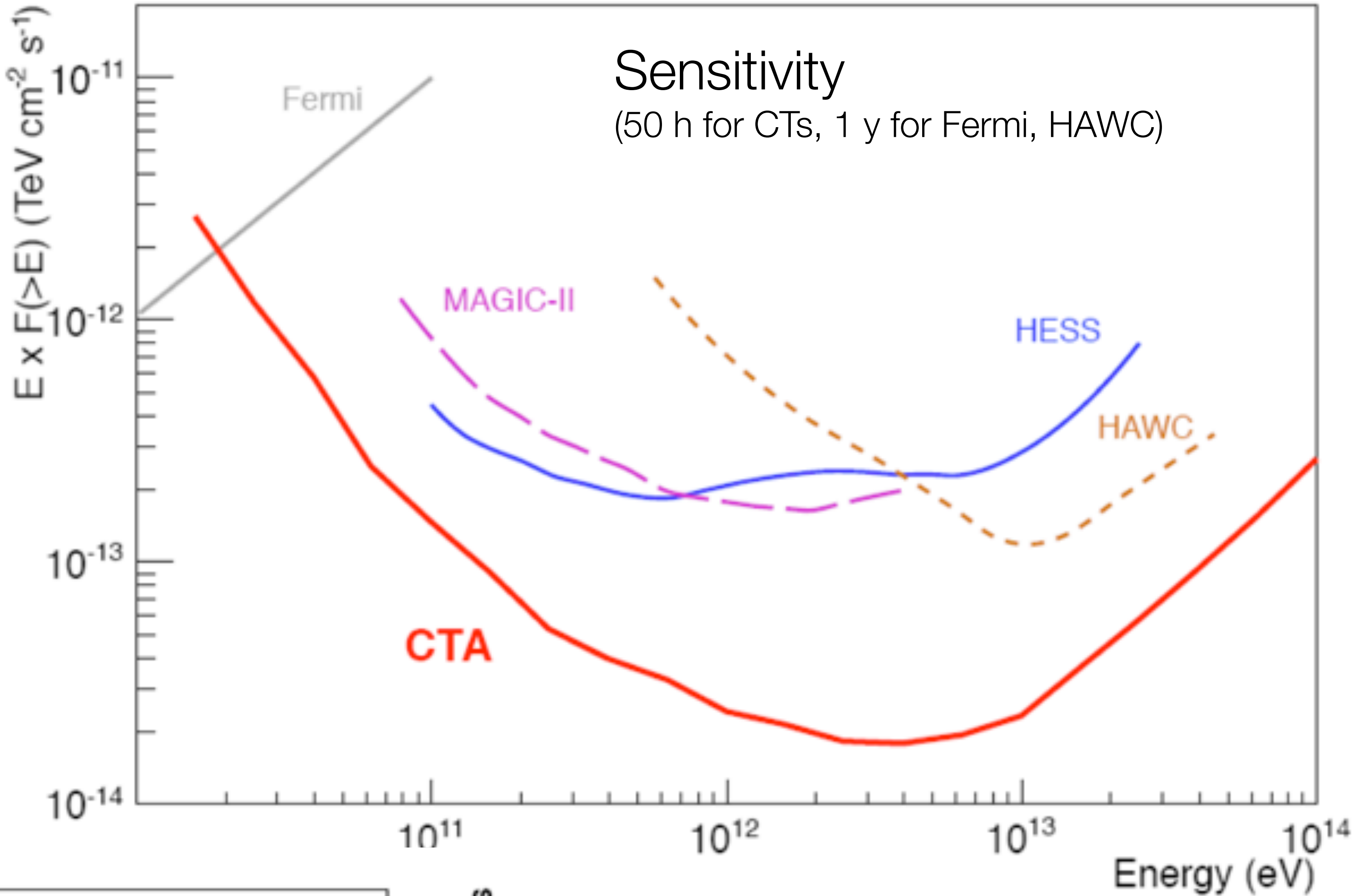
Sensitivity

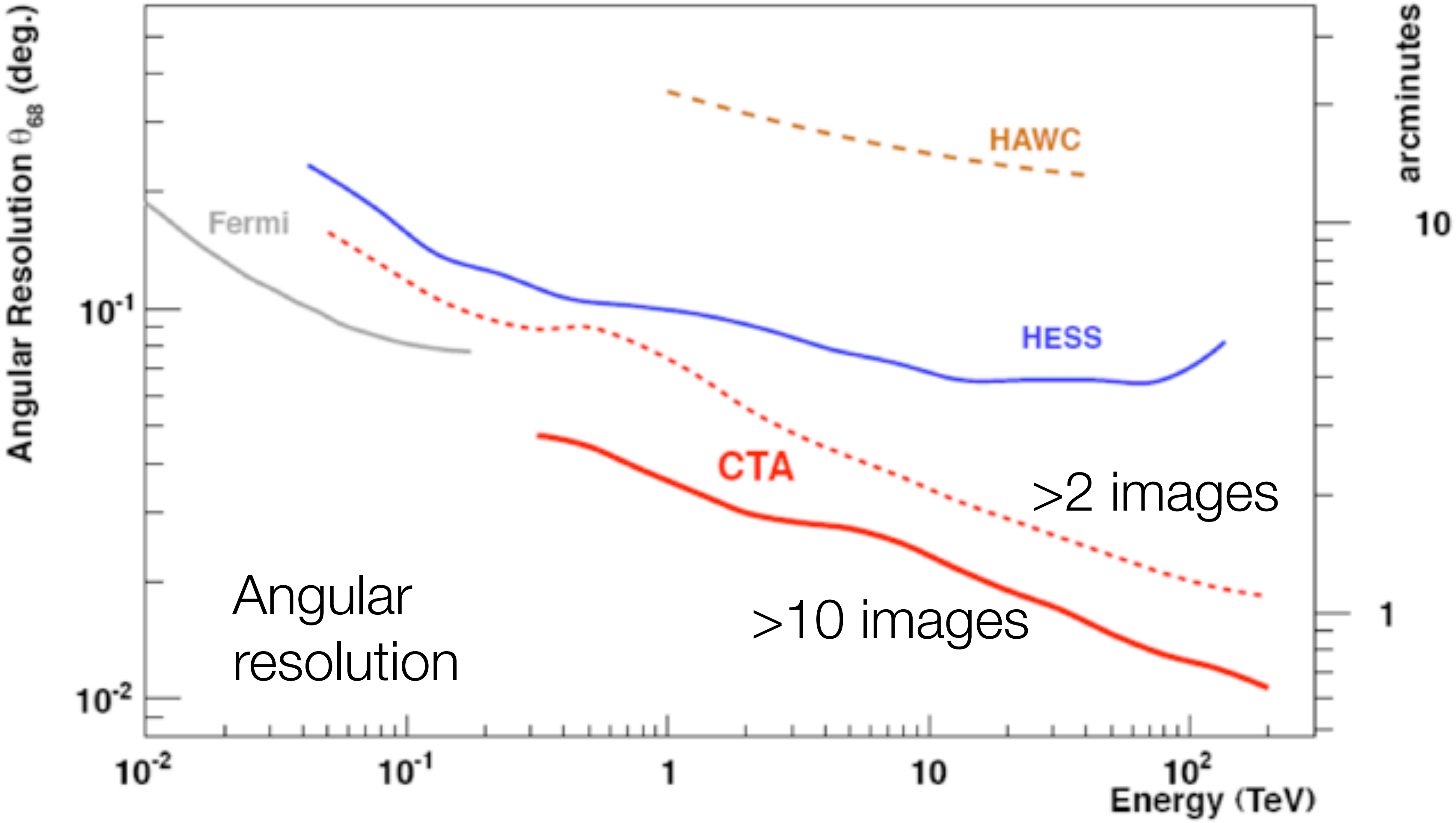


Bernlöhr et al., Aph 43, 171 (2013)

Performance

Significant improvements due to new analysis algorithms


Sensitivity
(50 h for CTs, 1 y for Fermi, HAWC)



Up to factor 10 compared to HESS or MAGIC

Arc-minute scale angular resolution at high energies

Physics ahead

Very subjective highlights

Unique science goals with CTA

Unique in the sense that no other instrument
has a similar ability in the same energy regime.

- SURVEY
    - The ability of producing the deepest surveys of the sky (with unprecedented angular and energy resolution, and energy coverage) at gamma-ray energies
- TIME DOMAIN
    - The ability to perform the first sensitive observation of short timescale phenomenology at gamma-ray energies

Which surveys is CTA required to provide and why?

- Galactic plane survey (GPS)
  - More than half of known VHE sources in the plane ($|b|<1.5^\circ$)
  - Most extended and non-variable (SNRs, PWNe)
  - Limited area to cover, homogeneous dataset

Objective: $|l|<60^\circ$ & $|b|<2^\circ$ in 240h at uniform sensitivity of ~3mCrab

(HESS survey: 1500h over $l \in [-90^\circ;60^\circ]$ sensitivity ranging in 20-85mCrab)

population studies, dark accelerators, target identification, CR-ISM diffuse, serendipity

- Allsky survey
  - CTA can improve on surveys by water Cherenkov arrays (except variability)
  - Such blind survey never done before by ACTs

Objective: 1/4th sky in ~300h at uniform sensitivity ≥100GeV of ~20mCrab

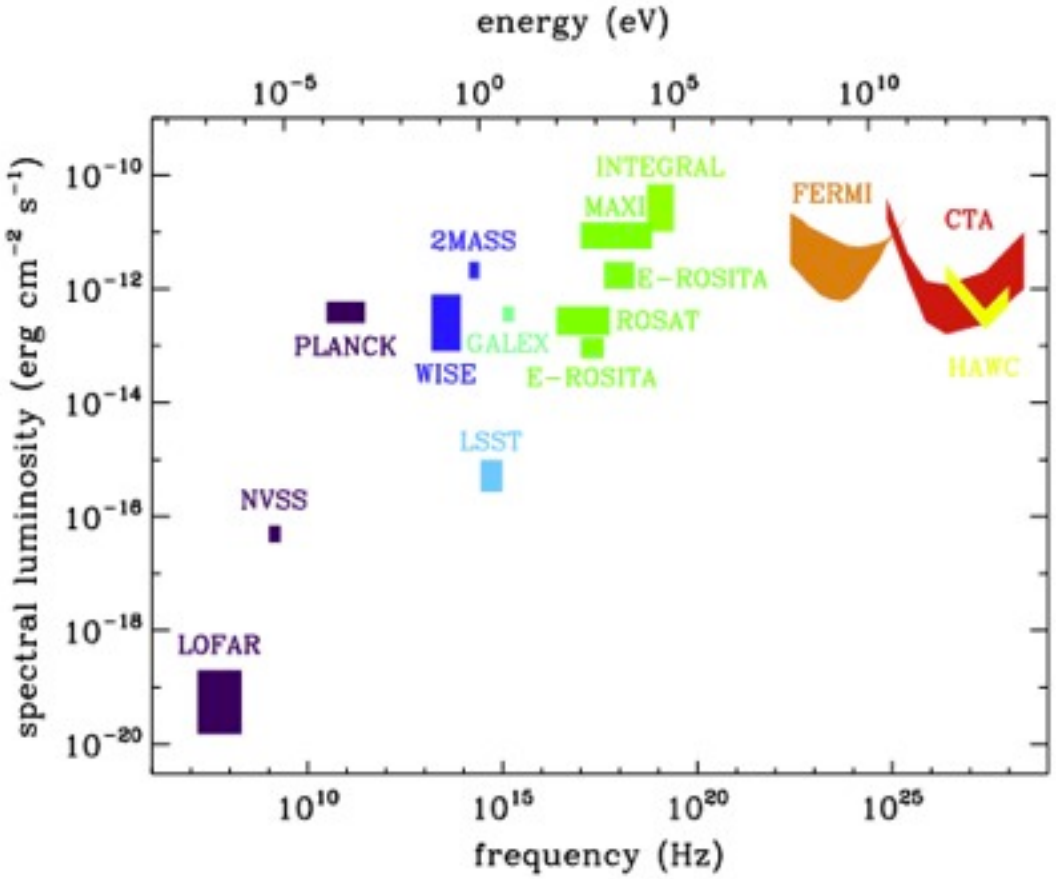
(Milagro: 300-600mCrab >1TeV in 3yrs. HAWC: 50mCrab >1TeV in 1yr with 1° ang. res.)

AGN census, Galactic wind/halo/cloudlets, dark matter subhalos, new objects

Uniqueness of possible surveys with CTA

- The deepest ever Galactic plane survey, with sensitivity comparable to the longest pointings made for any source

- The first extragalactic survey at these energies (blind, (at least) 1/4th of the sky survey of regions out of the Galactic plane); with sensitivity comparable to the faintest AGN currently detected at VHE



CTA:
Top: Blind, extragalactic
Bottom: Galactic

Fermi-LAT:
Top: 10 years Galactic
Bottom: 10 years, Extragalactic

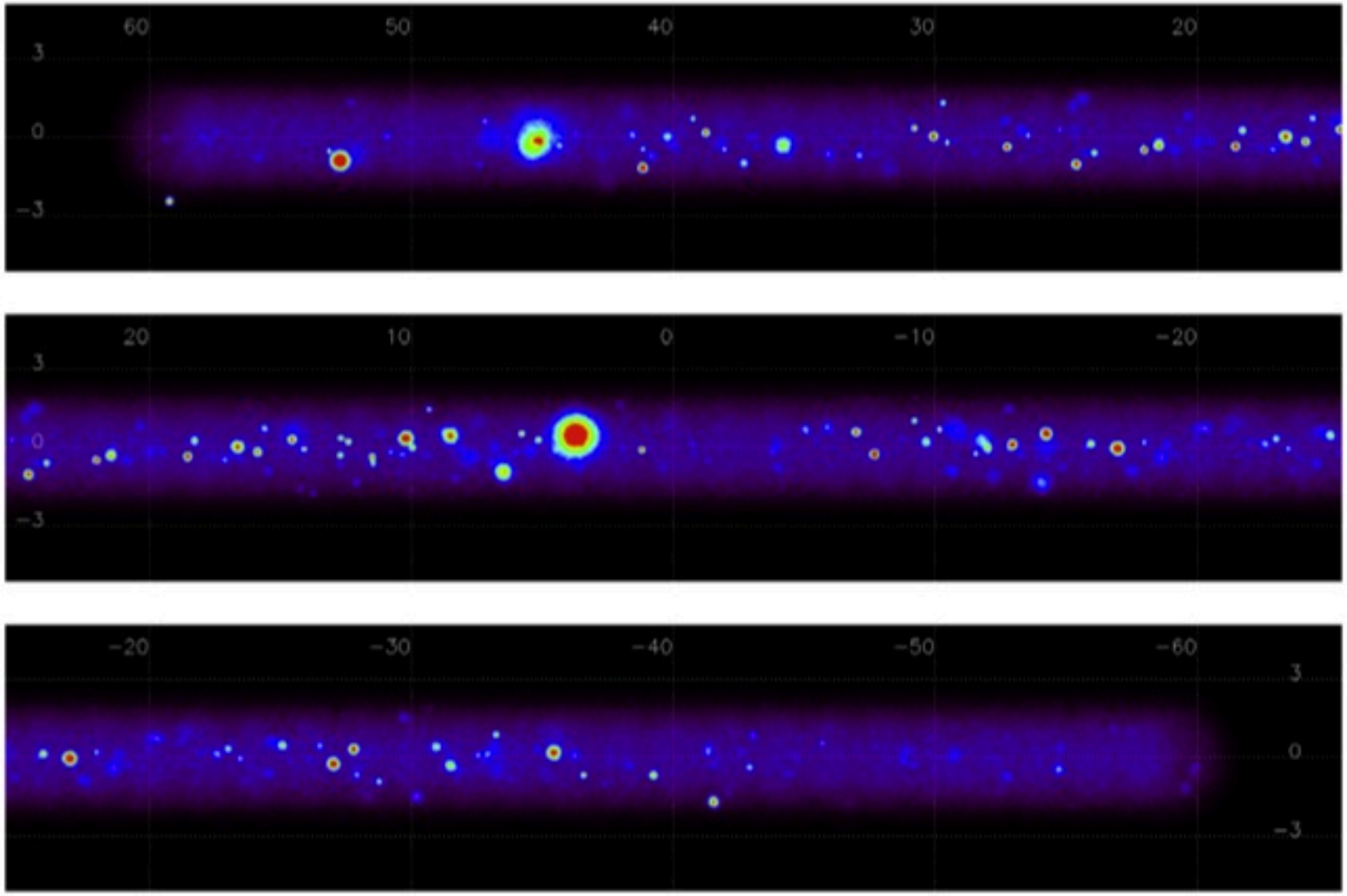
CTA required sensitivity probes fluxes comparable to the best X-ray or IR all-sky surveys.

Dubus et al., Aph 43, 317 (2013)

Surveys specifications put as examples

These are examples well within observational constraints (e.g. duty cycle)

- surveys can be extended in coverage
- surveys can be repeated in time

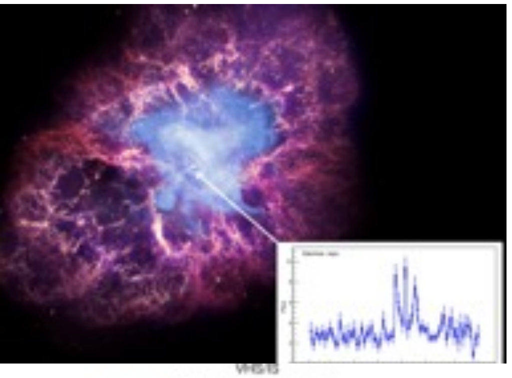


For instance in 2000 hours CTA can reach 1mCrab sources (better than any pointed observation conducted up to now).

In the plot, 500 PWNe as would be seen by CTA in the Galactic survey.

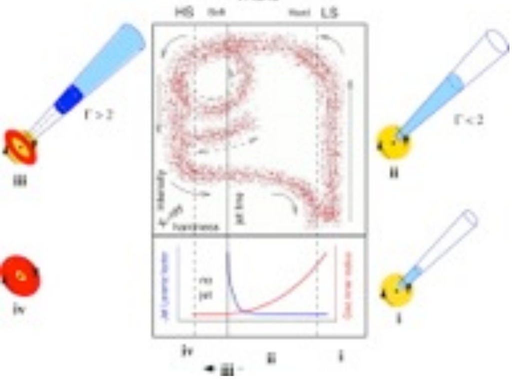
Dubus et al., Aph 43, 317 (2013)

Opening up short timescales in VHE astronomy



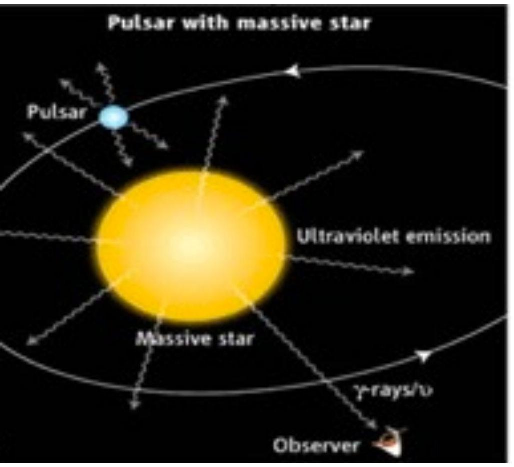
- Flares from pulsar nebulae?

  (Crab-flare-like phenomenology: What happens at high energies?)



- Observing the accretion-ejection interface?

  (possible counterparts of radio and X-ray transitions in binaries)

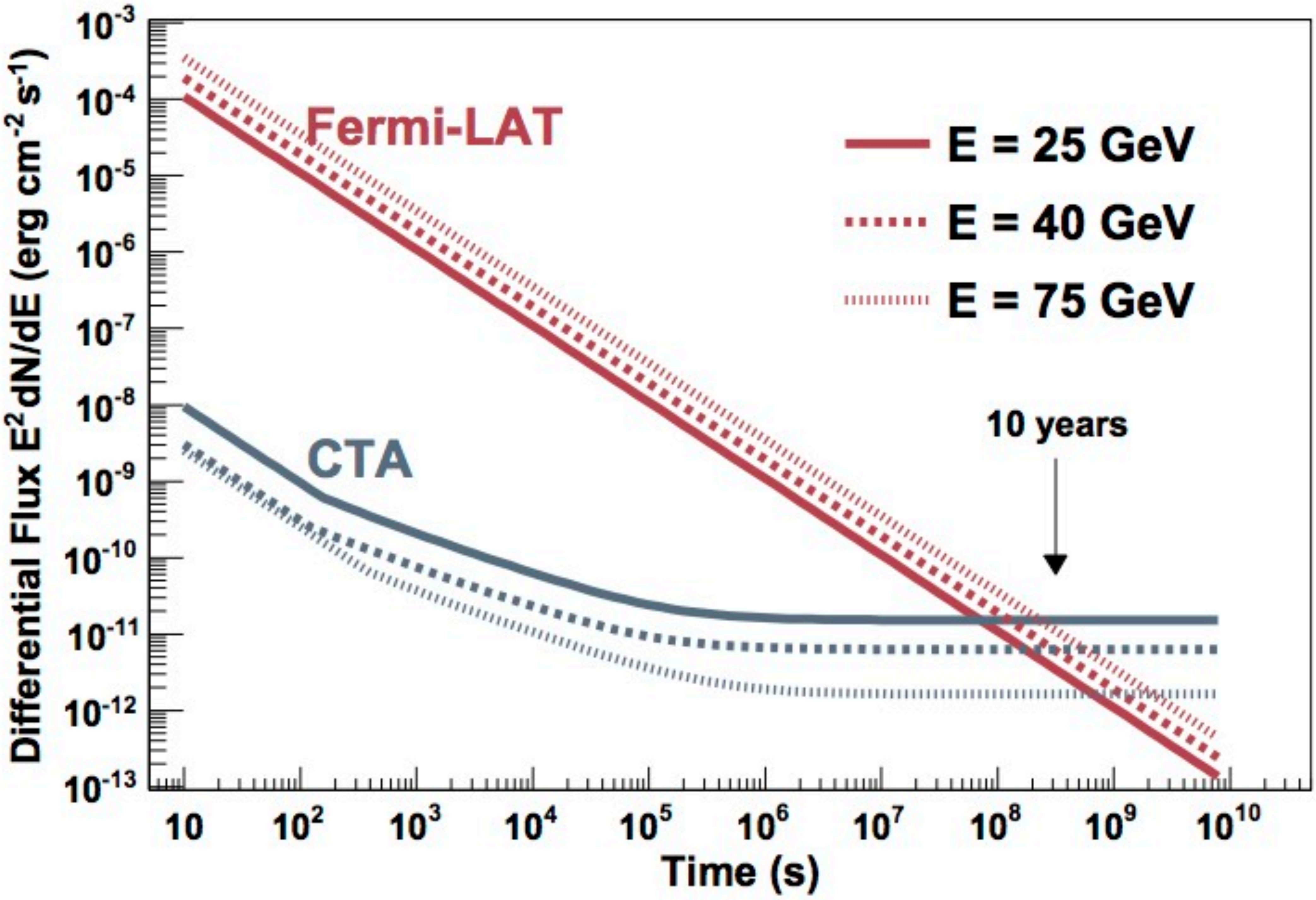


- Formation of relativistic outflows from highly magnetized binaries?

  (short timescale phenomenology/orbital changes in gamma-ray bin.)

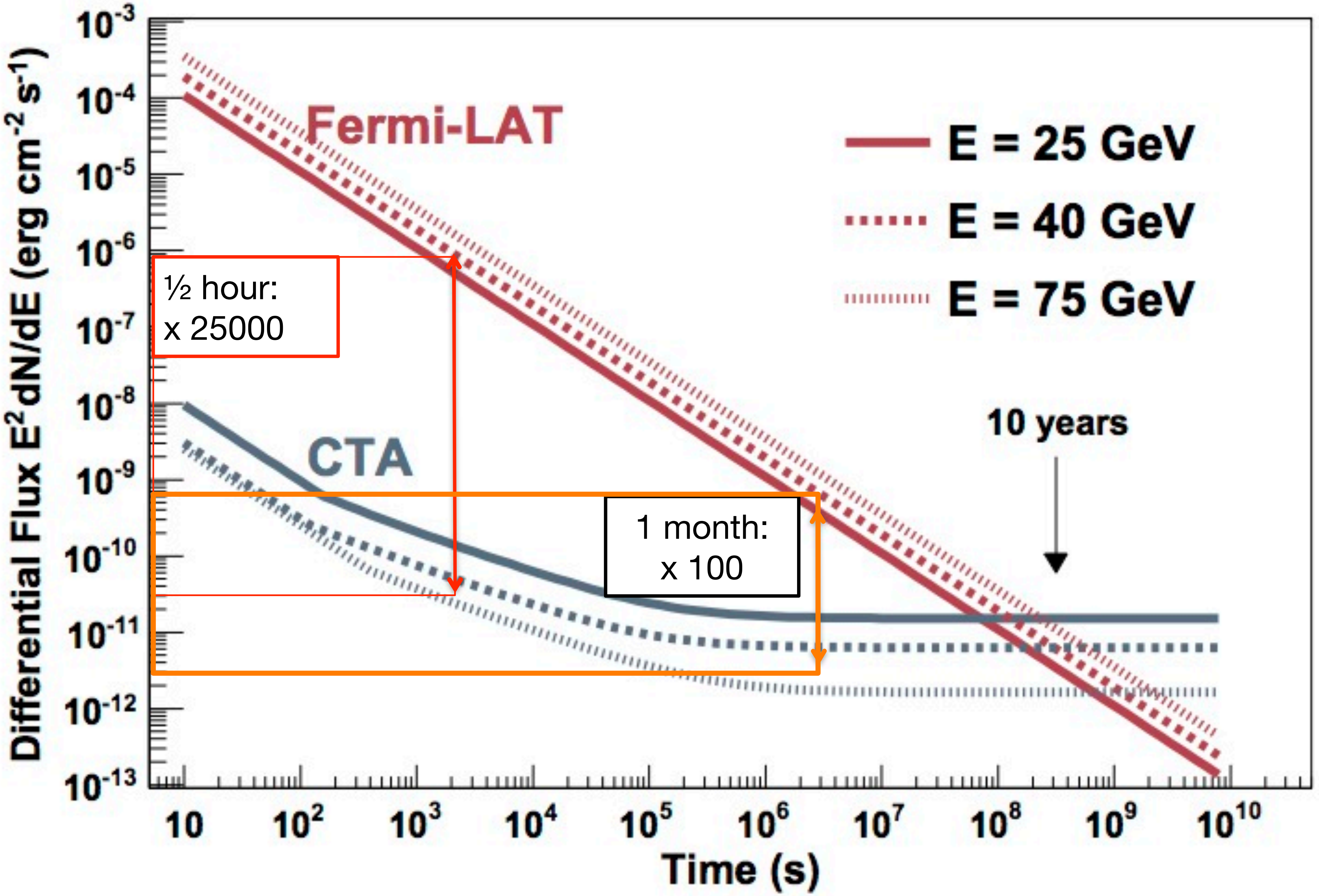
- Short timescale variability from black holes beyond the galaxy & GRBs

As a function of event duration / integration time



Funk & Hinton, Aph 43, 348 (2013)

As a function of event duration / integration time

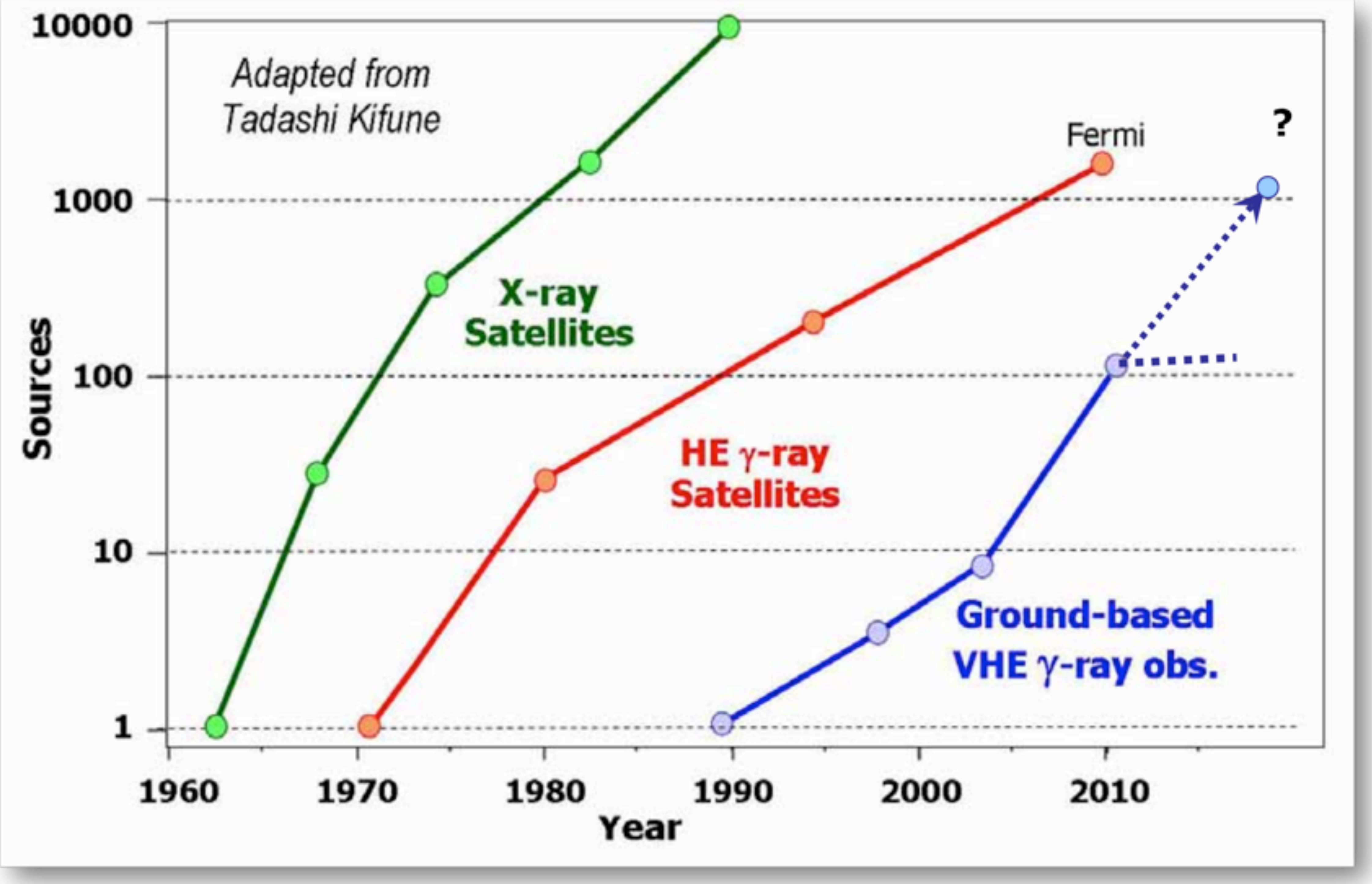


- On short time scales CTA is incredibly good
- Mind the gaps:
  - Fermi/LAT observes every source for **0.5h/3h**
  - CTA will observe a source (within 30% of the sky) up to **5h/24h**
- Bad weather and strong moon reduce observability with CTA

Funk & Hinton, Aph 43, 348 (2013)

Number of sources

Kifune plot



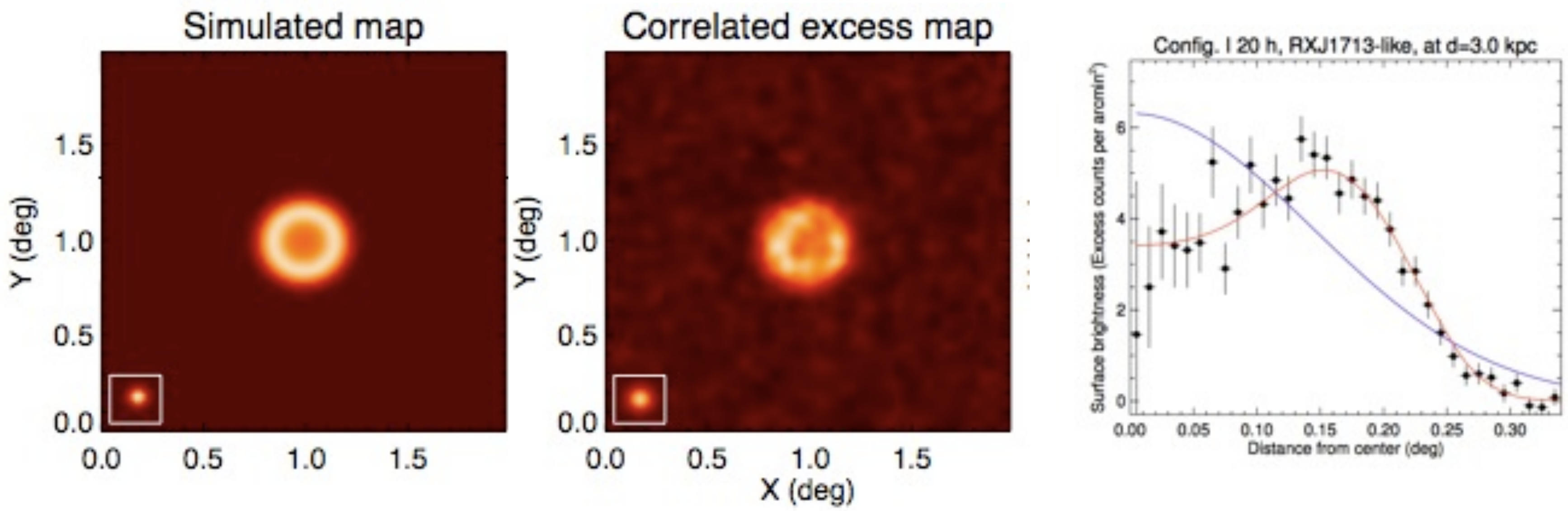
Selected physics cases

Very subjective highlights

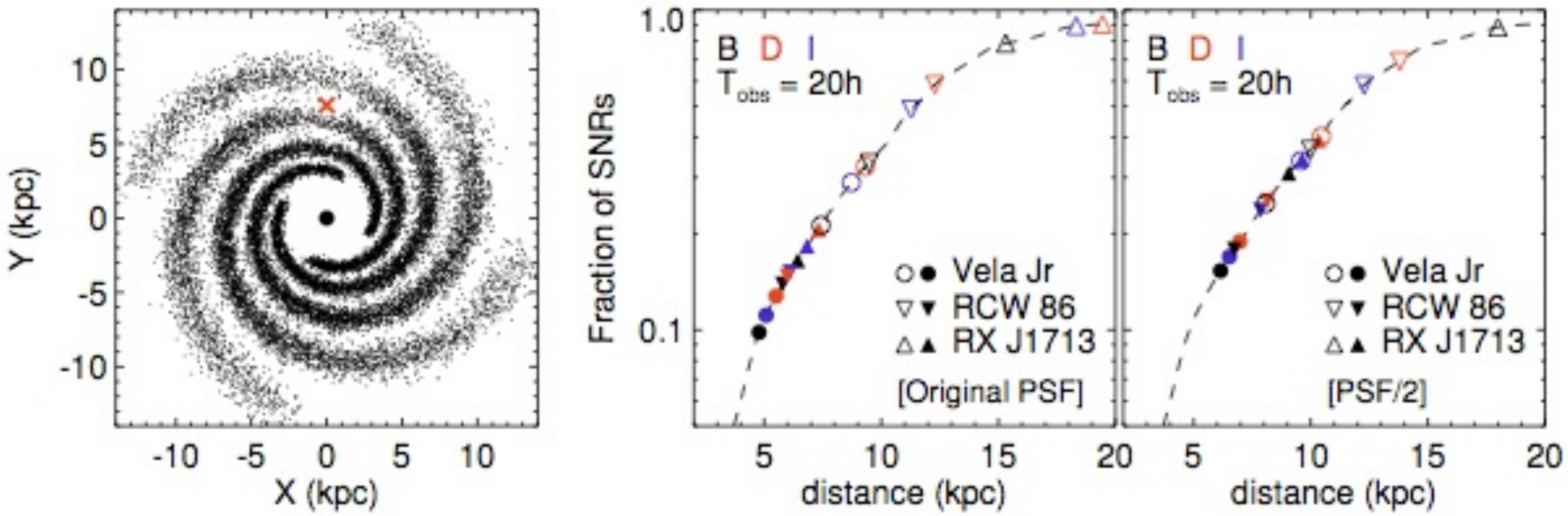
Cosmic ray accelerators

Acero et al., Aph 43, 276 (2013)

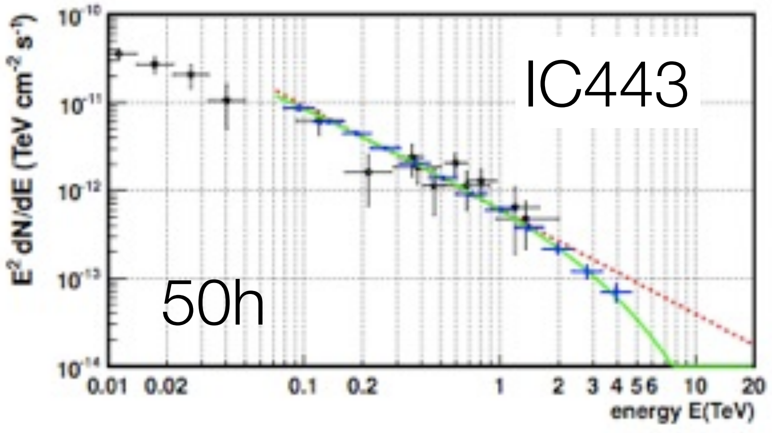
- Through much better imaging (angular resolution)

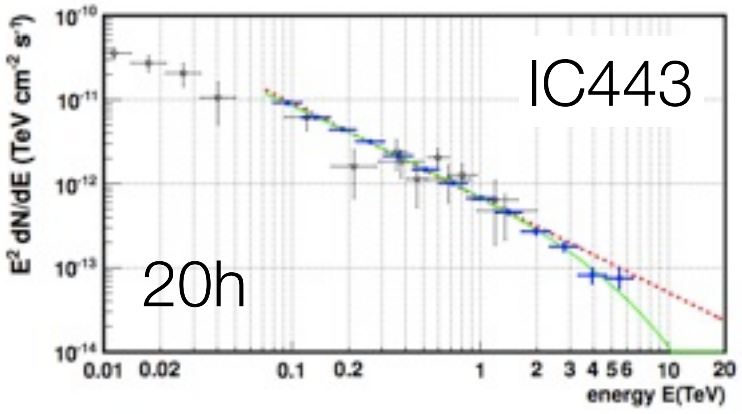


- Through detecting all bright SNR in the galaxy and resolving many



- Through spectral studies (e.g. finding energy cutoffs)

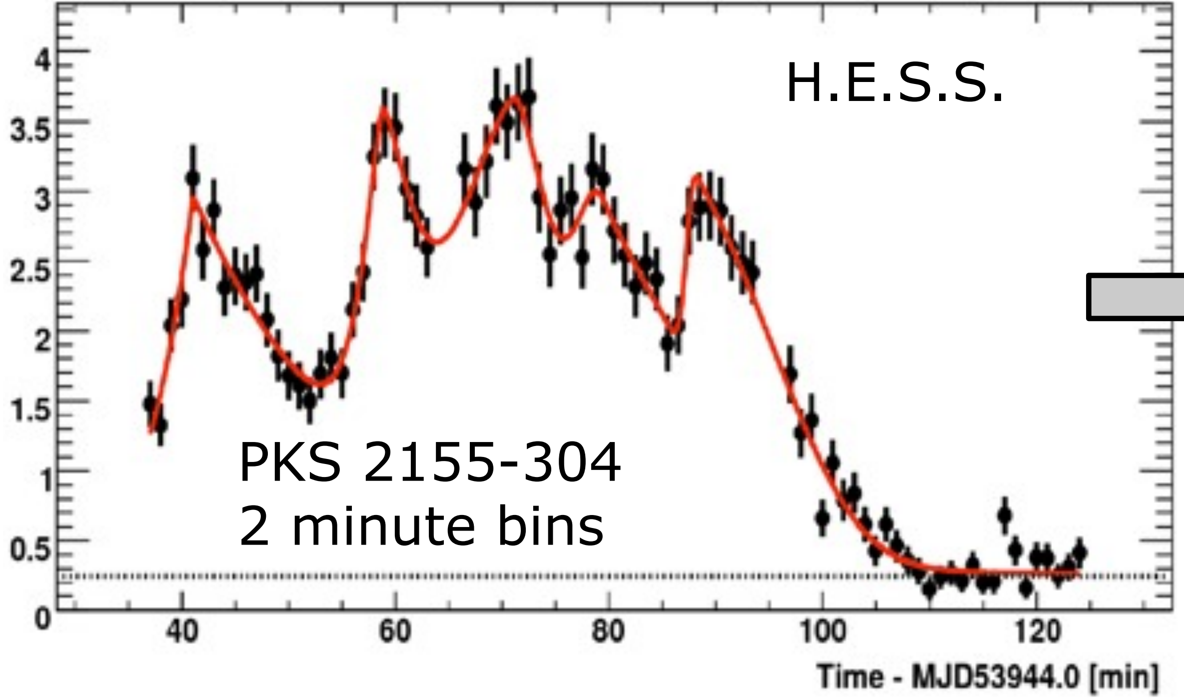




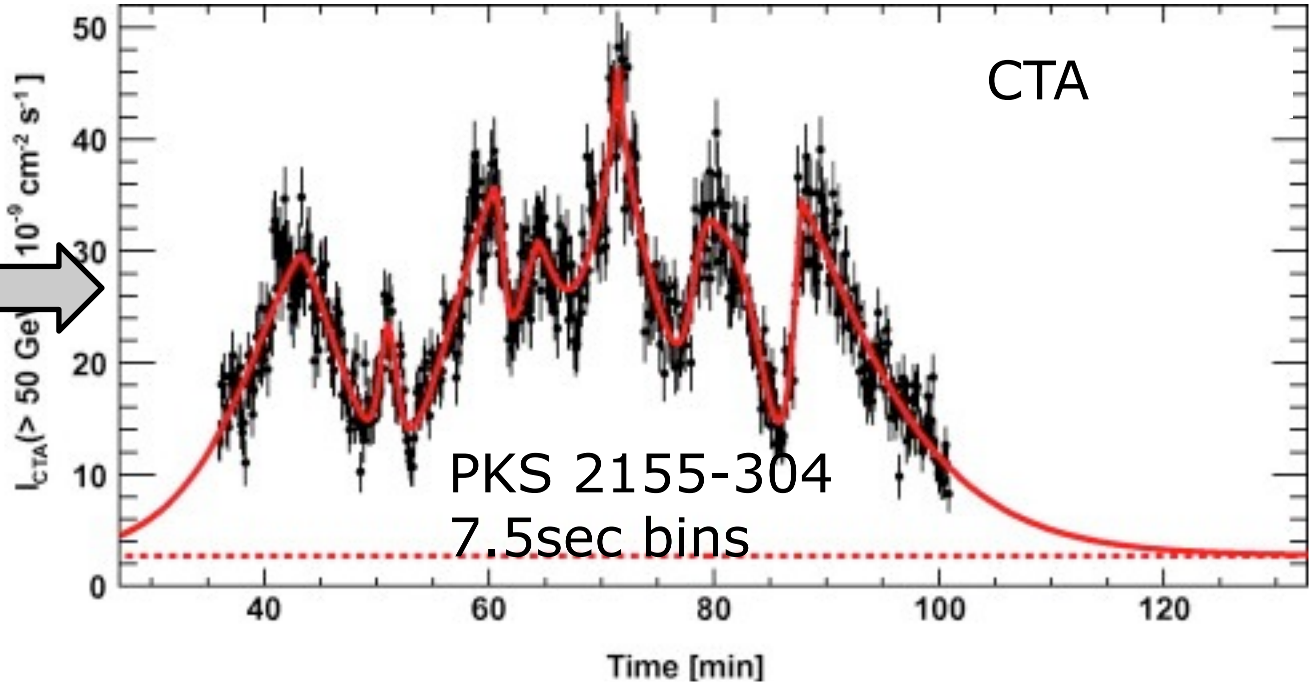
AGNs and GRBs (fast variability!!)

- Expect a quantitative jump in: Population studies, detecting sources at z>2, enormous progress in modeling of the emission, origin of variability

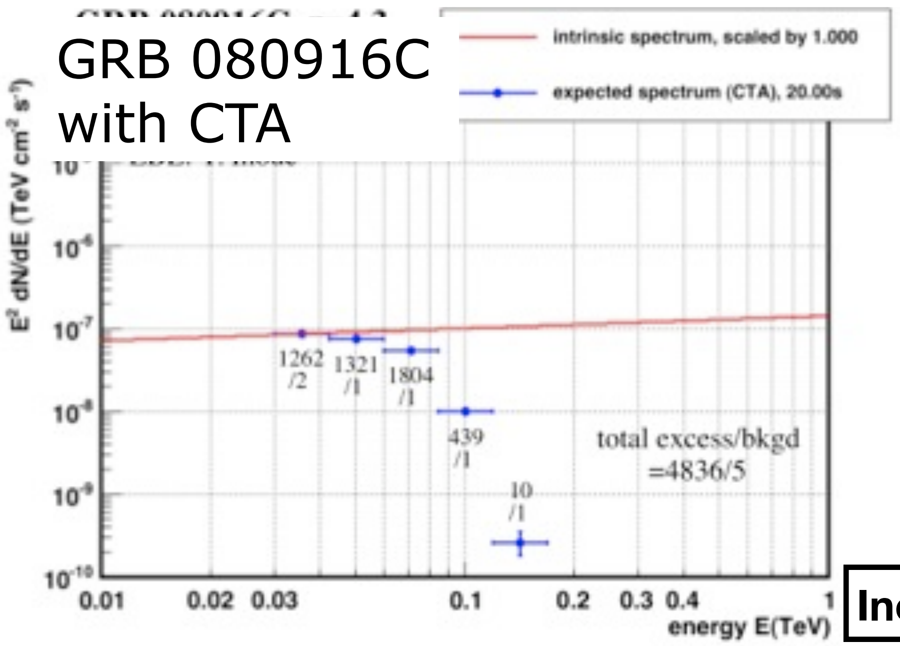
Sol et al., Aph 43, 215 (2013)

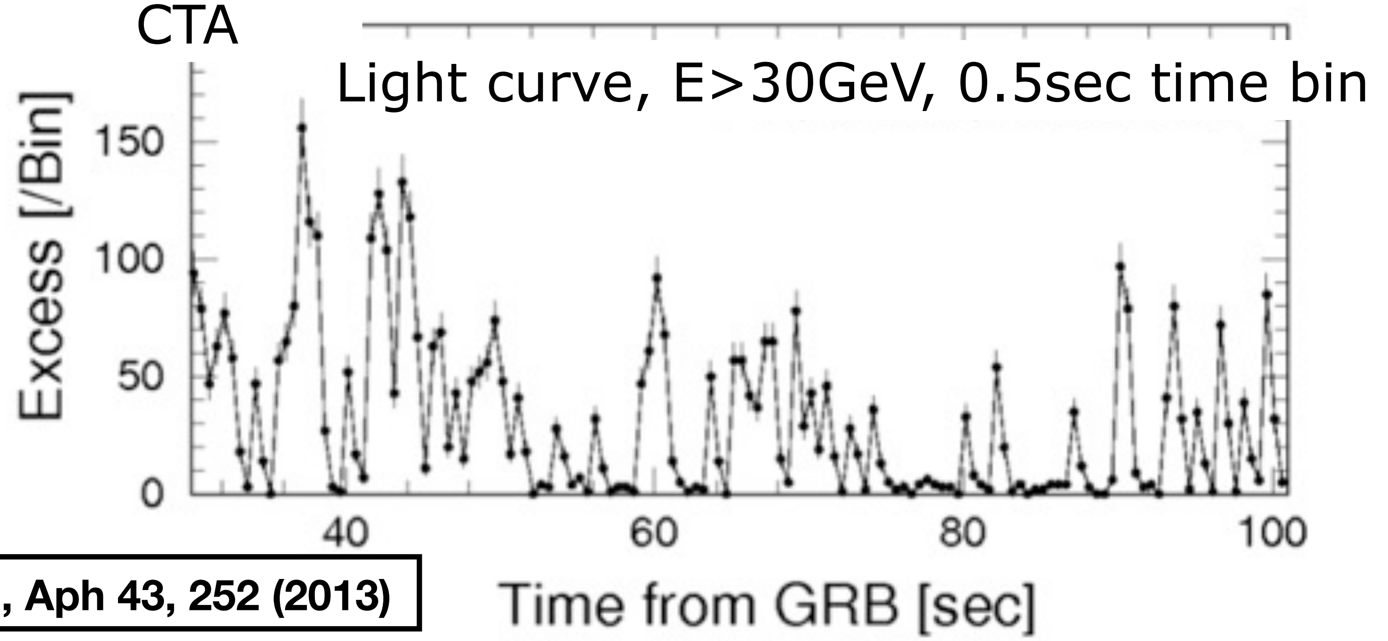

H.E.S.S.

PKS 2155-304
2 minute bins


CTA

PKS 2155-304
7.5sec bins


GRB 080916C
with CTA

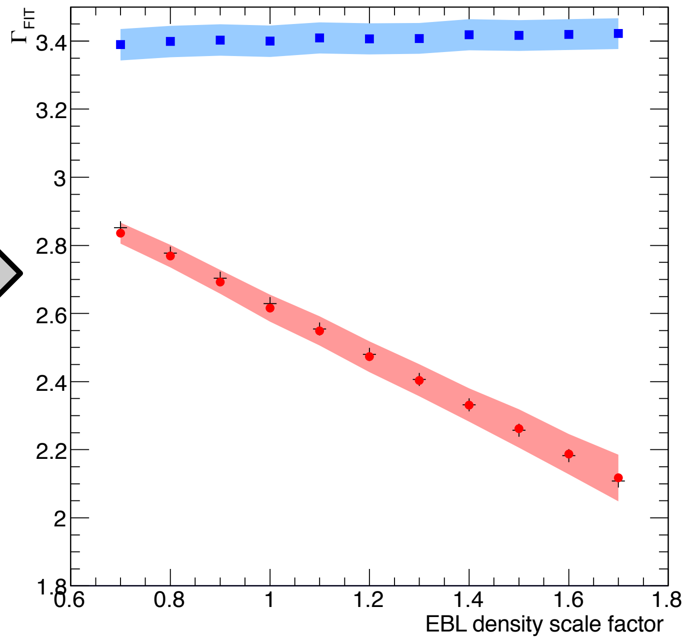

CTA

Light curve, E>30GeV, 0.5sec time bin

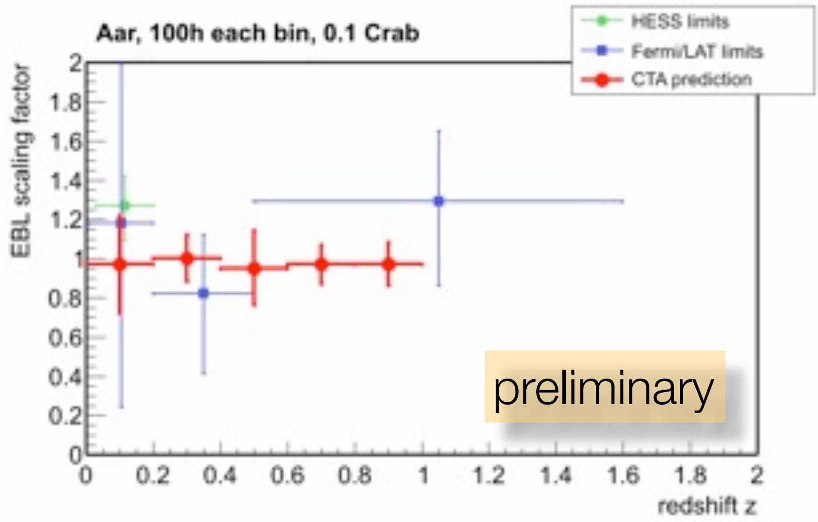
Inoue et al., Aph 43, 252 (2013)

Extragalactic Background light and Cosmology

- Simultaneous measurement of absorbed and unabsorbed parts of the energy spectrum

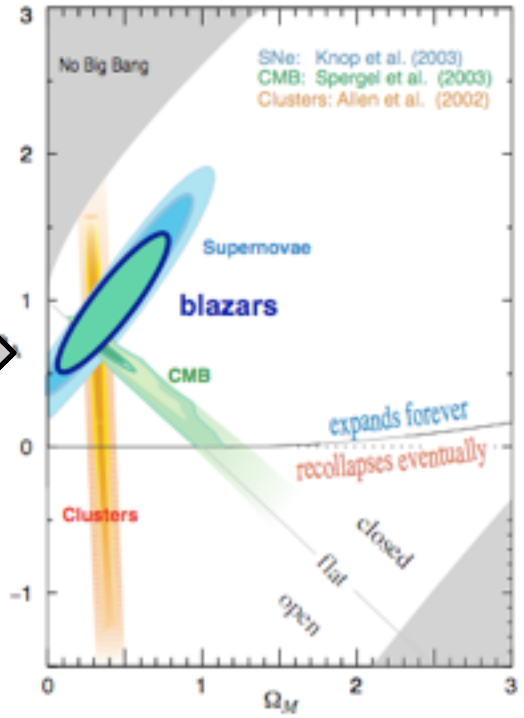


Mazin et al., Aph 43, 241 (2013)



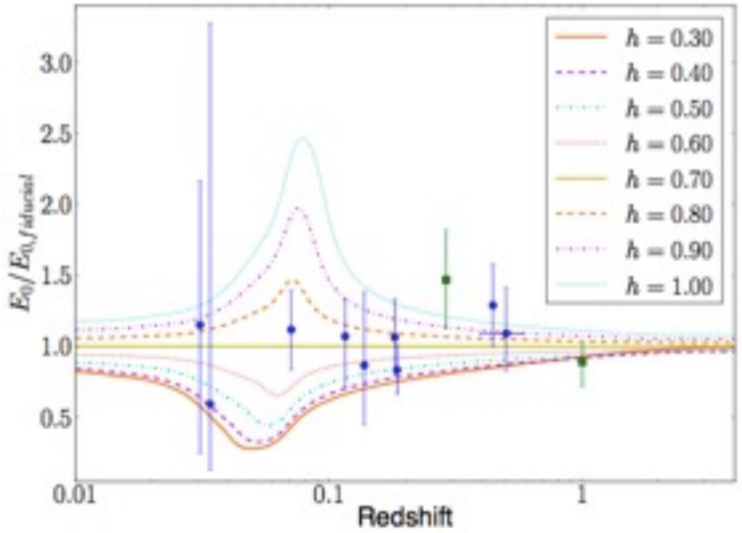
- Measuring EBL through resolved spectral features

- Once EBL is measured, use it to independently measure distance to sources and test cosmological model



Dominguez&Prada, ApJ 771, L34 (2013)

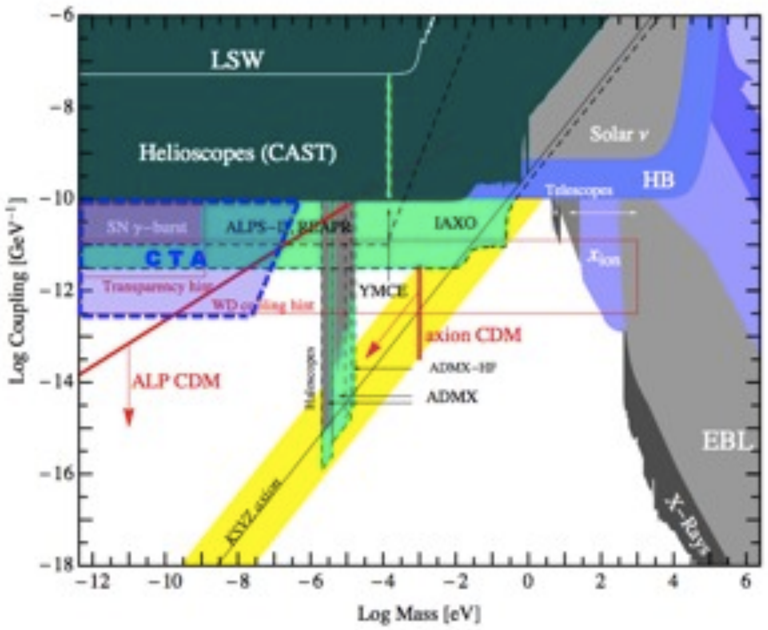
Hubble constant

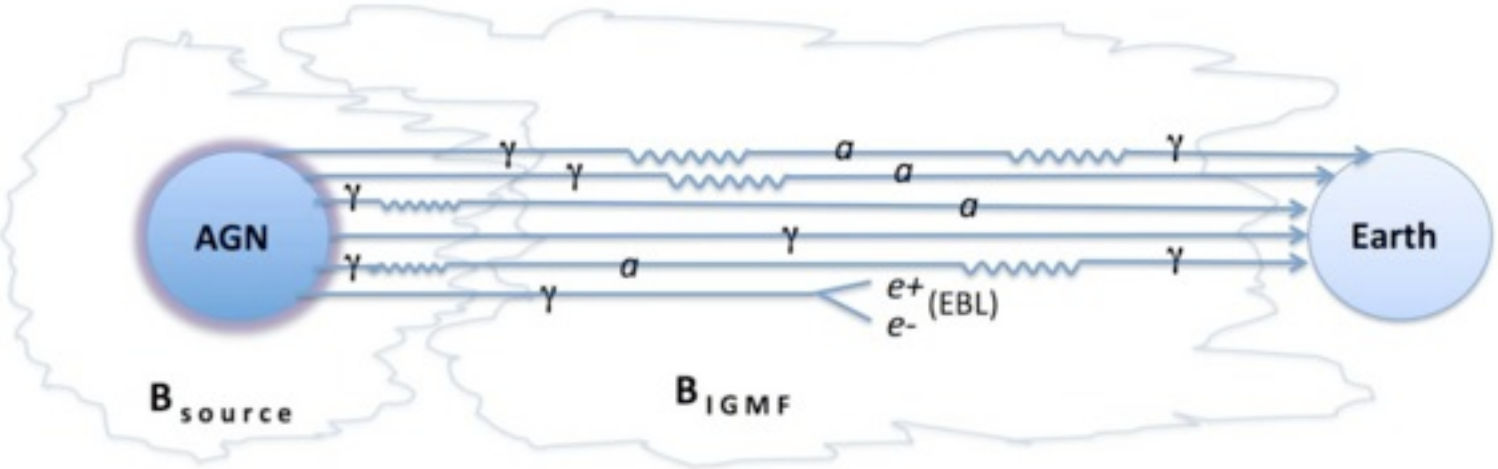


Fundamental physics

- Search of axion-like particles

Sanchez-Conde et al., arXiv:1305.0252

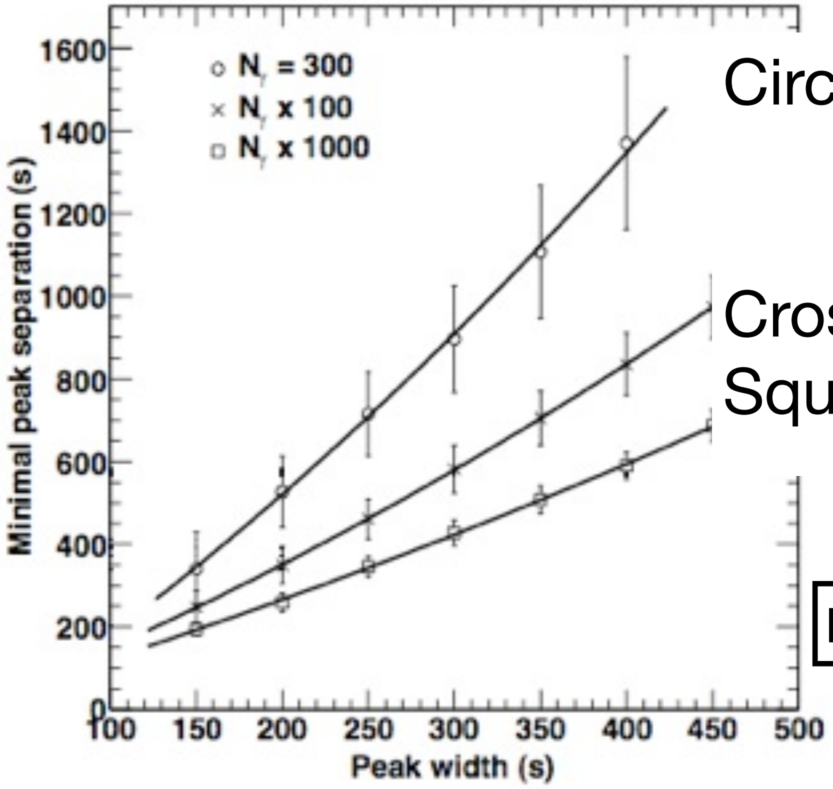




- High Energy Violation of Lorentz Invariance

$$\Delta t \simeq \left(\frac{\Delta E}{\xi_\alpha E_{\rm Pl}}\right)^{\alpha} \frac{L}{c}$$

with α=1 or 2



Circle: HESS-like

Crosses: CTA
Square: ideal

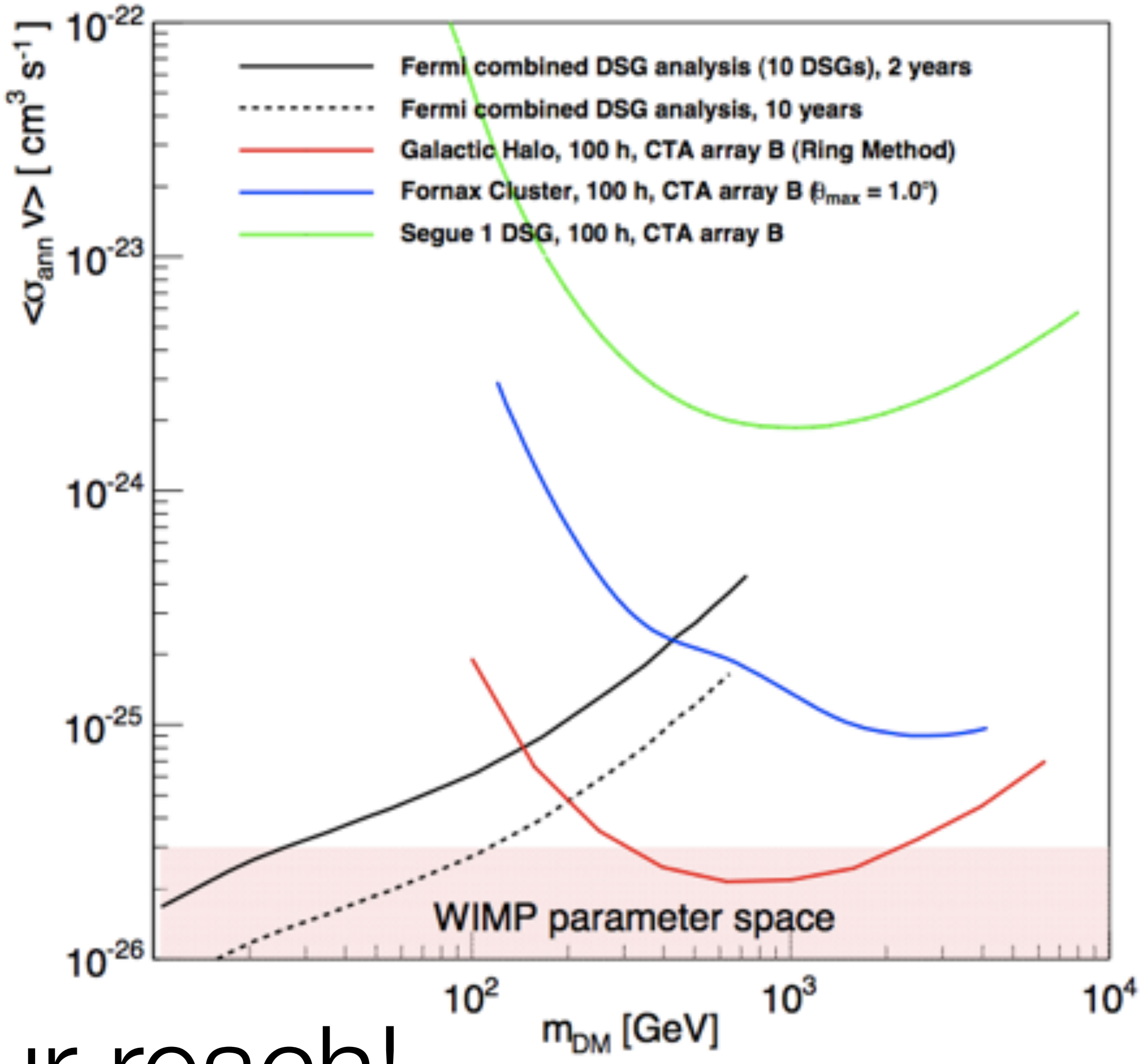
Doro et al., Aph 43, 189 (2013)

Dark matter

$$\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma} = \mathrm{B_F} \cdot \frac{1}{4\pi} \underbrace{\frac{\langle\sigma_{\mathrm{ann}} v\rangle}{2\, m_\chi^2} \sum_i \mathrm{BR}_i \frac{\mathrm{d}N_\gamma^i}{\mathrm{d}E_\gamma}}_{\textit{Particle Physics}} \cdot \underbrace{\widetilde{J}(\Delta\Omega)}_{\textit{Astrophysics}}$$

Many candidates to look at:

- Dwarf galaxies
- Galaxy clusters
- Galactic halo (most promising?)
- Galactic center



Might well be within our reach!

Doro et al., Aph 43, 189 (2013)

Status and plans

Design study phase concluded in Fall 2010

➜ Design Concepts for the Cherenkov Telescope Array (arXiv:1008.3703)

FP7-supported Preparatory Phase: Fall 2010 – Summer 2014

➜ Technical design, sites, construction and operation cost

➜ Legal, governance and finance schemes

➜ Small + medium-sized telescope prototypes

Aim for

- site decision early 2014
- start of construction in 2016
- first data in 2017/18
- base arrays complete in late 2018