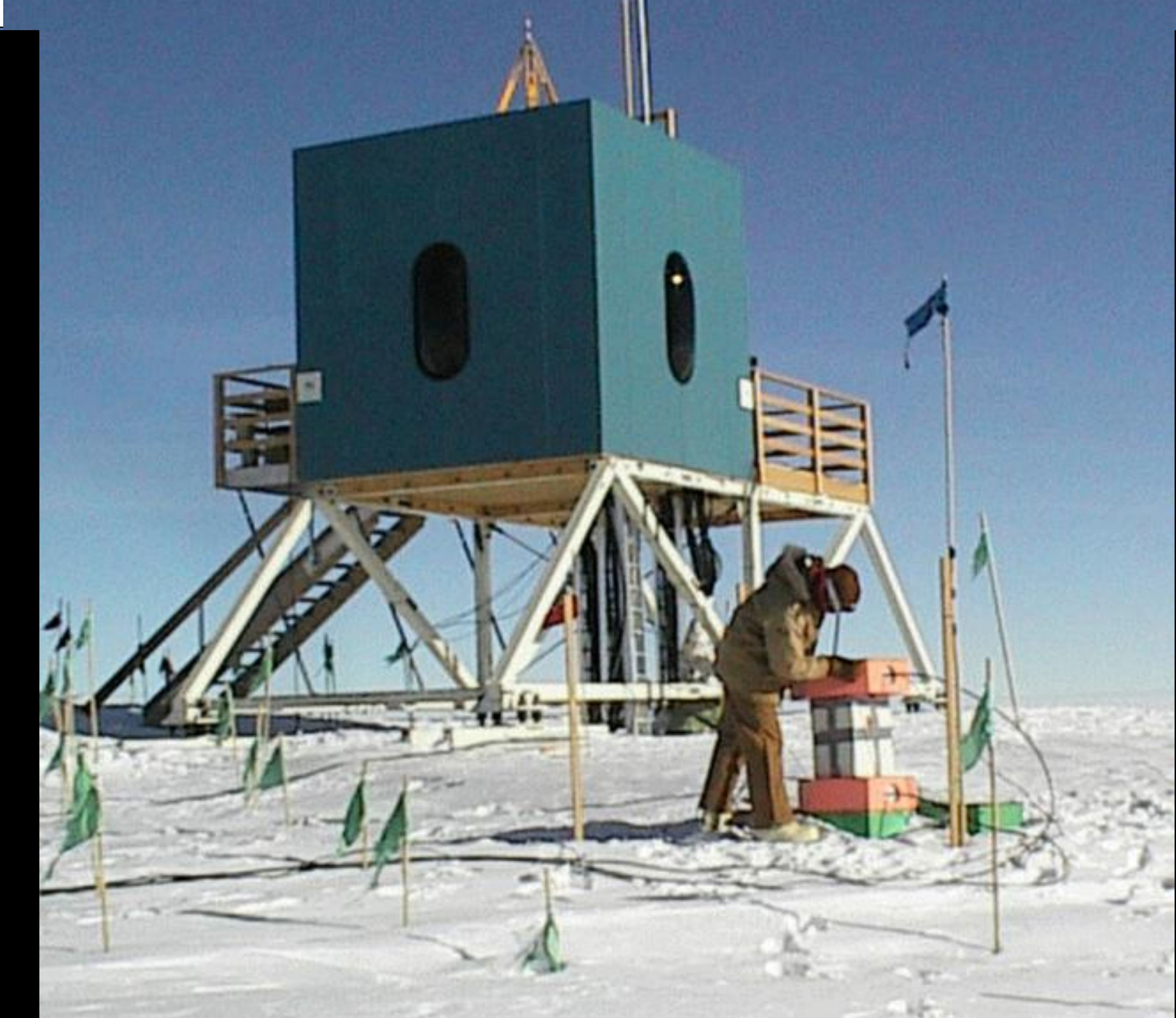


Ground-based Gamma-ray Astronomy

Jim Hinton
University of Leicester, UK

1st CAPPA School, Dublin, 8th July 2011

Outline

First Part

- Motivation
- Techniques
- Current Instruments

Second Part

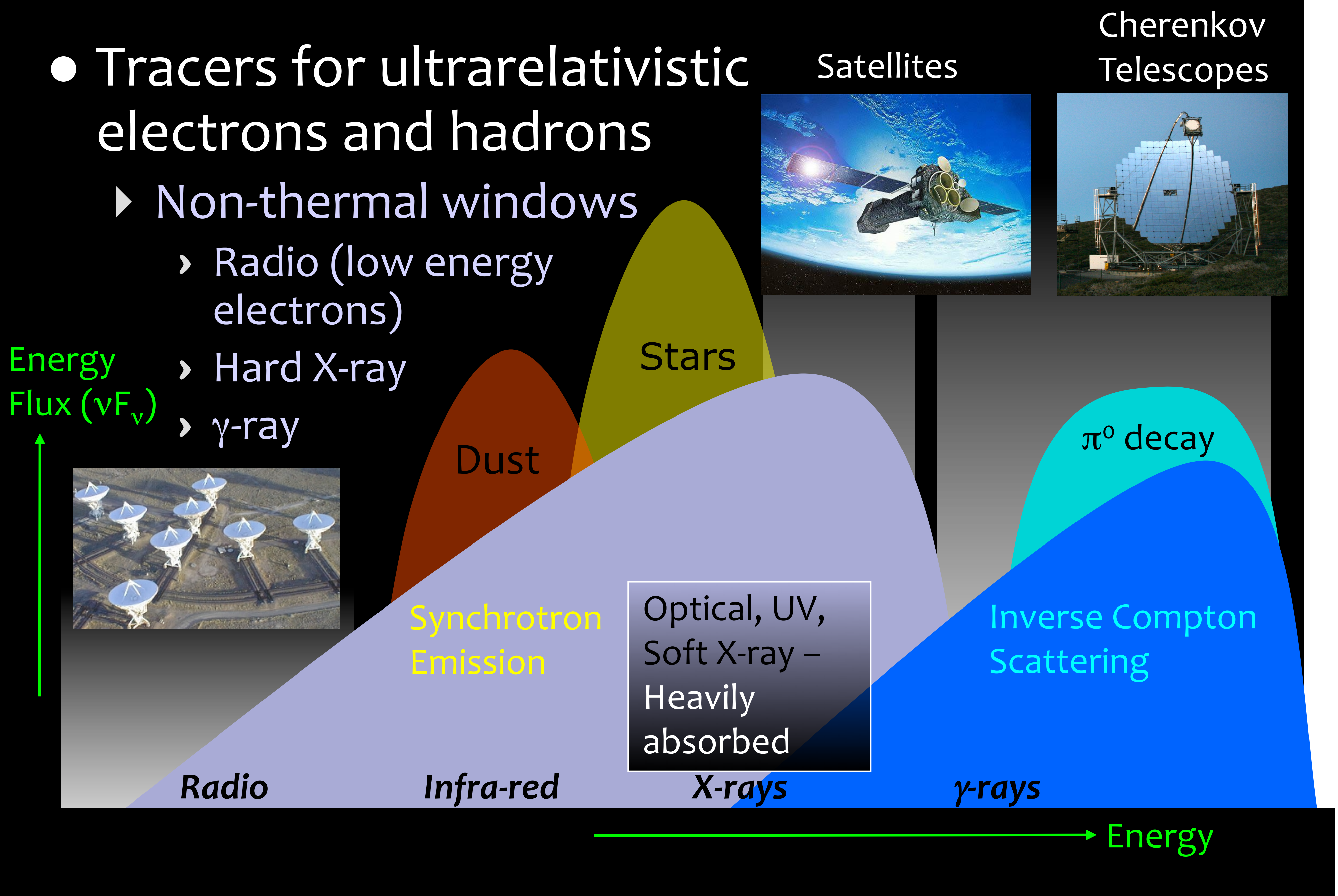
- The TeV Sky
- The Future

Why Ground-based?

- To do astronomy at the highest (photon) energies with high statistics
  - Typical flux ~10^{-12} erg cm^{-2} s^{-1} :
    - ~1 photon/day/m^2 @1 GeV
    - ~0.2 photons **per year per m^2** @ **1 TeV**
    - (or ~20 per **hour per km²**)
- Why?
  - Establish the origin and role of ultra-relativistic particles in astrophysical environments
  - Fundamental physics (LIV, DM, …)
  - Frontier astrophysics (discoveries!)

The ‘Non-Thermal Windows’

- Tracers for ultrarelativistic electrons and hadrons
  - Non-thermal windows
    - Radio (low energy electrons)
    - Hard X-ray
    - γ-ray

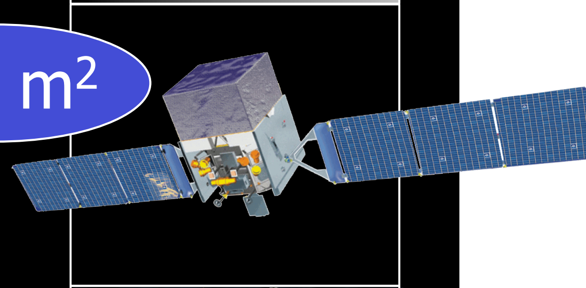


Comparison of Tracers

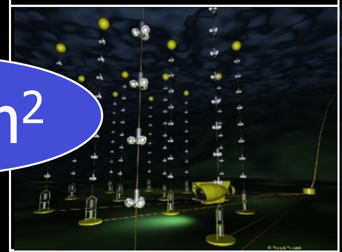
- X-rays
  - Soft X-rays still dominated by thermal emission
  - 2-10 keV band excellent resolution, very sensitive instruments
    - – but – Synchrotron emission gives information only on energetic electrons ($\times B^2$), usually small FoV
  - Hard X-ray detectors not yet as sensitive
- MeV-GeV γ-rays?
  - Hard to launch large detectors, poor angular resolution (< a few GeV), full sky coverage
- TeV Neutrinos?
  - Unambiguous, but small effective collection area (neutrino cross-section!), atmospheric background
- TeV γ-rays?
  - Large detection areas, better angular resolution…

Combination of **<u>all</u>** is extremely powerful

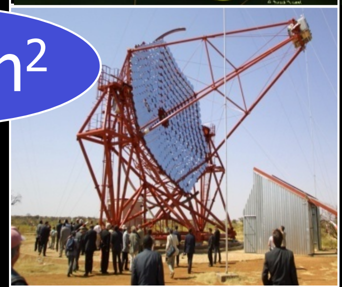
~ 1 m^2



~ 1 m^2

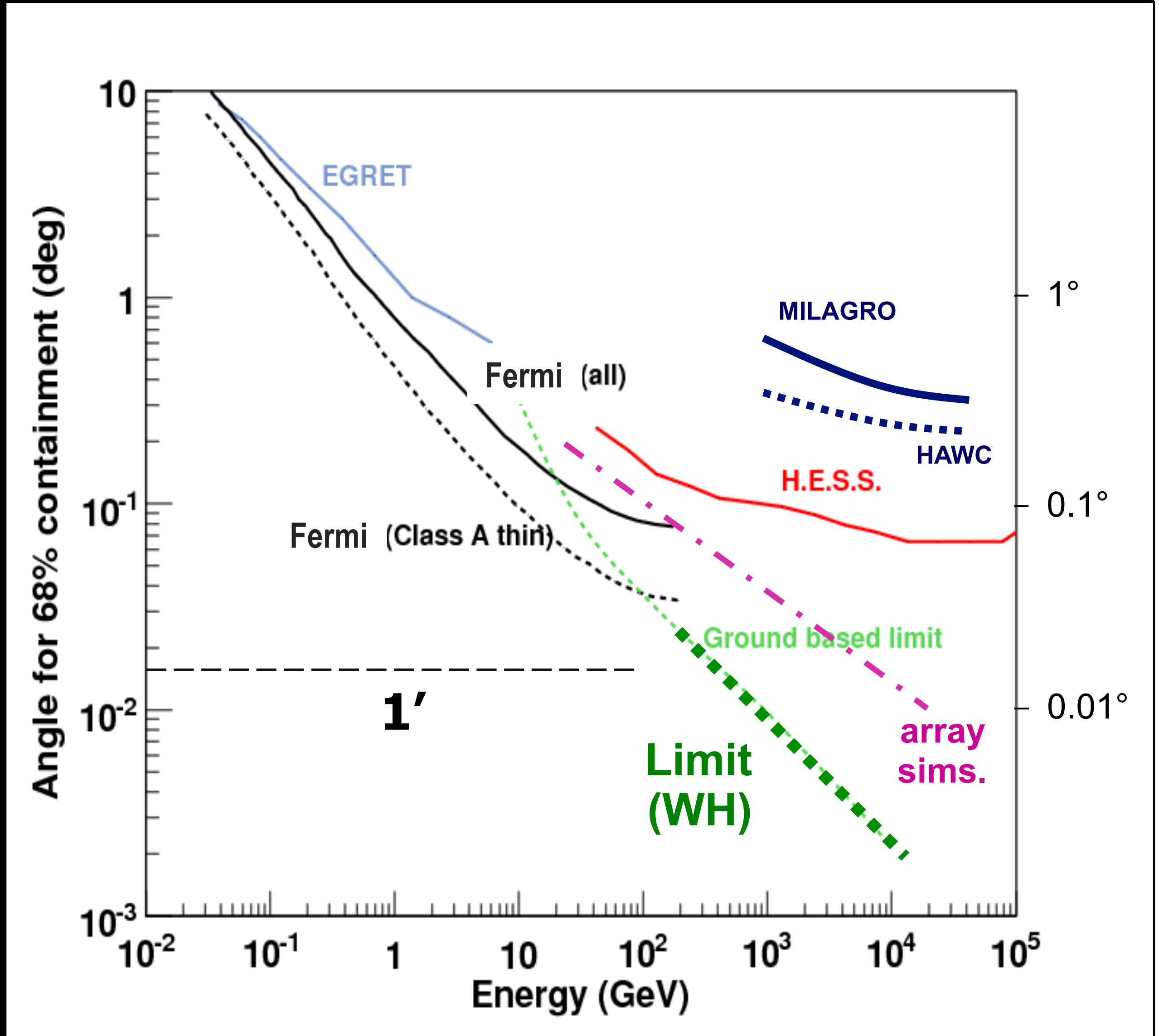


~ 1 km^2

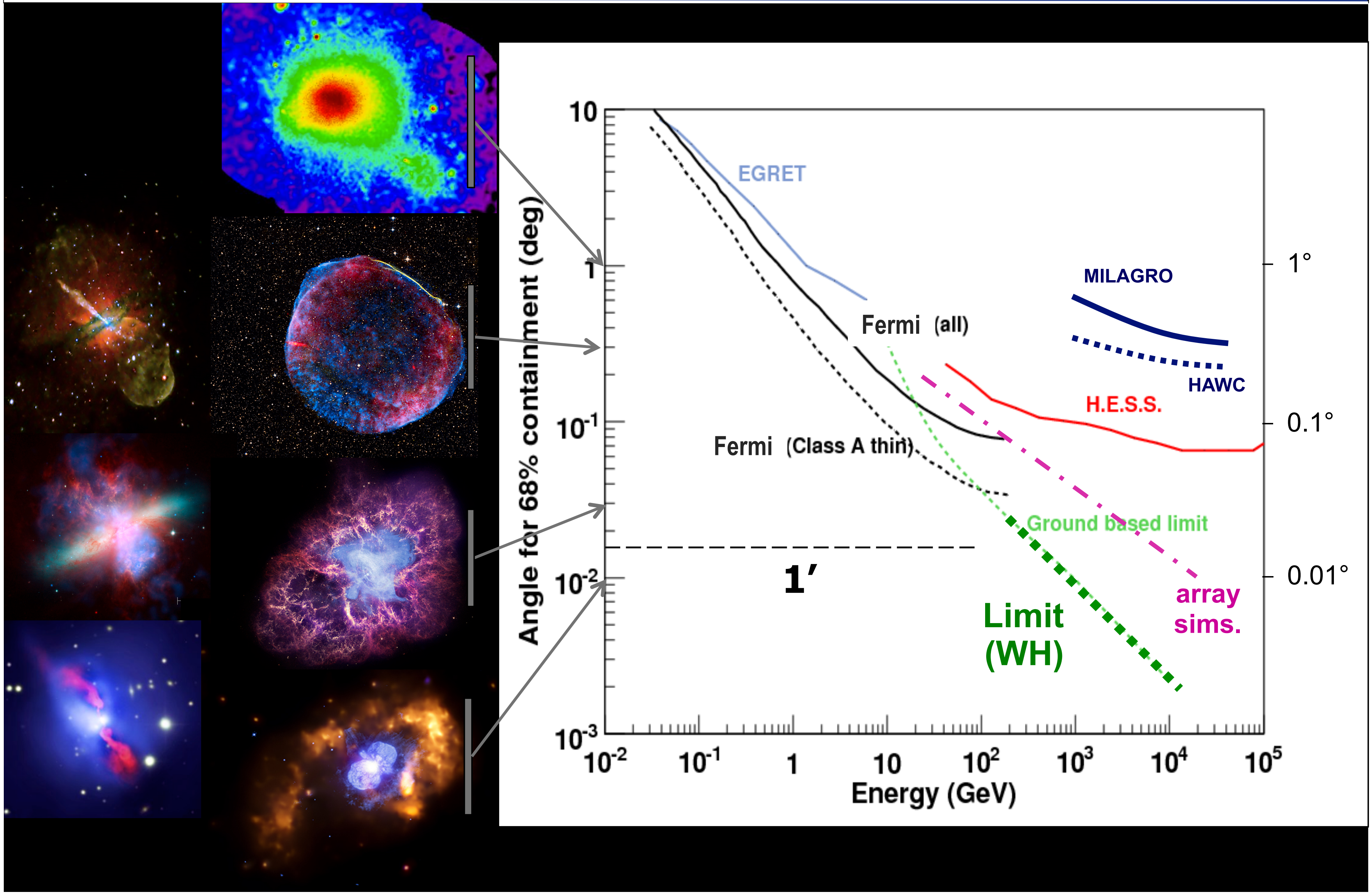


Angular Resolution

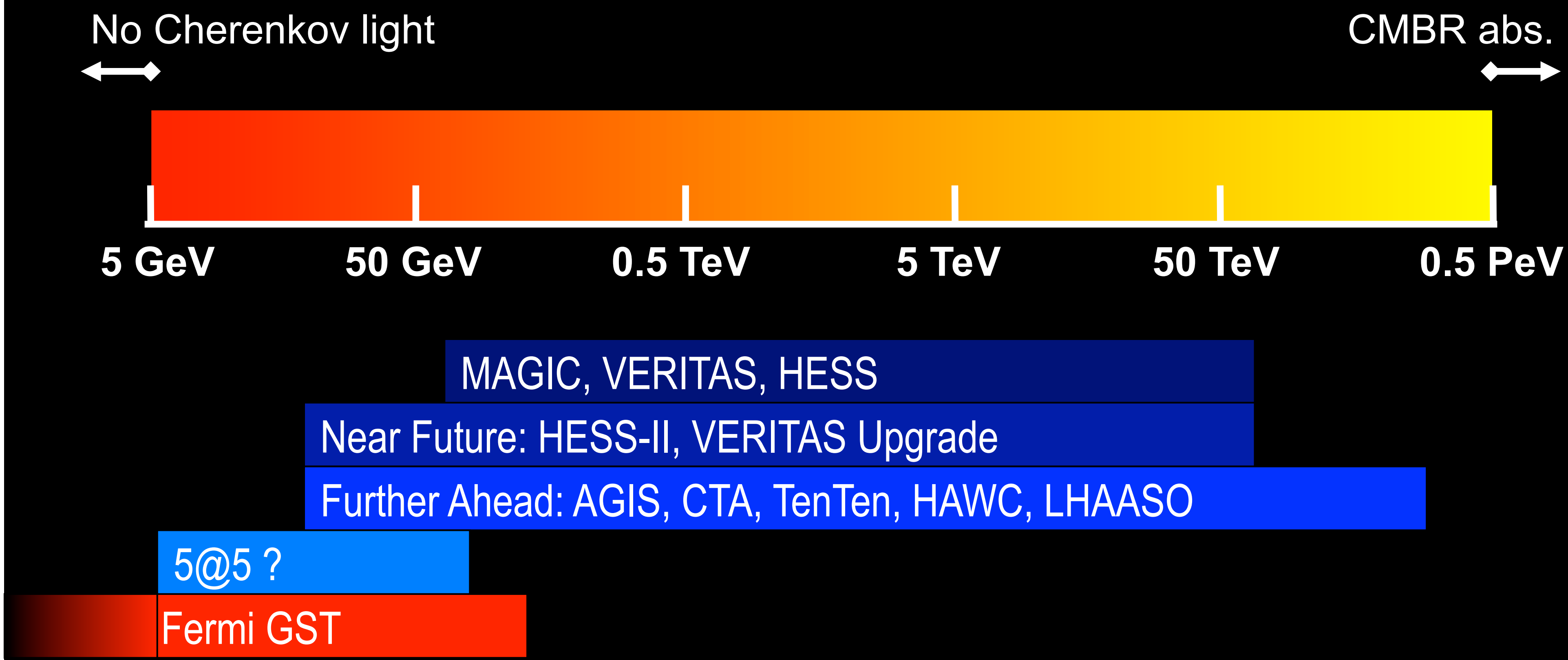
- ~1' resolution achievable with next generation IACT arrays
- Fundamental limit is ~10'' above a few TeV



Angular Resolution

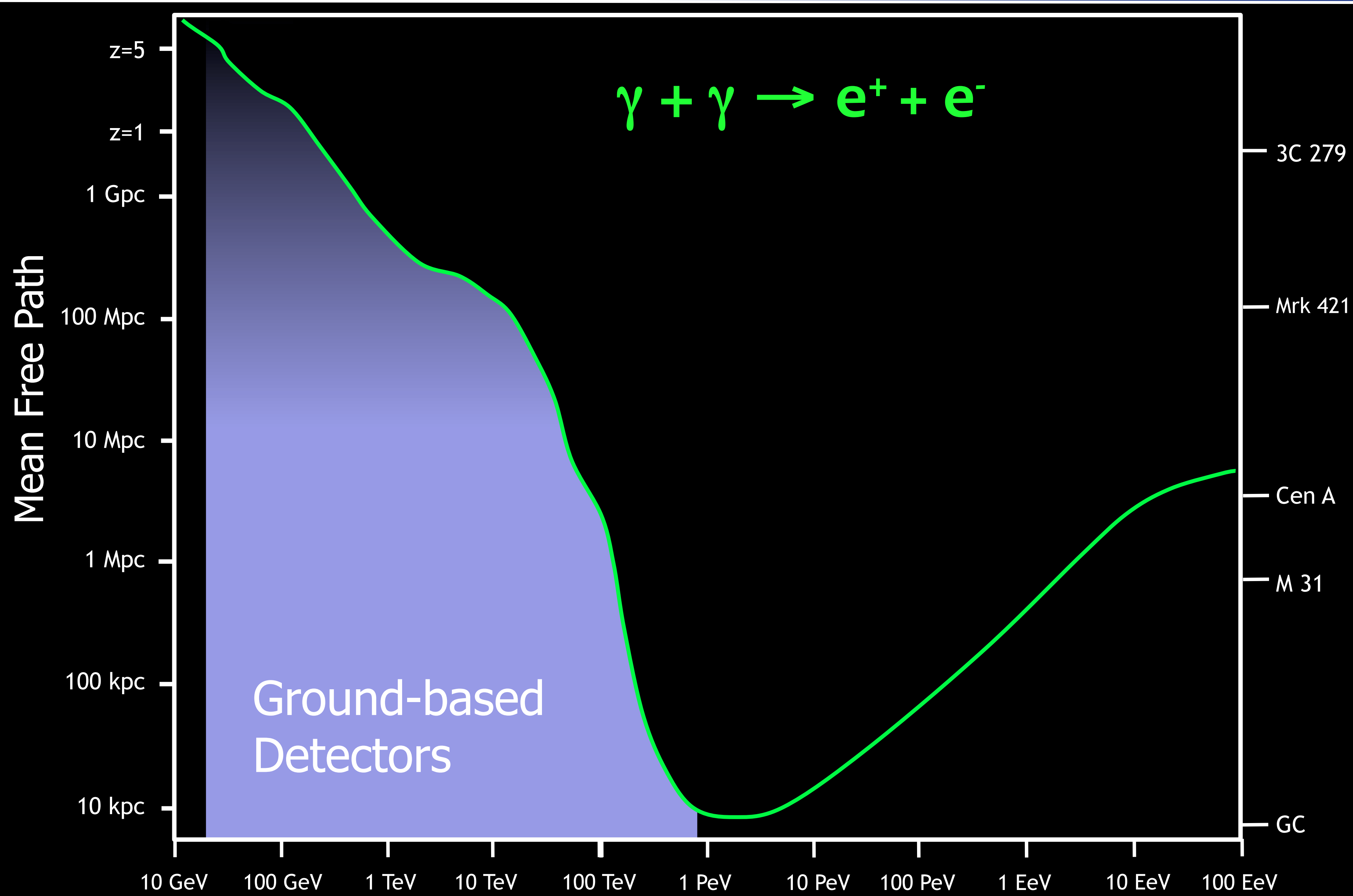


Ground-based Detectors

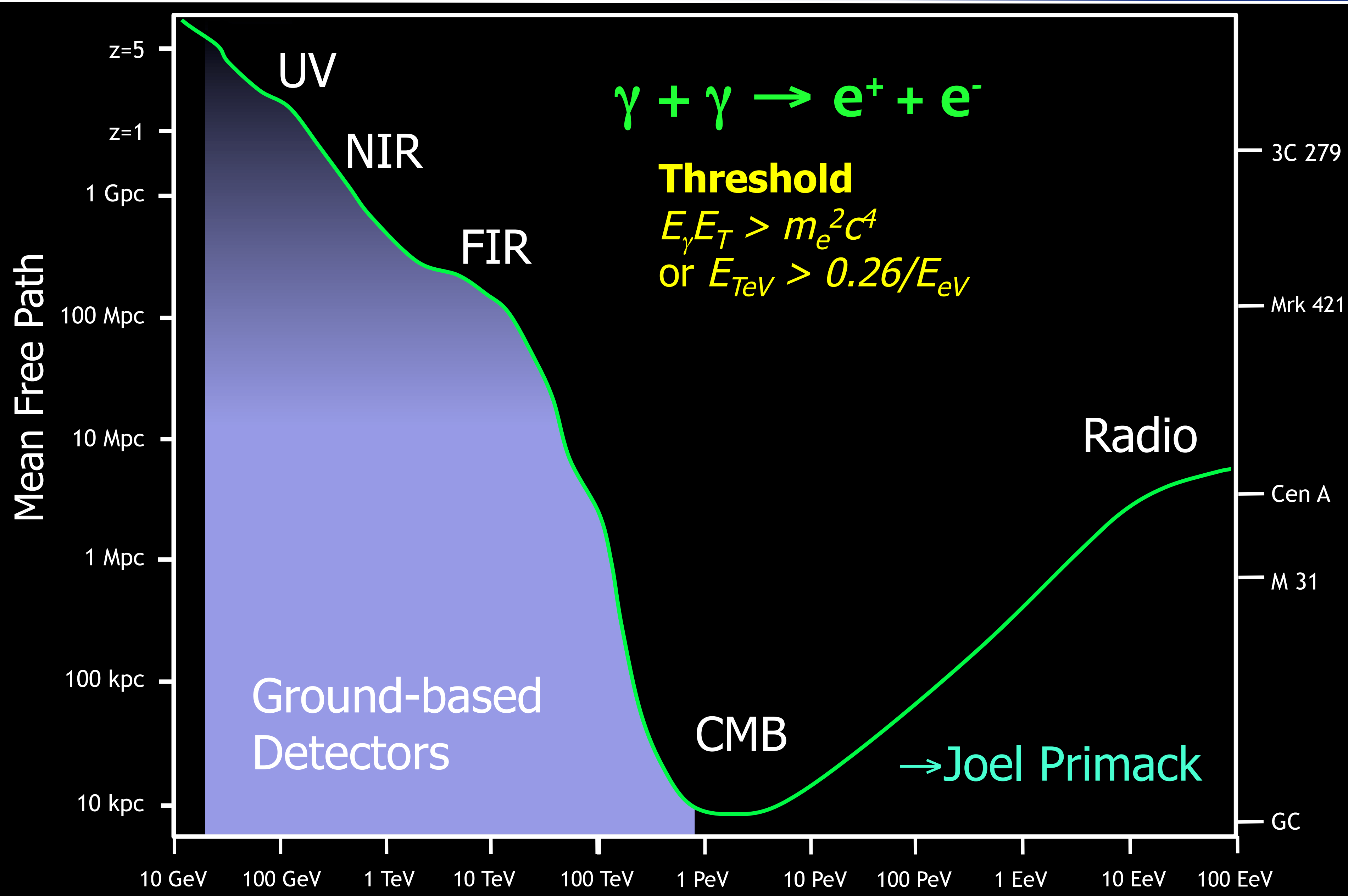


- 5 decades of energy are accessible from the ground for gamma-ray astronomy
- ~1 decade of overlap possible with satellites

The Gamma-ray Horizon



The Gamma-ray Horizon



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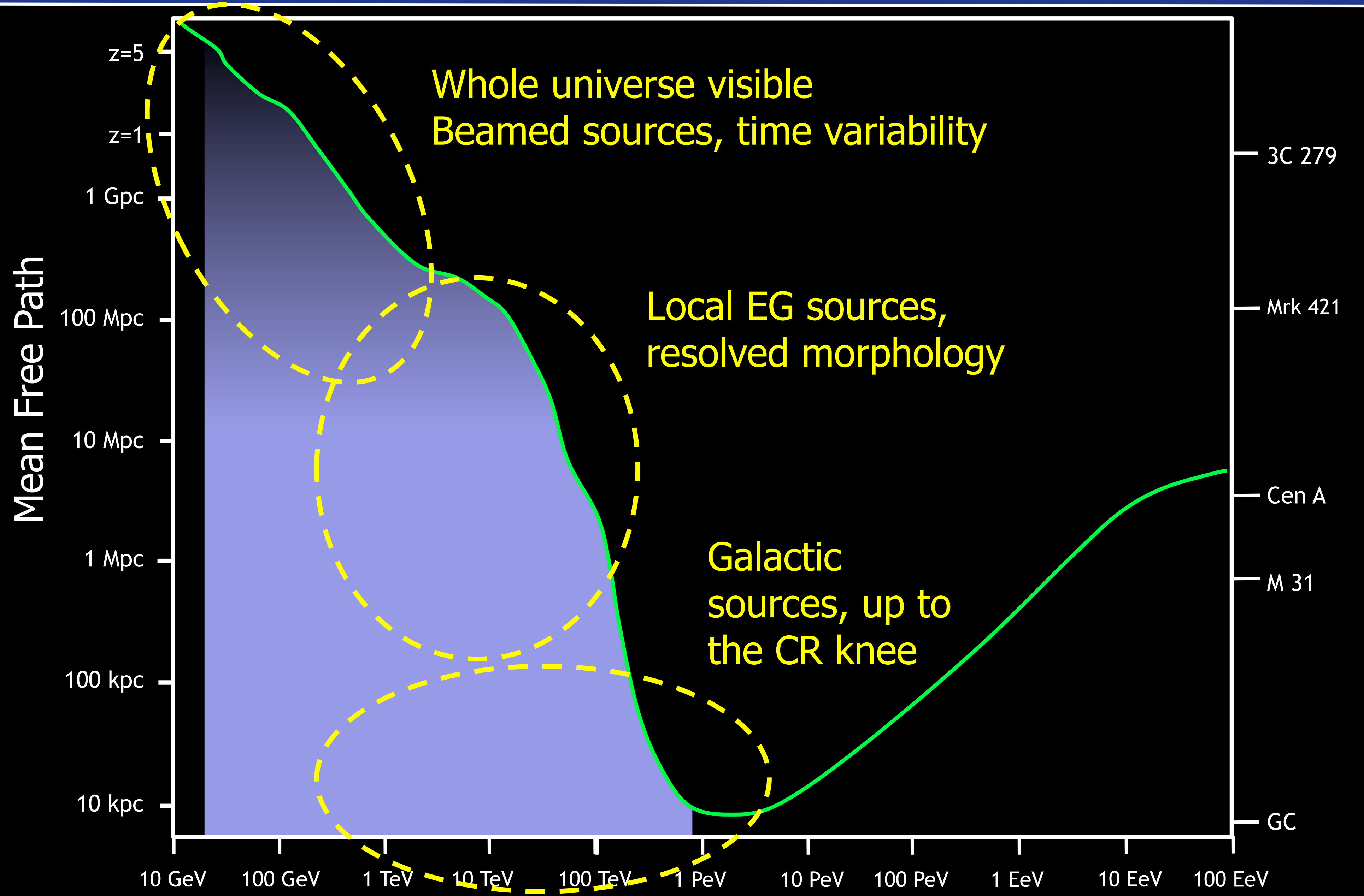
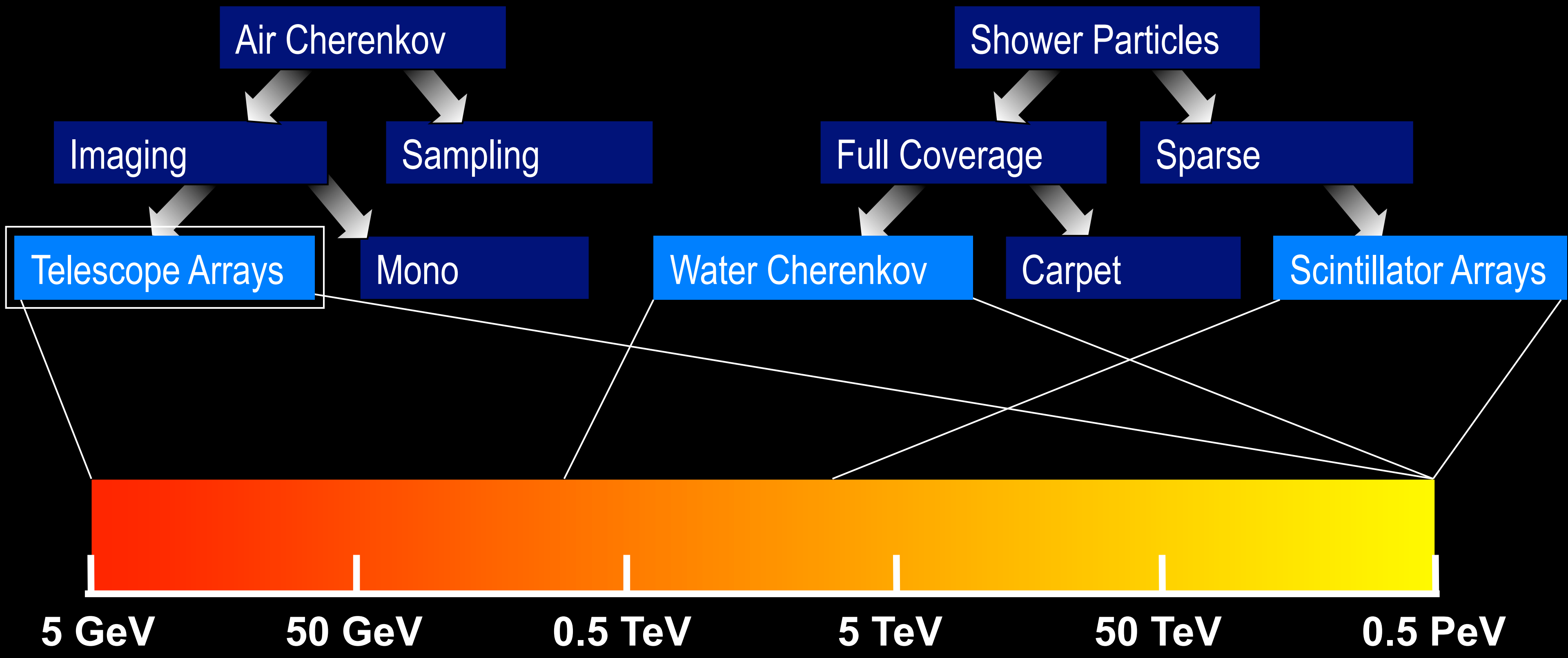


Ground-based Techniques



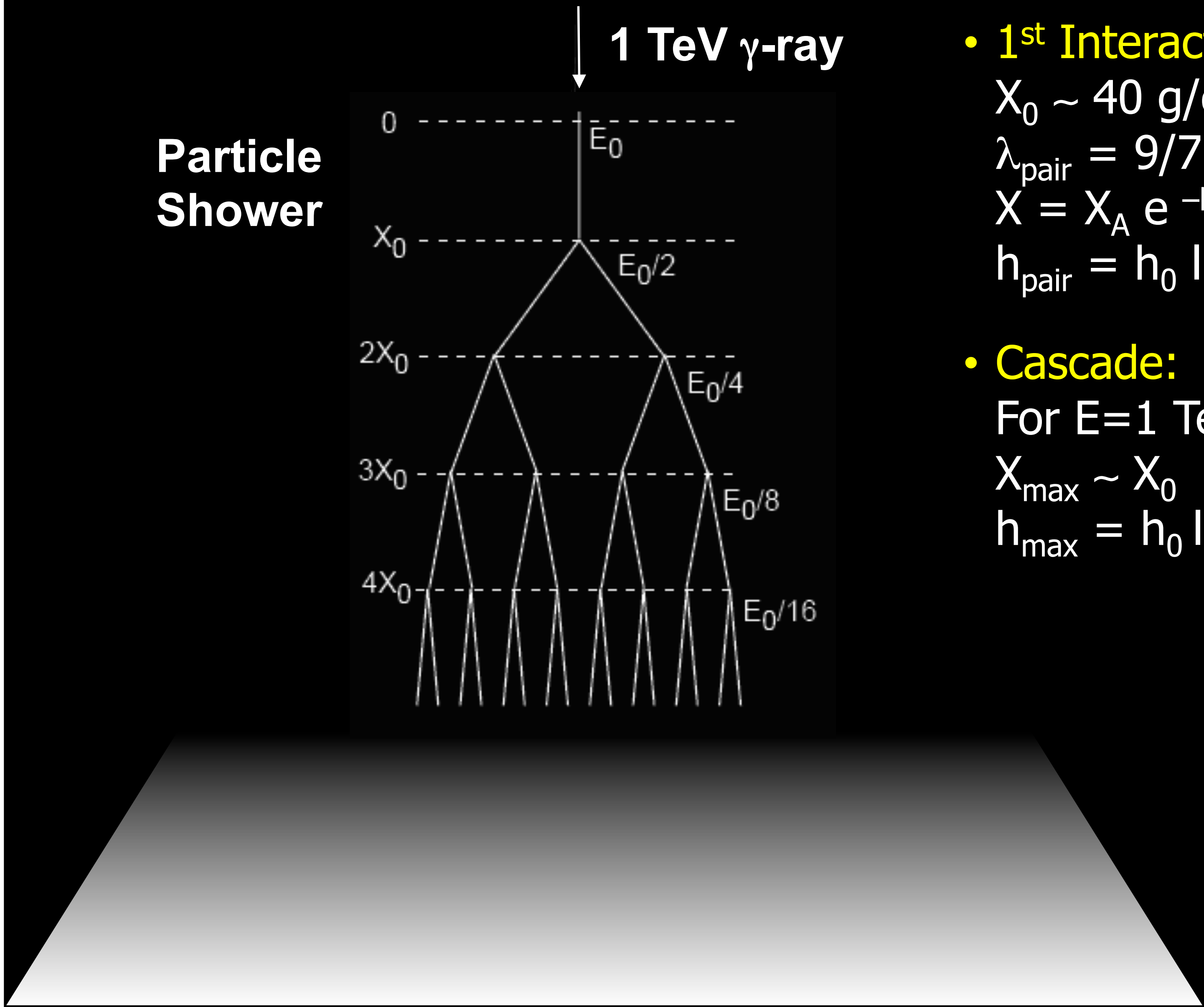
- Many different approaches have been tried
  - Major projects planned using three of them (not all worked well)
- All use *air-showers*

Air Showers

↓ **1 TeV γ-ray**

- 1st Interaction:
  $X_0 \sim 40$ g/cm^2
  $\lambda_{pair} = 9/7\ X_0 \sim 50$ g/cm^2
  $X = X_A\ e^{-h/h0}$ and $X_A \sim 10^3$ g/cm^2
  $h_{pair} = h_0 \ln(X_A/\lambda_{pair}) \rightarrow$ 20 km

Air Showers



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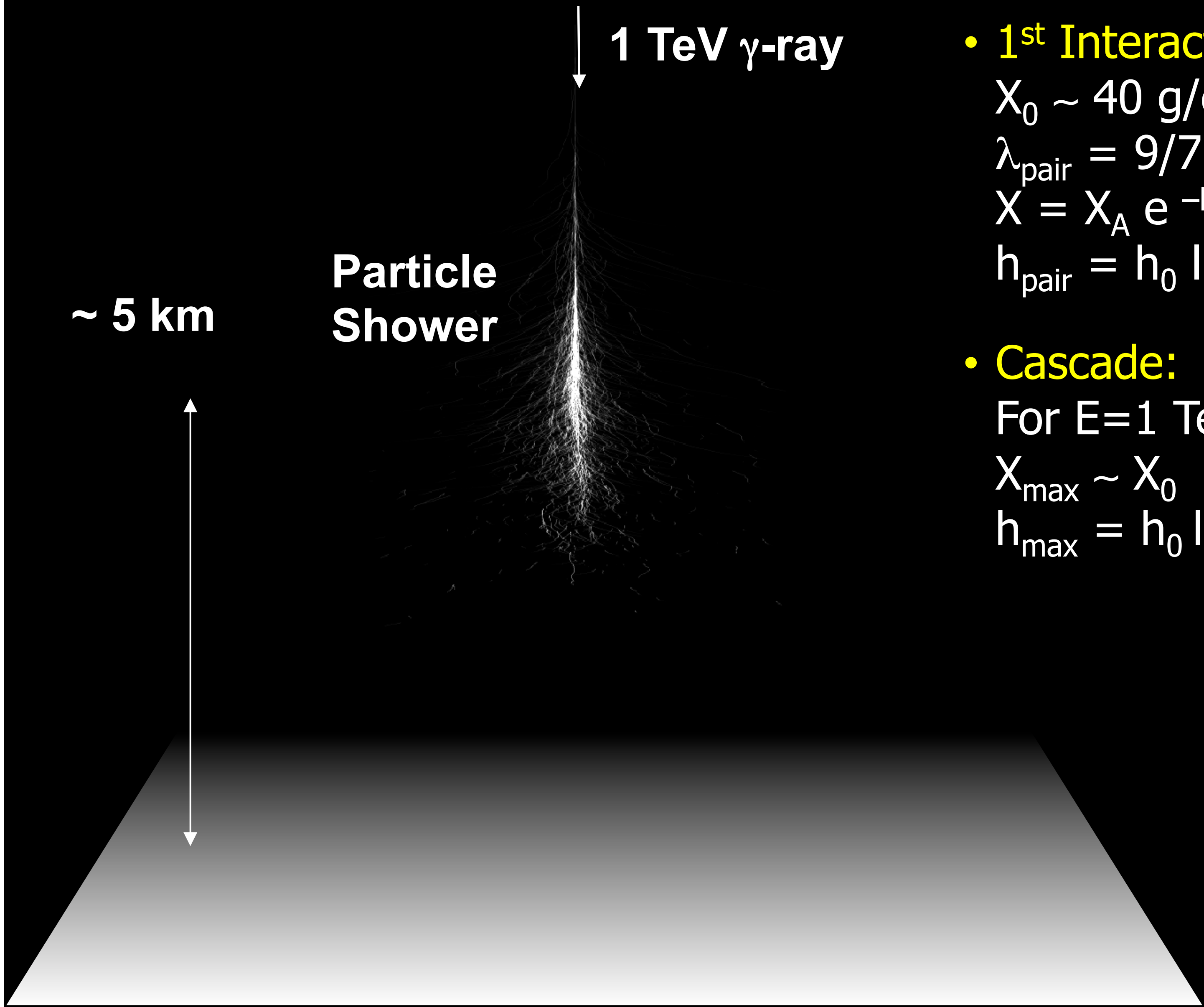
- Cascade:
  For E=1 TeV ($E_C \sim 80$ MeV)
  $X_{max} \sim X_0\ \ln(E/E_C) / \ln 2$
  $h_{max} = h_0 \ln(X_A/X_{max}) \rightarrow$ 5 km

Air Showers



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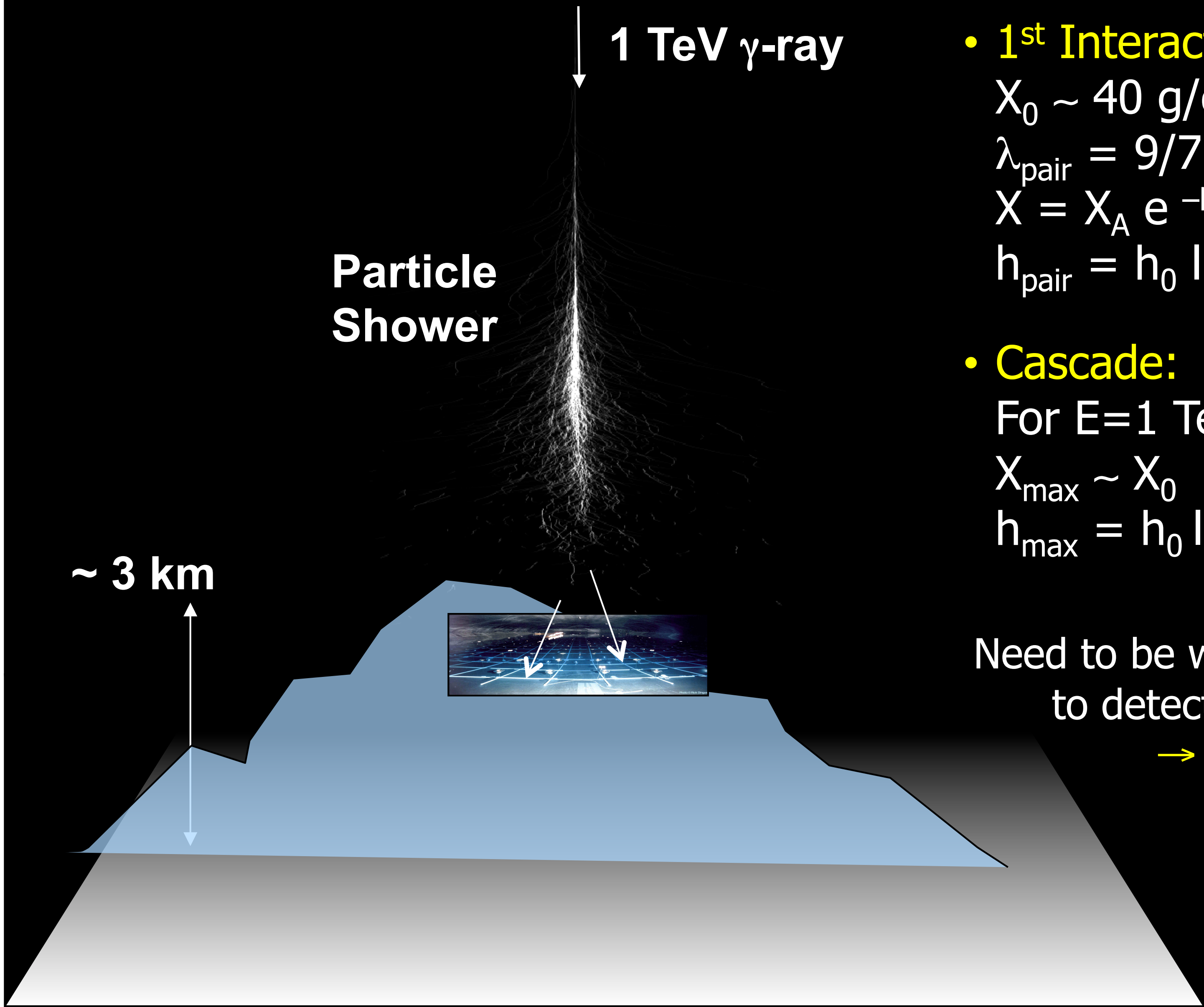
Shower Particle Detection



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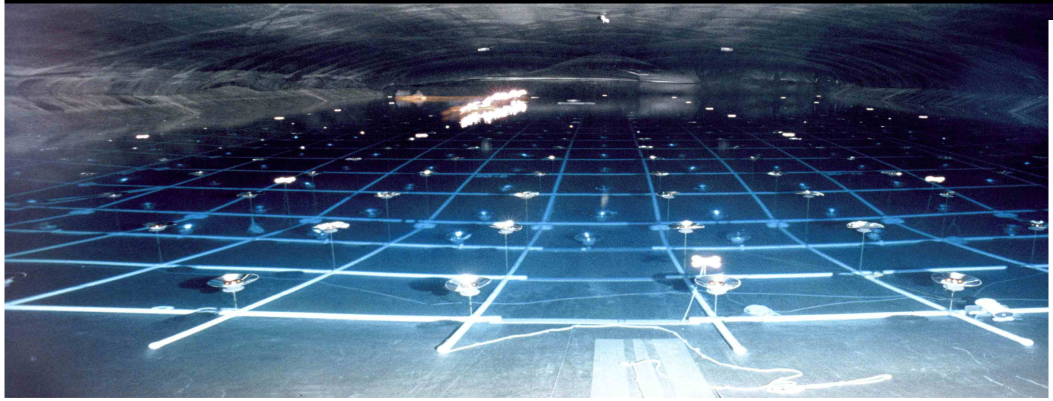
  $h_{max} = h_0 \ln(X_A/X_{max}) \rightarrow$ 5 km

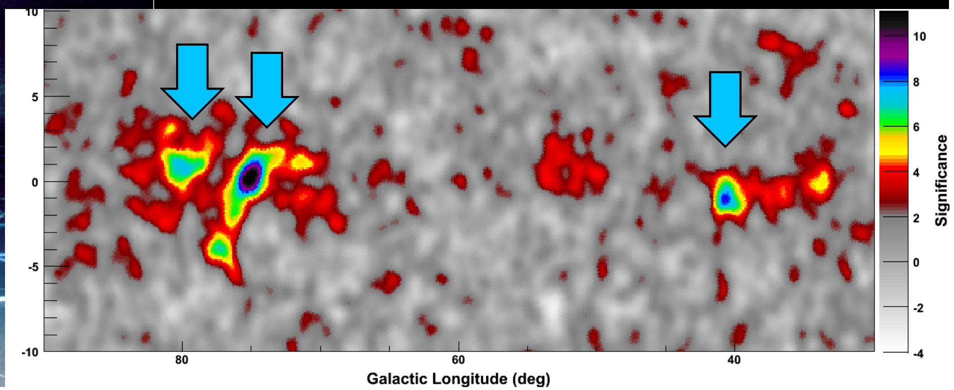
Need to be within a few X_0 of X_{max}
to detect particles directly
$\rightarrow$ 3-4 km alt.

MILAGRO

- Water pool (+outriggers) at Los Alamos, USA (2600 m a.s.l)
  - Water Cherenkov detector
  - ~0.5° direction reconstruction from arrival times
  - Modest sensitivity, BUT
  - 90% Duty Cycle, ~2 sr FoV
  - 3 >10 TeV sources discovered

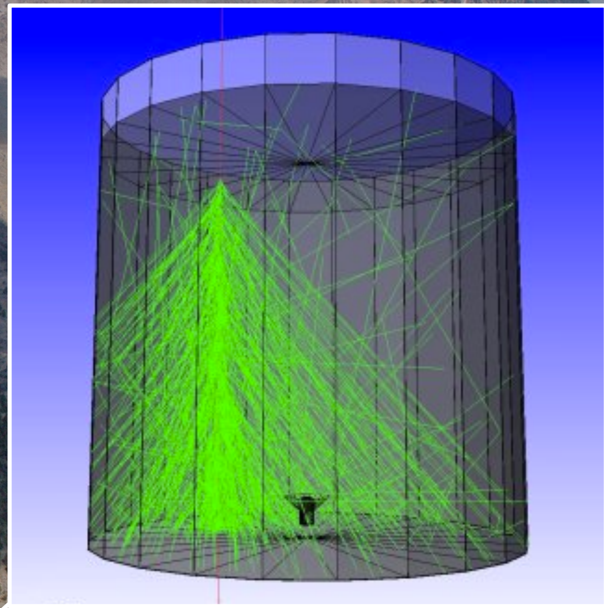
(Also ARGO in Tibet at 4300 m a.s.l)

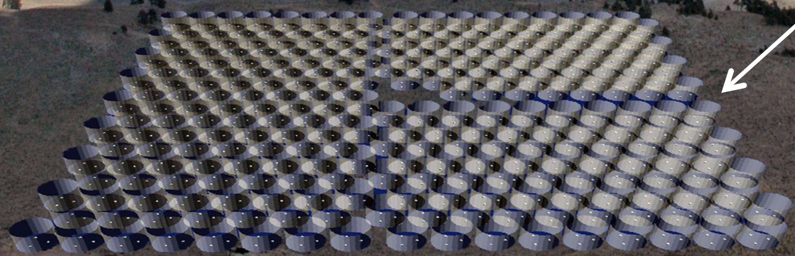




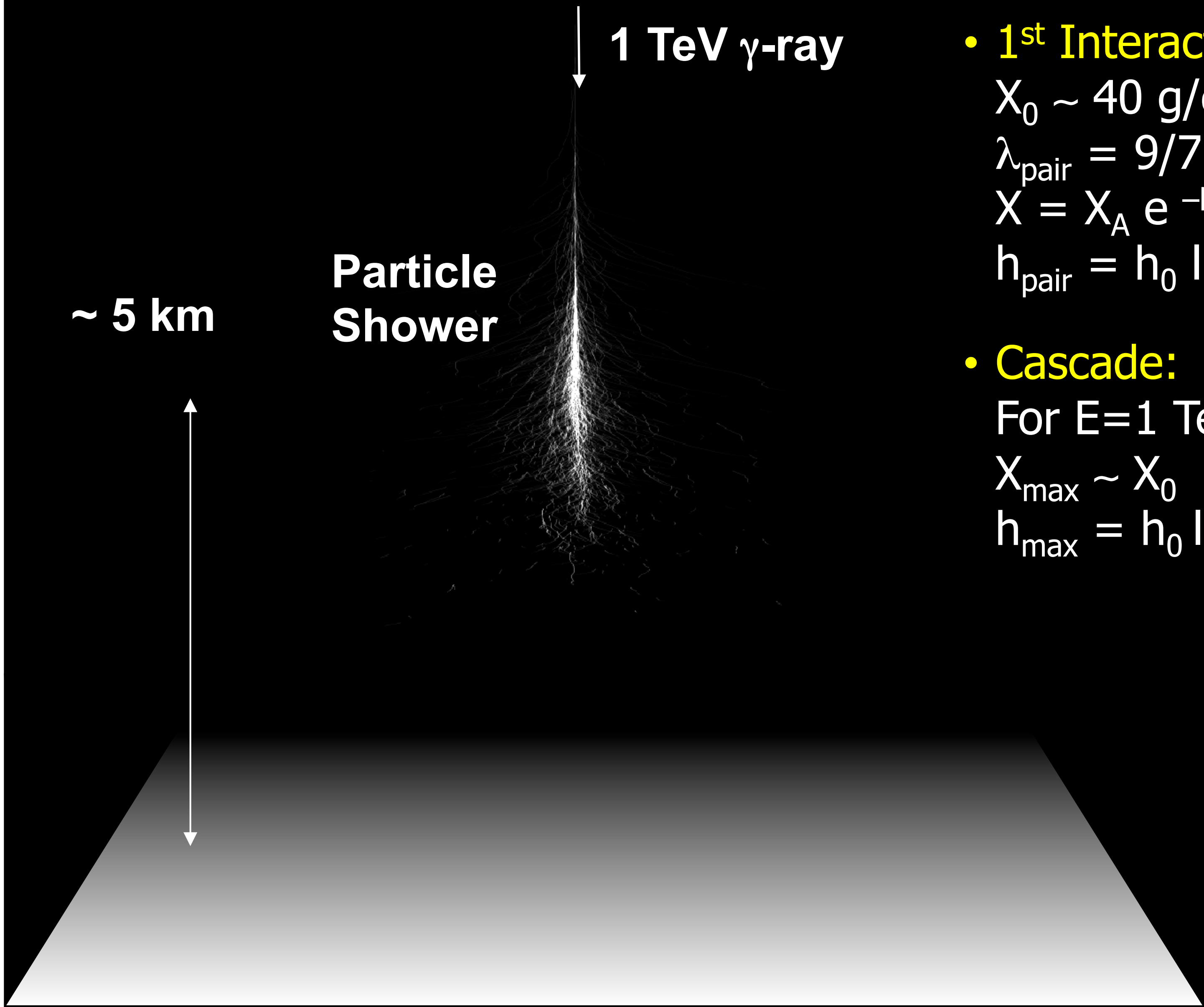
HAWC

- Redeploy MILAGRO components at 4100m a.s.l in Mexico
  - Individual water tanks, larger area coverage
- Factor 10 sensitivity improvement expected
  - First test tanks deployed





Air Showers



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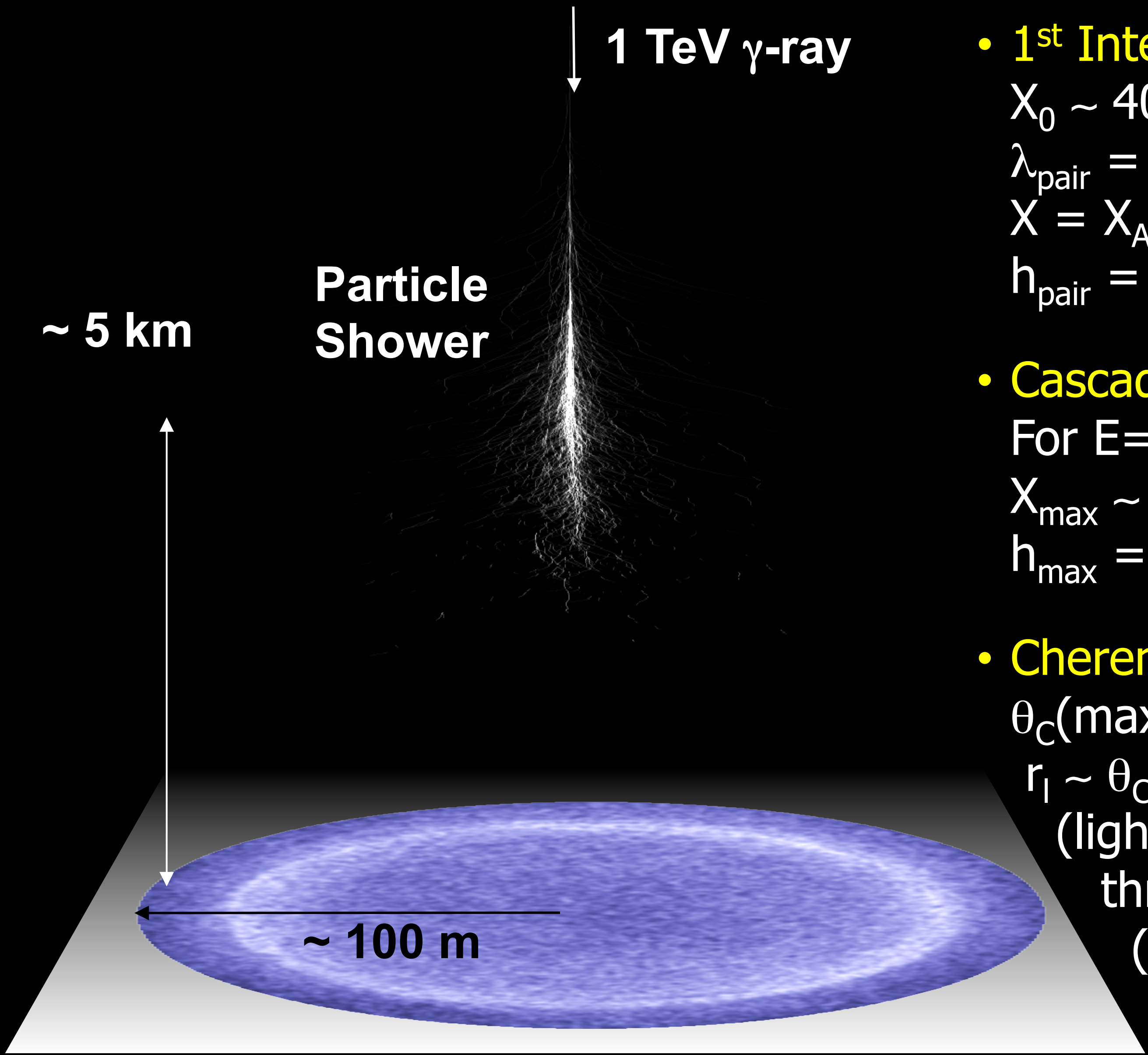
Cherenkov Light



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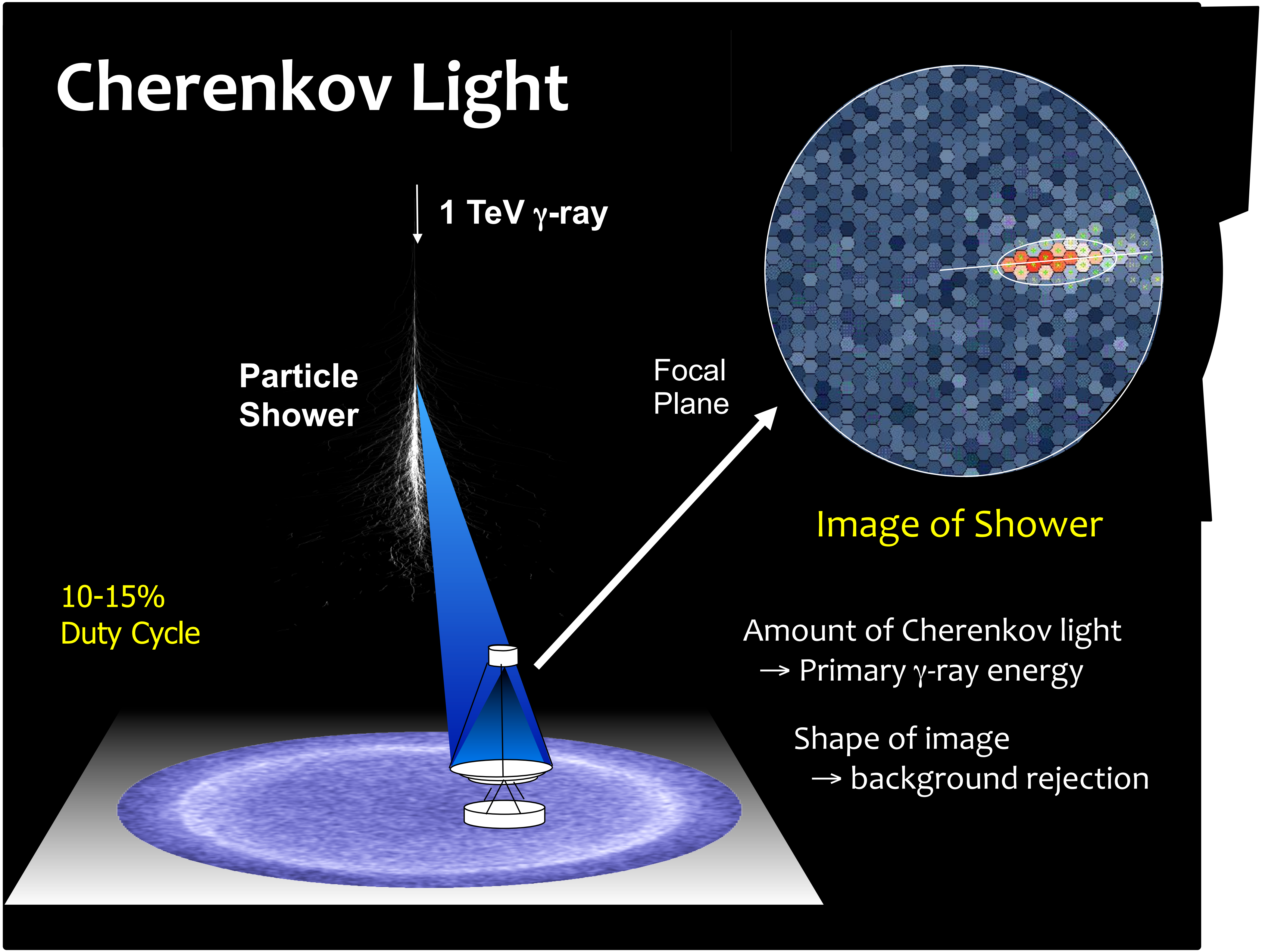
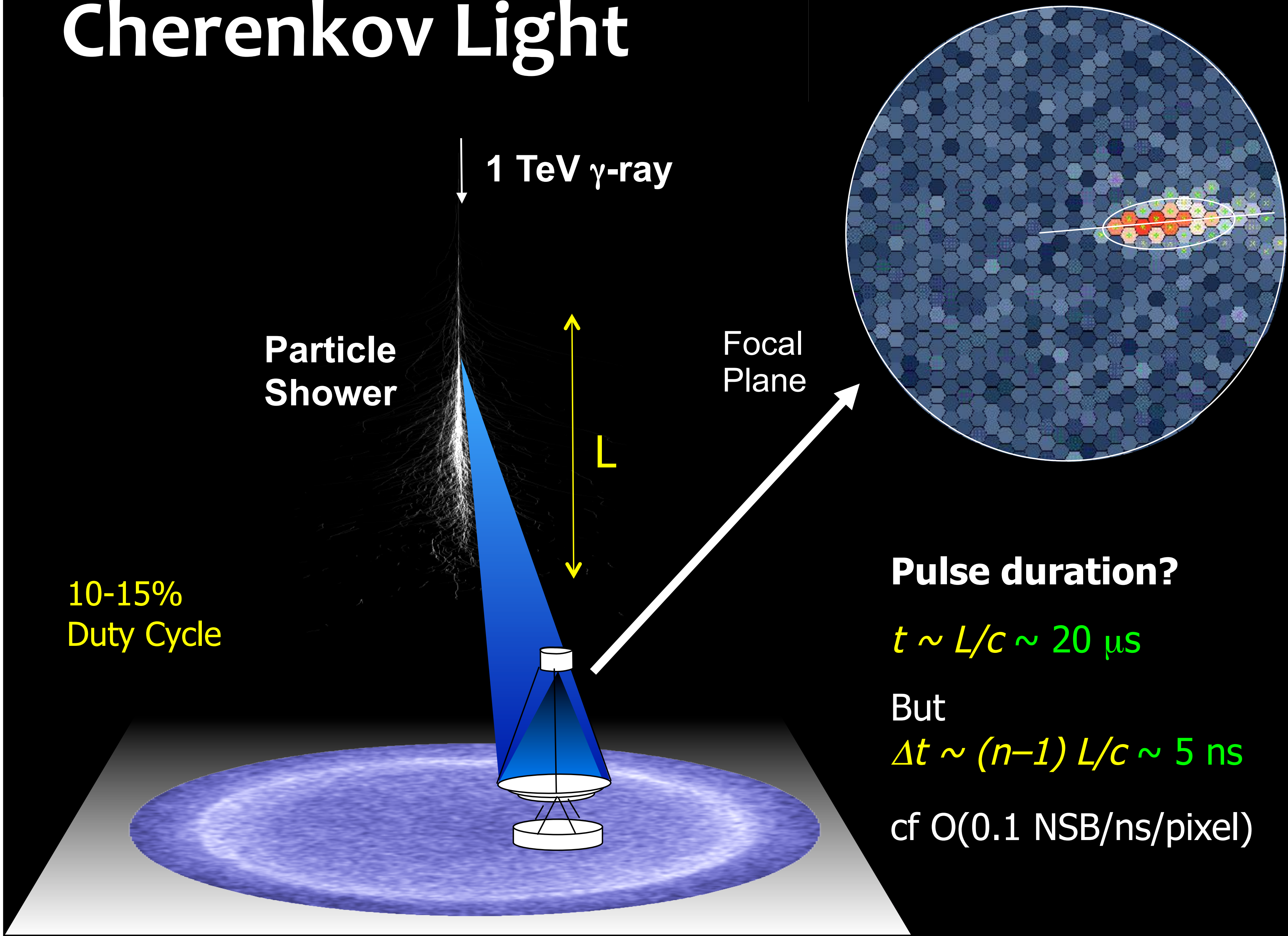
  $h_{max} = h_0 \ln(X_A/X_{max}) \rightarrow$ 5 km

- Cherenkov light:
  $\theta_C(\max) = \mathrm{acos}\,(1/n) \sim 1.4°$
  $r_l \sim \theta_C(\max)\, h_{max} \rightarrow$ 100 m
  (light pool radius)
  threshold ~20 MeV
  ($\beta > 1/n$ e^+/e^- sea level)


Cherenkov Light
1 TeV γ-ray
Particle Shower
Focal Plane
Image of Shower
10-15% Duty Cycle
Amount of Cherenkov light → Primary γ-ray energy
Shape of image → background rejection

Cherenkov Light



Pulse duration?

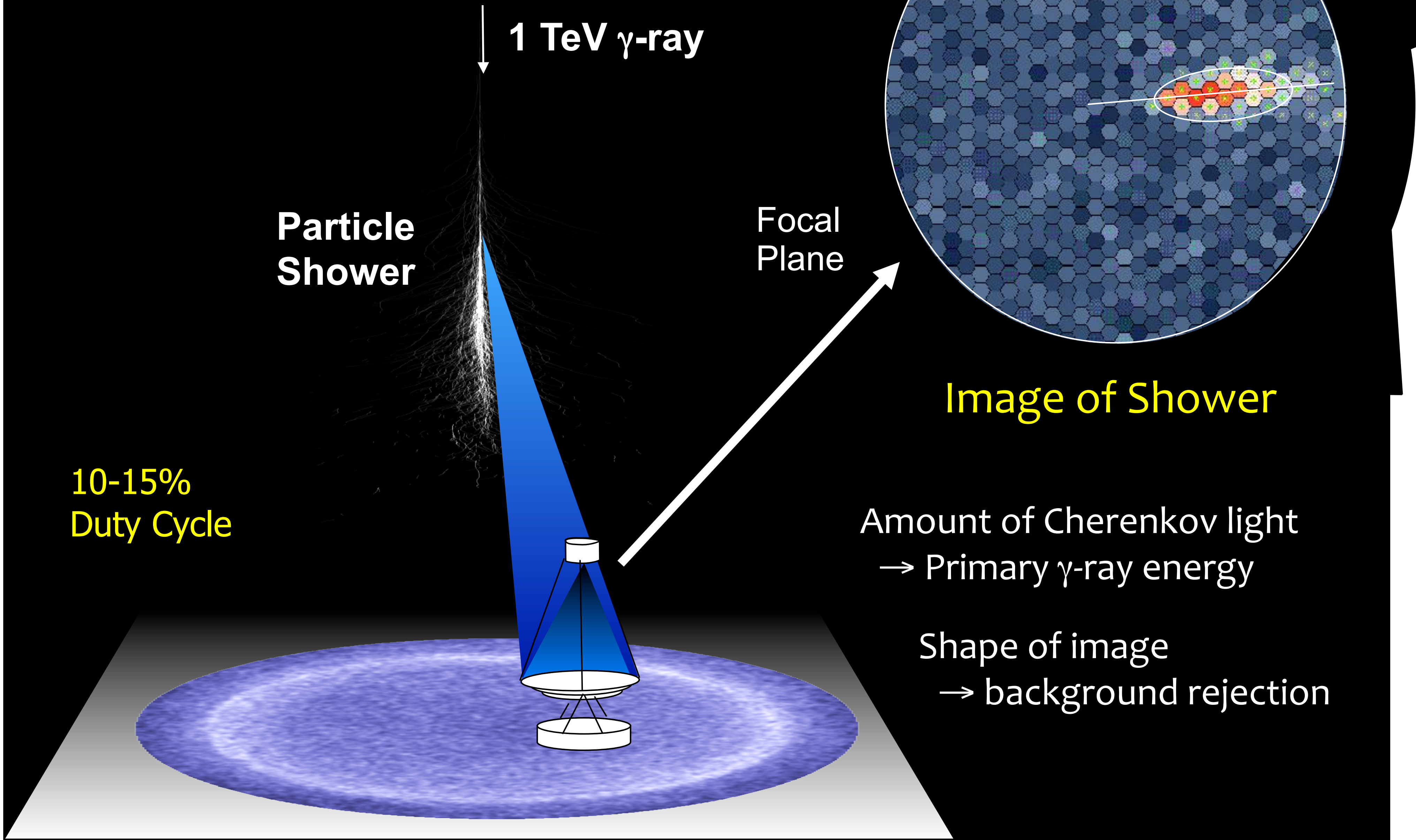
$t \sim L/c \sim 20\ \mu s$

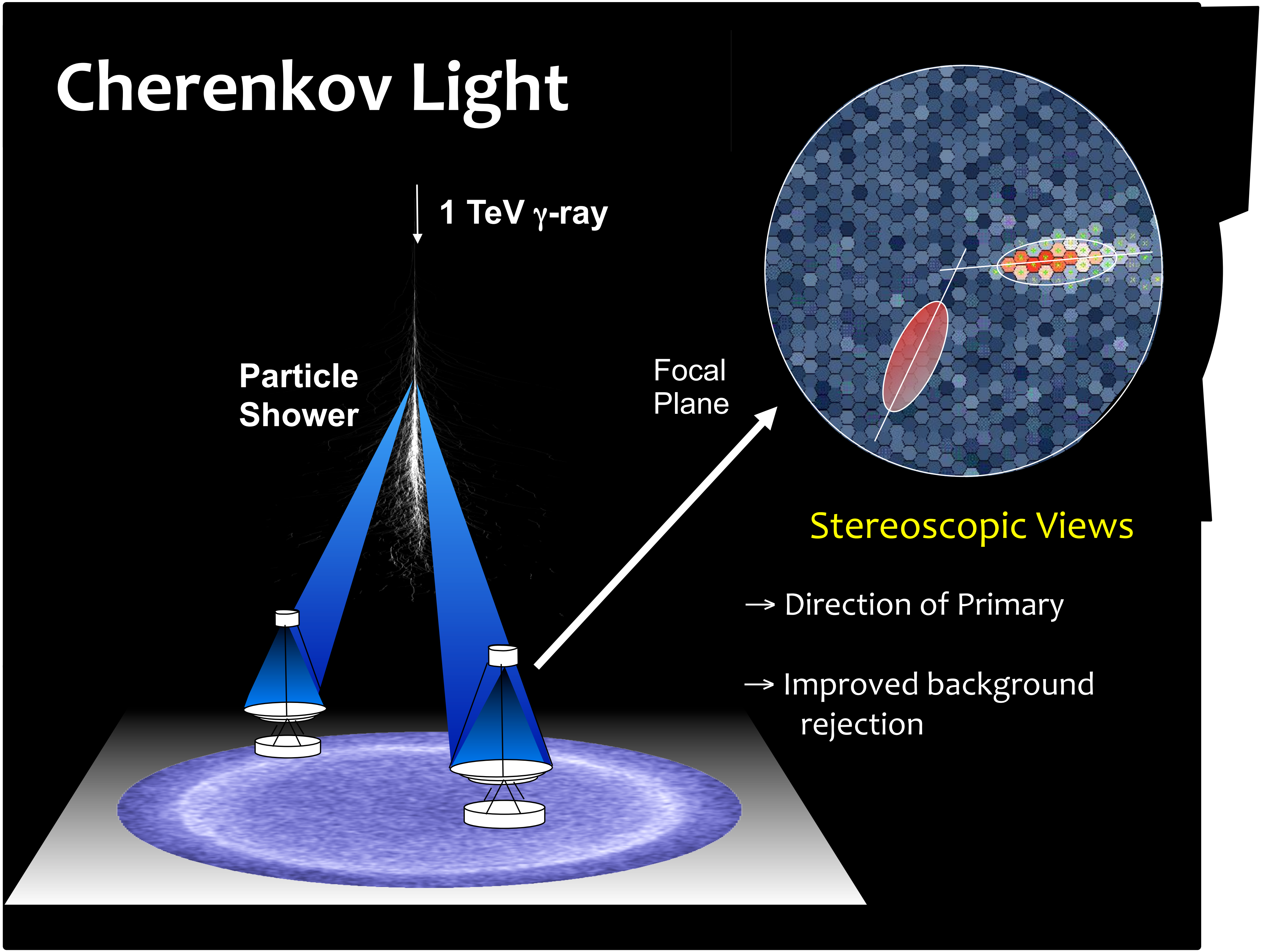
But

$\Delta t \sim (n-1)\ L/c \sim 5$ ns

cf O(0.1 NSB/ns/pixel)

Cherenkov Light

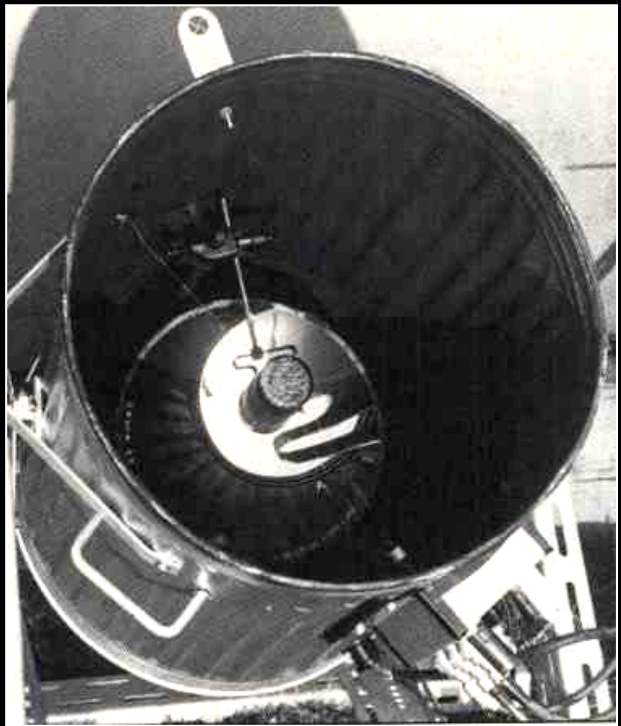




Cherenkov Light
1 TeV γ-ray
Particle Shower
Focal Plane
Stereoscopic Views
→ Direction of Primary
→ Improved background rejection

Super-brief History

- Galbraith & Jelley, 1953



Discovery of
Cherenkov Light
from air-showers

- Weekes et al. 1989

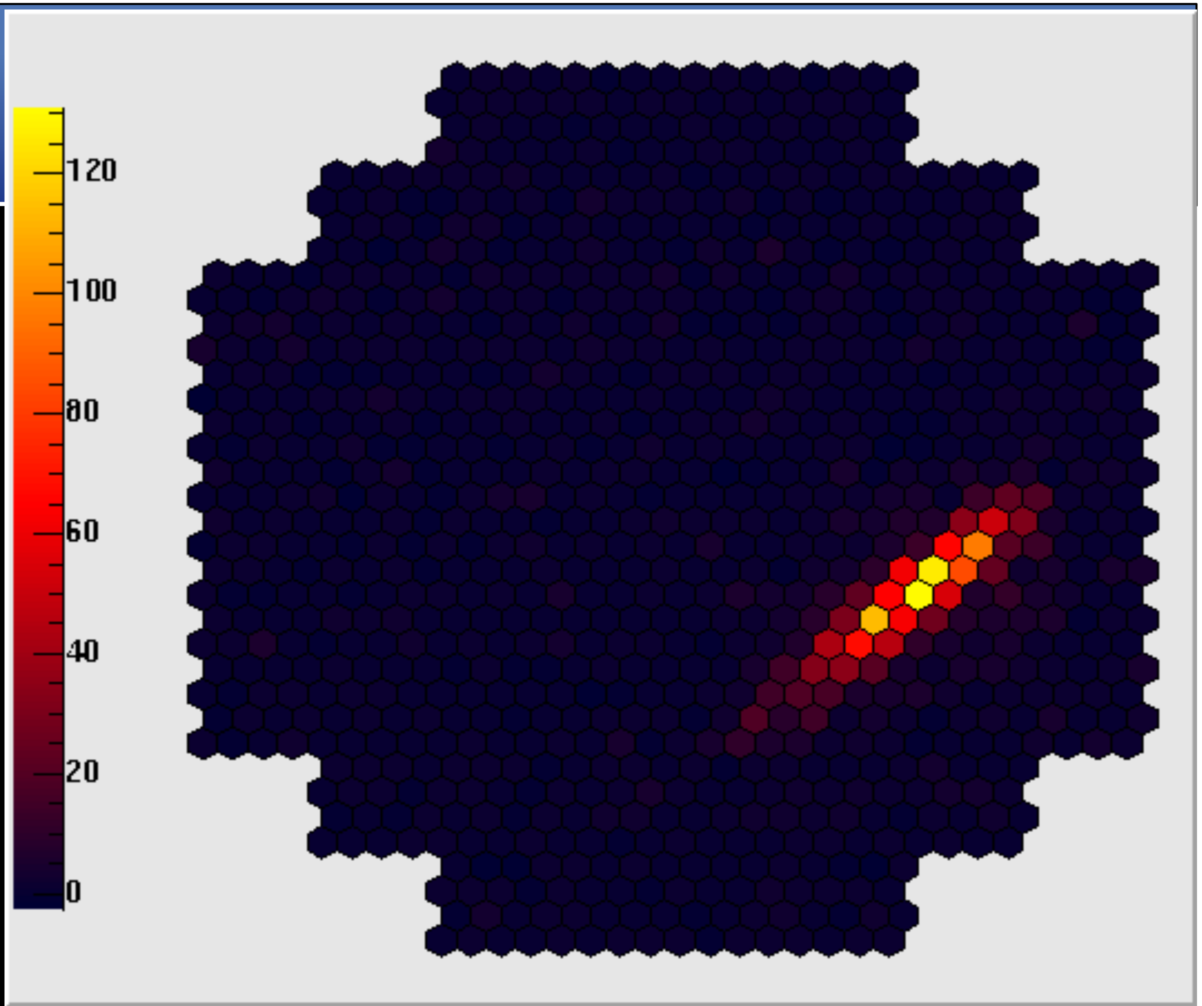
1st TeV gamma-ray source
(The Crab Nebula)

- 1990s

1st Telescope Arrays
Camera improvements
(Whipple, CAT, HEGRA, …)

Background

- Charged Cosmic Ray initiated showers
  - ~1000 events per second in current detectors
  - >> γ-ray rates



OG 9.5-3

CERENKOV LIGHT IMAGES OF EAS PRODUCED BY
PRIMARY GAMMA RAYS AND BY NUCLEI

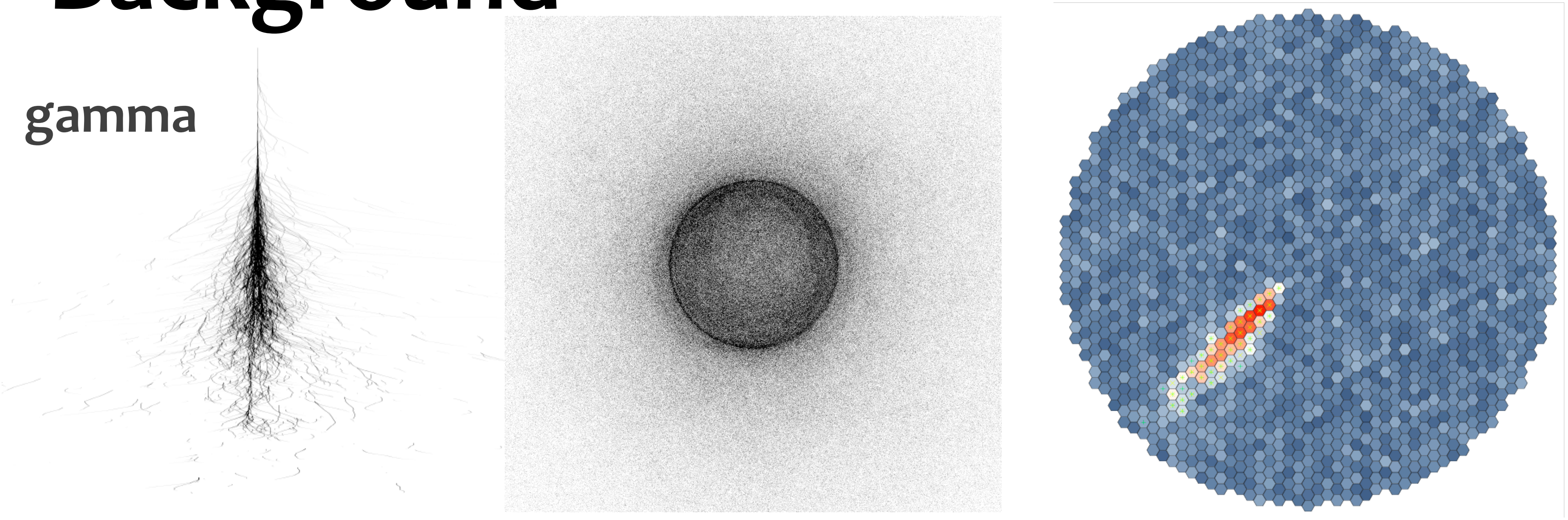
A. M. Hillas
Physics Department
University of Leeds, Leeds LS2 9JT, UK.

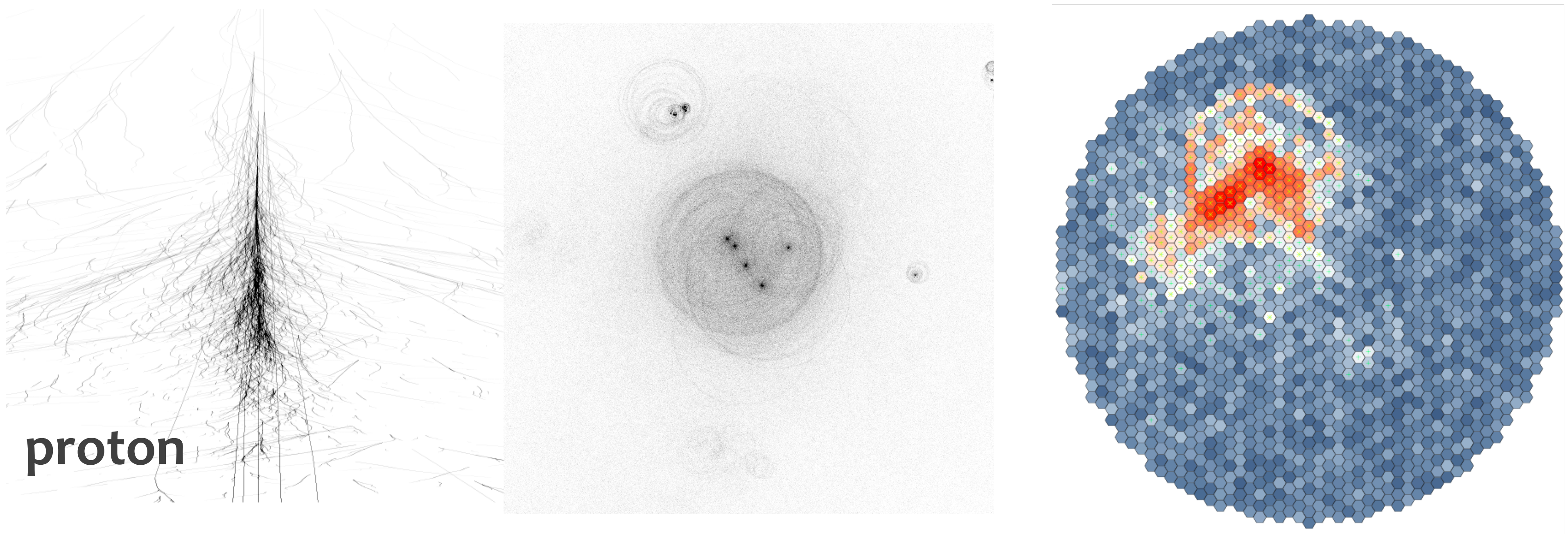
ABSTRACT

It is shown that it should be possible to distinguish very effectively between background hadronic showers and TeV gamma-ray showers from a point source on the basis of the width, length and orientation of the Cerenkov light images of the shower, seen in the focal plane of a focusing mirror, even with a relatively coarse pixel size such as employed in the Mt. Hopkins detector.

1985 ICRC

Background

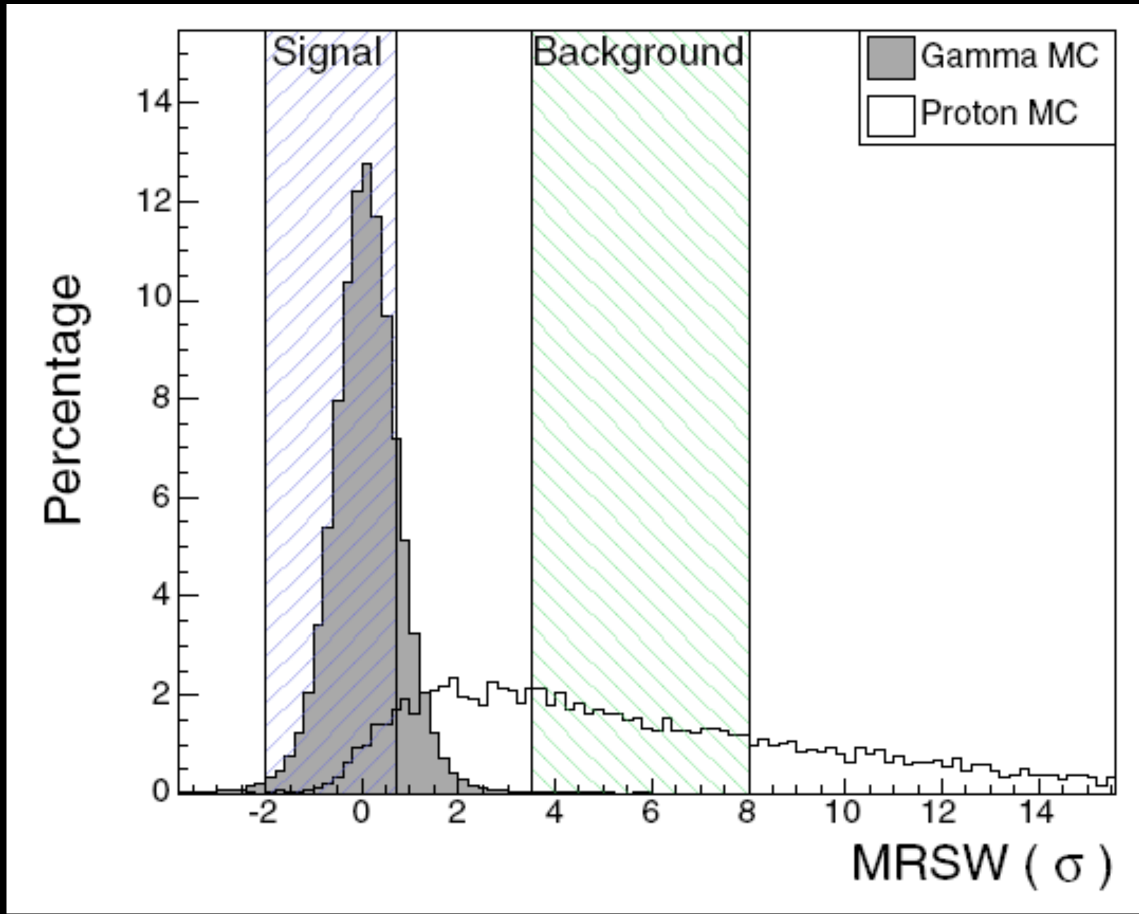




Background Suppression

- Main difference: Gamma-showers are narrower, e.g. Mean Reduced Scaled Width
- Many other differences
  - Image
    - Length
    - X_{max}
    - Sub-structure
  - Distribution of light on the ground
  - Time structure

(Often – Multi-variate analysis)



(Width - Expected Width) / (Expected Spread)

Functions of image size and impact distance

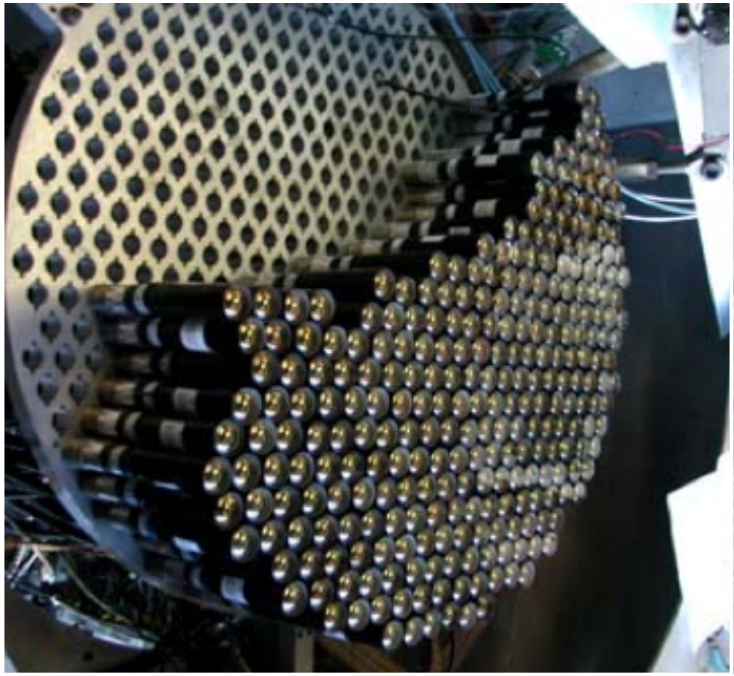
Major VHE Instruments

Major VHE Instruments

The Major IACTs

2 - 4 Telescopes
500-1000 pixel cameras
3.5 - 5.0° FoV
~0.1° angular res.
~15% energy res.

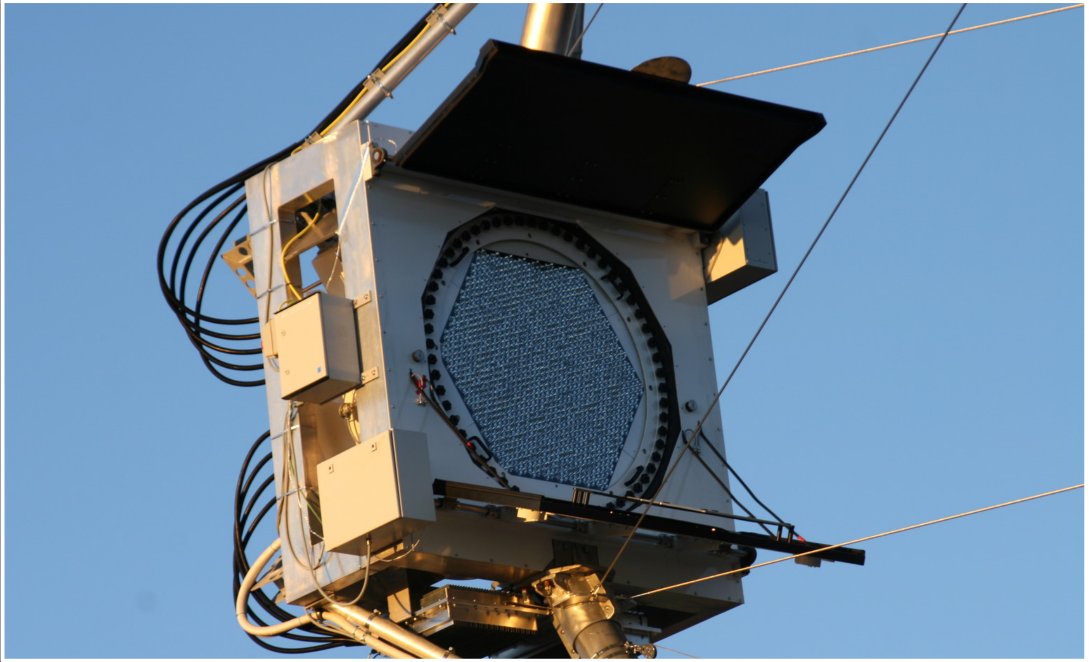
VERITAS



- 1270 m altitude site in Arizona, USA
- 4× 12 m telescopes, 3.5° Field of View
- Completed 2007
  - 2009 Upgrade (moved telescope)

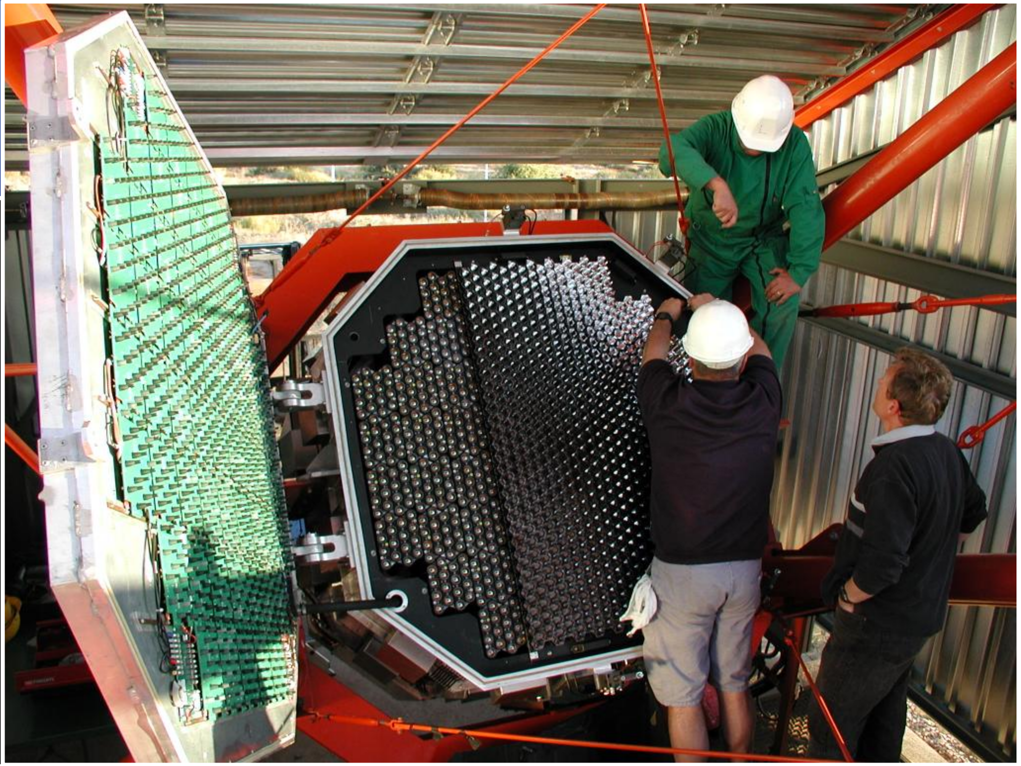
MAGIC

- 2×17m telescope system on La Palma (2200 m altitude)
- First telescope completed 2004
- Second telescope operational 2009
- 3.5° Field of View

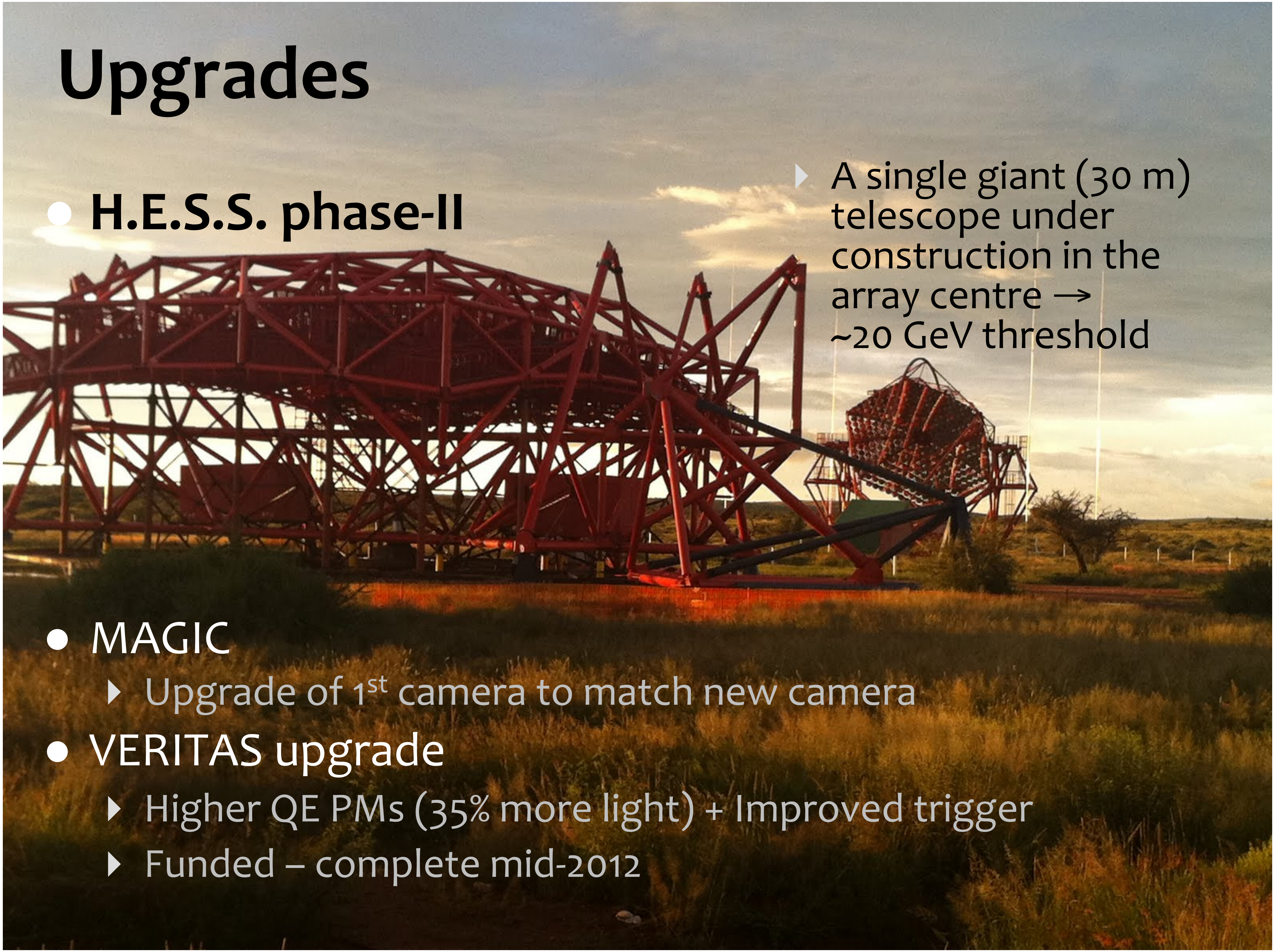


H.E.S.S.

- Four 12m diameter telescopes in Namibia
  - 1800 m altitude
  - 5° FoV
- Completed 2004

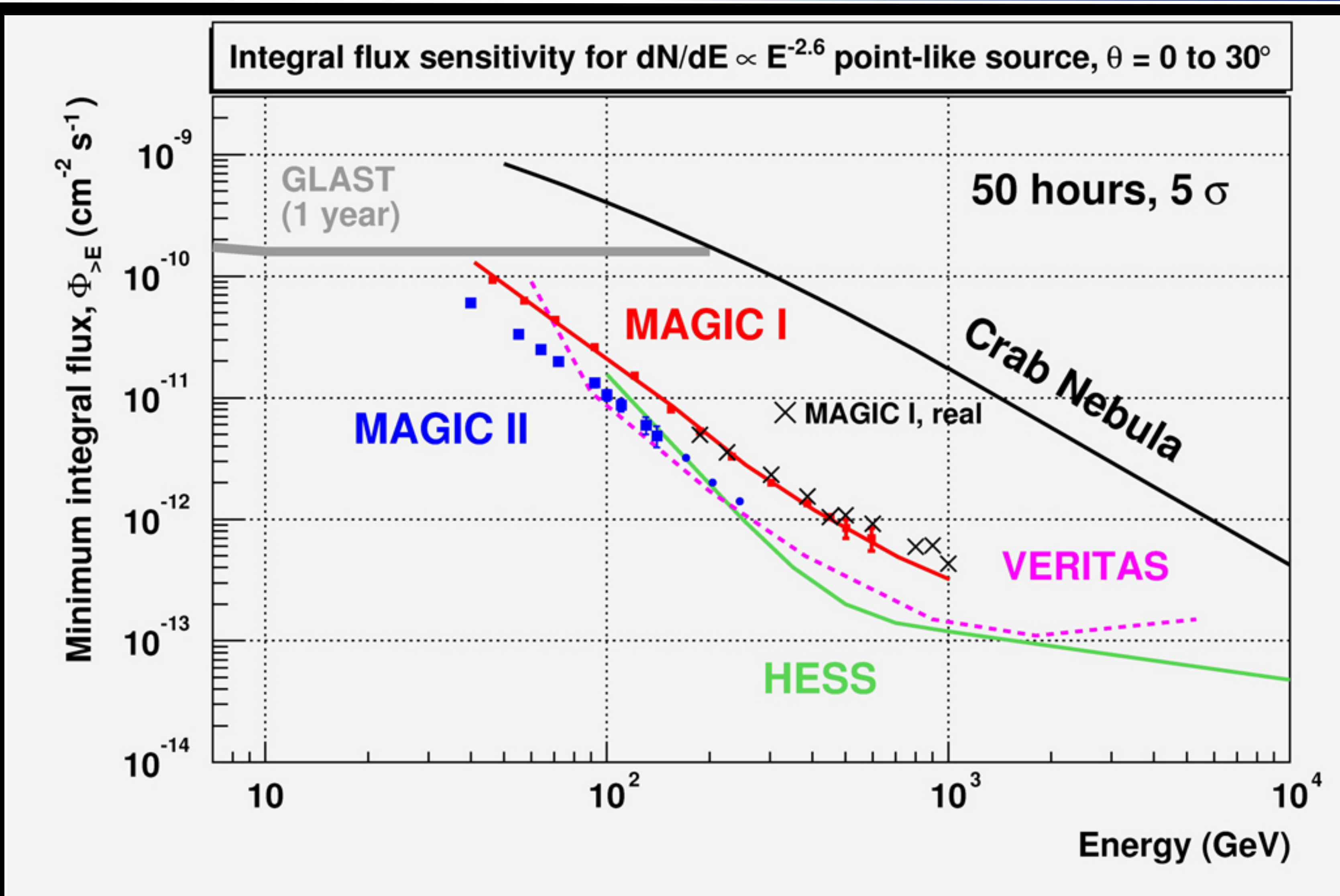


Upgrades



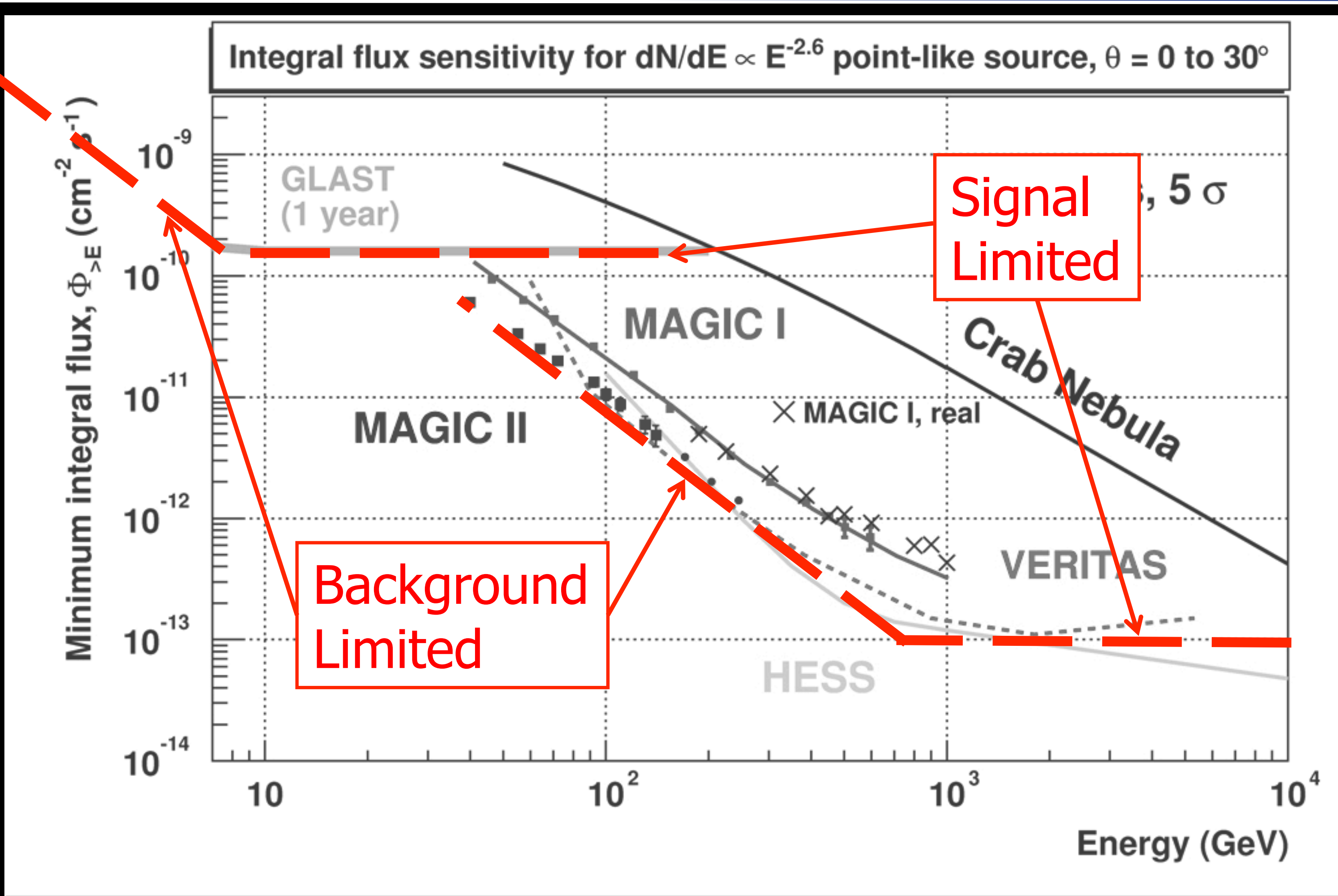
- **H.E.S.S. phase-II**
  - A single giant (30 m) telescope under construction in the array centre → ~20 GeV threshold
- MAGIC
  - Upgrade of 1st camera to match new camera
- VERITAS upgrade
  - Higher QE PMs (35% more light) + Improved trigger
  - Funded – complete mid-2012

Performance



- Crab Nebula detection in ~1 min. (90 hours in 1989!)

Performance



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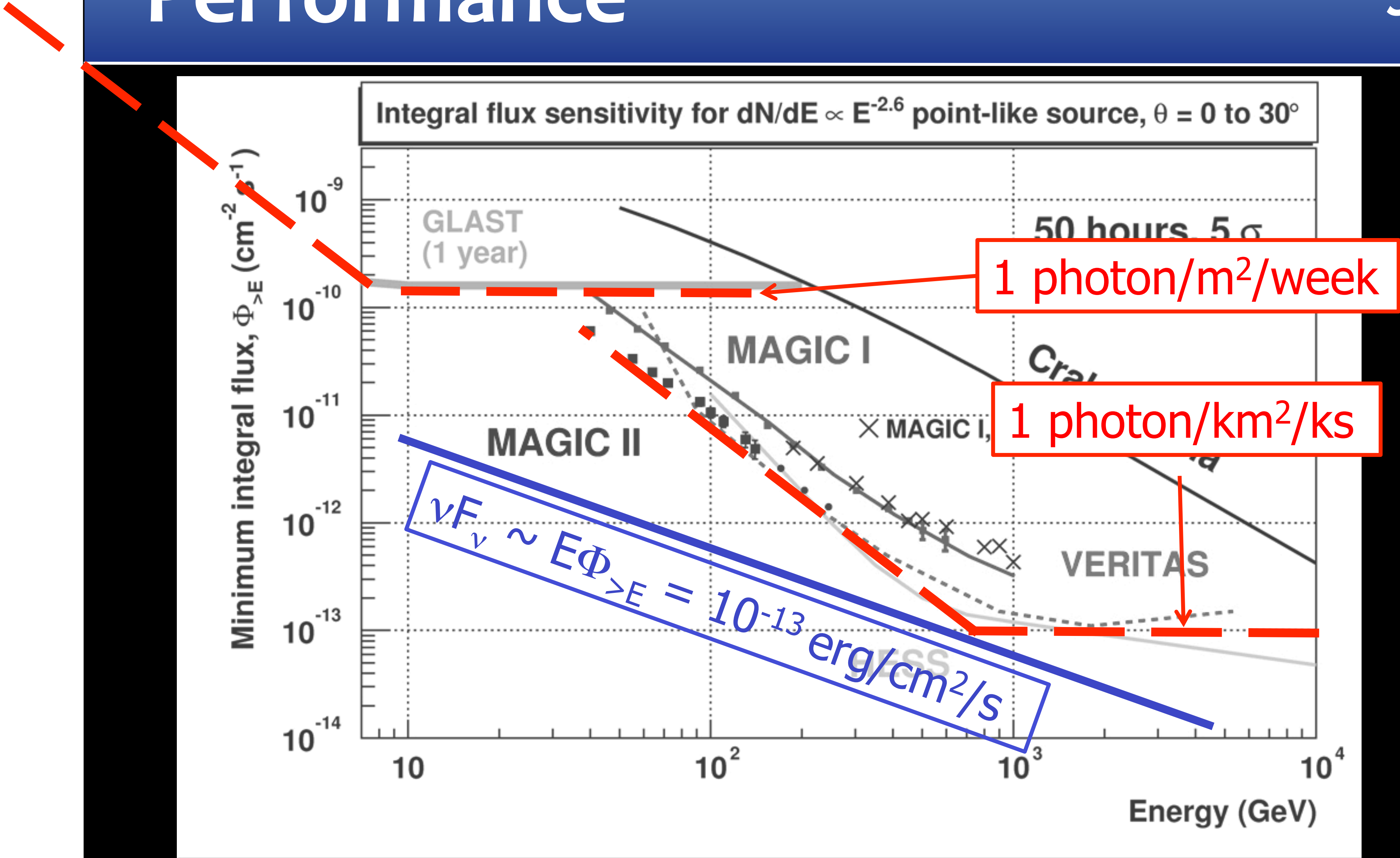


- Crab Nebula detection in ~1 min. (90 hours in 1989!)

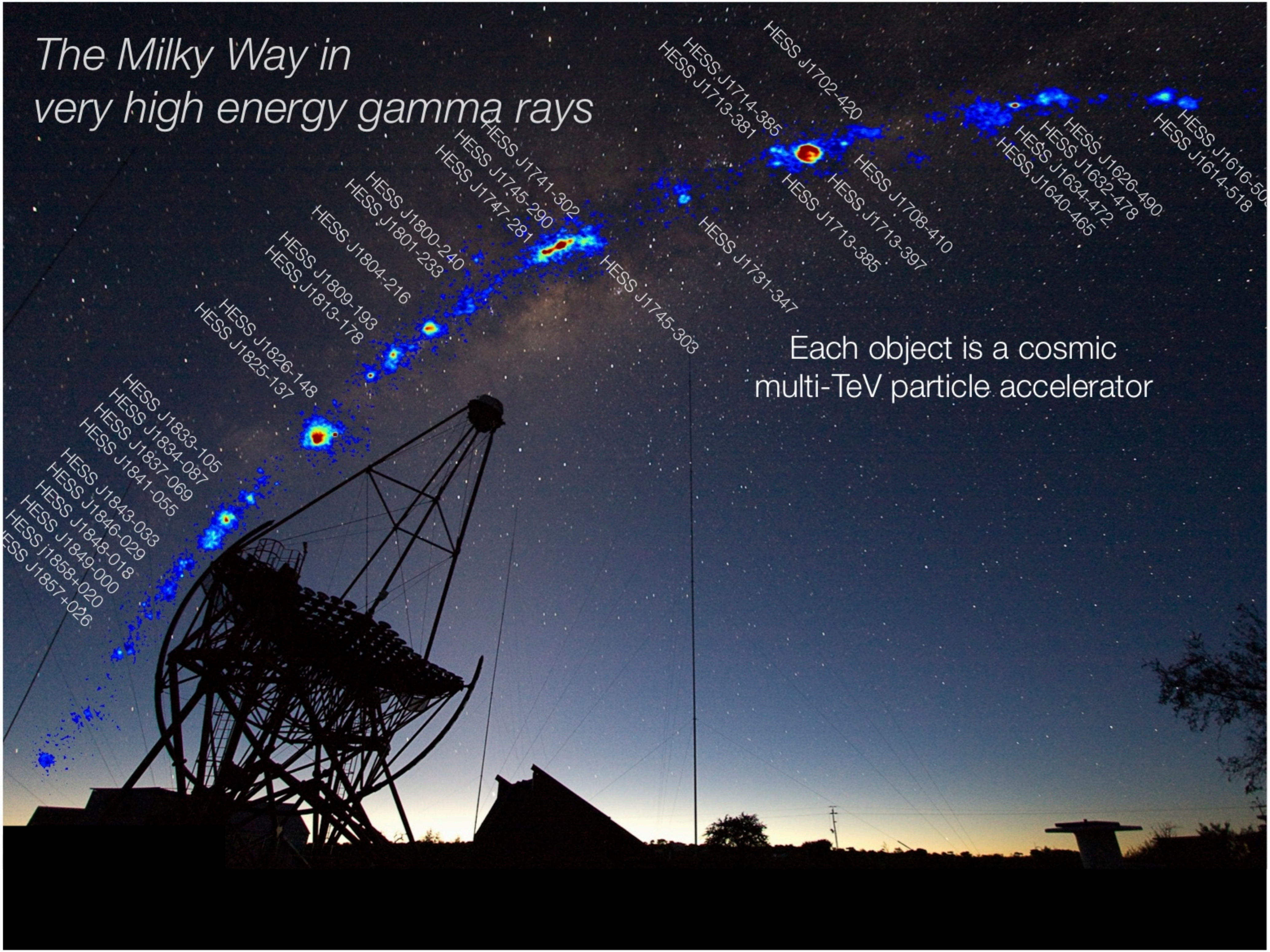
What are IACTs Good For?

- **Imaging** (better at higher E)
- **Spectroscopy** (better at higher E)
- **Short-timescale variability** (better at lower E)

- <u>NOT</u>
  - Long-timescale variability/monitoring
    - Sparsely sampled light-curves (moon, sun, weather)
  - Very extended emission (>> 1°, limited FoV)
  - Precision measurements at <<100 GeV (shower fluc.)

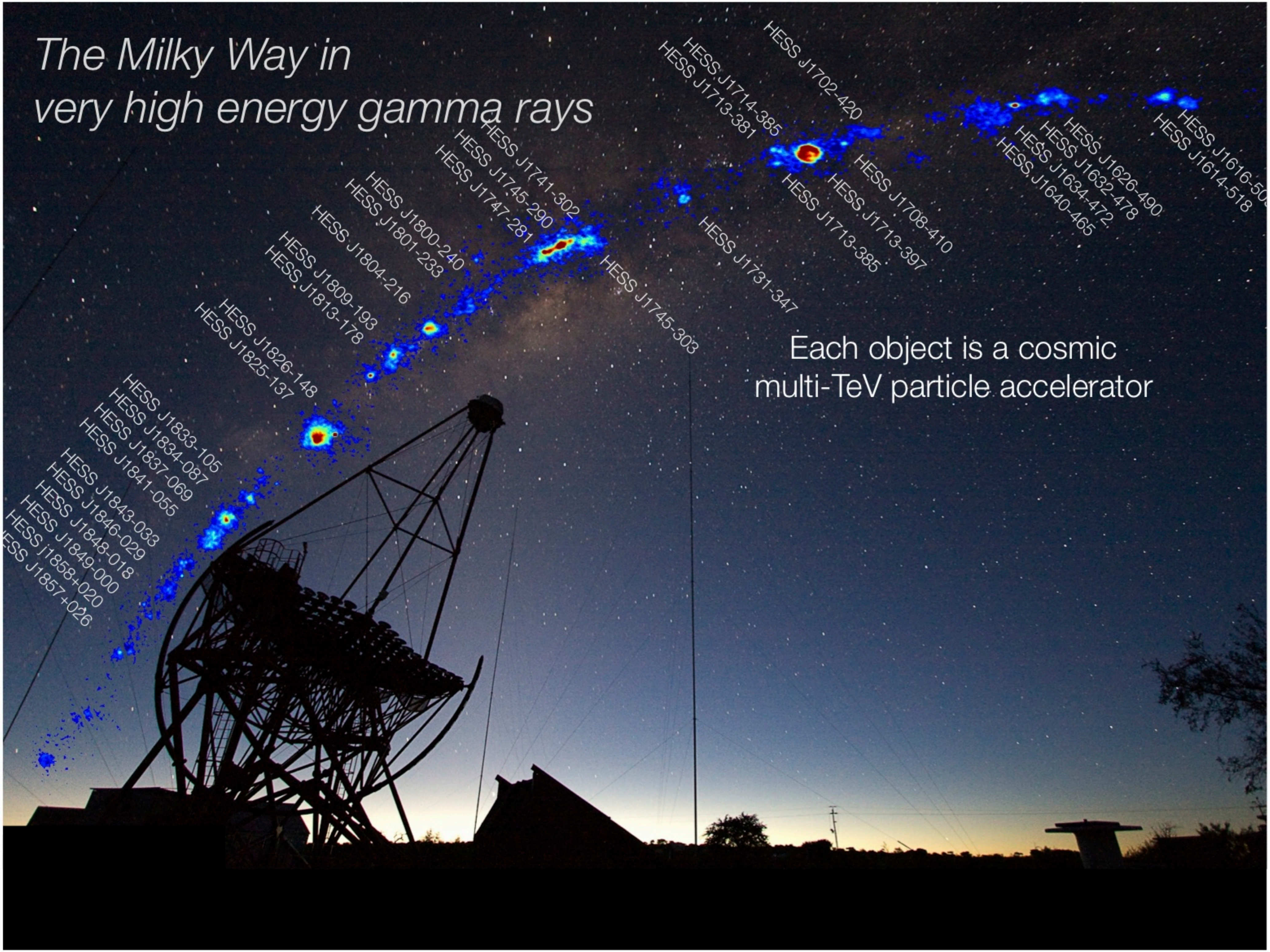
  - **Fermi** can do these things better <100 GeV
  - **HAWC** will (hopefully) do them > a few TeV


The Milky Way in
very high energy gamma rays


The Milky Way in
very high energy gamma rays
Each object is a cosmic
multi-TeV particle accelerator
HESS J1702-420
HESS J1714-385
HESS J1713-381
HESS J1741-302
HESS J1745-290
HESS J1747-281
HESS J1800-240
HESS J1801-233
HESS J1804-216
HESS J1809-193
HESS J1813-178
HESS J1826-148
HESS J1825-137
HESS J1833-105
HESS J1834-087
HESS J1837-069
HESS J1841-055
HESS J1843-033
HESS J1846-029
HESS J1848-018
HESS J1849-000
HESS j1858+020
HESS J1745-303
HESS J1731-347
HESS J1713-385
HESS J1713-397
HESS J1708-410
HESS J1640-465
HESS J1634-472
HESS J1632-478
HESS J1626-490
HESS J1614-518

Questions?

+ a few minute break



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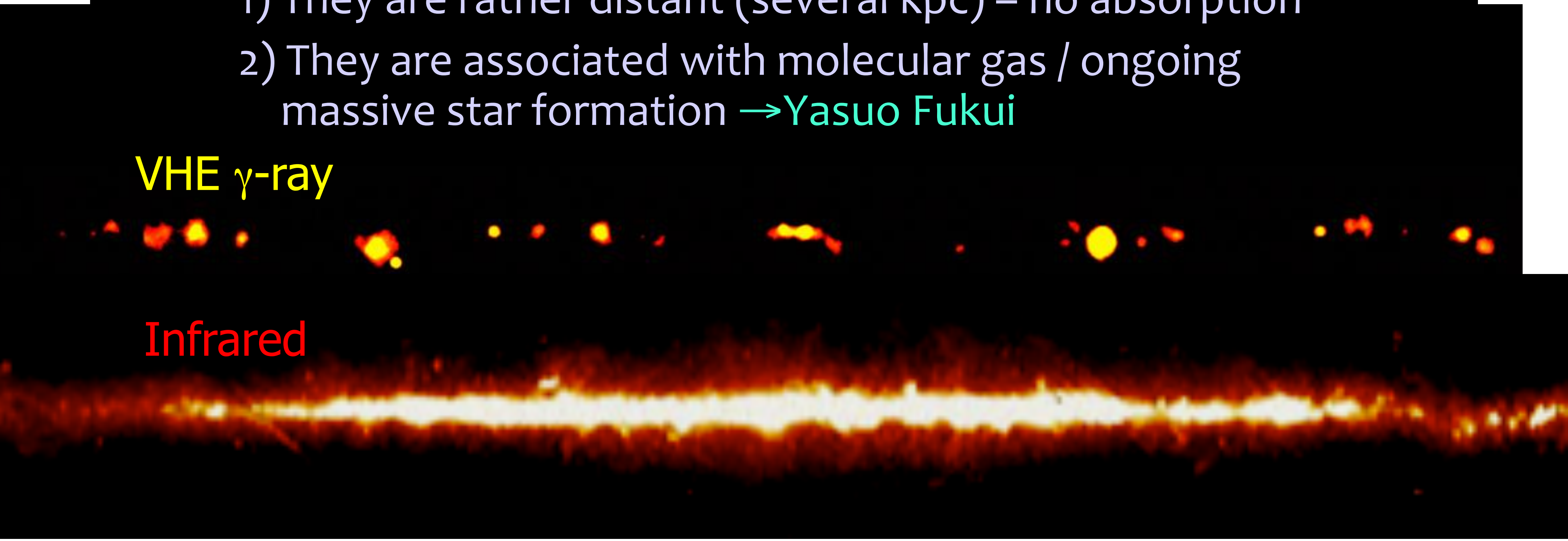
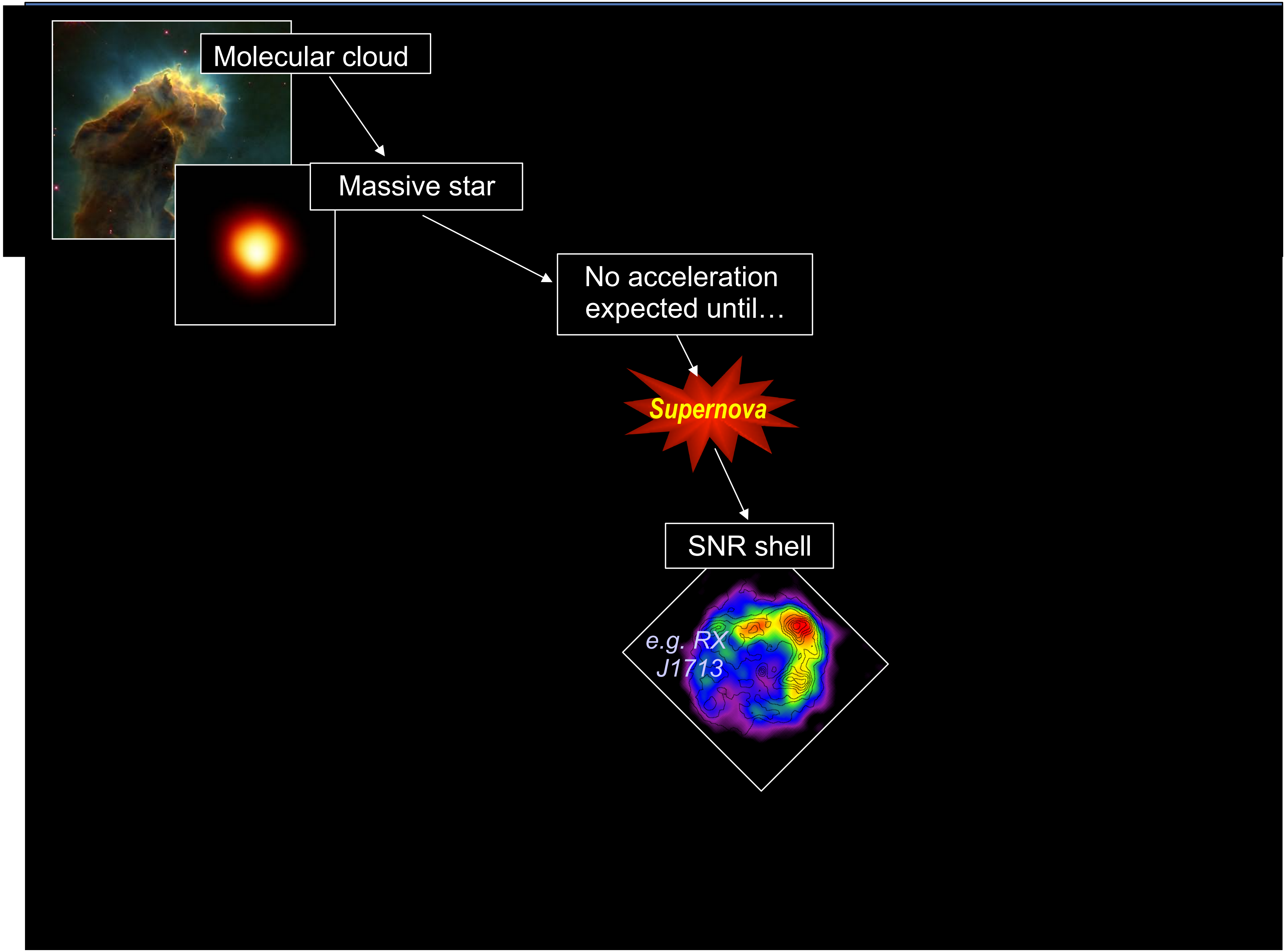
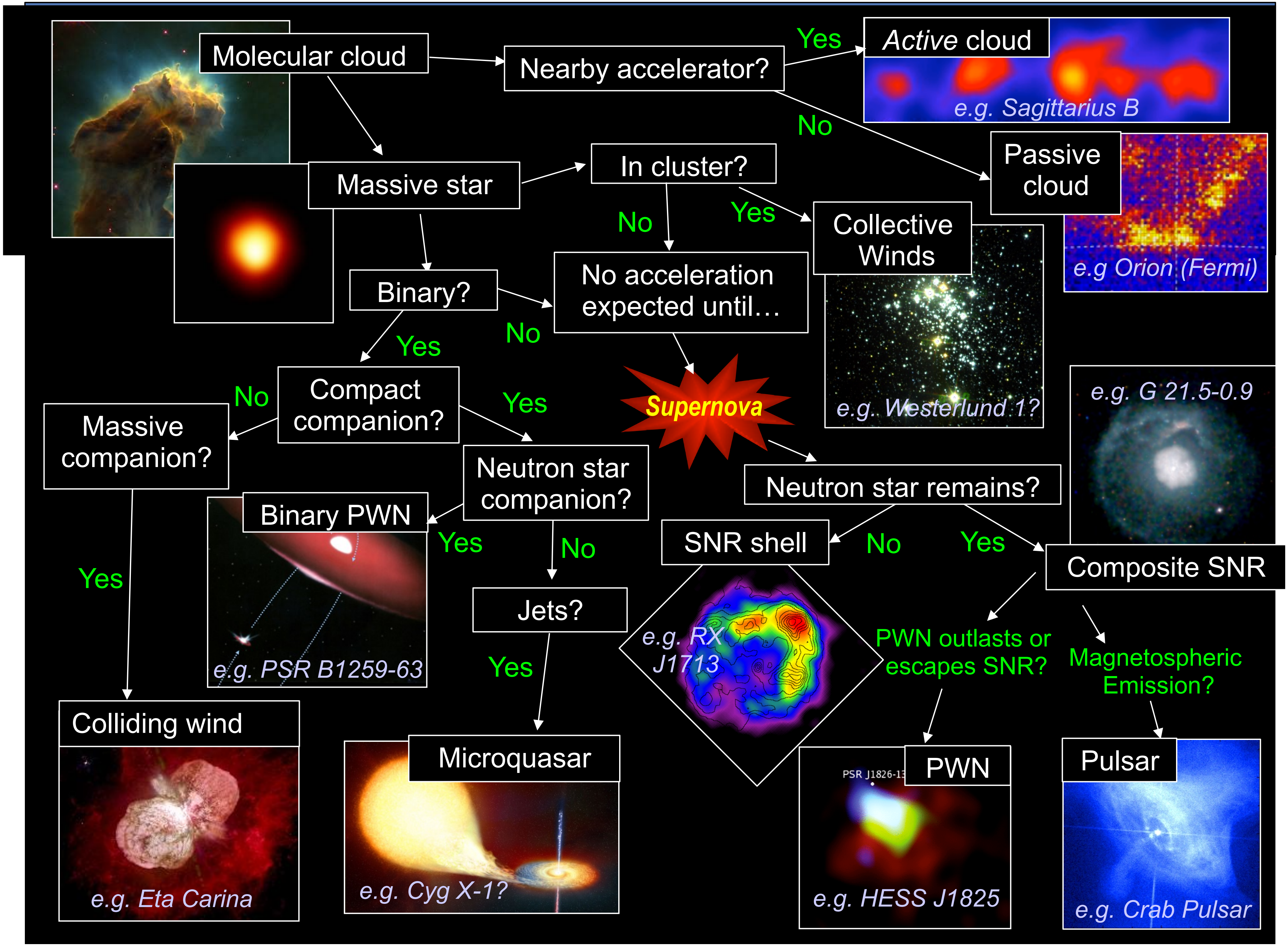
HESS J1634-472
HESS J1632-478
HESS J1626-490
HESS J1614-518

What are these Objects?

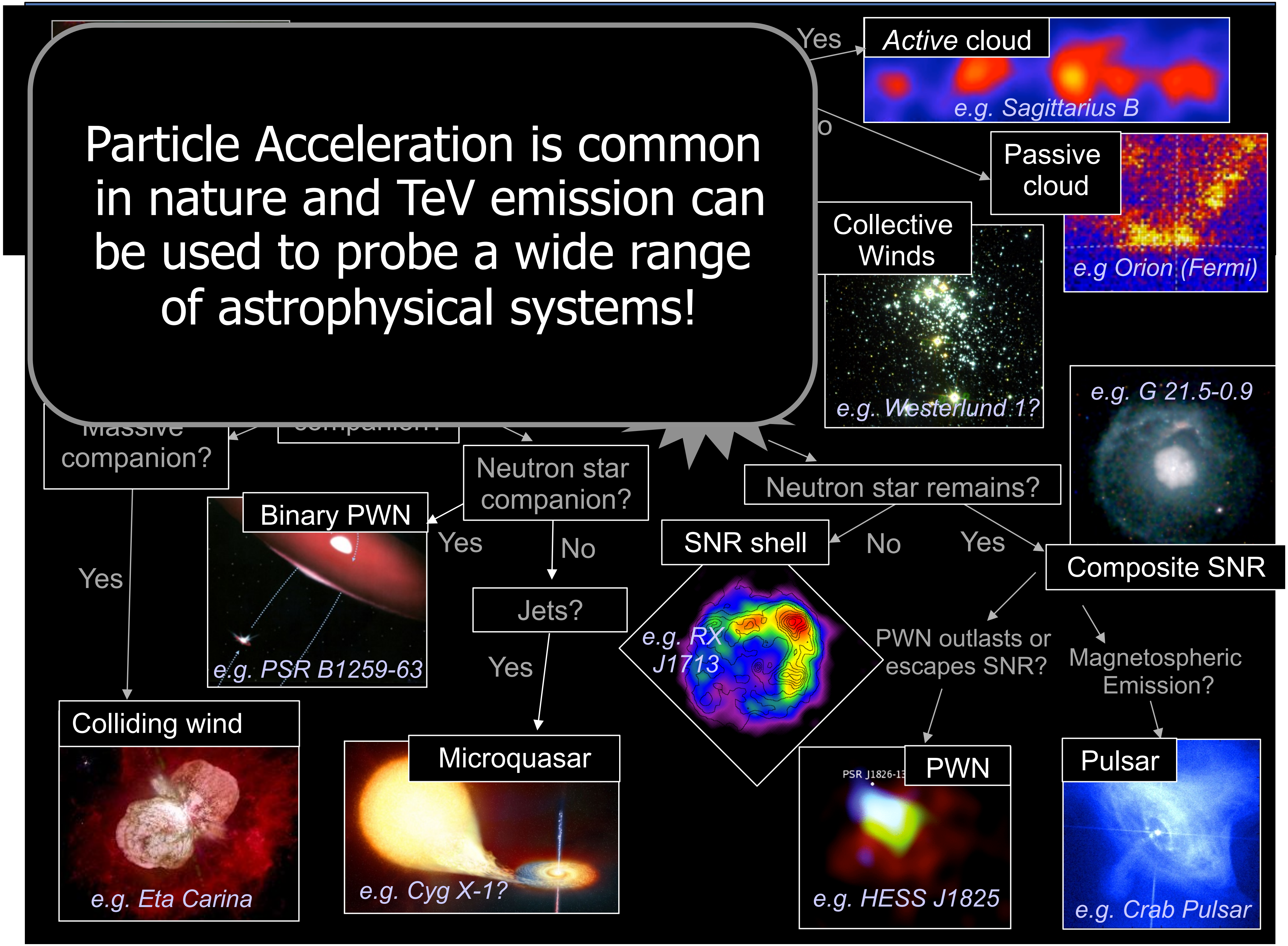
- Sites of particle acceleration
  - TeV emission requires >TeV particles (*cosmic rays*)
  - Associated with shocks? (DSA? →Tony Bell)
- Tightly clustered along the galactic plane
  1) They are rather distant (several kpc) – no absorption
  2) They are associated with molecular gas / ongoing massive star formation →Yasuo Fukui



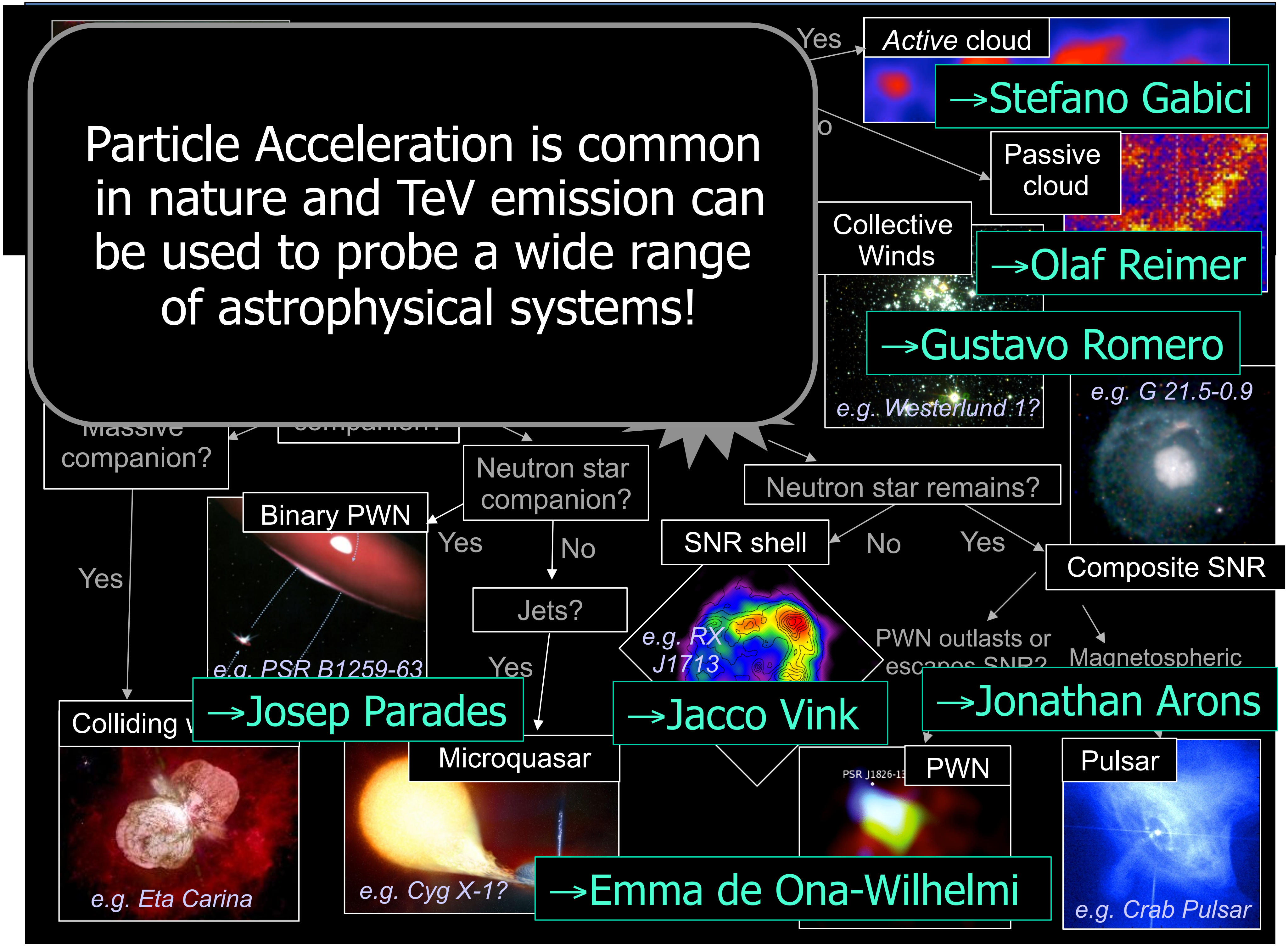

Molecular cloud
Massive star
No acceleration expected until…
Supernova
SNR shell
e.g. RX J1713



Molecular cloud
Nearby accelerator?
Yes
Active cloud
e.g. Sagittarius B
No
Passive cloud
e.g Orion (Fermi)
Massive star
In cluster?
No
Yes
Collective Winds
e.g. Westerlund 1?
Binary?
No acceleration expected until…
No
Yes
Compact companion?
No
Yes
Massive companion?
Supernova
e.g. G 21.5-0.9
Neutron star companion?
Neutron star remains?
Binary PWN
Yes
No
SNR shell
No
Yes
Composite SNR
e.g. PSR B1259-63
Yes
Jets?
e.g. RX J1713
PWN outlasts or escapes SNR?
Magnetospheric Emission?
Yes
Colliding wind
e.g. Eta Carina
Microquasar
e.g. Cyg X-1?
PWN
PSR J1826-13
e.g. HESS J1825
Pulsar
e.g. Crab Pulsar

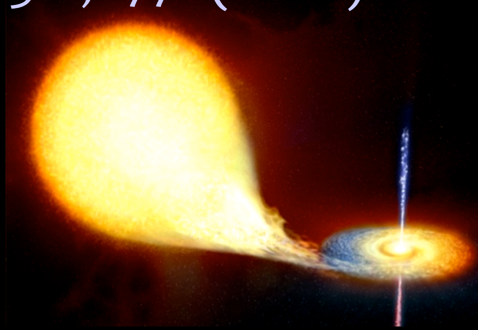


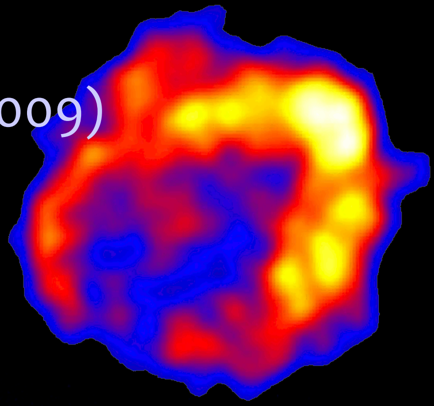
Particle Acceleration is common in nature and TeV emission can be used to probe a wide range of astrophysical systems!
Yes
Active cloud
e.g. Sagittarius B
Passive cloud
e.g Orion (Fermi)
Collective Winds
e.g. Westerlund 1?
e.g. G 21.5-0.9
companion?
Neutron star companion?
Binary PWN
e.g. PSR B1259-63
Yes
No
Jets?
Yes
Yes
Colliding wind
e.g. Eta Carina
Microquasar
e.g. Cyg X-1?
Neutron star remains?
SNR shell
No
Yes
Composite SNR
e.g. RX J1713
PWN outlasts or escapes SNR?
Magnetospheric Emission?
PWN
PSR J1826-13
e.g. HESS J1825
Pulsar
e.g. Crab Pulsar

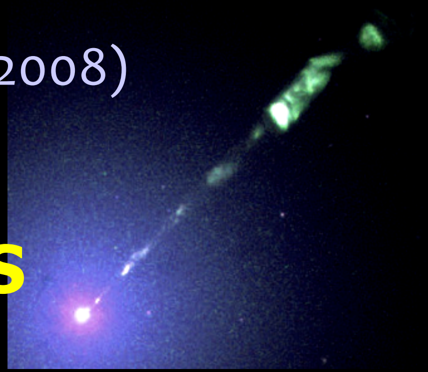

Particle Acceleration is common in nature and TeV emission can be used to probe a wide range of astrophysical systems!
Yes
Active cloud
→Stefano Gabici
Passive cloud
Collective Winds
→Olaf Reimer
→Gustavo Romero
e.g. Westerlund 1?
e.g. G 21.5-0.9
companion?
Neutron star companion?
Neutron star remains?
Binary PWN
Yes
No
SNR shell
No
Yes
Composite SNR
Yes
Jets?
e.g. RX J1713
PWN outlasts or
Magnetospheric
e.g. PSR B1259-63
Yes
Colliding
→Josep Parades
→Jacco Vink
→Jonathan Arons
Microquasar
PSR J1826-13
PWN
Pulsar
e.g. Eta Carina
e.g. Cyg X-1?
→Emma de Ona-Wilhelmi
e.g. Crab Pulsar

TeV Astronomy: Highlights

- *Microquasars:* Science 309, 746 (2005), Science 312, 1771 (2006)
- *Pulsars*: Science 322, 1221 (2008)
- *Supernova remnants*: Nature 432, 75 (2004)
- *The Galactic Centre*: Nature 439, 695 (2006)
- *Galactic Survey:* Science 307, 1839 (2005)
- *Starbursts:* Nature 462, 770 (2009), Science 326,1080 (2009)
- *AGN*: Science 314,1424 (2006), Science 325, 444 (2009)
- *EBL*: Nature 440, 1018 (2006), Science 320, 752 (2008)
- *Dark Matter:* Phys Rev Letters 96, 221102 (2006)
- *Lorentz Invariance*: Phys Rev Letters 101, 170402 (2008)
- *Cosmic Ray Electrons*: Phys Rev Letters (2009)



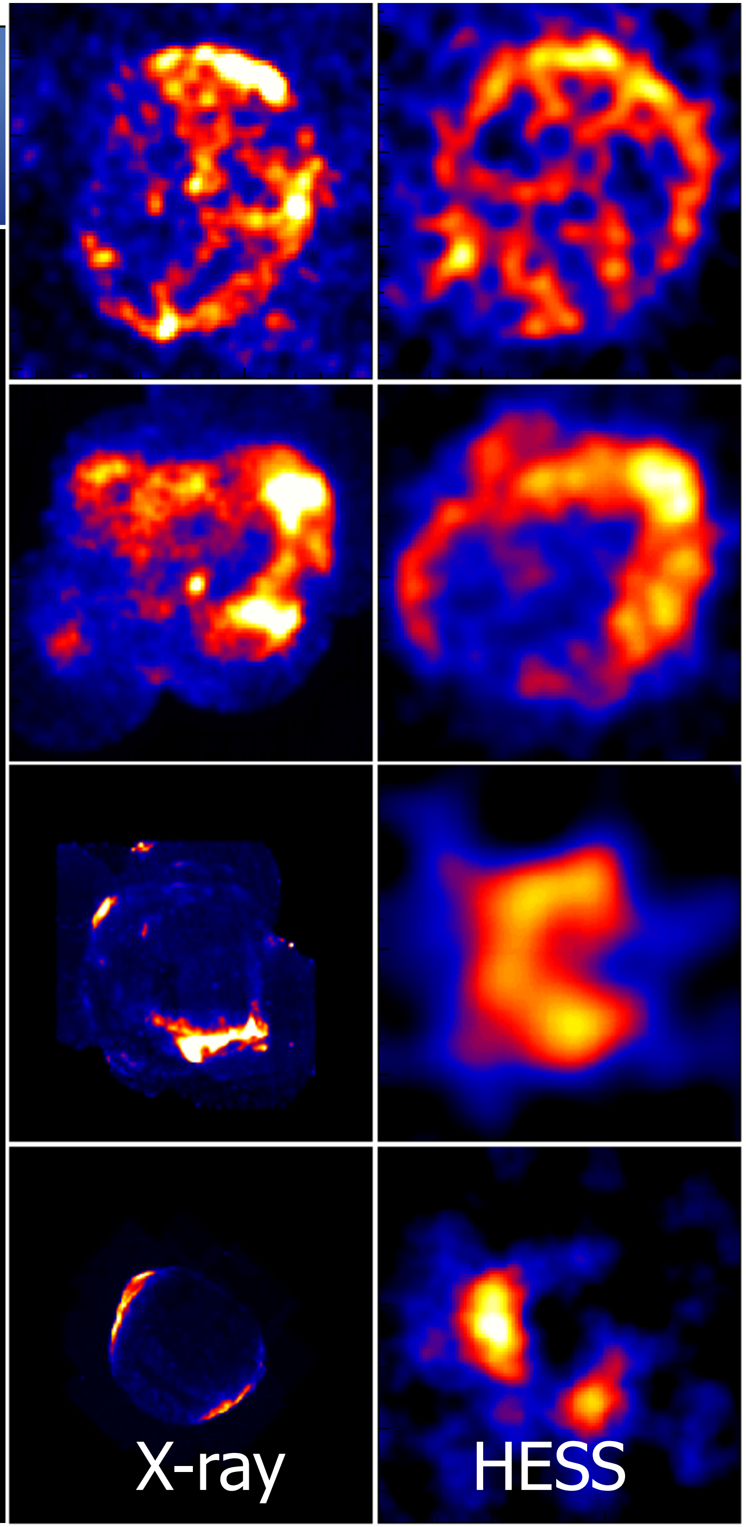




Results from **HESS, MAGIC** and **VERITAS**

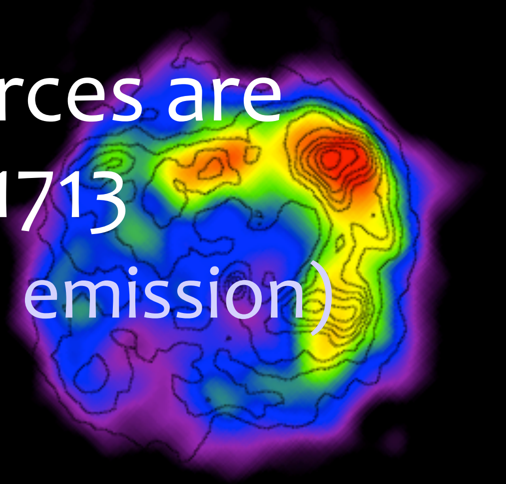
Supernova Remnants

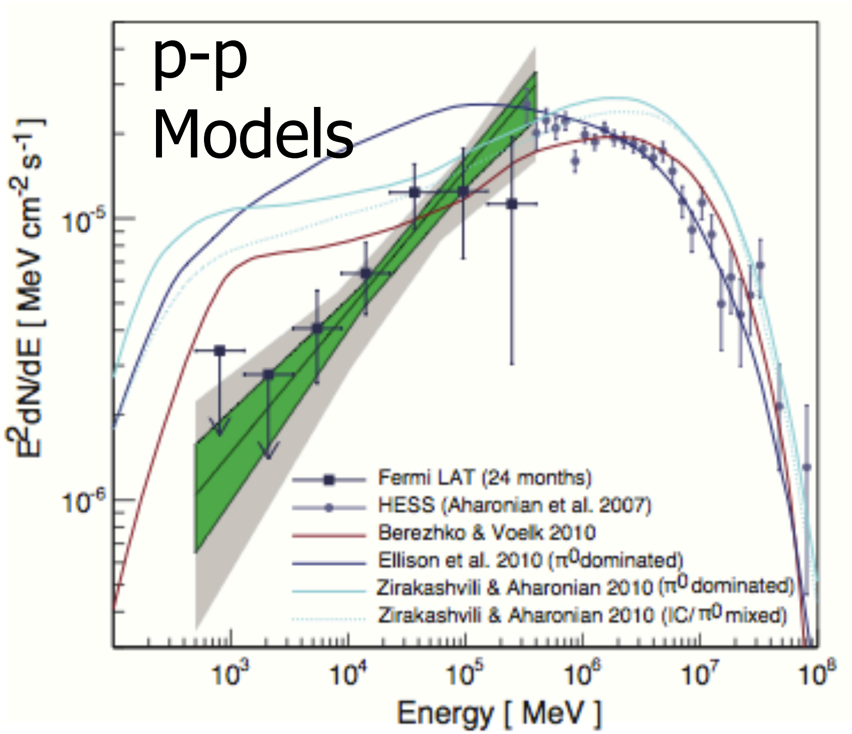
- But what about SNR?
- Are they the sources of the Galactic cosmic rays?
- Many SNRs now seen at TeV – including five resolved shells ➔
- Correlations with non-thermal (synchrotron) X-ray emission
- BUT – electrons or protons as the parents?

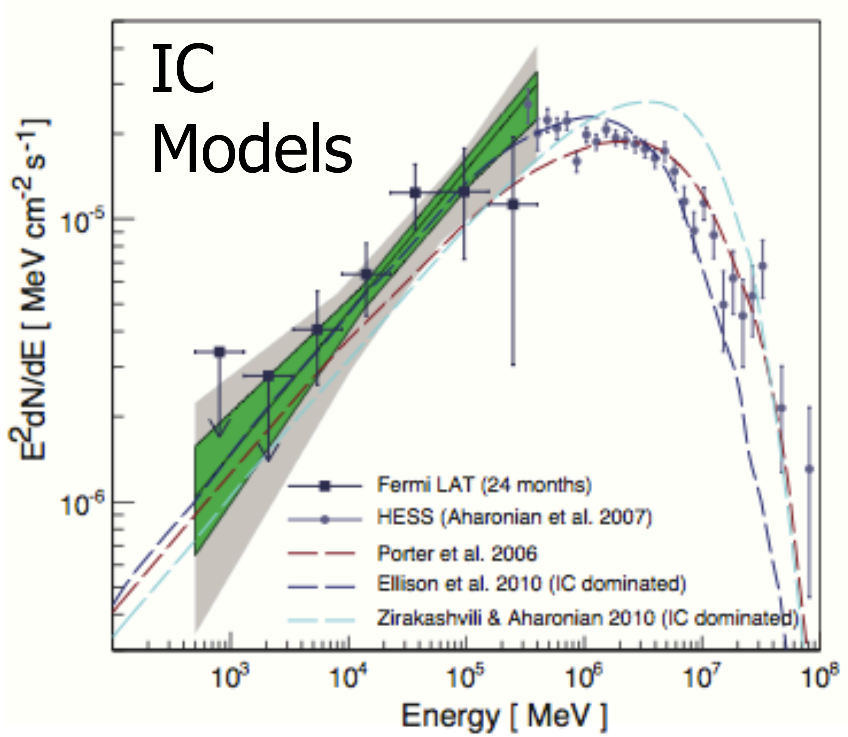


Protons and Nuclei?

- Plausible that the brightest TeV sources are dominated by IC emission, e.g. RX J1713
  - low density environments (no thermal emission)
  - high radiative efficiency for electrons





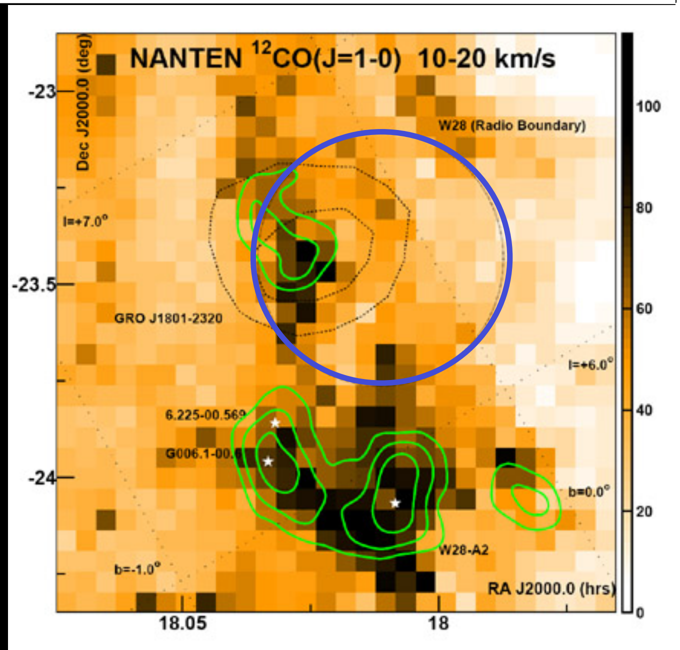


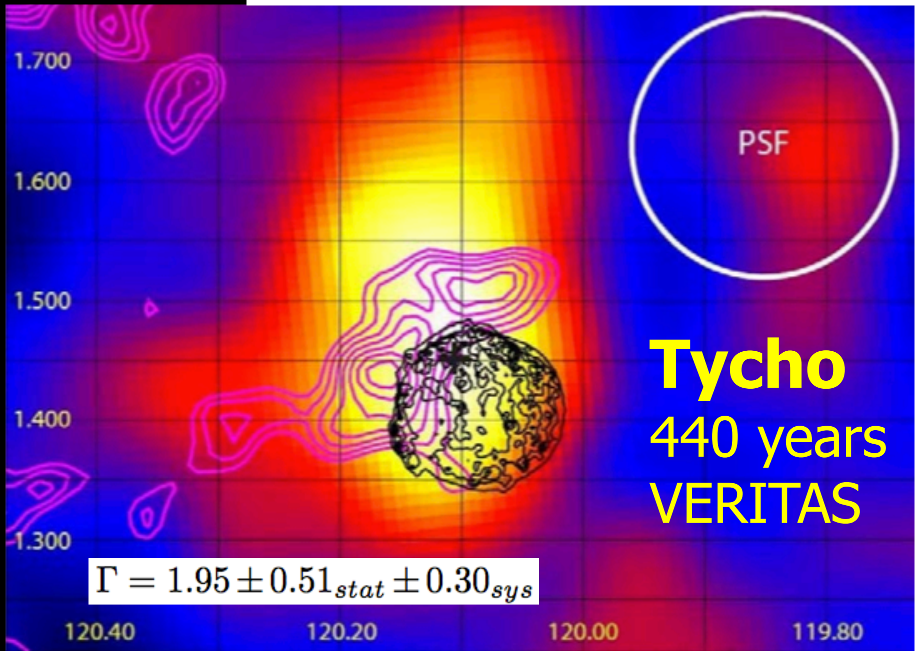
SNR and Clouds

- $F_{pp} \sim 4\times10^{-11} (E_{CR} / 10^{50}$ erg$) (n$ / 1 cm$^{-3}) (d$ / 1 kpc$)^{-2}$ erg/cm/s^2
  - ADV 1994, Dense targets?
- Molecular clouds near SNR
  - SNR will overtake cloud, and
  - Highest energy CRs may escape ahead of the shock (early)
- Many TeV candidates now
  - e.g. **W 28**, IC 443, W49B, W 51C … **and Tycho's SNR**

Bremsstrahlung? *(need n>240 cm^{-3} for dominance of Bremss. over IC (on the CMB) and n_e / n_p > 1/3)*

W 28
40 ky
HESS

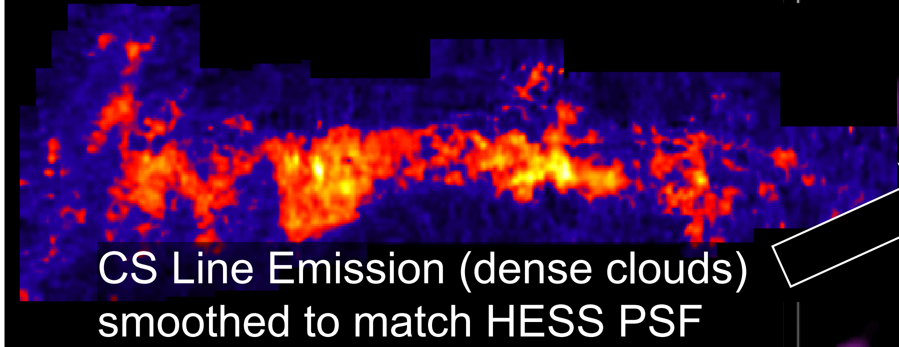


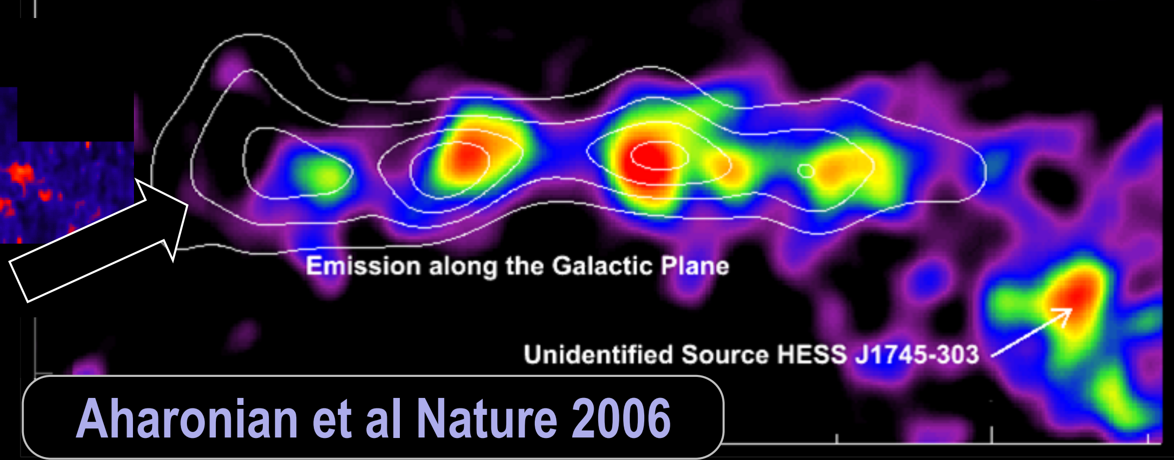


Tycho
440 years
VERITAS

The Galactic Centre Ridge

- Strong candidate for p-p interactions - the Galactic Centre (Central Molecular Zone):
  - But which accelerator? Sgr A*, Sgr A East?



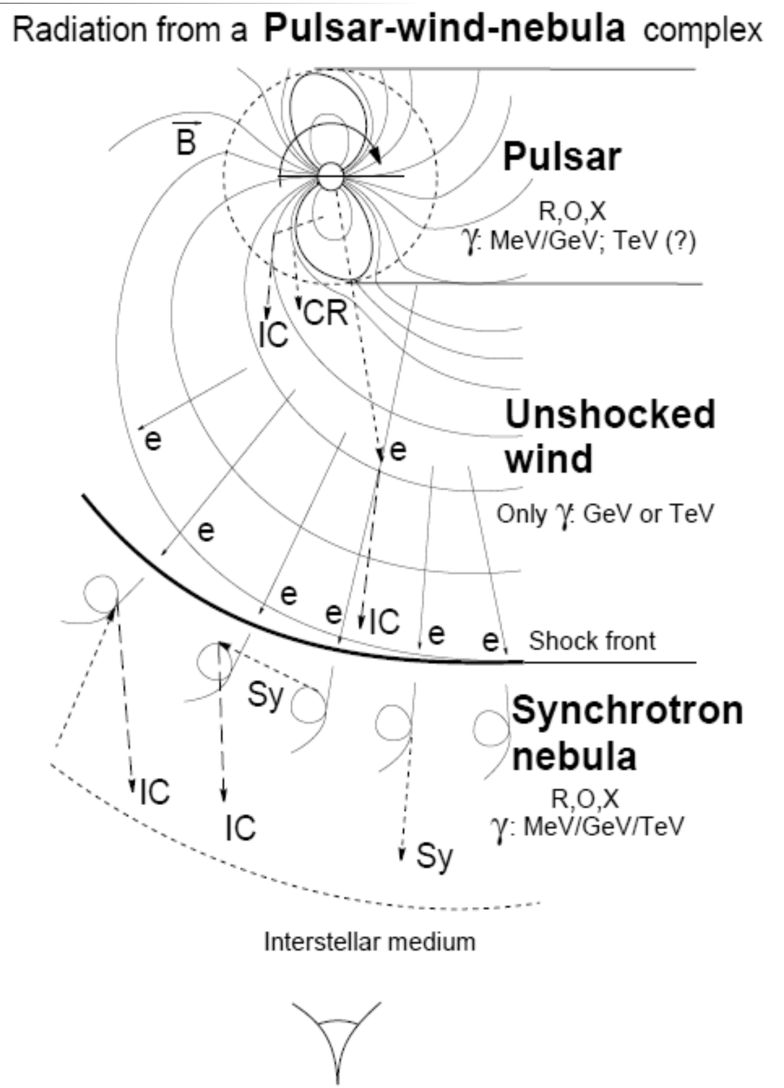


- Wish list
  - Much wider energy coverage
  - Better angular resolution
  - Much deeper galactic survey

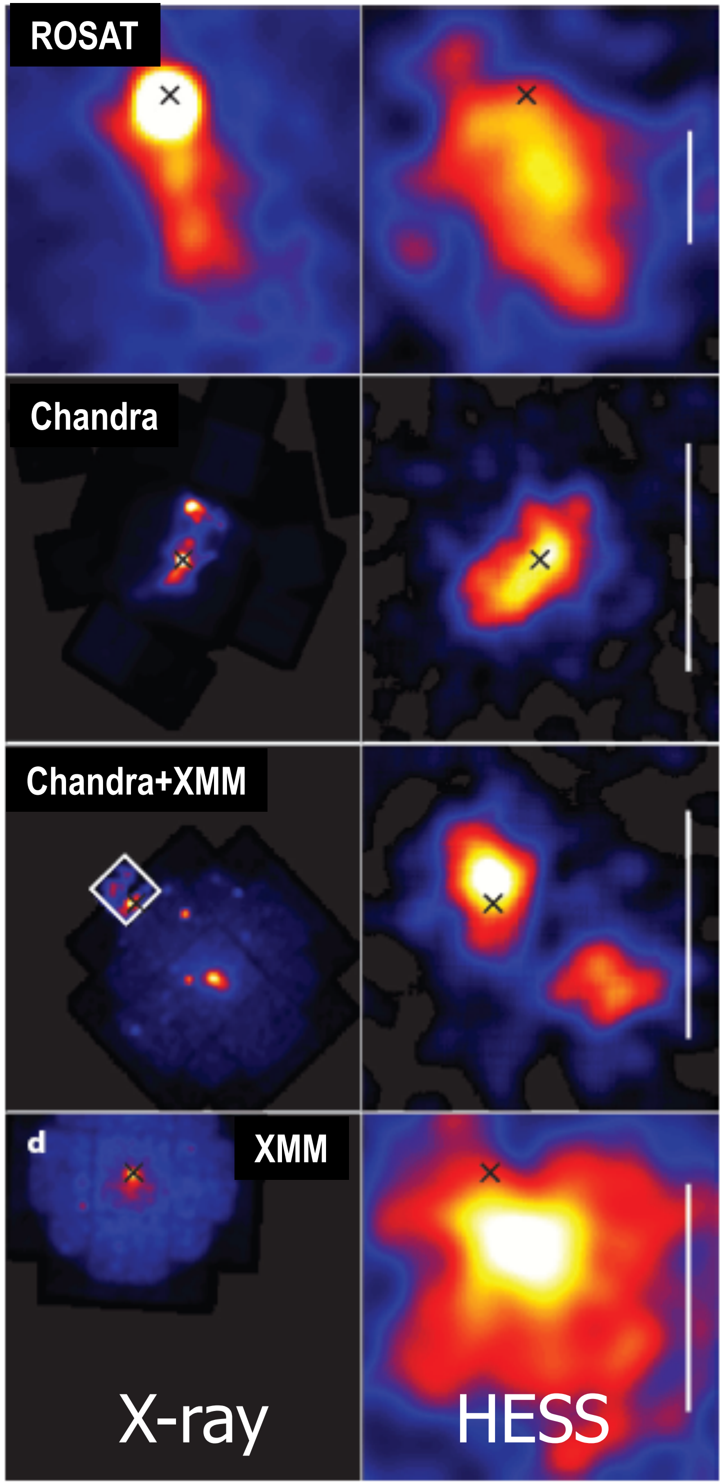
→Olaf Reimer

→Roland Crocker

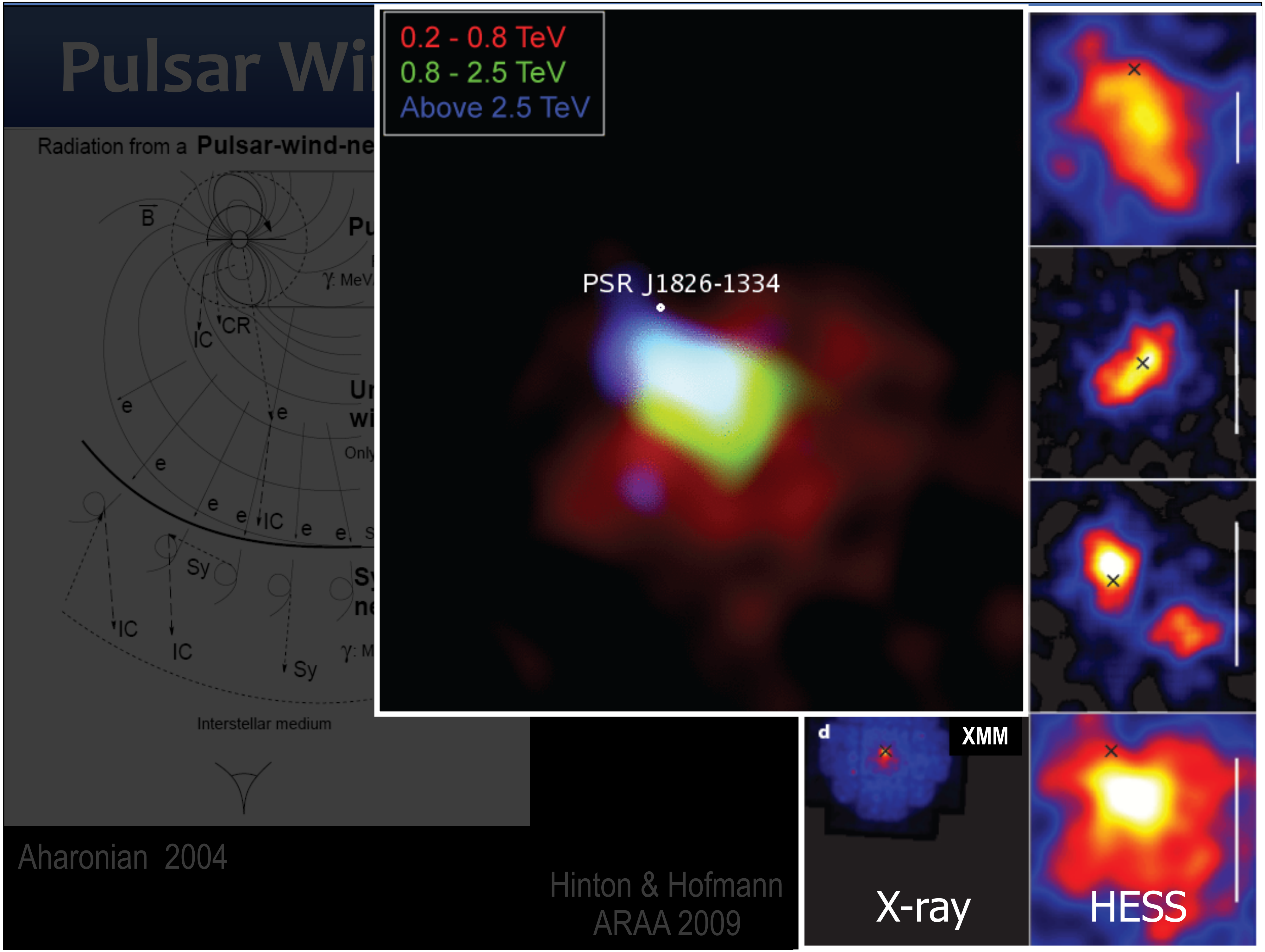
Pulsar Wind Nebulae



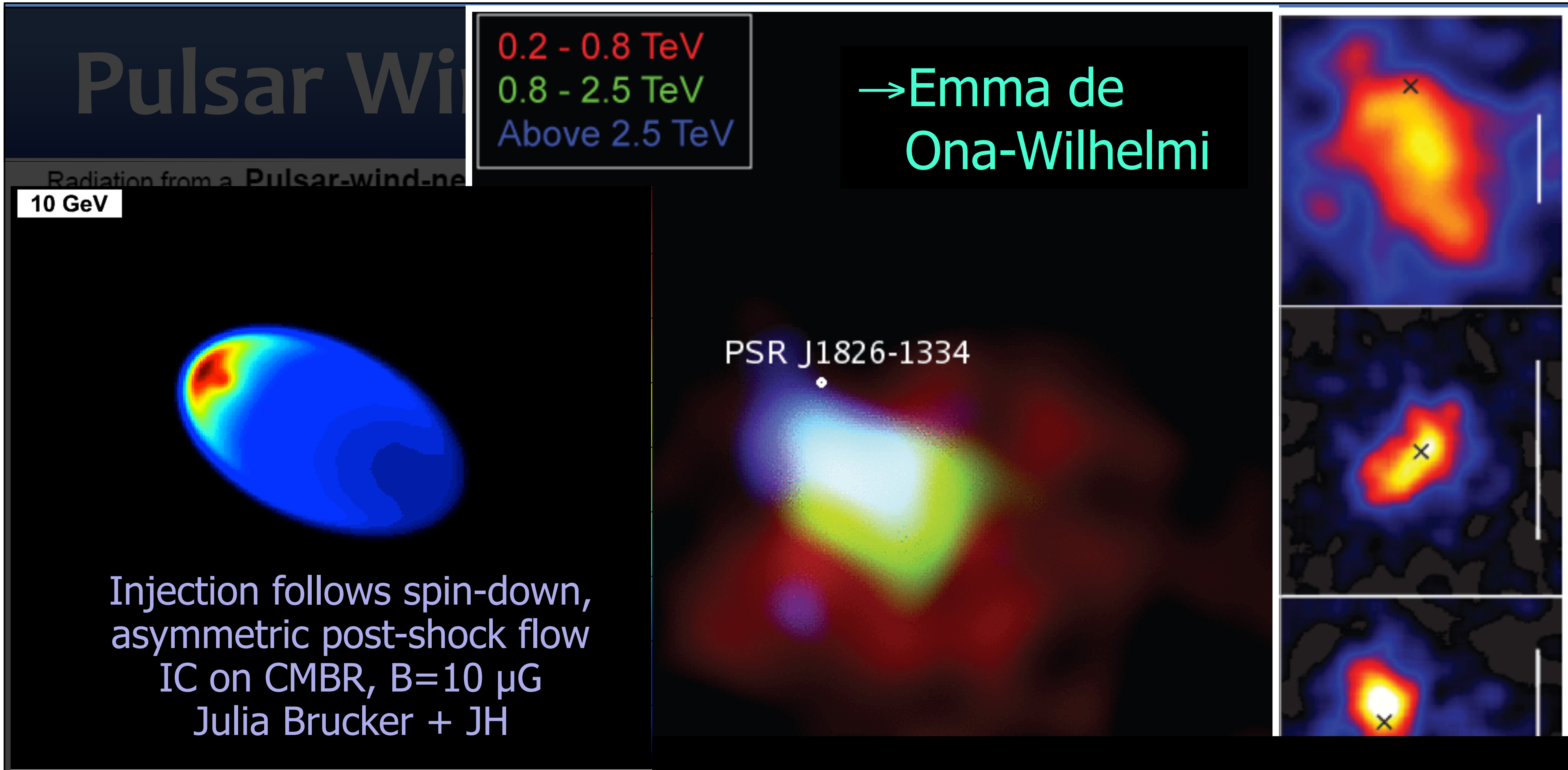
Aharonian 2004



Hinton & Hofmann ARAA 2009



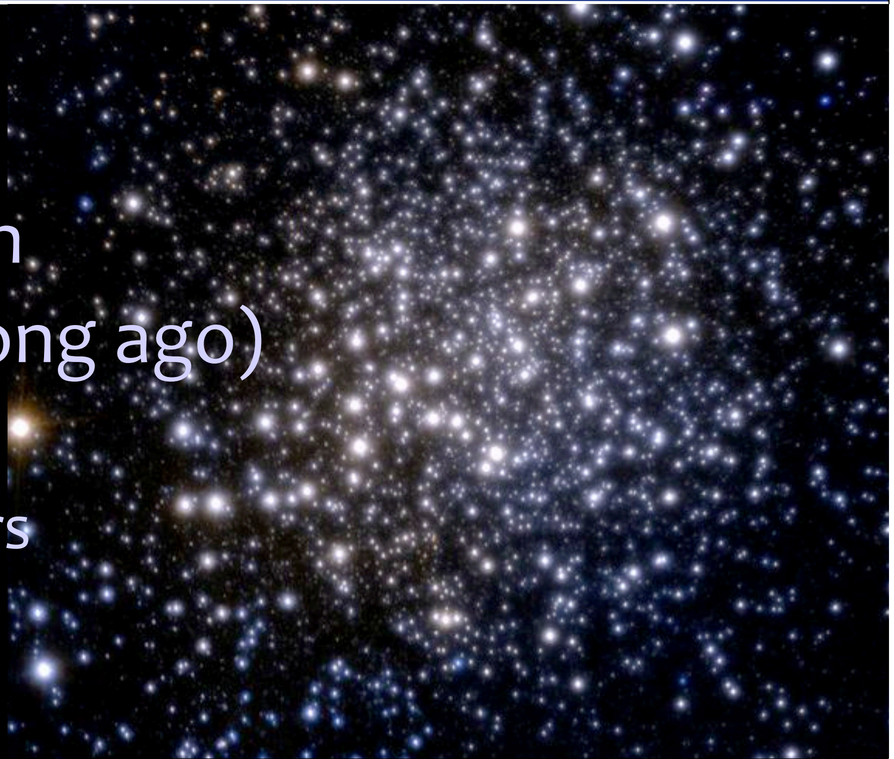
Pulsar Wi
Radiation from a Pulsar-wind-ne
B
CR
IC
e
Sy
Interstellar medium
Aharonian 2004
0.2 - 0.8 TeV
0.8 - 2.5 TeV
Above 2.5 TeV
PSR J1826-1334
d
XMM
X-ray
HESS
Hinton & Hofmann
ARAA 2009



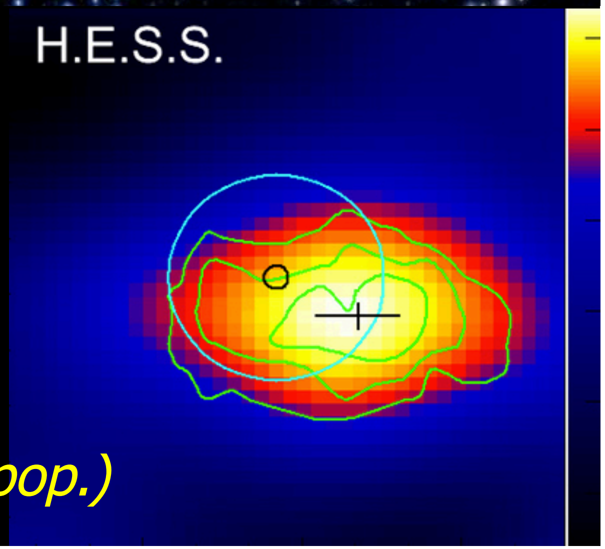
» IC & Synchrotron emission of VHE electrons

- **E_{sync} ~ 2 $(E_e/50\ \mathrm{TeV})^2$ (B/10 μG) keV**
- **E_{IC} ~ 1 $(E_e/10\ \mathrm{TeV})^2$ (on CMBR) TeV**
- **t_{cool} ~10^4 $(B/10\ \mu G)^{-2}$ $(E_e/10\ \mathrm{TeV})^{-1}$ years**
- ***PSR J1826-1334 was born ~2 10^4 years OK***

Something Completely Different? *58*

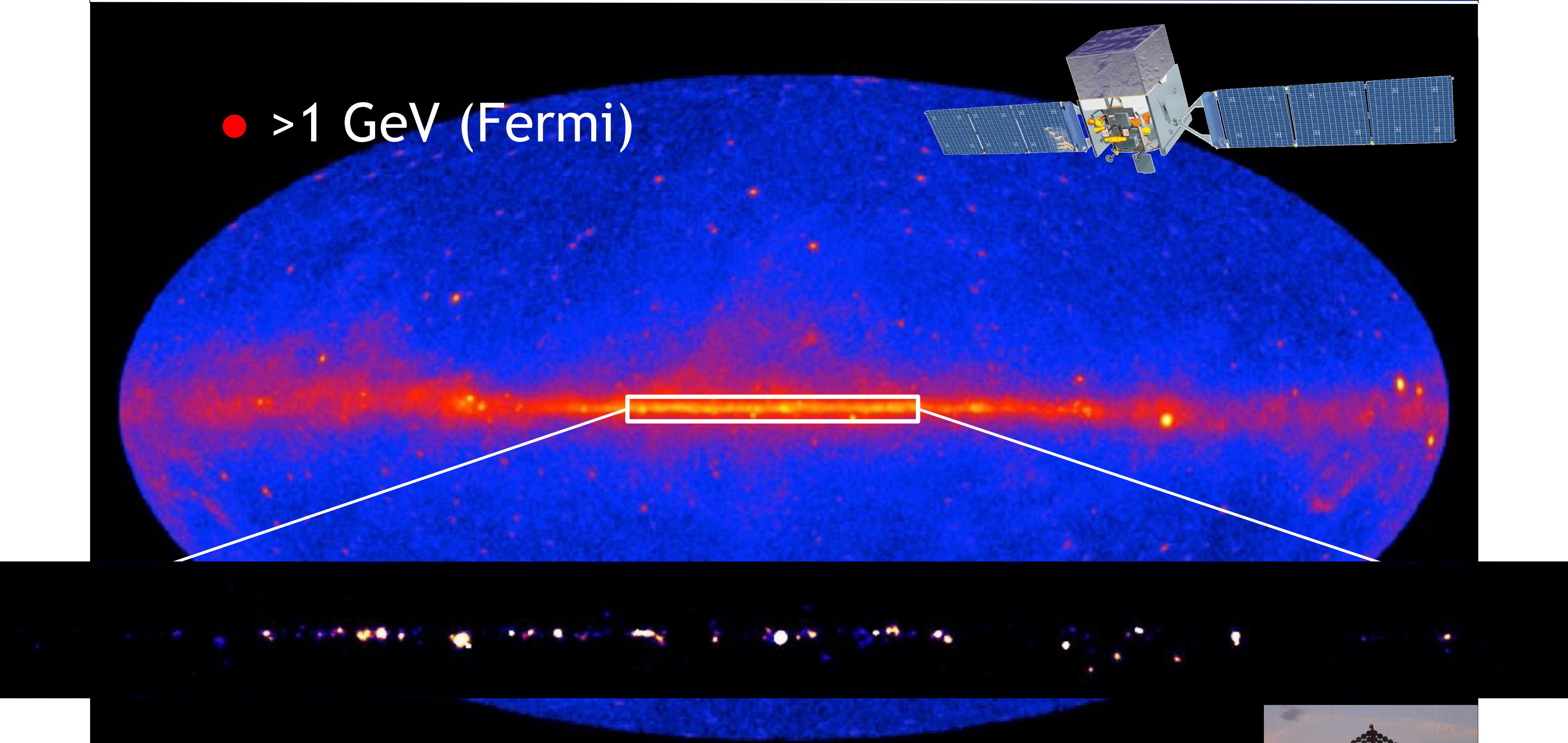


- Globular Clusters
  - very old stellar population
  - no massive stars (all SN long ago)
  - TeV emission?
    - perhaps millisecond pulsars
- Terzan 5
  - HESS detection 2011
    - Extended and offset emission
  - One theory – short GRB remnant
    - merger of two neutron stars
    - high-energy asymmetric explosion

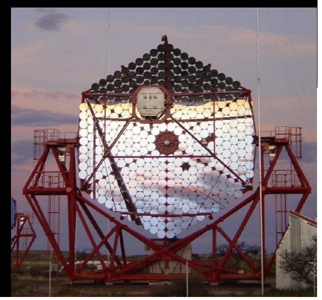


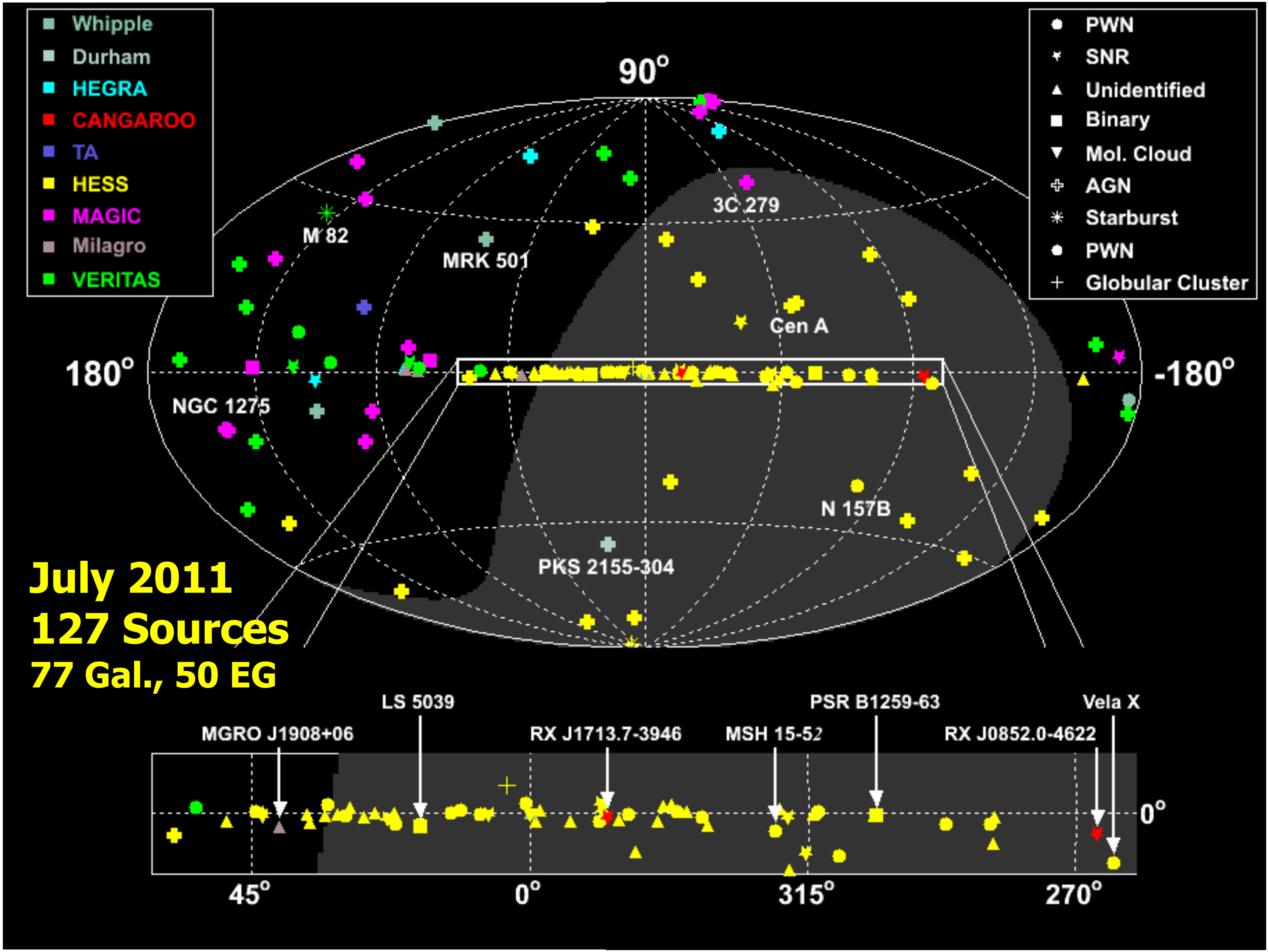
Chance coincidence? *(estimated as ≈10^{-4} from Gal. pop.)*

The High Energy Sky



• >5 GeV (Fermi) cf >200 GeV (HESS)



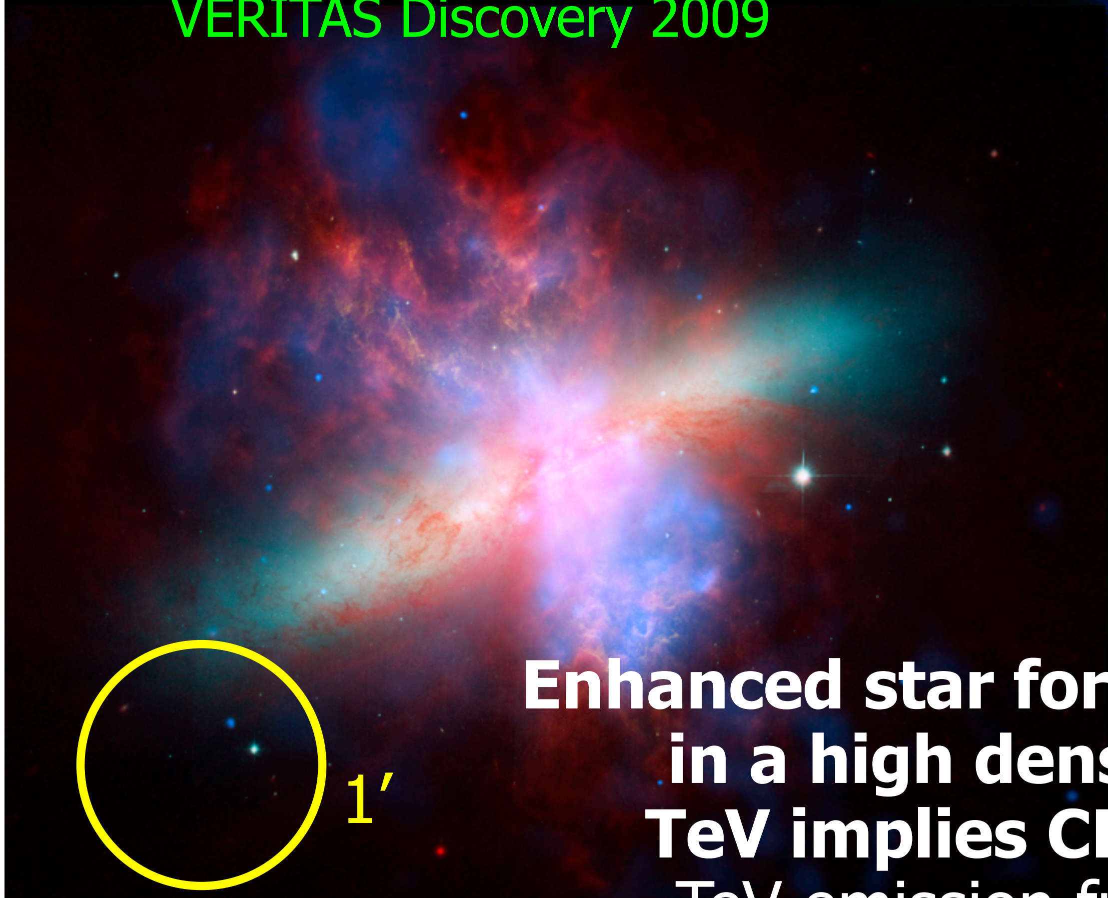


Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
PWN
SNR
Unidentified
Binary
Mol. Cloud
AGN
Starburst
PWN
Globular Cluster
90°
180°
-180°
M 82
MRK 501
3C 279
Cen A
NGC 1275
N 157B
PKS 2155-304
July 2011
127 Sources
77 Gal., 50 EG
LS 5039
PSR B1259-63
Vela X
MGRO J1908+06
RX J1713.7-3946
MSH 15-52
RX J0852.0-4622
0°
45°
0°
315°
270°

Starburst Galaxies

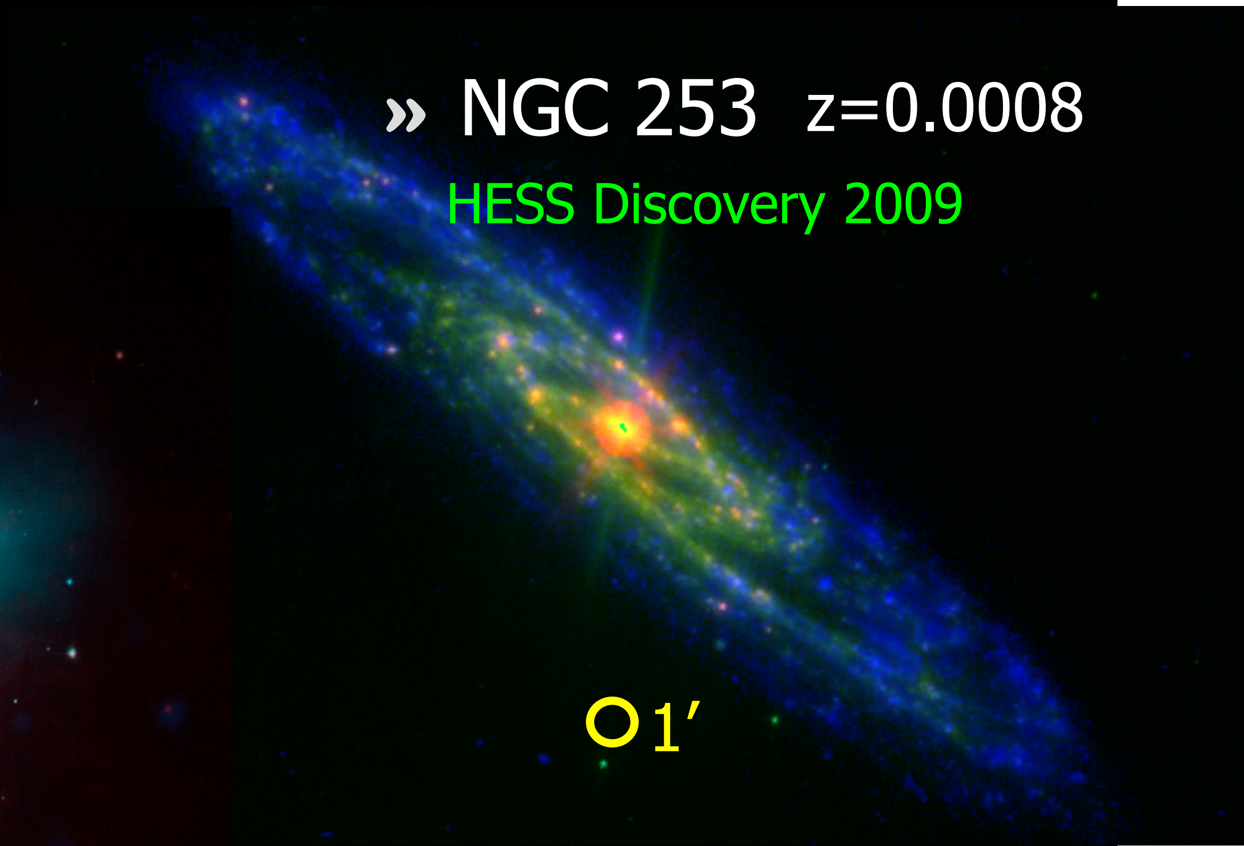
- M 82 z=0.0008

  VERITAS Discovery 2009



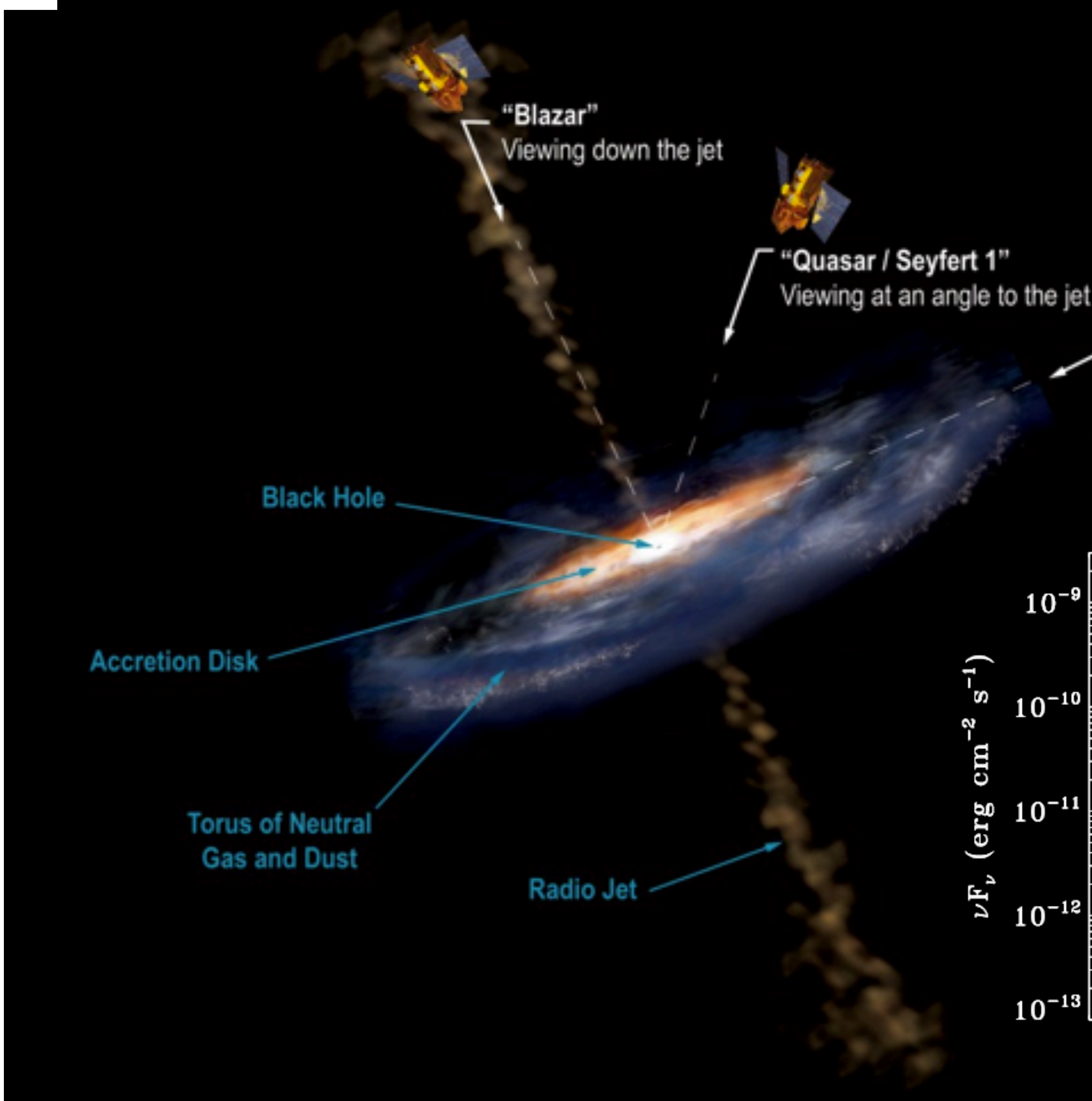
- » NGC 253 z=0.0008

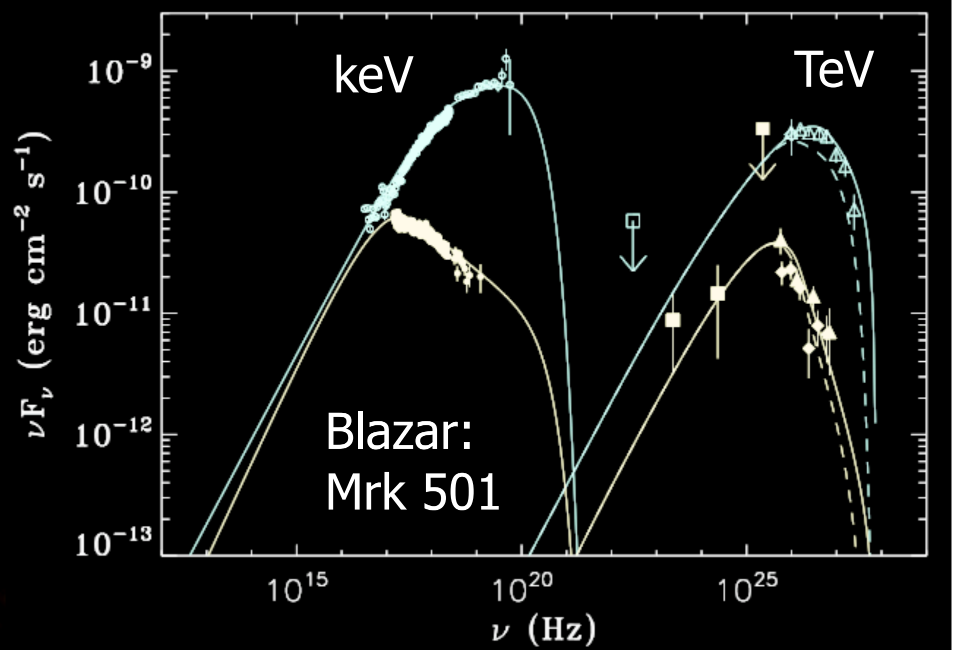
  HESS Discovery 2009



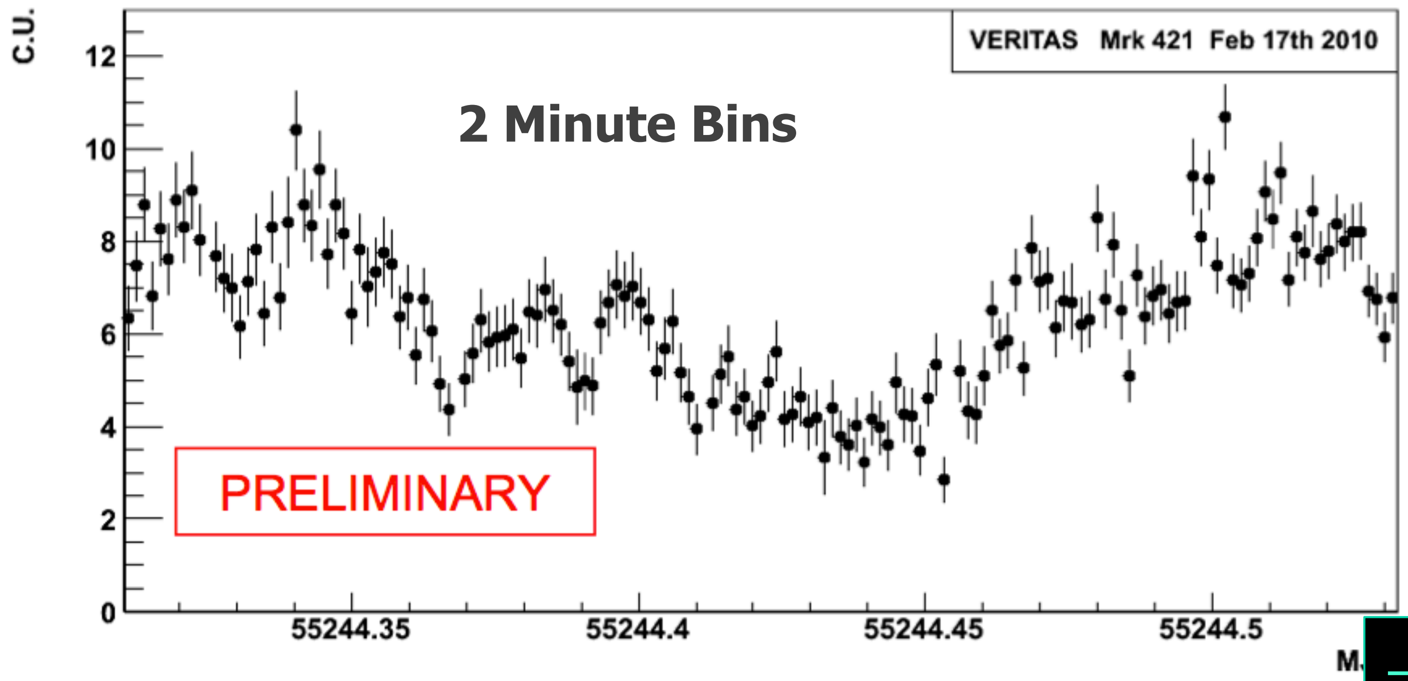
Enhanced star formation / supernova rate
in a high density starburst region
TeV implies CR density ~ SFR , but
TeV emission from π_0 inside starburst
or IC in superwind, …

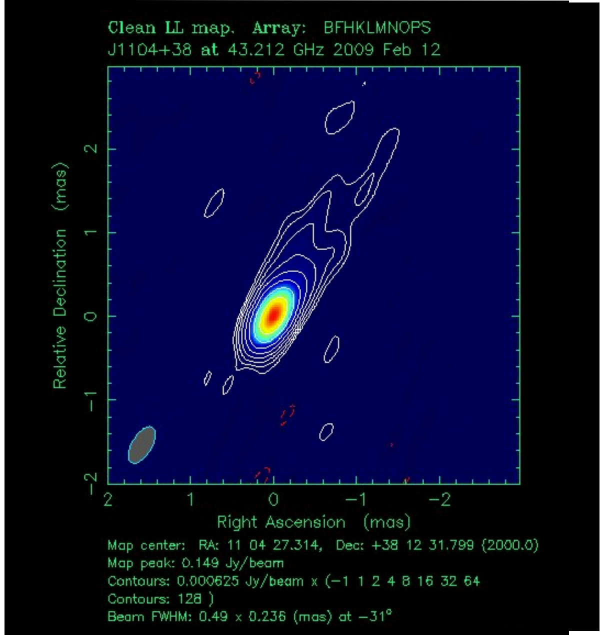
Active Galactic Nuclei





Blazars: e.g. Mrk 421

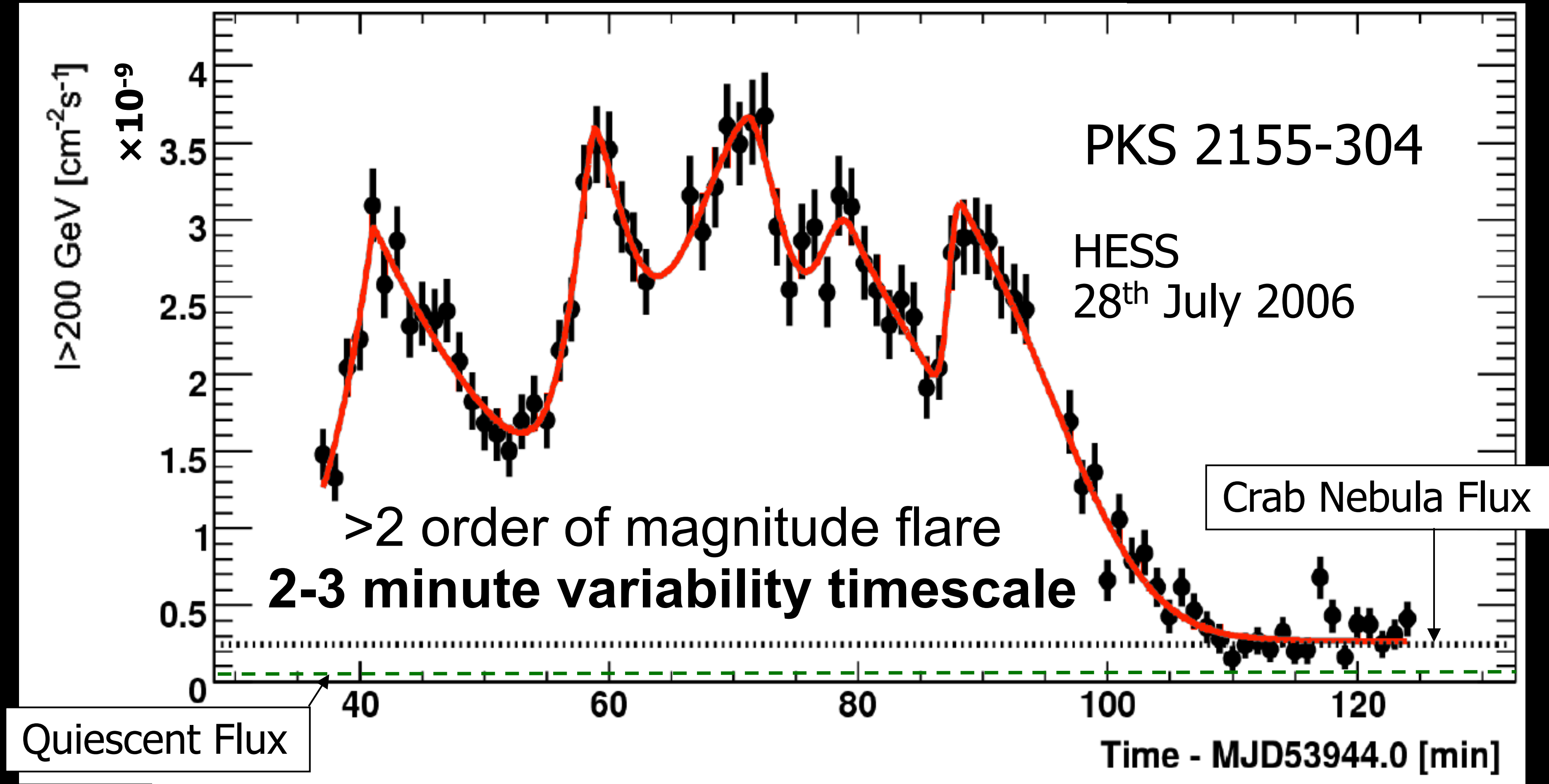




→Luigi Costamante

- One of the closest blazars – extremely bright
  - The first TeV emitting AGN – "a TeV blazar"
  - Classified as a HBL = High Frequency Peaked BL-Lac Object
- Very short timescale TeV variability
  - Origin? internal shocks in jet? driven by accretion variability?

Blazars: e.g PKS 2155-304

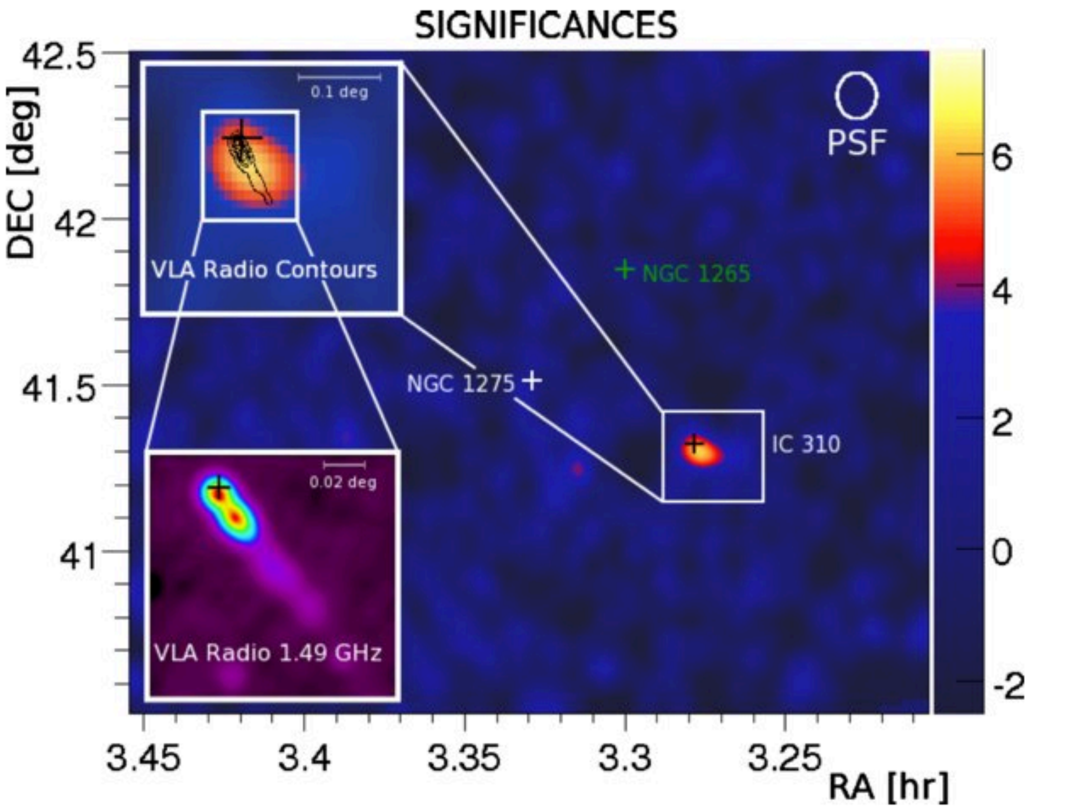


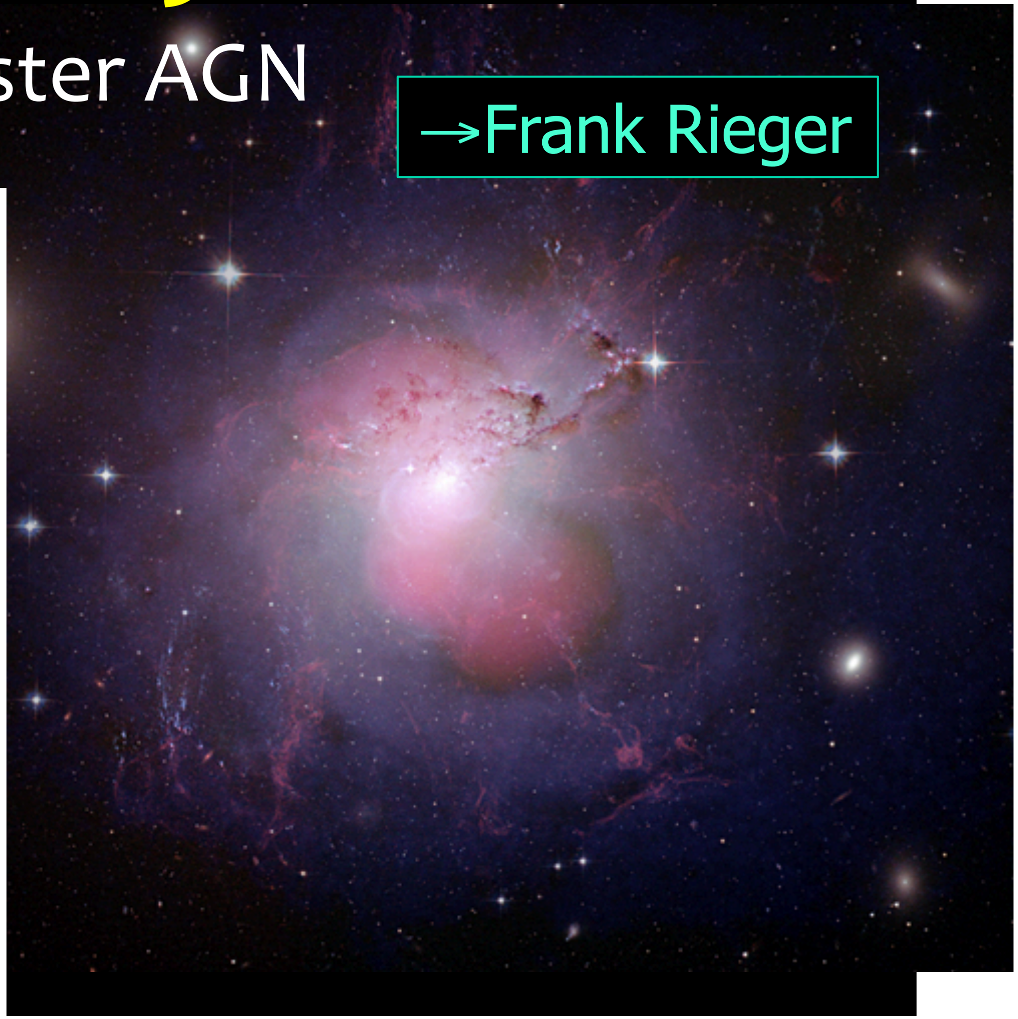
- *Variability timescale is ~1% R_S c* *Lag? <20 seconds/billion years/TeV*
  - Causality requires $R < ct_{var}\,\delta$, emission region is very small, and
  - *Implies bulk motion with $\Gamma > 50$* (**Begelman, Fabian, Rees 2008**)

Other Active Galaxies

- Cluster-centre AGN M 87 and **NGC 1275**
- Radio Galaxies Cen A and **IC 310**
- e.g. **MAGIC** Perseus Cluster AGN

→Frank Rieger





How Can We Do Better?

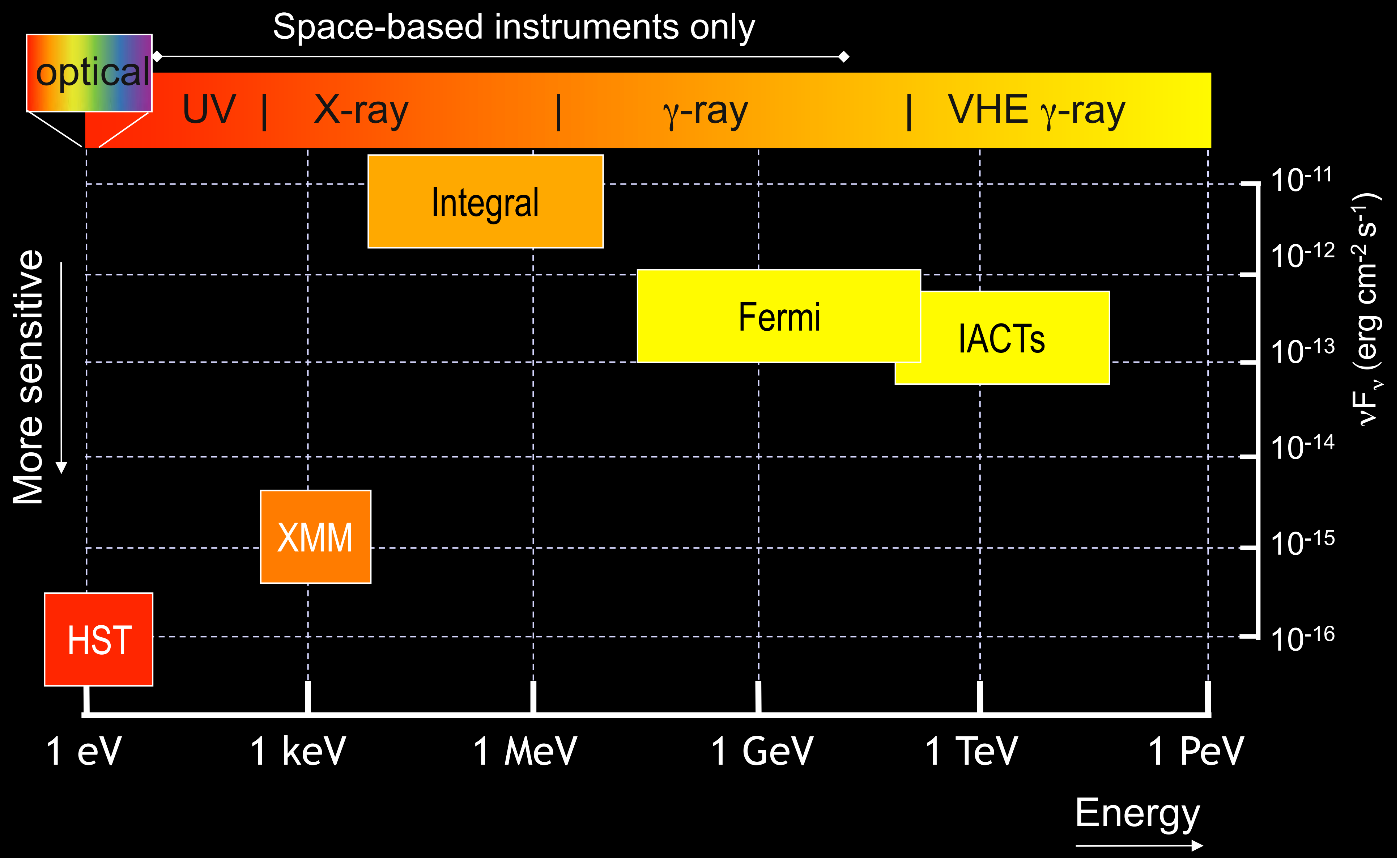
- A future > a few TeV observatory needs bigger collection areas than current instruments
  - Large arrays of telescopes
  - Wider field of view

More events

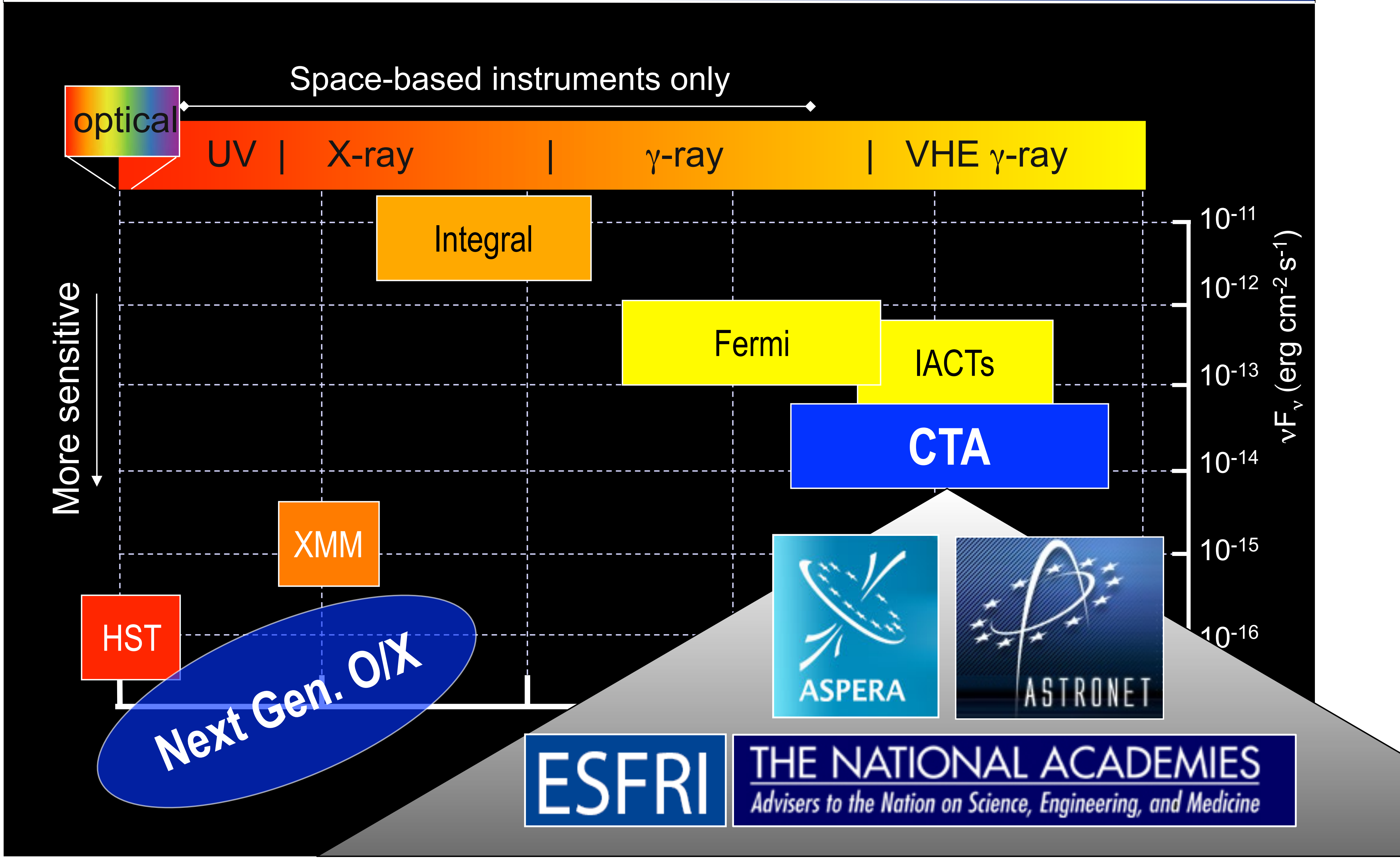
- A future < a few TeV observatory needs better background rejection than current instruments
  - Large arrays of telescopes (multiple shower images)
  - Wider field of view (multiple shower images)

Better events

Sensitivity

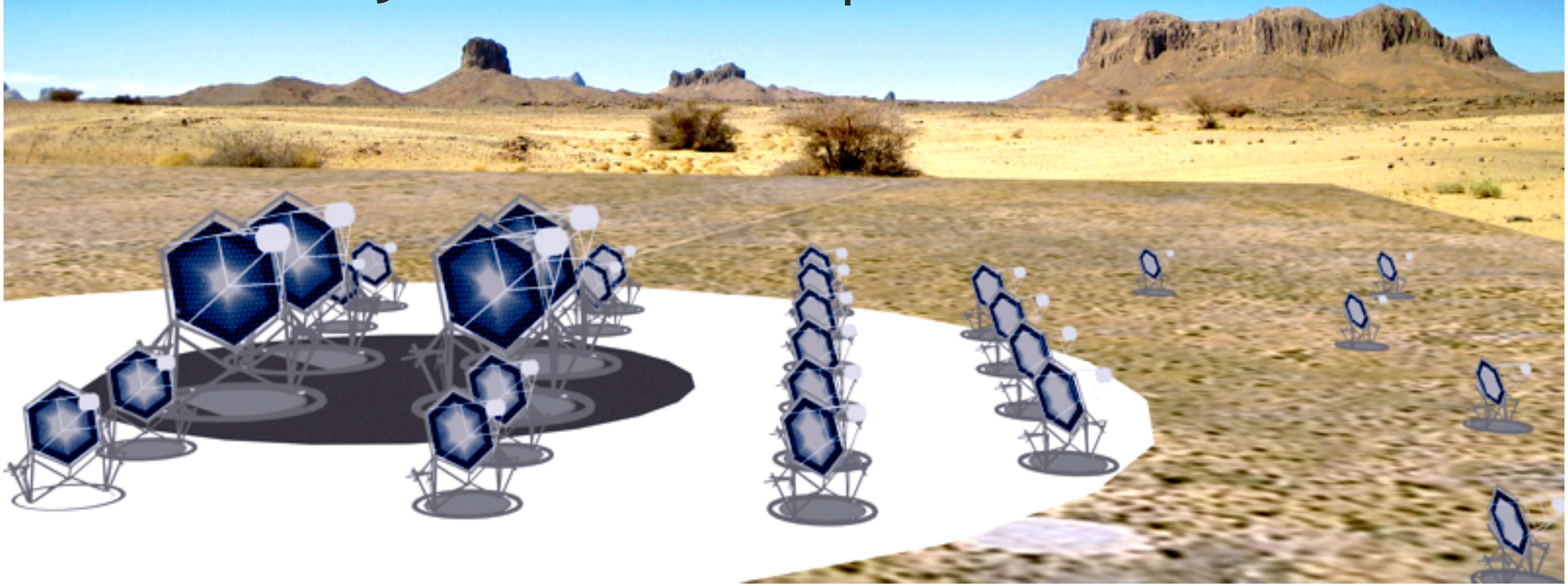


Sensitivity



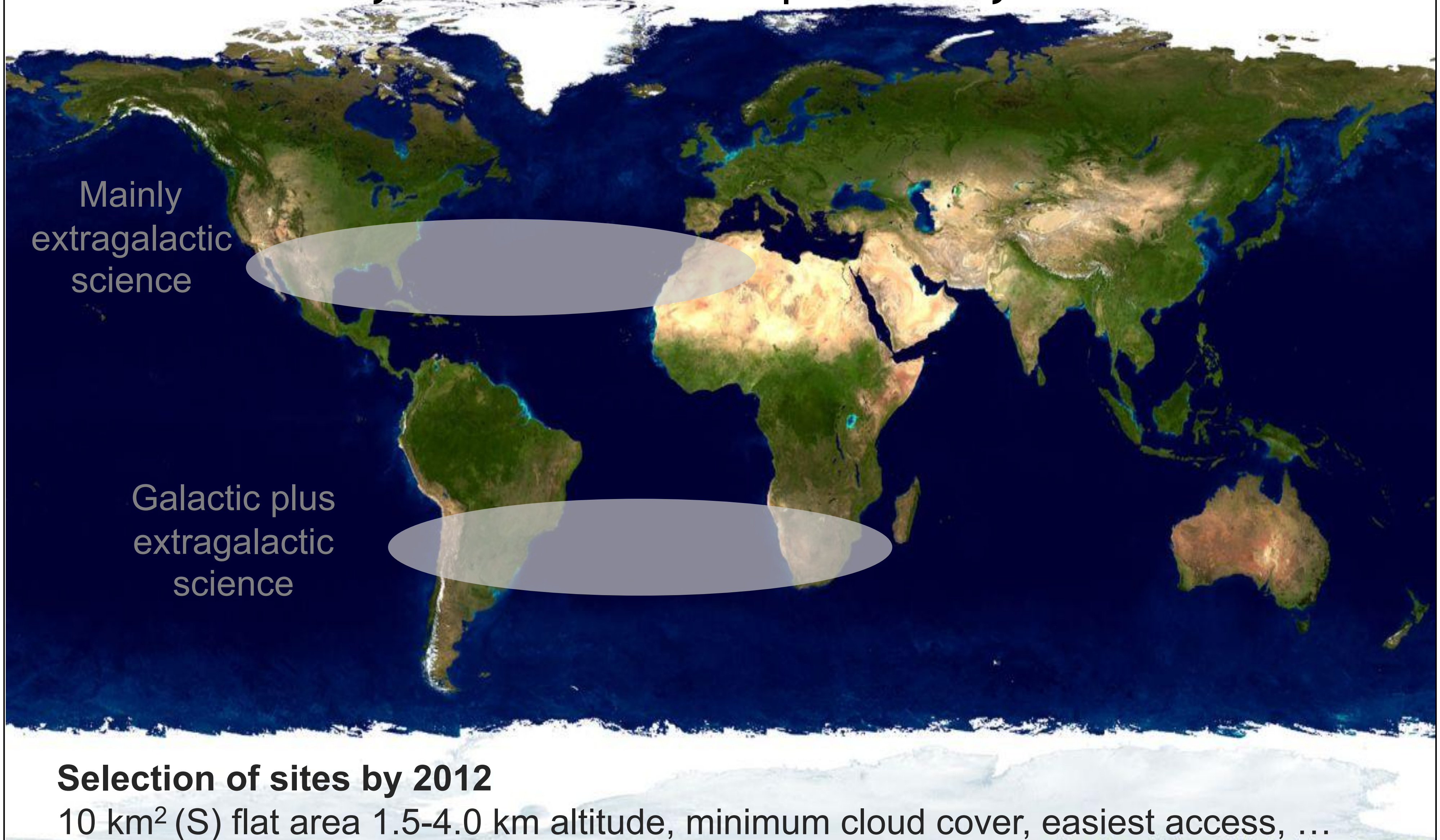
The Cherenkov Telescope Array

- A factor 10 more sensitive than current instruments
  - **Plus - much wider energy coverage, substantially better angular and energy resolution & wider field of view**
- A ~ €190M International Project
  - **>800 scientists and engineers in >100 institutes in 25 countries**
  - **Design 2008-2011, Prototyping 2011-13, Construction 2013-18**
  - **Baseline: 50-100 Cherenkov telescopes**



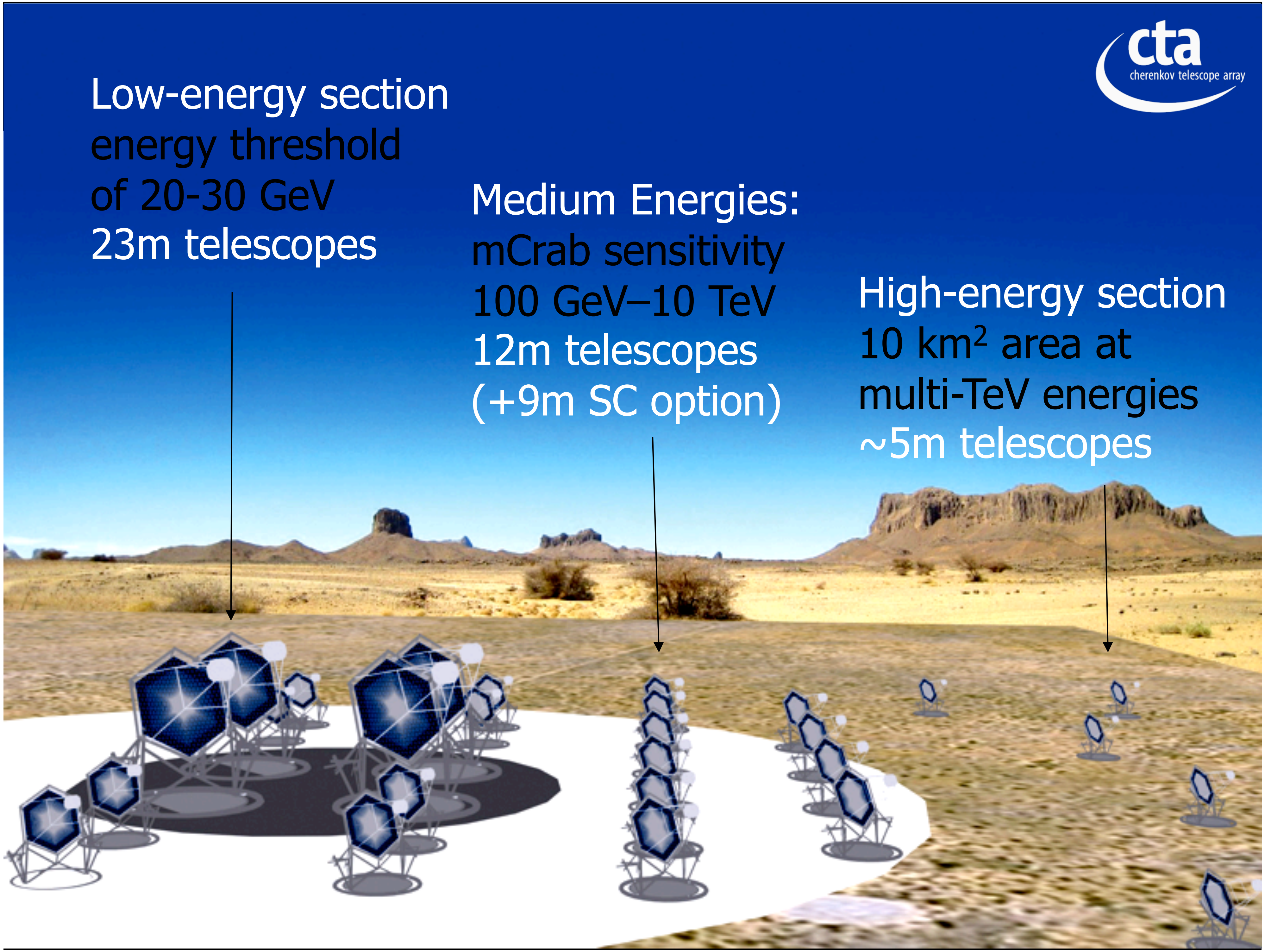
Sites

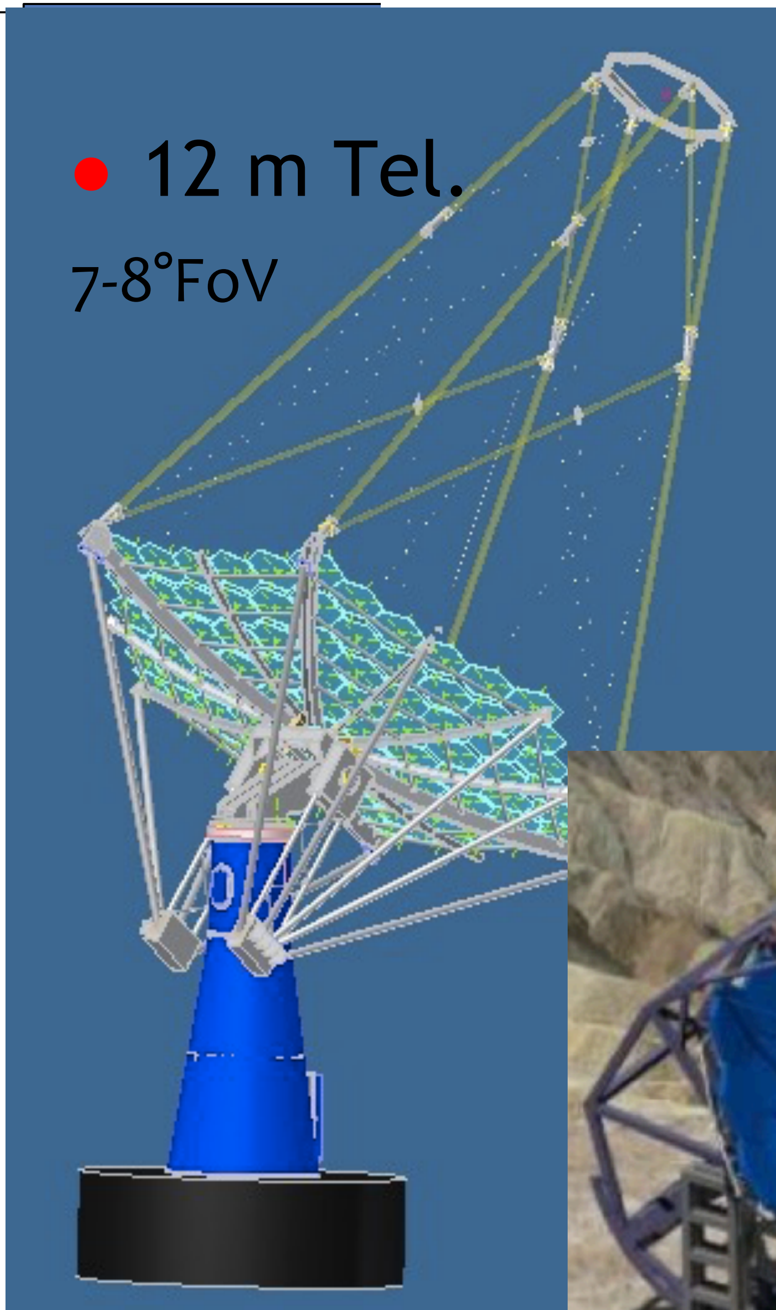
One observatory with two sites - operated by one consortium

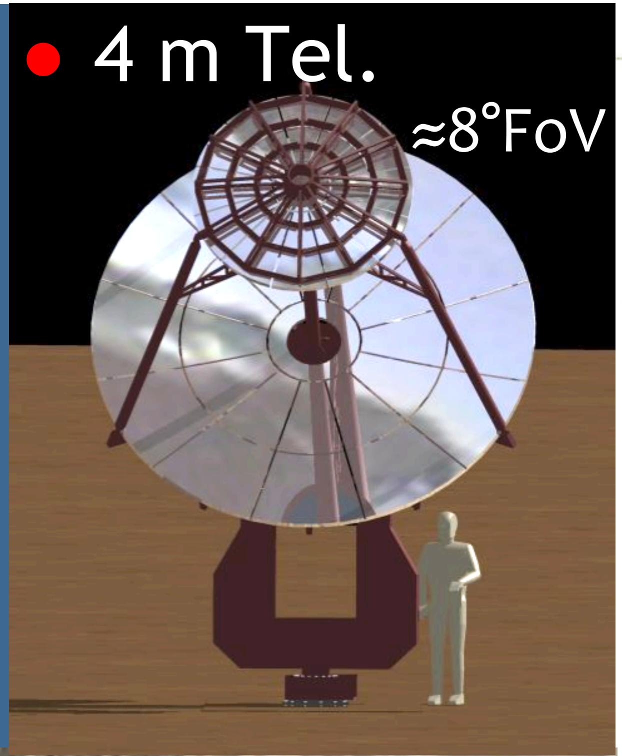


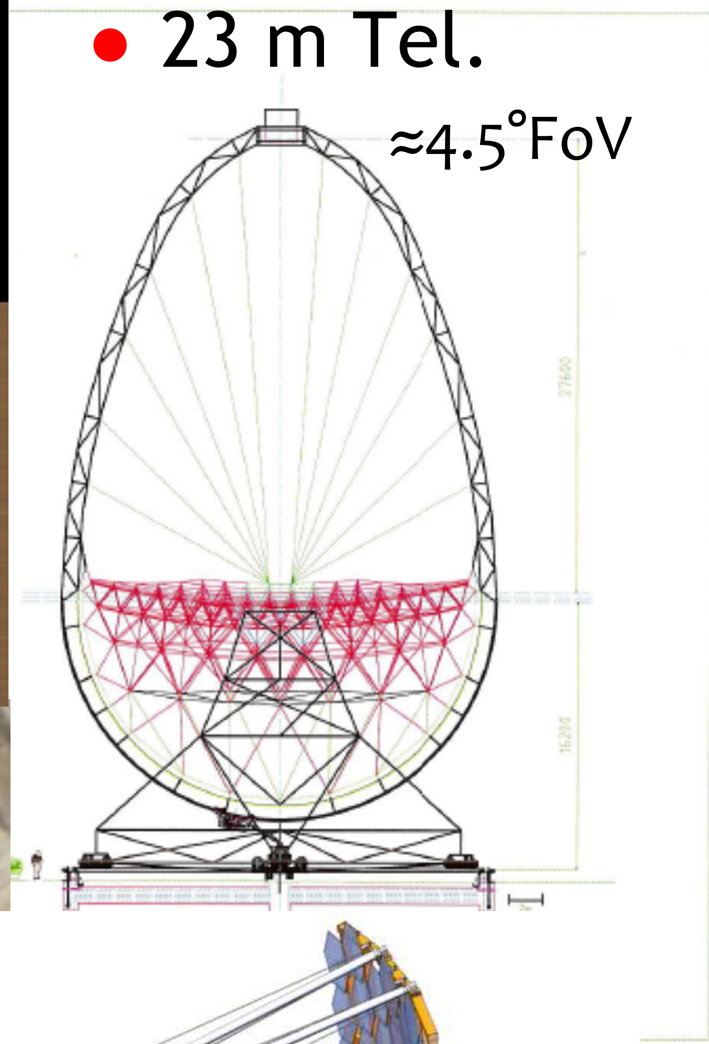
Selection of sites by 2012

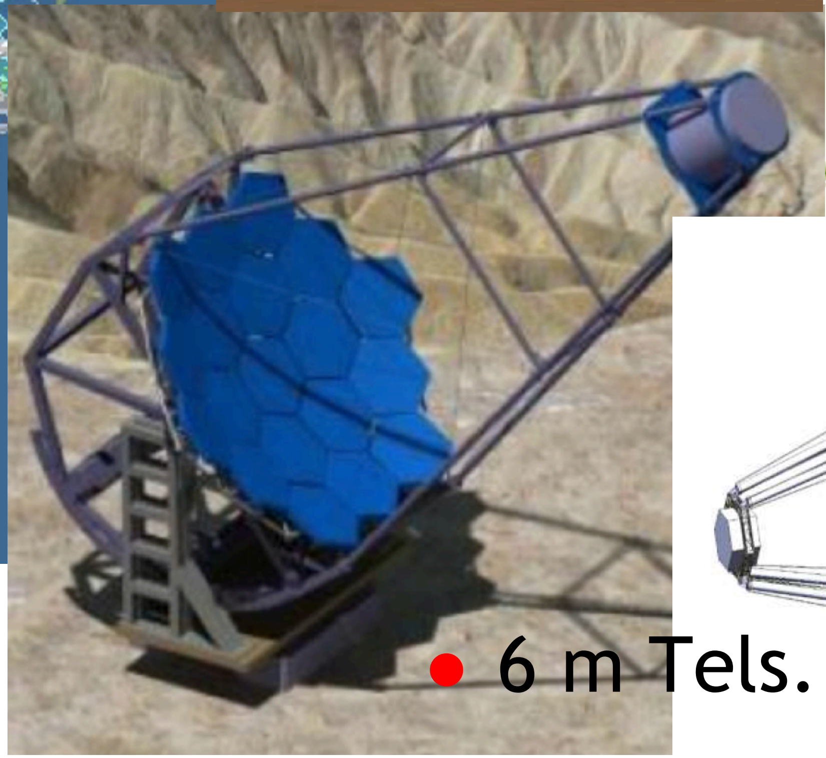
10 km^2 (S) flat area 1.5-4.0 km altitude, minimum cloud cover, easiest access, …

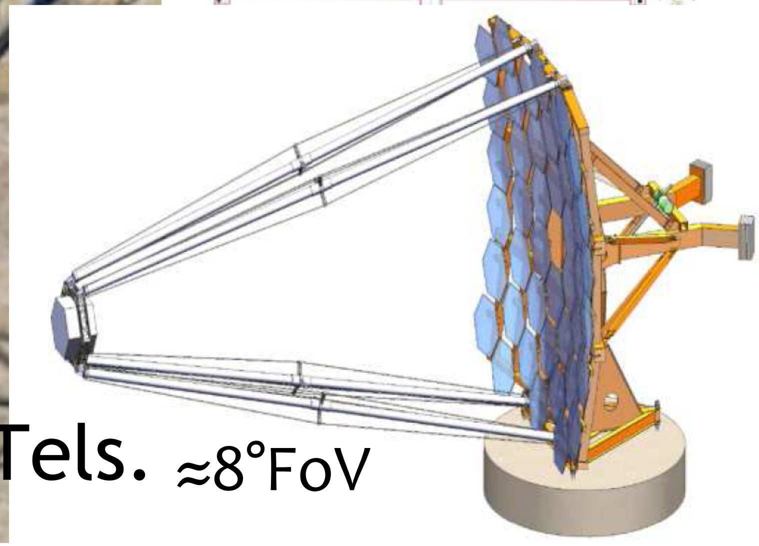

cta
cherenkov telescope array
Low-energy section
energy threshold
of 20-30 GeV
23m telescopes
Medium Energies:
mCrab sensitivity
100 GeV–10 TeV
12m telescopes
(+9m SC option)
High-energy section
10 km^2 area at
multi-TeV energies
~5m telescopes





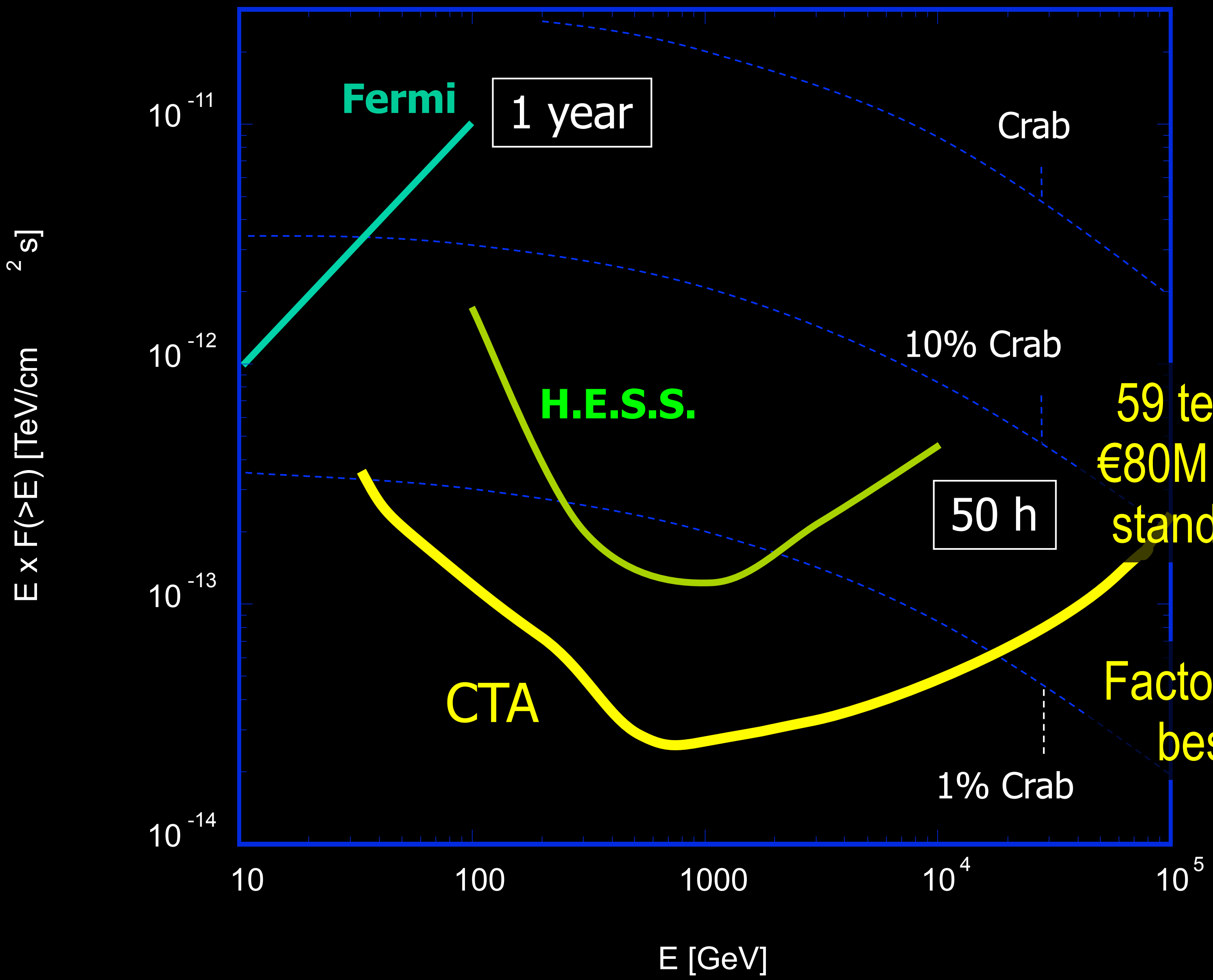






cta
cherenkov telescope array

CTA Sensitivity

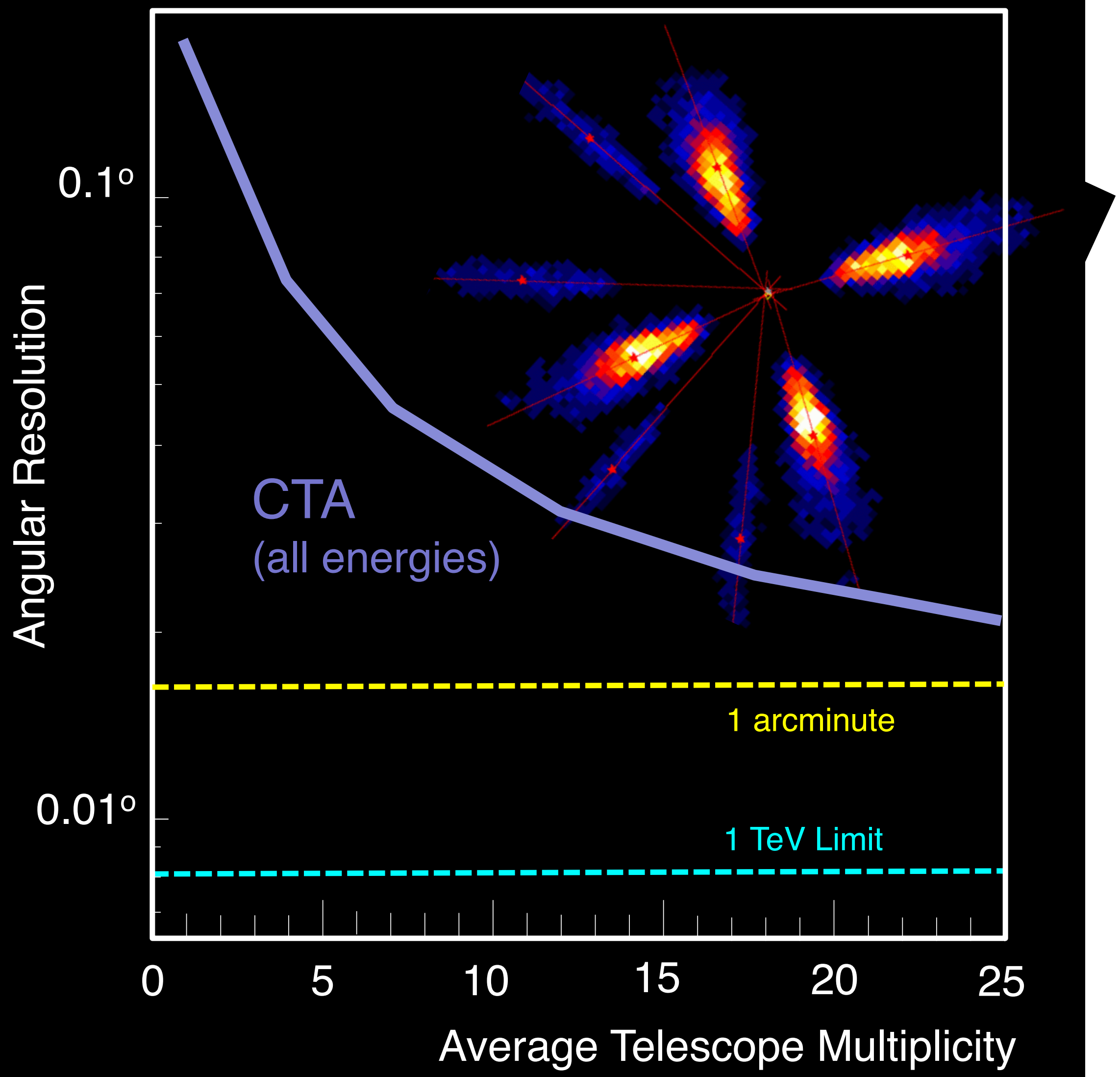


59 tel. config. “E”
€80M nominal cost
standard analysis

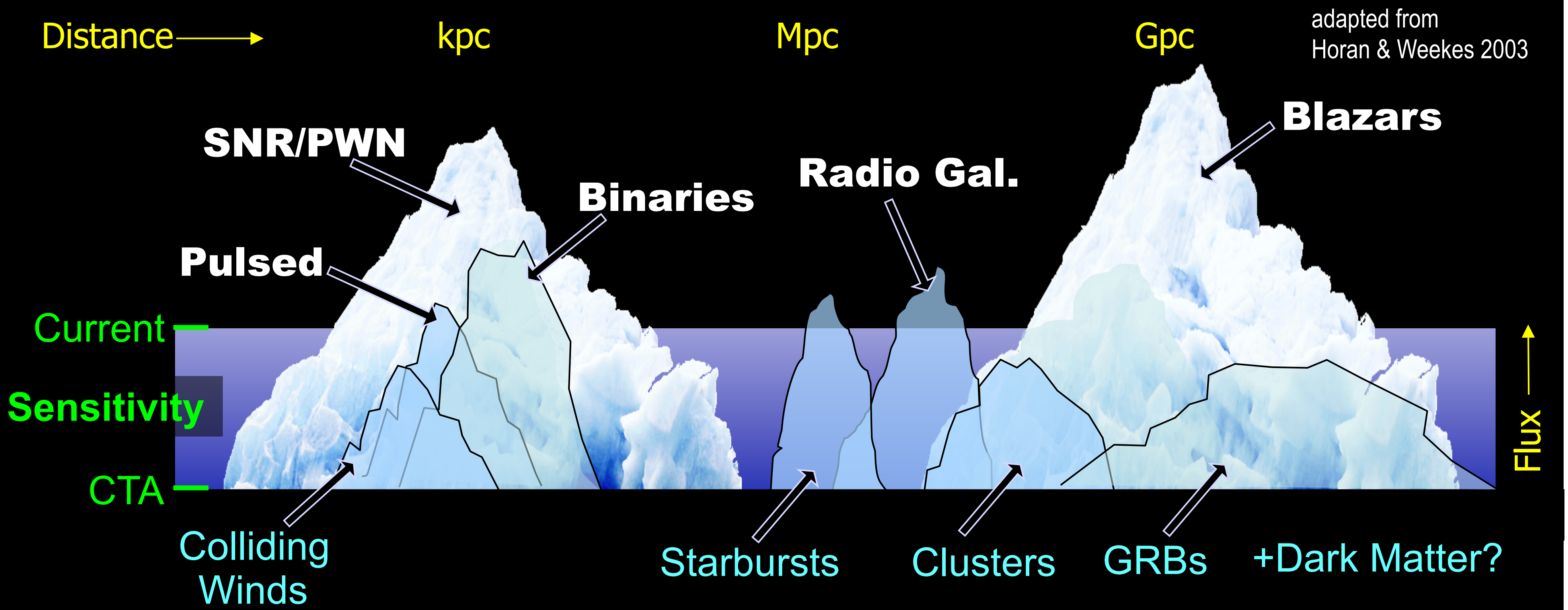
Factor 2 better with
best analyses

Precision

- Increase in the number of Cherenkov images measured in individual telescopes leads to improved angular and energy resolution
- Resolution also improves with energy

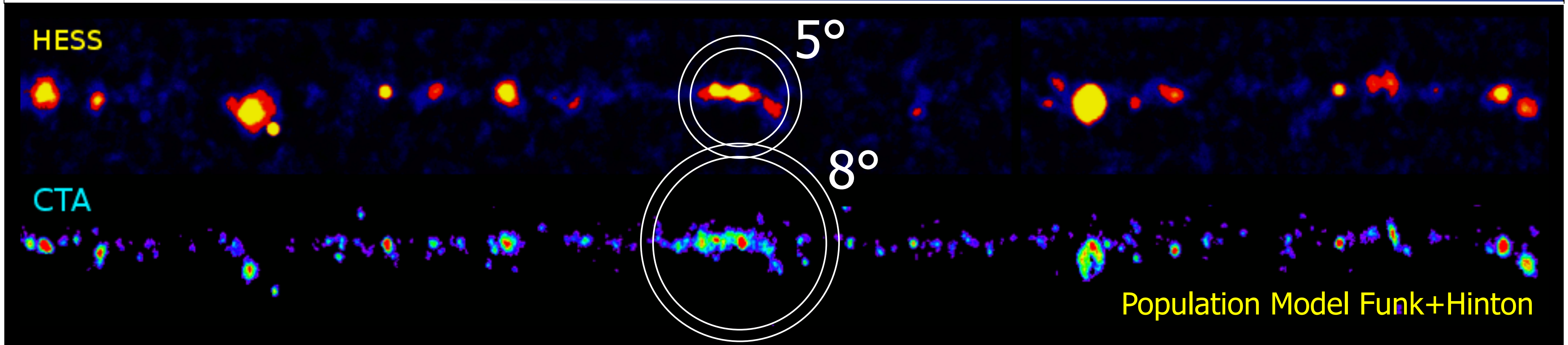


Science Potential



- Current instruments reveal a rich panorama, but this is clearly only the tip of the iceberg
- Broad and diverse program for CTA, combining guaranteed astrophysics with significant discovery potential

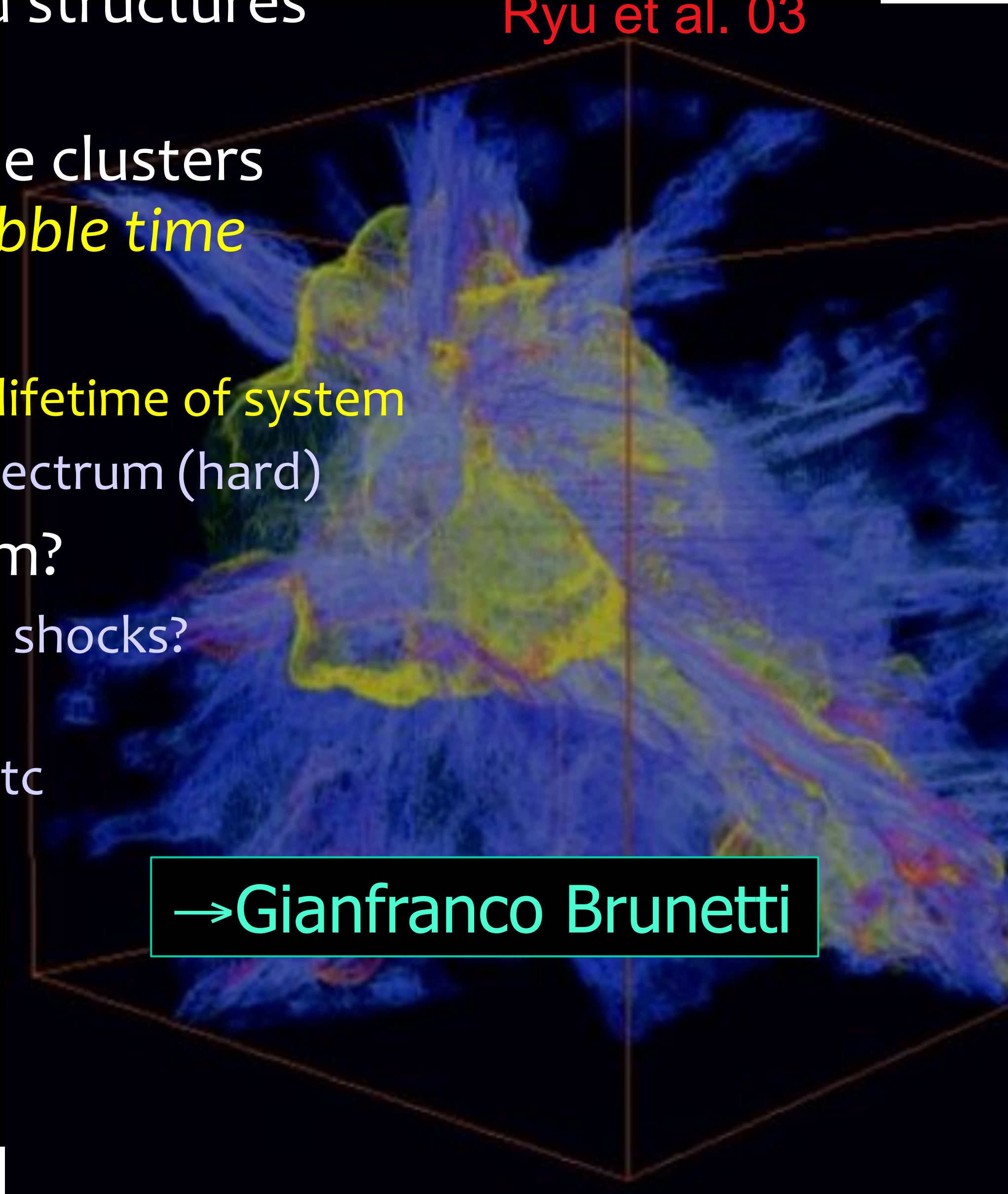
Surveys



- CTA will conduct a census of particle acceleration in the universe
  - Can survey **~500** times faster than HESS
  - Improved resolution avoids source confusion and helps MWL identification (3/4 of HESS)
  - A deep view of stellar birth/death and cosmic ray feedback in our own galaxy and up to the largest scales…

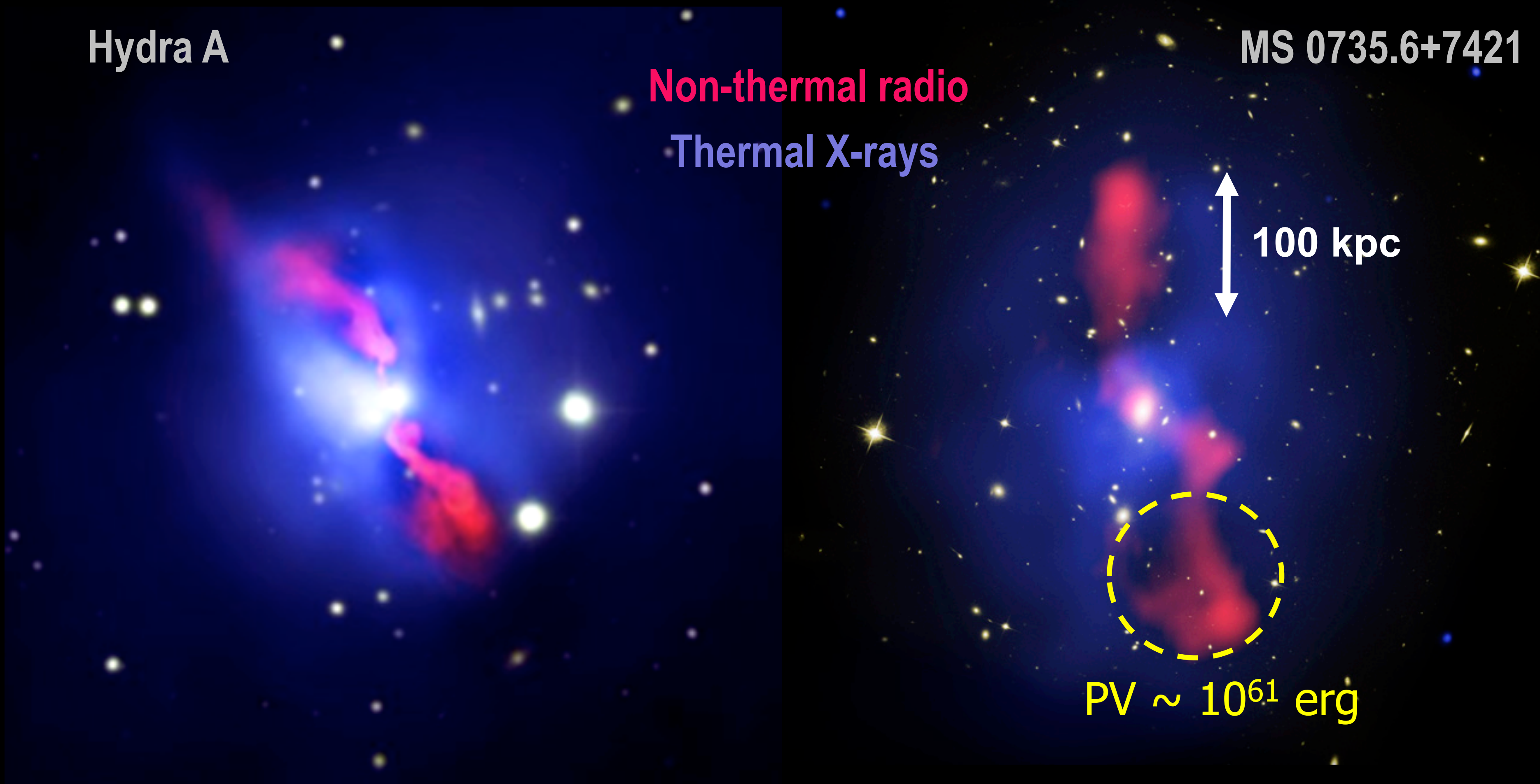
Clusters of Galaxies

- The largest gravitationally-bound structures in the universe
- Relativistic protons do not escape clusters (nor lose their energy) over a *Hubble time*
- No escape implies:
  - Cosmic ray density integrated over lifetime of system
  - Spectrum is identical to injection spectrum (hard)
- And where do protons come from?
  - Acceleration at structure formation shocks?
    - Accretion shocks, cluster mergers
  - 'Normal' galactic processes, SNRs etc
  - Outbursts of Active Galactic Nuclei
- Fluxes close to detectability?



→Gianfranco Brunetti

Cluster-scale AGN Outbursts

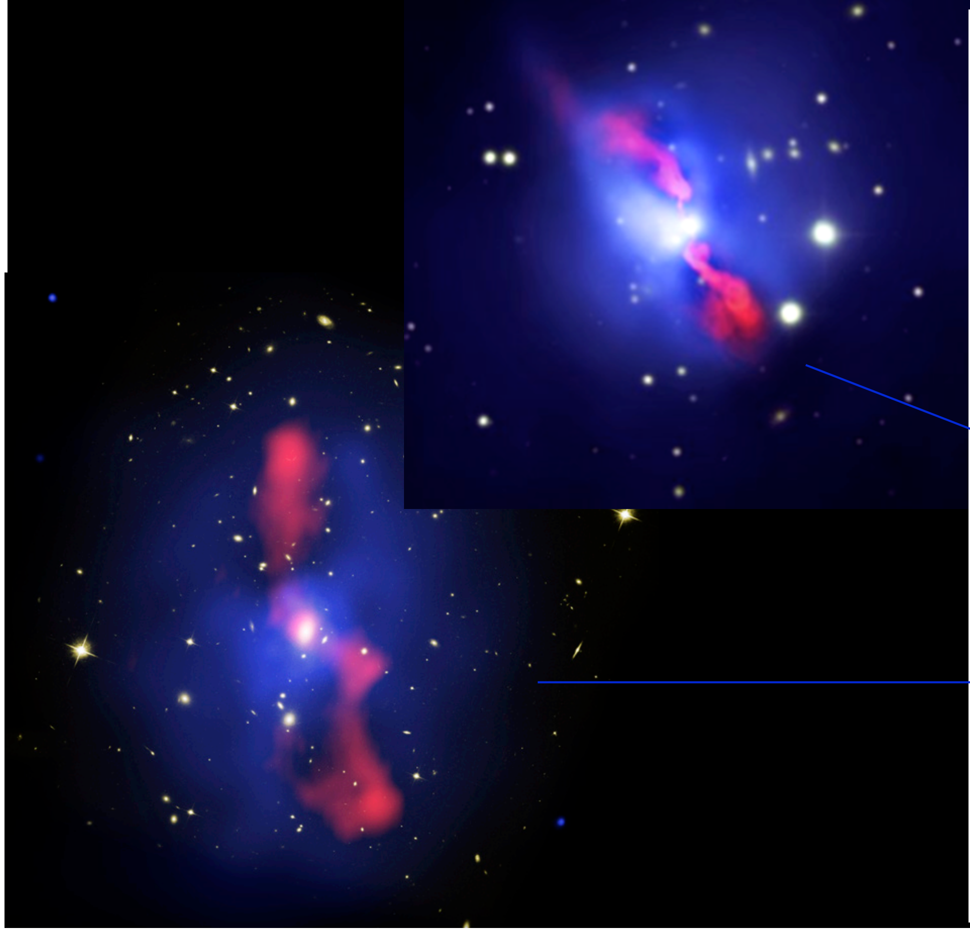


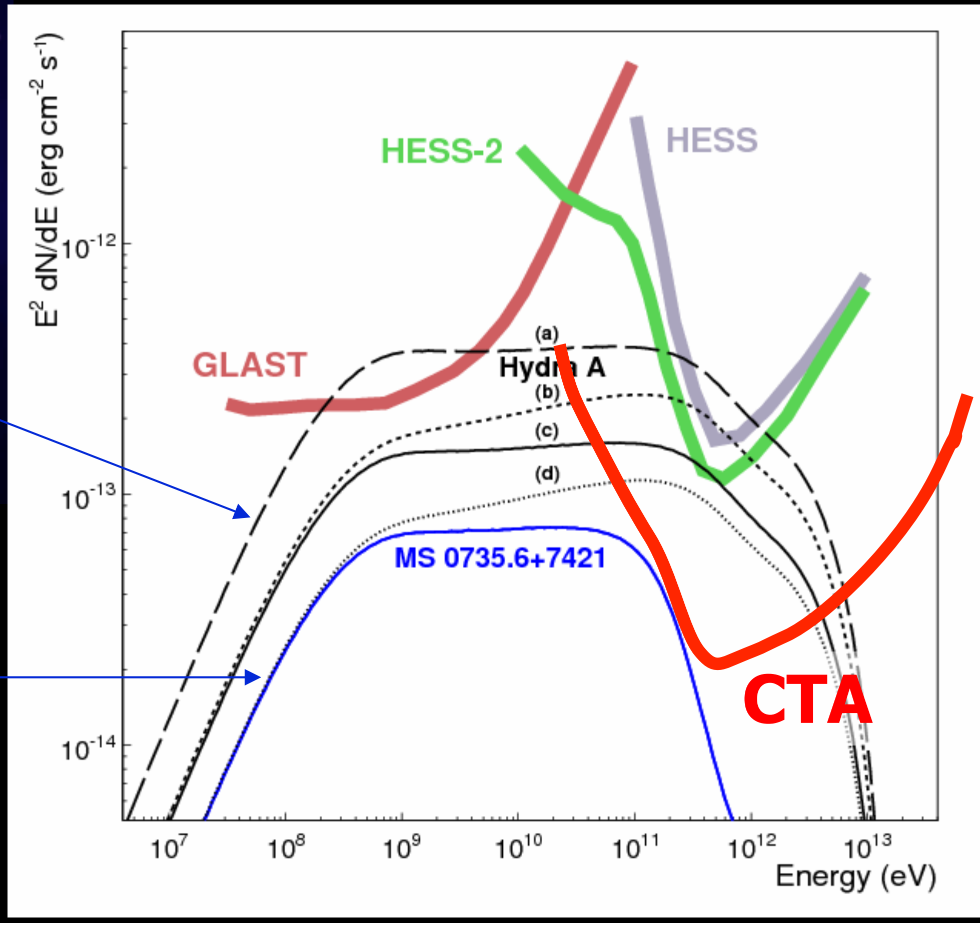
X-ray IC limits and lifetime arguments against just electrons+B-fields in bubbles

Cluster-scale AGN Outbursts

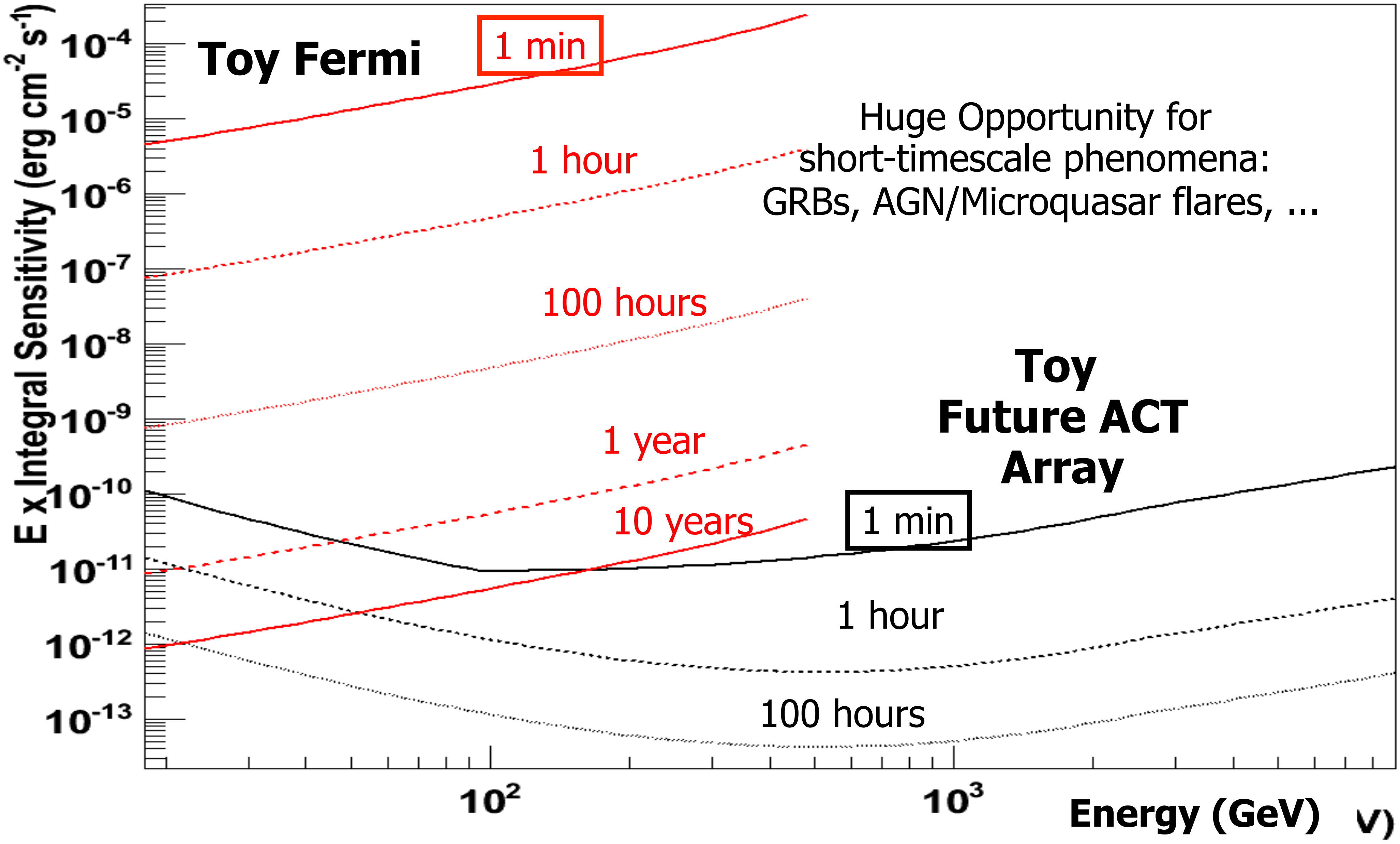
- If cavities in Hydra A are supported by cosmic ray pressure – they are very likely detectable with CTA

Hinton, Domainko & Pope MNRAS 2007

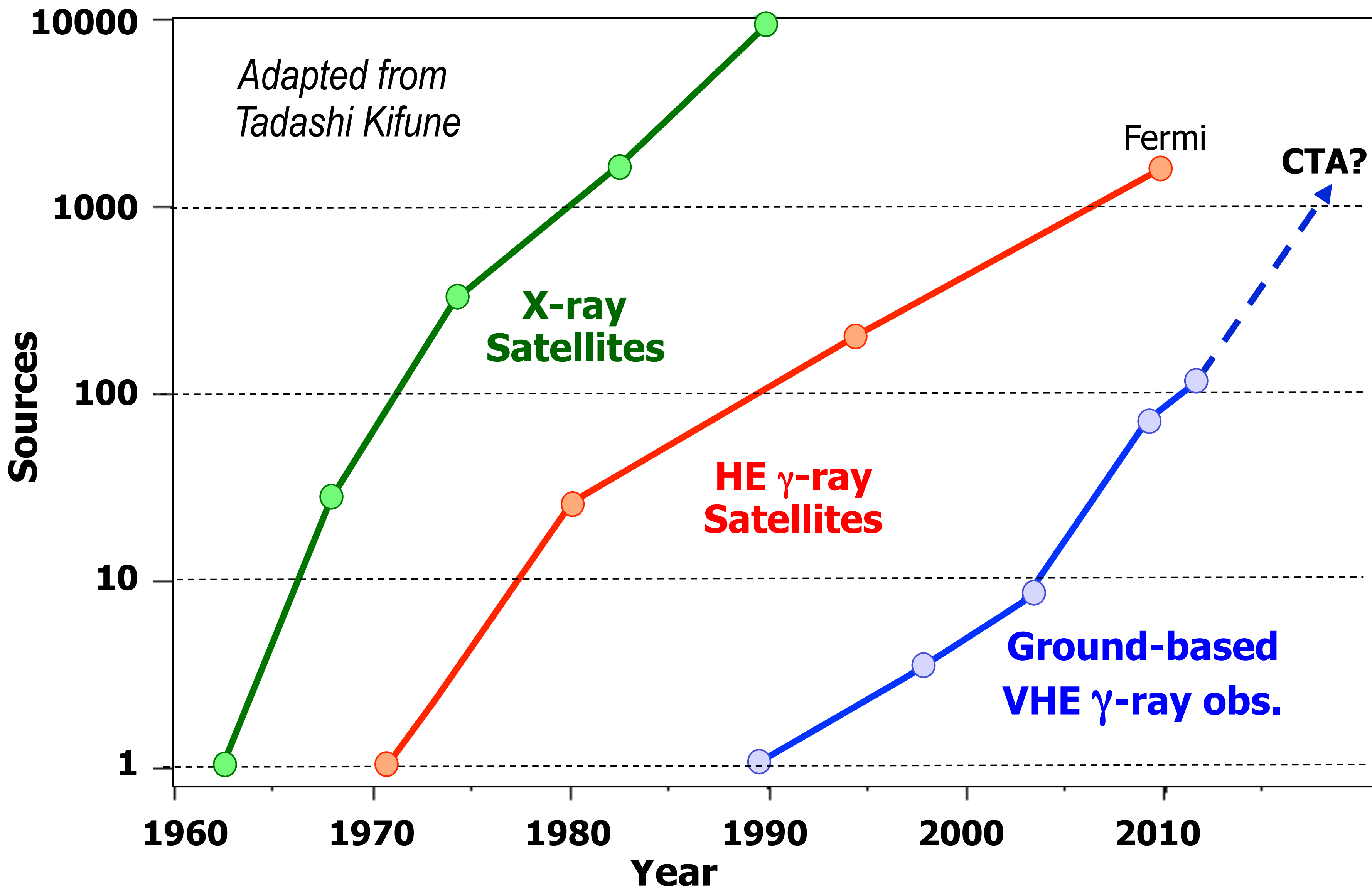




The Variable Universe



Source Numbers



Conclusion

- A bright future ahead for ground-based γ-ray astronomy
  - and the new generation of γ-ray astronomers!

Questions?