Le ciel aux plus hautes énergies

Deirdre HORAN
LLR / École Polytechnique
deirdre@llr.in2p3.fr

OUTLINE

1. Gamma rays
2. Gamma-ray Astrophysics
3. Space-based detection
4. Extensive Air Showers
5. **Cherenkov Radiation**
6. First Generation VHE Telescopes
7. The Imaging Atmospheric Cherenkov Technique
8. Gamma-ray Telescopes of Today
9. Astrophysical Sources of Gamma rays

Extragalactic Galactic Cosmology Astroparticle / Exotic

Gamma rays
- 1/9 -

Gamma rays ... intro (1/3)

the most energetic radiation (takes up 1/2 EM spectrum)

non-thermal origin

production - nuclear & non-nuclear

detection / interaction ... energy dependent

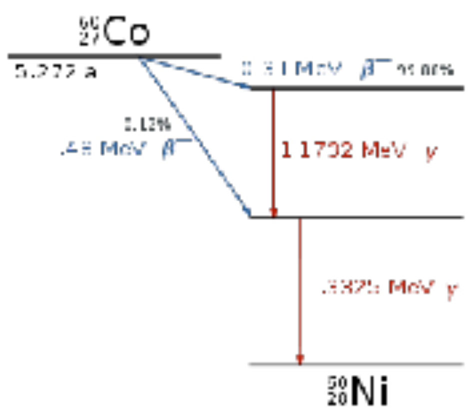
cannot be focused, imaged

neutral => point back to point of origin

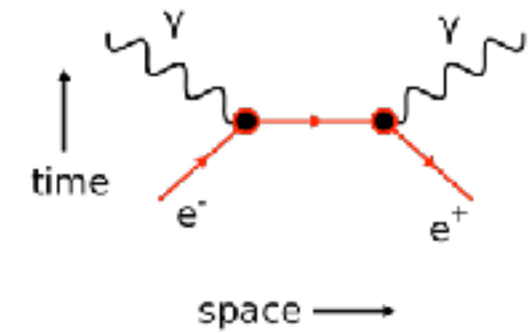
Gamma-rays - production ... intro (2/3)

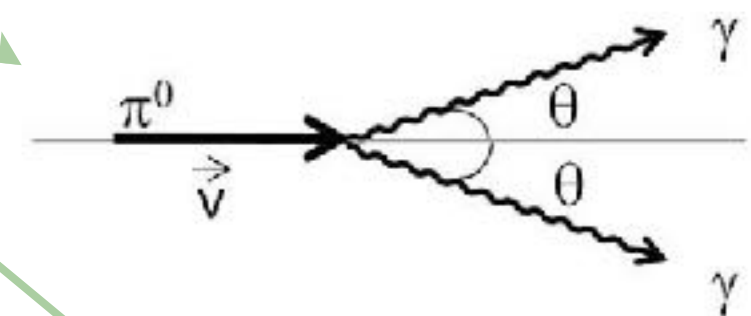
Nuclear & Non-nuclear

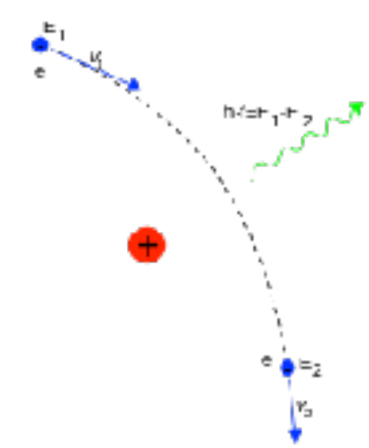
- nuclear decay

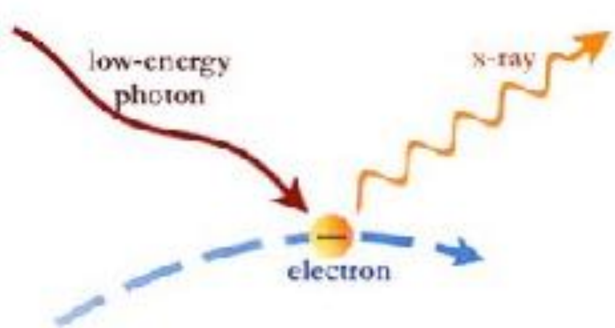


- electron-positron annihilation
- neutral pion decay
- bremsstrahlung / synchrotron
- inverse Compton scattering





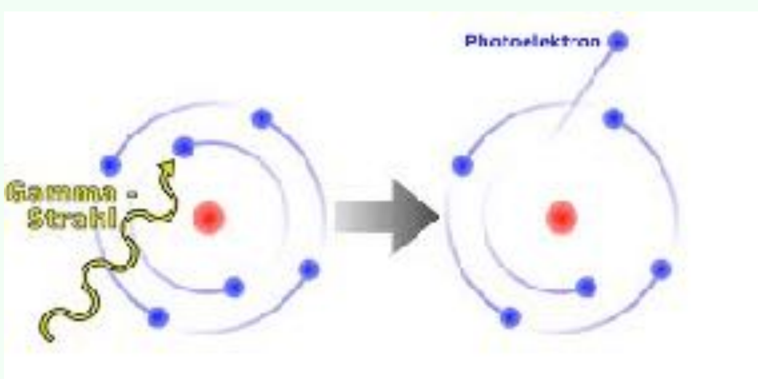




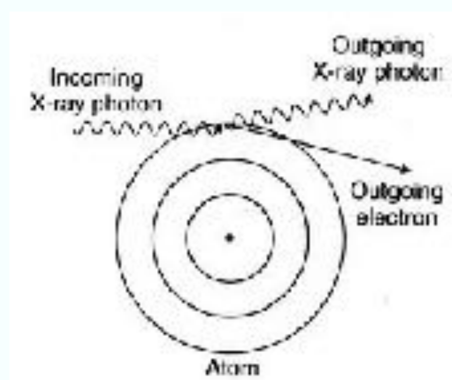
Gamma-rays - detection ... intro (3/3)

- gamma rays ionize matter when they pass through it
- the most likely way that a gamma ray will interact with matter depends on its energy

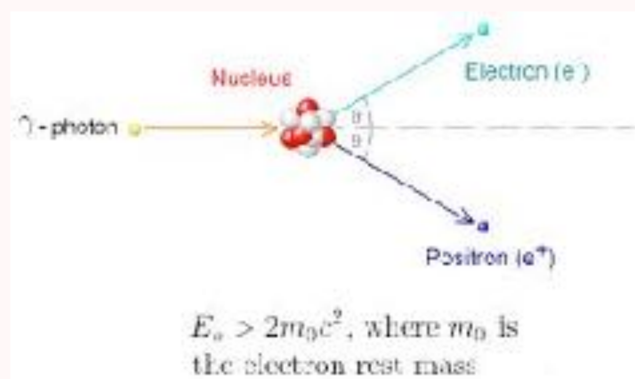
Photoelectric Effect

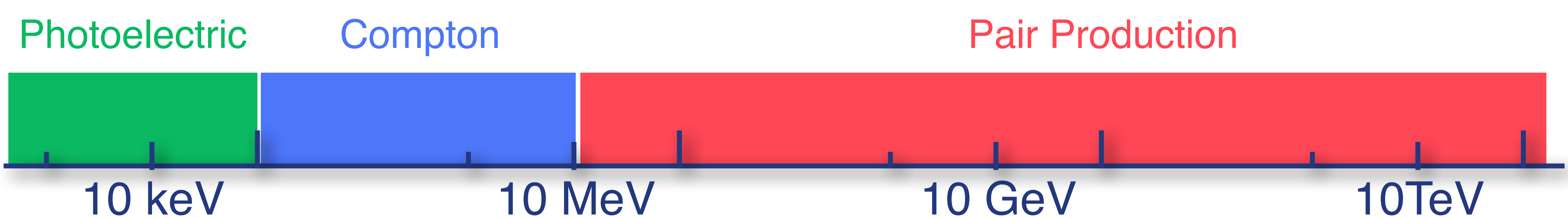


Compton Scattering



Pair Production





Gamma-ray Astrophysics
2/9

Gamma-ray Astrophysics 1/6

the most energetic radiation (takes up 1/2 EM spectrum)
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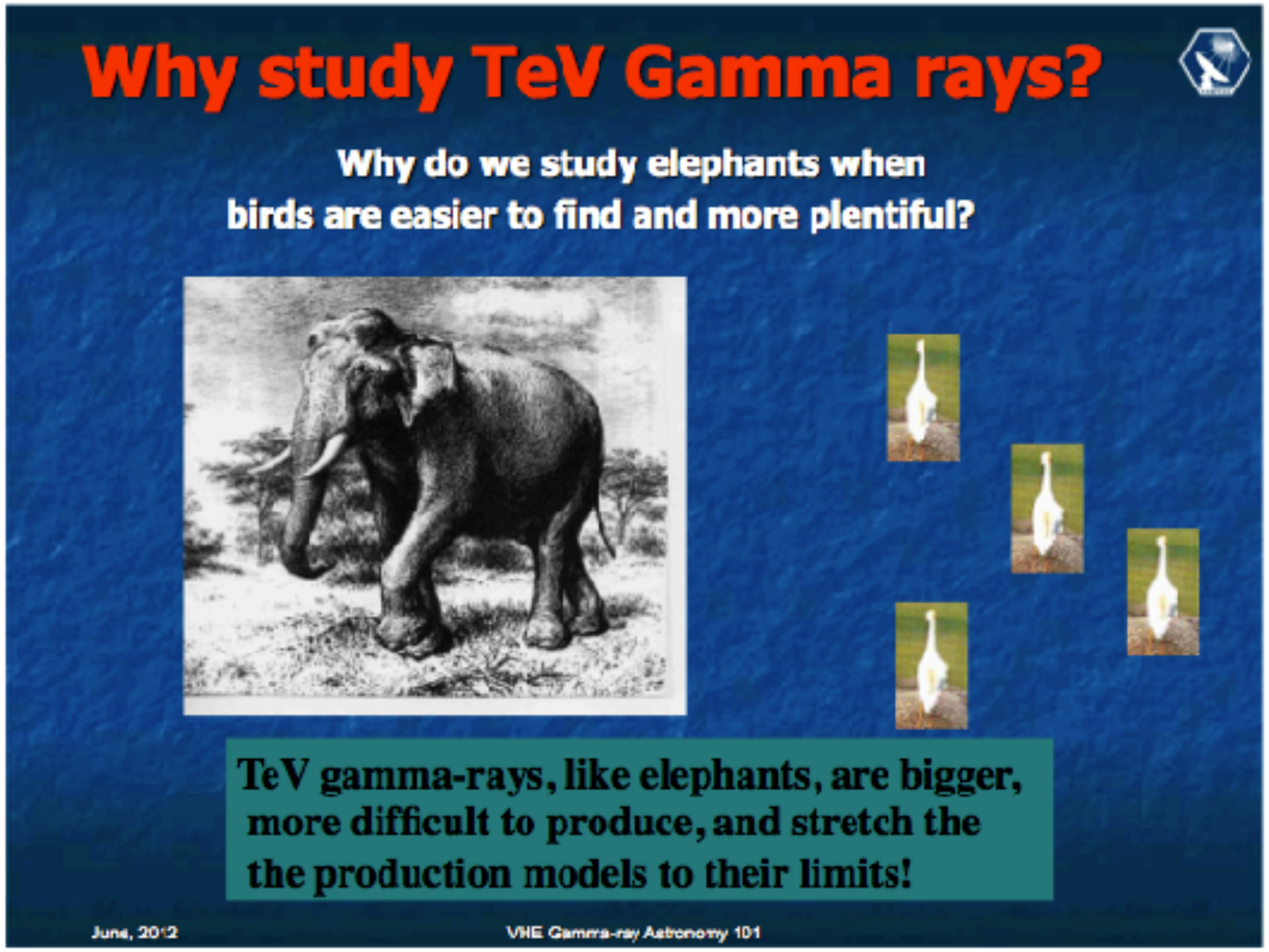
detection / interaction ... energy dependent

the most energetic radiation
(takes up 1/2 EM spectrum)

Trevor Weekes (Fermi Summer School 2012)



Gamma-ray Astrophysics 1/6

Gamma rays come from the most ~~violent~~ interesting?!? regions in our universe

Gamma-ray Astrophysics 2/6

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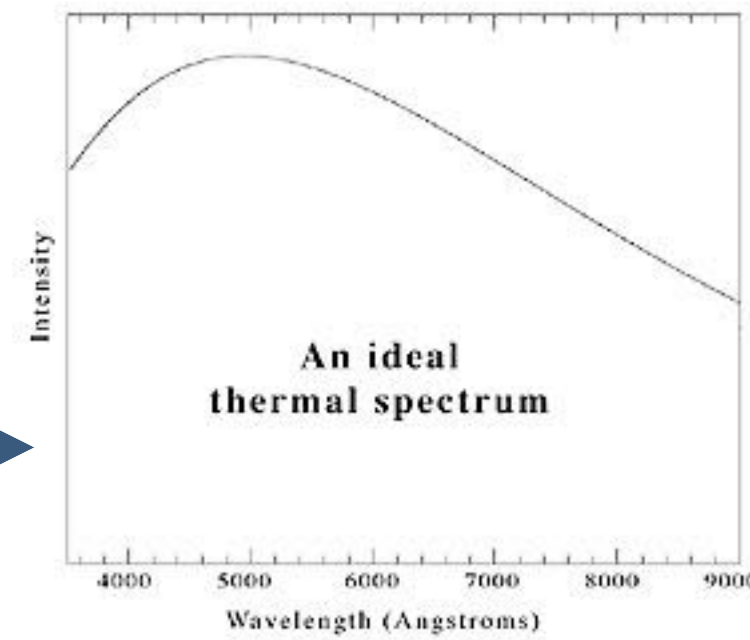
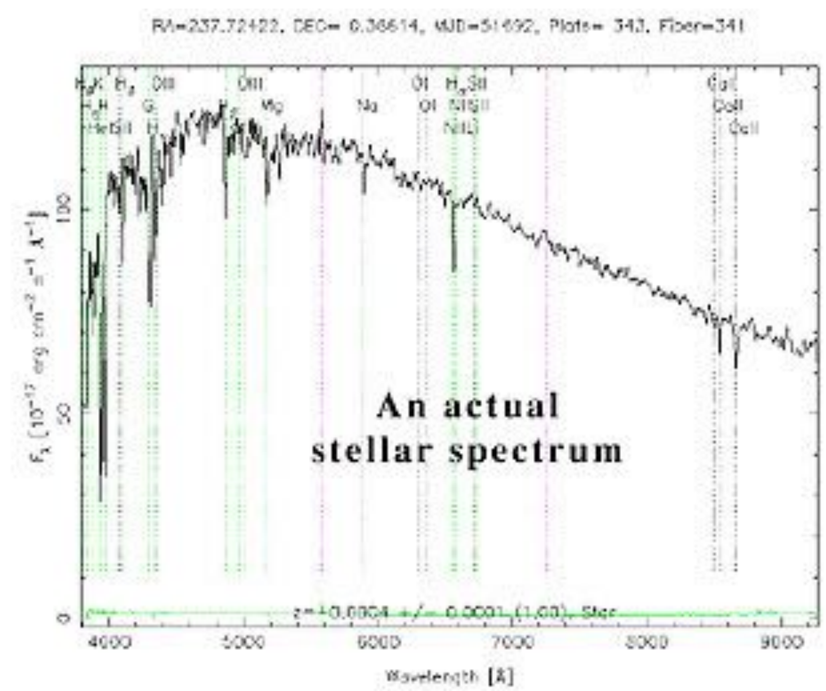
non-thermal origin

- all objects emit thermal radiation due to their non-zero temperature
- it is due to the thermal motion of charged particles in matter
- much of the radiation propagating throughout space and incident on Earth is of thermal origin

ideal thermal and typical stellar spectra





Gamma-ray Astrophysics 2/6

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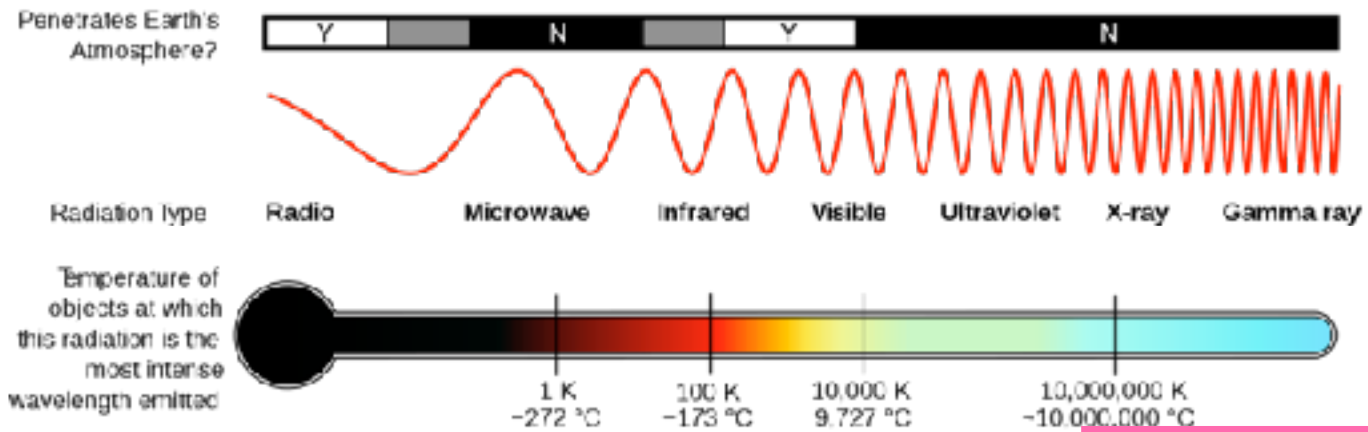
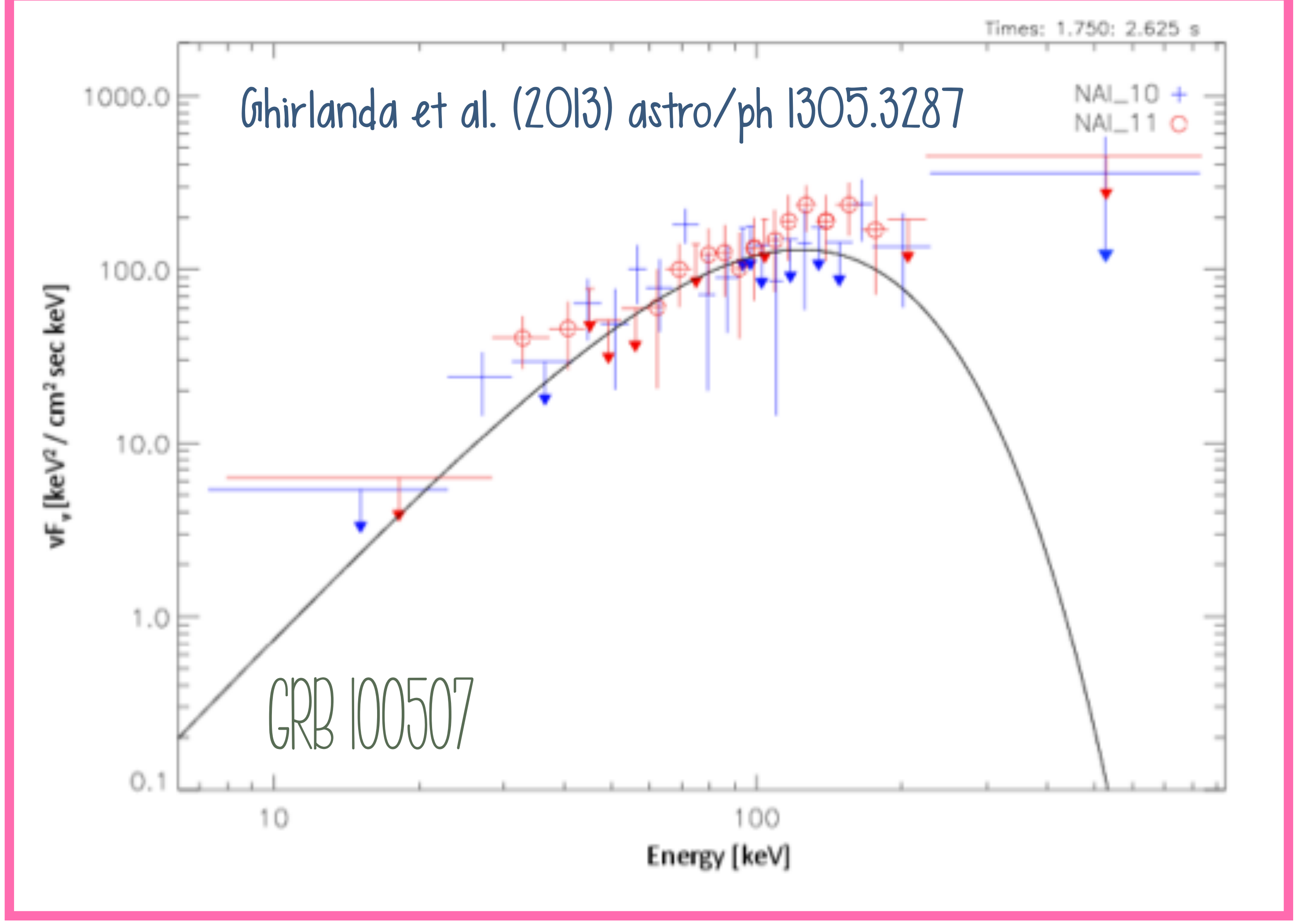
non-thermal origin



under extreme conditions
can get keV thermal emission



Gamma-ray Astrophysics 2/6

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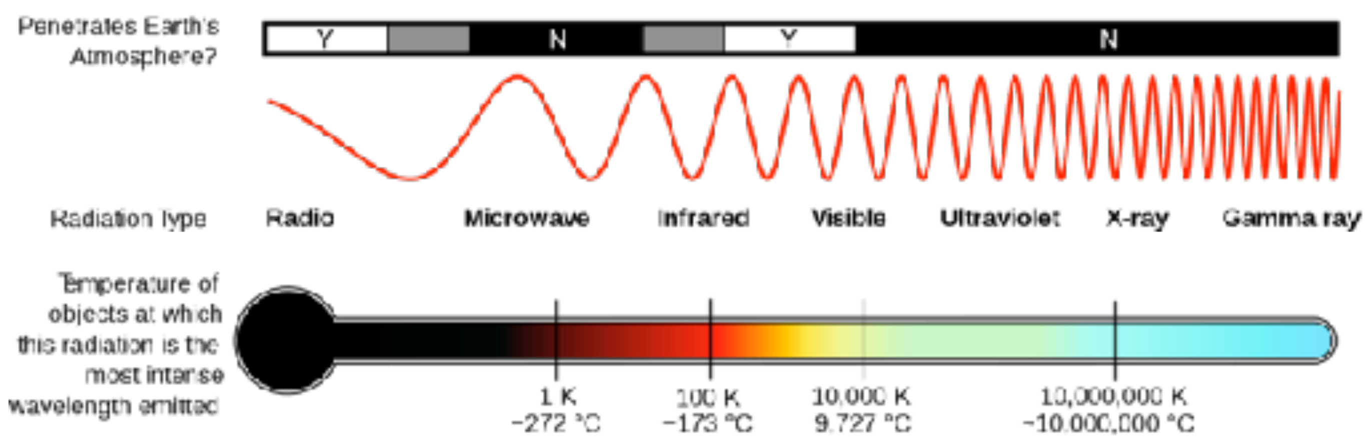
non-thermal origin



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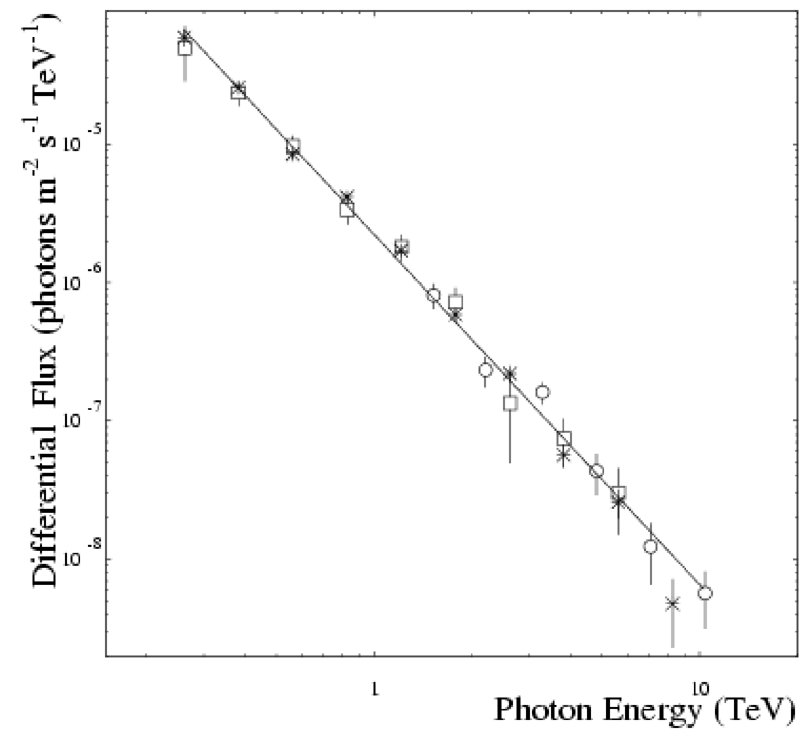

but...

gamma rays are always the result of non-thermal processes

POWER-LAW SPECTRA:

$$\frac{dN}{dE}(E) \propto E^{-a}$$

Gamma-ray Astrophysics 3/6

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production

- nuclear & non-nuclear

Hadronic

- neutral pion decay

Electromagnetic

- electron-positron annihilation
- bremsstrahlung/synchrotron*
- inverse Compton scattering

*proton synchroton

Gamma-ray Astrophysics 4/6

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cannot be focused, imaged

→ therefore: NO OPTICS

detector area IS the collection area!

→ the photon must pass through your detector system in order for it to be detected

- note -

in an optical telescope, the light-gathering power is proportional to the area of the objective lens or mirror

and...

gamma-ray flux is distributed as a power law --> falling RAPIDLY with INCREASING ENERGY!

Gamma-ray Astrophysics 4/6

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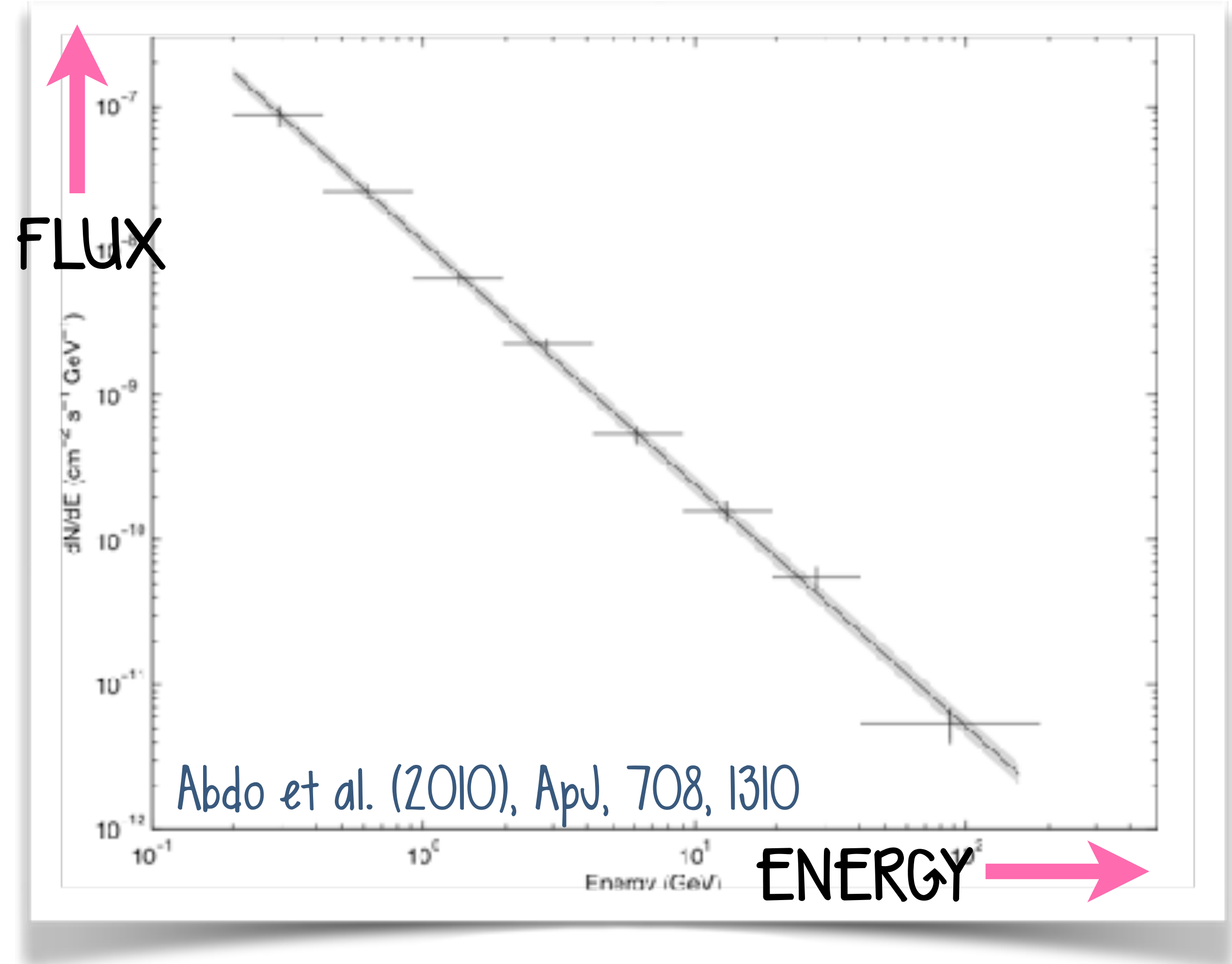

Abdo et al. (2010), ApJ, 708, 1310

Gamma-ray Astrophysics 5/6

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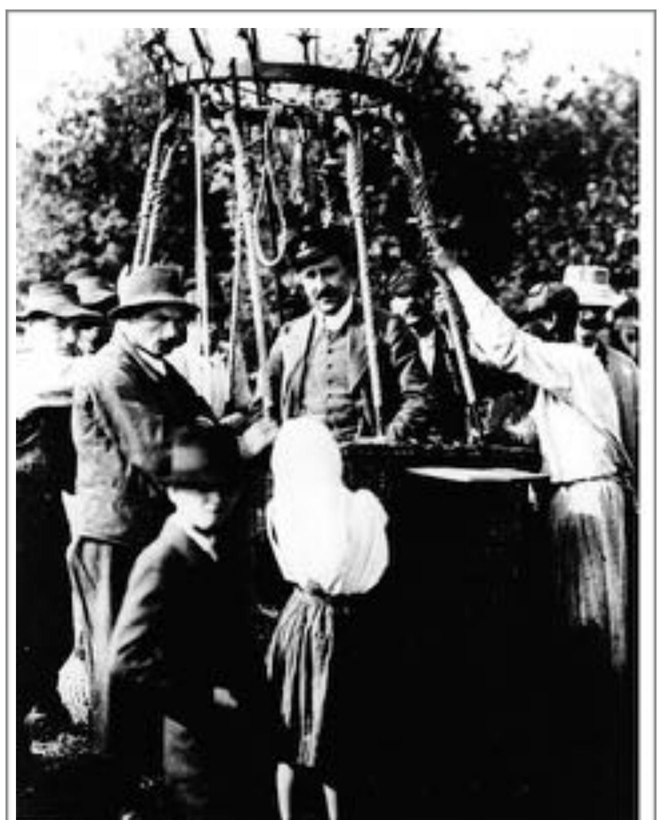
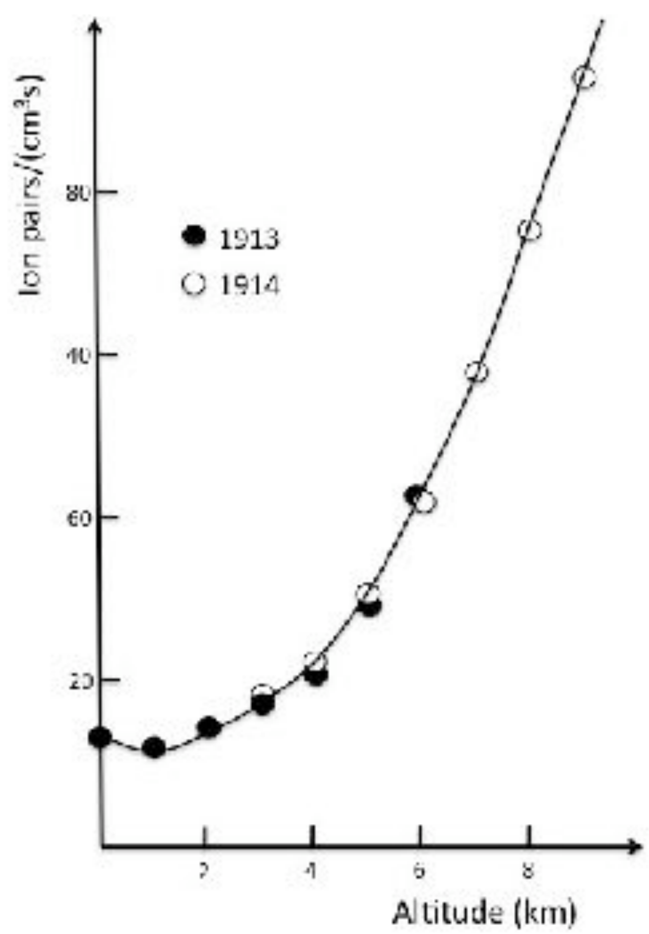
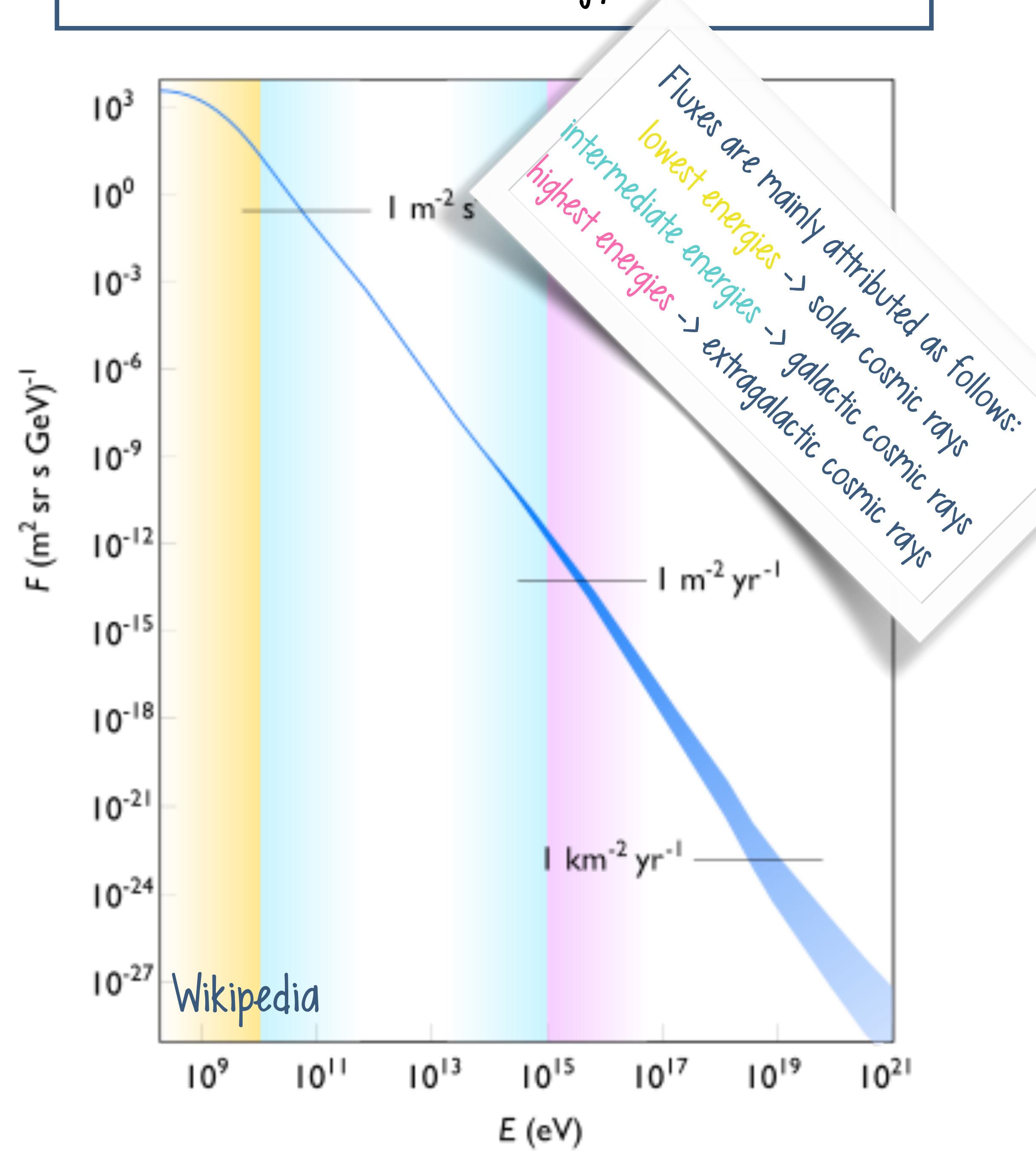
neutral => point back to point of origin

- one of the big motivations for gamma-ray astronomy was (is) the search for the origin of the high-energy cosmic rays
- their origin has been a mystery since their discovery 105 years ago by Victor Hess







Gamma-ray Astrophysics 5/6

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- cosmic rays are charged:

  ... MOSTLY PROTONS

- they do not point back to their point of origin because they get deflected in magnetic fields
- the sites of acceleration of cosmic rays would also be sources of high-energy gamma rays

SO... IF we could establish the hadronic origin of gamma rays from a class of sources, it would be a strong indication that this was the source of the high-energy cosmic rays

Gamma-ray Astrophysics 6/6

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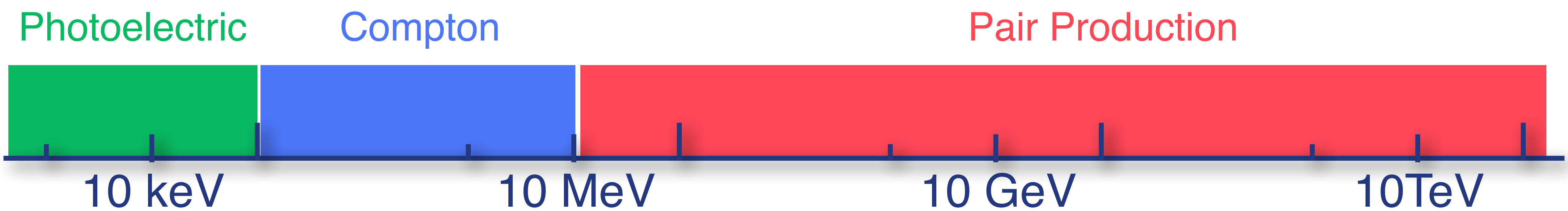
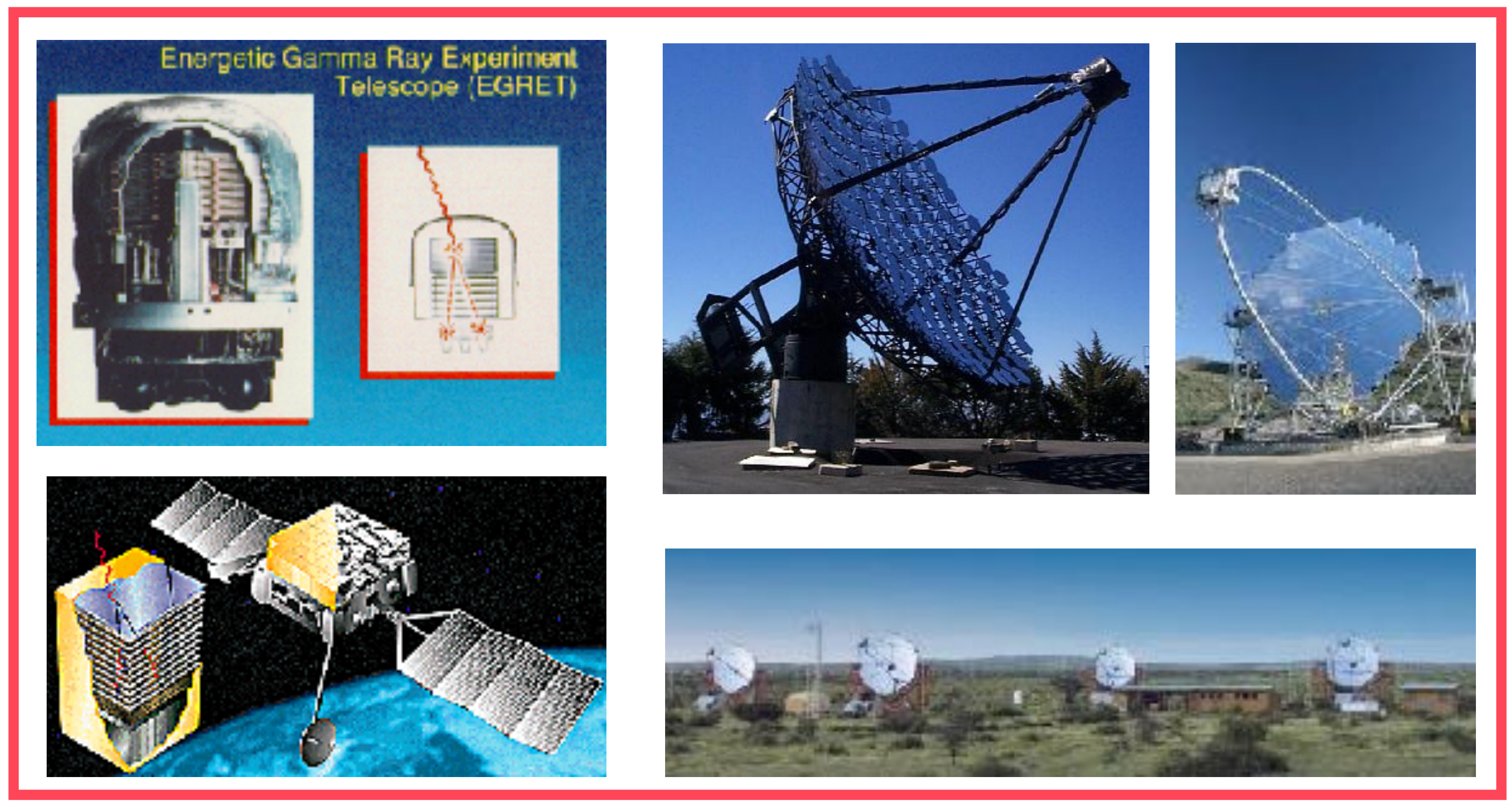


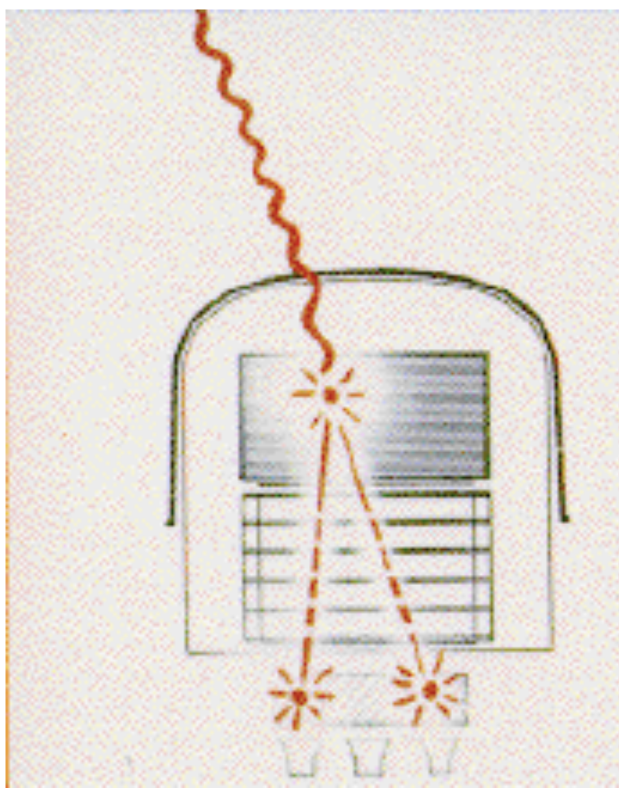


Gamma-ray Astrophysics 6/6

High Energy Regime | Very High Energy Regime

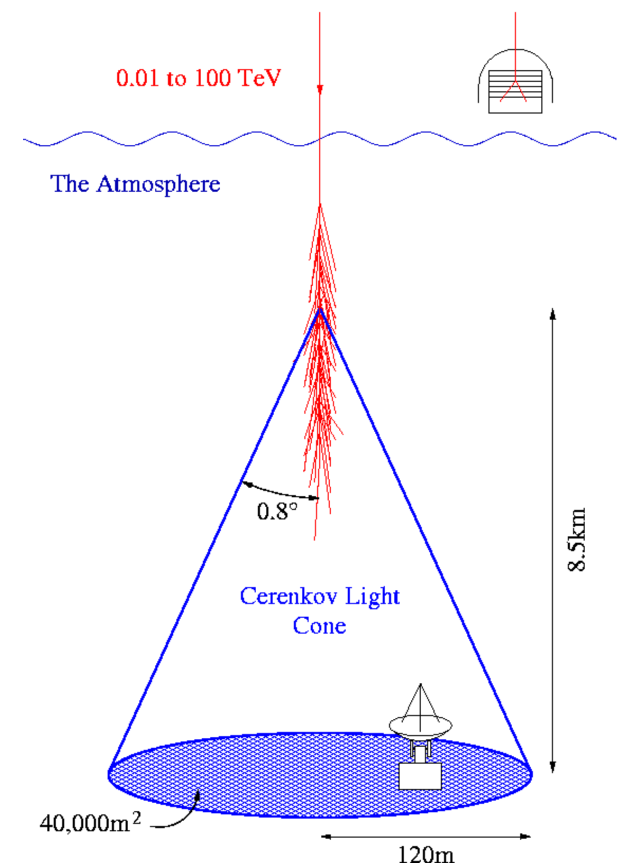
1MeV 10MeV 100MeV 1GeV 10GeV 100GeV 1TeV 10TeV 100TeV

- particle interacts directly in detector
- limited by physical size of detector



Fermi, EGRET, INTEGRAL ...

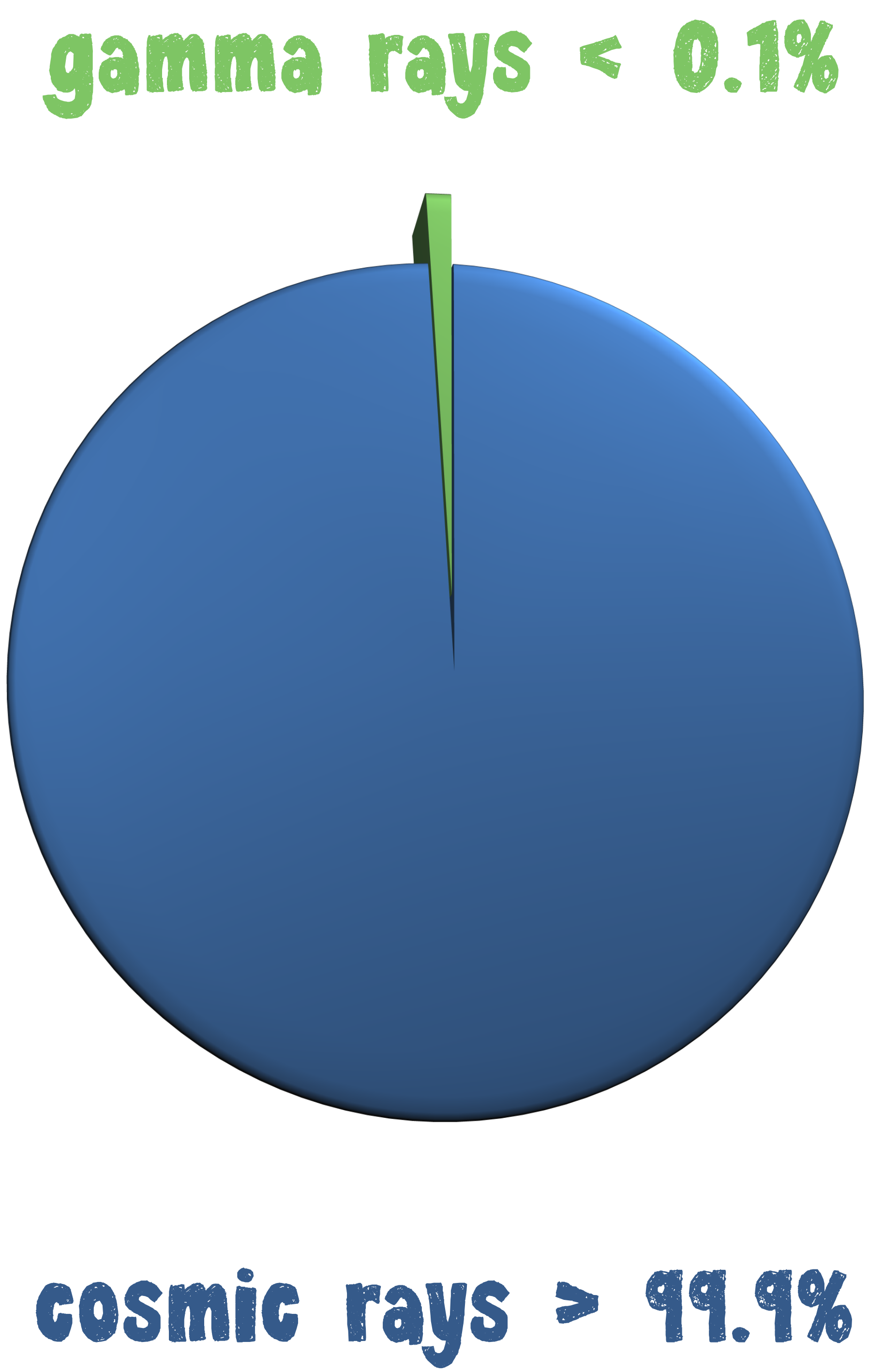
- particle interacts in the atmosphere
- large collection area



Whipple, VERITAS, HESS, MAGIC ...

Space-based detection
3/9

Space-based detection: HE range

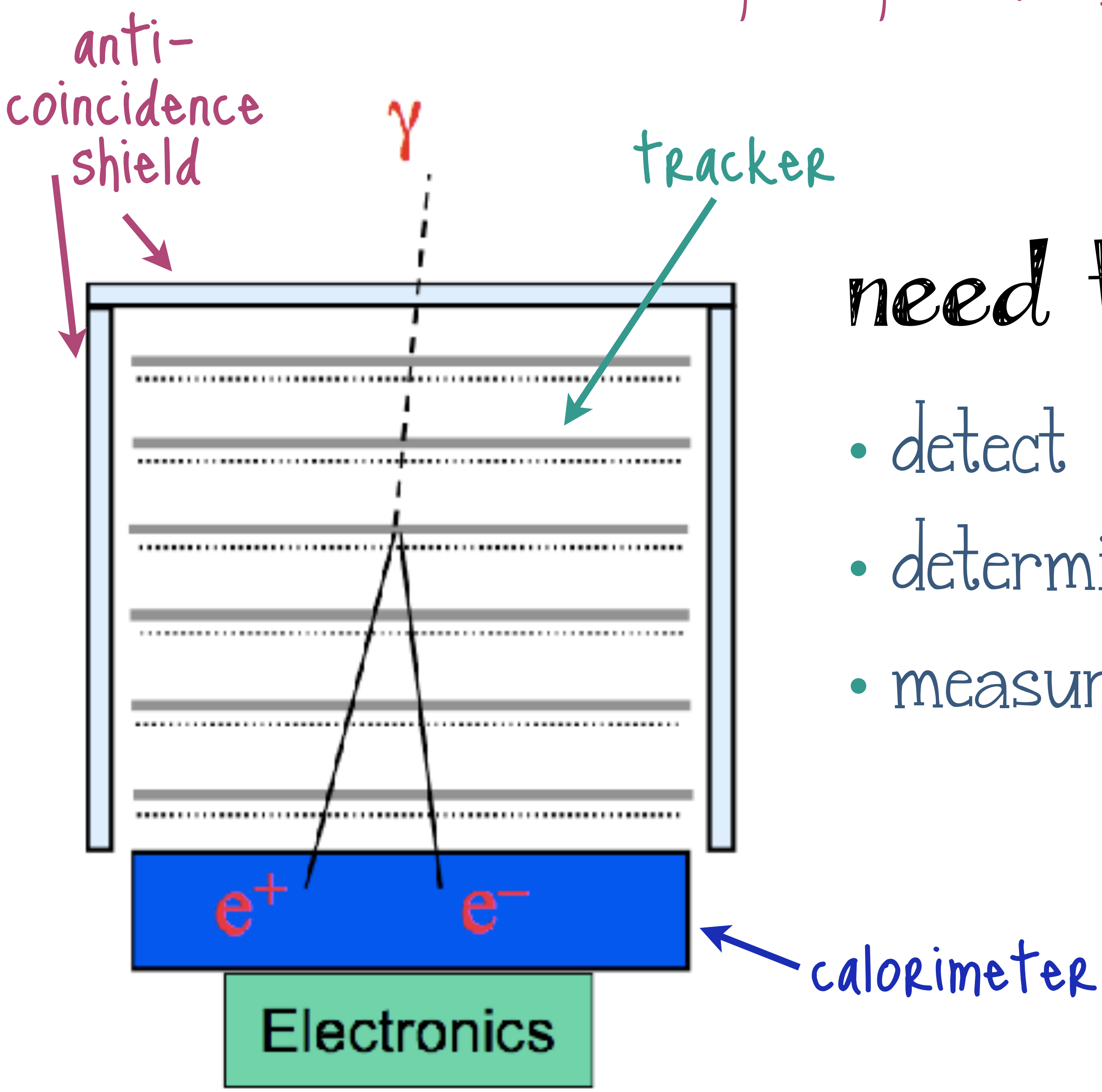


THE
BACKGROUND
IS A
THOUSAND
TIMES LARGER
THAN THE
SIGNAL
THAT WE WANT TO
MEASURE

Space-based detection: HE range

Gamma ray interacts directly in detector

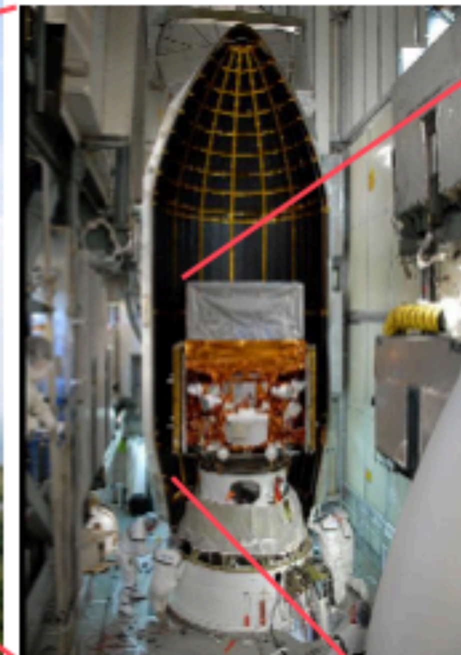
(pair produces)

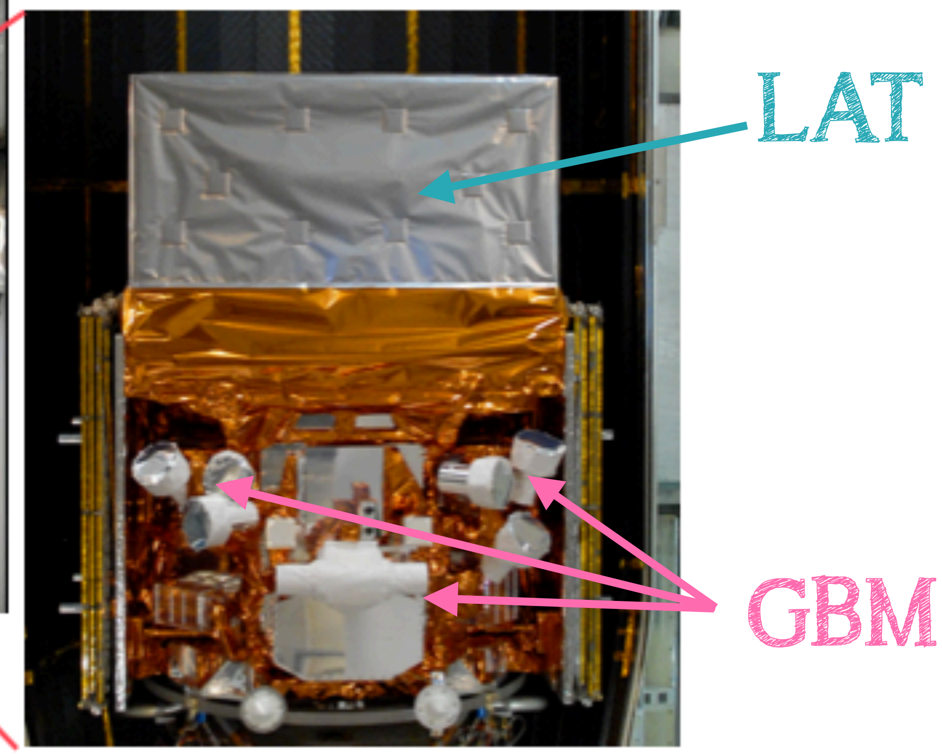


need to:

- detect gamma rays / reject background
- determine gamma-ray direction
- measure the energy of the gamma rays

Space-based detection: HE range





Fermi Gamma-ray Space Telescope

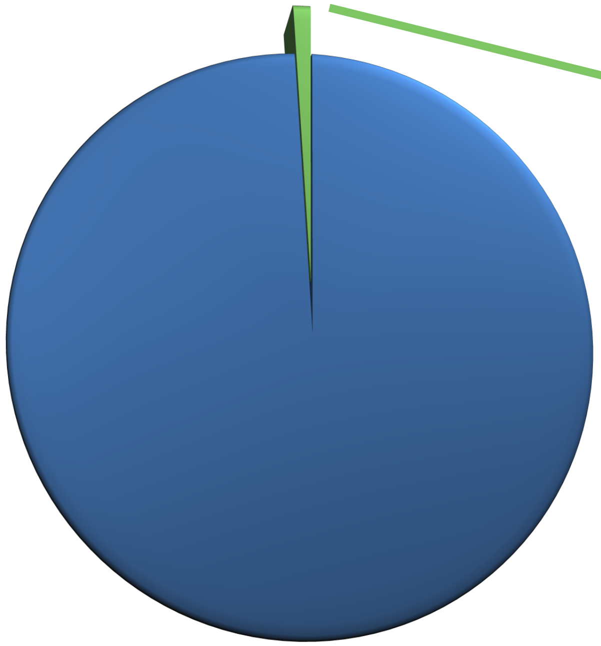
- launched June 2008
- ~~two instruments on board~~
- Large Area Telescope (LAT)
  - ~~100 MeV - 500 GeV ++~~
- Gamma-ray Burst Monitor (GBM)
  - 10 keV - 25 MeV

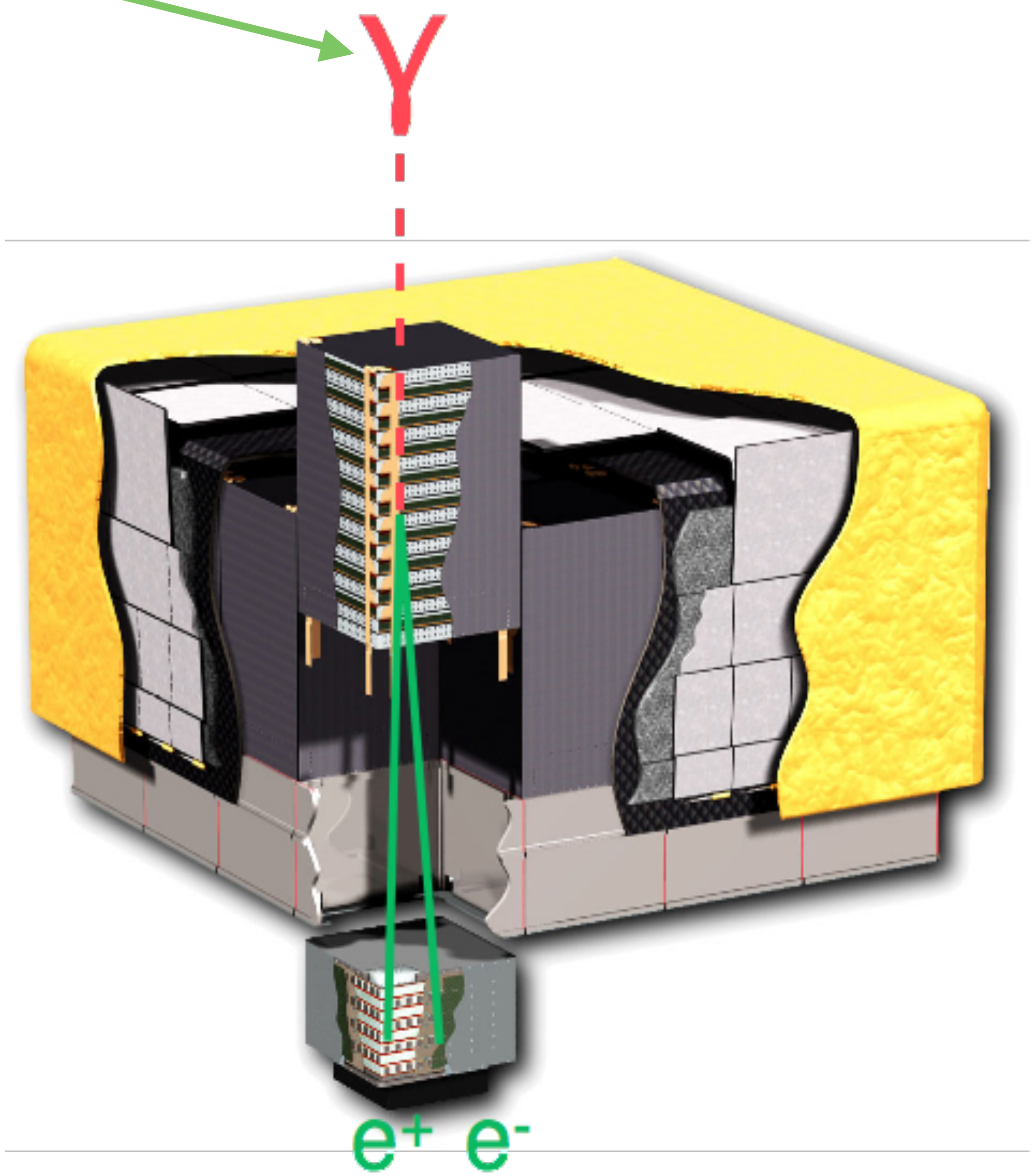
Space-based detection: HE range

The video that I showed on this slide (the Fermi satellite being launched) can be found here:
https://svs.gsfc.nasa.gov/10172

Lots more Fermi videos (including one relating to a question that we had about gravitational lensing of quasar emission from B 0218+357) can be found here:
https://www.nasa.gov/content/fermi/videos

Space-based detection: HE range



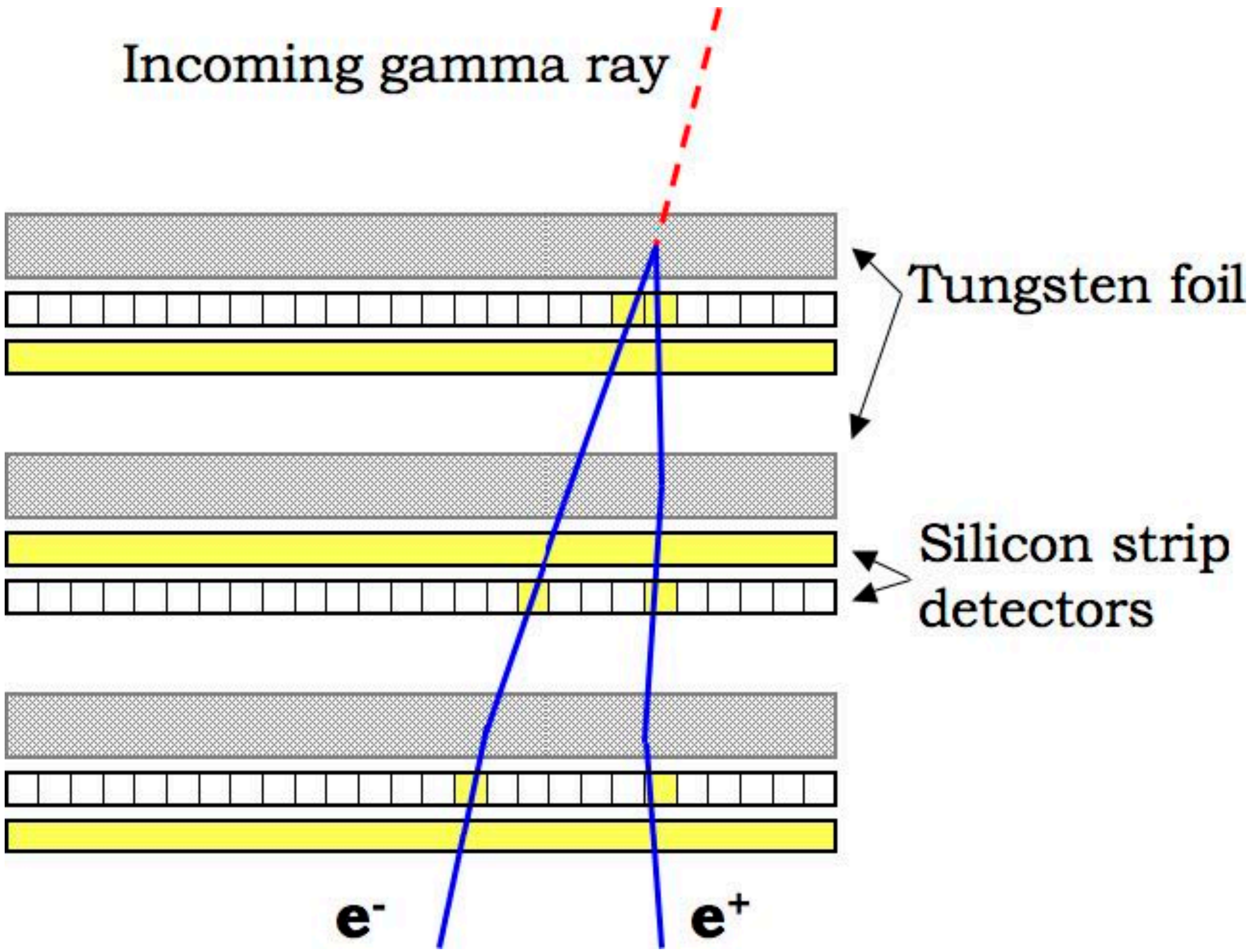


Space-based detection: HE range

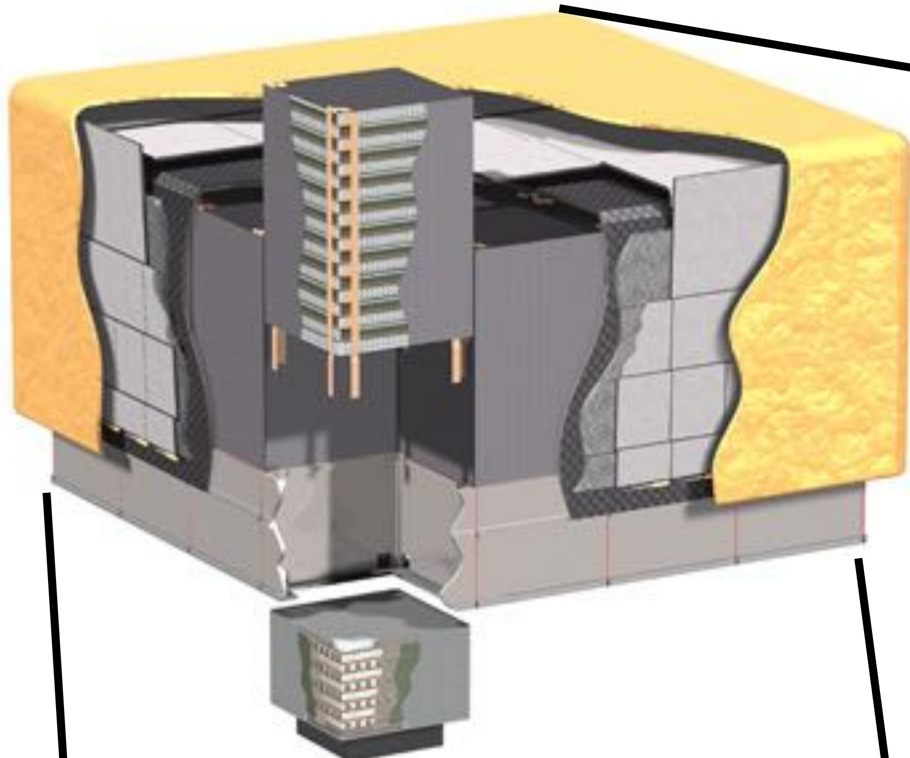
The video that I showed on this slide (a gamma ray converting in the LAT) can be found here:

https://www.youtube.com/watch?v=ESkHDCEAqZk

Space-based detection: HE range



Space-based detection: HE range



x 16 (4 x 4)

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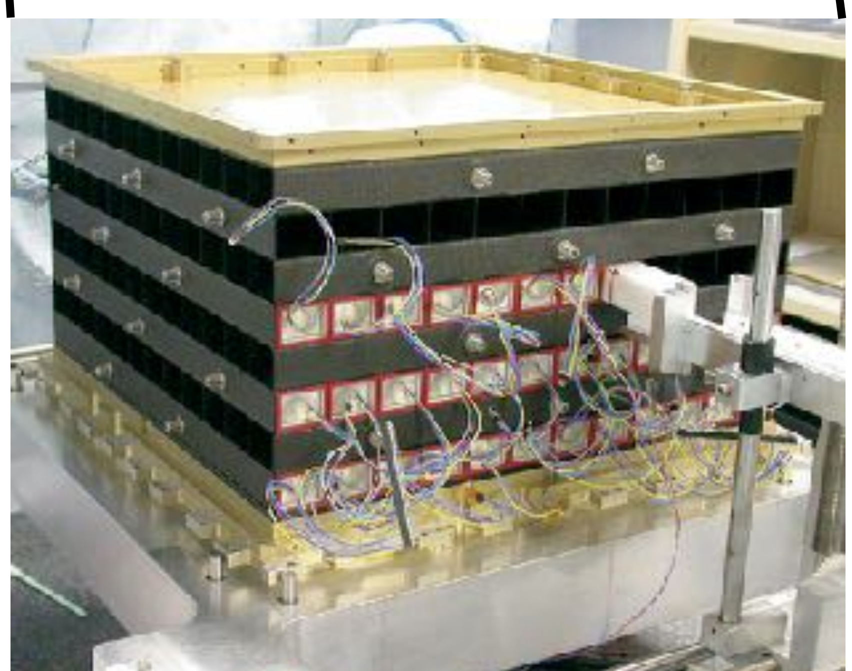
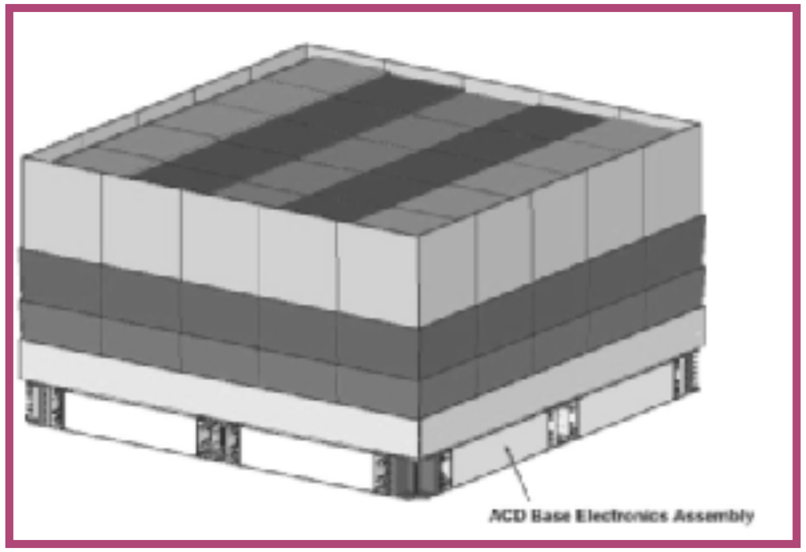


LAT

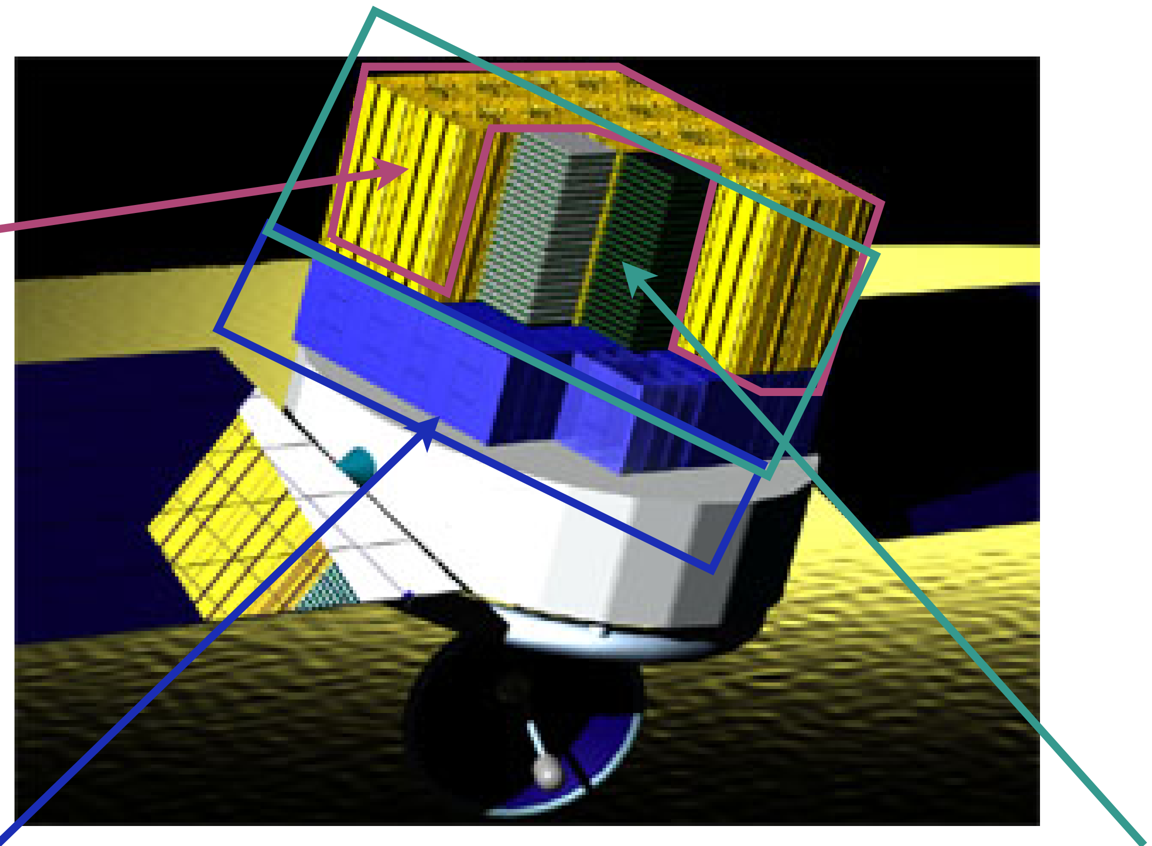
Large Area Telescpe

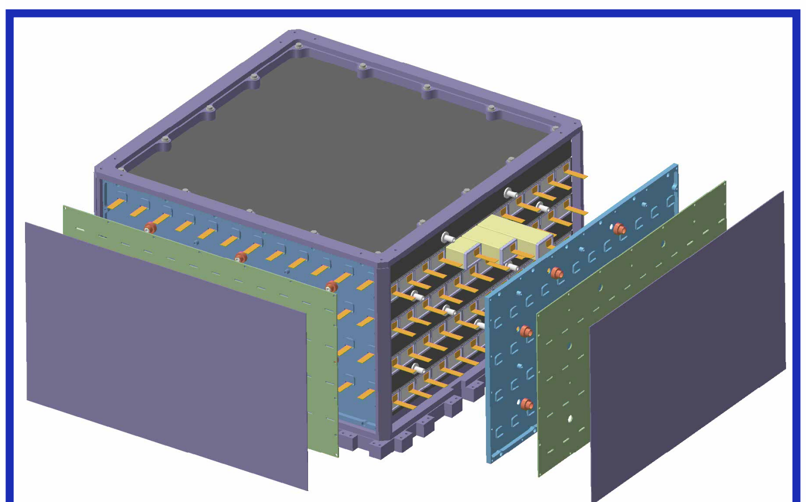
Space-based detection: HE range

Fermi LAT (2008 ...) large area telescope
energy range: 20 MeV - 300 GeV

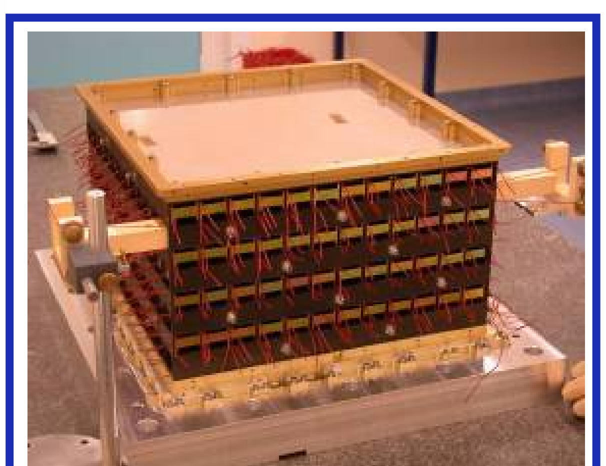


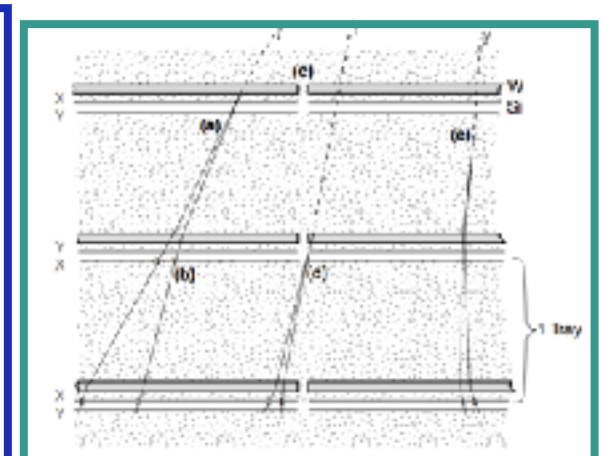
anti-coincidence shield - segmented





calorimeter - 1536 (16 x 96) crystals of CsI(Tl) - position and energy determination

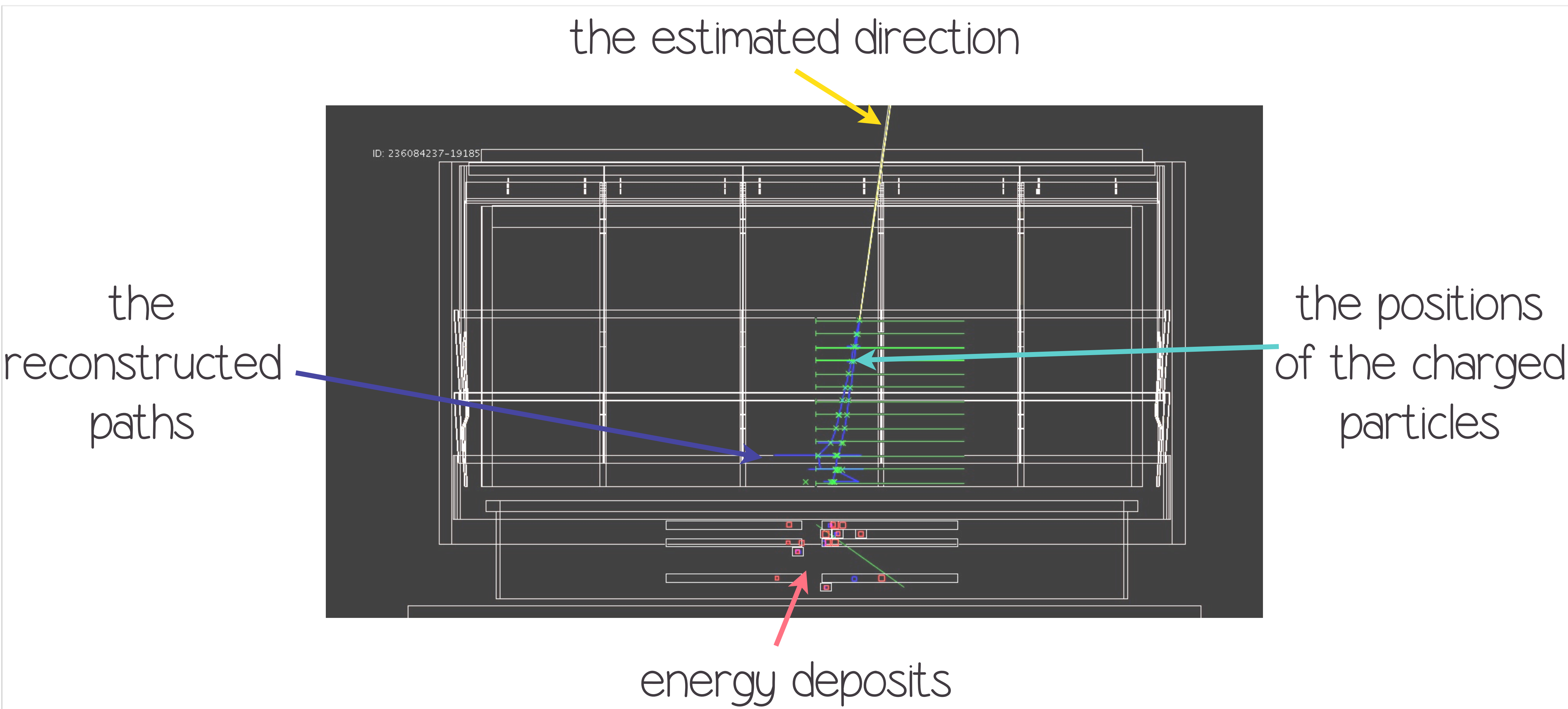




tracker- alternating layers of converter (tungsten) and detector (silicon strip)

Space-based detection: HE range

The three sub-detectors work together to reconstruct the e^+/e^- tracks and to estimate the energy of the primary particle

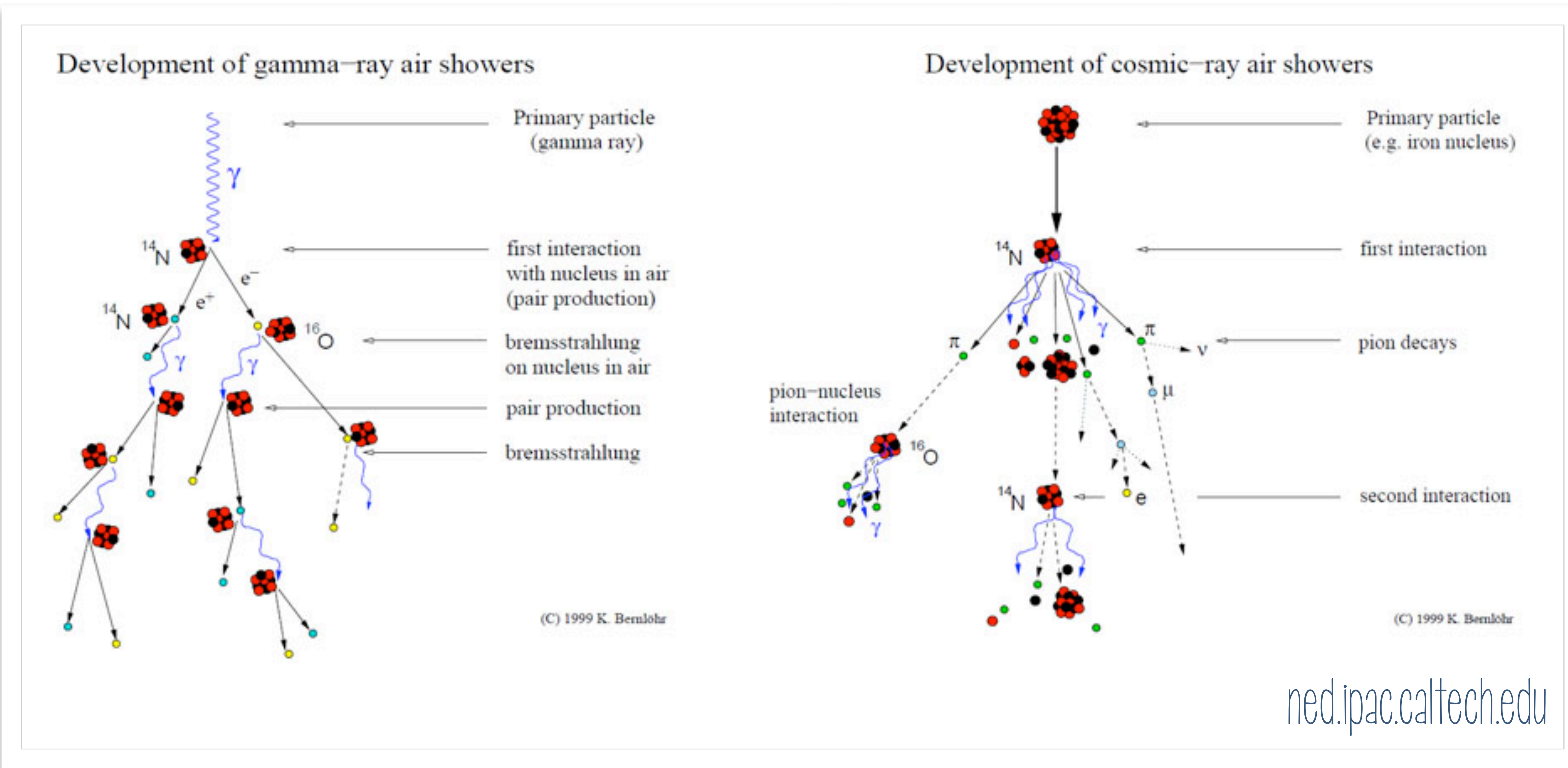


Extensive Air Showers

4/9

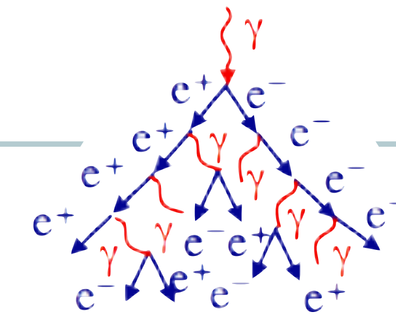
Extensive Air Showers (EAS)

When a high-energy proton or gamma ray enters the earth's atmosphere ...

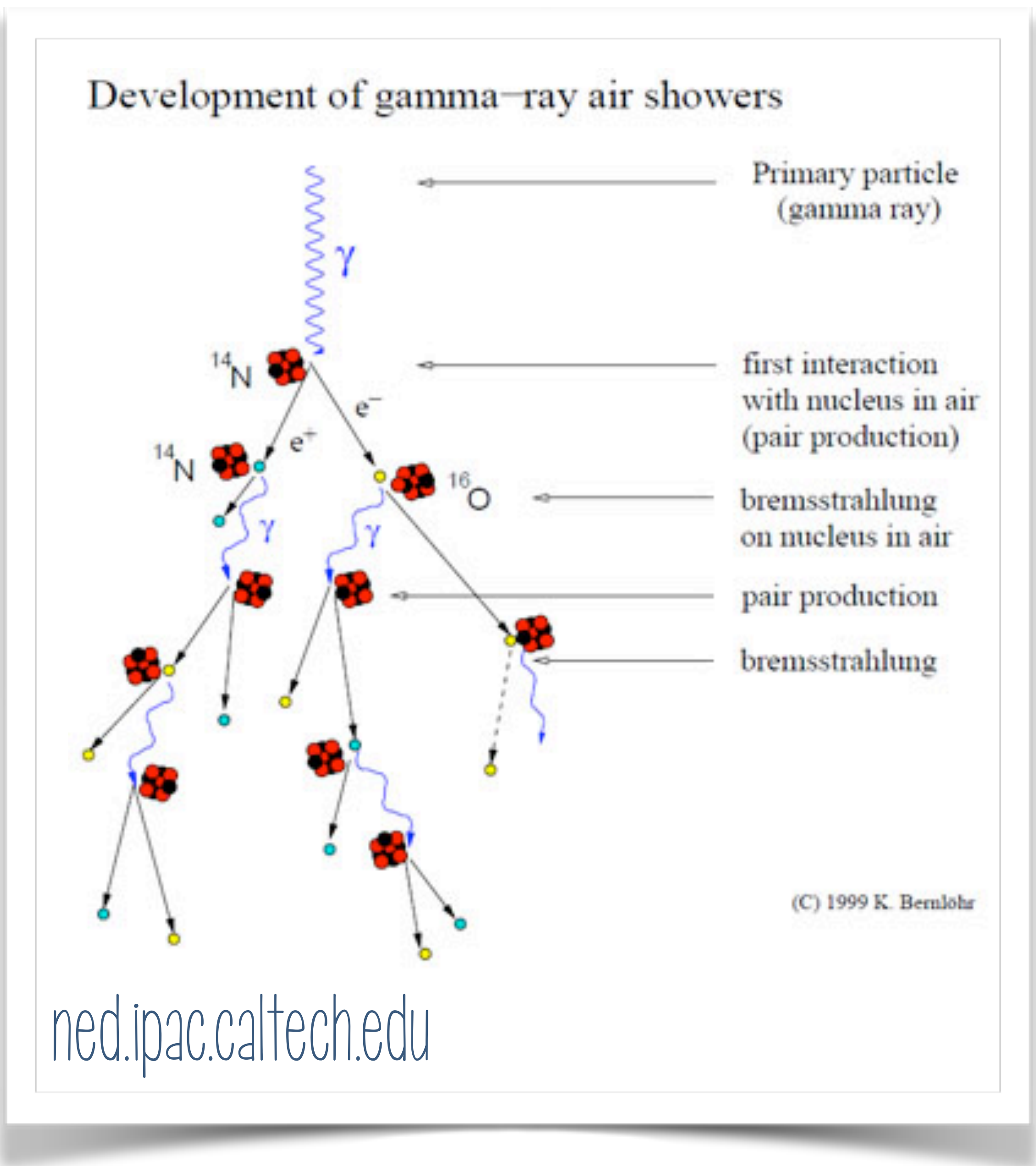


Extensive Air Showers

Extra slide: I did not show this in the presentation. Added it so that you have more background information



When a high-energy GAMMA RAY enters the earth's atmosphere …

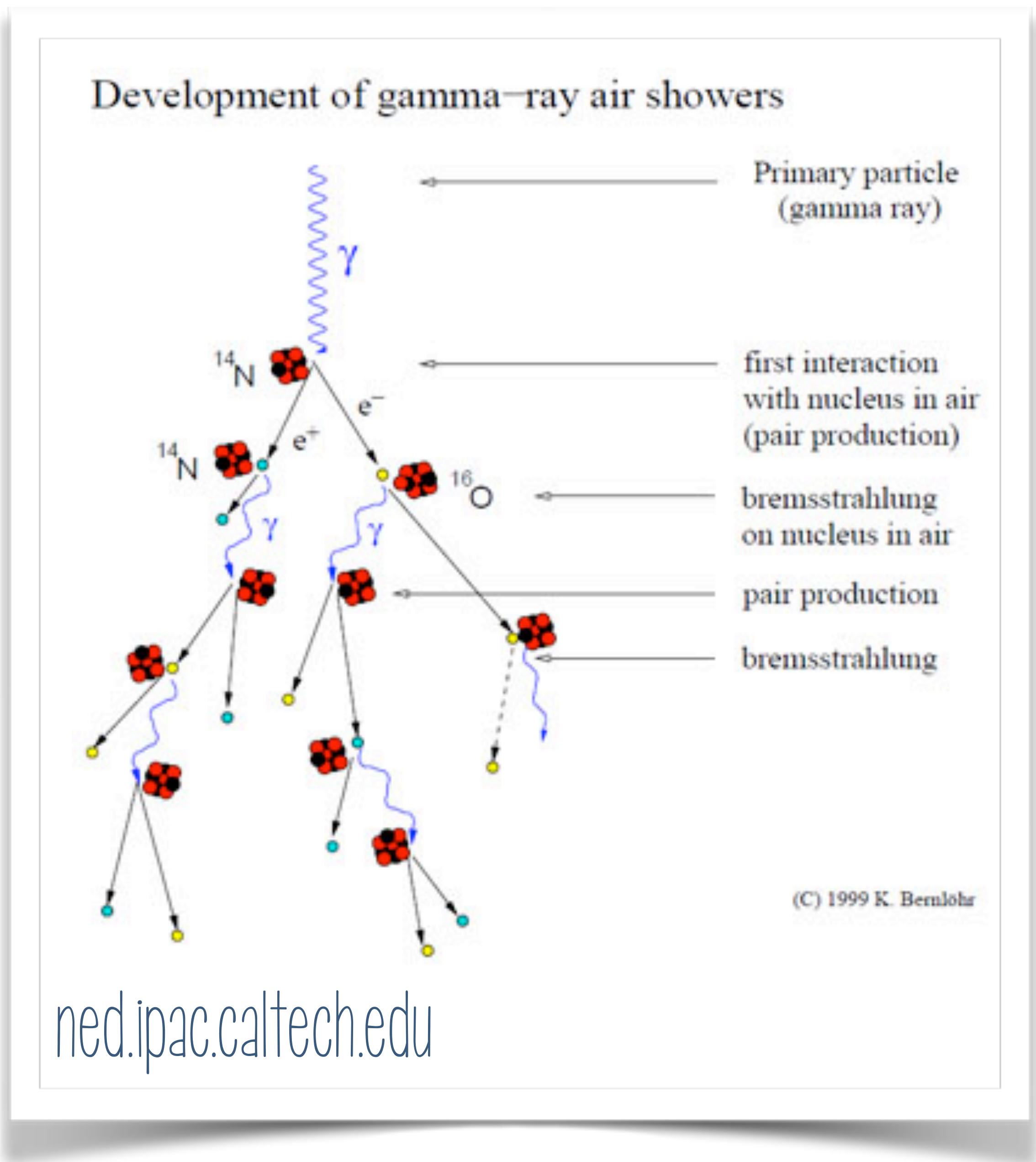


- when a high energy gamma ray passes close to an atomic nucleus in the Earth's atmosphere, it pair produces
  - radiation length = 37.7 g cm^{-2}
  - total atmospheric depth ~1000 g cm^{-2}
    - ➡ gamma ray interacts close to the top of the atmosphere
- e^+e^- pair subsequently undergo bremsstrahlung (similarly high cross-section as pair-production), resulting in the production of a high-energy gamma ray*
- this cycle of pair-production followed by bremsstrahlung continues, resulting in an exponentially growing cascade of particles and radiation, until shower maximum is reached
- at this point, the critical energy (84.2 MeV) at which the electrons lose energy equally by radiation and ionization is reached
  - ➡ beyond this stage, the electrons lose energy rapidly by ionization and cascade multiplication ceases with the particles then being absorbed

*Some muons can also be produced from pion production in photonuclear reactions, but the probability for this is low … about 10^{-4} times that of pair production

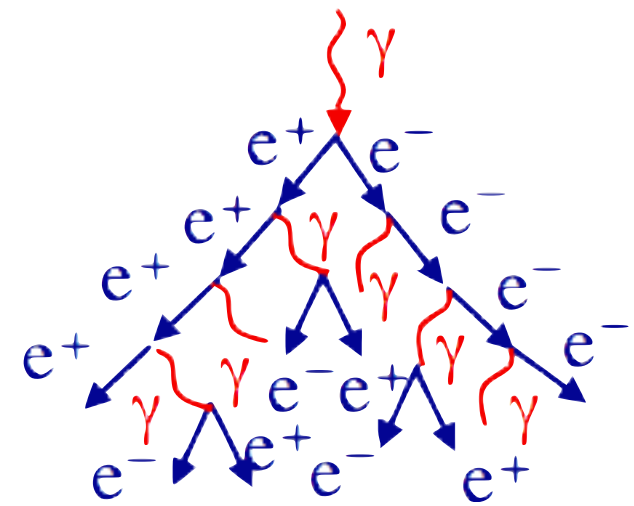
Extensive Air Showers (EAS)

When a high-energy GAMMA RAY enters the earth's atmosphere ...



L'essetiel:

pair production
↓
bremsstrahlung
↓
pair production
↓
bremsstrahlung



for each pair production, half the energy to e^- and half to e^+

... until e^-e^+ reach energy (84.2 MeV) at which they are as likely to ionise as to radiate
... from this point on on they lose energy rapidly by ionisation

*some muons can also be produced fr
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Extensive Air Show

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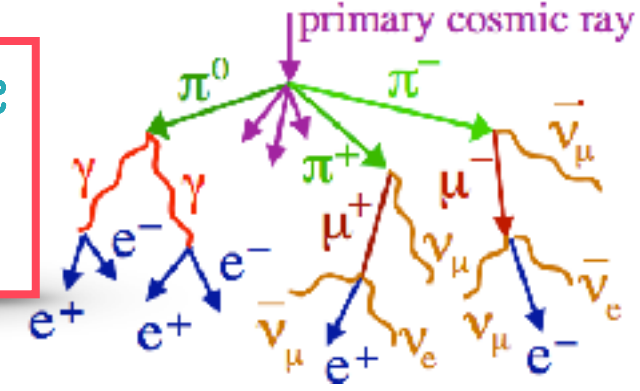
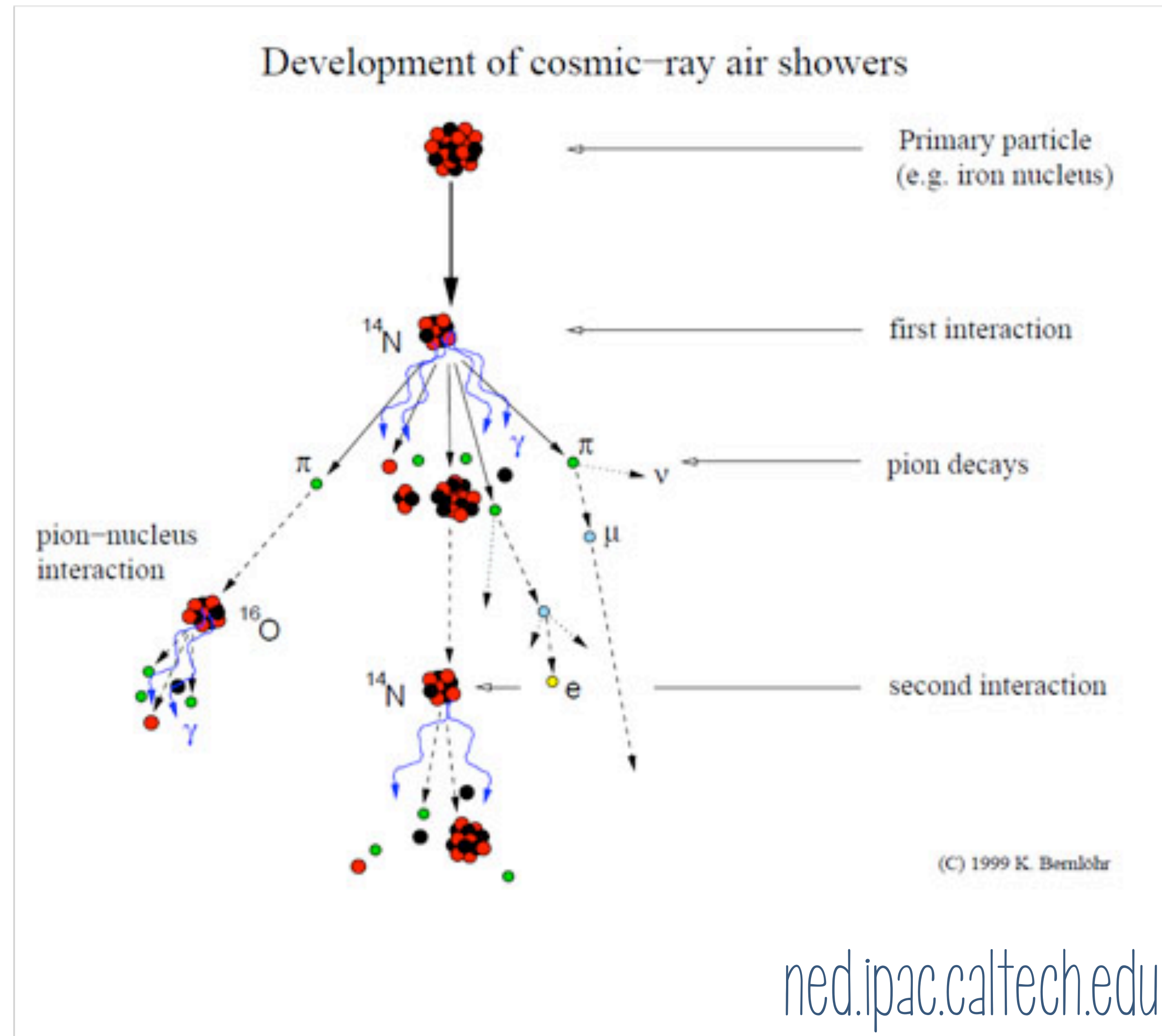


When a high-energy PROTON enters the earth's atmosphere ...

- **most air showers are hadronic**
- when these particles collide with oxygen and nitrogen, cascades of elementary particles and radiation are induced
- **the initial products include nucleons and kaons, but primarily consist of charged and neutral pions which subsequently decay through a number of decay chains**

$$\pi^+ \rightarrow \mu^+ + \nu, \quad \tau = 2.6 \times 10^{-8}\,s$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}, \quad \tau = 2.6 \times 10^{-8}\,s$$
$$\pi^0 \rightarrow \gamma + \gamma, \quad \tau = 8.4 \times 10^{-17}\,s$$

- since muons do not interact strongly, most of those produced penetrate to the Earth's surface.
  - ➡ relativistic effects: their lifetimes (~2.2μs) are effective-ively longer in atmosphere than in their rest frame.
  - ➡ in hadron showers, several percent of the particles reaching the ground are muons



ned.ipac.caltech.edu

Extensive Air Show

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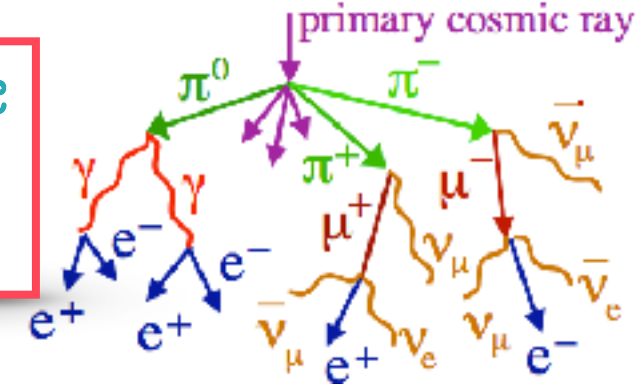

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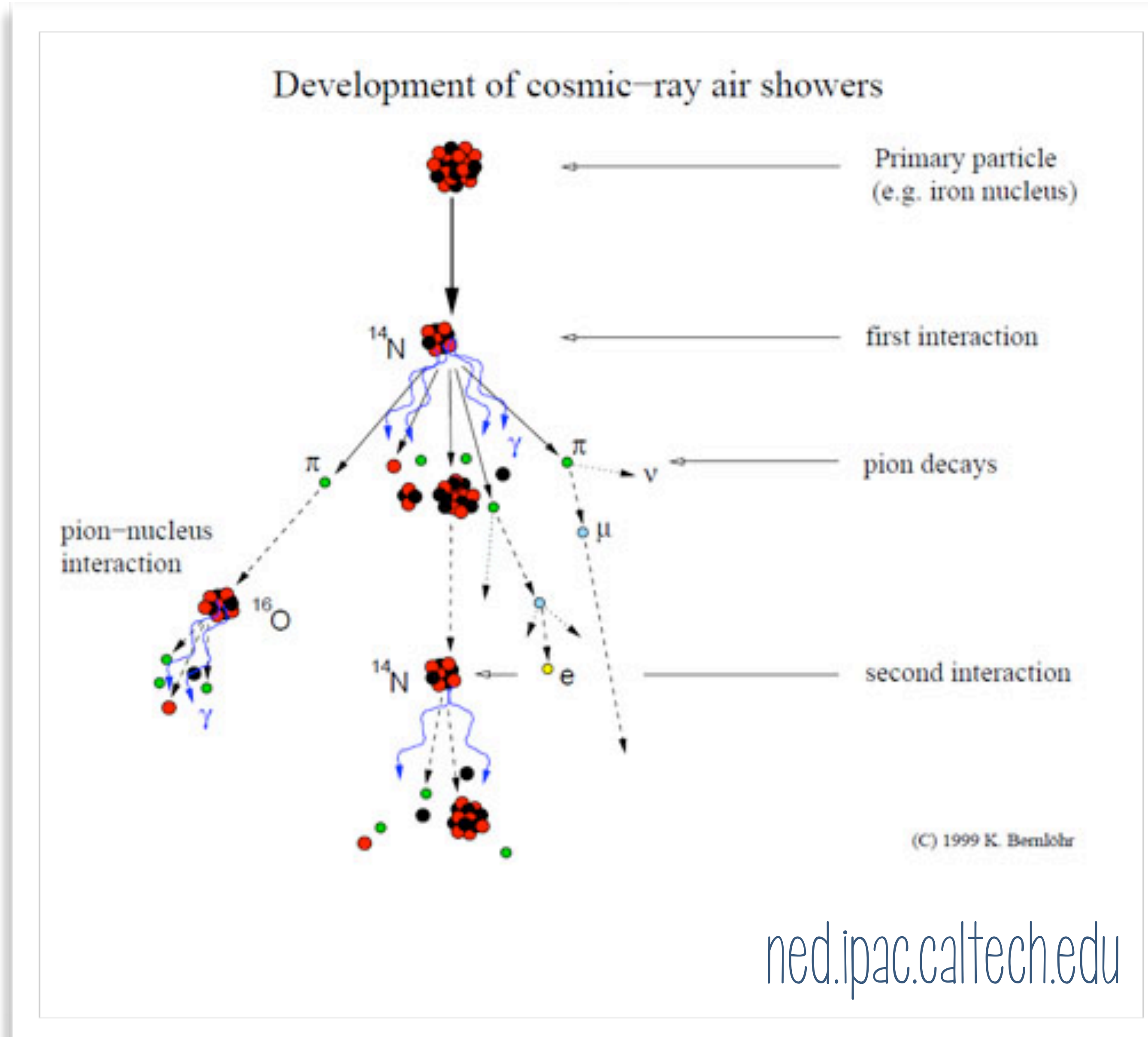
$\pi^- \to \mu^- + \bar{\nu}, \ \tau = 2.6 \times 10^{-8}\,s$

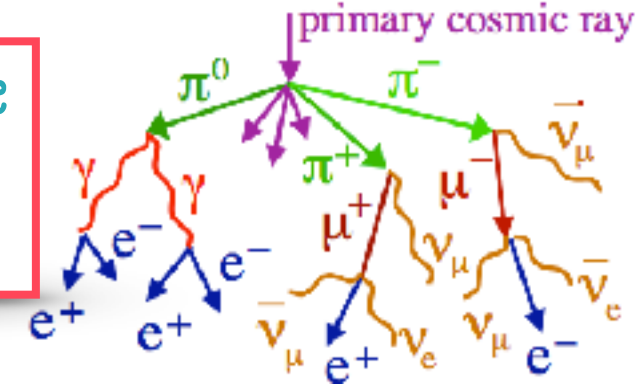
$\pi^0 \to \gamma + \gamma, \ \tau = 8.4 \times 10^{-17}\,s$

- At each generation of hadronic pion production ~1/3 of the pions are π^0s
  - ➡ immediately decay into two gamma rays (~70MeV)
  - ➡ these subsequently pair produce
  - ➡ electromagnetic cascades rapidly grow to comprise the dominant component within the hadronic cascade



Extensive Air Show

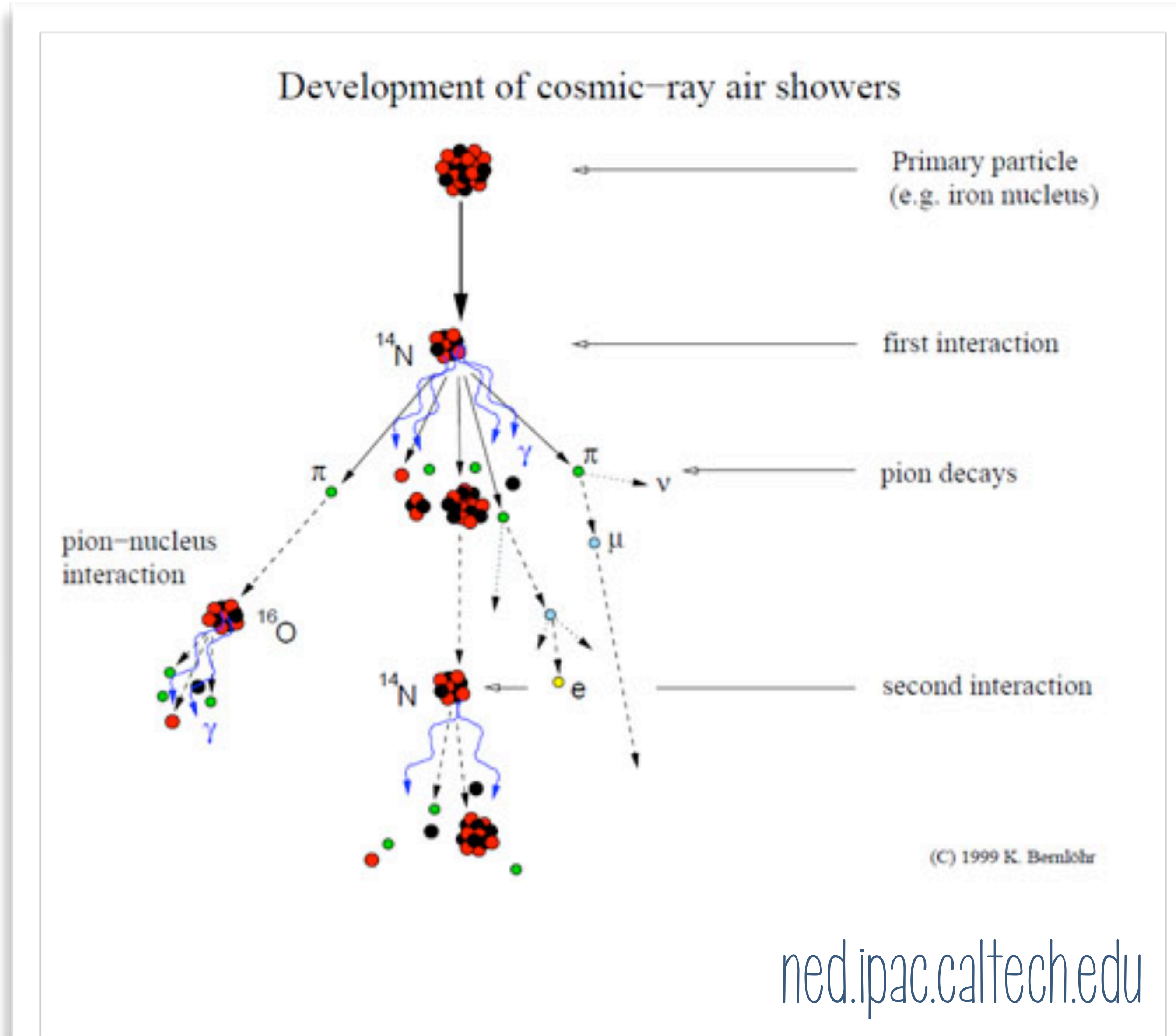
Extra slide: I did not show this in the presentation. Added it so that you have more background information



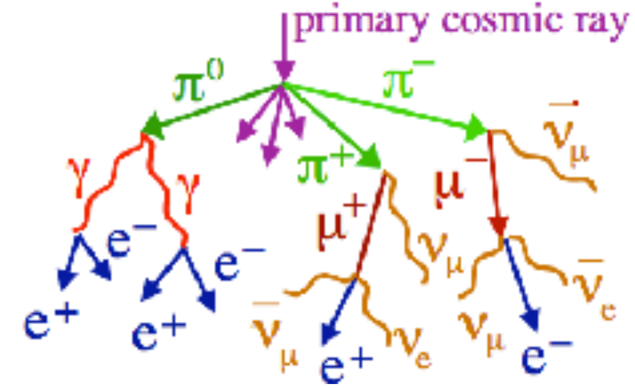
When a high-energy PROTON enters the earth's atmosphere …

- **the secondary nucleons and charged pions continue to multiply until the energy per particle is no longer above the threshold for multiple pion production (~1GeV)**
- eventually the cascade just consists of the electromagnetic component
- **once shower maximum is reached, the e^+s and e^-s are rapidly attenuated due to ionisation**
- the lateral spread of hadronic showers is usually much greater than that of gamma-ray showers
  - due to the large TRANSVERSE MOMENTUM given to pions in strong interactions
- these showers also have a longer penetrating tail, due to the large number of particles reaching ground level

important later



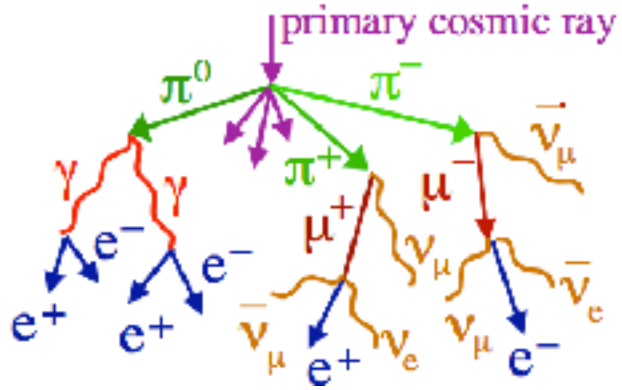
Extensive Air Showers (EAS)



When a high-energy PROTON enters the earth's atmosphere ...

L'essetiel:

initial products primarily consist of muons – charged & neutral



$\pi^+ \rightarrow \mu^+ + \nu,$

$\pi^- \rightarrow \mu^- + \bar{\nu},$

$\pi^0 \rightarrow \gamma + \gamma,$

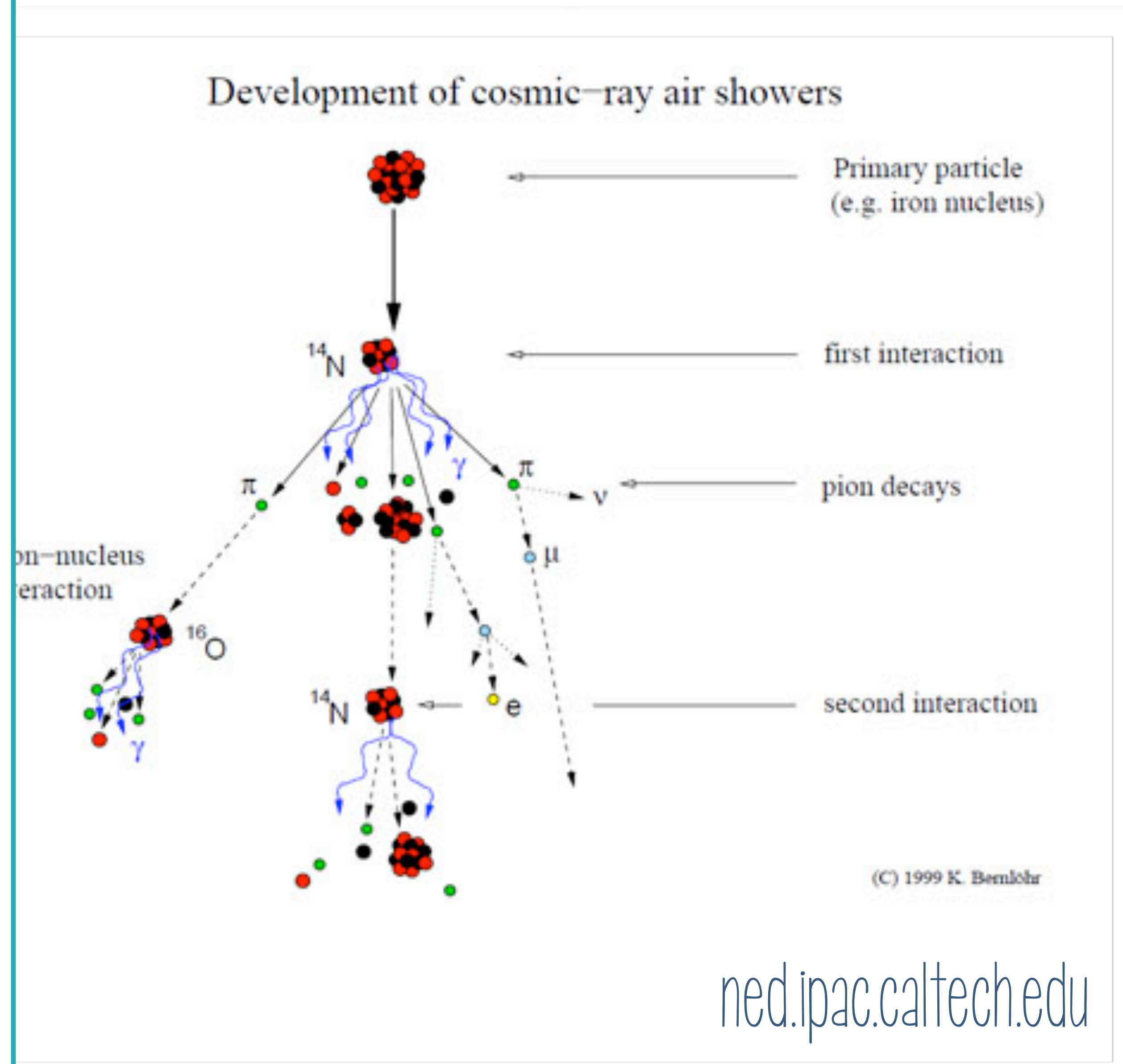
many of the charged muons reach the surface of the earth

- ~1/3 of the pions are π^0s
  - ➡ decay into two gammas
  - ➡ these pair produce

➡ electromagnetic cascades rapidly grow to comprise the dominant component within the hadronic cascade

... shower has a large lateral spread due to the transverse momentum of the strong interaction
... many muons reach the ground

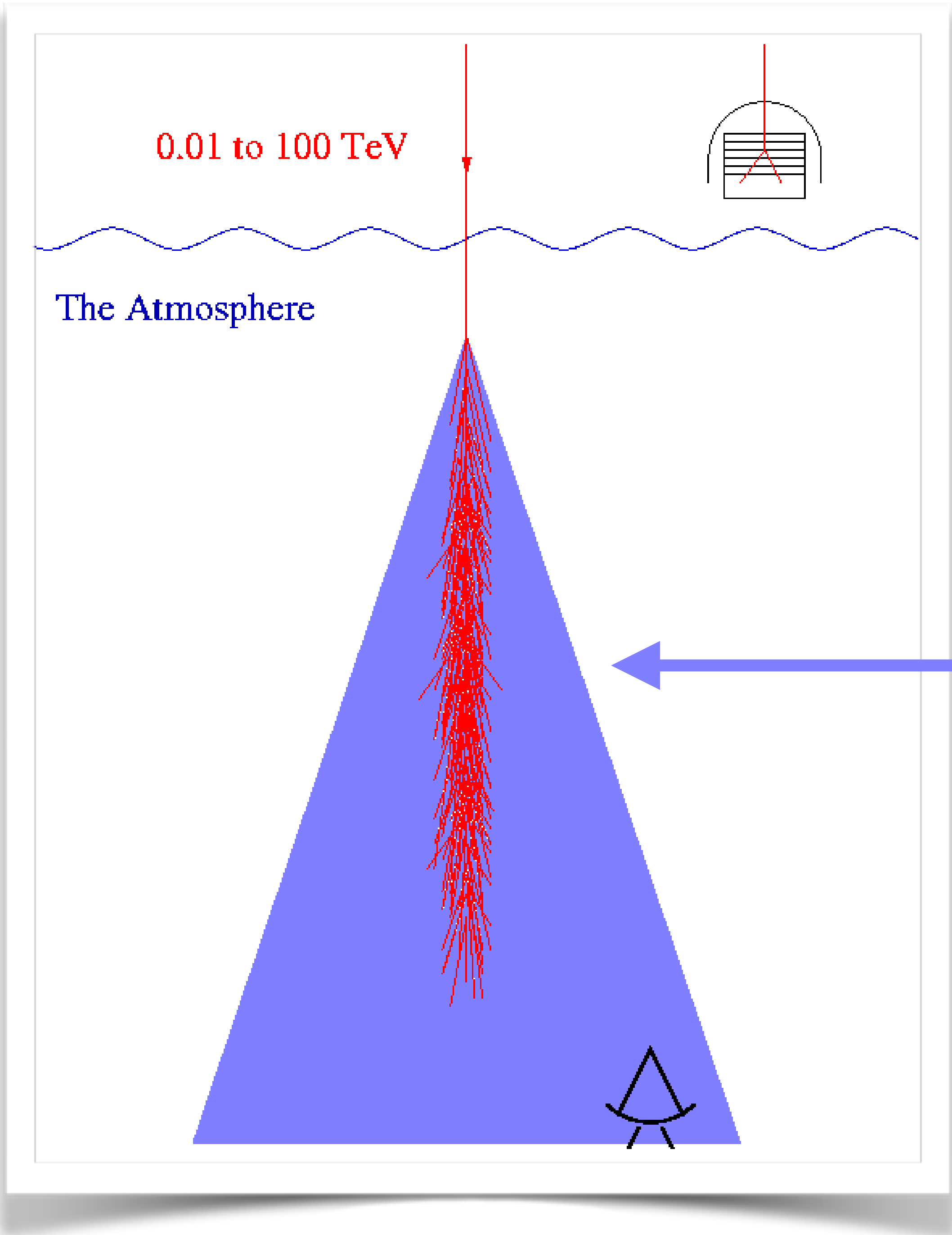
important later !



ned.ipac.caltech.edu

Extensive Air Showers (EAS)

When a high-energy particle or gamma ray enters the earth's atmosphere ...



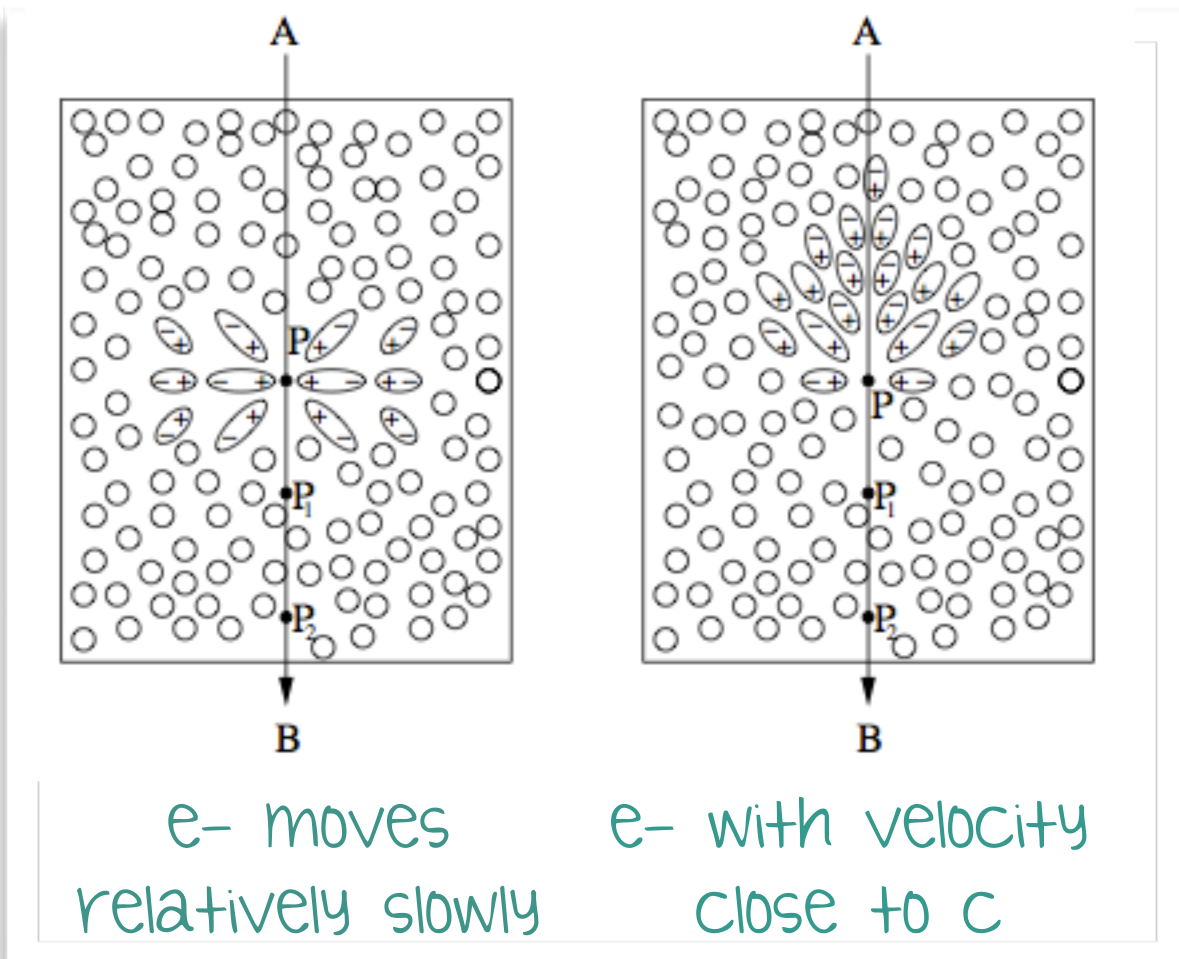
... the shower of charged particles is accompanyed by CHERENKOV RADIATION

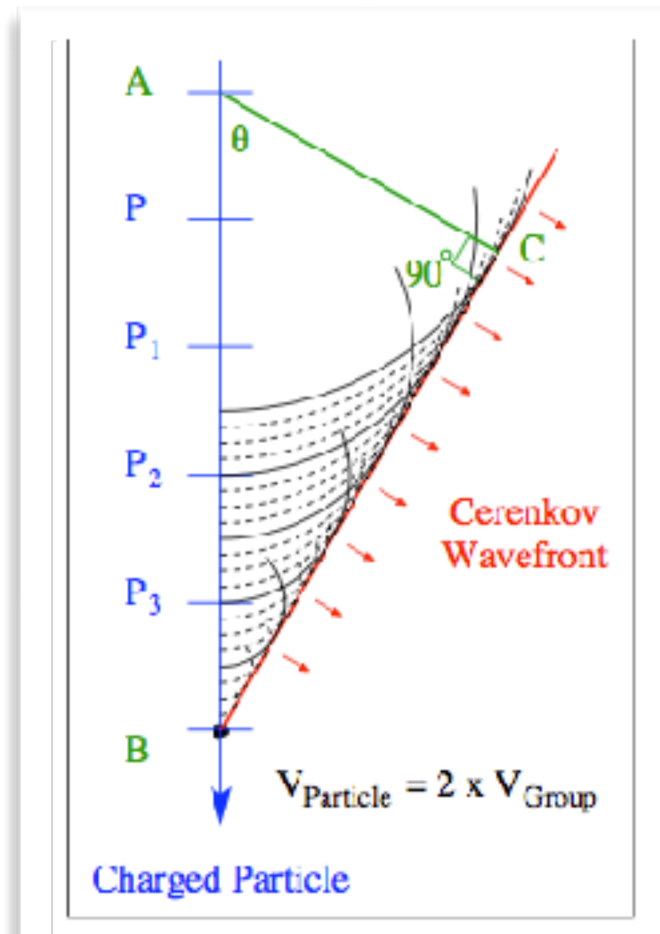
Cherenkov Radiation
5/9

Cherenkov* Radiation

*Čerenkov

CHERENKOV RADIATION: when a charged particle travels through a medium with a velocity greater than the velocity of light in that medium



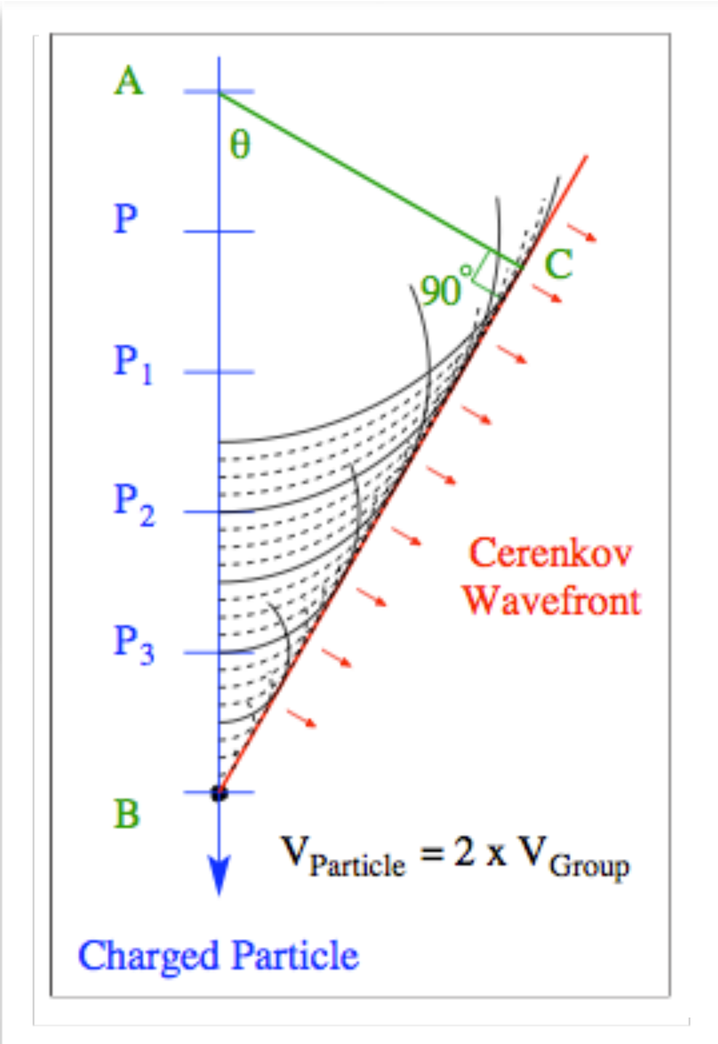


- When the charged particle (say, an e-), passes close to the atoms of a material, it distorts their alignment such that the positive charges of the nuclei are attracted towards it.
- When the e- has passed, the atoms relax back to their original shapes causing a brief electromagnetic pulse - polarisation moves on to be centred on P_1 etc...
- When the velocity of the e- is greater than the phase velocity of light in that medium, it is possible for the wavelets from all portions of the track to be in phase with one another, thus producing a coherent wave-front at a well defined angle to the path of the electron.
- This coherence occurs when the electron travels from A to B, in the same time as the radiation emitted by the atoms of the material, travels from A to C.

Cherenkov Radiati

Extra slide: I did not show this in the presentation. Added it so that you have more background information

CHERENKOV RADIATION: when a charged particle travels through a medium with a velocity greater than the velocity of light in that medium



e- has velocity βc & it travels from A to B in time Δt:

$$AB = \beta c \Delta t \quad \text{and} \quad AC = \frac{c}{n}\Delta t$$

since: $\cos\theta = \frac{AC}{AB}$

we can arrange the first two equations to get:

$$\cos\theta = \frac{1}{\beta n}$$

... the criterion for cherenkov radiation to be emitted

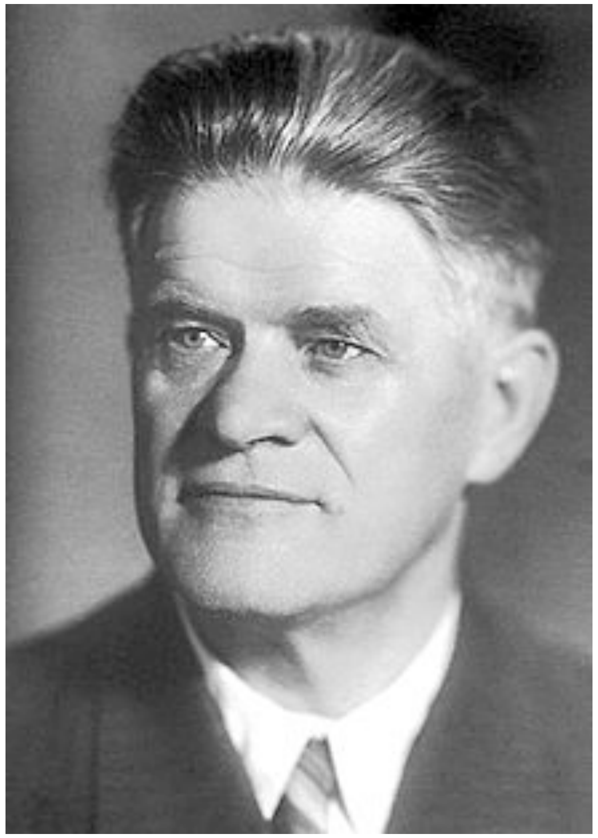
cherenkov angle is max for β=1. There is a min velocity for the charged particle & also a threshold energy

$$\theta_{max} = \cos^{-1}\frac{1}{n} \qquad \beta_{min} = \frac{1}{n} \qquad E_{min} = \frac{m_0 c^2}{\sqrt{1-\beta_{min}^2}}$$

The medium is the radiator - not the particles!

CHERENKOV RADIATION:

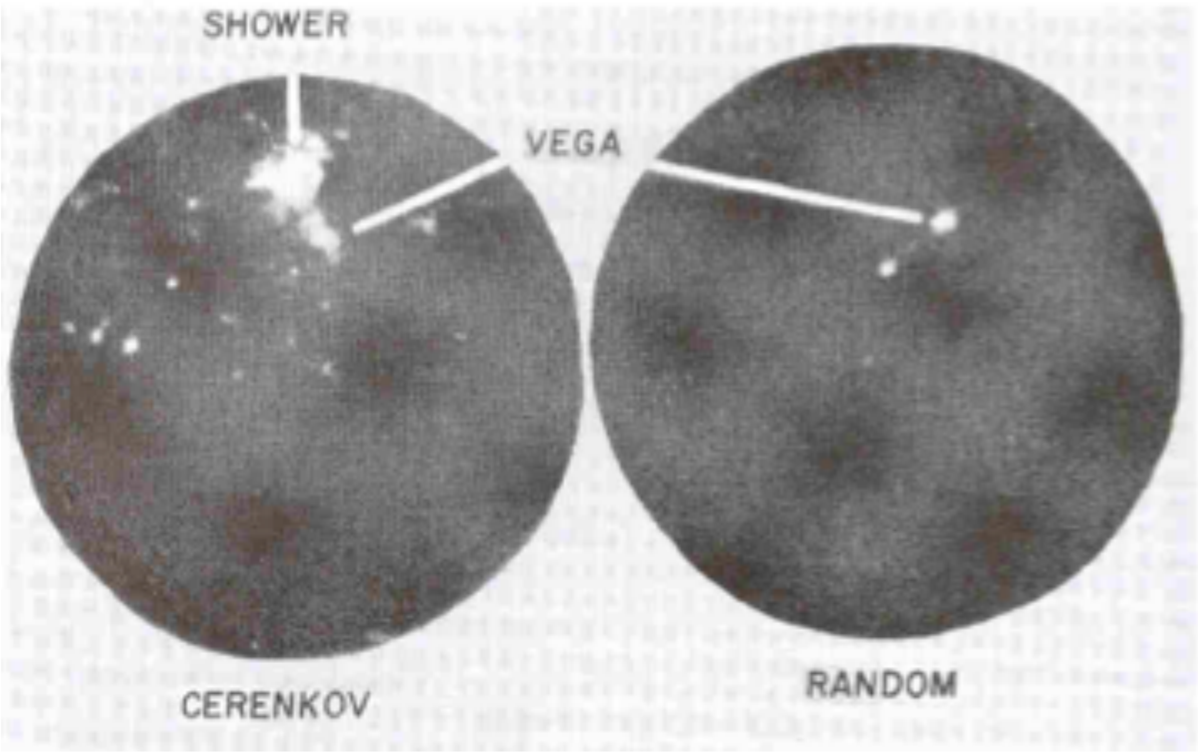
- It is named after the Russian scientist Pavel Alekseyevich Cherenkov. He shared the Nobel Prize in physics in 1958 with Ilya Frank and Igor Tamm for its discovery - made in 1934. He was the first to detect it experimentally.
- **Cherenkov radiation is blue - UV light**
- In 1948, it was suggested by Blackett that there should be a small contribution (10^{-4} of total starlight) to the light of night sky from Cherenkov radiation
- very briefly, it outshines the night sky - need very fast electronics to record it above this background



P. A. Cherenkov (1904 - 1990)

VHE Technique

image intensifier pictures of night sky
with and without Cherenkov shower

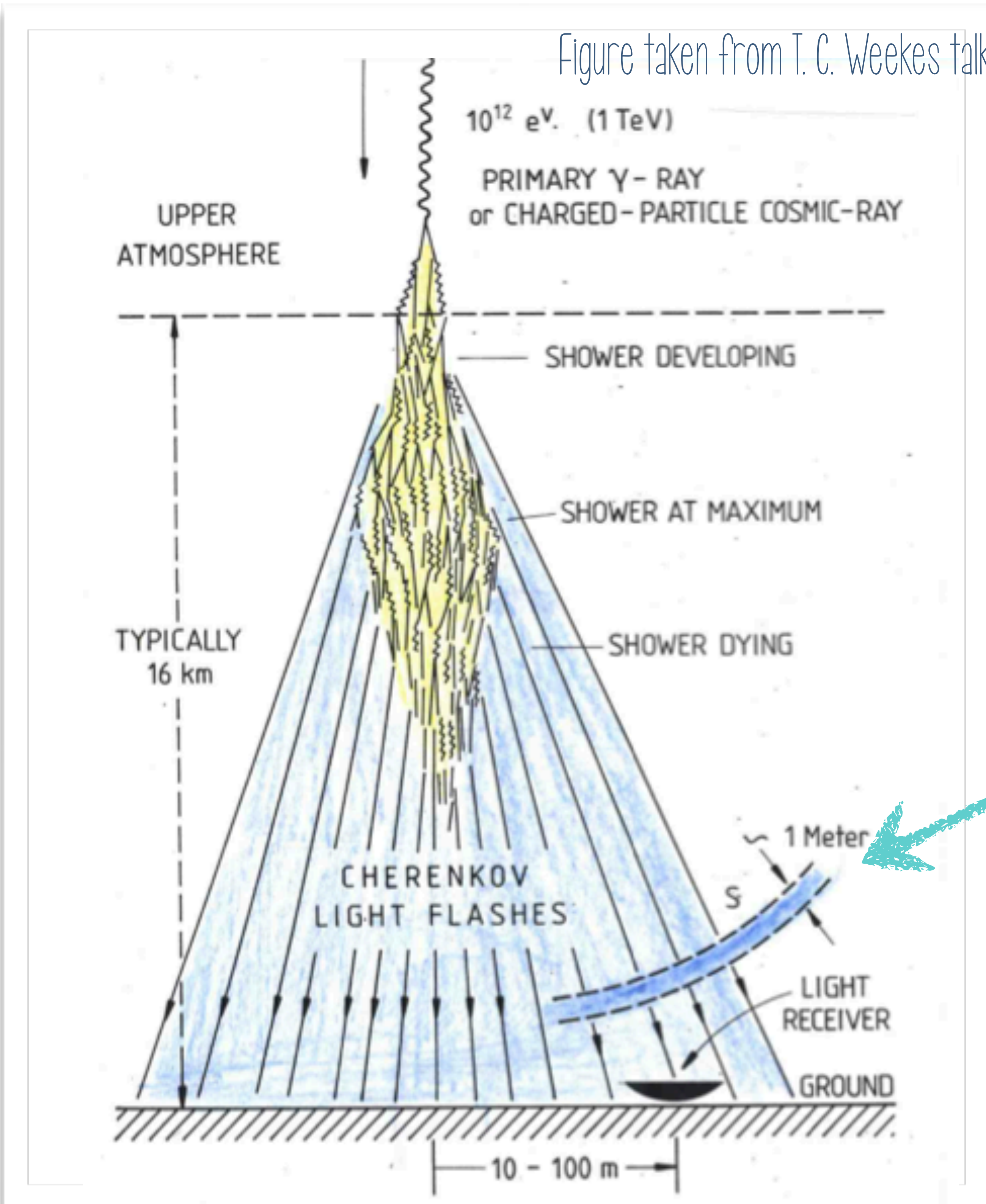


Work by David Hill (M.I.T.) and Neil Porter (U.C.D.) in 1960

on short timescales, the light from the
Cherenkov shower outshines Vega!*

* The FIFTH brighest star in the sky

Cherenkov Radiation



for a 100 GeV primary, get about 5 photons m^{-2} out to about 120m from the axis

at detector level, the shower results in a pool of light of:

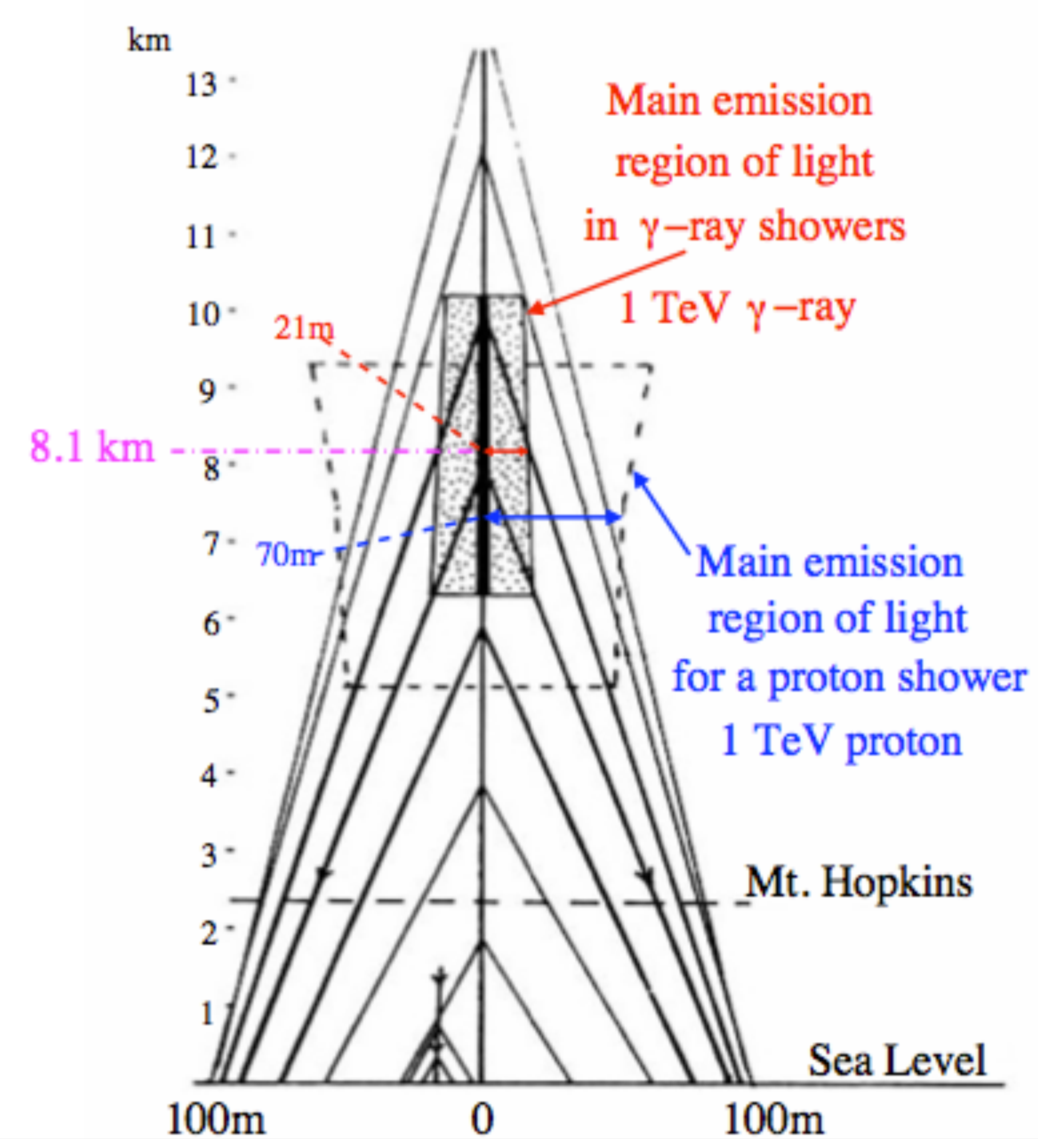
- ~120m diameter
- ~1m (2-3 ns) thickness

Cherenkov Radiati

Extra slide: I did not show this in the presentation. Added it so that you have more background information

- the stippled box contains the main emission of Cherenkov light in a 1 TeV gamma-ray shower
- **the median altitude is 8.1 km**
- at these heights, half the emission occurs at radial distances within the box
- the dashed-box indicates the main emission region for Cherenkov light in a proton shower of the same energy

Figure adapted from Hillas (1996), Space Science Reviews, 75, 17

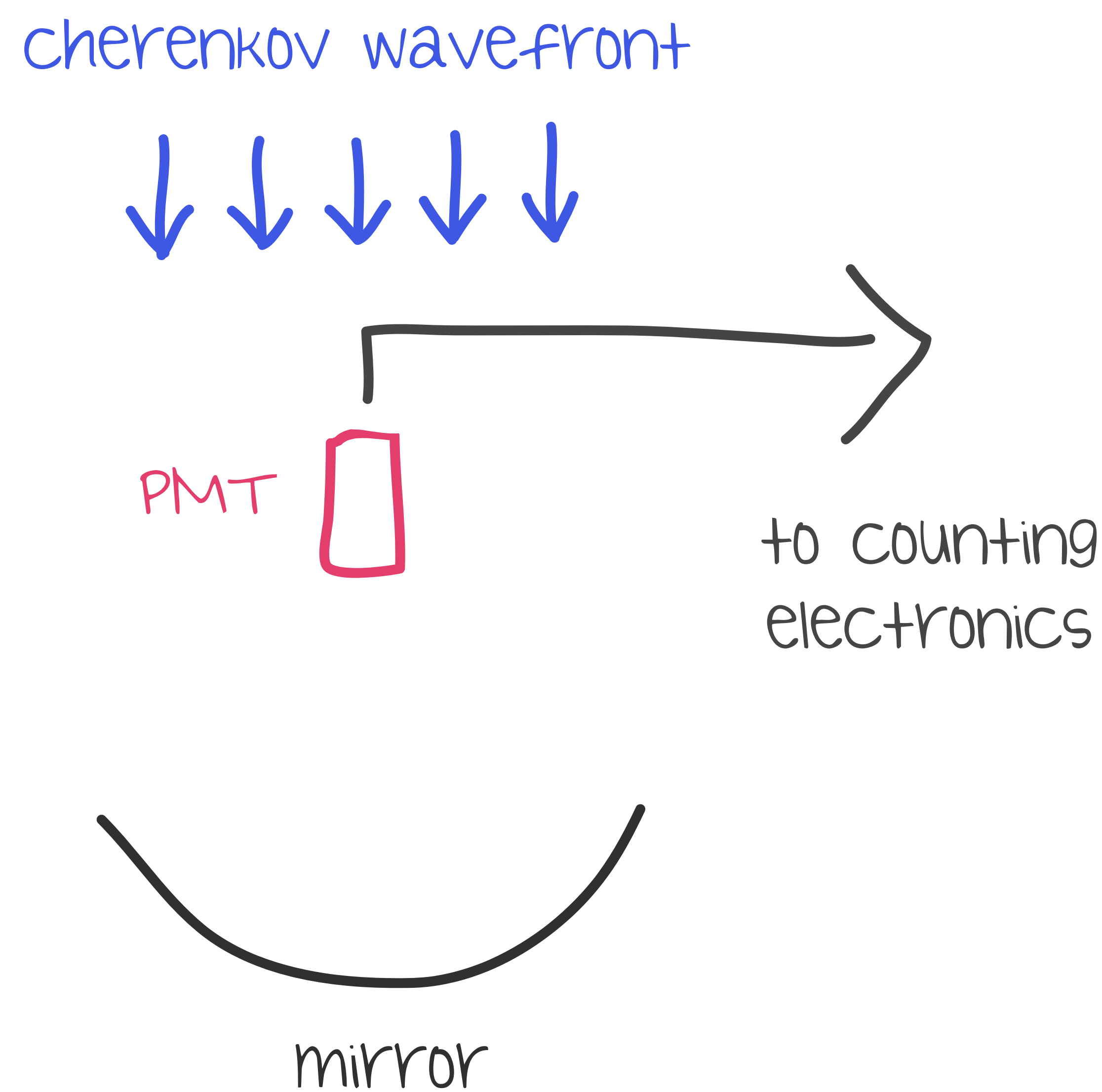


First Generation VHE Telescopes
6/9

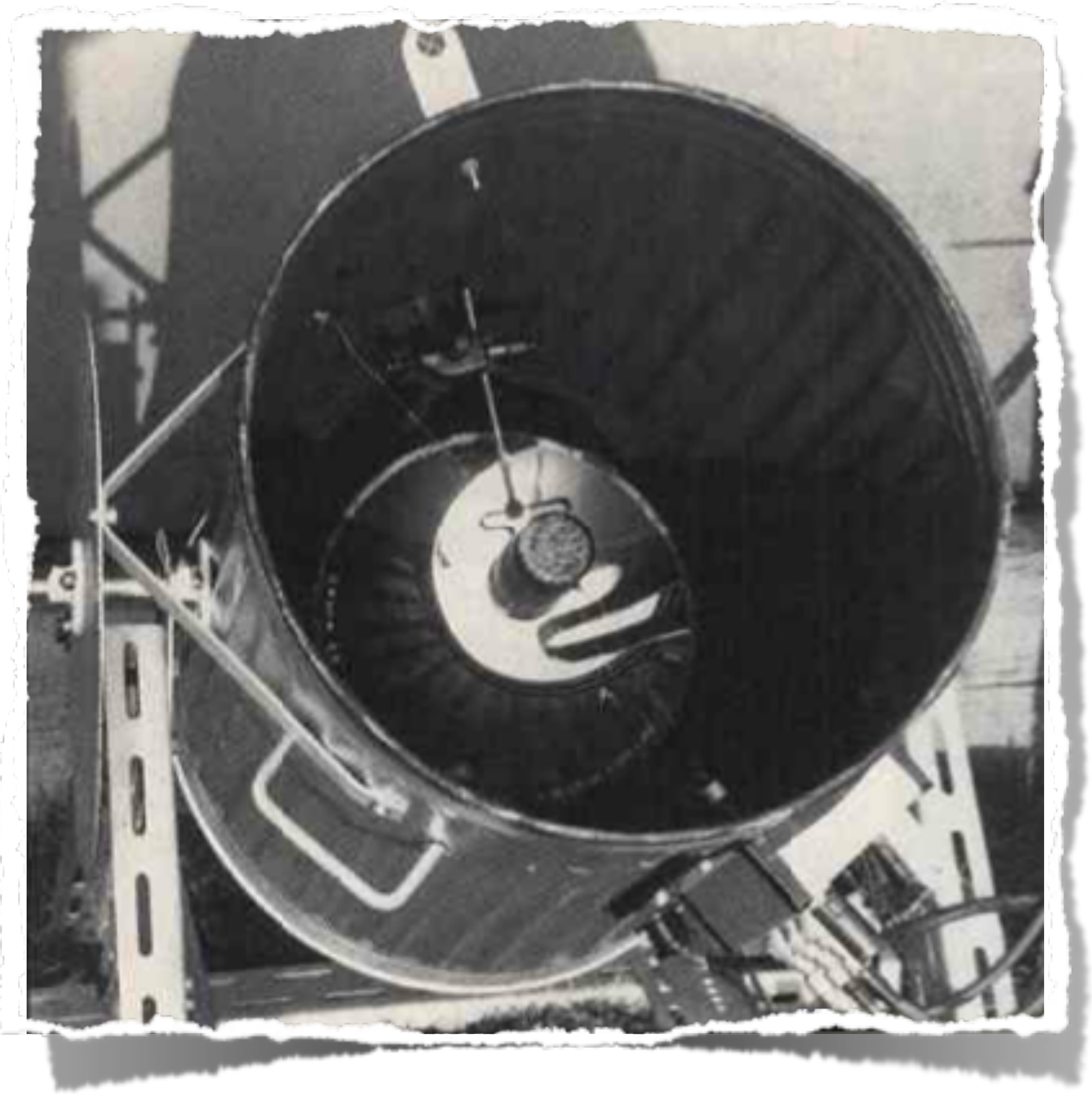
First Generation VHE Telescopes

To DETECT & record the Cherenkov light from an air shower, we need:

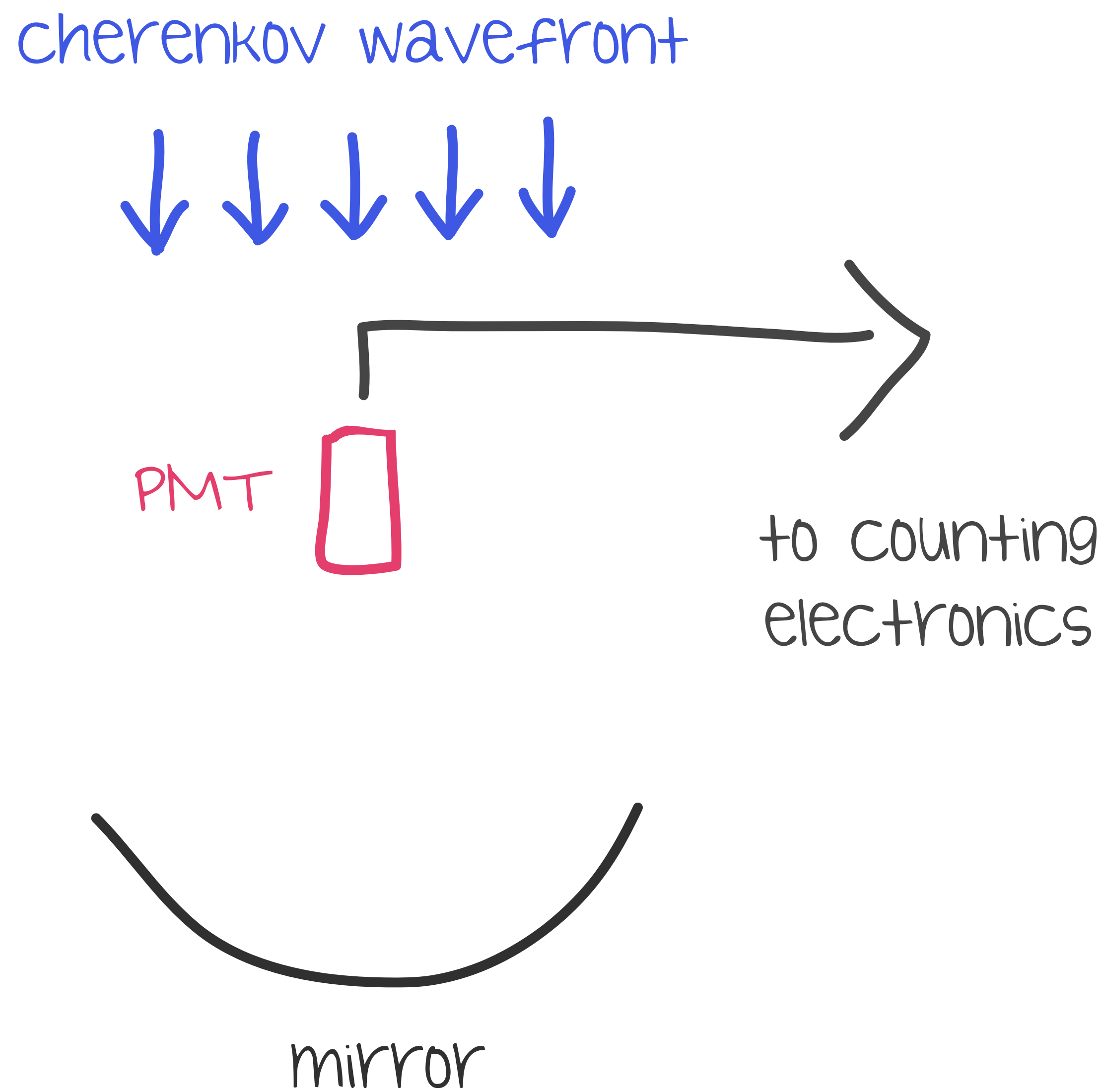
- a mirror to gather & focus the light
- a FAST detector
- a means to trigger/record the image



First Generation VHE Telescopes

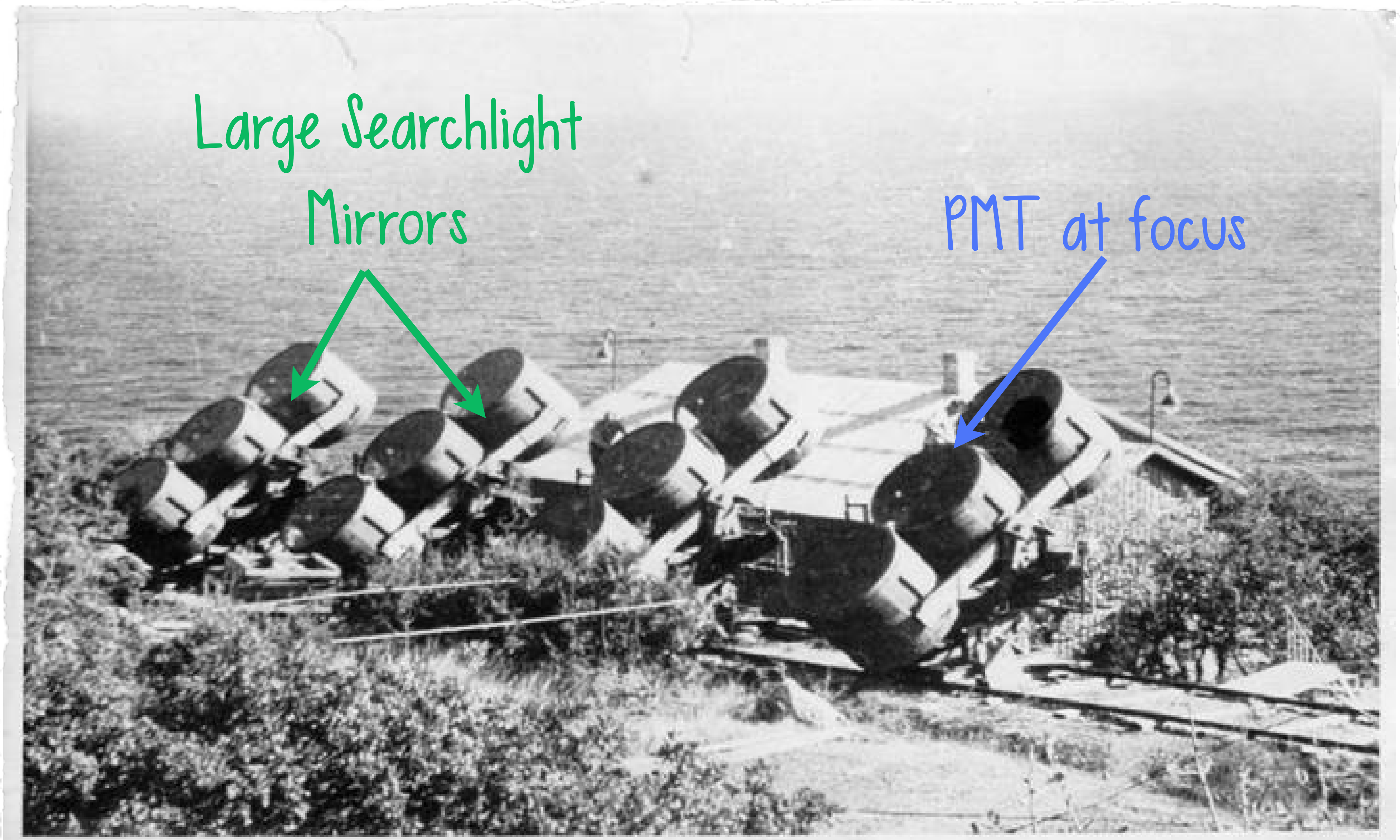


Galbraith and Jelley (1953), Harwell - U.K.



First Generation VHE Telescopes

The Early Days



Crimea Experiment 1960 - 1965

First Generation VHE Telescopes

The Early Days

Glencullen, Ireland
1962-66 (ish)

University College Dublin group*
- led by Neil Porter in collaboration with J. V. Jelley

WWII surplus gun mount and search-light mirrors

TARGETS: quasars, variable stars, supernova remnants, Crab

but...

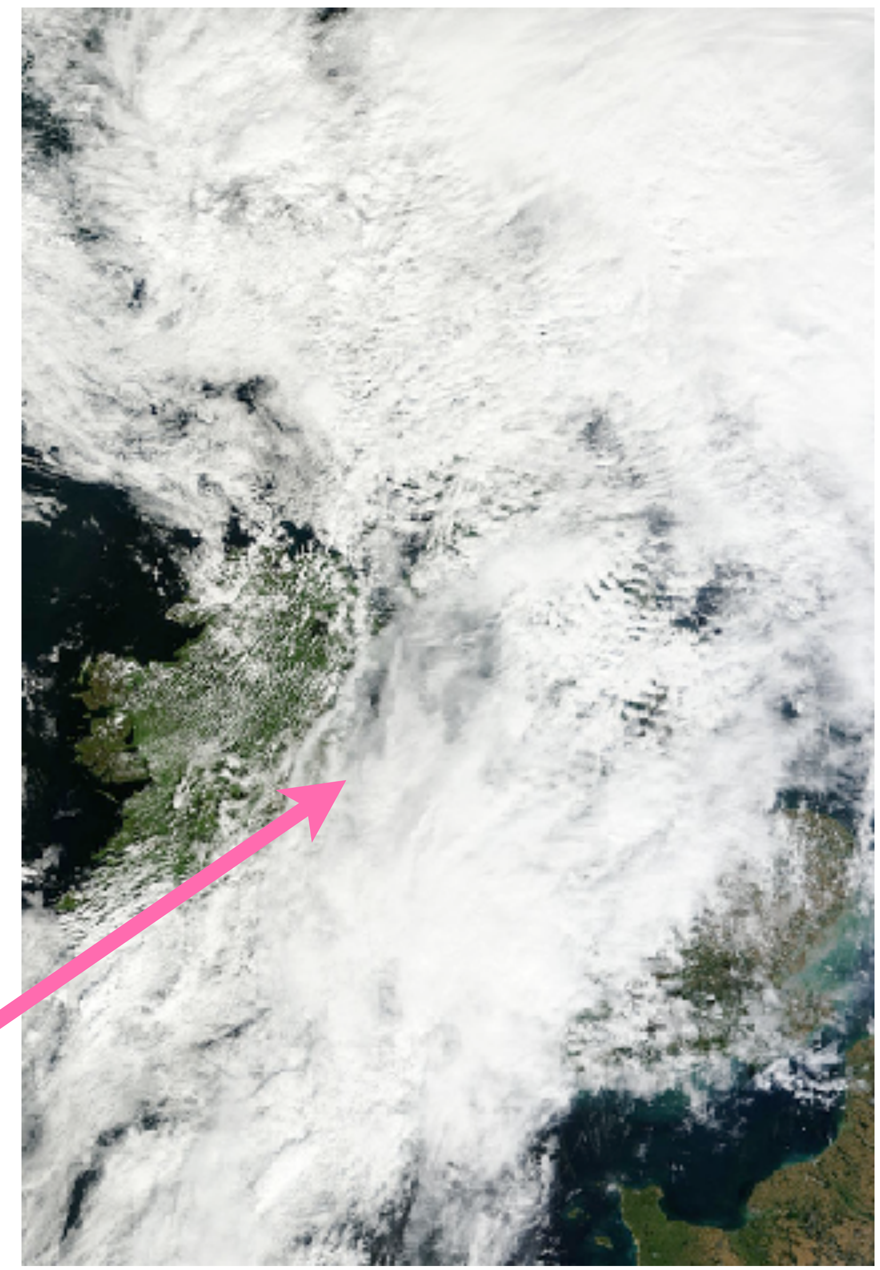
*Still very active in VHE gamma-ray astronomy

T. C. Weekes (2012 Fermi Summer School)

First Generation VHE Telescopes

The Early Days

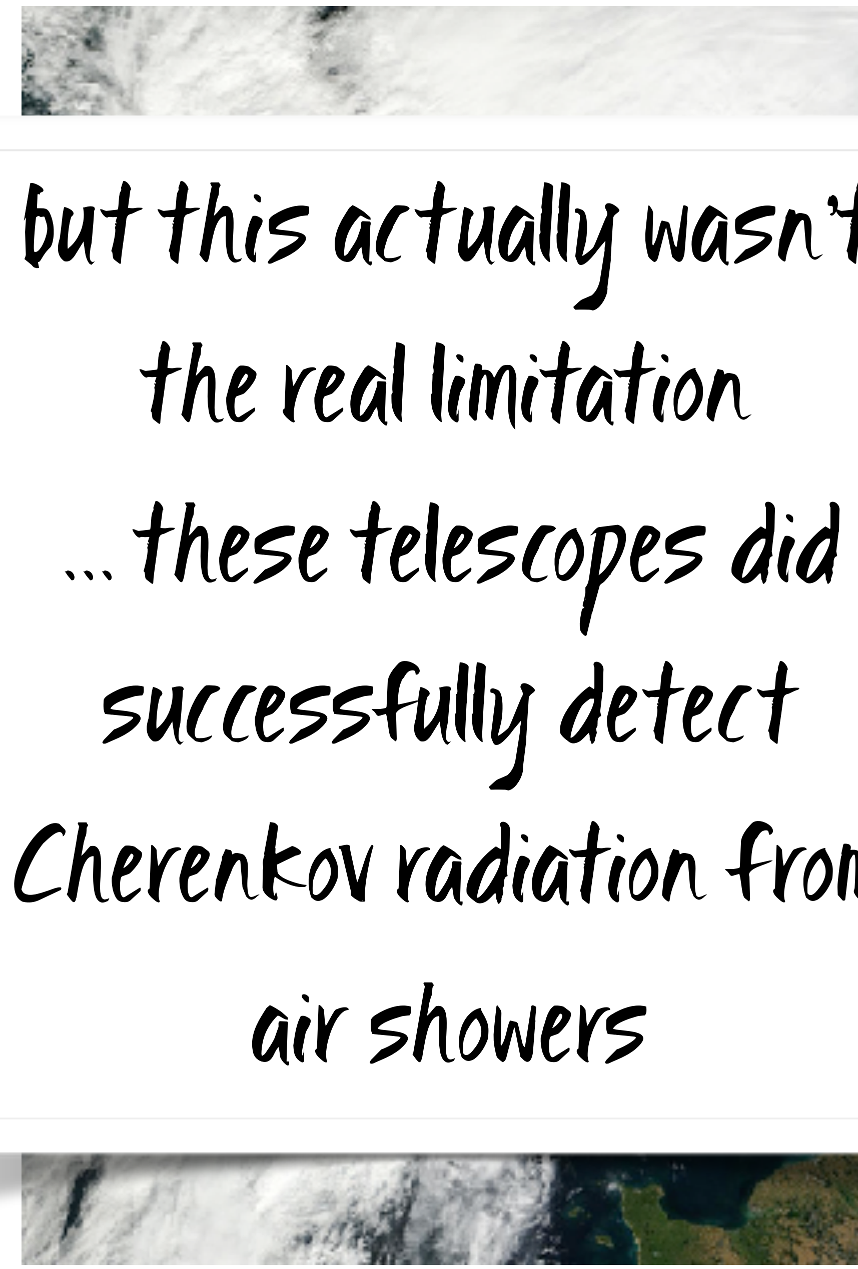
Glencullen, Ireland
1962-66 (ish)



First Generation VHE Telescopes

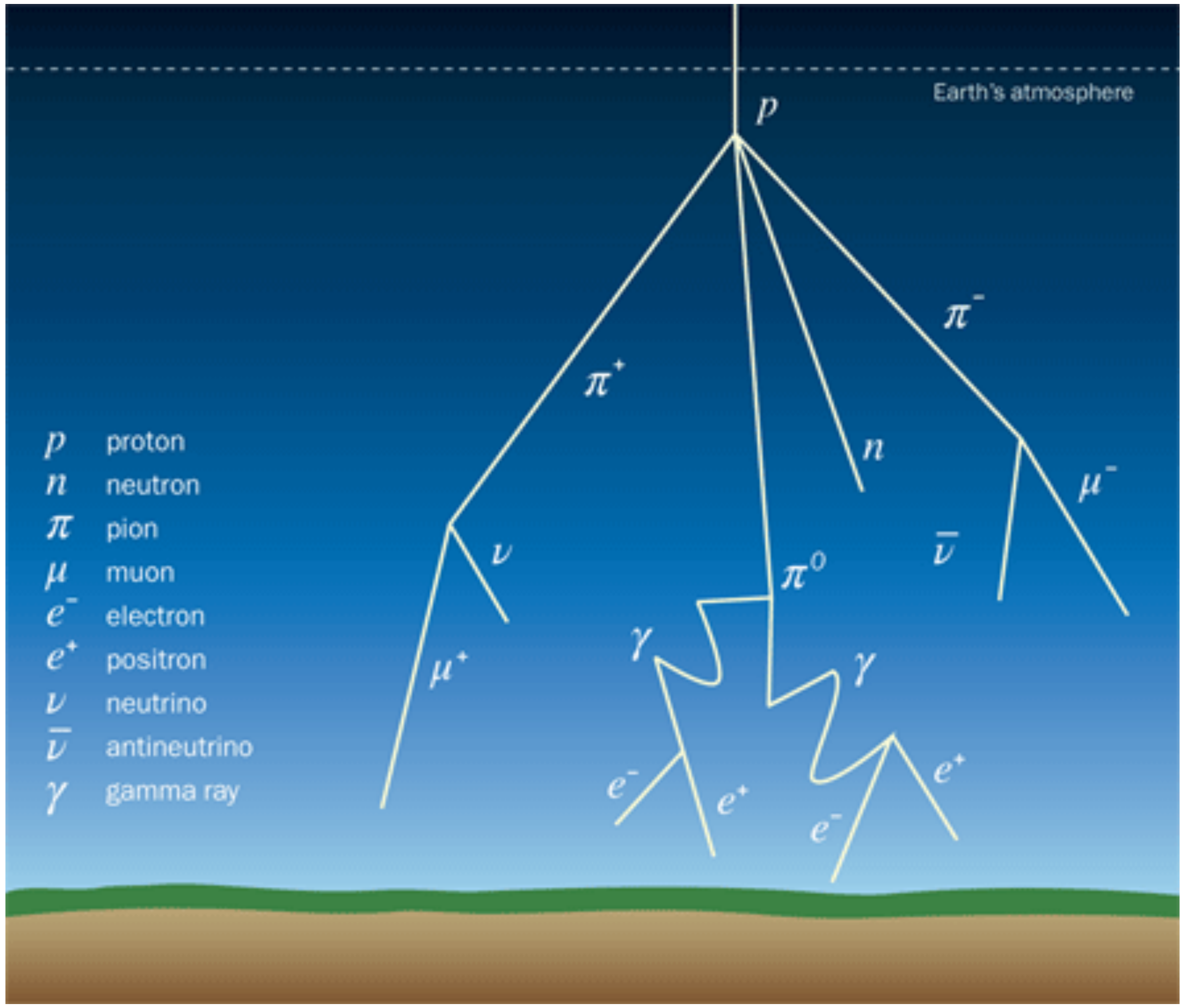
The Early Days

Glencullen, Ireland
1962-66 (ish)



but this actually wasn't the real limitation ... these telescopes did successfully detect Cherenkov radiation from air showers

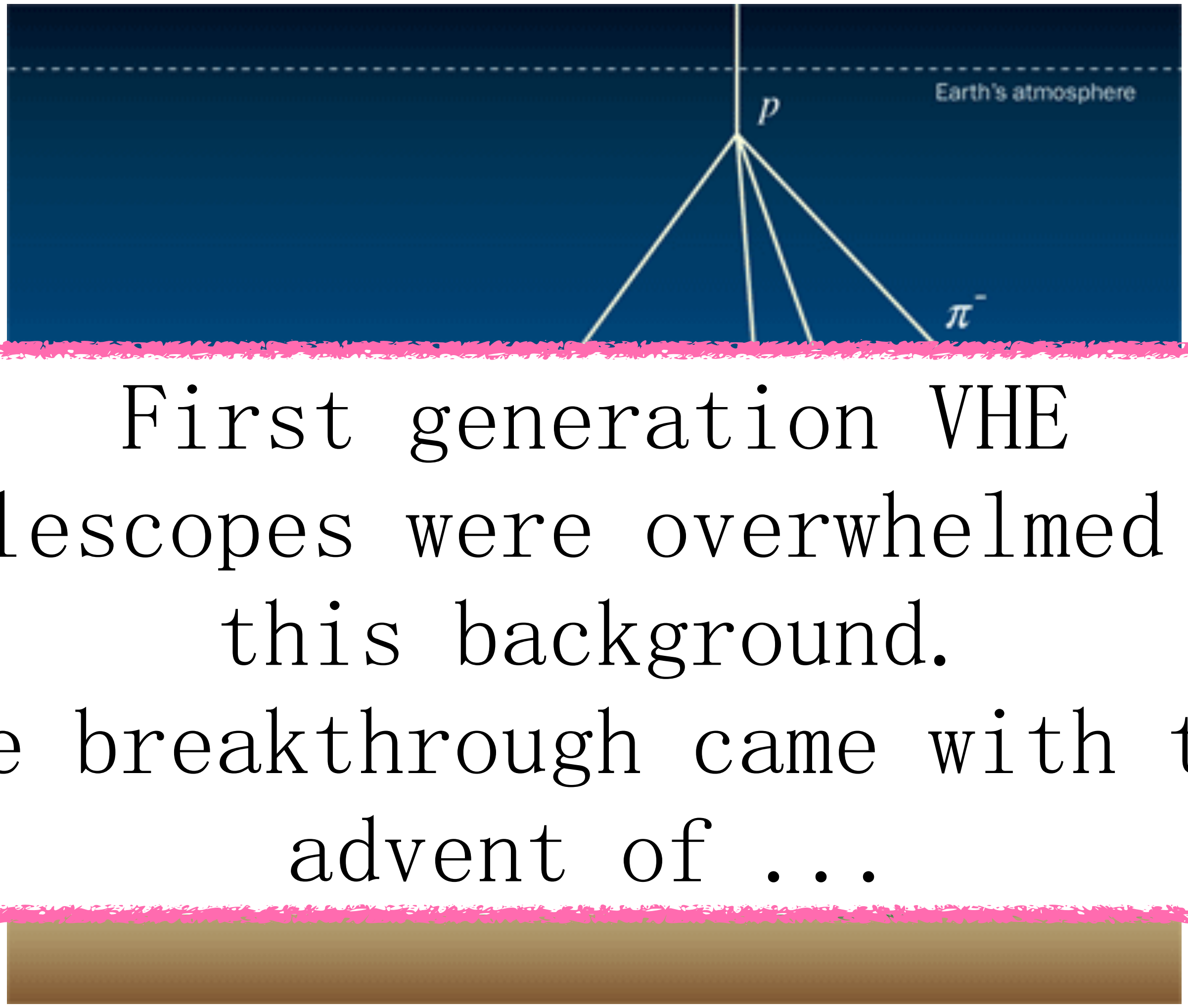
First Generation VHE Telescopes



The problem is that > 99% of the events that trigger the camera are induced by COSMIC RAYS

We need to extract the gamma-ray signal from this overwhelming background

First Generation VHE Telescopes



First generation VHE telescopes were overwhelmed by this background.
The breakthrough came with the advent of ...

The problem is that > 99% of the events that trigger the camera are induced by COSMIC RAYS

We need to extract the gamma-ray signal from this overwhelming background

The Imaging Atmospheric Cherenkov Technique 9/11

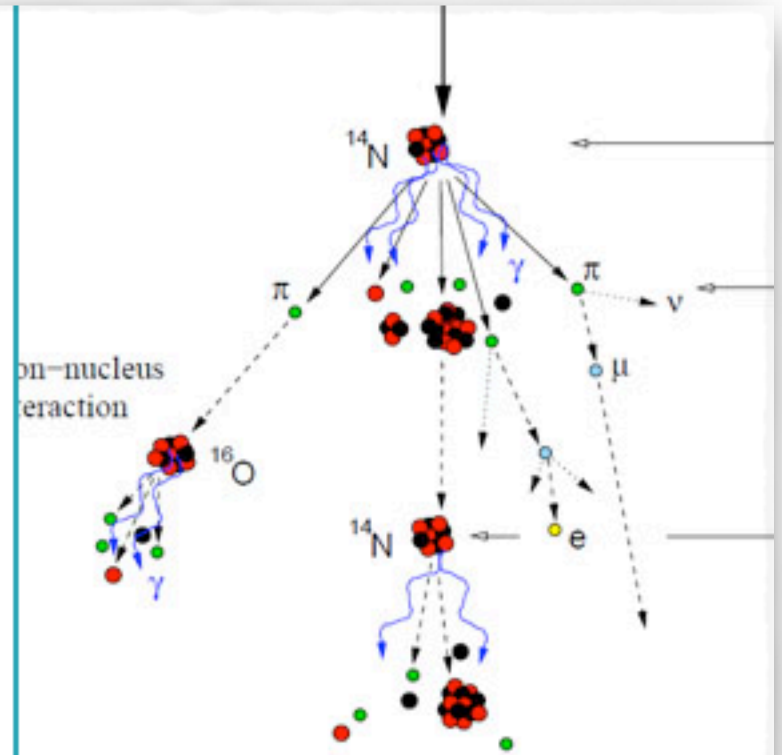
remember from earlier...

$\pi^+ \rightarrow \mu^+ + \nu,$
$\pi^- \rightarrow \mu^- + \bar{\nu},$
$\pi^0 \rightarrow \gamma + \gamma,$

many of the charged muons reach the surface of the earth

- ~1/3 of the pions are π^0s
  - ➡ decay into two gammas
  - ➡ these pair produce

➡ electromagnetic cascades rapidly grow to comprise the dominant component within the hadronic cascade



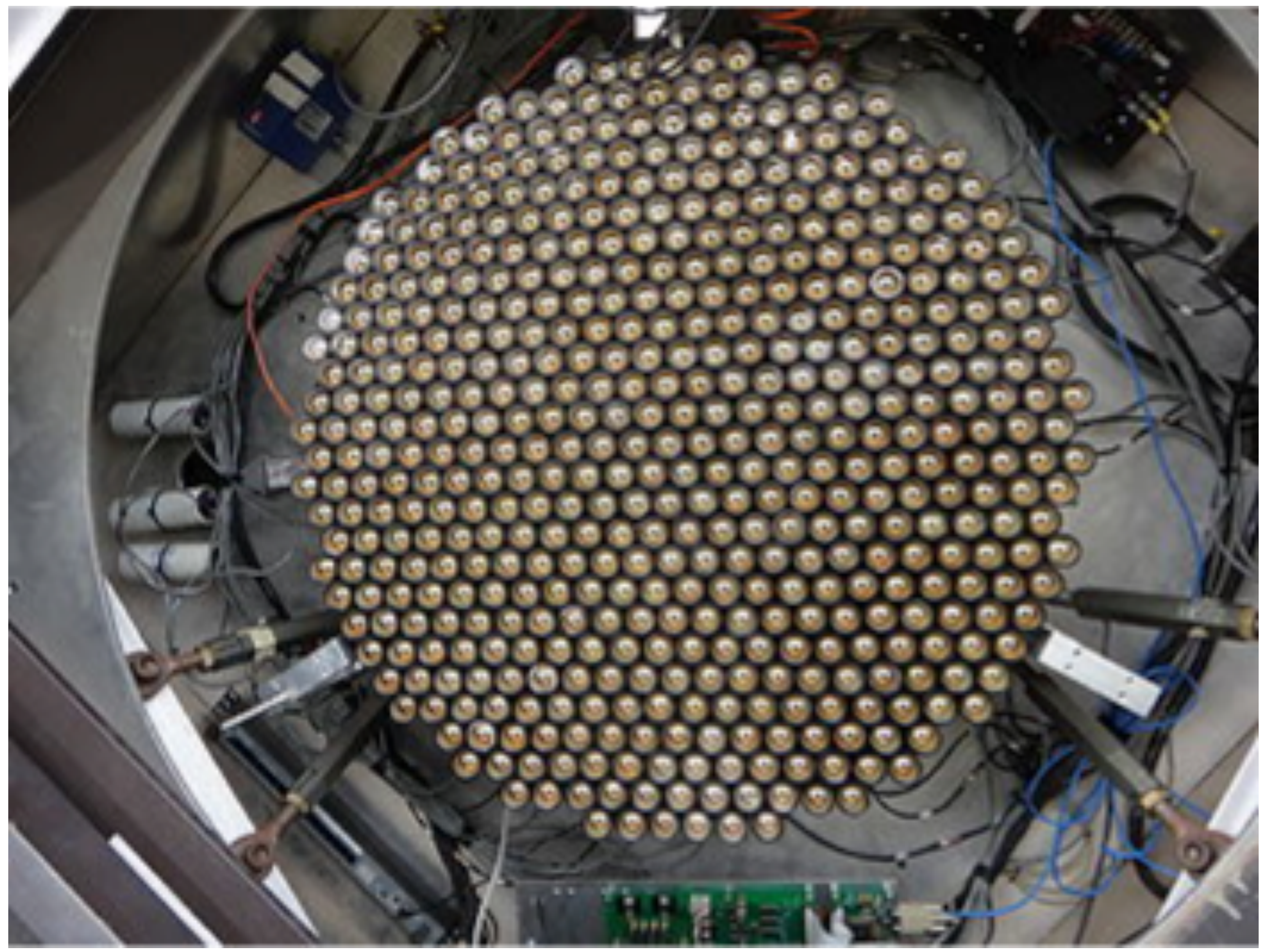
... shower has a large lateral spread due to the transverse momentum of the strong interaction

... many muons reach the ground

important later !

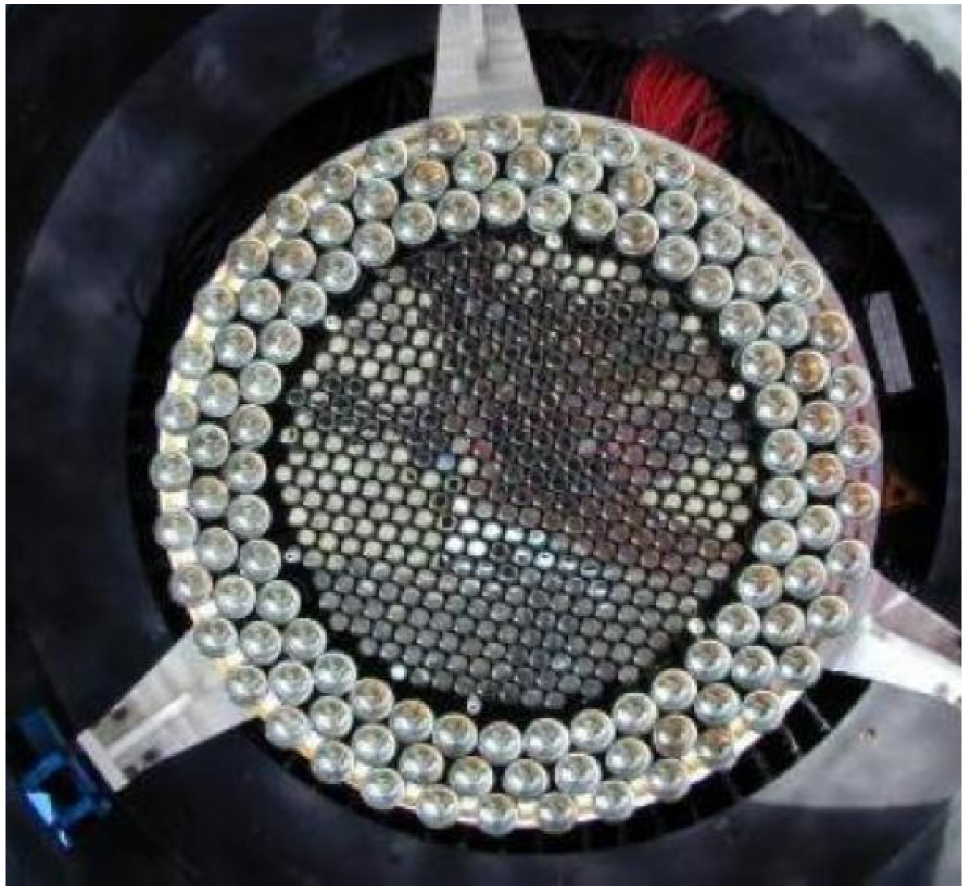
Imaging: Take a picture of the Cherenkov light from the air shower!

VERITAS Collaboration (Kieda, Dave B. for the collaboration) arXiv:1308.4849

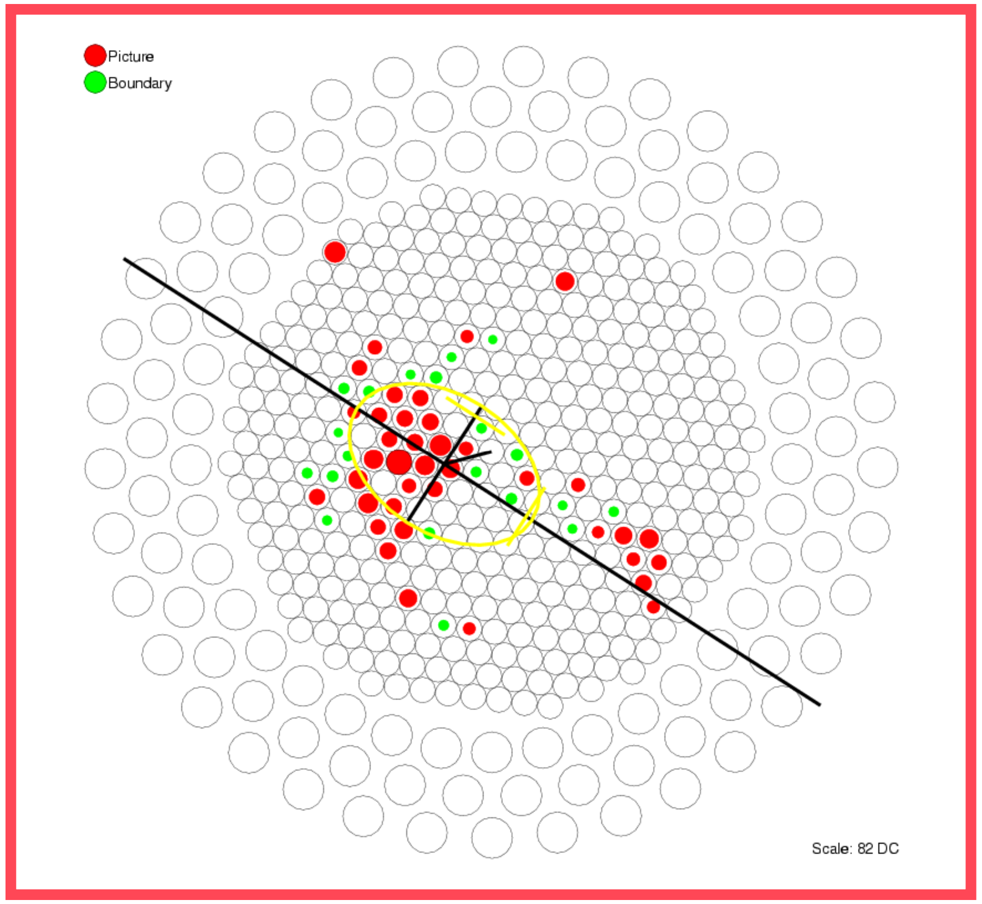


IMAGING CAMERA
499 PHOTOMULTIPLIER TUBES

The Imaging Atmospheric Cherenkov Technique

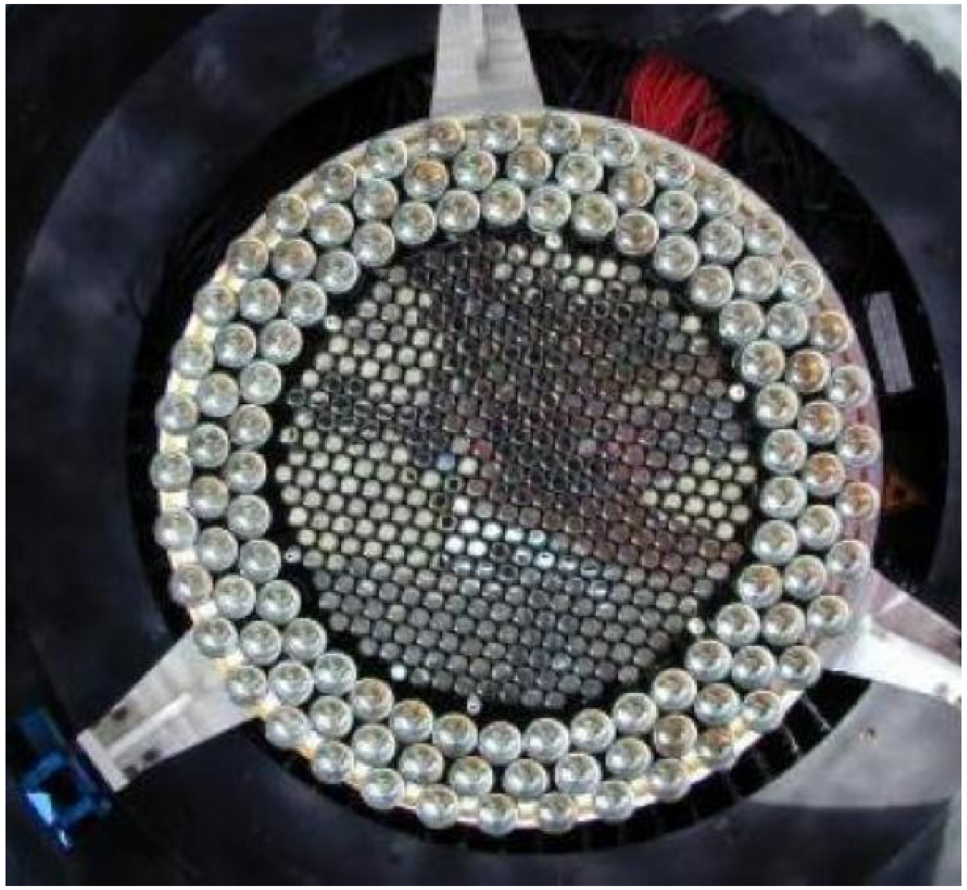


camera

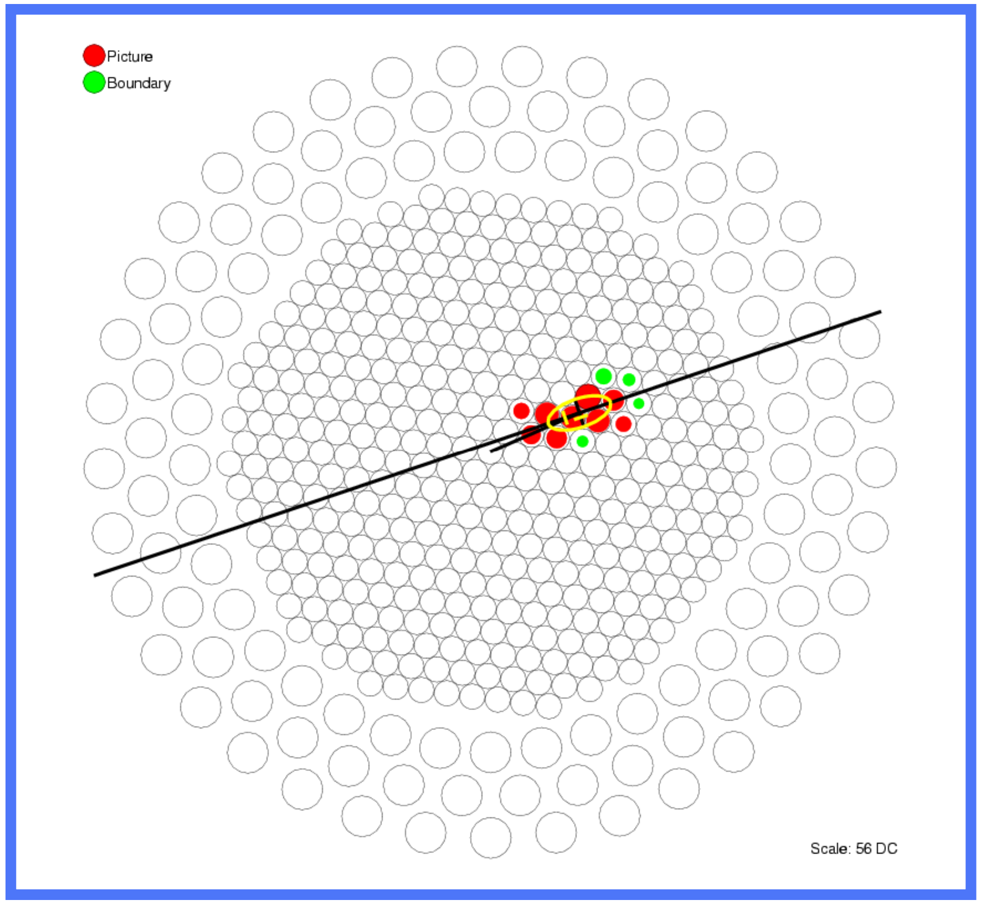


cosmic ray

The Imaging Atmospheric Cherenkov Technique



camera

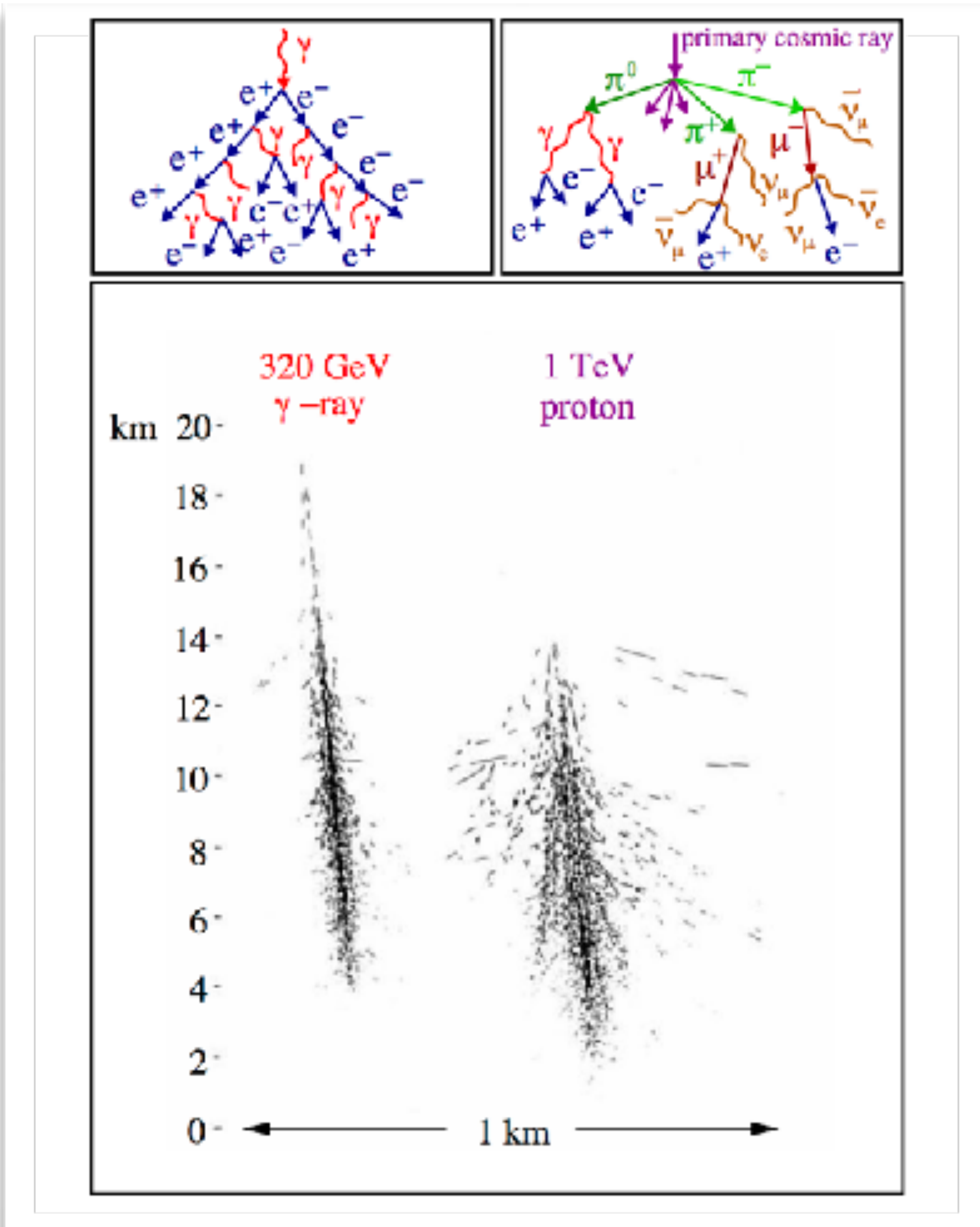


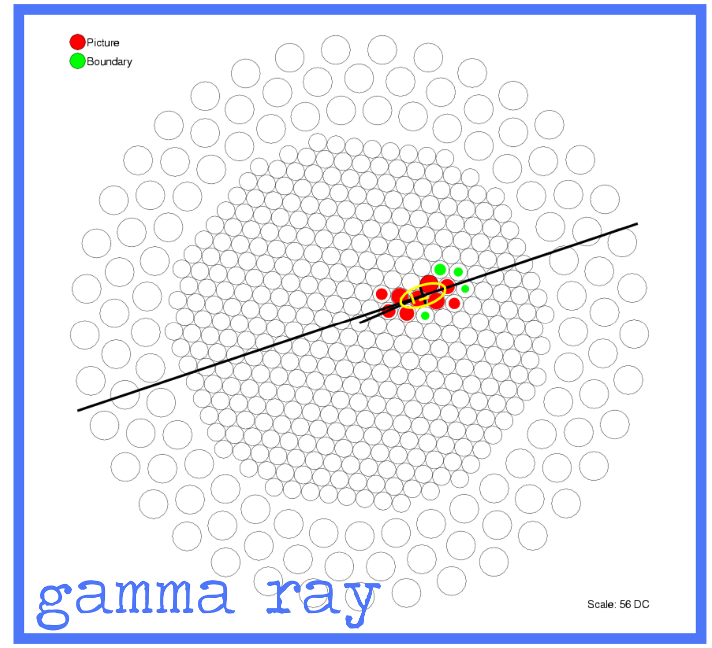
gamma ray

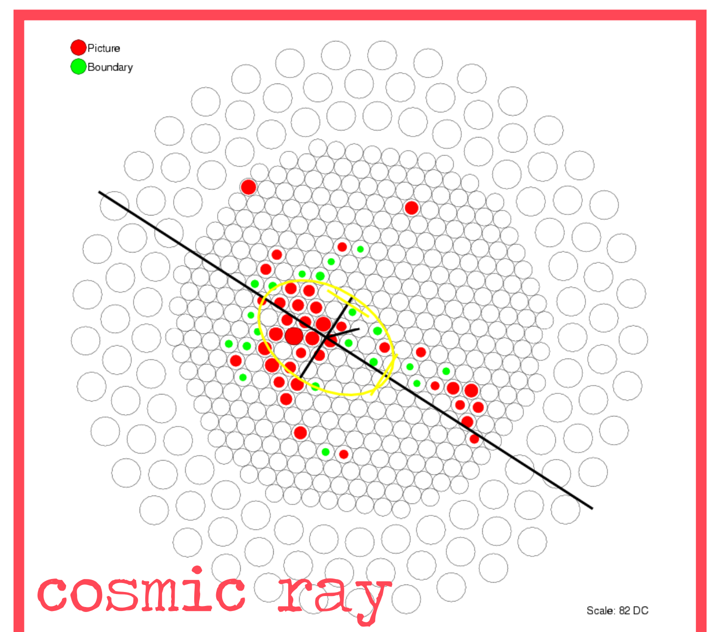
The Imaging Atmospher[…]hnique

Extra slide: I did not show this in the presentation. Added it so that you have more background information

the different physical mechanisms that take place in gamma-ray & cosmic-ray induced showers affect the characteristics of their Cherenkov images







The Imaging Atmospher hnique

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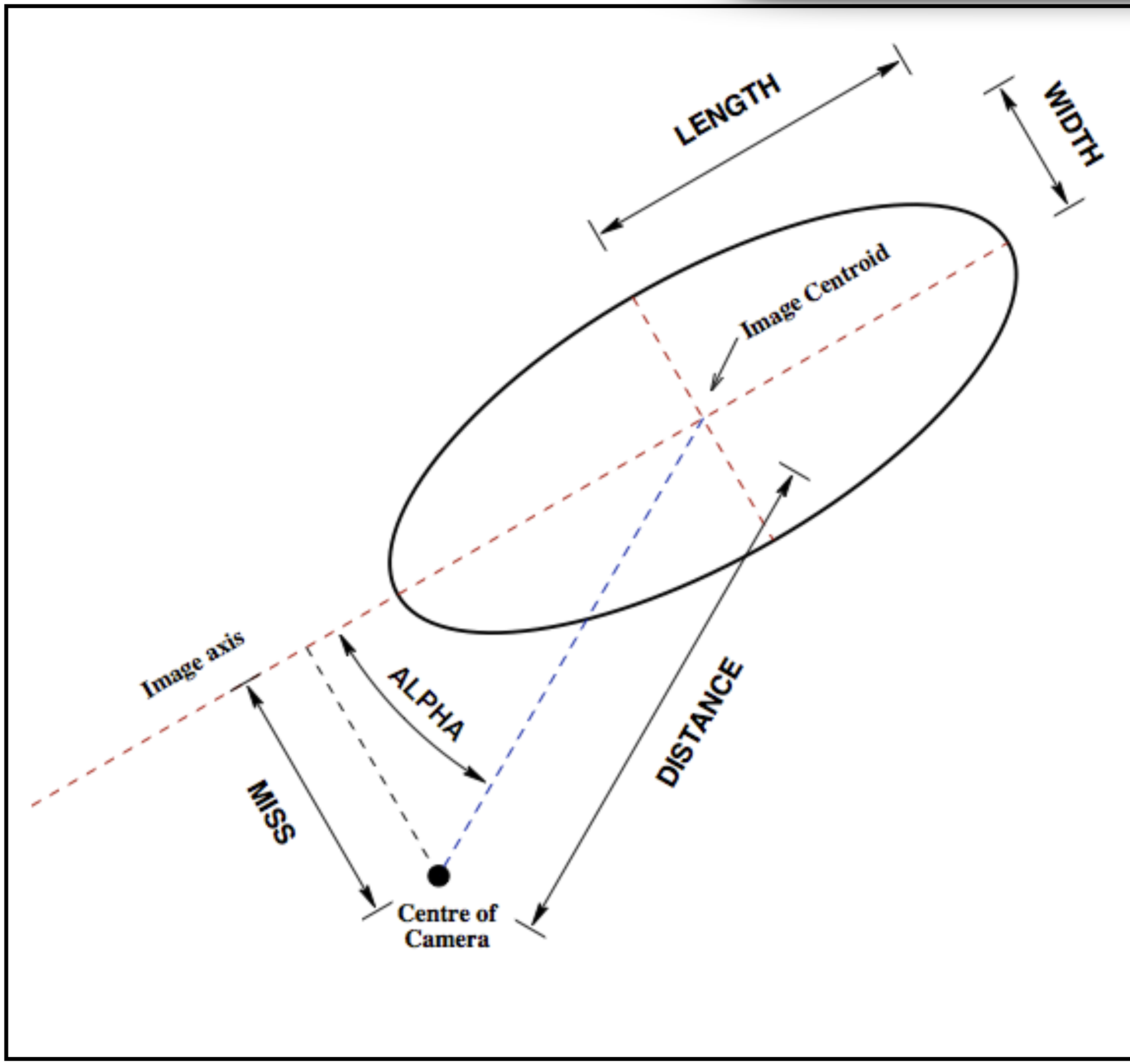
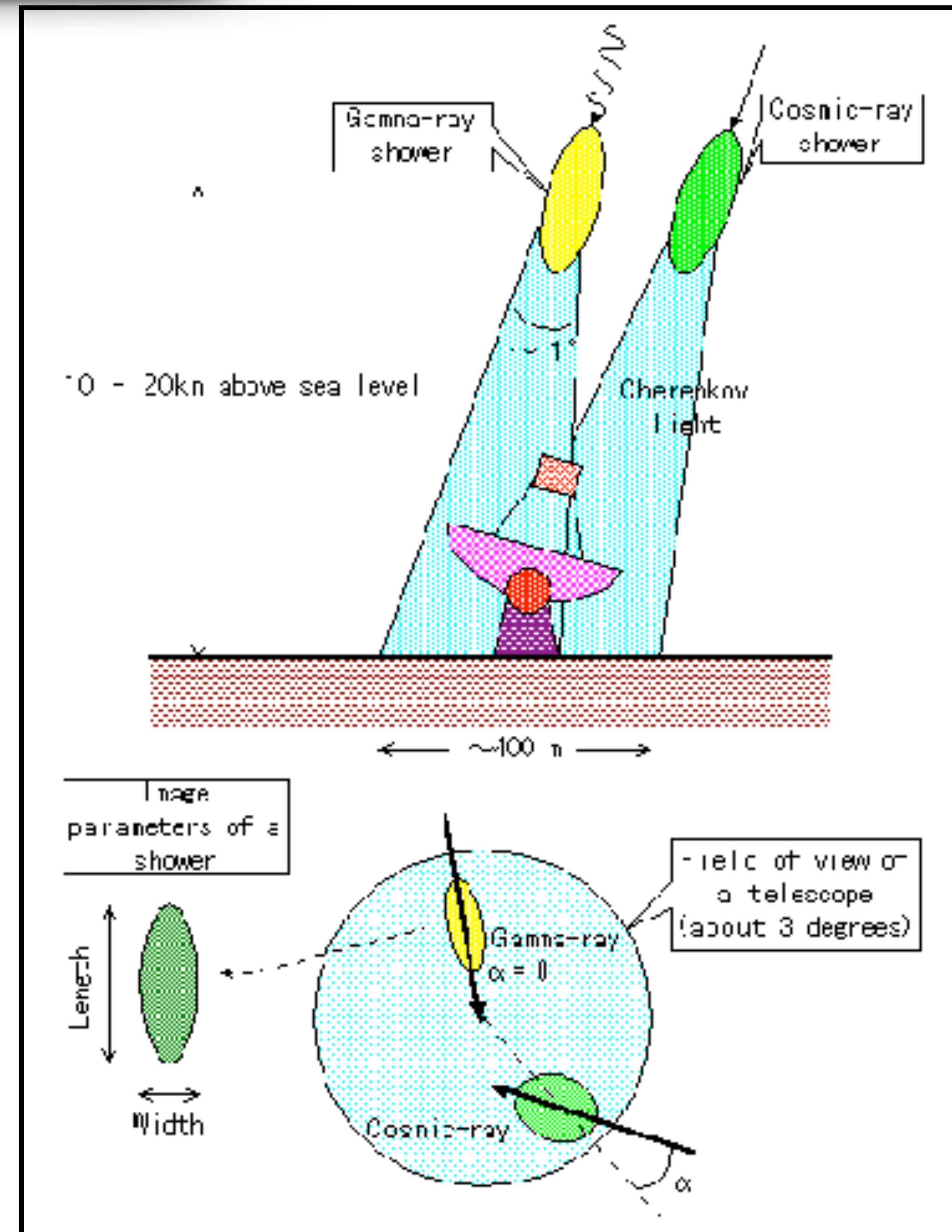




icrhp9.icrr.u-tokyo.ac.jp/method.html

"Hillas parameters" (length, width, distance, alpha...) after A. M. Hillas

"Cerenkov light images of EAS produced by primary gamma", Proc. 19th ICRC (La Jolla), Vol. 3, 445 (1985)

The Imaging Atmospher… …hnique

Extra slide: I did not show this in the presentation. Added it so that you have more background information

445

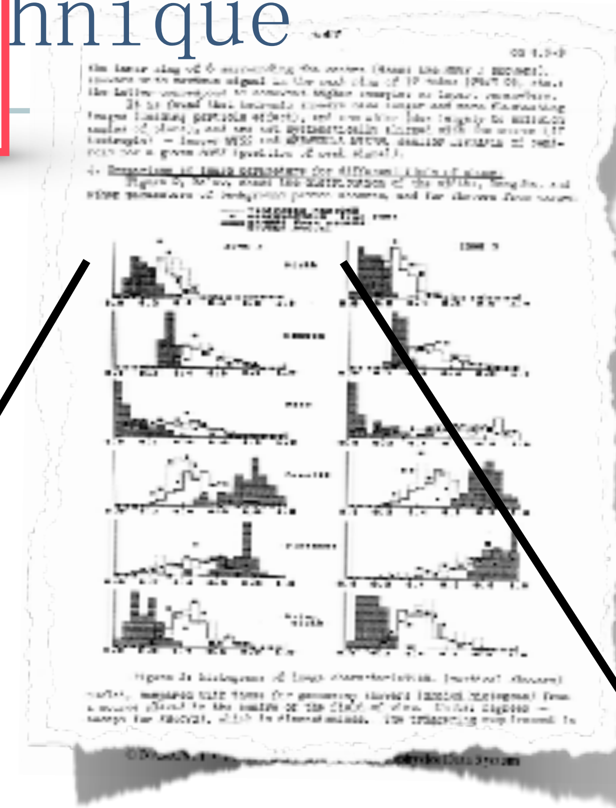
OG 9.5-3

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

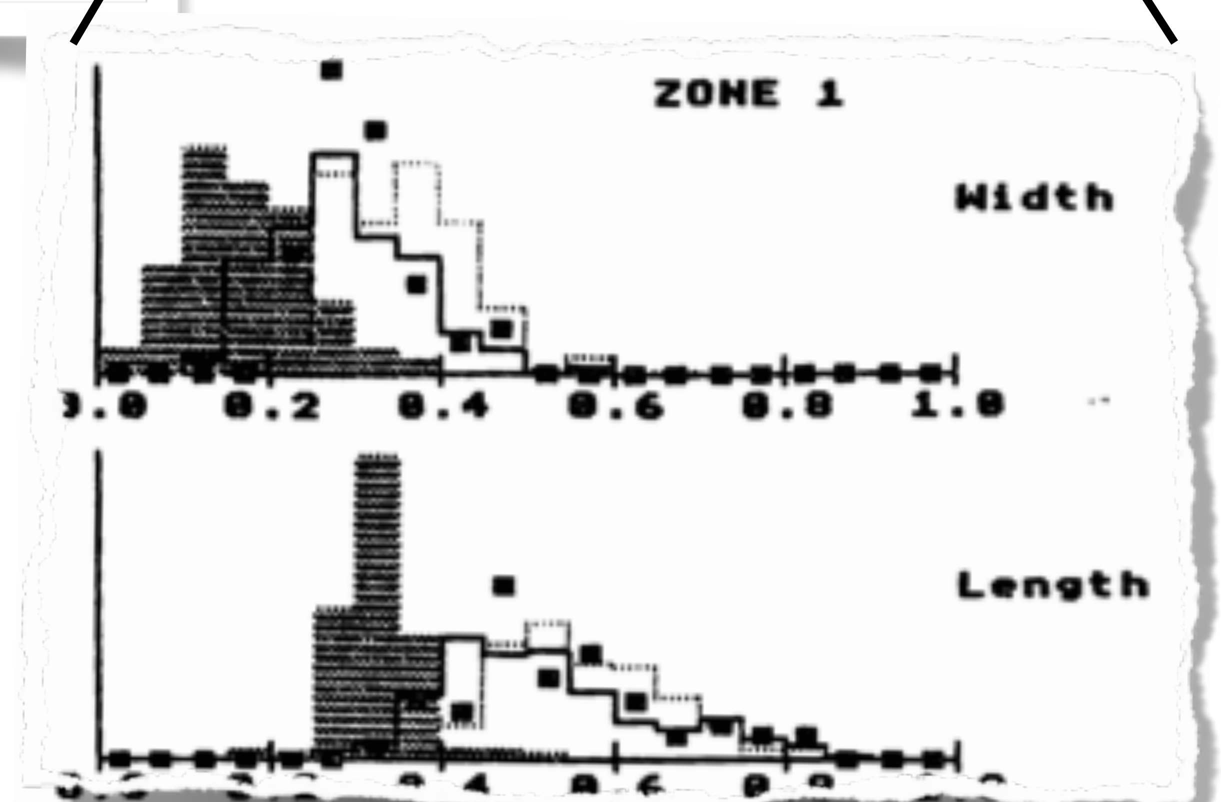
A. M. Hillas
Physics Department
University of Leeds, Leeds LS2 9JT, UK.

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.



distribution for gamma rays is shaded



"Cerenkov light images of EAS produced by primary gamma", Proc. 19th ICRC (La Jolla), Vol. 3, 445 (1985)

The Imaging Atmospher… hnique

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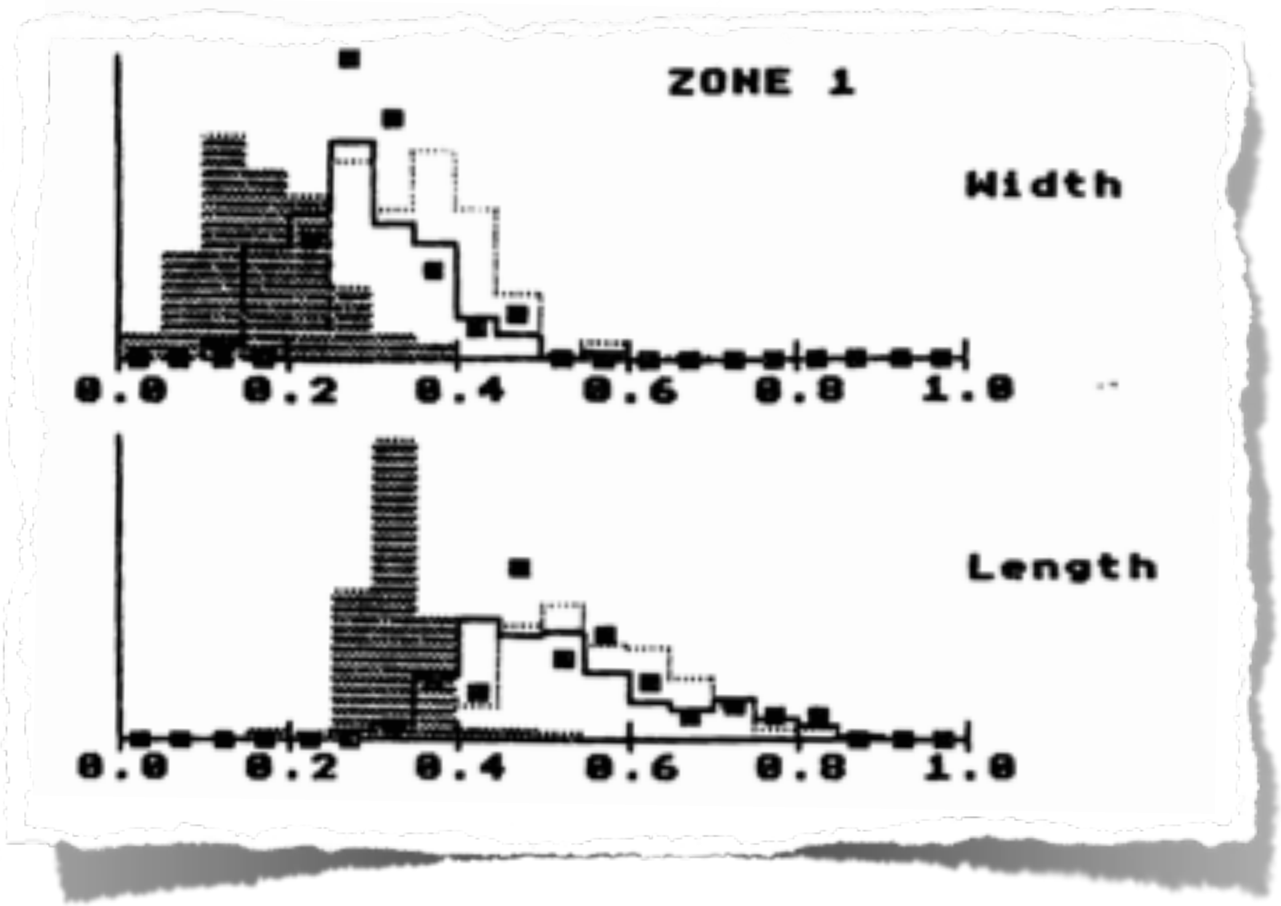
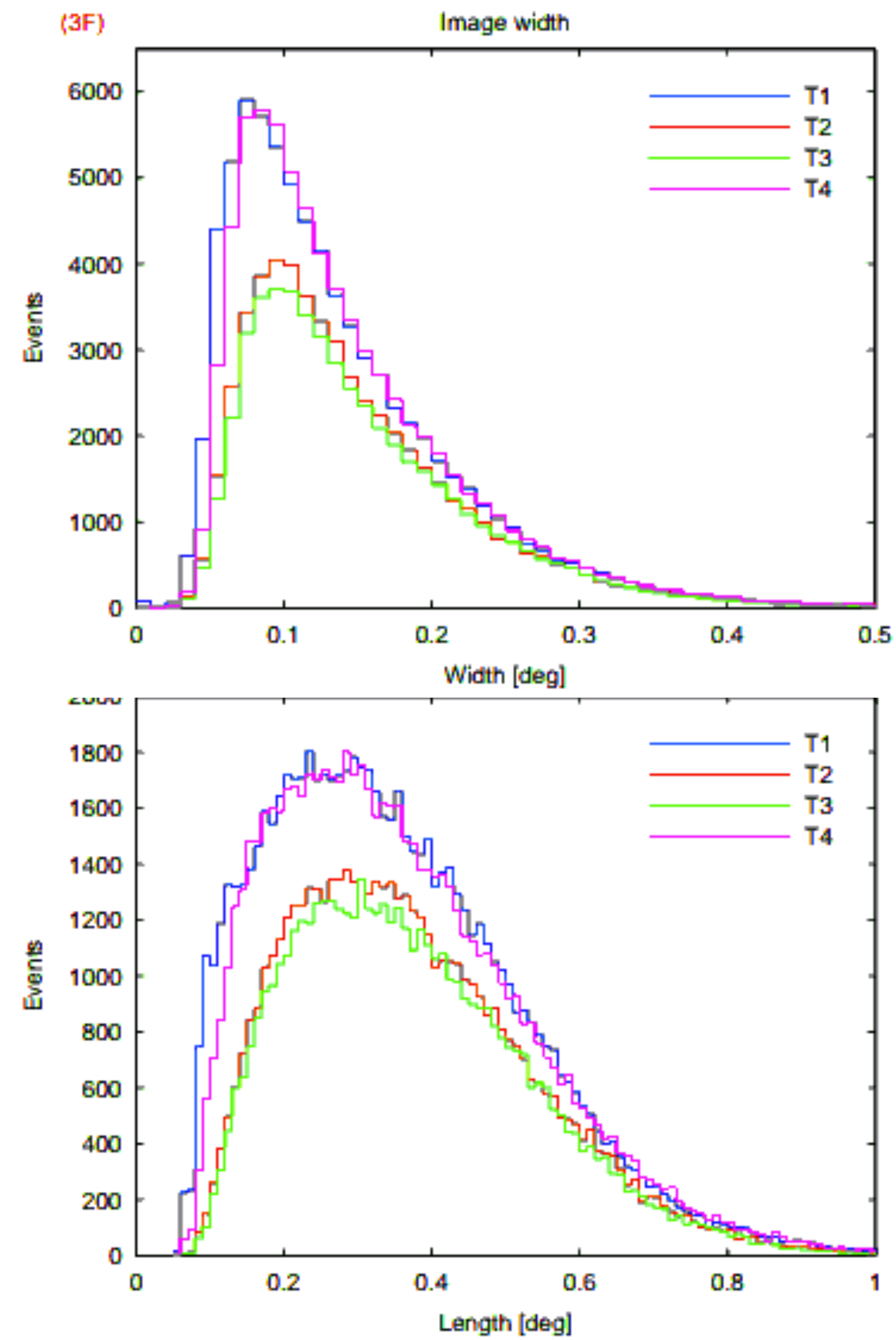
Original Hillas paper - simulated parameter distributions (1985)



shaded regions are gamma rays

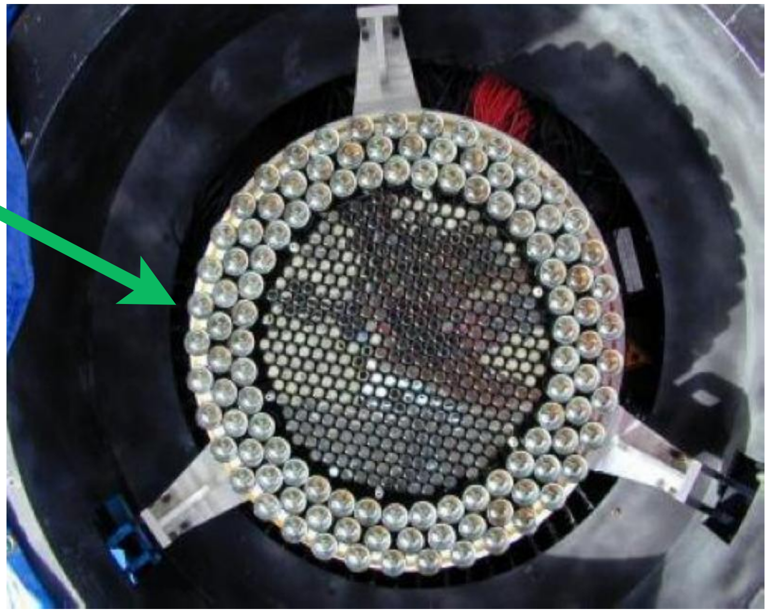
"Cerenkov light images of EAS produced by primary gamma", Proc. 19th ICRC (La Jolla), Vol. 3, 445 (1985)

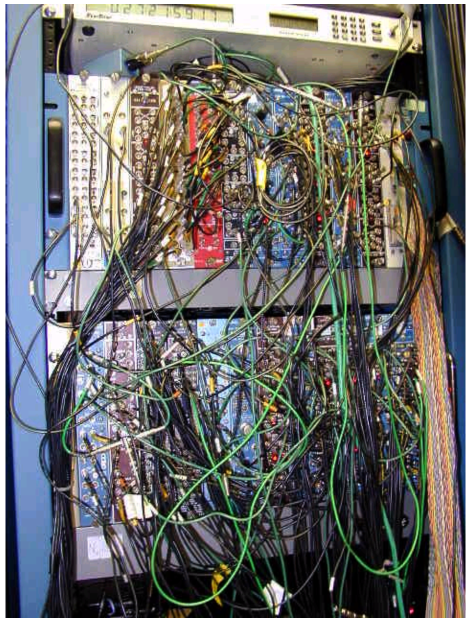
Actual parameter distributions from VERITAS (~2008)



The Imaging Atmospheric Cherenkov Technique

The Whipple 10m Telescope





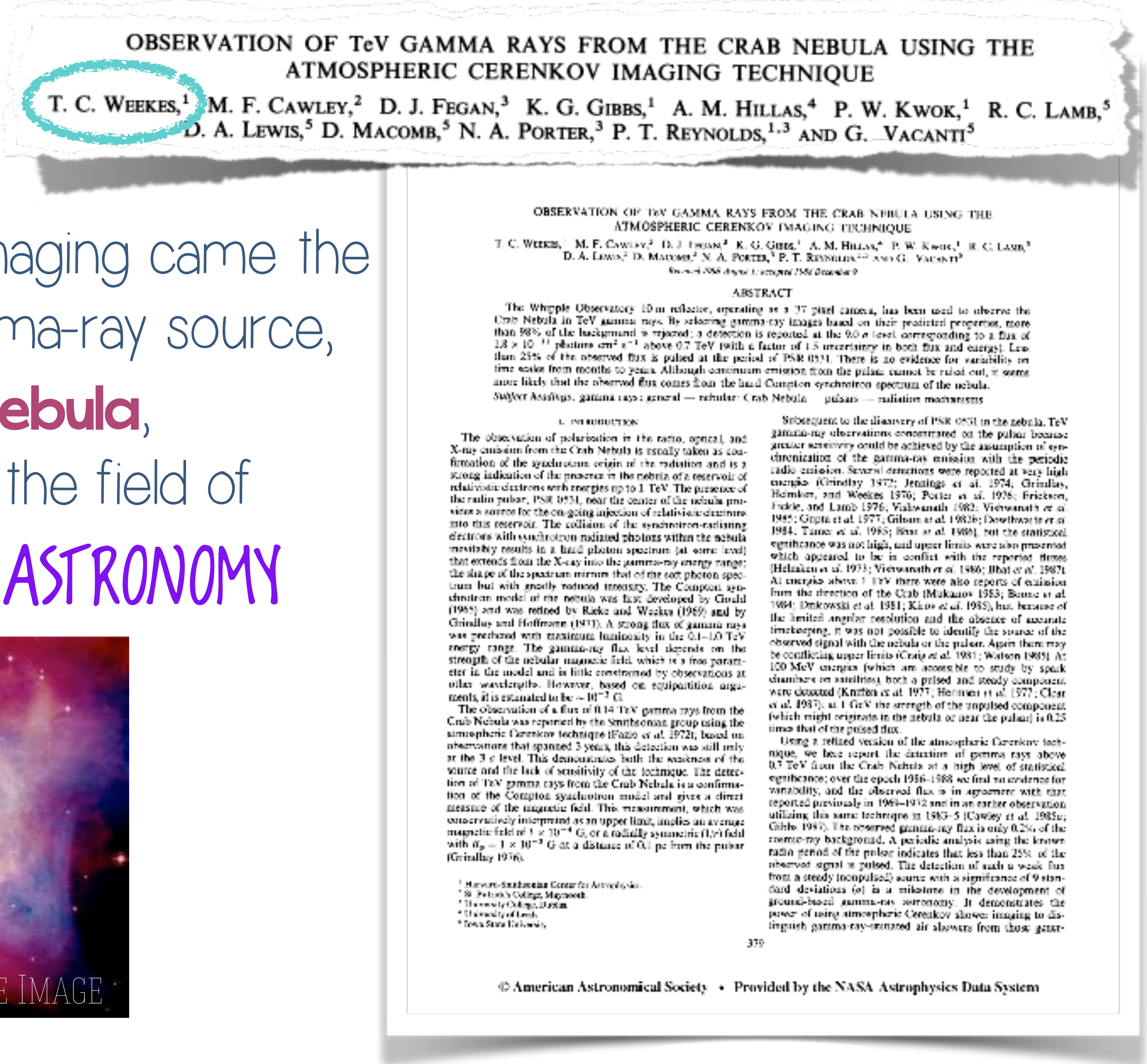
Pixelated Camera + ns electronics

= CHERENKOV IMAGES

The imaging technique was pioneered at the Whipple Telescope in Arizona

The Imaging Atmospheric Cherenkov Technique

The Astrophysical Journal, Vol. 342, 379 (1989)


OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

T. C. WEEKES,[1] M. F. CAWLEY,[2] D. J. FEGAN,[3] K. G. GIBBS,[1] A. M. HILLAS,[4] P. W. KWOK,[1] R. C. LAMB,[5] D. A. LEWIS,[5] D. MACOMB,[5] N. A. PORTER,[3] P. T. REYNOLDS,[1,3] AND G. VACANTI[5]

ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level corresponding to a flux of 1.8×10^{-11} photons cm^{-2} s^{-1} above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

Subject headings: gamma rays: general — nebulae: Crab Nebula — pulsars — radiation mechanisms

With the advent of imaging came the first ever TeV gamma-ray source,

the Crab Nebula,

thus establishing the field of

TeV GAMMA-RAY ASTRONOMY

The Imaging Atmospher… …hnique

Extra slide: I did not show this in the presentation. Added it so that you have more background information

The imaging atmospheric Cherenkov technique enabled the detection of the Crab nebula, thus establishing VHE gamma-ray astronomy as a viable new field

Imaging Atmospheric Cherenkov Telescopes (IACTs) were constructed at other locations around the world

In recognition of his contribution to the field of very-high-energy astrophysics, Trevor Weekes was awarded the Rossi prize* in 1997

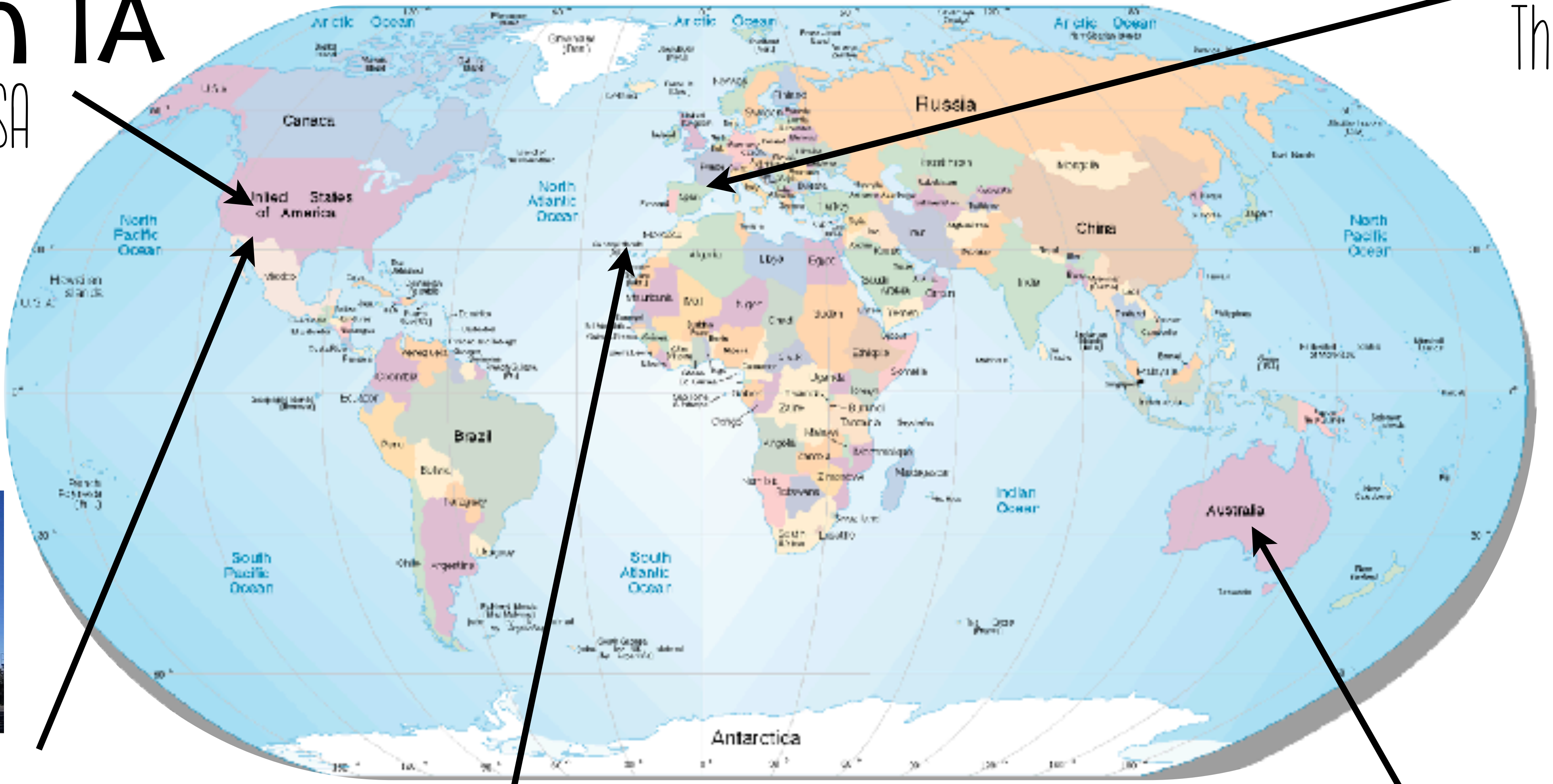
> "The 1997 Rossi Prize of the High Energy Division of the American Astronomical Society is awarded to Trevor C. Weekes for his key role in the development of very high energy gamma-ray astronomy and the discovery of TeV gamma radiation from the Crab nebula and Mrk 421."

*The Rossi Prize is awarded by the High Energy Astrophysics Division of the American Astronomical Society annually in honor of Bruno Rossi "for a significant contribution to High Energy Astrophysics, with particular emphasis on recent, original work."

"Second generation" instruments: 1989 - ~2003

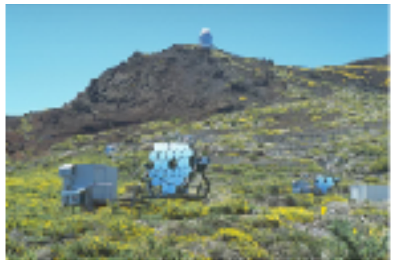
Seven TA
Utah, USA

CAT
Themis, France



Whipple
Arizona, USA

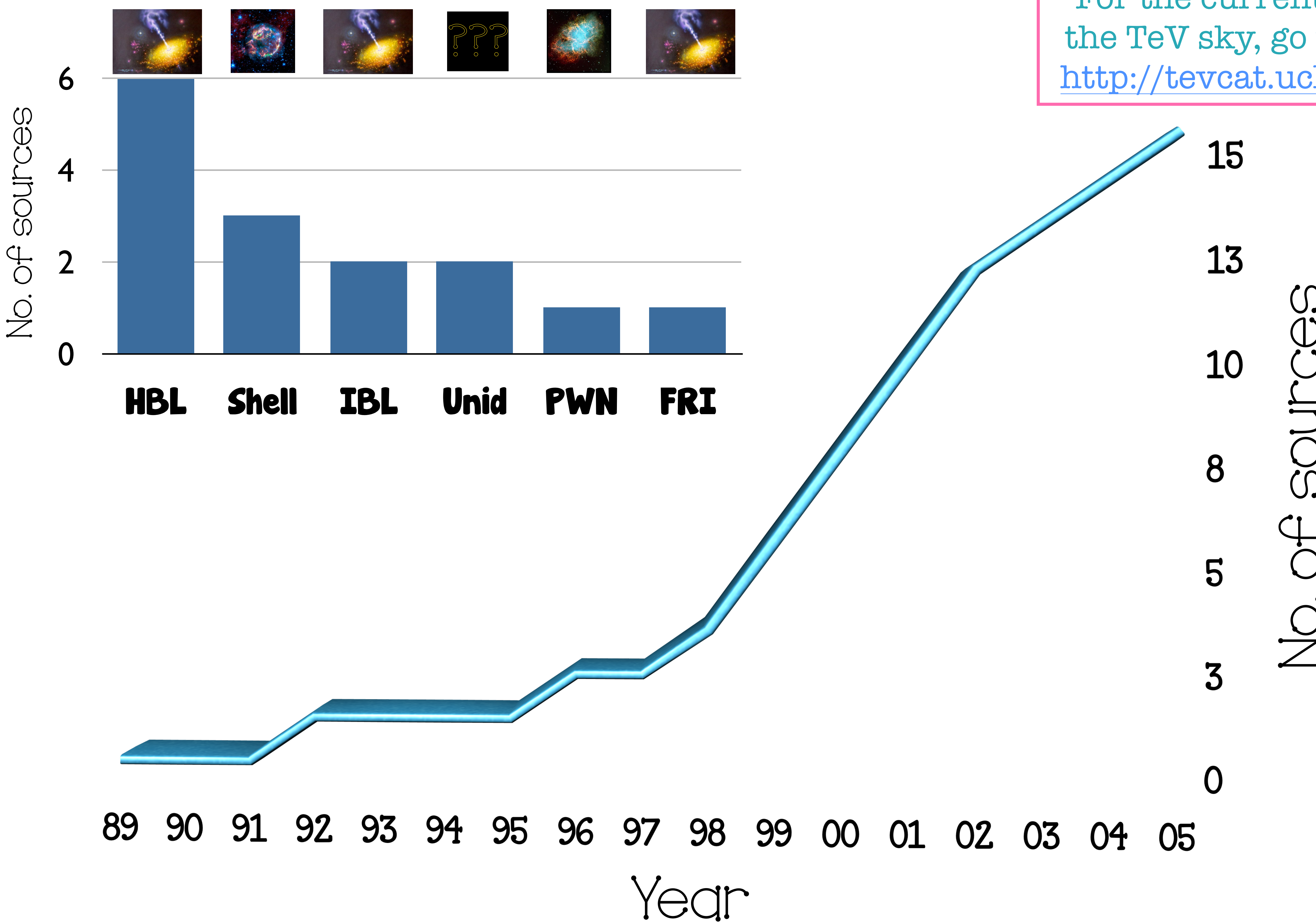
HEGRA
La Palma, Canary Islands



CANGAROO
Woomera, Australia

The Imaging Atmospheric Cherenkov Technique

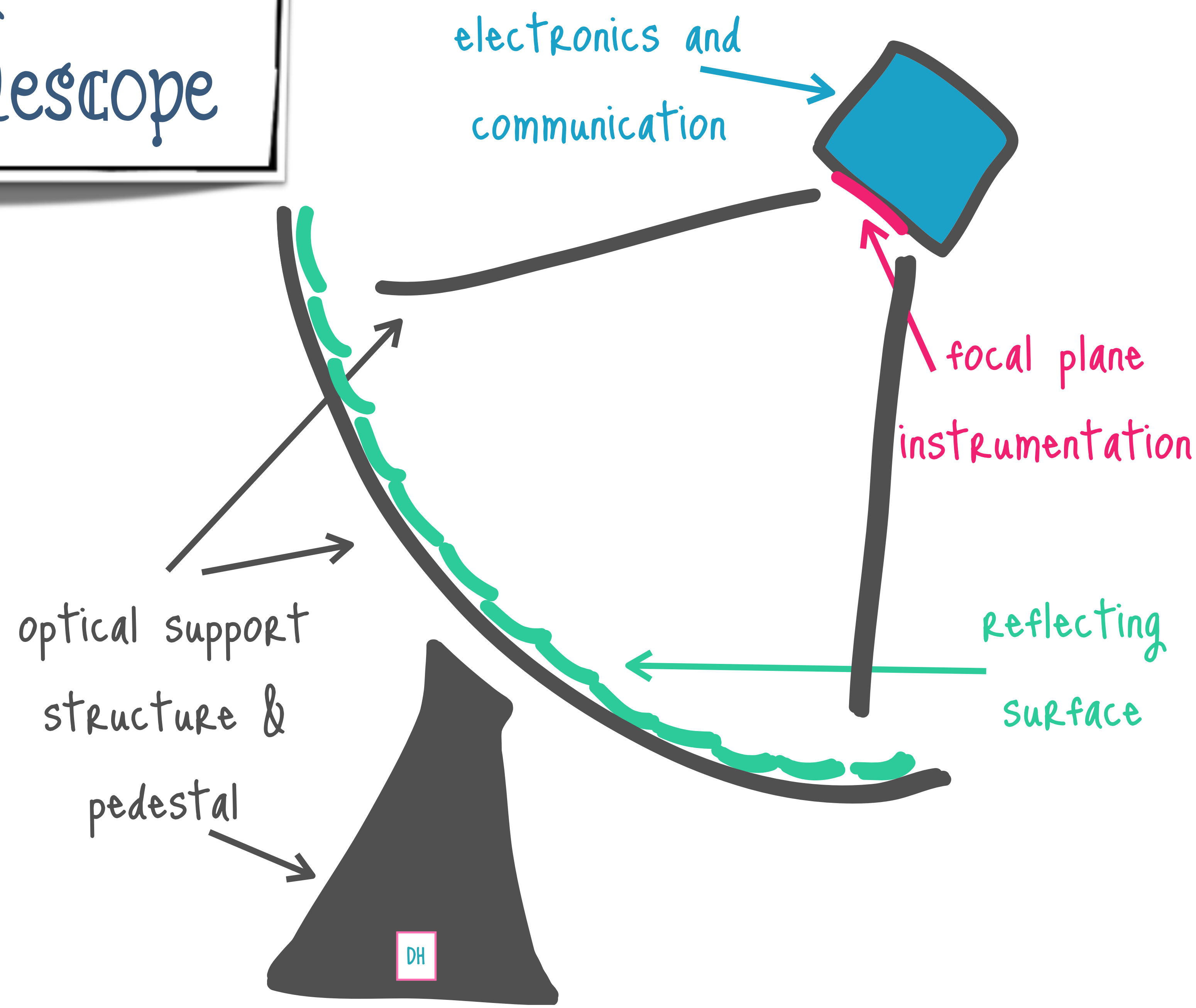
For the current status of the TeV sky, go to TeVCat: http://tevcat.uchicago.edu



The Imaging Atmospher hnique

Extra slide: I did not show this in the presentation. Added it so that you have more background information

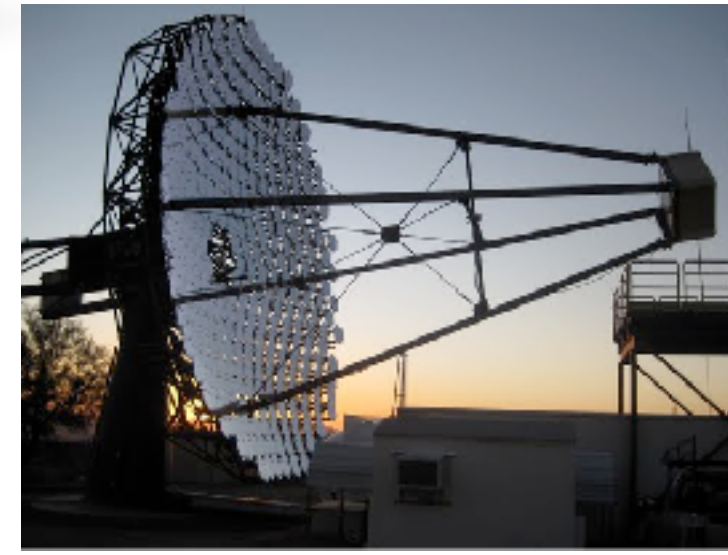
Anatomy of an IAC Telescope



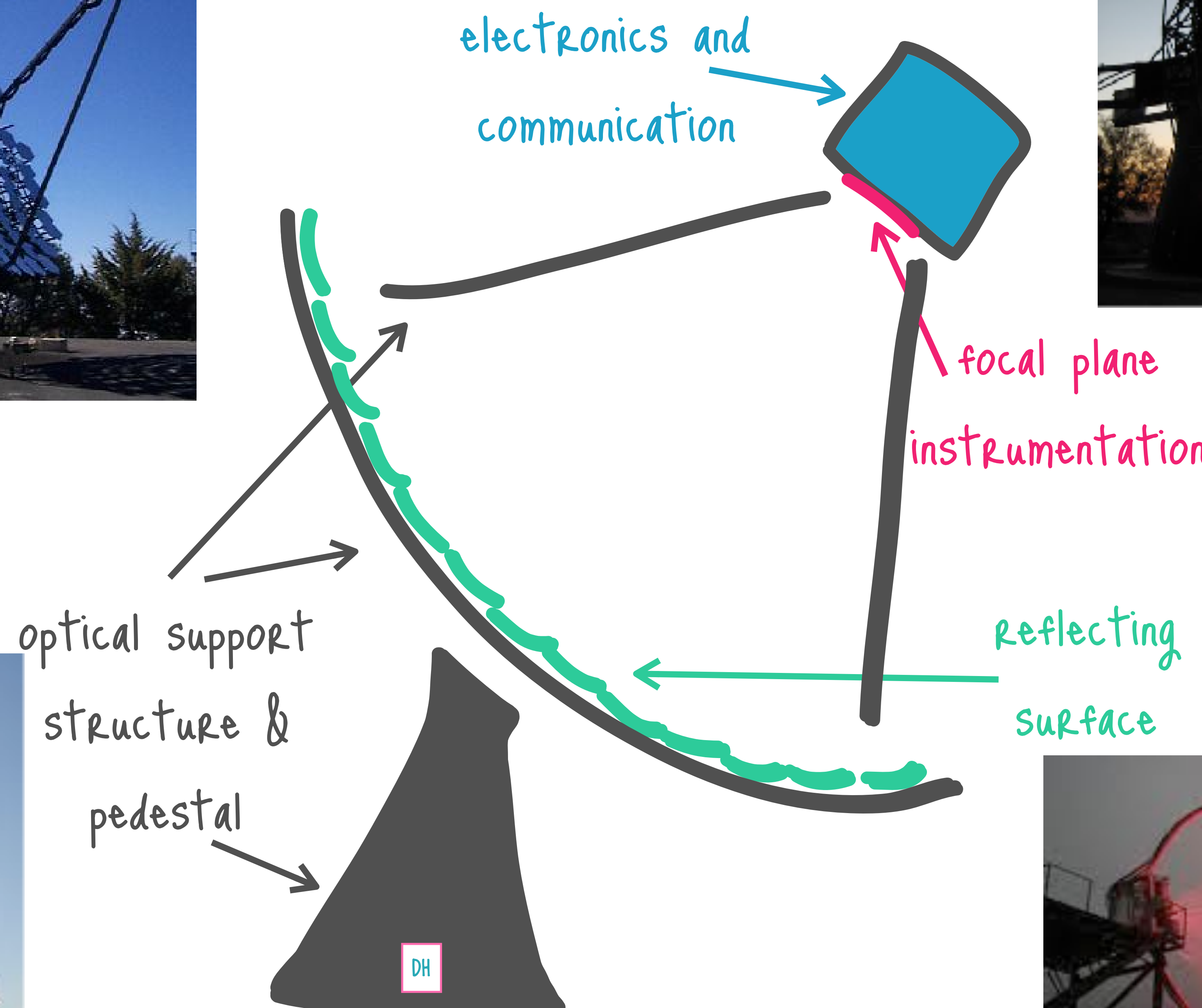
The Imaging Atmospher … hnique

Extra slide: I did not show this in the presentation. Added it so that you have more background information

WHIPPLE



VERITAS



H.E.S.S.

MAGIC

Some notes on the imaging atmospheric Cherenkov technique:

observations can only be performed on dark* nights
--> low duty cycle ~1000 hours per year

instruments are pointed
--> small fields of view therefore need targets

no calibration source** to determine the energy scale
--> rely on simulations to calibrate the instruments

Limitations:

low energy limit
--> local muons, night sky noise

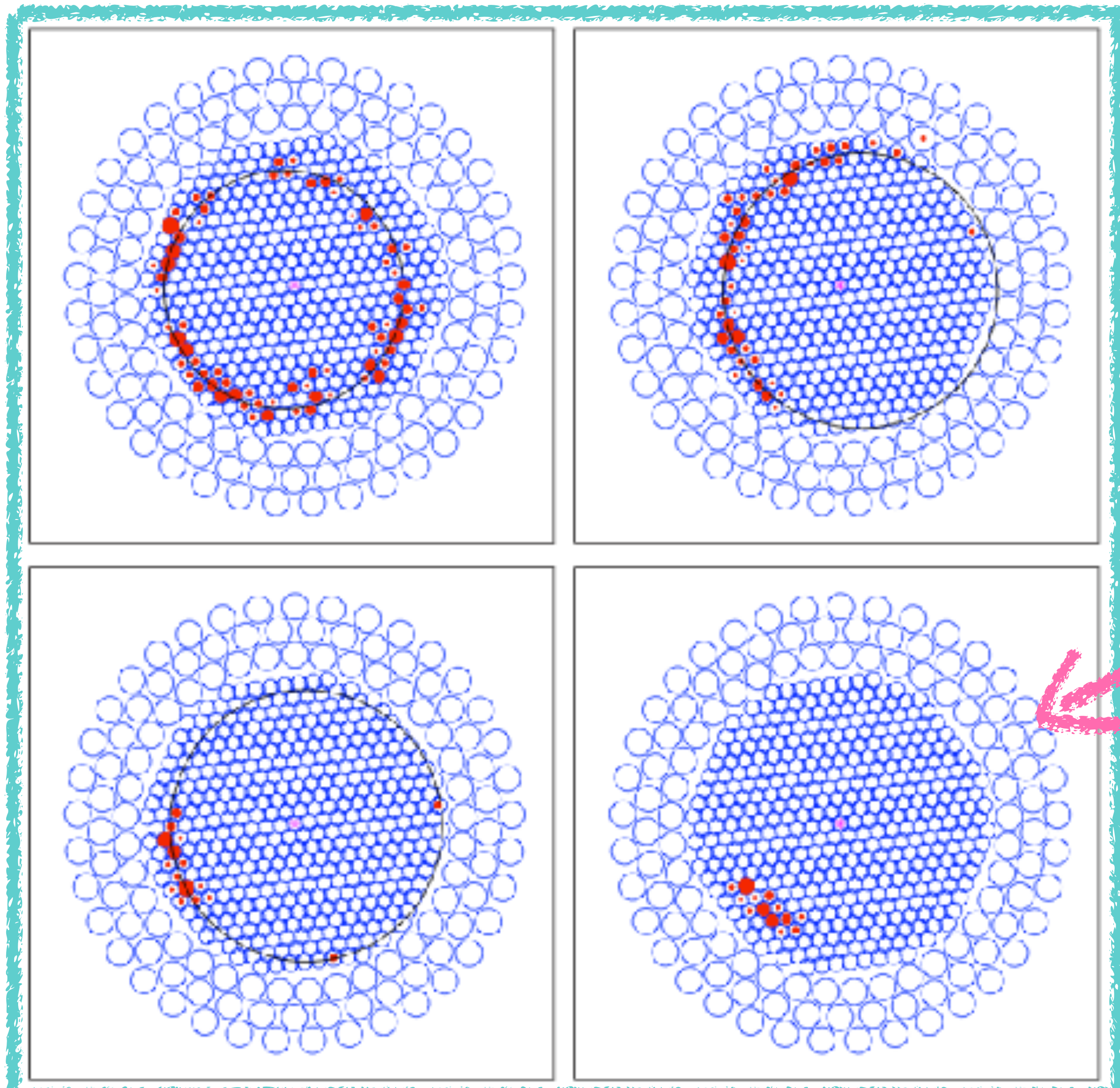
high energy limit
--> collection area

* moon-light observations
** Crab - steady?

Extra slide: I did not show this in the presentation. Added it so that you have more background information

Muons produced (mostly) in hadronic showers from pion decay

- do not interact strongly with matter so a large proportion reach the earth's surface
  - ➡ the "penetrating component" of cosmic rays



REAL & SIMULATED MUONS WITH DIFFERENT IMPACT PARAMETERS

Cherenkov light from local muons is indistinguishable from a low-energy gamma-ray shower

The Imaging Atmospher hnique

Extra slide: I did not show this in the presentation. Added it so that you have more background information

Muons produced (mostly) in hadronic showers from pion decay

- do not interact strongly with matter so a large proportion reach the earth's surface
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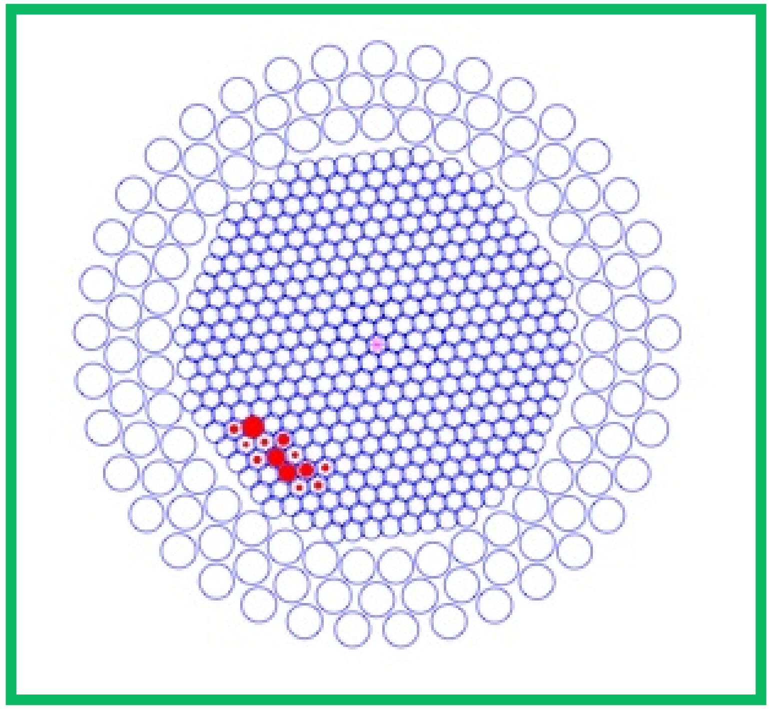
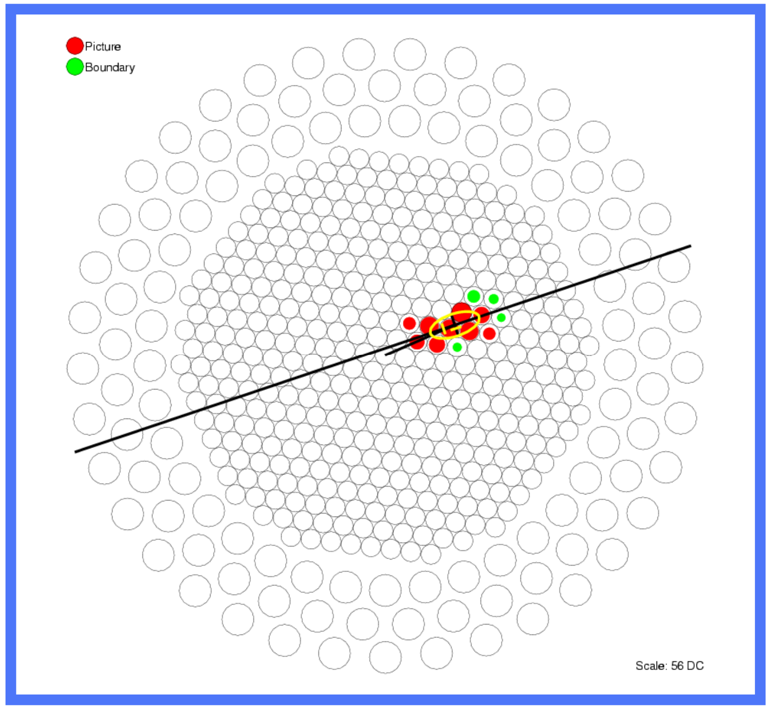


partial muon

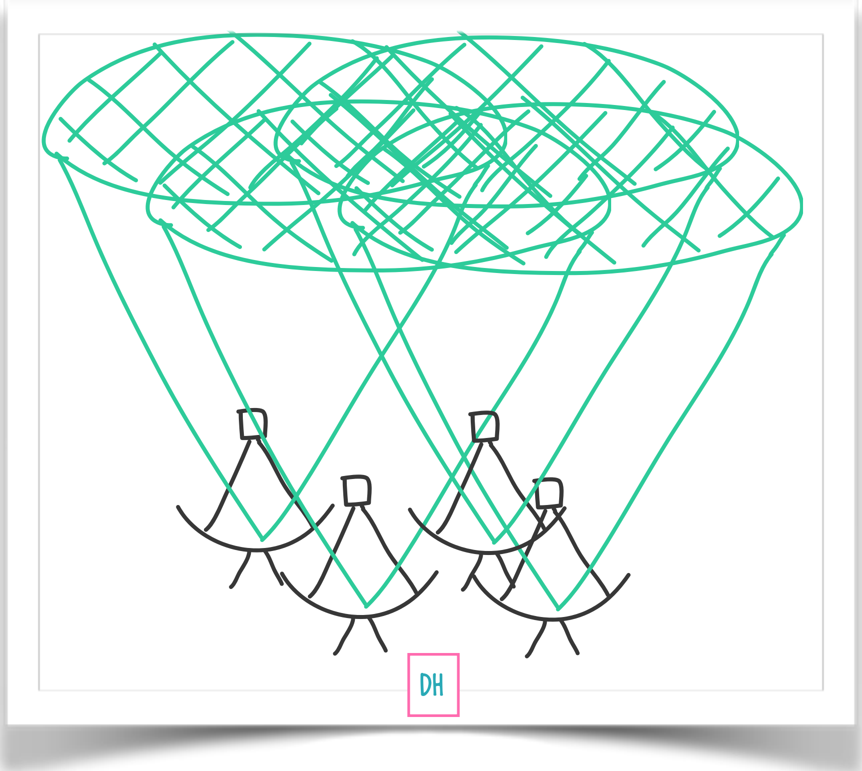


gamma ray

Gamma-ray Telescopes of Today
10/11

Gamma-ray Telescopes of Today

The success of Whipple, HEGRA, CAT and CANGAROO led to a growth in the field of ground-based gamma-ray astronomy. New instruments were developed (and the teams of people building them grew too).



- arrays*
- larger energy range
- more sensitive
- better energy resolution
- higher angular resolution

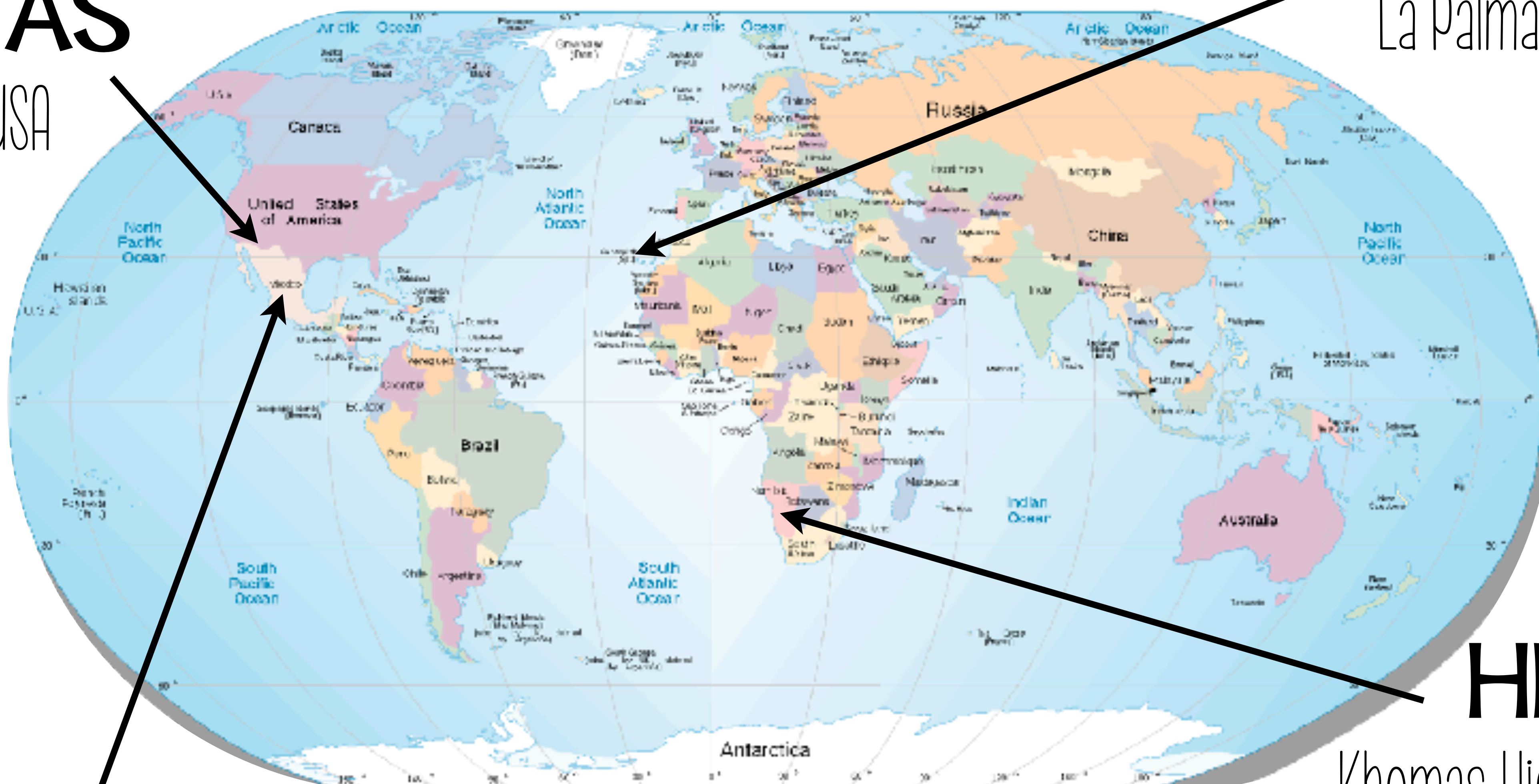
* HEGRA was an array; MAGIC was a single-telescope system at first

Gamma-ray Telescopes of Today

"Third generation" instruments: ~2003 - present

VERITAS
Arizona, USA

MAGIC
La Palma, Canary Islands



HESS
Khomas Highlands, Namibia

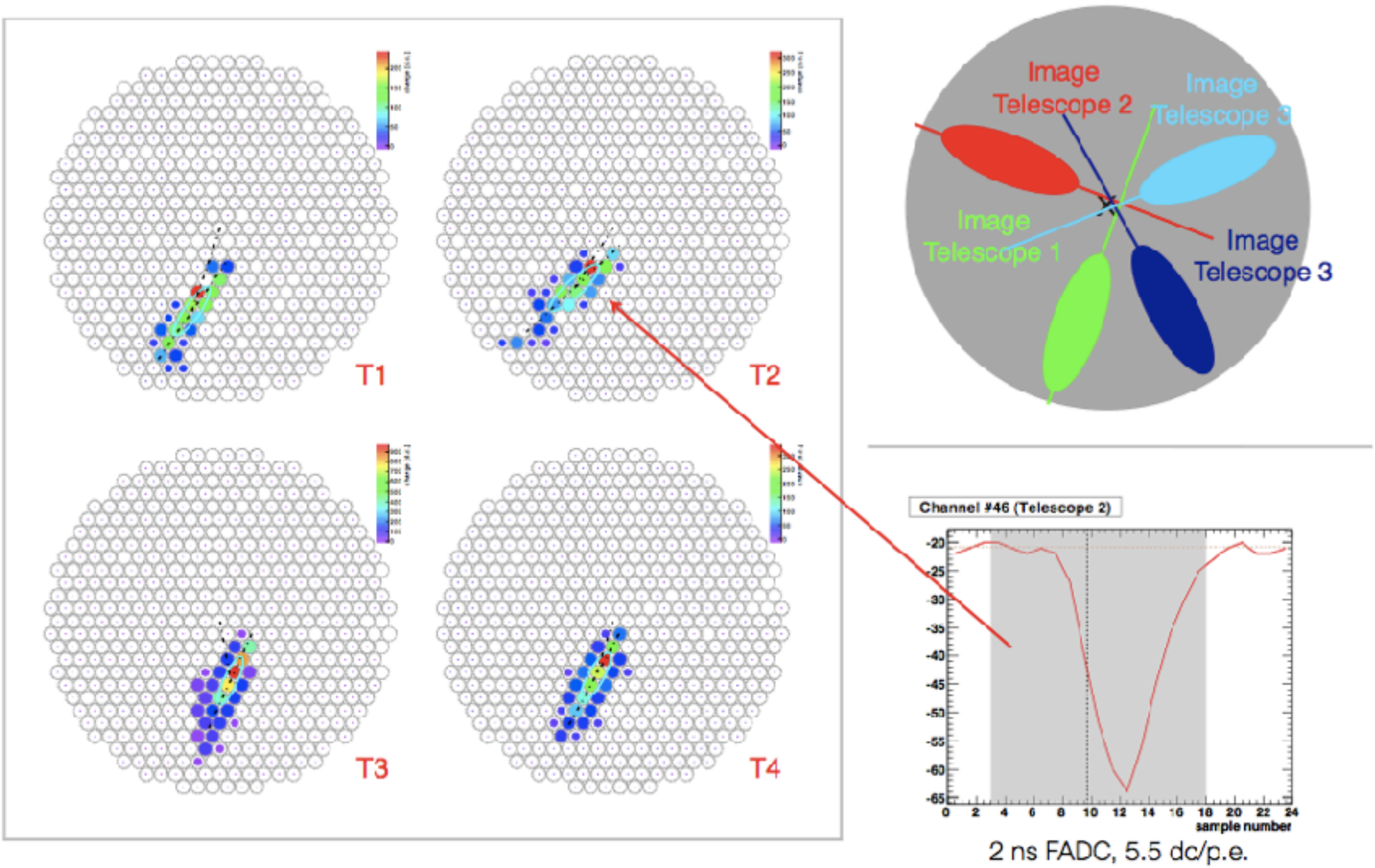
HAWC*
Sierra Negra, Mexico

* Water Cherenkov

Gamma-ray Telescopes of Today

Stereo observations enable us to distinguish local muons from low-energy gamma rays

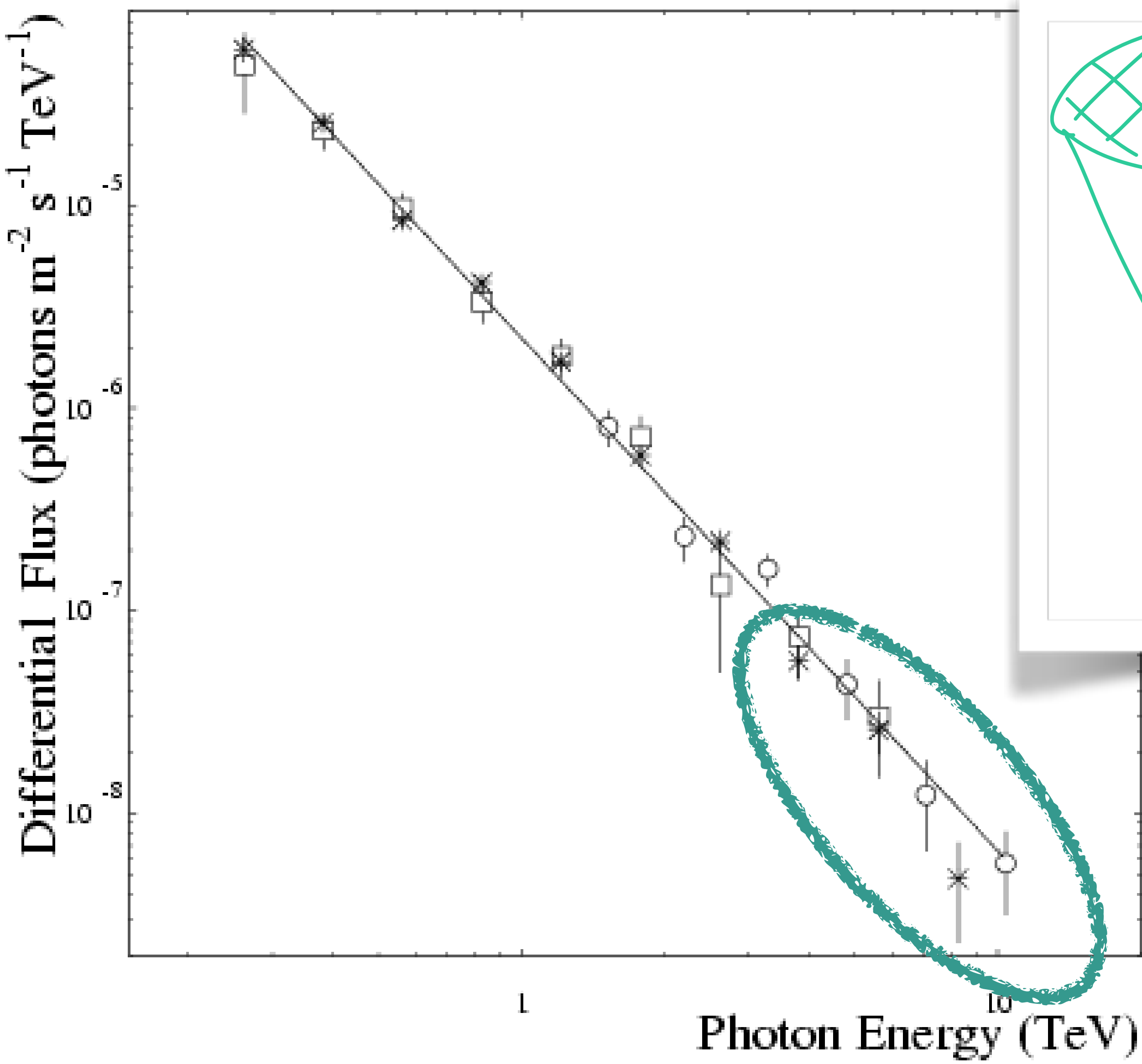
… multi-telescope trigger requirement helps us operate with lower energy threshold

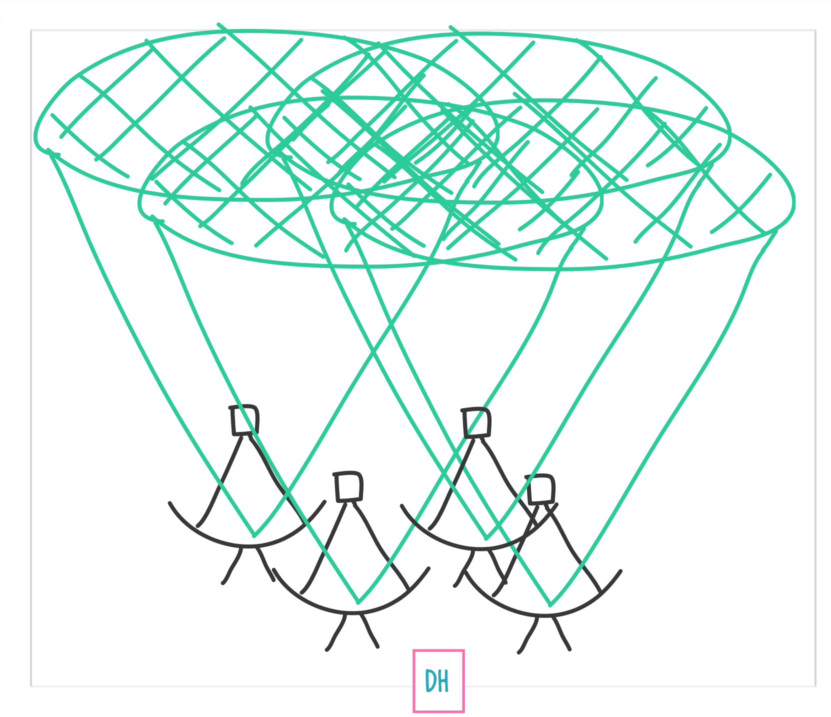


Gamma-ray Telesco

Extra slide: I did not show this in the presentation. Added it so that you have more background information

the gamma-ray spectra of all sources fall rapidly with increasing energy





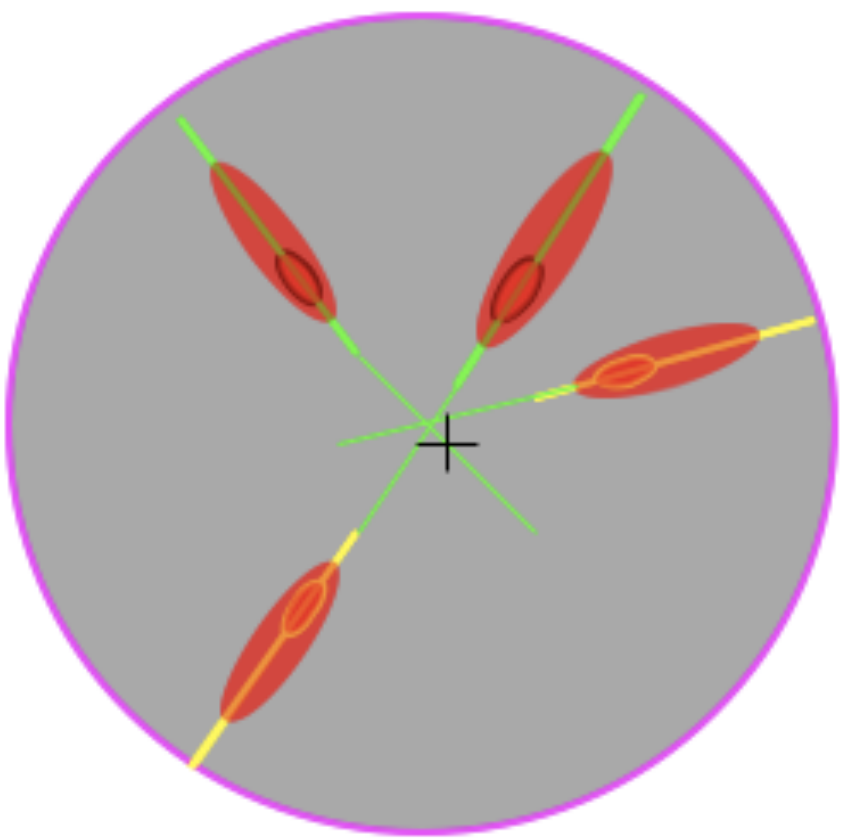
in order to gather as many of the highest energy particles as possible, we must increase the collection area

Gamma-ray Telesco

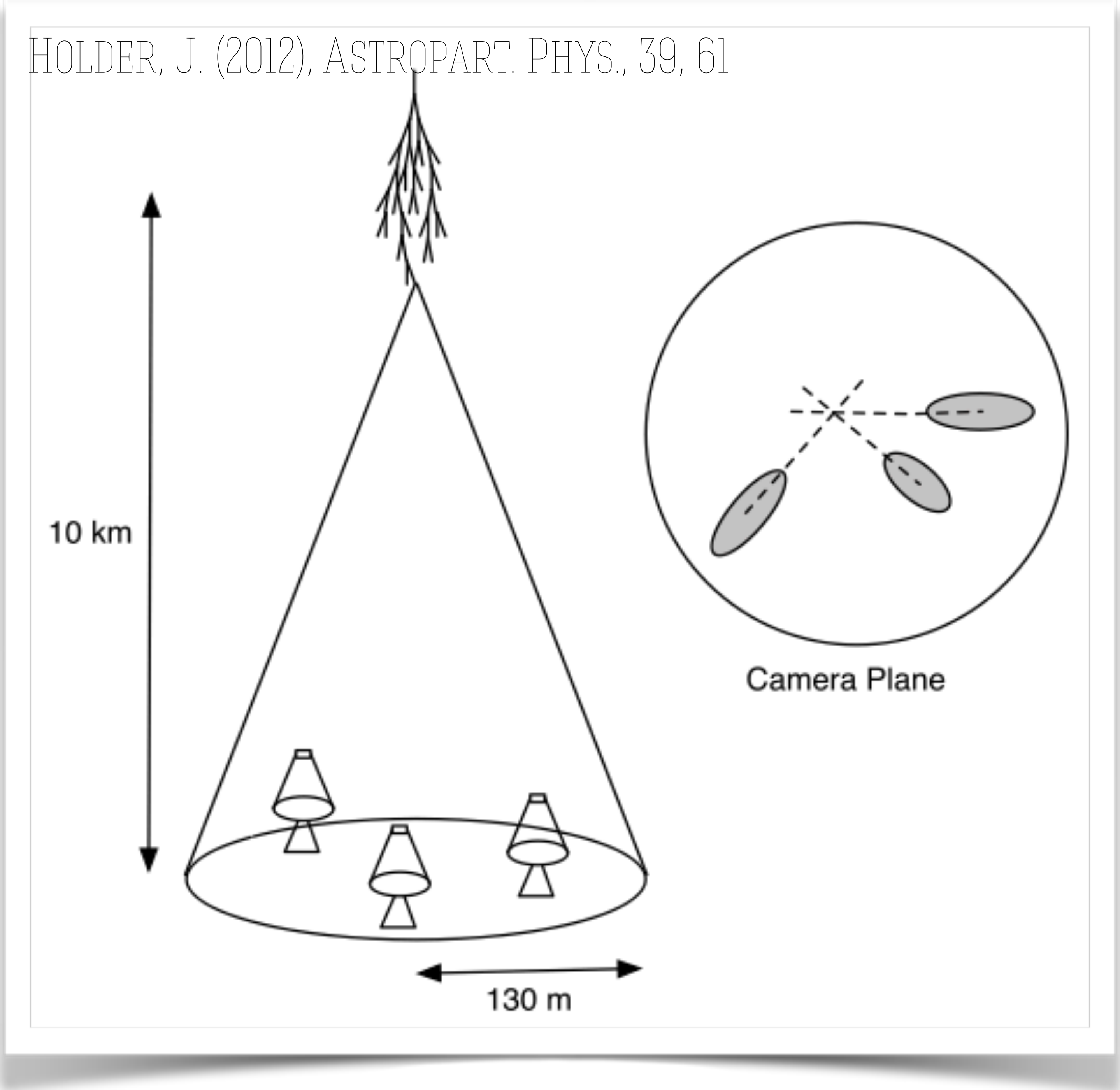
Extra slide: I did not show this in the presentation. Added it so that you have more background information

Stereo observations enable us more accurately characterise the properties of the gamma rays

More than one (up to 4) image of each shower



Position on Sky



Gamma-ray Telescopes

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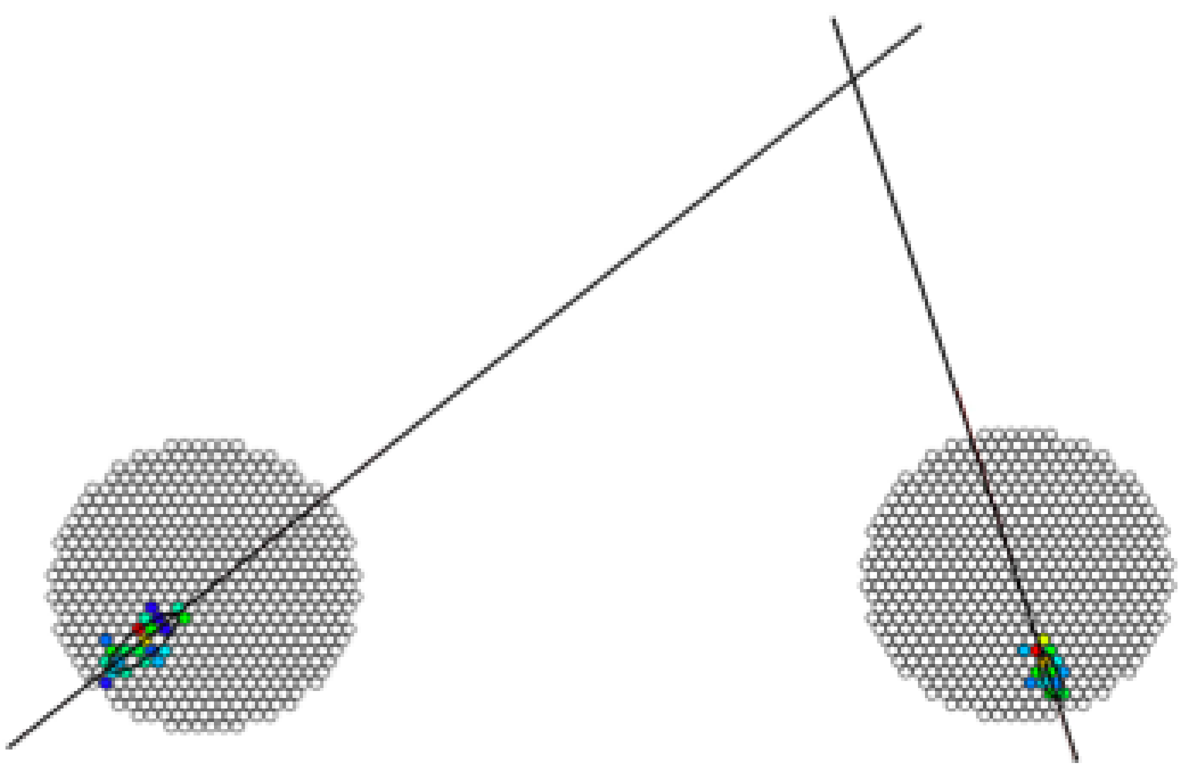
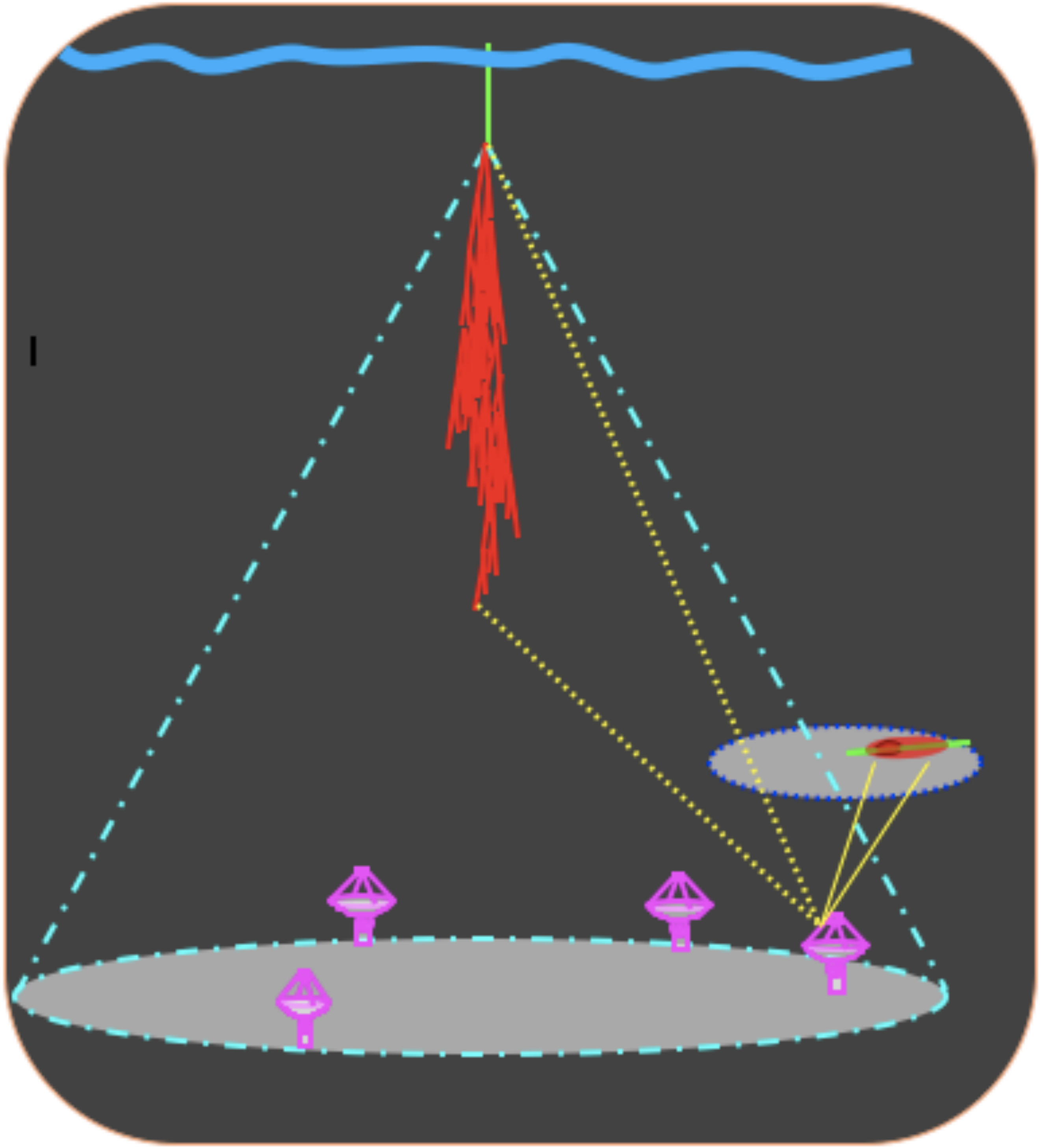
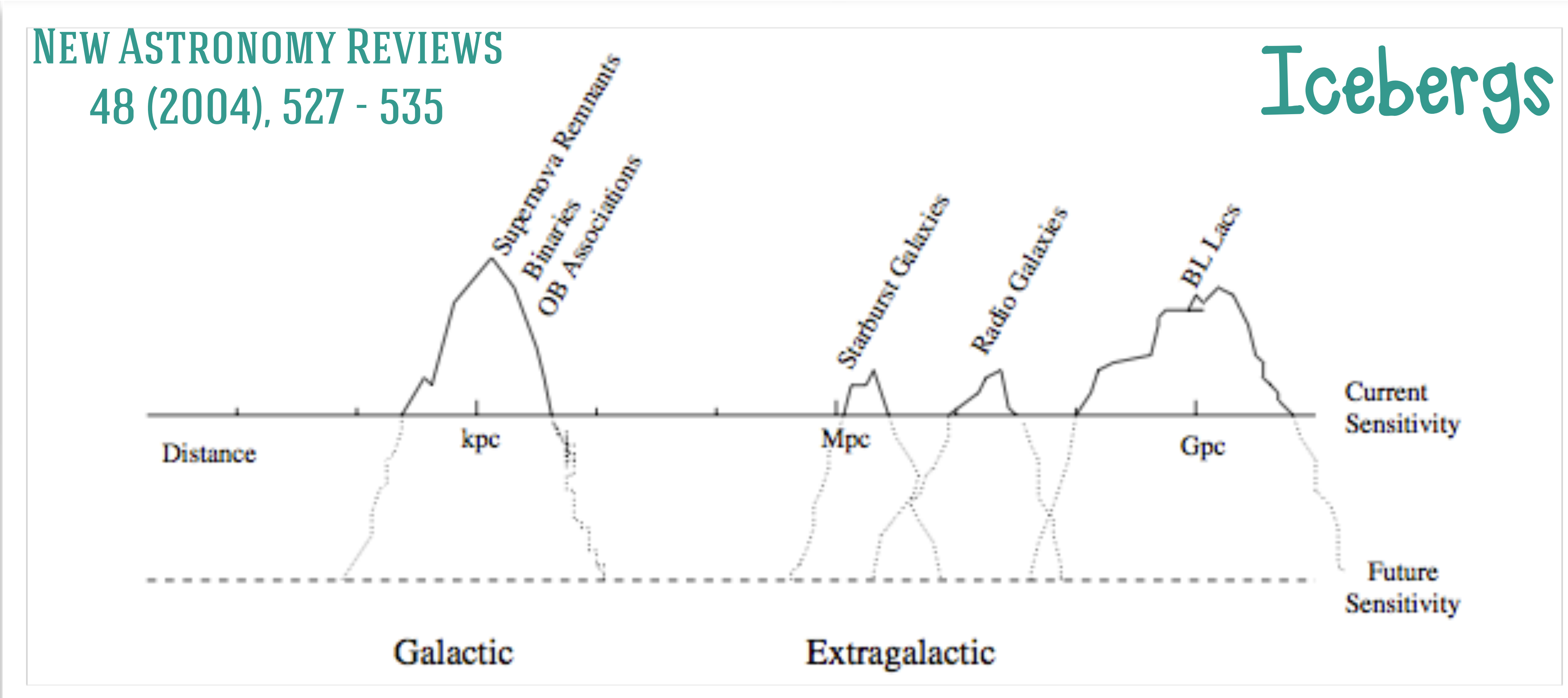


Core location on the ground



Gamma-ray Telescopes of Today

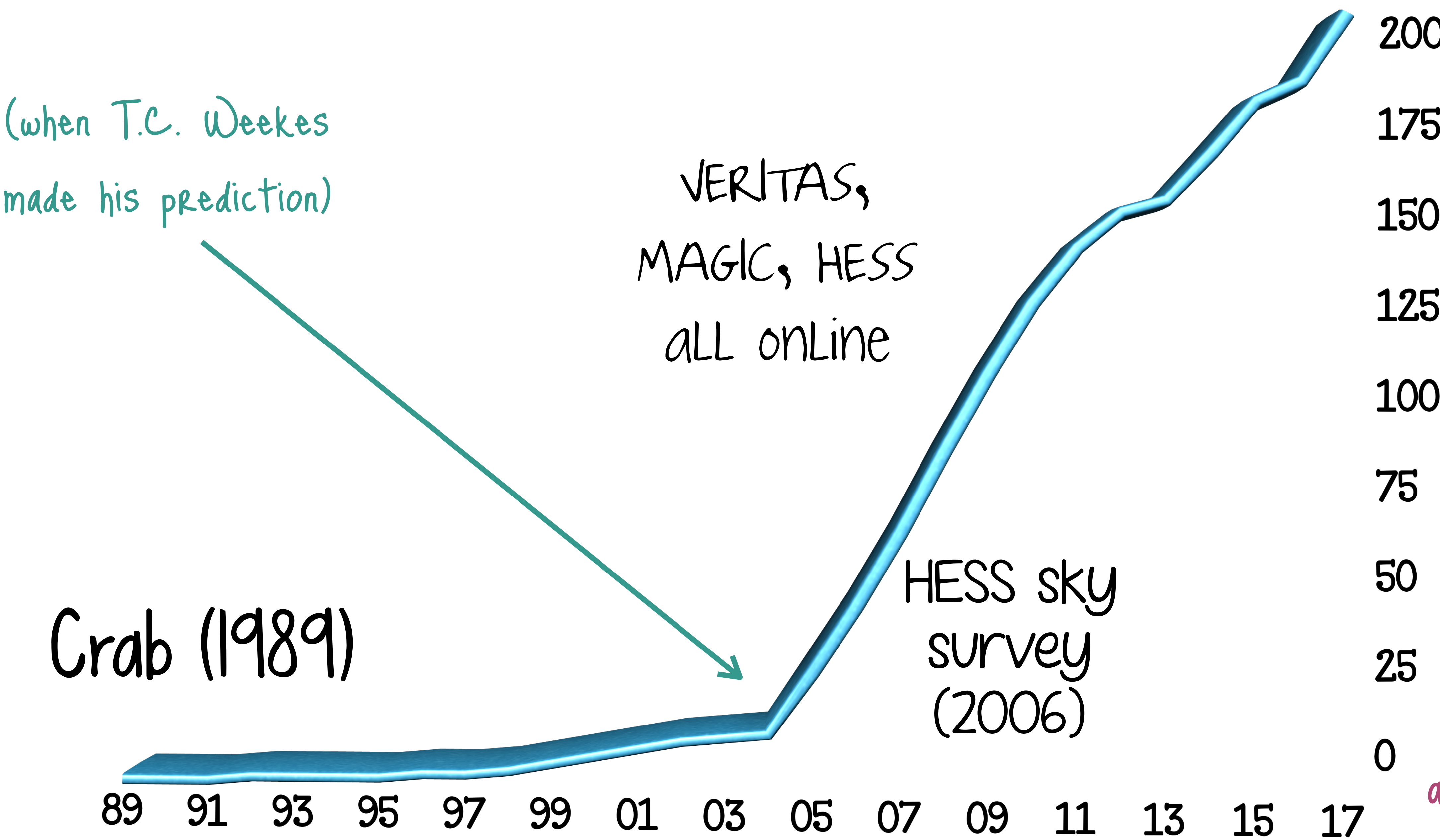
☼Just before the third generation telescopes came fully online



A figure that T. C. Weekes created in 2004☼ to illustrate his view on the status of the field

Gamma-ray Telescopes of Today

As of writing this talk, there are 198* sources in TeVCat

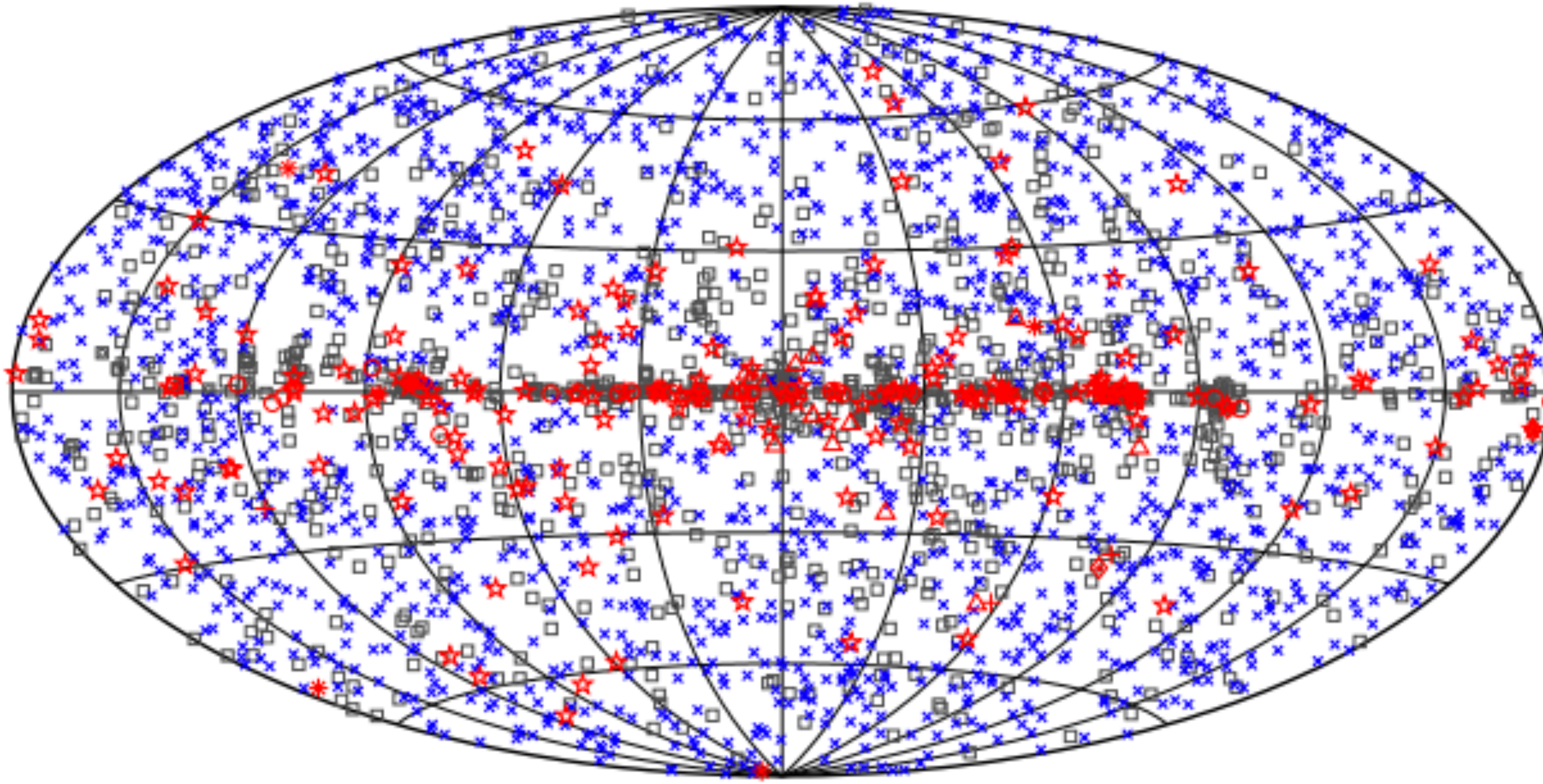


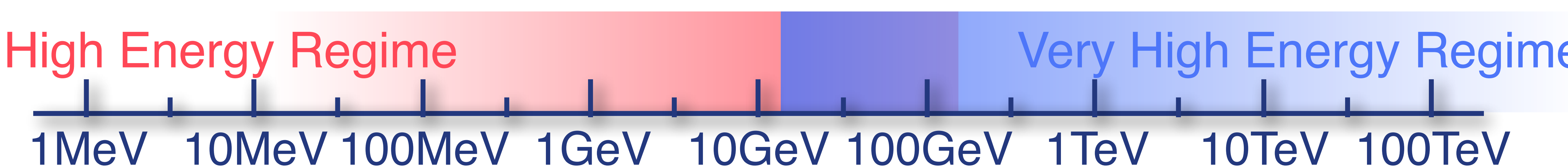
*Many new sources announced during the last 2 weeks at the International Cosmic Ray Conference in Korea

Astrophysical Sources of Gamma rays

11/11

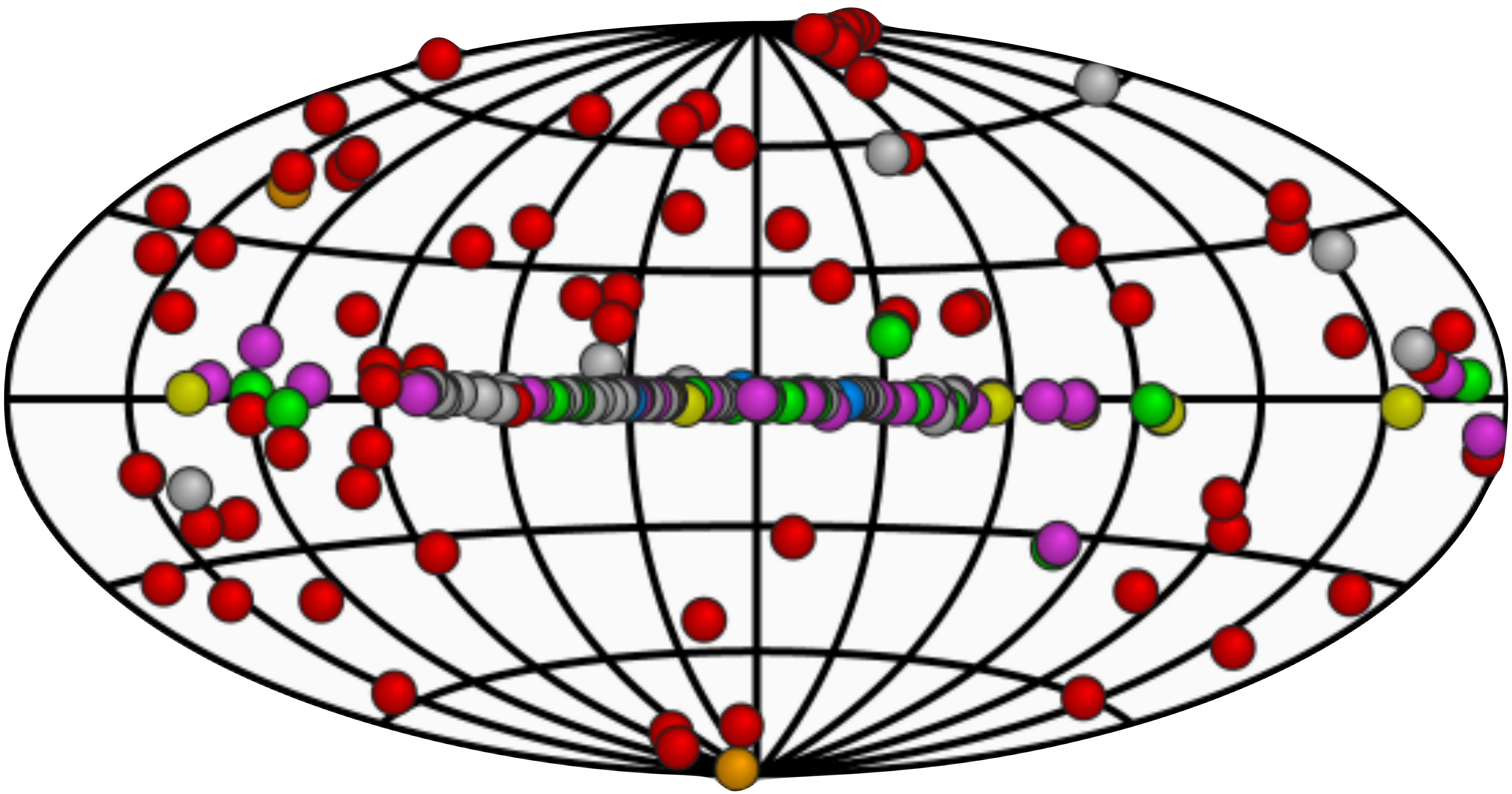
Astrophysical Sources of Gamma rays

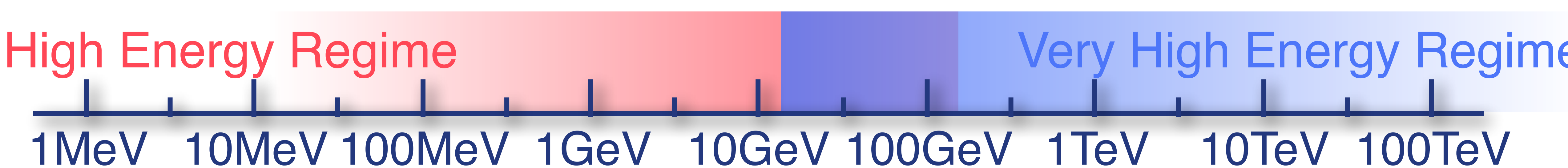




3033 sources at HE (0.1 - 300 GeV) - 198 sources at VHE (> 200 GeV)

Astrophysical Sources of Gamma rays





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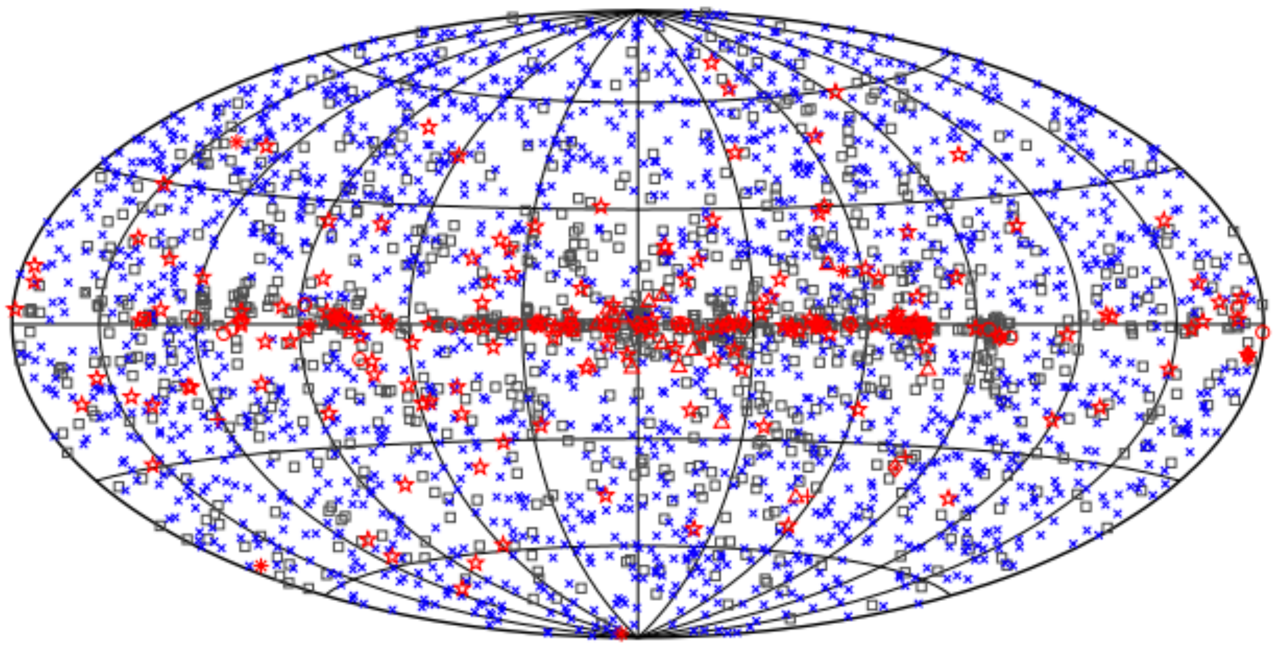
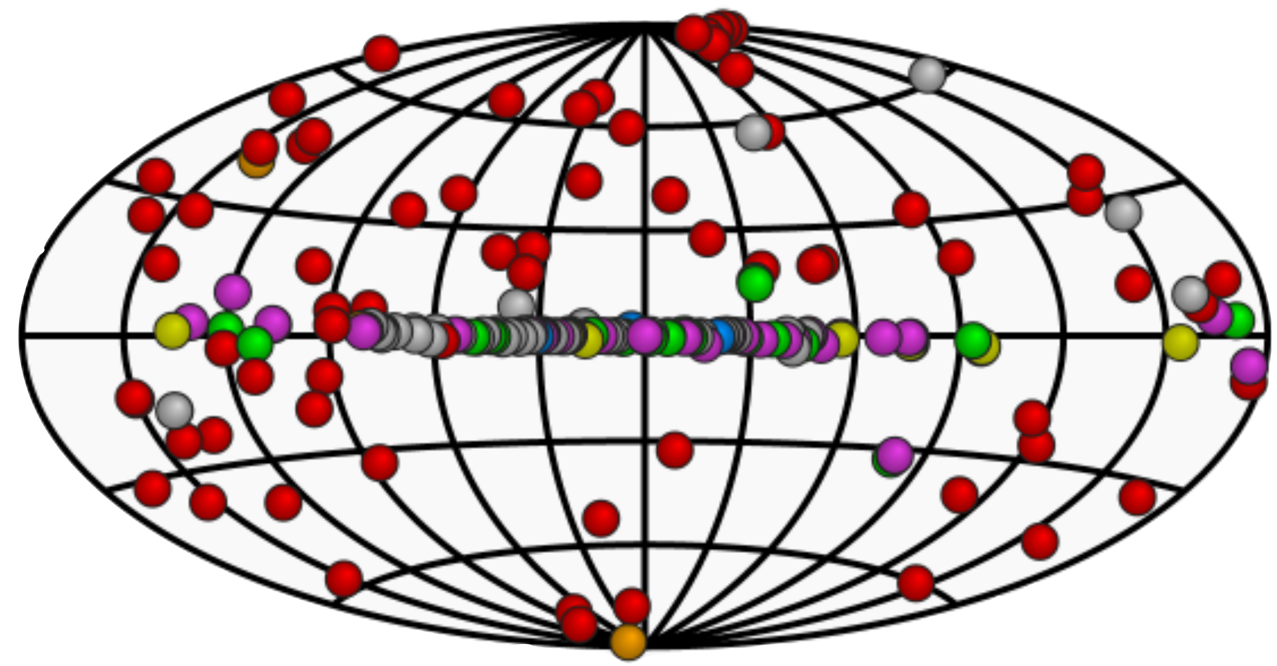
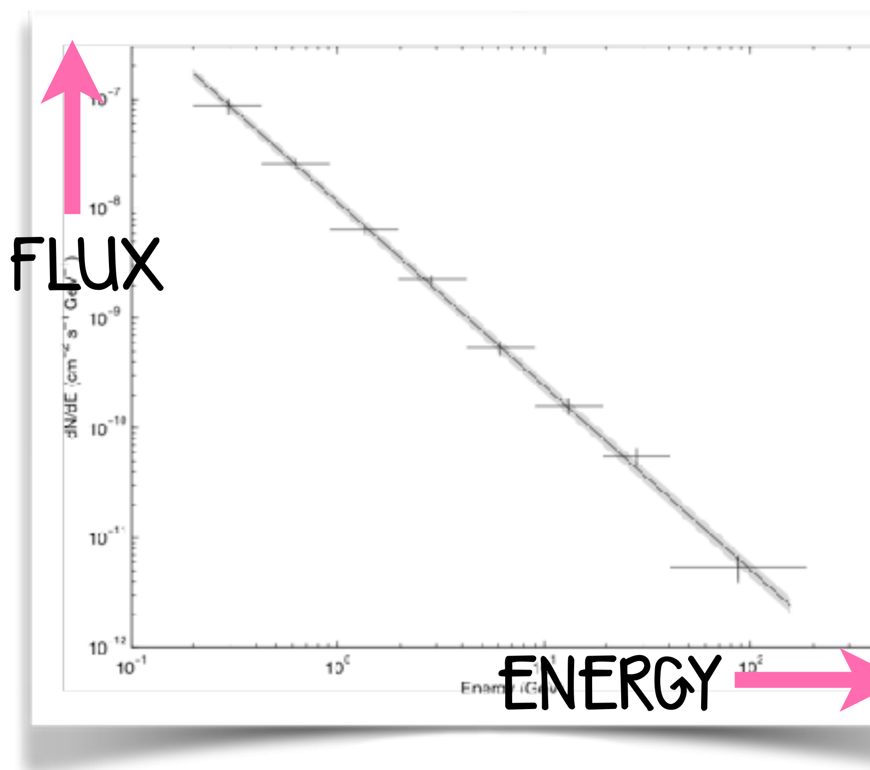
Astrophysical Sources of Gamma rays



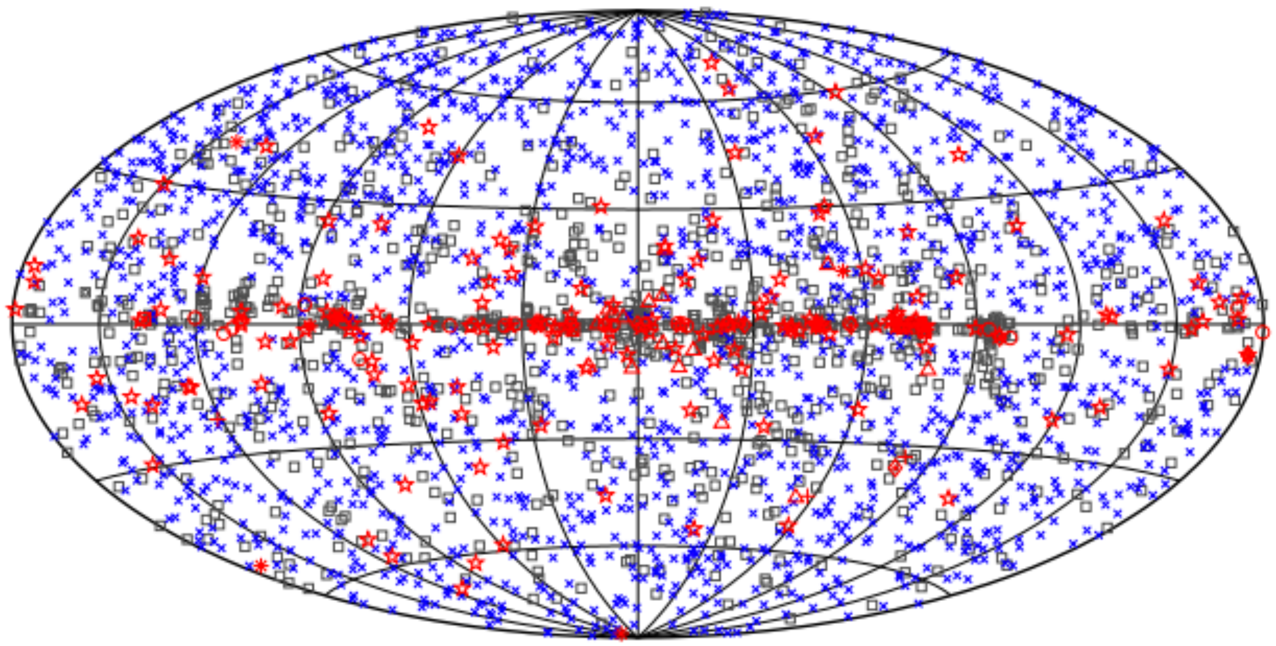


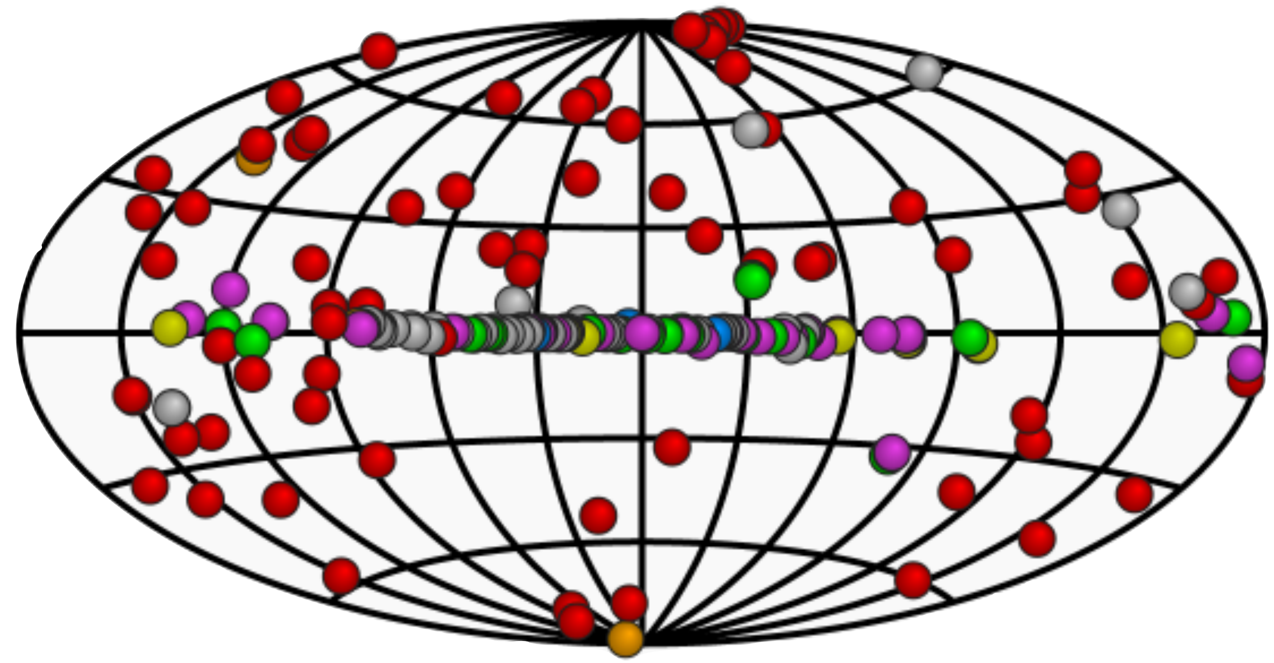
3033 sources at HE (0.1 - 300 GeV) - 198 sources at VHE (> 200 GeV)



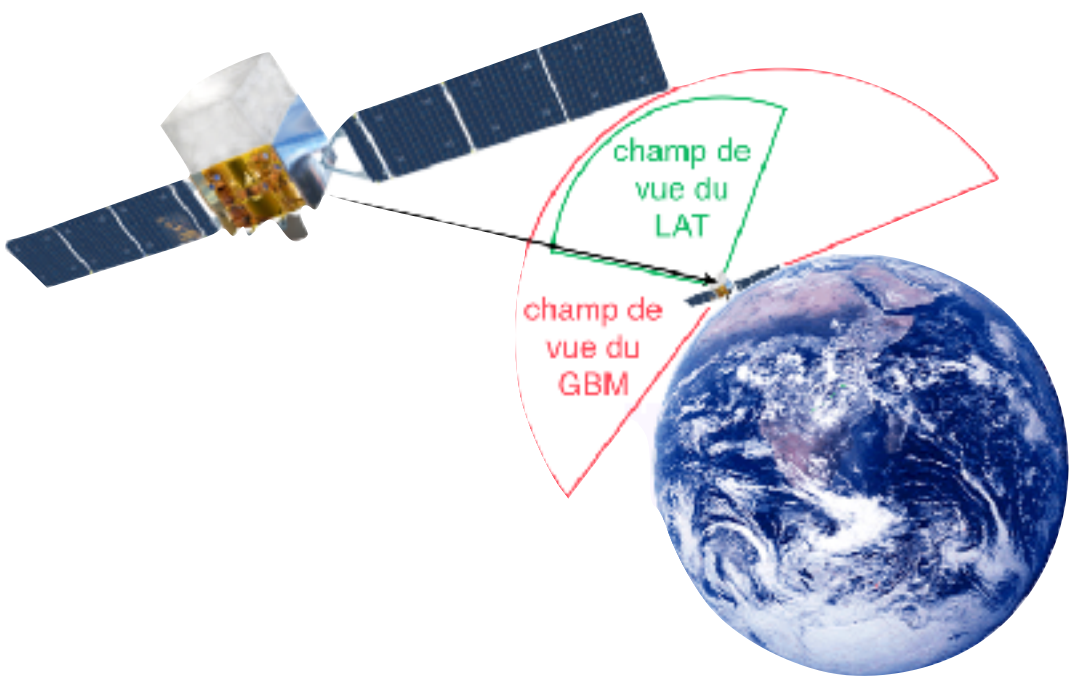
Abdo et al. (2010), ApJ, 708, 1310

Astrophysical Sources of Gamma rays





3033 sources at HE (0.1 - 300 GeV) - 198 sources at VHE (> 200 GeV)



Full sky observed every 3 hours

Field of view 3.5° ; 1000 hours / year

Astrophysical Sources of Gamma rays

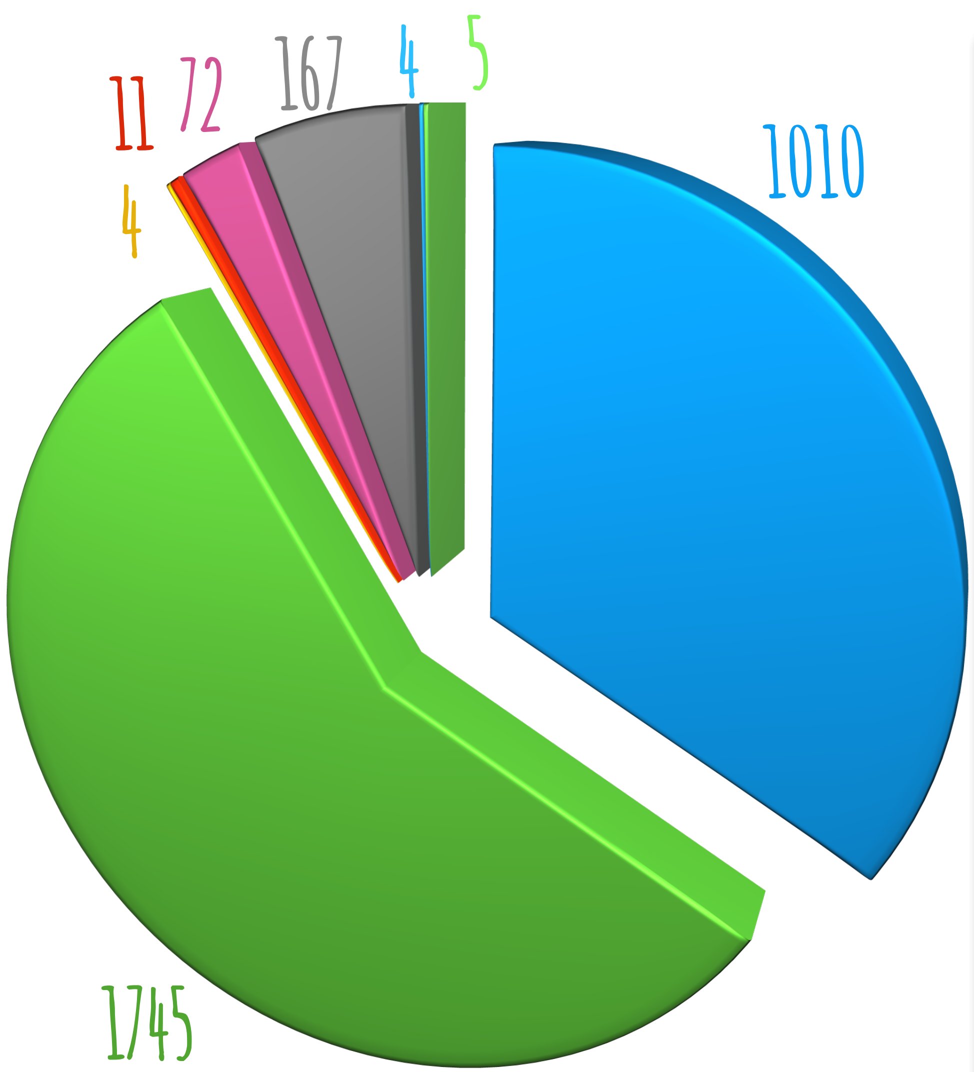
High Energy Regime

Very High Energy Regime

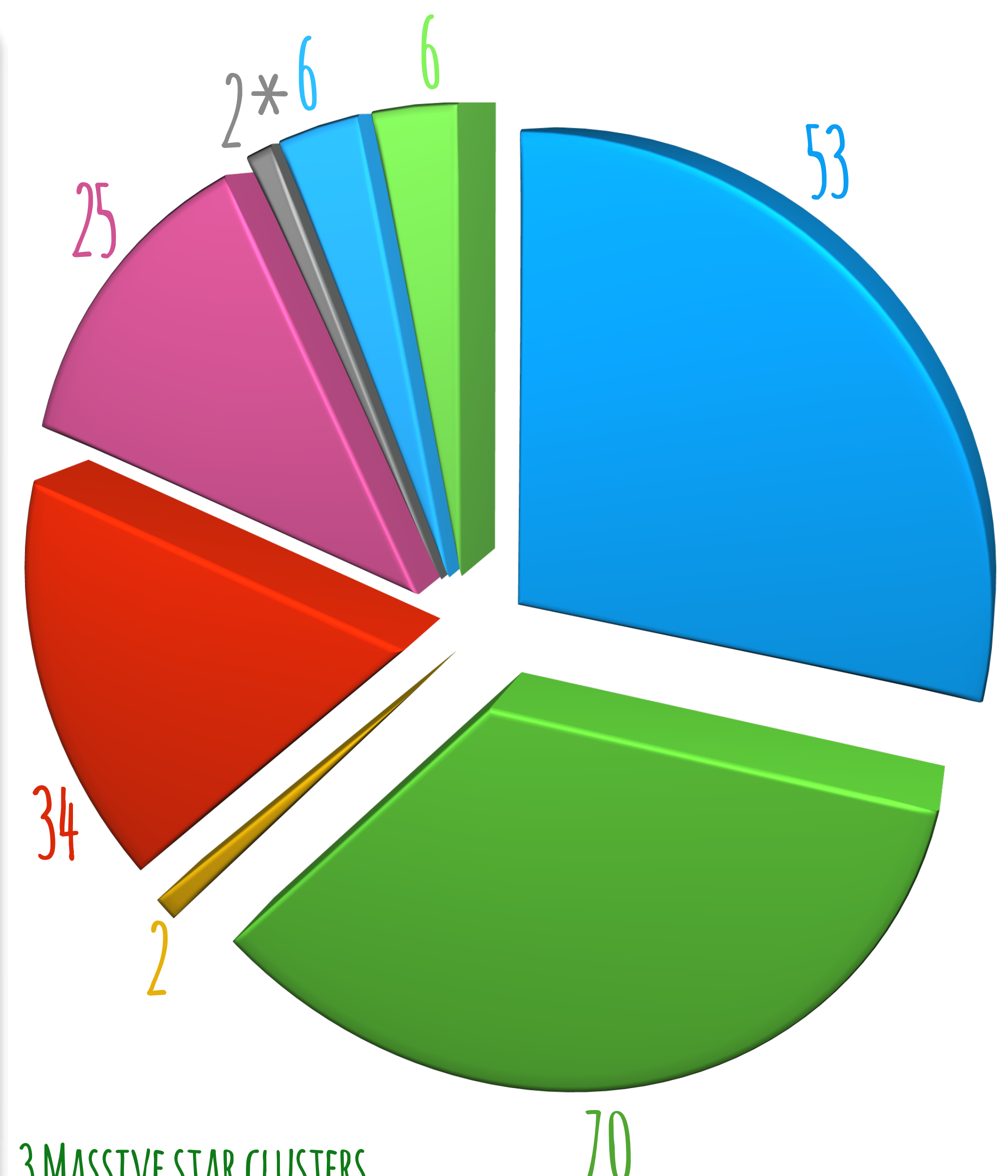
Astrophysical Sources of Gamma rays

High Energy: 3033 Sources — Very High Energy: 198 Sources

1MeV 10MeV 100MeV 1GeV 10GeV 100GeV 1TeV 10TeV 100TeV



UNIDENTIFIED
ACTIVE GALACTIC NUCLEI
STARBURST
PULSAR WIND NEBULAE
SUPERNOVA REMNANTS
PULSARS
BINARIES
"OTHER"



+ ~109 GAMMA RAY BURSTS

2 NORMAL GALAXIES
1 STAR FORMING REGION
1 NOVA

3 MASSIVE STAR CLUSTERS
2 SUPERBUBBLES
1 GLOBULAR CLUSTER

*NEW PSR ANNOUNVED AT ICRC

Astrophysical Sources of Gamma rays

- Unidentified
- Active Galactic Nuclei
- Starburst
- Pulsar Wind Nebulae
- Supernova Remnants
- Pulsars
- Binaries
- "Other"

For overview articles on gamma-ray astrophysics, check out the "TeV Astrophysics" section of TeVCat: http://tevcat.uchicago.edu/reviews.html

Astrophysical Sources of Gamma rays

1. Extragalactic Physics

- Active Galactic Nuclei

2. Galactic Physics

- Pulsar Wind Nebulae
- Supernova Remnants
- Binaries

Unidentified
Active Galactic Nuclei
Starburst
Pulsar Wind Nebulae
Supernova Remnants
Pulsars
Binaries
"Other"

3. Cosmology

- Extragalactic Background Light
- Intergalactic Magnetic Fields

4. Astroparticle / Exotic Physics

- Dark Matter Searches
- Lorentz Invariance

Extragalactic Physics

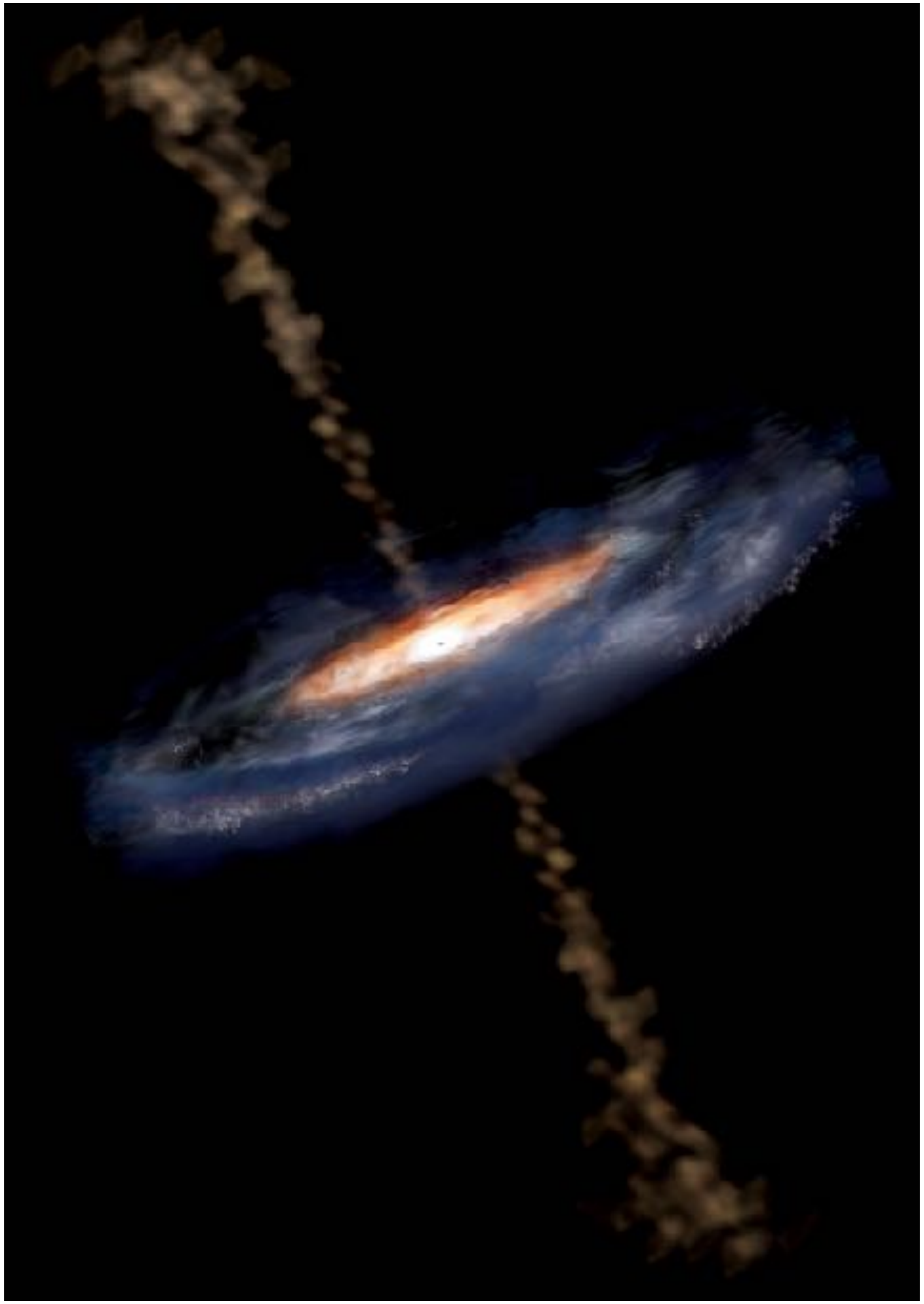
1.

Active Galactic Nuclei

Extragalactic Physics: Active Galactic Nuclei

CHARACTERISTICS

- **central nucleus outshines the rest of the galaxy**
- high luminosity (normally)
- **emission across entire spectrum ... radio to keV, MeV, TeV**
  ➡ non-thermal
- strong variability
- radio-loud sources:
  ➡ relativistic jets ... superluminal motion

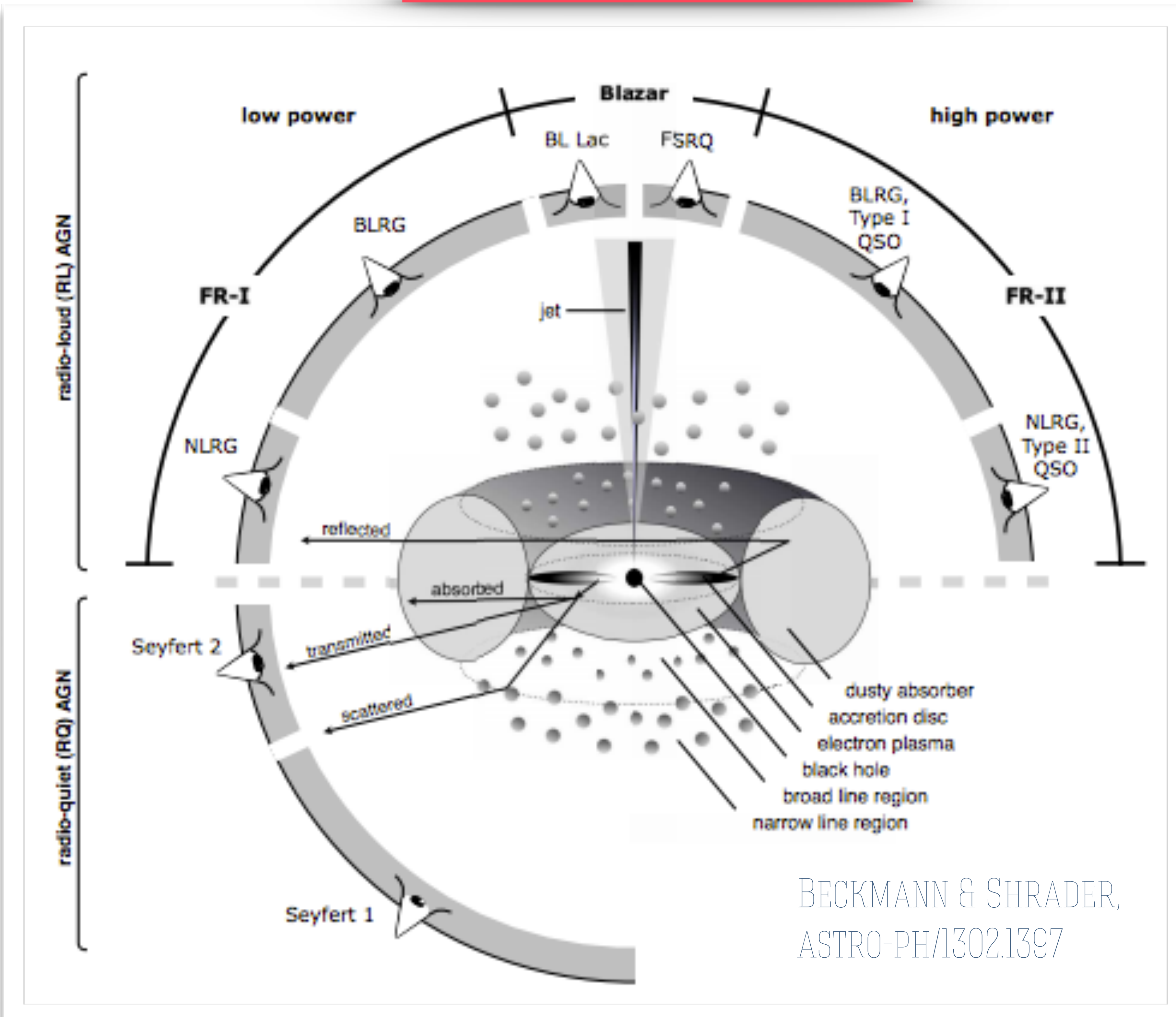


Extragalactic Physics: Active Galactic Nuclei

TAXONOMY

Extragalactic Physics … Nuclei

Extra slide: I did not show this in the presentation. Added it so that you have more background information

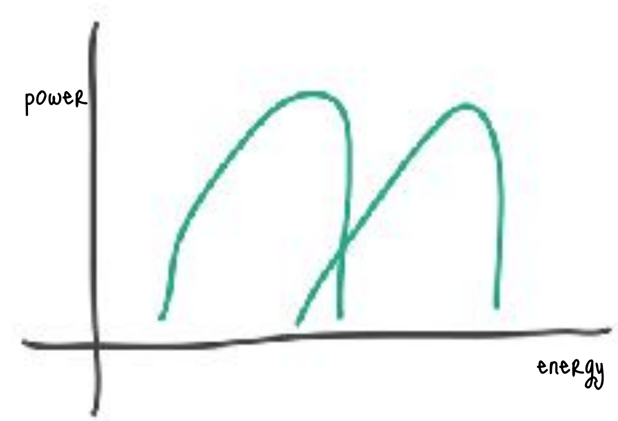


Beckmann & Shrader, astro-ph/1302.1397

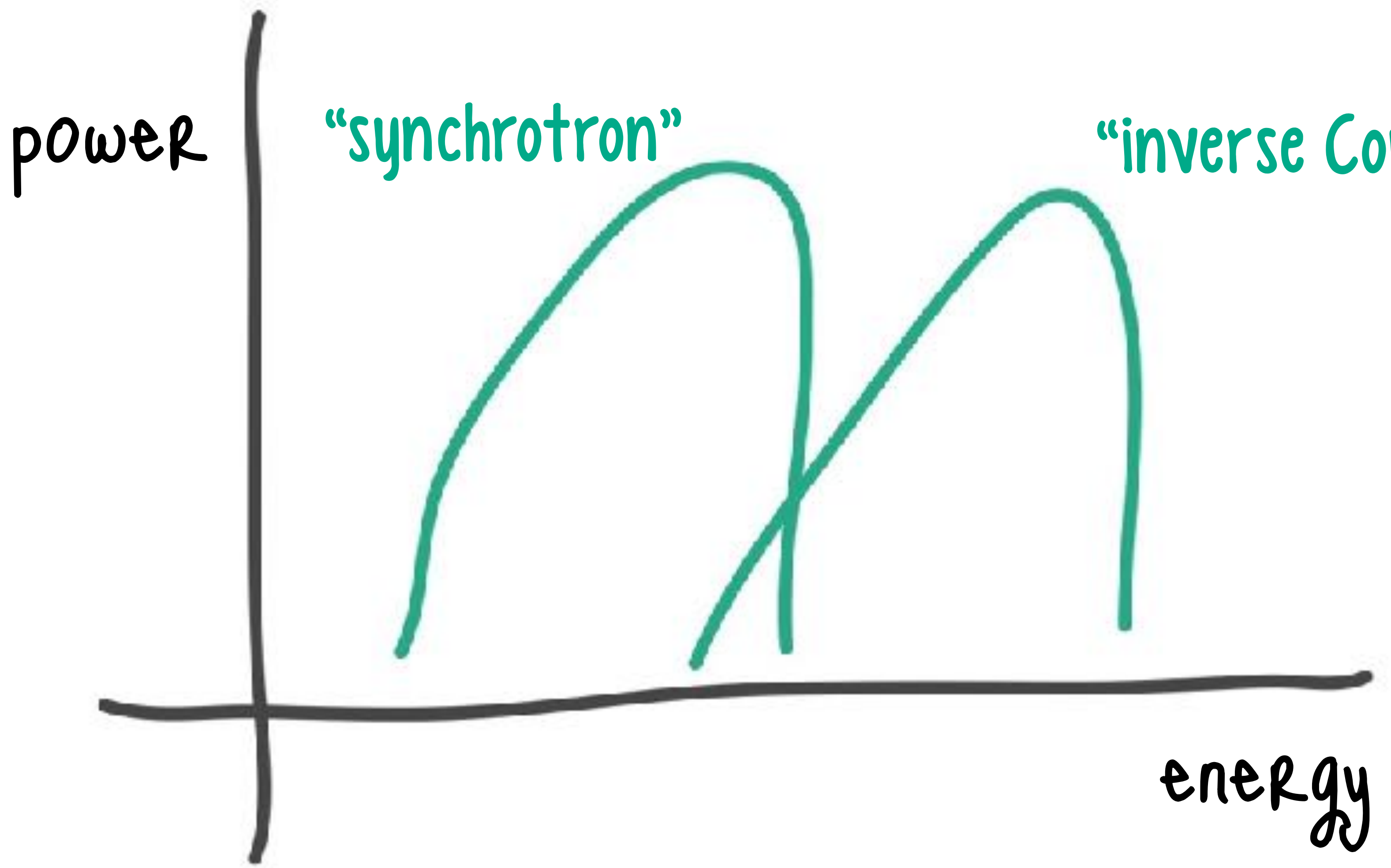
Extragalactic Physics: Blazars

CHARACTERISTICS

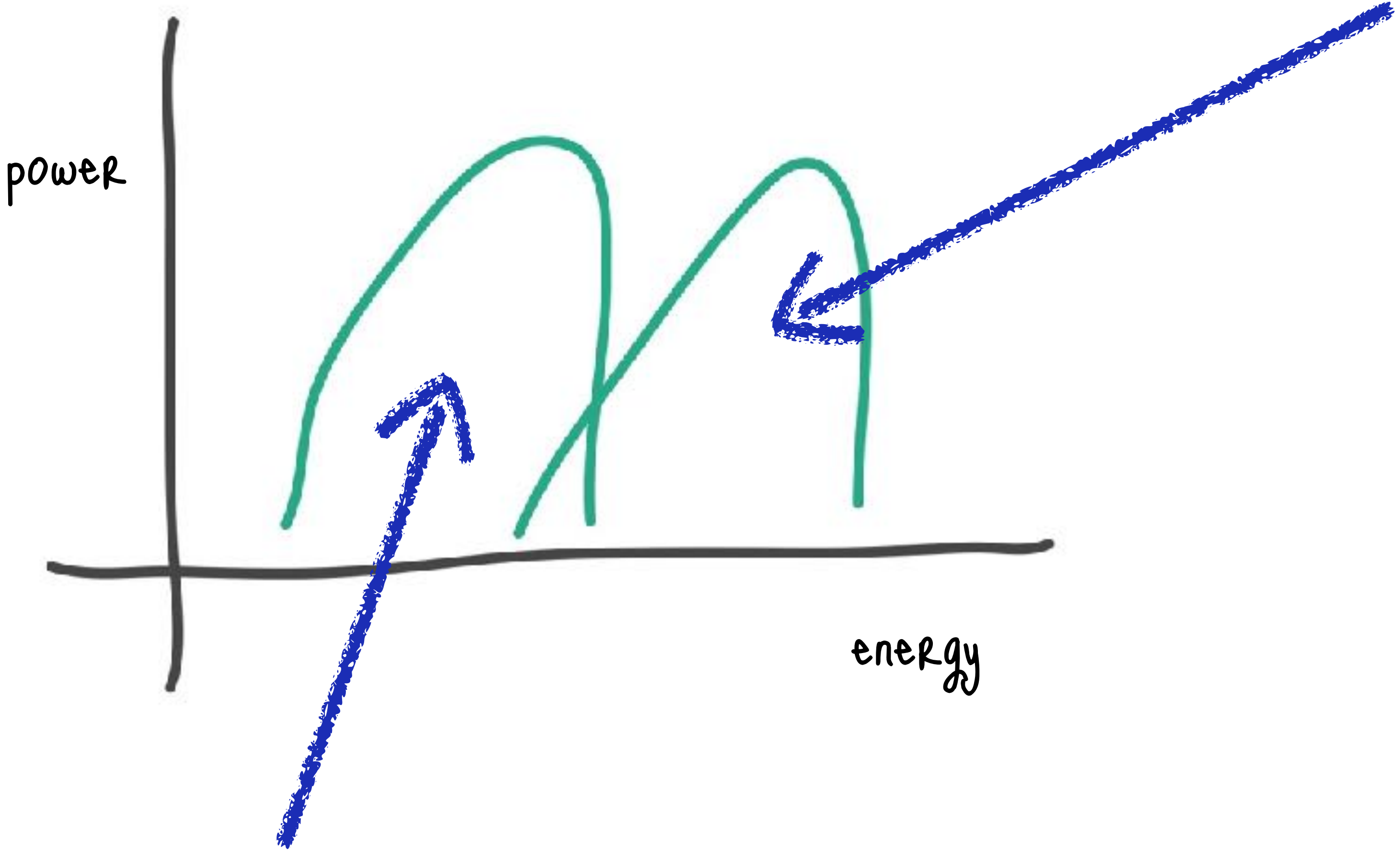
- <5% of all AGN
- jet points "at" us
- flat radio spectrum
- **radio loud AGN**
- large amplitude variability
- **optical polarisation**
- spectral energy distribution



SPECTRAL ENERGY DISTRIBUTION



Models of blazar emission

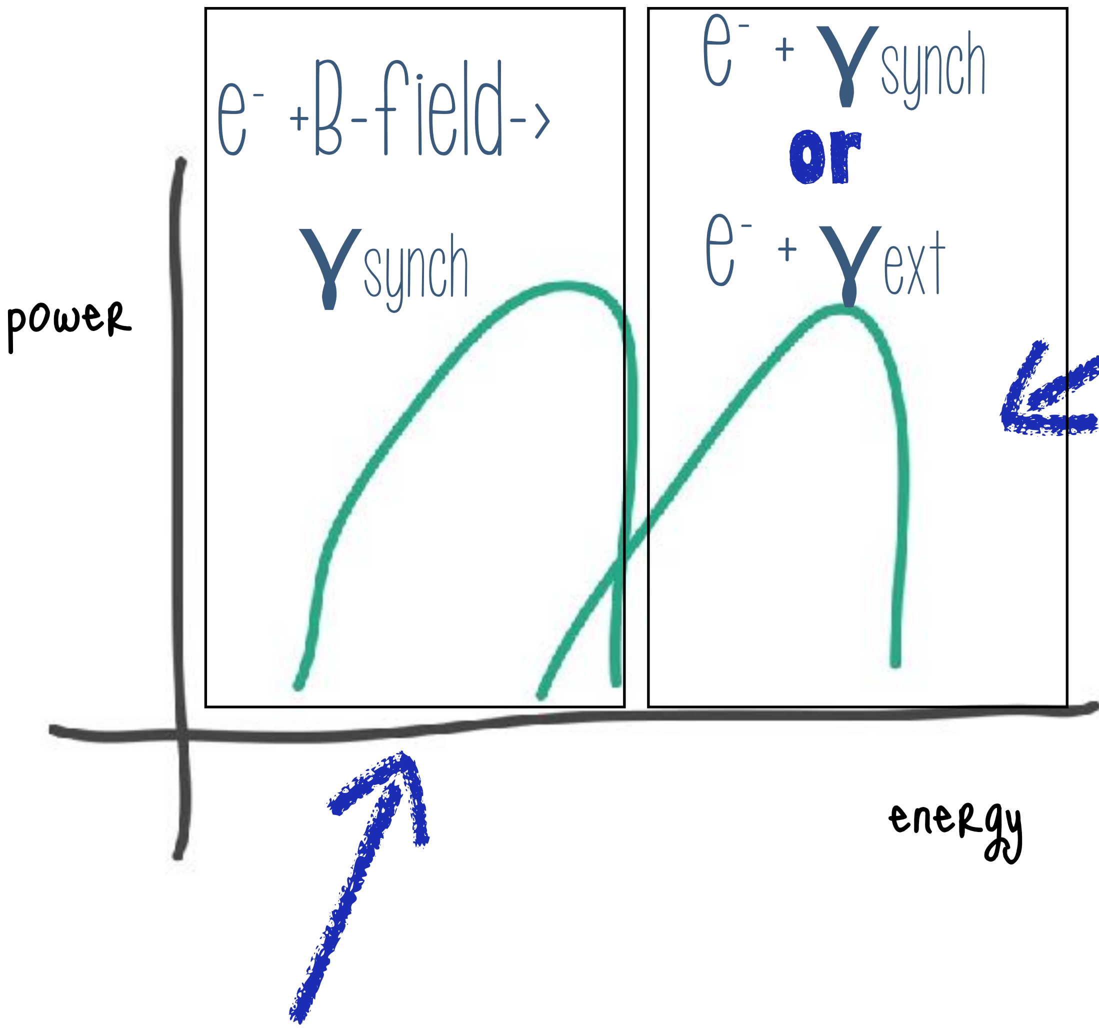


Two fundamentally different approaches to explain the higher energy emission

- Leptonic & Hadronic

Lower energy emission due to synchrotron emission from relativistic e^-s in the jet

Models of blazar emission



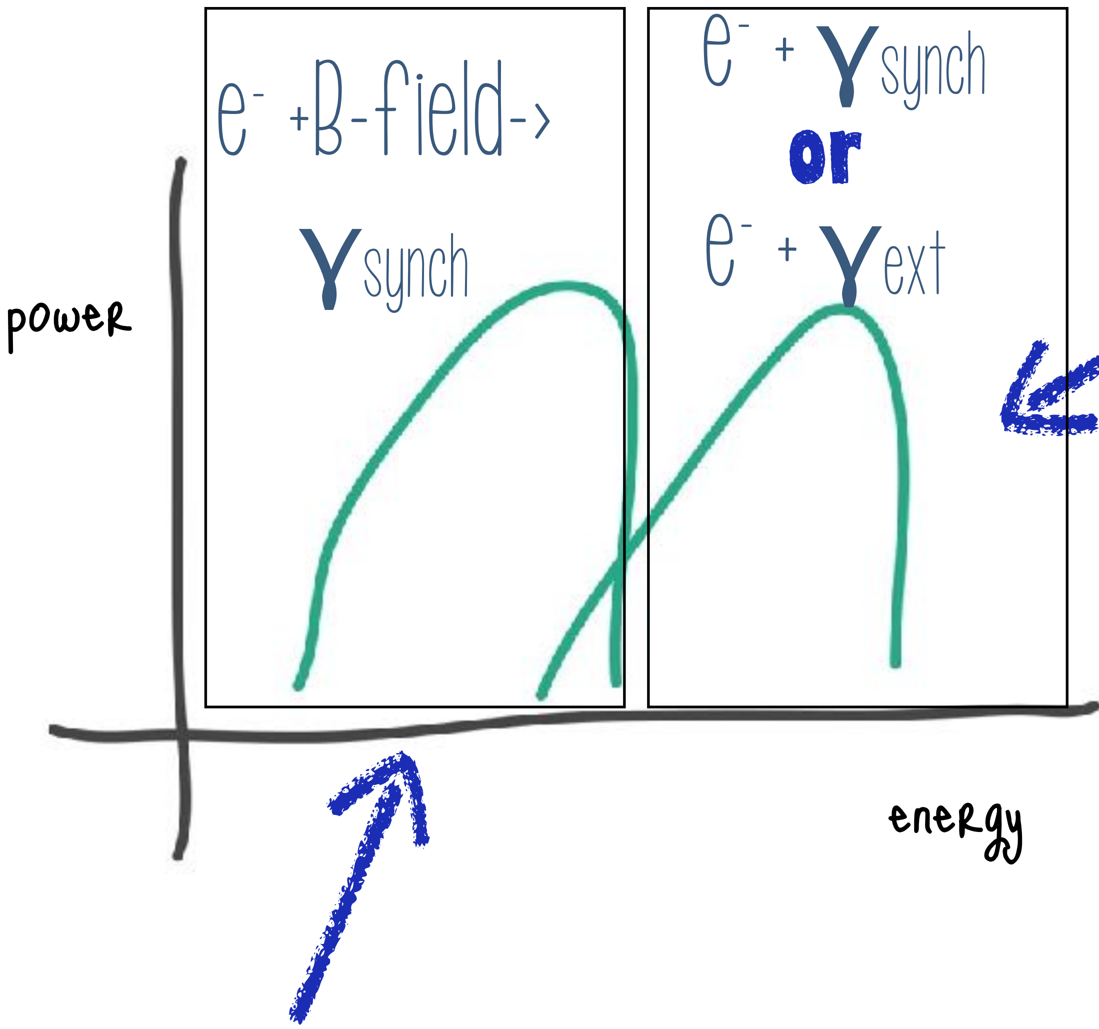
Lower energy emission due to synchrotron emission from relativistic e⁻s in the jet

Two fundamentally different approaches to explain the higher energy emission

- Leptonic & Hadronic

- radiative output dominated by e⁻/e⁺
- e⁻s that produced the synchrotron upscatter photons - which photons?
  - the low-energy photons responsible for first bump
    ➡ synchrotron self-Compton
  - photons from broad-line region, disc, torus ...
    ➡ external Compton

Models of blazar emission



Two fundamentally different approaches to explain the higher energy emission

- Leptonic & **Hadronic**

Lower energy emission due to synchrotron emission from relativistic e⁻s in the jet

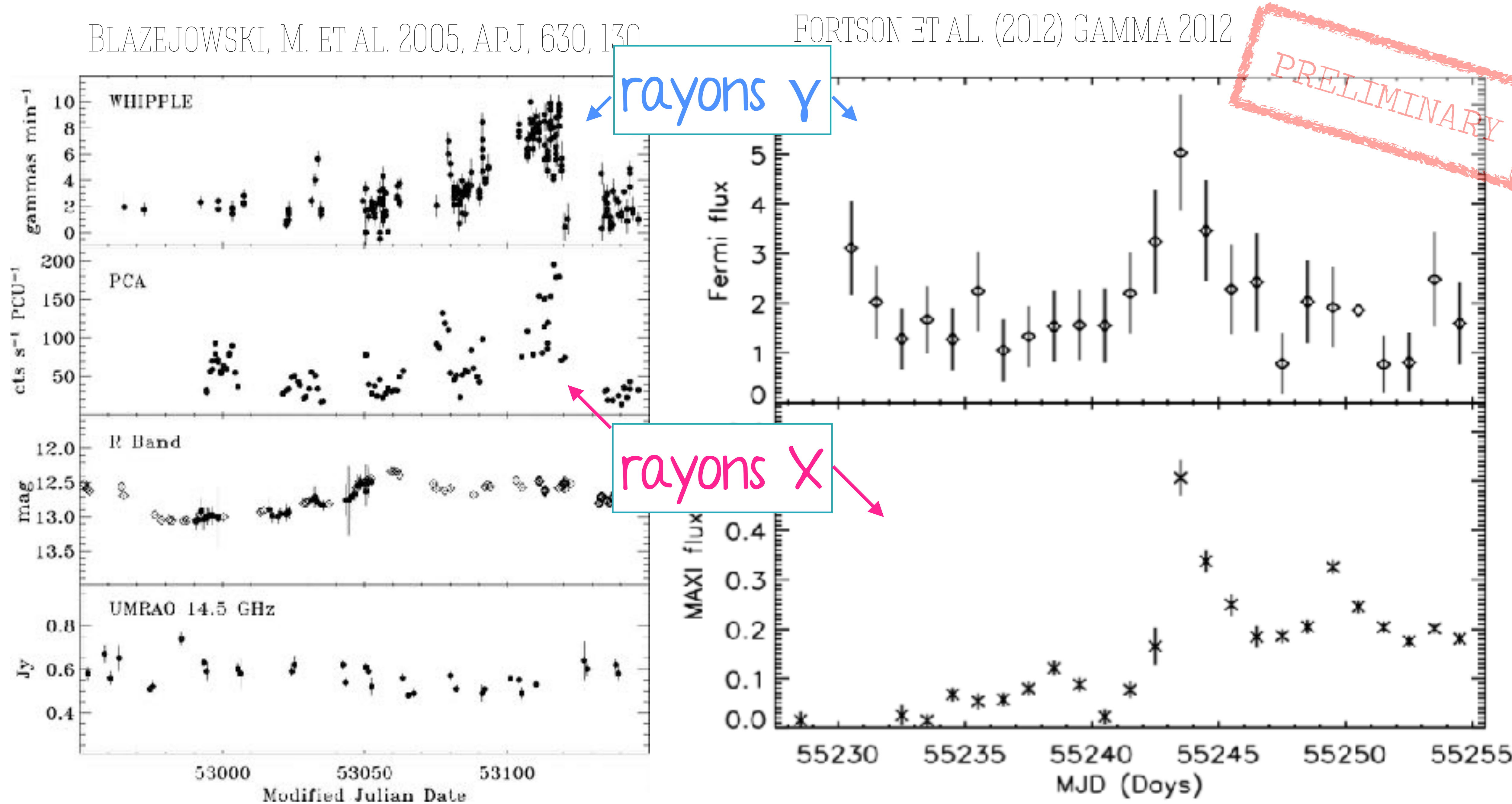
- both e^-/e^+ and p accelerated to ultra-relativistic energies
- p's exceed threshold for pγ photo-pion production on soft photon field in emission region
- high energy emission dominated by
  - ➡ proton synchrotron
  - ➡ π^0 decay photons
  - ➡ synchrotron and Compton emission from charged pions, muons

Boettcher, M. (2012) Fermi & Jansky, astro-ph/1205.0539
Boettcher M. (2013), ApJ 768, 54, astro-ph/1304.0605

- leptonic models provide good fits to many blazars
- **X-ray and gamma-ray emission often correlated - a fact naturally explained by SSC models**

Blazejowski, M. et al. 2005, ApJ, 630, 130

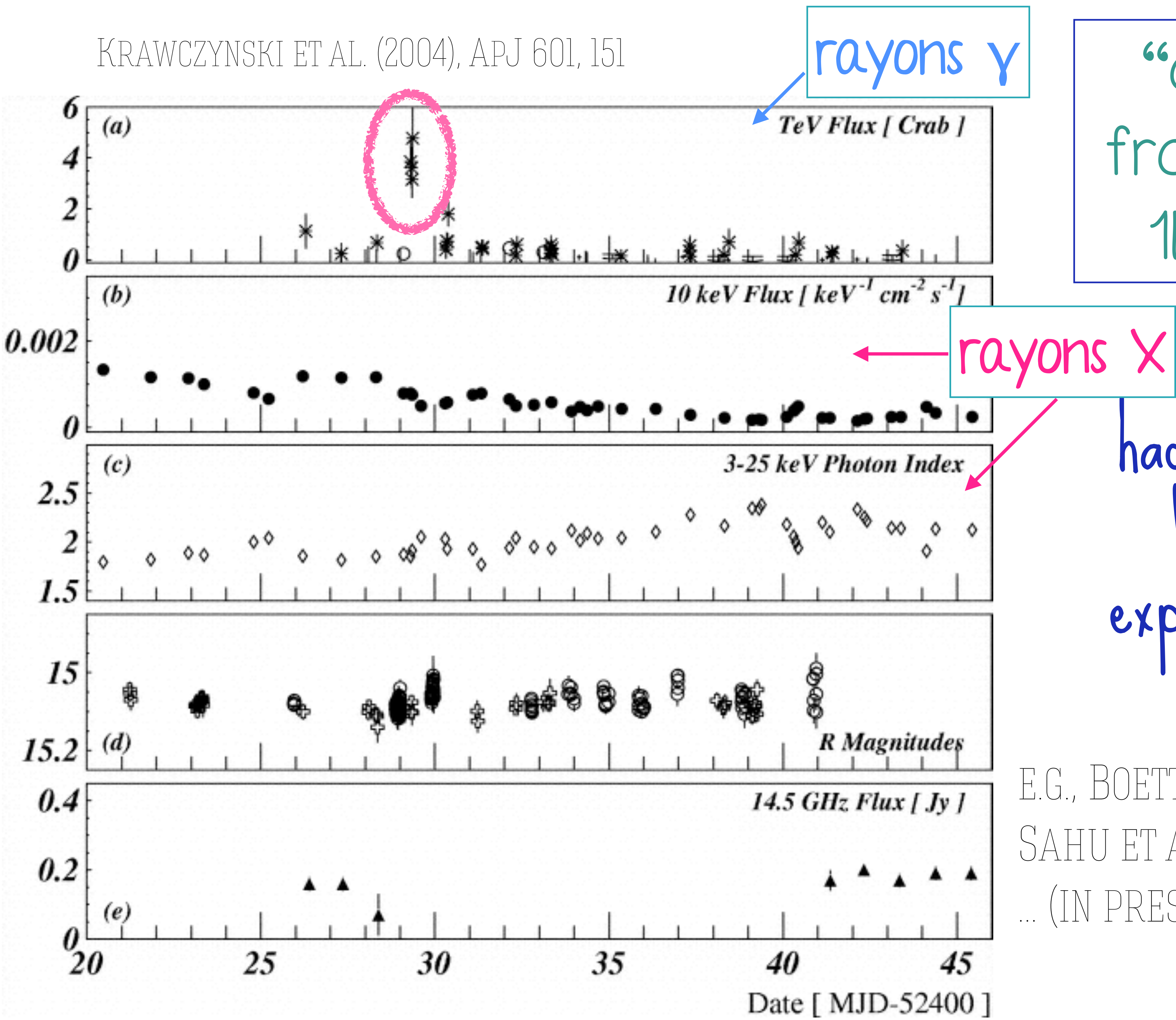
Fortson et al. (2012) Gamma 2012



Extragalactic Physics: Blazars

Models of blazar emission

Krawczynski et al. (2004), ApJ 601, 151

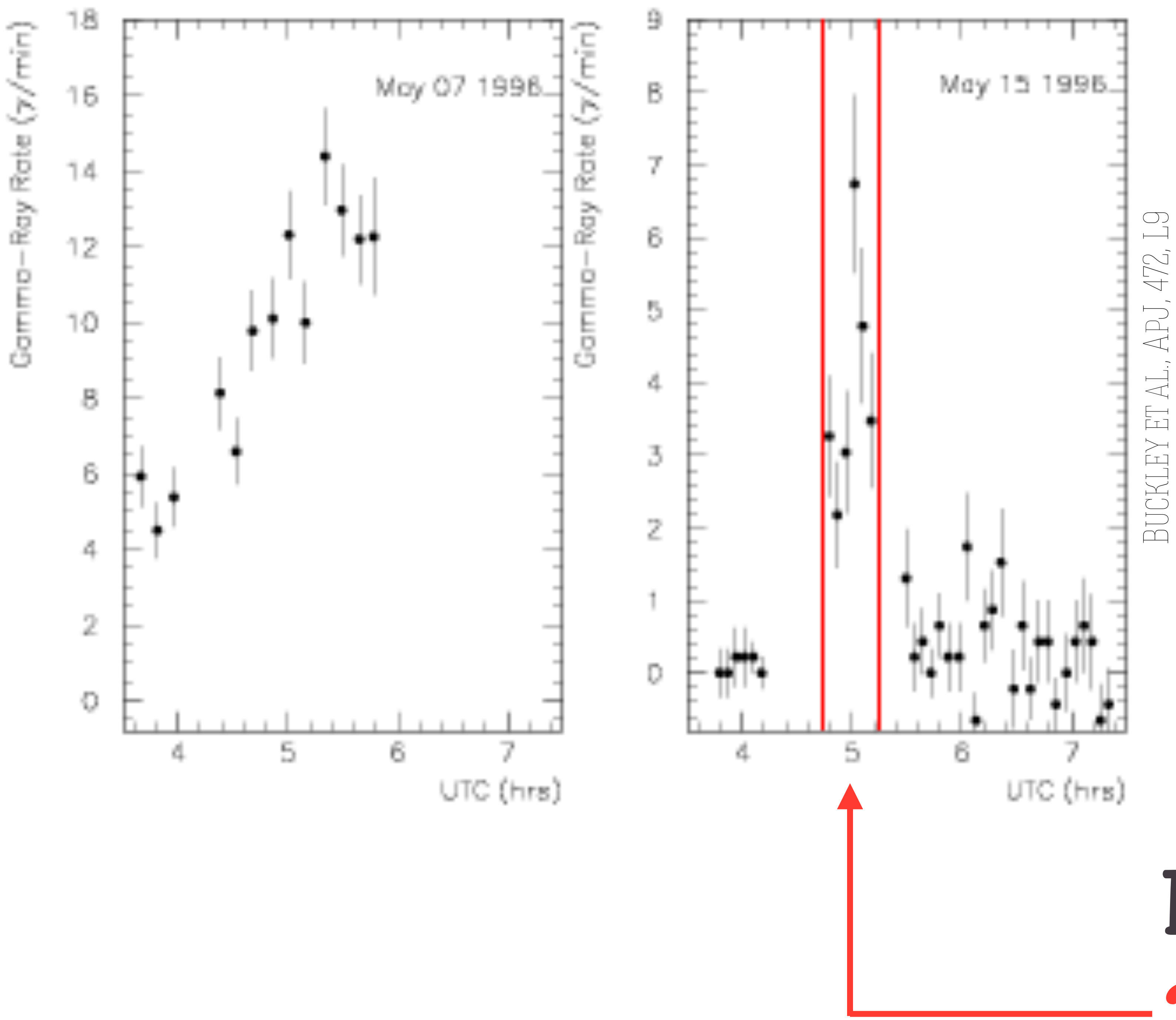


"orphan" flare from TeV blazar, 1ES 1959+650

hadronic models have been invoked to explain this behaviour

E.G., Boettcher (2005), ApJ, 621, 176
Sahu et al. (2013), Phys. Rev. D
... (in press) astro-ph/1305.4985

VARIABILITY

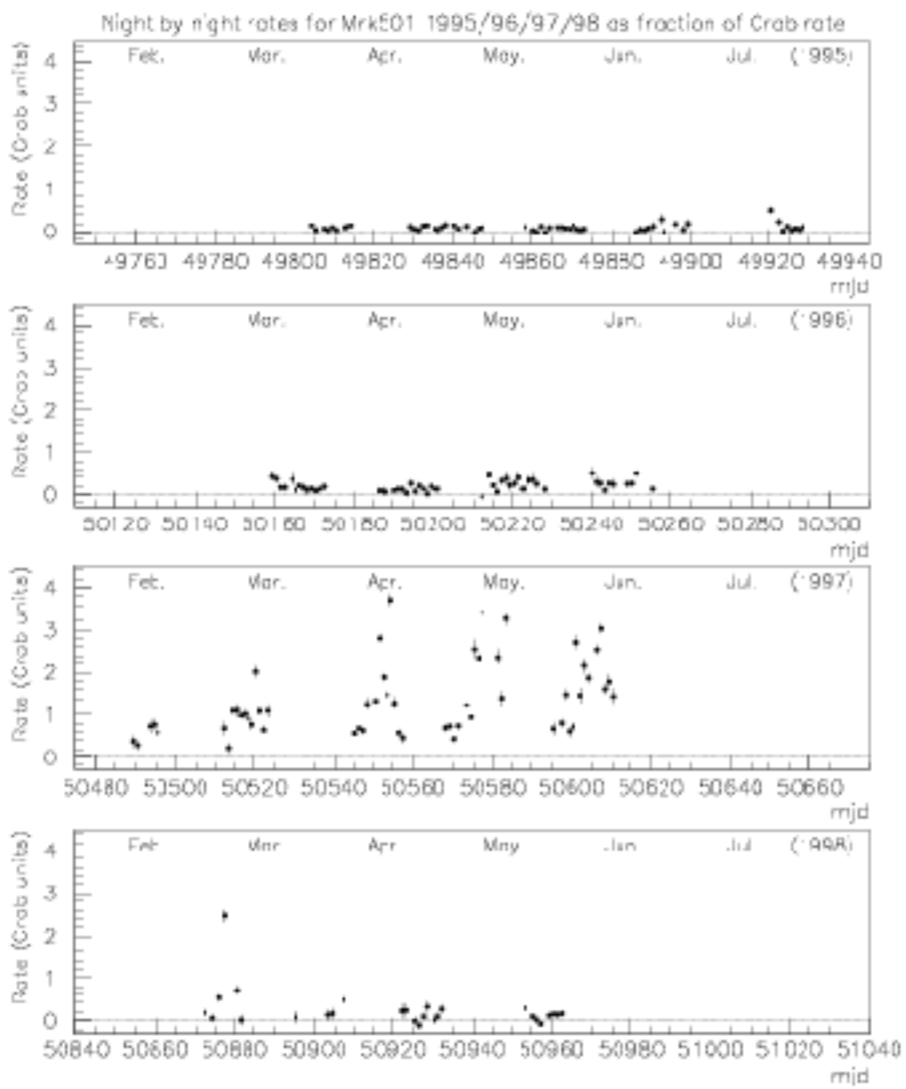


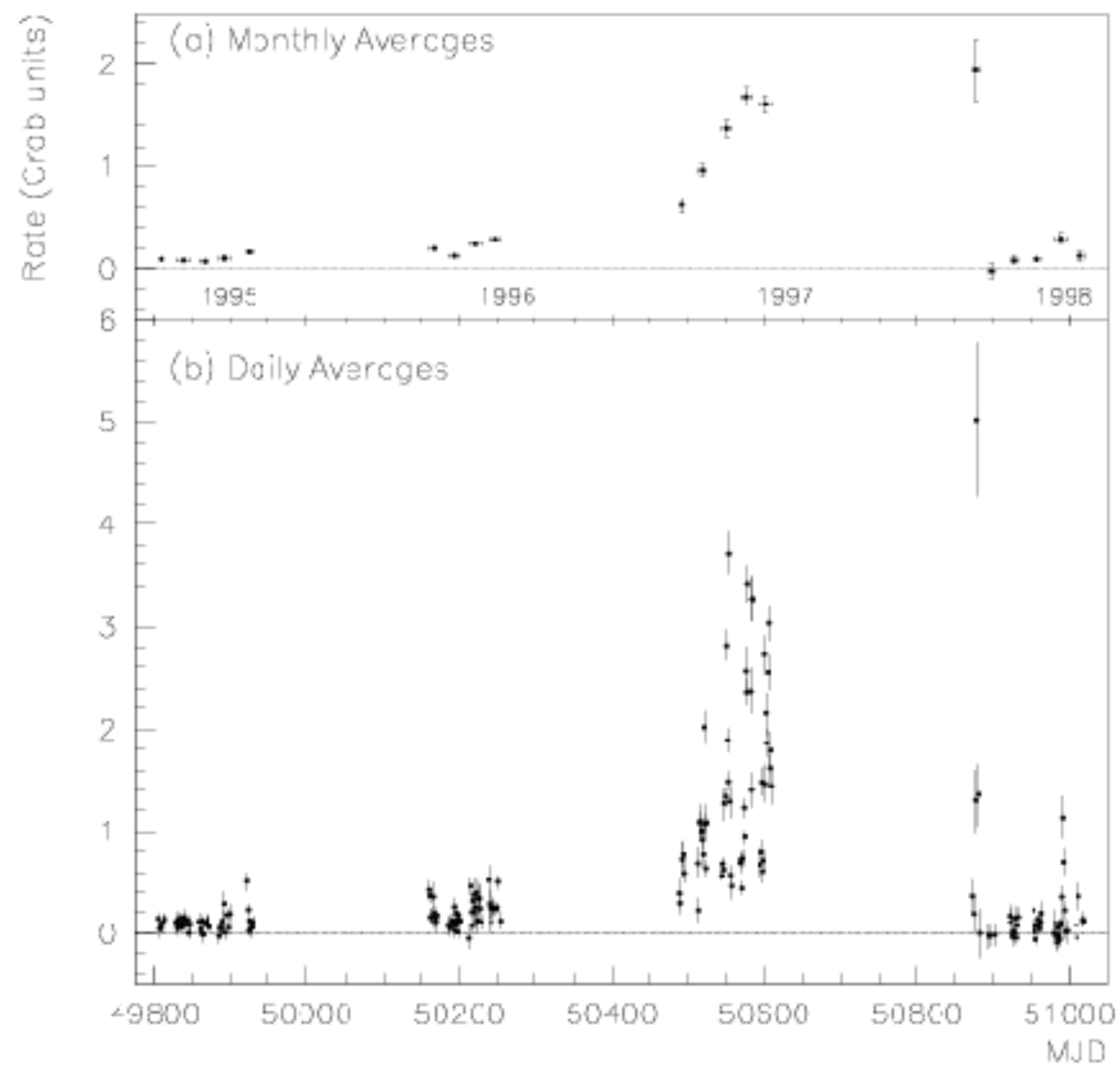
Markarian 421

20 minute erruption

BH mass: ~ 10^9 M_{sun}

VARIABILITY





QUINN ET AL., APJ, 518, 693 (1999)

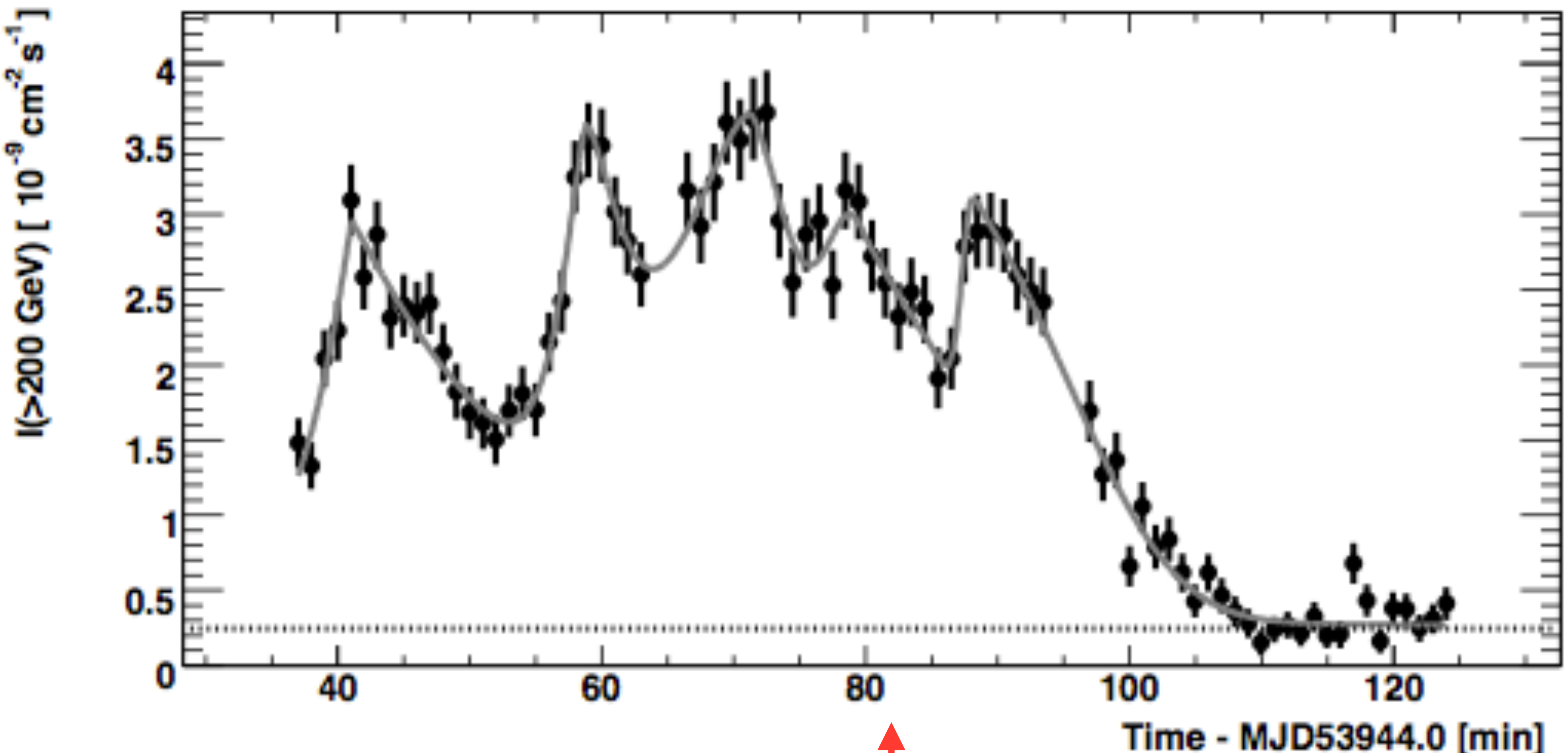
Markarian 501

Emission states change

BH mass: ~ 0.9 - 3.4 x 10^9 M_{sun}

Extragalactic Physics: Blazars

VARIABILITY



AHARONIAN ET AL. (2007), APJ, 730, L8

PKS 2155-304

1-minute time bins

BH mass: ~ 10^9 M_{sun}

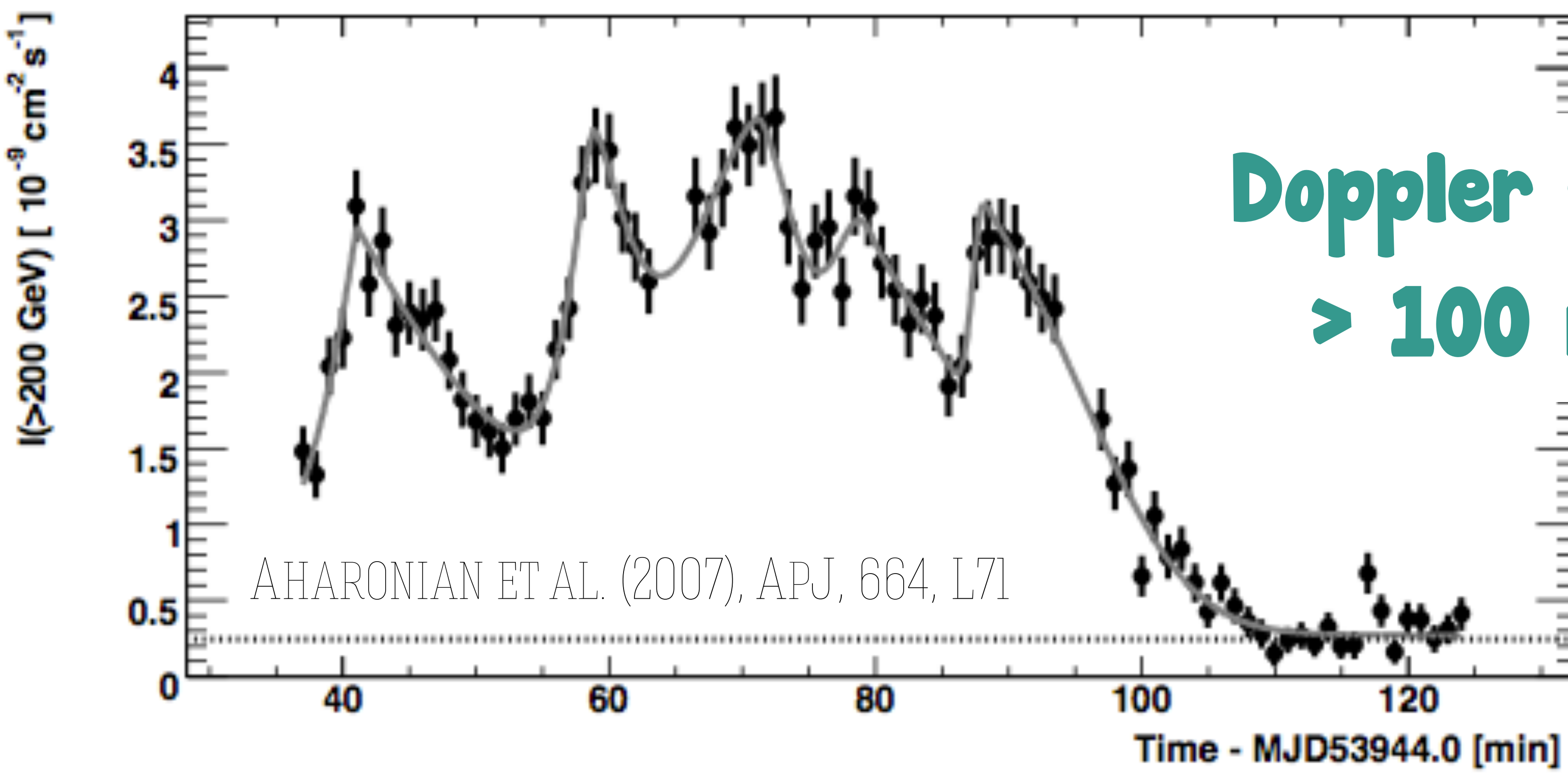
Extragalactic Physics

Extra slide: I did not show this in the presentation. Added it so that you have more background information

VARIABILITY

- leptonic models provide good fits to many blazars
- **X-ray and gamma-ray emission often correlated - a fact naturally explained by SSC models**
- in hadronic models, the cooling times are longer, which makes it more difficult to explain the rapid variability often seen in blazars

➡ proton synchrotron can produce rapid variability with very high energy protons in extremely magnetised, compact regions Holder, J. (2012), Astropart. Phys., 39, 61



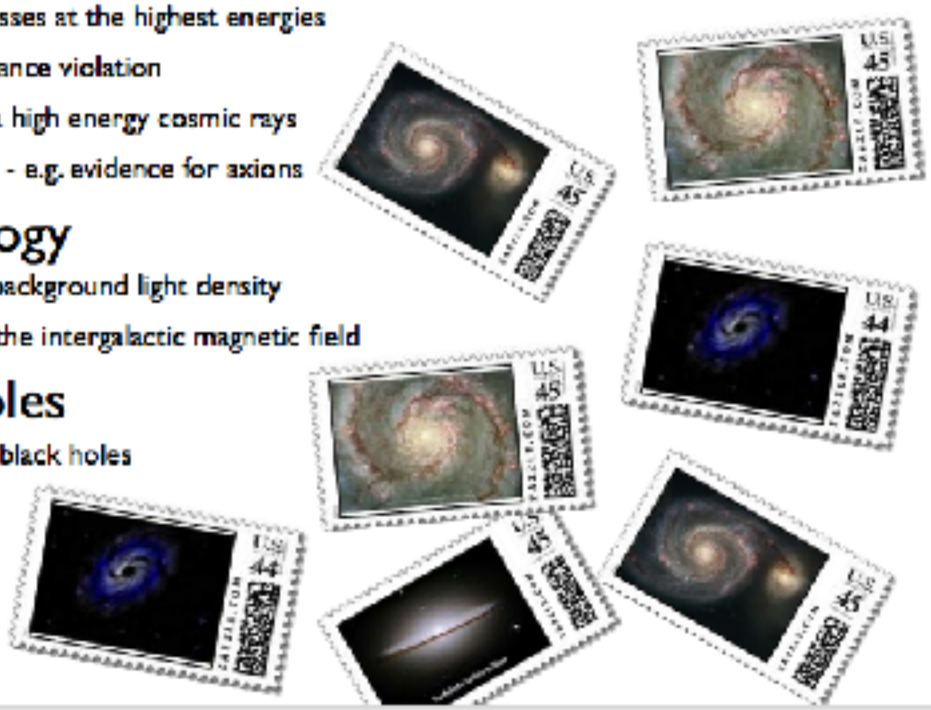
Doppler factors of > 100 required

Extragalactic Physics: Active Galactic Nu

AMY FURNISS TALK (VERITAS 10-YEAR CELEBRATION

The Ever Present Question: Why Observe Extragalactic Sources with VERITAS?

- Particle Physics and Fundamental Laws
  - Particle processes at the highest energies
  - Lorentz invariance violation
  - Origin of ultra high energy cosmic rays
  - Exotic physics - e.g. evidence for axions
- Cosmology
  - Extragalactic background light density
  - Magnitude of the intergalactic magnetic field
- Black holes
  - Supermassive black holes
  - Jet physics
  - Evolution



For a summary of some of the open questions in blazar research, see Amy Furniss' talk at VERITAS 10-year celebrations: http://veritasj.sao.arizona.edu/10Years/Speakers.html

AMY FURNISS TALK (VERITAS 10-YEAR CELEBRATION

10 Years to Address Fundamental Questions

- What types of galaxies produce gamma-ray emission?
- Where does the gamma-ray emission originate within radio galaxies and blazars?
- How is the gamma-ray emission produced within these sources?
- Is there any pattern or mode to the variability of the gamma-ray emission from these sources?
- How is the gamma-ray emission related to the lower-energy emission emerging from these sources?
- How do the spectral signatures of these sources change as the sources evolve?
- What is the astrophysical origin of ultra-high-energy cosmic rays?
- What secondary interactions do gamma rays undergo as they travel extragalactic distances?
- What is the density of the low redshift optical/IR light produced by stars and galaxies?
- What is the magnitude (and origin) or the intergalactic magnetic field?

Galactic Physics:

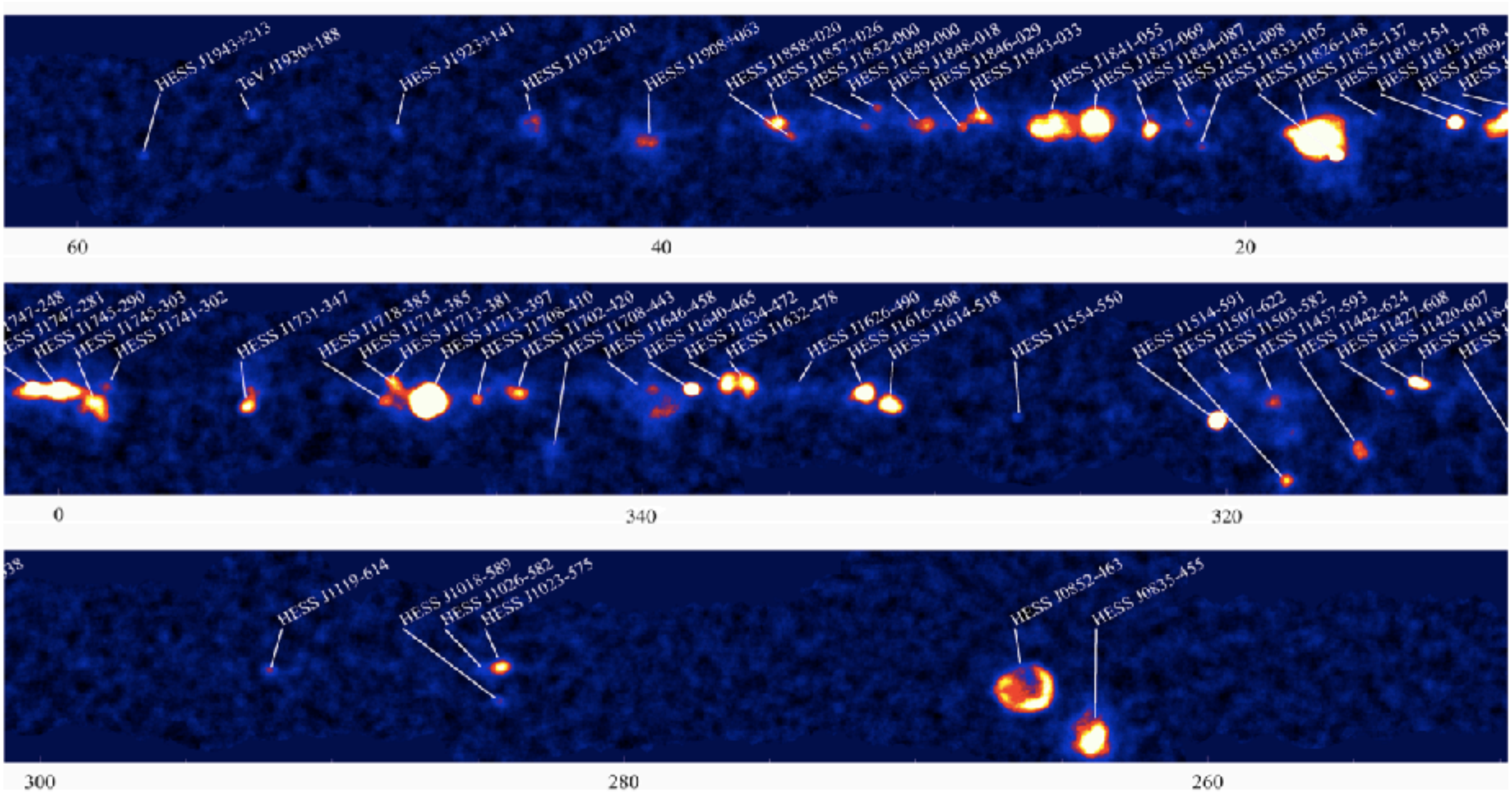
Galactic Physics **2.**

- Pulsar Wind Nebulae
- Supernova Remnants
- Binaries

Galactic Physics: H.E.S.S. Galactic Plane Survey

2005: HESS Sky survey released:

- first published in 2005 with 14 sources … since then has grown to include more than 60 sources*

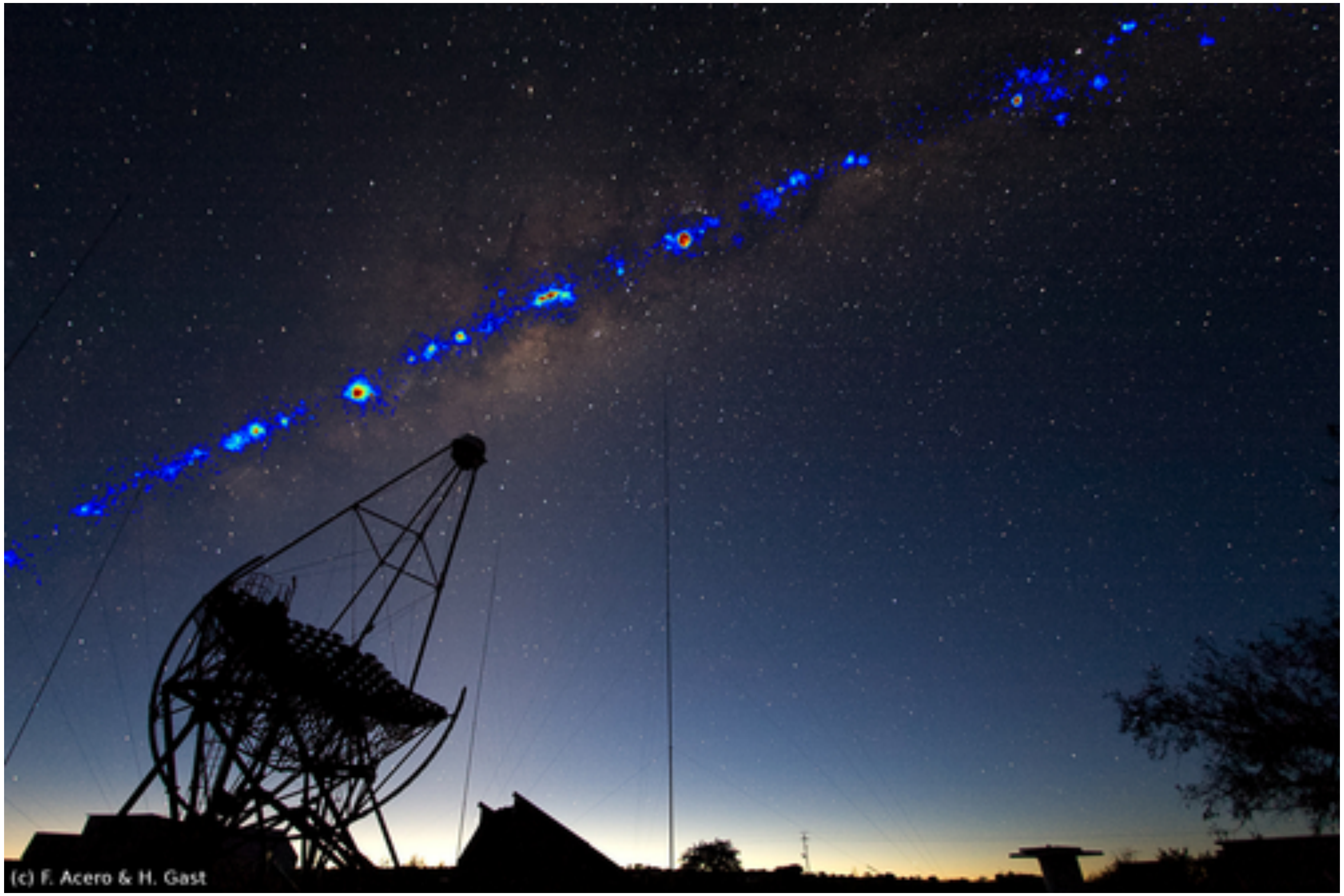


*New results coming soon!

Galactic Physics: H.E.S.S. Galactic Plane Survey

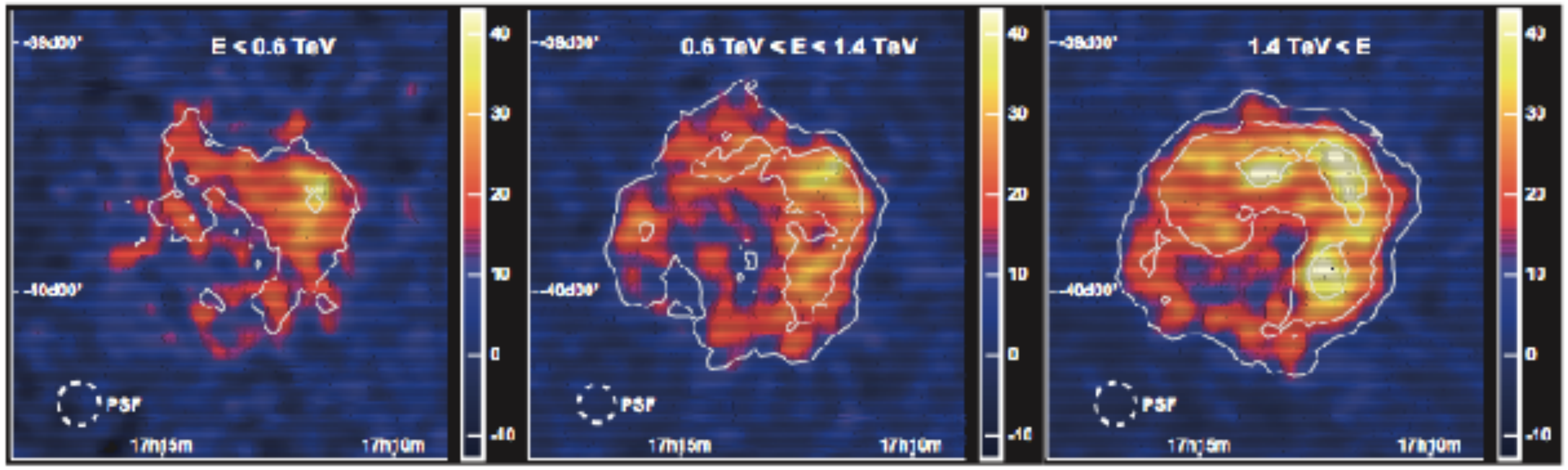
2005: HESS Sky survey released:

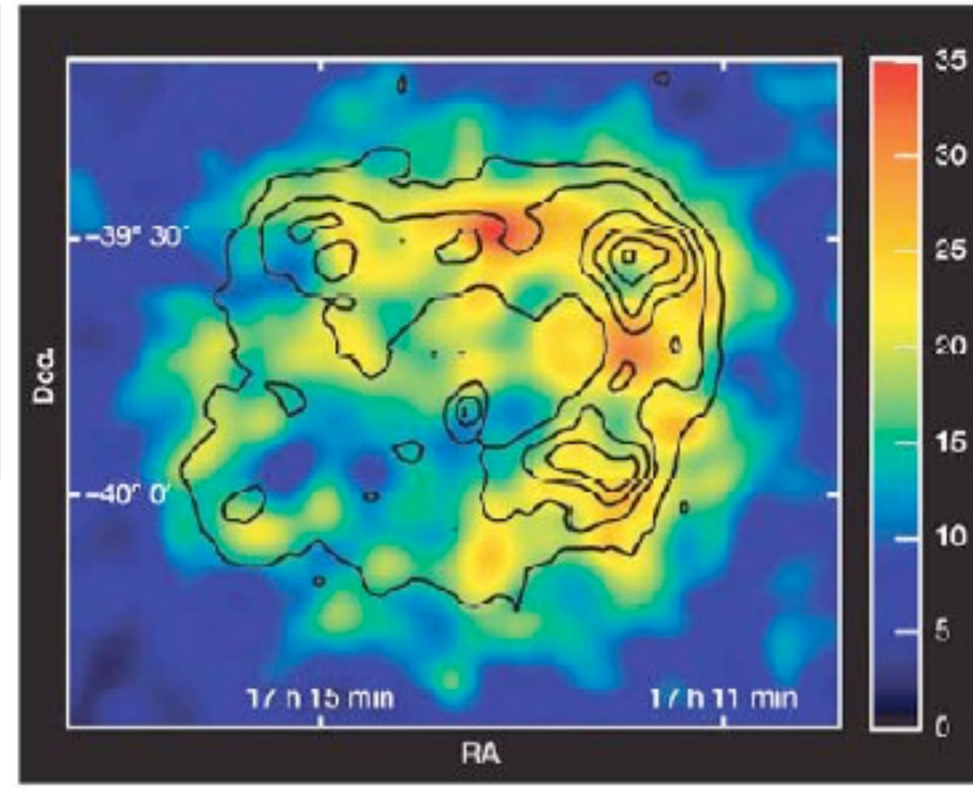
- first published in 2005 with 14 sources … since then has grown to include more than 60 sources*



*New results coming soon!

Galactic Physics: Supernova Remnants & Pulsar wind nebulae





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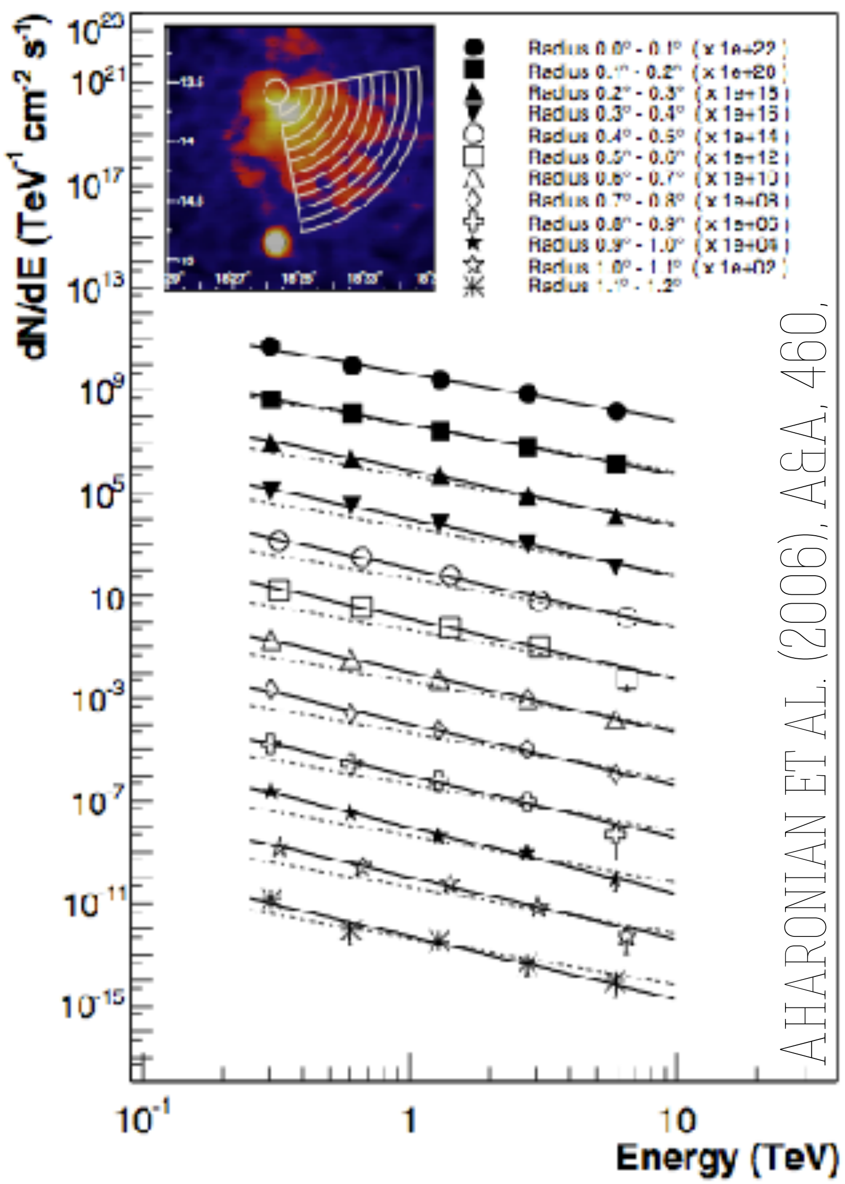


AHARONIAN ET AL. (2006), A&A, 460,

Morphological studies of RXJ1713.7-3946 &

HESS J1825-137

- spectra were derived for different energy bands

energy dependant morphology at TeV energies

Galactic Physics: A Pevatron at the Galactic Centre

10^{15} eV

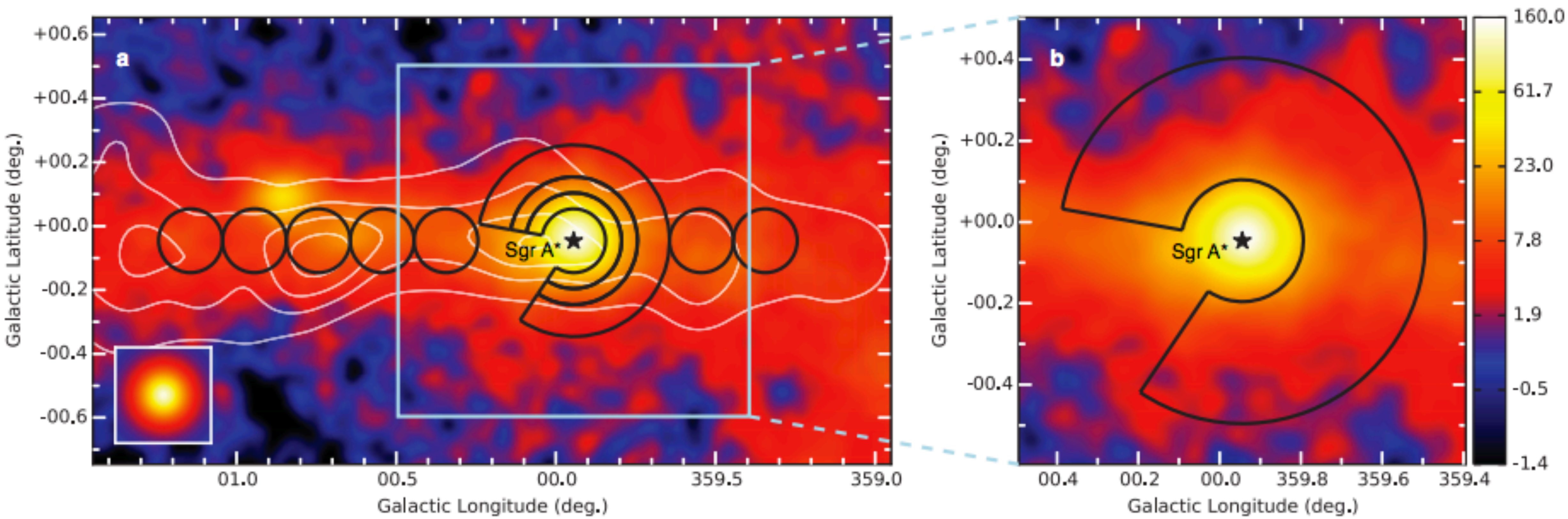
= CERN x 1000 !!

Galactic Physics: A PeVatron 10^{15} eV e Galactic Centre

It can be shown that galactic accelerators can accelerate particles to energies of ~10^{13} eV

HESS Collaboration (2016), Nature, 531, 476-479

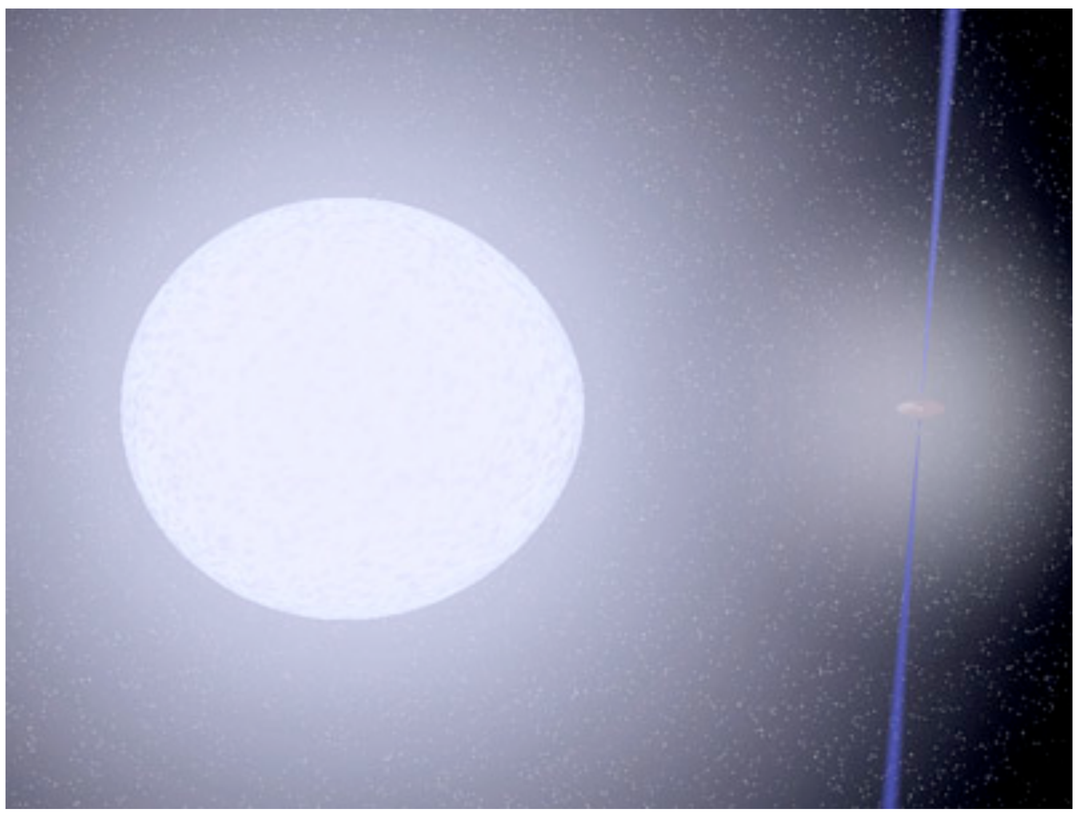
- The H.E.S.S. Collaboration carried out deep observations of the Galactic Centre
- They found evidence for particles being accelerated to petaelectronvolt energies
- They propose that the supermassive black hole, Sagittarius A* is linked to this PeVatron

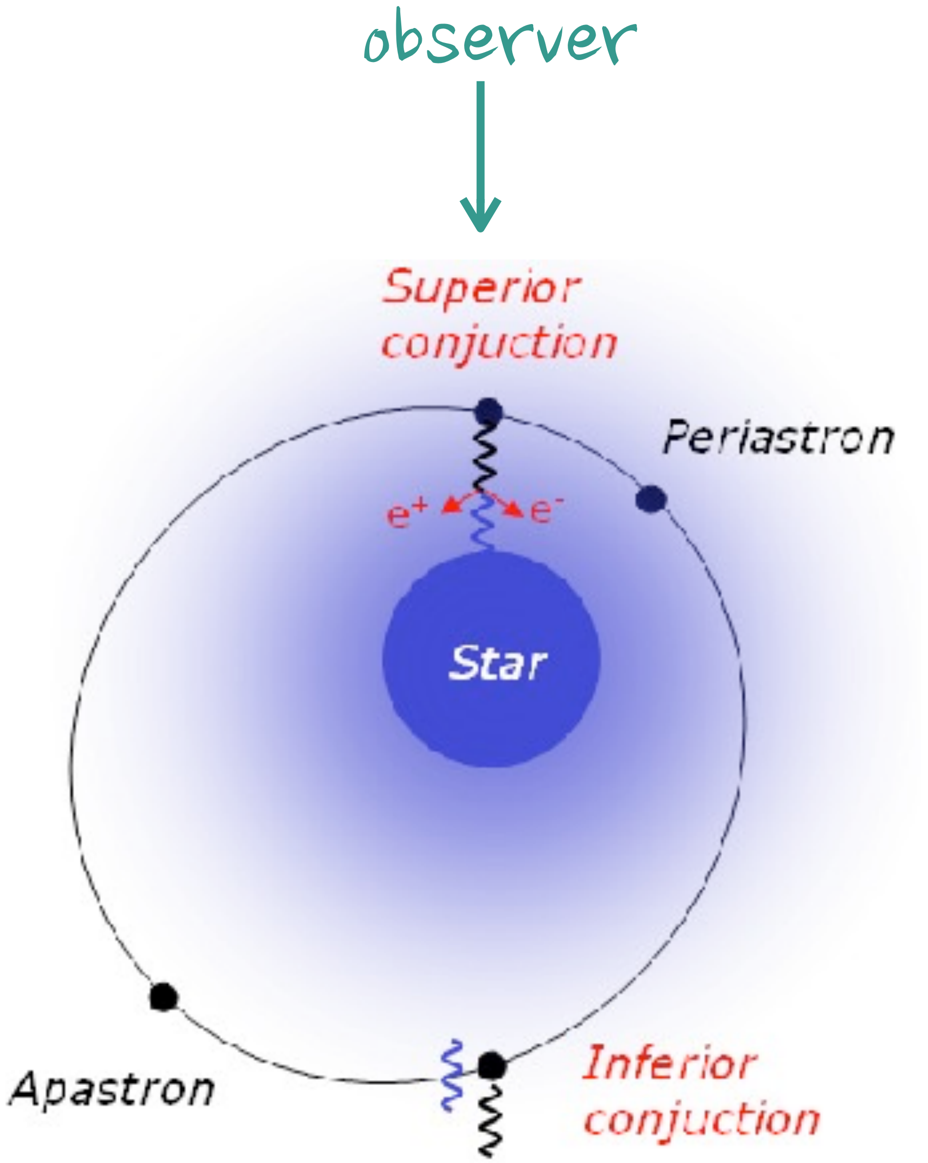


Galactic Physics: Binary systems

LS 5039: the first gamma-ray binary detected – now there are 6 gamma-ray binaries

- orbital period 3.902 +/- 0.005 days
- consists of a compact object (pulsar?) orbiting a massive star
- gamma-ray emission is variable but cyclic





sometimes called microquasars

WWW.MPI-HD.MPG.DE

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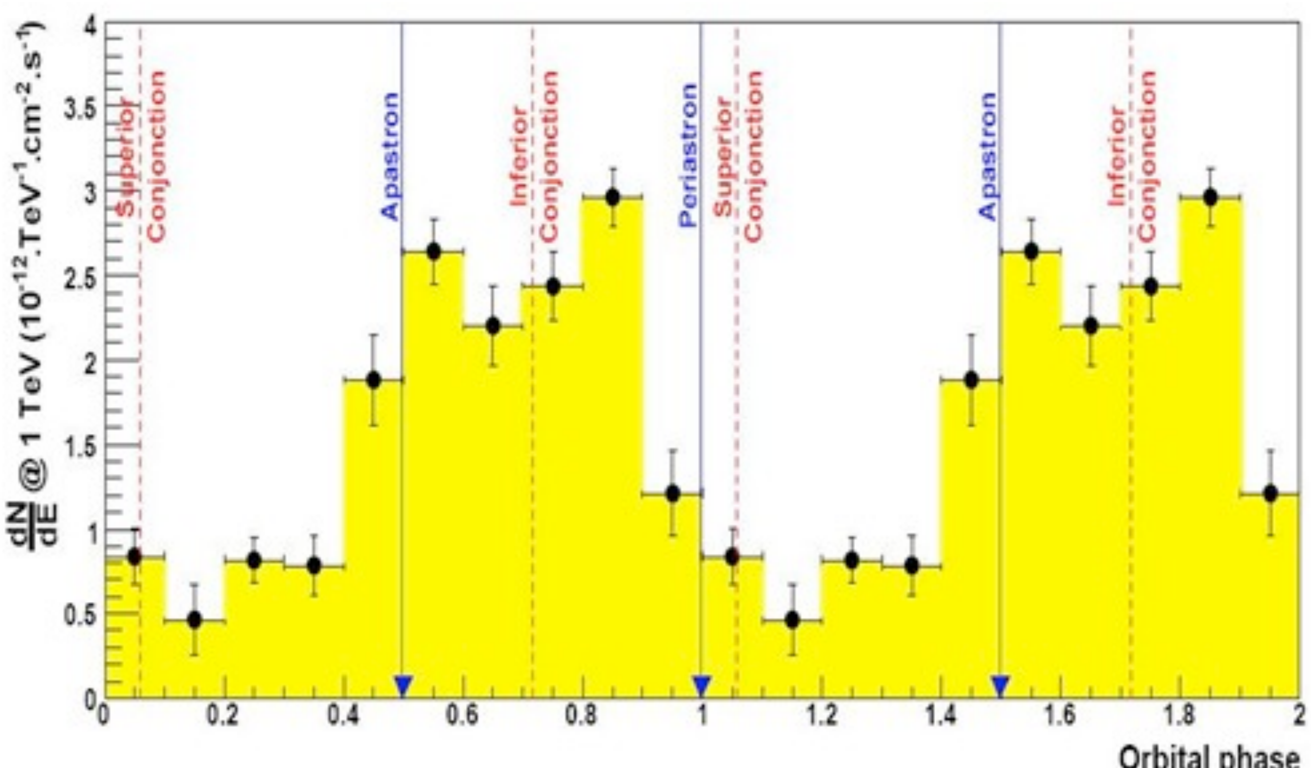
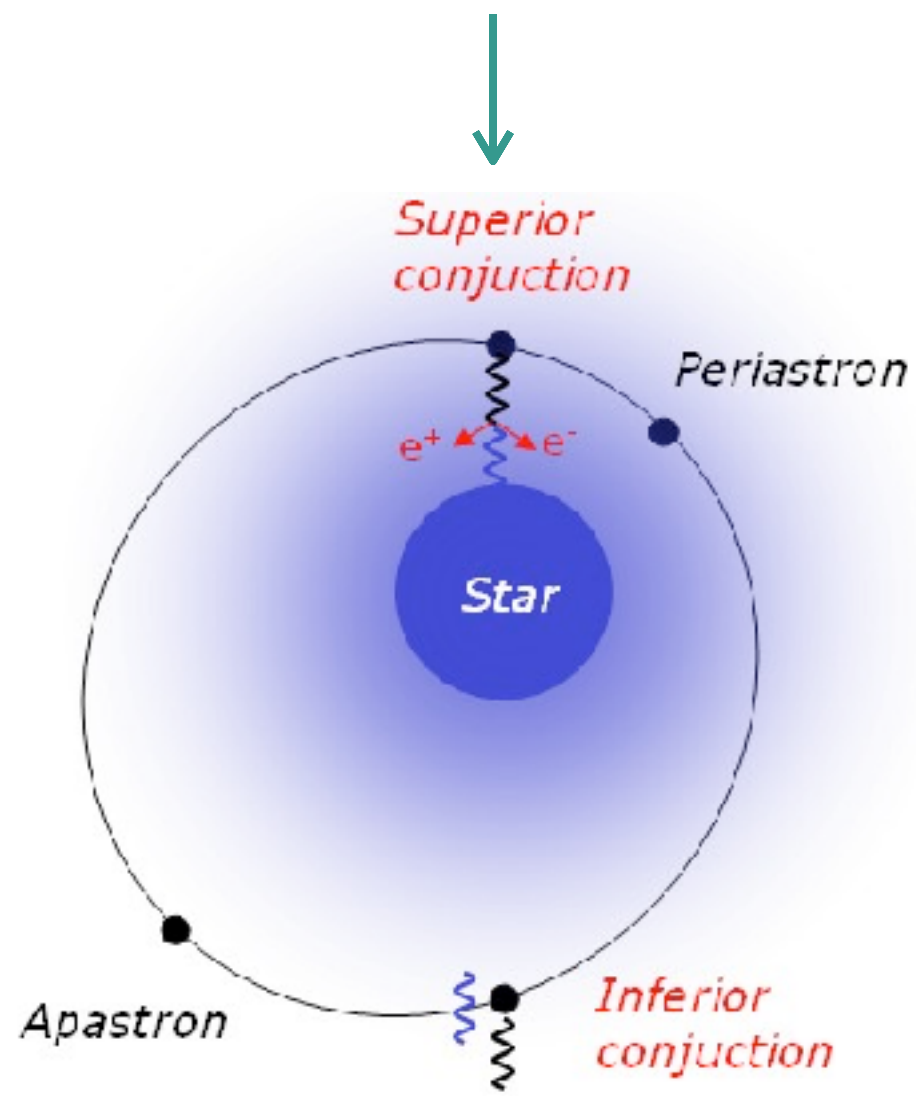


periodicity of signal established (2006)



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Galactic Physics: Binary systems

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- orbital period 3.902 +/- 0.005 days
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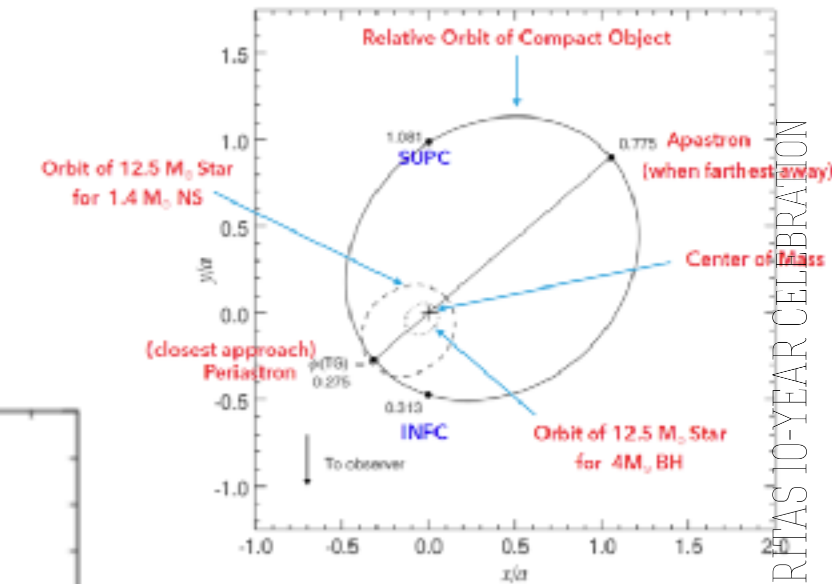
- gamma-ray emission is variable but periodic

but not always consistent!

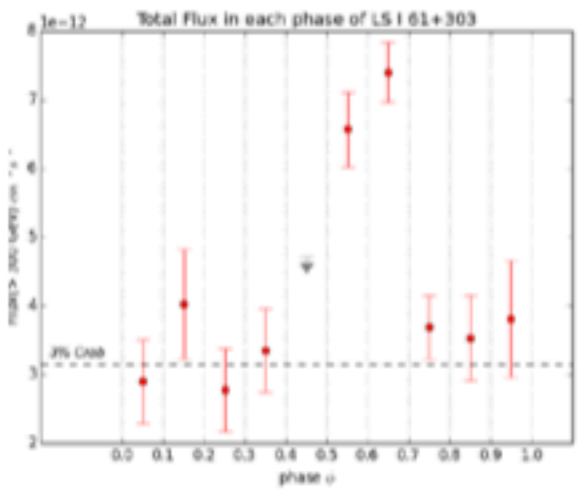
Galactic Physics: Binary systems

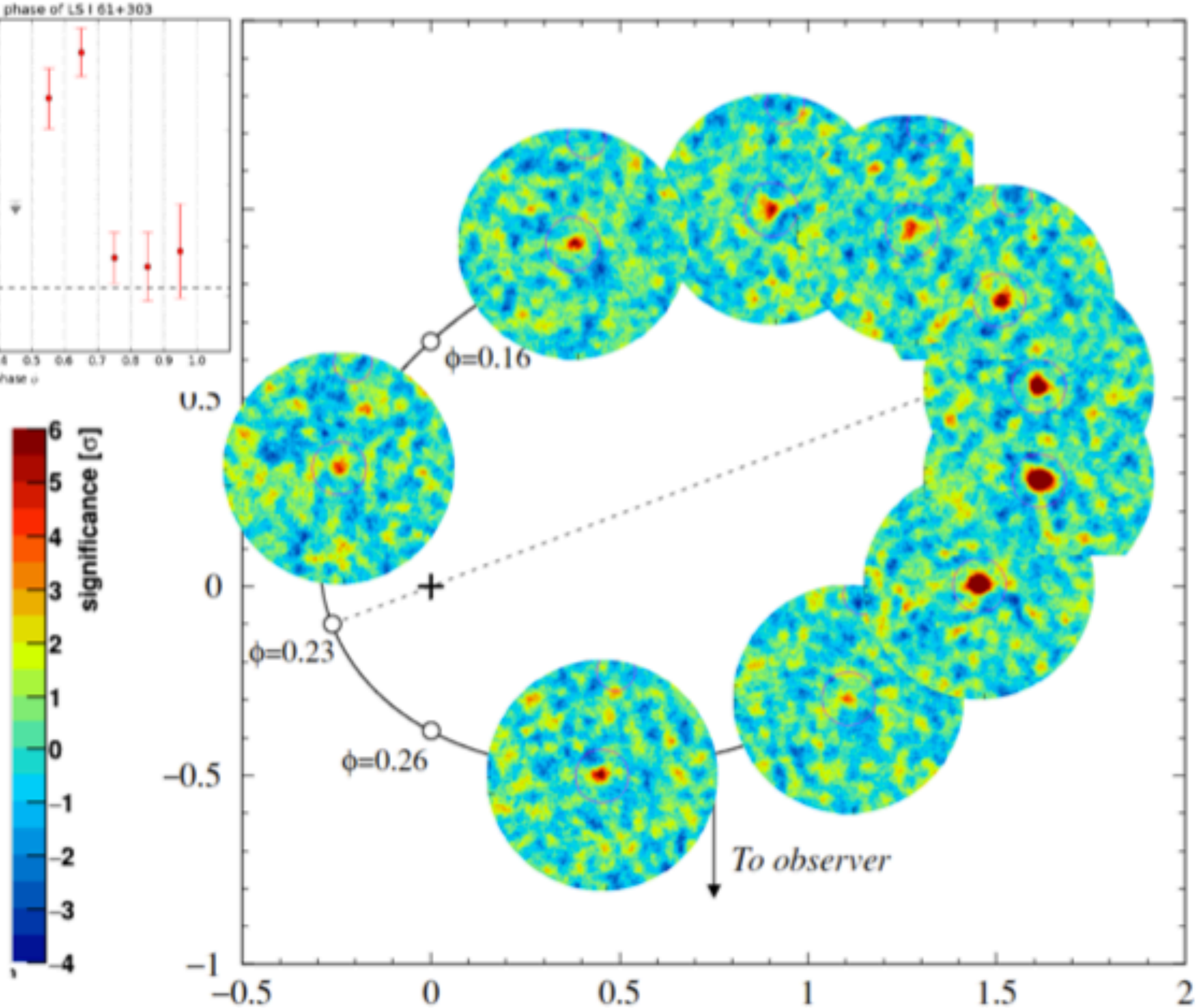
LS I + 61 303 : a compact object and a B0 Ve 25 star

- orbital period 26.6 +/- 0.5 days
- baseline TeV emission seen throughout orbit



MARTIN POHL'S TALK (VERITAS 10-YEAR CELEBRATION





Galactic Physics: Binary systems

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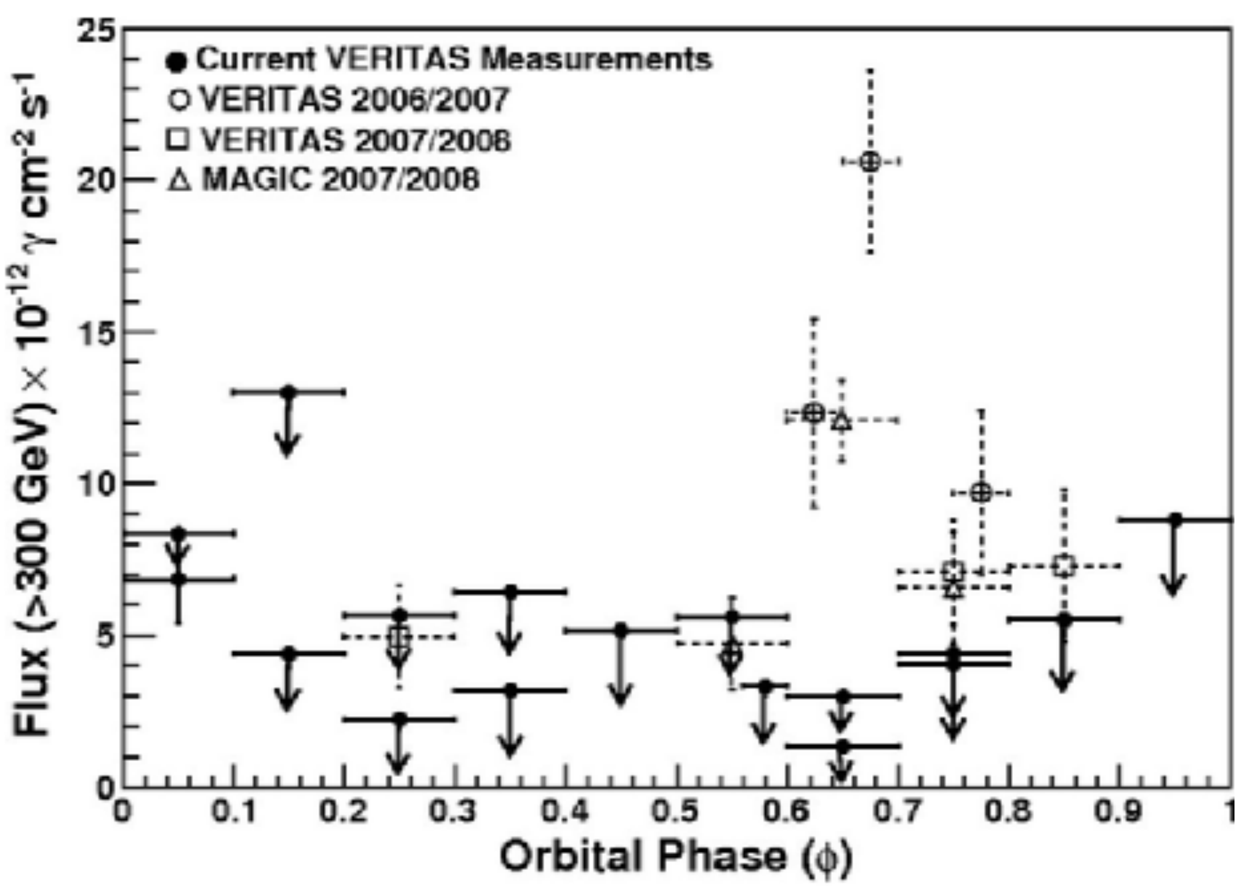
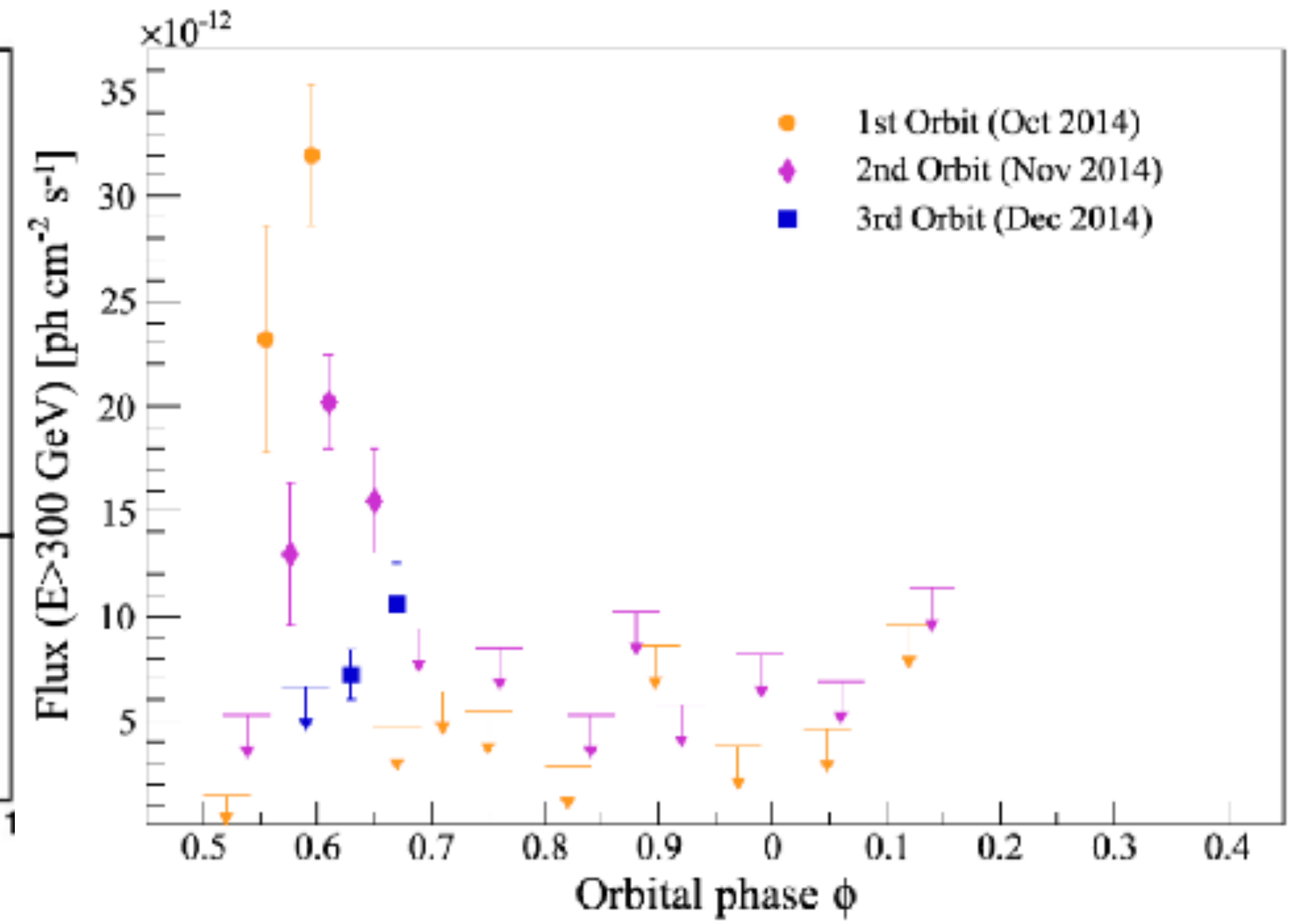
- strong gamma-ray flares in some orbits
- nightly TeV variability



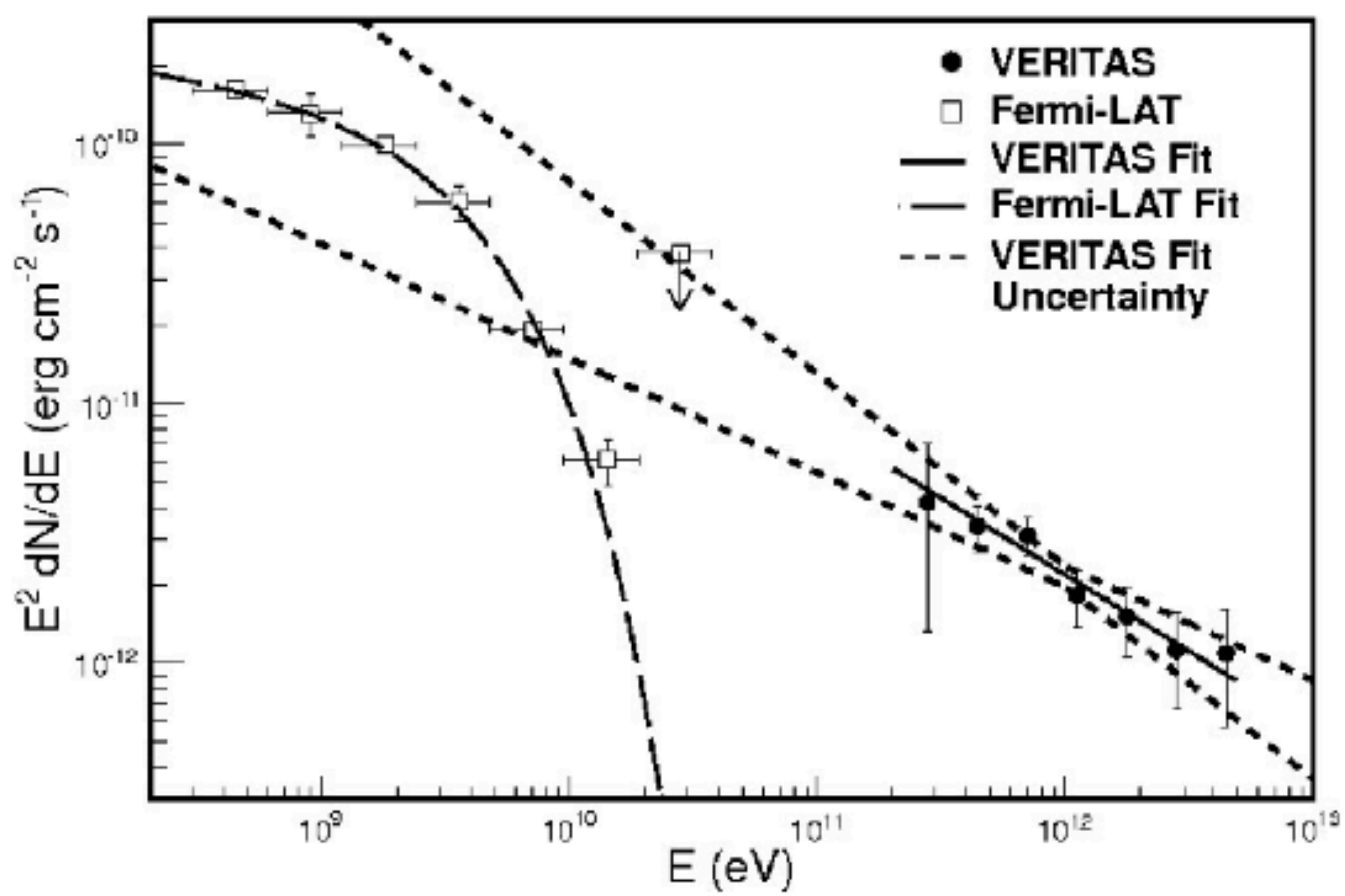


MARTIN POHL'S TALK (VERITAS 10-YEAR CELEBRATION

Galactic Physics: Binary systems

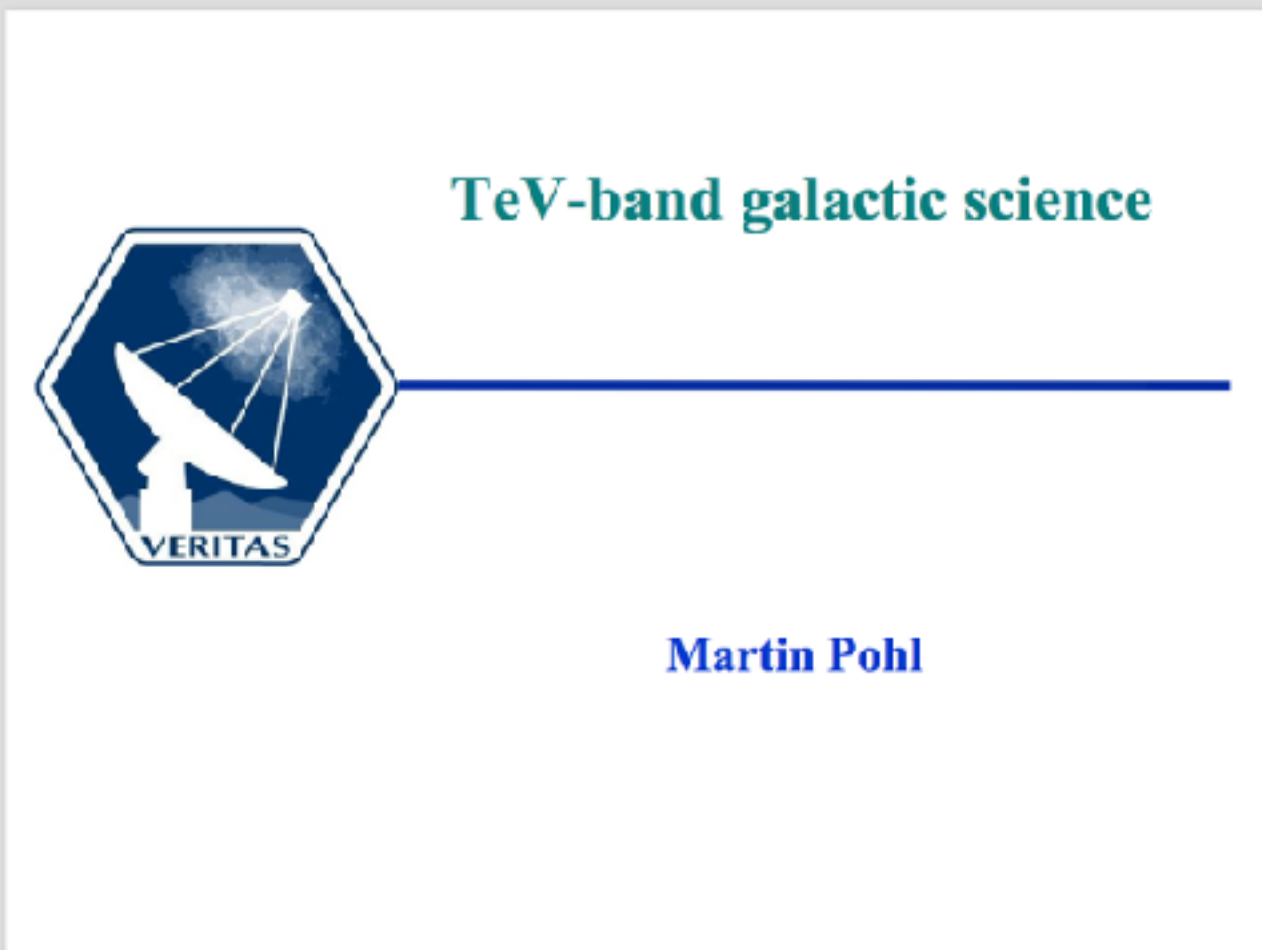
LS I + 61 303 : a compact object and a B0 Ve 25 star

- orbital period 26.6 +/- 0.5 days
- baseline TeV emission seen throughout orbit
- strong gamma-ray flares in some orbits
- nightly TeV variabilitiy
- uncorrelated GeV and TeV emission
- GeV spectrum similar to that of a pulsar



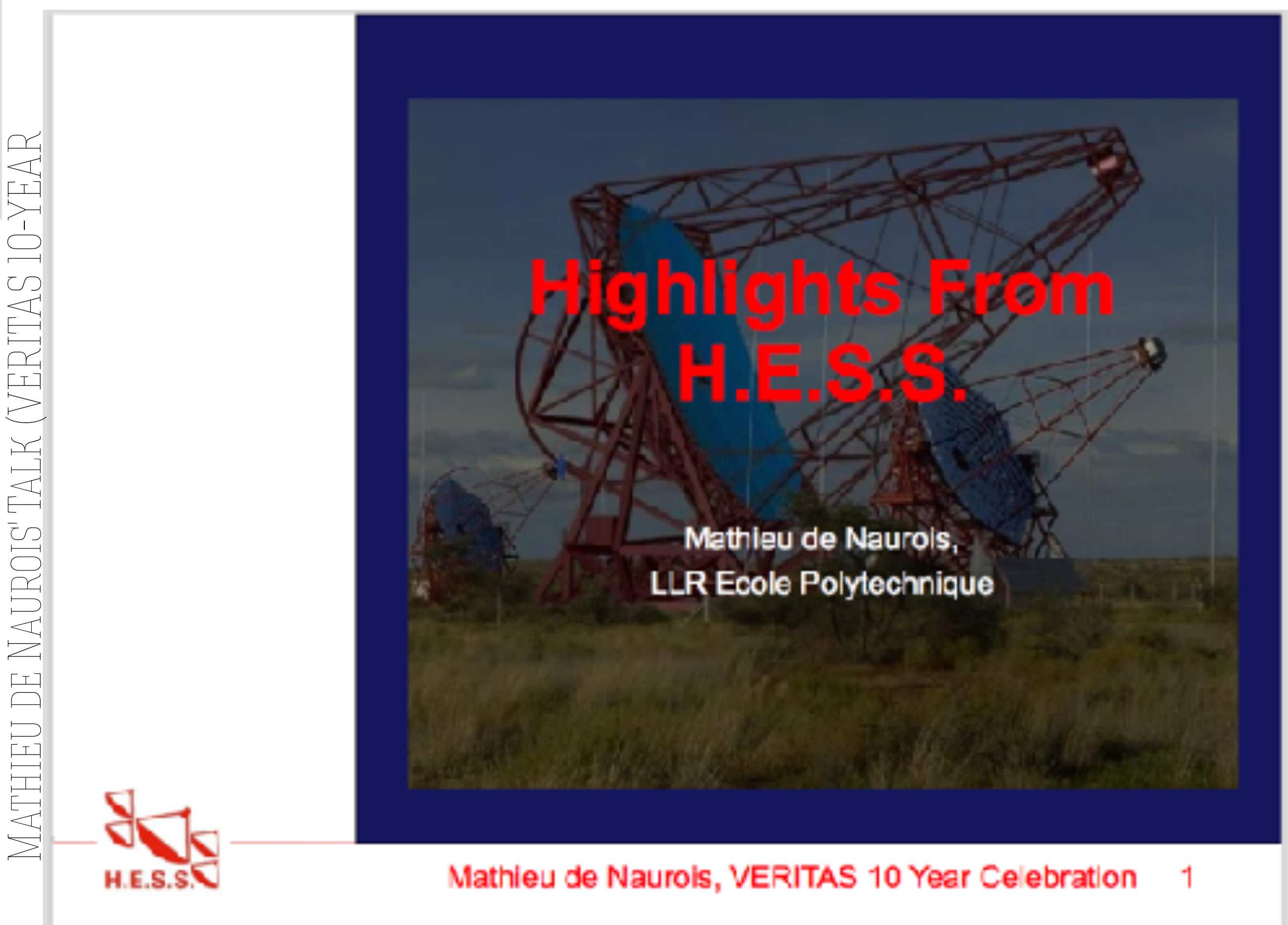
MARTIN POHL'S TALK (VERITAS 10-YEAR CELEBRATION

Galactic Physics: Binary systems



MARTIN POHL'S TALK (VERITAS 10-YEAR CELEBRATION

For more information on galactic astrophysics, see talks of Martin Pohl & Mathieu de Naurois at VERITAS 10-year celebrations: http://veritasj.sao.arizona.edu/10Years/Speakers.html



MATHIEU DE NAUROIS' TALK (VERITAS 10-YEAR

Cosmology

3.

Extragalactic Background Light

Intergalactic Magnetic Fields

Cosmology - Extragalactic Background Light

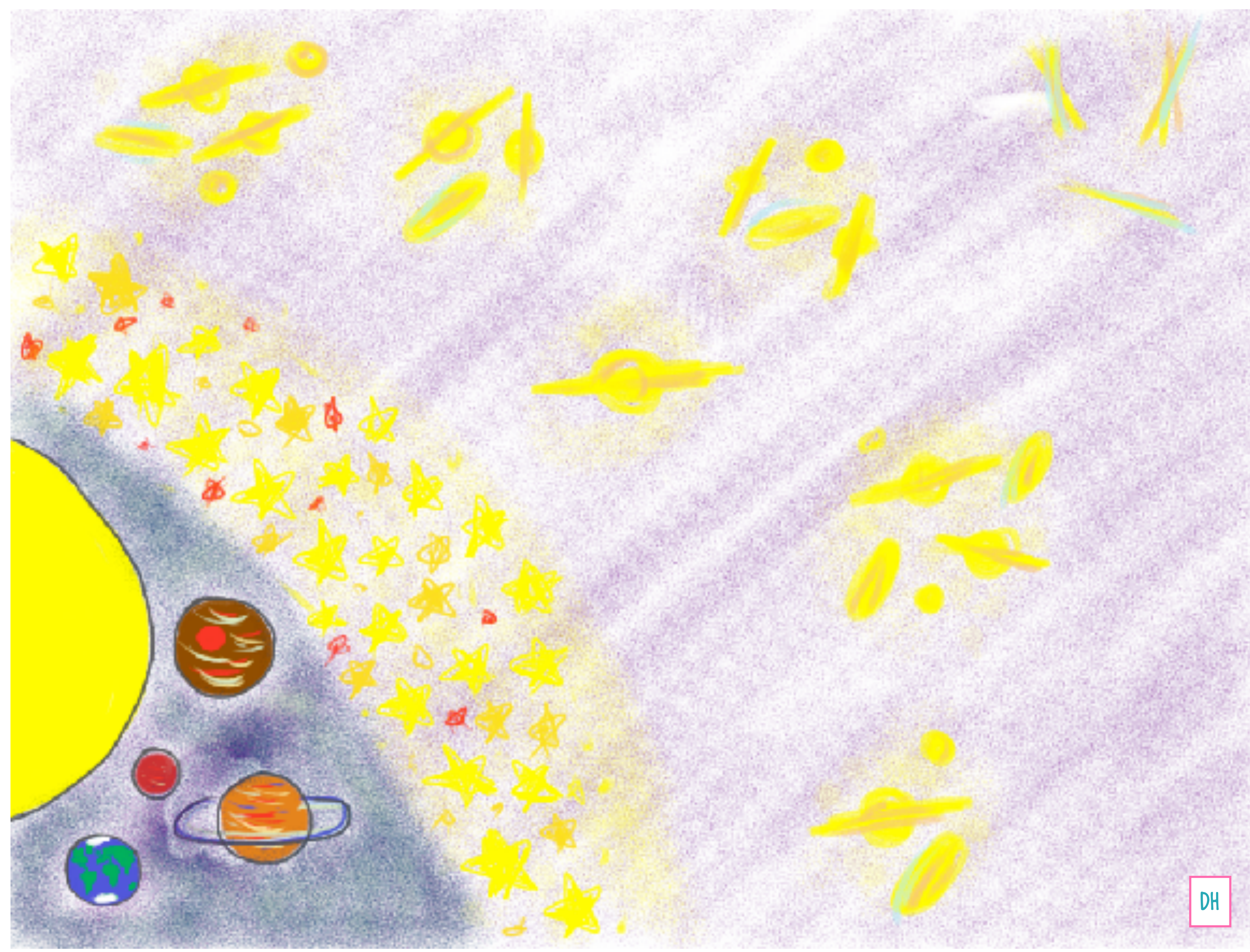
- The extragalactic background light is the second largest energy resevoir in the universe (after the cosmic microwave background radiation field)
- It comprises the accumulated emission from stars and dust that have lived at all ages of the universe
- It occupies the region of the spectrum from IR through optical to the UV (~0.1 - 1000 μm)
- Because of the strong foreground emissions from our solar system and galaxy - it's difficult to measure directly

but... **gamma-ray photons pair produce with the EBL photons and therefore get absorbed !**

PAIR PRODUCTION

$$\gamma_{TeV} + \gamma_{EBL} \longrightarrow e^{+}e^{-}$$

for gamma rays with E > ~200 GeV



Cosmology - Extragalactic Background Light

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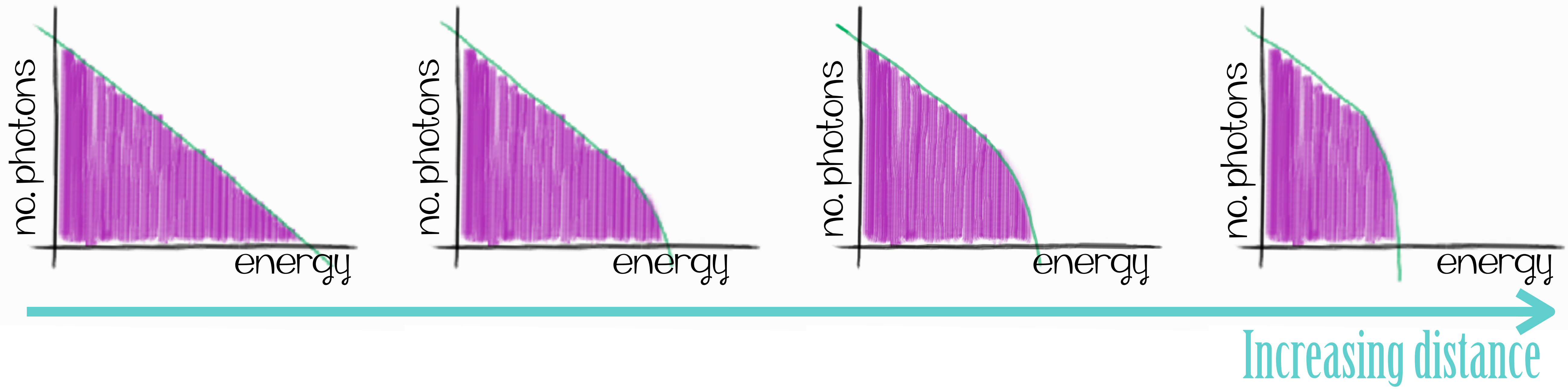
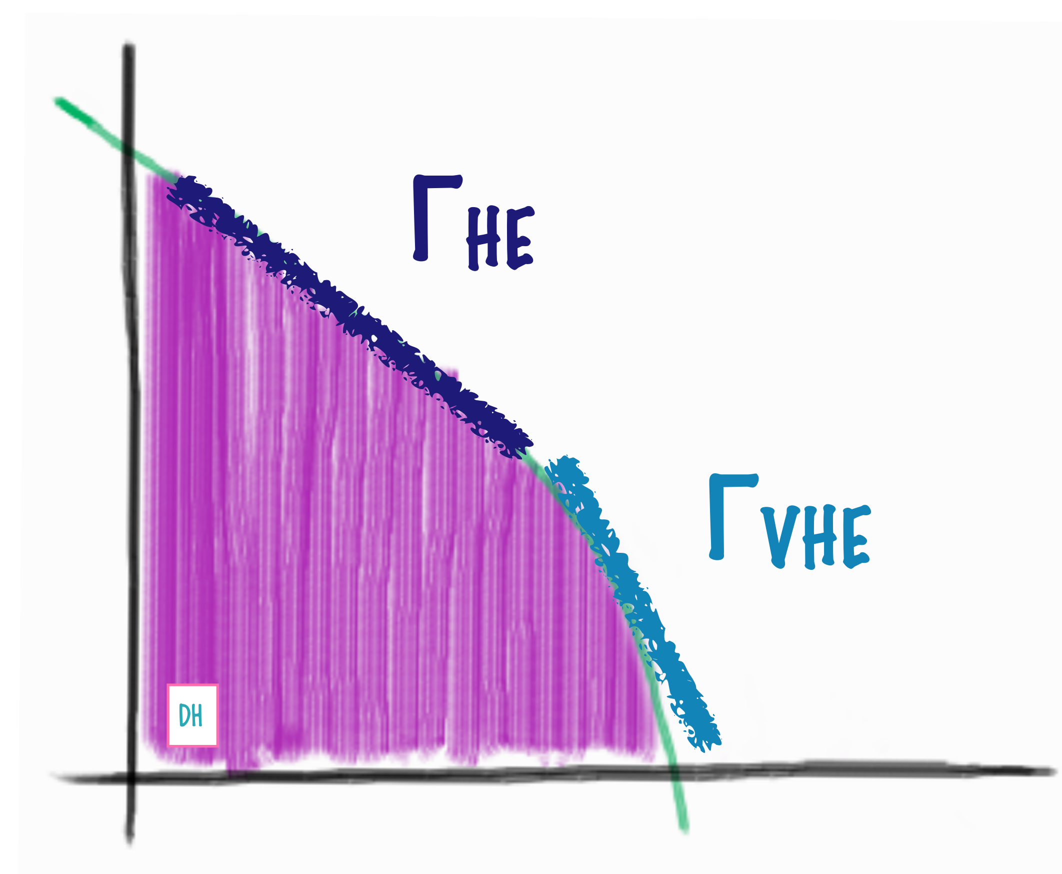
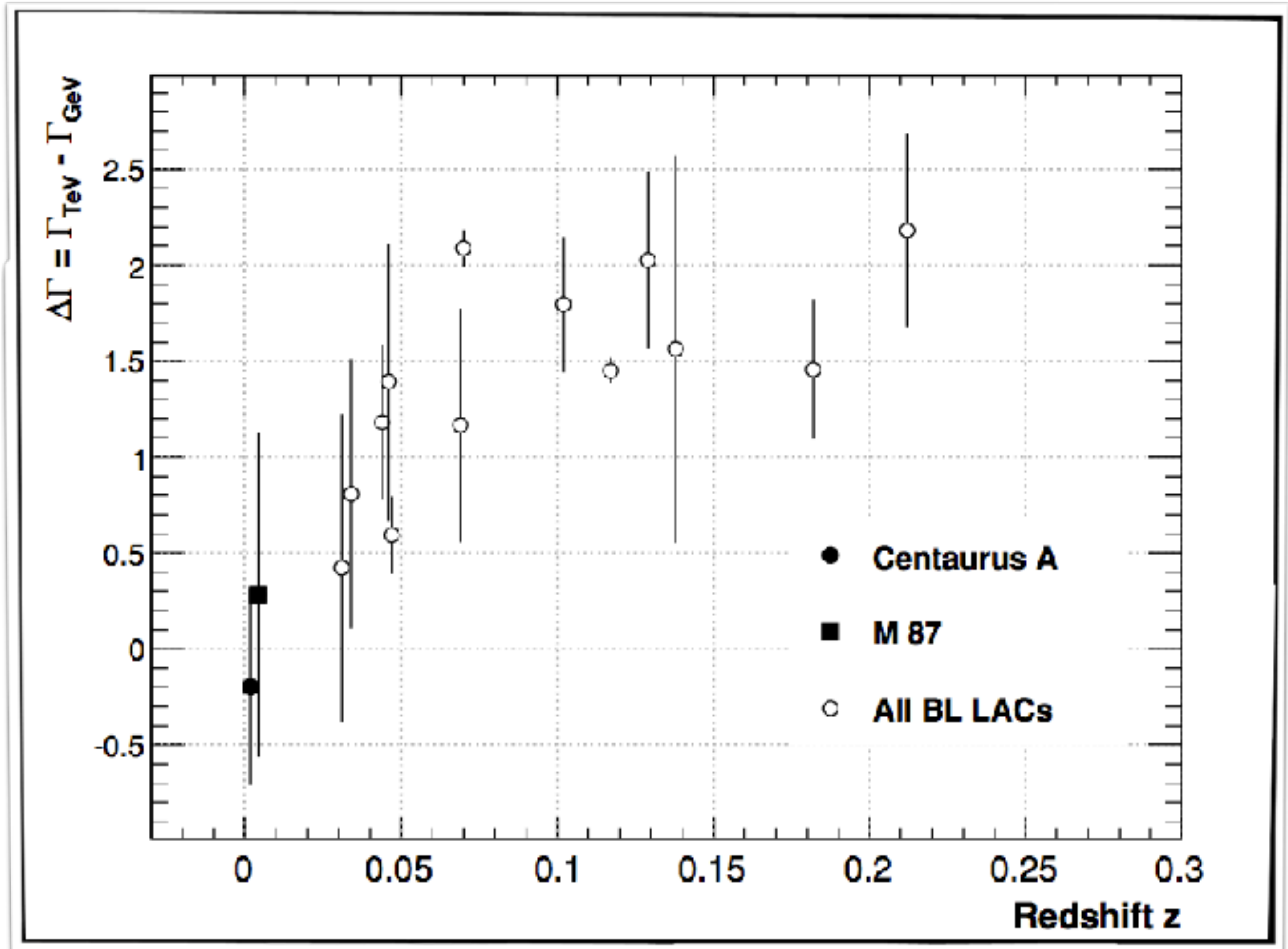


The further away the object we detect, the more its TeV photons are absorbed by the EBL - this results in a break in the spectrum



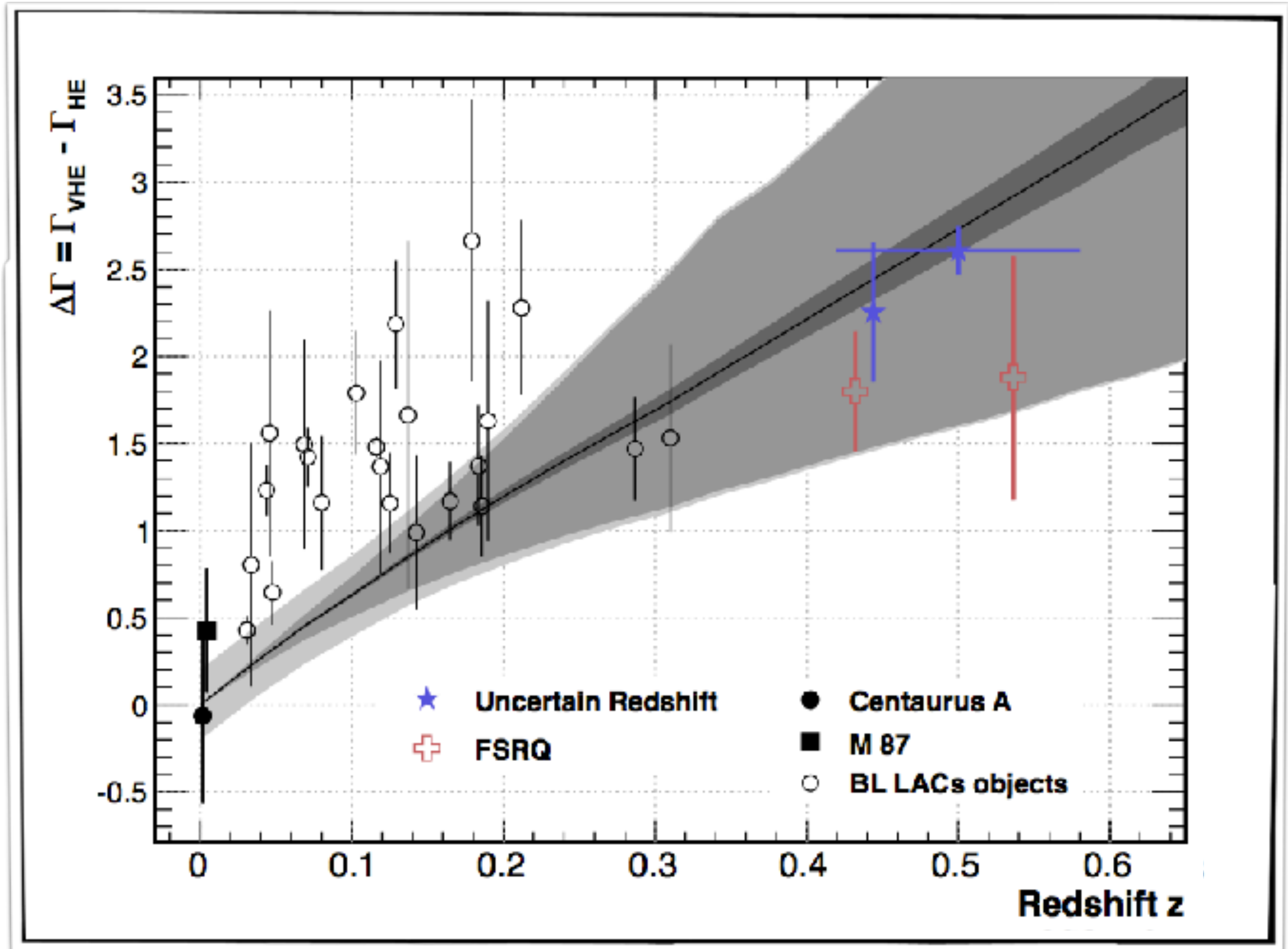
Cosmology - Extragalactic Background Light



Abdo et al. (2009), ApJ, 707, 1310

Sanchez, Fegan, Giebels (2013) in press, astro-ph/1303.5923

Cosmology - Extragalactic Background Light



ABDO ET AL. (2009), APJ, 707, 1310

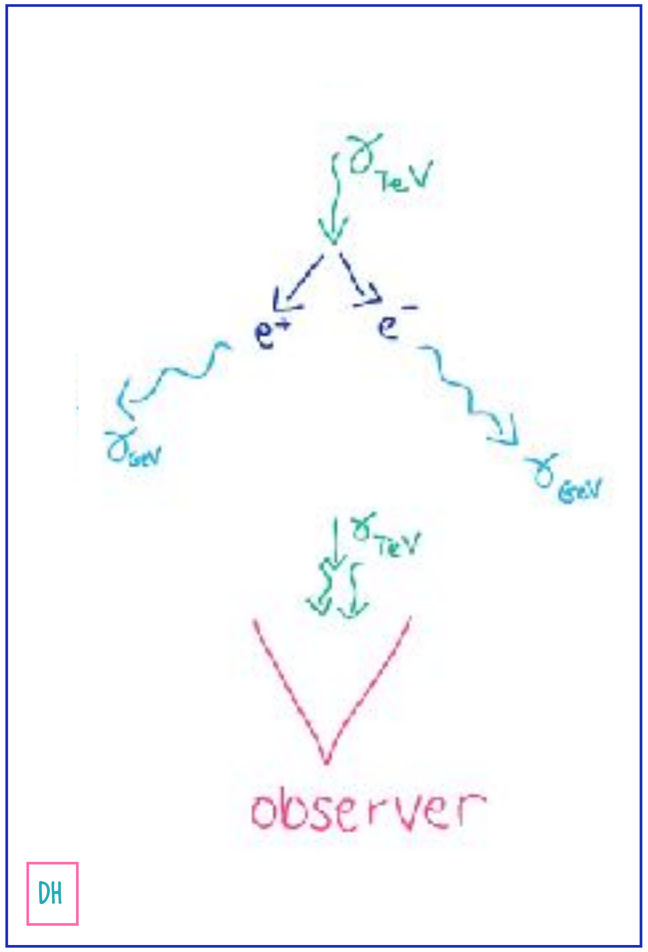
SANCHEZ, FEGAN, GIEBELS (2013) IN PRESS, ASTRO-PH/1303.5923

Cosmology - Intergalactic Magnetic Fields

- when we detect TeV gamma rays from a distant source, we know that the signal has already been attenuated - only a fraction of those emitted arrive on Earth

- the gamma rays collide with photons of the EBL en route from the source and pair produce

➡ **if there were NO magnetic fields in the universe, these charged pairs would not get deflected, they would travel in original direction until they Compton upscattered a CMB photon to MeV-GeV energies***



- in this way, the original TeV gamma rays get reprocessed to lower energy radiation

- IF we could identify a distant, steady** TeV source which had NO GeV emission, this could be an indication that the B-fields between the source and us deflected the charged pairs such that the reprocessed lower energy emission was "removed" (scattered) from the signal

* **the mean free path for e+/e- is low ~kpc** ** if the source is at a lower level now than when the TeV emission that we are detecting was emitted, it could be argued that, since the radiation due to the deflected pairs has longer to travel, it would be delayed by some time - and it hasn't arrived yet

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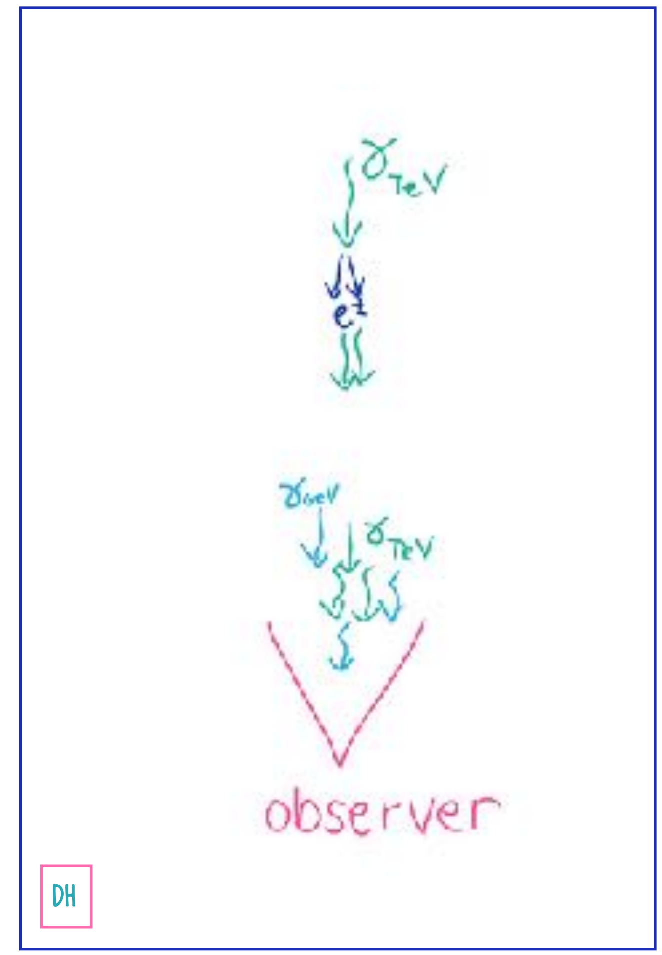

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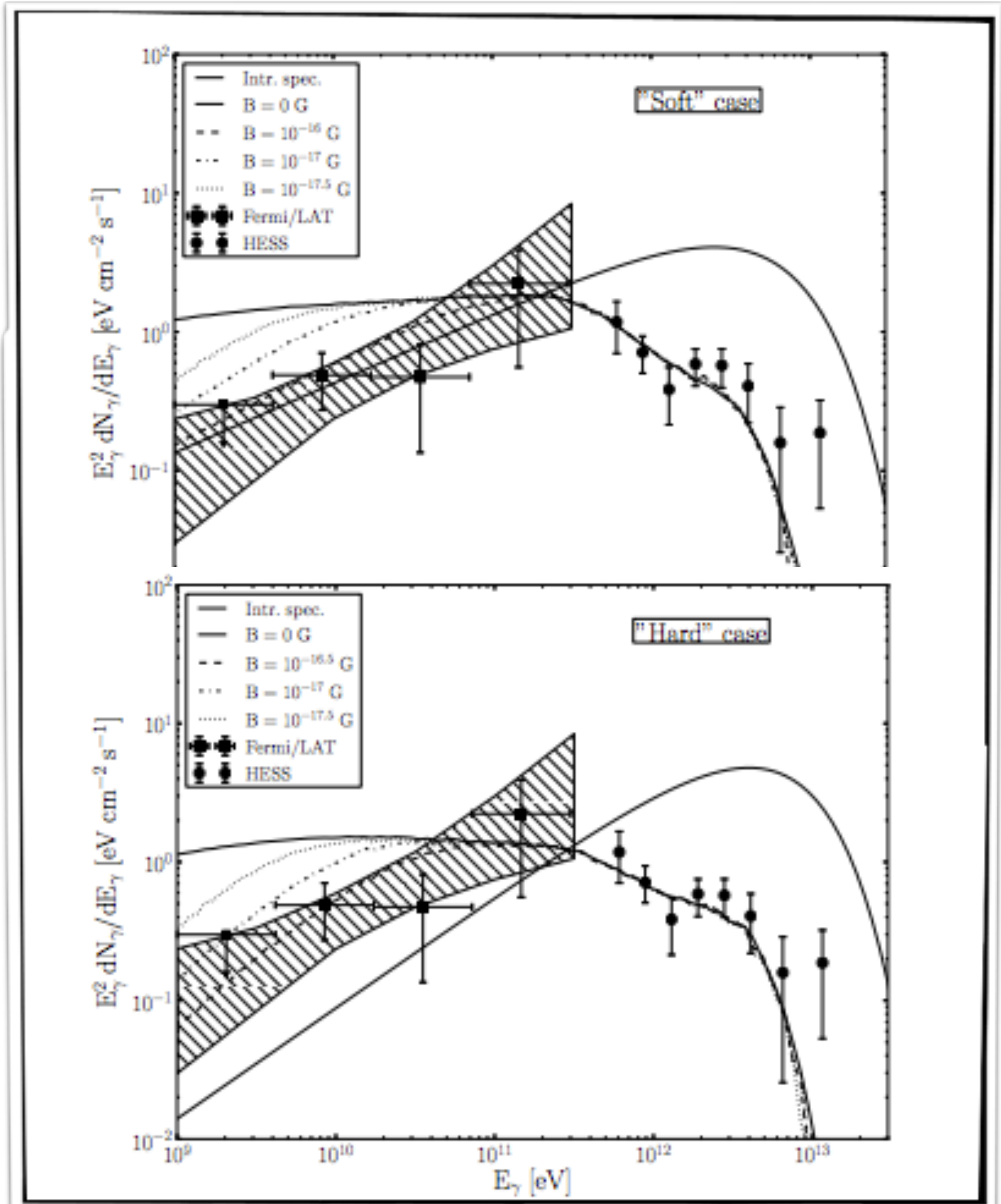
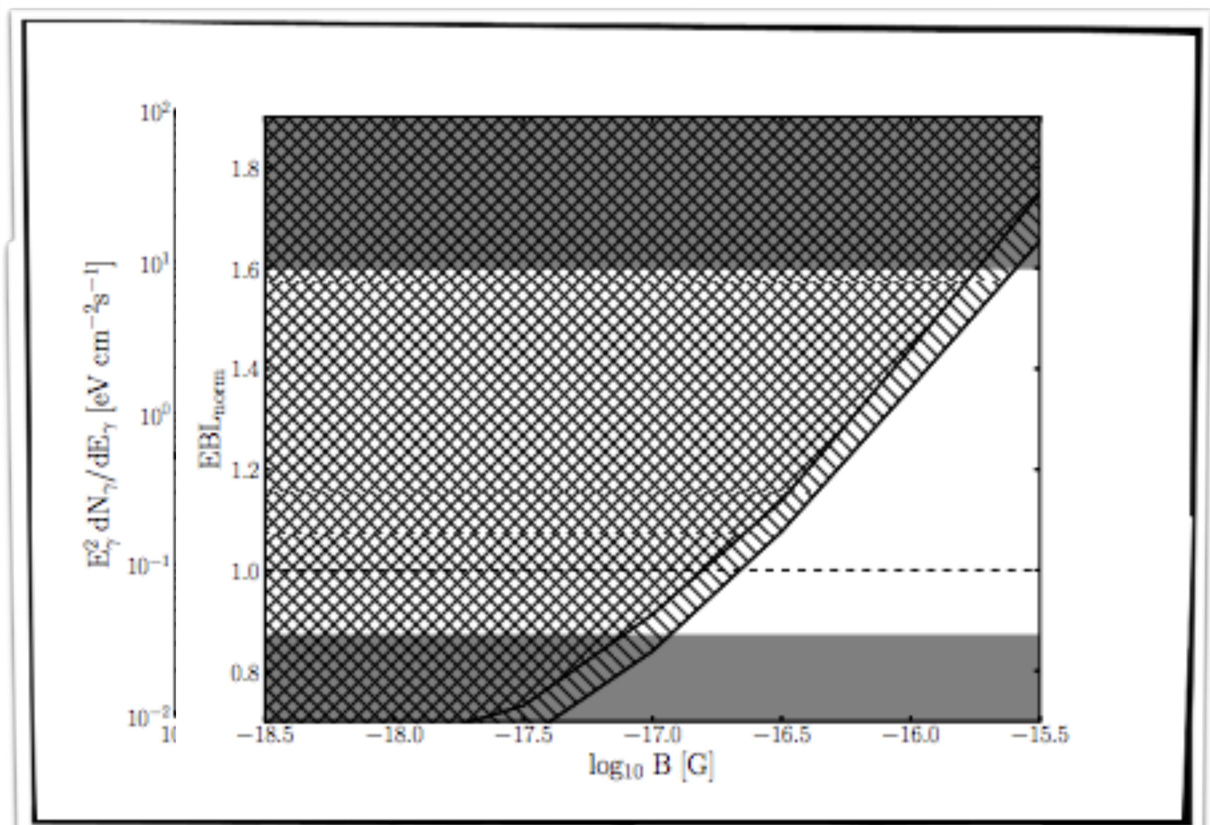
Cosmology - Intergalactic Magnetic Fields



Vovk, Taylor, Semikoz & Neronov (2012), ApJ, 747, L14

Place constraints on the intergalactic B-field strength using the direct and cascade components of the GeV-TeV spectrum of 1ES 0229+200



Astroparticle / Exotic Physics

Dark Matter Searches

Lorentz Invariance

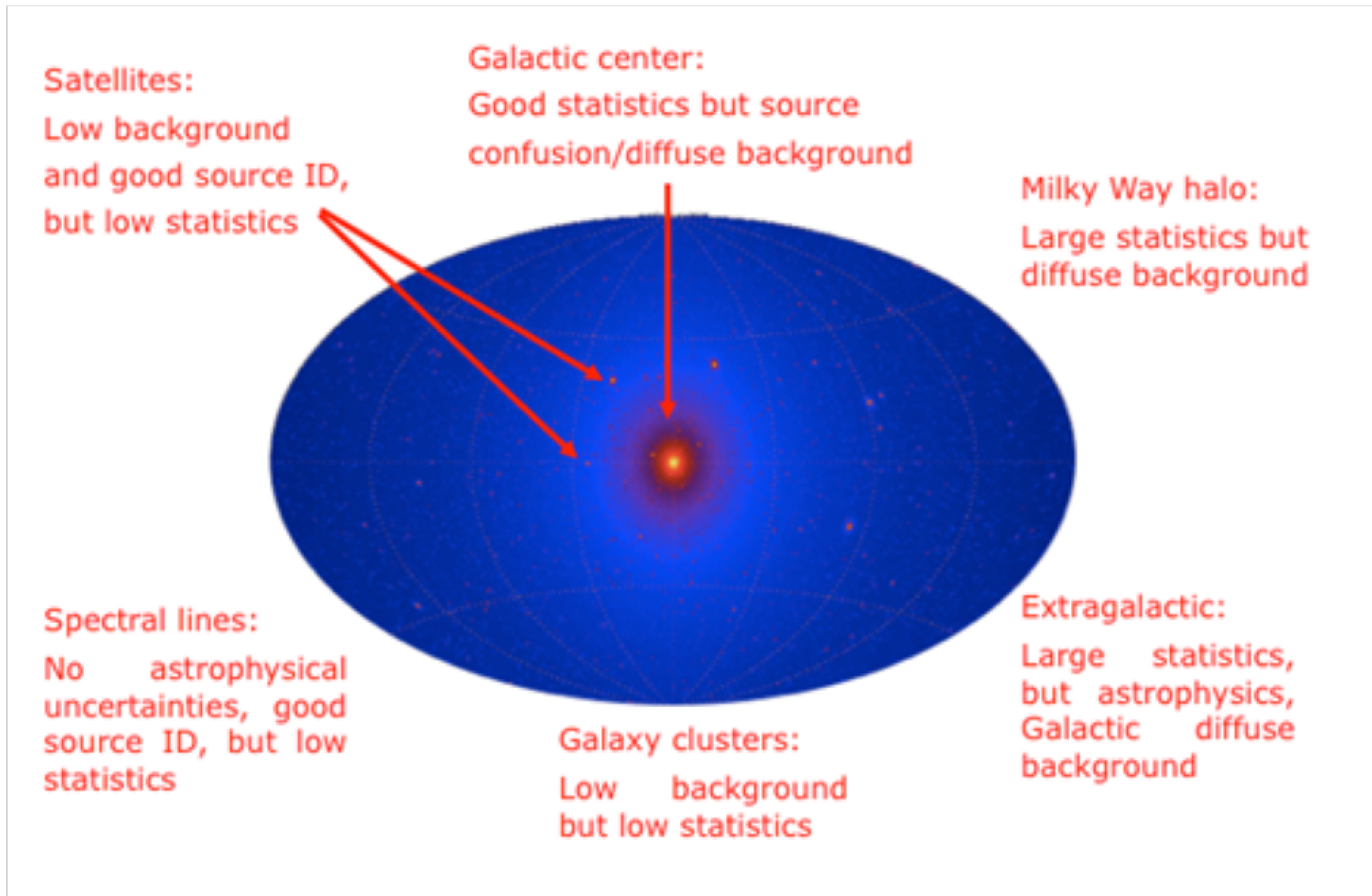
4.

Astroparticle / Exotic Physics - Dark Matter Searches

- We know that there was a large amount of dark matter in the early universe
- **We see it in the BAO - it comprses ~27% of the total energy budget of the universe**
- We see it astrophysically today e.g. galaxy rotation curves
- **We know that there has to be some particle associated with it and that that particle must be stable enough to have survived since the early universe**
    - **i.e. it desn't interact (much) with normal matter**
- One possibility is the WIMP - it is its own antiparticle (only interacts weakly)
- When this annhiliates with itself, it produces gamma rays
- It clusters in dense astrophysical environments

WEAKLY
INTERACTING
MASSIVE
PARTICLE

Astroparticle / Exotic Physics - Dark Matter Searches



HTTP://KIPAC-WEB.STANFORD.EDU/RESEARCH/FGST

Galactic Physics: Binary systems

For more information on dark matter, see Jim Buckley's talk at VERITAS 10-year celebrations: http://veritasj.sao.arizona.edu/10Years/Speakers.html

JIM BUCKLEY'S TALK (VERITAS 10-YEAR CELEBRATION

Astroparticle / Exotic Physics - Lorentz Invariance

- The assumption of Lorentz Invariance is one of the founding principles of Modern physics
- Certain theories that attempt to provide a unified model of quantum gravity predict that the vacuum could have an effective refractive index
- Thus photons with different energies would travel at different velocities becoming more pronounced as we approach the Planck Energy (10^{19} GeV)

To search for the signature of Lorentz Invariance Violation, our test sources should have the following properties:

- emit at the highest energies (effect of vacuum dispersion more pronounced)
- lie at a very large distance from us (time delay will be larger)
- exhibit rapid variability (or only emit over a very short time period) so that we "know" (assume) photons were all emited at the same time

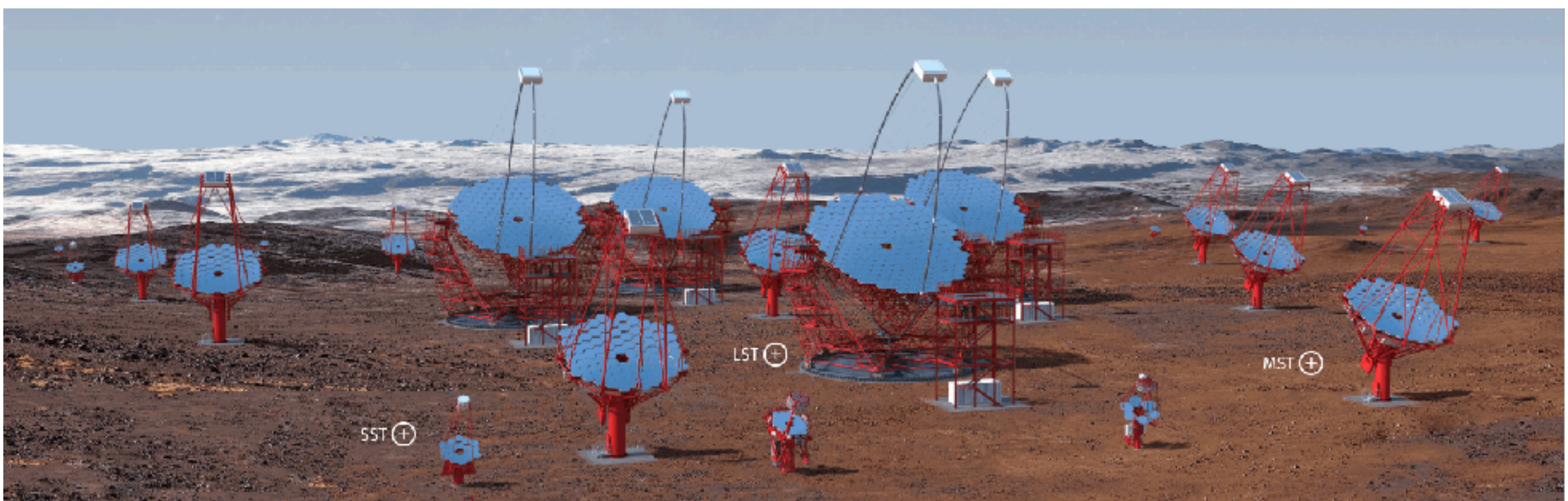
Constraints so far have come form the NON detection of differences in the arrival times of photons from distant gamma-ray bursts

Next-generation TeV instruments, such as the
Cherenkov Telescope Array (CTA)
will enable us to observe many sources and source classes as a function of redshift with high statistics so that we can disentangle the effects of
dispersion internal to a paritcular source or source class
and
dispersion due to vacuum birefringence

Cherenkov Telescope Array (CTA)

https://www.cta-observatory.org/

- CTA is the next generation gamma-ray observatory
- It will consist of more than 100 telescopes
- There will be two sites (North and South)
- CTA will have unprecedented sensitivity thus enabling us to study the gamma-ray sky as never before



Thank you

for

listening

deirdre@llr.in2p3.fr