Astroparticle Physics: γ–Rays

Lecture 1:

-Detection techniques

-Production of γ-rays

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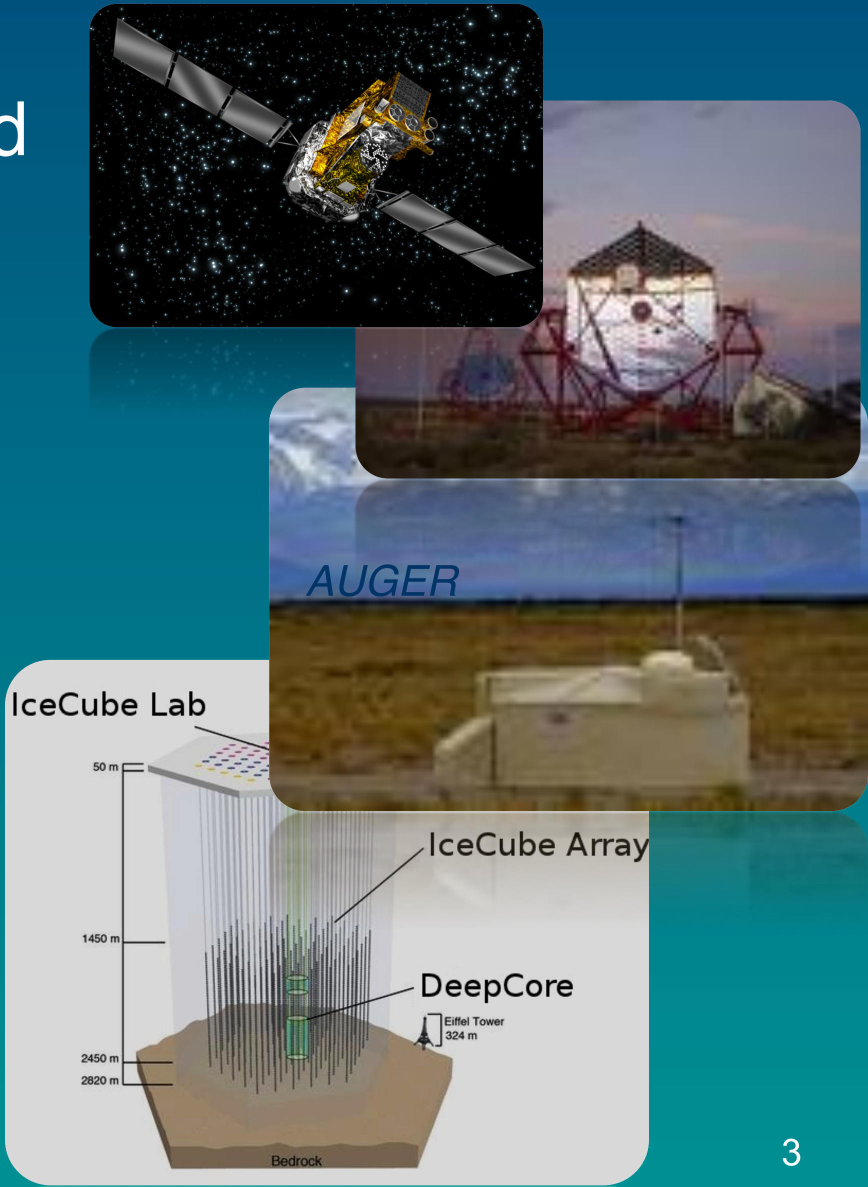
Outline

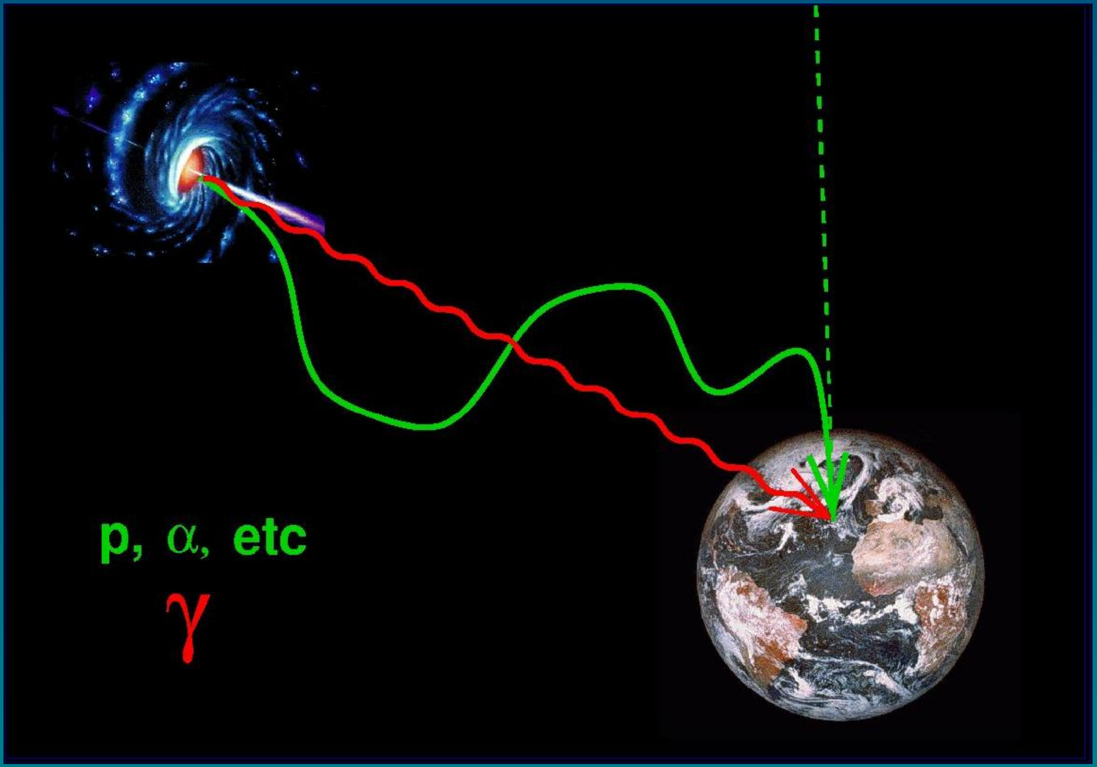
- Introduction
- Detectors and Detection techniques
- Origin of γ–rays in Astrophysical sources
  - Basic production processes
  - Acceleration mechanisms

Very High Energy Astrophysics

- Relatively new discipline, in between Particle physics and Astrophysics.
- Studies the Universe at energies E > 1 MeV
- Opens a window to the non-thermal Universe
- This field started with the discovery of cosmic rays
- Today it can be divided into:
  - *γ-ray astronomy*
  - *ν-astronomy*



Adventage of γ-rays

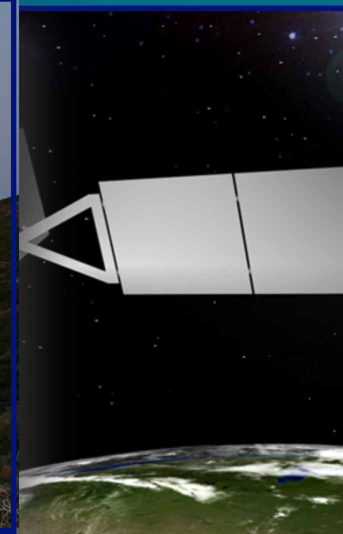


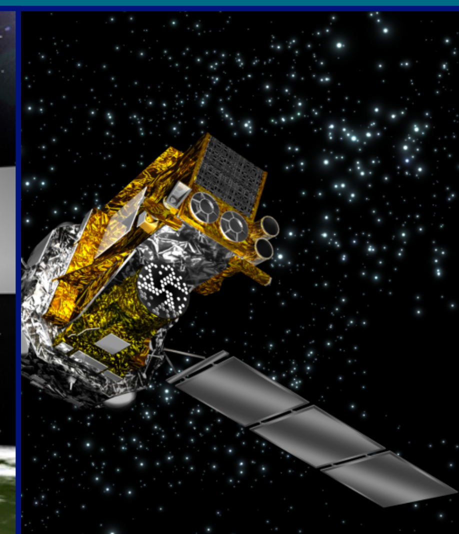
- Charged cosmic rays do not point to the source.
- Only γ's (and ν's) can be used to do astronomy

Observation techniques of γ-ray Astronomy

From ground *From space* *From space*

MAGIC





The bands of γ-ray astronomy

Low Energy	LE	0.1 – 100 MeV (10^6 eV)
High Energy	**HE**	**0.1 – 100 GeV (10^9 eV)**
Very High Energy	**VHE**	**0.1 - 100 TeV (10^{12} eV)**
Ultra High Energy	UHE	0.1 – 100 PeV (10^{15} eV)
Extremely High Energy	EHE	0.1 – 100 EeV (10^{18} eV)

Remember:

- *Optical photons: ~ 1 eV*
- *VHE γ-rays: ~ 10^{12} eV !!*

We will cover in these lectures the HE & VHE bands

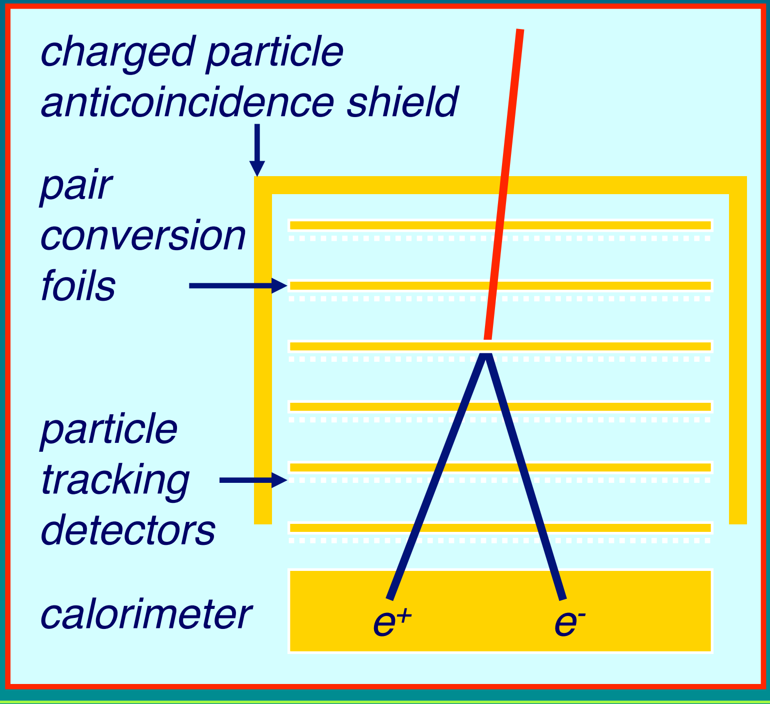
Detection tecniques

Detection techniques

Basic fact: γ-rays absorbed in atmosphere

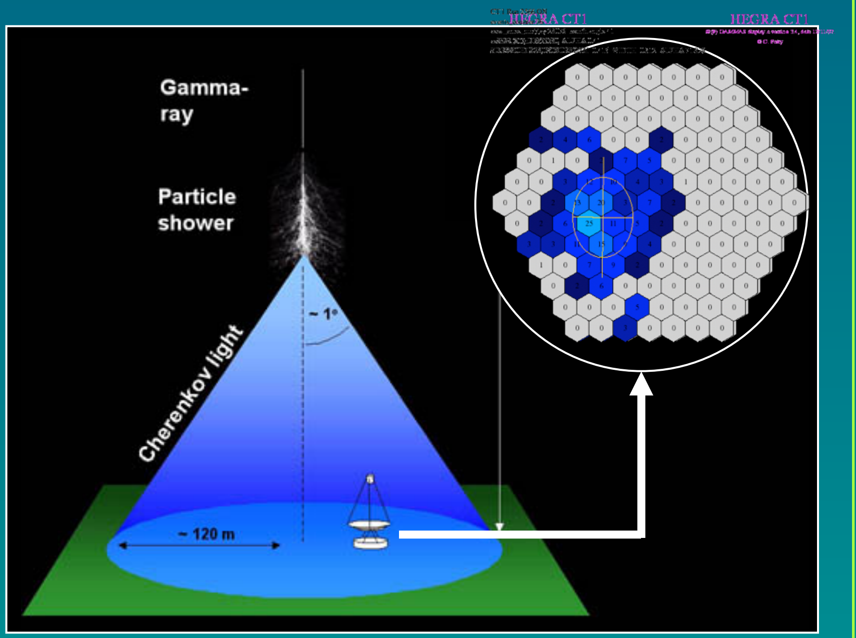
Satellites

- **Direct detection**
- Small background
- Small Effective Area ~$1 m^2$



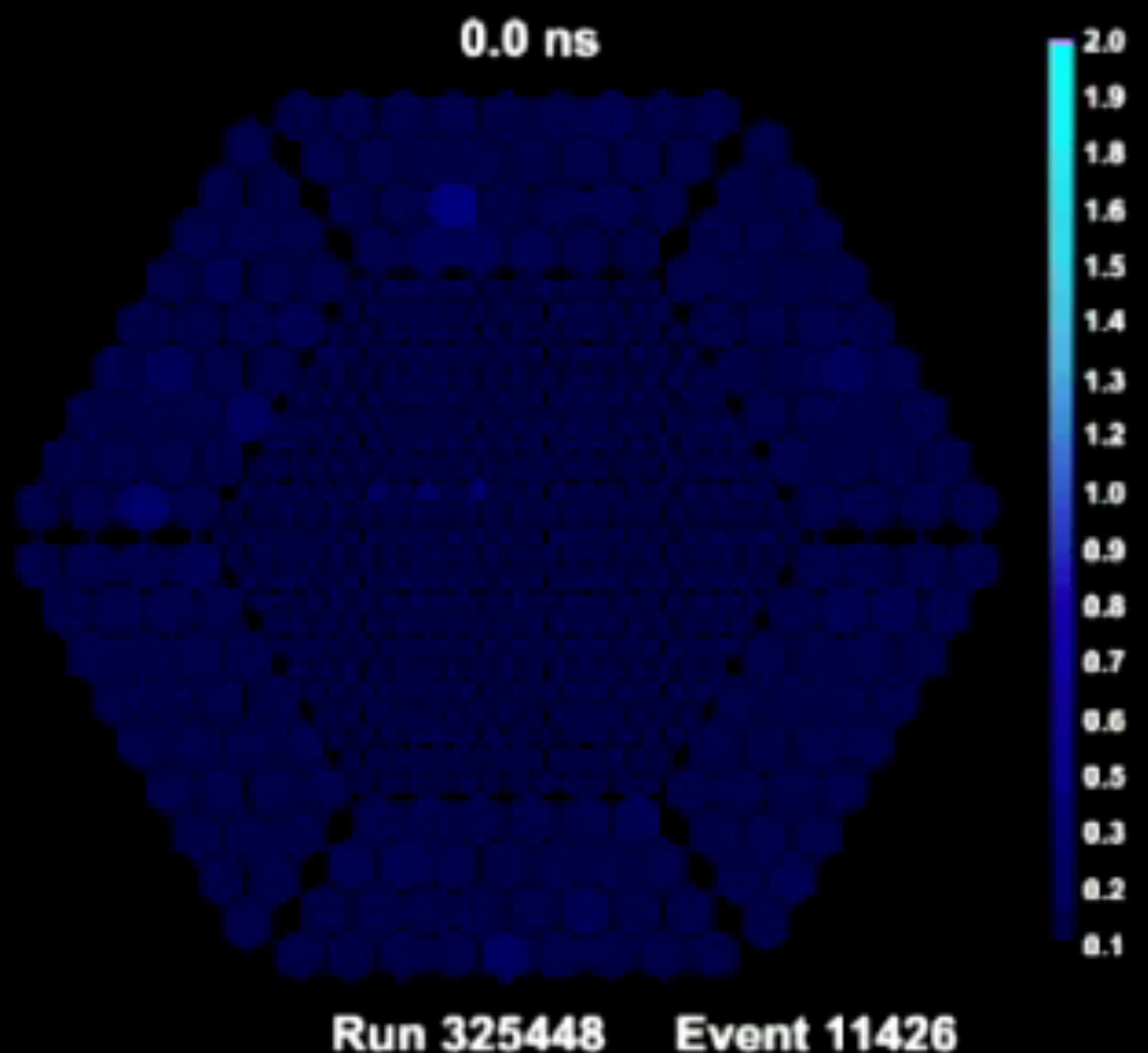
Ground Detectors

- **Indirect detection**
- Huge Effective Area ~ $10^5 m^2$
- Enormous hadronic background



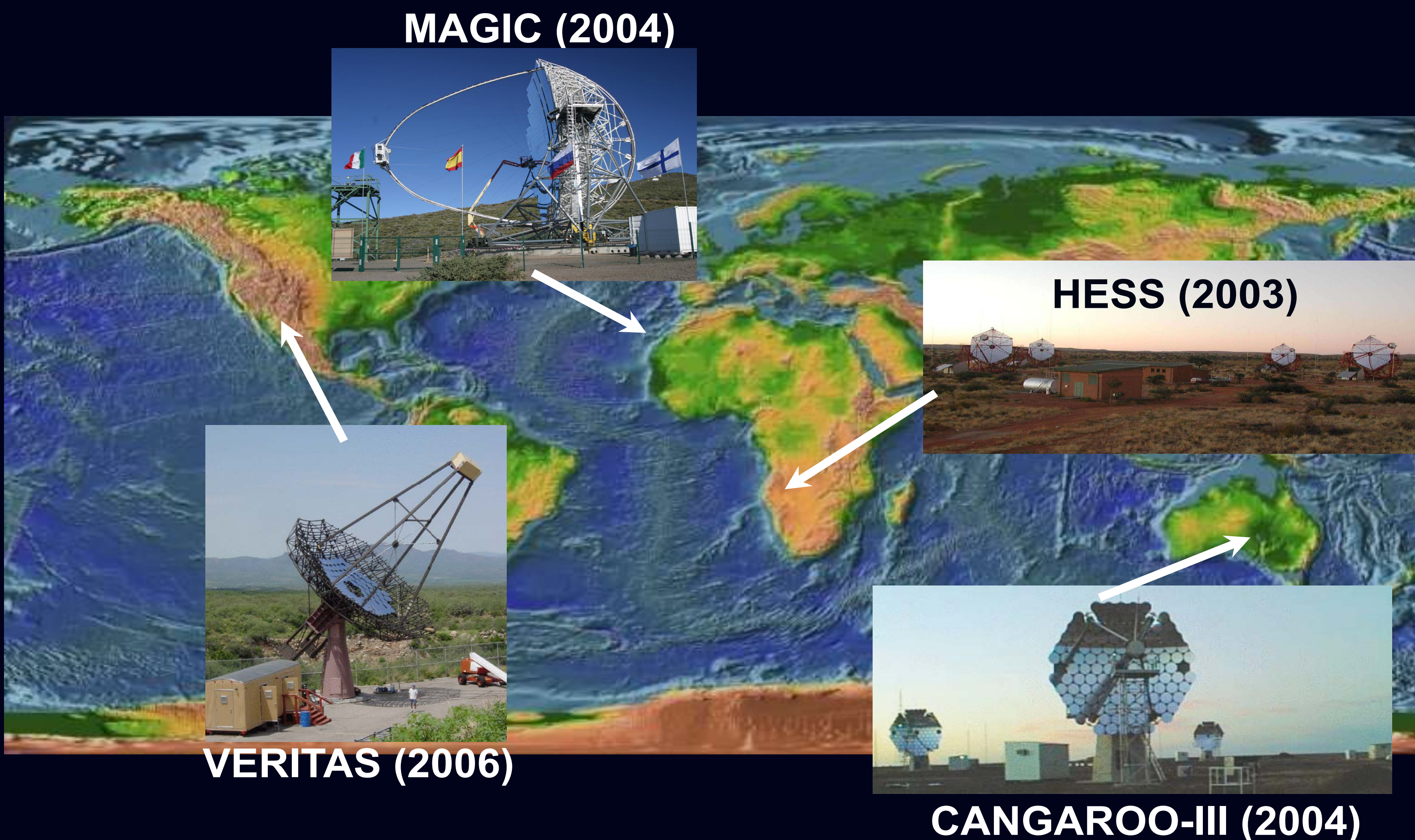
Detecting an atmospheric shower

Recorded events



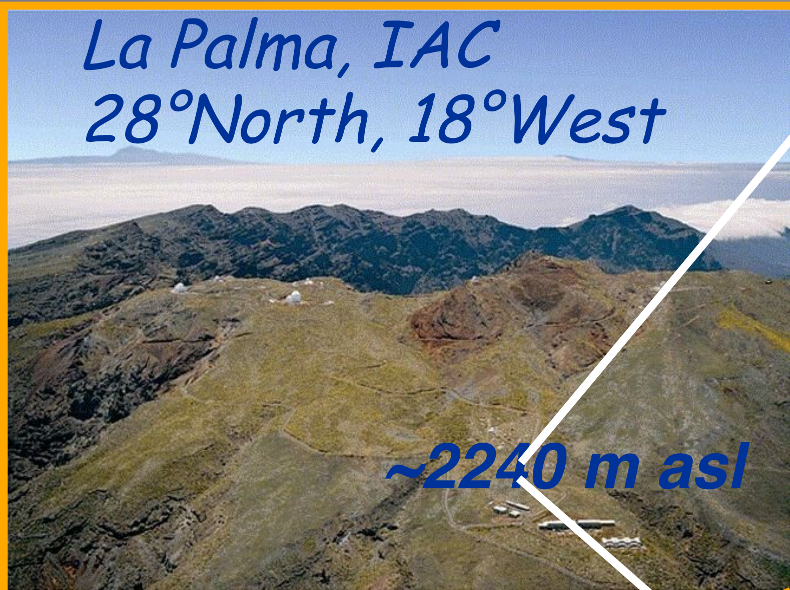
VHE Experimental World

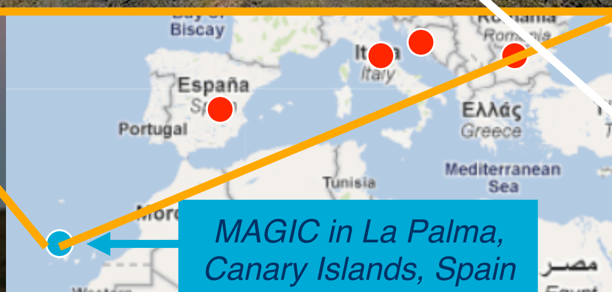
2nd generation of Cherenkov telescopes



The MAGIC Collaboration

Collaboration: ~ 150 Physicists, 21 Institutes, 8 Countries:

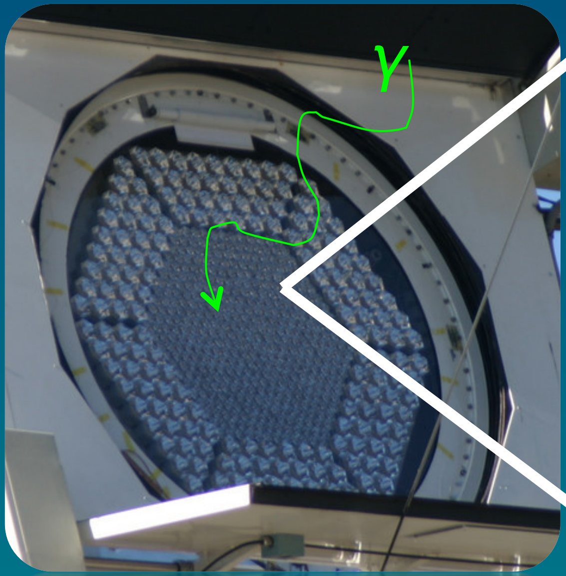


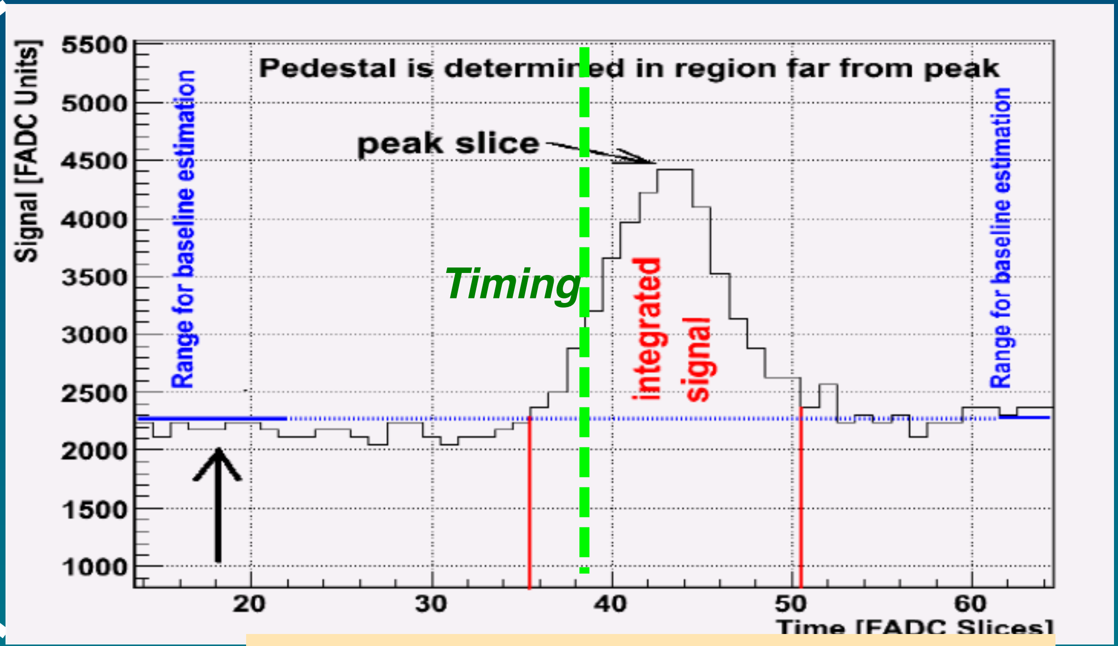


Goal: Achieve the lowest possible energy threshold

Close gap between space &
ground-based gamma-ray telescopes

How a CT works: Pixel signal extraction





Signal lasts for only ~ 5 ns

- For each pixel we get:
  - integrated charge Q (FADC counts)
  - arrival time T (ns)

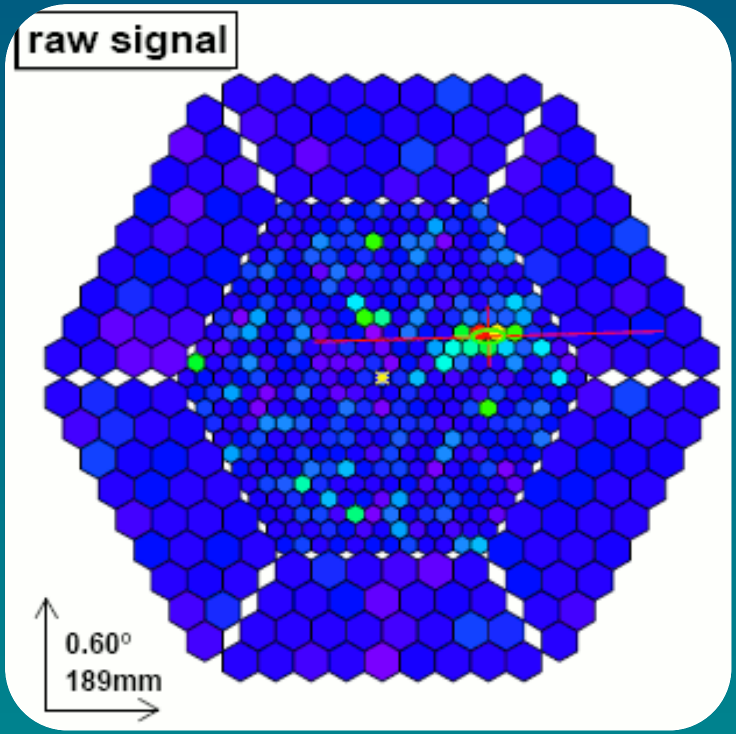
Signal in Photo-electrons

Raw Signal = pedestal + (Cherenkov light) x PDE x gain

Calibration

How a CT works: Pixel signal extraction

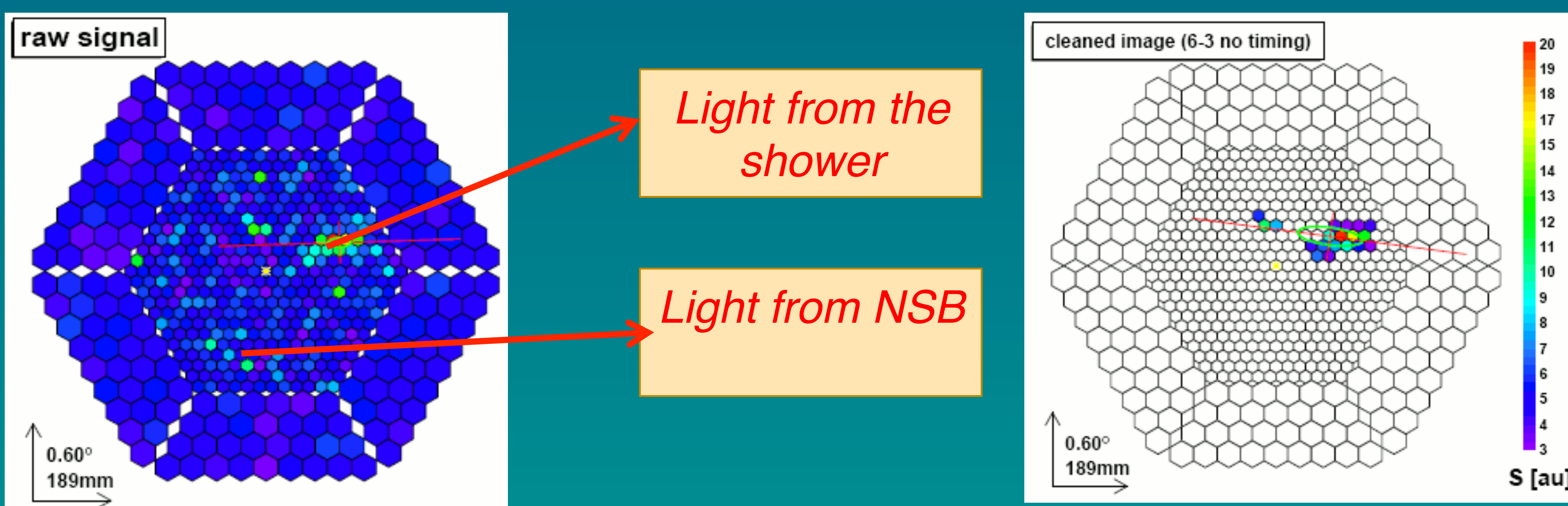
- Then we get a raw image of the shower.



How a CT works: Image Cleaning

NSB problem: The camera not only records the Cherenkov light but also the Light of the Nigh Sky Background (NSB)

- We need to remove it
- Very difficult @ Low energies (tens of GeV)



Gamma/hadron separation

Main Problem of Chrenkov telescopes: Overwhelming background of Cosmic Rays (1000 CRs per γ-ray)

- A method to identify the nature of particle which originated the recorded event is mandatory

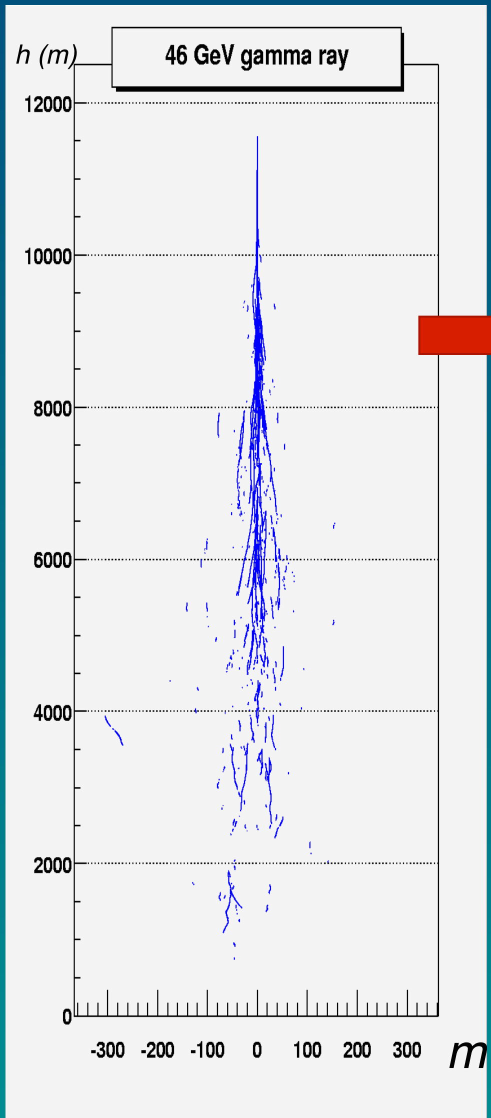
Idea:

Different kind of primary particles produce different kind of images in the camera

↓

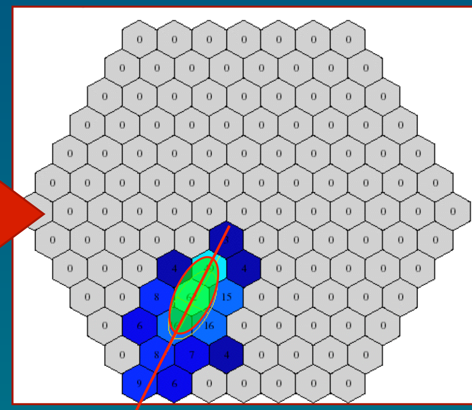
Different distributions of image parameters

Gamma/hadron separation



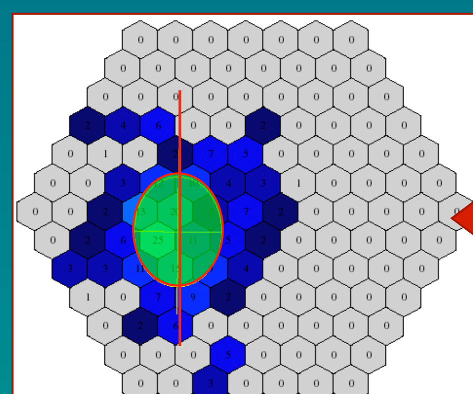
Gamma shower

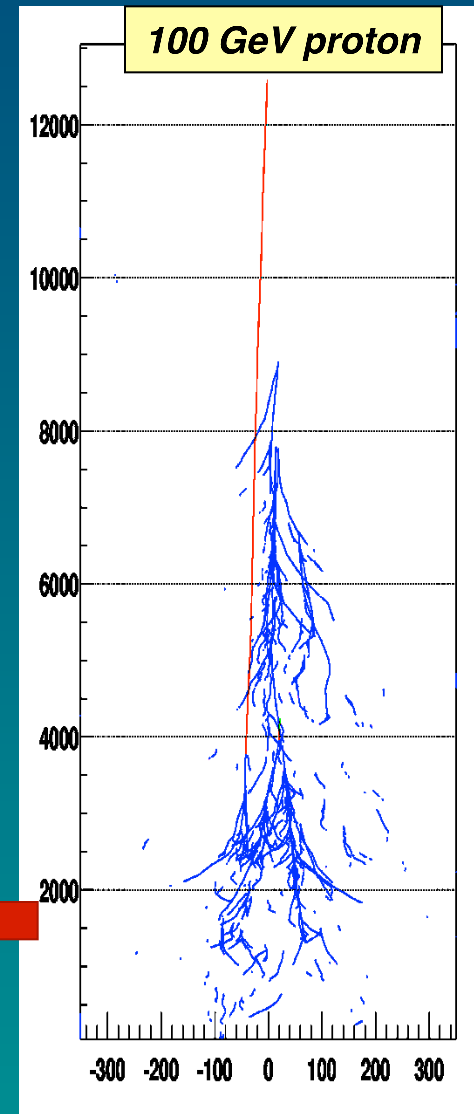
(narrow, points to source)



Proton shower

(wide, points anywhere)



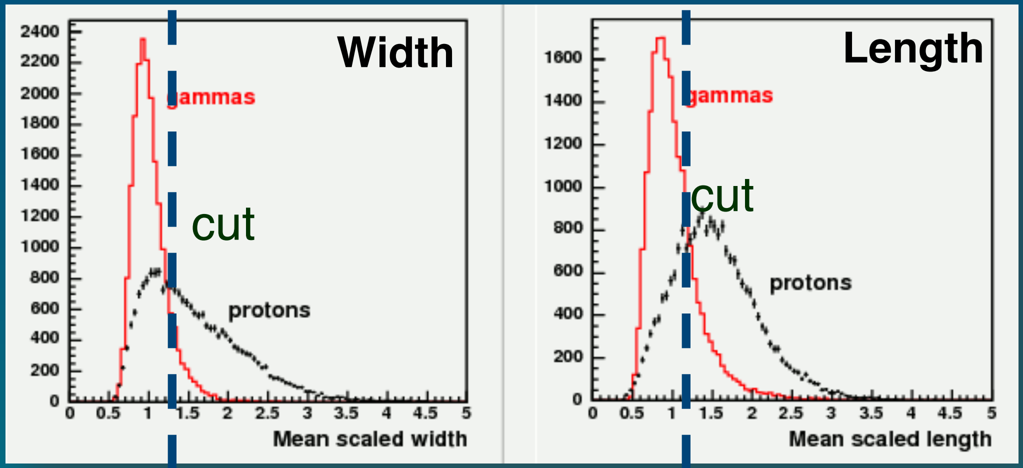


Gamma/hadron separation

Methods:

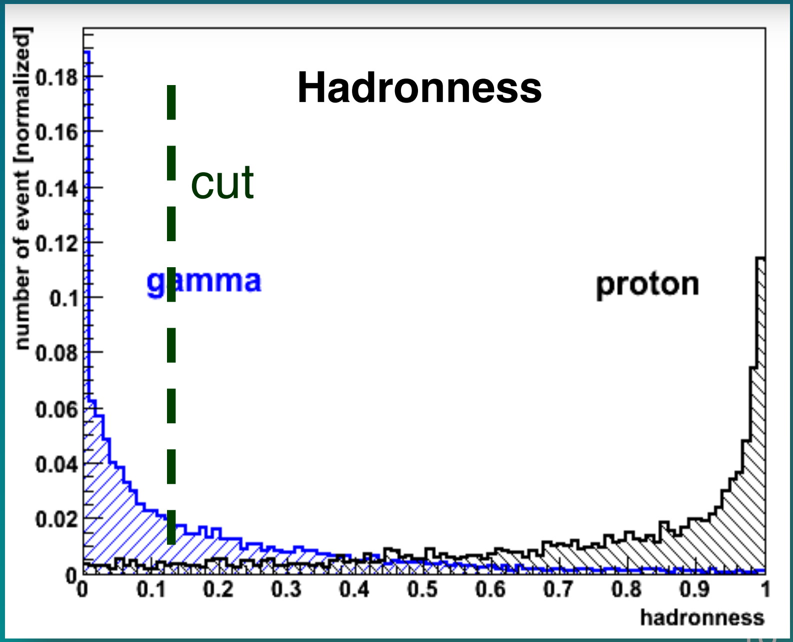
- **Simple Cuts:**

Cuts on image or/and shower parameters



- **Neural networks/ Random Forest:**

Optimized decision trees



- **Others**

Likelihood fit goodness of an analytic model

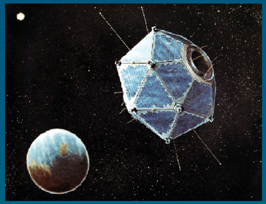
The γ-ray sky

The first views of the γ–ray Universe

The space era allowed to see the Universe with “new eyes”

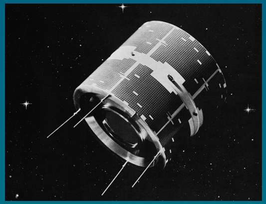
- **VELA satellites (60’s)**

They discovered the GRBs



- **COS-B (1975-1982)**

First detailed map of the Milky Way. Identified 24 sources



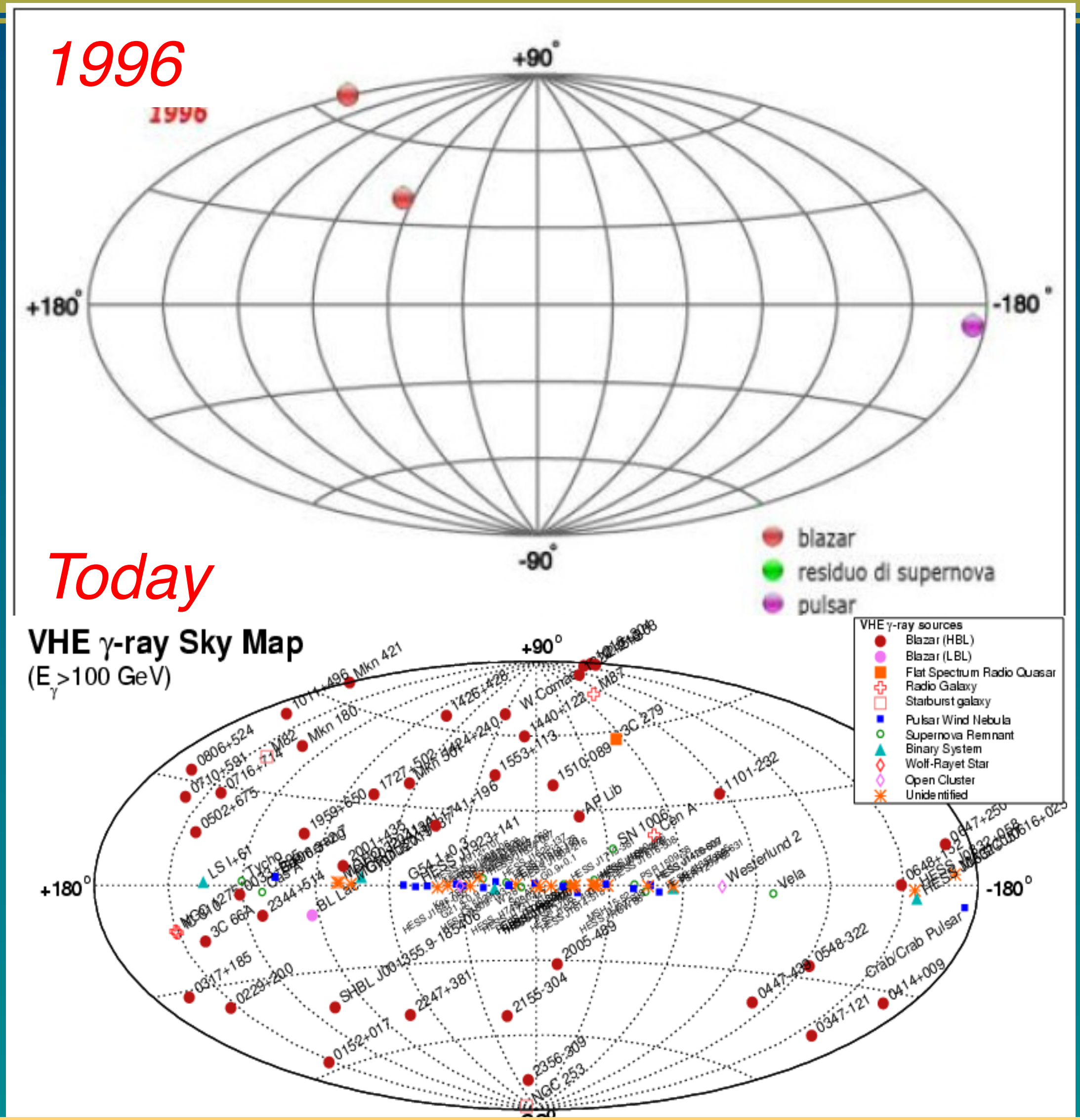
- **Compton Gamma-Ray Observatory (1991-2000)**

The first true γ-ray space telescope:

- Several instruments: EGRET, BATSE,…
- Discovered **271** sources: 7 pulsars, 66 AGN, 177 unidentified

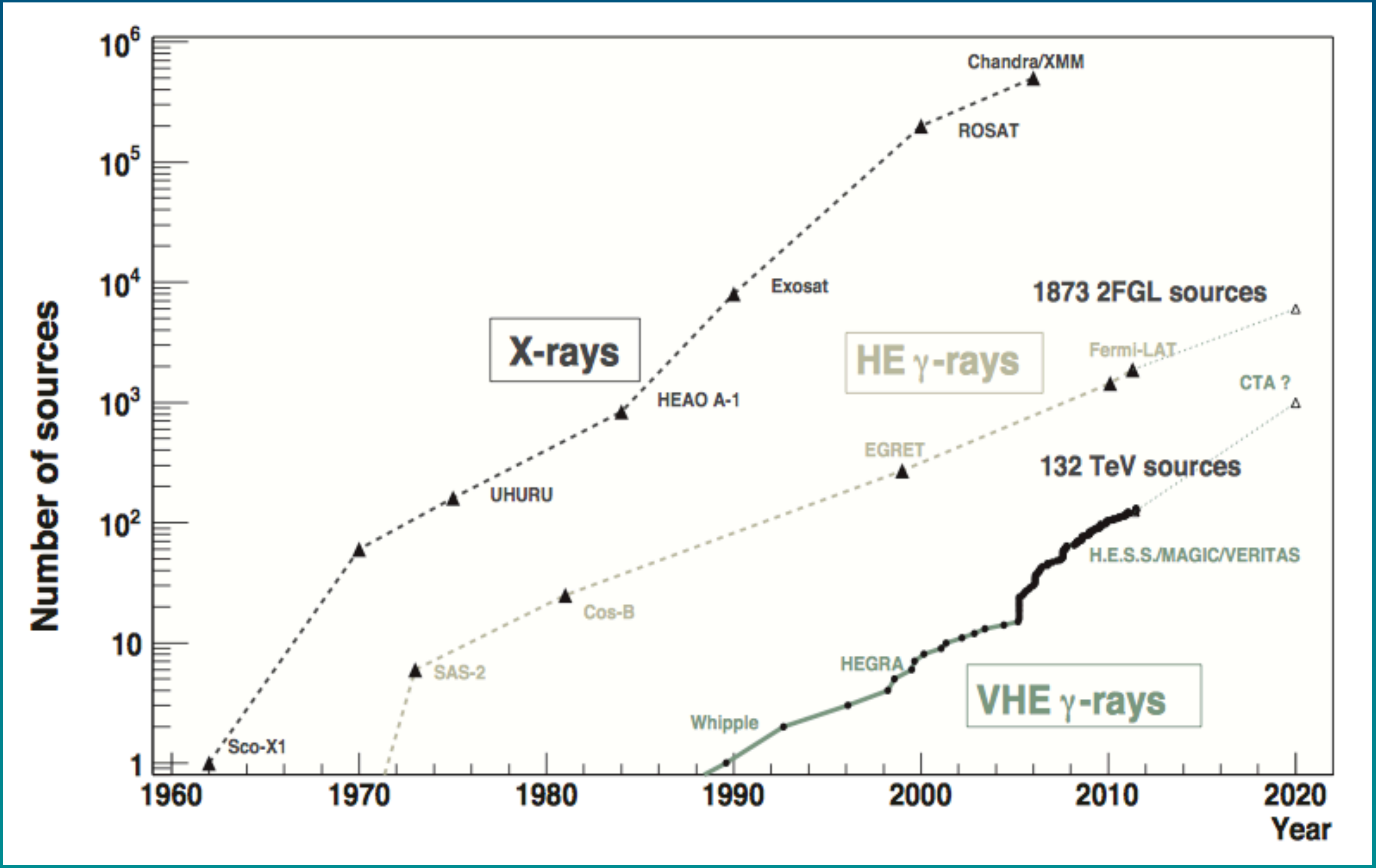
- **Fermi space telescope (>2008)**
  - More than 2000 sources

The VHE γ-ray sky (from ground)

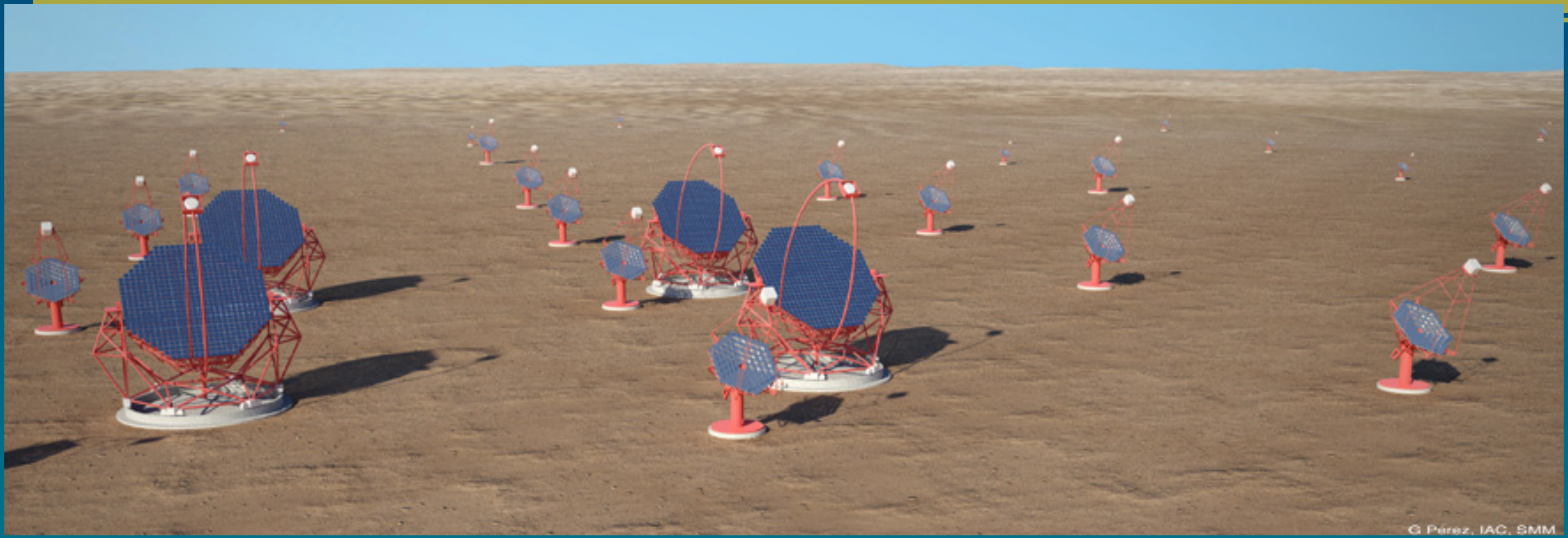


151 sources know today

The future of γ-ray astronomy



The CTA era

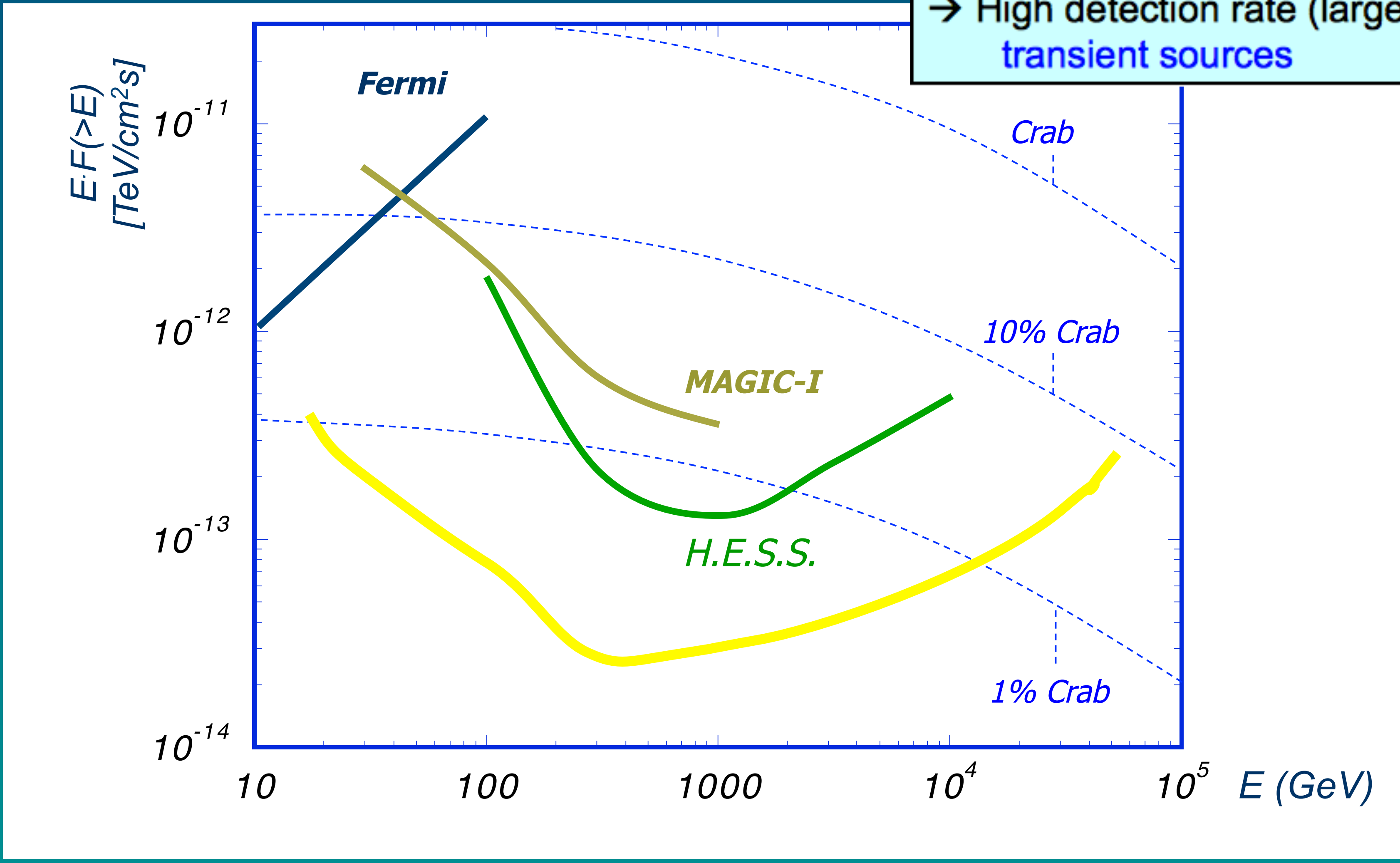


- CTA represents the next generation of CTs
  – A join effort of:
    HESS + MAGIC + VERITAS + new people
- Two observatories: North & South
- About 100 telescopes of 3 different sizes, for covering different energies ranges

The CTA era

Expected sensitivity

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



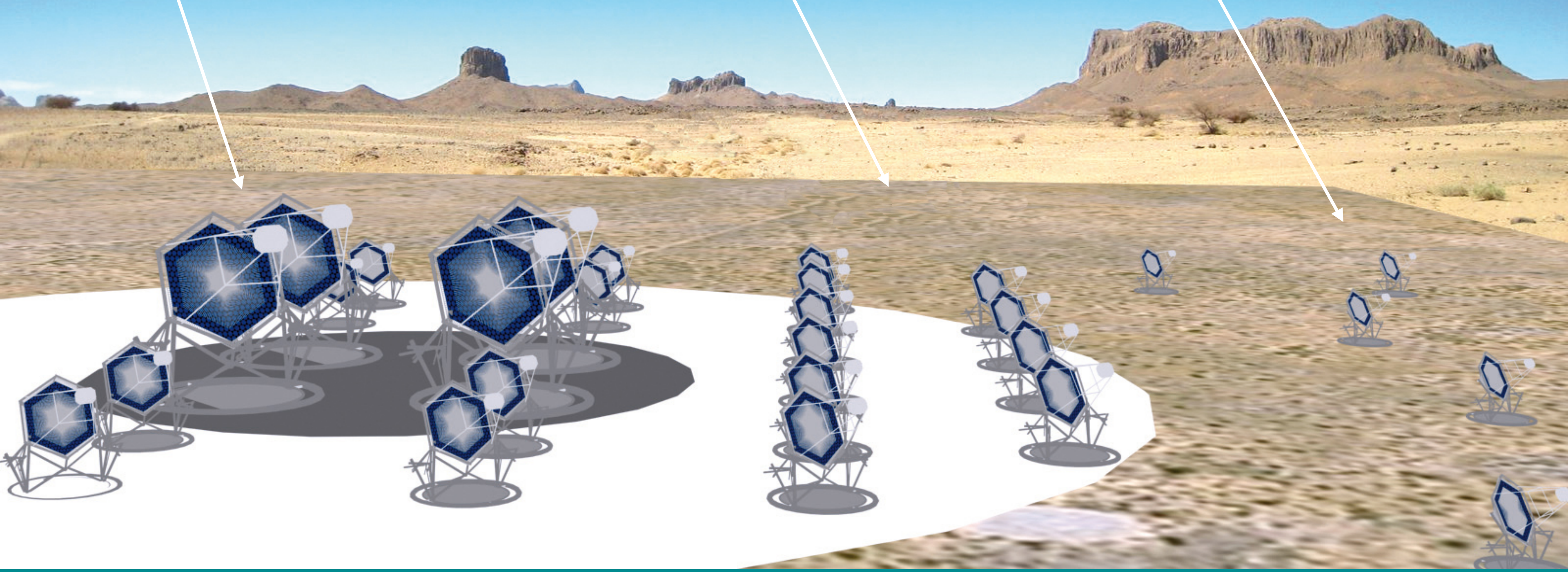
CTA Layout

(one) possible configuration

Low-energy section:
4 x 23 m tel. (LST)
- Parabolic reflector
- 100x100 m^2 area

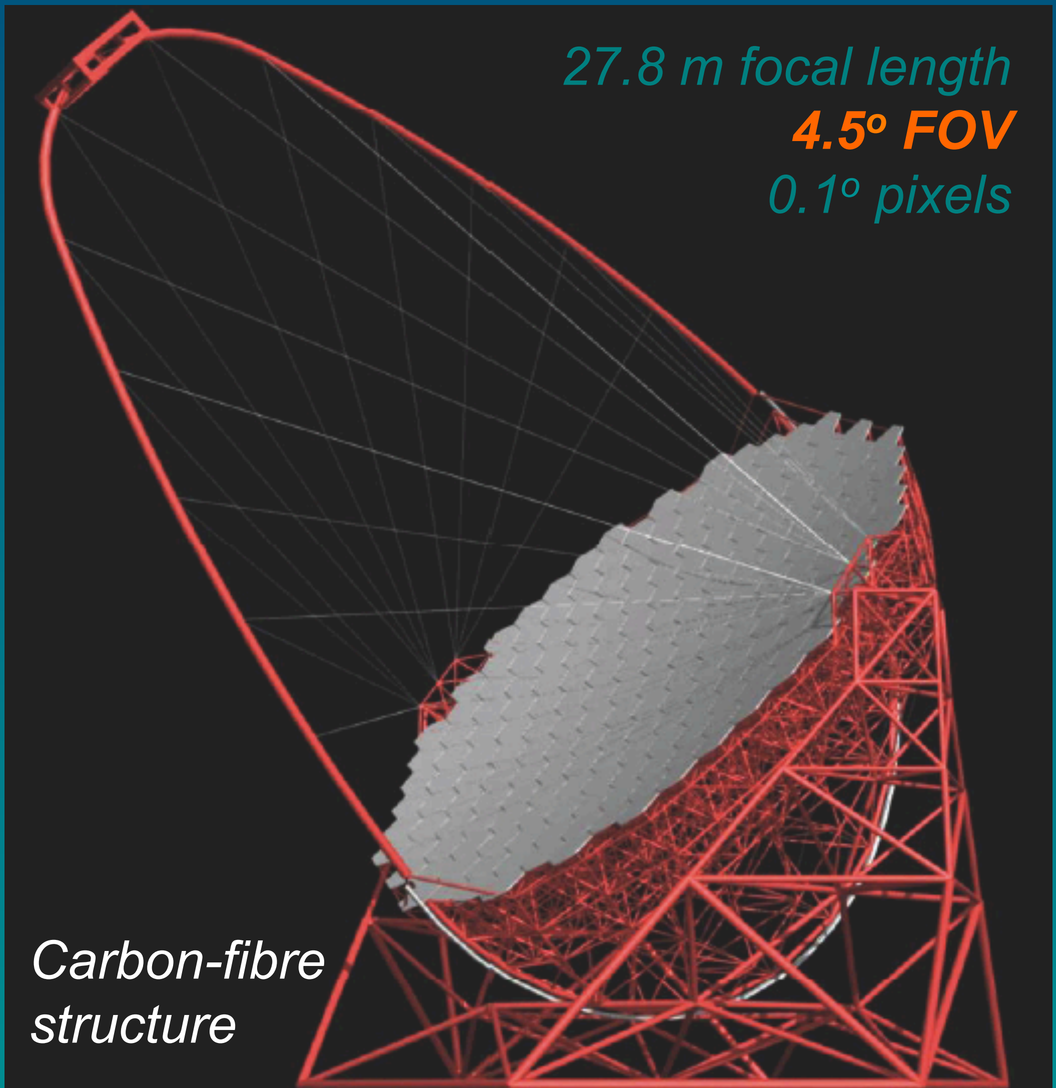
Core-energy array:
25 x 12 m tel. (MST)
- Davies-Cotton reflector
- (+ Schwarz.-Couder)
- 1x1 km^2 area

High-energy section:
70 x 4 m tel. (SST)
- Schwarzschild-Couder
- 3x3 km^2 area



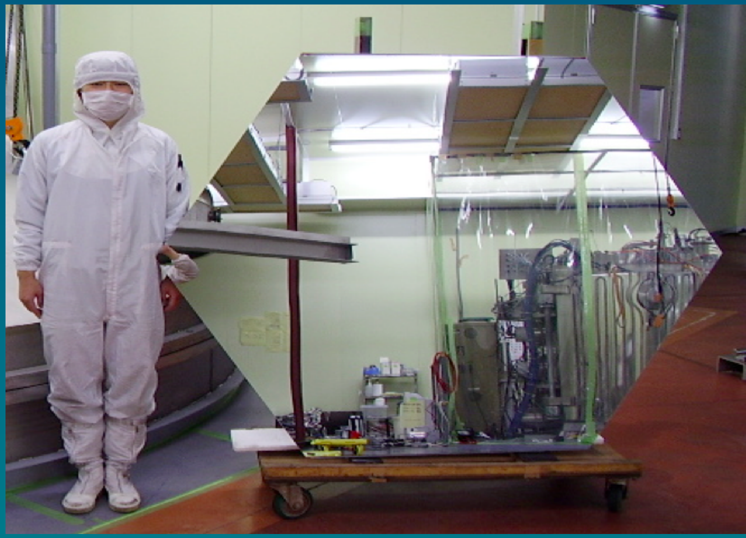
Large-Sized Telescopes

23 m *telescope for $E < 200$ GeV*

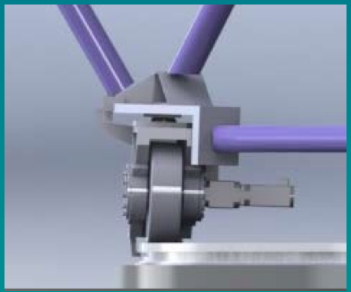


400 m² dish area

1.5 m spherical mirror facets



On (GRB) target in < 20 sec.

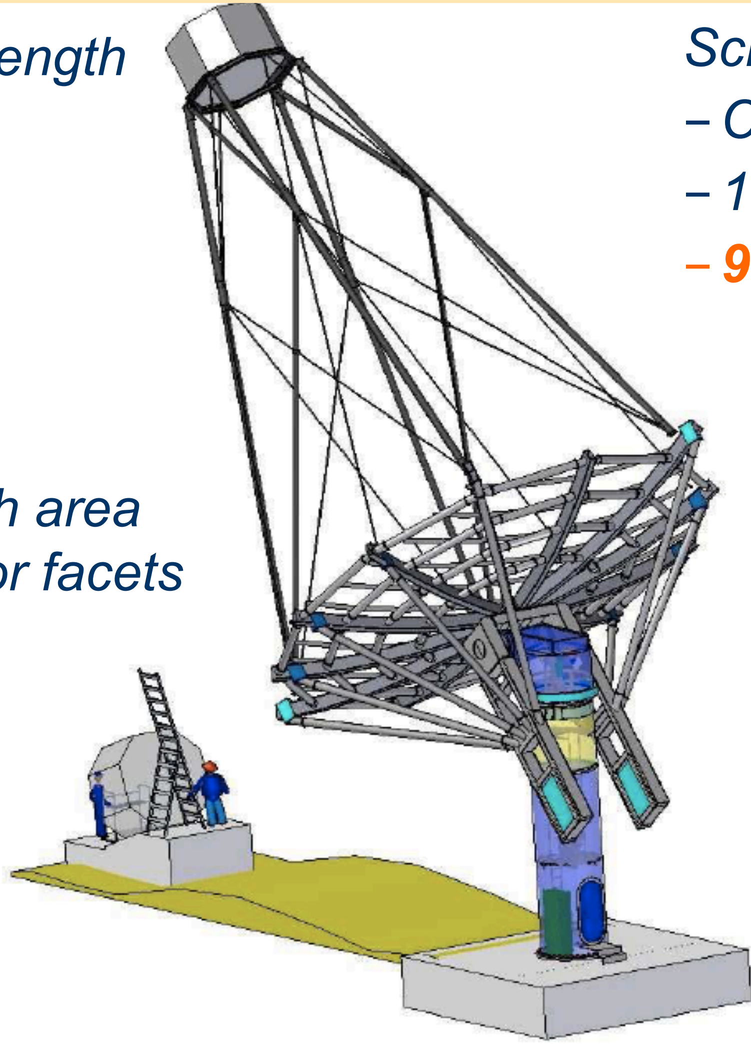


Medium-Sized Telescopes

12 m telescope for E: 100 GeV – 10 TeV

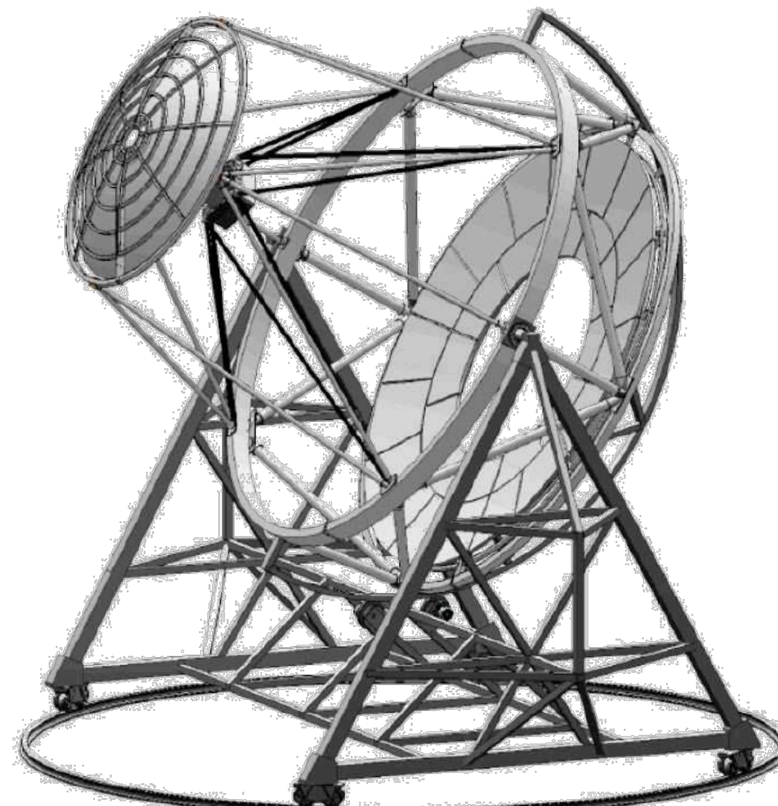
16 m focal length
8º FOV
0.18º pixels

100 m² dish area
1.2 m mirror facets



Schwarzchild-Couder MST (US):

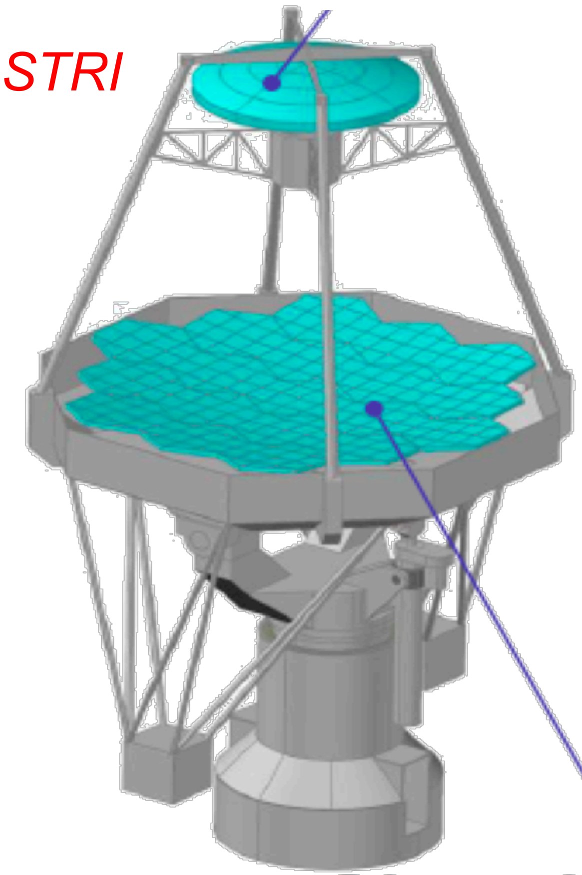
- *CTA South expansion: +36 SC-MST*
- *10 m primary*
- ***9º FOV***



Small-Sized Telescopes

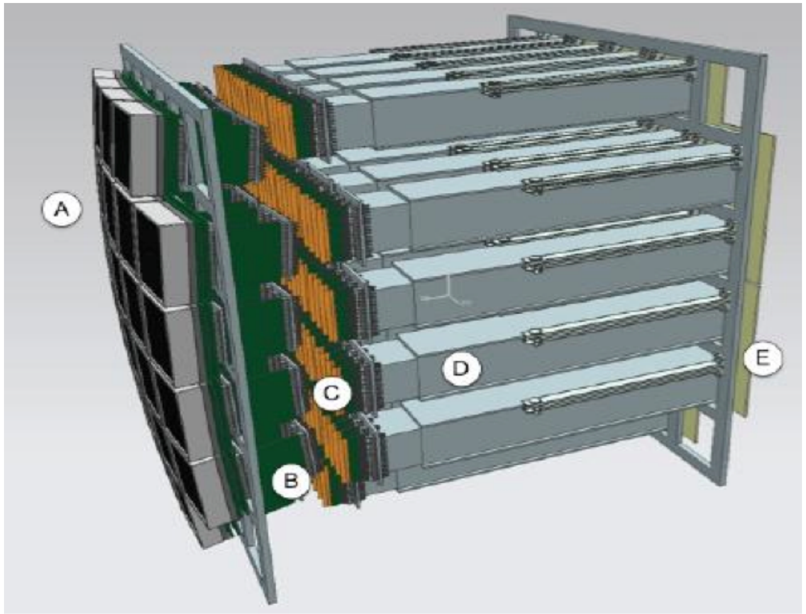
4 m SC telescope for E > few TeV

ASTRI



Baseline camera (SST & SC-MST):

- Silicon PMs
- **10º FOV**



The CTA era: recent news

First operative SST inaugurated this week in Sicily (Etna observatory)

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PRONTO IL PROTOTIPO DI UNO DEI TELESCOPI

Prove di CTA sull'Etna

Mercoledì 24 settembre presso la stazione osservativa di Serra la Nave dell'INAF-Osservatorio Astrofisico di Catania, inaugurazione di SST, il prototipo dei telescopi di piccola taglia che comporrà parte della estesa rete di rivelatori del Cherenkov Telescope Array (CTA). Giovanni Pareschi (INAF): «siamo il primo gruppo che farà un test con un telescopio prototipale completo che rispetta perfettamente i requisiti imposti dal programma CTA»

di Marco Galliani — venerdì 19 settembre 2014 @ 16:44

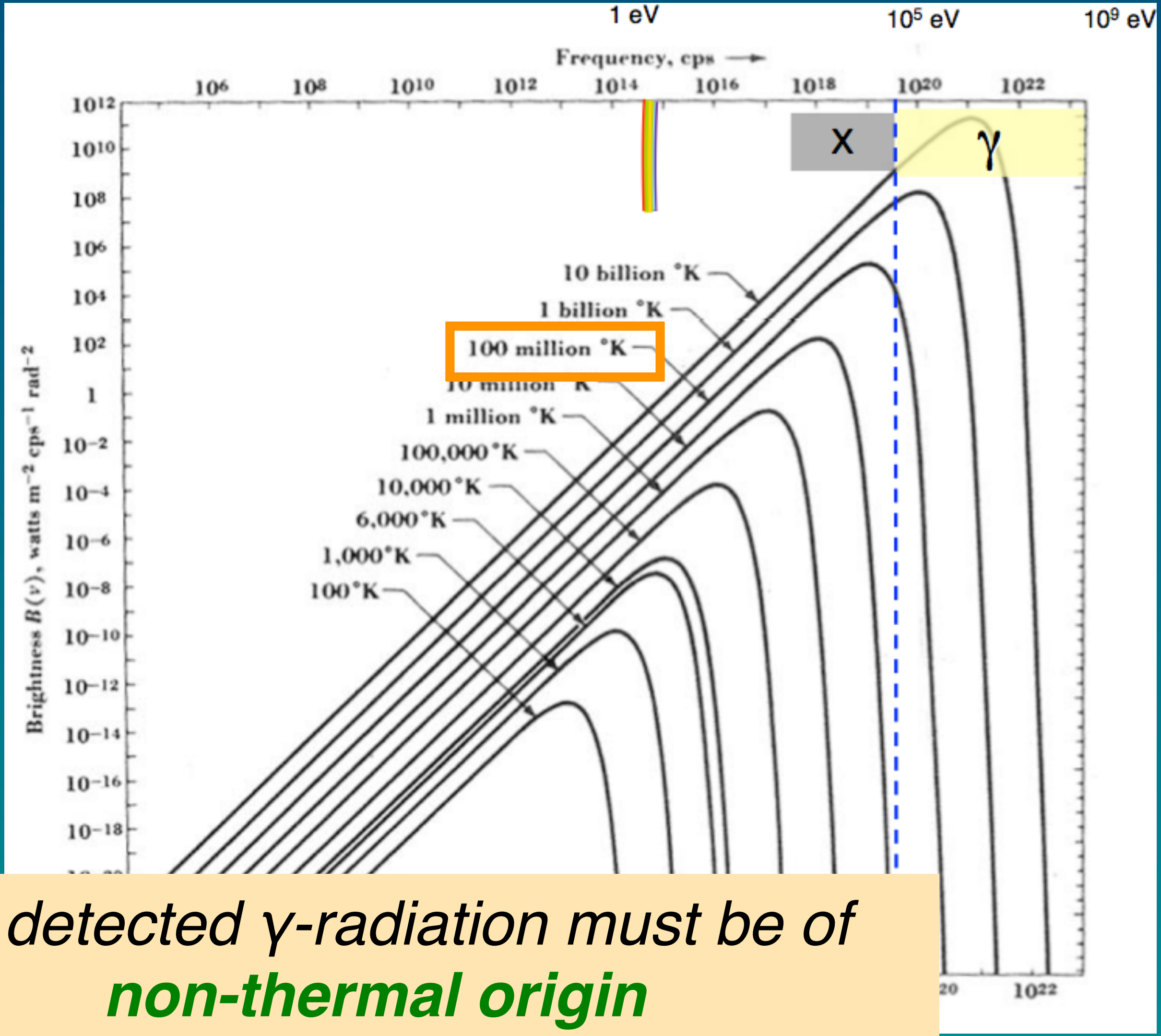
Deserto della Namibia o altipiani delle Ande? Forse meglio il complesso dell'Osservatorio astronomico del Leoncito in Argentina? La scelta del sito che ospiterà la porzione a sud dell'equatore del Cherenkov Telescope Array (CTA), una batteria di telescopi destinati a studiare le sorgenti di radiazione gamma provenienti dall'universo che, una volta realizzato, sarà il più potente e sensibile osservatorio per i raggi gamma mai costruito, non è stata ancora presa.

Di certo però ora c'è che il prototipo del gruppo di telescopi di piccola taglia che comporranno questa fantastica rete di strumenti per indagare i più violenti fenomeni che avvengono nello spazio è italiano e verrà inaugurato il 24 settembre prossi-

γ-ray production processes in Astrophysics

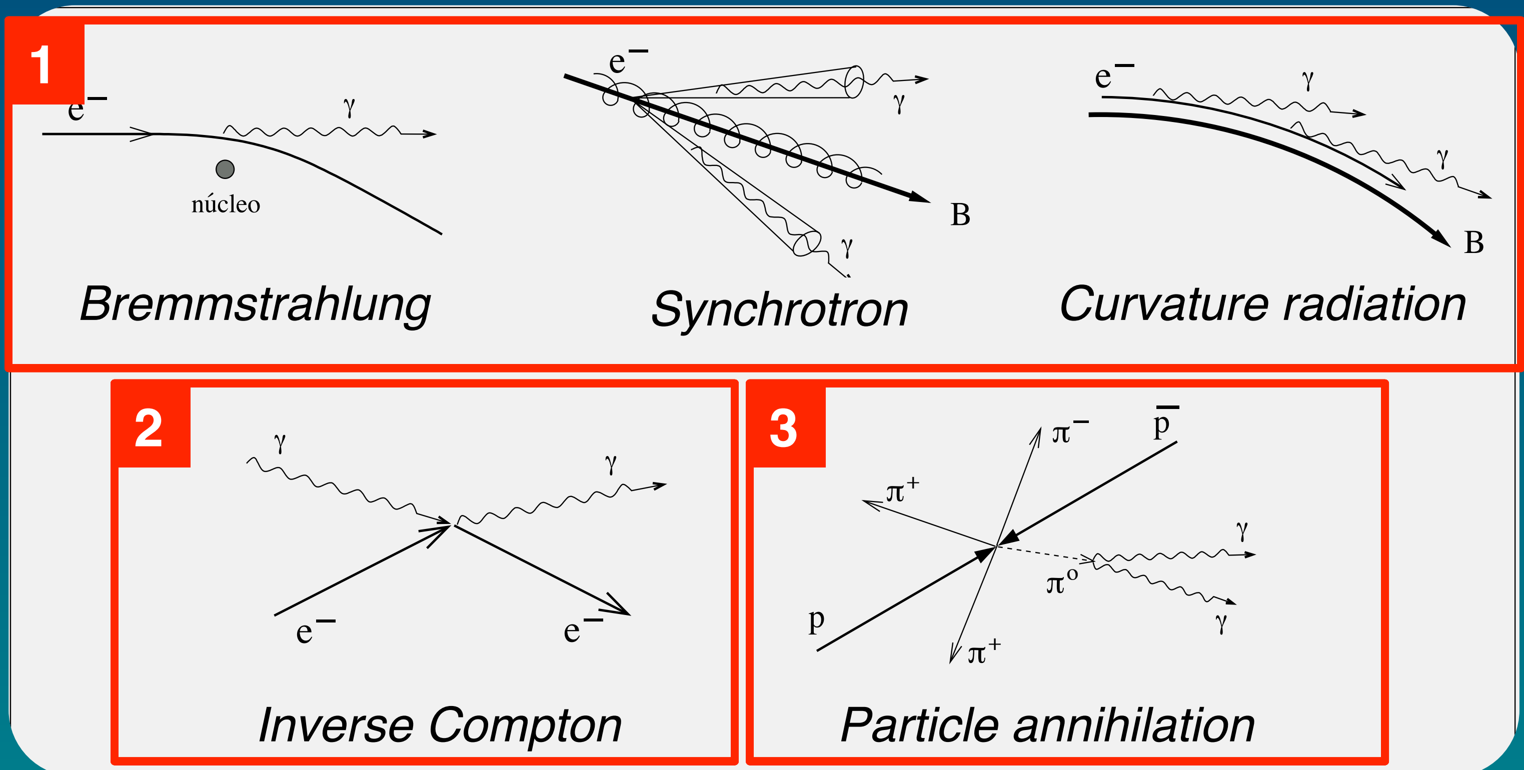
Non-termal origin of γ-rays

- EM radiation from the Sun and stars is mainly thermal
- A source emitting accordring to Blackbody spectrum cannot emit γ-rays unless **$T > 10^8$ K**



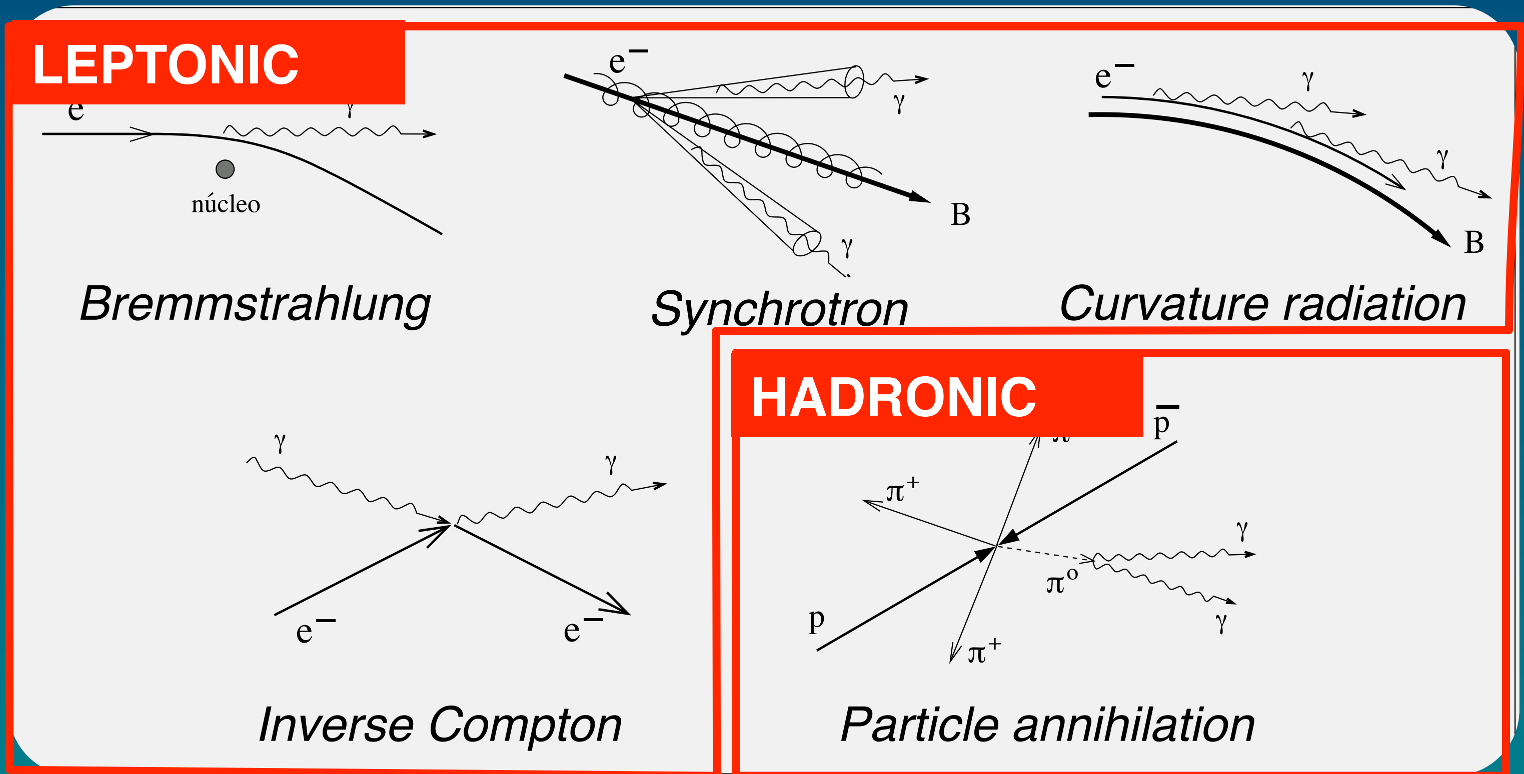
The detected γ-radiation must be of ***non-thermal origin***

Production of γ-rays



1. Acceleration of charged particles in EM fields
2. Inverse Compton effect
3. Disintegration of pions produced in the interaction of protons with the interstellar medium

Production of γ-rays



Theses mechanisms can be grouped into:

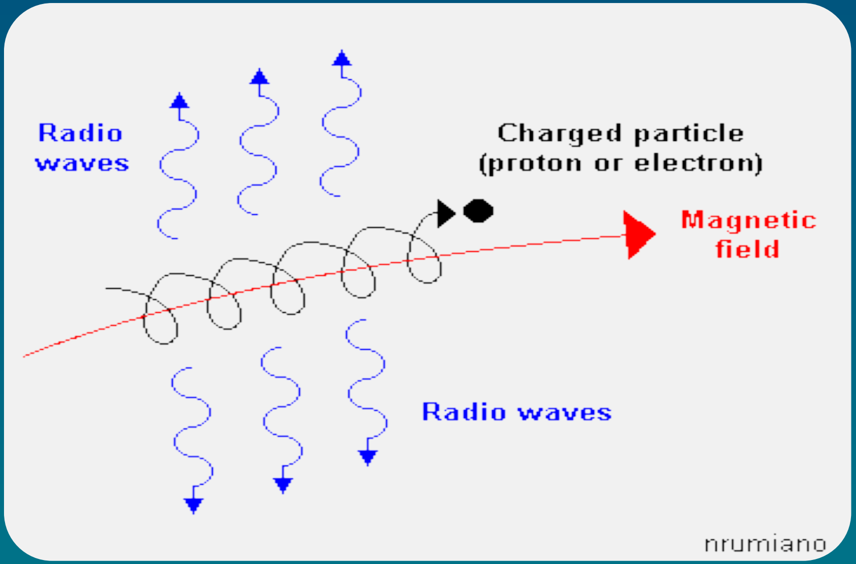
- Leptonic
- Ladronic

From high-energy e^- to γ-rays

Synchrotron, IC y SSC

Synchrotron radiation

- Emitted by charged particles accelerated along curved magnetic field lines
- Discovered for the first time in Astrophysics in 1957, in the jet of the M87 galaxy




The jet in M87 seen in X-rays by Chandra

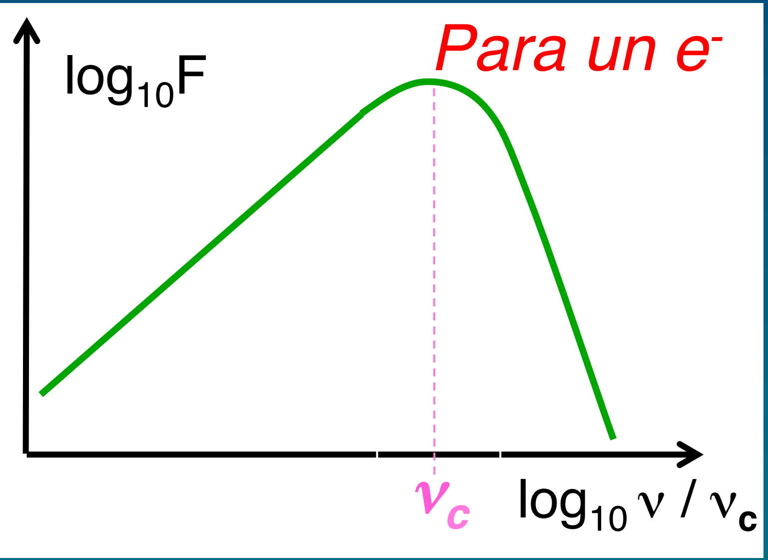
Synchrotron radiation

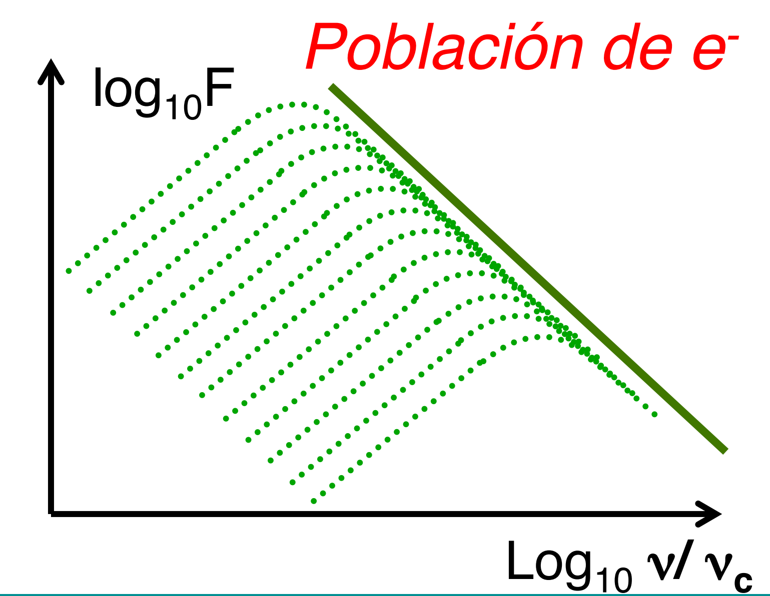
- The photon spectrum emitted by a single e^- accelerated along a field line B follows a power-law until a frencuency ν_c, beyond which it falls exponentially
- For a population of e^- which energies distributed according to a power-law: $n_{e^-} \propto \gamma^{-p}$

  the resulting photon spectrum is the sum of the spectrum emitted by each e^-:

$$\frac{dN_\gamma}{dE} \propto B^{\frac{p+1}{2}} \cdot E^{-\frac{p+1}{2}}$$

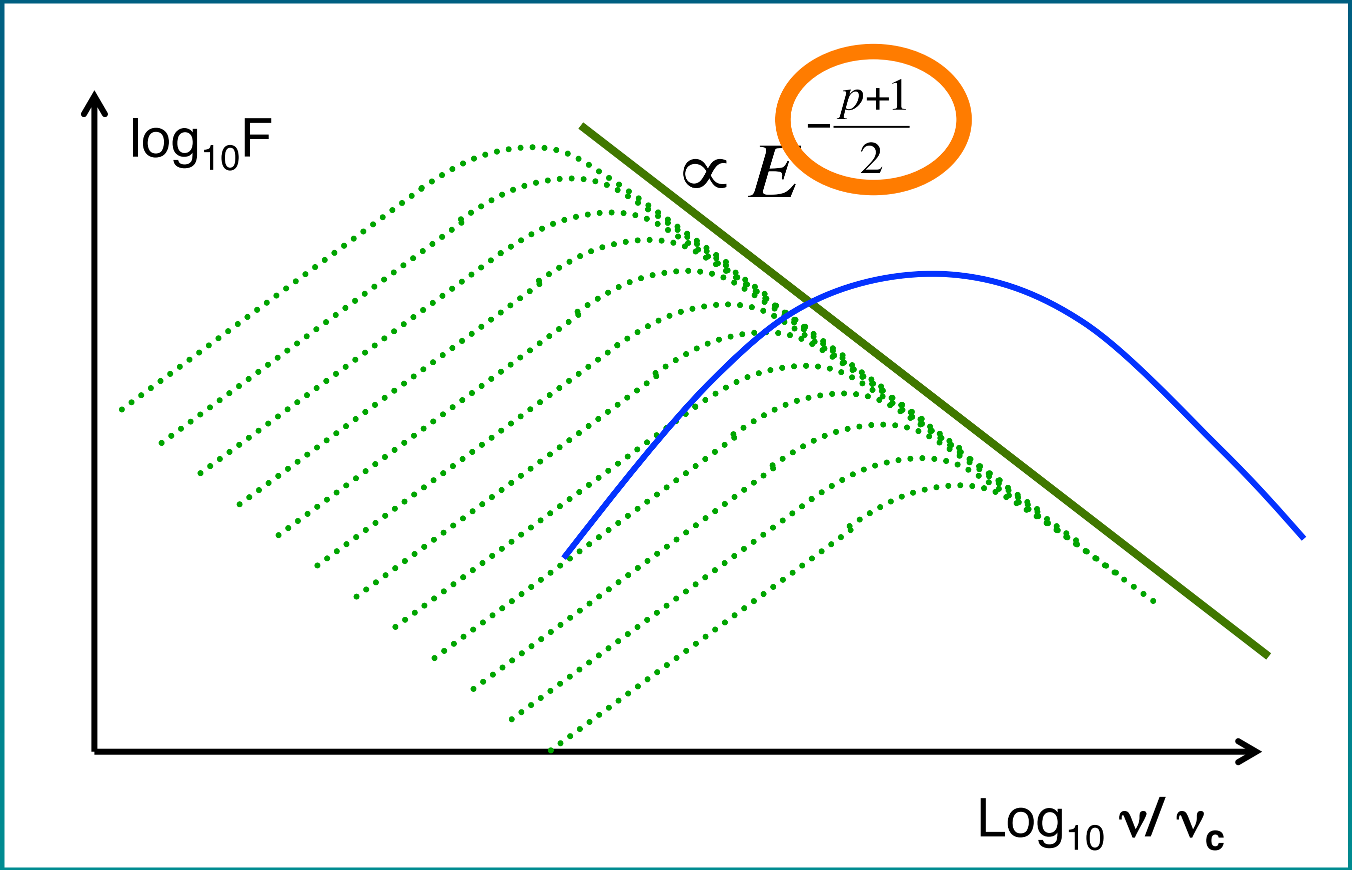
  - Now it falls like a power-law





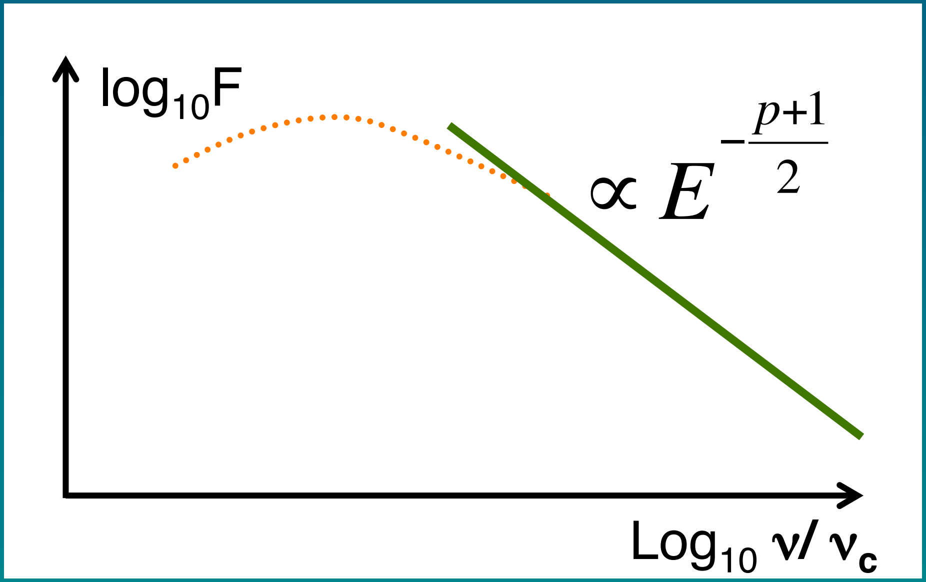
Synchrotron radiation

… the resulting spectrum is very different from the typical blackbody one



Synchrotron radiation

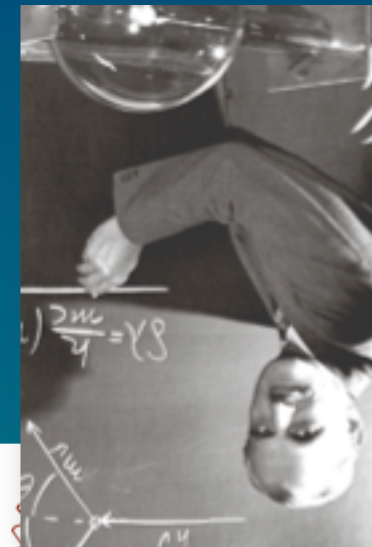
- In reality, the the spectrum doe not follow a power-law for all energies:
  - Low energy photons are ‘absorbed’ by the e⁻, process called Synchrotron self absorption

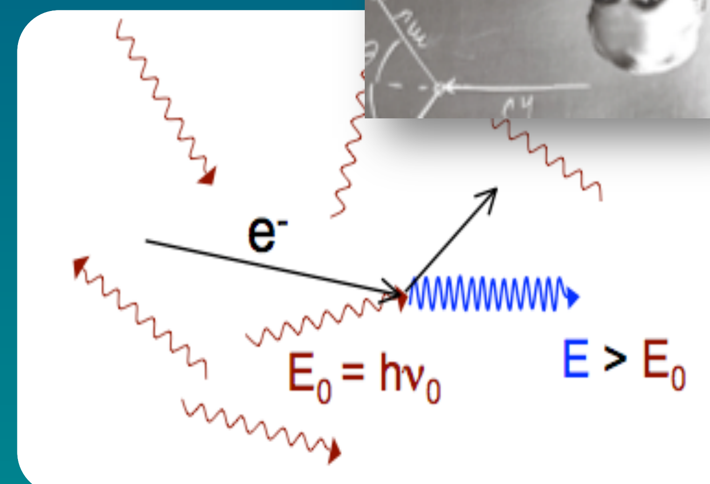


Synchrotron radiation emitted mainly in radio, but we will see that it is relevant for the production of γ-rays

Inverse Compton scattering (IC)

- Ingredients
  - Relativistic e^-
  - Background of ‘soft’ photons
    - E.g.: cosmic microwave background (CMB), optical photons from star or dust, Synchrotron photons
- Inverse because photons gain energy from the e^-





Inverse Compton scattering (IC)

Average energy gained by photons in Thomson limit ($\gamma h\nu_0 << m_e c^2$)

- Let's assume an e^- in an isotropic photon field, all photons having the same energy $h\nu_0$
- The average energy gained by the photons is:

Energy gained in one scattering

$$h\bar{\nu} = \frac{(dE/dt)_{IC}}{\sigma_T c U_{rad} / h\upsilon_0} = \frac{4}{3}\gamma^2 \left(\frac{V}{c}\right)^2 h\upsilon_0 \quad \xrightarrow{\beta\sim 1} \quad h\bar{\nu} \approx \frac{4}{3}\gamma^2 h\upsilon_0$$

Number of scattered photons per unit time

Electrons with $\gamma = 10^2$ - 10^3 exist in various astrophysical environments. They can convert low E photons in γ-rays via IC

E.g: 500 MeV e^- ($\gamma\sim 10^3$) with photons of $h\nu_0 \sim eV$ ➔ $h\bar{\nu} \sim MeV$

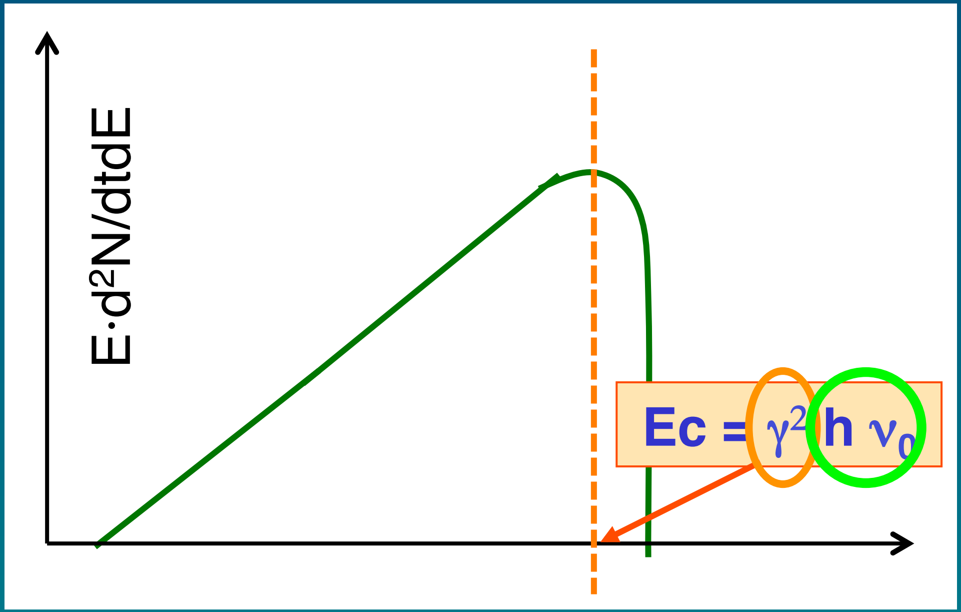
Inverse Compton scattering (IC)

IC Spectrum emitted by a single electron

(Thomson limit: $\gamma h\nu_0 \ll m_e c^2$)

- Follows a power-law, up to a critical energy Ec, beyond which it drops
- The maximum energy that photon can reach is:

Emax ~4 γ^2 h ν_0



IC spectrum emitted by a population of e- with energies distributed according to a power-law (p=2)

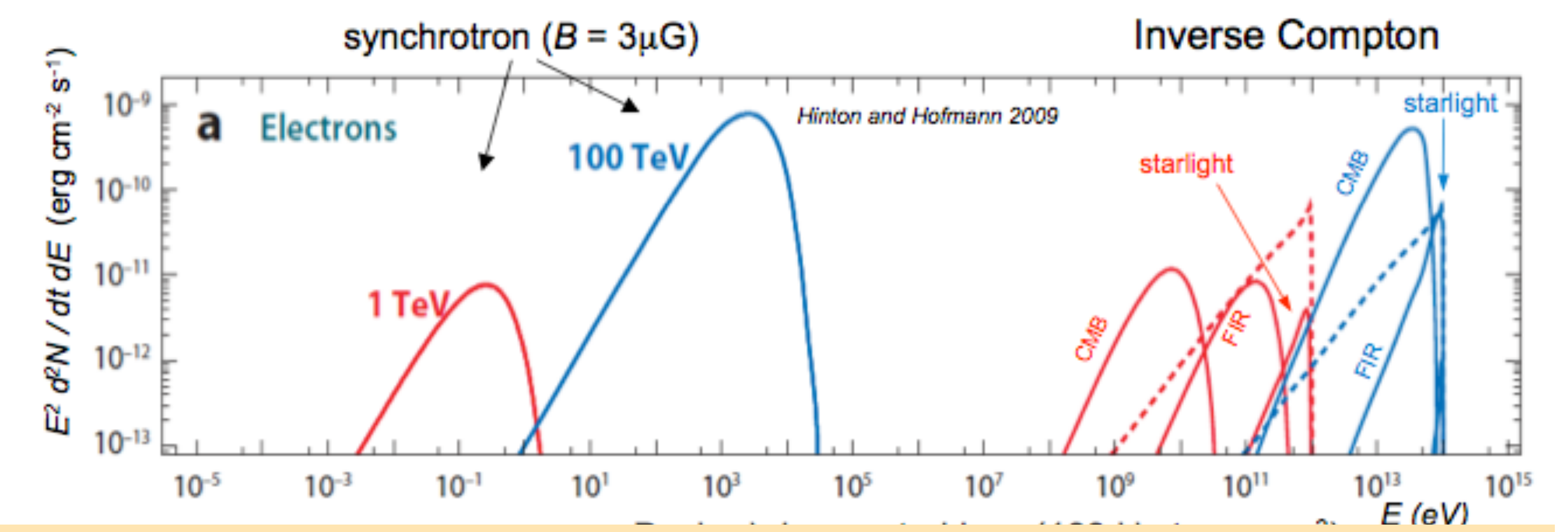
$$N_e(\gamma) \propto \gamma^{-p} \rightarrow \frac{dN}{dE} \propto E^{-(p+1)/2} = E^{-1.5} \text{ for } p = 2$$

Like in the Synchrotron case

Comparison Synchrotron Vs IC

Example: Mono-energetic e^- of 1TeV & 100 TeV on different photon fields:

- CMB: $kT = 2.35 \cdot 10^{-4}$ eV
- Light emitted by dust in the far IR (FIR): kT = 0.02 eV
- Optical stellar light: kT = 1.5 eV



100 TeV e^- on optical photons produce γ-rays of 100 TeV

Comparison Synchrotron Vs IC

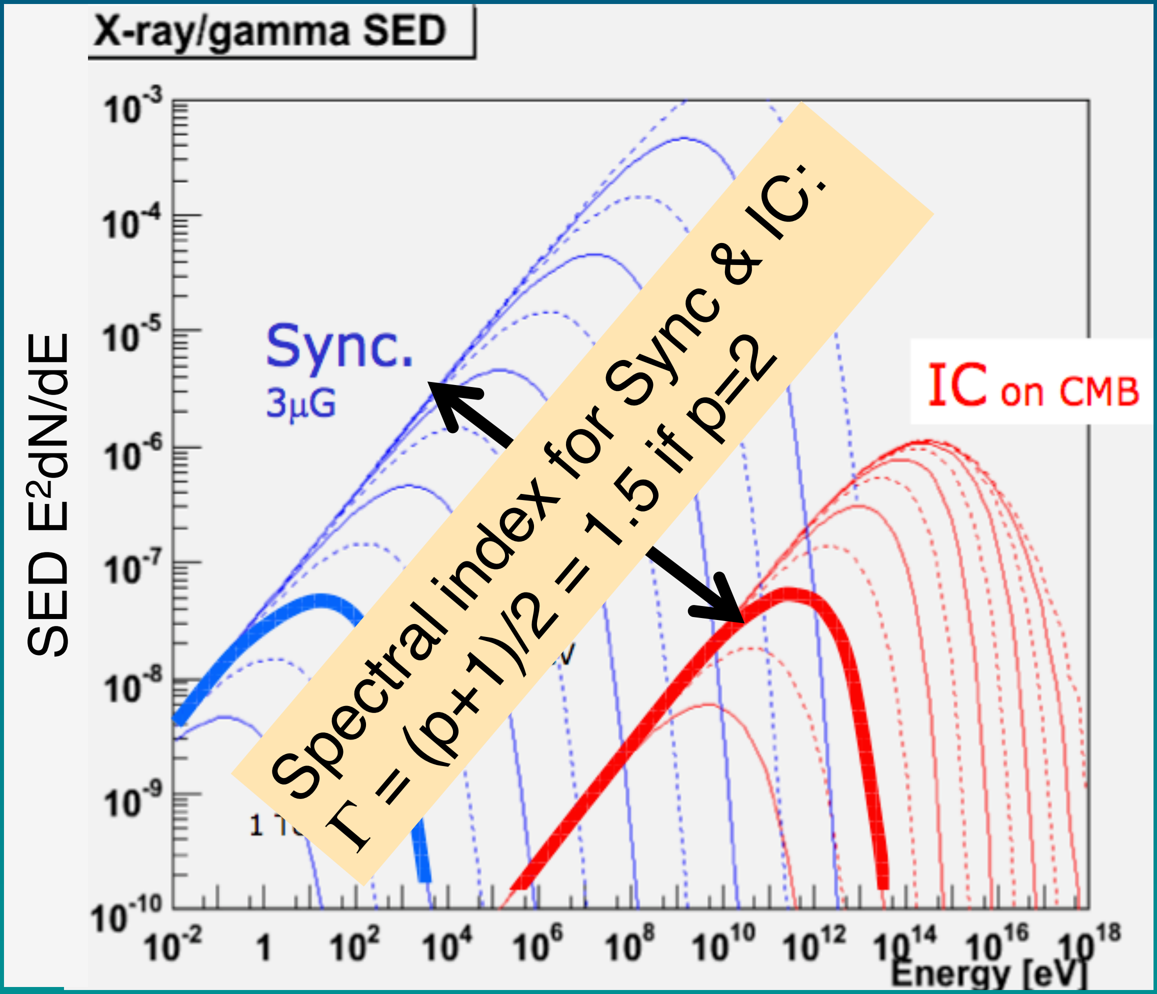
Example: population of e^- distributed according to a power-law of index p=2 interacting with CMB photons:

$$N_e(\gamma) \propto \gamma^{-p}$$

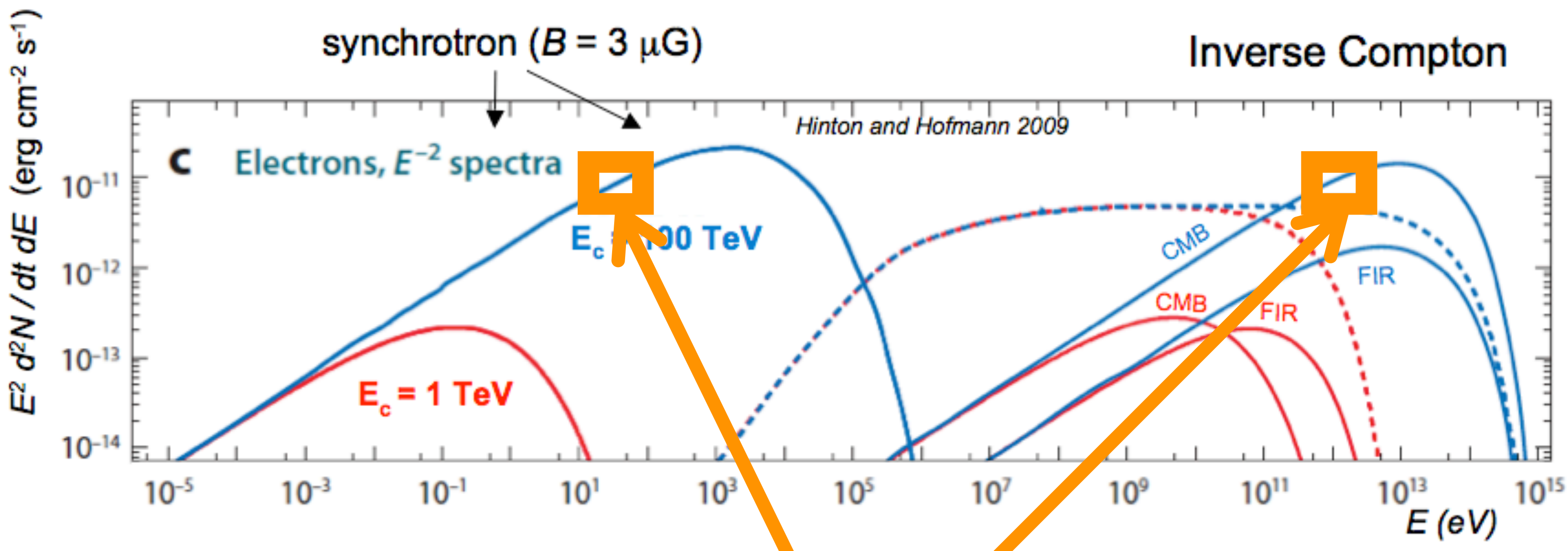
↓

$$\frac{dN}{dE} \propto E^{-(p+1)/2} = E^{-1.5}$$

- The spectrum is multiplied by E^2 (such the e^- spectrum is flat)



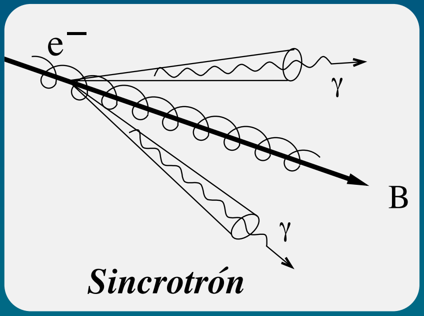
From electrons to γ-rays



Measuring simultaneously the Synch. and IC components, (multiwavelength observations) we can measure the B-filed in the emitting region

$$\frac{(Energy\ flux)_{Sync}}{(Energy\ flux)_{IC}} = \frac{(dE/dt)_{Sync}}{(dE/dt)_{IC}} = \frac{U_{mag}}{U_{rad}} = \frac{B^2}{2\mu_0 U_{rad}}$$

Synchrotron Self-Compton (SSC)



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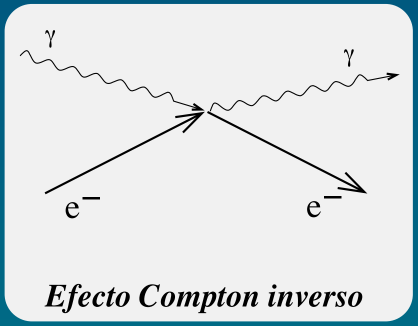

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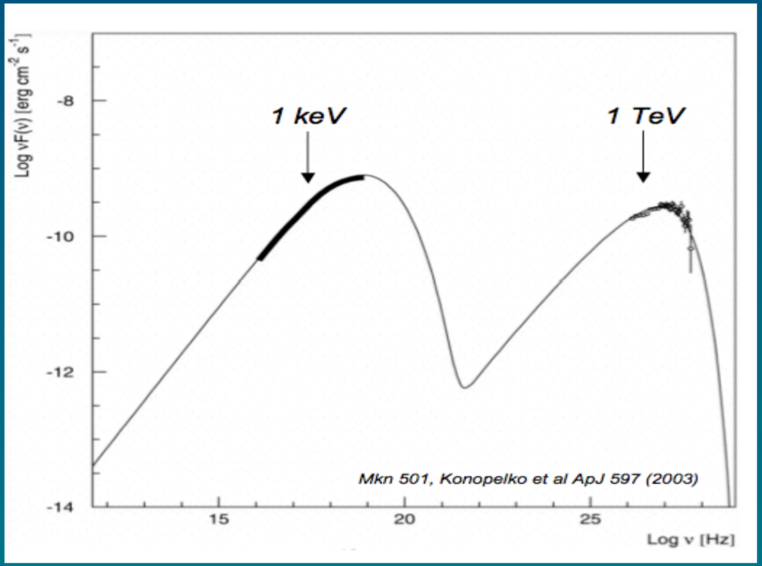


- Synchrotron photons can interact with the same e^- population which emitted them and gain energy via IC
- This is known as the SSC mechanism
- This explains the origin of γ−rays is many astrophysical sources, as AGNs, PWN,…

γ-rays from hadronic processes

$p \rightarrow \pi^0 \rightarrow \gamma\gamma$

Hadronic production of γ-rays

- High-energy protons (and nuclei) can also produce γ-rays
- **Main process:** inelastic collisions with ambient gas, producing pions

High-energy proton

proton of the interstellar medium

$$p + p \rightarrow \ldots + \pi \begin{cases} 33\%\ \pi^0 \begin{cases} \pi^0 \rightarrow \gamma + \gamma & (98.8\%) \\ \pi^0 \rightarrow e^+ + e^- + \gamma & (1.2\%) \end{cases} \\ 33\%\ \pi^- \rightarrow \bar{\upsilon}_\mu + (\mu^- \rightarrow e^- + \bar{\upsilon}_e + \upsilon_\mu) \\ 33\%\ \pi^+ \rightarrow \upsilon_\mu + (\mu^+ \rightarrow e^+ + \upsilon_e + \bar{\upsilon}_\mu) \end{cases}$$

Other particules

Minimum proton energy to produces pions: *Emin = 280 MeV*

Hadronic production of γ-rays

γ-ray spectrum from a proton population with a power-law energy distribution

- For a power-law distribution of protons the resulting γ-ray spectrum is also a power-law with the same spectral index

$$n_p \propto E^{-p} \rightarrow \frac{dN_\gamma}{dE} \propto E^{-p}$$

Same spectral index

- If proton spectrum has a cut-off exp(–Ep/ E^0), the γ-ray spectrum has it also, but at lower energies:

$$n_p \propto E^{-p} \cdot \exp\left(-\frac{E}{E_0}\right) \rightarrow \frac{dN_\gamma}{dE} \propto E^{-p} \cdot \exp\left(-\left(\frac{16E}{E_0}\right)^{1/2}\right)$$

Summary

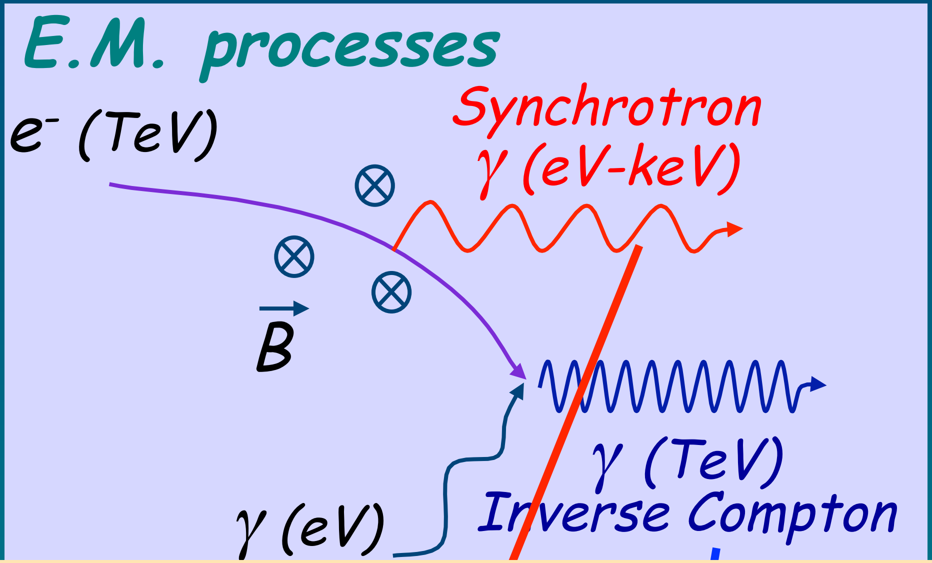
γ-ray spectra reflect the underlying spectra of the high energy particles which produce them:

- Electrons: E^{-p}
  - Synchrotron: $E_\gamma^{-(p+1)/2}$
  - Inverse Compton: $E_\gamma^{-(p+1)/2}$ (clasic regime: Thompson)
    $E_\gamma^{-(p+1)}$ (quatum regime: K-N)
- Protons or nuclei: E^{-p}
  - π^0 production & decay: E_γ^{-p}

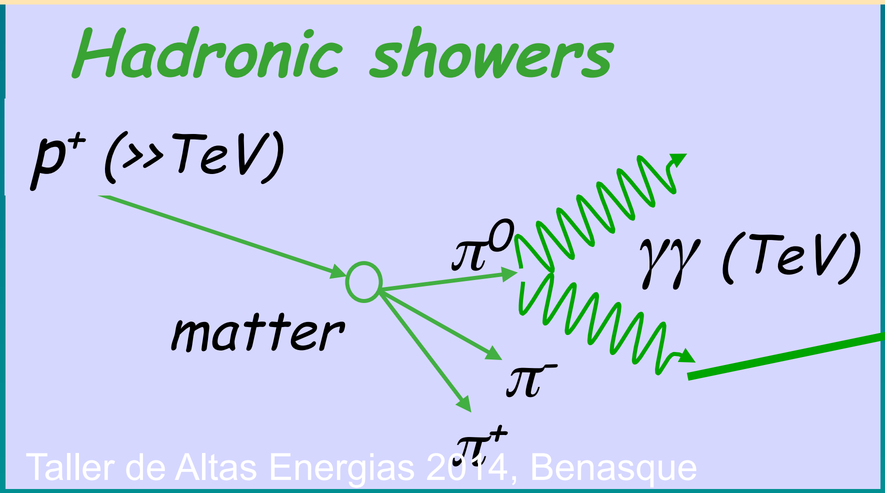
*Provide information on the conditions in the emission region (**B**, target matter density)*

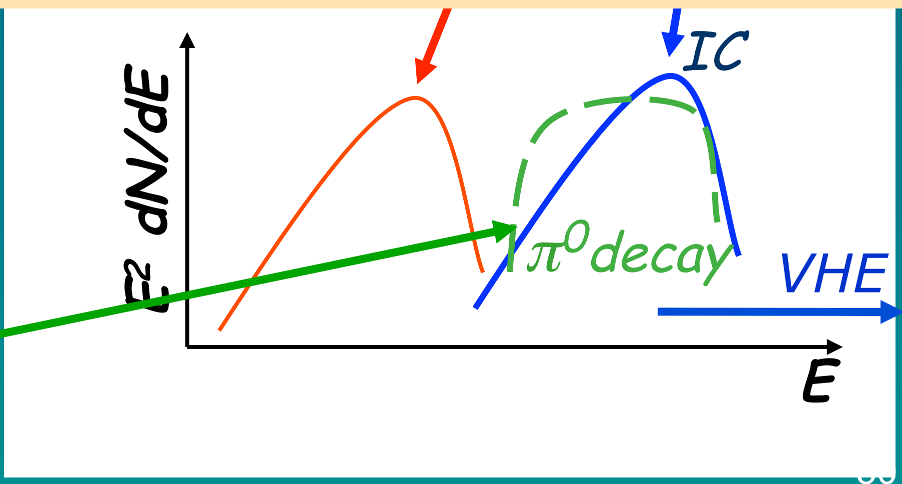
Dilema:
Leptonic or hadronic origin of γ-rays

To distinguish between leptonic or hadrnic scenarios we need to measure the γ-ray spectrum of the astrophysical sources



The SSC model explain most of the observed sources





- So far we have assumed that the energy distribution of particles (e^- or protons) follows a power-law of spectral index -2
- This was not an arbitrary election. We will see now why

Particle accelaration mechanisms

For producing high-energy γ-rays (> MeV) we need:

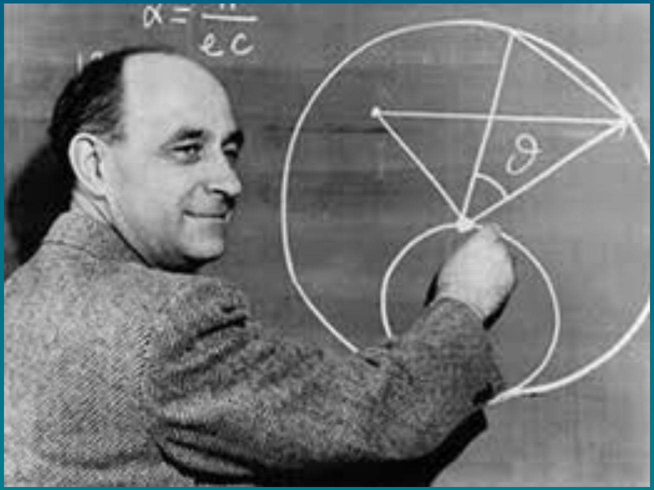
- High-energy particles

→ *Requires a mechanism to accelerate particles up to ultra-relativistic energies*

- A target (magnetic field, photons, matter)

Fermi acceleration mechamism

- Fermi proposed a mechanism to explain how the cosmic particles could reach ultra high energies
  E. Fermi: "On the Origin of the Cosmic Radiation" (1949)

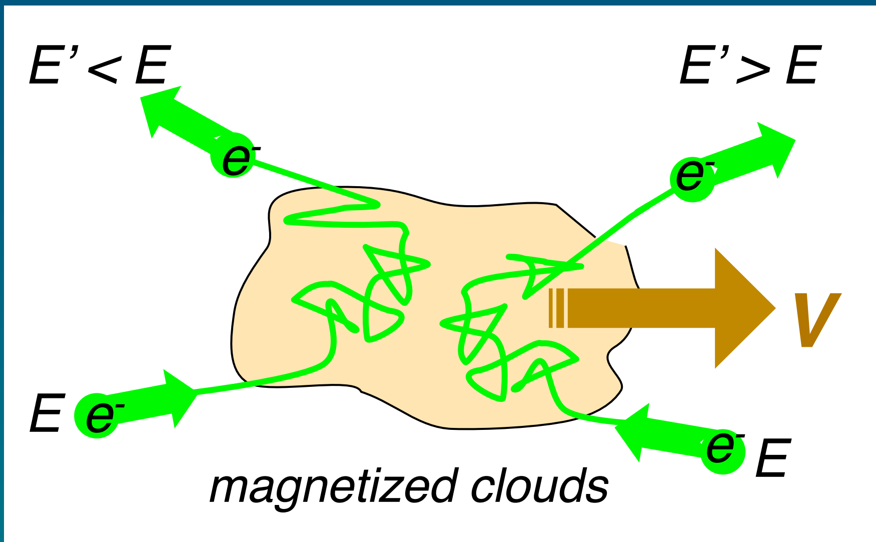


"... cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields."

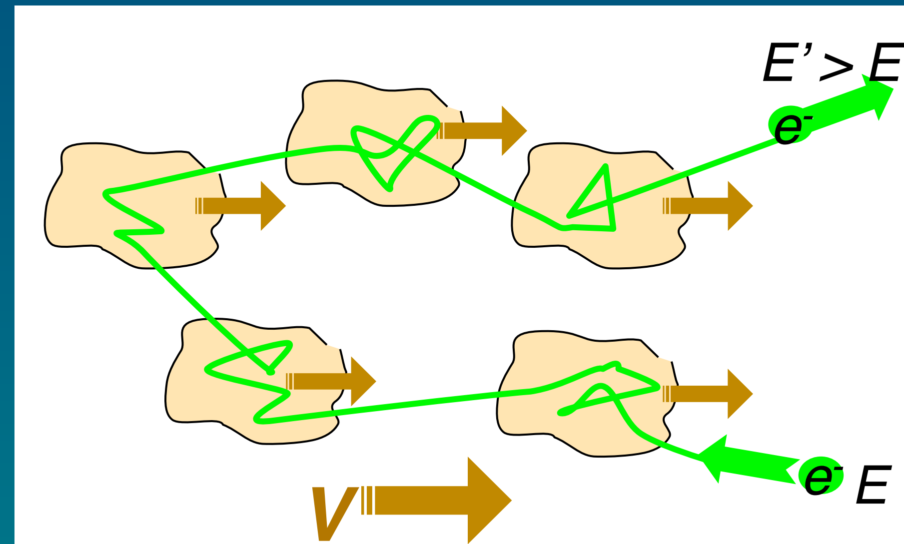
- **Idea:** Cosmic particles could gain energy if they are reflected by "magnetic mirrors" moving in random directions. The role of "magnetic mirrors" would be played by **magnetized clouds of interstellar material**

Second order Fermi acceleration

- Clouds move in random directions



Detail of the collision with one cloud



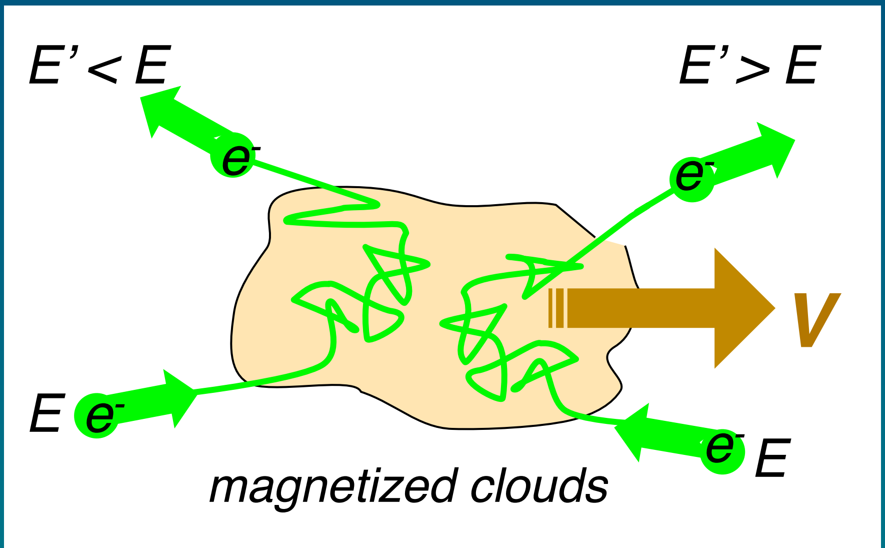
Result after colliding with many clouds

- Particle collides with the cloud:
  - gains energy in “head-on” collisions
  - loses energy in “overtaking” collisions
- Head-on collisions are more frequent

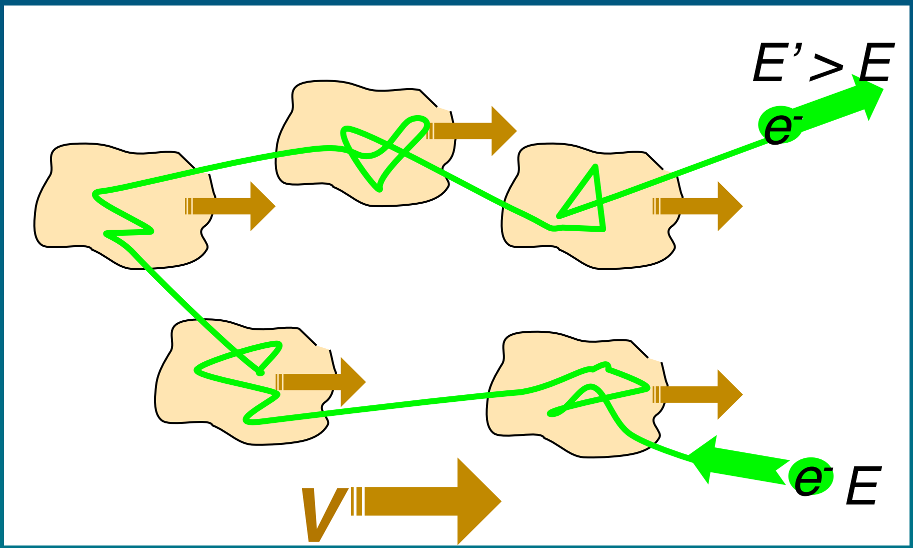
→ In average, there is a **net energy gain**

Second order Fermi acceleration

- Clouds move in random directions



Detail of the collision with one cloud



Result after colliding with many clouds

$$\left\langle \frac{\Delta E}{E} \right\rangle \sim \left(\frac{V}{c} \right)^2$$

The gained energy is proportional to the ***square*** *of the cloud velocity*

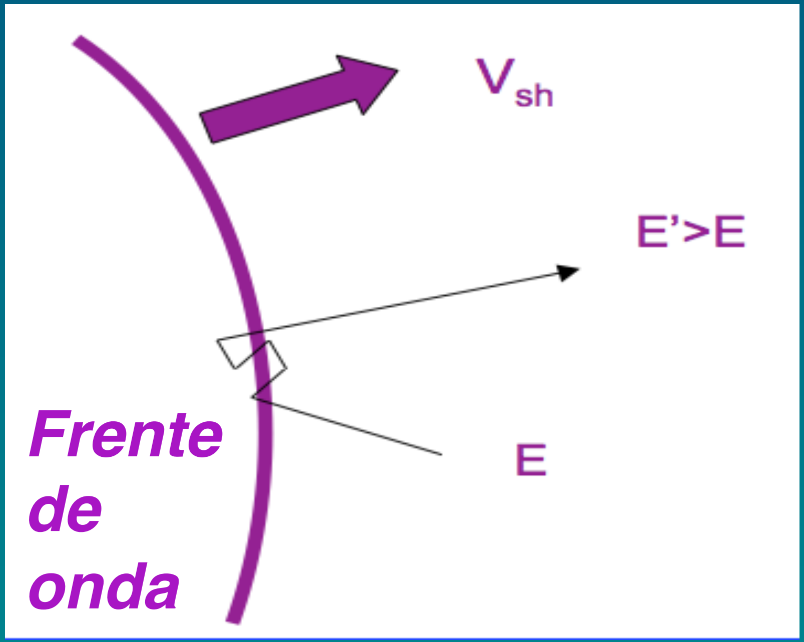
➔hence the name of second order mechanism

Problem: Is a very inefficient mechanism

$$\frac{V}{c} \sim 10^{-4} \Rightarrow \frac{\Delta E}{E} \sim 10^{-8}$$

First order Fermi acceleration

- To solve the inefficiency problem, Fermi proposed an alternative in which the particle collides with a shock front
- The particle gains energy every time it crosses the shock, independently from which side
  - Both in the upstream and downstream reference systems the particle sees the medium approaching



$$\left\langle \frac{\Delta E}{E} \right\rangle \sim \frac{V}{c}$$

$$\frac{V}{c} \sim 10^{-2} - 10^{-3}$$

Shock fronts move much faster than molecular clouds

It works: It's a efficient mechanism

First order Fermi acceleration

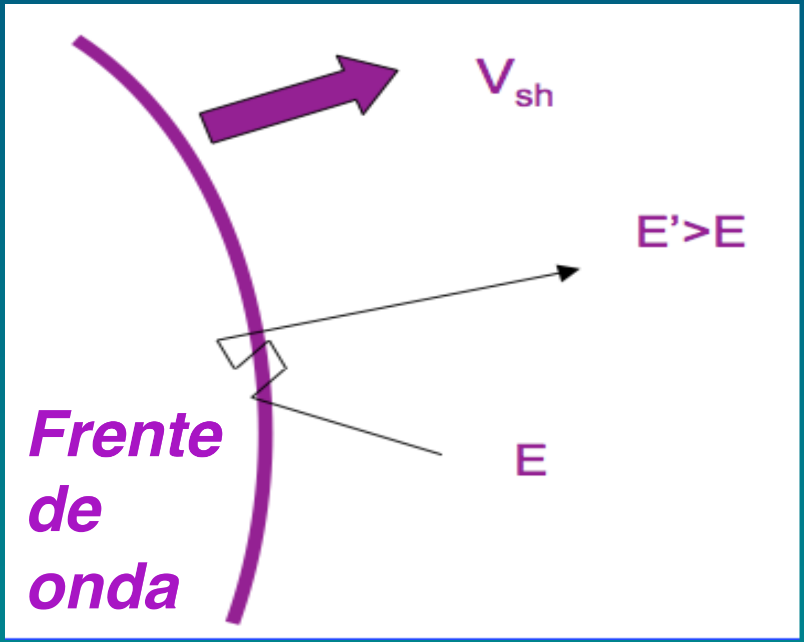
- To solve the inefficiency problem, Fermi proposed an alternative in which the particle collides with a shock front

- Predicts a power-law spectrum for the accelerated particles:

$$\frac{dN}{dE} = E^{-\frac{R+2}{R-1}}$$

R is the compression factor of the shock front. Typically R=4

$$\frac{dN}{dE} = E^{-2}$$



Astrophysical regions of particle acceleration

- Pulsar magnetoshpere
- Supernova Shock waves
- Accretion disks
- Relativistic Jets