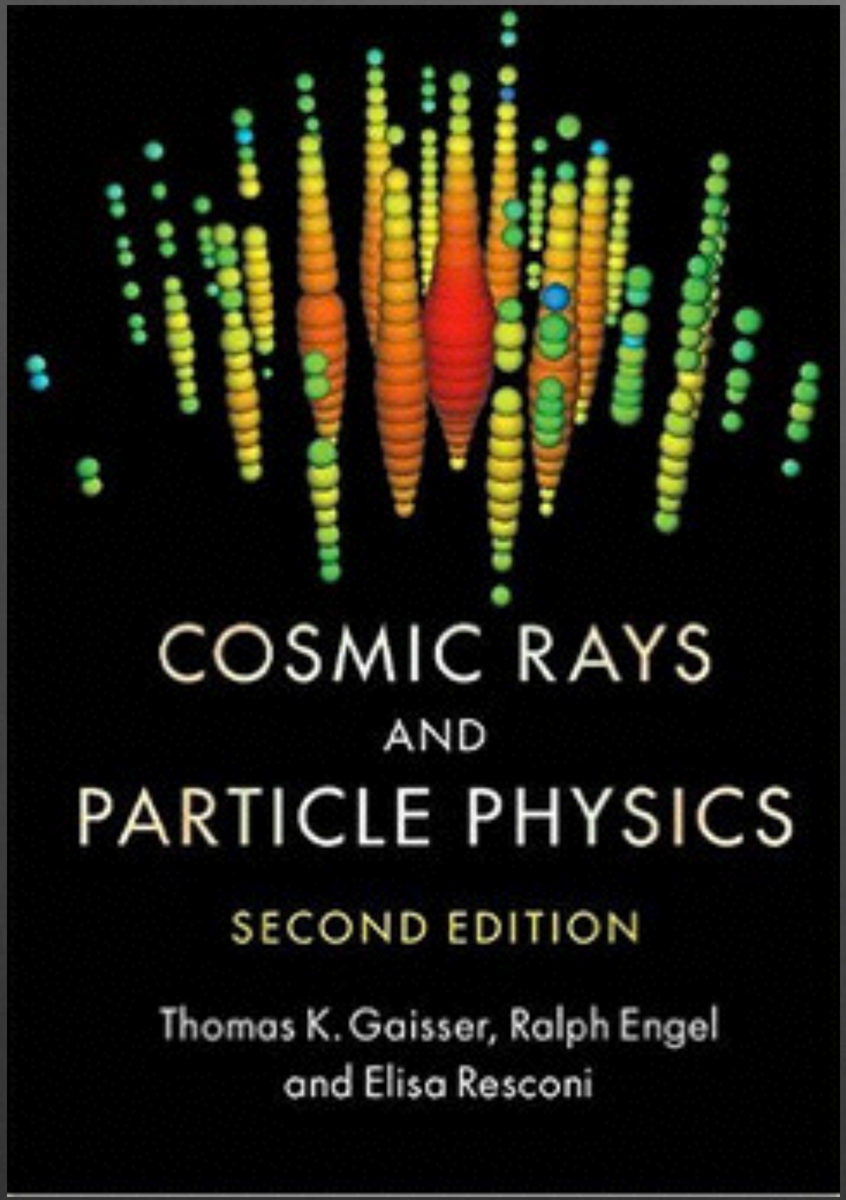
Cosmic Rays and Neutrino Astronomy, Part II

Elisa Resconi
Experimental Physics with Cosmic Particles

WS 2016/2017

Material for the course



Copies are available in the TUM library, PH department.

http://adsabs.harvard.edu/abstract_service.html

https://inspirehep.net

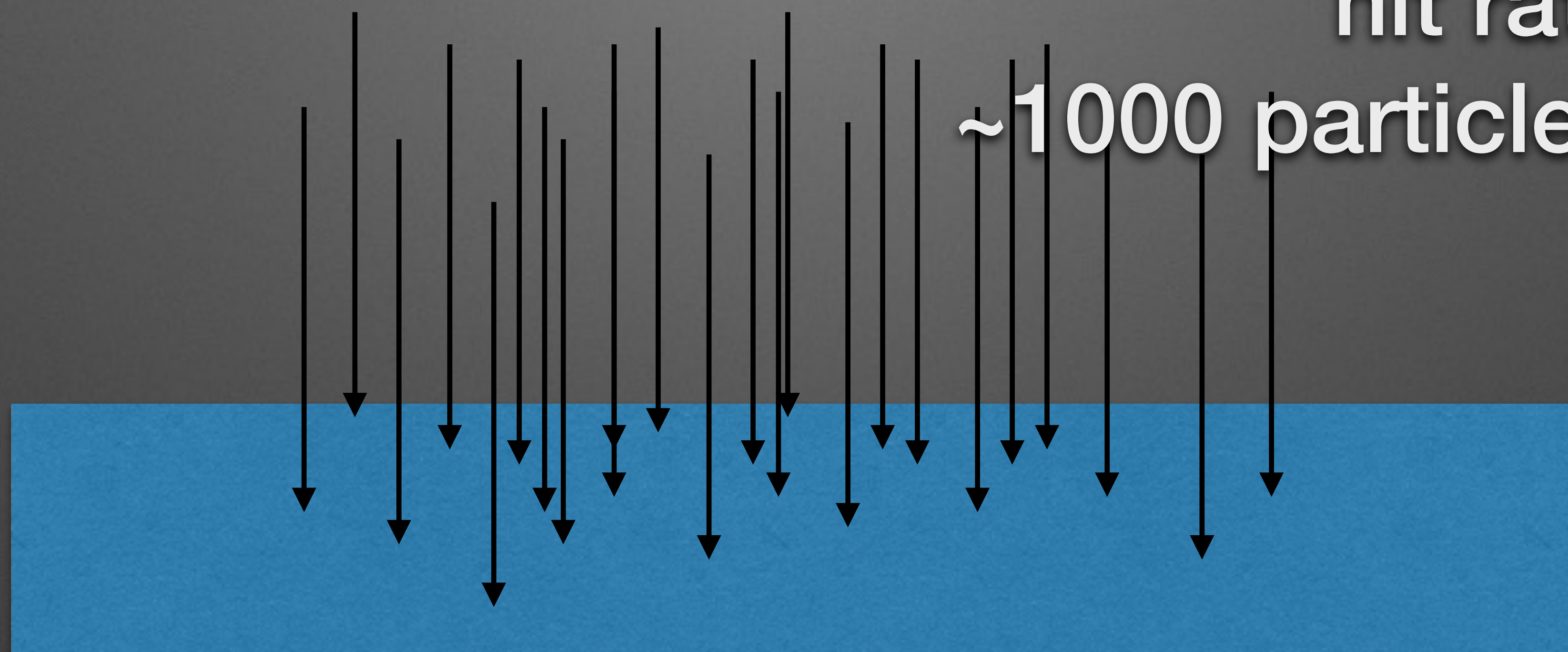
http://arxiv.org/list/astro-ph.HE/new

when / where this lecture?

Friday 10:00? conflict ….

Cosmic Rays =
relativistic particles and light nuclei hitting the Earth atmosphere

hit rate
~1000 particles / m^2 sec



- ionized nuclei: 90% protons, 9% alpha particles, heavier nuclei
- span 12 order of magnitude in energy
- relativistic or ultra-relativistic up to 10^{20} eV (~20 joules)
- highest energies ever observed

Where do they come from?
How are accelerated to such high energies?

What do we know:

- CRs come from outside the solar system
- during solar flares observed an anti correlation with the bulk of CR: effectively excluded from the solar neighbourhood during periods when the expanding magnetised plasma from the Sun is most intense
- CRs are within our Galaxy up to a certain energy
- the ultra-high energy CR have gyro radii in Galactic magnetic fields >> size of the Galaxy
- the highest end can not be of Galactic origin but …

here starts the complication!!

This lecture is divided in two modules, this is the No.2.

Goal of Module No.1:

- Investigate the connection between particle physics and CR physics
    - Historical connection (discovery of positron, muons, pion, kaon in the atmosphere)
    - Discovery of oscillation using atmospheric neutrinos (and also solar neutrinos)
- More recent:
    - astrophysics based on CR and their secondary products
    - dark matter searches

Where do they come from?
How are accelerated to such high energies?

This lecture divided in two module, this is the No.2.

Goal of Module No.2:

- Investigate the connection between astrophysical implication of CR physics: particle astrophysics
  - field experimentally driven: status of observations on
    - primary cosmic rays
    - gamma rays
    - cosmic neutrinos
  - cosmic accelerators
    - Galactic objects
    - Extragalactic objects
    - diffuse emissions

Program

CR_NA, WS16-17		
21.10		Multi-messenger Astronomy: status of experimental observations. Where are the sources of CR?
28.10		NO LECTURE
04.11		CR in the Galaxy, models of propagation
11.11		Astrophysical gamma-rays and neutrinos
18.11		Astrophysical accelerators and beam dumps
25.11		SNe in the Milky Way, Binary system
02.12	Jochen G.	GRBs
02.12		Extragalactic propagation of CR: GZK cutoff, FERMI diffuse
9.12	?	IceCube? nu astro?
16.12		Extragalactic diffuse interactions
13.01	Paolo P.	AGN
20.01		Neutrino Astronomy
27.01	David P.	Gamma Ray Astronomy
03.02		The road map to the sources of CRs.
10.02		

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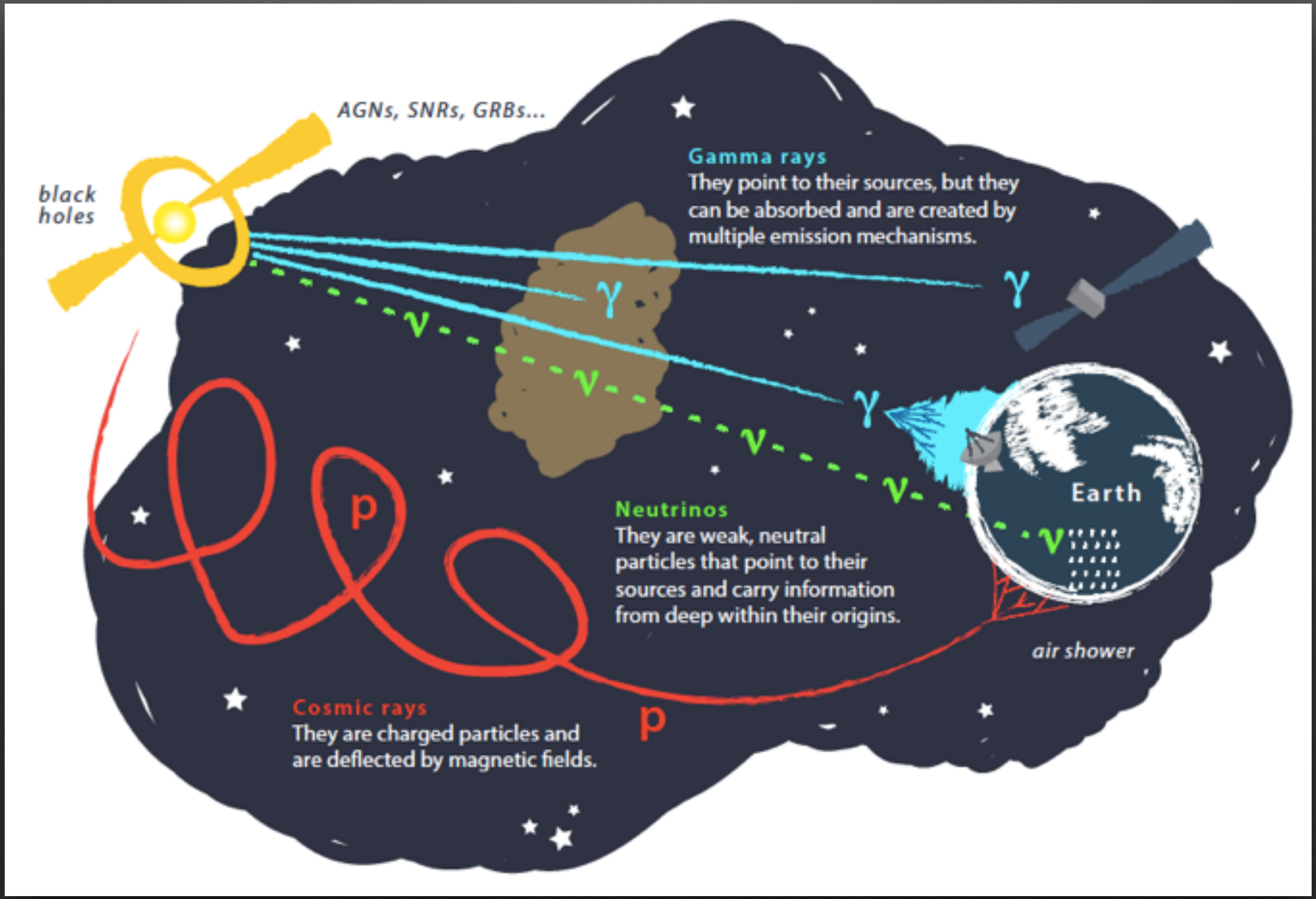
Multi-messenger what? the simplified picture



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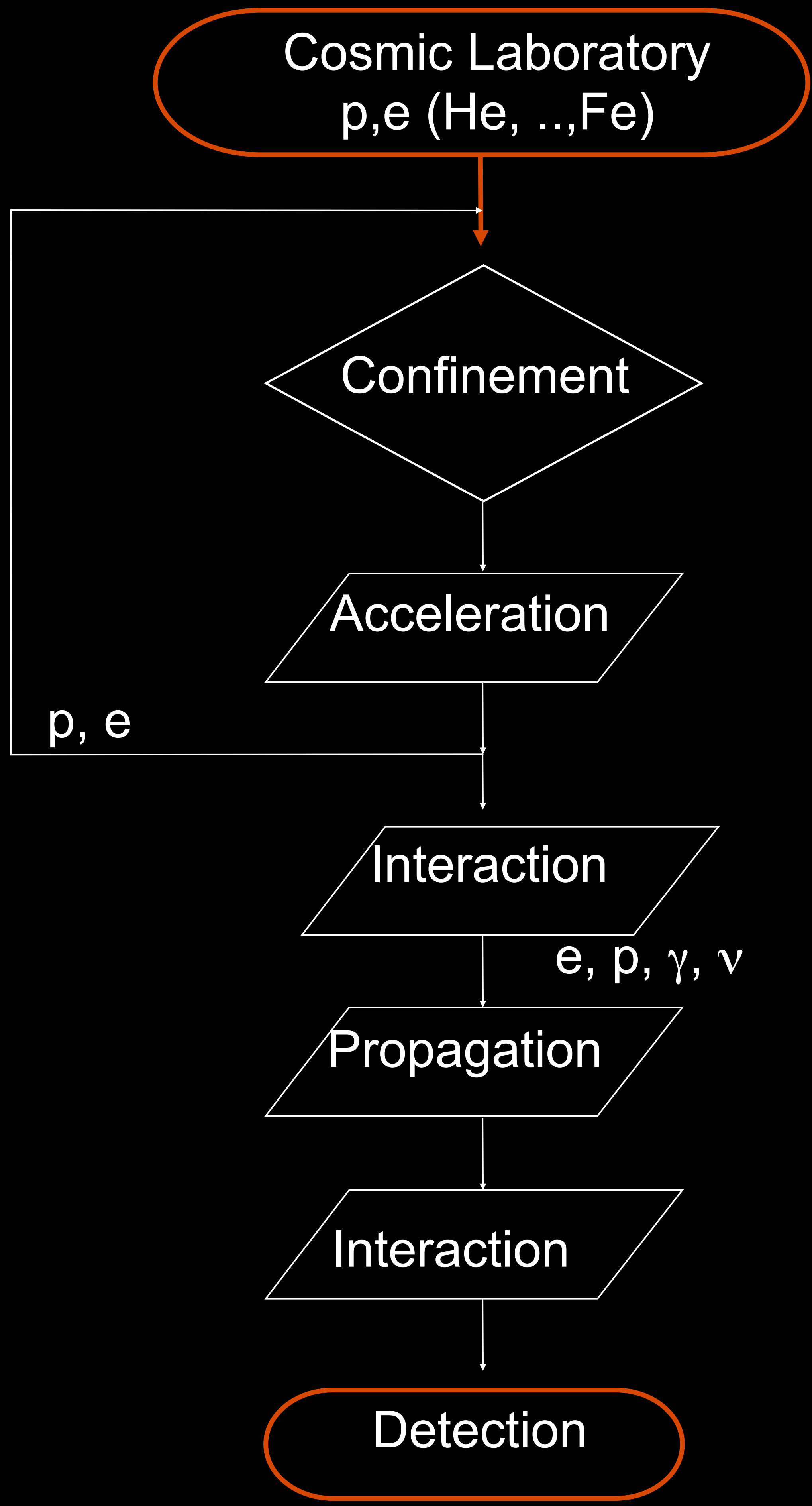
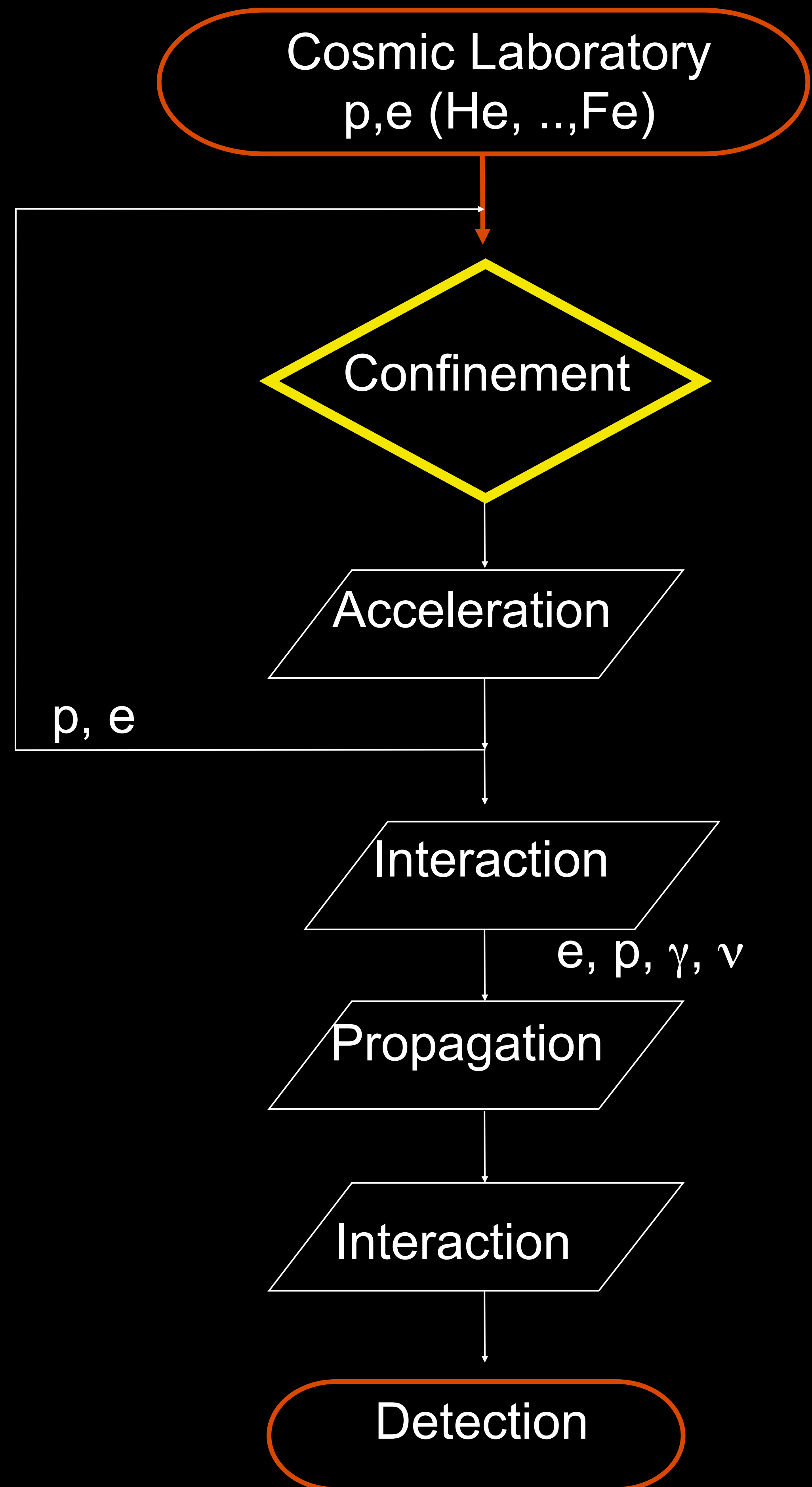
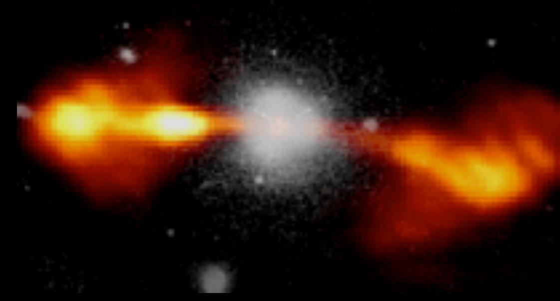
https : / /gallery.icecube.wisc.edu/internal/d/318865-1/physicus.pdf



Cosmic particles flowchart

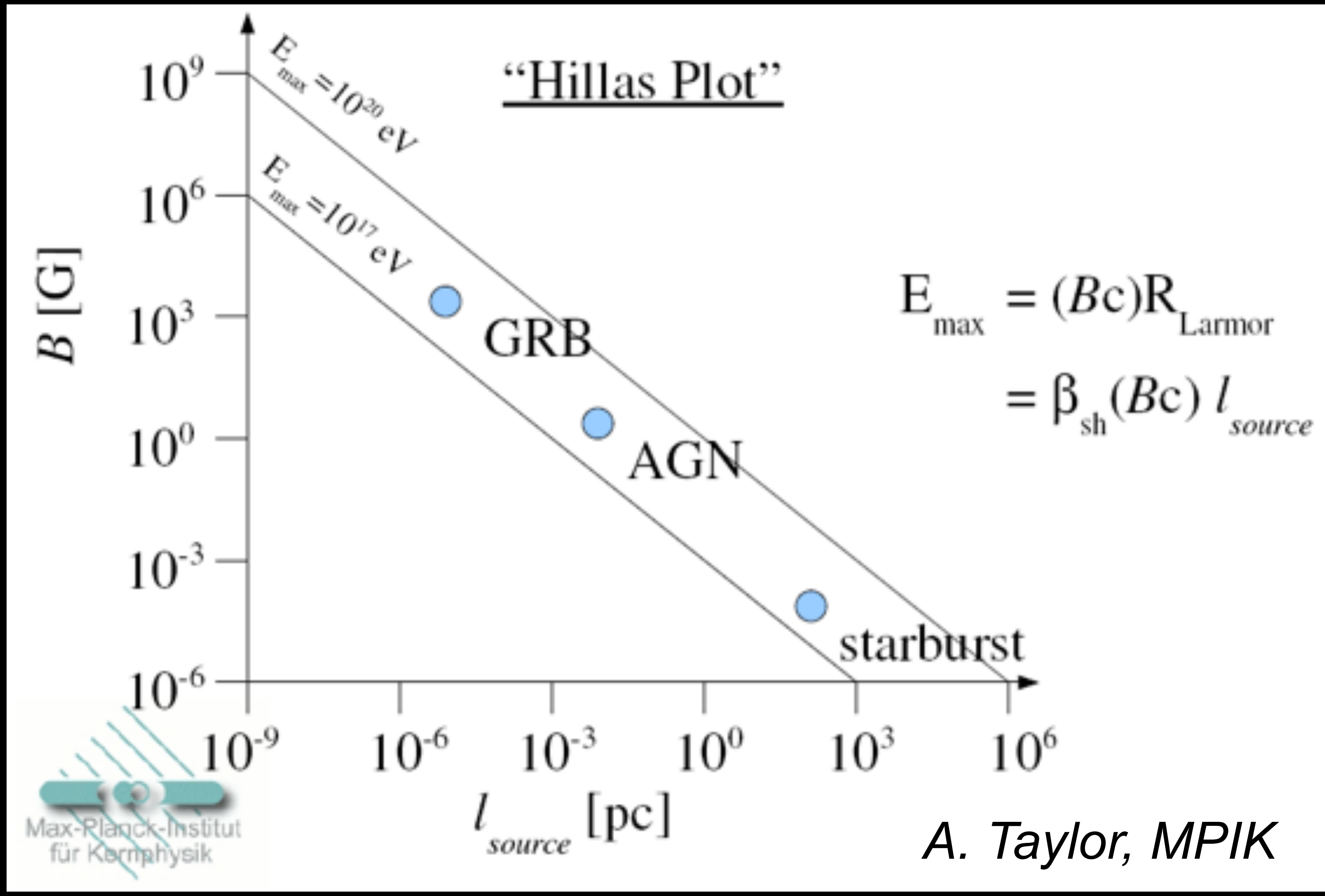


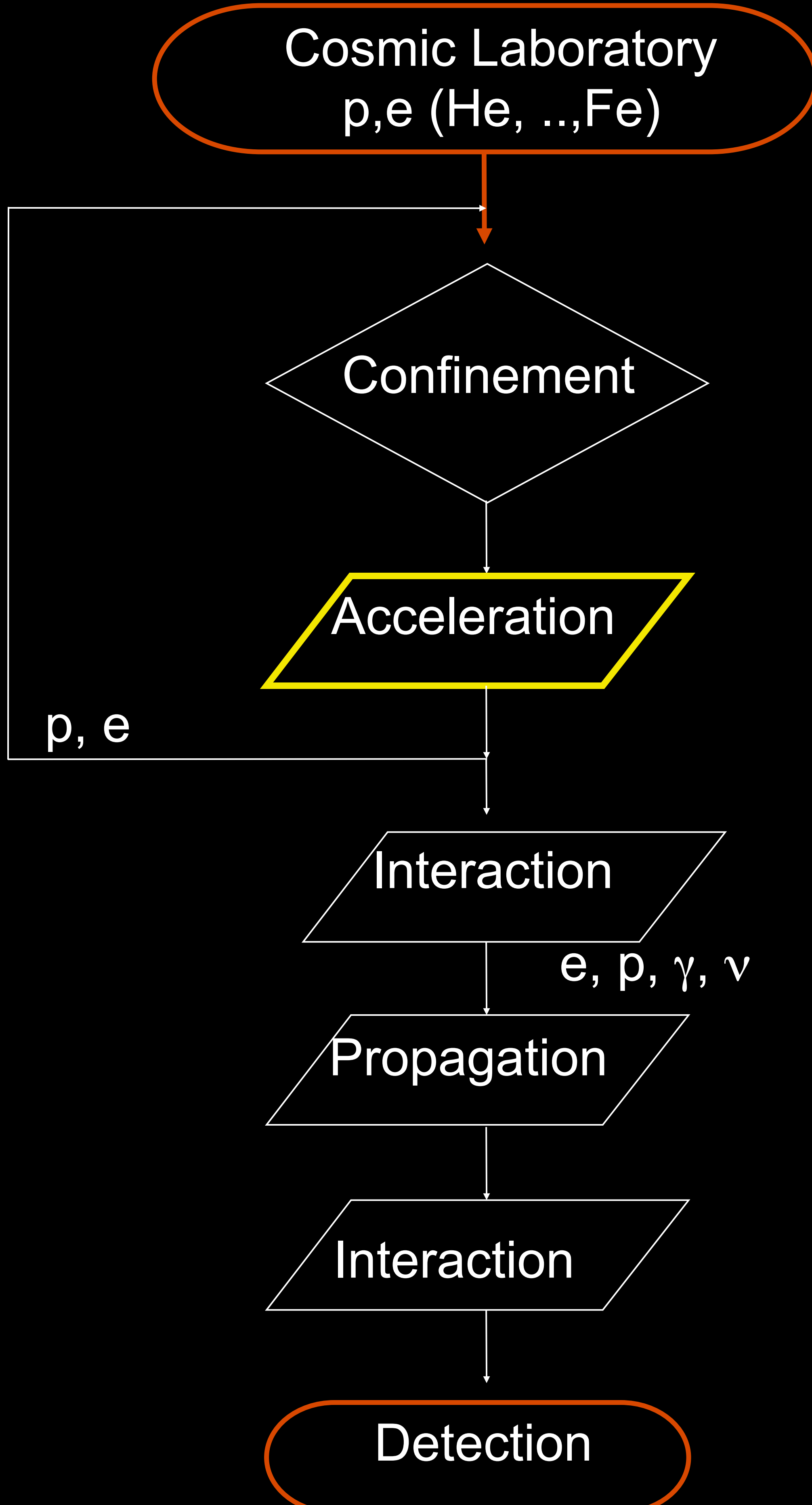


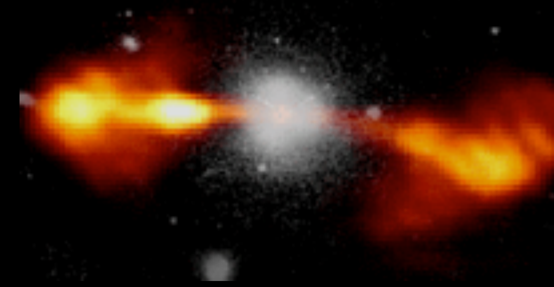
Cosmic particles flowchart

Source size, Magnetic Field

A. M. Hillas,
Ann. Rev. Astron. Astrophys. **22**, 425 (1984)

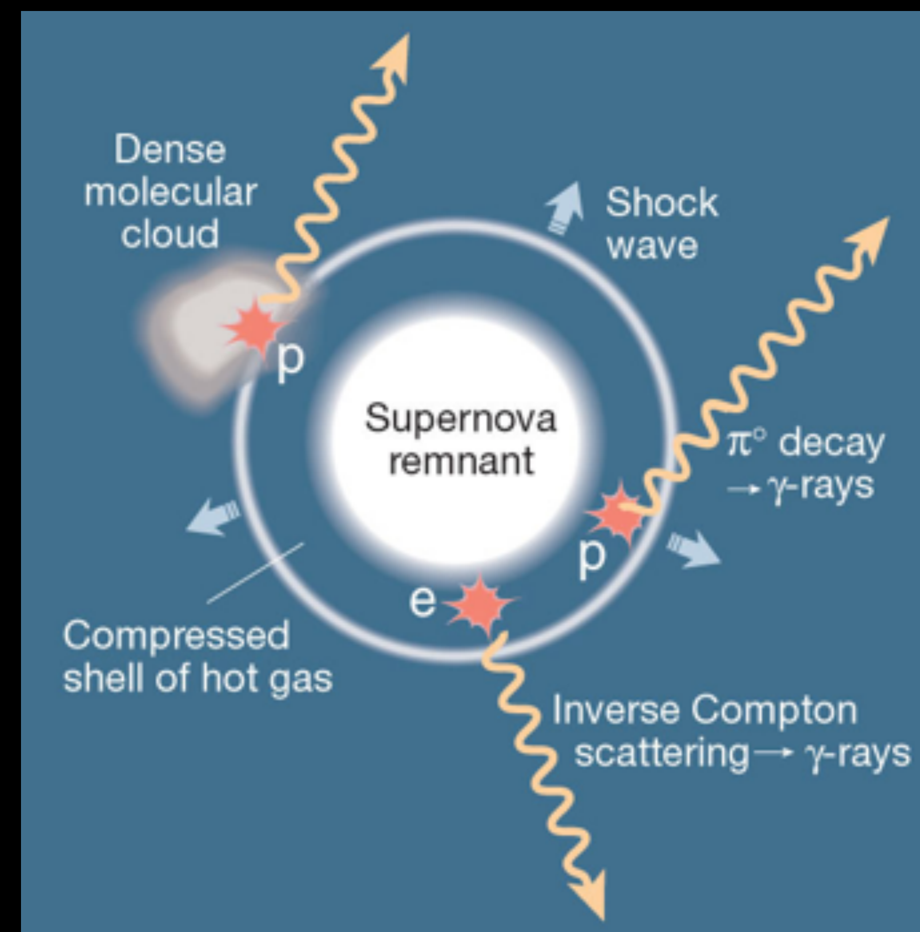






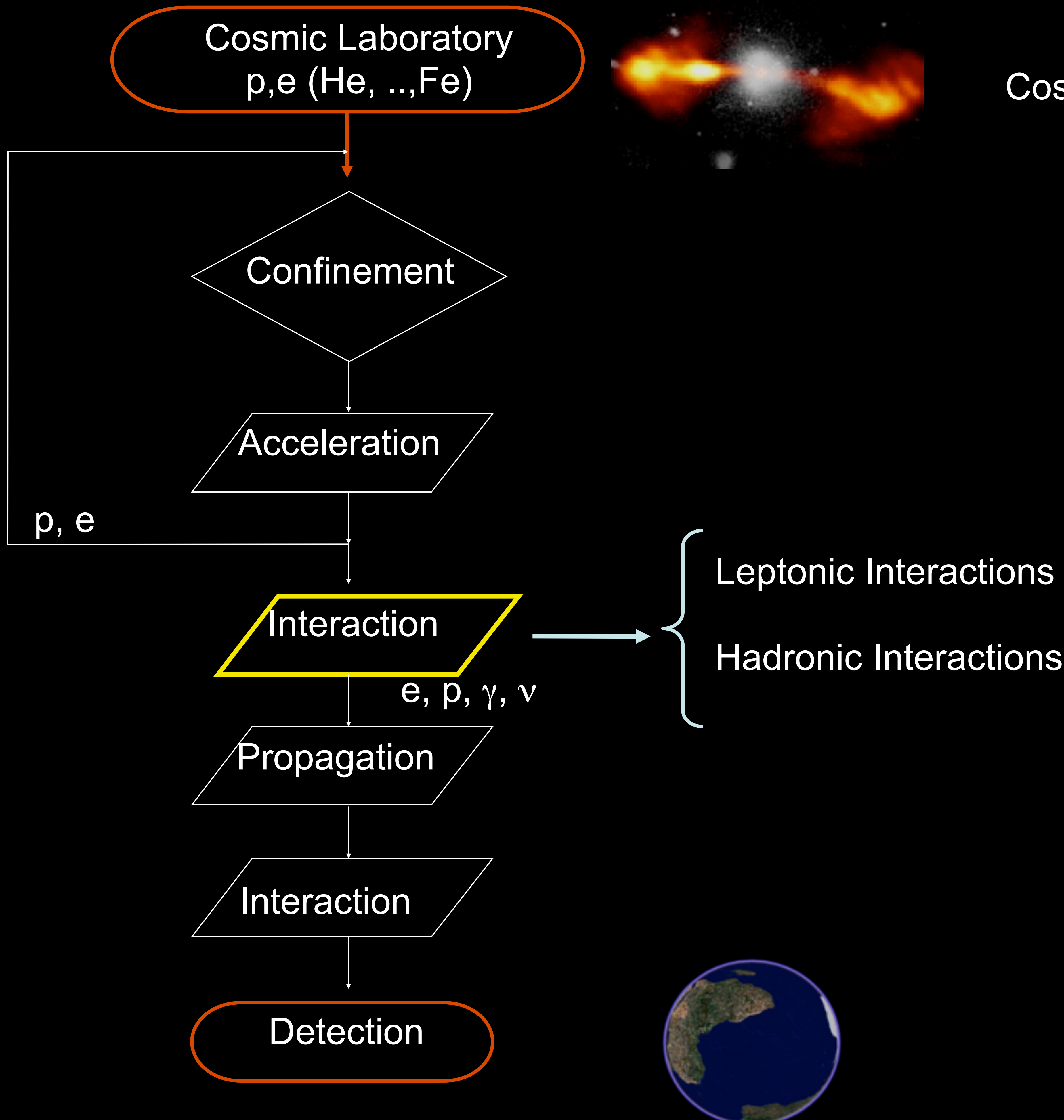
Cosmic particles flowchart

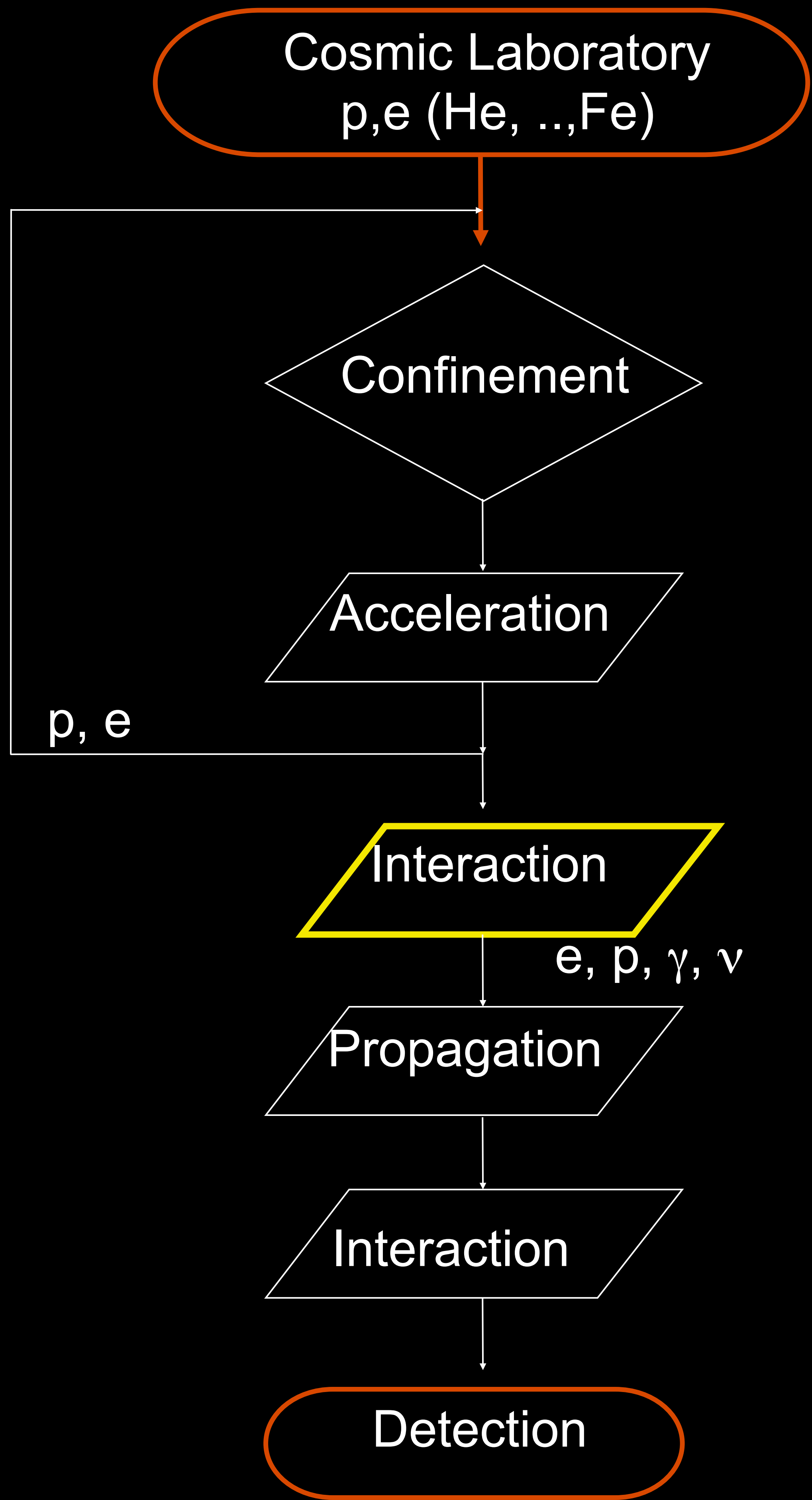
Various ideas:
Diffusive shock acceleration



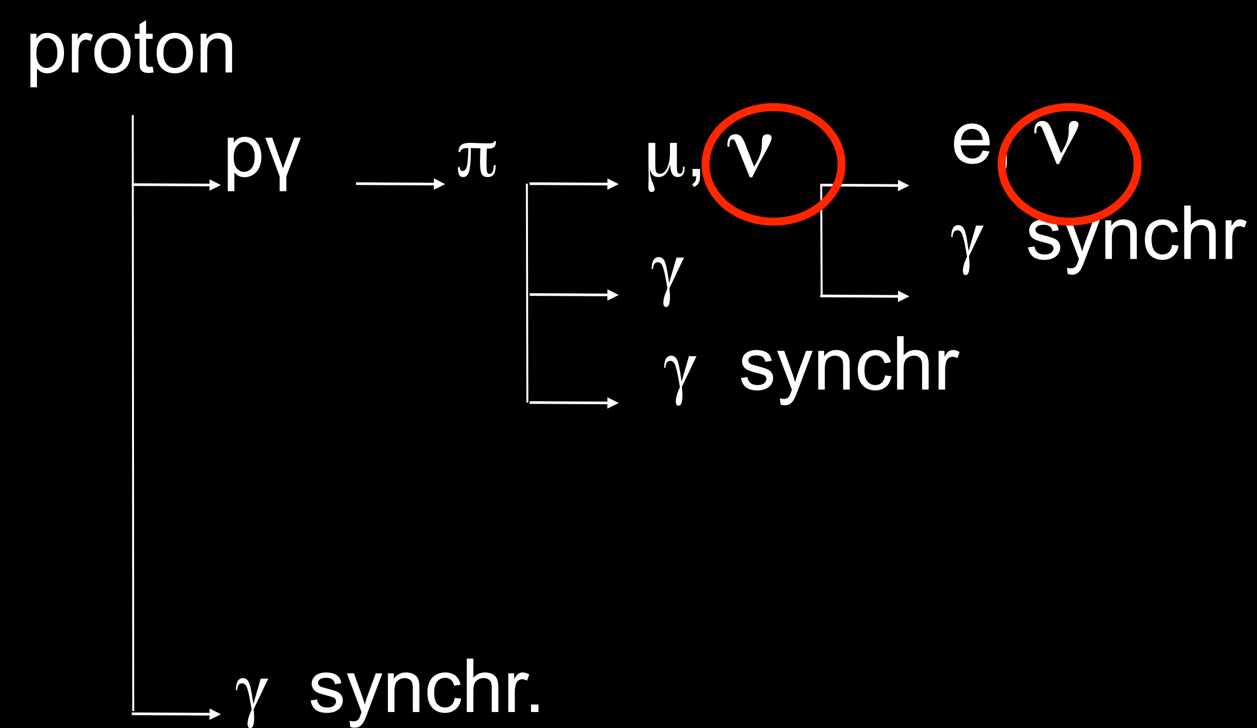
*Felix Aharonian, Nature **416**, 797-798,2002*

Cosmic particles flowchart





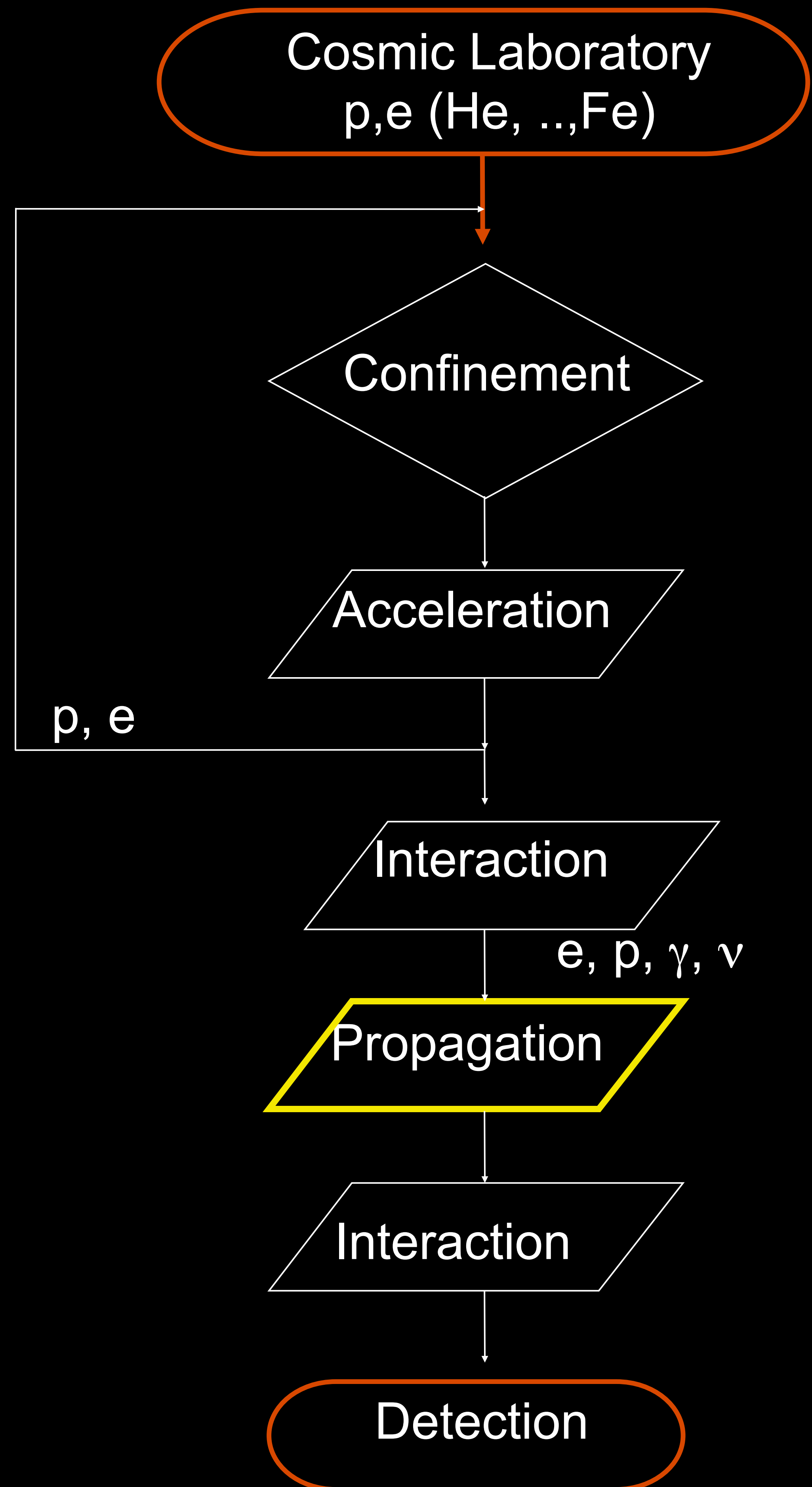
Cosmic particles flowchart

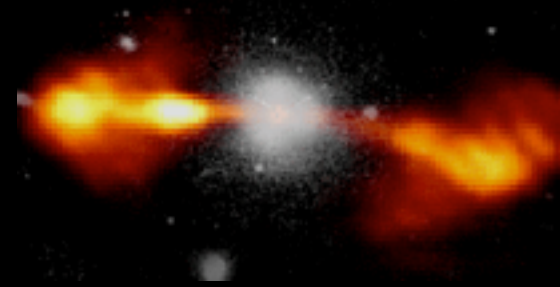


Three Messengers:

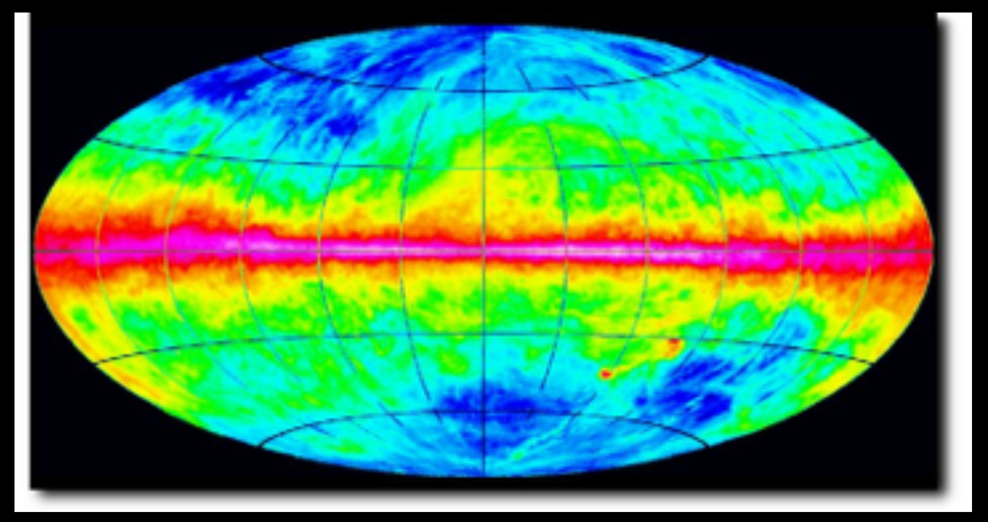
Charged Particles, Gamma-rays and Neutrinos

Cosmic particles flowchart





The Leiden/Argentine/Bonn (LAB) Survey of Galactic HI

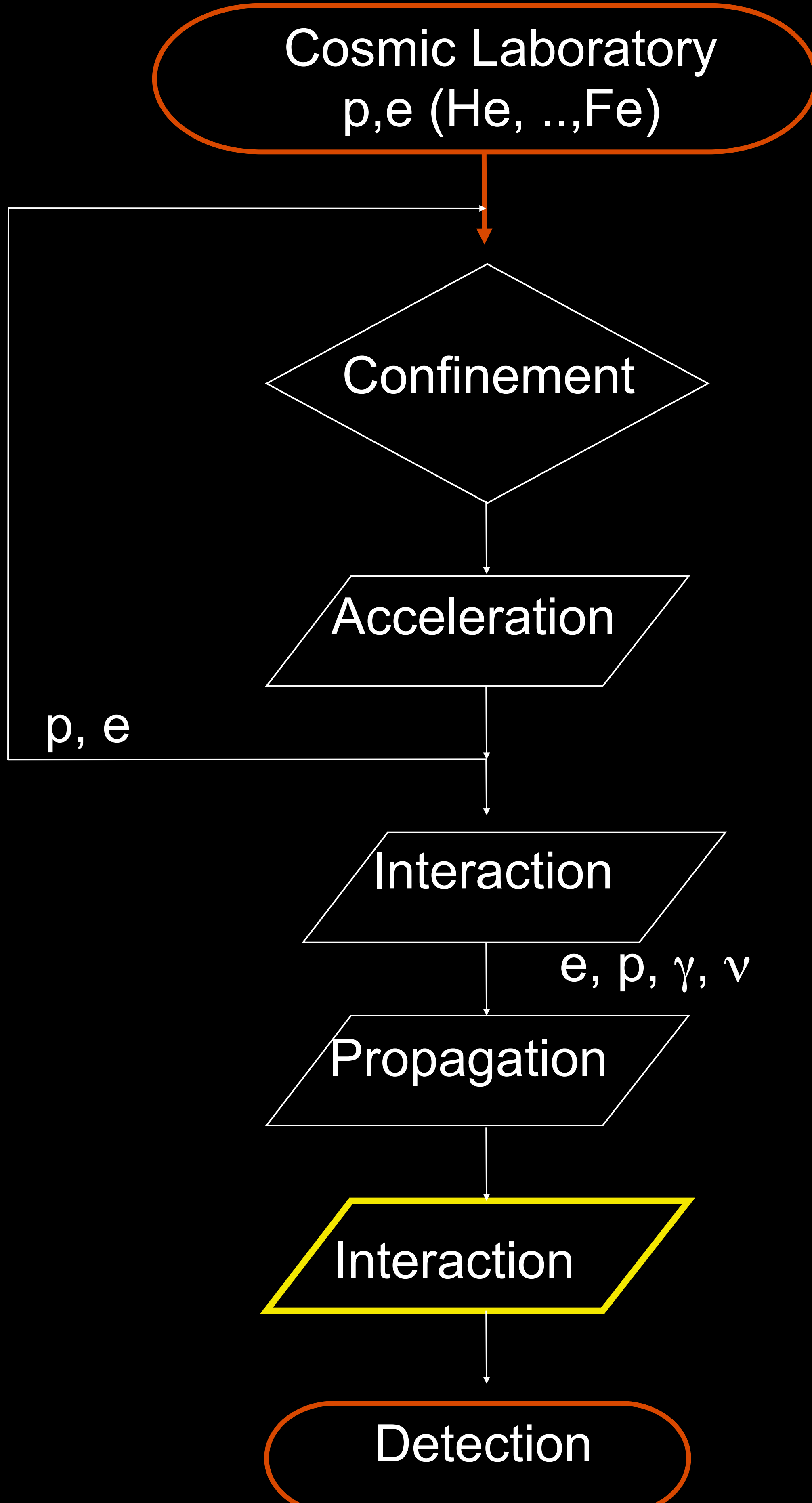


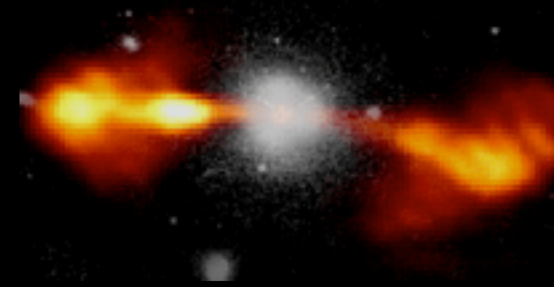
H2, NANTEN

Lorentz Invariance Violation?

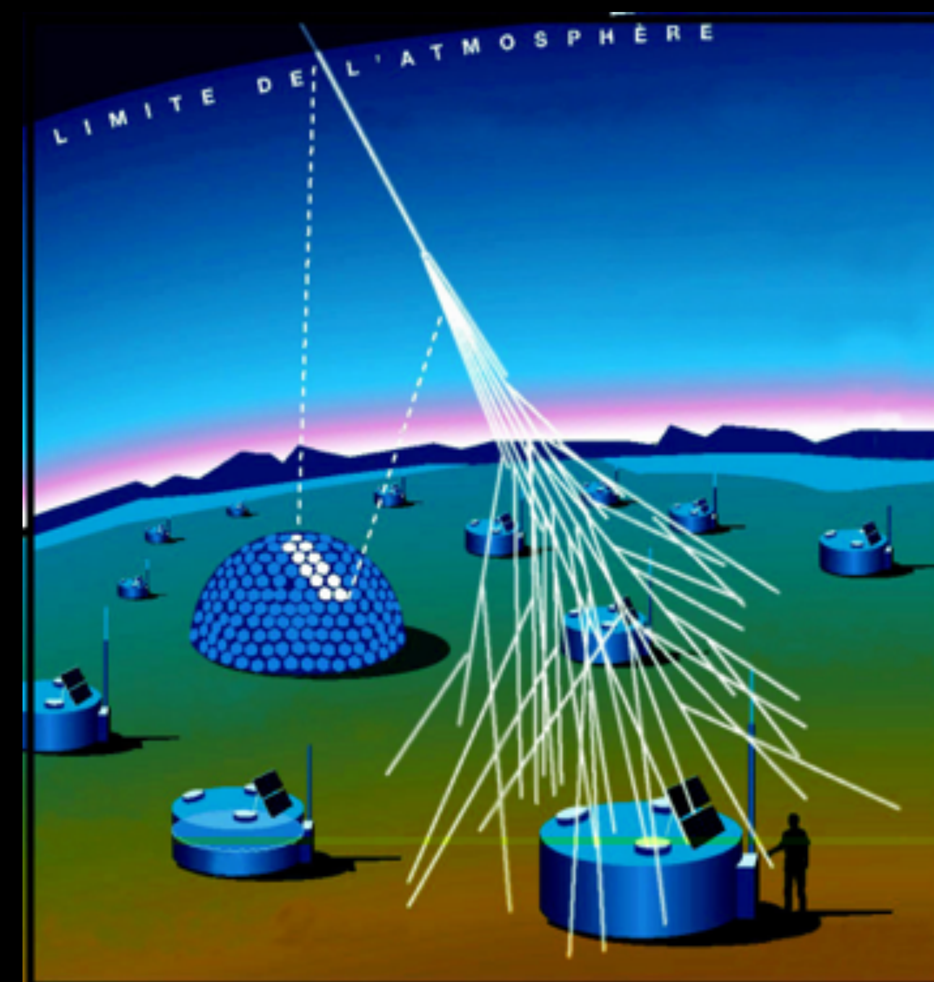
- p: magnetic field deviation
- γ: absorption
- ν: no interaction, point back to the source

Cosmic particles flowchart

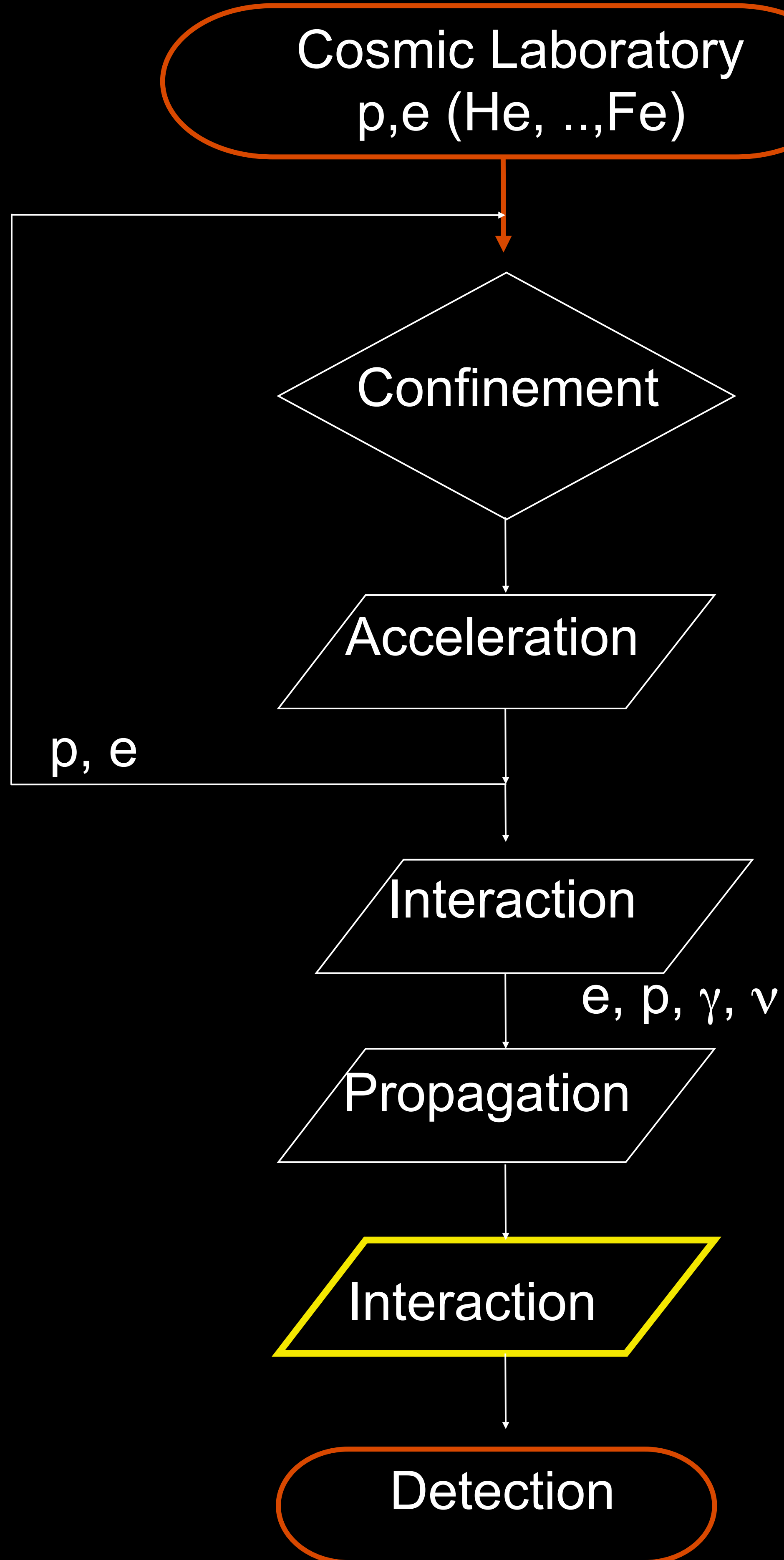


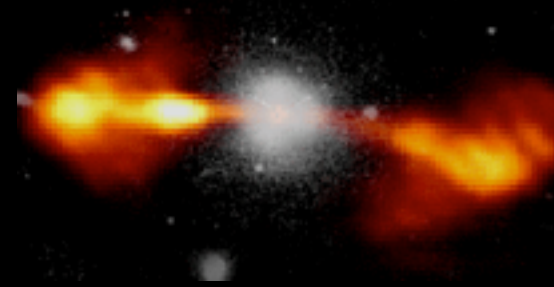


Proton and nuclei interaction in Earth atmosphere: Air showers

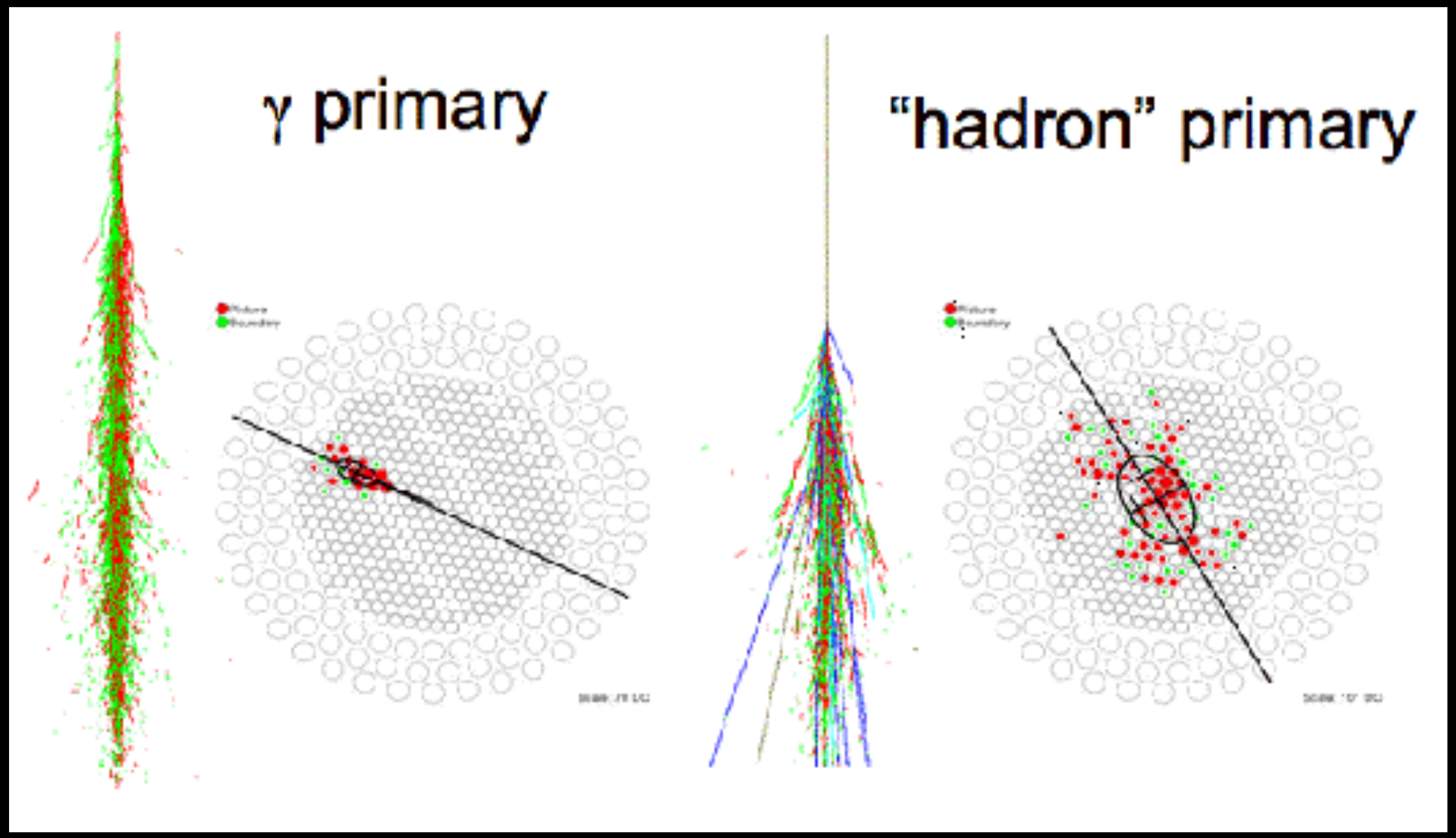


Cosmic particles flowchart

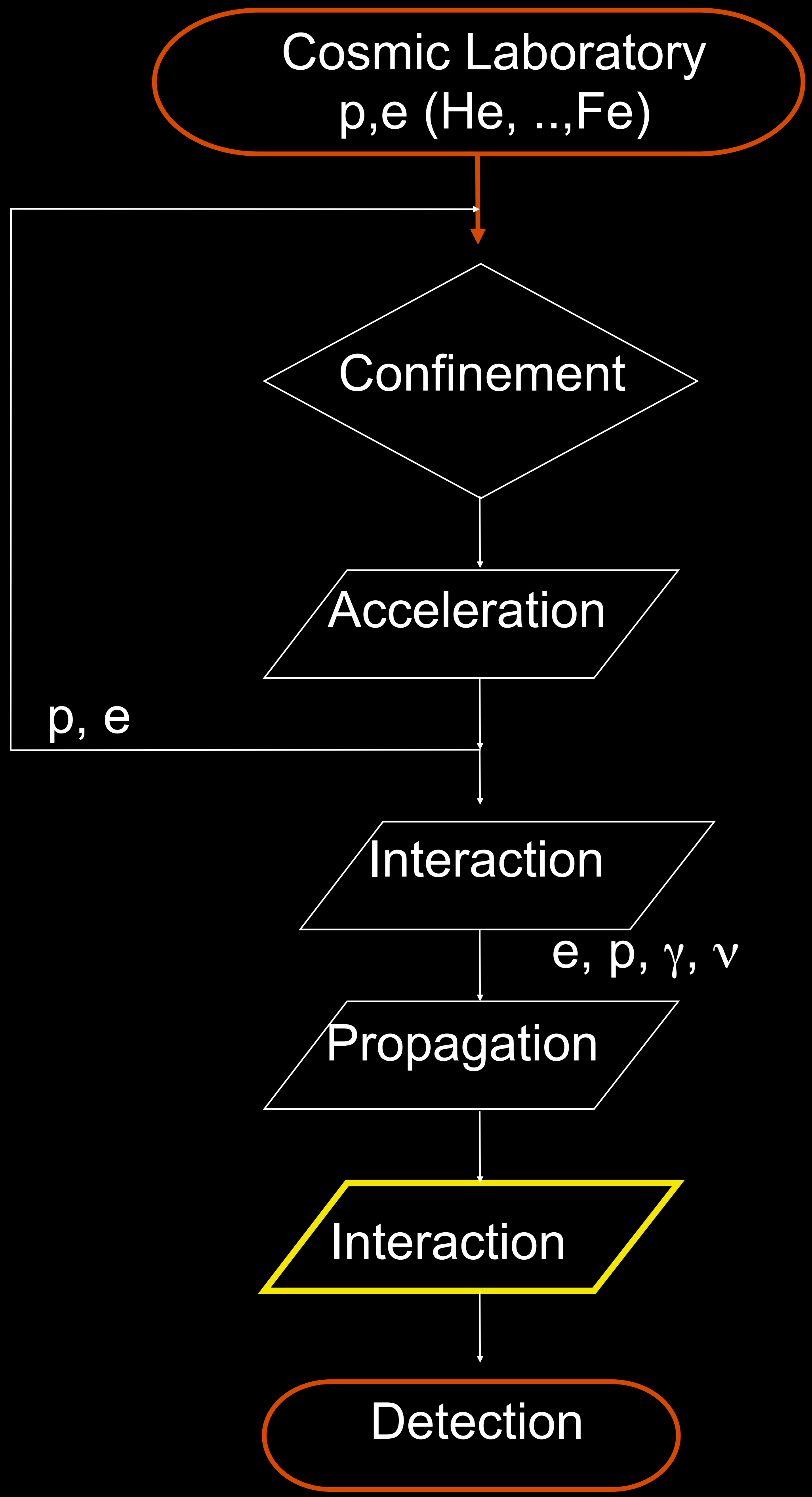


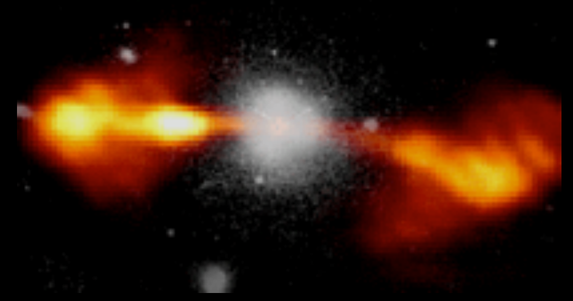


Proton and γ-rays interaction in Earth atmosphere
Air showers

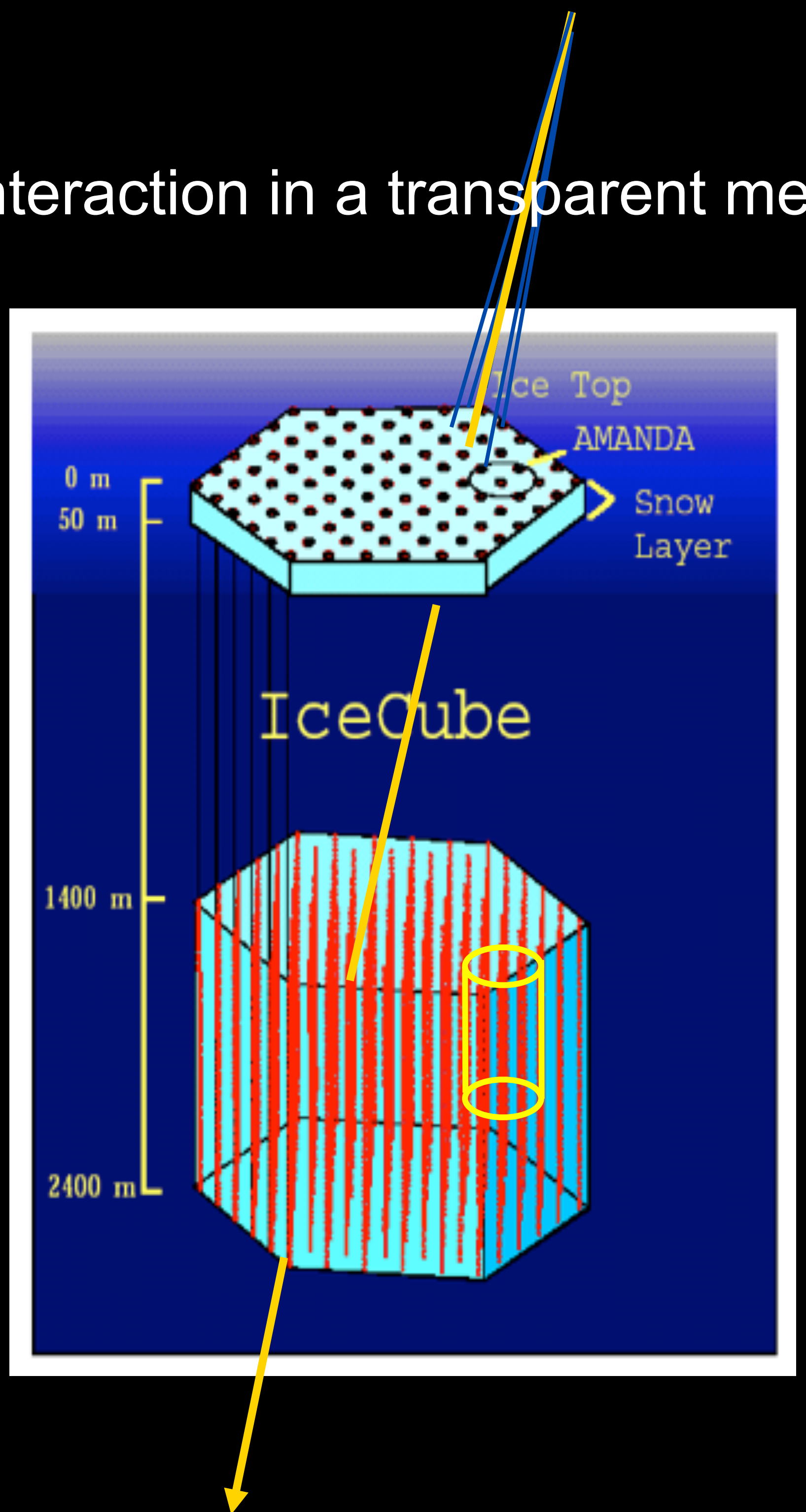


Cosmic particles flowchart





HE ν interaction in a transparent medium



The three messengers or the three musketeers

but they are 4 ???

The three musketeers

1- Primary Cosmic Rays:

- discovered by Victor F. Hess in 1912;
- charged nuclei and consequently deflected by magnetic fields according to the nuclei's rigidity
- CR directional information lost at low - medium energies
- at the highest energies directional information maintained, bending radius r_l large against the propagation distance.

momentum

magnetic rigidity

$$R = \frac{pc}{Ze} = B \times r_l$$

gyroradius multiplied by the magnetic field strength

deflection radius

charge

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The three musketeers

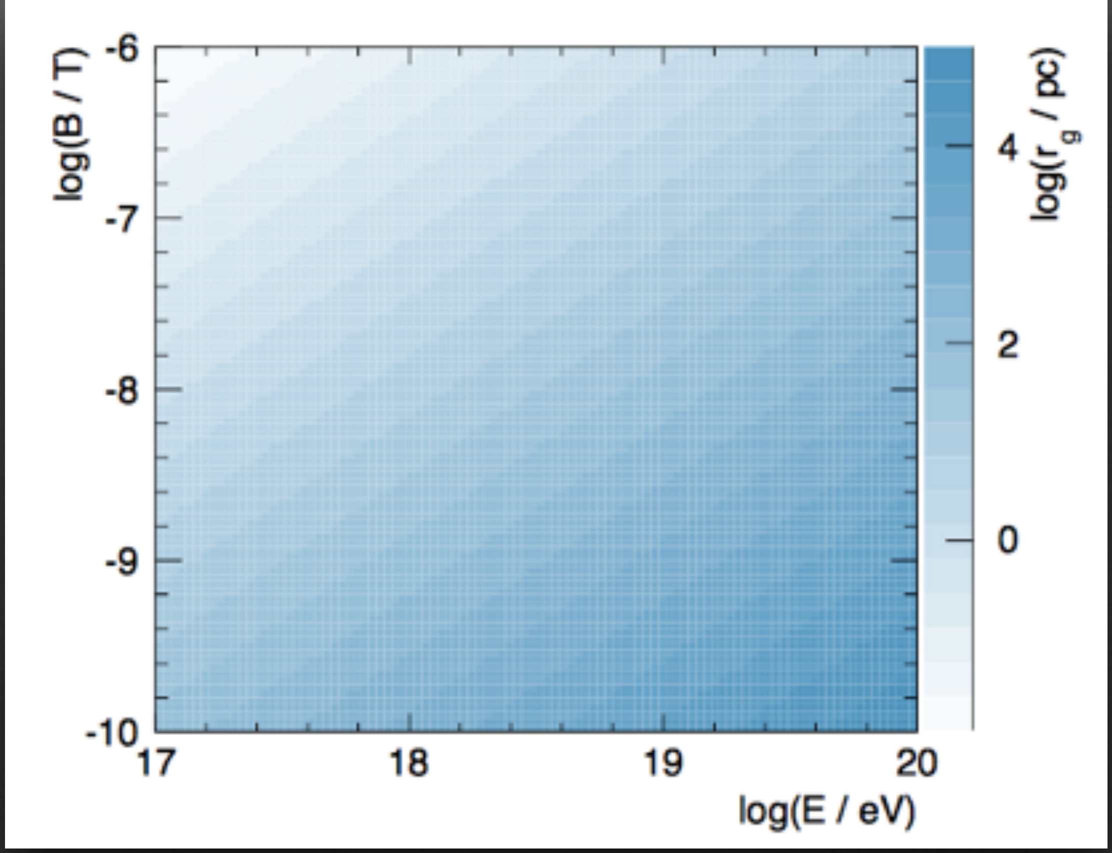
1- Primary Cosmic Rays:

$$R = \frac{pc}{Ze} = B \times r_l$$

$$r_g \approx (108\text{pc}) \frac{E/\text{EeV}}{Z(B/\text{nT})}$$

The gyroradius in the relativistic case it can be written as a rule-of-thumb expressing the physical quantities in appropriate units; with E the energy of the particle, Z its number of charge carriers and B the magnetic field strength; 1 pc = 30.857 × 10^{15} m.

Example: $r_g \approx 100$ pc, E=1EeV=10^{18}eV, B=1 nT;



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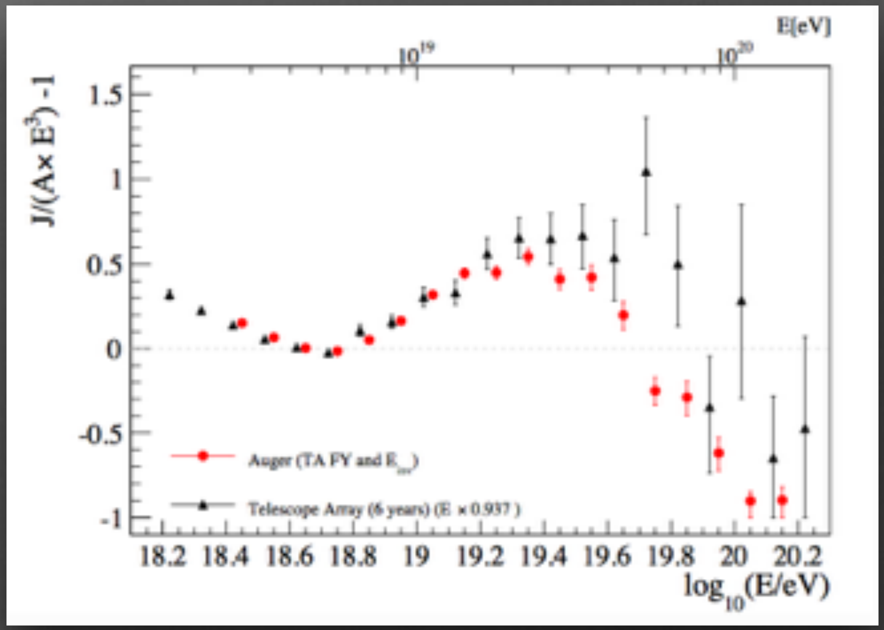
https://web.physik.rwth-aachen.de/~hebbeker/theses/grigat_phd.pdf

The three musketeers



1- Primary Cosmic Rays: attenuation effects

Propagation of UHE particles on cosmological distances involves interaction with other particles, as well as with electromagnetic fields, in the case of charged particles

1- Extragalactic background light (EBL)
2- Cosmic microwave background (CMB)
3- Cosmic neutrino background (CvB)

$$\gamma_1 + \gamma_2 \longrightarrow e^+ + e^-$$

$$\gamma_1 + \gamma_2 \rightarrow e^+ + e^- + e^+ + e^-$$

$$p + \gamma \longrightarrow p + e^+ + e^-.$$

GZK

$$\gamma + p \rightarrow \Delta^+ \rightarrow n + \pi^+$$

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

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https://arxiv.org/pdf/1503.07749v1.pdf

The three musketeers

1- Primary Cosmic Rays: attenuation effects

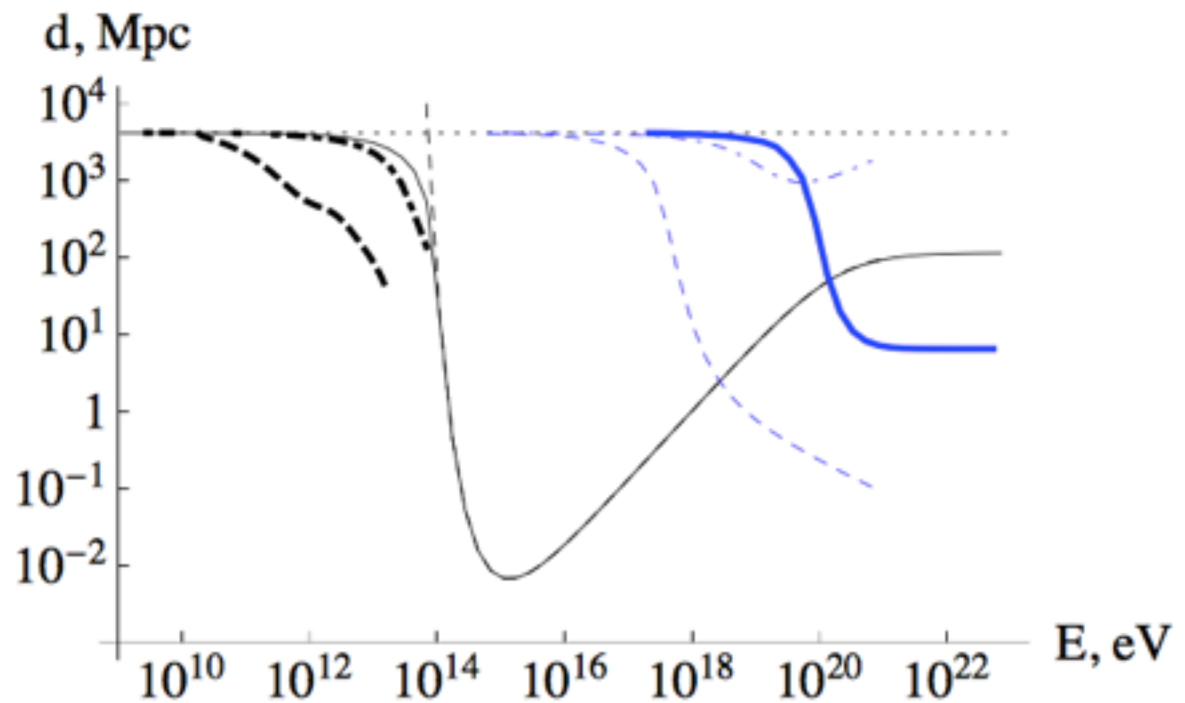
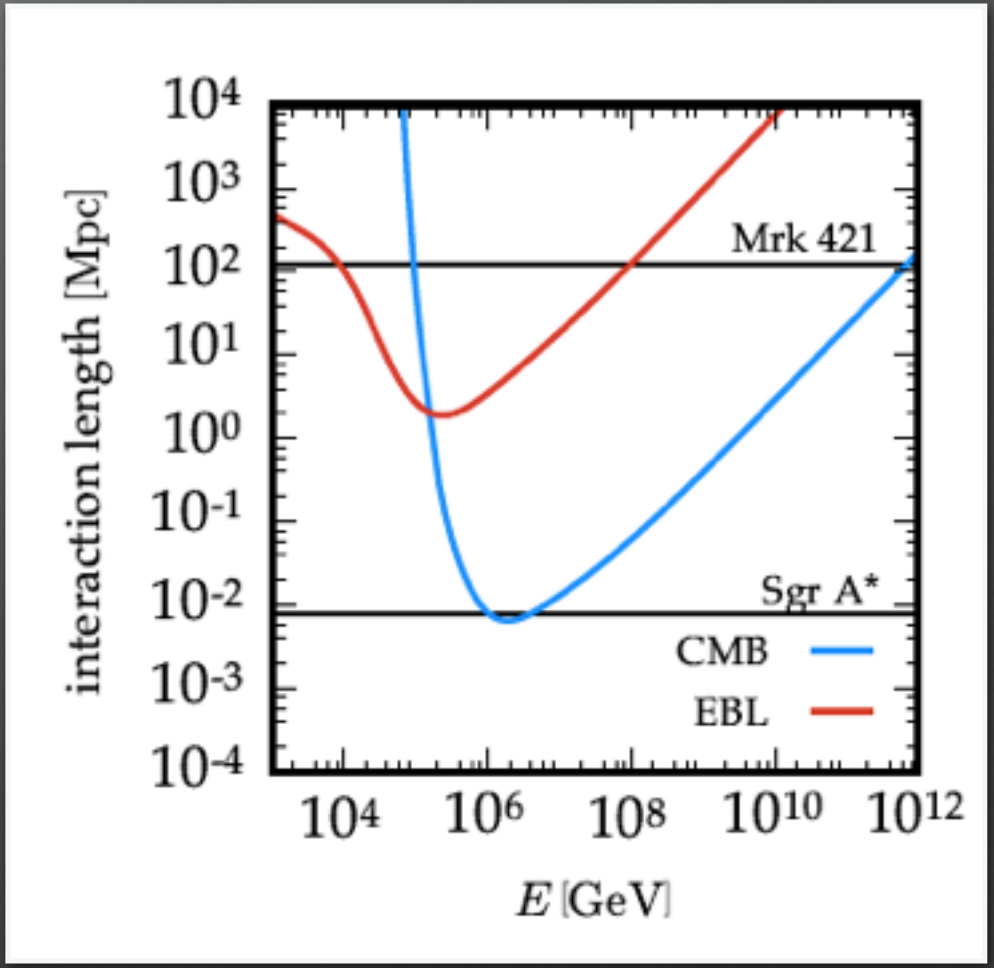


Figure 1. The mean free path, measured in megaparsecs as a function of energy E of UHE particles, measured in electronvolts. In the region above the curves the optical depth is larger than unity. Thin black curve shows the mean free path of UHE photons. Dashed black curve shows the photon mean free path computed without accounting for cosmological evolution (imposing $z = 0$). Thick blue dashed curve shows the boundary of transparency for extragalactic background light (EBL), according to the baseline model of Inoue et al. [29]. Thick blue curve shows the mean free path of UHE protons (GZK limit). Blue dashed (dotted-dashed) curve shows the mean free path (mean energy loss distance) for UHE protons due to Bethe-Heitler process. Dotted horizontal line shows cosmological horizon.

https://arxiv.org/pdf/1503.07749v1.pdf

The three musketeers

S. Coenders, PhD thesis



2- Gamma Rays (high energy photons):

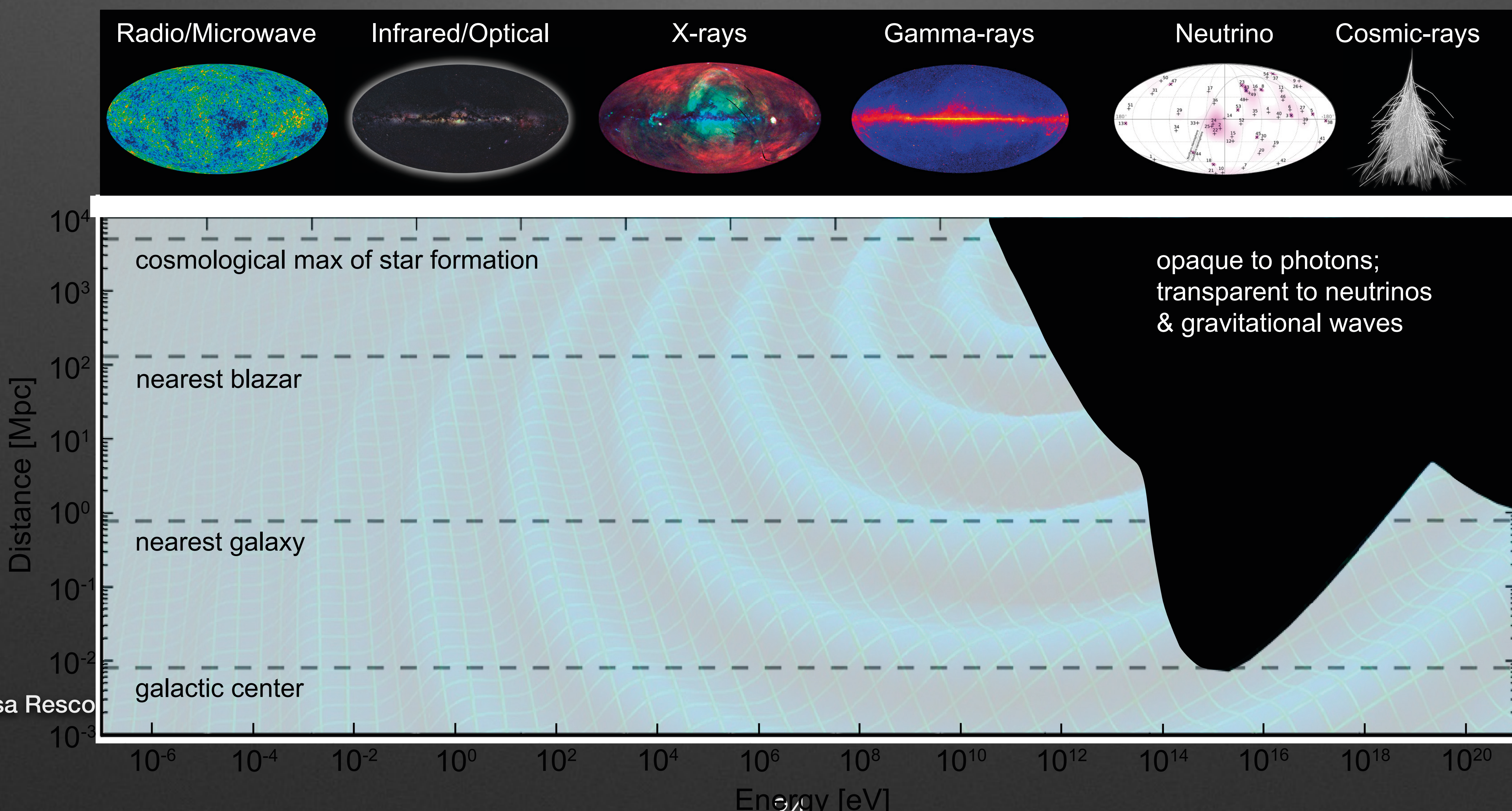
- neutral, point back;
- interact with charged particles via (inverse) Compton scattering, annihilation to electron-positron pairs;
- the observable distance in photons is limited!

Hinton, J. A. and Hofmann, W. "Teraelectronvolt astronomy". Ann. Rev. Astron. Astrophys. 47 (2009) 523 – 565 . arXiv:1006 .5210 [astro-ph.HE]

The three musketeers

3- Cosmic Neutrinos

- neutral, point back; three flavours;
- neutrinos do NOT interact with ambient particles; ideal messenger but ..
- cross sections very small, hard to detect

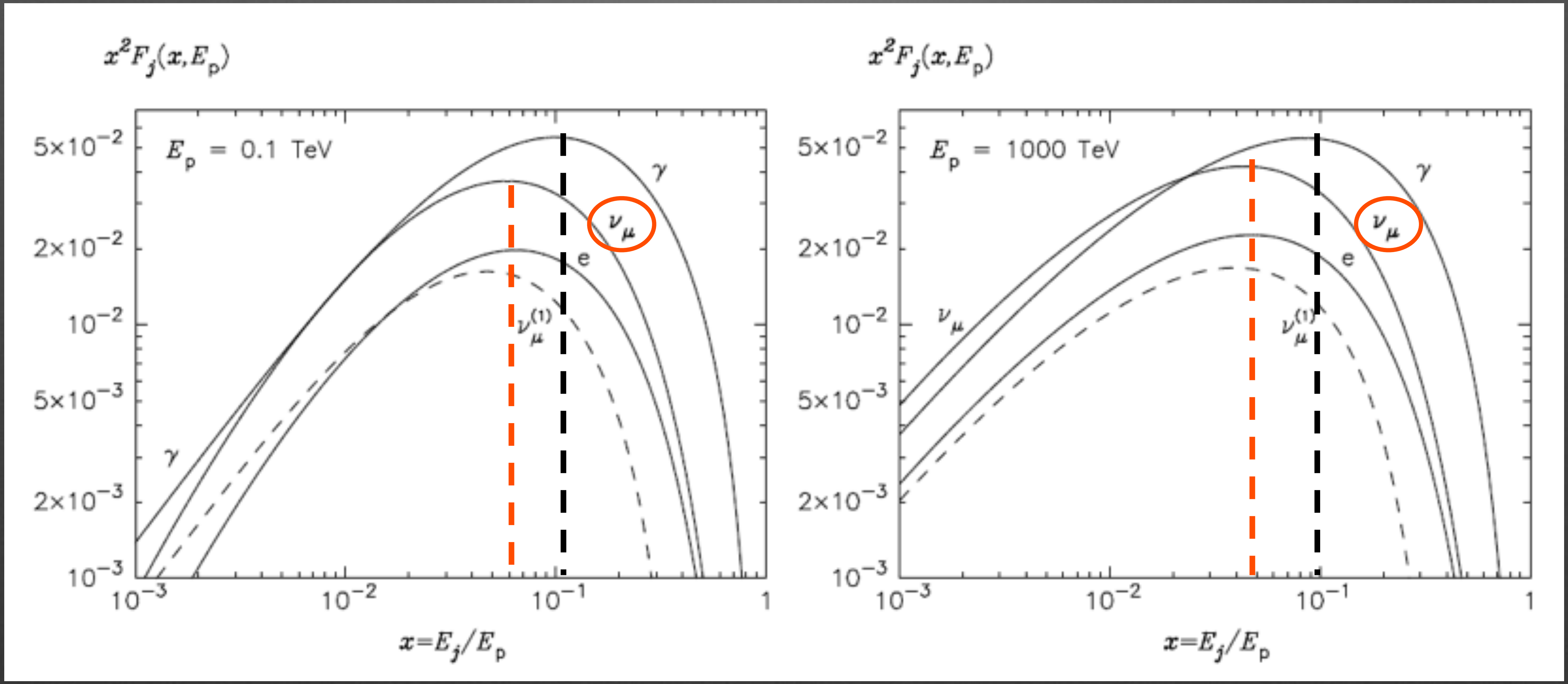


The three messengers or the three musketeers

so, then who is the 4th messenger?

The three musketeers: a simple relation among them

$E_p:E_\gamma:E_\nu$ = 1: 0.1: 0.05



- Reference:
- pp Interaction (S.R. Kelner, F. A. Aharonian,V.V. Bugayov, Phys.Rev.D74:034018,2006)
- pγ Interaction (S.R. Kelner, F.A. Aharonian, Phys.Rev.D78:034013,2008)
- A. Reimer et al., SOPHIA MonteCarlo, http://ebl.stanford.edu/

How are CR detected?

To be measured:

- Composition: abundance of the different nuclei
- Energy spectrum: distribution in energy of each component
- Arrival direction
- for photons and neutrinos also arrival time

The energy spectrum

(1) dN/dE [over 12 oder of magnitude of a steep falling population]

(2) $E \cdot dN/dE = dN / d\ln E$

$$\frac{d}{dx}(\ln\ x) = \frac{1}{x}$$

natural way to represent event rate in a detector that covers an energy range [E1, E2]

(3) $E^2 \cdot dN/dE = E \cdot dN / d\ln E = \nu F(\nu)$

ν = frequency of the photons

$\nu F(\nu)$ = spectral energy density

energy content per log interval of energy: it reflects the physics of a source

(4) $E^{2.5} \cdot dN/dE$, $E^3 \cdot dN/dE$

$dN/dE = N0\ E^{-\alpha}$

α = differential spectral index

to flatten the spectrum and study change in slopes, structures

CHECK UNITS!!

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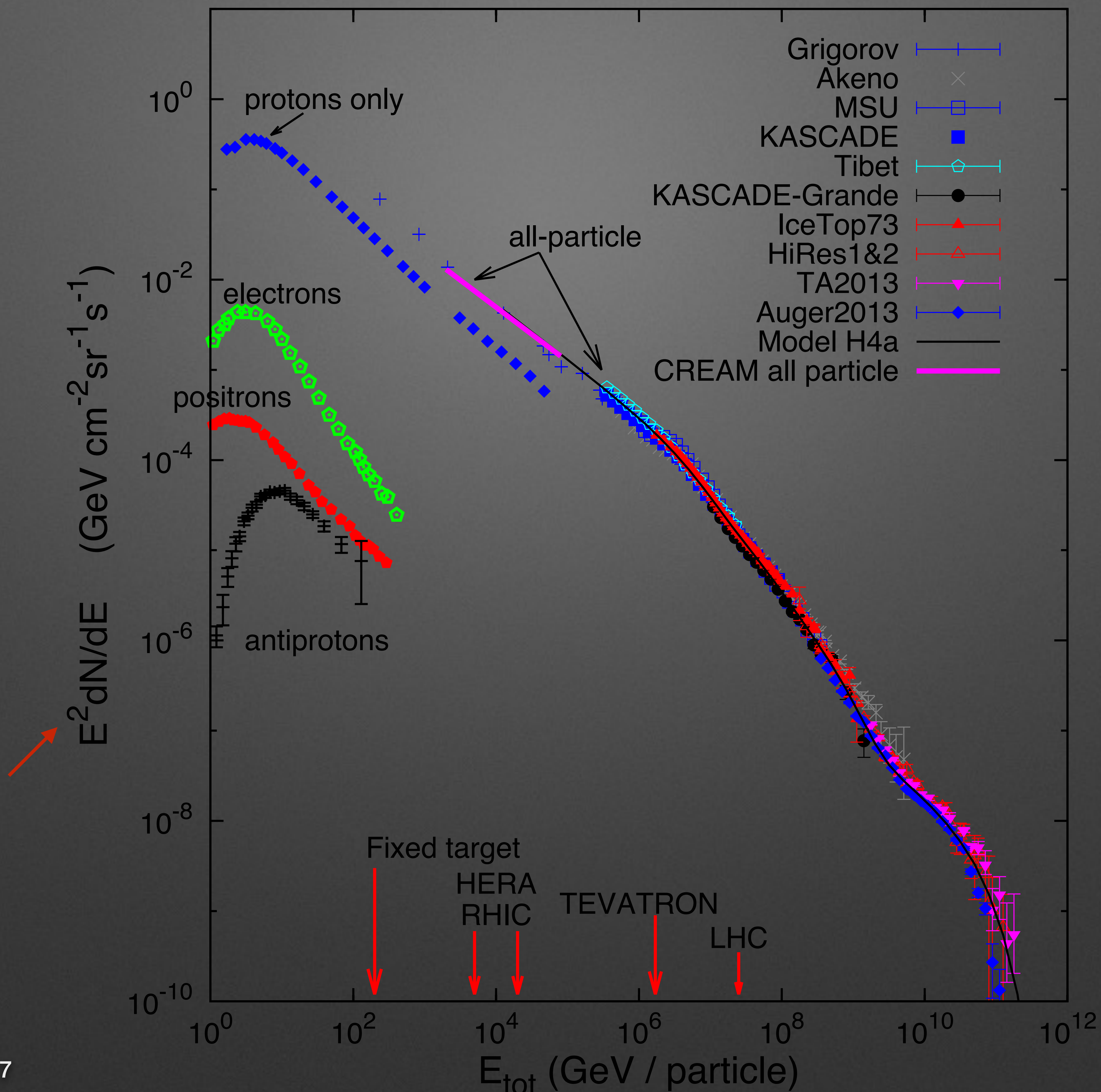
Energies and rates of the cosmic-ray particles

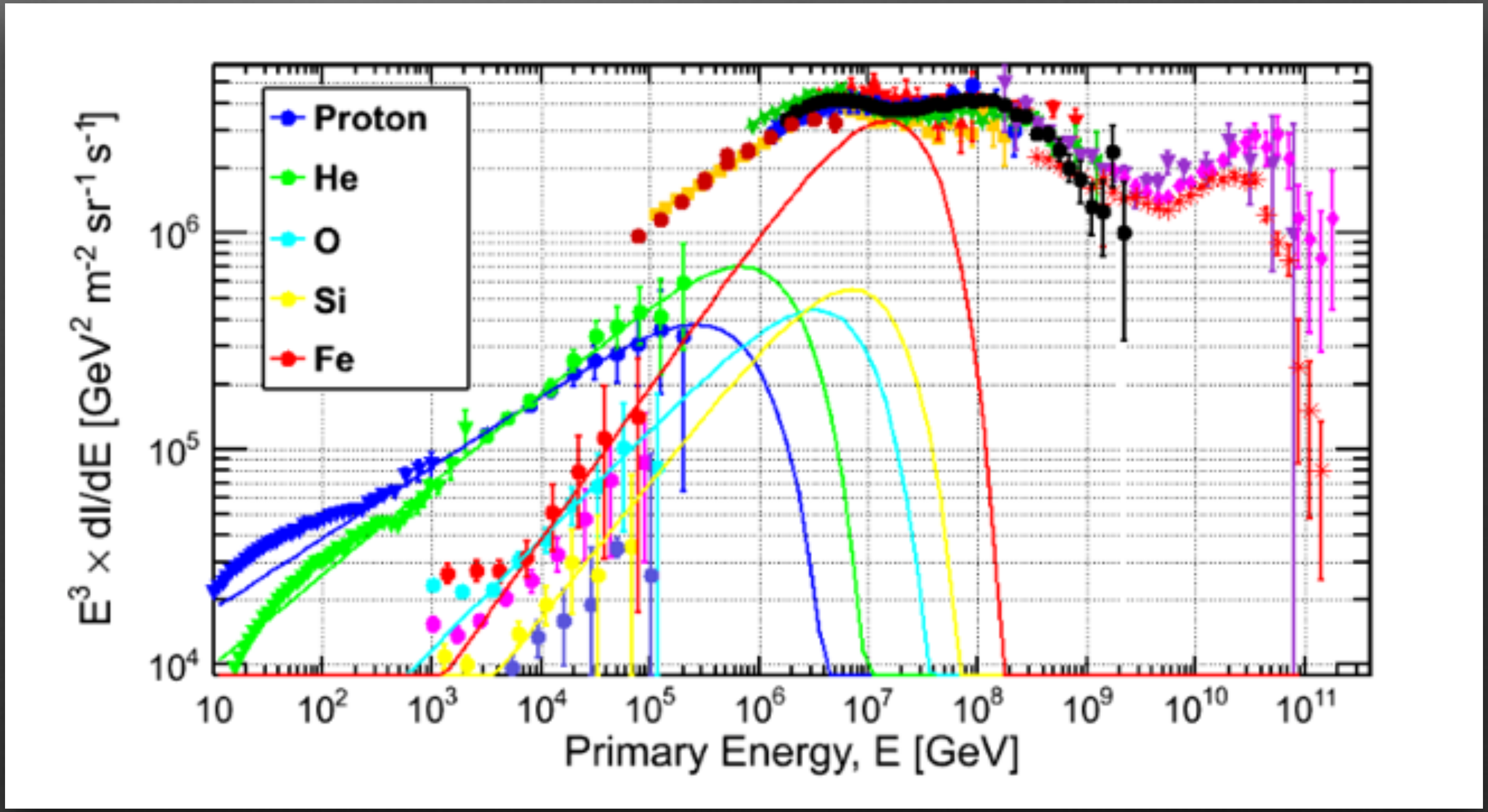


The Knee of the CR

Steepening of the spectrum > 3 PeV

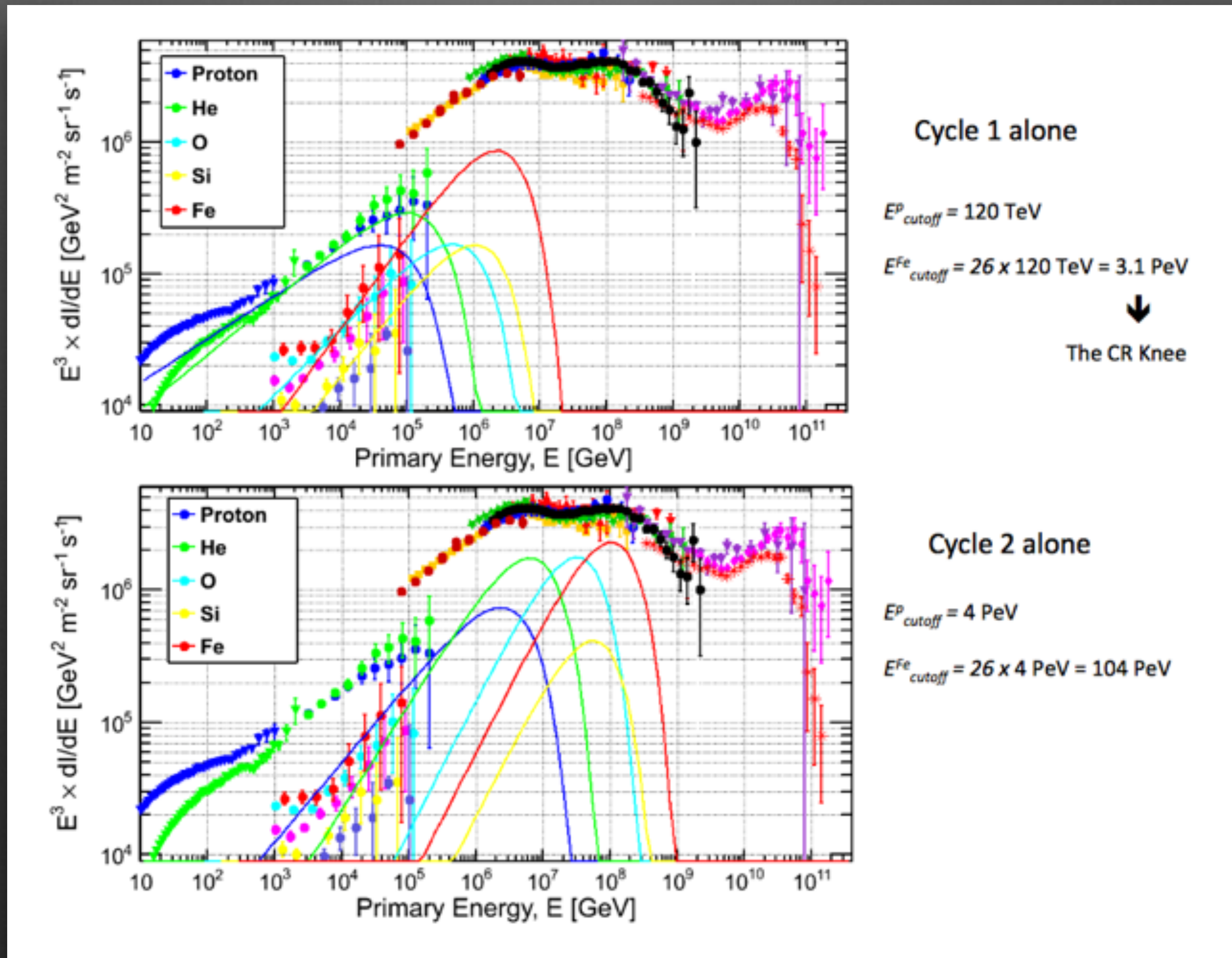
Propagation and acceleration depend on the action of magnetic fields

if the Knee is related to these processes changes in the spectrum should be characterised by magnetic rigidity



Peters' cycle: characteristic rigidity $R_c = pc / Ze \sim E / Ze$
then proton will steepen at $E = R_c$, helium at $E = 2 R_c$, oxygen at $E = 8 R_c$

n cycles, n populations?



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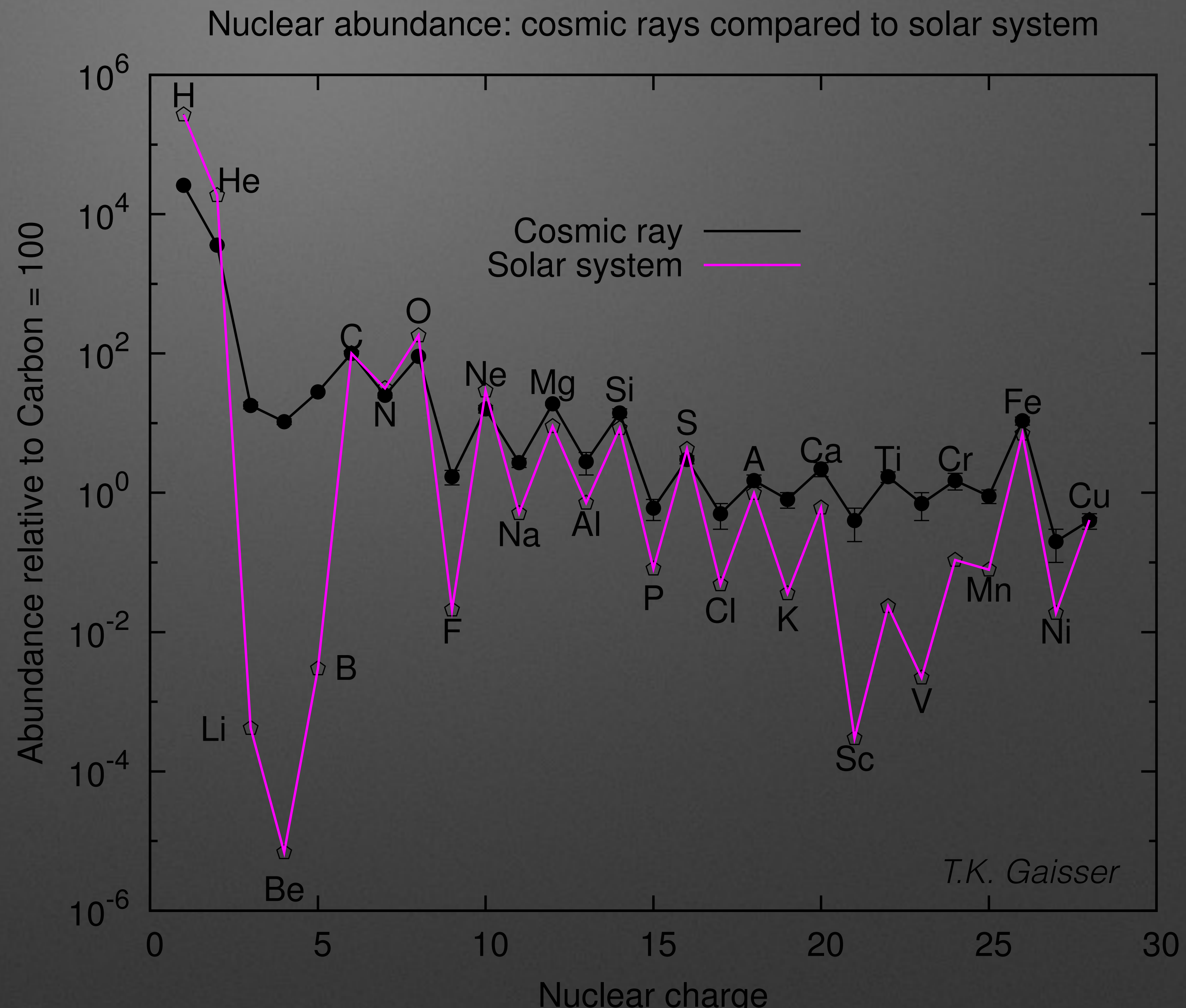
Composition (elemental abundance)

(1) Odd-even effect, more tightly bound nuclei more abundant

(2) Z>1: p/all higher for CR respect to solar. Not well understood.

(3) [Li, Be, B] and [Sc, Ti, V, Cr, Mn] more abundant in CR



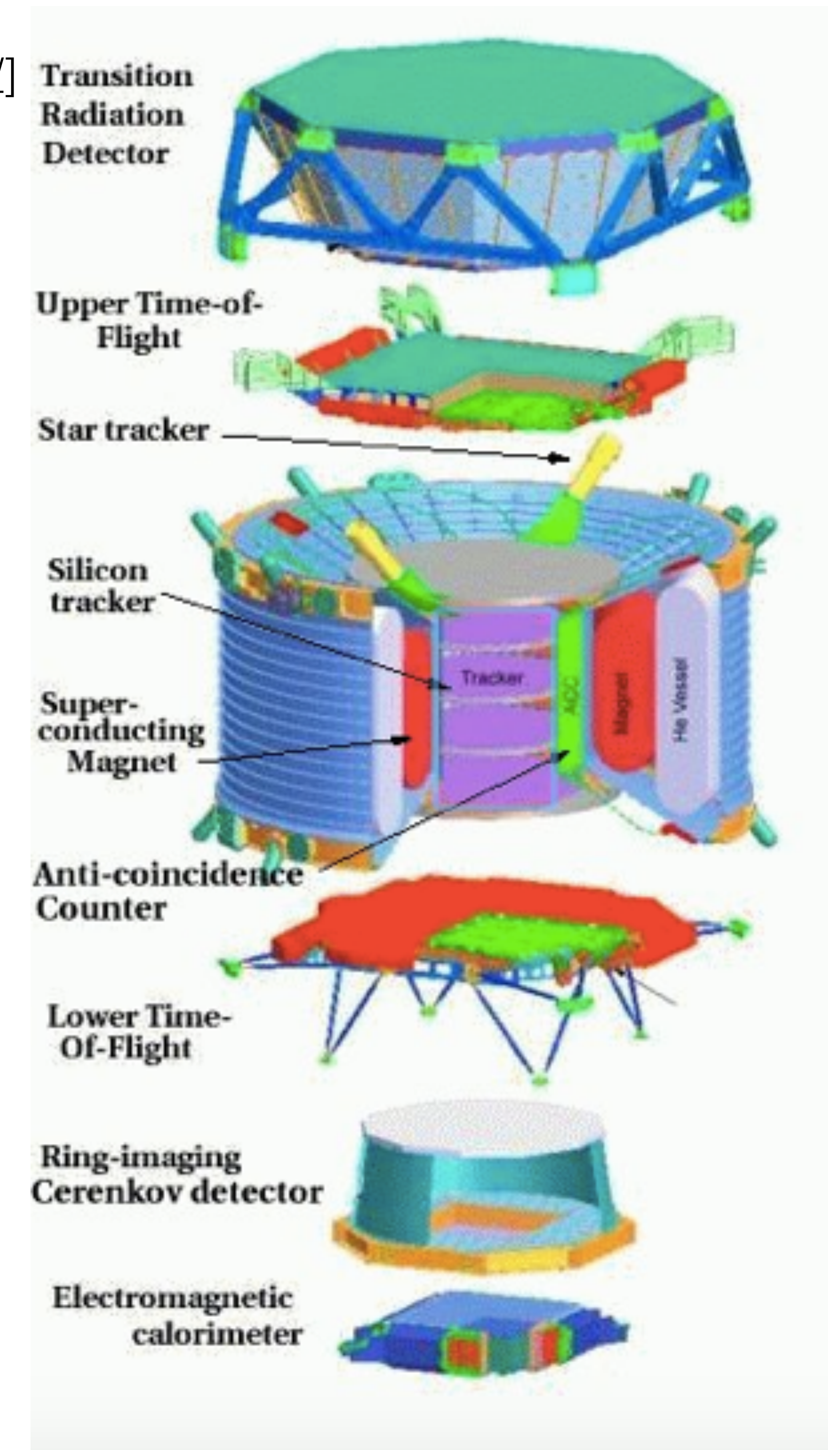
Additional references: M.Asplund et al., http://arxiv.org/pdf/0909.0948.pdf

Detection of CR (1)

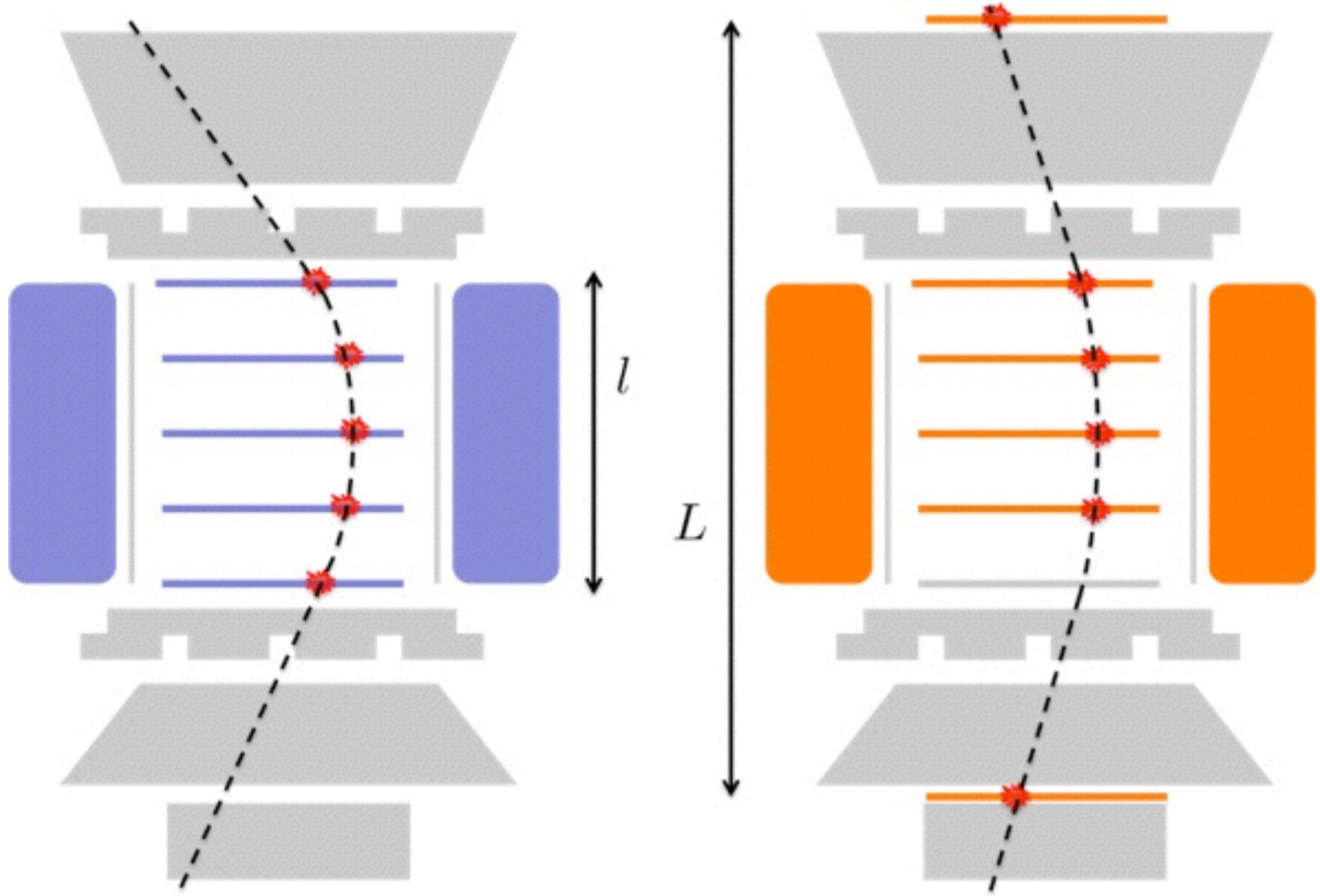
- E ~ 100 GeV: 2 particles / m^2 sr sec -> magnetic spectrometer in space

Alpha Magnetic Spectrometer (AMS) [http://cyclo.mit.edu/ams/]

- On top of AMS, a transition radiation detector **(TRD)** tells us the velocities the highest-energy particles.
- The silicon tracker follows a particle's path through the instrument.
- A superconducting magnet makes the particle's path curve.
- Two time-of-flight counters **(TOF)** tell us lower-energy particles' speeds.
- Two star tracker cameras measure AMS's orientation in space.
- Underneath AMS, a ring-imaging Cerenkov detector **(RICH)** makes an extremely-accurate velocity measurement for fast particles.
- Some particles crash violently into the electromagnetic calorimeter **(ECAL)**, which measures their energy and type.
- An anti-coincidence veto counter notices stray particles sneaking through AMS sideways.



http://www.ams.nasa.gov/Documents/AMS_Publications/NASA%20JUNE-2014C.pdf



Superconducting Magnet Scenario

$$\frac{\Delta R}{R} \propto \frac{1}{B_{\mathrm{scm}} l^2}$$

Permanent Magnet Scenario

$$\frac{\Delta R}{R} \propto \frac{1}{B_{\mathrm{pm}} l L}$$

http://www.ams02.org/wp-content/uploads/2010/05/MagnetSwitchScheme_600.jpg

Detection of CR (1)

Alpha Magnetic Spectrometer (AMS)

[http://www.ams.nasa.gov/Documents/AMS_Publications/ams_new_results_-_18.09.2014.pdf]

AMS-02 measured

- proton spectrum
- helium spectrum up to ~1 TeV
- electron, positron up to ~100 GeV

first observed by PAMELA

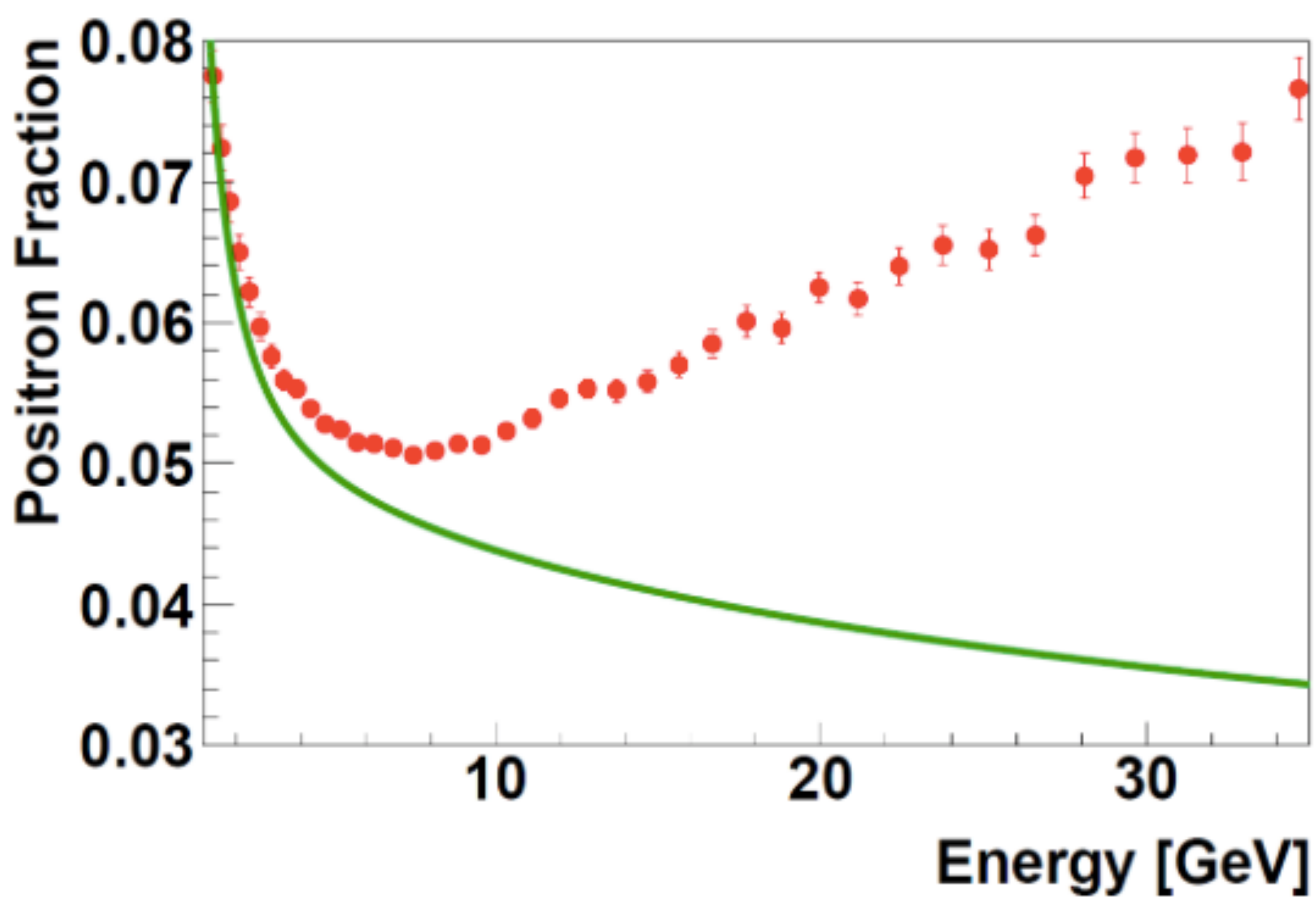


Figure 1. The positron fraction measured by AMS (red circles) compared with the expectation from the collision of ordinary cosmic rays showing that above 8 billion electron volts (8 GeV) the positron fraction begins to quickly increase. This increase indicates the existence new sources of positrons.

Detection of CR (2)

The Cosmic Ray Energetics and Mass (CREAM), http://arxiv.org/pdf/1003.5757.pdf
higher energies but still direct identification of primary particles

No magnetic spectrometer, calorimetric detector carried on several circumpolar balloon flight in Antarctica. It has measured, proton, helium & heavier nuclei above TeV - 100 TeV

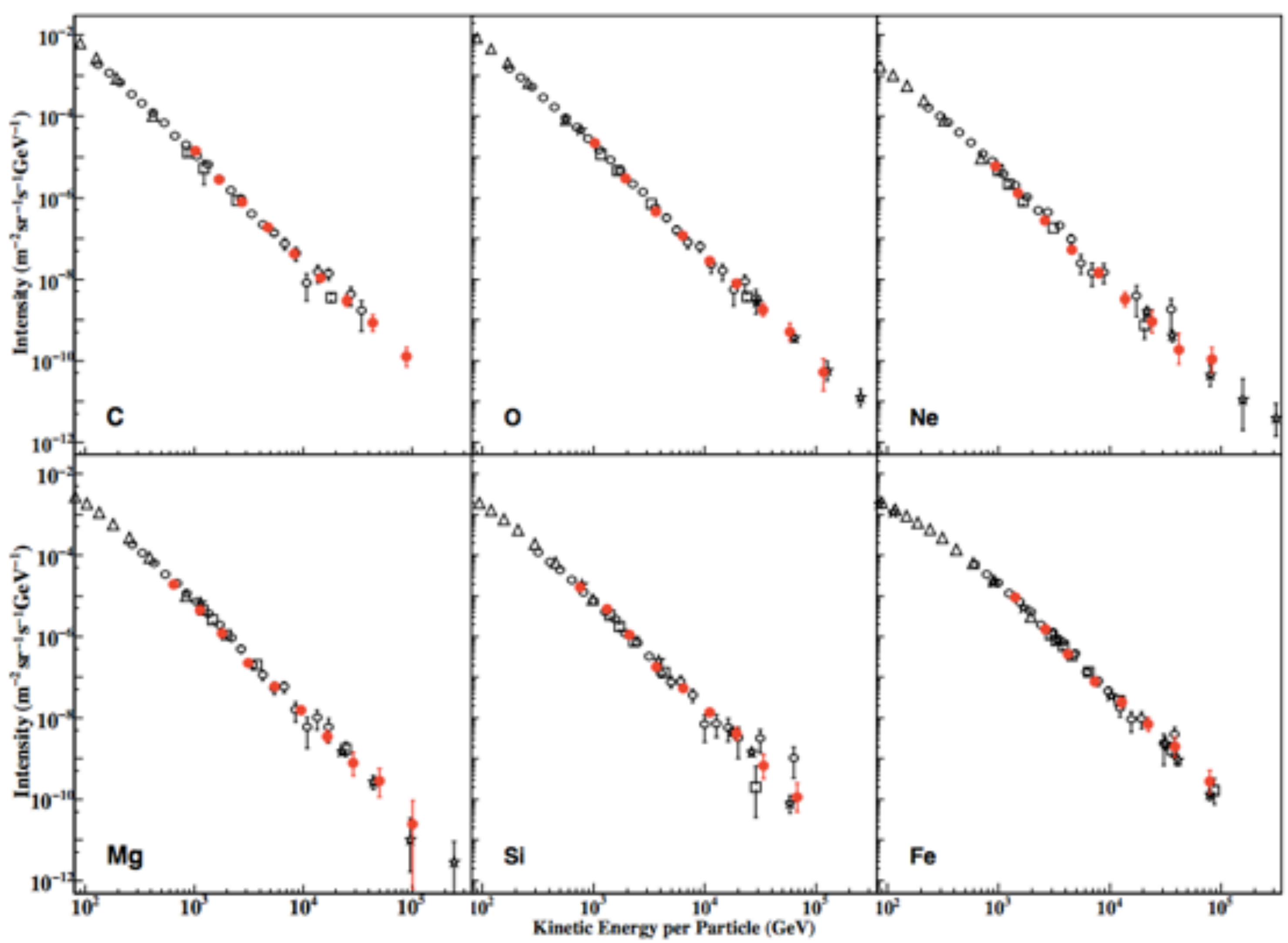
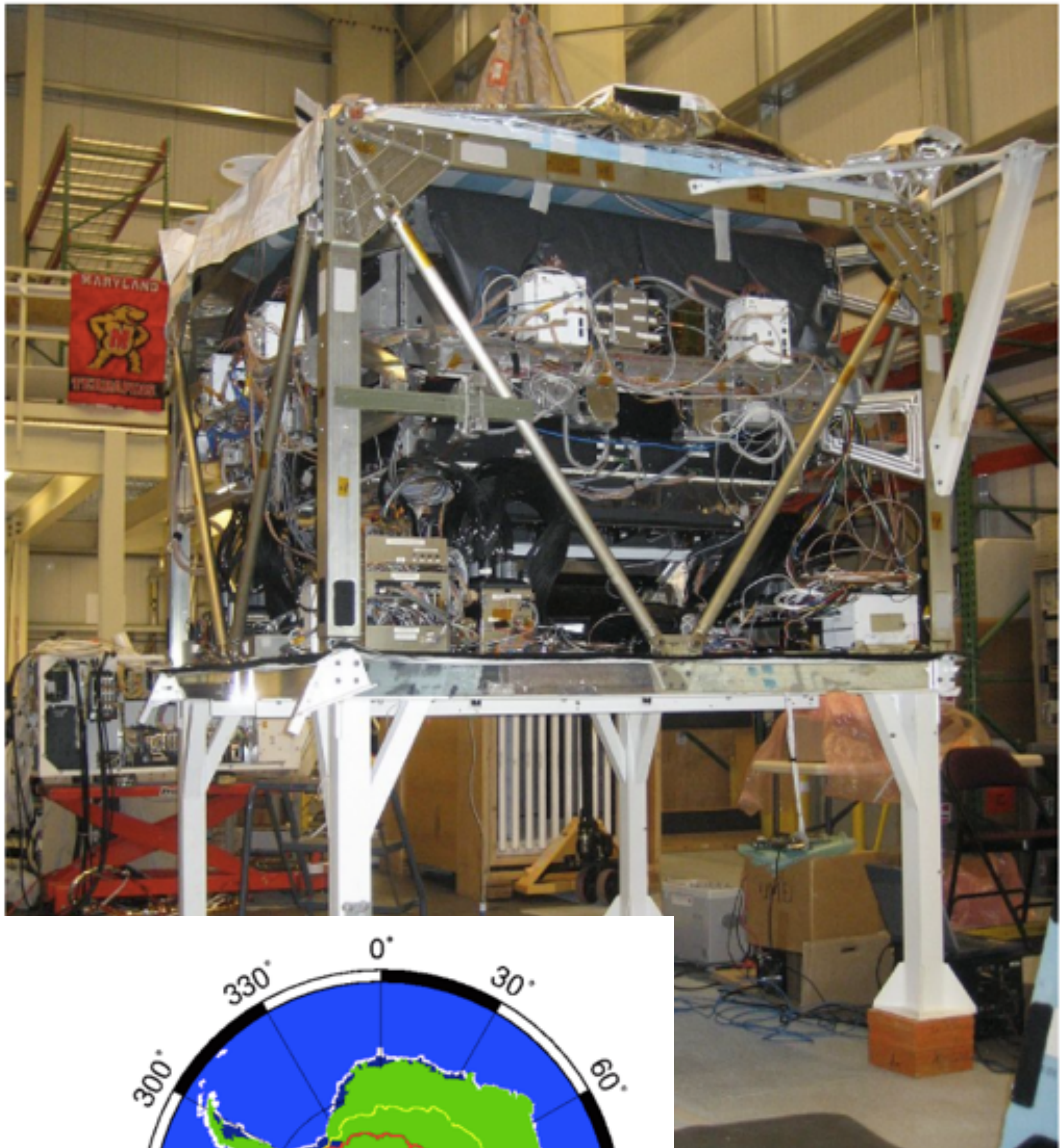
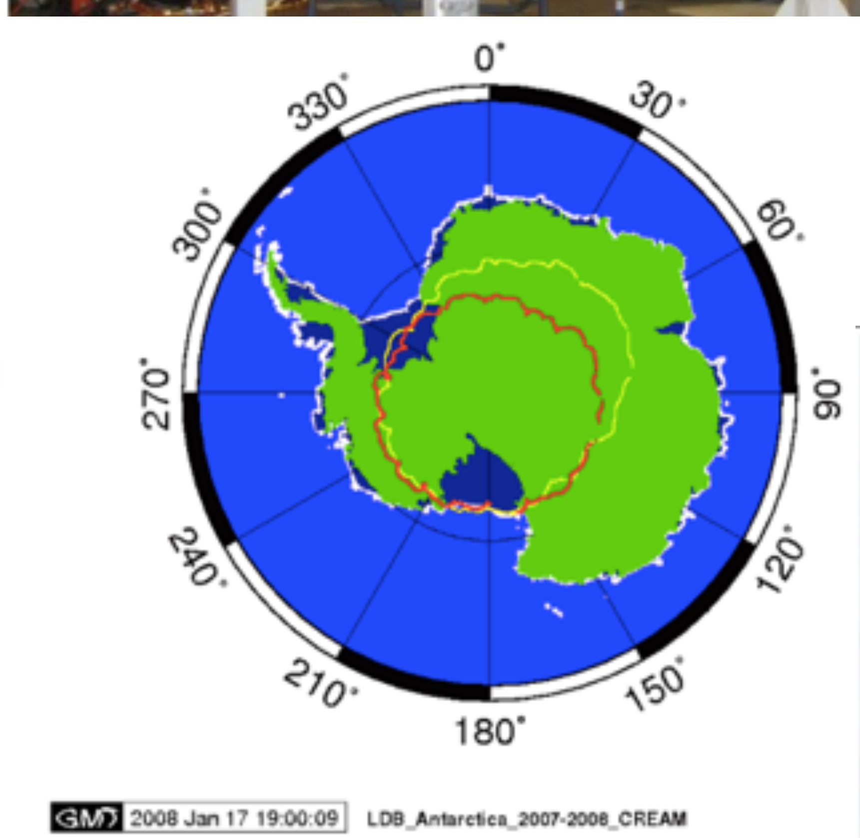


Figure 3. Energy spectra of the more abundant heavy nuclei. Results of CREAM-II (filled circles) are compared with measurements from HEAO [7] (triangles), CRN [8] (squares), ATIC [9] (open circles) and TRACER [10] (stars).





http://stratocat.com.ar/fichas-e/2007/MCM-20071219.htm

Detection of CR (3)

For higher energies: larger effective areas, longer exposure
Ground-based detectors: **air shower arrays**

No direct detection. Detection principle based on the remnants of the atmospheric cascade of particles; knowledge of particle physics needed!

The physics of the air showers is a central topic in this lecture. To be covered in the next.

[Li, Be, B] and [Sc, Ti, V, Cr, Mn] more abundant in CR

- Absent as end-products of stellar nucleosynthesis
- Produced as spallation products of higher mass elements
- Produced by collisions of CR in the insterstellar medium (ISM)

a cosmic laboratory of fundamental interest

- We know the cross sections for spallation
- let’s learn about the amount of matter traversed by CR between production and detection

[Li, Be, B] and [Sc, Ti, V, Cr, Mn] more abundant in CR

- We know the cross sections for spallation
- let's learn about the amount of matter traversed by CR between production and detection

- Mean amount of matter traversed: $X = 5$ g/cm^2
- Matter density in the galactic disk: $\rho_N = 1$ proton / cm^3
- Distance travelled:

$\ell = X \,/\, (m_p\, \rho_N) = 3 \cdot 10^{24}$ cm ~ 1000 kpc !!

$\ell >>$ 0.1 kpc = half-thickness of the disk of the Galaxy

CRs confinement is a diffusive process

CRs stay around for long period of time

What about antimatter in the CR?

- Positrons and anti-protons: both species are generated at 10^{-4} level as compared to protons from interactions in the ISM
- No heavy anti-nuclei in the cosmic rays,at a level of $<10^{-6}$ for antihelium/helium
- Detection of a single anti-helium nucleus would requires the existence of a anti-stars

▶ Cosmic rays do not provide new insight on the matter/ antimatter asymmetry of the universe.

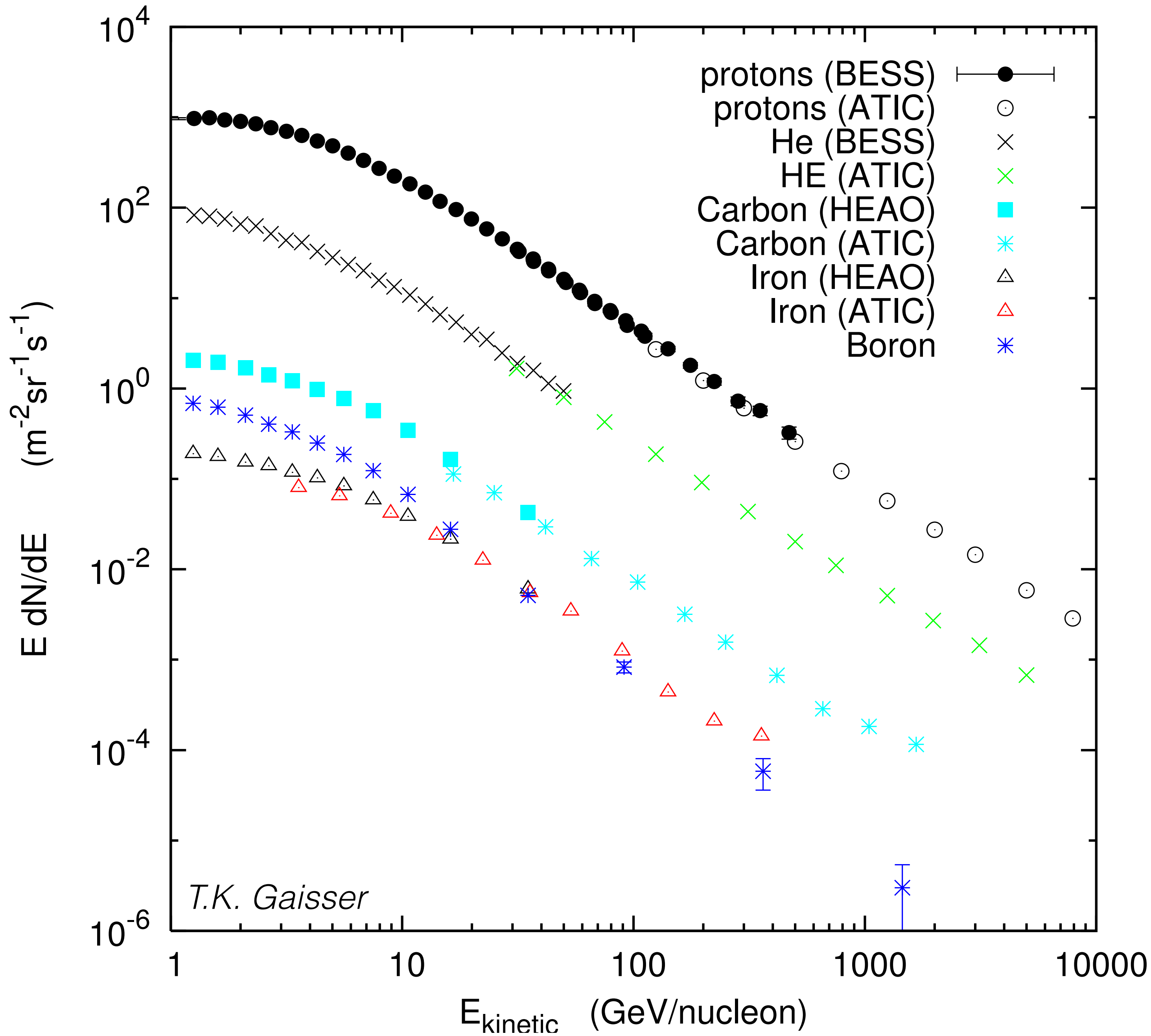
Energy Spectra

(1) Slopes are similar

(2) The one from B is steeper then parent O and C:

-> secondary/primary decrease at higher energy

-> higher energetic CR diffuse out of the Galaxy faster respect to the lower energetic ones.



Energy Spectra

total flux of nucleons (@ 11,5 GeV/nucleon) = 23 $m^{-1}s^{-1}\ sr^{-1}\ GeV^{-1}$

$$\frac{\mathrm{d}N}{\mathrm{d}E_N} = 1.7 \times 10^4\, E_N^{-2.7}\, \frac{\text{nucleons}}{\mathrm{m^2\,s\,sr\,GeV}} \quad \text{(differential)}$$

valid up to ~1 PeV

$$I(> E_N) = 10^4 (E_N/\mathrm{GeV})^{-1.7}\, \frac{\text{nucleons}}{\mathrm{m^2\,s\,sr}} \quad \text{(integral)}$$

E_N = total energy per nucleon

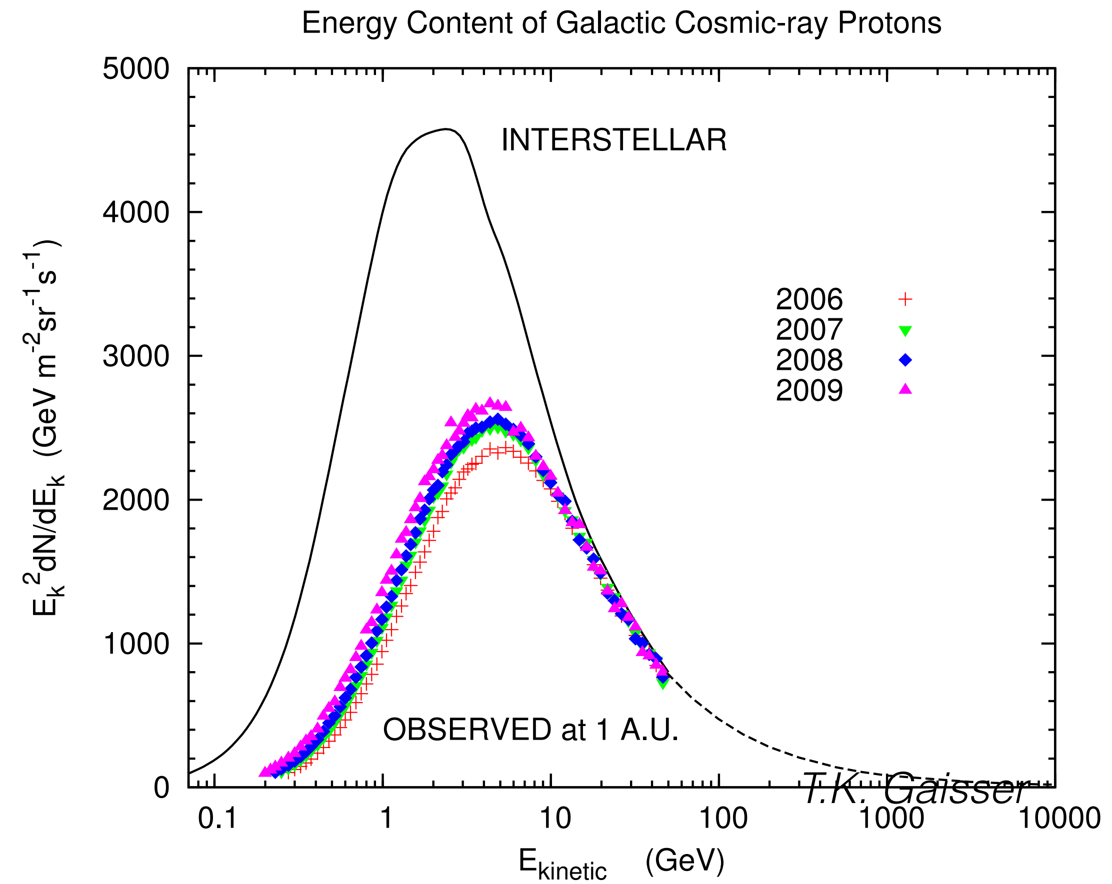
Of the total flux: 76.5% free proton,
11.7% protons in nuclei,
11.8% neutrons in nuclei

Energy density

Are CR Cosmic rays playing an important role in the dynamics of the interstellar medium ?

Is the cosmic-ray energy density sufficient to cause significant heating and ionization of the interstellar medium?

- energy density in CR in the ISM: **ρ_E ~ 0.5 eV/cm³**
- magnetic field energy density **~ 0.25 eV/cm³**
- the interaction between CR and magnetic fields in the Galaxy is mutual



The energy flux of protons: The data sets show measurements by the PAMELA spacecraft near Earth at various stages of the solar cycle, while the line shows an estimate of the energy flux of protons in interstellar space after correcting
the data for the effect of solar modulation