CERN SUMMER STUDENT - LECTURE II

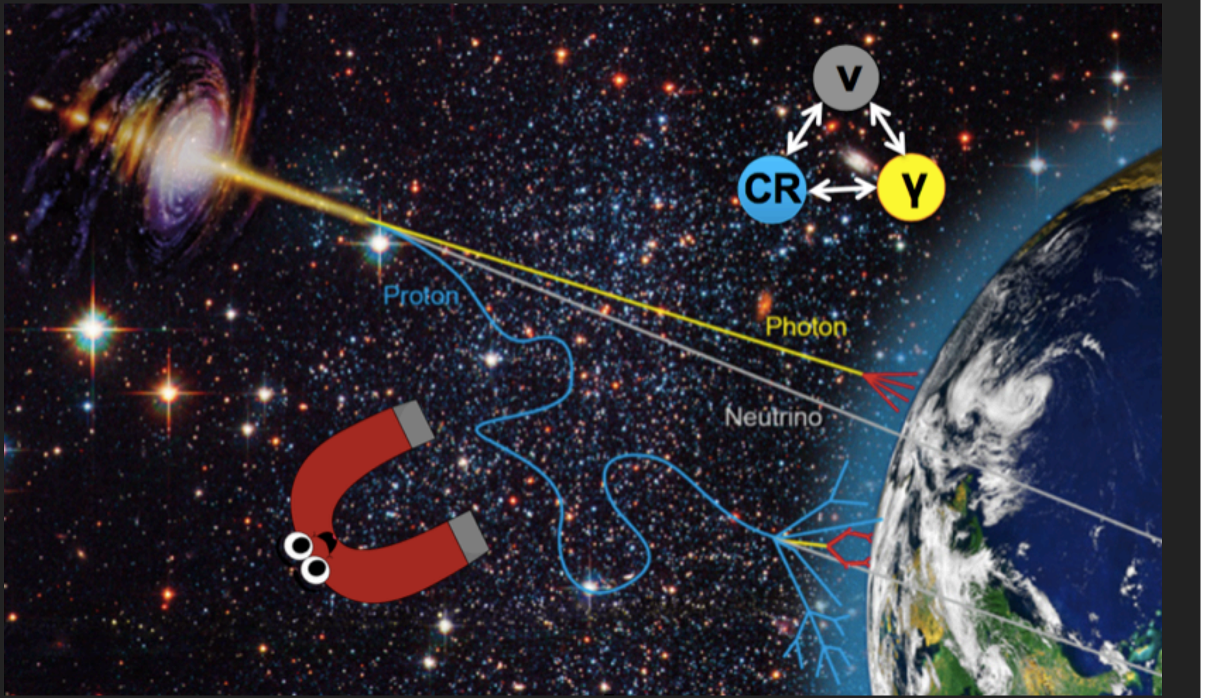
TERESA.MONTARULI@UNIGE.CH

ASTROPARTICLE II

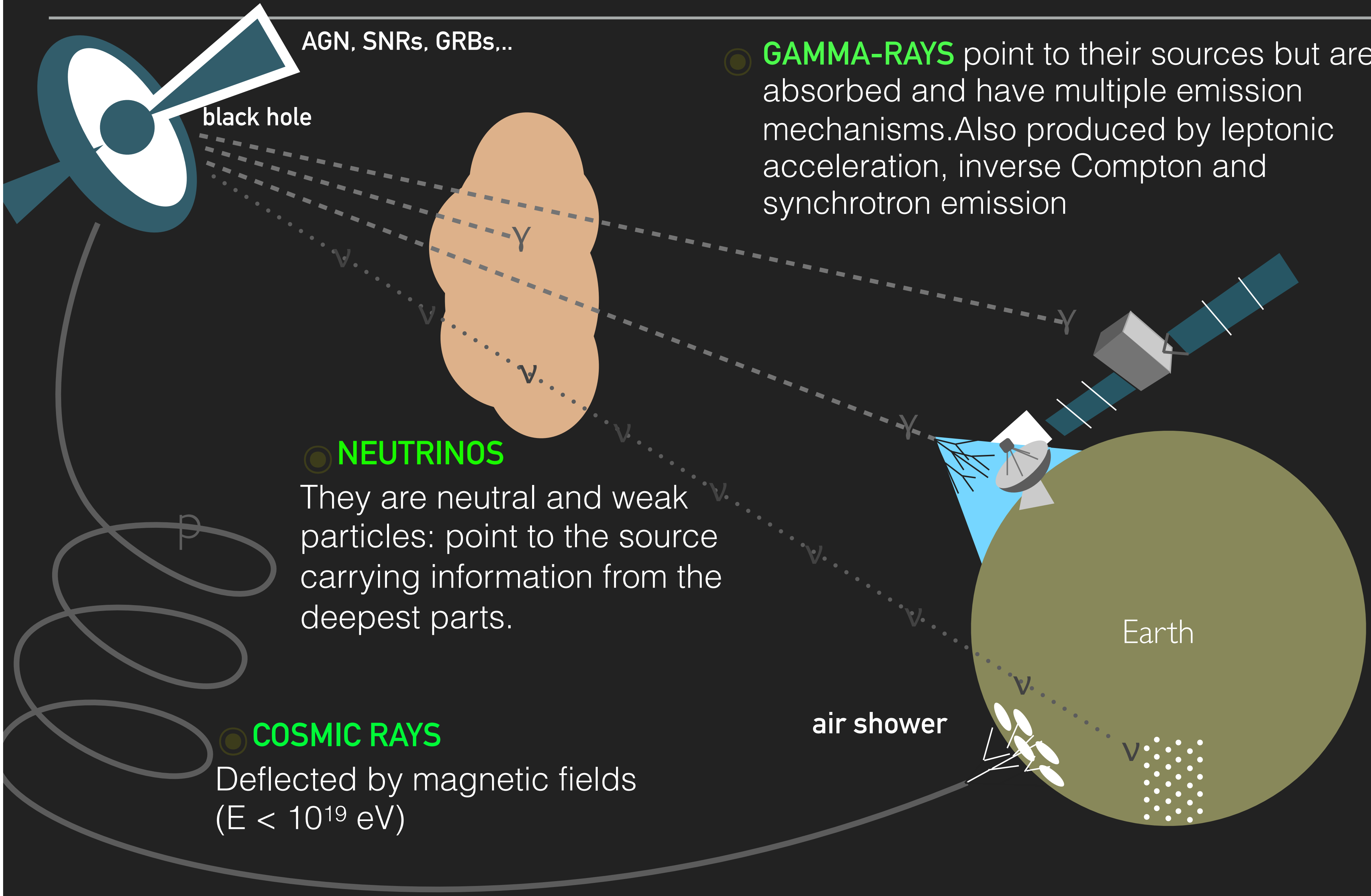
12 JULY 2018

CONTENTS OF TWO LECTURES

- Radiation from the universe and cosmic rays (CR)
- Cosmic ray observables: spectrum and composition
- Propagation and sources of cosmic rays
- The connection of CRs to other messengers :
- CRs with Ultra-High Energy CRs
    - Gamma-Rays
    - Neutrinos



THE MESSENGER PROPAGATION



GAMMA-RAYS point to their sources but are absorbed and have multiple emission mechanisms.Also produced by leptonic acceleration, inverse Compton and synchrotron emission

NEUTRINOS

They are neutral and weak particles: point to the source carrying information from the deepest parts.

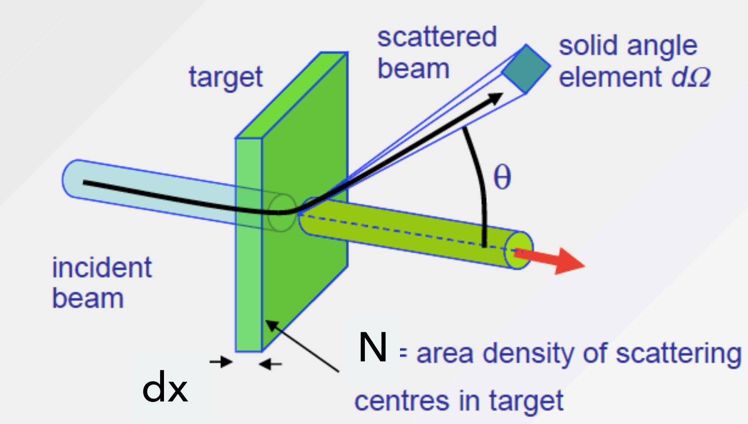
COSMIC RAYS

Deflected by magnetic fields ($E < 10^{19}$ eV)

THE INTERACTION LENGTH OF A PARTICLE

- Horizon = messenger mean free path (interaction length) in a medium
- X-section σ: area of the target intercepted by a beam measured as average fraction of scattered particles per unit time in the solid angle dΩ per unity of incident flux

$$\frac{d\sigma(E,\Omega)}{d\Omega} = \frac{1}{\Phi}\frac{dN_s}{d\Omega}$$



- Mean free path :

w = interaction probability = Nσdx, where N = n. of target particles/Volume

P(x) = prob. that a particle does not interact after traveling a distance x

P(x + dx) = P(x) (1-wdx) = prob. that a particle has no interaction between x and x+dx

$$\mathrm{P(x+dx) = P(x) + \frac{dP}{dx}dx = P(x) - P(x)wdx} \Rightarrow \frac{dP}{P} = -w dx \Rightarrow P(x) = P(0)e^{-wx}$$

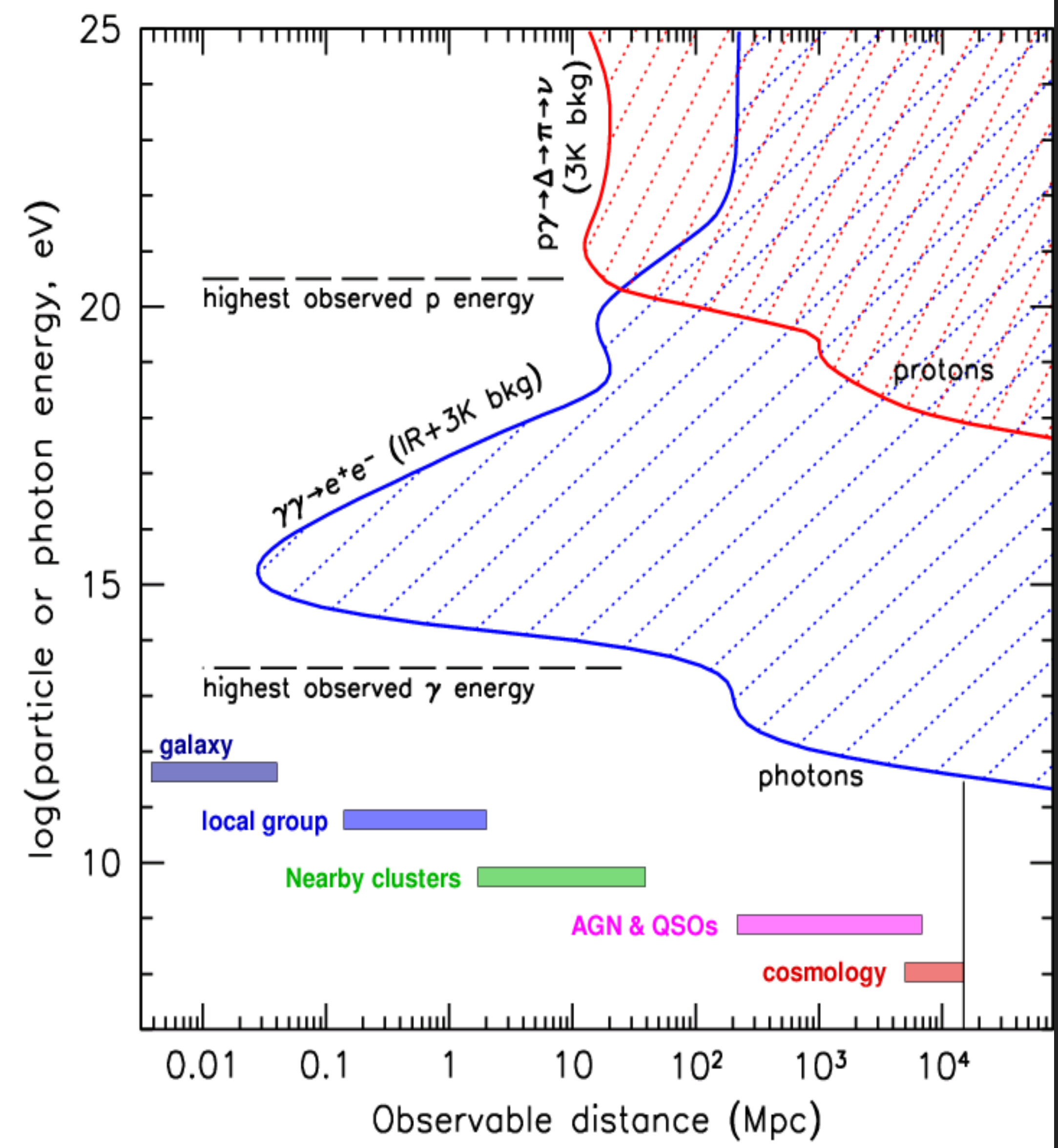
P(0) = 1 initially the particle did not interact

$$\lambda = \frac{\int \mathrm{xP(x)dx}}{\int \mathrm{P(x)dx}} = \frac{1}{\mathrm{w}} = \frac{1}{\mathrm{N}\sigma} = \frac{\mathrm{Am_p}}{\sigma\rho}$$

Target material

Particle properties

THE MESSENGER HORIZON = INTERACTION LENGTH IN THE COSMOS



Proton horizon (GZK cut-off):

$$p\gamma_{2.7K} \to \Delta^+ \to \pi^+ n$$

$$L_\gamma = \frac{1}{\sigma_{p-\gamma} n_\gamma} \sim 10\ \mathrm{Mpc}$$

$$\sim \frac{1}{10^{-28}\mathrm{cm}^2 \times 400\mathrm{cm}^{-3}}$$

The neutrino horizon is comparable to the observable universe!

$$\bar{\nu}\nu_{1.95K} \to Z \to X$$

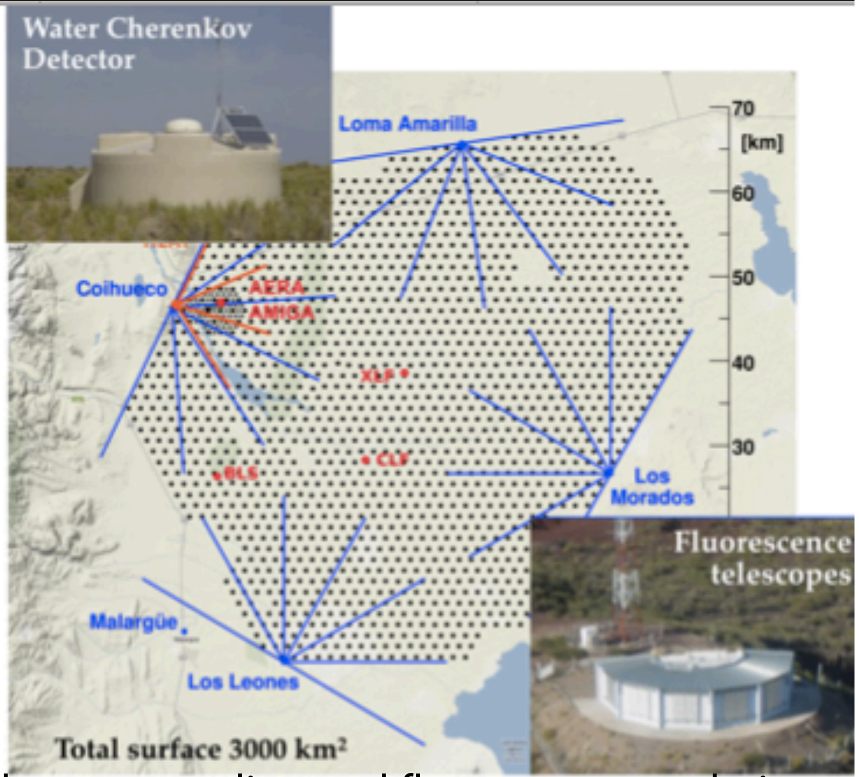
$$L_\nu = \frac{1}{\sigma_{res} \times n} = \frac{1}{5 \times 10^{31} cm^2 \times 112 cm^{-3}} \approx 6Gpc$$

arxiv.org/pdf/0811.1160v2.pdf

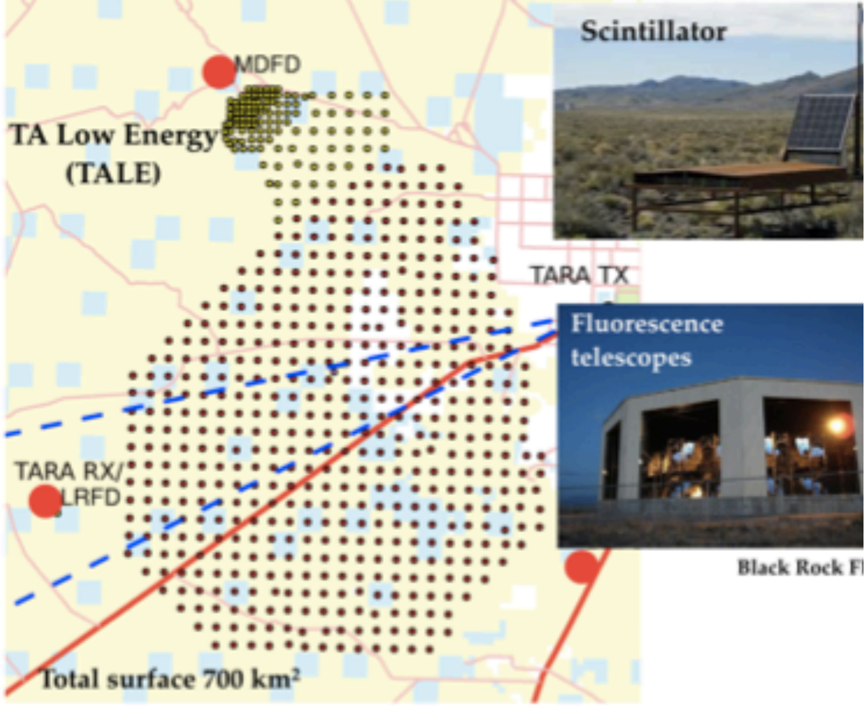
THE ANKLE REGION: UHE COSMIC RAYS

Can UHECR be cosmic messengers?

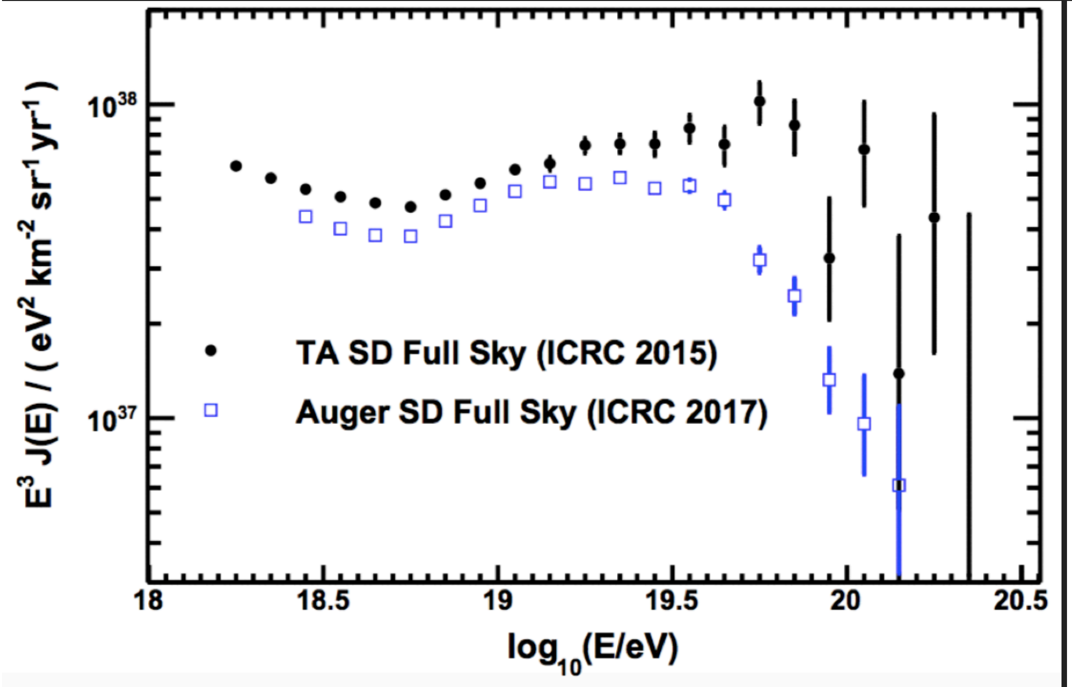
Yes ! But only in a tiny energy window between the minimum energy at which they are not deflected by B-fields and when they are not absorbed on cosmic radiation (GZK cutoff).

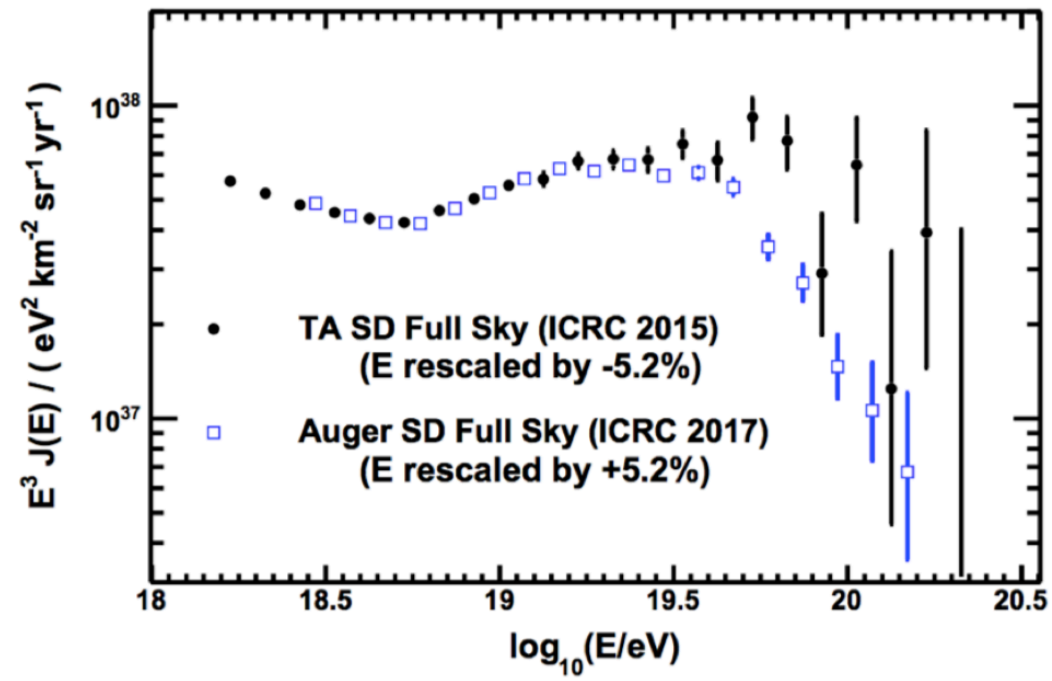


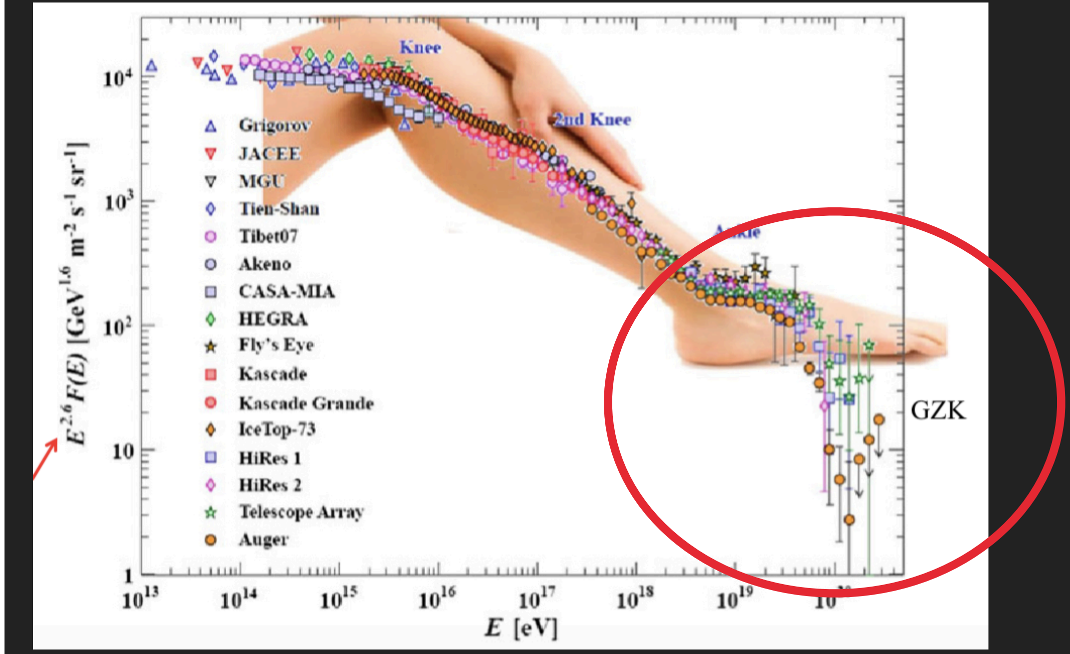
shower sampling and fluorescence techniques



CURRENT STATUS OF UHECR SPECTRUM: THE ANKLE







Rescaling due to systematic error on energy scale

MAGNETIC FIELD DEFLECTIONS OF UHECRS

If UHECR are not protons then astronomy with them will be not easy due to larger magnetic deflections.

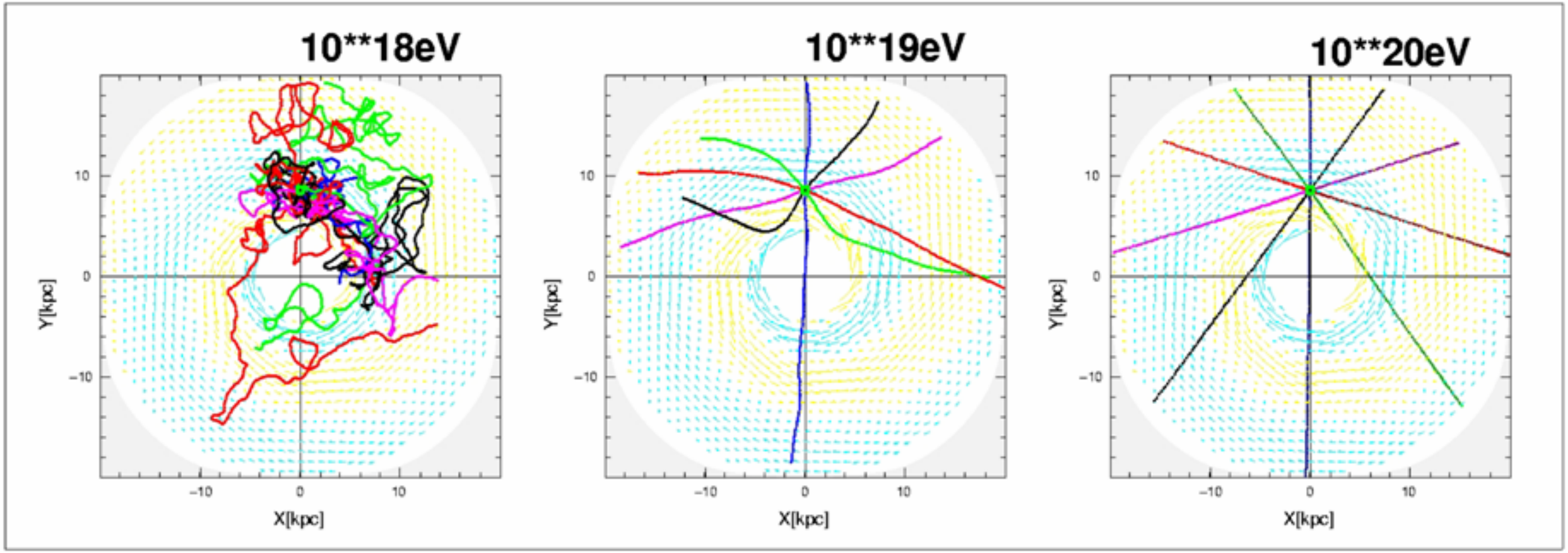
$$qvB = \frac{mv^2}{r_L} \rightarrow r_L = \frac{p}{ZeB}$$

$$R \equiv r_L Bc = \frac{pc}{Ze}$$

$$(10^{12} eV) = 10^{15} cm = 3 \times 10^{-4} pc$$

$$r = (10^{15} eV) = 10^{18} cm = 3 \times 10^{-1} pc$$

$$(10^{18} eV) = 10^{21} cm = 300 pc$$



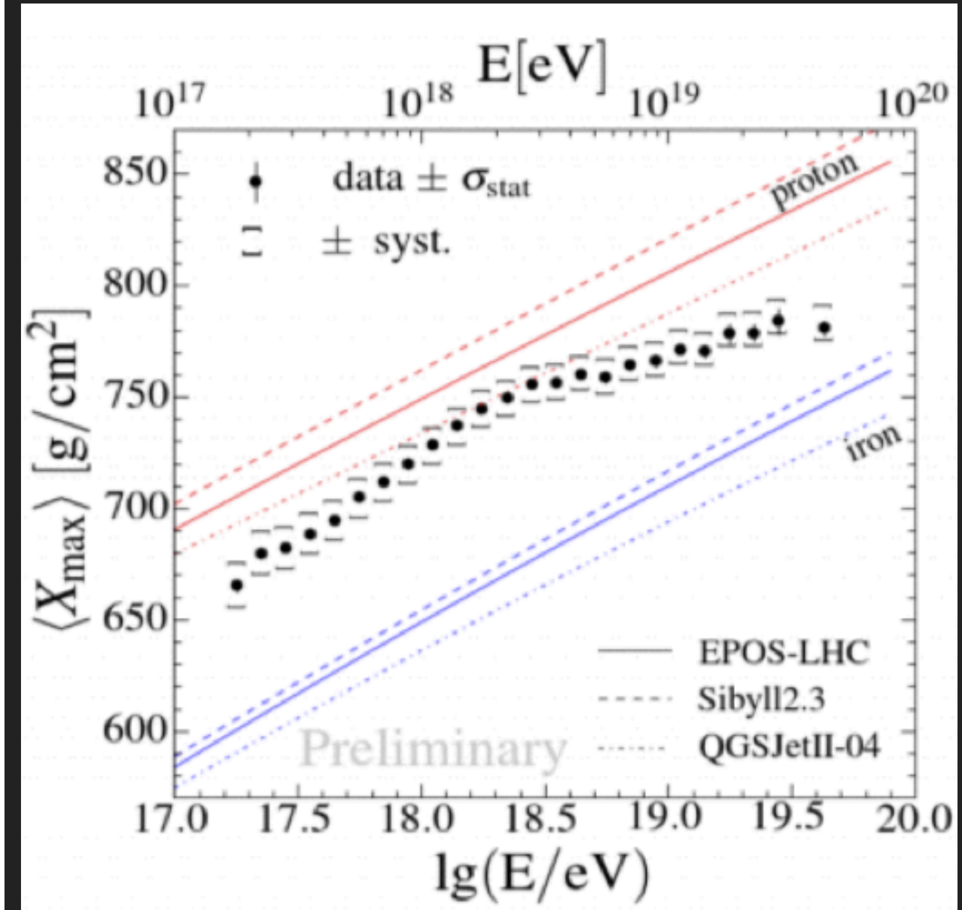
THE UHECR COMPOSITION

The atmosphere is a big calorimeter where decay and interaction of particles compete.

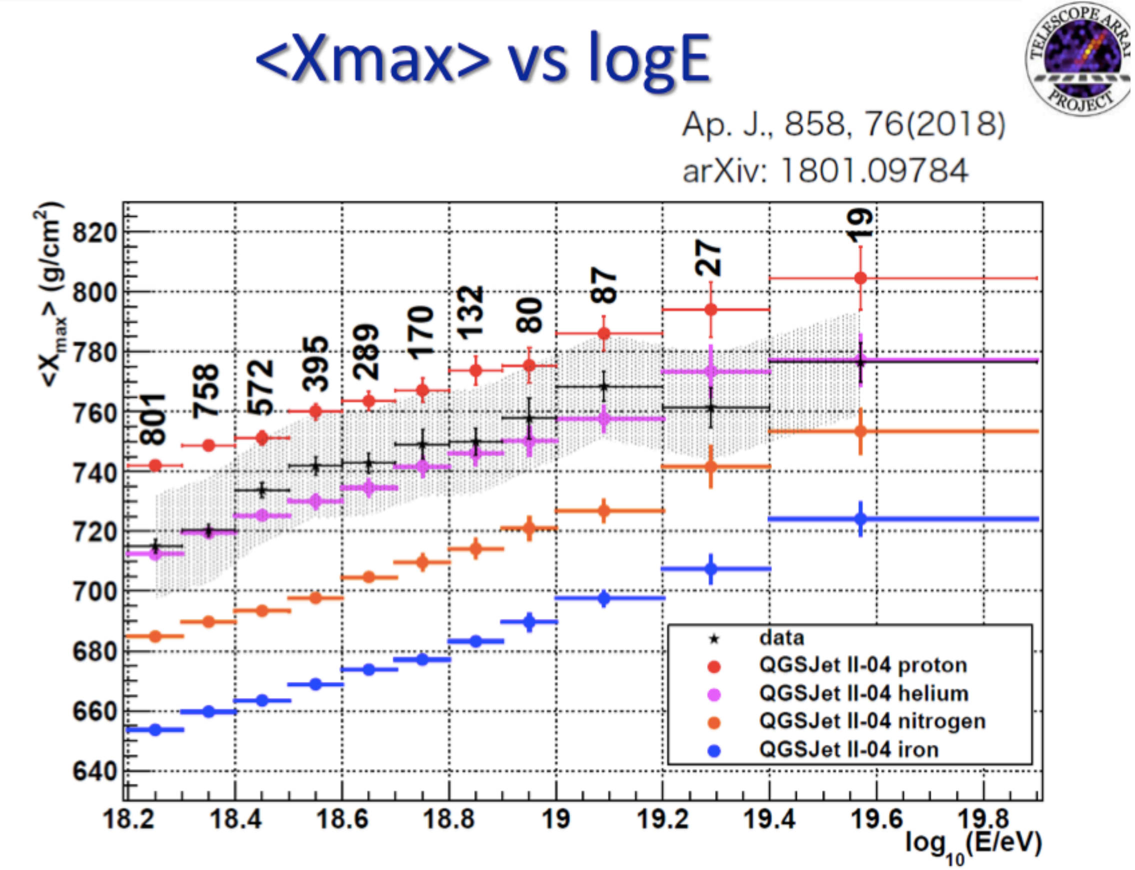
X_{max} = depth in the atmosphere where shows maximum occurs. It is an indictor of the composition since Fe showers penetrate less in the atmosphere than proton once principally due to the smaller interaction length.

Composition of UHECRs seems to be not as light as protons!! Hadronic models have large uncertainties in this region of energy.

Pierre Auger

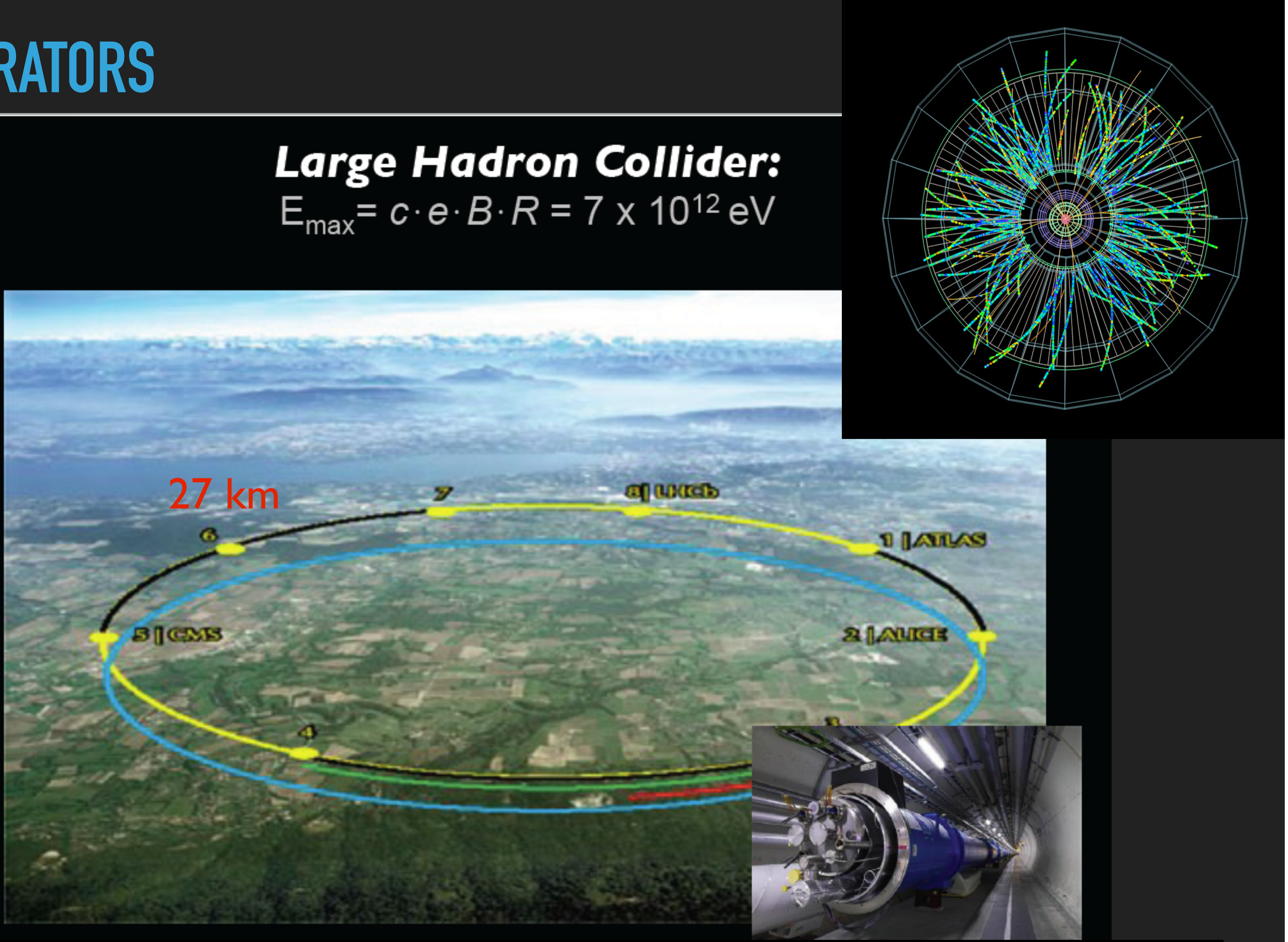


Telescope Array



Ap. J., 858, 76(2018)
arXiv: 1801.09784

ACCELERATORS



Large Hadron Collider:

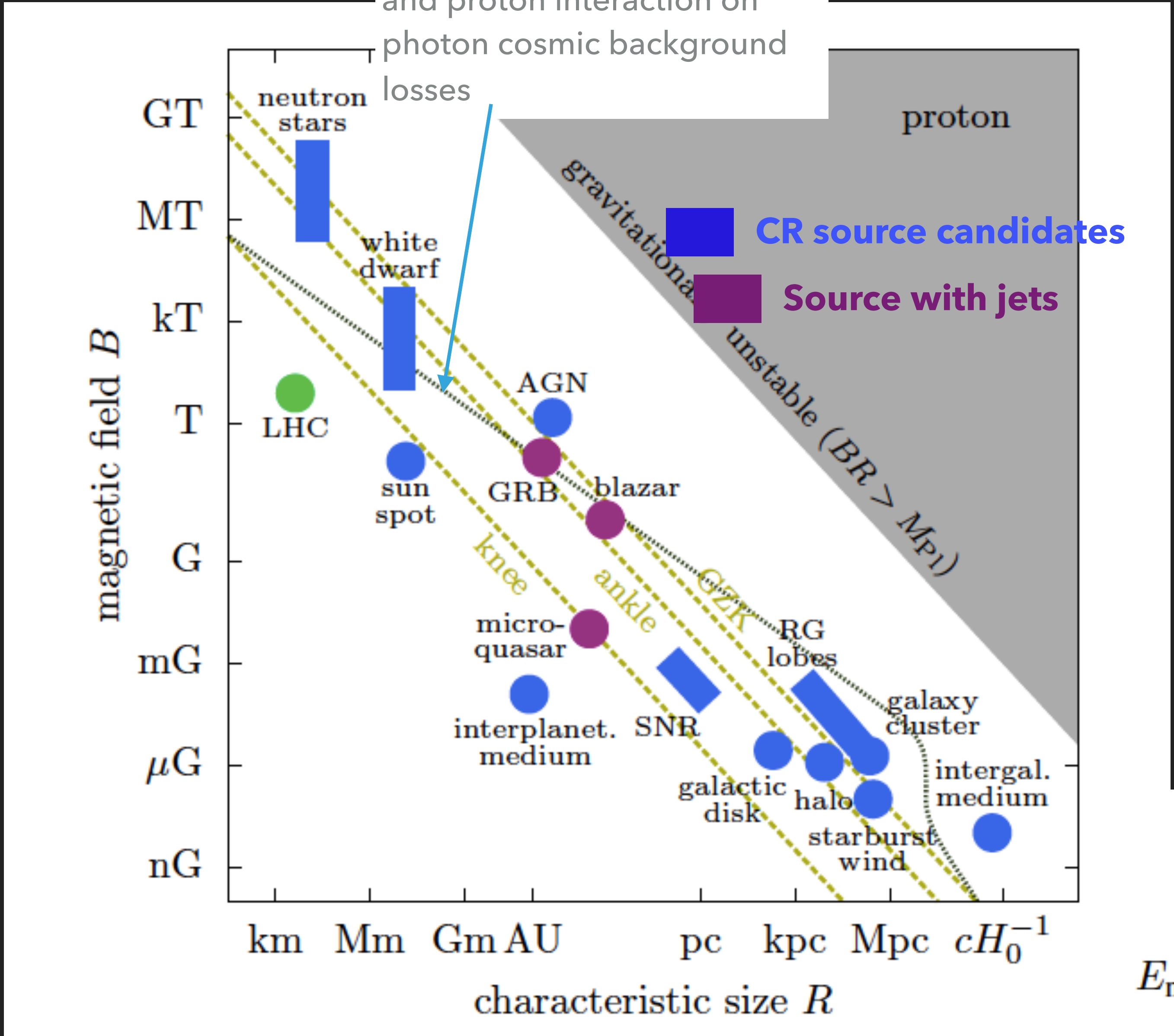
$E_{max} = c \cdot e \cdot B \cdot R = 7 \times 10^{12}$ eV

9593 superconducting magnets at -271.3 °C accelerate protons to collide in 4 points instrumented to analyze matter and its constituents in which it decomposes at these extreme conditions similar to 3×10^{-15} seconds after the Big Bang(15 TeV correspond to abt. 10^{17} Kelvin)

COSMIC ACCELERATORS

An LHC with the radius of the Mercury orbit could accelerate protons to 10^{20} eV = 10^7 x LHC!

MESSENGER ACCELERATION: THE HILLAS' PLOT



Upper limit from synchrotron and proton interaction on photon cosmic background losses

■ CR source candidates

■ Source with jets

Lorentz force

$$F_L = qvB = m\frac{v^2}{R}$$

Imposing that the Larmour is equal to the accelerating region

R = R$_{acc}$

We find the maximum energy at which the charged relativistic particle with q = Ze can be accelerated

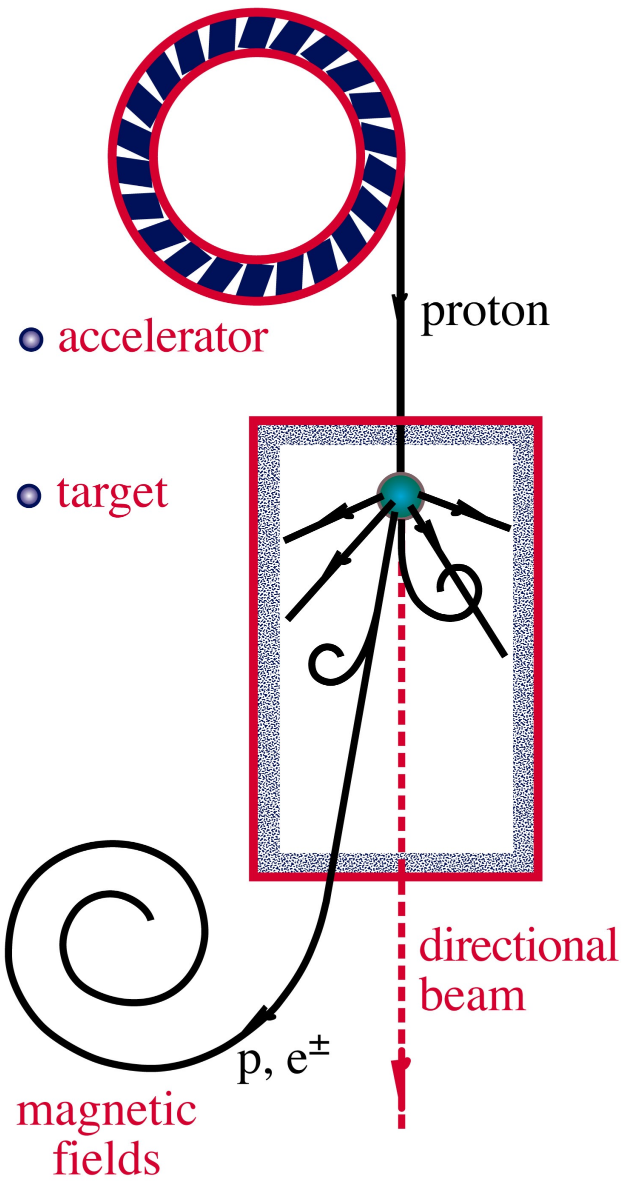
$$R_L = \frac{cp}{ZeB} \approx 100\,\text{pc}\,\frac{3\mu\text{G}}{B}\,\frac{E}{Z \times 10^{18}\text{eV}}$$

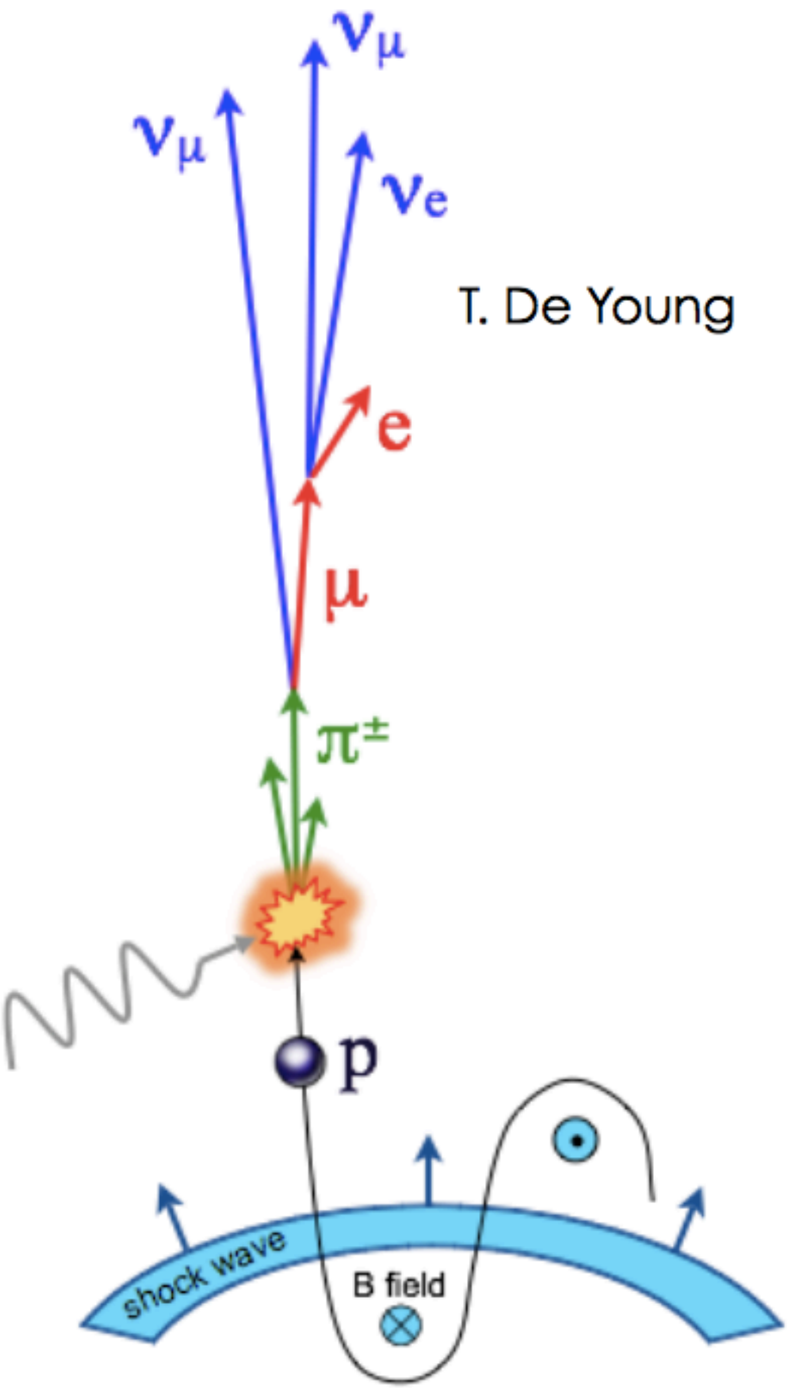
$$E_{\rm max} \simeq Z\left(\frac{B}{\mu\text{G}}\right)\left(\frac{R_{\rm source}}{\text{kpc}}\right) \times 10^9\ \text{GeV}$$

For jets with Lorentz factors Γ, E$_{max}$ ≅ Γ ZBR (maximum energy depends on cosmic ray charge Z!!)

THE GENERIC MESSENGER SOURCE: EARTH & HEAVEN

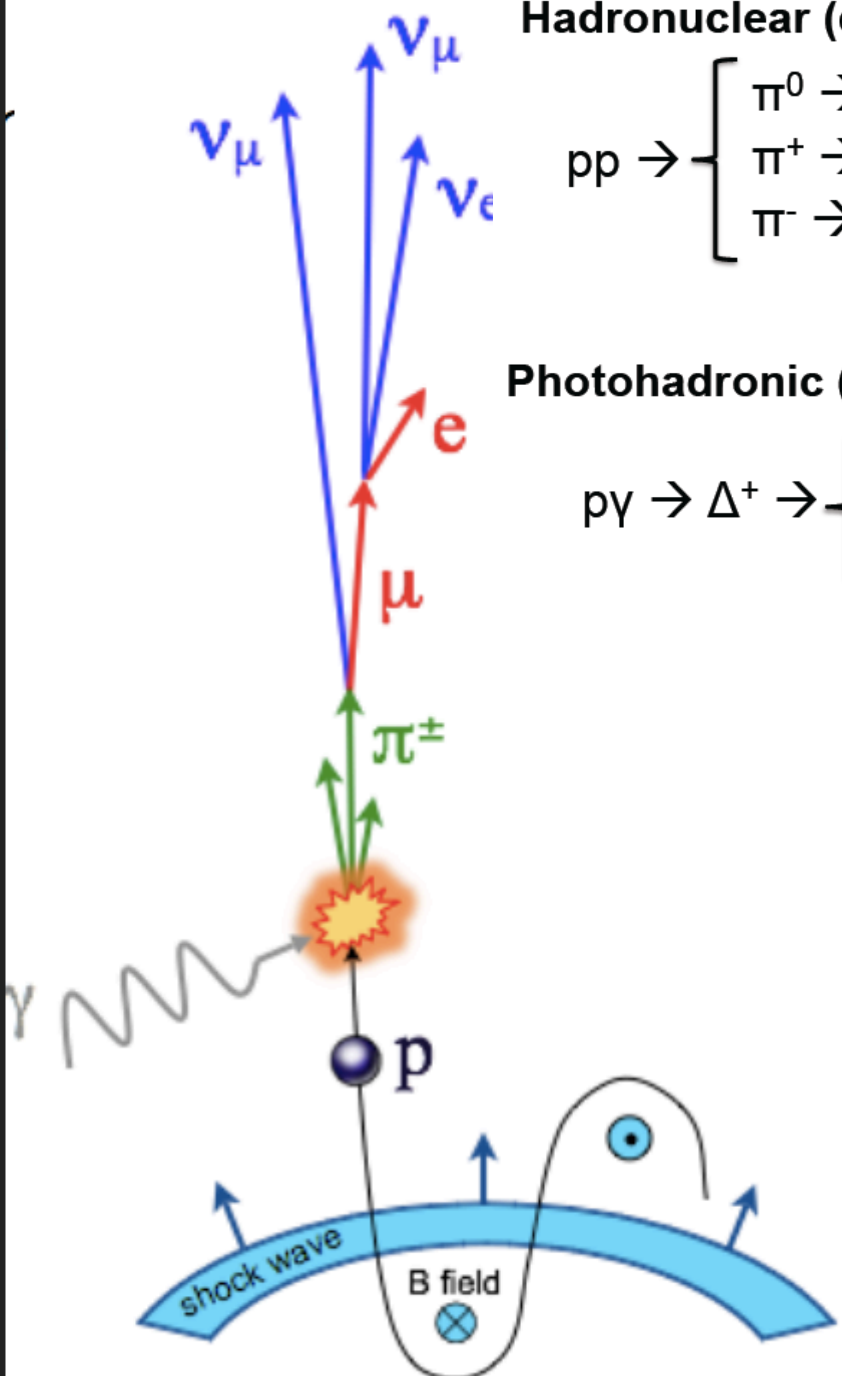
F. Halzen





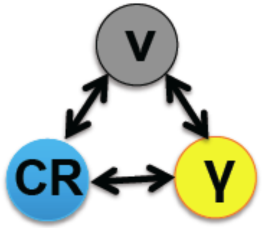
T. De Young

THE GENERIC MESSENGER SOURCE : A COSMIC BEAM DUMP



Hadronuclear (e.g. star burst galaxies and galaxy clusters)

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+\,\nu_\mu \rightarrow e^+\,\nu_e\,\nu_\mu\,\bar{\nu}_\mu \\ \pi^- \rightarrow \mu^-\,\bar{\nu}_\mu \rightarrow e^-\,\bar{\nu}_e\,\bar{\nu}_\mu\,\nu_\mu \end{cases}$$



Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow \boxed{p\,\gamma\,\gamma} \\ n\,\pi^+ \rightarrow n\,\mu^+\,\nu_\mu \rightarrow \boxed{n}\,e^+\,\boxed{\nu_e\,\bar{\nu}_\mu\,\nu_\mu} \end{cases}$$

cosmic ray + gamma

cosmic ray + neutrinos

Neutrino flavour ratio at source:

pion-muon decay

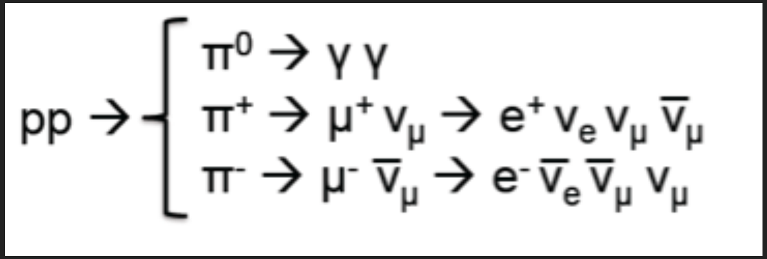
$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 2 : 0$$

Oscillations average out over cosmic baselines

$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$$

MULTI-MESSENGER RELATION

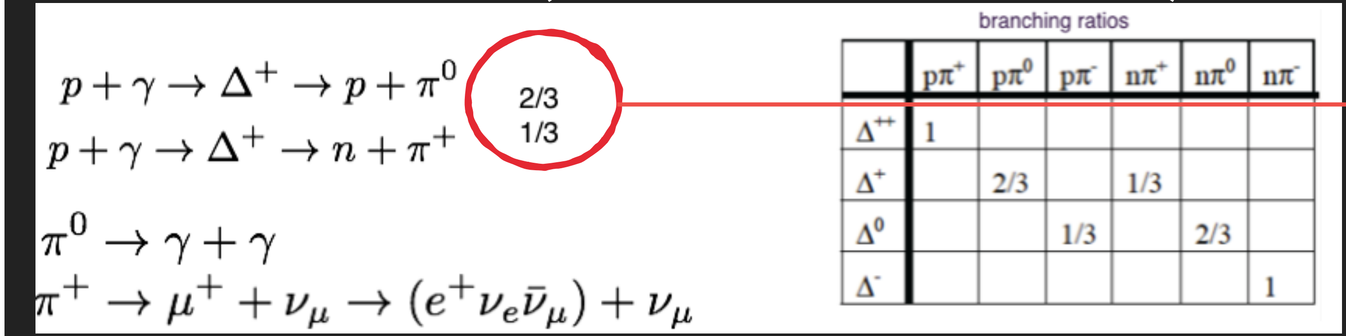
Proton-proton interactions on sources or in the interstellar matter in the galactic disk



$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

1 neutral pion and 2 charged pions : pion multiplicity $N_\pi = 2$

At higher energies (the Delta resonance threshold is higher than pion one) proton-photon interactions dominate (for instance for black holes)



$$p+\gamma \rightarrow \Delta^+ \rightarrow p+\pi^0 \quad 2/3$$

$$p+\gamma \rightarrow \Delta^+ \rightarrow n+\pi^+ \quad 1/3$$

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow (e^+\nu_e\bar{\nu}_\mu) + \nu_\mu$$

branching ratios

	$p\pi^+$	$p\pi^0$	$p\pi^-$	$n\pi^+$	$n\pi^0$	$n\pi^-$
Δ^{++}	1					
Δ^+		2/3		1/3		
Δ^0			1/3		2/3	
Δ^-						1

This factors are modified by non-resonant pion production into ½ and ½

The total inelasticity of pp and p-gamma interactions is 0.5 and 0.2 respectively (S. R. Kelner et al., PRD74(2006)79, J. Rachen PhD Thesis, Ahlers & Halzen, PTEP 2017, 12A105). For pp and p-gamma the average inelasticity per pion is:

$$\kappa_\pi = \kappa / N_\pi \simeq 0.2$$

Neutrinos from pion and muon decays take about 1/4 of the pion energy!

Gammas from neutral pion decay take about 1/2 of the pion energy!

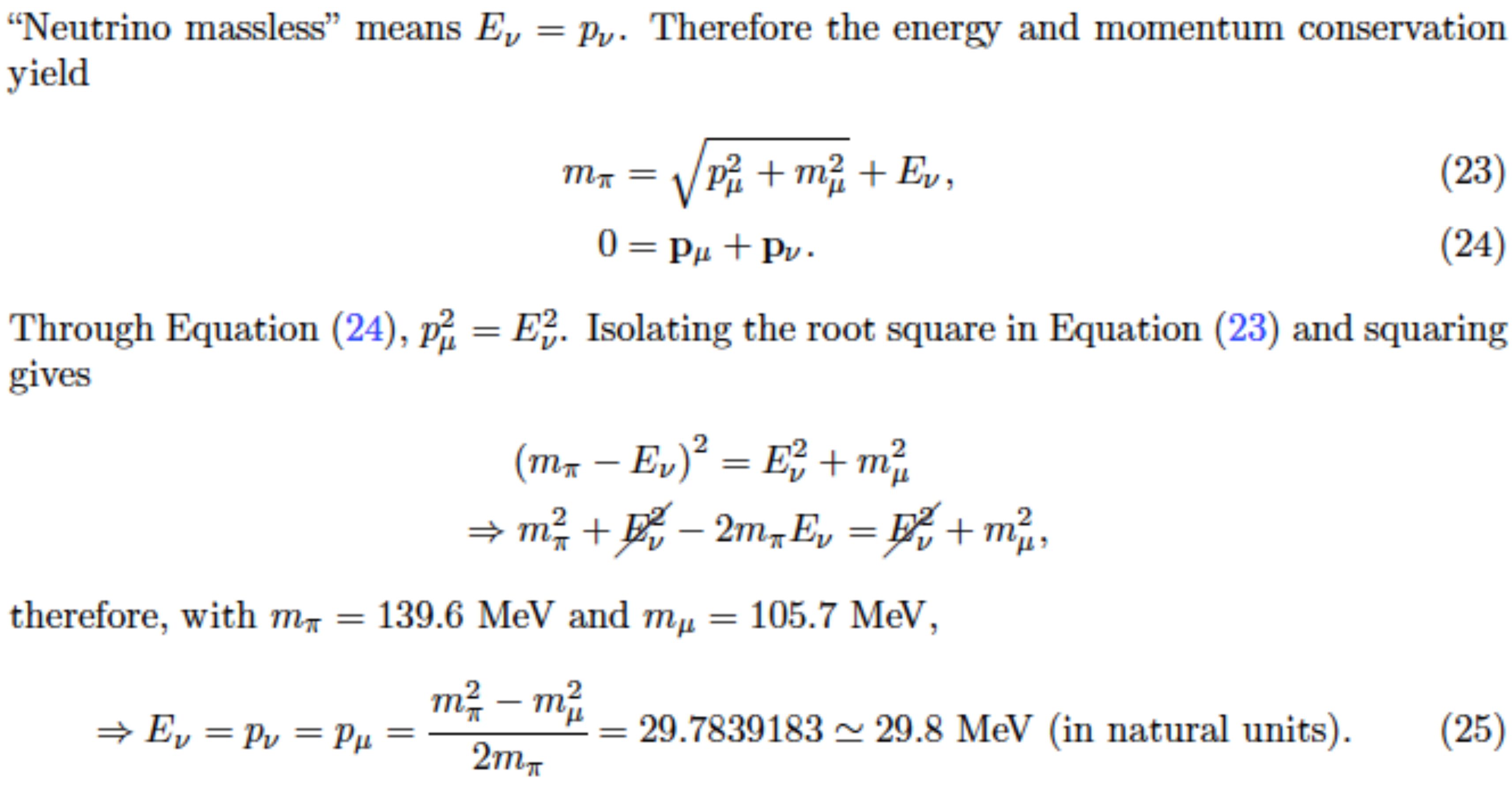
The energy fractions:

$$x_\nu = \frac{E_\nu}{E_p} = \frac{1}{4}\kappa_\pi \simeq \frac{1}{20} \text{ and } x_\gamma = \frac{E_\gamma}{E_p} = \frac{1}{2}\kappa_\pi \simeq \frac{1}{10}.$$

Two Body Decay Kinematics

Each neutrino takes about 1/4 of the pion energy (on average)

In the Lab (pion at rest)



"Neutrino massless" means $E_\nu = p_\nu$. Therefore the energy and momentum conservation yield

$$m_\pi = \sqrt{p_\mu^2 + m_\mu^2} + E_\nu\,, \tag{23}$$

$$0 = \mathbf{p}_\mu + \mathbf{p}_\nu\,. \tag{24}$$

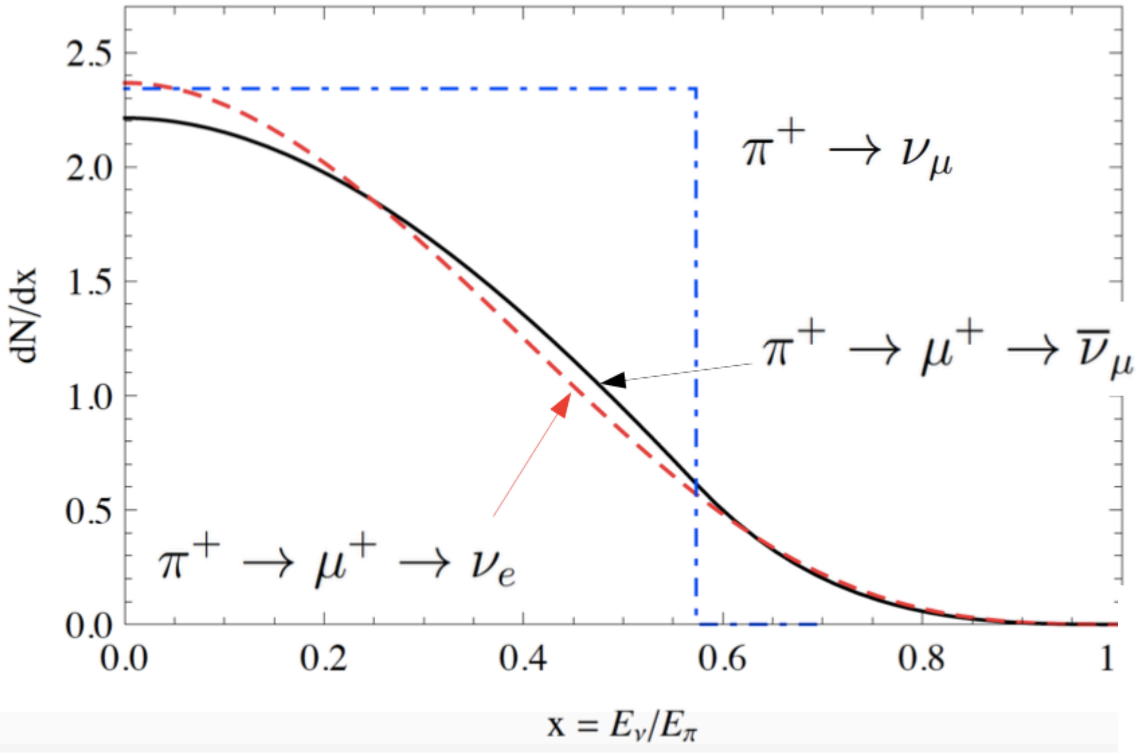
Through Equation (24), $p_\mu^2 = E_\nu^2$. Isolating the root square in Equation (23) and squaring gives

$$\begin{aligned} (m_\pi - E_\nu)^2 &= E_\nu^2 + m_\mu^2 \\ \Rightarrow m_\pi^2 + \cancel{E_\nu^2} - 2m_\pi E_\nu &= \cancel{E_\nu^2} + m_\mu^2, \end{aligned}$$

therefore, with $m_\pi = 139.6$ MeV and $m_\mu = 105.7$ MeV,

$$\Rightarrow E_\nu = p_\nu = p_\mu = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} = 29.7839183 \simeq 29.8 \text{ MeV (in natural units).} \tag{25}$$

Three Body Decay Kinematics



the LAB and for $E_\pi >> m_\pi$

ss of electrons/neutrinos neglected)

$$E_{\nu,\max} = \frac{1}{m_\pi}(E_\pi E_\nu^0 + p_\pi p_\nu^0) \approx \lambda E_\pi \,,$$

where

$$\lambda = 1 - m_\mu^2/m_\pi^2 = 0.427 \,.$$

RELATIONSHIP BETWEEN NEUTRINO AND GAMMA-RAY FLUXES

Assuming at the source : $\frac{dN_p}{dE_p} \propto E_p^{-2}$ => $\frac{dN_p}{dE_p} \propto E_p^{-2} = E_\nu^{-2} x_\nu^2$ and

Since : $\frac{E_\nu}{E_p} = x_\nu \sim \frac{1}{20}$ => $dE_p = x_\nu^{-1} dE_\nu$

- For pp: 1 neutral pion produces 2 photons, 2 charged pions produce 2 muon neutrinos each

$$\frac{dN_\gamma}{dE_\gamma} = 1 \times \frac{dN_p}{x_\gamma dE_p} \propto 1 E_\gamma^{-2} x_\gamma \propto 0.1 E_\gamma^{-2}$$

$$\frac{dN_{\nu_\mu}}{dE_{\nu_\mu}} = 2 \times \frac{dN_p}{x_\nu dE_p} \propto 2 E_\nu^{-2} x_\nu \propto 0.1 E_\nu^{-2}$$

$$\frac{dN_\nu}{dE} \sim \frac{dN_\gamma}{dE} \text{ for pp}$$

- For p-gamma: 1 charged pions and 1 muon neutrinos with BR 1/2

$$\frac{dN_\gamma}{dE_\gamma} = \frac{1}{2} \times \frac{dN_p}{x_\gamma dE_p} \propto 0.5 E_\gamma^{-2} x_\gamma \propto 0.05 E_\gamma^{-2}$$

$$\frac{dN_{\nu_\mu}}{dE_{\nu_\mu}} = \frac{1}{2} \times \frac{dN_p}{x_\nu dE_p} \propto 0.5 E_\nu^{-2} x_\nu \propto 0.025 E_\nu^{-2}$$

$$\frac{dN_\nu}{dE} \sim \frac{1}{2} \frac{dN_\gamma}{dE} \text{ for p} - \gamma$$

NEUTRINO SPECTRA FROM COSMIC RAY AND GAMMA SPECTRA

Neglecting gamma-ray absorption and including standard neutrino oscillations

Muon neutrinos (red data)

$$\frac{dN_\nu}{dE} = \frac{1}{2}\frac{dN_\gamma}{dE} \text{ for p} - \text{p}$$

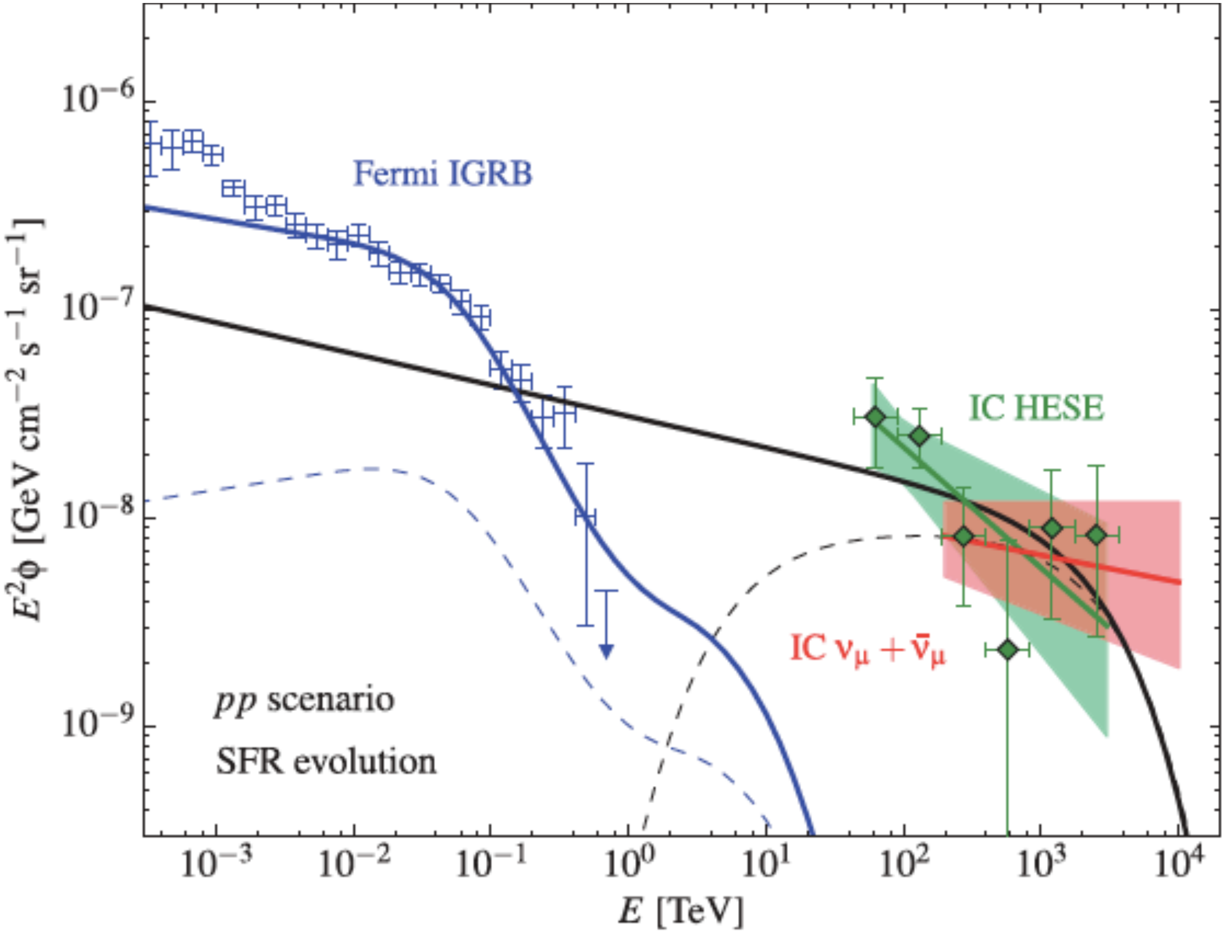
$$\frac{dN_\nu}{dE} = \frac{1}{4}\frac{dN_\gamma}{dE} \; for\, p - \gamma$$

If analysis measures all flavour neutrinos (HESE green IceCube curve) then

$$\frac{dN_\nu}{dE} = \frac{dN_\gamma}{dE} \text{ for p} - \text{p}$$

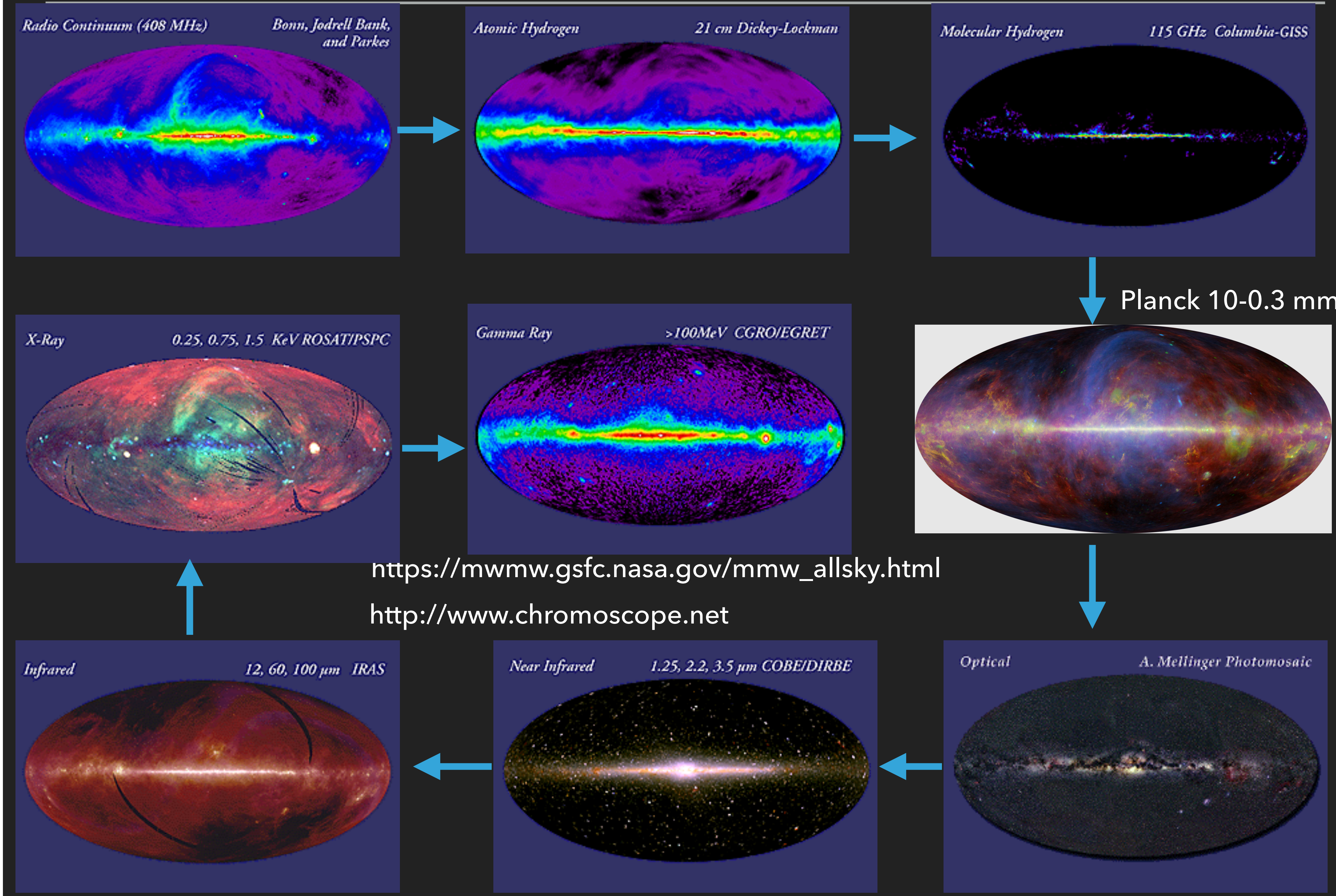
$$\frac{dN_\nu}{dE} = \frac{1}{2}\frac{dN_\gamma}{dE} \; for\, p - \gamma$$

Two possible models fitting IceCube data and compatible to Fermi observed diffuse isotropic gamma-ray background (IGRB)



But gamma-rays cascade down to lower energies where Fermi measures them!

THE MULTIWALENGTH SKY



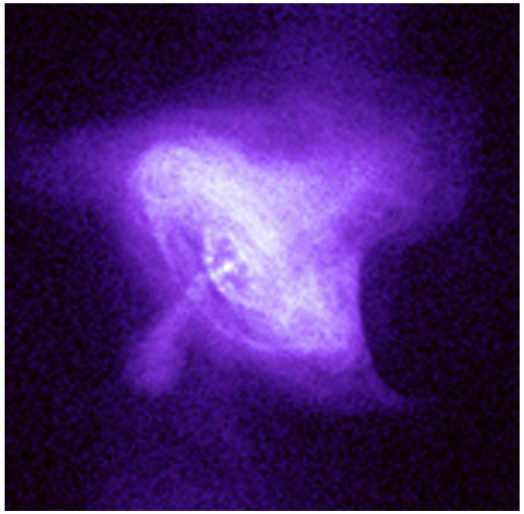
Planck 10-0.3 mm

https://mwmw.gsfc.nasa.gov/mmw_allsky.html

http://www.chromoscope.net

Multi-wavelength observations: The Crab Nebula

Hystorical Supernova remnant observed in the year 1054 by Chinese Astronomers

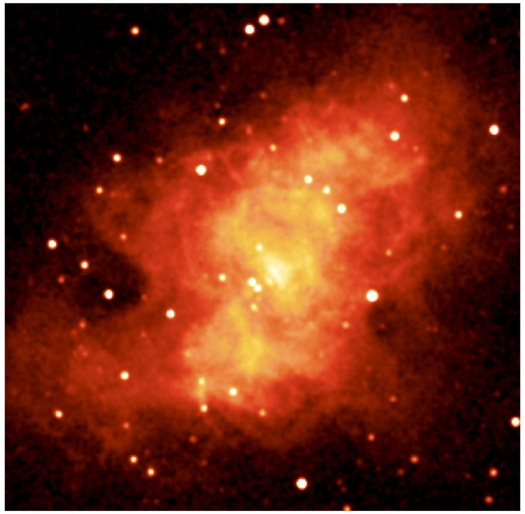


X-ray

$\sim 10^{4}$ eV

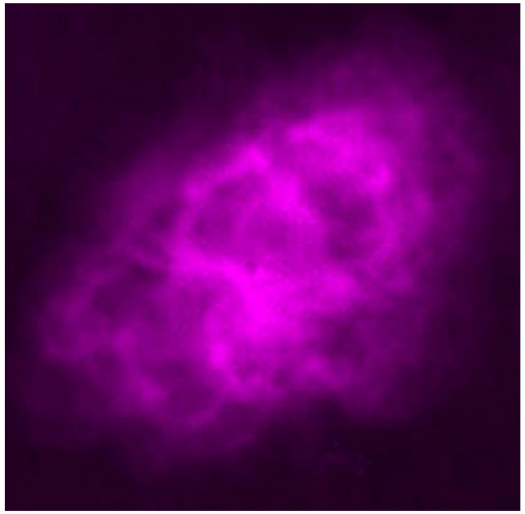
Optical

~ few eV



Infrared

~ 1 eV



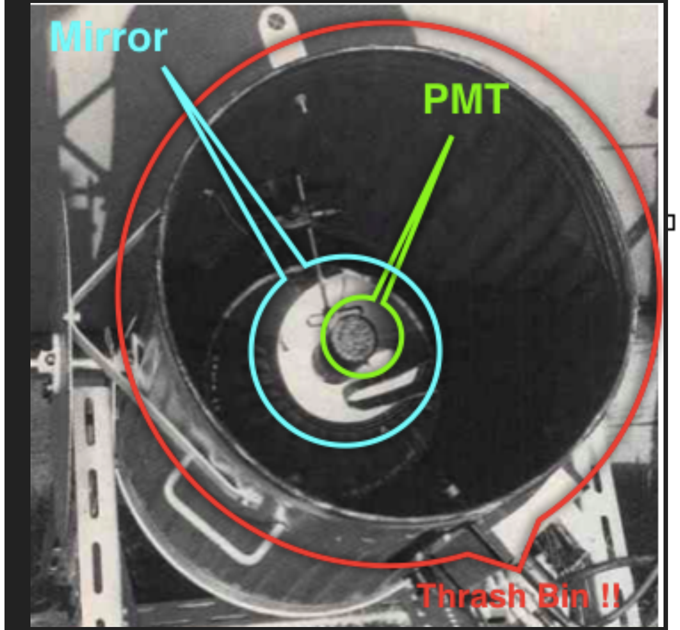
Radio

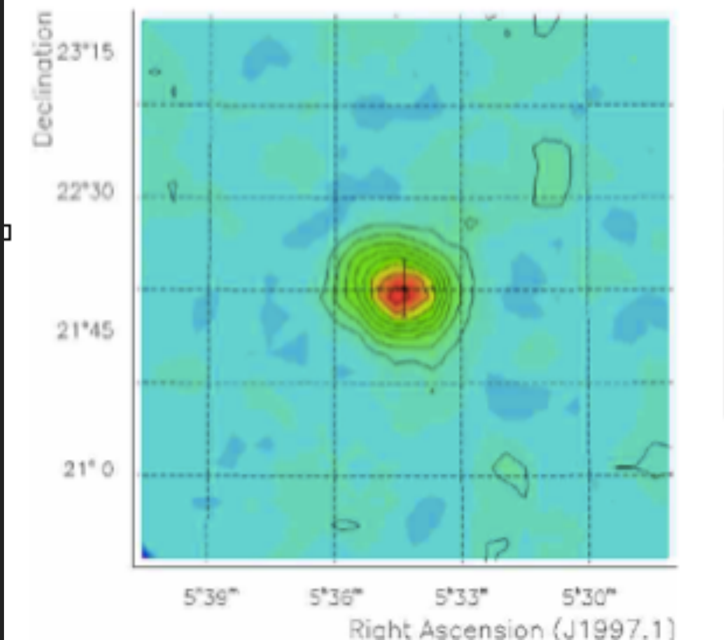
$\sim 10^{-4}$ eV

Credit: NASA/CXC/SAO (X-ray), Paul Scowen and Jeff Hester (Arizona State University) and the Mt. Palomar Observatories (optical), 2MASS/UMass/IPAC- Caltech/NASA/NSF (infrared), and NRAO/AUI/NSF (radio)

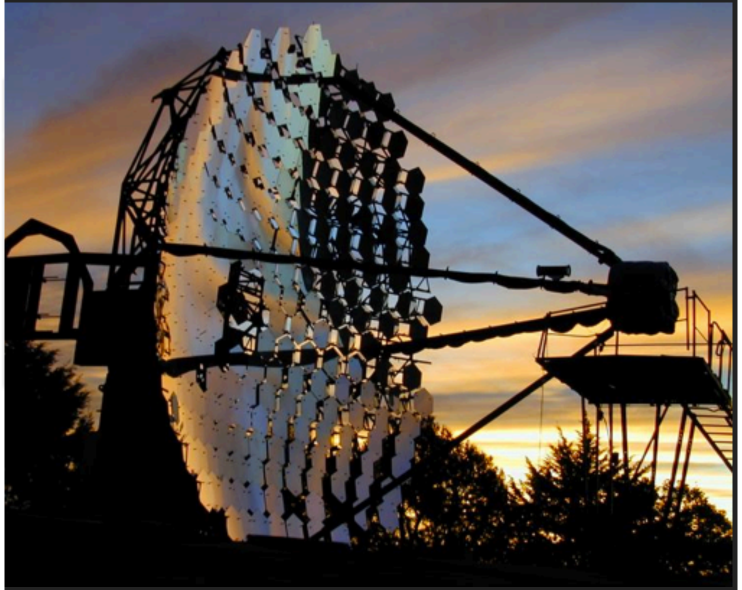
GAMMA-RAY ASTRONOMY : HISTORICAL HINTS

- 2002: Nobel prize to Koshiba-Davis-Giacconi (for birth of X-ray astronomy)
- 1952: Galbraight and Kelley build first rudimental Cherenkov telescope with a garbage can (birth of gamma-ray astronomy)
- Whipple discovers Crab Nebula after about 20 years exploiting the gamma/hadron discrimination of shower images on a 37 PMT camera with 3.5° FoV
- In 1989 Crab was the only TeV source, nowadays …

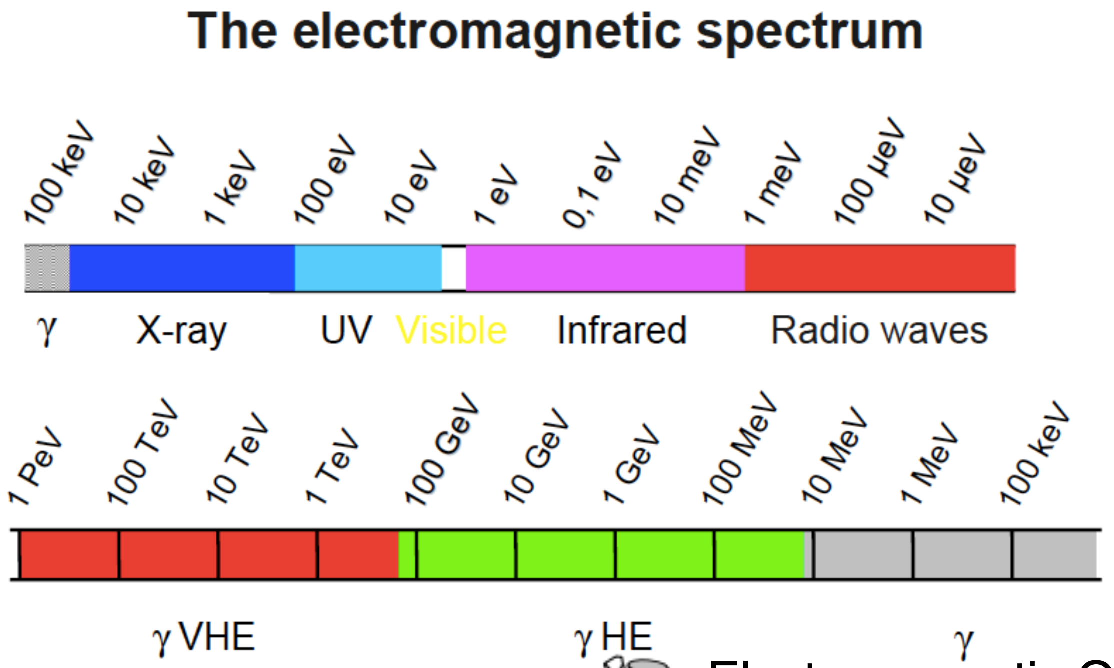




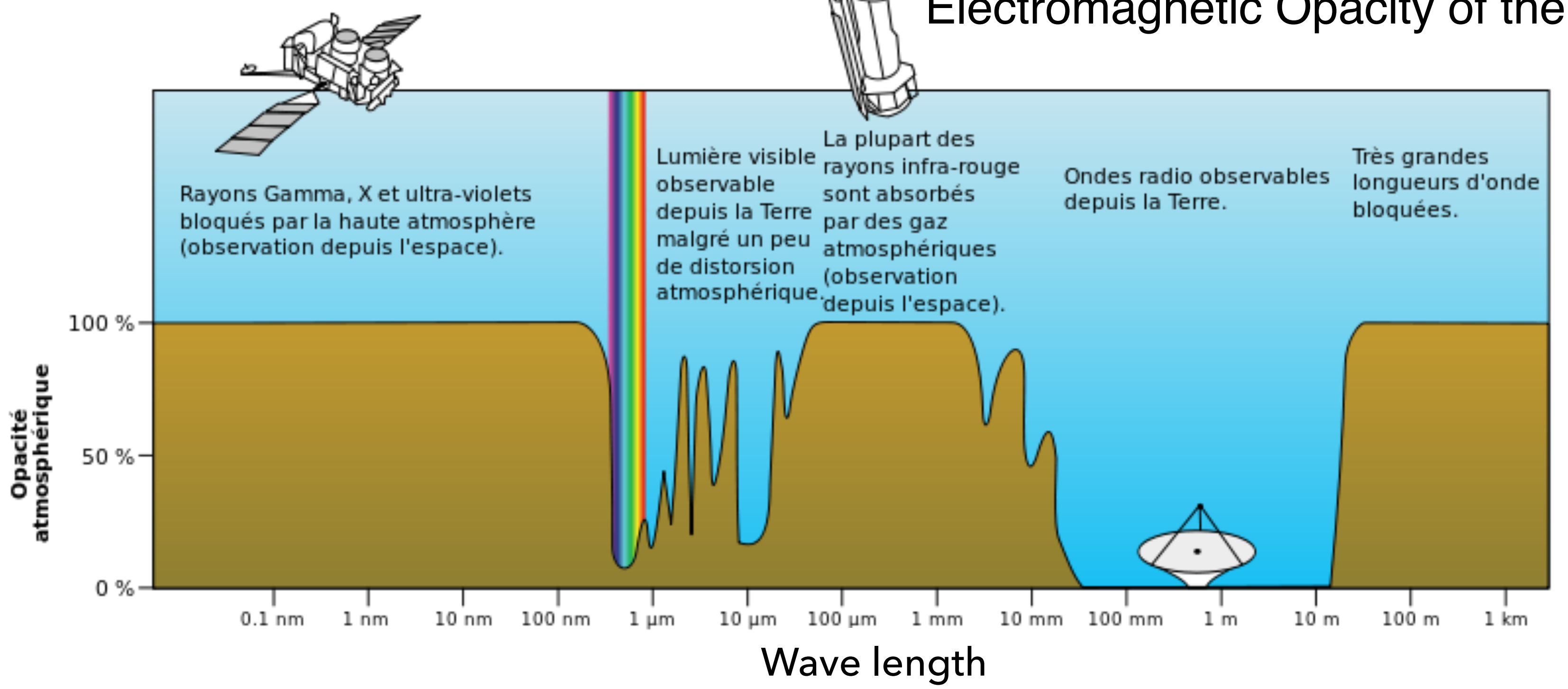
Lorenz & Wagner, arXiv:1207.6003



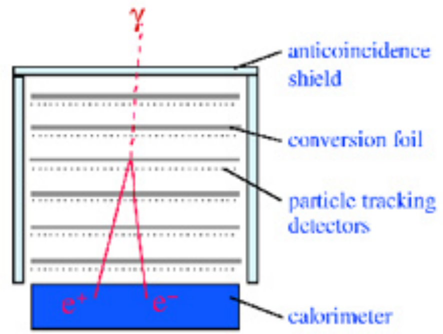
MULTIWALENGTH ASTRONOMICAL OBSERVATIONS

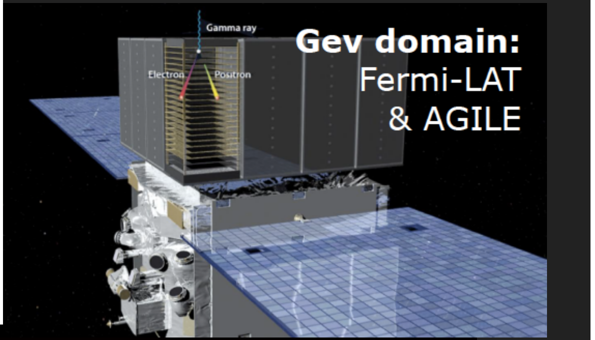


Electromagnetic Opacity of the atmosphere

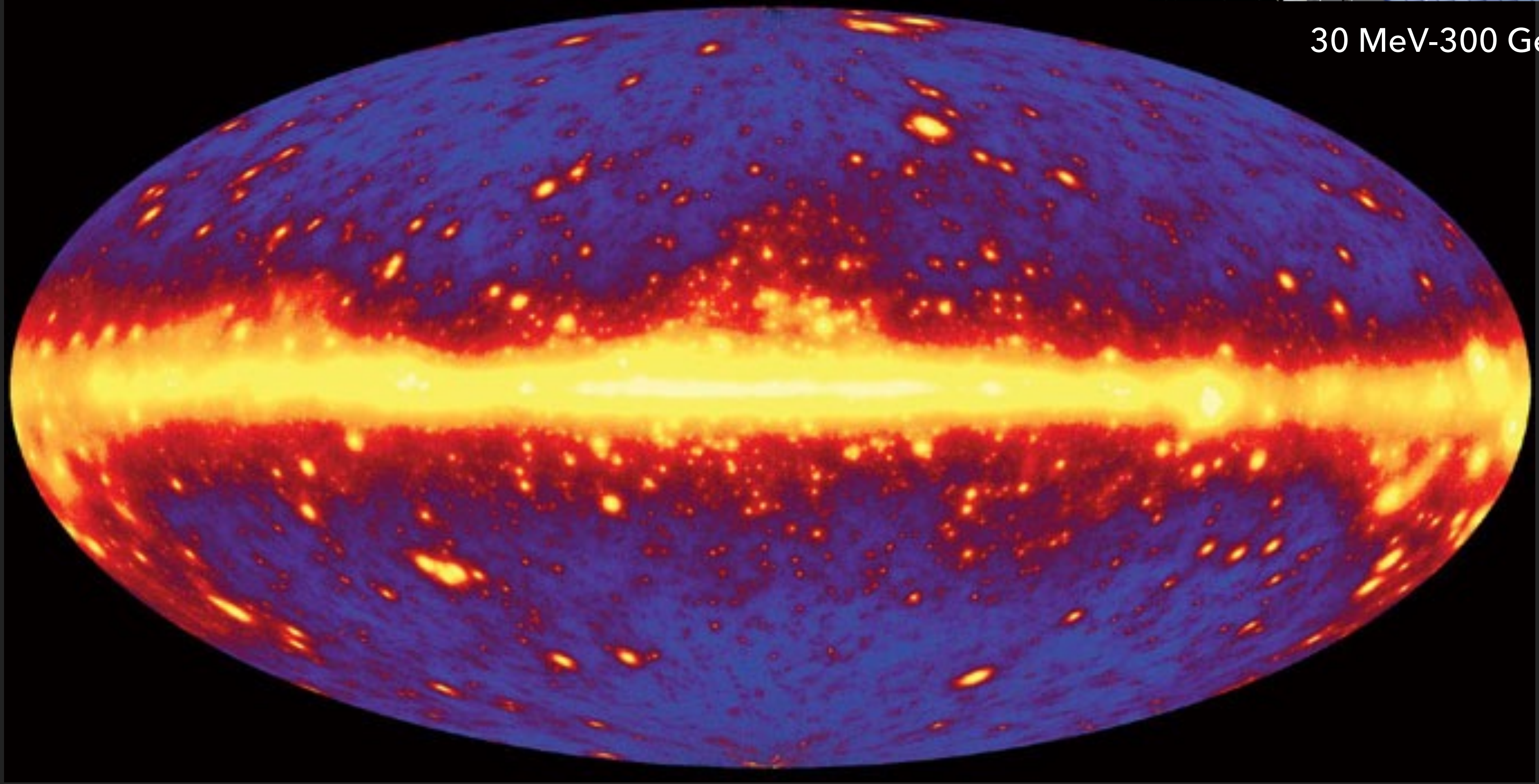


THE ACCELERATORS SKY IN THE TEV SEEN BY FERMI-LAT





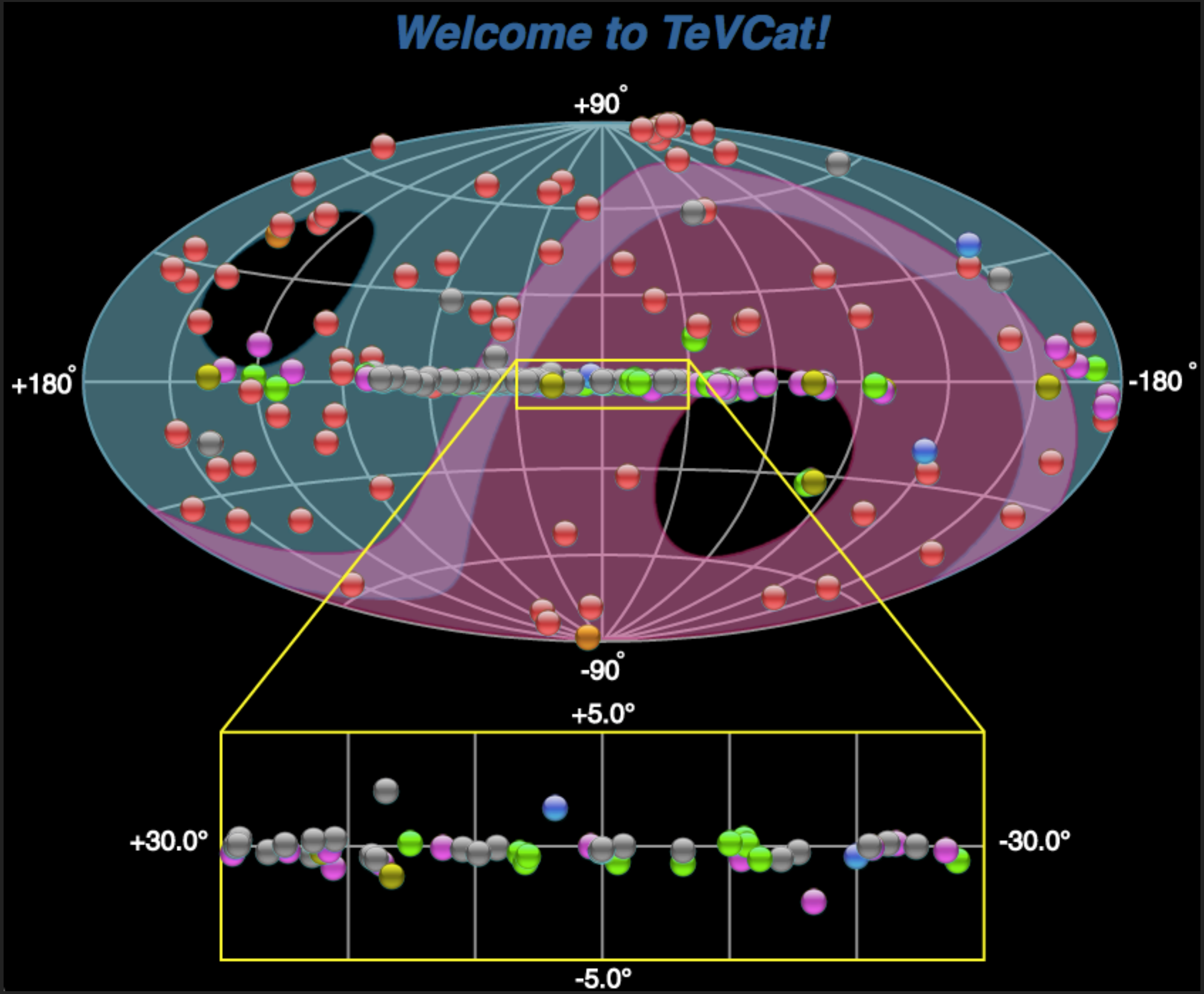
Gev domain:
Fermi-LAT
& AGILE



30 MeV-300 GeV

http://www.nasa.gov/mission_pages/GLAST/news/gammaray_best.html

THE TEV SKY

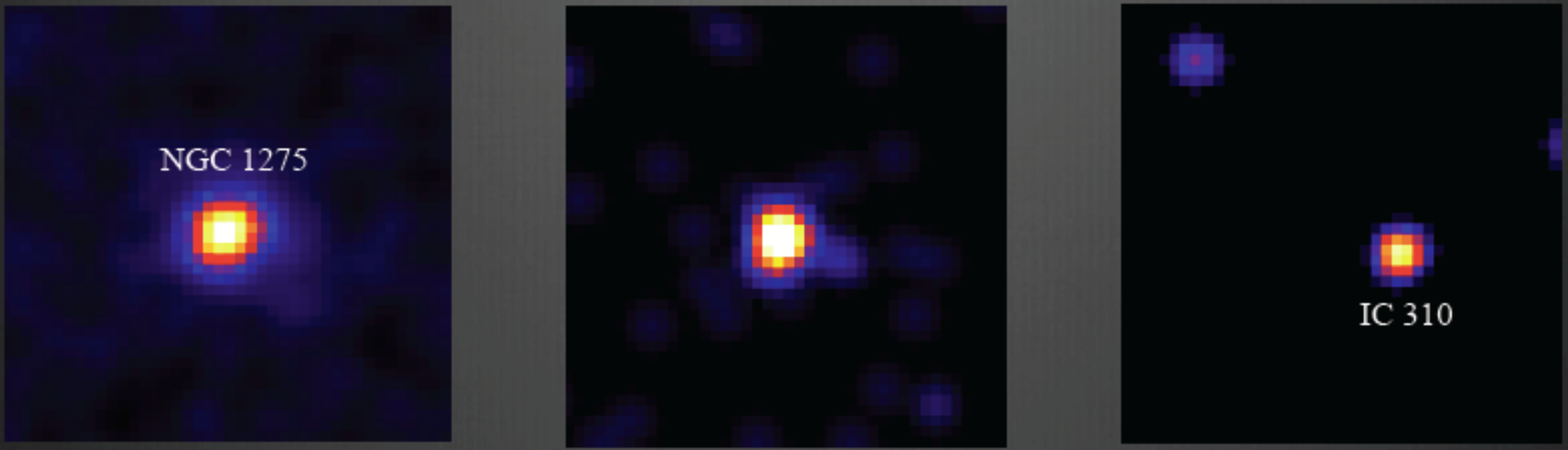


tevcat.uchicago.edu

Source Types

- ● Extended TeV Halo PWN
- ● Binary XRB PSR Gamma BIN
- ● HBL IBL FRI FSRQ Blazar LBL AGN (unknown type)
- ● Shell SNR/Molec. Cloud Composite SNR Superbubble
- ● Starburst
- ● DARK UNID Other
- ● uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR

NEW SOURCES IN THE TEV REGION



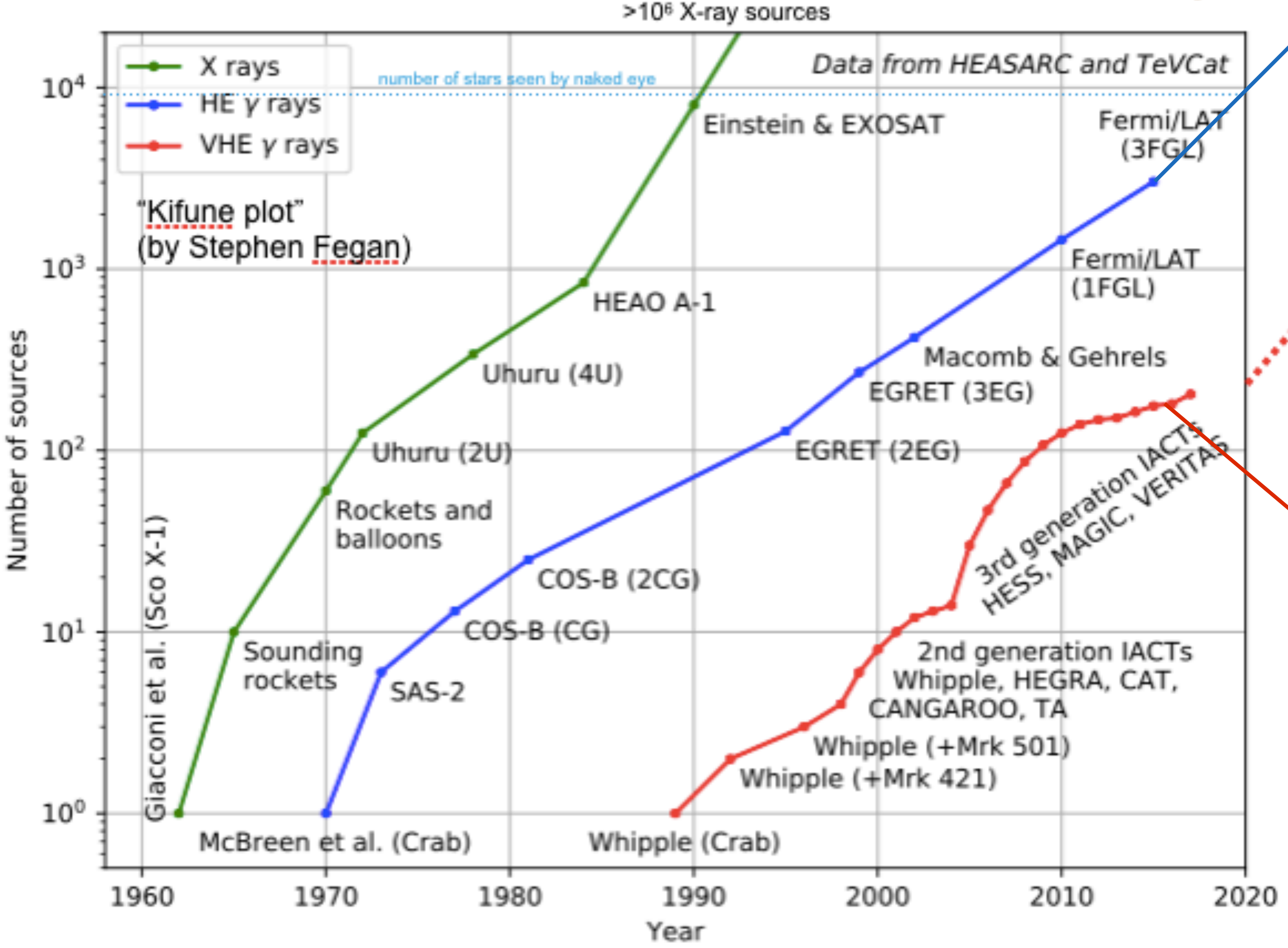
1-10 GeV 10-100 GeV >100 GeV

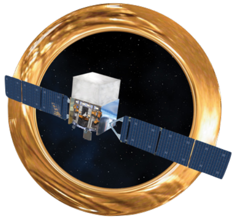
At energies below 10 GeV, only the radio galaxy NGC 1275 (Perseus A) is visible, but above 10 GeV a second source (to the lower right) emerges. Above 100 GeV, only this source, the head-tail galaxy IC 310, remains. From Neronov et al (2010)

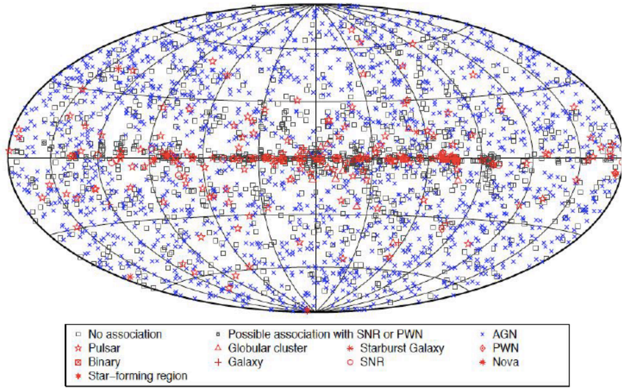
New sources and features emerge in the gamma-ray sky with increasing energy

Gamma-ray Sources & Detection Technique Advancement

“Kifune plot”
(by Stephen Fegan)





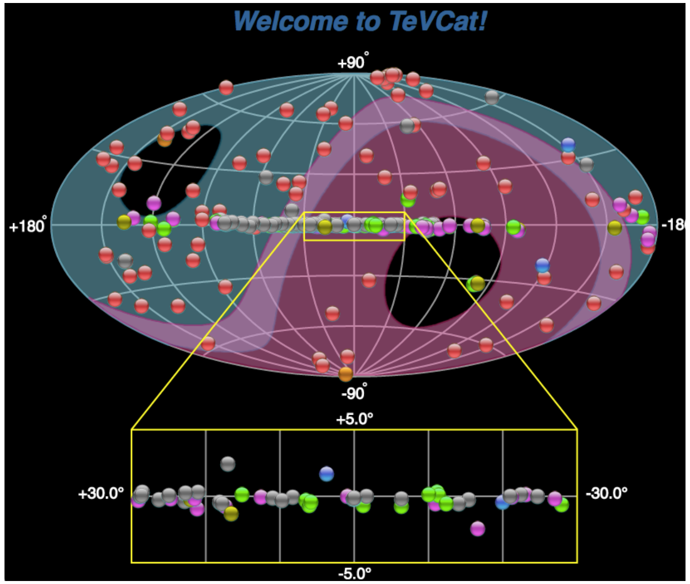


Acero, F. et al. 2015

F.Longo et al. – 30

3FGL 3034 sources > 100 MeV
95% extragalactic!
21% BL Lacs
16% FSRQ
19% unclassified blazars +
22% unassociated high lat

Still lots of classification work to come!



About 210 TeV sources > 100 GeV

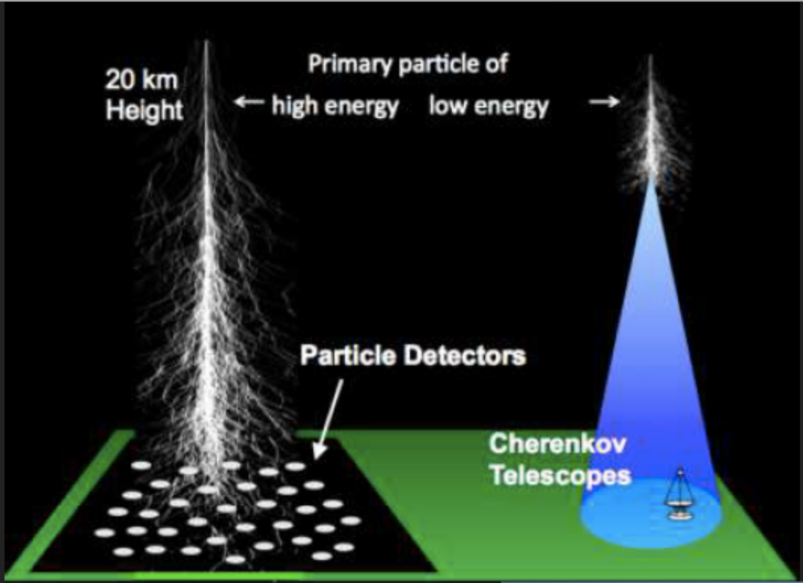
tevcat.uchicago.edu

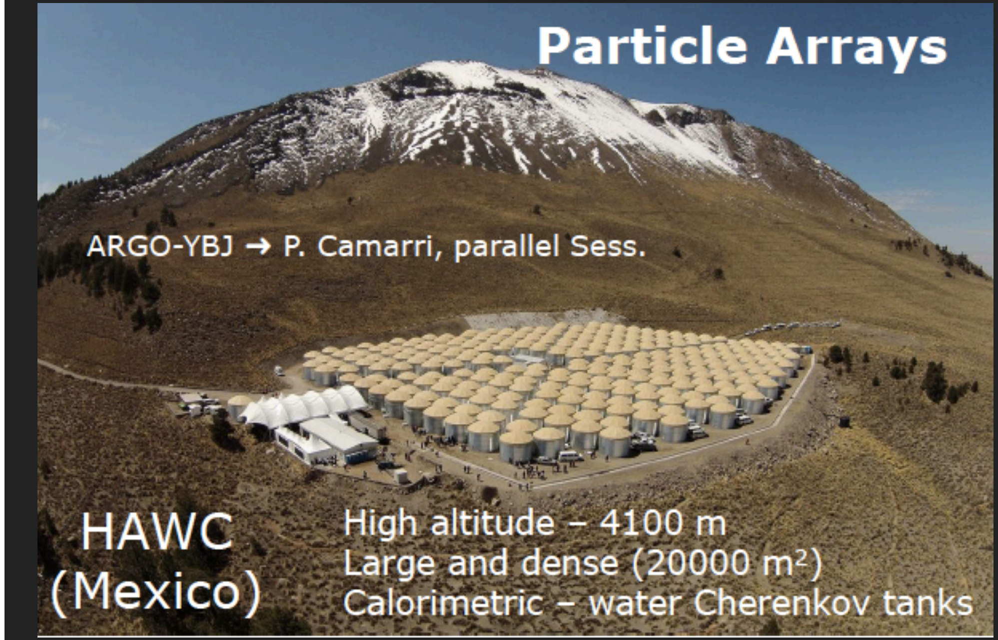
THE SERENDIPITOUS SKY: THE FERMI BUBBLES

Finkbeiner et al., 2010; Karen Yang, Ruszkowski, Zweibel et al, 2018

- 23’000 light-years above the plane of the Milky Way
- Energy ~1-100 GeV;
- Gamma-ray power ~ 4.0 × 10^{37} erg s^{-1}
- enough cool gas to create 2M x M_{Sun}
- ~$E^{-2.4}$ hard gamma-ray emission ~ latitude independent.
- Counterpart of WMAP haze (Planck) which fades beyond 35°.
- HST (ApJ 2017) : “big meal” by Sgr A* of a gas cloud which fired off jets of matter ~6-9Myrs ago (tidal disruption)

TWO MAJOR TECHNIQUES TO DETECT GAMMA-RAYS AT GROUND



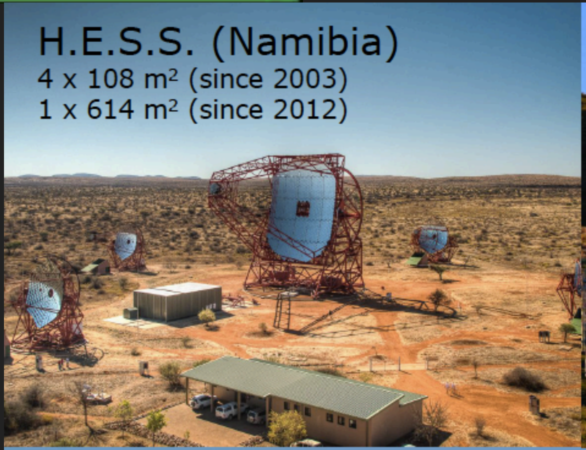


Particle Arrays

ARGO-YBJ ➜ P. Camarri, parallel Sess.

HAWC
(Mexico)

High altitude – 4100 m
Large and dense (20000 m²)
Calorimetric – water Cherenkov tanks



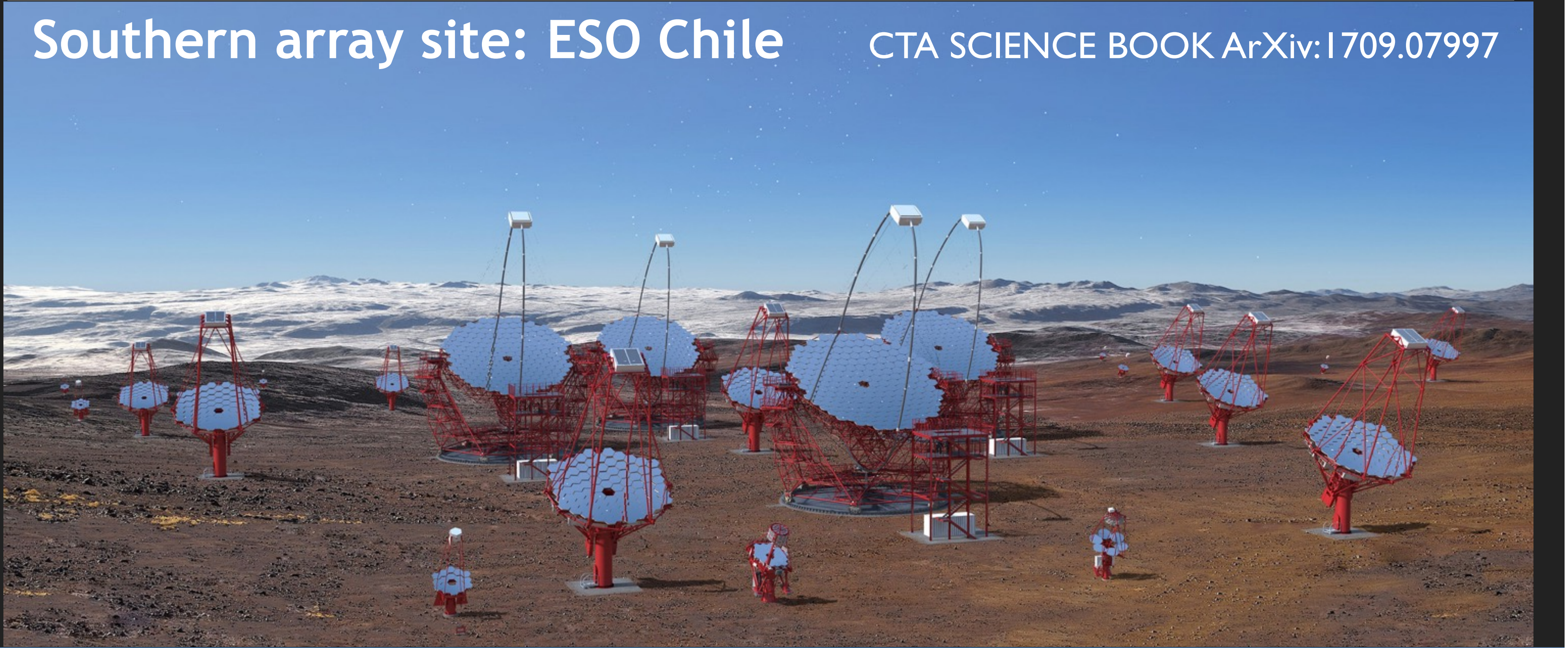
H.E.S.S. (Namibia)
4 x 108 m² (since 2003)
1 x 614 m² (since 2012)

MAGIC (La Palma)
2 x 236 m² (since 2003 / 2009)
& FACT

VERITAS (Arizona)
4 x 110 m² (since 2007)

Cherenkov Telescopes
(TeV Domain)

THE NEW GENERATION TEV GAMMA-RAY OBSERVATORY


Southern array site: ESO Chile

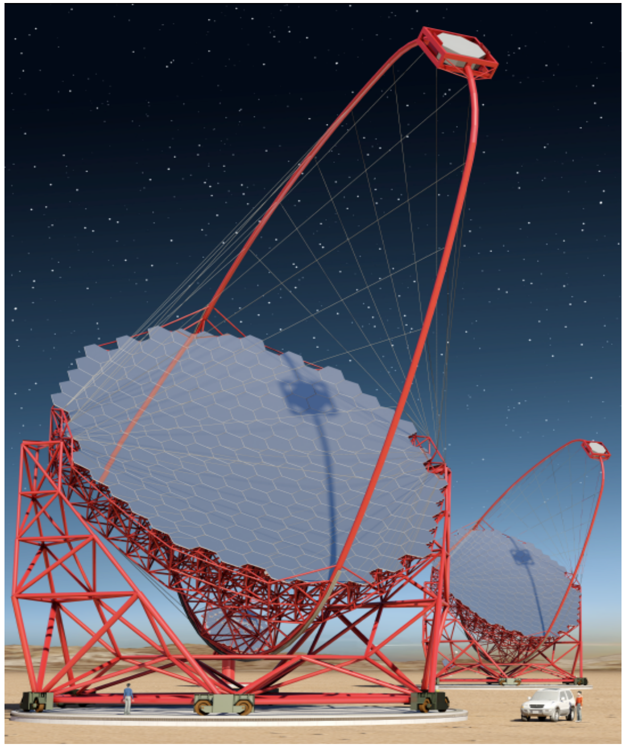
CTA SCIENCE BOOK ArXiv:1709.07997


Northern array: Roque de los Muchachos Observatory in La Palma

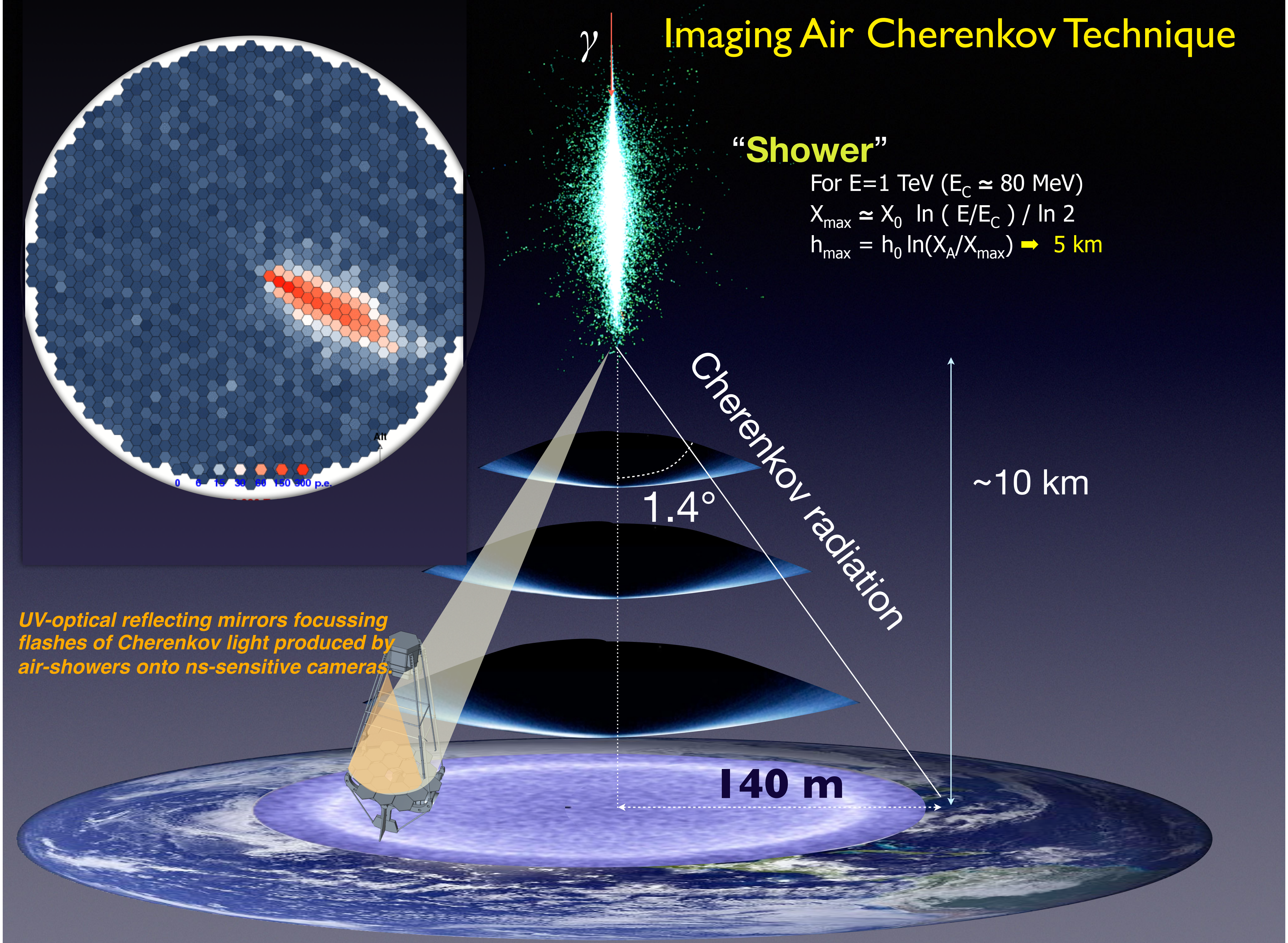
The first large size telescope at La Palma

23 m diameter
389 m² dish area
28 m focal length
1.5 m mirror facets
Active mirror control

4.5° field of view
0.1° pixels
Camera ∅ over 2 m
Carbon-fibre structure
for 20 s positioning



Imaging Air Cherenkov Technique



“Shower”

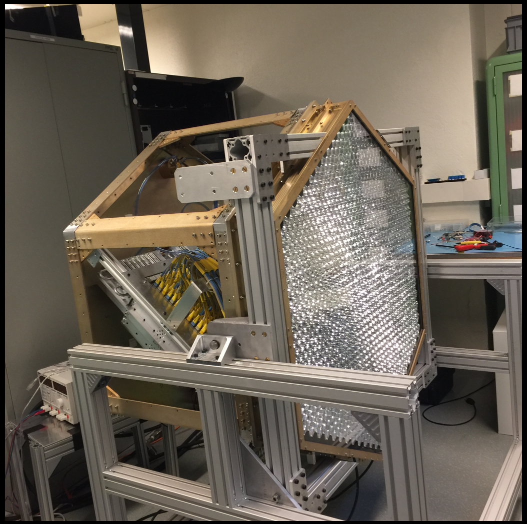
For E=1 TeV ($E_C \simeq 80$ MeV)

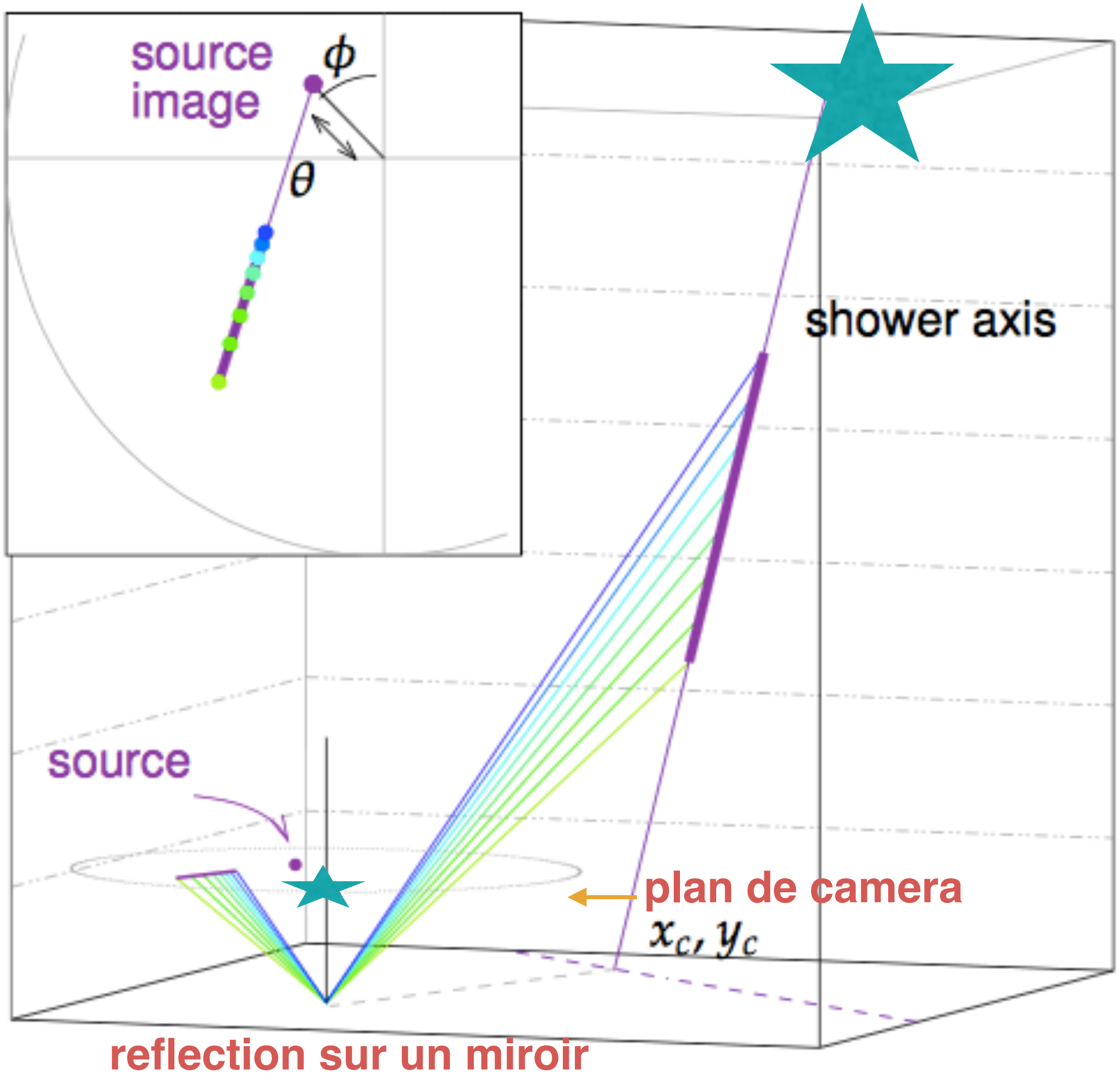
$X_{max} \simeq X_0 \ \ln (E/E_C) / \ln 2$

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

UV-optical reflecting mirrors focussing flashes of Cherenkov light produced by air-showers onto ns-sensitive cameras.

IACT detection in detail





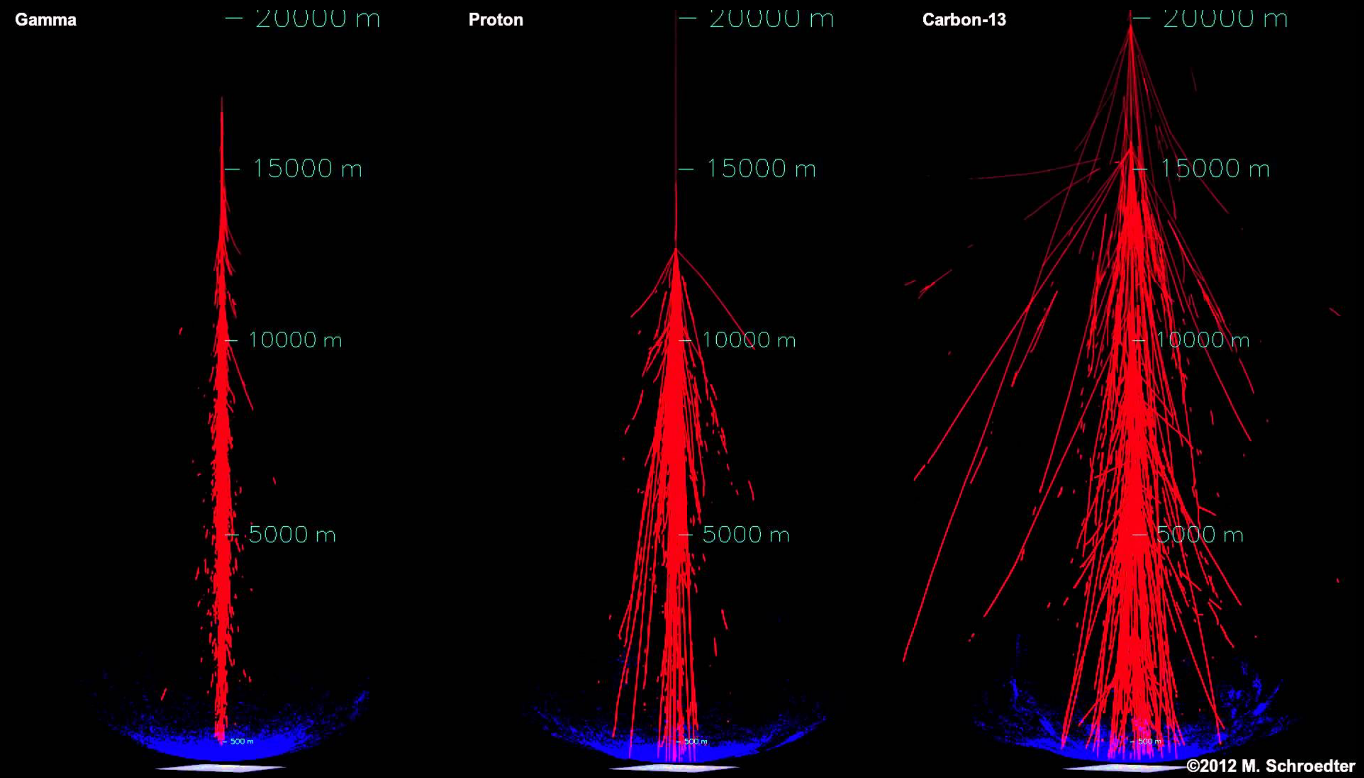
- the camera images the shower piece by piece on hit pixels with ns precision

- we can reconstruct where is the **source of gamma-rays** !

- With more than a telescope, **the precision on the position** of the source improves

Can we identify gamma-rays?

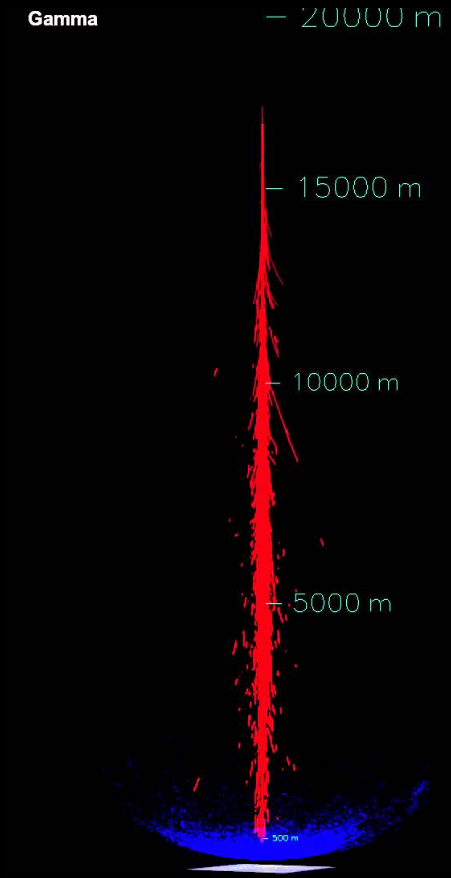
- ➡ It is not so simple….

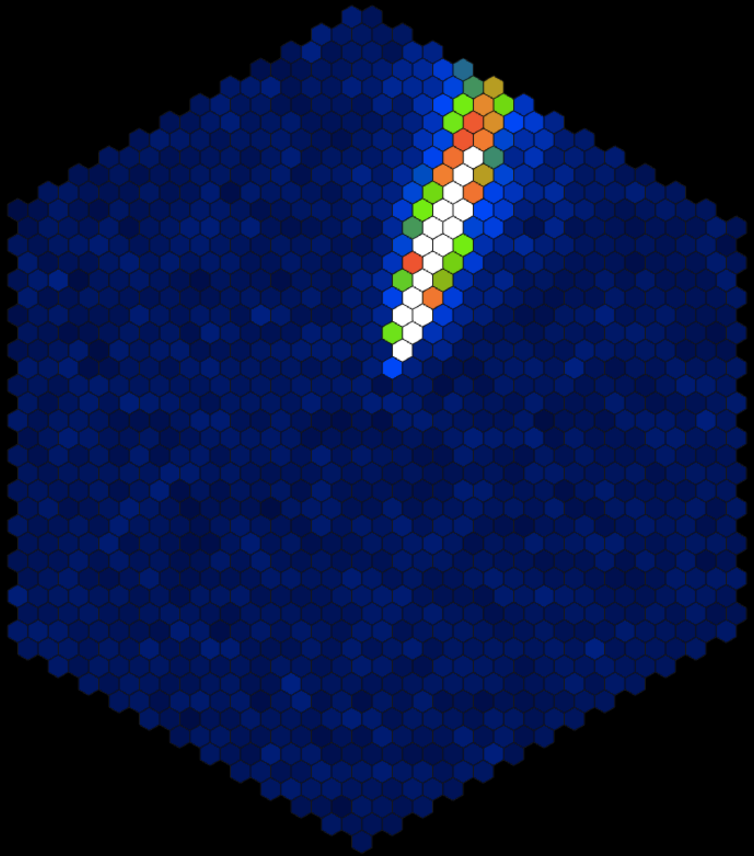


©2012 M. Schroedter

- ➡ there are about 10^5 more cosmic ray hadronic showers,
- ➡ energy and inclination of showers affect them and when energy is low it is tough to have clear images
- ➡ the core of the shower (the Centre of Mass of the charge) can be close or far from the telescope

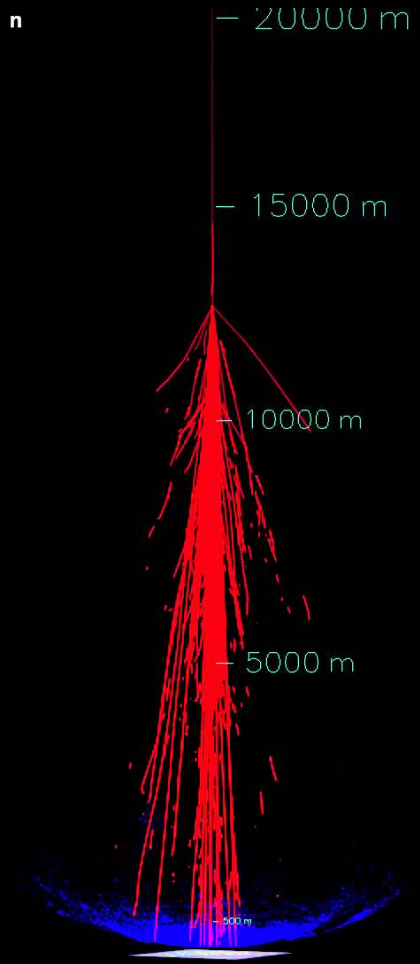
The signature of a gamma-ray



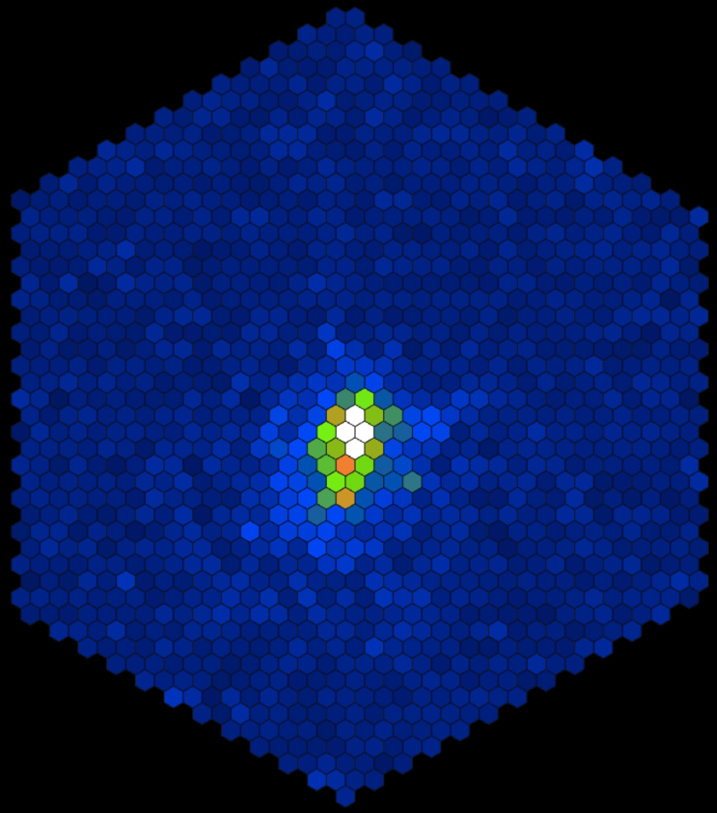


- ➡elongated shape
- ➡regular charge development

The signature of an hadron



➡The development of the shower is sparse on the plane of te camera



➡The shape is more round and sometimes with sparse charge on far away pixels

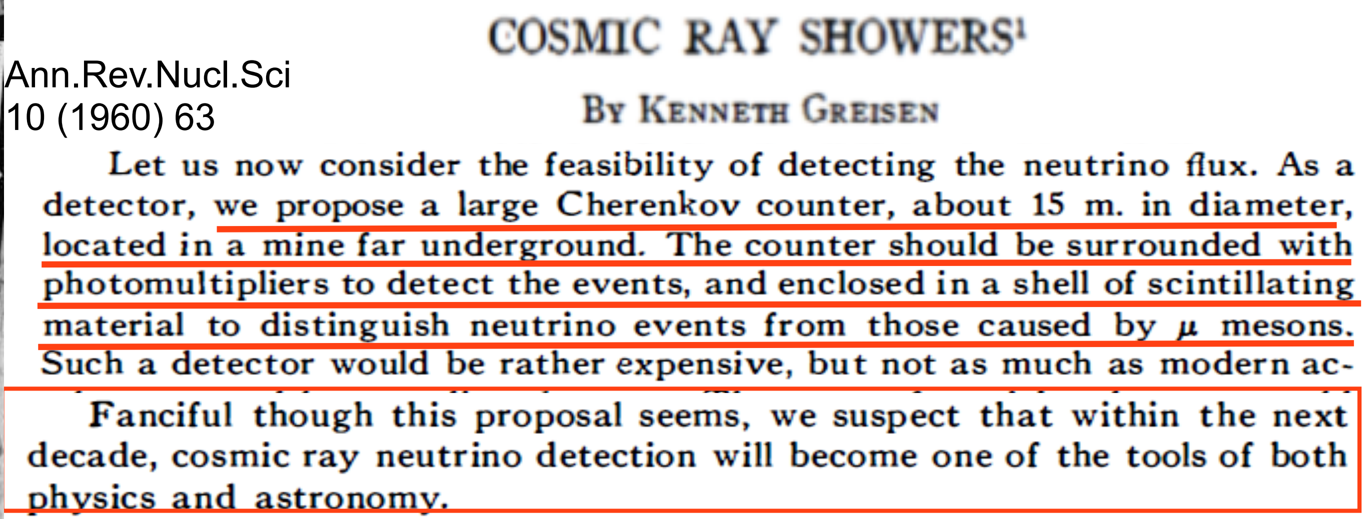
➡not a preferential direction

NEUTRINO ASTRONOMY INITIAL HISTORY

1965: F. Reines detects neutrino with Cherenkov technique in South African mine

Neutrino telescope concept birth

Ann.Rev.Nucl.Sci
10 (1960) 63



COSMIC RAY SHOWERS[1]

By Kenneth Greisen

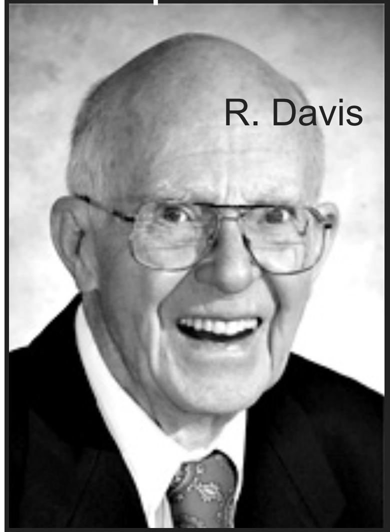
Let us now consider the feasibility of detecting the neutrino flux. As a detector, we propose a large Cherenkov counter, about 15 m. in diameter, located in a mine far underground. The counter should be surrounded with photomultipliers to detect the events, and enclosed in a shell of scintillating material to distinguish neutrino events from those caused by μ mesons. Such a detector would be rather expensive, but not as much as modern ac-

Fanciful though this proposal seems, we suspect that within the next decade, cosmic ray neutrino detection will become one of the tools of both physics and astronomy.

M.Markov,1960: We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particleswith th e help of Cherenkov radiation.
Proc. 1960 ICHEP

NOBEL PRIZE WINNERS IN THE NEUTRINO SECTOR

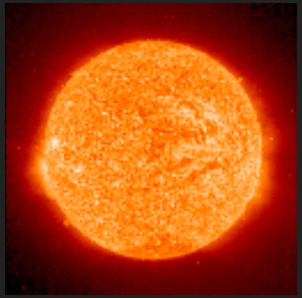
Nobel prize 2002



Oscillations with neutrinos from thermonuclear reactions in the Sun

$\sim 6 \times 10^{10}$ vs per cm^2 per s^1 with $E_\nu \sim 0.1 - 20$ MeV produced in thermonuclear reactions in the Sun

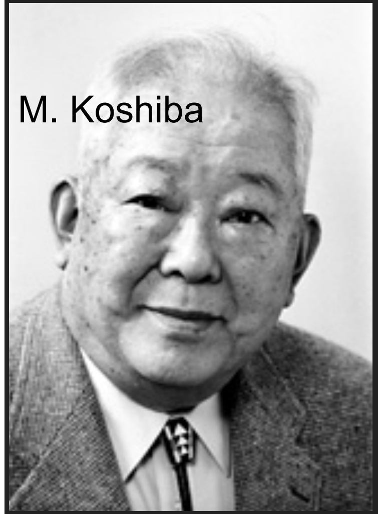
$$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e$$



means ~ 100,000 billion solar neutrinos pass through your body/s

Nobel prize 2015

T. Kajita



Supernova 1987A Neutrinos :
~ 10 s bursts of 10 MeV vs from stellar collapse

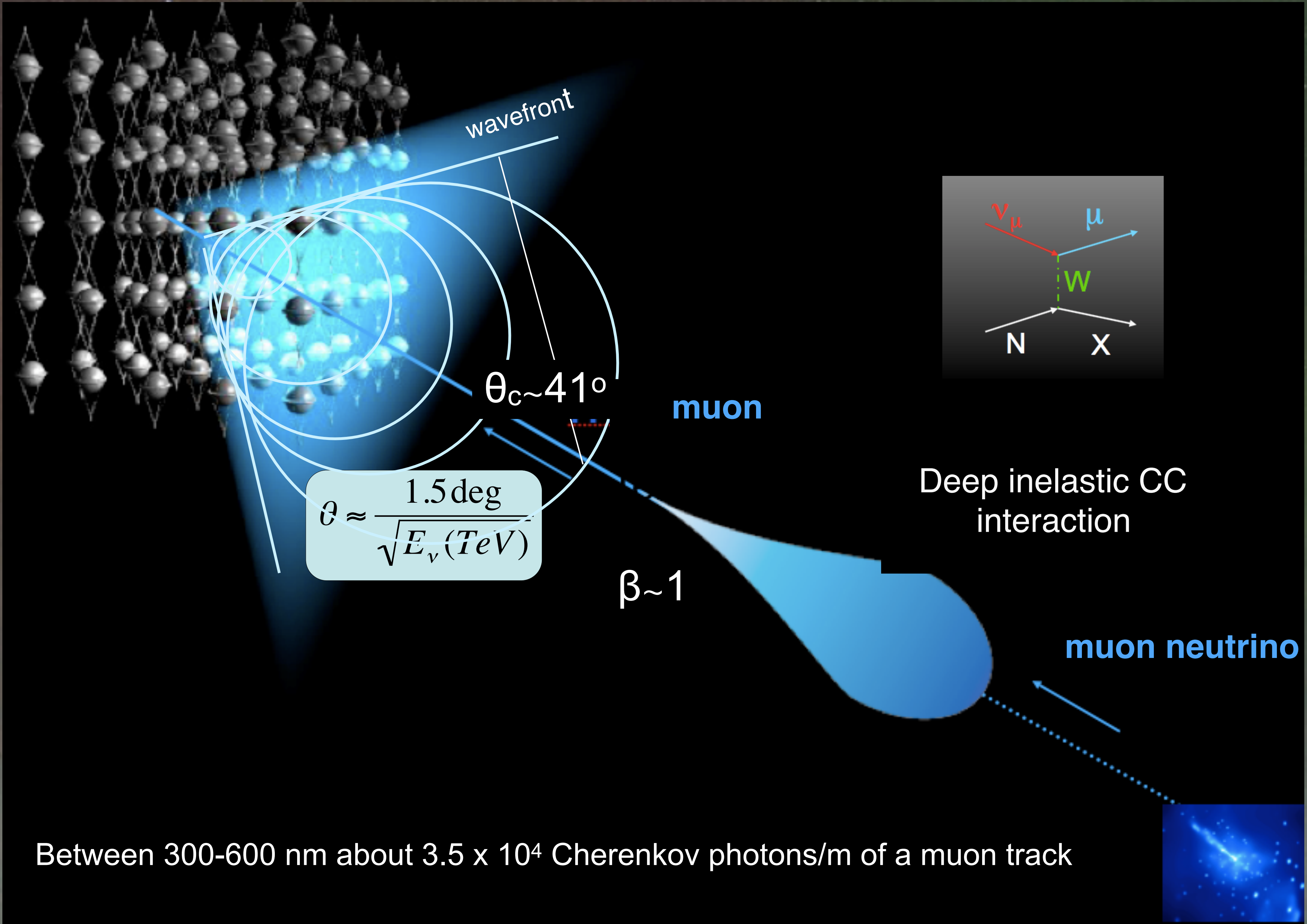
$$e^- + p \rightarrow n + \nu_e$$

$$e^- + e^+ \rightarrow \bar{\nu} + \nu$$

Nobel prize 2016

Oscillations with atmospheric neutrinos

CHERENKOV NEUTRINO TELESCOPE DETECTION PRINCIPLE

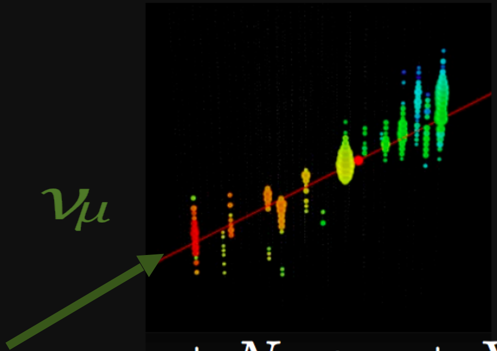


$$\theta \approx \frac{1.5\,\mathrm{deg}}{\sqrt{E_\nu(TeV)}}$$

Between 300-600 nm about 3.5×10^4 Cherenkov photons/m of a muon track

NEUTRINO TOPOLOGIES

CC Muon Neutrino

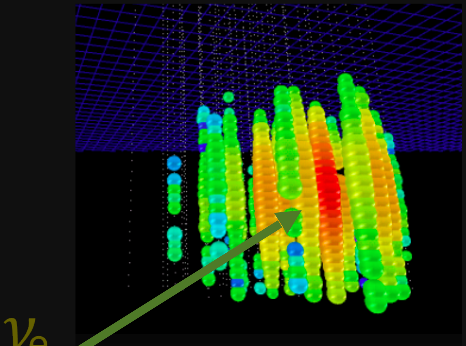


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current /Electron Neutrino



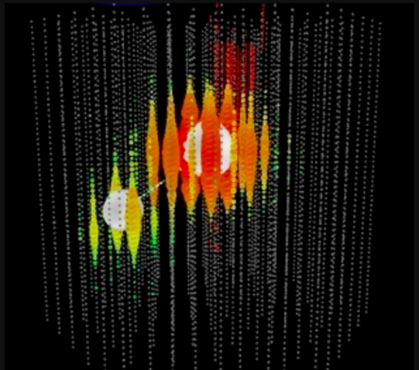
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies > 100 TeV)

CC Tau Neutrino



$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” and other signatures (simulation)

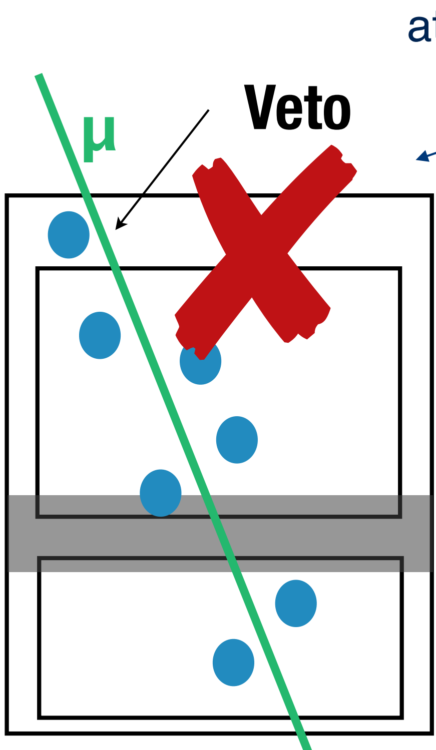
(not observed yet)

Martin Wolf, IceCube/NSF

Vetoing atmospheric backgrounds

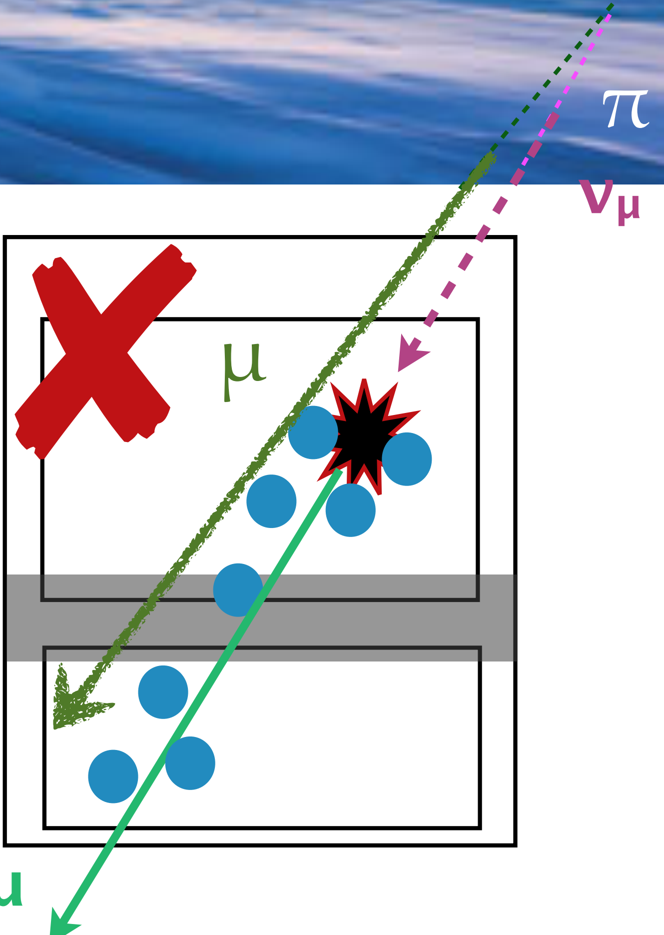
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

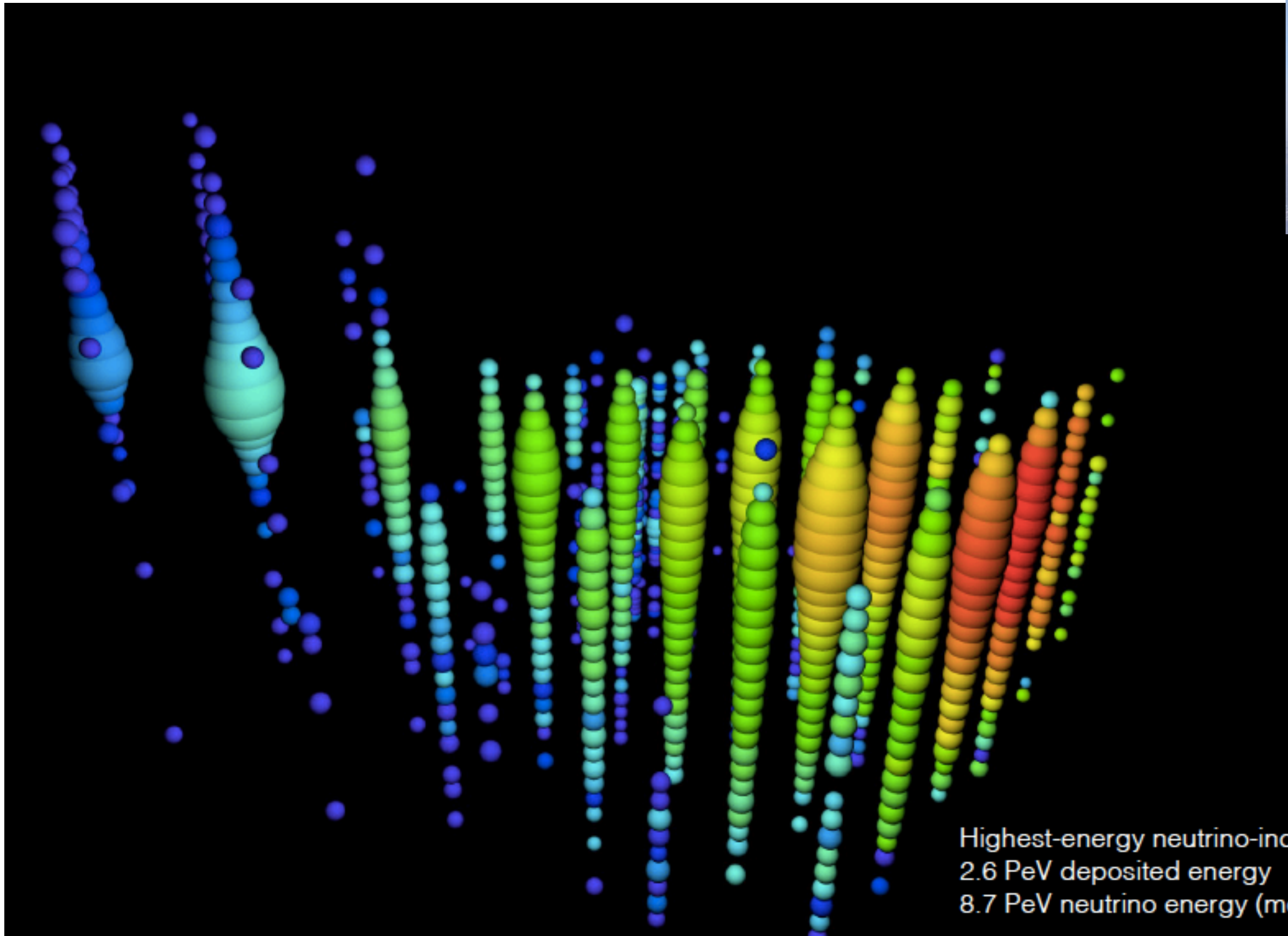


atmospheric muon tag

atmospheric neutrino tag

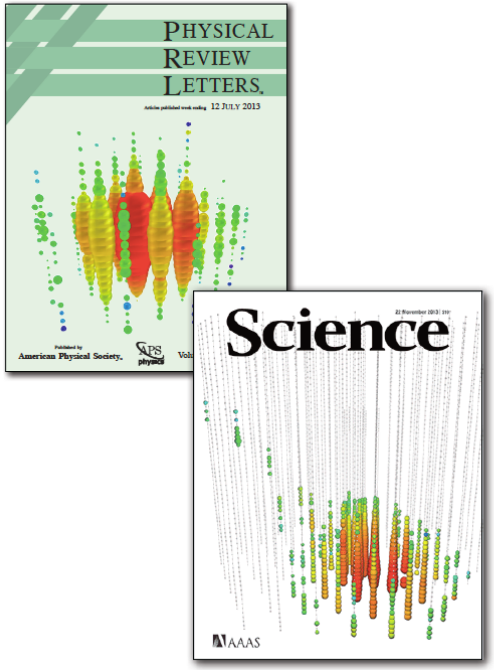


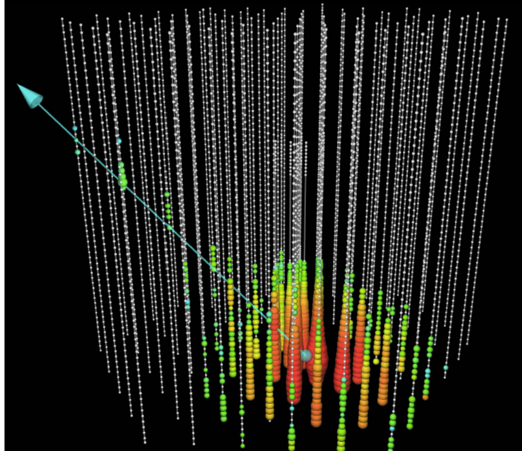
SIGNALS FROM THE HEAVENS

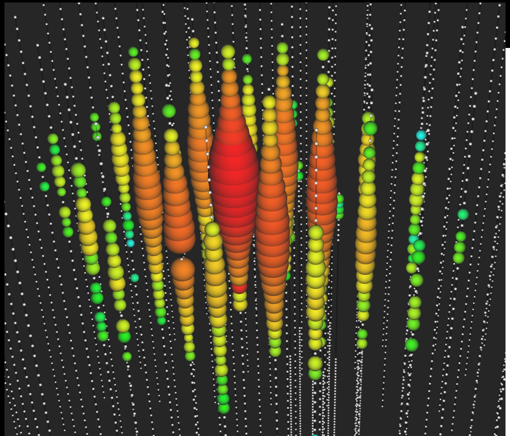


Highest-energy neutrino-induced muon
2.6 PeV deposited energy
8.7 PeV neutrino energy (median)

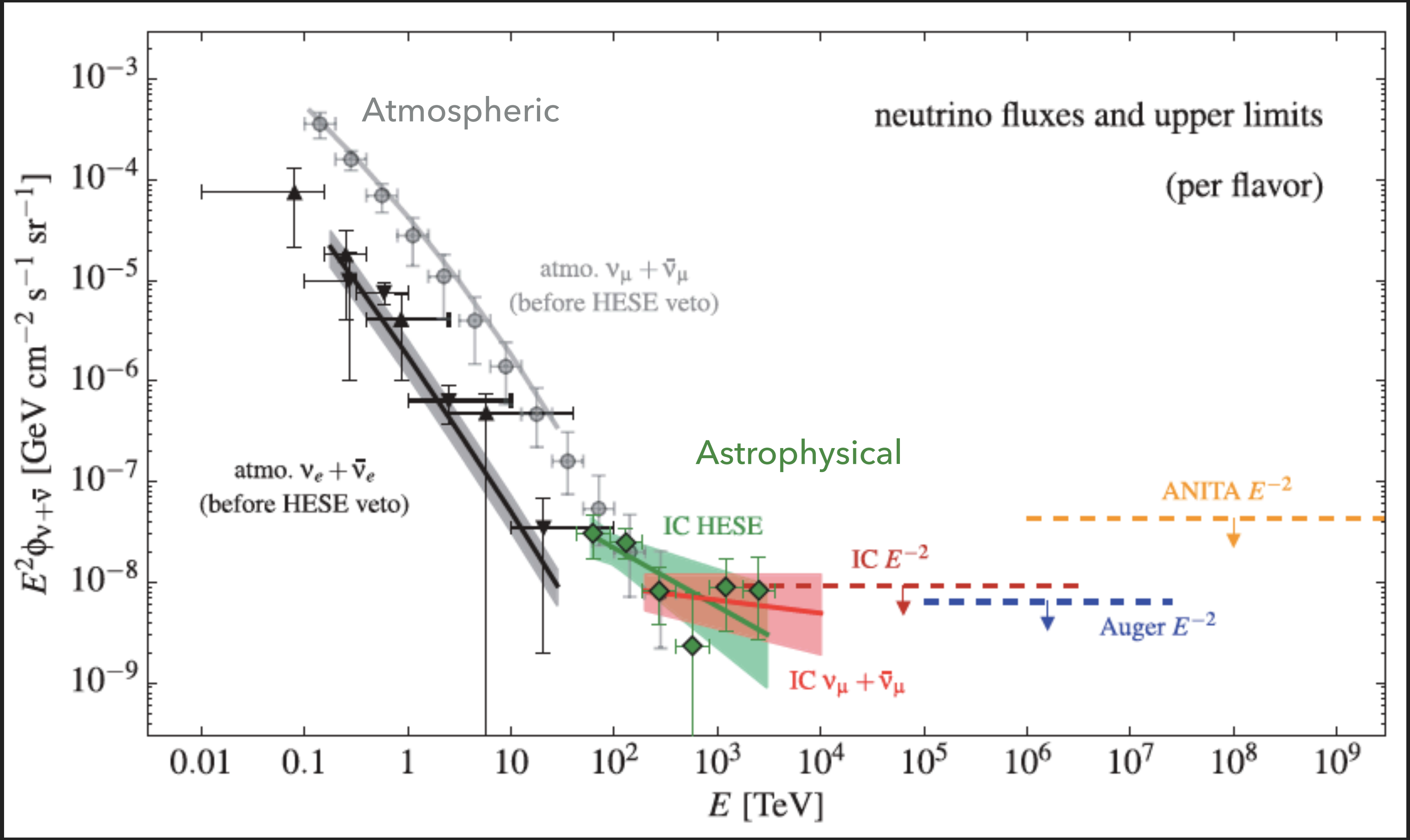
Astrophys.J. 833 (2016) no.1, 3



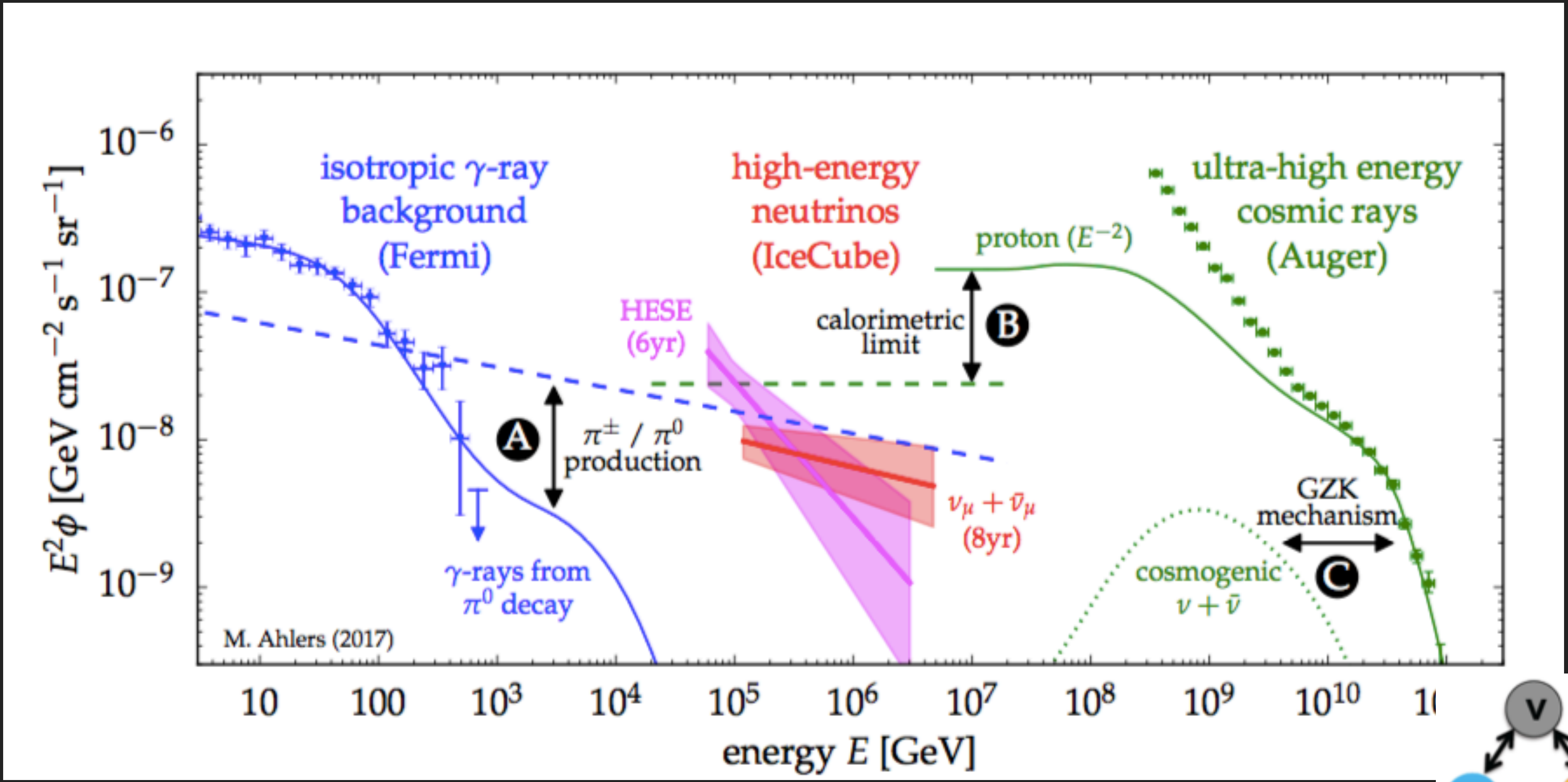




ICECUBE NEUTRINO FLUXES

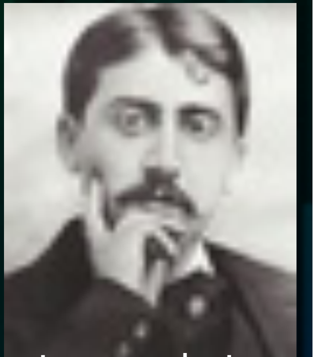


Cosmic gamma-rays and neutrino origin from UHECRs
Fermi diffuse isotropic gamma background (IGRB) constrains cosmic neutrino diffuse emission (Murase, Ahlers & Lacki’13; Chang & Wang’14)



https://arxiv.org/pdf/1805.11112.pdf

The real voyage of discovery consists not in seeking new landscapes, but in having new eyes. ***(Marcel Proust)***



Stay tuned this afternoon at 17:00! Great results from IceCube and press conference will be live streamed at https://www.youtube.com/c/VideosatNSF/live

Illustration by Guy Billout