Outlook:

Open questions and future challenges

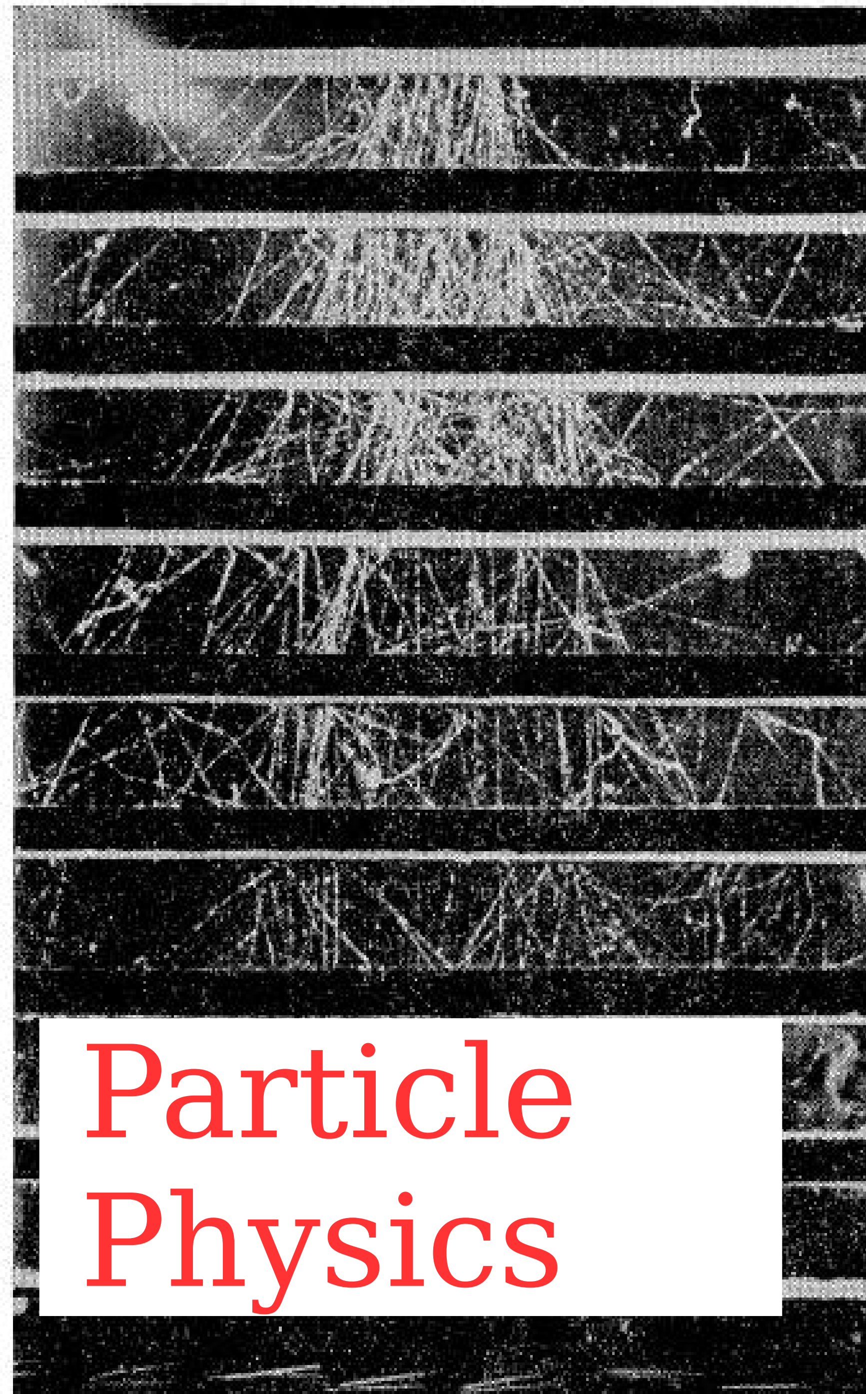
ISVHECRI-2014

International Symposium on Very High Energy Cosmic Ray Interactions

Paolo Lipari, INFN Roma “Sapienza”

CERN 22nd august 2014

Victor Hess
before the balloon flight of 1912



102 years ago,
the discovery of Cosmic Rays

A completely unexpected source of
very high energy relativistic particles:

- The first glimpse into the "High Energy Universe"

- Birth of Particle Physics

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Where are we now ?

.... we are HERE at CERN

The place where
(with an extraordinary effort)
the *last crucial element*

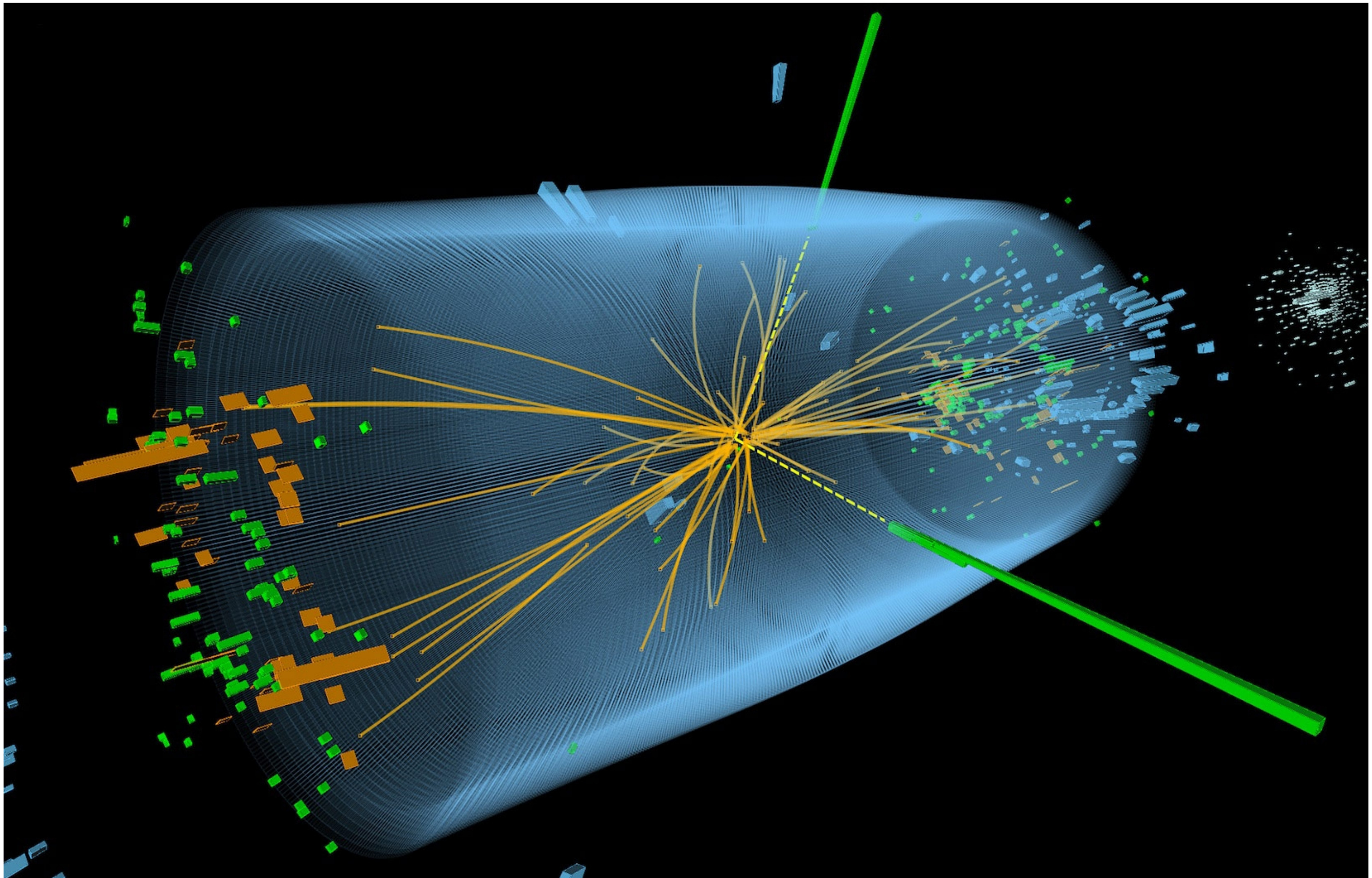
[the "**Englert-Brout-Higgs Boson**]

of a quite extraordinary intellectual construction

The **"STANDARD MODEL"** of Particle Physics

has been discovered.

Where is *Fundamental Science* after the discovery of the Englert-Brout-Higgs particle ?



The discovery of the Higgs boson and
is a cause of celebration and great joy.
for those who performed it (!) [*but also for all scientists*]

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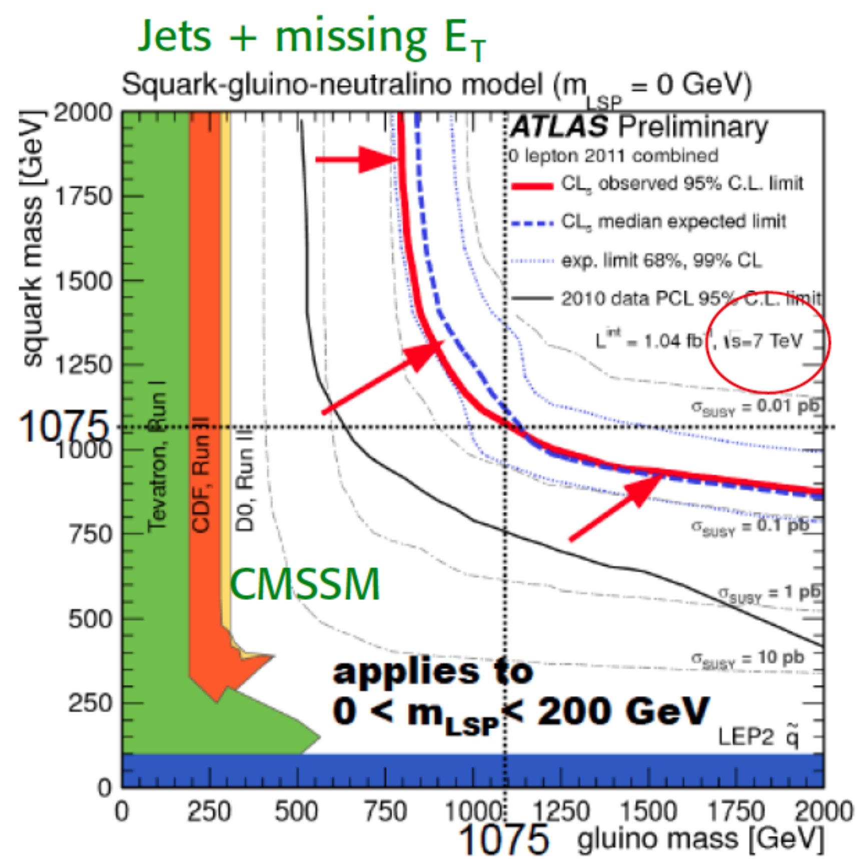
But ...., are we seeing too much success for
the Standard Model ?

A "negative" surprise:

No production of new particles
No sign of New Physics
(expected on theoretical grounds)

Is New Physics "beyond the corner"
or beyond the reach of LHC ?

A large new territory explored
with the result of a validation
of the Standard Model



Compelling Motivations
for “Physics Beyond the Standard Model”

Evidence for Dark Matter
(not a field of the Standard Model)
[Explicit “classic” experimental discrepancy]

Quantization of Gravity

Dark Energy

Inflaton field

Matter/anti-Matter asymmetry

....

History of Particle Physics
has been characterized by a continuous flow
of discoveries (new particles, new phenomena....),

The triumph of the Standard Model
has been accompanied by   a slow-down
In the rate of surprises and new discoveries.

Will LHC soon open the window
of a new set of phenomena ?

if not ... then   *“What's Next”?*

We have “Deep Problems” we want to address
but need new observations, new laboratories to explore
the open questions on the “Boundaries of Science”.

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but need new observations, new laboratories to explore
the open questions on the “Boundaries of Science”.

The laboratories to “explore the boundaries”
could be future accelerators.
(perhaps already LHC 13 TeV)

but also [in many cases only] in

Astrophysical objects/environments

and in
Cosmology studies

Cosmic Rays

The first hint of the existence,

and a fundamental probe for the study of the

“High Energy Universe”.

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Astrophysical Objects, mechanisms that
generate very high energy (non-thermal) particles

Multi-Messenger Astro(Particle)Physics

Cosmic Rays

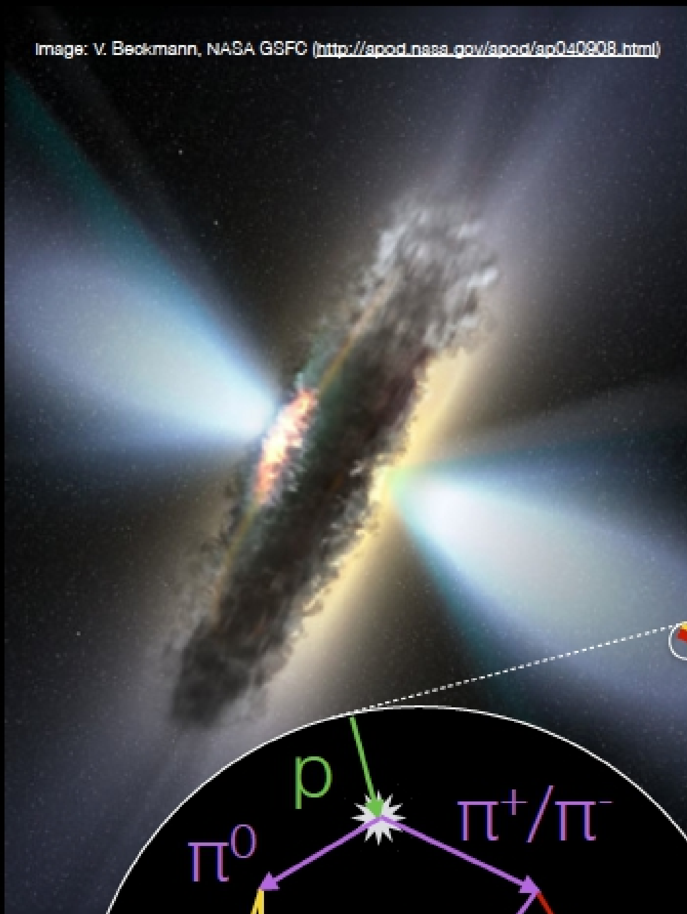
Gamma Rays

Neutrinos

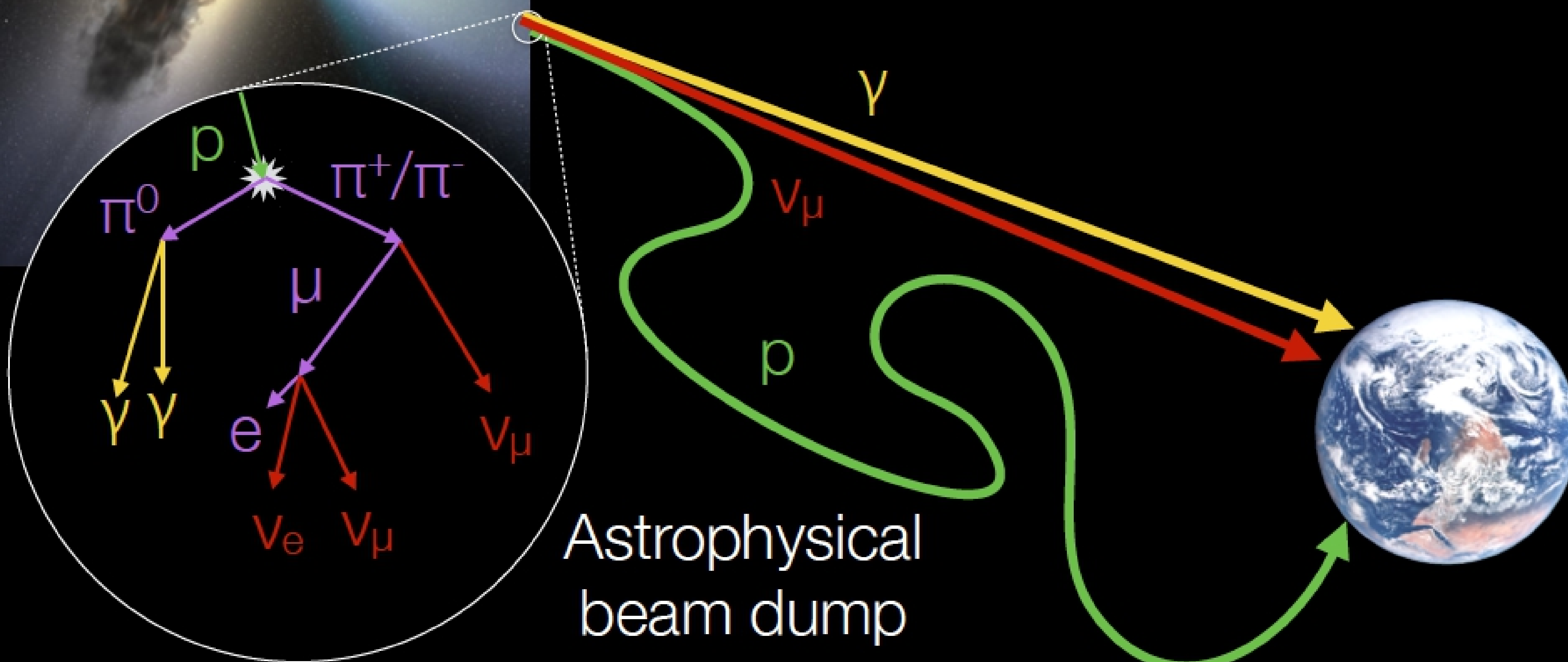
[Gravitational Waves]

Multi-messenger astrophysics

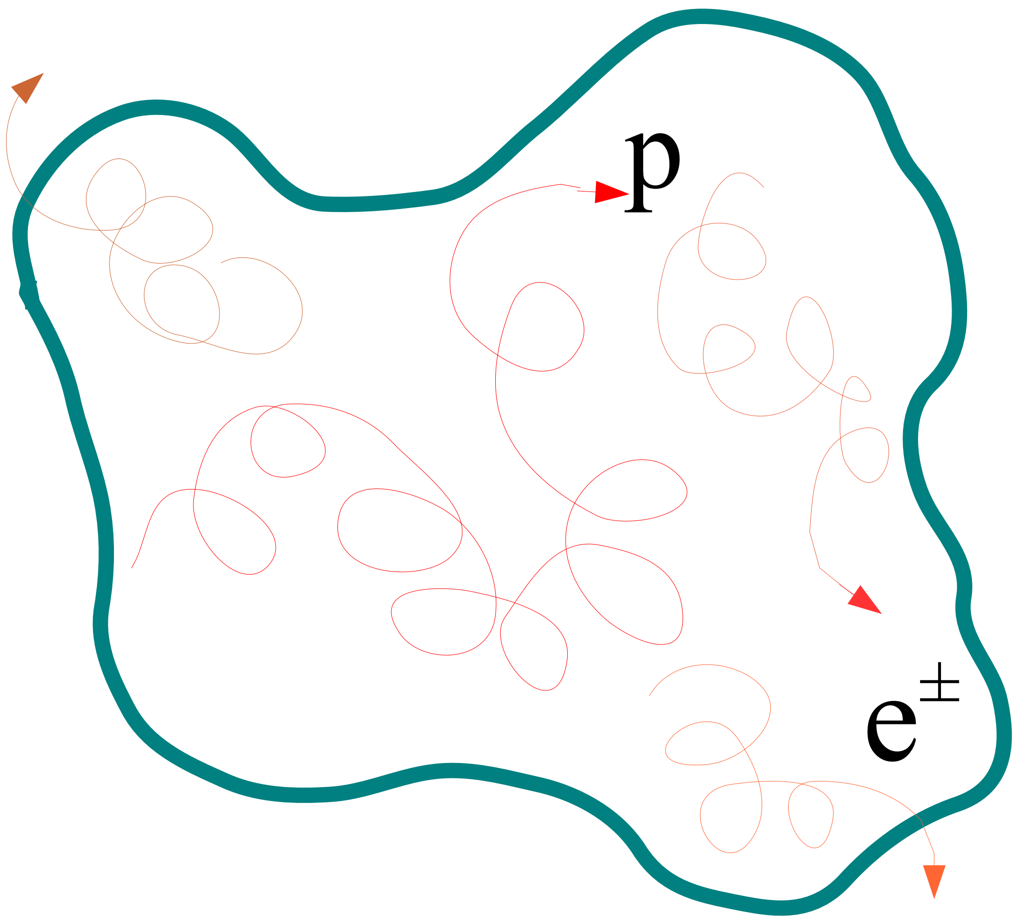
Jakob van Santen



- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed
- **Neutrinos** are difficult to stop and travel in straight lines



Cosmic Ray Accelerator



Proton, nuclei + electrons, positrons

Astrophysical object accelerating particles to relativistic energies

Contains populations of relativistic protons, Nuclei electrons/positrons

Emission of

COSMIC RAYS

PHOTONS

NEUTRINOS

$$p + \text{target} \rightarrow \text{many particles}$$

$$\rightarrow p(n) + \pi^{+} + \pi^{-} + \pi^{\circ}$$

$$\mu^{+} + \nu_{\mu}$$

$$\gamma + \gamma$$

$$e^{+} + \nu_{e} + \overline{\nu}_{\mu}$$

"Hadronic Emission"

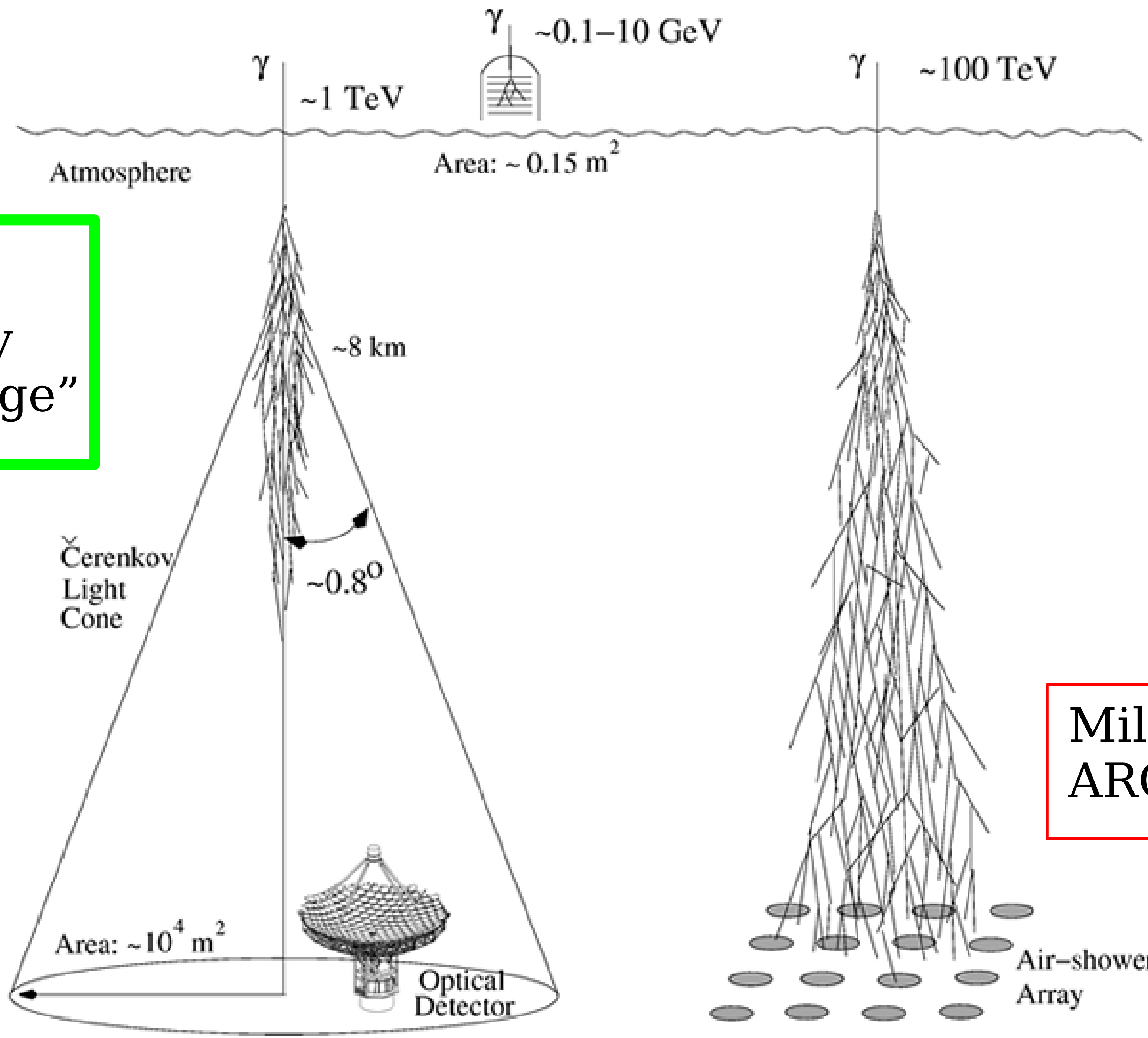
"Leptonic Emission"

$$e^{\mp} + B \rightarrow e^{\mp} + \gamma_{\text{synchrotron}}$$

$$e^{\mp} + \gamma_{\text{soft}} \rightarrow e^{\mp} + \gamma_{\text{Inverse Compton}}$$

Egret
Agile
Fermi

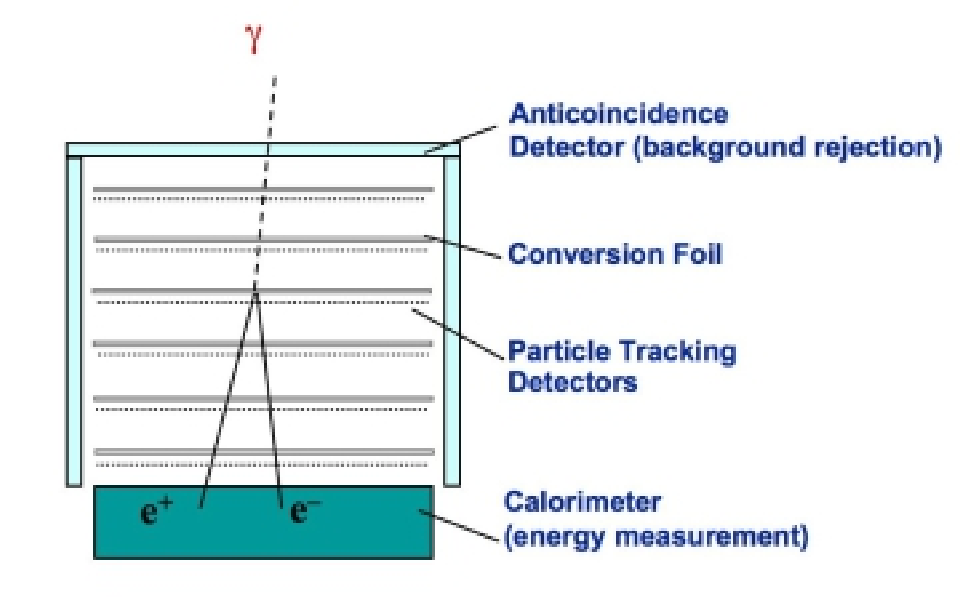
Gamma
Astronomy
“Golden Age”

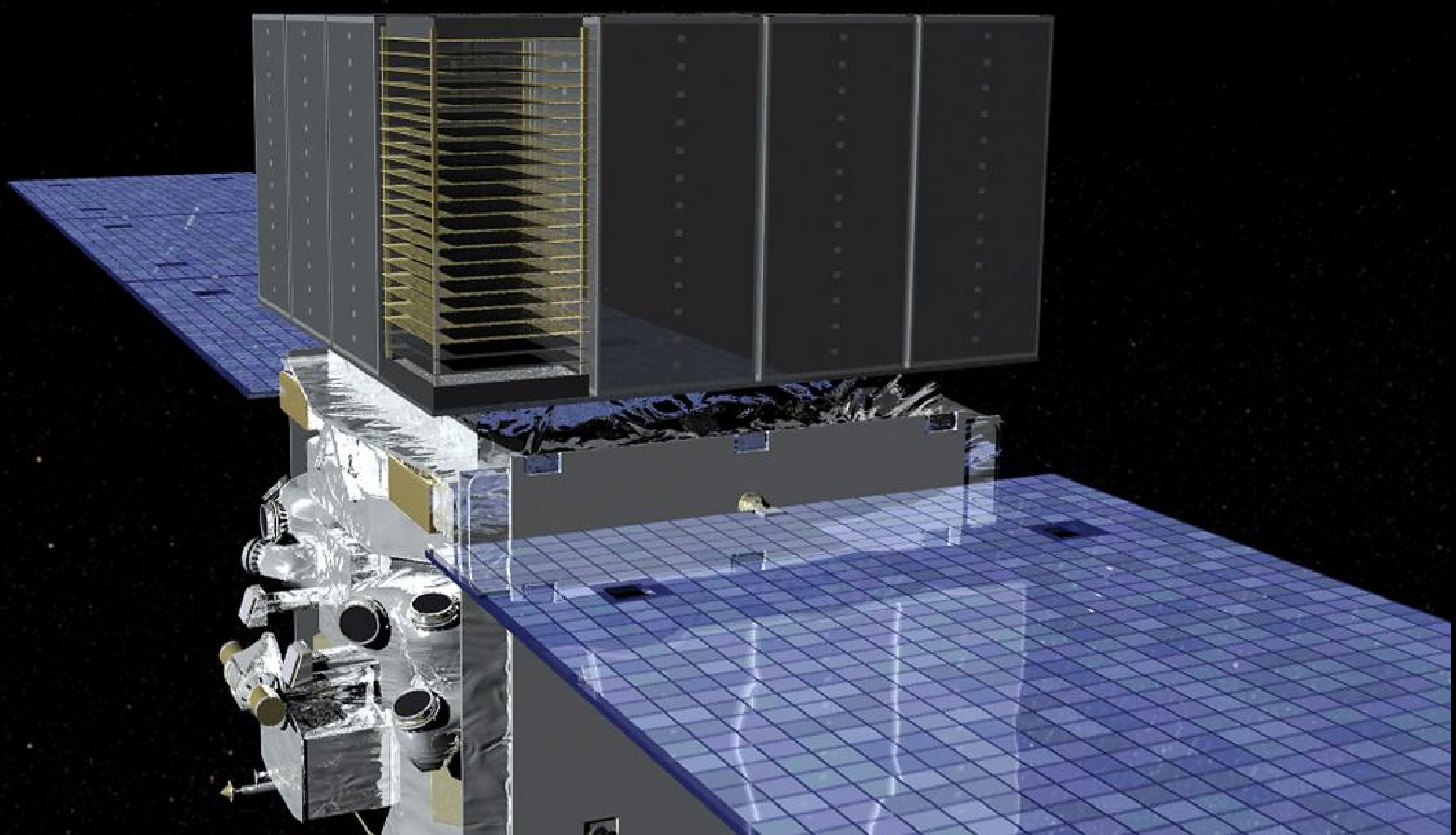


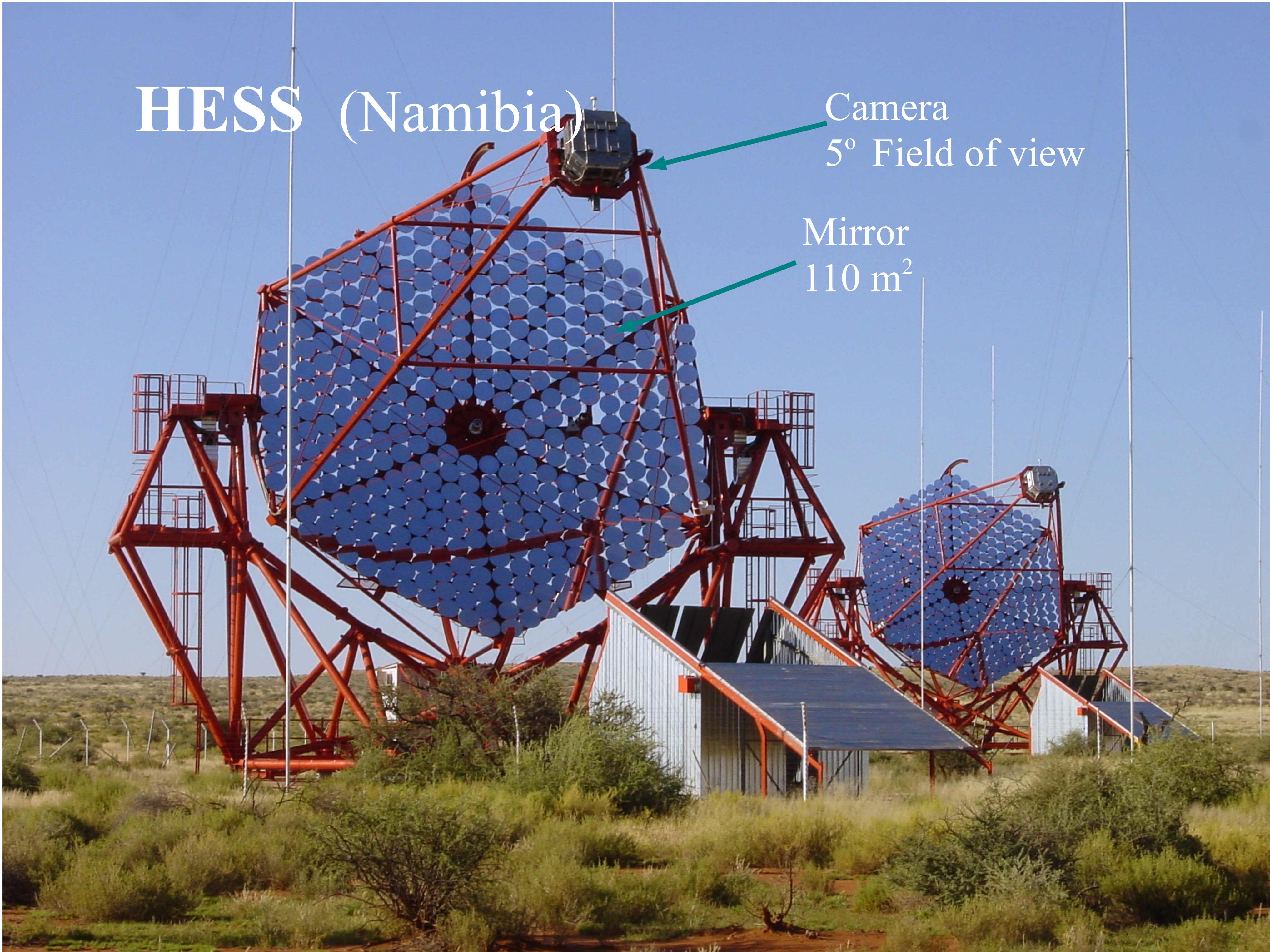
Hess
Magic
Veritas

Milagro
ARGO

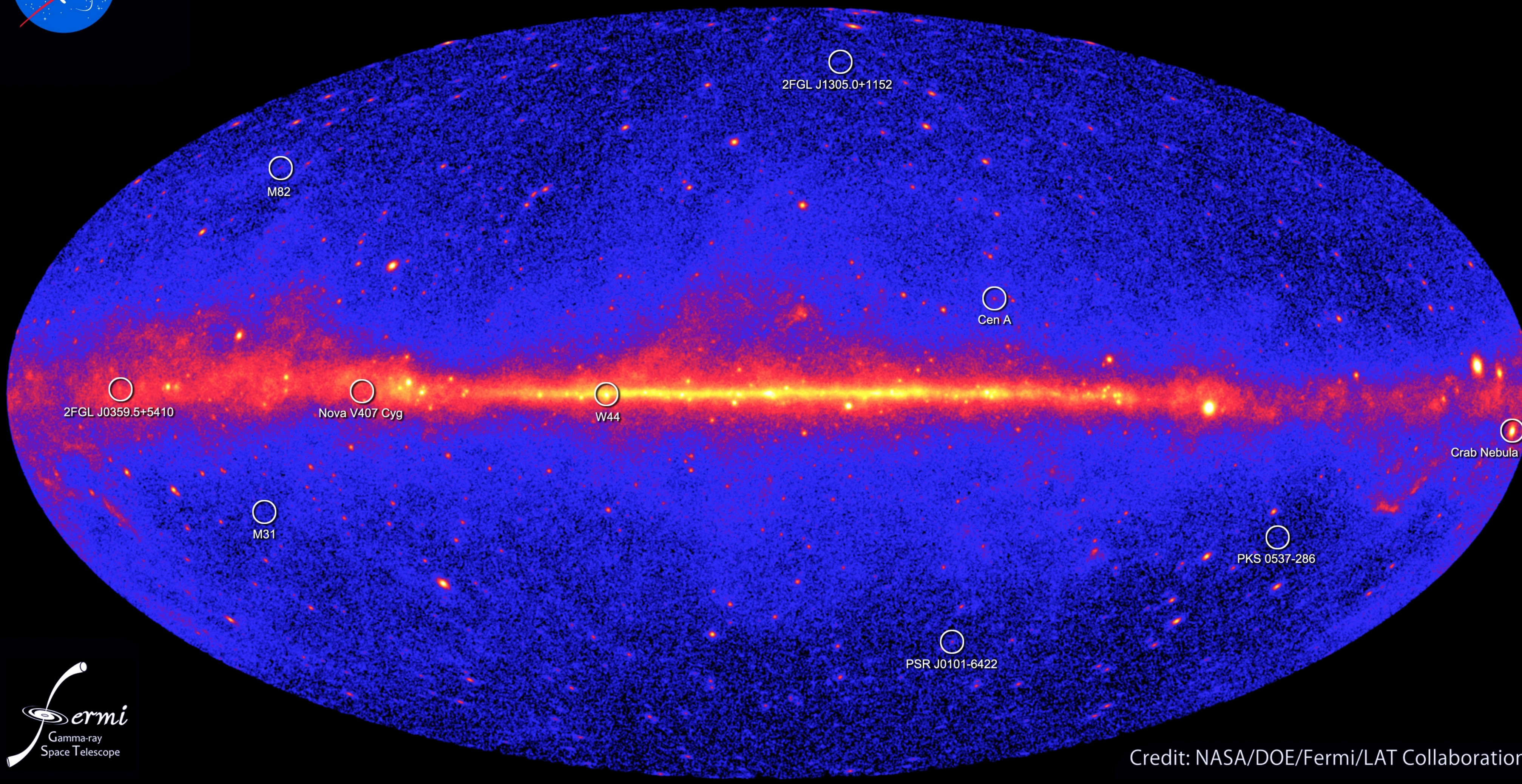
FERMI telescope



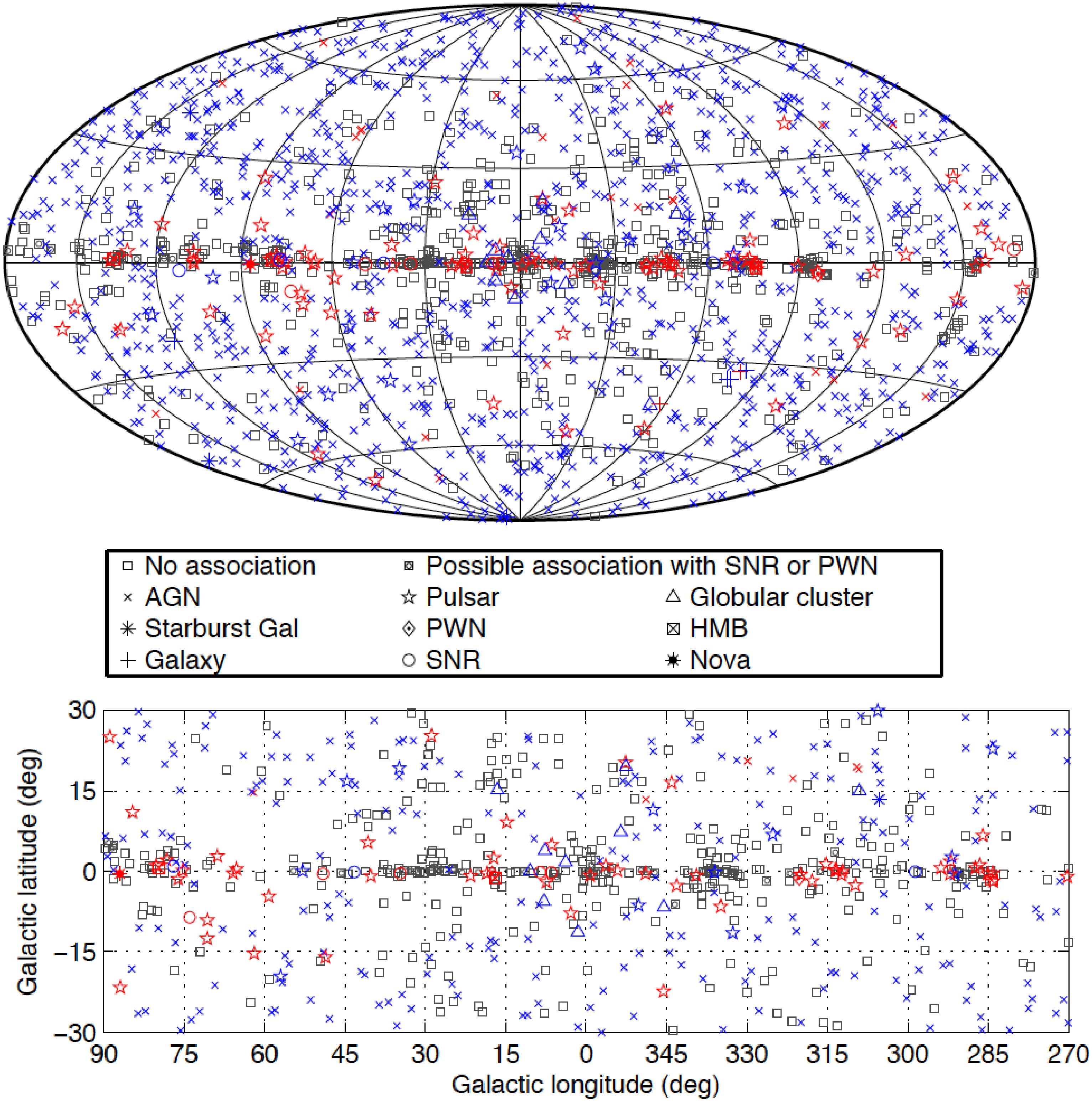



HESS (Namibia)
Camera
5° Field of view
Mirror
110 m²

Fermi two-year all-sky map



Superposition of a “diffuse flux” (disk of the Galaxy) and an ensemble of point-like or quasi point-like sources



2FGL

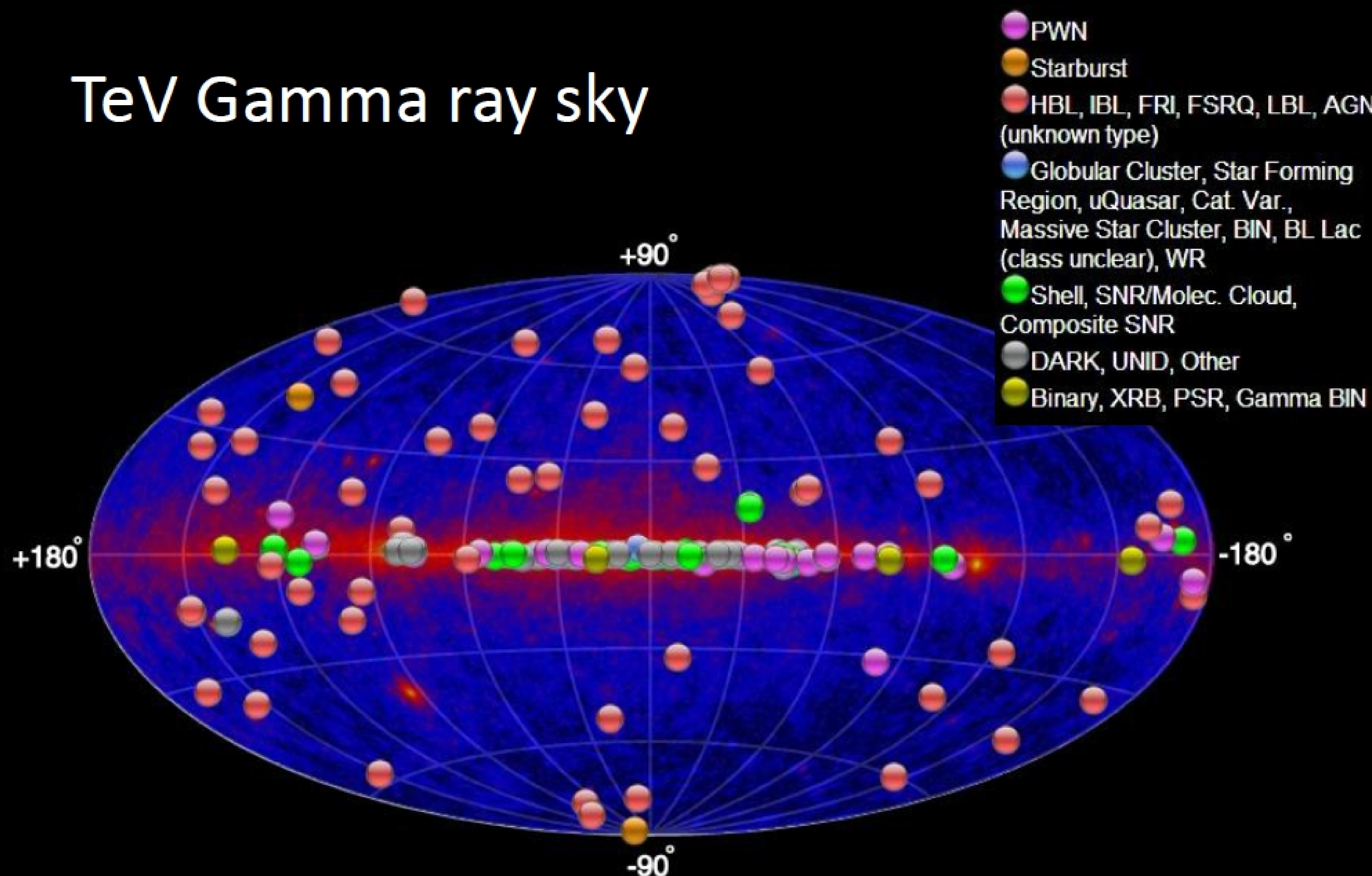
2nd FERMI Catalog

24 months
of observations

1873 sources

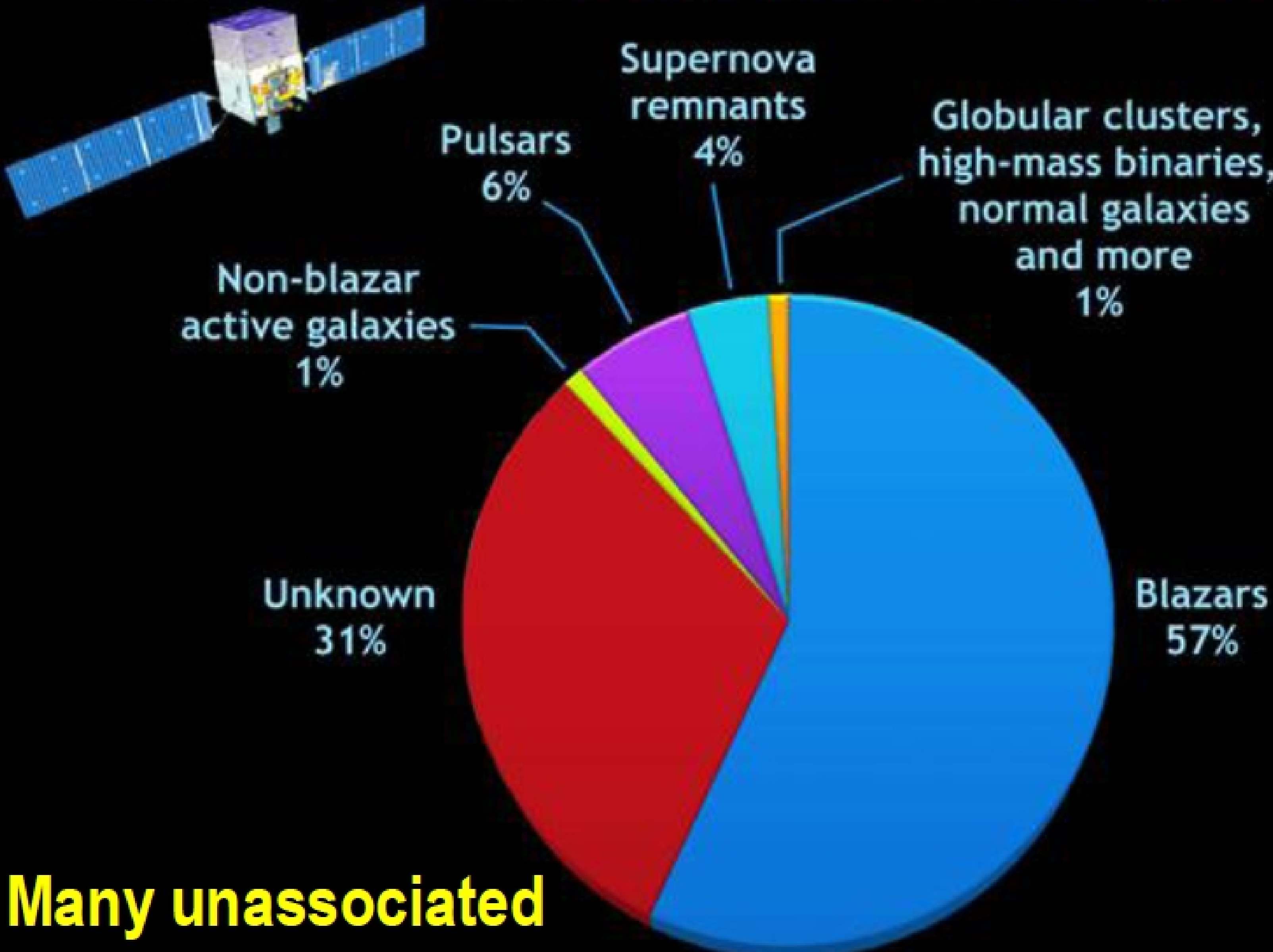
E > 100 MeV

TeV Gamma ray sky



~150 sources

What has Fermi found: The LAT two-year catalog



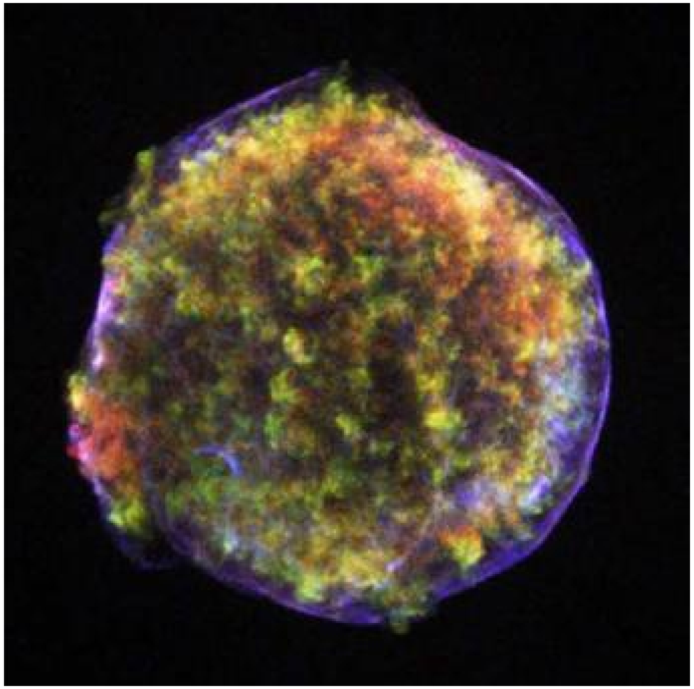
Many unassociated sources...

Credit: NASA/Goddard Space Flight Center

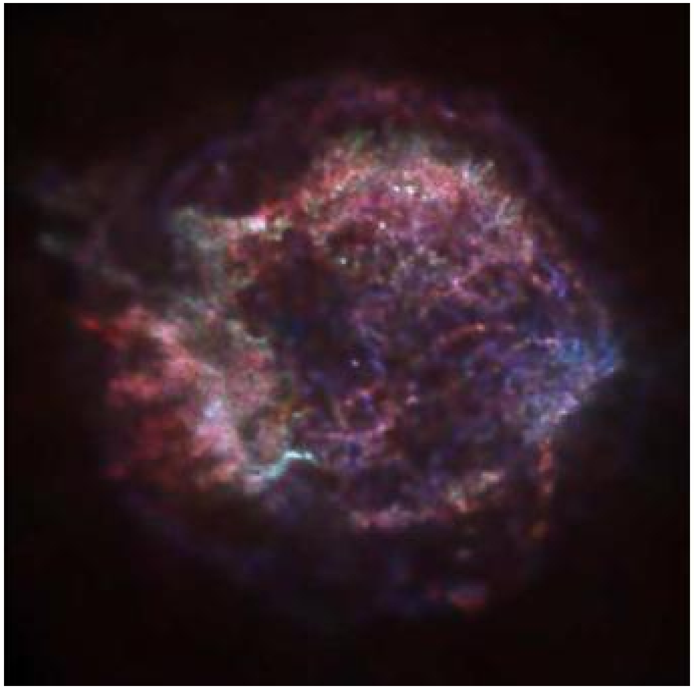
SuperNova Remnants

Chandra X-Ray images

SN1006

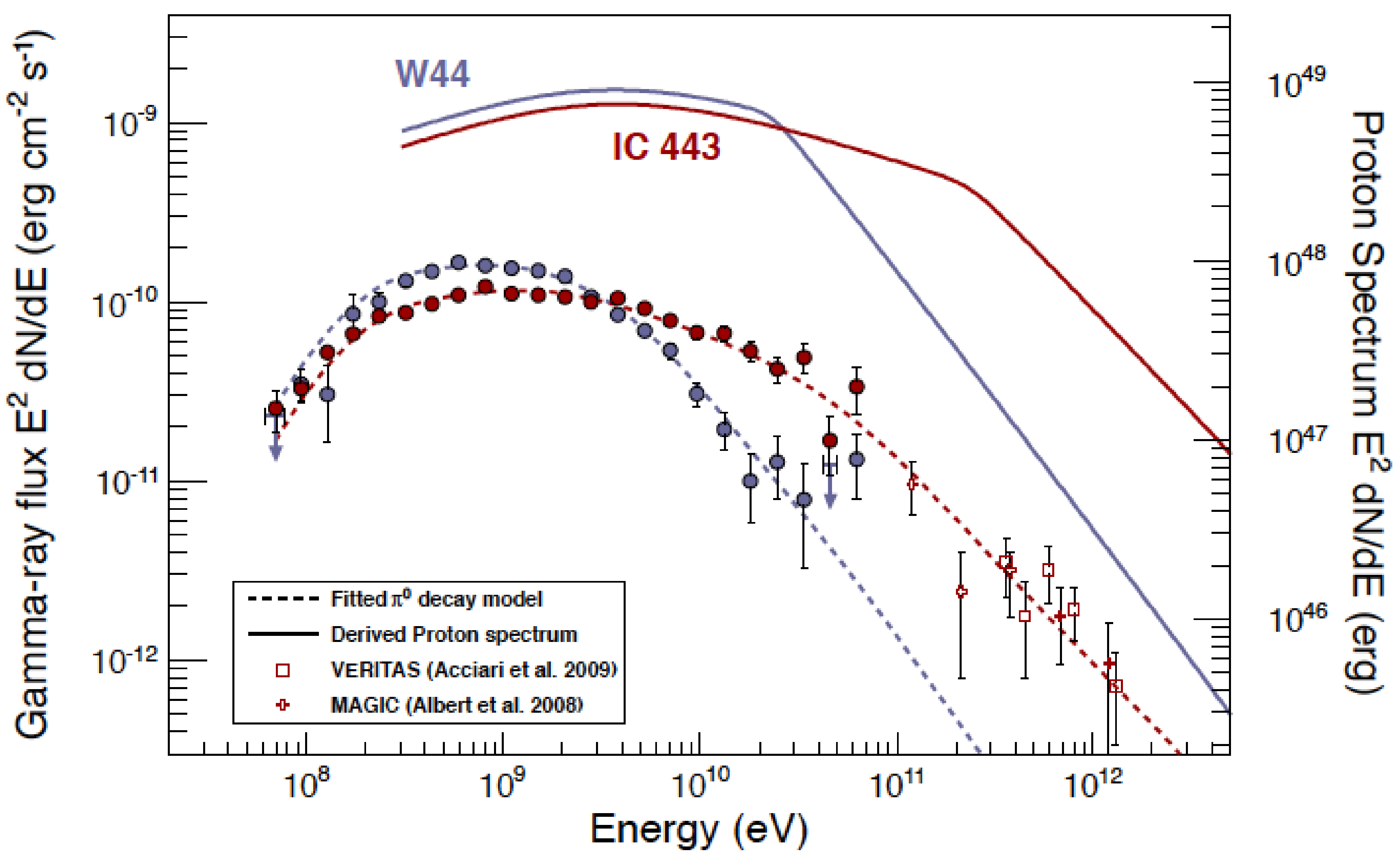


Tycho

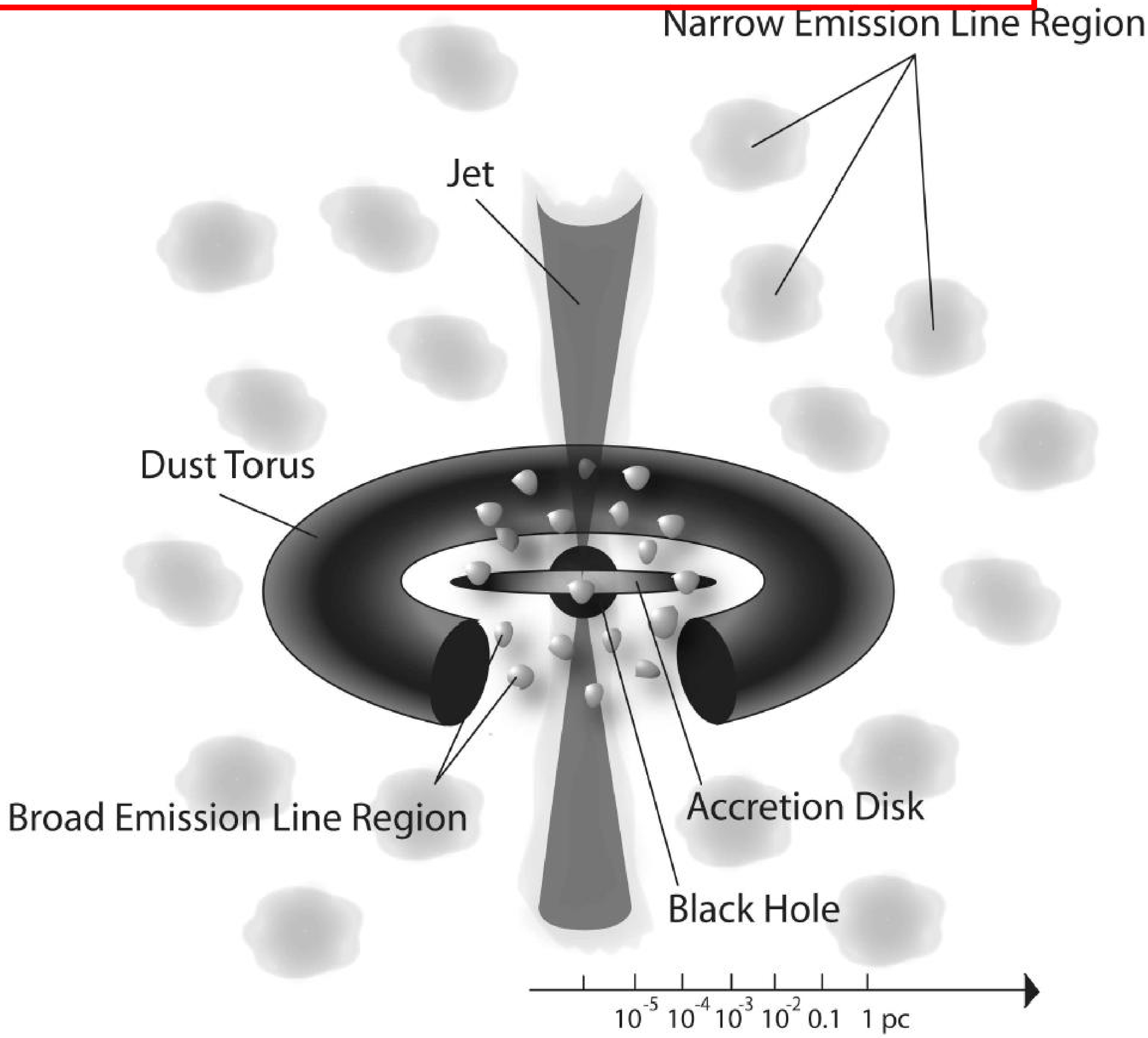


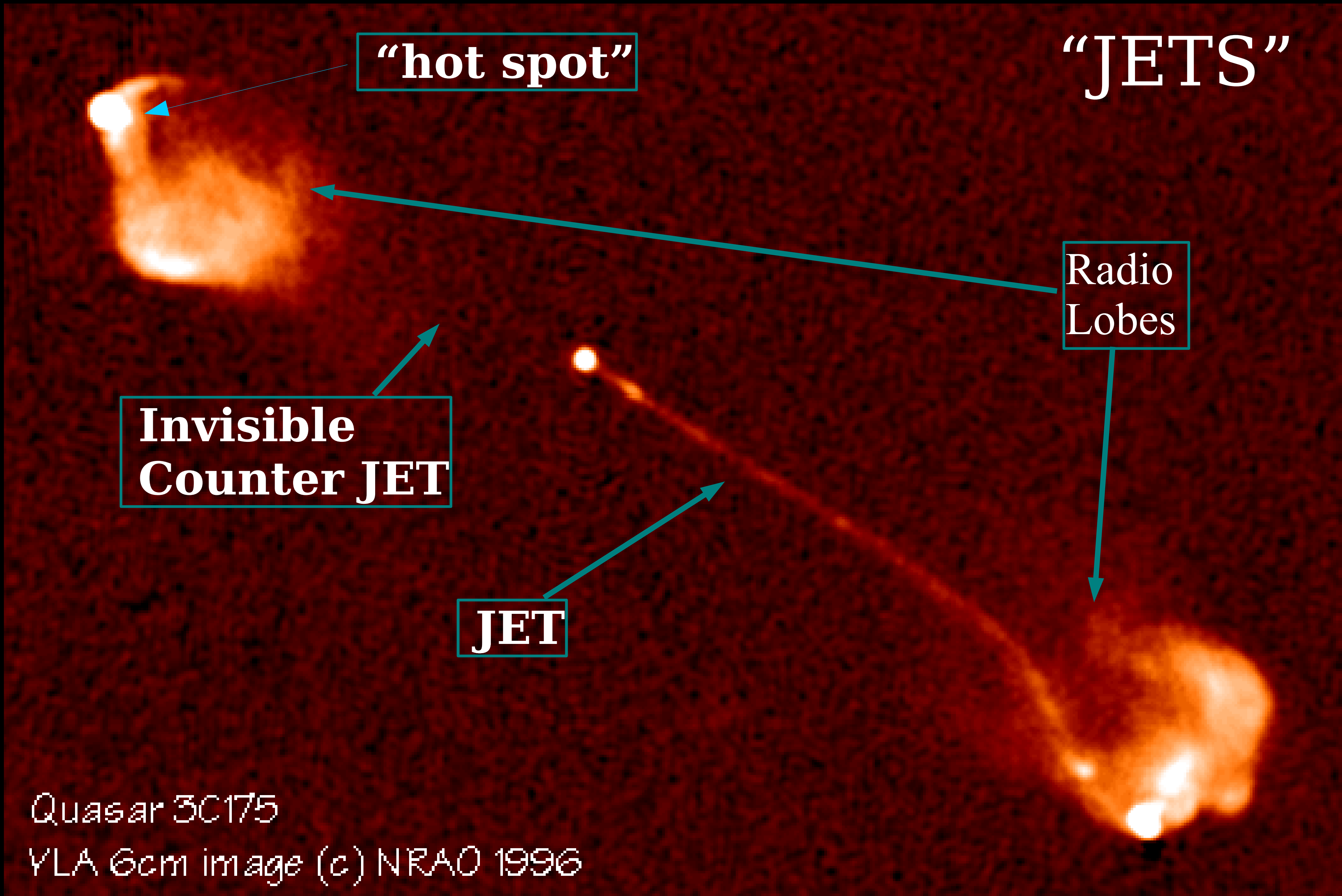
Cas A

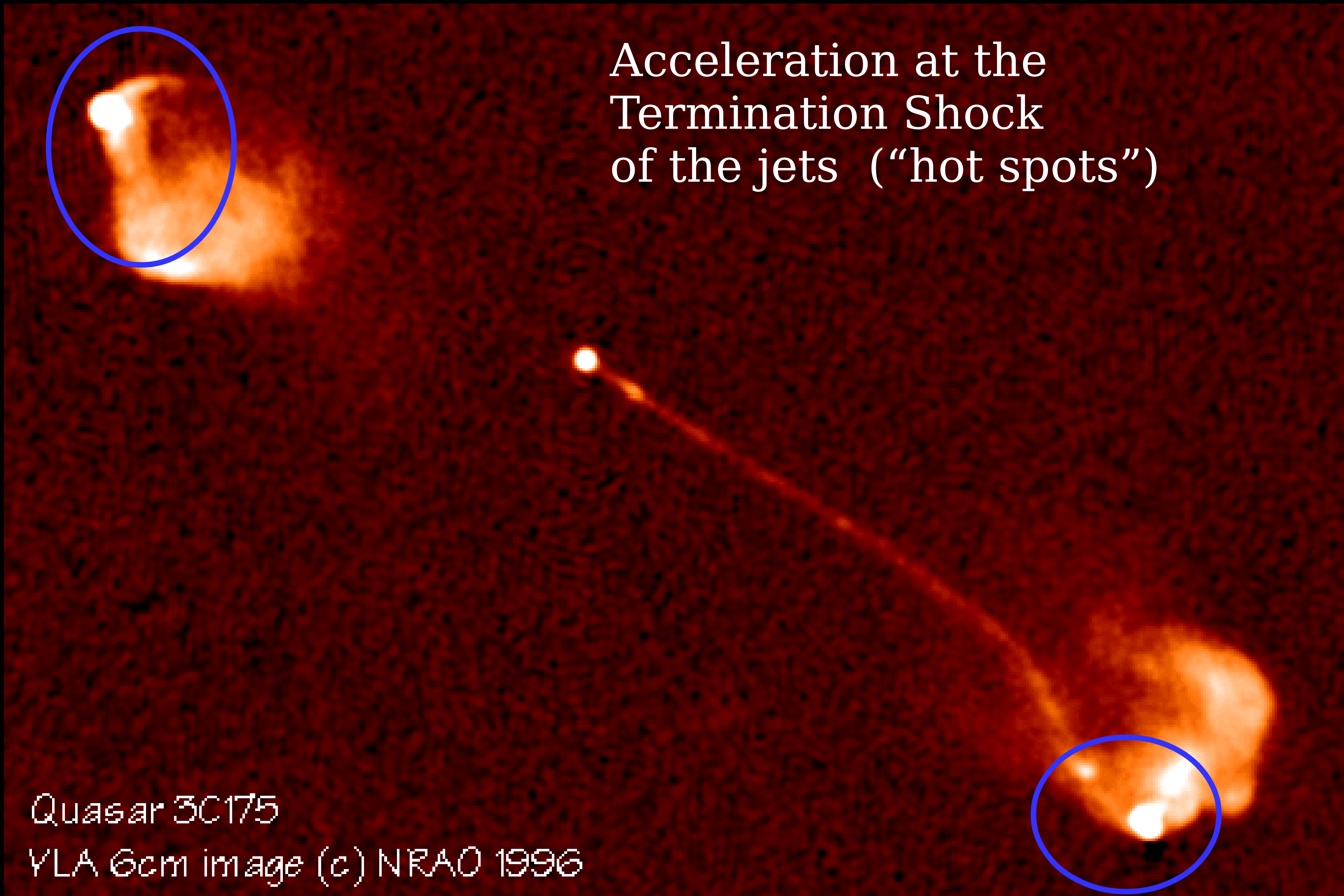
Reconstruction of the Proton population
Inside the two SuperNova shells



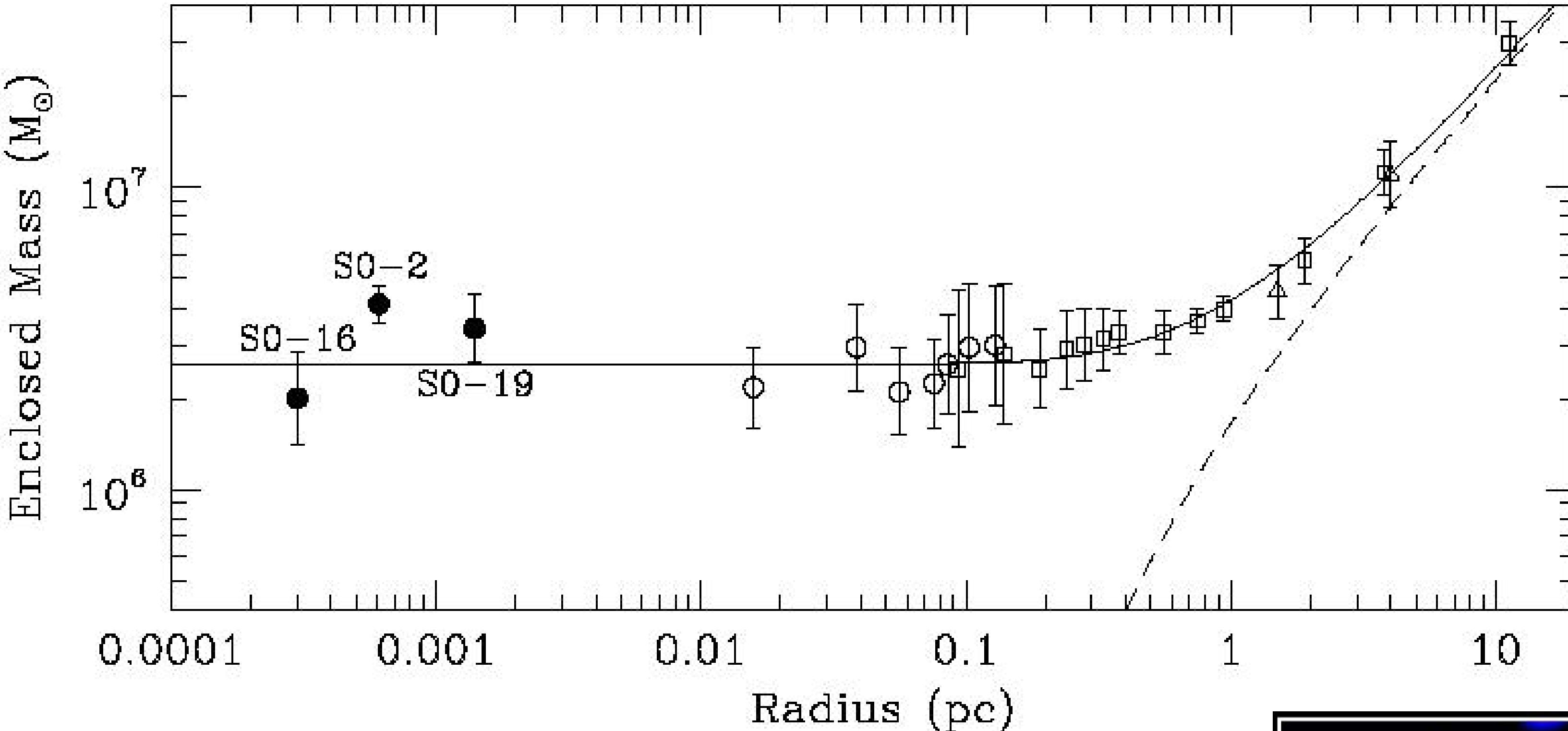
ACTIVE GALACTIC NUCLEI



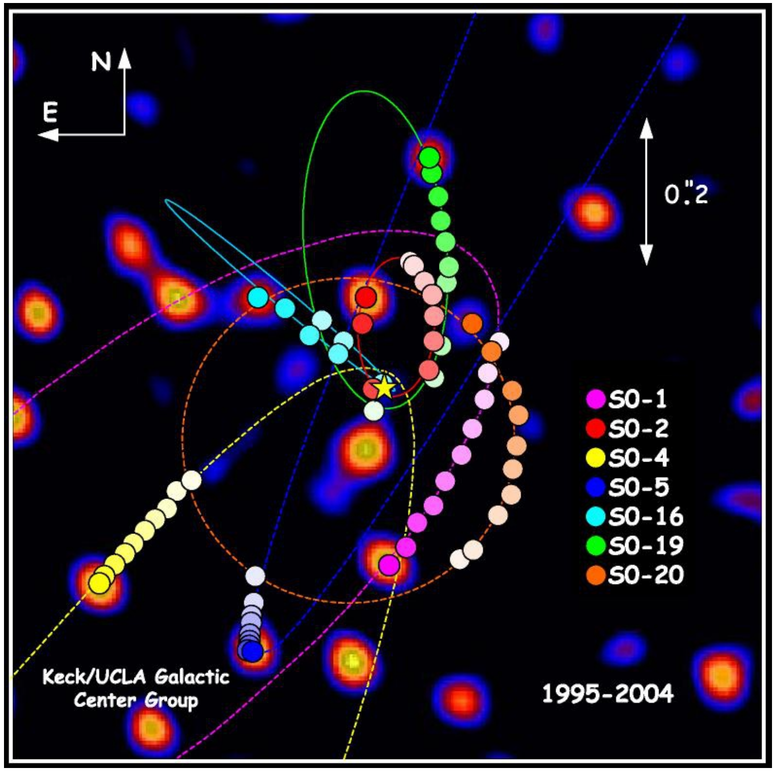

"JETS"
"hot spot"
Radio Lobes
Invisible Counter JET
JET
Quasar 3C175
VLA 6cm image (c) NRAO 1996


Acceleration at the
Termination Shock
of the jets (“hot spots”)
Quasar 3C175
VLA 6cm image (c) NRAO 1996

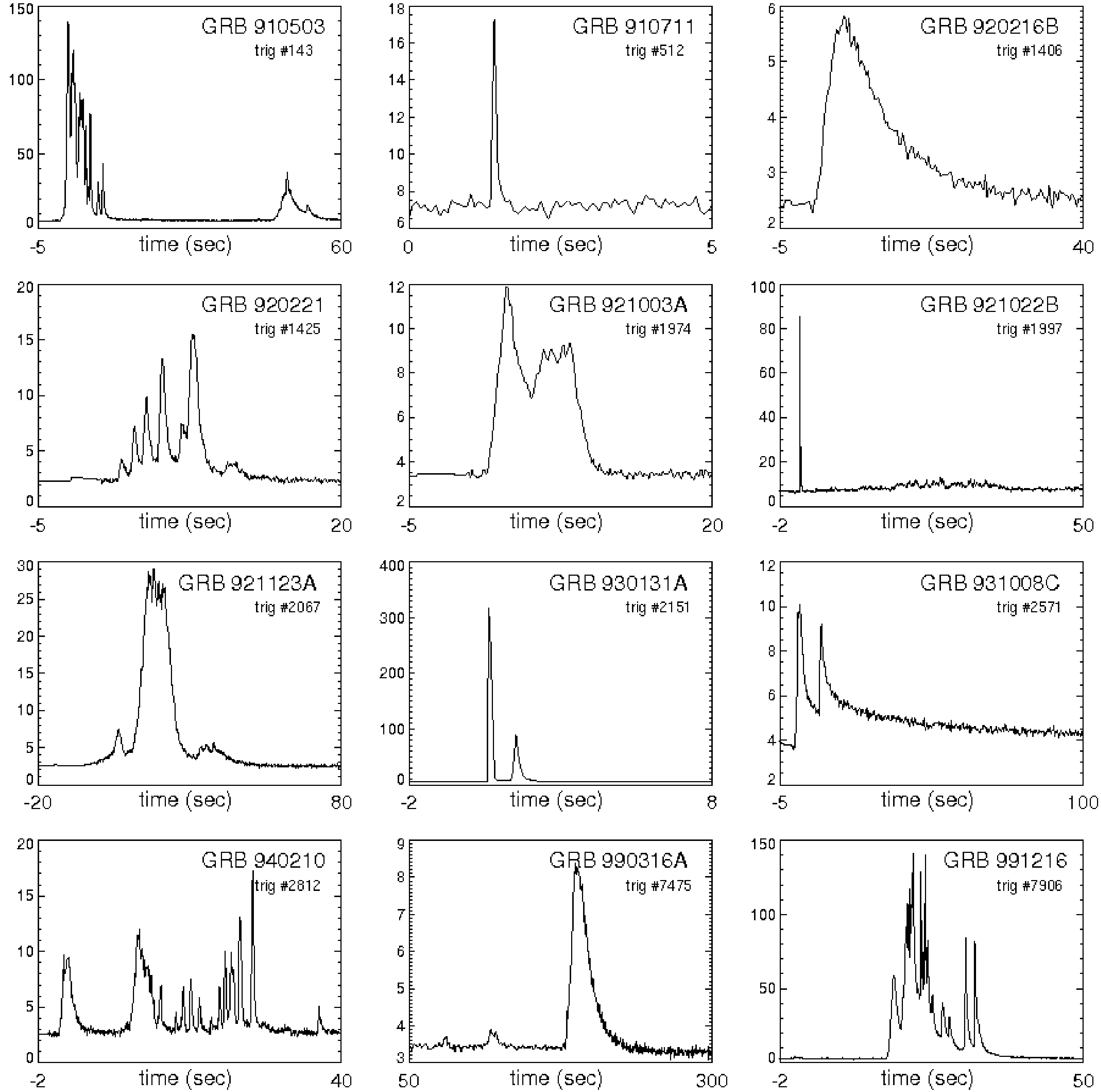
The Milky Way Galactic center

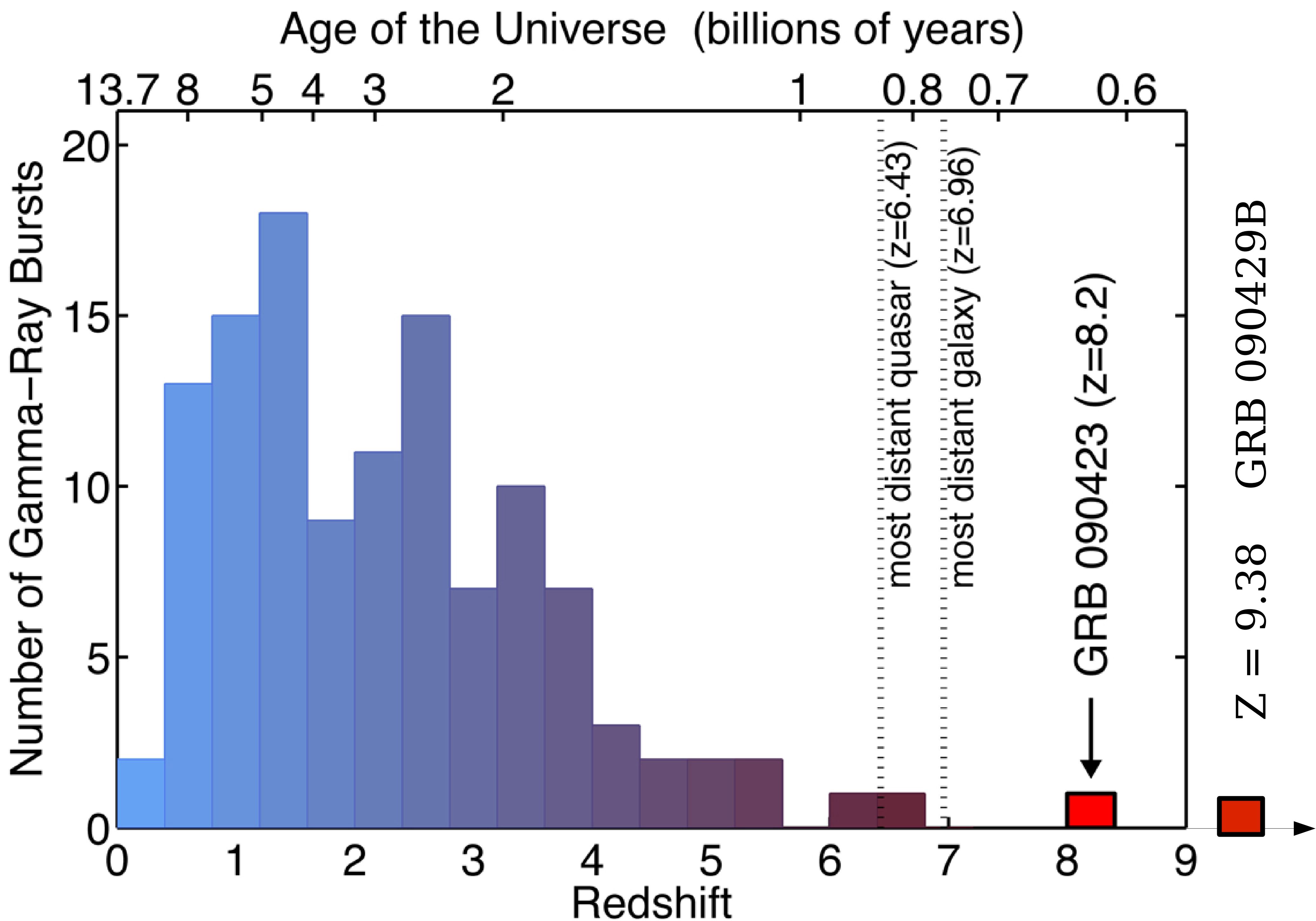


Star	Mass ($10^6 M_\odot$)
S0-2	4.1 ± 0.6
S0-16	3.0 ± 0.7
S0-19	3.4 ± 0.9
Average	3.6 ± 0.4



Gamma Ray Bursts

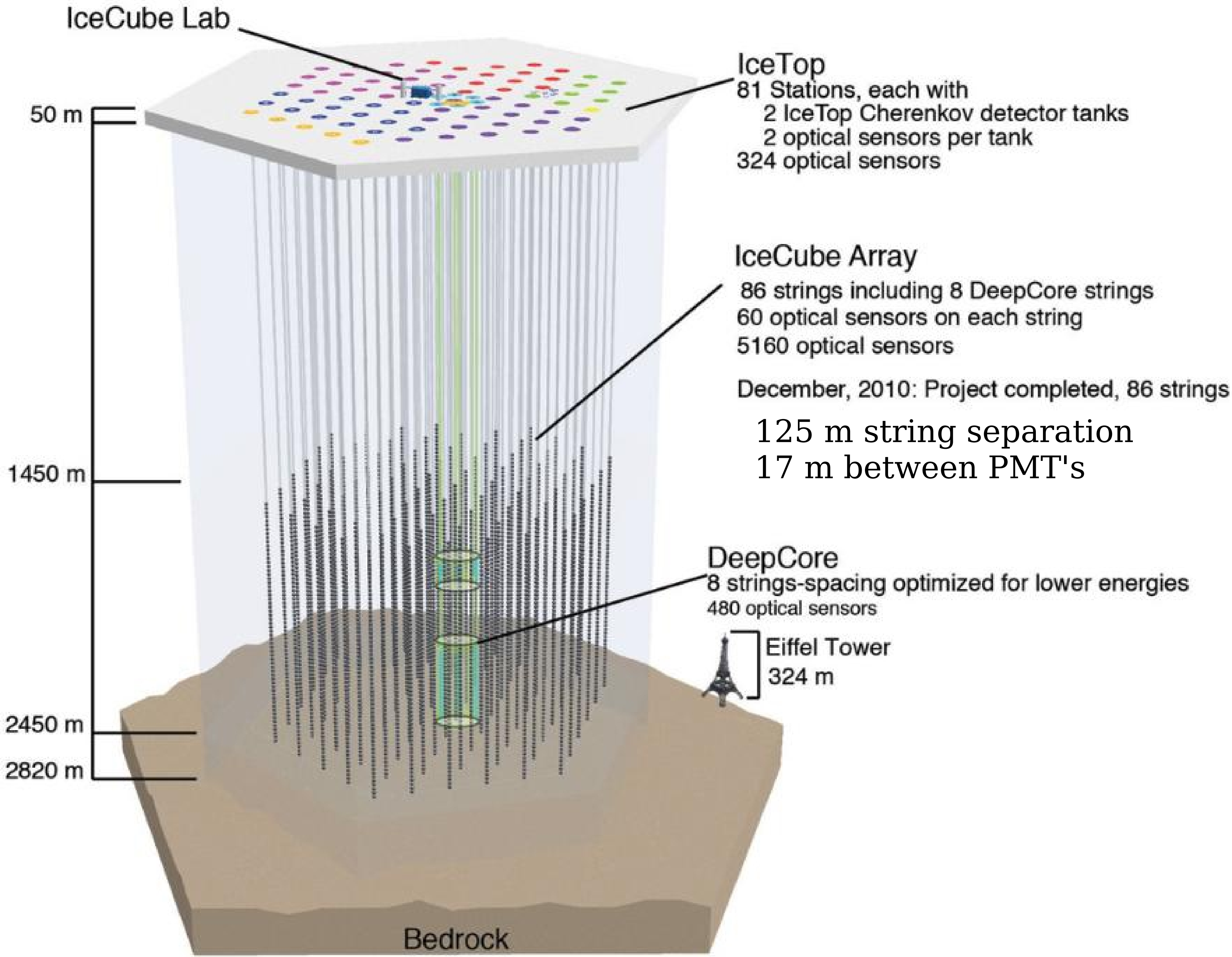

GRB 910503
trig #143
time (sec)
GRB 910711
trig #512
time (sec)
GRB 920216B
trig #1406
time (sec)
GRB 920221
trig #1425
time (sec)
GRB 921003A
trig #1974
time (sec)
GRB 921022B
trig #1997
time (sec)
GRB 921123A
trig #2067
time (sec)
GRB 930131A
trig #2151
time (sec)
GRB 931008C
trig #2571
time (sec)
GRB 940210
trig #2812
time (sec)
GRB 990316A
trig #7475
time (sec)
GRB 991216
trig #7906
time (sec)

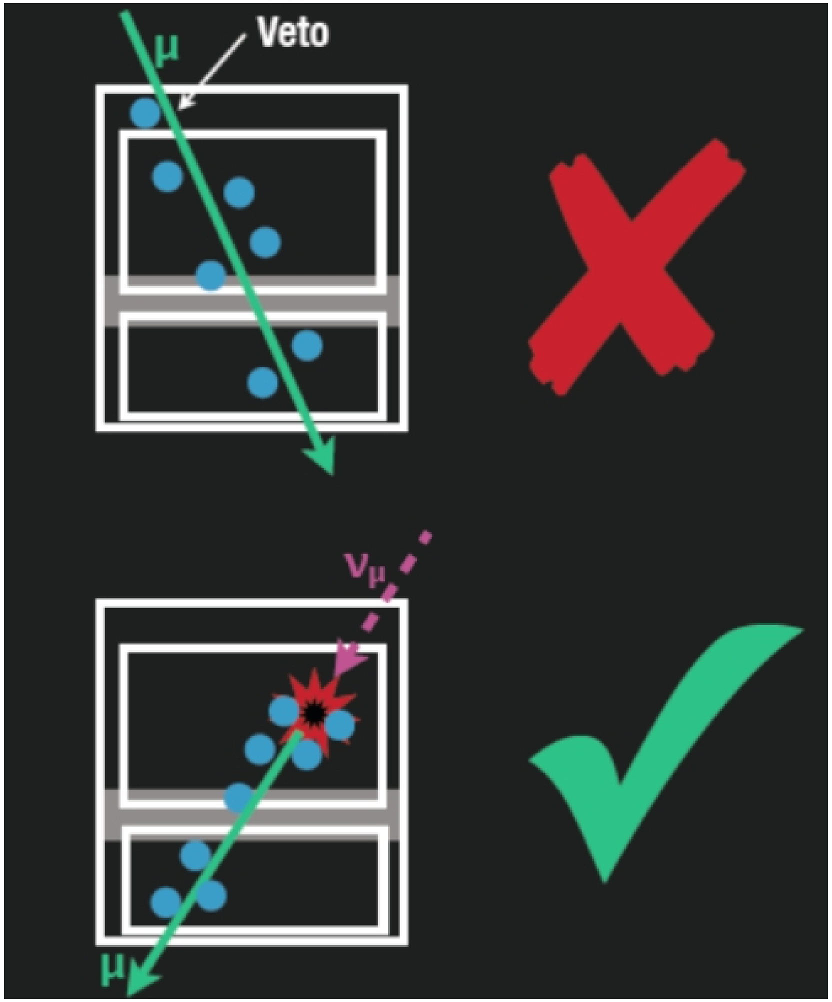

Age of the Universe (billions of years)
13.7 8 5 4 3 2 1 0.8 0.7 0.6
Number of Gamma-Ray Bursts
0 5 10 15 20
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)
GRB 090429B
Z = 9.38
0 1 2 3 4 5 6 7 8 9
Redshift

IceCube evidence for extra-terrestrial neutrinos

Evidence becoming compelling.
Interest of the community very strong
Excellent contribution at this workshop.

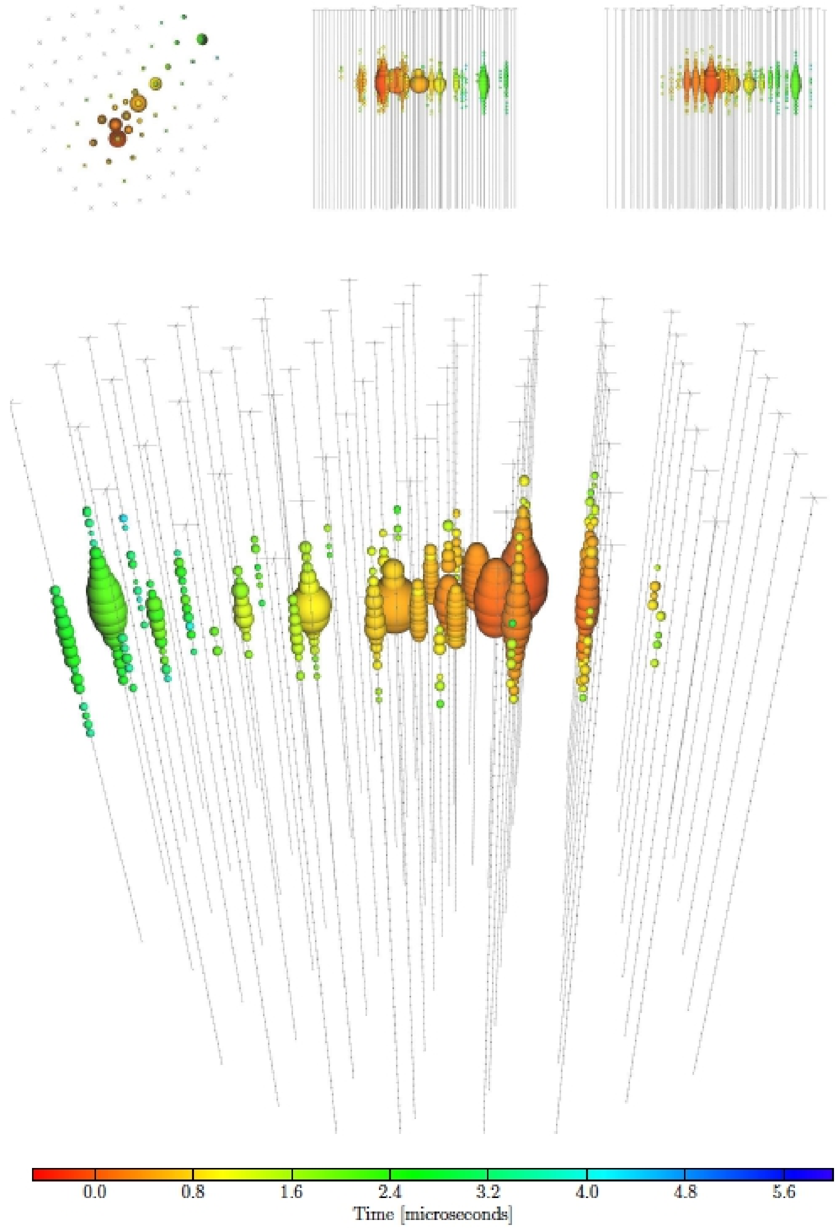
"A glimpse of the promised land"
(Christian Spiering)


IceCube Lab
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
125 m string separation
17 m between PMT's
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock



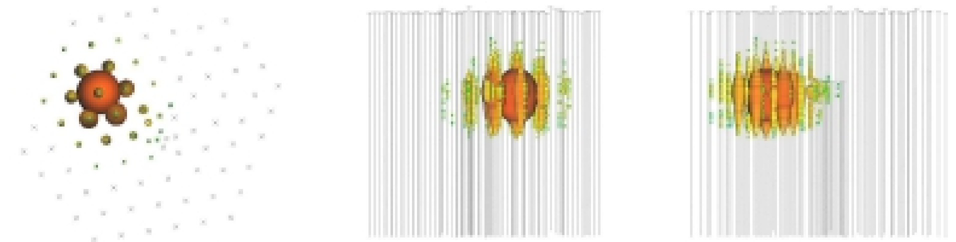
Study of Contained Events

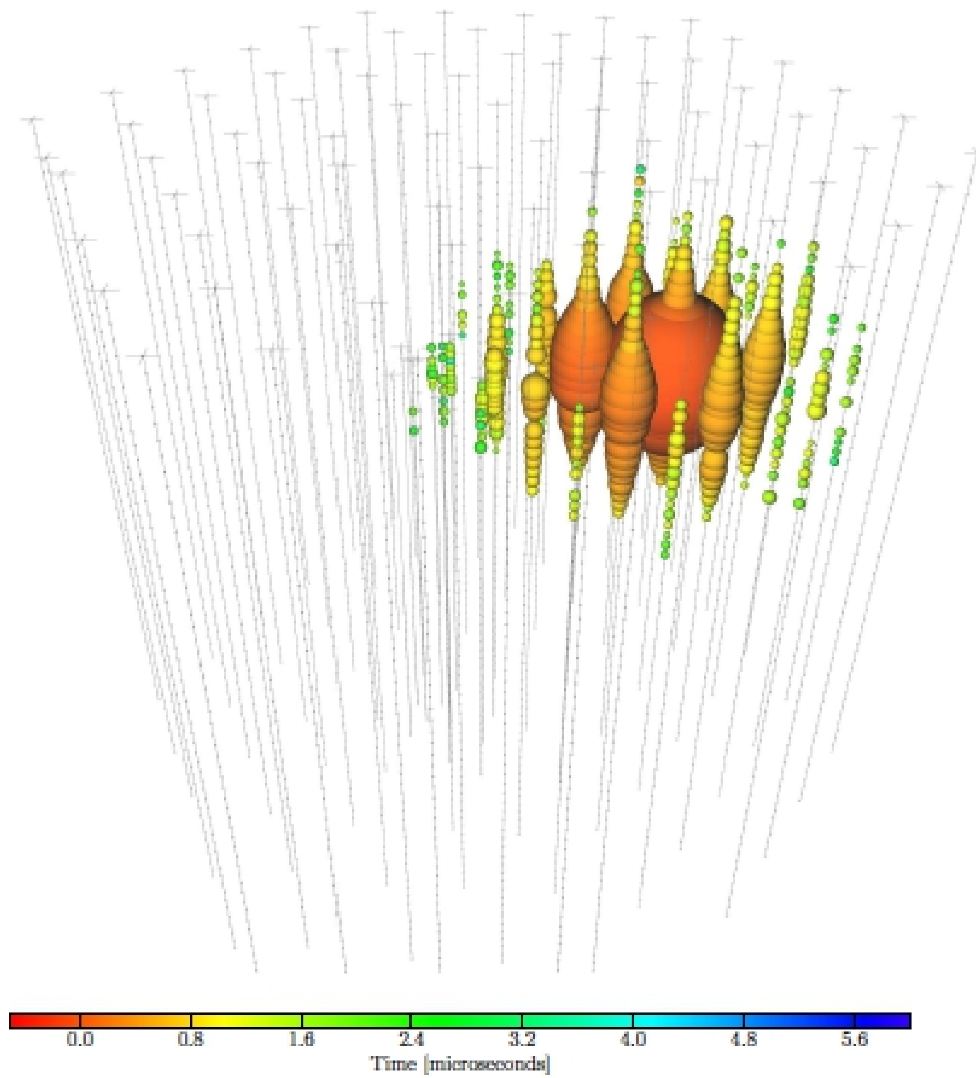
A “track”



Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$71.4^{+9.0}_{-9.0}$	55512.5516214	-0.4	110.6	$\lesssim 1.2$	Track

A “shower”



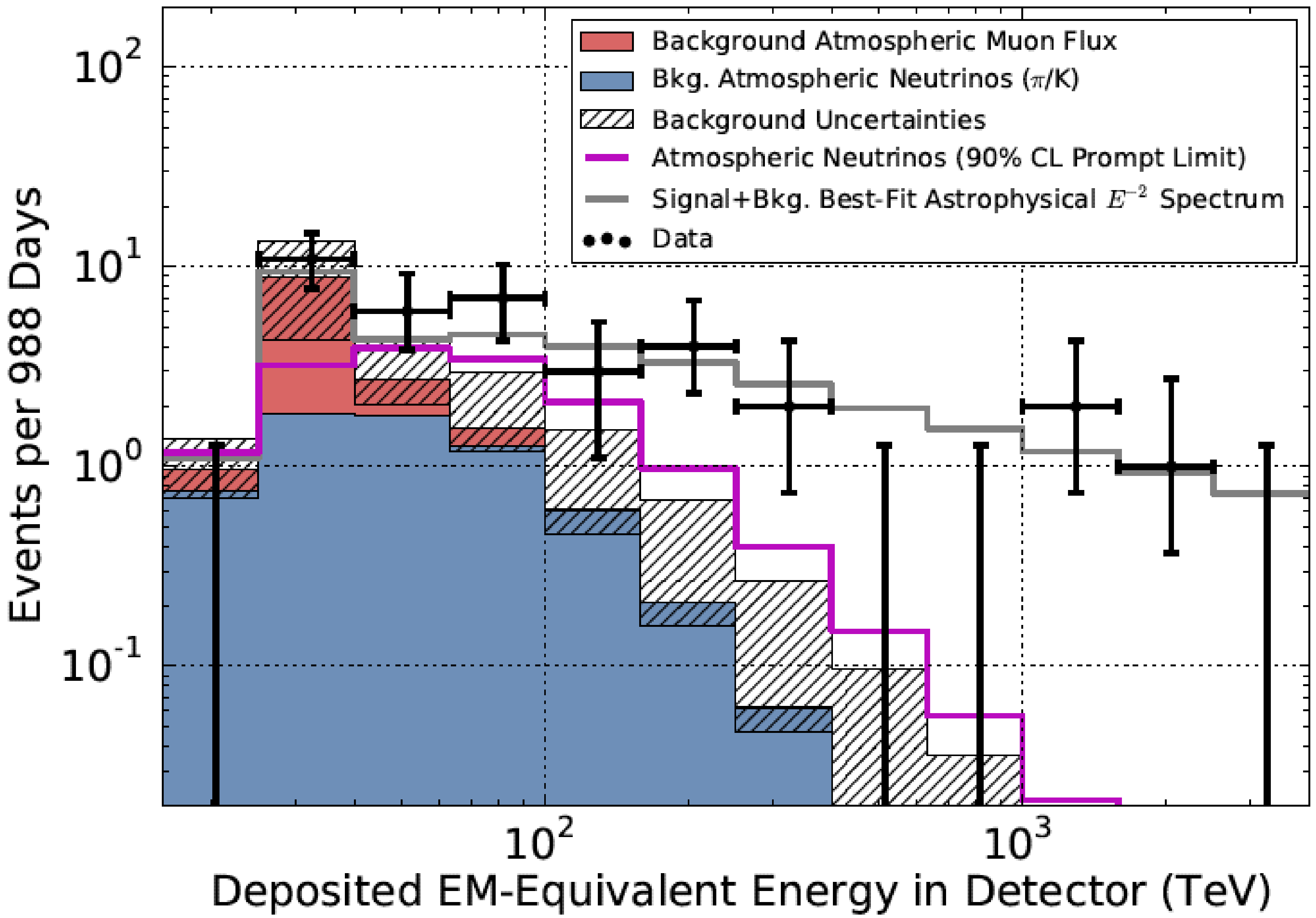


Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$1040.7^{+131.6}_{-144.4}$	55782.5161816	−27.9	265.6	13.2	Shower

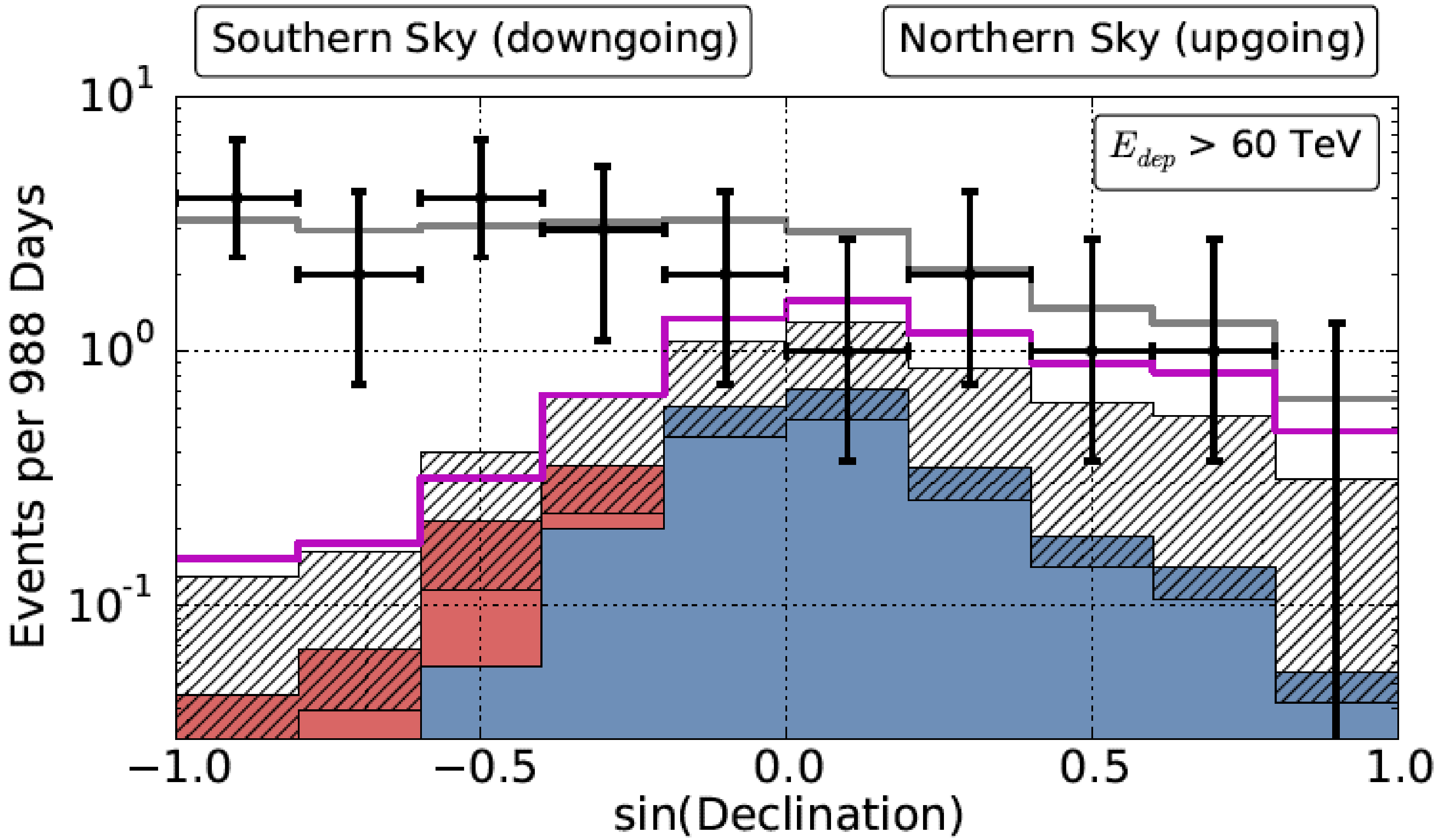
Total Number of Events :	37
Background from Down-going Muons	8.4 ± 4.2
Atmospheric Neutrinos	$6.6^{+5.9}_{-1.6}$

Excess = 5.7 sigmas

Energy distribution



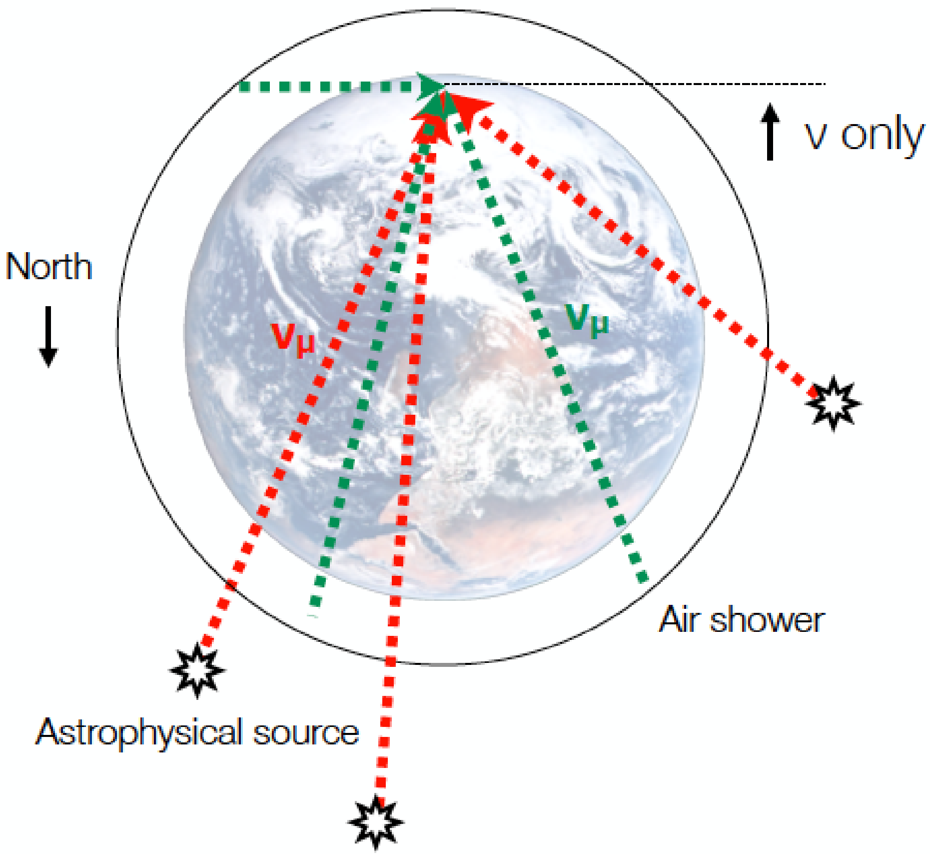
Declination, Zenith angle distribution

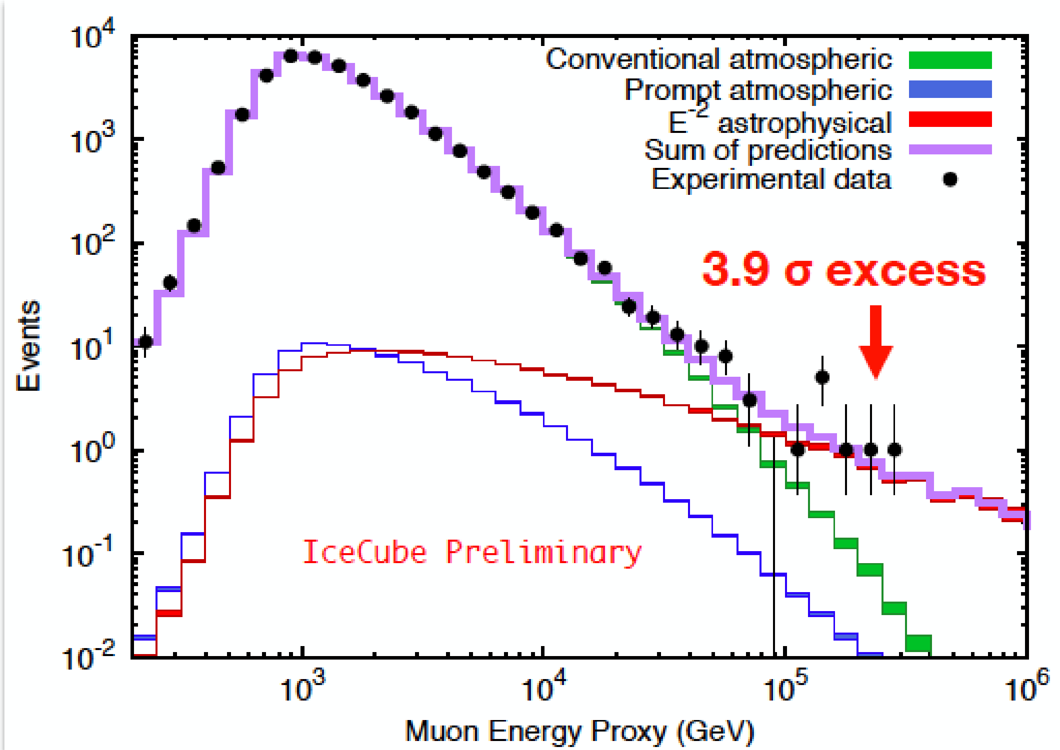


What about the northern sky ar

Confirming Evidence from neutrino-induced muons !

The high-energy starting event sample is dominated by cascades from the southern sky.



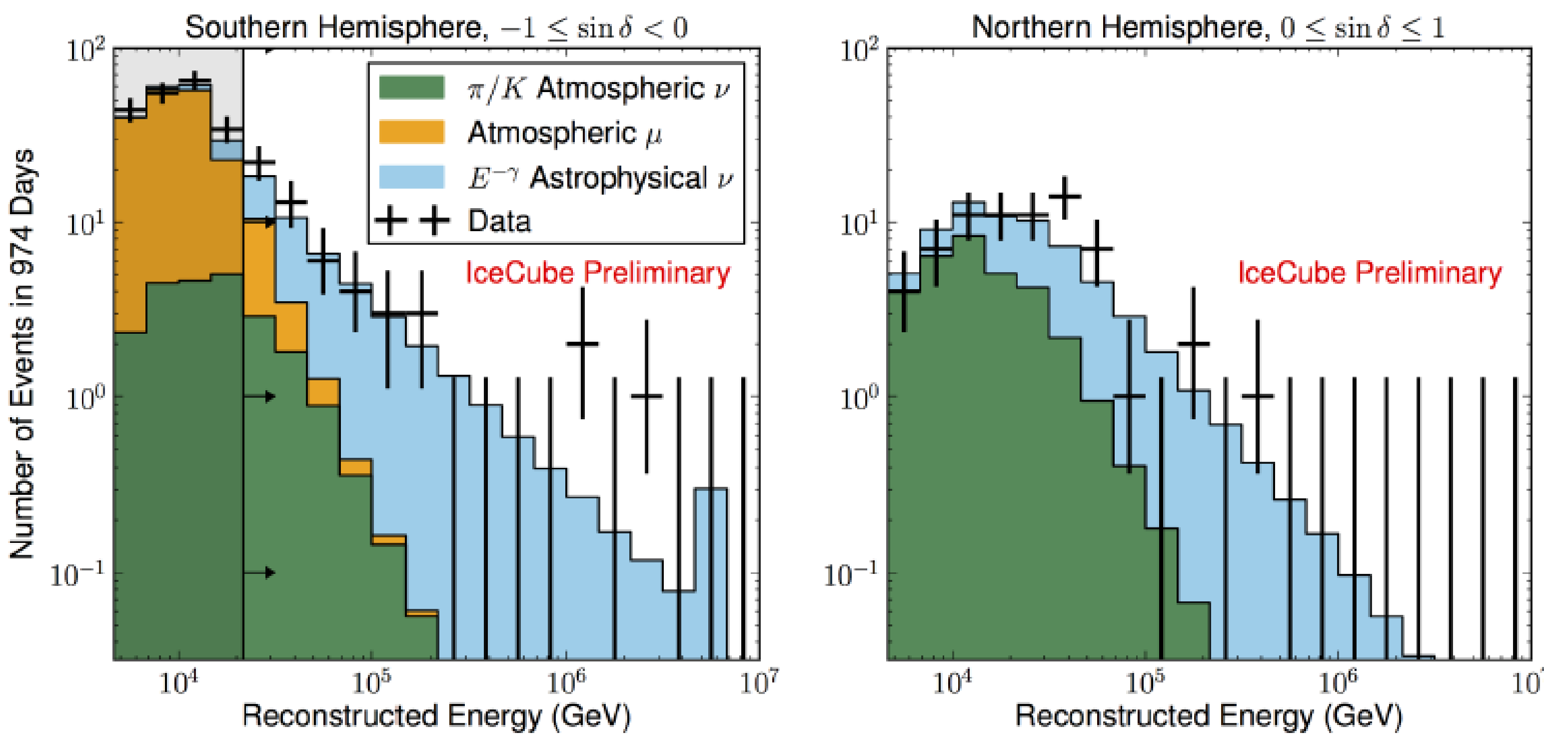


$$E_\nu^2 \Phi_\nu = \begin{cases} 0.95 \pm 0.3 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,sr^{-1}\,s^{-1}} & \text{High-energy starting events} \\ 1.01 \pm 0.35 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,sr^{-1}\,s^{-1}} & \text{Upgoing } \nu_\mu \end{cases}$$

LOW ENERGY extension !

Gary Binder

Fit Results



- Data is well-described by a power-law astrophysical spectrum (p-value = 0.31):

$$\Phi(E) = \Phi_0 \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-\gamma}$$

$$\Phi_0 = 2.32^{+0.42}_{-0.57} \times 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}$$

$$\gamma = 2.64^{+0.15}_{-0.17}$$

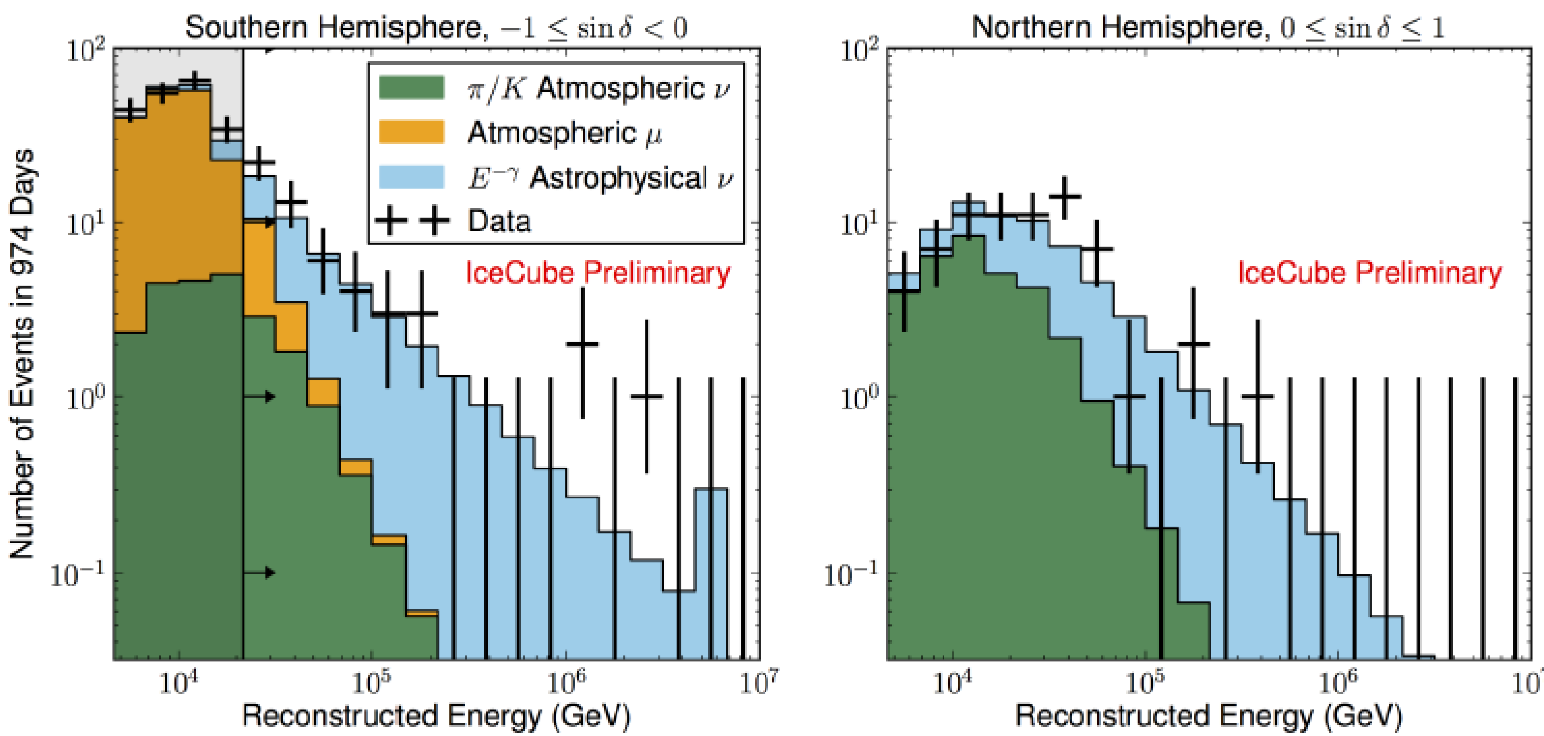
- Favored by 2.3σ over E^{-2}
- Best-fit charm flux is 0 x ERS* model
- Limits on charm depend on assumptions on the shape of the astrophysical spectrum

IceCube Preliminary

*ERS: Enberg, Reno, Sarcevic, Phys. Rev. D 78: 043005

LOW ENERGY extension !

Gary Binder



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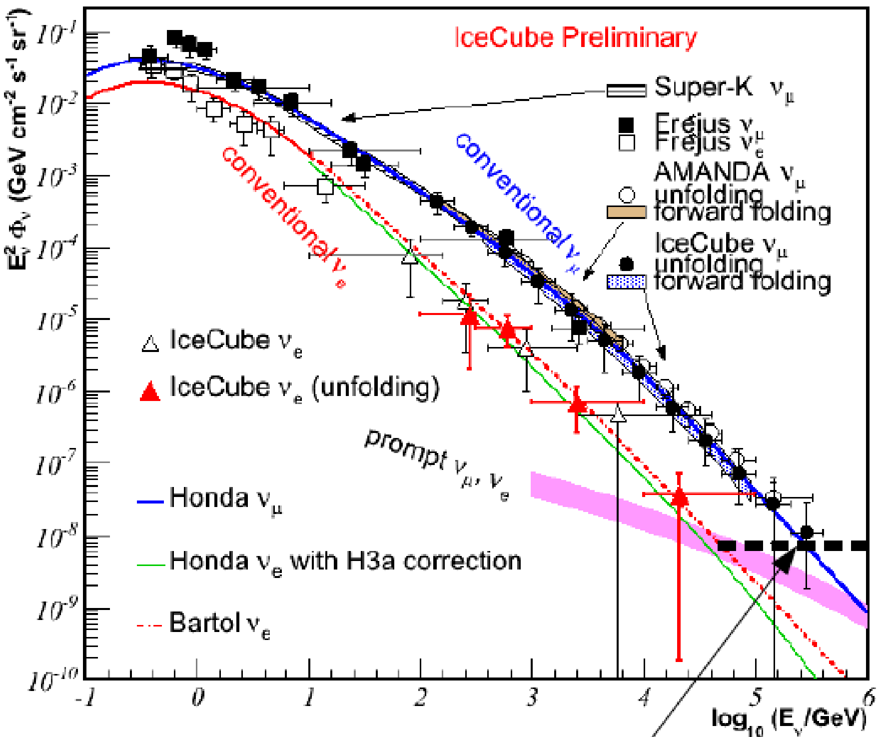
*ERS: Enberg, Reno, Sarcevic, Phys. Rev. D 78: 043005

Disentangling the Components

Standard
Atmospheric
Standard

Atmospheric
Charm

Astrophysical

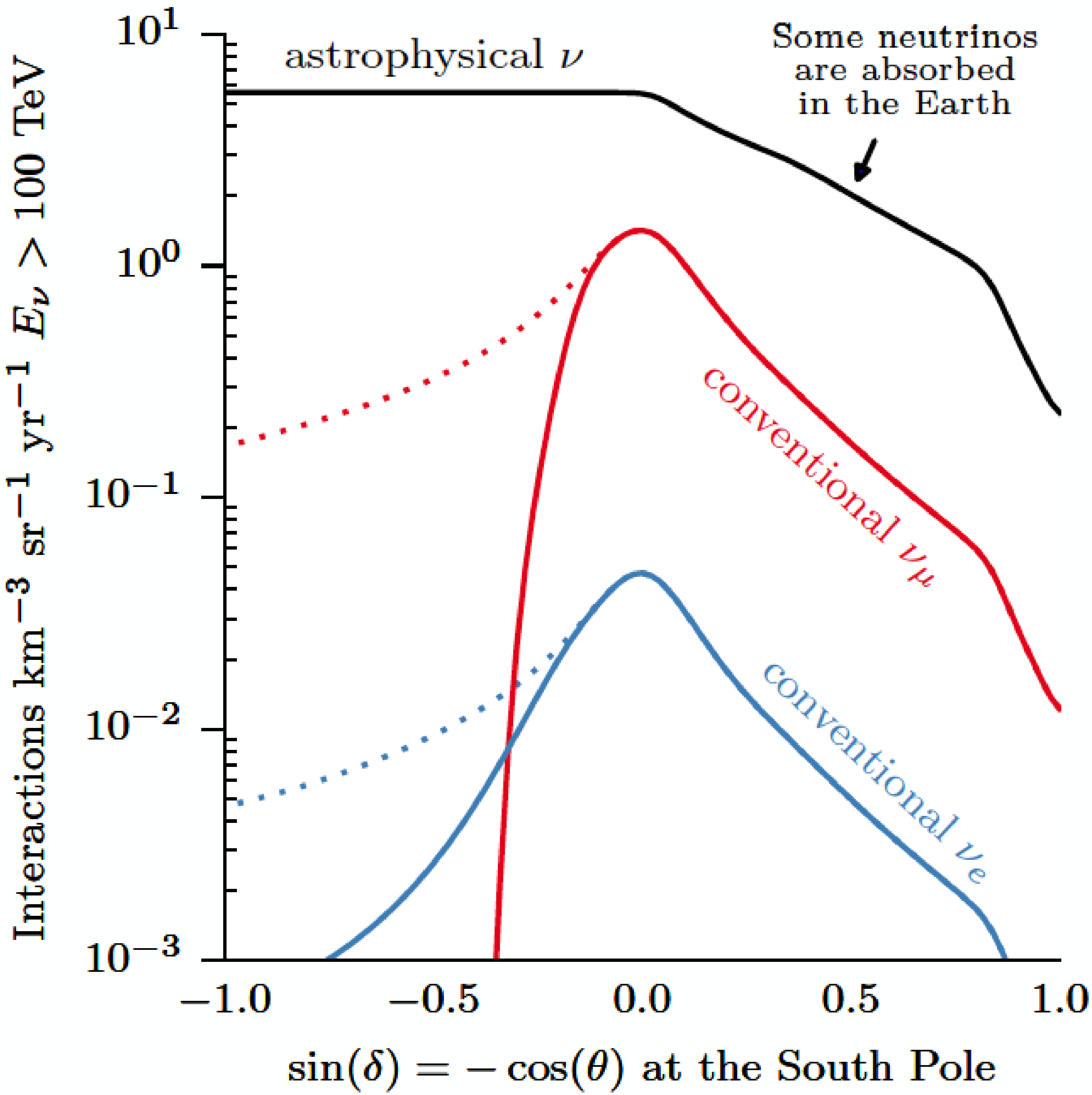


Red: Latest IceCube ν_e measurement

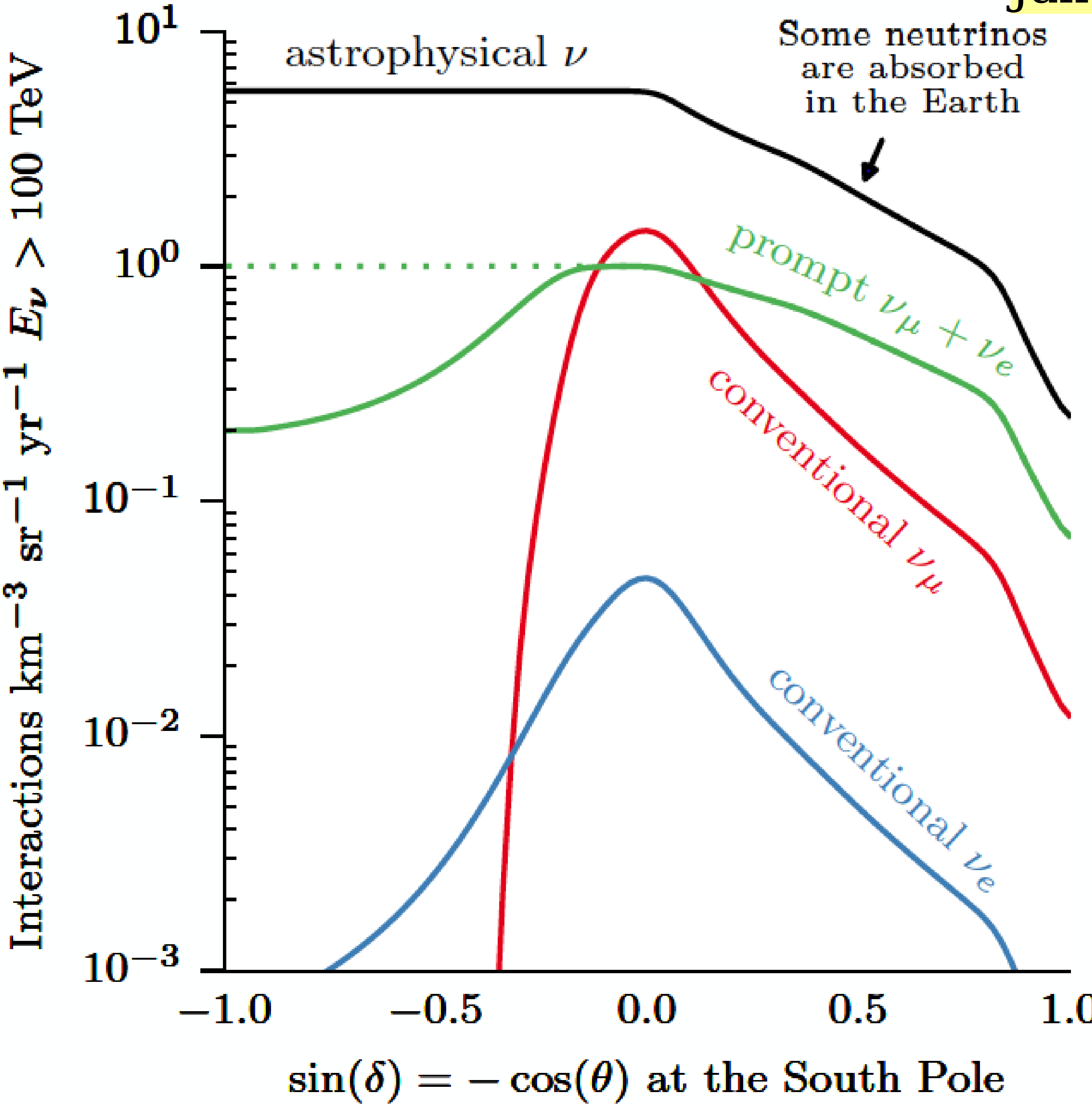
Current best estimate of E^{-2} flux

Atmospheric neutrino self-veto

Jakob van Santen



Jakob van Santen



Conclusions

IceCube observes a diffuse astrophysical neutrino flux

in multiple channels, but its sources are still unknown.

Astrophysical excess observable down to 10 TeV in the southern sky.

An active muon veto removes atmospheric neutrinos when the overburden is small enough.

Constraints on atmospheric charm depend on astrophysical model assumptions.

We need independent constraints from penetrating muons!

This is an exciting time for neutrino telescopes. Stay tuned for more data!

Constraints on atmospheric charm depend on astrophysical model assumptions.

We need independent constraints from penetrating muons!

….. or perhaps the reverse ?

The astrophysical flux measurement depends on the charm production cross section

Constraints on atmospheric charm depend on astrophysical model assumptions.

We need independent constraints from penetrating muons!

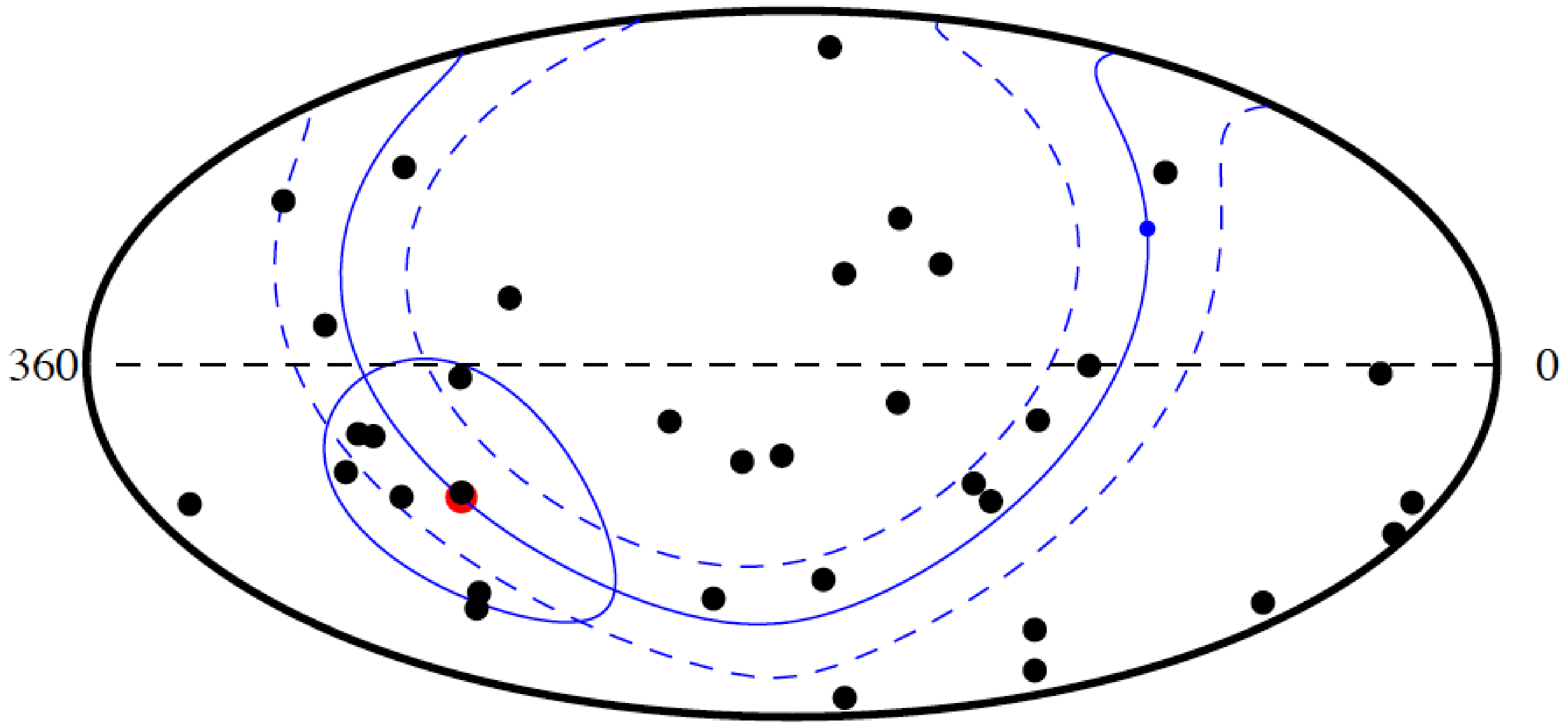
….. or perhaps the reverse ?

The astrophysical flux measurement
depends on the charm production cross section

Lot of attention to the charm production cross section
at this meeting.

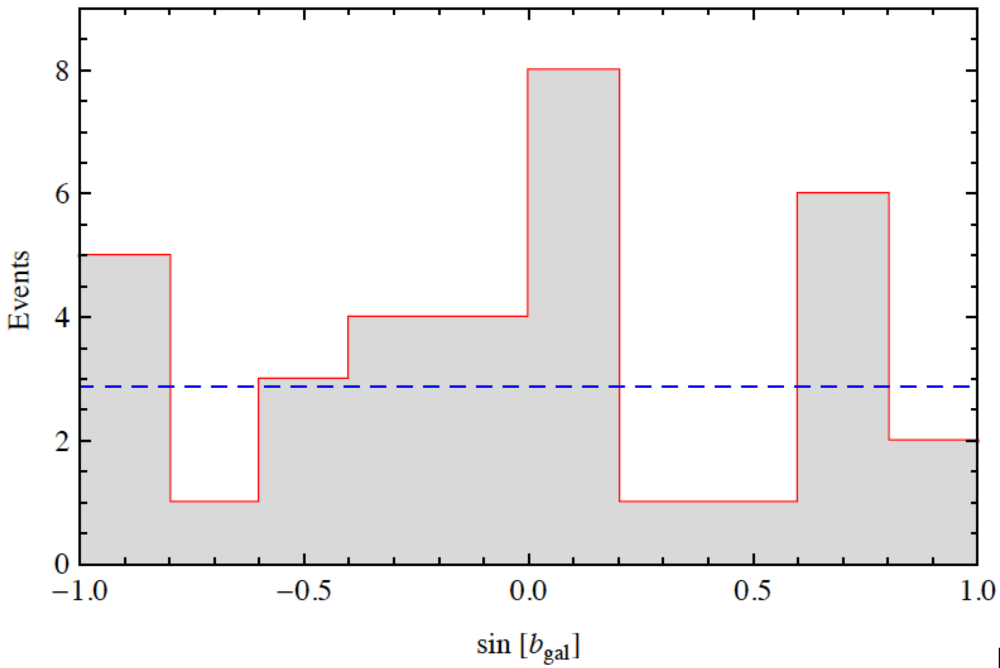
EXTRA-GALACTIC or include

GALACTIC contribution ?



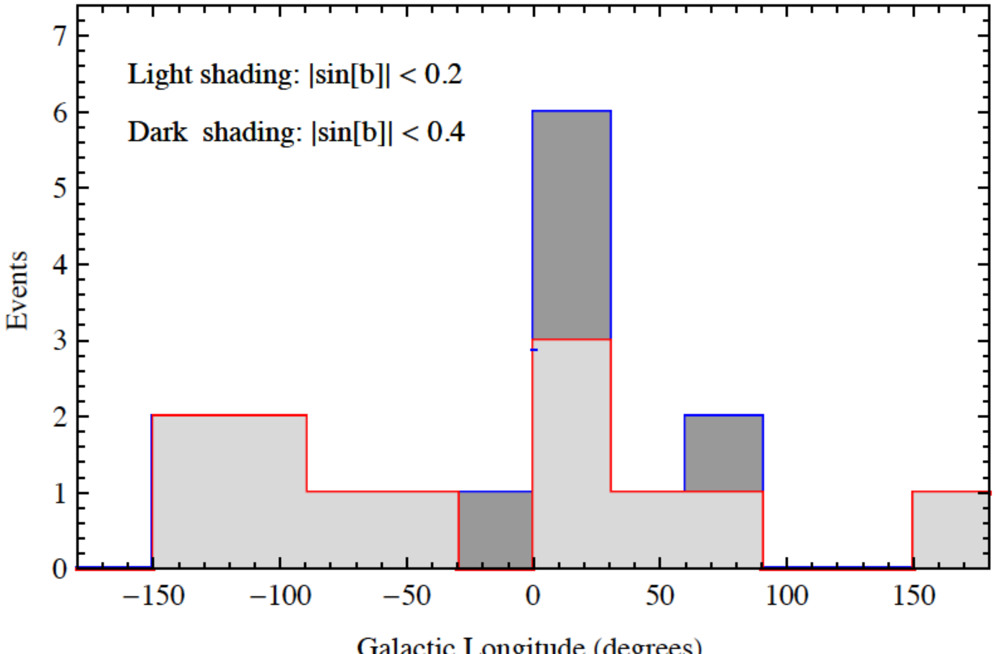
Distribution in Galactic Latitude

(concentration on the galactic plane?)

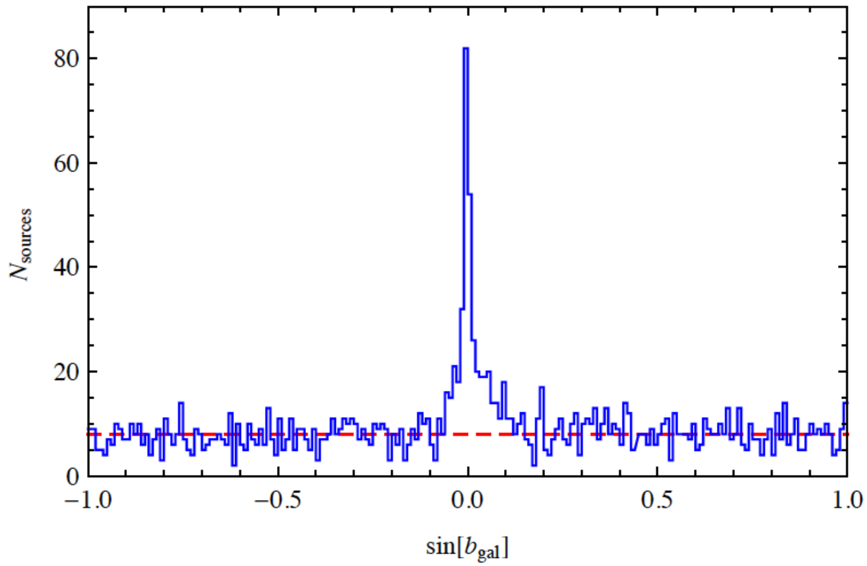


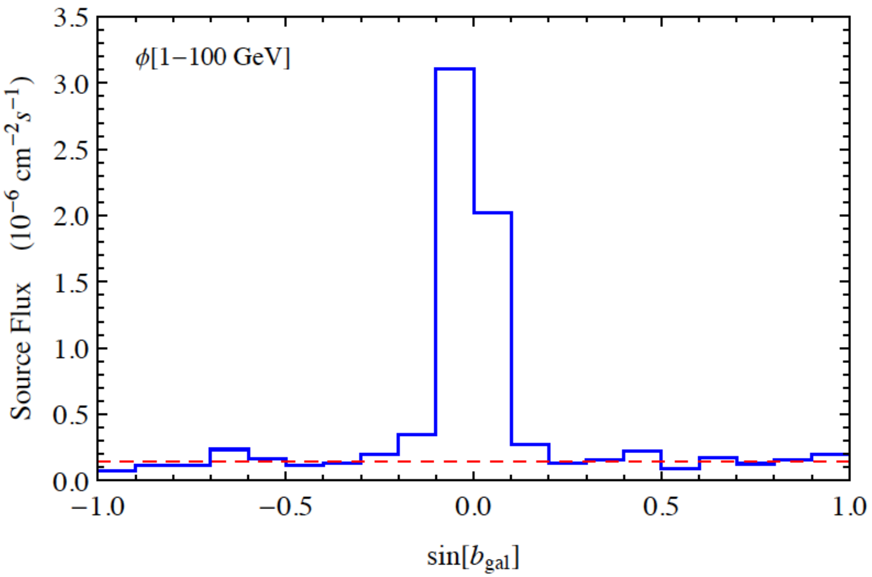
Distribution in Longitude

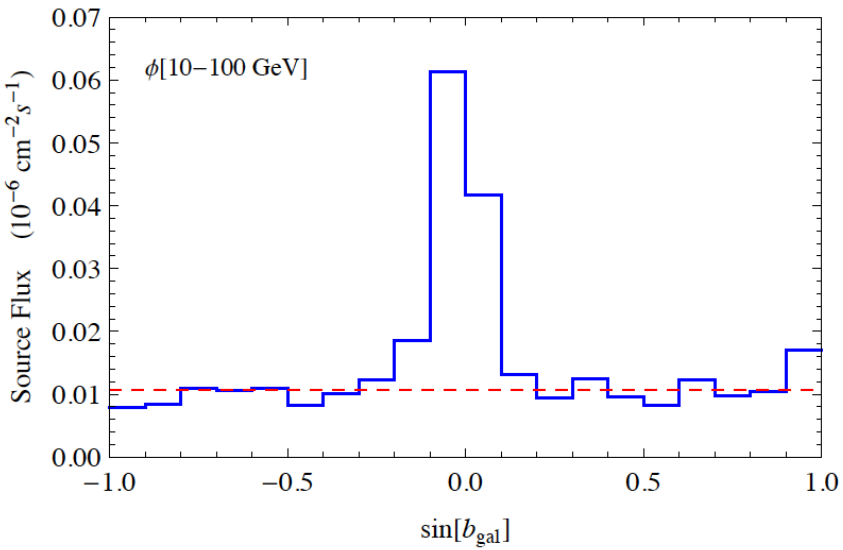
(concentration near galactic center ??)



Gamma Ray Sources





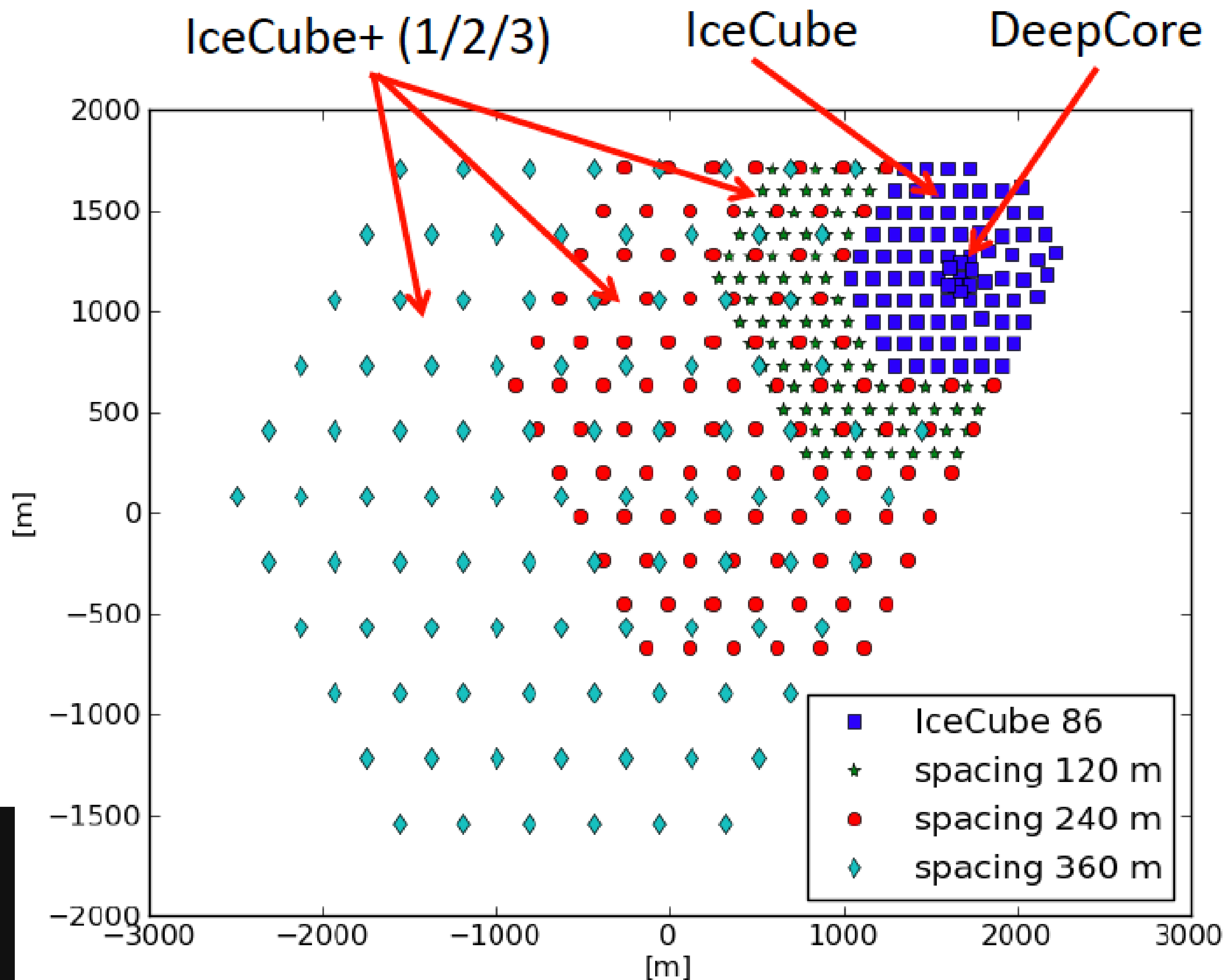


“Wild Speculation, dangerously playing with
Small numbers.....

	[2 years data]	[3rd year]
Down-going	24	4
Up-going	4	5

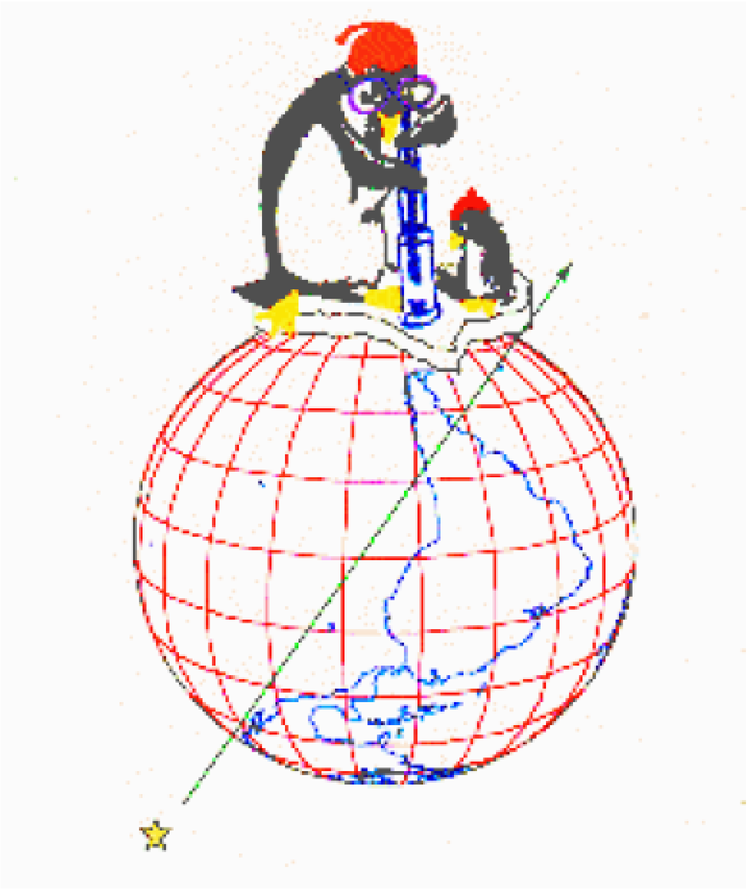
Time dependence ?!
(at 3 sigma level)

Possible extensions of IceCube

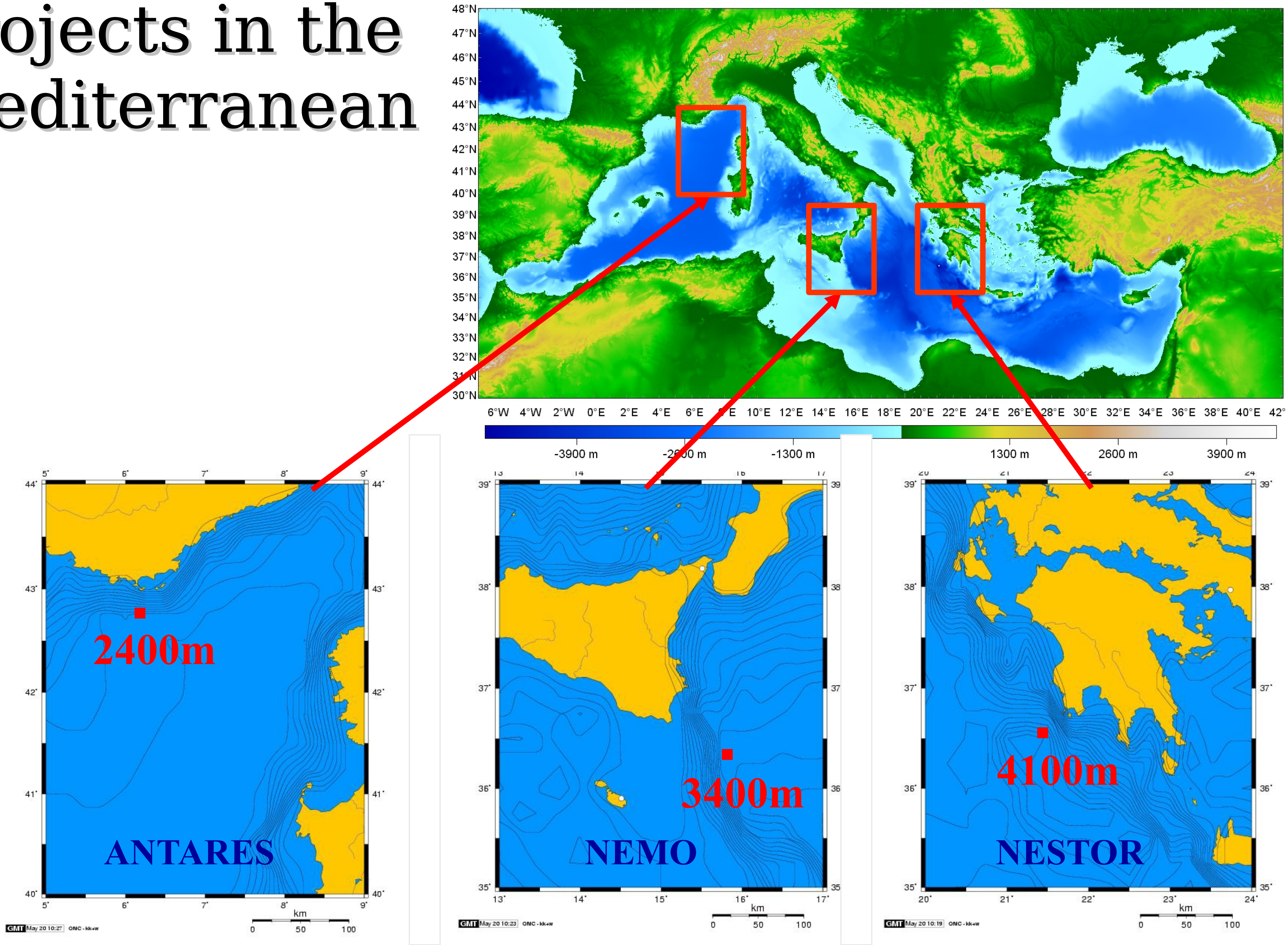


- IceCube: 1 km^2
- +HEX 120m: 2.3 km^2
- +HEX 240m: 6.3 km^2
- +HEX 360m: 12.6 km^2

old IceCube logo
(from the Economist)
.... may be obsolete ?

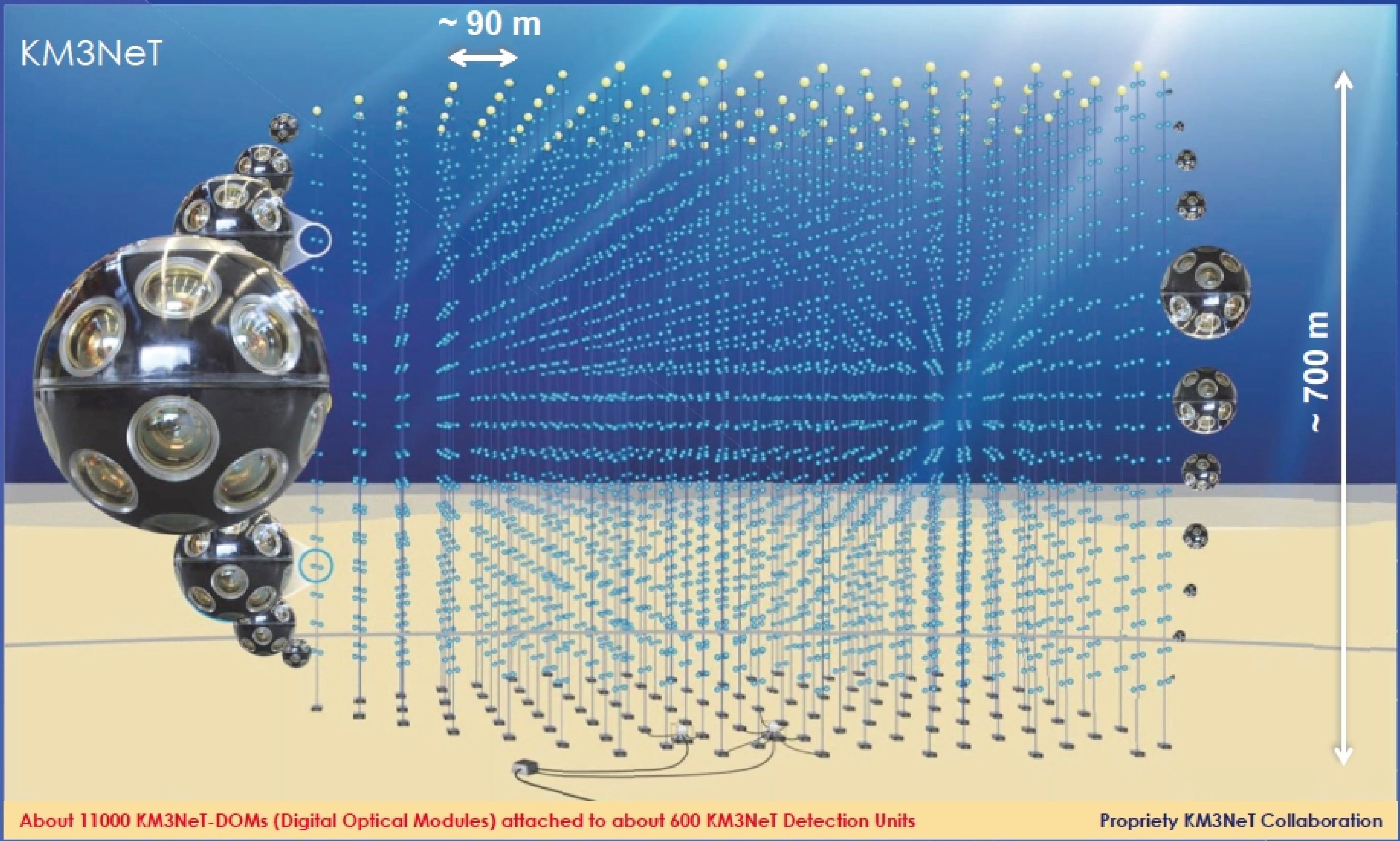


Projects in the Mediterranean



The KM3NeT Detector

TDR : ISBN 978-90-6488-033-9 (2010)

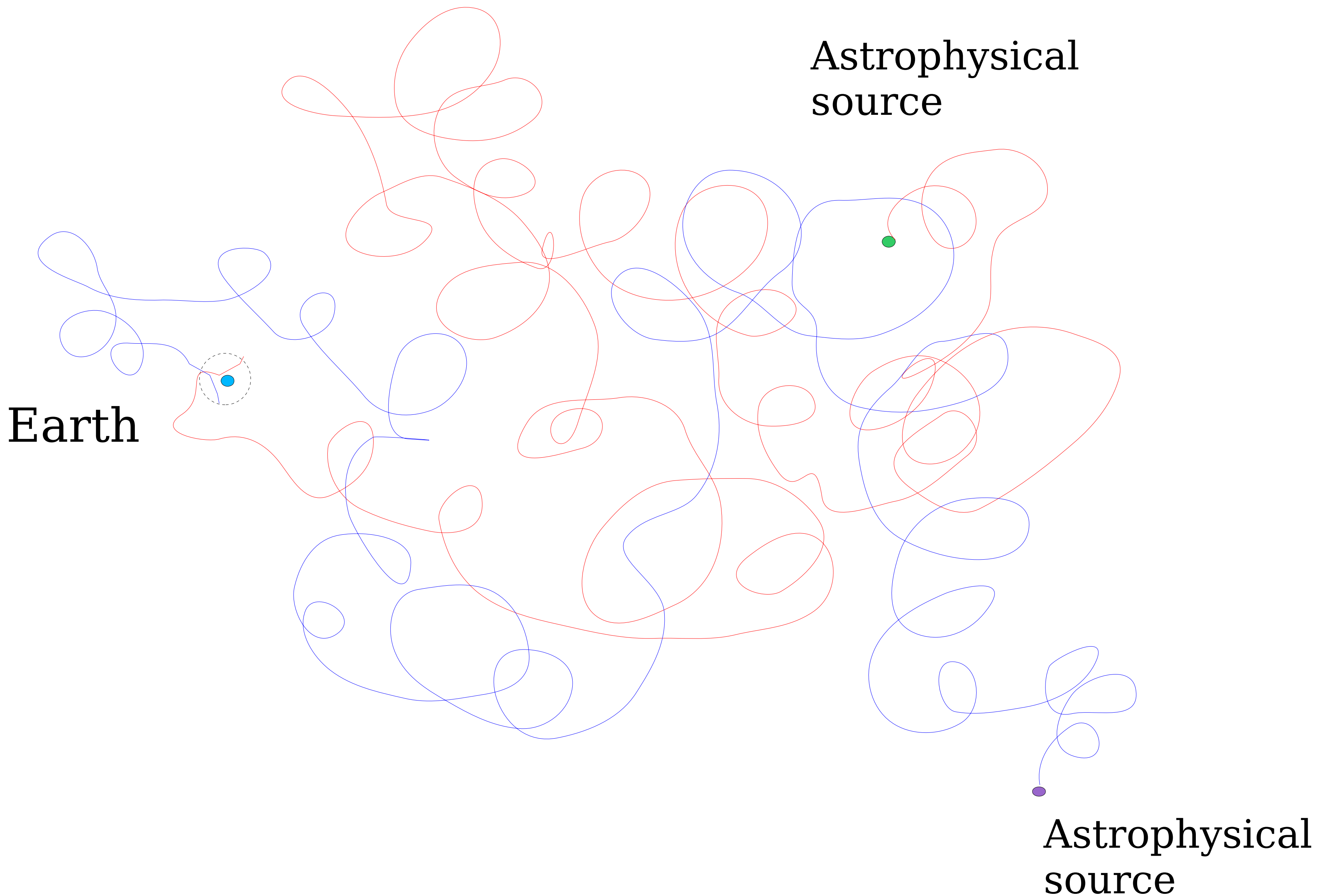


18 optical modules per detection unit
First optical module above seabed ~ 100m

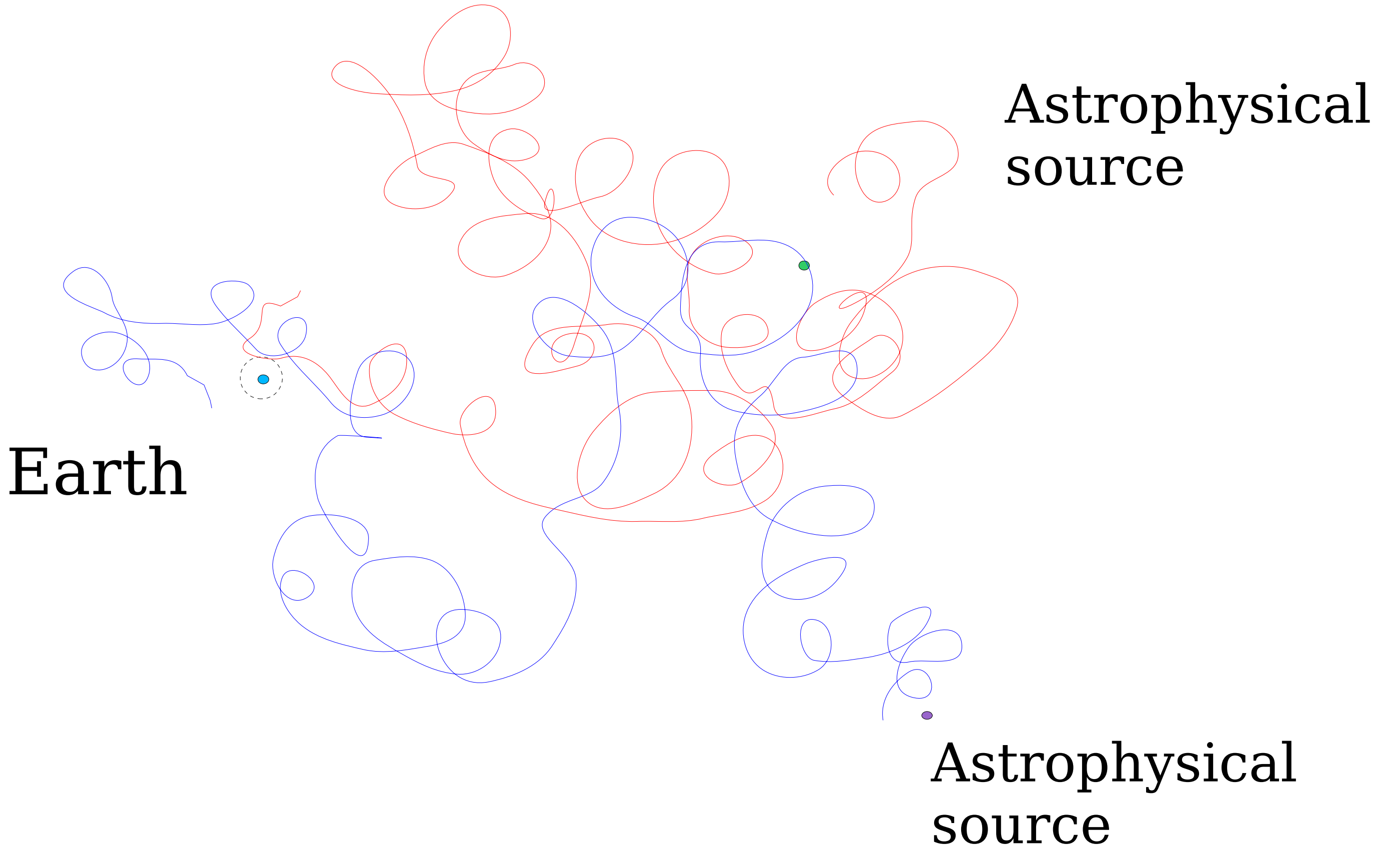
Distance between optical modules ~ 36 m

The Energy Spectrum of Cosmic Rays

The main problem with cosmic rays……



Measure the energy spectrum of an ensemble of sources, averaged in time, and modified by propagation effects

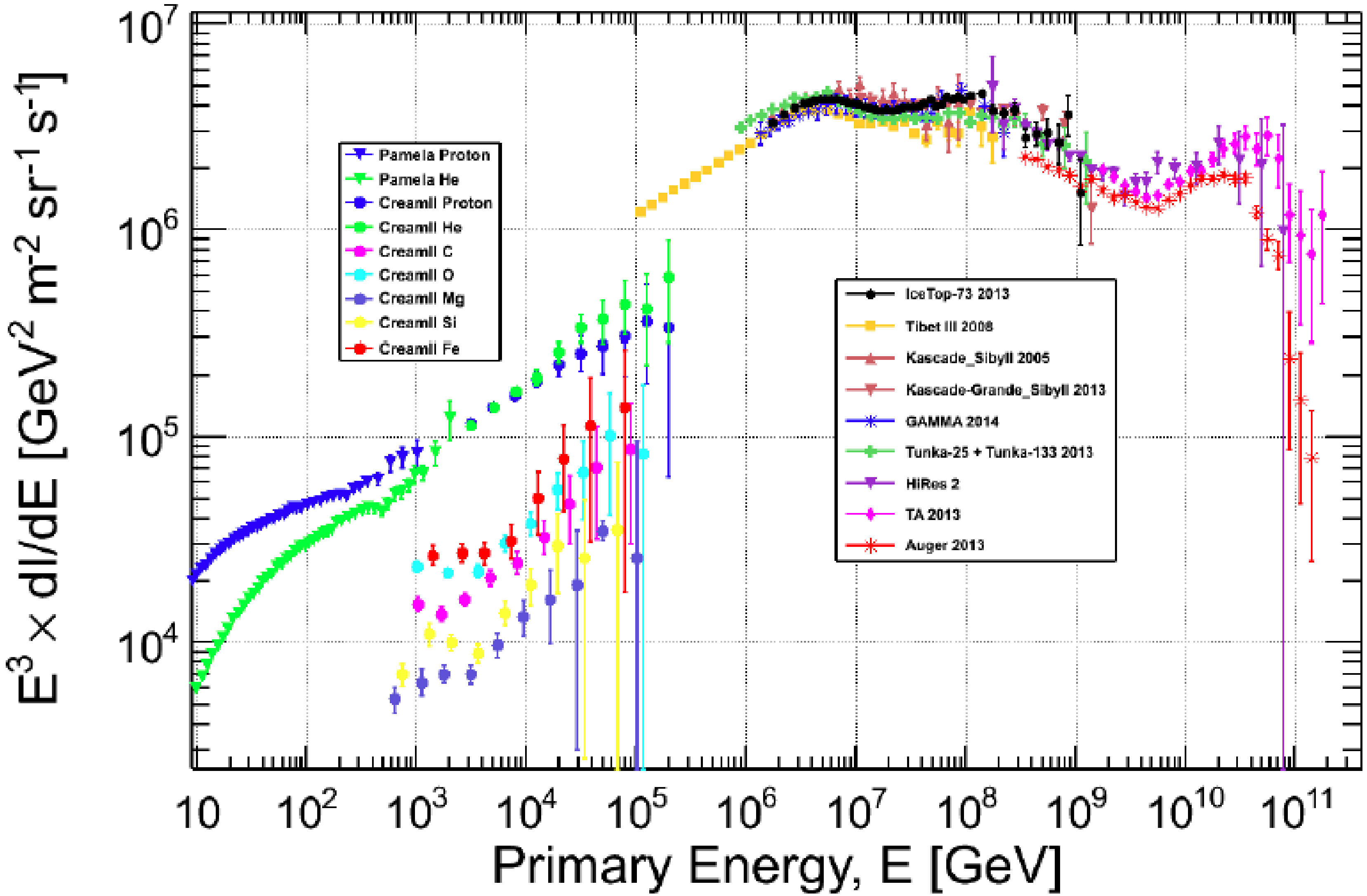


Serap Tilav

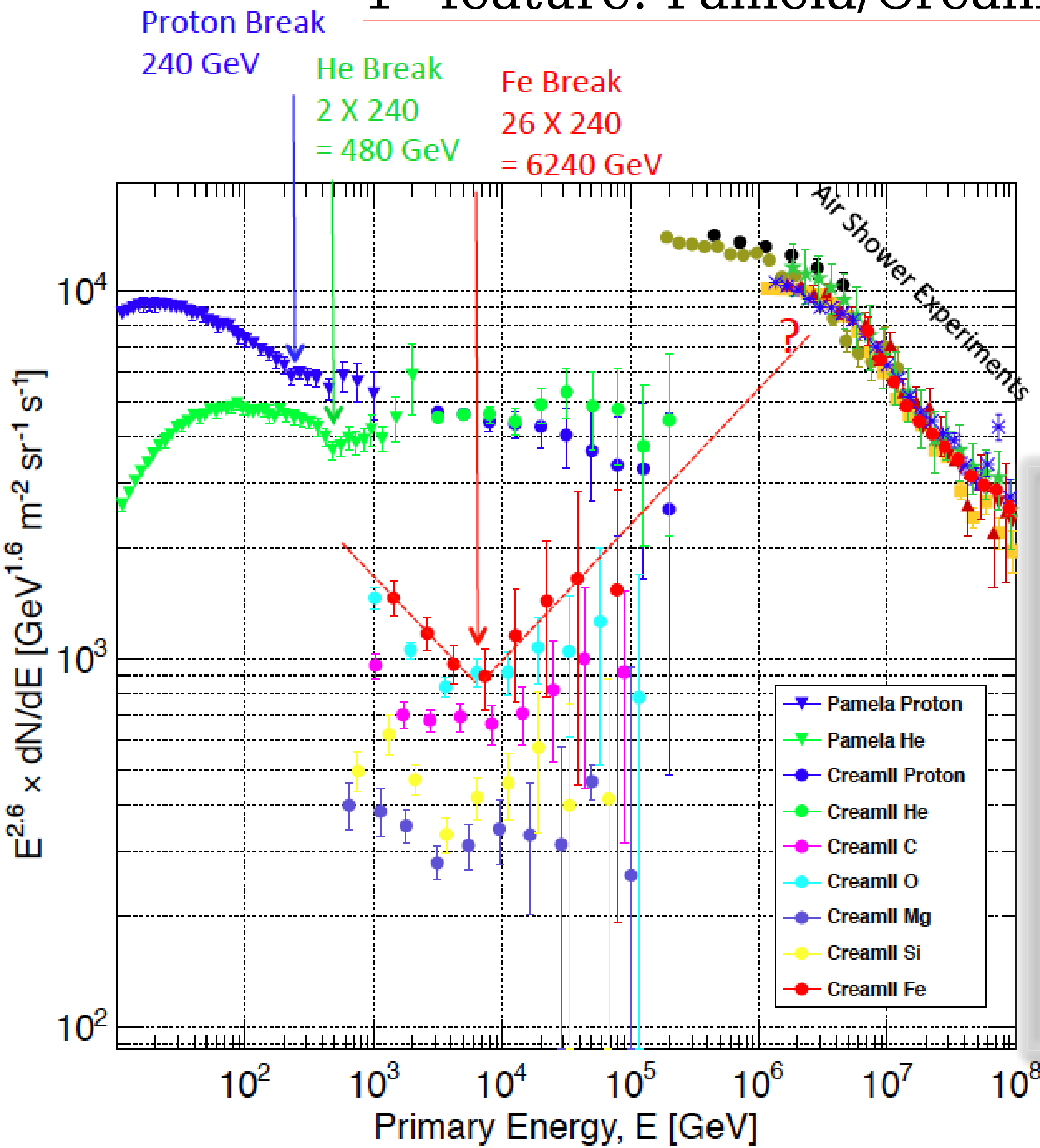
When looked in detail the CR spectrum is not a boring simple power law

Direct Measurements
Satellite, Balloon

Indirect Measurements
Air Shower Experiments



1st feature: Pamela/Cream hardening at 240 GV



PAMELA / ATIC / CREAM reveal rigidity dependent spectral breaks and remarkable hardening after the breaks

Perfect demonstration of Peters cycle:

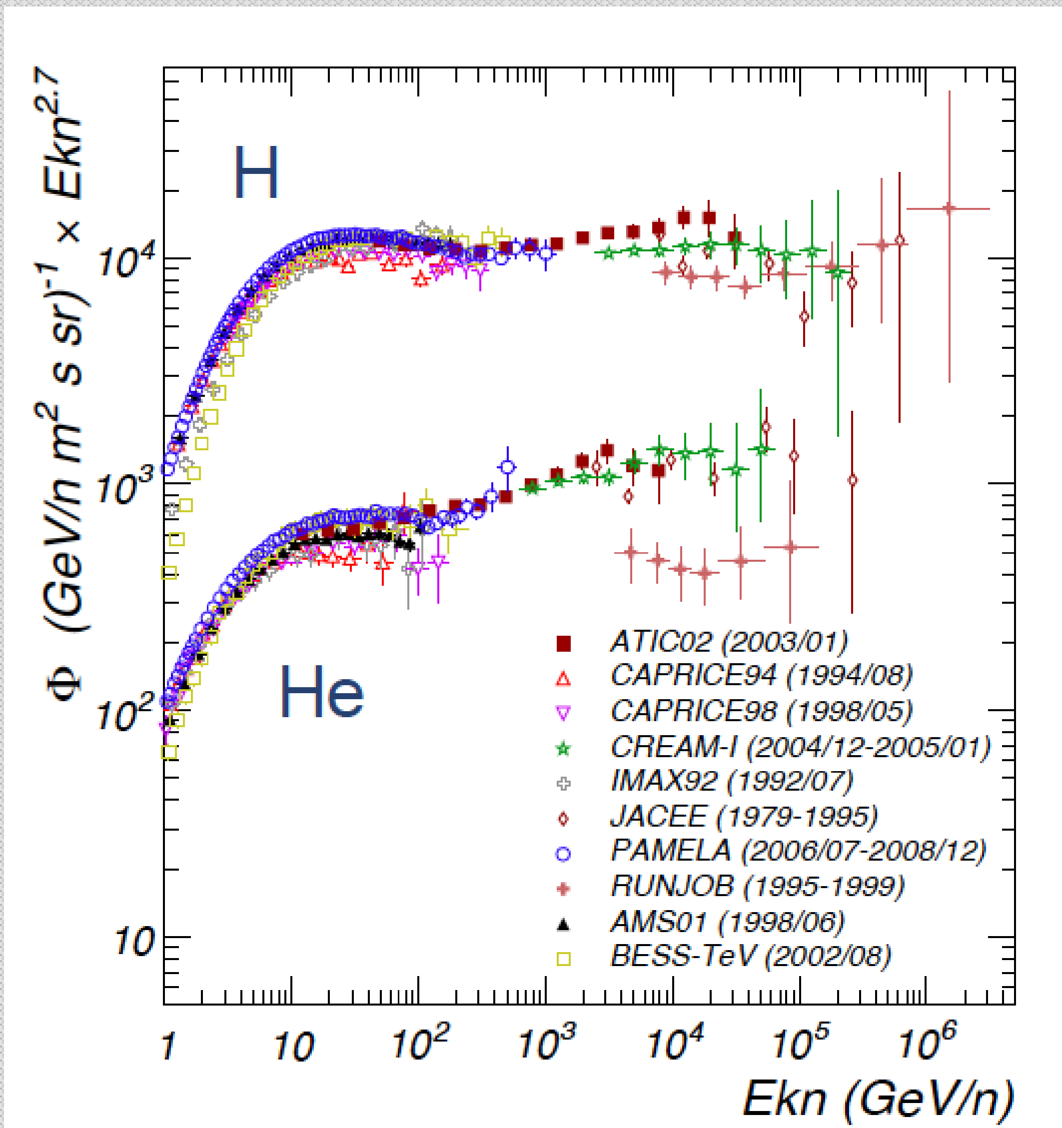
When protons accelerated to E^p_{max} a nucleus with Ze will be accelerated up to
$E^z_{max} = Ze \times R = Z \times E^p_{max}$

where magnetic rigidity
$R = Pc/Ze$

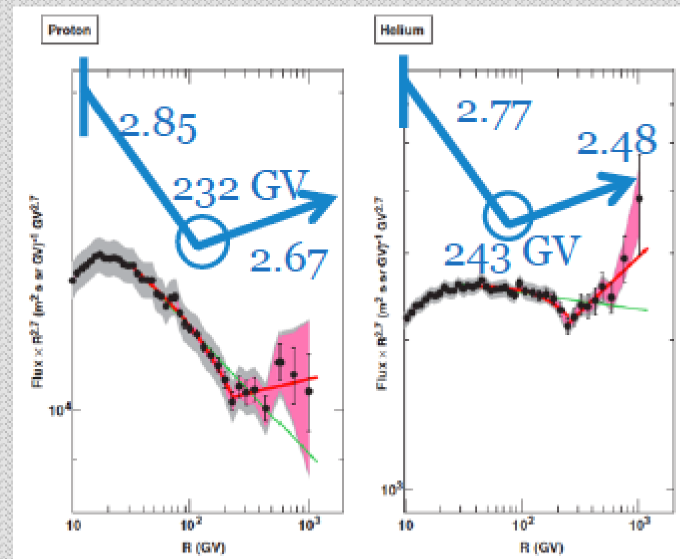
Bernard Peters 1961

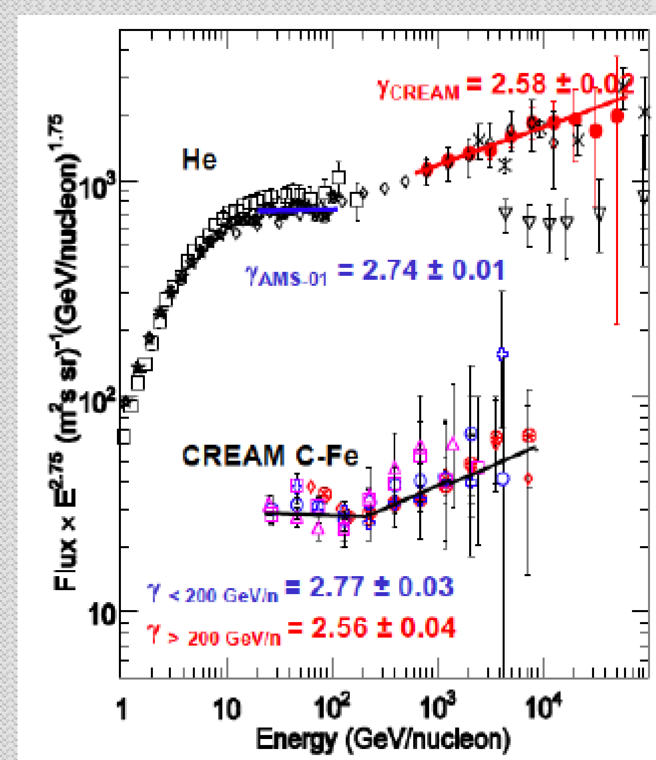
Bruna Bertucci

p/He spectra



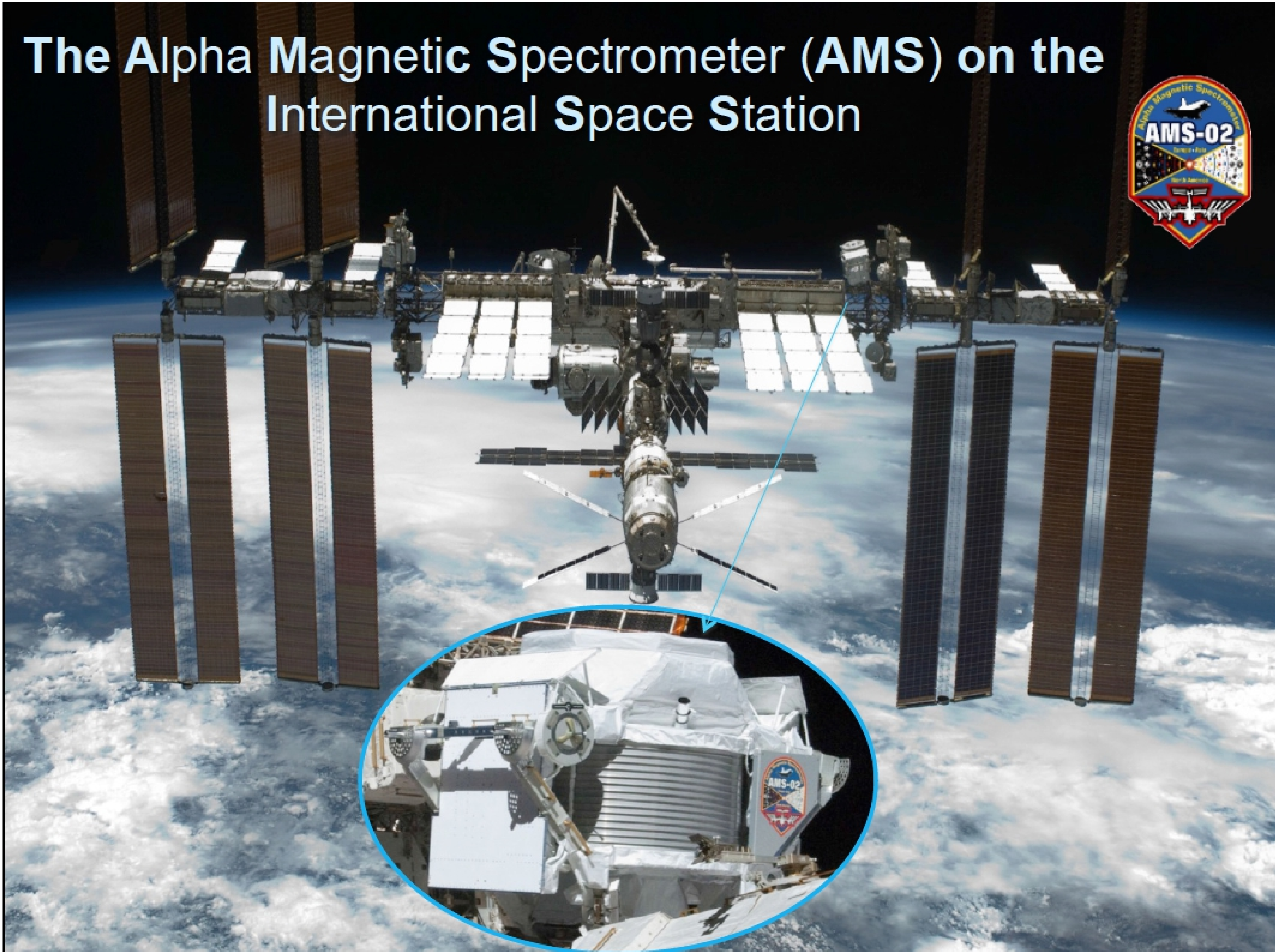
Adriani, Science 32,69 (2011)

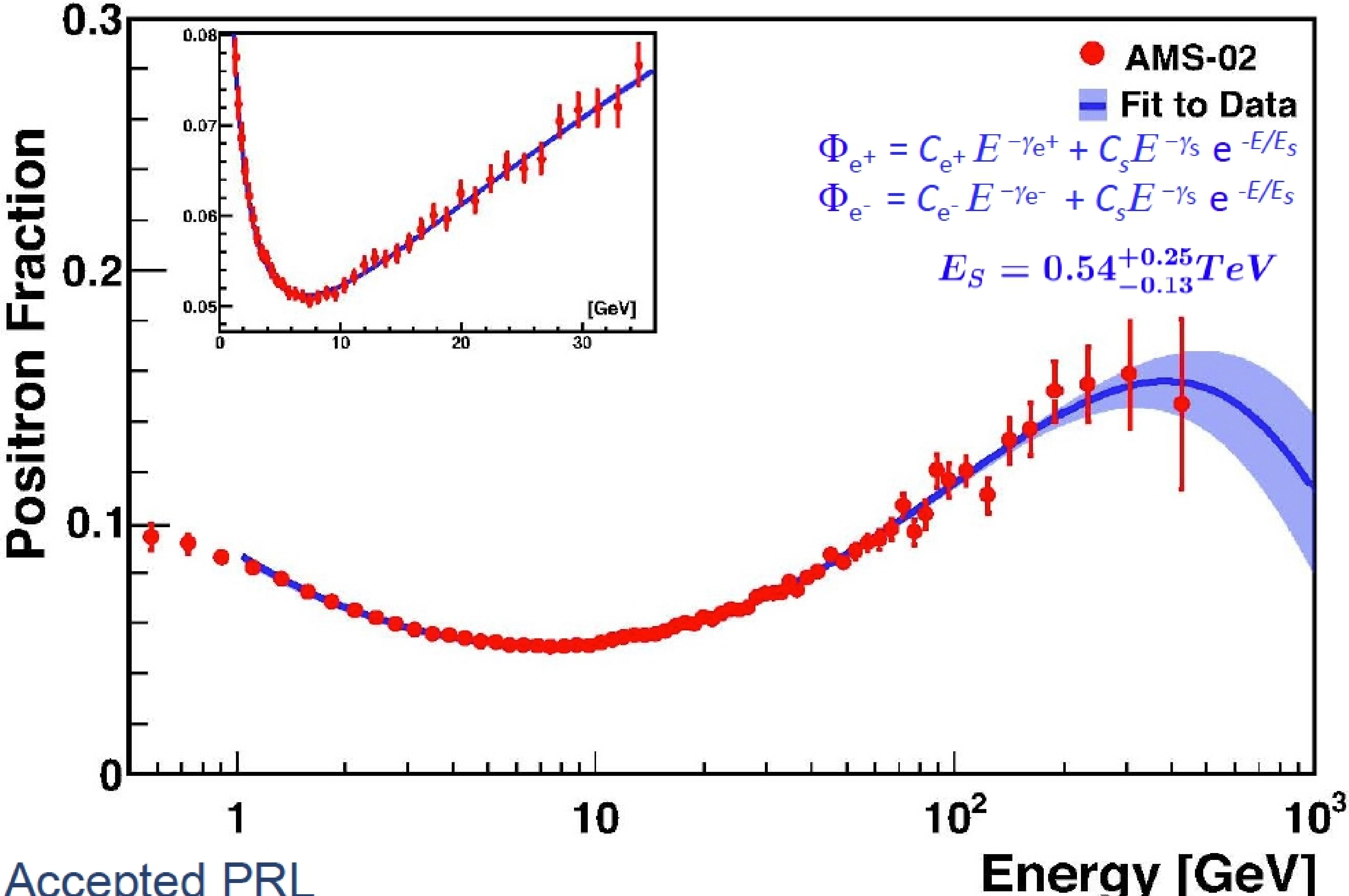




Still waiting for full CREAM statistics

AMS-02 publication soon….(< 2015)

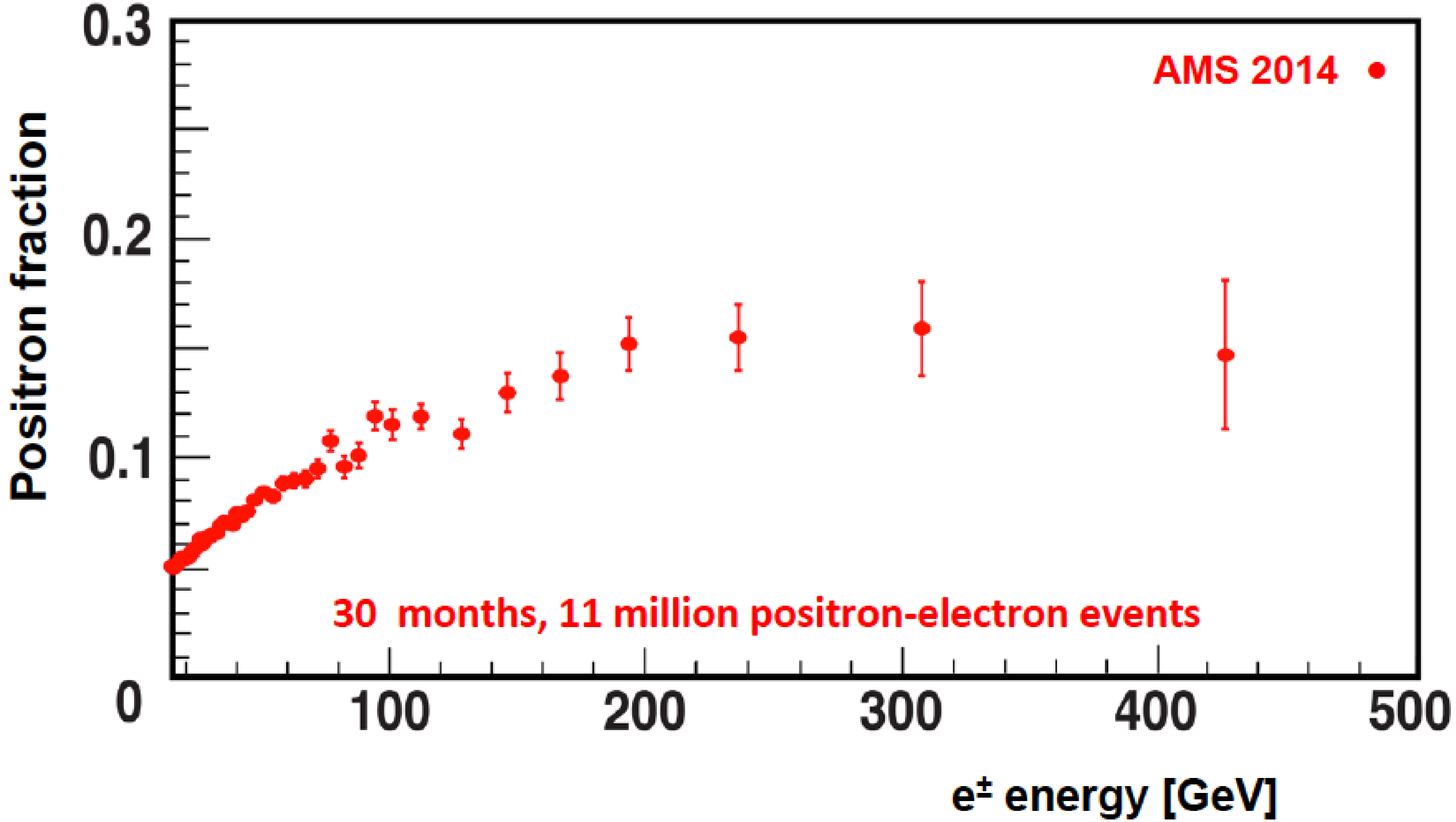

The Alpha Magnetic Spectrometer (AMS) on the International Space Station
Alpha Magnetic Spectrometer
AMS-02
AMS-02



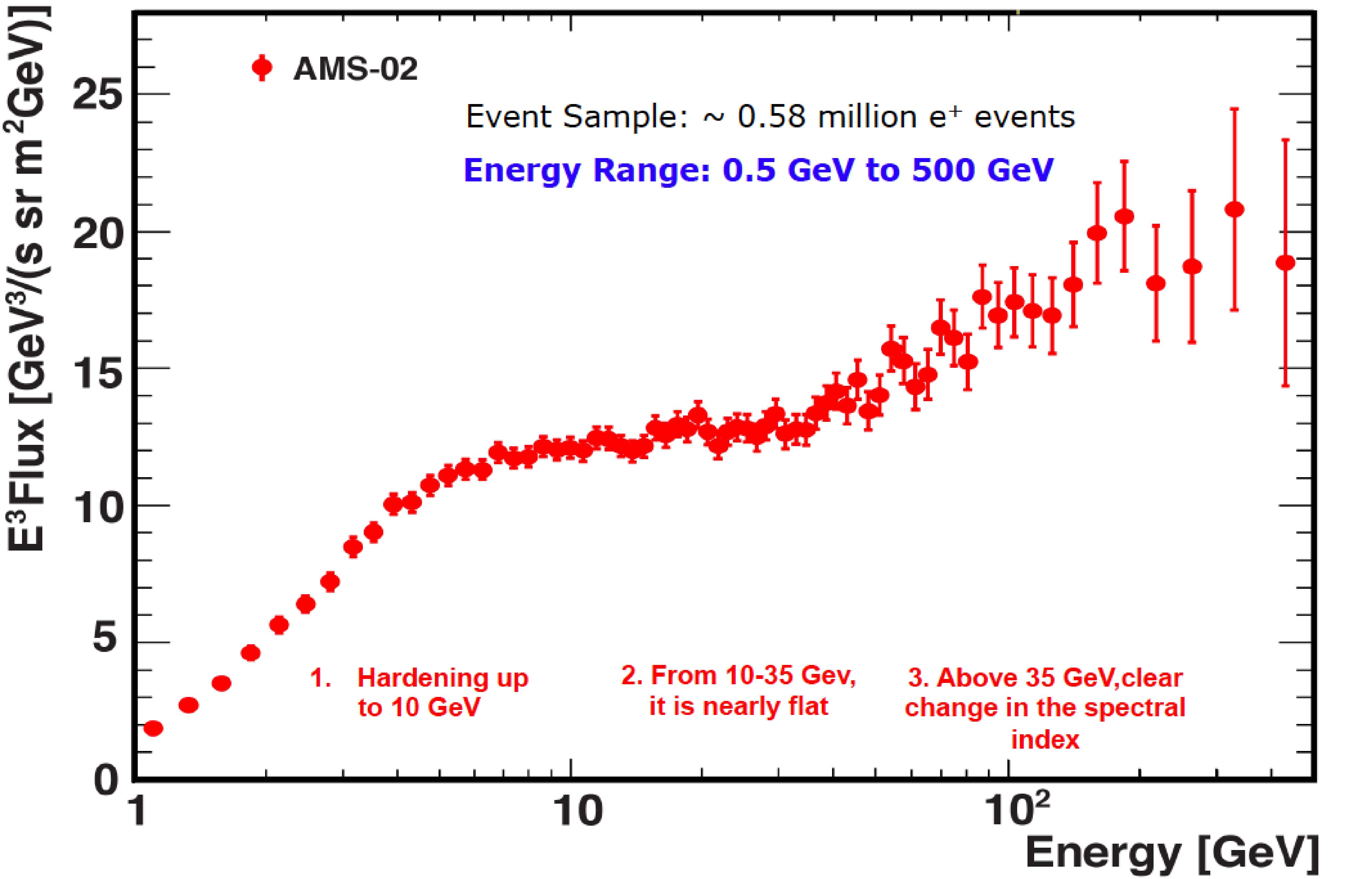
Accepted PRL

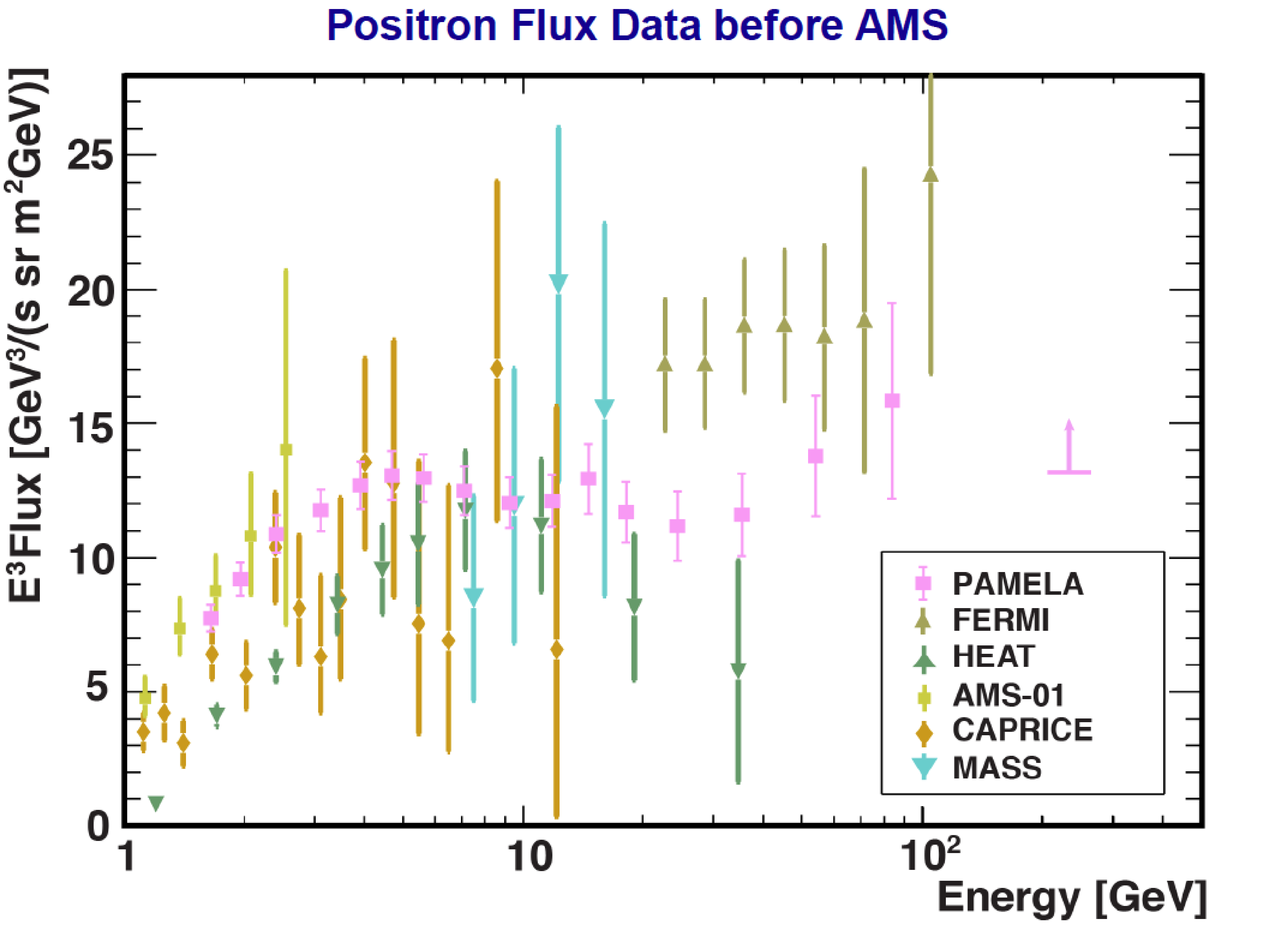
FIG. 4. The positron fraction measured by AMS and the fit of a minimal model (solid curve, see text) and the 68% C.L. range of the fit parameters (shaded). For this fit both the data and the model are integrated over the bin width. The error bars are the quadratic sum of the statistical and systematic uncertainties. Horizontally, the points are placed at the center of each bin. The insert shows the detail of the positron fraction behavior at low energies.

2014: New Results on Positron Fraction

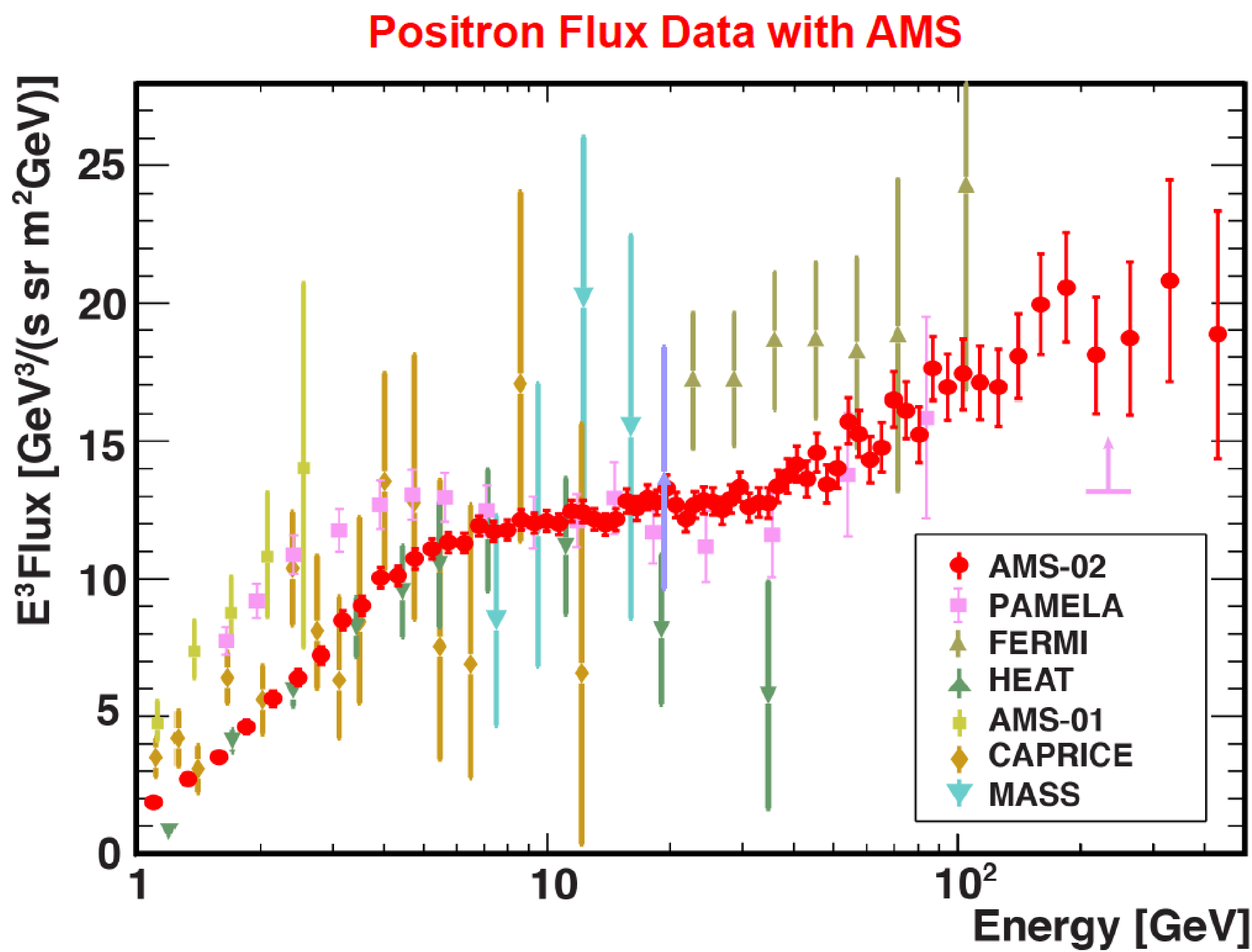


New AMS Results: Measurement of Positron Flux.
The Positron Flux exhibits 3 unexpected behaviours

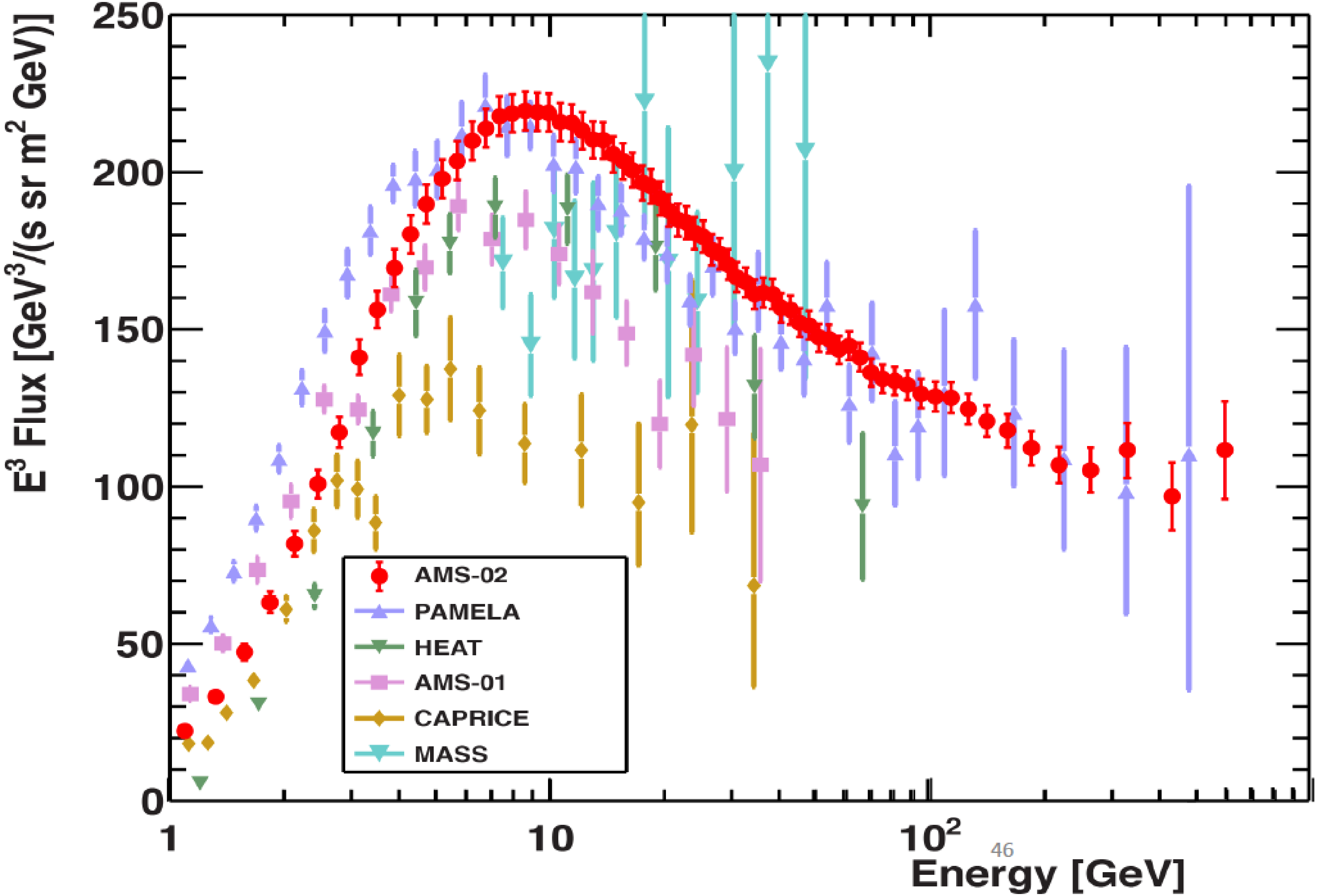




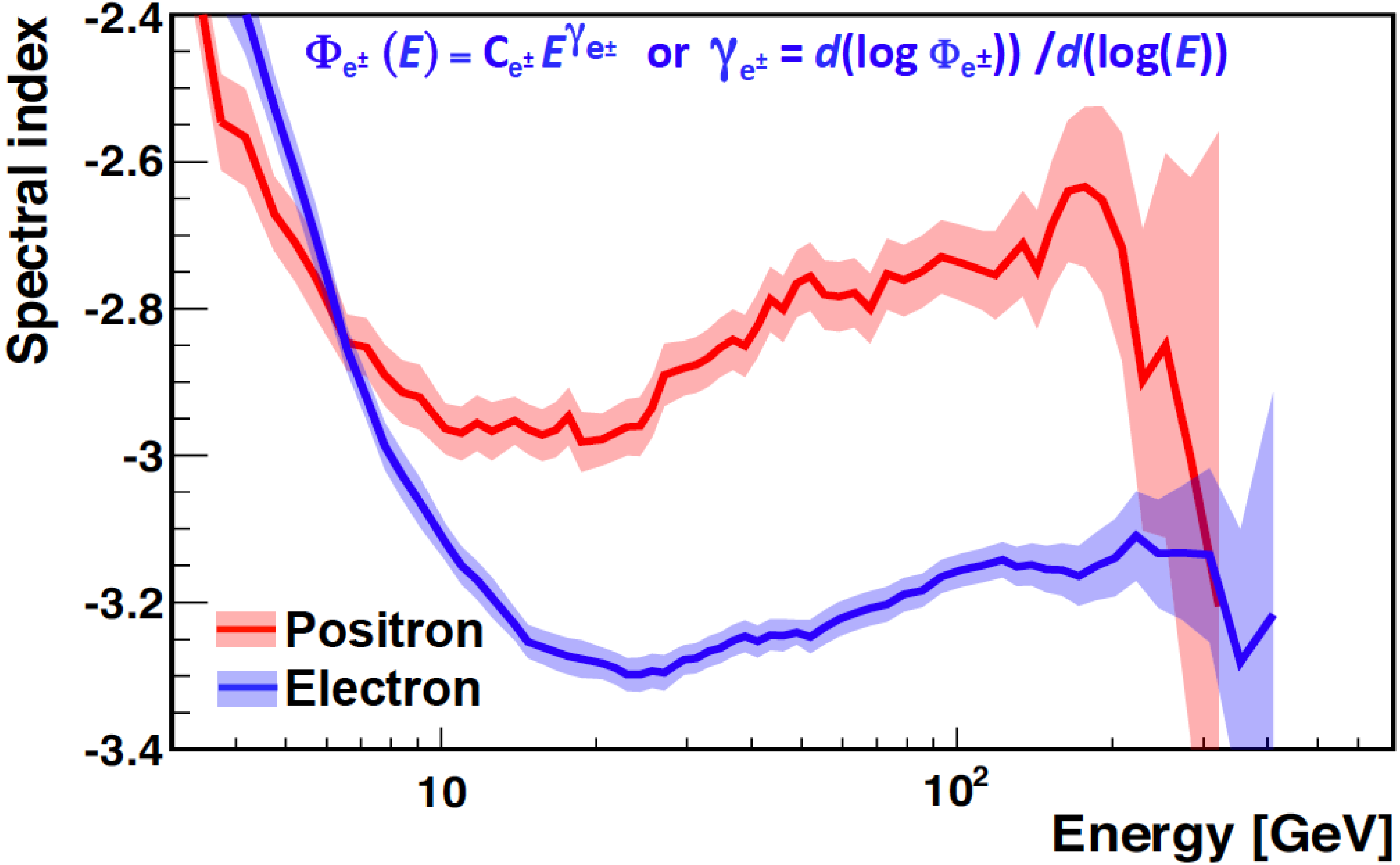
Positron Flux Data before AMS
E³Flux [GeV³/(s sr m²GeV)]
0
5
10
15
20
25
1
10
10²
Energy [GeV]
PAMELA
FERMI
HEAT
AMS-01
CAPRICE
MASS


Positron Flux Data with AMS
E³Flux [GeV³/(s sr m²GeV)]
0
5
10
15
20
25
1
10
10²
Energy [GeV]
AMS-02
PAMELA
FERMI
HEAT
AMS-01
CAPRICE
MASS

Electron flux measurement with AMS



Positron and Electron fluxes with Running spectral Indexes



The “Pamela Positron Anomaly”:
[The fact that positrons have a harder spectrum than electrons]

has been the most discussed
topic in cosmic ray physics in the last few years.

Dark Matter interpretation
[but what about anti-protons ?]

The “anomaly can be explained with:

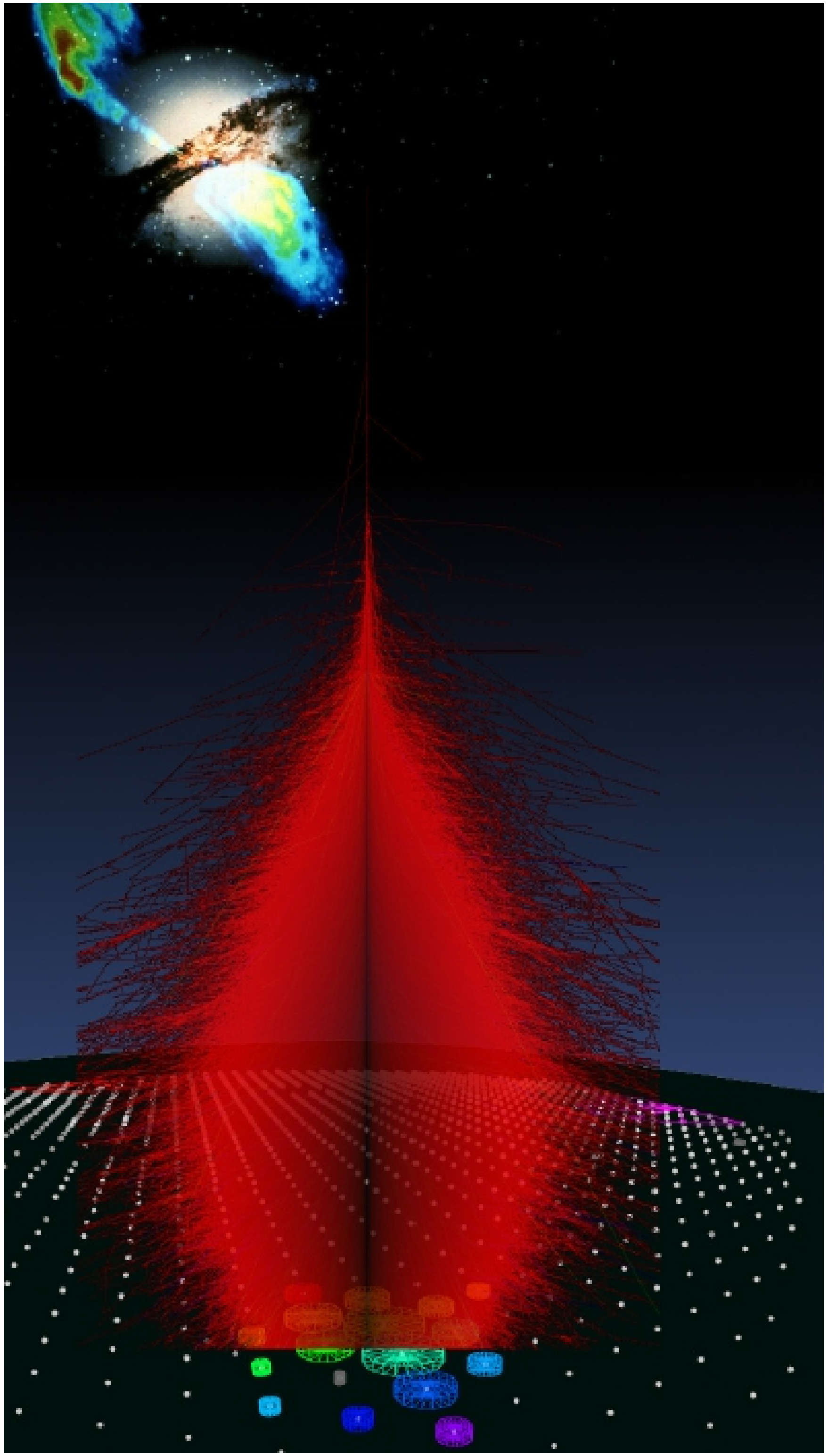
an additional, unexpected, hard source of positrons (or more likely positrons and electrons).
Most popular hypothesis acceleration in Pulsars

Also explanations in terms of propagation
(e.g. Eli Waxman) have been offered

Air Shower Observation of Cosmic Rays

The fundamental motivation
for this series of workshops

image by Ralf Ulrich

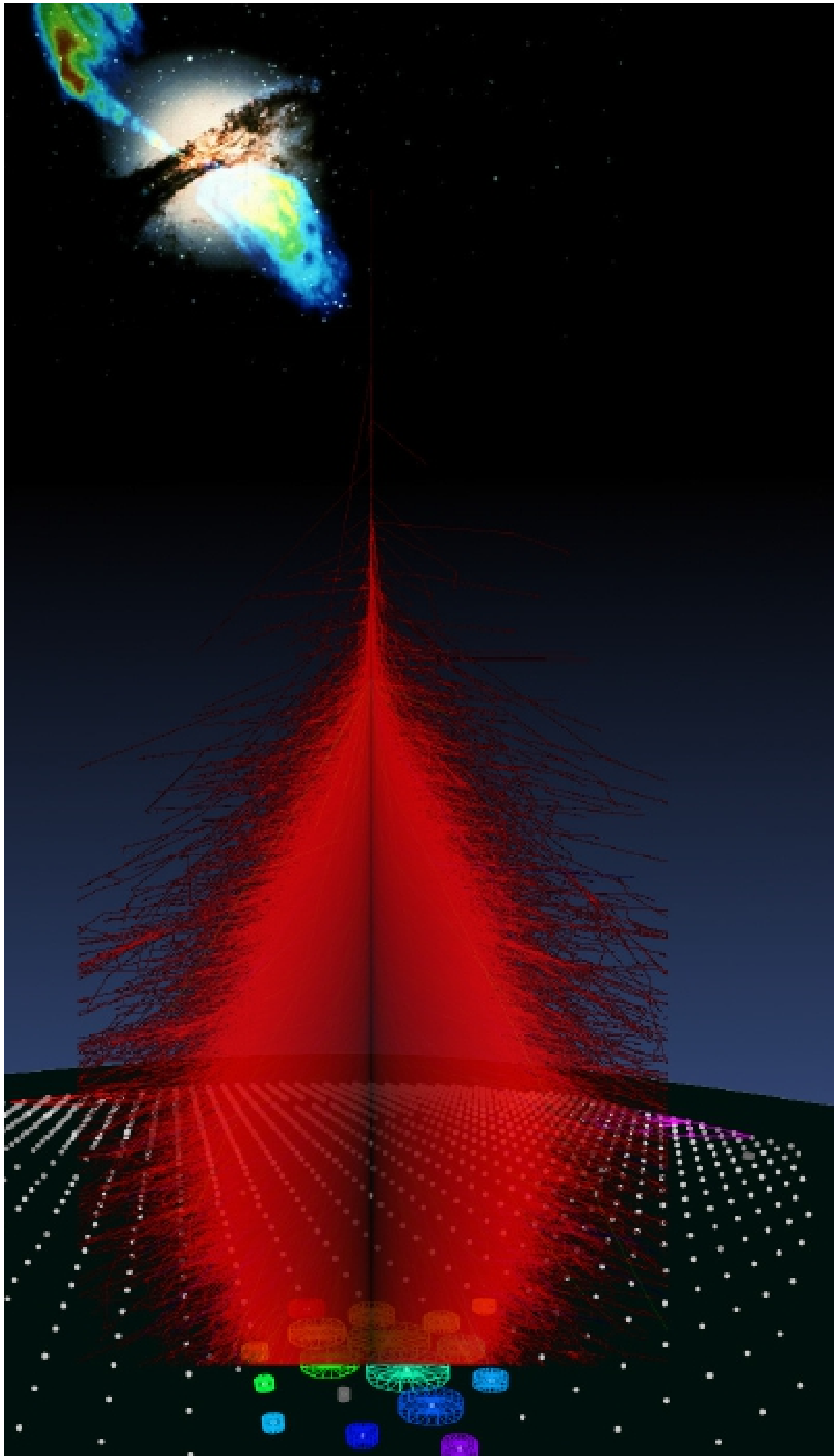


the Source

the Shower

the Data

image by Ralf Ulrich



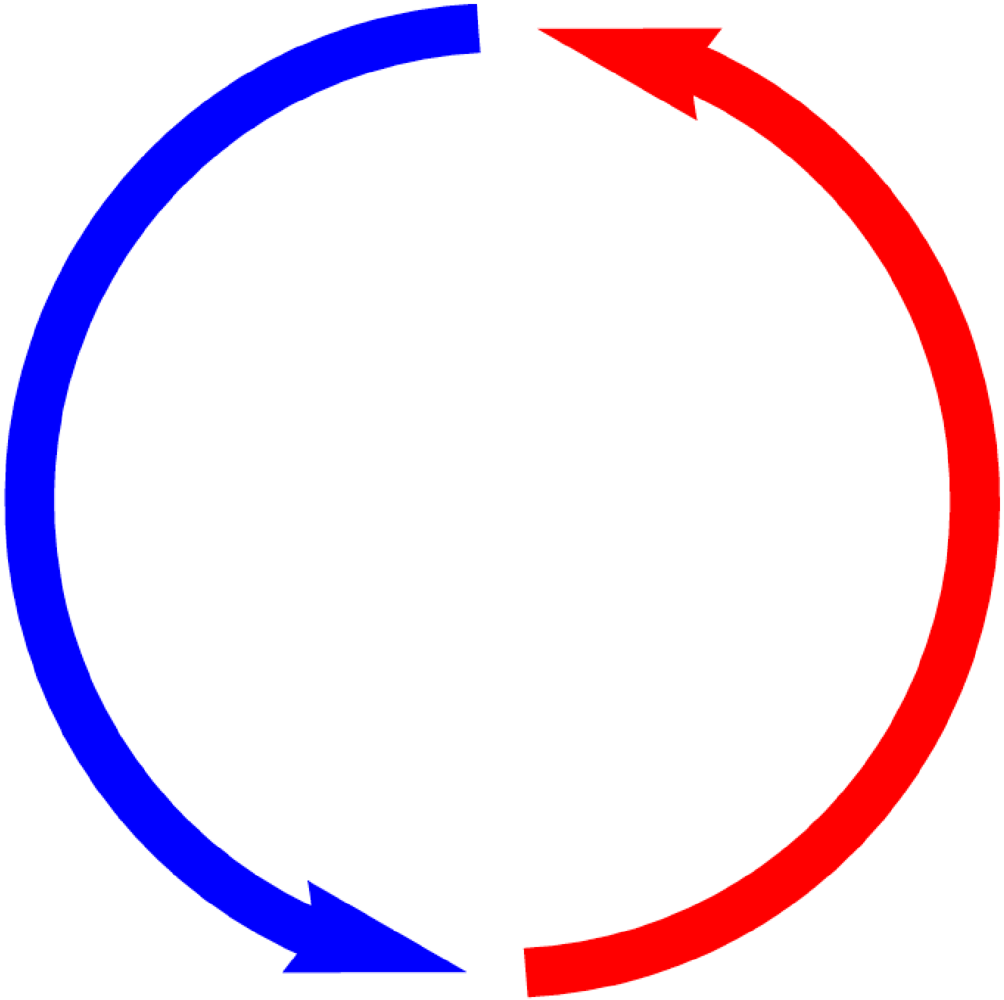
the Source

the Shower

[The estimate of the Energy and Mass of the shower requires the detailed modeling of shower development]

the Data

PARTICLE PHYSICS



COSMIC RAYS ASTROPHYSICS

Theory (QCD) +
[Accelerator Data]

UHE Cosmic Ray
Data

"Direct Route" Program:

1. Obtain data at accelerators (LHC ! + others)

2. Develop a sound theoretical framework to extrapolate to high energy.

3. Interpret the CR data

Theory (QCD) +
[Accelerator Data]

UHE Cosmic Ray
Data

"Direct Route" Program:

1. Obtain data at accelerators (LHC ! + others)
2. Develop a sound theoretical framework to extrapolate to high energy.
3. Interpret the CR data

Questions:

1. What new measurements are most important/possible ?
2. What are the best theoretical instruments to guide the extrapolation?
3. Where are we?
4. What can we achieve ?

Is it possible to obtain information about Particle Physics from the UHECR data ?

Particle Physics
[hadronic interactions, "exotica" ?]

UHE Cosmic Ray Data

Is it possible to obtain information about Particle Physics from the UHECR data ?

Particle Physics
[hadronic interactions, “exotica” ?]

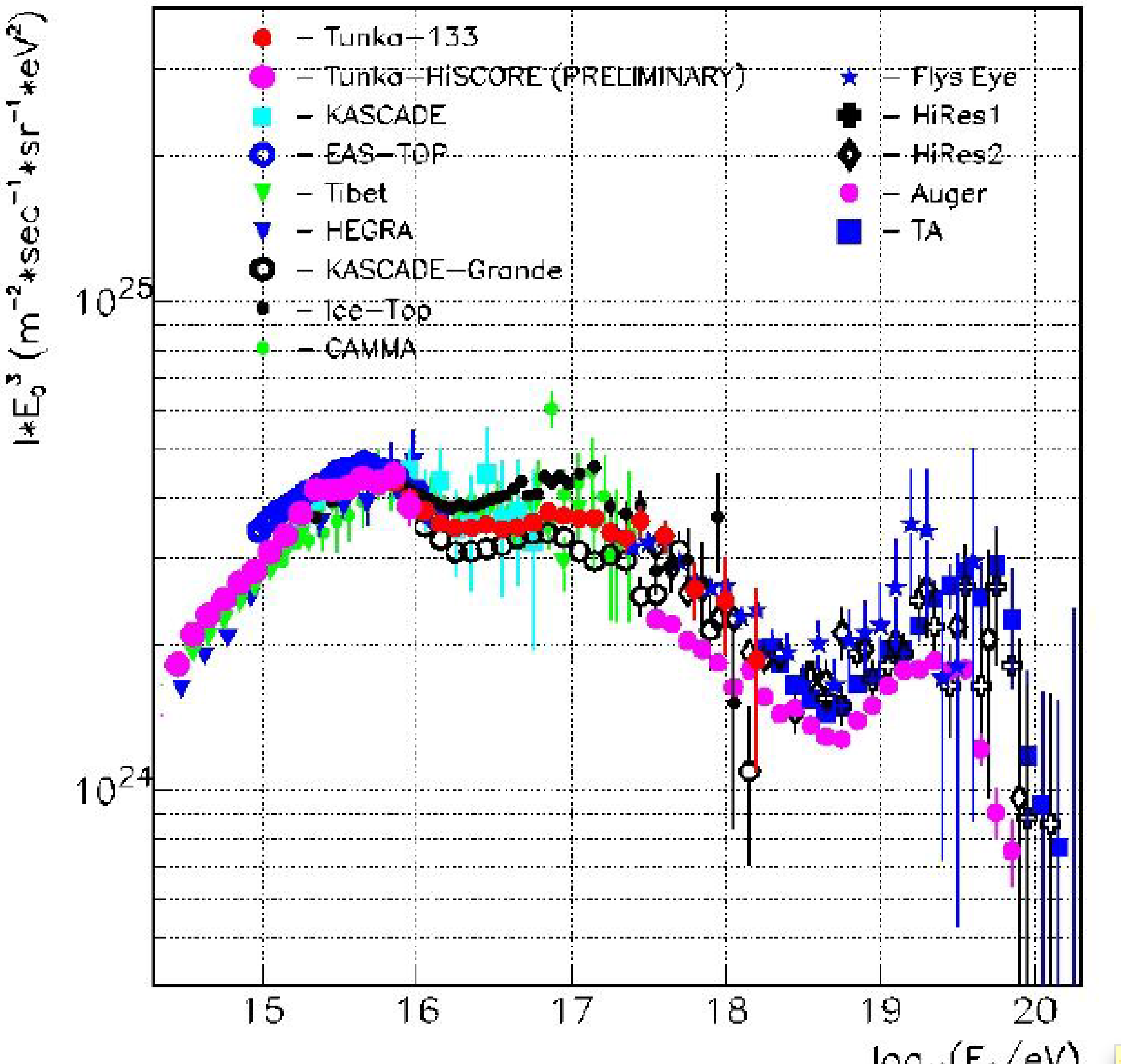
Isn't (the lack of information about) composition an “impossible obstacle” ?

1. Astrophysical composition measurements:
   * Magnetic deviations
   * Energy losses imprints on the energy spectrum

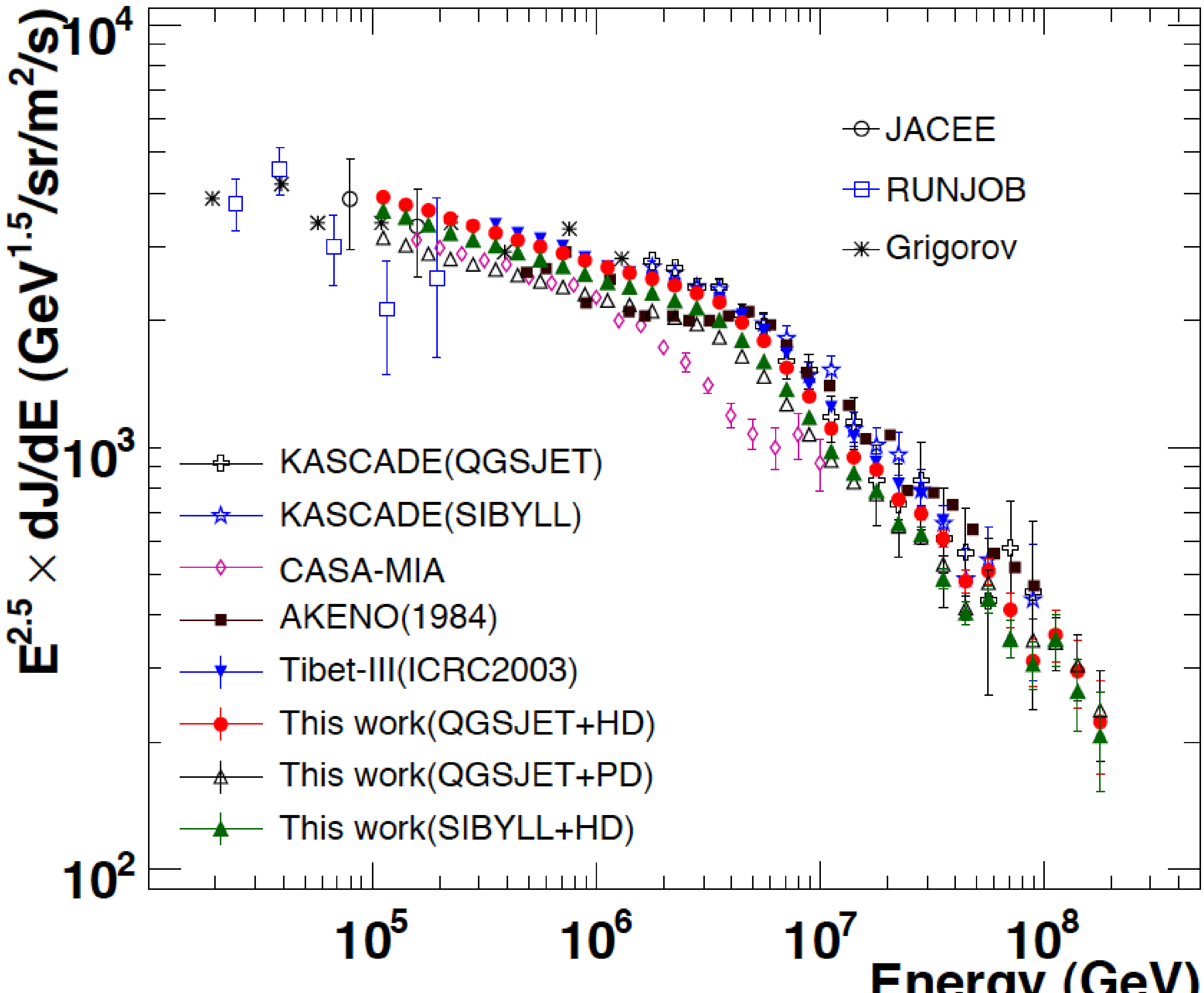
2. “Self-consistency” or “Bootstrap” ?

UHE Cosmic Ray Data

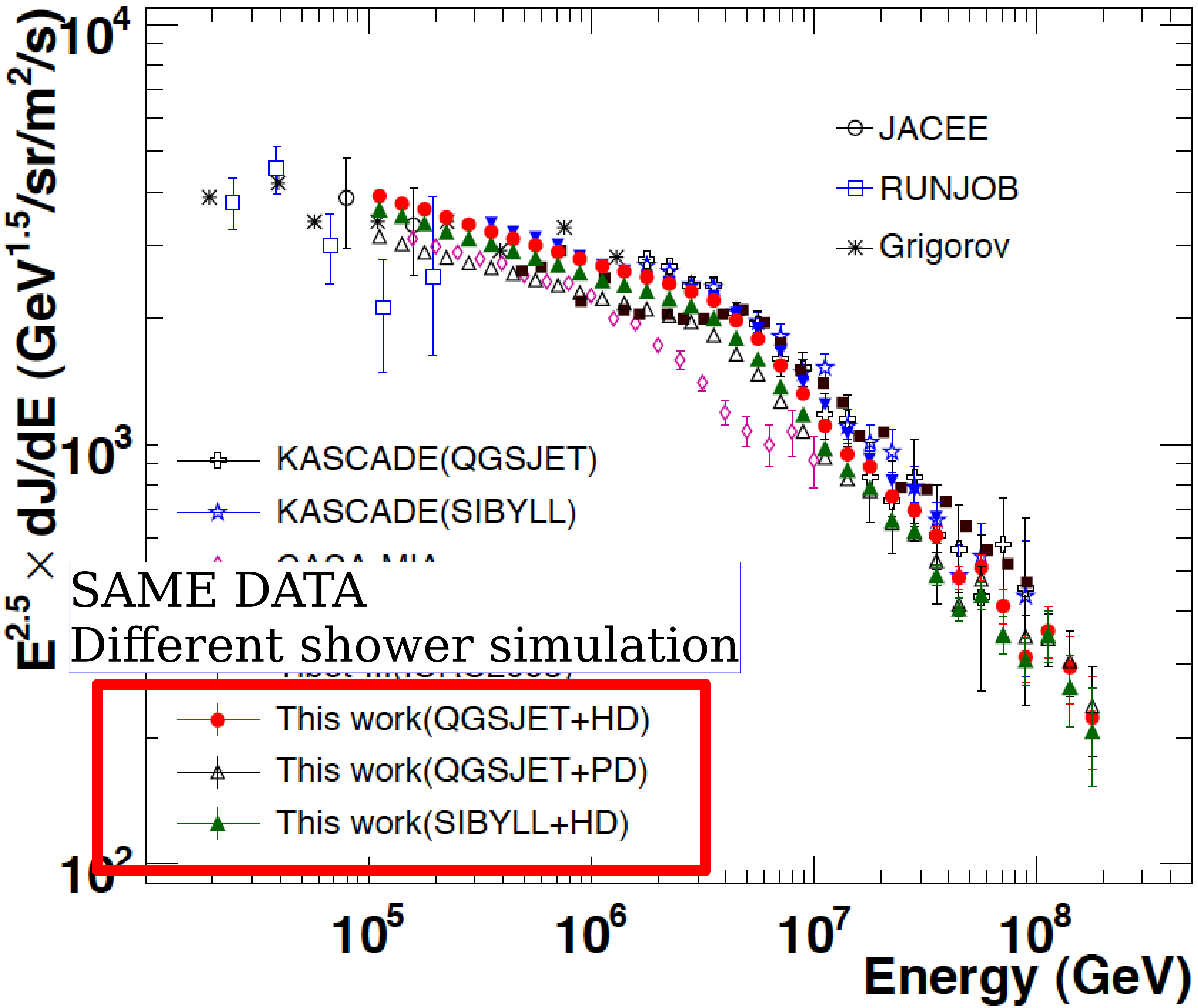
Structures in the CR spectrum



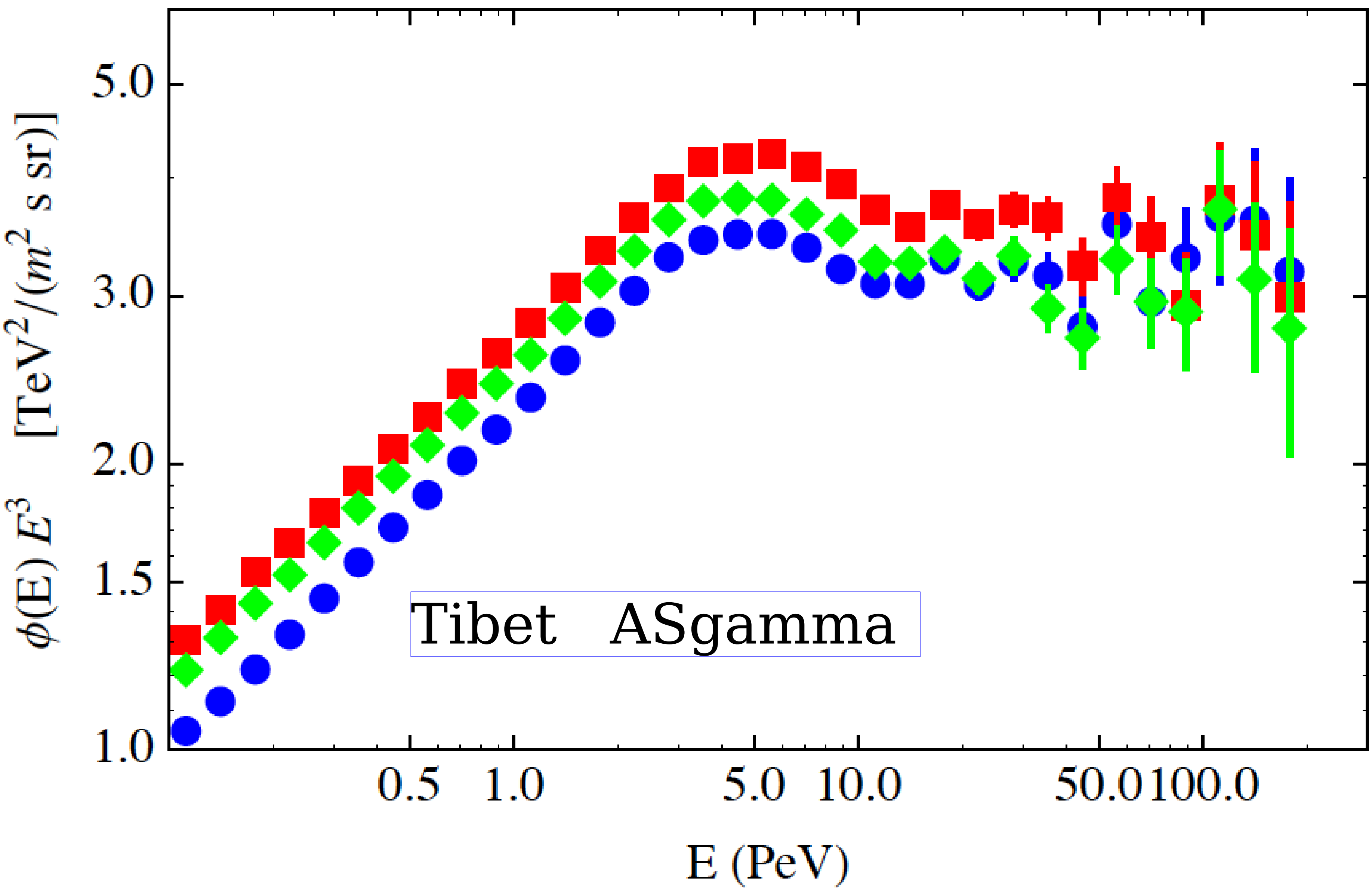
Tibet Air Shower Energy Spectrum



Tibet Air Shower Energy Spectrum

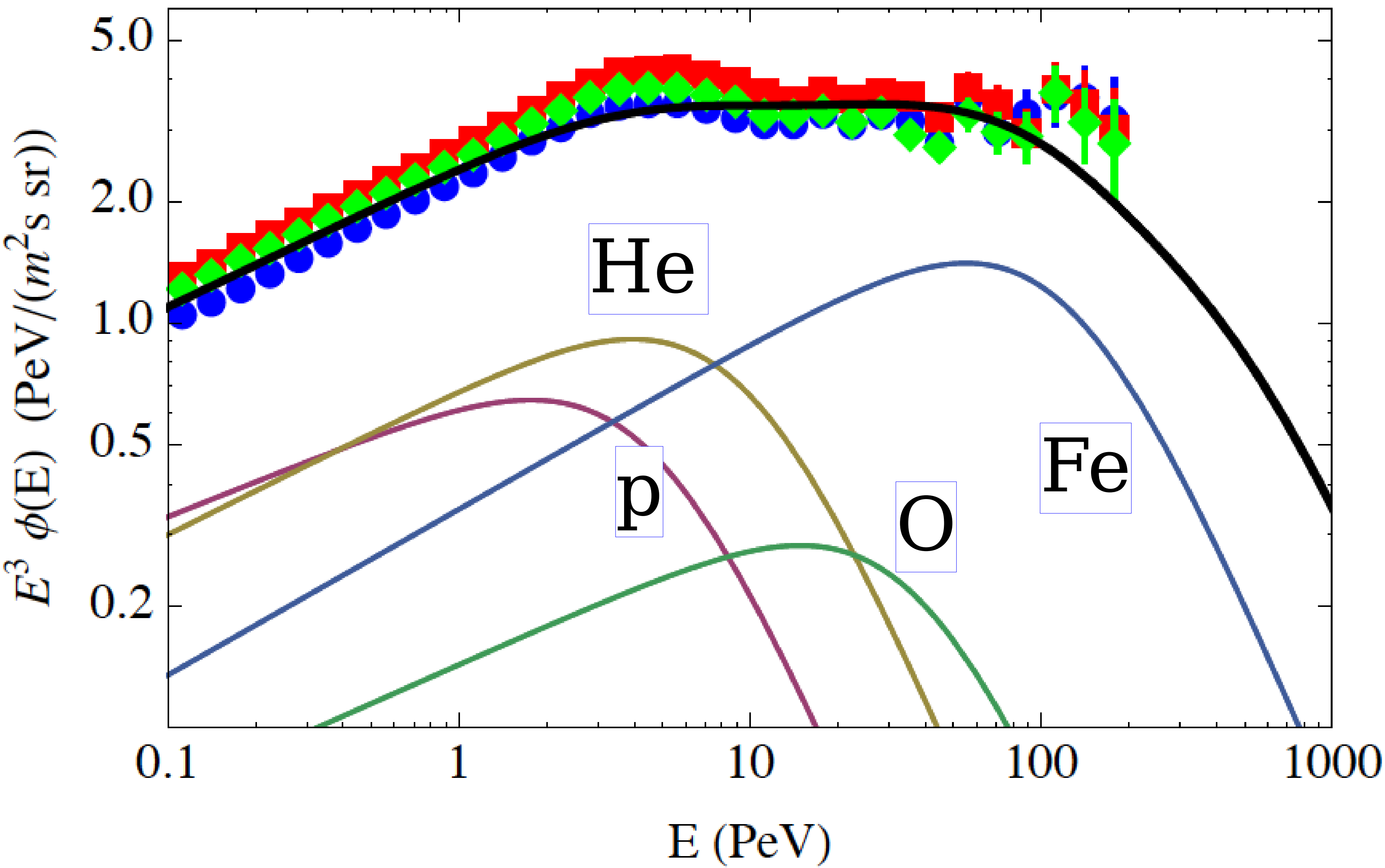


The "Shape of the KNEE"

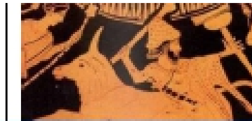


Horandel Model (largely motivated by Kascade data)
for the evolution of composition o

Same structure [“Peters cycle”] repeated “rescaled in Z”

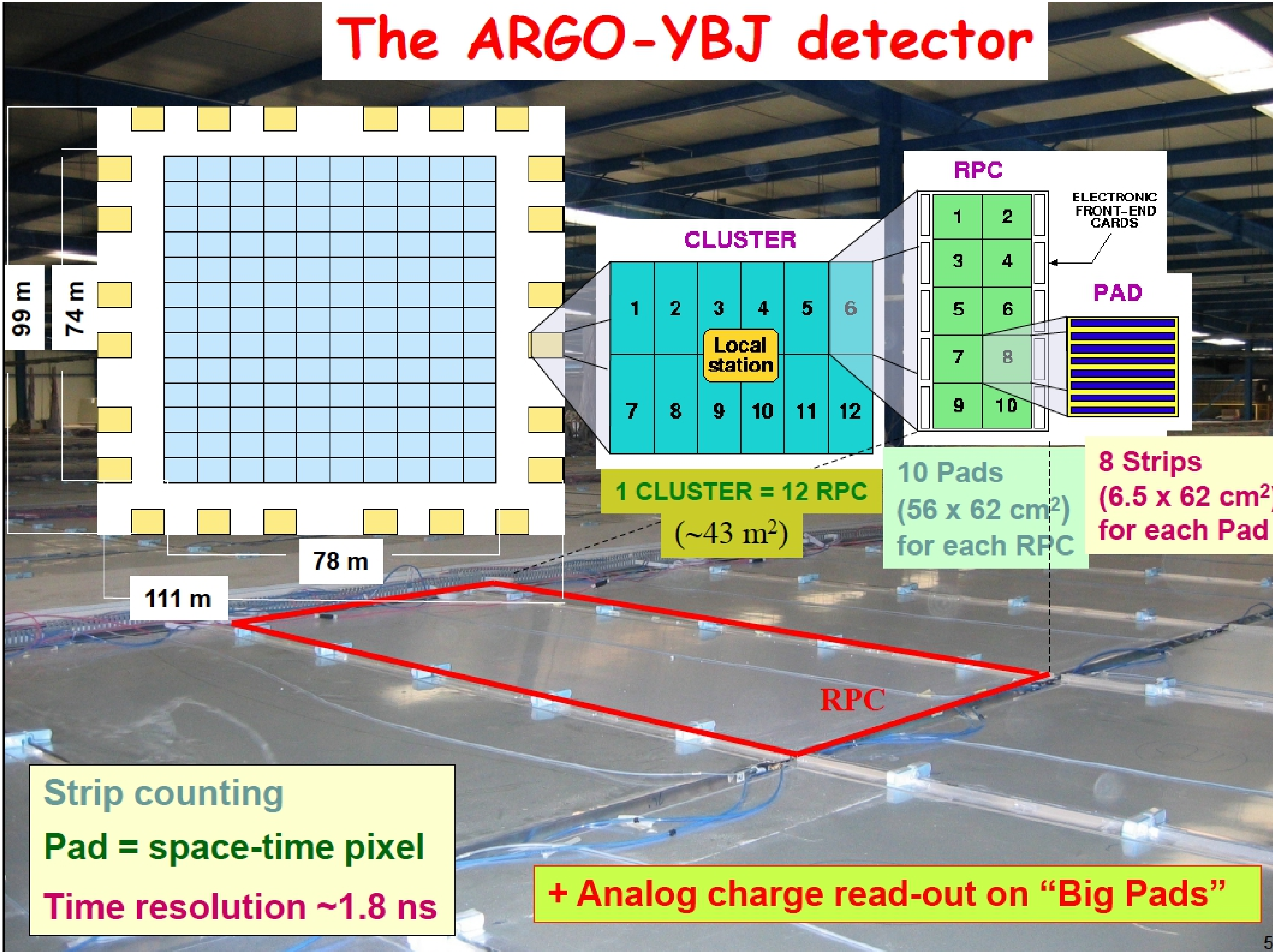


The ARGO-YBJ experiment



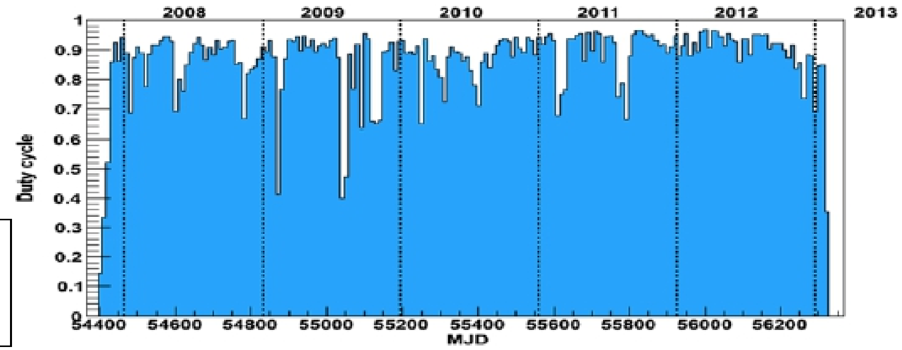
High Altitude Cosmic Ray Observatory @ YangBaJing,Tibet, China

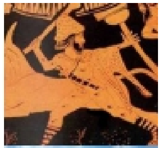
Site Altitude: 4,300 m a.s.l. , ~ 600 g/cm^2


The ARGO-YBJ detector
99 m
74 m
78 m
111 m
CLUSTER
1
2
3
4
5
6
Local station
7
8
9
10
11
12
1 CLUSTER = 12 RPC
(~43 m²)
RPC
ELECTRONIC FRONT-END CARDS
1
2
3
4
5
6
7
8
9
10
10 Pads
(56 x 62 cm²)
for each RPC
PAD
8 Strips
(6.5 x 62 cm²)
for each Pad
RPC
Strip counting
Pad = space-time pixel
Time resolution ~1.8 ns
+ Analog charge read-out on "Big Pads"

EAS reconstruction

Data taking with full configuration:
November 2007- February 2013

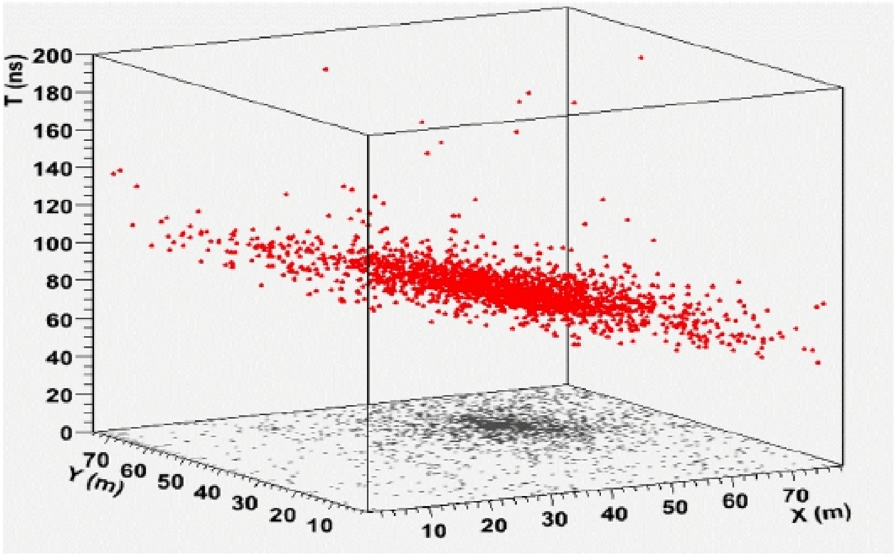




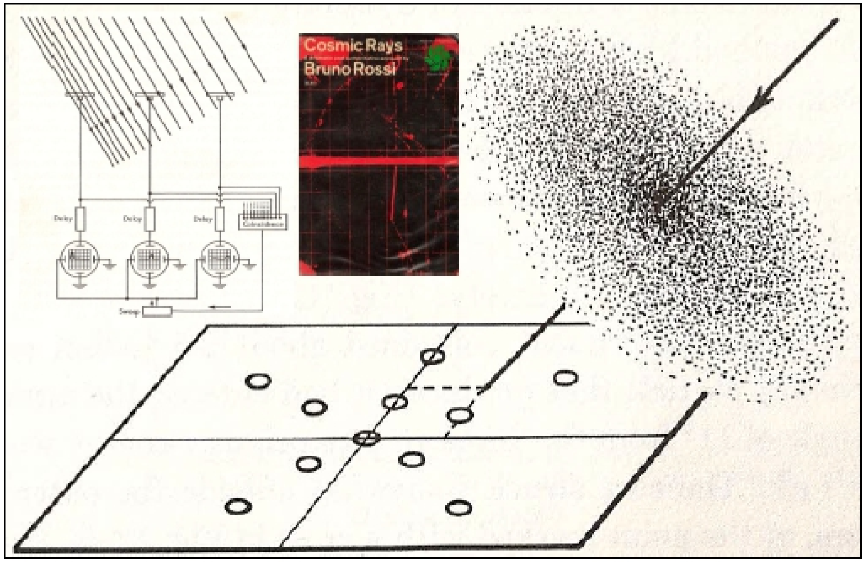
Event Rate ~ 3.5 kHz for N_{hit} >20 - Duty cycle ~ 86% - 10^{11} evts/yr – 100TB/yr

High space/time granularity
+ Full coverage
+ High altitude

detailed study on the EAS space/time structure with unique capabilities

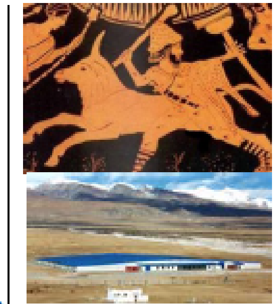


3-D view of a detected shower

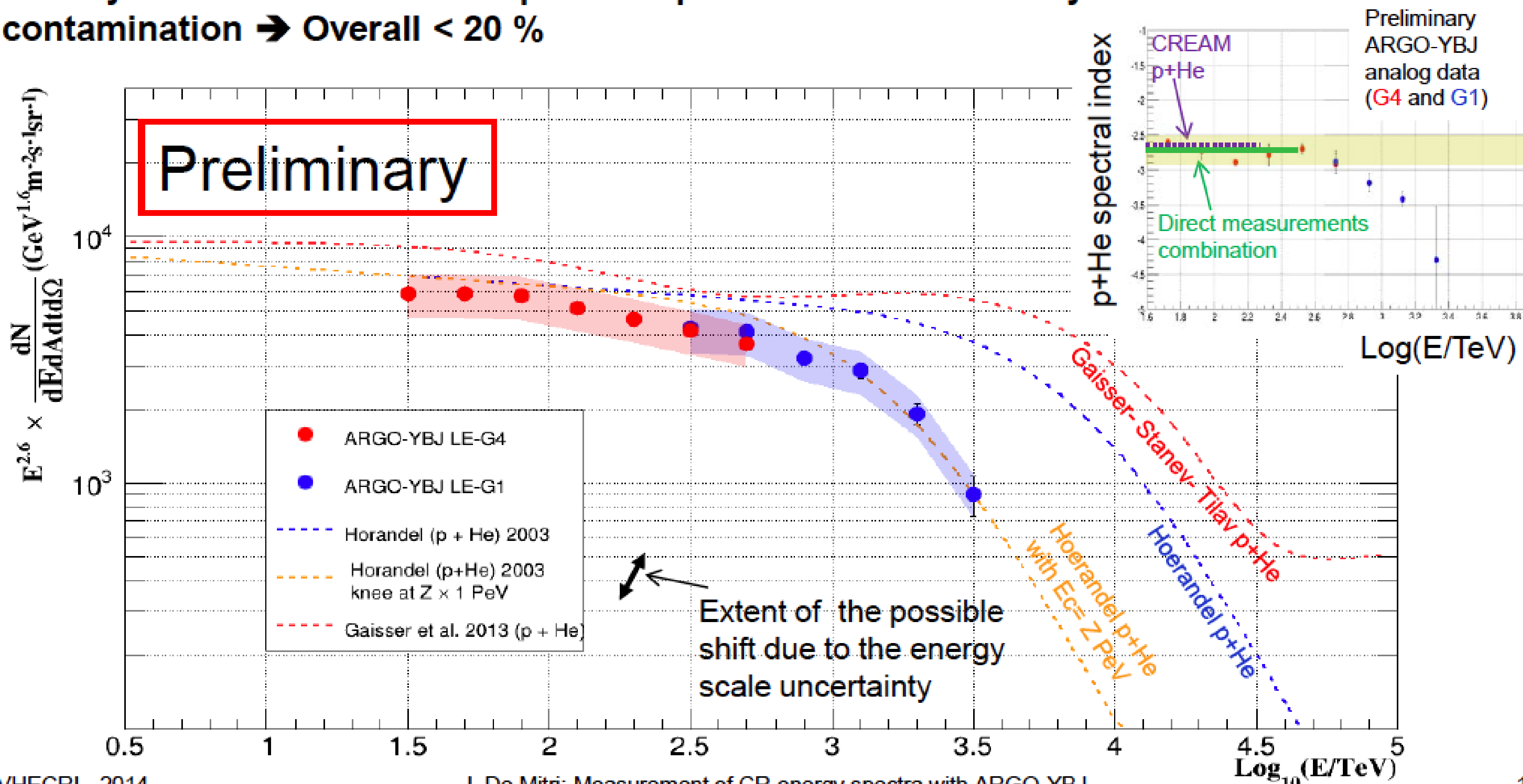


Bruno Rossi conceptual EAS detector

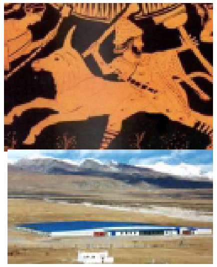
The p+He spectrum



- Same considerations as for the all-particle spectrum
- Gradual change of the slope starting around 700 TeV
- Agreement with other two ARGO-YBJ independet analyses (see next two slides)
- Consistent with previous hints (MACRO, CASA-MIA, Chacaltaya, EAS-TOP,...) and YAC-Tibet spectrum
- Overlap with direct measurements at low energy
- Flux systematics as for the all particle spectrum ⊕ < 14% mainly for the CNO contamination ➔ Overall < 20 %

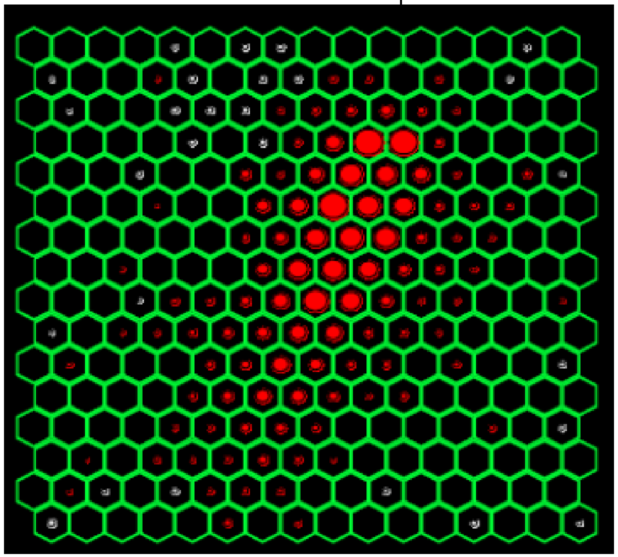


p+He spectrum: measurement of Cerenkov light



Wide Field of View Cerenkov Telescope (Array): (WFCTA)

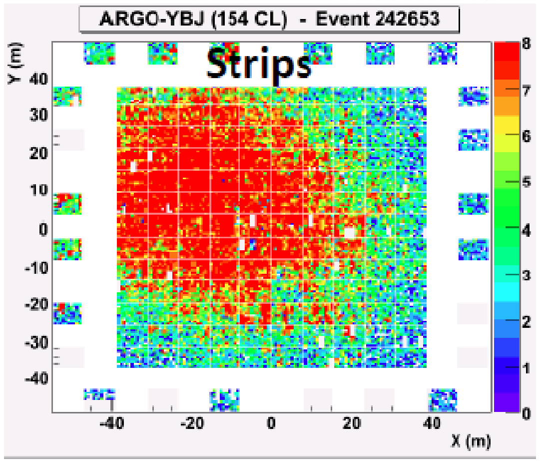
$5m^2$ spherical mirror
16×16 PMT array
$14^\circ \times 16^\circ$ Field Of View
Elevation angle: 60°

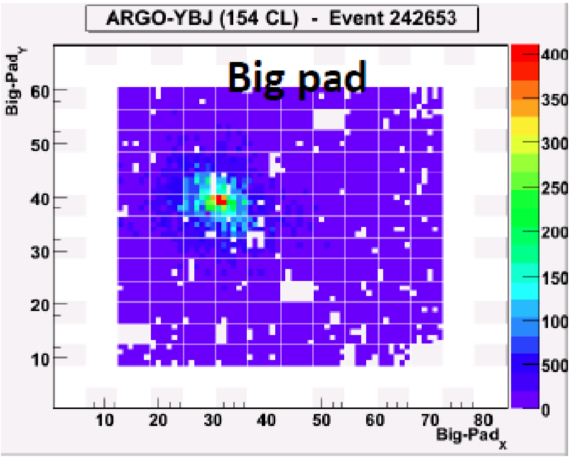


Energy easurement by using the Cerenkov signal and the shower geometry as reconstructed with the ARGO-YBJ analog data.

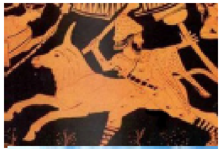
Light elements are selected by using information of particle desity near the core (ARGO-YBJ) and the shape of the Cerenkov image

Chin. Phys. C 38 (2014) 045001



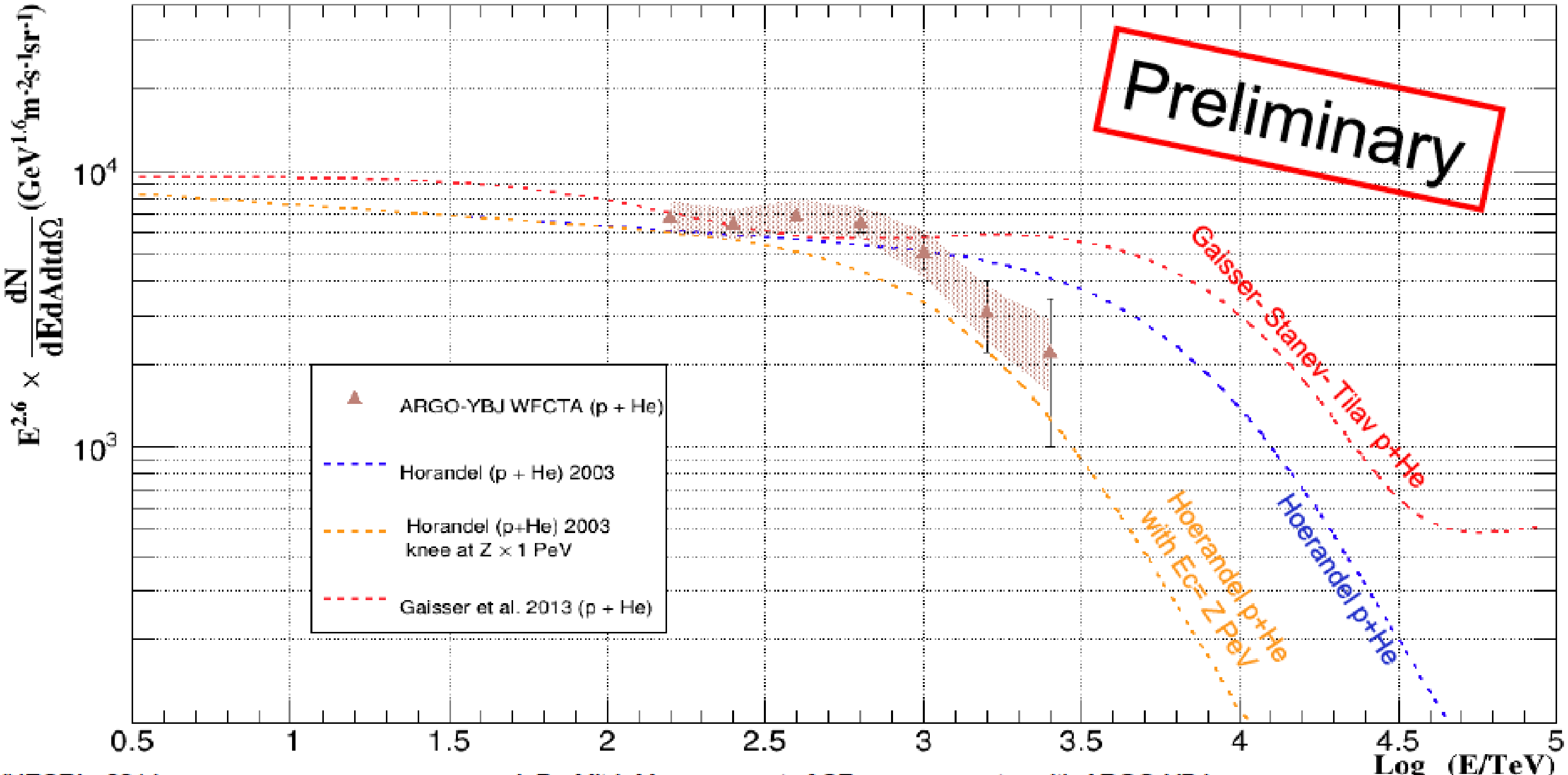


p+He spectrum: measurement of Cerenkov light



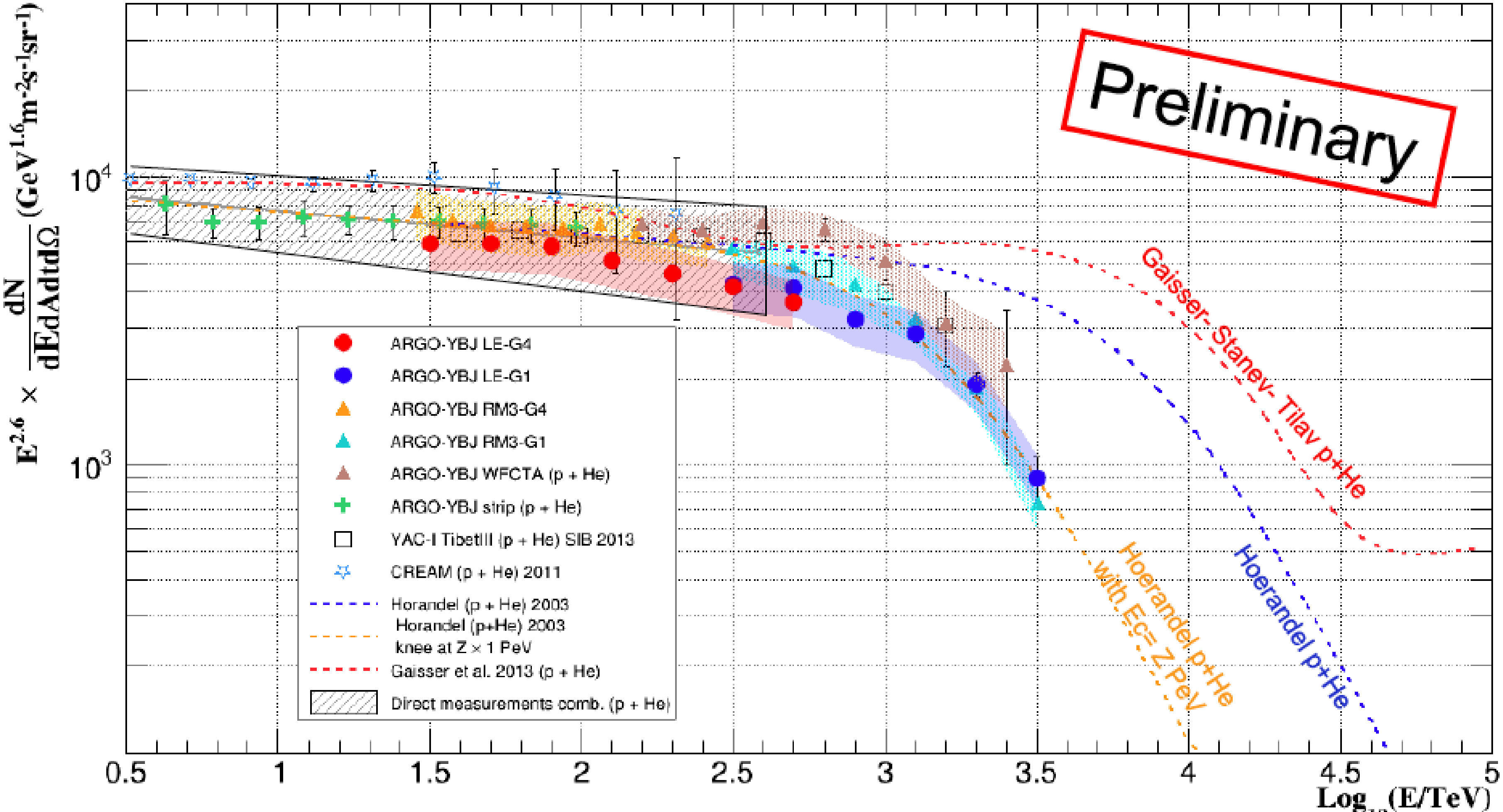
Results are consistent with previous analyses. May be different shape.

Different data/detector, different fiducial cuts, inclined events,…



Comparison with other p+He measurements

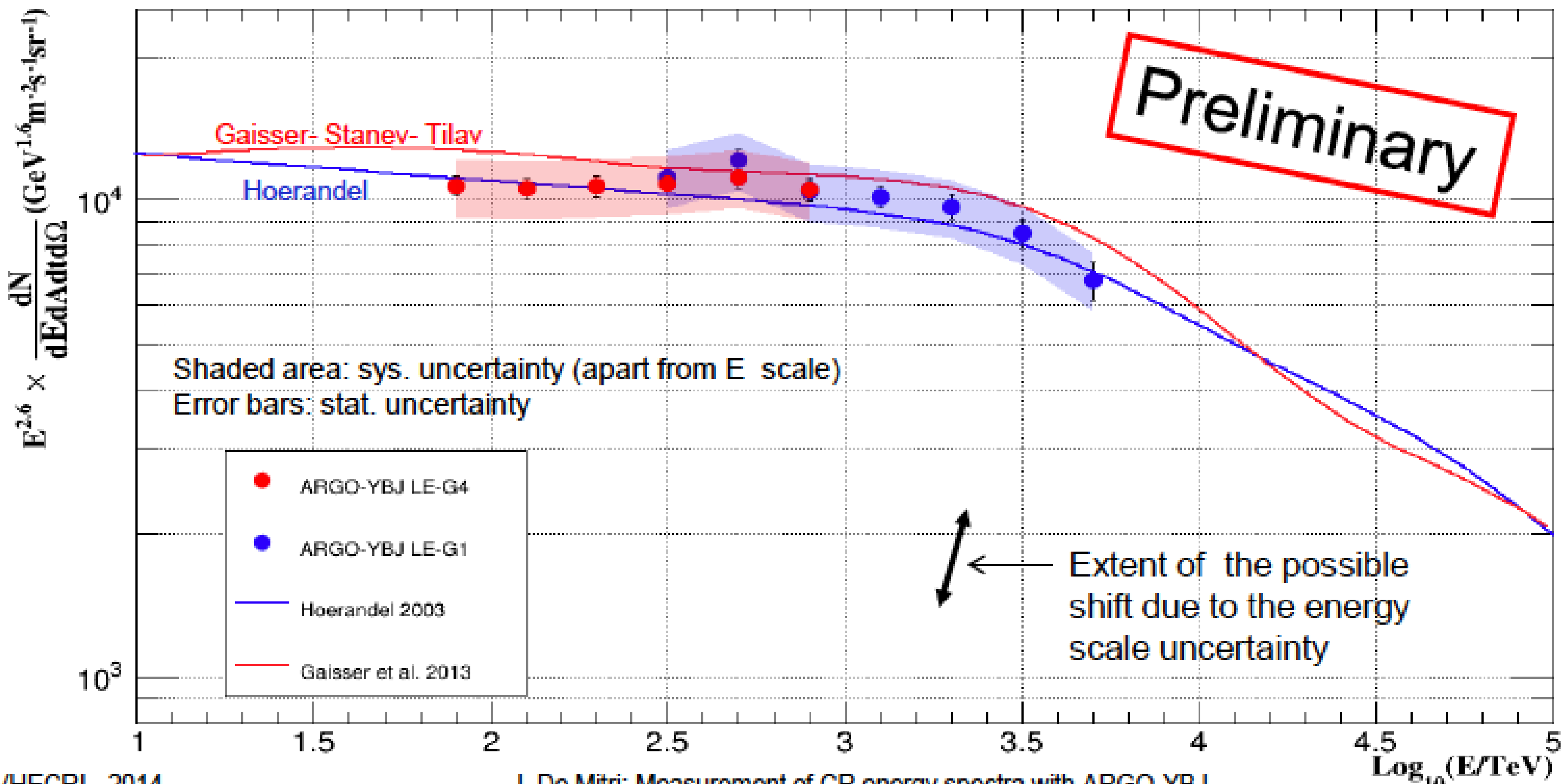
Consistent results with direct measurements (i.e. below 200 TeV) and YAC-Tibet



The all particle spectrum

- Consistent picture with models and previous measurements
- Nice overlap with the two gain scales (different data,…)
- Suggest spectral index of -2.6 below 1 PeV and smaller at larger energes

- Ongoing extension to about 10 PeV thanks to more statistics and G0 and inclined data



If this “early bending” measurement of the bending of the proton/helium component is correct, this is important.

Questions/Comments after looking at the ARGO result:

Why the discrepancy with previous measurements ?

Different method of mass measurement

KASCADE : Muon content [Large A = large Nmu]

ARGO : Shape of the lateral distribution of the shower

Does this has something to do with the modeling of the shower ?

If this “early bending” measurement of the bending of the proton/helium component is correct, this is important.

Questions/Comments after looking at the ARGO result:

1. Why the discrepancy with previous measurements ?

Different method of mass measurement

KASCADE : Muon content [Large A = large Nmu]

ARGO : Shape of the lateral distribution of the shower
[Shape of the Cherenkov light image]

2. Does the discrepancy has something to do with the modeling of the shower ?

Important to Verify

Energy Region

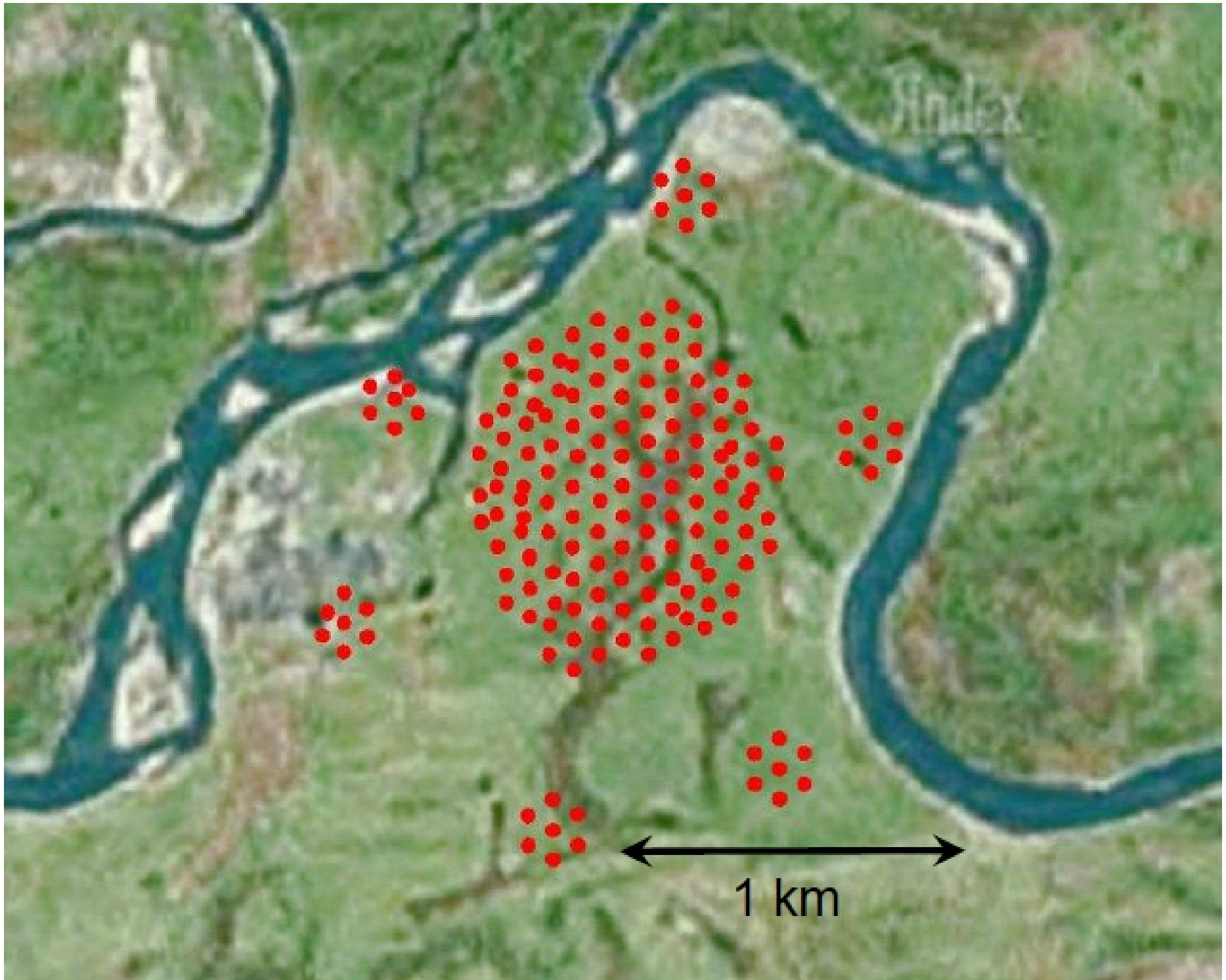
“from the Knee to the Ankle”

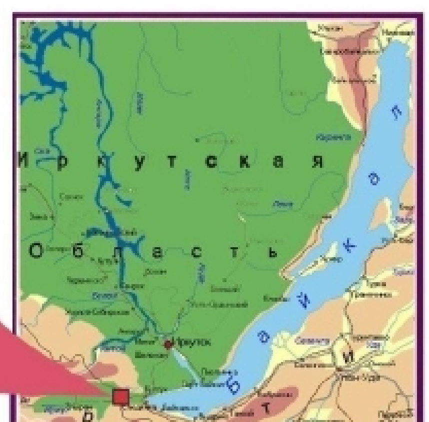
TUNKA

TELESCOPE ARRAY / TALE

KASCADE GRANDE

Vasily Prosin

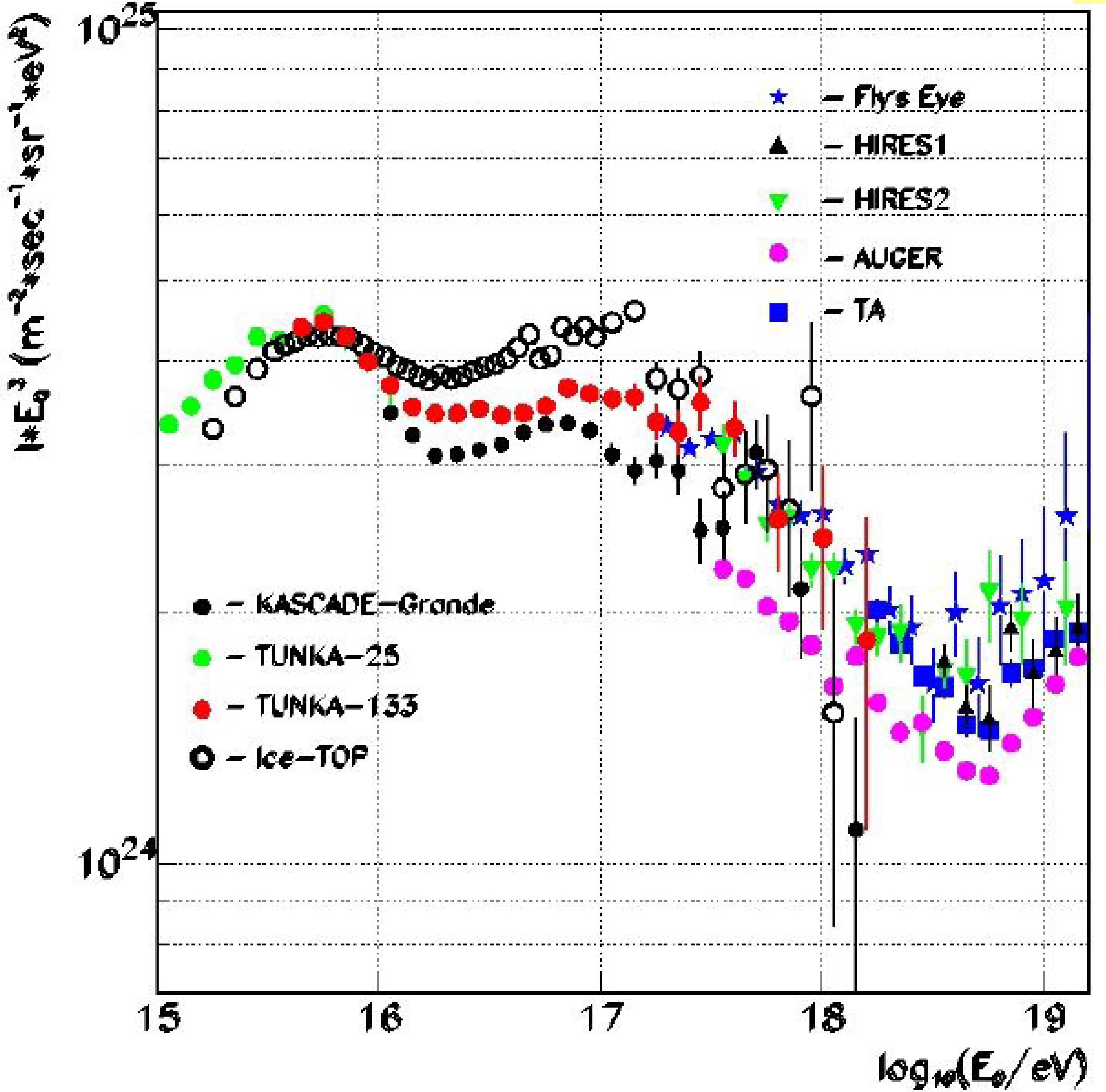




51° 48' 35" N
103° 04' 02" E
675 m a.s.l.

175 optical detectors
EMI 9350 and HAMAMATSU Ø 20 cm

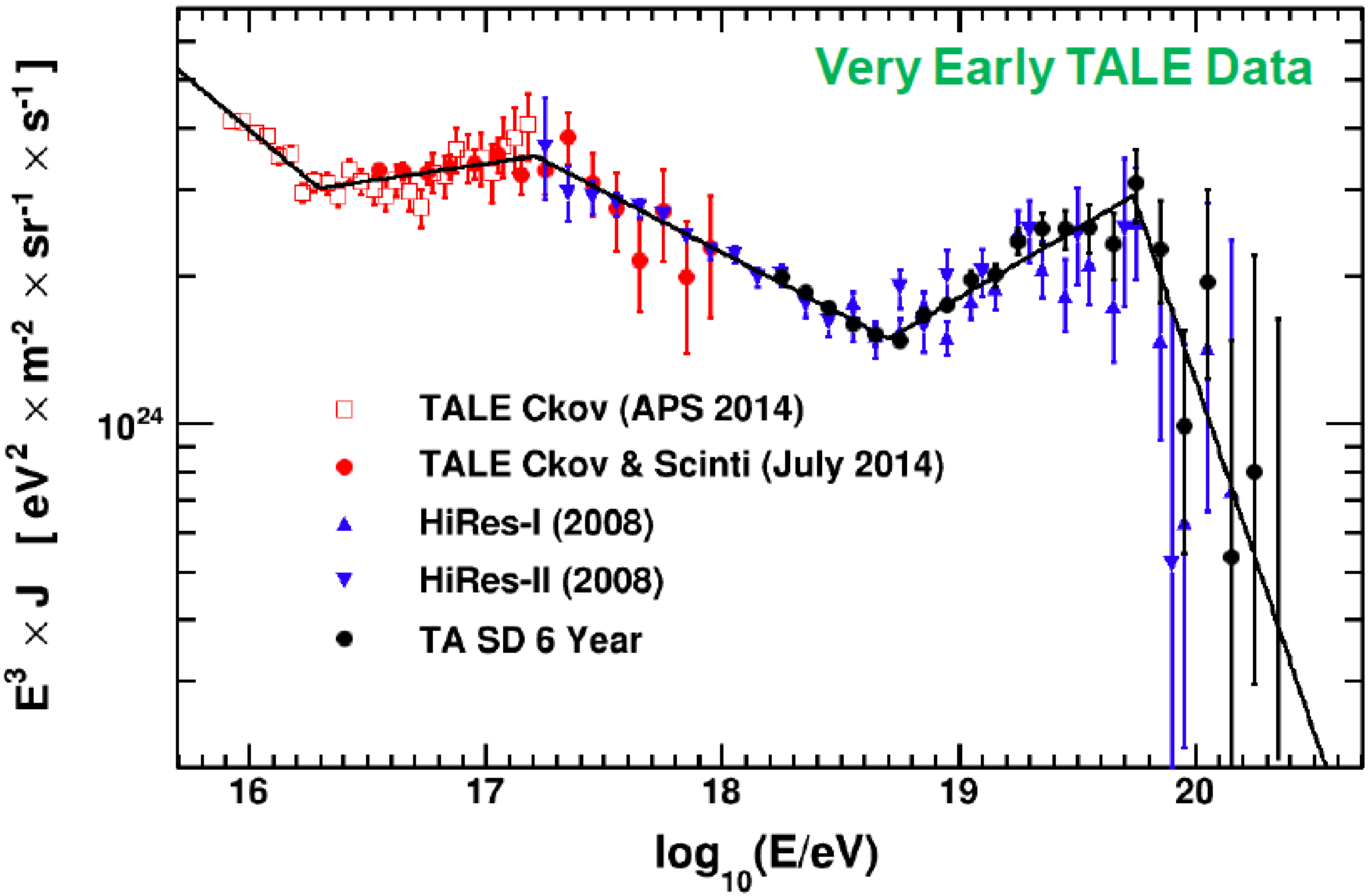
Vasily Prosin



Masaki Fukushima

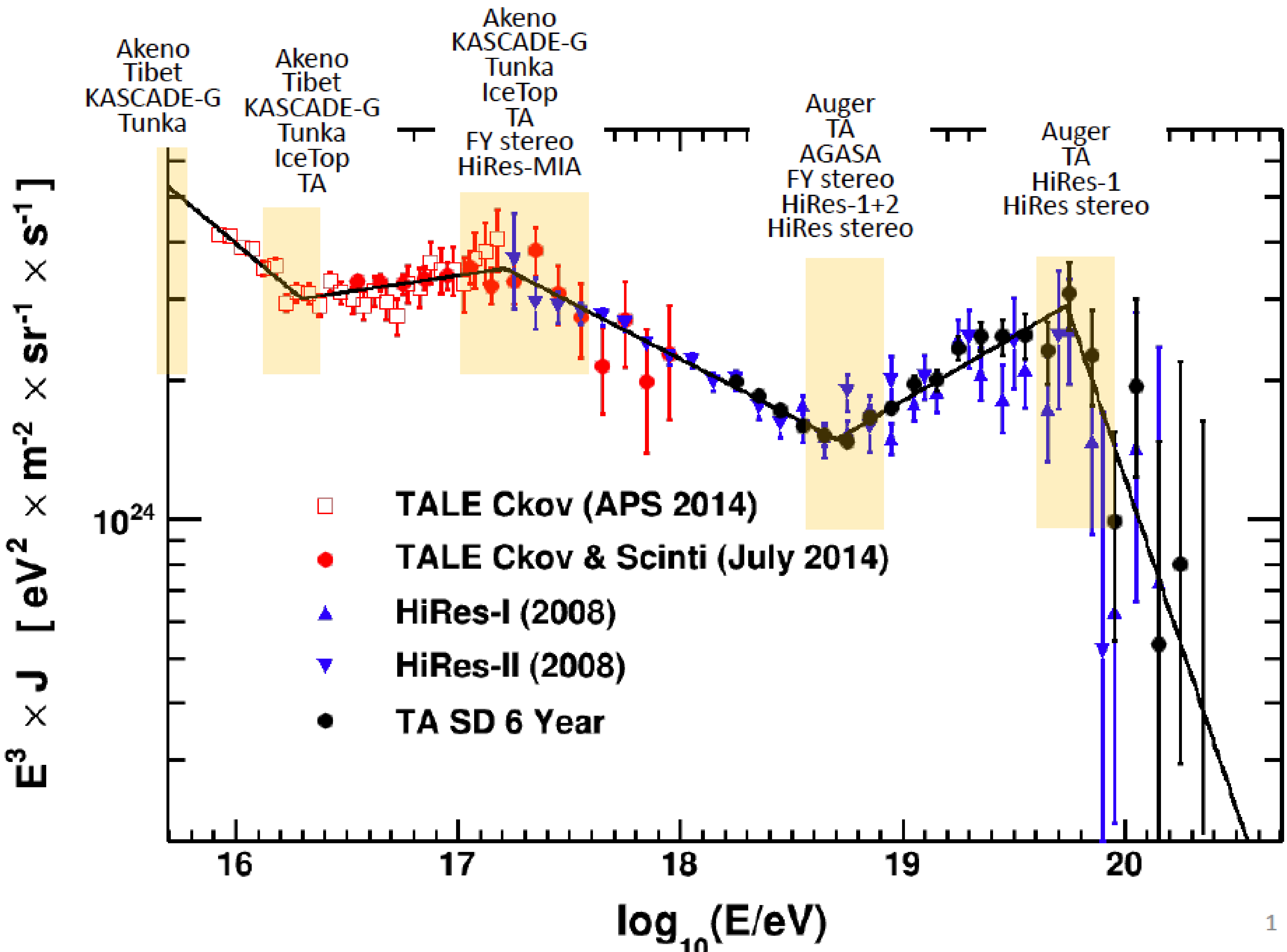
CR Spectrum

SD Data (6 Yrs: 20080511-20140511)
+ high elevation TALE telescopes (no MD so far) and events with large Cerenkov contribution



Masaki Fukushima

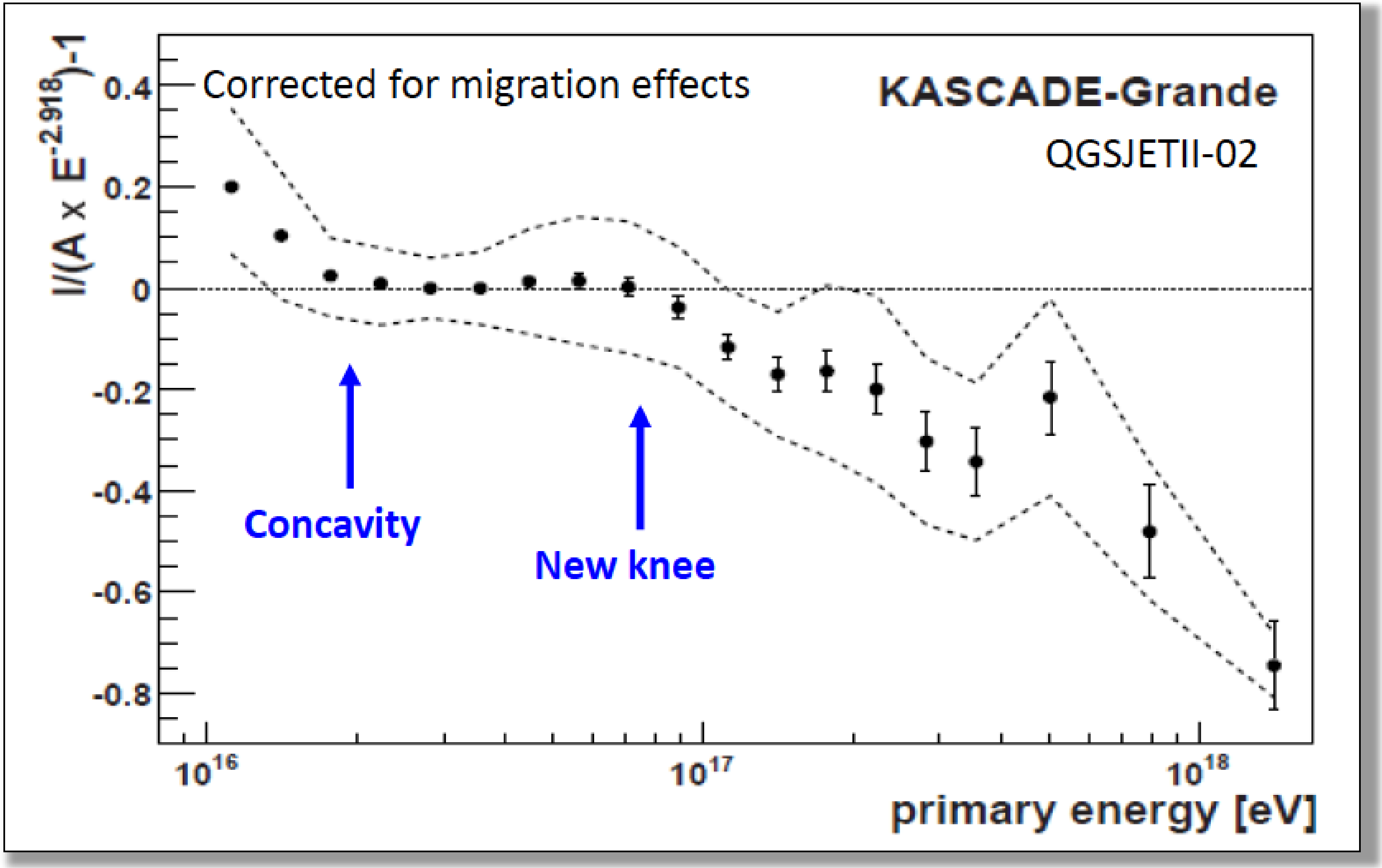
SPECTRUM: from Knee to Cutoff



3) KASCADE-Grande experiment

Energy spectrum: K-method

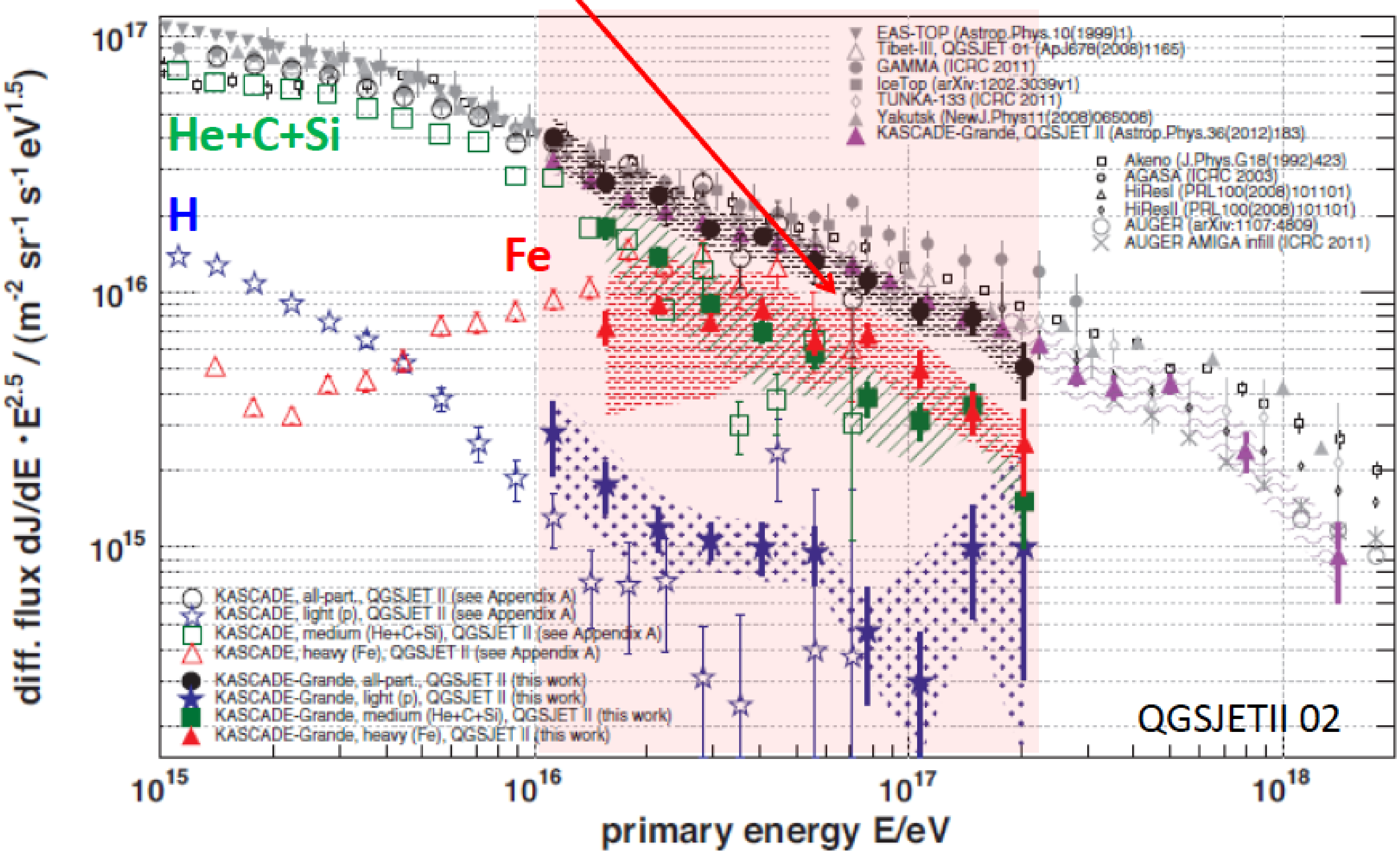
W.D.Apel, Astrop. Phys. 36 (2012) 183



3) KASCADE-Grande experiment

Iron knee (E ≈ 80 PeV)

Consistent with position of break-off in heavy knee from K-method



KASCADE-Grande Coll., Astropart. Phys. 47 (2013)

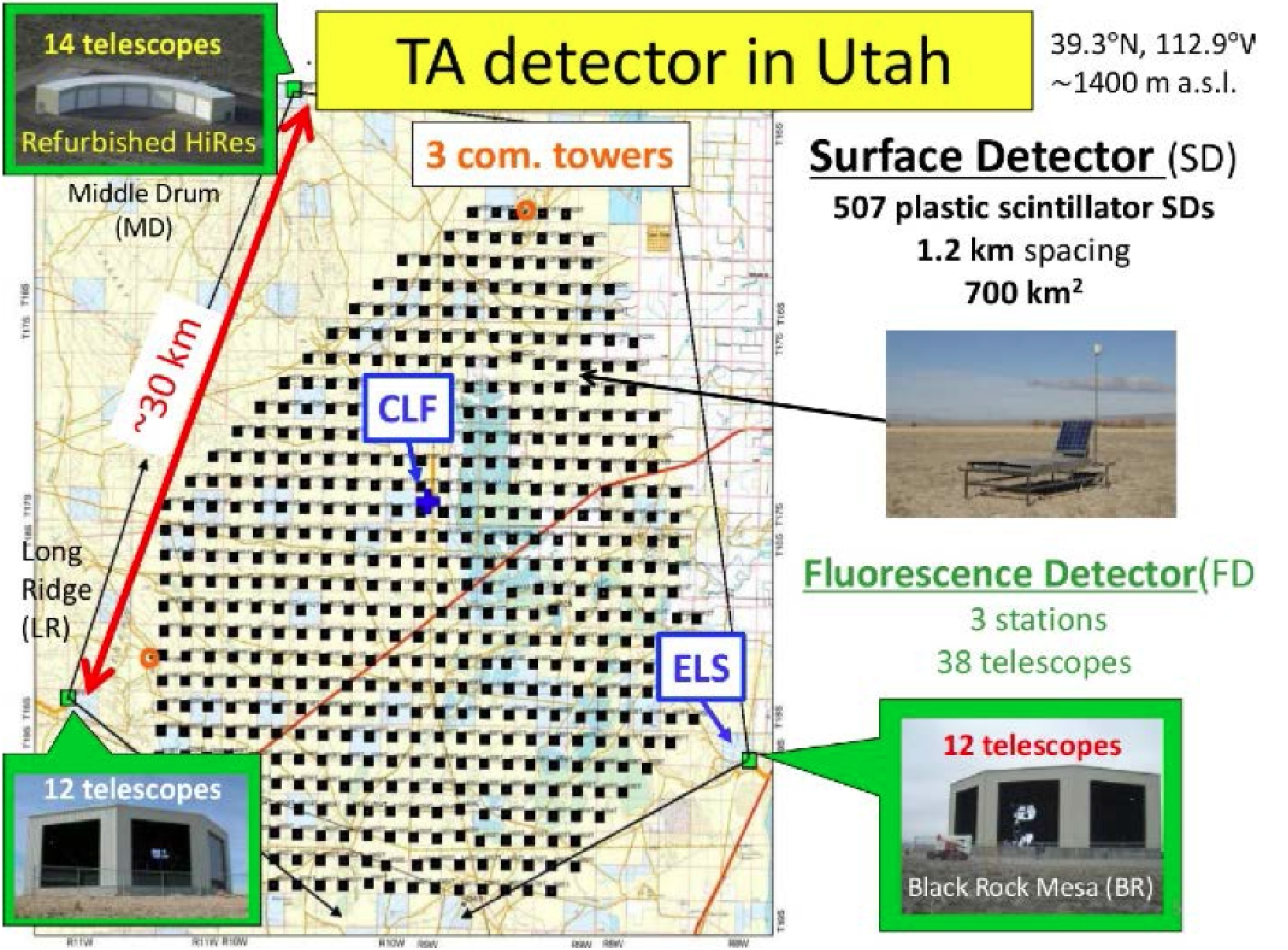
ULTRA HIGH ENERGY COSMIC RAYS

Where the interplay between

Hadronic physics and
Cosmic Ray Astrophysics

is most important and most interesting

AUGER Observatory
TELESCOPE ARRAY

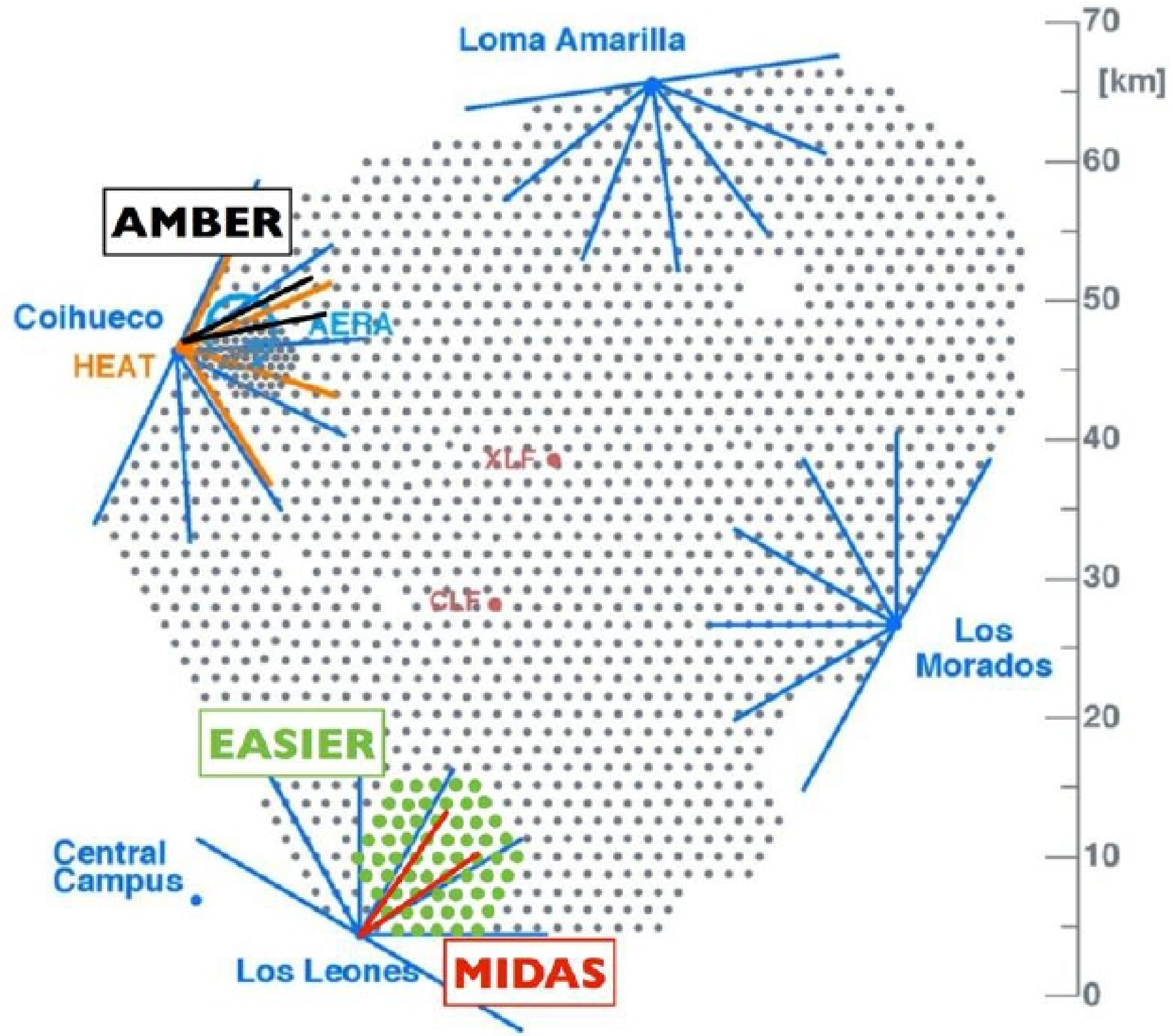


TA detector in Utah
39.3°N, 112.9°W
~1400 m a.s.l.
14 telescopes
Refurbished HiRes
Middle Drum
(MD)
3 com. towers
Surface Detector (SD)
507 plastic scintillator SDs
1.2 km spacing
700 km²
~30 km
CLF
Long
Ridge
(LR)
Fluorescence Detector(FD)
3 stations
38 telescopes
ELS
12 telescopes
12 telescopes
Black Rock Mesa (BR)

Pierre Auger Observatory

Fluorescence: 4 telescopes

Surface Array: covers 3000 km^2
1650 water-Cherenkov detectors
(10 m^2 , 1.5 km separation)



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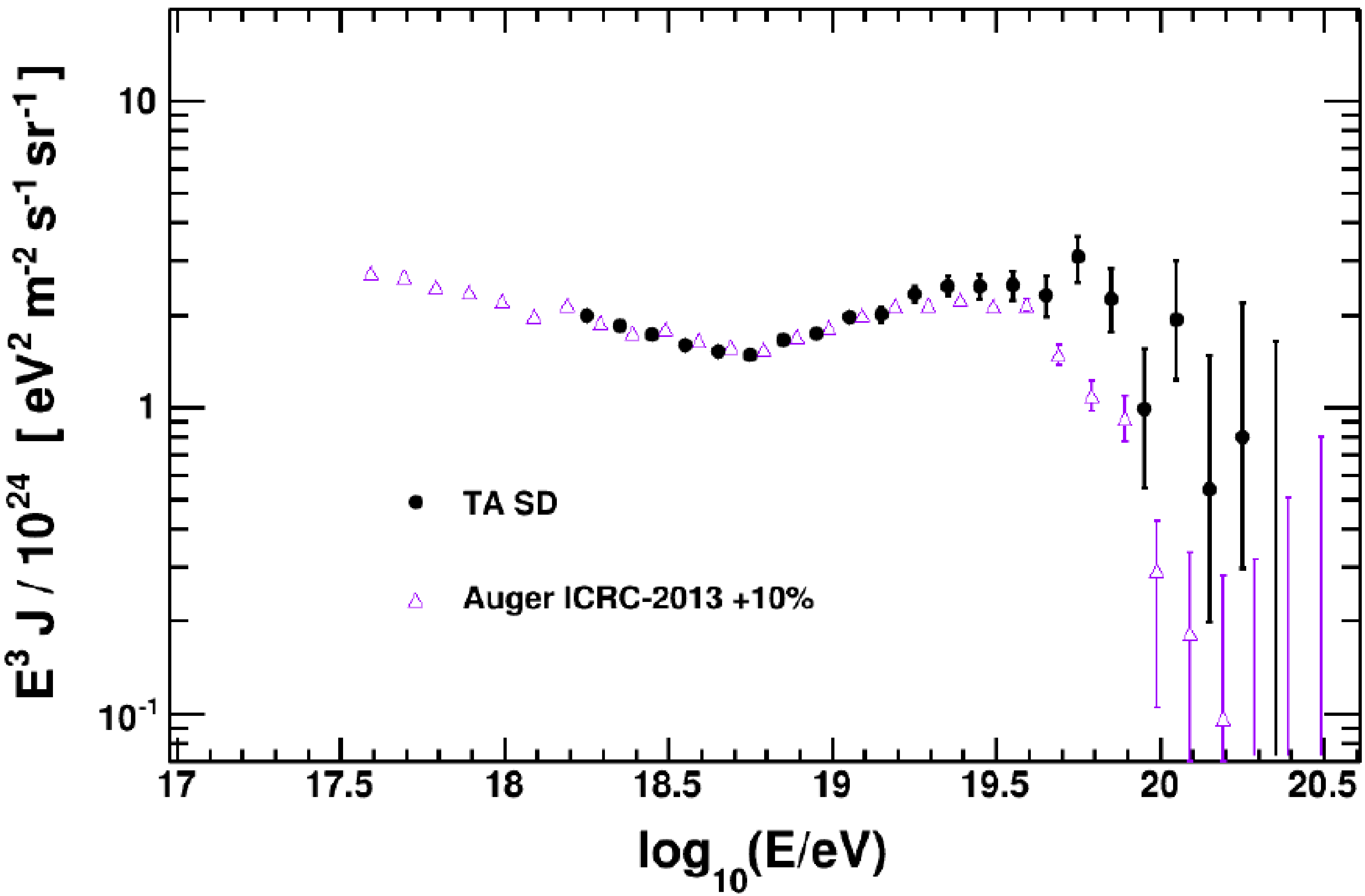
CR Spectrum

SD Data (6 Yrs: 20080511-20140511)

Comparison with Auger: ICRC 2013 + 10%



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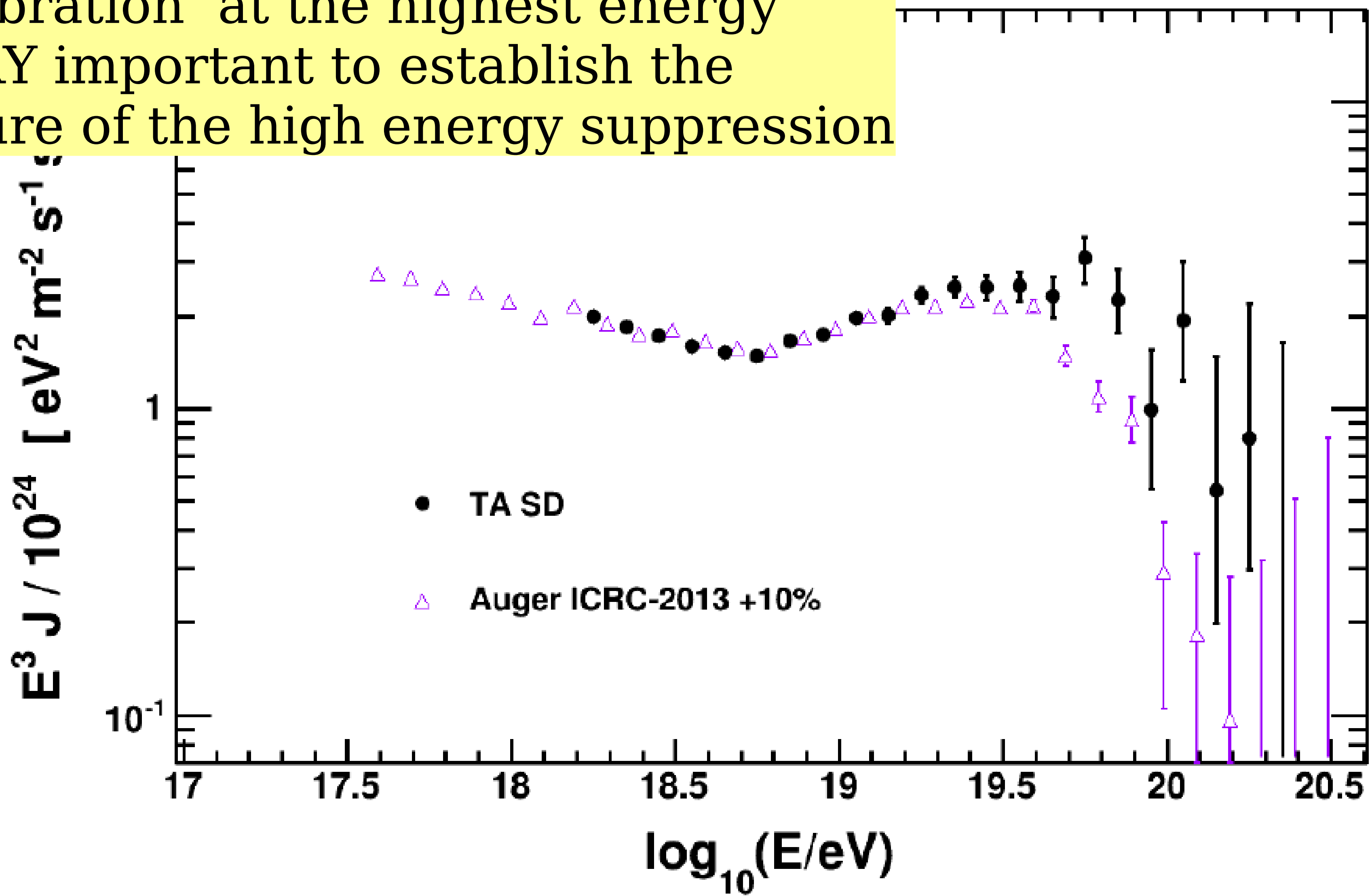
Beautiful agreement !
[Model independent
 (quasi calorimetric)
method to measure energy.

Calibration at the highest energy
VERY important to establish the
nature of the high energy suppression

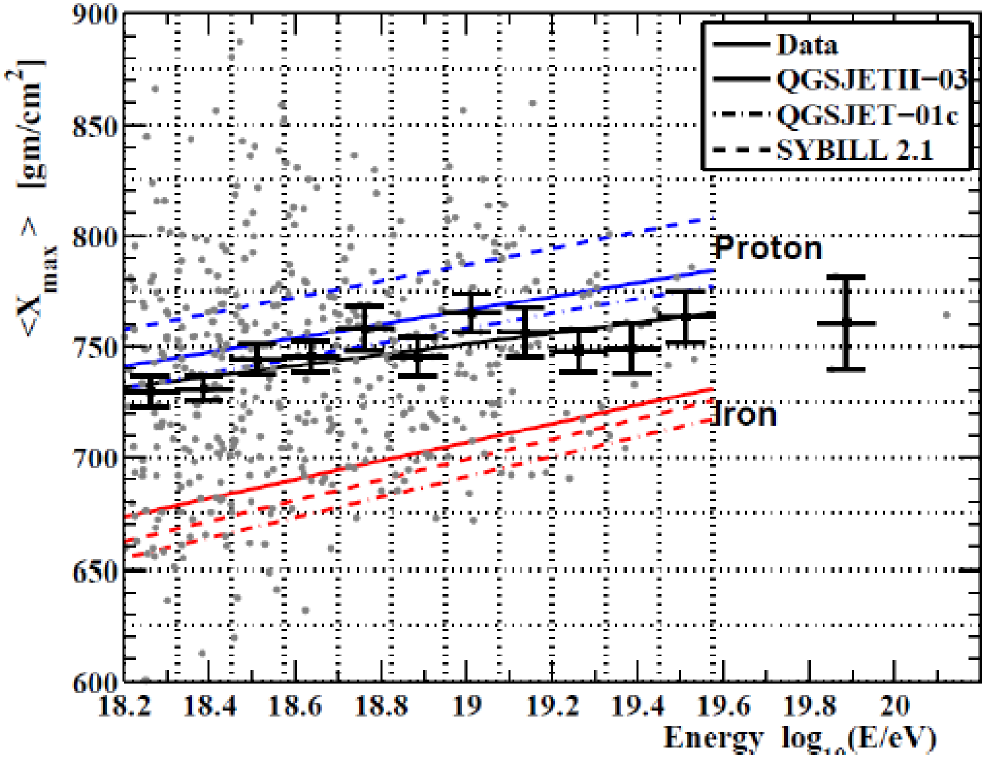
um

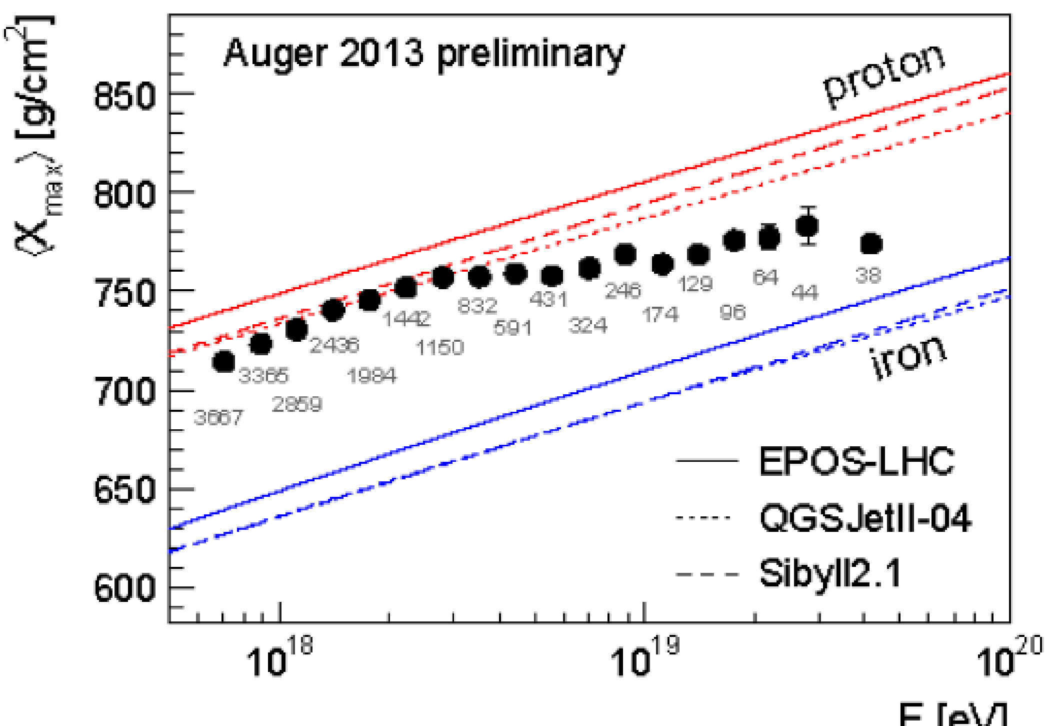
1-20140511)

RC 2013 + 10%



Jim Matthews





Composition

Measured using **depth of shower maximum** (*closely related to interaction length of primary*)

TA and Auger apparently differ

(Opinion: the data differ less than the interpretation based on models)

Abbasi et al. arXiv:1408.1726v1

Letessier-Selvon et al. arXiv:1310.4620

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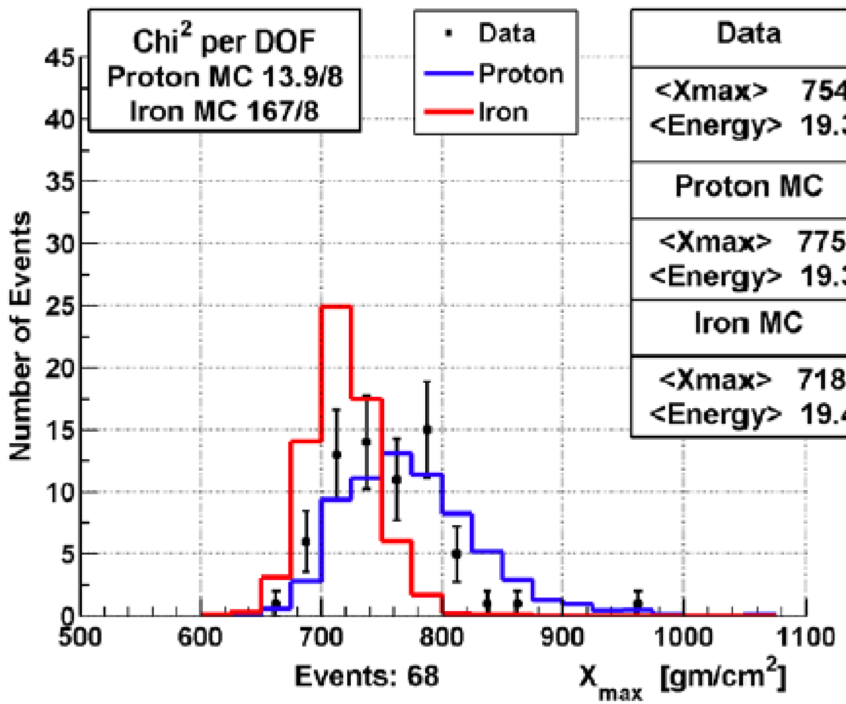
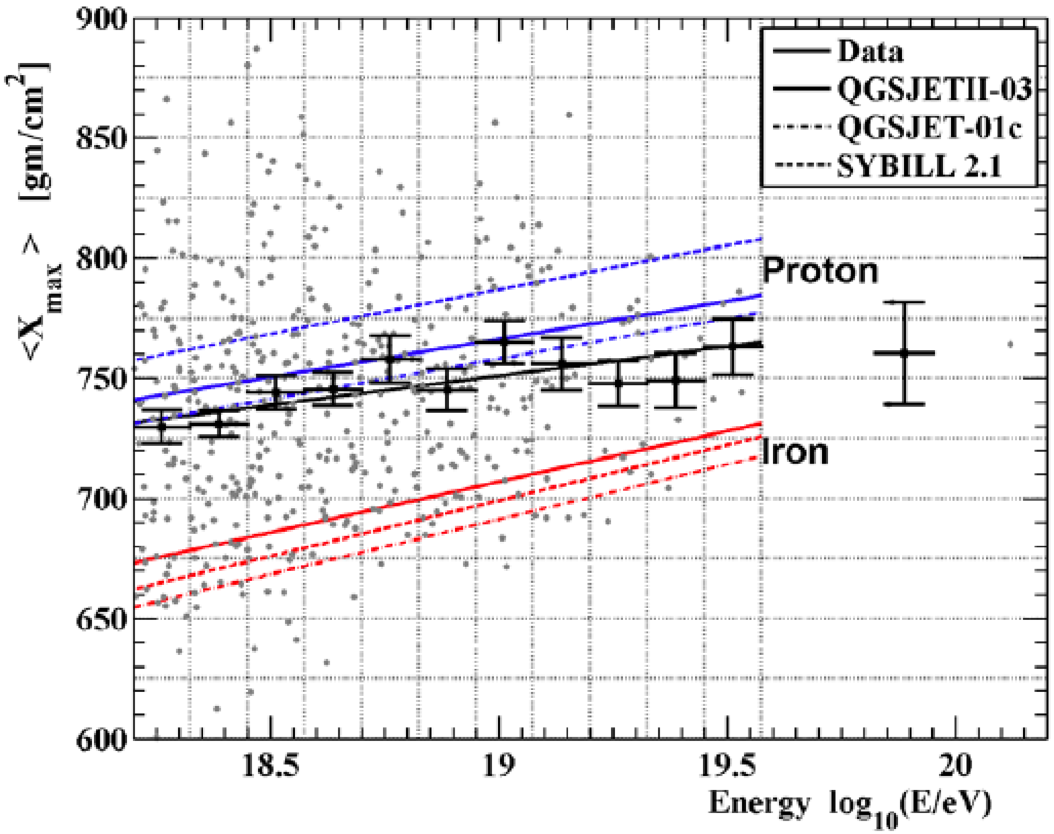
Xmax in Energy Slices
Comparison to p/Fe MC



Log10(E/eV) > 19.0



Results are consistent with proton at all energies and inconsistent with iron.

Telescope Array

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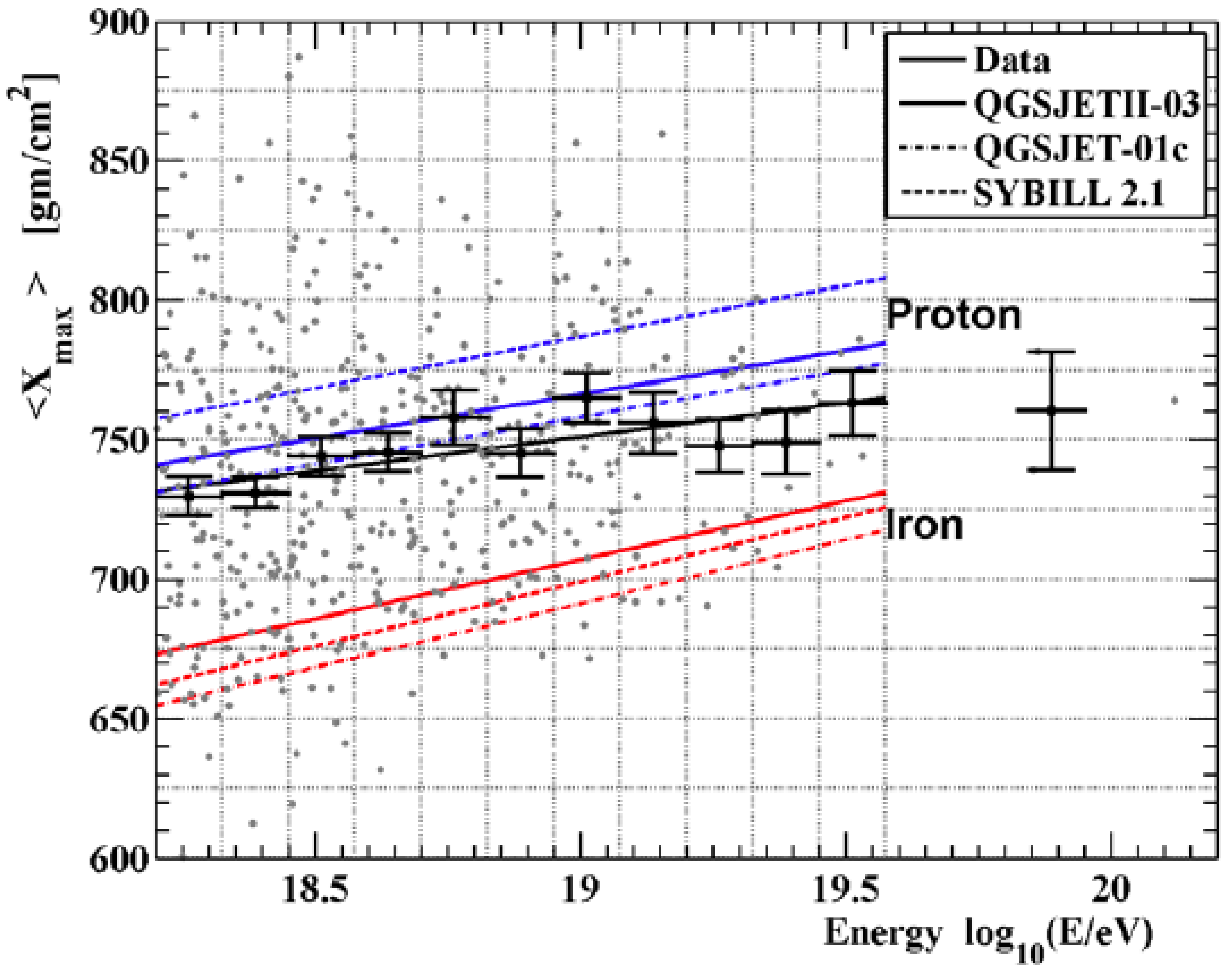
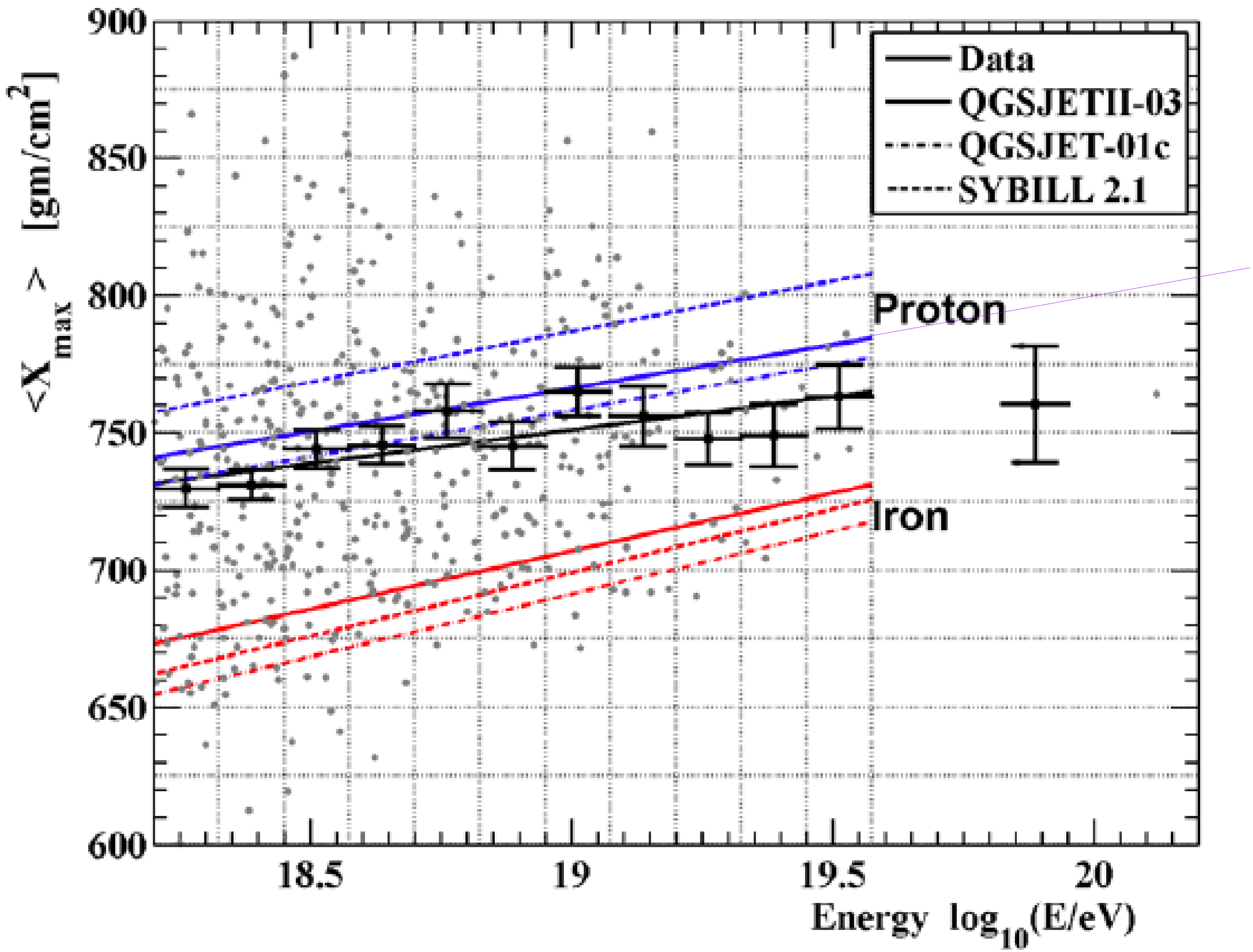
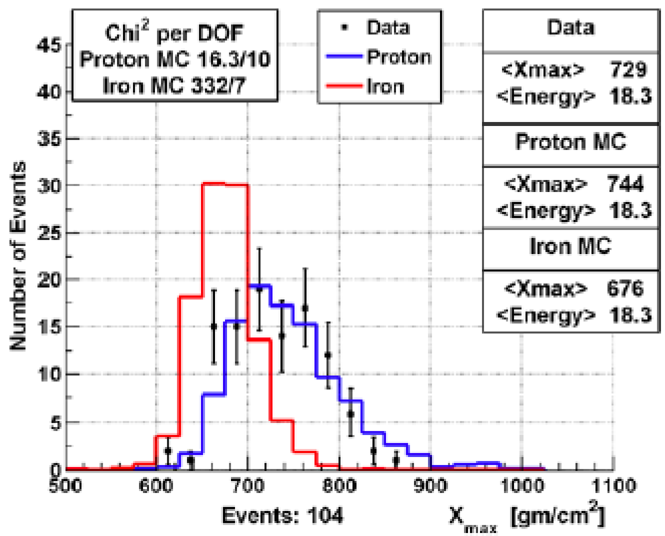


Telescope Array

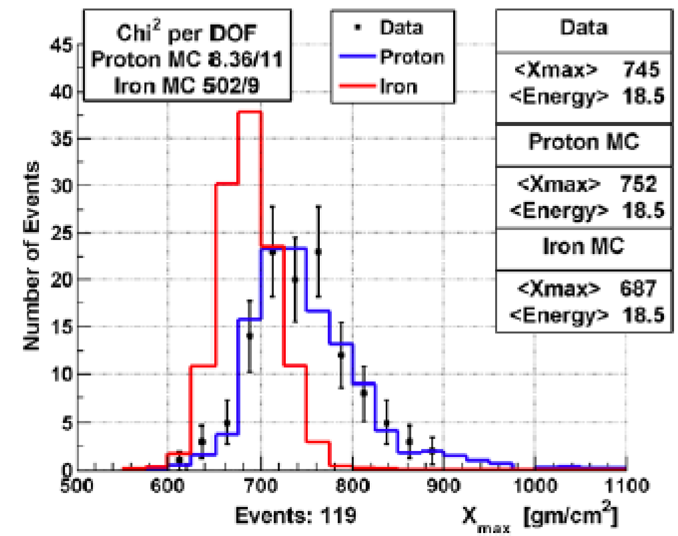
Masaki Fukushima



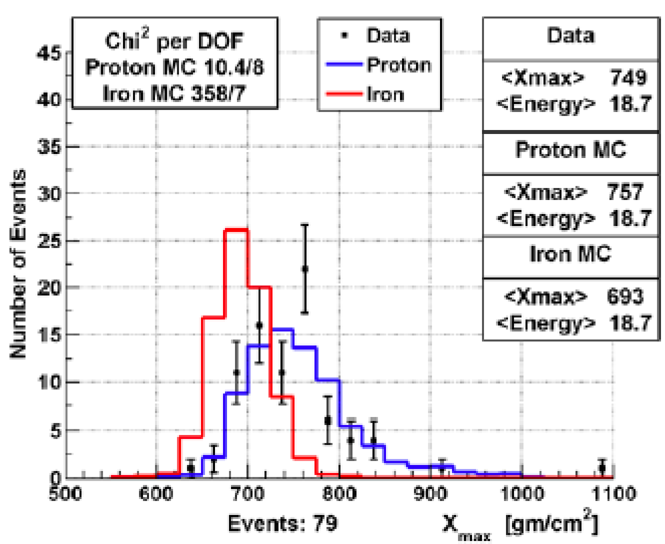
Xmax in Energy Slices Comparison to p/Fe MC



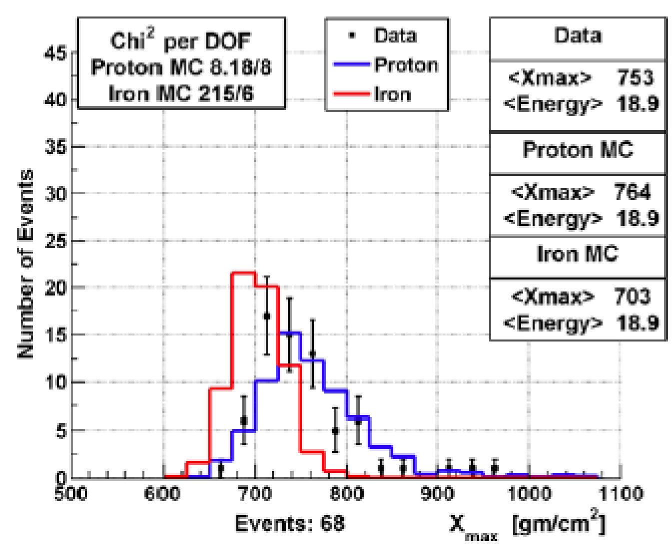
18.2 < Log10(E/eV) < 18.4



18.4 < Log10(E/eV) < 18.6



18.6 < Log10(E/eV) < 18.8



18.8 < Log10(E/eV) < 19.0

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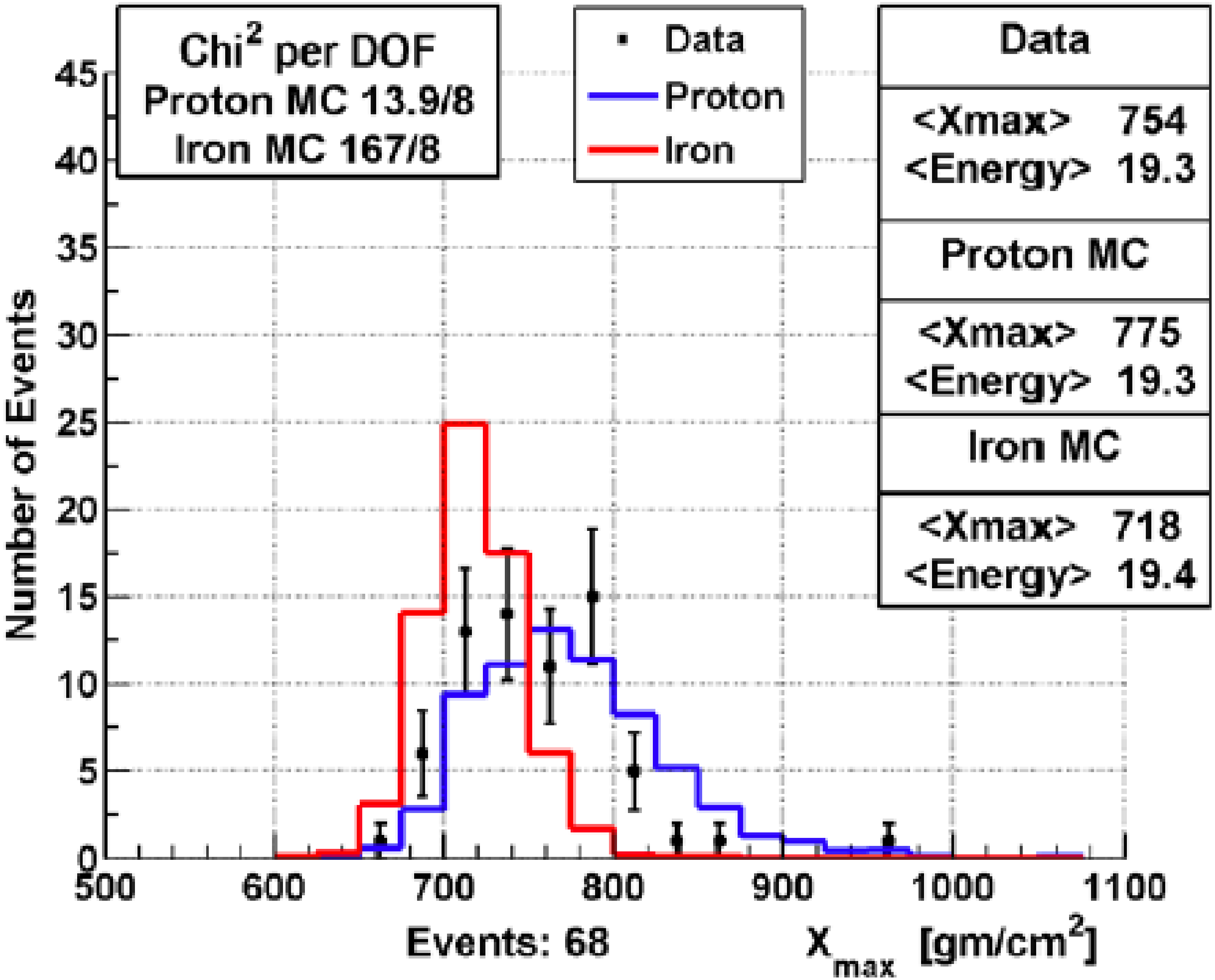
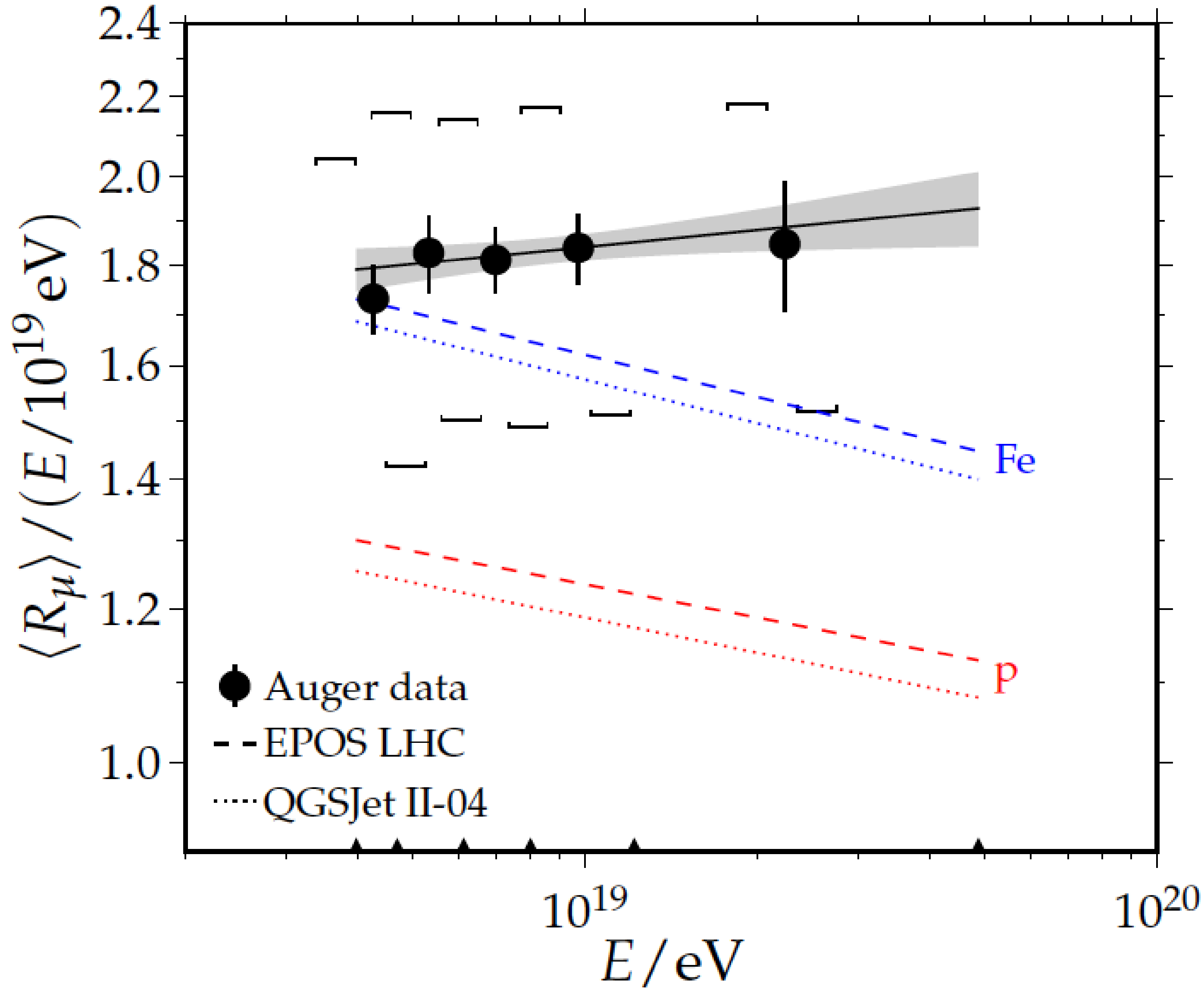


Log10(E/eV) > 19.0

AUGER Coll.
astro/ph 1408.4121

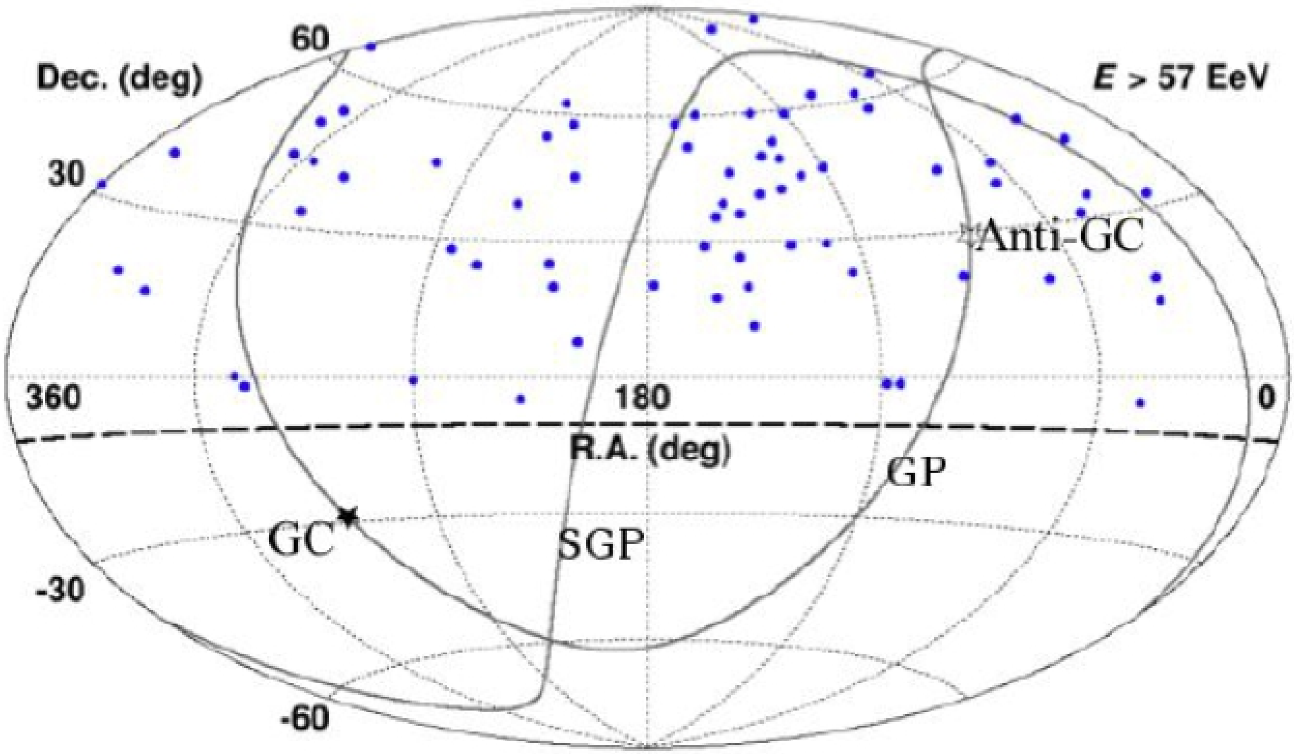
Average Muon number
in UHECR hybrid events

$R_\mu = 1$ corresponds to $N_\mu = 1.455 \times 10^7$



Hotspot

arXiv:1404.5890

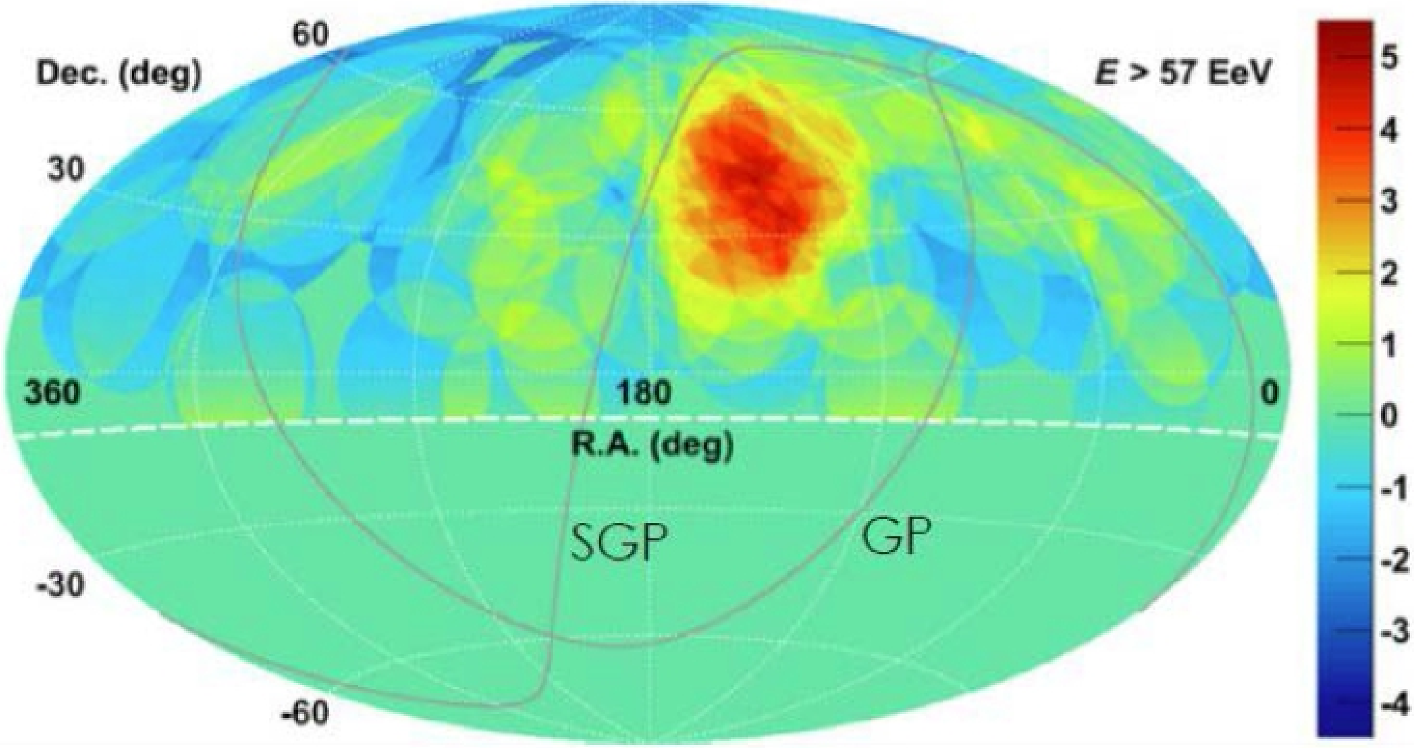


- ❖ Loose cut data: 72 events >57EeV, θ<55°, No boundary cut
- ❖ E resol. and Angular resol. do not change very much

For more detailed, see arXiv:1404.5890
Event list (>57EeV) has been published.

Hotspot

arXiv:1404.5890



- Loose cut data: 72 events >57EeV, θ<55°, No boundary cut
- Angular resolution does not change very much
- Oversampling with 20°-radius circle

- Hotspot center R.A.=146.7°, Dec. = 43.2° (max. 5.1σ)
- Chance probability from Isotropic sky : 3.7 x 10^{-4} (3.4 σ)

  i.e. 5.1σ enhancement anywhere in TA's FoV & any size r=15, 20,... 35°.

Masaki Fukushima

The TA Hotspot, Update

- 72 events (5 years) + 15 events (6th year) total with $E > 57$ EeV
- 19 events (5 years) + 4 events (6th year) in hotspot
- 5.1σ Li-Ma significance goes to 5.55σ
- 3.4σ (with sampling penalty) goes to 4.0σ
- For 6th year only, 4/15 events in previous hotspot: 7% probability

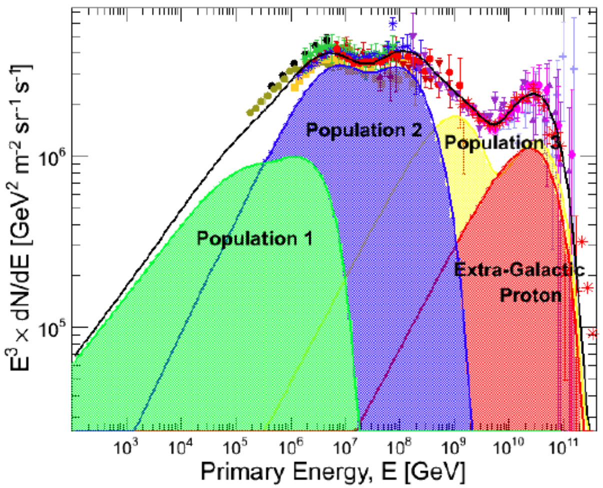
- The hotspot is getting hotter!

Scientific significance
of a real anisotropy effect
is remarkable

Interpretation of the Cosmic Ray spectral features

Interpretation of the Cosmic Ray spectral features

"Bold" synthesis of Gaisser, Stanev and Tilav



Population 1: The classical supernovae cutting around 100 TeV

Population 2: "Galactic PeVatron" → TeV neutrinos

Population 3: "Galactic EeVatron" → PeV neutrinos

Population 4: Extragalactic Proton: superposed on Population 3, cuts off due to GZK effect

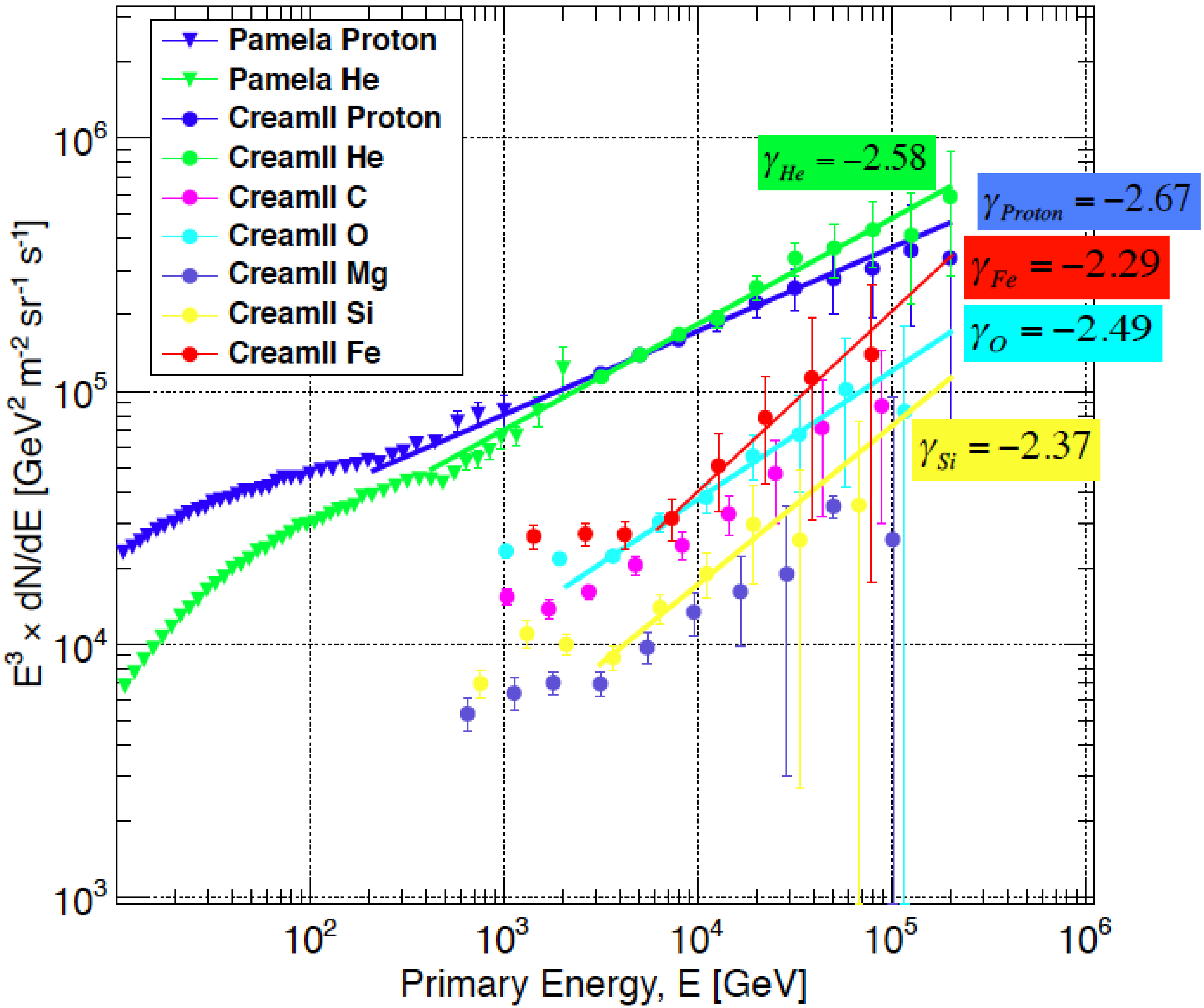
- Spectral index of 2.7 is the superposition of much harder indices of different elements (e.g. Proton:2.4, middle nuclei:2.3, Fe:2.2)

Fit the combined spectrum with Gaisser's formulation of Peters cycle

$$E\frac{dN}{dE} = \sum_{i}^{elements} A_i E^{-\gamma_i} e^{-\frac{E}{Z_i E_{cutoff}}}$$

A	Amplitude
γ	spectral index
E_{cutoff}	cut-off energy

Spectral Indices of the hard component



All Structure in the CR spectrum
attributed to effects in the accelerators

Propagation is a smooth (power law), featureless
softening effect.

All Structure in the CR spectrum
attributed to effects in the accelerators

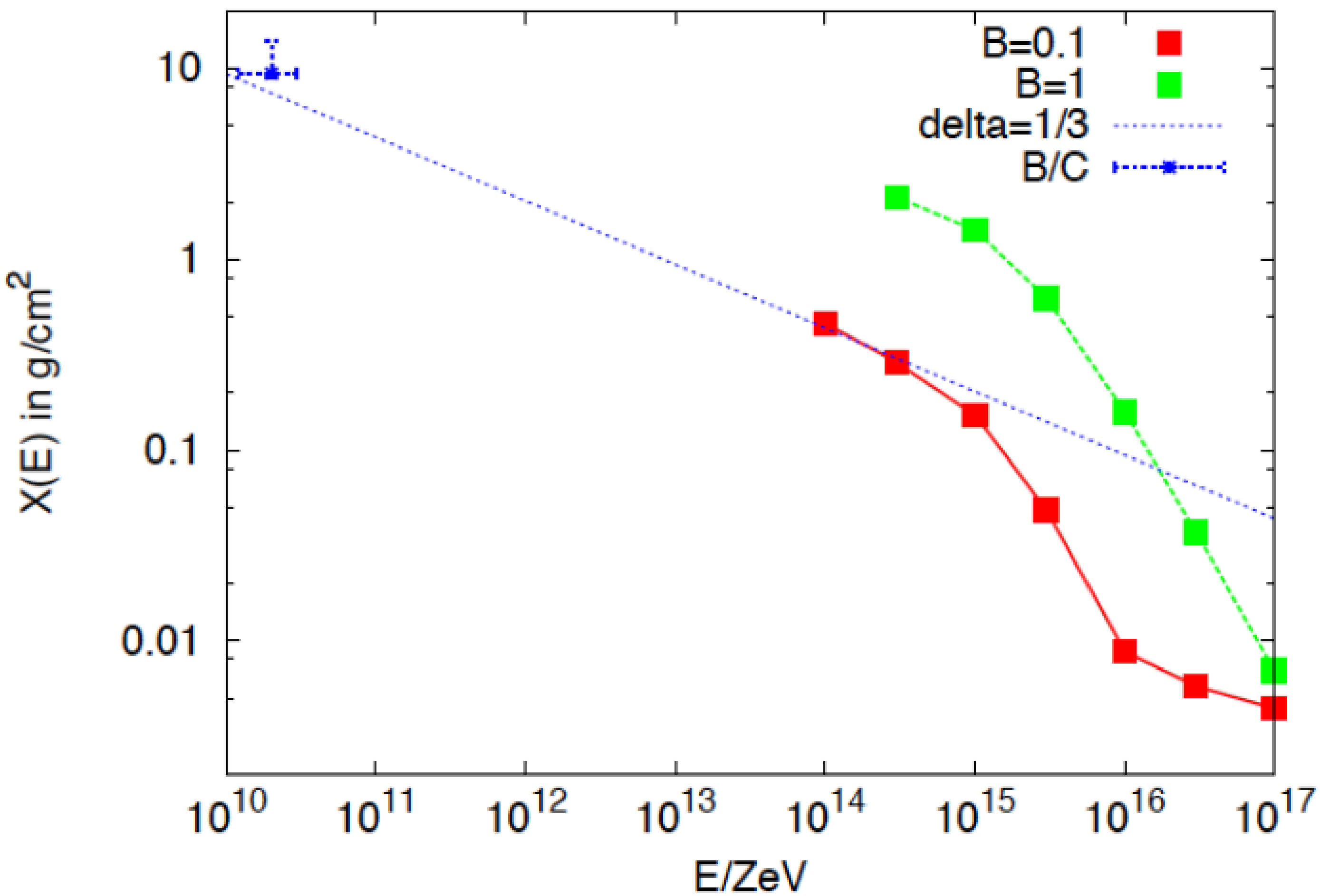
Propagation is a smooth (power law), featureless
softening effect.

Opposite assumption (for the knee)
By Dmitri Semikoz

All structure due to propagation:

Cosmic Ray Knee

- $l_{\rm coh}$ and regular field $\boldsymbol{B}(\boldsymbol{x})$ fixed from observations
- determine magnitude of random $\boldsymbol{B}_{\rm rms}(\boldsymbol{x})$ from grammage $X(E)$



Modeling of

HADRONIC INTERACTIONS

Quantum
Chromo
Dynamics

Quantum
Chromo
Dynamics

Instant history
of QCD in 4 nobel prizes

The proton is NOT point-like
(1955-1956)

$$\sqrt{\langle r^2 \rangle} \simeq 0.81 \text{ fm}$$

$$1 \text{ fm} \equiv 10^{-13} \text{ cm}$$

Robert Hofstadter

1961 Nobel prize to Robert Hofstadter
“for his pioneering studies in electron scattering
in atomic nuclei and for his thereby achieved discoveries
Concerning the structure of the nucleons

$$\left.\frac{d\sigma}{dQ^2}\right|_{ep\to ep} \simeq \left.\frac{d\sigma}{dQ^2}\right|_{\text{point}} \times \left|F(Q^2)\right|^2$$

$$F(Q^2) = \frac{1}{(1+Q^2\, r_0^2)^2}$$

$$q = k - k'$$

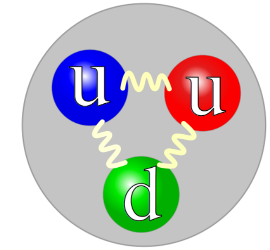
$$Q^2 = -q^2$$

The electromagnetic form factor of the proton

$$\rho_p(r) \propto e^{-r/r_0}$$

$$\boxed{\sigma_{pp} \sim \pi\, R_p^2 \simeq\ 3\ \text{fm}^2 \simeq 30\ \text{mbarn}}$$

A SCHEMATIC MODEL OF BARYONS AND MESONS *



M. GELL-MANN

California Institute of Technology, Pasadena, California

Received 4 January 1964

Baryons and Mesons are (formally) made of "Fundamental Entities"

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

6) James Joyce, Finnegan's Wake (Viking Press, New York, 1939) p.383.

Three quarks for Muster Mark!

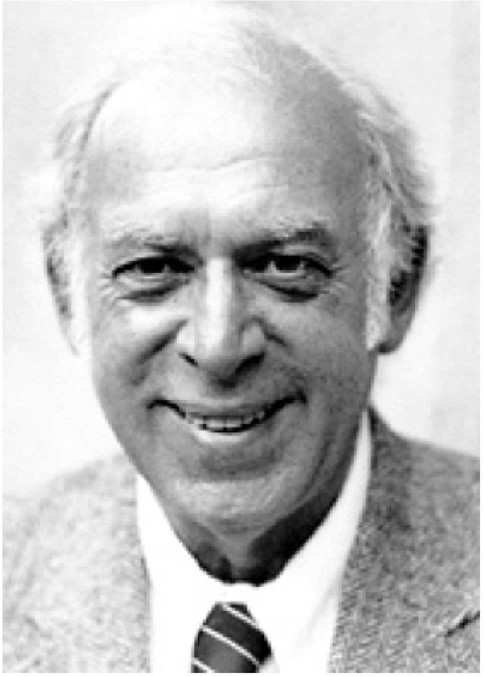
Sure he has not got much of a bark

And sure any he has it's all beside the mark.

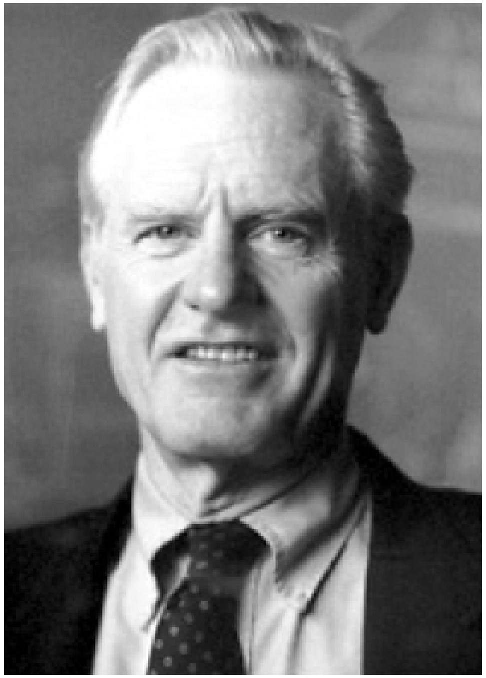
—James Joyce, *Finnegans Wake*[44]

The Nobel Prize in Physics 1990
Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

Quarks as “Partons” (1969)



Jerome I. Friedman



Henry W. Kendall

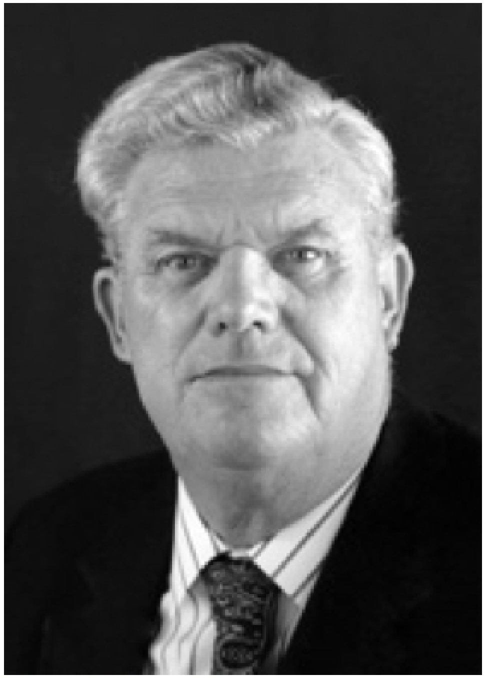


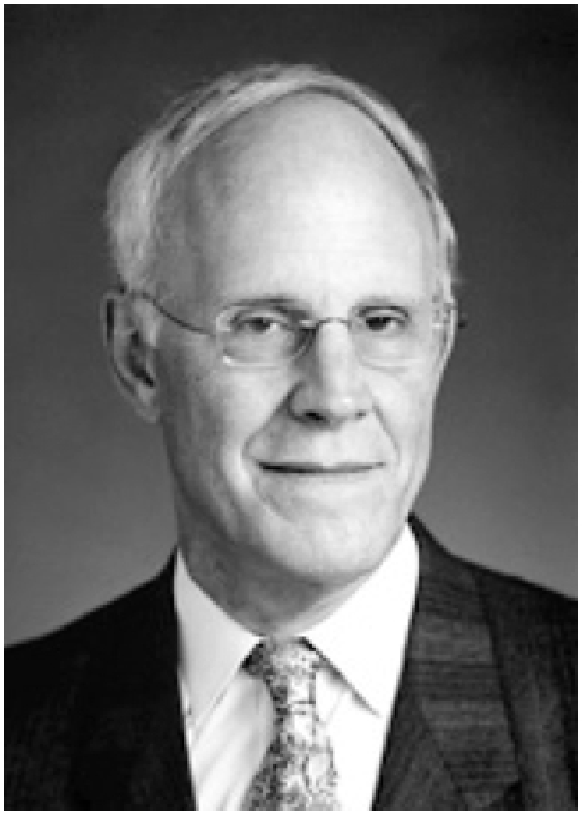
Photo: T. Nakashima

Richard E. Taylor

The Nobel Prize in Physics 1990 was awarded jointly to Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor *"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"*.

The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

QCD

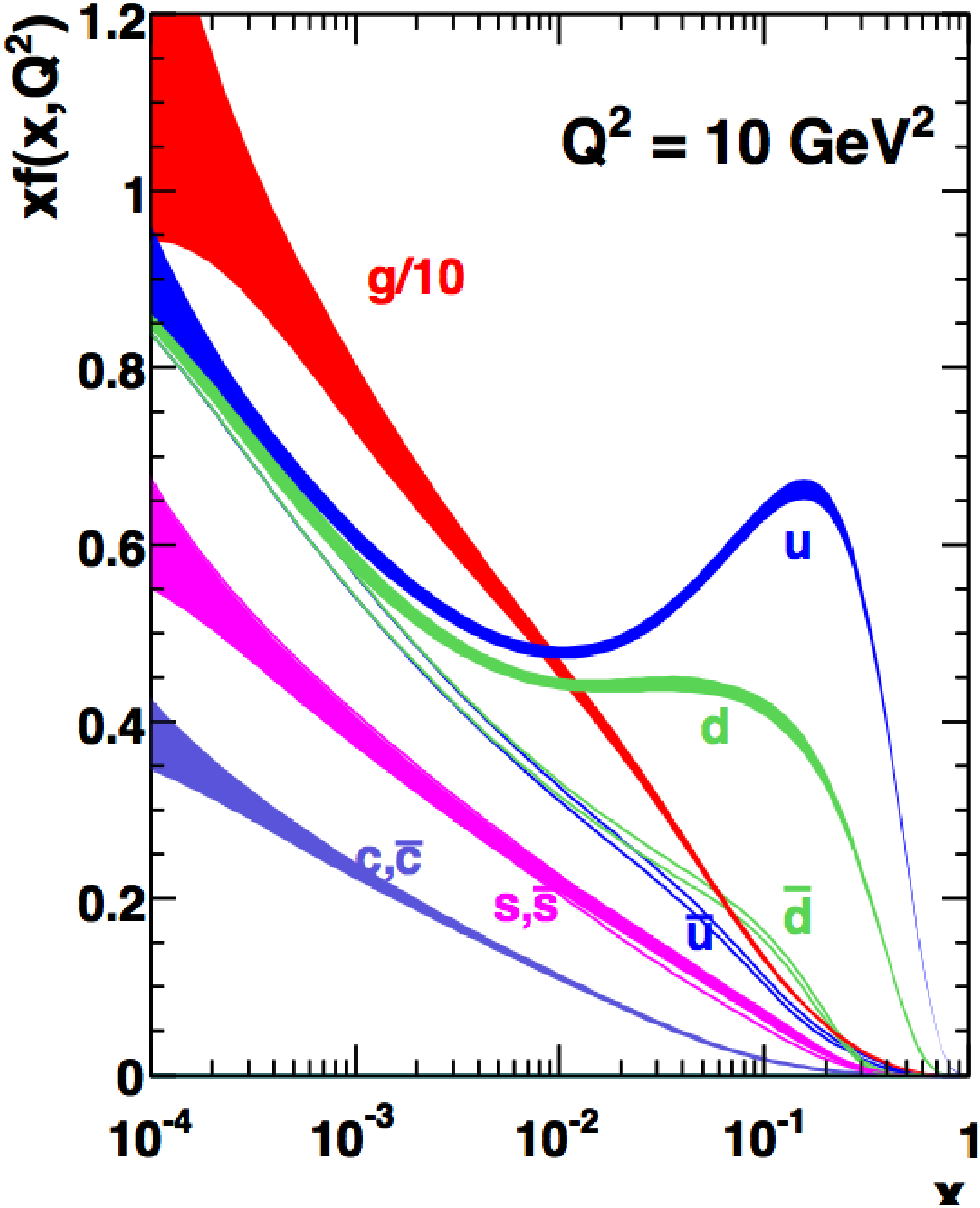


David J. Gross

H. David Politzer

Frank Wilczek

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.



Parton Distribution Functions

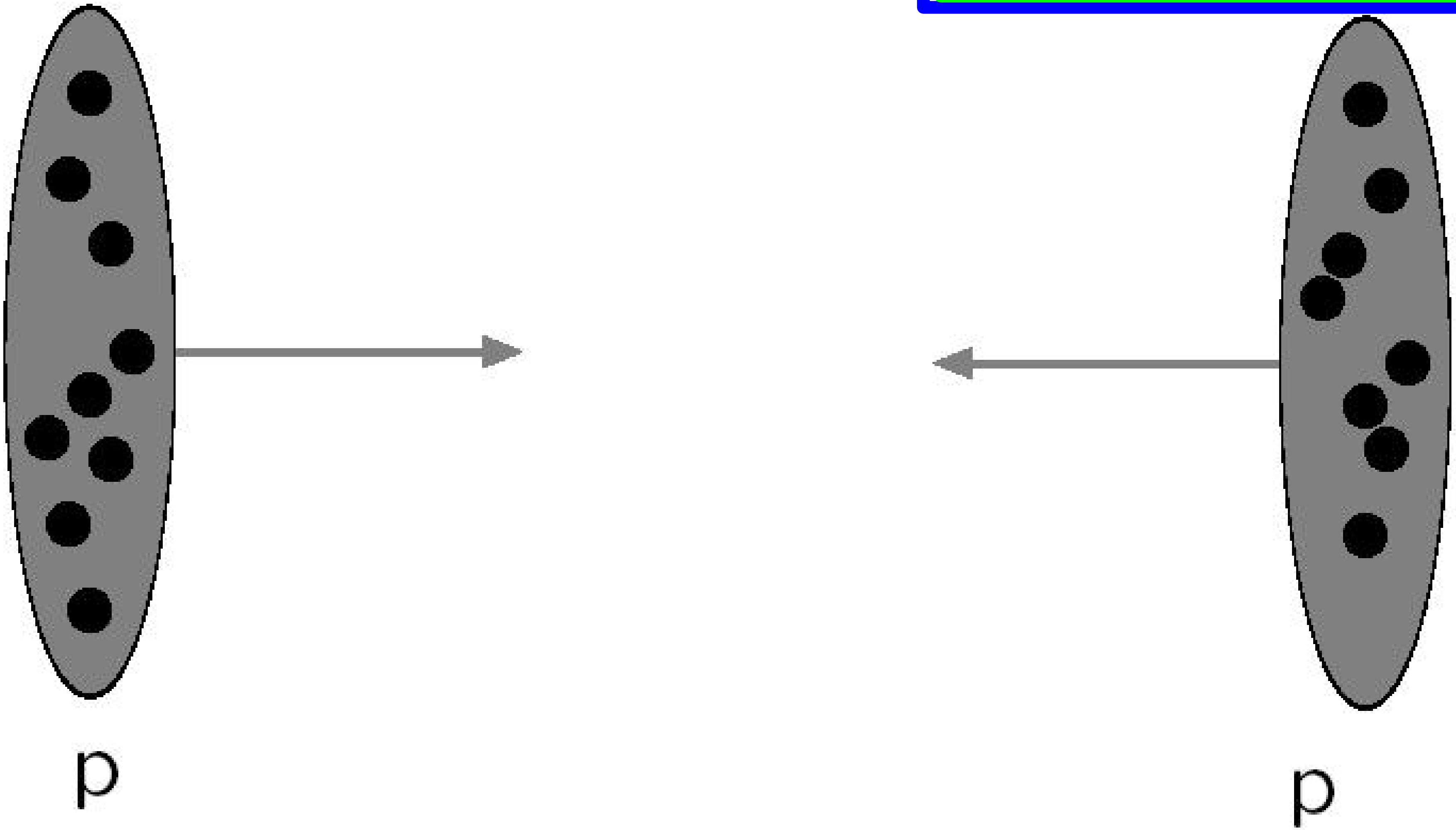
$$f_j(x) \propto \frac{1}{x^{1+\delta}}$$

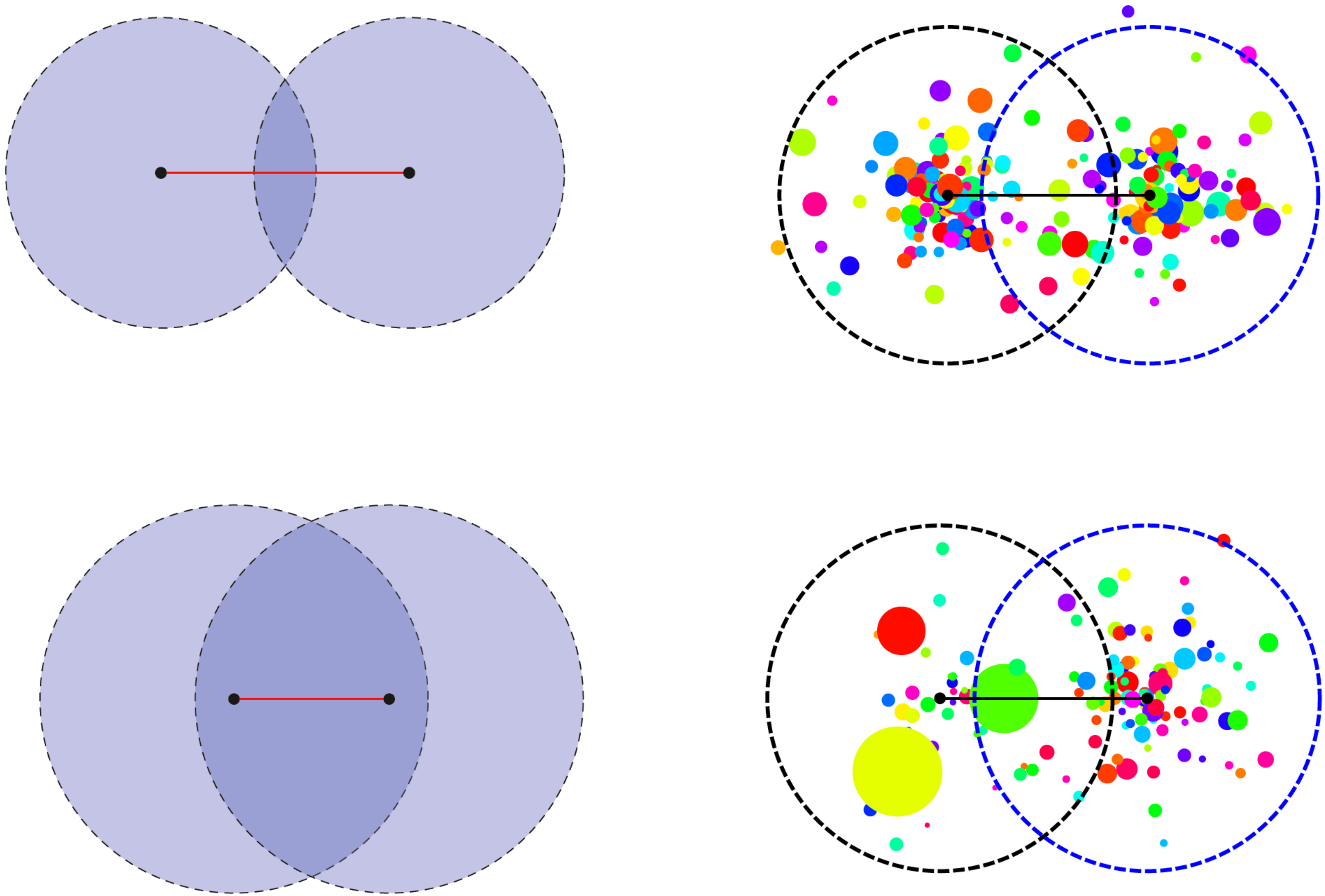
Rapid growth for $x \to 0$

Hadronic Interactions

Composite (complex) Objects
Multiple interaction structure

QCD



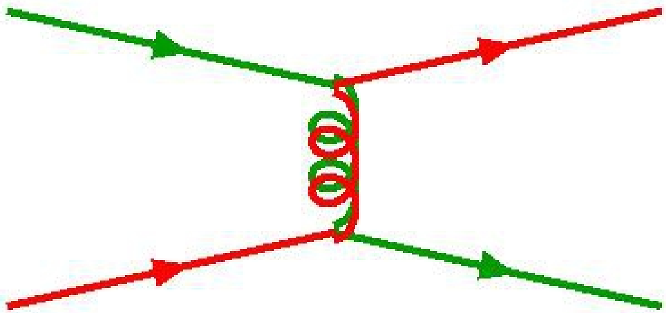


Multiple Parton Interactions
(in the same collision)
is the essential element in the modeling

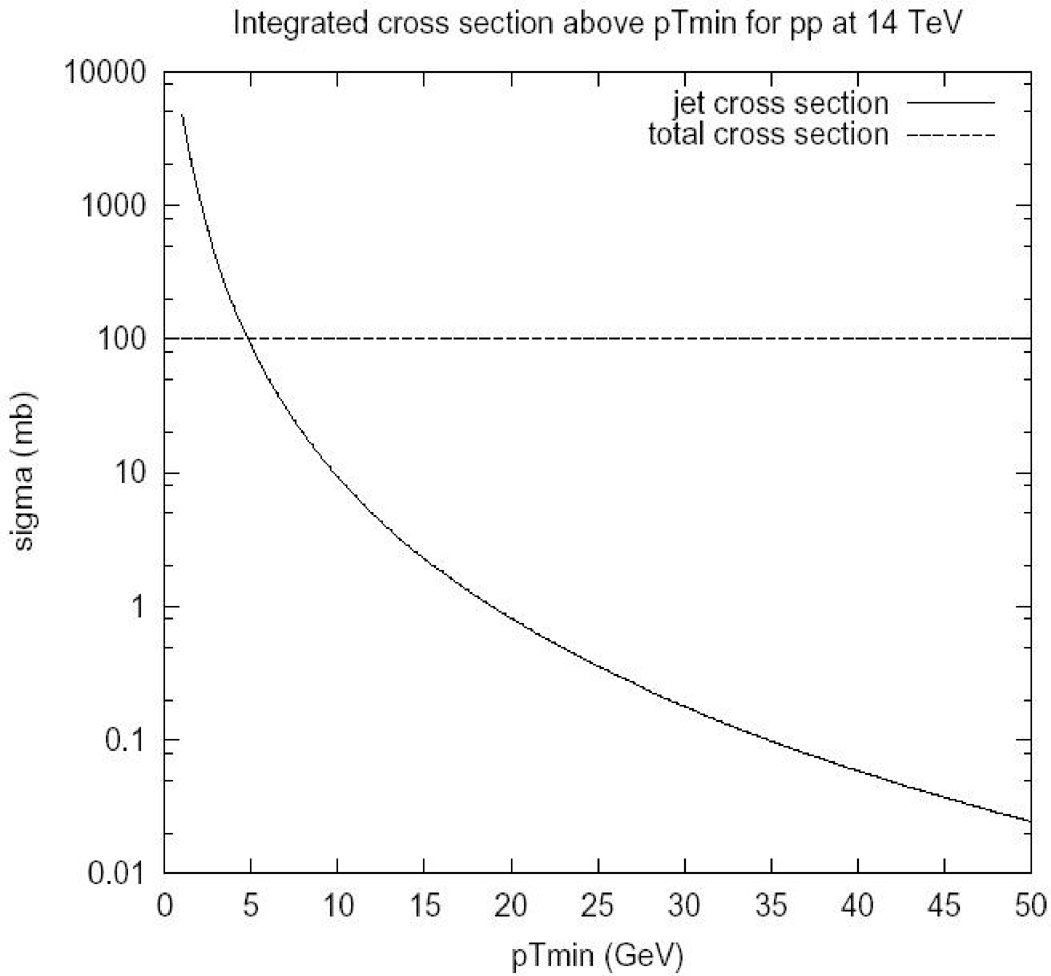
Problem of
"correlated PdF's" (energy conservation).

Problem of the "b-dependence" of the PdF's.
[briefly discussed by Anna Stasto]

QCD $2 \to 2$



$$qq' \longrightarrow qq'$$
$$q\overline{q} \longrightarrow q'\overline{q}'$$
$$q\overline{q} \longrightarrow gg$$
$$qg \longrightarrow qg$$
$$gg \longrightarrow gg$$
$$gg \longrightarrow q\overline{q}$$



$$\mathrm{d}\sigma/\mathrm{d}p_\perp^2 \approx 1/p_\perp^4 \text{ for } p_\perp \to 0.$$

$$\hat{s} = s\, x_1\, x_2$$

(c.m. energy)^2
of parton-parton system

$$Q^2 \leq \frac{\hat{s}}{2}$$

Interacting Partons

$$x_1 \;\; x_2 \gtrsim \frac{(\Lambda_{\rm QCD})^2}{s}$$

all

$$x_1 \;\; x_2 \gtrsim \frac{Q^2_{\rm min}}{s}$$

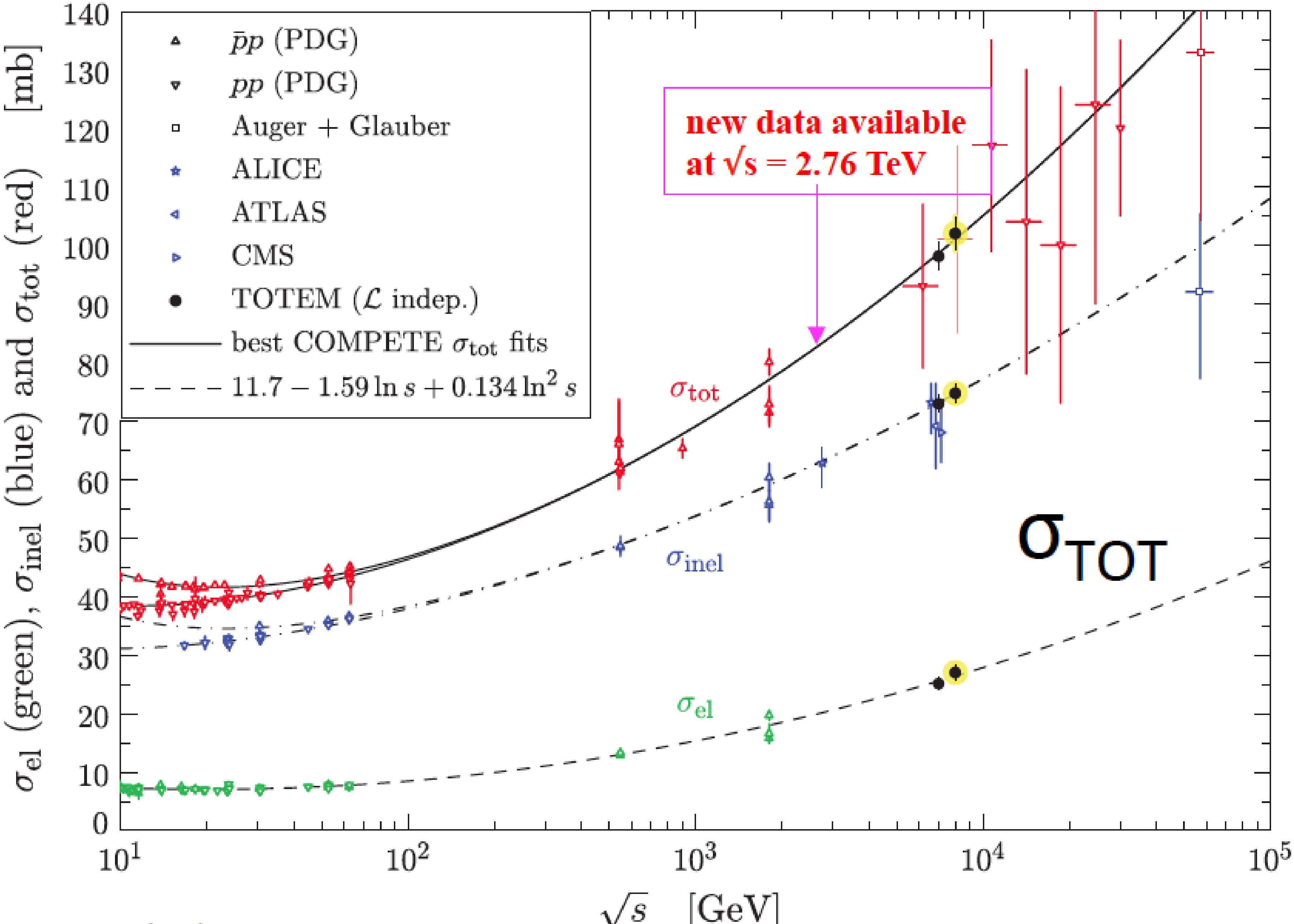
hard

Increasing the
c.m. Energy:

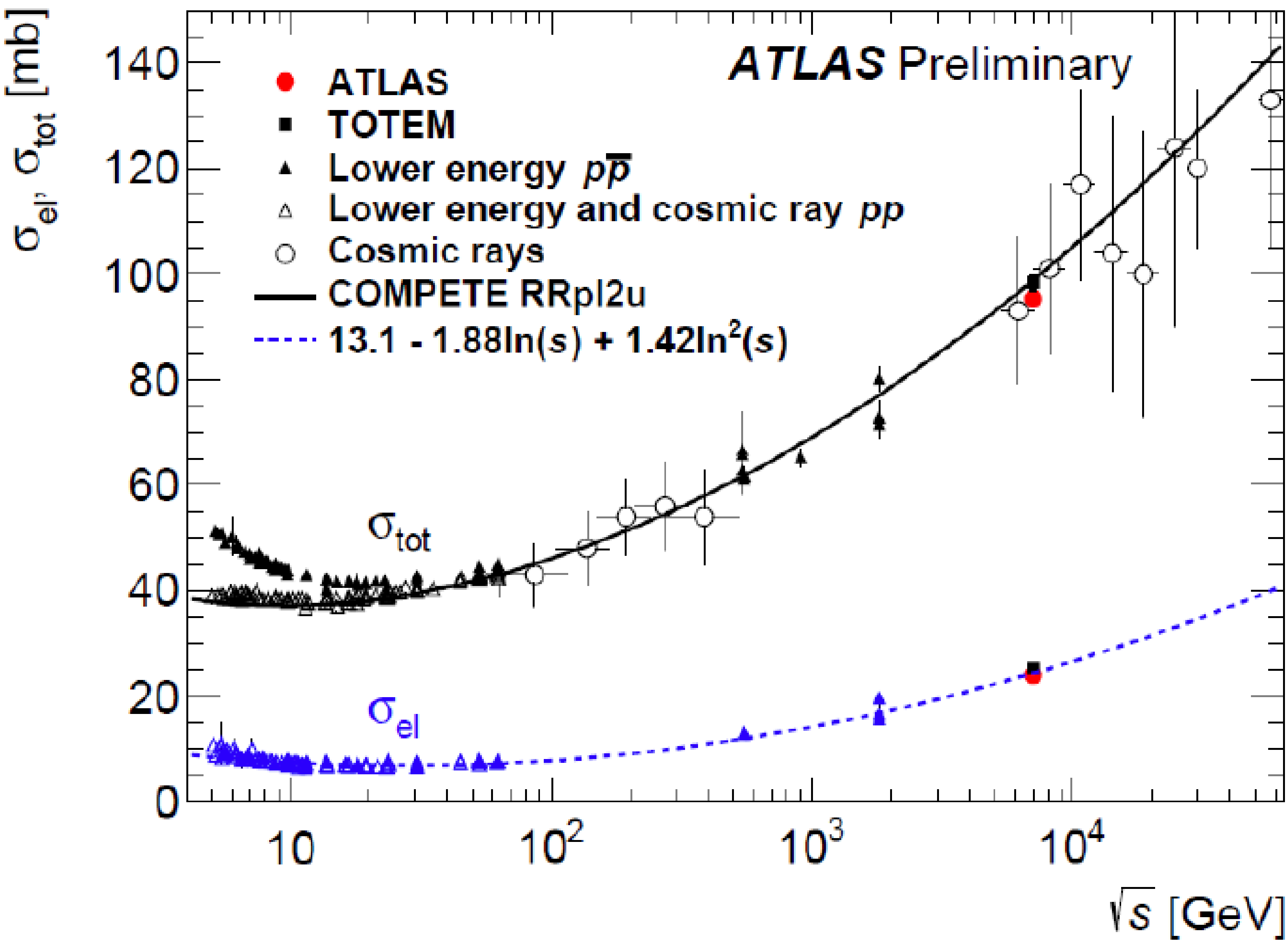
More parton-parton
Interactions

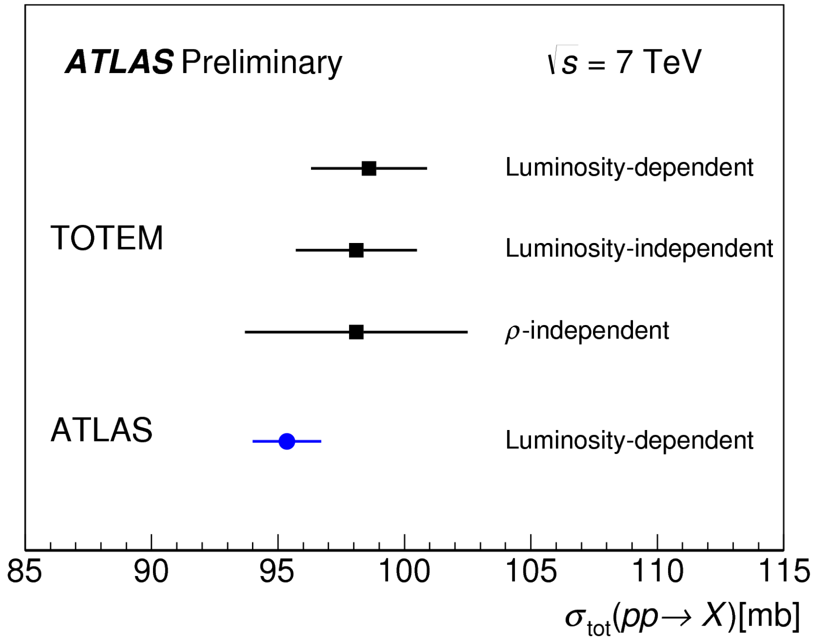
pp cross section grows
Higher multiplicity.
More complex event.
Softer energy spectra.

TOTEM measurements of total, elastic, I inelastic cross sections sqrt[s] = 7,8 TeV



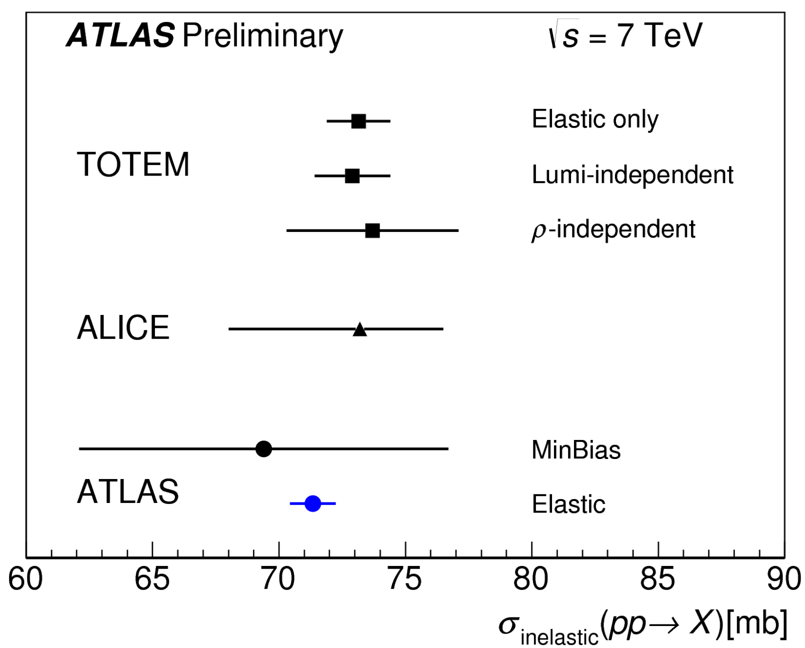
Recent ATLAS measurement at 7 TeV

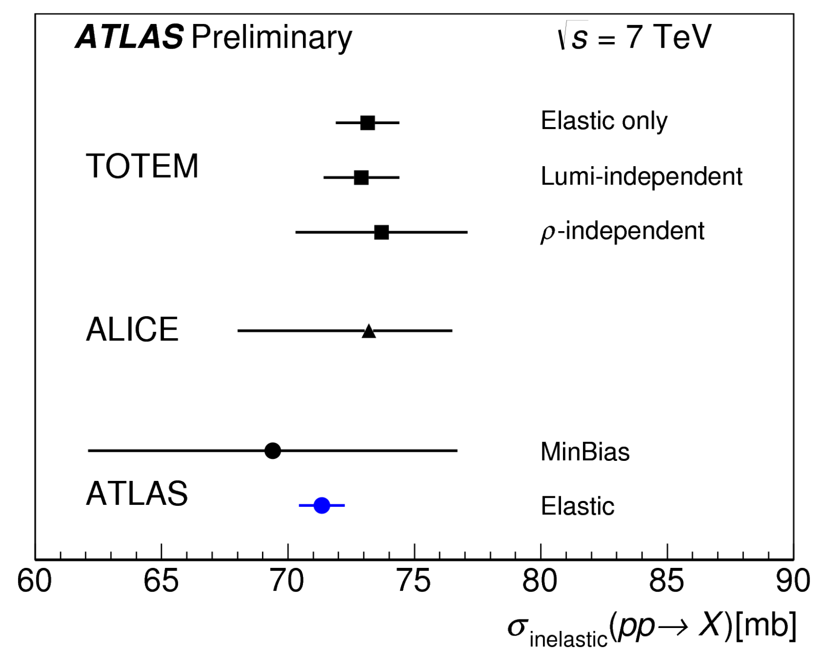




ATLAS $\sigma_{tot} = 95.4 \pm 1.4$ mb

TOTEM $\sigma_{tot} = 98.6 \pm 2.2$ mb





$$\sigma_{\mathrm{tot}} \qquad \sigma_{\mathrm{el}} \qquad \frac{d\sigma_{\mathrm{el}}}{dt}$$

$$\frac{dN_{\mathrm{ch}}}{dy} \qquad \frac{dN_{\mathrm{ch}}}{d\eta} \qquad \frac{dN_{\mathrm{ch}}}{dp_{\perp}\,dy}$$

$$\sigma_{\text{diffractive}}$$

$$\sigma_{\text{FD}} \qquad \sigma_{\text{BD}} \qquad \sigma_{\text{DD}}$$

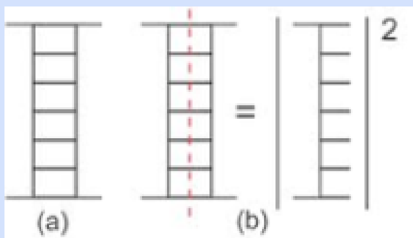
$$\frac{d^2\sigma_{\text{diff}}}{dt\,dM_X^2}$$

Peter Skands

Soft Physics : Theory Models

See e.g. Reviews by MCnet [arXiv:1101.2599] and KMR [arXiv:1102.2844]

A Regge Theory



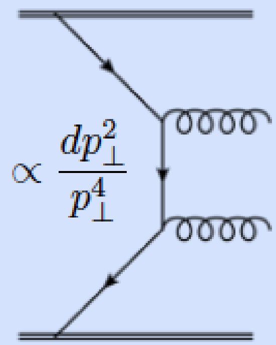
Optical Theorem
+ Eikonal multi-Pomeron exchanges

$\sigma_{\mathrm{tot,inel}} \propto s^{\varepsilon}$ or $\log^2(s)$

Cut Pomerons → Flux Tubes (strings)
Uncut Pomerons → Elastic (& eikonalization)
Cuts unify treatment of all soft processes
EL, SD, DD, … , ND

Perturbative contributions added above Q_0

B Parton Based



$$d\sigma_{2\to 2} \propto \frac{dp_\perp^2}{p_\perp^4} \otimes \mathrm{PDFs}$$

+ Unitarity & Saturation

→ Multi-parton interactions (MPI)
+ Parton Showers & Hadronization
Regulate dσ at low p_{T0} ~ few GeV
Screening/Saturation → energy-dependent p_{T0}

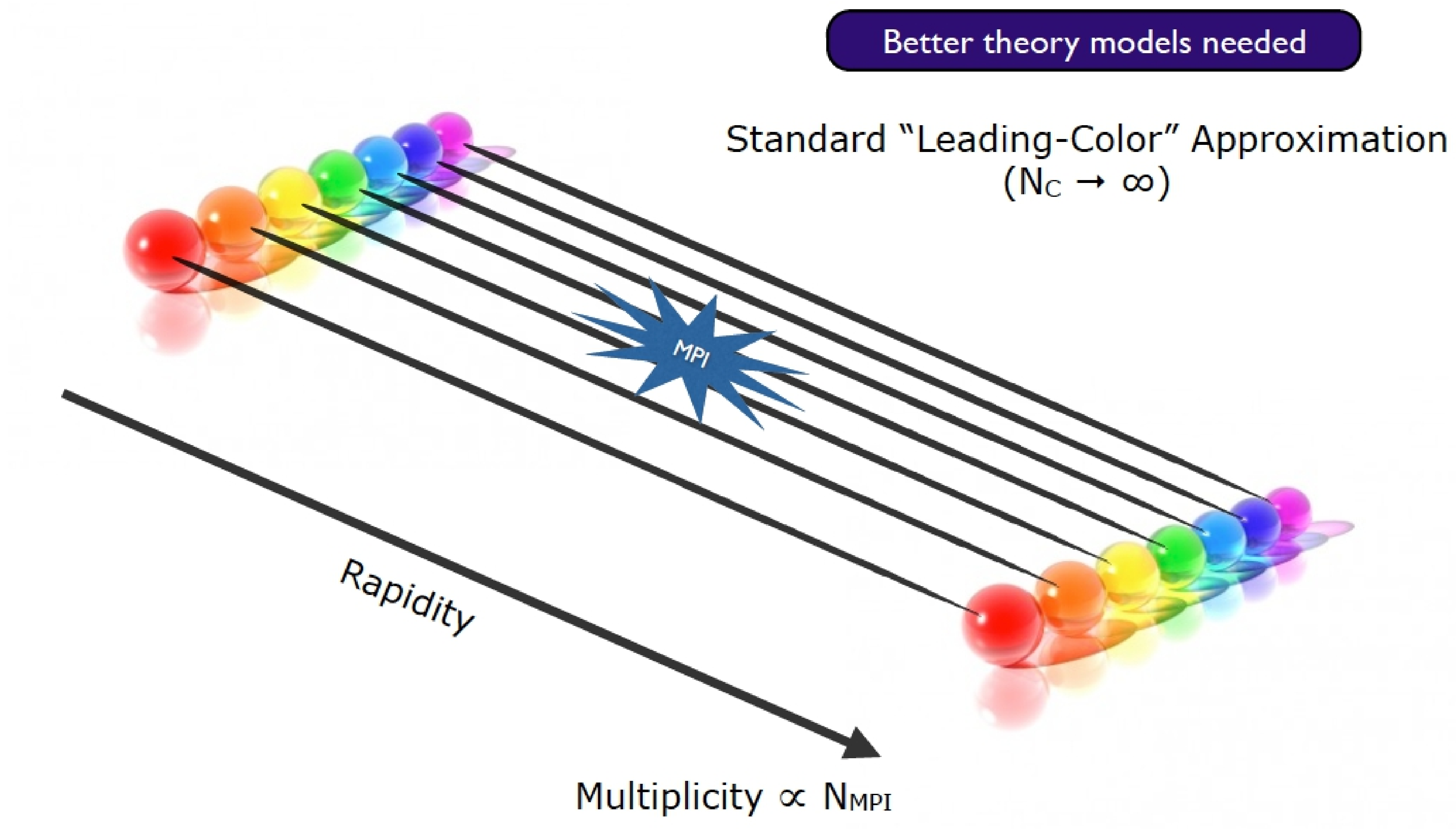
Total cross sections from Regge Theory
(Donnachie-Landshoff + Parametrizations)

E.g., QGSJET, SIBYLL

+ "Mixed"
E.g., PHOJET, EPOS, SHERPA-KMR

E.g., PYTHIA, HERWIG, SHERPA

MPI and Colour

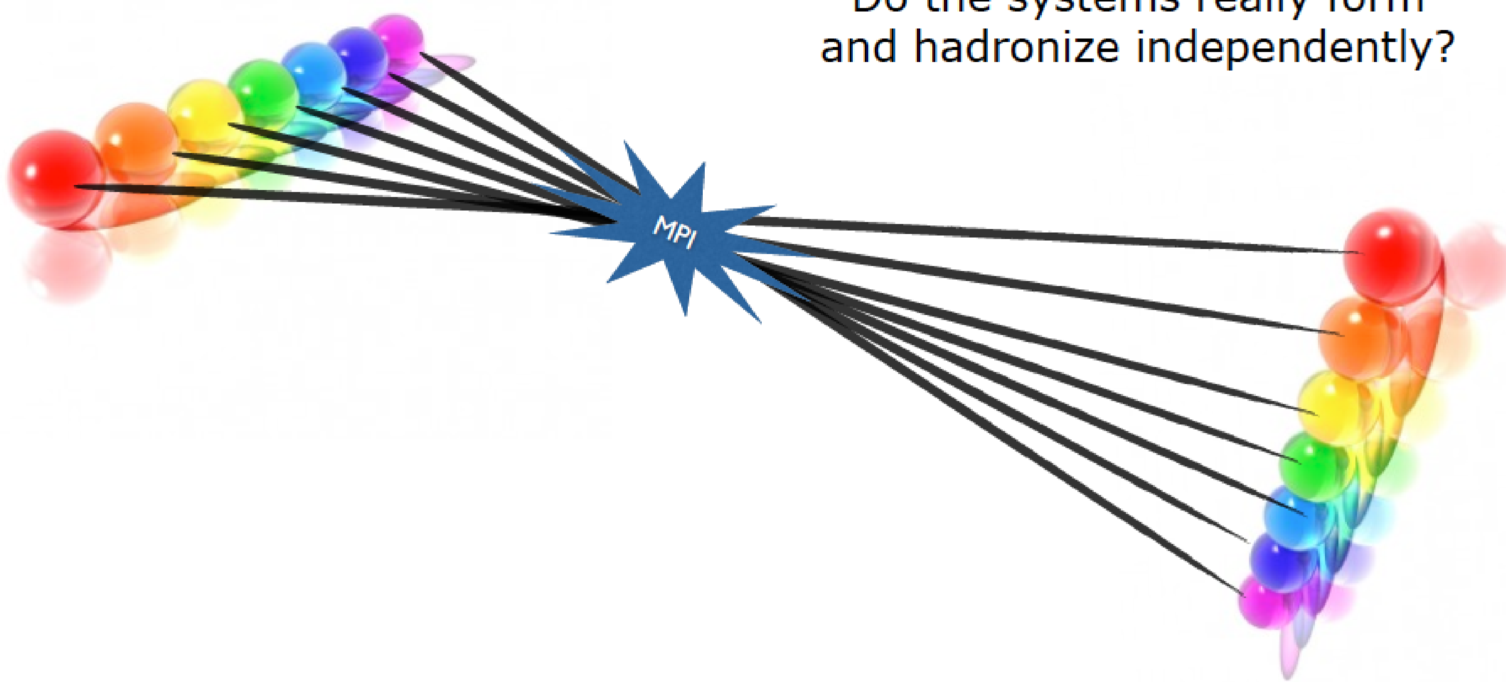


Color Reconnections?

E.g.,
Generalized Area Law (Rathsman: Phys. Lett. B452 (1999) 364)
Color Annealing (Skands, Wicke: Eur. Phys. J. C52 (2007) 133)
Herwig++ model (Gieseke, Rohr, Siodmok : Eur.Phys.J. C72 (2012) 2225)

Better theory models needed

Do the systems really form
and hadronize independently?



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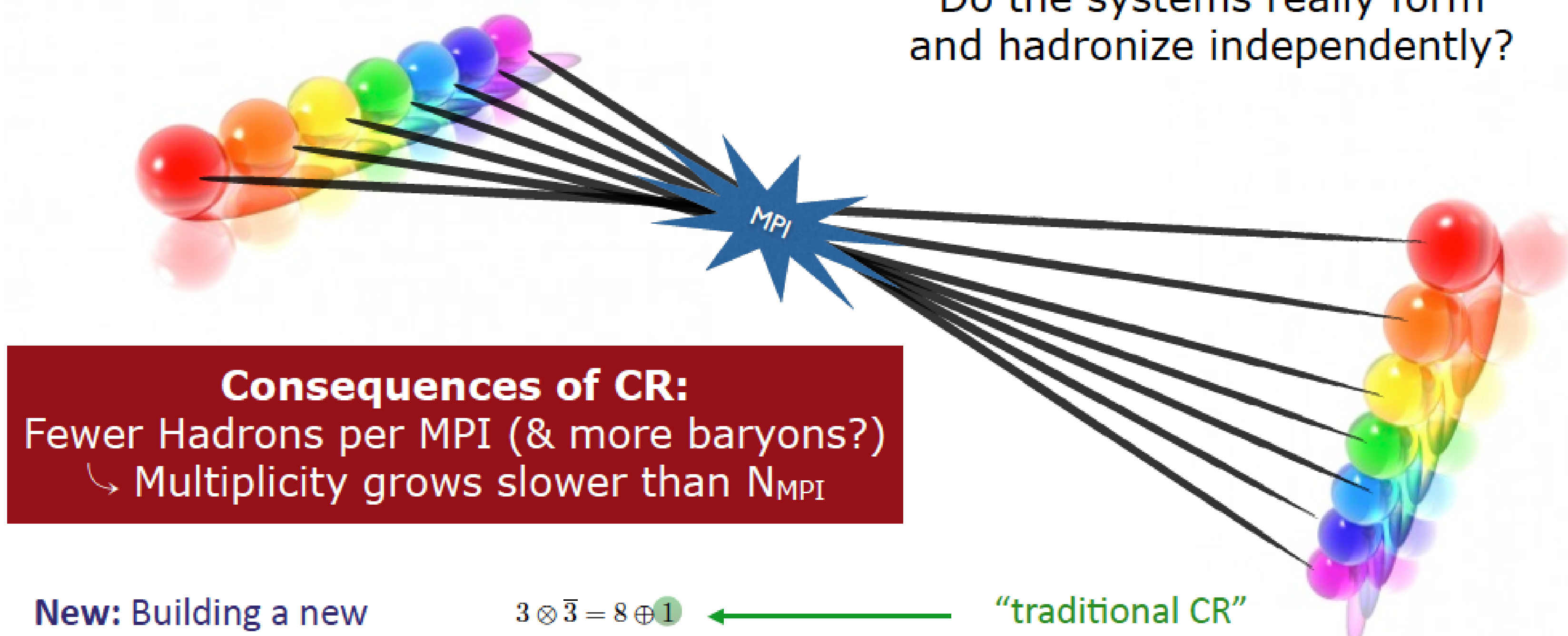


Consequences of CR:
Fewer Hadrons per MPI (& more baryons?)
↳ Multiplicity grows slower than N_{MPI}

New: Building a new model for PYTHIA 8, based on SU(3) weights
[with J. Christiansen (Lund U)]

$3 \otimes \bar{3} = 8 \oplus 1$ ← "traditional CR"

$3 \otimes 3 = 6 \oplus \bar{3}$ ← "new" sources of baryons (& antibaryons)

$8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1,$

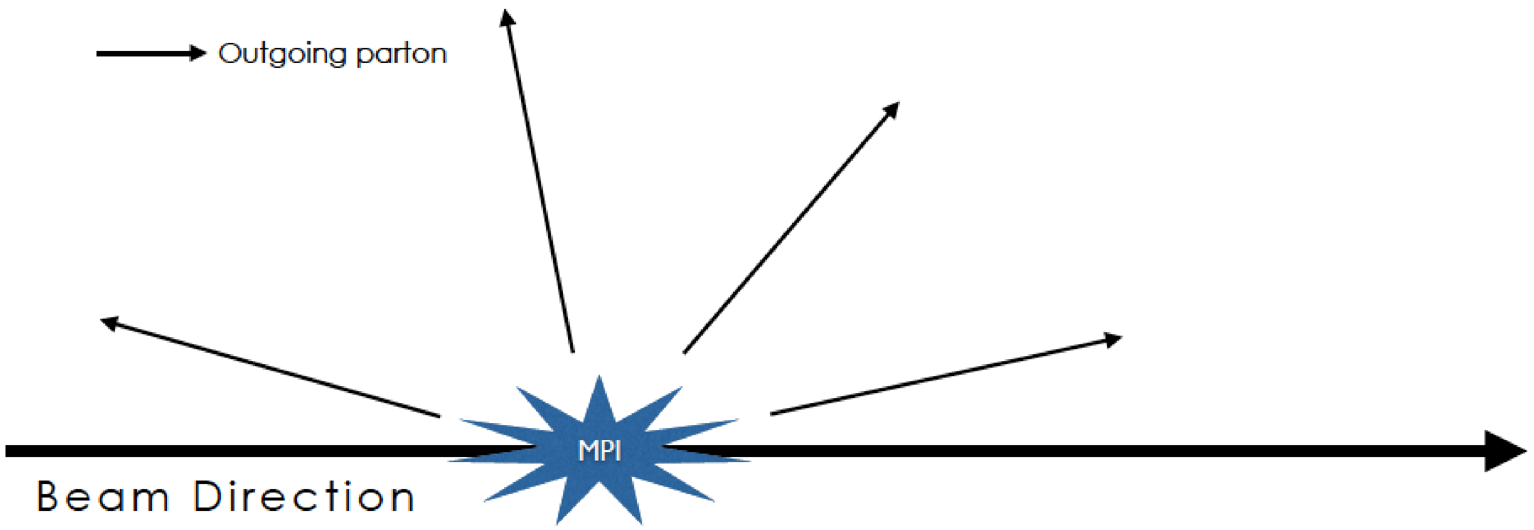
$3 \otimes 8 = 15 \oplus 6 \oplus 3,$

also indicated by LHC data!

Collective Flow?

See also Ortiz et al., Phys.Rev.Lett. 111 (2013) 4, 042001

Without Colour Reconnections
Each MPI hadronizes **independently** of all others



Collective Flow?

See also Ortiz et al., Phys.Rev.Lett. 111 (2013) 4, 042001

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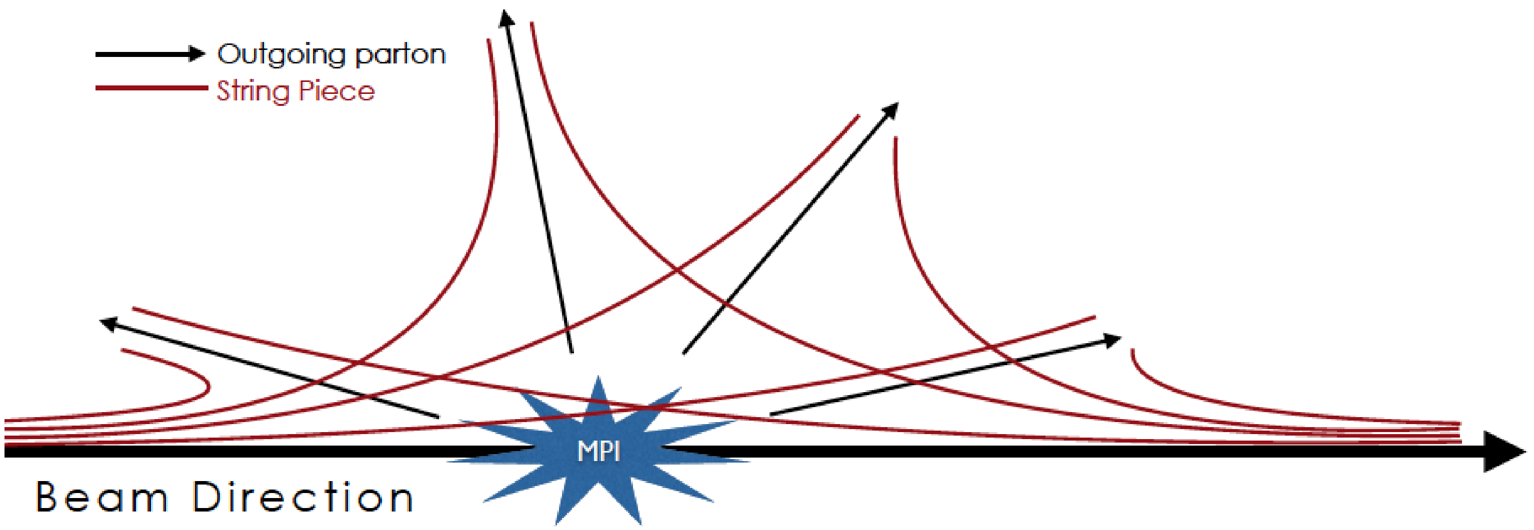
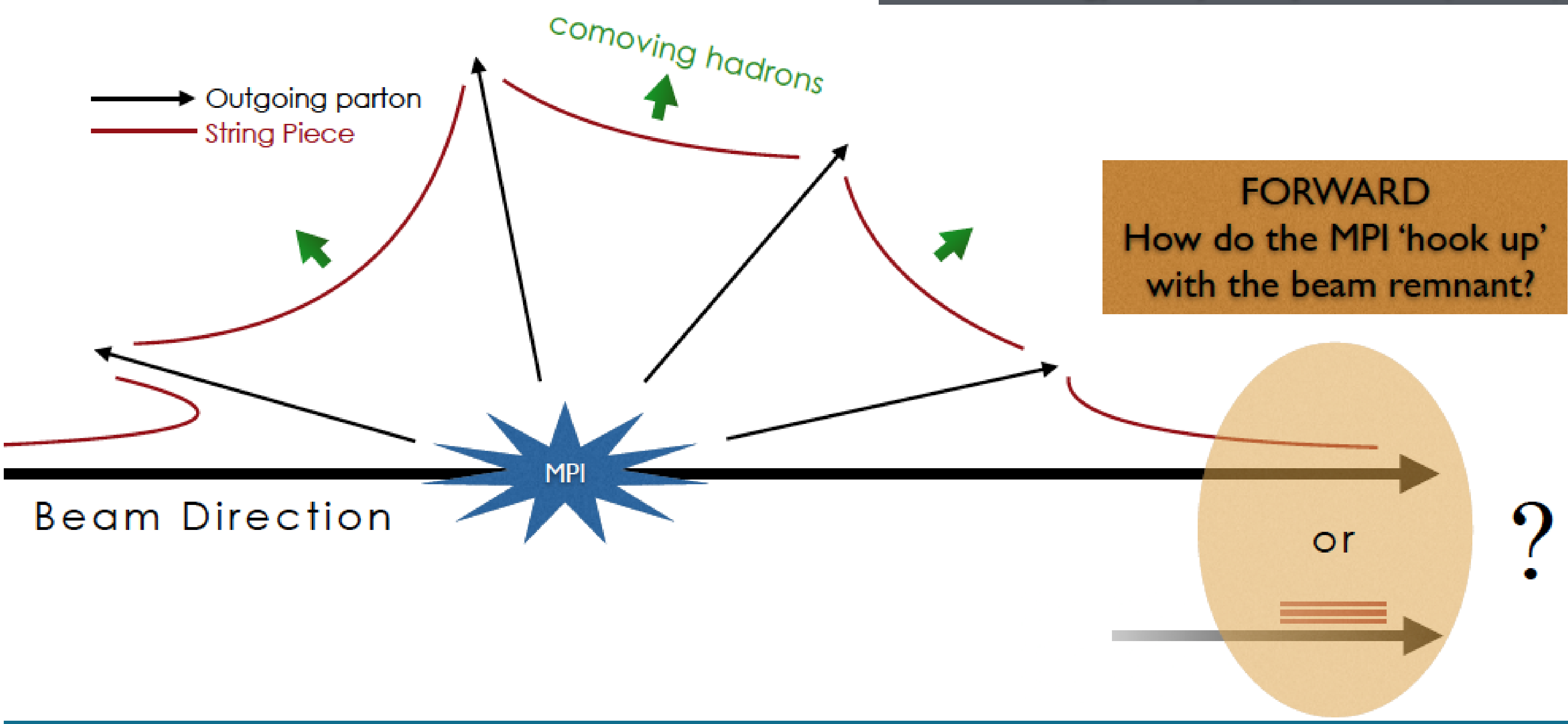


... from boosted strings?

See also Ortiz et al., Phys.Rev.Lett. 111 (2013) 4, 042001

With Colour Reconnections
MPI hadronize **collectively**

Highly important theory question now
Is there collective flow in pp? Or not?
Is it stringy, or hydrodynamic ? (or …?)



Peter Skands

Summary & Puzzles

HEP MC Models mainly target (and rooted in) high-p_T perturbative scattering processes

- Jets and Jet Structure (ISR & FSR: parton showers) + hadronization (strings/clusters)

Lesson from Tevatron (Rick Field): Underlying Event mandates MPI

- Already hinted at from AFS, SPS. No doubt after LHC

PYTHIA, HERWIG, and SHERPA all include MPI models

- Under quite active development, mainly in response to LHC
- Also used as basis to model (nondiffractive) minimum-bias

Check e.g.:
mcplots.cern.ch

Lessons from LHC

- Energy scaling is somewhat faster than we thought (larger UE)
- More strangeness (?) and more baryons
- Flow-like spectra? Nch and Mass dependencies. Correlations? (cf RHIC, Tevatron)
- Forward measurements: baryon transport, low-x, forward E, ET, and jets
- The role and modeling of diffraction, from low to high masses? Gap fractions.

Quo Vadis?

- Understand process of color neutralization (CR) vs hydro flow?
- Spacetime picture of MPI
- Understand connection with initial state: saturation, color-glass condensates?

My personal appeal to Peter Skands (and to the LHC Montecarlo builders)

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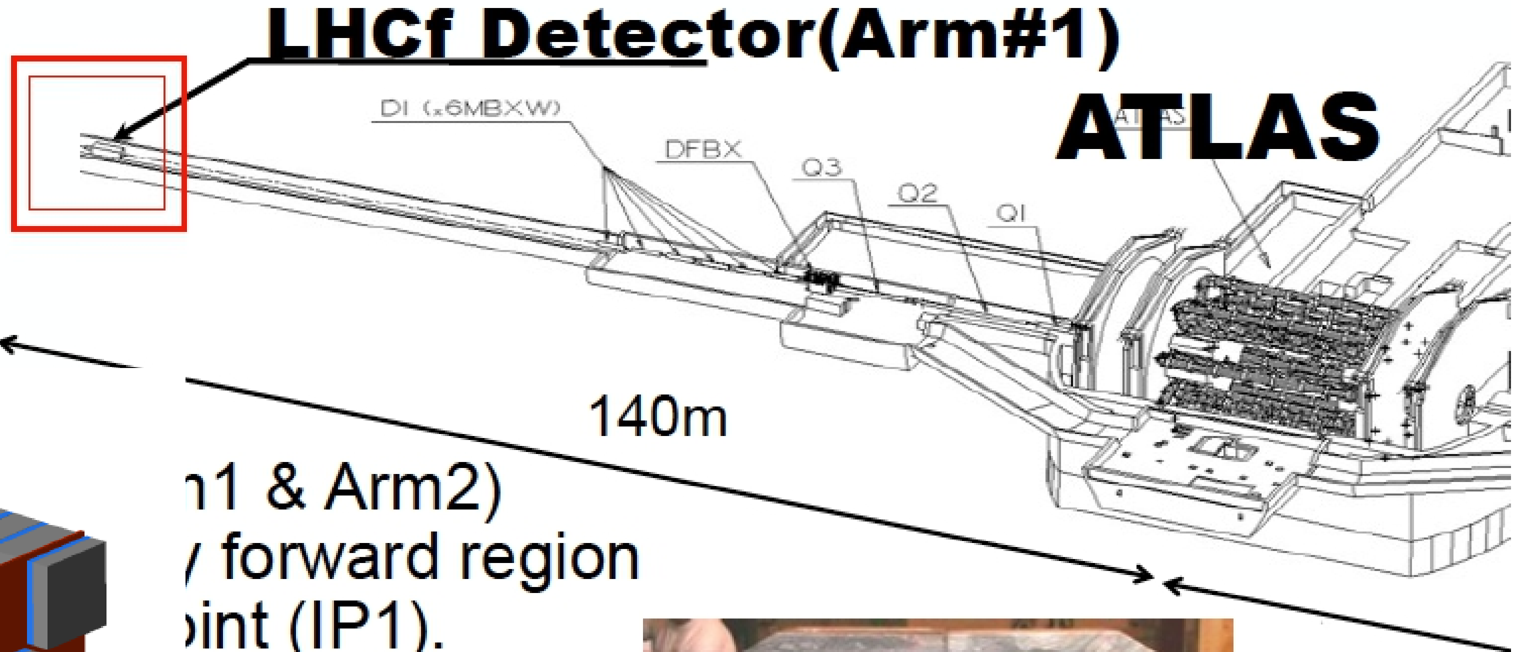
Develop your model also for
interactions of proton-nucleus, nucleus-nucleus
(and the interactions of meson-nucleus)

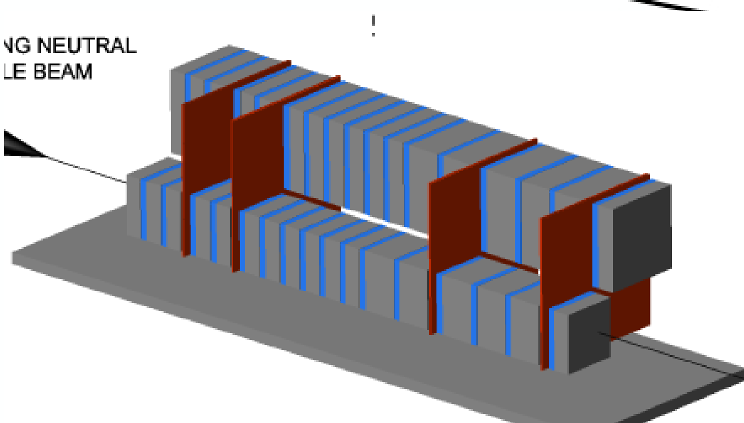
This seems to be clearly of interest to test
many ideas and insights,
and of great value for cosmic ray studies.

The separation between MC codes for accelerators
and MC codes for cosmic ray studies has technical
Motivations, but it is of course unnecessary and undesirable

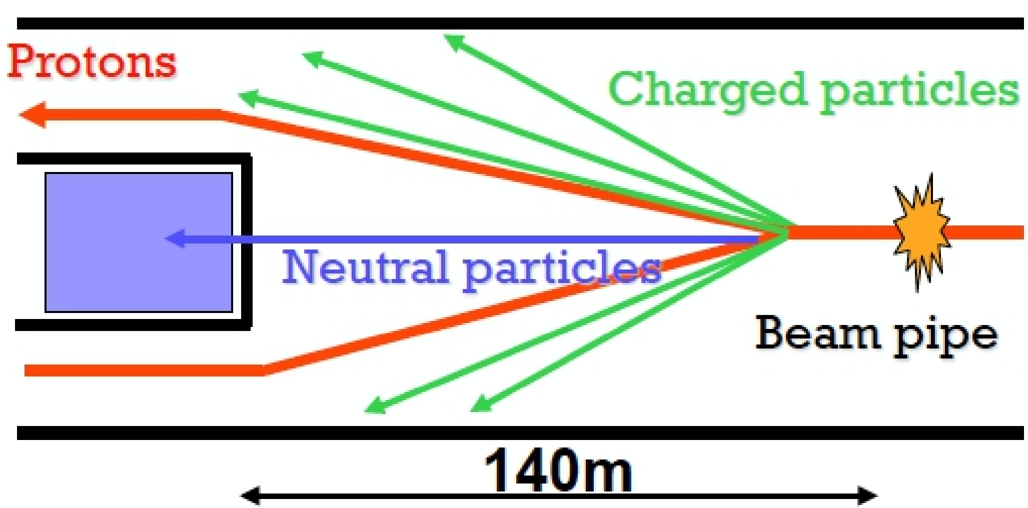
LHCf Experiment

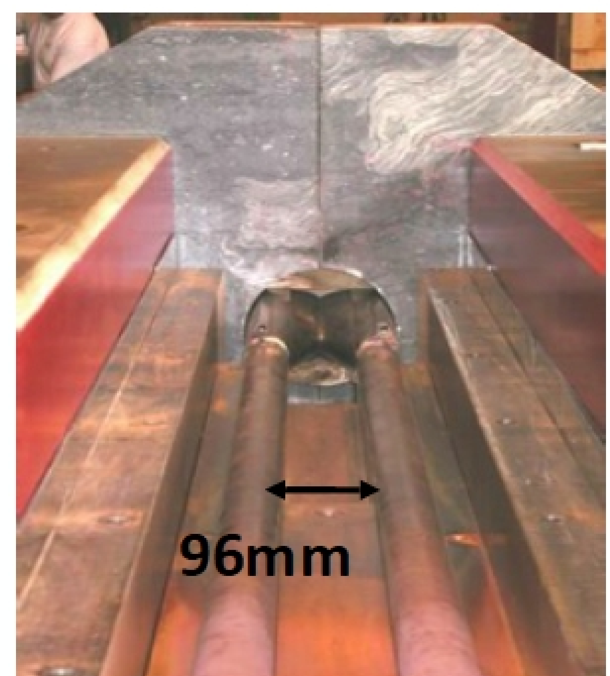
Yoshitaka ITOW
Hiroaki MENJO



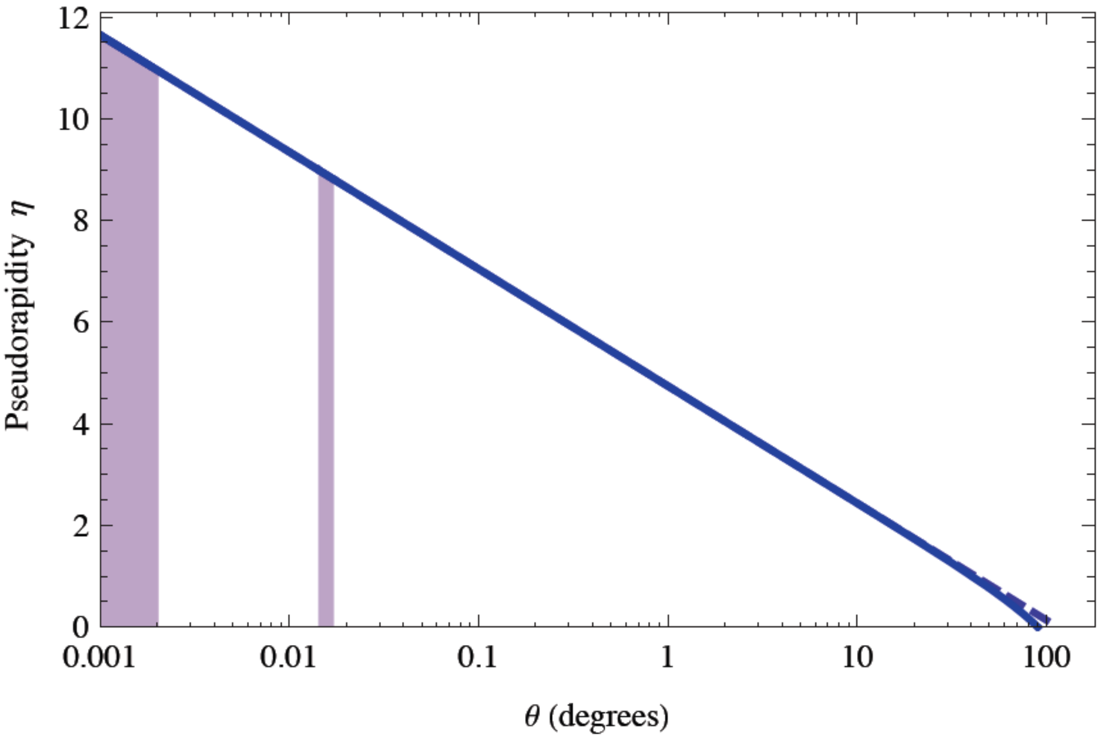


1 & Arm2)
/ forward region
oint (IP1).
al particles
e **η > 8.4.**

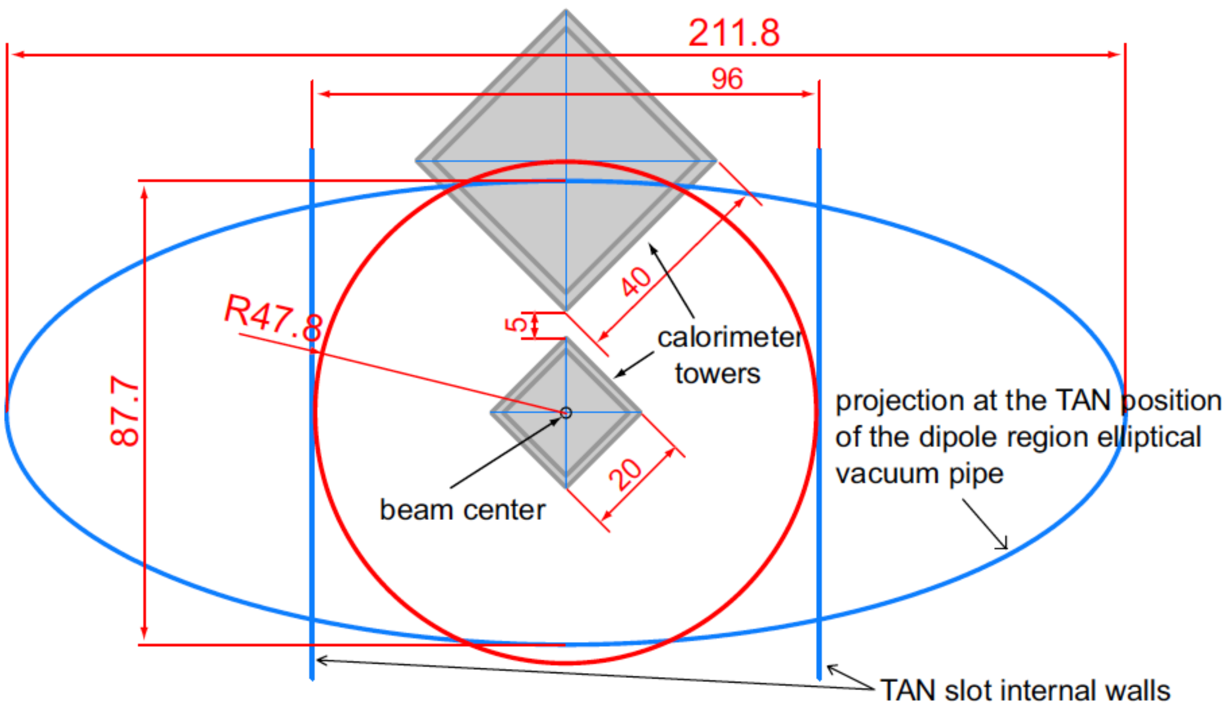




Pseudo-Rapidity versus angle:

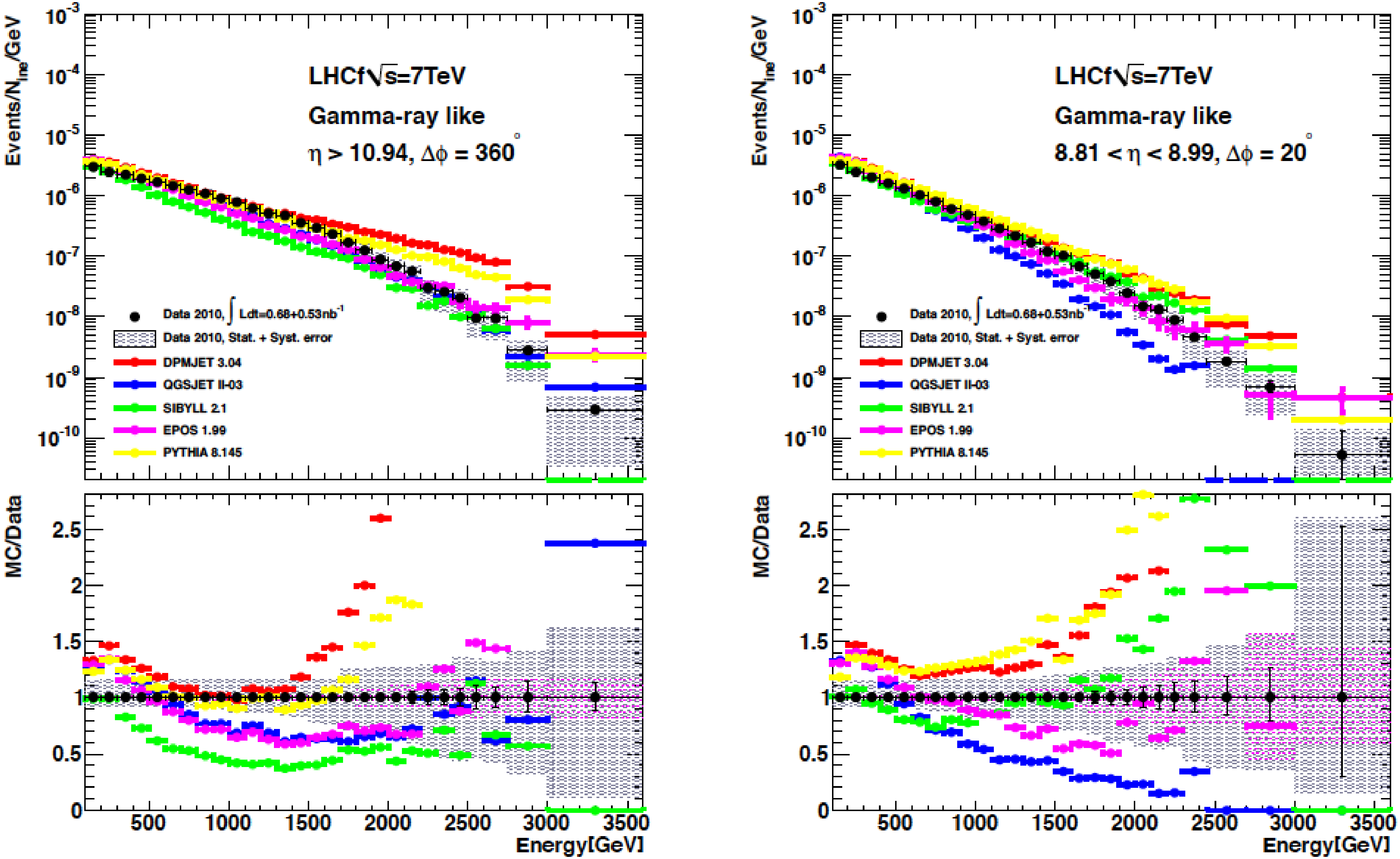


Very small angle production:



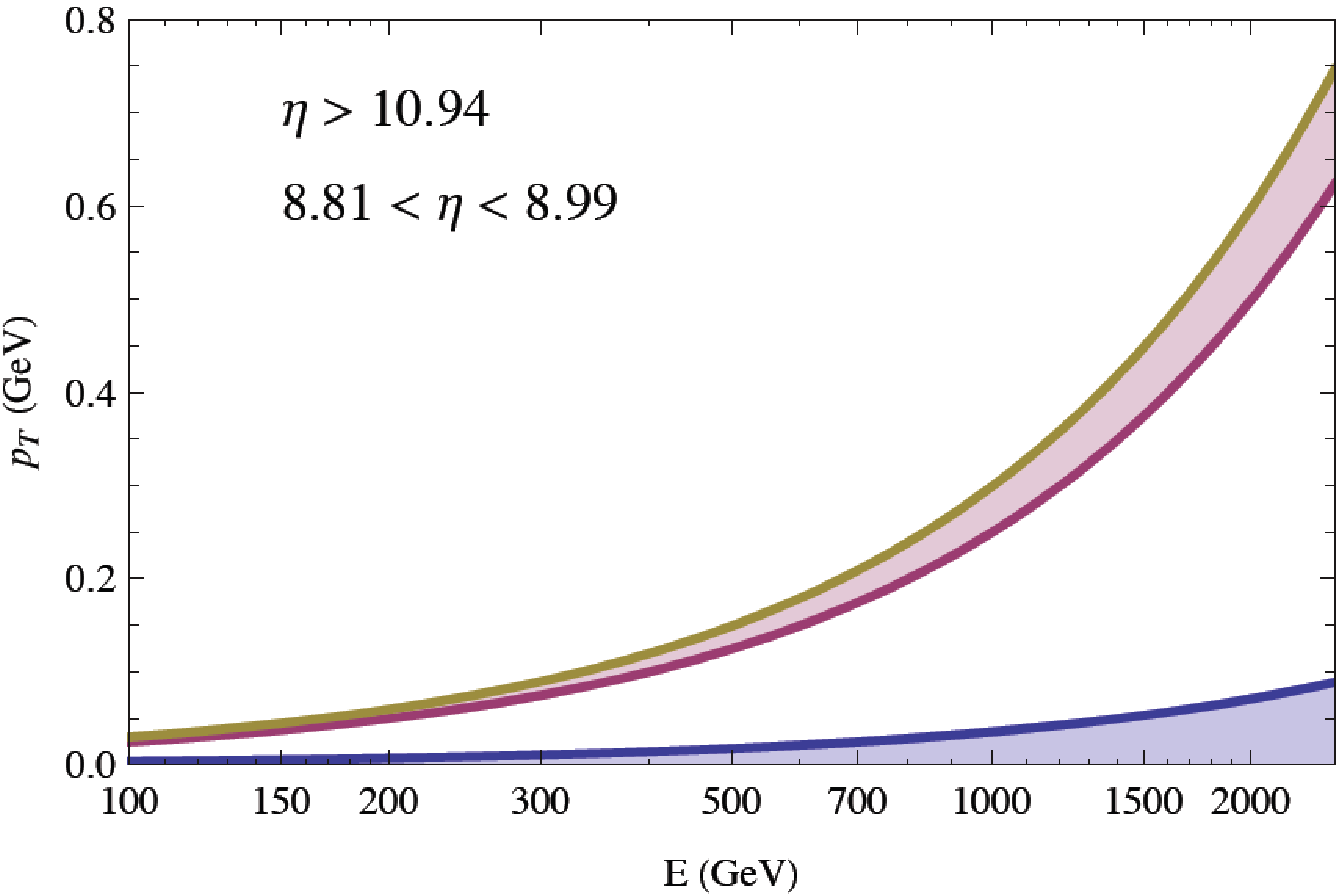
LHCf data hep-ex/1104.5294

[photon distributions in 2 very forward angular regions]



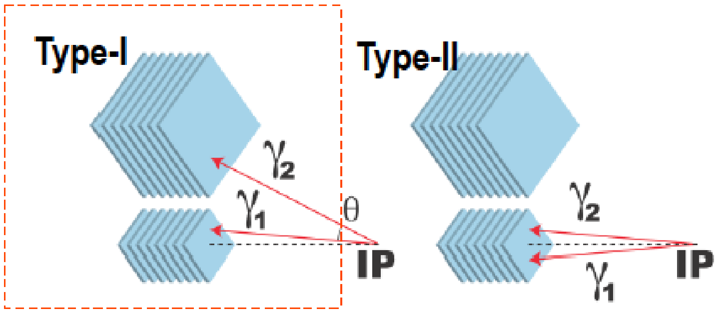
$$p_\perp = \sqrt{E^2 - m^2}\ \sin\left[2\ \tan^{-1}\left(e^{-\eta}\right)\right]$$

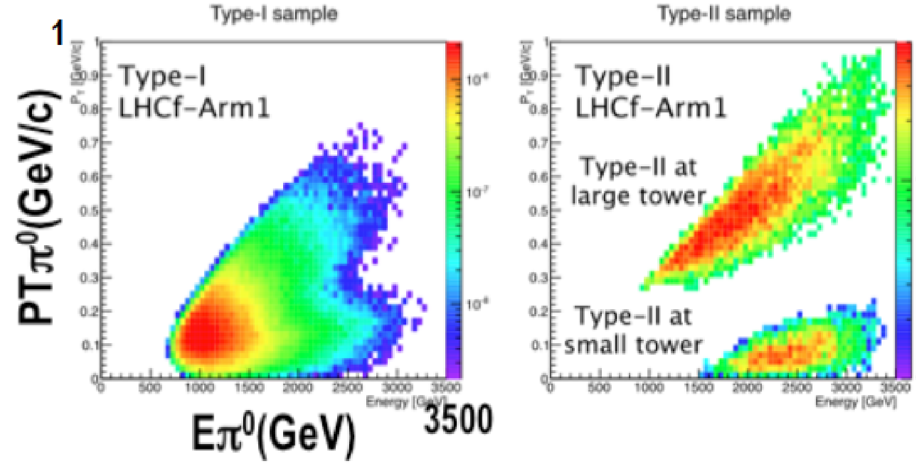
$$p_\perp \simeq p\ 2\ e^{-\eta}$$

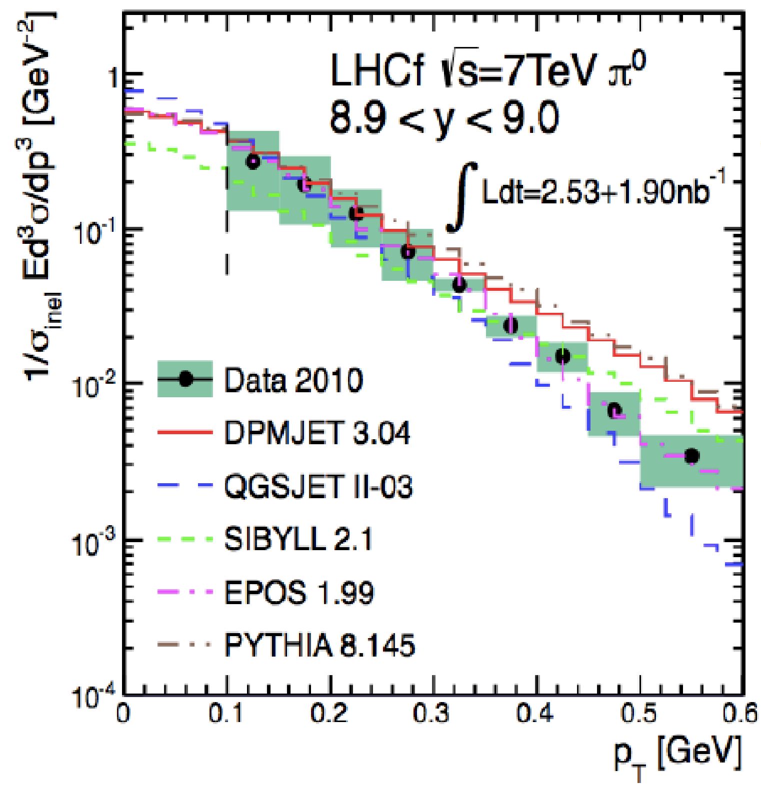


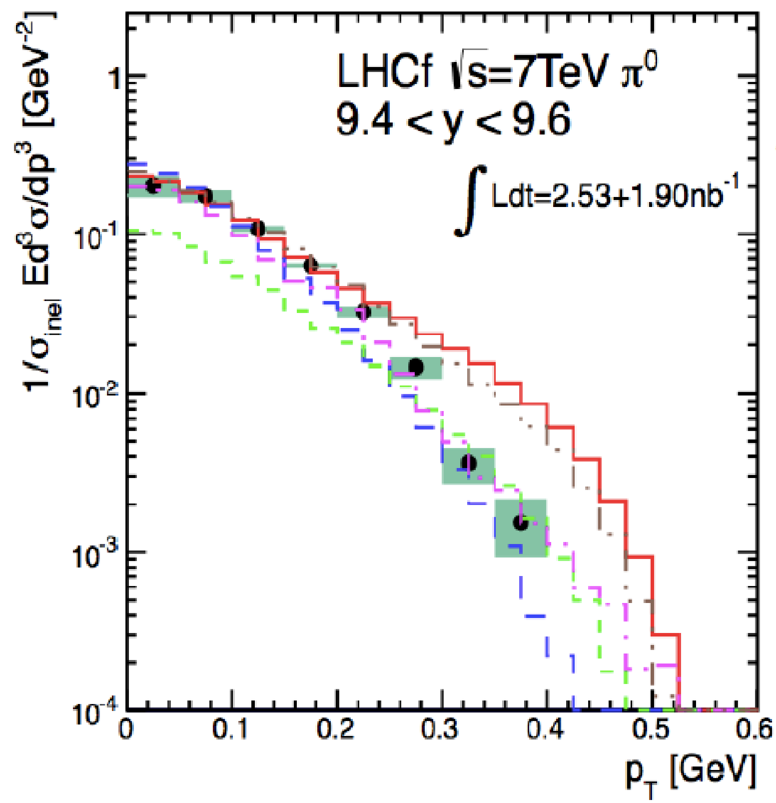
LHCf π^0 P_T at 7TeV pp

PRD 86 (2012) 092001





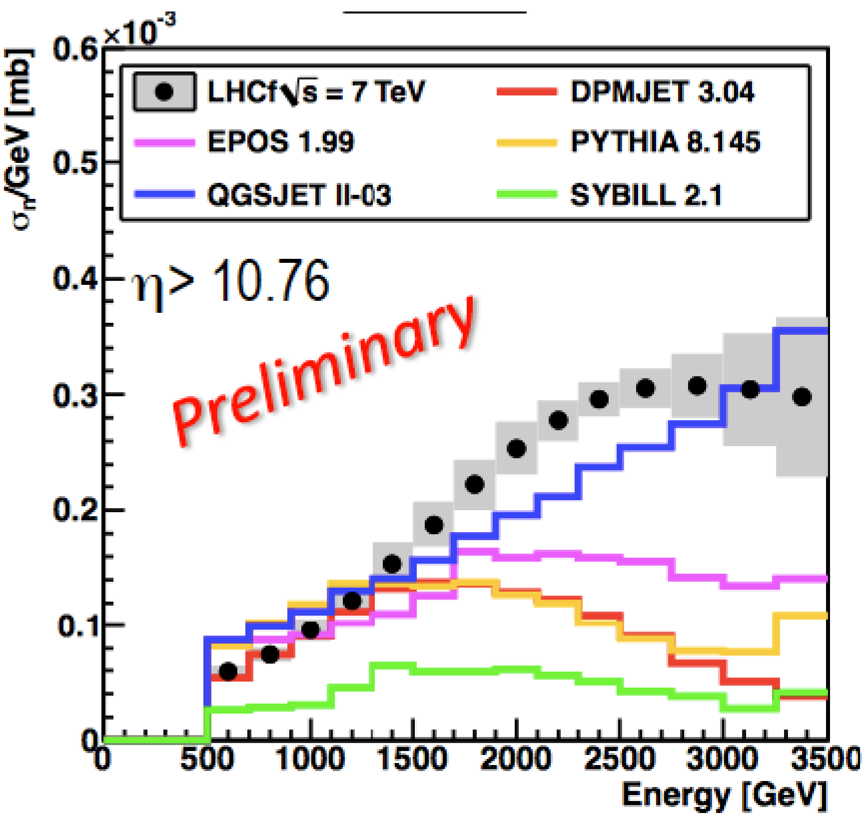


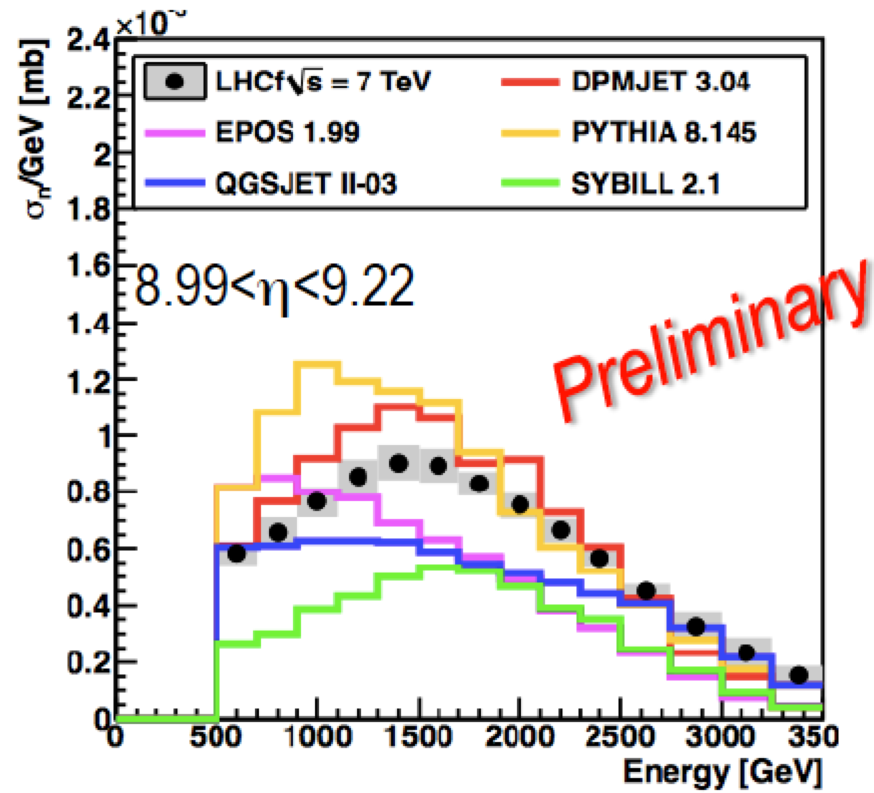


Very forward neutron at 7TeV p-p

- η>10.76 : QGSJET03 good, >h>9.22 DPMJET3 good
- Larger neutron / gamma ratio than expected

40% E res. unfolded

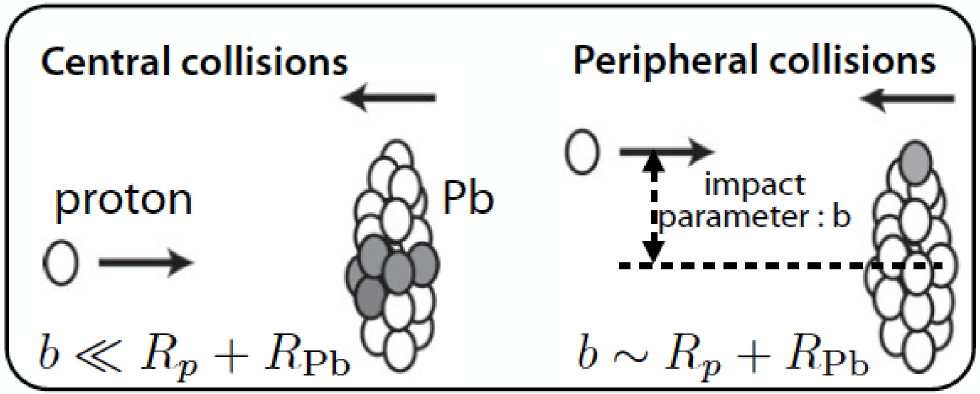


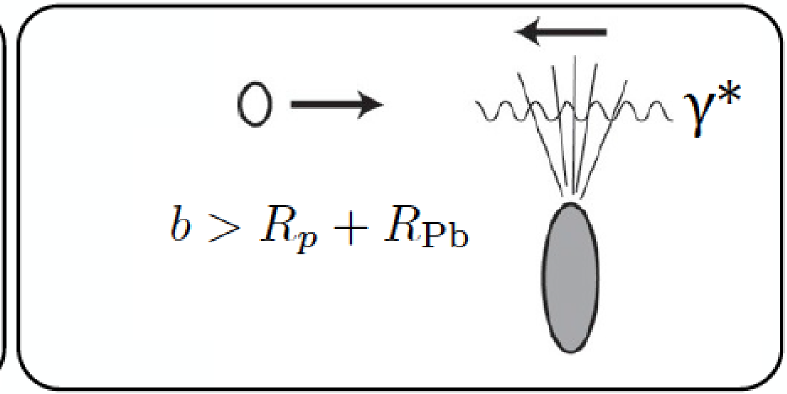


π^0 event analysis in p-Pb collisions

(Soft) QCD :
central and peripheral collisions

Ultra peripheral collisions :
virtual photon from rel. Pb collides a proton.





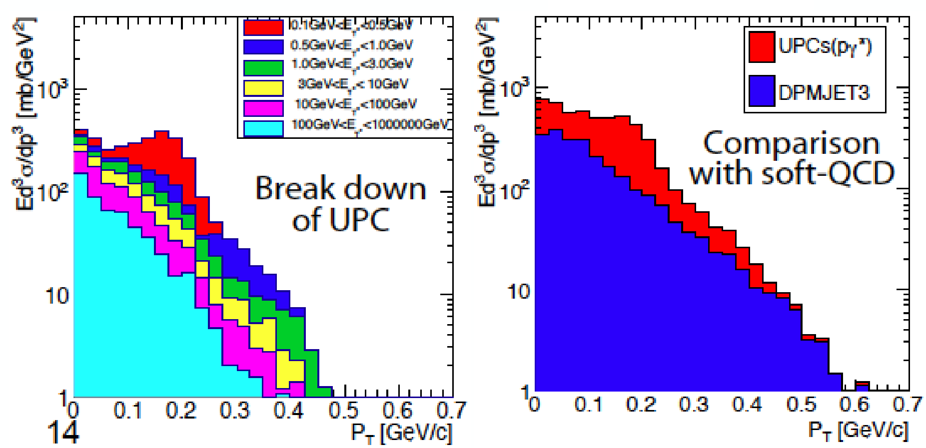
Momentum distribution of the UPC induced secondary particles is estimated as
1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation.
2. photon-proton collisions are simulated by the SOHIA model (E > pion threshold).
3. produced mesons and baryons by γ-p collisions are boosted along the proton beam.

] proton rest frame

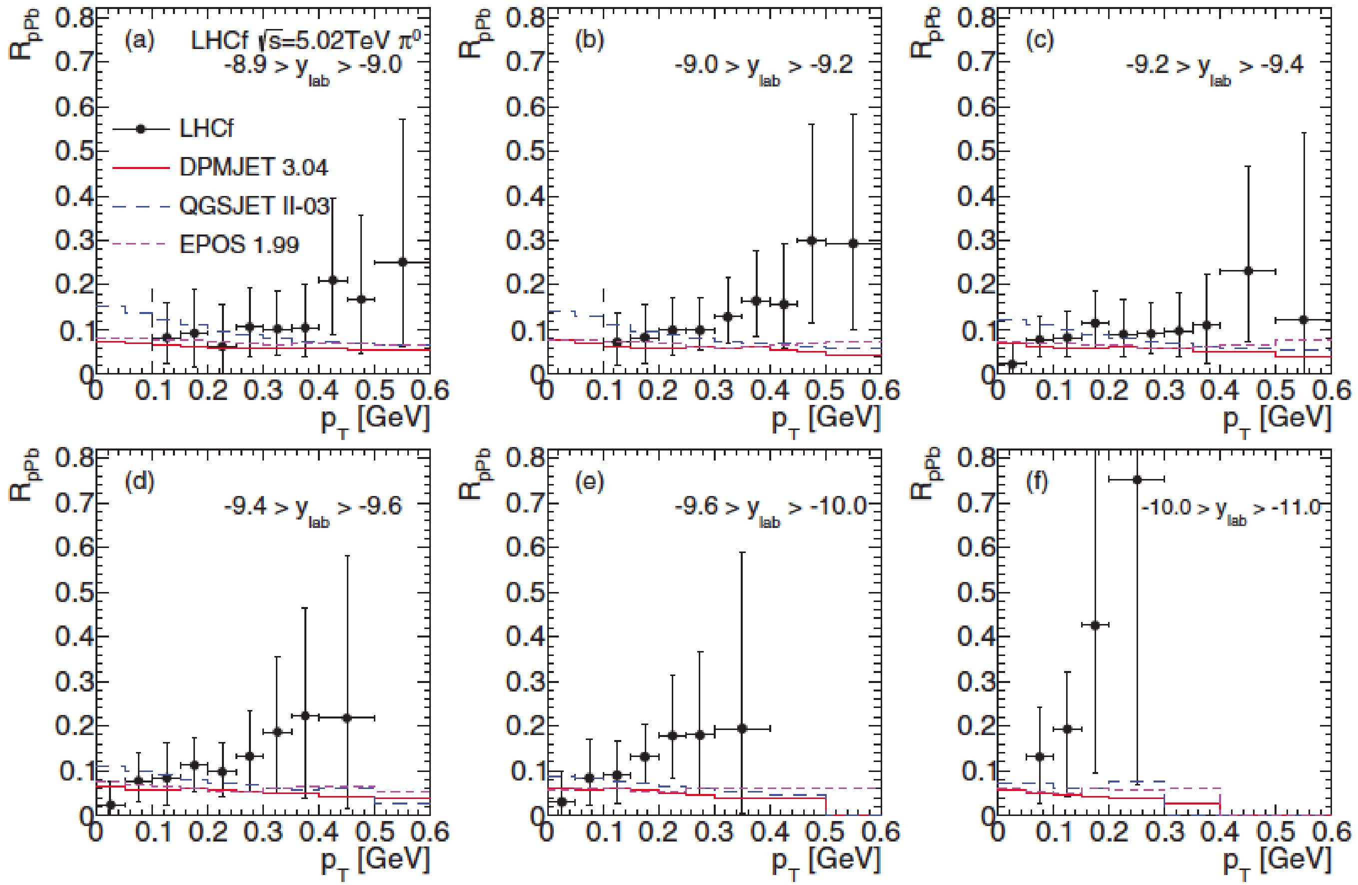
Dominant channel to forward π^0 is

$$\gamma + p \to \Delta(1232) \to p + \pi^0$$

About half of the observed π^0 may originate in UPC, another half is from soft-QCD.



Nuclear modification factor

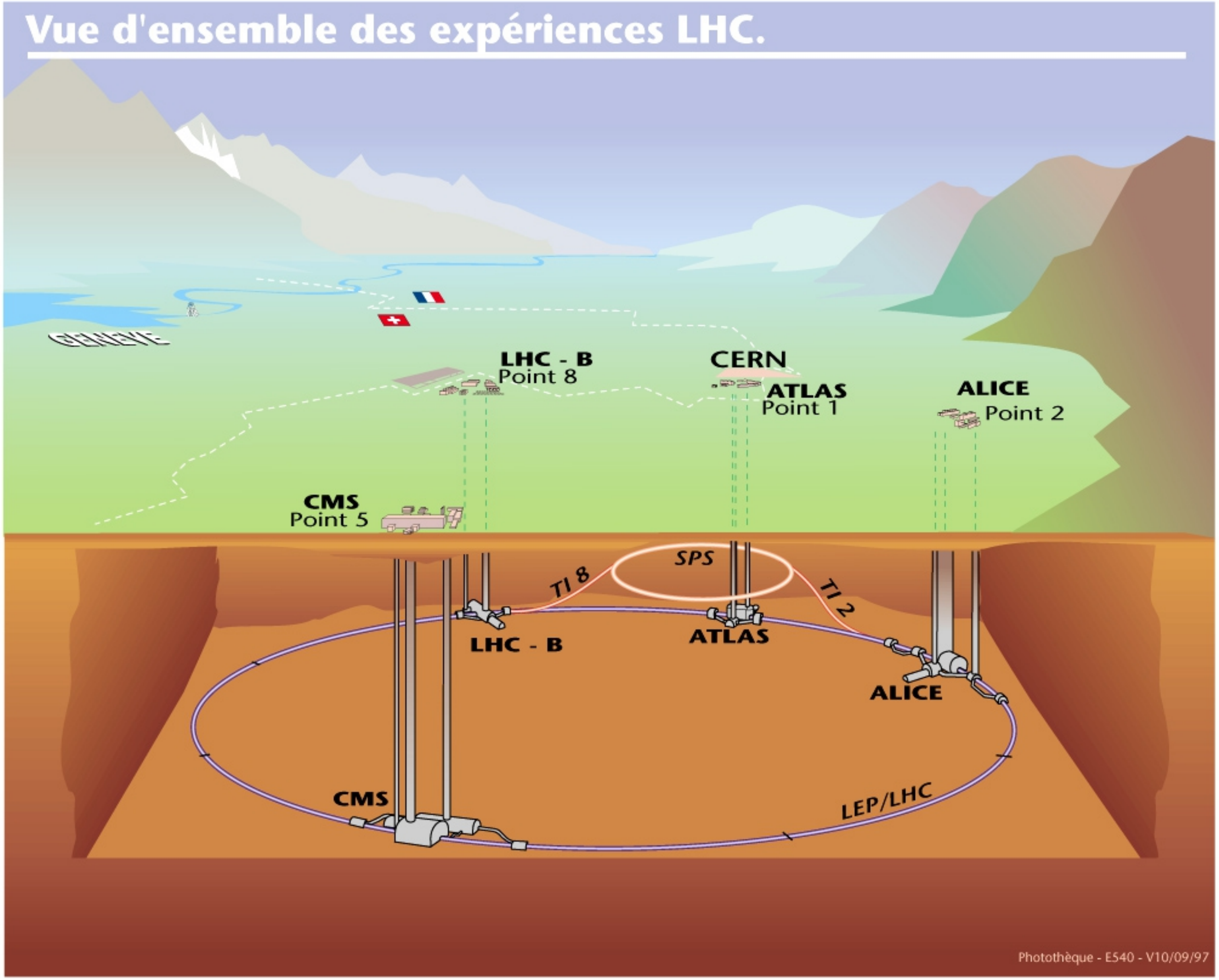


$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) \equiv \frac{d^2N^{\mathrm{pPb}}_{\pi^0}/dydp_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle d^2N^{\mathrm{pp}}_{\pi^0}/dydp_{\mathrm{T}}}$$

$\langle N_{coll} \rangle = 6.9$

- Both LHCf and MCs show strong suppression.
- But LHCf grows as increasing p_T, understood by the softer p_T spectra in p-p at 5TeV than those in p-Pb.

What have we learned at LHC about “soft” hadronic interactions ?



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…. of course the answer is : “A LOT !!”

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How well constrained is the modeling of Cosmic Ray showers in light of our deeper and more extended knowledge ?

below LHC energies
(above LHC energies [extrapolation needed])

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How well constrained is the modeling of Cosmic Ray showers in light of our deeper and more extended knowledge ?

below LHC energies
(above LHC energies [extrapolation needed])

.... I'm personally somewhat more cautious than at least some of my colleagues.
Our models stands reasonably well, but uncertainties still quite significant.

What are the most significant measurements
(for cosmic ray studies) to be performed at LHC ?

0. c.m. Energy extension (...obvious)

1. *Observed* ***Phase Space*** *extension*
(very difficult .. but in my view also very important)

2. Better **diffraction cross section** determination.

3. Program of **proton/light-nucleus** observations

3a. Program of nucleus/light-nucleus

Is a p-light nucleus of interest
for the ALICE/Heavy Ions community at CERN ?

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for the ALICE/Heavy Ions community at CERN ?

…. well of course the most fascinating science
is in Lead-Lead collisions. This is where
New behaviours (Quark-Gluon-Plasma…)

But (it seems to me) that it is possible to
construct a robust argument that to develop
a full understanding of “normal behavior”
In nucleus-nucleus collisions,
a more full span of Phase Space is very important

The interest of the Cosmic Ray community in the continuation (and development !) of The “forward Physics”, (Full Phase Space) programs at LHC is VERY STRONG !

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A full understanding of the Multi-Parton-Interaction structure of inelastic collisions *requires* a coverage of the entire phase space including the Very-forward – very/backward Fragmentation region.

So significant “intrinsic” (Particle Physics) interest in these programs

More in general:

Uncertainties on soft hadronic interactions remain
a significant source of systematic uncertainties
for many different studies on a broad energy range

[From very low energy: pp → p p + few pions]
Study of acceleration in SN remnants
Production of neutral pions (that decay into gammas)

[Up to sqrt[s] = 430 TeV

Bridging the Gap

between

Soft and Hard

Hadronic Interactions

Bridging the Gap

between

Soft and Hard

Hadronic Interactions

Problem of CONFINEMENT

SOFT QCD studies

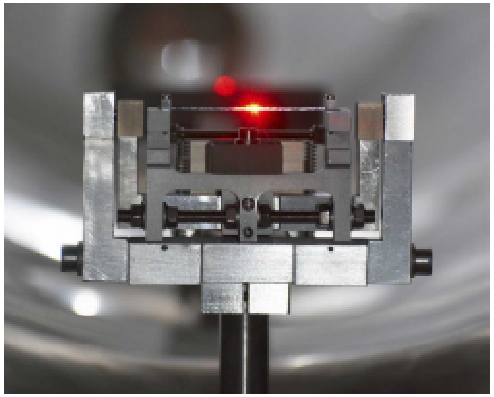
Have NOT only a simple "engineering" interest
as a instrument to reconstruct the primary particle
mass and energy in a shower.

They confront a very significant scientific
open problem for the Standard Model

(In my view) they deserve a strong, broad
Experimental *and theoretical* program.

Fixed Target with LHC Beam

Bent crystal, UA9:



e.g. PRL 87 (2001) 094802

A Fixed Target ExpeRiment at LHC

arXiv/hep-ph 1207.3507

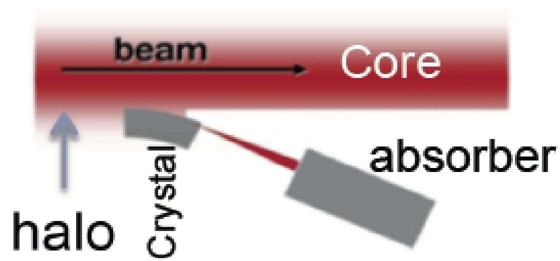
- Precision QCD
- W/Z studies,
- Quarkonia physics
- Cosmic Rays, Neutrino Production

First steps

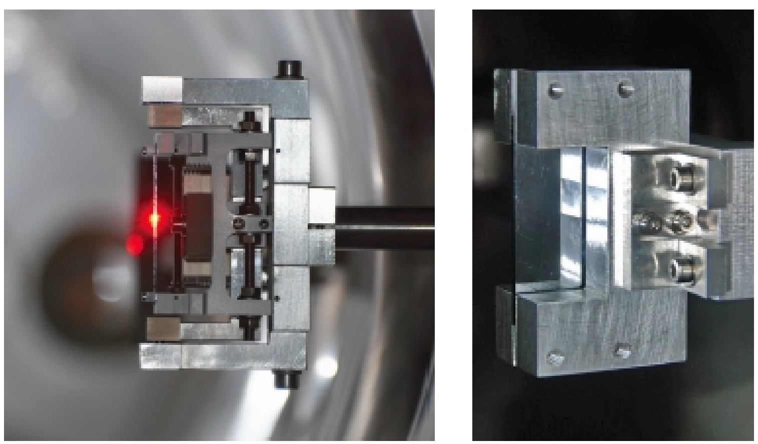
IDHEFIX Proposal in H2020, 1st AFTER week at CERN Nov/2014

CRYSBEAM basic idea

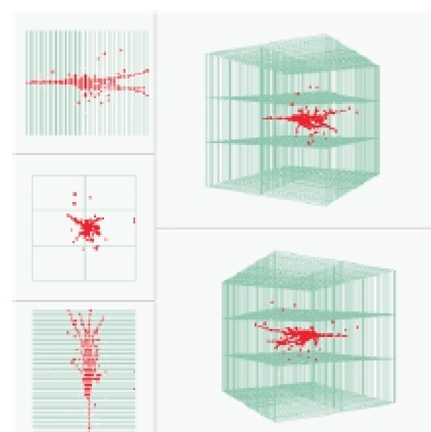
PARASITIC** EXTRACTION of BEAM with **a bent crystal
*in **channeling orientation***
Low background, continuous extraction of the beam halo
10^8 particle per second might be possible



Instrumented ("smart") absorber to measure the hadronic shower structure



UA9 crystals



CALICE Digital HCAL

My final message:

The interconnection between

Particle Physics

and

Cosmic Ray science

[High Energy, multi-messenger-Astrophysics]

has a very long past-history

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... and a very promising future.