Status & Developments in High-Energy Cosmic Ray Physics.

An attempt of a summary
of the field and the conference.

(apologies for the personal and biased view
and for not being complete)

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DESY Zeuthen

25^{th} ECRS, Torino, 4-9 Sep 2016

CR Overview

Cosmic Rays

energetic (elementary) **particles**
from space (Sun, Milky Way, distant galaxies)
bombard Earth continuously.

Energies from <MeV .... >10^{20} eV

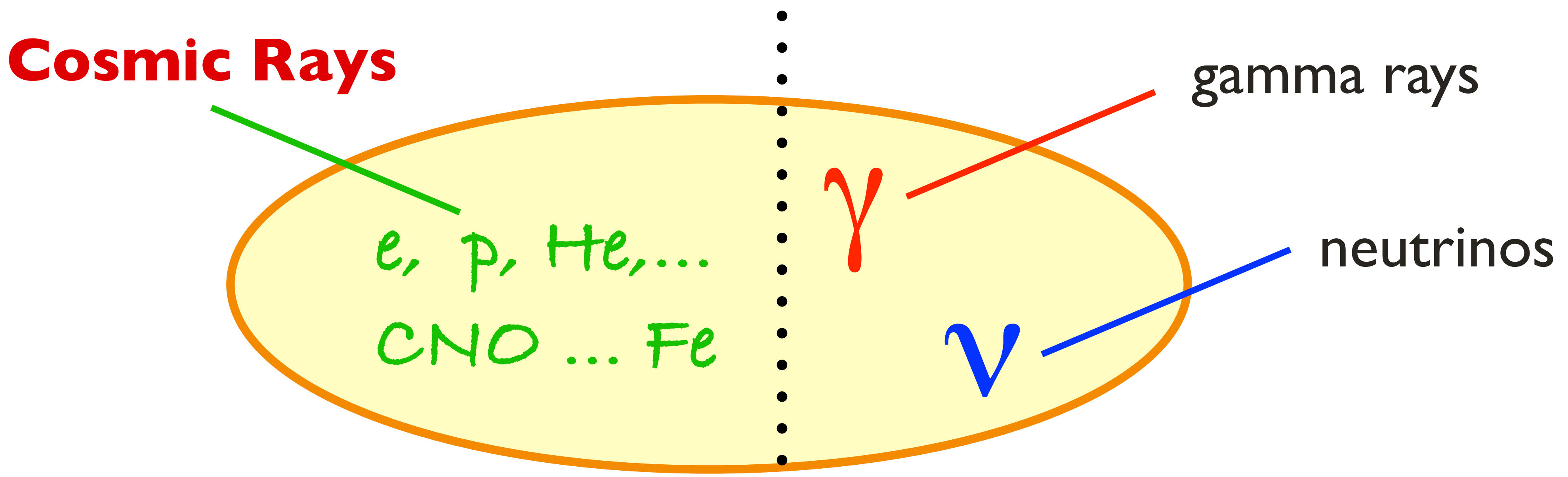
most relativistic particles in the Universe

Astroparticle Physics:

Astrophysics with photons and particles.
Particle physics with probes of astrophysical origin.

What are these cosmic particles?

must be stable (to survive travel to us)

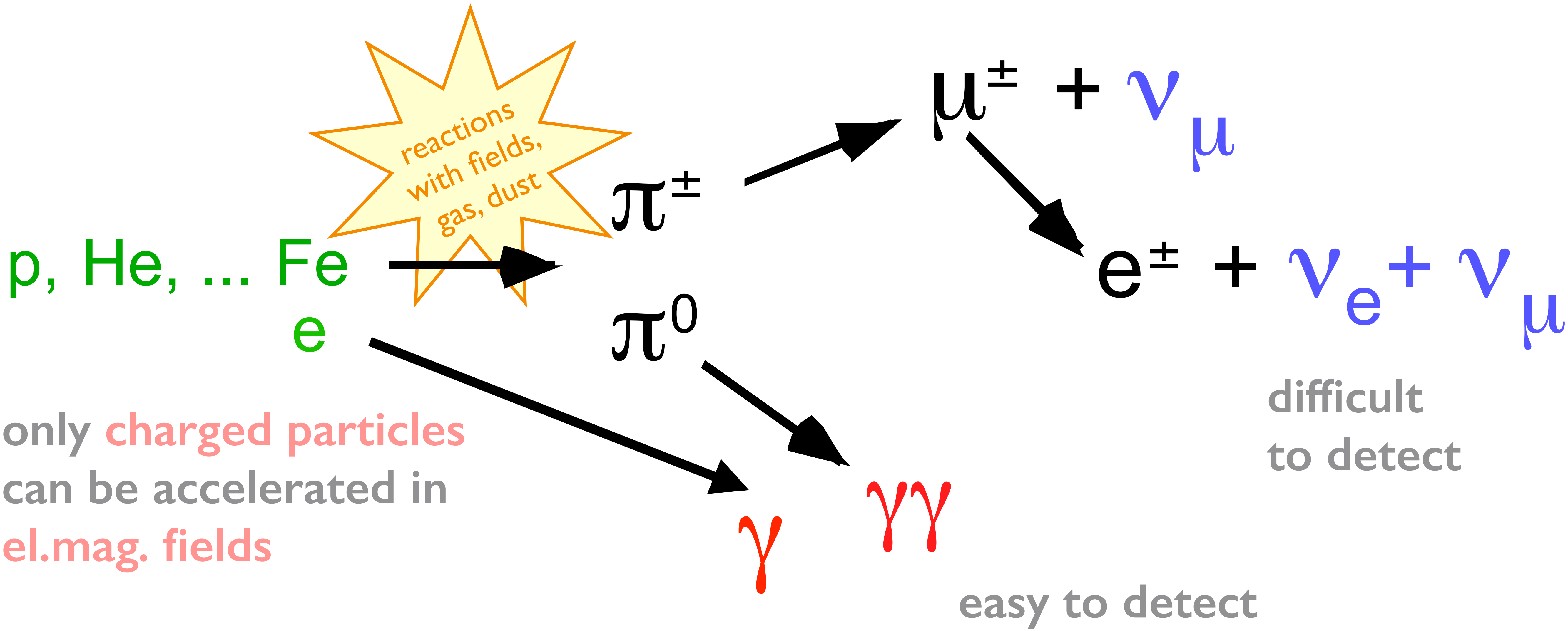


electrically charged | neutral

\+ can be accelerated
– are deflected in el.mag. fields

\+ **move in straight lines (astronomy)**
– secondaries

Cosmic rays, gamma rays and neutrinos come likely from the same sources



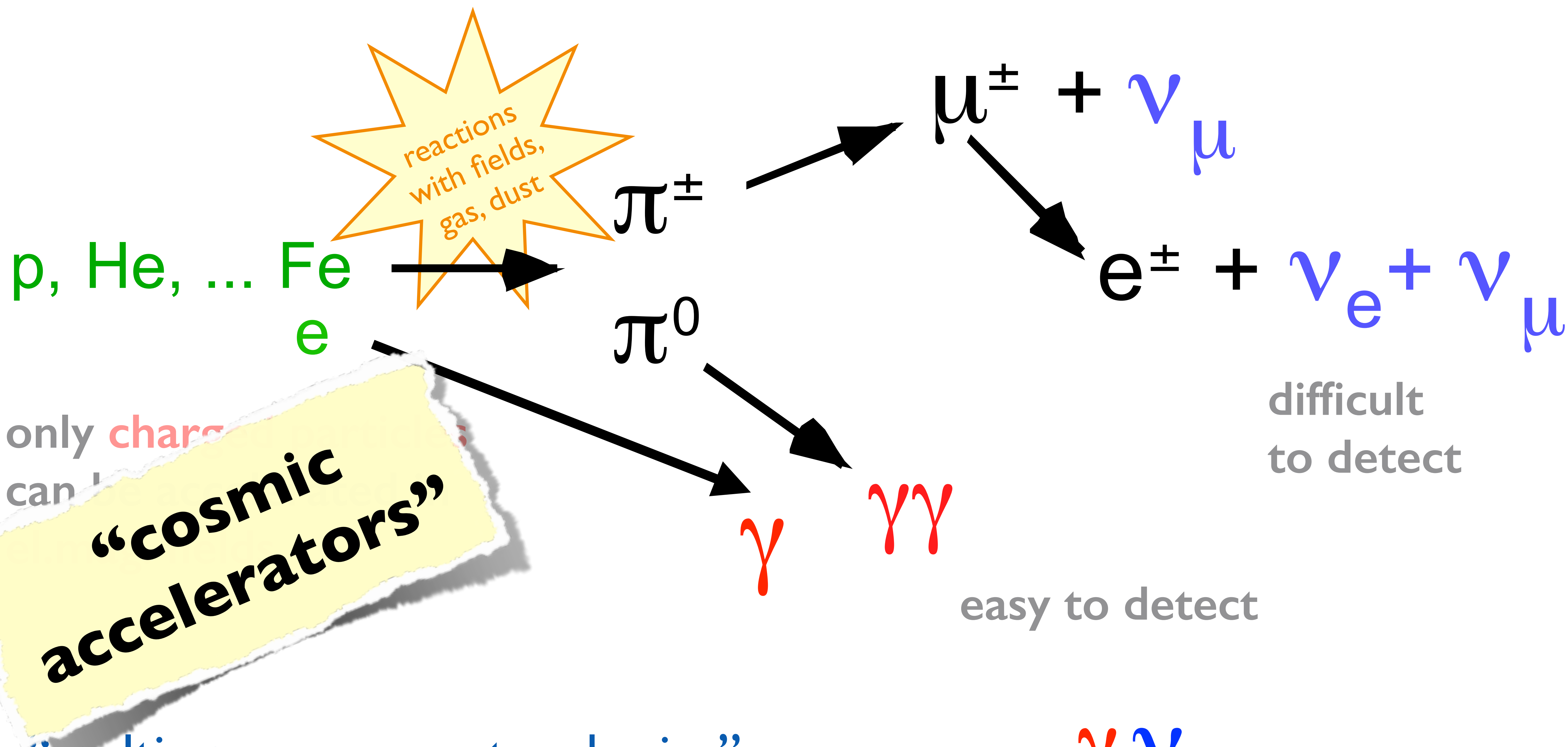
"multi-messenger astrophysics"

but gamma rays are currently the most "productive" messengers.

γ, ν

point back to sources (good for astronomy)
but serious backgrounds

Cosmic rays, gamma rays and neutrinos come likely from the same sources



“multi-messenger astrophysics”

but gamma rays are currently the most “productive” messengers.

γ, ν

point back to sources (good for astronomy)
but serious backgrounds

Cosmic accelerators

The highest-energy particles come from the most violent environments
(physics in extreme conditions)

The highest-energy CRs, γ and ν come likely from the same sources.

"multi-messenger" approach

Energy scale:

the range of astroparticle physics

radio IR visible light UV X rays γ rays

meV ... eV ... keV ... MeV ... GeV ... TeV ... PeV ... EeV ... ZeV

10^{-3} ... 1 ... 10^{3} ... 10^{6} ... 10^{9} ... 10^{12} ... 10^{15} ... 10^{18} ... 10^{21} eV

non-thermal processes

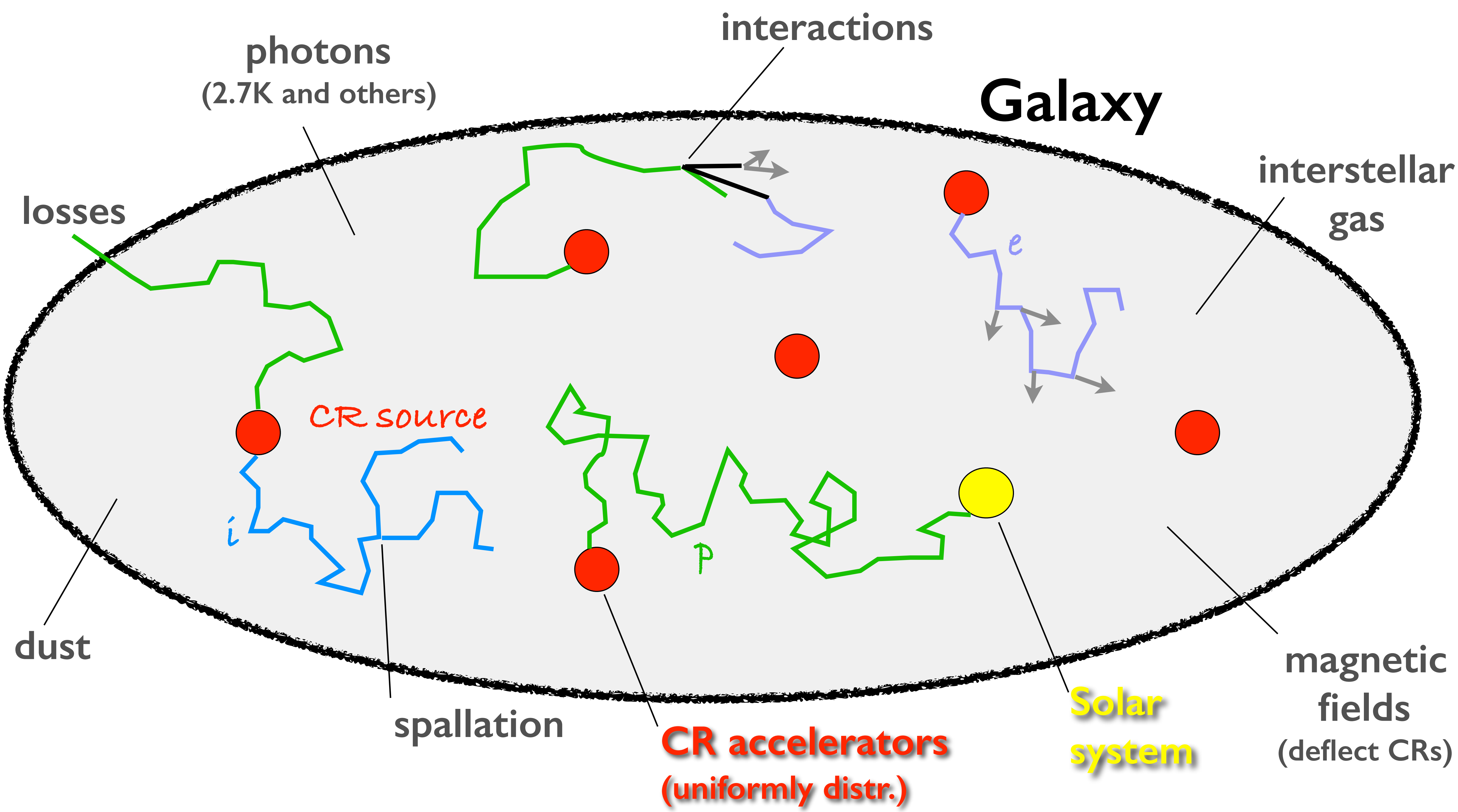
Photons: astronomy

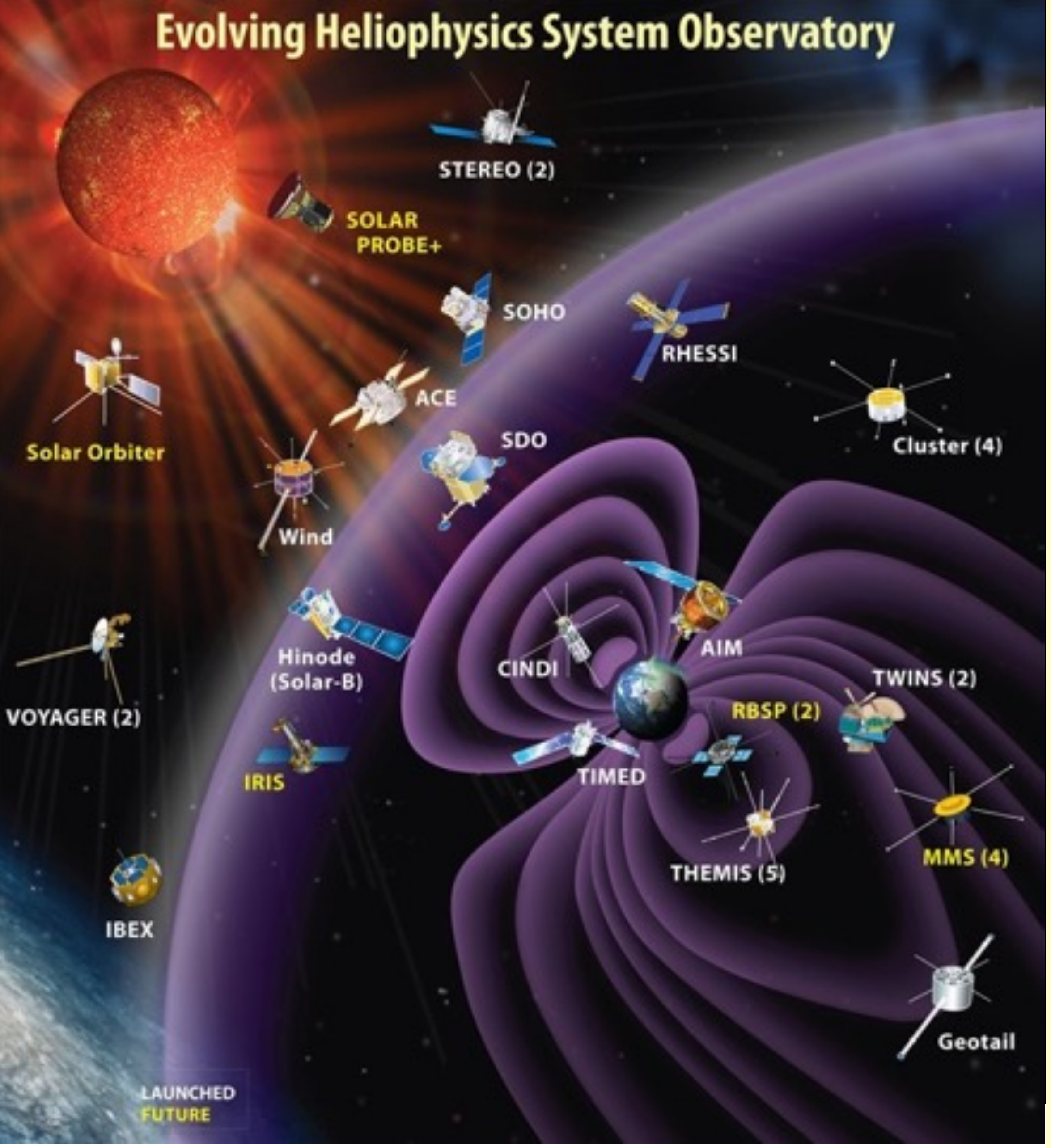
charged: p, He, ... Fe, ... completely ionised nuclei

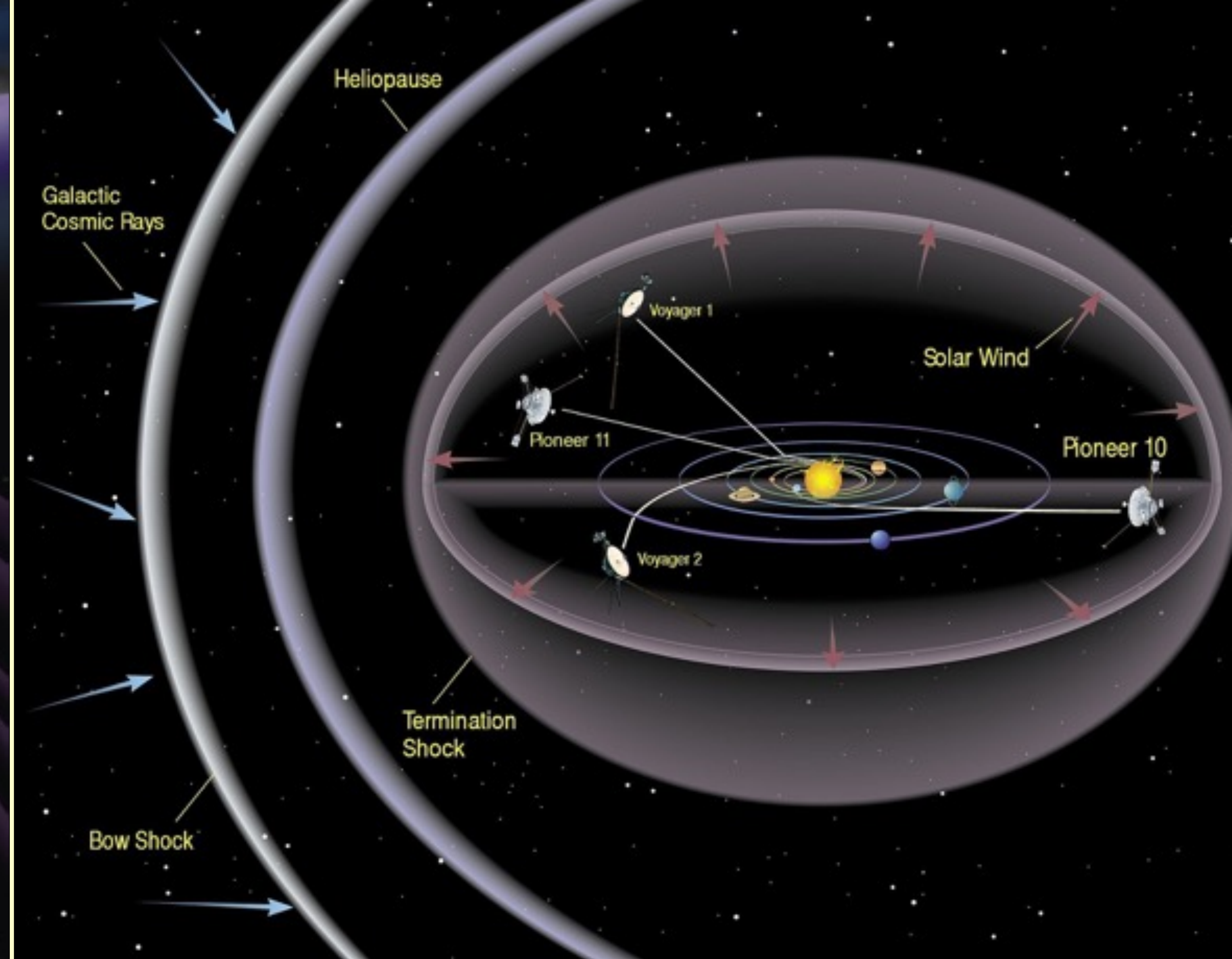
electrons

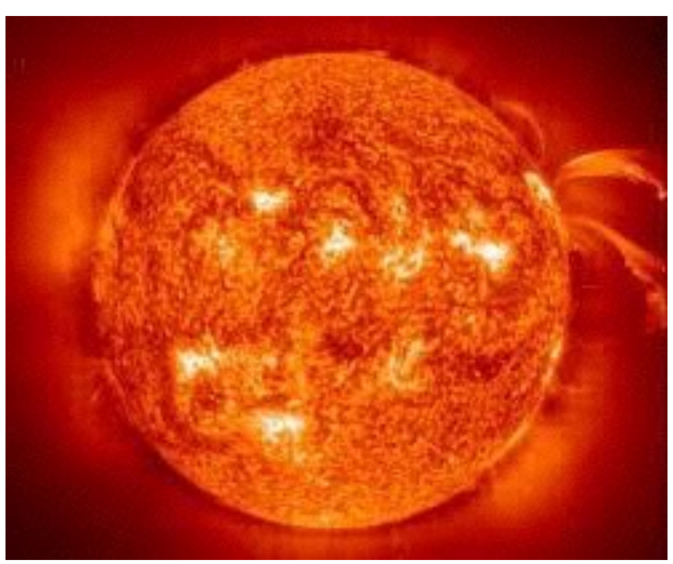
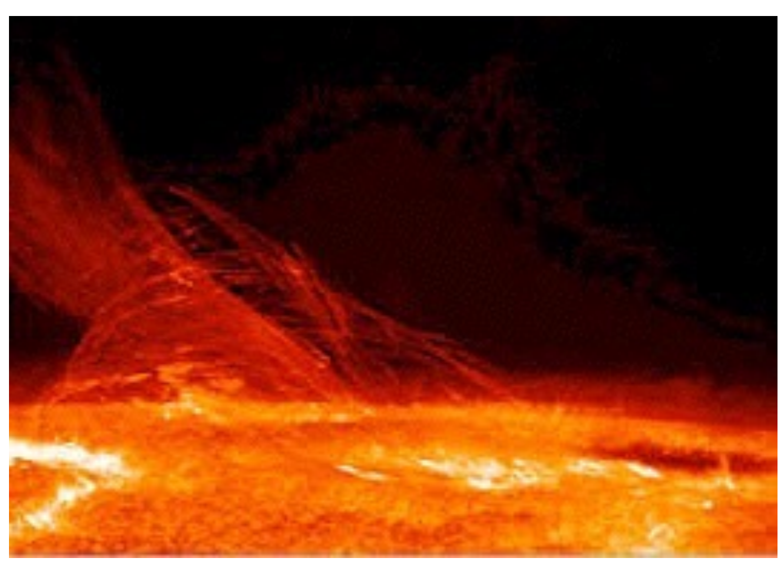
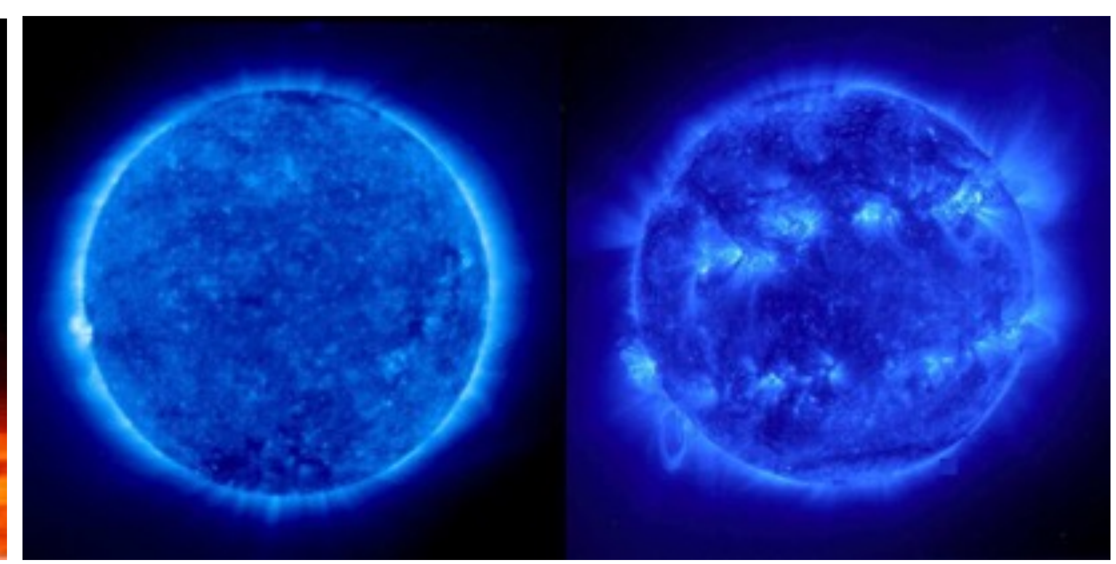
Neutrinos:

The (simple) world of galactic cosmic rays



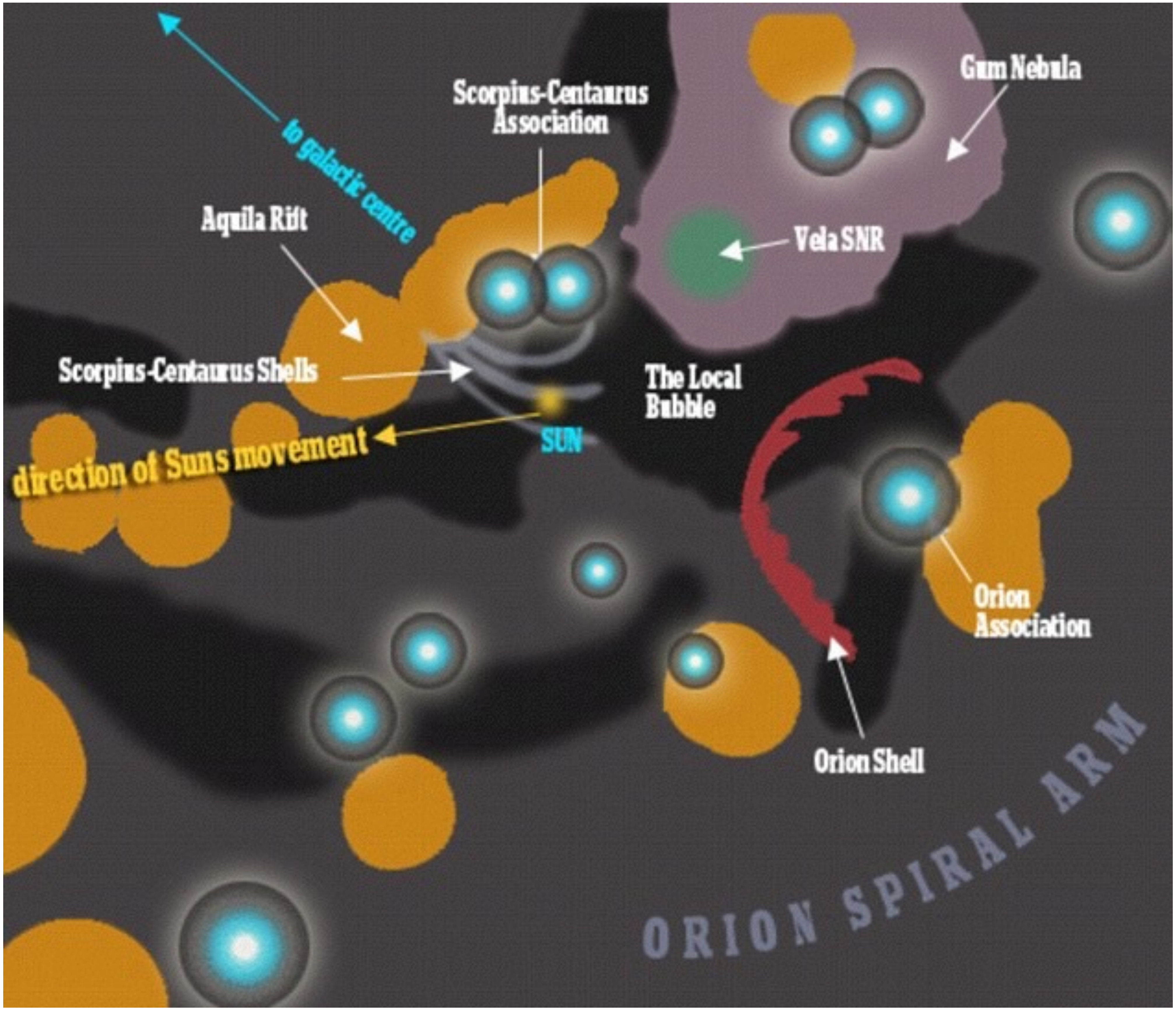




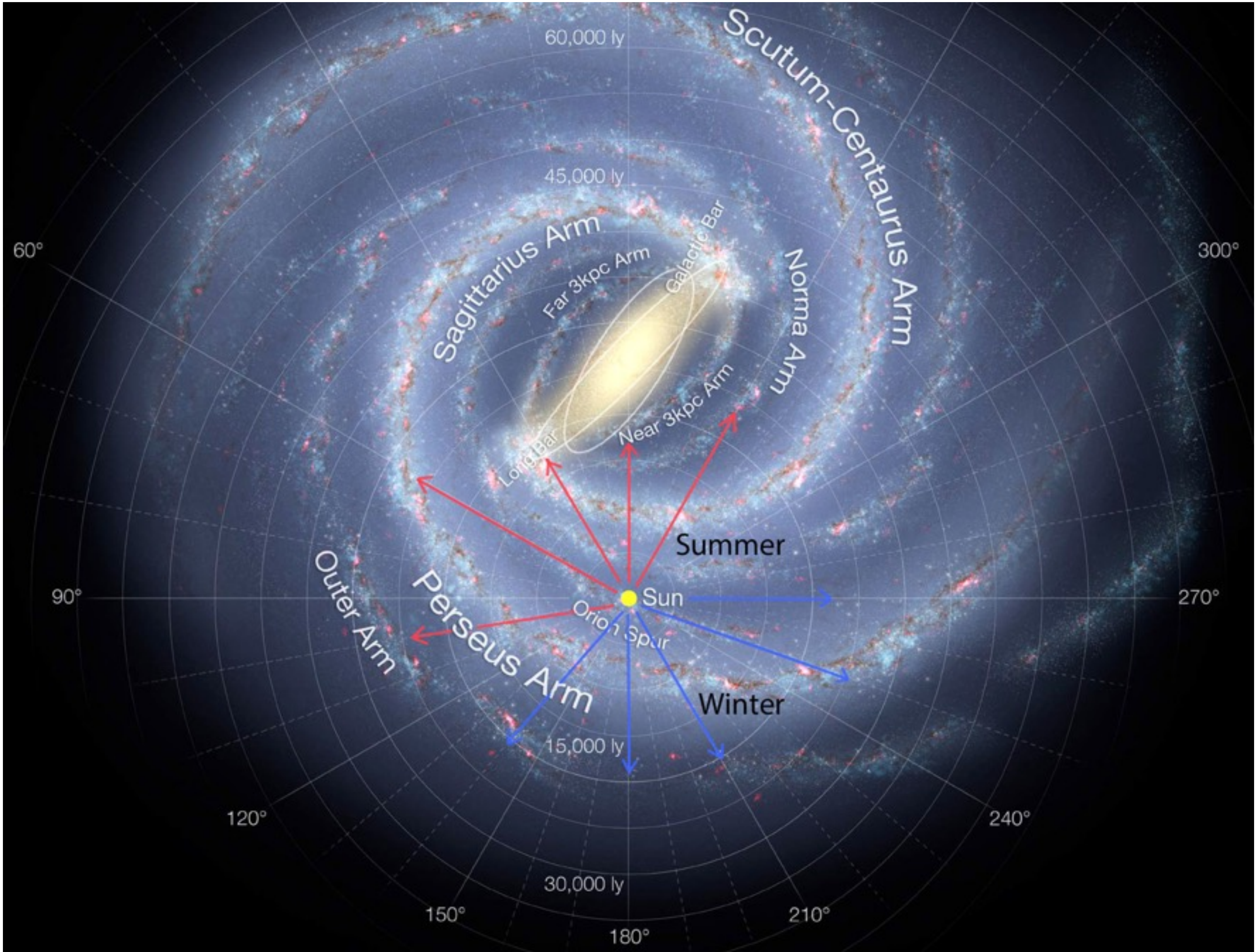




The Sun: close, dominant, reachable…

The Local Bubble: many objects shape the environment



Our Galaxy: ~10^9 stars, CR lifetime: ~10^7 yrs



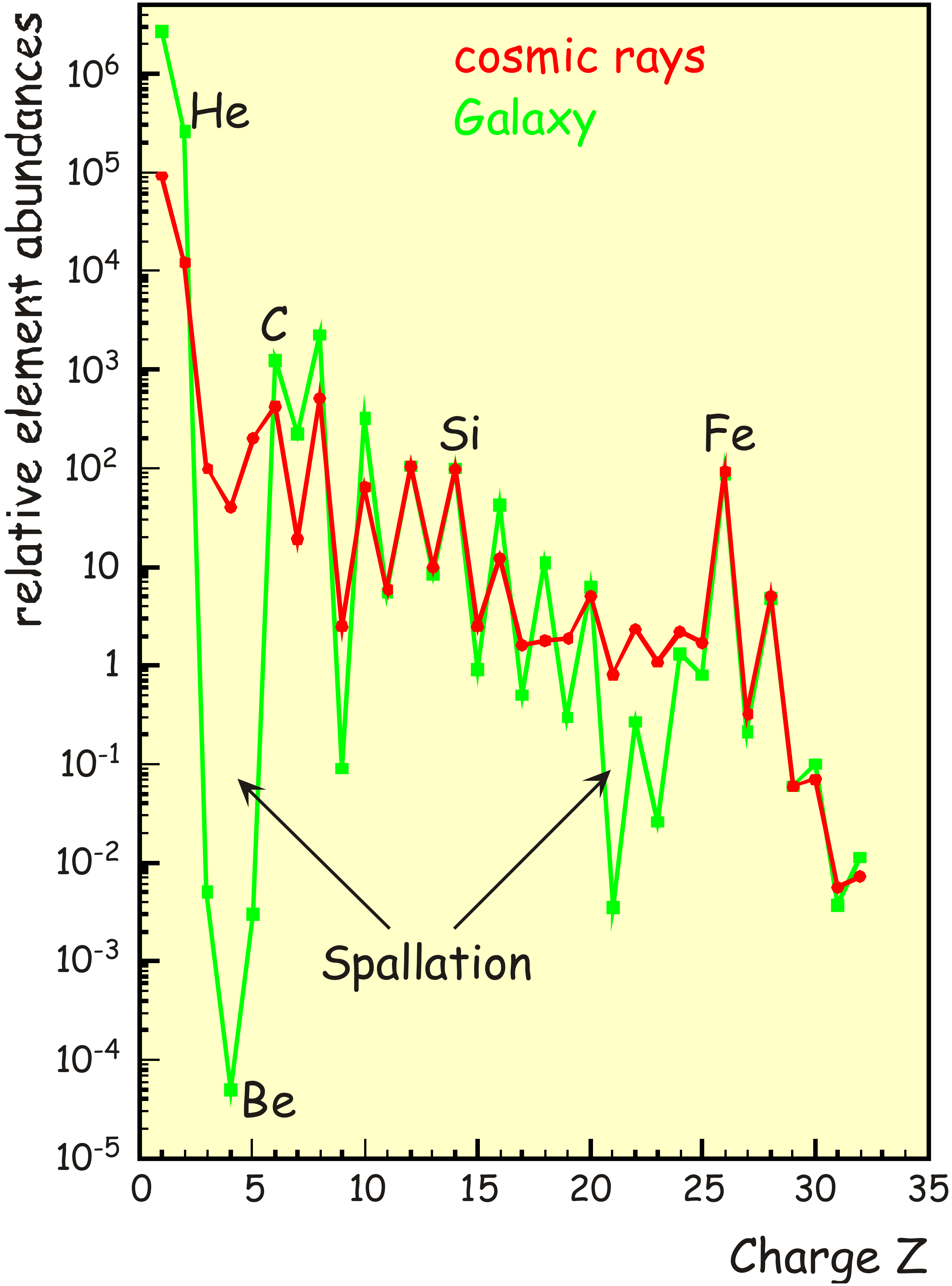
CR Mass Composition
(in 1 GeV range)

element and isotope composition well known (for E < GeV)

89% p, 9% He, 2% other nuclei
<1% electrons
"CRs are star matter"

secondary/primary nuclei:
~ 10 g/cm^2

unstable/stable secondaries:
~ 10^7 years
(decreases with ~$E^{-0.6}$)

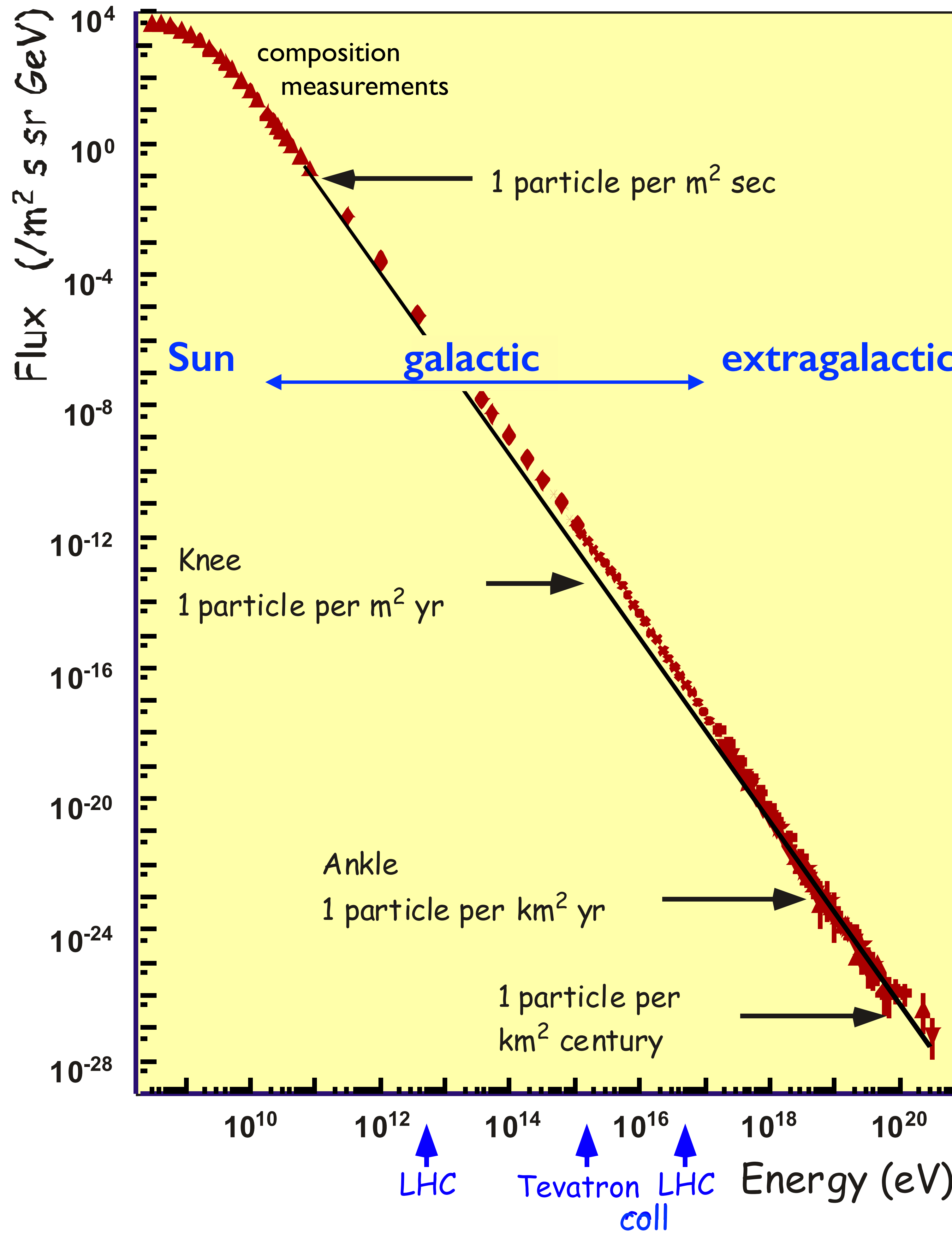



many galaxies,
intergal. medium:
absorption in EBL,
deflection

CR spectrum

Almost featureless over
11 orders of magnitude.

A sign of a lot of averaging.



At energies >10^{14} eV:

Large, natural volumes become part of the detectors:

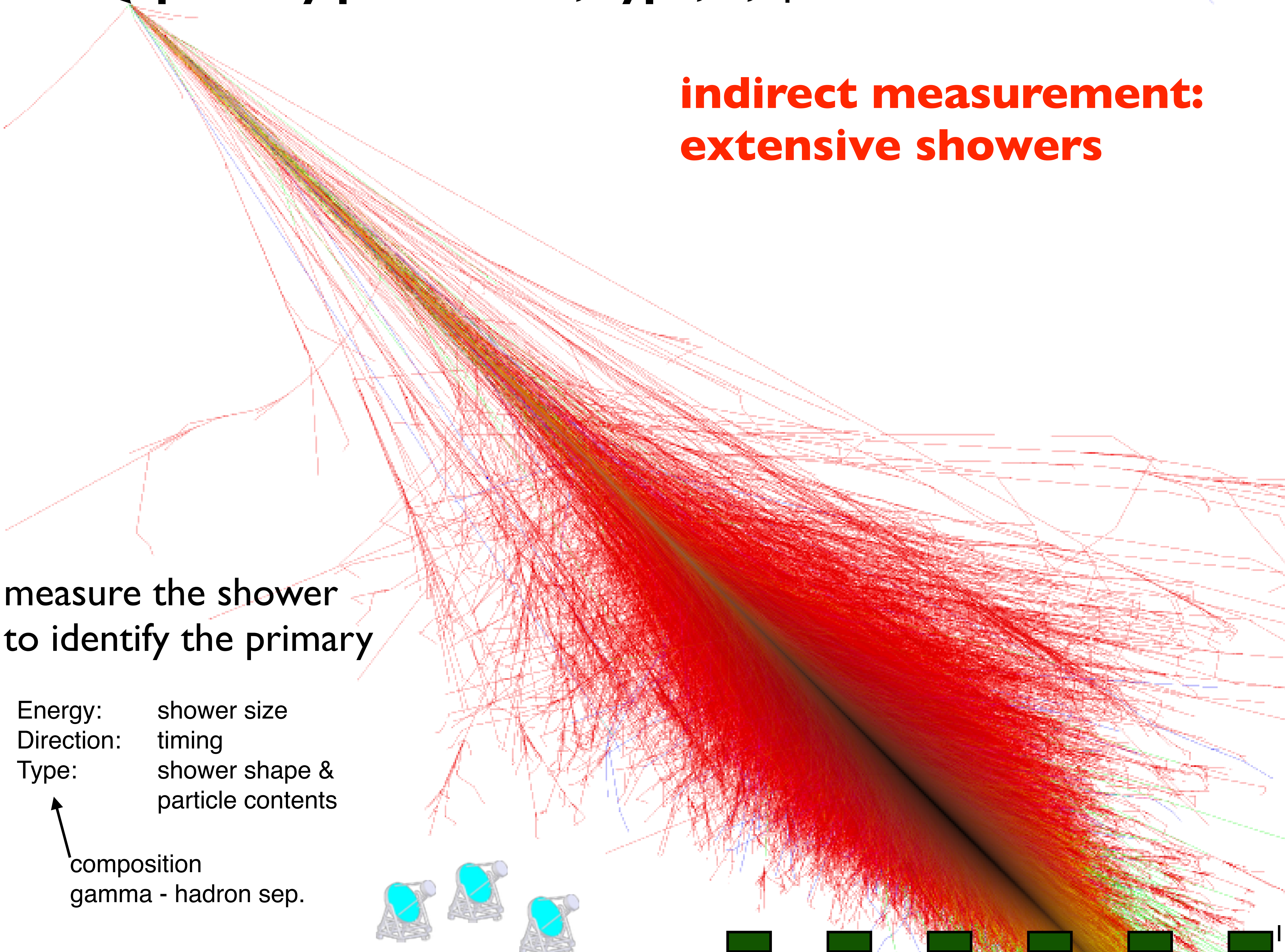
atmosphere,
ice shields,
oceans,
...

instrument (sparsely) to record secondaries produced by particle interactions

understand / monitor the "target"

primary particle: E, type, θ, φ

indirect measurement: extensive showers

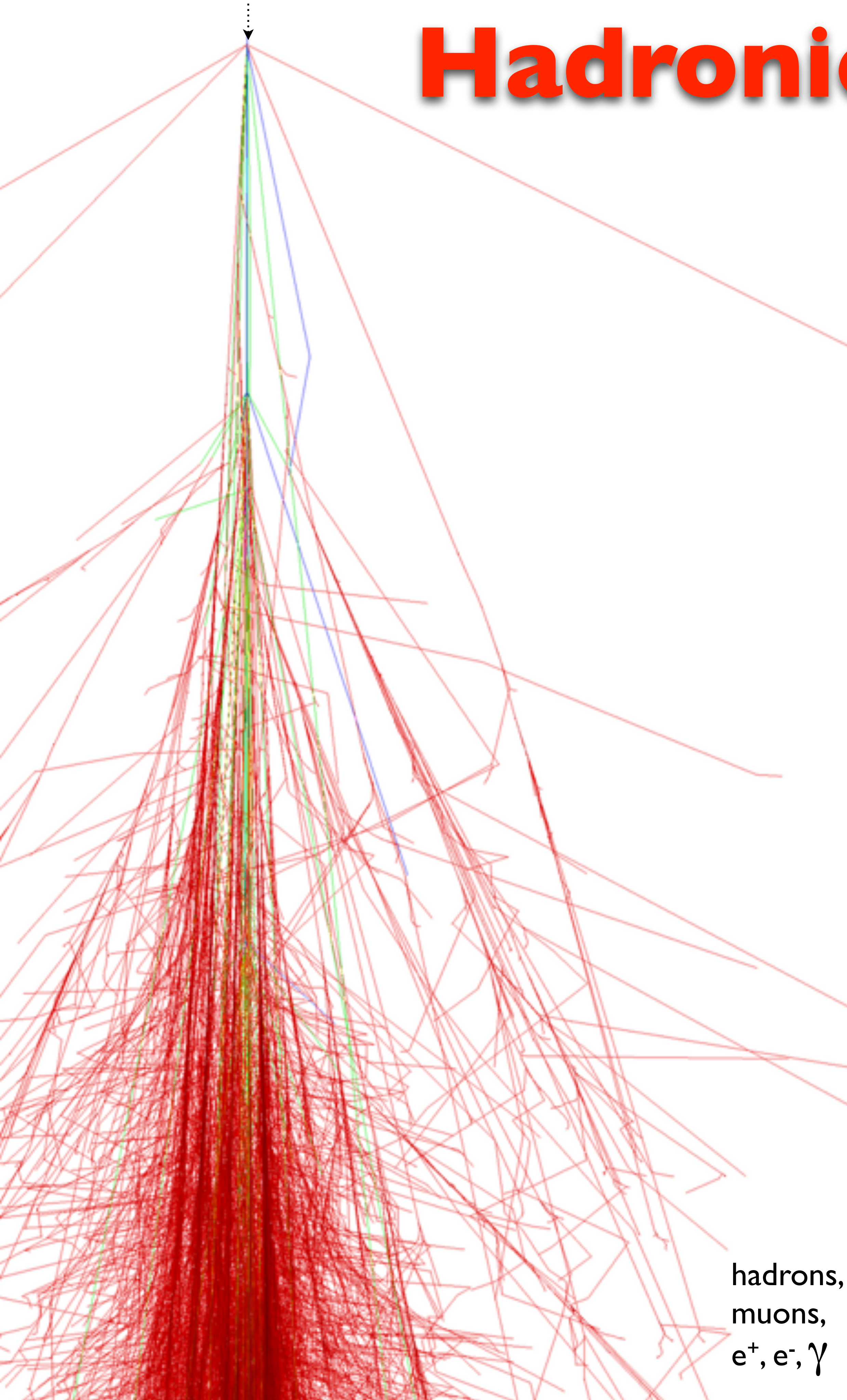


measure the shower
to identify the primary

Energy: shower size
Direction: timing
Type: shower shape & particle contents

composition
gamma - hadron sep.

Hadronic Interactions ...



from MeV … 10^{20} eV
very forward directions (~0°)
diffractive / non diffractive / nuclear
heavy quark production and decay
fragmentation, p_T, baryons, …
for all particles (primary & secondaries)

"Particle physics with astroparticles"

To connect shower observables
to primary particle.
Models are evolving and improving,
but are nor perfect yet.

What we see at Earth:

A mix of particles from many different sources / source types
from all over our Galaxy

solar - local galactic - galactic - extragalactic

different populations dominate at different energies

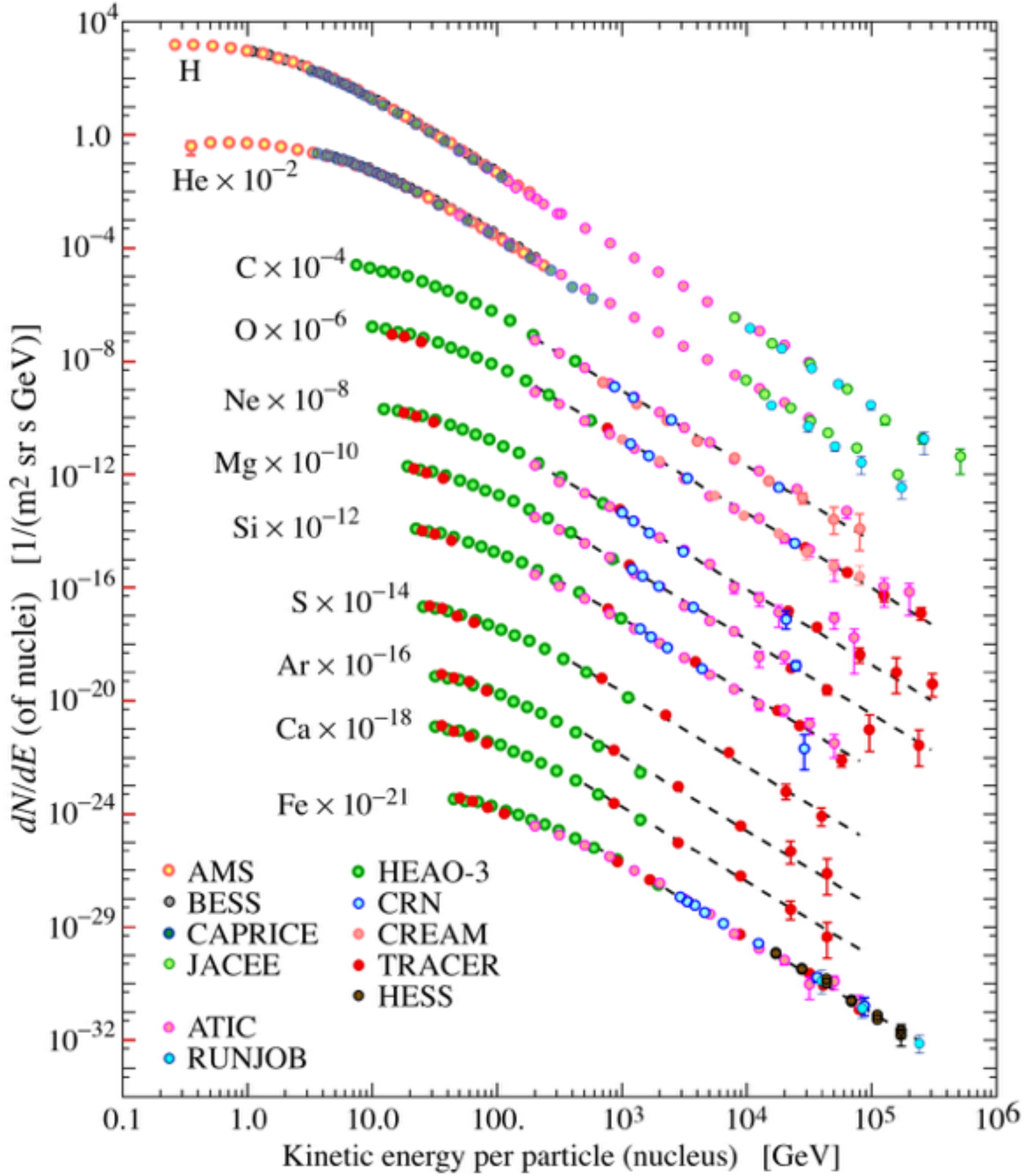
Processed over long times: Myrs, (gal) …. Gyrs (? extragal)

Mostly diffusion, directions largely randomised
modified / absorbed in propagation

CRs: are a non-thermal / relativistic local fog

Destructive interaction CRs in atmosphere,
to be detected by sparse and imperfect detectors.

Large uncertainties in every step from source to measurement.



direct measurements

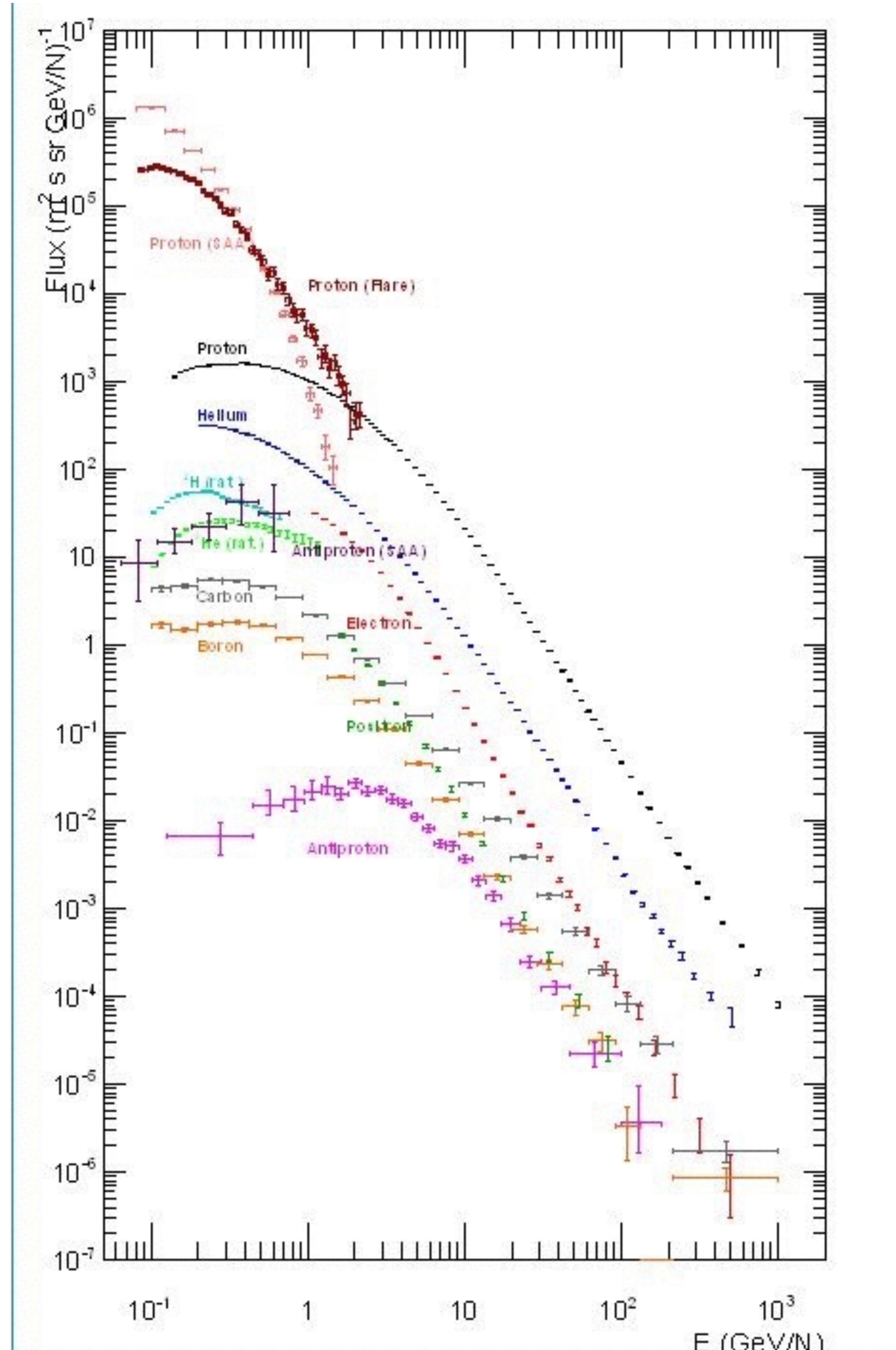
Figure 28.1: Fluxes of nuclei of the primary cosmic radiation in particles per energy-per-nucleus are plotted vs energy-per-nucleus using data from Refs. [2–13]. The figure was created by P. Boyle and D. Muller.

PAMELA overall results

- Results span 4 decades in energy and 13 in fluxes

The PAMELA Mission: Heralding a new era in precision cosmic ray physics

Physics Reports 544 (2014) 323-370



air showers

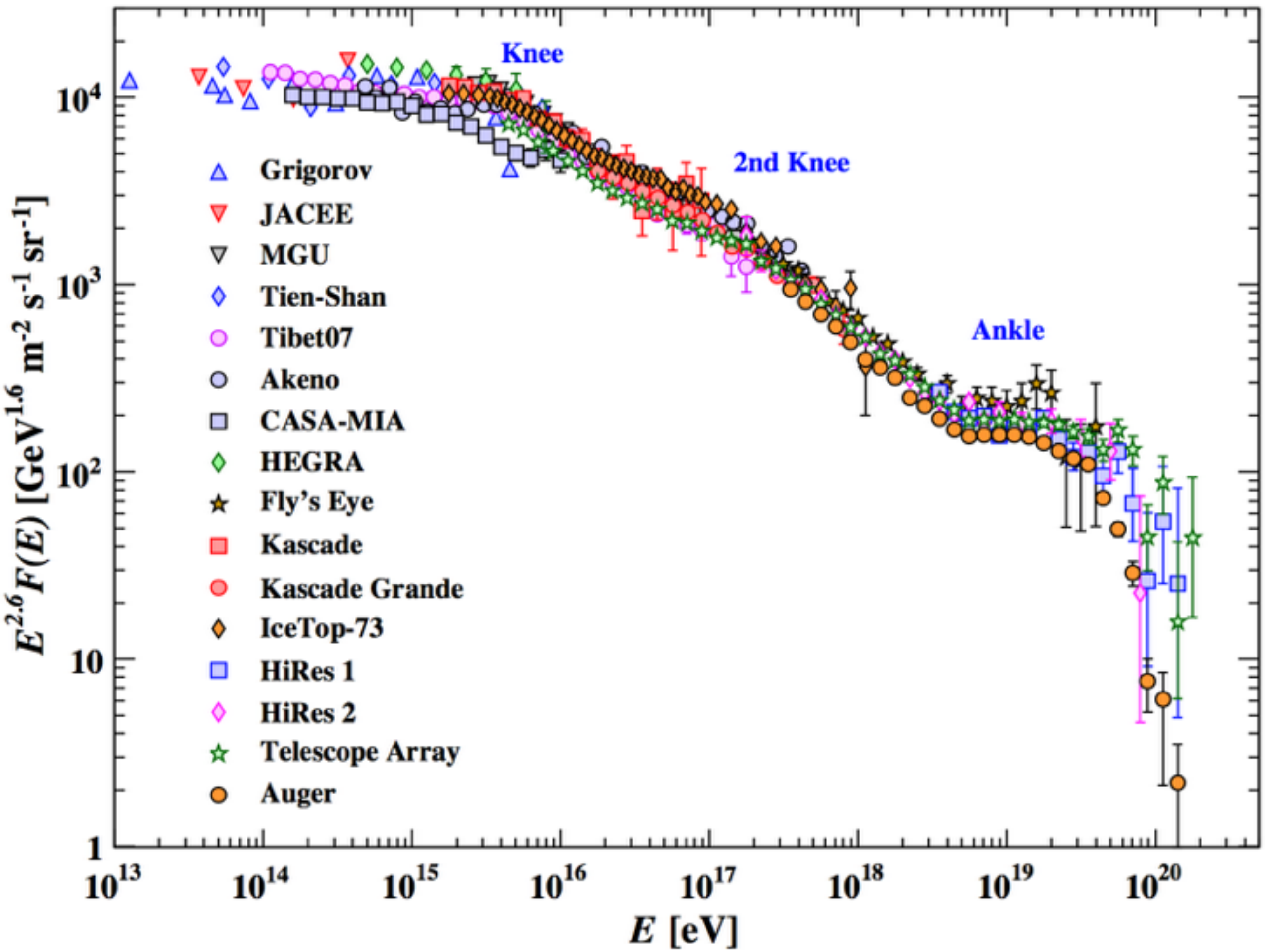
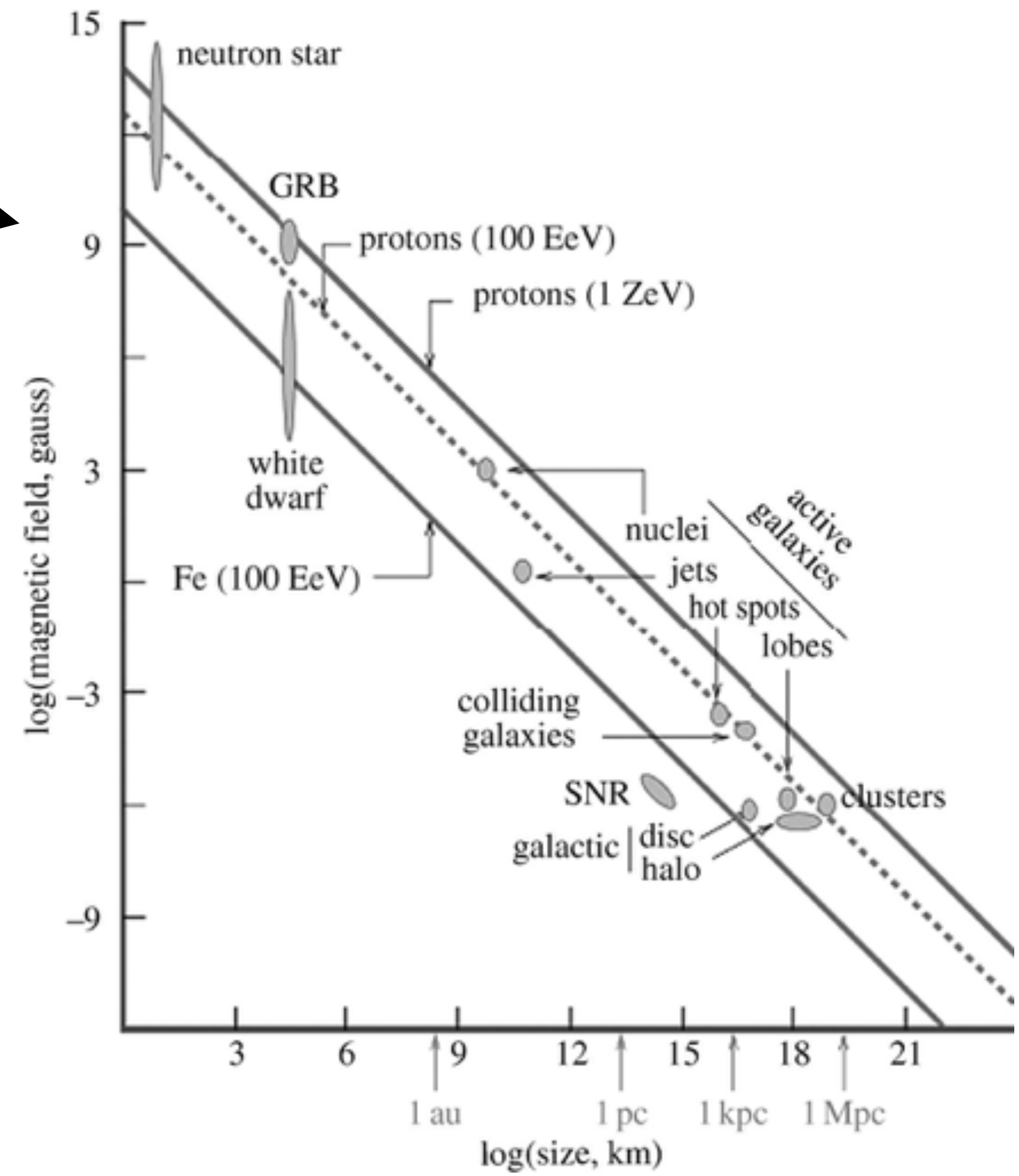


Figure 28.8: The all-particle spectrum as a function of E (energy-per-nucleus) from air shower measurements [90–105].

About all we can say about CR origin:

Hillas Plot
spectrum
composition

What exactly to infer from it?



“It is impossible to identify the CR origin from CR measurements alone.”

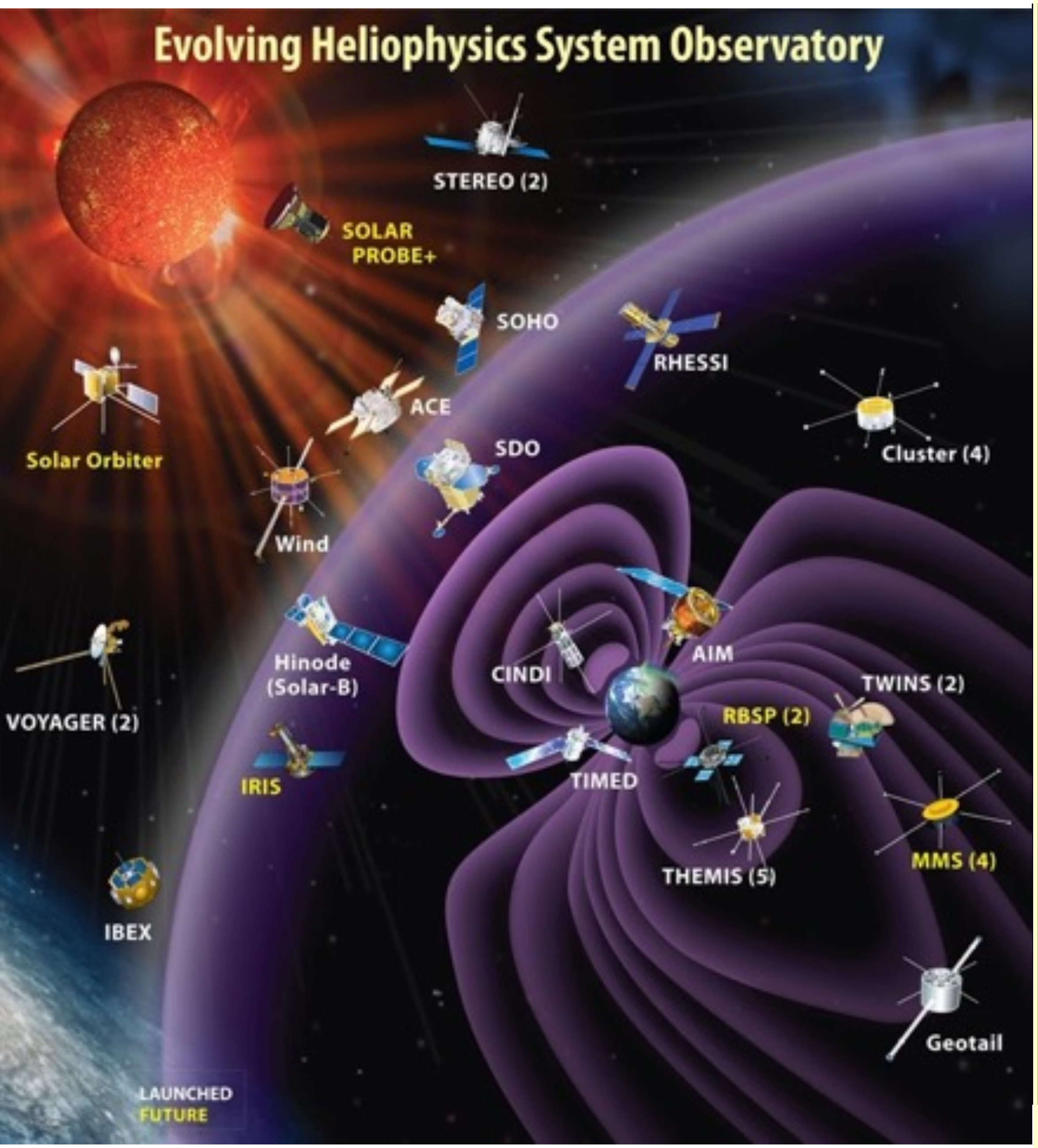
“It is impossible to identify the CR origin from CR measurements alone.”

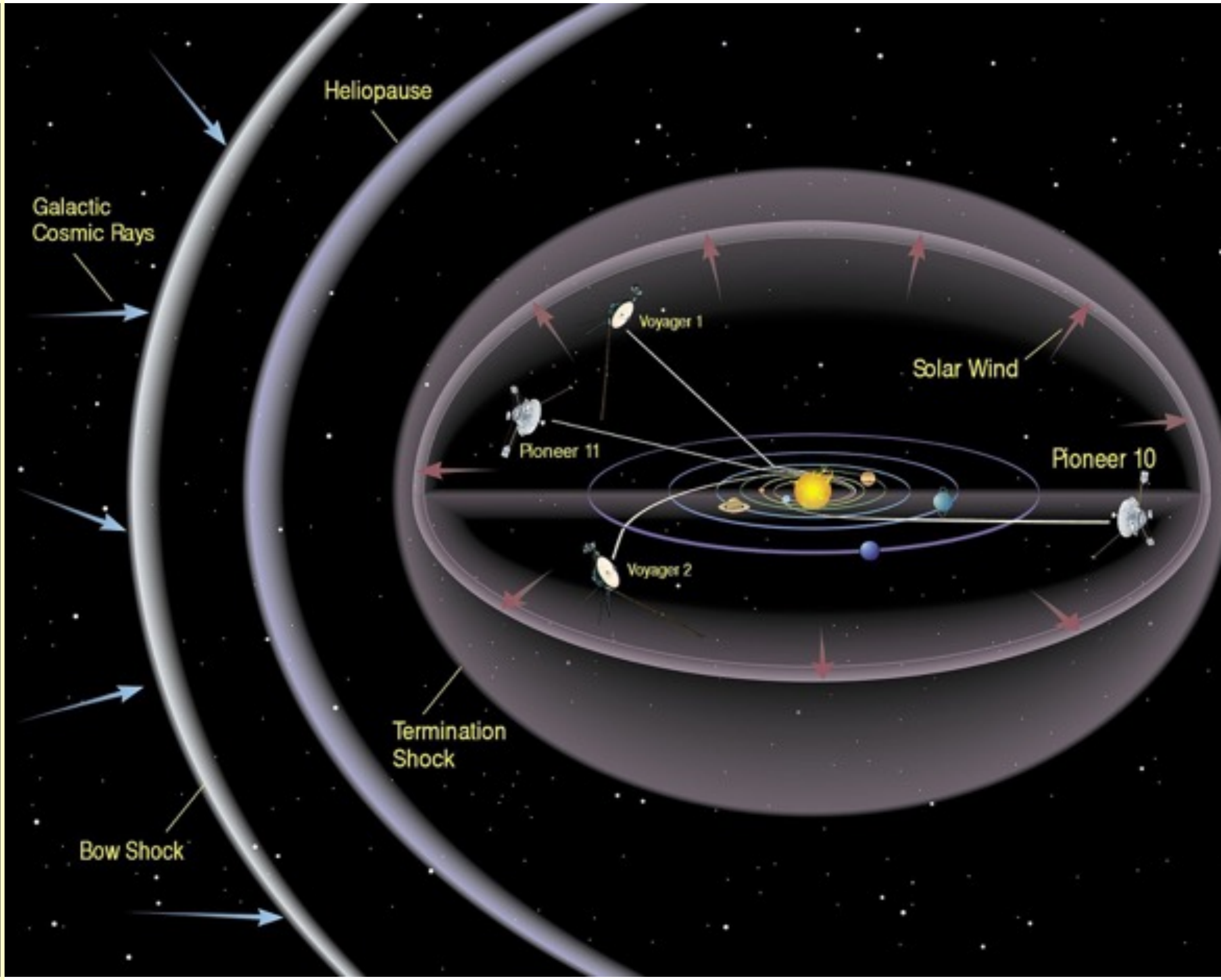
but we can

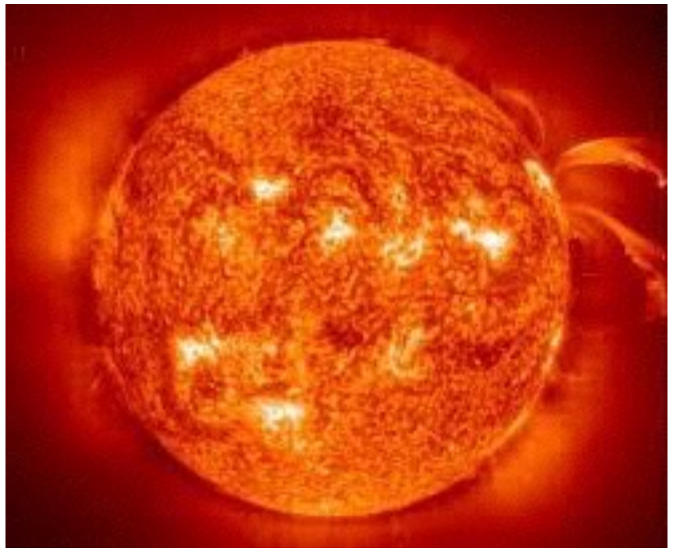
- investigate certain aspects where answers are possible
- make progress in small steps towards a larger, coherent picture of the overall CRs in the future

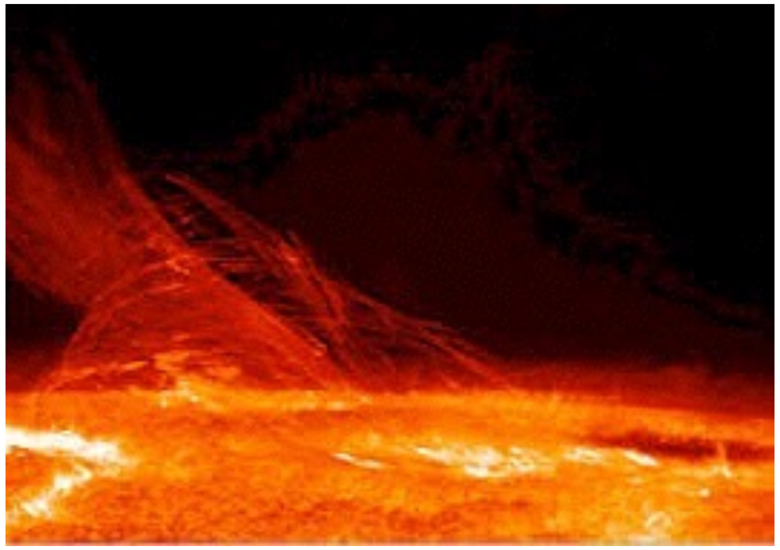
… the hard chores of Cosmic Ray Physics

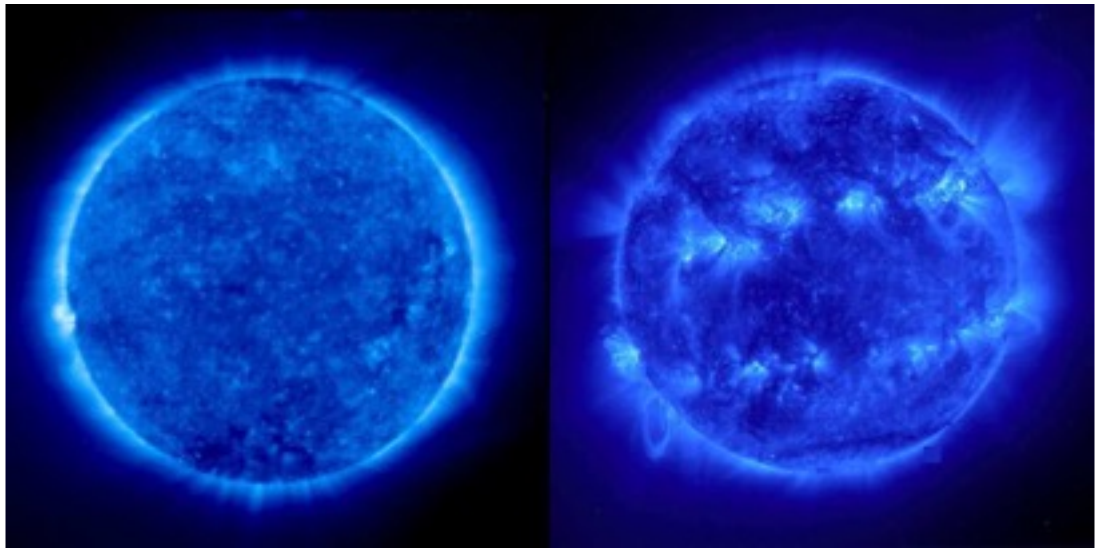
The Sun: close, dominant, reachable…











Particle Physics:

man-made accelerators / controlled lab conditions

fundamental interactions,
basic understanding of processes that are now crucially important in studies of
acceleration, sources, propagation, detection of astroparticles

Astronomy: study individual remote objects

photons (meV - UHE)

easy to detect, reasonably high fluxes, many sources,
non-thermal processes relate to CRs

neutrinos (MeV - UHE)

very difficult to detect, very low fluxes, no sources (yet),
relate to CRs.

UHECR ($> 10^{20}$ eV)

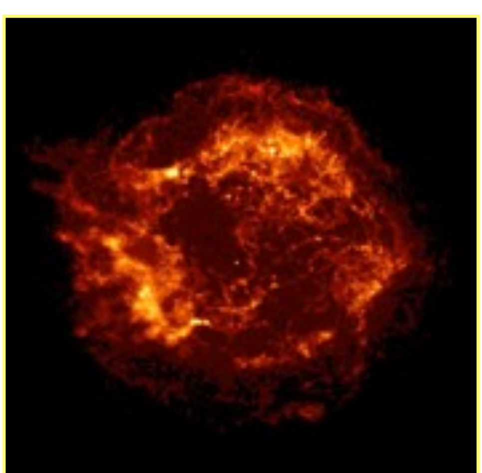
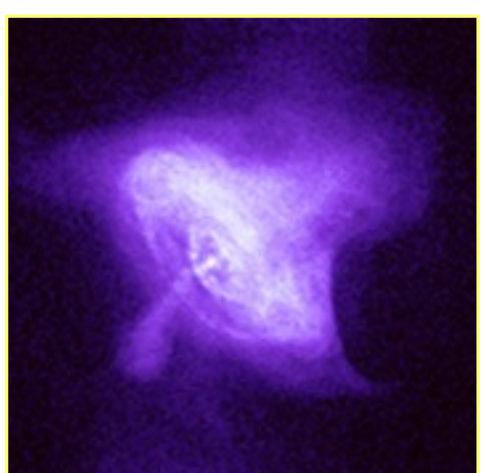
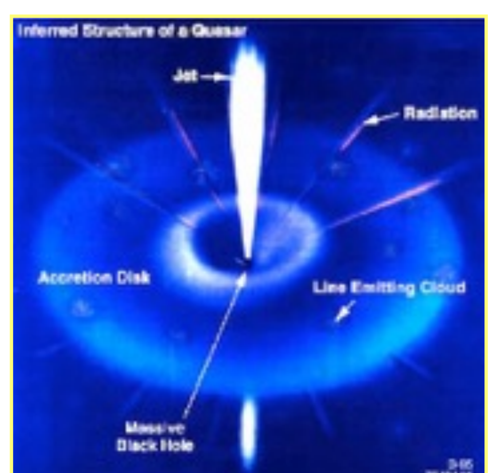
do they point back to sources?
difficult to detect, very low fluxes, no sources (yet)

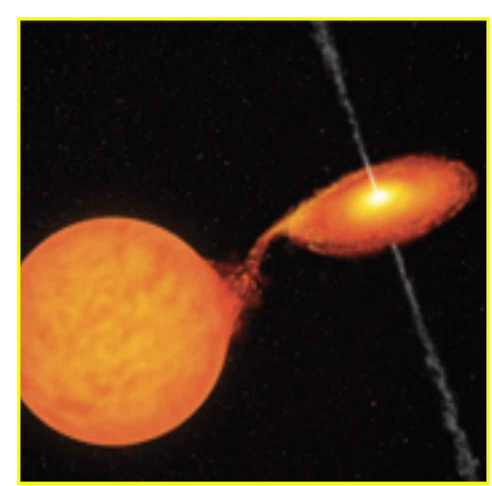
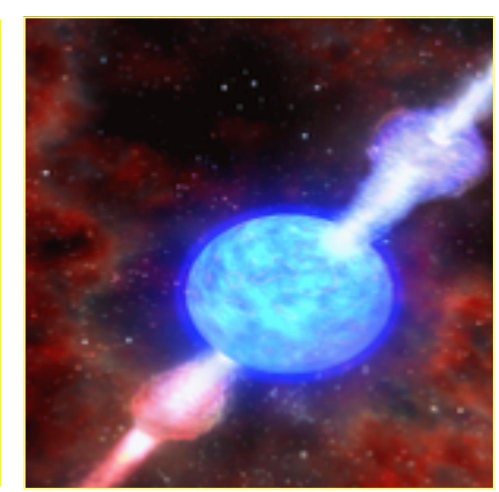
Much of what we know about cosmic rays
is known from photon astronomy,

largely in wavelength ranges
relating to non-thermal processes:

radio - X-ray - GeV gamma ray - VHE gamma rays

but also optical and other wave lengths
to characterise astronomical objects.

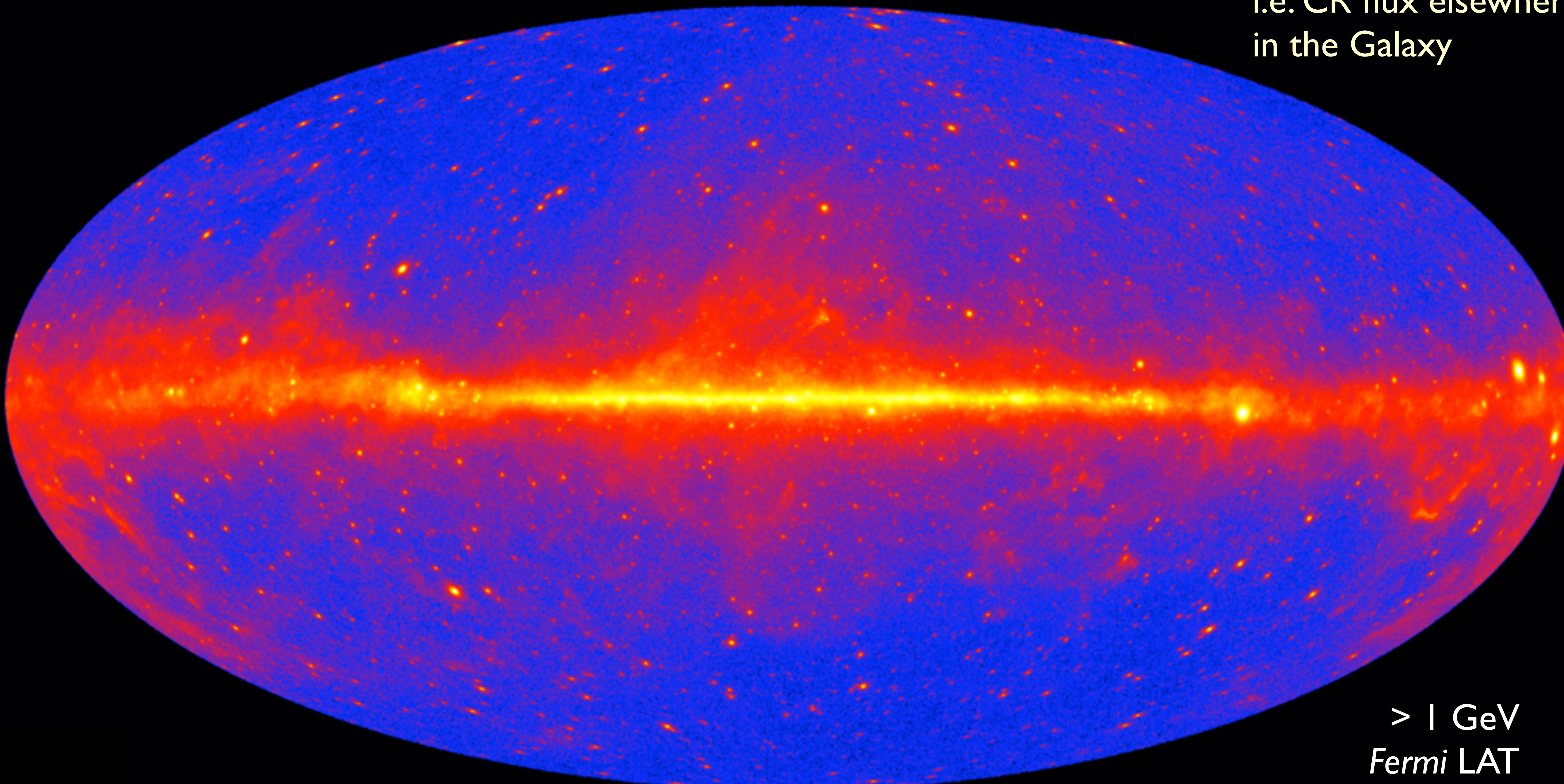
Gamma Ray Astronomy

lots of results on CR physics

The Fermi γ-ray sky

point sources, extended sources and diffuse emission, ...

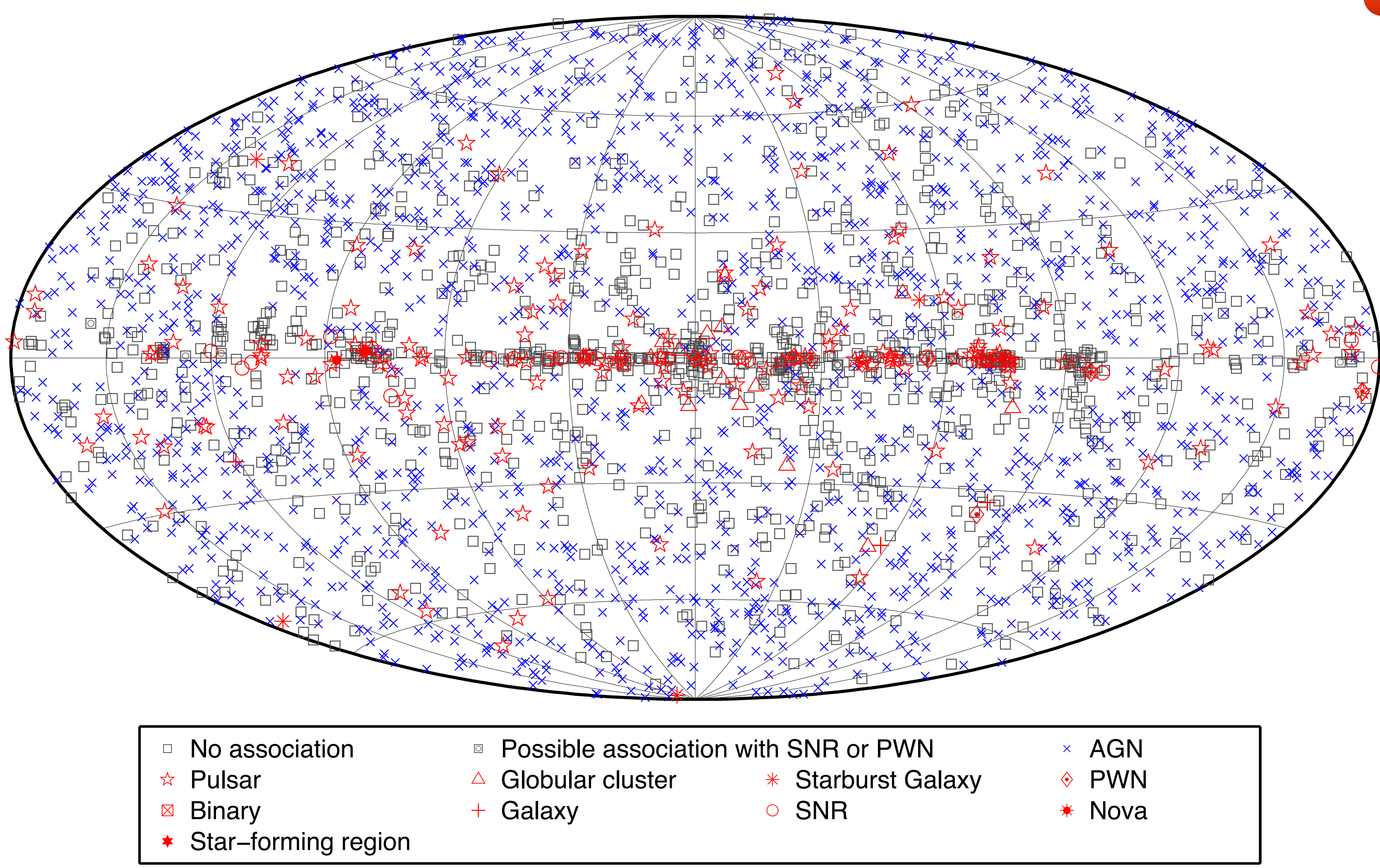
i.e. CR flux elsewhere in the Galaxy

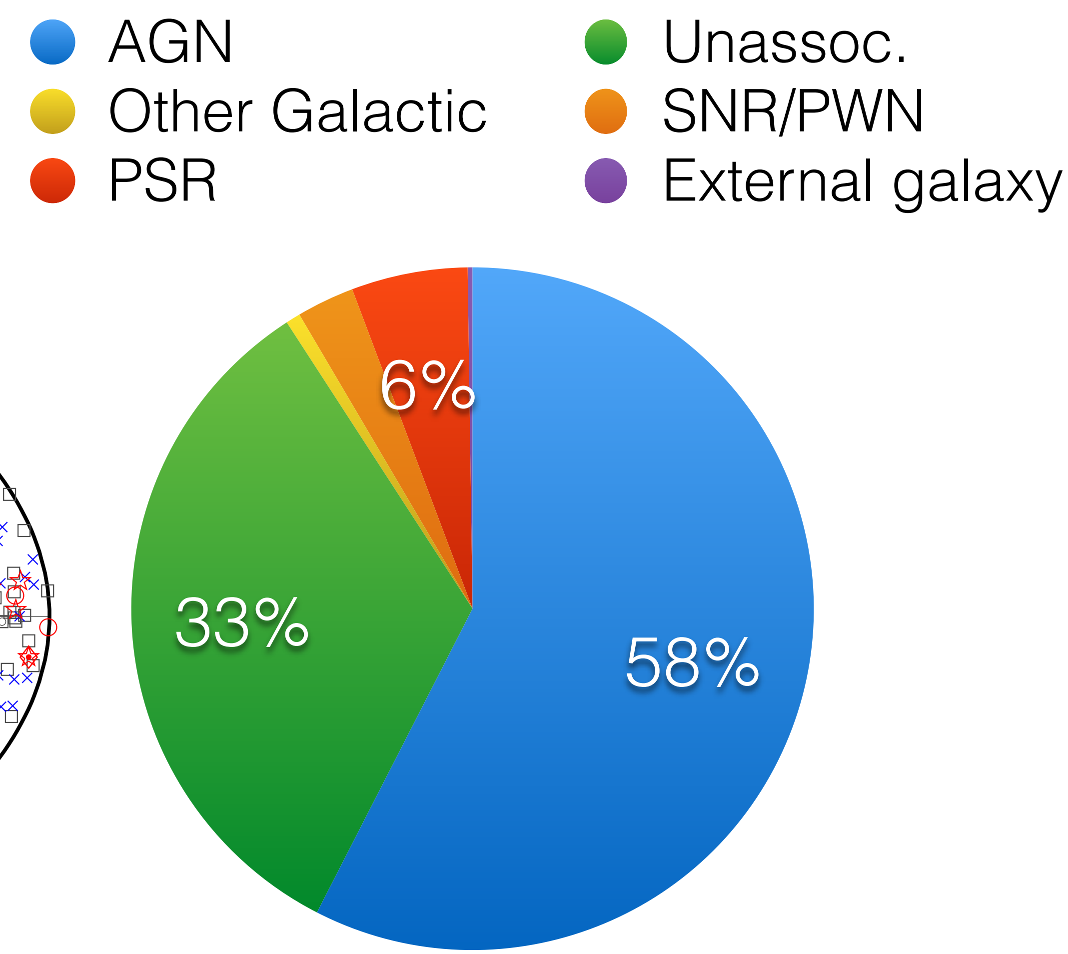


> 1 GeV
Fermi LAT
2008-2015
NASA/DoE/*Fermi*-LAT collaboration

Resolving the γ-ray sky: sources

- general catalogs, e.g., 3FGL
  - 4 years, 100 MeV-300 GeV
  - 3033 sources (> 4.1σ)
- specific source classes/energy ranges



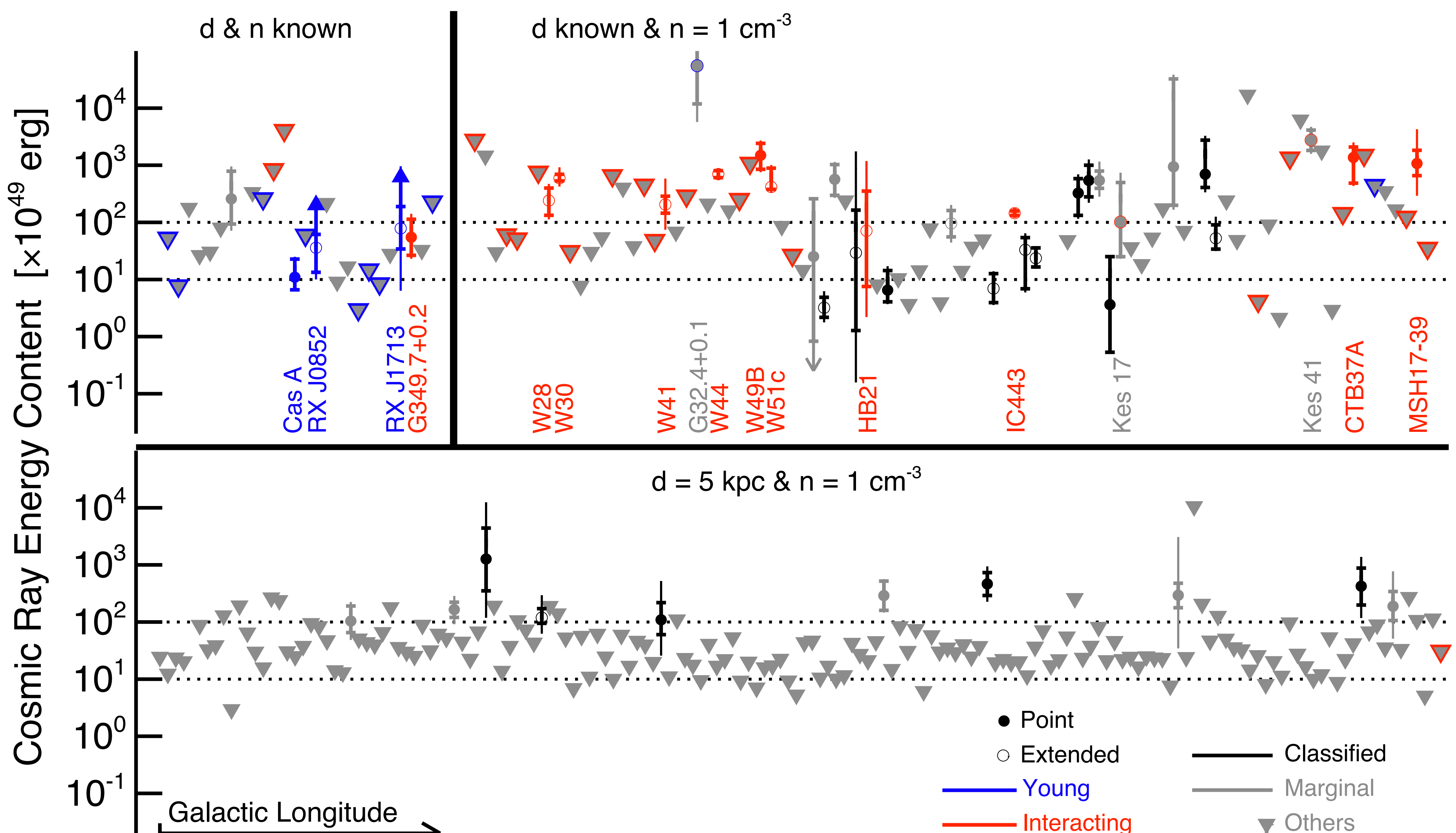


Fermi LAT collab. ApJS 218 2015 23A

CR origin: testing the SNR paradigm

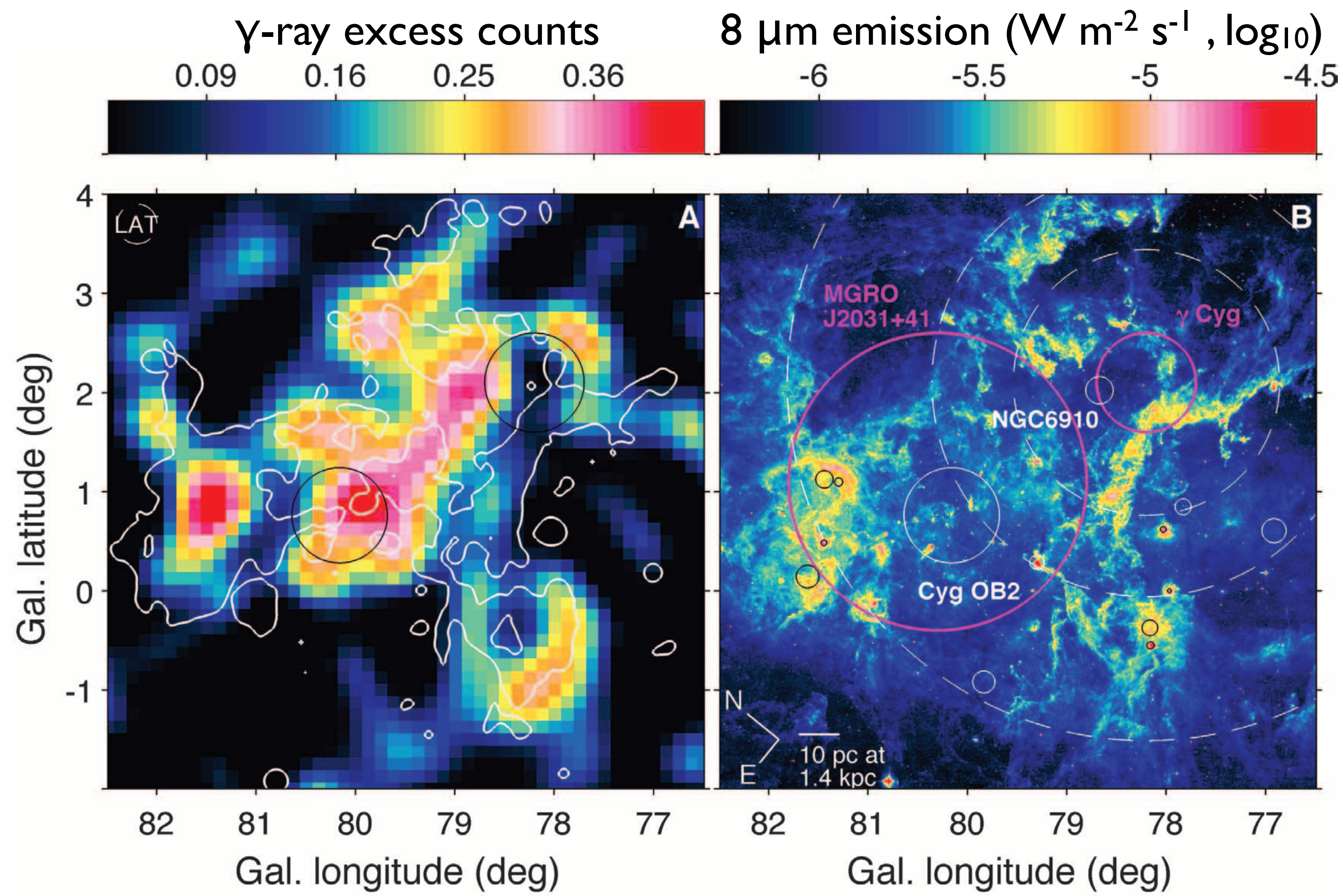
- SNR paradigm: 10% of SN energy into cosmic rays
- LAT SNR Catalog, 1-100 GeV
  - 30 sources classified as SNRs
  - 14 marginal candidates
  - 245 upper limits on radio SNRs

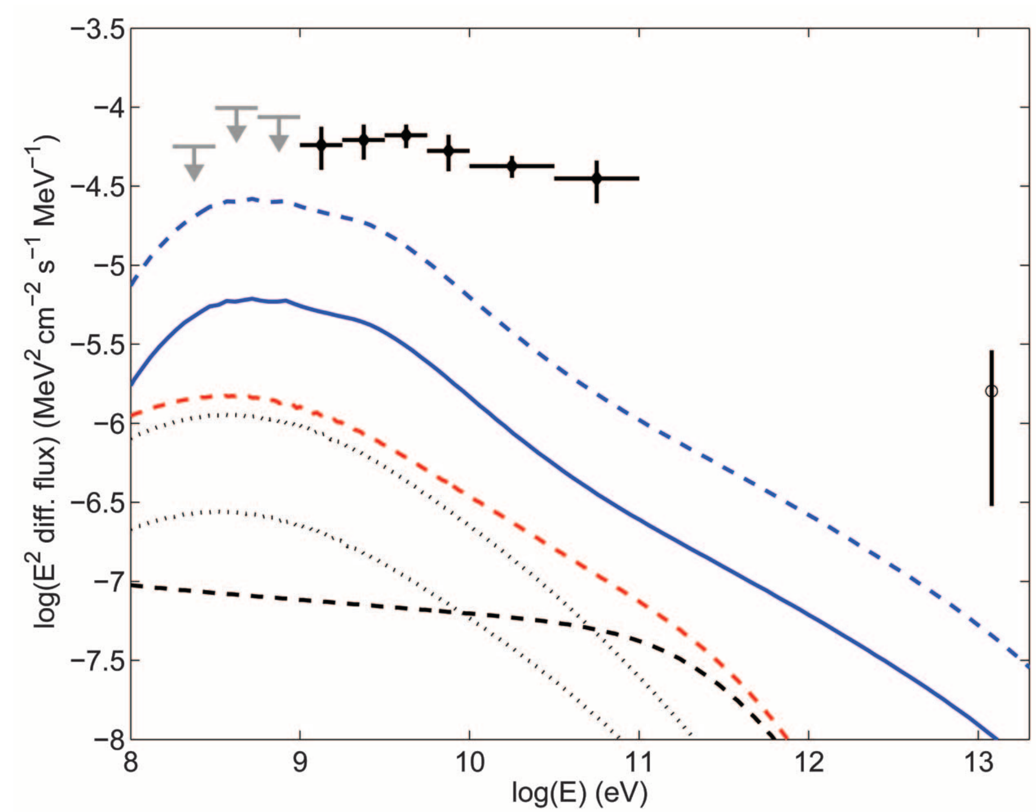
Fermi LAT collab. ApJS 224 2016 8A



A cocoon of freshly accelerated CRs in Cygnus

- massive star-forming regions
  - CR isotopic abundances (^{22}Ne, trans-iron)
  - 80% SN = gravitational collapse of massive star
  - superbubbles
- CR cocoon in Cygnus
  - single source or superbubble?
  - advection? confinement?



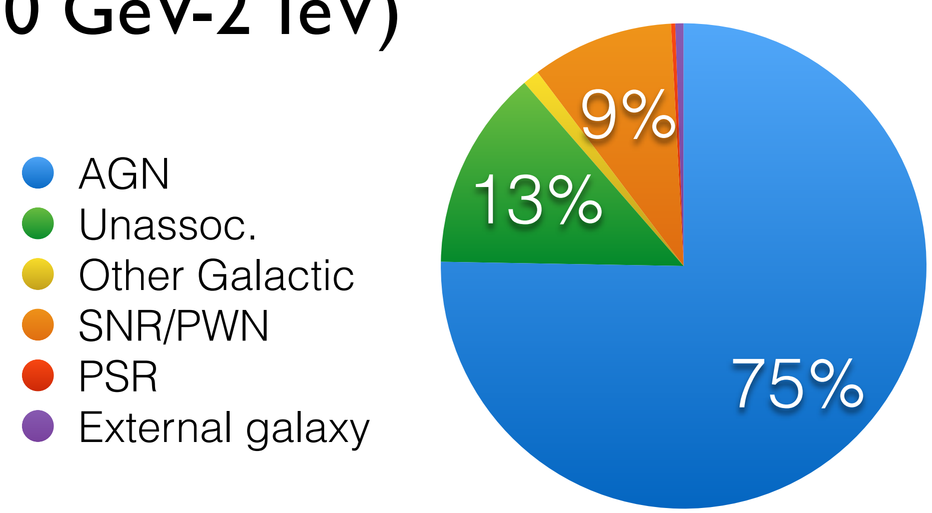


Fermi LAT collab. Science 334 2011 1103

L. Tibaldo

Extension to TeV energies

- segmented ACD/calorimeter: reduce back-splash self-veto
- Pass8 analysis
  - reliable energy estimate up to 2 TeV
  - 25% larger effective area > 10 GeV
- 2FHL Catalog
  - 80 months, 50 GeV-2 TeV
  - 360 sources → 75% previously unknown
- upcoming: 3FHL (1720 sources, 10 GeV-2 TeV)



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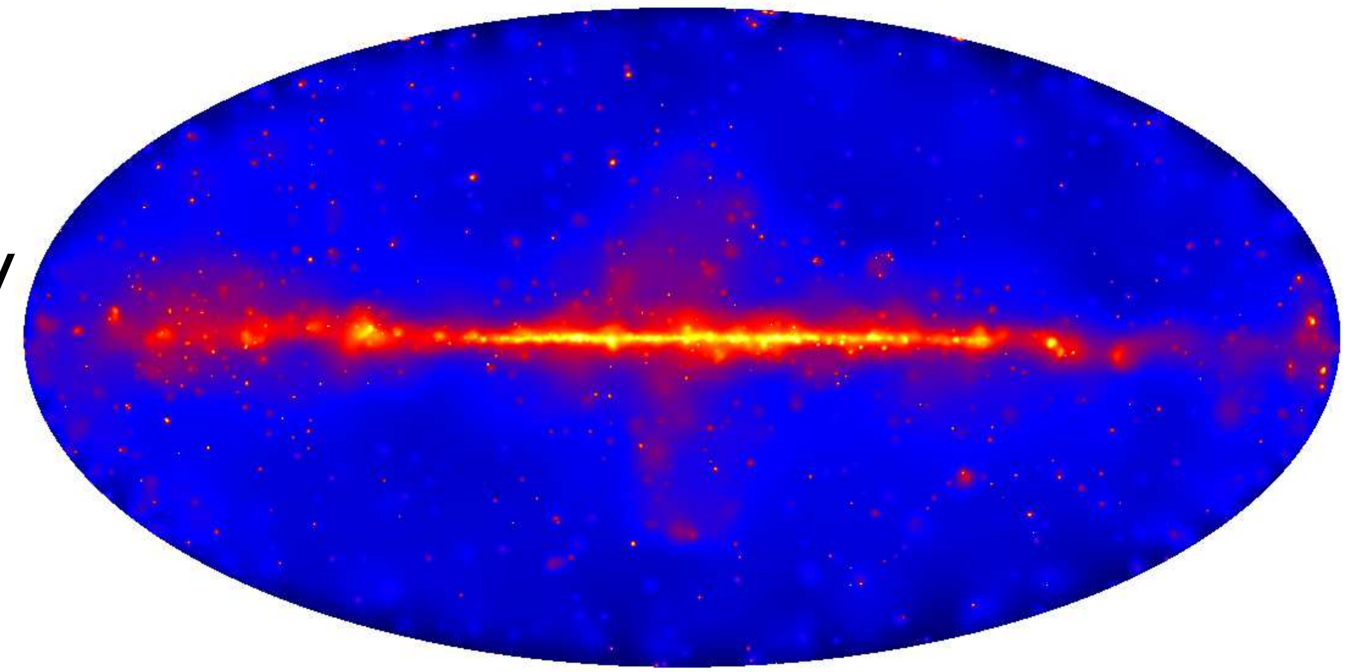
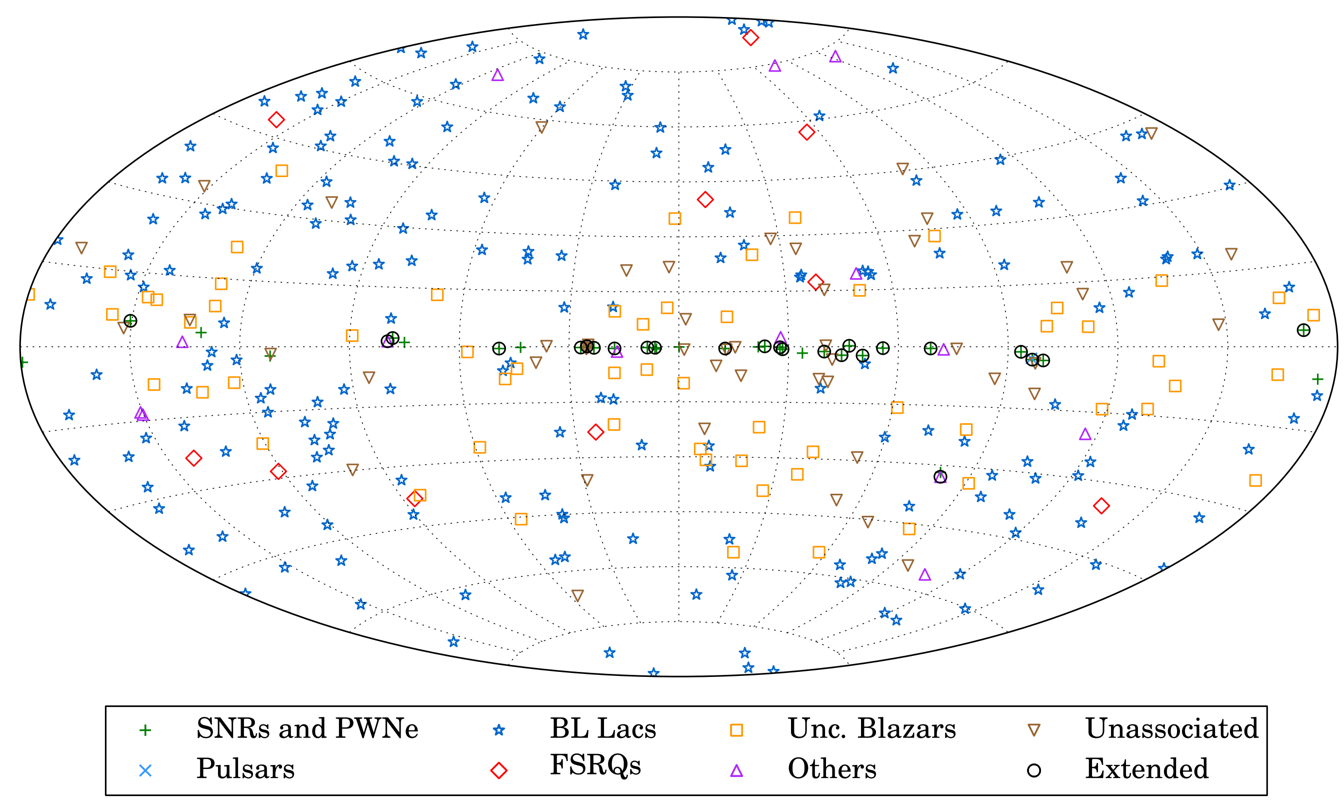
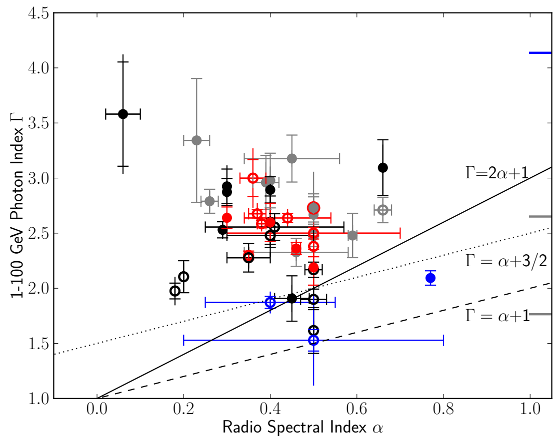
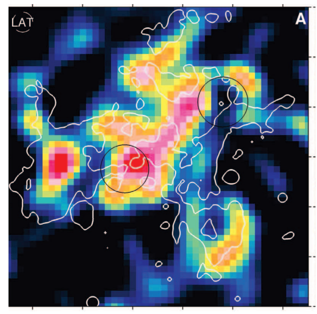


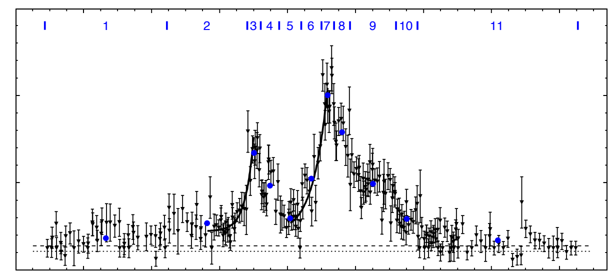


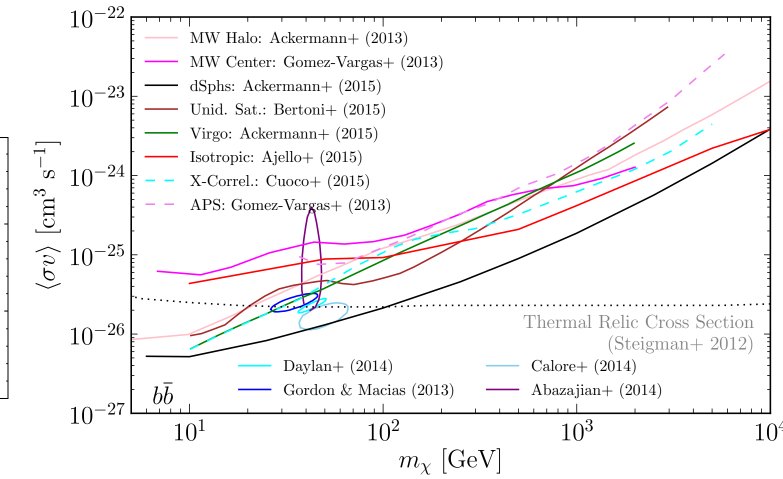
Summary

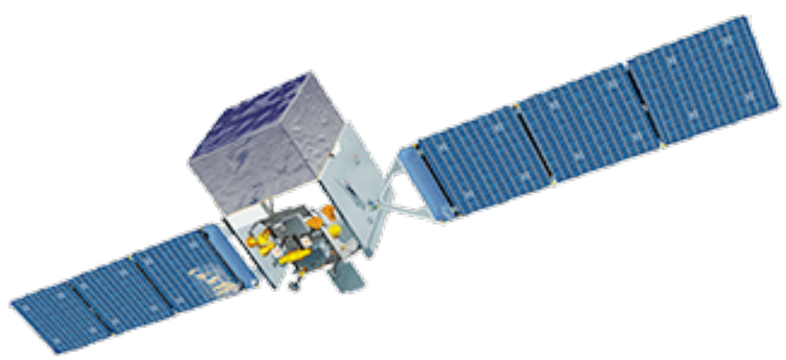
new results

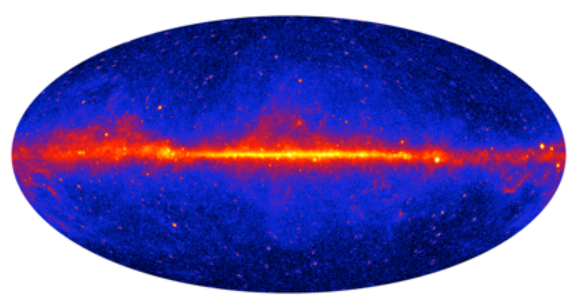


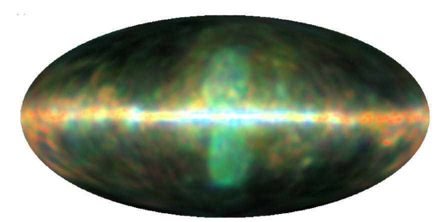


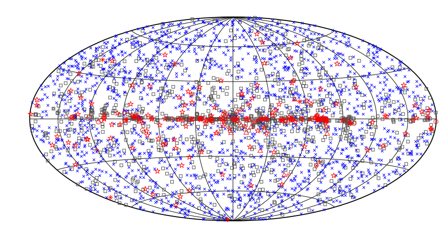




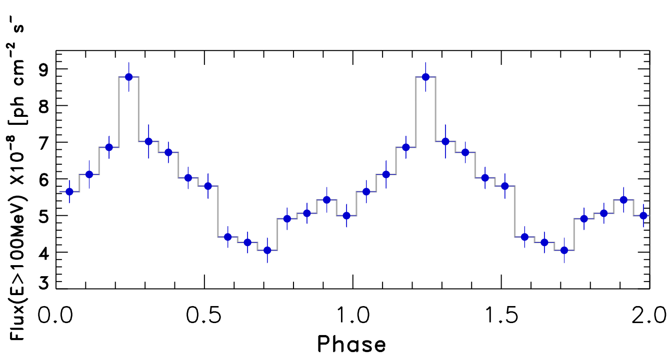


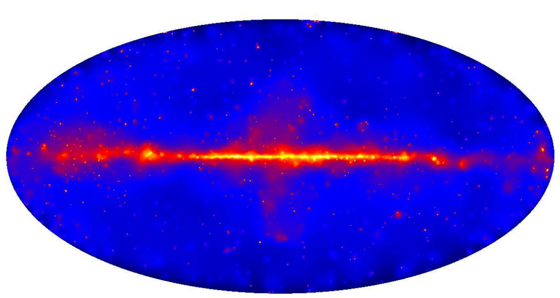


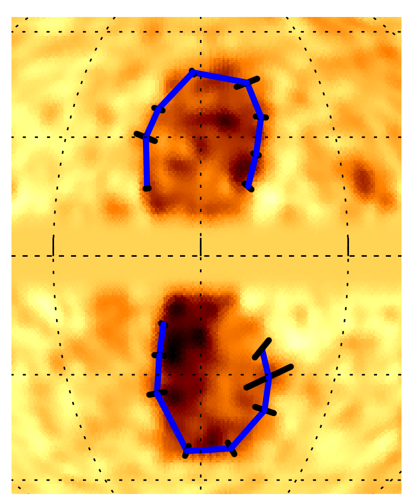




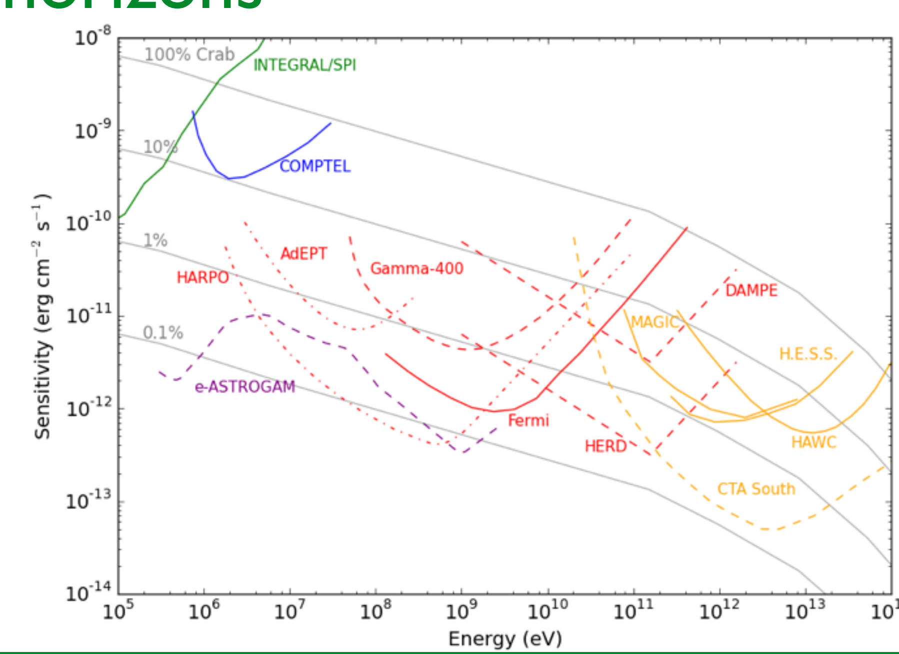
new frontiers



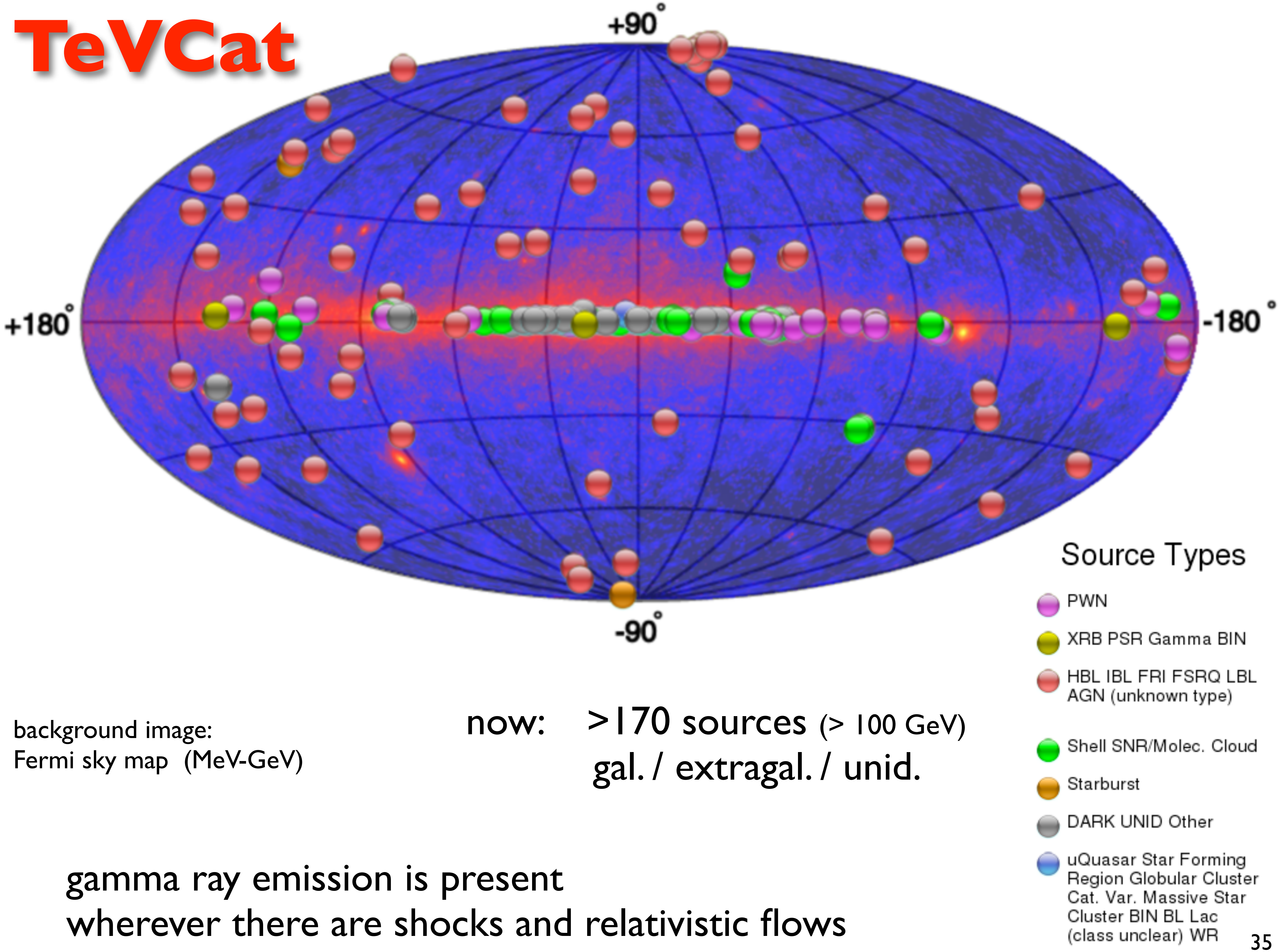




new horizons



TeVCat

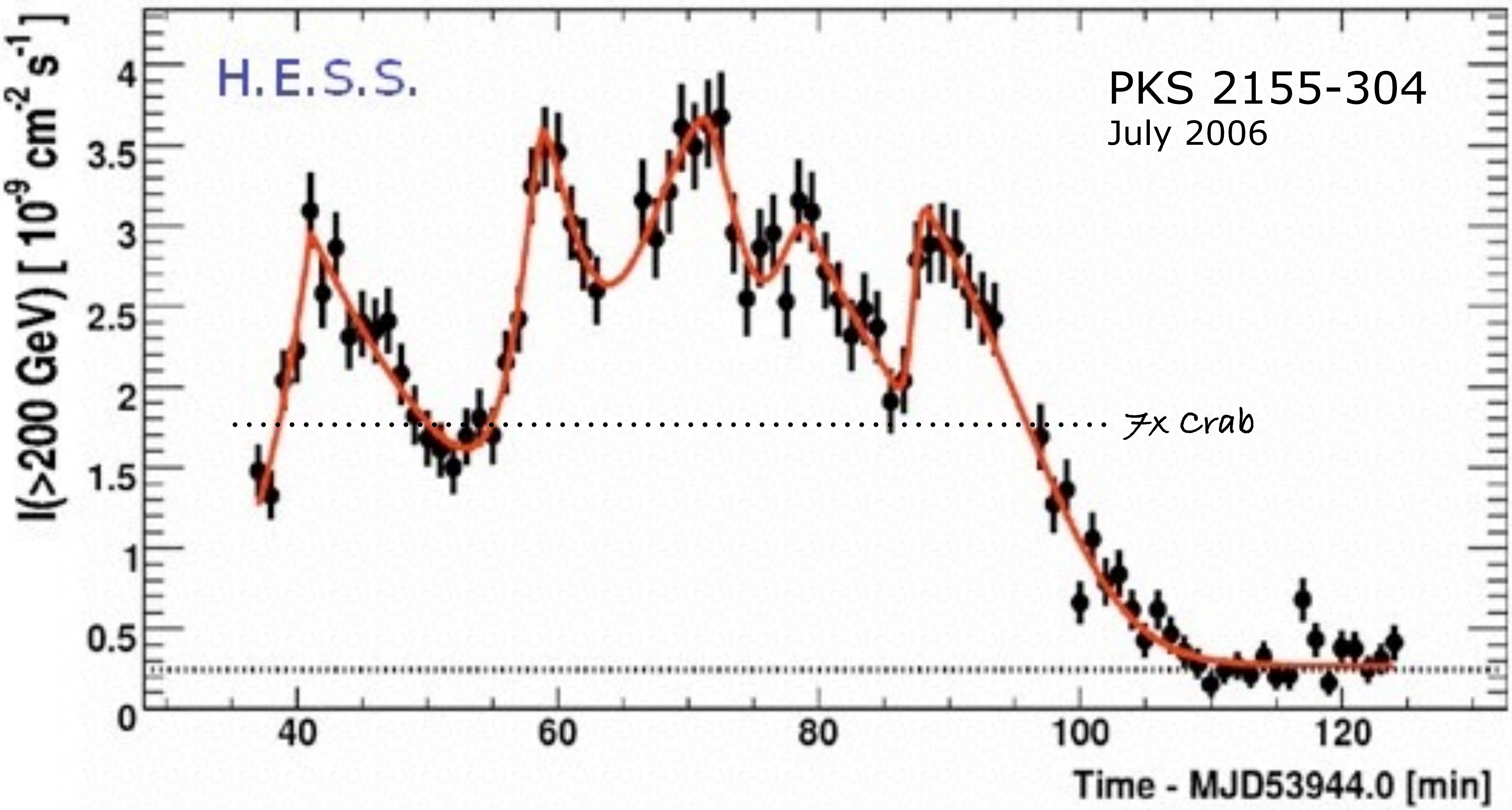


background image:
Fermi sky map (MeV-GeV)

now: >170 sources (> 100 GeV)
gal. / extragal. / unid.

gamma ray emission is present
wherever there are shocks and relativistic flows

Variability

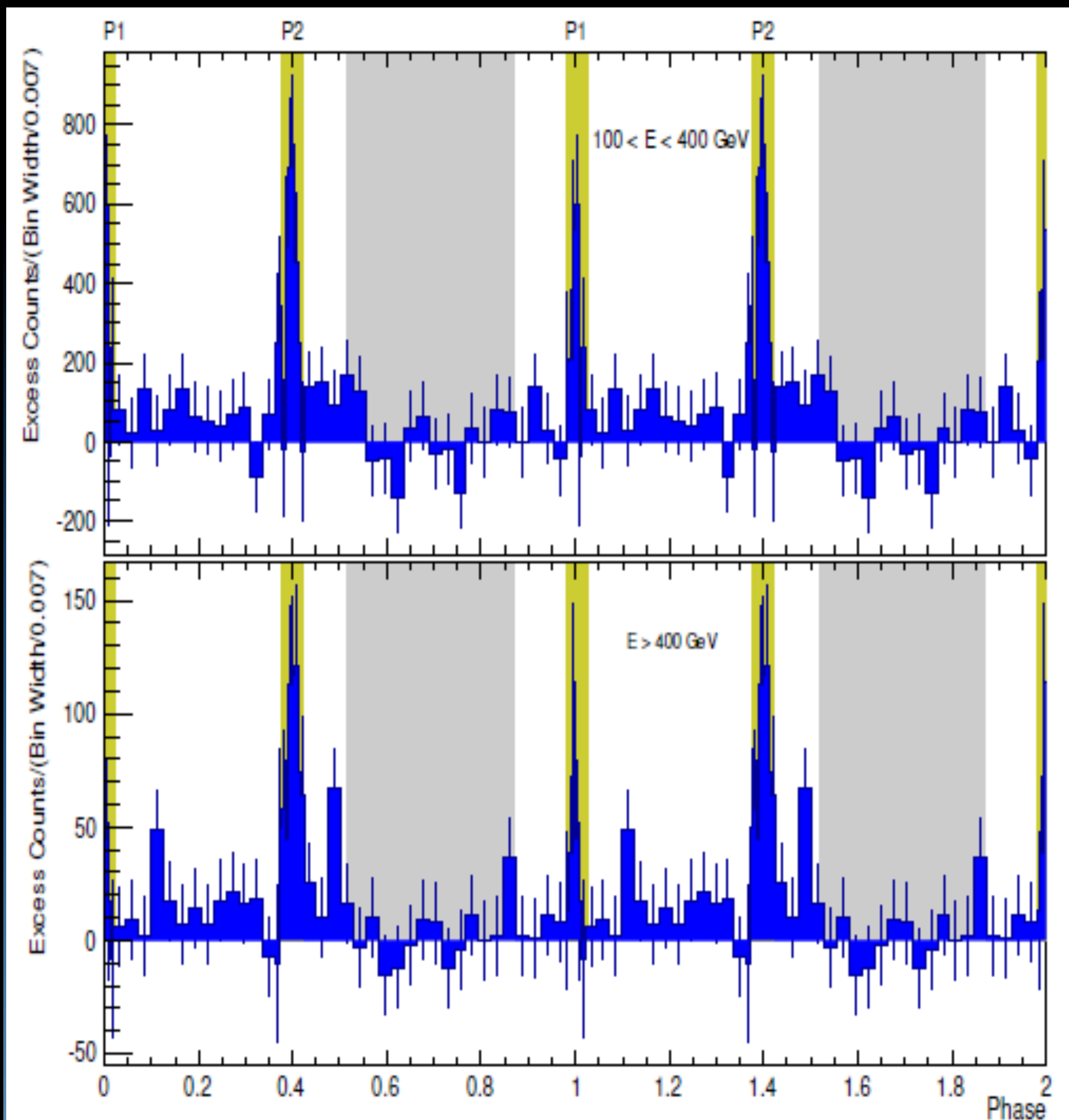


BL Lac object $z = 0.116$

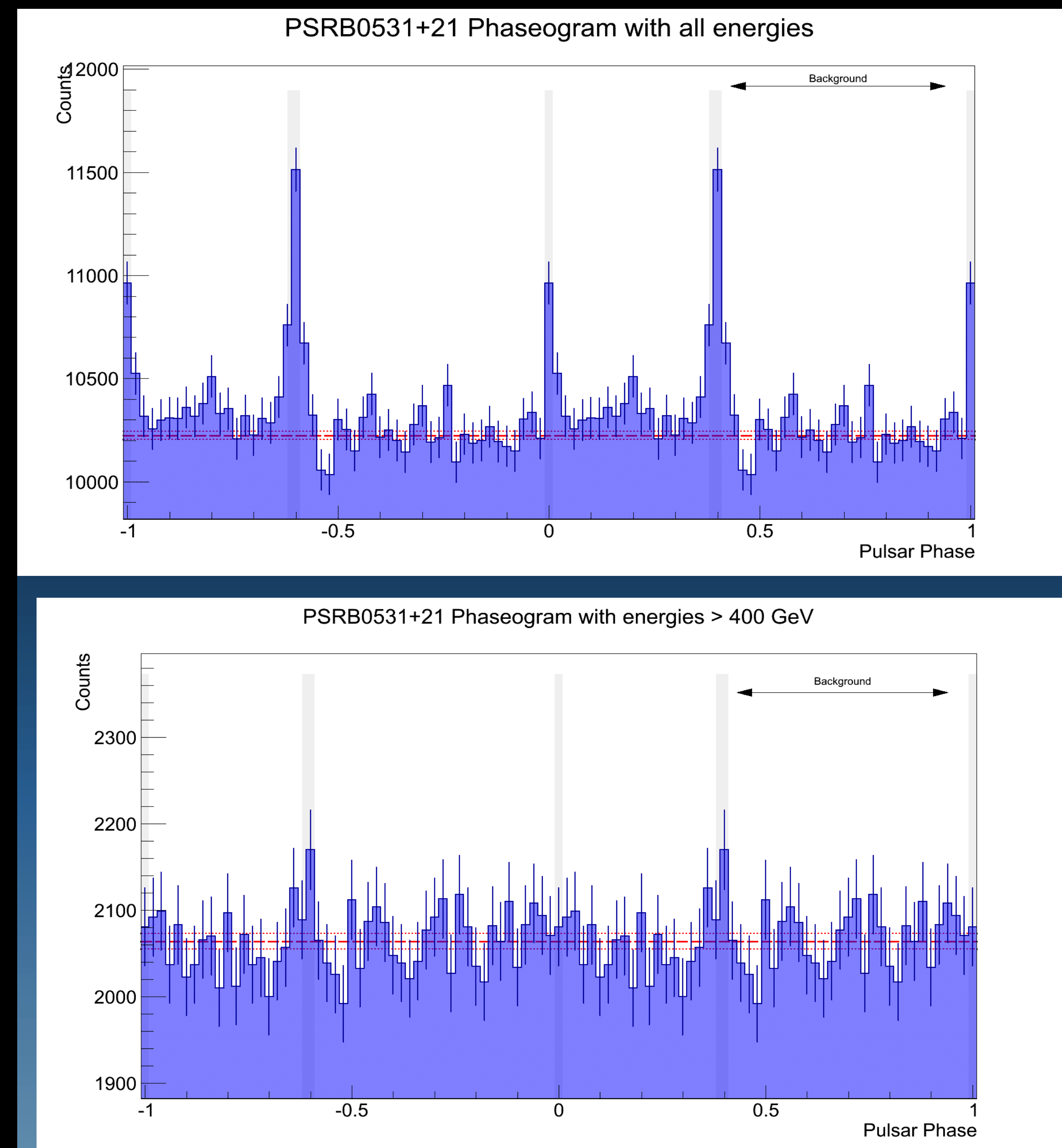
bursts on minute scales

$\Gamma \geq 100$ are required

Crab Pulsar >400 GeV Emission

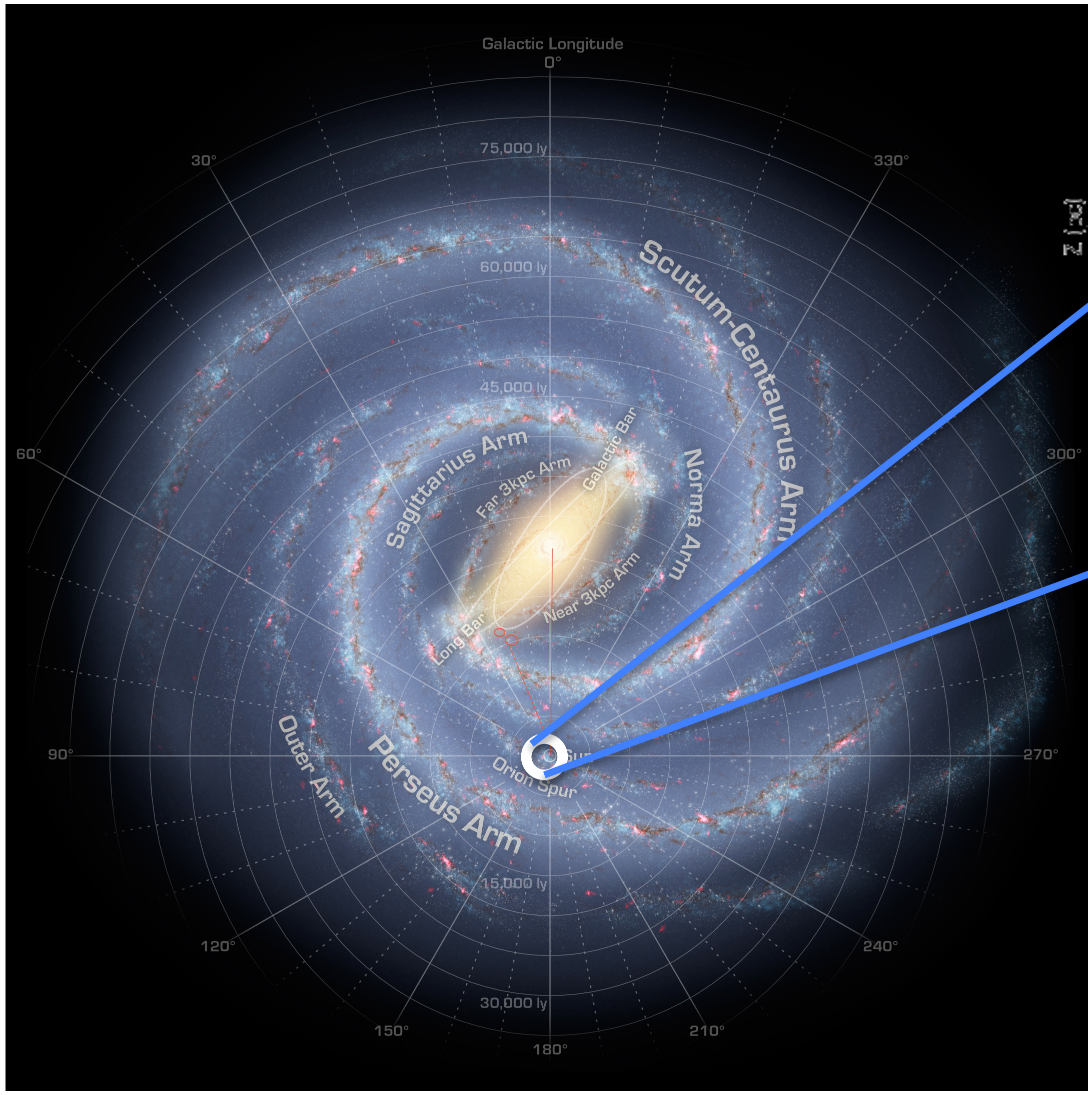


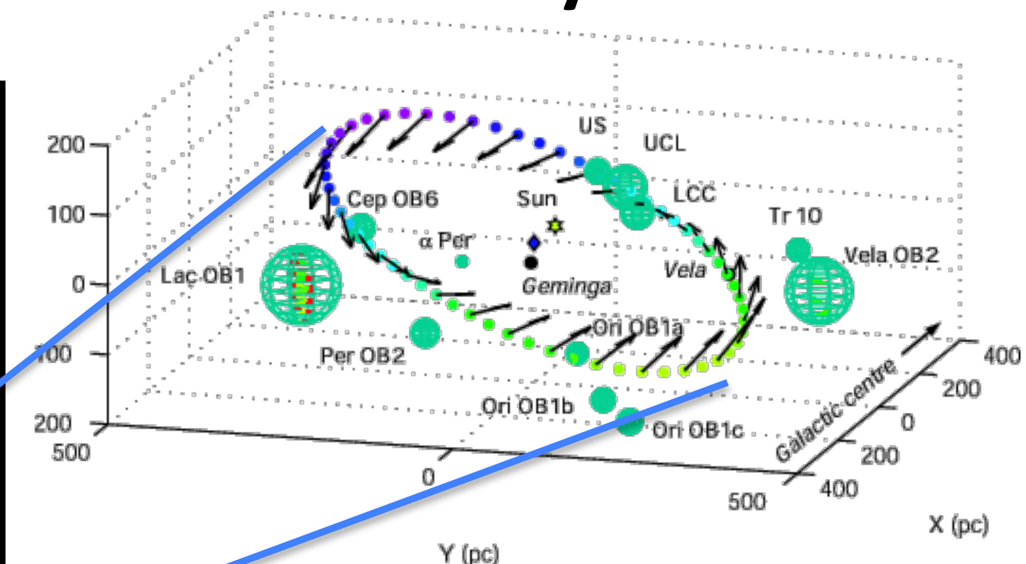
MAGIC

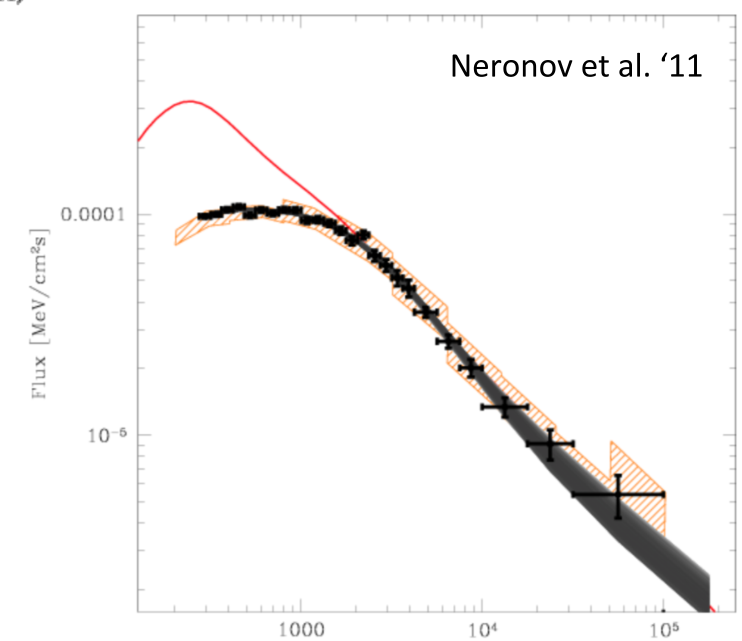


VERITAS

CR spectrum in the local Galaxy

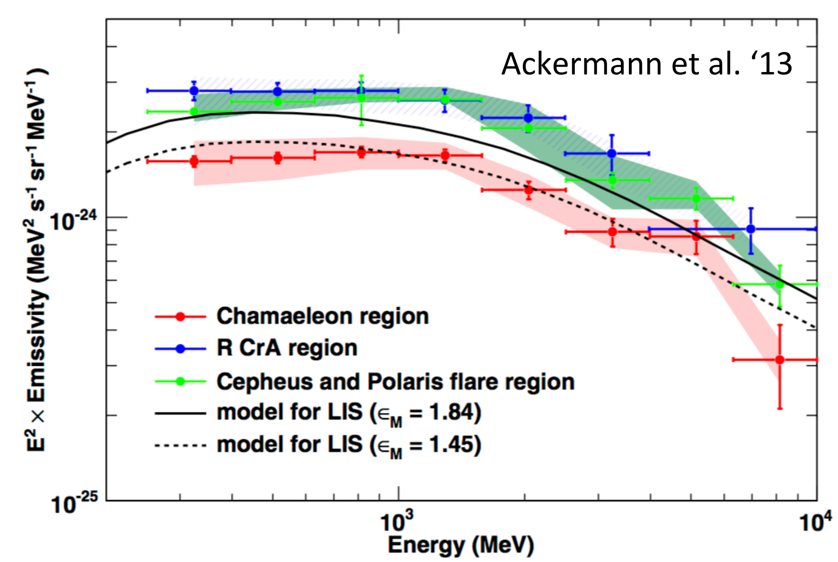




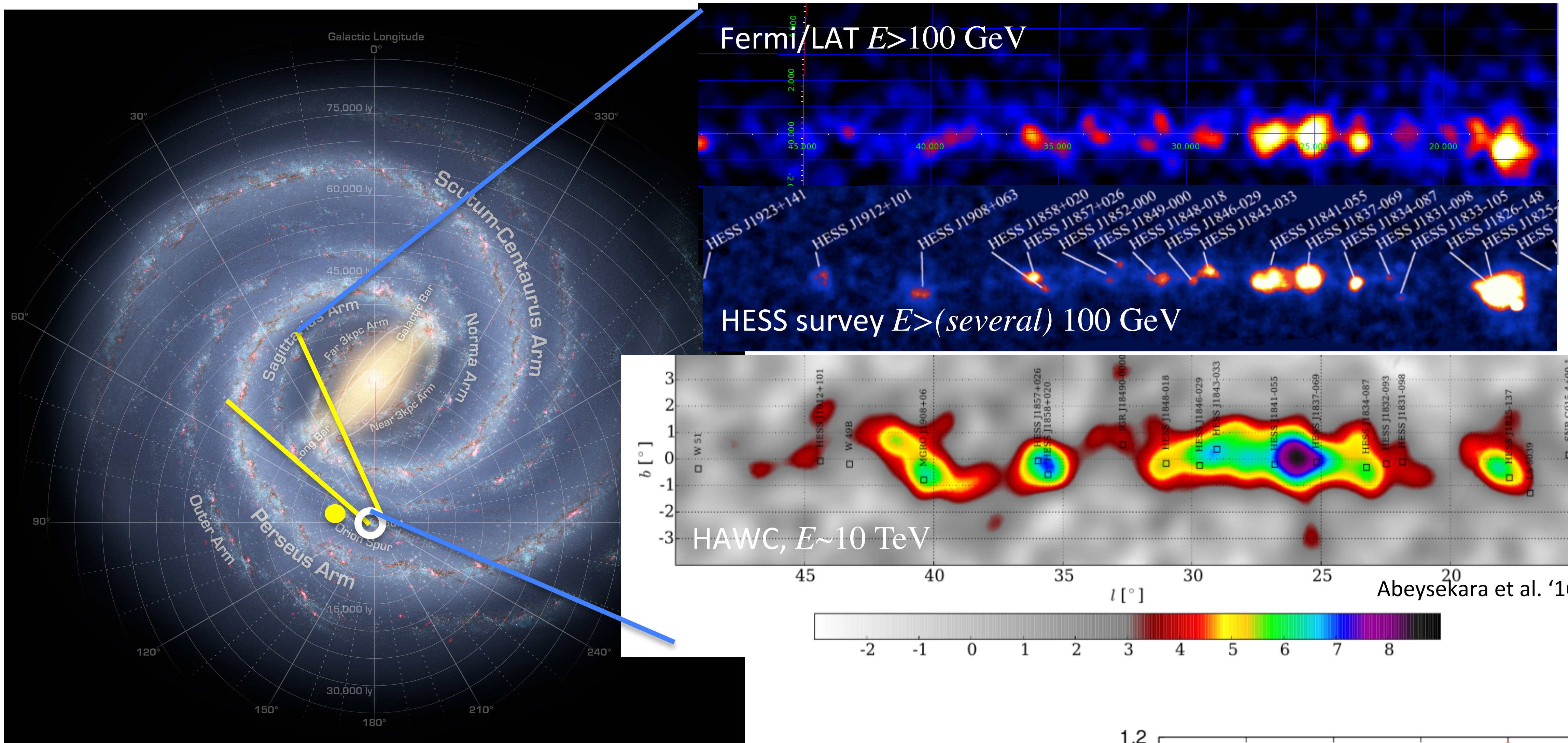


Molecular clouds in the local Galaxy form a ring-like structure, the Gould Belt of diameter ~ 1 kpc. Spectrum of gamma-ray emission from CR interactions in the clouds provides a measurement of the CR spectrum in the local Galaxy (free from the Solar modulation effect:

– CR spectrum in the local interstellar medium is soft ($\Gamma=2.9\pm0.1$) in 10-100 GeV band … consistent with the locally measured one.



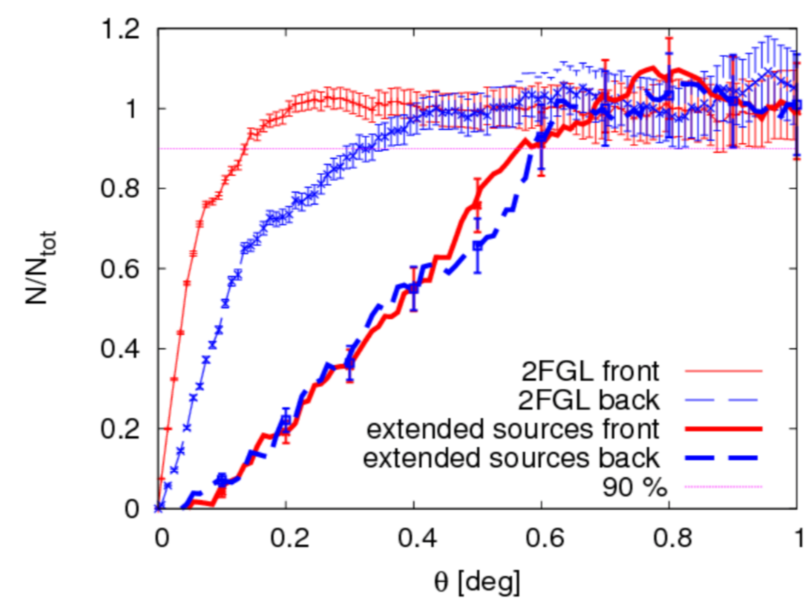
CR spectrum in distant regions of Galactic Plane



Abeysekara et al. '16

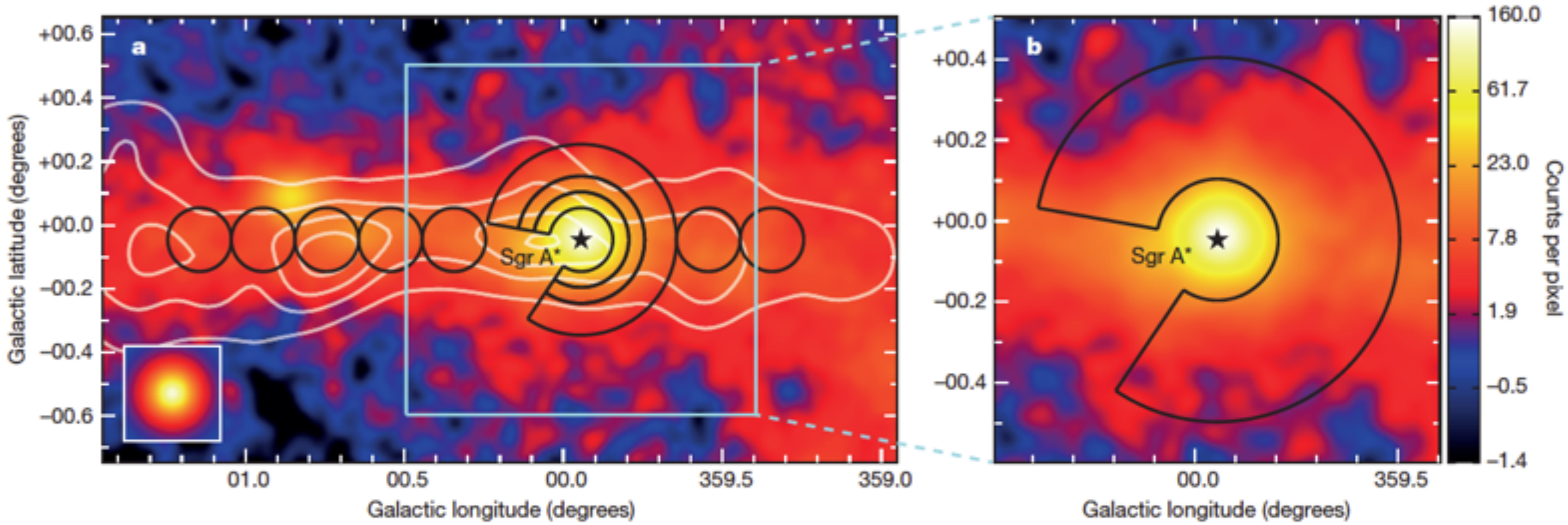
Galactic Plane surveys with Fermi/LAT, HESS, HAWC reveal a set of sources, not obviously identified with supernova remnants or pulsar wind nebulae

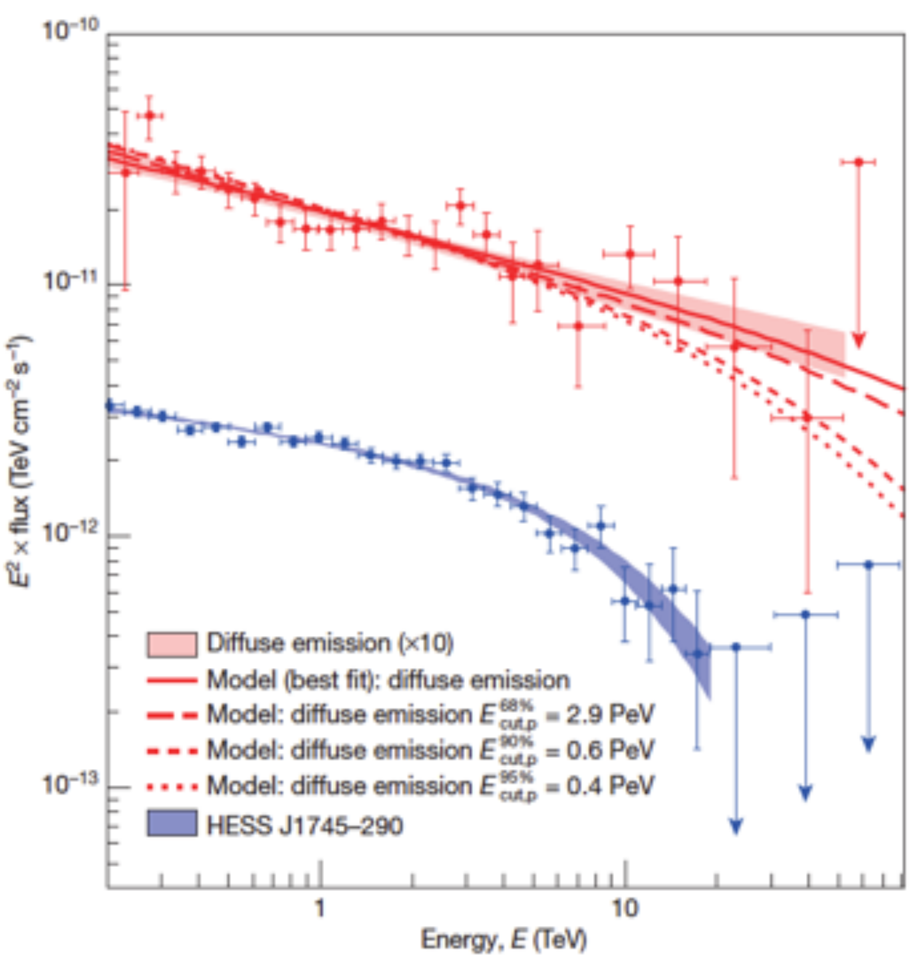
– large number of sources have degree-scale extensions, which corresponds to ~100 pc at ~4 kpc distance. Typical size of an OB association like Cygnus OB2 (too large for an isolated SNR or PWN).

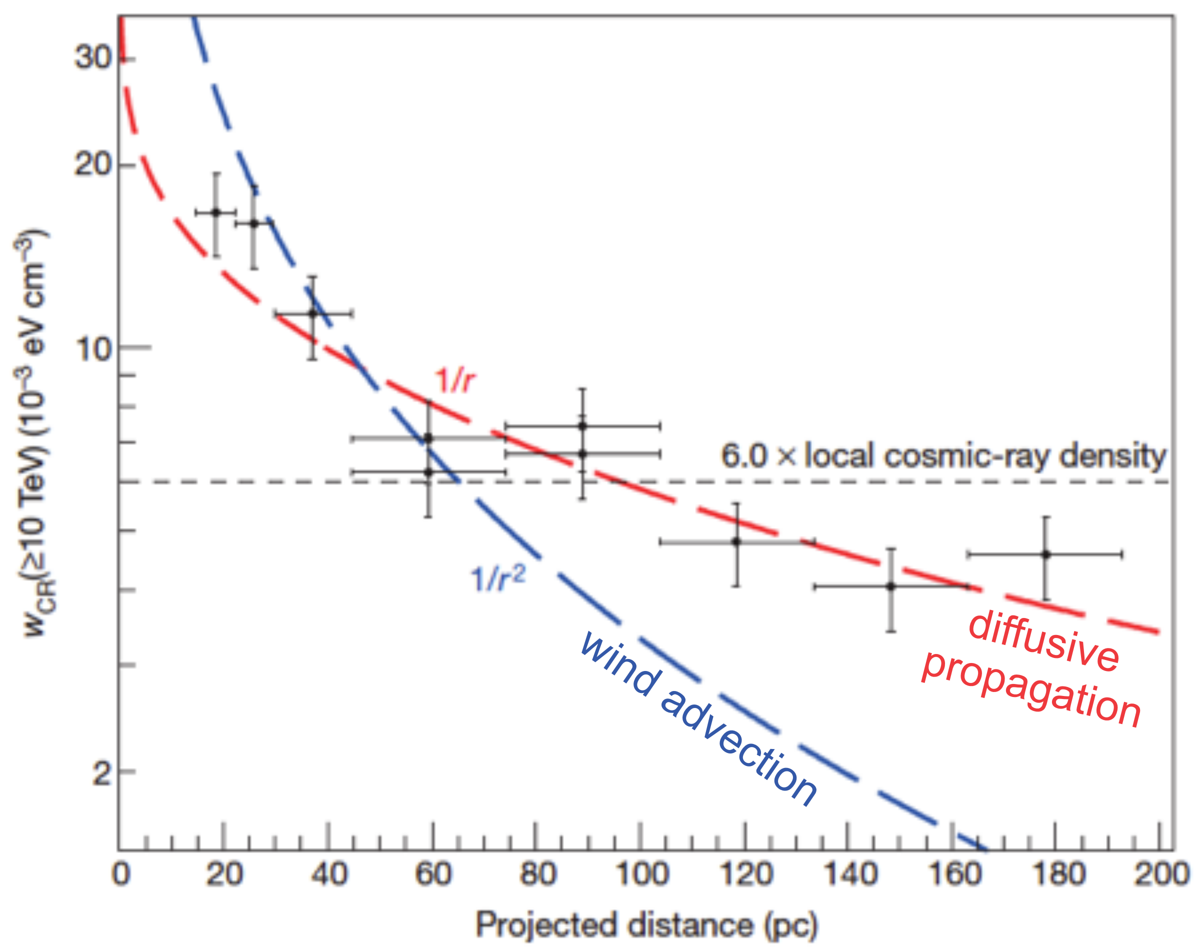


Neronov, Semikoz et al. '12

Neronov

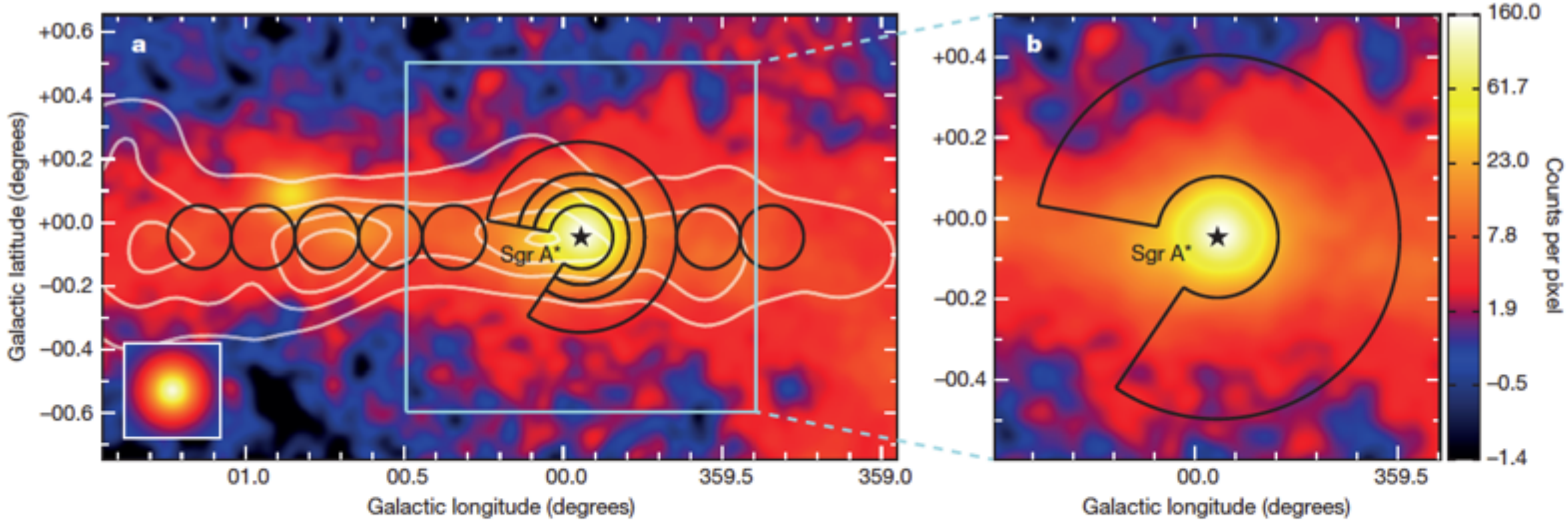


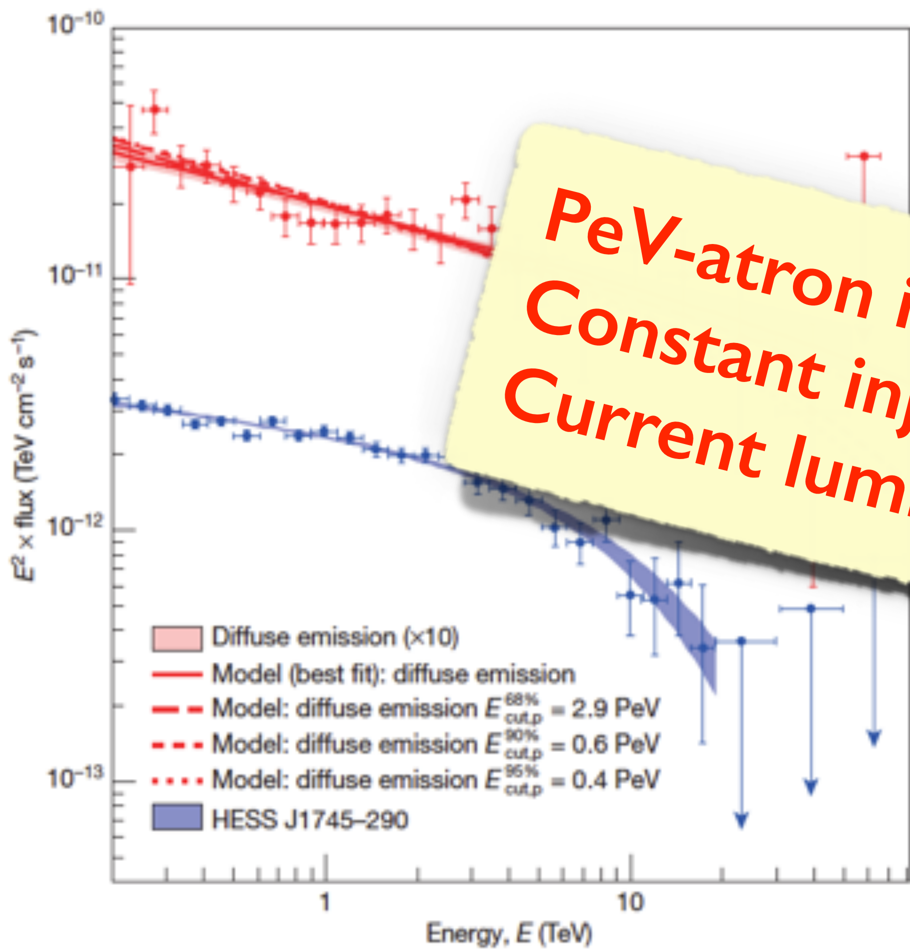


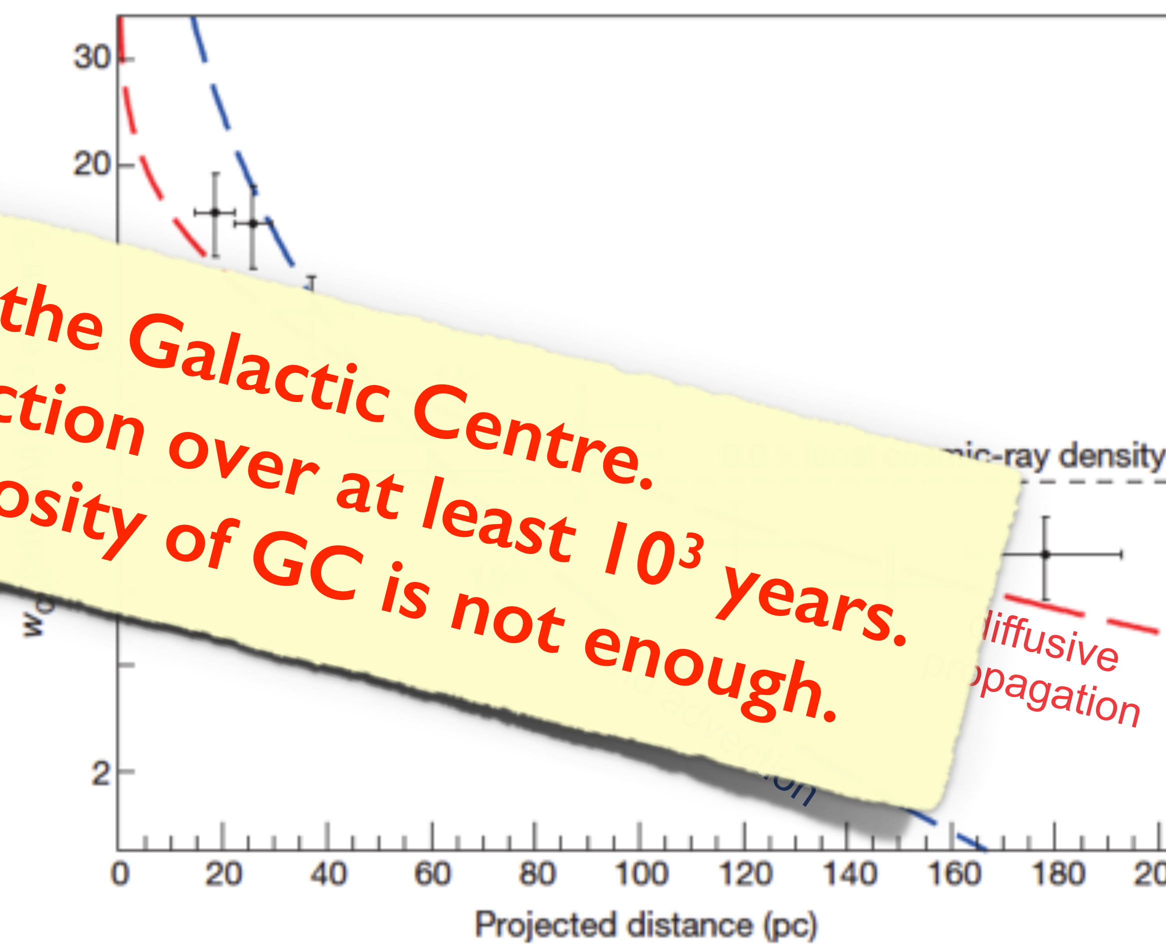


Very hard emission, no cutoff, untypical for extended emission

Cosmic ray density profile using matter densities from molecular line surveys.





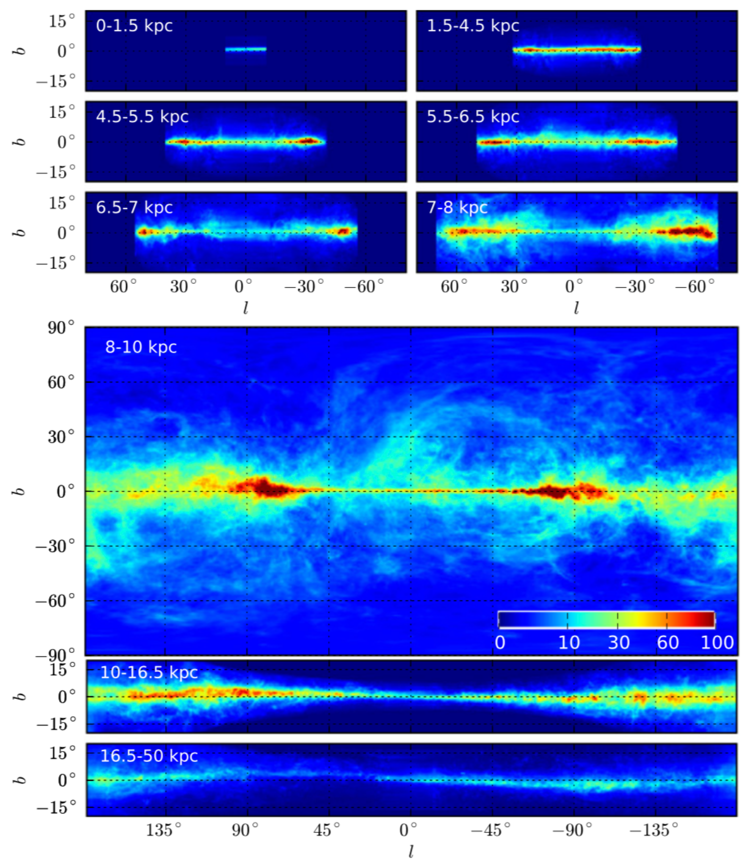


PeV-atron in the Galactic Centre.
Constant injection over at least 10^3 years.
Current luminosity of GC is not enough.

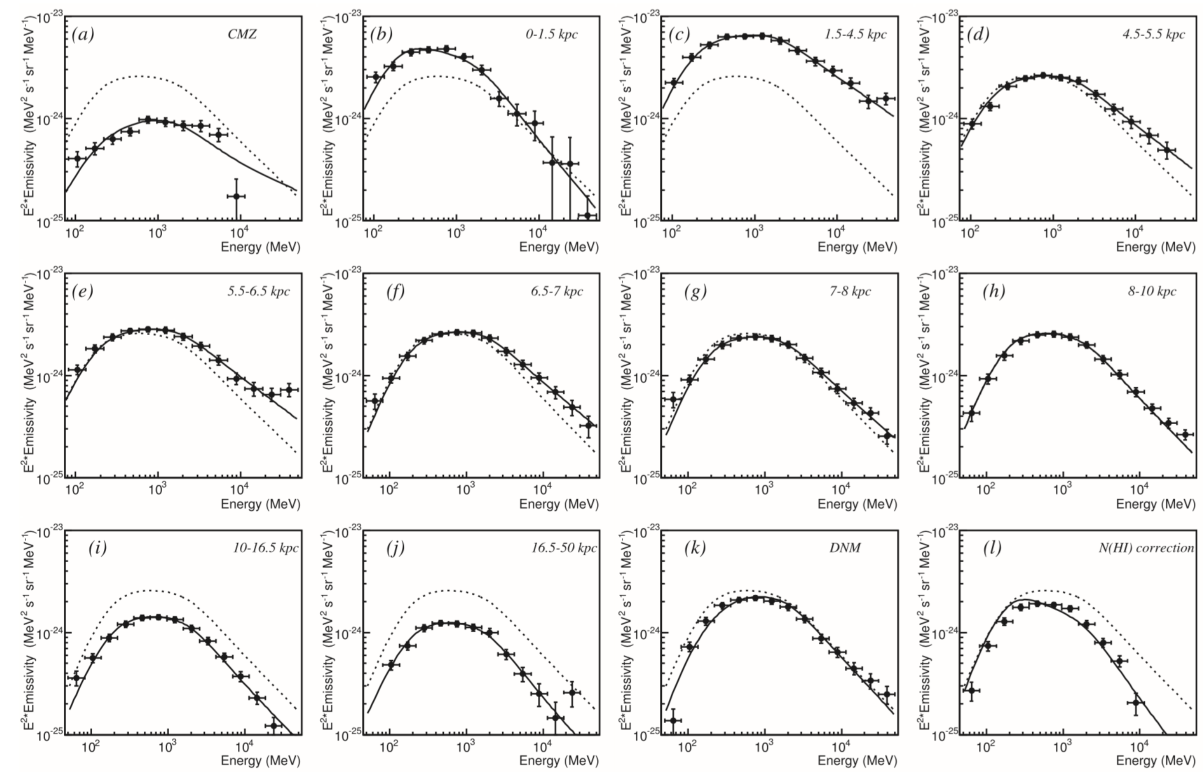
Very hard emission, no cutoff, untypical for extended emission

Cosmic ray density profile using matter densities from molecular line surveys.

Average CR spectrum in the Galaxy

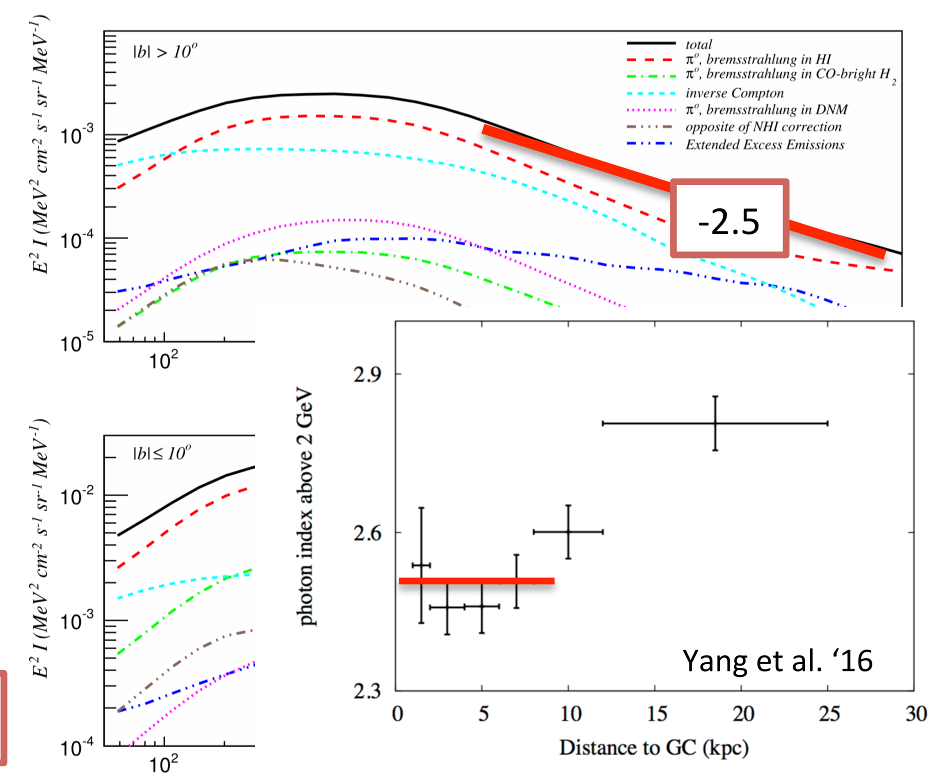


Acero et al. '16



New analysis of diffuse emission by Fermi Collaboration has introduced Galactocentric-distance-dependent pion decay emission templates.

- average slope of the CR spectrum appears variable with distance from the Galactic Centre. It is typically harder within the Solar distance, compared to the locally observed slope.
- pion decay spectrum slope above ~10 GeV is found to be consistent with ~2.5.

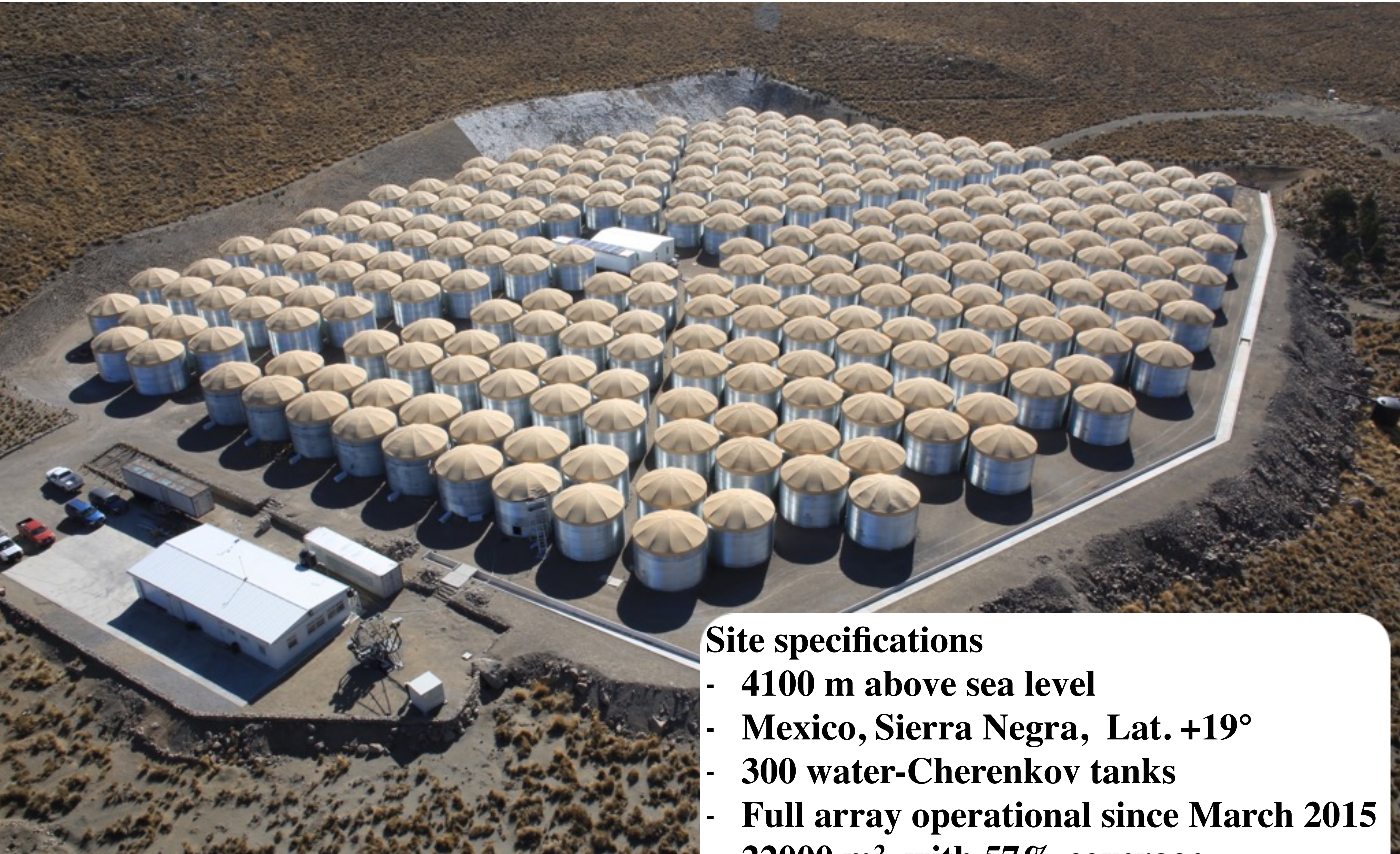


Γ=? ; δ=?

$-(\Gamma+\delta)=2.5$

Neronov

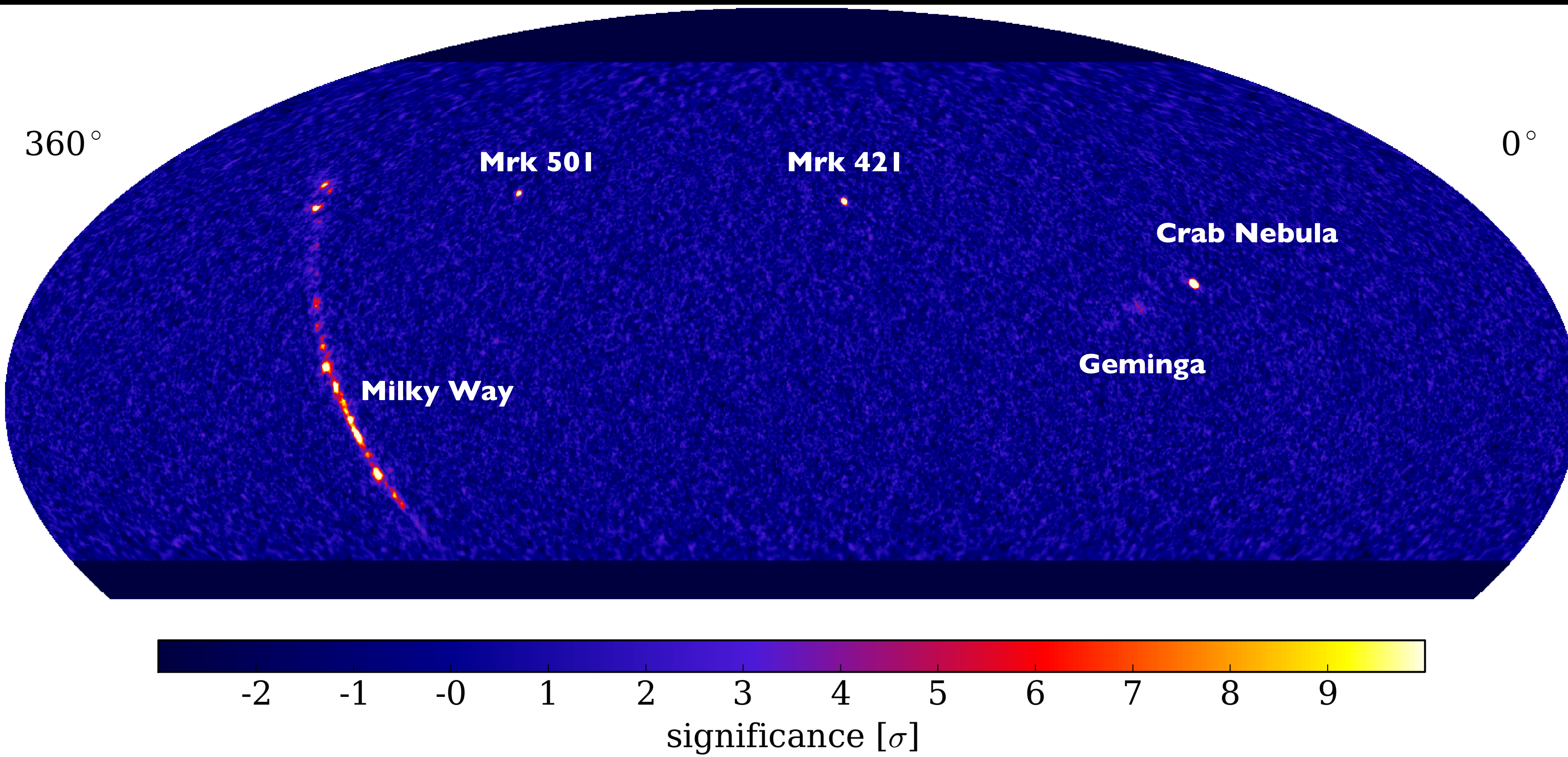
The HAWC observatory



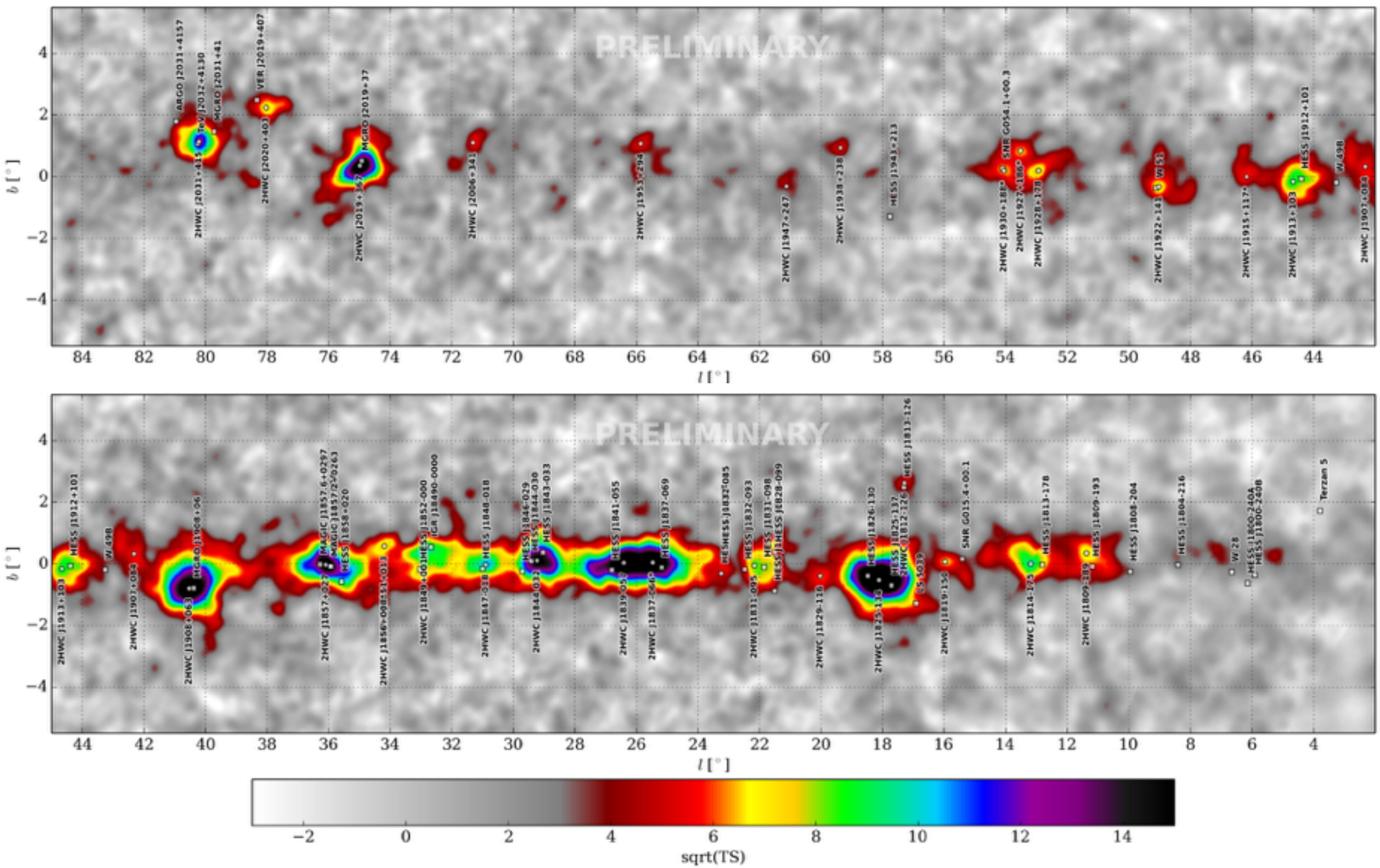
Site specifications

- **4100 m above sea level**
- **Mexico, Sierra Negra, Lat. +19°**
- **300 water-Cherenkov tanks**
- **Full array operational since March 2015**
- **22000 m², with 57% coverage**

HAWC View of the Sky

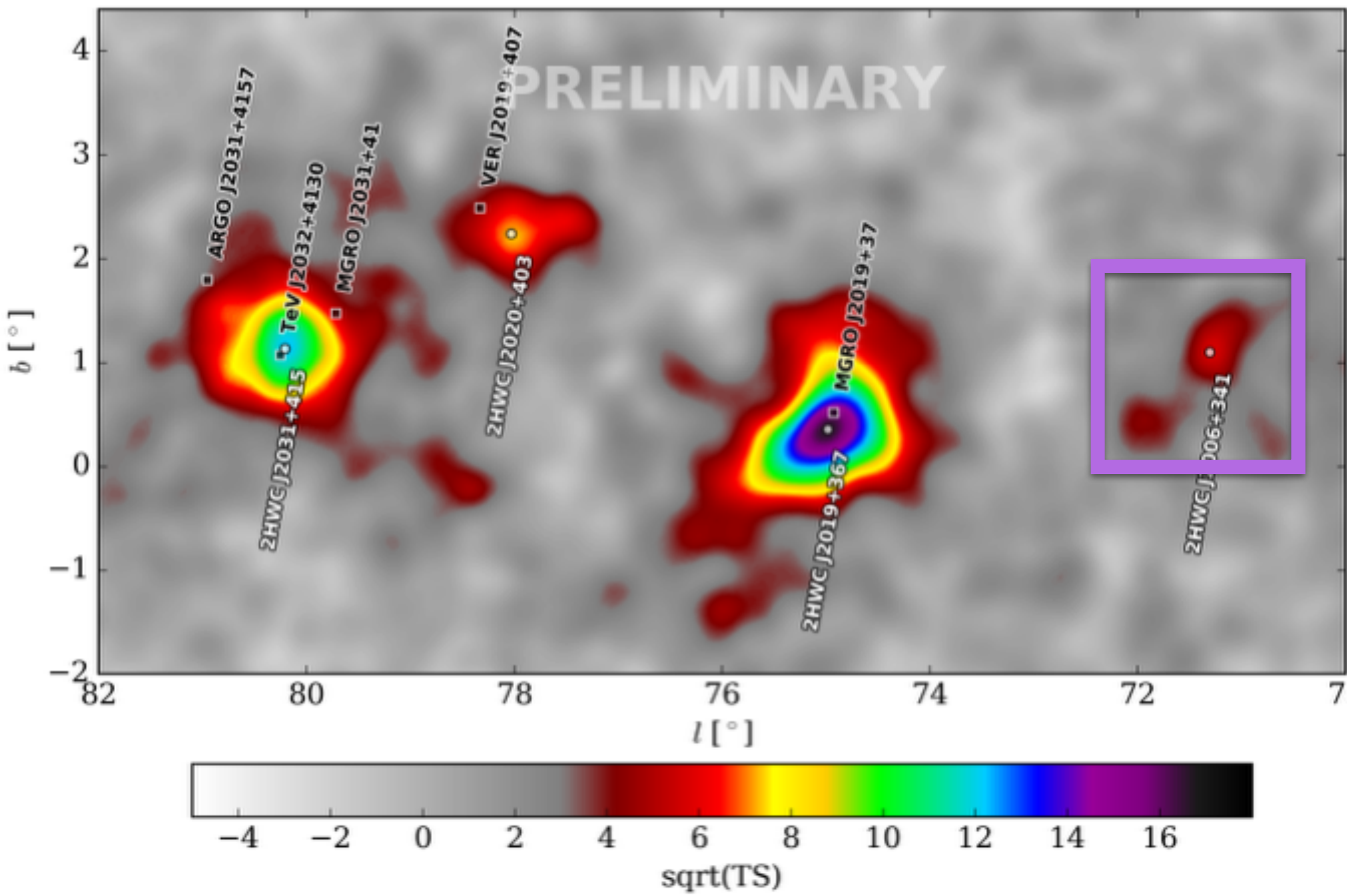


Galactic sources: inner galactic plane (403 days)

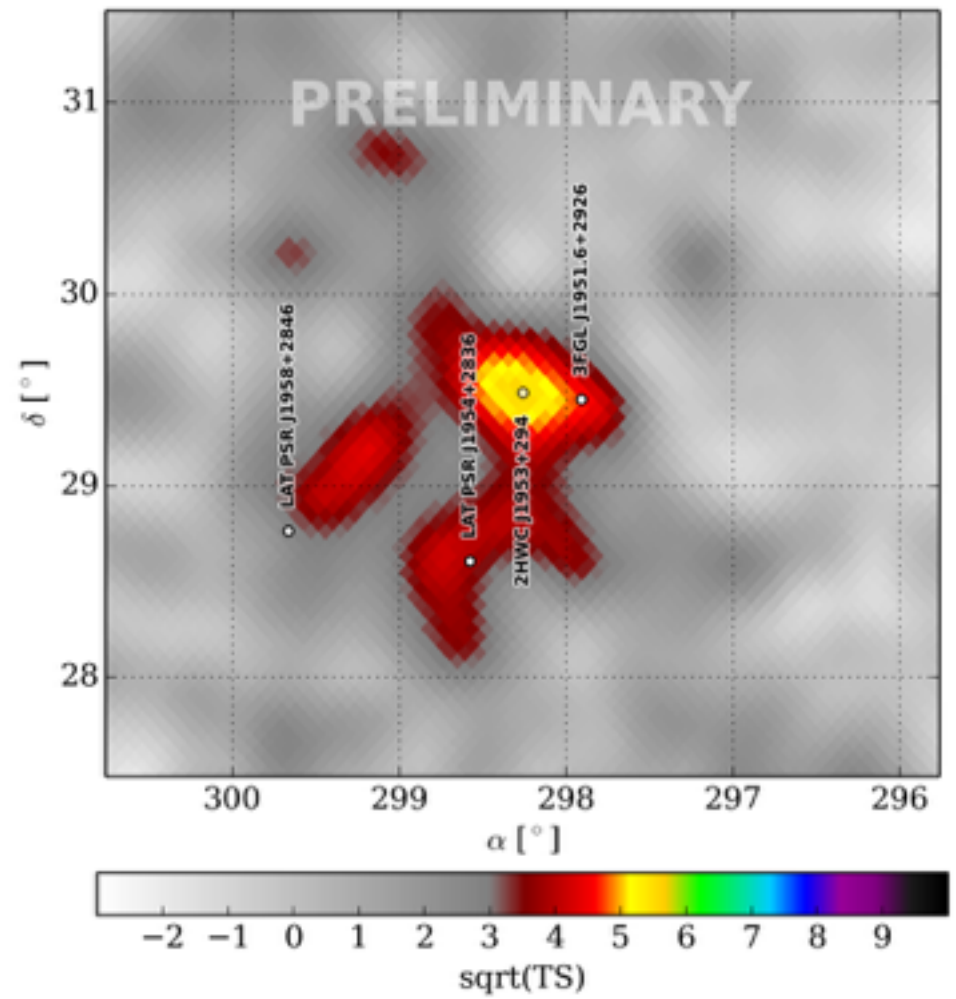


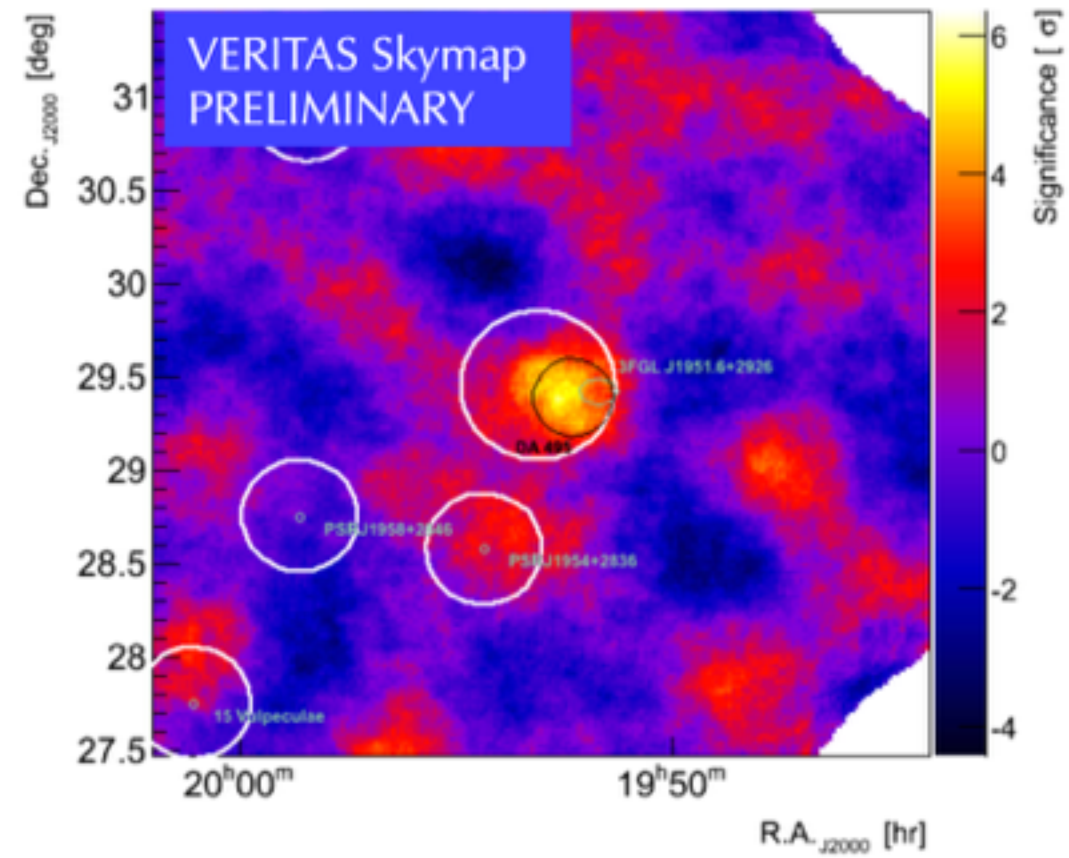
Galactic sources: Cygnus region (403 days)

New TeV source:
2HWCJ2006+341
 > 6σ pre-trails



Galactic sources: HAWC source confirmed by Veritas



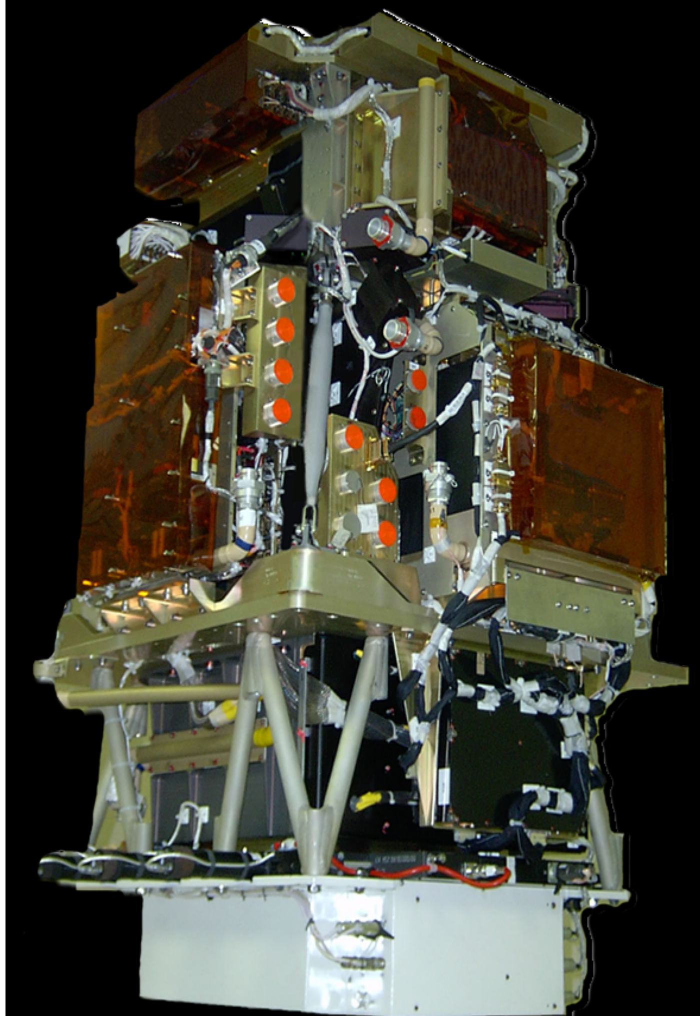


Name	$\sqrt{TS}$	Index	Flux for index at 7 TeV $[\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$
2HWC J1953+294	5.58	-2.76 ± 0.15	1.1e-14 ± 4.2e-15

Direct Detection of CRs
AMS - Pamela

The largest topic of the conference:
3 plenary, 14 parallel presentations

PAMELA launched on 15th June 2006 recently celebrated 10 years



GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

Elliptical orbit 350 – 610 km
70° inclination
in operation at 560 km

Time-Of-Flight

plastic scintillators + PMT:
Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX

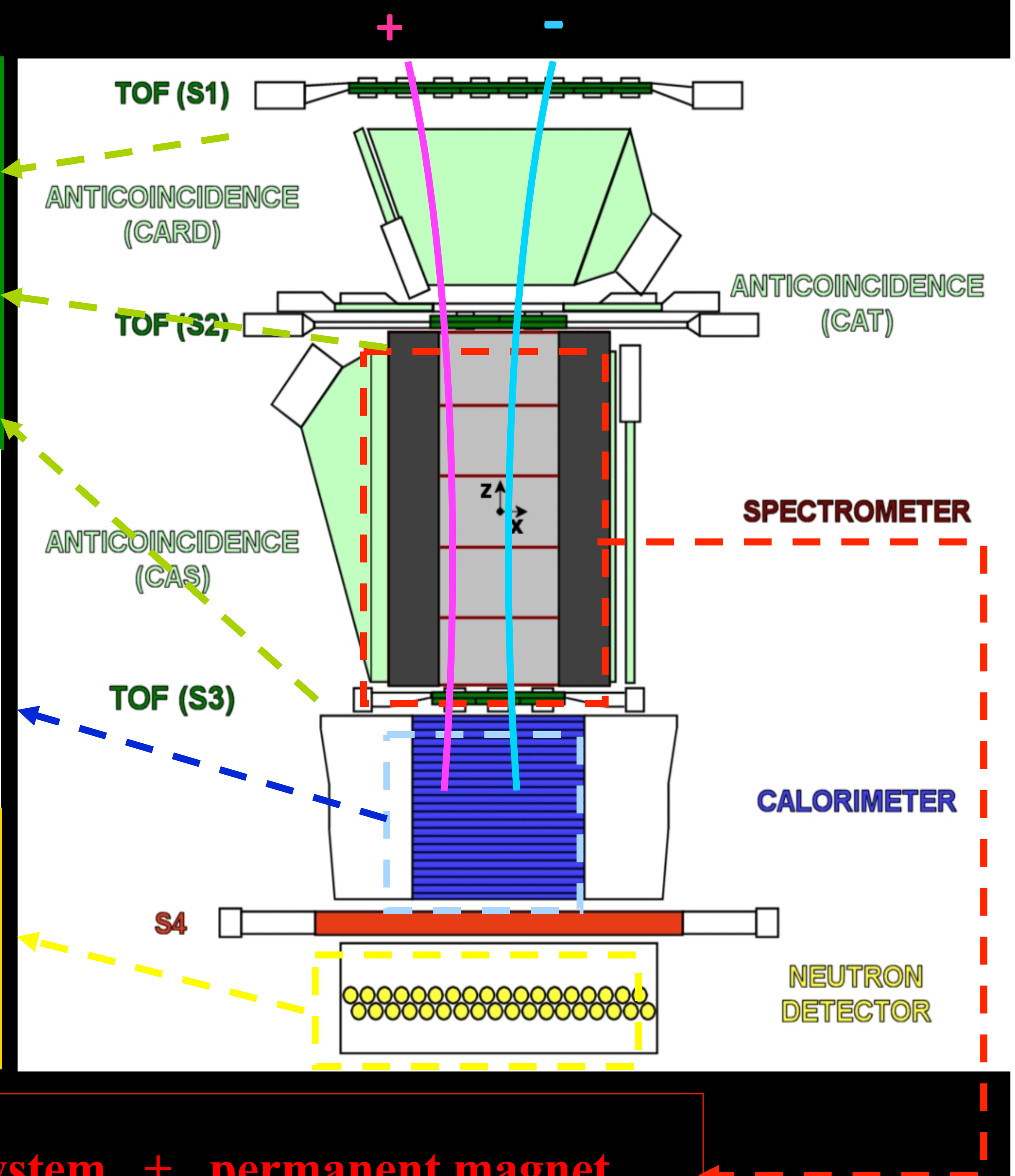
Electromagnetic calorimeter

W/Si sampling (16.3 X_0, 0.6 λI)
Discrimination e+ / p, anti-p/e^-

(shower topology)
- Direct E measurement for e^-

Neutron detector

^3He tubes + polyethylene moderator:
- High-energy e/h discrimination



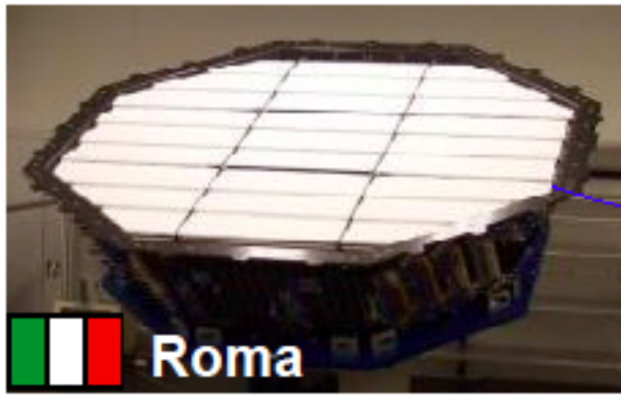
microstrip silicon tracking system + permanent magnet
provides: - *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

Launched in 2011: 5 years aboard the ISS

AMS-02: A TeV precision, multipurpose spectrometer

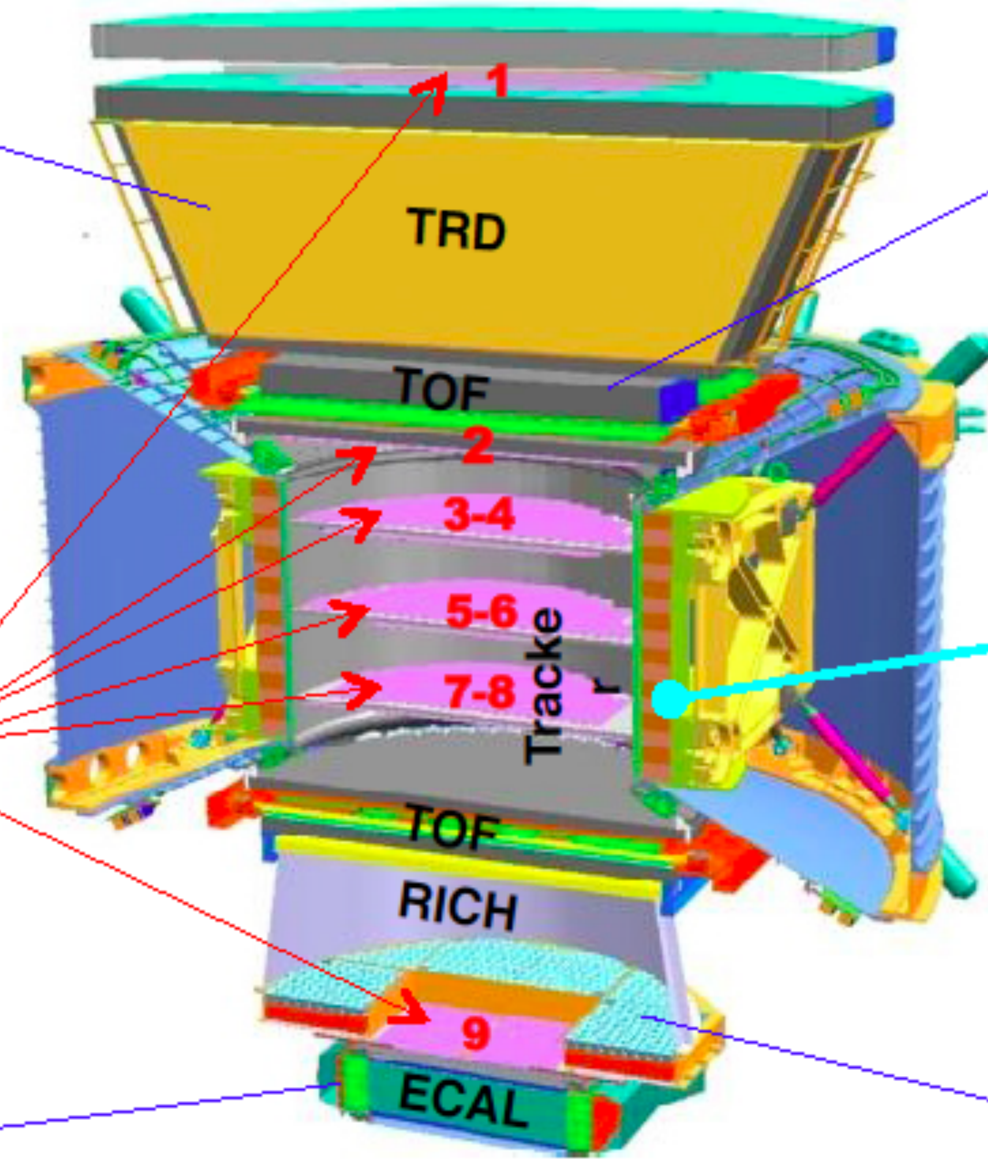
Particles and nuclei are defined by their charge (Z) and energy (E)

Transition Radiation Detector (TRD)
Identify e^+, e^-



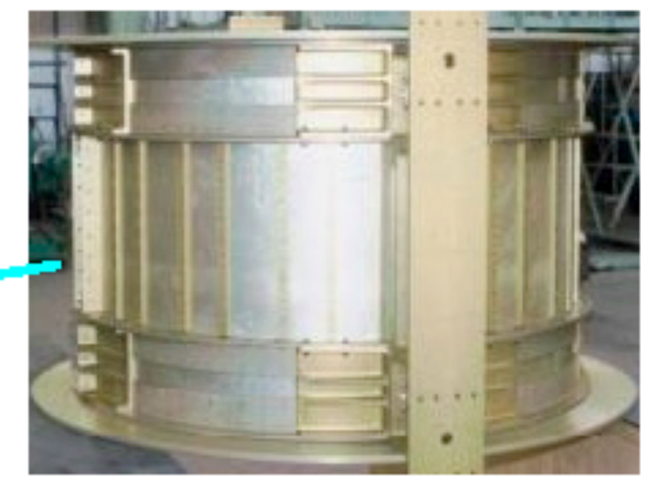
Silicon Tracker
Z, P

Electromagnetic Calorimeter (ECAL)
E of e^+, e^-, γ



Time of Flight (TOF)
Z, E

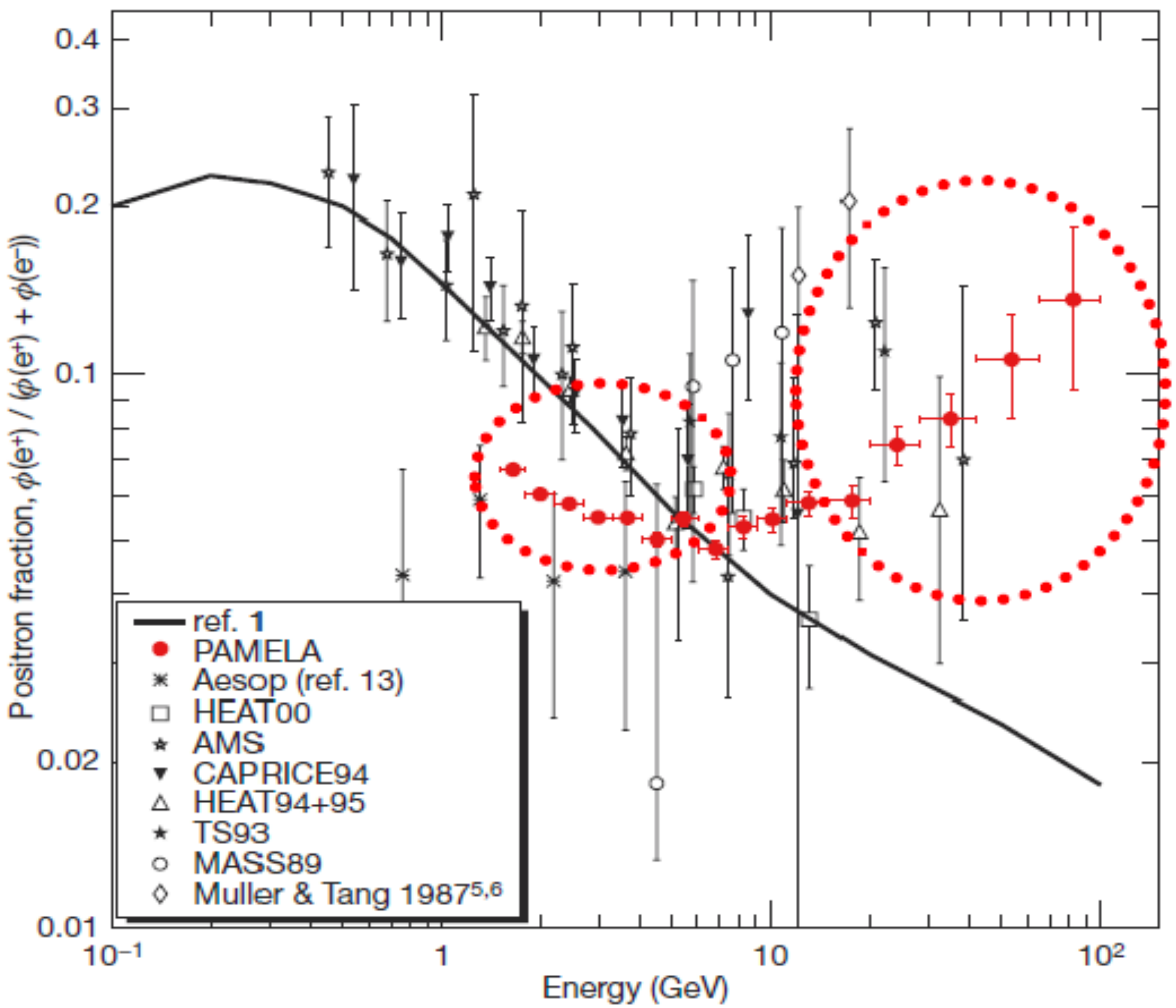
Magnet (0.15 T)
±Z



Ring Imaging Cherenkov (RICH)
Z, E

Z, E, R, β
for the same particle are measured independently by the Tracker, RICH, TOF and ECAL

PAMELA: first unambiguous evidence of the rise of the positron fraction above 10 GeV



nature International weekly journal of science

August 2009

LETTERS

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

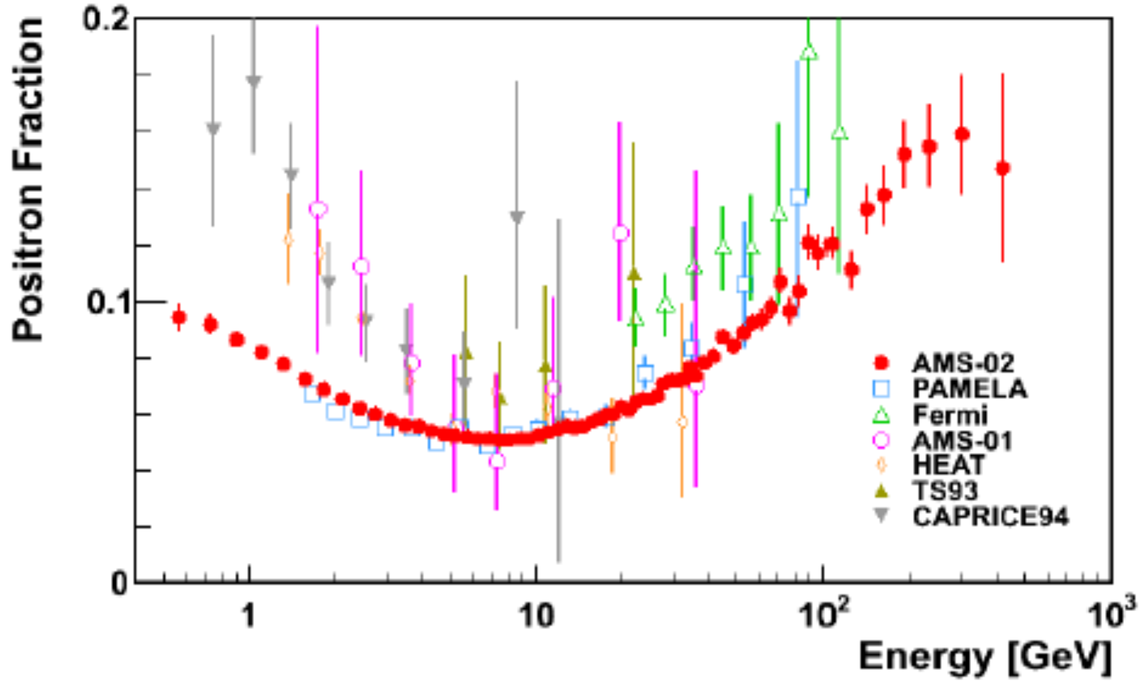
O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, R. Bellotti, M. Boezio, E. A. Bogomolov, L. Bonechi, M. Bongi, V. Bonvicini, S. Bottai, A. Bruno, F. Cafagna, D. Campana, P. Carlson, M. Casolino, G. Castellini, M. P. De Pascale, G. De Rosa, N. De Simone, V. Di Felice, A. M. Galper, L. Grishantseva, P. Hofverberg, S. V. Koldashov, S. Y. Krutkov, A. N. Kvashnin, A. Leonov, V. Malvezzi, L. Marcelli, W. Menn, V. V. Mikhailov, E. Mocchiutti, S. Orsi, G. Osteria, P. Papini, M. Pearce, P. Picozza, M. Ricci, S. B. Ricciarini, M. Simon, R. Sparvoli, P. Spillantini, Y. I. Stozhkov, A. Vacchi, E. Vannuccini, G. Vasilyev, S. A. Voronov, Y. T. Yurkin, G. Zampa, N. Zampa & V. G. Zverev

Citations: 1338

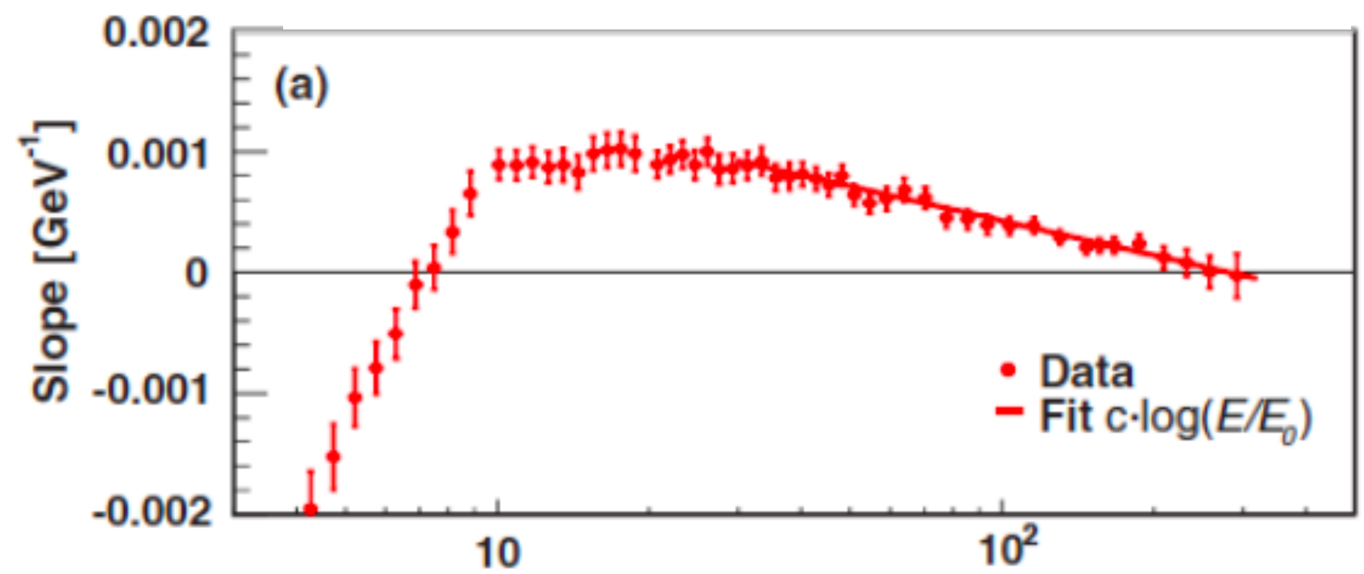
AMS-02: positron fraction

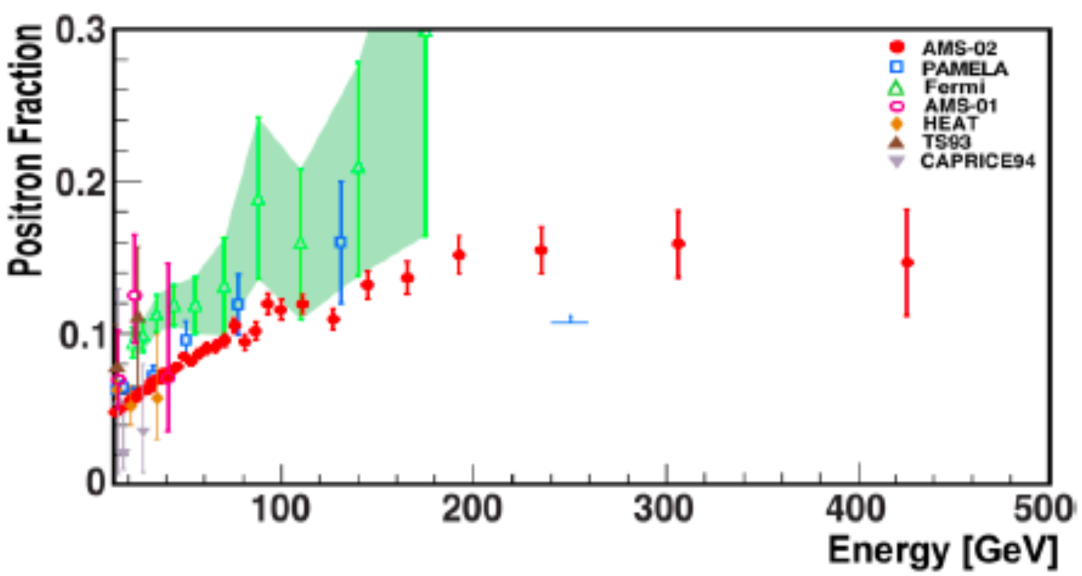
- ✓ No sharp structures
- ✓ Steady increase of the positron content up to ≈ 275 GeV
- ✓ Well described by an empirical model with a common source term for e^+/e^-

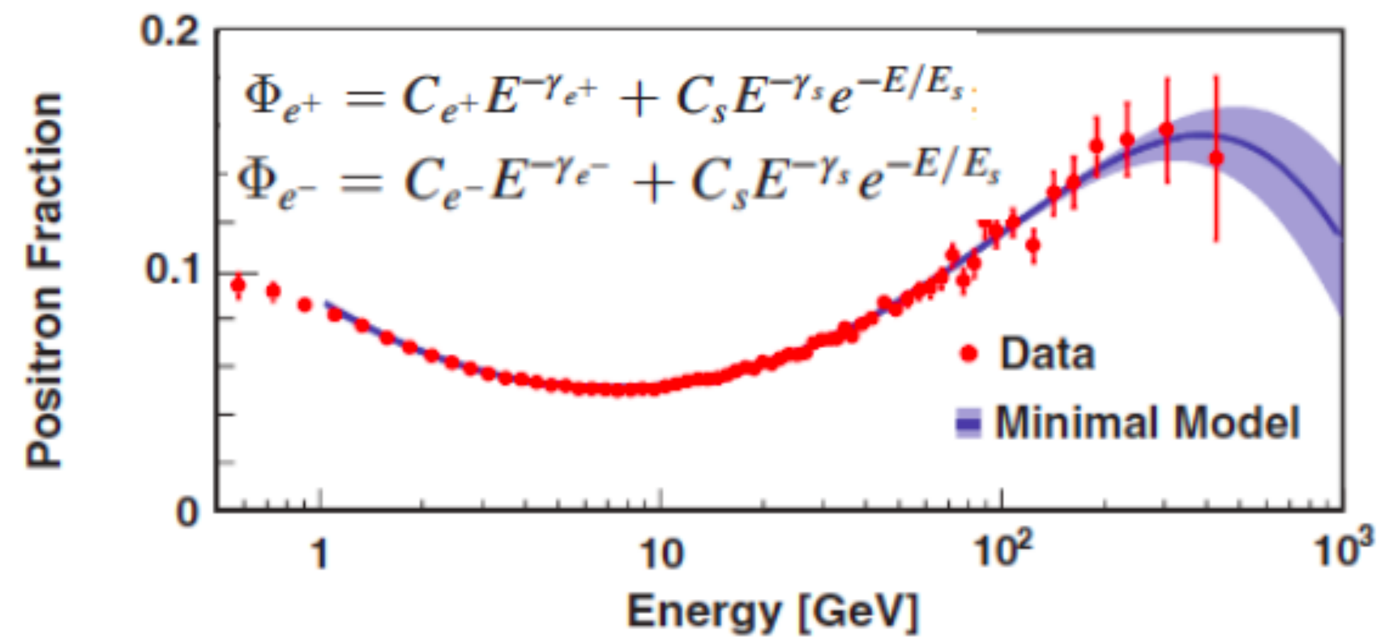
[B. Bertucci @LNGS - July 2016]



[M. Accardo et al., PRL 113 (2014) 121101]







The CR leptonic sector puzzle *(observations)*

① Positron spectrum: is *harder than* e^- above 50 – 60 GeV and has *similar Rigidity dependence as proton.* Incompatible with secondary origin since at these energies radiative losses (~E^2) are dominant during propagation.

② Electron spectrum: *featureless* up to at least 1 TeV and *more steep than* e^+

③ Inclusive $e^+ + e^-$ spectrum: direct measurements < 1 TeV => power law index ~ -3.17

Spectrum above 1 TeV: only preliminary or indirect measurements.

"Great Expectations" from CALET and DAMPE.

Potential discovery of local source(s) at kpc distance

✧ Anisotropy in e^+ and e^- data: *no anisotropy observed* at all angular scales by PAMELA

Electron measurements at high energy are challenging due to the large proton background. High proton rejection power (> 10^5) is required.

The CR leptonic sector puzzle *(theoretical interpretations)*

✧ Positron excess from Astrophysical sources including:

- **Pulsar Wind Nebulae** (PWN) where the pulsar produces e^+e^- pairs
  + acceleration away from the neutron star (at termination shock)
- **SuperNova Remnants** (SNR) for a recent eview e.g.: [P.Serpico, Astropart. Phys. 39-40 , 2]
- **Local source(s)**: order 0.1% anisotropy expected at ~ 100 GeV

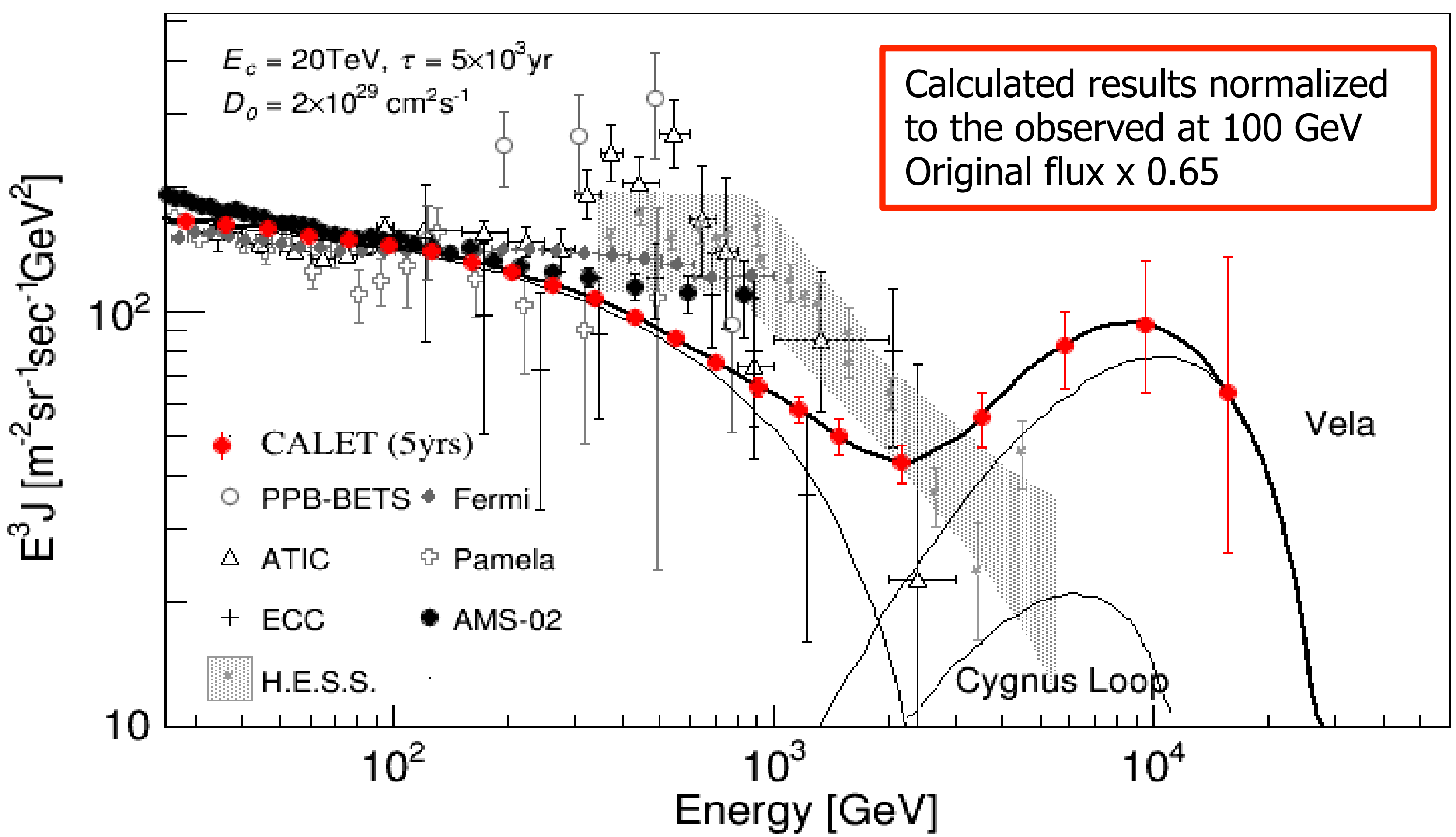
✧ Positron excess from Dark Matter for a recent review e.g.: [M. Cirelli - Dark Matter phenomena - Rapporteur Talk at ICRC2015]

New experiments: CALET Identification of Electron Sources

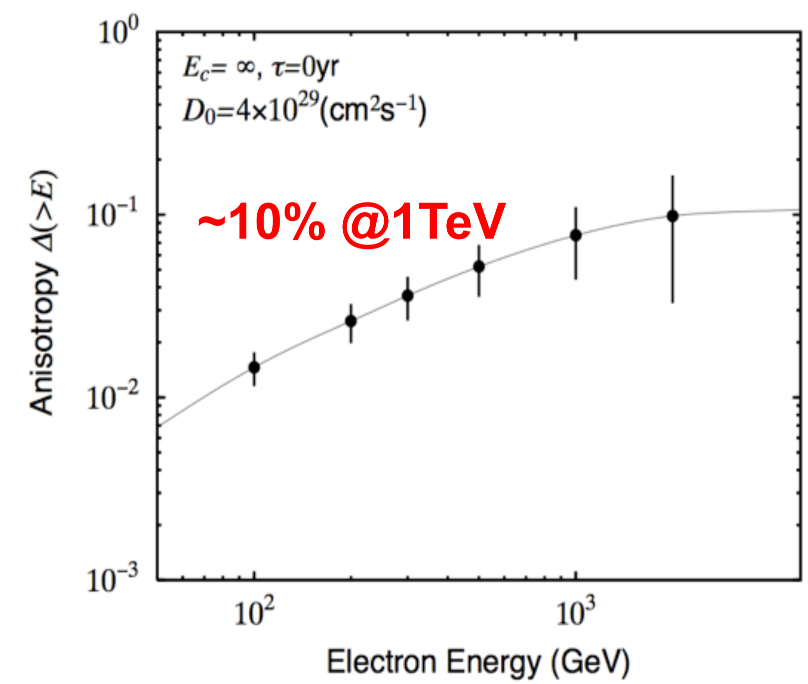
Some nearby sources, e.g. Vela SNR, might have unique signatures in the electron energy spectrum in the TeV region (Kobayashi et al. ApJ 2004)

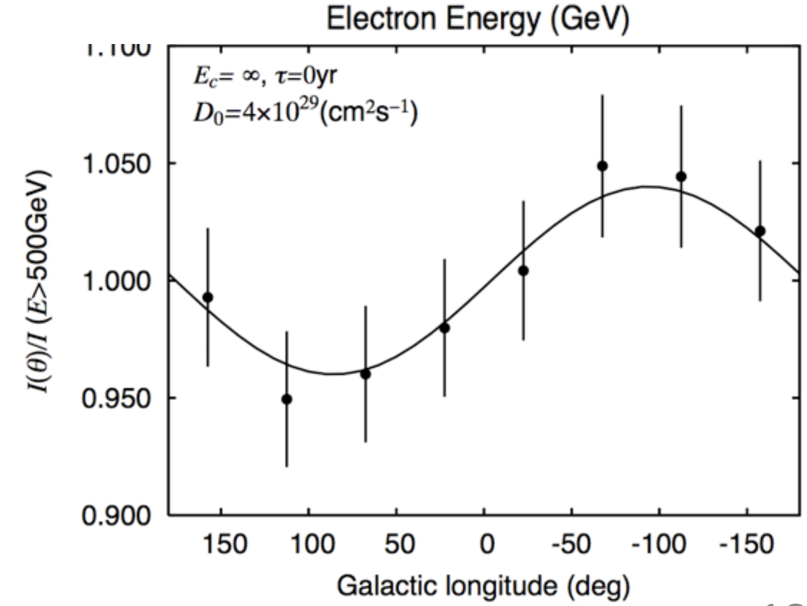
Expected flux for 5 year mission

> 10 GeV	~ 2.7×10^7
>100 GeV	~ 2.0×10^5
>1000 GeV	~ 1.0×10^3



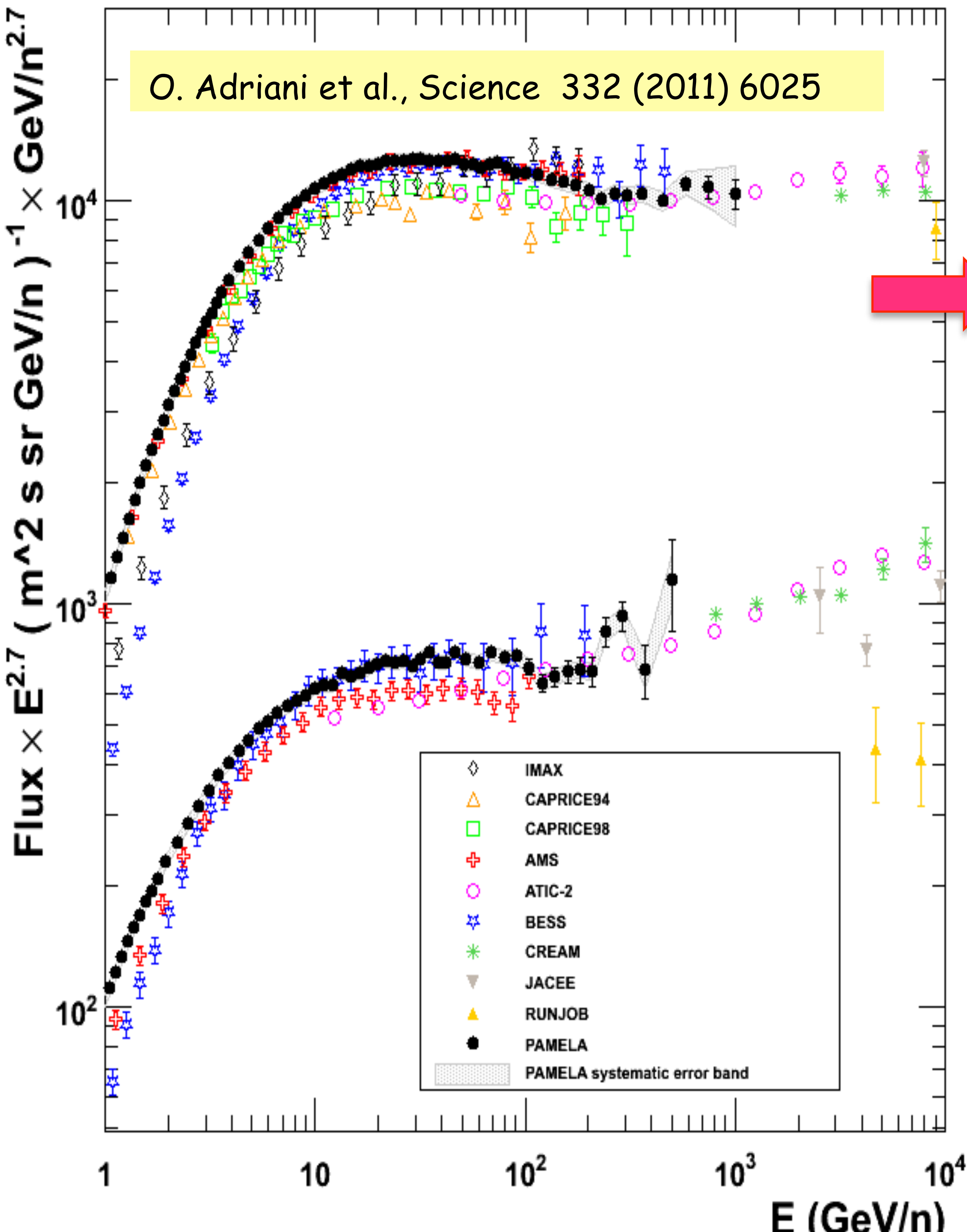
Expected Anisotropy from Vela SNR



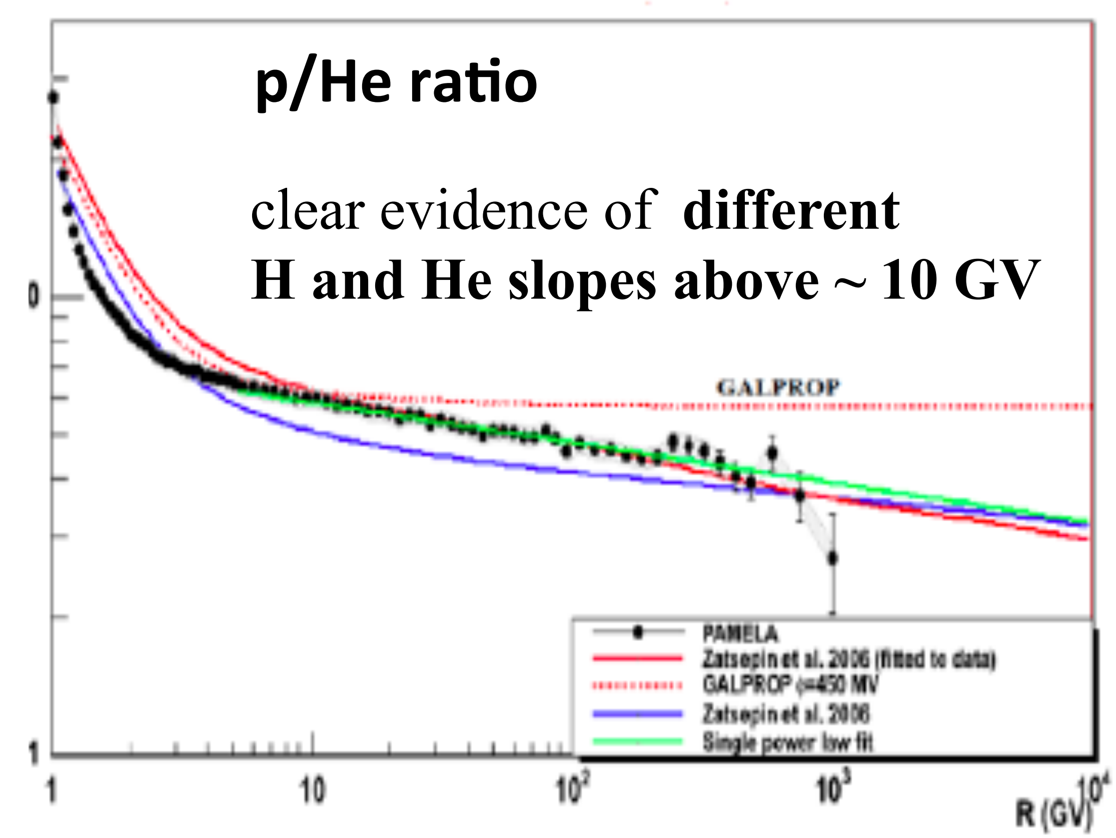


Identification of the unique signature from nearby SNRs, such as Vela in the electron spectrum by CALET

PAMELA: Proton and Helium Nuclei Spectra & H/He ratio



- **First high-statistics and high-precision measurement over three decades in energy**
- Deviations from single power law (SPL):
  - Spectra gradually soften in the range 30÷230GV
  - Spectral hardening @ R~235GV Δγ~0.2÷0.3
    Single power-law rejected at 98% CL



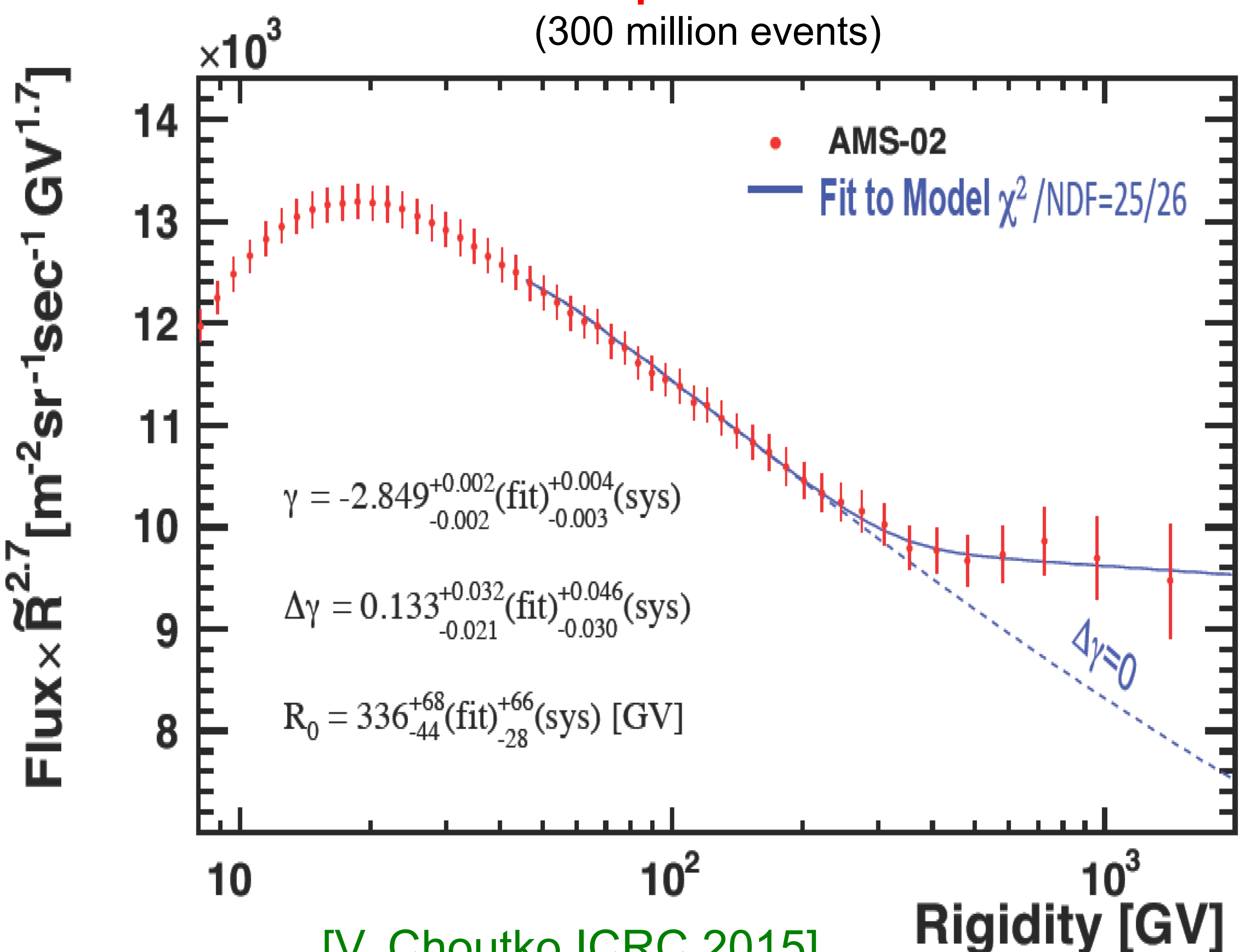
Proton and He fluxes measured by AMS-02

Two power laws with a characteristic transition rigidity R_0 and a smoothness parameter s are used by AMS-02 to fit the measured H and He spectra:

$$\Phi = C\left(\frac{R}{45GV}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

AMS proton flux

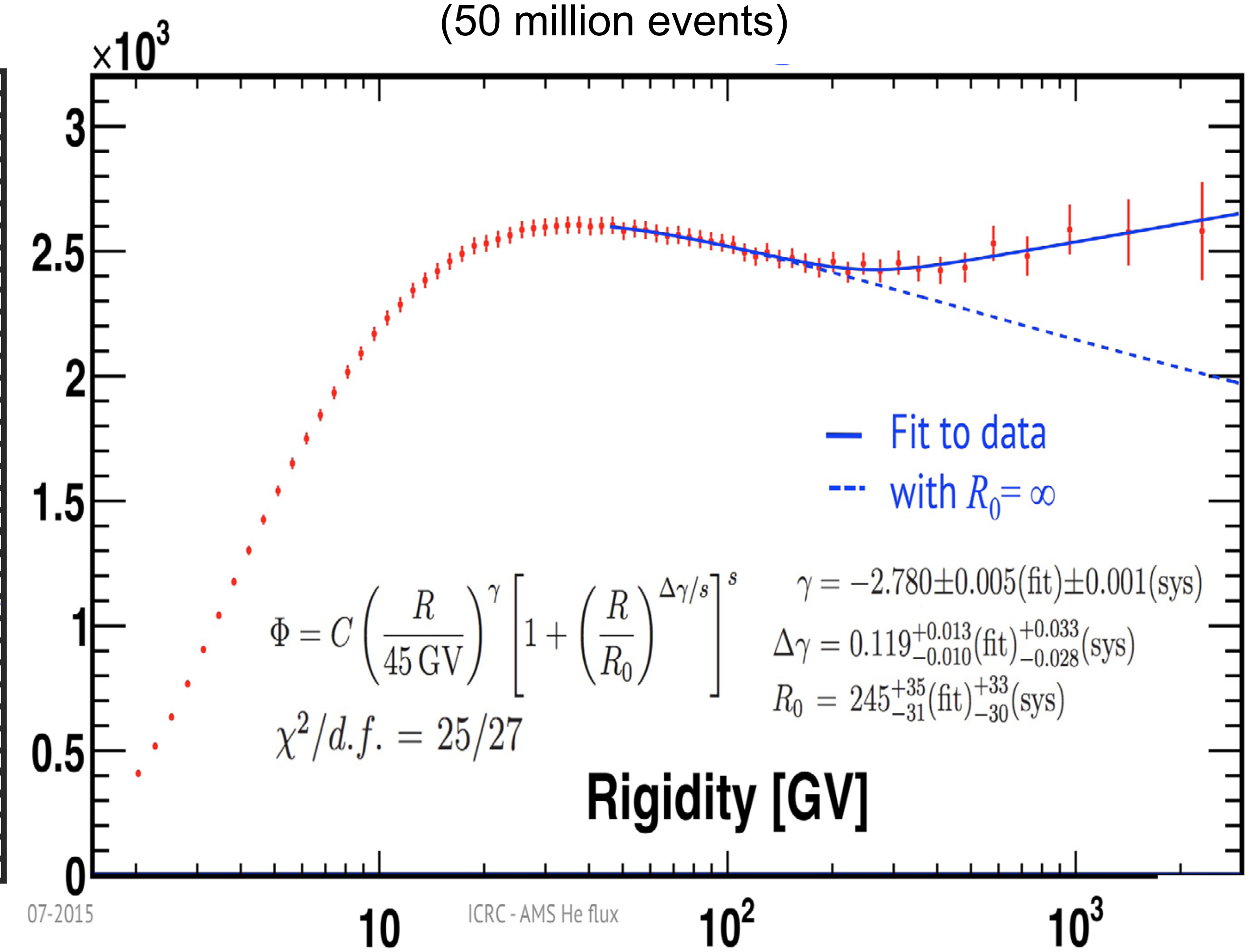
(300 million events)



[V. Choutko ICRC 2015]

AMS He flux

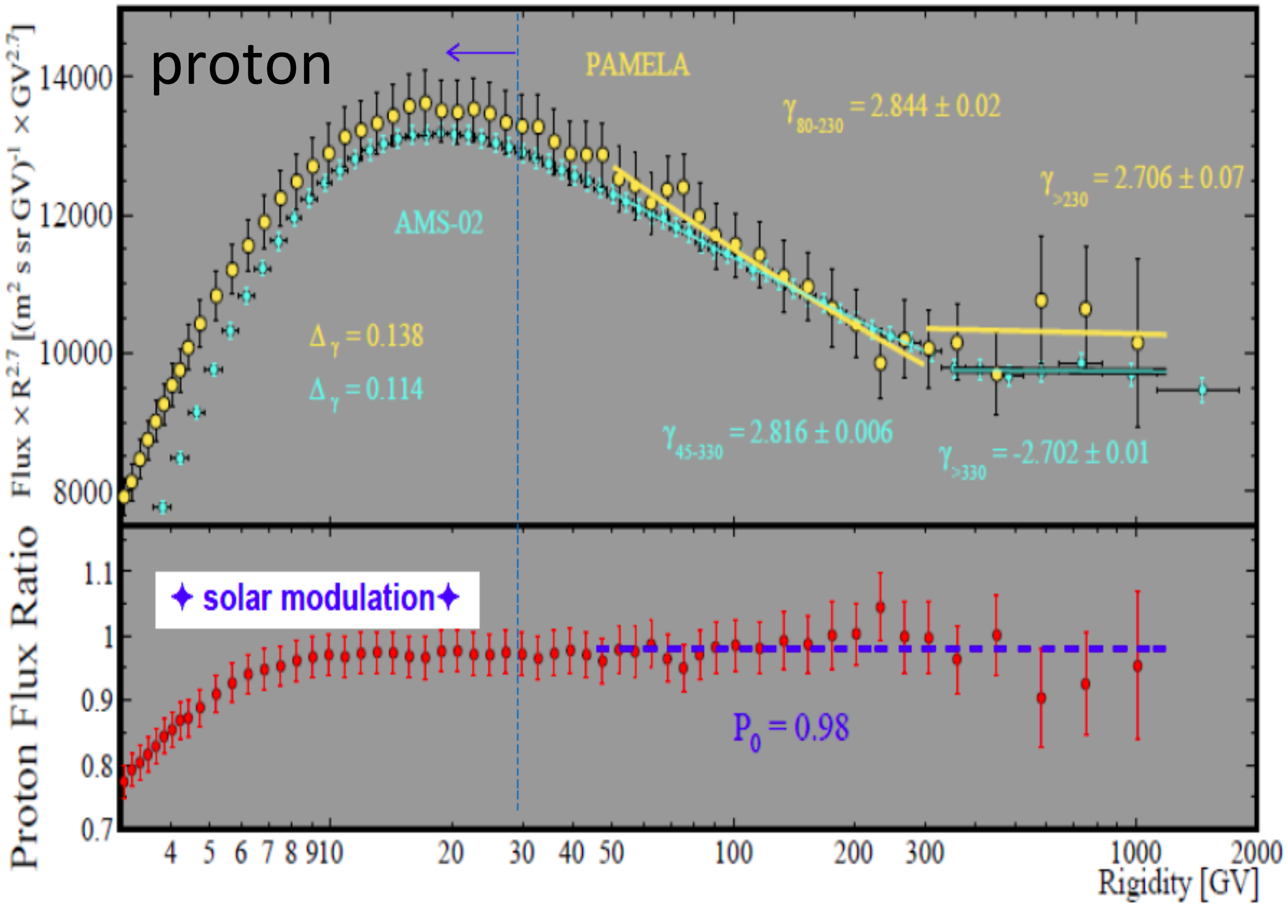
(50 million events)

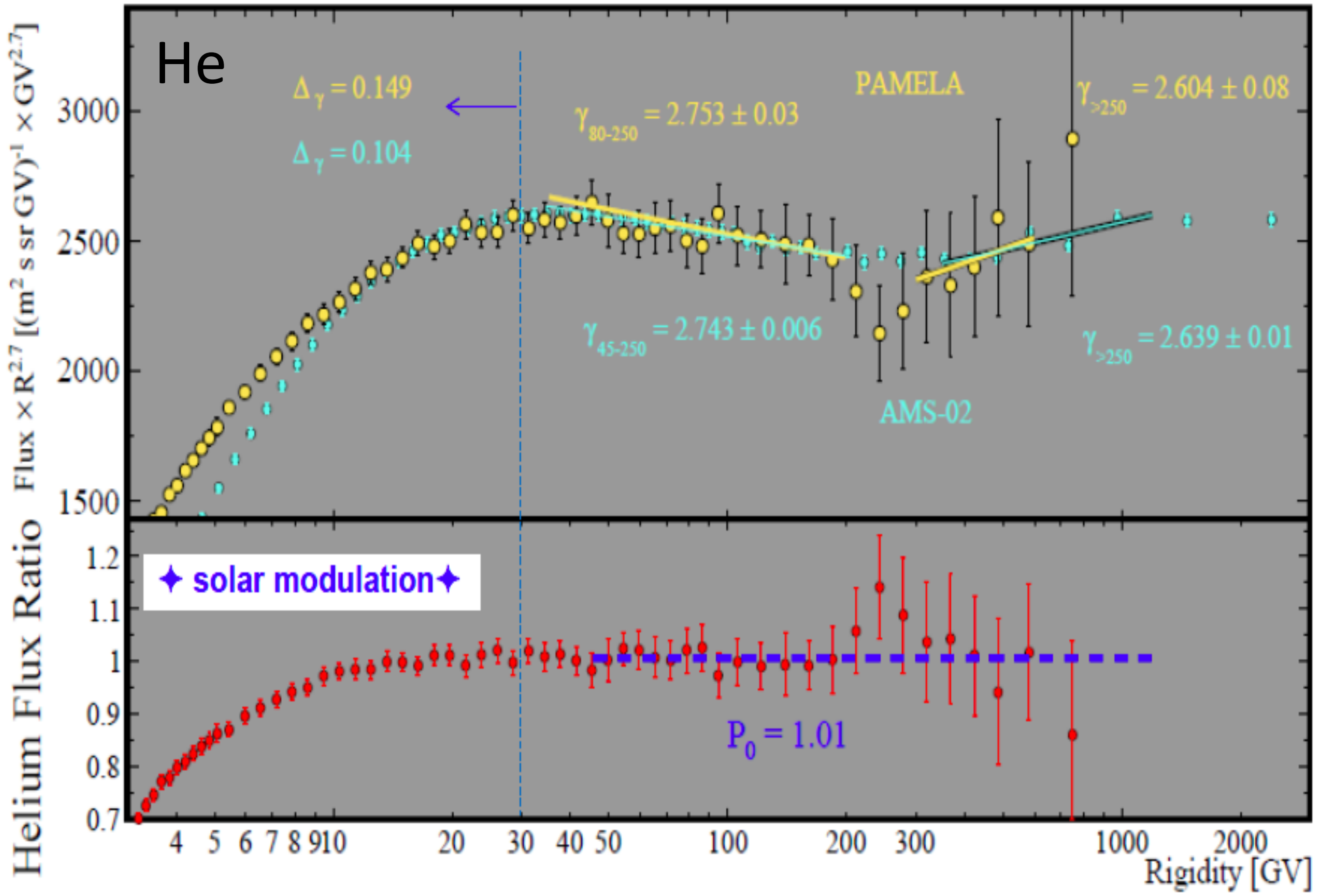


[S. Haino ICRC 2015]

New era of precision spectral measurements:

✧ good agreement between PAMELA and AMS-02 on p and He spectra





[M.Boezio @LNGS Jul 2016]

O. Adriani et al., Phys. Rep. 544 (2014) 323 ; M. Aguilar et al., PRL 114 (2015) 171103

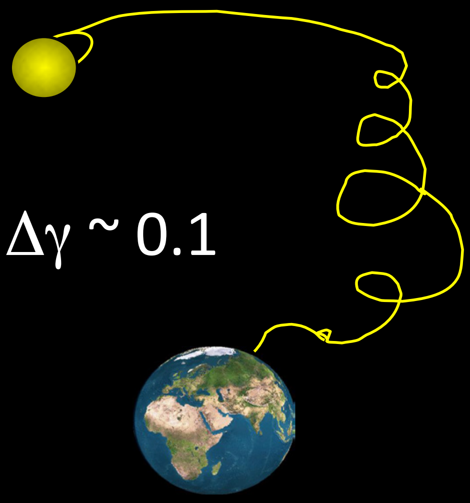
O. Adriani et al., Science 332 (2011) 6025 ; M. Aguilar et al., PRL 115, (2015) 211101

	fit range proton	γ_p	fit range He	γ_{He}
PAMELA	80-230 GV	-2.844±0.02	80-250 GV	-2.753±0.03
AMS-02	45-330 GV	-2.816±0.006	45-250 GV	-2.743±0.006

The CR hadronic sector puzzle (*observations*)

Emerging picture from current observations:

- break in power law in rigidity around 200-300 GV for p, He, Li, ...
- violation of univerality of spectral indices: protons spectrum is softer by $\Delta\gamma \sim 0.1$



Still to be clarified experimentally:

① sharp spectral break or continuos curvature ?

② is there a break also in C spectrum (unclear from preliminary data)

③ Is He index identical to C, O ... Fe ?

- accurate measurements of p, He bridging in energy PAMELA and AMS to CREAM data:
  - position and $\Delta\gamma$ of spectral break vs. nuclear species
  - precision differential measurement of spectral $d\gamma/dE$ + extension to higher energy

❖ Multi-TeV region largely unexplored

The CR hadronic sector puzzle *(theoretical interpretation)*

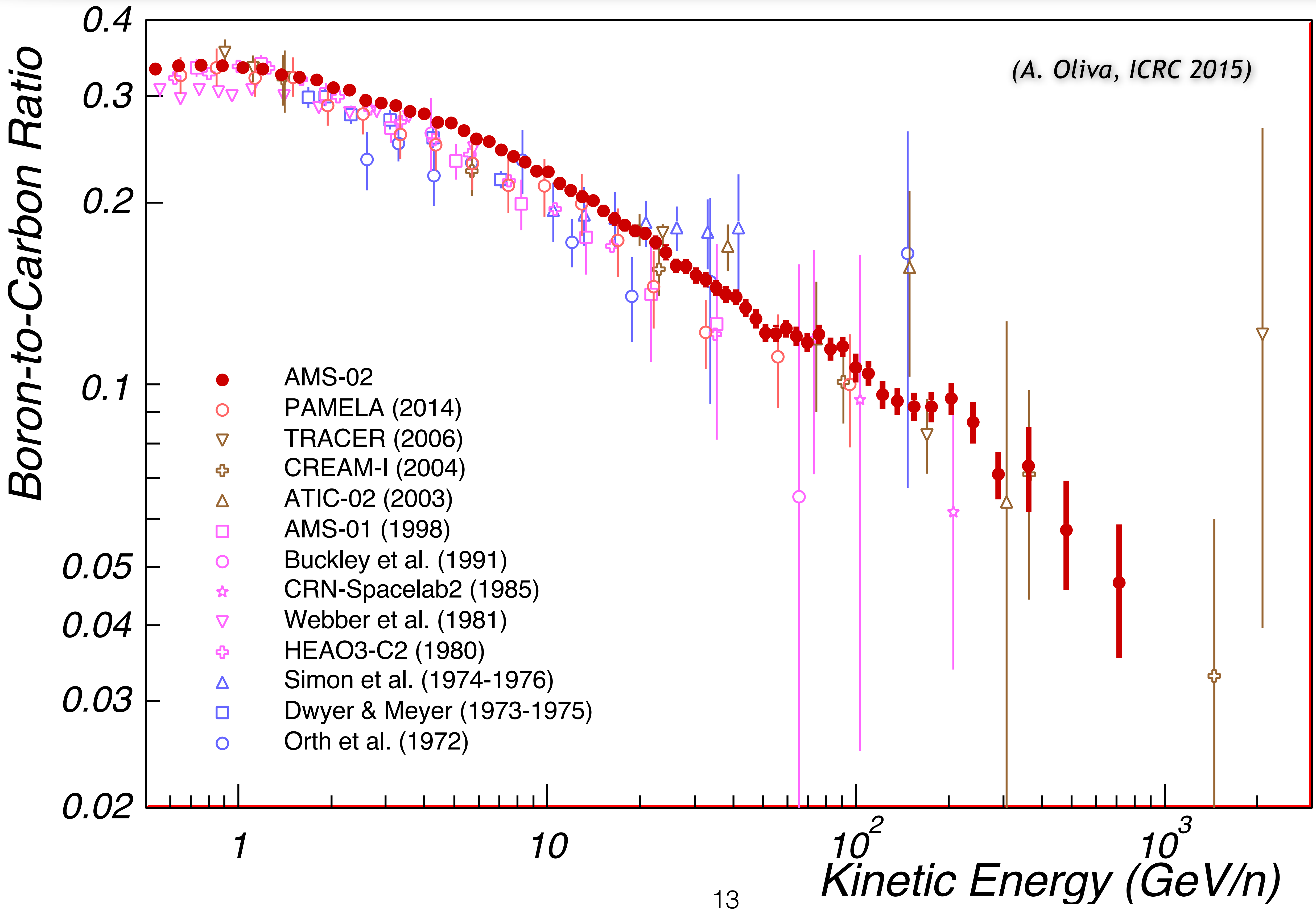
Broken power law interpretations include:

- *diffusion effects* (source spectra assumed to be single power law):
  - non factorizable spatial and rigidity dependence of diffusion coefficient [N. Tomassetti, Astrophys. J. 752 , L13]
  - non linear diffusion on external turbolence (self-generated waves) above (below) the break [Blasi,Amato,Serpico, PRL 109]
- *acceleration effects* (observed features are imprinted on production spectra):
  - DSA acceleration non-linear effects (CR feed-back) [V. Ptuskin, V. Zirakashvili and E. S. Seo, Astrophys. J. 763]
  - Acceleration by different sources (e.g.: OB associations, SuperBubbles, W-R stars) [TStanev, Biermann & Gaisser, Astron. Astrophys. 274 , 902]
  - Weak re-acceleration [E. Seo and V. Ptuskin, Astrophys. J. 431]
- *local sources*:
  - Young nearby objects accounting for He harder spectrum are in tension with anisotropy measurements [Blasi, Amato, JCAP 1201 , 011]

Violation of universality of spectral indices interpretations include:

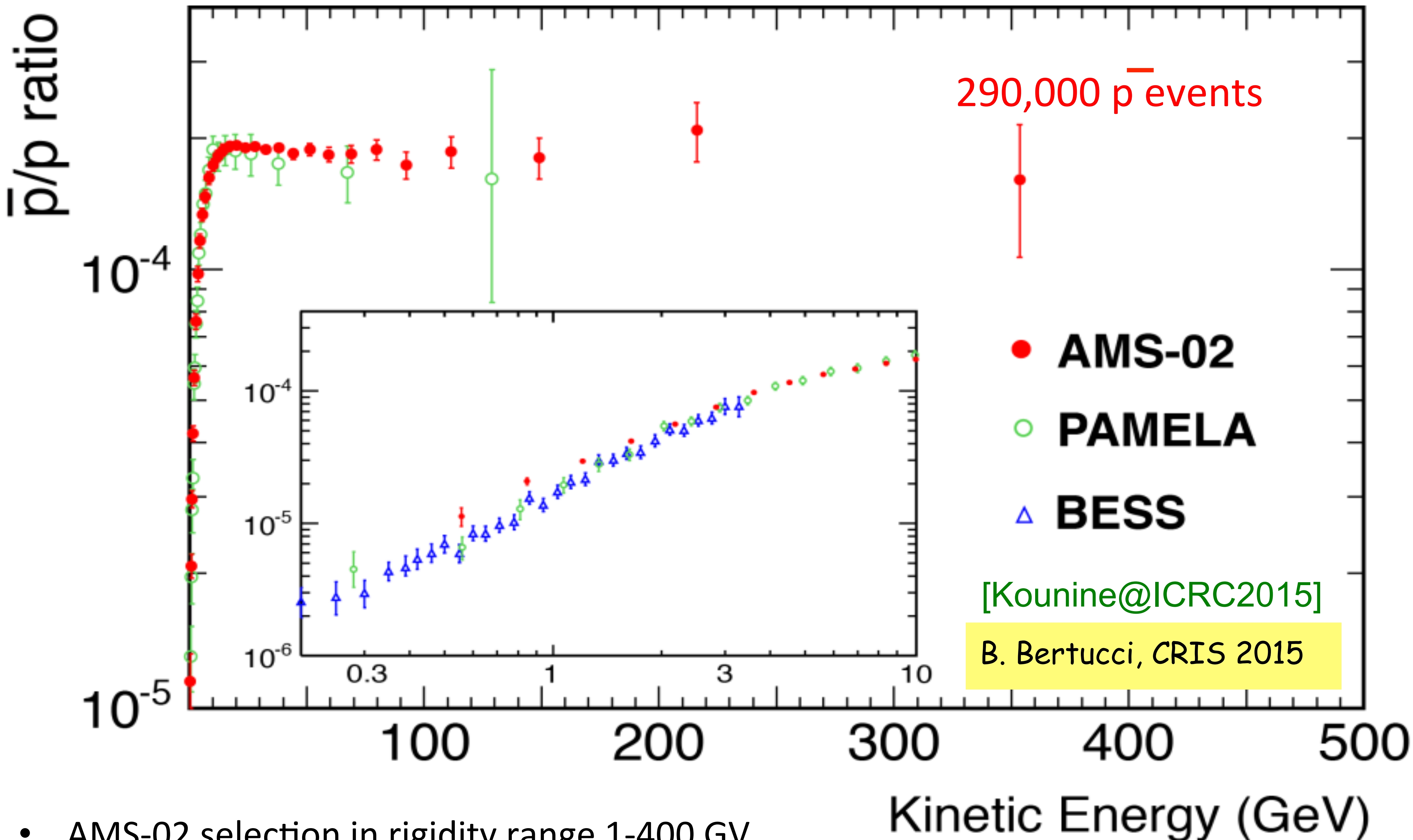
- e.g.: He accelerated "earlier" (with higherMach number than proton) ?
  - He more efficient at injection than proton + slower decline with Mach number [Malkov, Diamond & Sagdeev, Phys. Rev. Lett. 108]
  - Variable He/p ion concentration in the medium swept by shocks [L. O. Drury, Mon. Not. Roy. Astron. Soc. 415 , 1807]

B/C current result



anti-proton/proton ratio

AMS-02 vs PAMELA & BESS



- AMS-02 selection in rigidity range 1-400 GV
- PAMELA data from 60 MeV to 350 GeV

Experiment	e^+ | e^- (present data)	e^++e^- (Energy range)	CR nuclei (Energy range)	charge Z	gamma	Type	Launch
PAMELA	e^+ < 300 GeV e^- < 625 GeV	1-700 GeV (3 TeV with cal)	1 GeV-1.2 TeV (extendable -> 2TeV)	1-8	-	SAT	2006 Jun 15
FERMI	-	7 GeV – 2 TeV	50 GeV-1 TeV	1	20 MeV – 300 GeV GRB 8 KeV – 35 MeV	SAT	2008 Nov 11
AMS-02	e^+ < 500 GeV e^- < 700 GeV	1 GV-1 TV (extendable)	1 GV-1.9 TV (extendable)	1-26 ++	1 GeV-1 TeV (calorimeter)	ISS	2011 May 16
NUCLEON	-	100 GeV-3 TeV	100 GeV-1 PeV	1-30	-	SAT	2014/12/26 Dec 26
CALET	-	1 GeV-10 TeV (extendable -> 20TeV)	10 GeV-1 PeV	1-40	10 GeV-10 TeV GRB 7-20 MeV	ISS	2015 Aug 19
DAMPE	-	10 GeV-10 TeV	50 GeV-500 TeV	1-20	5 GeV-10 TeV	SAT	2015 Dec 17
ISS-CREAM	-	100 GeV-10 TeV	1 TeV-1 PeV	1-28 ++	-	ISS	~ 2017
CSES	-	3-200 MeV	30-300 MeV	1	-	SAT	~ 2017
GAMMA-400	-	1 GeV-20 TeV	1 TeV-3 PeV	1-26	20 MeV-1 TeV	SAT	~2023-25
HERD	-	10(s) GeV–10 TeV	up to PeV	TBD	10(s) GeV–10 TeV	CSS	~2022-25
HELIX	-	-	< 10 GeV/n	light isotopes	-	LDB	proposal
HNX	-	-	~ GeV/n	6-96	-	SAT	proposal
GAPS	-	-	< 1GeV/n	Anti-p, D	-	LDB	proposal

Pamela & AMS: a good competition

lots of results, initially contradicting
surprising and potentially very interesting findings

very detailed study of systematics (for years!!)
good statistics

now: fair agreement of results
critical assessment of remaining differences

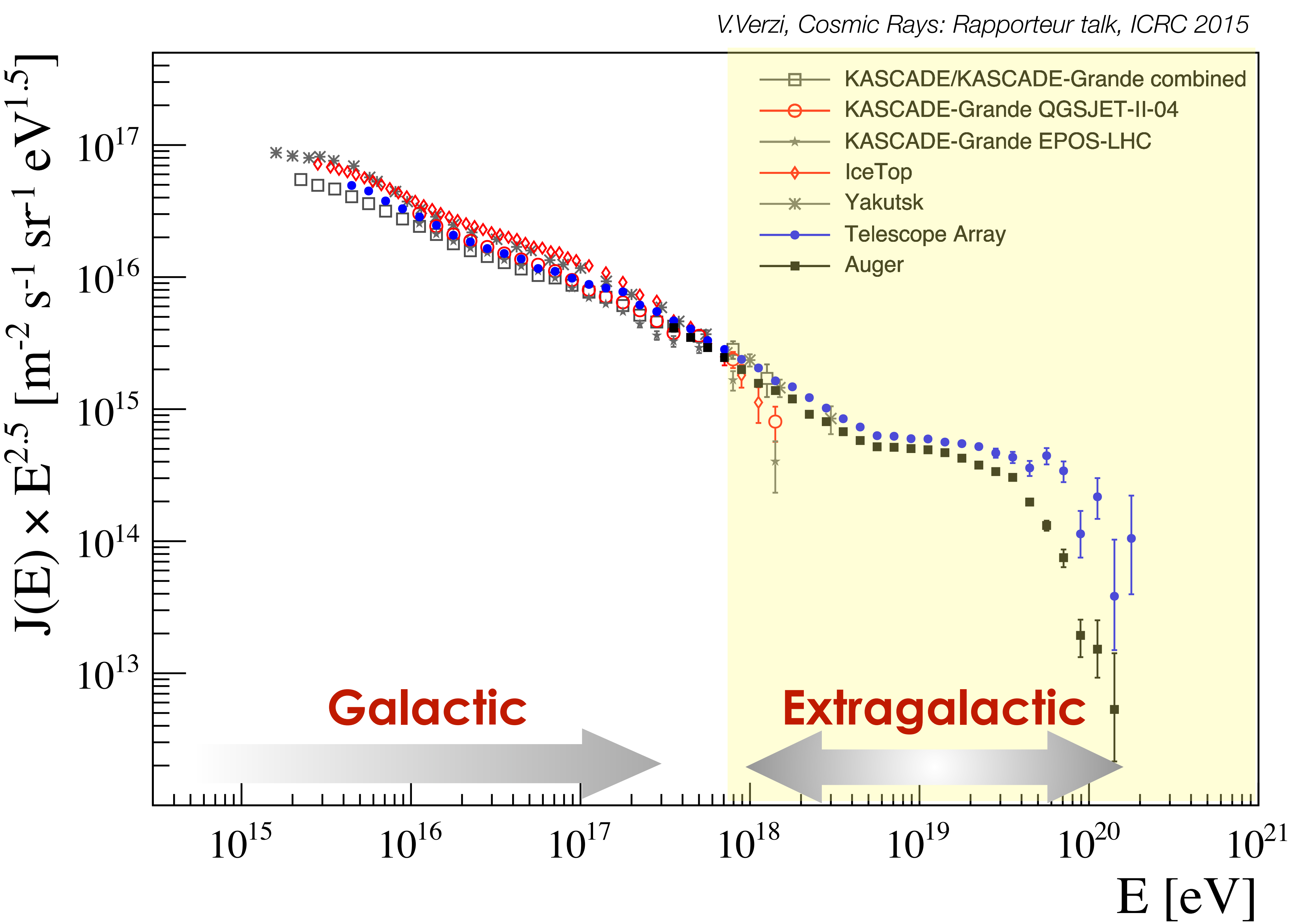
only through such a process can
community be convinced of reliability of results.

Many new missions upcoming and planned
with improved performance.

Extragalactic CRs

Auger & TA

The ultra-high-energy regime



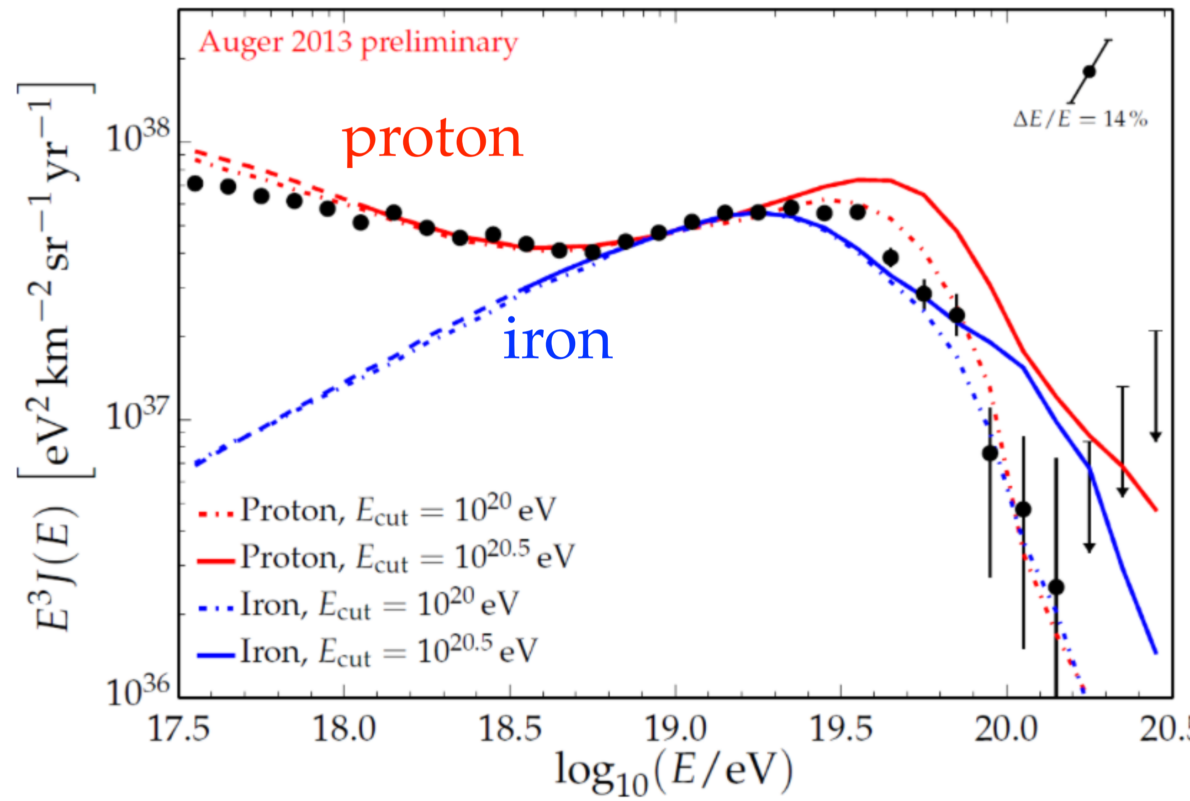
Propagation effect or source exhaustion?

1. Propagation scenario (GZK / photo-disintegration)

$p + \gamma_{CMB} \rightarrow n + \pi^+$ → cosmogenic neutrinos

$\rightarrow p + \pi^0$ → cosmogenic photons

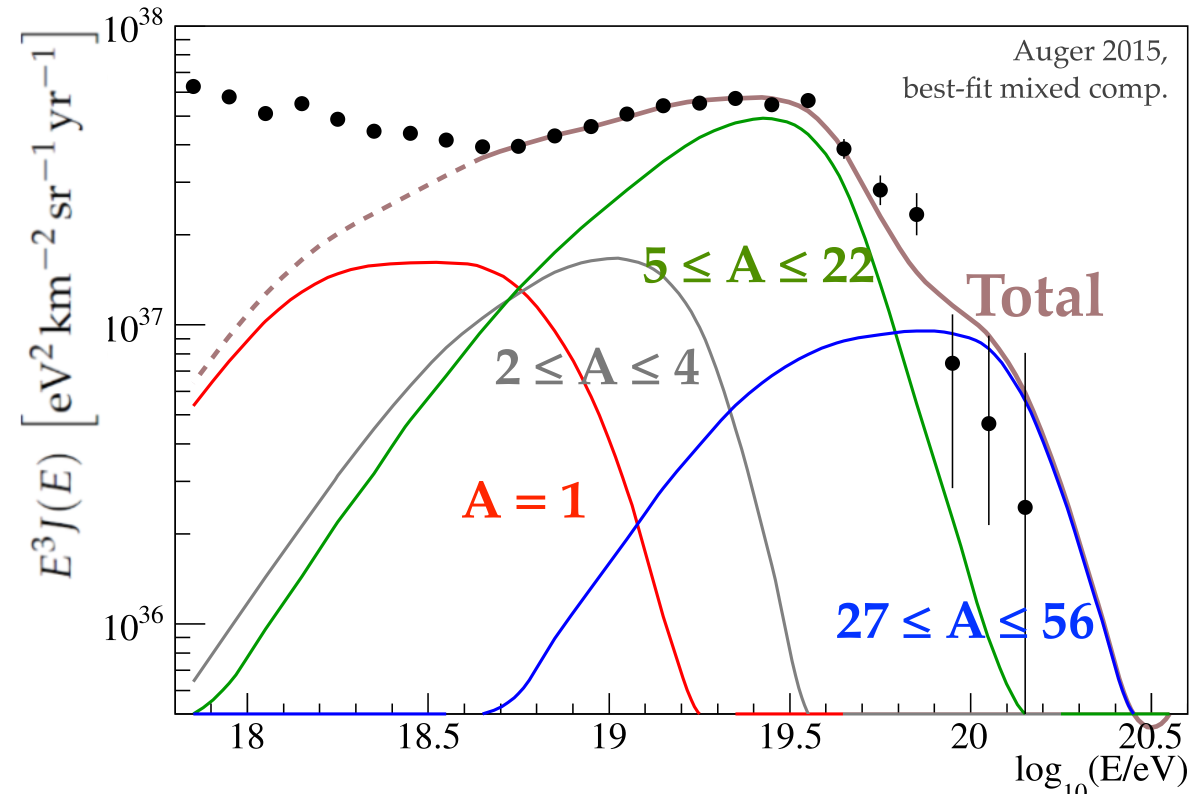
$E \gtrsim 10^{19.5}$ eV, "horizon" ~ 100 Mpc



2. Limitation of the maximal energy at the source

mixed composition

$$E_Z^{max} \propto Z \times E_p^{max}$$



How to discriminate the two scenarios?

- **Energy Spectrum features**
  increase statistics, pile-up for the GZK scenario

- **Mass composition** (in the GZK region)

- **Observation of cosmogenic photons/neutrinos**
  specific signature of GZK process (or new physics)

- **Anisotropy**
  small scale in case of a light composition (see next talk)

OUTLINE

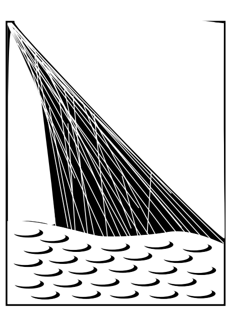
Detection techniques,

experiments in operation and some recent results

Two observatories for UHECRs

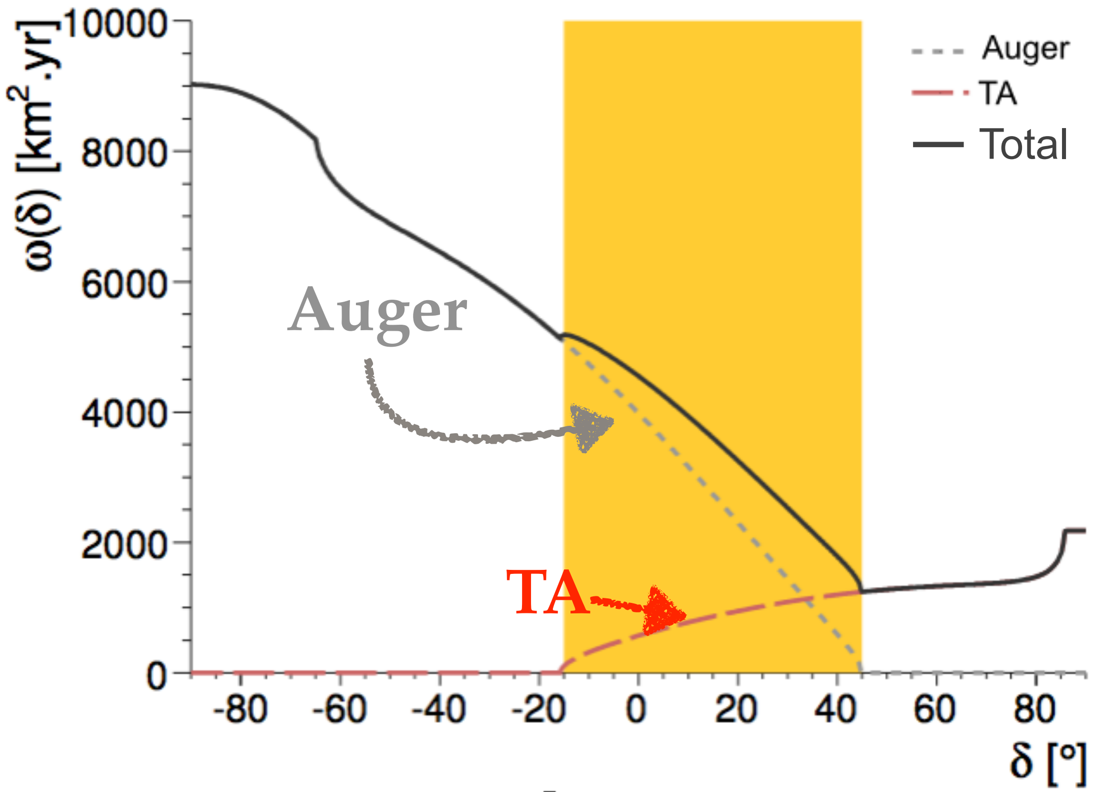
Telescope Array
Millard County, Utah, USA,
700 km²,1400 m a.s.l.
since 2008

Pierre Auger Observatory



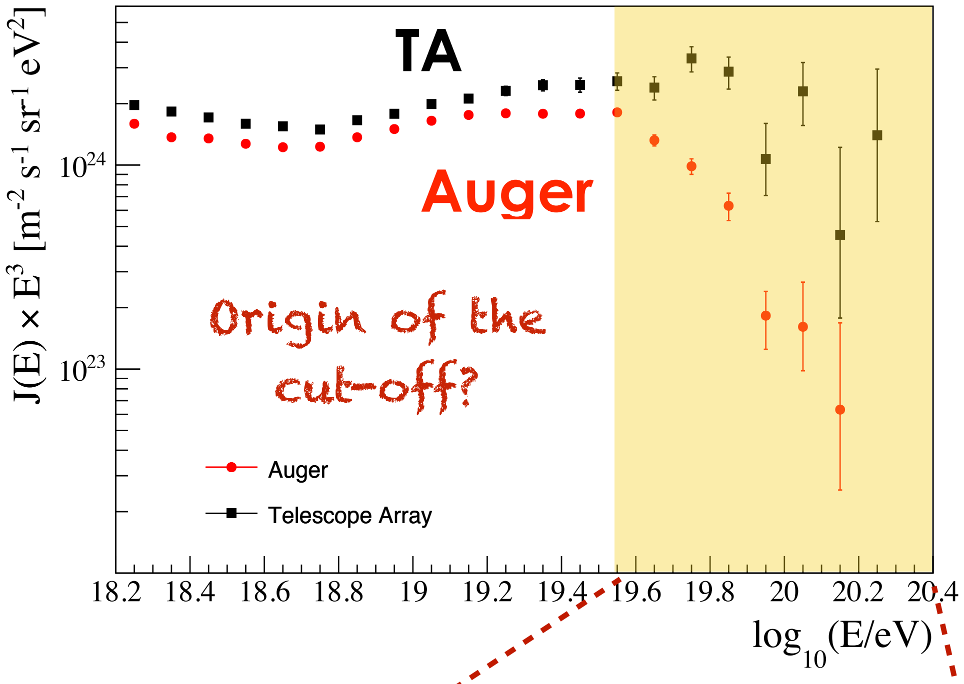
Malargue, Argentina,
3000 km², 1400 m a.s.l.
since 2004

One in each hemisphere:
different skies observed!

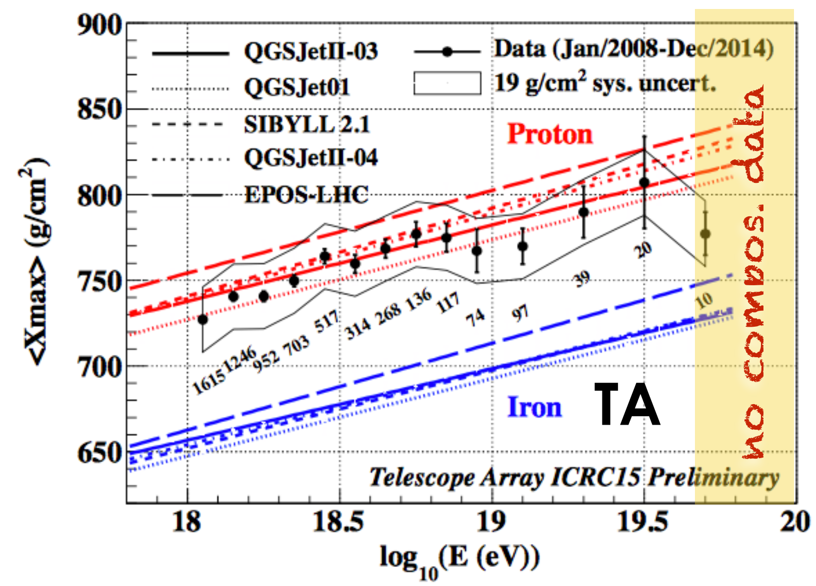


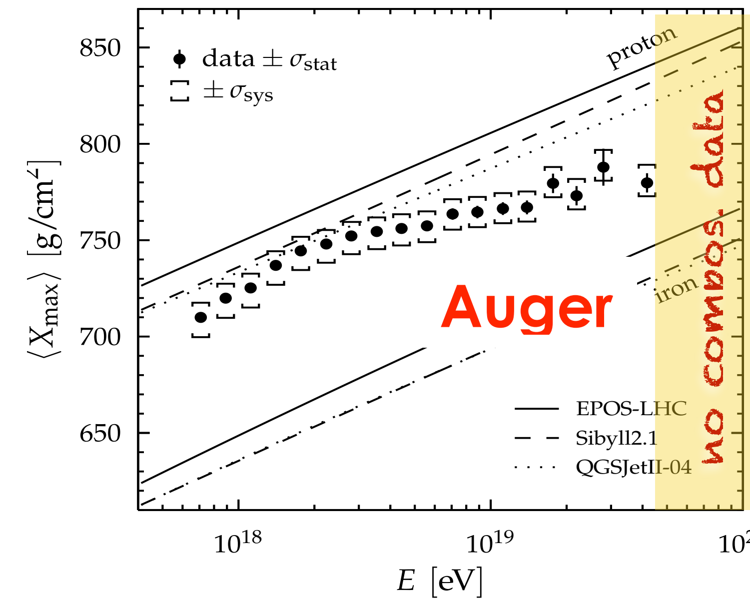
Auger exposure:
50000 km² sr yr
~ 10 times larger than TA

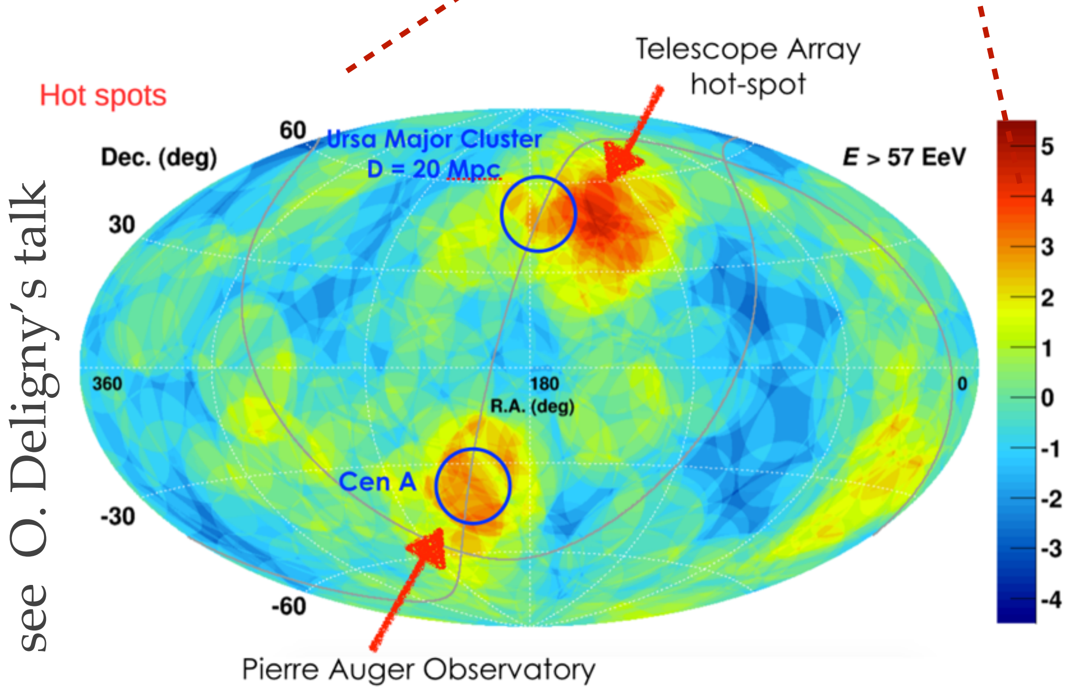
What have we learnt?

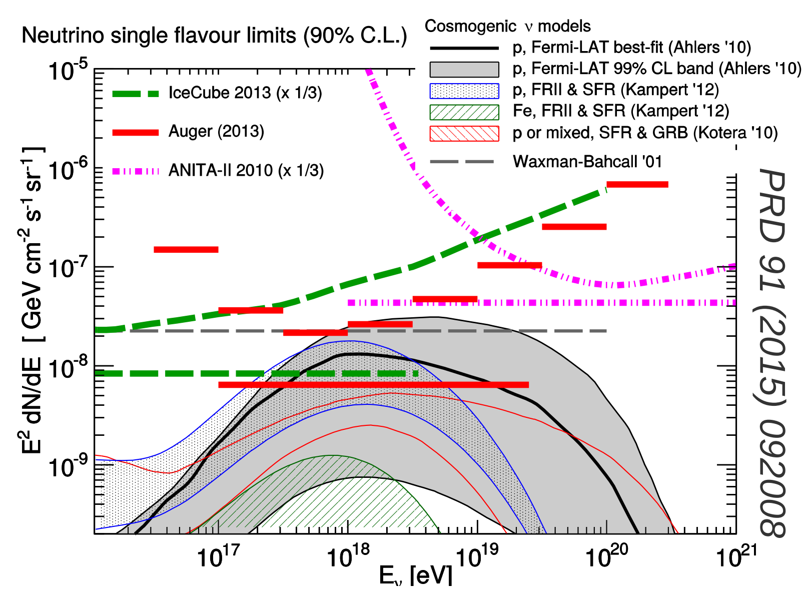


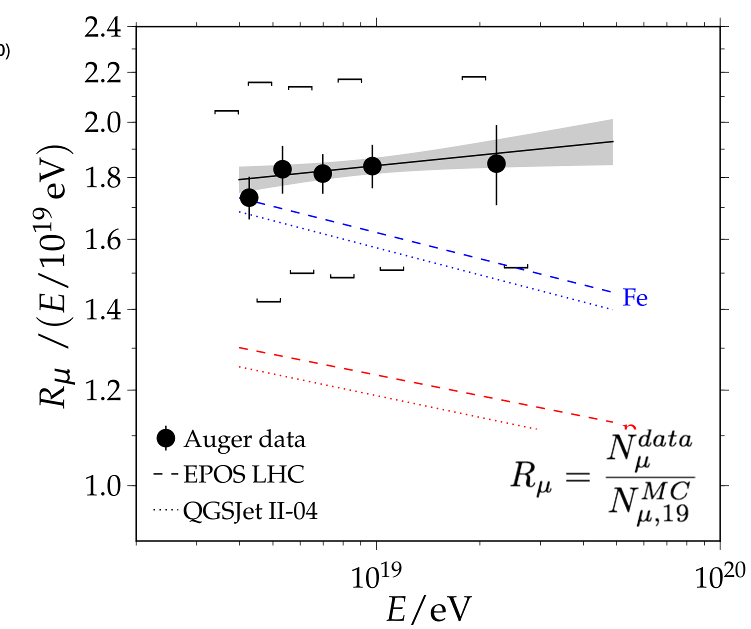
mass composition: light or mixed?







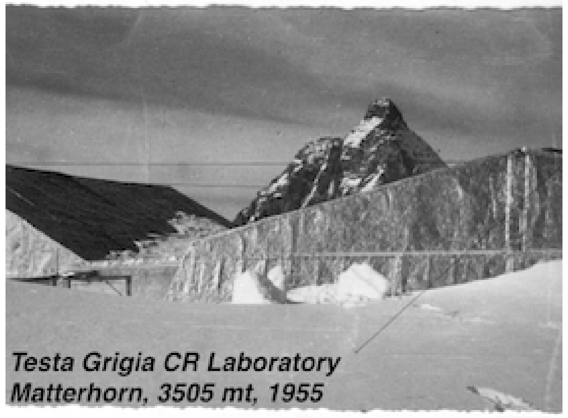




No anisotropy at small angular scale.
weak signal at ~ 20° angular scale

neutrino and photon limits constrain source properties

muon deficit in simulation



XXV ECRS 2016

Torino - Italy

Measurement of the depth of maximum of air-shower profiles and its composition implications

PIERRE AUGER OBSERVATORY

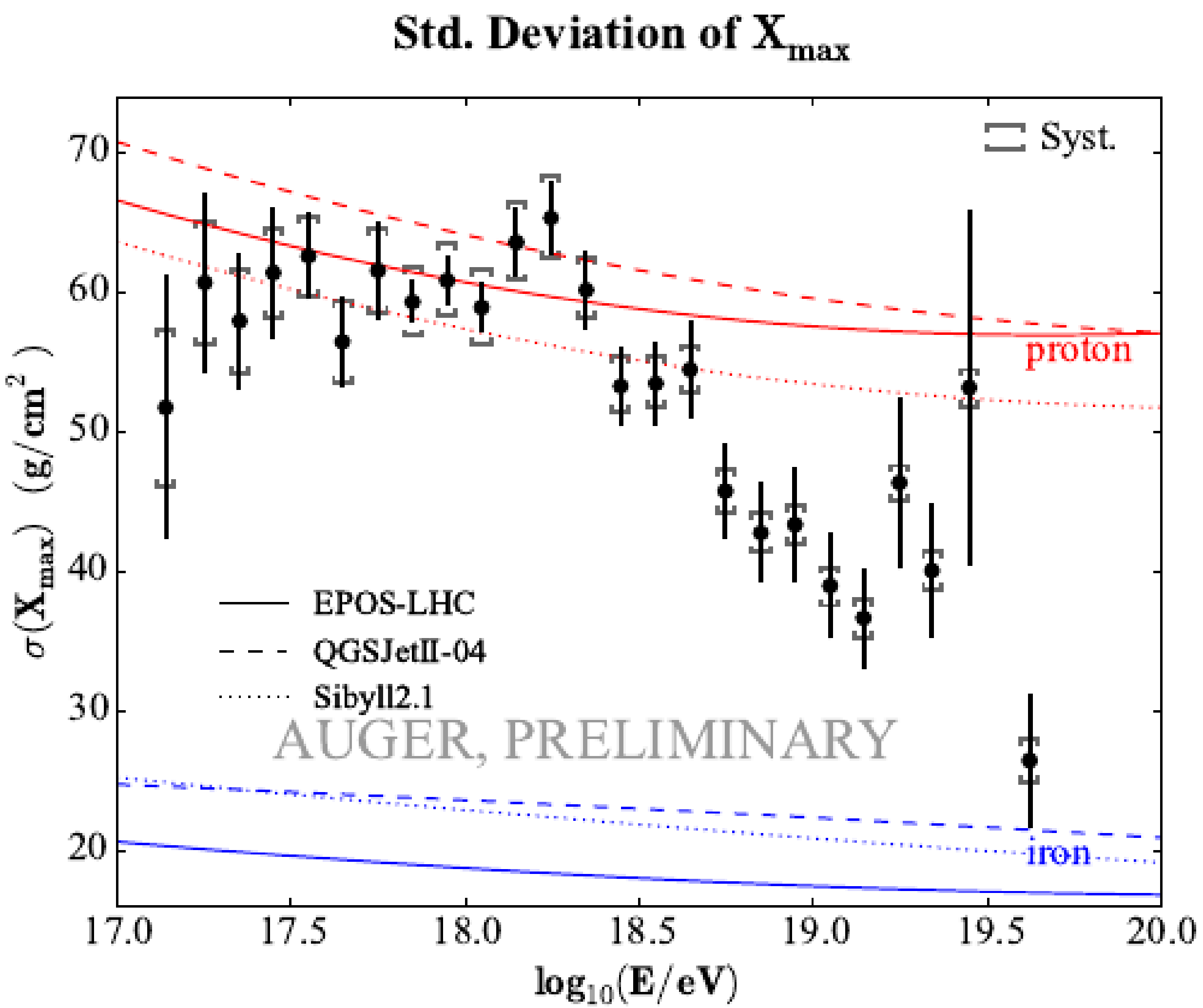
The Pierre Auger Collaboration

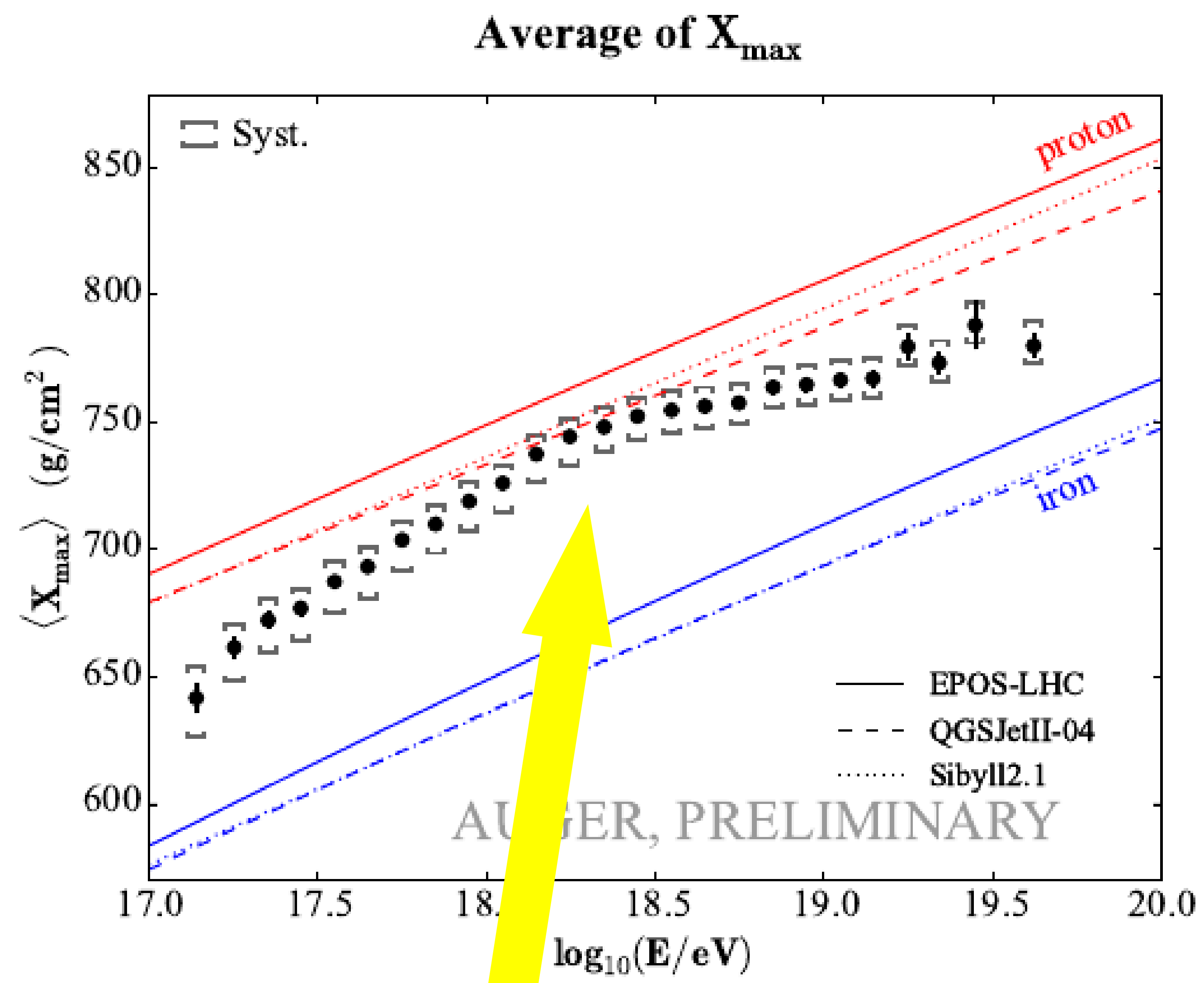
Av. San Martin Norte 304, 5613 Malargüe, Argentina

http://www.auger.org/archive/authors_2016_08.html

Presenter: Vitor de Souza (University of Sao Paulo-Brazil)

moments

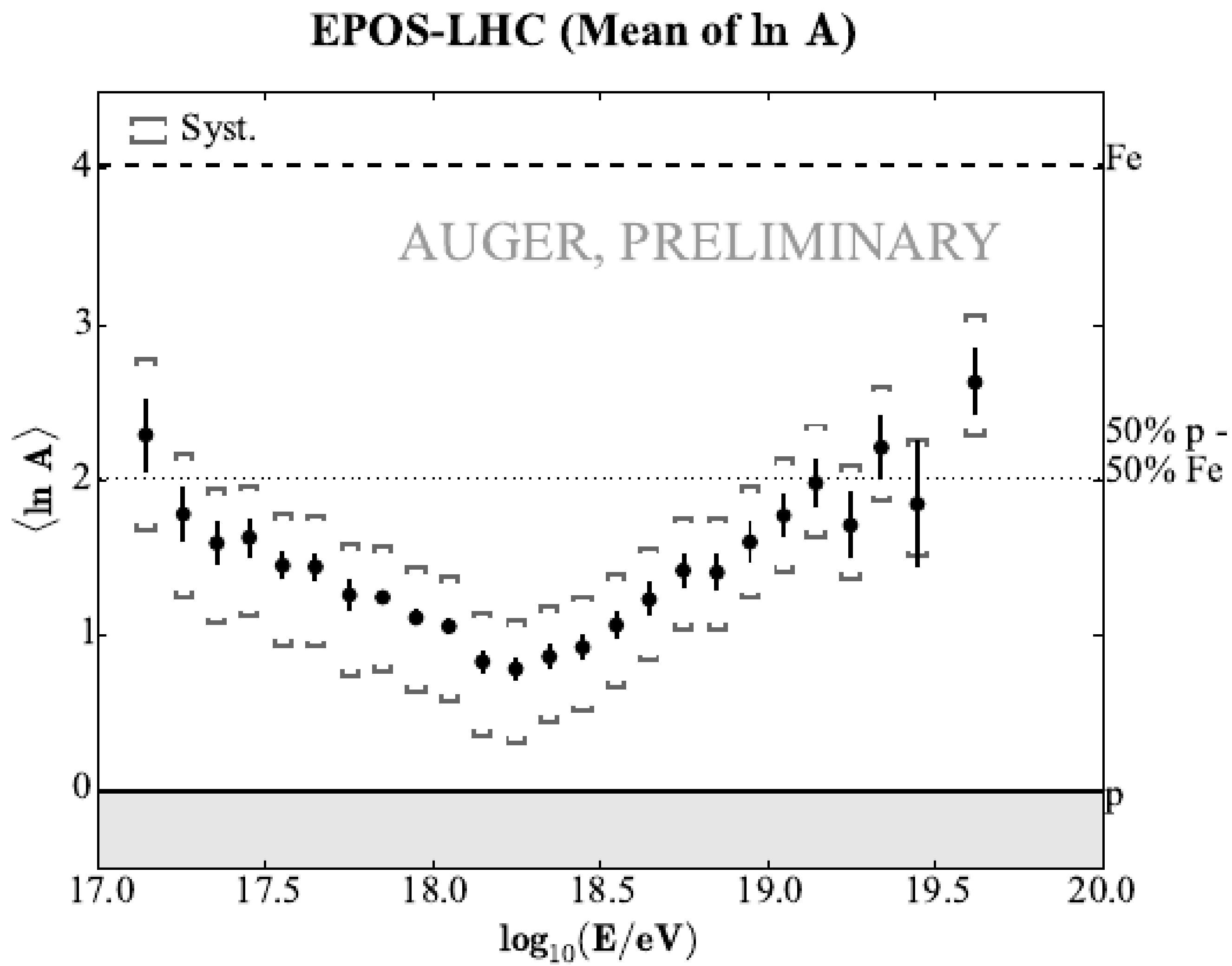


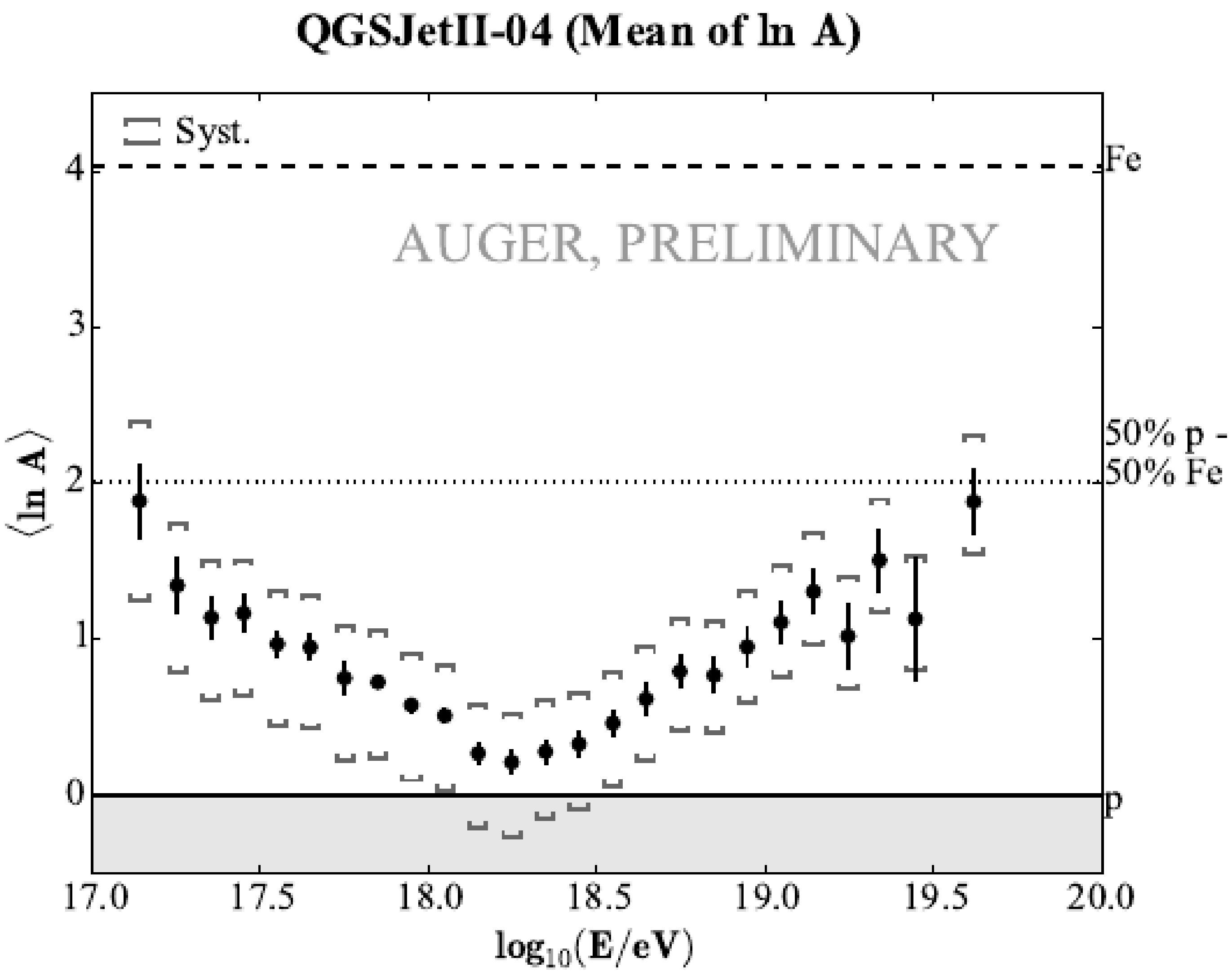


Clear break @

$$\lg(E_0/\,\text{eV}) = 18.27 \pm 0.04\,(\text{stat.})\,^{+0.06}_{-0.07}\,(\text{sys.})$$

Mean ln A





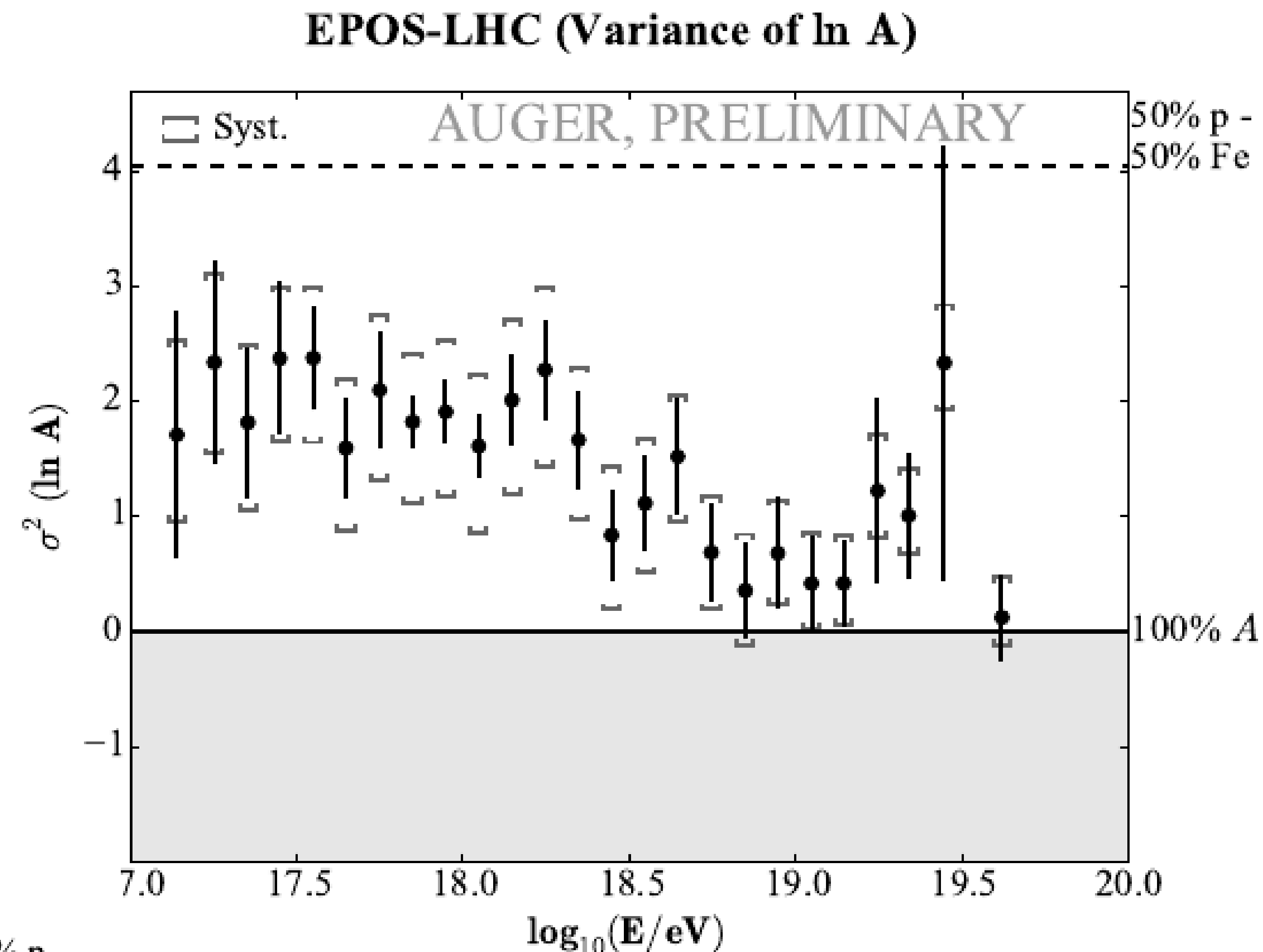
Clear trend:

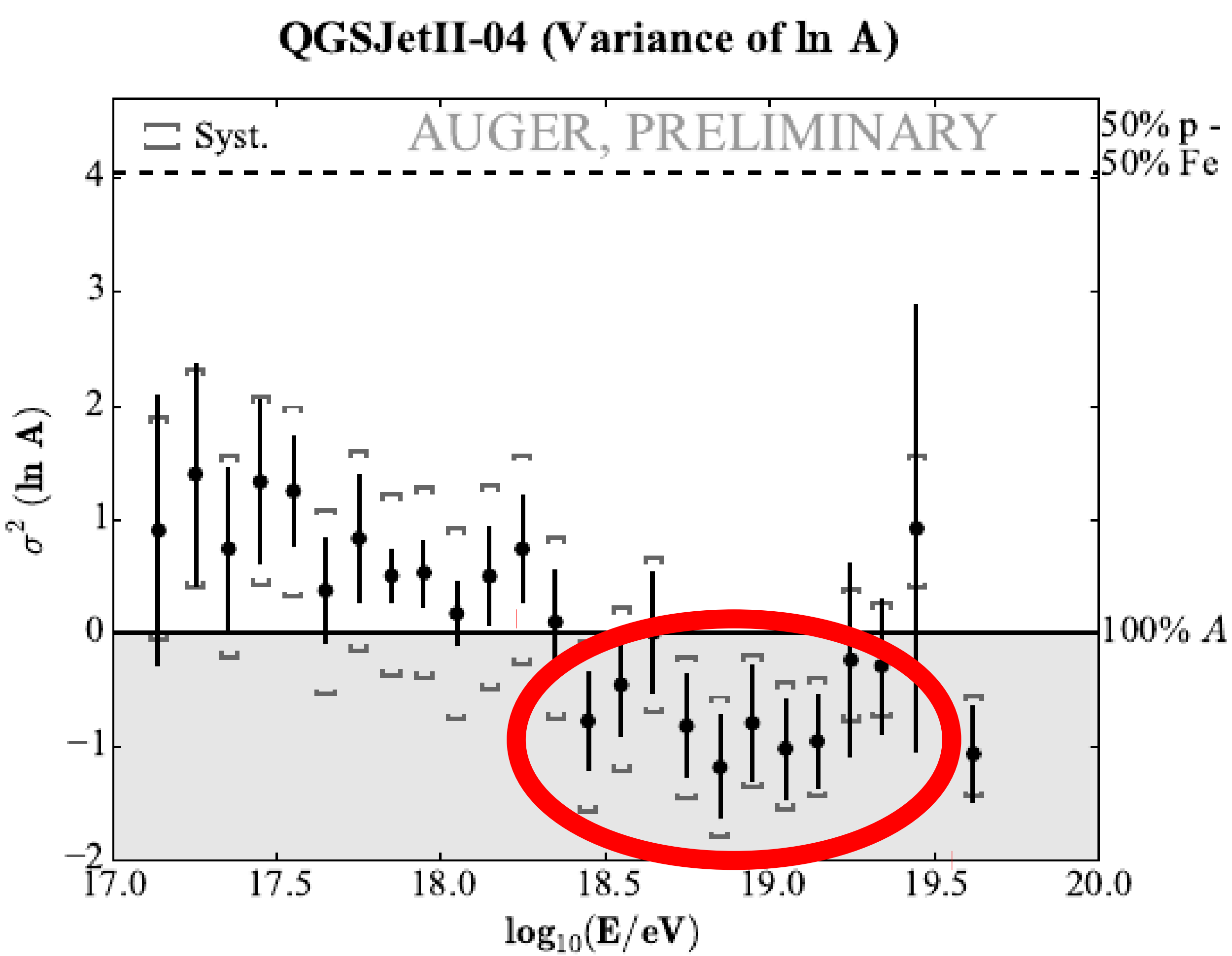
$10^{17} <$ E $< 10^{18.27}$ eV: getting ligther

E $> 10^{18.27}$ eV: getting heavier

Variance of ln A

$\sigma^2 (\ln A)$



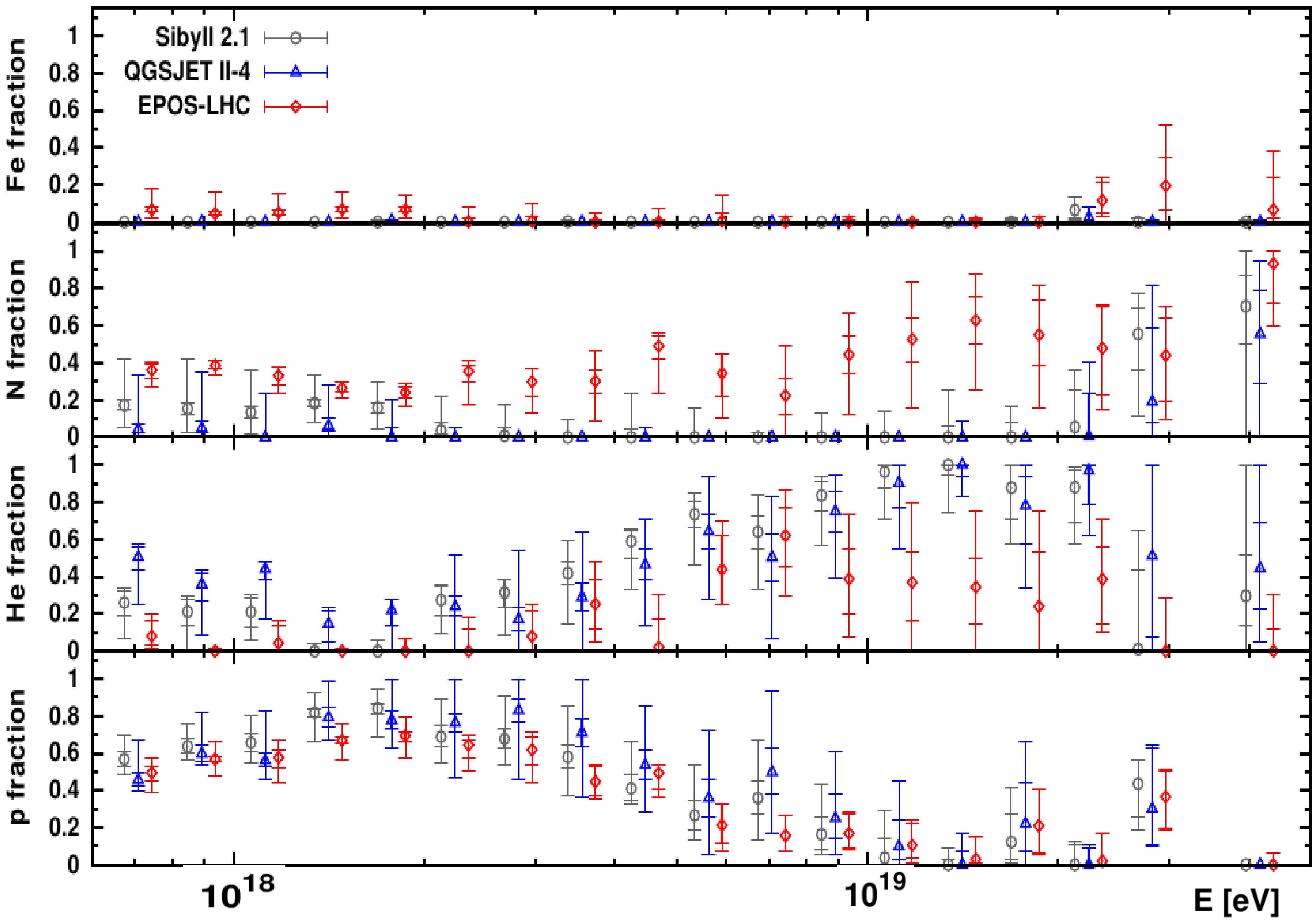


$\sigma^2 (\ln A)$ measures the purity of the sample:

- pure A → $\sigma^2 (\ln A) = 0$
- 50:50 Pr:Fe → $\sigma^2 (\ln A) \approx 4$

J. Lisley, ICRC 1985

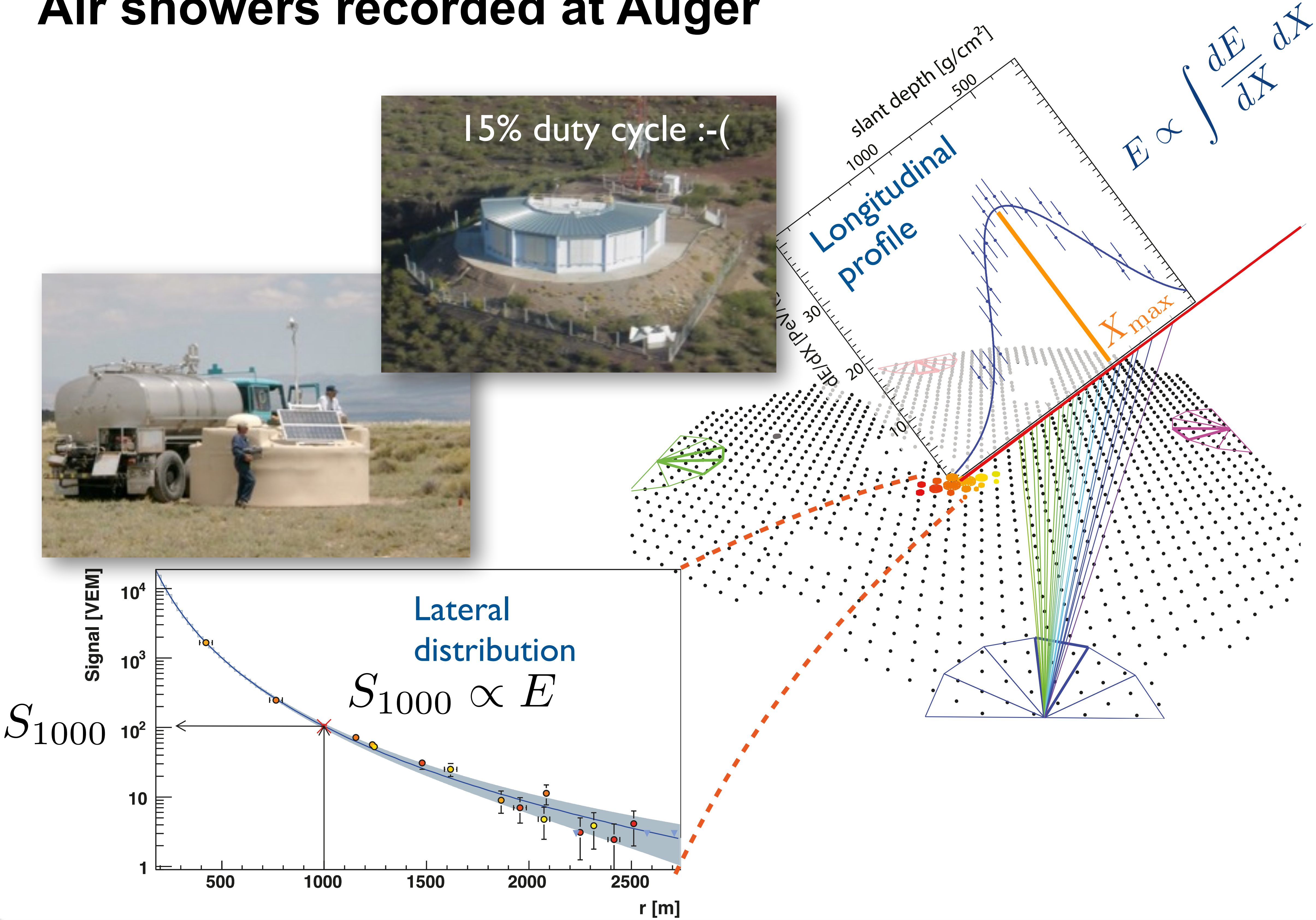
proton + helium + nitrogen + iron



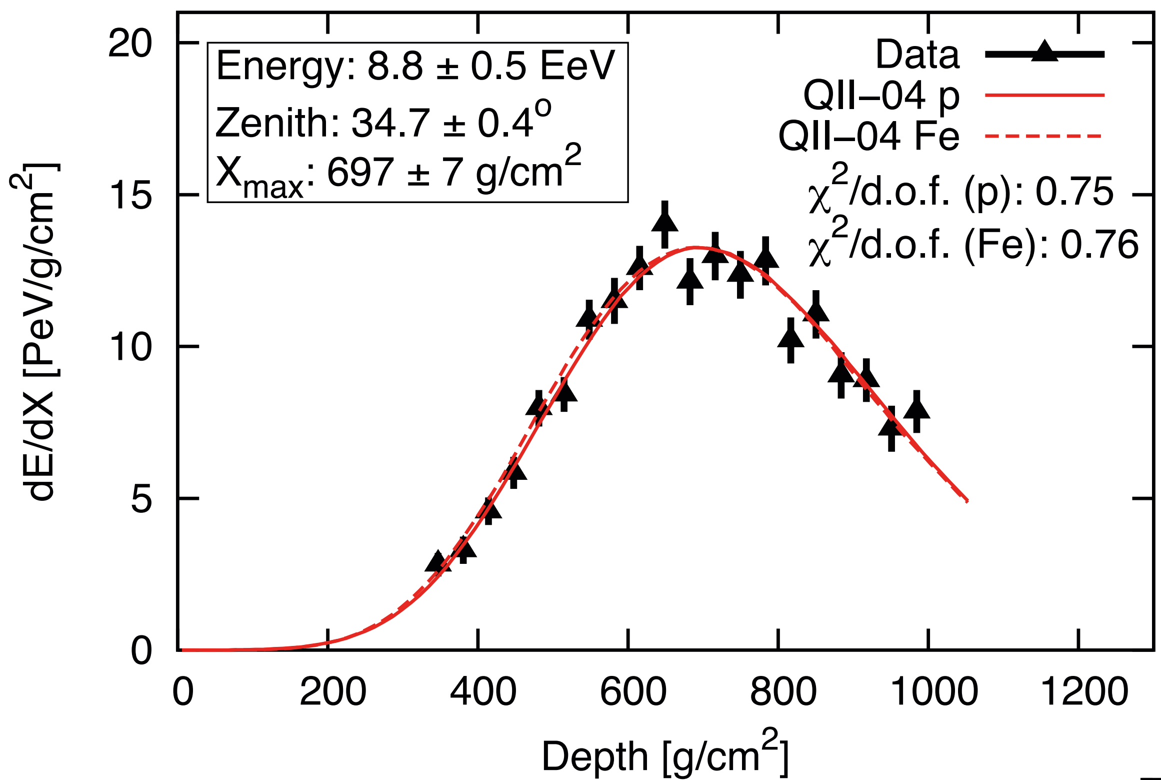
final remarks

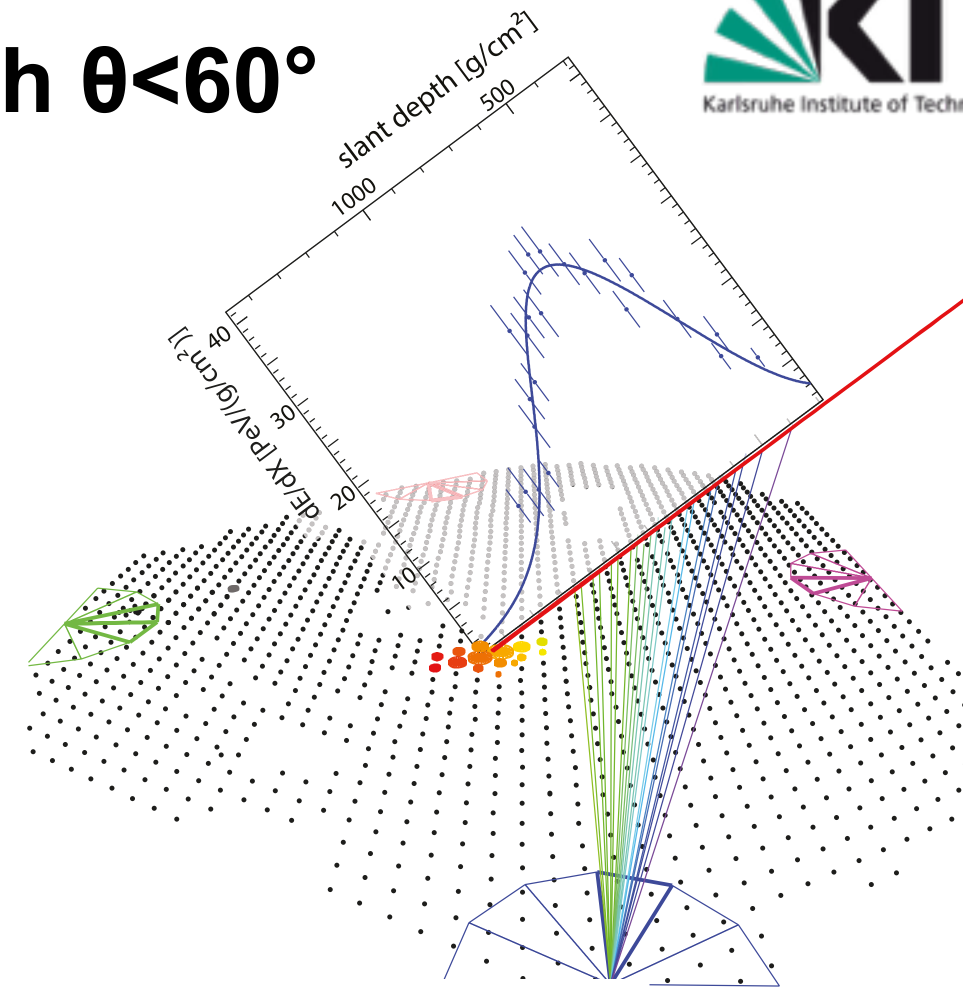
- data
  - all information is public: distributions, resolution, systematics and acceptance
  - largest statistics with controlled systematics
- Xmax moments
  - clear break @ log (E/eV) = 18.27
  - showers with E > $10^{18.27}$ eV are shallower and fluctuate less than proton simulations

Air showers recorded at Auger

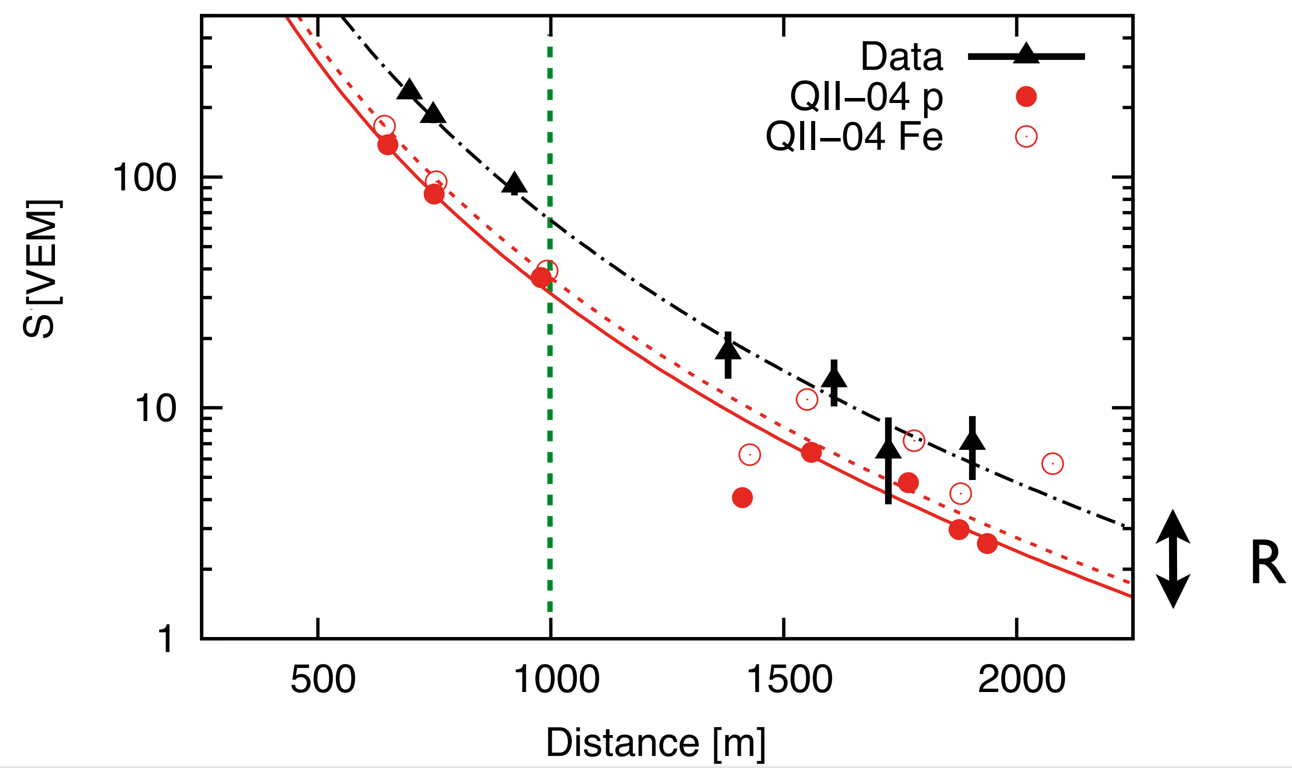


Muon number in hybrid events with θ<60°





- $E = 10^{18.8}$ - $10^{19.2}$ eV
- Zenith angles [0°, 60°]
- 411 hybrid events after quality cuts

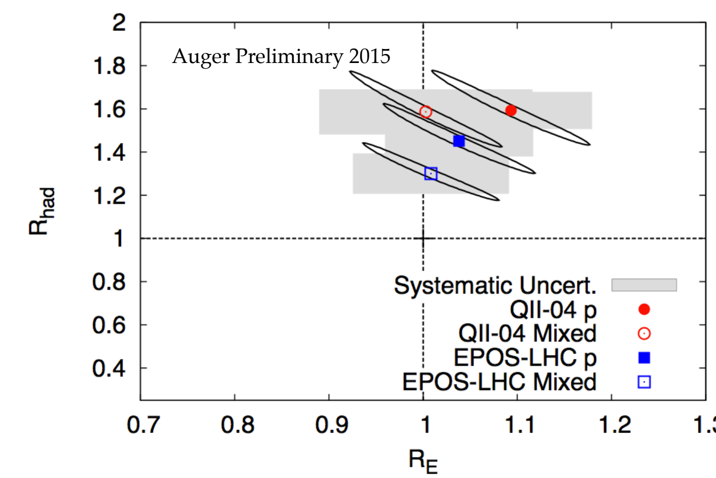


Karlsruher Institut für Technologie (KIT)
Institut für Kernphysik, Karlsruhe, Germany

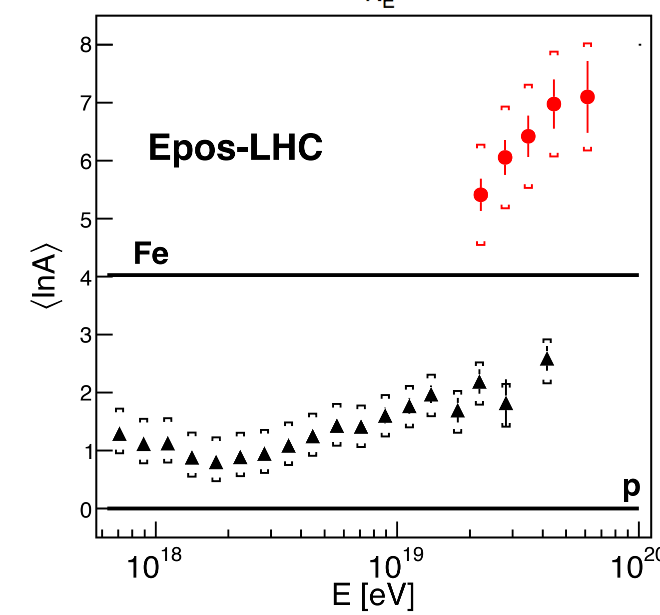
Summary

- $\langle X_{max} \rangle$, $\sigma(X_{max})$, $r_G(X_{max}/S(1000))$
  ➙ Mixed composition around and above the ankle
  (if LHC-inspired extrapolations are ok)
- Muon number
  ➙ At odds with predictions for mixed composition
  ➙ Muon deficit in simulations
- Muon production depth vs. X_{max}
  ➙ QGSjetII-04: marginally compatible
  ➙ EPOS-LHC: incompatible

Auger is going to extend the composition measurements up to highest energies
measuring $e^{\pm}/\gamma$ & muons with 2 arrays:
AugerPrime
(szintillators accompanying WCDs; see Tiina’s talk)

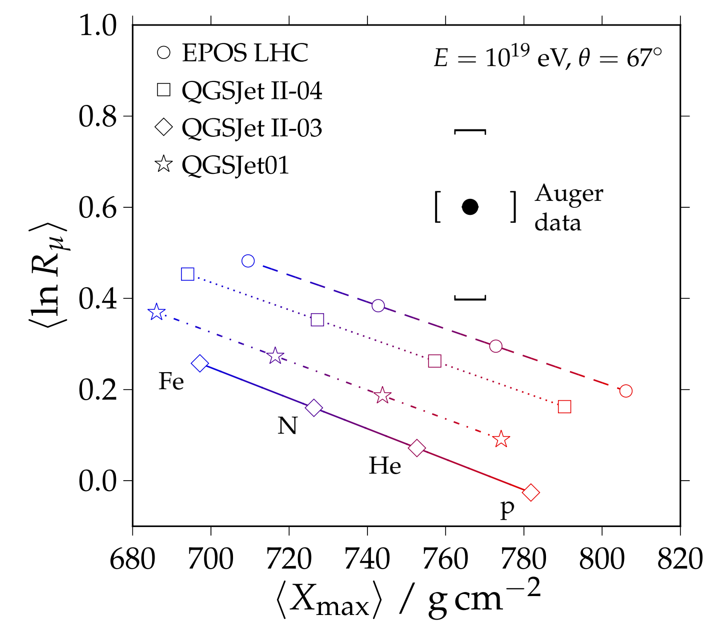


R_E, R_{had}



X^{μ}_{max}

X_{max}



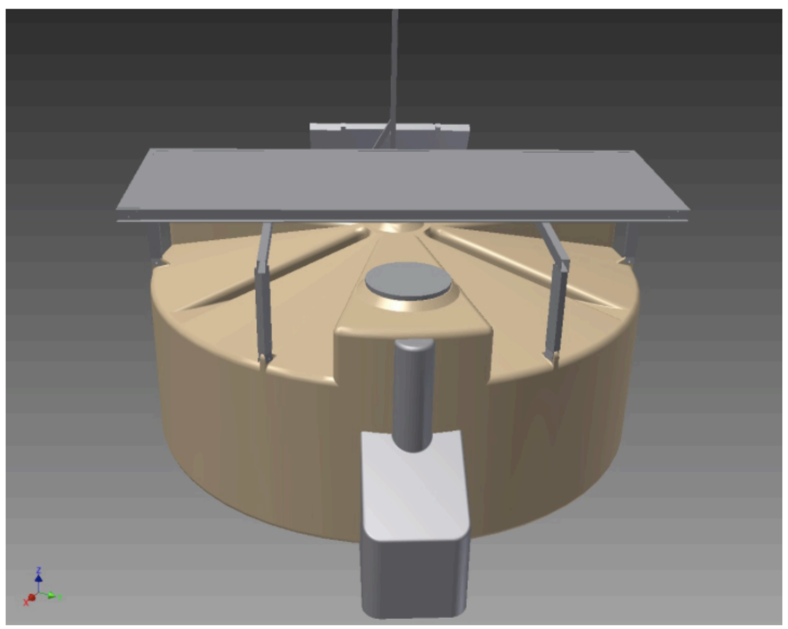
R_{μ}

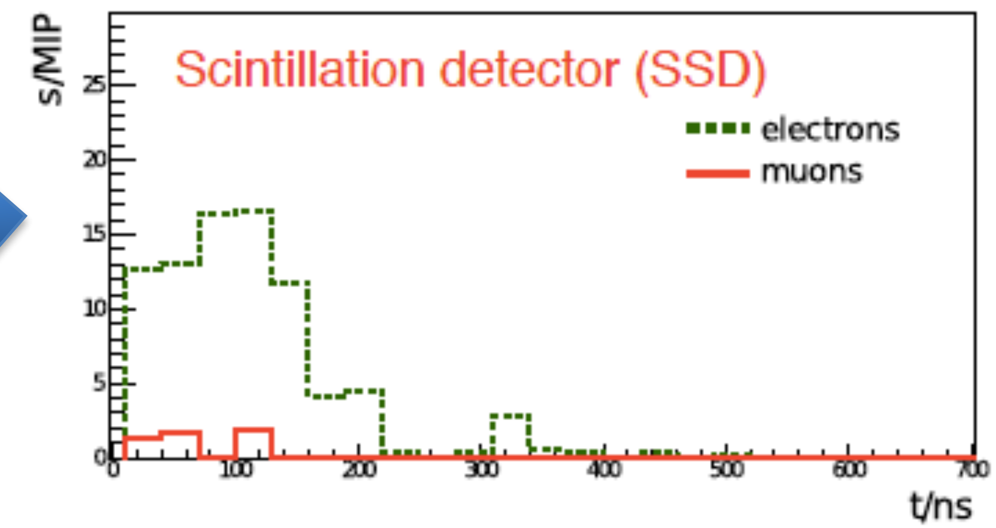
Karlsruher Institut für Technologie (KIT)
Institut für Kernphysik, Karlsruhe, Germany

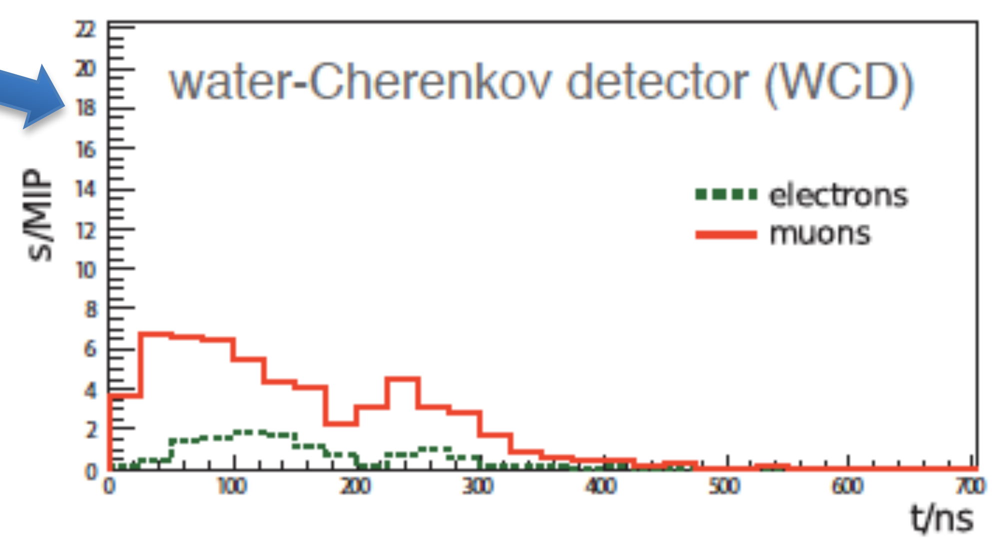
Auger upgrade for better composition sensitivity

PIERRE AUGER OBSERVATORY

WCD+SSD measurements







Complementarity of particle response will be used to discriminate electromagnetic and muonic components of air showers.

Matrix based method $S_{\mu,\mathrm{WCD}} = a S_{\mathrm{WCD}} + b S_{\mathrm{SSD}}$

Other methods based on the multivariate analysis or on the shower universality

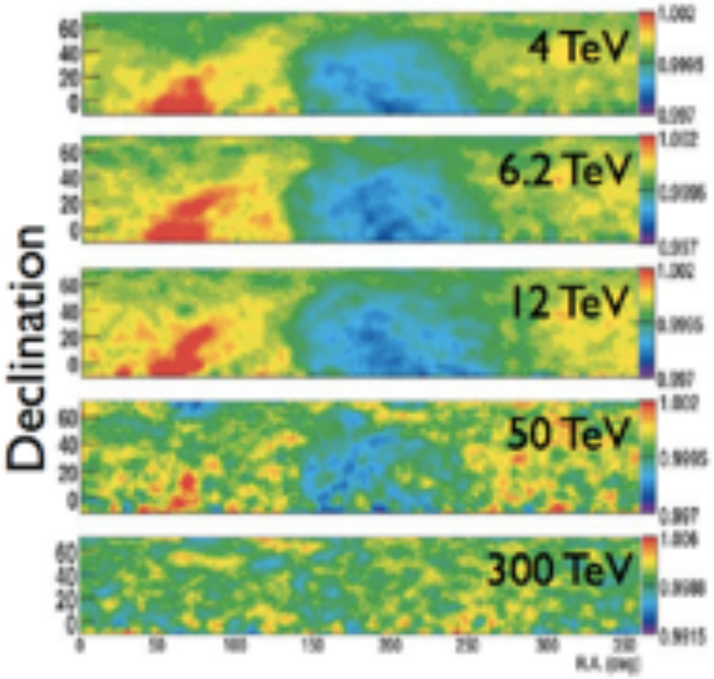
Anisotropy

Dipole Observations

O. Deligny, Orsay
… a nice review

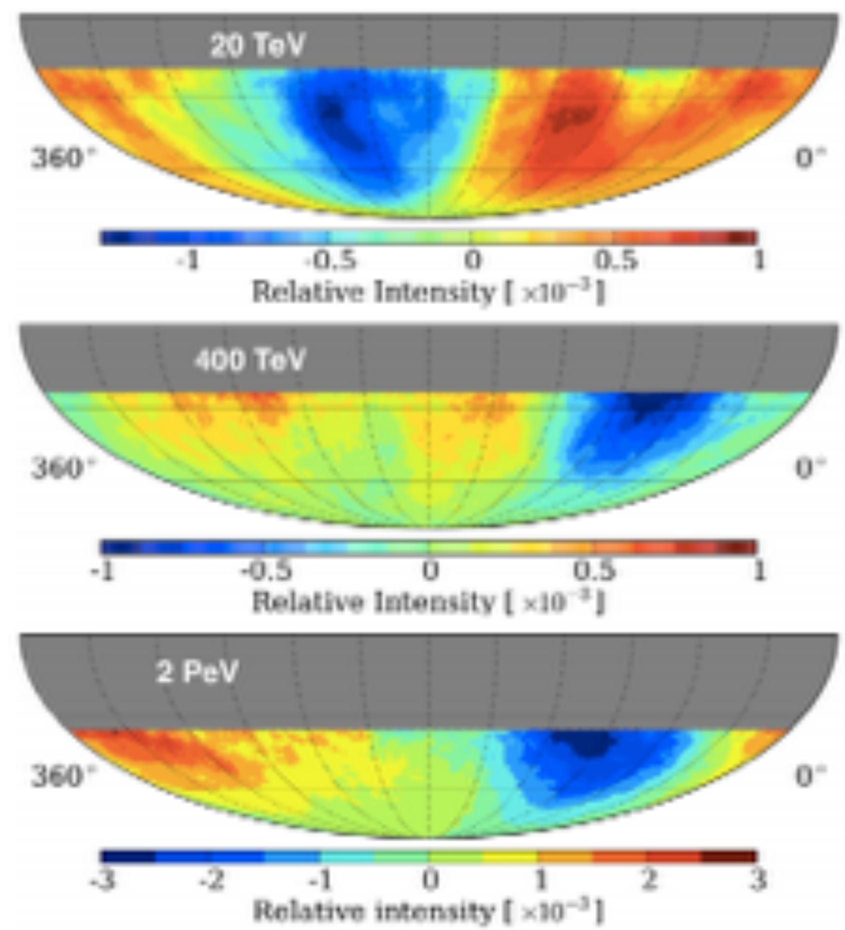
- Northern hemisphere: Tibet ASγ, Super-Kamiokande, Milagro, EAS-TOP, MINOS, ARGO-YBJ
- Southern hemisphere: IceCube/IceTop

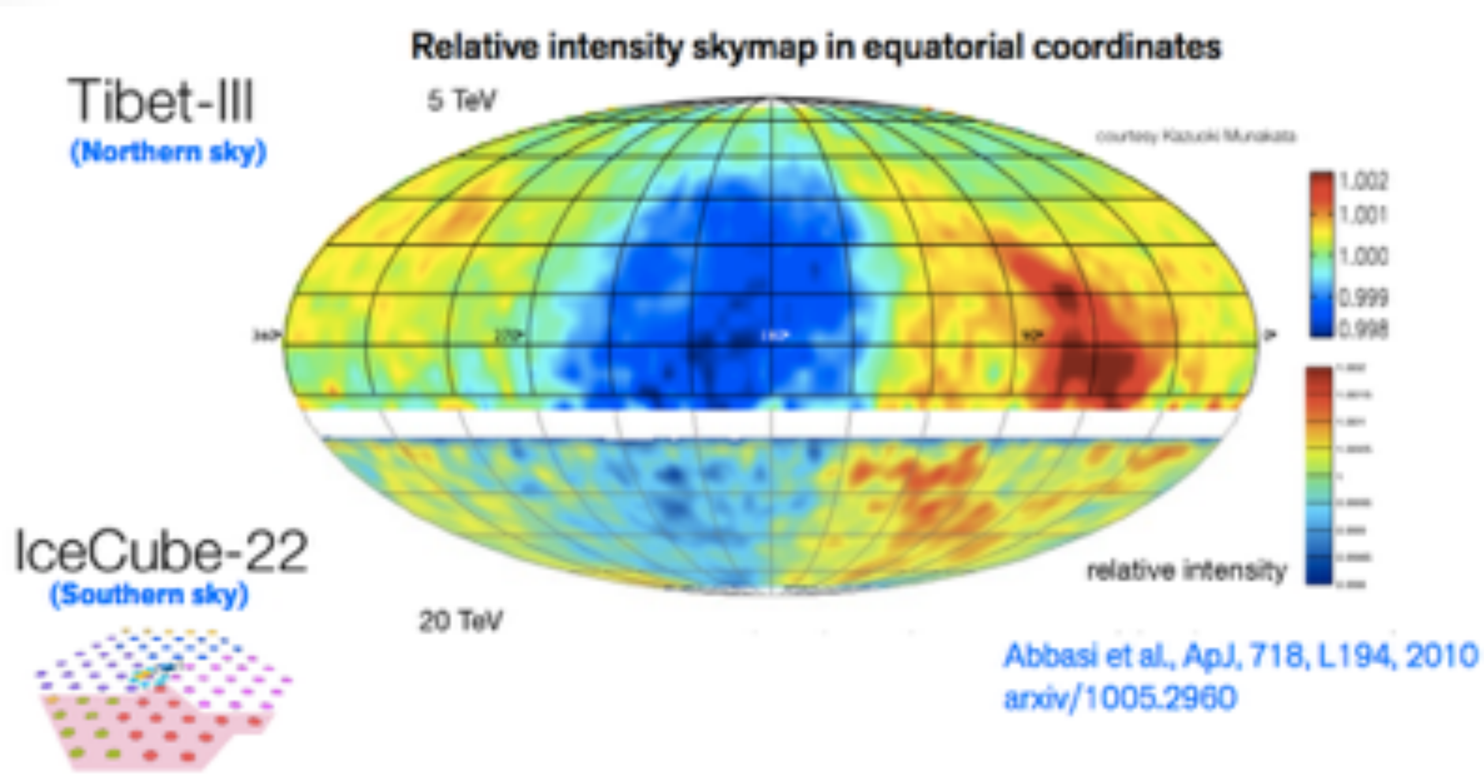
Tibet



$\approx 10^{-3}$
anisotropy
contrast

IceCube/IceTop



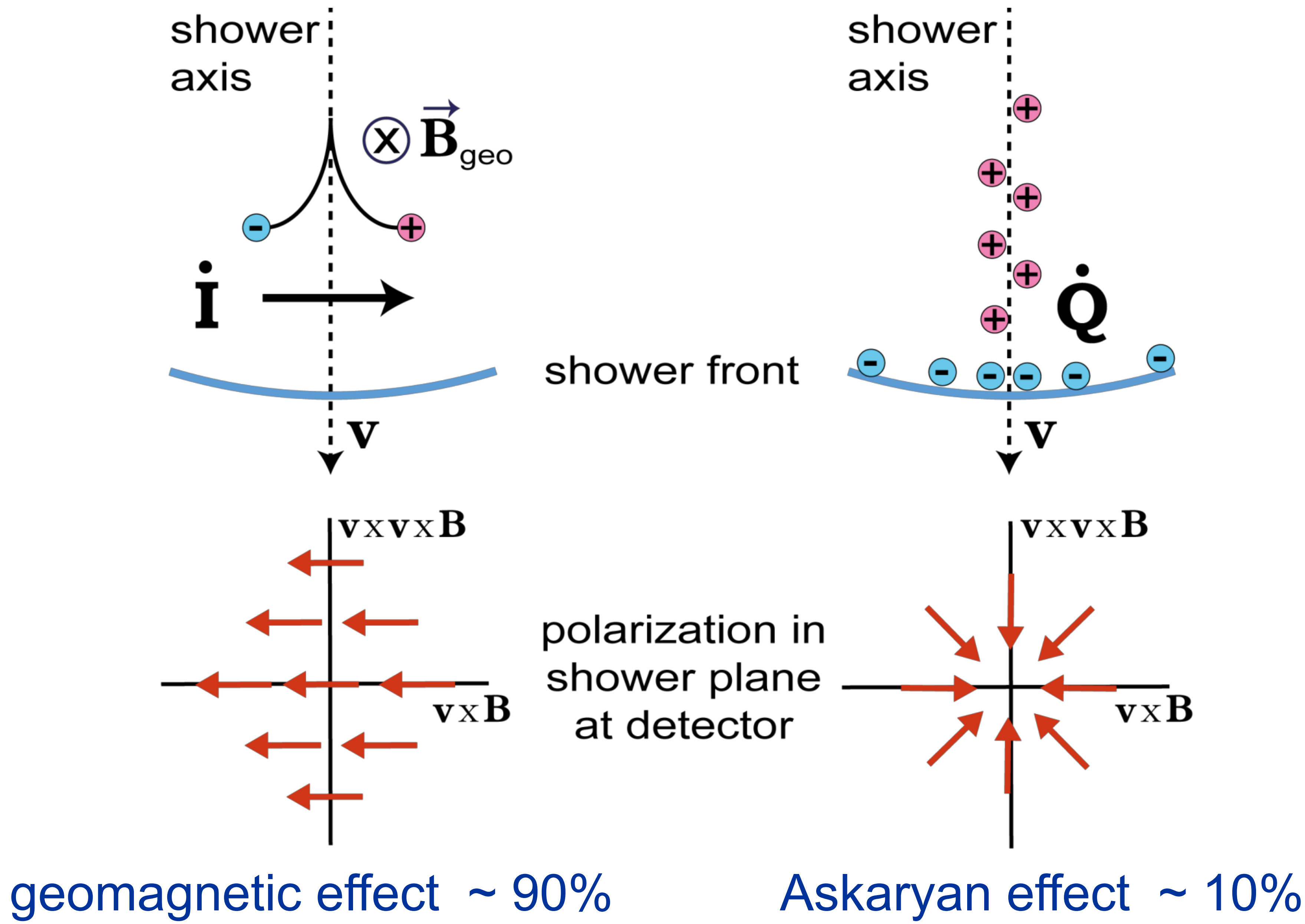


Summary

- Anisotropies up to ≈PeV energies well established
  - Not only dipoles!
  - Important developments for local CR propagation
- Quest of UHECR origin more difficult than expected
  - No small-scale clustering observation, only dipoles seem at reach!
  - Need for composition-based searches
  - Need for (much) larger exposure keeping similar resolutions…

Radio Technique

Emission mechanisms



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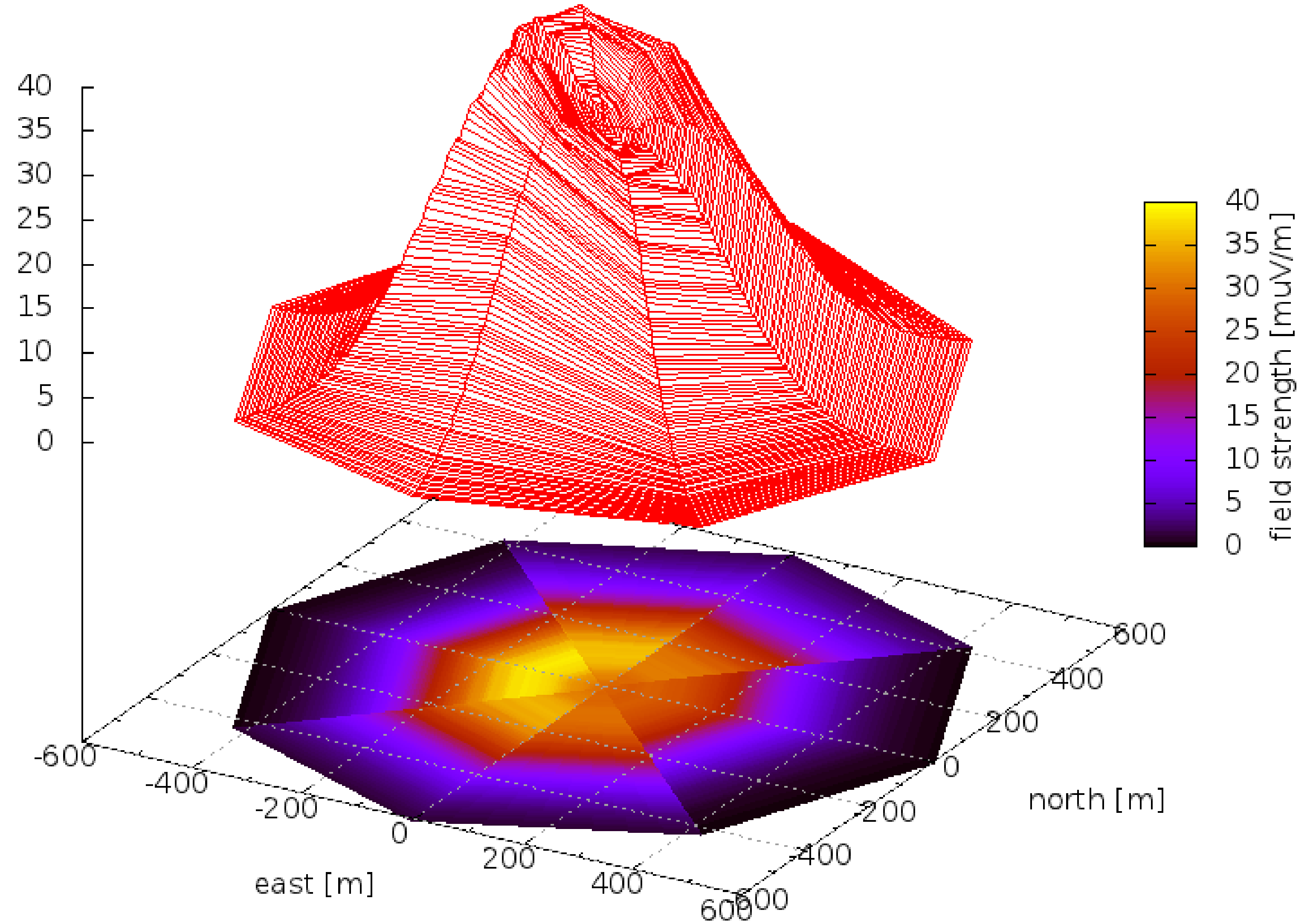
Tim Huege, Phys Rep 2016

Conical radio emission with asymmetric footprint



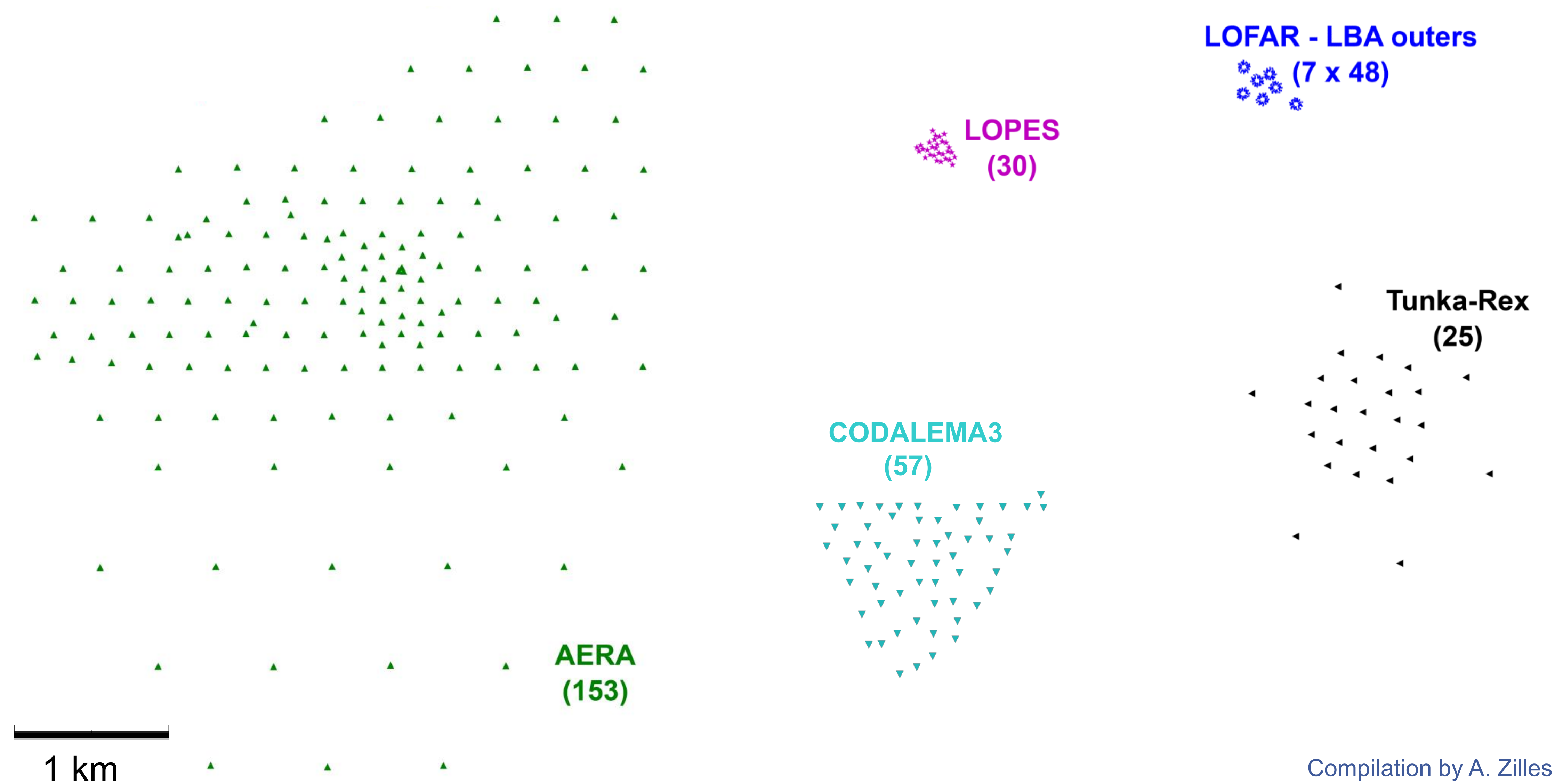
shower inclination:
θ = 45°

CoREAS simulations
By T. Huege et al., ARENA2012

43 – 74 MHz

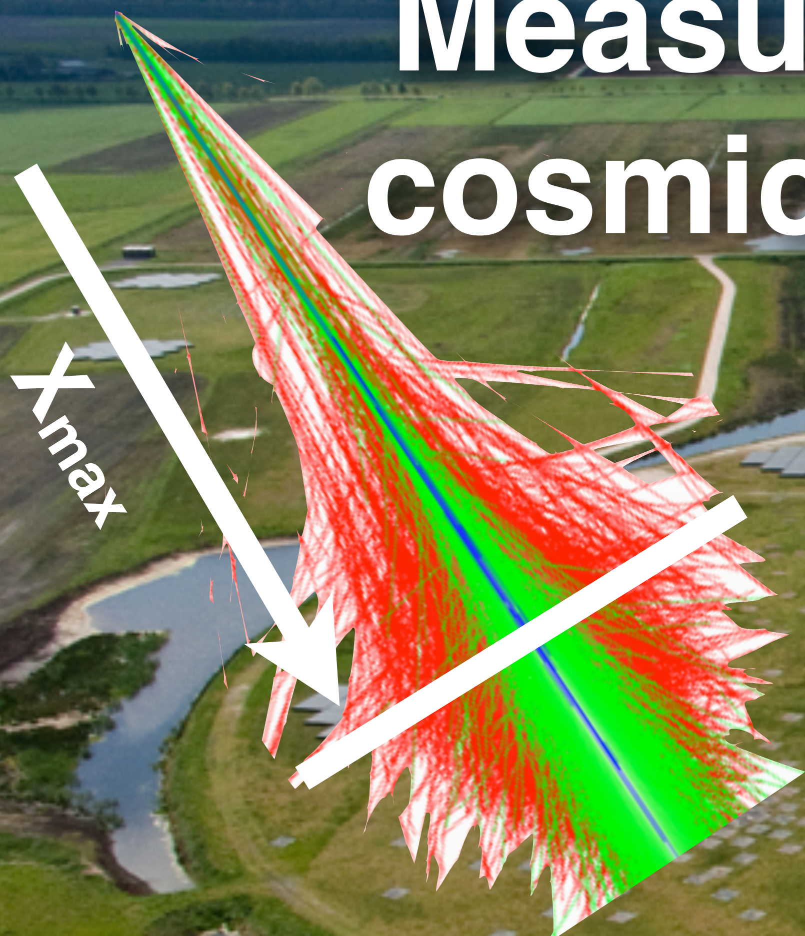
Radio emission well understood.
How to use it best for improved CR measurements??

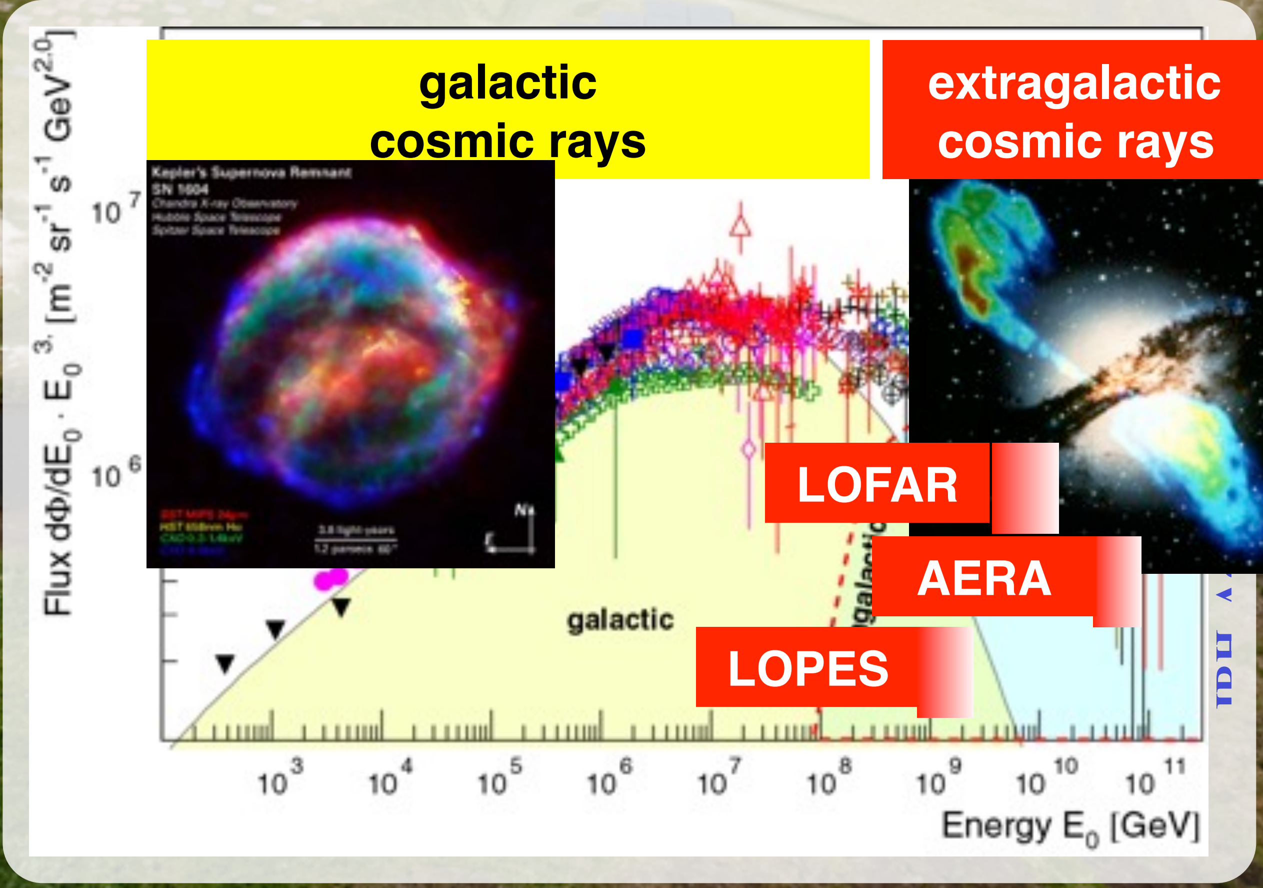
Designs of modern radio arrays
(mostly externally triggered)



XXV European Cosmic Ray Symposium
4-9 September 2016

Measurement of the properties of cosmic rays with the LOFAR radio telescope





characterize cosmic rays:
- direction
- energy
- mass

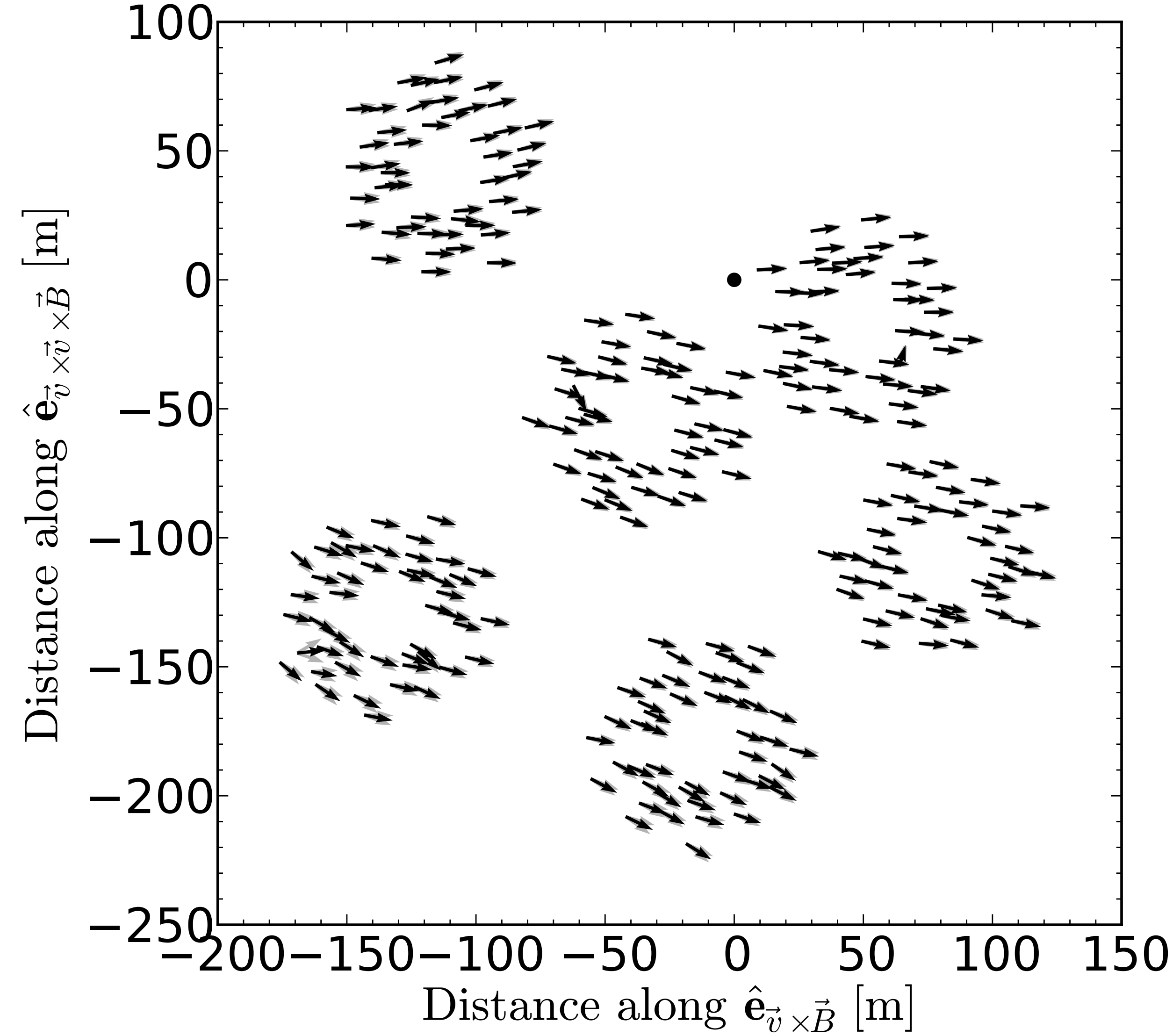
@100% duty cycle

LOFAR

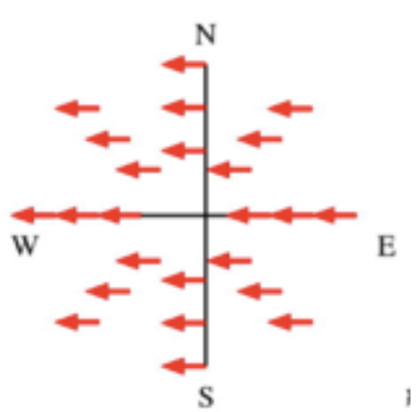
Jörg R. Hörandel Radboud University Nijmegen & Nikhef http://particle.astro.ru.nl

Polarization footprint

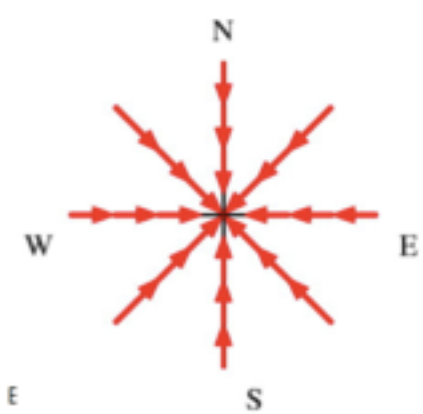
of an individual air shower



geomagnetic



Askaryan

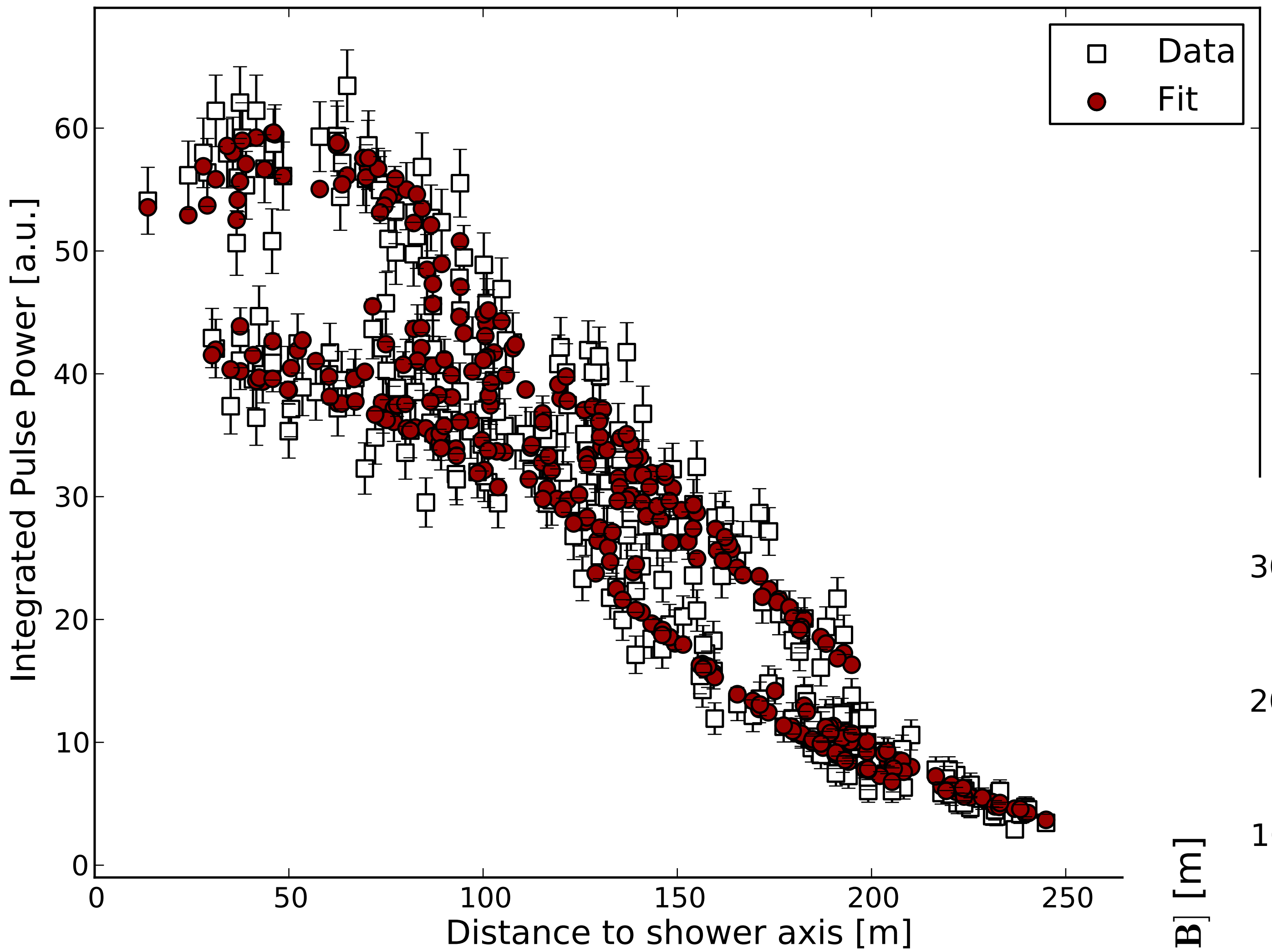


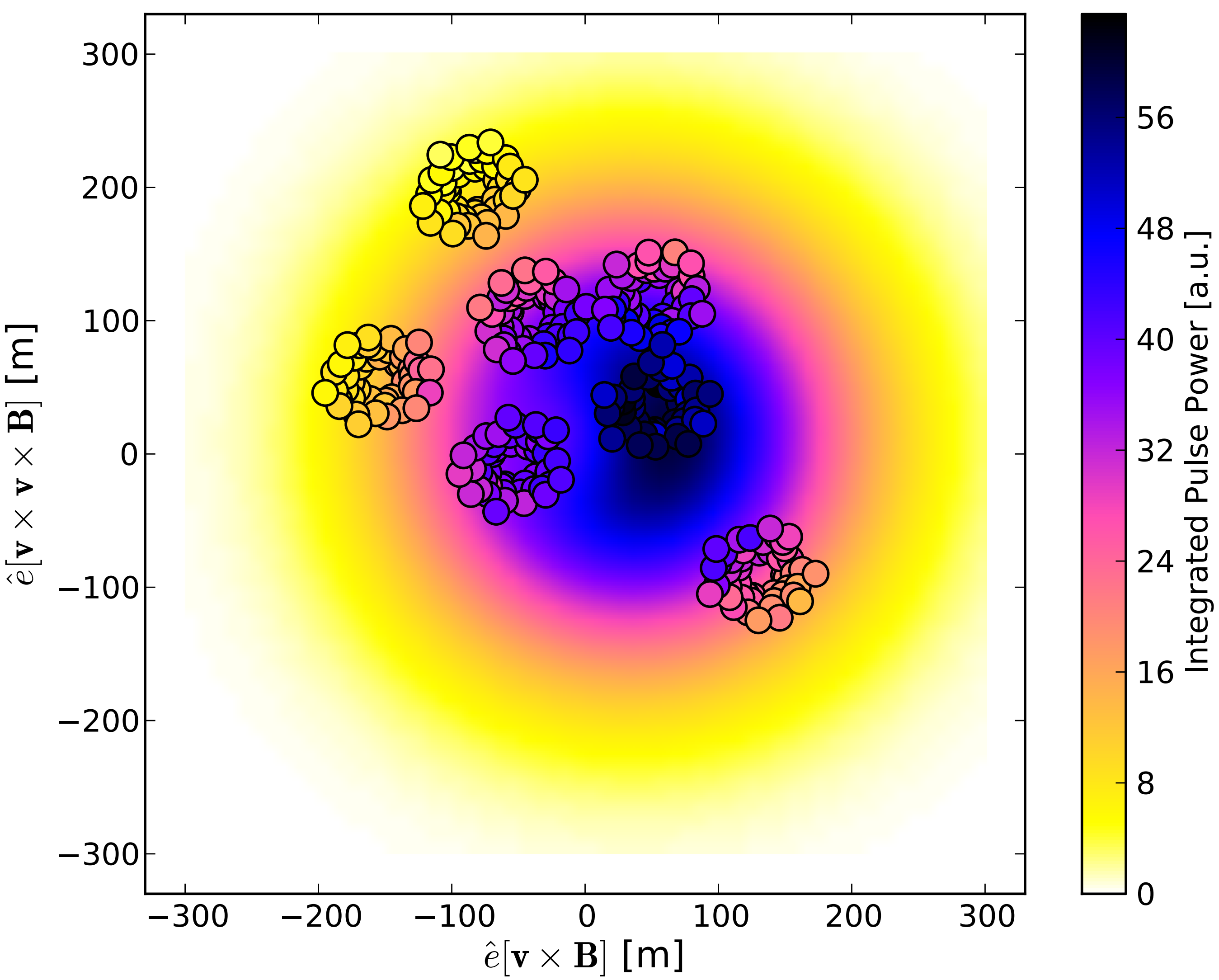
LOFAR

P. Schellart et al., JCAP 10 (2014) 014

Lateral distribution of radio signals

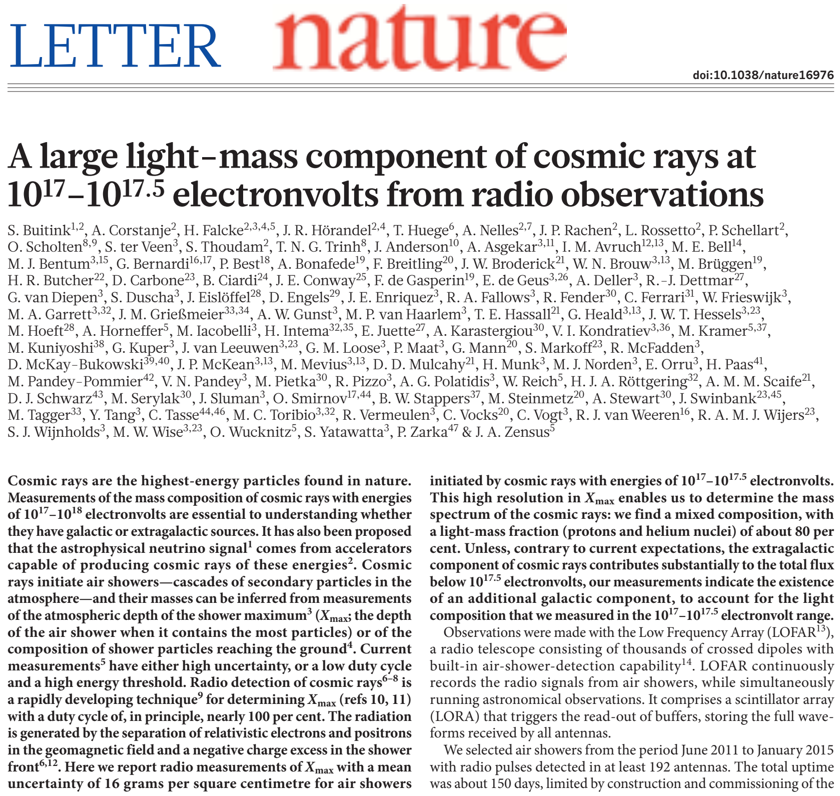
as measured by LOFAR





A. Nelles et al., Astropart. Phys. 60 (2015) 13

Depth of the shower maximum



LETTER nature
doi:10.1038/nature16976

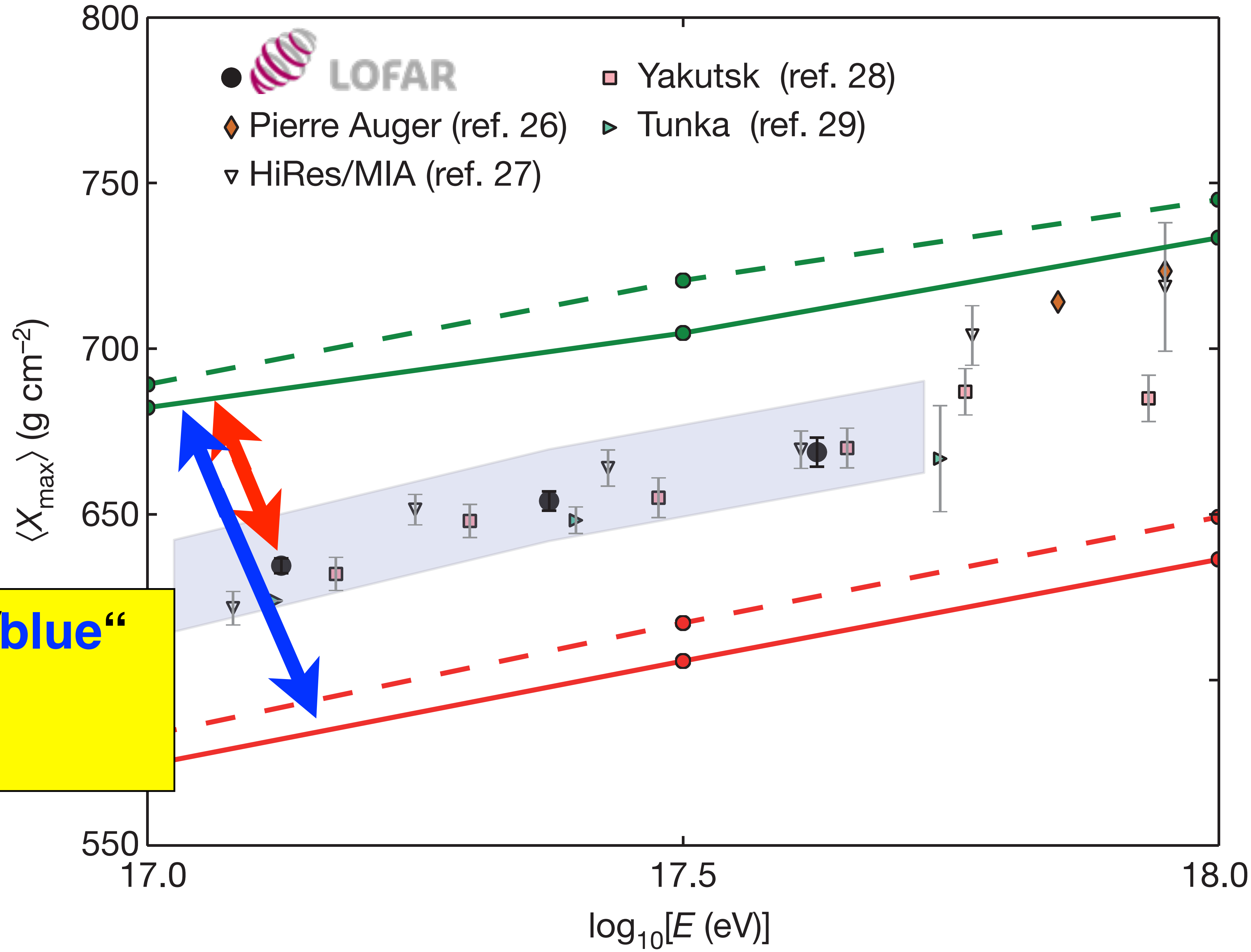
A large light-mass component of cosmic rays at 10^{17}–$10^{17.5}$ electronvolts from radio observations

S. Buitink[1,2], A. Corstanje[2], H. Falcke[2,3,4,5], J. R. Hörandel[2,4], T. Huege[6], A. Nelles[2,7], J. P. Rachen[2], L. Rossetto[2], P. Schellart[2], O. Scholten[8,9], S. ter Veen[3], S. Thoudam[2], T. N. G. Trinh[8], J. Anderson[10], A. Asgekar[3,11], I. M. Avruch[12,13], M. E. Bell[14], M. J. Bentum[3,15], G. Bernardi[16,17], P. Best[18], A. Bonafede[19], F. Breitling[20], J. W. Broderick[21], W. N. Brouw[3,13], M. Brüggen[19], H. R. Butcher[22], D. Carbone[23], B. Ciardi[24], J. E. Conway[25], F. de Gasperin[19], E. de Geus[3,26], A. Deller[3], R.-J. Dettmar[27], G. van Diepen[3], S. Duscha[3], J. Eislöffel[28], D. Engels[29], J. E. Enriquez[3], R. A. Fallows[3], R. Fender[30], C. Ferrari[31], W. Frieswijk[3], M. A. Garrett[3,32], J. M. Grießmeier[33,34], A. W. Gunst[3], M. P. van Haarlem[3], T. E. Hassall[21], G. Heald[3,13], J. W. T. Hessels[3,23], M. Hoeft[28], A. Horneffer[5], M. Iacobelli[3], H. Intema[32,35], E. Juette[27], A. Karastergiou[30], V. I. Kondratiev[3,36], M. Kramer[5,37], M. Kuniyoshi[38], G. Kuper[3], J. van Leeuwen[3,23], G. M. Loose[3], P. Maat[3], G. Mann[20], S. Markoff[23], R. McFadden[3], D. McKay-Bukowski[39,40], J. P. McKean[3,13], M. Mevius[3,13], D. D. Mulcahy[21], H. Munk[3], M. J. Norden[3], E. Orru[3], H. Paas[41], M. Pandey-Pommier[42], V. N. Pandey[3], M. Pietka[30], R. Pizzo[3], A. G. Polatidis[3], W. Reich[5], H. J. A. Röttgering[32], A. M. M. Scaife[21], D. J. Schwarz[43], M. Serylak[30], J. Sluman[3], O. Smirnov[17,44], B. W. Stappers[37], M. Steinmetz[20], A. Stewart[30], J. Swinbank[23,45], M. Tagger[33], Y. Tang[3], C. Tasse[44,46], M. C. Toribio[3,32], R. Vermeulen[3], C. Vocks[20], C. Vogt[3], R. J. van Weeren[16], R. A. M. J. Wijers[23], S. J. Wijnholds[3], M. W. Wise[3,23], O. Wucknitz[5], S. Yatawatta[3], P. Zarka[47] & J. A. Zensus[5]

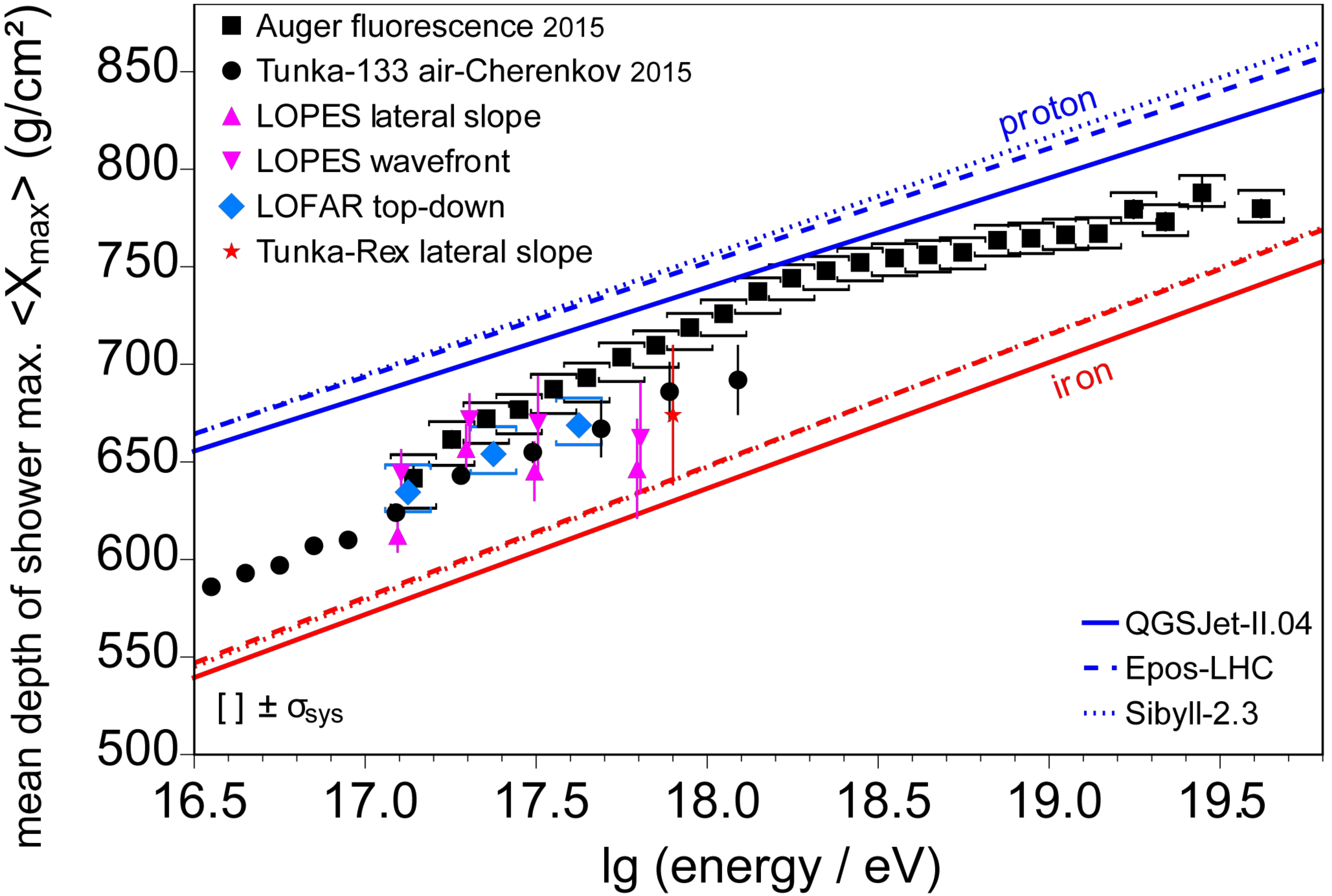
Cosmic rays are the highest-energy particles found in nature. Measurements of the mass composition of cosmic rays with energies of 10^{17}–10^{18} electronvolts are essential to understanding whether they have galactic or extragalactic sources. It has also been proposed that the astrophysical neutrino signal[1] comes from accelerators capable of producing cosmic rays of these energies[2]. Cosmic rays initiate air showers—cascades of secondary particles in the atmosphere—and their masses can be inferred from measurements of the atmospheric depth of the shower maximum[3] (X_{max}; the depth of the air shower when it contains the most particles) or of the composition of shower particles reaching the ground[4]. Current measurements[5] have either high uncertainty, or a low duty cycle and a high energy threshold. Radio detection of cosmic rays[6–8] is a rapidly developing technique[9] for determining X_{max} (refs 10, 11) with a duty cycle of, in principle, nearly 100 per cent. The radiation is generated by the separation of relativistic electrons and positrons in the geomagnetic field and a negative charge excess in the shower front[6,12]. Here we report radio measurements of X_{max} with a mean uncertainty of 16 grams per square centimetre for air showers initiated by cosmic rays with energies of 10^{17}–$10^{17.5}$ electronvolts. This high resolution in X_{max} enables us to determine the mass spectrum of the cosmic rays: we find a mixed composition, with a light-mass fraction (protons and helium nuclei) of about 80 per cent. Unless, contrary to current expectations, the extragalactic component of cosmic rays contributes substantially to the total flux below $10^{17.5}$ electronvolts, our measurements indicate the existence of an additional galactic component, to account for the light composition that we measured in the 10^{17}–$10^{17.5}$ electronvolt range.

Observations were made with the Low Frequency Array (LOFAR[13]), a radio telescope consisting of thousands of crossed dipoles with built-in air-shower-detection capability[14]. LOFAR continuously records the radio signals from air showers, while simultaneously running astronomical observations. It comprises a scintillator array (LORA) that triggers the read-out of buffers, storing the full waveforms received by all antennas.

We selected air showers from the period June 2011 to January 2015 with radio pulses detected in at least 192 antennas. The total uptime was about 150 days, limited by construction and commissioning of the



S. Buitink et al., Nature 531 (2016) 70



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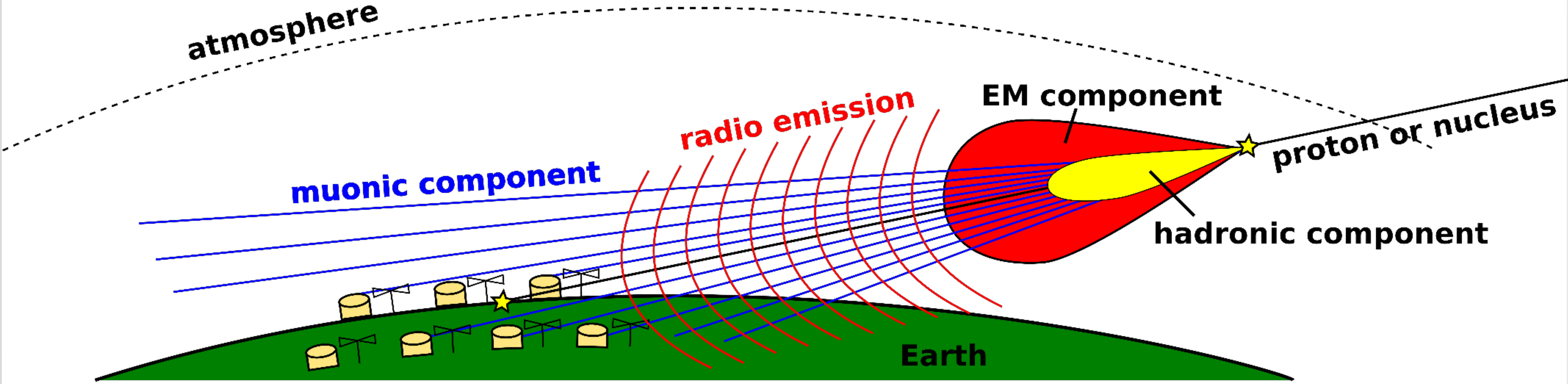
Institut für Kernphysik

Composition sensitivity for inclined showers



- Only radio emission + muons survive for inclined showers
  - Complementary information on shower → primary particle type

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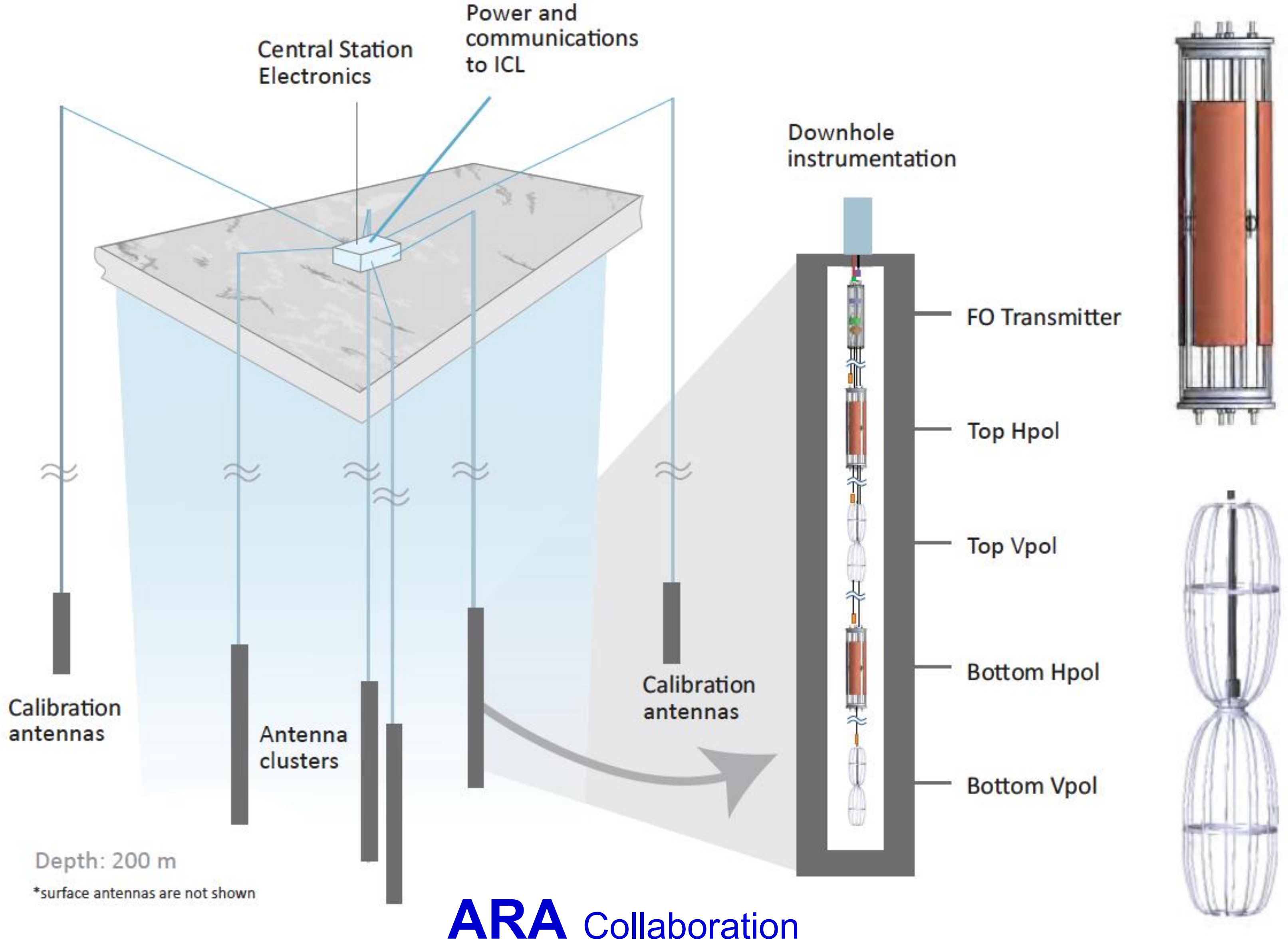
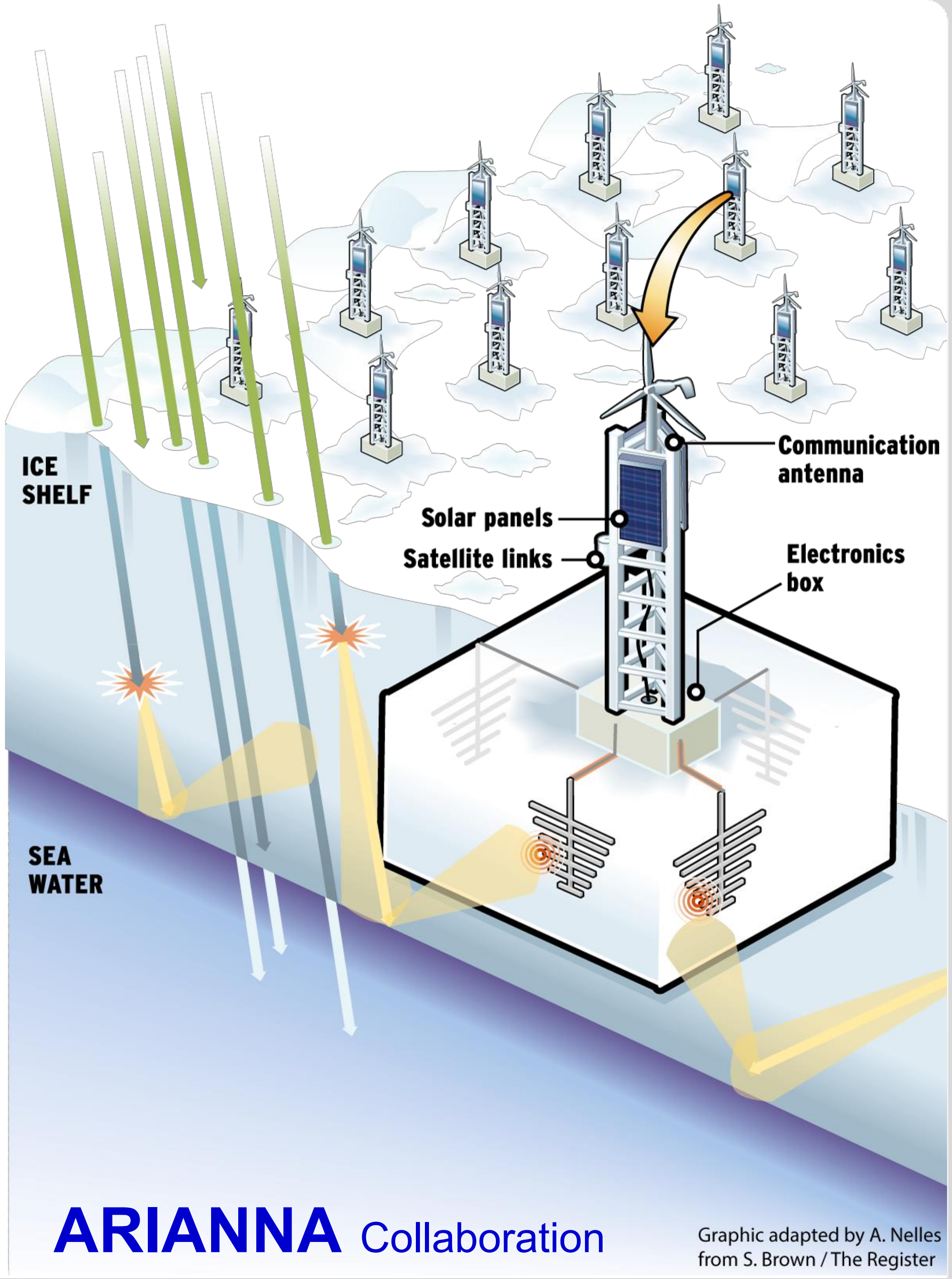
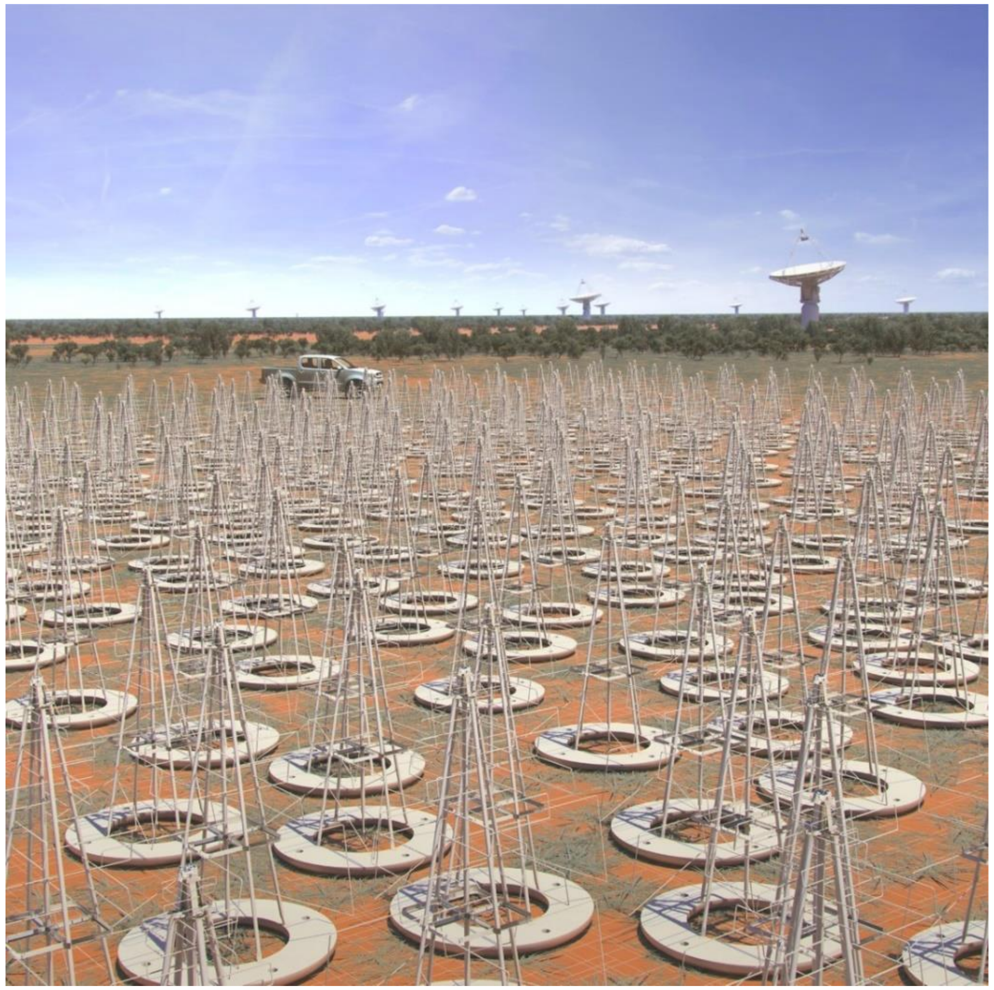
Neutrino-induced showers in ice

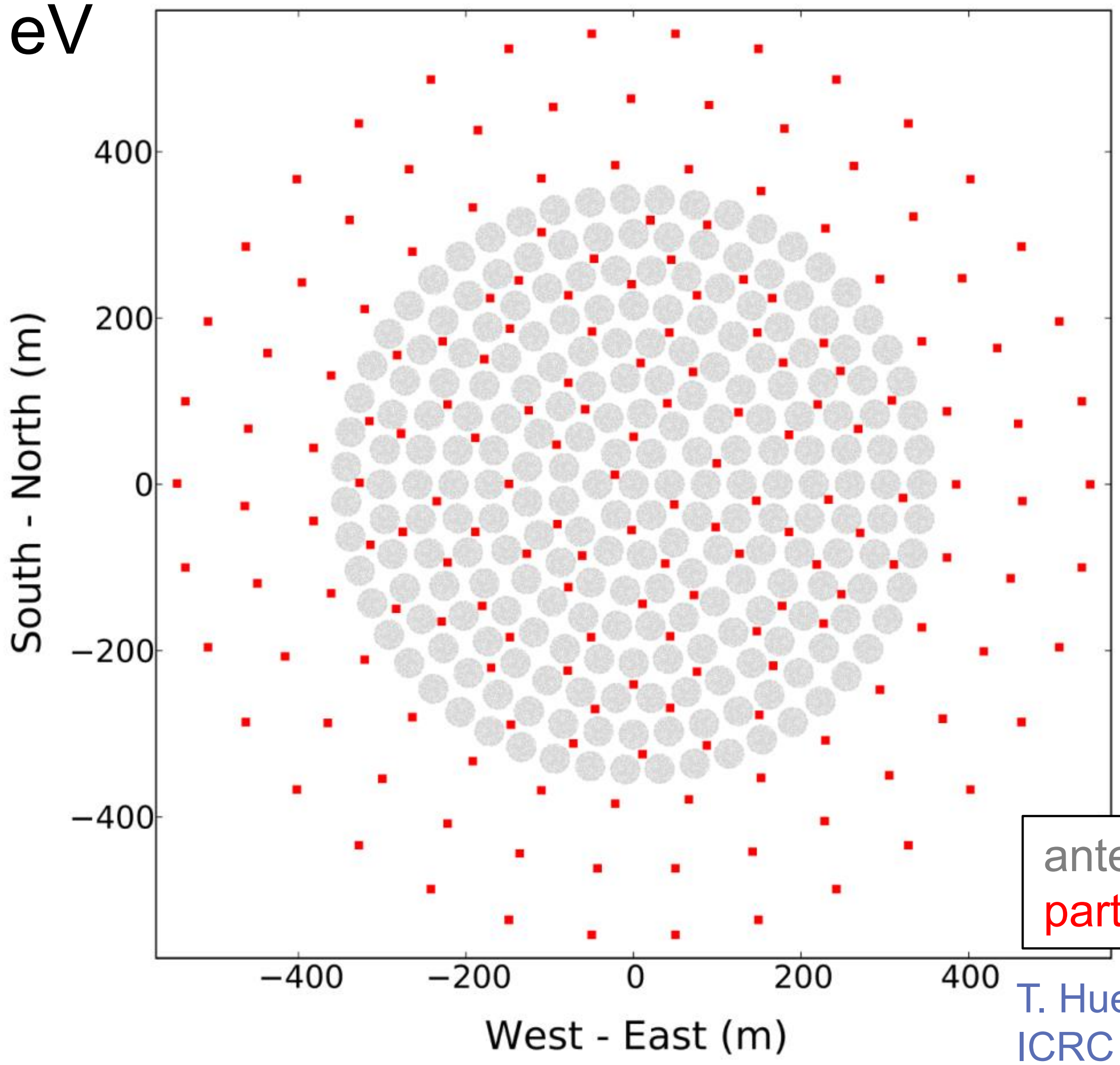




The Square Kilometer Array: ultra high precision

- Phase 1: ~ 60,000 antennas on ½ km²
- Scintillator array planned for E > 10^{16} eV





T. Huege et al.,
ICRC 2015, Den Haag

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Not sure yet whether Radio Emission can make a transformational difference for CR experiments.

Galactic CRs
Spectra & Composition

Knee - 10^{18} eV

Kascade
Kascade Grande
Tunka
IceTop
Auger HEAT
TALE

Energy: Knee - 10^{18} eV
Composition: light - heavy

Difficult to see a coherent picture.
Experiments with very different systematics ?

Modelling

Cosmic-Ray Acceleration (and Propagation)

D Caprioli

SNR paradigm:

- SNRs have the right energetics
- Diffusive Shock Acceleration produces power-laws
- B amplification enhances particle diffusion

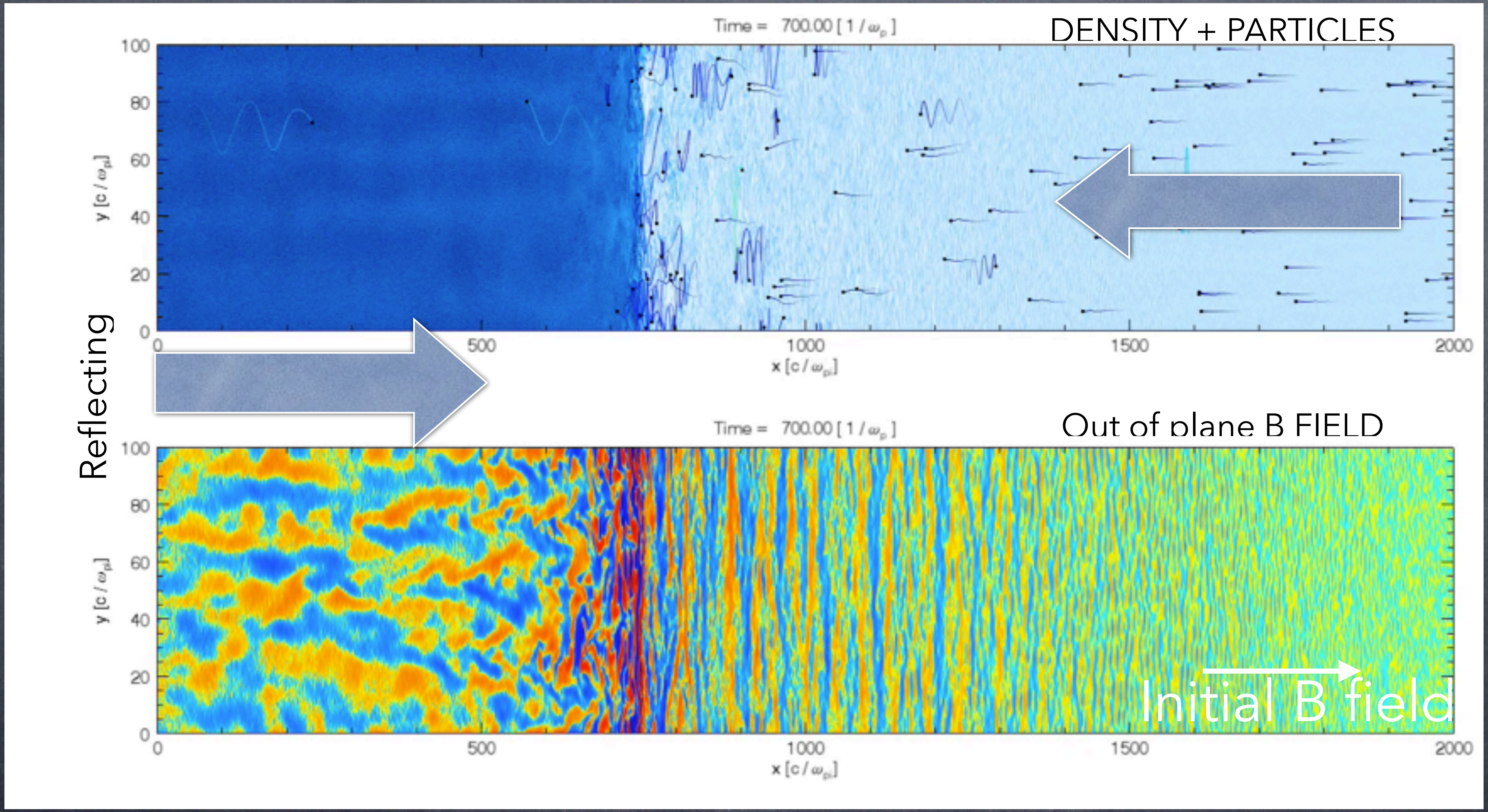
BUT

- Is acceleration at shocks efficient? When?
- How do CRs amplify the magnetic field?
- How are particles injected in DSA?

Collisionless shocks

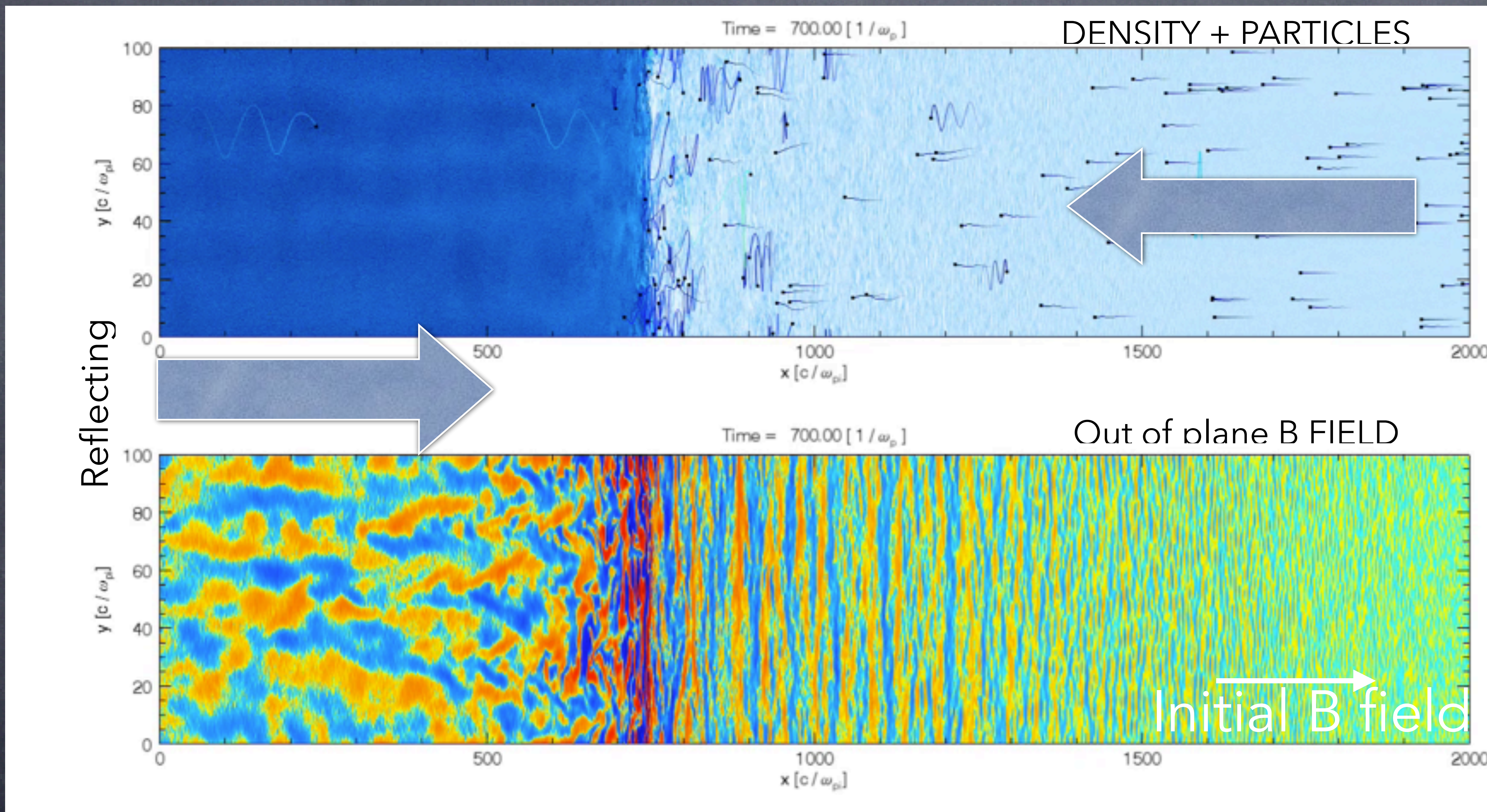
- Mediated by collective electromagnetic interactions
- Show prominent non-thermal activity

Hybrid simulations of collisionless



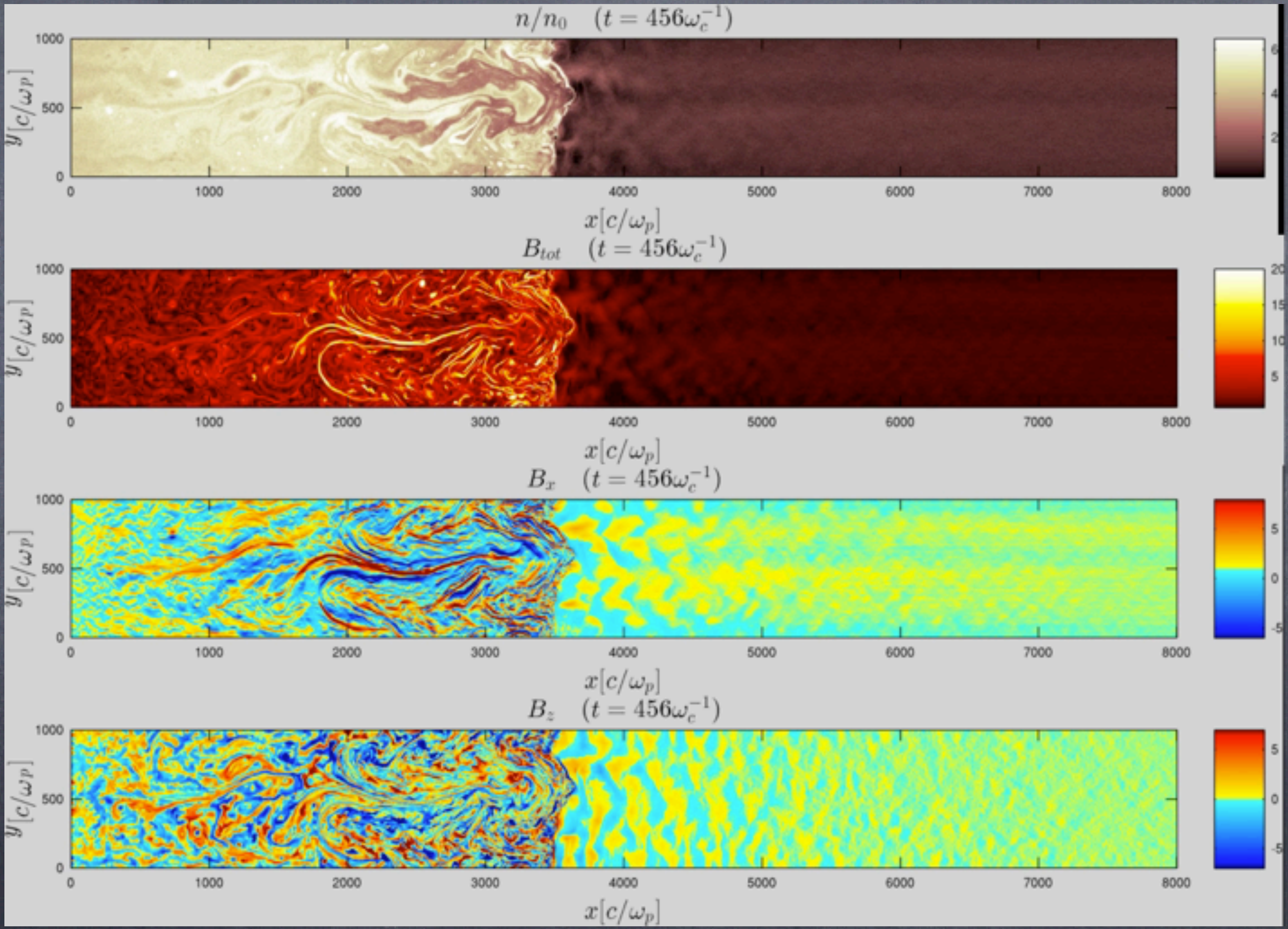
- **dHybrid** code (Gargaté et al, 2007; DC & Spitkovsky 2014)

Hybrid simulations of collisionless



- **dHybrid** code (Gargaté et al, 2007; DC & Spitkovsky 2014)

CR-driven instability

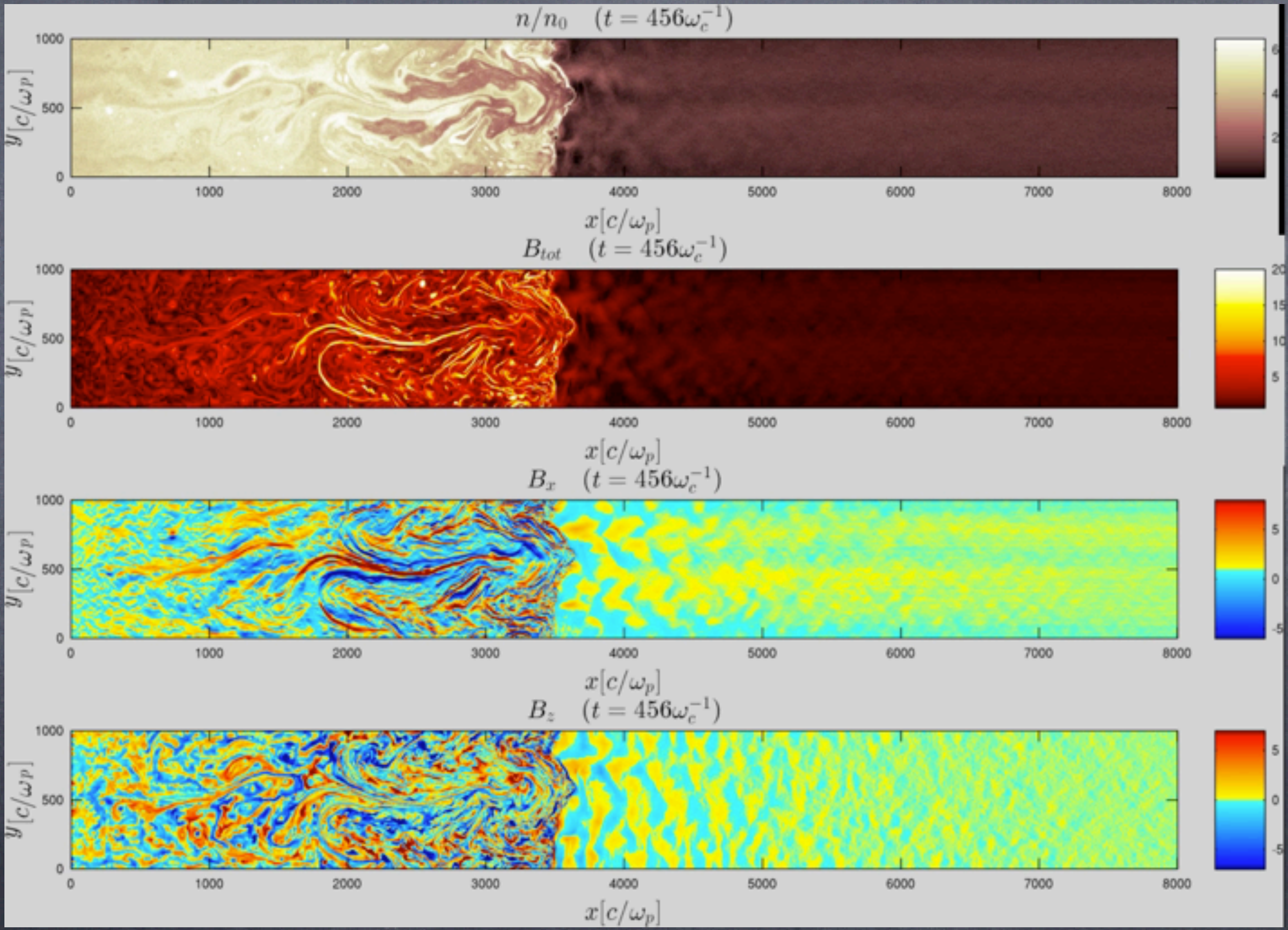


Initial B field

$M_s = M_A = 30$

DC & Spitkovsky, 2013

CR-driven instability



Initial B field

$M_s = M_A = 30$

DC & Spitkovsky, 2013

What do we need to do better

What you can do for CRs

- Kinetic simulations
  - Electron physics, heavy nuclei, plasma instabilities
- Multi-scale approach
  - From microphysical to phenomenological scales
- Gamma-ray/neutrino observatories
  - More spatially-resolved sources

What can CRs do for you?

- Active role of CRs in galactic dynamics
  - Generation of B fields, ionization, CR-driven winds

CR Propagation: GALPROP

THE GALPROP TEAM:
I. Moskalenko and A. Strong (original developers),
S. Digel, G. Johannesson, E. Orlando, T. Porter, A. Vladimirov

http://*galprop.stanford.edu*

It solves the transport equation (energy losses, diffusion, acceleration, convection, fragmentation, radioactive decay) for all CR species

The GALPROP code for cosmic-ray transport and diffuse emission production

GALPROP is a numerical code for calculating the propagation of relativistic charged particles and the diffuse emissions produced during their propagation. The GALPROP code incorporates as much realistic astrophysical input as possible together with latest theoretical developments. The code calculates the propagation of cosmic-ray nuclei, antiprotons, electrons and positrons, and computes diffuse γ-rays and synchrotron emission in the same framework. Each run of the code is governed by a configuration file allowing the user to specify and control many details of the calculation. Thus, each run of the code corresponds to a potentially different ``model''. The code itself continues to be developed and is available to the scientific community via this website.

What's cooking?

Dxx ≠ DZZ

3D ISRF

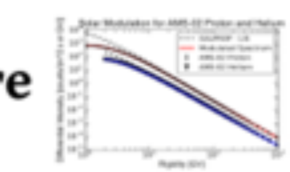
Updated 3D B-field

3D CR sources

Anisotropic IC

"non-standard" propagation models

HelMod:
The Modulation Model for Heliosphere
Online Calculator
(version 3.0.0)



Stay tuned !

Hadronic Interaction Models for Air shower simulations
(QGSJET-II-04)

Sergey Ostapchenko

Valuable new data from LHC

Improved understanding of model subtleties.

Tensions with Auger experimental findings persist for now.

1. LHC studies of pp collisions constrained interaction models
   - most important for CR physics: $\sigma_{pp}^{\mathrm{tot/el}}$ by TOTEM & ATLAS
   - of importance: to resolve the diffraction issue
2. Differences for predicted $K_{p-\mathrm{air}}^{\mathrm{inel}}$ ($\Rightarrow X_{\mathrm{max}}$):
   model assumptions for constituent parton Fock states
   - can be discriminated by combined measurements with forward & central detectors
   - e.g. studies of CMS-TOTEM correlation may refute SIBYLL
3. Present uncertainties for EAS predictions:
   largely due to the treatment of pion-air interactions
   - can be constrained by X_{max}^{μ} measurements in CR experiments
4. Present PAO data on X_{max}^{μ}: push towards a light composition
   - but: conflict with PAO results on RMS(X_{max})

Main Themes of the Current Discussions

The three “S” of Cosmic Ray Research:

The three "S" of Cosmic Ray Research:

Systematics

The three “S” of Cosmic Ray Research:

Systematics

Systematics

The three "S" of Cosmic Ray Research:

Systematics

Systematics

Systematics

Most results in CR physics are plagued by systematics
on various levels.

difficult questions tackled with too simple experiments

differences between similar experiments.
differences between data and sims.
differences between model variants.

Need to investigate / discuss the systematics
in great detail, and lay it open to scrutiny
by the wider community

An experimental result without extensive discussion of the systematics is not credible.

good examples for detailed systematic studies:

e.g. AMS, Pamela, Auger,
(a lot of work …)

Experimental results should ideally get
an independent confirmation.

Competition is healthy and improves greatly
the quality of results and the overall understanding.

(e.g. AGASA - Fly's Eye, Auger - TA, KASCADE - IceTop,
Pamela - AMS, Galprop - CRpropa, QGSjet - EPOS, …)

Many CR experiments start out with
an experimental setup that turns out not to be
good enough to answer credibly the science question
originally aimed at.

Leads to: add-ons, extensions, upgrades
in the hope to achieve (more) conclusive results.

Define clearly / quantify the scientific objective
of your planned experiment.
Check first that the experiment can actually deliver
what it is supposed to do.

CR physics is difficult / complicated
and scientists tend to be too optimistic.

But better planning is now possible:

simulation tools can tell what performance can be reached, before building / extending an experiment.

Don’t take a “suck and see” approach.

“Extraordinary claims require
extraordinary evidence”

and also:

extraordinary control of the experiment
openness on calibration & analysis
detail in documentation

efforts to convince the community

If you cannot convince the community, it’s not good enough.

Is your result well acknowledged & cited?
Does it make it into text books ?
the PDG reviews?

Keep the **measurements** and
the **interpretation of results** well separated.

The former should remain unchanged with time,
The latter should be revised, as more knowledge accumulates.

Make data and analysis publicly available
(data preservation) so that others can redo the analysis later.

Summary I

good incremental progress has been achieved recently on many fronts.

We saw vibrant reports on a broad cross-section of exciting scientific questions.

Progress is limited more by systematics than by statistics.

A large range of new experiments are planned which undoubtedly extend our knowledge on Cosmic Rays.

Frustrated about the slow progress in Cosmic Ray research?

Frustrated about the slow progress in Cosmic Ray research?

26 years ago

Rapporteurs talks of
ICRC 1990 Adelaide

COSMIC RAY SOURCES AND ACCELERATION

Donald C. Ellison

Department of Physics, North Carolina State University
Raleigh, NC 27695-8202 USA

ABSTRACT

This paper is based on a rapporteur talk for session OG 9 given at the 21st International Cosmic Ray Conference in January 1990 at Adelaide, Australia. The session contained 38 papers.

I. INTRODUCTION

My understanding of the origin of cosmic rays after the 21st ICRC can be summarized as follows: The most likely accelerator of the bulk of cosmic rays below $\sim 10^{14-15}$ eV remains supernova remnants (SNRs). Above $\sim 10^{16}$ eV many theoretical problems remain, and I see is no fully satisfactory scenario yet for the origin of these high energy cosmic rays. The origin of the highest energy cosmic rays, those above 10^{19-20} eV, remains one of the great unsolved mysteries in astrophysics. While the case for a SNR source for the bulk of the cosmic rays has been strengthened by the work presented at this session, little was said concerning the acceleration of higher energy cosmic rays.

SNR, Fermi acceleration at strong shocks,
Radio (synchrotron), X-rays to study acceleration in SNRs
UHECR ???

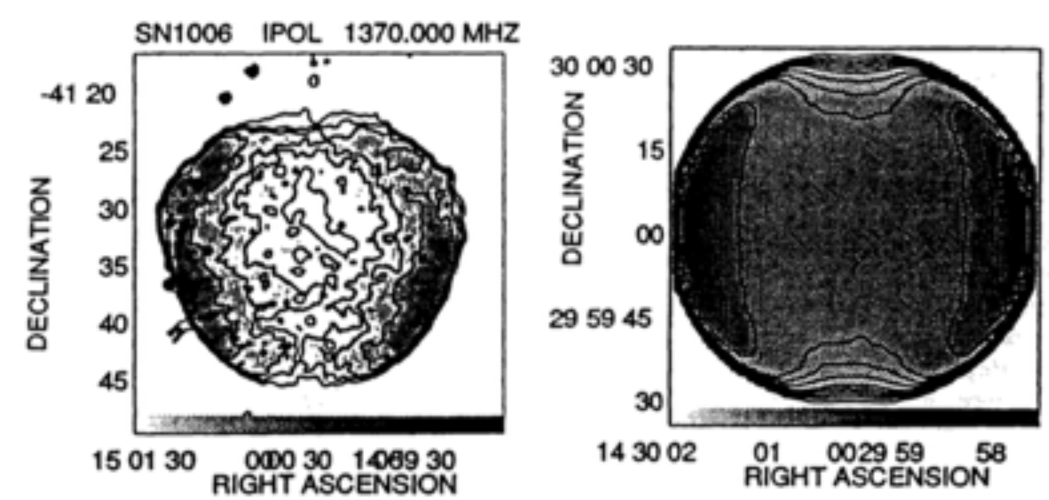


Fig. 7. (Left) VLA radio image of SN 1006 AD at 1370 MHz (Reynolds and Gilmore 1986). (Right) Synthetic image with an aspect angle of 90° and 'quasi-perpendicular' acceleration. Note the strongly bipolar and symmetric structure in both cases. Figure

GAMMA RAY ASTRONOMY AT ENERGIES ABOVE 0.3 TeV

DAVID J. FEGAN

Physics Department, University College Dublin, Ireland.

INTRODUCTION.

This paper is a somewhat expanded version of the rapporteur talk delivered during the 21st International Cosmic Ray Conference which was held in Adelaide during January 1990. The subject matter is concerned with those papers contributed in sessions OG 4.1,4.2, 4.3, 4.5 and 4.6. A total of 87 papers were delivered covering all aspects of γ-ray astronomy at energies >0.3 TeV, with the exceptions of SN1987A, diffuse emission and most source models. This extensive number of papers reflects the tremendous upsurge of interest in ground-based γ-ray astronomy, driven to a large degree by the emergence of newer, more dedicated instruments and installations which in many instances, have been specifically designed and optimised to find point sources. No less important is the arrival in the field of individuals who bring with them innovation and expertise from other disciplines. The prime motivation of ground based γ-ray astronomy is the discovery and identification of sources - a process which ultimately will answer the age-oldquestion as to the origin of cosmic radiation. Ground based γ-ray astronomy is also of relevance to satellite γ-ray programs of the 1990's such as GRO, which is expected to detect between 10 and 100 new objects which might themselves represent primary targets for ground based observations. The field of TeV and PeV γ-ray astronomy must also hold some fascination for high energy particle physicists interested in understanding the nature of electromagnetic and hadronic interactions in an energy domain not currently accessible to accelerators.

1989: Crab nebula in TeV gamma rays

Hype in gamma detection:
many sources, claimed at
TeV … PeV …EeV

Her X1, Cyg X3, Cen-A, Sco-X1,
3C273, 3C279, M87, …
not confirmed as claimed.

TABLE 8

Source	TeV	PeV	EeV	Comment
Crab Nebula	√	√	-	TeV steady, PeV impulsive
Cygnus X-3	√	√	√	Declining at TeV/PeV
Hercules X-1	√	√	-	Episodic, with blue shifting
Vela X-1	√	√ ?	-	
Cen X-3	√	?	-	

NEUTRINOS

G.J. Thornton
Dept of Physics and Mathematical Physics,
University of Adelaide, Adelaide, SA, Australia

INTRODUCTION

HE5 dealt mainly with neutrinos of atmospheric or astrophysical origin. Solar neutrinos and neutrinos associated with dark matter are dealt with elsewhere. Within the proceedings there are two major subdivisions: HE5.1, low energy and oscillations, and HE5.2, high energy and neutrino astronomy. The division is not clear cut or exclusive, but the main emphasis of most of the papers falls comfortably into one of the two sections. In general I will follow the same scheme.

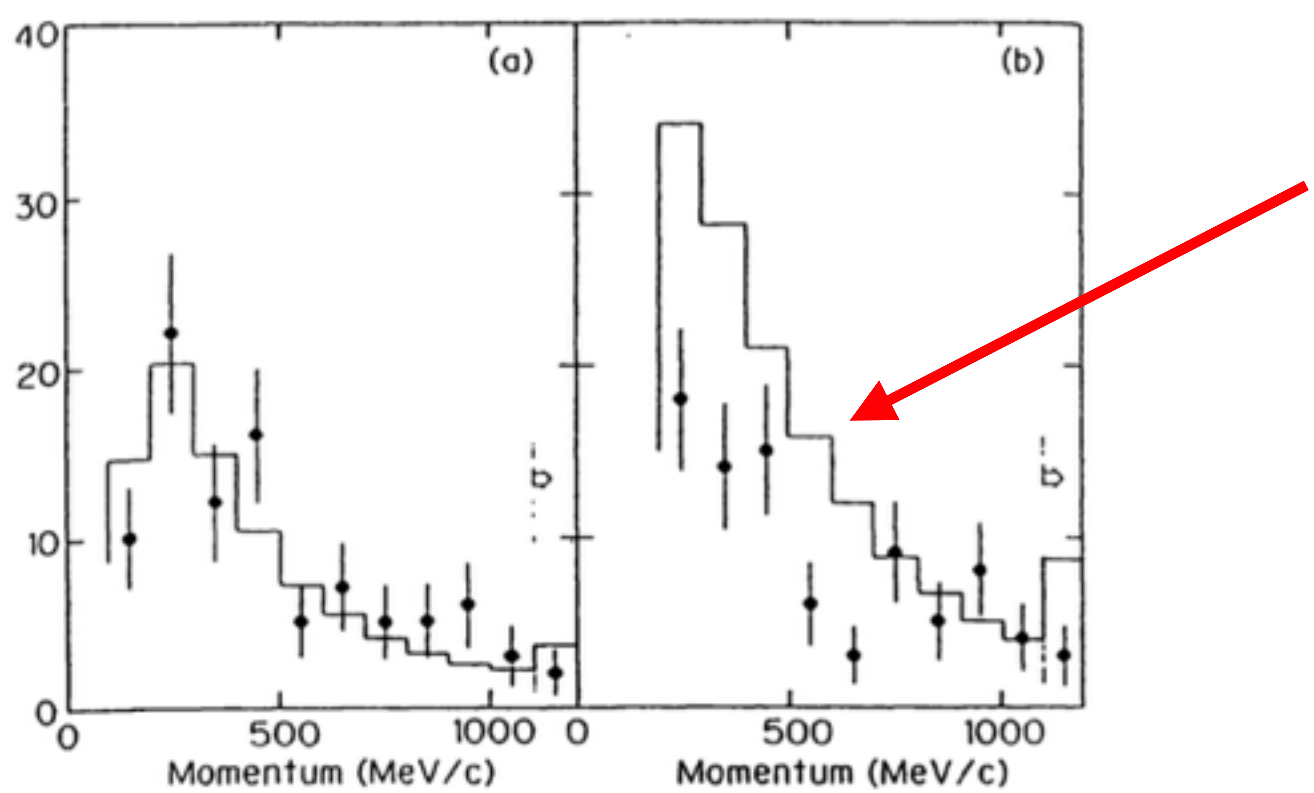


FIGURE 1: The Kamiokande neutrino problem. Points are the data, histograms Monte Carlo distributions, for (a) electron- and (b) muon-like events.

SN 1987a: neutrinos seen !!

indications of deficit in muon neutrinos:
oscillations

TeV neutrinos expected from putative gamma sources. IMB, KGF, Kamiokande, …
atmospheric neutrino background discussed

DUMAND planned (cancelled 1995)
Baikal: first strings deployed.

Supernova 1987A and Cosmic Rays with E > 1 TeV/amu (Composition, Spectrum and Anisotropy)*

T. Kifune

Institute for Cosmic Ray Research
University of Tokyo, Tokyo 188, Japan

Abstract

The high-energy particle production by SN1987A is one of the most important subjects of recent high energy γ-ray astronomy. A number of papers in the session OG 4.4 of the conference are aimed at determining an estimate of cosmic ray luminosity of this object, presumably having a newborn pulsar. Studies of cosmic ray protons and nuclei above 1 TeV are also described (sessions OG 6.1, 6.2, 6.3 and 6.4) and evaluated to infer the origin of cosmic rays in this high energy region. The cosmic ray spectrum, composition and anisotropy are discussed, and effects due to cosmic ray point sources are mentioned.

SN 1987a: high expectations
TeV… PeV gamma ray claimed, not confirmed

composition below the knee:
CRN, Sokol, Jacee

above: Fly's Eye, Yakutsk
protons, but shifted X_max

at UHE: no ankle no GZK cut-off.

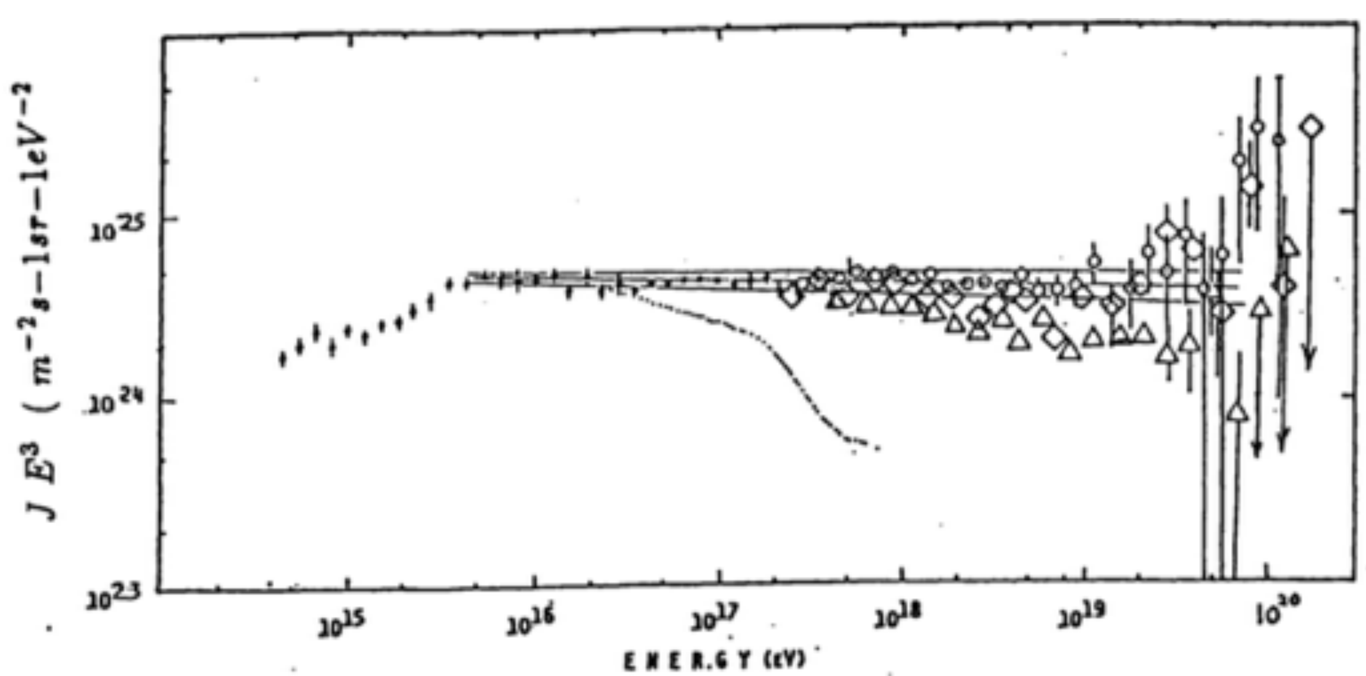


Fig. 19. Spectrum of cosmic ray. The symbols, • and ○ are for 1 km² and 20 km² array of Akeno, and △ and ◇ are Fly's Eye and Haverah Park data, respectively. The dotted curve indicates Moscow State University data.

22th ICRC, Adelaide, Jan 1990

HE 7.3–3

AIR SHOWER SIMULATIONS FOR KASCADE

J.N.Capdevielle[1], P.Gabriel, H.J.Gils, P.K.F.Grieder[2], D.Heck, N.Heide, J.Knapp, H.J.Mayer, J.Oehlschläger, H.Rebel, G.Schatz, and T.Thouw

Kernforschungszentrum und Universität Karlsruhe,
D-7500 Karlsruhe, Federal Republic of Germany
[1]Laboratoire de Physique Théorique, Université de Bordeaux,
F-33170 Gradignan, France
[2]Physikalisches Institut der Universität Bern,
CH-3012 Bern, Switzerland

Abstract

A detailed simulation program for extensive air showers and first results are presented. The mass composition of cosmic rays with $E_0 \geqq 10^{15}$eV can be determined by measuring electrons, muons and hadrons simultaneously with the KASCADE detector.

Since then: lots of new experiments / activities / techniques / tools:

AGASA, Hires, Auger, TA, …
Kascade, Kascade Grande, IceTop, …
balloon expts: HEAT, Cresst, Tracer, Cream, …   LD balloonflights
Space expts. … CGRO, Fermi, Pamela, AMS …

Cherenkov telescopes,
Neutrino telescopes (DUMAND planning, Baikal first strings deployed)
Hybrid expts. (array + fluorescence)
Radio detection of air showers
FD from space

CORSIKA, QGSjet, EPOS, GEANT
Galprop, CRPropa,
mag. field amplification,
numerical simulations of acceleration processes,

multivariate analyses, neural nets, …
massive computing power,

multi wavelength, multi messenger approach

Summary II

HUGE progress has been achieved in the last 26 years, much of it in small, incremental steps.

There is no reason why this should slow down in the next decades.

Key to success:

Imagination & Motivation of Scientists,

Good reliable results to keep community and funding agencies supportive for new experiments

A warm **“Thank You”**

to the organisers of this meeting and
to all participants for presentations, posters
and fruitful discussions.