Summary of Cosmic Rays
News & Progress

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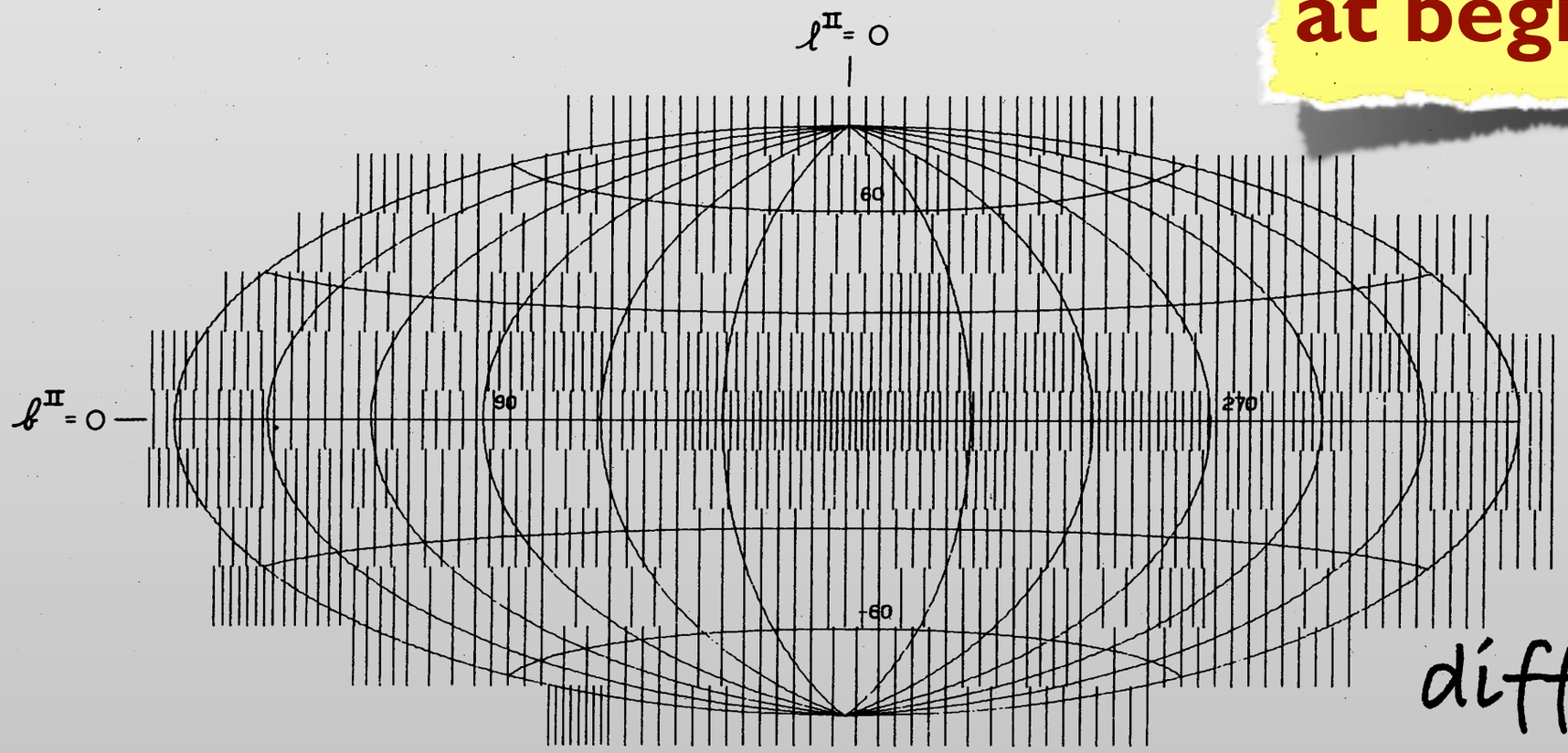
BERGISCHE
UNIVERSITÄT
WUPPERTAL

Slides stolen from welcome address by Werner Hofmann

Steinke apparatus at Hafelekar station to measure CR flux

Instruments and γ-sky at beginning of 1970s

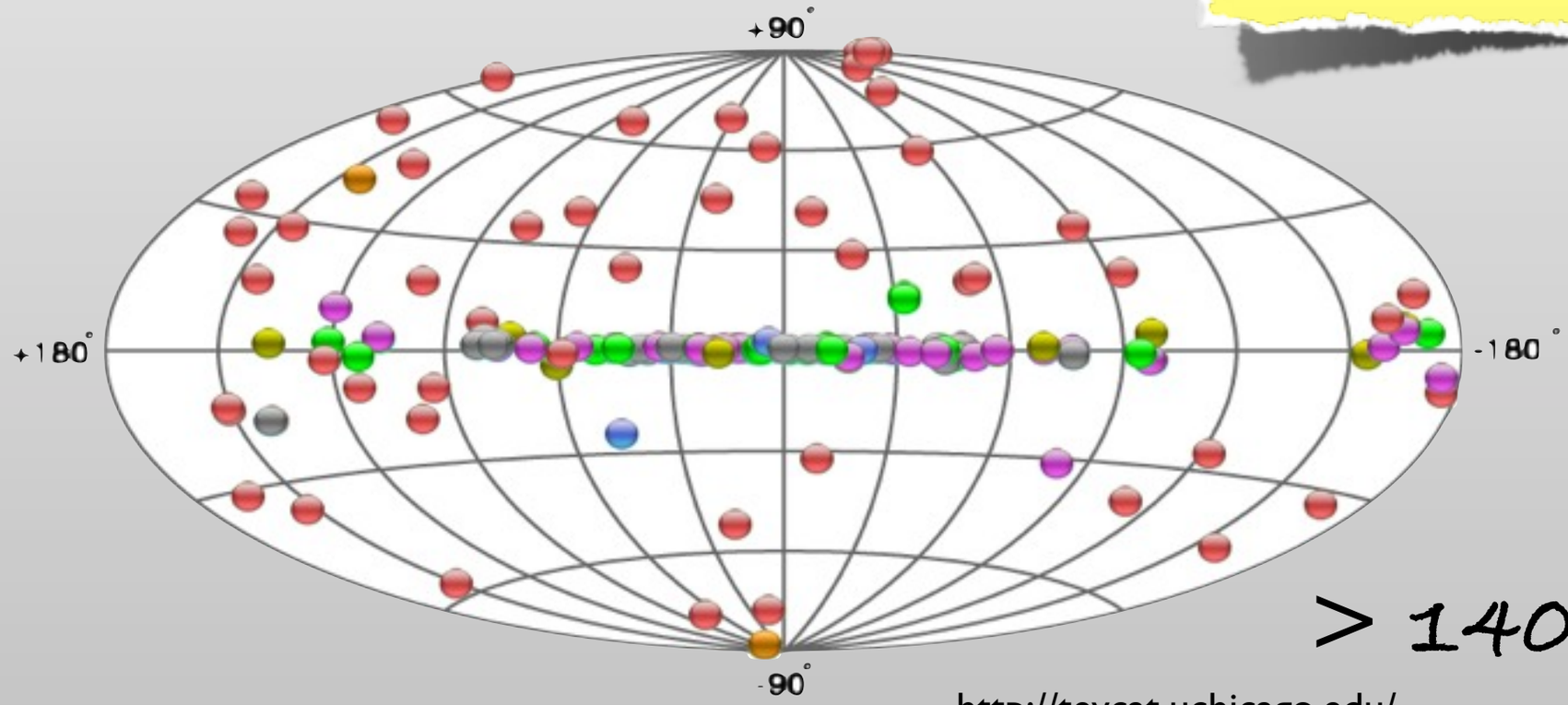


diffuse γ sky 1972

FIG. 8.—Sky map of the γ-ray intensity in galactic coordinates. The element of area on the map to which the formula given in the text applies is approximately 245 square degrees.

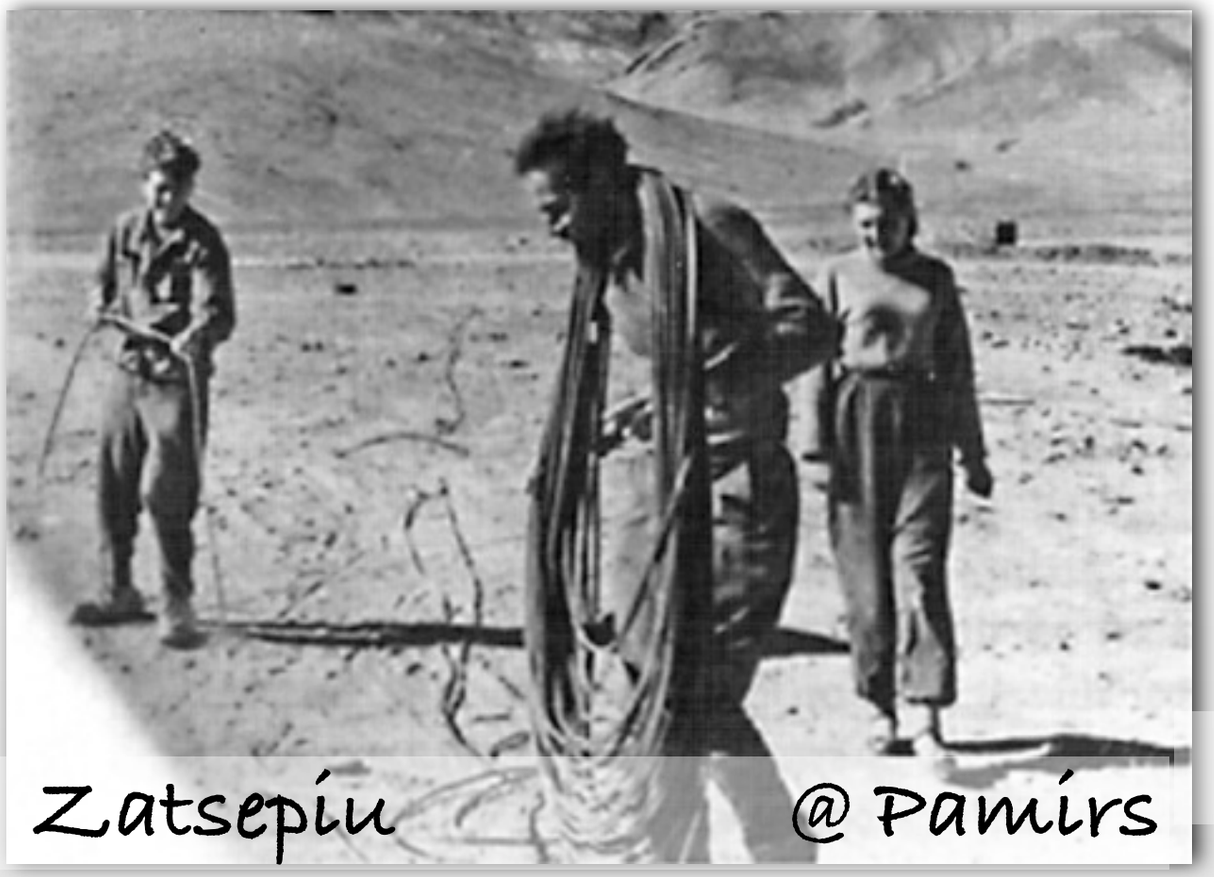
Slides stolen from welcome address by Werner Hofmann

Instruments and γ-sky
... as of today



> 140 sources (2012)

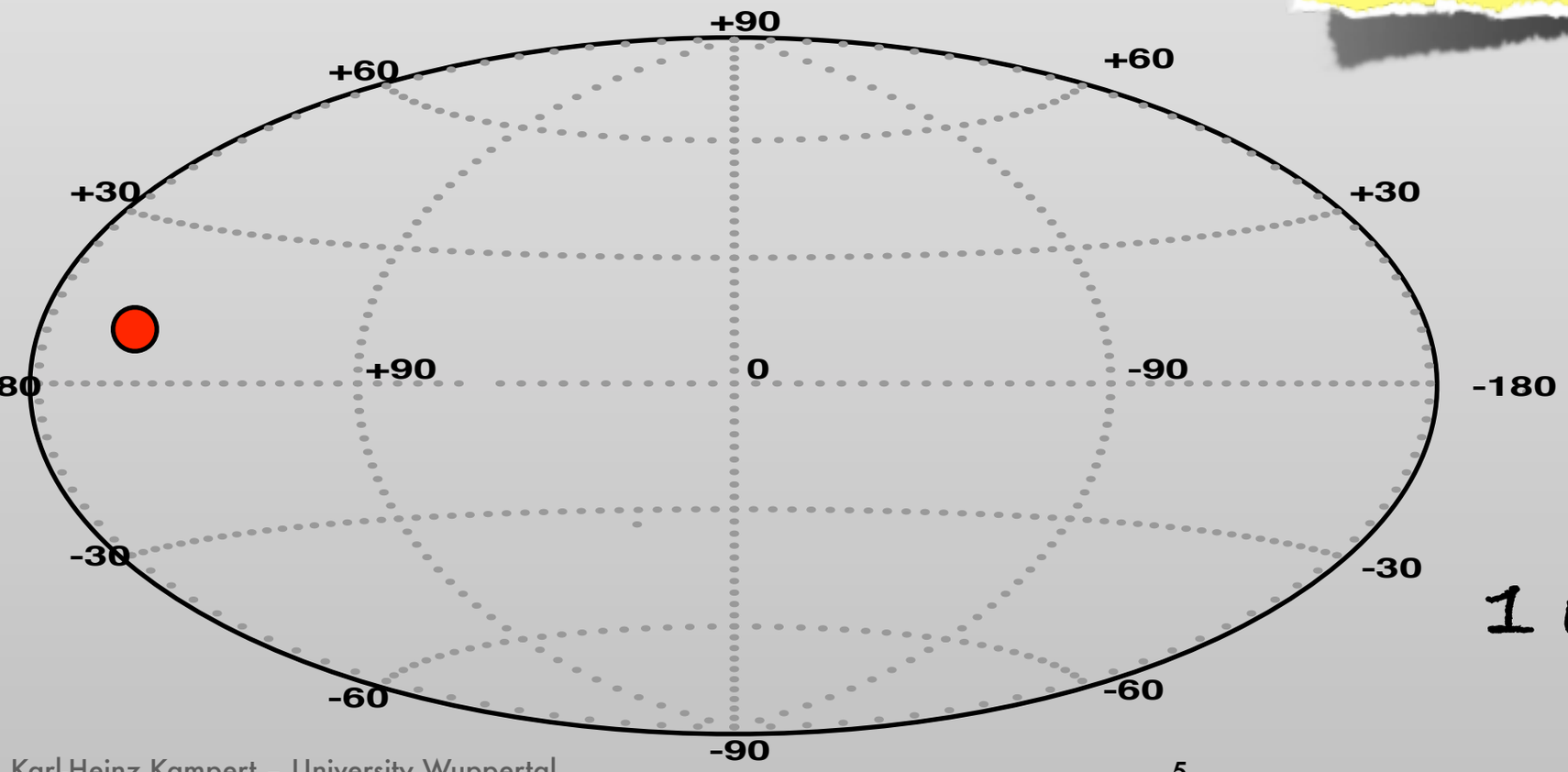
http://tevcat.uchicago.edu/



Zatsepin @ Pamirs

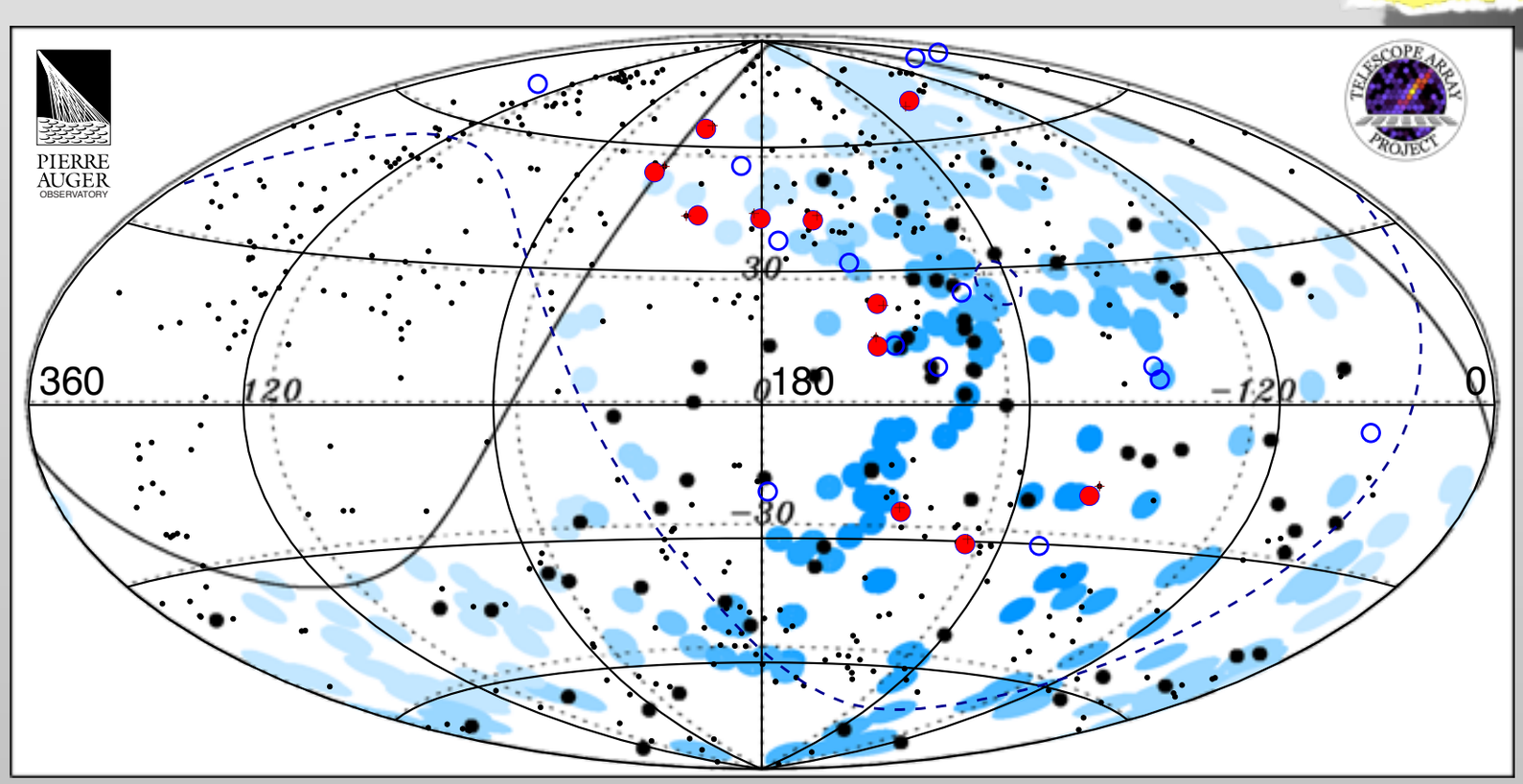
Linsley @ Volcano Ranch

Instruments and CR-sky at beginning of 1960s



1 event at 10^{20} eV...

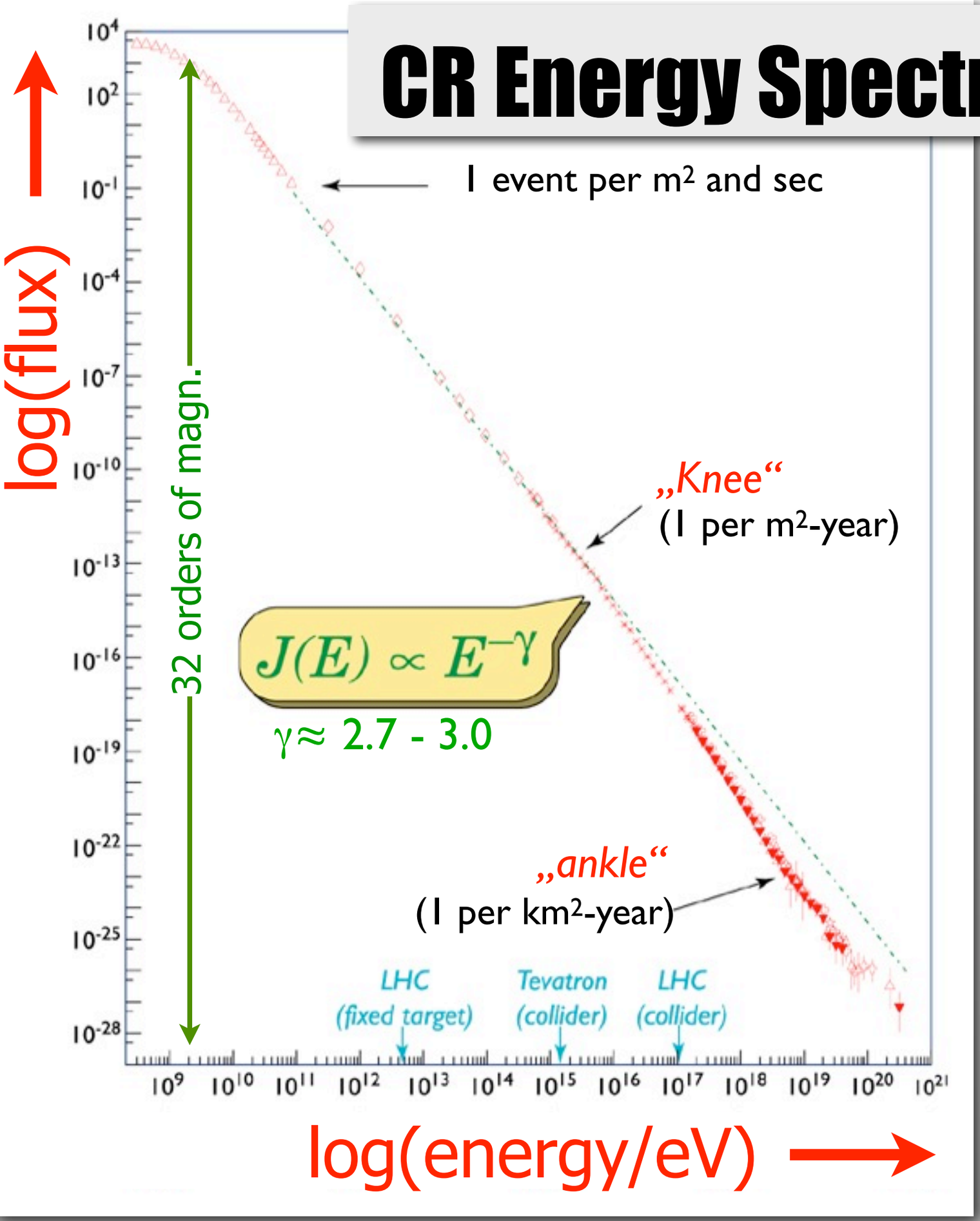
Instruments and CR-sky
... as of today



>140 events (>55 EeV),

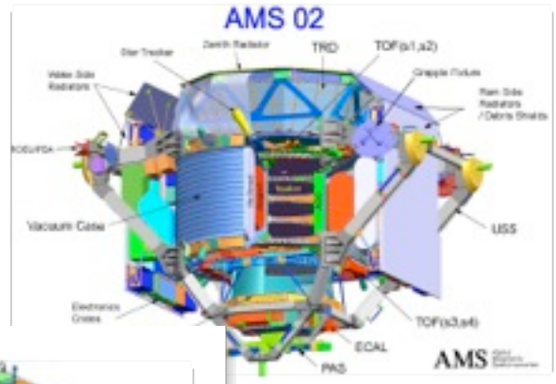
no CR source...

CR Energy Spectrum



Main Players

AMS



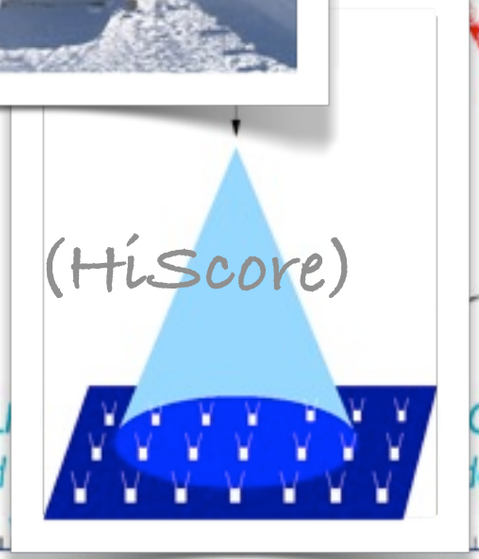
(CALET)

KASACDE-Grande

Tunka

IceTop

(HiScore)



Telescope Array

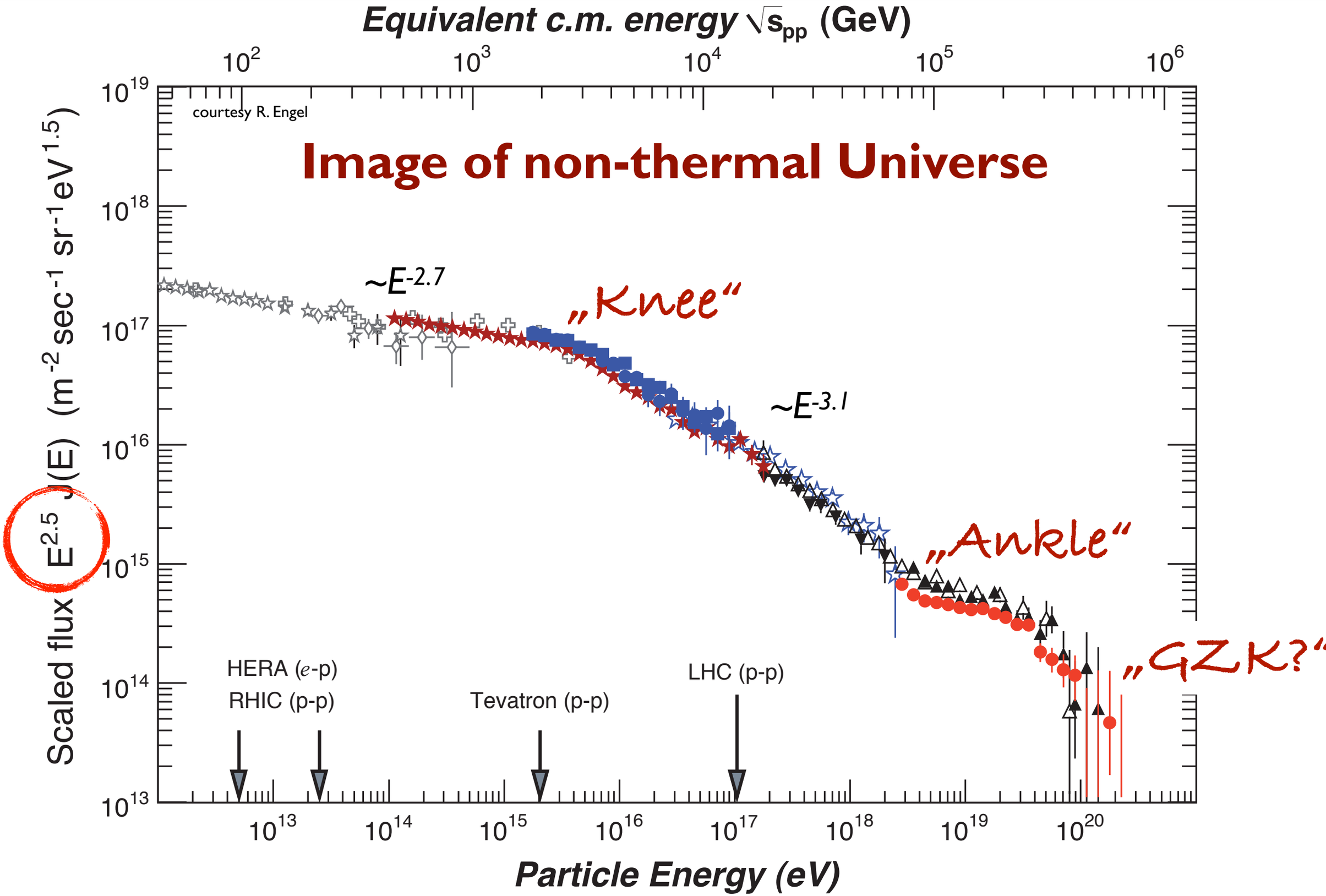
Auger

log(flux)

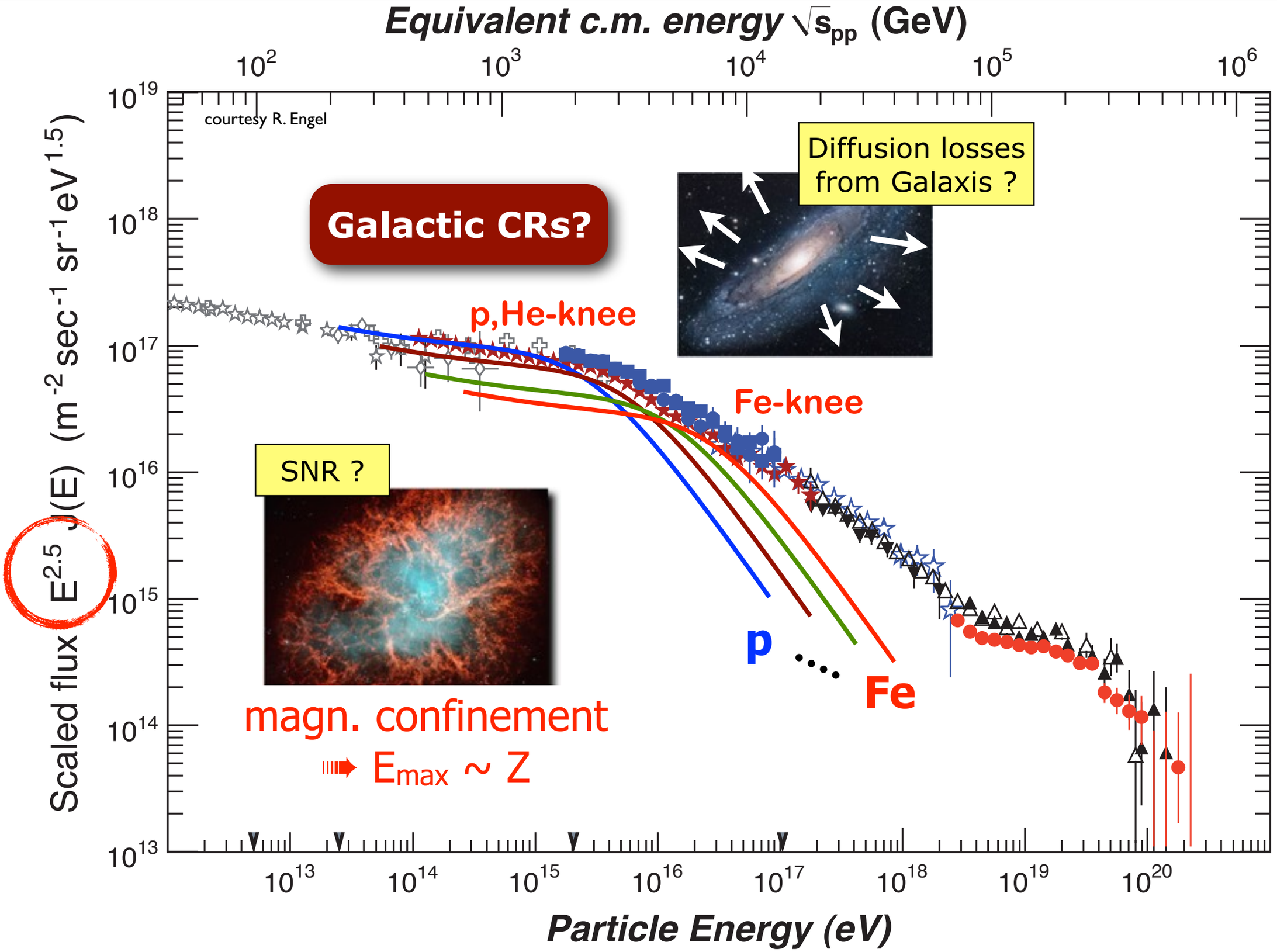
32 orders of m

log(energy/eV)

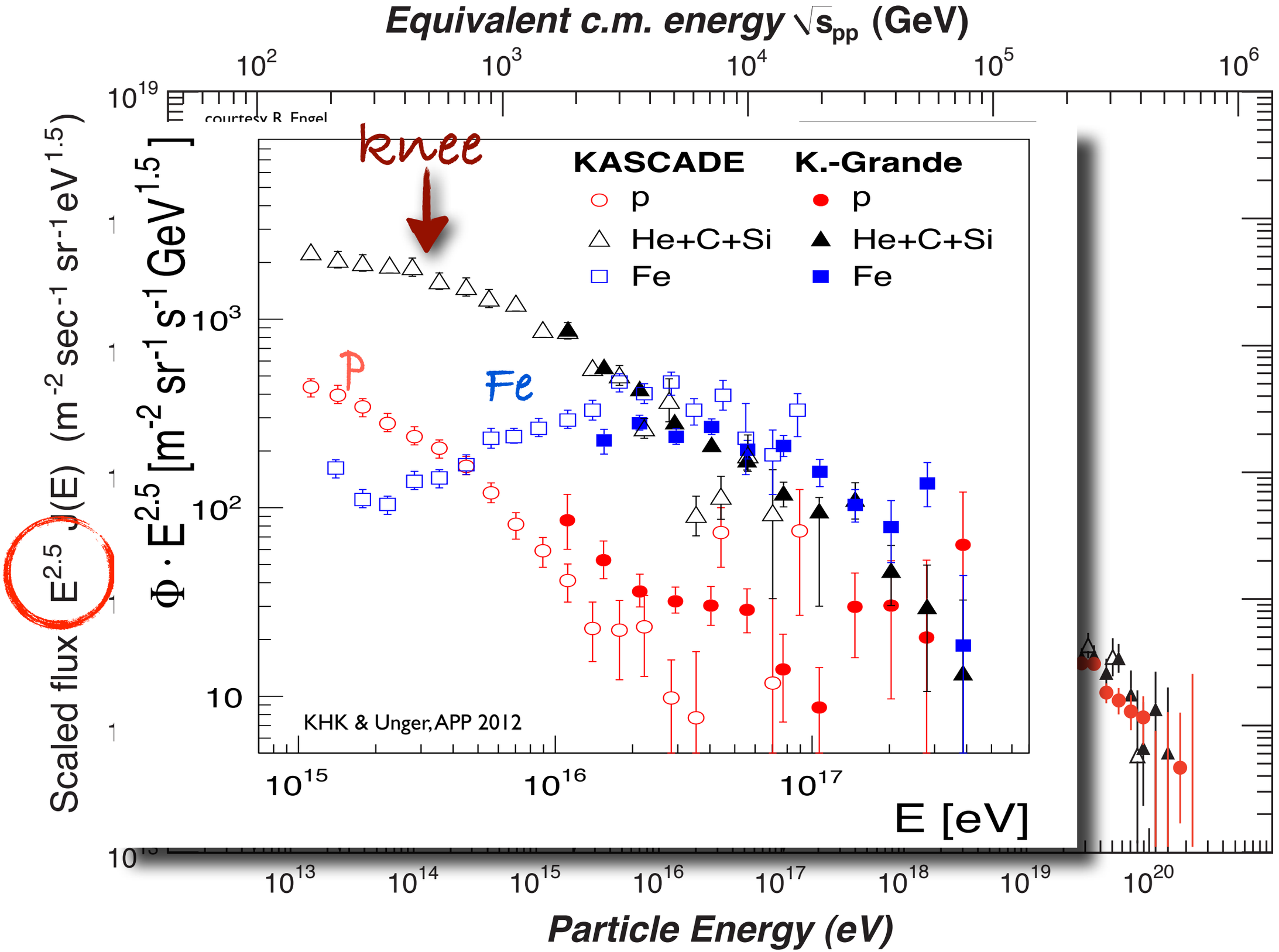
Features of CR spectrum



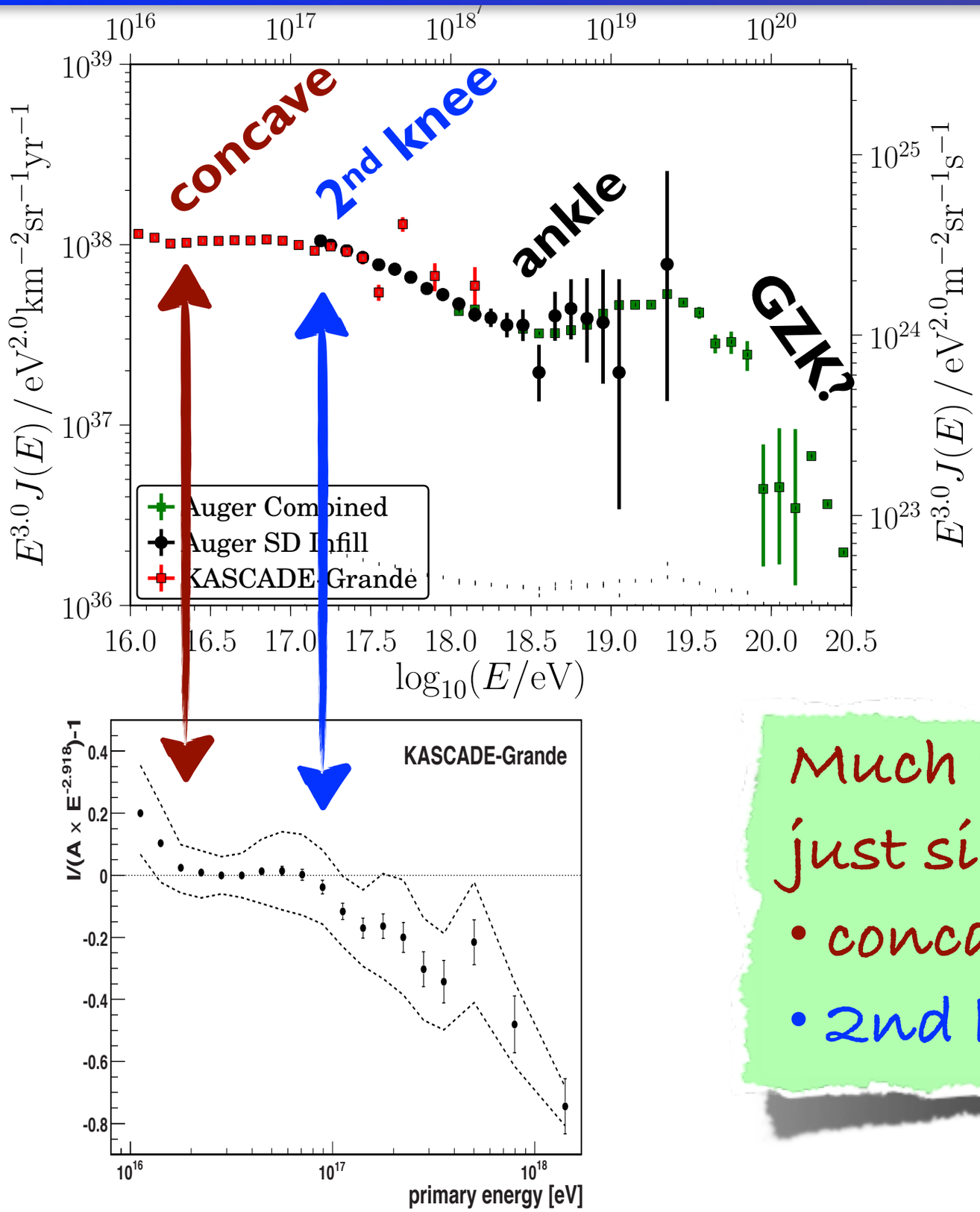
The Classical Picture



Latest Data


Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
courtesy R. Engel
knee
KASCADE
p
He+C+Si
Fe
K.-Grande
p
He+C+Si
Fe
p
Fe
10^{19}
10^3
10^2
10
$\Phi \cdot E^{2.5}$ [m^{-2} s^{-1} sr^{-1} $GeV^{1.5}$]
Scaled flux $E^{2.5}$ J(E) (m^{-2} sec^{-1} sr^{-1} $eV^{1.5}$)
KHK & Unger, APP 2012
10^{15}
10^{16}
10^{17}
E [eV]
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Particle Energy (eV)

All-Particle Spectrum: KA-Grande+Auger

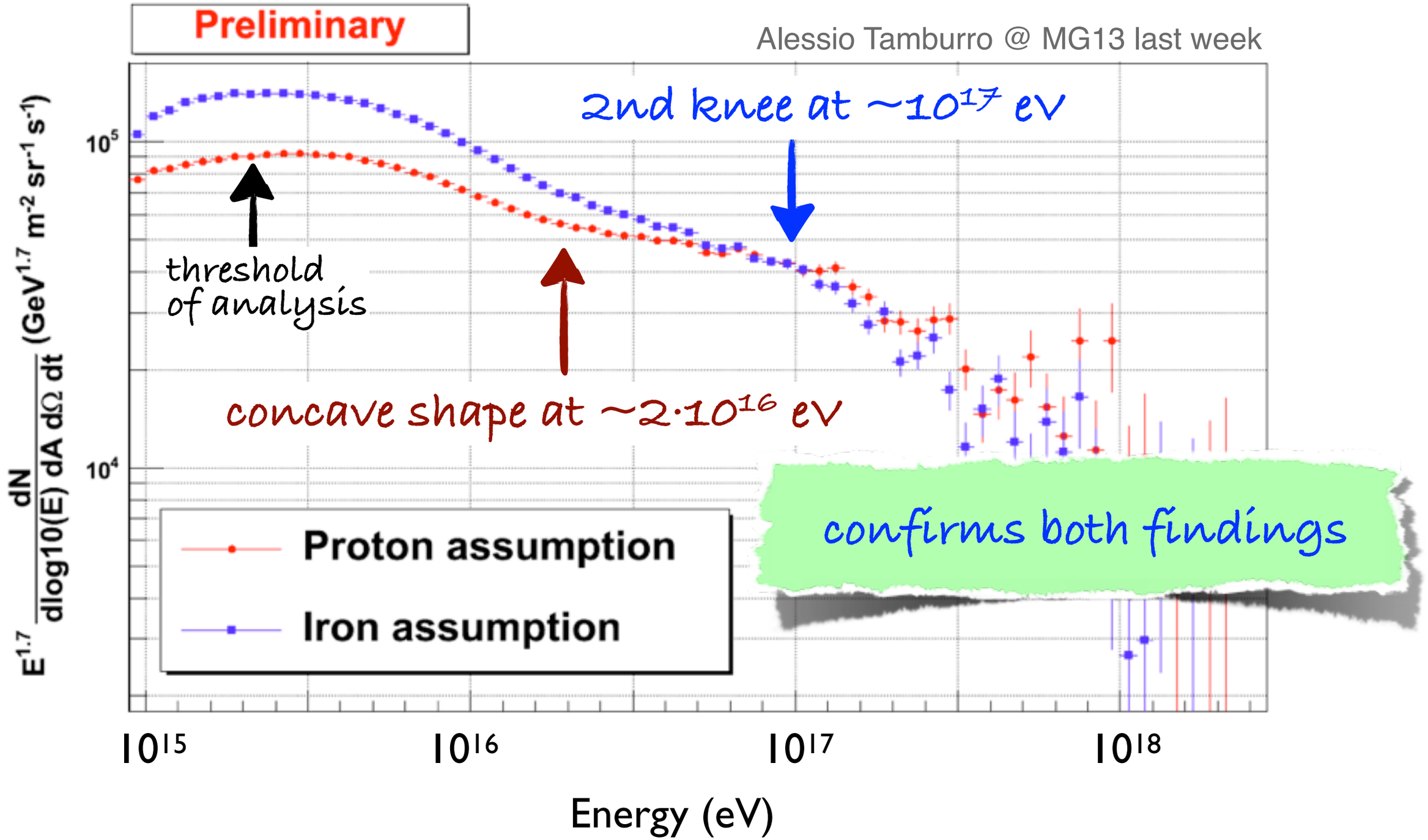


Much richer structure than just simple power law

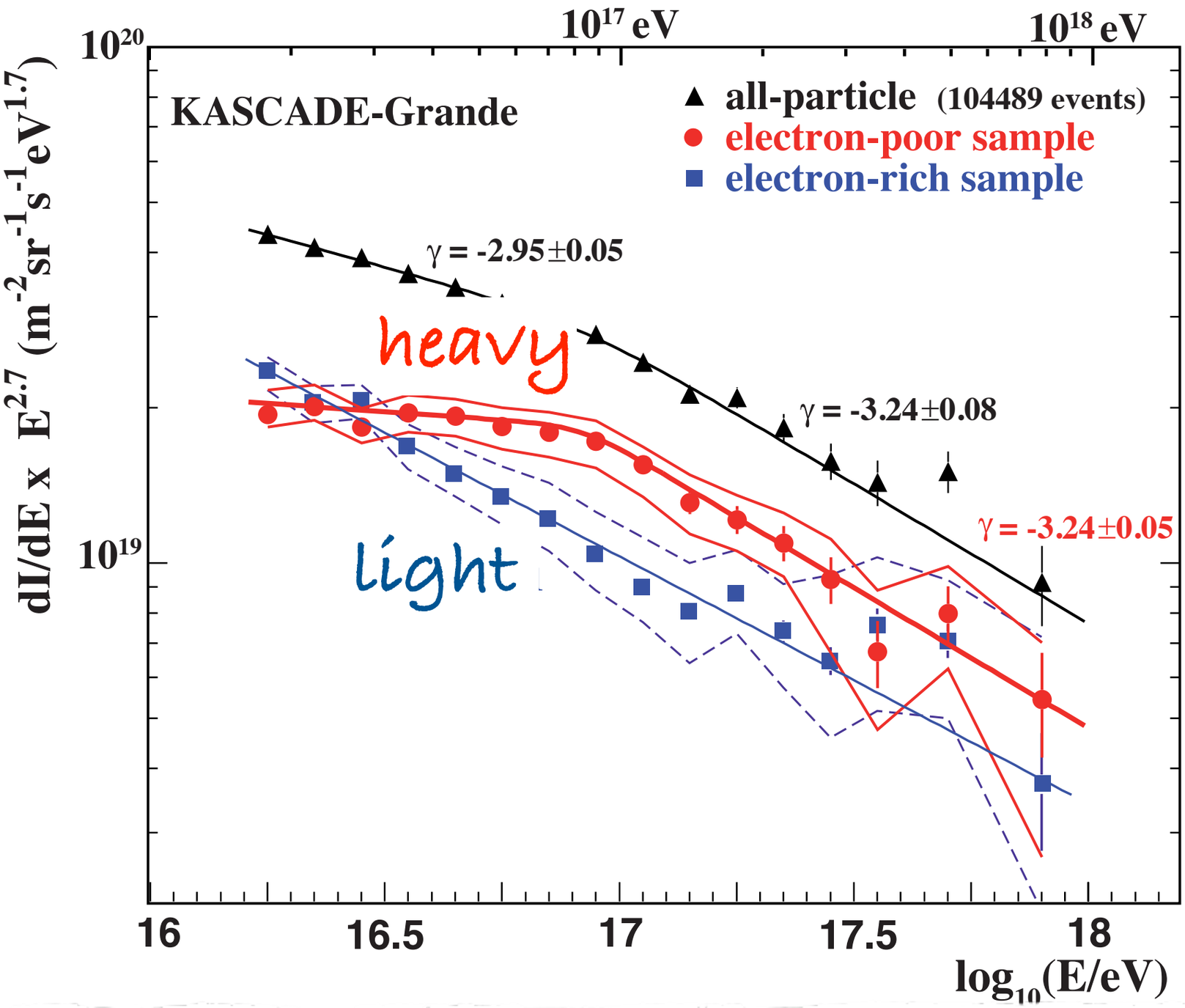
- concave shape at ~$2 \cdot 10^{16}$ eV
- 2nd knee at ~$8 \cdot 10^{16}$ eV

KASCADE-Grande, APP 36 (2012) 183

All-Particle Spectrum: IceTop



Heavy vs Light Primaries



KASCADE-Grande,
PRL 107 (2011) 171104

Structures appear to originate from heavy component

Take Home Message 1

Major progress in 10^{16} eV to 10^{18} eV energy range:

➙ evidence for 2nd knee at ~$8 \cdot 10^{16}$ eV
originates from heavy primaries

➙ some evidence for concave curvature @ ~ $2 \cdot 10^{16}$ eV
may be caused to onset of heavy component

Bumpiness of spectrum
due to less galactic diffusion / nearby sources ?

Would be good to confront source and acceleration scenarios such as were discussed at this meeting to data
... and to be combined also with galactic propagation

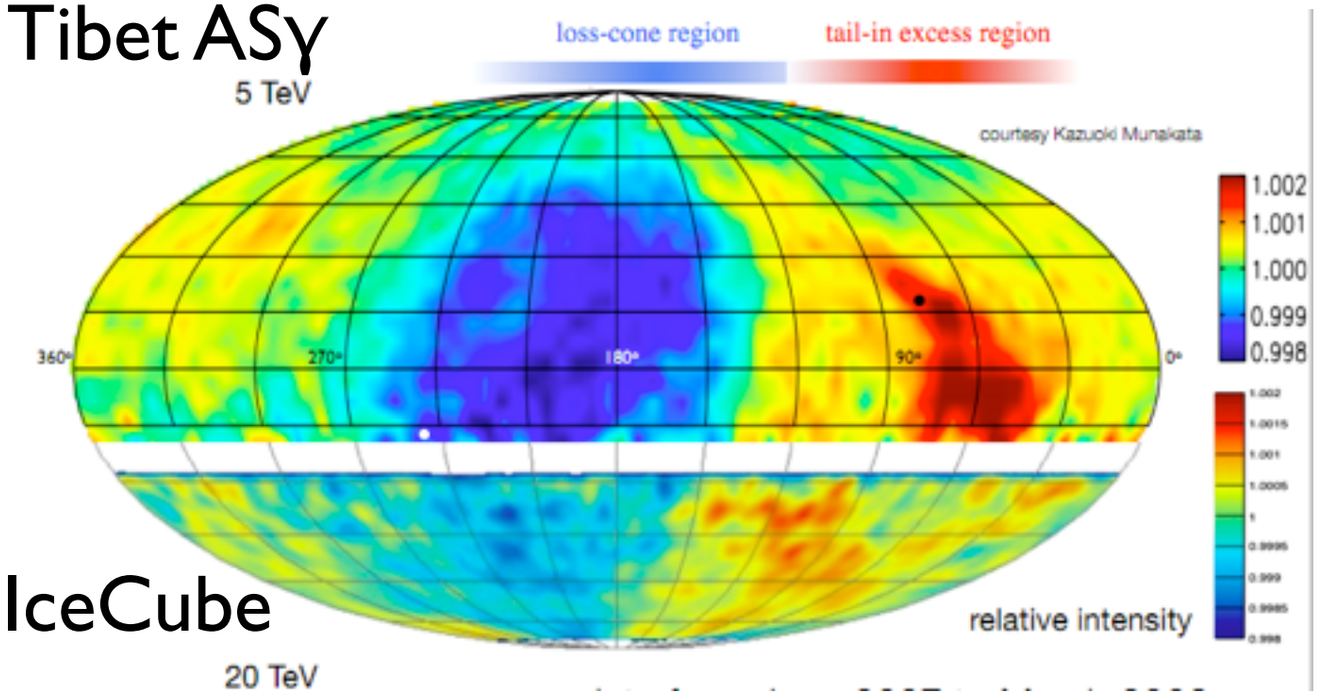
CR Sky at TeV energies

see talk & poster by S. Westerhoff

Large-scale anisotropy (>60°) at the level of 10^{-3} observed in the northern and southern sky.

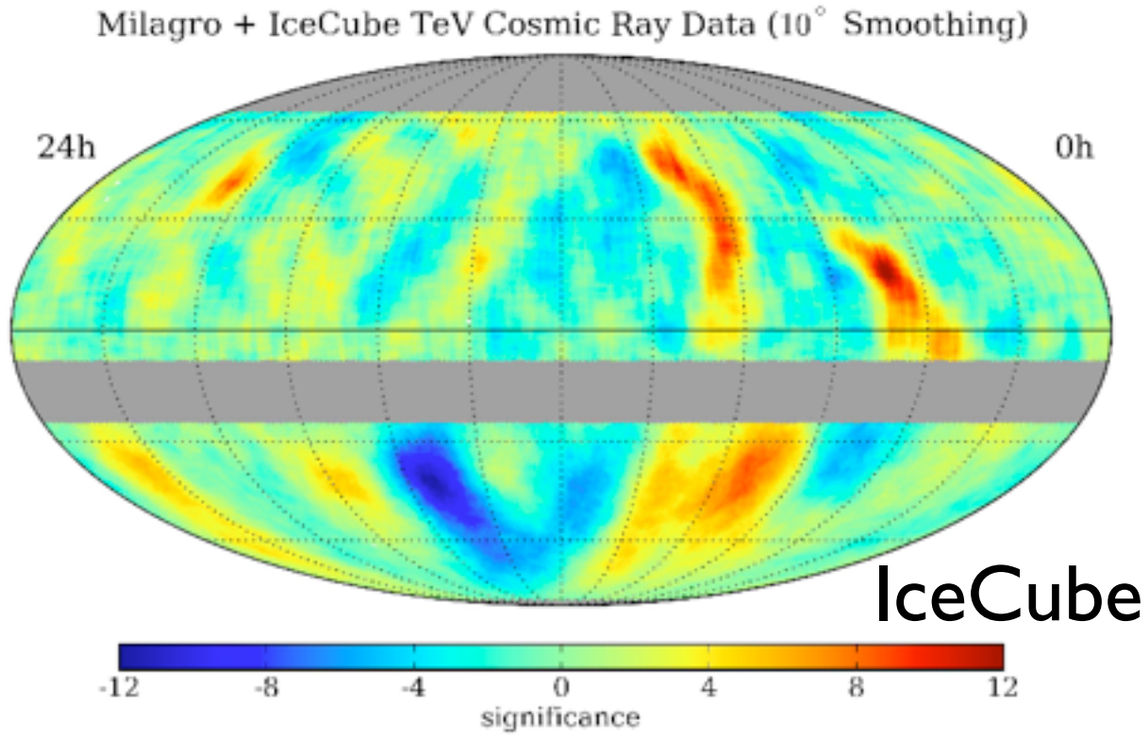
Small-scale anisotropy (10°-20°) the level of 10^{-4}

Tibet ASγ



IceCube

Milagro

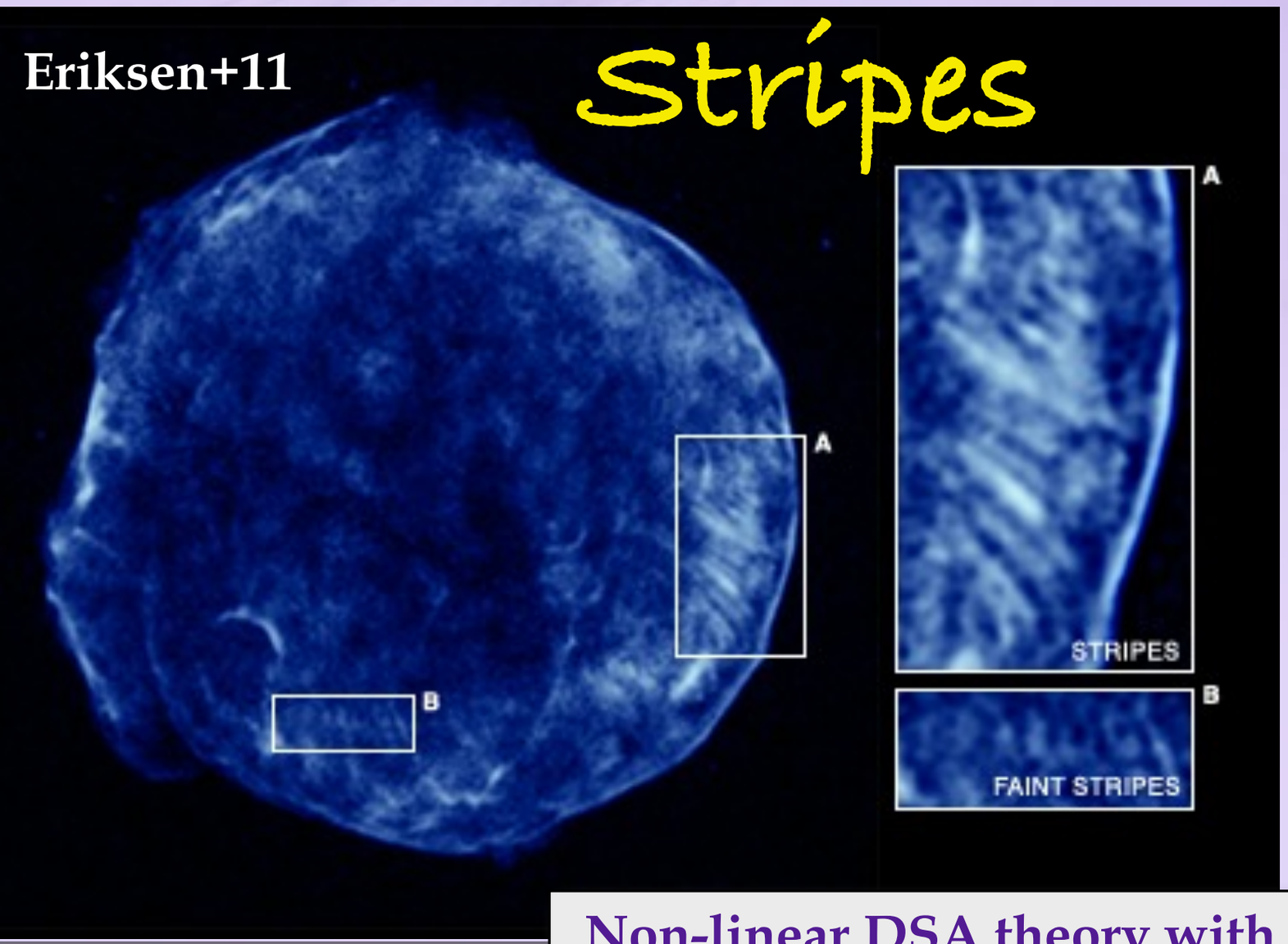


IceCube

Could be indicative again for a few nearby SNR sources a/o local turbulent B-field

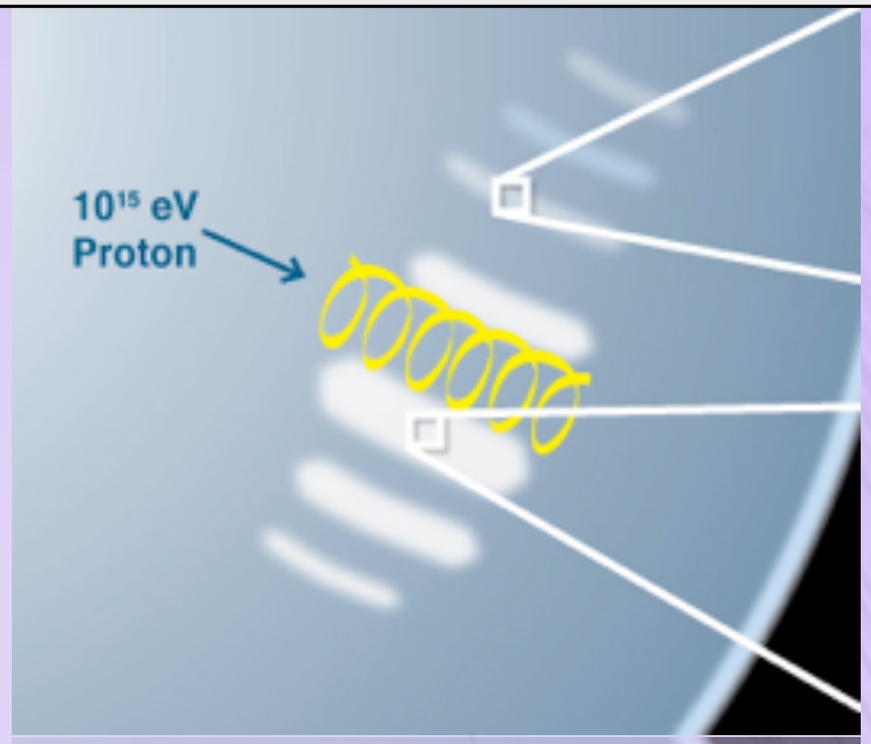
see also poster by G. Giacinti

PeV Protons in Tycho SNR ?



Separation of stripes:

Gyroradius of highest energy protons (~10^{15} eV)



Non-linear DSA theory with magnetic field amplification due to CR current driven instability can explain the stripes (Bykov+11):

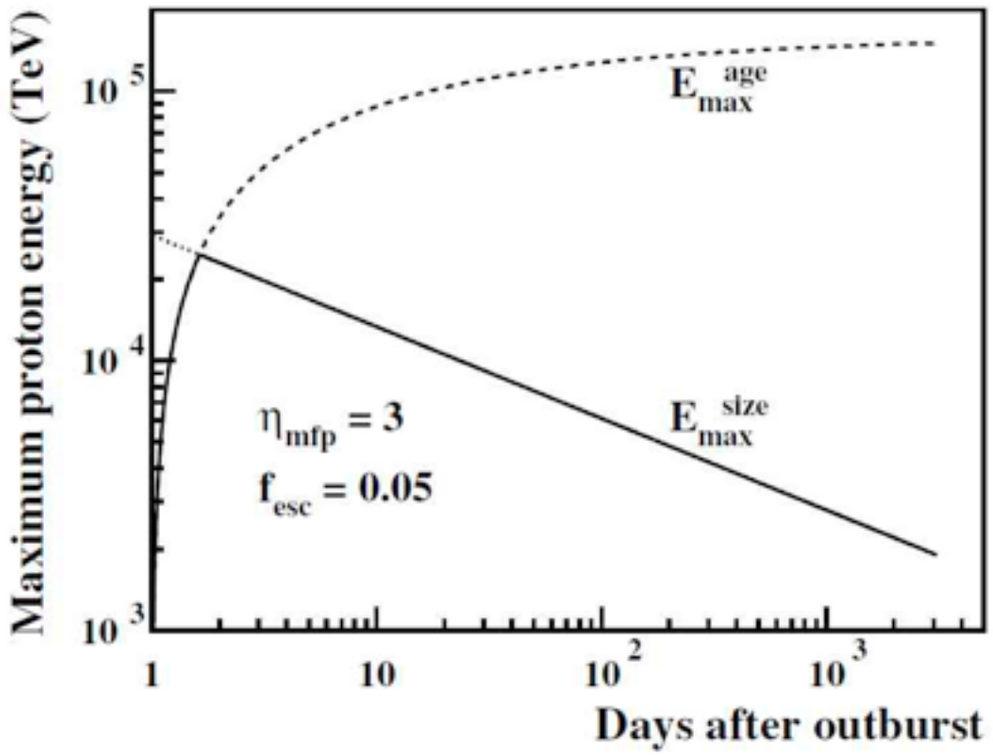
- **magnetic turbulence wave spectrum may have a peak, if turbulence cascading along the mean field is suppressed (Vladimirov+09)**

A. Bykov

Y. Uchiama

PeV Protons in SNRs

Tony Bell, B. Reville: Young high velocity SNRs may reach PeV scale protons, but need amplified B-Field



Matthieu Renaud: SN1993a ~10^{16} eV protons within a few days !!?

Vikram Dwarkadas: E_{max} reached fast, 10s of years

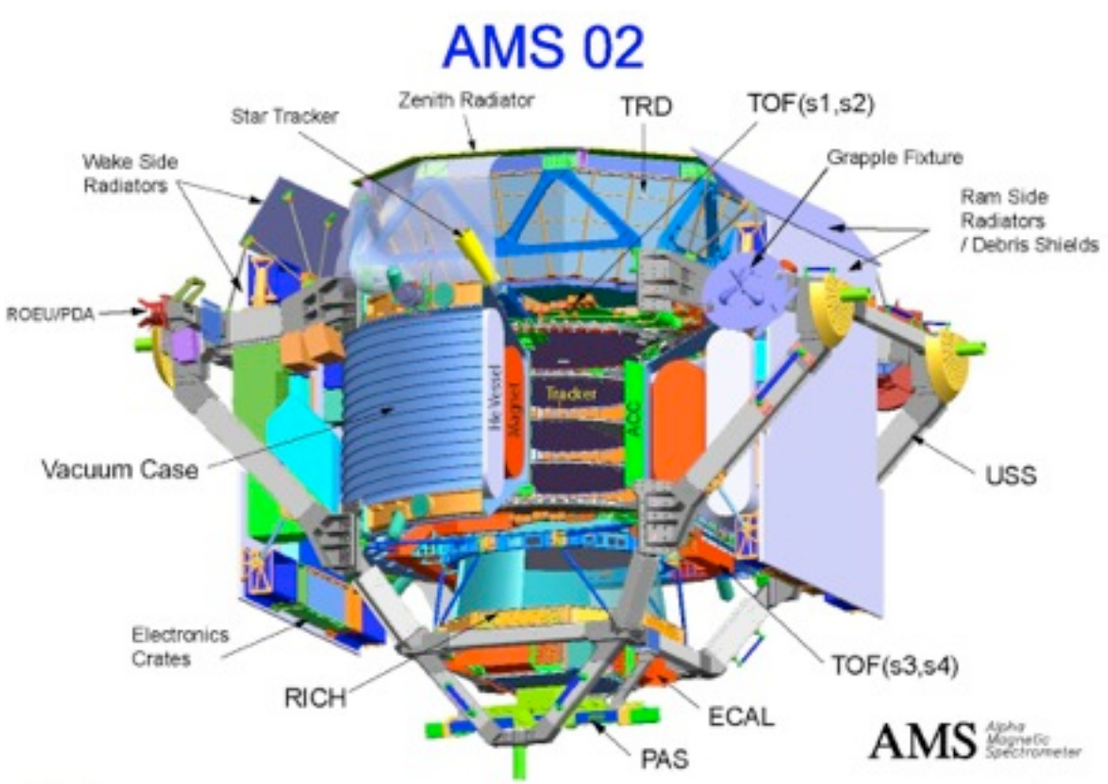
L.T. Ksenofontov: SN1006 from HESS obs. → ~ 2PeV

G. Morlino, D. Caprioli: Tycho efficient CR accel. ε~12%, E_{max}~0.5 PeV

Mikhail Malkov: strong self confinement of escaping CRs

.. and many more specific models

Ongoing and New Projects @ GeV-range

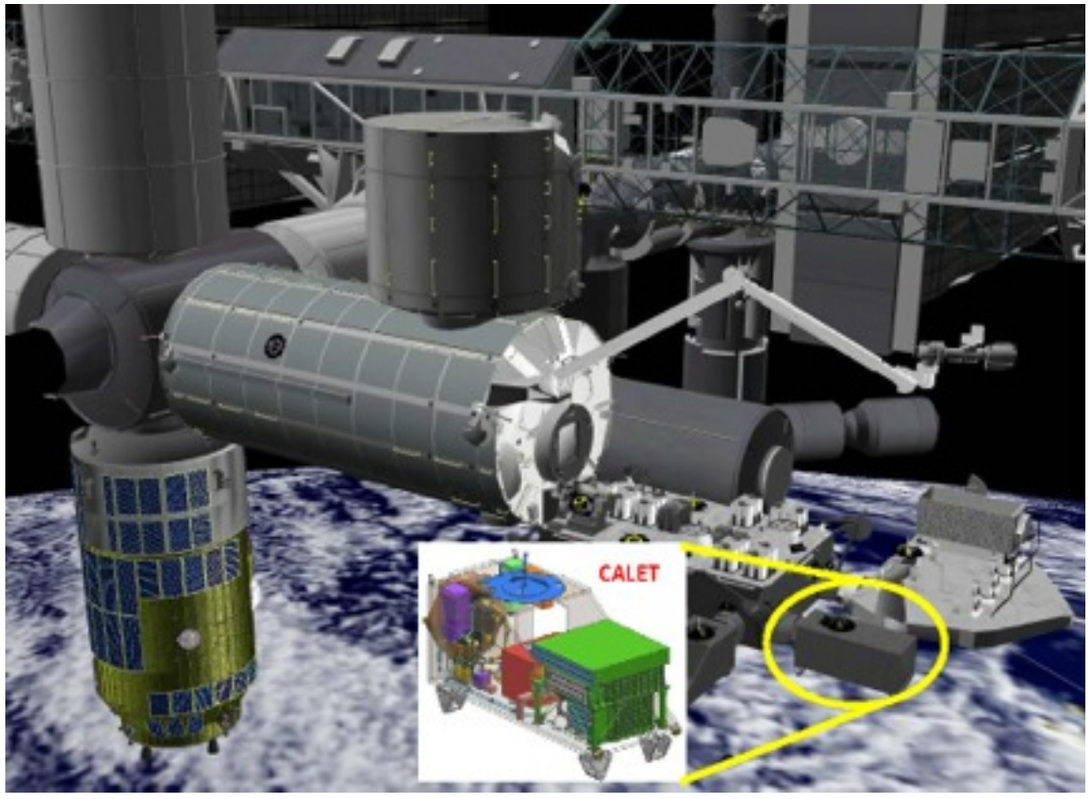


AMS

- most complex instrument
- launched 16.05.2011
- will measure light CR isotopes
- ~400 MeV - ~ 10 GeV

➙ improve understanding of CR propagation in galaxy

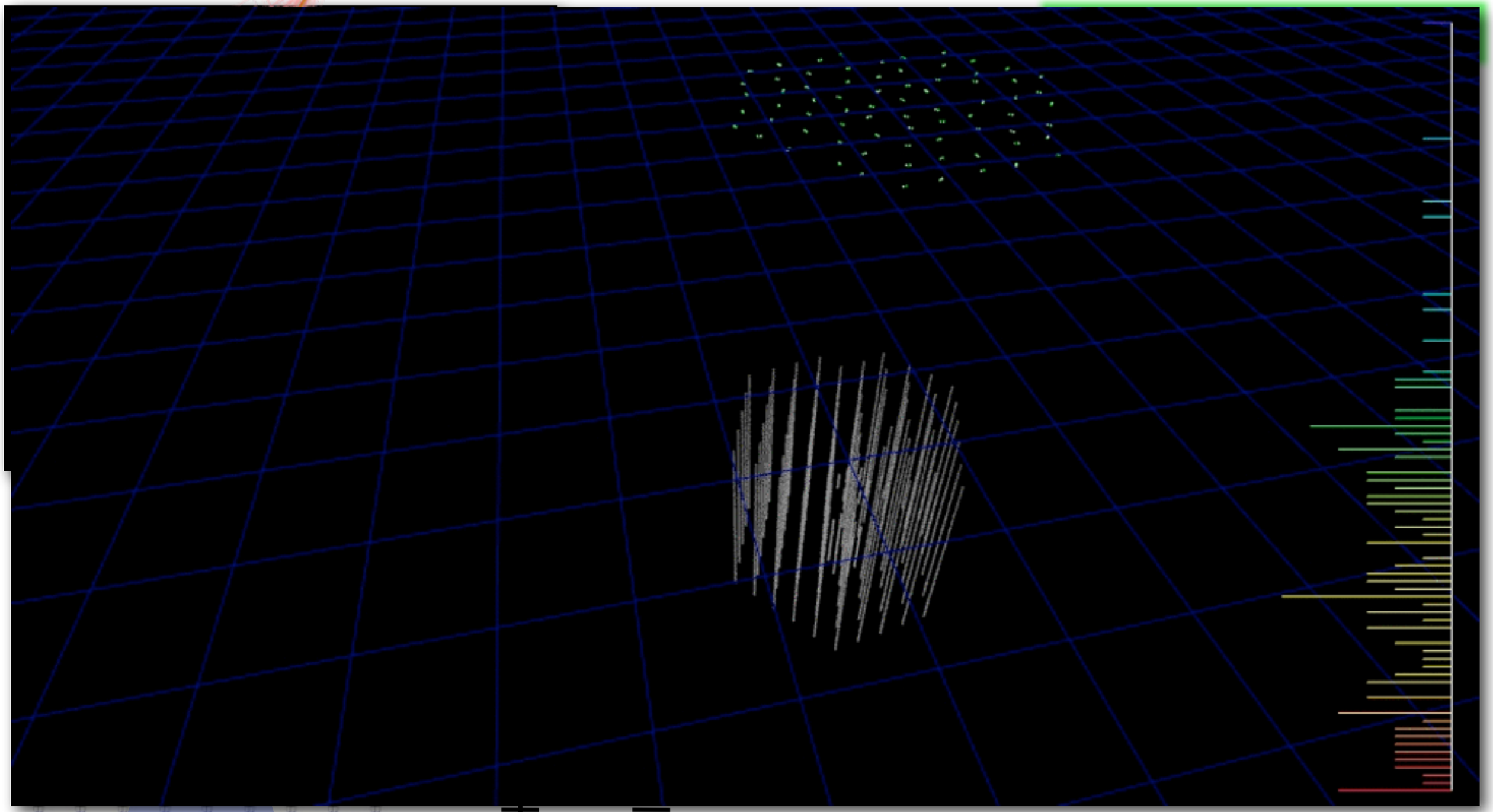
- still calibrating, no data release yet



CALET *(see Poster by M. Mori)*

- CALorimeteric Electron Telescope
- 0.12 m^2 sr
- 30 X_0 calorimeter
- dedicated for electrons
- nuclei 50 GeV - ~100 TeV

Ongoing and New Projects @ PeV-range

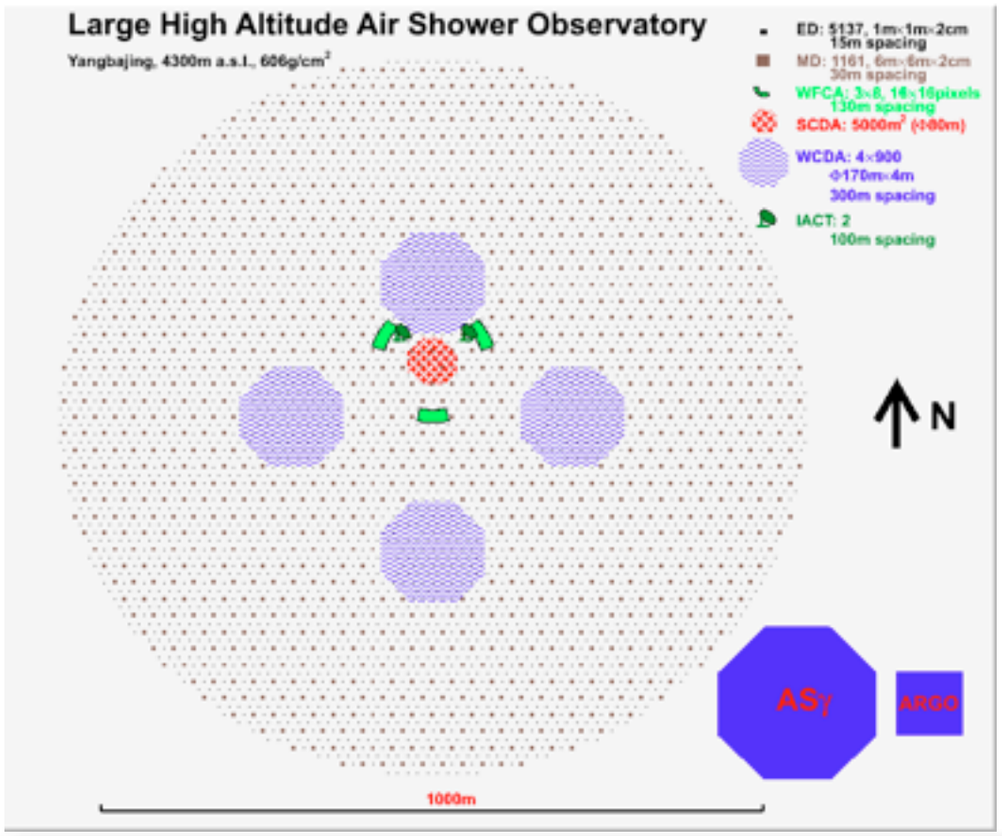


Cherenkov light cone

Radio detection

(see poster by M.Tluczykont)

Ongoing and New Projects @ PeV-range



LHAASO

- γ sky above 100 GeV
- γ spectra above 100 TeV
- CRs above 30 TeV

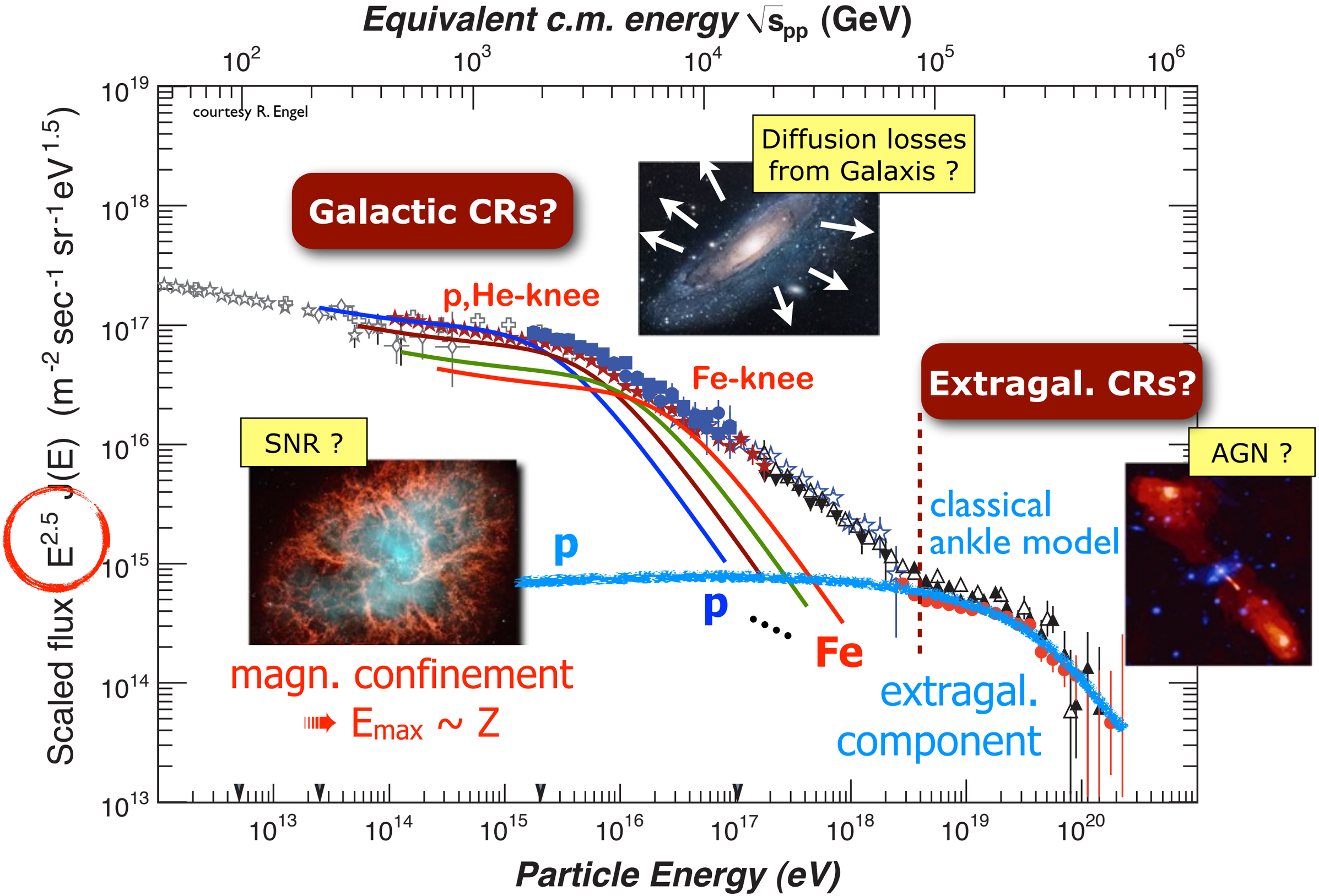
→ *preparatory phase, mostly driven by China*

HAWK *(see talk by A. Sandoval)*

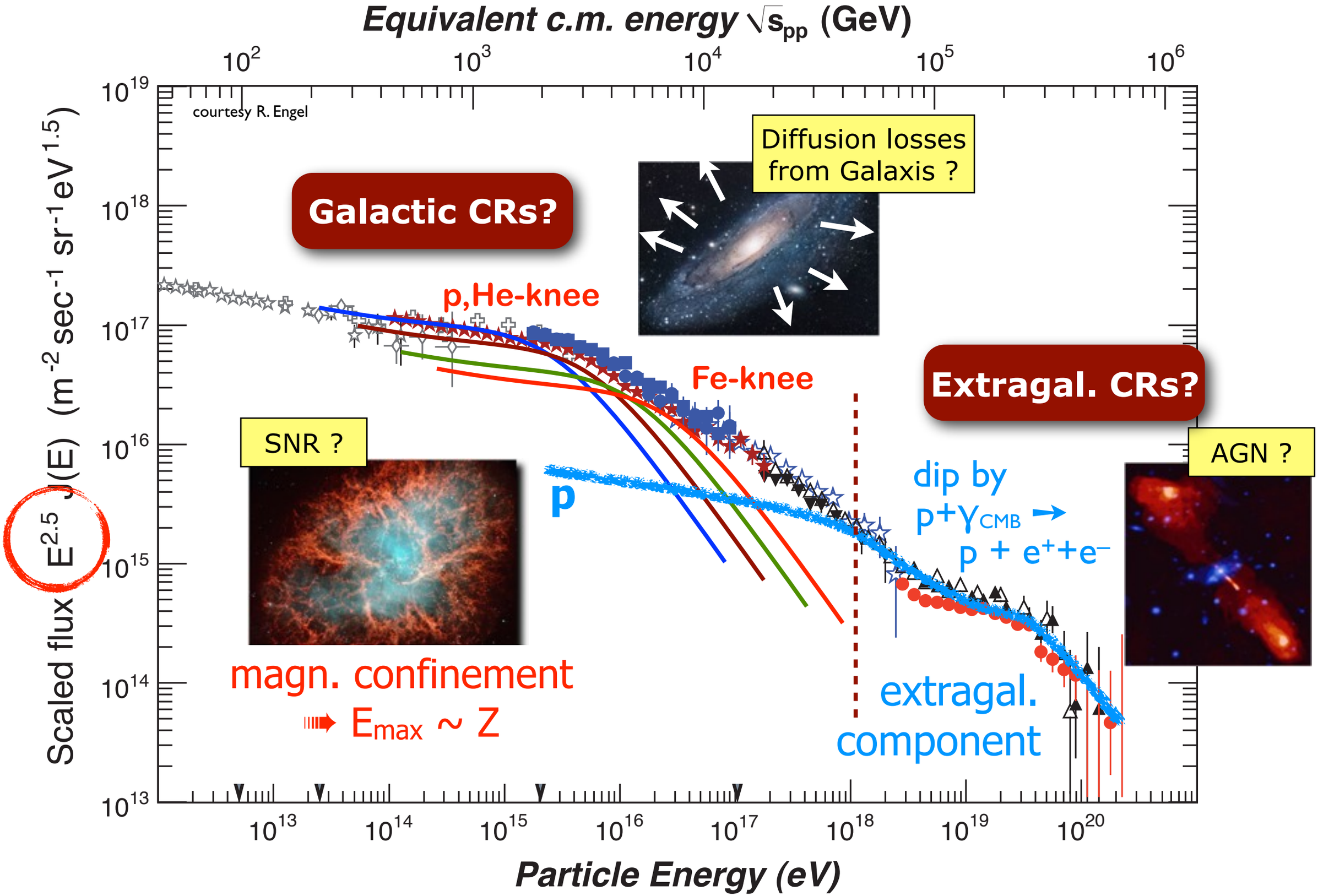
- γ sky above 100 GeV
- CR anisotropies @ TeV-scale

→ *under construction*

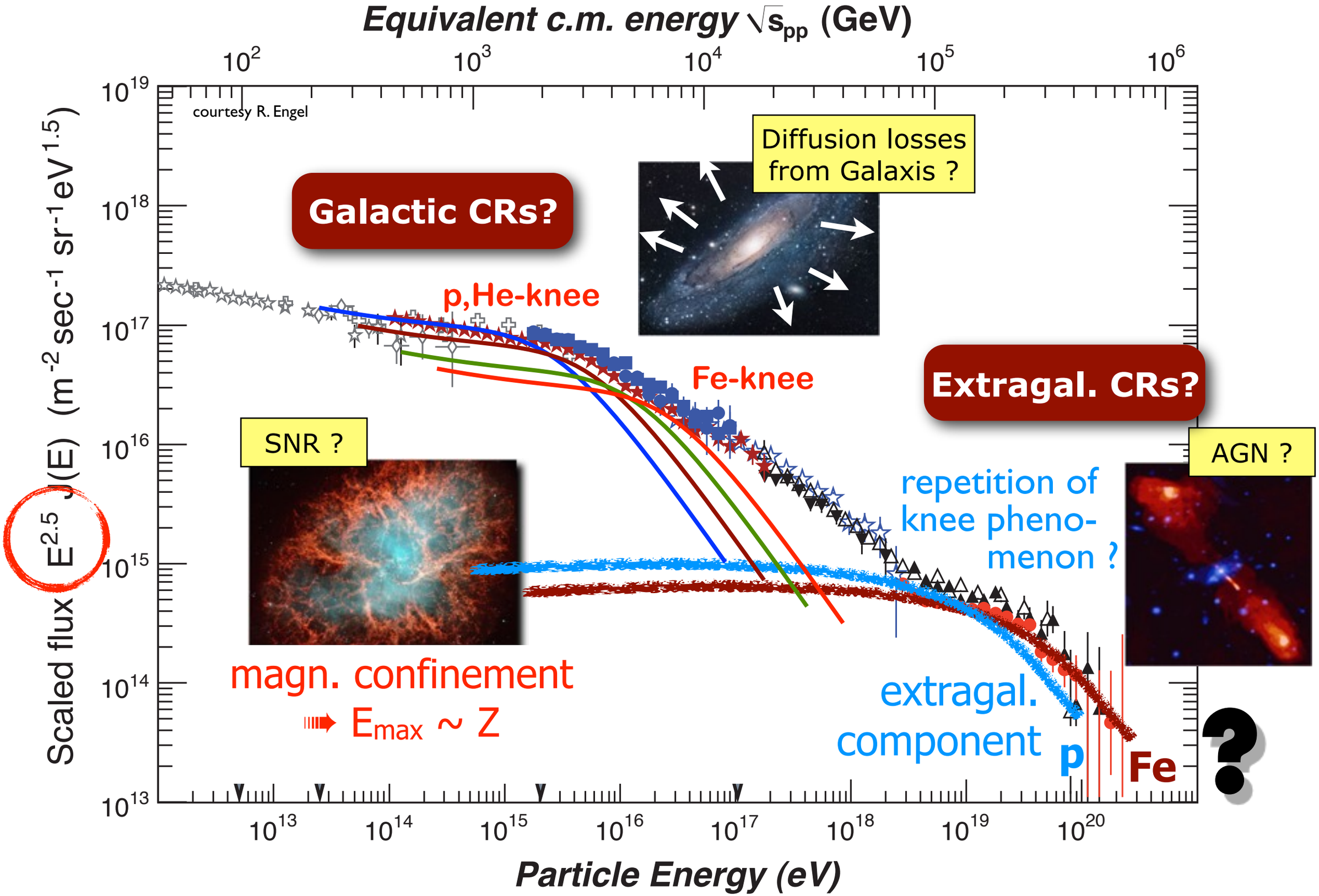
Towards the Ankle and GZK-region



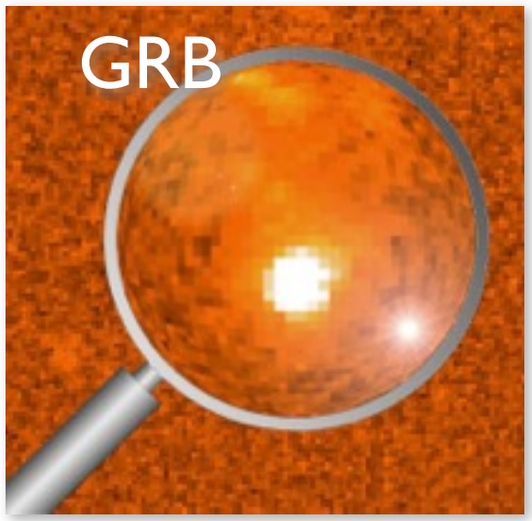
Towards the Ankle and GZK-region

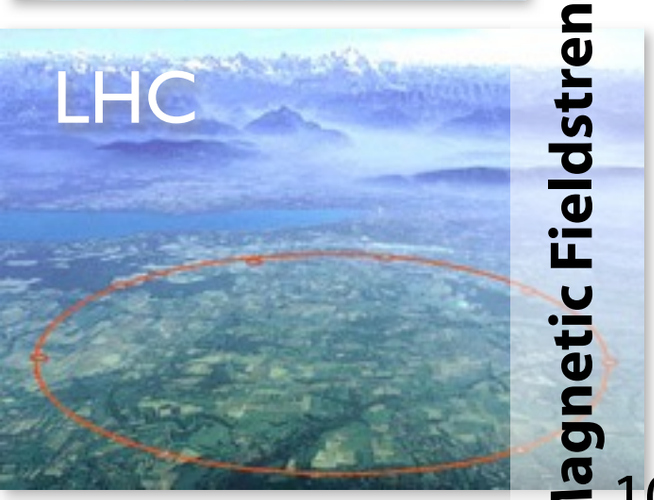


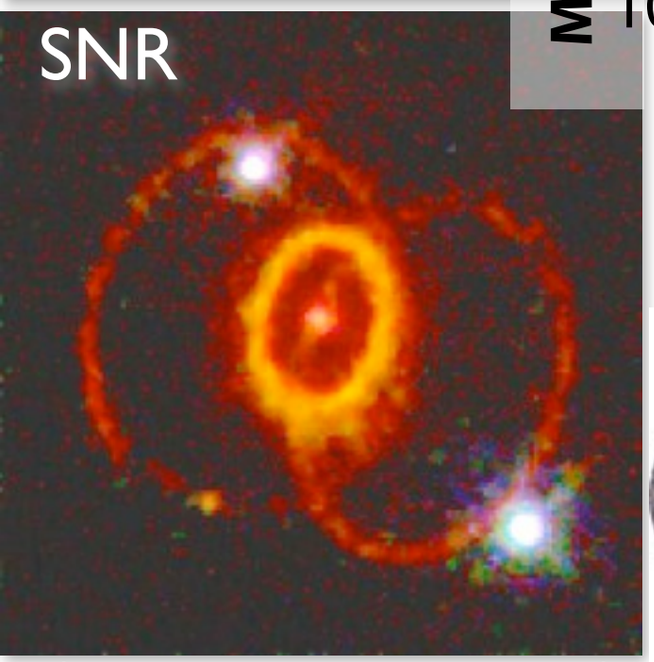
Towards the Ankle and GZK-region

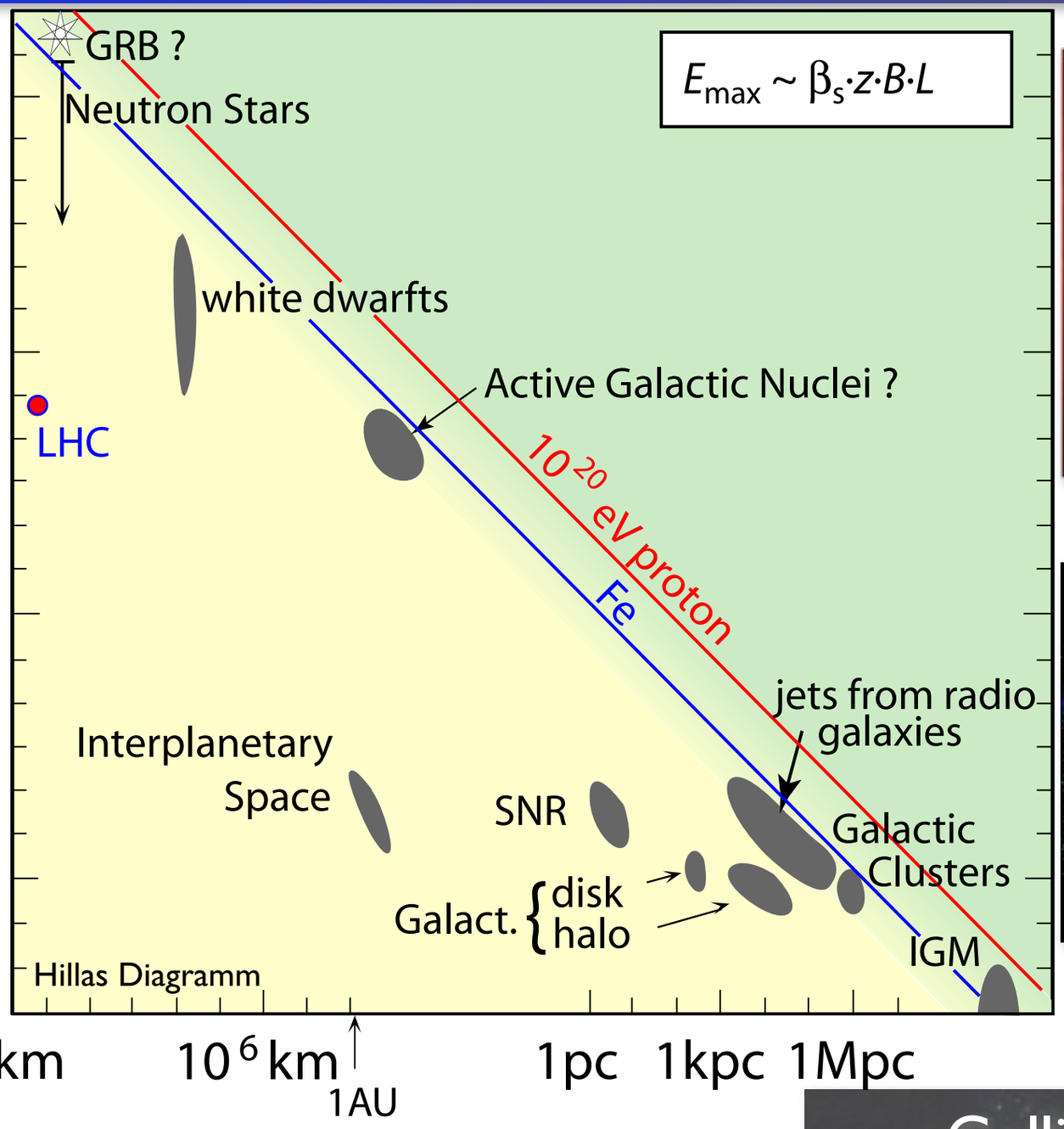


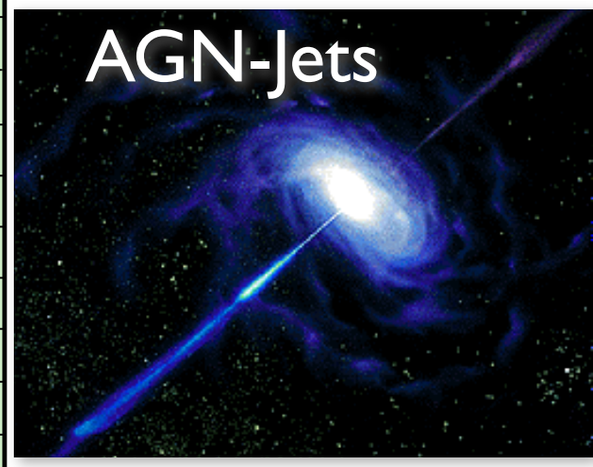
Cosmic Ray Accelerators





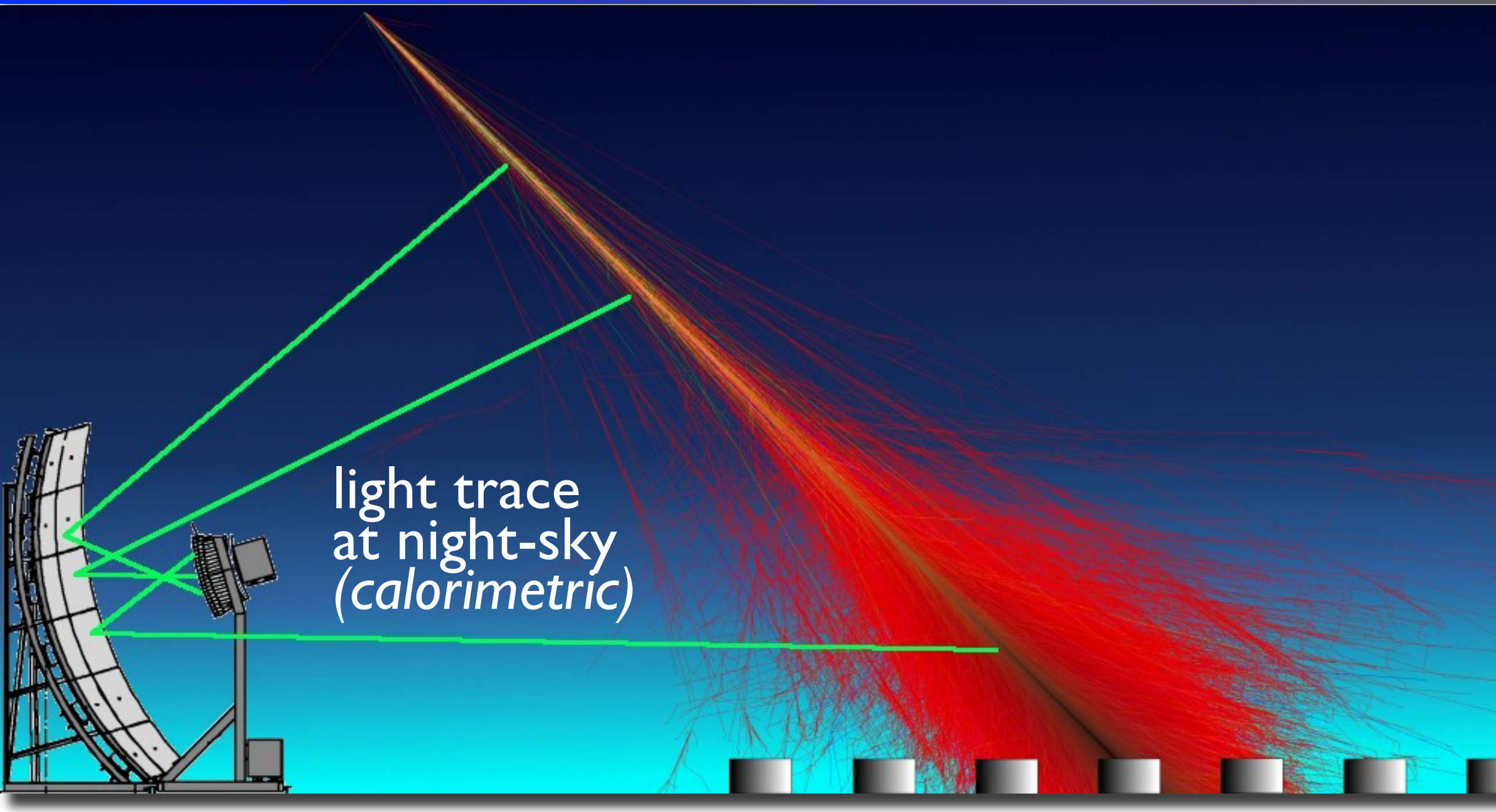






Size

Hybrid Observation of EAS



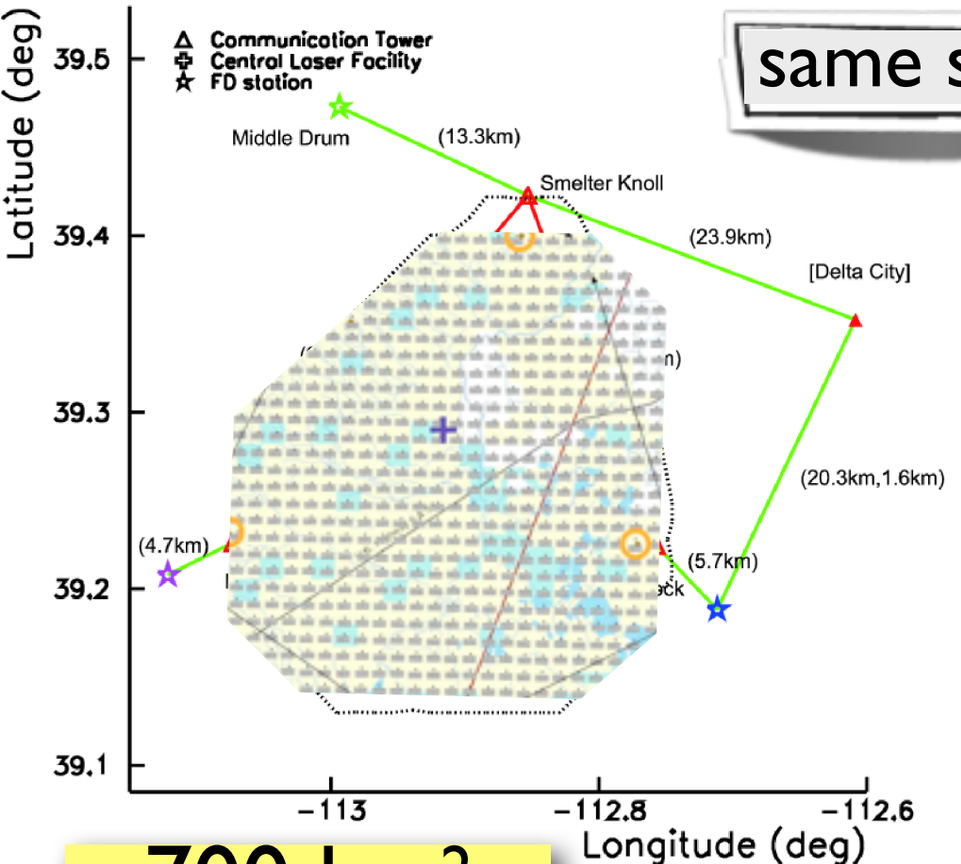
Fluorescence light

Particle-density and
-composition at ground

Also:
Detection of Radiosignals

The UHECR Hybrid Generation

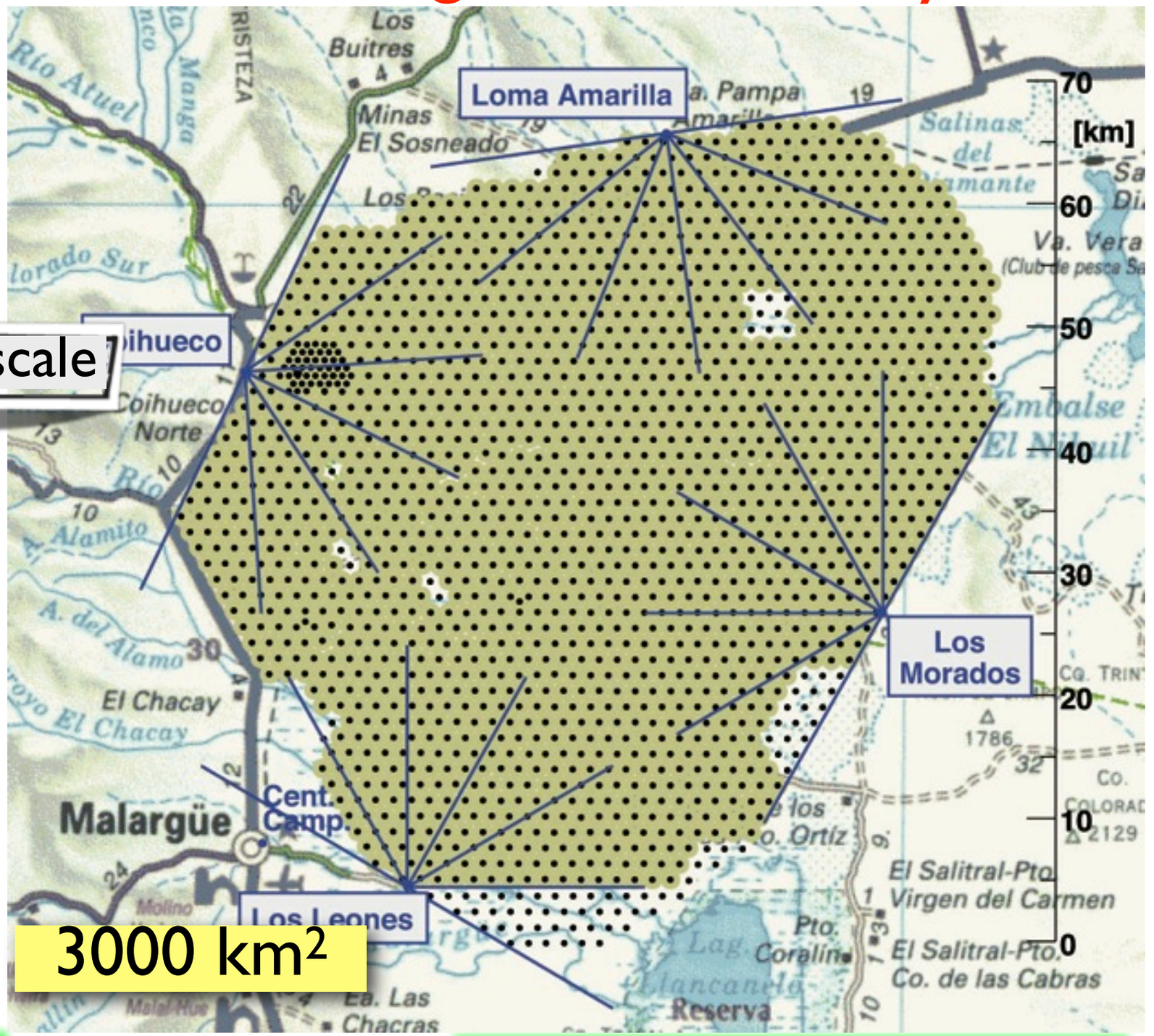
Telescope Array



700 km²

same scale

Pierre Auger Observatory



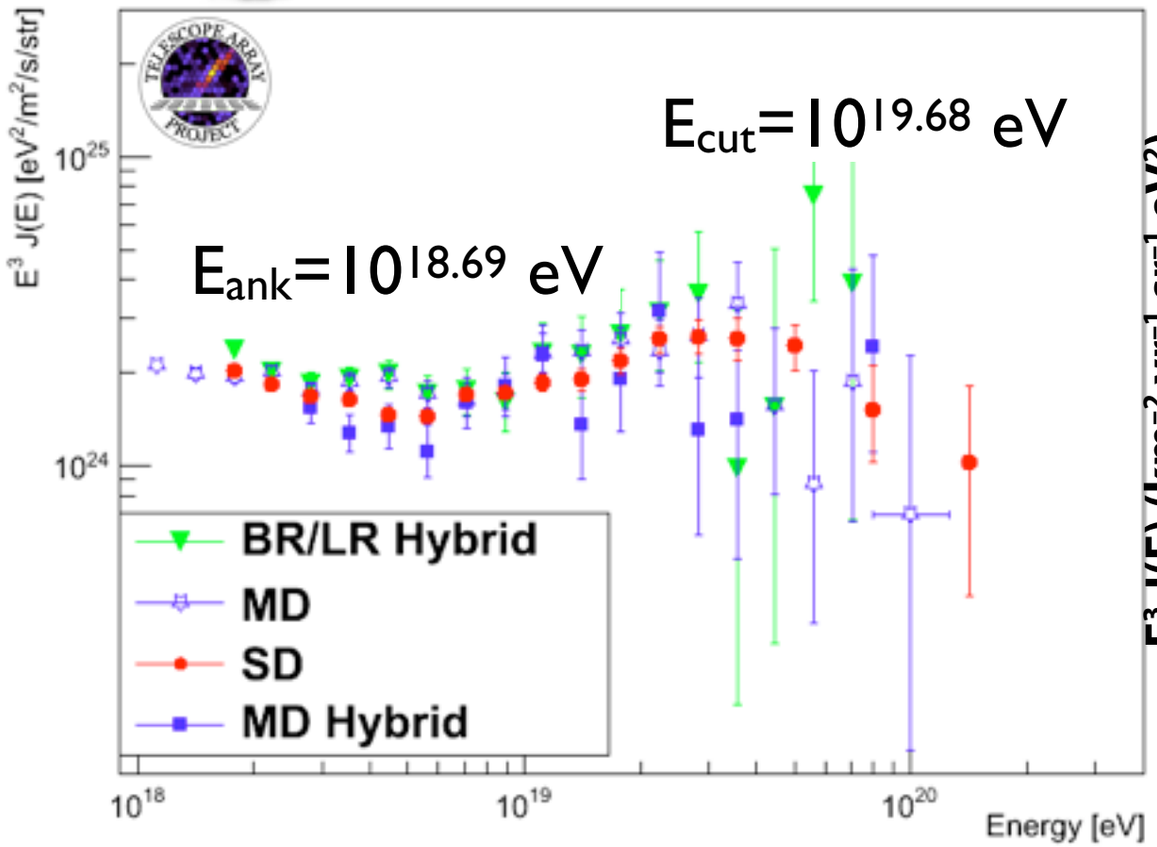
3000 km²

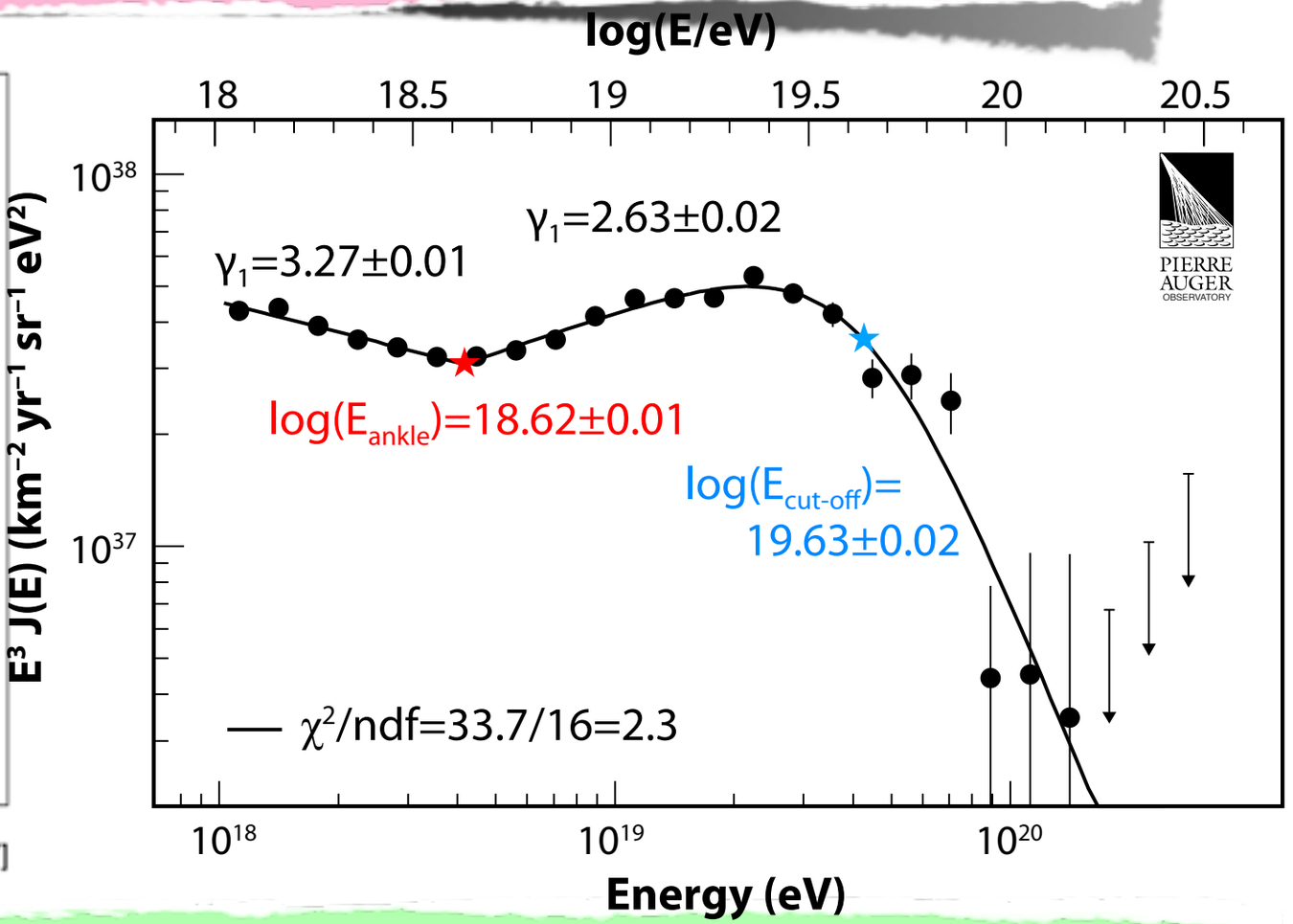
poster by T. Nonaka

talk by Stefan Westerhoff

Energy Spectra

Is this the GZK cut-off ?





- Auger has about 10 times larger statistics
- Spectra are consistent within their systematic uncertainties
- Can be brought to agreement by constant energy shifts (TA E × 0.906, Auger E × 1.102).

CR Mass Composition

CR Mass Composition

For distant sources **GZK-effect** will
- rapidly photodisintegrate nuclei (if they were present)
- degrade proton energy

➙ composition will be **light** in GZK-domain

➙ expect secondary (cosmogenic) **γ's and ν's**

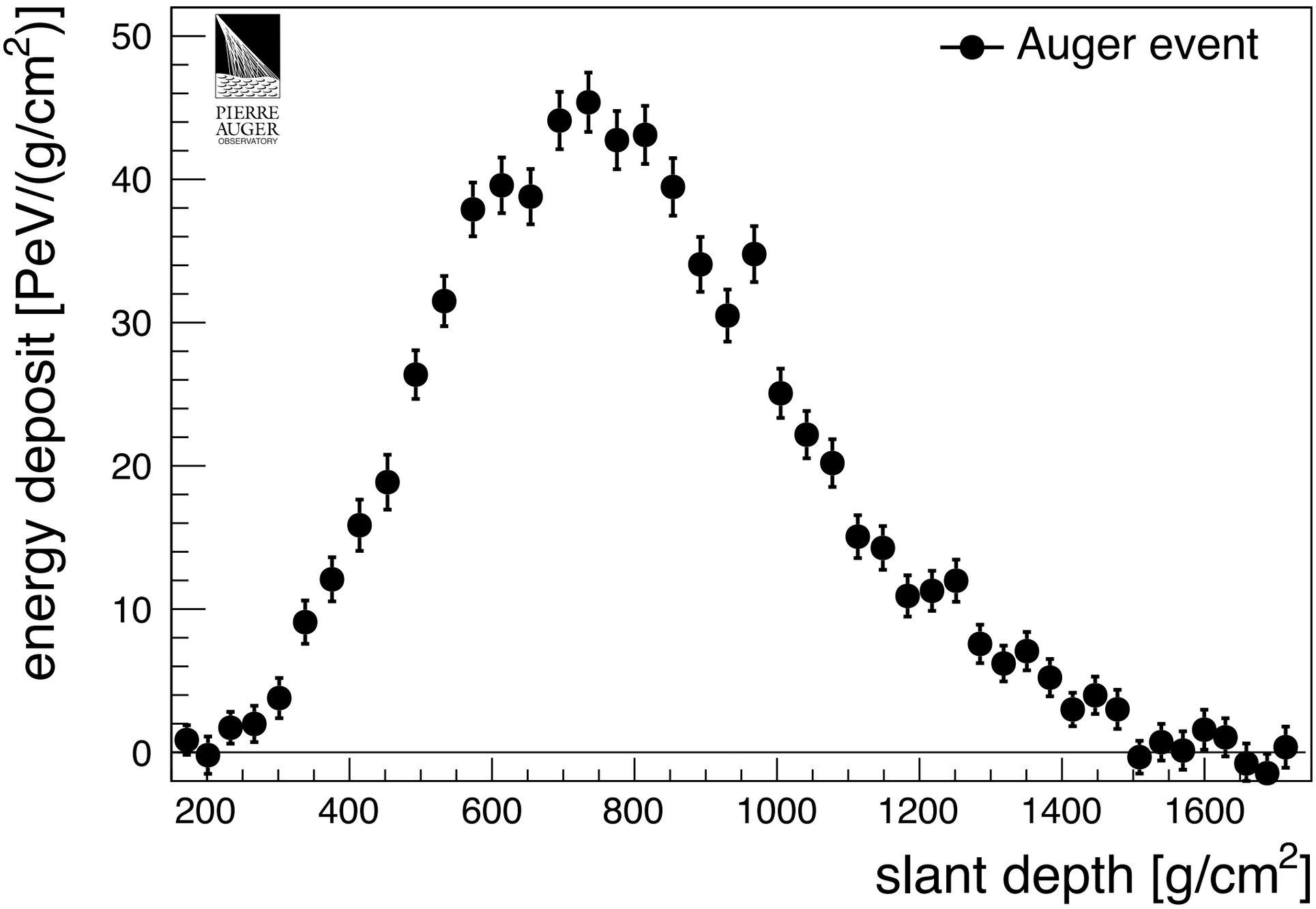
Maximum energy of nearby sources will
- naturally enhance heavy primaries by $E_A = Z \times E_p$ (same effect as kmown from knee)

➙ compos. will become **heavy** towards cut-off region

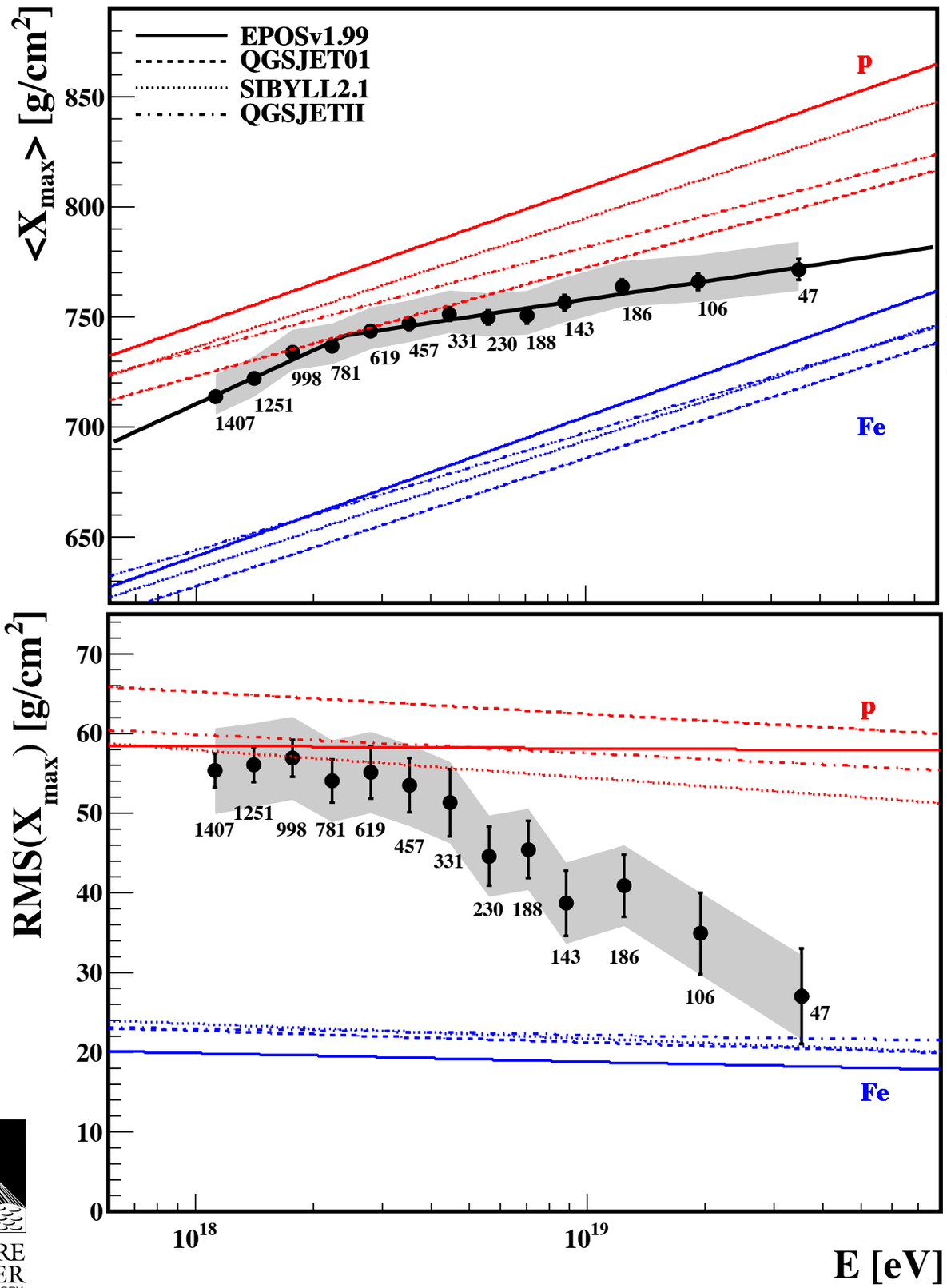
Longitudinal Shower Development

KHK, Unger APP 2012
EPOS 1.99 Simulations

Example of a $3 \cdot 10^{19}$ eV EAS event



$\langle X_{max} \rangle$ and RMS(X_{max}) from Auger



Auger Collab. PRL 104, 2010, updated: Facal, ICRC 2011

change of composition from light to heavy ?

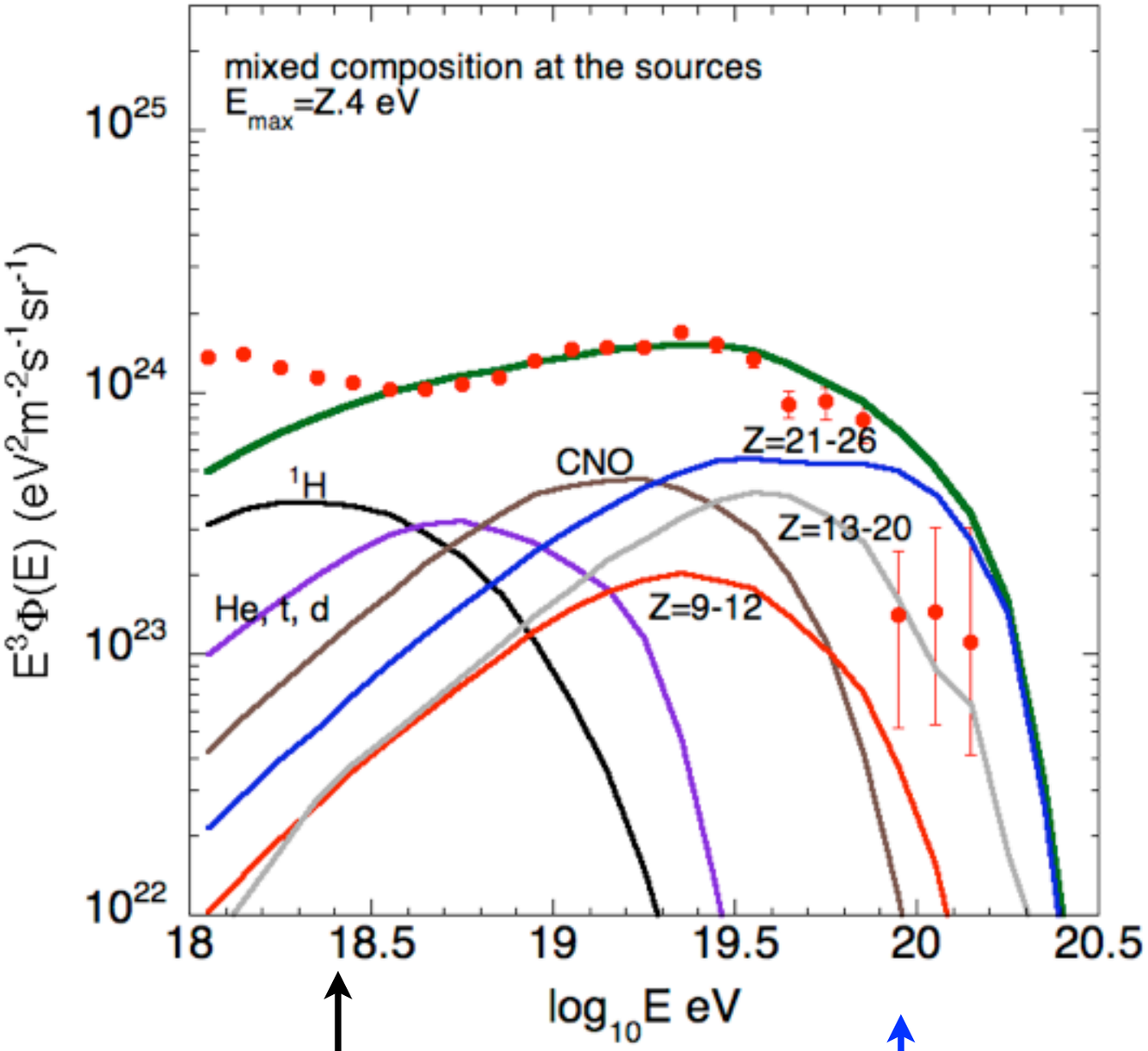
Independent confirmation from other composition indicators

Sys. uncertainty: 13 g/cm² (mean)
6 g/cm² (RMS)

talk by Stefan Westerhoff

Does Auger see the limiting energy of CR sources?

(Allard, arXiv:1111.3290, APP 2012)

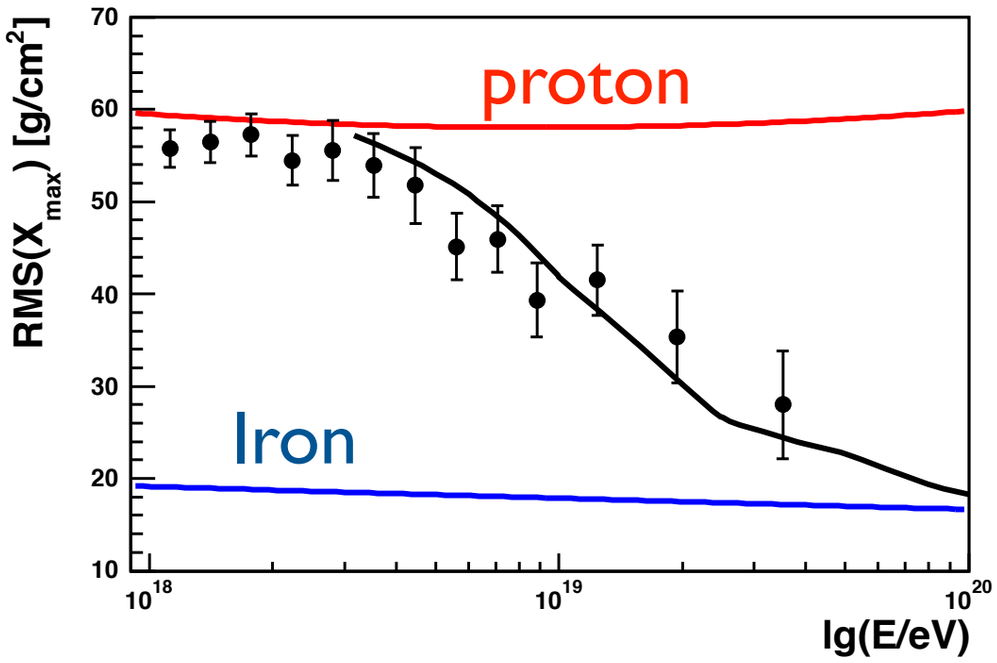


Protons $E_{max,p} = 10^{18.4}$ eV

Iron $E_{max,Fe} = 26\ E_{max,p}$
$= 10^{20}$ eV

Natural transition to heavier composition at high energy !

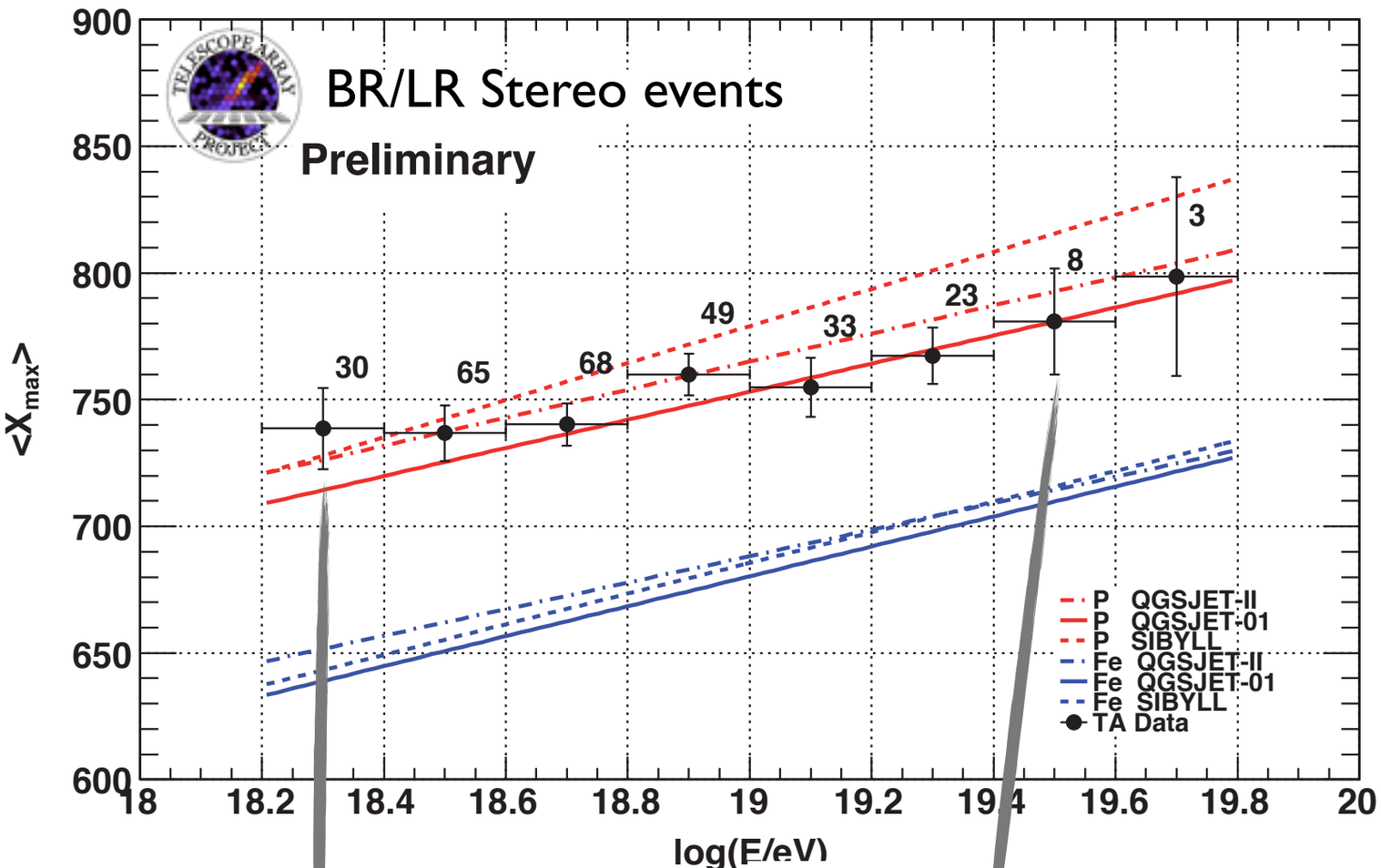
Flucutations of X_{max}

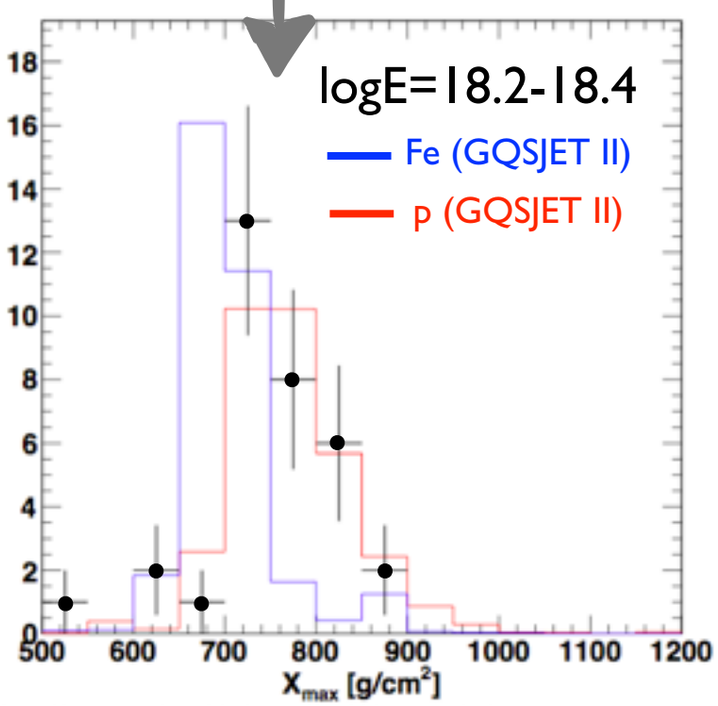


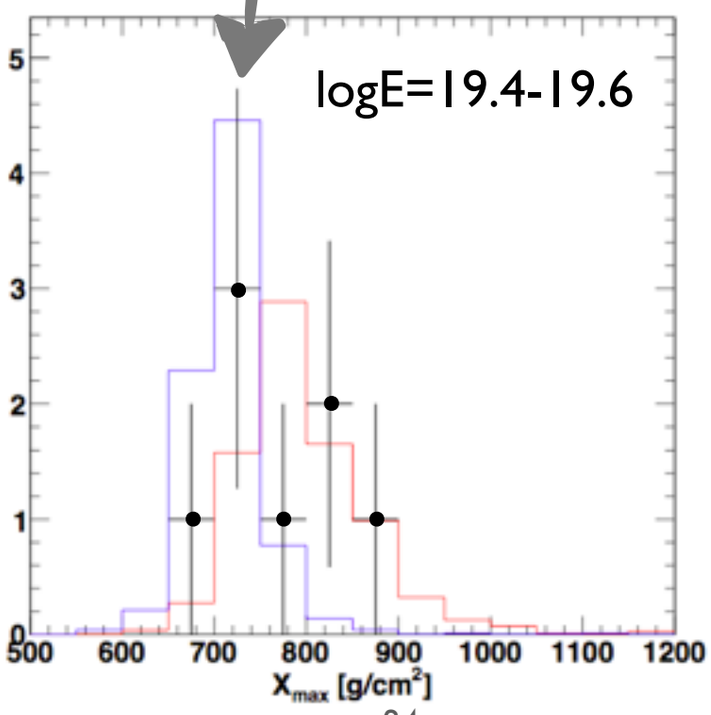
Note: In this picture flux is not suppressed by GZK!

(see also talk by M. Hardcastle)

$\langle X_{max} \rangle$ and RMS(X_{max}) from TA







light composition at all energies

Sys. uncertainty:
13 g/cm^2 (mean)

poster T. Nonaka

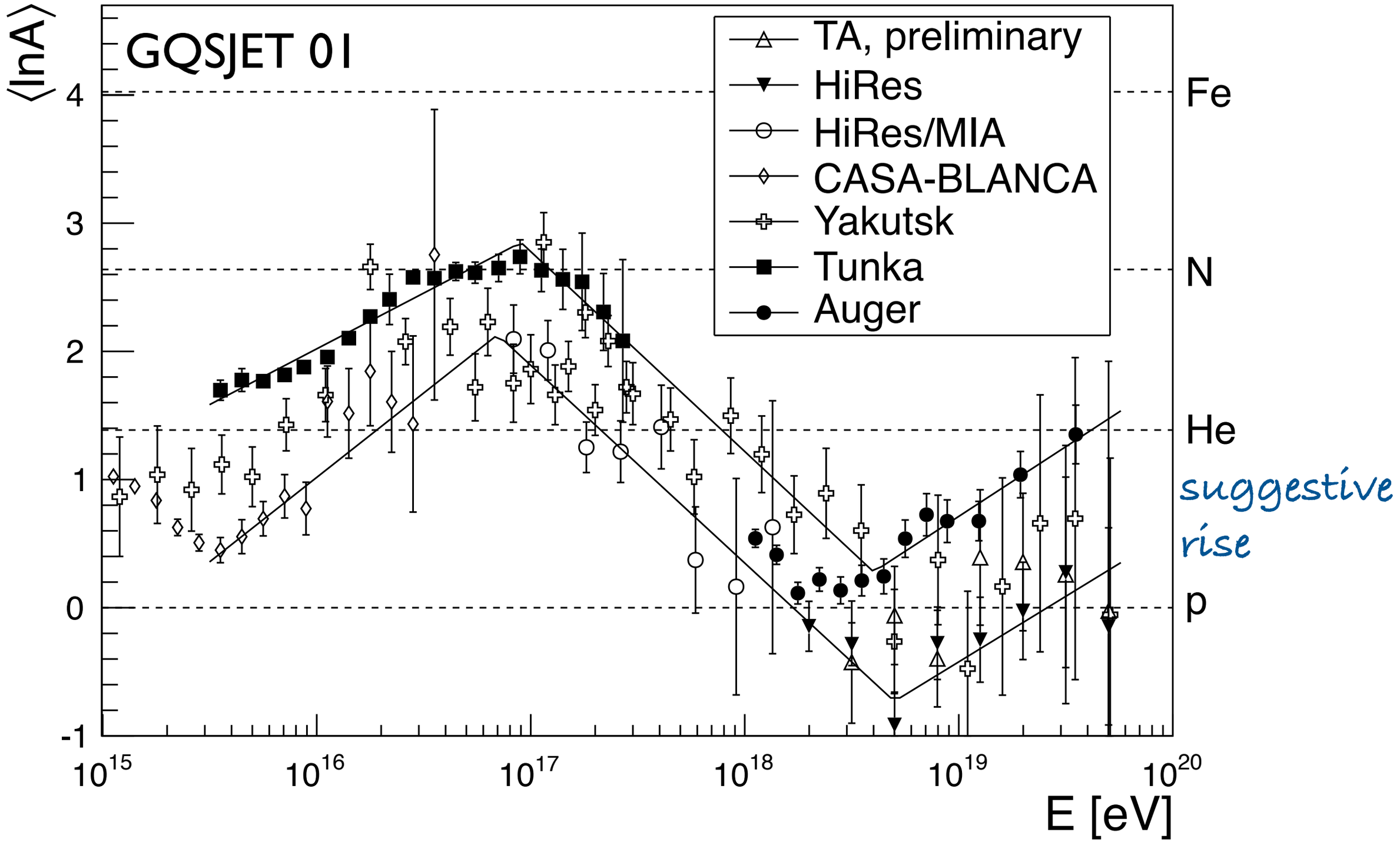
Auger and TA data are not consistent

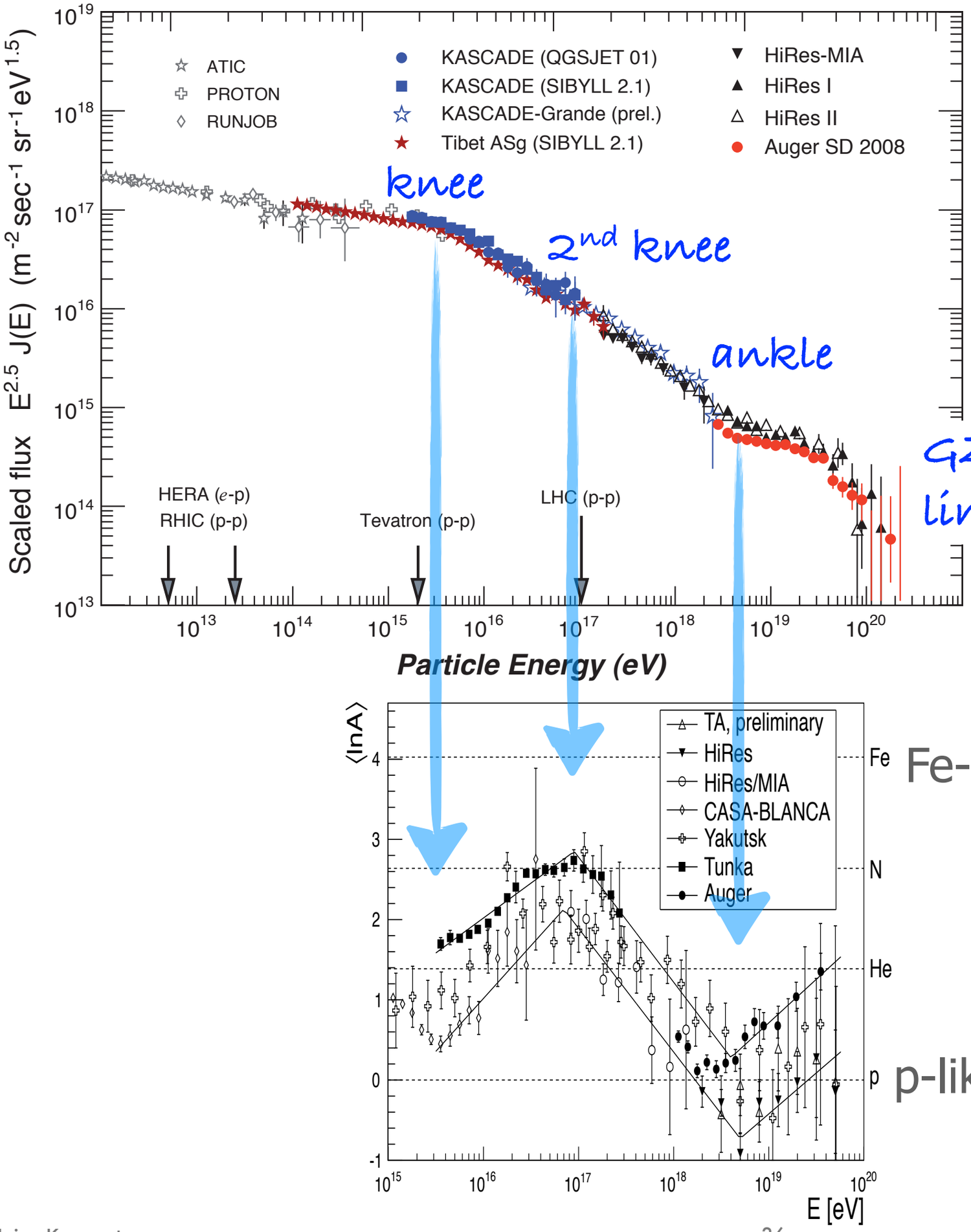
No issue of analyses identified so far

Collaboration working to solve/ understand issue

CR Composition: World Compilation

KHK, Unger APP 35:660 (2012)





Structures in spectrum correlate with change of composition

GZK?
limiting energy ?

Fe-like

p-like

KHK, Unger APP 35:660 (2012)

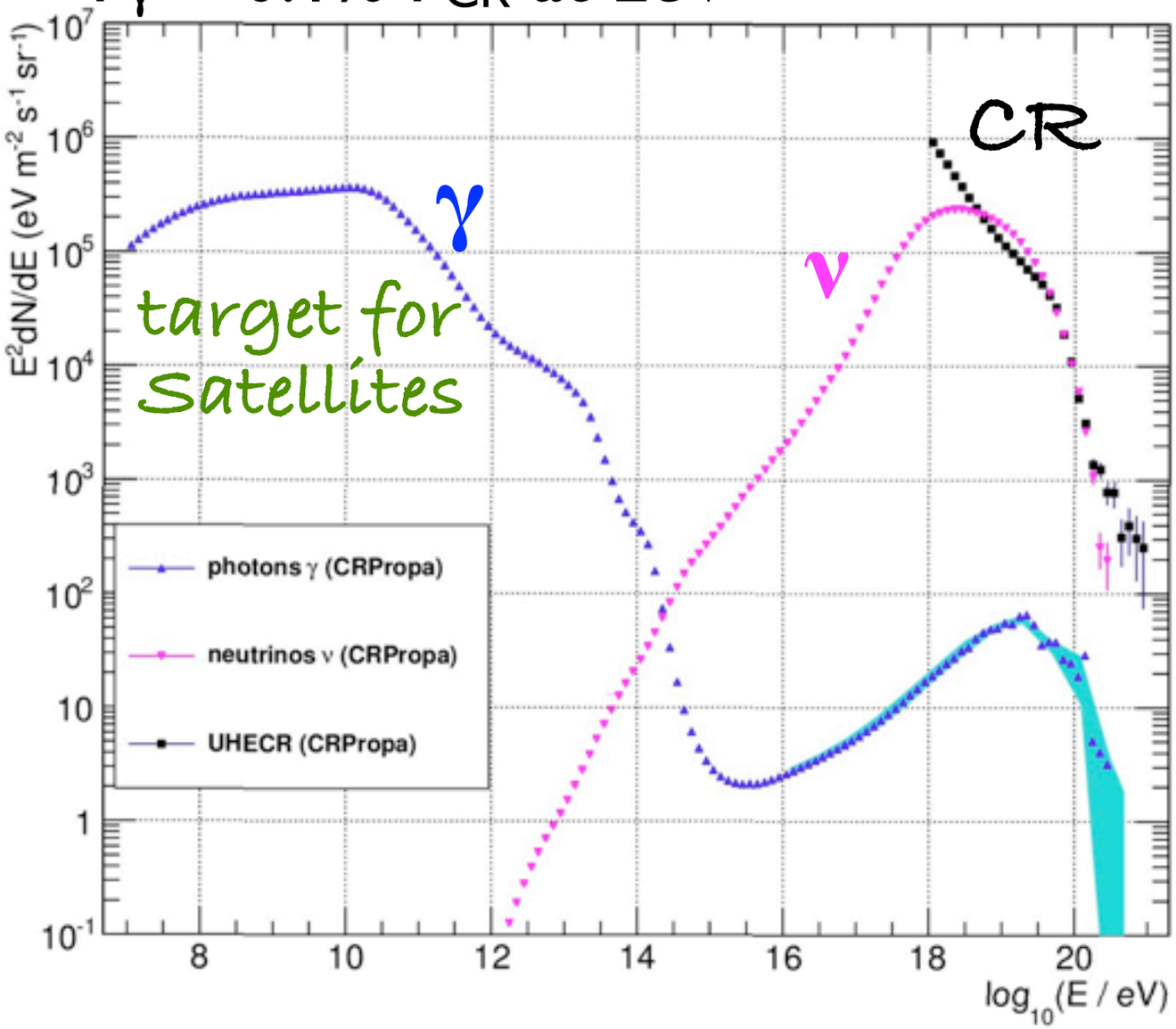
Complementary Info from γ's and ν's

$$p_{cr} + \gamma_{CMB} \rightarrow p + \pi$$
$$\rightarrow \gamma + \nu$$

distant sources:

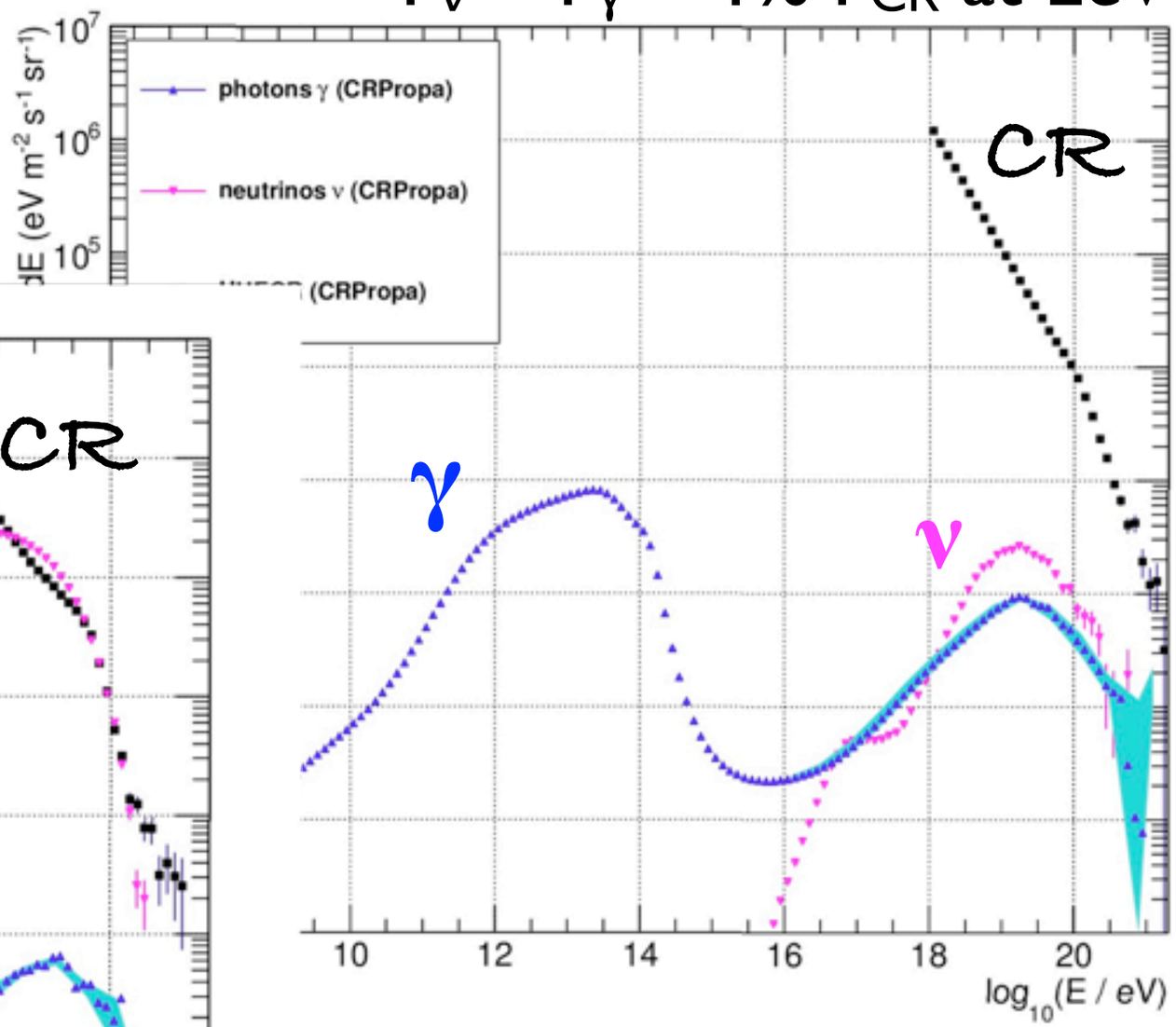
$F_\nu \sim F_{CR}$

$F_\gamma \sim 0.1\%\ F_{CR}$ at EeV



nearby source (10 Mpc) :

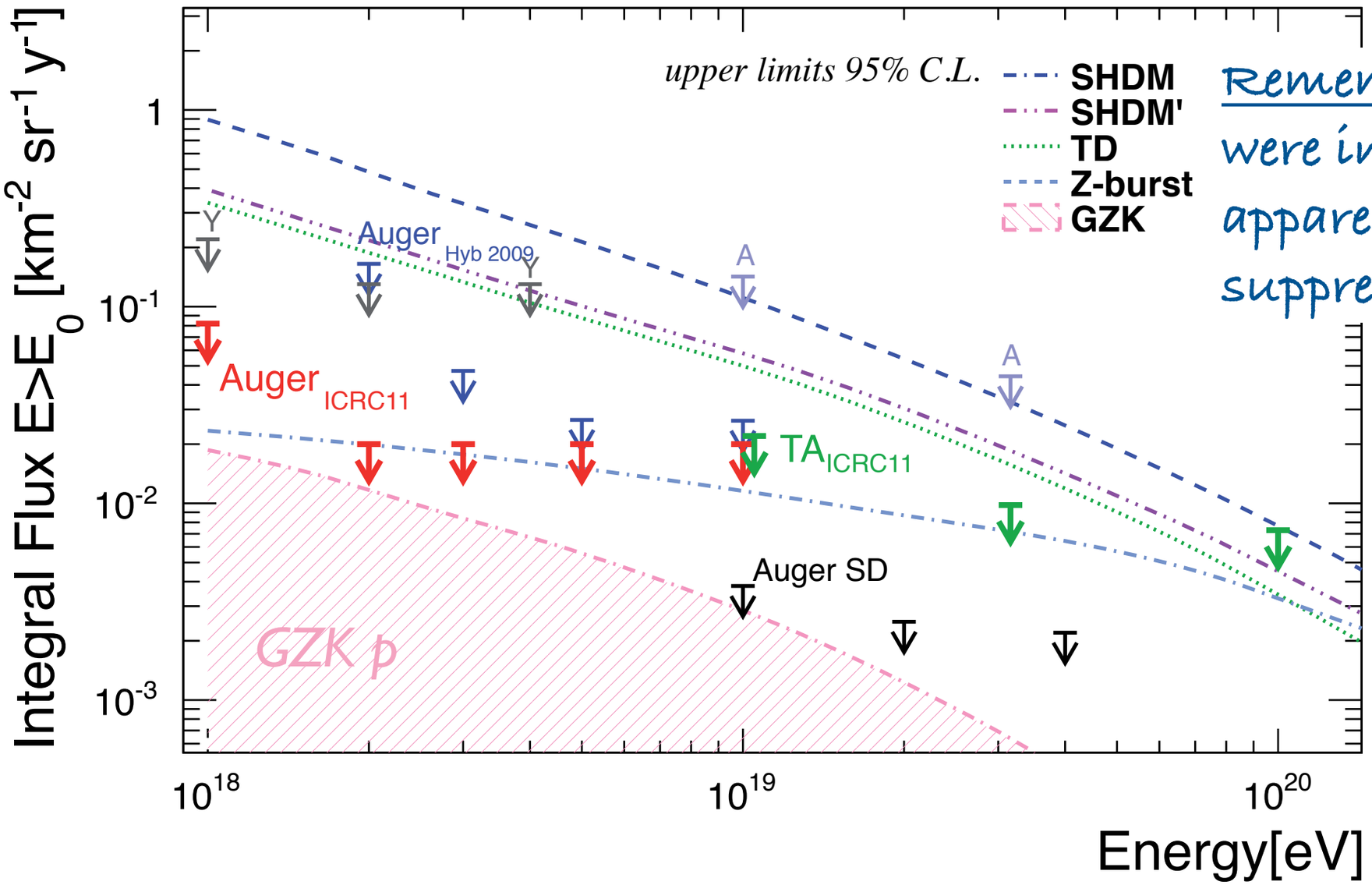
$F_\nu \sim F_\gamma \sim 1\%\ F_{CR}$ at EeV



(N. Nierstenhöfer, A. van Vliet)

Photon Limits

Exotic Models of CR origin disfavored, GZK not yet reached

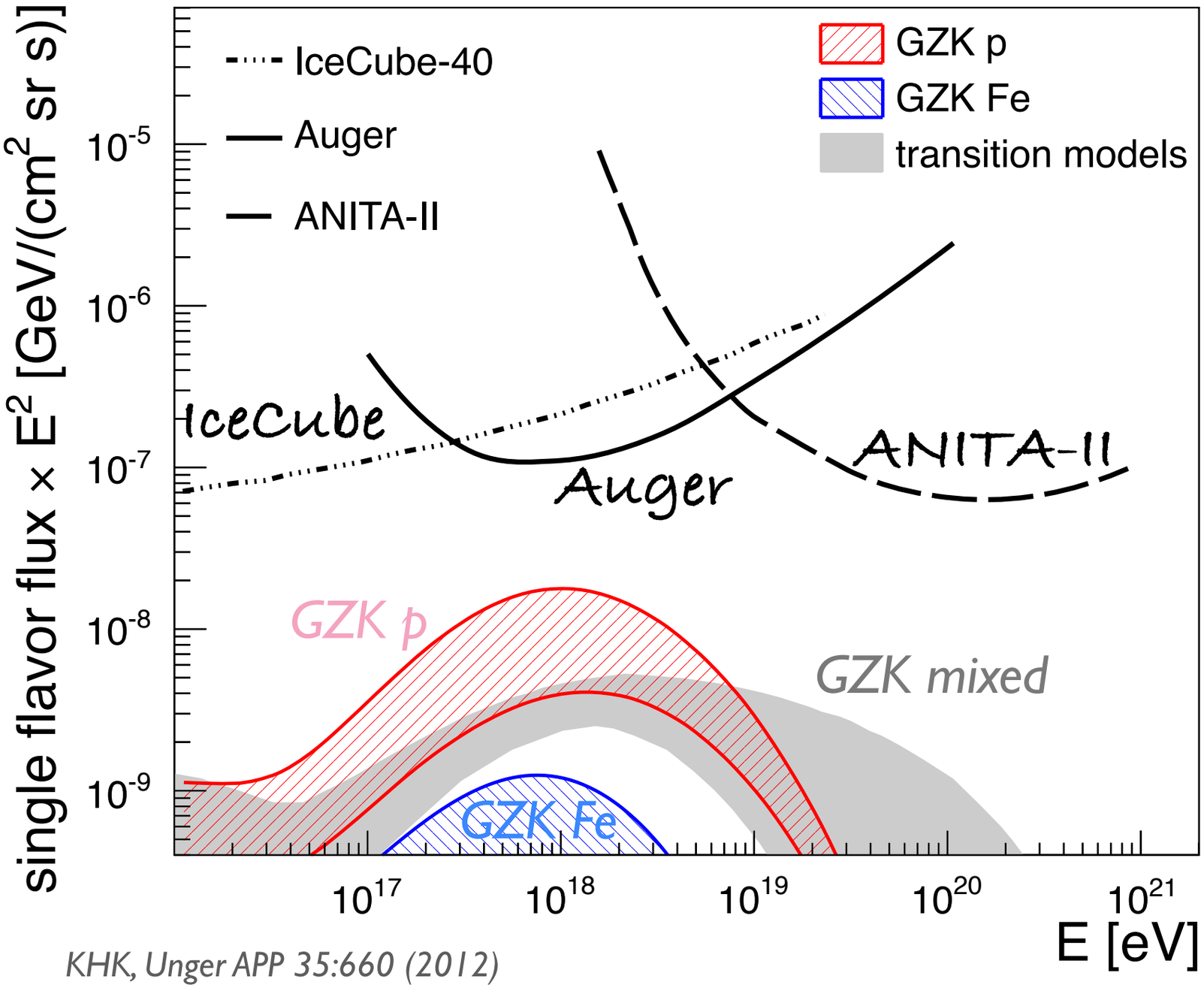


Remember: exotic models were invented to explain apparent absence of GZK-suppression

γ-showers penetrate deeper into atmosphere and contain almost no μ's

GZK γ's may be in reach, if p-sources

Neutrino Limits



KHK, Unger APP 35:660 (2012)

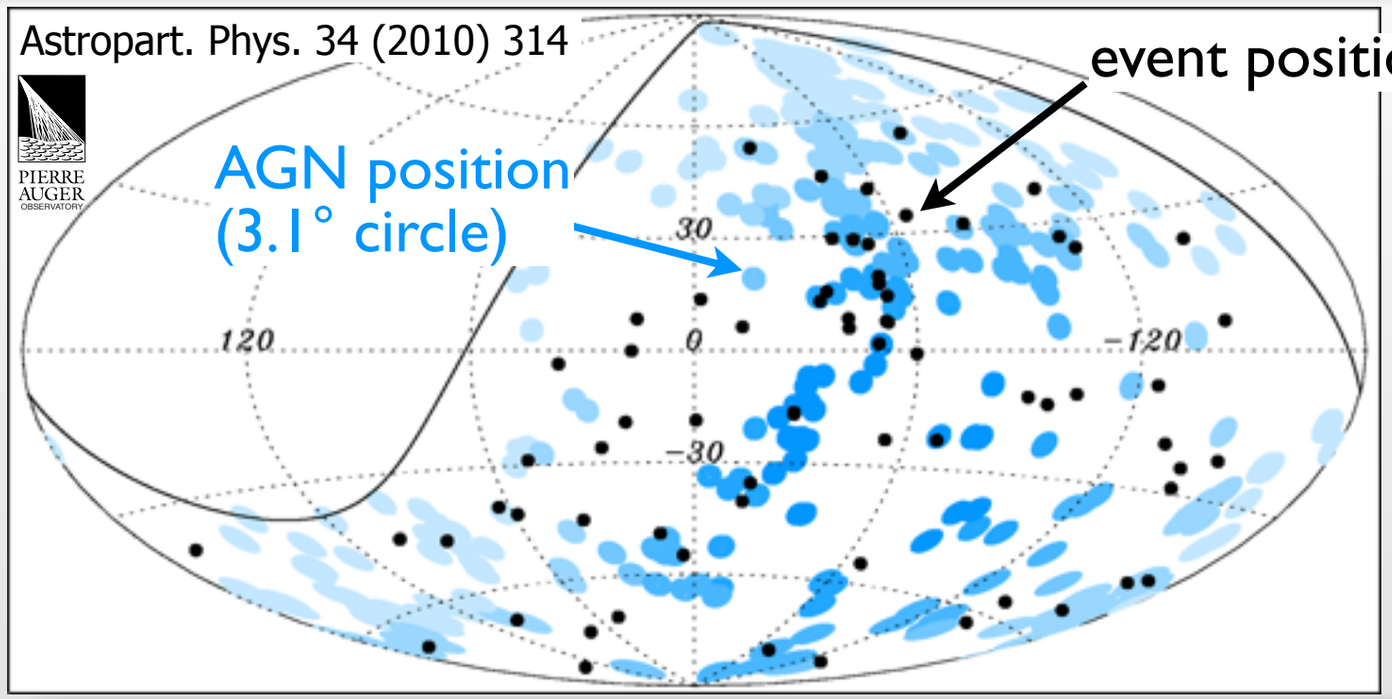
GZK ν's or γ's could be the smoking gun for GZK-effect!

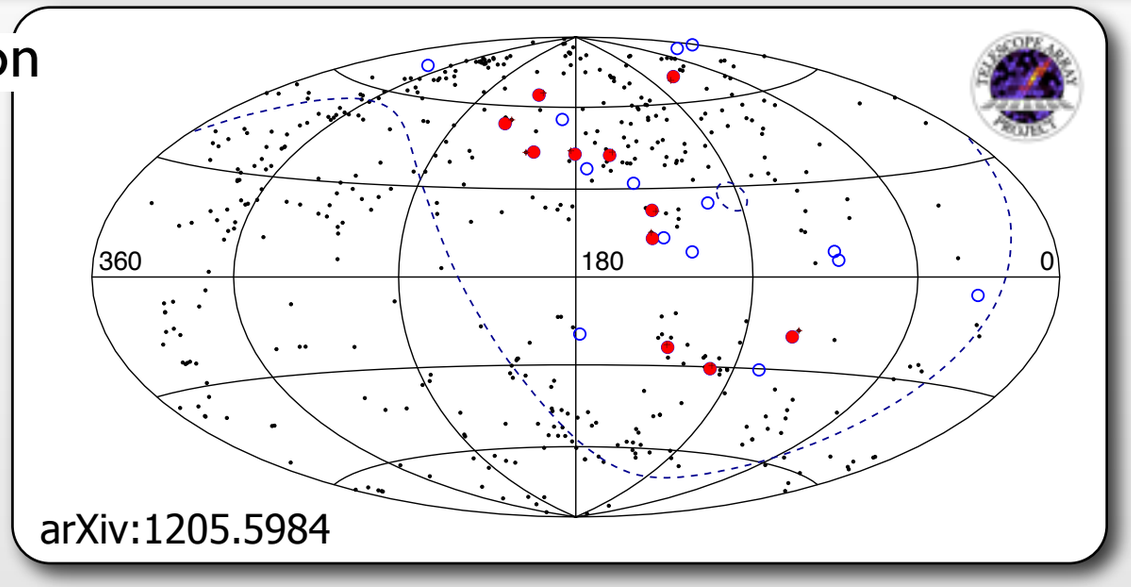
Talk by I.Taboada:

IceCube found 2 ν events but at lower energies, GZK origin very unlikely

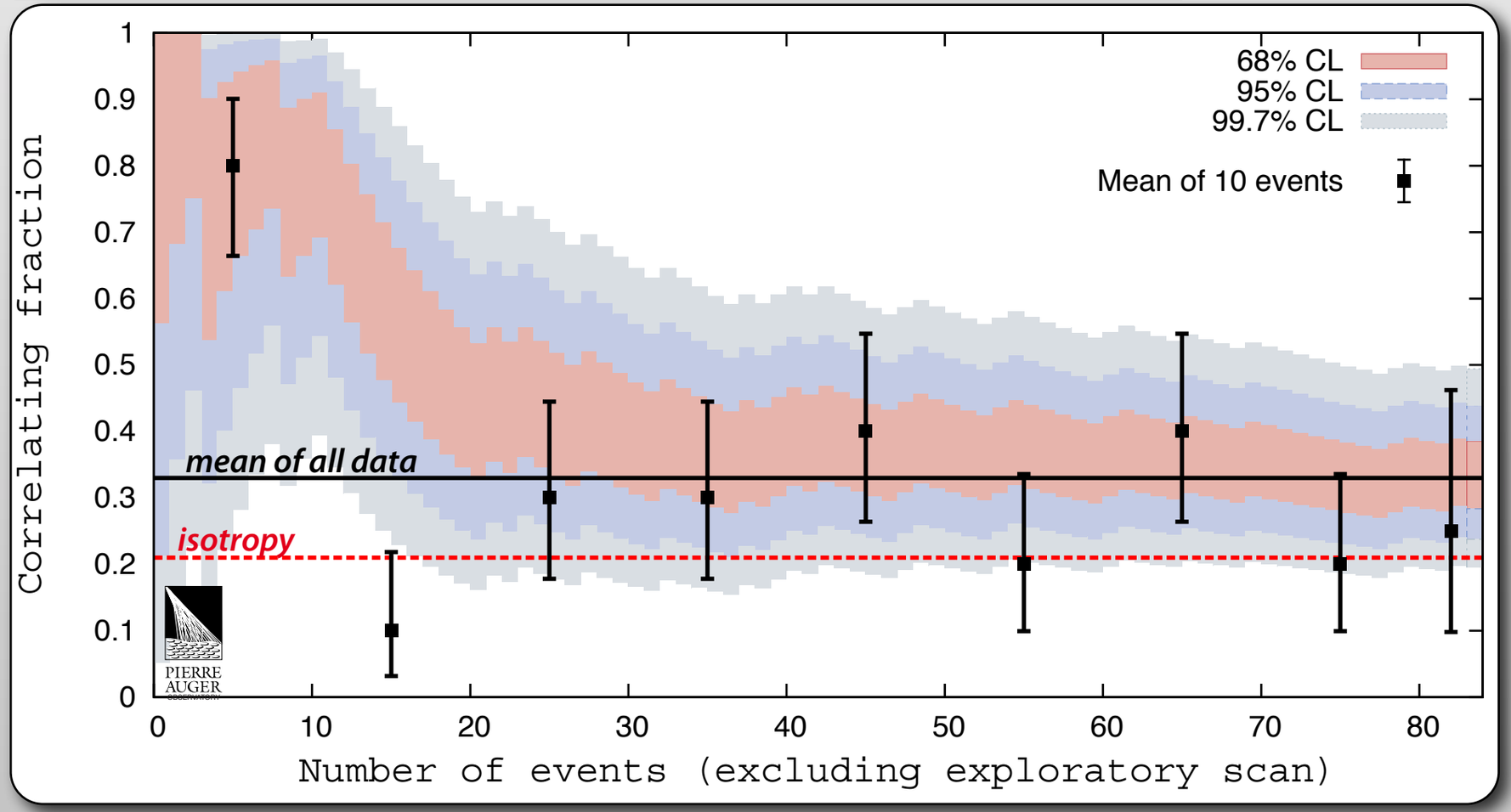
CR Astronomy

Current Status of Correlation with AGN





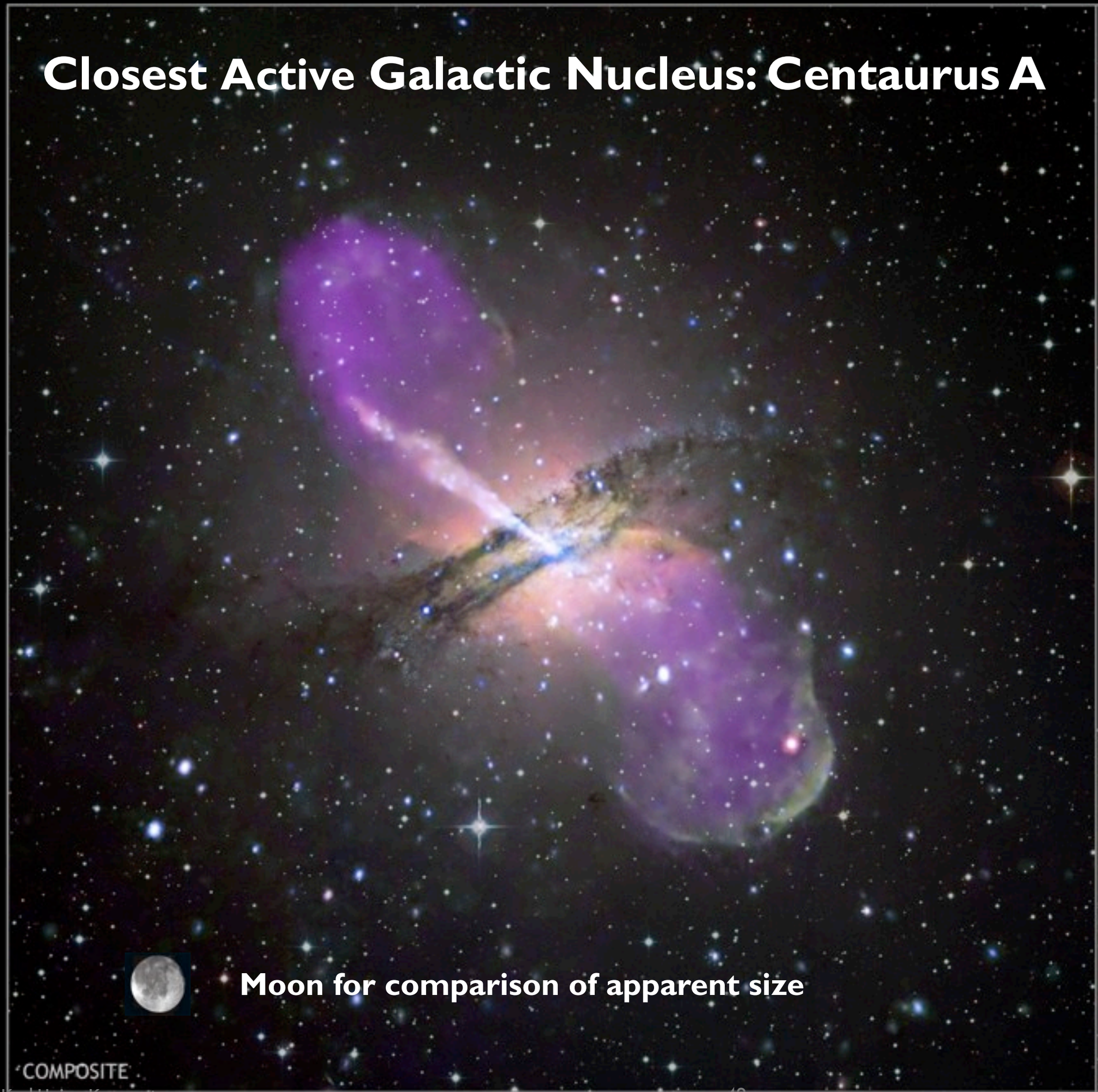
Telescope Array:
11/25 = 44%
with iso-bkg = 24%
→ 2% chance probability
→ agree with Auger



33±5%
Total: 28/84
P=0.006

poster T. Nonaka
talk by S. Westerhoff

Closest Active Galactic Nucleus: Centaurus A

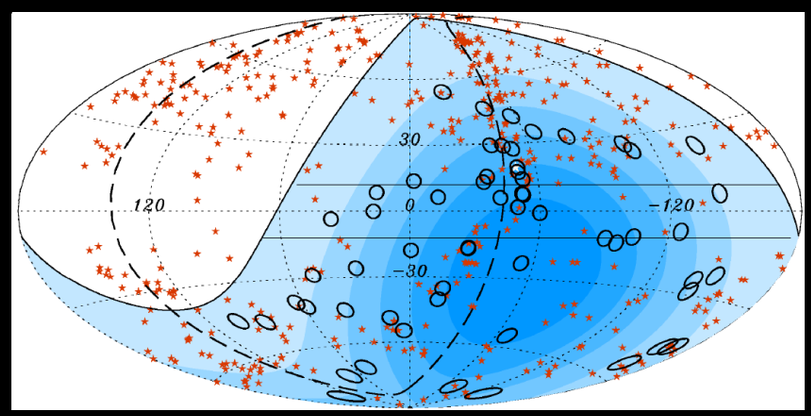


Moon for comparison of apparent size

Cosmic ray constraints

- RGs can accelerate protons to the highest observed energies in the lobes (MJH+ 09, MJH 10) but:
  - Must be FRIs (no FRIIs < GZK)
  - Lobes must be large + luminous (Hillas criterion)
  - Mag. fields in lobes must be >~ equipartition
  - Alfven speeds in lobes must be high
  - Substantial energy in turbulent component of magnetic field.

Martin Hardcastle



A plausible (but disappointing) model: MJH 10

- RG giant lobes are the main or only sources of UHECR acceleration. They operate below the optimal conditions – protons get up to ~ 10^{19} eV and light nuclei to ~10^{20} eV.
- The accelerated particle popula… entrained by the jet on kp… **metal-enriched** by stella…
- Light nu… giant lobes of Cen A (3.7 M… excessively deflected and can be … excess (Liu+ 12).
- … other sources' light nuclei at larger distances will be deflected by IG mag fields… no other discrete source will ever be detected.

… but origin of UHECR would be answered !

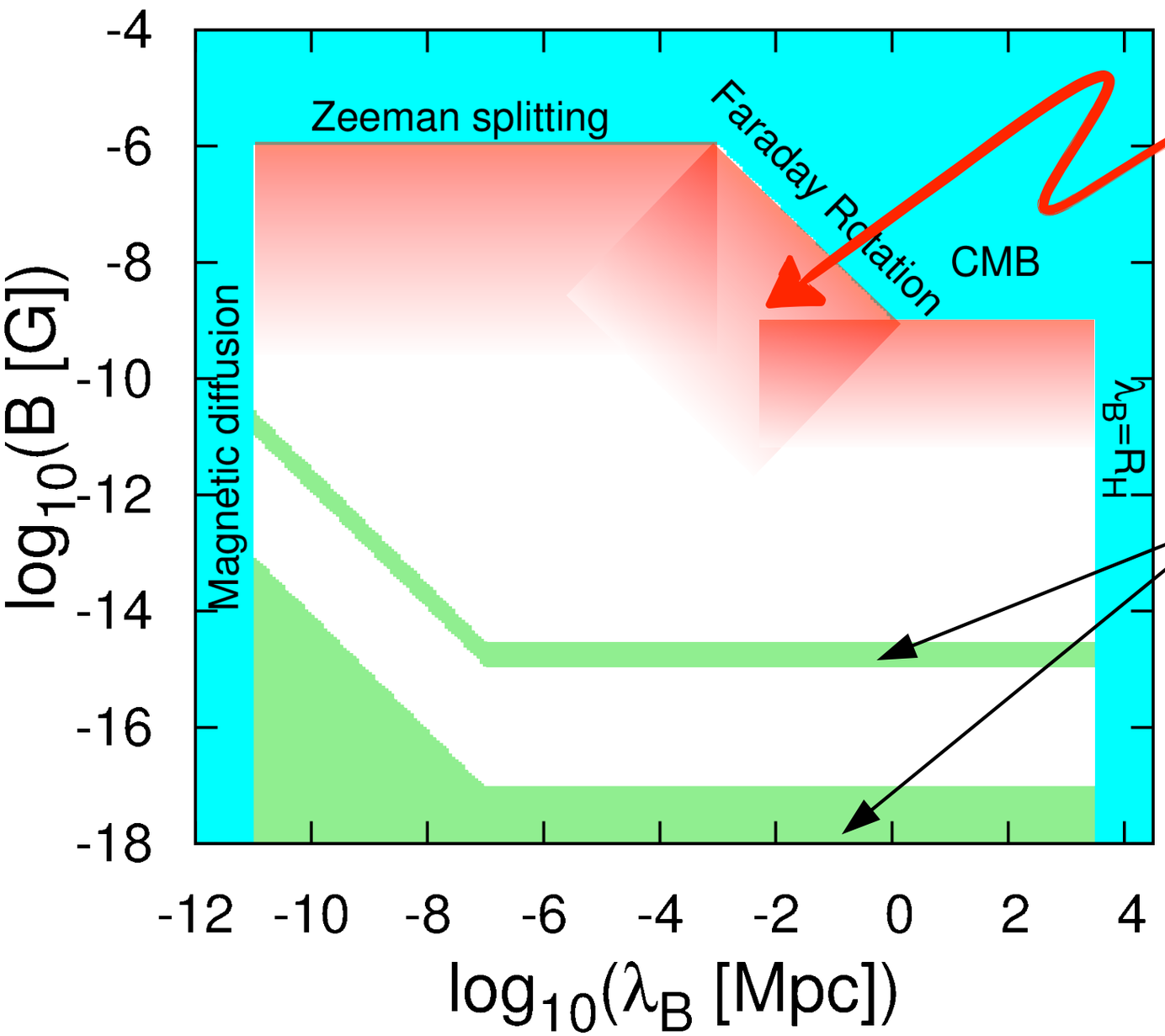
Martin Hardcastle

A slightly altered plausible model

- RG giant lobes are the main or only sources of UHECR acceleration. They operate up to their limits
  – protons get up to ~ 10^{19} eV and light nuclei to ~10^{20} eV.
- The accelerated particle population is the matter entrained by the jet on kpc scales – **significantly metal-enriched** by stellar winds.
- Light nuclei originating in the giant lobes of Cen A (3.7 Mpc away) will not be excessively deflected and can be detected as an excess.
- But other sources' light nuclei at larger distances will be deflected by IG mag fields ~~– no other discrete source will ever be detected.~~

really depends on EGMF and E_{max}

Strength of EGMF



critical region

Andrew Taylor

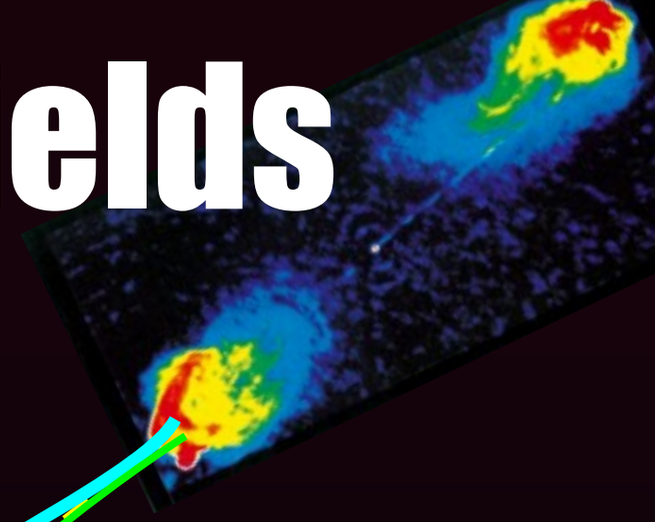
New exclusion regions from Blazar measurements

related: *Alexander Kusenko*

CR Deflections in B-Fields

Cosmic Magnetic Fields

R_L = kpc Z^{-1} (E / EeV) (B / μG)$^{-1}$
R_L = Mpc Z^{-1} (E / EeV) (B / nG)$^{-1}$



γ, n

weak deflection
E > 10^{19}eV

Halo B?

Milky way
B ~ μG

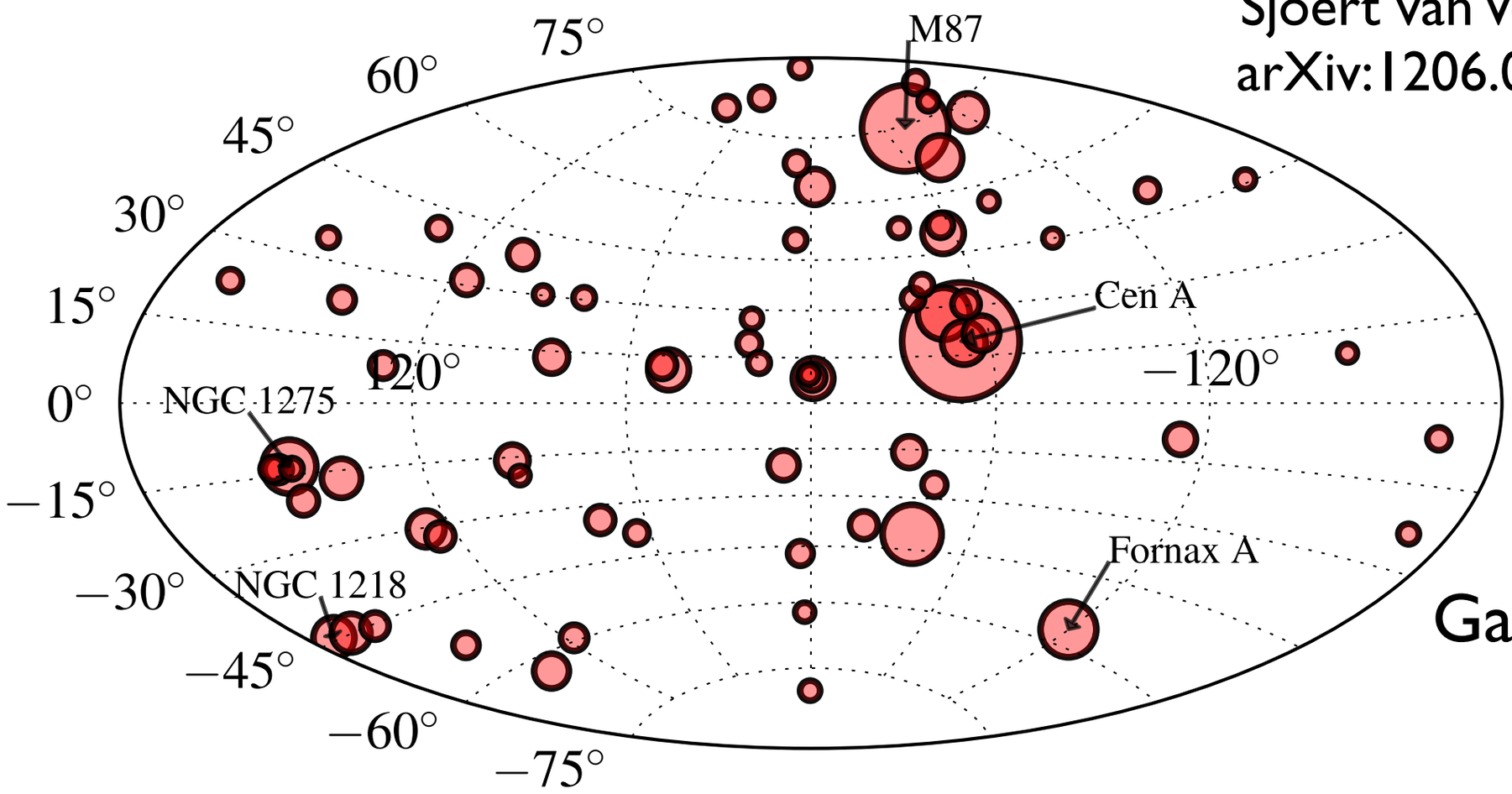
strong deflection
E < 10^{18}eV

Extra-galactic B < nG ?

$$\theta(E,Z) \approx 0.8^\circ \left(\frac{10^{20}\ \mathrm{eV}}{E}\right) \sqrt{\frac{L}{10\ \mathrm{Mpc}}} \sqrt{\frac{L_{\mathrm{coh}}}{1\ \mathrm{Mpc}}} \left(\frac{B}{1\ \mathrm{nG}}\right) \cdot Z$$

Volume limited all-sky catalog of RG

Sjoert van Velzen, KHK, et al.
arXiv:1206.0031, ApJ in press



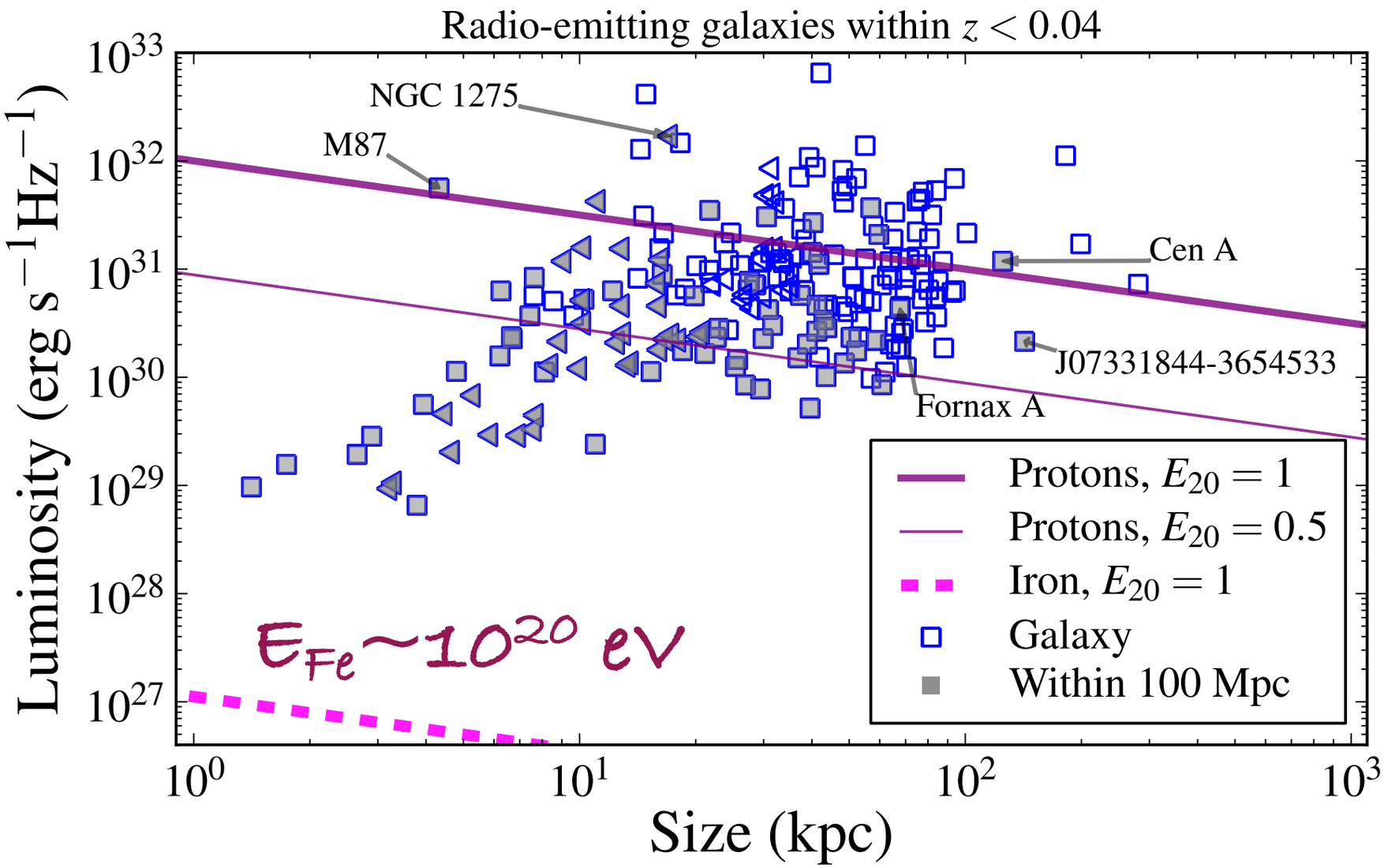
constructed from NVSS and SUMSS radio surveys + 2MASS Redshift Survey (2MRS)

Galactic coordinates

- $z < 0.03$
- $K > 11.75$ & ($F_{1400} > 213$ mJy or $F_{843} > 289$ mJy)
- total of 575 sources
- area of circles ~ radio flux of the source

Hillas Diagram of RG

Sjoert van Velzen et al. (work in progress)



$E_p \sim 10^{20}$ eV

$\sim 5 \cdot 10^{19}$ eV

Magnetic field inferred from radio luminosity and size

$$B = \left(\frac{L_\nu / \epsilon}{10^{31}\ \mathrm{erg\ s^{-1} Hz^{-1}}} \right)^{2/7} \left(\frac{R}{100\ \mathrm{kpc}} \right)^{-6/7} \left(\frac{\nu}{\mathrm{GHz}} \right)^{1/7} \mu\mathrm{G}$$

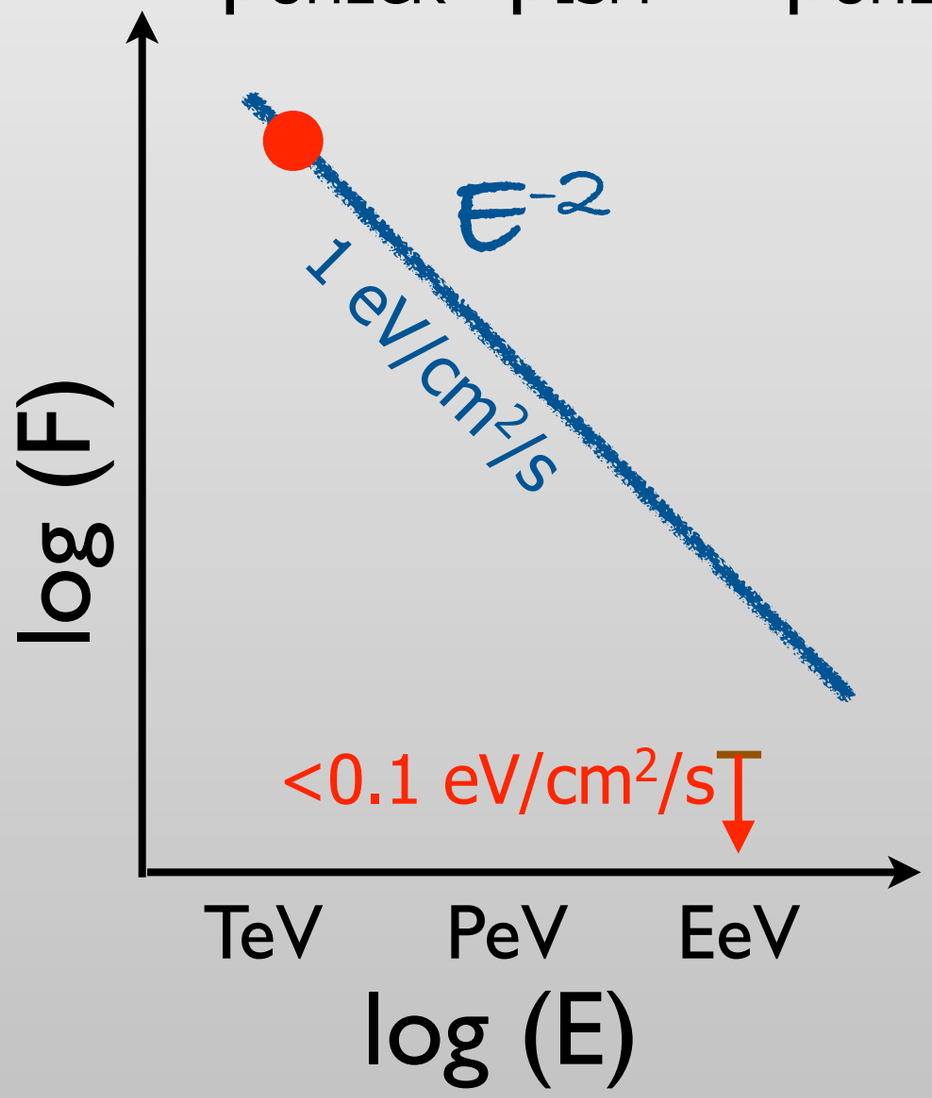
Neutron Astronomy

d_{decay} = 9.2 kpc × E (EeV)

→ above 2 EeV see most of galactic disk

produced more efficiently than γ's from π^0:

- $p_{UHECR} + p_{ISM} \rightarrow n_{UHECR} + p_{ISM} + \pi^+$ (n takes most of energy)
- $p_{UHECR} + p_{ISM} \rightarrow p_{UHECR} + p_{ISM} + \pi^0$ (π^0 takes small energy only)



→ galactic TeV sources should plausibly produce neutrons

energy flux some γ sources exceed 1 eV/cm²/s at Earth

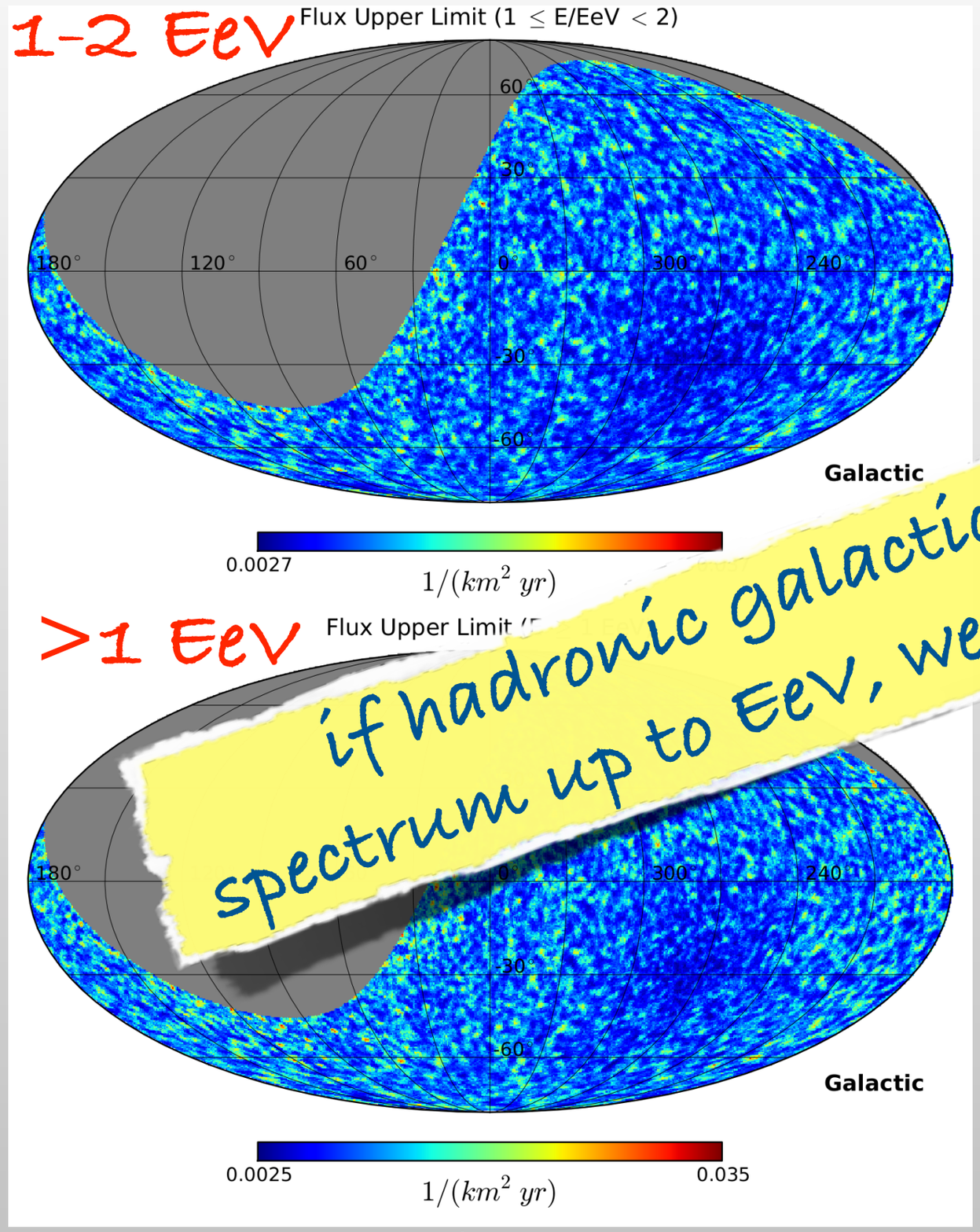
→ assuming E^{-2} spectrum expect also 1 eV/cm²/s @ EeV energy

upper limits of neutrons further down by more than a factor of 10!

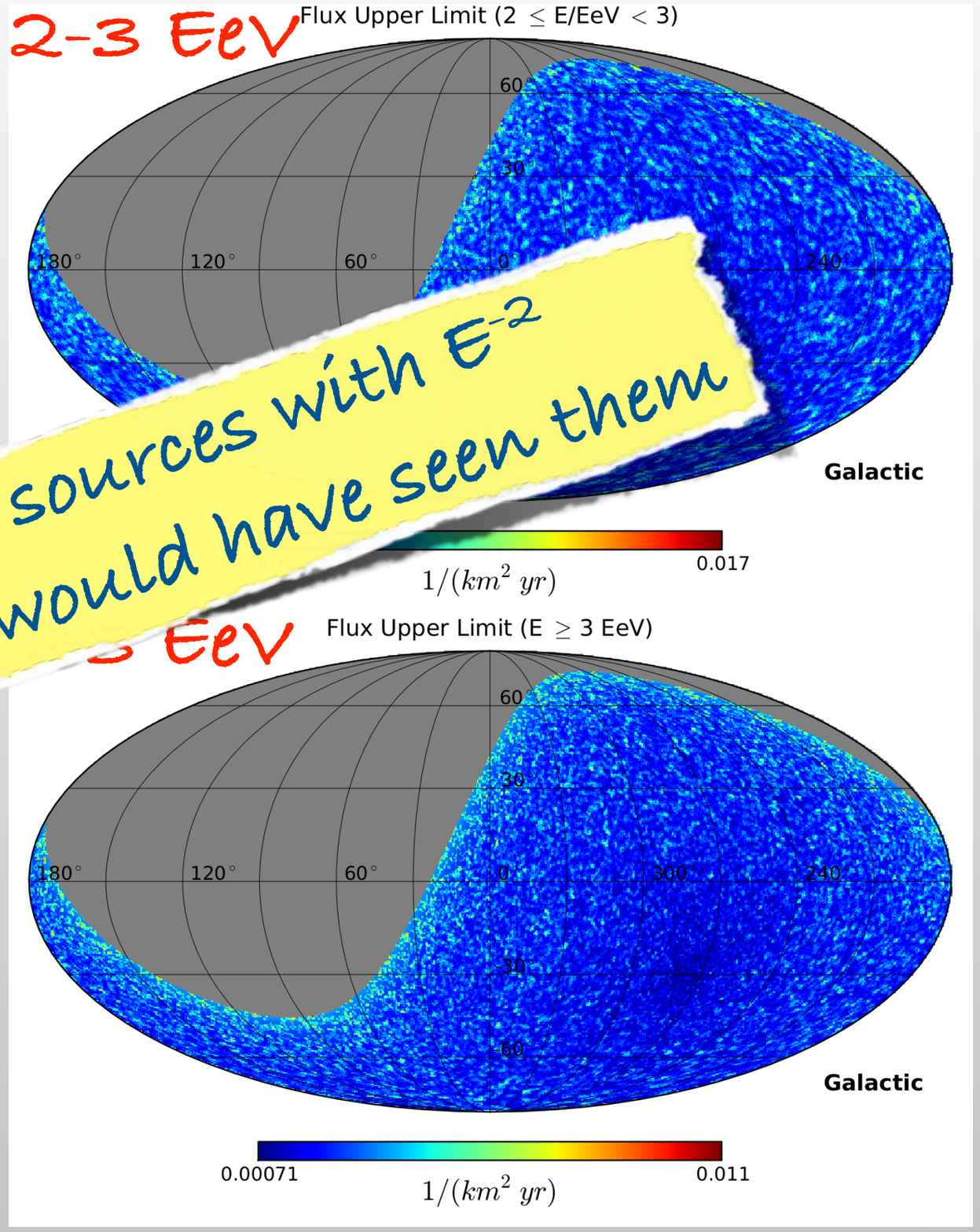
Neutrons Upper Limit Sky-Maps

Auger (ICRC 2011), submitted to Journal

1-2 EeV



2-3 EeV



>1 EeV

EeV

if hadronic galactic sources with E^{-2} spectrum up to EeV, we would have seen them

Where do we go at highest energies...

- **Ground based observatories** (Auger, TA, Yakutsk) have formed **joint working groups** with joint analysis of data
- **Upgrades** of present observatories
  - mostly to enhance capabilities
- Ongoing R&D program for **future ground based World-Observatory**
  - understanding the origin of UHECR will require high precision data
  - opportunity for doing particle physics at $E_{cms} = 10 \times E_{LHC}$
- **... and rich physics (astro)program to be exploited by running observatories**

UHECRs γ1912+100

Sorry, Victor, we couldn‘t find the sources yet...
... but we can smell them!

- 2nd („Fe“)-knee now established
- rich structure in the energy spectra, no simple power-laws
- no exotic models of UHECR origin needed
- Flux suppression unambiguously established
  - Is it the GZK suppression or limiting source energy ?
- Composition may provide the key
  - No unambiguous conclusion yet
  - No composition data for highest energies > 5×10^{19} eV
- Indications for weak anisotropy
- Particle physics with air showers
  - Model predictions bracket LHC data
  - Extension of energy range beyond LHC possible
  - Deficit in predicted number of muons at ground

} not addressed at this meeting