Searching for the Origin of UHECR with Michael Hillas (Aug 2014- Dec 2016)

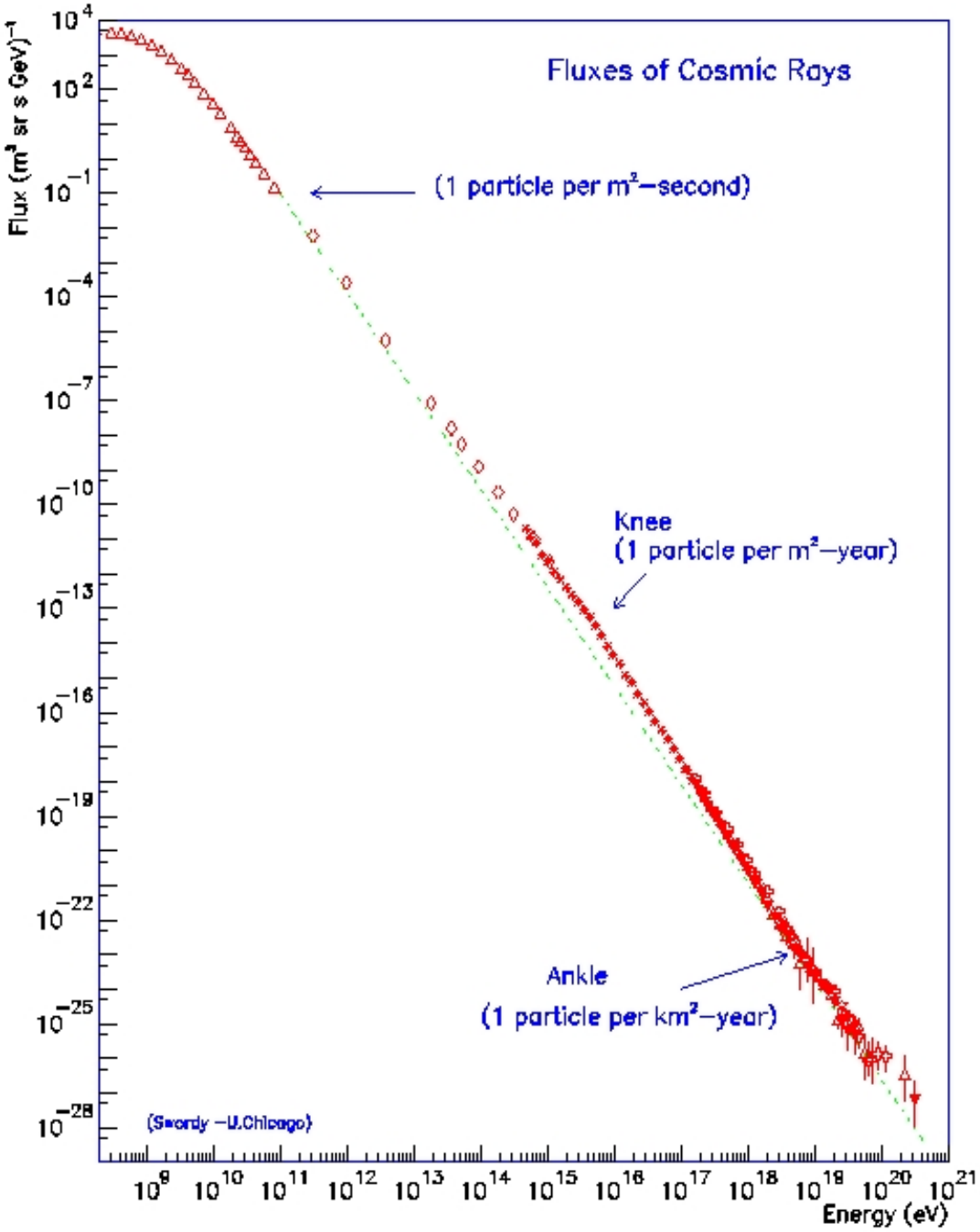
Andrew Taylor

Michael's Painting-
Renoir's Nightmare!

Andrew Taylor

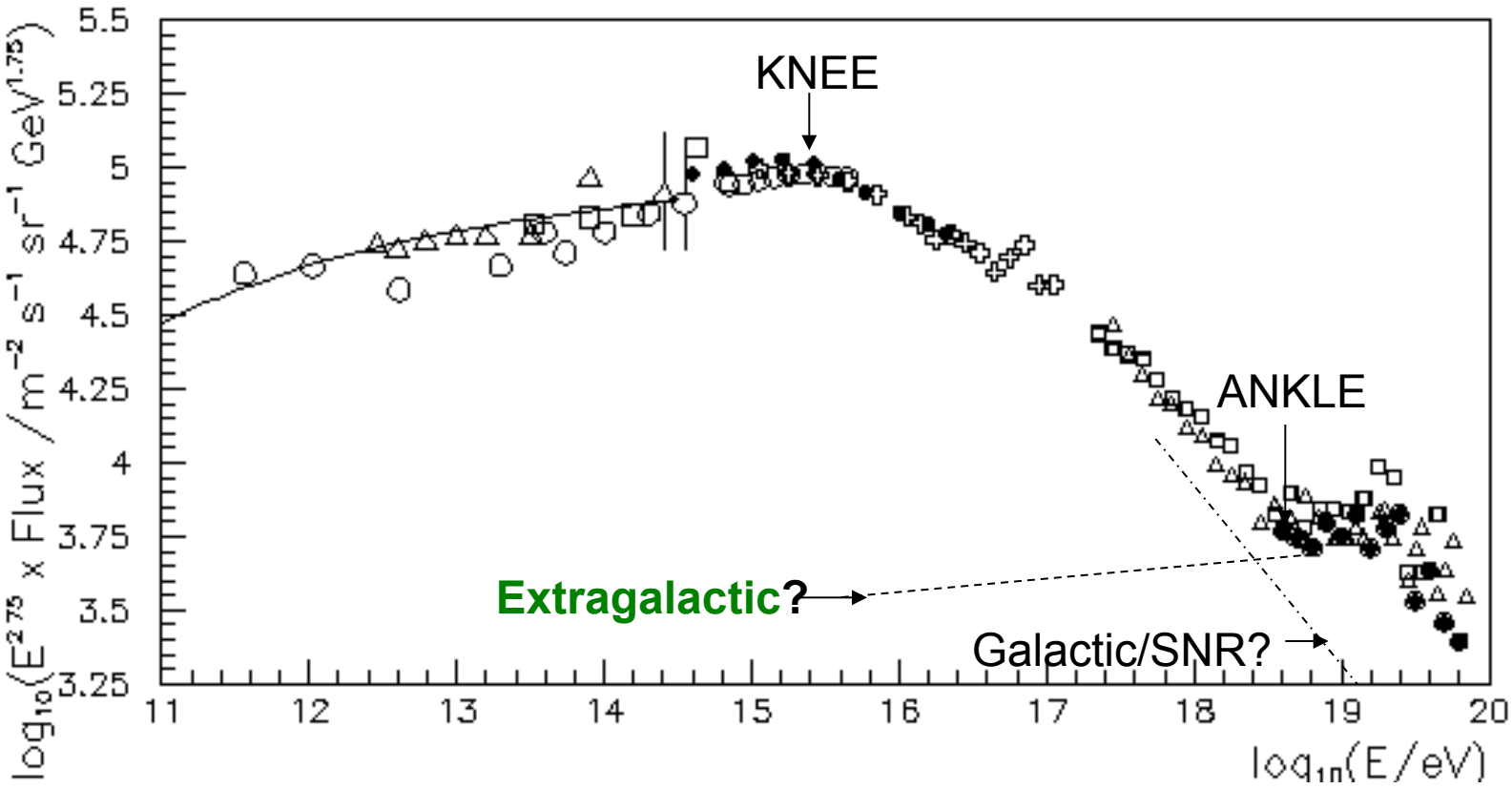
Meeting at Dunsink (2014)

Cosmic Ray Spectrum



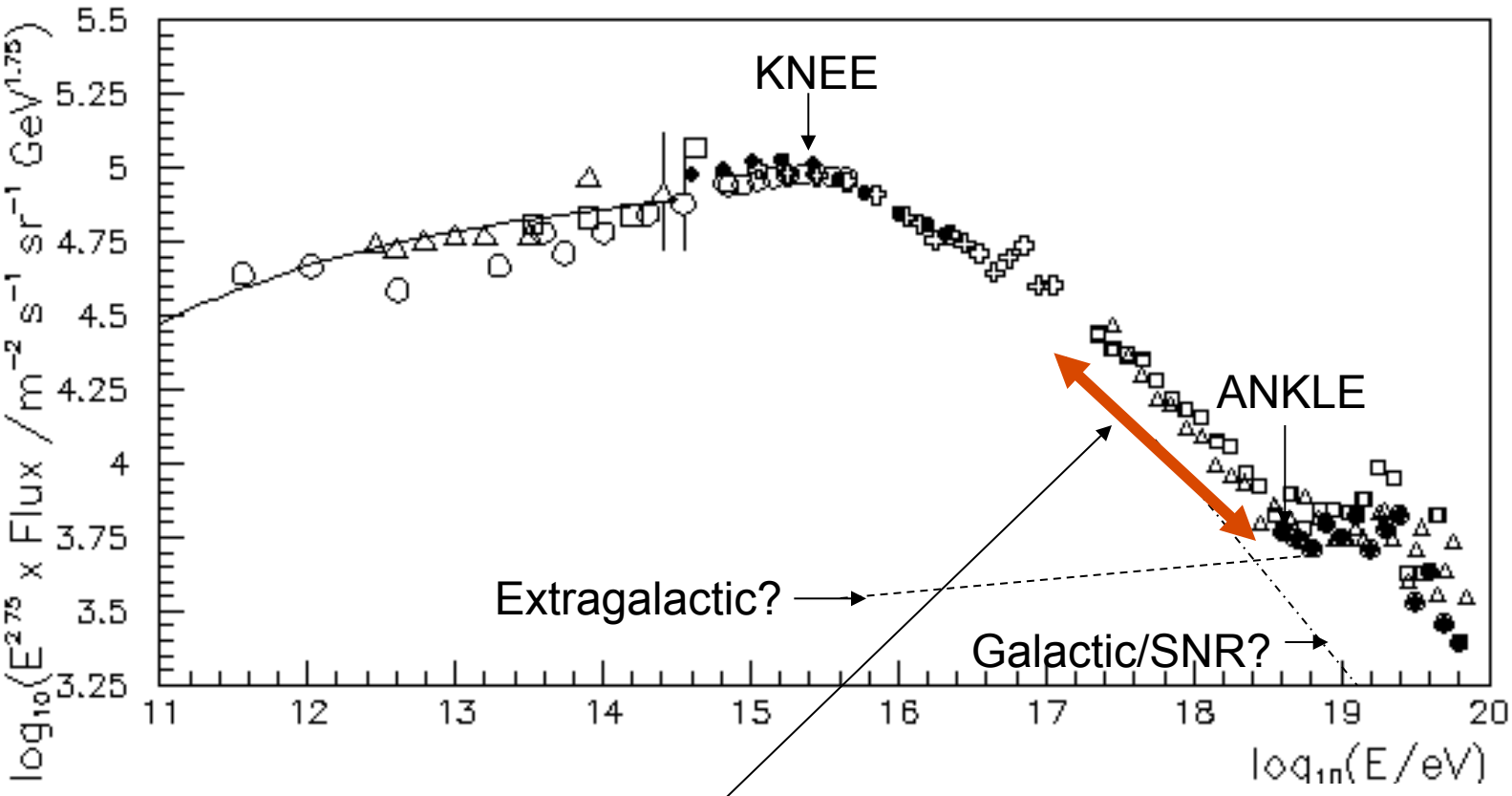
It is surprising how much detail lurks here

Enlarged Plot To Show Bend in Spectrum



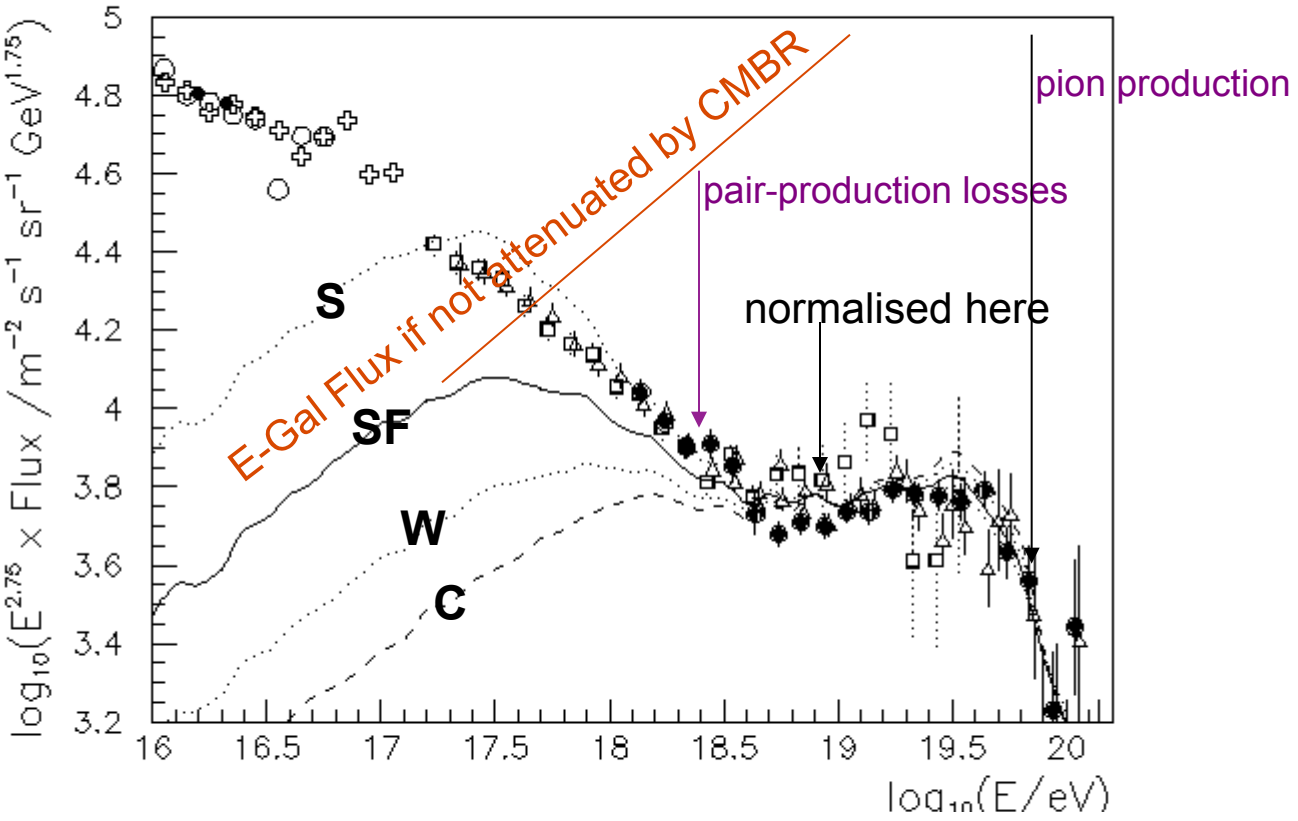
The knee and ankle bends show up, but it is probable that this traditional **interpretation** of the ankle greatly underestimates the low energy presence of extragalactic cosmic rays.

. . An Obvious Interpretation of a Graph is Not Always Right!



Observations at Haverah Park and elsewhere looked for signs (anisotropy) that the Galactic particles were increasingly leaking away, but found none. Michael thought the particles were already largely extragalactic- why?

Particles From Extragalactic Sources



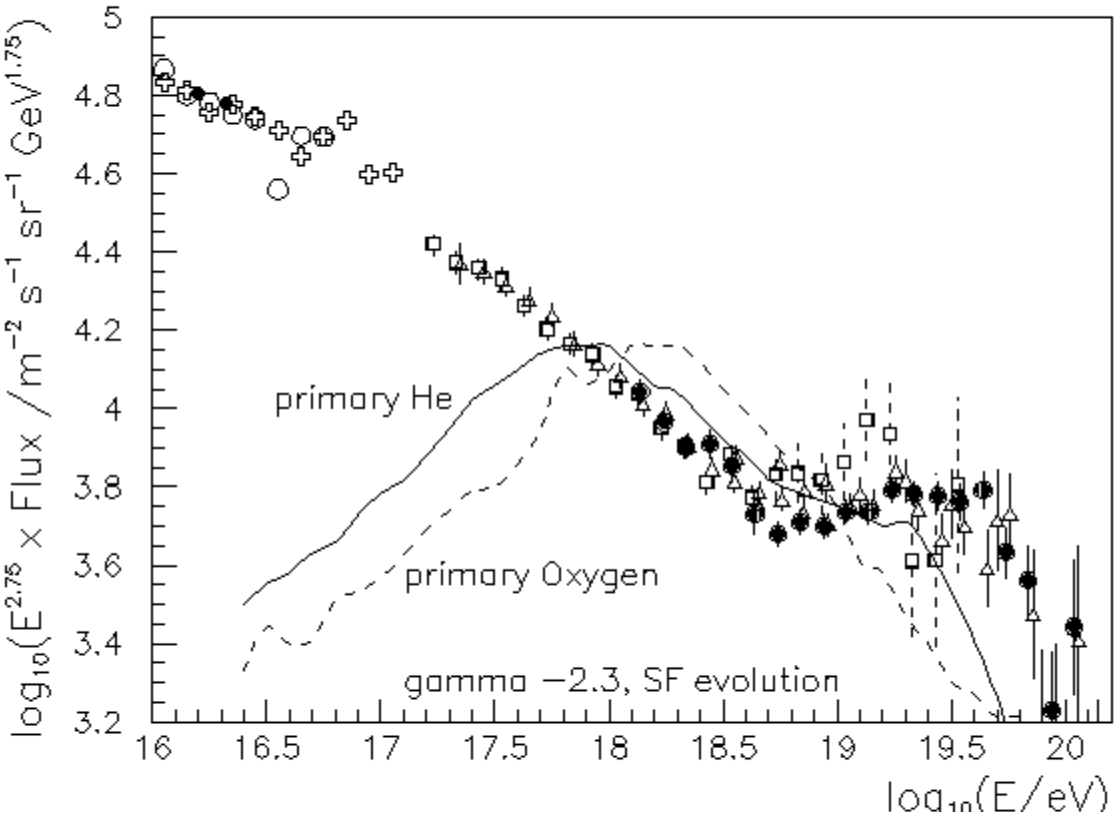
Spectrum of protons after struggling through the microwave treacle:

If initial spectrum dN/dE ~ $E^{-2.3}$,

Production rate in universe: **SF** = like Porciani-Madau star formation rate SF2; **C**=constant; **W**=PM $^{0.5}$; **S**= PM $^{1.5}$

The (e^+e^-)energy losses in CMBR produce an ANKLE in right place.

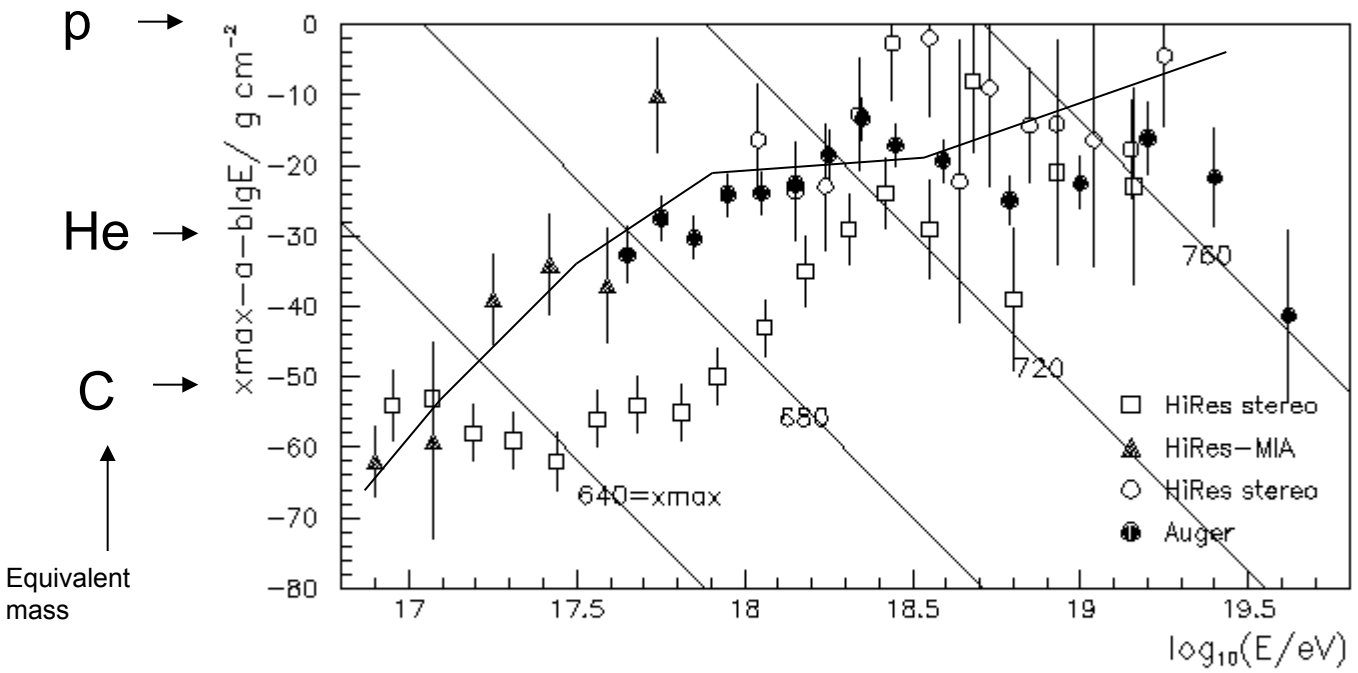
Particles From Extragalactic Sources



And this is the flux that reaches us if one starts with He or O nuclei instead if protons: they also suffer nuclear fragmentation. (Reaction thresholds at different place.)

NOTE- the energy losses do not produce the ankle feature.

Can We Detect The Change To Light Nuclei Near 3×10^{17} eV?



The x_{max} test (depth of maximum of extensive air shower)

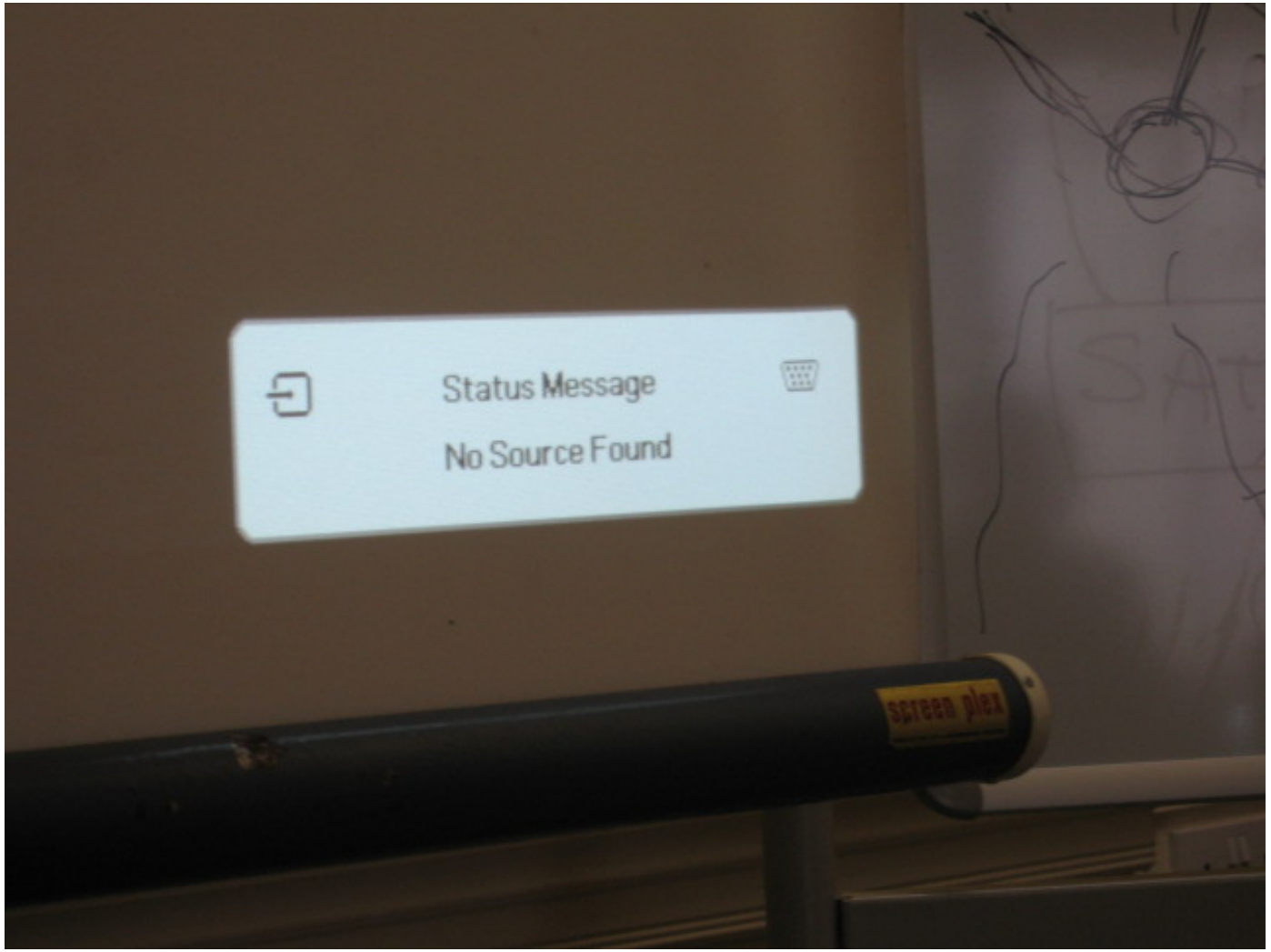
(If the primary particle is a large nucleus, the individual nucleons have less energy and their showers die out at a lesser atmospheric depth.)

Here, "x_{max}" – a – b.logE is plotted to make the line horizontal if the nuclear mass is unchanged with energy. *(b is the "elongation rate"; a is arbitrary.)*

(Line is "best spectrum fit" 5%-of-normal He and metals.)

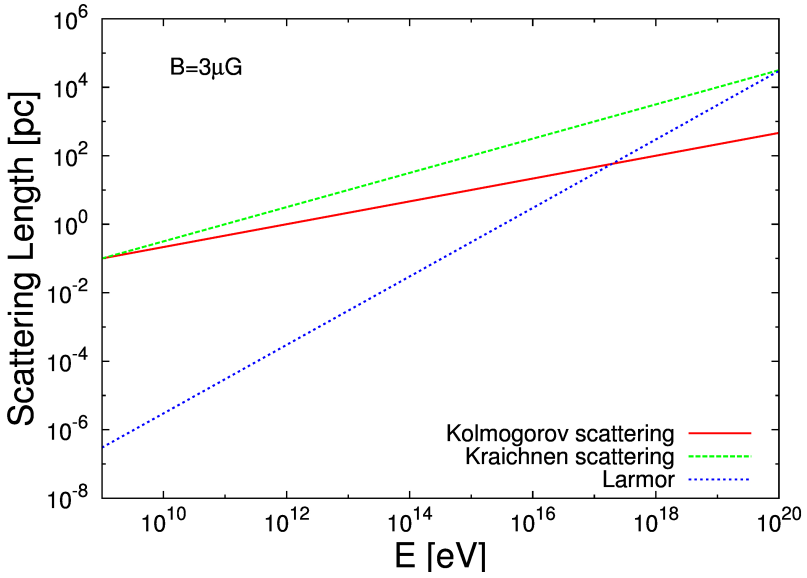
The older pioneering "Stereo Fly's Eye" data look discordant: there does appear to be a rapid change to light nuclei here.

Michael's Conclusion!

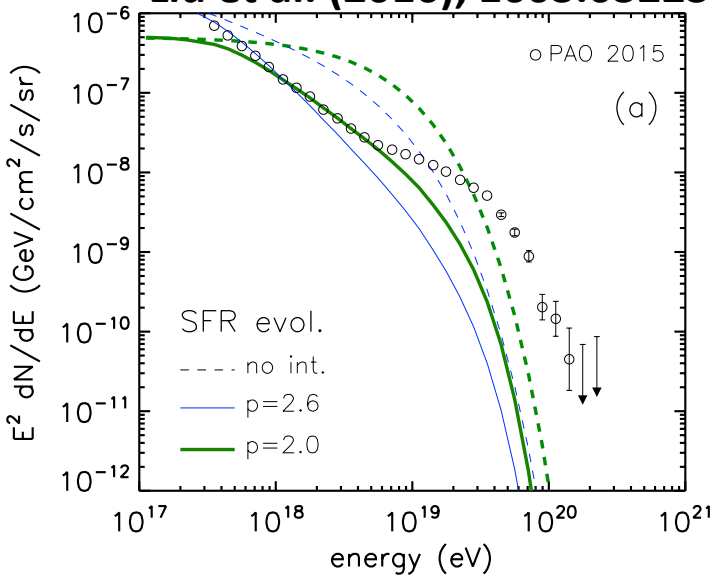


Michael's poignant wit!

My Own Motivation for Considering Extragalactic Cosmic Rays Below the Ankle

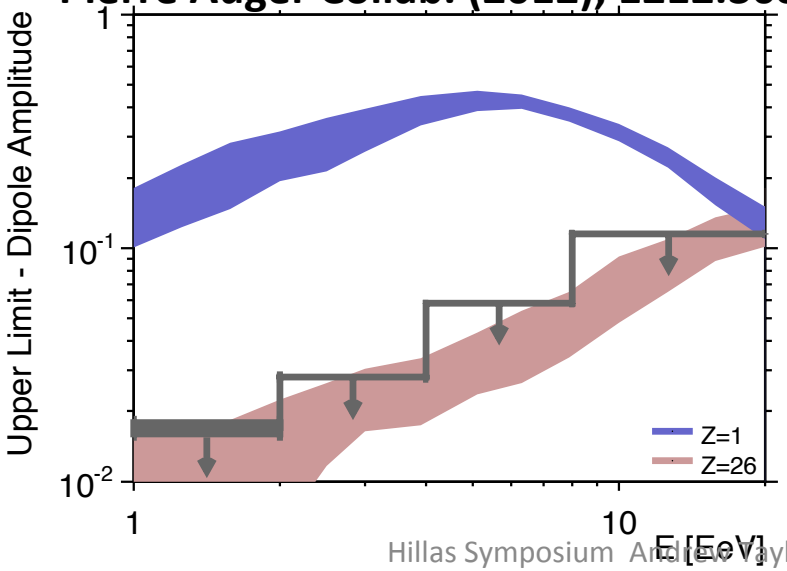


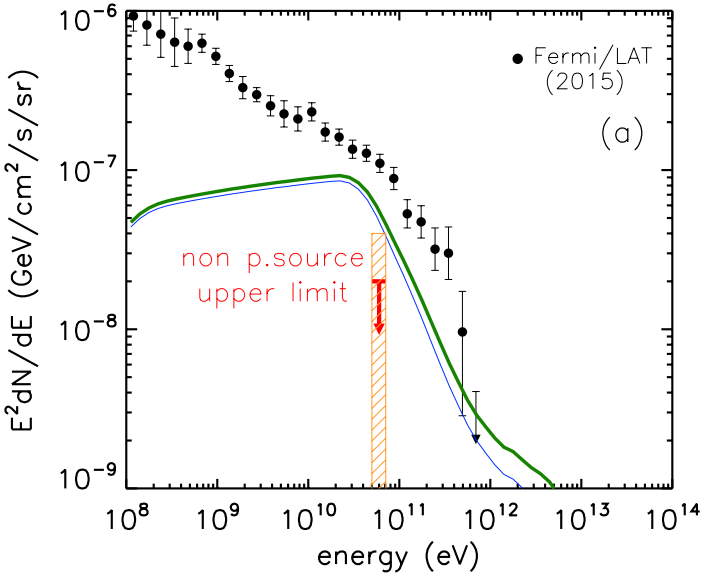
Liu et al. (2016), 1603.03223



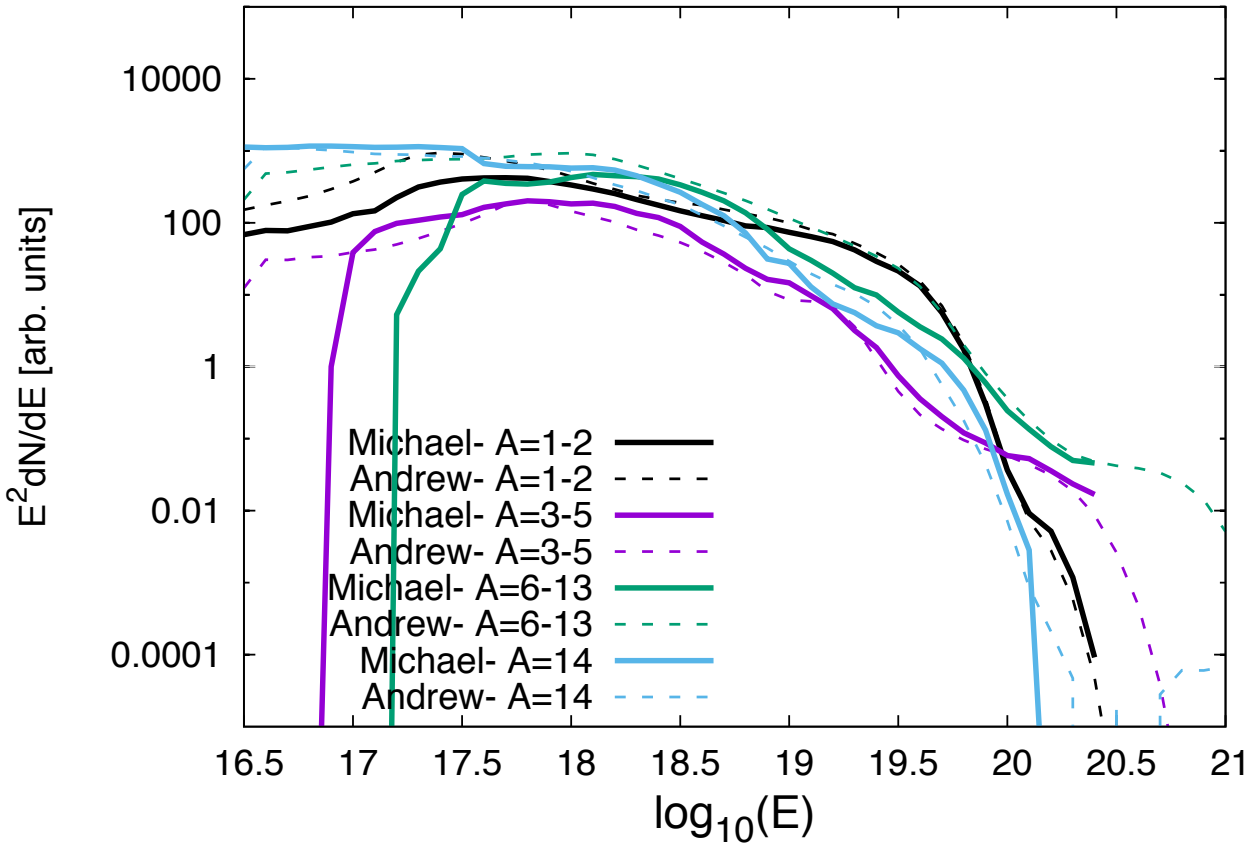
Giacinti et al. (2011), 1112.5599

Pierre Auger Collab. (2012), 1212.3083





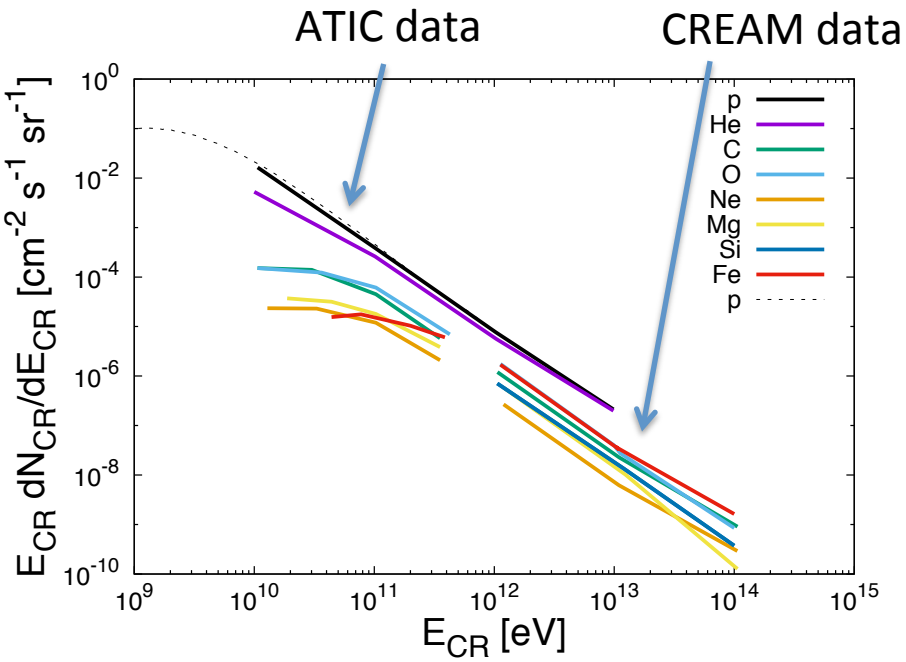
Cross Check of Nuclei Propagation Results...Michael learnt this very quickly!

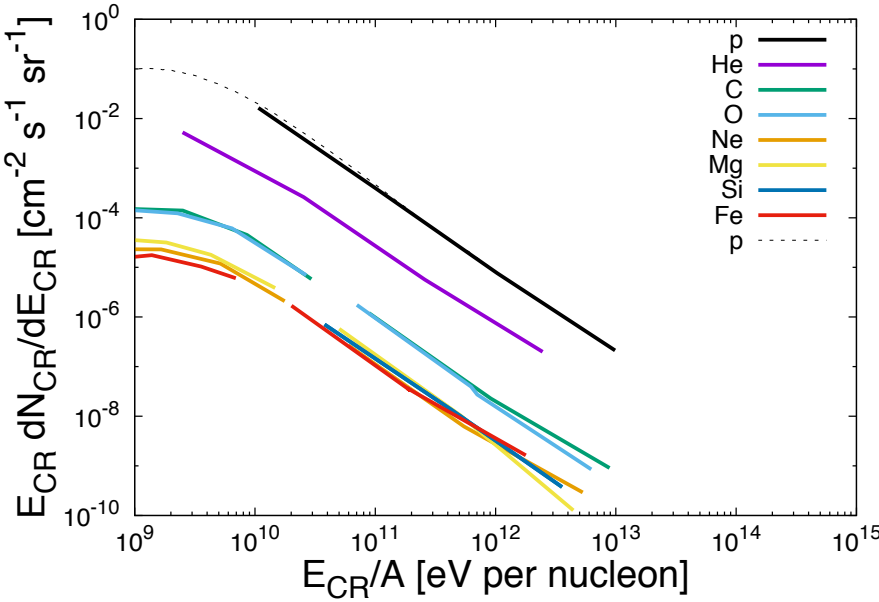


Low Energy CR Composition Investigation

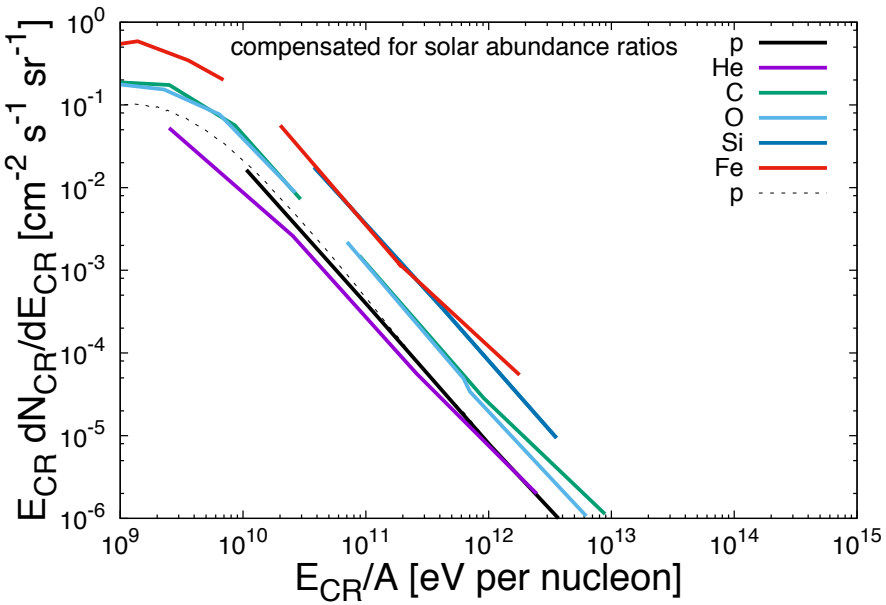
composition ratios of CR at 10~GeV per nucleon

	proton	He	C	O	Si	Fe
x_i	1.0	0.04	0.001	0.001	0.0002	0.0002





Low Energy CR Composition Investigation



solar system abundance ratios

	proton	He	C	O	Si	Fe
x_i	1.0	0.1	0.0004	0.0008	0.00003	0.00003

$$\mathbf{E_A \frac{dN_A}{dE_A}\left(\frac{E_A}{A}\right) = f_A E_p \frac{dN_p}{dE_p}(E_p)}$$

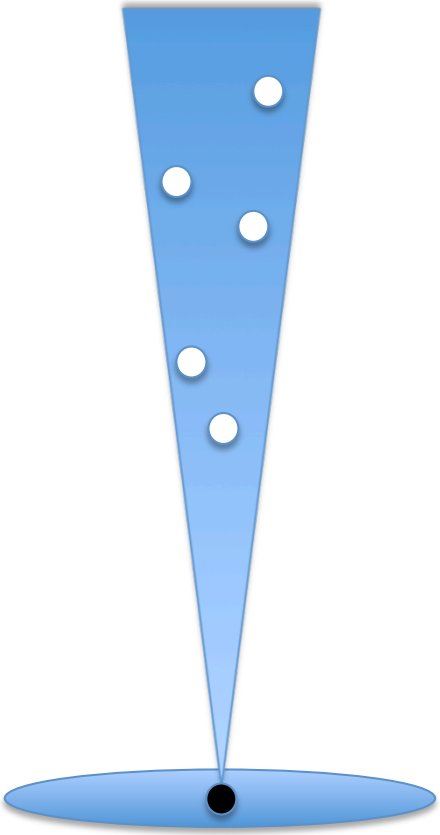
$$\mathbf{f_A = \frac{Z^2}{A} f_{SA}}$$

Cosmic Ray Spectrum from Cen A?

Abundance by Mass

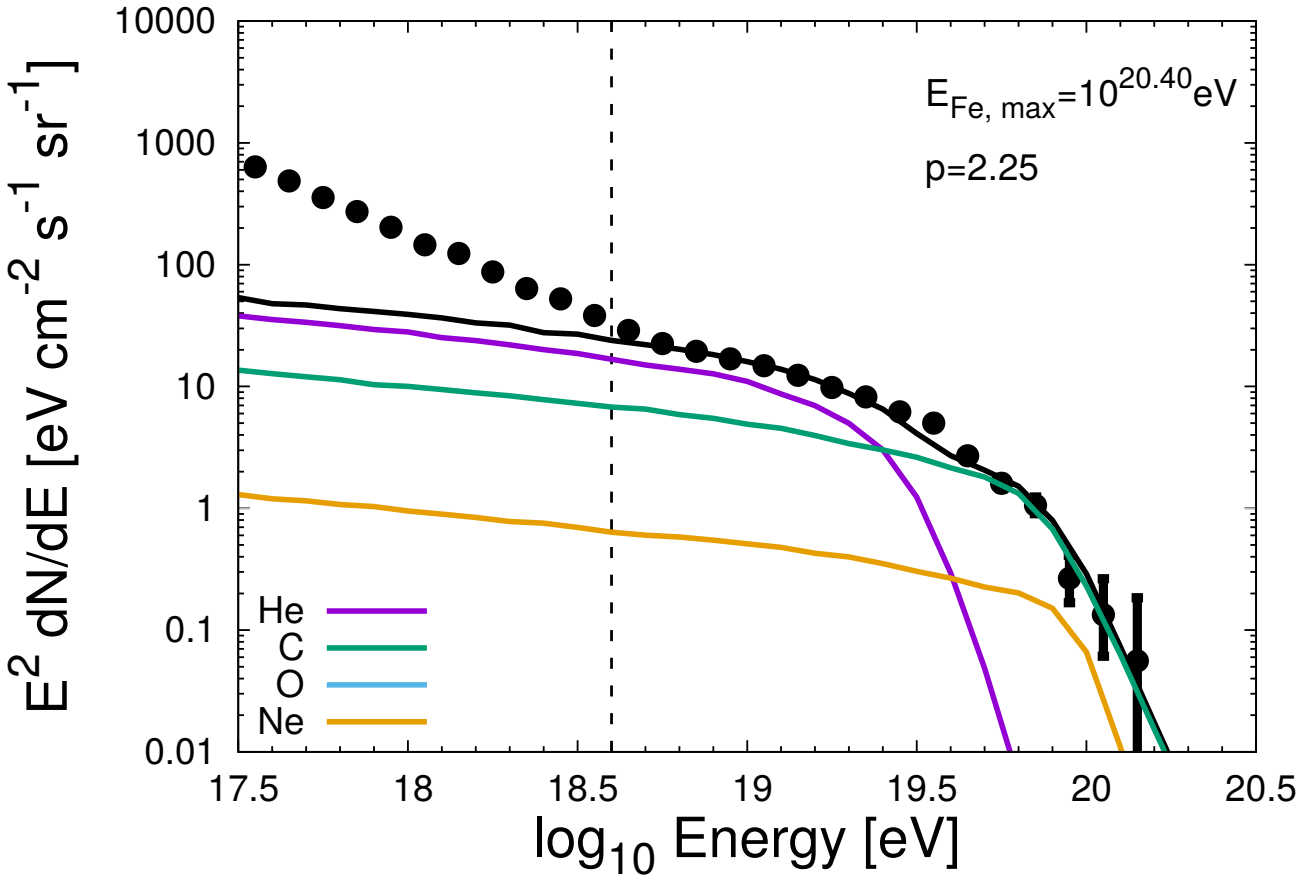
Abundance by Number

isotope	mass entrained (single lobe) ($M_\odot$)	mass rate (twin lobes) ($M_\odot\,\mathrm{yr}^{-1}$)	number rate (twin lobes) (s^{-1})
^{1}H	7.4×10^{4}	2.6×10^{-4}	1.0×10^{46}
^{3}He	3.1×10^{1}	1.1×10^{-7}	1.4×10^{42}
^{4}He	2.7×10^{4}	9.6×10^{-5}	9.1×10^{44}
^{12}C	9.5×10^{1}	3.4×10^{-7}	1.1×10^{42}
^{14}N	7.2×10^{1}	2.6×10^{-7}	7.0×10^{41}
^{16}O	3.3×10^{2}	1.2×10^{-6}	2.8×10^{42}
^{20}Ne	5.5×10^{1}	2.0×10^{-7}	3.7×10^{41}
^{22}Ne	5.0×10^{0}	1.8×10^{-8}	3.1×10^{40}
^{24}Mg	1.8×10^{1}	6.4×10^{-8}	1.0×10^{41}
^{26}Mg	2.7×10^{0}	9.6×10^{-9}	1.4×10^{40}
^{28}Si	2.3×10^{1}	8.2×10^{-8}	1.1×10^{41}
^{32}S	1.6×10^{1}	5.7×10^{-8}	6.8×10^{40}
^{56}Fe	4.1×10^{1}	1.5×10^{-7}	9.9×10^{40}



astro-ph: 1706.08229

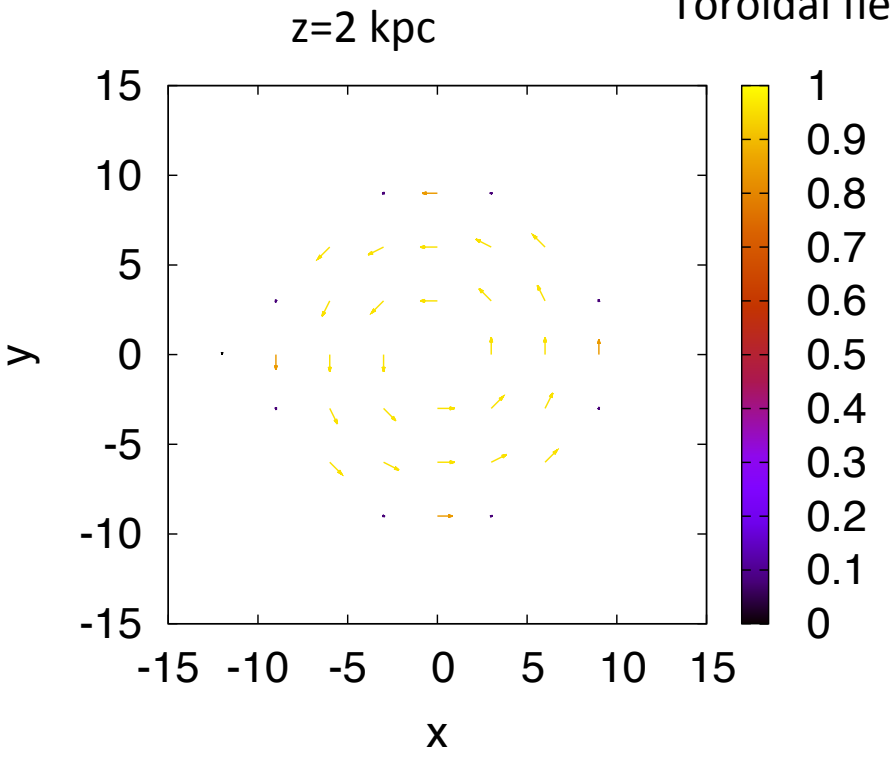
Cosmic Ray Spectrum from Local Sources Like Cen A

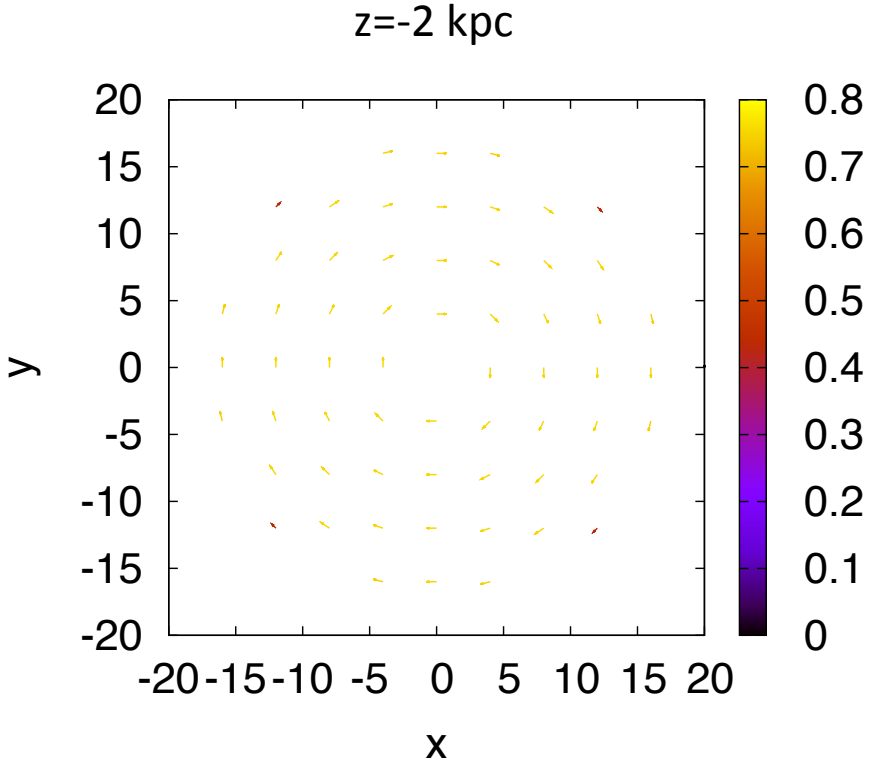


Note- no hardening of the spectrum at low energies has here been taken into account

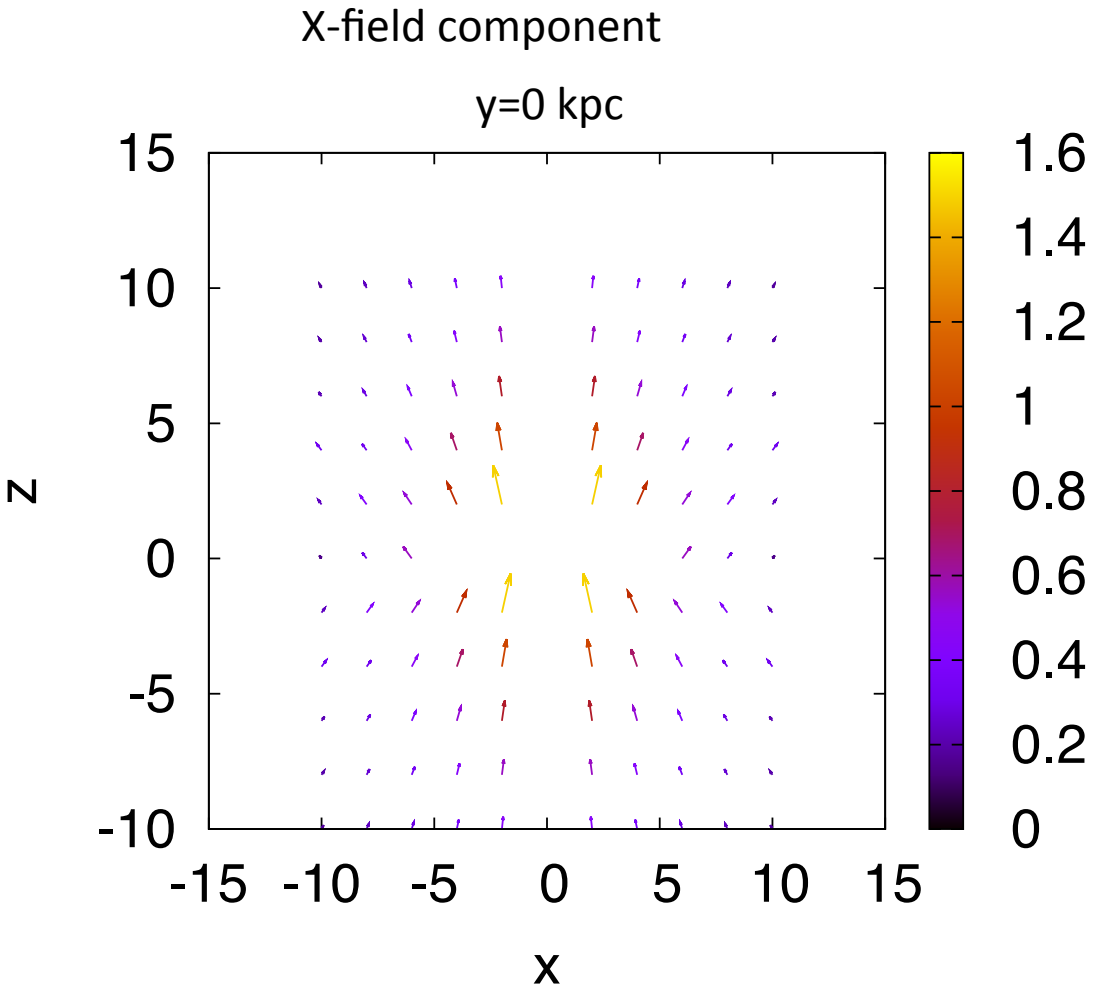
Step 2: Galactic B-field Interaction with Cen A CR Flux

Toroidal field component



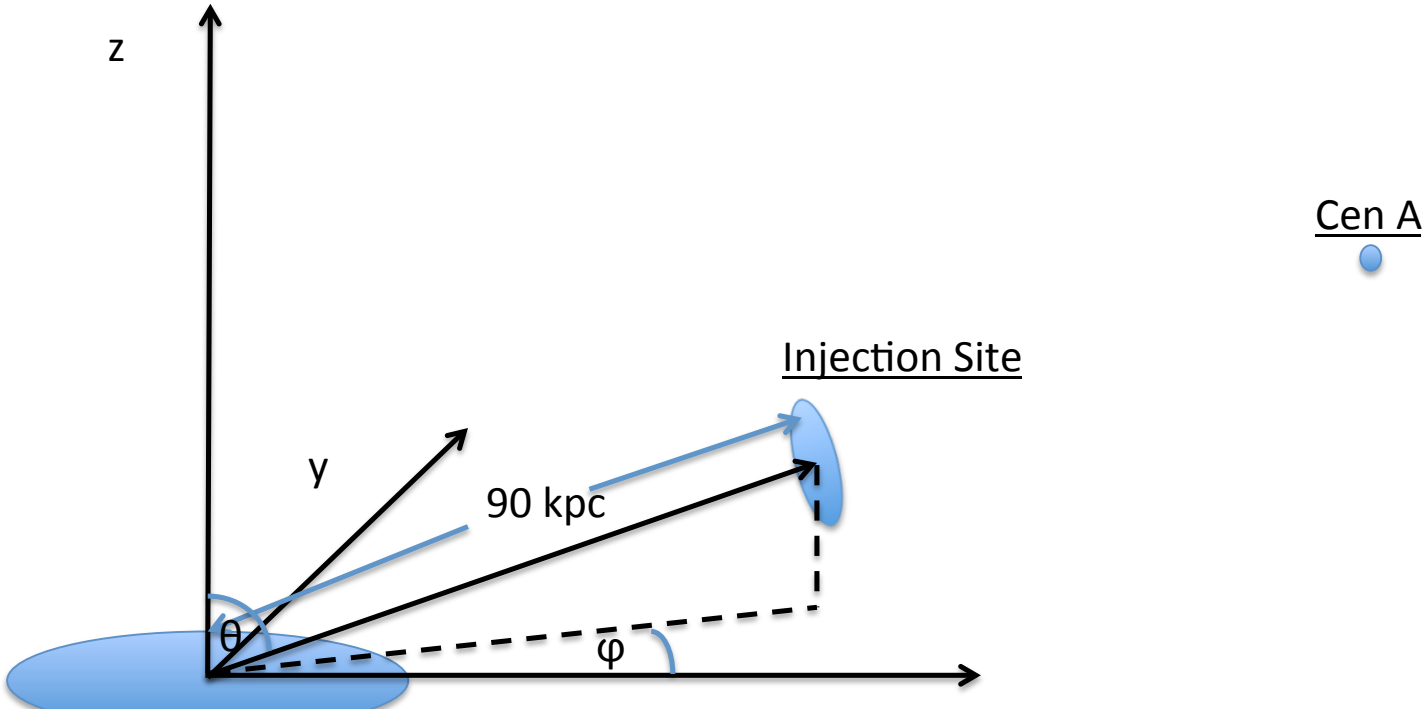


Galactic B-field Interaction with Cen A CR Flux



“Low Energy” Spectral Suppression of CR from Cen A

System Setup



Galactic Magnetic Field "Shadowing"

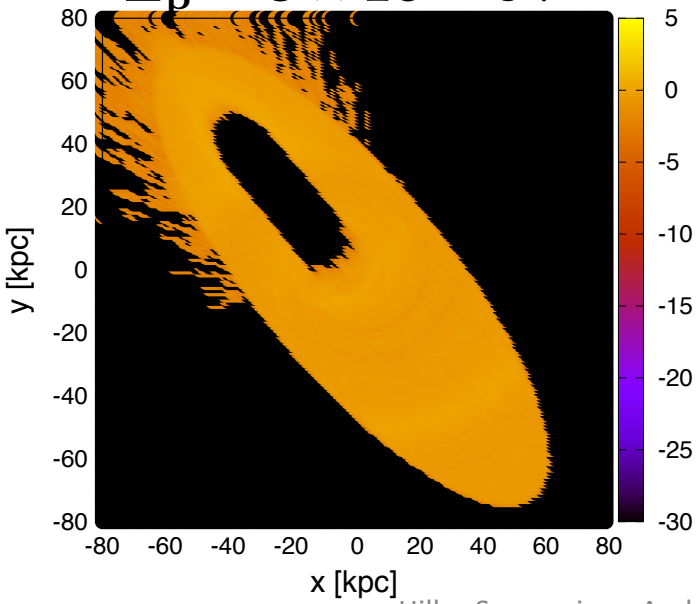
$$U_B^{disk} = 8 \times 10^{53}\ erg$$

$$U_B^{toroid} = 4 \times 10^{54}\ erg$$

$$U_B^{X-field} = 3 \times 10^{54}\ erg$$

$$U_{CR} \approx 10^{55}\ erg$$

$$E_p = 3 \times 10^{18}\ eV$$



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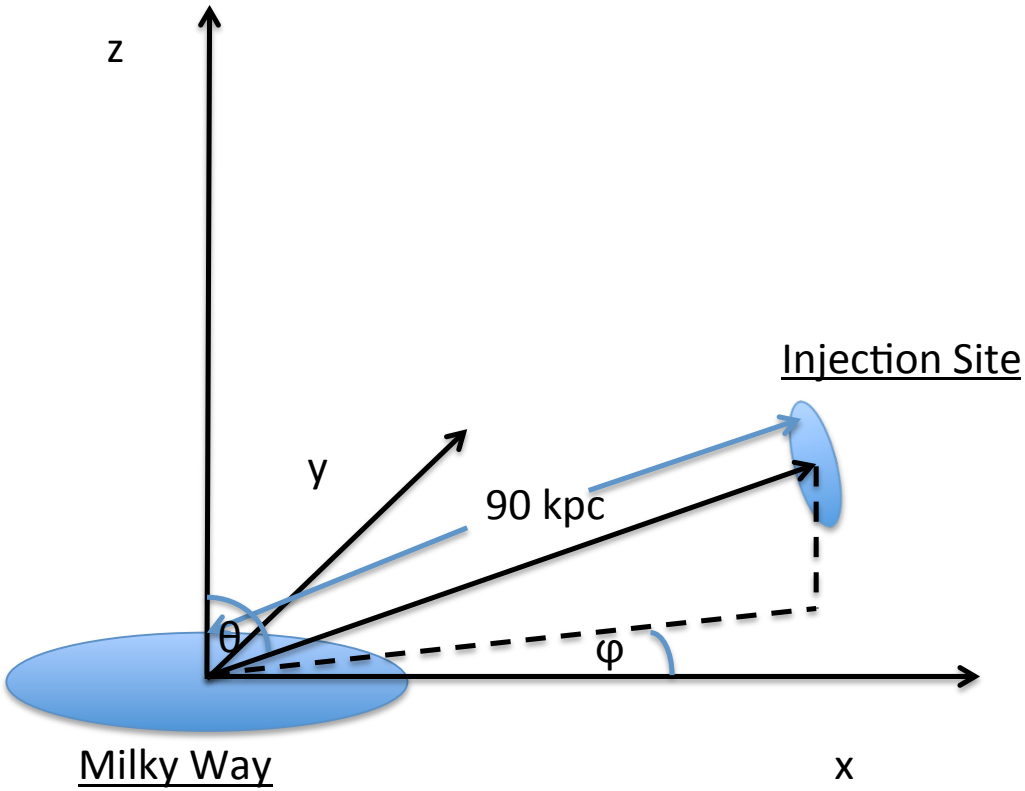

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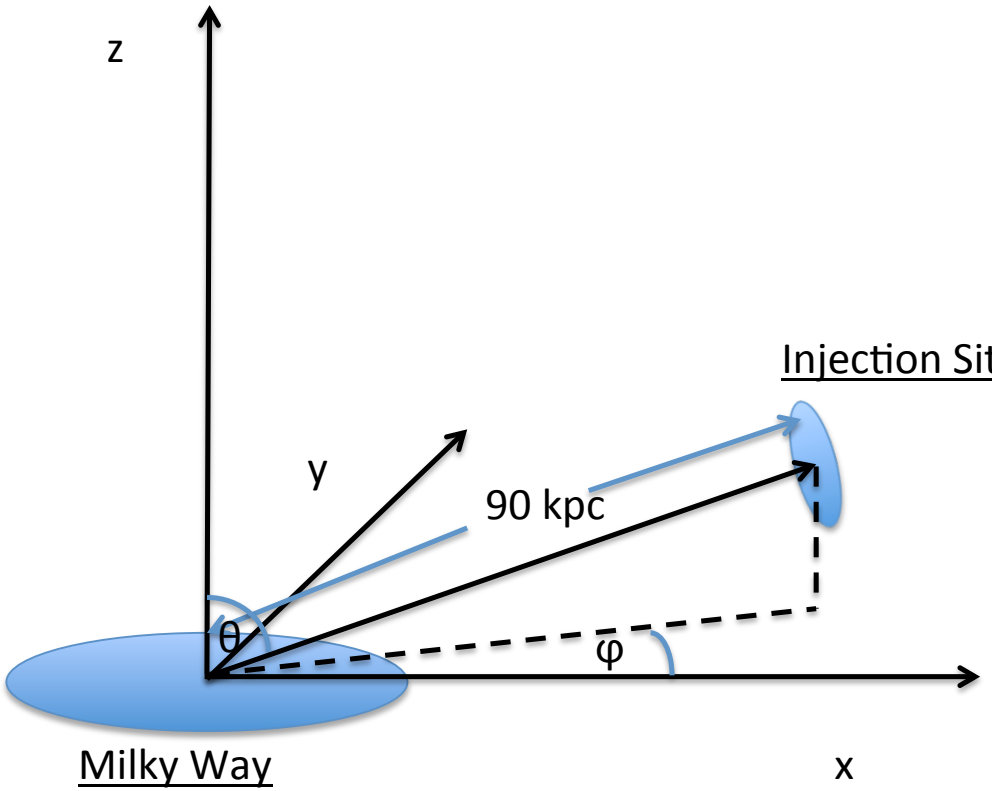
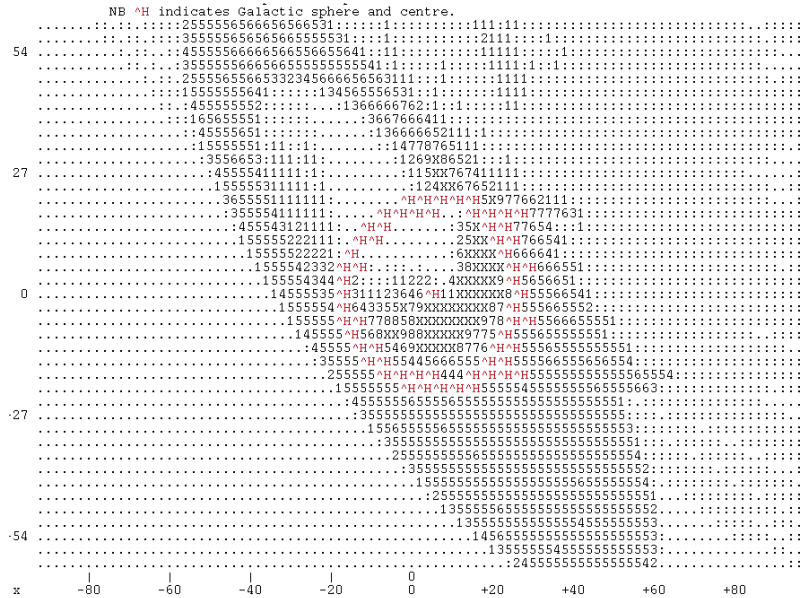
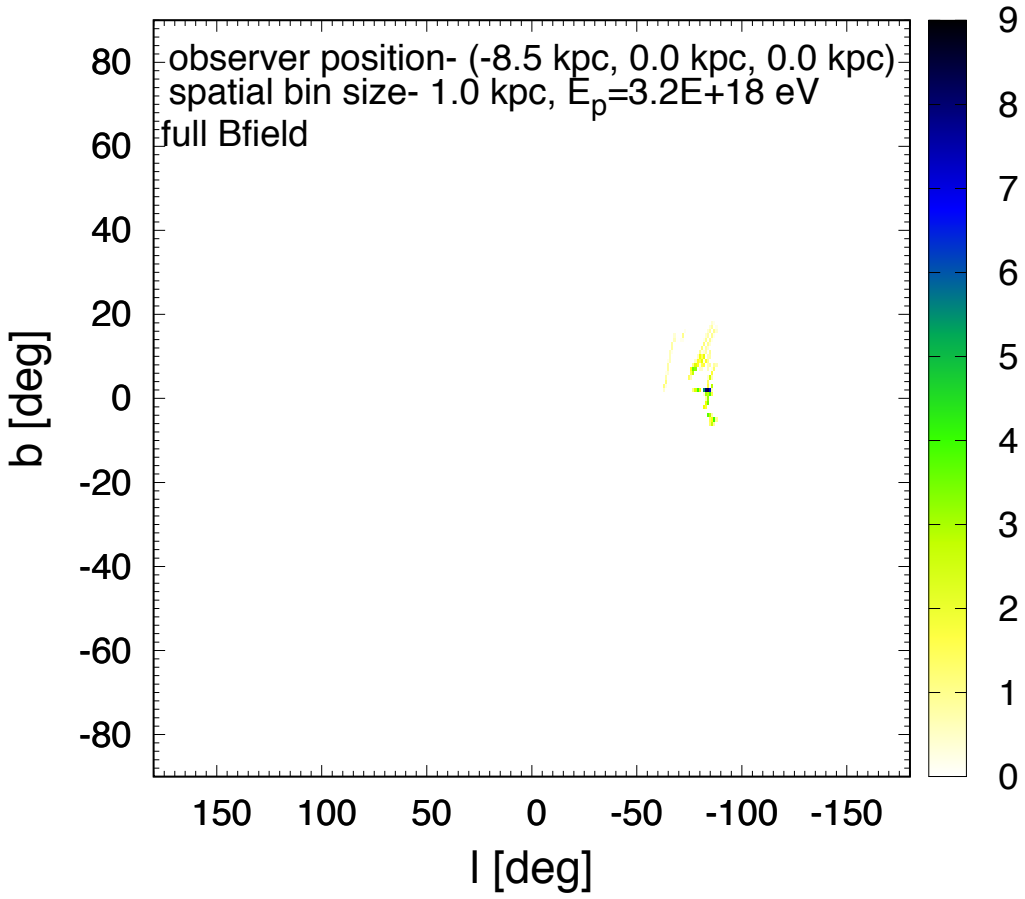




Michael & I had intended to produce a short paper on this "shadowing" effect

Cosmic Ray Anisotropy from Cen A?

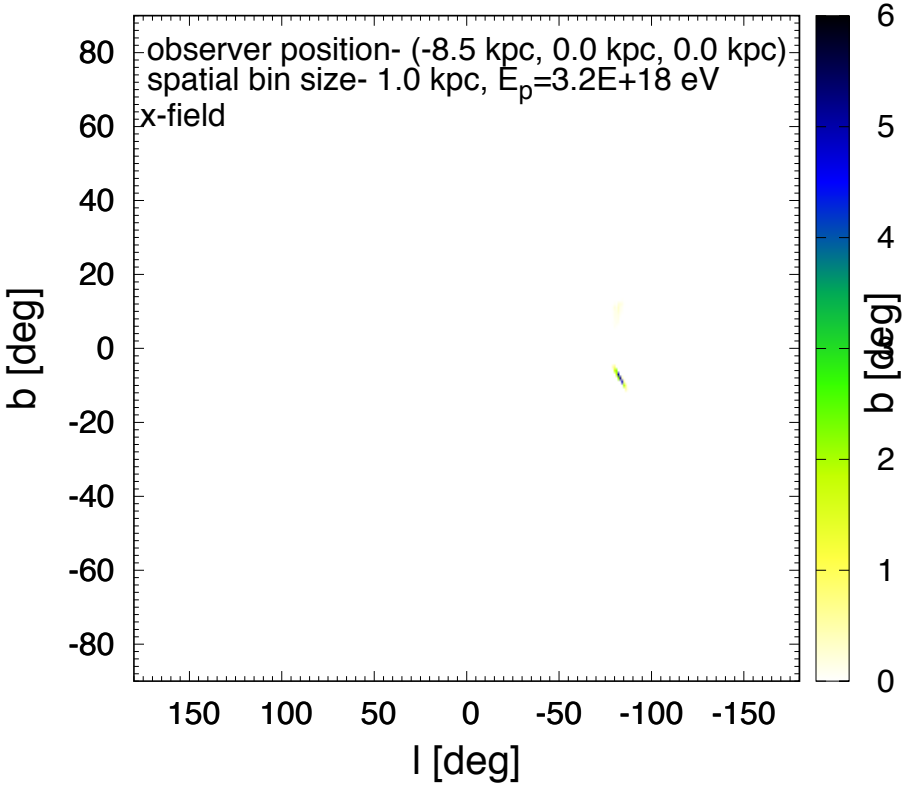
Angular arrival distribution of parallel beam from Cen A fired at Galactic magnetic field



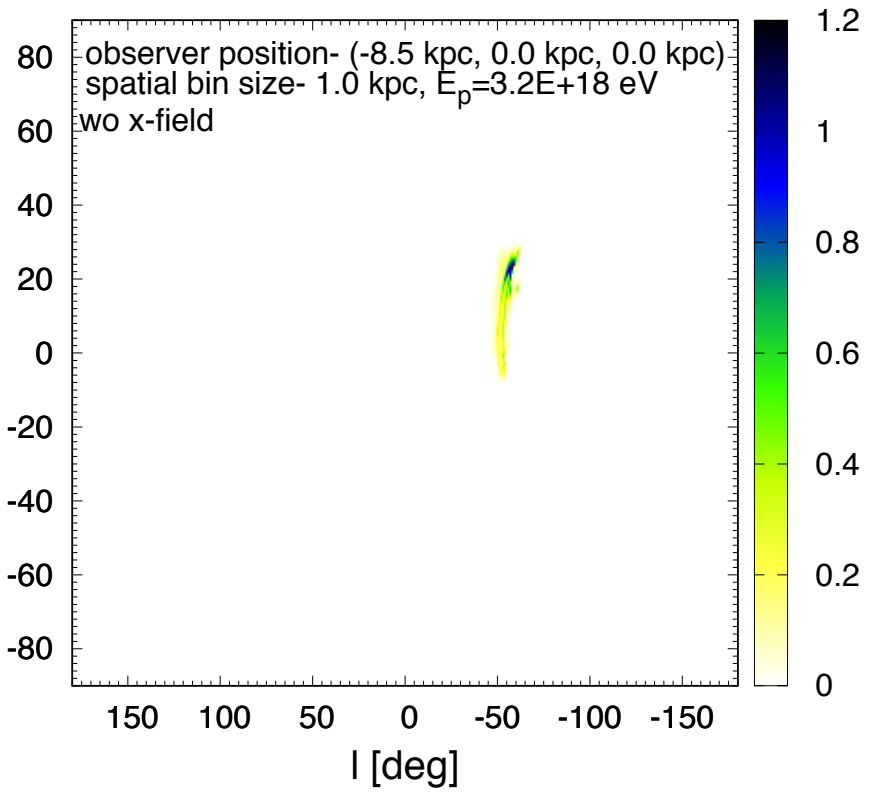
Cosmic Ray Anisotropy from Cen A?

Importance in role of X-field component of the Galactic Magnetic in shifting position of Cen A in arriving flux from beam injected

Only X-field

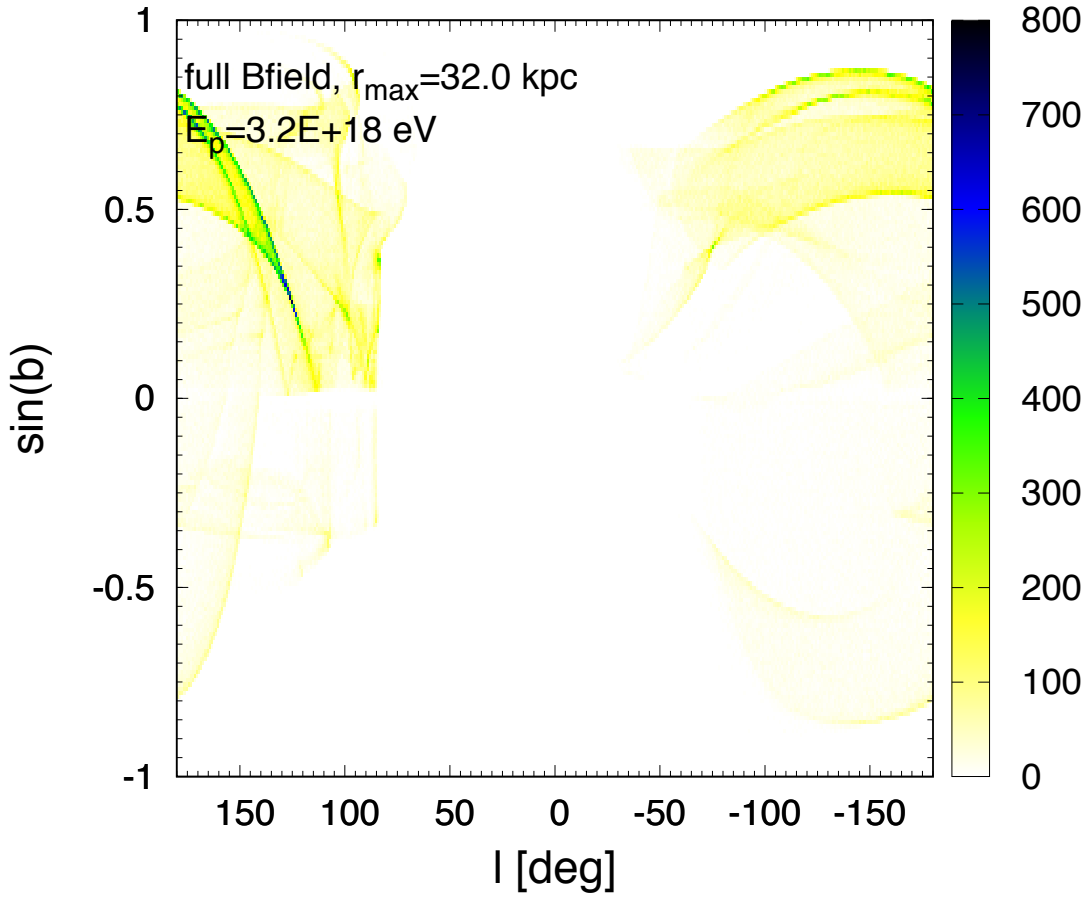


Only Toroidal + Disk Fields



How Isotropic Cosmic Rays at Earth Sample the Isotropic Extragalactic Sky

….and lastly, back-tracking isotropic particles from Earth to see which parts of extragalactic sky are preferentially sampled at these energies

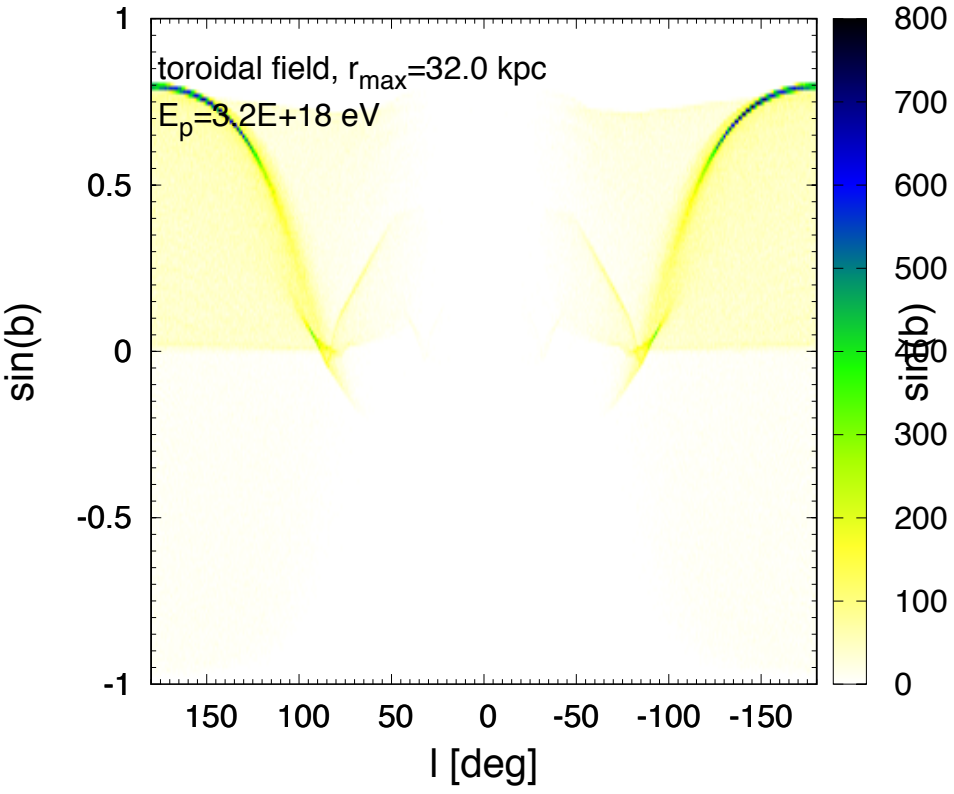


Michael named this effect “tunnel vision”!

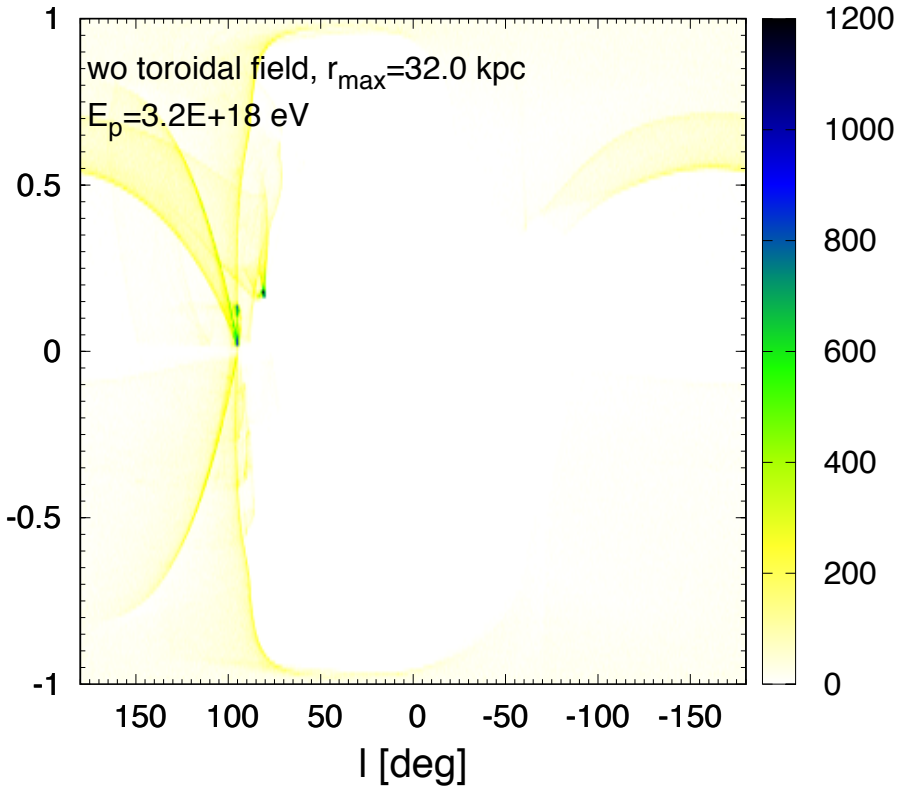
How Isotropic Cosmic Rays at Earth Sample the Isotropic Extragalactic Sky

Importance in role of Toroidal Field in Selecting Extragalactic Regions Probed

Only Toroidal Field



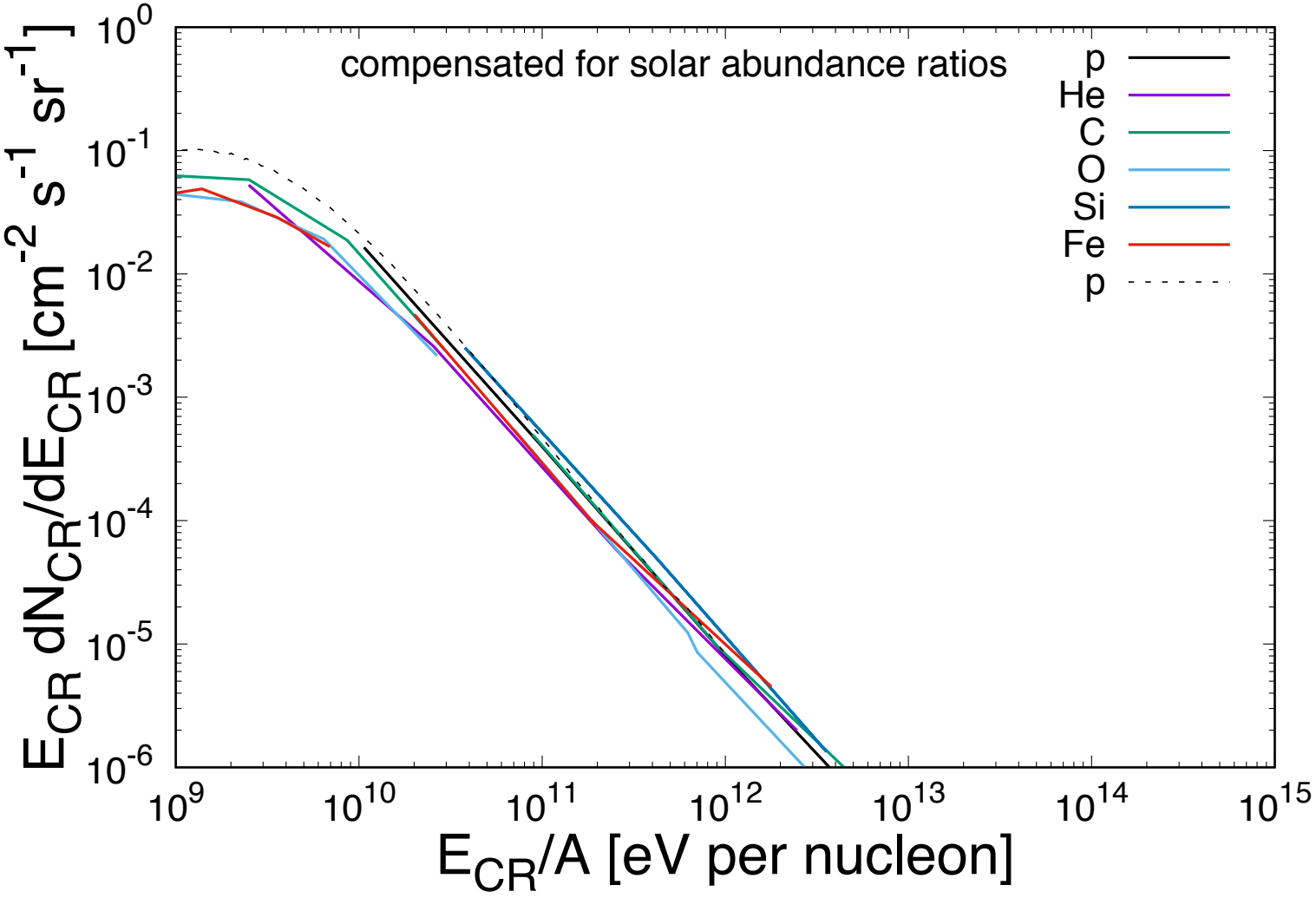
Only Disk + X-Field



Farewell to Michael

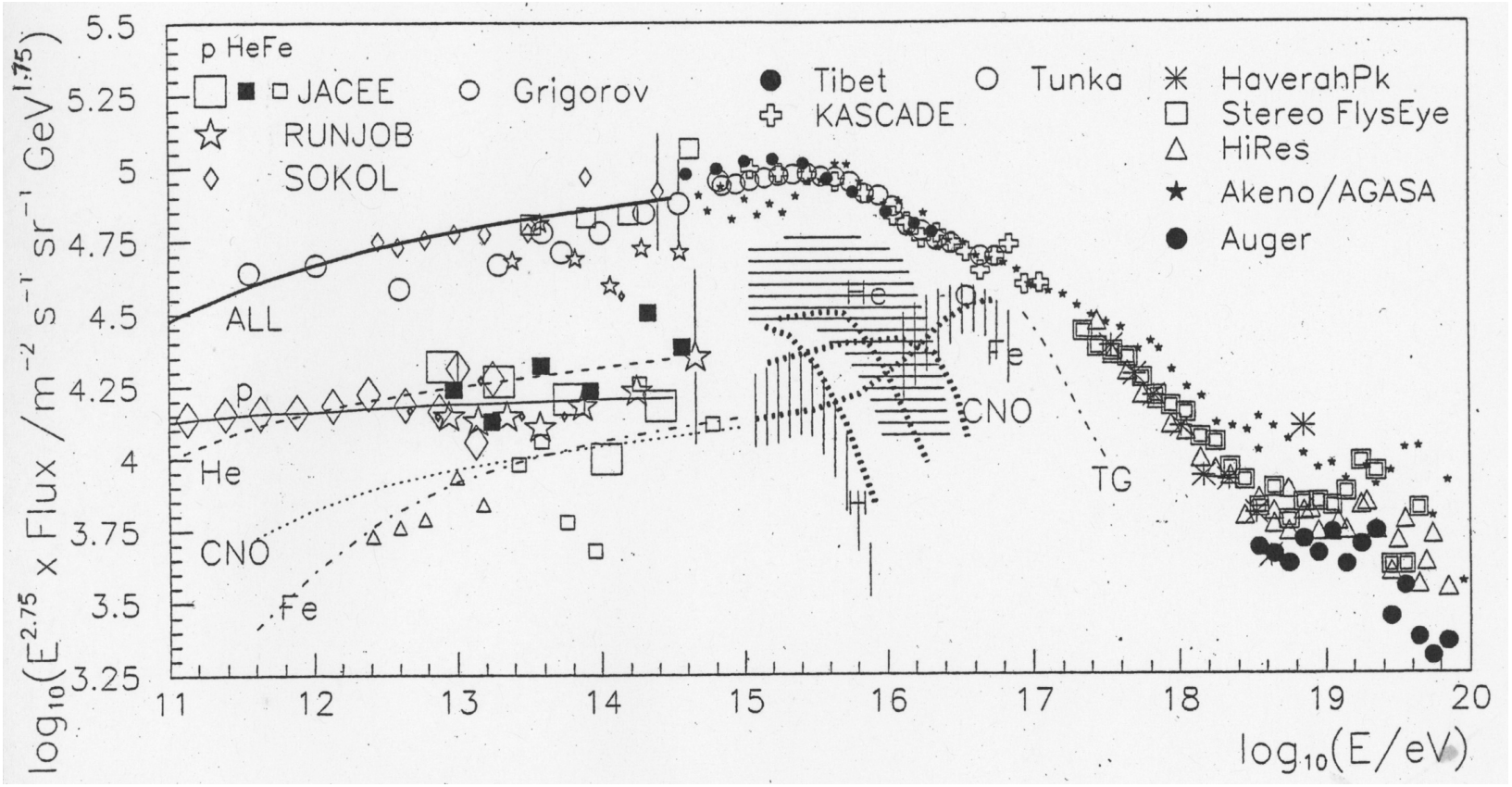
I wanted to finish with an effort to convey the joy that it was to work with Michael. I only knew him in the evening of his life, but still his enthusiasm for astrophysics was infectious and his tenaciousness remarkable (emails with right arm “out of action” following car crash!). He will be sorely missed, but I’m grateful for having known him.

Extra Slides


compensated for solar abundance ratios
p
He
C
O
Si
Fe
p
$E_{CR}\ dN_{CR}/dE_{CR}$ [cm^{-2} s^{-1} sr^{-1}]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
E_{CR}/A [eV per nucleon]

Anatomy Of The Knee

showing some component nuclei



TG indicates how the total of “galactic” components could thus appear

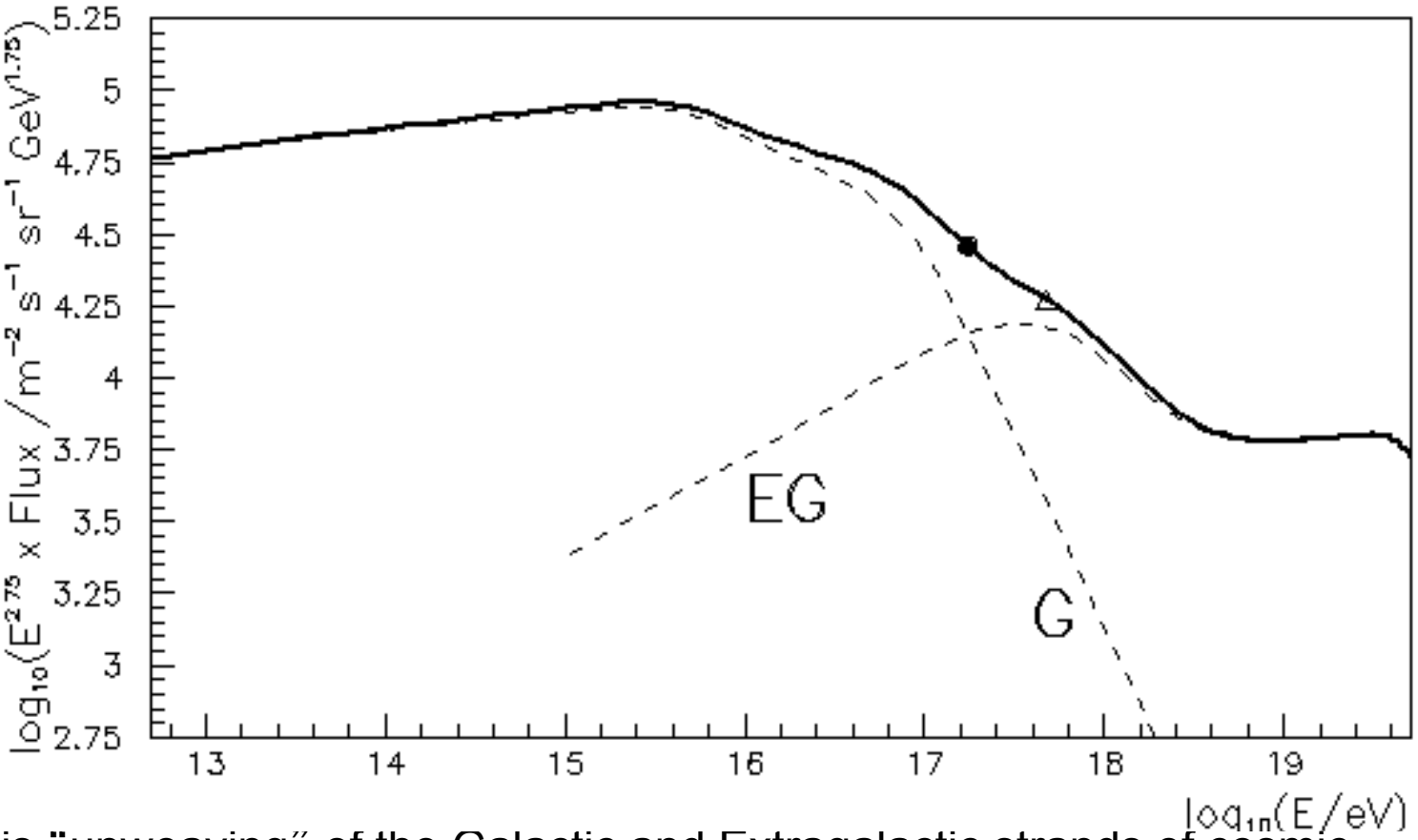
Particles From Extragalactic Sources

Note:
I have skipped over many details –
►How does the Galactic flux fall off? The KASCADE experiment gave strong indication of an initial sharp fall in the H and He components, but does it fall less steeply after the first fall by a factor ~3, say?
►Does the extragalactic CR production rate vary more, or less, steeply than the nominal star-formation rate?
►One must ensure that the energy injection required is not impossibly high, and that electron/gamma-ray production is within observational gamma-ray-flux constraints. (Work still in progress in this area.)
►What is the spectral exponent at production?
►Is there a significant level of elements heavier than H?
►(And, becoming important as one nears 10^{20} eV, where does the production spectrum tail off?)

The best values of these parameters to fit the observed spectral shape and the energy at which the UHE x_{max} rises were adopted and shown.

(These different factors tend to affect different regions of the spectrum, and there is not a great freedom of choice.)

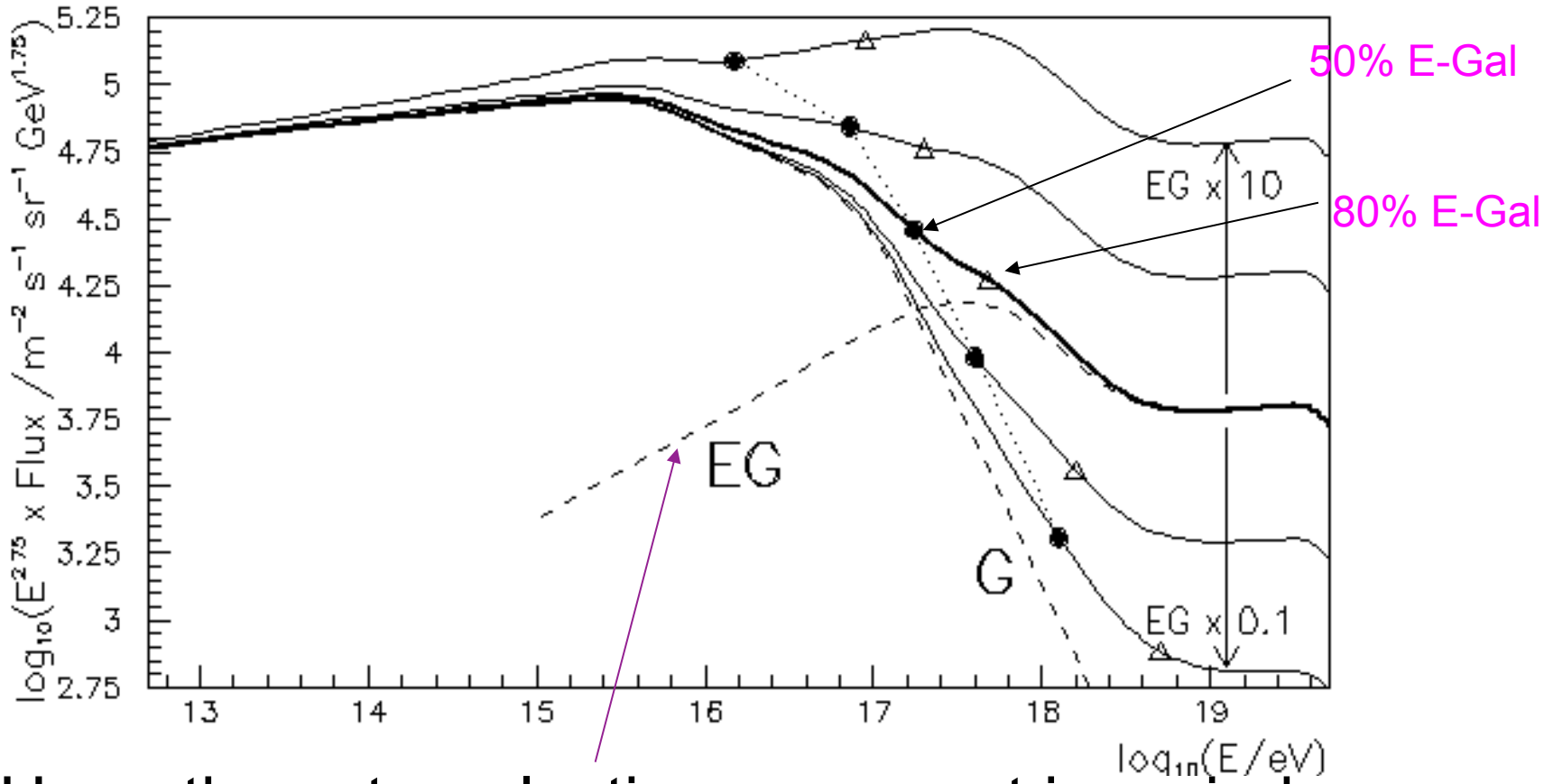
→ NOW, the extragalactic and galactic parts look like this:



This ¨unweaving´´ of the Galactic and Extragalactic strands of cosmic rays **looks weird and contrived**, but is based on physics.

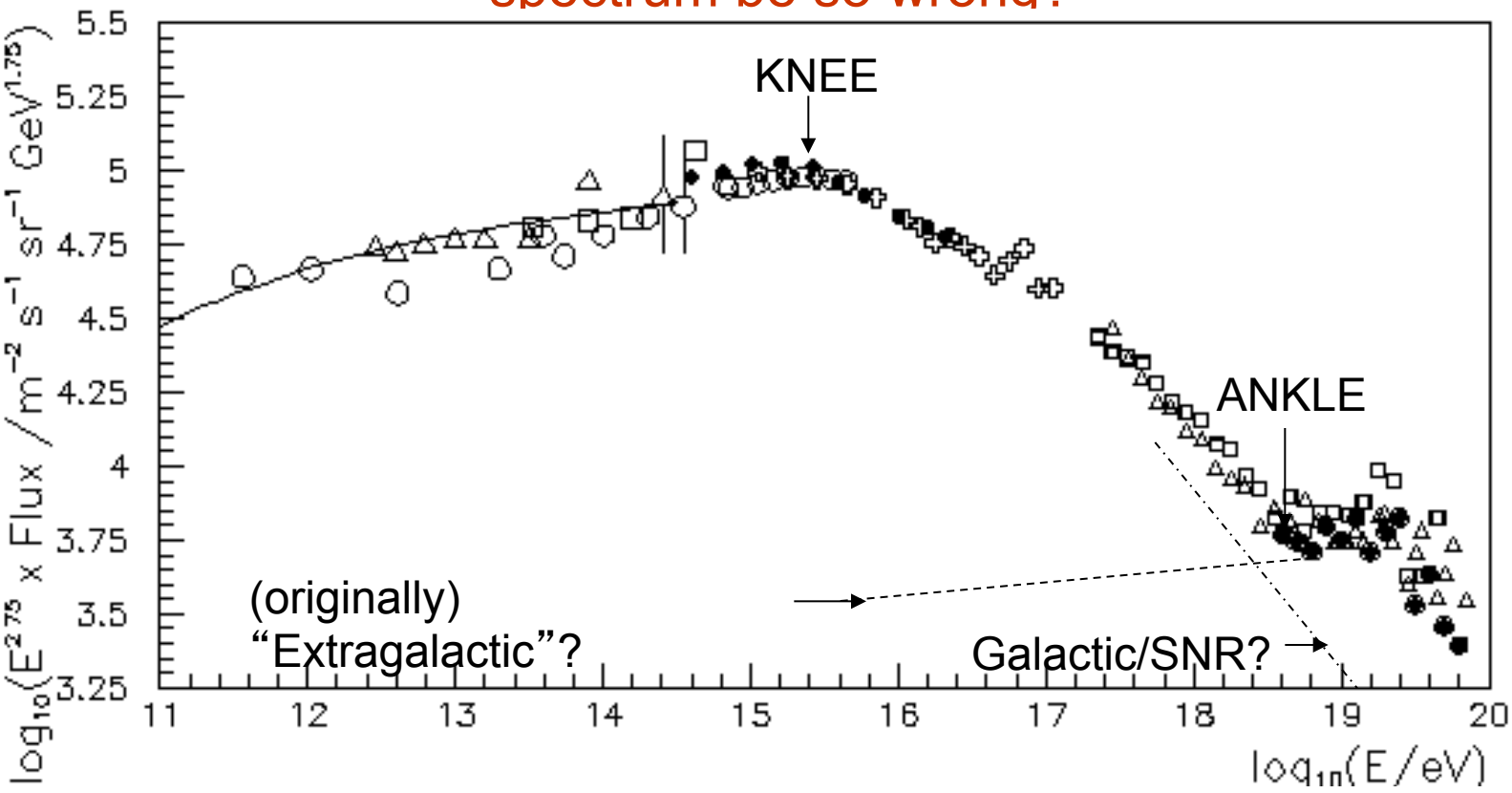
"Surely such a near-invisible join is an unlikely accident?"

No !



Here, the extragalactic component is varied over a factor 100 — nowhere does the 50/50 mix point ● tally with an upward bend. It is a bad clue.

Anyway, how could the obvious original interpretation of the spectrum be so wrong?



This was the originally proposed split between galactic and extragalactic particles

Cosmic Ray Spectrum

Faced with this immense nearly-smooth graph, cosmic-ray enthusiasts like to concentrate on interpretations of the bends.

It is notable how wrong one original guess was: the major transition to an extra-galactic component is invisible.