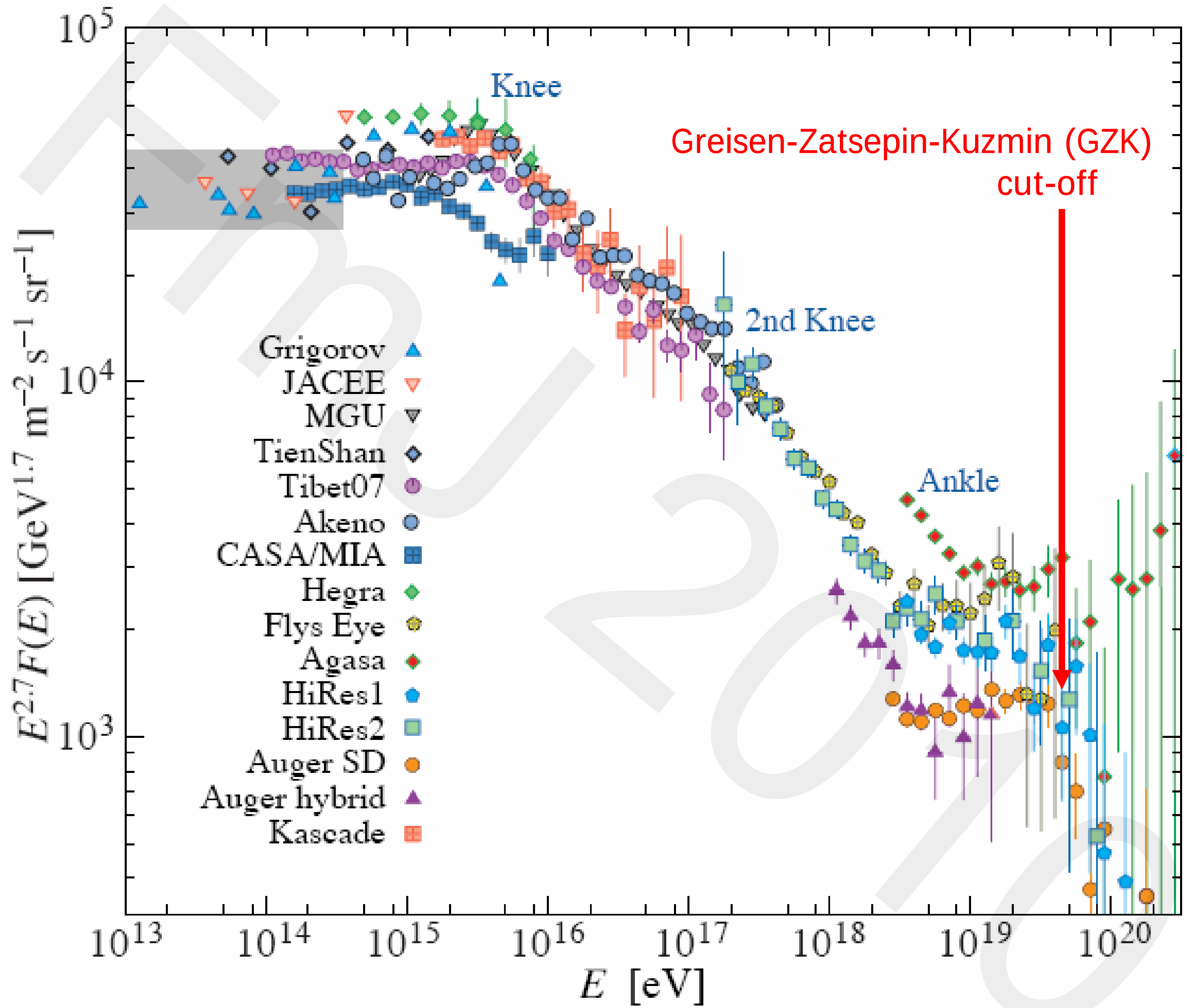
Centaurus A as a Cosmic Ray Accelerator

R. J. Protheroe (University of Adelaide)

Fermi meets Jansky – AGN in Radio and gamma-Rays, MPIfR 23 June 2010



Gaisser & Stanev, 2007 Particle Data Group.

Cosmic Ray Acceleration

Acceleration depends on "magnetic rigidity", $\rho = E/Ze$, rather than energy.

In magnetic field B the rigidity gain rate can be given by

$$r_{\rm gain}(\rho) \equiv (1/\rho)(d\rho/dt) = \xi(\rho) c^2 B \rho^{-1}$$

where $\xi(\rho) < 1$ is the acceleration rate parameter

Subject to $r_g < R_{\rm max}$ the maximum energy is found by solving

$$r_{\rm gain}(E_{\rm max}) - r_{\rm loss}(E_{\rm max}) - r_{\rm synch}(E_{\rm max}) - 1/t_{\rm max} = 0.$$

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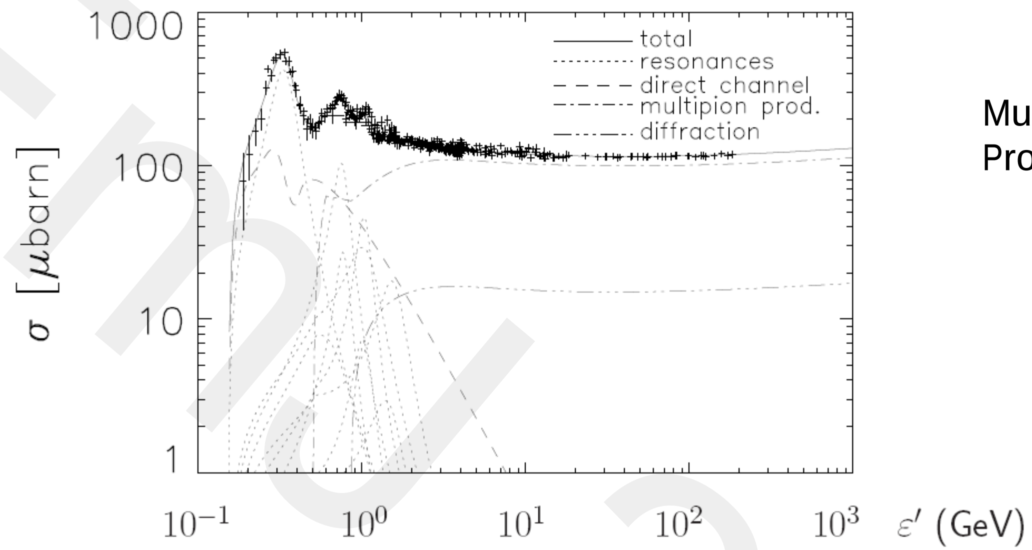
Pion photoproduction cross section vs gamma-ray energy



Muecke, Engel, Rachen, Protheroe & Stanev (2000)

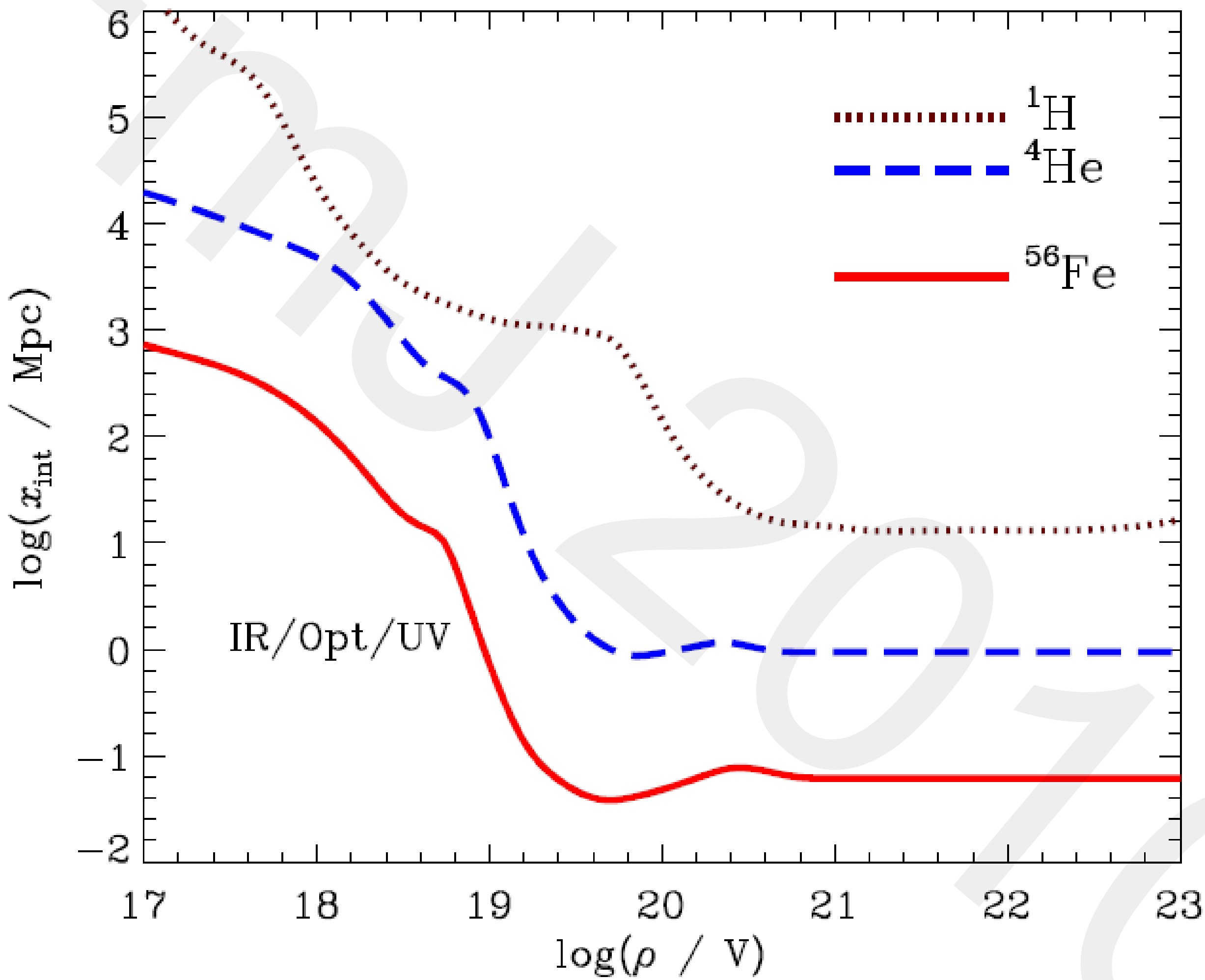
In the rest frame of a 10^{20} eV proton, 2.725 K CMB photons are gamma-rays!

• Photoproduction may cut off UHE CR acceleration, cause the GZK cut-off and initiate cascading down to ~GeV energy gamma-rays.

•For nuclei photo-disintegration on the CMB and IR/Opt/UV fields are important (e.g. Rachen 1993).

The interaction mean free path on the CMB plus IR/Opt/UV EBL

(m.f.p. plotted vs "magnetic rigidity" rather than energy)



rigidity $\rho \approx E/Ze$

Data from Allard & Protheroe (2009)

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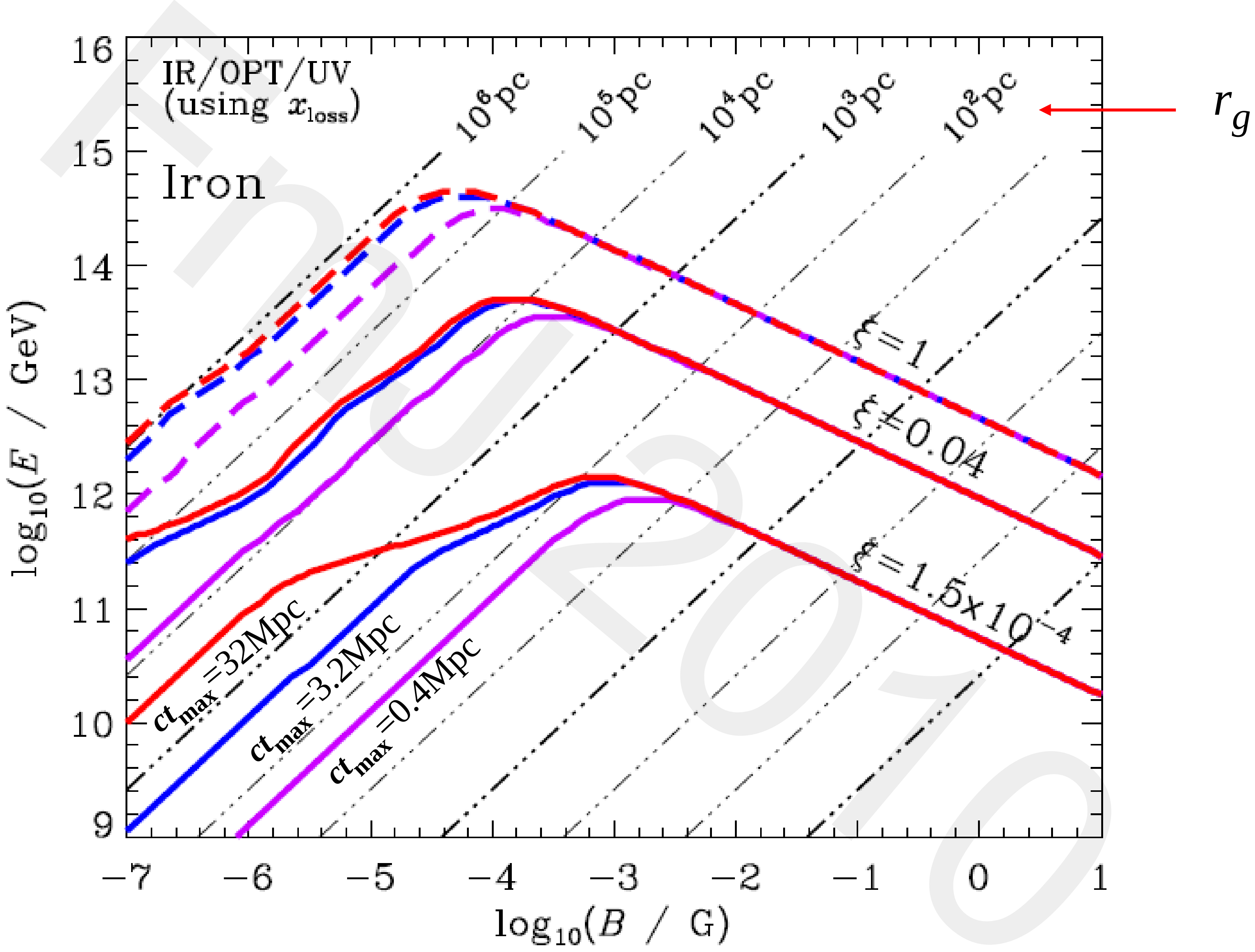
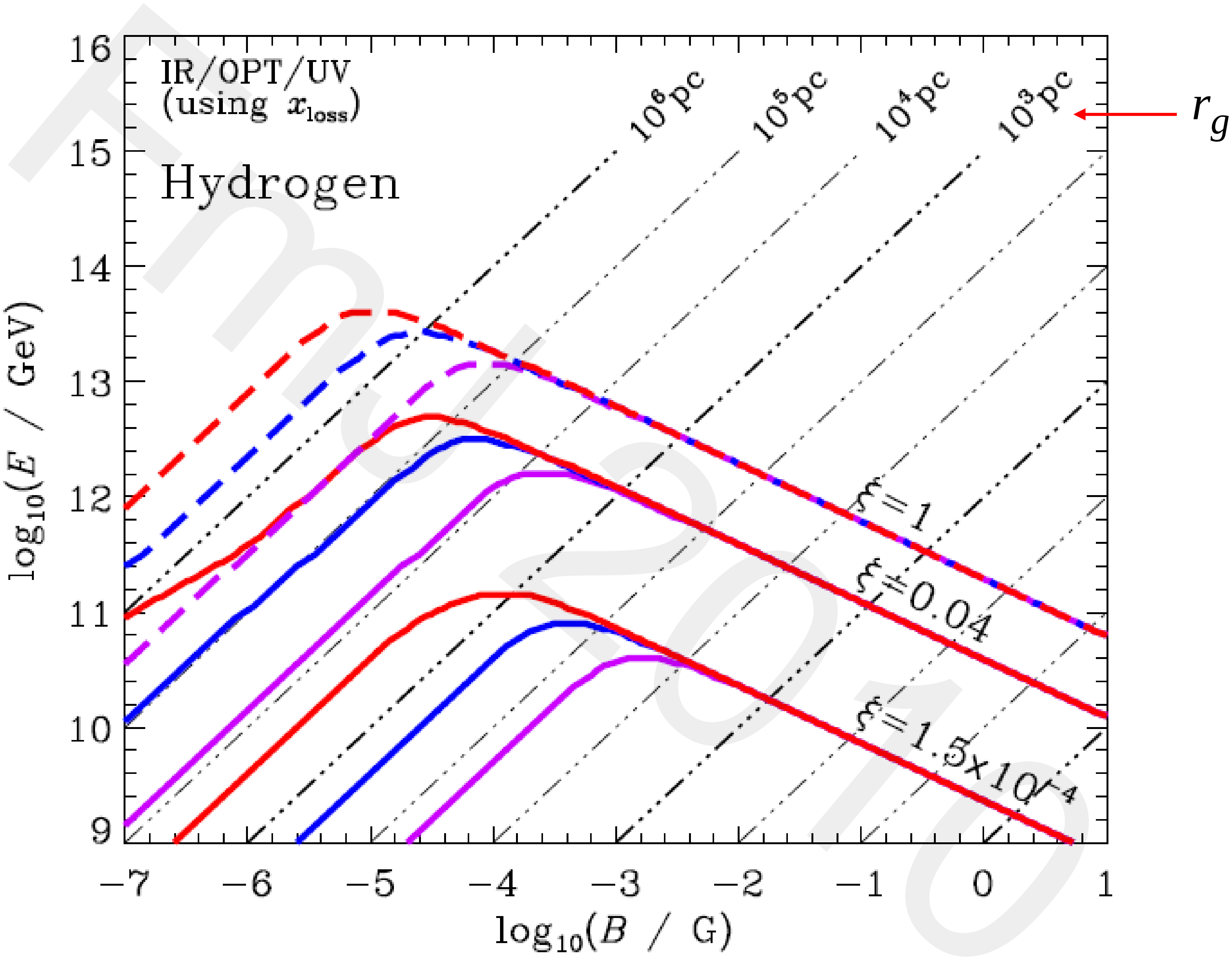
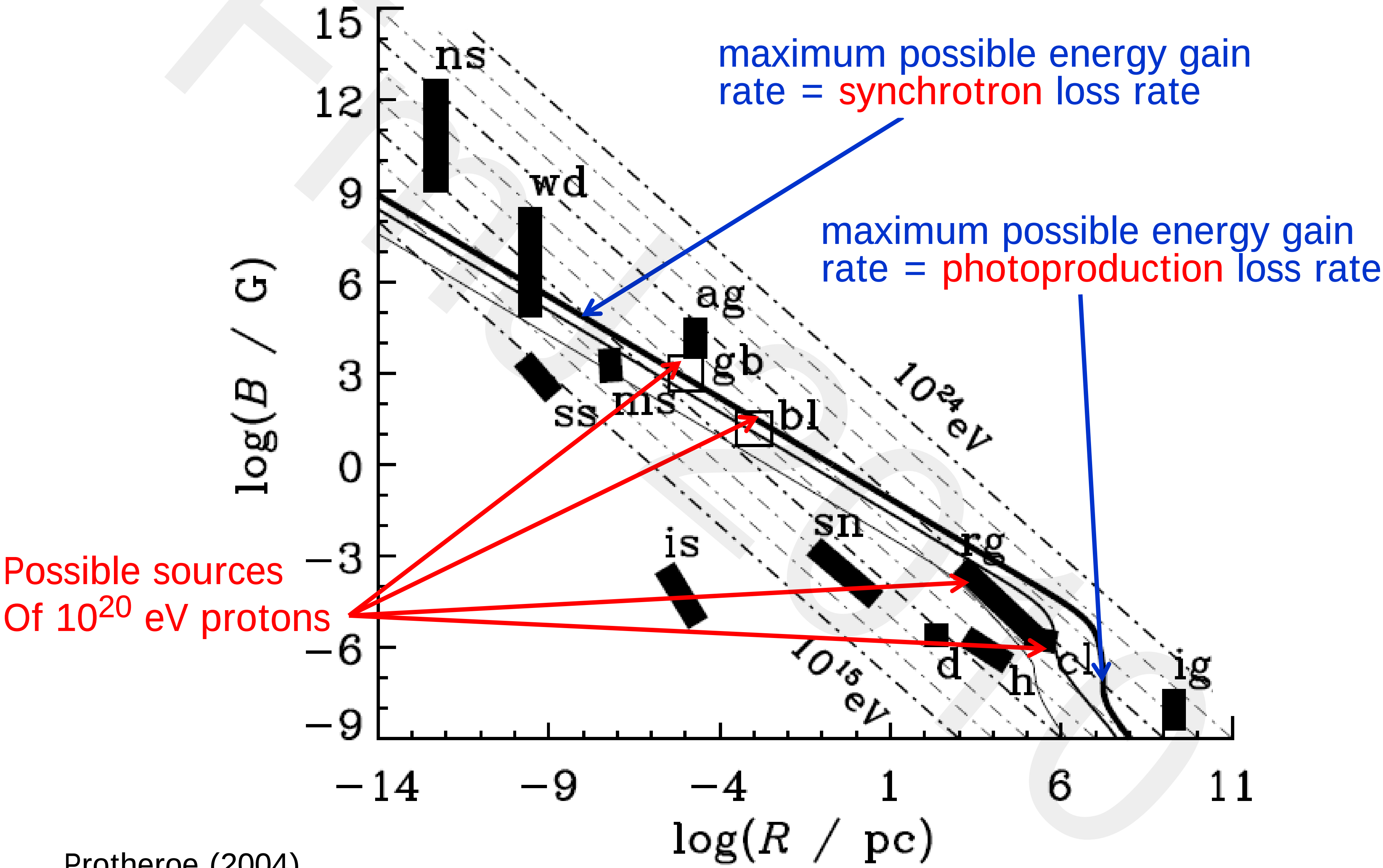


IR/OPT/UV
(using x_{loss})
Iron
10^6pc
10^5pc
10^4pc
10^3pc
10^2pc
r_g
$\xi = 1$
$\xi = 0.04$
$\xi = 1.5\times10^{-4}$
ct_{max}=32Mpc
ct_{max}=3.2Mpc
ct_{max}=0.4Mpc
$\log_{10}(E$ / GeV)
$\log_{10}(B$ / G)



IR/OPT/UV
(using x_{loss})
Hydrogen
10^6pc
10^5pc
10^4pc
10^3pc
r_g
$\xi = 1$
$\xi = 0.04$
$\xi = 1.5\times10^{-4}$
$\log_{10}(E$ / GeV)
$\log_{10}(B$ / G)
16
15
14
13
12
11
10
9
−7
−6
−5
−4
−3
−2
−1
0
1

A revised "Hillas Plot" for shock-accelerated protons

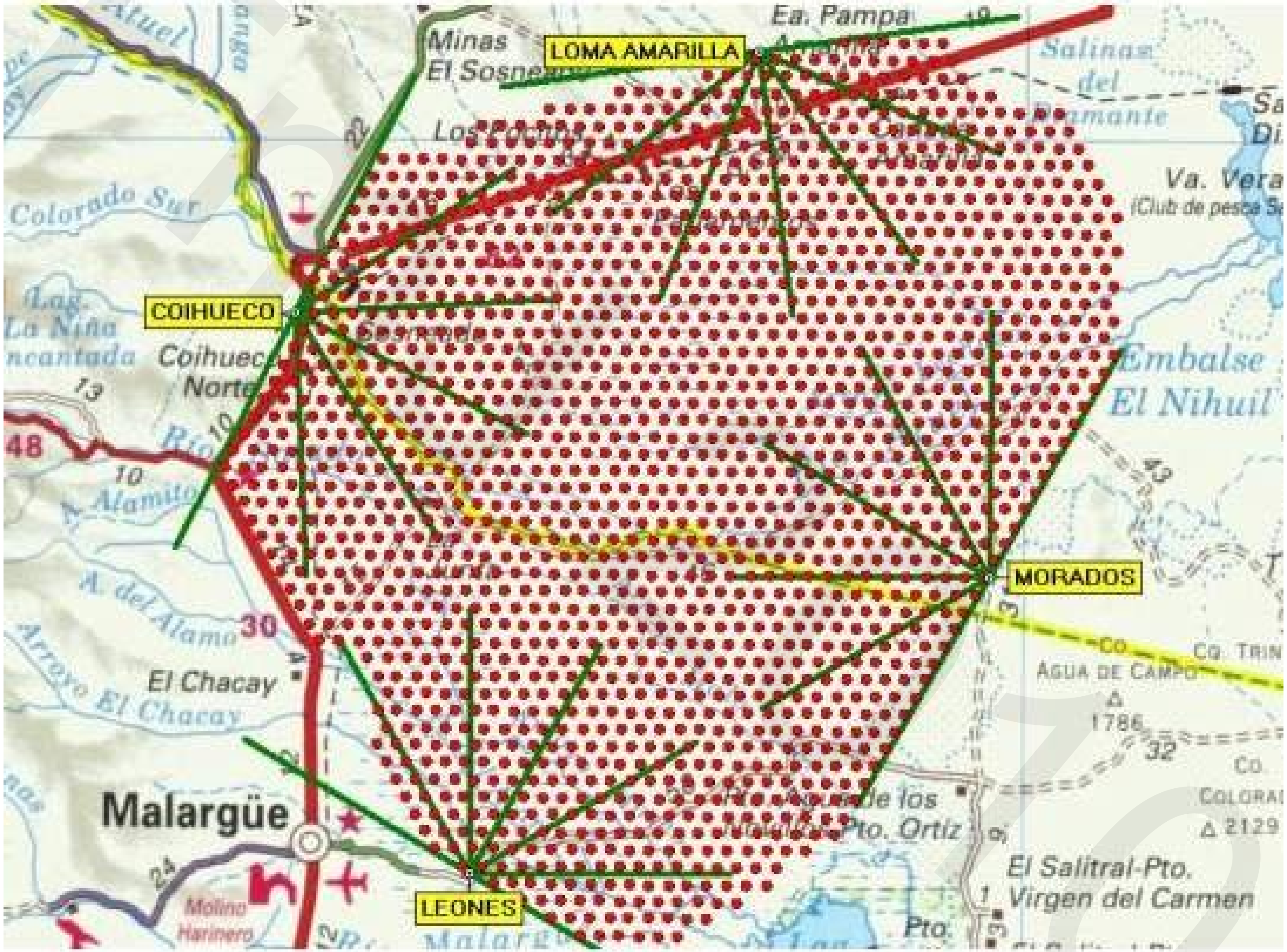


Protheroe (2004)

Detectors of the Pierre Auger Array

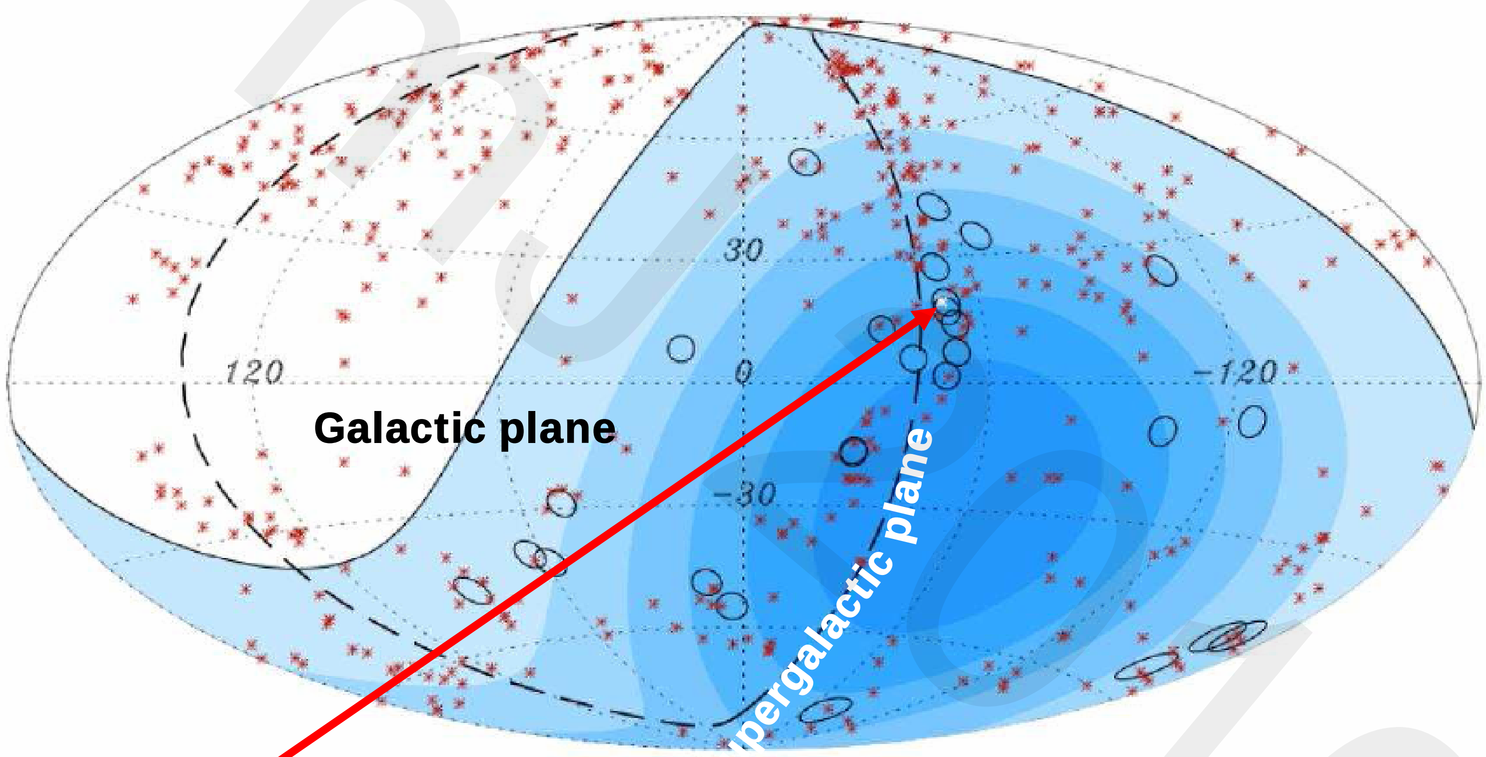
Particle detector (foreground) and fluorescence detector (on hill)

Layout of the Pierre Auger Array



Why Centaurus A?

Arrival directions of UHE CR above 57 EeV (circles) observed by the Auger Observatory compared with nearby AGN (crosses). (57 EeV = 5.7×10^{19} eV)



Centaurus A, the nearest Active Galactic Nucleus (AGN) could be Responsible for some or most of the UHE CR.

The latest Auger data does not strengthen this correlation with Cen A, but because of its proximity Cen A remains an interesting possibility.

Cosmic Ray Acceleration at Cen A

Cuoco & Hannestad (2008)

- *predicted the flux of UHE neutrinos from the Centaurus A jets using a model of an optically thick pion photo-production source described by Mannheim et al. (2001).*
- *They assume that accelerated cosmic ray protons are perfectly magnetically contained, and escape only through photo-hadronic interactions which convert them to neutrons.*

Kachelriess et al. (2009)

- *They assume a CR flux com-posed of protons, normalized with the assumption that 2 ofthe UHE Auger events are from Centaurus A. They consider several possible proton injection spectra, with acceleration occurring either in regular electromagnetic fields close to the core of the AGN or through shock acceleration in the jets, and predict the resulting neutrino and gamma-ray spectra for each.*
- *They argue that the jet acceleration scenarios are excluded by TeV gamma-ray data.*

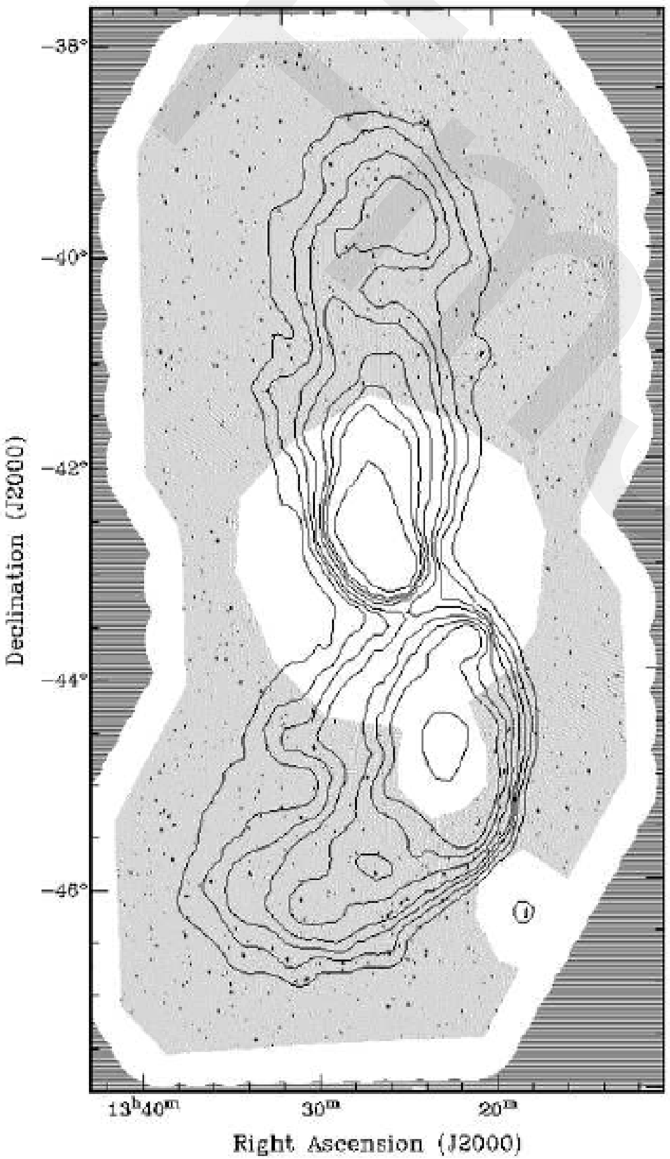
Rieger & Aharonian (2009)

- *Suggest that shear acceleration along the kpc jet may accelerate protons beyond 5×10^{19} eV.*

Gopal-Krishna, Biermann, de Souza & Wiita (ApJ, in press)

- *Show that UHECR production at a spatially intermediate location about 15 kpc northeast from the nucleus, where the jet emerging from the nucleus is observed to strike a large star-forming shell of gas, is plausible.*
- *Many cosmic rays arising from a starburst, with a composition enhanced in heavy elements near the knee region around PeV, are boosted to ultra-high energies by the relativistic shock of a newly oriented jet.*
- *They are able to predict the composition suggested by the Auger data as well as an anisotropy in the hemisphere toward Cen A.*

Acceleration in giant lobes of Cen A



Lobes: northern ~300 x 120 kpc,
southern ~ 250 x 200 kpc.

The gyroradius in a 1mG of a 10^{20} eV proton field is 100 kpc, and for a 10^{20} eV iron nucleus is ~3 kpc.

Hardcastle et al. (2009)

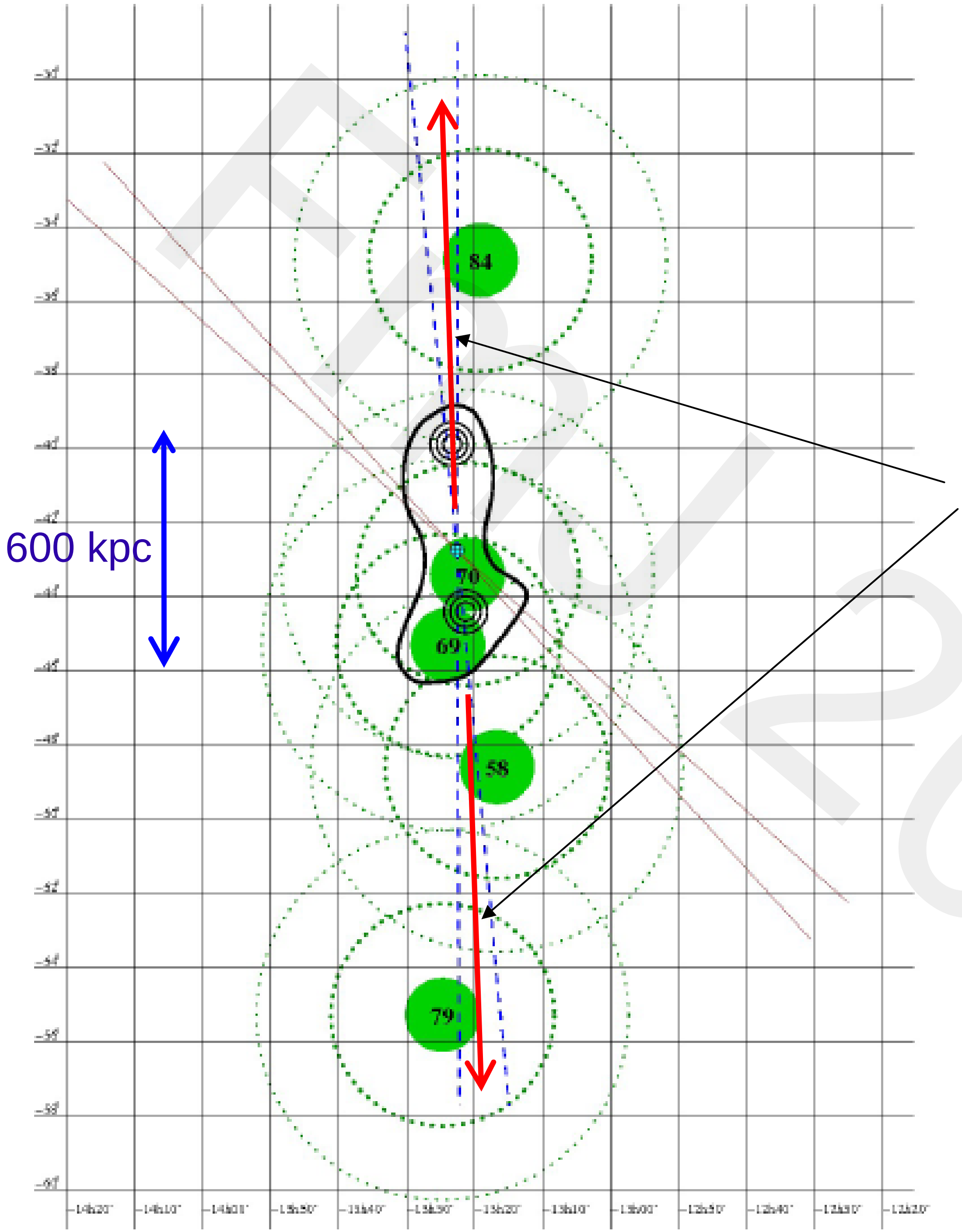
- Analyzed 408MHz – 90GHz WMAP data. B~3.3μG. Expect turbulent modes lose to speed of light. Conclude stochastic acceleration to UHECR possible.

Feain et al (2010).

- Faraday rotation of 121 sources behind the lobes.
- If $B=1.3B_1$ μG then $\langle n_e \rangle < 5\text{x}10^{-5} B_1$ cm^{-3}.

Benford & Protheroe (2008)

- Acceleration in the "fossil" lobes, by electric fields induced as the magnetic field settles down to an ordered field such as a spheromak configuration produced in plasma physics experiments, or during decay of such fields as a result of reconnection may be possible.

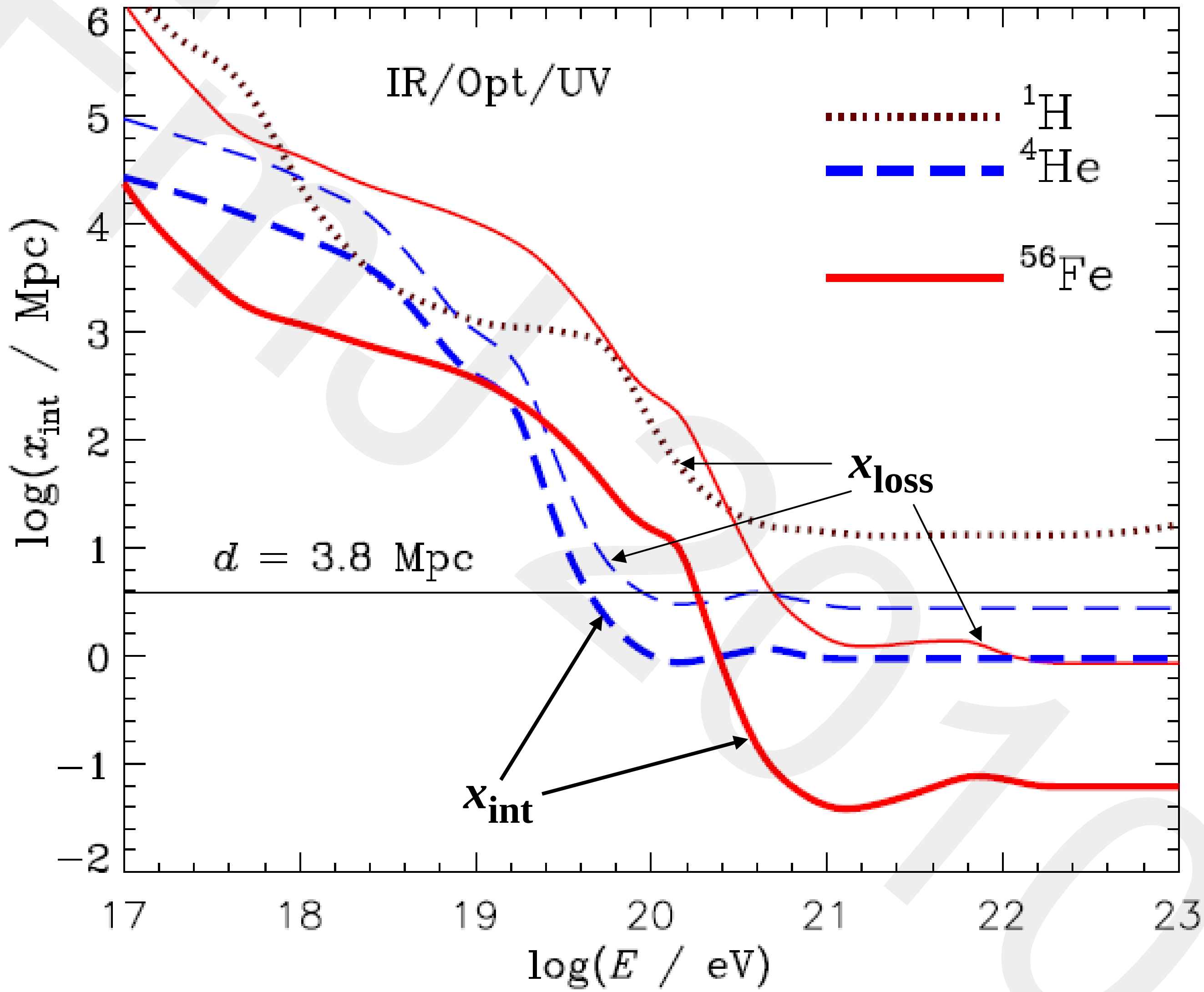


Rachen (2009).

- *The present jets are weak and unlikely to be responsible for UHE CR.*
- *Giant lobes must have been produced by an earlier more powerful jets aligned N-S.*
- *These earlier jets could have been responsible for the cluster of Auger events (shown green).*

FRI 2010

Propagation from Cen A



Frank 2010

Data from Allard & Protheroe (2009)

Time delay in propagating from Cen A

The propagation time will depend on distance *d*, rigidity ρ, coherence length l_c and magnetic field *B*.

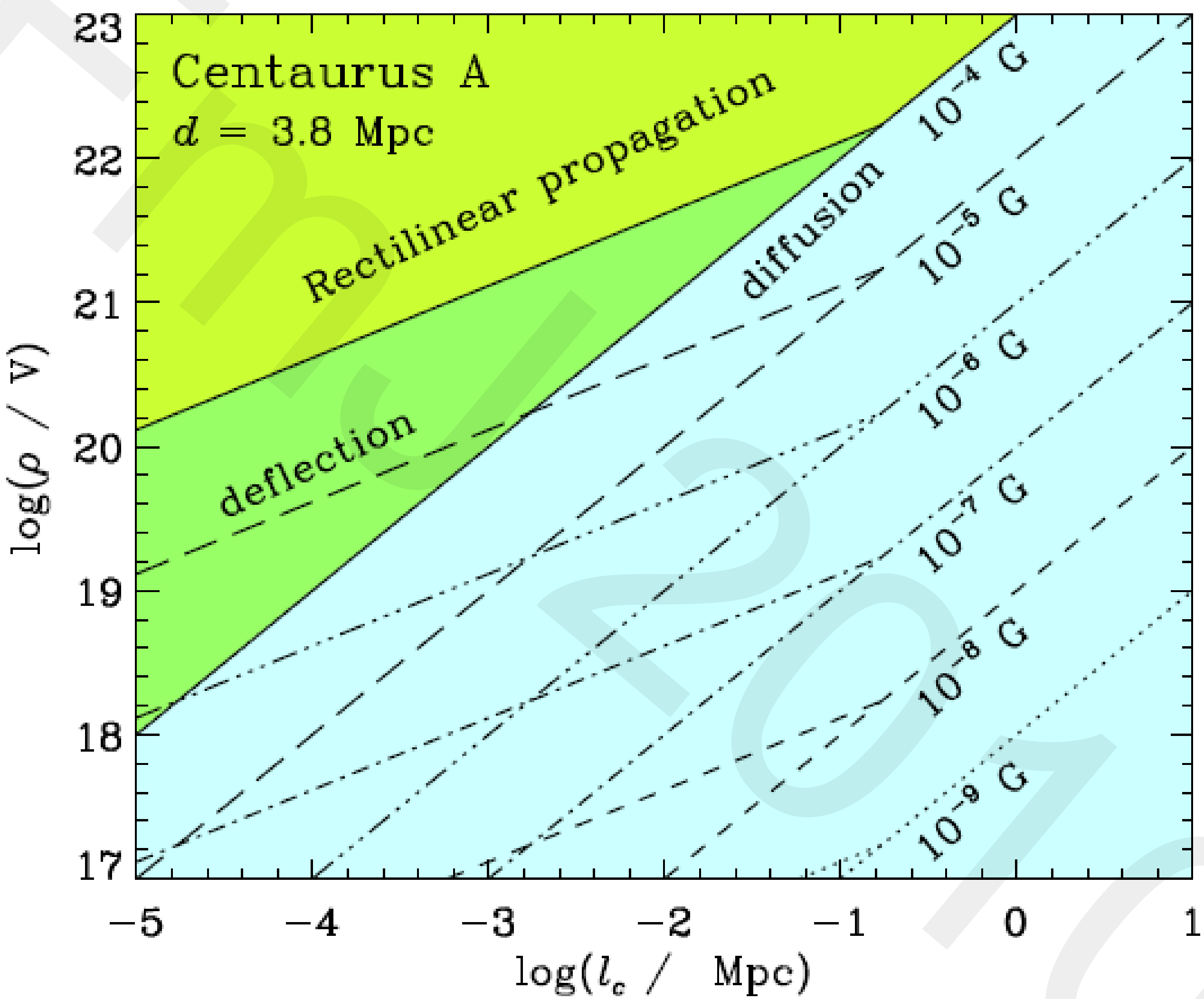
For gyroradii $r_g > l_c$ the additional delay due to multiple deflections is (e.g. Sigl)

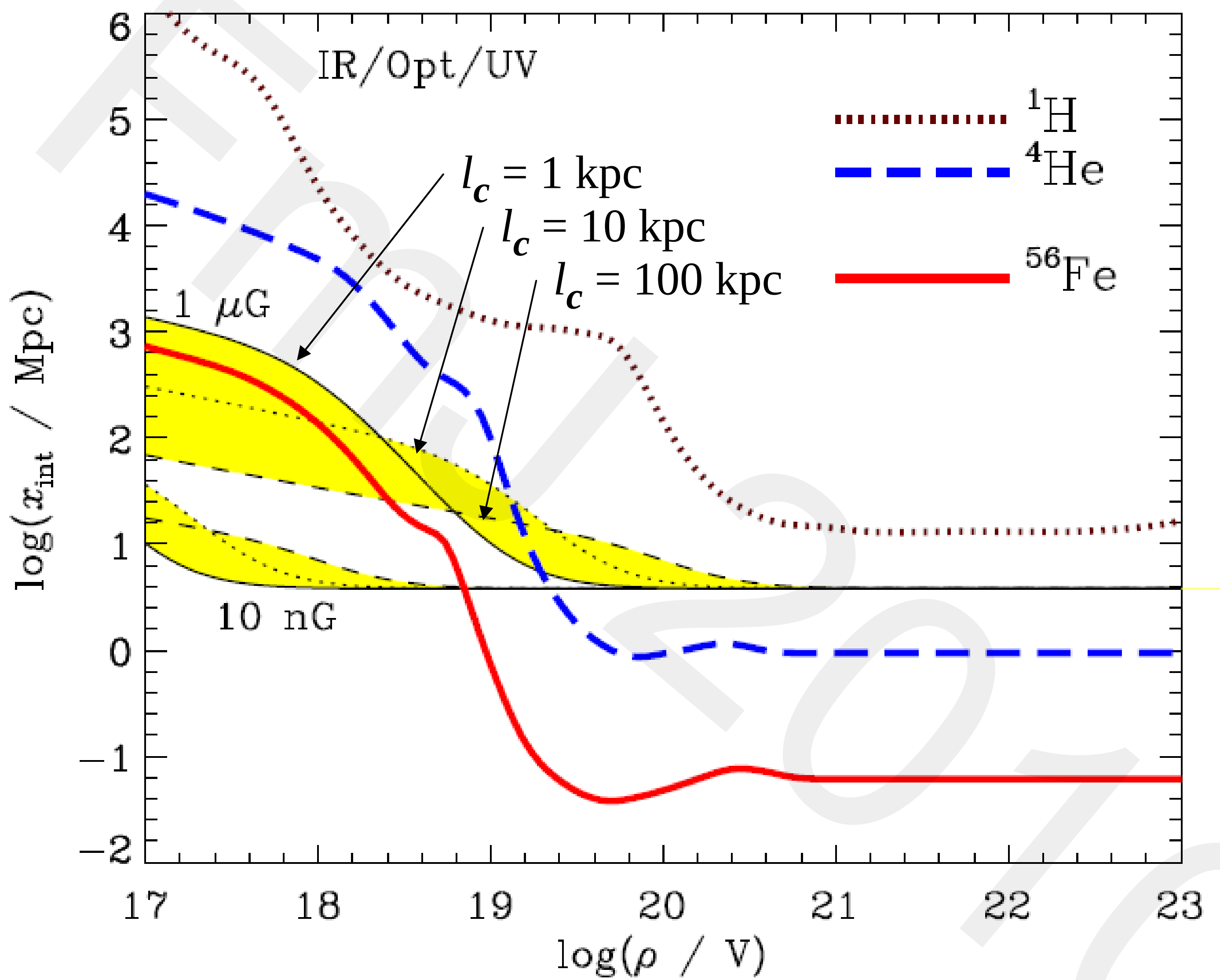
$$c\,t_{\rm defl}(\rho,d) \;=\; 0.045\left(\frac{\rho}{10^{20}\ {\rm V}}\right)^{-2}\left(\frac{d}{1\ {\rm Mpc}}\right)^{2}\left(\frac{l_c}{\rm Mpc}\right)\left(\frac{B}{10^{-7}\ {\rm G}}\right)^{2}\ {\rm Mpc}$$

For gyroradii $r_g < l_c$ the delay due to diffusion is with diffusion coefficient $D = D_0\,\rho^{1/3}$ is

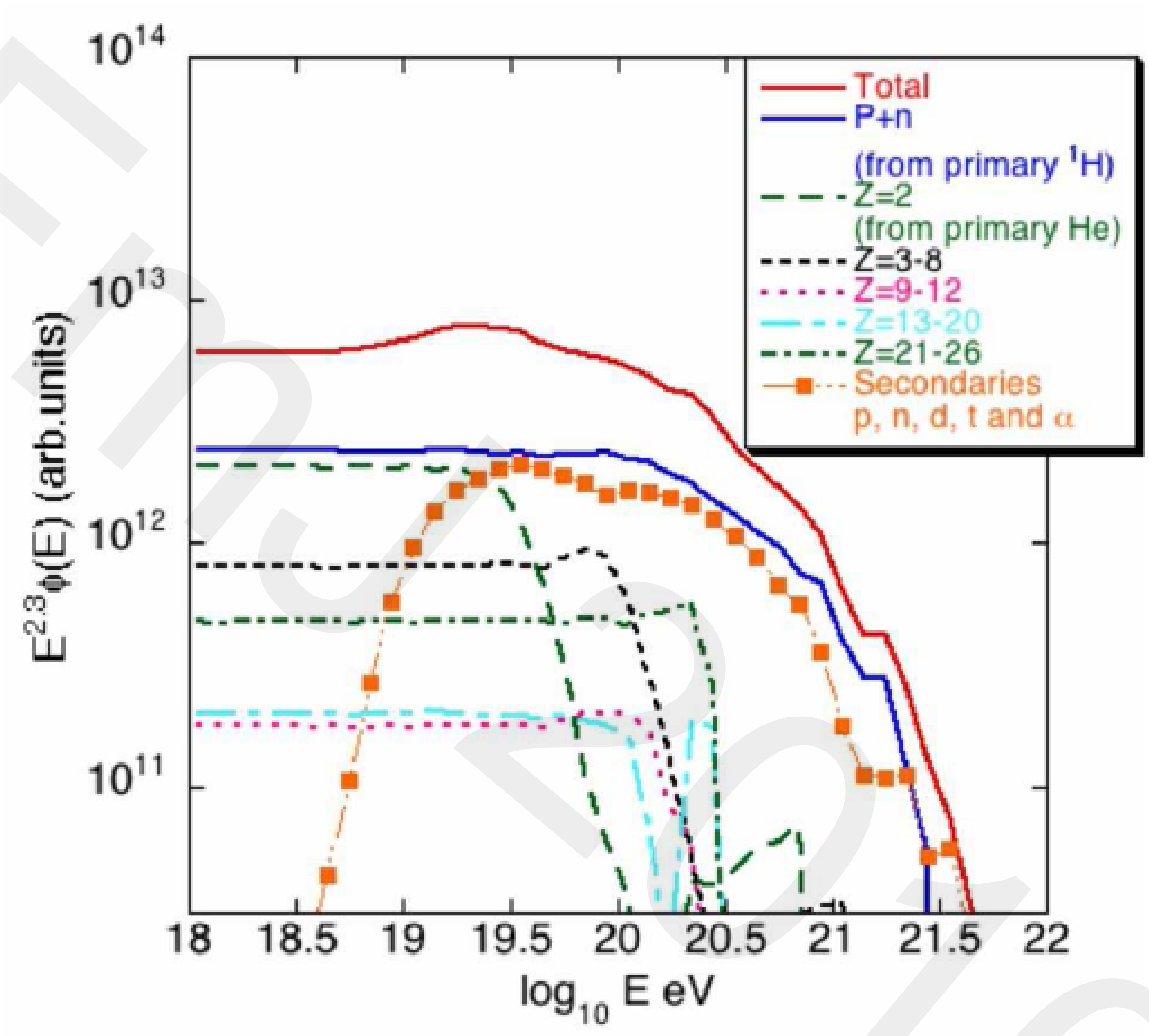
$$c\,t_{\rm diff}(\rho,d) \;=\; ct_{\rm defl}(\rho_{r_g-l_c},d)\left(\frac{\rho}{\rho_{r_g-l_c}}\right)^{-1/3}.$$

FMJ 2010


Centaurus A
d = 3.8 Mpc
Rectilinear propagation
deflection
diffusion
10^-4 G
10^-5 G
10^-6 G
10^-7 G
10^-8 G
10^-9 G
log(ρ / V)
log(l_c / Mpc)
23
22
21
20
19
18
17
−5
−4
−3
−2
−1
0
1



rigidity $\rho \approx E/Ze$

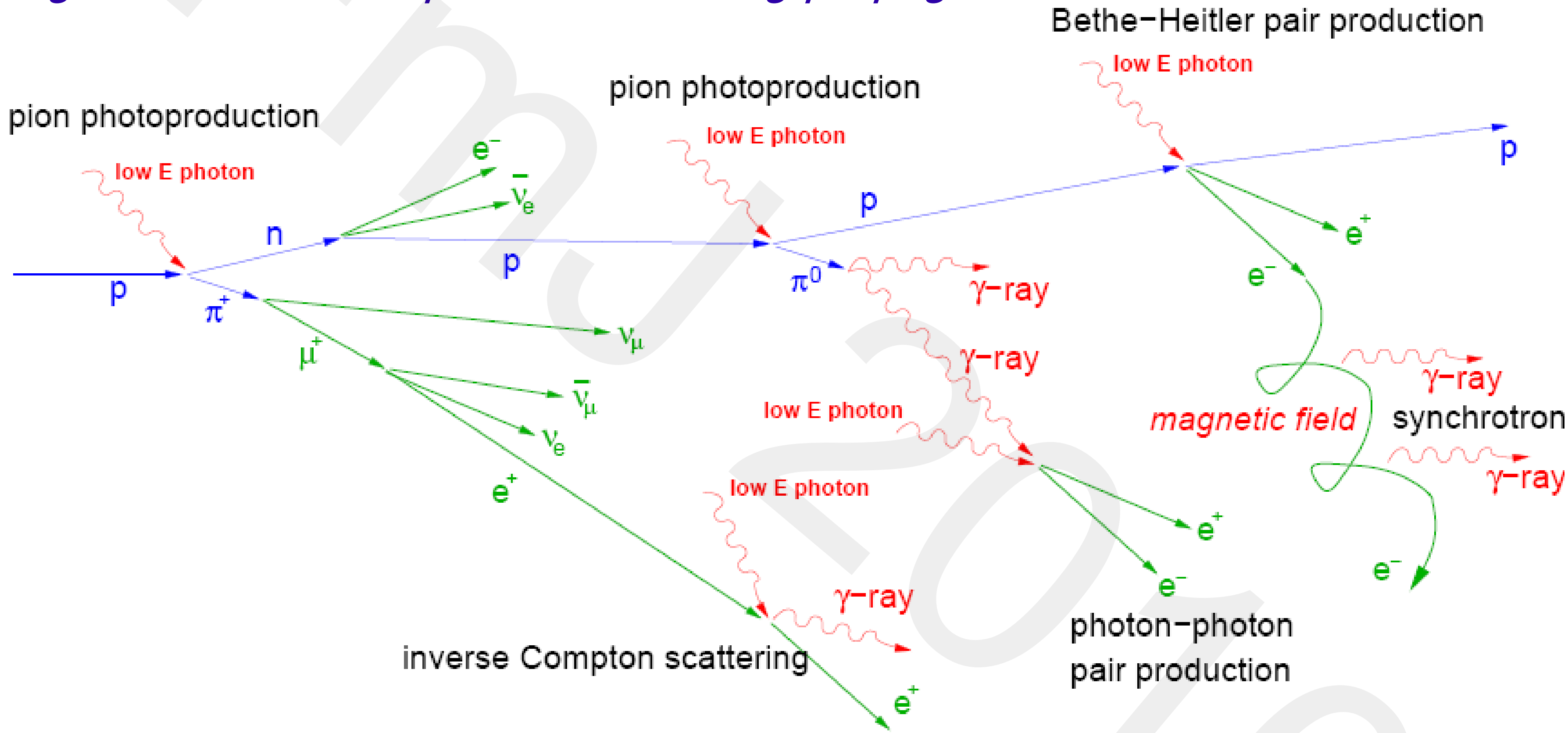


Propagation of a mixed Galactic composition accelerated at Cen A for $E^{-2.3}$ and $E_{max}=Z\mathrm{x}10^{21}$ eV (D. Allard, private communication).

FINAL 2010

Neutrinos from Cen A? (for amusement if time permits)

In general, pion photoproduction interactions during acceleration and propagation result in neutrino production, but Cen A is too near for significant neutrino production during propagation.

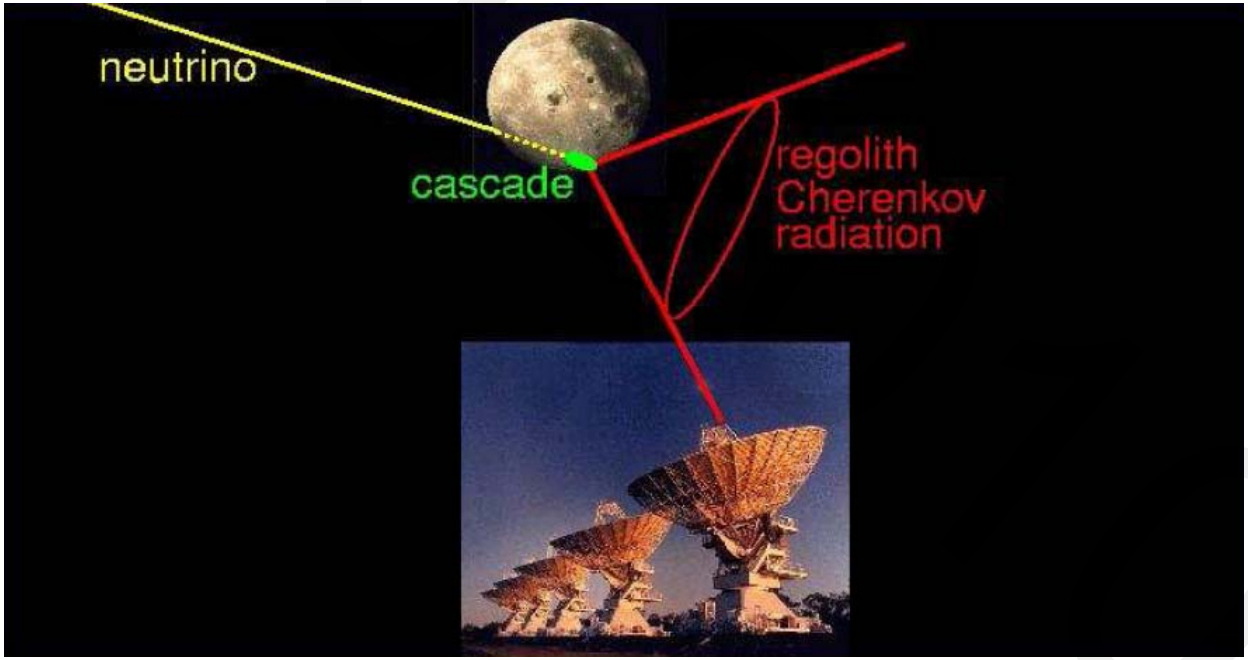


The cascading results in a flux of gamma-rays at energies below ∼10 GeV, and neutrinos above $\sim 10^8$ GeV.

EMJ 2010

Lunar Cherenkov Technique

- **Pioneered by Hankins, Ekers and O'Sullivan (1996) using the Parkes radio telescope.**
- **Relies on the "Askaryan effect" whereby cascades in dense media acquire a negative charge excess due to positron annihilation and scattering of atomic electrons into the cascade – for cascade dimensions shorter than the observing wavelength the Cherenkov emission process is coherent.**
- **Very non-standard radio astronomy – search for nanosecond duration pulses.**
- **Uses specialized hardware with more in common with accelerator experiments.**



LUNASKA Collaboration

C. W. James[1,2⋆], R. J. Protheroe[2], R. D. Ekers[3], J. Alvarez-Muñiz[4], R. A. McFadden[3,5], C. J. Phillips[3], P. Roberts[3], J. D. Bray[2,3]

[1]*IMAPP, Radboud University, Nijmegen, The Netherlands*
[2]*School of Chemistry & Physics, Univ. of Adelaide, Australia.*
[3]*Australia Telescope National Facility, CSIRO Astronomy & Space Science, Epping, Australia.*
[4]*Dept. Fisica de Particulas & IGFAE, Univ. Santiago de Compostela, Spain.*
[5]*School of Physics, Univ. of Melbourne, Australia.*

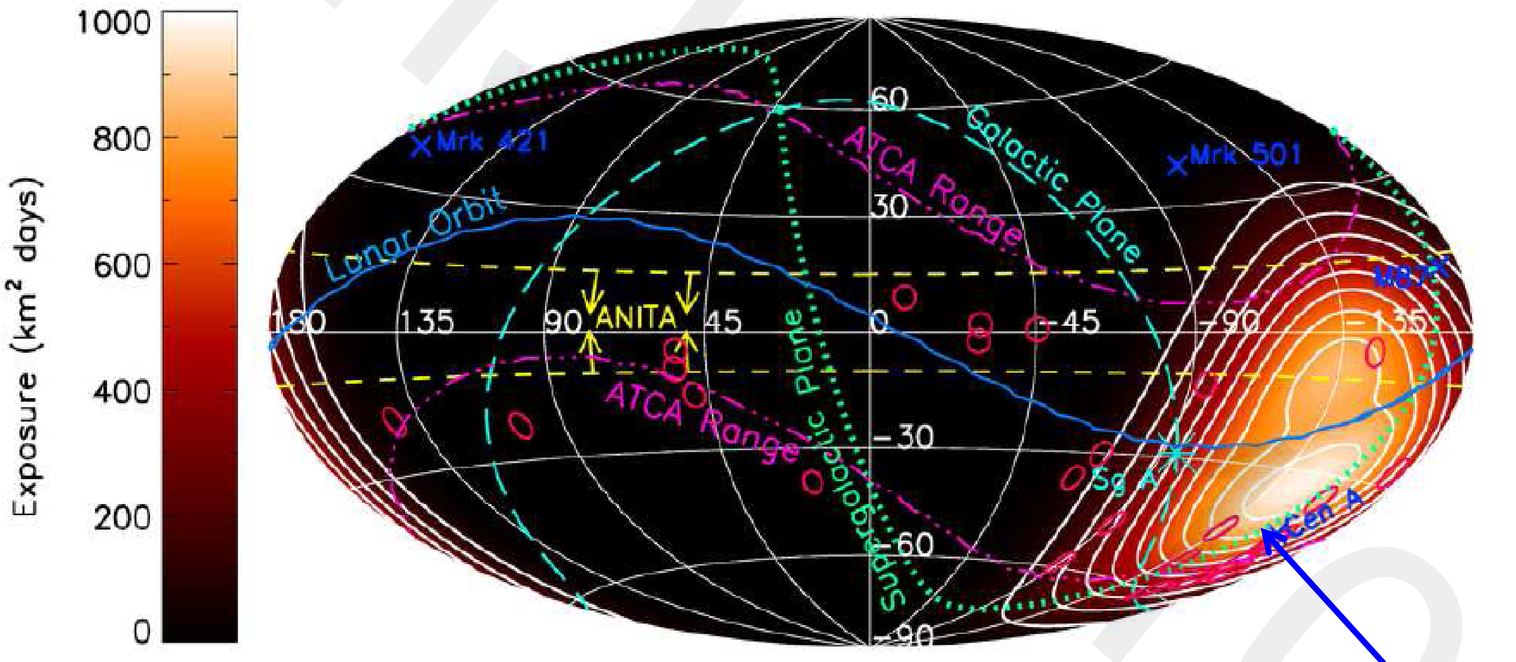
plus

Anita Reimer (Innsbruck University, Austria),
Peter Hall (Curtin University, Perth, Australia),
Todor Stanev (University of Delaware, USA),
John O'Sullivan (Australia Telescope National Facility, Sydney)

The LUNASKA Collaboration has been actively developing the lunar Cherenkov technique and has searched for UHE neutrinos from Cen A.

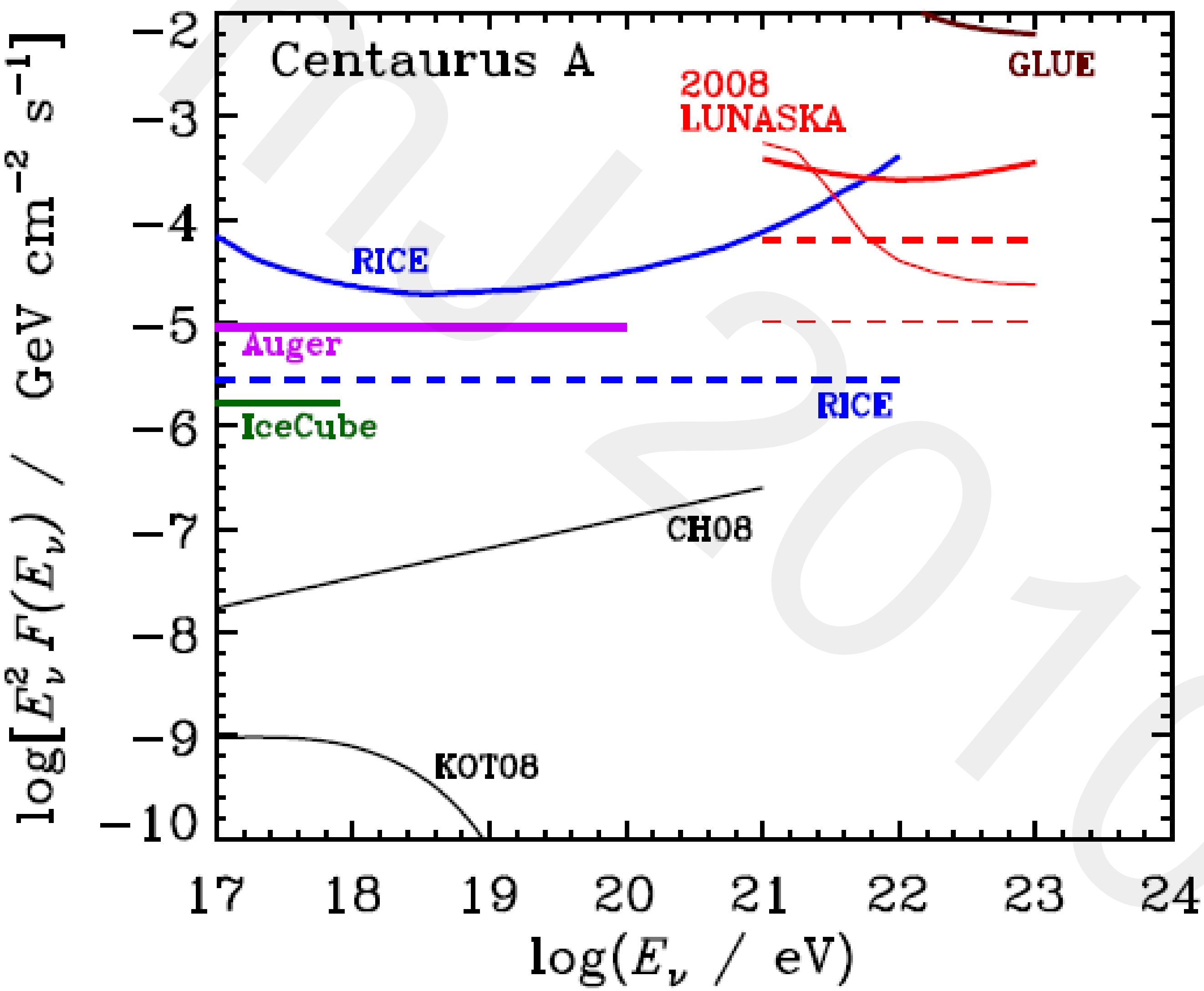
LUNASKA 2008 observations using Australia Telescope Compact Array

We chose observing dates/times to give the greatest combined exposure to Cen A.



The small circles show the directions of UHE CR events above 5.6×10^{19} eV

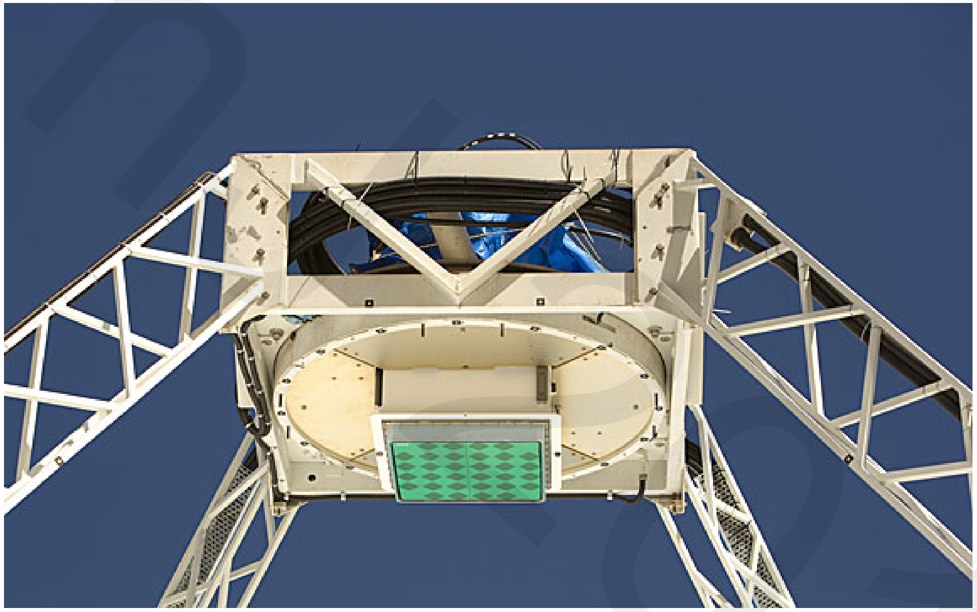
We have calculated flux limits for GLUE and RICE based on their published data, as well as for our 2008 observations.



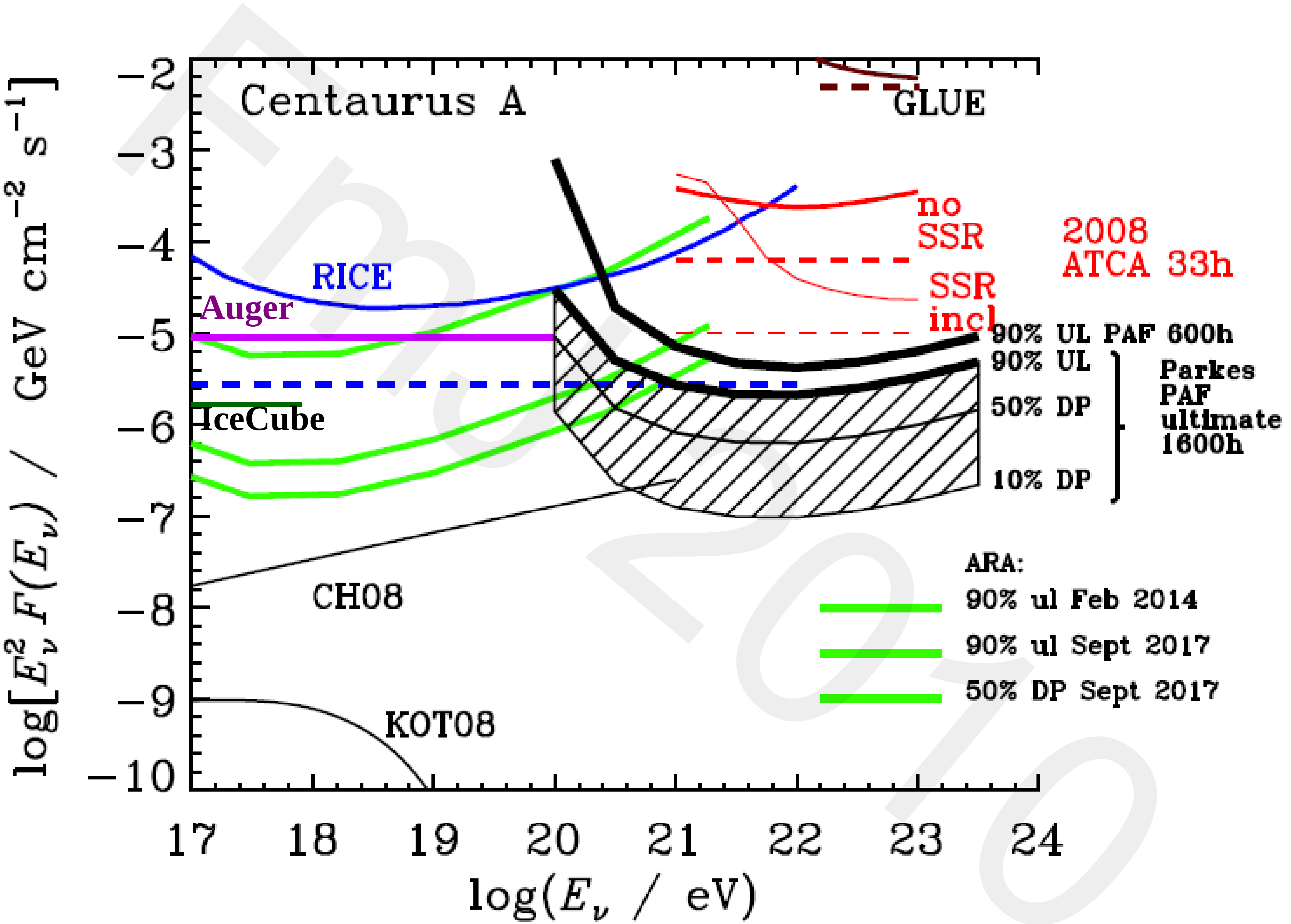
2010-2014: LUNASKA-Parkes

Our 2010-11 observations use the multi-beam receivers (right) In the focal plane of the Parkes radio telescope (left).

*Our 2012 observations "**Parkes PAF**" will use the Australian SKA pathfinder (ASKAP) phased array feed (PAF) hardware in the focal plane of the Parkes radio telescope enabling the whole Lunar limb to be observed simultaneously (funding applied for).*



A prototype ASKAP PAF is shown on an ASKAP test antenna. It is being designed by a team led by John O'Sullivan who developed in 1995 the WLAN technology we all use - he is also a LUNASKA member.



Centaurus A
GLUE
no
SSR
2008
ATCA 33h
SSR
incl
RICE
Auger
IceCube
90% UL PAF 600h
90% UL
50% DP
10% DP
Parkes
PAF
ultimate
1600h
CH08
KOT08
ARA:
90% ul Feb 2014
90% ul Sept 2017
50% DP Sept 2017
$\log[E_\nu^2 F(E_\nu)$ / GeV cm^{-2} s$^{-1}]$
$\log(E_\nu$ / eV)
−2
−3
−4
−5
−6
−7
−8
−9
−10
17
18
19
20
21
22
23
24

Conclusion

- Cen A may be responsible for some of the observed UHE cosmic rays.
- Despite its proximity, there will be composition changes during propagation – while protons are unaffected, all Fe above 1.5×10^{19} eV will be photo-disintegrated, but there will be “heavy” spallation products remaining.
- Time delays due to magnetic deflection of due to diffusion will be rigidity-dependent and so affect protons and heavey nuclei of the same energy differently.
- Time delays of up to tens of Myr are possible, implying the cosmic rays arriving now may have been accelerated when Cen A was a much more powerful AGN.
- If the spectrum of accelerated protons is cut off due to pion photoproduction, then there may be a detectable UHE neutrino flux from Cen A.

Email 2010