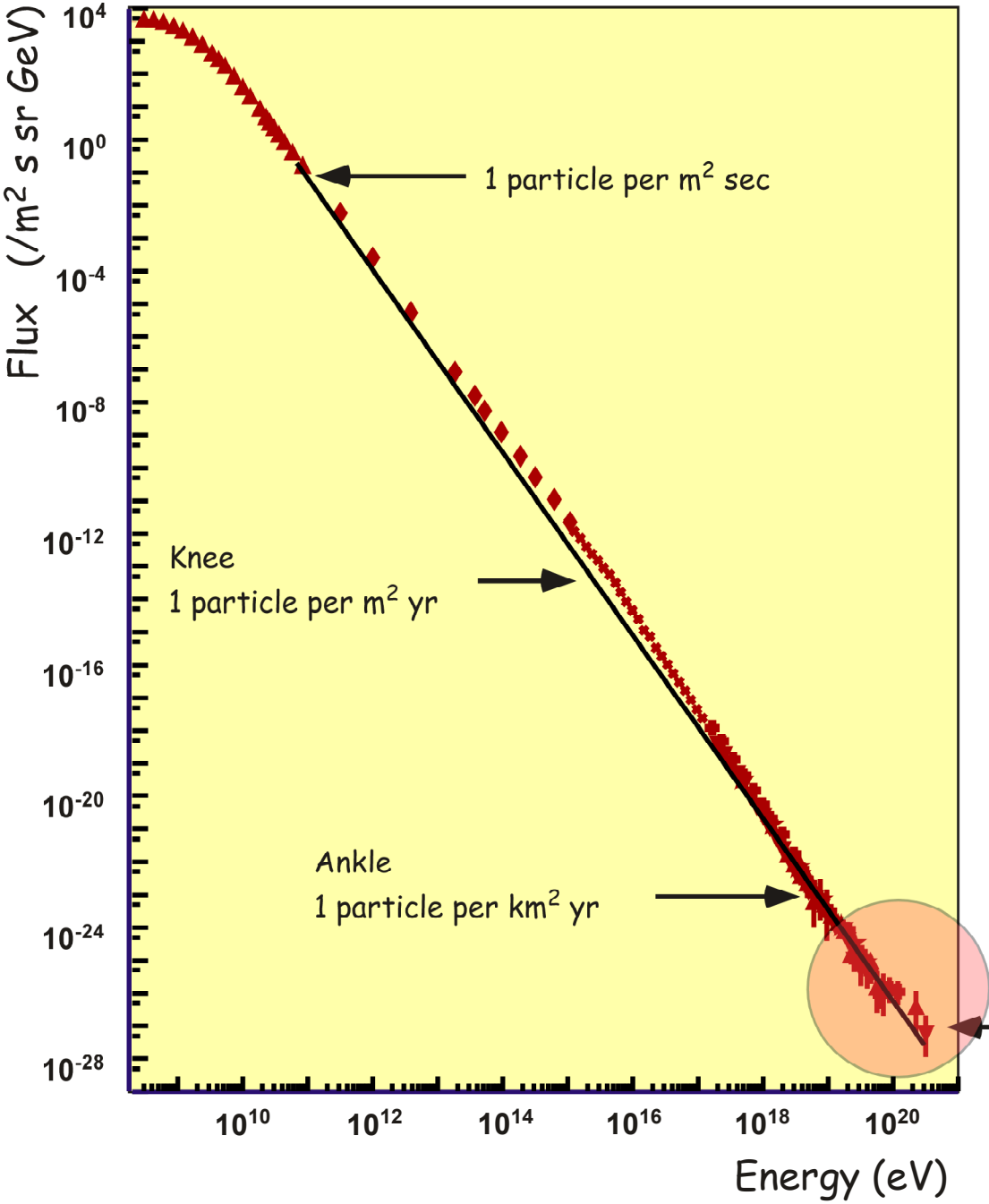
Ultra High Energy Cosmic Rays (UHECR): The Puzzle

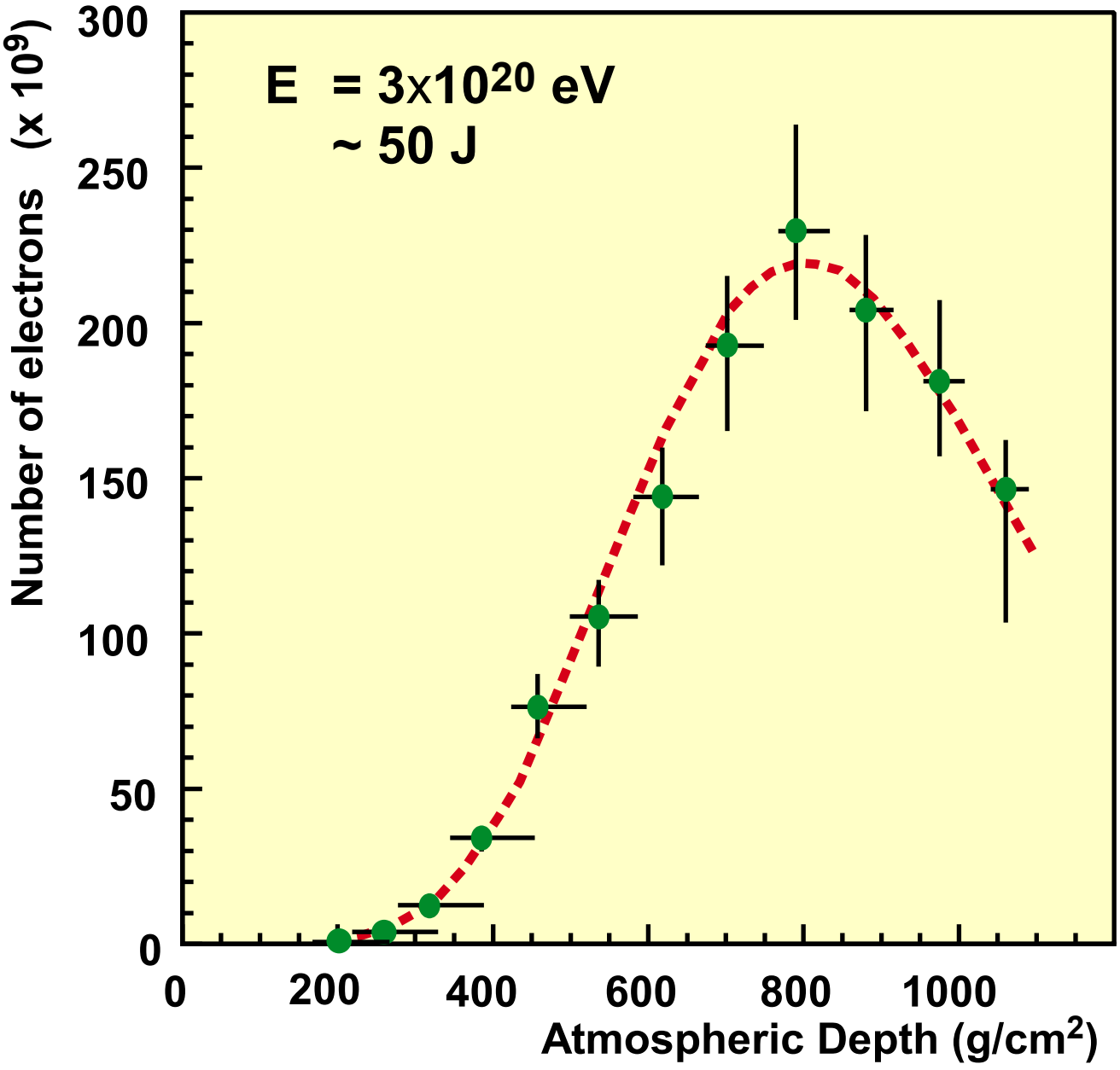


Spectrum extends well beyond
- the knee and
- the energies that can be produced by shock acceleration in known shocks.

A new component is needed.

~1 particle per km² century

The Fly's Eye Event



Catalogue of UHECRs (i.e. $E > 10^{20}$ eV)

Volcano Ranch/USA	Scintillator Array 1962		
	1 event	$E > 100$ EeV	
Haverah Park/UK	array of water-Cherenkov detectors 1970 - 1980		
	4 events	$E > 100$ EeV	
Yakutsk/Sibiria	Scintillators & atmospheric Cherenkov 1989		
	1 event	$E > 120$ EeV	
Dugway/USA	atmospheric fluorescence 1991		
	1 event	$E > 320$ EeV	
Akeno/Japan	Scintillators & Muon Detectors 1990 - present		
	~15 events	$E_{max} > 330$ EeV	

Energy resolution : ~ 30%

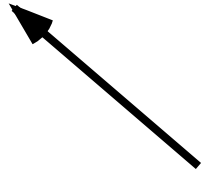
Flux at $E > 100$ EeV : ~ 1 per km^2 and century

These events are no artifacts !

There are “accelerators” out there that make $> 10^{20}$ eV particles.

Where ???

How ???



Tony Bell & Luke Drury to tell us ?

Particle Type ?

- no neutrinos,

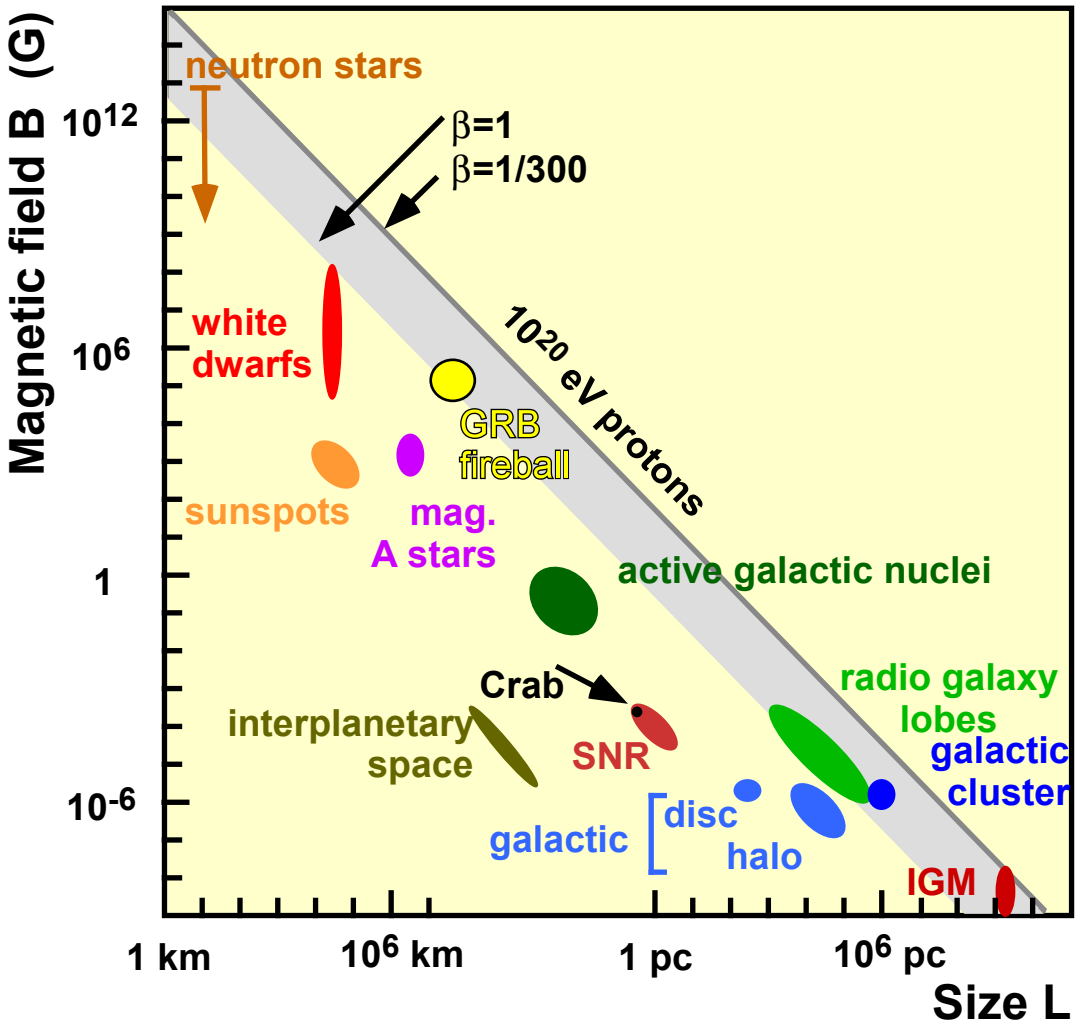
  since distribution of start points of shower
  peak in upper atmosphere

- no photons,

  since shower form different from expectation for photons

Showers look like showers from p and nuclei
at lower energies, ... just much larger.

Possible Acceleration Sites to 10^{20} eV



A.M. Hillas 1984

$B_{\mu G} \times L_{kpc} > 2\, E_{EeV} / Z$

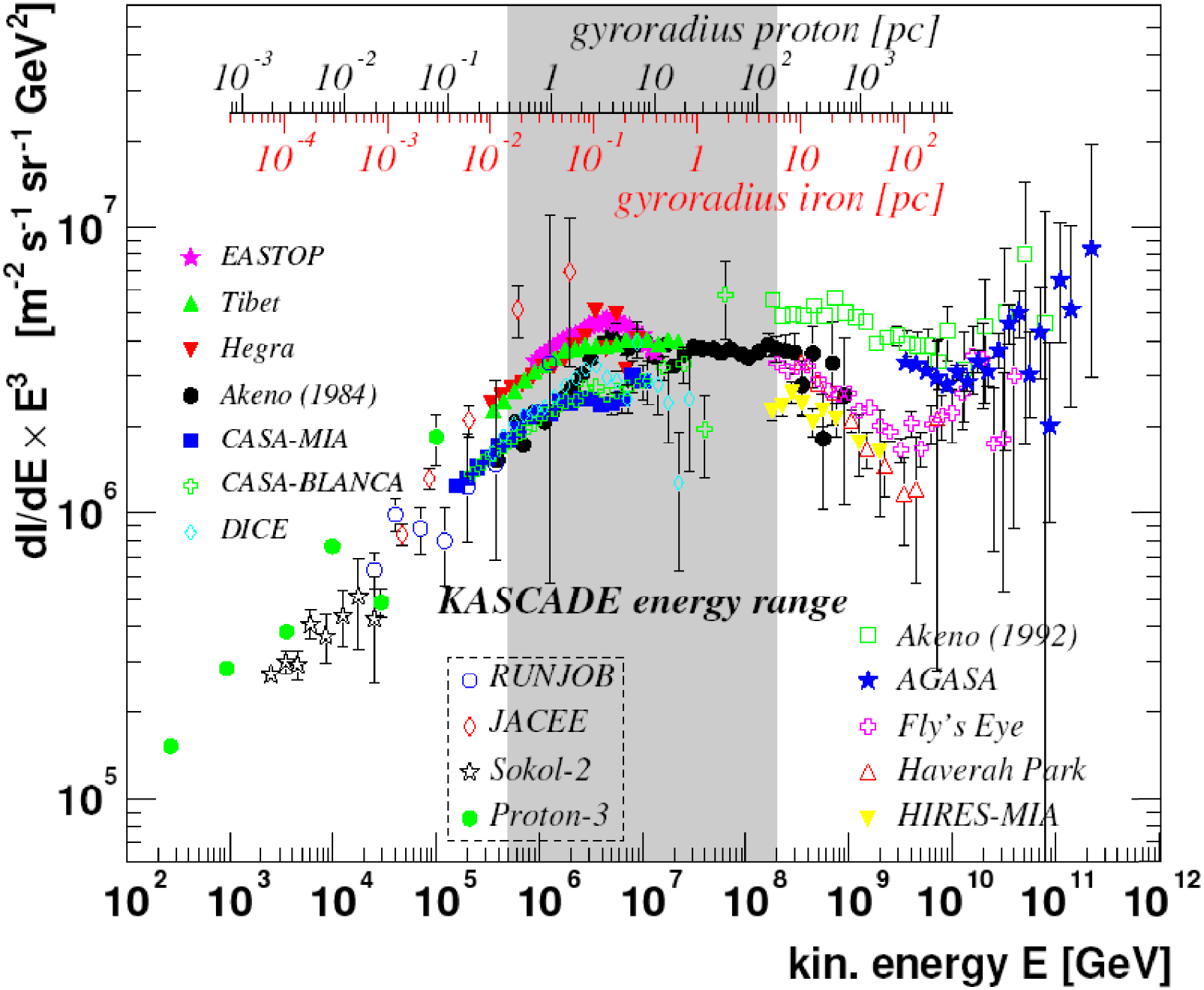
$B_{\mu G} \times L_{kpc} > 2\, (c/v)\, E_{EeV} / Z$

to fit gyro radius within L and
to allow particle to wander
during energy gain

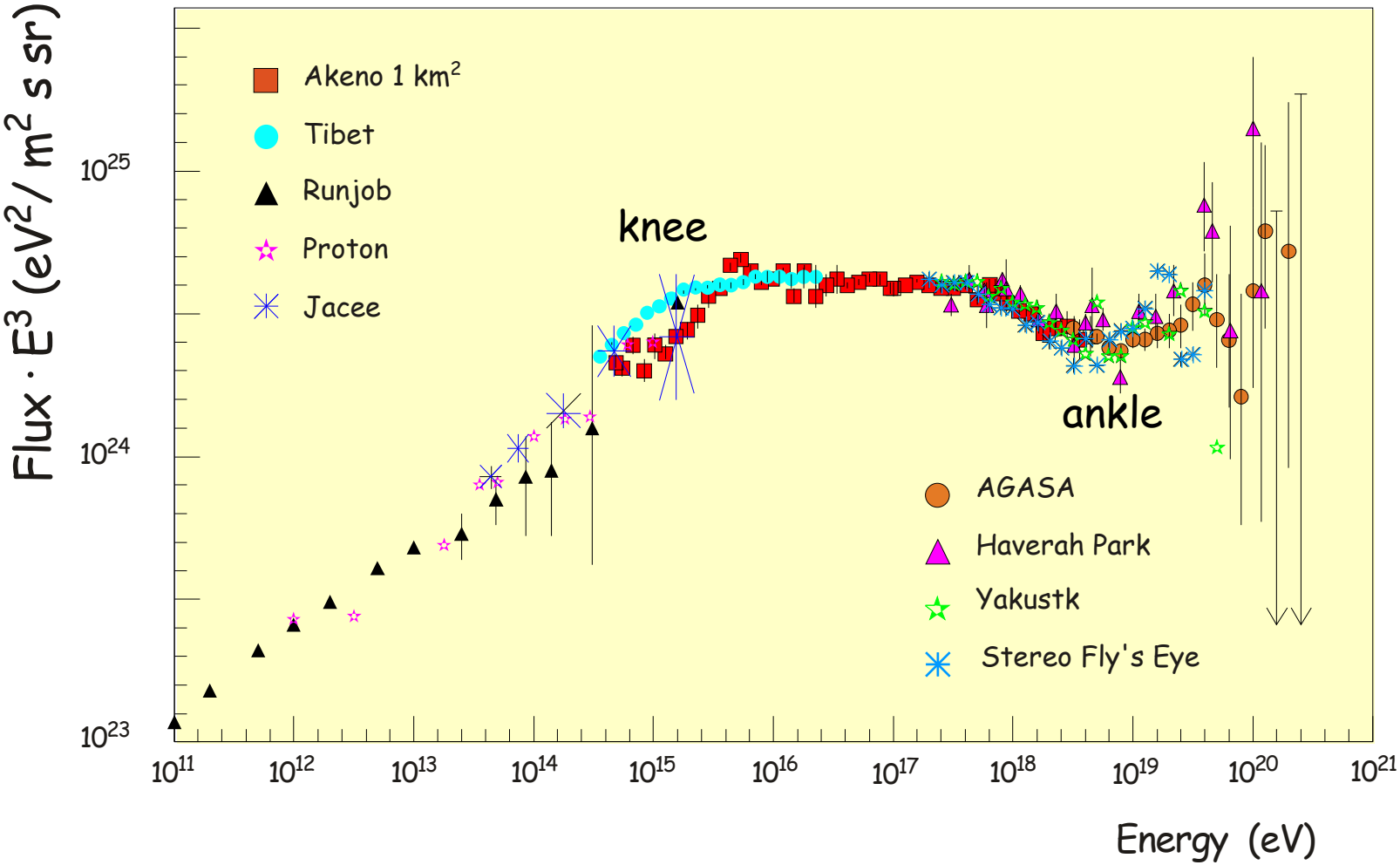
But also:
gain should be more rapid than
losses due to magnetic field
(synchrotron radiation)
and photo-reactions.

No obvious candidates ....

Differential Energy Spectrum

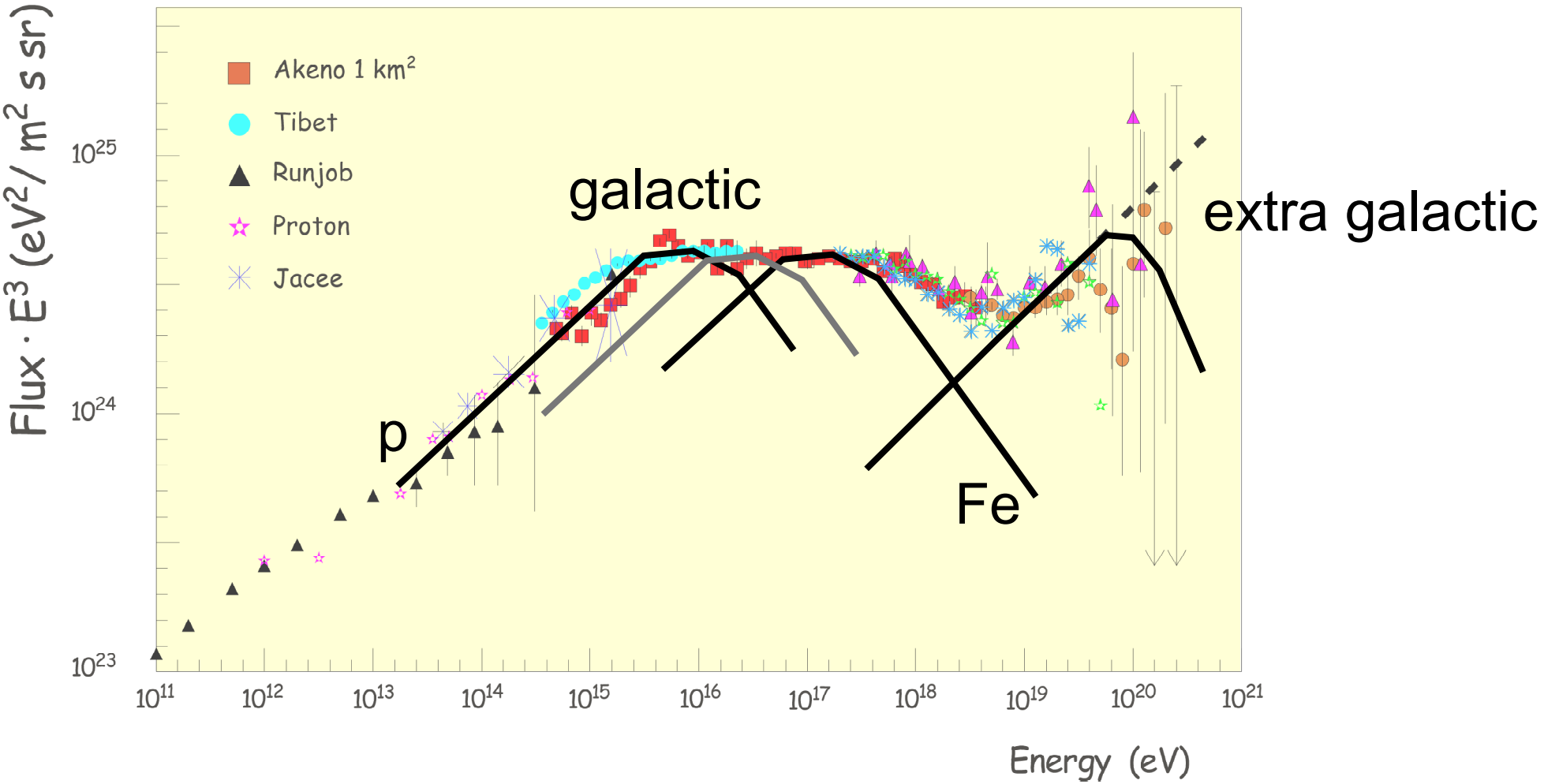


Differential Energy Spectrum



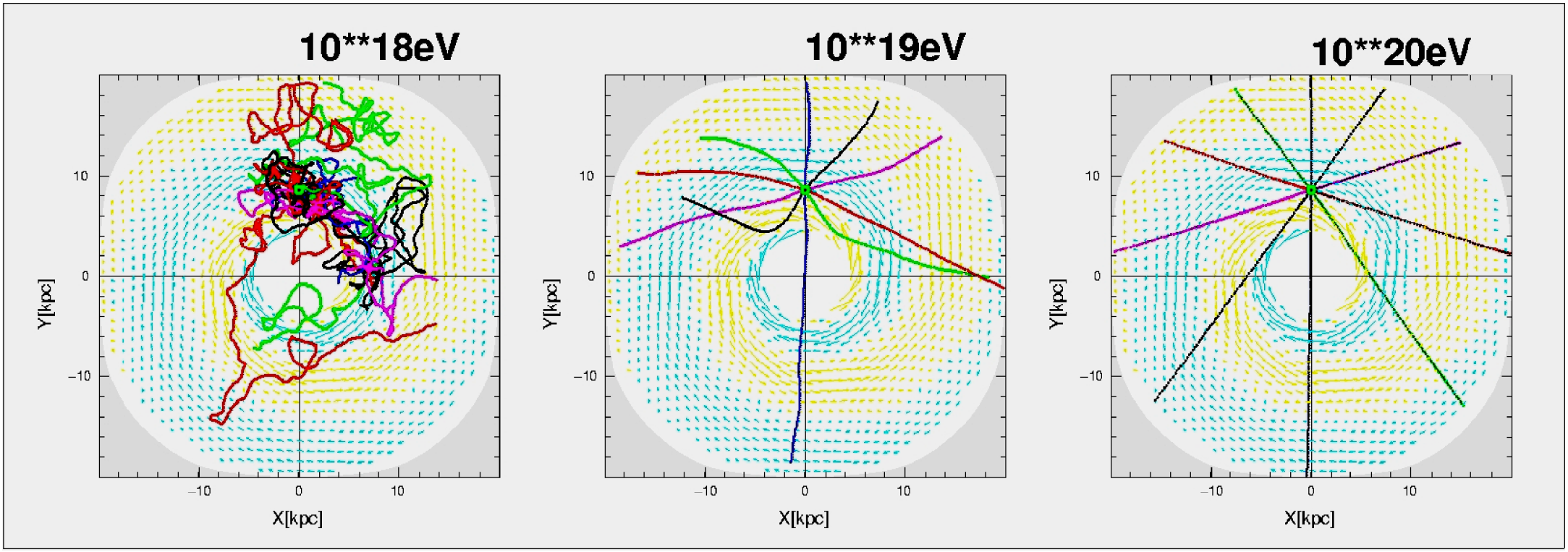
adjusted by
± 15% in energy

Agreement: < ± 45 % in flux at 10^{19} eV
< ± 15 % in energy



... more about this in talk of Michael Hillas

Highest-energy particles must be extragalactic



deflection < 1°

Extra Galactic Sources

(AGNs, radio galaxies, ...)

For a homogeneous distribution of sources in the universe UHECRs are dominated:

either by the distant sources

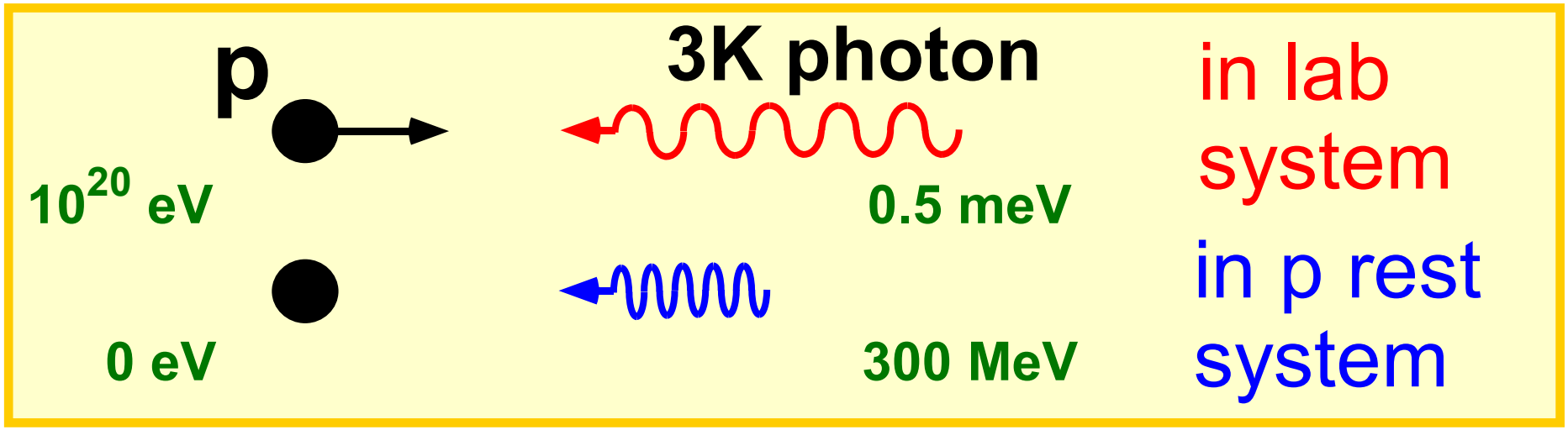
or by one very close source

If our Galaxy is typical, most of the UHECRs come from great distances.

But reactions with 2.7 K photons should affect particles above few 10^{19} eV and absorb those coming from far: Greisen-Zatsepin-Kuzmin Cutoff expected

GZK Cut-Off

Greisen Zatsepin Kuzmin



$p + \gamma_{3K} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$ (+ γ)

$\rightarrow n + \pi^{+}$ (+ ν)

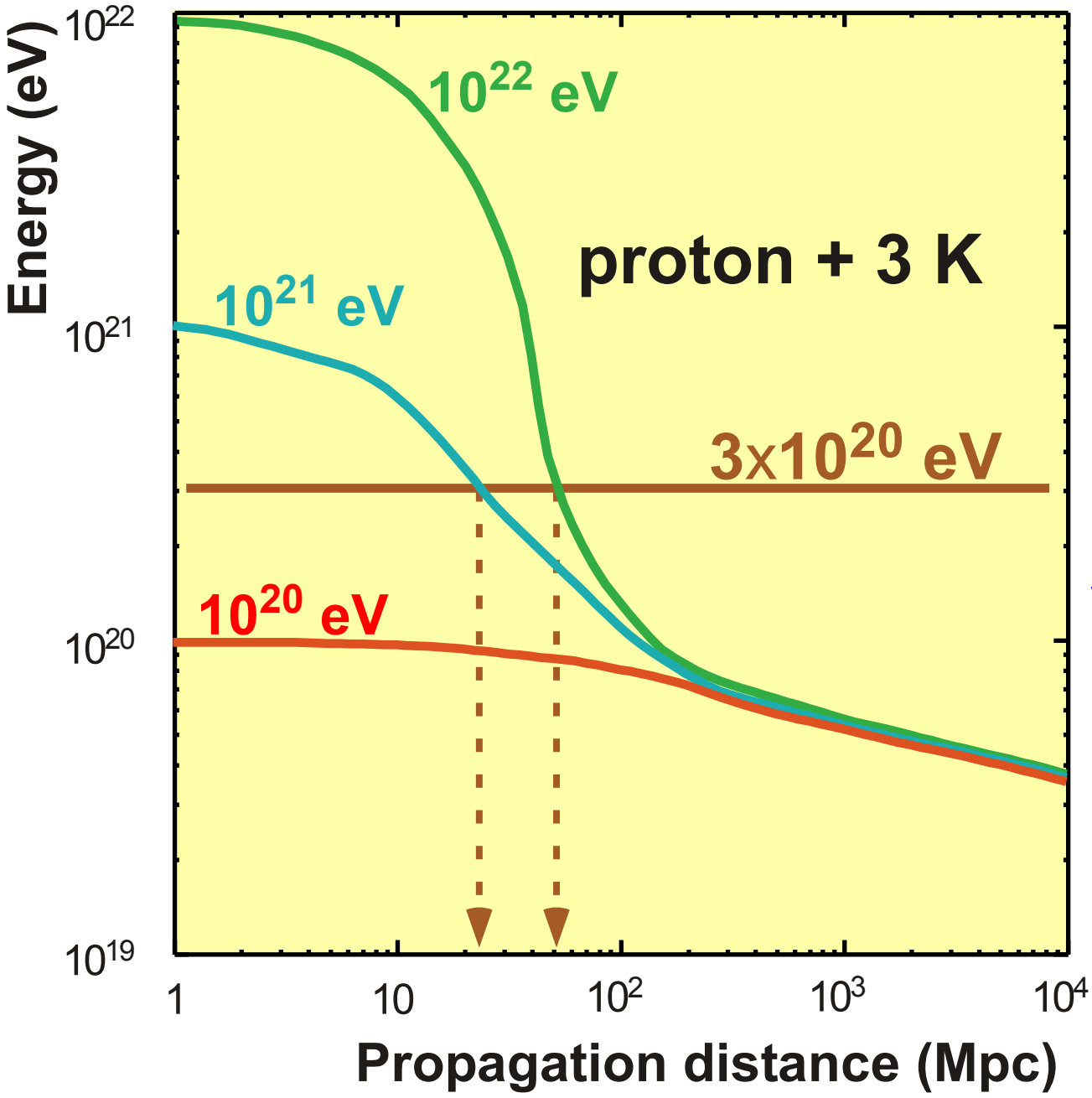
Photo-pion production

$^{56}Fe + \gamma_{3K} \rightarrow {}^{55}Fe + n$

Photo dissociation

Universe is opaque for $E > 5 \cdot 10^{19}$ eV

Energy Loss of Protons



sources must be close
(d < 50 Mpc, z < 0.01)

but:

no suitable energetic objects known

Nuclei ?

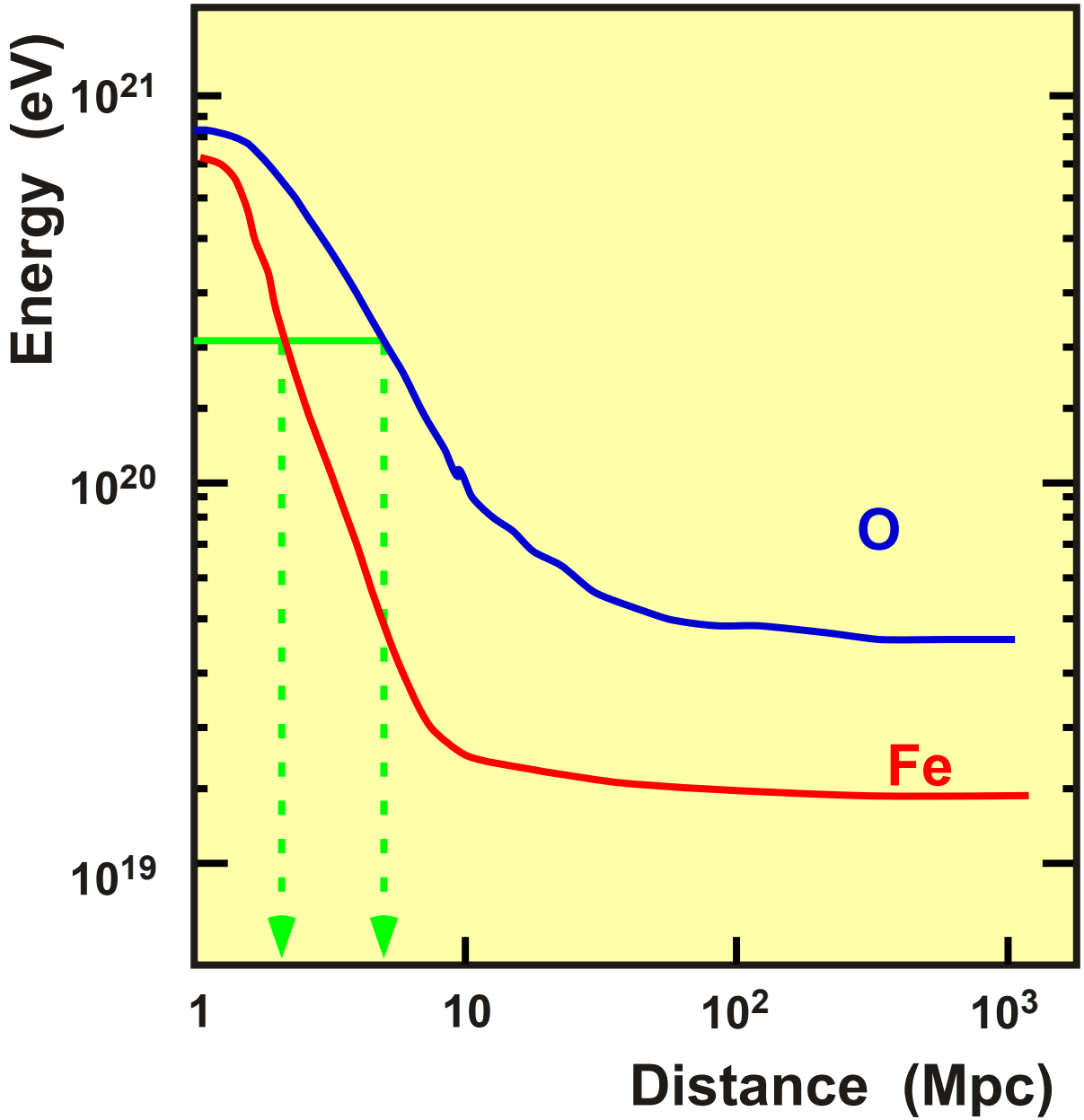


Photo disintegration :

$$A + \gamma \longrightarrow A\text{-}1 + n$$

loss: ~4 nucleons/Mpc

If GZK cut-off is seen:

then sources are distant,

CRs are p (or He... Fe)

Lorentz invariance holds up to $\gamma \sim 10^{11}$

… and we can do particle physics with 10^{20} eV beam

If GZK cut-off is not seen:

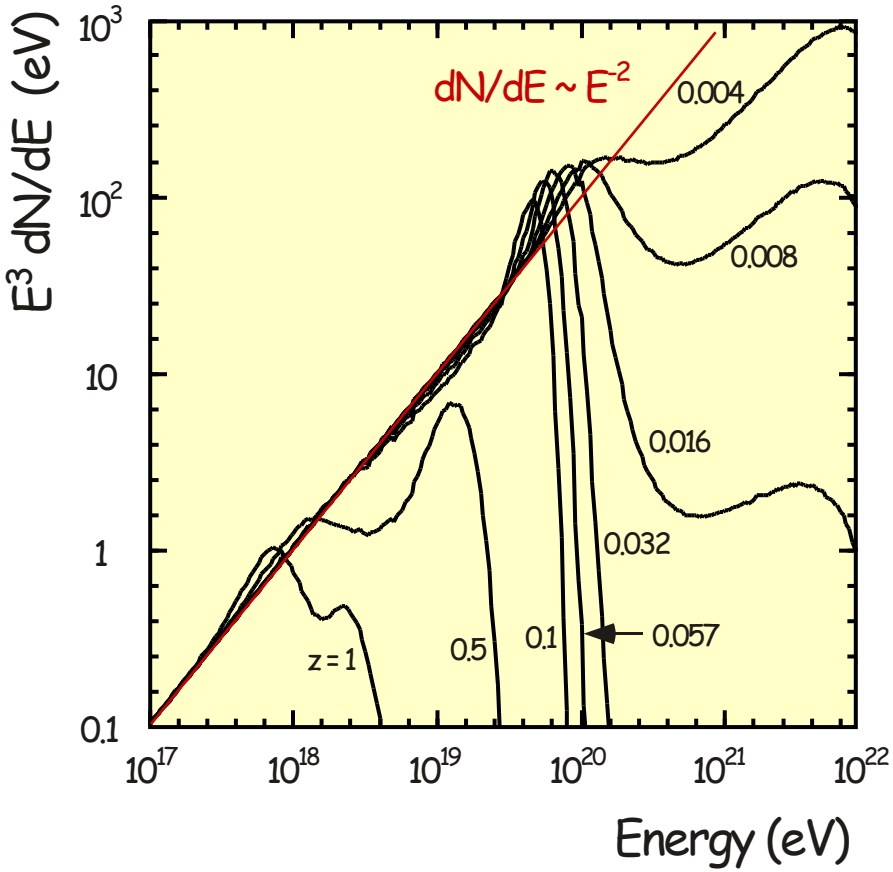
then sources must be < 100 Mpc

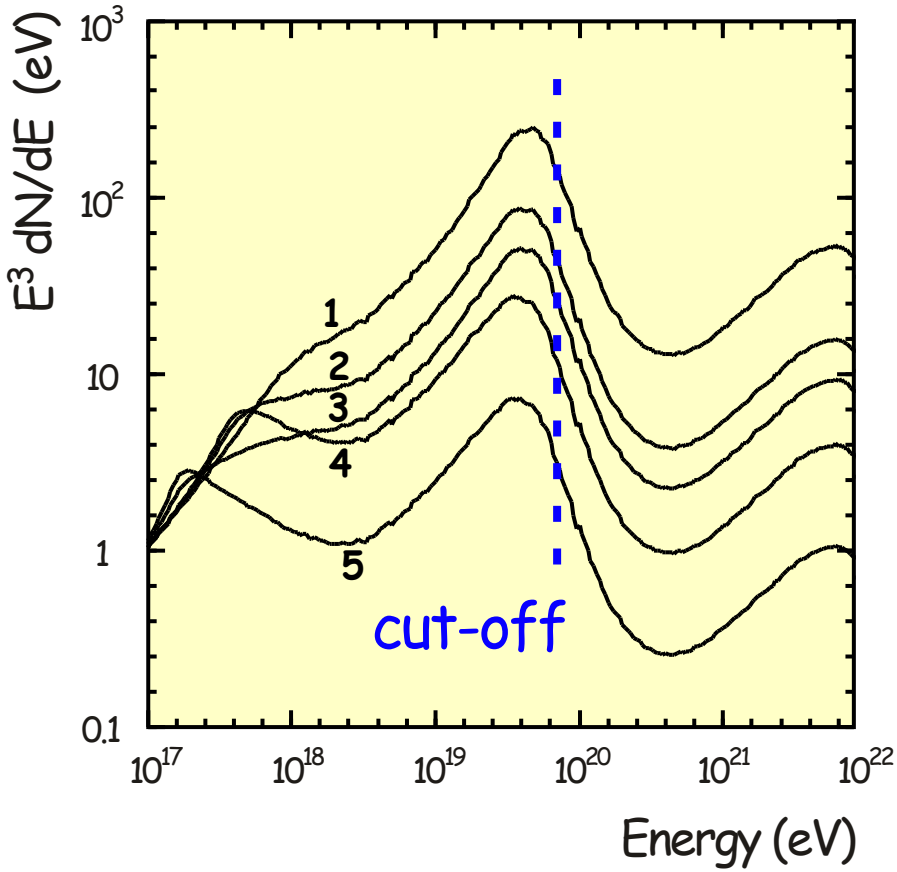
or CRs are not p, ... Fe

or Lorentz invariance is violated

or ...

Form of Energy Spectrum

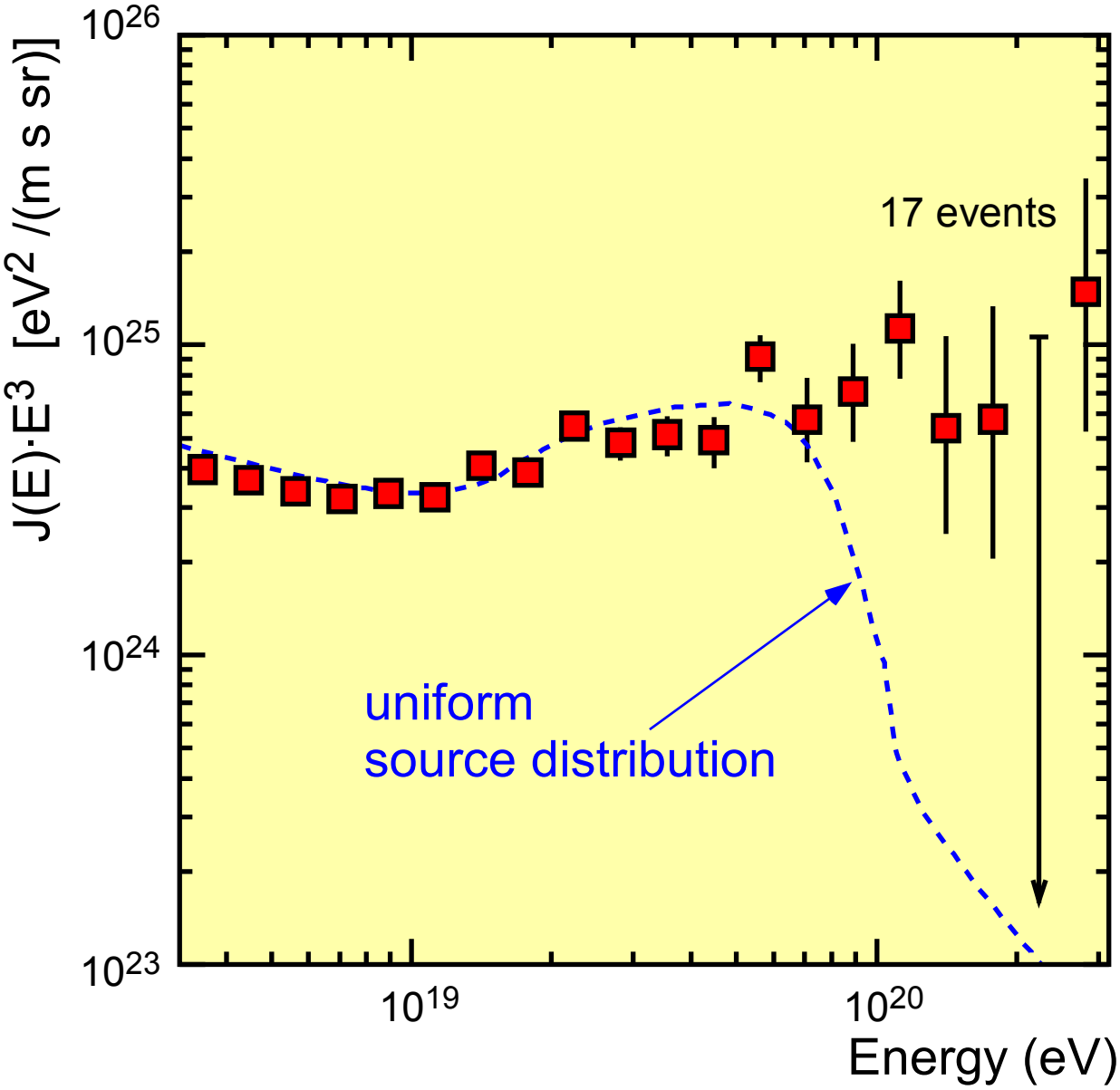




fixed source distance:
z = 0.004 ... 1
(2...5000 Mpc)

different source distributions
over cosmological distances

AGASA: ICRC 2001 p. 333



all data until May 2001
+ evts. from 20 km^2 array,
$\theta < 60^o$

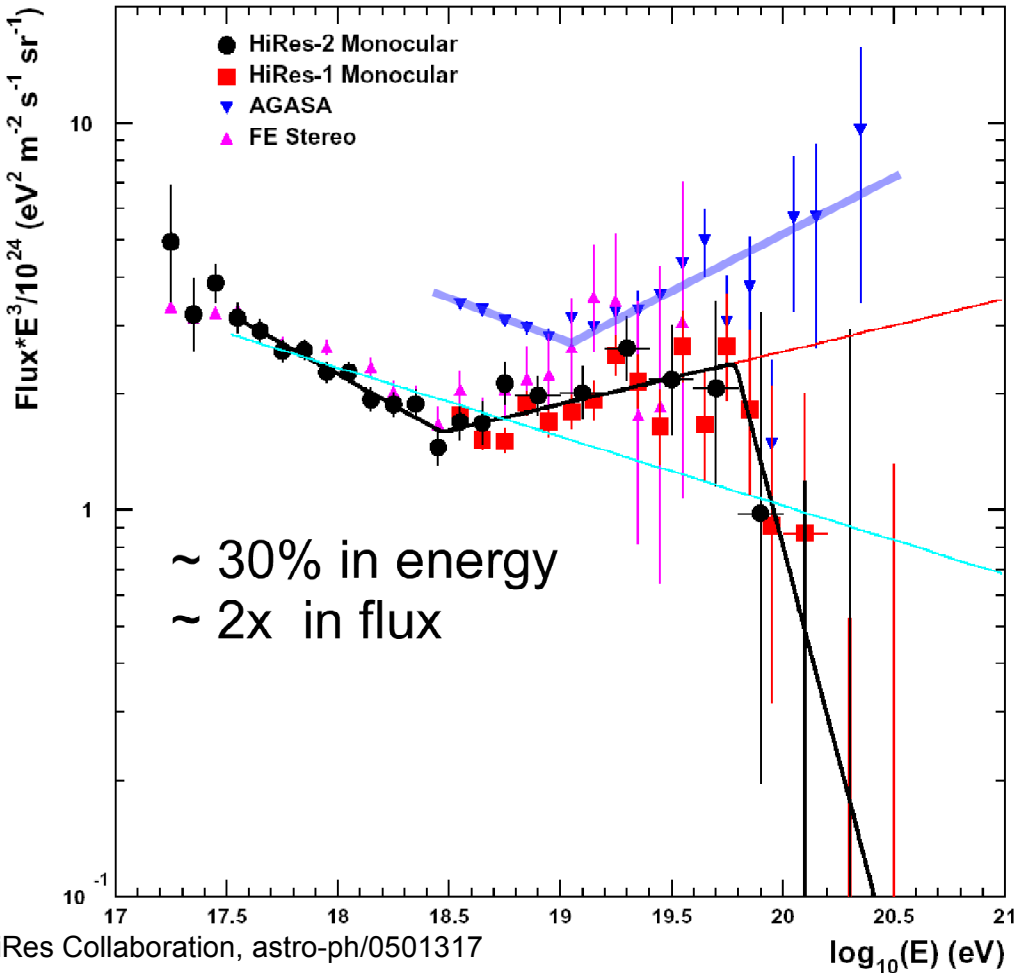
(large-angle events
withdrawn)

No evidence for cut-off at 5×10^{19} eV

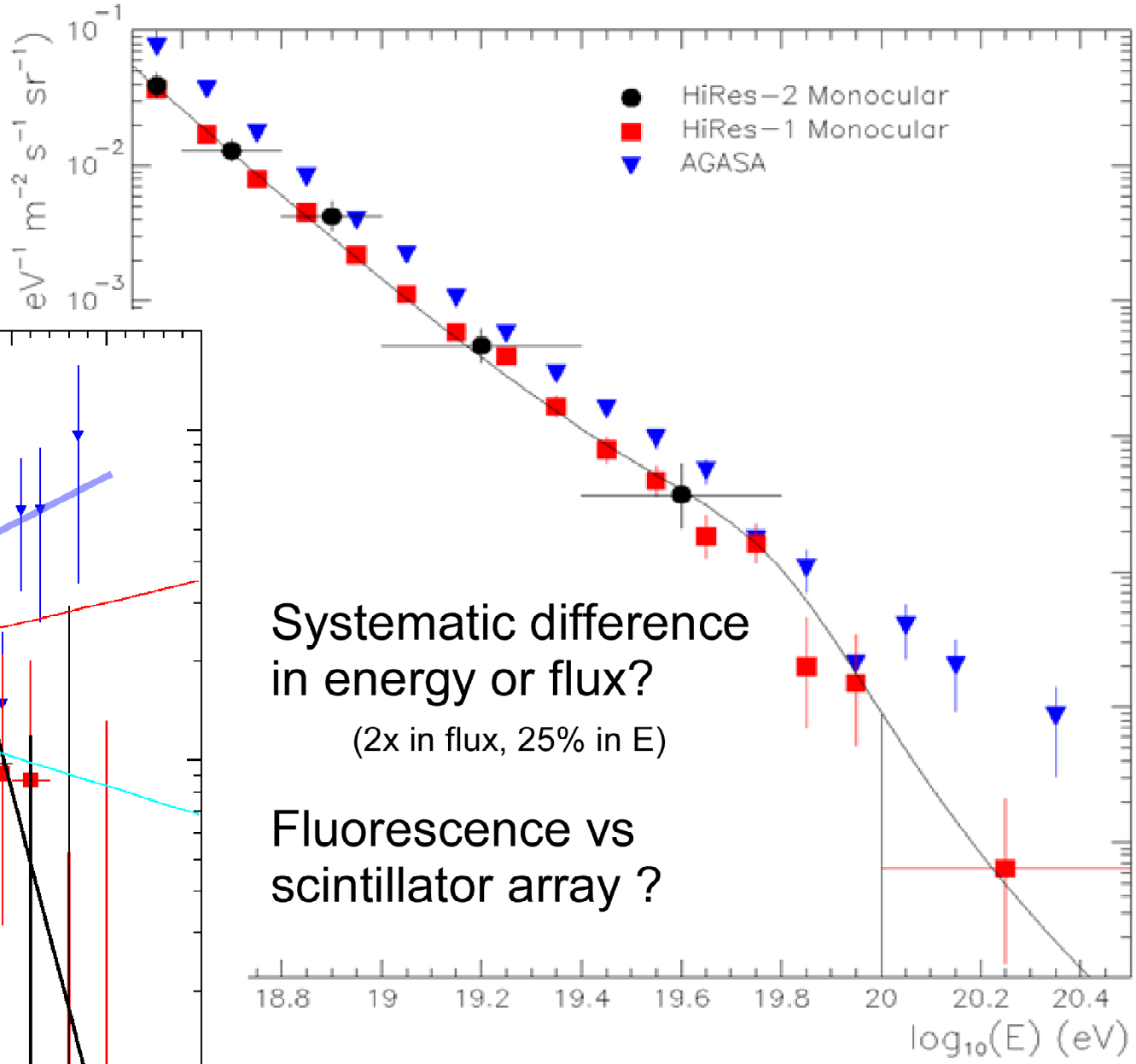
AGASA vs HiRes

GZK cut-off or not ?

difference only ~2σ



HiRes Collaboration, astro-ph/0501317



Systematic difference in energy or flux?

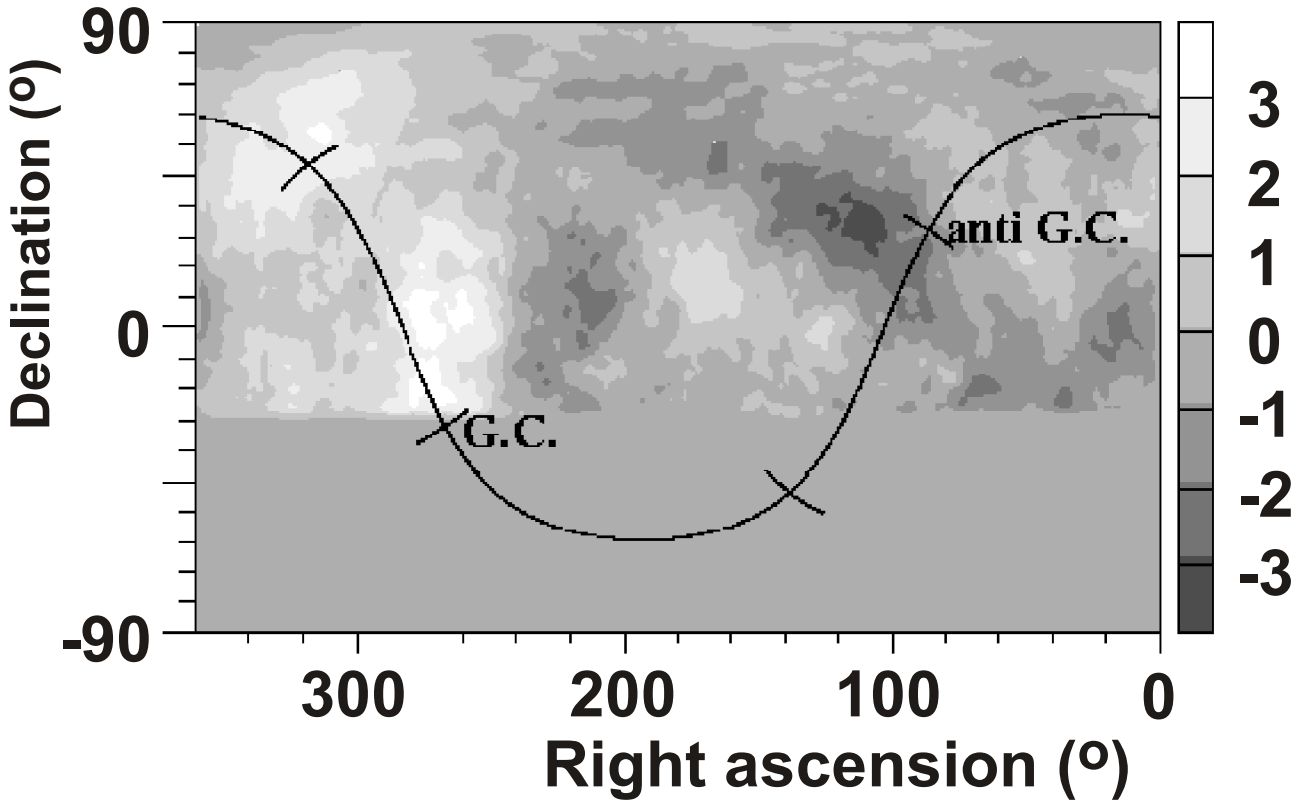
(2x in flux, 25% in E)

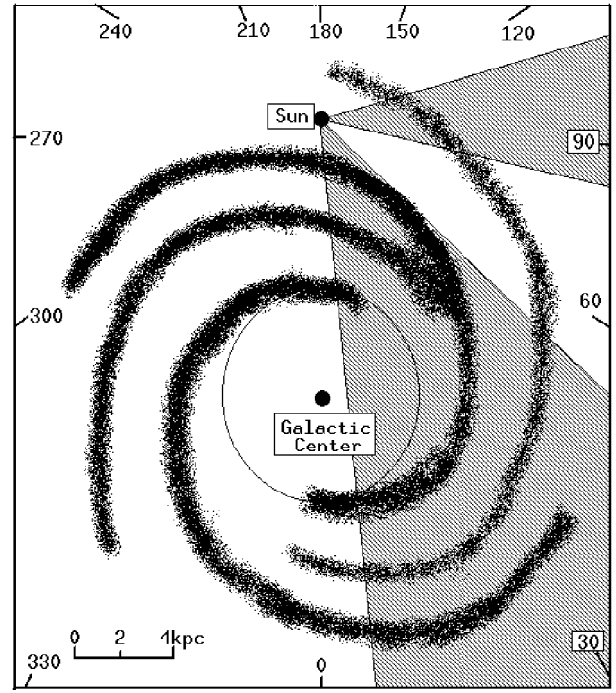
Fluorescence vs scintillator array ?

Statistics is not sufficient: need much more events & control of systematics

Isotropy

AGASA : 4% anisotropy at 10^{18} eV

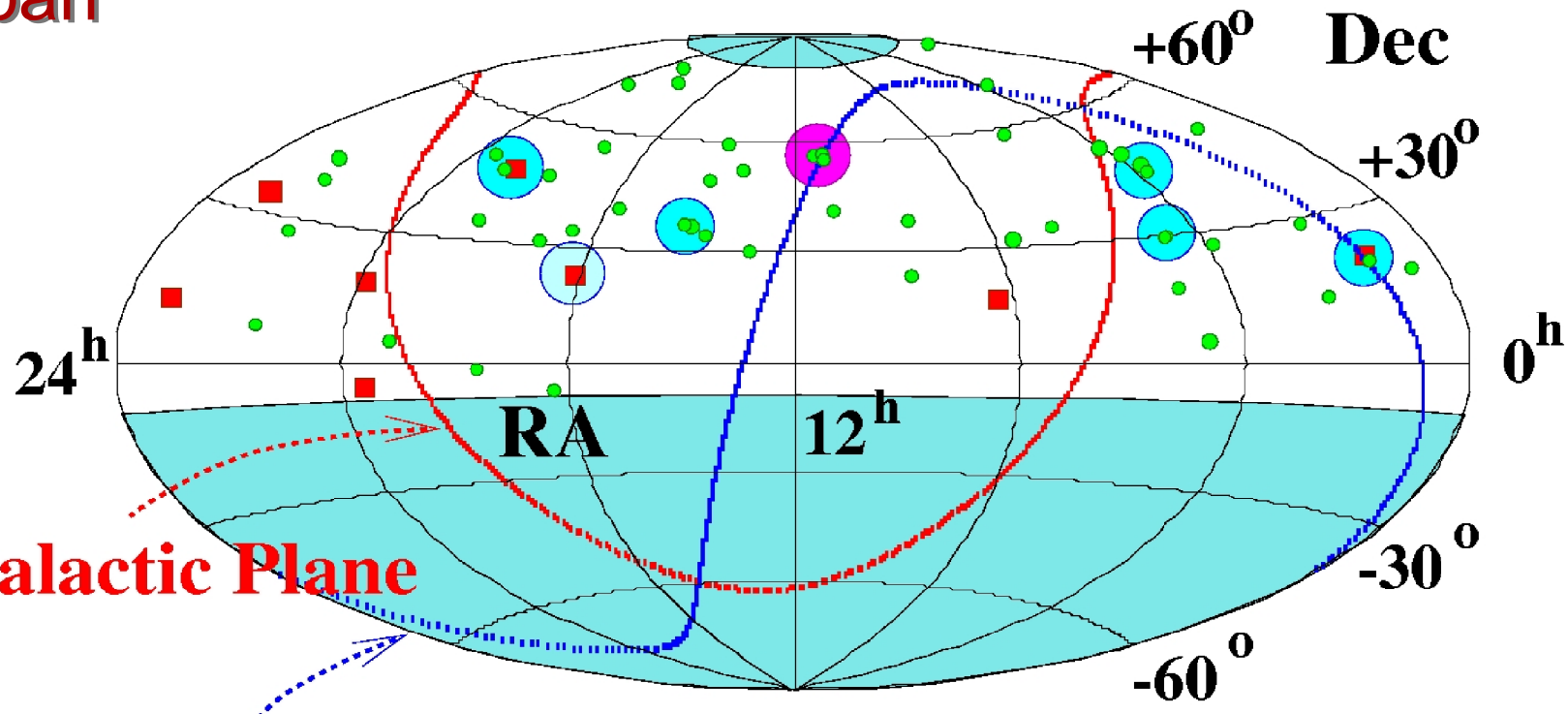


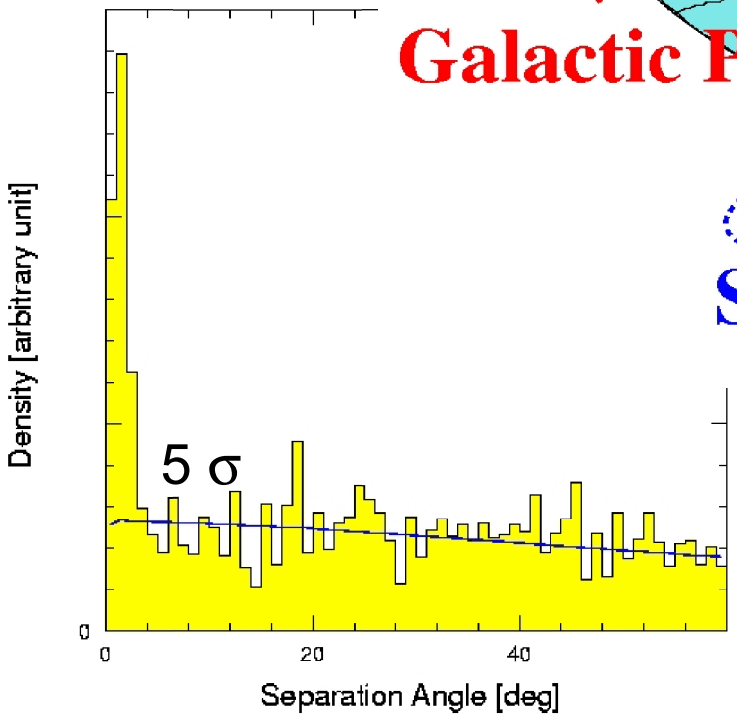


at lower energies: CRs are completely isotropic

(scrambled in magnetic fields)

Arrival directions of Cosmic Rays with E > 4 x 10^{19} eV
AGASA, Japan

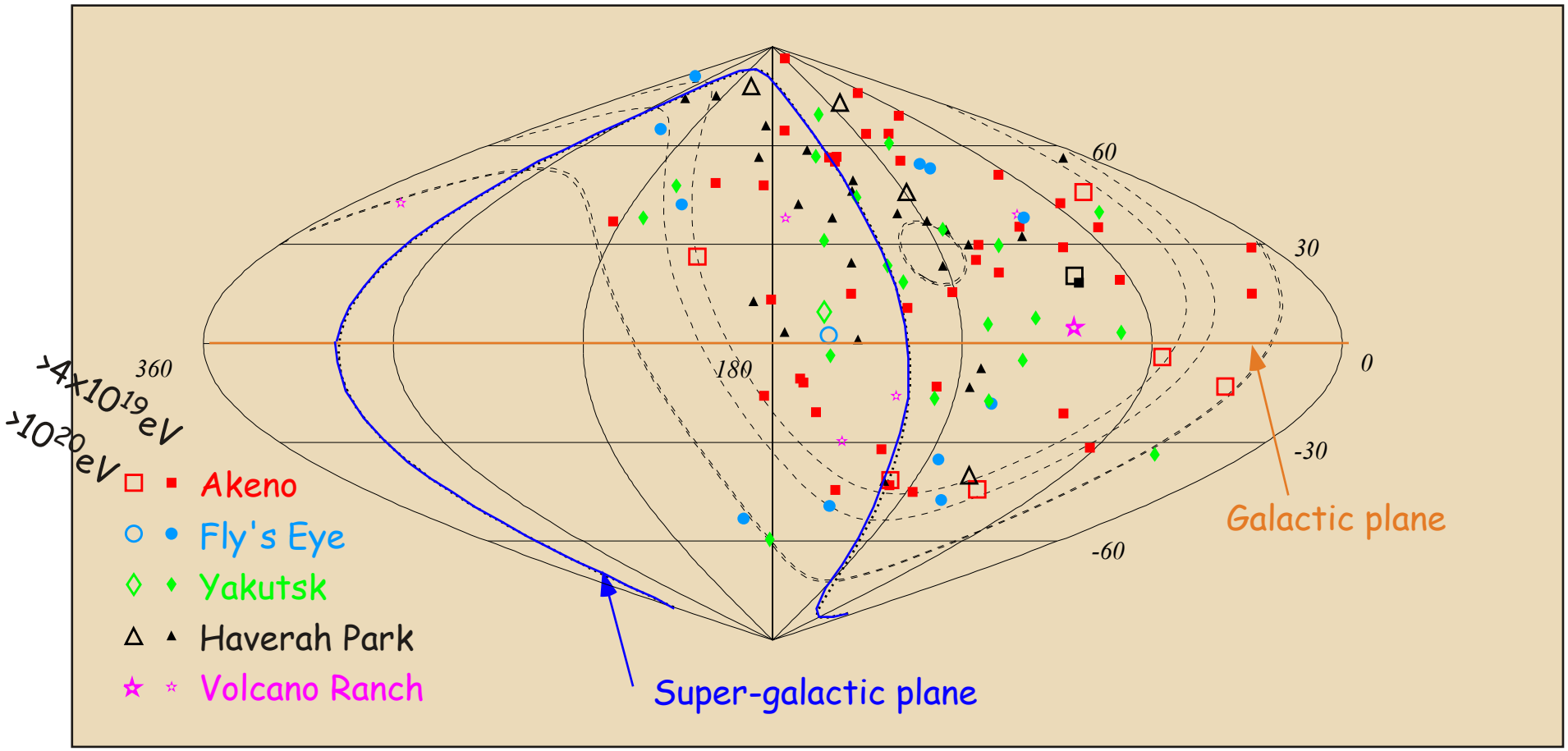




No obvious correlation with nearby matter
(supergalactic plane, quasars, ...).

6 doublets and one triplet
Isotropy or indication of point sources?

Arrival directions of cosmic particles with $E > 4 \times 10^{19}$ eV



no clear anisotropy or correlation with galactic or super-galactic plane.

but : 6 Doublets & 1 Triplet (chance probability < 1% ??)

Indication of first sources, or random associations ?

.... again: much more statistics needed !

If anisotropy/sources are seen:

then start “charged particle astronomy”,
probe magnetic fields,
spectrometry
...

If no anisotropy/sources are seen:

then indication of top-down origin,
or re-think propagation,
or ...

Proposed Solutions (1/week)

Astrophysical solutions (bottom-up)

Hot Spots in AGN-Jets	Biermann
AGNs	Biermann
Pulsars	Bell
Galaxy collisions, wind shocks	Cesarsky, Morfill, Jokipii
Shocks at formation of gal. clusters	Biermann et al
GRBs	Milgram, Usov, Waxman, Vietri

Heavy particle decays (top-down)

ν annihilation with relic-ν	Weiler et al.
Superheavy relic particles	Ellis, Sarkar et al.
Topologic defects - Monopoles	Schramm, Sigl
- Necklaces	Berezinsky et al.
Dirac Monopoles	Weiter & Kiphart et al

New Physics Exotica

New SUSY particles S_0 (uds+gluino: 2 GeV)	Farrar et al.
UHECRON (m ~ 10 GeV)	Farrar & Kolb
Deviation from Lorentz invariance	Coleman & Glashow

The Pierre Auger Observatory

Scientific goals:

- measure CRs with $E > 10^{19}$ eV with good statistics

  (2×3000 km^2, 6000 evts/yr)

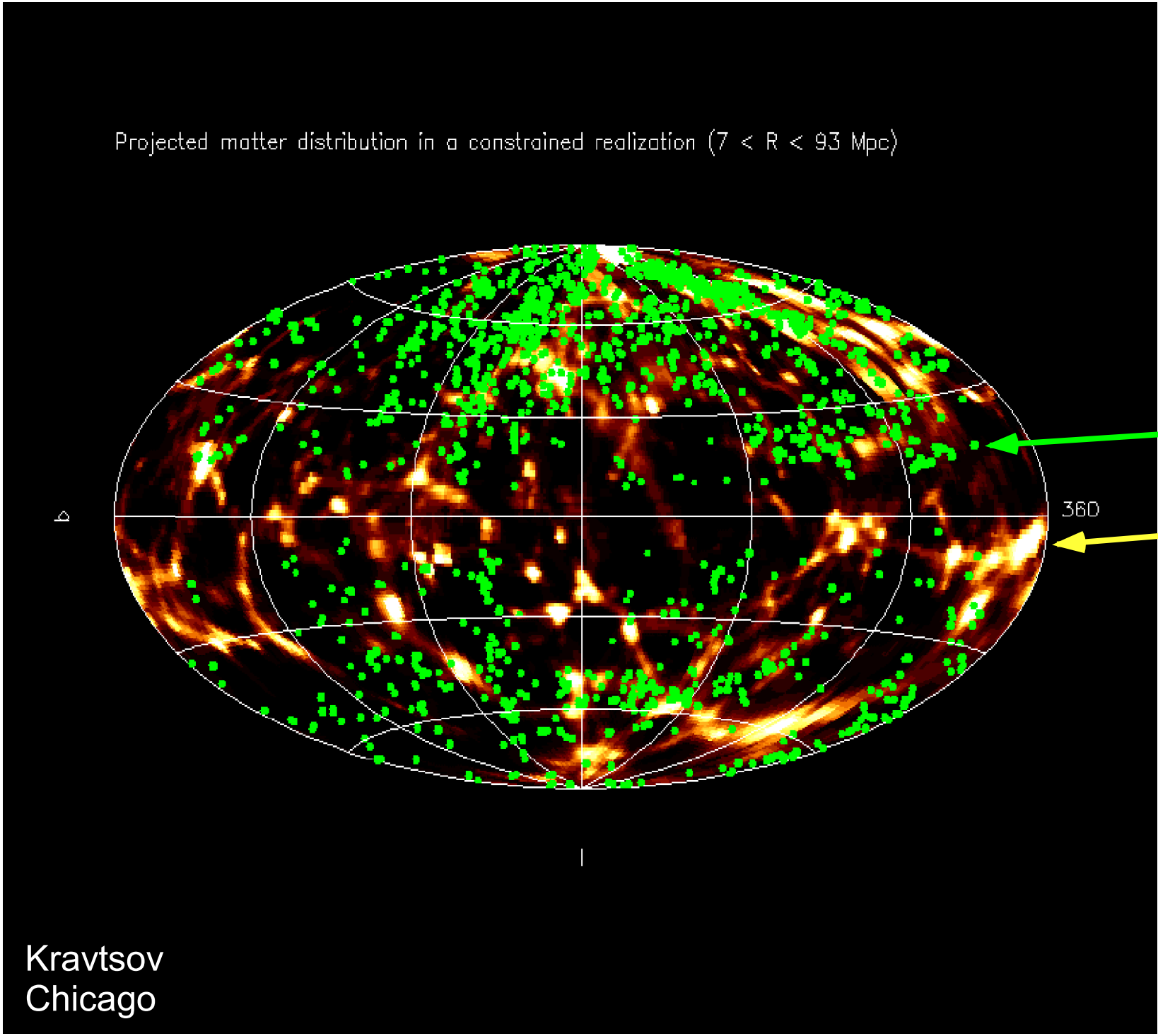
- measure energy spectrum: Is there a GZK cut-off ?
- are there point sources ? View the entire sky with two observatories (South + North).
- composition of CRs ? combine array & fluorescence det.

first ideas: Workshop in Paris 1990

design studies: 1994-1995

Collaboration forming, fund raising, site selection

1998 begin of funding
2001 engineering array operational
2002 begin of mass production and construction
2006 southern site complete



7 < R < 93 Mpc

Galaxies

Dark Matter

North and South are different

Kravtsov
Chicago

Hybrid Detector

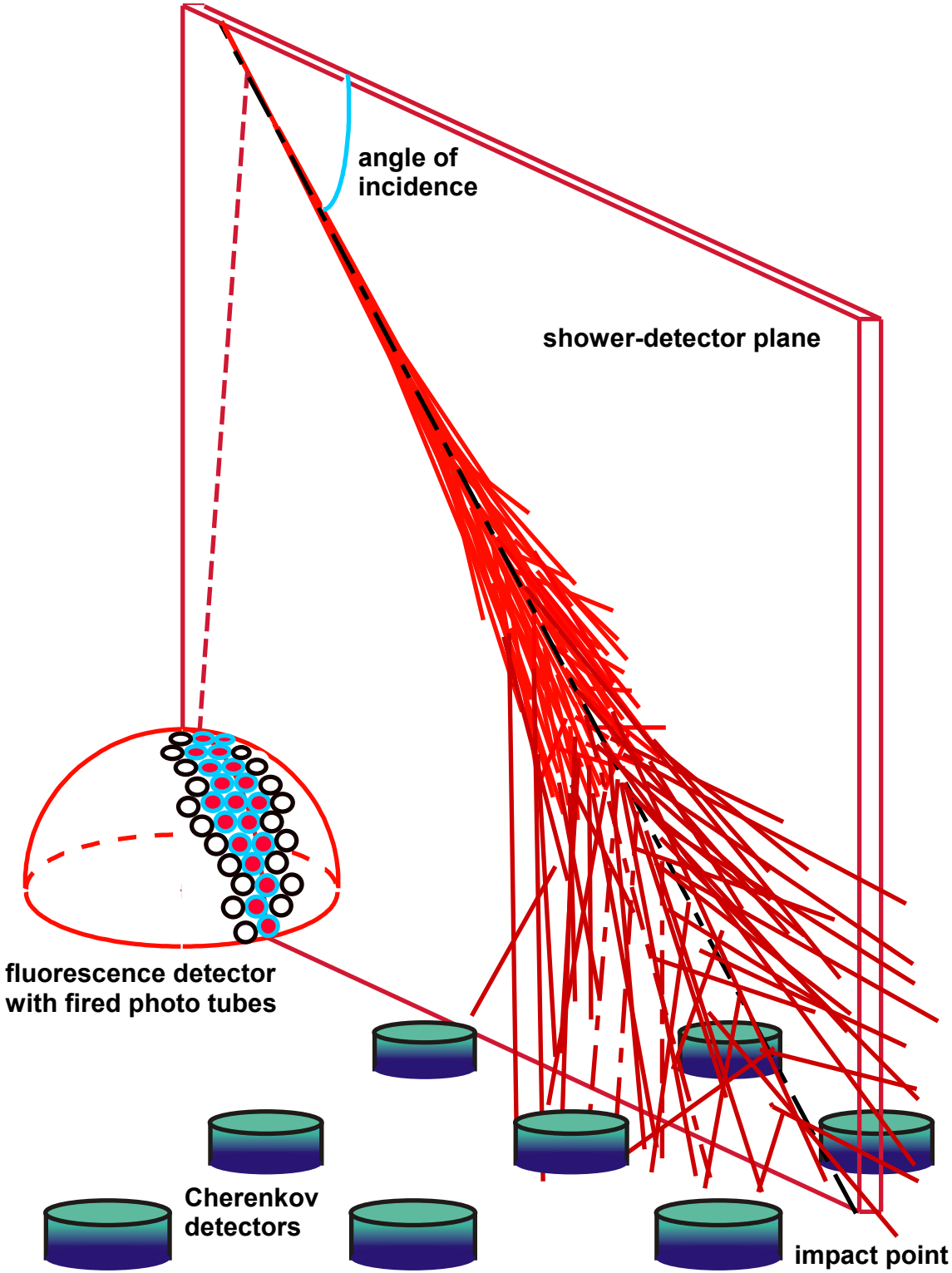
allows cross-calibration of energy scale
control of systematics

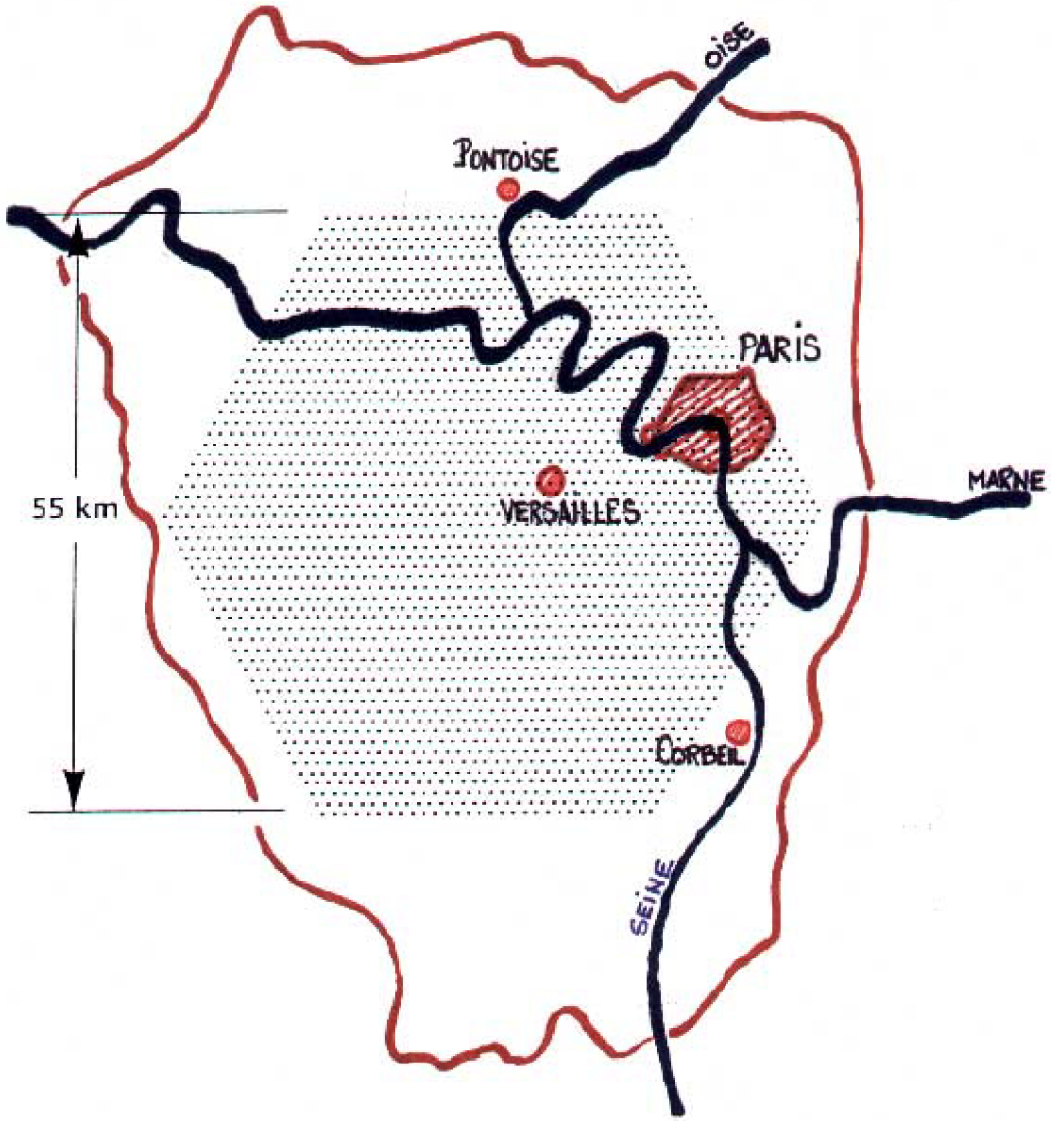
FD: calorimetric energy measurement
X_{max} directly measured,
stereo imaging, good geometry,
low energy threshold (~10^{18} eV)

SD: 100% duty cycle, high statistics,
(rel.) simple detectors, cheap,
easy to calculate aperture

24 fluorescence telescopes (30^o x 30^o)

1600 water Cherenkov detectors
on 3000 km^2
arranged in hexagonal grid
with 1.5 km grid spacing





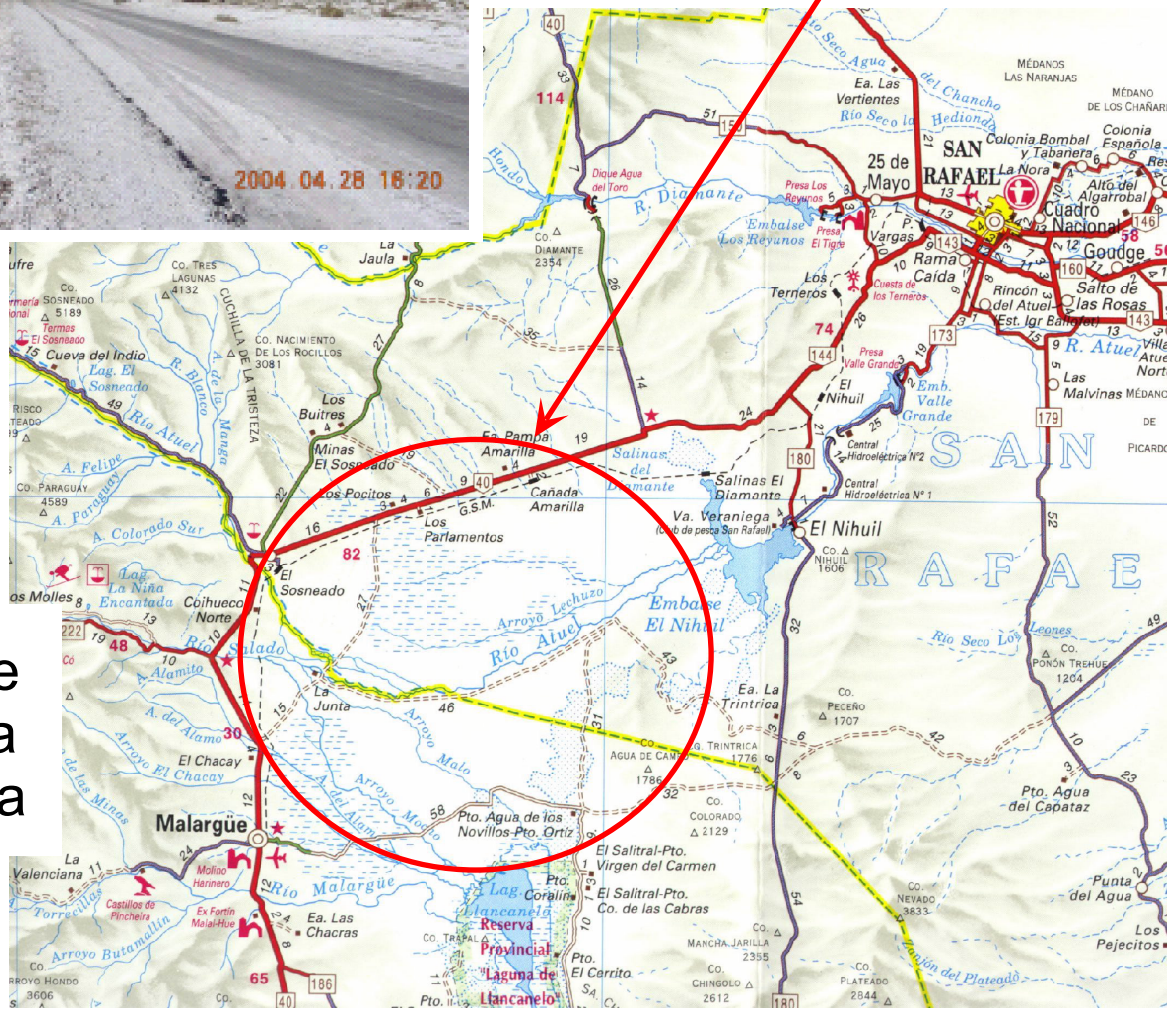
3000 km^2

F: 25x size of Paris

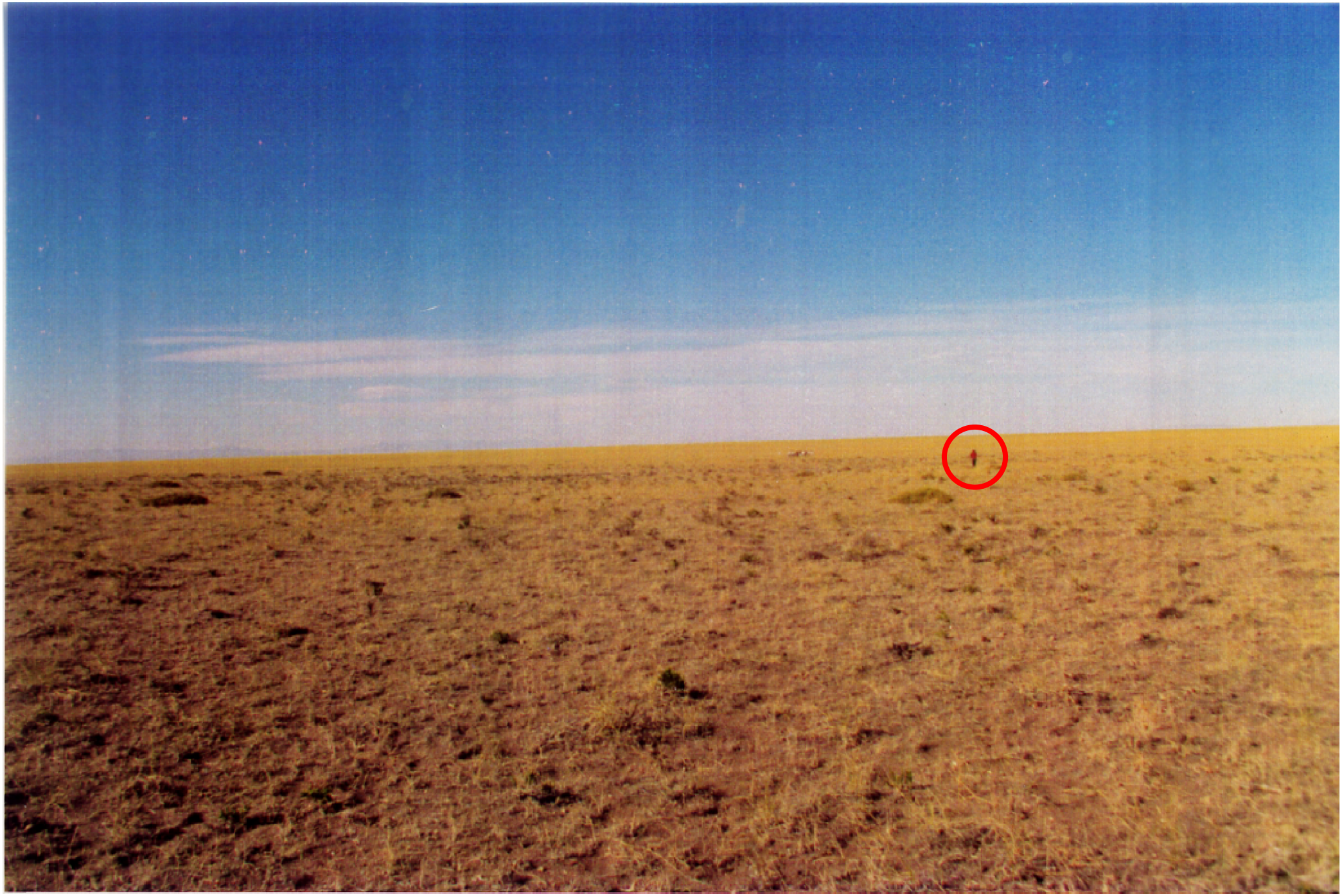
UK: size of Lancashire area inside M25

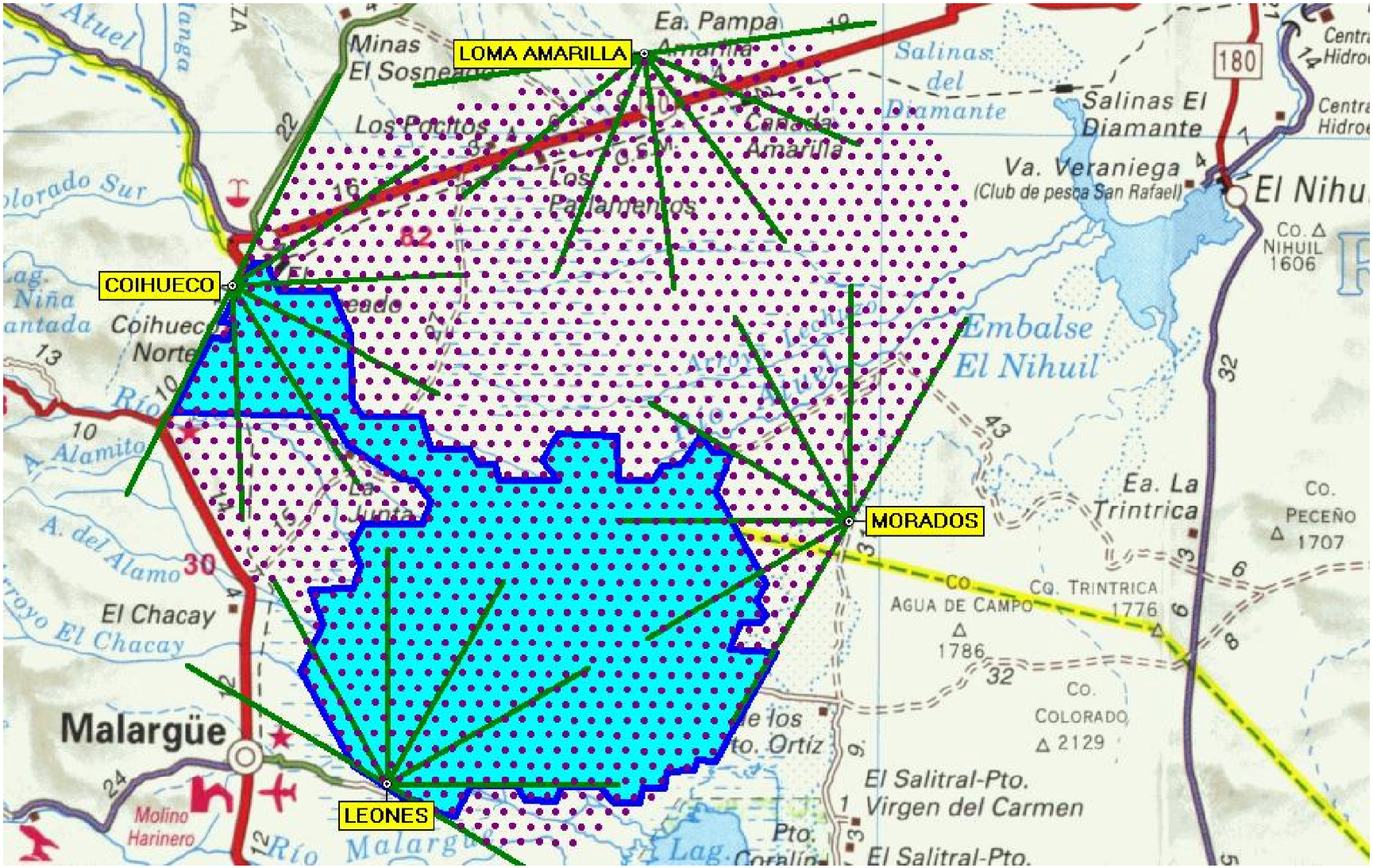
D: size of Saarland

Auger South
(1400 m a.s.l.,
35.2° S, 69.2° W)



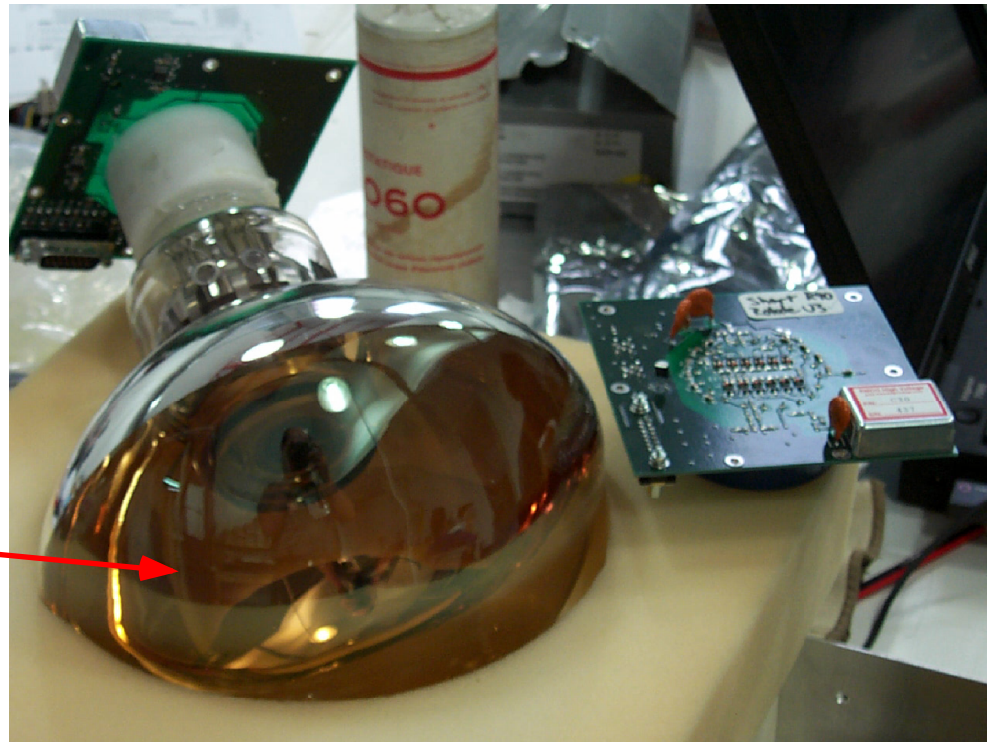
Malargüe
Mendoza
Argentina



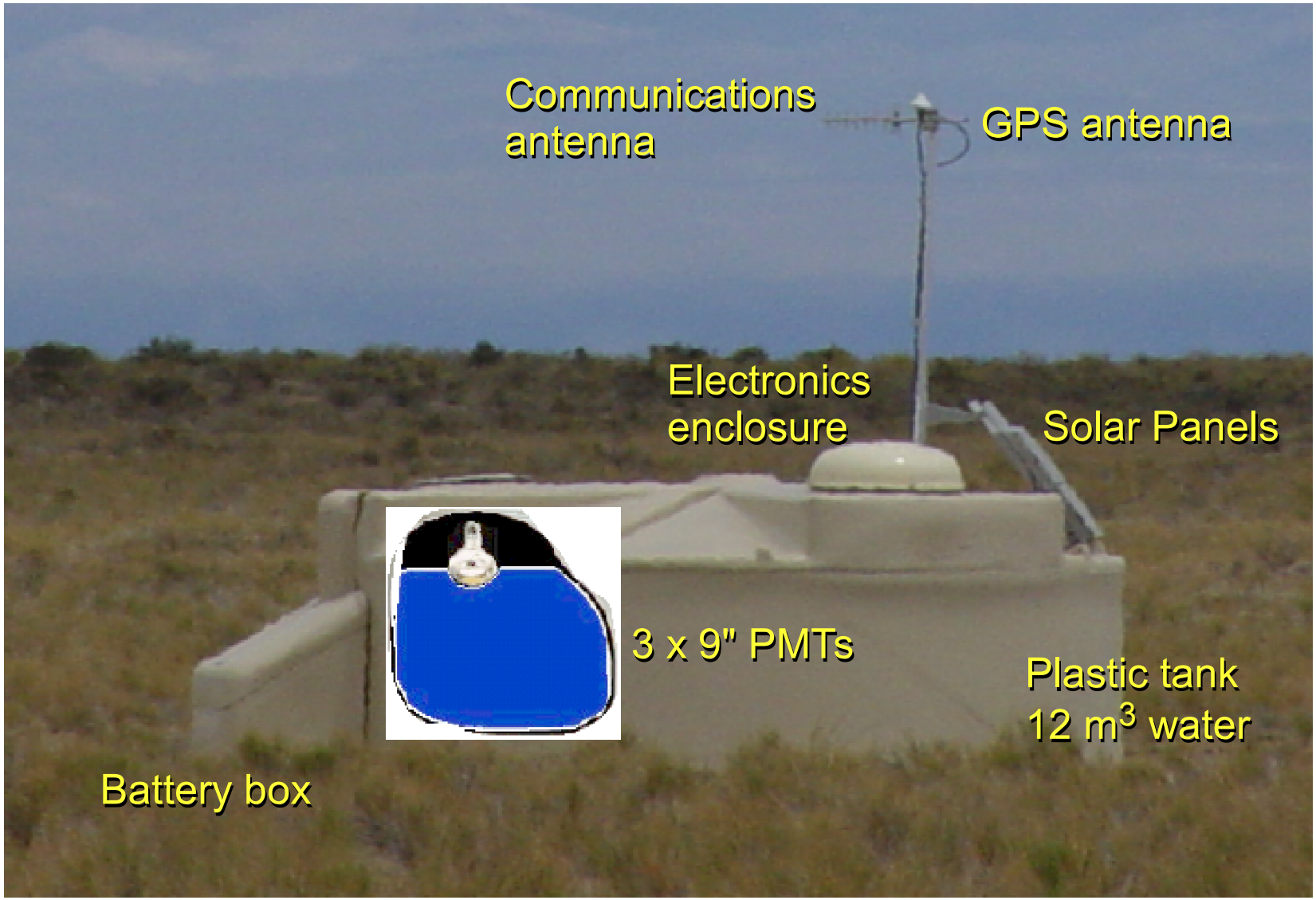


presently ~700 array detectors and
12 fluorescence telescopes operational

10 m^2 x 1.2 m water
viewed by 3 PMTs,
solar panel & batteries
(power budget 10 W)
electronics box
radio antenna



three
9" PMTs


Communications antenna
GPS antenna
Electronics enclosure
Solar Panels
3 x 9" PMTs
Plastic tank
12 m3 water
Battery box


EZRA