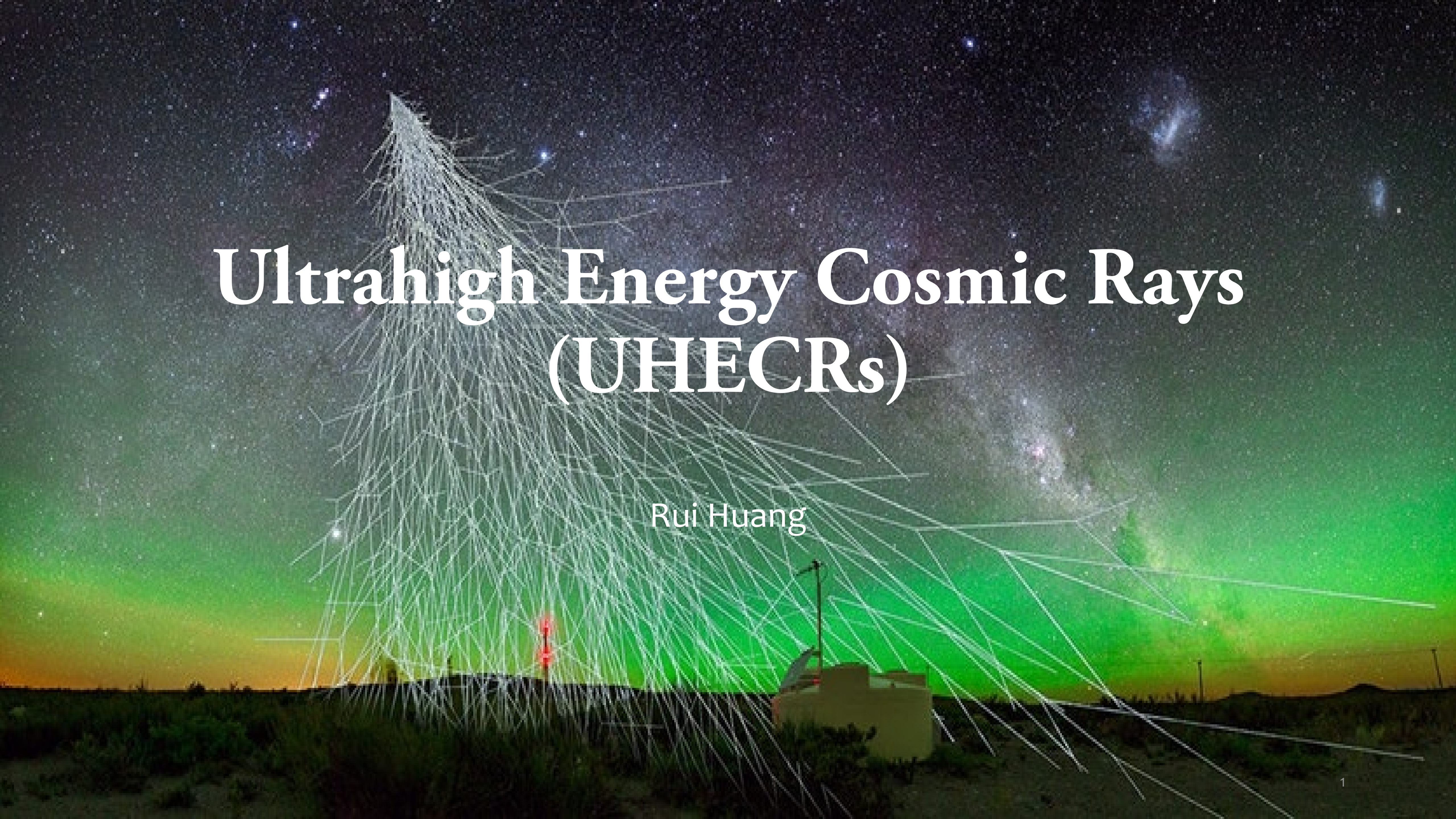


Ultrahigh Energy Cosmic Rays (UHECRs)

Rui Huang

Outline

- Observation
- Spectrum
  - GZK cutoff
- Candidates and acceleration mechanism
- Spatial distribution
- composition
- Summary

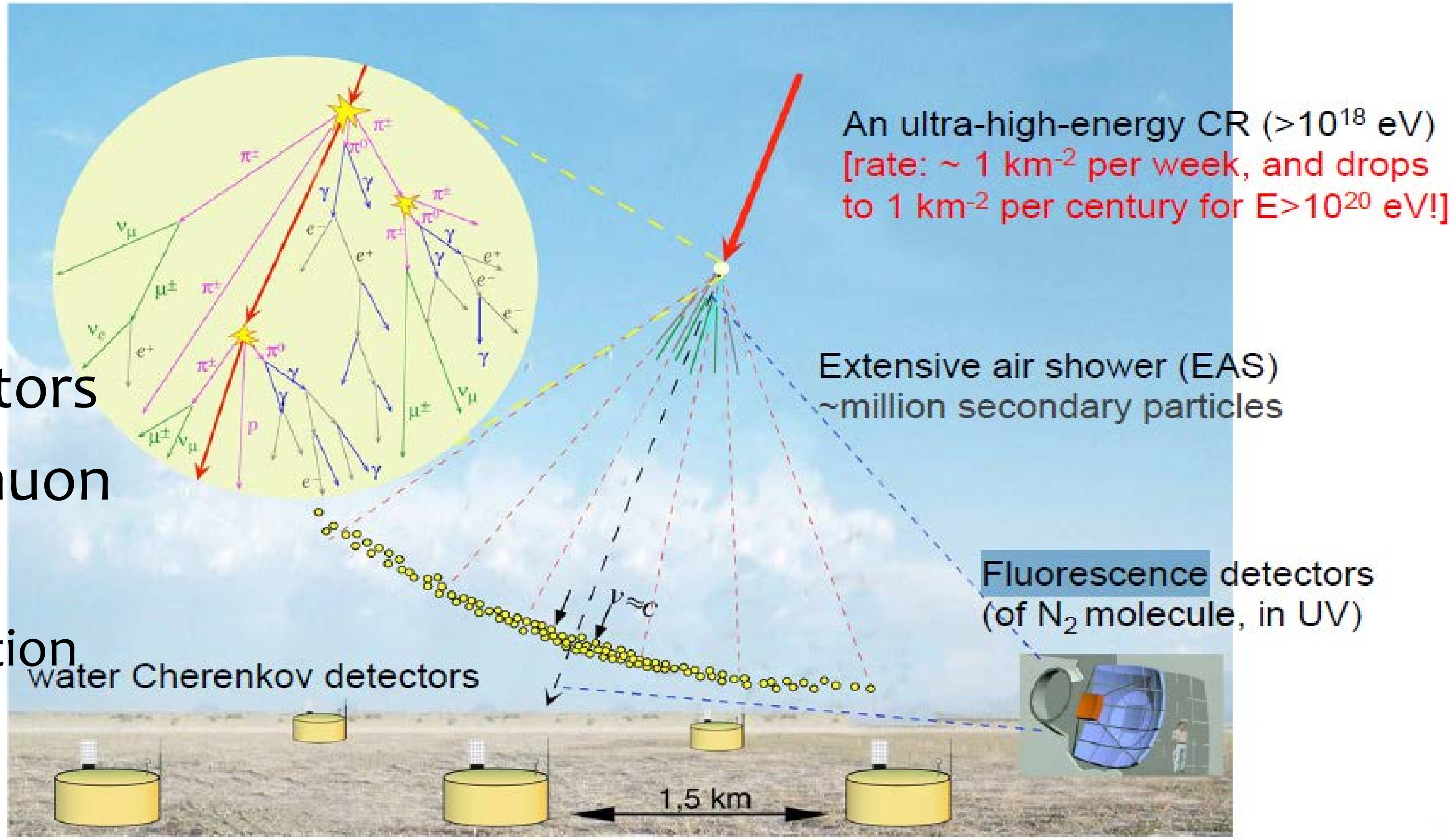
Detection method

- Extensive air shower
  - secondary particles
  - Cherenkov radiation

- water Cherenkov detectors

  secondary particles :muon

Fluorescence detectors
  - ionized nitrogen’s radiation



Auger Observatory

Total surface area: ~3000 km^2 (1600 tanks)

Observatory

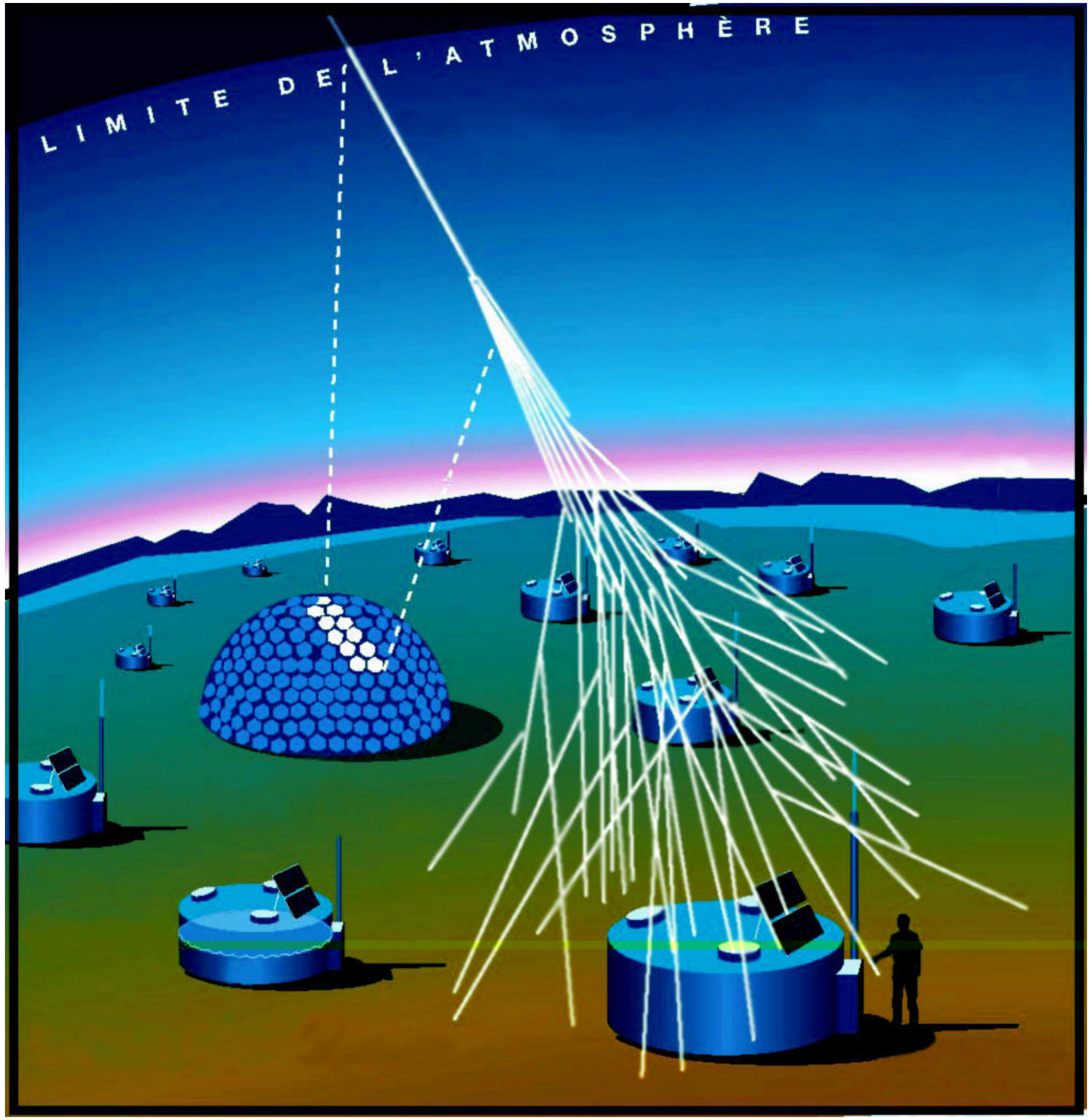
- Chinese contribution
  - Tibet Asr 1989-now co: Japan
  - ARGO-YBJ 2006-2013 co: Italy
  - LHAASO constructing(Sichuan)
  - Wukong observatory

near or below 10^{15}eV

electrons

- the High Resolution Fly's Eye (HiRes)
  - a pair of fluorescence telescopes that operated in Utah until 2006
- Pierre Auger Observatory (Auger)
  - a 3,000 km2 array of water Cherenkov stations with 1.5 km spacing

UHECRs $>10^{18}$eV



Spectrum

- UHE >10^{18}eV
- Larmor radius:

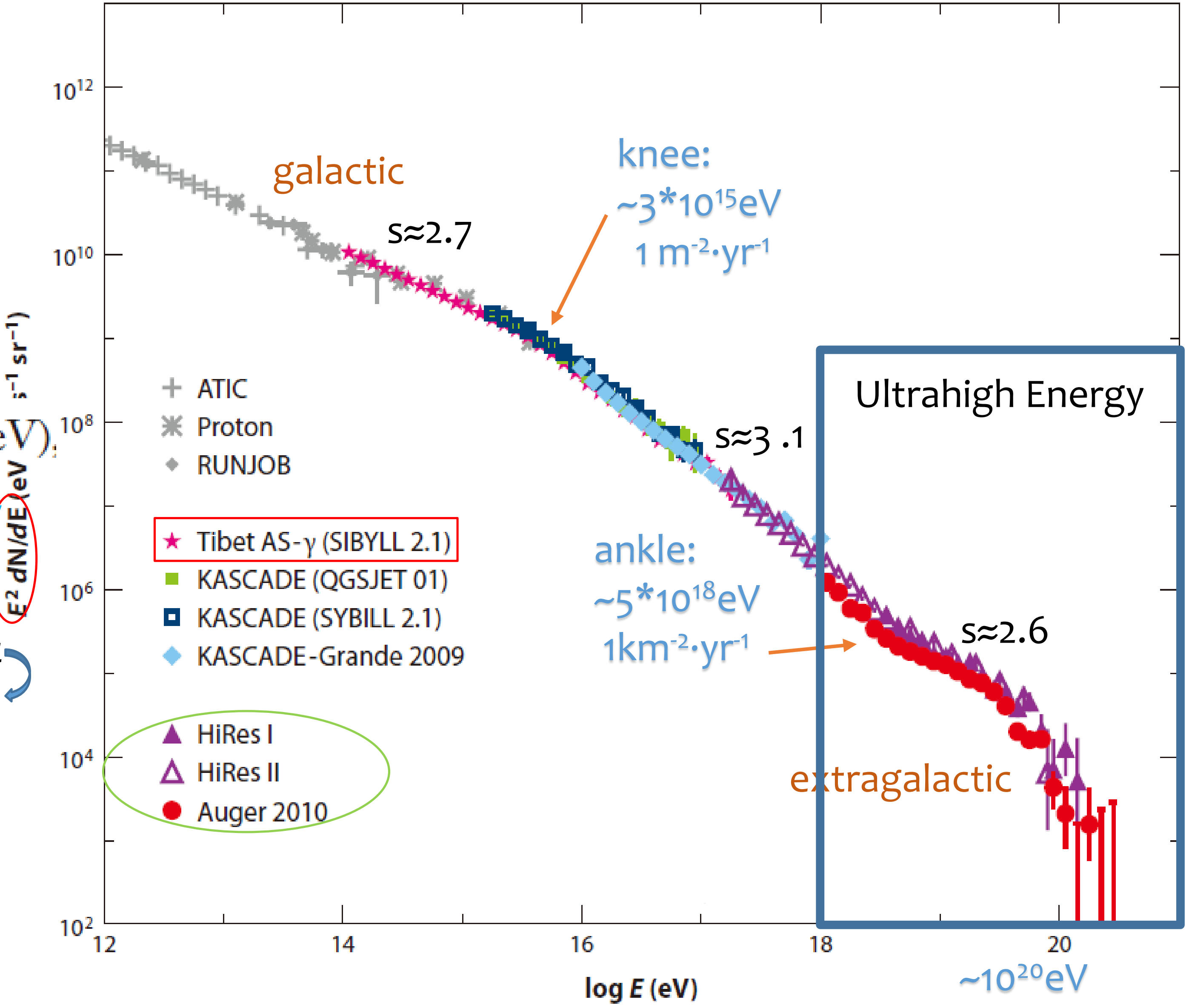
$$r_L = E/ZeB \sim 110\ \mathrm{kpc}\ Z^{-1}(\mu G/B)(E/100\ \mathrm{EeV}),$$

LHC's highest energy : 14TeV=$1.4*10^{13}$eV

pingpong: 17 m/s@2.7g
W=$mv^2/2$=3.9 J macroscopic
Particle: E=10^{20}eV = 16 J microscopic

The highest energy event reported by Auger thus far is of 142 EeV (Abreu et al. 2010).

- GZK Cutoff



galactic

s≈2.7

knee:
~$3*10^{15}$eV
1 $m^{-2}·yr^{-1}$

s≈3 .1

ankle:
~$5*10^{18}$eV
1$km^{-2}·yr^{-1}$

s≈2.6

Ultrahigh Energy

extragalactic

~10^{20}eV
1km^{-2}·century^{-1}

Kotera and Angela V. Olinto 2011

GZK cutoff

Greisen, 1966, PRL; Zatsepin & Kuzmin, 1966, JETPL

- In the frame of UHE particles, a CMB photon becomes a gamma-ray photon.

- pair production
  - threshold~0.8EeV=0.8*10^{18}eV

$$p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$$

- pion production
  - threshold~200EeV

$$p + \gamma_{CMB} \rightarrow p + \pi^{0}$$
$$p + \gamma_{CMB} \rightarrow n + \pi^{+}$$

Let's consider a 10^{18}eV proton

$\gamma m_p c^2 = 10^{18}$eV

Energy of proton's rest energy: $938.3\mathrm{MeV} \approx 10^{9} eV$

Lorentz $factor$: $\gamma \sim 10^{9}$,

CMB photon: $k_B T = 1.38 * 10^{-23}$[J/K]*3[K] =4.2*10^{-23}J

~10^{-4}eV

in the frame of proton:

$\gamma m_\gamma c^2 = 10^{5}$eV

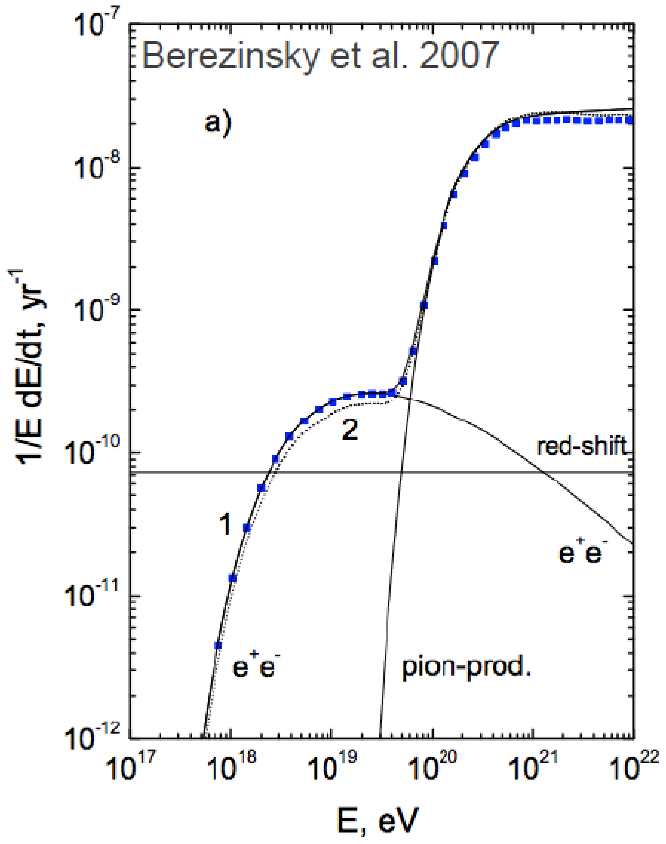
electron pair: 511keV ~ 10^{5}eV

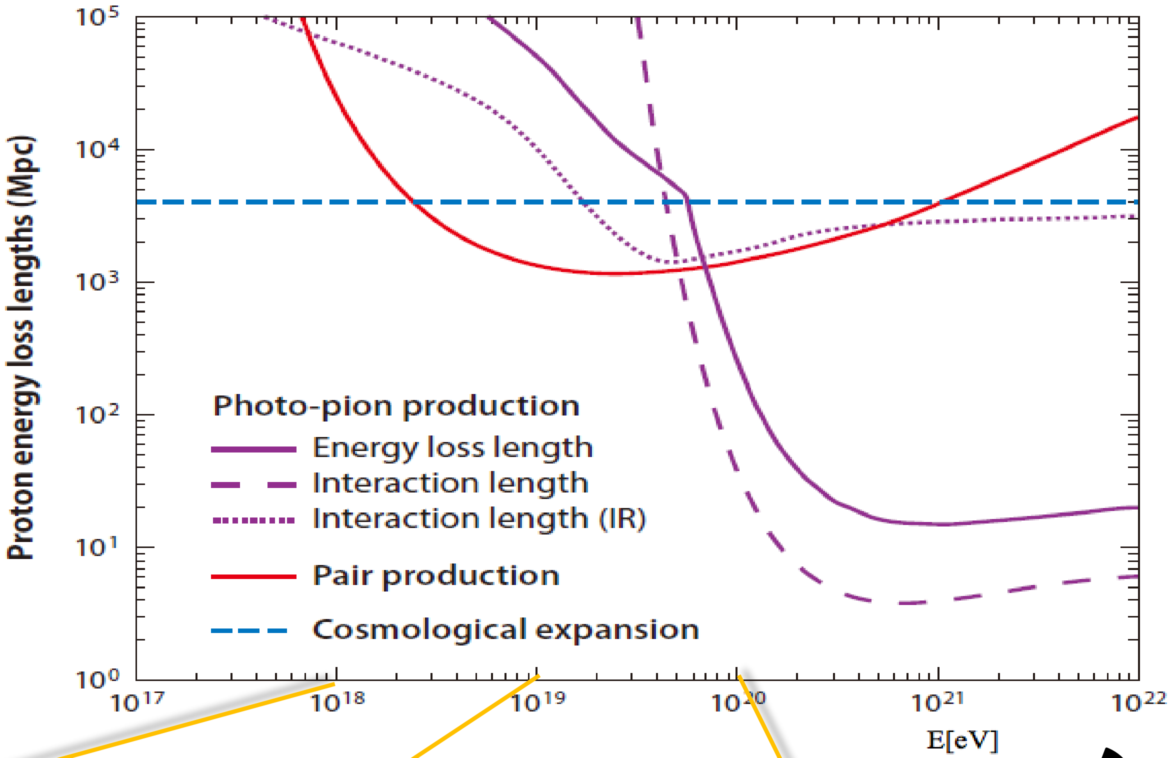
GZK cutoff

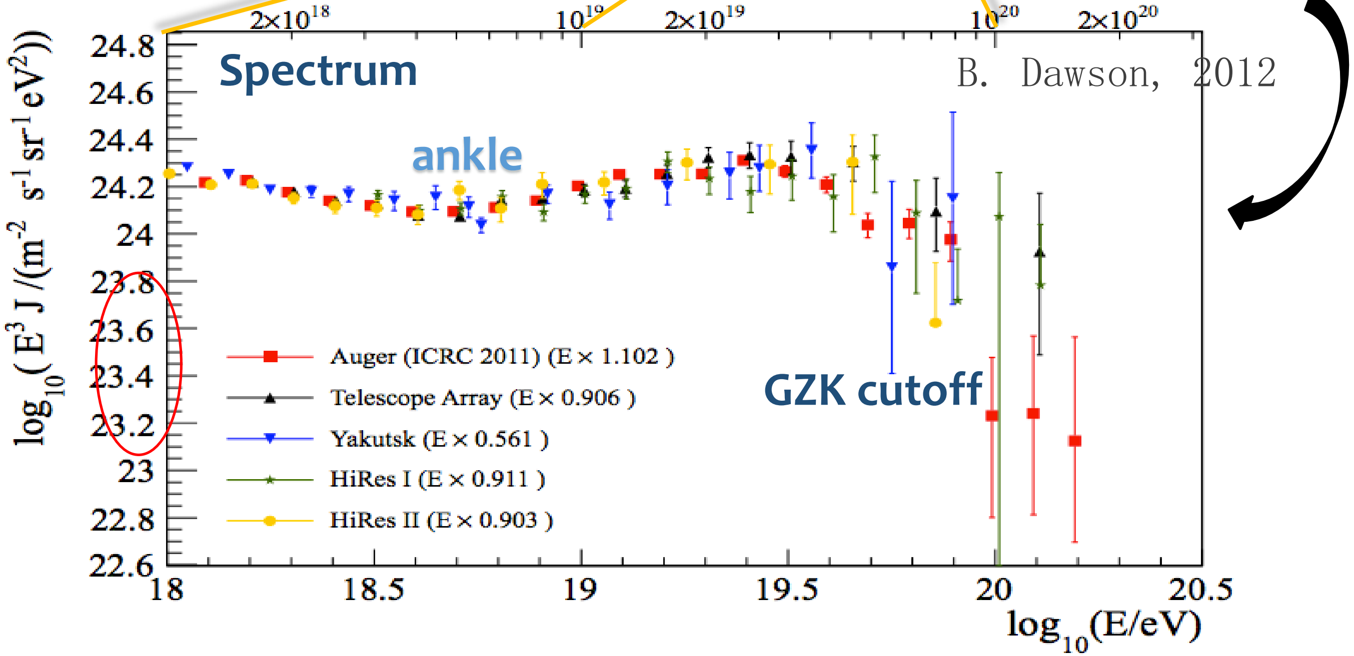
0.8EeV $p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$

200EeV $p + \gamma_{CMB} \rightarrow p + \pi^{0}$

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







Candidates sources/acceleration mechanism

Charged particles confined by magnetic field

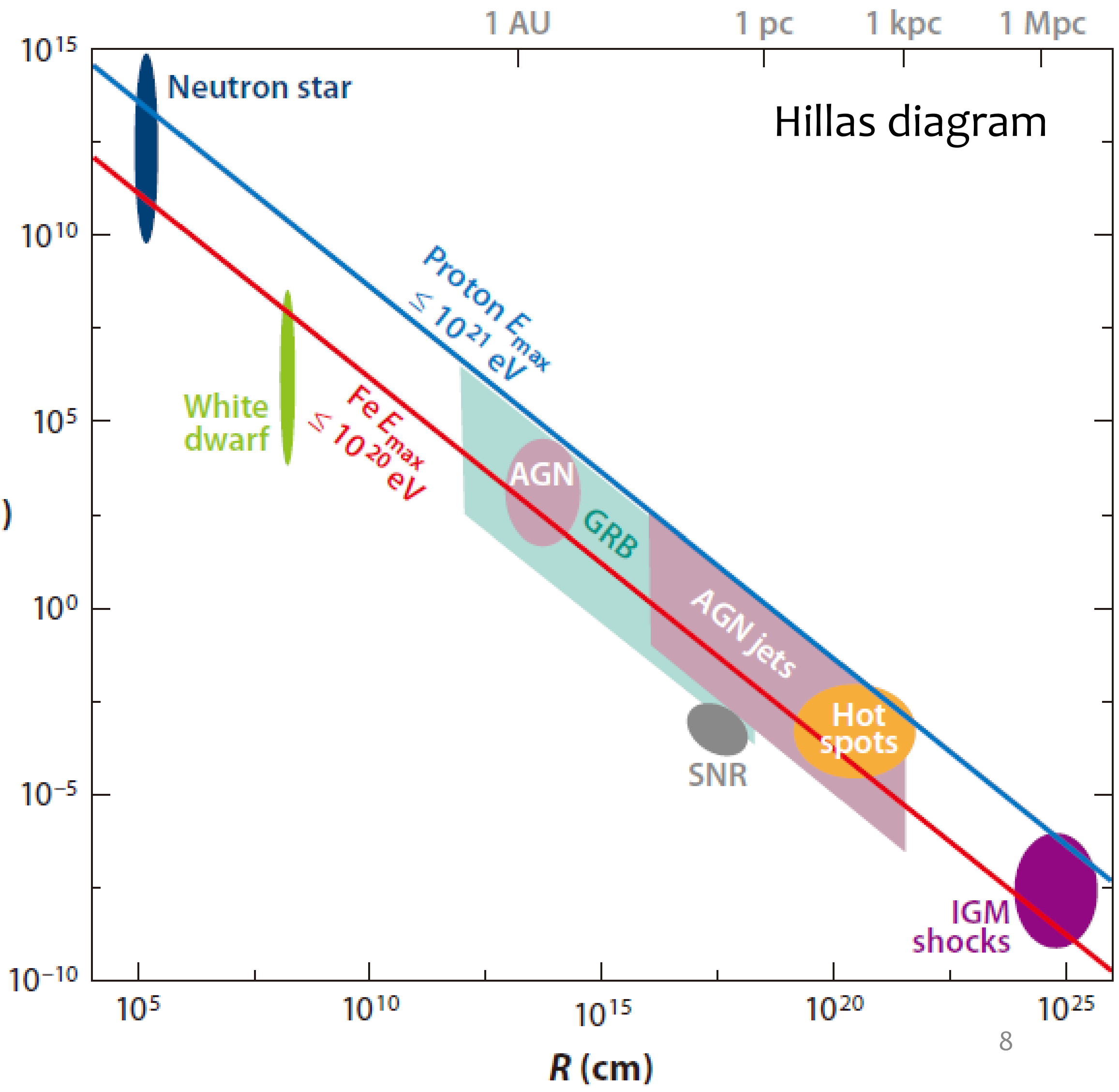
- Hillas criterion (Hillas,1984)

$r_{\mathrm{L}} = E/ZeB$ (Larmor radius)

$r_{\mathrm{L}} \leq R$

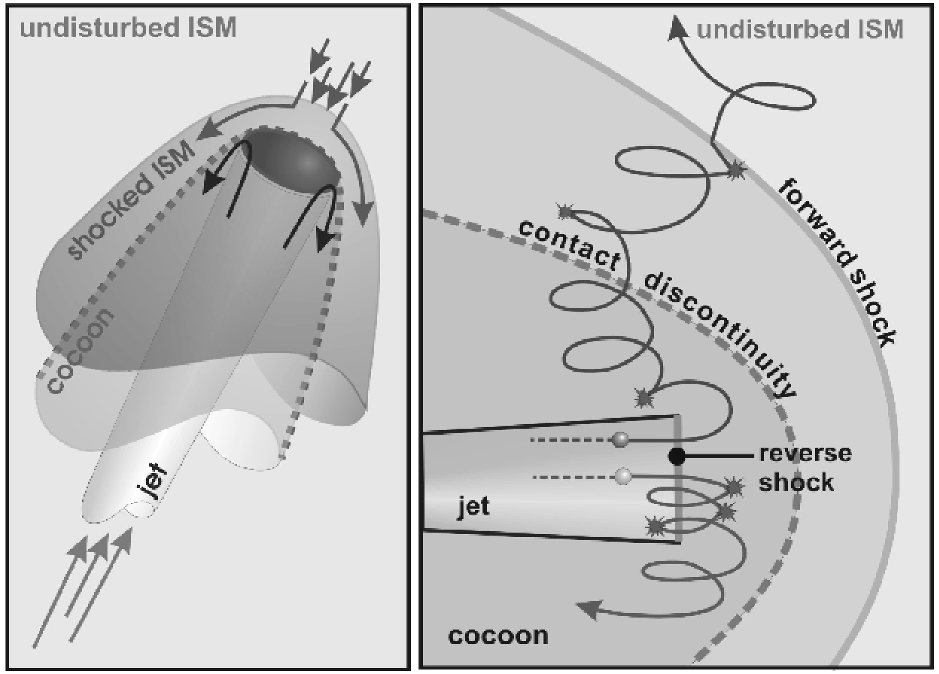
$E \leq E_{\mathrm{max}} \sim 1\,\mathrm{EeV}\,Z(B/1\,\mu\mathrm{G})(R/1\,\mathrm{kpc})$G)

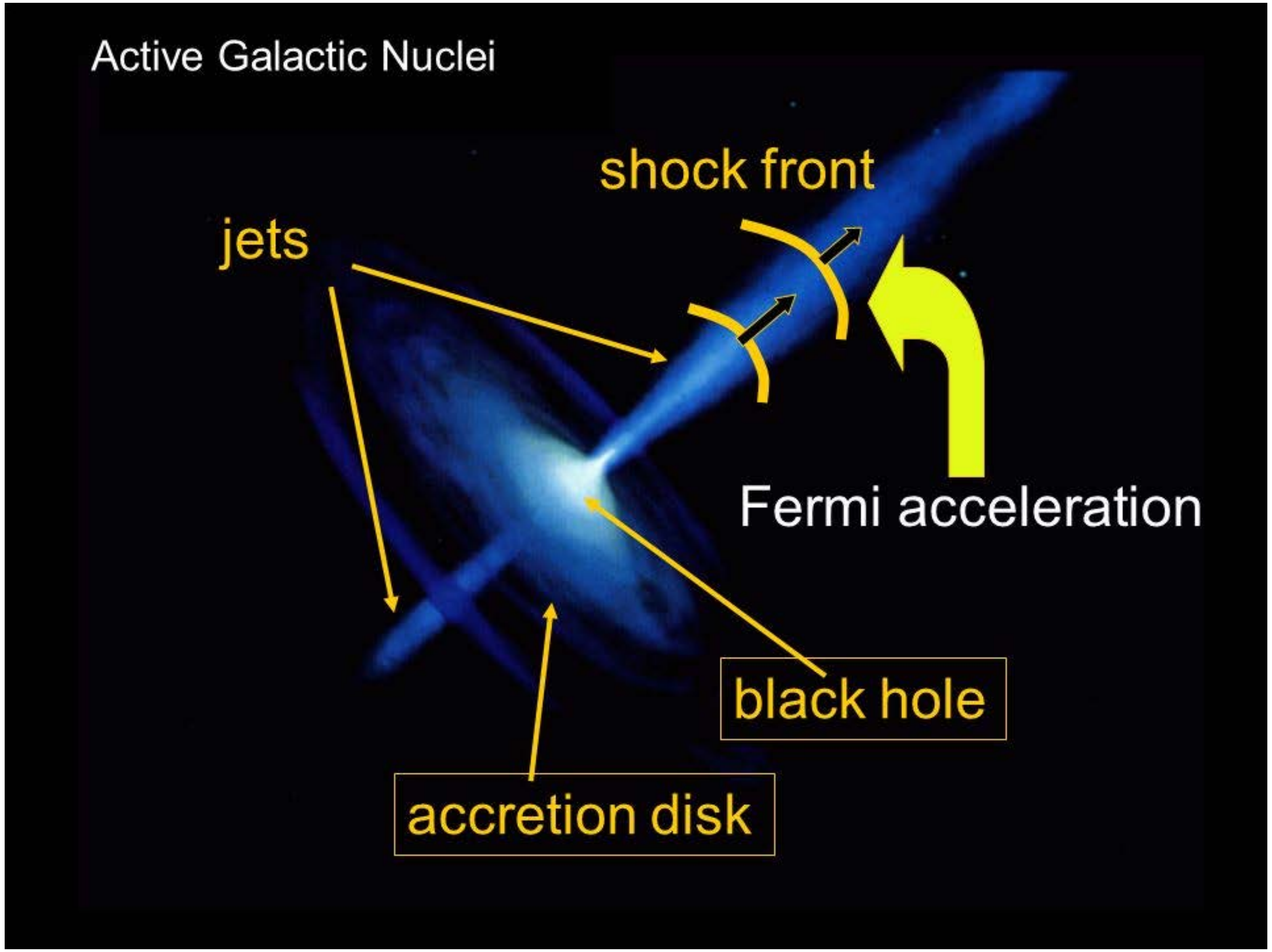
- example :
  - Fermi acceleration
    - AGN jet
  - unipolar inductor
    - Neutron star
  - ……



Fermi acceleration

- AGN jet
  - ultra-relativistic shock





Unipolar inductor in neutron star assuming millisecond pulsar

dipole magnetic field
unipolar inductor
quadrupole field

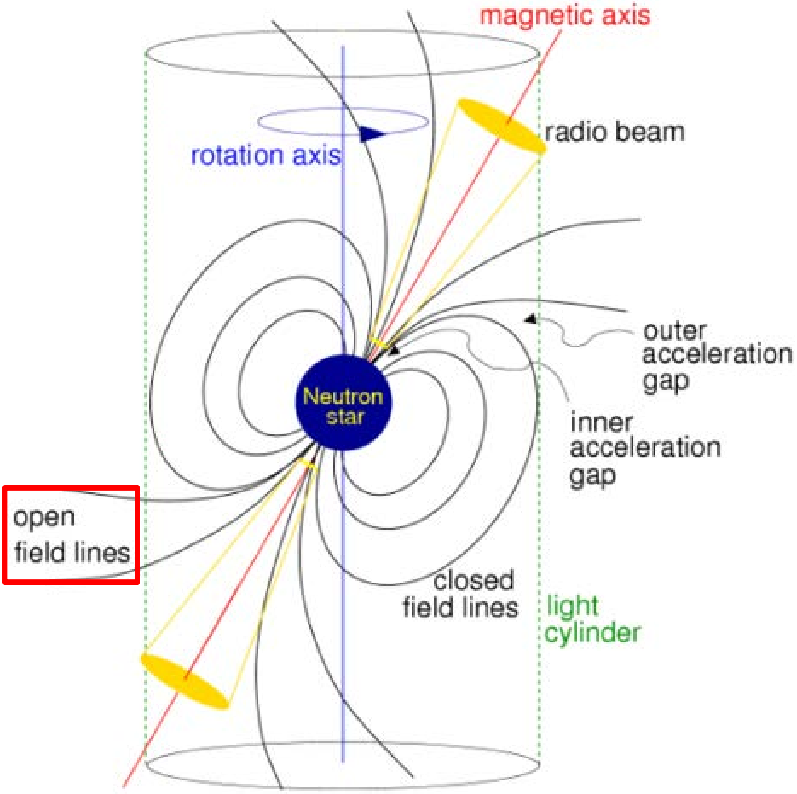
$$\boldsymbol{F} = \frac{q\boldsymbol{V}\times\boldsymbol{B}}{c} = q\boldsymbol{E};\ V = \Omega\times r \qquad \boldsymbol{E} = -\frac{(\boldsymbol{\Omega}\times\boldsymbol{r})}{c}\times\boldsymbol{B}$$

In *the polar cap*: *particles can slide along magnetic lines*

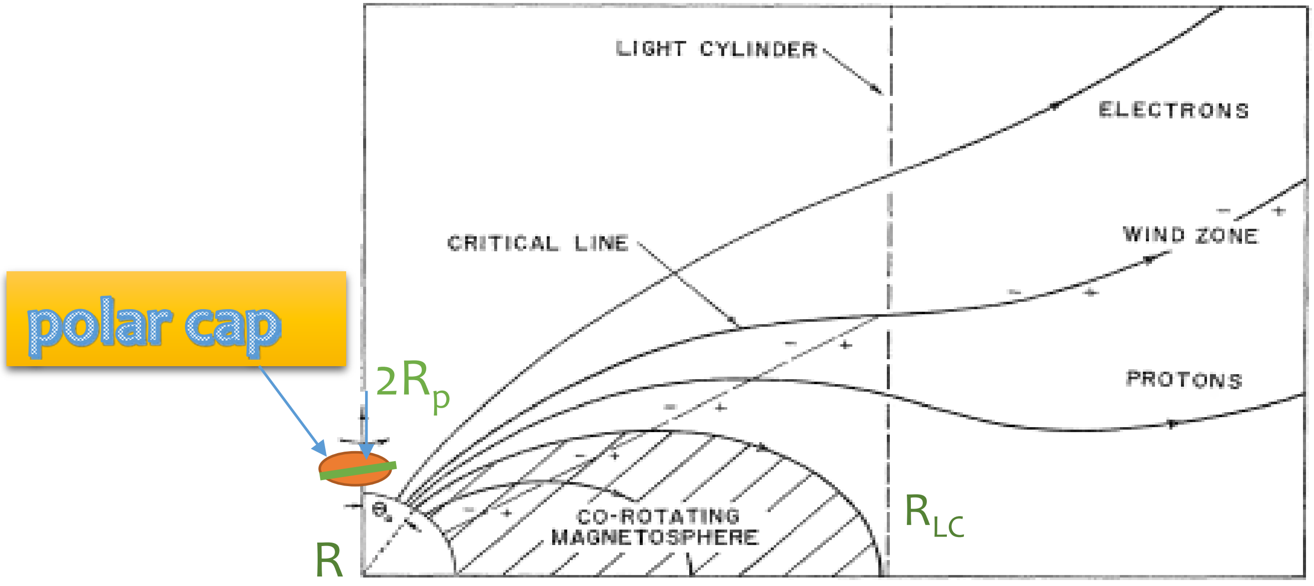
$$R_{LC} = \frac{c}{\Omega},\ \ r = RLC\sin^2\theta,\ sin\theta_p = \sqrt{\frac{R}{R_{LC}}},$$

$$if\ R{=}10km,\ \mathrm{P} = 1ms,\ \Omega = \frac{2\pi}{\mathrm{P}},\ B = 104G \rightarrow$$

$$R_p{=}Rsin\theta_p = \sqrt{\frac{R^3}{R_{LC}}}\approx 4.6km\ \rightarrow\ \Delta\phi\approx\frac{\Omega B r^2}{2c} = \frac{2\pi\cdot 10^{14}\mathrm{G}\cdot(4.6km)^2}{2c\cdot 10^{-3}s}\approx 10^{20}V$$



Pulsar Astronomy by Lorimer and Kramer



Goldreich, P & Julian, W H. 1969

Anisotropy

- <100Mpc

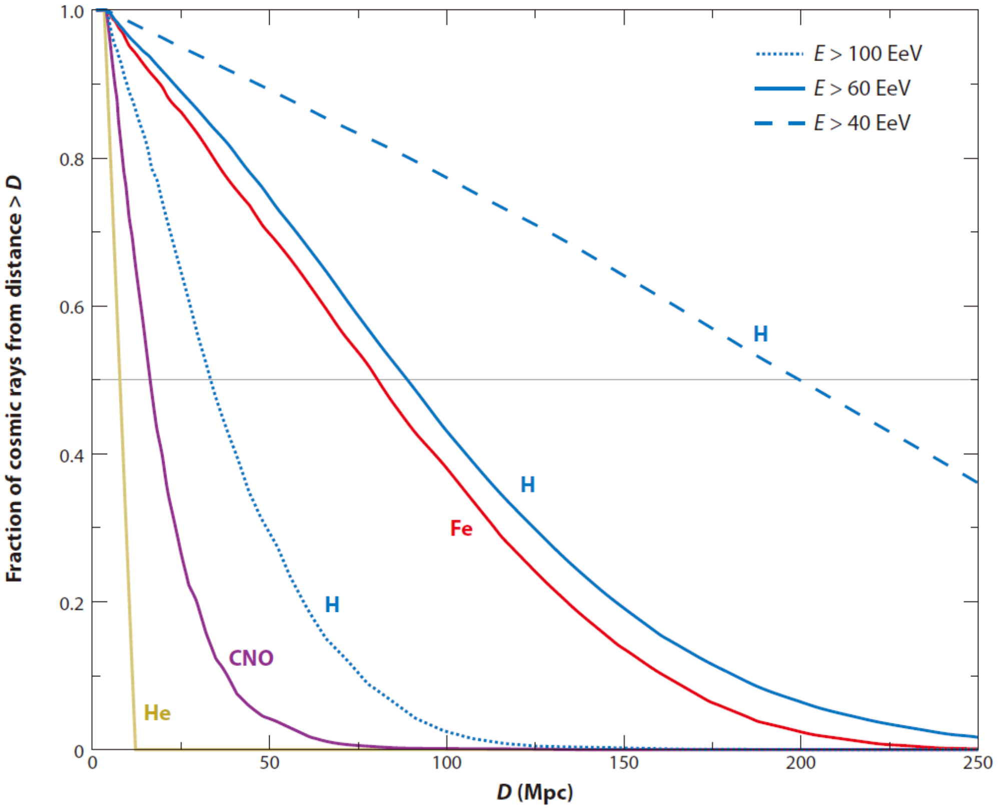
GZK cutoff

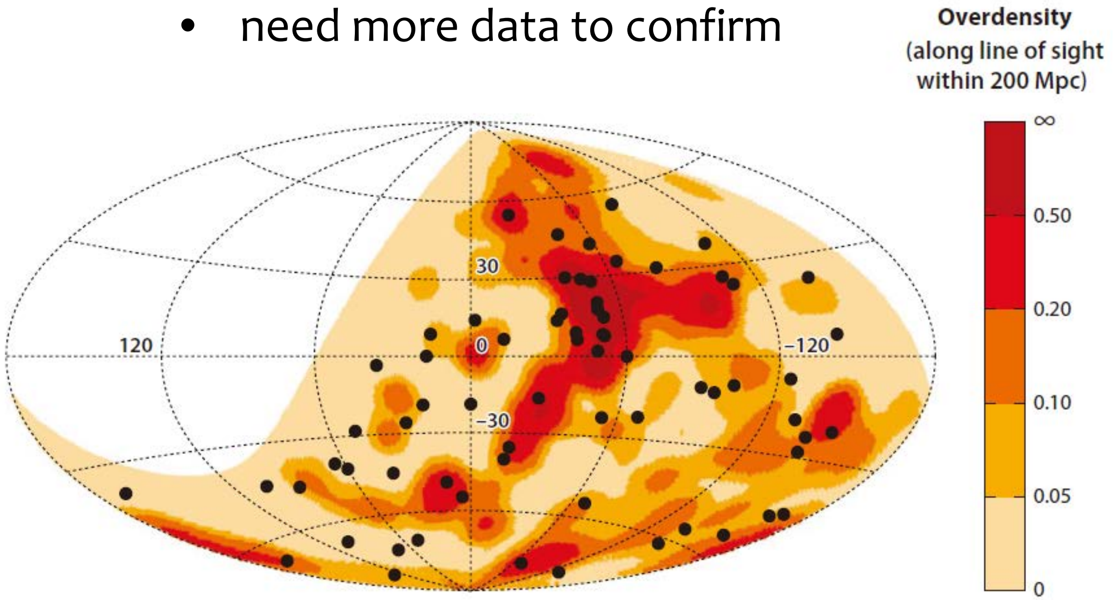
UHECRs from ~100Mpc can’t reach us, they should be produced nearby.

Matter is distributed inhomogeneously

- Early results from the Auger Observatory showed tentative correlation between the UHECR arrival directions and nearby BL Lacs objects
- Not substantiated by increased events

- Recently work, correlation with AGN (in figure below)
- need more data to confirm



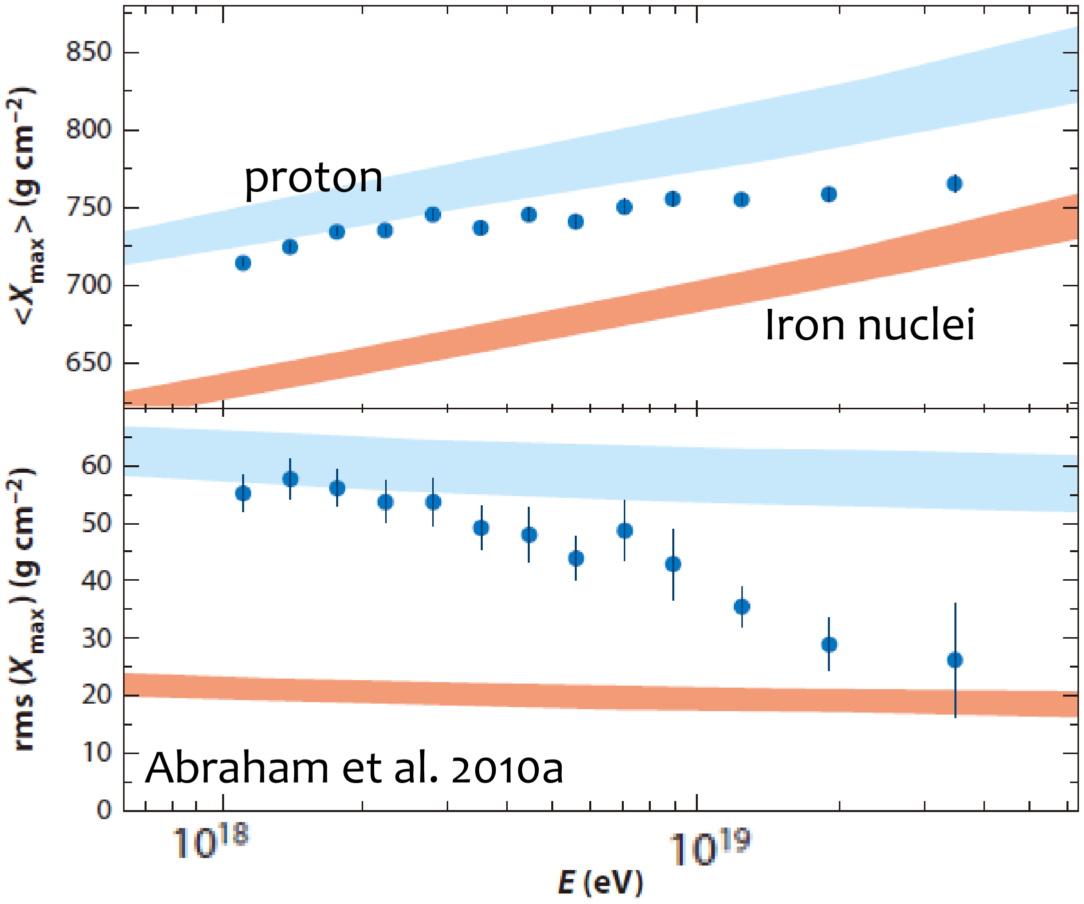


Dot: direction of cosmic rays E>55 EeV
shaded area: a smoothed density map of AGNs within 200 Mpc from 2MRS catalog over the Auger Observatory field of view (Abreu et al. 2010).

Composition

derived from observed development and particle content of extensive shower

- $<X_{max}>$: the depth in the atmosphere of air shower
- the indicator of composition of primary particles
- $<X_{max}> \propto \ln(E/A)$;E energy,A atomic mass
- $<X_{max}{}^{p}> > <X_{max}{}^{Fe}>$
- $<X_{max}>$ of protons fluctuate more



- But HiRes argued the trend remains closer to light primaries.

unclear

X_{max} : maximum depth

Summary

- Observation: extremely difficult
- Energy spectrum:
  - knee , ankle
  - Hint of GZK cutoff
- Origin and acceleration mechanism is still unsure
  - GRB ,
  - AGN jet ,
  - neutron star ,
  - ……
- Spatial distribution : anisotropy ?
- Composition
  - the detailed composition is still to be understood ,
    but it’s clear that primaries are not dominated by protons

- Thank you for listening!

exercise: $\mathrm{p} + \gamma_{CMB} \rightarrow \mathrm{n} + \pi^{+}$

- CMB photo :

$k_B T = 1.38 * 10^{-23} [J/K] * 3 [K]$
$= 4.2 * 10^{-23} J = 2.63 * 10^{-4} eV$

- $\mathrm{p} = \begin{pmatrix} E/c \\ \vec{p} \end{pmatrix}$ 4 momentum vector

Energy and momentum conservation
Special relativity

Energy of proton:

$$\begin{aligned} E_P &= \frac{(939.6+139.6)^2 - 938.3^2\ [\mathrm{MeV}^2]}{4 \times 2.6 \times 10^{-10}\ [\mathrm{MeV}]} \\ &= \boxed{3 \times 10^{20} \mathrm{eV}.} \end{aligned}$$

In the frame of barycenter

$$(\mathbf{p_p} + \mathbf{p_\gamma})^2 = (\mathbf{p_n} + \mathbf{p_\pi})^2$$

rest mass

$$(\mathbf{p_n} + \mathbf{p_\pi})^2 = -(M_n + M_\pi)^2 c^2$$

$$\begin{aligned} (\mathbf{p_p} + \mathbf{p_\gamma})^2 &= (\mathbf{p_p} + \mathbf{p_\gamma}) \cdot (\mathbf{p_p} + \mathbf{p_\gamma}) \\ &= \mathbf{p_p^2} + 2\mathbf{p_p} \cdot \mathbf{p_\gamma} + \mathbf{p_\gamma^2}, \end{aligned}$$

$$\begin{aligned} \mathbf{p_p^2} &= -M_p^2 c^2 \\ \mathbf{p_\gamma^2} &= 0 \end{aligned} \qquad \mathrm{p}_\gamma = \begin{pmatrix} E_\gamma/c \\ -E_\gamma/c \end{pmatrix} \qquad \mathrm{p_P} = \begin{pmatrix} E_p/c \\ E_p/c \end{pmatrix}$$

$$-M_p^2 c^2 + 2\mathbf{p_p} \cdot \mathbf{p_\gamma} = -(M_n + M_\pi)^2 c^2.$$

$$\begin{aligned} \mathbf{p_p} \cdot \mathbf{p_\gamma} &= -\frac{E_p E_\gamma}{c^2} + \left(\frac{E_p}{c}\right)\left(\frac{-E_\gamma}{c}\right) \\ &= \frac{-2E_p E_\gamma}{c^2}. \end{aligned}$$

$$M_p^2 c^2 + \frac{4E_p E_\gamma}{c^2} = (M_n + M_\pi)^2 c^2$$

$$E_p = \frac{(M_n c^2 + M_\pi c^2)^2 - (M_p c^2)^2}{4E_\gamma}$$