Potential UHECR accelerators: constraints, demography, CR composition

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1. Constraints on astrophysical accelerators:

- "Hillas plot"

  important experimental updates

- radiation losses

  for specific mechanisms

2. Implications for spectrum and composition

- acceleration capabilities

- demography: populations of sources

  number of sources, distance to the nearest source

- injected spectra and composition

  acceleration mechanism + astro-chemistry

- propagation ⇨ observations

Constraints on astrophysical accelerators: "Hillas plot" + radiation losses

(electrodynamics)

Assumption:

- particle is accelerated by electromagnetic forces inside an astrophysical accelerator

General limitations:

- geometry
  energetic particles leave the accelerator
- radiation losses
  accelerating charges radiate and loose energy

geometry: the Hillas criterion:
Larmor radius < size of accelerator
(otherwise lefts the accelerator)

$$\mathcal{E} < ZeBR$$

maximal energy

charge

magnetic field

size of the accelerator

Constraints on sources

radiation losses

$\mathcal{E}$ gain rate < $\mathcal{E}$ loss rate

$$\frac{d\mathcal{E}^+}{dt} > \frac{d\mathcal{E}^-}{dt}$$

depend on the acceleration mechanism

$$\frac{d\mathcal{E}^+}{dt} = ZeE \ \sim ZeB$$

$$\frac{d\mathcal{E}^-}{dt} = \frac{2Z^4e^4}{3m^2c^3}\left(\frac{\mathcal{E}}{mc^2}\right)^2\left(\left(\mathbf{E}+\frac{1}{c}[\mathbf{v}\times\mathbf{H}]\right)^2-\frac{1}{c^2}(\mathbf{E}\cdot\mathbf{v})^2\right)$$

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$$\frac{d\mathcal{E}^-}{dt} = \frac{2Z^4e^4}{3m^2c^3}\left(\frac{\mathcal{E}}{mc^2}\right)^2\left(\left(\mathbf{E}+\frac{1}{c}[\mathbf{v}\times\mathbf{H}]\right)^2-\frac{1}{c^2}(\mathbf{E}\cdot\mathbf{v})^2\right)$$

$$\frac{d\mathcal{E}^-}{dt} \propto F_\perp^2 + \left(1-\frac{v^2}{c^2}\right)F_{||}^2$$

synchrotron

$$\frac{d\mathcal{E}^-}{dt} = \frac{2}{3}\left(\frac{Ze}{Am_pc^2}\right)^4 c\,\mathcal{E}^2B^2$$

curvature

$$\frac{d\mathcal{E}^-}{dt} = \frac{2Z^2e^2c}{3R^2}\left(\frac{\mathcal{E}}{Am_pc^2}\right)^4$$

Limitations due to radiation losses:

disagreement on their importance?

• protons can be accelerated "to (3-5)$\times 10^{21}$ eV …
At energies $\geq 10^{22}$ eV the cosmic ray primaries have to be heavy nuclei"   *Aharonyan et al. 2002*

• "Practically, all known astronomical sources are not able to produce cosmic rays with energies near few times 10^{20} eV"   *Medvedev 2003*

Different acceleration regimes:

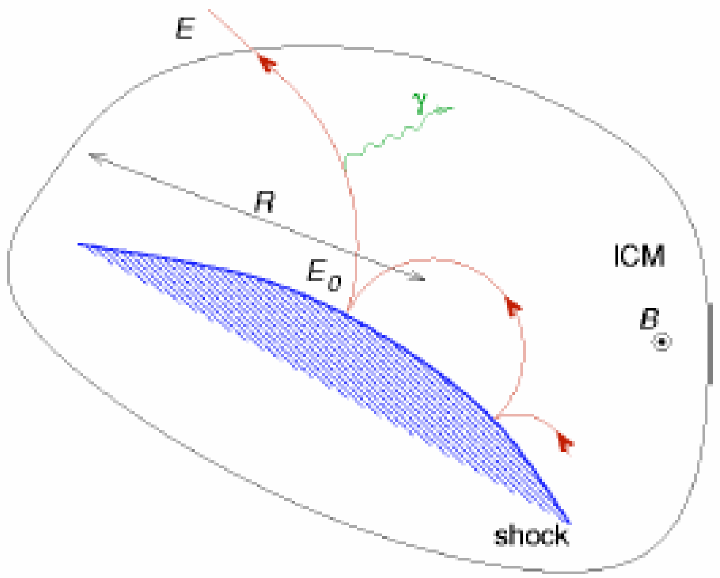
- diffusive (shocks)

- inductive (one-shot)

    - synchrotron-dominated losses
    - curvature-dominated losses

Different acceleration regimes:

• diffusive (shocks)



plot: Medvedev 2003

gets a hit from time to time,
radiates synchrotron continuously

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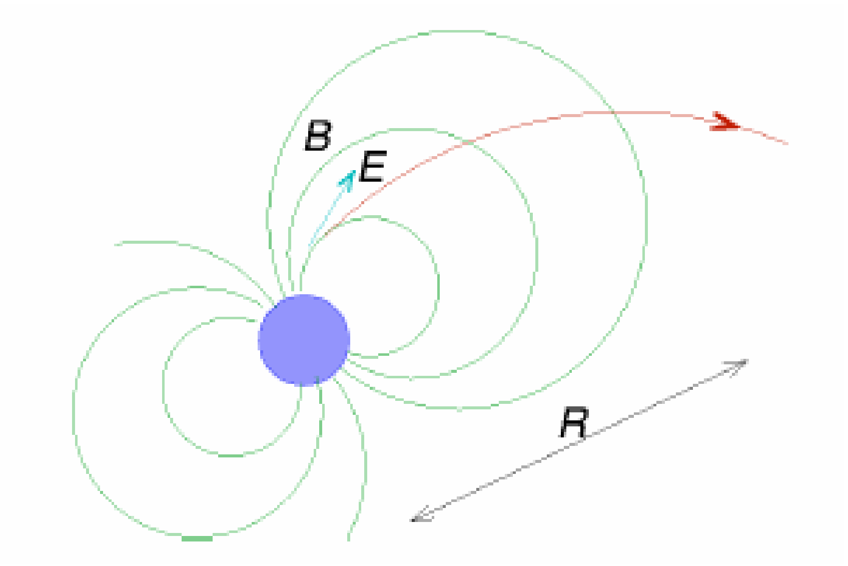

plot: Medvedev 2003

is accelerated and radiates continuously

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general field configuration

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general field configuration

specific field configuration

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is accelerated and radiates continuously

- **synchrotron**-dominated losses
- **curvature**-dominated losses

general field configuration

specific field configuration

E* || *B

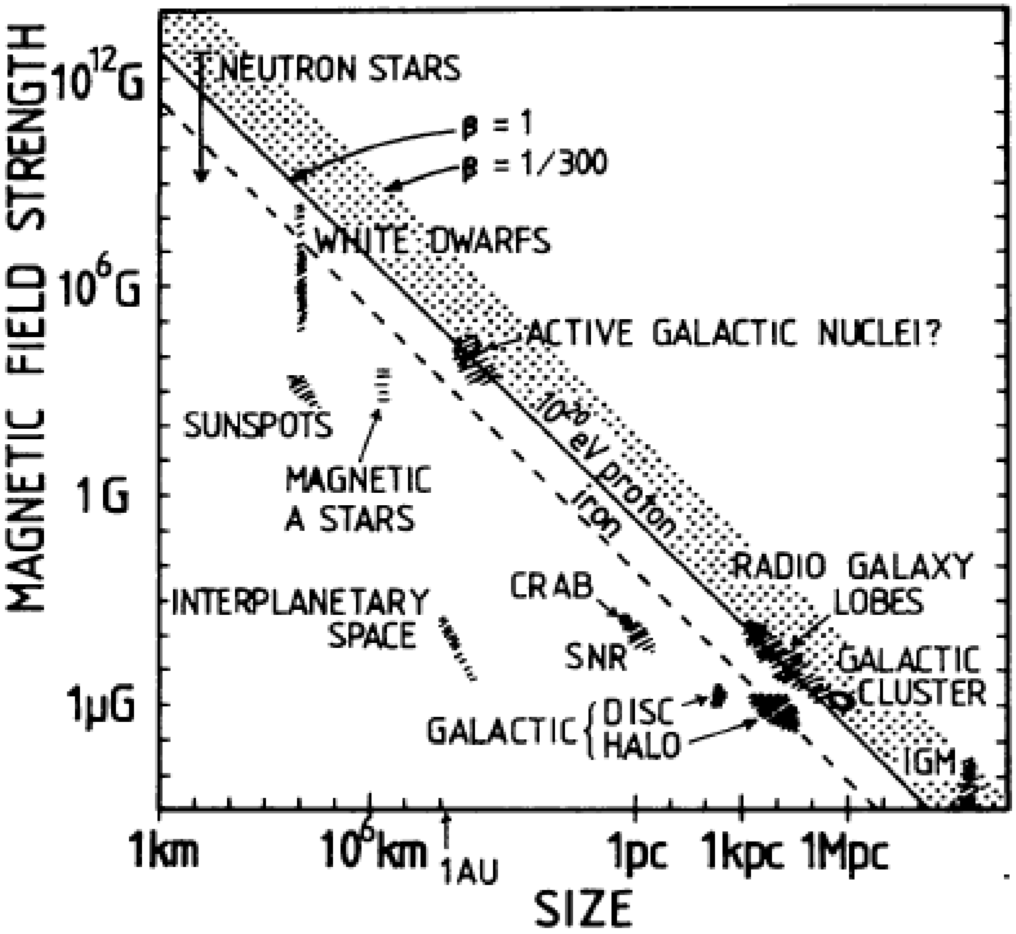
(close to a black hole)

Both geometrical and radiation-loss constraints are expressed in terms of B and R

⇩

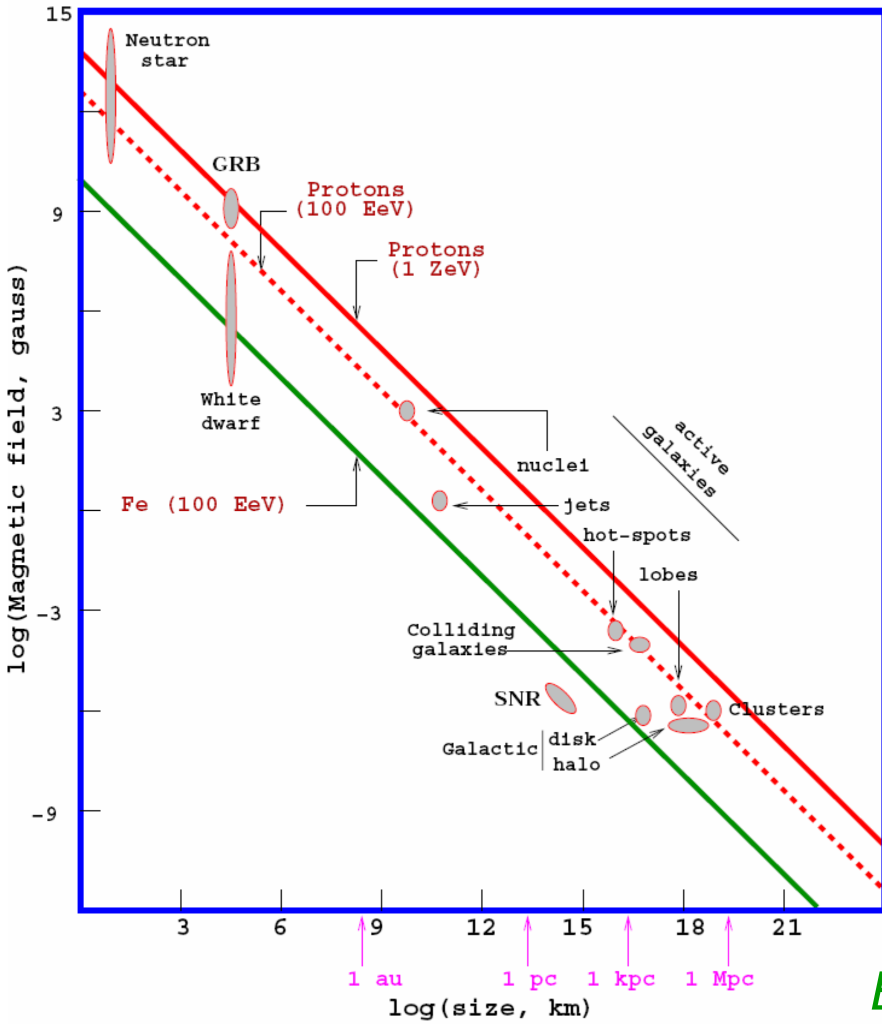
Hillas plot!

the (original) Hillas plot



Hillas 1984

(almost) no changes since then?



Boratav et al. 2000

1984 – 2008: revolution in astronomy!

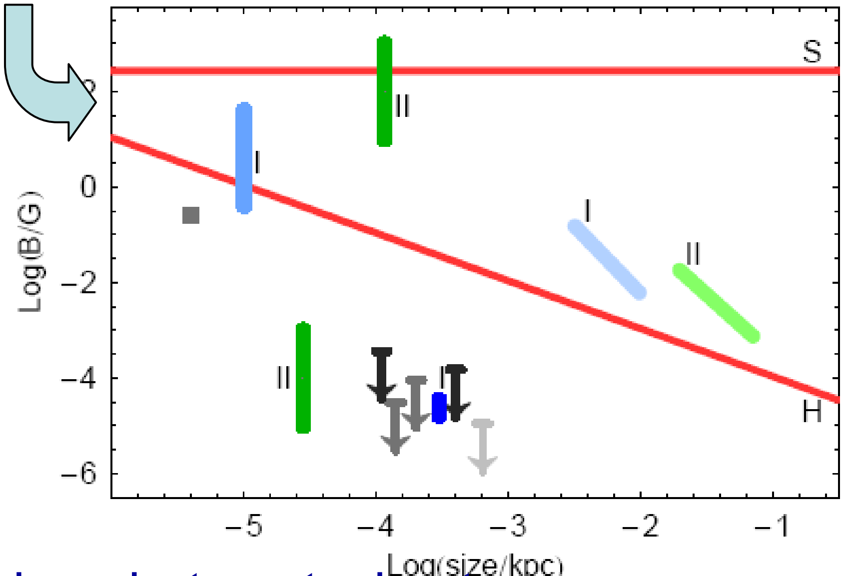
HST, Chandra, XMM, VLBA….
high-precision instruments

quantitative constraints on magnetic fields

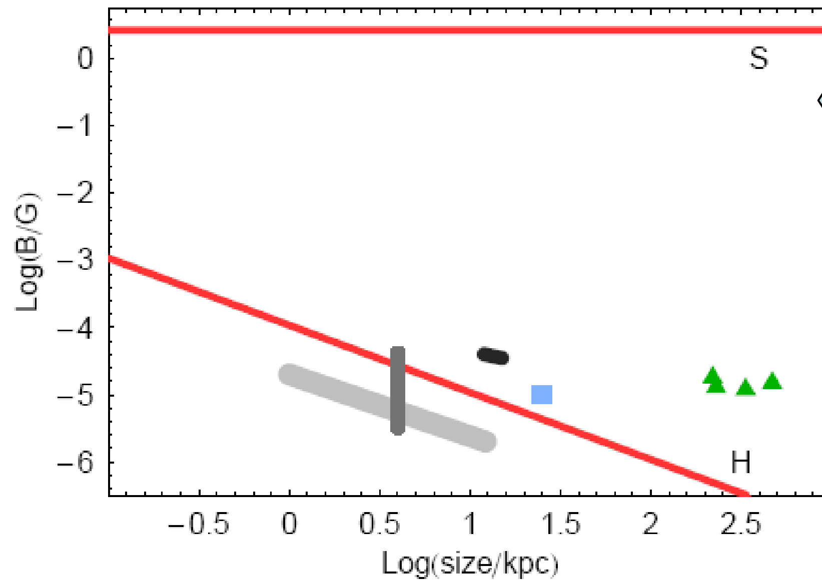
update the Hillas plot!

B measurements…

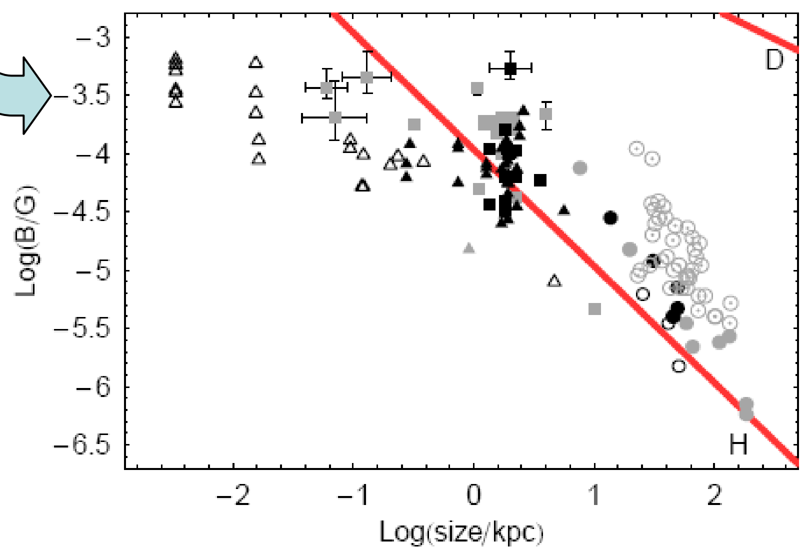
AGN central parts



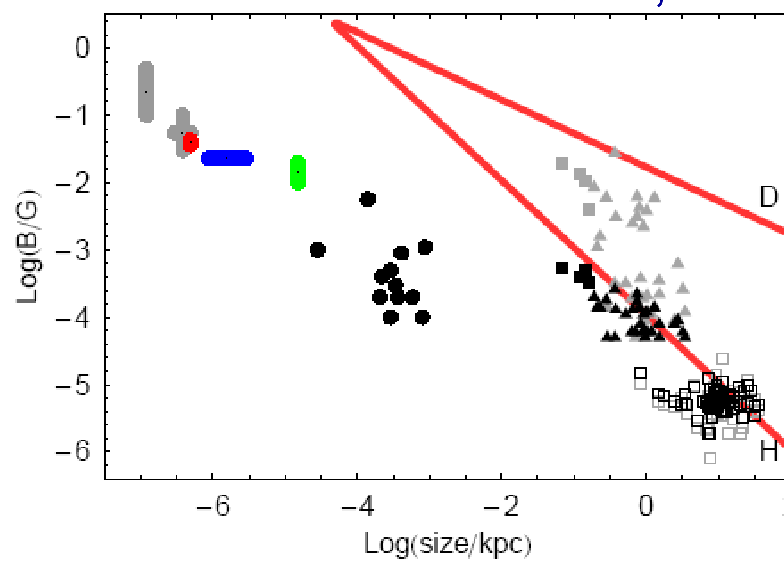
jets



lobes, hot spots, knots

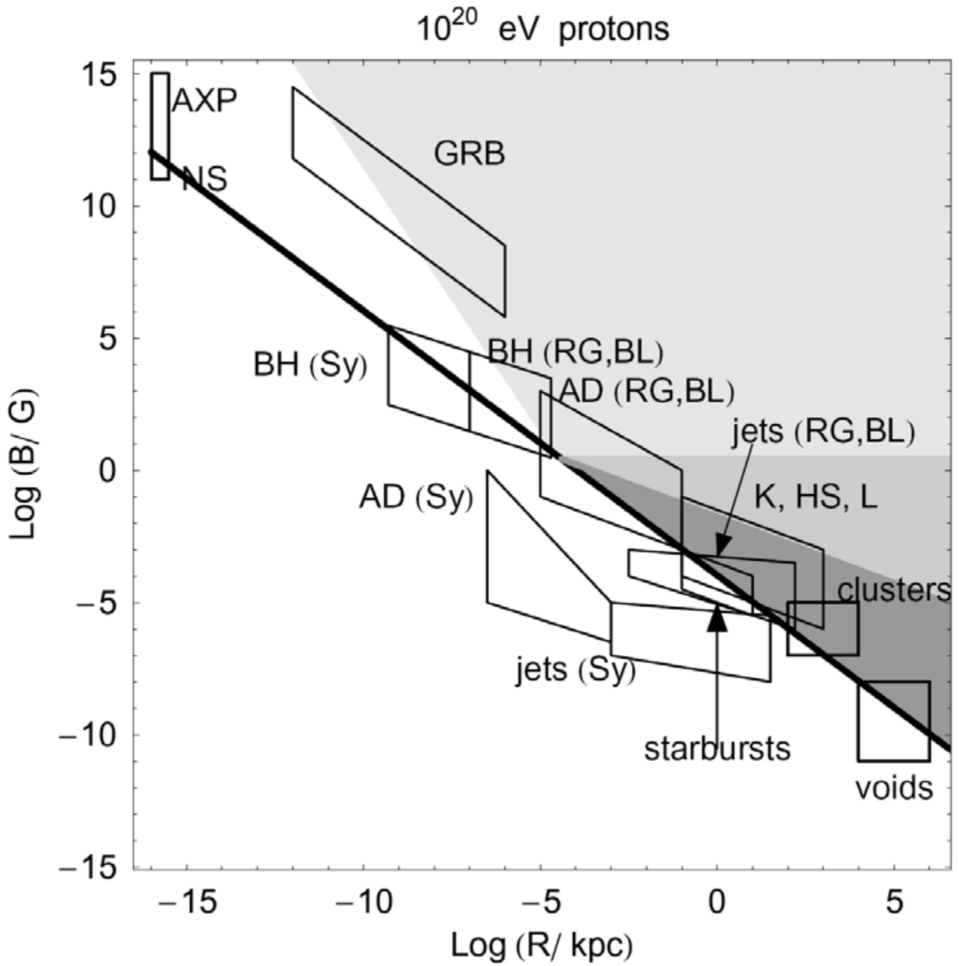


SFR, starbursts



The updated Hillas plot

(+ radiation losses)



protons 10^{20} eV

Ptitsyna, ST 2008

The updated Hillas plot

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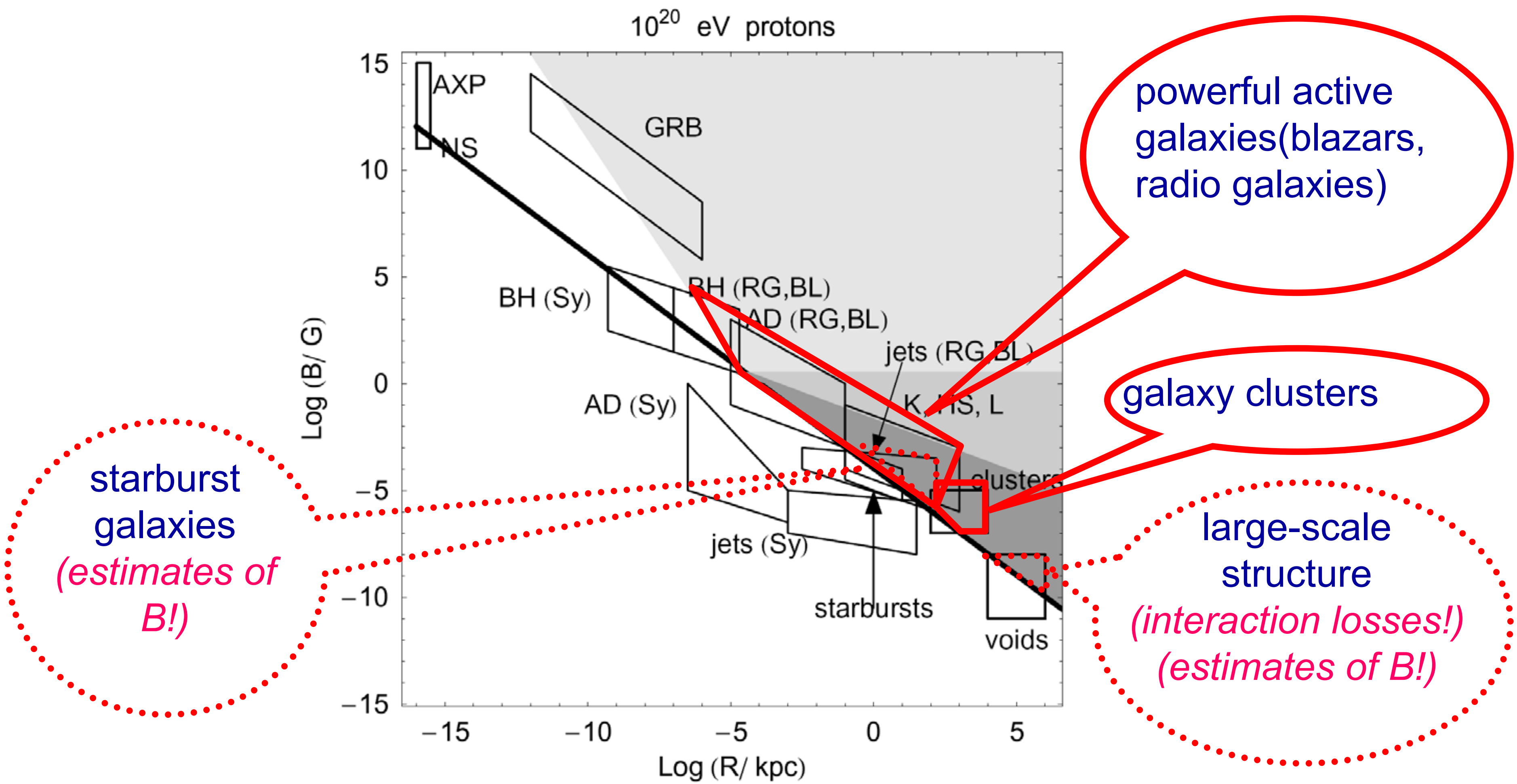


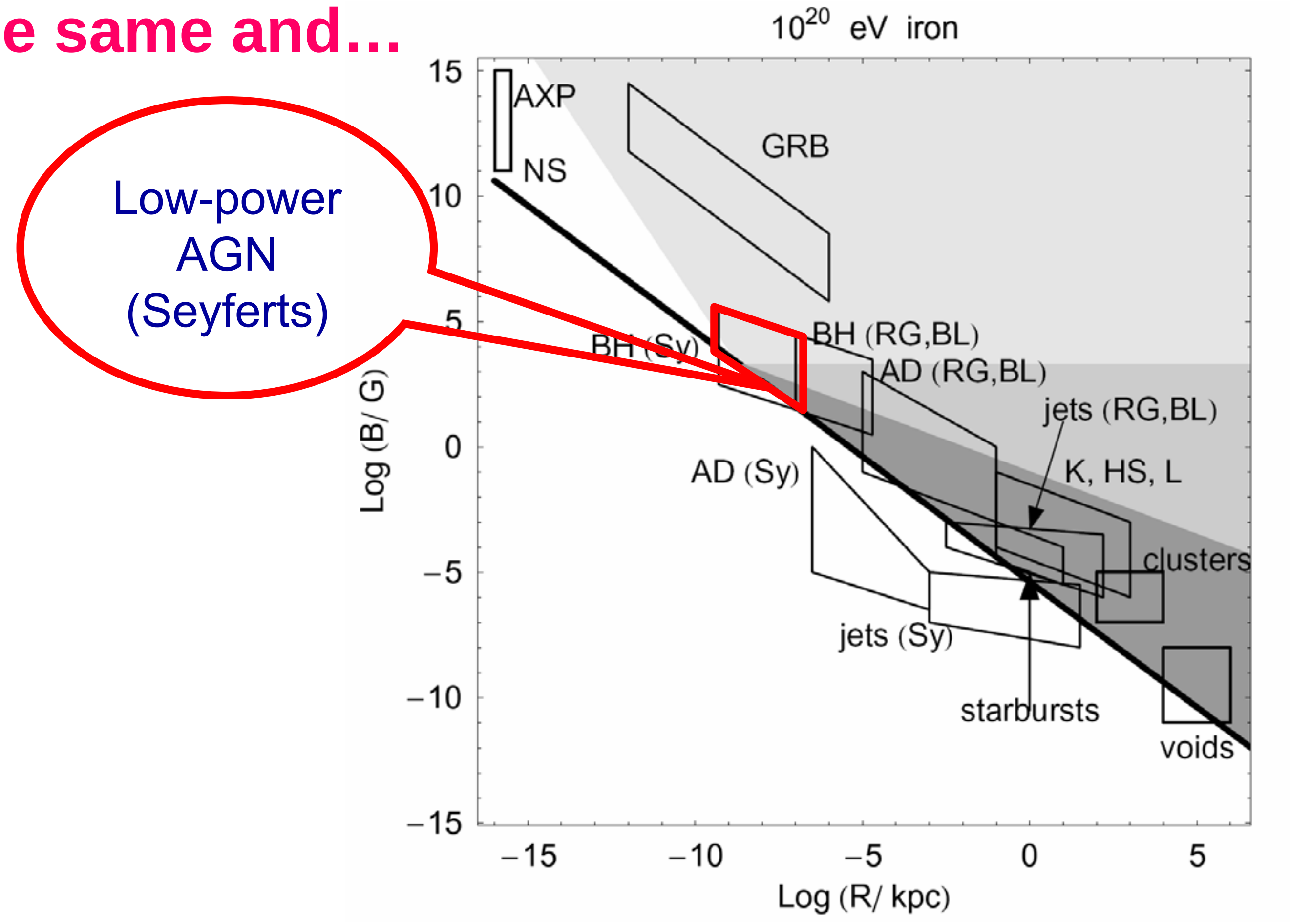
protons 10^{20} eV

Ptitsyna, ST 2008

The updated Hillas plot

(+ radiation losses)

the same and…



iron nuclei 10^{20} eV

Ptitsyna, ST 2008

Potential sources

conclusions about 10^{20} eV UHECR sources:

• protons
  - powerful, distant, rare active galaxies
  - galaxy clusters

• heavy nuclei
  - low-power, nearby, numerous active galaxies

Ptitsyna, ST 2008

Populations of sources quantifiable!

- know acceleration capabilities of particular sources
- know demography (density/ distance from us)
- know chemical composition in the source
- acceleration mechanism → injection spectrum
- propagation → observables

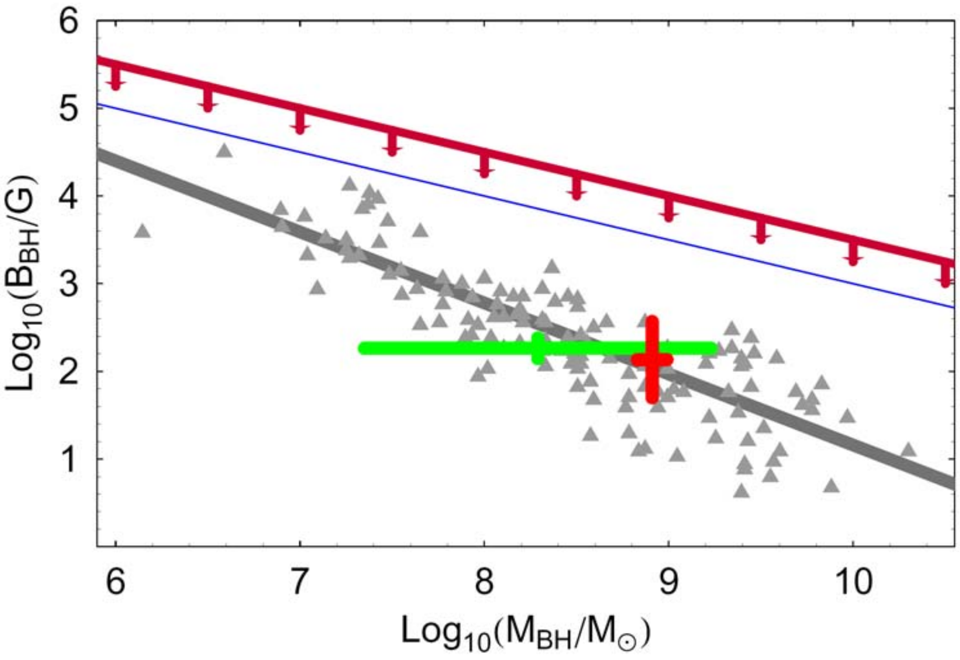
Example scenarios:

1. Jets/lobes/hot spots
- diffusive acceleration
- energy Hillas-limited, $\mathcal{E}_{max} \sim Z$
- distant sources → protons remain, pure GZK

2. AGN central black holes
- inductive acceleration, curvature-radiation losses
- injection hard, $\alpha \leq 1.5$
- energy losses-limited, $\mathcal{E}_{max} \sim A^{1/4}/Z^{1/2}$
- numerous nearby sources can accelerate nuclei
  - ♦ interesting physics at 10^{20} eV

    (*Auger, Yakutsk suggest heavy nuclei)*
  - ♦ GZK or $\mathcal{E}_{max}$ or both?

AGN central black hole environment: both *B* and *R* governed by M_{BH}



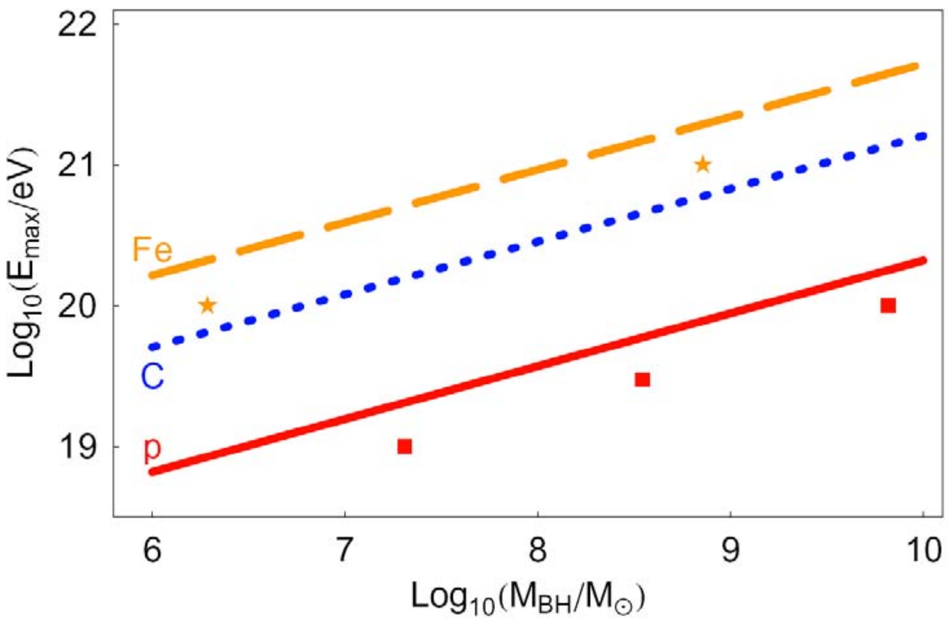
Znajek 1978

Shakura, Sunyaev 1973
Novikov, Thorne 1973

Zhang, Lu, Zhang 2005

Ptitsyna, ST 2008

AGN central black hole environment: $\mathcal{E}_{max}$ governed by M_{BH}



★ Fe

■ p

Neronov, Semikoz, Tkachev 2007

Ptitsyna, ST 2008

Population of the sources:

"optimistic": $\mathcal{E}_{max} = 5.5\times10^{19}$ eV $(A/Z^{1/4})\ x^{3/8}$

"realistic": $\mathcal{E}_{max} = 1.9\times10^{19}$ eV $(A/Z^{1/4})\ x^{0.2975}$

SMBH mass function: $\varphi = \varphi_0\ x^{\alpha+1} \exp(1-x)$

expected $z_{min} = 0.0012\ x^{-0.23} \exp((x-1)/3)$

$\alpha = -0.32$, $\varphi_0 = 10^{-2.76}$ /Mpc^3/dex, $x = M_{BH}/(10^{8.45}\ M_{\odot})$

Population of the sources:

flux (proportional to the accretion rate) – use scaling

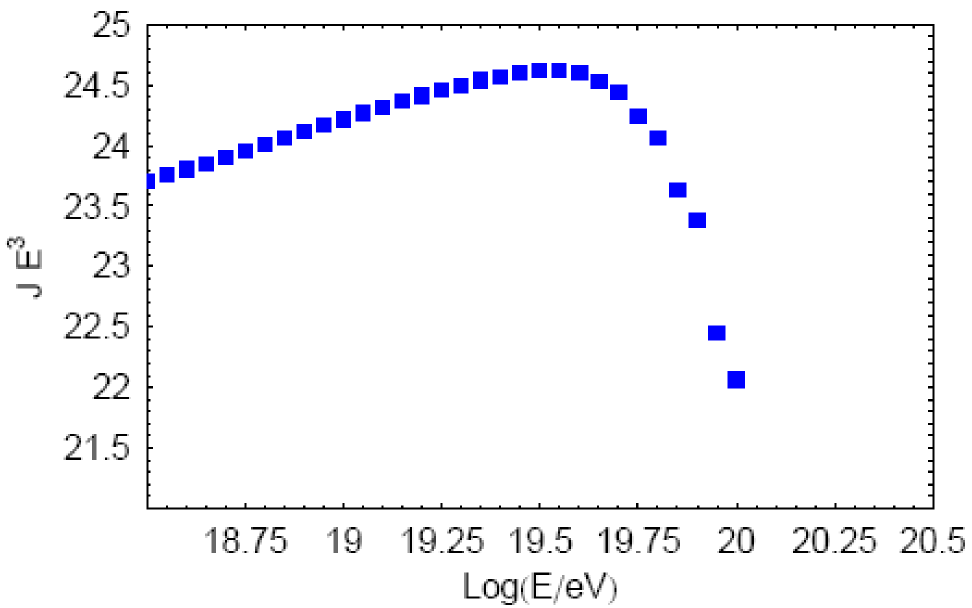
composition at injection – a la Allard et al.
(derived from Galactic ISM abundances)

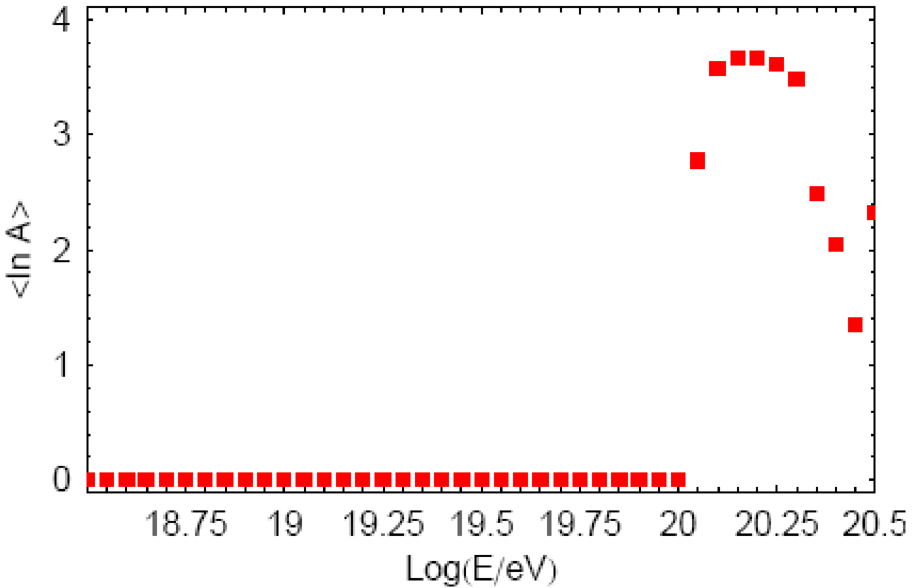
composition will be a problem!
[p/Fe]=54000
allow for arbitrary metallicity to get some heavy nuclei

Implications for composition: can we get nuclei?

natural scenario:

- $\mathcal{E}_{max}$(p)>10^{20} eV
- realistic Fe abundances
- GZK cutoff seen
- light composition at Earth

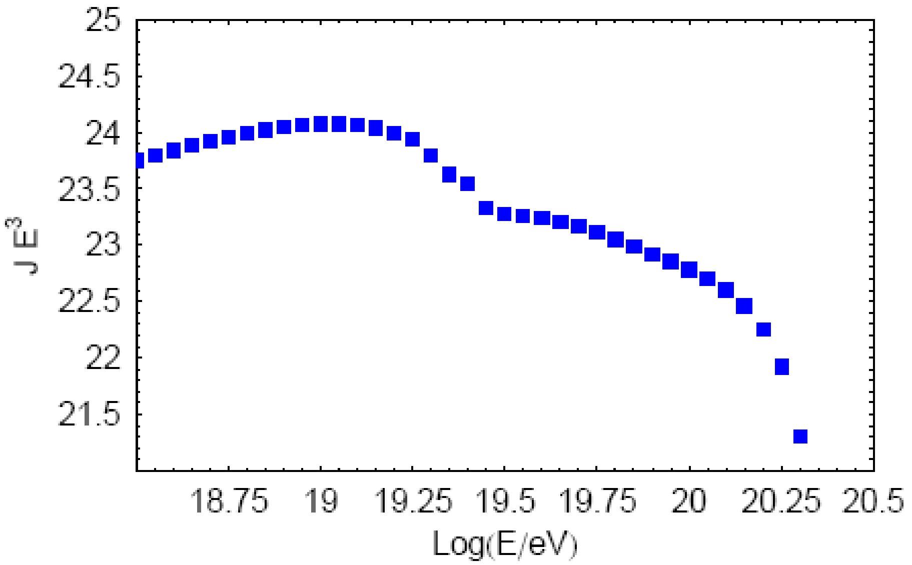


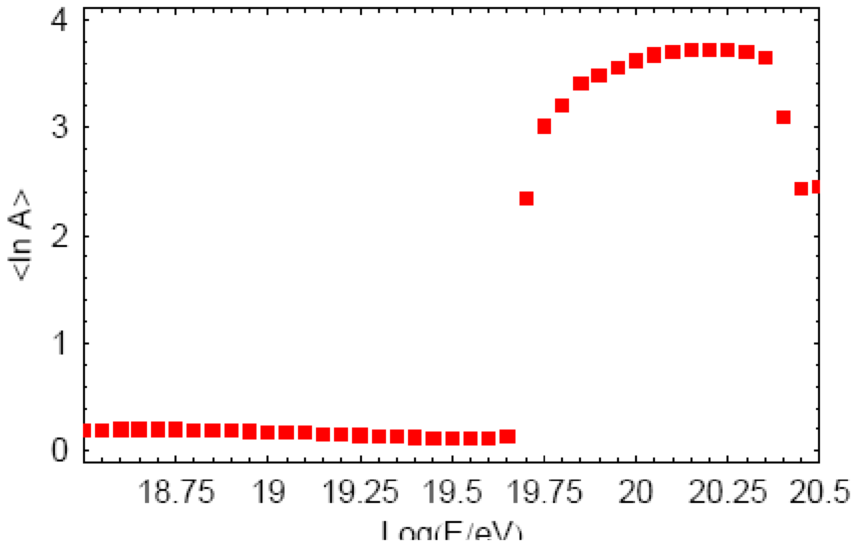


Implications for composition: can we get nuclei?

weird scenario:

- $\mathcal{E}_{max}(p) < 10^{20}$ eV
- Fe abundances ×10000
- no GZK cutoff!
- heavy composition at Earth





Implications for composition: can we get nuclei?

how to get heavy composition AND GZK cutoff?

- occasionally close, relatively weak, high-metallicity source!
- Fe abundances ×1000
- $\mathcal{E}_{max}$(Fe)~10^{20} eV for this particular source
- heavy composition at Earth governed by this source
- GZK cutoff governed by other sources + $\mathcal{E}_{max}$ for this source

fine tuning, but Cen A…

North-South difference?

Conclusions:

- updated constraints on the UHECR accelerators
- active galaxies=plausible accelerators
- low-power Seyferts: heavy nuclei

  powerful BL Lacs and radio galaxies: protons
- acceleration in AGN: $\mathcal{E}_{max}$ is governed by the black-hole mass → demography known
- spectrum and composition may be predicted
- very difficult to have heavy nuclei + GZK
- a nearby source???