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Constraints on direct acceleration of UHECRs in astrophysical sources

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Outline

1. Data favour large number density of UHECR sources; problems with astrophysics
2. Direct (inductive) acceleration near supermassive black holes may help
3. Modelling the population of non-identical sources
4. Outlook

The consistency problem

10-15 years ago: super-GZK events

? lack of local overdensity of sources

Now:

lack of nearby sources again!

Numerous sources:
lack of clustering

[$E>5\tilde{\times}10^{19}$ eV, assume protons]

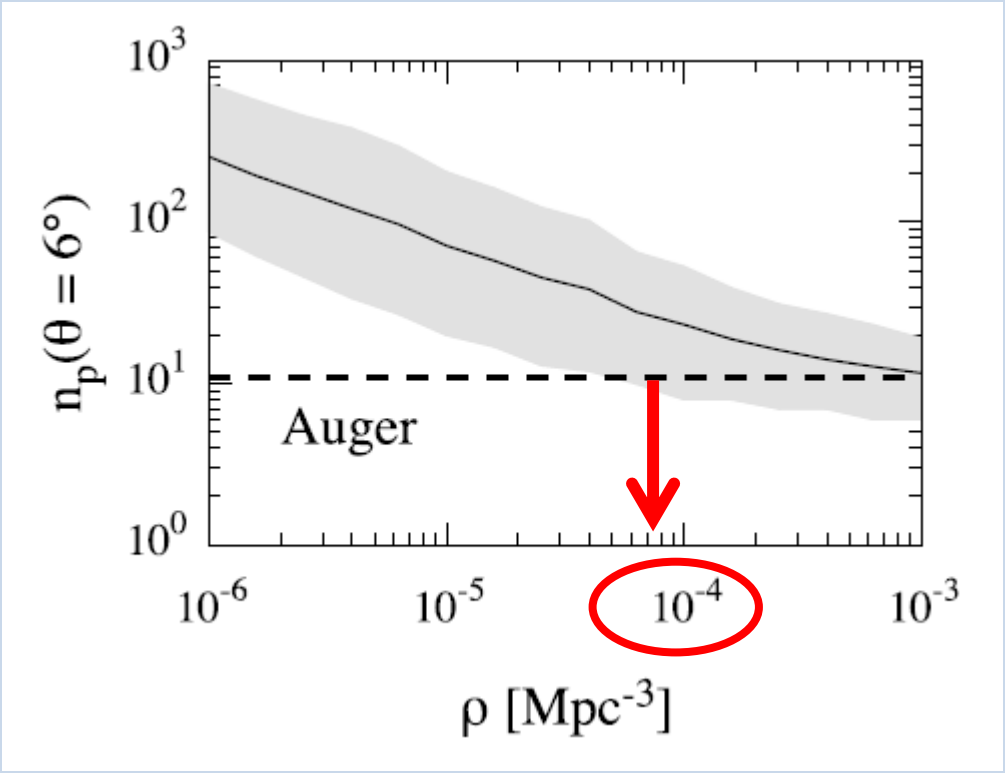
Statistics of clustering ⇒ number of sources

Dubovsky et al. 2001

PAO 2011:

$E>6\times10^{19}$ eV

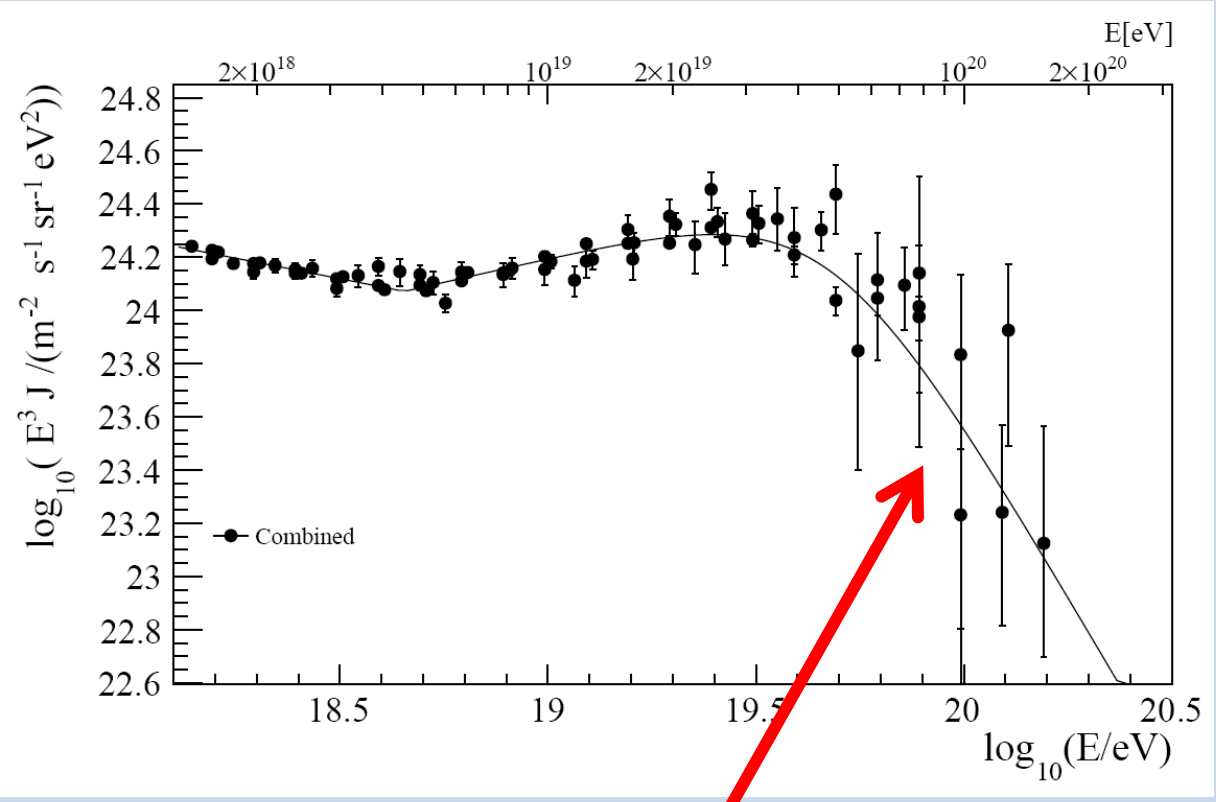
deflection<6°



$\gtrsim 10^{-4}$ Mpc^{-3}, 90%CL

Nearby sources:
mild GZK suppression

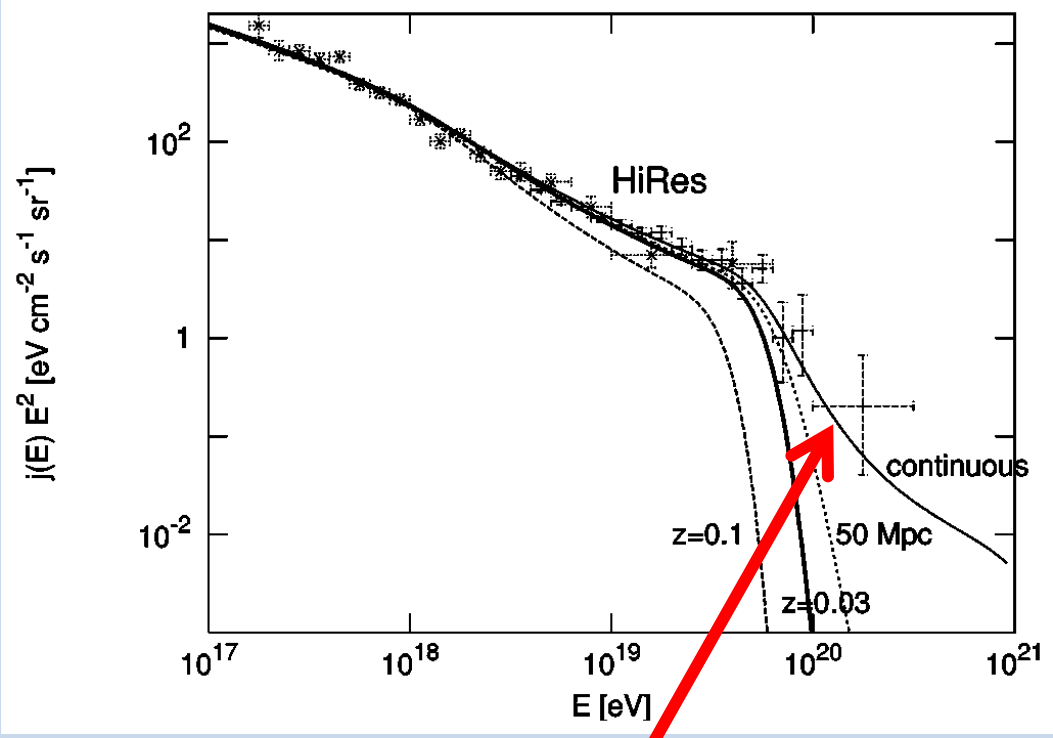
[***currently less precise argument***]



only nearby sources contribute at 10^{20} eV

Nearby sources:
mild GZK suppression

[*currently less precise argument*]

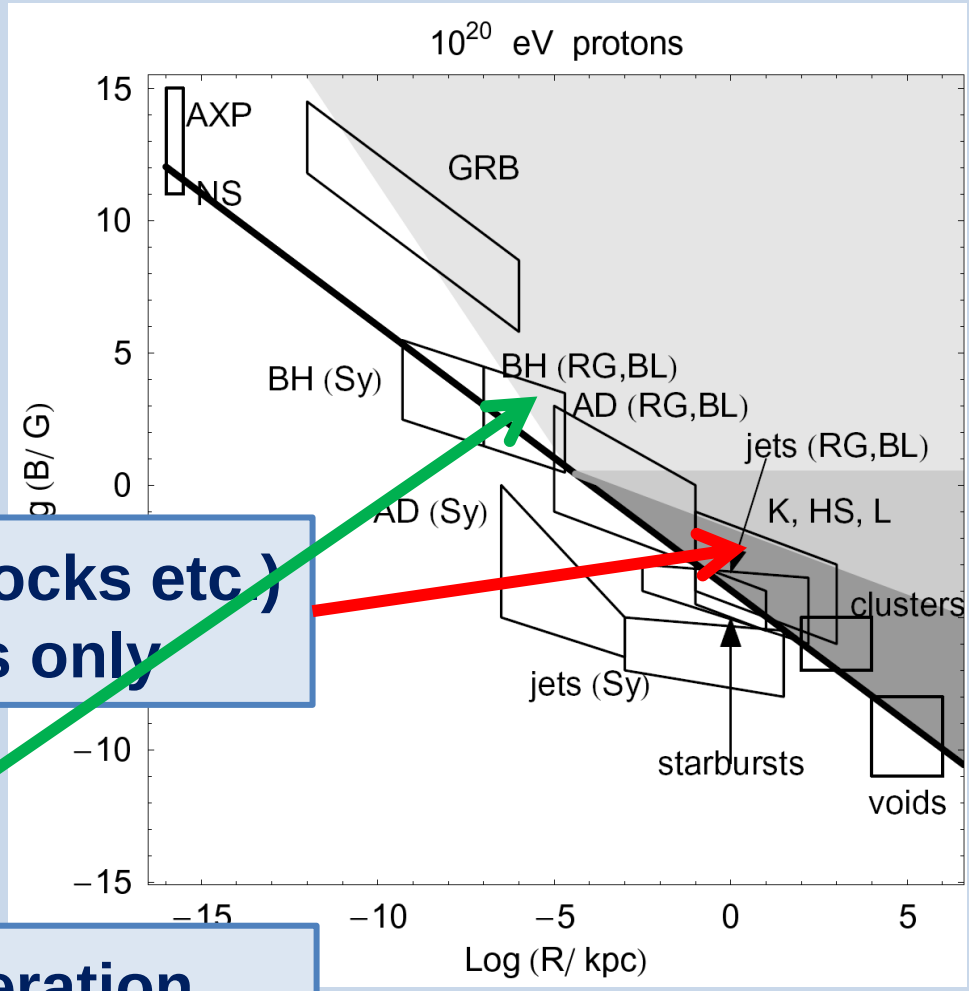


Kachelriess et al. 2003

only nearby sources contribute at 10^{20} eV

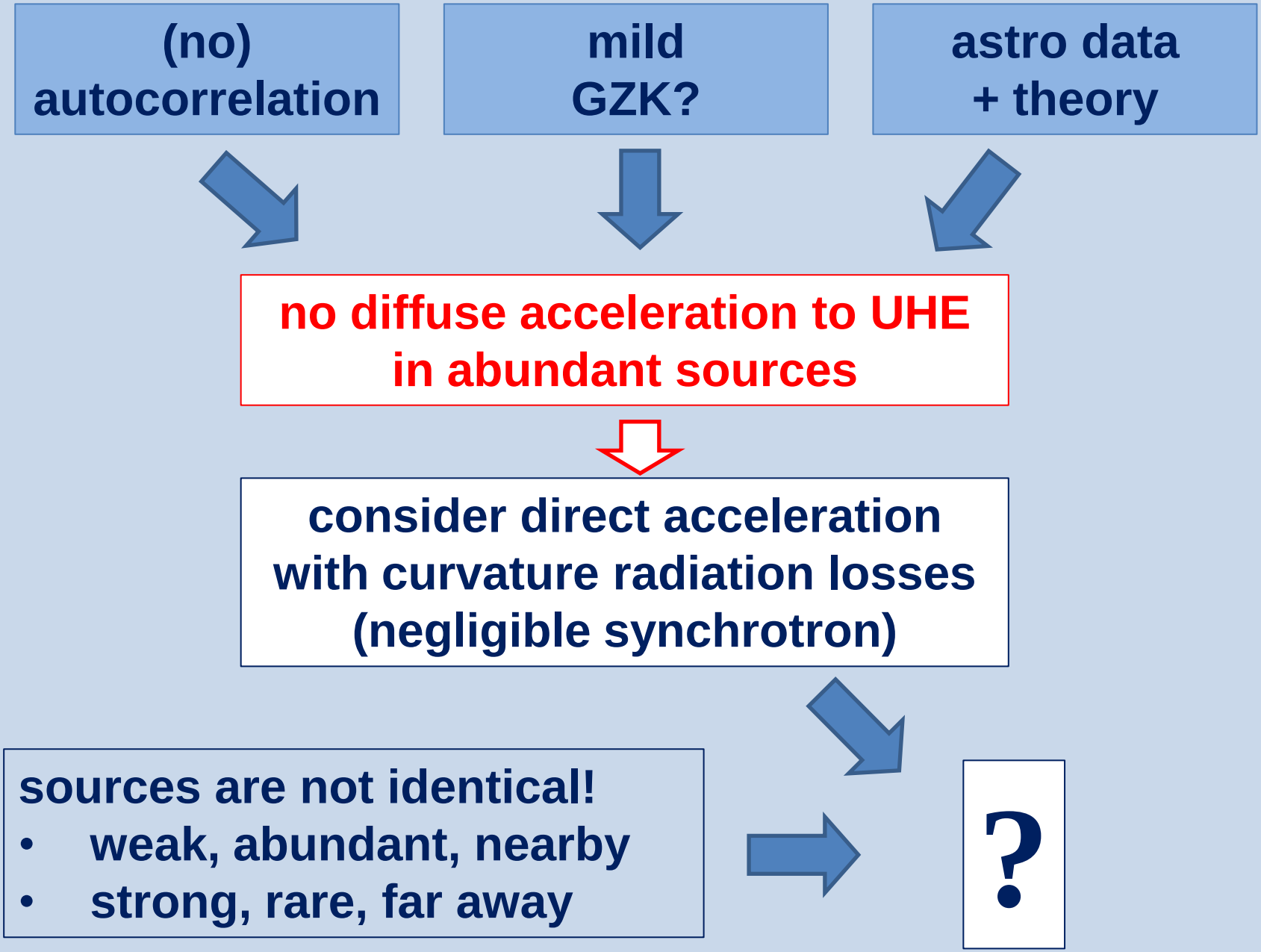
Astrophysics:
potential sources are rare

Hillas plot
+ radiation losses:



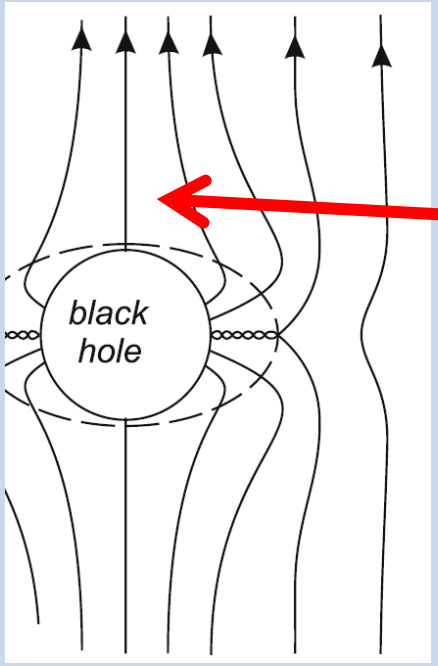
- **diffuse acceleration (shocks etc.) works in extreme sources only**

- **direct (inductive) acceleration, curvature vs. synchrotron losses!**


(no) autocorrelation
mild GZK?
astro data + theory
no diffuse acceleration to UHE in abundant sources
consider direct acceleration with curvature radiation losses (negligible synchrotron)
sources are not identical!
• weak, abundant, nearby
• strong, rare, far away
?

A model:
acceleration in black-hole magnetospheres

[*Neronov, Semikoz, Tkachev 2000*]



polar cap:
***E*||*B*, no synchrotron,**
curvature radiation only

- **exact solution for *E*, *B* (up to |*B*|)**
- **max energy determined by losses**

A model:
acceleration in black-hole magnetospheres

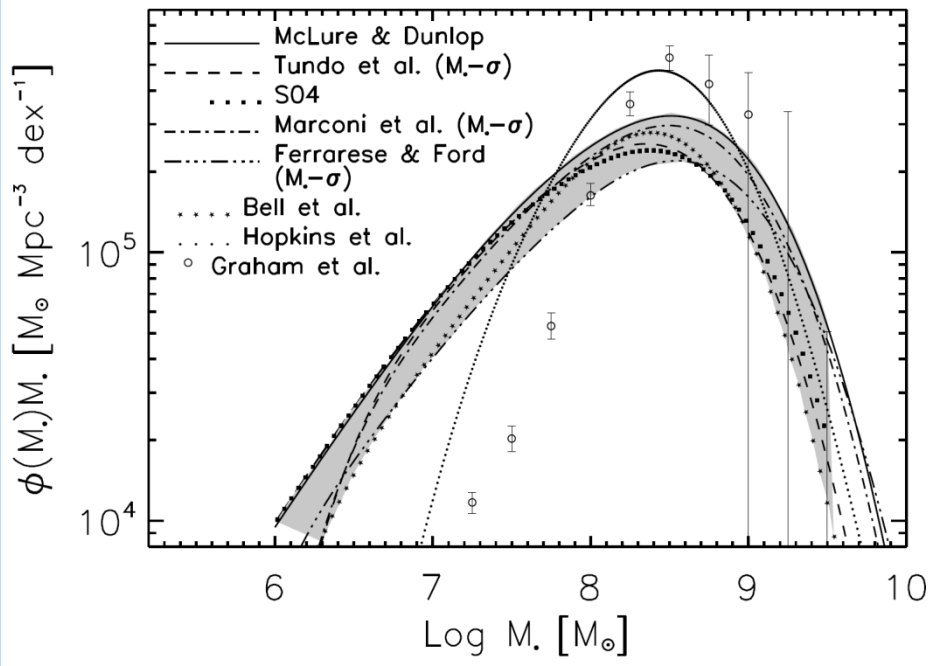
[*Neronov, Semikoz, Tkachev 2000*]

PARAMETERS:

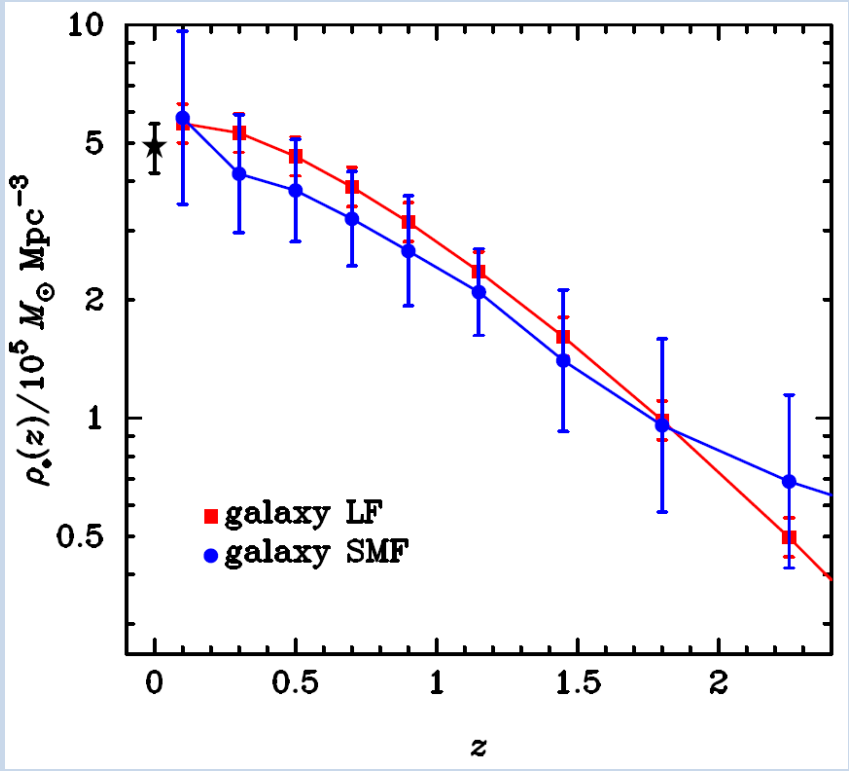
- injection spectrum ~ monochromatic – **fixed**
- max energy ⟸ losses ⟸ B, geometry ⟸ M_{BH}
- source population – BH mass function – **fixed**
- mean individual source power
- fraction of "working BHs"

} **free**, assume ~ M_{BH}^{α}

Population of sources:
supermassive-black-hole mass function



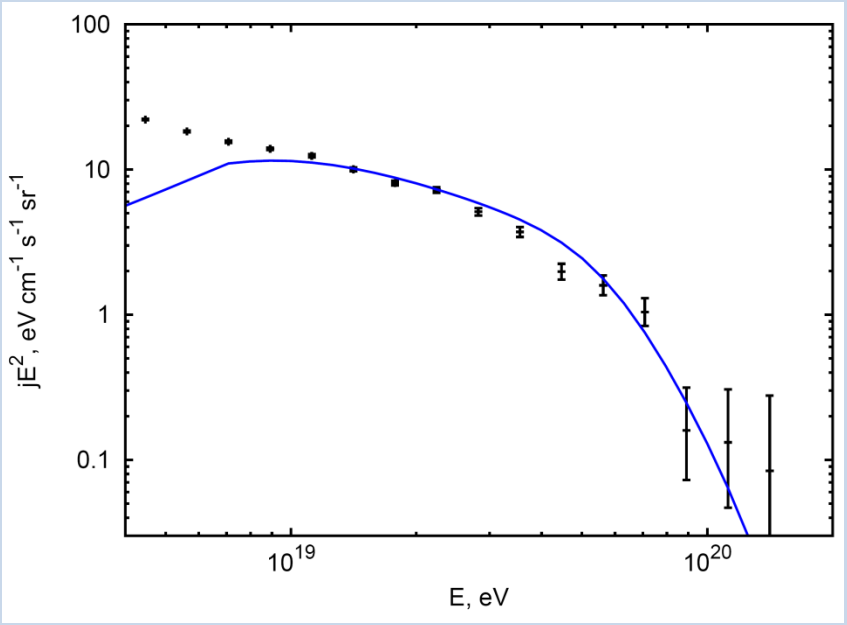
[*Shankar 2009*]



evolution with z →

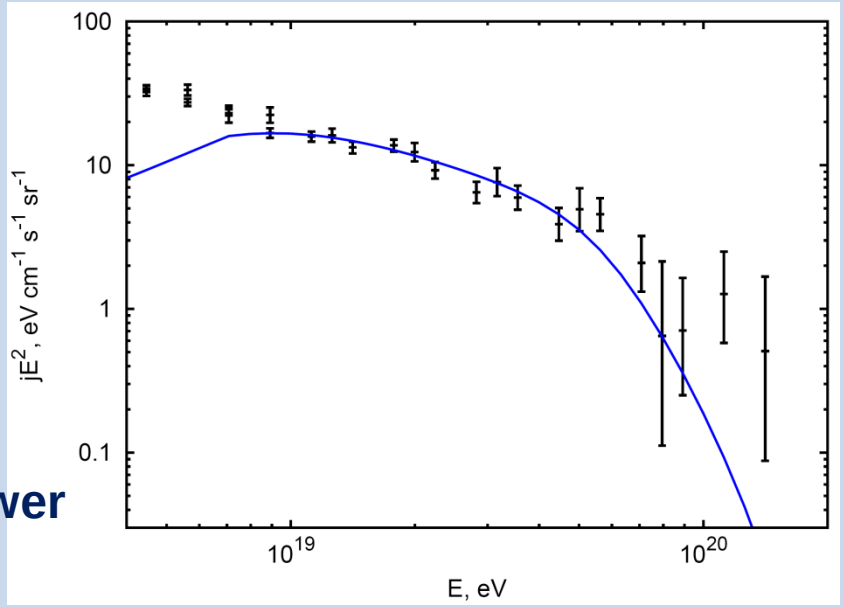
[*Li et al. 2011*]

Population of sources:
fit to the cosmic-ray spectrum



Auger

HiRes



2 parameters:

- ❑ **normalization**
- ❑ **α**

$\sim M_{BH}^{\alpha}$

- **mean individual source power**
- **fraction of "working BHs"**

Constraints:
secondary gamma rays

- loss-limited acceleration: many photons emitted

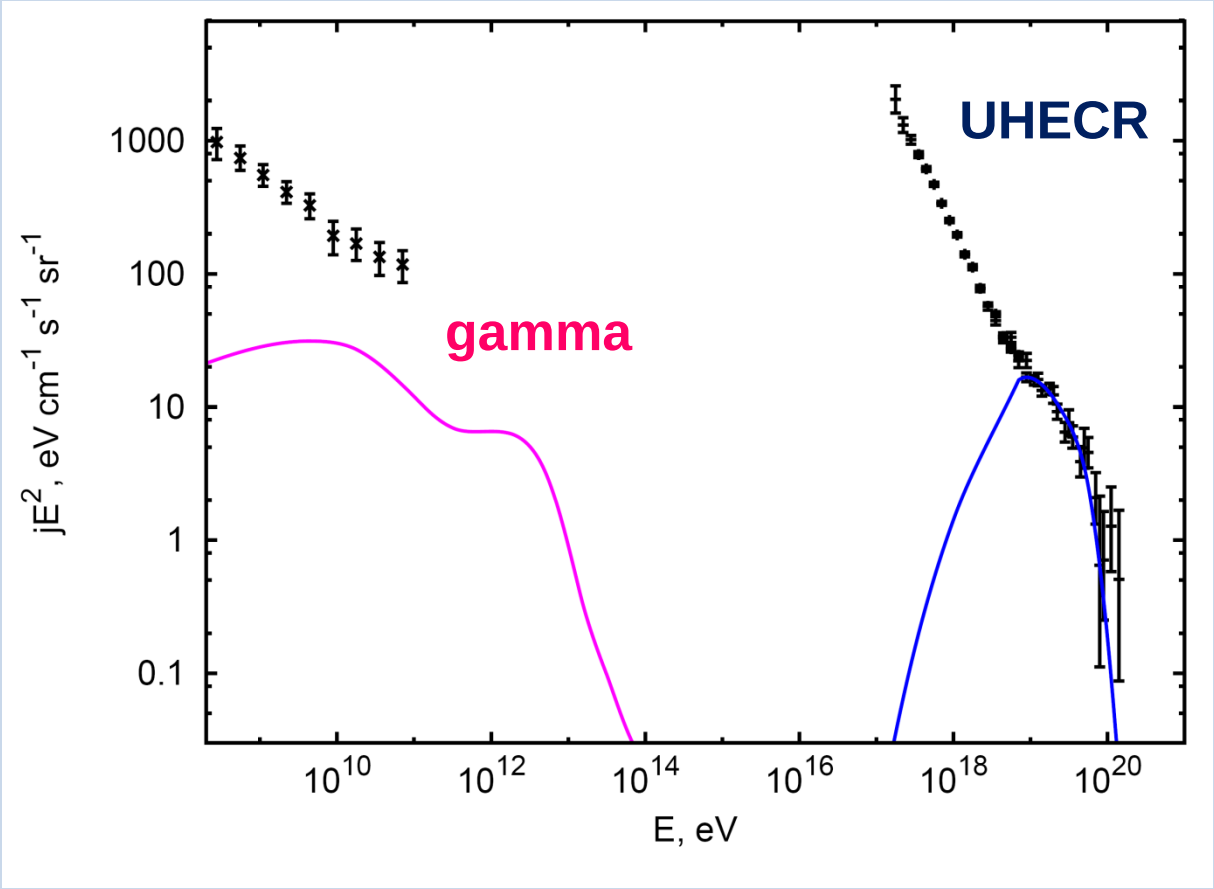
- curvature radiation:
  O(10) times CR energy emitted in ~(1-10) TeV photons

- cascades on extragalactic background light
  ⇨ diffuse ~GeV background
  should not exceed the GeV diffuse background
  (FERMI-LAT)

- naïvely kills
  (whole Universe contributes to gamma but
  a small fraction contributes to cosmic rays)

Constraints:
secondary gamma rays

evolution saves the day!
BLACK HOLES GROW FAST



Beyond this talk:

- **low-mass black holes and neutron stars:**
  possible galactic sources of UHECRs,
  may work up to extreme energies

- **nuclei:**
  may be accelerated to higher energy, but
  concentration unknown (probably low)

- **fluctuations in the population:**
  possible direction dependence

Conclusions I

- Data ⇨ high number density of CR sources
- Astrophysics ⇨ lack of source candidates that numerous
  [direct/inductive acceleration helps]
- Numerous (⇨ nearby) sources
  [need to consider a population of non-identical sources]
- Acceleration in the SMBH magnetosphere
  [a simple model seems to work well]

Conclusions II

- **We are still far from understanding UHECR sources**
- **The (direction-dependent) shape of the (GZK) suppression and (direction-dependent) composition at GZK energies should be known precisely**

- **Need for large-aperture full-sky instruments (both hemispheres or space)**

  and large-aperture arrays of muon detectors in both hemispheres…

Backup:
contributions from various redshifts