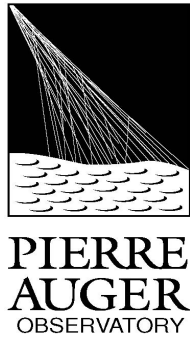
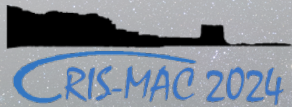


# Astrophysical interpretations of the data measured at the Pierre Auger Observatory



**Teresa Bister** for the Pierre Auger Collaboration



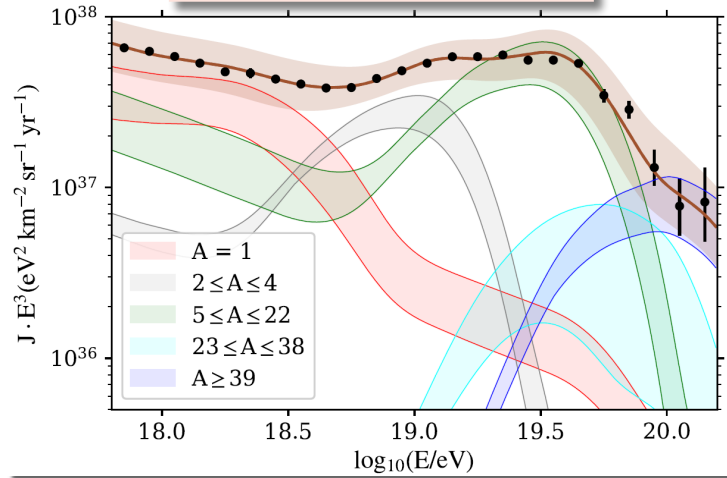
Radboud University



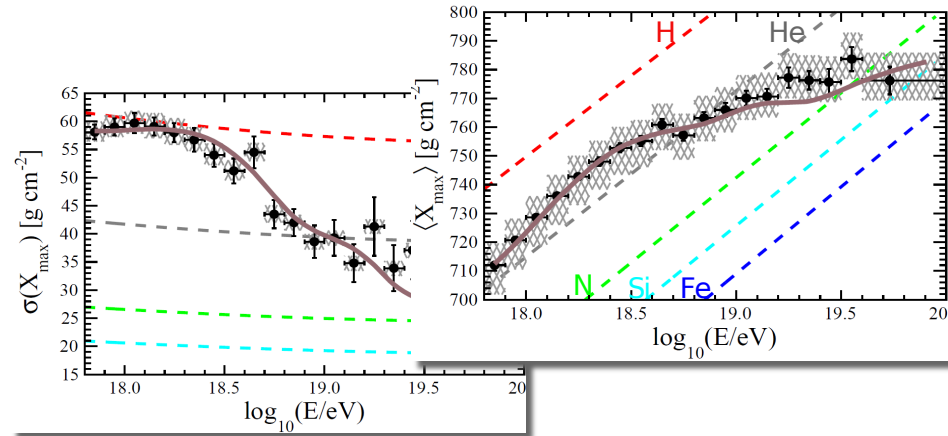
Nikhef

# Ultra-high-energy cosmic ray data and interpretation

energy spectrum



mass composition

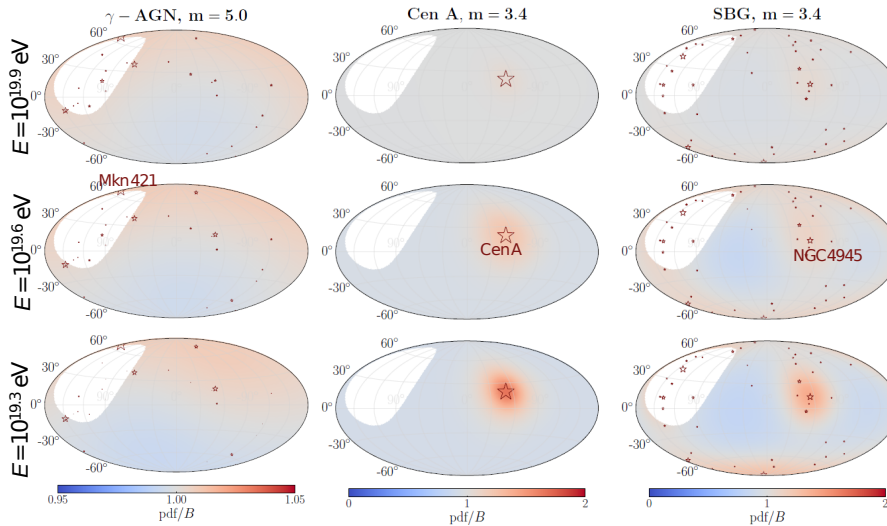


- can both be well explained by homogeneously distributed extragalactic sources!
  - need at least two populations
- can draw **conclusions about injection at the source:**
  - intermediate masses, hard spectrum (unlike shock acceleration expectation)

# Arrival directions and magnetic fields

extensions of model:

- hard spectral index could be explained by diffusion in strong **extragalactic magnetic field**
- including **arrival directions** in the fit:
- all data well described by contribution from nearby starburst galaxies → **4.5 $\sigma$  significance!**



## Astrophysical interpretations of the data measured at the Pierre Auger Observatory

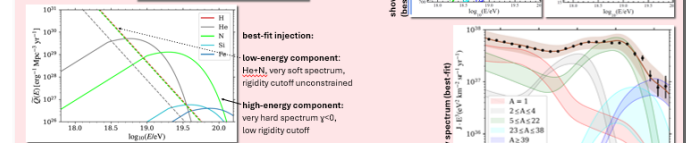
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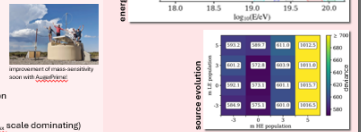
### How can we explain the ultra-high-energy cosmic ray data measured at the Pierre Auger Observatory?

- explain energy spectrum and shower depth measurements [1]:
- two extragalactic populations of identical sources
- uniform distribution, evolution:  $(1+z)^m$ ,  $m \in \{0, 3.4, 5.0\}$
- Peters cycle injection:  $\dot{Q}_i(E) = \dot{Q}_i \left(\frac{E}{E_0}\right)^{\gamma} \frac{1}{\exp(1 - \tau E/E_0)}$   $E \leq E_{cut}$ ,  $E > E_{cut}$



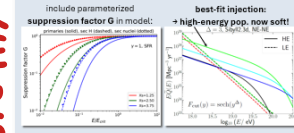
### Conclusions:

- data well described by two extragalactic populations
- ankle shaped by transition of populations
- suppression by maximum energy + propagation effects
- high-energy component with very hard injection  $\gamma < 0$
- similar goodness-of-fit also for same high-energy population
- protonic low-energy population + N-dominated Galactic population
- strong source evolution disfavored (also from neutrino fluxes [2])
- conclusions stable with respect to systematic uncertainties ( $E_{max}$  scale dominating)



### What influence could the extragalactic magnetic field have?

- extragalactic magnetic field (EGMF) can suppress lower energy particles (diffusion)
- effect could explain hard best-fit spectral index at injection
- alternative: e.g. magnetic confinement in source



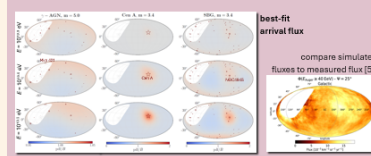
### Conclusions:

- EGMF can have strong effect on injection, but only for:
- steep injection cutoff
- & source densities  $< 10^{-9}$  / Mpc<sup>3</sup>
- & very strong magnetic field strength  $B_{100} = 10-200$  nG between Earth and closest sources
- then: can reach  $\gamma = 2$

References:  
[1] The Pierre Auger Collaboration: JCAP 09 024 (2009)  
[2] G. Patuško for the Pierre Auger Collaboration: JCAP 09 024 (2009)  
[3] The Pierre Auger Collaboration: arXiv:2003.12331v1  
[4] The Pierre Auger Collaboration: JCAP 01 022 (2004)  
[5] The Pierre Auger Collaboration: JCAP 09 024 (2009)

### What can we learn from the arrival directions?

- extension of simple model:
- nearby source candidates [5] + homogeneous background sources (as above)
- active galactic nuclei (AGN): flux weighted by  $\gamma$ -ray flux + bg with  $m=5$
- starburst galaxies (SBG): bg with  $m=3.4$  (starformation rate)
- nearby radio galaxy Centaurus A + different bps
- fit to spectrum, shower depths & energy-dependent arrival directions



### Conclusions:

- AGNs strongly disfavored
- $\gamma$ -ray flux-weighting overweights Mkn 421
- SBG model describes data very well!
- 4.5 $\sigma$  significance compared to model with only homogeneously distributed sources
- best fit  $\sim 20\%$  from SBGs at 40 EeV,  $\sim 20\%$  blurring for proton at 10 EeV
- Centaurus region well described by local source at  $\sim 4$  Mpc

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