UHECR propagation and interpretation of UHECR data

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Outline

1. Introduction
   - Ultra-high-energy cosmic rays
   - Extragalactic cosmic ray propagation
2. Uncertainties
   - Hadronic interactions → mass composition
   - Extragalactic background light spectrum and evolution
   - Intergalactic and Galactic magnetic fields
   - Disagreement between Auger and TA at highest energies
   - Various others
3. Outlook for the future

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3. Outlook for the future

Ultra-high-energy cosmic rays

- **Ultra-high-energy cosmic rays** (UHECRs):
  charged particles with energies $E \geq 1\ \text{EeV} = 10^{18}\ \text{eV} \approx 0.16\ \text{J}$
- **Their flux**: $\sim 0.3\ \text{km}^{-2}\ \text{yr}^{-1}\ \text{sr}^{-1}$ above 10 EeV,
  steeply decreasing with energy
- **Their composition**: mostly protons; most likely also some heavier nuclei at the highest energies
- **Their sources**: unknown, but most likely extragalactic

- **Main experiments**:
  Pierre Auger Observatory 3 000 km^2, Argentina (35.2° S)
  Telescope Array 700 km^2, Utah, United States (39.3° N)

Extragalactic cosmic ray propagation

- During their journey, extragalactic cosmic rays undergo:
  - Adiabatic energy loss due to the expansion of the Universe
  - Interactions with diffuse extragalactic background radiation
  - Deflections by intergalactic and Galactic magnetic fields

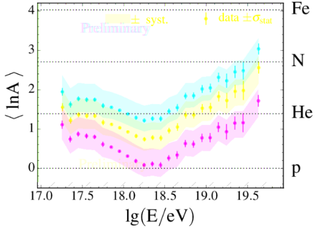
→ **Very** nontrivial to infer source properties from observations

- Various codes have been developed to simulate this:
  - *SimProp* (R. Aloisio et al., JCAP **11** (2017) 009)
  - CRPropa (R. Alves Batista et al., JCAP **05** (2016) 038)
  - TransportCR (O. Kalashev and E. Kido, JETP **120** (2015) 790)
  - HERMES (M. De Domenico, arXiv:1305.4364)

Outline

Systematic uncertainties on mass composition

- UHECR composition estimates need to rely on extrapolations of hadronic interaction models well past LHC energies, with sizeable differences even among modern models.



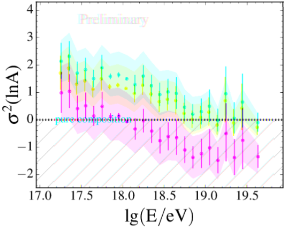
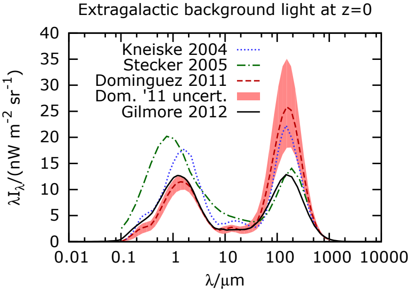


Figure: UHECR mass composition from Auger measurements as interpreted according to the EPOS-LHC, **QGSJet II-04**, and **Sibyll 2.3** hadronic interaction models (adapted from PoS (ICRC 2017) 506)

EBL spectrum and evolution

- The IR/visible/UV extragalactic background light is hard to measure (much brighter foreground: the zodiacal light)
- Factor-of-2 uncertainty in the far IR, even in modern models



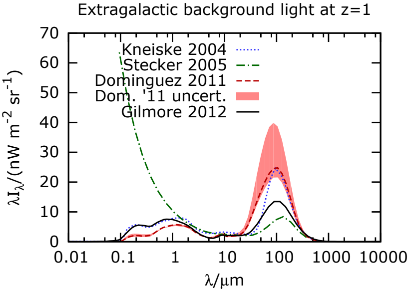


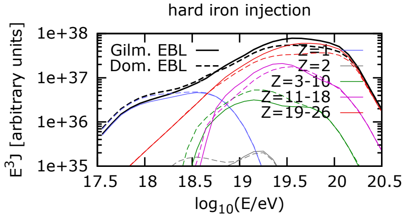
Figure: Various estimates of the EBL spectrum, from JCAP **10** (2015) 063

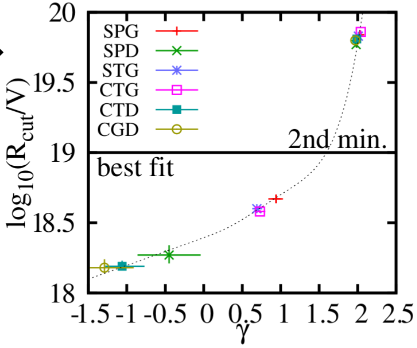
Consequences of EBL uncertainties

Brighter EBL (especially in the far infrared)
→ More photodisintegration of nuclei
→ Fewer surviving nuclei at high E, more secondary p, n at low E
→ Softer spectrum at Earth for a given injection spectrum
→ Harder injection spectrum needed to reproduce a given observed spectrum

Auger, PoS (ICRC 2015) 249 →

JCAP **10** (2015) 063 ↓





Intergalactic magnetic field

- **Huge** uncertainty in the IGMF strength → in the energy below which the propagation is diffusive (rather than ballistic, hardening the spectrum)
- Stronger IGMF → softer injection spectrum required
- E.g., in PoS (ICRC 2017) 563:

strong IGMF $\to \gamma_{\text{inj}} = 1.61$
no IGMF $\to \gamma_{\text{inj}} = 0.61$

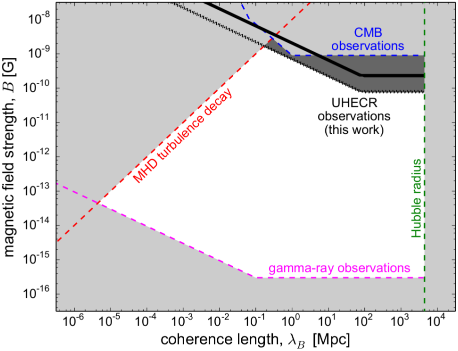


Figure: From J. Bray and A. Scaife, Astrophys. J. **861** (2018) no.1, 3

Galactic magnetic field

- The GMF cannot be measured as a function of position in 3D, only line-of-sight integrals weighed by electron densities can — and the data are very noisy. Various shapes can be assumed.

→ Large uncertainties in what extragalactic source positions would correspond to a given arrival direction at Earth

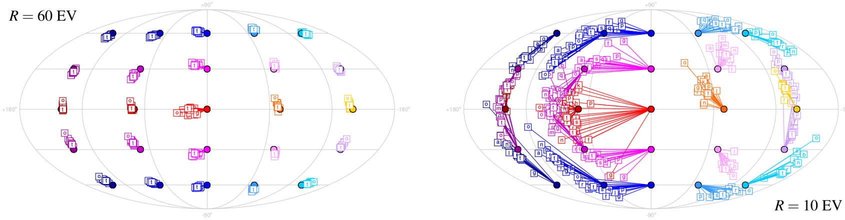
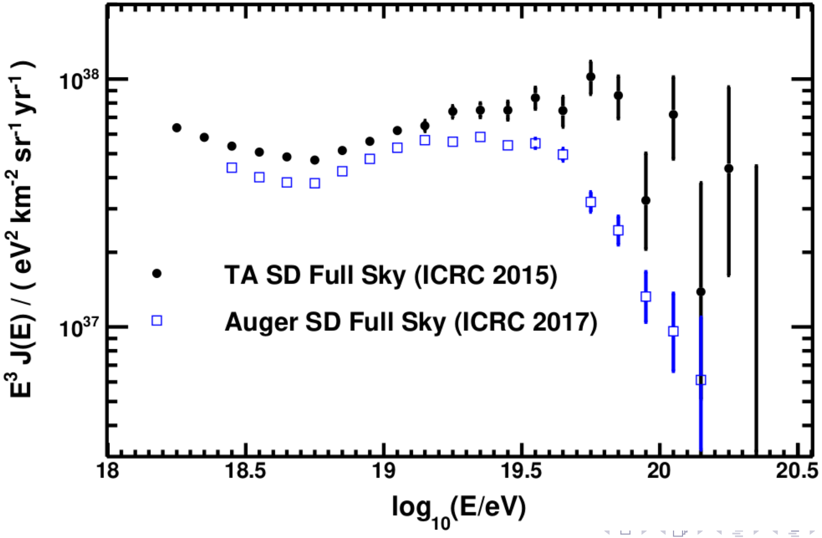


Figure: Various estimates of UHECR deflections by the GMF, from M. Unger and G. Farrar, PoS (ICRC 2017) 558

Auger and TA spectra

Note: $\sigma_{\text{syst}} = 14\%$ in Auger, 21% in TA



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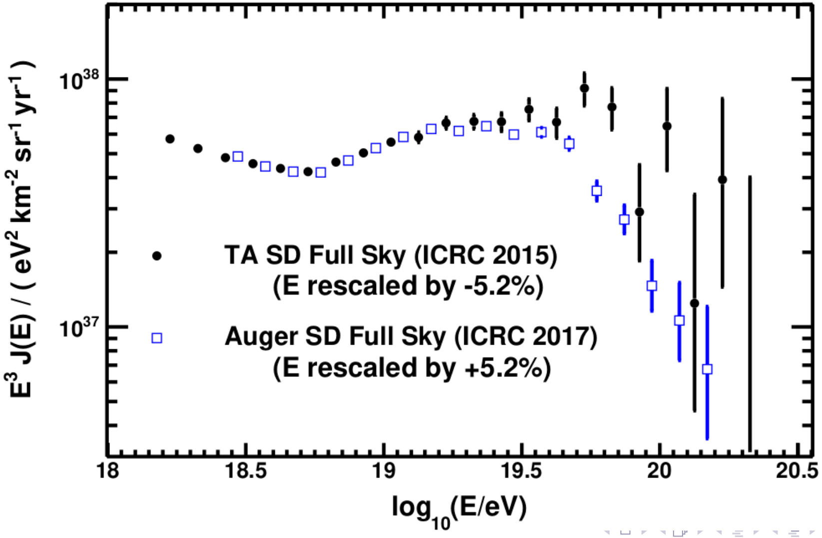
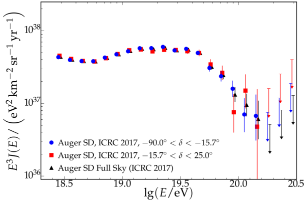
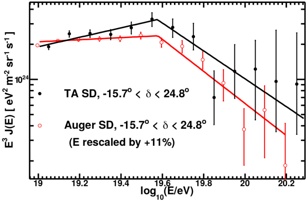
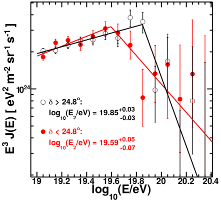


Anisotropy or instrumental effect? or both?







TA – 10%, north		
	large difference	arXiv:1801.07820
TA – 10%, equator		
	small difference?	PoS (ICRC 2017) 498
Auger, equator		
	no difference	PoS (ICRC 2017) 486
Auger, south		

- Looks like the effect is mostly real.

Other sources of uncertainty

In photodisintegration cross sections: similar effect to that of uncertainties in the EBL, but much weaker (larger cross sections → lower required γ_{inj})

In source evolution: "positive" evolution (emissivity decreases with time) → lower required γ_{inj}, and vice versa

See Pierre Auger collab., JCAP **04** (2017) 038 for an overview

Outline

Outlook for the future

- Auger–TA joint working groups → better understanding of instrumental systematics (hopefully)
- AugerPrime: plastic scintillators on Auger water Cherenkov SD stations → less model-dependent composition estimates
- TA×4: fourfold expansion of the TA SD array → Northern Hemisphere data with more statistics
- Gamma-ray measurements (e.g. CTA) → better constraints on the EBL spectrum and evolution
- Gaia, PASIPHAE: stellar parallax and polarization data → first 3D measurement of the GMF
  (see G. Magkos and V. Pavlidou, arXiv:1802.03409)
- ARIANNA, ARA, POEMMA, GRAND: UHE neutrino flux measurements → constraints on UHECR source evolution