Surprises from extragalactic propagation of UHECRs

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Cosmic Ray International Seminar
14–16 September 2015
Gallipoli, Lecce, Italy

Outline

1. Introduction
   - History of UHECR propagation studies
   - Protons or nuclei?
2. Modelling issues
   - Monte Carlo simulation codes
   - Poorly known quantities (σ_{disi} and EBL) and their effects
3. Fitting source models to the data
4. Conclusions and future directions

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Prehistory

1911 V.F. Hess discovers cosmic rays

1931 G. Lemaître proposes the Big Bang model, but most people continue to believe in the Steady State model

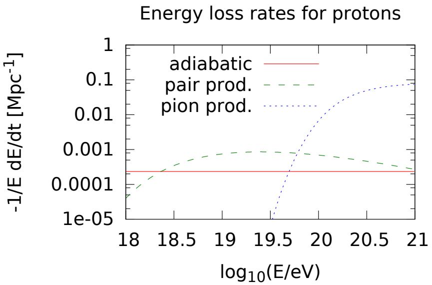
1948 R.A. Alpher and R. Herman predict the Big Bang would result in a cosmic microwave background (CMB)

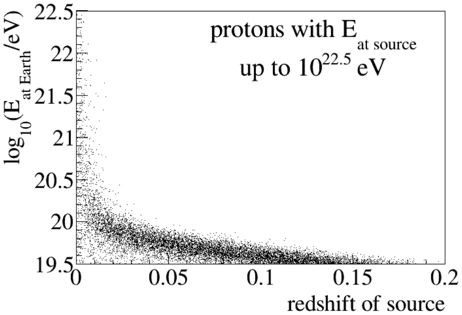
1962 Volcano Ranch detects a cosmic ray with $E > 10^{20}$ eV

Empty space is not empty: the GZK effect

1965 A.A. Penzias and R.W. Wilson accidentally discover the CMB, confirming the Big Bang model

1966 K. Greisen, G.T. Zatsepin and V.A. Kuz'min realize that $p + \gamma_{\mathrm{CMB}} \to p + \pi^0$ and $p + \gamma_{\mathrm{CMB}} \to n + \pi^+$ set a limit ($\approx 10^{20}$ eV) to the energy of protons reaching us from distant sources



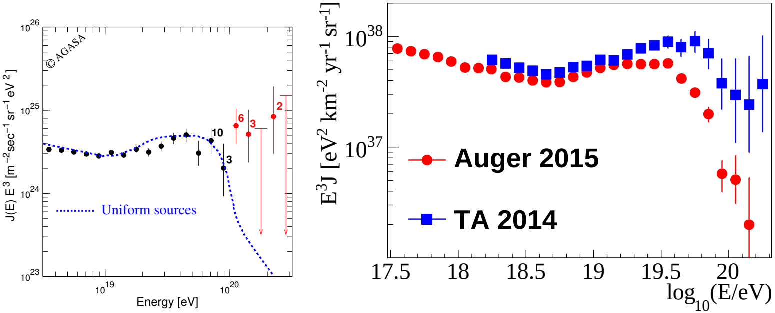


What do we see?

1998 AGASA observes a power-law spectrum of cosmic rays with no cutoff up to 2×10^{20} eV

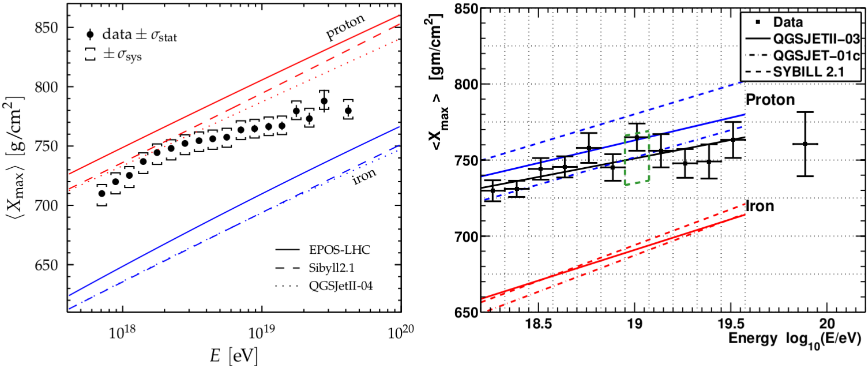
2007 HiRes and the Pierre Auger Observatory do see a high-energy suppression in the cosmic ray spectrum

Today No other experiment has confirmed the AGASA result, though Auger and Telescope Array disagree about the position of the cutoff



Protons or nuclei?

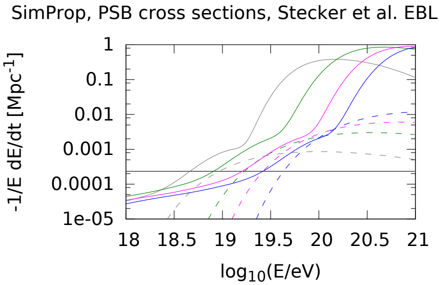
- Auger data suggest CRs between $10^{19.5}$ and 10^{20} eV mostly nuclei with $A \approx 14$ (but TA data also compatible with protons)

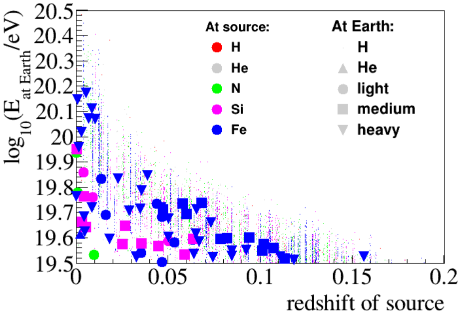


- (In the rest of this work, we will only consider Auger data.)
- This changes the possible interpretations of the observed cutoff ...

Photodisintegration and Gerazimova–Rozental' limit

- Pion production threshold A times that for protons … …but photodisintegration also possible: ${}^{A}Z + \gamma_{\text{CMB or EBL}} \to {}^{A-1}Z + \text{n}$, etc.
- Very short mean free path (especially for light nuclei)
- Secondary nucleons produced with energy E/A





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Simulations of UHECR propagation

Monte Carlo codes developed to simulate UHECR propagation, taking into account:

- Adiabatic redshift energy loss (expansion of the Universe)
- Pair production, $N + \gamma_{\text{CMB}} \to N + e^+ + e^-$
- Disintegration, ${}^{A}Z + \gamma_{\text{CMB or EBL}} \to {}^{A-1}Z + \text{n}$, etc.
- Pion production, $\text{p} + \gamma_{\text{CMB}} \to \text{p} + \pi^0$, $\text{p} + \gamma_{\text{CMB}} \to \text{n} + \pi^+$, etc.

Publicly available ones include:

- *SimProp*, `SimProp-dev@aquila.infn.it`
- CRPropa, `http://crpropa.desy.de/`

See R. Alves Batista, D. Boncioli, AdM, A. van Vliet and D. Walz, `arXiv:1508.01824` for comparisons between them.

What we know and what we don't know

Things we know reasonably well:

- The expansion of the Universe (FLRW metric)
- The CMB spectrum and evolution (blackbody with $T = (1+z)T_0$, $T_0 = (2.7255 \pm 0.0006)$ K)
- $\mathrm{p} + \gamma \to \mathrm{p} + \mathrm{e}^+ + \mathrm{e}^-$ cross sections (Bethe–Heitler formula)
- $\mathrm{p} + \gamma \to$ hadrons cross sections (lots of measurements)
- Total photodisintegration cross sections for certain nuclides

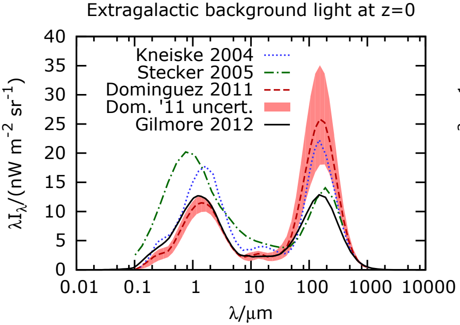
Things we know poorly or not at all:

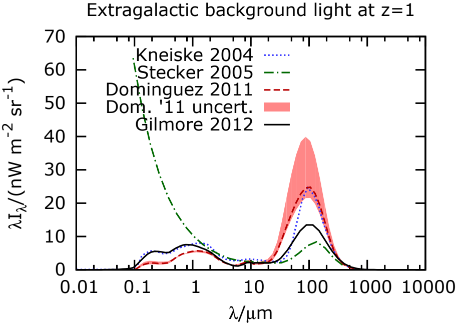
- The EBL spectrum and evolution
- Photodisintegration branching ratios
- Details of hadronic interactions in the atmosphere

The extragalactic background light

- Hard to measure, due to large foreground (the zodiacal light)
- Can be estimated from:
  - observations of galaxy populations (e.g. Domínguez+ '11)
  - semi-analytical models of galaxy formation (e.g. Gilmore+ '12)

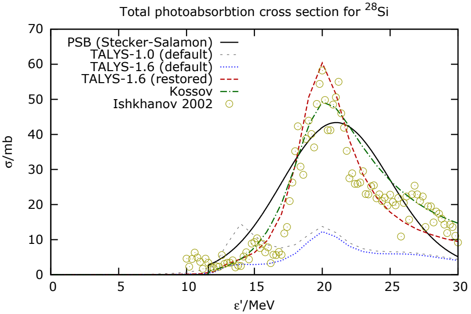
but results don't agree well, especially in the far IR and at high z





Photodisintegration cross sections: What we know

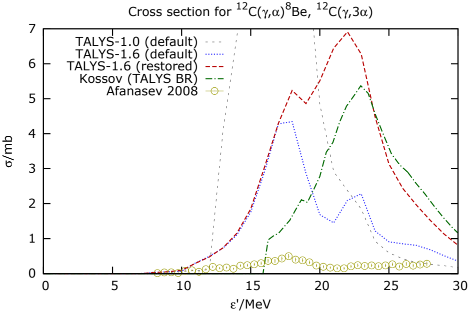
- Measurements of total cross sections available for many nuclides
- Phenomenological models in reasonable agreement with them; can be used to estimate cross sections for the other nuclides



- Exclusive channel for one-neutron ejection also easily measured

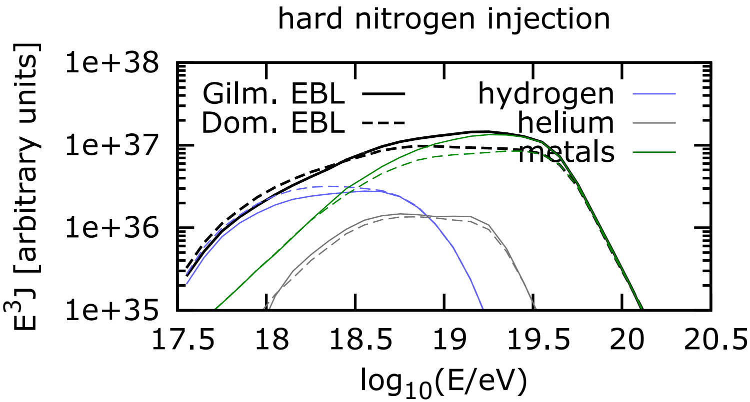
Photodis. cross sections: What we don't know

- Exclusive channels for charged ejectiles hard to measure (ejectiles multiply scattered in the target)
- Measurements available for very few such channels; phenomenological models not always compatible with them



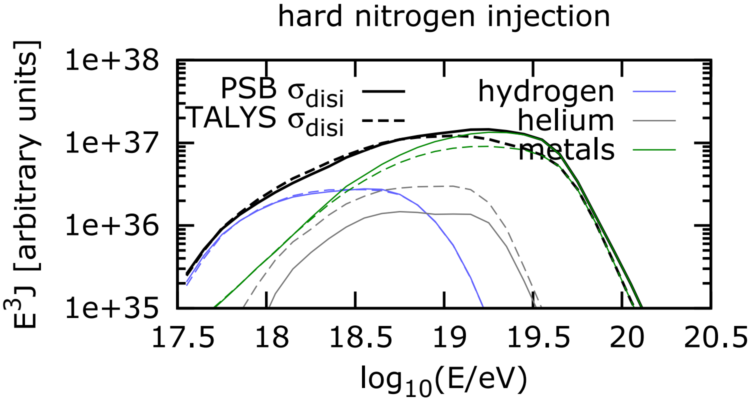
- α-particle ejection results in secondaries with $4\times$ the energy of nucleon secondaries $\rightarrow$ different effect on UHECR spectrum

Effect of different EBL models on propagated spectra



- Brighter EBL → softer spectrum at Earth, lighter composition
- See `arXiv:1508.01824` for details

Effect of different σ models on propagated spectra



- Larger $\sigma_\alpha \to$ softer spectrum at Earth, lighter composition
- See `arXiv:1508.01824` for details

Outline

Models and data

- Auger spectrum and $X_{\max}$ data fitted above $10^{18.7}$ eV (the ankle)
- Sources assumed to be identical, homogeneously distributed, injecting ^{1}H, ^{4}He, ^{14}N and ^{56}Fe with a power-law spectrum with rigidity-dependent broken exponential cutoff

$$\frac{\mathrm{d}N_{\mathrm{inj},i}}{\mathrm{d}E} = \begin{cases} J_0 p_i \left(\frac{E}{1\ \mathrm{EeV}}\right)^{-\gamma}, & E/Z_i < R_{\mathrm{cut}} \\ J_0 p_i \left(\frac{E}{1\ \mathrm{EeV}}\right)^{-\gamma} \exp\left(1 - \frac{E}{Z_i R_{\mathrm{cut}}}\right), & E/Z_i > R_{\mathrm{cut}} \end{cases}$$

- Various models for the propagation and air interactions used
- See AdM for the Auger Collab., PoS(ICRC2015)249 for details

Fit results

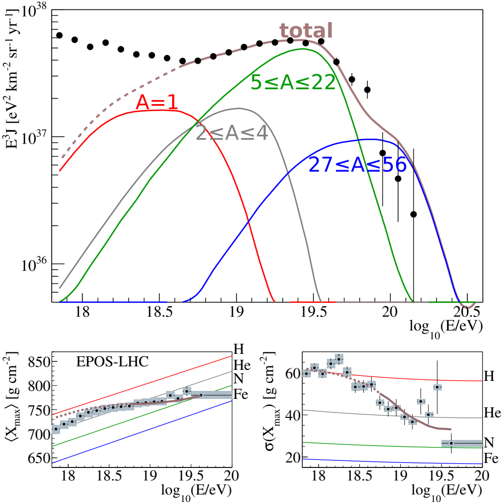
Models

- *SimProp* propagation
- PSB cross sections
- Gilmore+ '12 EBL
- EPOS-LHC air interactions

Best-fit parameters

- $\gamma = 0.94^{+0.09}_{-0.10}$
- $R_{\mathrm{cut}} = 10^{18.67 \pm 0.03}$ V
- $0.0^{+29.9}\%$ H, $62.0^{+3.5}_{-22.2}\%$ He, $37.2^{+4.2}_{-12.6}\%$ N, $0.8^{+0.2}_{-0.3}\%$ Fe

$D/n = 178.5/119$ ($p = 0.026$)



Fit results

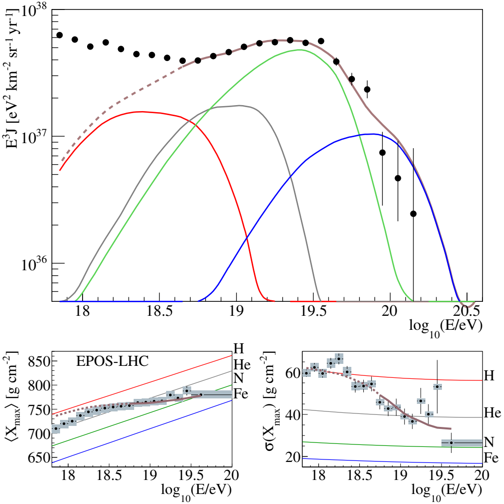
Models

- *SimProp* propagation
- TALYS cross sections
- Gilmore+ '12 EBL
- EPOS-LHC air interactions

Best-fit parameters

- $\gamma = 0.69^{+0.07}_{-0.06}$
- $R_{\mathrm{cut}} = 10^{18.60\pm0.01}$ V
- 0.00% H, 0.00% He, 98.95% N, 1.05% Fe

$D/n = 176.5/119$ ($p = 0.028$)



Fit results

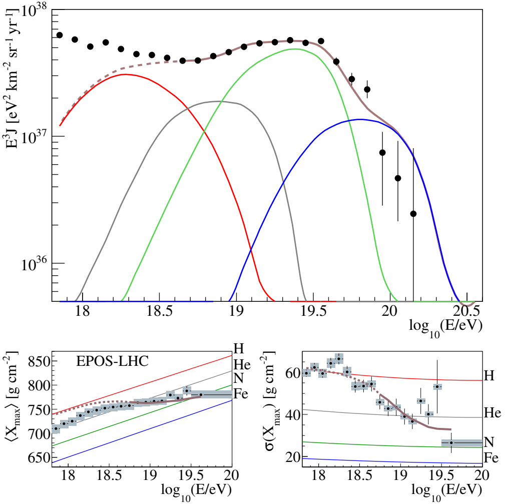
Models

- *SimProp* propagation
- PSB cross sections
- Domínguez+ '12 EBL
- EPOS-LHC air interactions

Best-fit parameters

- $\gamma = -0.45 \pm 0.41$
- $R_{\text{cut}} = 10^{18.27^{+0.07}_{-0.06}}$ V
- 76.10% H, 21.99% He, 1.91% N, 84 ppm Fe

$D/n = 193.4/119$ ($p = 0.004$)



For comparison . . .

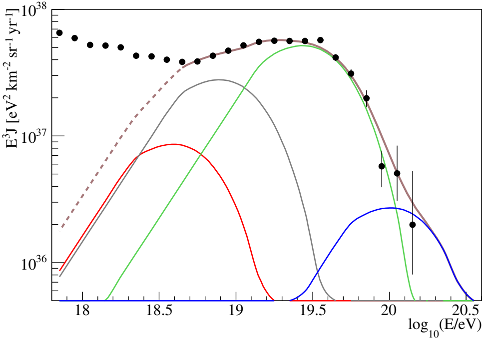
Models

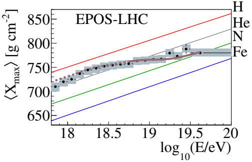
- No interactions, no energy losses in propagation
- (i.e., spectrum fitted at the top of the atmosphere)
- EPOS-LHC air interactions

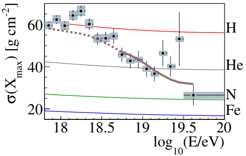
Best-fit parameters

- $\gamma = 1.15$
- $R_{\text{cut}} = 10^{18.32}$ V
- 48.48% H, 43.52% He, 7.96% N, 0.04% Fe

$D/n = 177.4/119$ ($p = 0.027$)







Differential vs integral mass fractions

Note:

- Mass fractions defined at 1 EeV
- Compositions in terms of total luminosity ($\propto p_i Z_i^{2-\gamma}$) less different

	H	He	N	Fe
PSB, Gilmore	0.0%	28.9%	65.5%	5.5%
TALYS, Gilmore	0.0%	0.0%	94.4%	5.6%
PSB, Domínguez	17.1%	27.0%	50.4%	5.5%
none	28.7%	46.4%	24.6%	0.3%

Outline

Conclusions

- Propagation strongly sensitive to poorly known details of photodisintegration and EBL
  - This was unexpected until recently – most analyses had only used one photodisintegration model and one EBL model at a time.
  - Improved photodisintegration or EBL measurements would be useful, but we aren't holding our breath.
- Auger data favour very hard, metal-rich injection spectra (especially for large σ_α and bright EBL), and dim EBL
- Data also compatible with no interactions
  - But local sources unlikely (limits on anisotropy)
  - On the other hand, no interactions predicted by some Lorentz-invariance-violating models, see Boncioli+ PoS(ICRC2015)521

Future directions

Things that still need to be done:

- What if we consider more than four possible elements at injection?
- What happens below the ankle?
  - An extra component would likely spill over above the ankle

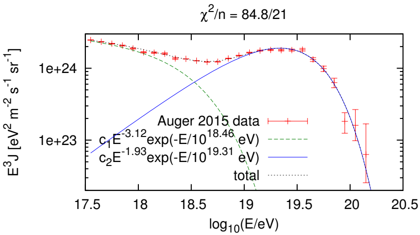


Figure: 22% of flux at $10^{18.75}$ eV from dashed component in this model

- What about non-uniform source distributions?

Outline

5 Back-up slides
- Second local minimum in the combined fit
- Effects of source cutoff shape
- Effects of air interaction models and systematics

Second local minimum results

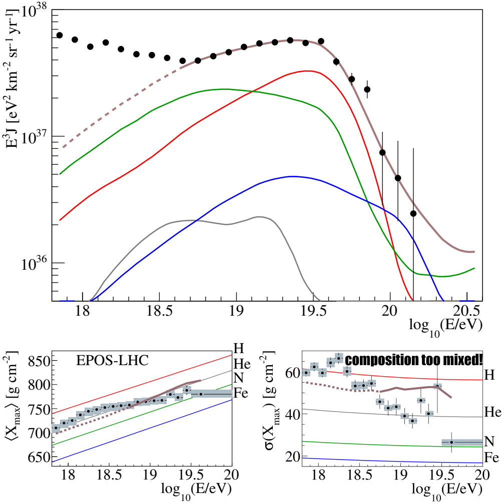
Models

- *SimProp* propagation
- PSB cross sections
- Gilmore+ ’12 EBL
- EPOS-LHC air interactions

2nd minimum parameters

- $\gamma = 2.03 \pm 0.01$
- $R_{\text{cut}} = 10^{19.84 \pm 0.02}$ V
- 0.0%, 0.0% He, 94.2% N, 5.8% Fe

$D/n = 235.5/119$ ($p = 5 \times 10^{-4}$)



Effects of source cutoff shape

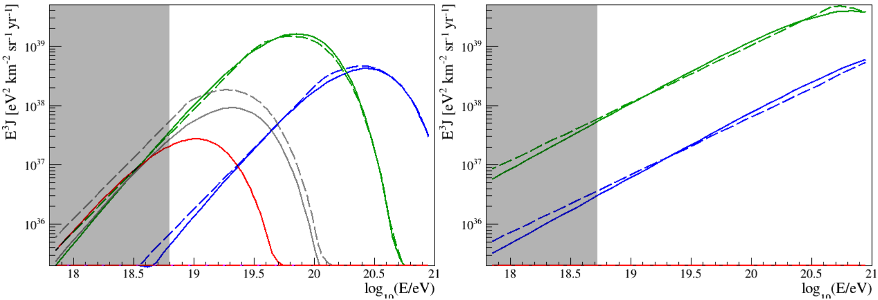


Figure: best fit (left), 2nd min (right), broken exp (dashed), simple exp (solid)

cutoff	best fit γ	best fit R_{cut}/V	best fit D_{min}	2nd min γ	2nd min R_{cut}/V	2nd min D_{min}
broken exp	$0.94^{+0.09}_{-0.10}$	$10^{18.67\pm0.03}$	178.5	2.03	$10^{19.84}$	235.0
simple exp	$0.53^{+0.21}_{-0.18}$	$10^{18.63^{+0.09}_{-0.06}}$	177.2	1.89	$10^{19.94}$	221.0

Effects of air interaction models and systematics