Unmasking the ultrahigh energy cosmic ray origin

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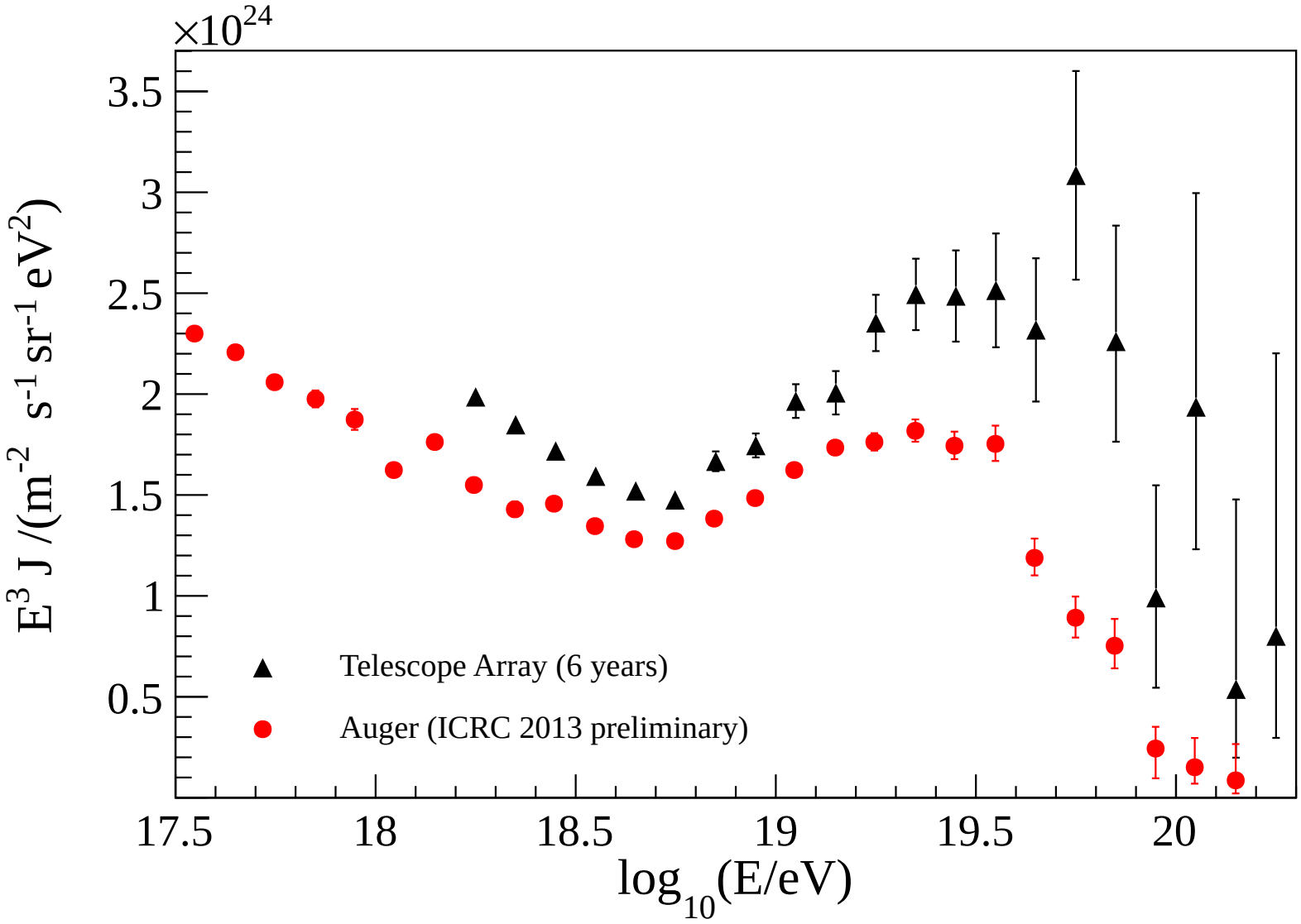
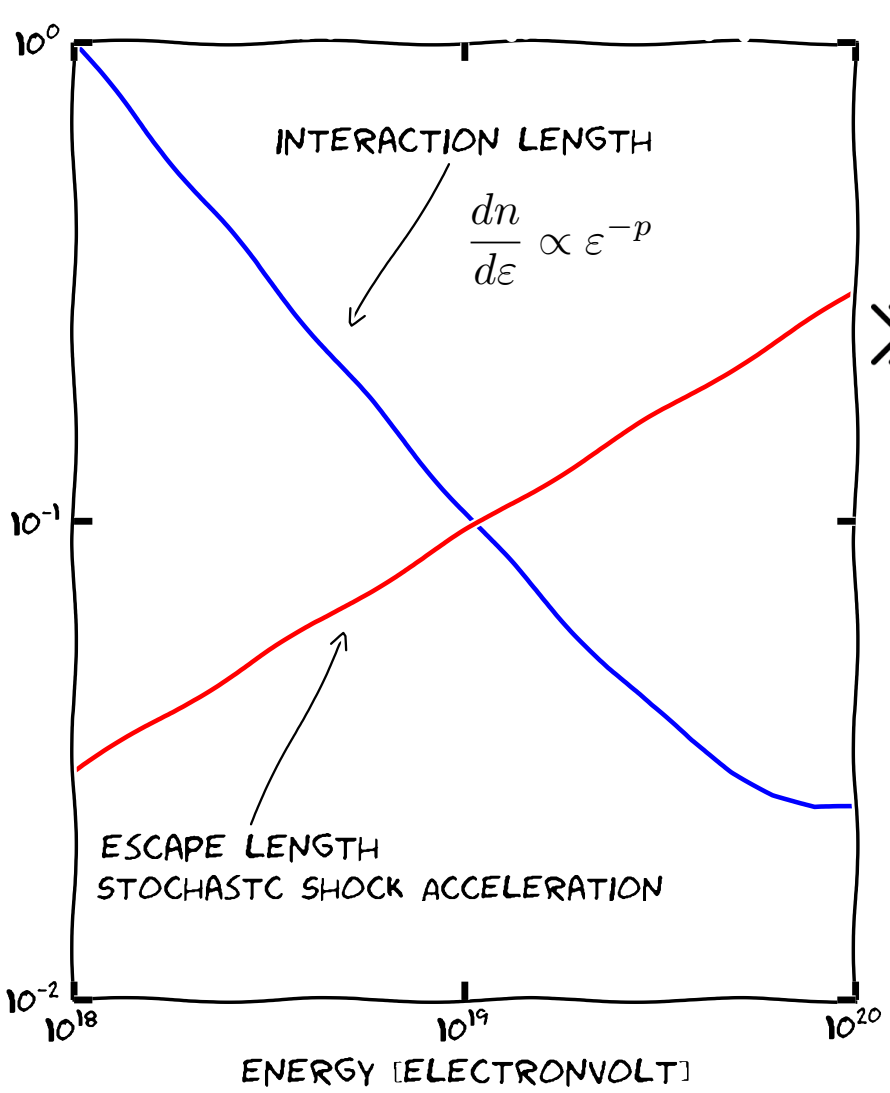
High energy end of CR spectrum

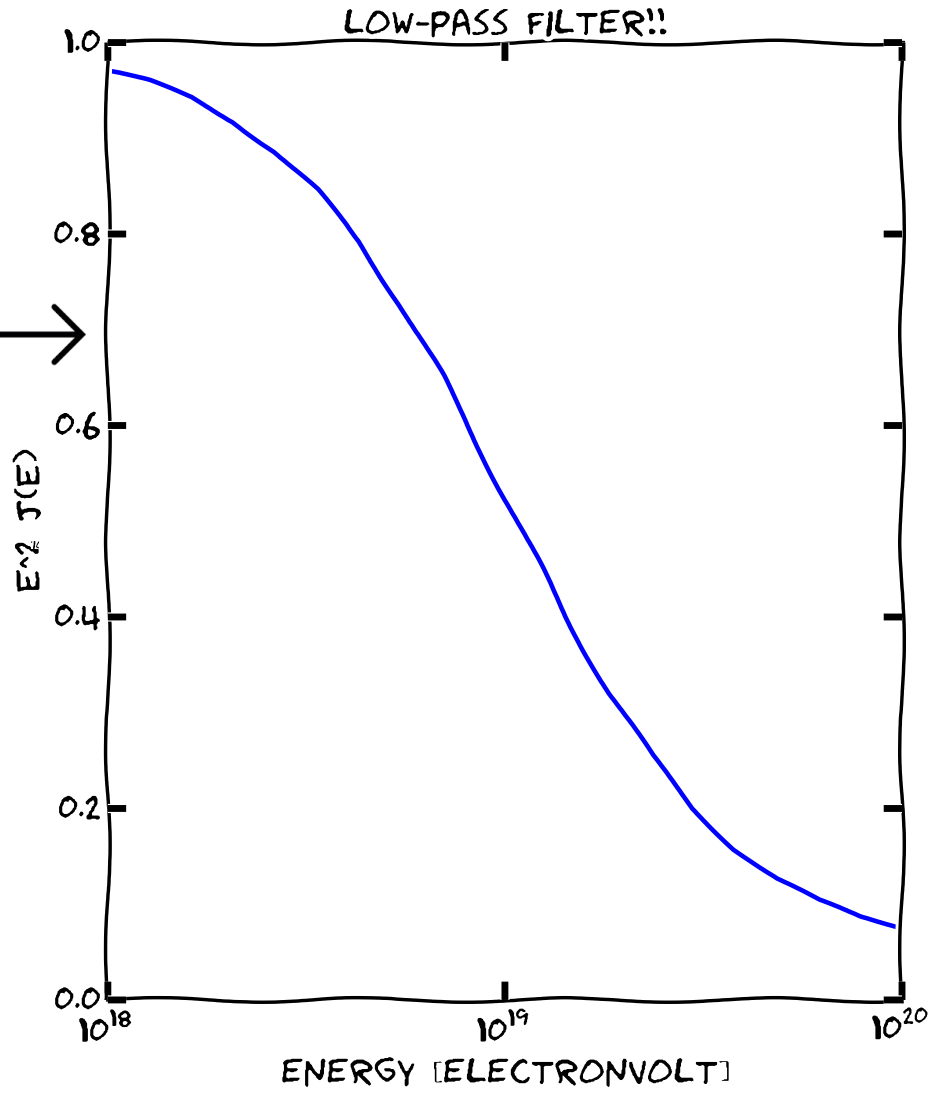


UHECR conundrum

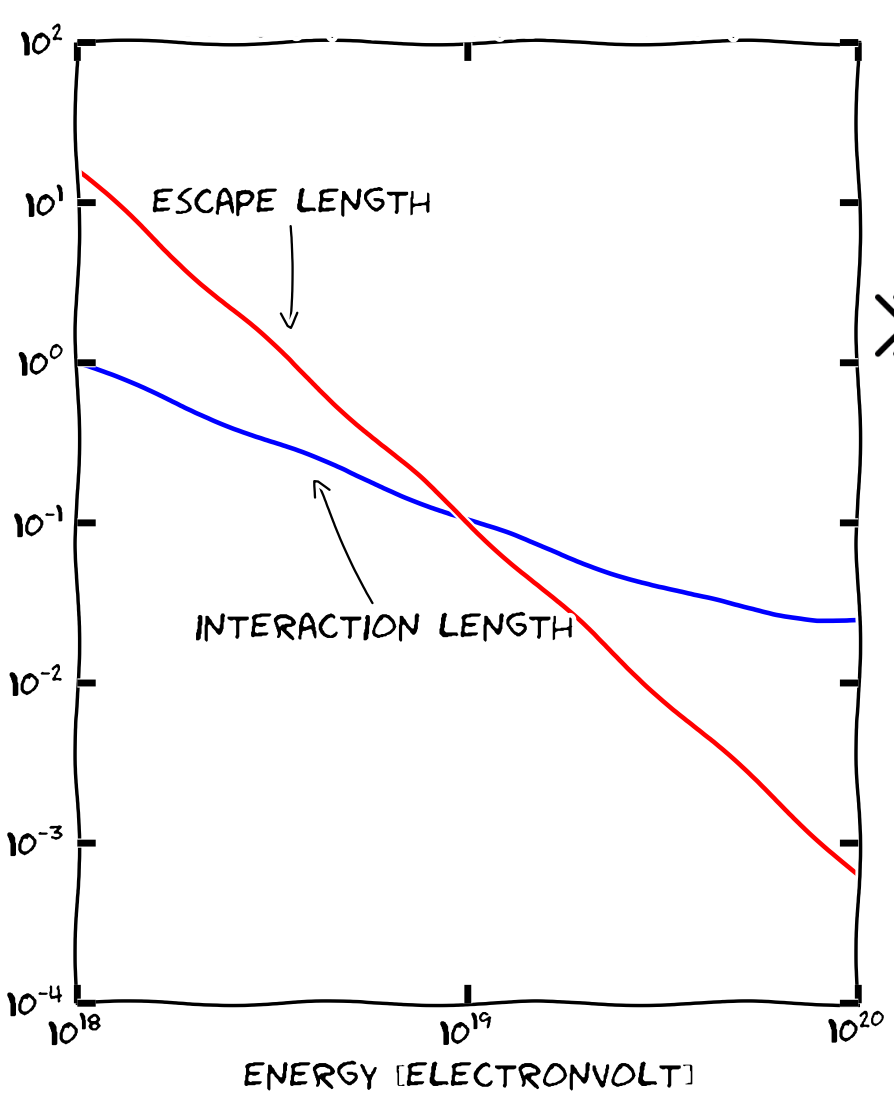
1. Ankle shape readily produced by superposition of two power-laws
   Natural candidate: transition between GCRs and EGCRs
   - Original models ☞ transition from Galactic ^{56}Fe to EG protons
     (Bird+,1993)
   - Recent models ☞ transition from G ^{56}Fe to EG heavies
     (Allard-Olinto-Parizot,2007)
2. Ankle feature also naturally arises as dip in spectrum
   from e^+e^- energy loss of EG protons propagating in CMB
   (Berezinsky-Gazizov-Grigorieva,2002)
3. Auger data ☞ light but EG component near and below ankle
   + intermediate/heavy composition above
   (Auger Collaboration,2014,2016,2017)
4. Possible solution ☞ fit Auger spectrum and composition
   at price of adding an *ad hoc* light EG component below ankle
   with a steep injection spectrum $\propto E^{-2.7}$
   (Aloisio-Berezinsky-Blasi,2014)

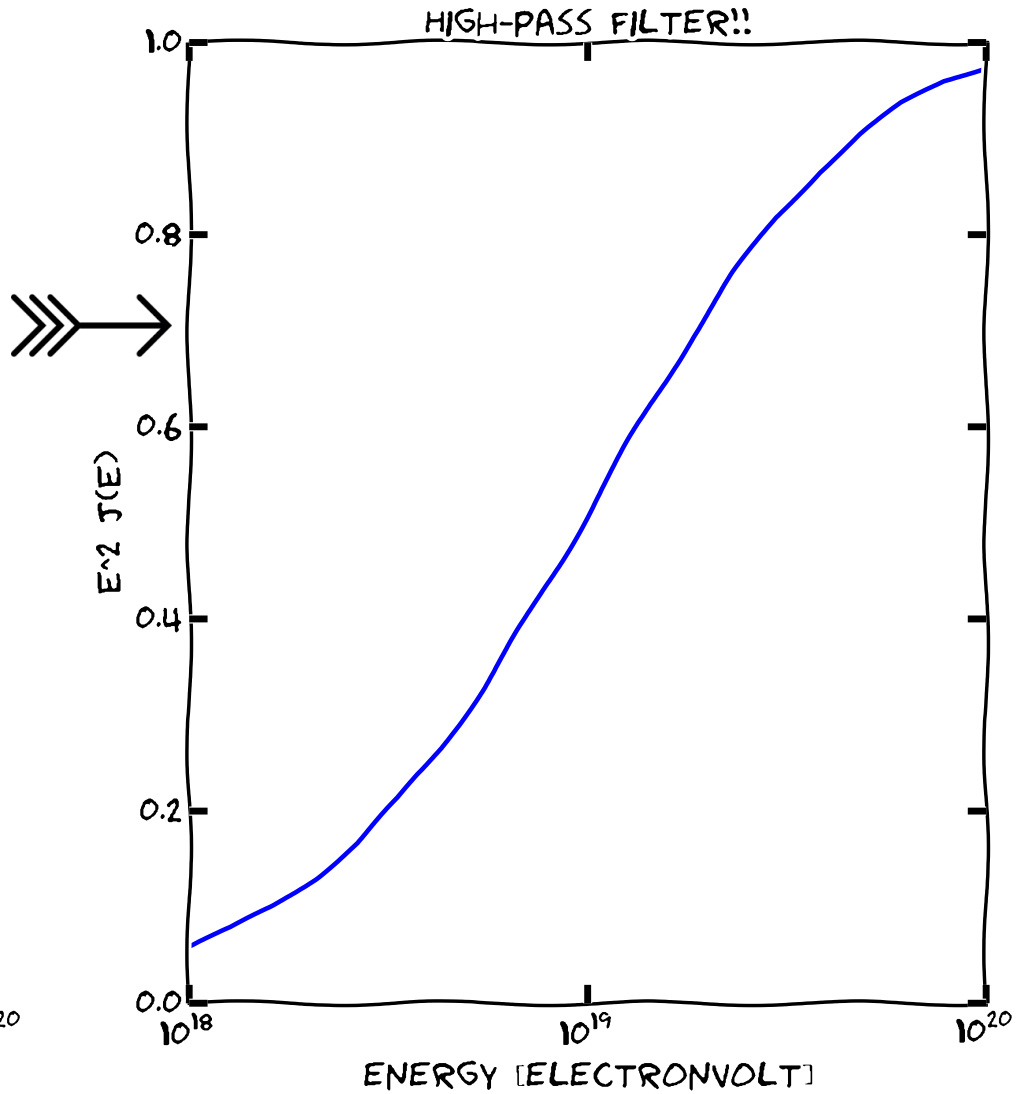
Photo-nuclear interactions during acceleration



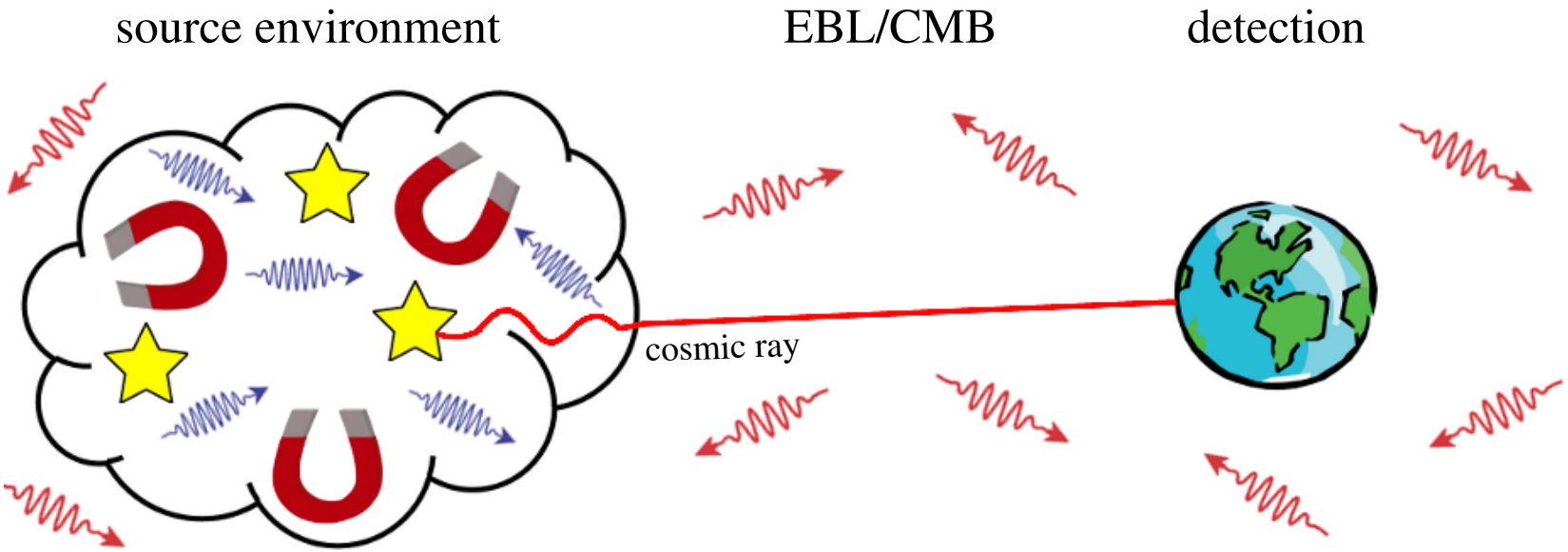


Alternative viewpoint: photodisintegration after acceleration





Our model: Photodisintegration in medium outside the accelerator



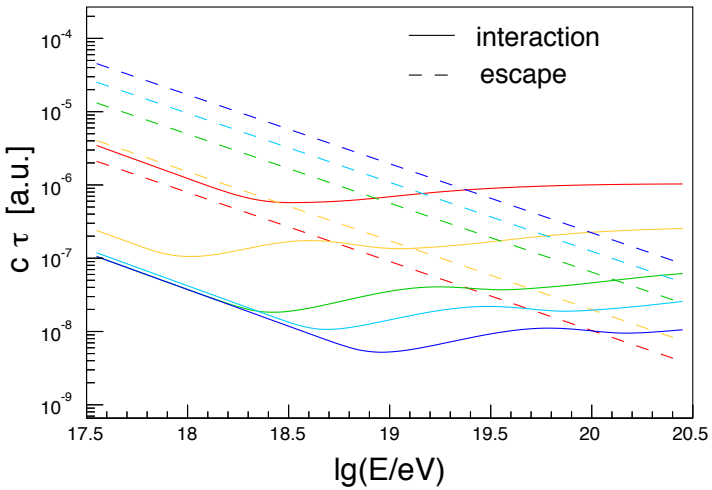
- All nuclei below energy filter interact
  scattering off far-infrared photons source environment
- photonuclear interactions produce steep spectrum nucleons
  overtaken by harder spectrum of surviving nucleus @ $E \sim 10^{9.6}$ GeV
- These overlapping spectra
  could carve ankle-like feature into source emission spectrum

(Unger-Farrar-LAA,2015)

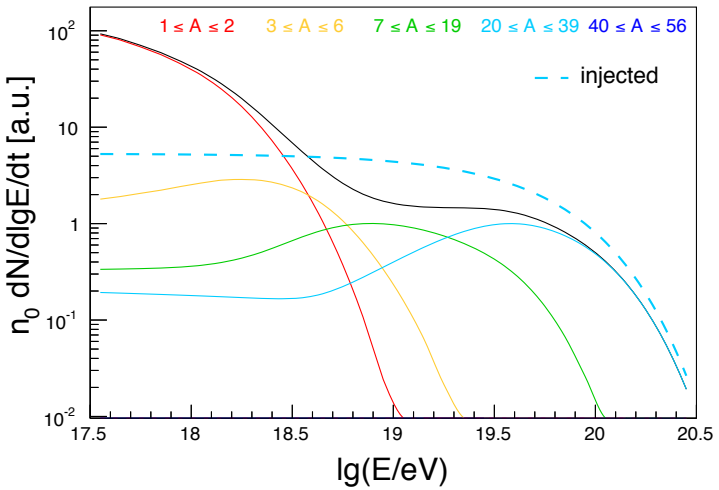
Model Parameters

- injection spectrum $\propto E^{-\gamma}$
- nucleus baryon number: A
- UHECR power density: $\dot{\epsilon}$
- source evolution with z ☞ SFR
- interaction/escape time: $R_{19}^{\rm Fe}$
- maximum energy: $E_{\rm p}^{\rm max}$

Impact of source environment depends on photon field ☞ example



$\tau_{\rm int}$ and $\tau_{\rm esc}$



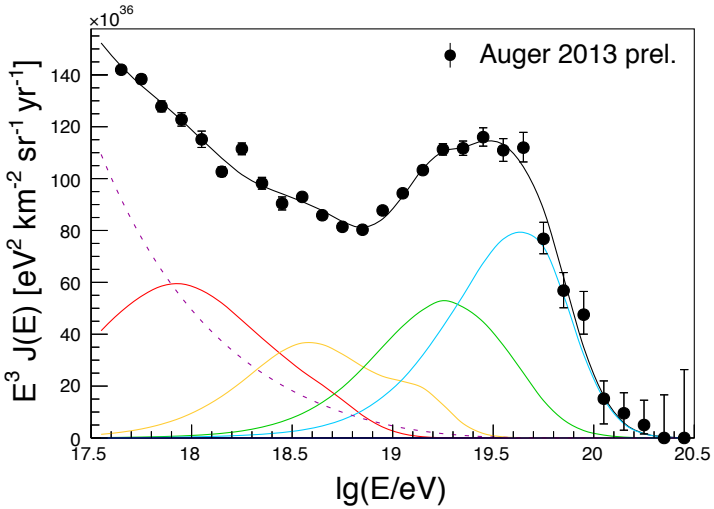
Injected and escaping fluxes

(Unger-Farrar-LAA, 2015)

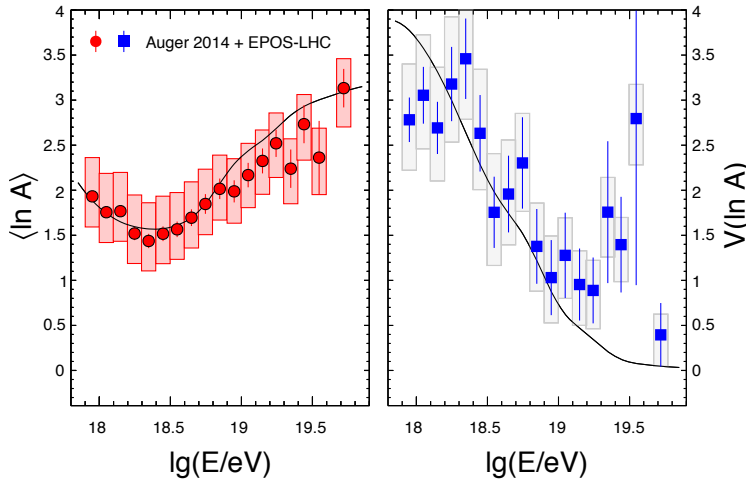
Example fit ☞ Auger data

- injection spectrum $\propto E^{-1}$
- $A = 29$
- $\dot{\epsilon} = 1.3 \times 10^{45}$ erg Mpc^{-3}yr^{-1}
- source evolution with z ☞ SFR
- $R_{19}^{\rm Fe} = 3.7 \times 10^2$
- $E_{\rm p}^{\rm max} = 10^{9.6}$ GeV

Systematic sensitivity (spectrum $1\sigma \uparrow$ and $\langle X_{\rm max}\rangle$ $1\sigma \downarrow$)



Flux at Earth



Composition at Earth

(Unger-Farrar-LAA,2015)

Galaxies with bursts of massive star formation

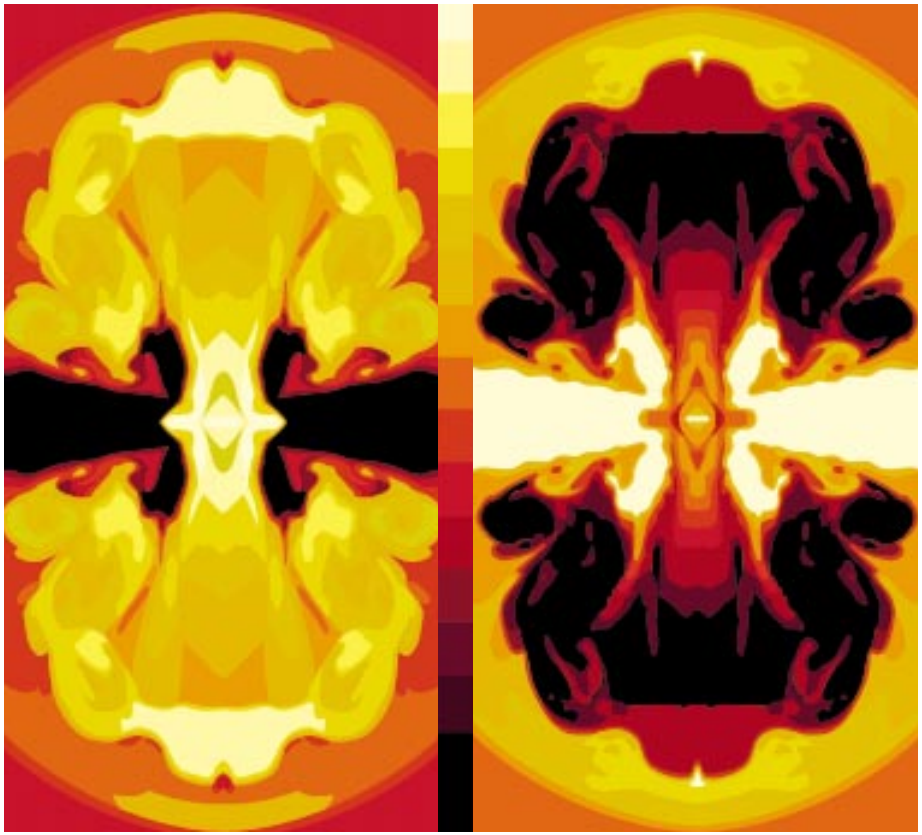
Telescopic snapshot of M82

Figure courtesy of Leonardo Orazi

Starburst features

- High supernovae rate ☞ $0.1\ \mathrm{yr}^{-1}$
- Strong IR emission by dust
- Strong UV spectra from Lyman-α emission of hot OB stars
- collective effect of supernovae and winds from massive stars lead to galactic-scale superwind
- High SN rate forms hot gas cavity with $t_{\mathrm{cooling}} \gg t_{\mathrm{expansion}}$
- Cavity quickly expands producing strong shock on contact surface with cool interstellar medium
- Dust contained in clouds is revealed as it reddens starlight

UHECR acceleration ☞ two step process



Temperature map ☞ bright = hot (left)

Gas density map ☞ bright = dense (right)

Figure courtesy of Gerald Cecil

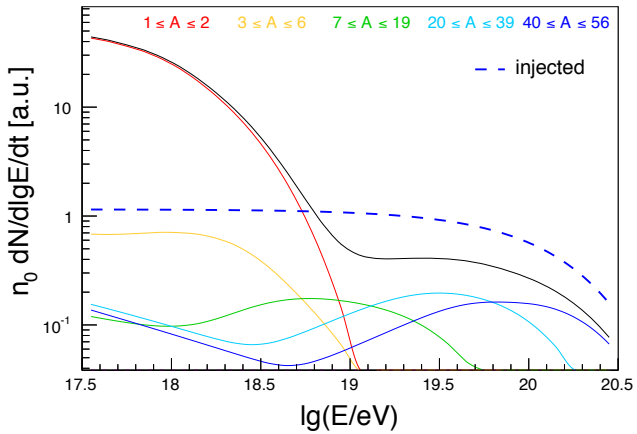
- CR acceleration: prevalence of supernovae starbursts should posses large neutron star density
- Unipolar induction: hard spectrum $\propto E^{-1}$

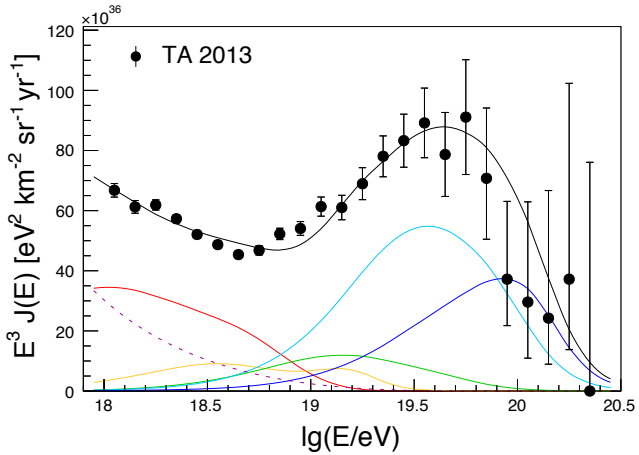
  (Blasi-Epstein-Olinto,2000)
- Galactic-scale superwind: low gas density far- and mid-IR γ's
- Pulsars ☞ central engine superwind high-pass filter
- CR re-acceleration: superwind terminal shock
- More involved model relaxes constraint on A

(LAA-Romero-Combi,1999 & LAA-Barger-Weiler,2017)

Take home message

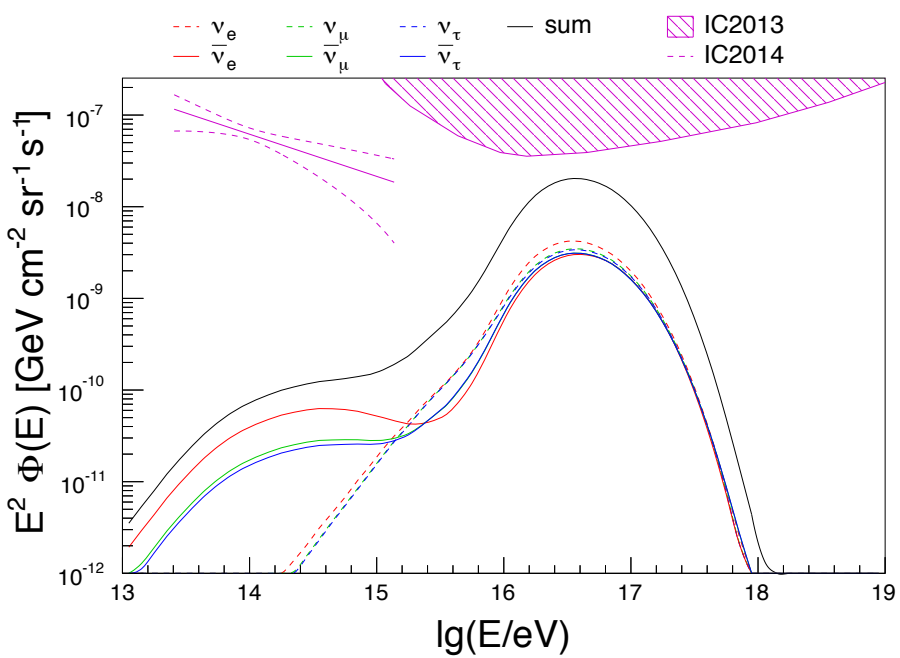
- Ankle and light extragalactic CRs below it, can be explained by photodisintegration of UHECRs *in region surrounding accelerator*
  - Auger composition *and* spectrum explained within systematics
  - What about TA data?
    If flux cutoff is at higher energies ☞ as suggested by TA data
    larger fraction ^{56}Fe at source can be incorporated



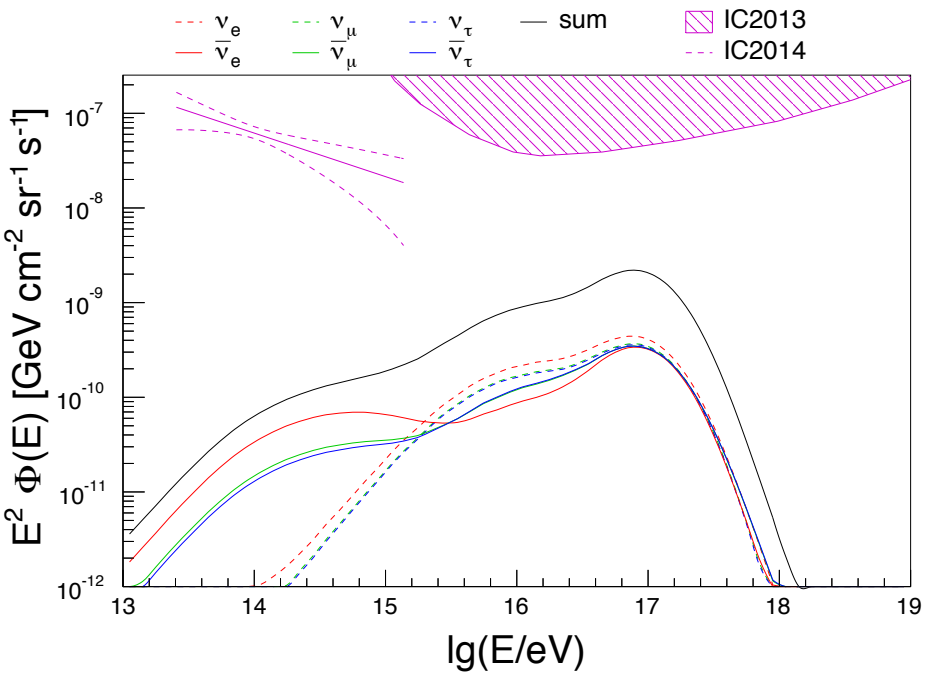


- Astrophysical realizations: Starbursts ☞ ideal working example
- New AugerPrime and POEMMA data ☞ ultimate test of model

Multimessenger astrophysics: ν's



ν-signal for example in slide 9



ν-signal$_{\rm min}$ allowed by model

(Unger-Farrar-LAA,2015)