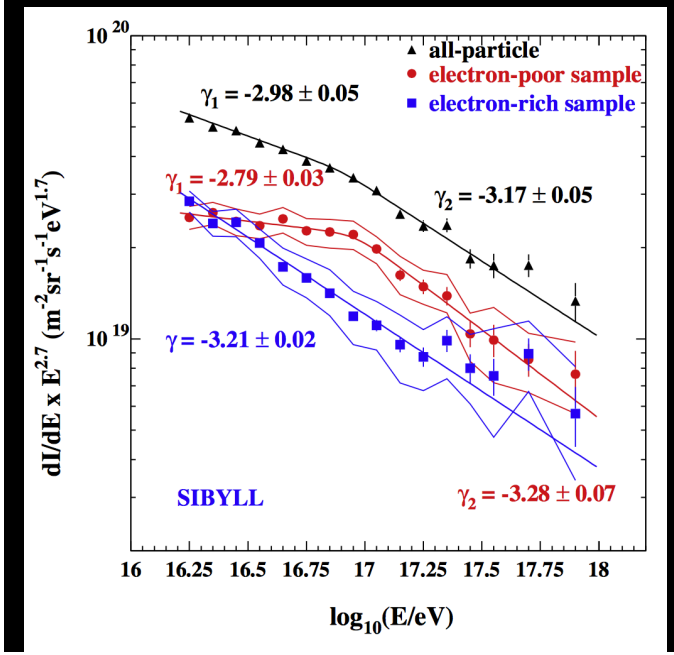
Origin of the Ankle and the protons below

Michael Unger (KIT,NYU), Luis Anchordoqui (Lehman)
Glennys Farrar (NYU)

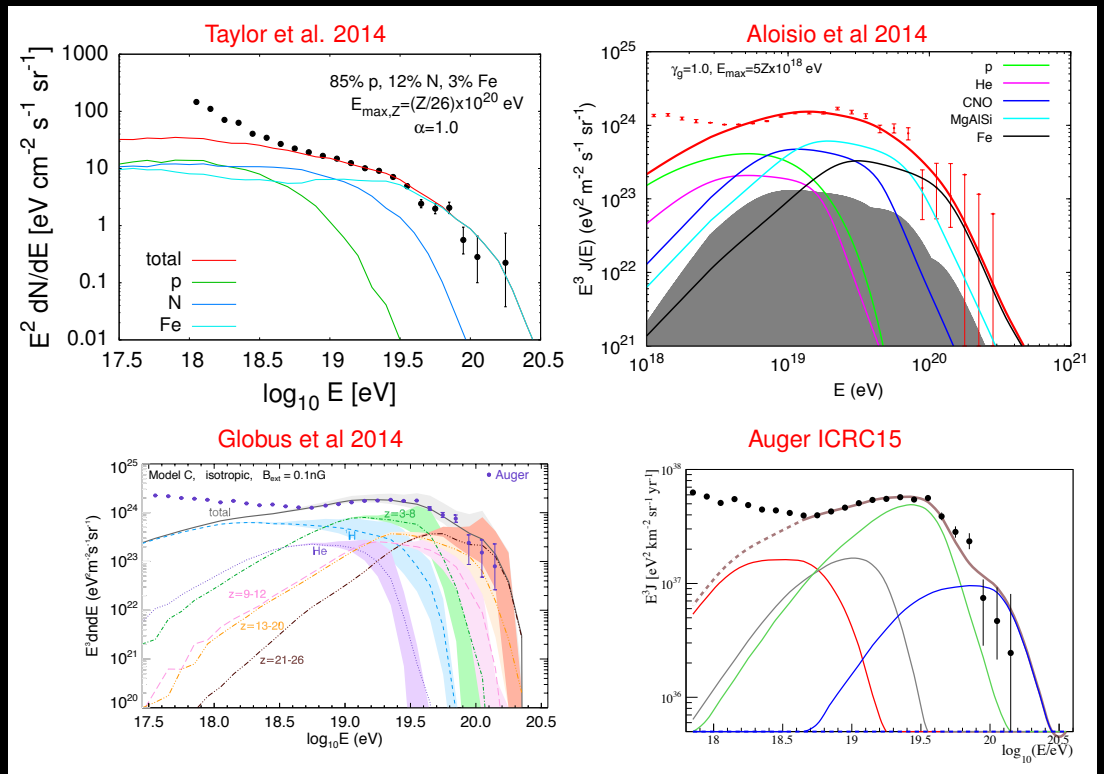
M. Unger, GRF, L. Anchordoqui arXiv:1505.02153 (UFA)

Problem: What fills the gap between Galactic and EGCRs?

Kaskade-Grande: Heavy Galactic component breaks at ~ 10^{17} eV



UHECR fits: shortfall below ~ $10^{18.5}$ eV



Is there a ***natural*** explanation for the **ankle,** and the **light extragalactic** CRs **below**?

(apart from the dip model)

Natural means:

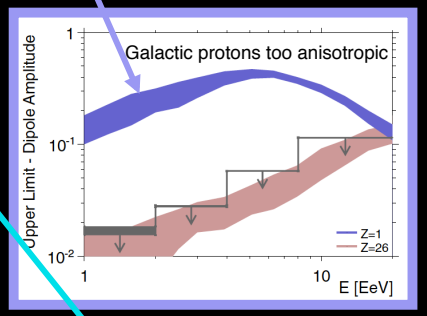
- **Position is predicted** (c.f., dip model)
- **Composition makes sense**

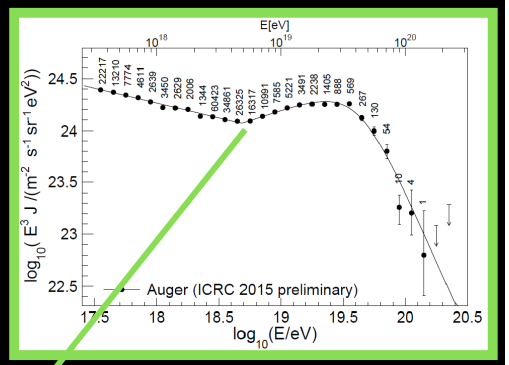
(If its a new component, why isn't it heavy at its hi-E end, like the Galactic and UHE components?)

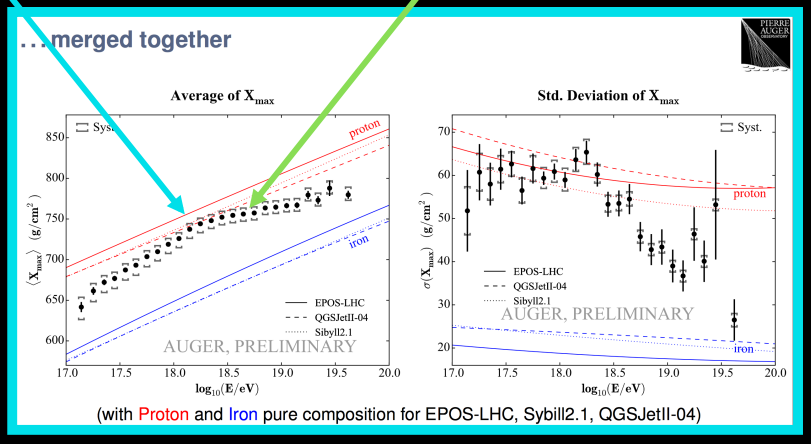
- **Shape of spectrum is right**

If there is no natural explanation, maybe new physics in hadronic interactions is fooling us, and the composition is really pure proton.

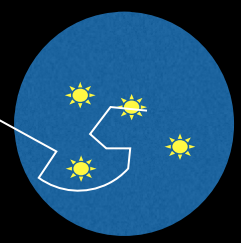
Then spectrum & composition would be natural, and some astrophysicist would be happier.







UFA proposal: Extragalactic CRs below the ankle are protons from the spallation of UHECRs by photo-disintegration.



Accelerator: Spectral index and composition of UHECRs escaping accelerator.

Inevitable consequences of UFA mechanism:

- EG composition below the ankle is pure **proton**.
- Position of the ankle is fixed.
- Anti-ν_e spectrum fixed (and large).

Spectrum & composition of UHECRs above the ankle:

- Processing depends on t_{esc} / t_{int}, and its energy dependence.
- => UHECR data constrains crucial features of the environment: Properties of the radiation field, size of the PD region relative to R_L , …
- spectrum & composition: A SMOKING GUN FOR SOURCEs?!

UFA proposal: Extragalactic CRs below the ankle are protons from the spallation of UHECRs by photo-disintegration.

Attractive candidate – young NS or magnetar:

- Blasi, Epstein, Olinto, Arons,…
  - ✓ Spectral index ~ -1
  - Detailed studies +Fang, Kotera, …
- Found primarily in regions of high star formation. (Produced by collapse of massive stars which evolve quickly.)
- ULIRGs (ultraluminous IR galaxies)
  - very common in the past
  - local example Arp 220 is very well studied: several SNe/yr.
  - Environmental conditions of Star Forming Regions is quite universal (dust, temperature from OB stars,…)

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Technicalities

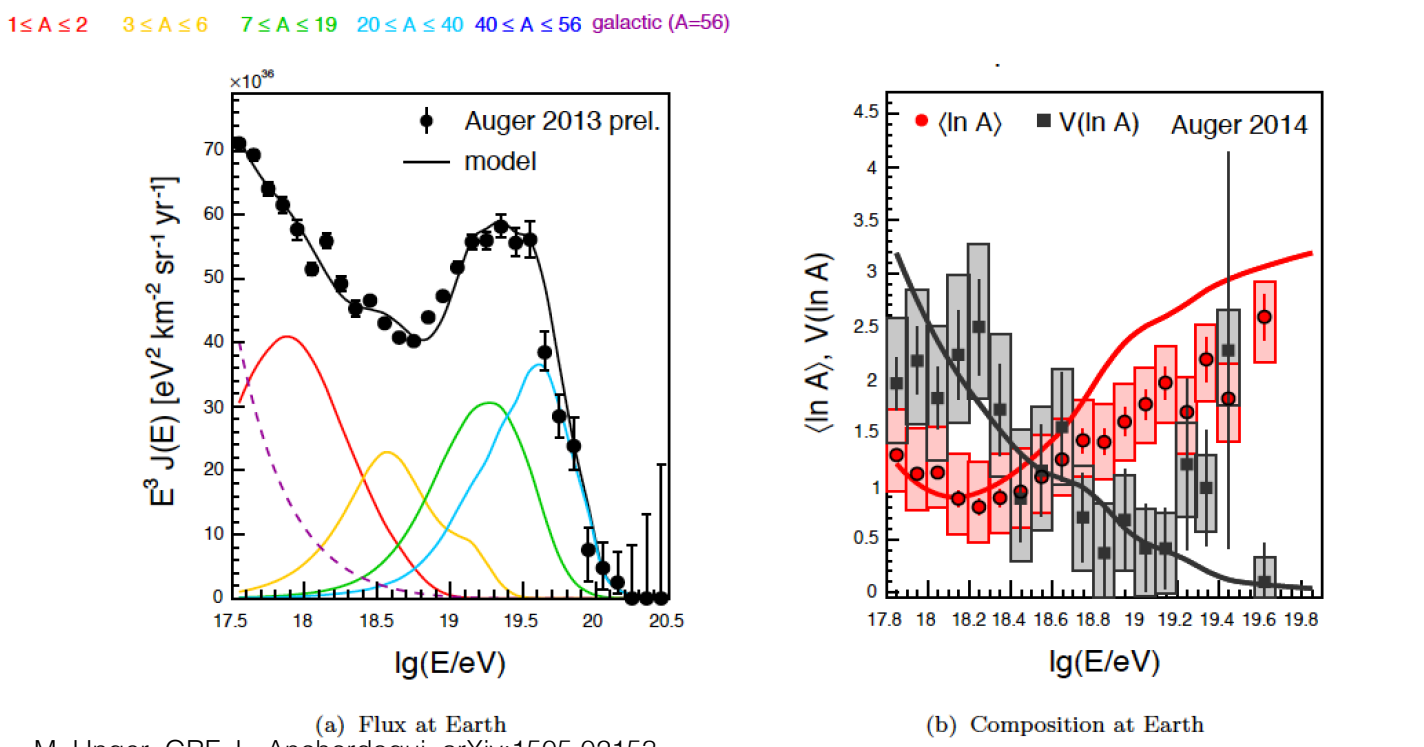
- Generic leaky box model for CR propagation in source environment after injection from accelerator:
  - Allows efficient treatment of propagation/spallation – essential for exploring parameter space.
  - $t_{esc} \sim E^{\delta}$ (generally insensitive in range $-1 \leq \delta \leq -1/3$)
  - t_{int} calculated from CRPropa with TALYS for 4 radiation fields
    - peak photon energy ε_0 is key parameter.
- Accelerator:
  - Power law E^{γ}
  - Spectrum depends on rigidity: $E_{A,max} = Z\, E_{p,max}$
- Propagate to Earth with CRPropa
  - Tried several different EBL models; makes little difference (when using lastest models).

"Fiducial Model"

source parameters			
power law index of injected nuclei	γ	fix	-1
mass number of injected nuclei	A'	free	28
maximum energy	$E^p_{\max}$	free	$10^{18.5}$ eV
cosmic ray power density, $E > 10^{17.5}$ eV	$\dot{\epsilon}_{17.5}$	free	$8.2 \times 10^{44}\ \frac{\mathrm{erg}}{\mathrm{Mpc}^3\,\mathrm{yr}}$
evolution	$\xi(z(t))$	fix	star formation rate [37]
source environment			
energy of maximum of photon field density	ε_0	fix	50 meV
power law index of photon spectrum ($\varepsilon < \varepsilon_0$)	α	fix	$+\frac{5}{2}$
power law index of photon spectrum ($\varepsilon \geqslant \varepsilon_0$)	β	fix	-2
power law of escape length	δ	fix	-1
ratio of interaction and escape time	R^{Fe}_{19}	free	275
propagation to Earth			
infra-red photon background	–	fix	Kneiske04 [36]
spectrum of Galactic cosmic rays			
power law index at Earth	γ_{gal}	free	-4.2
mass number of Galactic nuclei	A_{gal}	fix	56
flux fraction at $10^{17.5}$ eV	f_{gal}	free	56%

TABLE I: Parameters of the fiducial model.

Mechanism works!



(a) Flux at Earth

(b) Composition at Earth

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Fiducial Model

$dN/dE \sim E^{-1}$

$dn_\gamma \sim (\varepsilon/\varepsilon_0)^{5/2,-2}$

$\varepsilon_0 = 50$ meV

($T_{bb} \sim 200$ K)

evolution: SFR

Single A_{inj}

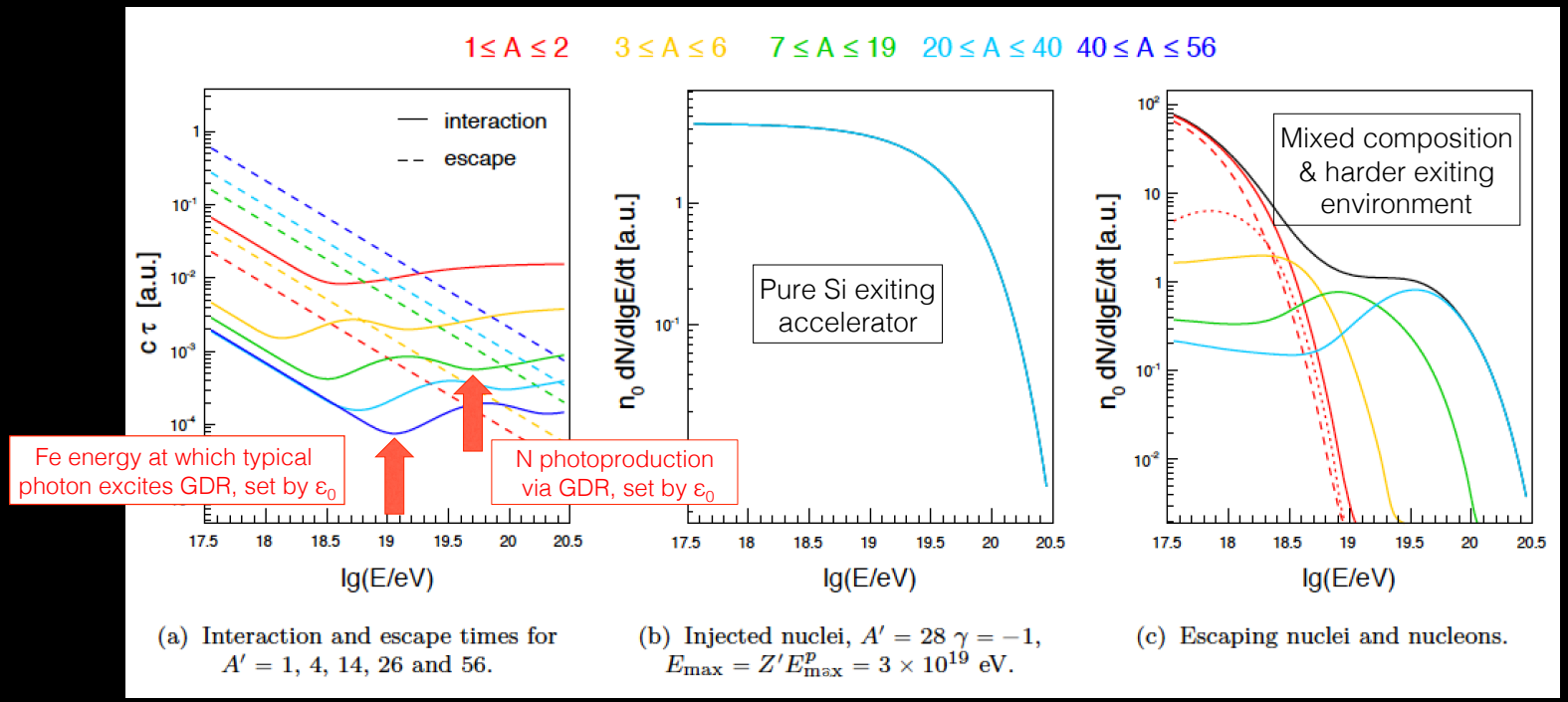
Fitted for:

A_{inj} , $E_{p,max}$

R_{19}: (t_{esc}/t_{int}) for Fe at 10^{19} eV

How does it work?

What features are poorly/well constrained?
Sensitivity to spectral index, temperature, pure initial composition?



(a) Interaction and escape times for $A' = 1, 4, 14, 26$ and 56.

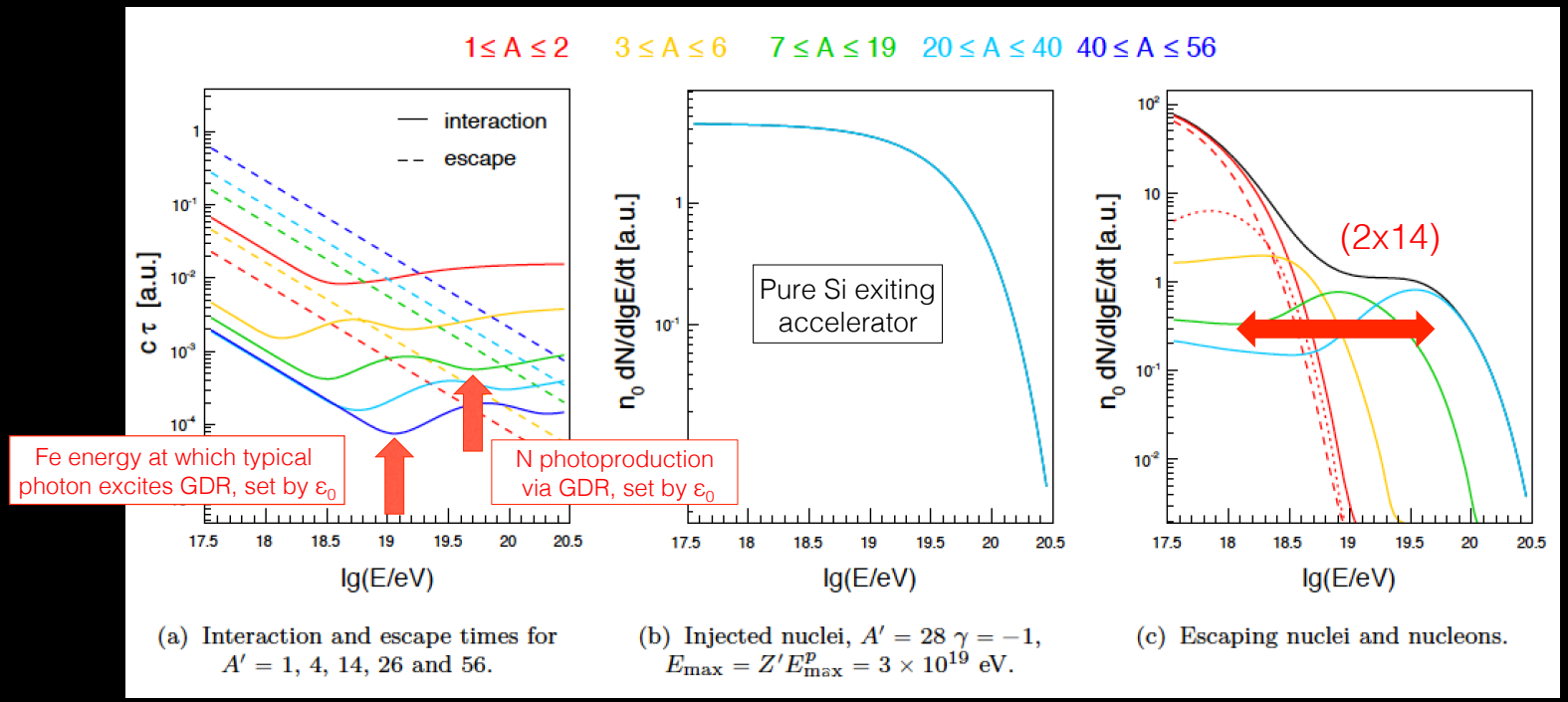
(b) Injected nuclei, $A' = 28$ $\gamma = -1$, $E_{\max} = Z' E^{p}_{\max} = 3 \times 10^{19}$ eV.

(c) Escaping nuclei and nucleons.

Ankle position is fixed by accelerator, not environment!

Spallation spectrum ~ injected spectrum with

$E_{spallation} = 1/A\ E_{Z^*,inj}\ (= ½\ E_{p,max})$



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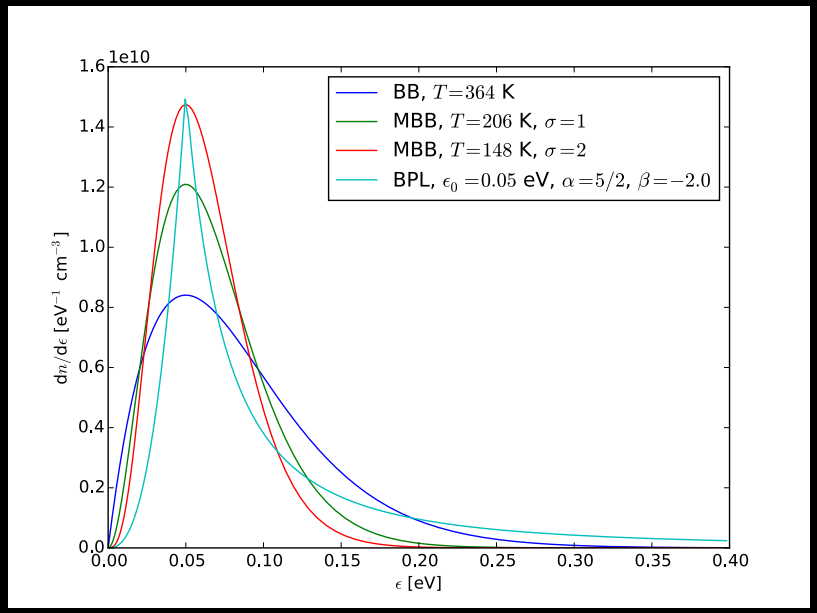
Parameter scan

- Peak energy of radiation field
  - black-body, modified bb (bb multiplied by $(\varepsilon/\varepsilon_0)^{1,2}$), & broken power law
- Source density evolution: SFR, $(1+z)^m$
- Injection index
- Escape index
- Composition

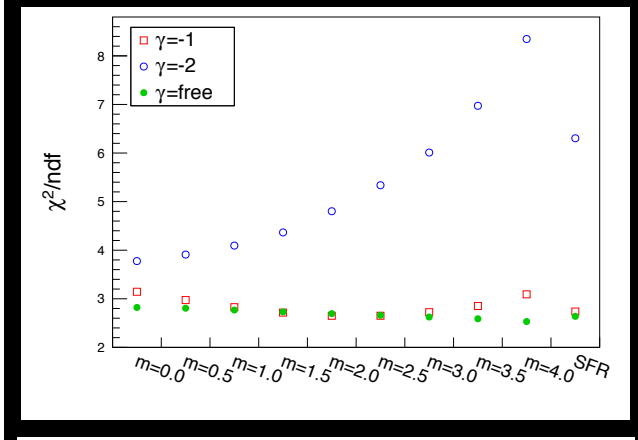
Also:

+- 1 sigma_sys (energy scale, lnA)

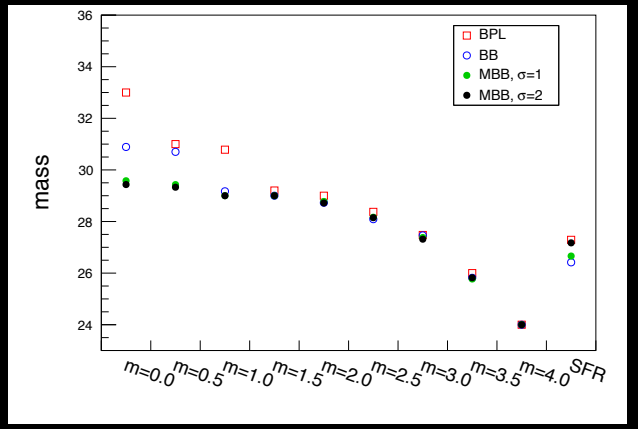
TA vs Auger spectrum

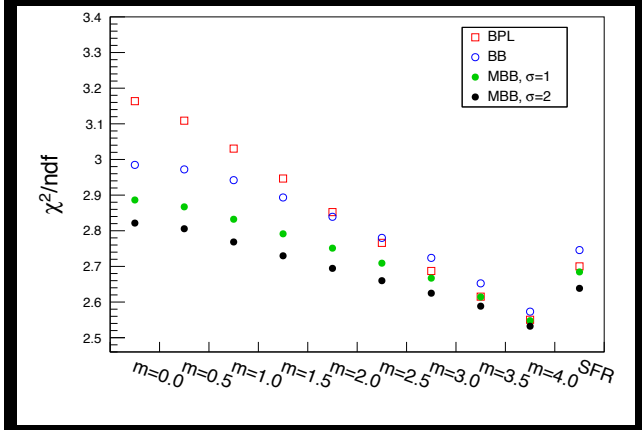


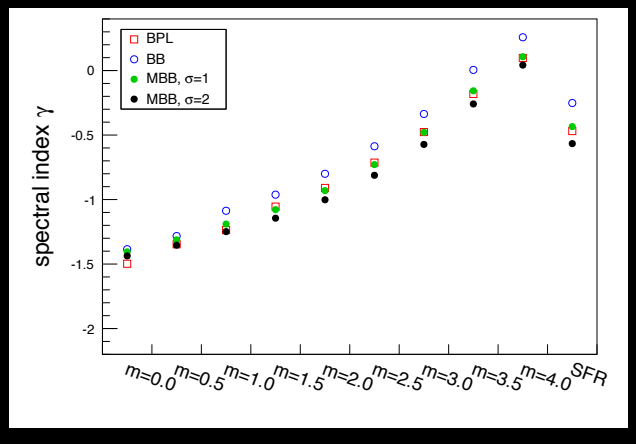
Using source evolution as display variable…

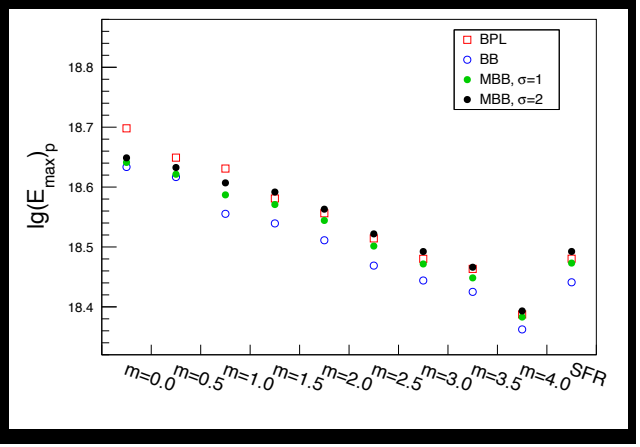


- Spectral index likes -1
  (but decreases m<0 c.f., Taylor+15)
- Fit quality insensitive to functional form of radiation field.
- Max mass & $E_{max,p}$ vary little over scan.
- Composition "compensation" for non-leading masses.

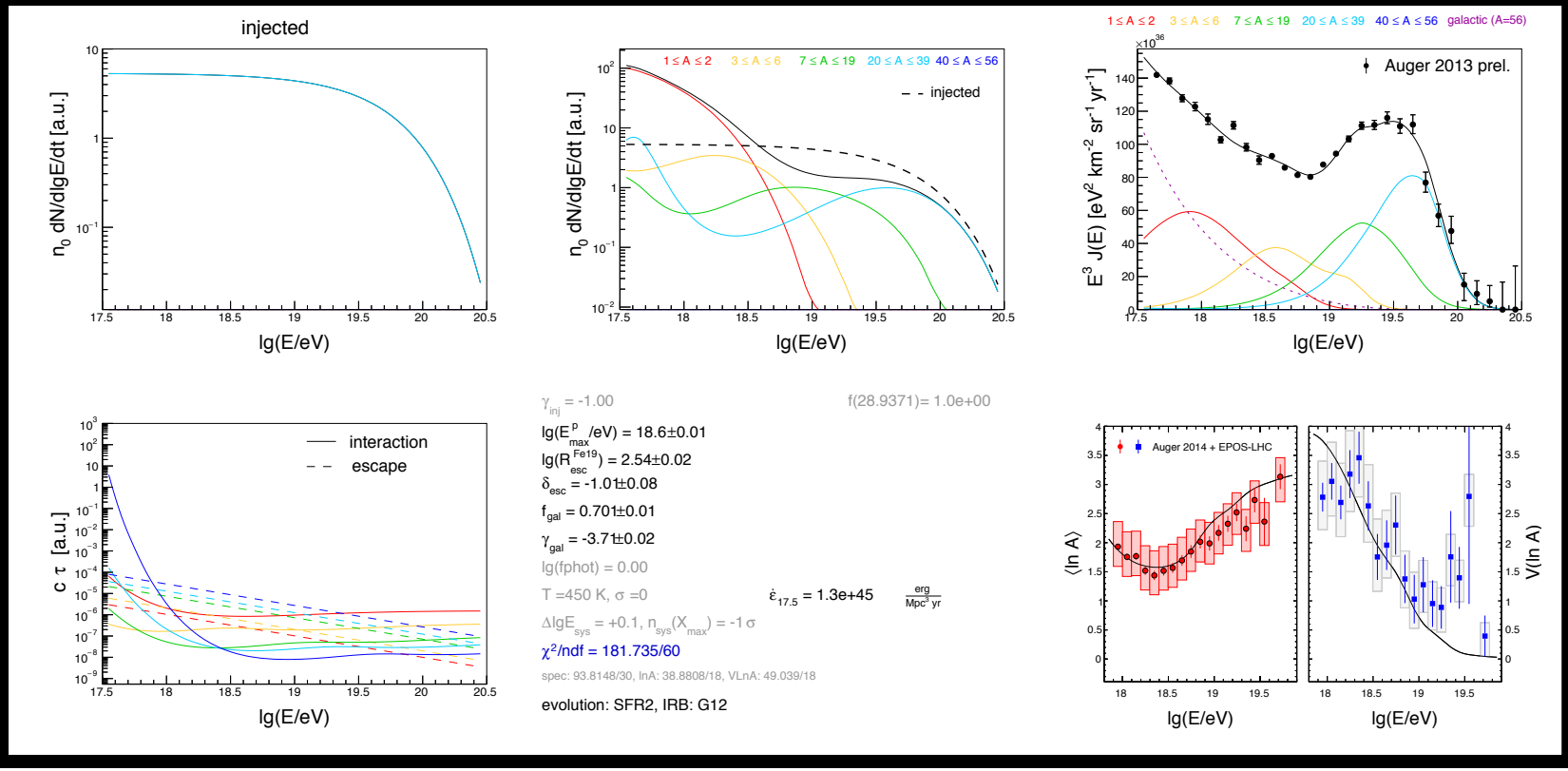








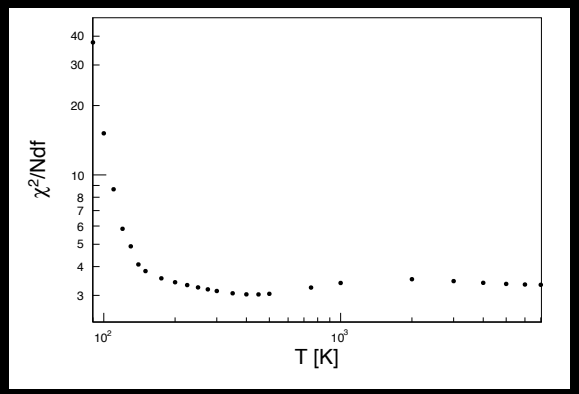
Minimalist model (E^{-1}, single mass)



Key results of parameter scans

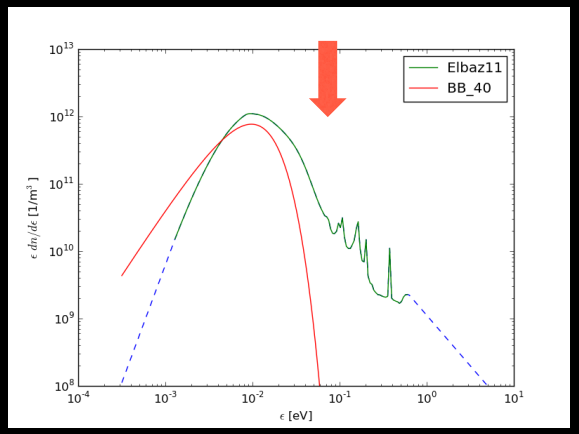
Peak energy of photo-dissociation environment is sharply constrained.

- Must be > ~0.05 eV ⇔ T_{eff} = 200 K



Death-knell for young magnetar/NS scenario?

ULIRG (intense SFR): ε_0 <0.01 eV -- factor 10 too low:



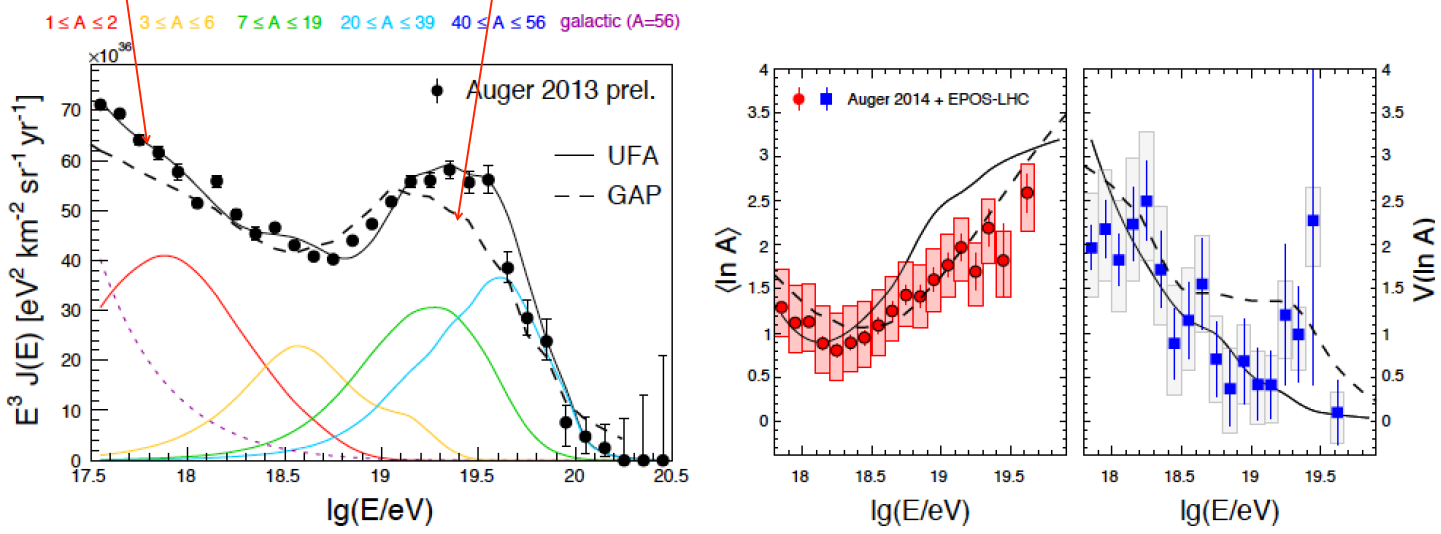
Only maximum-Z component from accelerator is significantly constrained in this scenario.

- Sub-leading components can be compensated by more/less spallation in environment or propatation (evolution).

Can spectrum/composition discriminate sources?

UFA Fiducial model vs. GRB with strong evolution (Globus, Allard, Parizot)

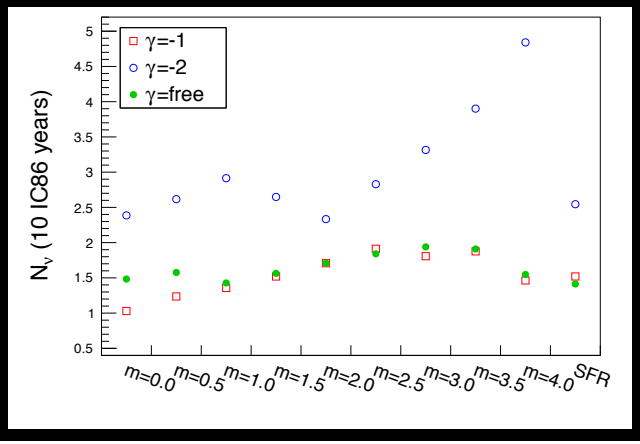
- GRB model tuned to UHE data (Globus2014)
- adjust low-E p/n via source evolution

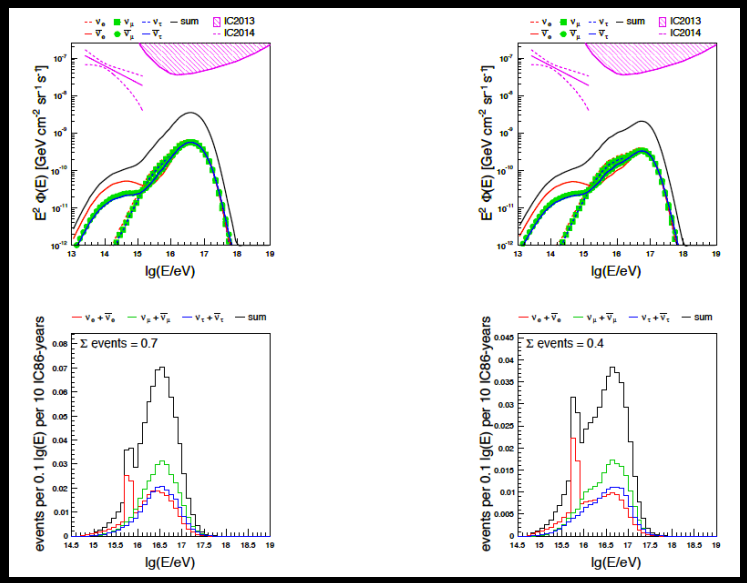


Key Predictions of Spallation Mechanism

- ✓ Position of the ankle relative to UHE cutoff
- ✓ Composition (extragalactic component) below ankle pure p
- ? Anti-electron neutrinos

  1-2 per year in IC Gen2





Conclusions & up-next:

- Detailed shape of spectrum INCLUDING ANKLE gives strong constraints on radiation field surrounding (in?) UHECR accelerators.

- Appears capable of discriminating between (at least some) source types
  -- Requires photon energies > ~50 meV
  -- Larmor radius relative to size => constrains magnetic field of environment

- Magnetar and young magnetars have positive aspects, but problems too.

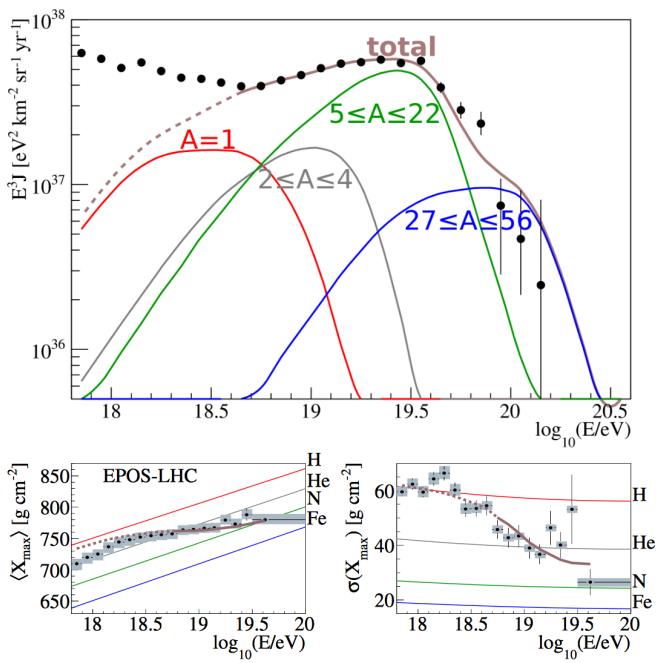
- Its premature to draw strong conclusions, until systematic uncertainties on UHECR composition and energy scale are reduced (including hadronic interactions)

- To do: more specific modeling of AGNs.

Backup slides

Auger best fit *without* spallation

The best fit (SPG propagation, EPOS-LHC air interactions)



- $J_0 = 7.17 \times 10^{18}$ eV^{-1} Mpc^{-3} yr^{-1} (at 10^{18} eV) ($\mathcal{L}_0 = 5.15 \times 10^{44}$ erg Mpc^{-3} yr^{-1} total)
- $\gamma = 0.94^{+0.09}_{-0.10}$
- $R_{\rm cut} = 10^{18.67 \pm 0.03}$ 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 (at 10^{18} eV) (0.0% H, 28.9% He, 65.6% N, 5.5% Fe total)
- $D/n = 178.5/119$ ($D_J = 18.8$, $D_{X_{\rm max}} = 159.8$)
- $p = 0.026$

Pure Fe, happiest with TA spectrum