The Complementarity of Neutrinos and Cosmic Rays for UHE Astrophysics

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High-Energy Messengers: Connecting the Non-Thermal Extragalactic Backgrounds
University of Chicago/KICP
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THE OHIO STATE UNIVERSITY

CCAPP

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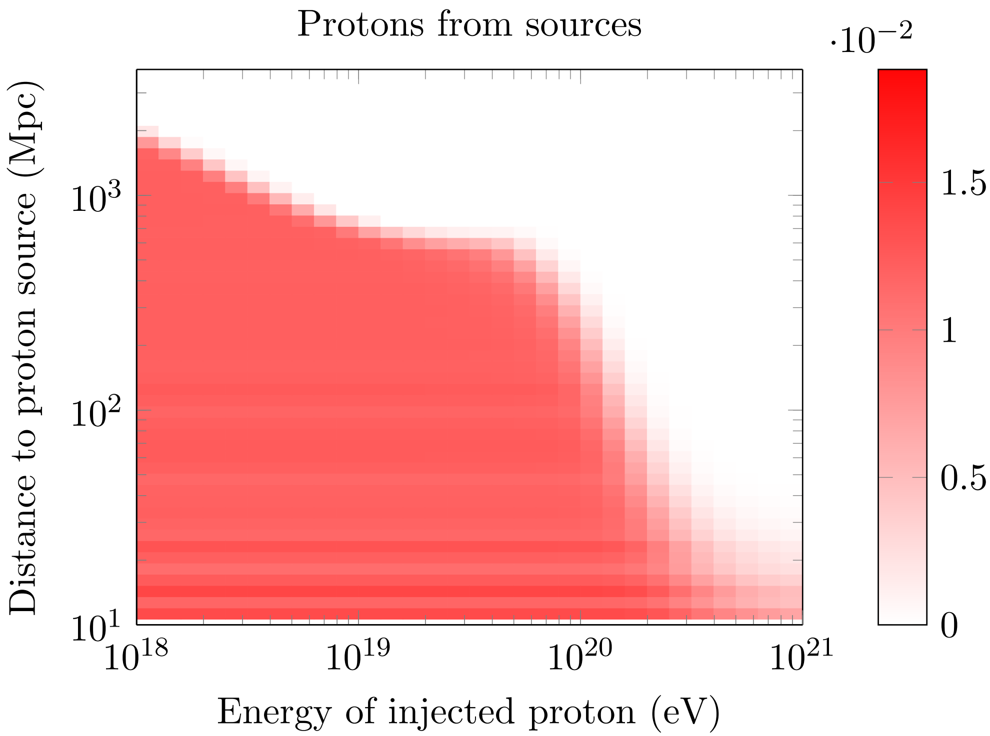
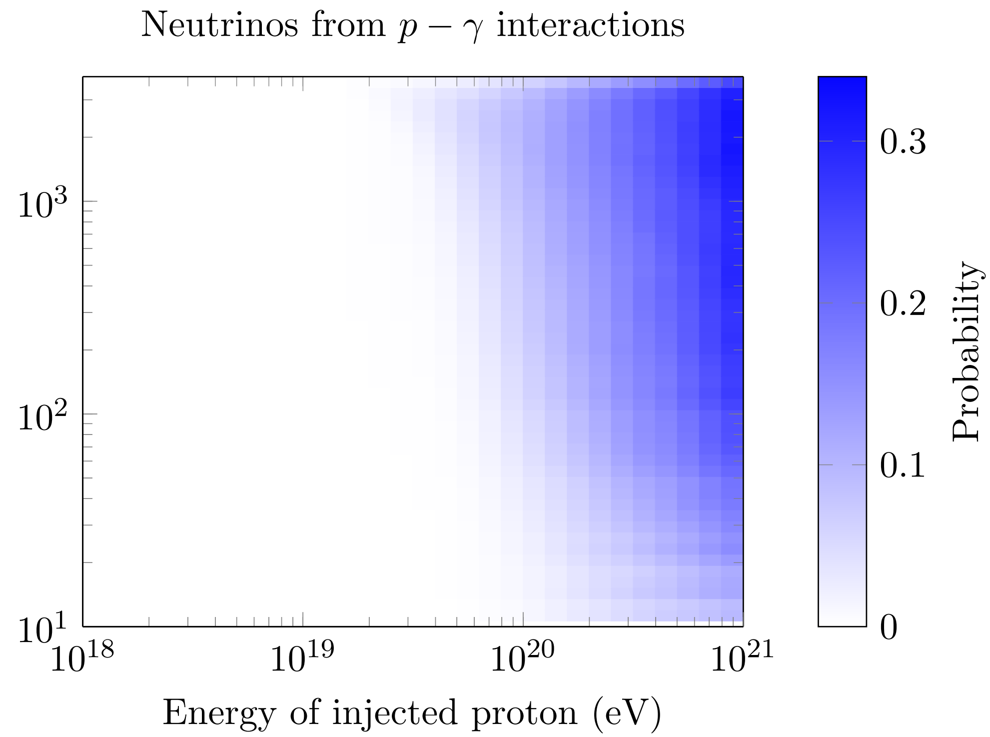
Outline

- Motivation for this multi-messenger study
- New cosmic ray fits (work in progress)
  - Implications for neutrino fluxes
- Implications of neutrino flux constraints on UHE source properties
- What we can expect in the future

Motivation

Protons and neutrinos are complementary probes of UHE sources



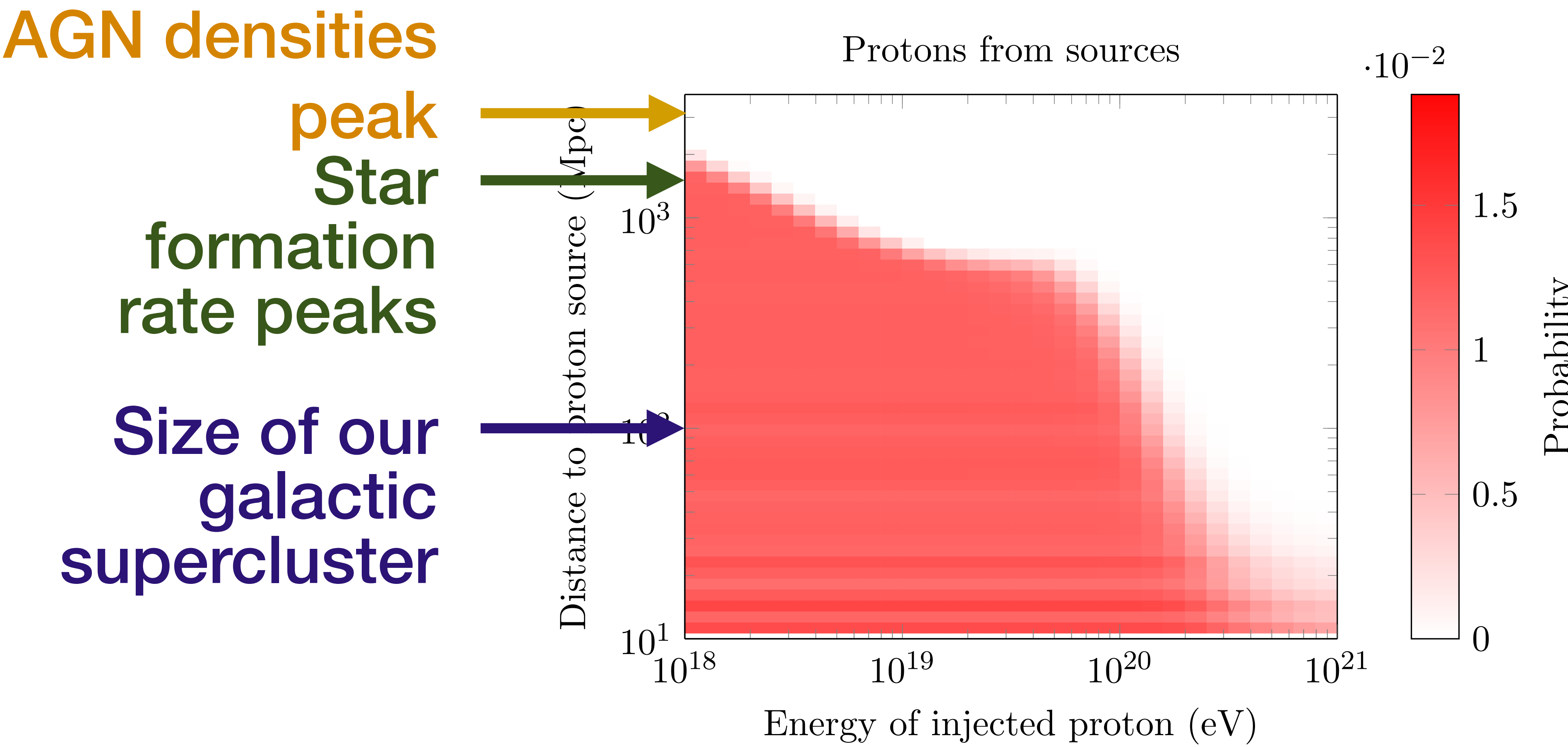


Protons that keep at least half their energy

Neutrinos that reach earth with >$10^{17.5}$ eV

Using CRPropa program, generated protons from sources with flat spectrum, flat redshift dependence to 4 Gpc, propagate through GZK interactions

Protons and neutrinos are complementary probes of UHE sources

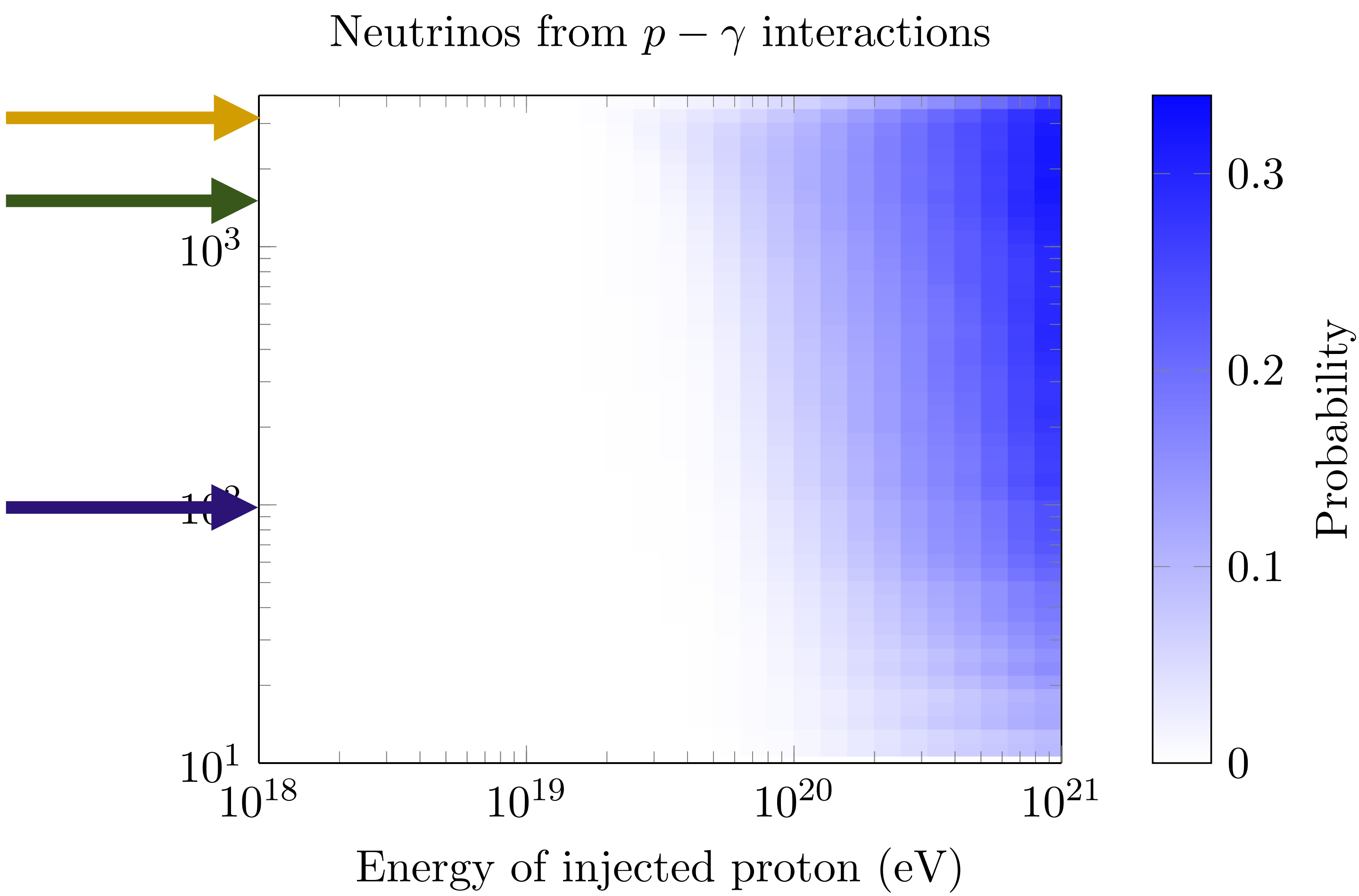


Protons and neutrinos are complementary probes of UHE sources

AGN densities peak

Star formation rate peaks

Size of our galactic supercluster



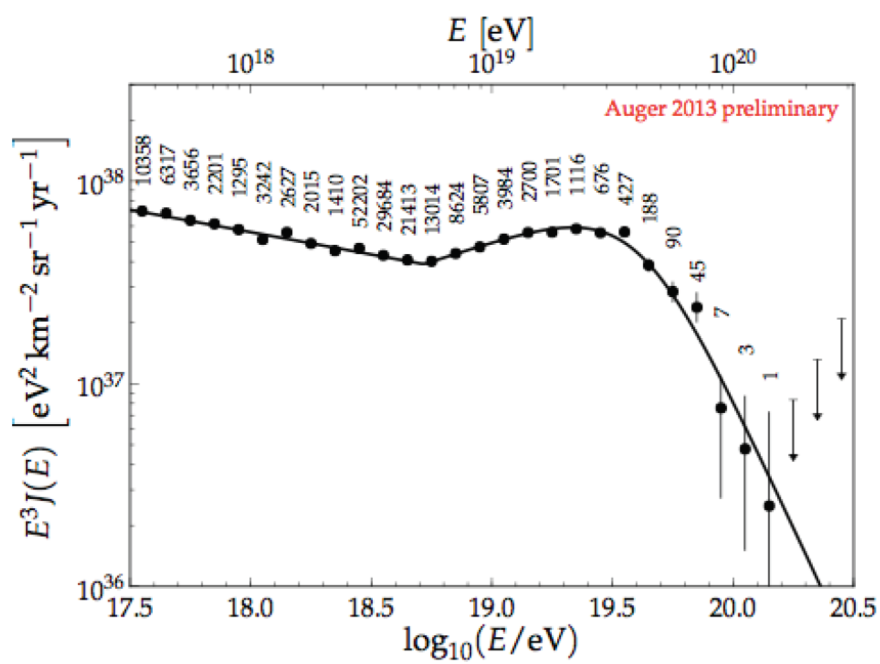
Purpose

- We set out to answer the questions:
  - How do current ν, CR results constrain the properties of the UHE sources?
  - What can we learn about UHE astrophysics with 100 UHE ν's?

New fits to source spectra from CR data

- In the process, performed new fits of UHE source spectra to CR data:
  - Use measured redshift evolutions
  - De-weight highest energy CR’s (local)
  - Use CR systematic energy shift as nuisance parameter

Use latest data reported by Auger at ICRC2013 in Rio



Procedure

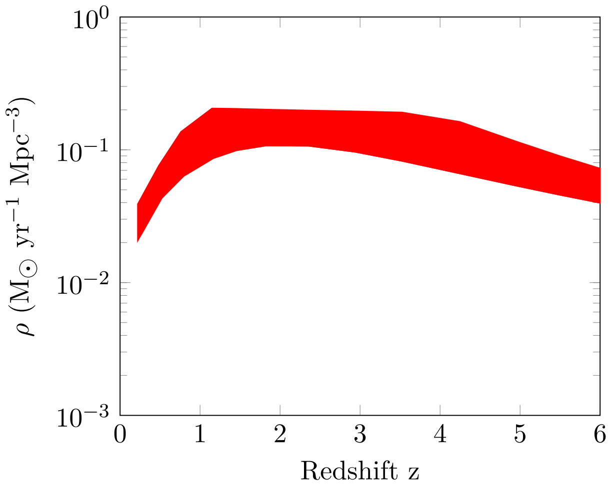
Model parameters

- Source redshift evolution: **$\rho(z)$**
  - Many take $\rho \propto (1+z)^m$, $\mathbf{z_{min}} < z < \mathbf{z_{max}}$
  - We take measured evolutions, consider systematics:
    - Star formation rate (SFR)
    - Gamma ray bursts (GRB)
    - Active Galactic Nuclei (such FR-II)
- Injected spectrum at the source: $L \propto \mathbf{L_0}(E_i/E_0)^{-\alpha}$ up to $\mathbf{E_{max}}$
- **Ankle** vs. **Dip**:
  - Ankle: Extragalactic (EG) $\gtrsim E_{min}=10^{18.8}$ eV
  - Dip: EG $\gtrsim E_{min}=10^{17-17.5}$ eV (we take $E_{min}=10^{17.6}$ eV)

- Protons only, 8 distinct models (4 evolutions, ankle&dip)

Source redshift evolutions

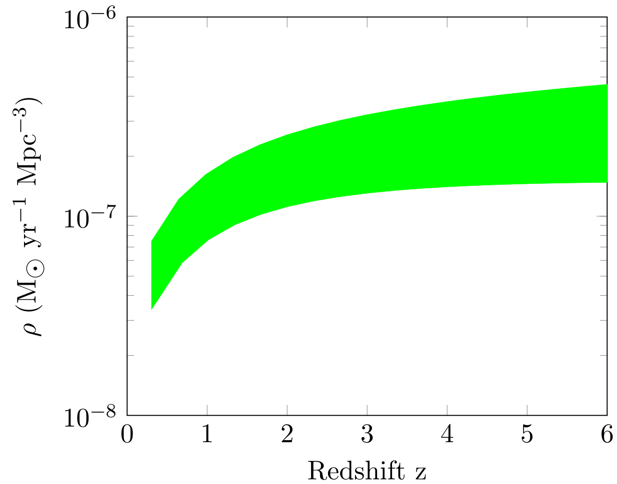
Star Formation Rate



Use function form from H. Yuksel *et al.* (2008) fitted to latest SFR data

Test against Cole *et al.* (2001) functional form fitted to SFR data (upper)

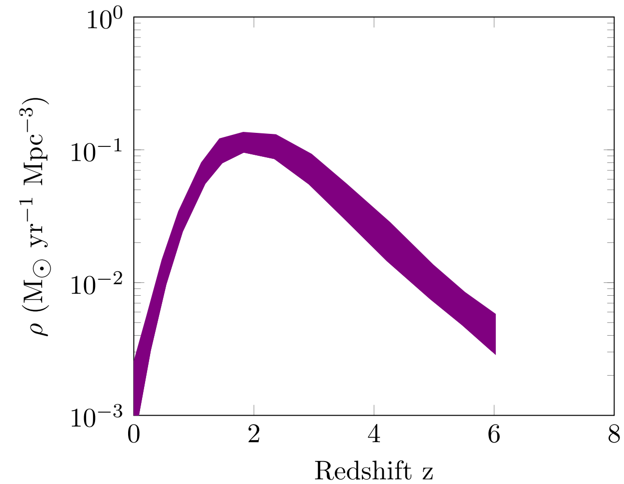
Gamma Ray Bursts



Use function form from T. Le & C. Dermer (2007) SFR5

Test against T. Le & C. Dermer (2007) SFR6

FRII type AGN



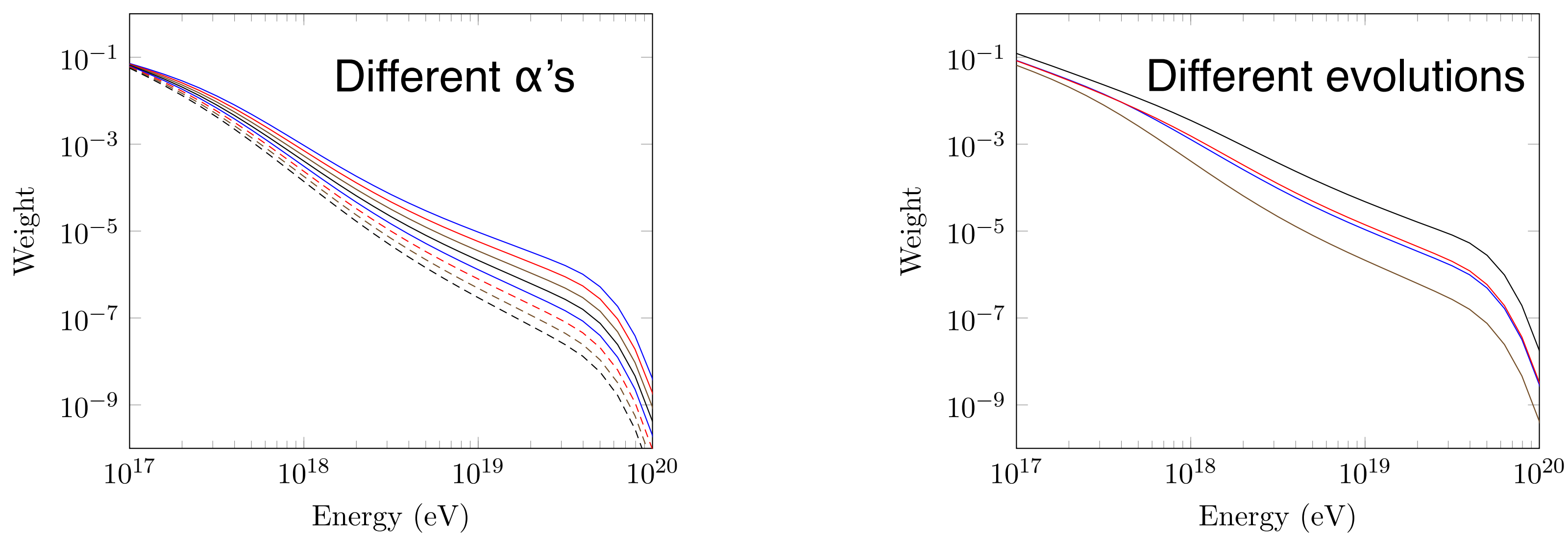
Use Wall *et al.* (2005) mid Fig. 10

Test against Wall *et al.* (2005) upper Fig. 10

De-weighting "local" CRs

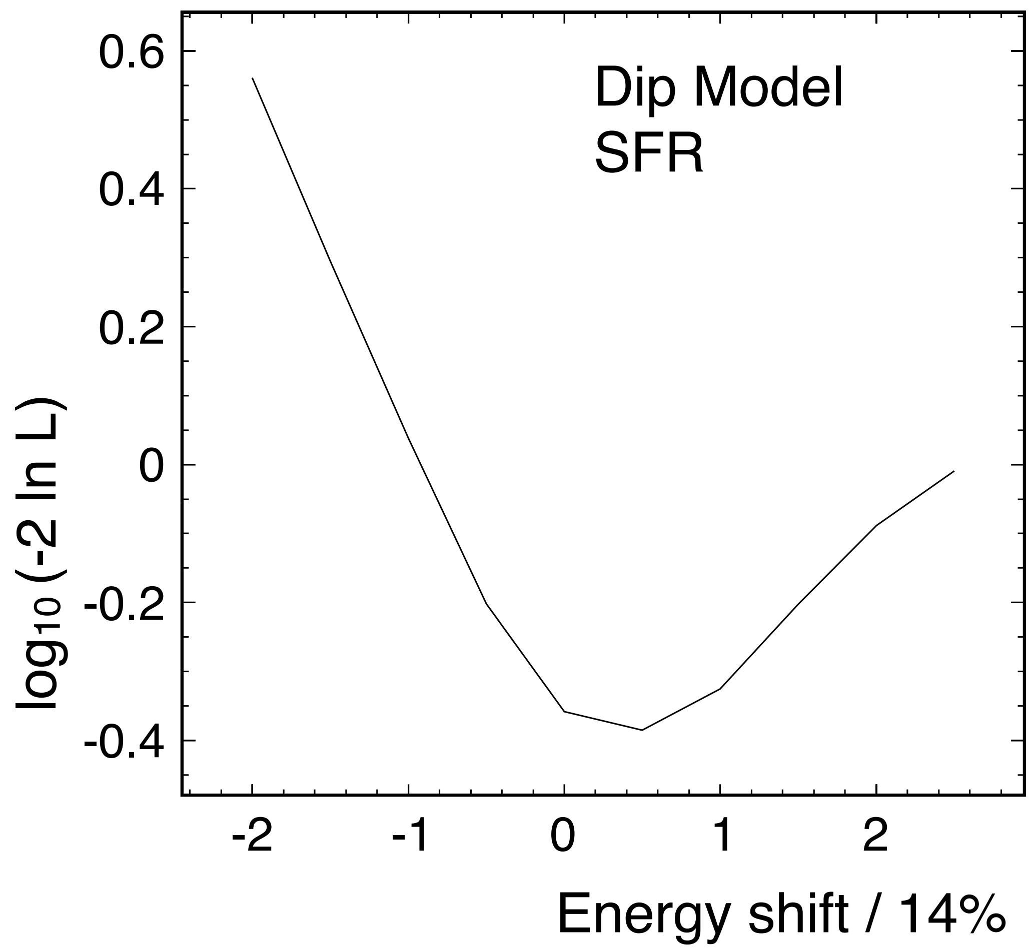
- Highest energy cosmic rays are "local" and may not be representative of the "cosmic" spectra
  - Source properties could evolve, local universe could be a fluctuation
- Perform weighted likelihood to fit models to CR data
- For each model, assign weight to an energy bin *i*:

$$w_i = \frac{\text{\# cosmic rays arriving in an energy bin } i \text{ from beyond = 100 Mpc}}{\text{\# cosmic rays injected at any distance with any initial energy}}$$



CR energy scale systematic as "nuisance parameter"

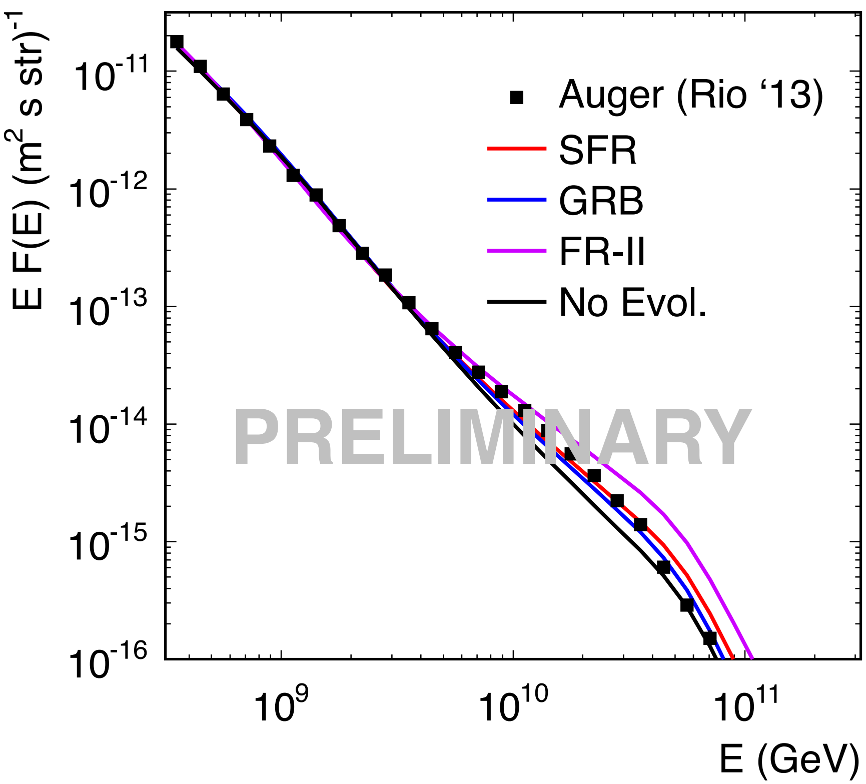
- Latest Auger results (Rio `13) report 14% uncertainty on energy scale
  - Treat this a nuisance parameter in our fits
- Consistently find data prefers to be shifted ~0.8*14%=11% higher



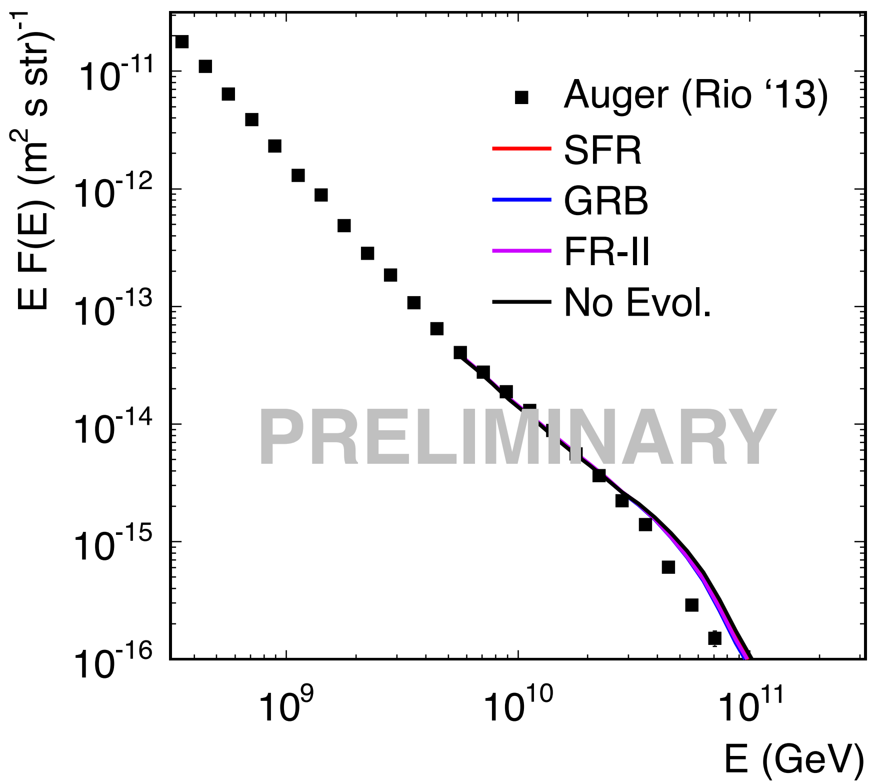
Fit results

A. Connolly (OSU), S. Horiuchi (UC Irvine), N. Griffith (OSU), in preparation

Dip Scenario



Ankle Scenario

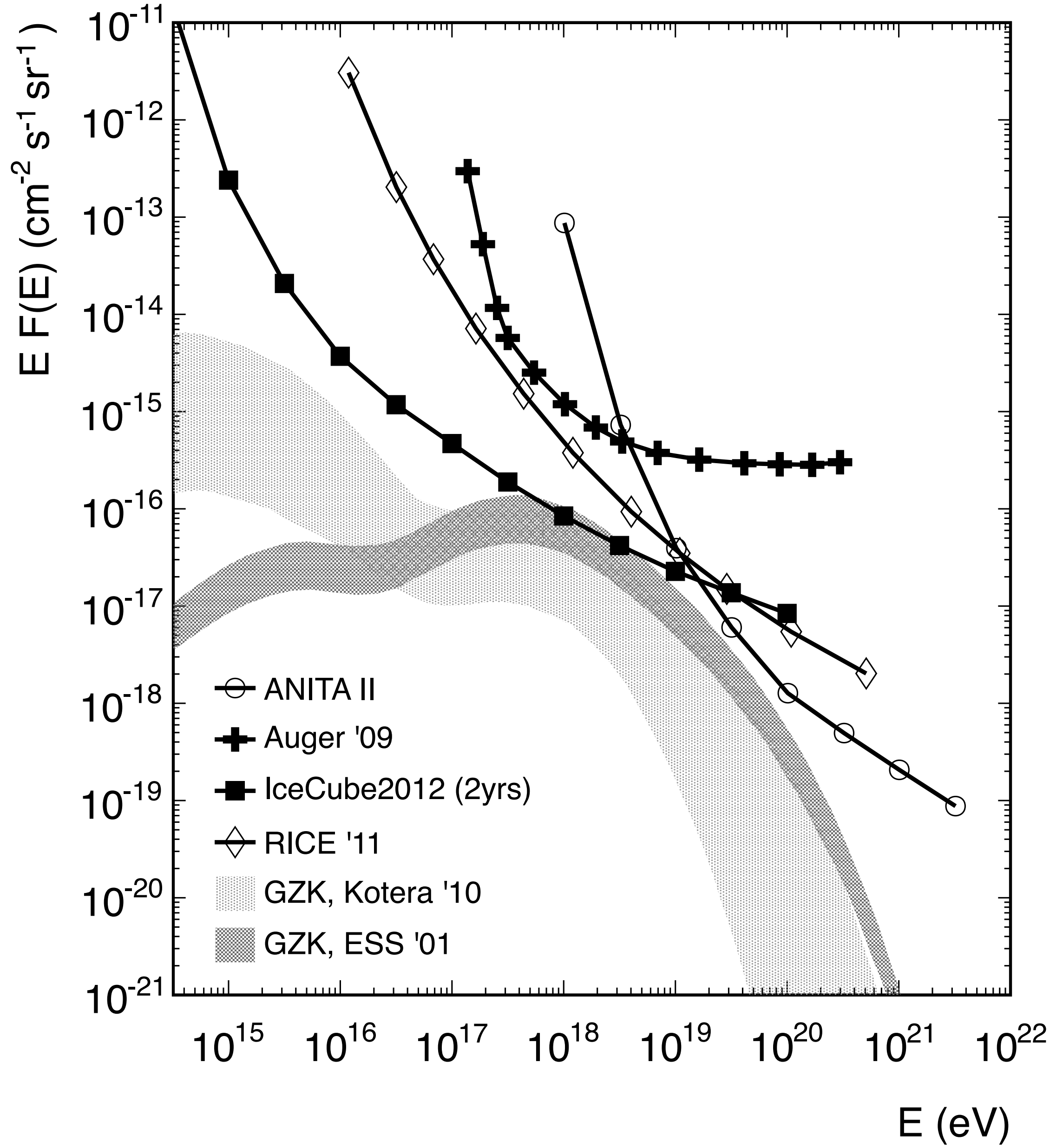


With the UHE “local” CR’s de-weighted, the best-fit cosmic spectrum naturally overshoots at the highest energies → higher neutrino flux expectations

Constraining the UHE sources using limits on GZK-induced neutrino fluxes

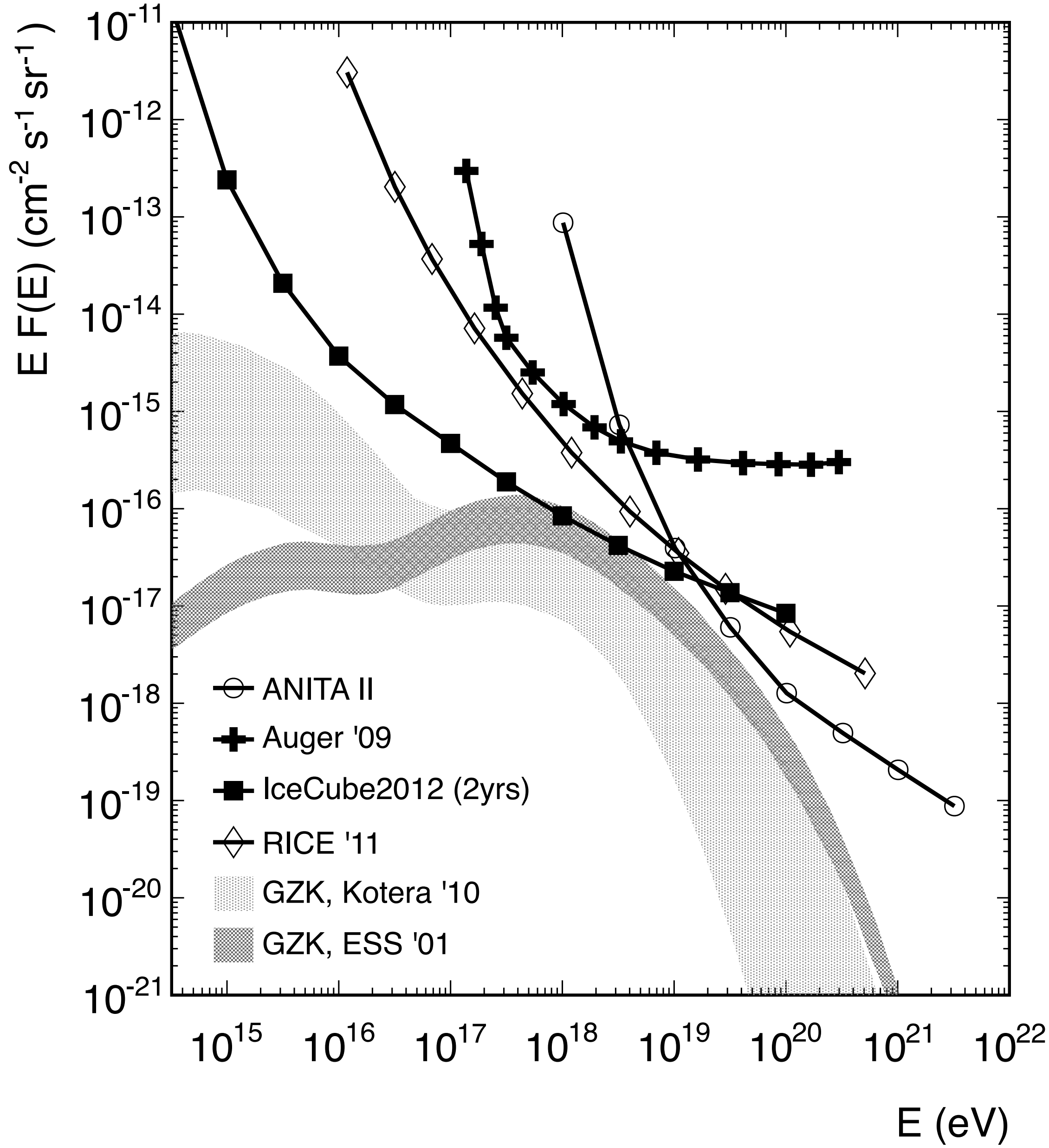
GZK models - current constraints

- IceCube: Best constraints $E_\nu \lesssim 10^{19}$ eV
  - Cutting into most optimistic data-inspired models
  - Radio *in situ* arrays will overtake IceCube for $E_\nu > 10^{17.5-18}$ eV
- ANITA: Best constraints for $E_\nu \gtrsim 10^{19}$ eV
  - EVA: higher gain, lower threshold



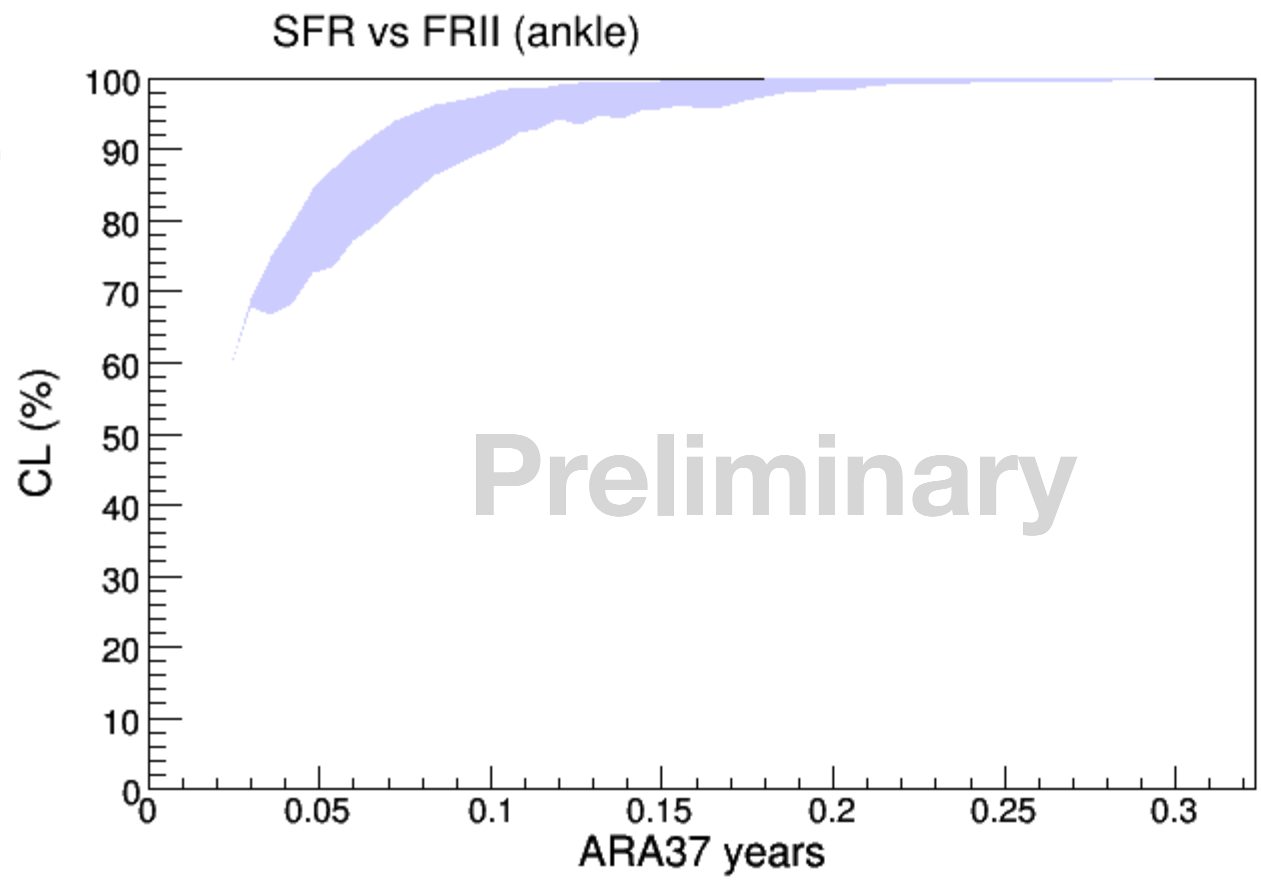
Which type of models has IceCube excluded?

- Excluded models have strong source evolutions
- Example:
  - FR-II (AGN) redshift evolution
    α=2.3, dip,
    $E_{max}=10^{20.5}$ eV
    Kotera *et al.* (2010)



in situ arrays will constrain the redshift evolution From A. Connolly, S. Horiuchi & N. Griffith, in preparation.

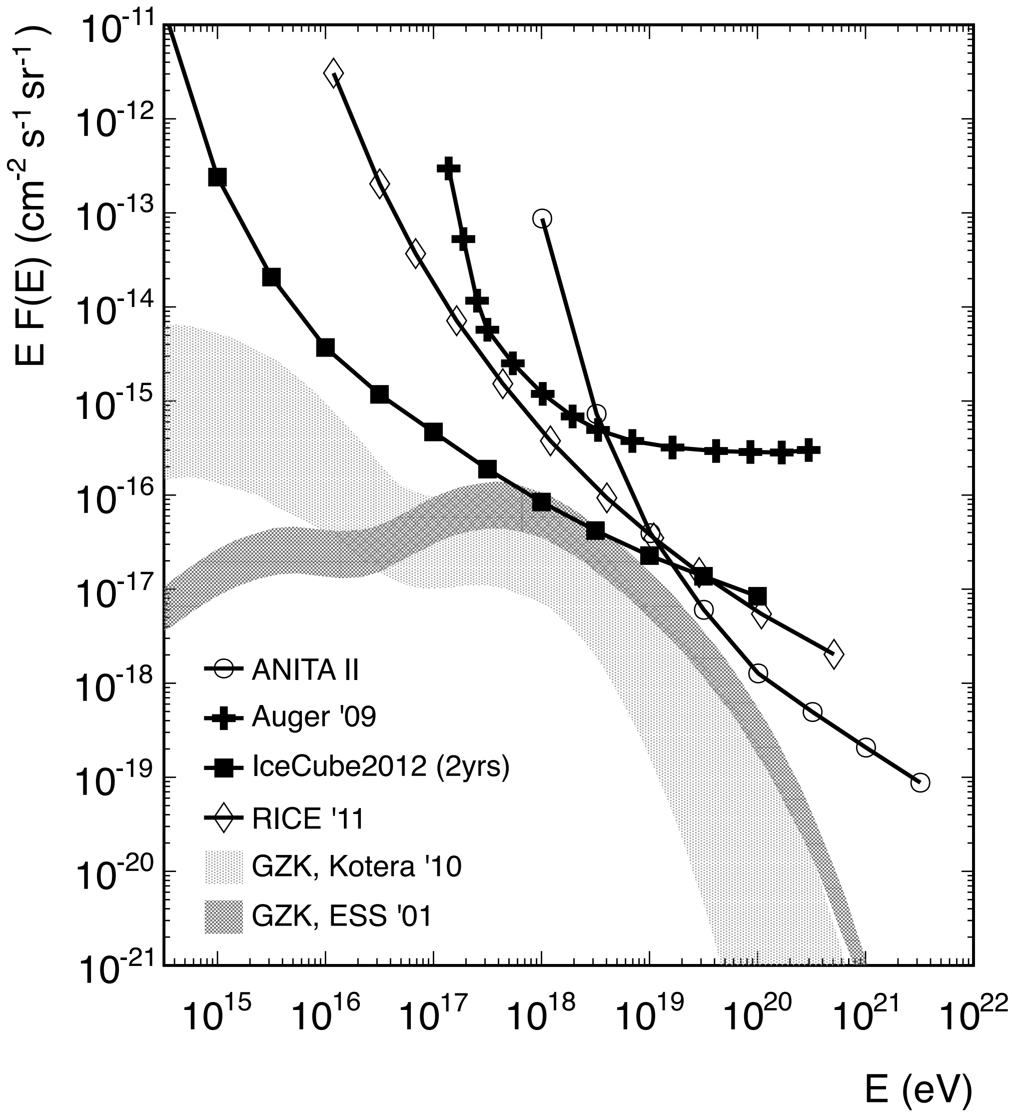
- In ~7 station-years, ARA can distinguish between Star Formation Rate and AGN evolutions



From Connolly, Horiuchi & Griffith, in preparation.

Balloons: be careful when comparing sensitivity to cosmogenic ν fluxes

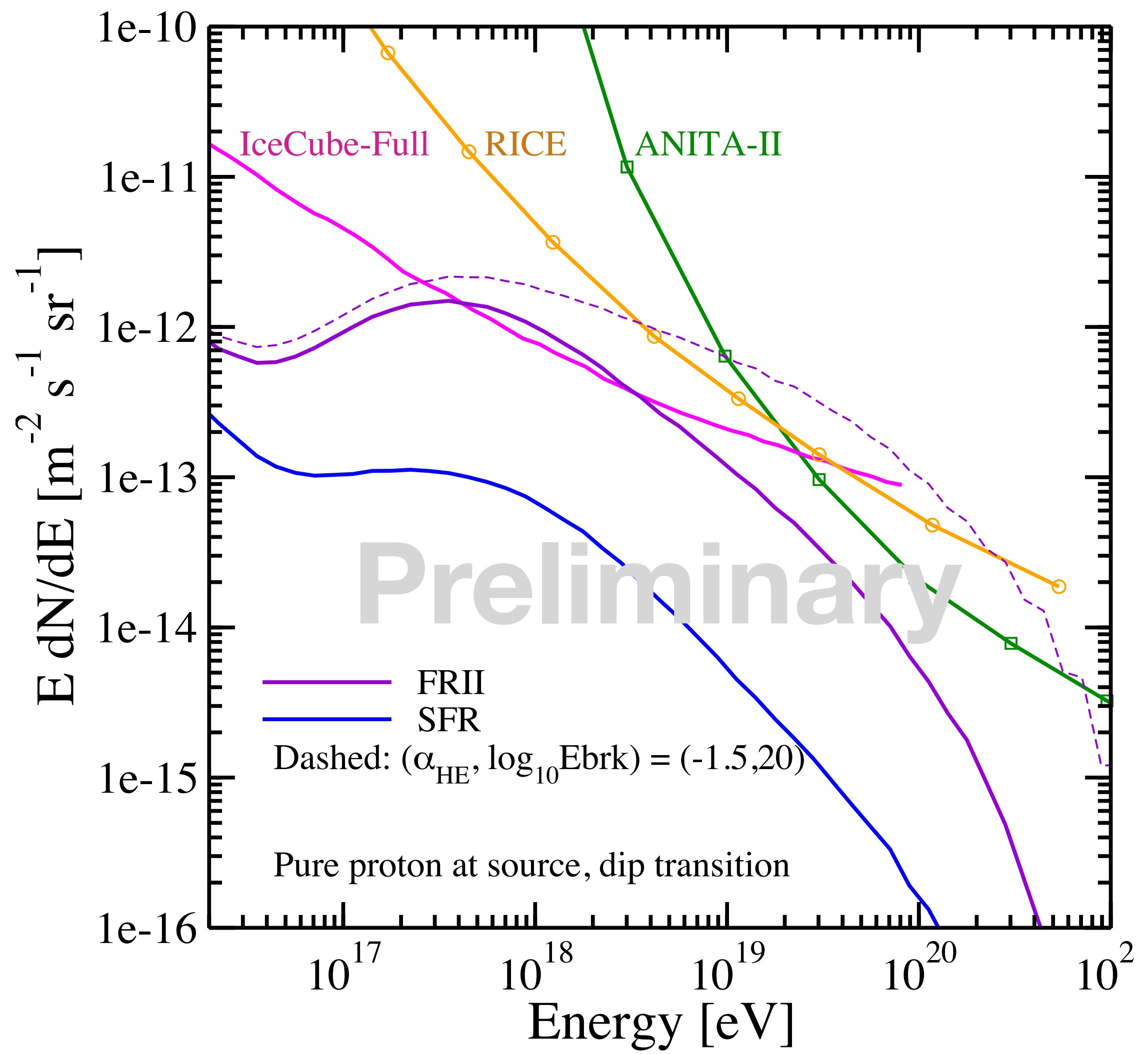
E_{max} is unknown!



Which type of models has ANITA excluded?

- Balloons ideal for probing the highest energy features of spectrum
- Dotted line:
  - FR-II (AGN) redshift evolution, but with higher E_{max} @ 10^{22} eV, stiffening of α to 1.5

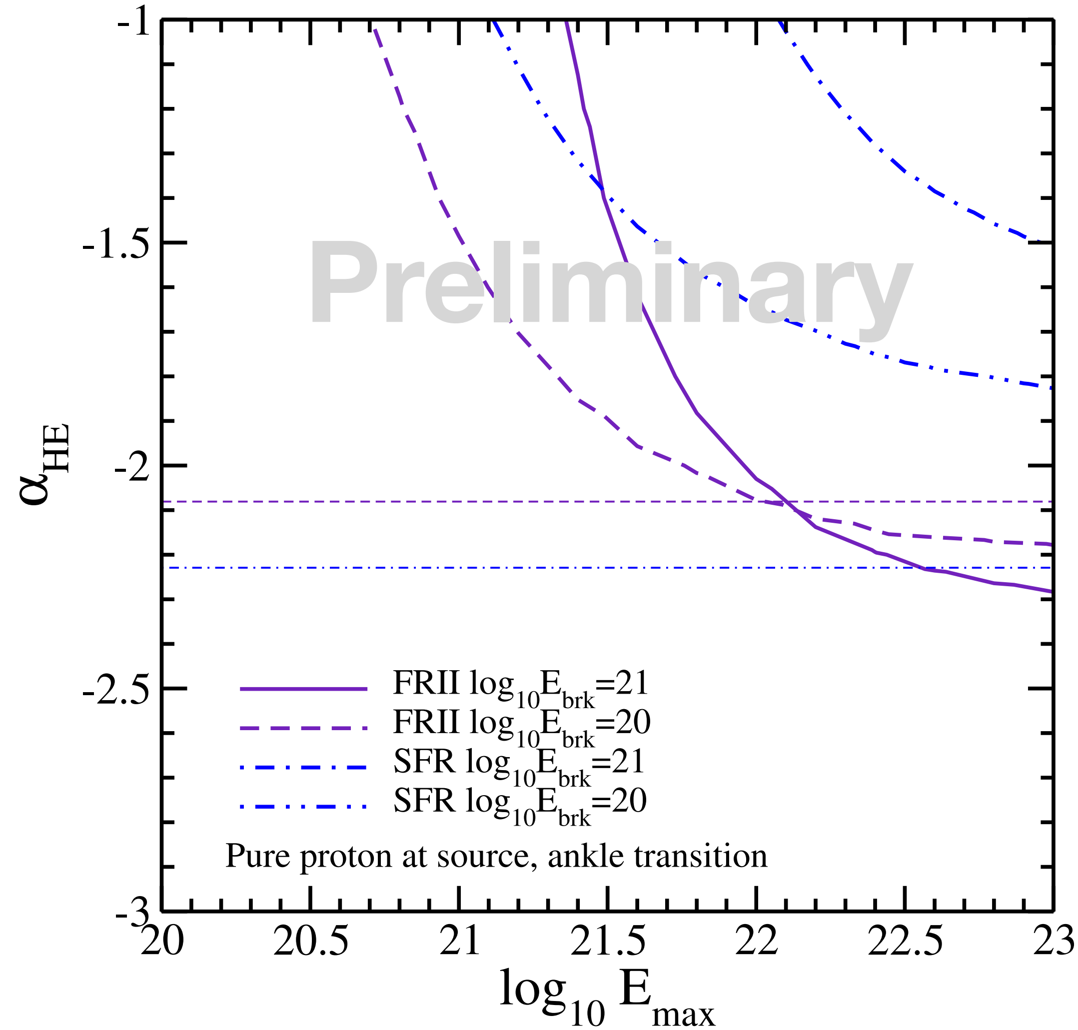
FR-II Evolution, Dip



Which type of models has ANITA excluded?

- Balloons can constrain E_{max}
- ANITA excluded:
  - FR-II (AGN) redshift evolution, $E_{max} > 10^{22}$ eV

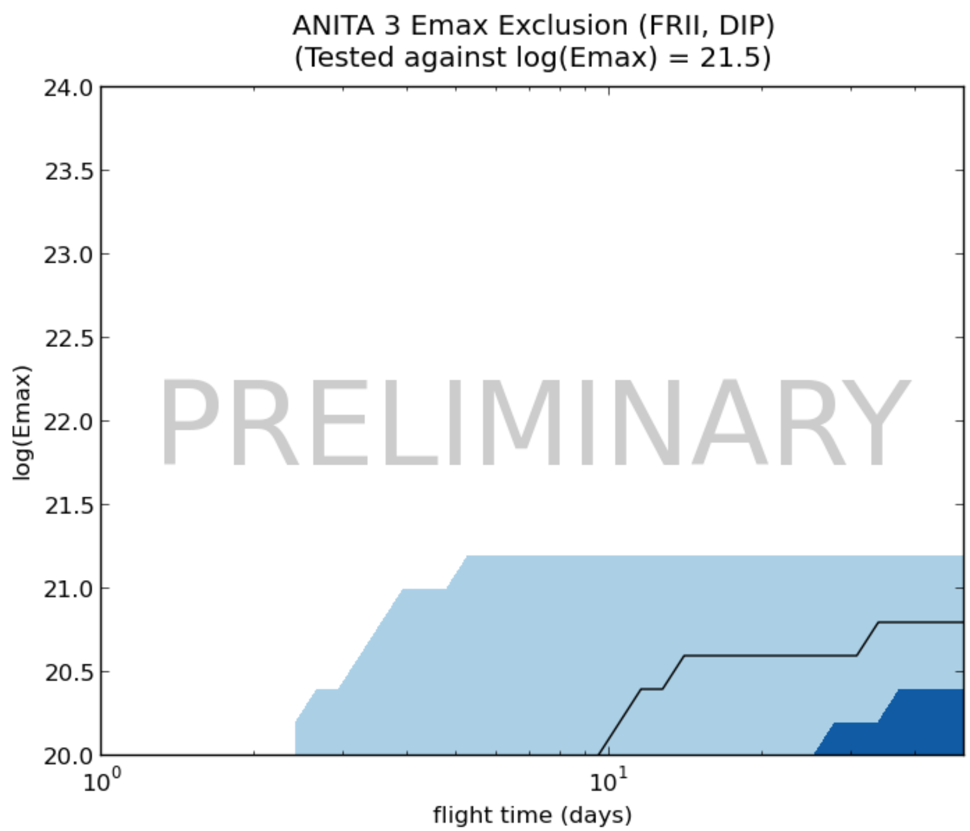
FR-II Evolution, Dip



ANITA 3 will do more

A. Connolly (OSU), S. Horiuchi (UC Irvine), N. Griffith (OSU), in preparation

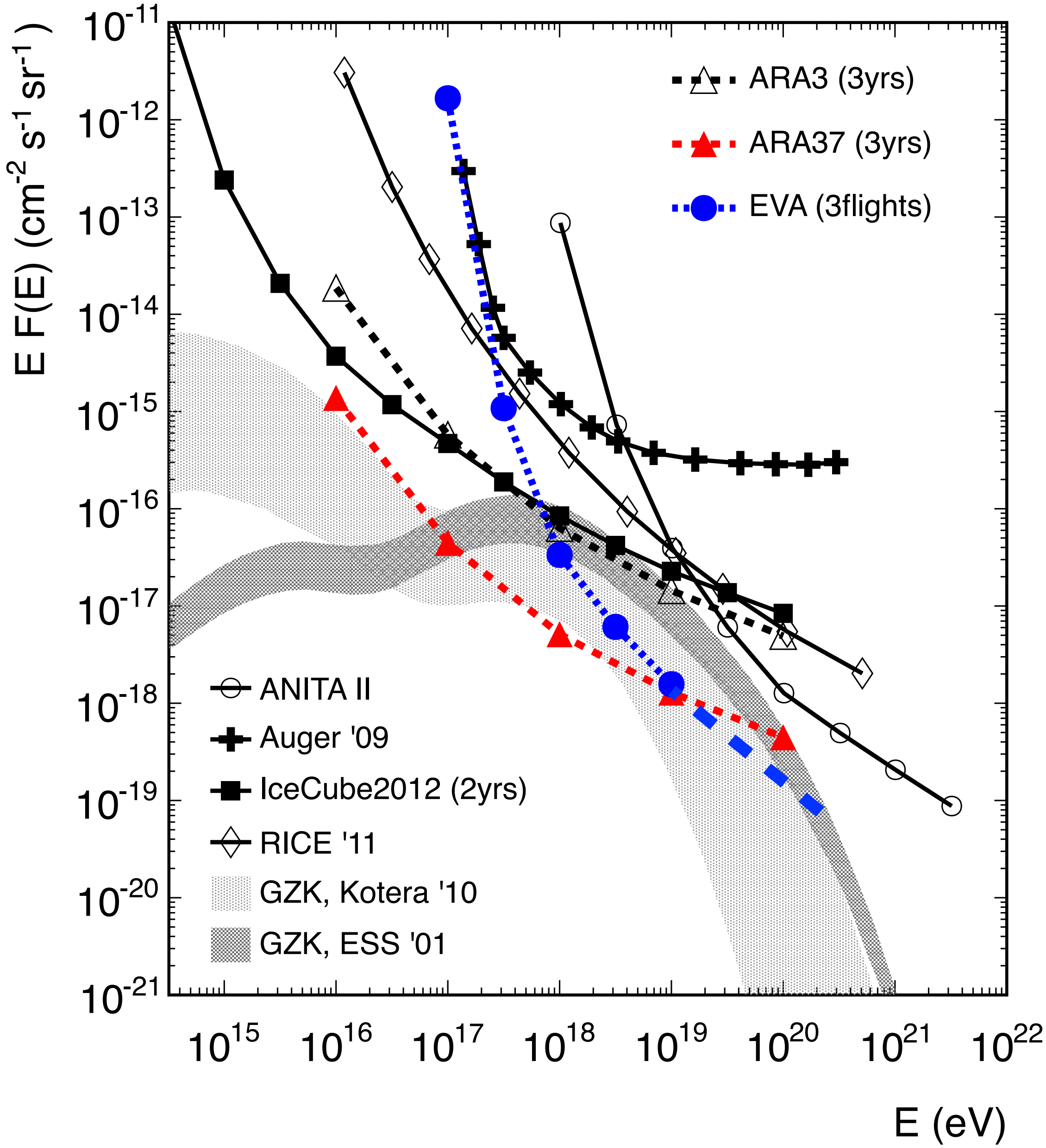
FR-II Evolution



- If $E_{max} = 10^{21.5}$ eV, ANITA 3 expected to exclude $E_{max} < 10^{20.5}$ eV for FR II assumption
- EVA will be powerful in this variable - predictions soon

What we can expect in the future

Future



E F(E) (cm^{-2} s^{-1} sr^{-1})
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21} 10^{22}
E (eV)
ARA3 (3yrs)
ARA37 (3yrs)
EVA (3flights)
ANITA II
Auger '09
IceCube2012 (2yrs)
RICE '11
GZK, Kotera '10
GZK, ESS '01

Summary

- Neutrinos and cosmic rays are complementary messengers to the UHE universe
- Performed new fits of source spectra parameters to latest Auger `13 data
- Current UHE limits constraining models with strong redshift evolutions
- Balloons have a unique sensitivity to E_{max}
- *in situ* arrays will constrain evolution of sources
- Proposed experiments can even reach "minimal" models where CR's are heavy