GRBs
and the connection to HECR

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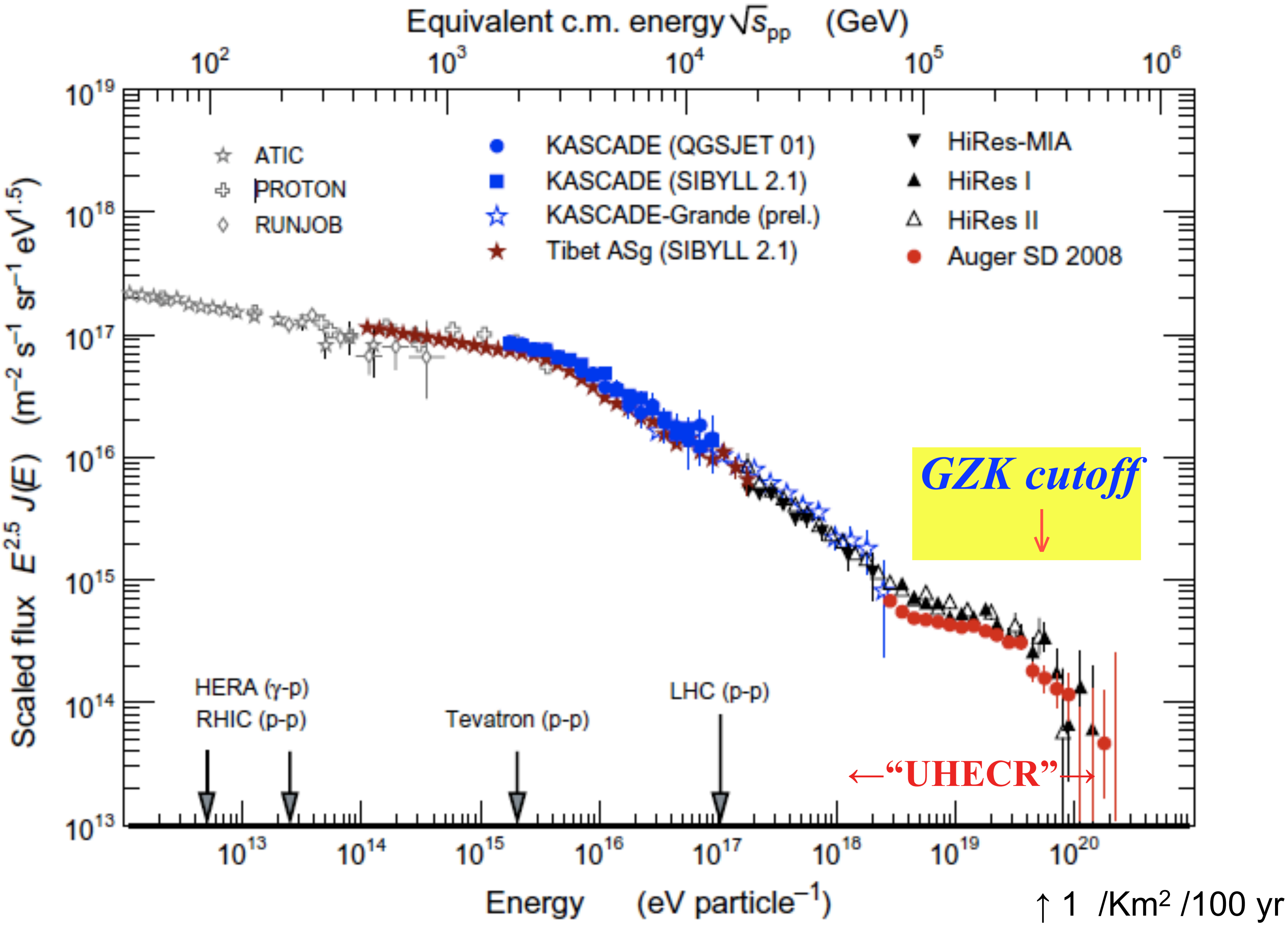
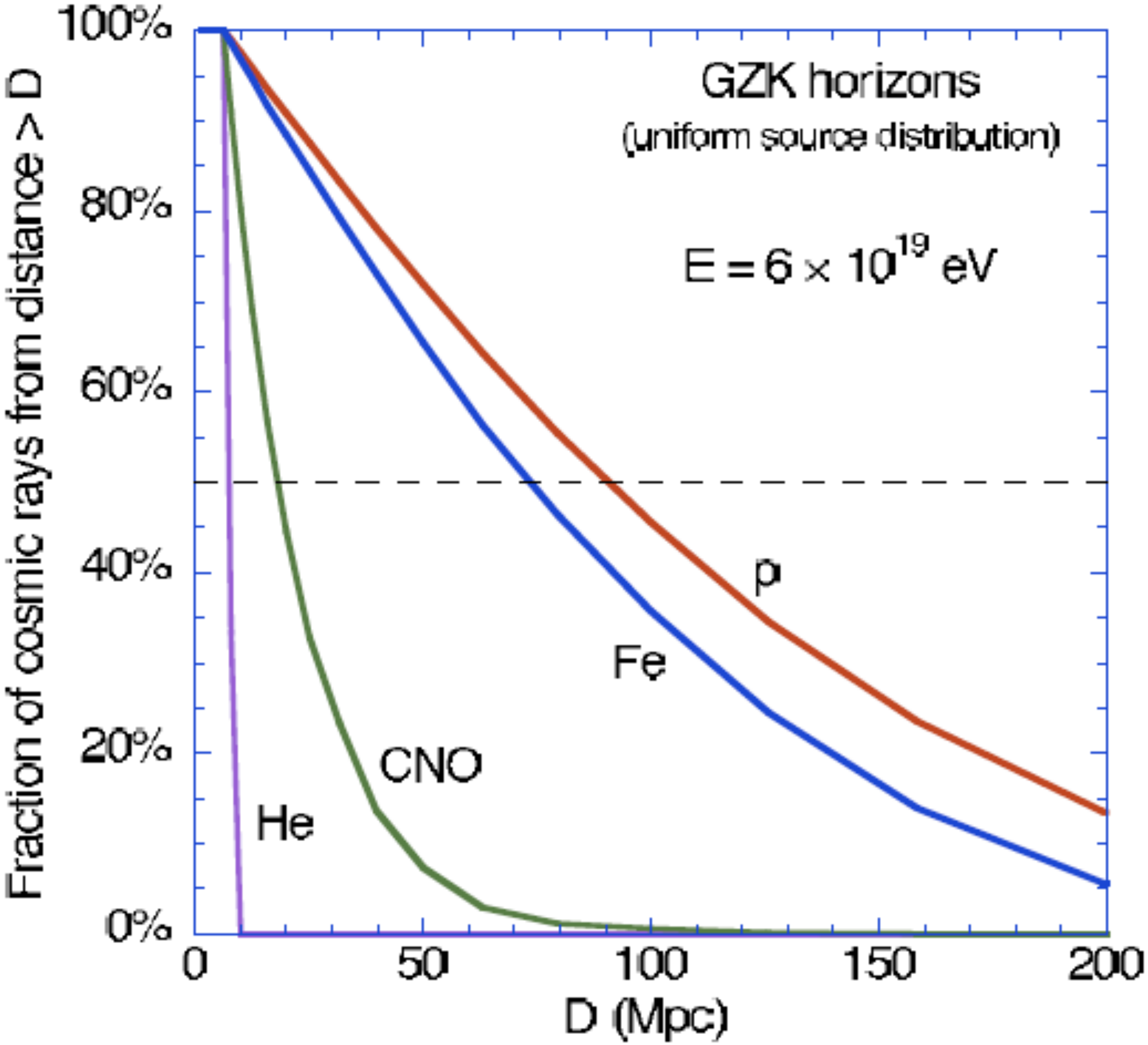
Albanova, 2011

Cosmic ray spectrum (2011)



How far do they come from?

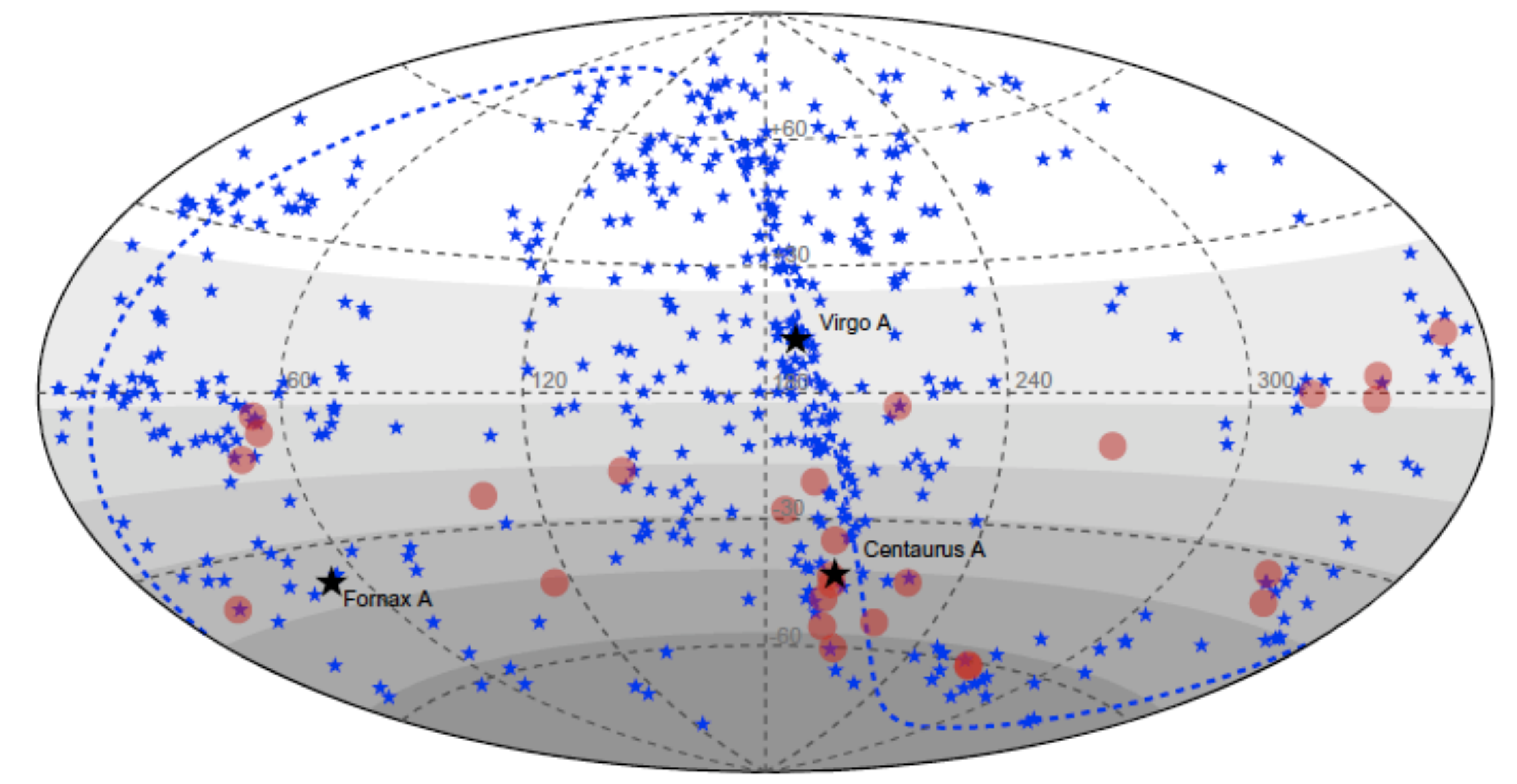


proton + γ_{cmb}
→ π + nucleon

heavy nucl. + γ_{IR}
→ photodissoc.

"GZK radius"
≲ 75-100 Mpc
(~200-300 Mlyr)

AUGER :
UHECR spatial correlations with AGNs (or LSS)



- Dashed line: supergalactic equator
- Circles (proton): Events E> $5x10^{19}$ eV, D<75 Mpc
- Asterisks : Veron-Cety catalog AGNs

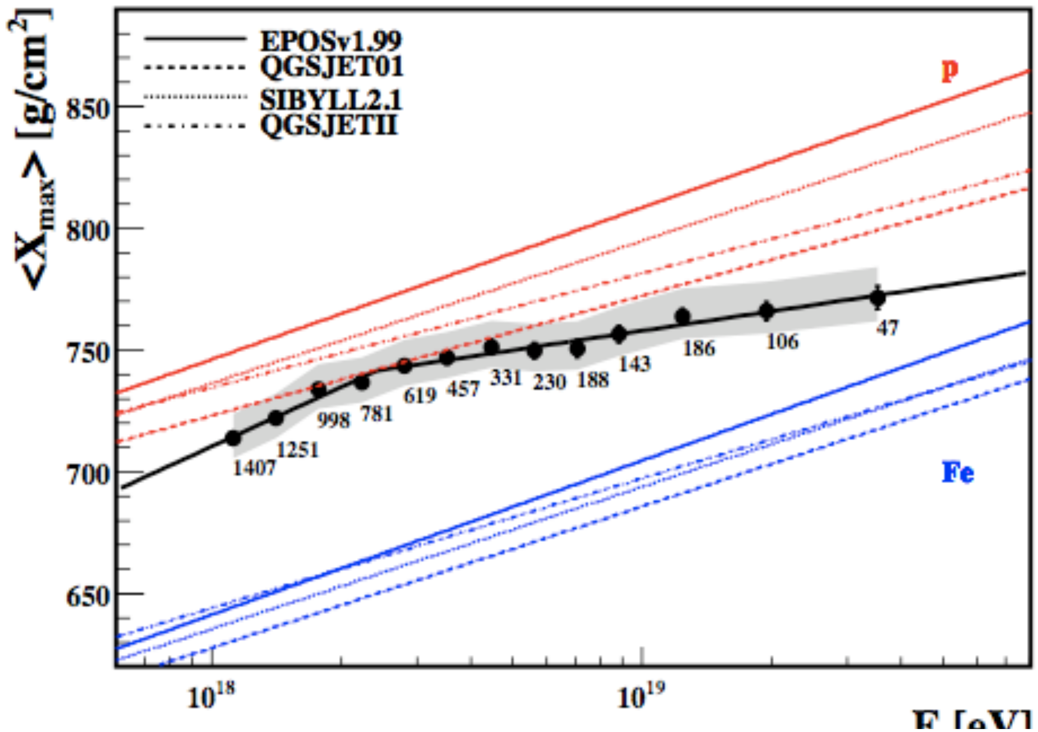
Science Nov 2007; newer: arXiv:1009.1855; also ICRC 11

Auger spatial correlation

- Initially found 3-σ corr. with VC AGNs within $\theta \leq 3.5^o$ and D< 75 Mpc, for 27 events $E > 4.5 \times 10^{19}$ eV (Science, 2007)
- The above correlation would suggest protons
- But: there is even better correlation with "average" galaxies
- If heavy: r_L smaller, rms. dev. angle $\theta \sim n^{1/2}\,\theta_s \sim (r/\lambda_B)^{1/2}\,(\lambda_B/r_L) \sim (r\lambda_B)^{1/2}/r_L$ is larger, many more gals. inside error circle
- ***Also: (*** arXiv:1009.1855, etc.): ***now (>2010) the VCV-AGN significance has weakened to*** $\lesssim$ ***1.5σ***
- ***Low or no VC AGN corr.: also from HiRes (Sagawa talk)***

→ ***Could be sources are in galaxies - GRB ? HNs? MGRs? Or in other, less extreme and more common galaxies?***

→ ***Or could be they are heavy nuclei, larger error circle?***



Auger : UHECR nuclear composition

X_{max} vs. E ↑

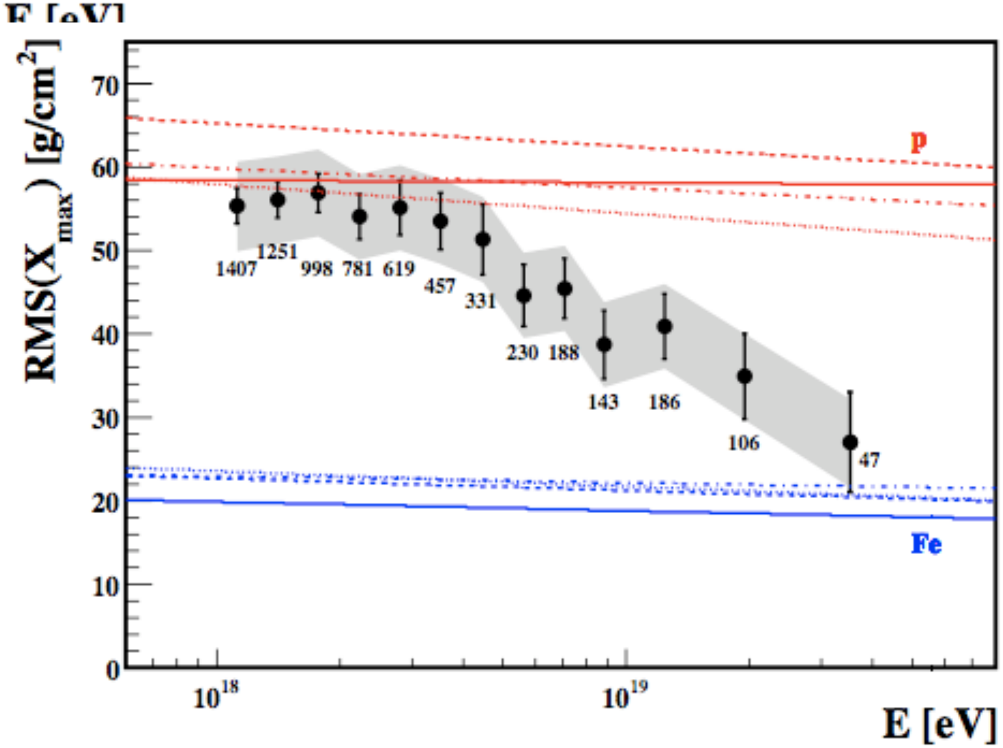
rms(X_{max}) vs. E →

Xmax: depth of shower maximum

Dots: data points. Lines: Monte Carlo models

Fe: shallower showers, less dispersion than p, data indicates increased heavy comp. @ hi.en.

(PAO coll., ICRC 2011, arXiv:1107.4804; ***also talks by Monasor & Ostapchenko here***



(Depth of muons, shower long.devel., etc: same trend)

Rigidity-dependent acceleration: anisotropy expectations

(Lemoine, Waxman, 2009, JCAP 11:009)

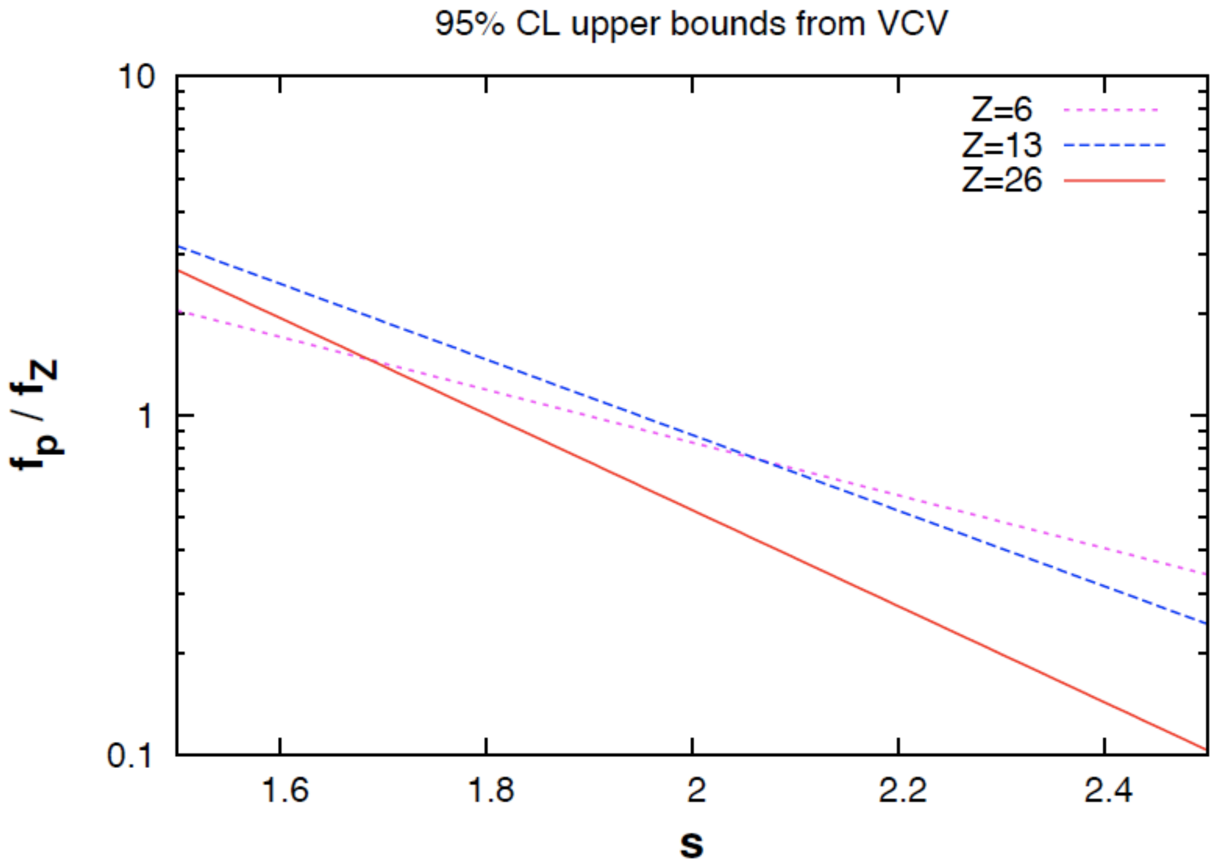
If ***excess*** observed in spatial regions @ VCV AGNs at energies ***E_{th} >5.5 10^{19} eV***, and this is due to ***nuclei Z***, then must expect ***protons*** to show excesses in the same regions at energies ***E/Z.***

Acceleration controlled by rigidity, ⇒ $$\frac{\mathrm{d}n_Z}{\mathrm{d}E} = k_Z \Phi(E/Z)$$

thus $$N_p(> E_{th}/Z) = \frac{k_p}{Z k_Z} N_Z(> E_{th}).$$

If $\Phi \propto (E/Z)^{-s}$, get bounds on the low en. abundance ratio $$\frac{k_p}{k_Z} = \frac{f_p}{f_Z} Z^s.$$

Rigidity-dep. accel. composition: test



(Abreu & PAO coll, arXiv:1106.3048)

obtain a bound

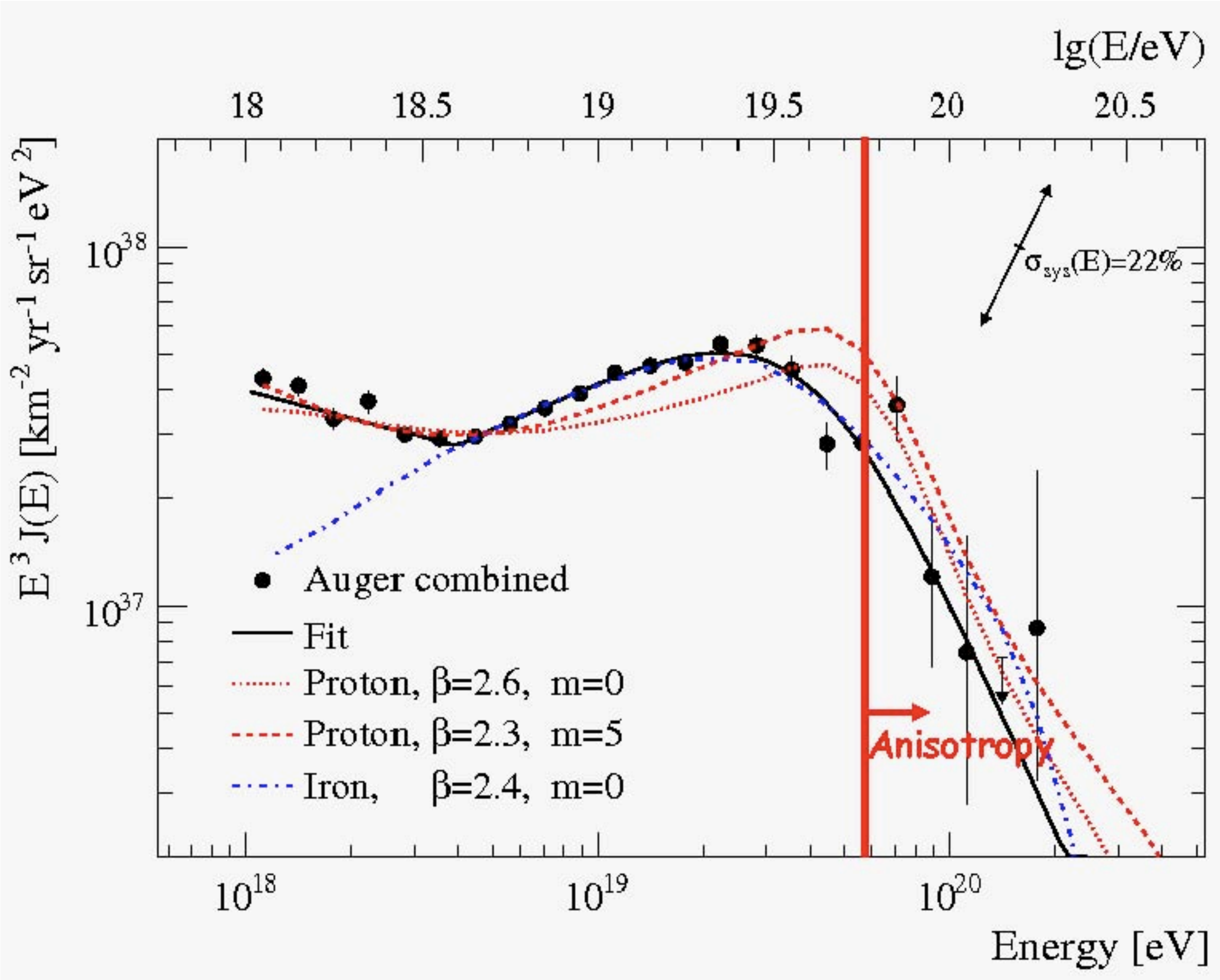
$$(f_p / f_Z) \leq K Z^{2-s}$$

where K~(0.5-2), s=spectral slope

i.e. at odds with heavy composition at high E

Conclusion: ***either*** E>5. 10^{19} eV UHECR are mainly protons, ***or else*** it's all heavy nuclei, also at low E (?...)

Auger spectrum compared to models



(flux mult. by E^3, > 2011)

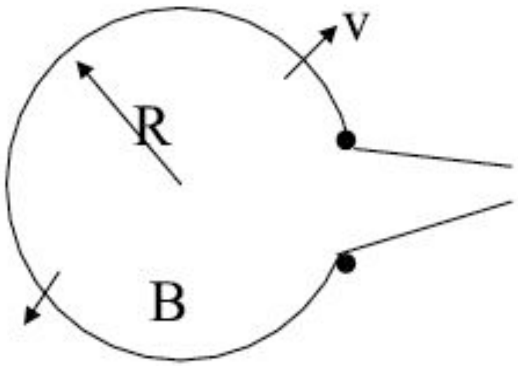
Cut-off: clearly present

BUT: sources? spectrum?

UHECR : maximum energy ?

gyroradius: $r_L \sim ct_{gy} \sim m_p c^2 \gamma / ZeB = \varepsilon_p / ZeB < R$ (*size of accel.*)

or (EM analog):



$$V = \frac{1}{c}\dot{\Phi} \sim \frac{1}{c}\frac{BR^2}{R/\mathrm{v}} = \beta BR$$

$$\rightarrow \varepsilon_p < \beta eBR$$

$$\Rightarrow L > 4\pi R^2 \frac{B^2}{8\pi} v > \frac{1}{2\beta}\left(\frac{\varepsilon_p}{e}\right)^2 c$$

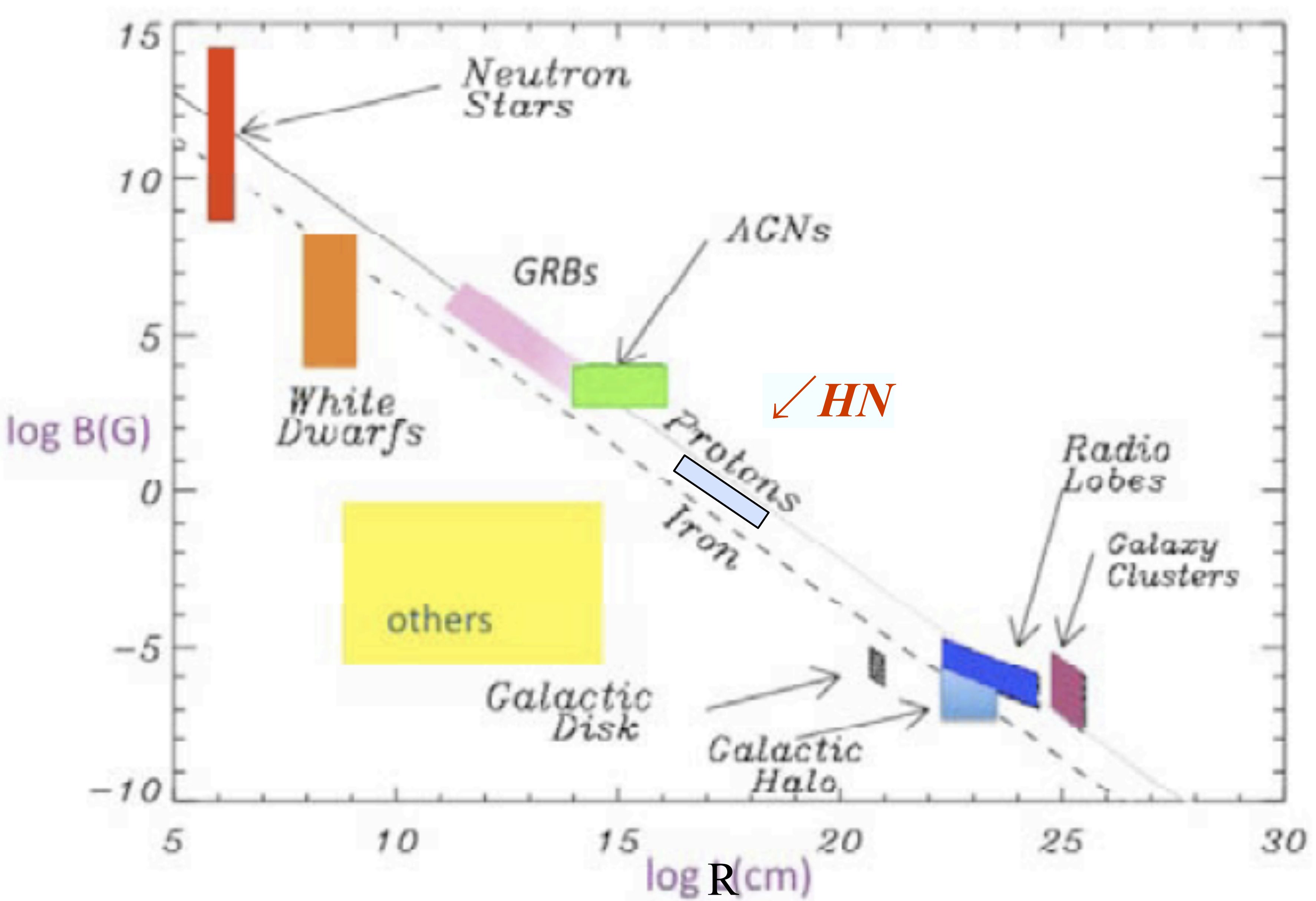
But if relativistic expansion, bulk Lorentz factor $\Gamma >> 1$,
then $\mathrm{time}_{obs} \sim R/c\Gamma$, and $\mathrm{size}_{obs} \sim R/\Gamma$, hence need

$$\Rightarrow L > 2\frac{\Gamma^2}{\beta}\varepsilon^2_{p,20} \times 10^{45}\mathrm{erg/s}$$

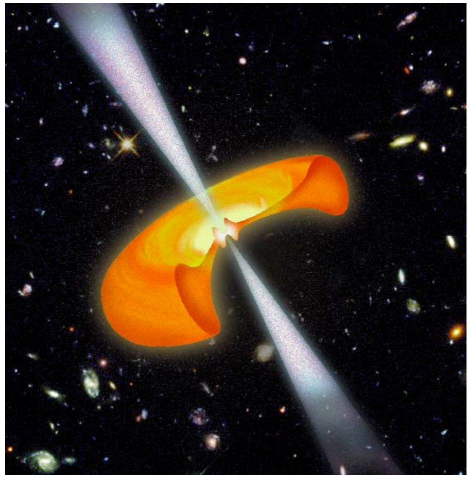
⇒ GRB, AGN..?

(only strongest qualify !)

Maximum E_p for various sources (Hillas plot)



GRB ? E_{max} :



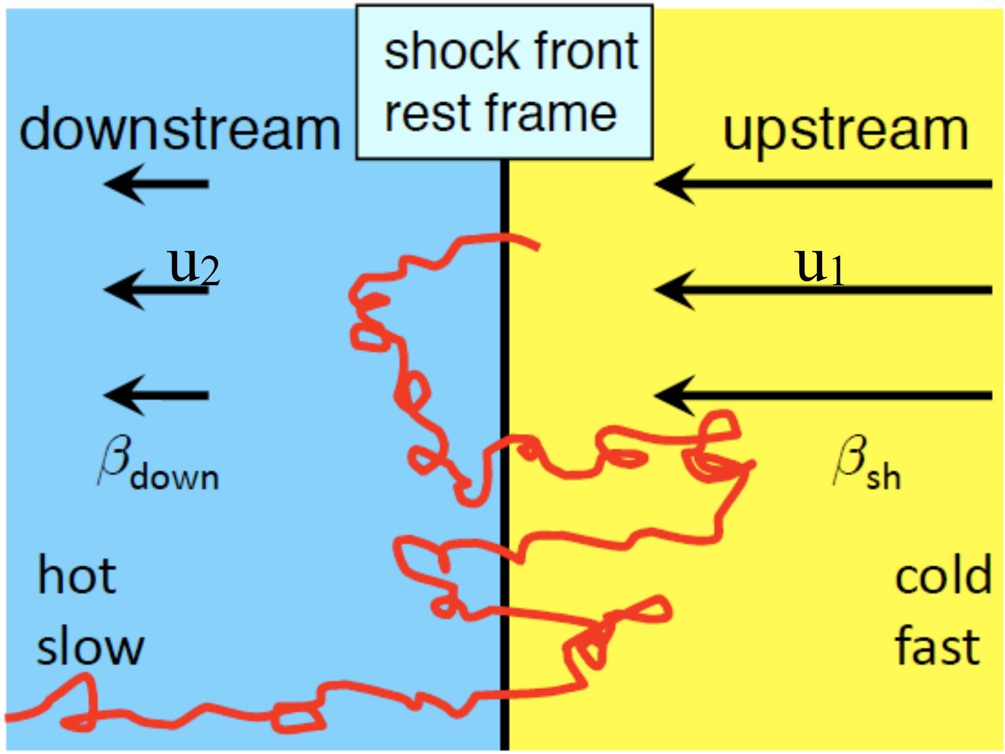
- Require : $r'_L = E'/ZeB' \geq R'$)
- $\Rightarrow$ $E_{max} \sim \Gamma\, Z\, e\, B'\, R'$

- primed: comoving;
- unprimed : lab frame;
- Γ: jet Lorentz factor

- but, what are R', B' for a GRB?
- we have $R' \sim R/\Gamma$; and external shock occurs at R where $E_0 \sim n\, m_p\, c^2\, R_{dec}^3\, \Gamma^2$
  $\rightarrow R \sim R_{dec} \sim (E_0/n m_p c^2)^{1/3}\, \Gamma^{-2/3}$
- for B', energy equip. : $B'^2/8\pi \sim \varepsilon_B\, n\, m_p\, c^2\, \Gamma^2$
  $\rightarrow\ B' \sim \varepsilon_B^{1/2} (8\pi\, n\, m_p\, c^2)^{1/2}\, \Gamma$, so
- $E_{max} \sim Ze(8\pi\varepsilon_B)^{1/2}\, E_0^{1/3}\, (n\, m_p\, c^2)^{1/6}\, \Gamma^{1/3}$, or
- $E_{max} \sim 2\times 10^{20}\ Z\, E_{53}^{1/3}\, \varepsilon_{B,-2}^{1/2}\, \Gamma_2^{1/3}\ n^{1/3}\ eV$

Fermi (shock) acceleration spectrum

Assume: shock, $u/c \ll 1$, $\Delta u/c \ll 1$, scattering ~ isotropic



particles get accelerated as they bounce back and forth across the shock wave

P_{esc} = escape prob. per cycle
f = energy gain per cycle

$$P_{esc} = \frac{u_2 N_2}{(1/4) N_1 c} \simeq \frac{4u_2}{c}$$

$$\bar{f} \simeq \frac{2\Delta u}{c} \equiv \frac{4}{3}\frac{\Delta u}{c}$$

Plausible for non-relat., →
e.g. GRB internal shocks

$$\frac{dN}{dE} = (E/E_0)^{-1-(P_{esc}/\bar{f})} \simeq (E/E_0)^{-2}$$

GRB: energetics OK?

- Luminosity function: $\Phi(L)=(L/L_{*})^{-\alpha}$,
  where α=(0.2, 1.4) for ($L< L_{*}$, $L> L_{*}$) (Wanderman-Piran '10)
- $L_{*} = L_{*,\gamma,iso} \approx 10^{52}$ erg/s (0.01-10MeV)
- $\Delta T \sim 10$ s/(1+z) ~ 4 s (long GRB duration in RF)
- $E_{*,\gamma,iso} \approx L_{*} \Delta T \approx 10^{52.5}$ erg
- $(dn_{GRB}/dt) \approx 10^{-9}$ Mpc^{-3} yr^{-1} (GRB rate @ z=0)
- $Q_{\gamma,GRB} \approx 10^{-9}\, 10^{52.5} \approx 10^{43.5}$ erg Mpc^{-3} yr^{-1}
- $Q_{p,10^{19}eV} = E_p^2\,(dn_p/dE) \approx 10^{43.5}$ erg Mpc^{-3} yr^{-1} ✓

Note: This is if $E_p \sim E_\gamma$. If extrapolate E_p with spectrum -2 down to ~GeV, need E_p~10 E_γ, and $E_{GRB} \sim 10^{53.5}$ erg (OK). But if E_p spectrum is -2.3, need $E_{GRB} \sim 10^{55.5}$ erg (too much)

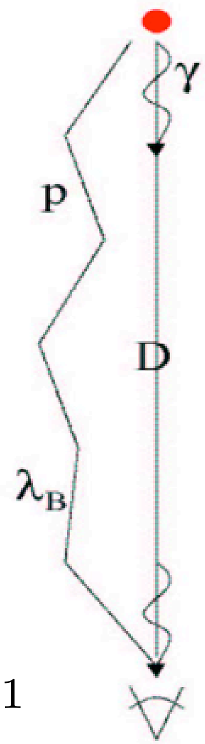
Number of sources?

- $N_{cr} \sim 10^2$ CR events @ $E \geq 10^{19.5}$ eV
- If no repeaters $\Rightarrow$ # sources $N_s > N_{cr}^2$
- Each source produces on avg. $\sim N_{cr}/N_s$ events, so
  $\Rightarrow$ Probability of repeating $P_{rep} \sim N_{cr}^2 / N_s << 1$
- $\Rightarrow$ Require $N_s \gtrsim 10^4$ sources (all-sky) ,
  $\Rightarrow$ source density: $\boldsymbol{n_s \gtrsim 3x10^{-4}\ Mpc^{-3}}$
  (at $E > 10^{19.5}$ eV, within D<200 Mpc) ; while, e.g.,
- Density of normal galaxies: $\boldsymbol{n_G \sim 10^{-2}\ Mpc^{-3}}$
- Density of "active" galaxies: $\boldsymbol{n_{AGN} \sim 10^{-4}\ Mpc^{-3}}$
- Rate density of GRB : $\boldsymbol{(dn_{GRB}/dt) \sim 10^{-9}\ Mpc^{-3}\ yr^{-1}}$

But: protons in random intergal. magnetic field

$$\theta \simeq 0.3^o \left(\frac{D_f}{1Mpc}\right)\left(\frac{f}{0.1}\,\frac{d}{100Mpc}\,\frac{\lambda}{10kpc}\,\frac{\epsilon_B}{0.01}\right)^{1/2}\left(\frac{E/Z}{10^{20}eV}\right)^{-1}$$

Mean deflection angle (Kotera, Lemoine 08 PRD 77:123003), where



- f= volume filling fraction of magn. filaments
- D_f = filament diameter
- λ = field coherence lenght
- ε_B = mag. energy density/thermal energy density

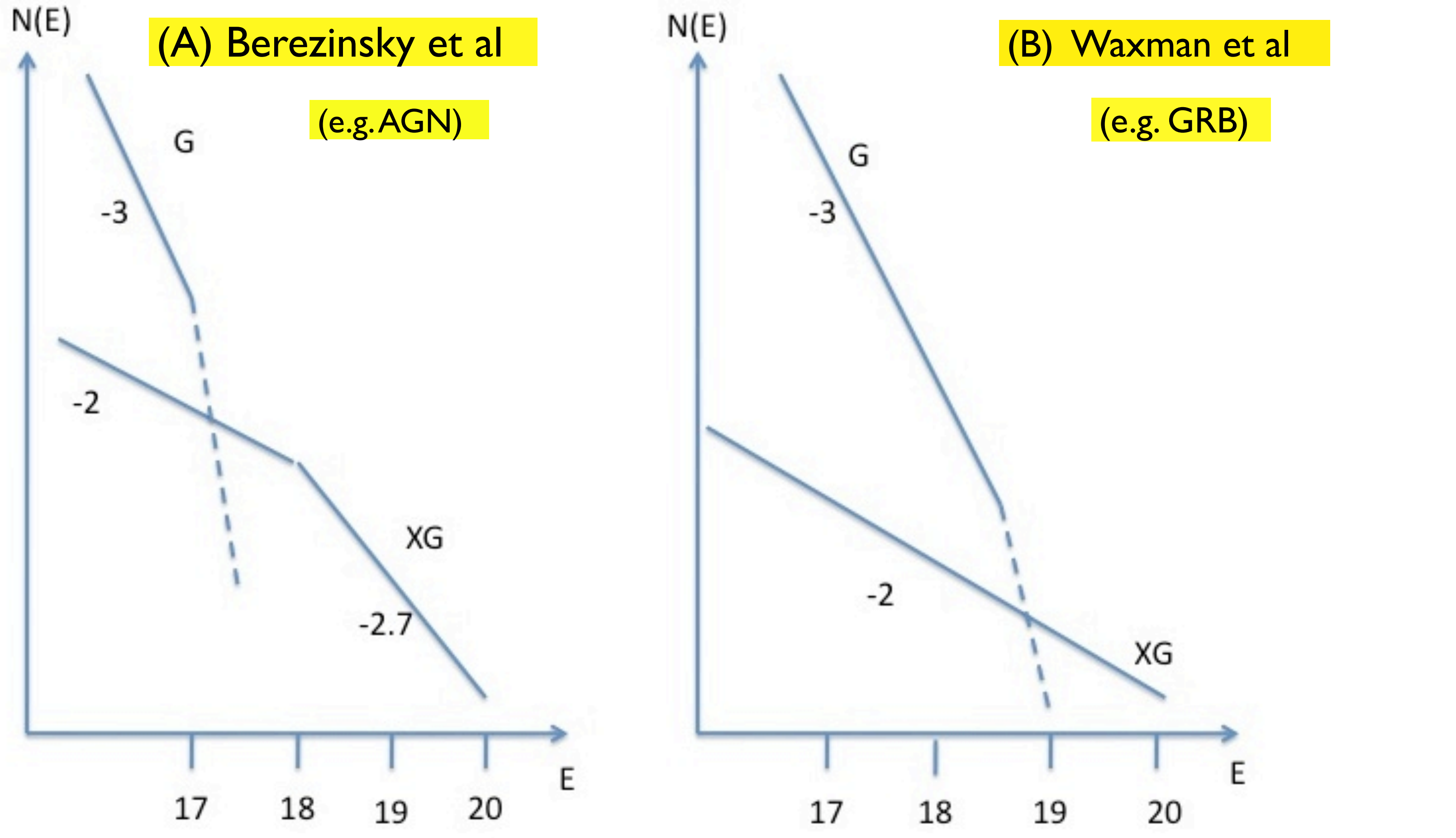
and dispersion time delay

$$\Delta t(E,d) \simeq \theta^2 \left(\frac{d}{c}\right) \simeq 2\times 10^5\text{yr}\left(\frac{d}{200Mpc}\right)\left(\frac{E/Z}{10^{19.5}eV}\right)^{-1}$$

Hence, if transient sources:

- $n_{GRB} \sim (dn_{GRB}/dt)\ .\ \Delta t(E,d) \sim 10^{-9}\ .\ 2 \times 10^{5} \sim 2 \times 10^{-4}$ Mpc^{-3} , ✔ comparable to minimum number of sources required, n_s
- Could do similar argument with flaring AGNs, but AGN flare rate unknown inside 200 Mpc.
- Or might do similar argument with hypernovae in normal gals. inside 200 Mpc (but HN can only accel. heavies up to 10^{20} eV)

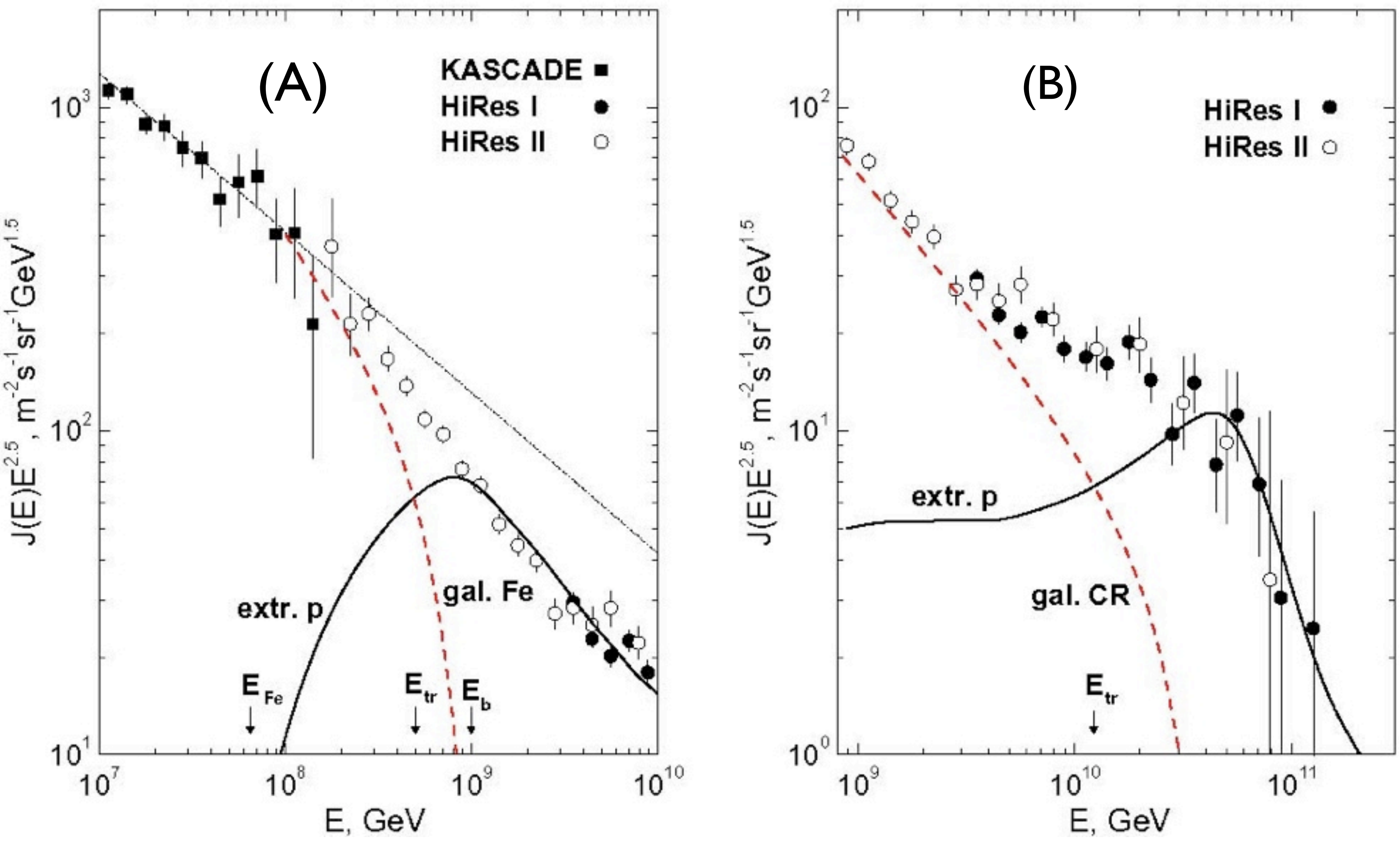
Two ≠ views on G-XG spectral shape

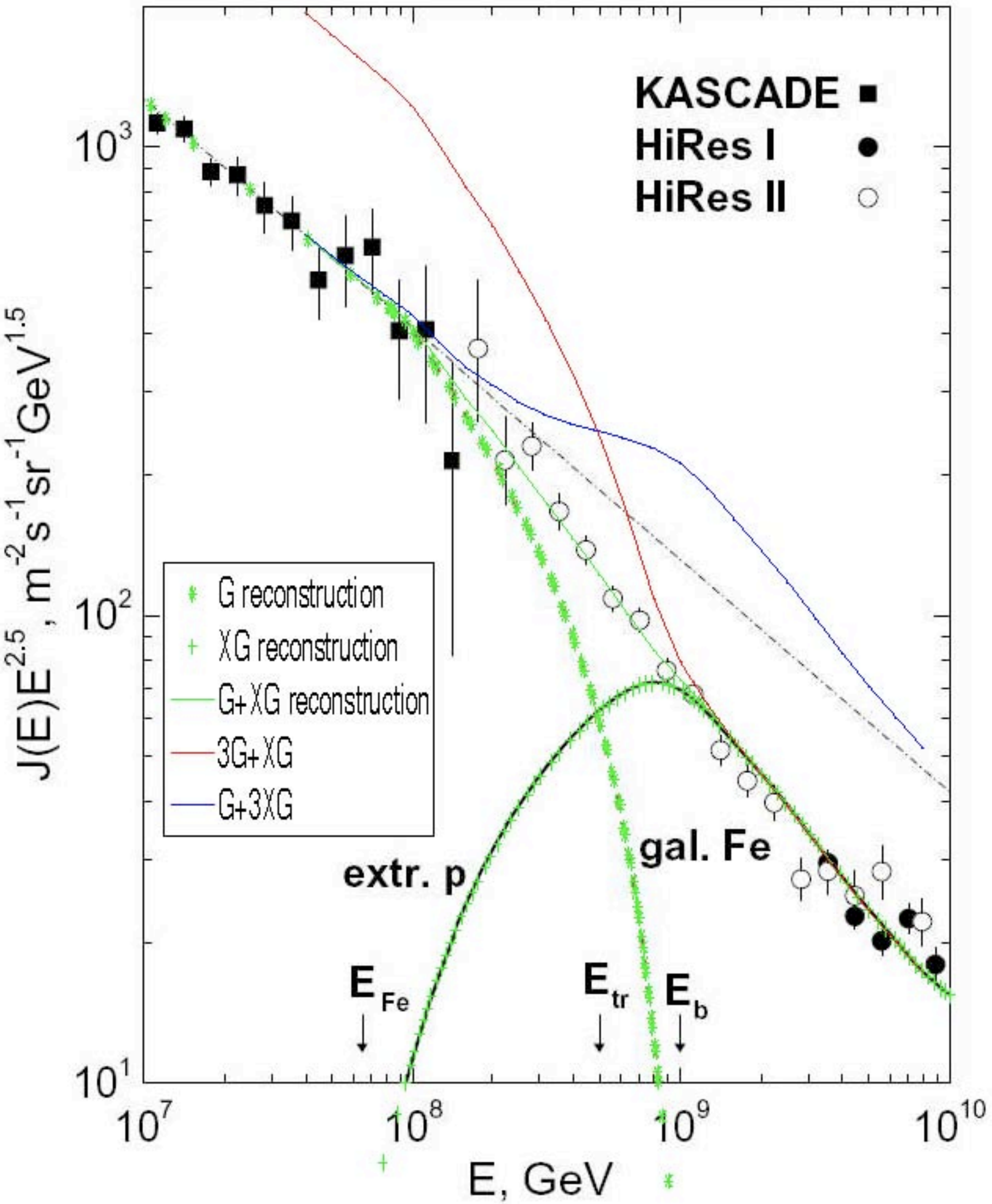


G: "low" cutoff
XG: -2 to avoid energy blow-up
-2.7 to get p,γ→p,e+,e- "dip"

G: "high" cutoff
XG: -2 from diff.shock accel.

... and how they mesh





(A): fine tuning?

(Katz, Budnik, Waxman 09, JCAP 03, 020)

- Any smooth match between two steep (G, slope 3 and XG, slope 2.7) spectra requires fine tuning (flattening caused by dip)
- E.g. if increase XG by 3 or G by 3, would get extra flattening bumps, not seen
- Whereas match between G slope 3 and XG slope 2 always lead to a smooth flattening

but, (B):

need G ~ XG @ E~10^{19} eV; and it is unclear what G source can get up to that energy

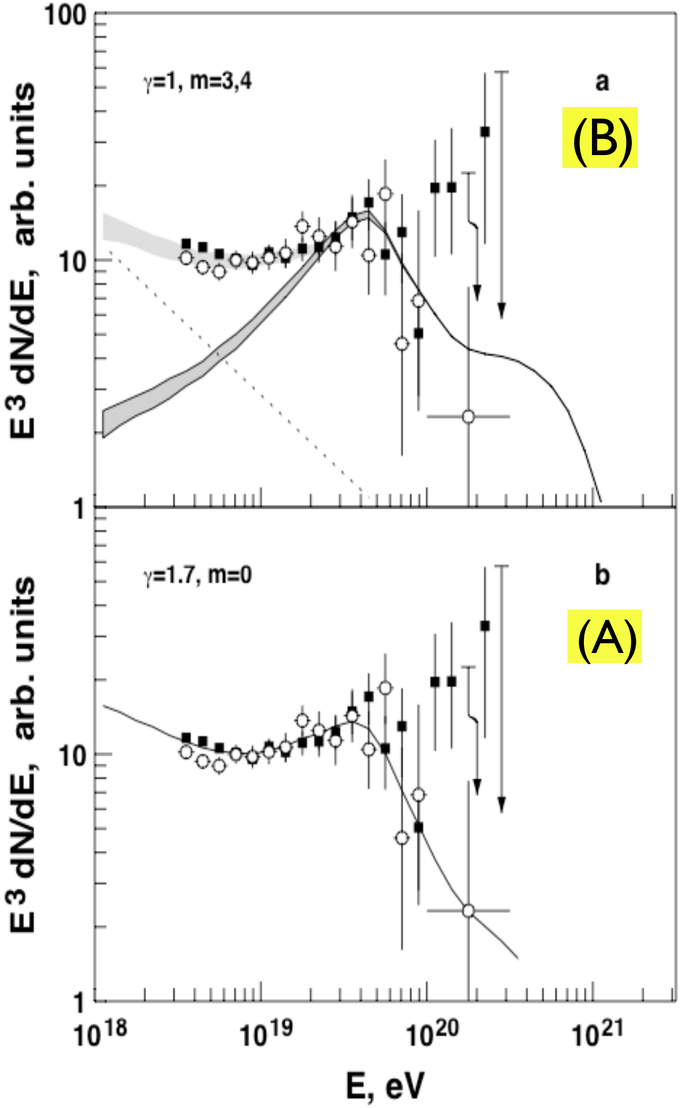
Cosmogenic Neutrinos

2 ≠CR models
↓ same GZK CR fit

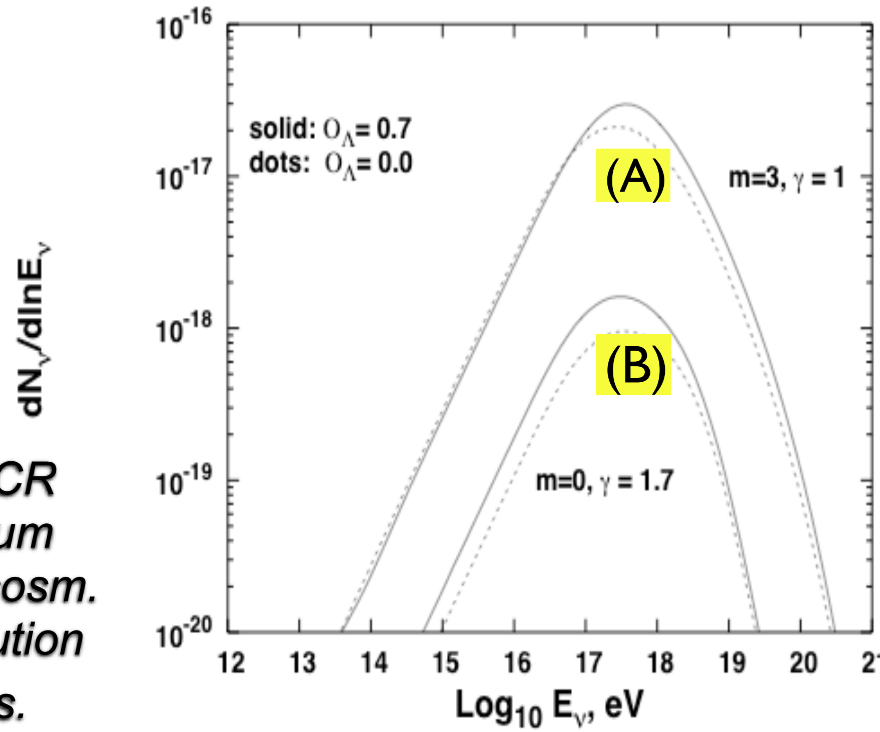
from **GZK CRs** *to* **GZK νs**

get $E_\nu \gtrsim 10^{19}$ *eV ?*

But … lead to ≠ *GZK ν flux* ↓



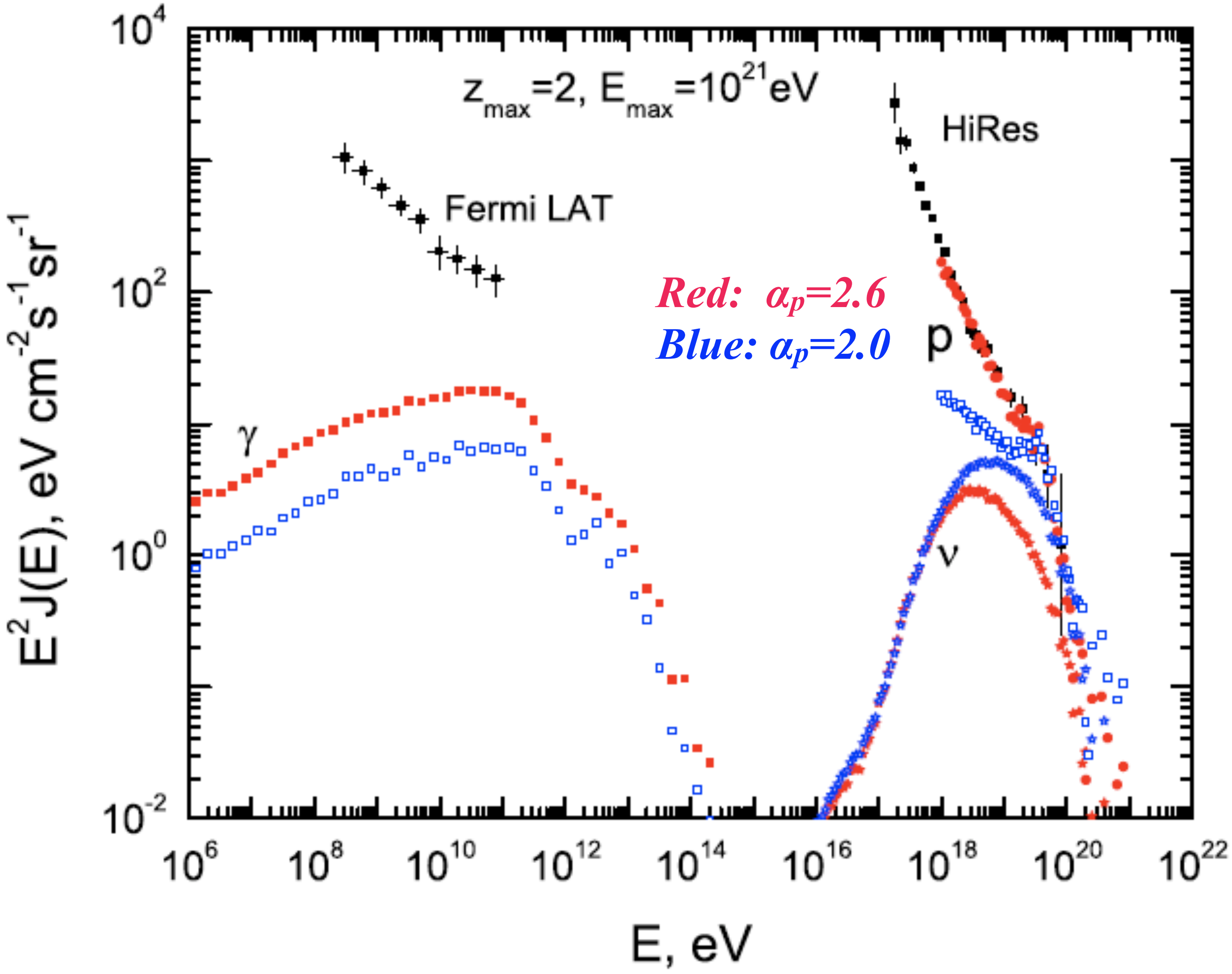
Can infer GZK CR injection spectrum and/or source cosm. luminosity evolution via their GZK νs.



Seckel & Stanev 2005, PRL 95:1101

“A” and “B” UHECR constr. from LAT

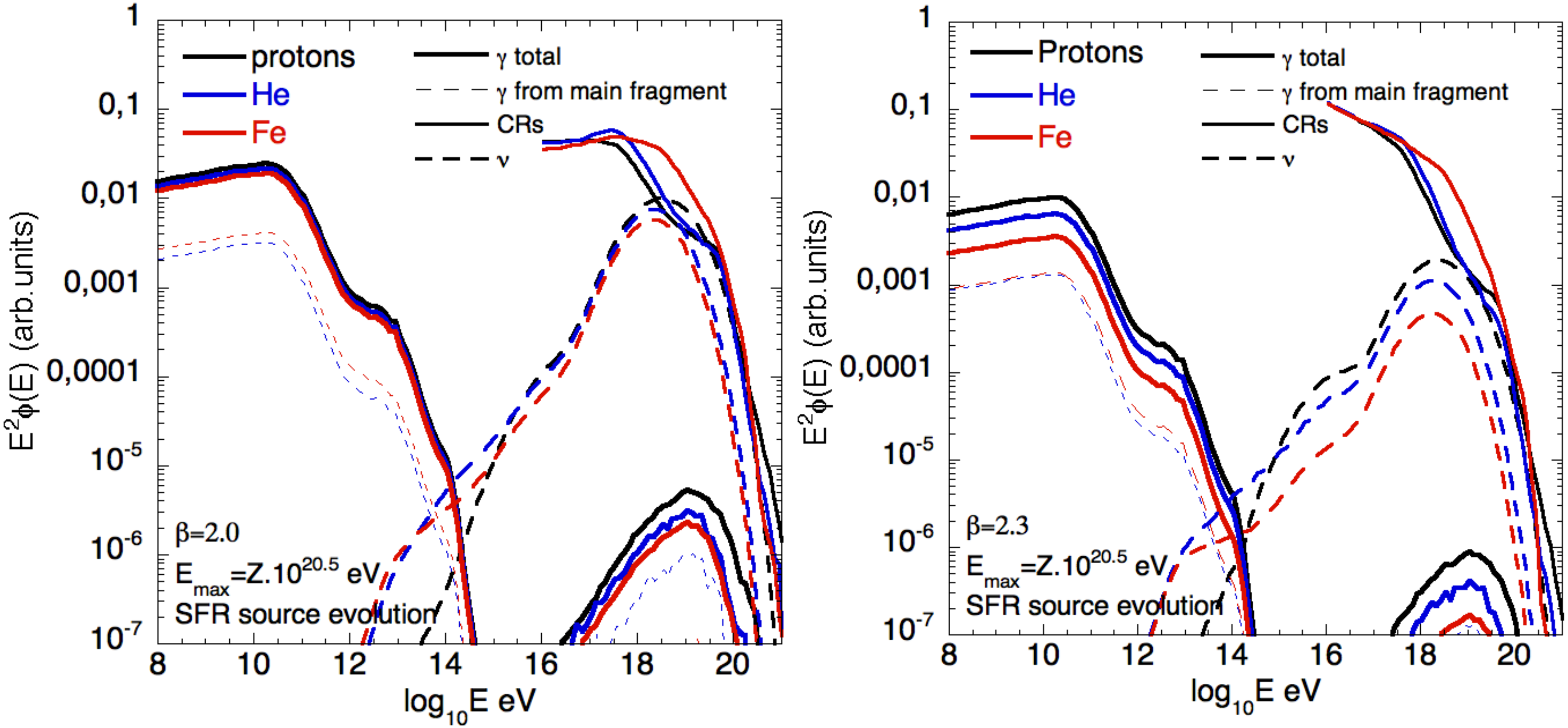
Berezinsky et al, 2011, Phys.Lett.B, 695:13



- Use FERMI obs. diffuse γ-ray backgr. to check if compatible w. EM cascade production
- Can restrict the CR spectrum & evolution law
- Evol. $(1+z)^m$ with m>3 are excluded
- ←Plotted is m=0

Generic GZK PL UHECR cosmogenic γ,ν

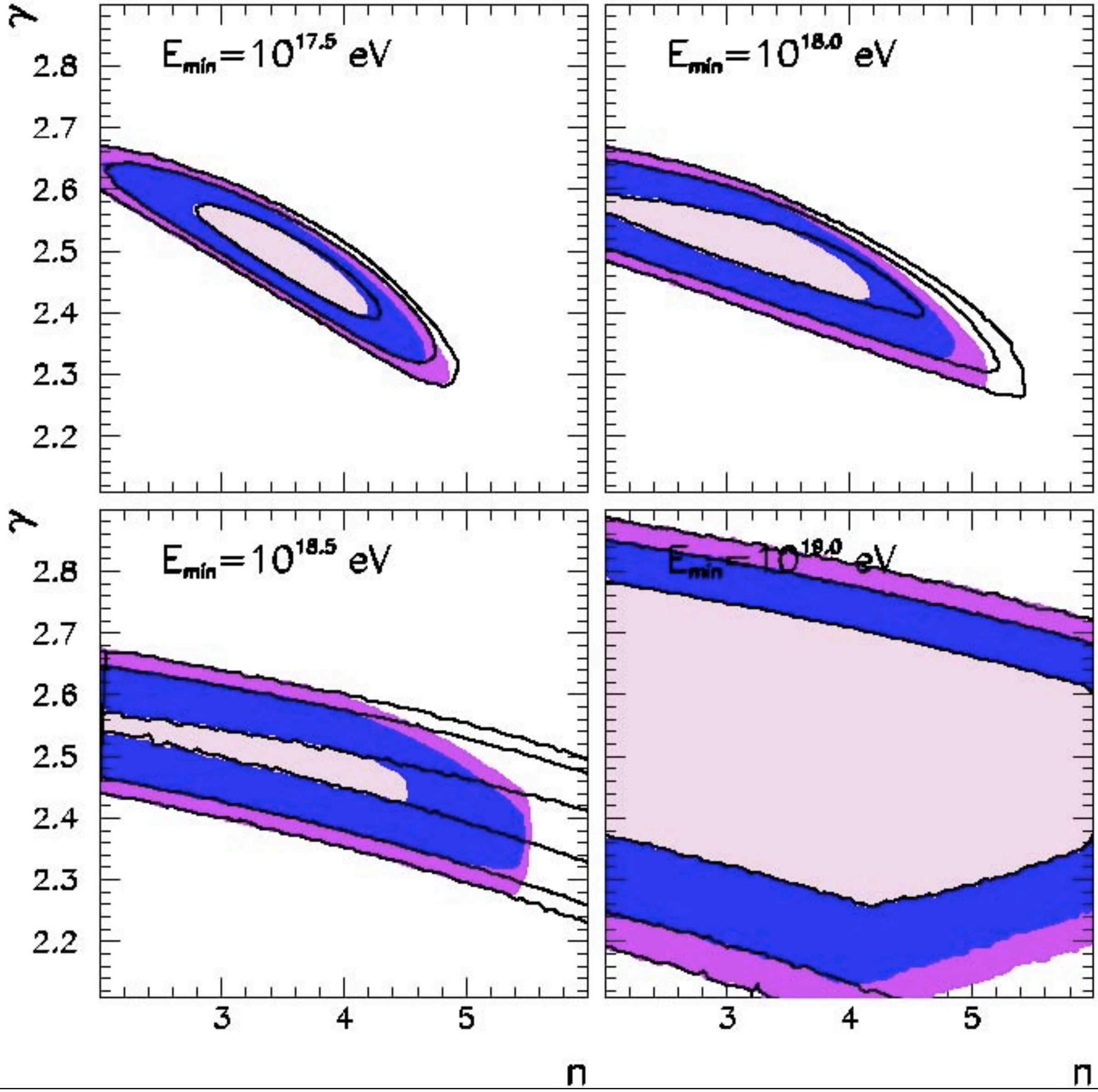
Decerprit & Allard (1107.3722)



- Difference between secondaries from PL with β=2 and β=2.3 are significant
- Also differences between secondaries from different compositions
- Current diffuse γ-bkg ***not*** constraining, could expect obs. diffuse ν-bkg

Generic HiRes-LAT joint GZK fits

Ahlers et al, 2010, ApPh 34:106

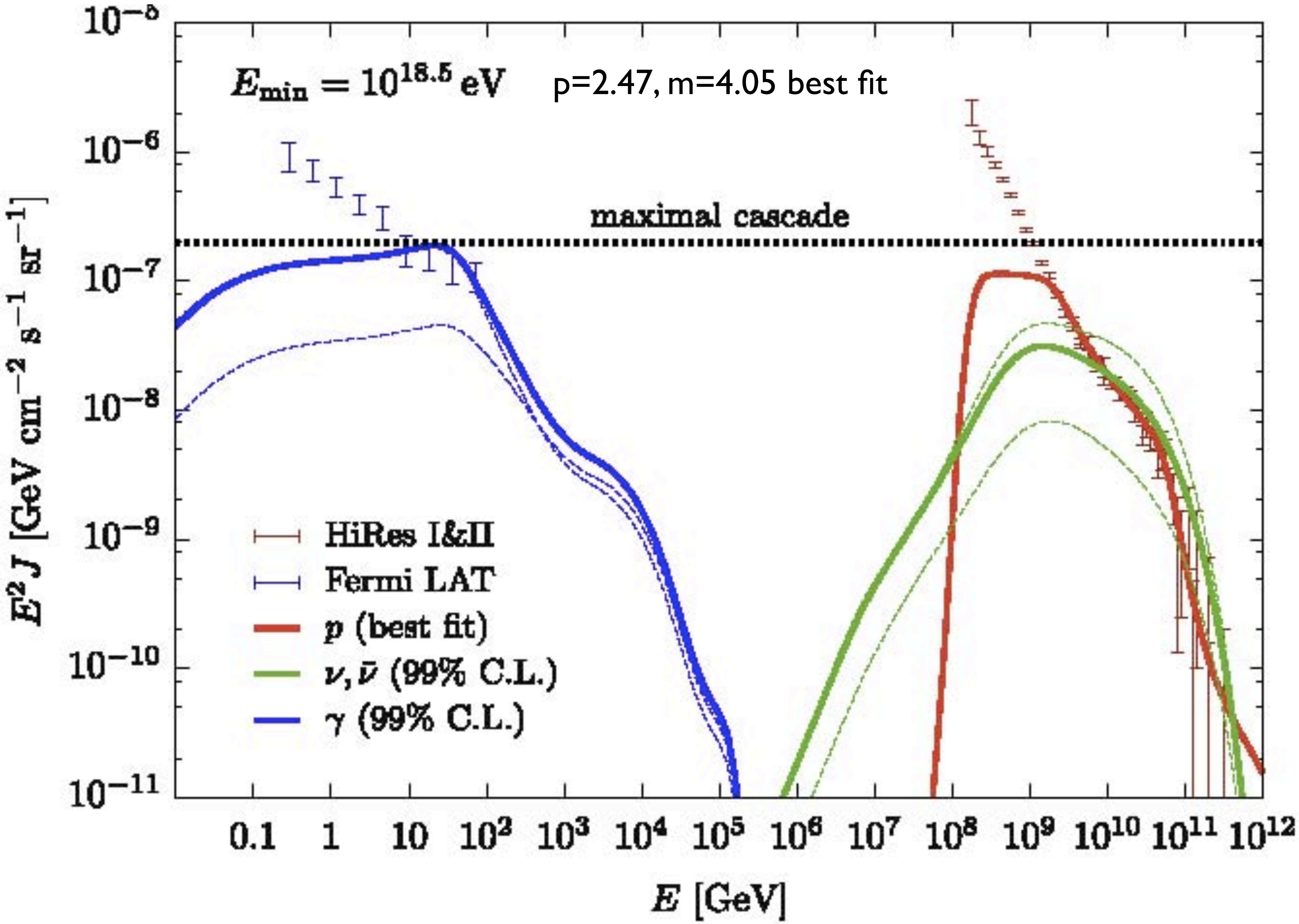


γ≡p : proton diff. index
n≡m : redshift evol. index

- Use Fermi LAT diffuse γ-ray flux to constrain, via EM cascades, the allowed proton diff. spectral index p and redshift evol. index m
- Pink 68%, Blue 85%, Magenta 99% CL, includ. LAT constraint
- (Black lines: same CL limits but without LAT constraints)

HiRes-LAT joint GZK fits

Ahlers et al, 2010, ApPh 34:106



UHECR Auger/HiRes spectr. params. with LAT constraints for GRB evol.

Ahlers, et al, arXiv:1103.3421

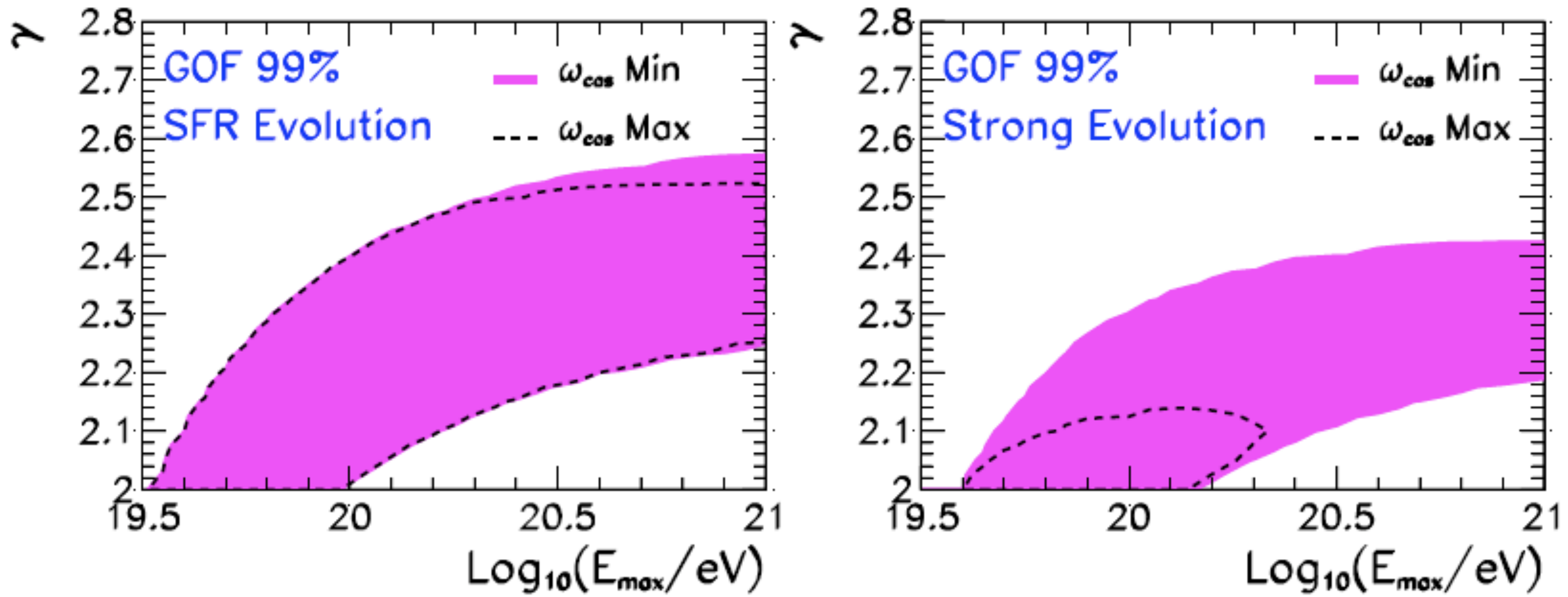
$\gamma \equiv p$: proton diff. index

$H_{sfr}(z) = (1+z)^{3.4}$ $z<1$

$(1+z)^{-0.3}$ $1<z<4$

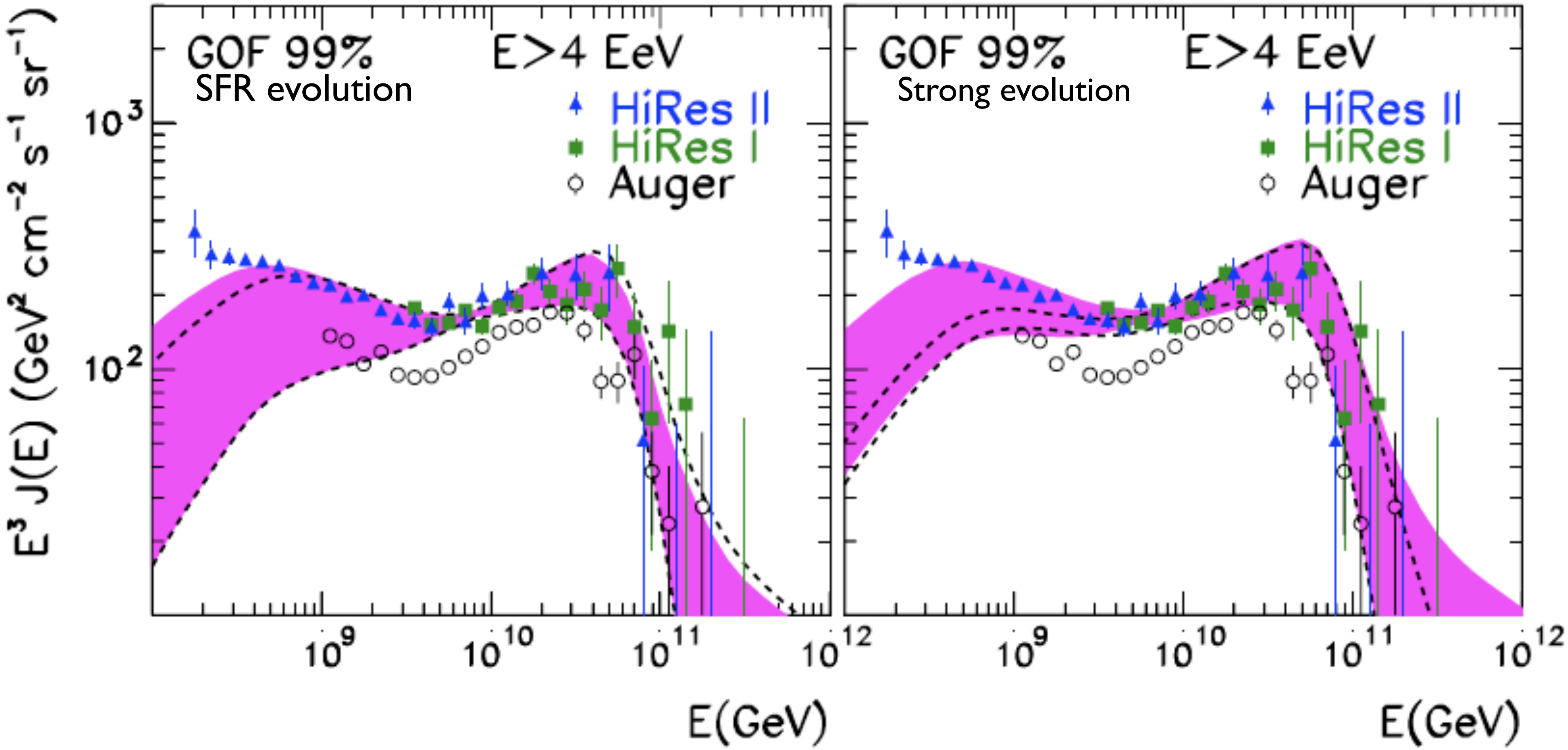
$(1+z)^{-3.5}$ $z>4$

$H_{strong} = H_{sfr}(1+z)^{1.4}$



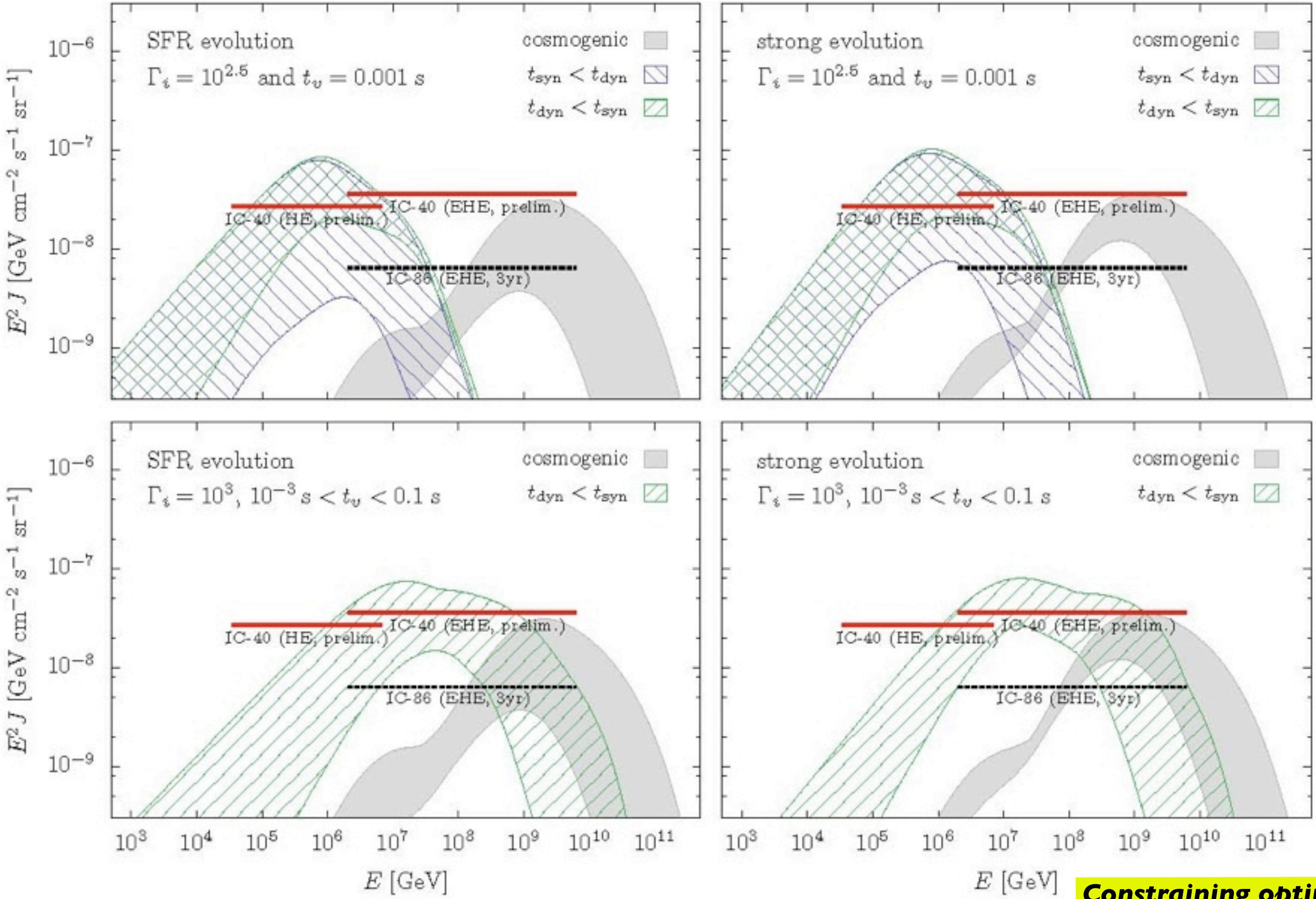
UHECR spectra w. LAT constraints

Ahlers, et al, arXiv:1103.3421



Nu-flux from GRB *internal* shock CR satisfying LAT constraints

Ahlers, et al, arXiv:1103.3421



- ***Assume*** CR are accelerated in GRB ***internal*** shocks
- Escaping CRs are ***neutrons***
- Satisfy observed HiRes CR spectr.
- $p\gamma \rightarrow \pi^0 \rightarrow 2\gamma$
- EM cascades also satisfy constraints set by FERMI LAT diffuse γ- bkg
- $p\gamma \rightarrow \pi^+ \rightarrow \nu$, are not limited by GZK horizon
- Steeper CR spectra γ= p > 2.2-2.4 give ***higher*** nu-bkg.
- Even the flat γ= p=2 spectra are ***pushing IC3-40 limits***

Constraining optimistical internal shock proton acceleration model!

Another alternative: Hypernovae?

← *supernova*
SN 1006 (X-ray)

- Hypernovae: similar but ~ 10-10^2 times ***more energetic***; and portion of ejecta reaches ≥ ***semi-relativistic*** speed, possibly anisotropic

~500 times the rate density of GRBs

Hypernova ejecta as UHECR sources

(Wang et al, 2007, PRD 76:3009; Budnik et al, 2008, ApJ 673:928)

- Type Ib/c but isotropic equiv ***E_{HN}~3-5x10^{52} erg***
- ***500*** times GRB rate, and ***10^{-1}-10^{-2}*** usual SNIa ***rate***
- ***Semi-relativistic (v~c, or Γβ≥1)*** comp. in outflow (shock accelerates down the envelope gradient)
- Assume shock expands in WR progenitor wind, magnetic field fraction ε_B of equipartition

$$B^2/8\pi = 2\epsilon_B \rho_w(R) c^2 \beta^2 \qquad \rho_w(R) \propto R^{-2}$$

Max. CR energy: $$\varepsilon_{\max} \simeq ZeBR\beta = 4\times 10^{18} Z \times \epsilon_{B,-1}^{1/2} \left(\frac{v}{10^{10}\mathrm{cm s^{-1}}}\right)^2 \left(\frac{\dot M}{3\times10^{-5}\mathrm{M_\odot yr^{-1}}}\right)^{1/2} v_{w,3}^{-1/2}\mathrm{eV}$$

→ Proton: E_{max} ~10^{19} eV, and Fe: E_{max} ~2.6 10^{20} eV

Is flat spectrum result of CR escape from relativistic shocks (GRB, HN)?

Katz, Mészáros, Waxman 2010,
JCAP 10:012 (arXiv:1001.0134)

Approximations - assume:

- Relativistic ejecta of approximately uniform velocity
- CRs accelerated in ext. shock have constant fraction f of post-shock thermal energy, indep. of radius R
- ***Instantaneous*** spectrum produced is $N(E) \propto E^{-2-x}$
- Expand into some medium of density $\rho \propto R^{-\delta}$
- Max. CR energy E_{max} is some power of radius, and the CRs at $E \equiv E_{max}$ are the ***only ones that escape*** upstream, and these are the CRs observed at E

- CR energy escaping @ E_{max}: $Q = E^2 N(E) \sim f\,\eta\,E_{kin}$ where $E_{kin} \propto \Gamma^2 M \propto \Gamma^2 R^{3-\delta}$, $\eta \propto (E_{max}/E_{min})^{-x}$, and $E_{max} \propto B' R \propto \rho^{1/2} \Gamma R$, $E_{min} \propto \Gamma^2$
- $\Gamma \propto R^{-(3-\delta)/2}$ (impulsive, energy-conserving)
- $E_{kin} \propto \Gamma^2 R^{3-\delta} \propto R^0 \propto E^0$; assume $f \sim$ const.
- $E = E_{max} \propto \rho^{1/2} \Gamma R \propto R^{-1/2}$, $E_{min} \propto \Gamma^2 \propto R^{-(3-\delta)}$, so
- $\eta \propto (E_{max}/E_{min})^{-x} \propto (\rho^{1/2} R/\Gamma)^{-x} \propto R^{-[(5-2\delta)/2]x} \propto E^{(5-2\delta)x}$,
- $Q = E^2 N(E) \propto \eta \propto E^{(5-2\delta)x}$, and $N(E) \propto E^{-2+(5-2\delta)x}$, i.e.
- $\boldsymbol{N(E) \propto E^{-2+5x}}$ ($\delta=0$), and $\boldsymbol{N(E) \propto E^{-2+x}}$ ($\delta=2$), in both cases ***harder than -2!*** ($E > E_{*CR} \sim 10^{19}$ eV)

(Reason: E_{min} decreases with radius faster than E_{max}, so at later times, corresponding to lower high end $E_{max}=E$, there is less escaping CR energy, i.e. less CRs at low E, i.e. flatter spectrum.)

- *and*, after ejecta becomes non-relativistic ($E < E_{*CR} \sim 10^{19}$ eV): escaping spectrum ≡ instant. injected spectrum: $\boldsymbol{N(E) \propto E^{-2-x}}$

(2010, JCAP 10:012 ; arXiv:1001.0134)

Or another alternative: RQ AGNs

Pe'er, Murase, Mészáros, 2009, PRD 80, 123018 (0911.1776)

- Could be that culprits are radio-quiet **(RQ) AGNs**
- Enough number inside GZK radius (10x more common)
- Evidence for small jets in RQ AGNs
- Evidence for heavy CR composition (X_{max} vs. E)
- Can accelerate **heavy elements** to right GZK energies, $E_{max} \sim ZeBR \sim 10^{20} Z_{26} B_{-3} R_{10}$ eV (if $B \sim 10^{-3}$ G, $R \sim 10$ pc)
- Can survive photo-dissociation
- Heavy elements have larger rms. deviation angles
- Correlation with matter (gal) distribution is good.

Outlook

- ***The sources of the UHECR are still unknown***
- ***They are almost certainly astrophysical sources (not TD)***
- ***GRB remain good candidates, together with AGN, maybe HNe, MGR***
- ***Will increasingly constrain such possibilities with GeV and TeV photon observations***
- ***Will learn even more if & when astrophysical UHENUs are observed from any type of source***
- ***Constraints from diffuse (and intrasource) γ-ray emission will be very useful, and may remain for a long time the main constraint***
- ***Composition will also provide important clues, as will***

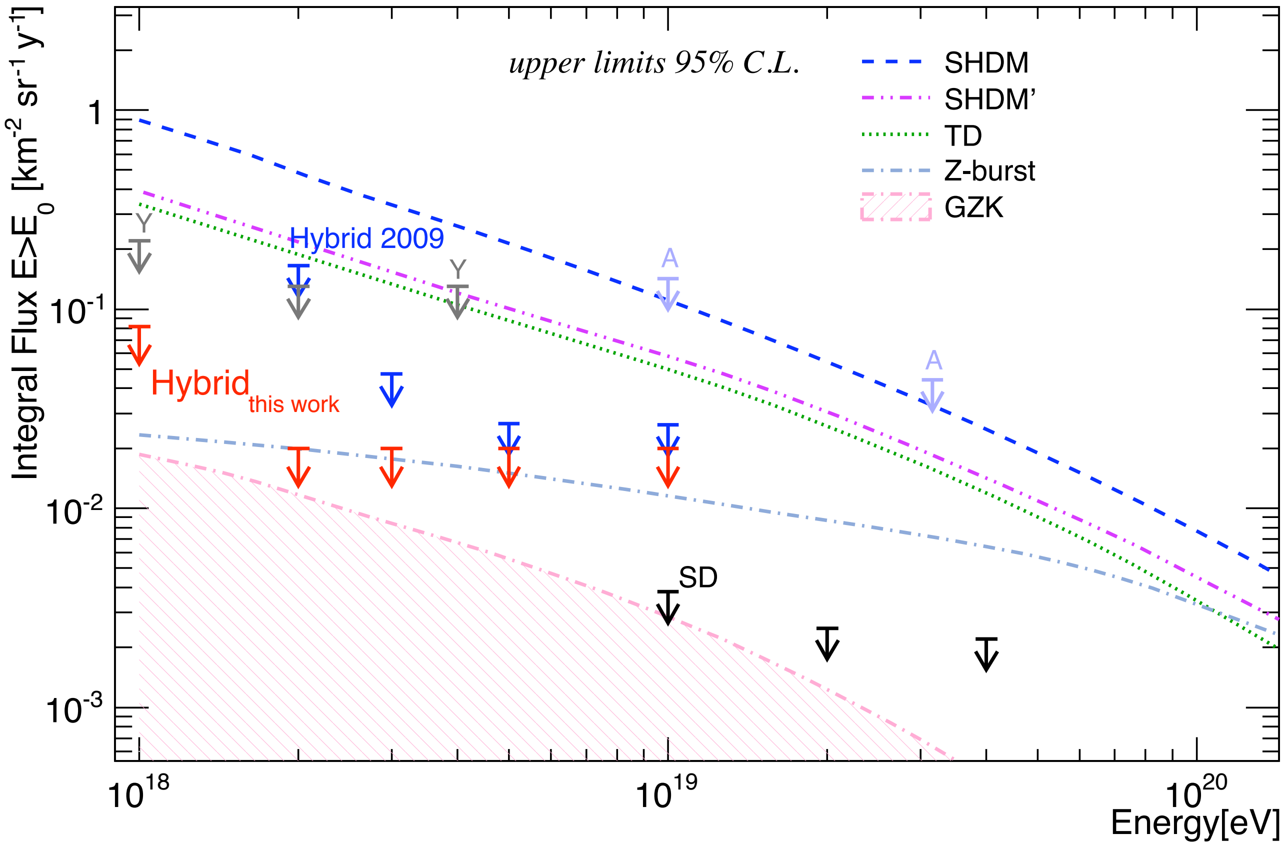


Figure 5: Upper limits on the photon flux above 1, 2, 3, 5 and 10 EeV derived in this work (red arrows) compared to previous limits from Auger (SD [1] and Hybrid 2009 [7]), from AGASA (A) [19] and Yakutsk (Y) [20]. The shaded region and the lines give the predictions for the GZK photon flux [2] and for top-down models (TD, Z-Burst, SHDM from [2] and SHDM' from [21]). The Hybrid 2009 limits on the photon fractions are converted to flux limits using the integrated Auger spectrum.

Auger ***photon fraction*** (ICRC'11)

- Top-Down (TD) largely ruled out
- Z-burst (maybe?)
- GZK photons: compatible