Gamma-ray bursts & ultrahigh energy cosmic rays

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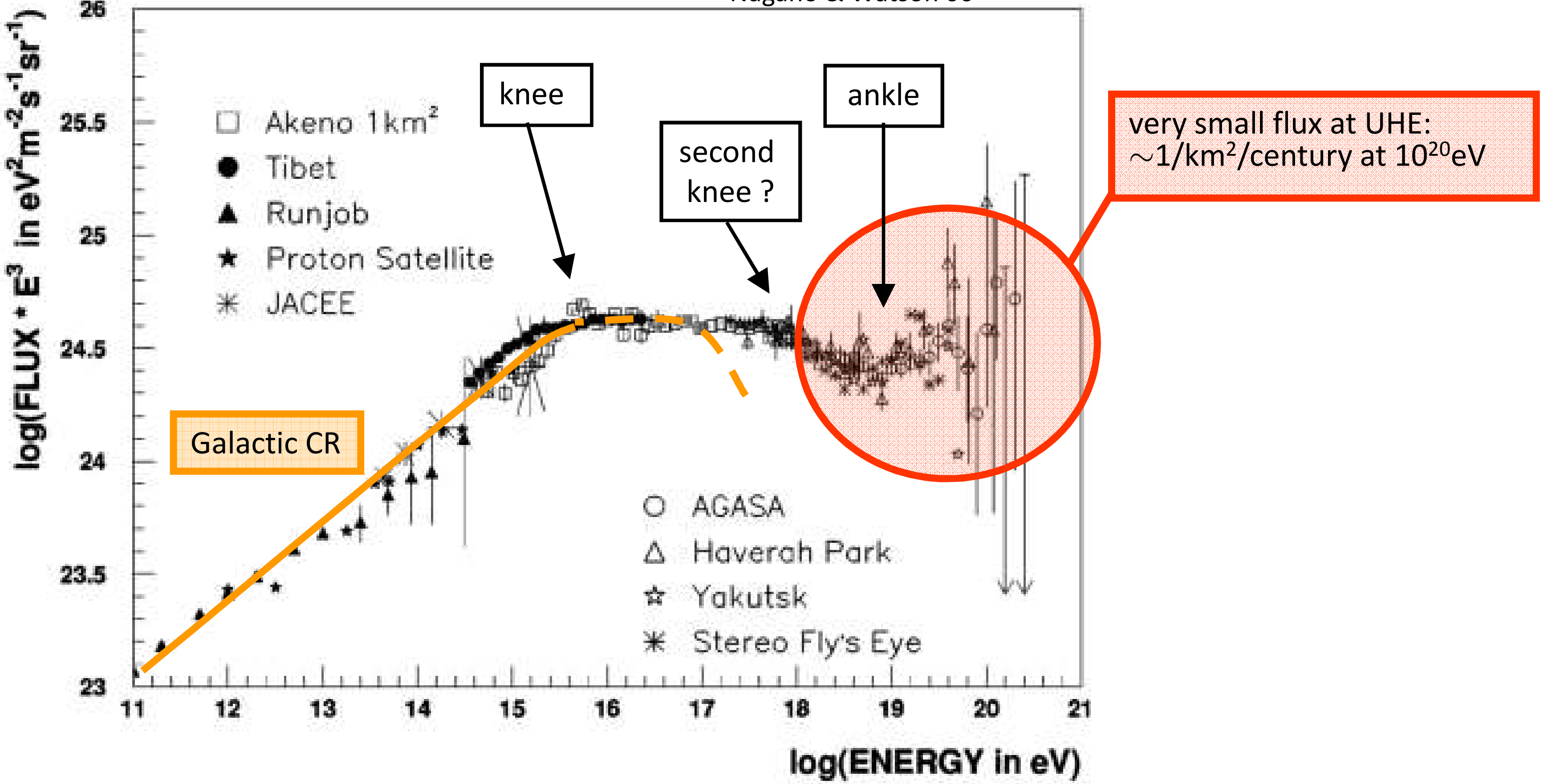
Nagano & Watson 00



Many questions ... a few hints...

- **What is the source of ultrahigh energy cosmic rays ?**

  → what is the fundamental acceleration process to ultrahigh energies?

  [... quite a few scenarios for acceleration in GRB outflows...]

- **Where does the cosmic ray spectrum stop?**

  → HiRes and Auger have detected a high energy cut-off at the expected location for the Greisen-Zatsepin-Kuzmin cut-off $\sim 6\ 10^{19}$ eV

  [... fits well with all astrophysical models of UHECR origin, GZK cut-off ⇔ sources are distributed on cosmological scales...]

- **What are ultrahigh energy cosmic rays: protons, nuclei, photons, neutrinos?**

  → the giant air showers are typical of hadronic showers

  → HiRes sees protons at UHE, Auger sees an increasing fraction of heavies...?

  [... one generally expects protons, but a heavy enriched composition cannot be ruled out for GRB: what injection mechanism? ...]

- **Should we expect to see the source in the arrival directions of UHECR?**

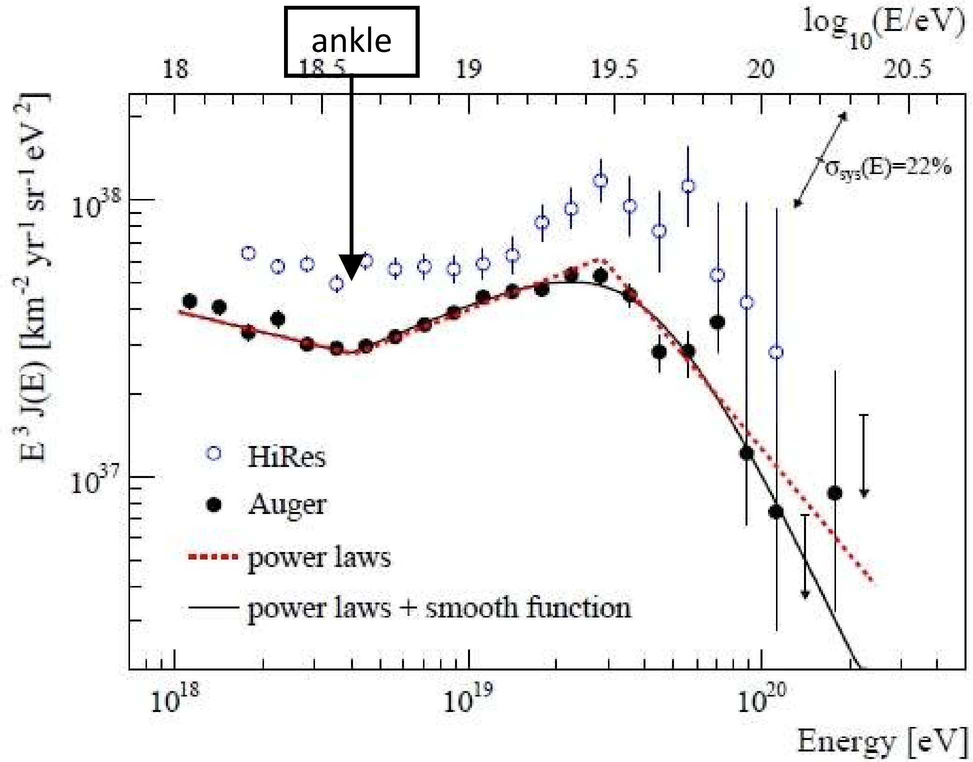
  → what are the effects of the Galactic and extra-galactic magnetic fields?

  → no powerful source seen in the arrival directions of highest energy CR...?

  → Auger has reported 99% c.l. detection of anisotropy of arrival directions!

  [... no counterpart expected for GRB, but anisotropies up to magnetic deflection..]

Many questions ... a few hints...



Auger 2010

HiRes 2010

<u>Greizen-Zatsepin-Kuzmin cut-off:</u> CMB becomes opaque to pion production through p+$\gamma_{cmb} \rightarrow \pi$ + ... for E $\gtrsim$ 6 10^{19} eV

... detecting the GZK cut-off $\Leftrightarrow$ UHECR are protons (or heavy nuclei) and sources are distributed on cosmological scales

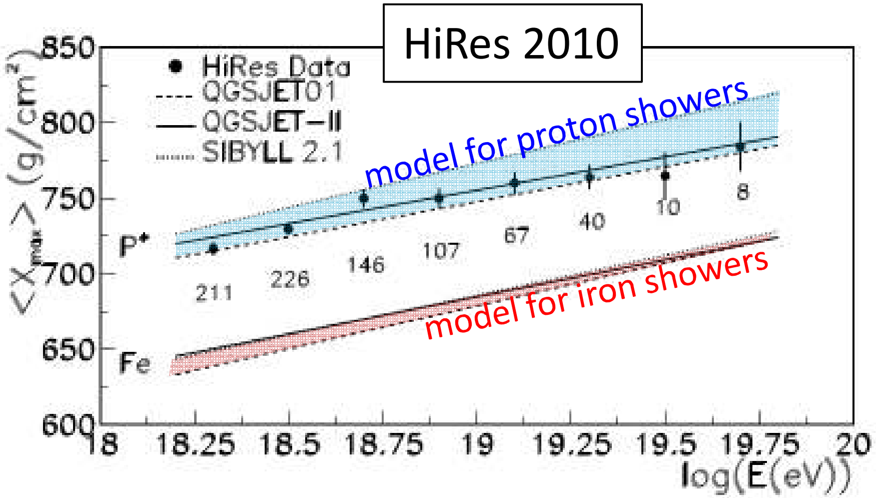
... **BUT** this cut-off might also represent the maximal energy at the source...

Many questions ... a few hints...

- What is the source of ultrahigh energy cosmic rays ?

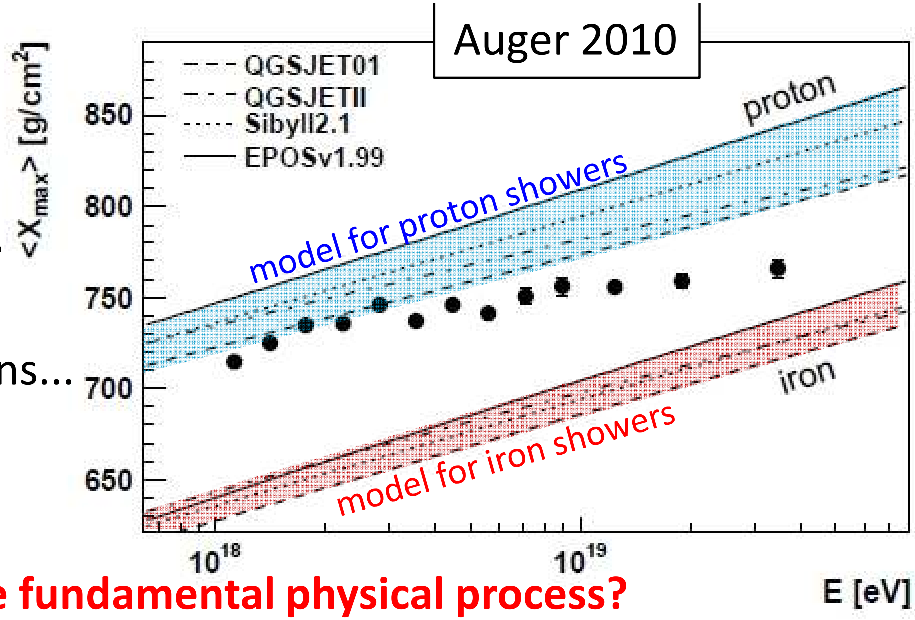
HiRes:

light composition above ankle



Auger:

composition becomes **heavier** above ankle...
also seen in shower fluctuations...
but various observables are inconsistent...

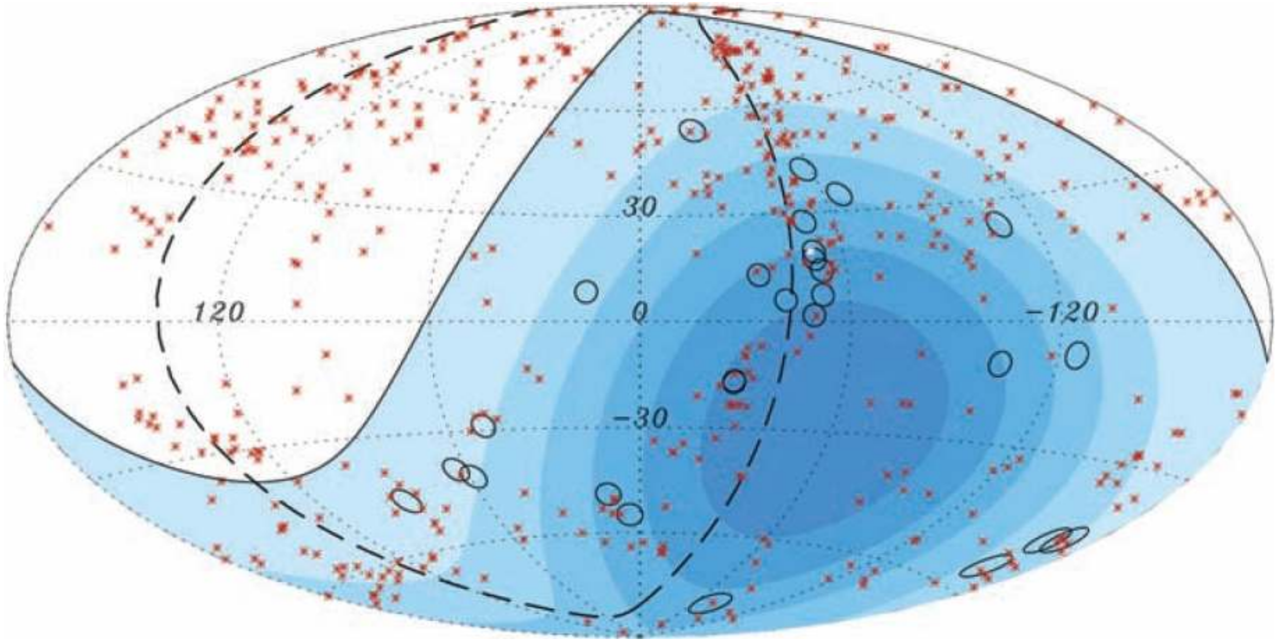


... discrepancy related to some fundamental physical process?
... a proton or iron composition bears a crucial impact on phenomenology...

? any signal from arrival directions of UHECR ?

Many questions ... a few hints...

▶ What is the source of ultrahigh energy cosmic rays ?



Auger (07,08) has reported excess correlation of UHECR arrival directions with nearby (weak) AGN -- **as of 2009, 99% c.l. rejection of isotropy of arrival directions ...**
... but HiRes rejects correlation with galaxy and AGN catalogs at 95% cl...

excess of events in the region of Centaurus A... but note that direction of Cen A coincides with direction of largest amount of extra-galactic matter within 200Mpc!

arrival directions (as of 2008) agree with a distribution according to large scale structure (Kashti & Waxman 08)

Many questions … a few hints…

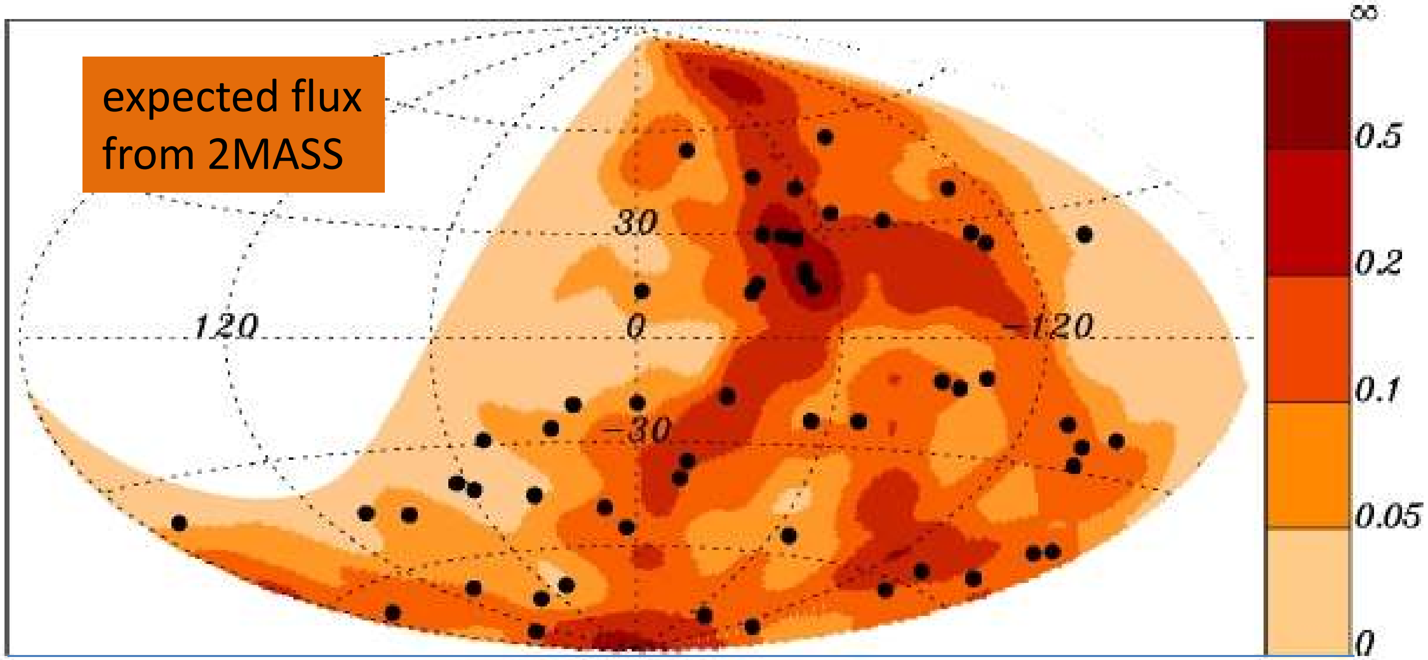
- What is the source of ultrahigh energy cosmic rays ?

Latest results of Auger (10):

→ 69 events above 5.6×10^{19} eV, rejects isotropy of arrival directions at 99% c.l. when correlated to VC-V AGN catalog

→ isotropy rejected only at 90% c.l. when looking at angular auto-correlations of events

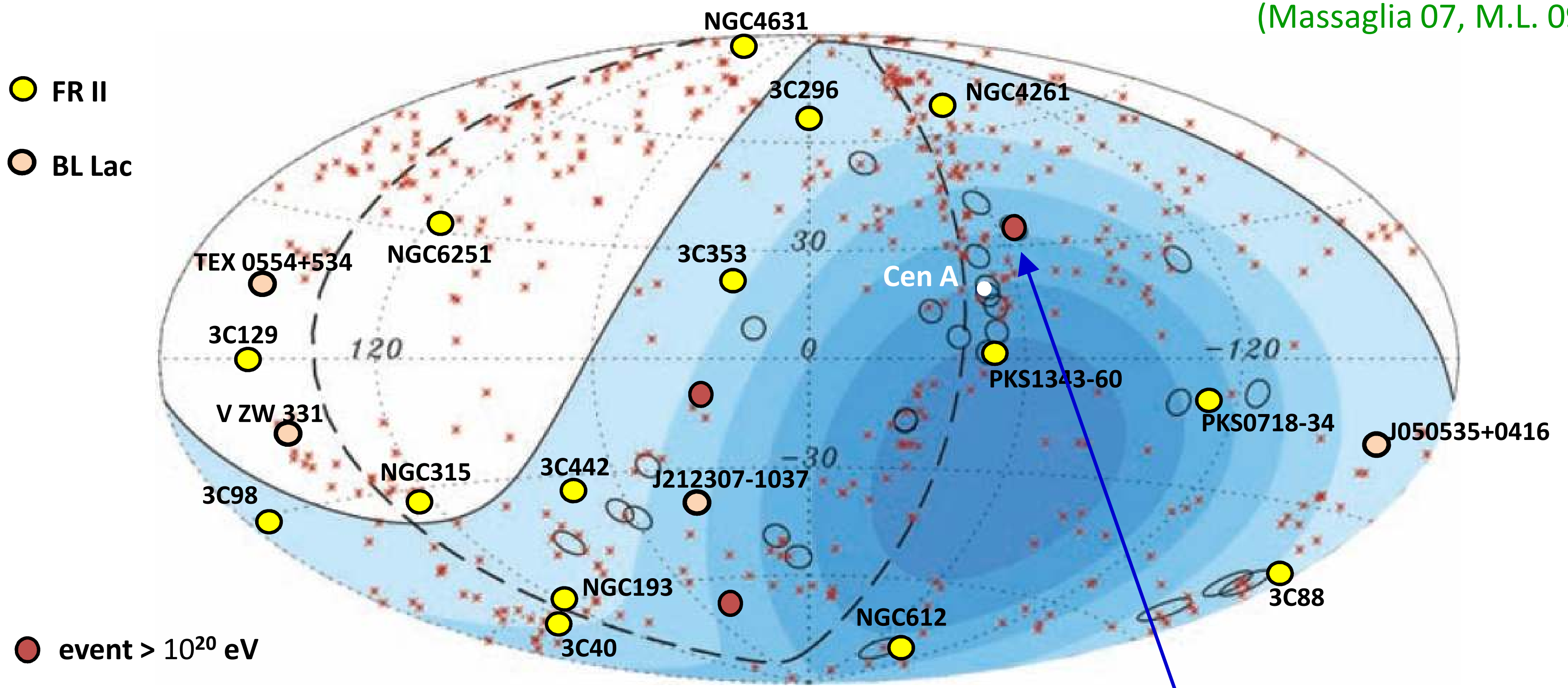
→ excess in the direction of Centaurus A (also of Centaurus supercluster) maintained



Auger events above 6 10^{19} eV and powerful AGN

▶ Distribution on the sky of FR-II galaxies located within the horizon of >6 10^{19} eV particles:

(Massaglia 07, M.L. 09)



highest energy event : E = 1.48 $\pm$ 0.27 $\times$ 10^{20} eV$\pm$ 22%

... if UHECR are protons, the lack of correlation with giant AGN favors sources camouflaged in ordinary galaxies: gamma-ray burst, young magnetars, ...?

... note that the last GRBs of Cen A could reproduce part of the observed excess around Cen A (M. L. & Waxman 09)...

Many questions ... a few hints...

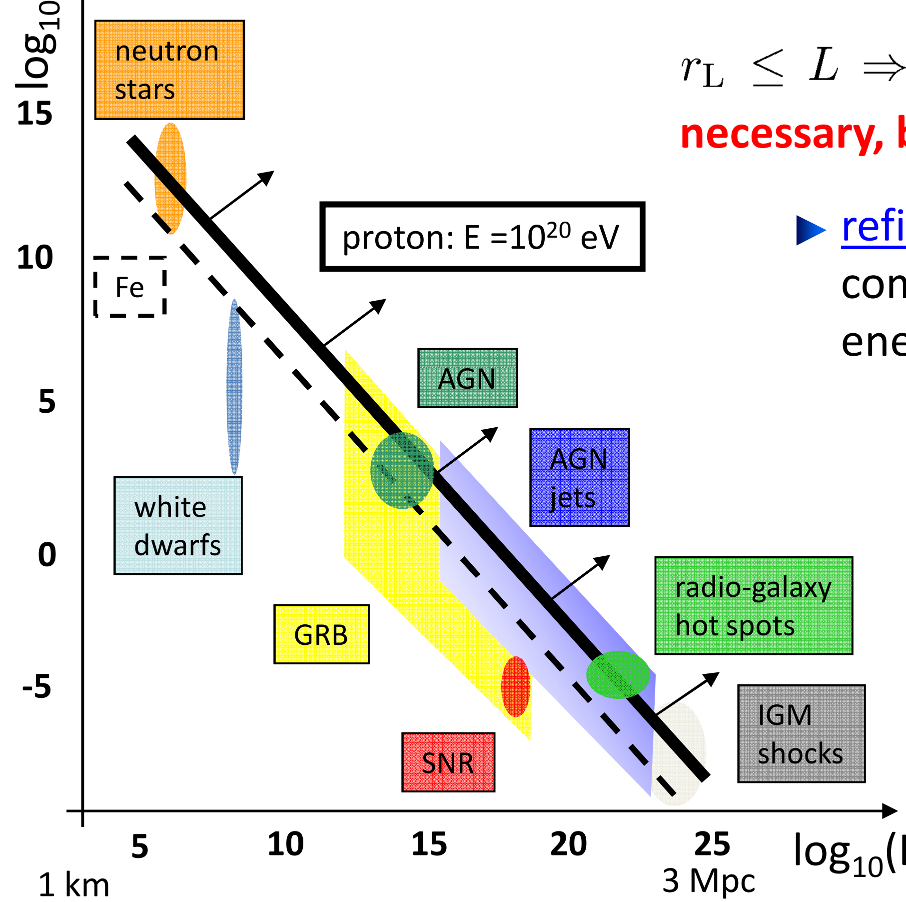
▶ What is the source of ultrahigh energy cosmic rays ?

▶ <u>a simple criterion:</u> to find which object ***might*** be a source of UHE cosmic rays:

a particle gets accelerated as long as it is confined in the source:

$$r_L \leq L \Rightarrow E \leq 10^{20}\,\mathrm{eV}\, Z B_{\mu G} L_{100\,\mathrm{kpc}}$$ Hillas 84

necessary, but by no means sufficient!



▶ <u>refined criterion:</u>

compare acceleration timescale with energy loss timescale and escape timescale

$$t_{\rm acc} \leq t_{\rm loss},\quad t_{\rm esc}$$

t_{acc} depends on acceleration mechanism...

t_{esc} depends on magnetic field...

t_{loss} depends on environment...

⇒ requires an object by object study...

Norman et al. 95

... magnetars, gamma-ray bursts and giant radio-galaxies are promising candidates...

→ any signal from arrival directions of UHECR ?

Acceleration – a luminosity bound

(Lovelace 76, Norman et al. 95, Waxman 95, 05, Lyutikov & Ouyed 05, M.L. & Waxman 09)

- A generic case: acceleration in an outflow

  - acceleration timescale (comoving frame): $t_{\rm acc} = \mathcal{A}\, t_{\rm L}$

    $\mathcal{A} \gtrsim 1$, $\mathcal{A} \sim 1$ at most:

    - for non-relativistic Fermi I, $\mathcal{A} \sim g/\beta_{sh}^2$ with $g \gtrsim 1$

  - time available for acceleration (comoving frame): $t_{\rm dyn} \approx \dfrac{R}{\beta\Gamma c}$

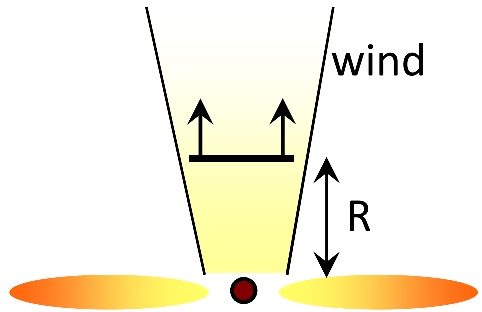
  - maximal energy: $t_{\rm acc} \leq t_{\rm dyn} \Rightarrow \boxed{E_{\rm obs} \leq \mathcal{A}^{-1} ZeBR/\beta}$

  - 'magnetic luminosity' of the source: $L_B = 2\pi R^2 \Theta^2 \dfrac{B^2}{8\pi}\Gamma^2 \beta c$

  - lower bound on total luminosity: $L_{\rm tot} \geq 0.65 \times 10^{45}\, \Theta^2\Gamma^2\mathcal{A}^2\beta^3 Z^{-2} E_{20}^2\, {\rm erg/s}$

    10^{45} ergs/s is robust: for $\beta \to 0$, $\mathcal{A}^2\beta^3 \geq 1/\beta \geq 1$

    for $\Theta\Gamma \to 0$, $L_{\rm tot} \geq 1.2 \times 10^{45}\, \mathcal{A}\beta \dfrac{\kappa}{r_{\rm L} c} Z^{-2} E_{20}^2\, {\rm erg/s}$



- Lower limit on luminosity of the source: $L_{\rm tot} > 10^{45}\, Z^{-2}\, {\rm erg/s}$

  low luminosity AGN: $L_{bol} < 10^{45}$ erg/s

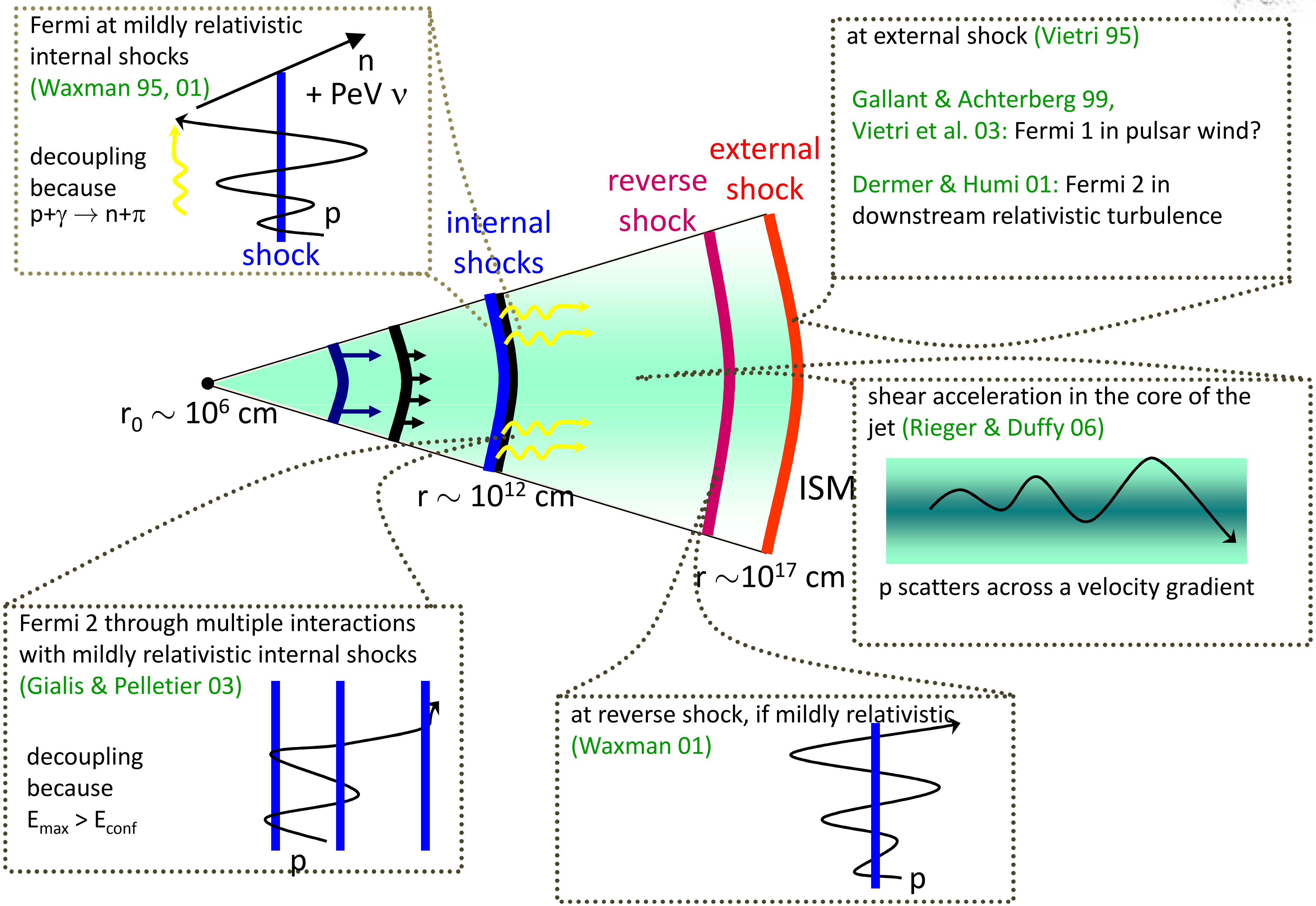
  Centaurus A: $L_{jet} \sim 10^{43}$ erg/s

  high luminosity AGN: $L_{bol} \sim 10^{45}$-10^{48} erg/s

  gamma-ray bursts: $L_{bol} \sim 10^{51}$ erg/s

$\Rightarrow$only most powerful AGN jets, GRBs or magnetars

Acceleration to UHE in gamma-ray bursts fireballs



Acceleration to UHE in gamma-ray bursts fireballs

▶ **There is always a price to pay to pull the maximal energy up to 10^{20}eV:**

$\rightarrow$ e.g. acceleration in internal shocks: needs $\epsilon_B \sim 0.1$, Bohm regime $t_{acc} \sim t_L$, an optical depth to pion production of order unity for the particle to escape as a neutron
[... implies a neutrino signal at PeV with $E_\nu^2\, dN_\nu/dE_\nu \sim E_{CR}^2\, dN_{CR}/dE_{CR}$ ... Waxman 01]

$\rightarrow$ e.g. acceleration in shear flows appears quite efficient, but quite model dependent (Rieger & Duffy 06)

$\rightarrow$ e.g. acceleration at the external forward shock is quite difficult, as the Fermi process is inhibited/slowed down at ultra-relativistic shock waves (M.L.& Pelletier 10)
[... acceleration in mildy relativistic shocks appear more promising...]
[... BUT: the steep decay of the early X-ray afterglow has been interpreted as the haemorrhage of the blast wave energy (radiative regime) due to escaping UHECR (Dermer 07) ...]

$\rightarrow$ e.g. acceleration downstream of external shock in Fermi process requires $\epsilon_B \sim 1$ (Dermer & Humi 01)

Gamma-ray burst rate vs UHE cosmic ray flux...

▶ UHECR flux from GRBs: (Waxman 95, Vietri 95, Dermer & Humi 01, Katz et al. 09, Eichler et al. 10)

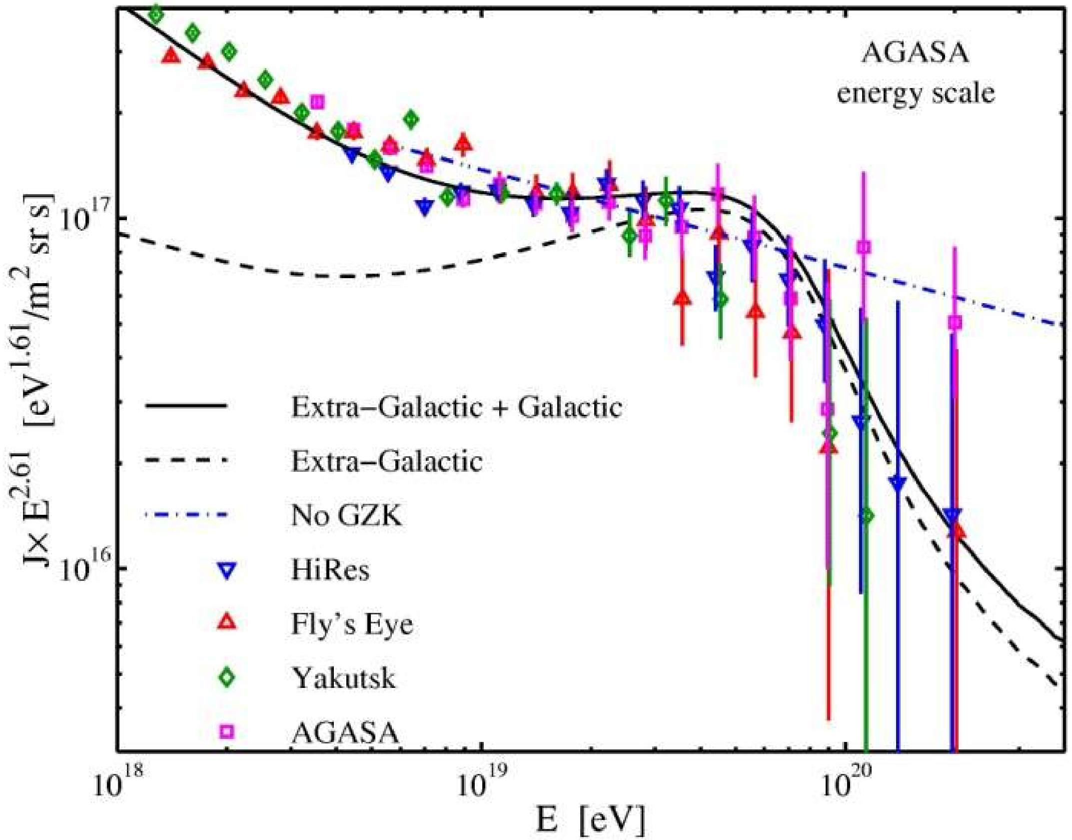
$\rightarrow$ flux of UHECR above 10^{19} eV requires an energy input rate: $\sim$ **10^{44} erg/Mpc^3/yr**

$\rightarrow$ with a GRB rate $\dot{n}_{\rm GRB}$ this requires per GRB:

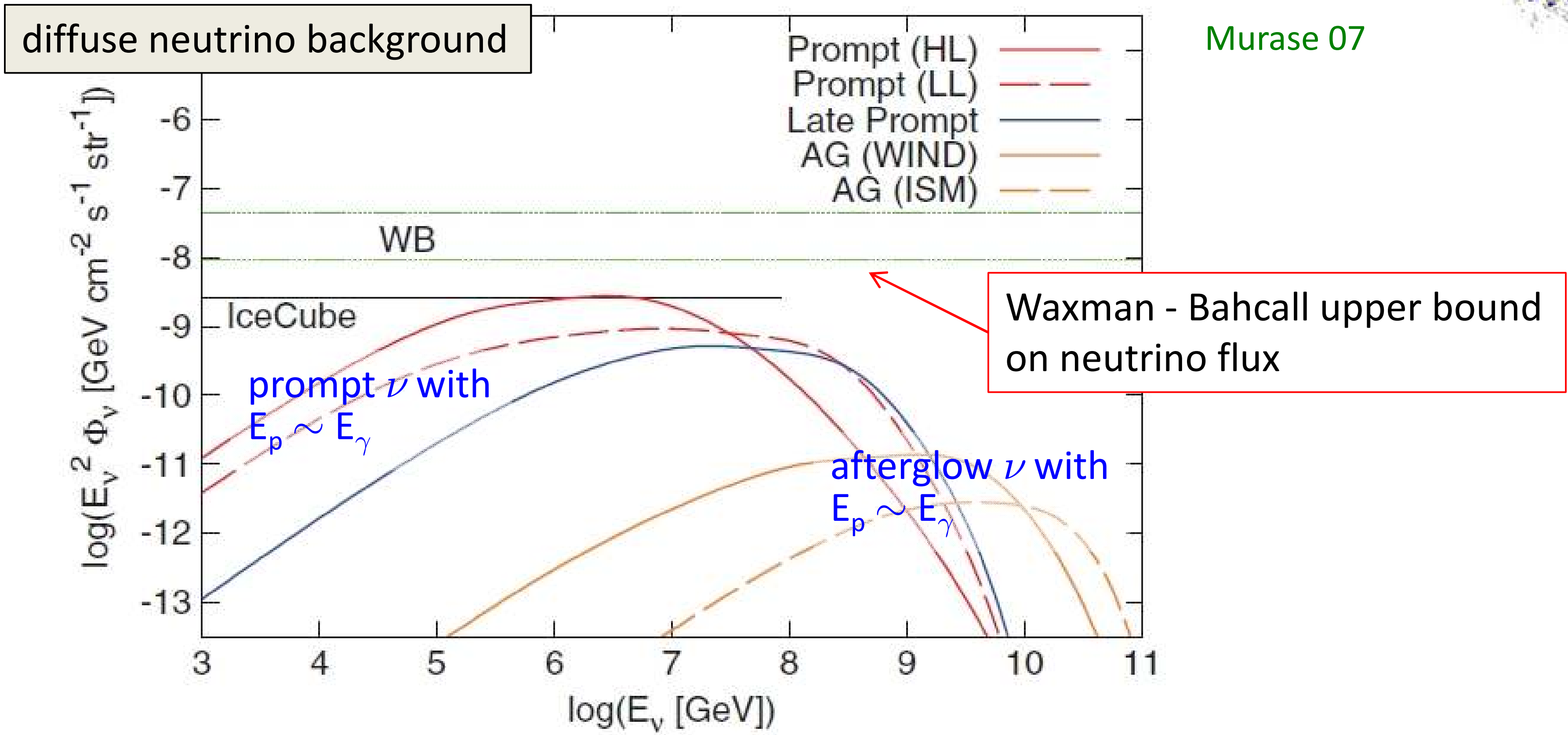
$$E_{\rm UHECR/GRB} \approx 10^{53}\,{\rm erg}\left(\frac{\dot{n}_{\rm GRB}}{1\,{\rm Gpc^{-3}yr^{-1}}}\right)^{-1}$$

$\rightarrow$ **$E_{UHECR/GRB}/E_{\gamma/GRB} \sim$ 10 - ...?**

$\rightarrow$ role of low luminosity GRB?



Neutrino signatures...



→ VHE neutrino signal: $p + \gamma_{GRB} \rightarrow \pi + \ldots$, $\pi \rightarrow \mu + \nu_\mu$, $\mu \rightarrow e + \nu_e + \nu_\mu$

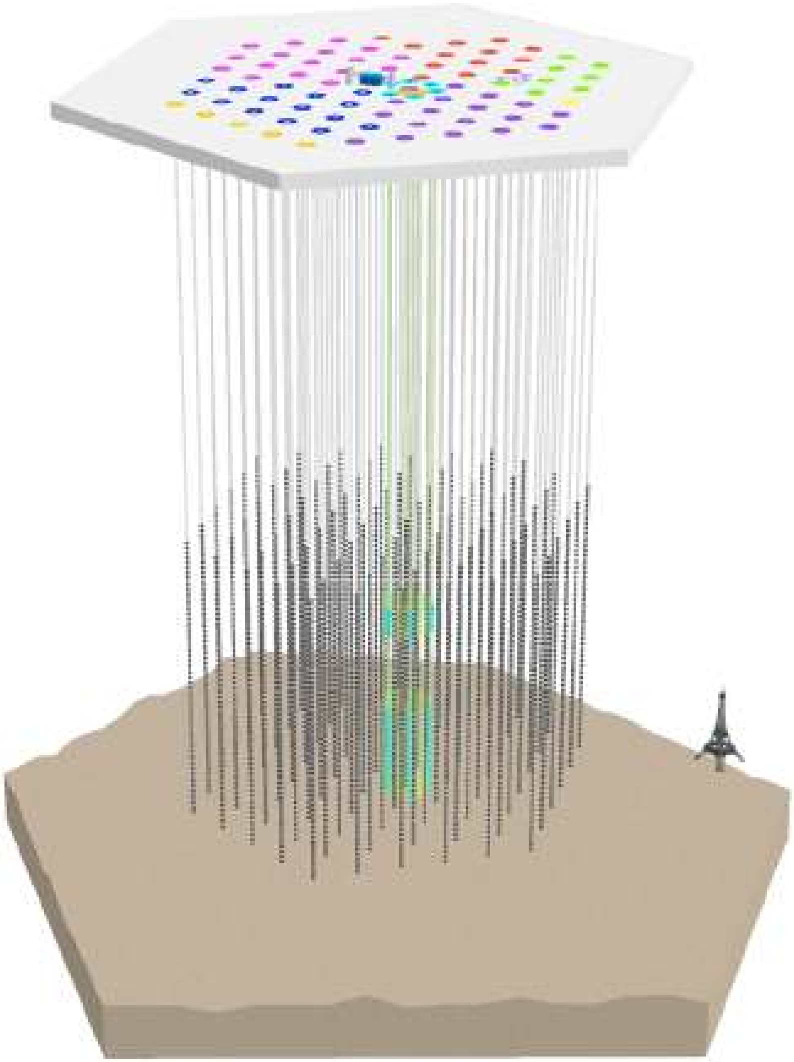
shape of neutrino spectrum: parent proton spectrum modulated by pion production optical depth (dependent on target photon density above threshold...)

→ if GRBs accelerate UHECR in internal shocks, prediction is raised to the WB bound

→ other (promising) GRB sources of neutrinos: p-p or n-p inelastic collisions (GeV), neutron decay (<GeV), choked GRB jets (TeV),...

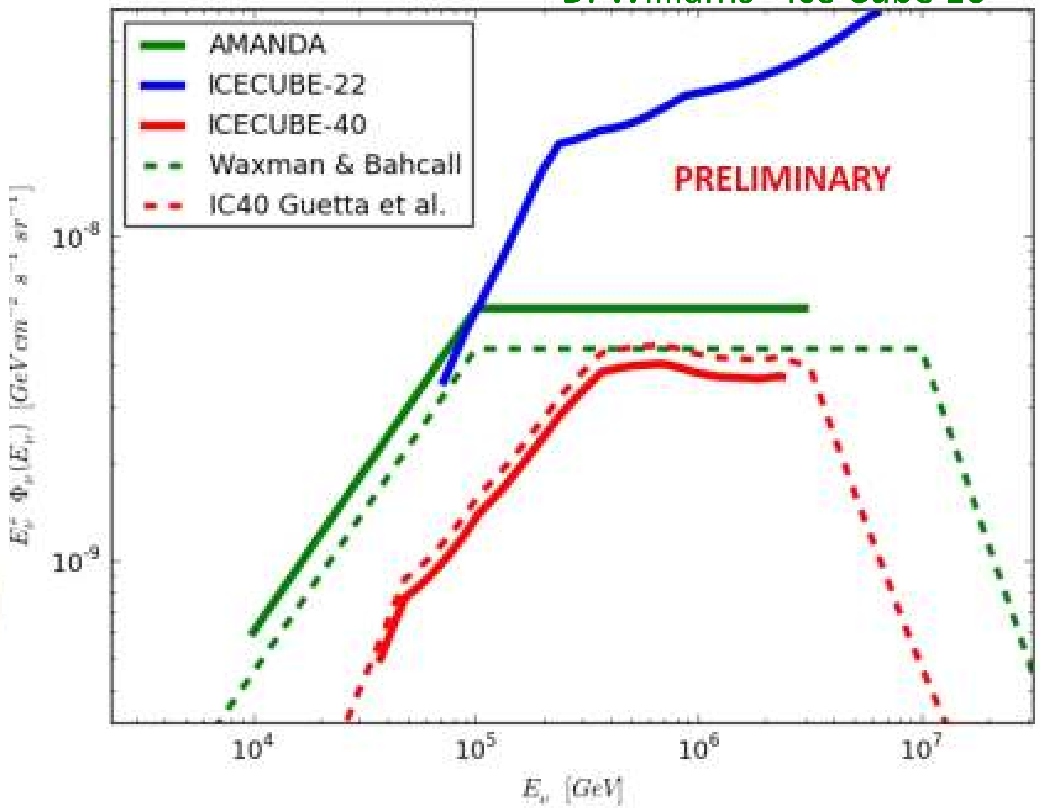
Ice Cube limits as of 2010...

km^3 neutrino detector at the South Pole



→ **IceCube is now probing the WB bound!**

D. Williams - Ice Cube 10



Abbasi et al. (Ice Cube, 2010): stacking analysis with IC22 for 41 GRB, no event

Conclusions

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  [... quite a few scenarios for acceleration in GRB outflows...]

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  $\rightarrow$ HiRes sees protons at UHE, Auger sees an increasing fraction of heavies...?

  [... one generally expects protons, but a heavy enriched composition cannot be ruled out for GRB: what injection mechanism? ...]

- **What should we expect from GRB?**

  ... optimistically, >PeV neutrinos from shock accelerated protons...

  ... if UHECR are protons, anisotropies and spectral distorsions at extreme energies...

  ... but, if UHECR are heavy nuclei, not much ...??