Xth RENCONTRES DU VIETNAM
Very High Energy Phenomena in the Universe

Quy Nhon, 3-9 August 2014

Ultrahigh-Energy Cosmic Rays and Neutrinos from Gamma-Ray Bursts

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Nha Trang 1997-1998

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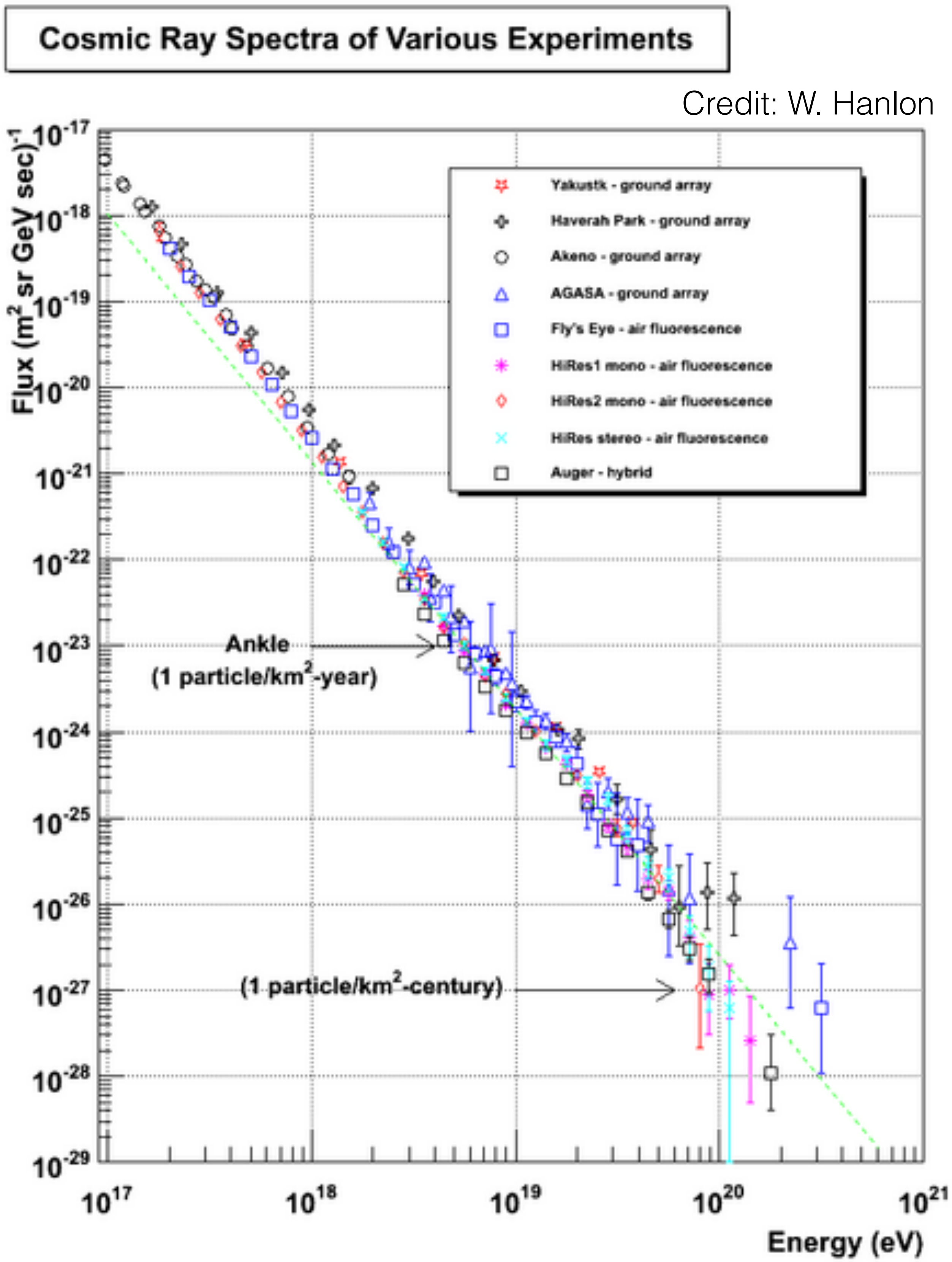
Ultrahigh-Energy Cosmic Rays



AUGER Collab. 2010

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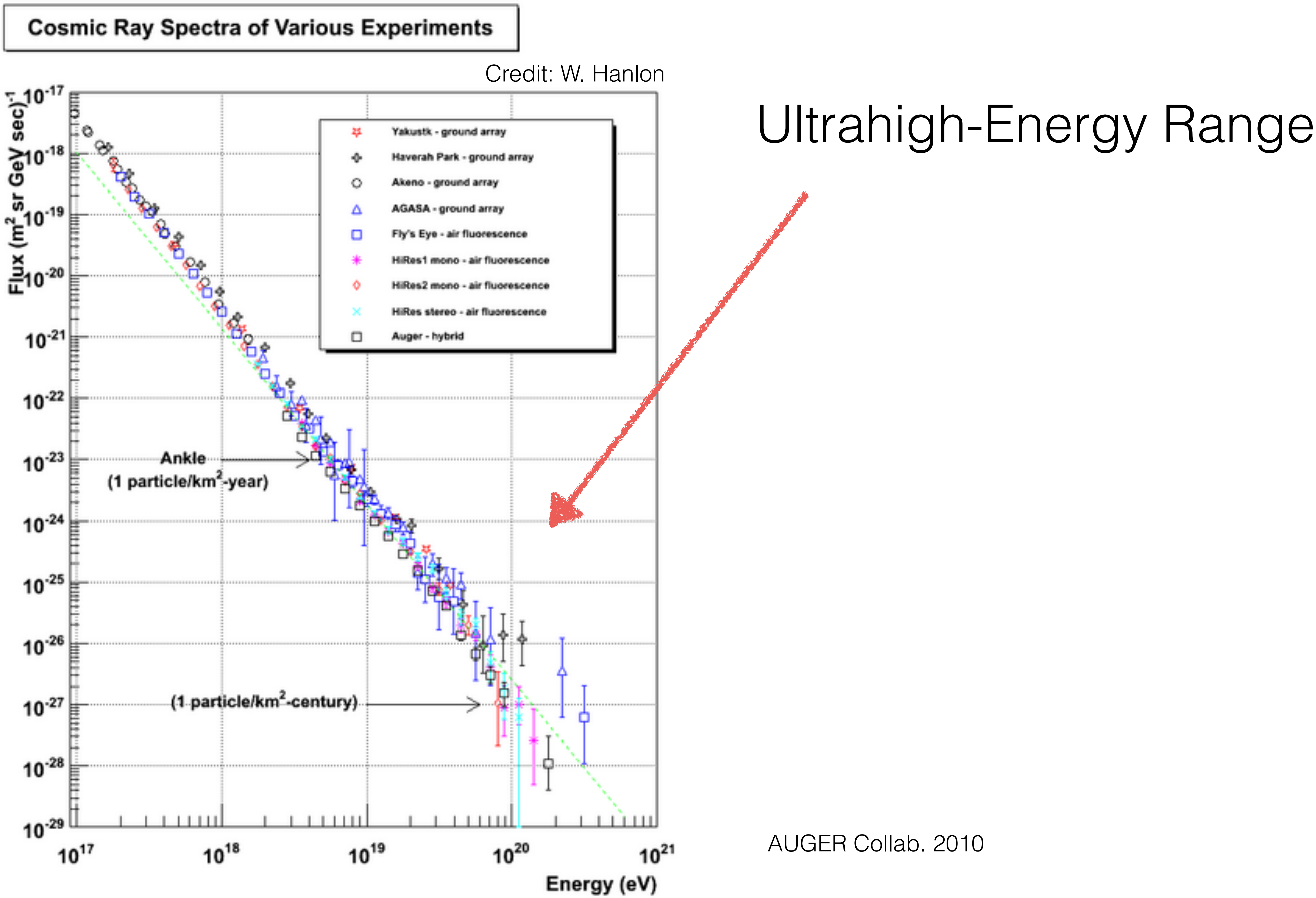

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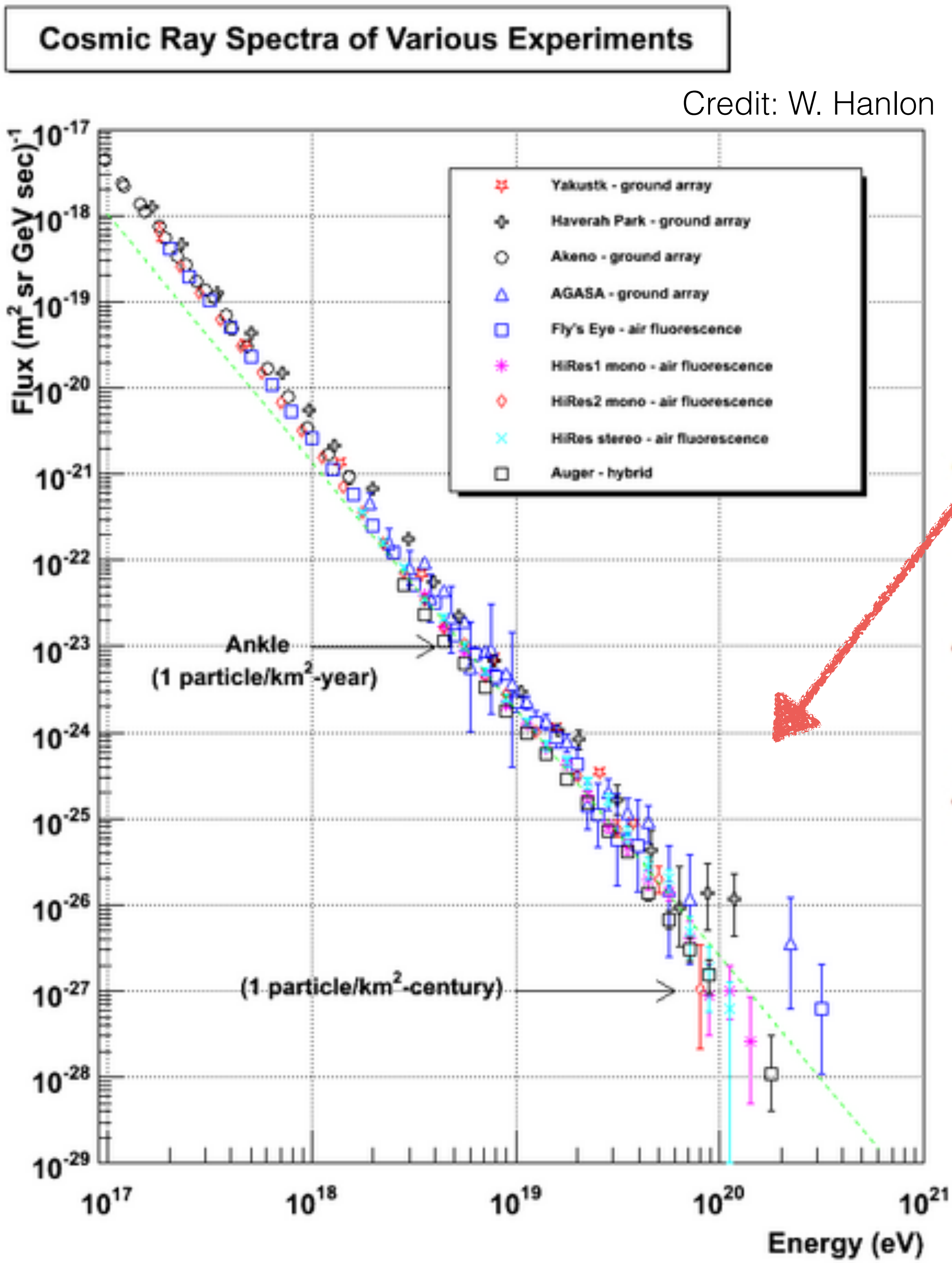
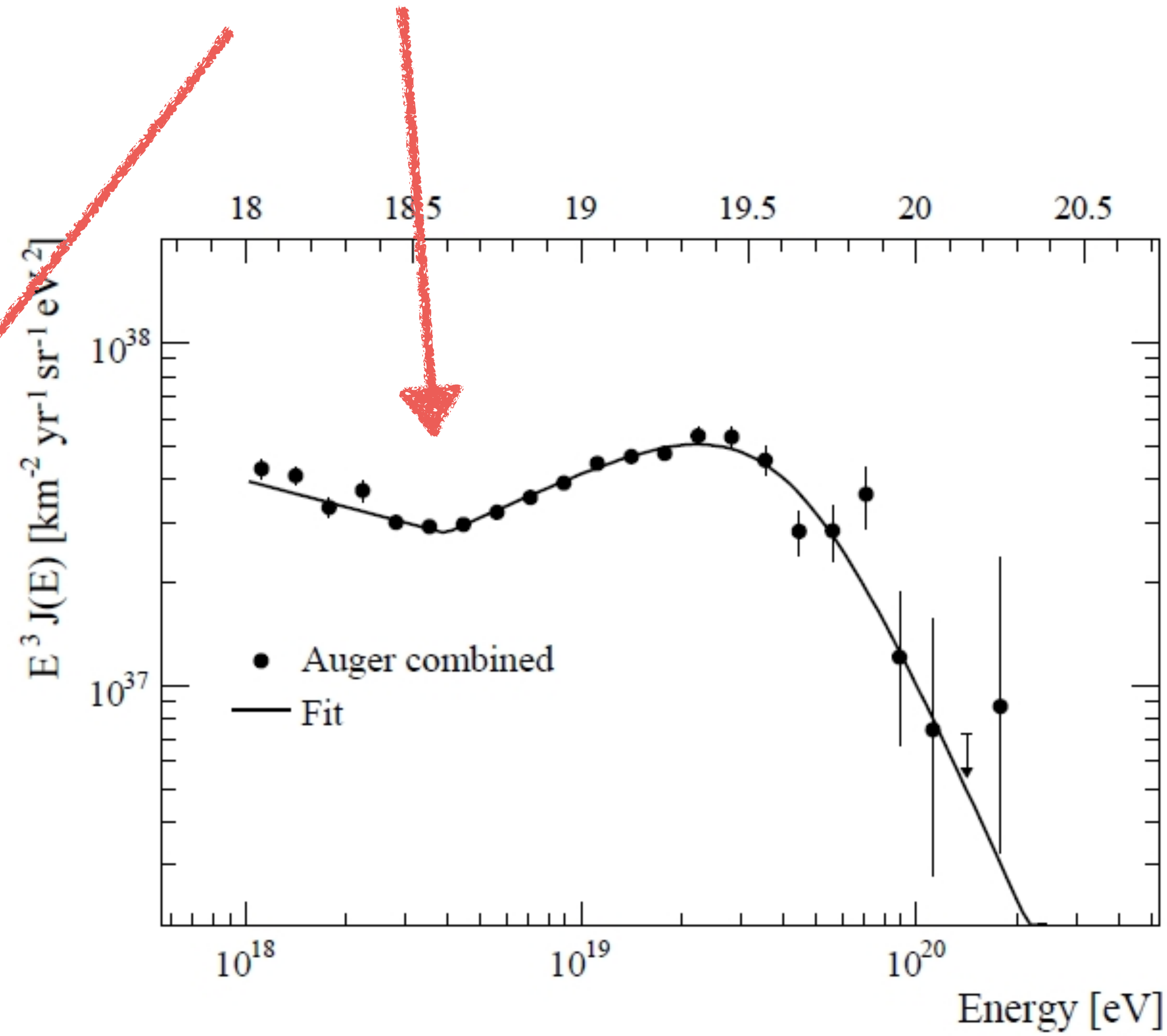
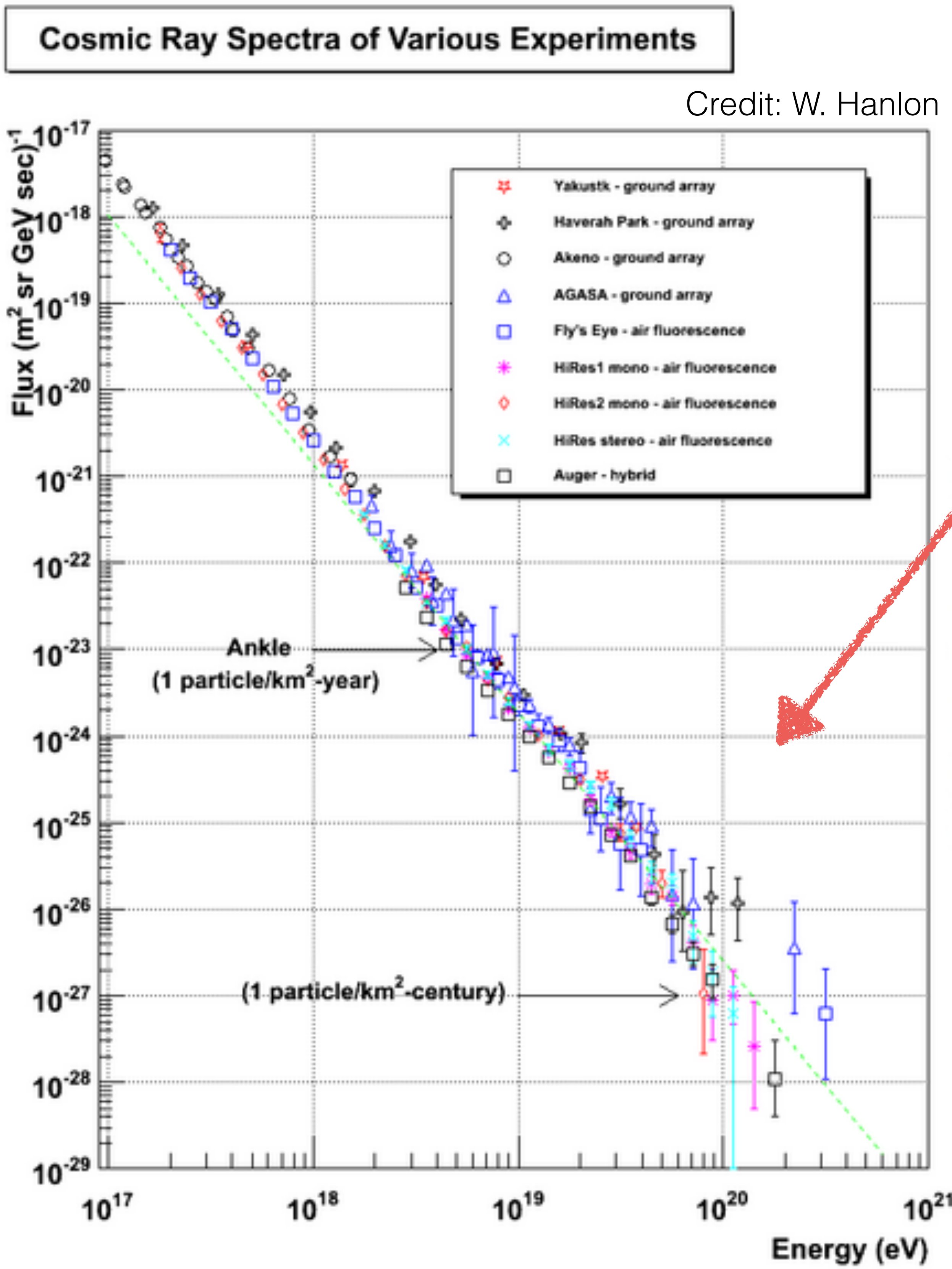


Ultrahigh-Energy Range



AUGER Collab. 2010

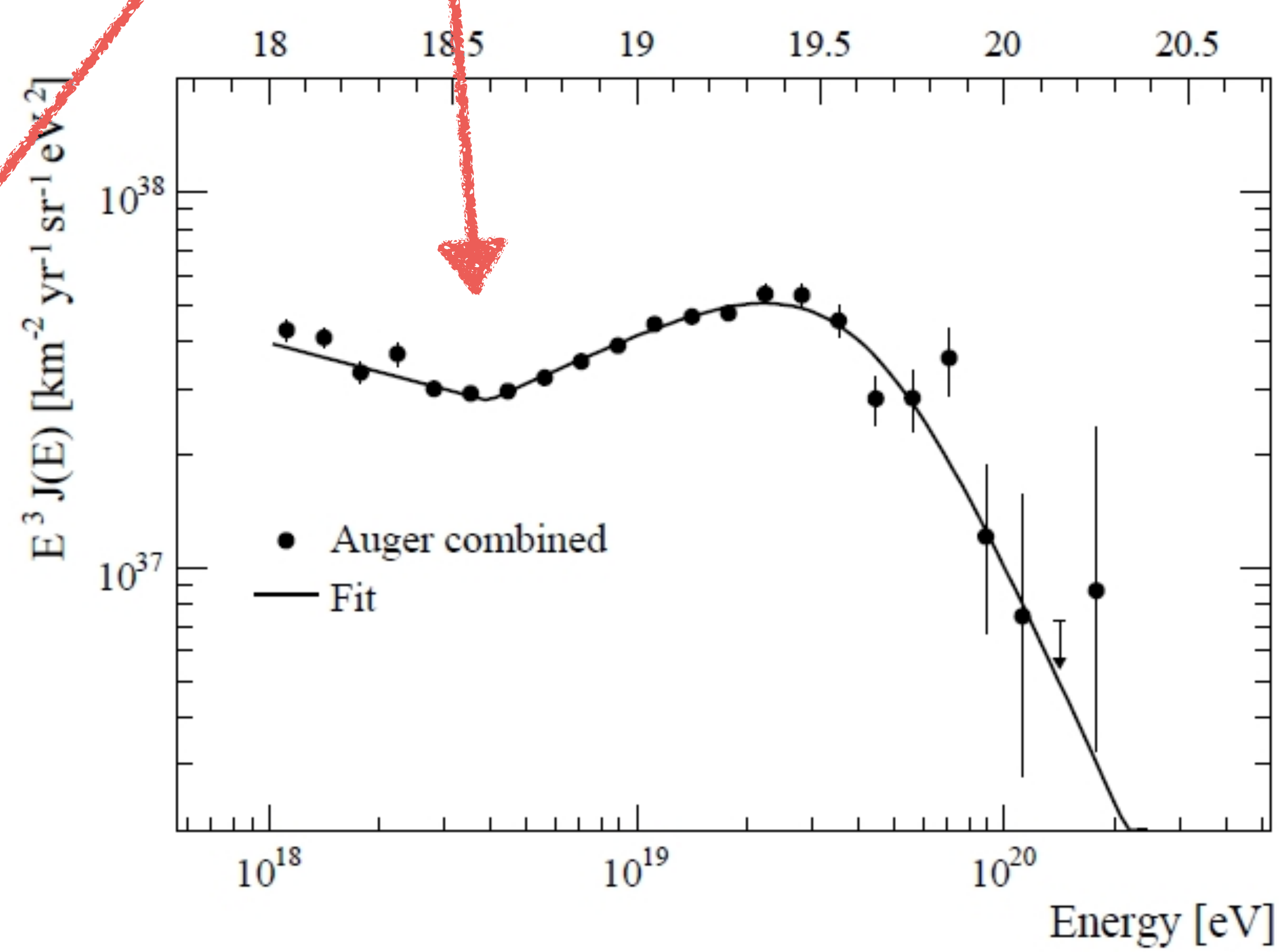
Ultrahigh-Energy Cosmic Rays



Credit: W. Hanlon

Ultrahigh-Energy Range

What is the origin?



AUGER Collab. 2010

Why Gamma-Ray Bursts?

Long-duration (> 2 s) GRBs are the most luminous objects in the gamma-ray sky

↑ $L_\gamma \sim 10^{51}$ erg/s

Isotropic-equivalent

↑ **Non-thermal**

→ **particle acceleration**

→ GRBs as sources of UHECRs: Waxman 1995; Vietri 1995

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Energy injection rate in UHECRs

Baryon loading>1

$$\dot{E}_{\rm CR} \sim 10^{51}\ \frac{\rm erg}{\rm GRB} \cdot \frac{20\,\rm GRB}{\rm Gpc^3\ yr} \eta_{\rm bol}\eta_p \sim 2\times10^{43}\eta_{\rm bol}\eta_p\ \frac{\rm erg}{\rm Mpc^3\ yr}$$

Local true GRB rate

Bolometric factor<1

Energy in UHECRs

Energy injection rate in UHECRs from data

$$\dot{E}_{\mathrm{UHECR}} \approx 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

Need baryon-loading factor > ~ 50

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How many GRBs within the GZK volume (100 Mpc)?

- Depends on the Inter-Galactic Magnetic Field (IGMF)

$$\Delta t_{\rm CR} \sim 3.2 \times 10^4\, Z^2 \left(\frac{B_{\rm IG}}{1\,{\rm nG}}\right)^2 \left(\frac{E_{\rm CR}}{60\,{\rm EeV}}\right)^{-2} \left(\frac{\lambda_{\rm IG}}{1\,{\rm Mpc}}\right)^{3/2}\ {\rm yr}$$

- $$N_{\rm GRB} \sim \frac{20\,{\rm GRB}}{{\rm Gpc^3 yr}} \cdot V_{\rm GZK} \Delta t_{\rm CR} \sim 3 \times 10^3$$

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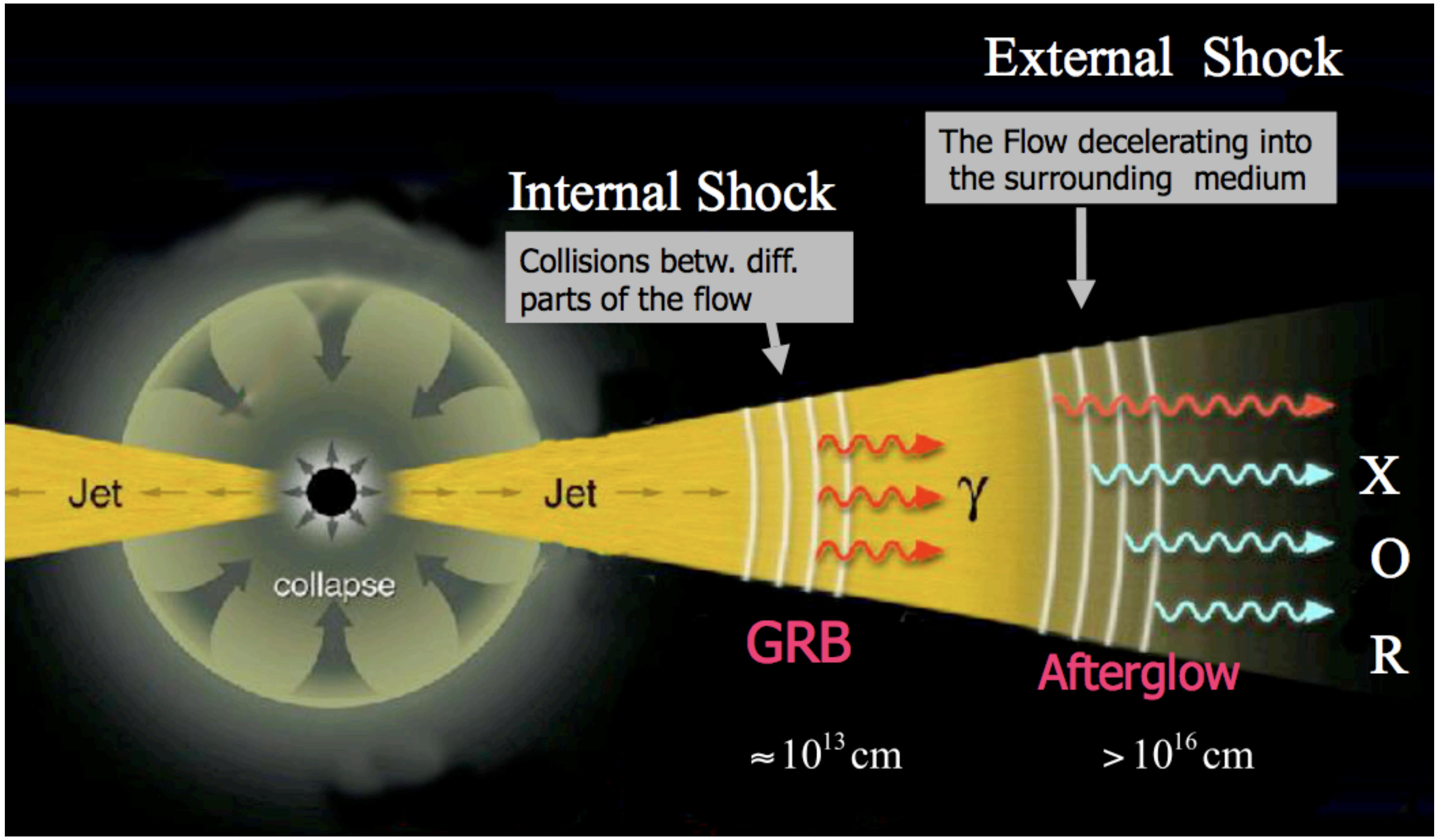
→ $$N_{\rm GRB} \sim \frac{20\,{\rm GRB}}{{\rm Gpc^3 yr}} \cdot V_{\rm GZK}\Delta t_{\rm CR} \sim 3 \times 10^3$$

A fraction (~1/200) of these GRBs have their jets pointing to us

beaming angle correction

When UHECRs are made in GRBs?

Fireball shock model of long-duration GRBs



Rees, Meszaros, Shemi, Piran, Daigne, Mochkovitch, …

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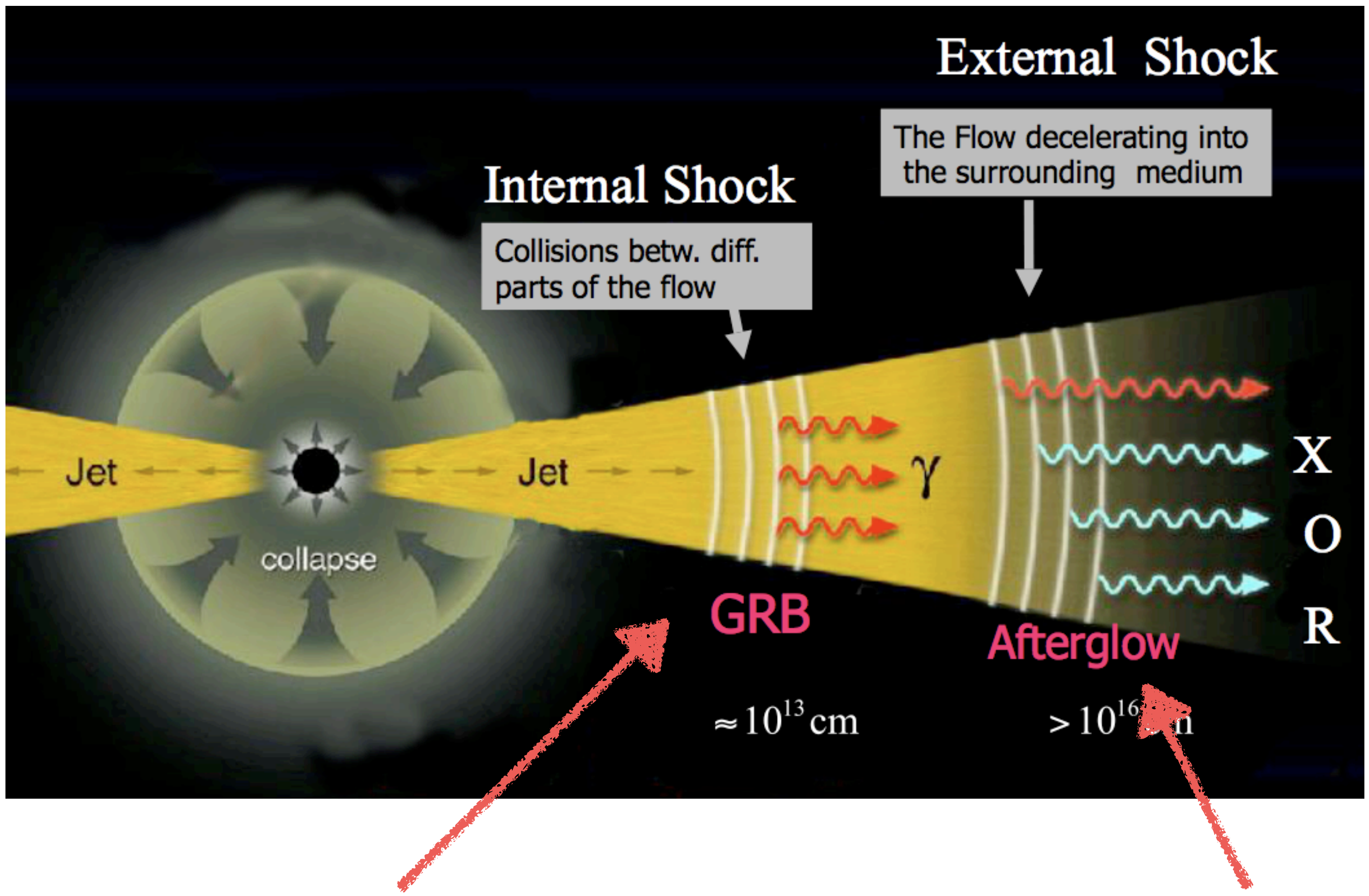

Prompt gamma-ray emission ~10 s

Afterglow emission ~10 s - year

Rees, Meszaros, Shemi, Piran, Daigne, Mochkovitz, …

Acceleration in Internal Shocks

Chain of logic

Comoving frame

Isotropic-equivalent gamma-ray luminosity

Energy density for gamma rays: $$u'_\gamma \approx \frac{L_\gamma}{4\pi r_{\rm sh}^2 \Gamma_b^2 c}$$

Shock radius

Bulk Lorentz factor

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Shock radius

Bulk Lorentz factor

Energy density for particles: $u'_e = u'_\gamma$ ⇨ **electrons (fast-cooling)**

Baryons (n/p) loaded jet: $u'_e = u'_\gamma = \epsilon_e u'_p$ **energy density in p/n**

Dominant (kinetic) energy carrier

fraction <1

Acceleration in Internal Shocks

Chain of logic

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Energy density for magnetic field: $u'_B \equiv \frac{B'^2}{8\pi} = \epsilon_B u'_p$

Magnetic field:

Typical values for prompt gamma rays

$$B' \approx \sqrt{\frac{2\epsilon_B L_\gamma}{\epsilon_e r_{\rm sh}^2 \Gamma_b^2 c}} \sim 8\times 10^4 \sqrt{\frac{\epsilon_B}{\epsilon_e}} \left(\frac{L_\gamma}{10^{51}\,{\rm erg/s}}\right)^{1/2} \left(\frac{r_{\rm sh}}{10^{13}\,{\rm cm}}\right)^{-1} \left(\frac{\Gamma_b}{316}\right)^{-1}\ {\rm G}$$

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Maximum CR energy: $E_{\rm max} \sim ZeB' r_{\rm sh}$

$$E_{\rm max} \sim 2 \times 10^{20} \sqrt{\frac{\epsilon_B}{\epsilon_e}} \left(\frac{L_\gamma}{10^{51}\,{\rm erg/s}}\right)^{1/2} \left(\frac{\Gamma_b}{316}\right)^{-1} \ {\rm eV}$$

Acceleration in External Shocks

External forward shock - Blast wave

Relativistic jet running into surrounding environment

Deceleration time scale from total energy in blast wave equal to kinetic energy

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Constant density medium

$$t_{\mathrm{dec},i} \approx 33.3\,(1+z)\left(\frac{n}{1\ \mathrm{cm}^3}\right)^{-1/3}\left(\frac{\Gamma_b}{316}\right)^{-8/3}\left(\frac{E_k}{10^{55}\ \mathrm{erg}}\right)^{1/3}\ \mathrm{s}$$

Wind medium, R^{-2} density

$$t_{\mathrm{dec},w} \approx 1.5\,\frac{1+z}{A_\star}\left(\frac{\Gamma_b}{316}\right)^{-4}\left(\frac{E_k}{10^{55}\ \mathrm{erg}}\right)\ \mathrm{s}$$

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Self-similar evolution of the blast wave

Blandford & McKee 1976

Bulk Lorentz factor

$$\Gamma_{ad,i}(t) = \Gamma_0(t_{\mathrm{dec},i}/4t)^{3/8}, \qquad \Gamma_{ad,w}(t) = \Gamma_0(t_{\mathrm{dec},w}/4t)^{1/4},$$

$$\Gamma_{ra,i}(t) = \Gamma_0(t_{\mathrm{dec},i}/7t)^{3/7}, \qquad \Gamma_{ra,w}(t) = \Gamma_0(t_{\mathrm{dec},w}/7t)^{1/3},$$

Acceleration in External Shocks

Adiabatic blast wave in constant density

$$\Gamma_{\mathrm{ad},i} \approx 124\,(1+z)^{3/8}\left(\frac{n}{1\,\mathrm{cm}^3}\right)^{-1/8}\left(\frac{E_k}{10^{55}\,\mathrm{erg}}\right)^{1/8}\left(\frac{t}{100\,\mathrm{s}}\right)^{-3/8}$$

Blast wave radius: $$r_{\mathrm{sh}} \approx \frac{4\times 10^{17}}{(1+z)^{1/4}}\left(\frac{n}{1\,\mathrm{cm}^3}\right)^{-1/4}\left(\frac{E_k}{10^{55}\,\mathrm{erg}}\right)^{1/4}\left(\frac{t}{100\,\mathrm{s}}\right)^{1/4}\ \mathrm{cm}$$

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Magnetic energy from shock energy: $B'^2/8\pi = \epsilon_B(4\pi r_{\mathrm{sh}}^2 n m_p c^2 \Gamma_{\mathrm{ad},i}^2)$

$$B' \approx 15(1+z)^{3/8} \left(\frac{\epsilon_B}{0.1}\right)^{1/2} \left(\frac{n}{1\,\mathrm{cm}^3}\right)^{3/8} \left(\frac{E_k}{10^{55}\,\mathrm{erg}}\right)^{1/8} \left(\frac{t}{100\,\mathrm{s}}\right)^{-3/8}\ \mathrm{G}$$

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Energy in UHECRs

Minimum CR energy: $E_{\rm min} \sim m_p c^2 \Gamma^2 \sim 10^{14} - 10^{15}\,{\rm eV}$ **early on**

fraction <1

Total cosmic-ray energy: $\mathcal{E}_{\rm CR} \approx \epsilon_p \frac{4}{3}\pi r_{\rm sh}^3 m_p c^2 \Gamma^2 = \frac{1}{2}\epsilon_p E_k$

Energy extraction rate by cosmic rays is quite slow

$$\Gamma_{{\rm ad},i} \approx 1\,(1+z)^{3/8} \left(\frac{n}{1\,{\rm cm}^3}\right)^{-1/8} \left(\frac{E_k}{10^{55}\,{\rm erg}}\right)^{1/8} \left(\frac{t}{1\,{\rm yr}}\right)^{-3/8}$$

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$$\dot{E}_{\rm CR} \sim 10^{55}\ \frac{\rm erg}{\rm GRB} \cdot \frac{20\,{\rm GRB}}{{\rm Gpc}^3\,{\rm yr}} \eta_{\rm bol} \epsilon_p \sim 2 \times 10^{47} \eta_{\rm bol} \epsilon_p\ \frac{\rm erg}{{\rm Mpc}^3\,{\rm yr}}$$

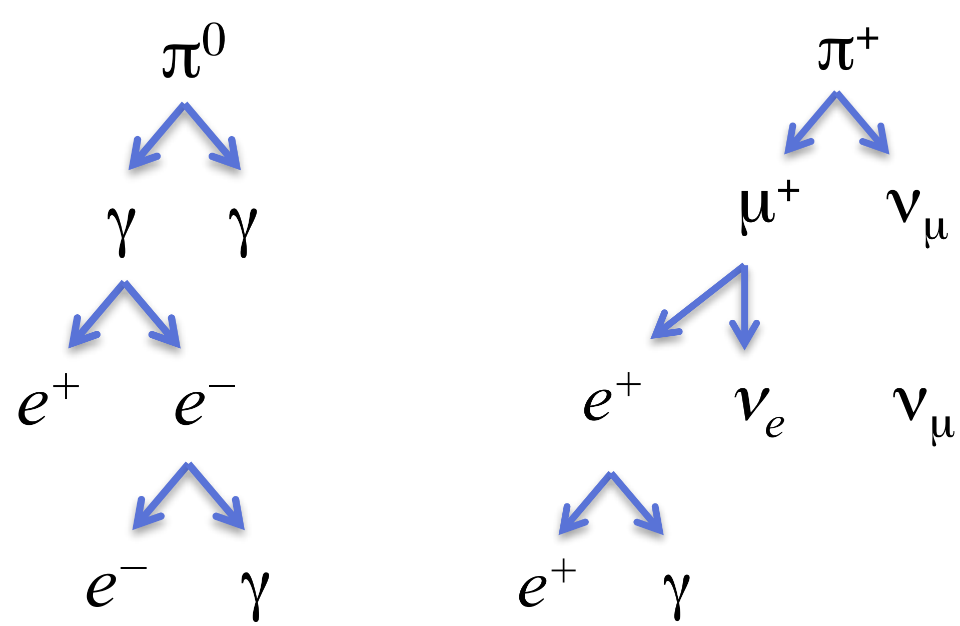
High Energy Neutrinos from GRBs

Interaction channels for cosmic rays in the vicinity

$$p\gamma \rightarrow \pi^0\,,\ \pi^+\,,\ \pi^-\,,\ K^+\,,\ K^-\,,\ etc.$$

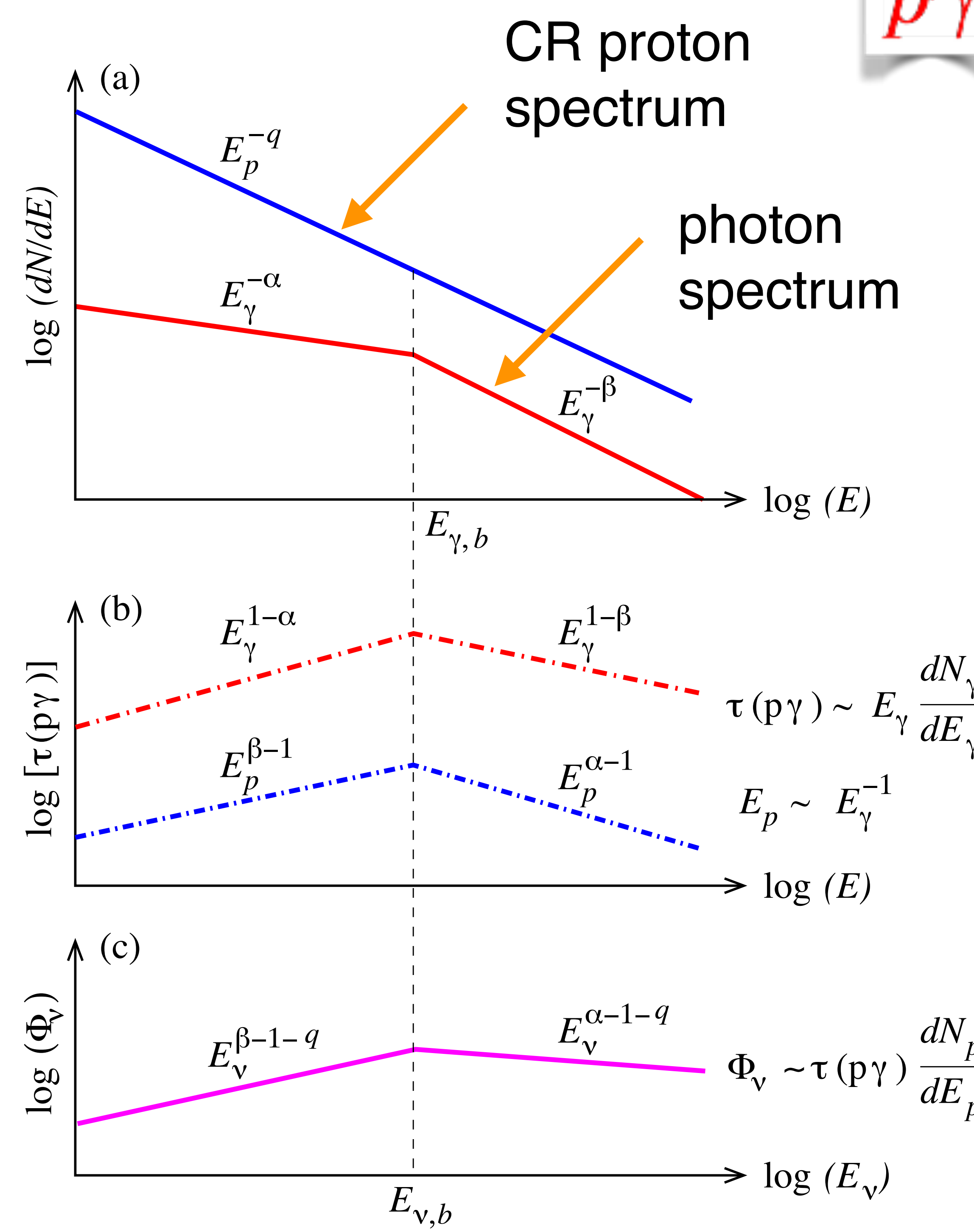
$$pp \rightarrow \pi^0\,,\ \pi^+\,,\ \pi^-\,,\ K^+\,,\ K^-\,,\ etc.$$

Pion decay chain



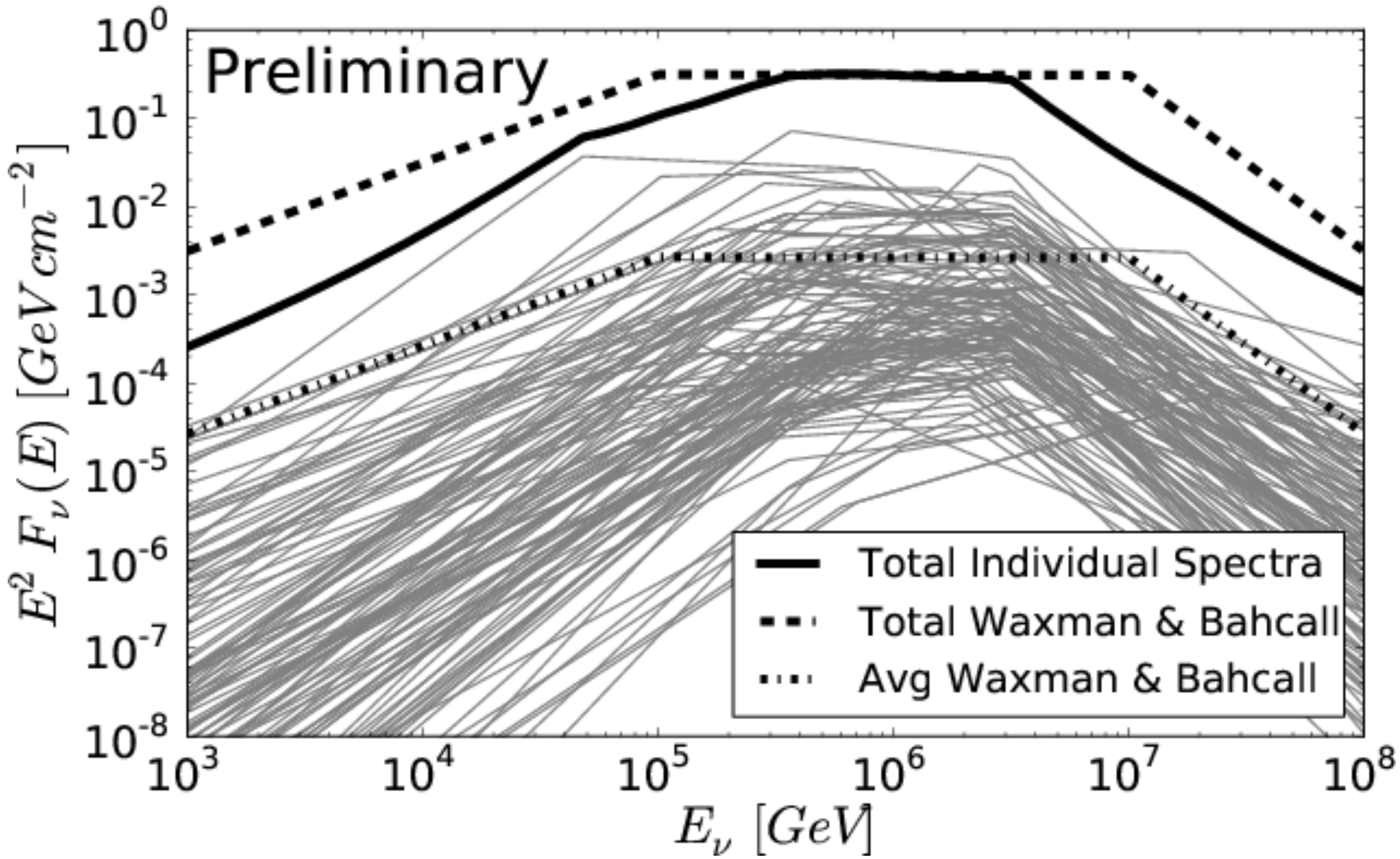
Energy for each neutrino flavor
~ 5% of CR energy

pγ



Neutrinos from Internal Shocks

Calculation after Waxman & Bahcall



IceCube Collab.

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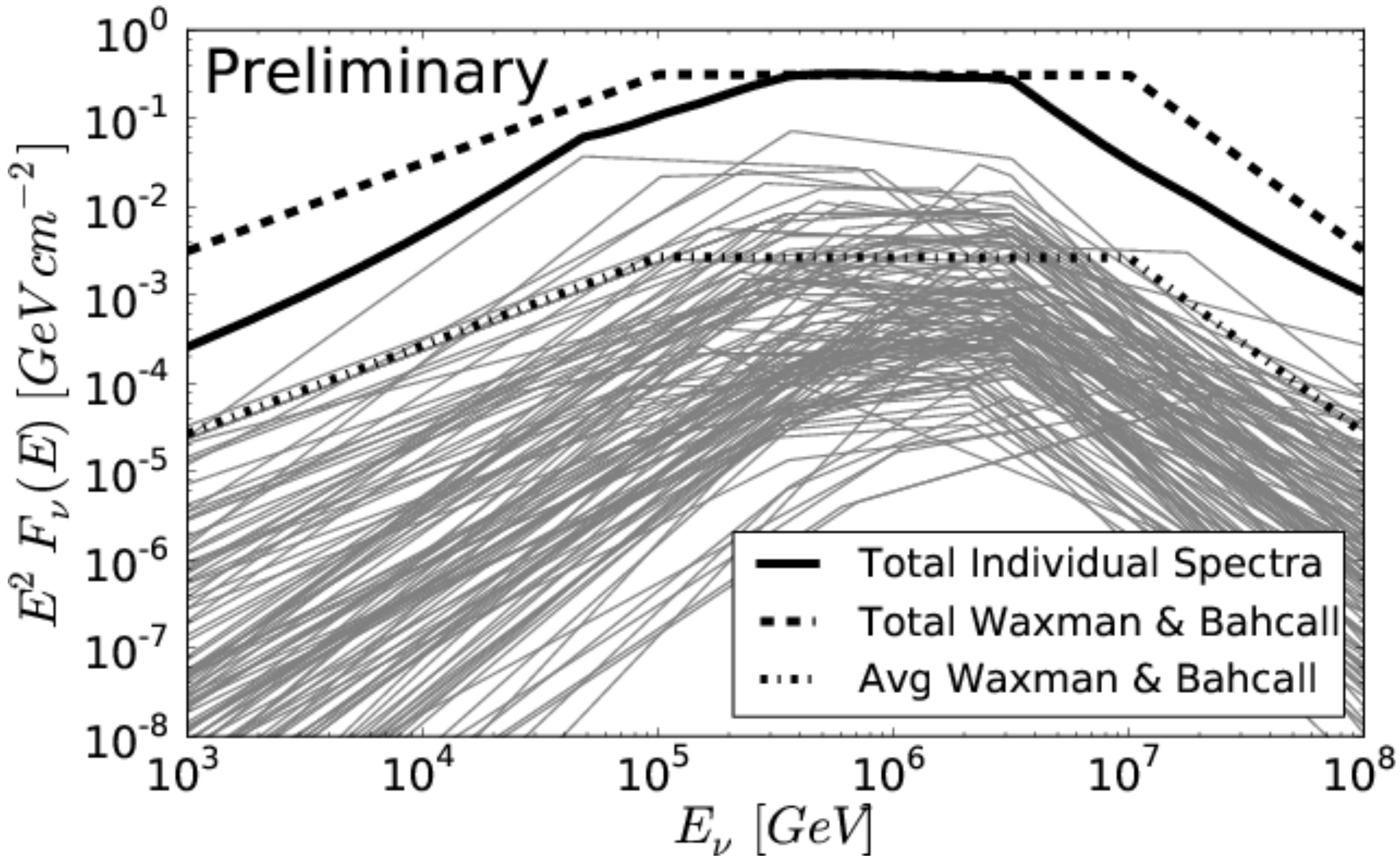
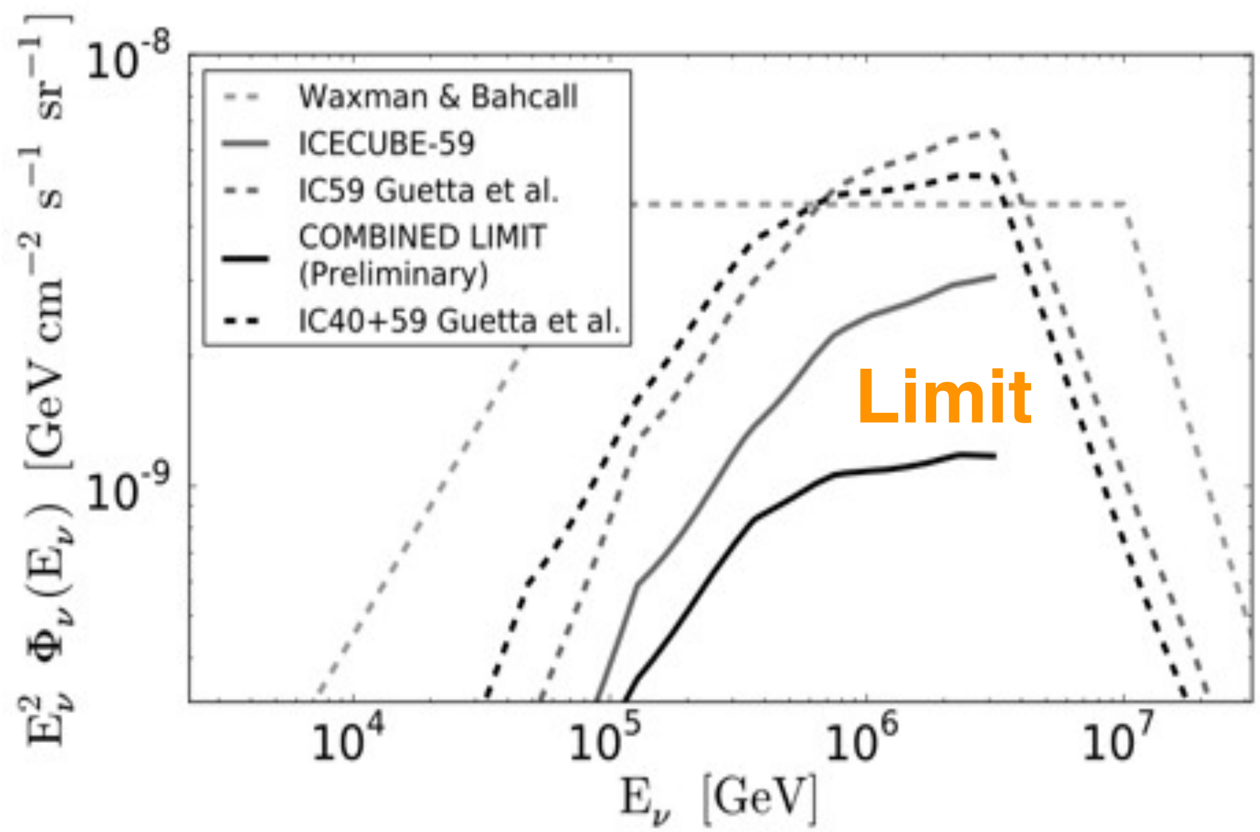


IceCube Collab.

Yet no detection!

IceCube limit on prompt neutrinos



IceCube Collab.

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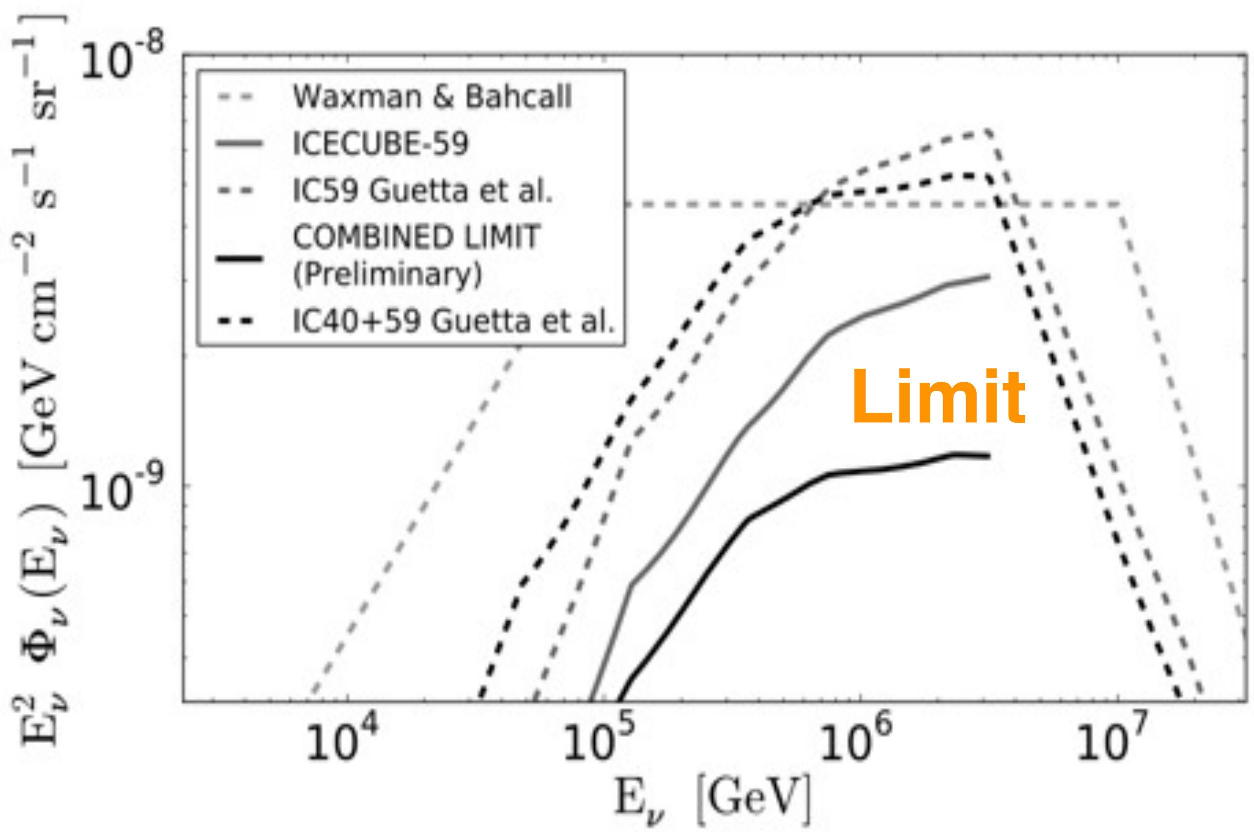

IceCube Collab.

What's going on?

- **UHECRs are not accelerated in internal shocks**
- **Neutrinos are not produced significantly**

Constraint on Bulk Lorentz factor

Number density of target photons
for p-gamma interaction in IS

$$n'_\gamma \approx \frac{L_\gamma/\epsilon_e}{4\pi r_{\rm sh}^2 c\Gamma_b \varepsilon_{\rm pk}} \propto \Gamma_b^{-5}$$

p-gamma interaction opacity/efficiency; $\tau_{p\gamma} \sim n'_\gamma \sigma_{p\gamma} r'_{\rm sh} \propto \Gamma_b^{-4}$

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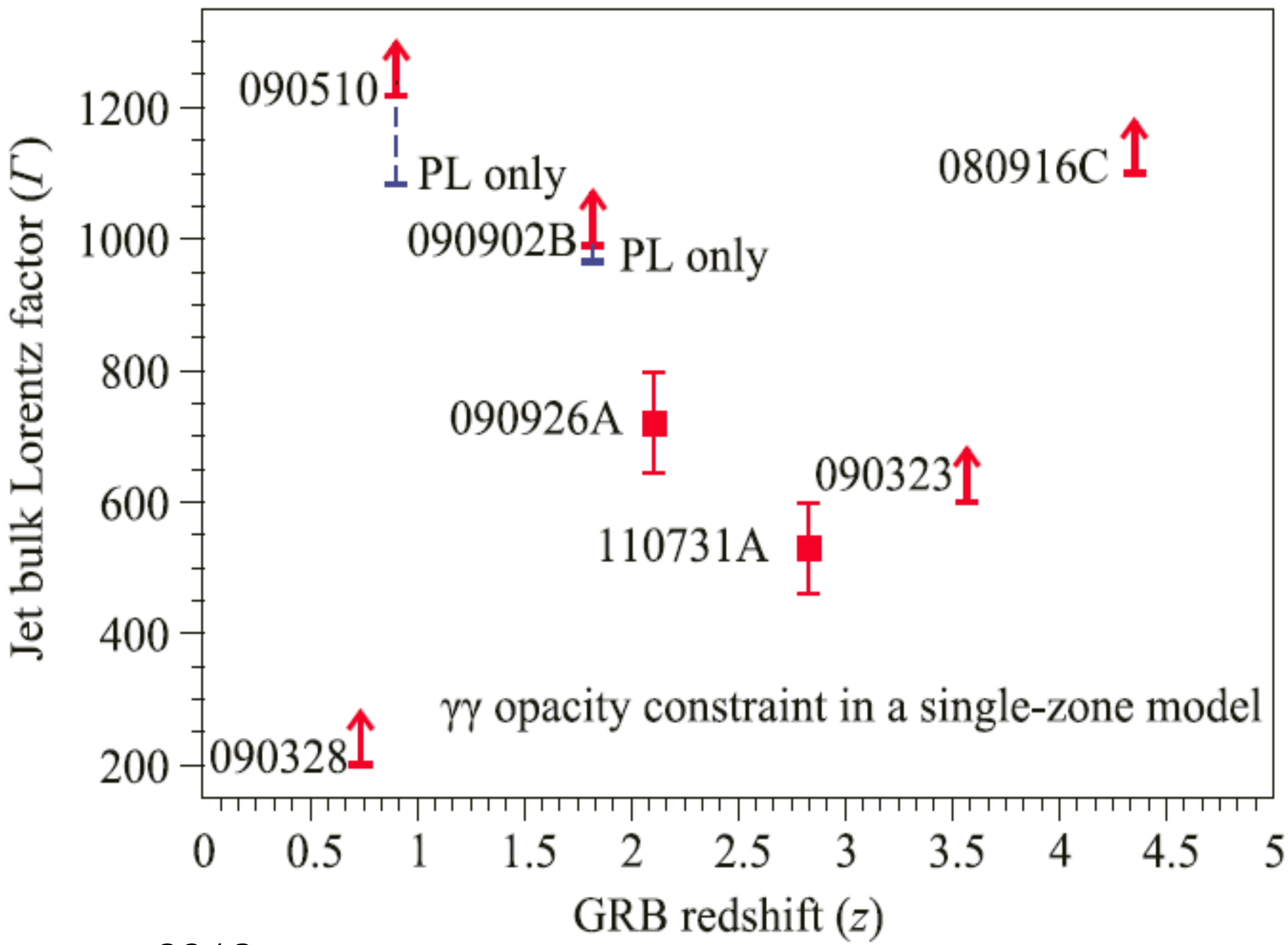
Large bulk Lorentz factor → Extremely low efficiency

Typical $\tau_{p\gamma} \sim 0.2(\Gamma_b/316)^{-4}$

Independently from gamma-ray data

Constraint on Bulk Lorentz factor

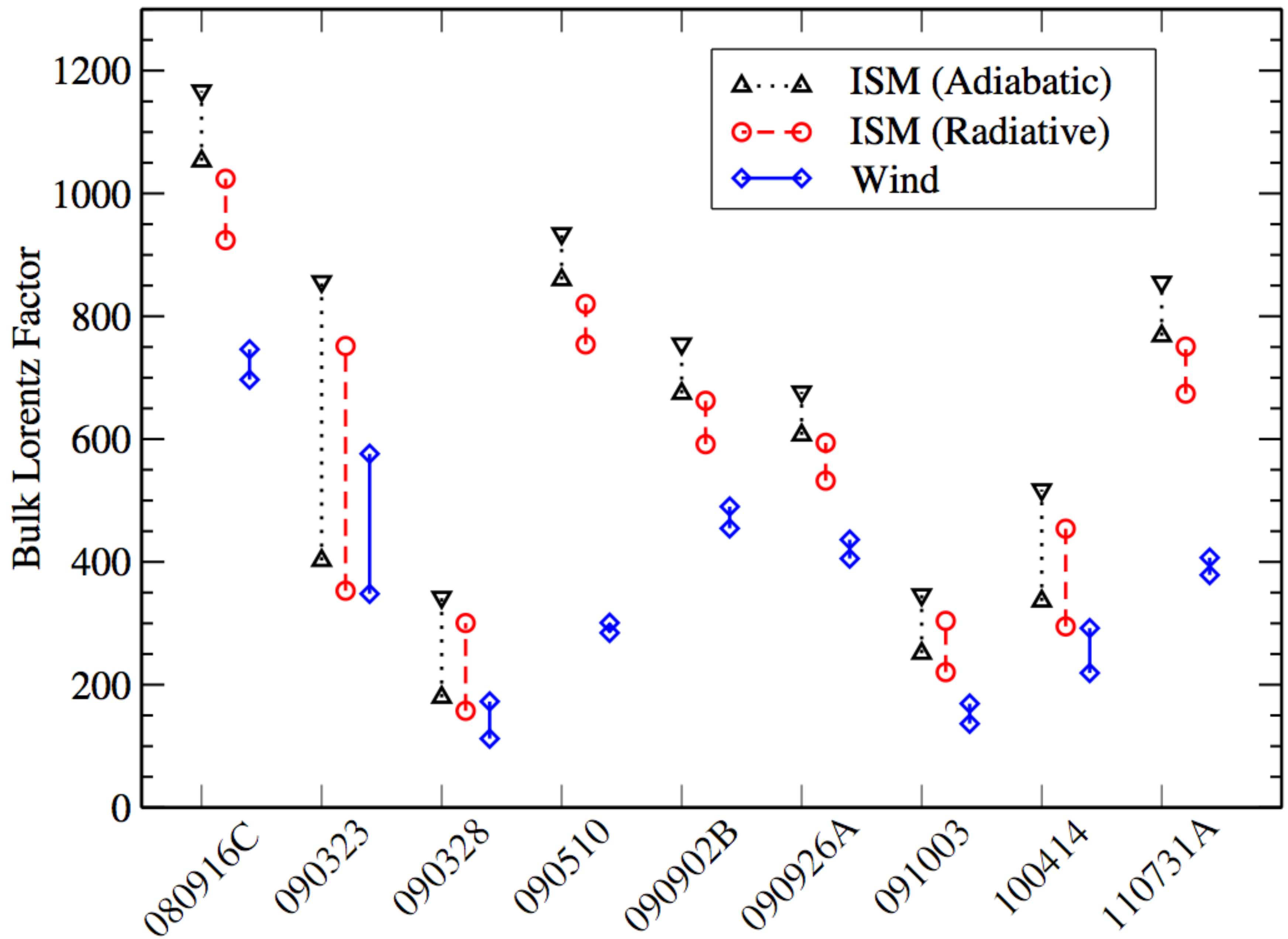
Constraint on the bulk Lorentz factor from gamma-gamma pair production opacity from >10 GeV photons



Gehrels & Razzaque 2013

Constraint on Bulk Lorentz factor

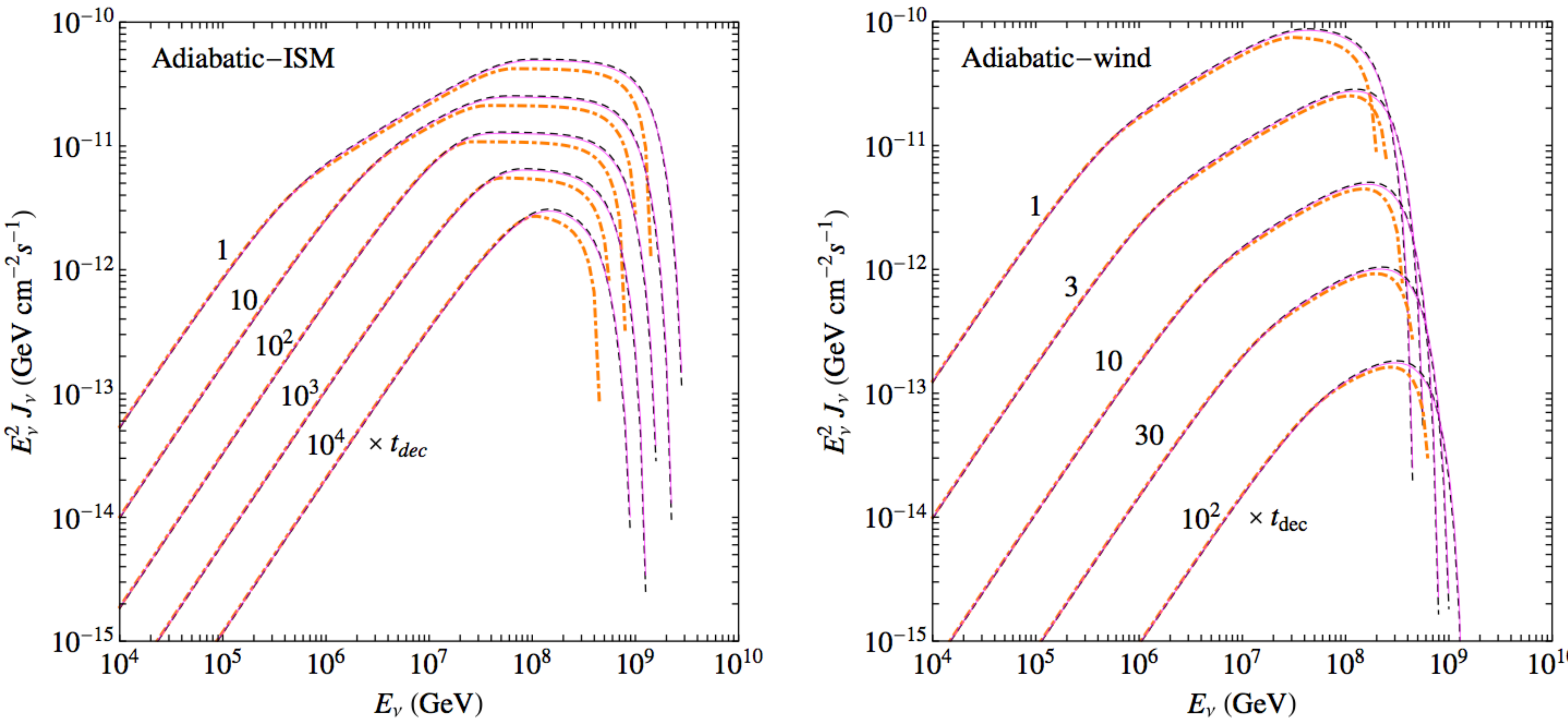
Constraint on the bulk Lorentz factor from
onset time of the afterglow



Fermi-LAT Collab. 2013

Neutrinos from external FS

Long-lived neutrino flux from interaction of UHECR and afterglow photon



Razzaque 2013

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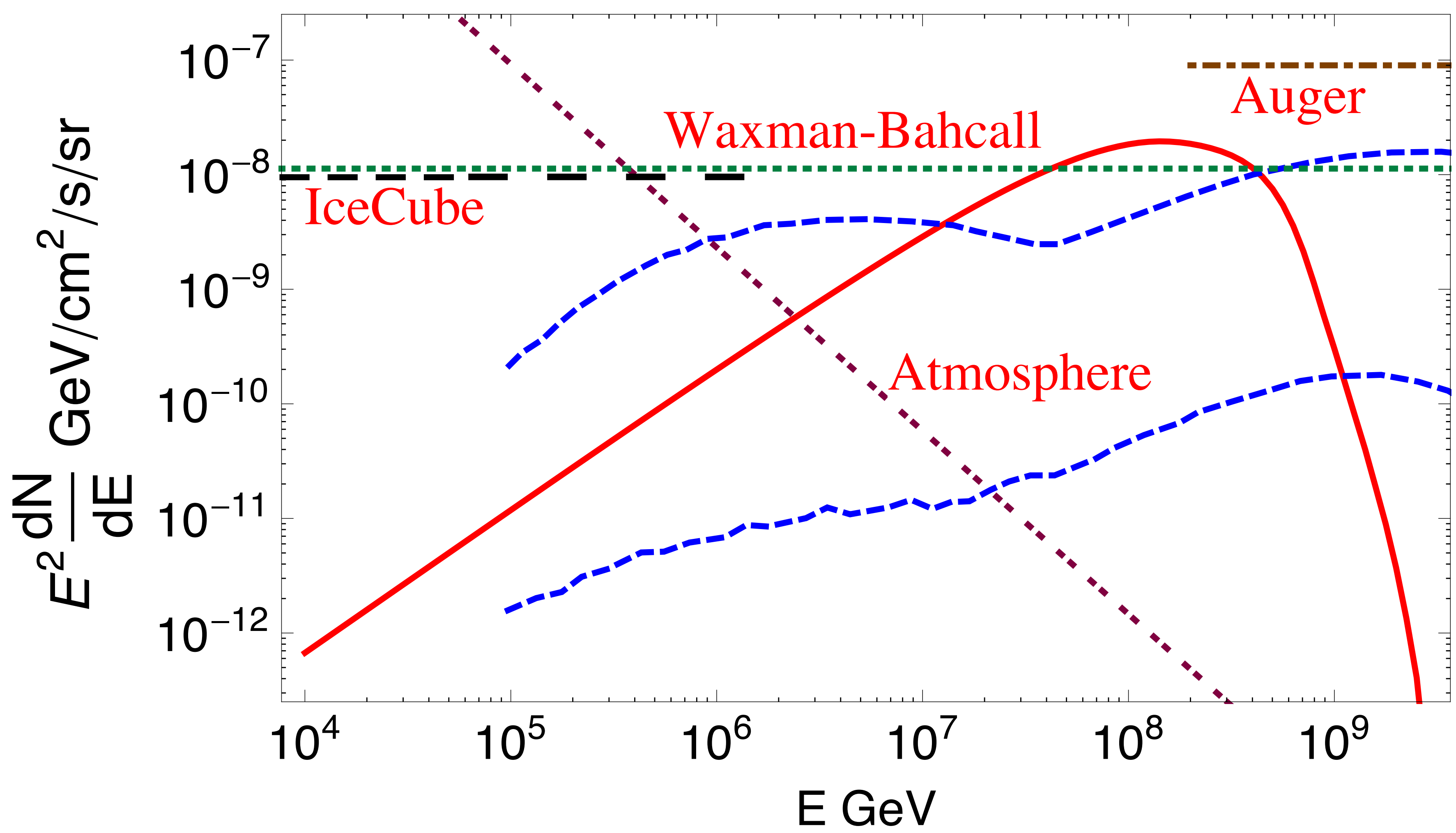
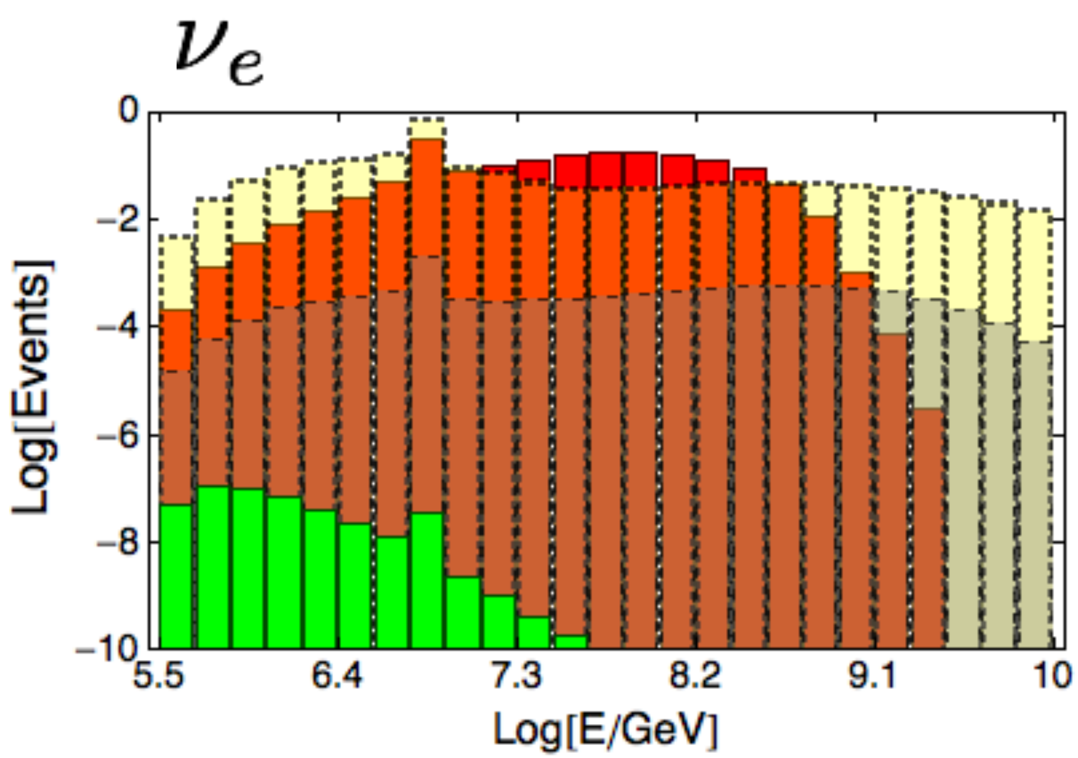
Diffuse flux



Razzaque & Yang, in prep.

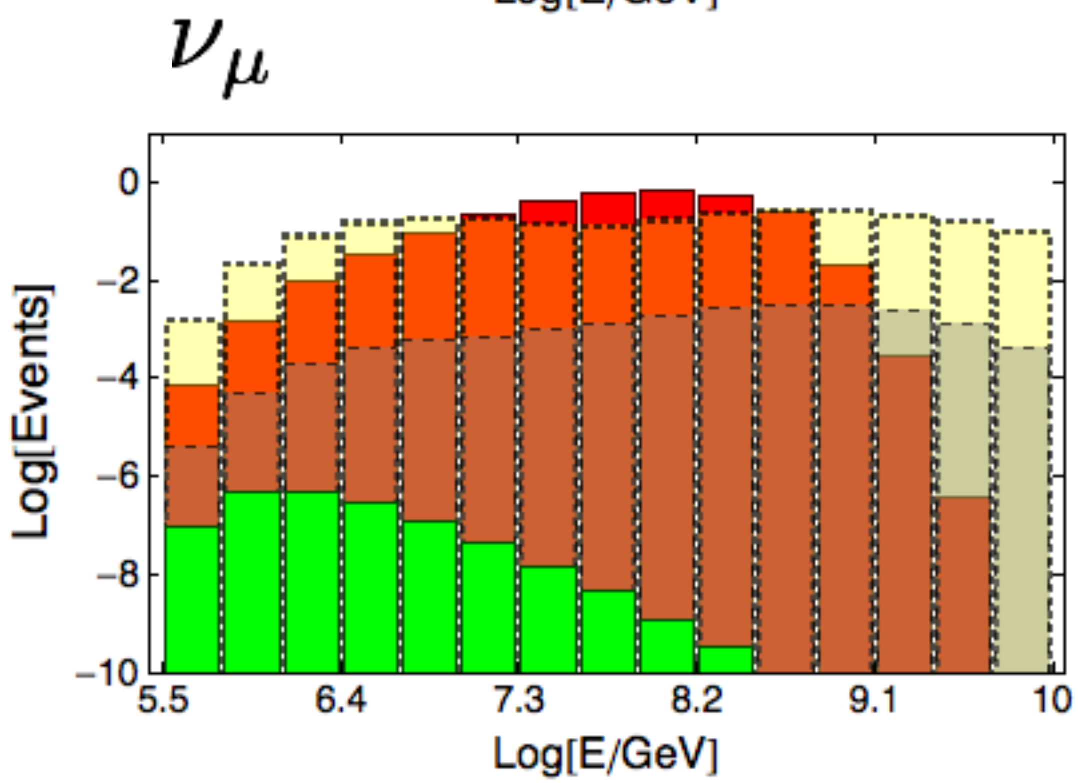
Neutrinos from external FS

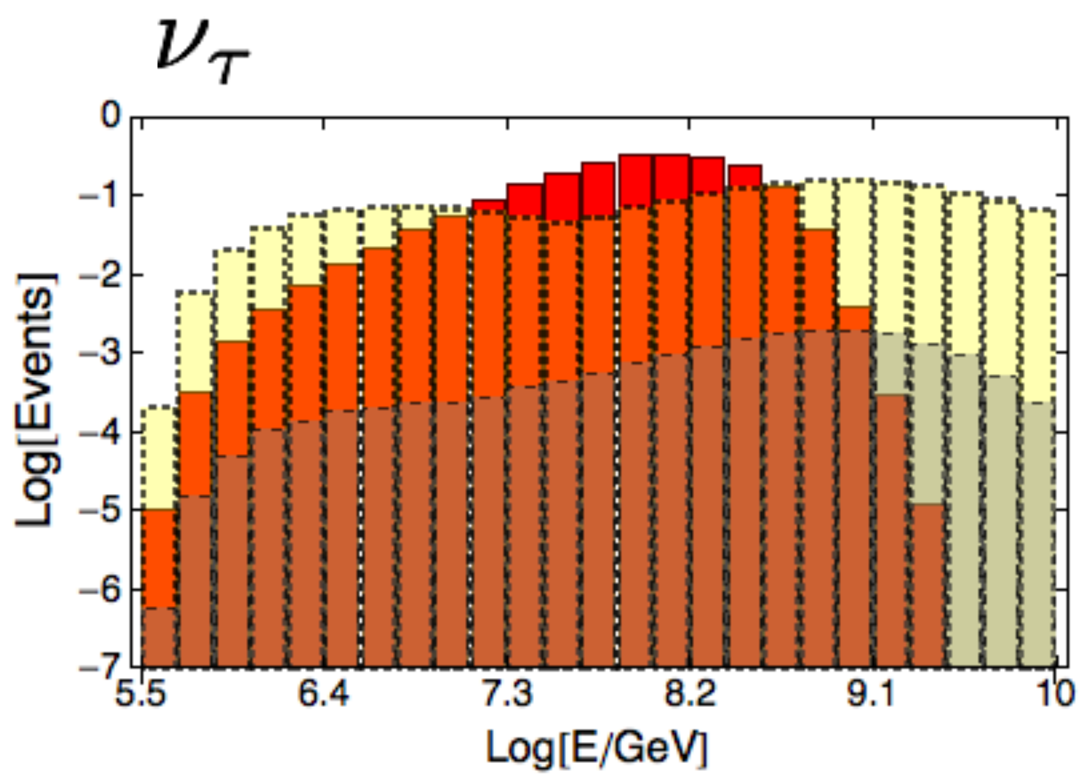


10 year events in IceCube

Preliminary

Razzaque & Yang, in prep.





Neutrinos from external FS

3 year events in IceCube

Preliminary

Log_{10}E(GeV)	5.5-7	7-8.5	8.5-10
GRB	0.38 (0.13) [0.09]	1.00 (2.25) [1.63]	0.07 (0.24) [0.21]
Atm.	3.97×10^{-7} (1.36×10^{-6}) [—]	2.78×10^{-9} (5.86×10^{-8}) [—]	2.32×10^{-12} (1.10×10^{-10}) [—]
GZK_{Fe}	3.31×10^{-3} (3.58×10^{-6}) $[8.94 \times 10^{-4}]$	2.95×10^{-3} (4.68×10^{-5}) $[5.05 \times 10^{-3}]$	2.7×10^{-3} (1.8×10^{-4}) $[9.7 \times 10^{-3}]$
GZK_p	1.45 (1.32×10^{-3}) [0.31]	0.36 (0.02) [0.54]	0.25 (0.07) [0.92]

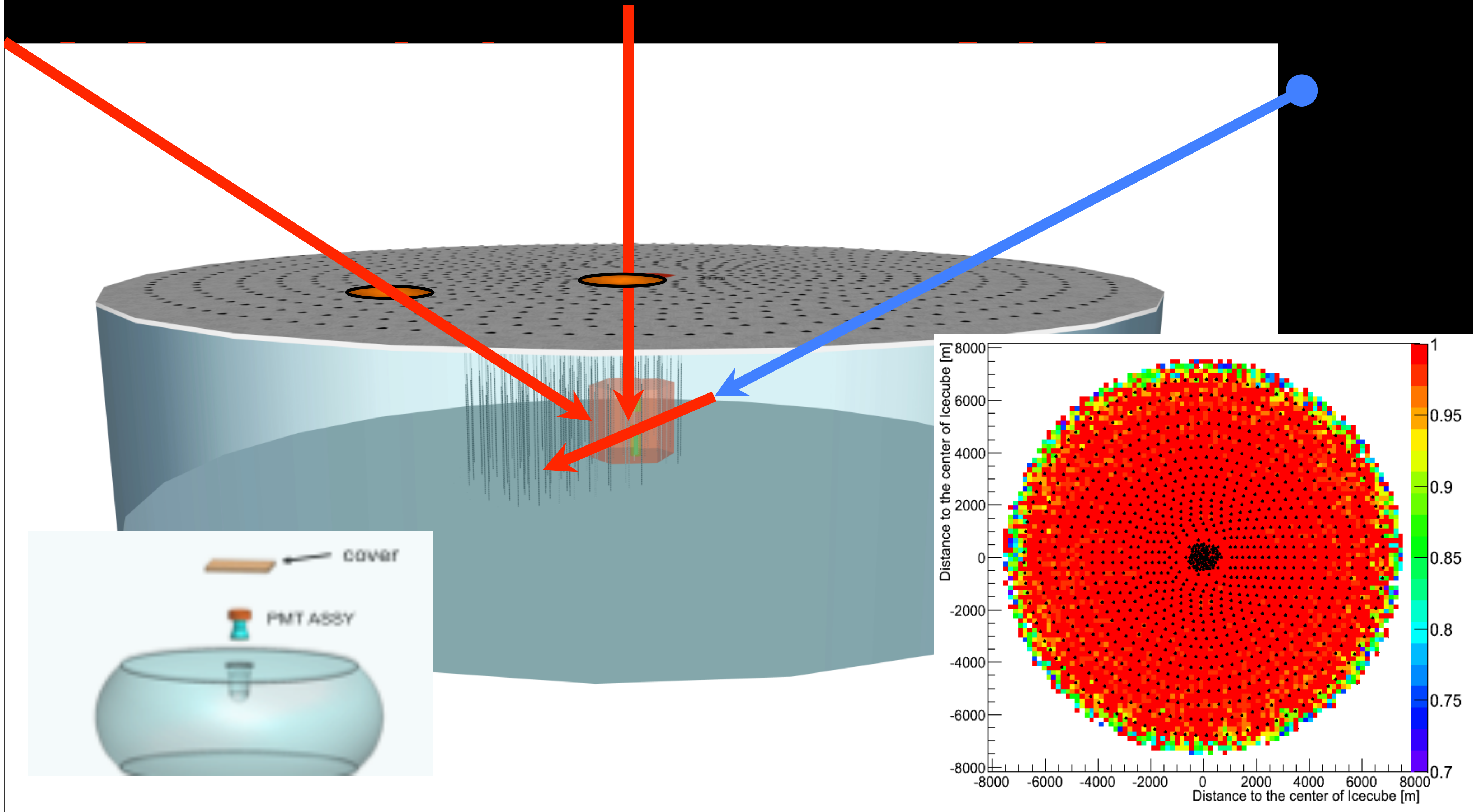
Razzaque & Yang, in prep.

Future IceCube HE Extension

Slide from Garry Hill in NEUTRINO 2014, Boston

1 PeV (cosmic primary) veto: reject most atmospheric muon AND neutrino background above 100 TeV.

An efficient surface veto, 100 km^2, for 3–5 sr background free cosmic muon neutrino and some shower detection

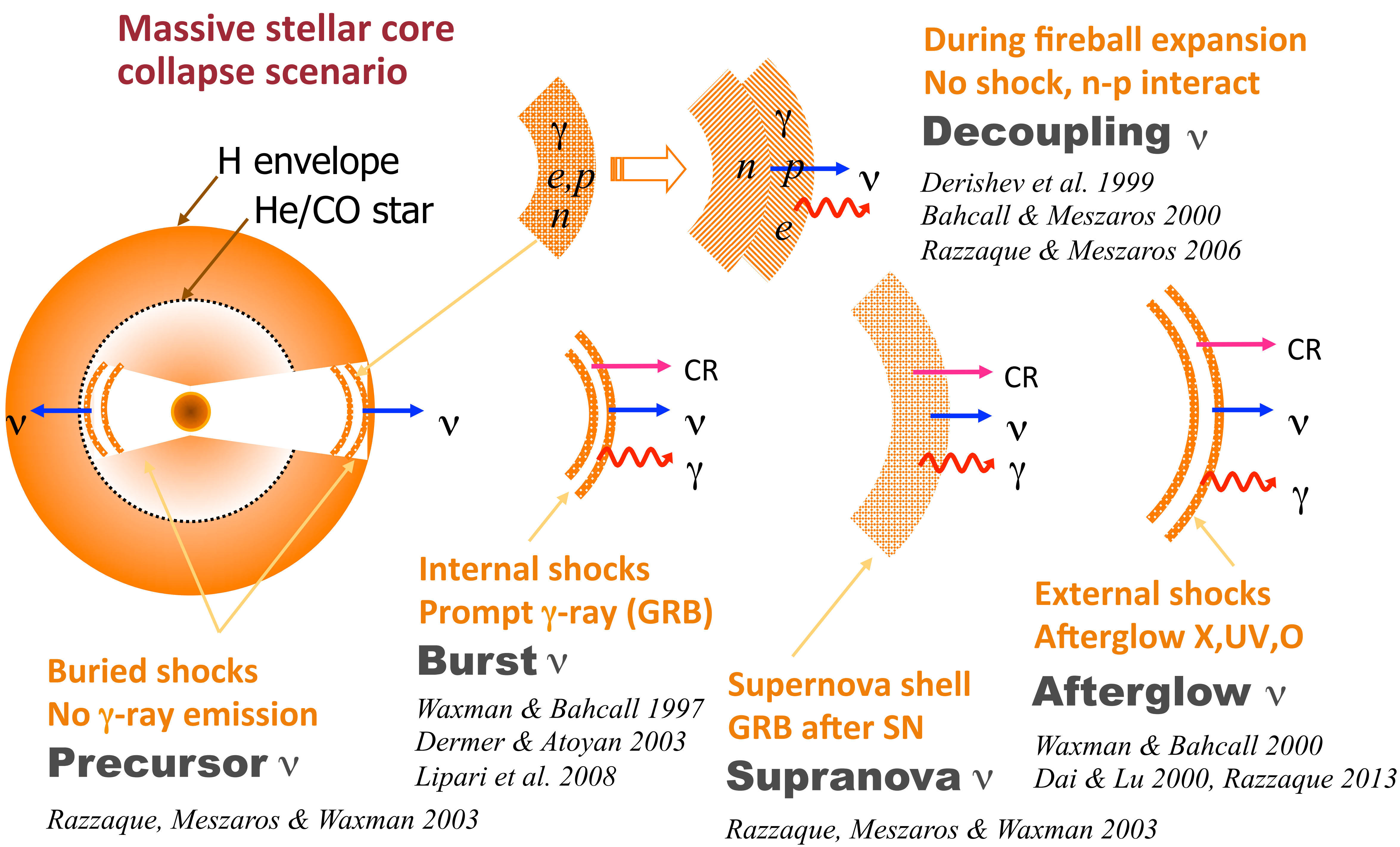


Summary and Outlook

- Acceleration of UHECRs in GRB jets is possible
  - Both internal shocks and external shocks
  - Requires large baryon loading / kinetic energy
- UHE neutrinos are expected to be produced at the acceleration sites
  - IceCube limit on prompt ~100 TeV-10’s of PeV flux is consistent with large jet bulk Lorentz factor
  - Long-lived PeV-EeV neutrinos from external shocks may be detectable with IceCube and future experiments

Backup Slides

High-Energy Neutrinos from GRBs



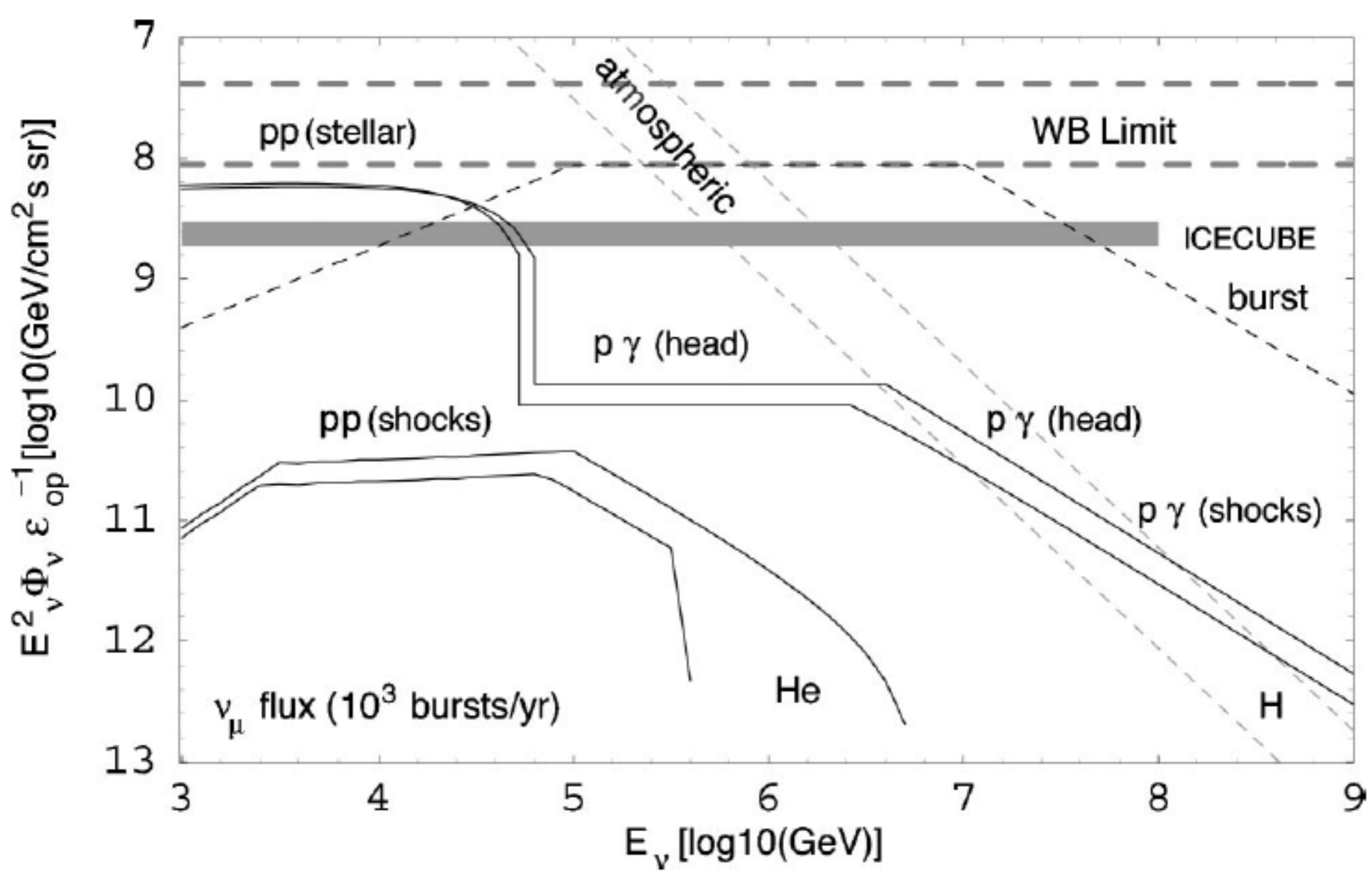
Jet buried inside collapsing star

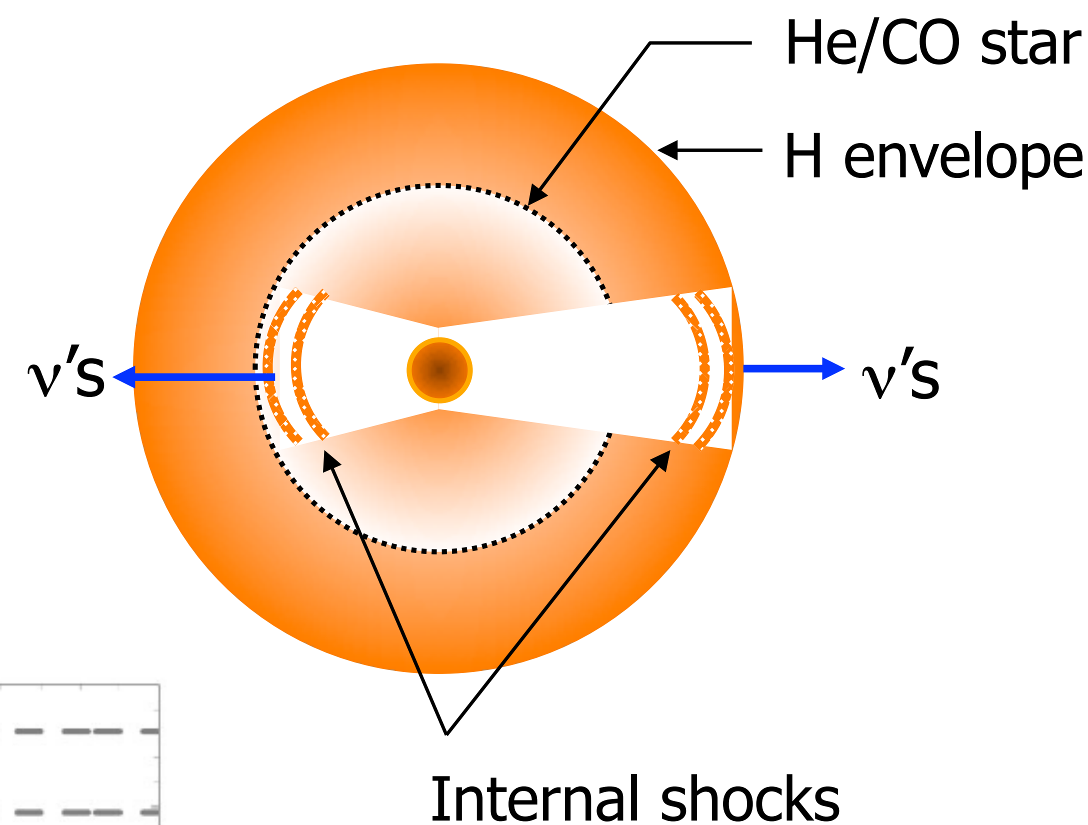
Razzaque, Meszaros & Waxman 2003

→ Optically thick shocks
→ High density of thermal γ-rays and target protons

$pp \rightarrow \nu' s$ — Low energy

$p\gamma \rightarrow \nu' s$ — High energy





$$R_i < R_\star \approx \begin{cases} 10^{11}\ cm\ (He) \\ 10^{12.5}\ cm\ (H) \end{cases}$$

← **Diffuse flux**

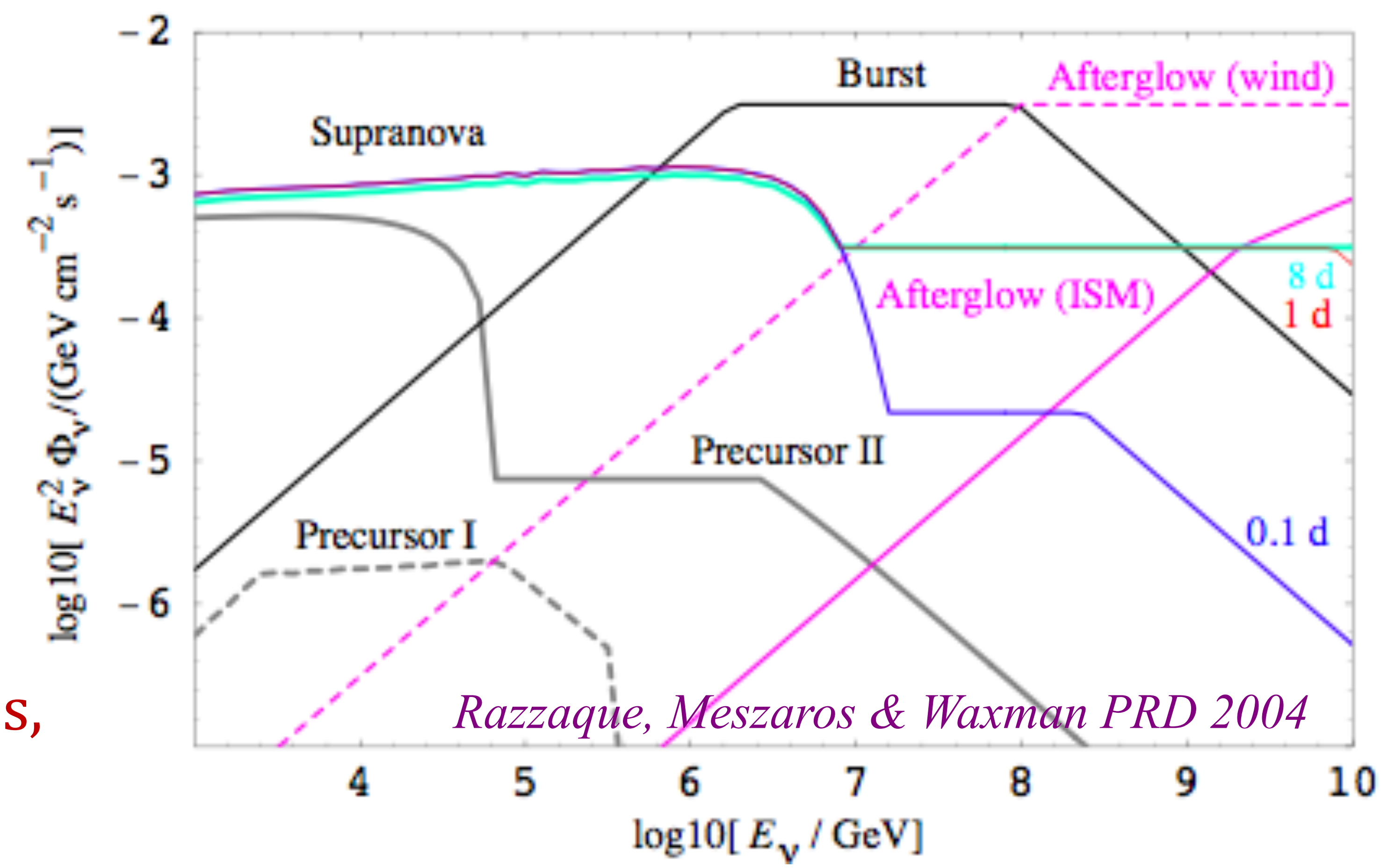
No. of choked jets can be Larger than the no. of GRBs

Prospects for HE neutrino detection

Projected ν events for IceCube		
Flux model	ν_μ	ν_e
Precursor I (He)	-	-
Precursor II (H)	4.1	1.1
Burst/prompt	3.2	0.3
Afterglow (ISM)	-	-
Afterglow (wind)	0.1	-
Supranova (>0.1 d)	13	2.4

$E_\nu >$ TeV, no oscillation

GRB 030329/SN 2003dh
Typical long duration GRB with bright SN
~10^{51} ergs/s luminosity at redshift $z = 0.17$

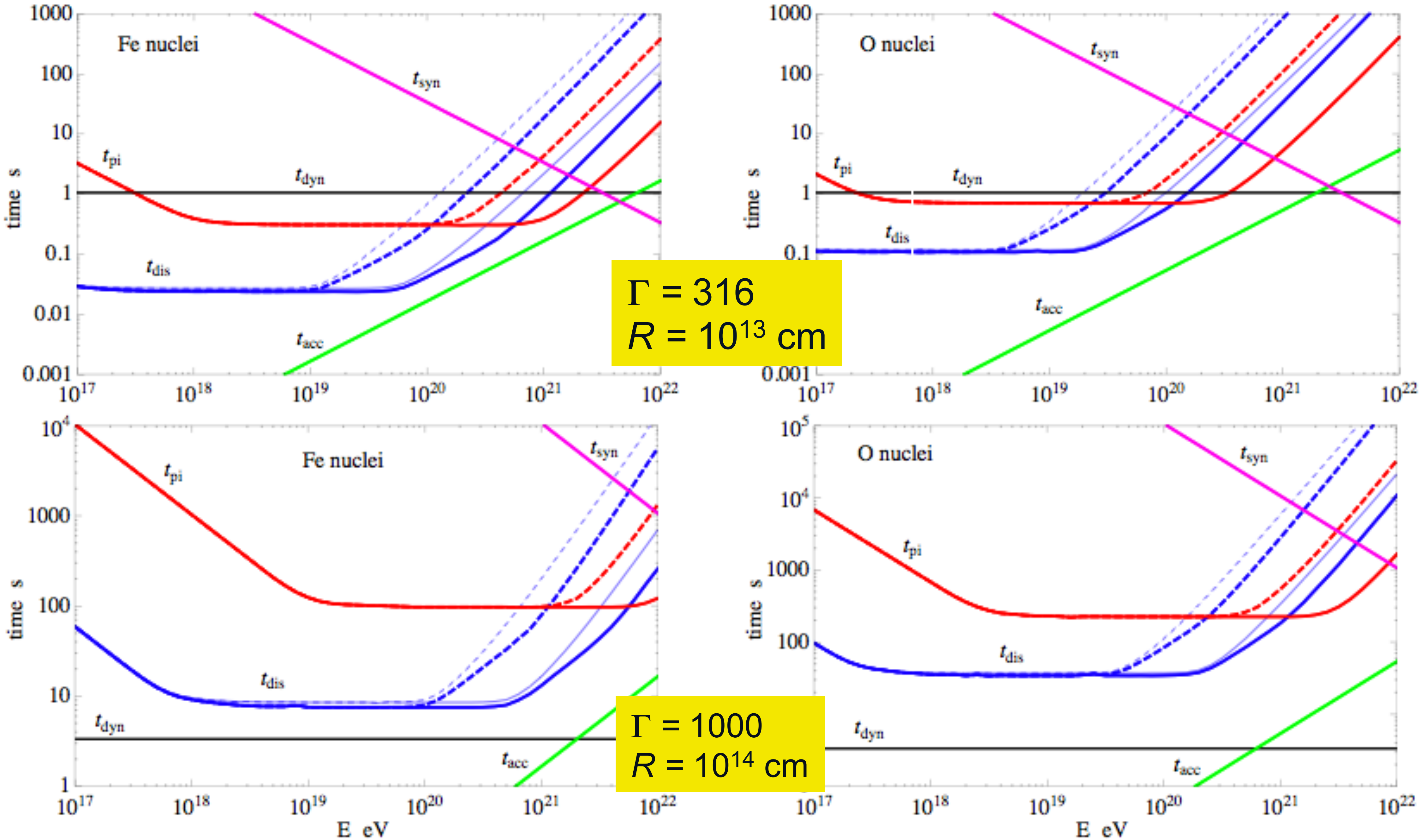


- Expected prompt muon neutrinos, after oscillation ~1.6
- Current non-detection of neutrinos from GRB 130427A (z=0.34) is consistent with prediction

Neutrino flux models:
Dai & Lu 2000 (afterglow wind)
Razzaque, Meszaros & Waxman, PRL 2003 (supranova)
Razzaque, Meszaros & Waxman, PRD 2003 (precursor)
Waxman & Bahcall 2000 (afterglow ISM)
Waxman & Bahcall 1997 (burst/prompt)

Heavy Nuclei in GRBs

Nuclei from stellar core



Wang, Razzaque, Meszaros, ApJ 2008