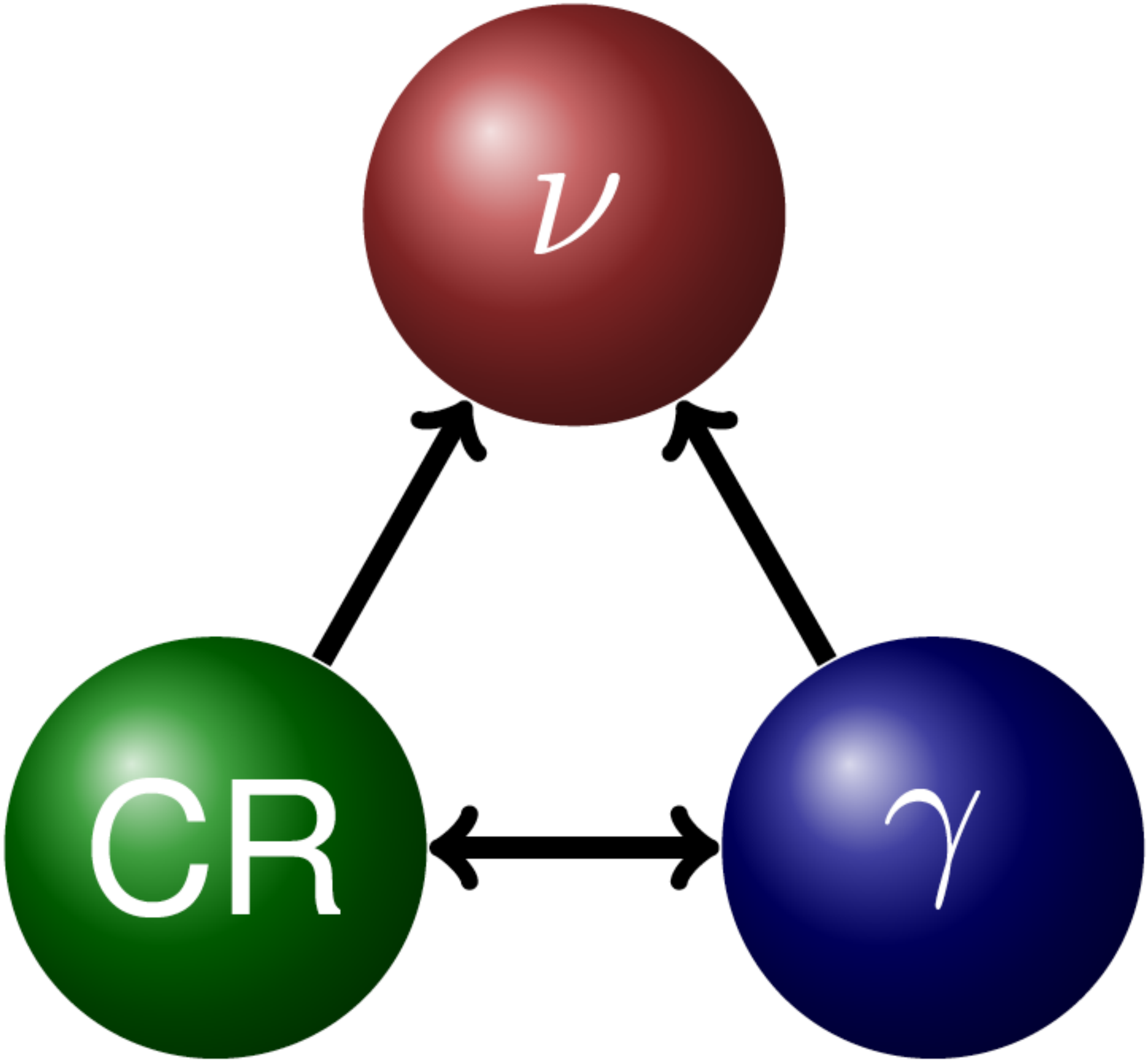
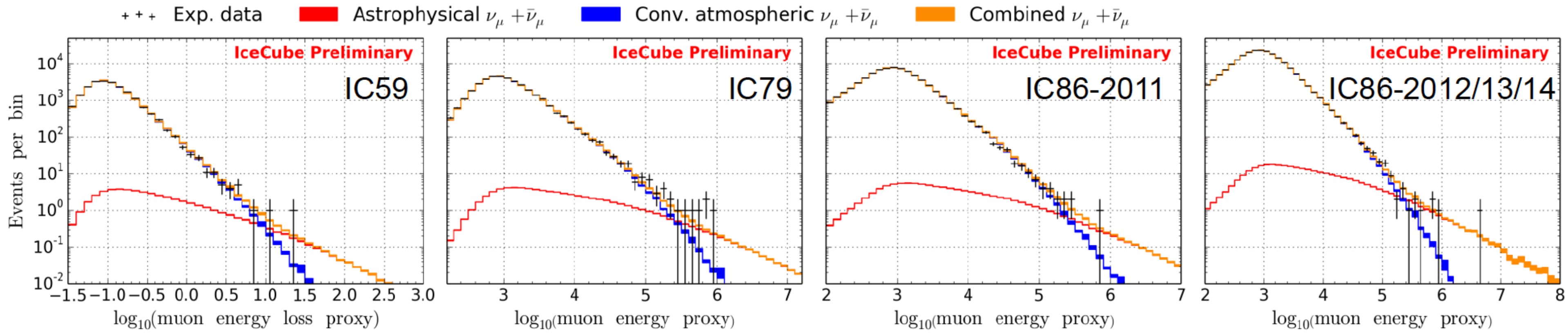
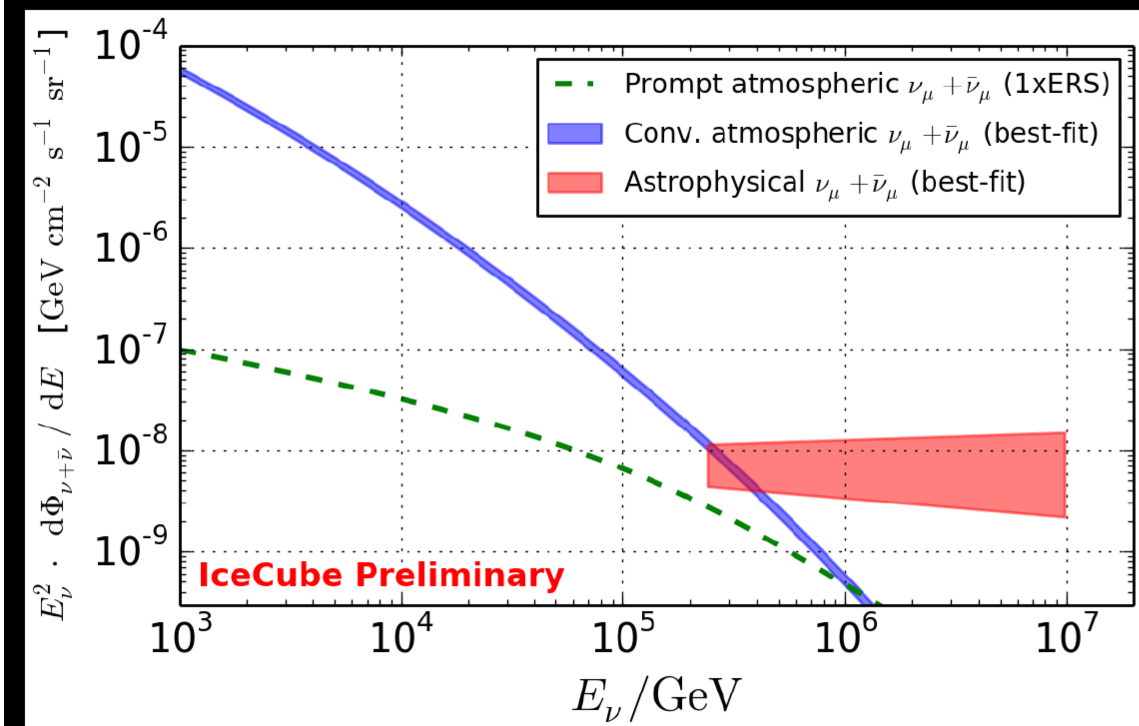


ν
CR
γ

after 6 years: 3.7→ 6.0 sigma





- Best-fit astrophysical normalization:

$$\left(0.78^{+0.29}_{-0.25}\right) \times 10^{-18}\ \mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$$

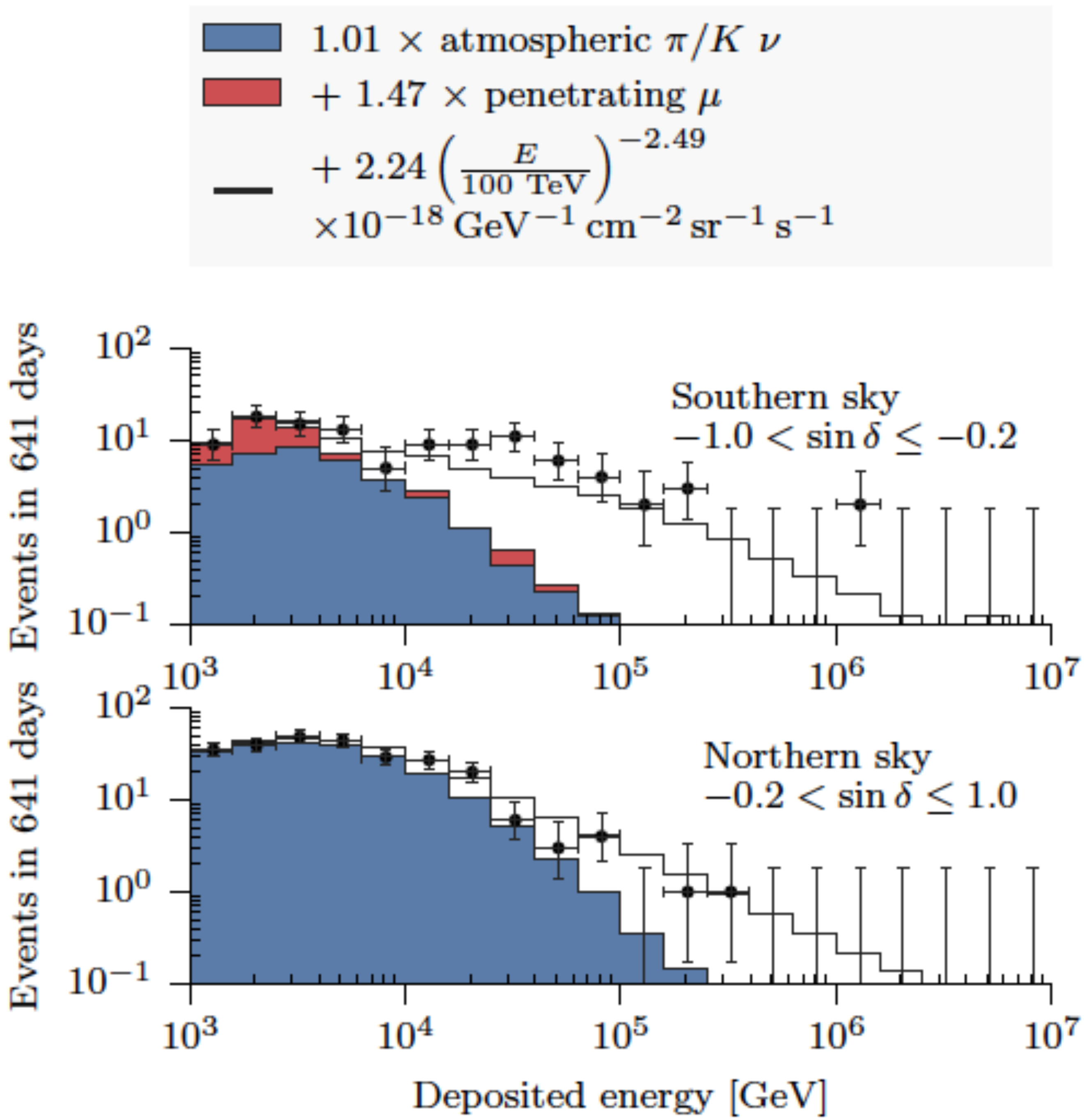
- Best-fit spectral index:

$$\gamma_{astro} = 2.06 \pm 0.13$$

- Energy ranges:

240 TeV – 10 PeV

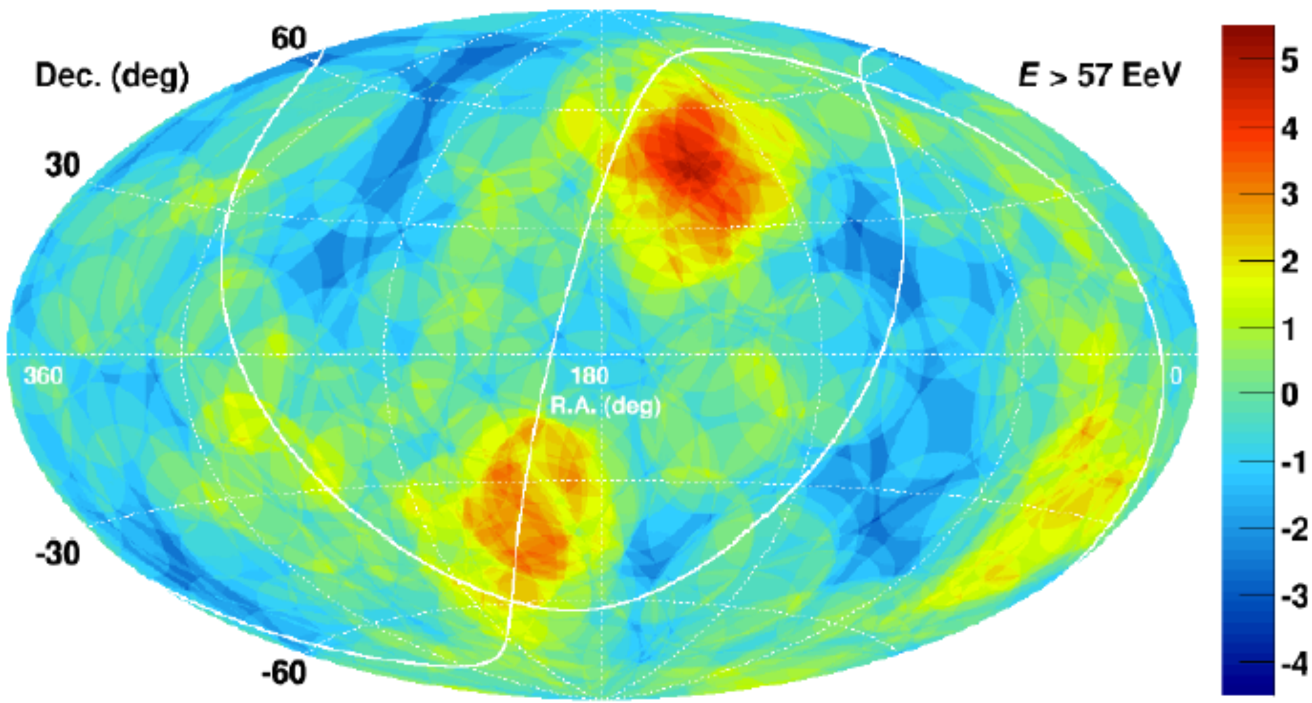
- Atmospheric-only hypothesis excluded by 6.0σ



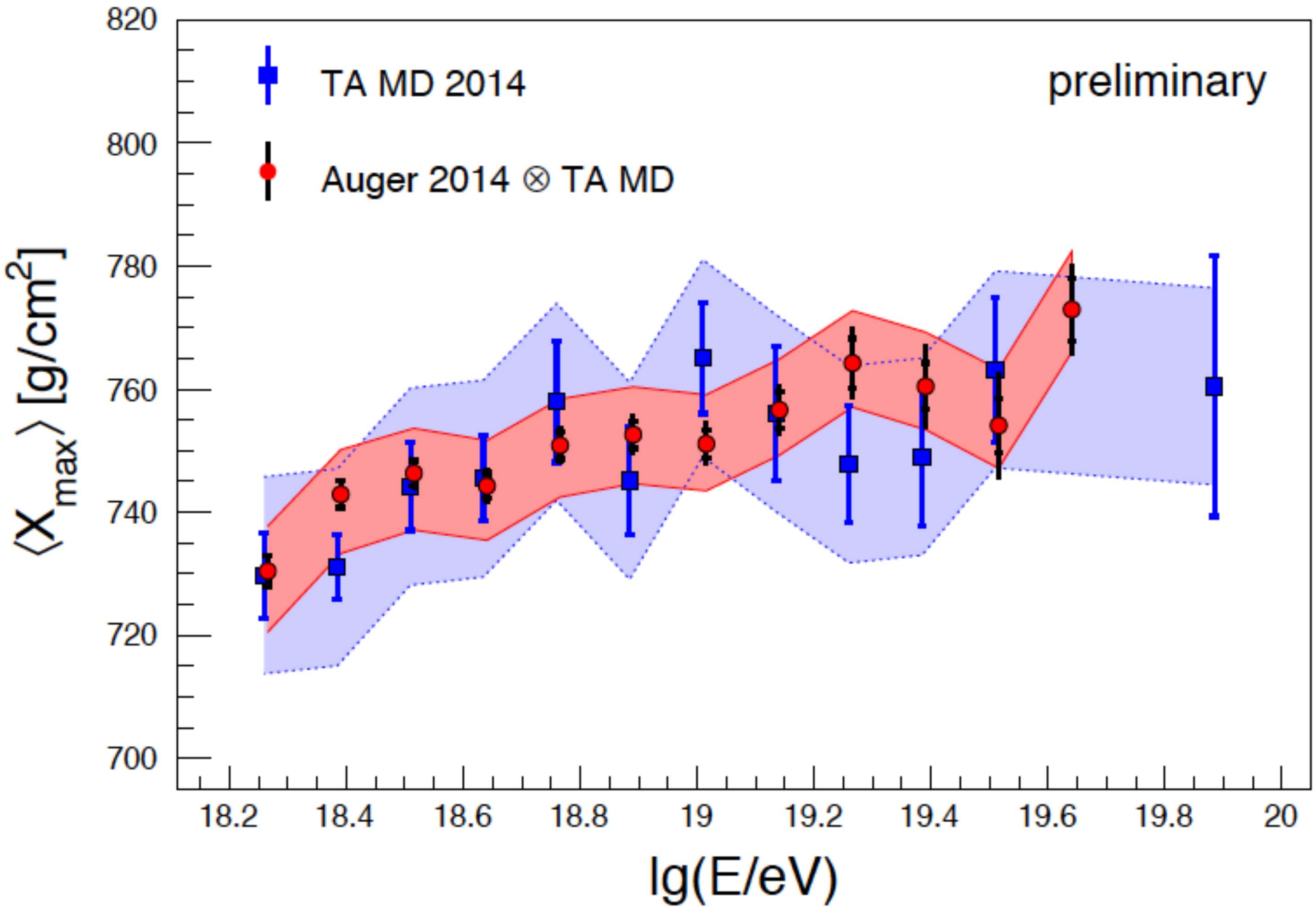
1.01 × atmospheric π/K ν
+ 1.47 × penetrating μ
+ 2.24 (E / 100 TeV)^−2.49
×10^−18 GeV^−1 cm^−2 sr^−1 s^−1
Southern sky
−1.0 < sin δ ≤ −0.2
Northern sky
−0.2 < sin δ ≤ 1.0
Events in 641 days
Events in 641 days
Deposited energy [GeV]

Attempt at full-sky coverage

- E > 57EeV
- r = 20˚

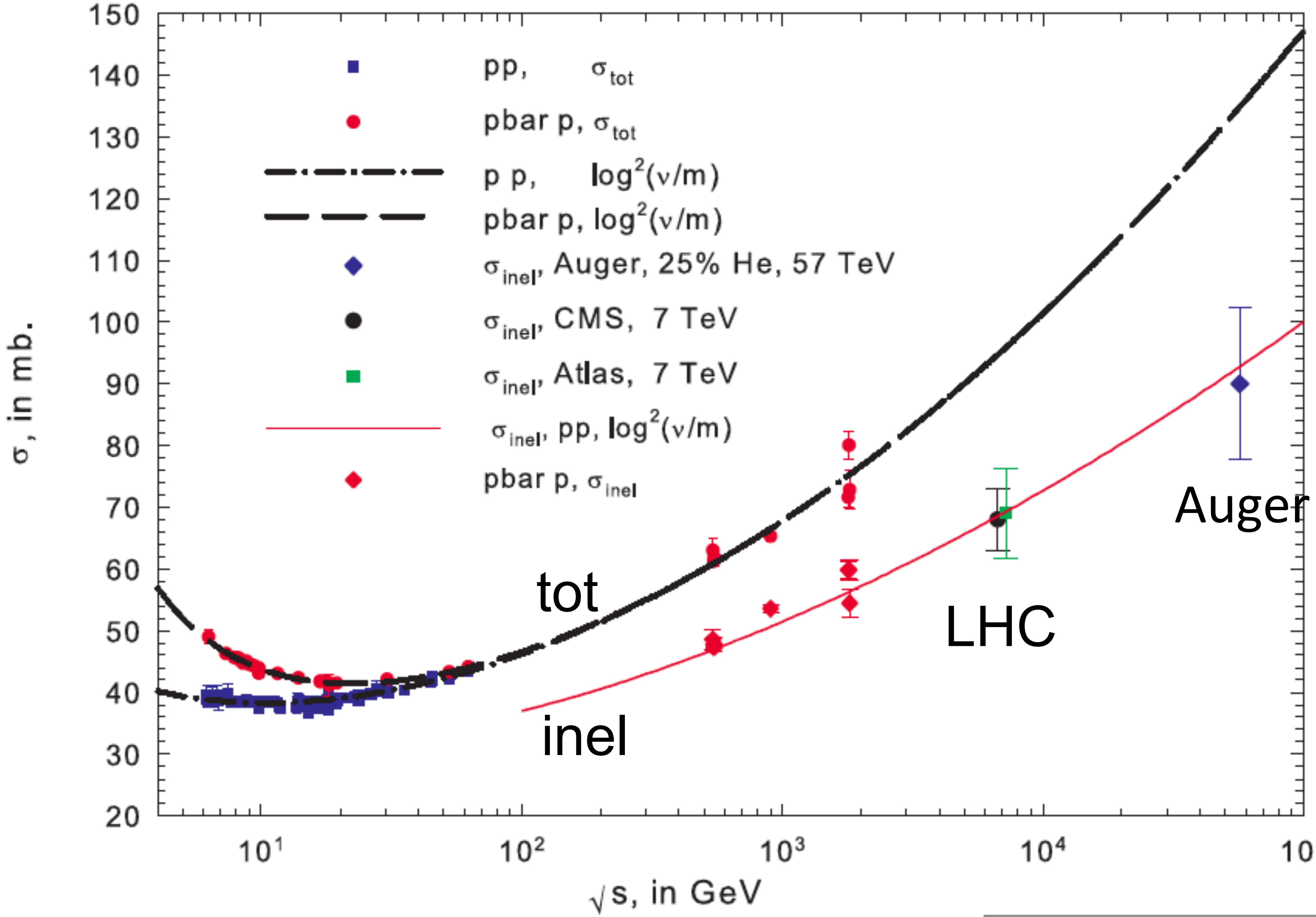


Average Shower Maximum: Comparison to TA



$\langle \Delta \rangle = (2.9 \pm 2.7 \text{ (stat.)} \pm 18 \text{ (syst.)}) \text{ g/cm}^2$

MU for the Pierre Auger and TA Collaborations, Proc. 34th ICRC, arXiv:1511.02103

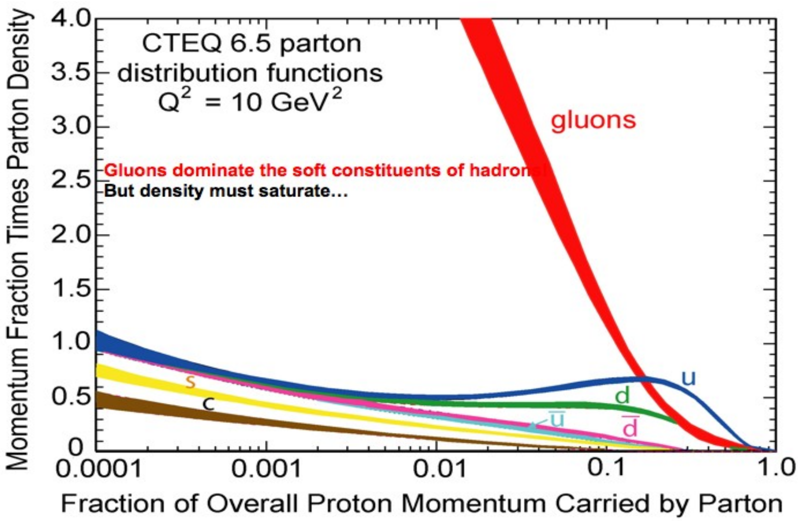


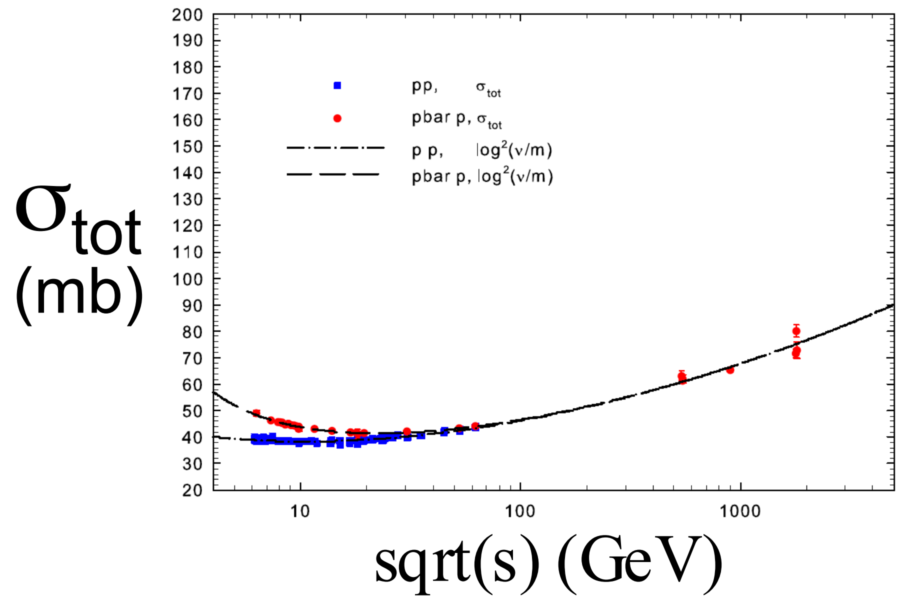
Block and collaborators

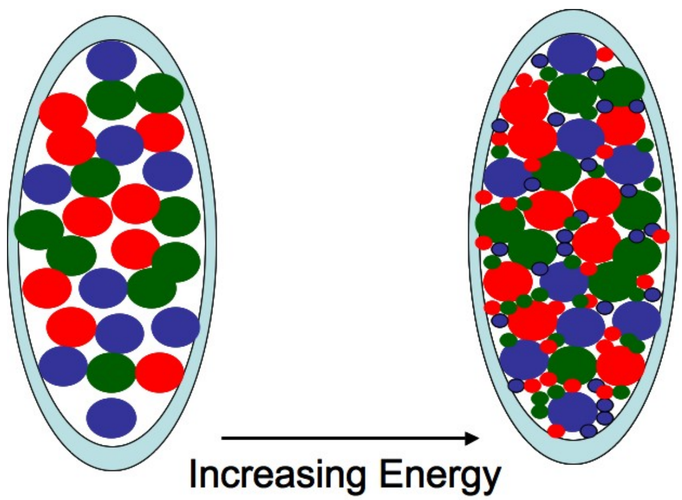
QCD evolution and gluon saturation

as the partons evolve, the number of gluons becomes large

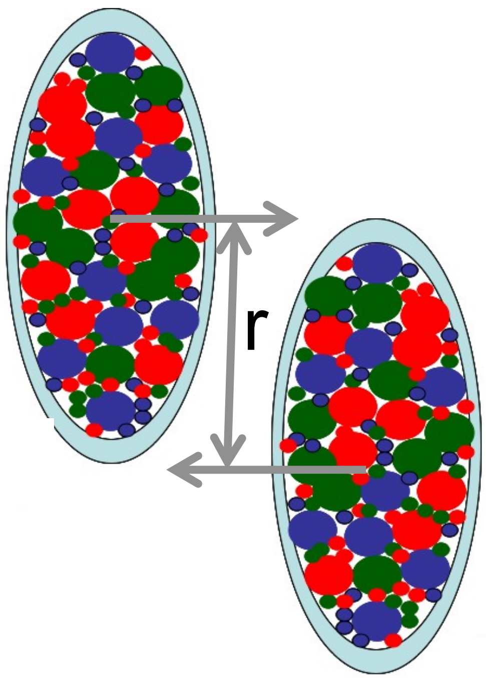
they must fit inside a hadron that does not increase in size







- at high energy gluons are Lorentz contracted to sit atop one another and act coherently, like nucleons in a nucleus
- density per unit rapidity is large and increases with energy as log (E/Λ)
- the asymptotic proton is a black disk of gluons



- scattering of two protons by the exchange of a particle with mass m (range 1/m)

$$P(r,E) \propto e^{-2mr} e^{S(E)}$$

where *S(E)* is the density of final states.

- *P* becomes of order one for

$$R = \frac{S(E)}{2m}$$

- for the gluon condensate the number of final states grows as a QCD-logarithm in energy

$$S(E) \propto \log\left(\frac{E}{\Lambda}\right)$$

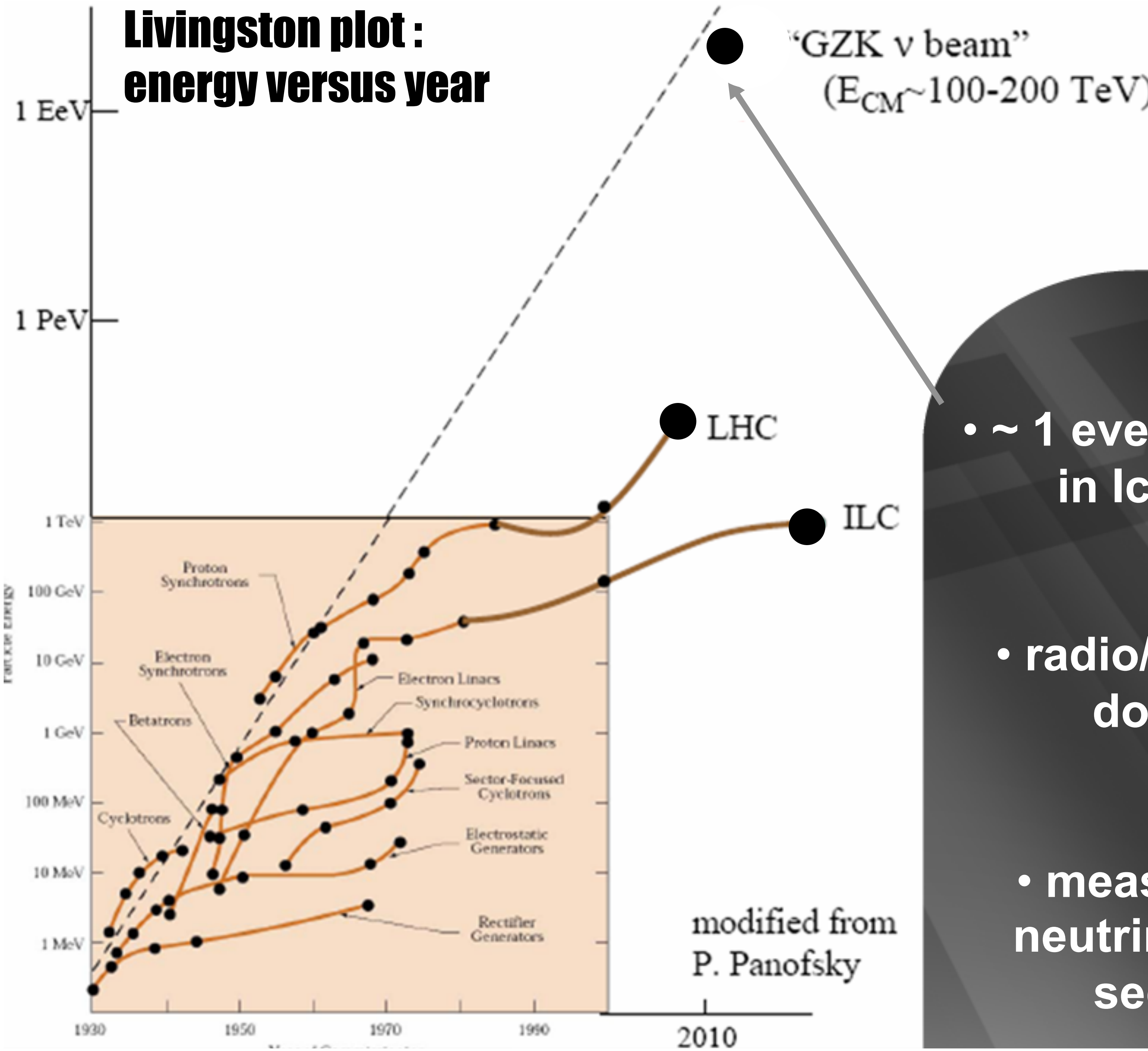
you can think of it as the entropy of the gluon gas (also known as color glass condensate)

- the total cross section for shadow scattering is

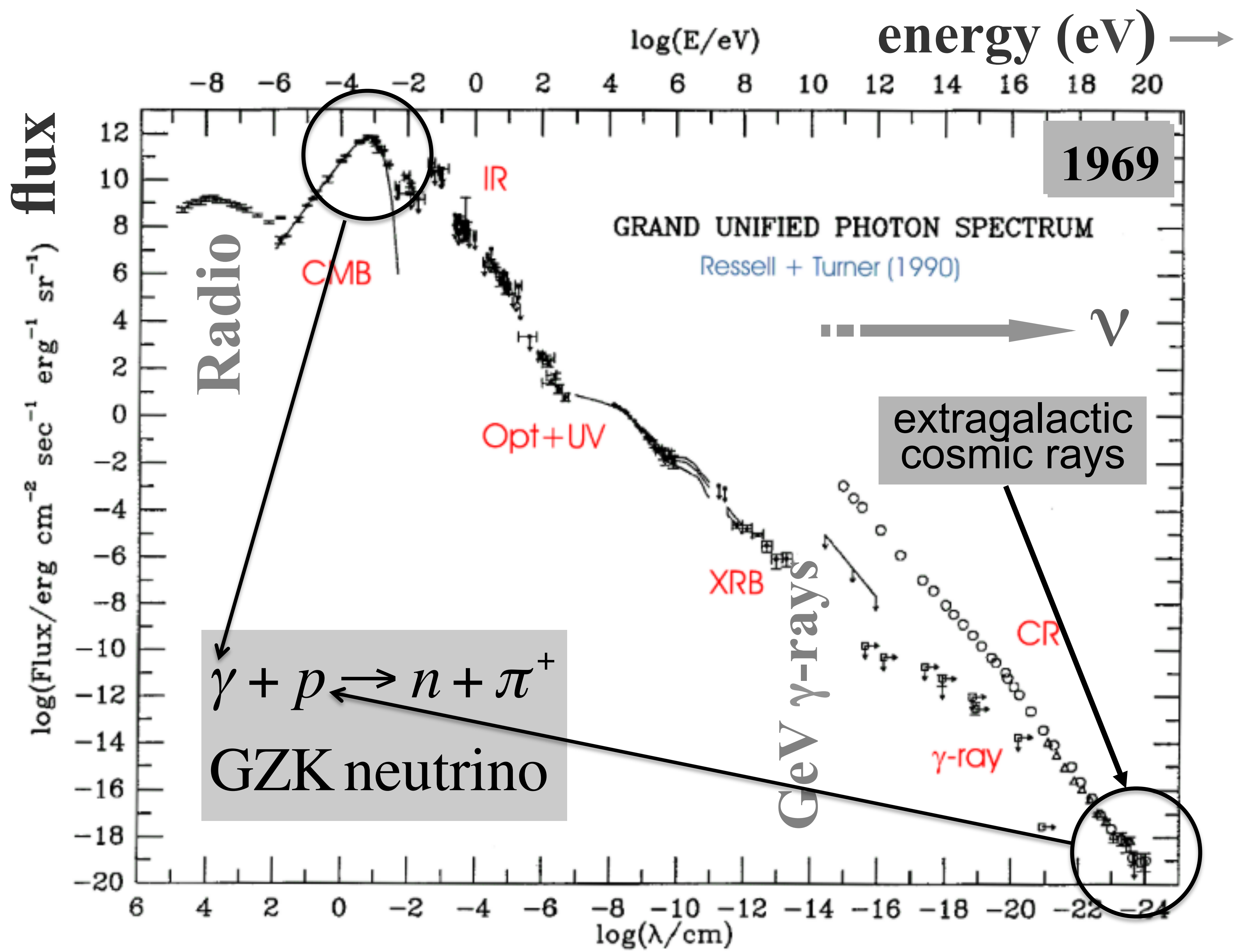
$$\sigma = 2\pi R^2 = \frac{1}{4m^2} S^2$$

$$\sigma \propto \frac{1}{m^2} \log^2\left(\frac{E}{\Lambda}\right)$$

Livingston plot : energy versus year



- ~ 1 event per year in IceCube
- radio/acoustic domain
- measure the neutrino cross section



energy (eV)
log(E/eV)
flux
1969
GRAND UNIFIED PHOTON SPECTRUM
Ressell + Turner (1990)
Radio
CMB
IR
Opt+UV
XRB
GeV γ-rays
γ-ray
CR
ν
extragalactic cosmic rays
$\gamma + p \rightarrow n + \pi^+$
GZK neutrino
log(Flux/erg cm⁻² sec⁻¹ erg⁻¹ sr⁻¹)
log(λ/cm)

cosmic rays interact with the microwave background

$$p + \gamma \rightarrow n + \pi^{+} \ and \ p + \pi^{0}$$

cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

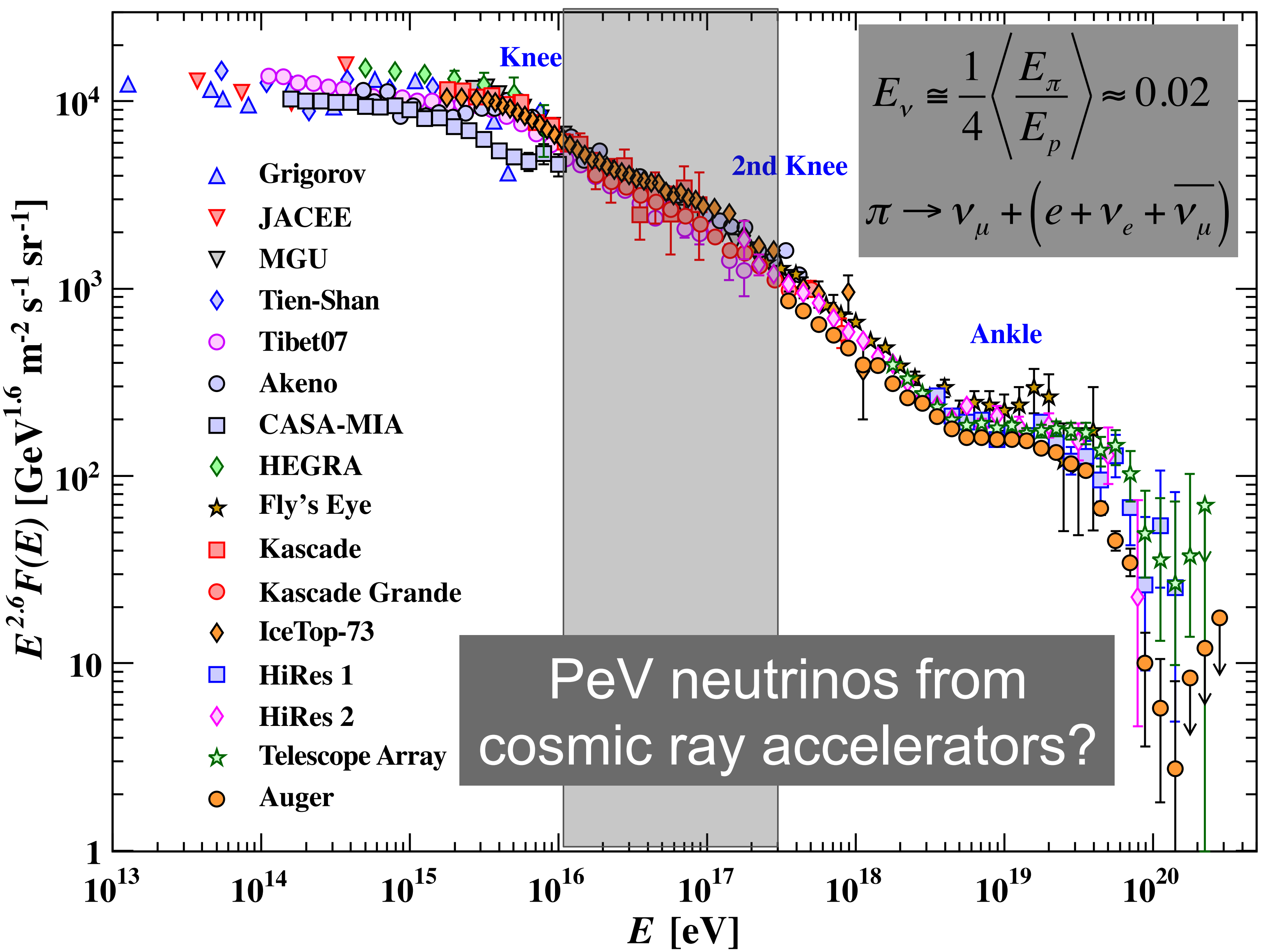
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \overline{\upsilon_{\mu}} + \upsilon_{e}\} + \upsilon_{\mu}$$

1 event per cubic kilometer per year

...but it points at its source!

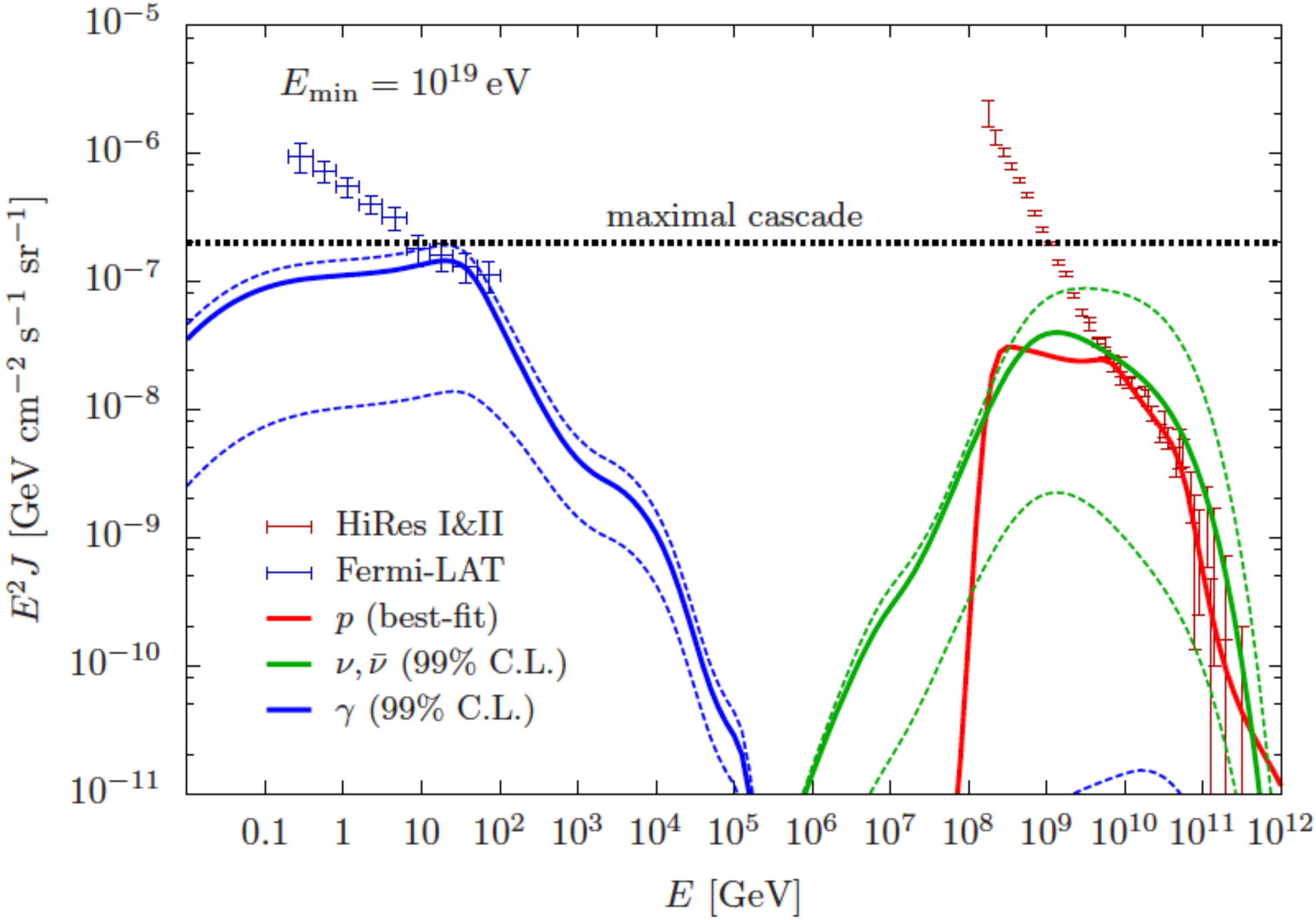
the extragalactic accelerator: knobs to turn

- power-law energy dependence with a slope
- minimum energy
- maximum energy
- composition → assume protons
- cosmological evolution



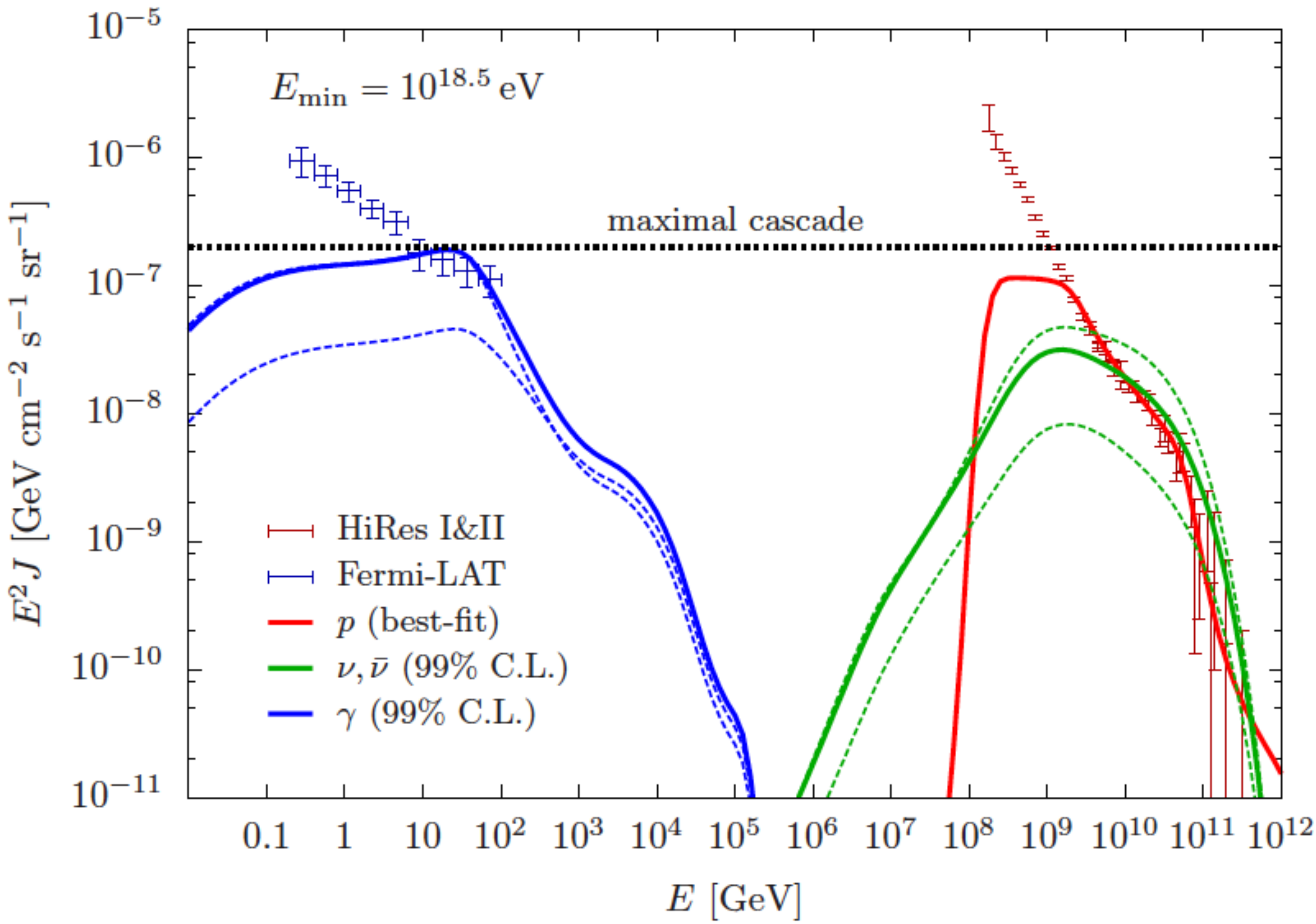
Knee
2nd Knee
Ankle
$E_\nu \cong \frac{1}{4}\left\langle \frac{E_\pi}{E_p} \right\rangle \approx 0.02$
$\pi \rightarrow \nu_\mu + \left(e + \nu_e + \overline{\nu_\mu}\right)$
PeV neutrinos from
cosmic ray accelerators?
Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
CASA-MIA
HEGRA
Fly's Eye
Kascade
Kascade Grande
IceTop-73
HiRes 1
HiRes 2
Telescope Array
Auger
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]

Cosmogenic neutrinos from CR protons



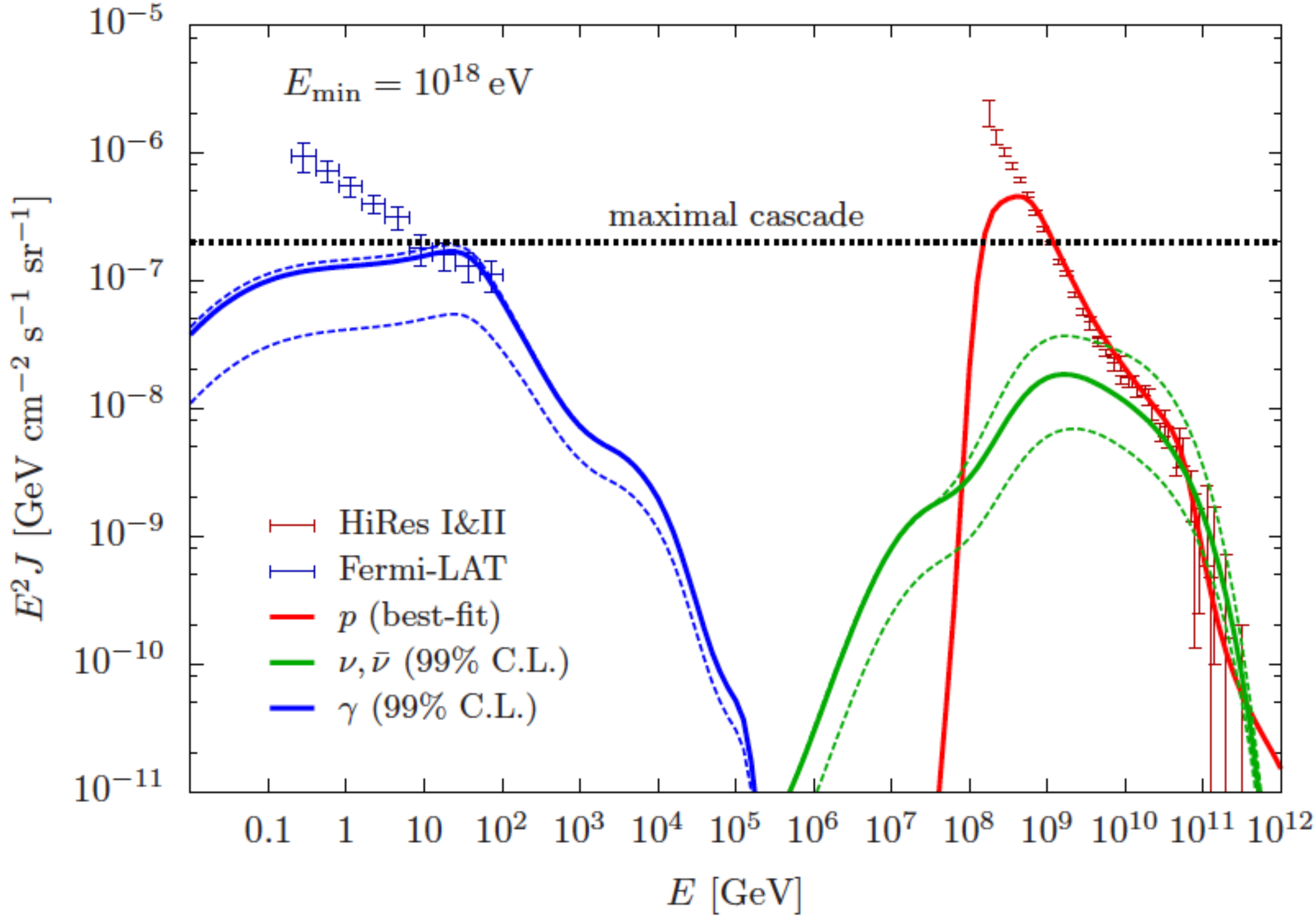
[MA, Anchordoqui, Gonzalez-Garcia, Halzen & Sarkar '11]

Cosmogenic neutrinos from CR protons



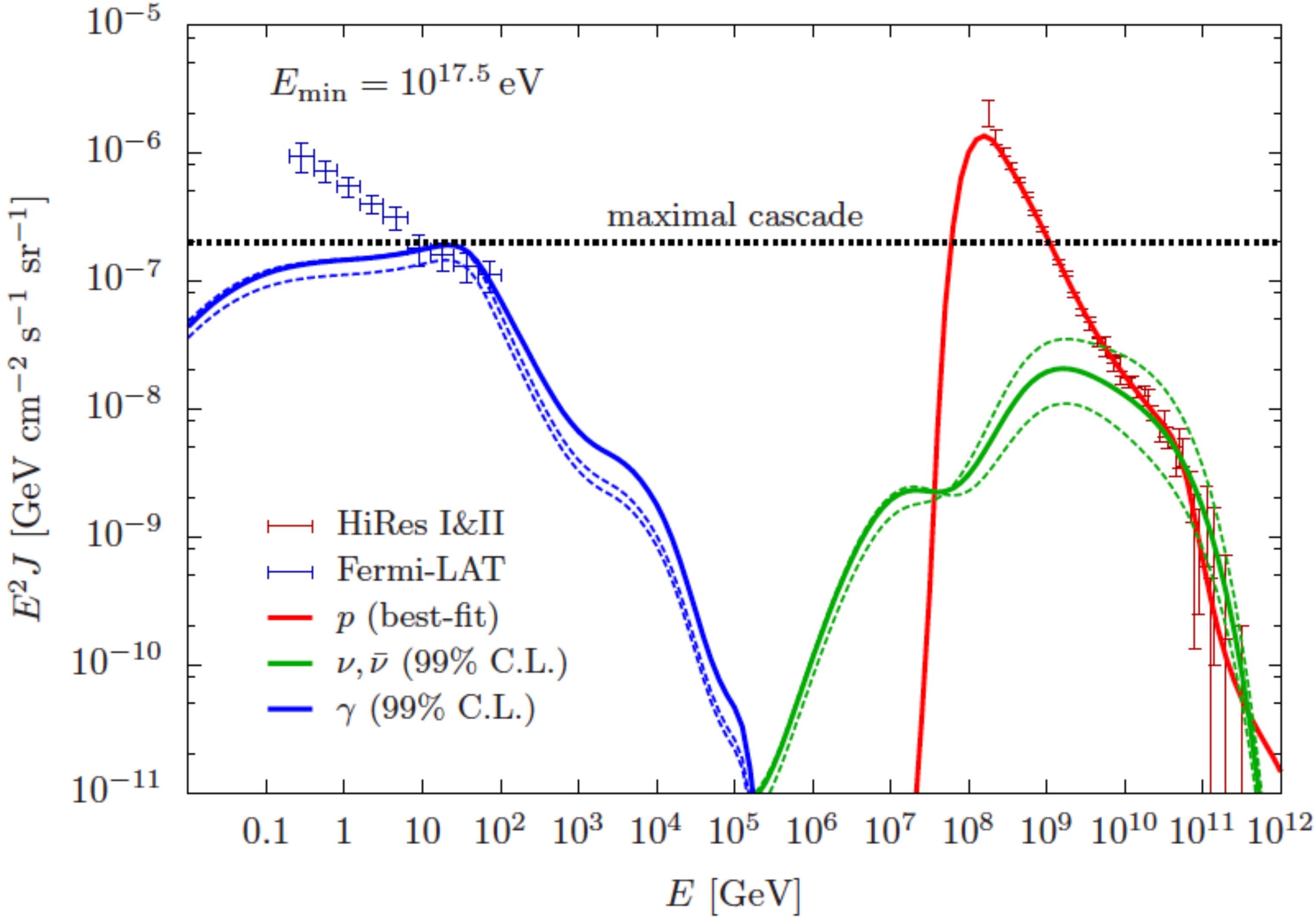
[MA, Anchordoqui, Gonzalez-Garcia, Halzen & Sarkar '11]

Cosmogenic neutrinos from CR protons

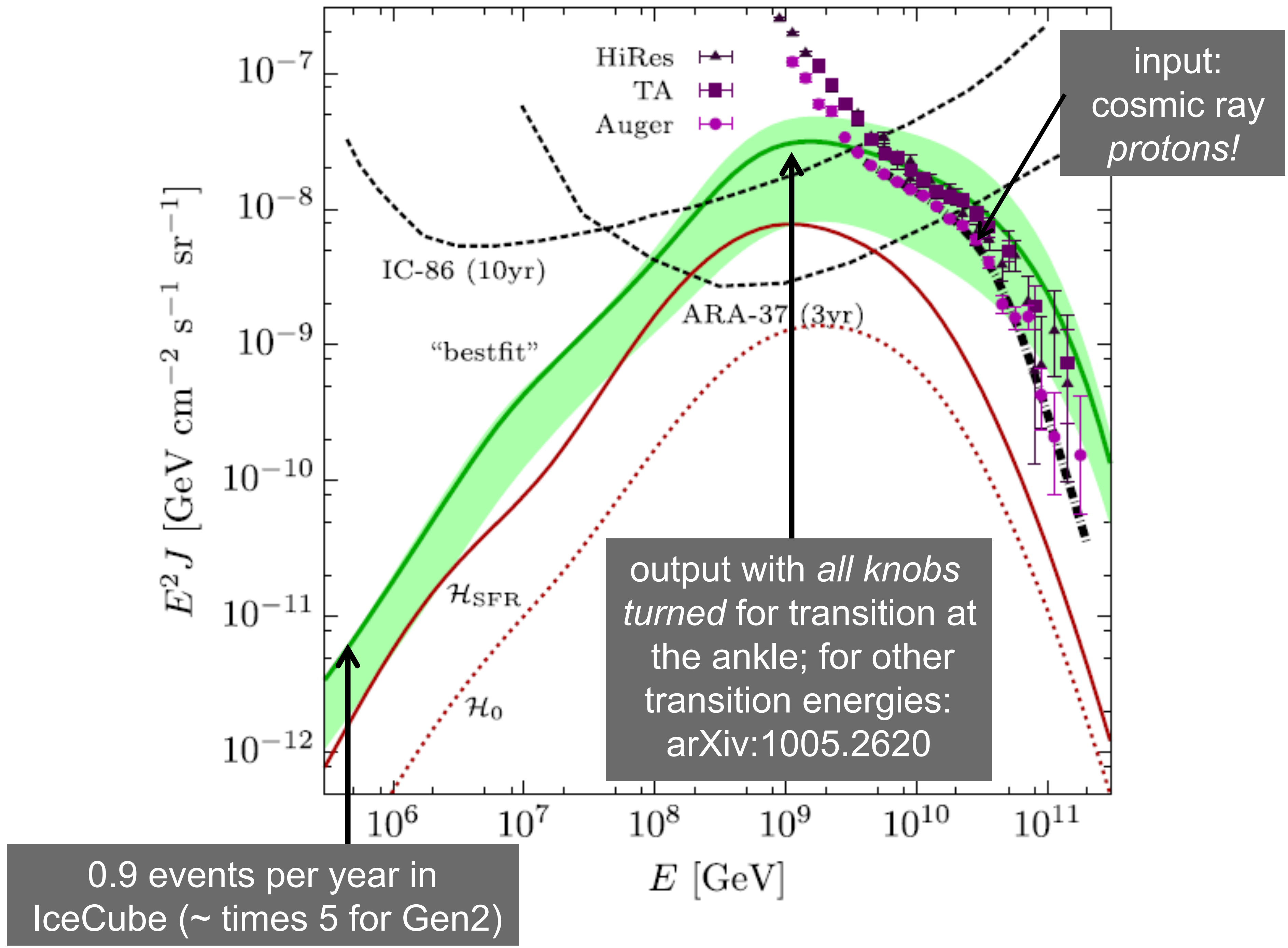


[MA, Anchordoqui, Gonzalez-Garcia, Halzen & Sarkar '11]

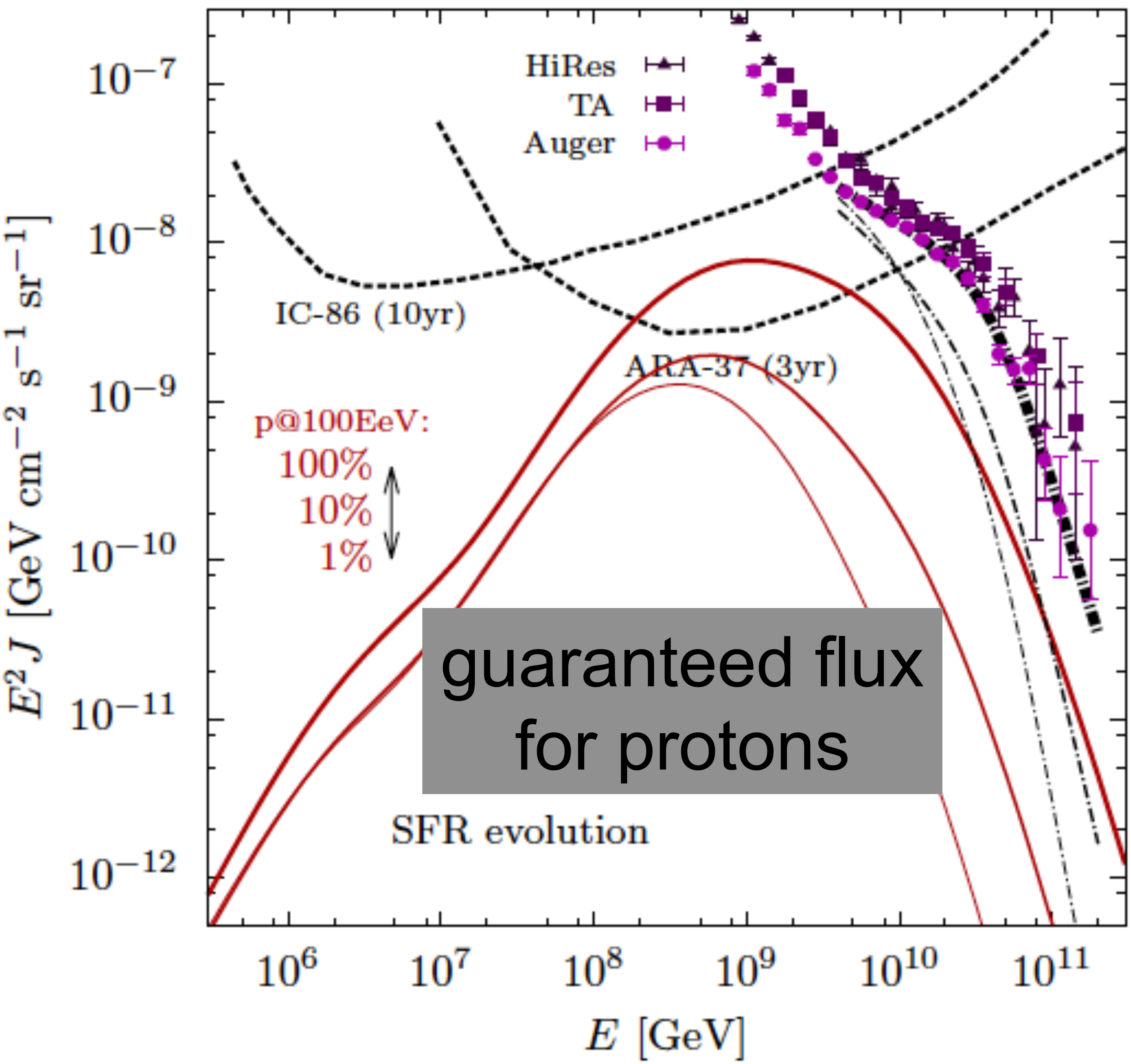
Cosmogenic neutrinos from CR protons



knobs to turn: inject accelerator slope, minimum and maximum energy, evolution with z



HiRes
TA
Auger
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{SFR}$
$\mathcal{H}_0$
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
input: cosmic ray *protons!*
output with *all knobs turned* for transition at the ankle; for other transition energies: arXiv:1005.2620
0.9 events per year in IceCube (~ times 5 for Gen2)



HiRes
TA
Auger
IC-86 (10yr)
ARA-37 (3yr)
p@100EeV:
100%
10%
1%
guaranteed flux
for protons
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]

Guaranteed cosmogenic neutrinos

➜ nucleon spectrum for observed mass number $A_{\rm obs}$:

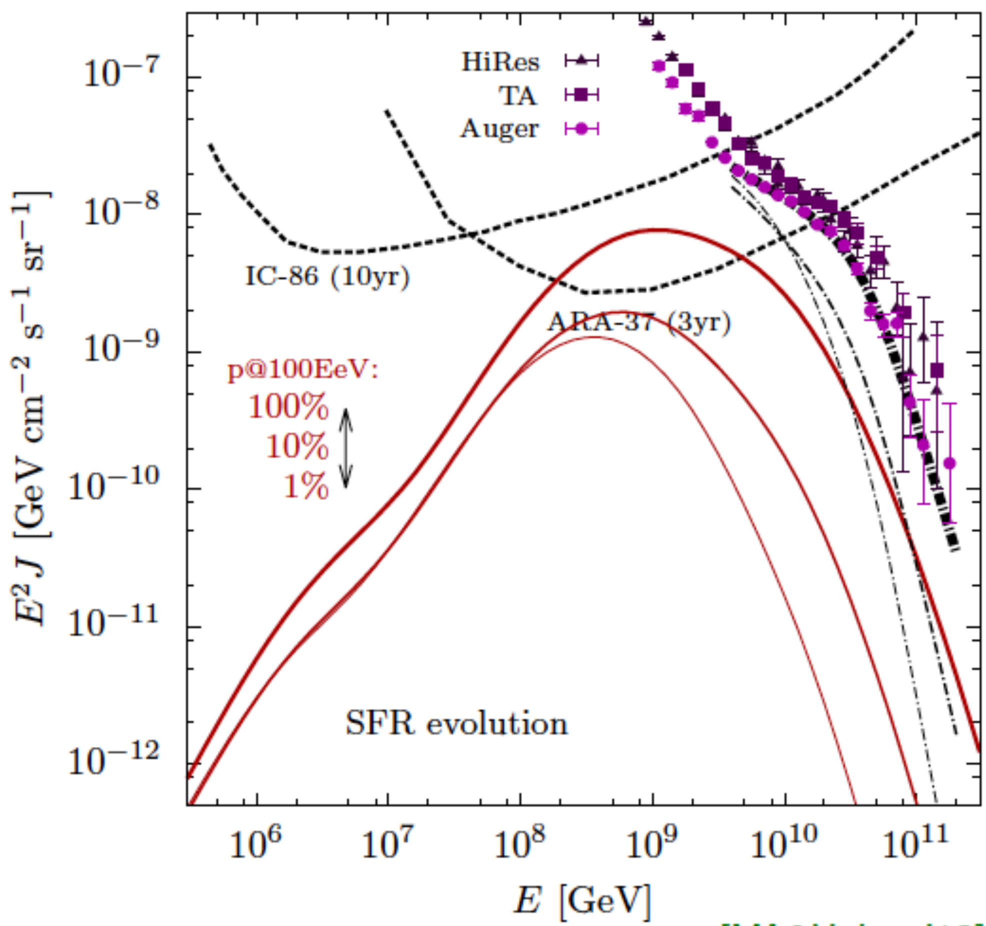
$$J_N^{\rm min}(E_N) = A_{\rm obs}^2 J_{\rm CR}(A_{\rm obs}E_N)$$

- dependence on cosmic evolution of sources:
  - no evolution (dotted)
  - star-formation rate (solid)

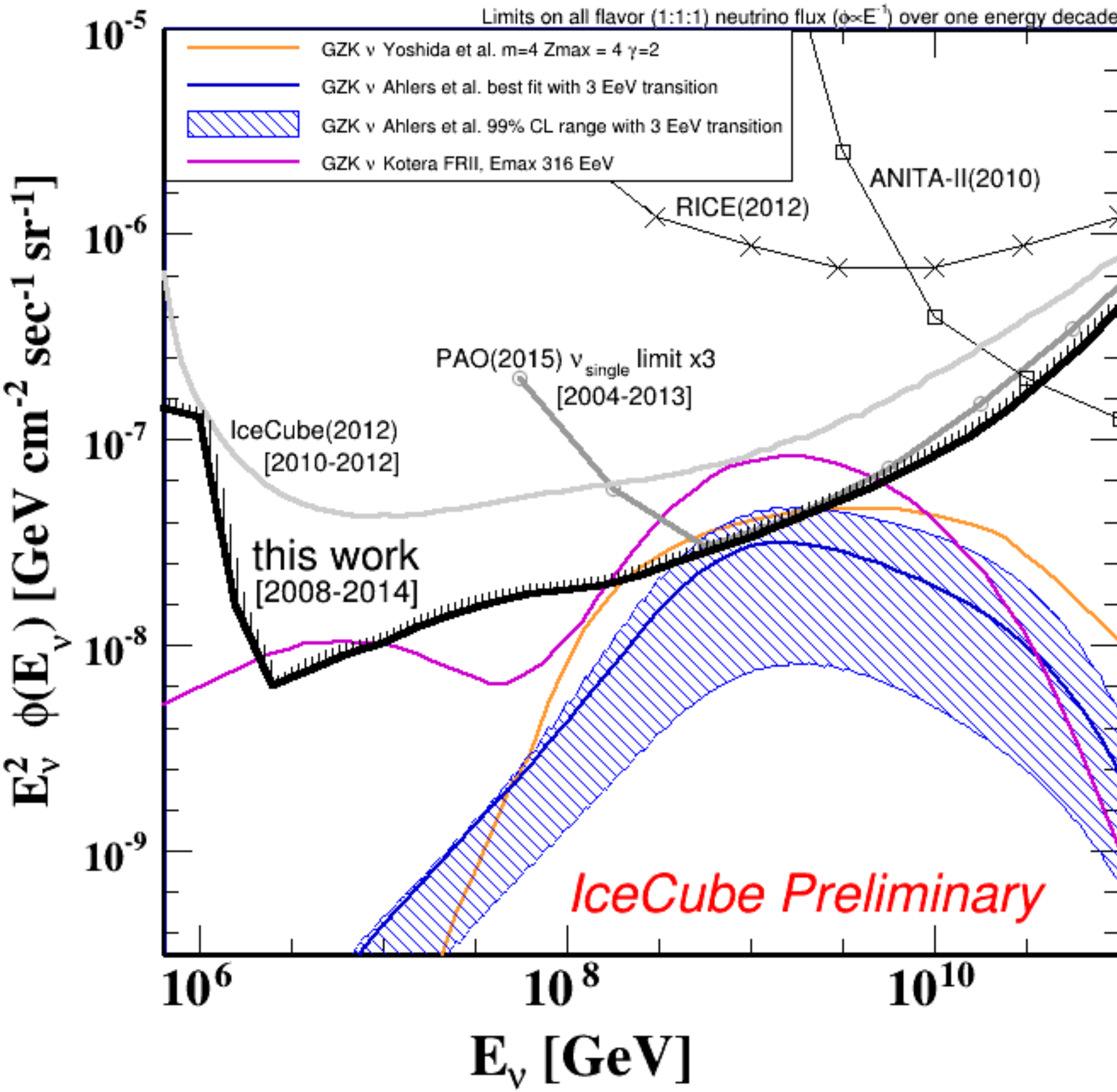
➜ **ultimate test** of UHE CR proton models with **ARA-37**

➜ generalization to arbitrary composition via

$$J_N^{\rm min}(E_N) = \sum_i f_i(A_iE_N)A_i^2 J_{\rm CR}(A_iE_N)$$

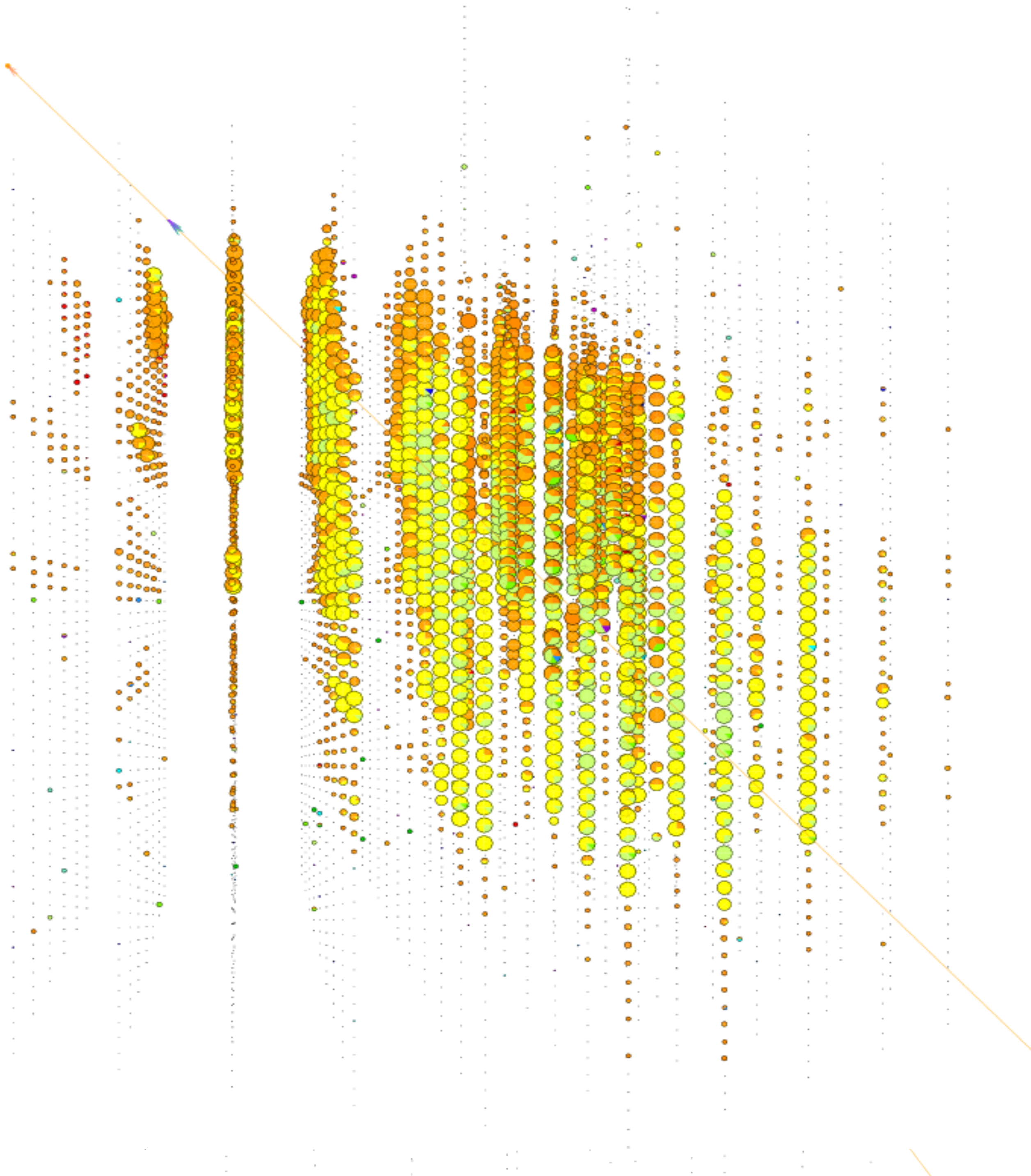


[MA&Halzen'12]

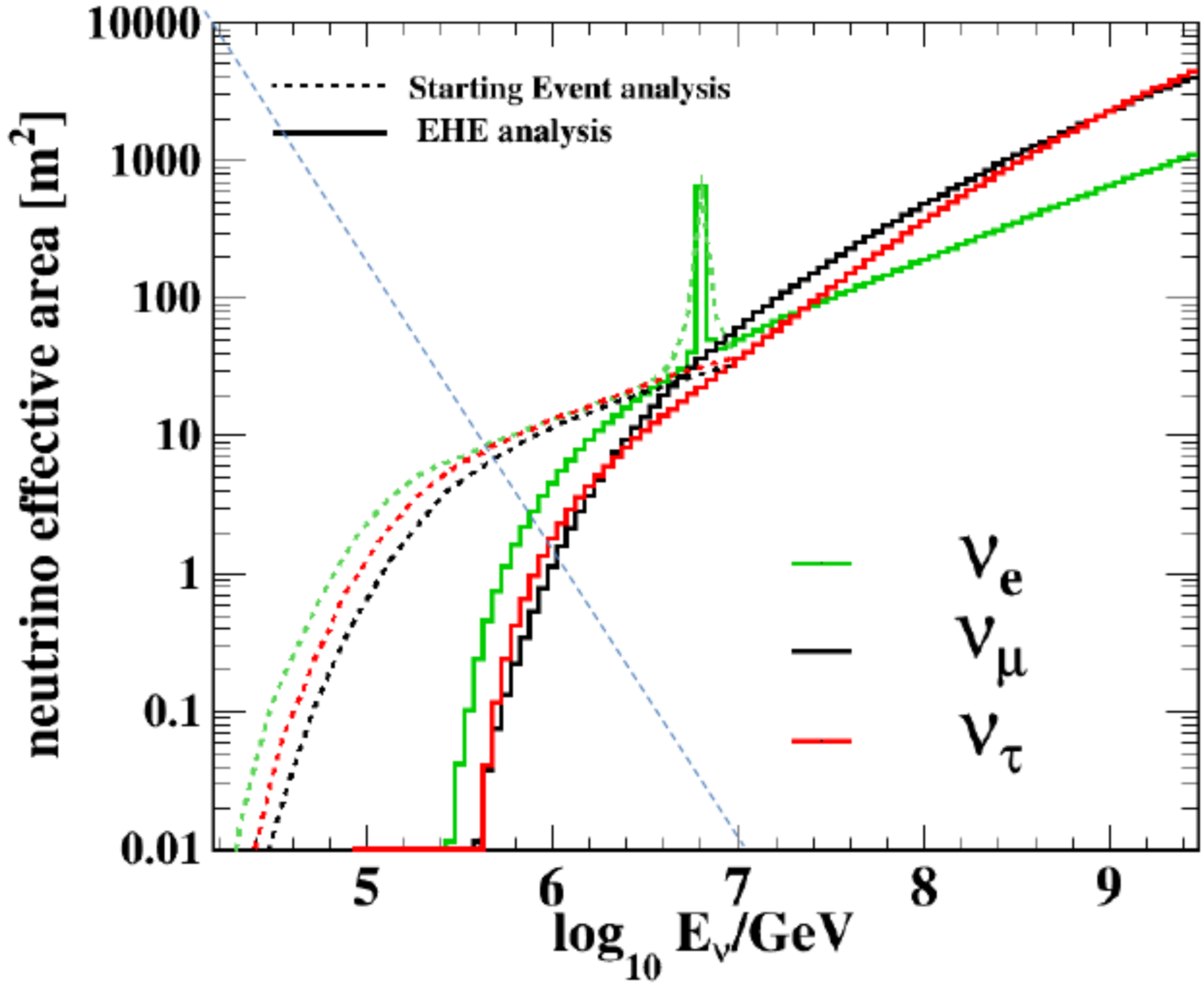


Limits on all flavor (1:1:1) neutrino flux (φ∝E⁻¹) over one energy decade
GZK ν Yoshida et al. m=4 Zmax = 4 γ=2
GZK ν Ahlers et al. best fit with 3 EeV transition
GZK ν Ahlers et al. 99% CL range with 3 EeV transition
GZK ν Kotera FRII, Emax 316 EeV
ANITA-II(2010)
RICE(2012)
PAO(2015) ν single limit x3
[2004-2013]
IceCube(2012)
[2010-2012]
this work
[2008-2014]
IceCube Preliminary
$E_\nu^2\ \phi(E_\nu)$ [GeV cm⁻² sec⁻¹ sr⁻¹]
E_ν [GeV]

GZK
AMANDA
&
IceCube



Area x ν flux x 4π x livetime = event rate

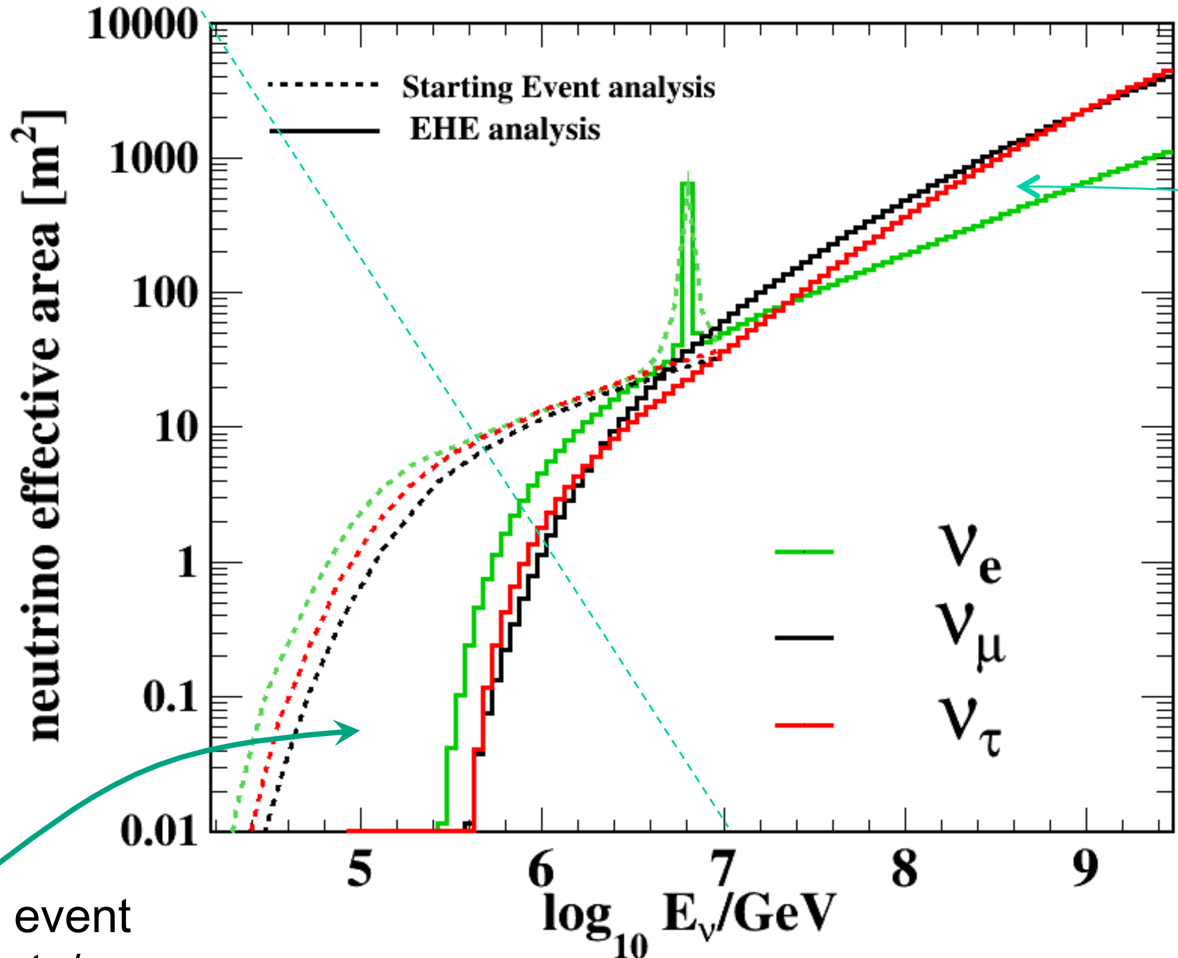


effective area in m^2

	10 TeV	100 TeV	10 PeV	1 EeV
IC through mu	10	10^2	10^3	10^3
IC starting		1	30	
IC GZK			30	4×10^3
ARA			10	10^4
NTA 4		10	10^4	10^5

IceCube GZK effective area

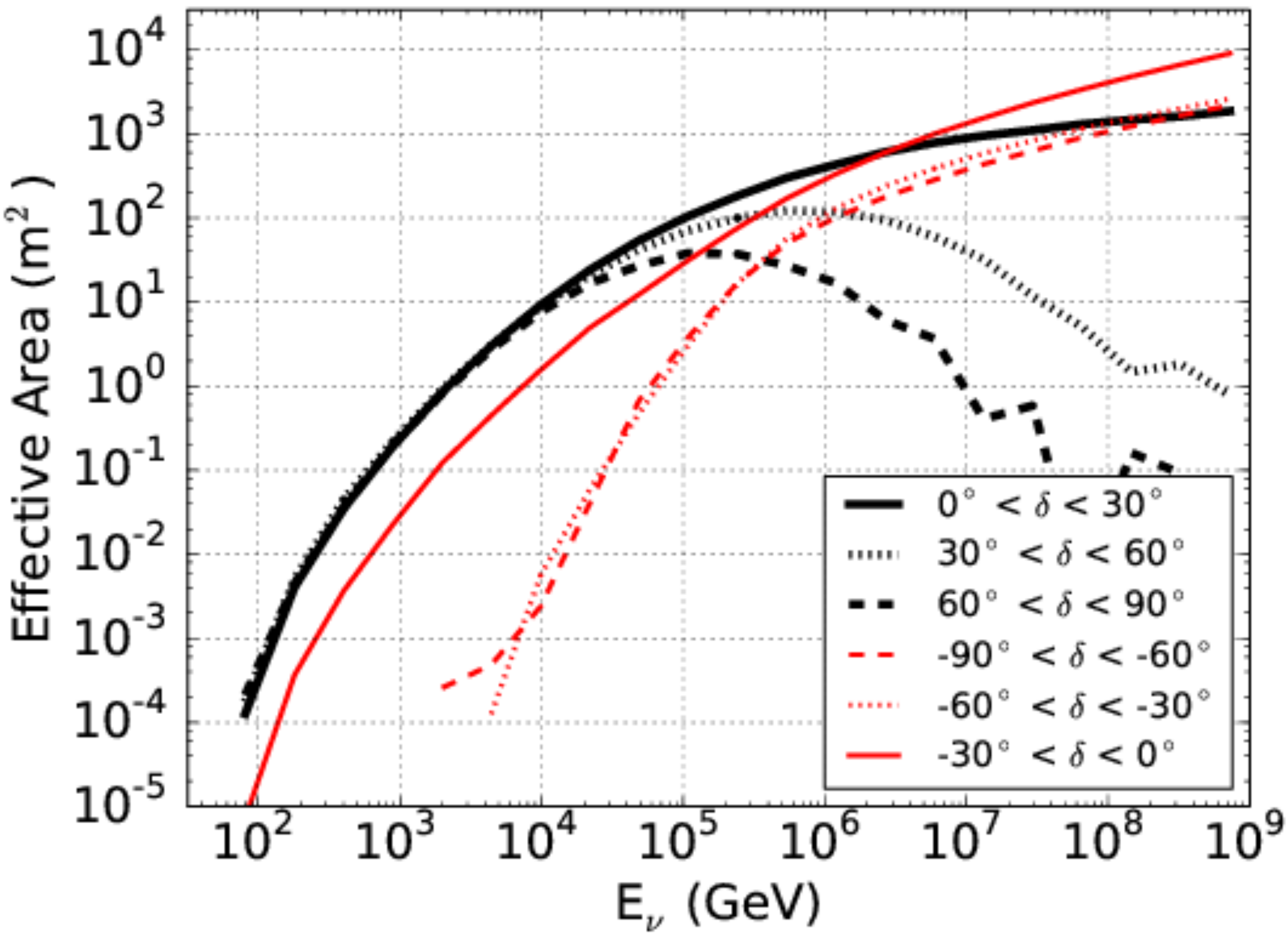
Area x ν flux x 4π x livetime = event rate

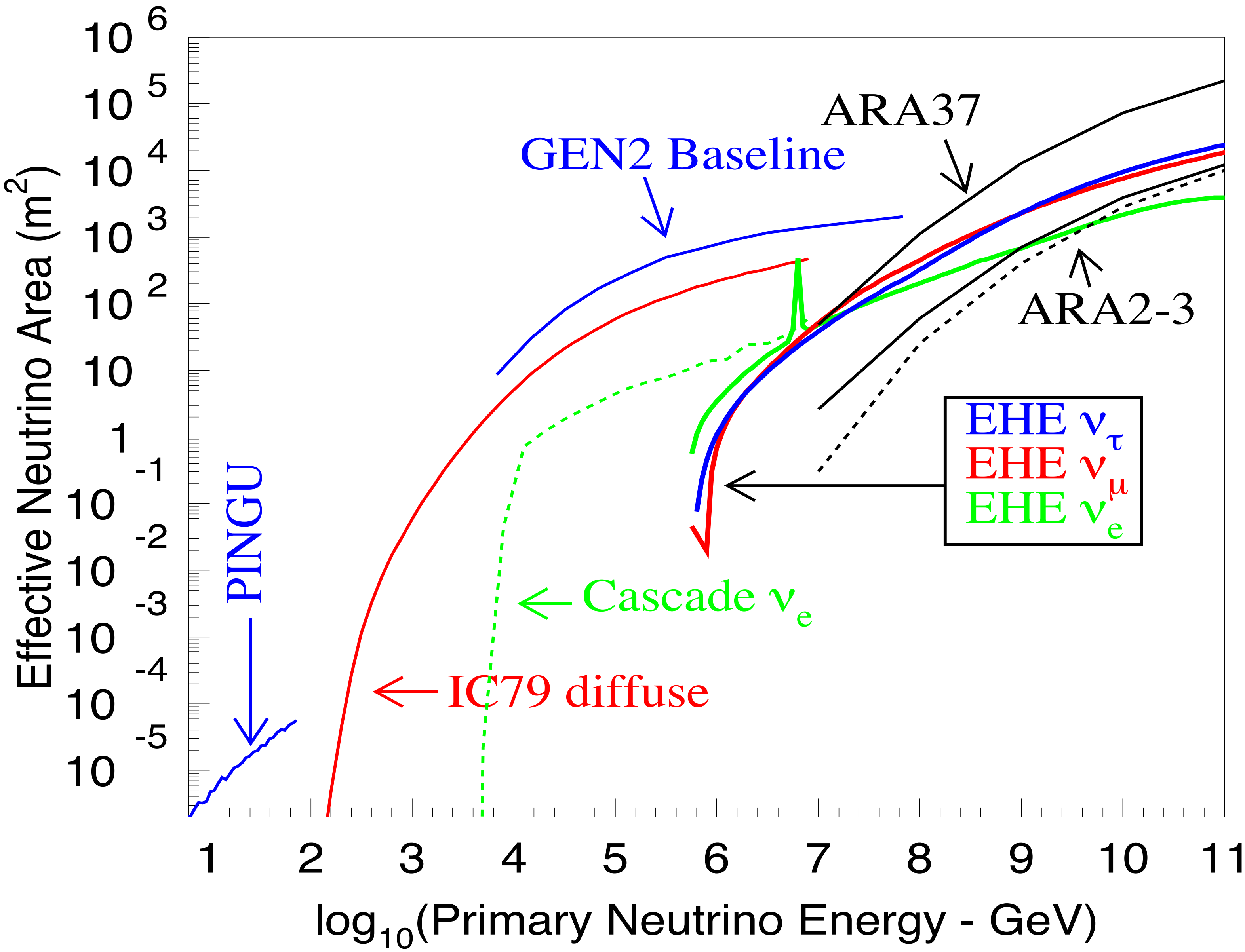


Extremely HE
0.04 BG events/year

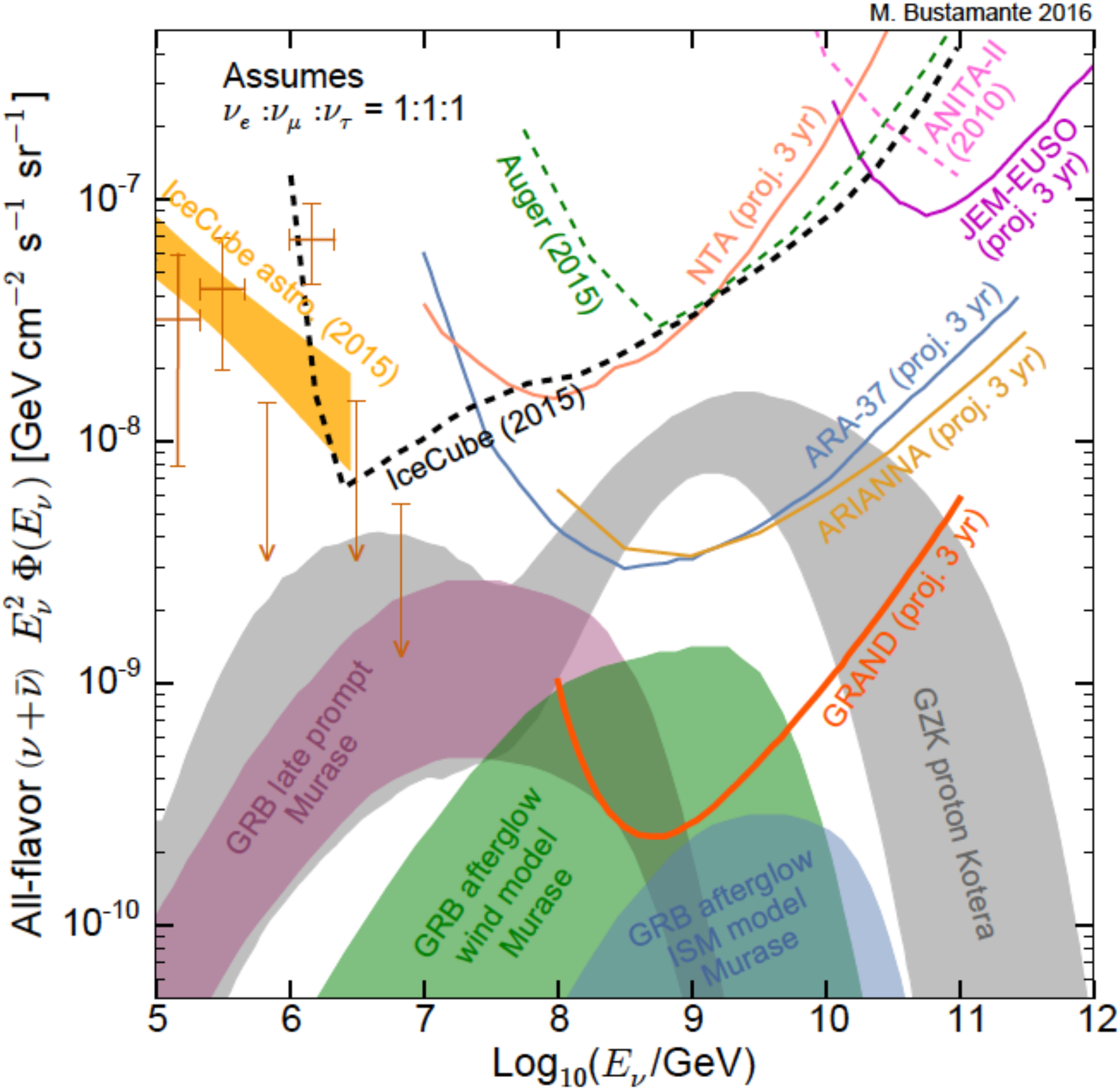
starting event
6 BG events/year

effective area upgoing muons





Effective Neutrino Area (m^2)
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
2
3
4
5
6
7
8
9
10
11
log$_{10}$(Primary Neutrino Energy - GeV)
GEN2 Baseline
ARA37
ARA2-3
PINGU
Cascade ν_e
IC79 diffuse
EHE ν_τ
EHE ν_μ
EHE ν_e



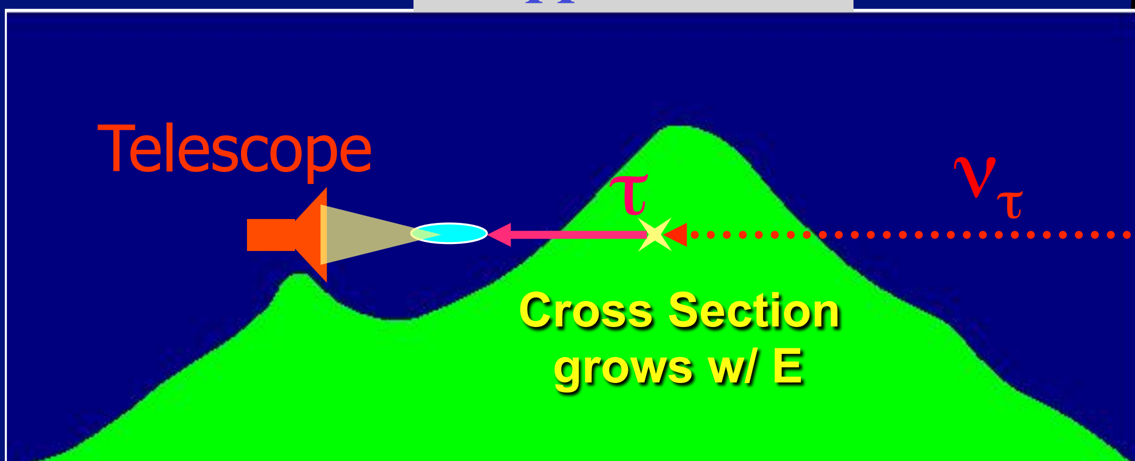
M. Bustamante 2016
Assumes
$\nu_e : \nu_\mu : \nu_\tau$ = 1:1:1
IceCube astro (2015)
IceCube (2015)
Auger (2015)
NTA (proj. 3 yr)
ANITA-II (2010)
JEM-EUSO (proj. 3 yr)
ARA-37 (proj. 3 yr)
ARIANNA (proj. 3 yr)
GRAND (proj. 3 yr)
GZK proton Kotera
GRB late prompt Murase
GRB afterglow wind model Murase
GRB afterglow ISM model Murase
All-flavor $(\nu+\bar{\nu})$ $E_\nu^2\ \Phi(E_\nu)$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
5
6
7
8
9
10
11
12
Log$_{10}(E_\nu$/GeV)

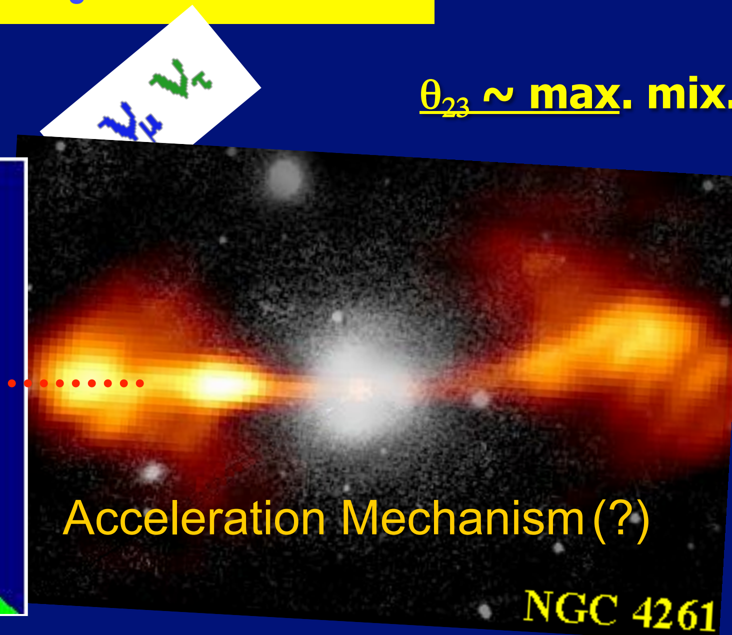
Detection Mechanism

II. Earth-Skimming ν_τ Method

θ_{23} ~ max. mix.

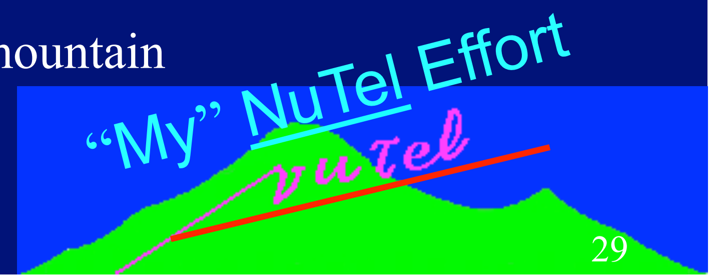
τ Appearance!





τ *Decay*: Air Shower
→ ns Cherenkov

ν_e: electron energy mostly absorbed in mountain
ν_μ: no extensive air shower



Acceptance: Air & Tau vs Water & Muon

1. We use the ν_τ distribution from CTEQ4 [14], inelasticity parameter from [13], and parameterize energy loss in Earth by [12, 15].
2. We use τ decay from TAUOLA and air-shower generation of Gaisser-Hillas + NKG [16].
3. For detector simulation, we incorporate light collection and throughput with simplified triggering logic. Event reconstruction is not yet implemented.

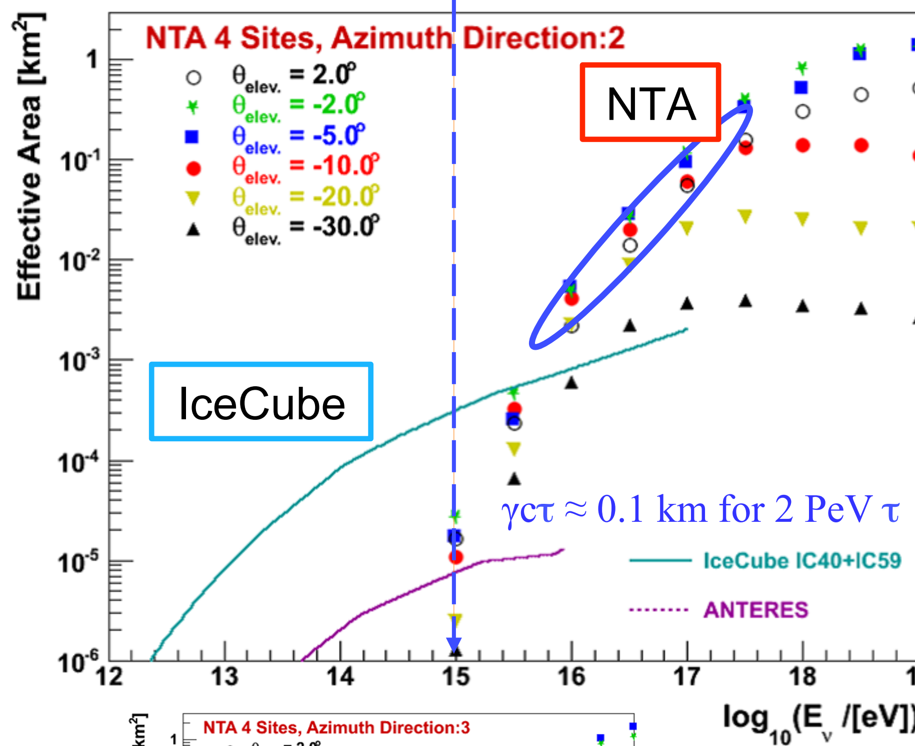
Assumed FOV

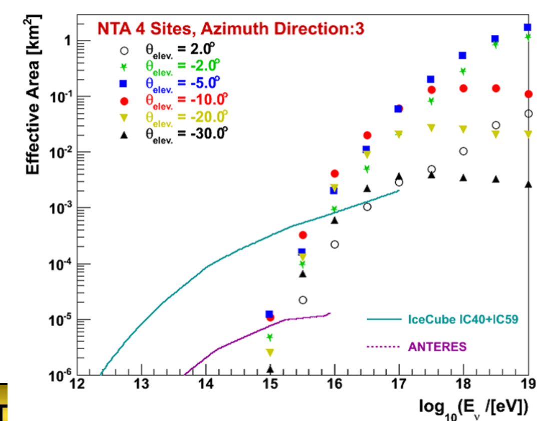
LC:	32° X 32°
Trigger Pixel:	0.5° X 0.5°
Sensor Pixel:	0.125° X 0.125°

trigger conditions:

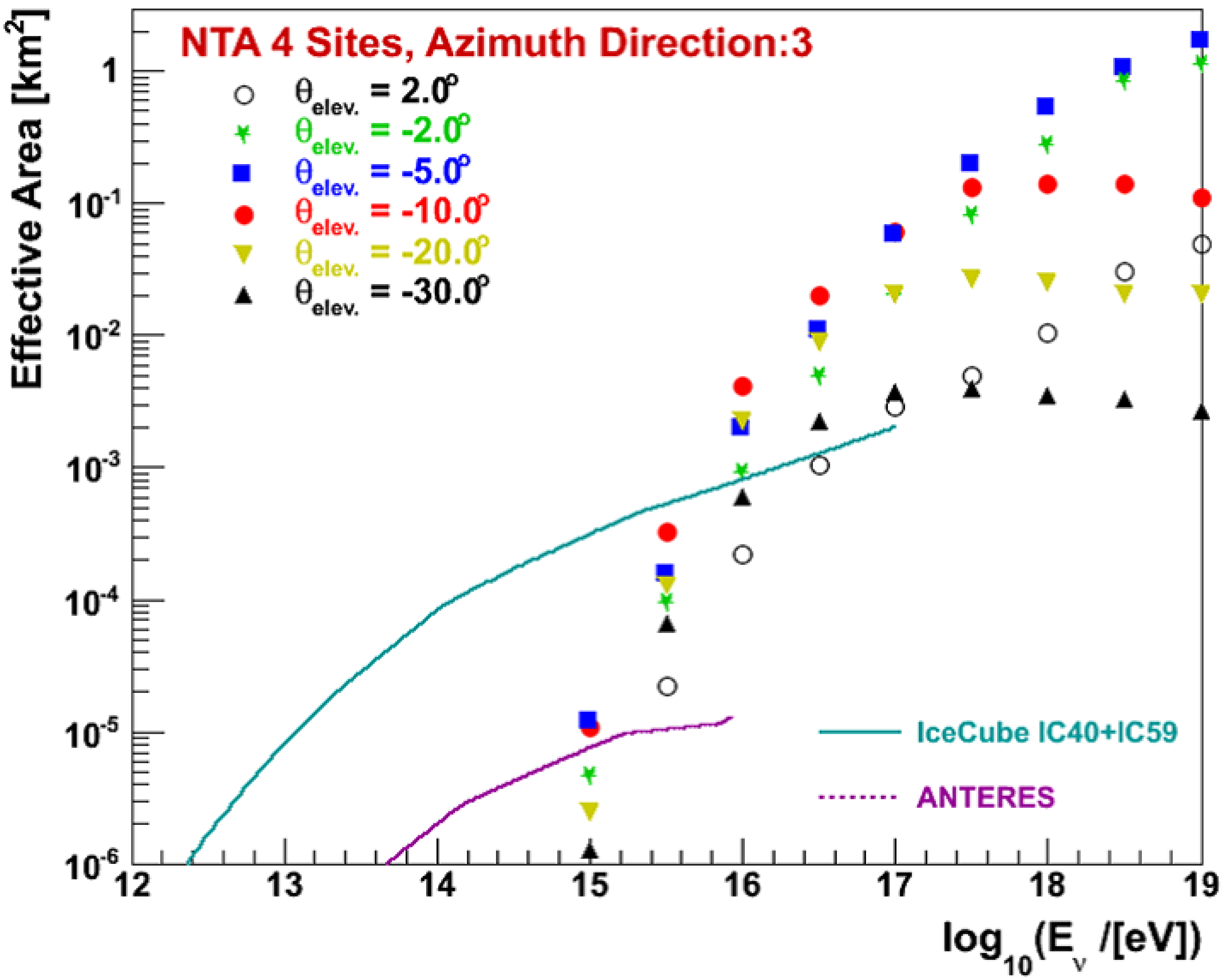
- Number of detected photoelectrons per LC > 61.
- S/N estimated in track-associated 4 pixels × 64 pixels box (air-shower track included) > 4 [17].

Point source, arrival dir. Mauna Loa





dir. Hualalai


NTA 4 Sites, Azimuth Direction:3
θelev. = 2.0°
θelev. = -2.0°
θelev. = -5.0°
θelev. = -10.0°
θelev. = -20.0°
θelev. = -30.0°
IceCube IC40+IC59
ANTERES
Effective Area [km²]
log10(Eν /[eV])
1
10-1
10-2
10-3
10-4
10-5
10-6
12
13
14
15
16
17
18
19

Window of Opportunity

Still Survives

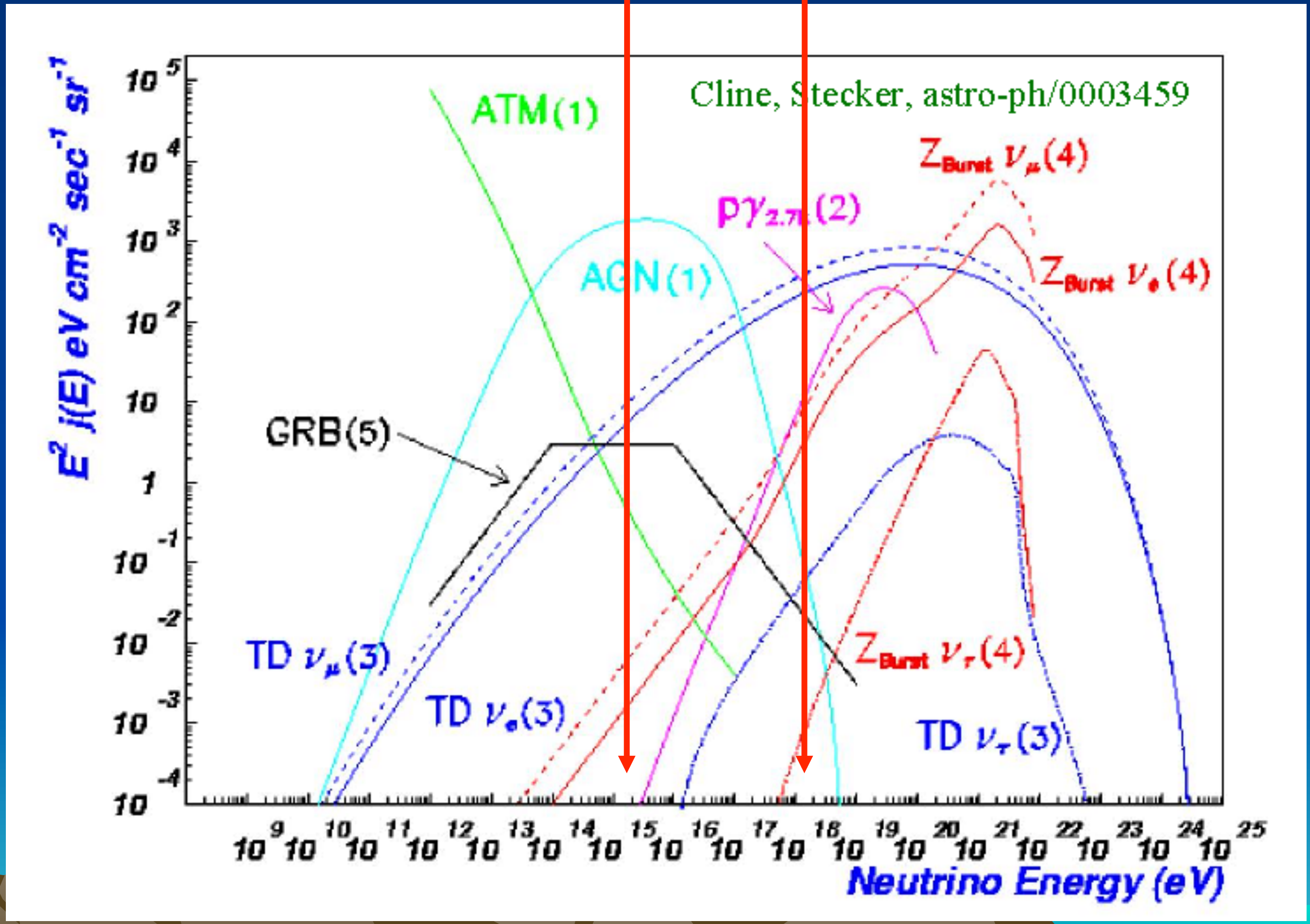
IceCube

Conventional ν Detector

?

UHECR ν Detector

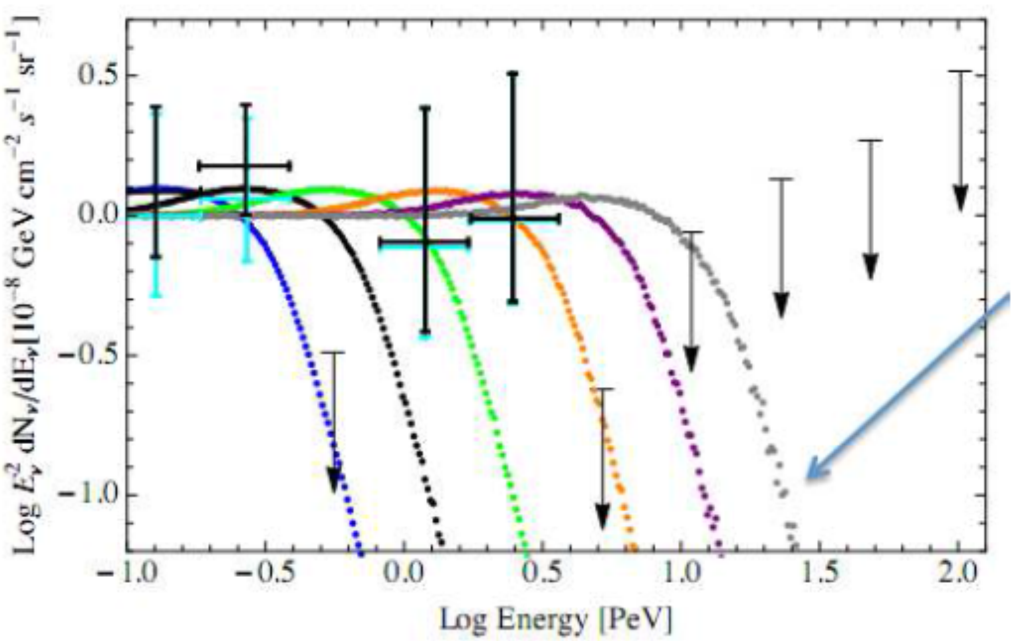
Auger



a plot I first used ~ 2002

Lorentz violation

Existence of high energy neutrinos limits on superluminal velocity:

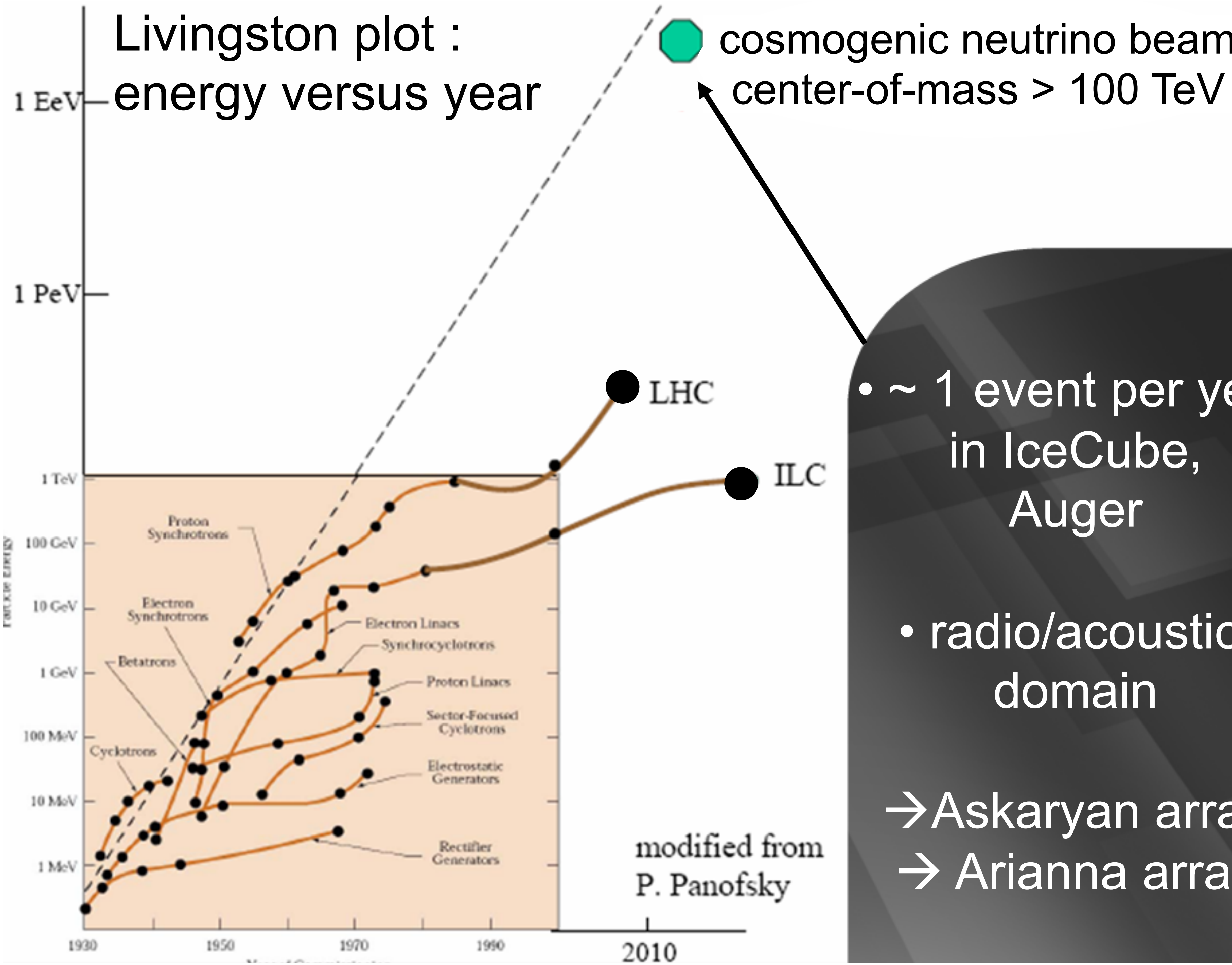


δ_υ-$\delta_e < 5.2 \times 10^{-21}$

Pair-production threshold of 10 PeV required for consistency with IceCube

Reason for cut-off could be vacuum pair emission (astrophysics more likely ...)

improved test with every new record event



- ~ 1 event per year in IceCube, Auger

- radio/acoustic domain

→Askaryan array

→ Arianna array