Advances in Particle Astrophysics

Session IV: IceCube's neutrinos

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Weizmann Institute

CERN academic training 11-15/04/2016

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We will focus on theory implications from discoveries made w/ this Gton of ice.

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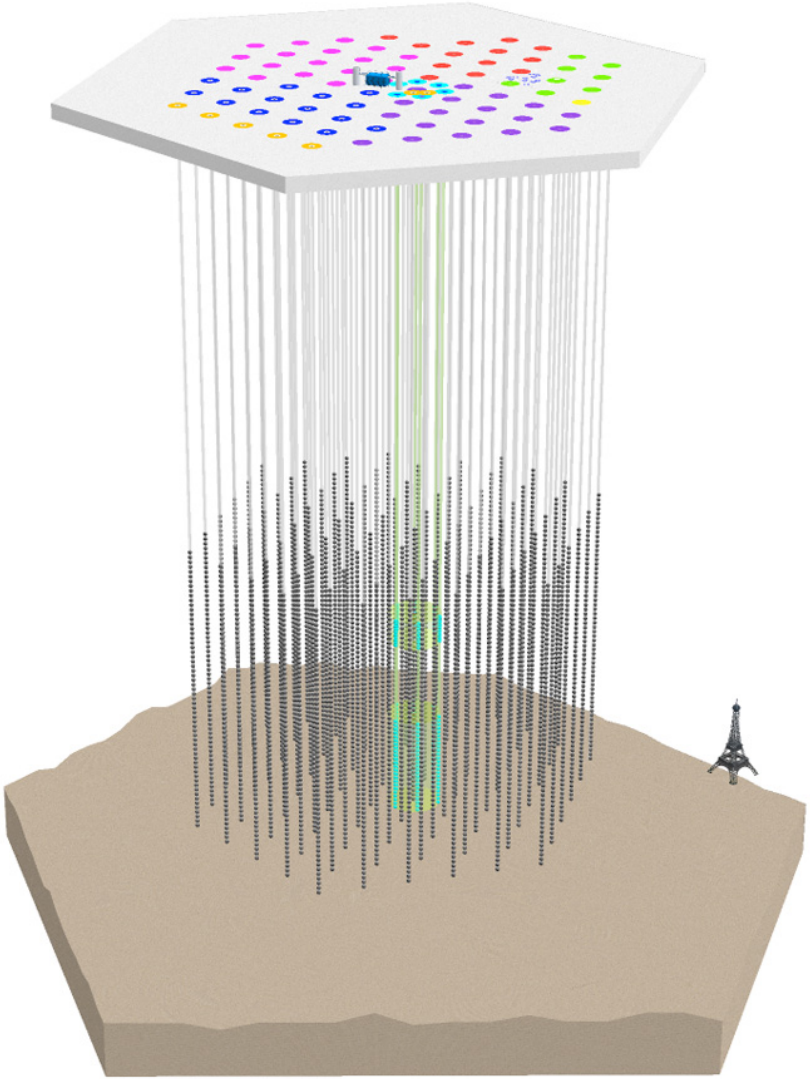

10^{14} x

5000 x

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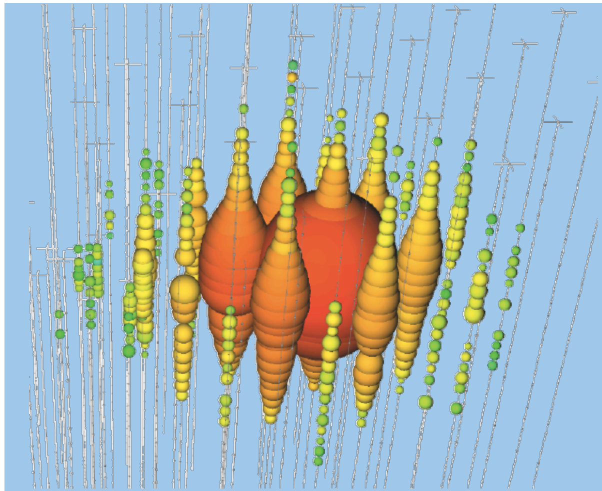
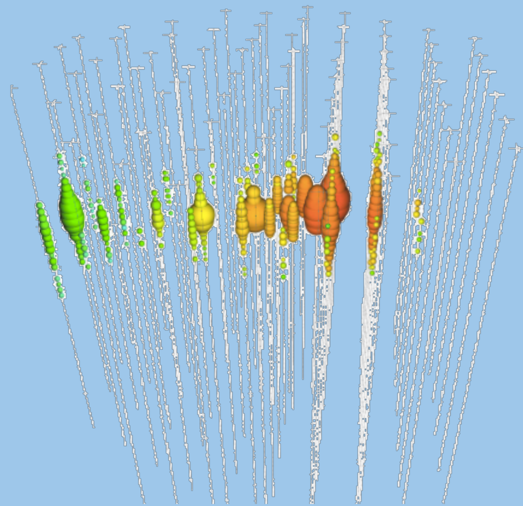
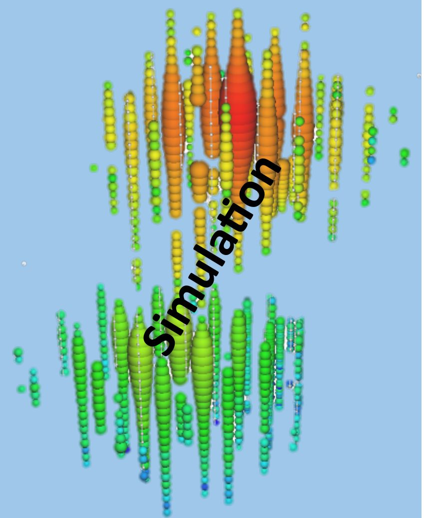


$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$



$$\nu_\mu + N \rightarrow \mu + X$$



$$\nu_\tau + N \rightarrow \tau + X$$

$$\tau \rightarrow \nu_\tau + X$$

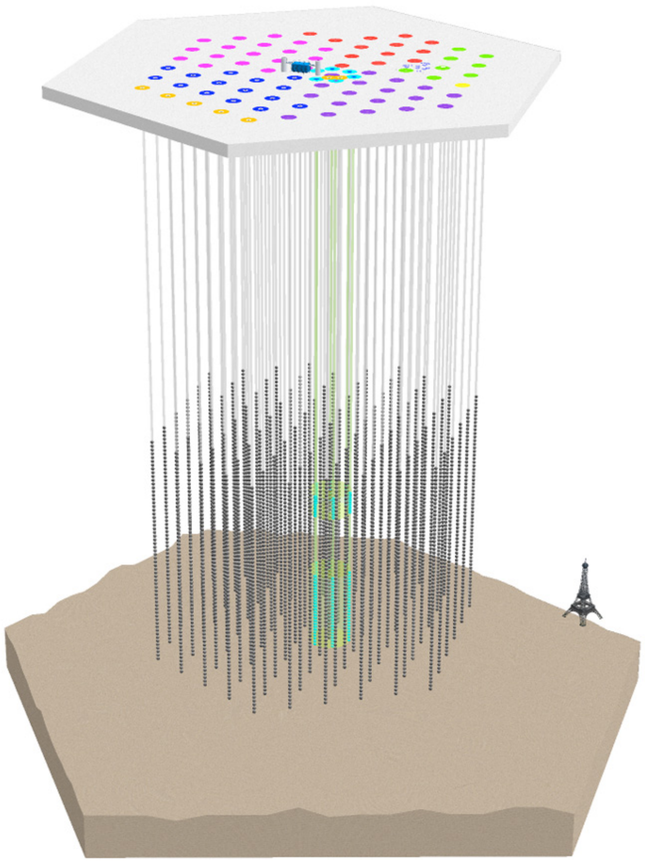
Jan Auffenberg, Moriond 2016

Outline:

…in 2013, IC **announced a discovery** of high-energy astrophysical neutrinos.

What's making it?

What will it teach us?



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WB going *backwards*
Some predictions.

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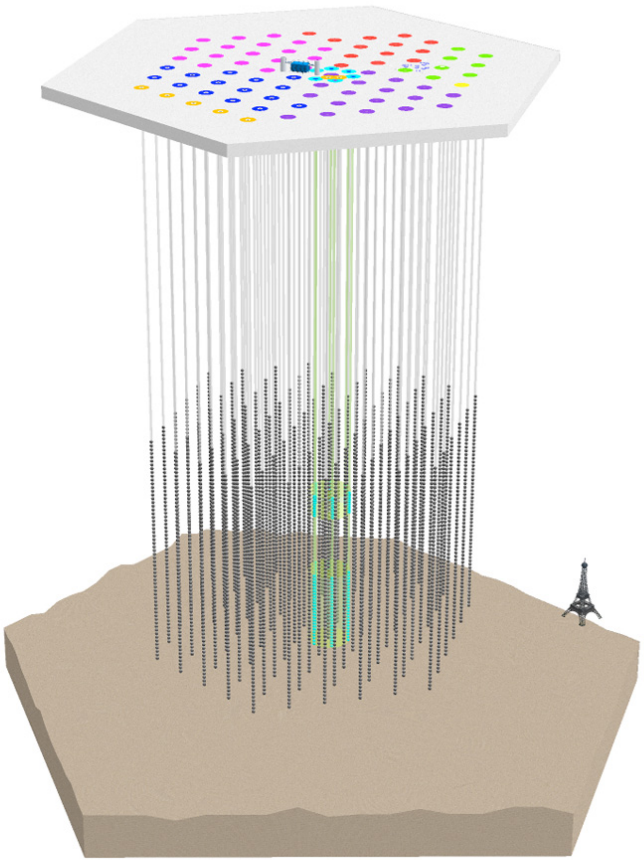

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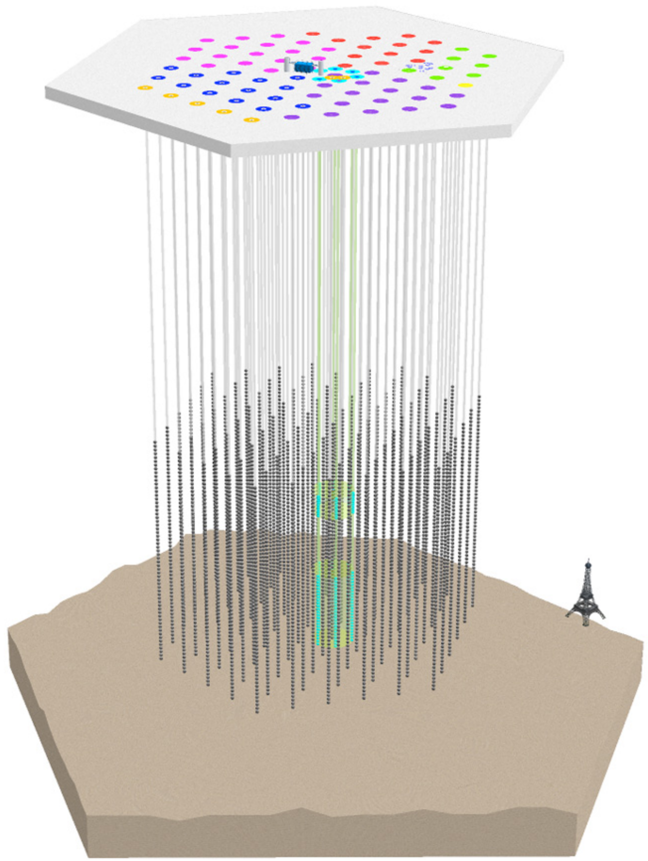
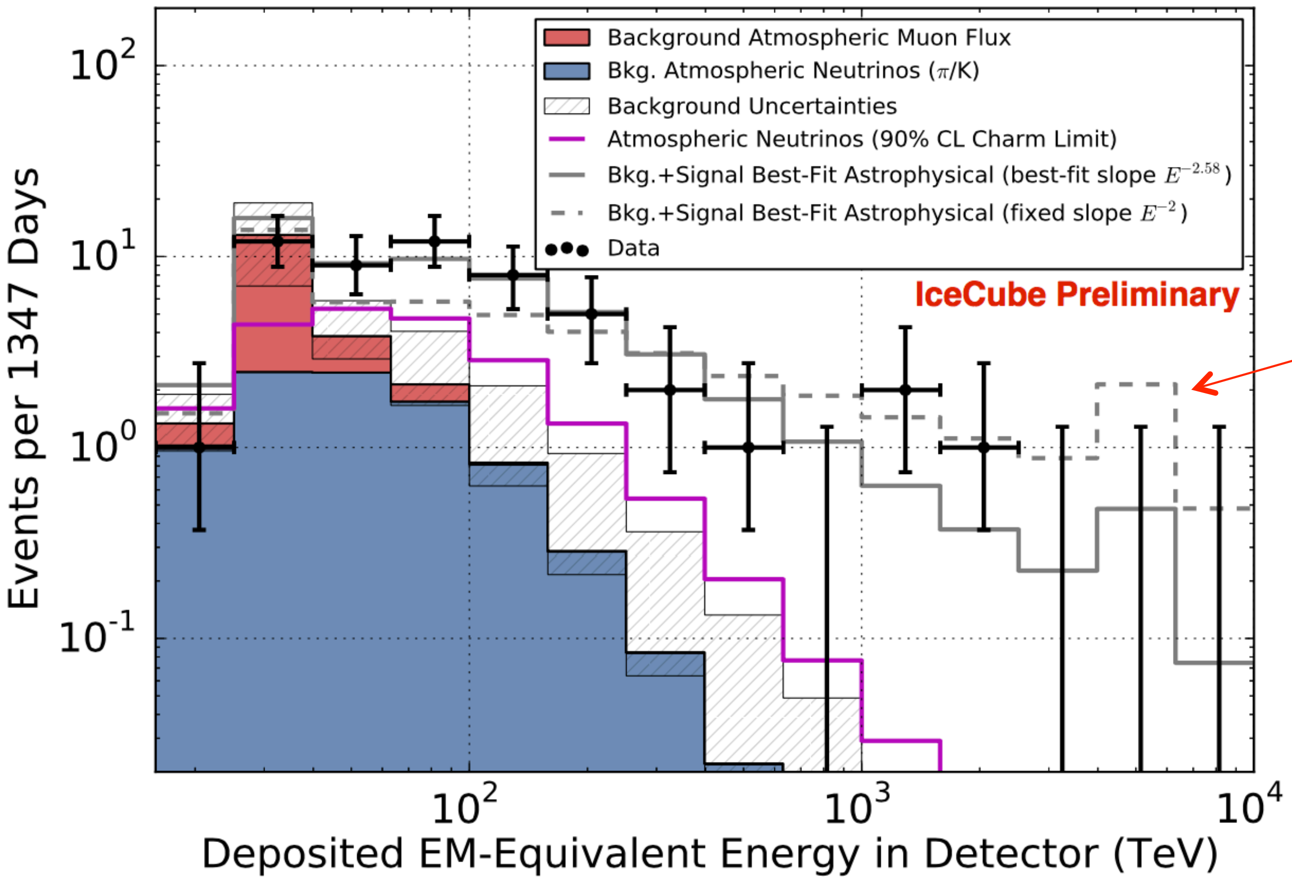


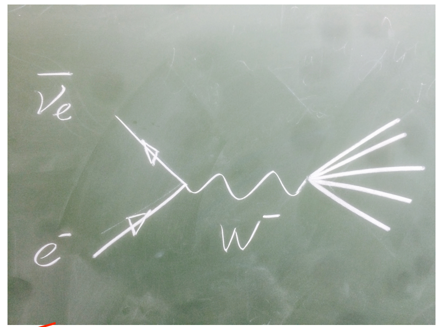
What will it teach us?
Likely: sources of (U)HECRs
Possibly: neutrino surprises?

Time permits, we will toy with
exotic possibilities

Moriond 2016 (Jan Auffenberg)
also 1510.05223

Consistent w/ power law, $dn/dE \sim E^{-\gamma}$, with $\gamma \sim 2$





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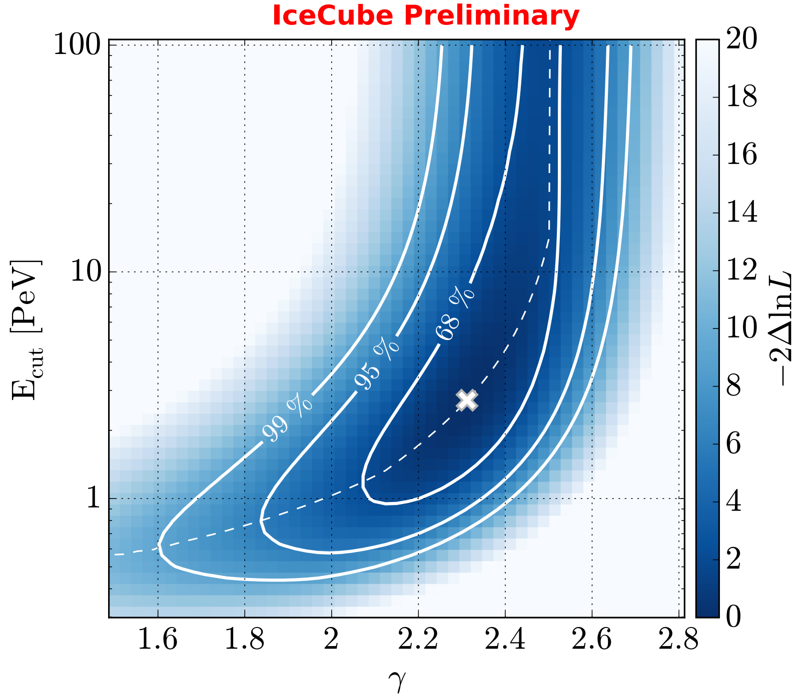
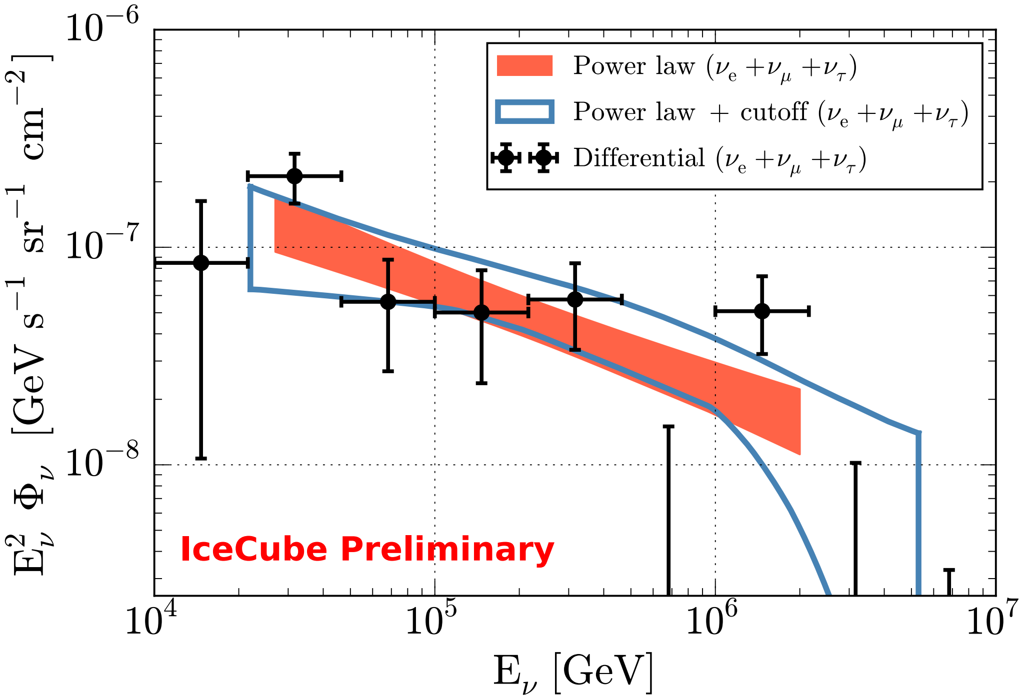




Break around PeV: reasonable.

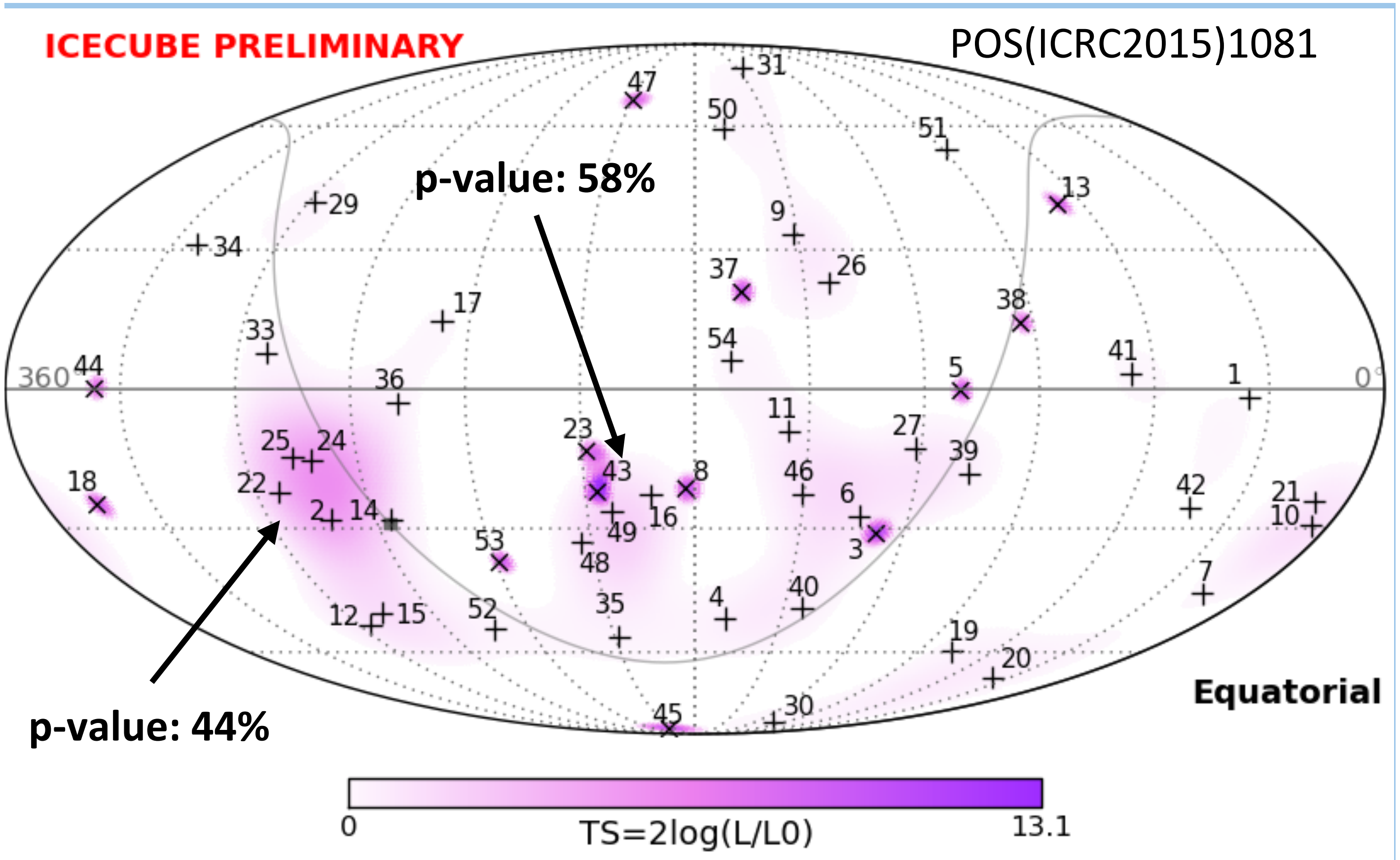
Suggests γ close to 2.

Param.	Unit	Hyp. A	Hyp. B
ϕ_{conv}	HKKMS	$1.10^{+0.20}_{-0.15}$	$1.11^{+0.20}_{-0.15}$
ϕ_{prompt}	ERS	$0.0^{+0.7}_{-0.0}$	$0.0^{+0.8}_{-0.0}$
ϕ	$10^{-18}\,\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{cm}^{-2}$	$7.0^{+1.0}_{-1.0}$	$8.0^{+1.3}_{-1.2}$
γ	—	$2.49^{+0.08}_{-0.08}$	$2.31^{+0.14}_{-0.15}$
E_{cut}	PeV	—	$2.7^{+7.7}_{-1.4}$
$-2\Delta\ln L$		+1.94	0

Table 2: Best-fit results for the energy spectrum. The quoted uncertainties are at $1\,\sigma$ confidence level.

Moriond 2016
1510.05223

4yr data >60TeV



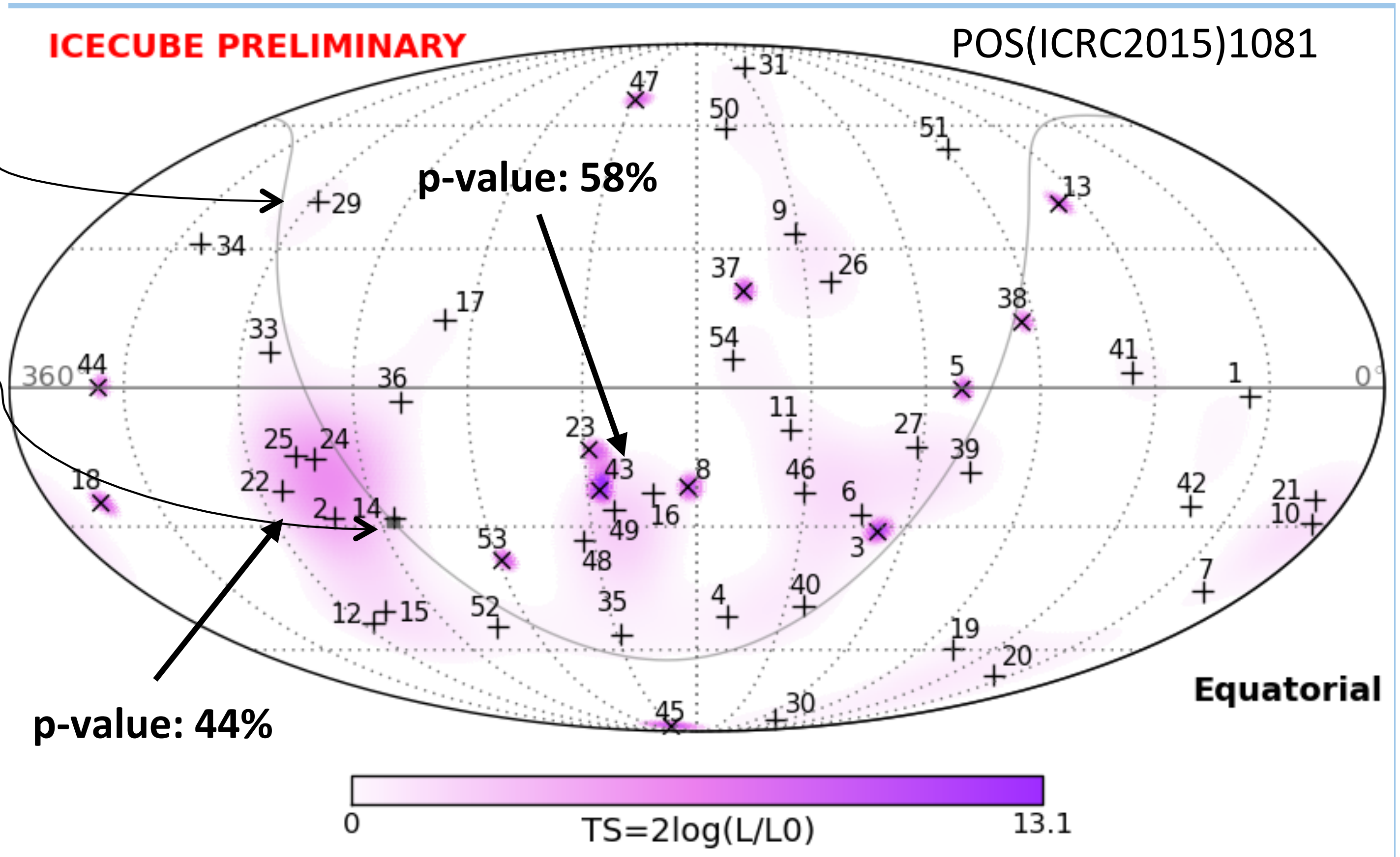
Many events point away from MW disk/bulge.
Consistent w/ isotropy.

Moriond 2016
1510.05223

MW disk

SgrA*

4yr data >60TeV



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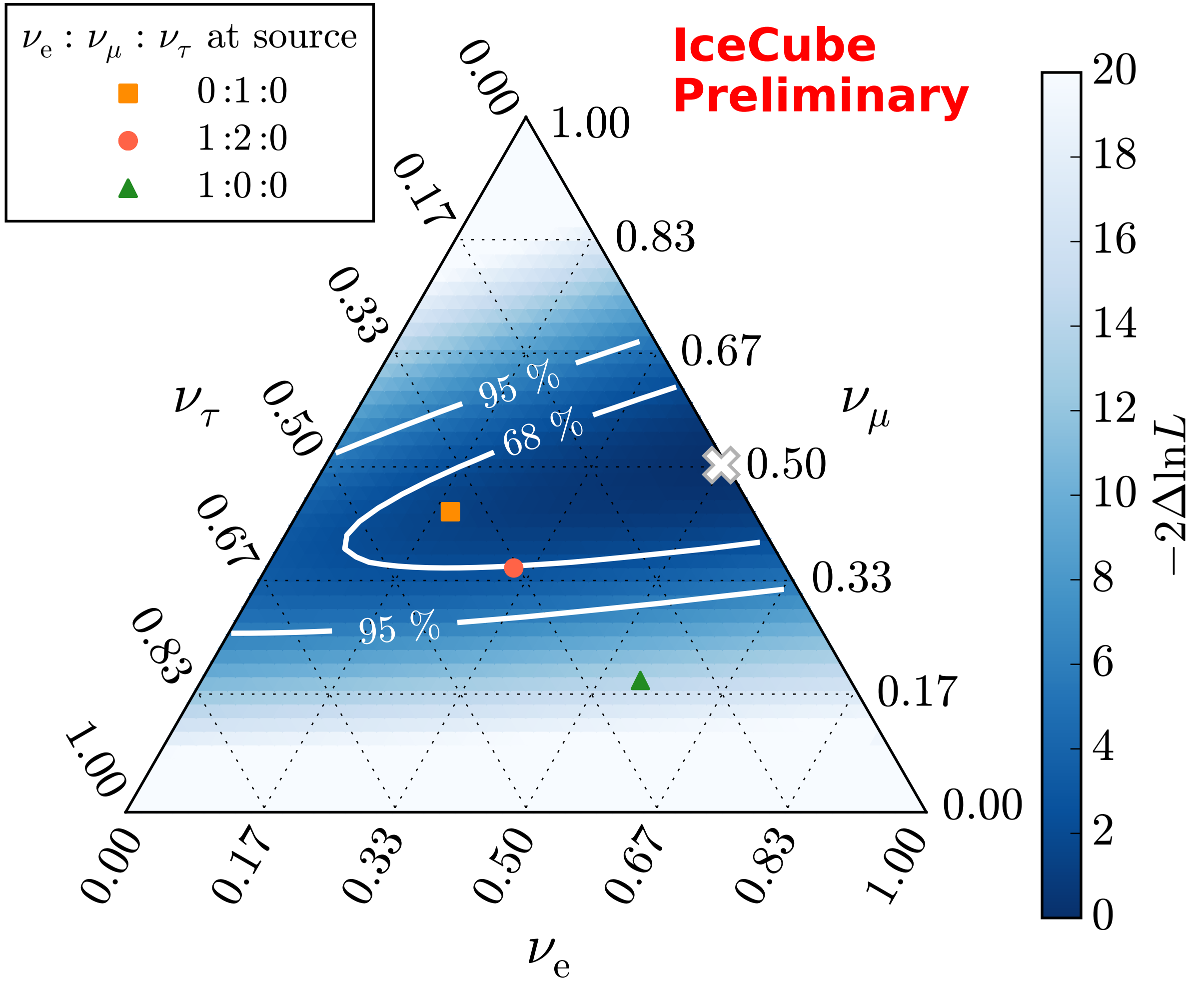
Moriond 2016
1510.05223

Pion source
1:2:0 ➔ 1:1:1

Muon-damped
0:1:0 ➔ 1:1.8:1.8



IceCube's neutrinos in context:

Flux normalization and rough spectral shape

Angular distribution

Flavor content

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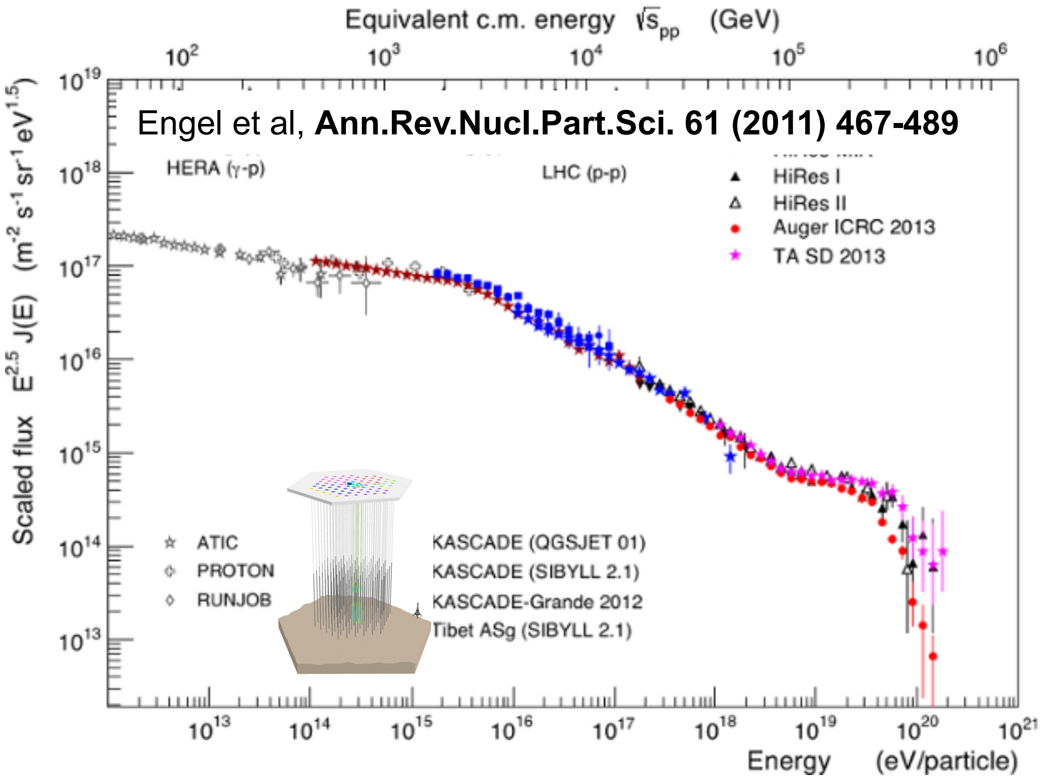

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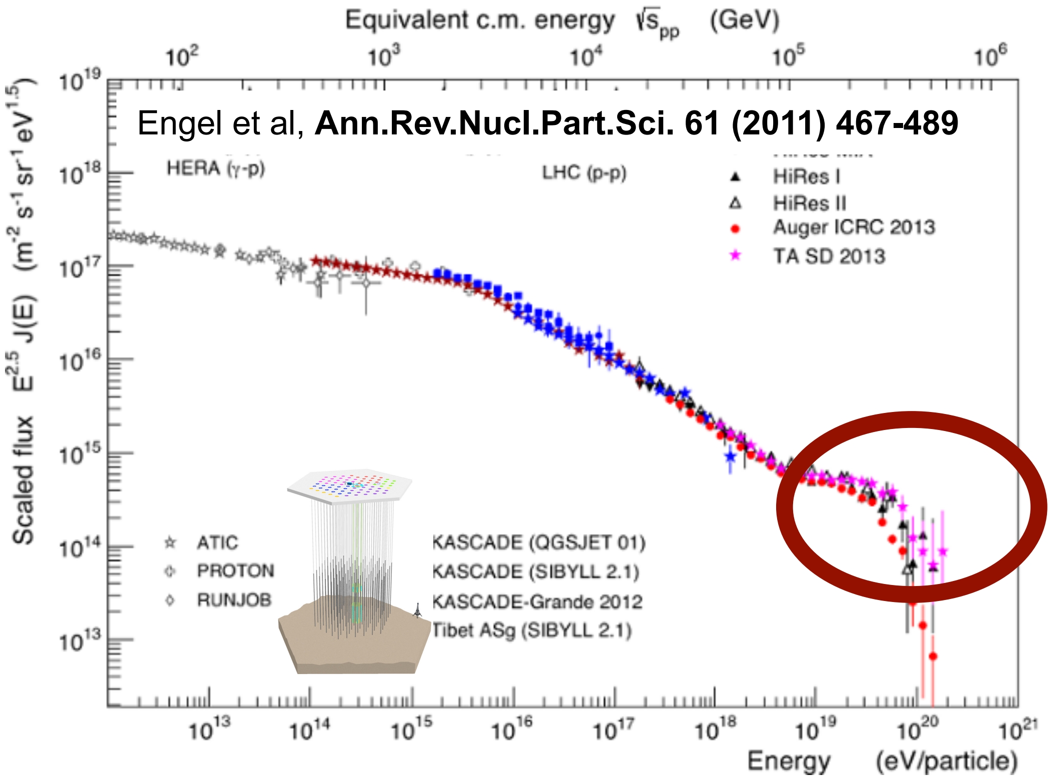

IceCube’s neutrinos and UHECRs

Waxman & Bahcall, PRD59, 023 (1998)

IceCube's neutrinos and UHECRs

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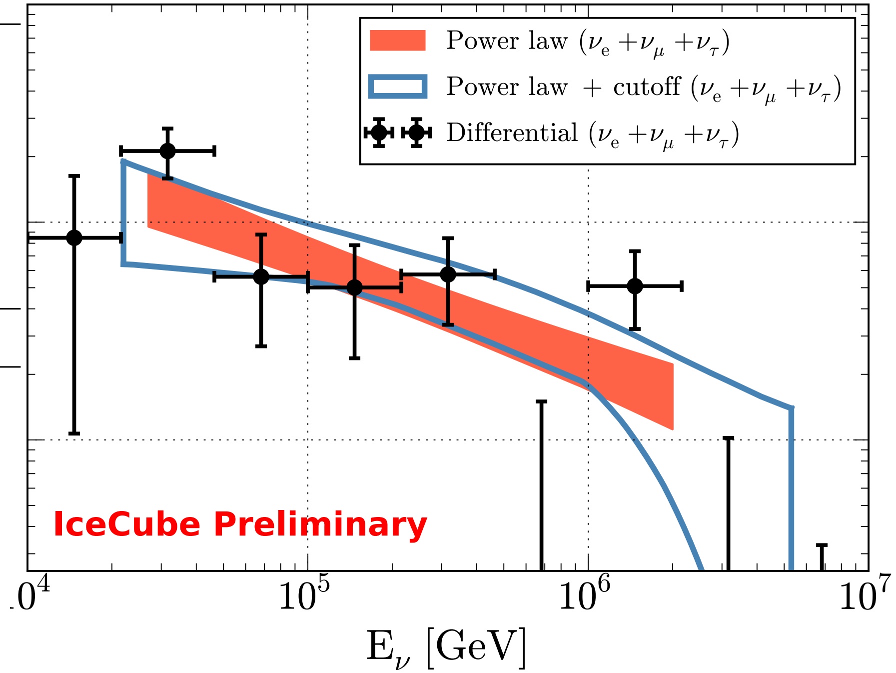


Waxman & Bahcall, PRD59, 023 (1998)

Advances in particle astrophysics:

use IceCube data, run WB argument *backwards.*

see recently, e.g. Yoshida & Takami, PRD90 (2014) no.12, 123012

UHECR and the Waxman-Bahcall bound

$$n_\nu(>\epsilon) = \int_0^{t_0} dt\, \dot{n}_\nu\left[>(1+z)\epsilon\,;\, z\right]$$

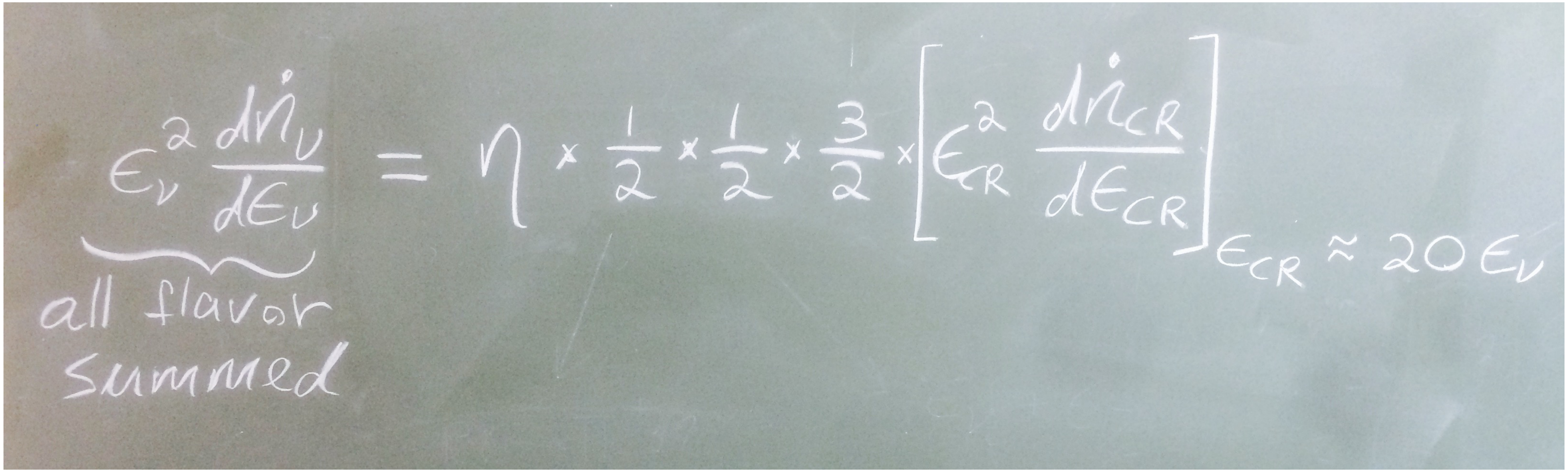
$$= \int_0^{\infty} \frac{dz}{(1+z)H(z)}\, \dot{n}_\nu\left[>(1+z)\epsilon\,;\, z\right]$$

$$= \frac{\dot{n}_\nu(>\epsilon, z=0)}{H_0} \int_0^{\infty} \frac{dz\, f(z)}{(1+z)^{\gamma}\sqrt{0.7+0.3(1+z)^3}}$$

$$\Rightarrow \left.\frac{dn_\nu}{d\epsilon_\nu}\right|_{z=0} = \left.\frac{d\dot{n}_\nu}{d\epsilon_\nu}\right|_{z=0} \times \frac{1}{H_0} \int_0^{\infty} \frac{dz\, f(z)}{(1+z)^{\gamma}\sqrt{0.7+0.3(1+z)^3}}$$

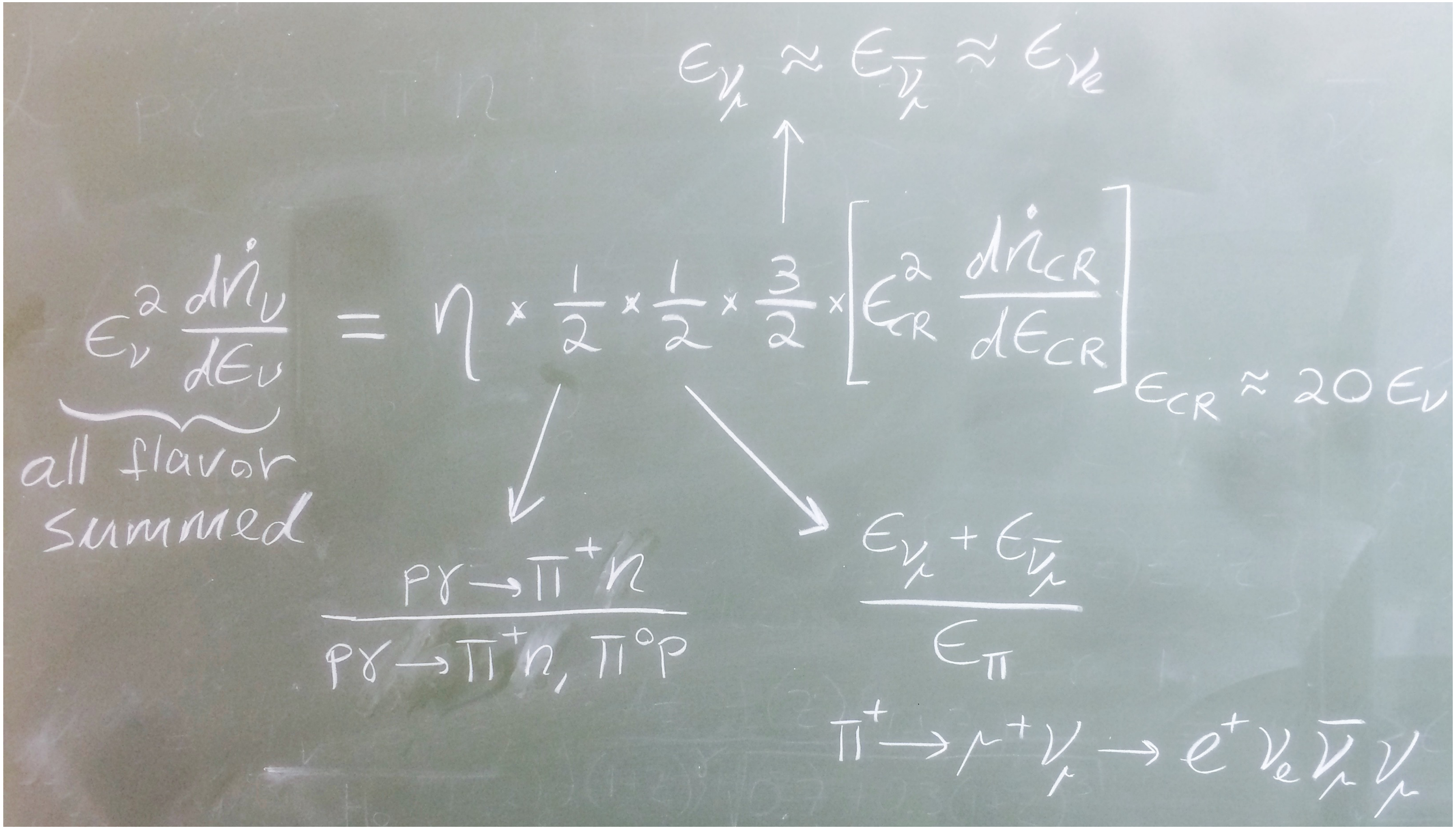
UHECR and the Waxman-Bahcall bound

If each CR proton loses fraction **η** of its energy at the CR source to pγ collisions before escaping:



(result the same to factor of 2 if losses are hadronic, pp instead of pγ)

UHECR and the Waxman-Bahcall bound



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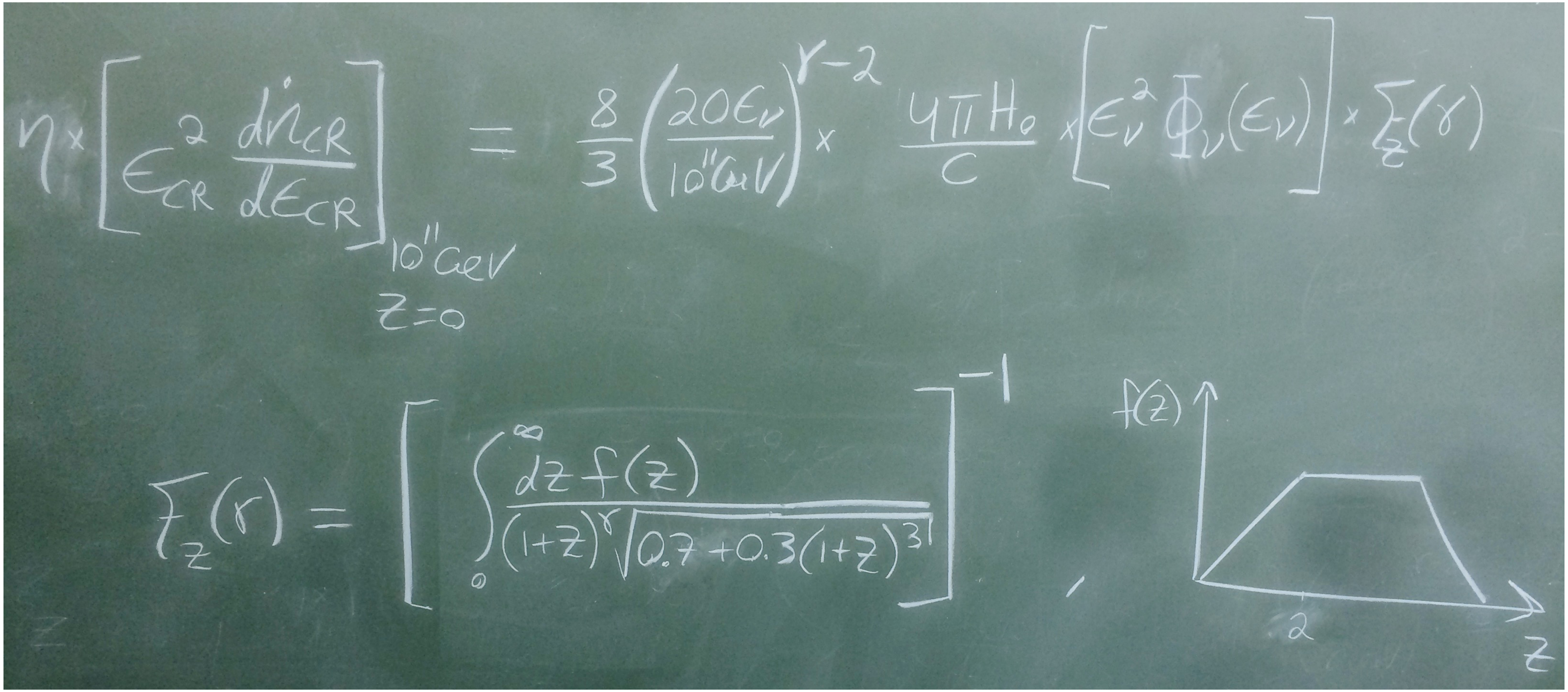


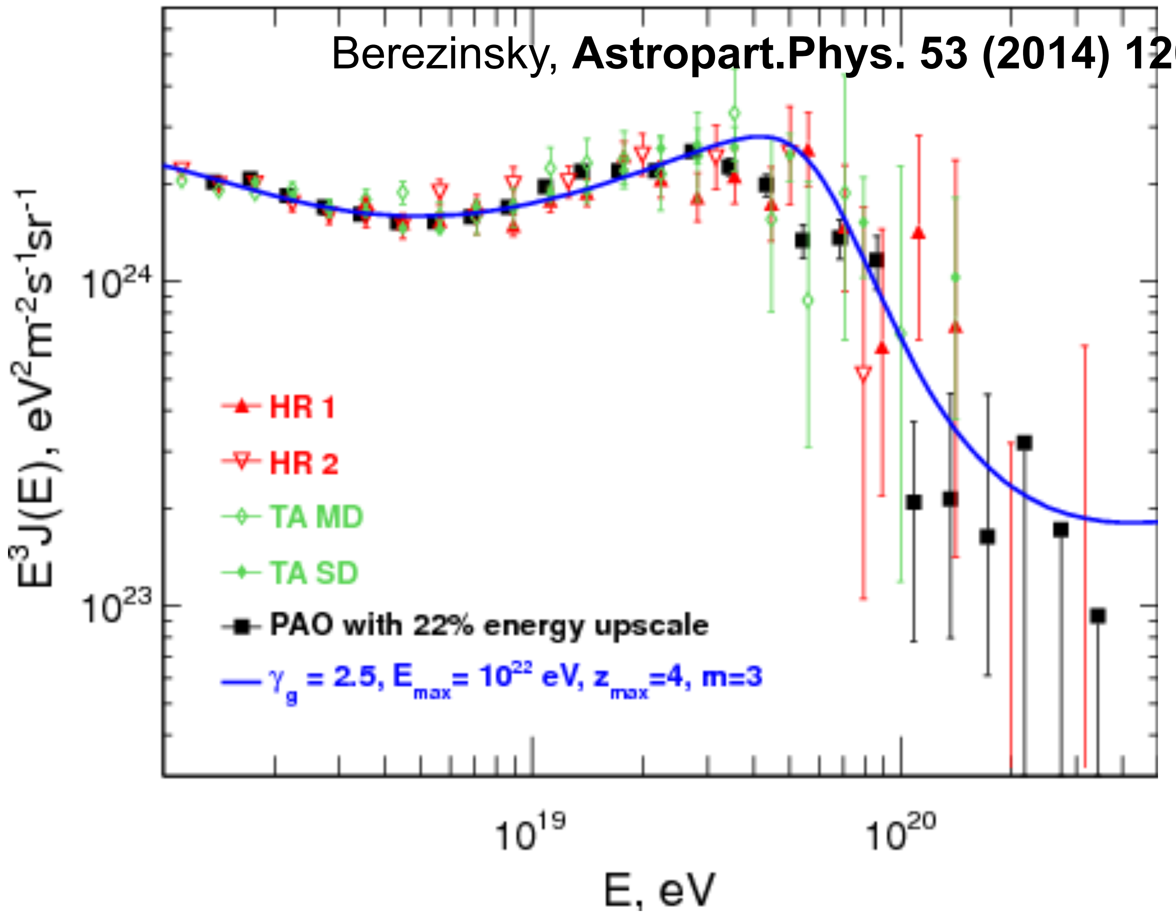
UHECR and the Waxman-Bahcall bound

UHECR source power at z=0 constrained from observation of GZK cutoff.

Katz, Budnik, Waxman, **JCAP 0903 (2009) 020**

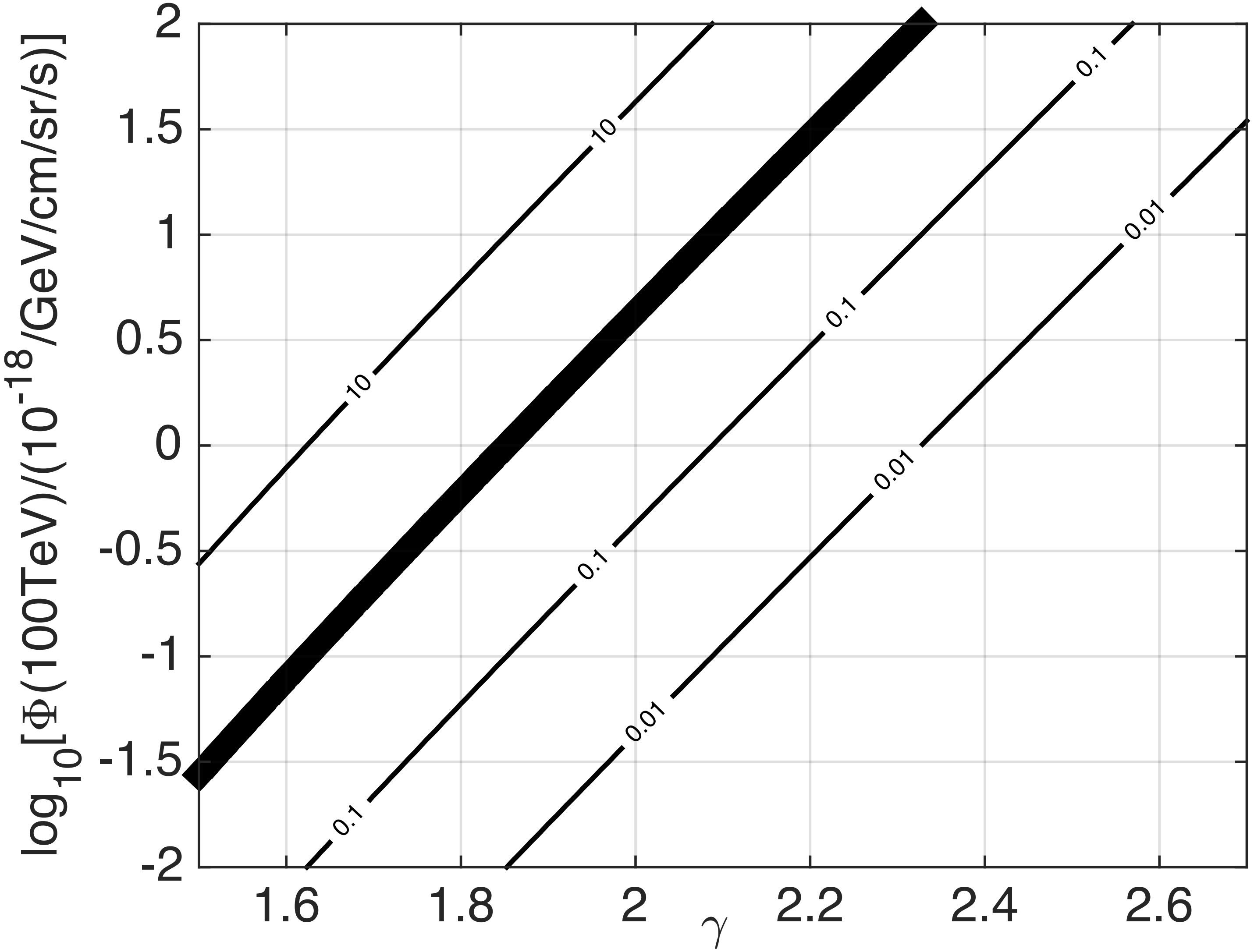
$$\varepsilon^2 d\dot{n}/d\varepsilon(z=0) = (0.45 \pm 0.15)(\alpha - 1) \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$$

Berezinsky, **Astropart.Phys. 53 (2014) 120-129**



UHECR and the Waxman-Bahcall bound

Contours: required UHECR η x power @10^{11}GeV normalized to observed $(0.45\pm0.15)(\gamma-1)10^{44}$ erg/Mpc^3/yr



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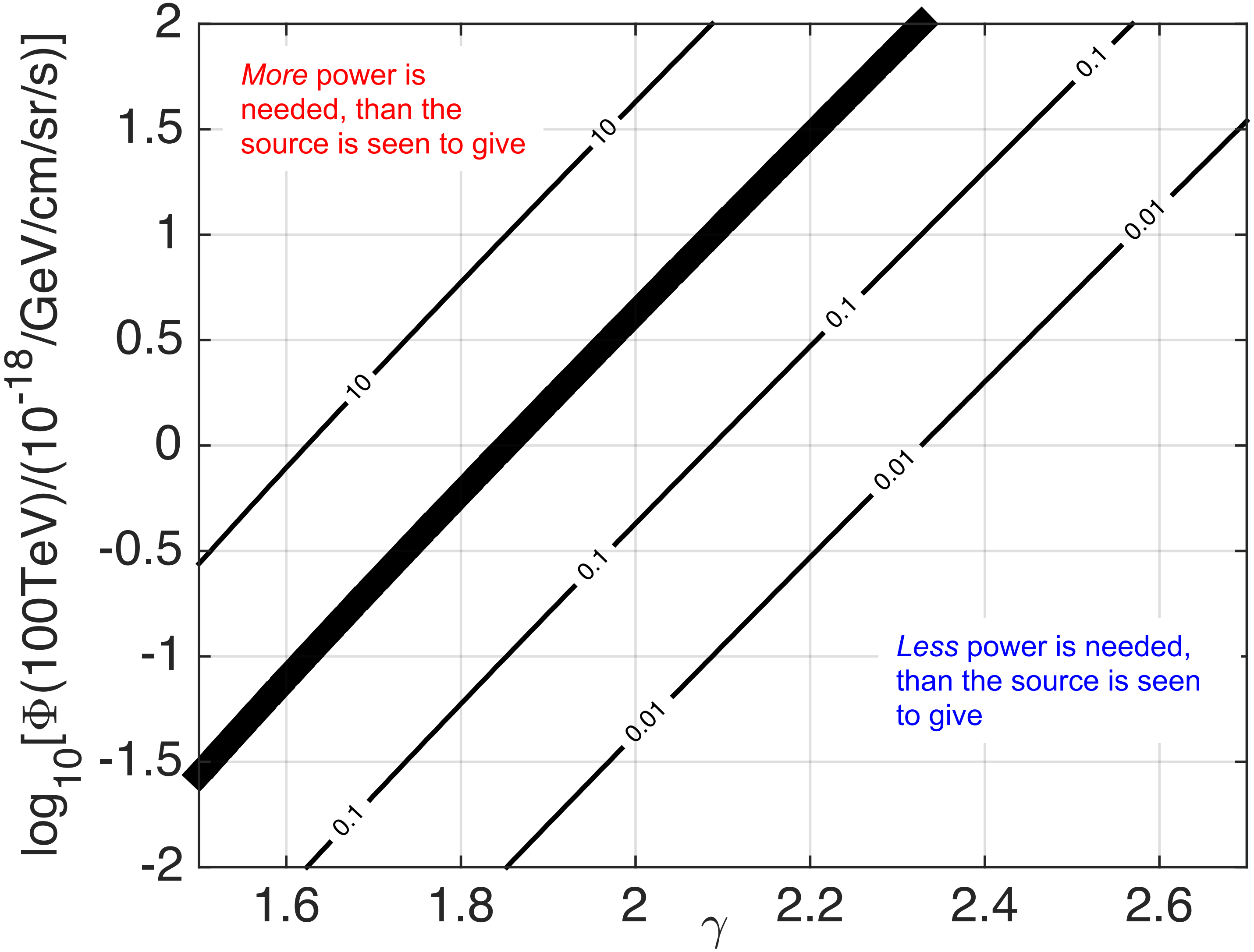

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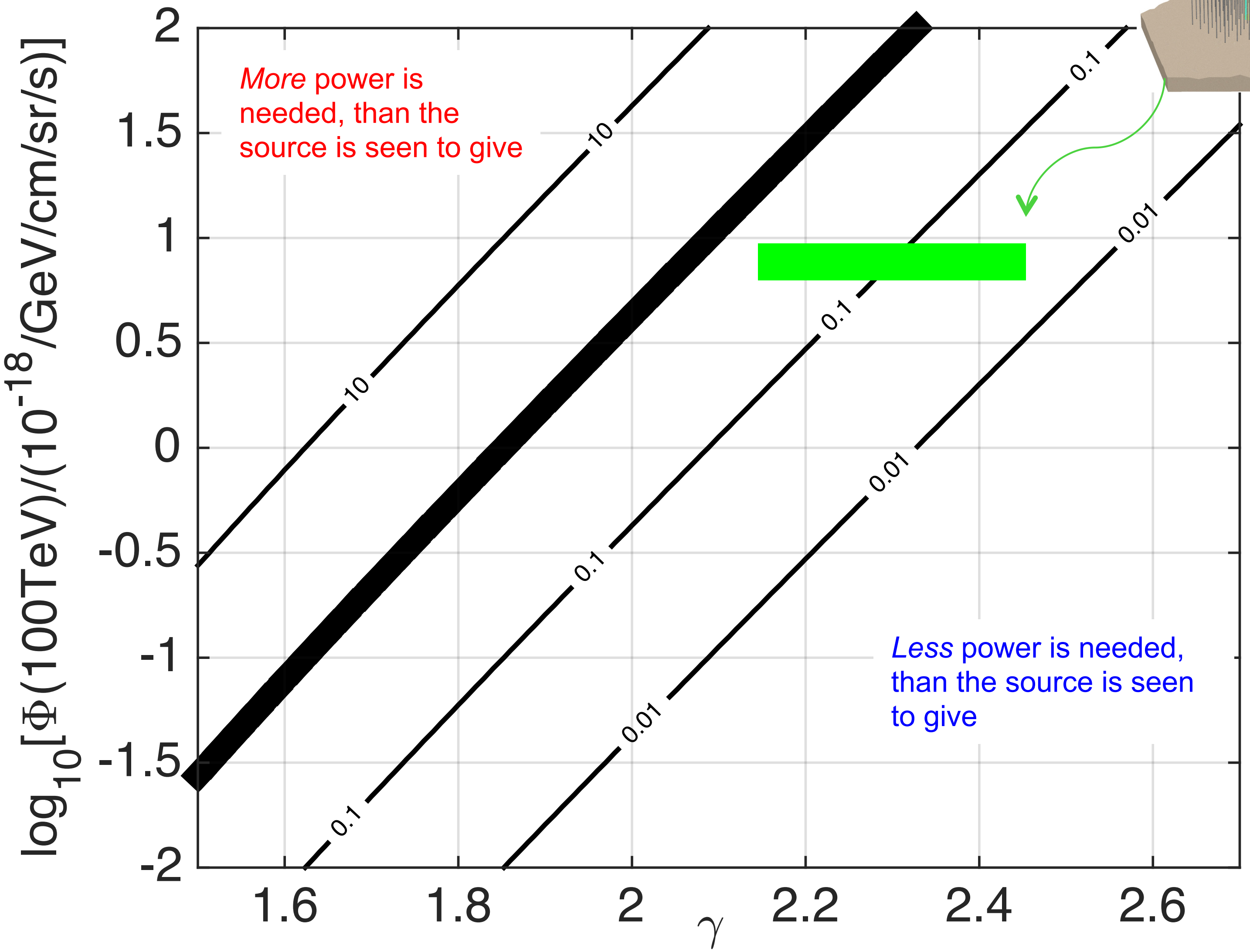

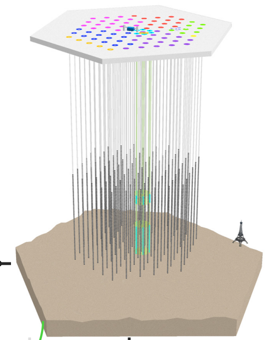

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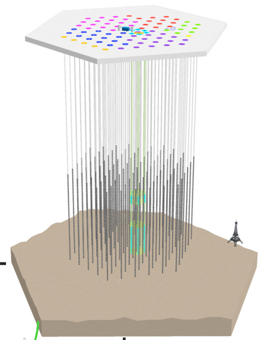

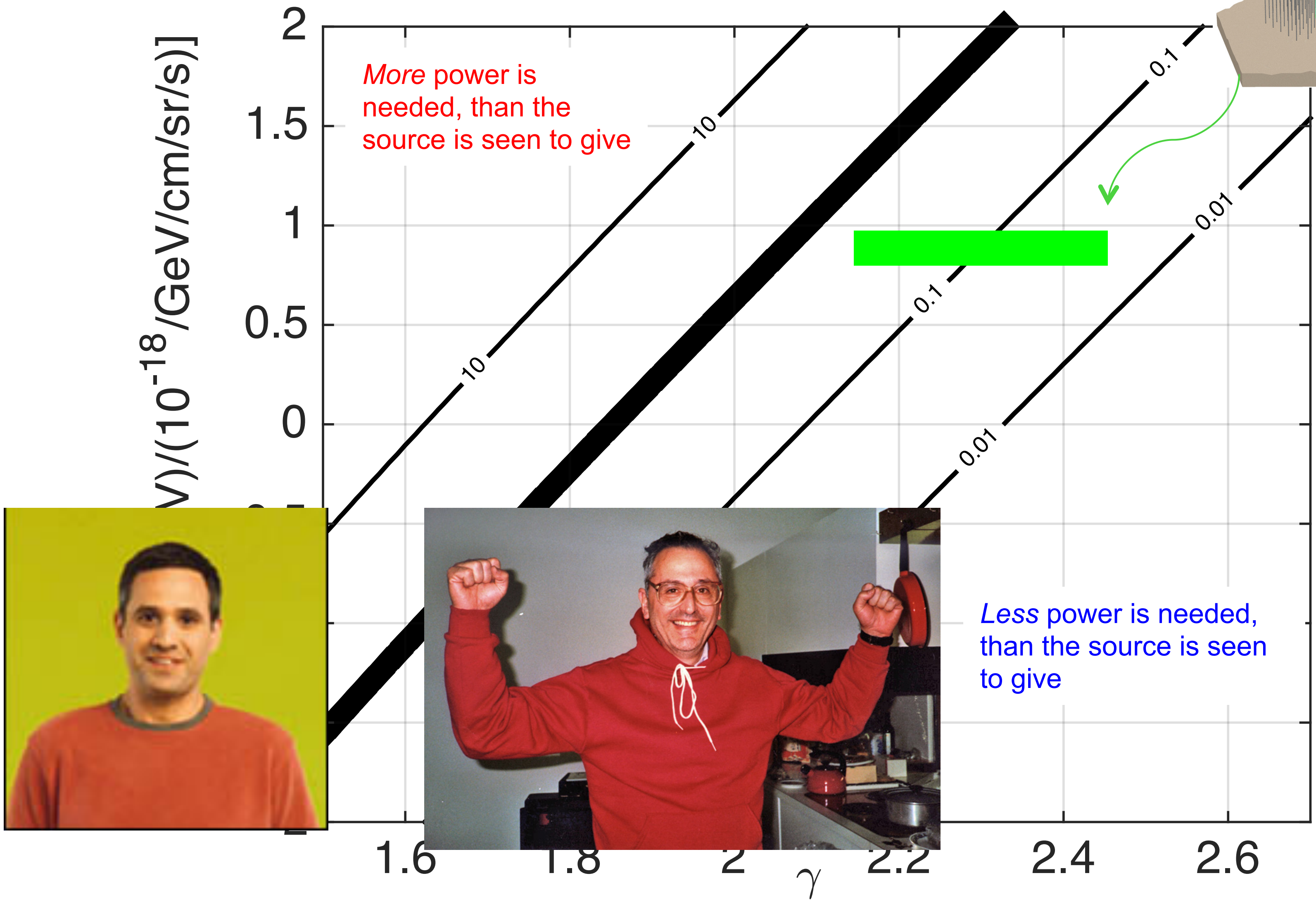

IceCube's neutrinos and diffuse gamma rays

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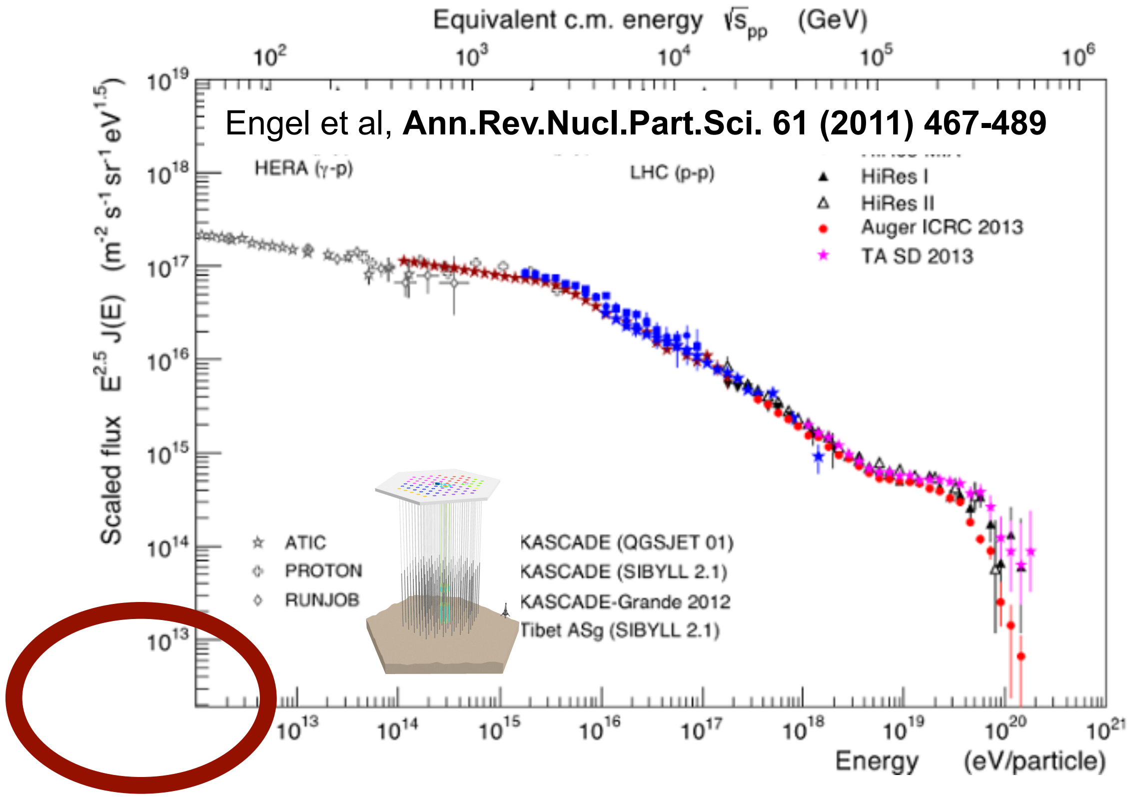
$pp \rightarrow pn\pi^{+}$ $\qquad \pi^{+} \rightarrow \mu^{+}\, \nu_{\mu} \rightarrow e^{+}\, \nu_{e}\, \overline{\nu}_{\mu}\, \nu_{\mu}$

$pp \rightarrow pp\pi^{0}$ $\qquad \pi^{0} \rightarrow \gamma\gamma$



IceCube's neutrinos and diffuse gamma rays

$pp \rightarrow pn\pi^+$ $\quad\quad$ $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$

$pp \rightarrow pp\pi^0$ $\quad\quad$ $\pi^0 \rightarrow \gamma\gamma$

$\gamma < 2.2$

to not overshoot
diffuse gamma rays

Murase, Ahlers, Lacki, **PRD88 (2013) no.12, 121301**