New physics from the high energy IceCube data?

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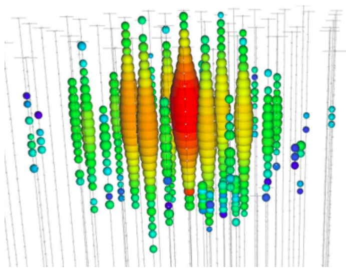

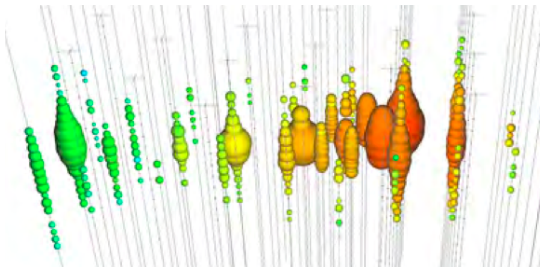

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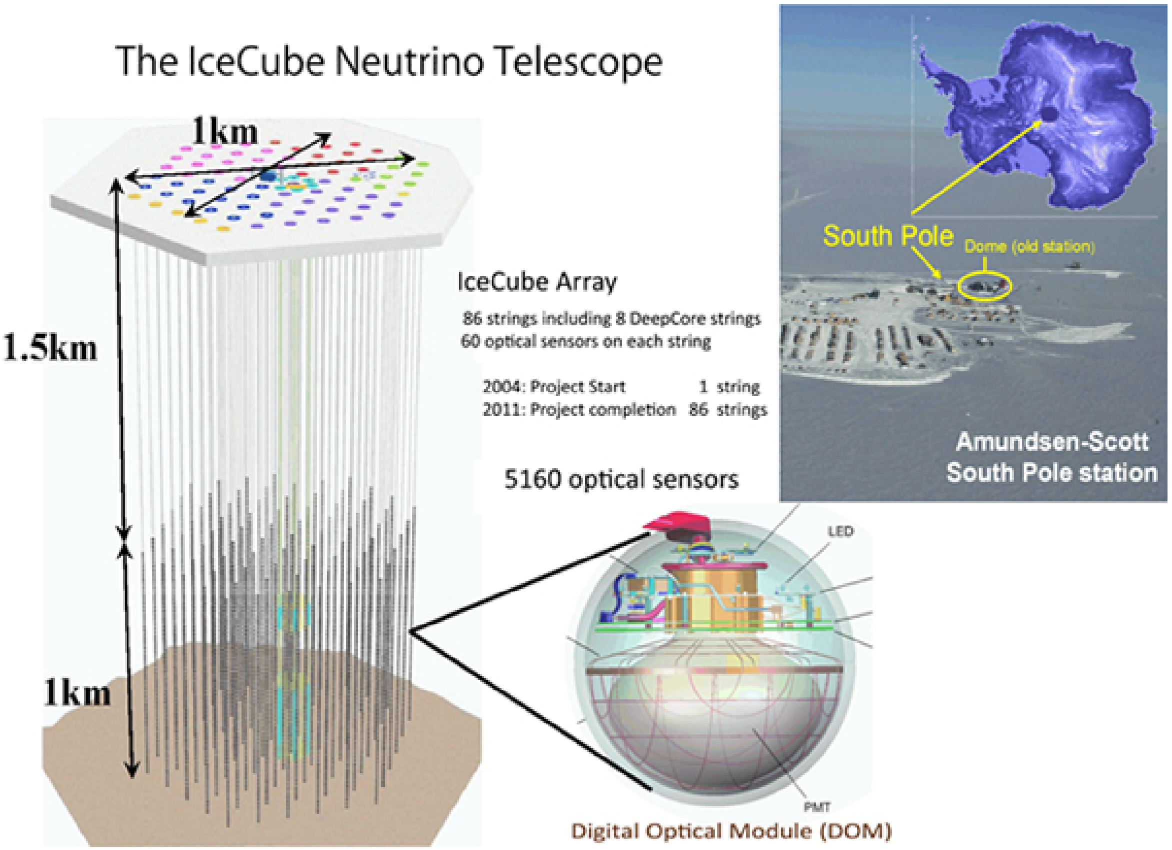
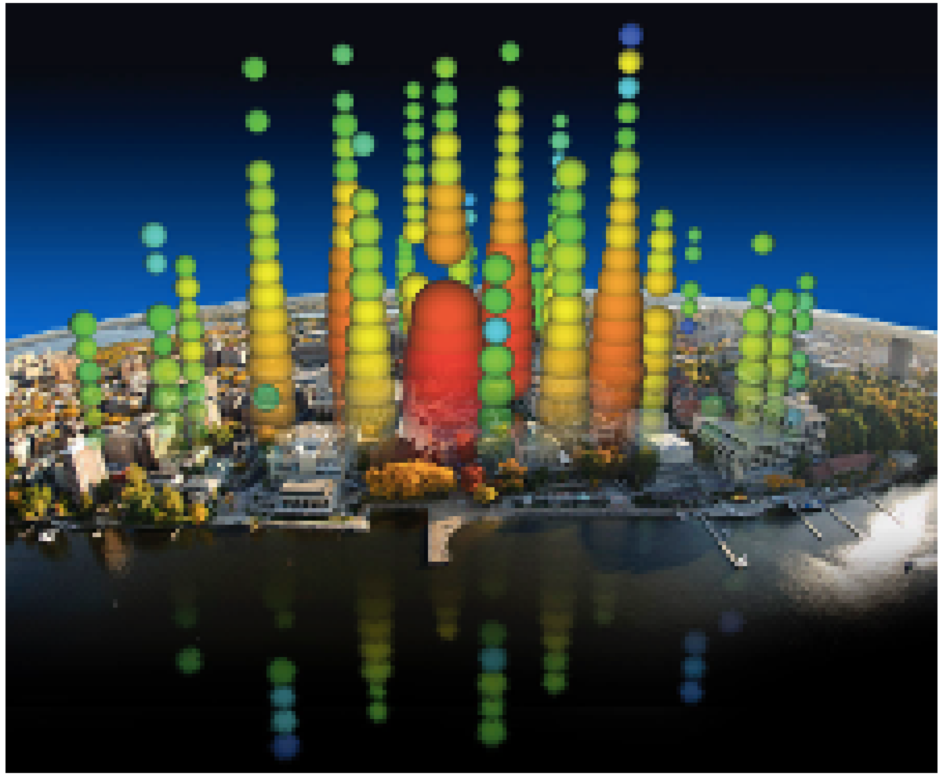
Motivation IceCube

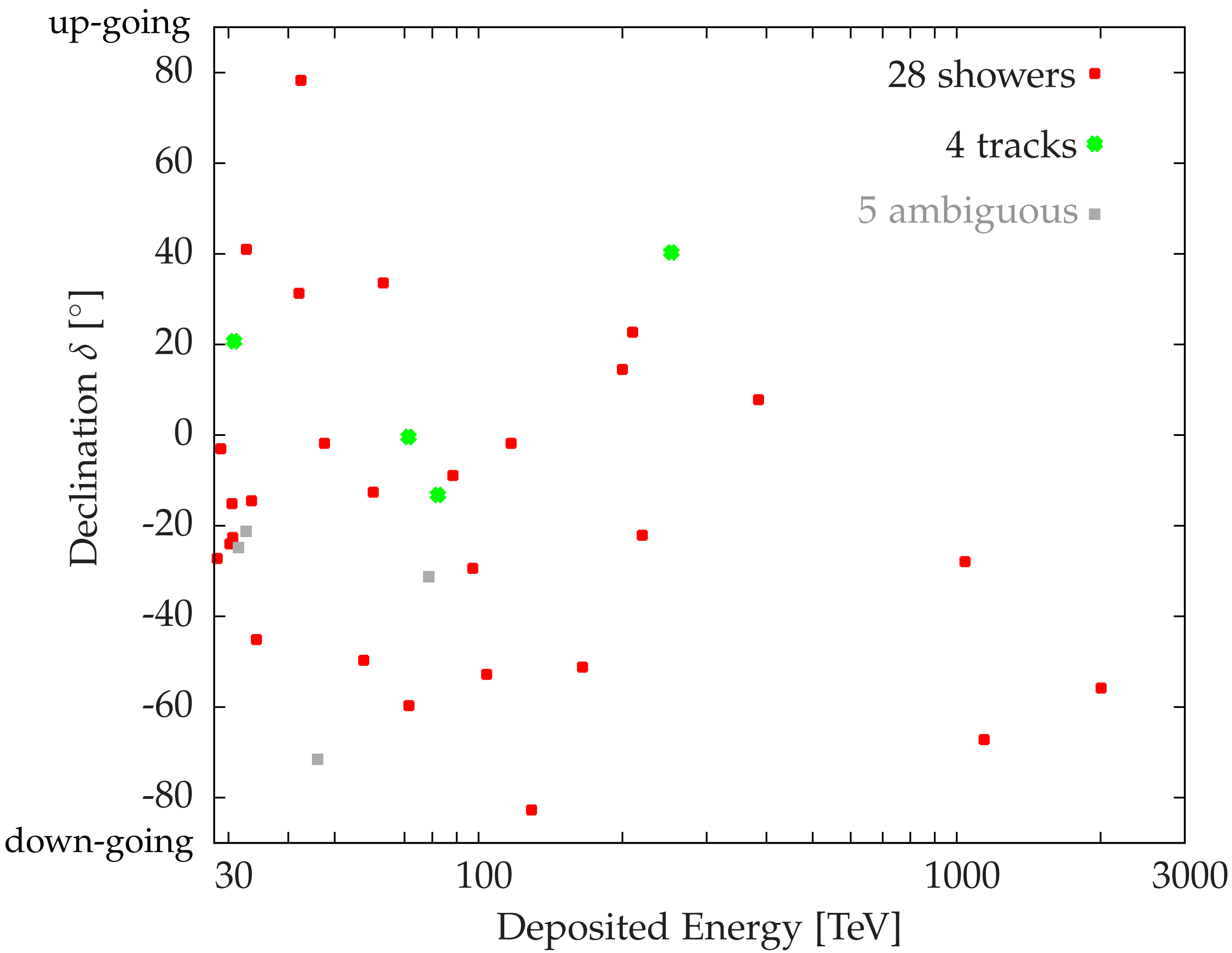




Motivation | IceCube events

- 32 events of $E \gtrsim 30$ TeV in $T = 988$ days (2010–2013) [IceCube '14]

  (+5 μ background compatible with 8.4 ± 4.2 expected: *ambiguous*)



$\Rightarrow$ atm + extraterrestrial !!

- The event rate is neutrino flavor (ν) and interaction (int) dependent:

$$N_{\nu,\text{int}} = T N_A \int \mathrm{d}\Omega \int_{E_\text{thres}} \mathrm{d}E_\nu \, M_\text{eff}^{\nu,\text{int}}(E_\nu) \frac{\mathrm{d}\phi_\nu}{\mathrm{d}\Omega \mathrm{d}E_\nu} P_\text{surv}^\nu(\theta_z, E_\nu) \int_{y_\text{min}}^{y_\text{max}} \mathrm{d}y \frac{\mathrm{d}\sigma_\text{int}}{\mathrm{d}y}$$

$$\mathrm{d}\Omega = 2\pi \, \mathrm{d}\cos\theta_z \qquad\qquad y = 1 - E'/E_\nu \text{ (inelasticity)}$$

- Two interpretations depending on which interactions/flux:

1. Usual: SM physics and astrophysical $E_\nu^{-\gamma}$ flux (*fit* to the excess to atm)

2. Ours: New physics (*generic*) and cosmogenic neutrino flux (*predicted*):

   – Model of TeV gravity:

   $$\langle y \rangle \sim 10^{-5} \text{ (eikonal interactions)}$$

   – Cosmogenic neutrinos from scattering of CRs off CMB radiation

   $$E_\nu \sim 10^8 - 10^{10} \text{ GeV}$$

Motivation **Extra dimensions?**

- If gravity can propagate in n spatial flat extra dimensions of size R

$$\text{Gauss's law} \;\Rightarrow\; F_4 S_4 = F_D S_D\,, \quad D = 4+n$$

$$r \gtrsim R: \quad F_4 \sim -\frac{1}{M_P^2}\frac{m_1 m_2}{r^2}$$

$$r \lesssim R: \quad F_D \sim -\frac{1}{M_D^{2+n}}\frac{m_1 m_2}{r^{2+n}}$$

$\Rightarrow$

– Gravity gets stronger ($\propto r^{-2+n}$) for $r \lesssim R$ with

$$R \sim \frac{1}{M_D}\left(\frac{M_P}{M_D}\right)^{\frac{2}{n}}$$

– Planck scale M_P (derived) $= M_D$ (fundamental) times a volume factor

$$M_P^2 \sim M_D^{2+n} R^n$$

Motivation — TeV gravity (flat extra dimensions)

- If $M_D \sim 1$ TeV flat model ruled out:

n	R		
1	~ 1 AU	(solar system)	$(10^{-27}\text{ GeV})^{-1}$
2	~ 1 mm	(torsion-balance)	
3	~ 1 nm	*	
...	...		
7	~ 10 fm	*	$(20\text{ MeV})^{-1}$

* Astrophysical and cosmological constraints:

- Compact dimension(s) $\Rightarrow$ KK gravitons with masses $m_j = j m_c, \quad m_c = R^{-1}$

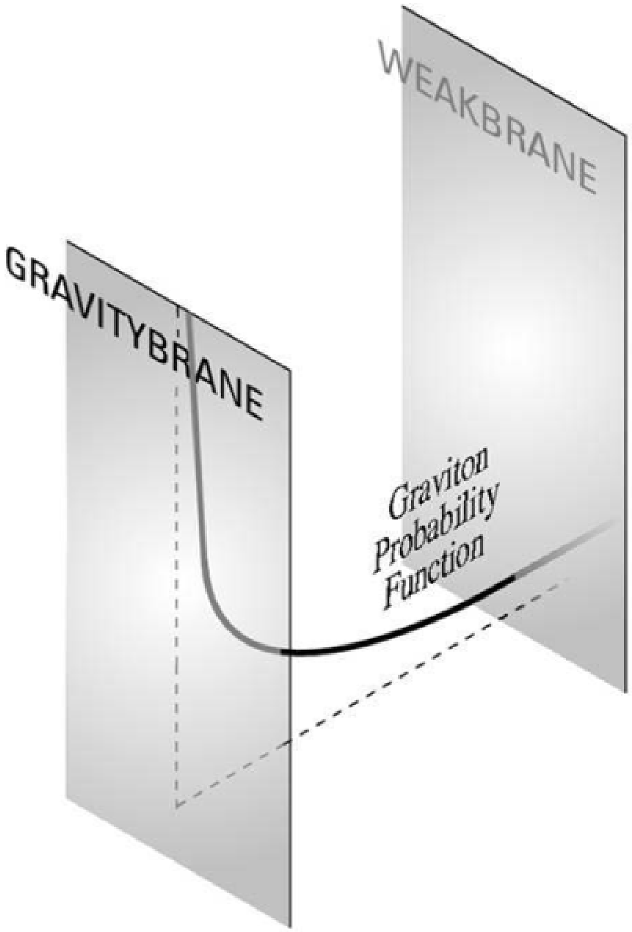
$\Rightarrow$ Supernovas and primordial nucleosynthesis would require

$$\boxed{m_c > 50\text{ MeV}}$$

- **Note**: gravity gets stronger when KK gravitons can be excited, i.e. at $r \lesssim m_c^{-1}$

Motivation | TeV gravity (one slightly warped extra dimension)

- D=5 ($n=1$): Two branes (4D slices separated by πR in the fifth dimension y)



$$ds^2 = e^{k|y|}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

Then

$$M_P^2 \sim M_5^3 \frac{e^{2k\pi R}-1}{k}$$

(large warping $e^{2\pi kR}$ compensates small $k^{-1} \ll R$)

Take $R^{-1} \ll k \ll M_5$ **hybrid** model

[Giudice, Plehn, Strumia '04 (E: '11)]

If $k \ll R^{-1}$ (small 5D curvature) one recovers flat case: $M_P^2 \sim M_5^3 R$

Motivation — Consistent model of TeV gravity in 5D (How it works)

	Flat	Hybrid
	$M_P^2 \sim M_5^3 R$	$M_P^2 \sim M_5^3 (e^{2k\pi R} - 1)/k$
1st KK mass	$m_c \sim R^{-1}$	$m_c \sim k \gg R^{-1}$ (much larger)
# KK at scale μ	$N \sim \frac{\mu}{m_c}$ (too many!)	$N \sim \frac{\mu}{m_c}$ (much less)
coupling KK–matter	$\sqrt{\alpha} \sim \frac{\mu}{M_P}$ (very small)	$\sqrt{\alpha} \sim \sqrt{\frac{k}{M_5^3}}\,\mu$ (much larger)
gravi strength	$\alpha_{\text{eff}} \sim N\alpha \sim \frac{\mu}{m_c}\frac{\mu^2}{M_P^2}$	$\alpha_{\text{eff}} \sim N\alpha \sim \frac{\mu}{m_c}\frac{k}{M_5^3}\mu^2$
at $\mu \sim M_5$	$\alpha_{\text{eff}} \sim 1$	$\alpha_{\text{eff}} \sim 1$

In fact, in the **Hybrid** model ($n = 1$) m_c is free and one can have

$M_5 \sim 1$ TeV and $m_c = 50$ MeV $= (4\text{ fm})^{-1}$ with $R = 40$ fm $\quad (k = 10R^{-1})$

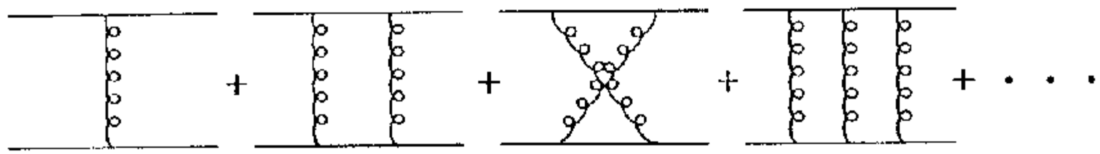
For $Q = \sqrt{y\hat{s}} \sim r^{-1} \gg m_c$ gravity is 5D and XD $\sim$ flat. Otherwise $e^{-m_c/Q}$ supp

Motivation | **Consistent model of TeV gravity in 5D** (How it works)

- Phenomenology of transplanckian collisions ($\sqrt{\hat{s}} \gg M_5$)

$$\sqrt{\hat{s}} \gg M_5 \quad \Rightarrow \quad \text{(Schwarzschild) } R_S > \lambda_P = M_5^{-1} \text{ (Planck length)}$$

  - Short distance ($r \lesssim R_S$): black hole formation (BH)
    ν destroyed, $\sigma \simeq \pi R_S^2$
  - **Long distance** ($r \gg R_S > \lambda_P$): eikonal (eik)
    quasielastic (low Q^2), higher σ, **classical** gravity, dominant

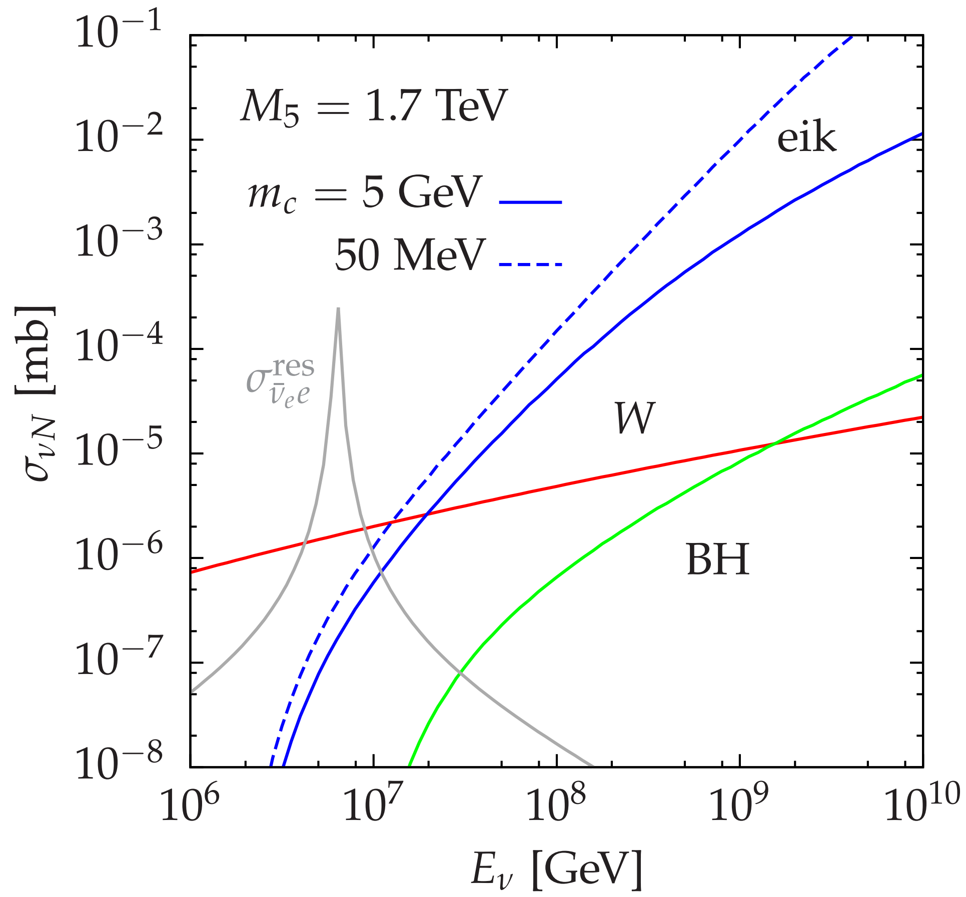


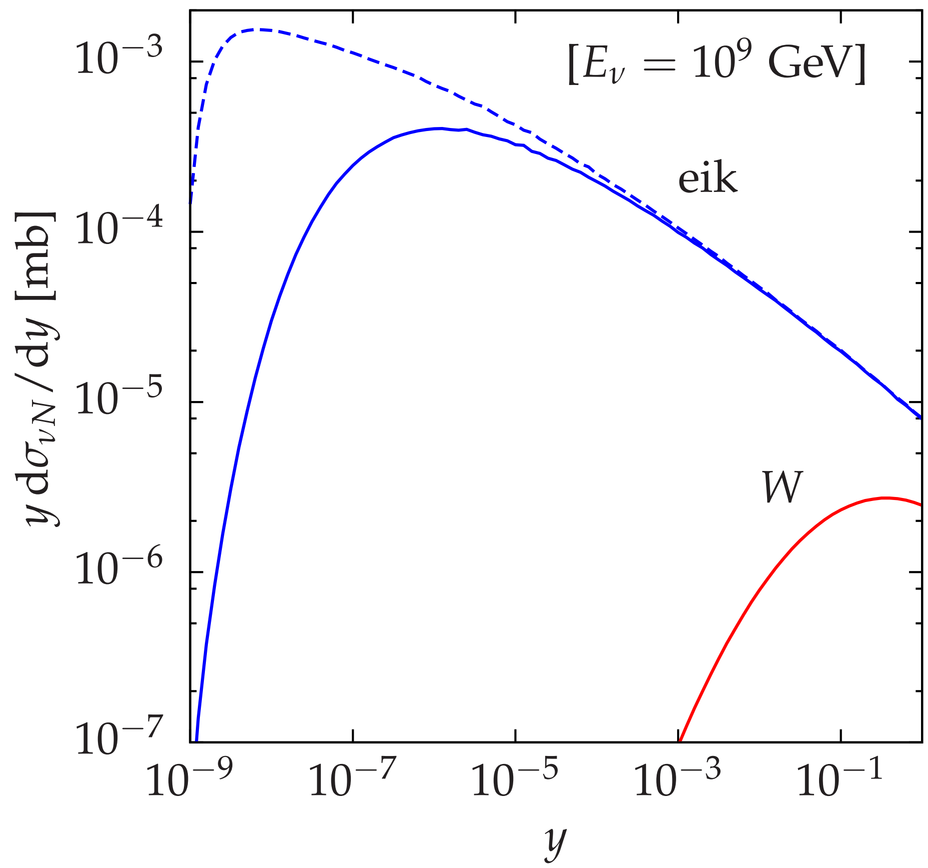
- Astrophysical and cosmological bounds: evaded when $\sim m_c \gtrsim 50$ MeV
- Collider bounds:
  from BH (high multiplicity events and large MET) $\Rightarrow M_5 \gtrsim 1.5 - 2.4$ TeV [LEP]
  BUT model dependent (fermion localization in extra dimension)
  and ultraforward physics remains unconstrained

Ingredients | Cross sections

- Standard Model (νN) interactions: $\sigma_{\text{int}} = \sigma^{\text{CC}}_{\nu N}$ (W–exchange), $\sigma^{\text{NC}}_{\nu N}$ (subdominant) (and $\sigma^{\text{res}}_{\bar{\nu}_e e}$ at $E_\nu = M_W^2/(2m_e) \sim 6.3$ PeV)

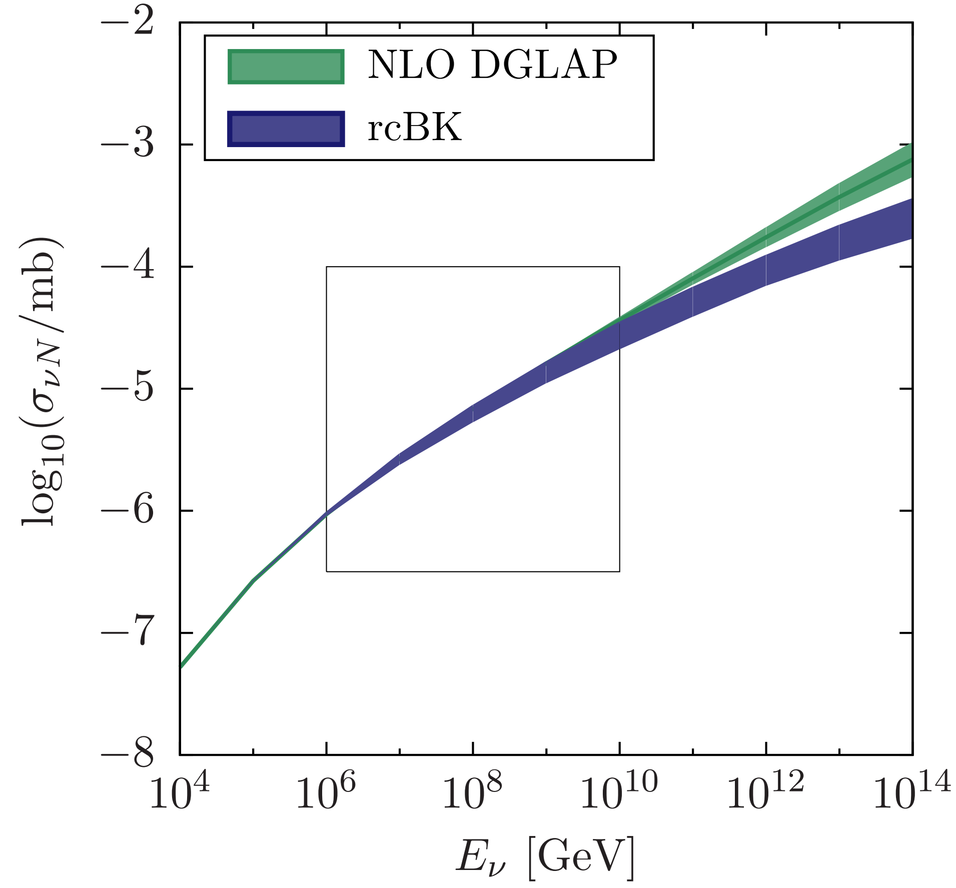
- Eikonal (νN) interactions: $\sigma_{\text{int}} = \sigma^{\text{eik}}_{\nu N}$ [large for $E_\nu \gg M_5^2/(2m_N) \gtrsim 3$ PeV]





Ingredients **About SM νN uncertainties** [Albacete, JI, Soto-Ontoso: 1505.06583]

- At UHE, Bjorken $x \lesssim 10^{-7}$ is probed.
  Compare DGLAP (usual) to BK (includes saturation effects)



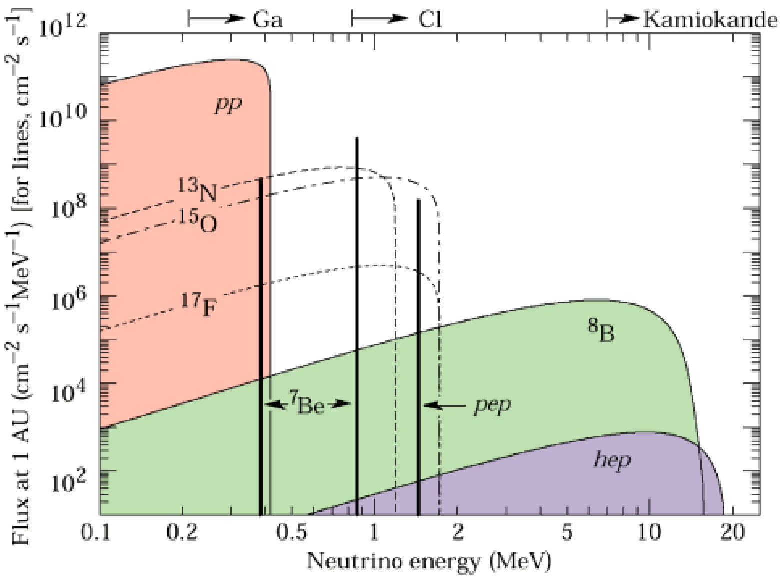
$\Rightarrow$ $\sigma_{\nu N}$ can be reduced by up to $\sim$ 50% at 10^{10} GeV

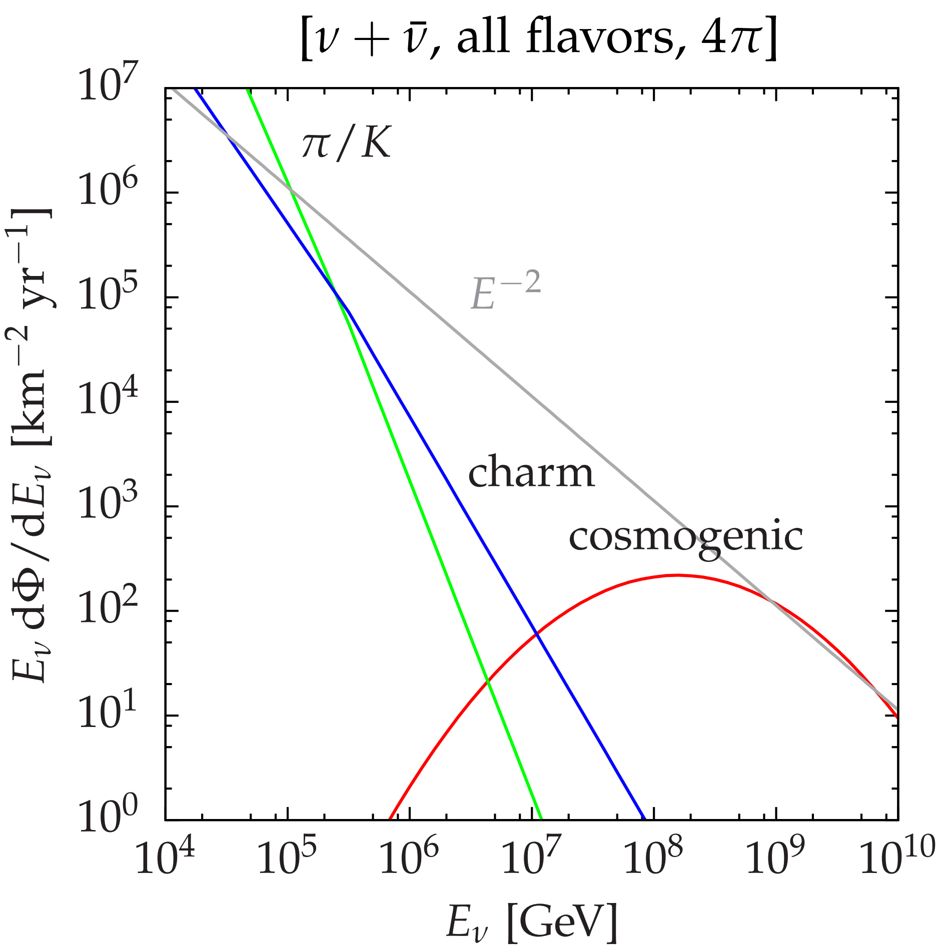
Ingredients — Neutrino fluxes

		$(\nu_e : \nu_\mu : \nu_\tau)_\oplus$
Atmos	π/K dcys ($\sim \cos^{-1}\theta_z$)	$(1:17:0)$
	Charm decays*	$(48:48:2)$
ET*	Cosmogenic	$(1:1:1)$
	E_ν^{-2}	$(1:1:1)$

* isotropic

Note: Solar are $\mathcal{O}$(MeV)

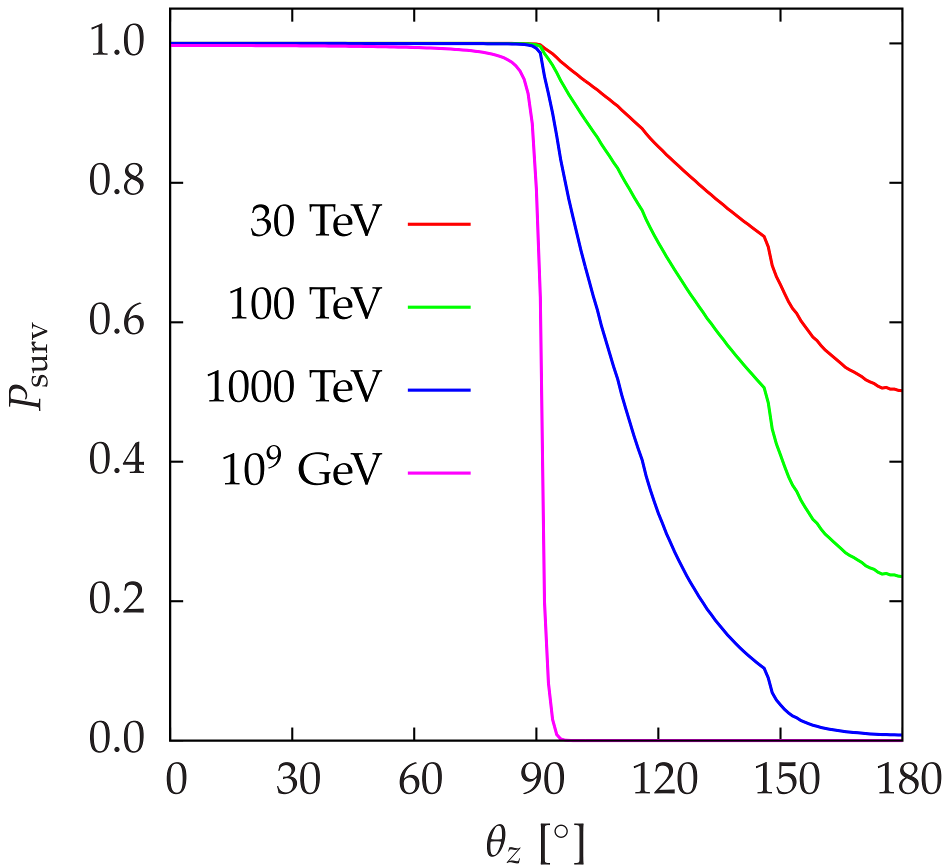




Ingredients **Survival probability**

- Neutrinos *stopped* by CC interactions and (for $E_\nu \gtrsim 10^9$ GeV) BH formation

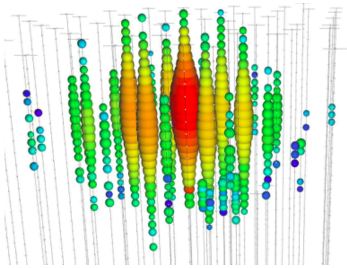
$$P^{\nu}_{\rm surv}(\theta_z, E_\nu) = \exp\left\{-N_A\sigma(E_\nu)\int \rho_\oplus(\theta_z)\mathrm{d}\ell\right\}\ , \quad \sigma = \sigma^{\rm CC}_{\nu N} + \sigma^{\rm BH}_{\nu N}$$



Earth opaque at UHE for $\theta_z \gtrsim 90°$

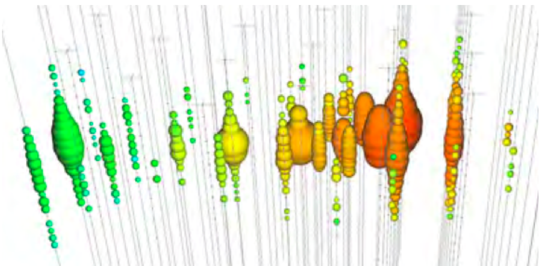
Ingredients | Showers vs Tracks

- Deposited energy



Showers (by electrons and hadrons)

$N_{\nu_i,\text{NC}}$; $E_{\text{sh}} = yE_\nu$	
$N_{\nu_e,\text{CC}}$; $E_{\text{sh}} = E_\nu$	$N_{\nu_i,\text{eik}}$; $E_{\text{sh}} = yE_\nu$
$N_{\nu_\tau,\text{CC-had}}$	NP $\Rightarrow$ showers only
$N_{\nu_\tau,\text{CC-electrons}}$	

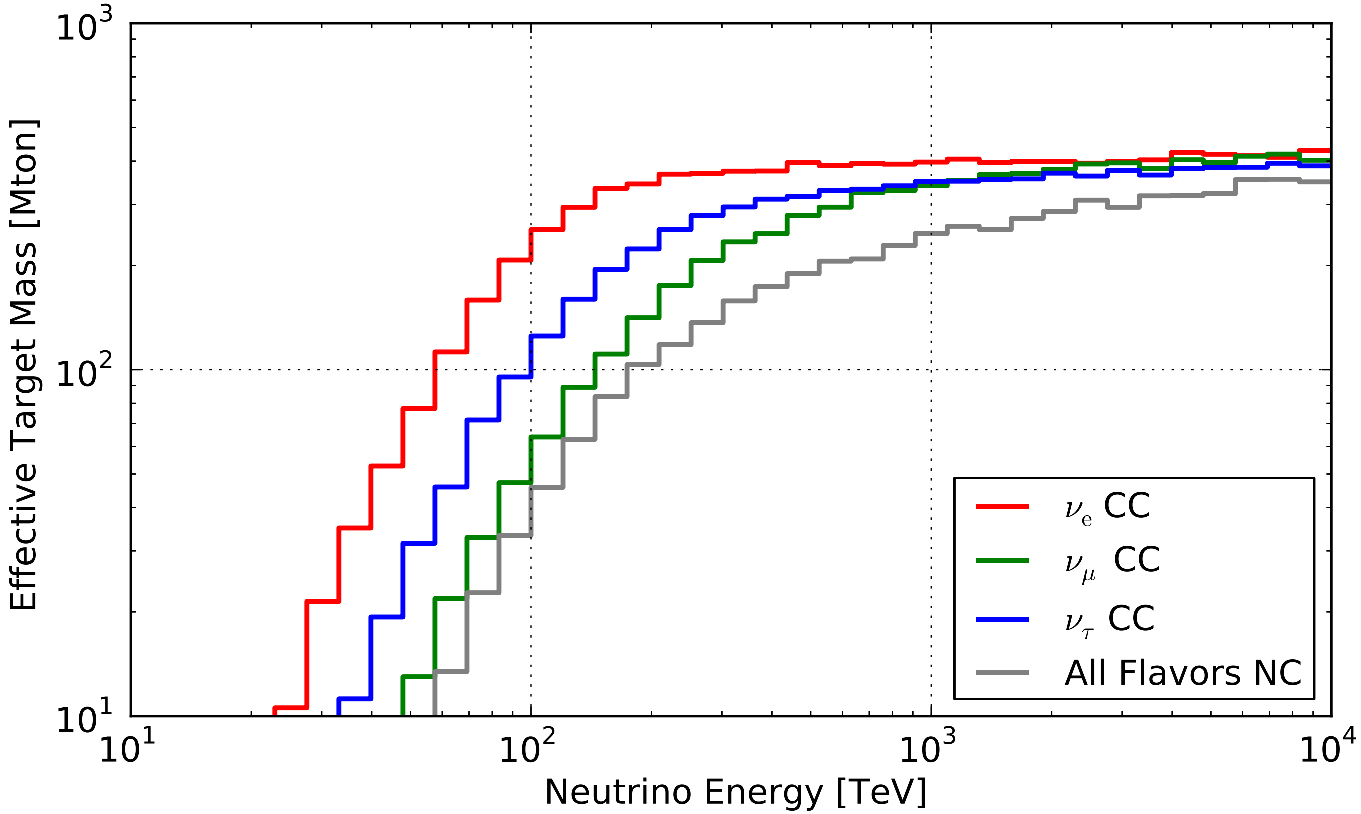


Tracks (by muons)

$N_{\nu_\mu,\text{CC}}$; $E_{\text{sh}} = yE_\nu$	$N_{\nu_\mu,\text{eik}} = 0$
$N_{\nu_\tau,\text{CC-muons}}$	

Ingredients | Effective IceCube mass

- The effective mass is interaction, flavor and energy dependent: [IceCube '14]

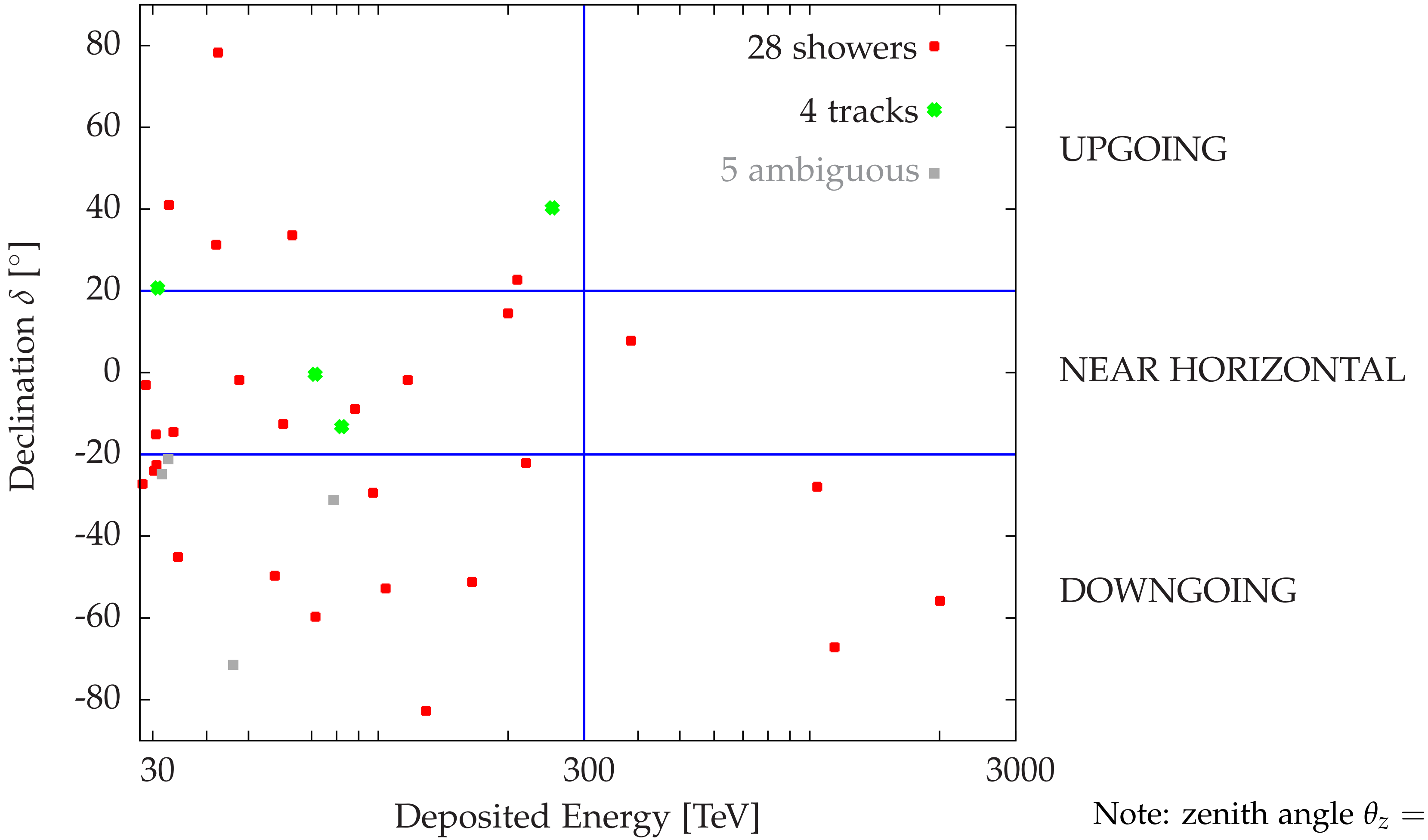


⇒ About 500 Mton, that is 0.5 km^3 of ice, at ultrahigh energy

Our analysis

- 2×3 bins of energy and angle

3 angular bins ($\Delta \cos\theta_z \approx 2/3$) $\Rightarrow$ disentangle cosmogenic from E_ν^{-2} neutrinos



Note: zenith angle $\theta_z = 90^\circ + \delta$

Our analysis | Tracks from atmospheric ν

	Data	Atm			Data	Atm			
Tracks	2	0.8			0	0.0			UPGOING
Tracks	2	3.5			0	0.0			NEAR HORIZONTAL
Tracks	0	0.2			0	0.0			DOWNGOING
	30 – 300 TeV				300 – 3000 TeV				

- Number and distribution of tracks *roughly* explained by atmospheric neutrinos (4.5 expected, 4 observed)

Our analysis | Showers from atmospheric ν

	Data	Atm			Data	Atm			
									UPGOING
Showers	5	2.7			0	0.0			
									NEAR HORIZONTAL
Showers	8	5.9			1	0.2			
									DOWNGOING
Showers	11	0.6			3	0.0			
	30 – 300 TeV				300 – 3000 TeV				

- Shower excess (extraterrestrial) especially significant in downgoing direction:

$11 - 0.6 = 10.4$ (30 – 300 TeV)	$3 - 0 = 3$ (30 – 300 TeV)

Our analysis | **Astrophysical E_ν^{-2} hypothesis**

	Data	Atm	E_ν^{-2}		Data	Atm	E_ν^{-2}		
Tracks	2	0.8	0.6		0	0.0	0.1		UPGOING
Showers	5	2.7	3.6		0	0.0	0.7		
Tracks	2	3.5	1.5		0	0.0	0.5		NEAR HORIZONTAL
Showers	8	5.9	6.4		1	0.2	2.6		
Tracks	0	0.2	1.6		0	0.0	0.6		DOWNGOING
Showers	11	0.6	6.5		3	0.0	2.9		
	30 – 300 TeV				300 – 3000 TeV				

- Provides extra (✓) showers and extra (?) tracks: $\sim$ 4 or 5 showers per track
- Same number extra showers from downgoing and near-horizontal directions
- How about Glashow resonance: $\sim$ 2 evts expected at $E \sim 6$ PeV, none observed

Our analysis | **NP and cosmogenic neutrinos hypothesis**

	Data	Atm		NP	Data	Atm		NP	
Tracks	2	0.8		0.0	0	0.0		0.0	UPGOING
Showers	5	2.7		0.0	0	0.0		0.0	
Tracks	2	3.5		0.0	0	0.0		0.0	NEAR HORIZONTAL
Showers	8	5.9		4.2	1	0.2		1.9	
Tracks	0	0.2		0.0	0	0.0		0.0	DOWNGOING
Showers	11	0.6		8.0	3	0.0		3.5	
	30 – 300 TeV				300 – 3000 TeV				

- Provides no extra tracks (✓)
- Double extra showers from downgoing that from near-horizontal directions

Our analysis — Comparison of both hypotheses

	Data	Atm	E_ν^{-2}	NP	Data	Atm	E_ν^{-2}	NP	
Tracks	2	0.8	0.6	0.0	0	0.0	0.1	0.0	UPGOING
Showers	5	2.7	3.6	0.0	0	0.0	0.7	0.0	
Tracks	2	3.5	1.5	0.0	0	0.0	0.5	0.0	NEAR HORIZONTAL
Showers	8	5.9	6.4	4.2	1	0.2	2.6	1.9	
Tracks	0 (5)	0.2 (7.6)	1.6	0.0	0	0.0	0.6	0.0	DOWNGOING
Showers	11	0.6 (0.8)	6.5	8.0	3	0.0	2.9	3.5	
	30 – 300 TeV				300 – 3000 TeV				

- Likelihood (E_i = prediction, X_i = data)

$$-2\ln\lambda = \sum_i^{\text{nbin}} 2\left(E_i - X_i + X_i \ln\frac{X_i}{E_i}\right) = \begin{cases} 5.9 \;\; (7.3) \text{ for NP} \\ 15.4 \; (15.1) \text{ for } E_\nu^{-2} \end{cases} \text{ excl. (incl.) 5 } \textit{ambiguous } \mu$$

Conclusions

- So far, our scenario with NP + cosmogenic neutrinos provides a better fit to data

  [TeV gravity model is a particular realization of a generic type of models where UV physics is dominated by long wave lengths: *classicalization*] [Dvali et al, '10]

- How to discriminate between both interpretations?
  - Multiple bangs?
  - Glashow resonance?

- Wait for **more** statistics!
  - Check in particular the ratio of downgoing to near-horizontal showers:

    (2:1) for NP versus (1:1) for E_ν^{-2} (lower energy SM int)

Conclusions