Advanced Workshop on Physics of Atmospheric Neutrinos - PANE 2018

Tau tracks: a new signal in IceCube and Intrinsic Charm: a guaranteed contribution to atmospheric prompt neutrinos

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Thanks to my collaborators: Matthew D Kistler and Stanley J Brodsky

1605.08781 (accepted in Phys. Rev. Lett.)

and 1607.08240 (Phys. Rev. D96 2017 no.12, 123002)

Contents

- Tau tracks in IceCube
- Intrinsic charm in atmospheric neutrino experiments

Neutrino signatures in IceCube

(I will be talking about Standard Model physics)

What are the neutrino signatures in IceCube?

$\nu_\mu + N \rightarrow \mu^- + N'$
and the corresponding interaction by $\overline{\nu}_\mu$
(an exception will be discussed later)

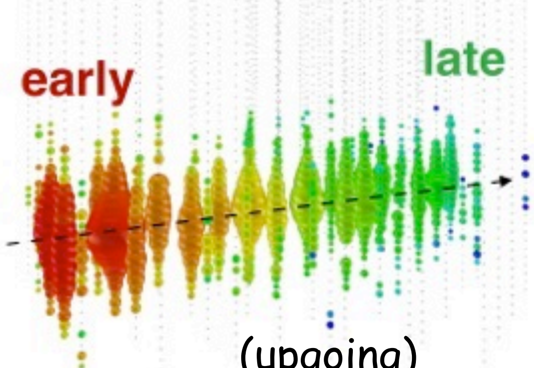
$\nu_e + N \rightarrow e^- + N'$
and the corresponding interaction by $\overline{\nu}_e$
+ neutral current interactions

$\nu_\tau + N \rightarrow \tau^- + N'$
and the corresponding interaction by $\overline{\nu}_\tau$

Learned and Pakvasa Astropart.Phys. 3 (1995) 267-274

track
(data)

IceCube collaboration

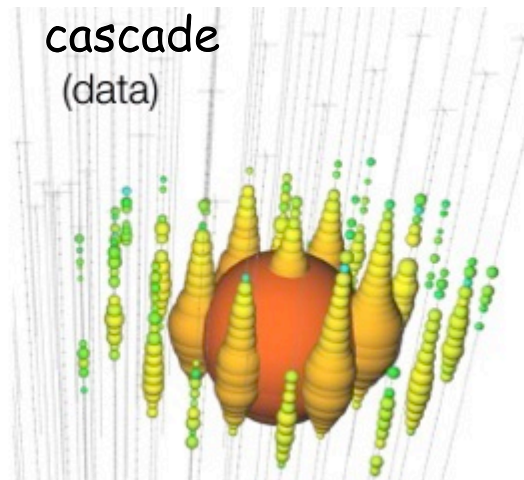


(upgoing)

Factor of ~2 energy resolution

< 1^0 angular resolution

cascade
(data)



IceCube collaboration

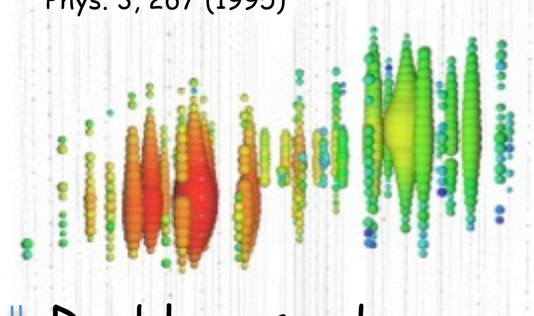
Isolated energy deposition (cascade) with no track

15% deposited energy resolution

10^0 angular resolution (above 100 TeV)

double bang
(simulation)

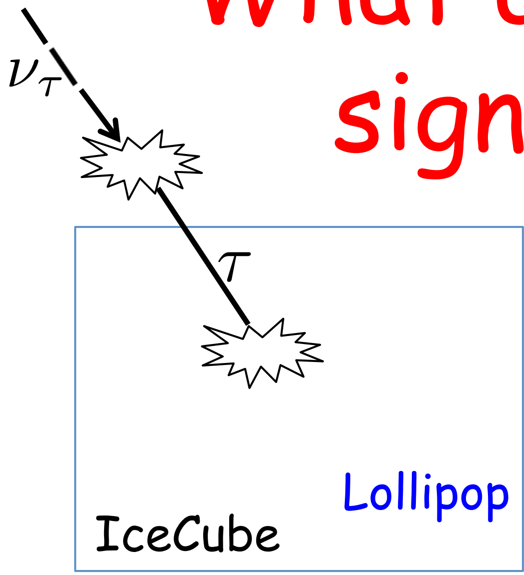
Learned and Pakvasa Astropart. Phys. 3, 267 (1995)



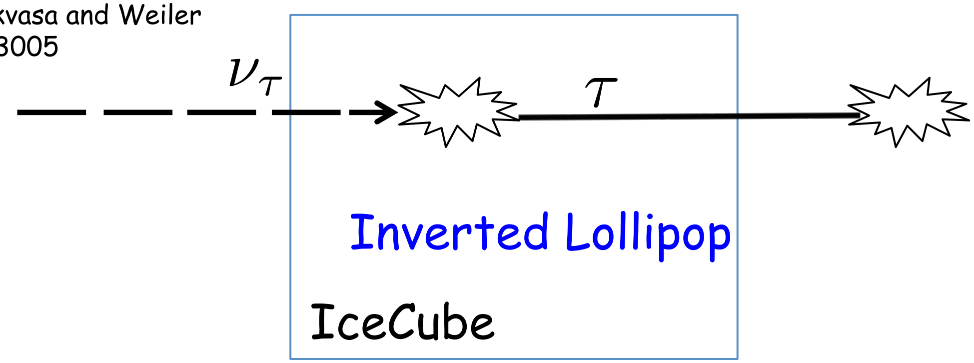
Double cascade / double bang / double pulse

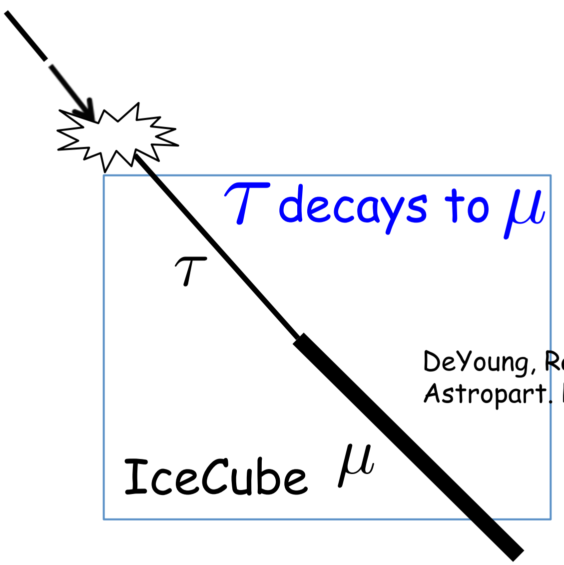
resolvable above O(100) TeV deposited energy

What are the other neutrino signatures in IceCube?



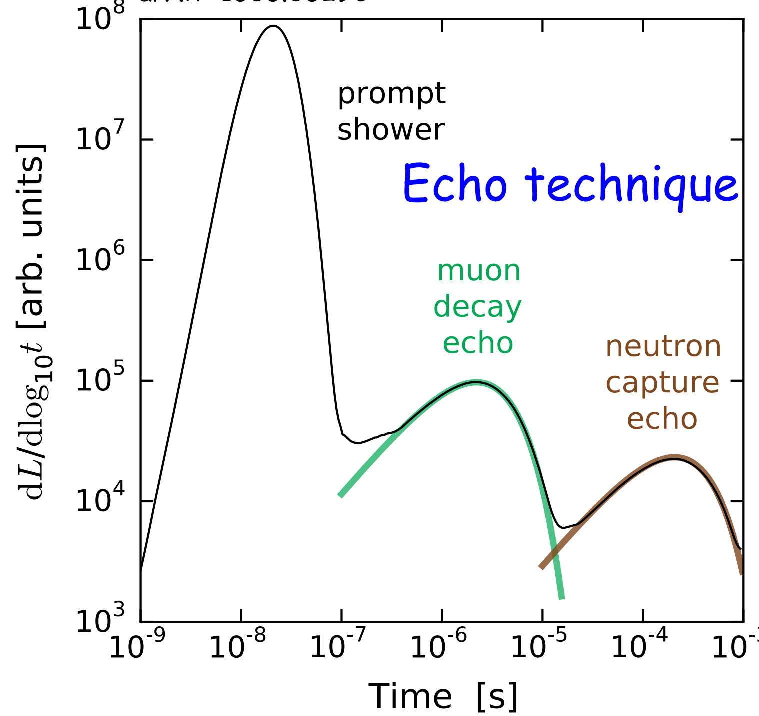
Beacom, Bell, Hooper, Pakvasa and Weiler
Phys.Rev. D68 (2003) 093005





DeYoung, Razzaque and Cowen
Astropart. Phys. 27 (2007) 238-243

Li, Bustamante and Beacom
arXiv: 1606.06290



Are there other neutrino signtures in IceCube?

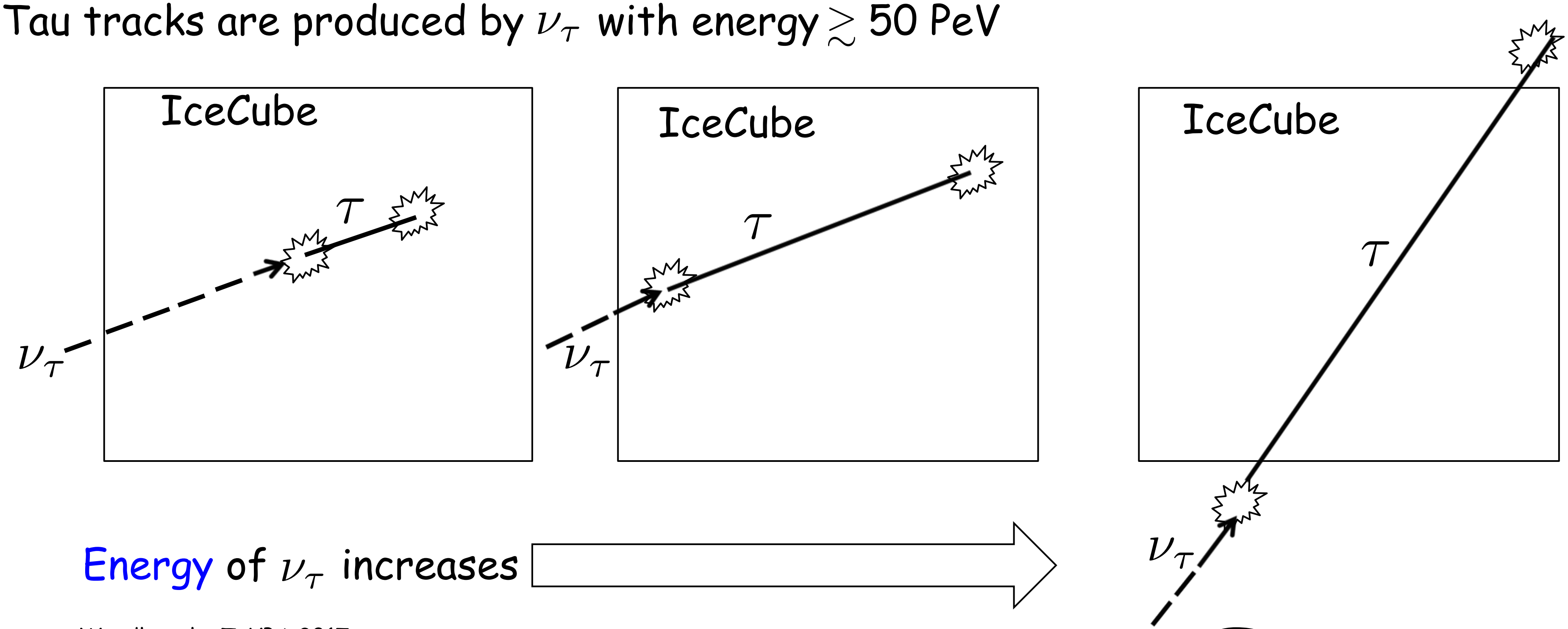
Tau tracks

1605.08781 (accepted in Phys. Rev. Lett.) with Matthew D Kistler

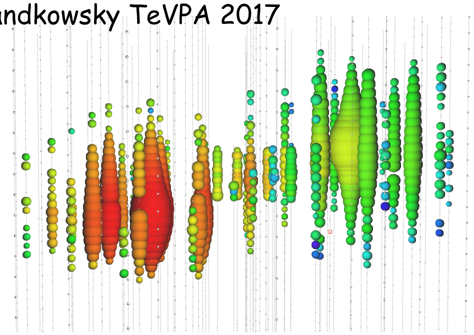
Tau tracks

Kistler and Laha arXiv: 1605.08781 (PRL)

Tau tracks are produced by ν_τ with energy $\gtrsim$ 50 PeV



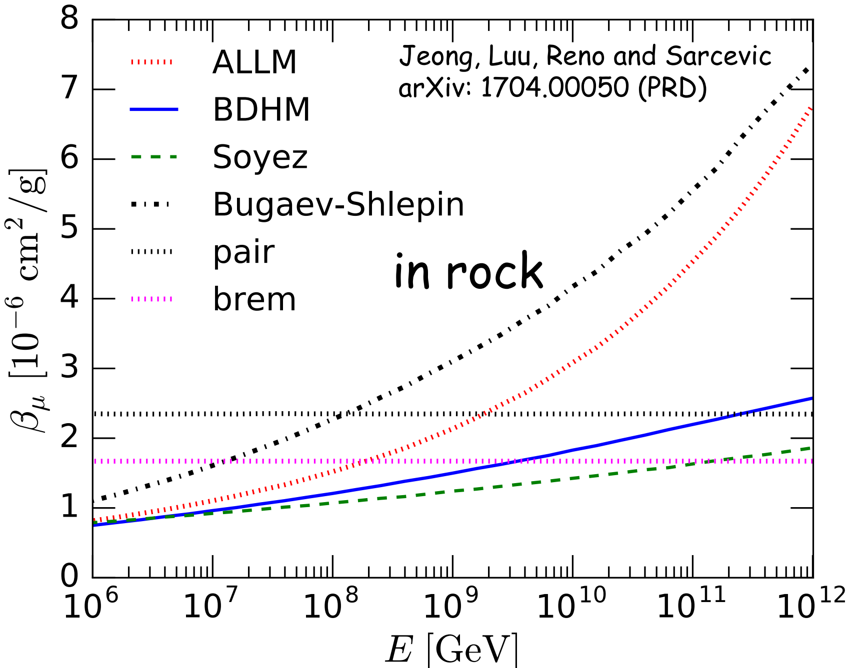
Wandkowsky TeVPA 2017

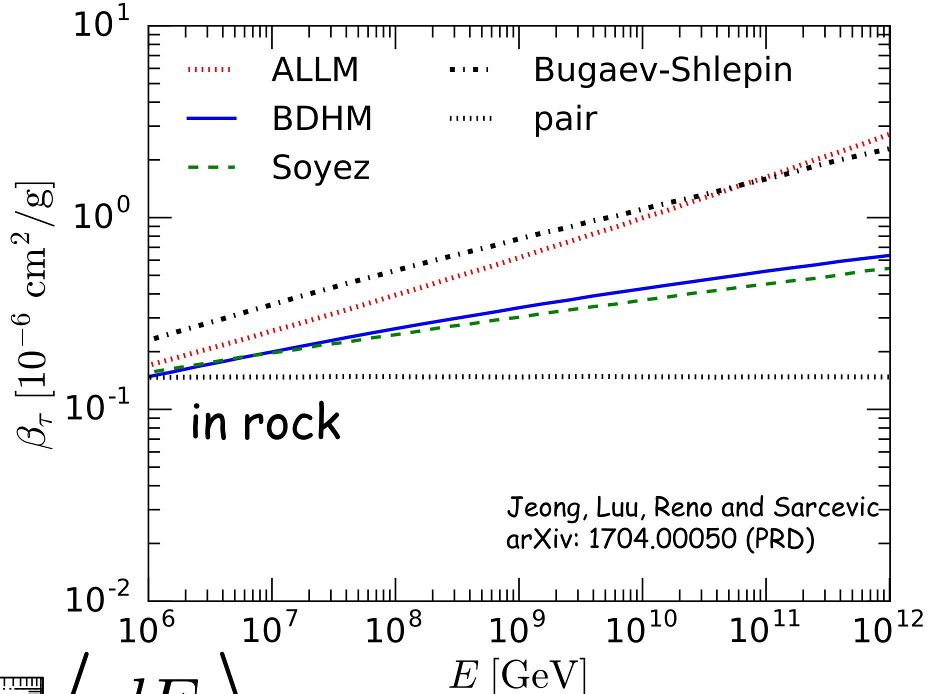


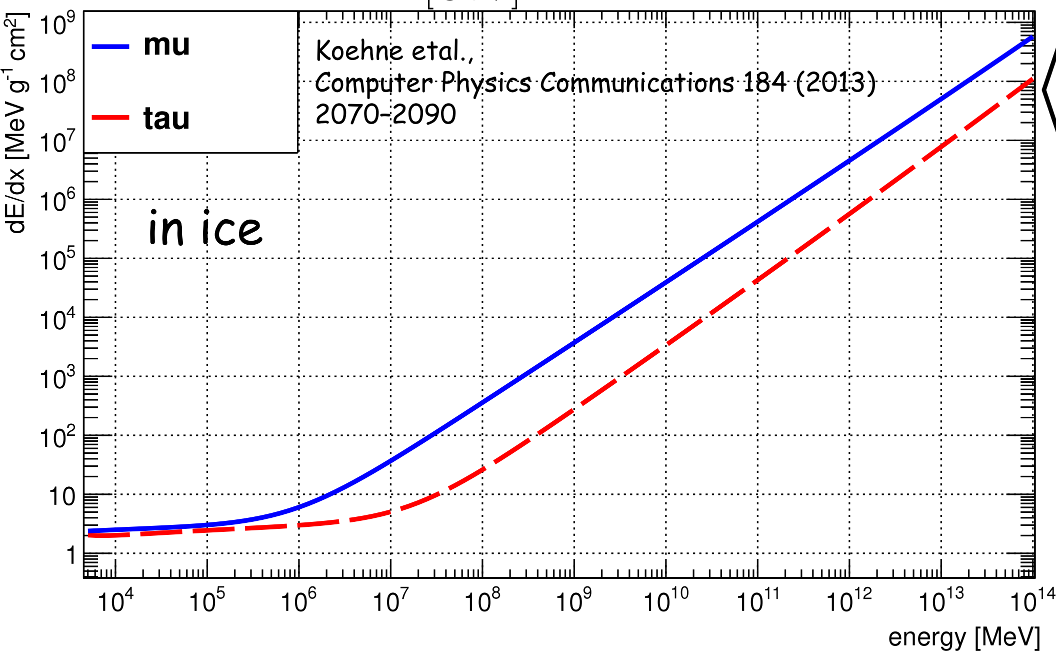
$$\nu_\tau + N \rightarrow \tau + X$$

How do tau tracks look in IceCube?

Muon energy loss v/s tau energy loss







$$\left\langle \frac{dE}{dX} \right\rangle_\ell \approx -\beta_\ell E \qquad \ell \in \mu,\ \tau$$

Fluctuations in dE/dx can distinguish between muon and tau tracks

To deposit the same energy, a through going tau must have an order of magnitude more energy than a muon

Ranjan Laha

Illustrative example with the 2.6 PeV track event

Discovery of high-energy astrophysical neutrinos

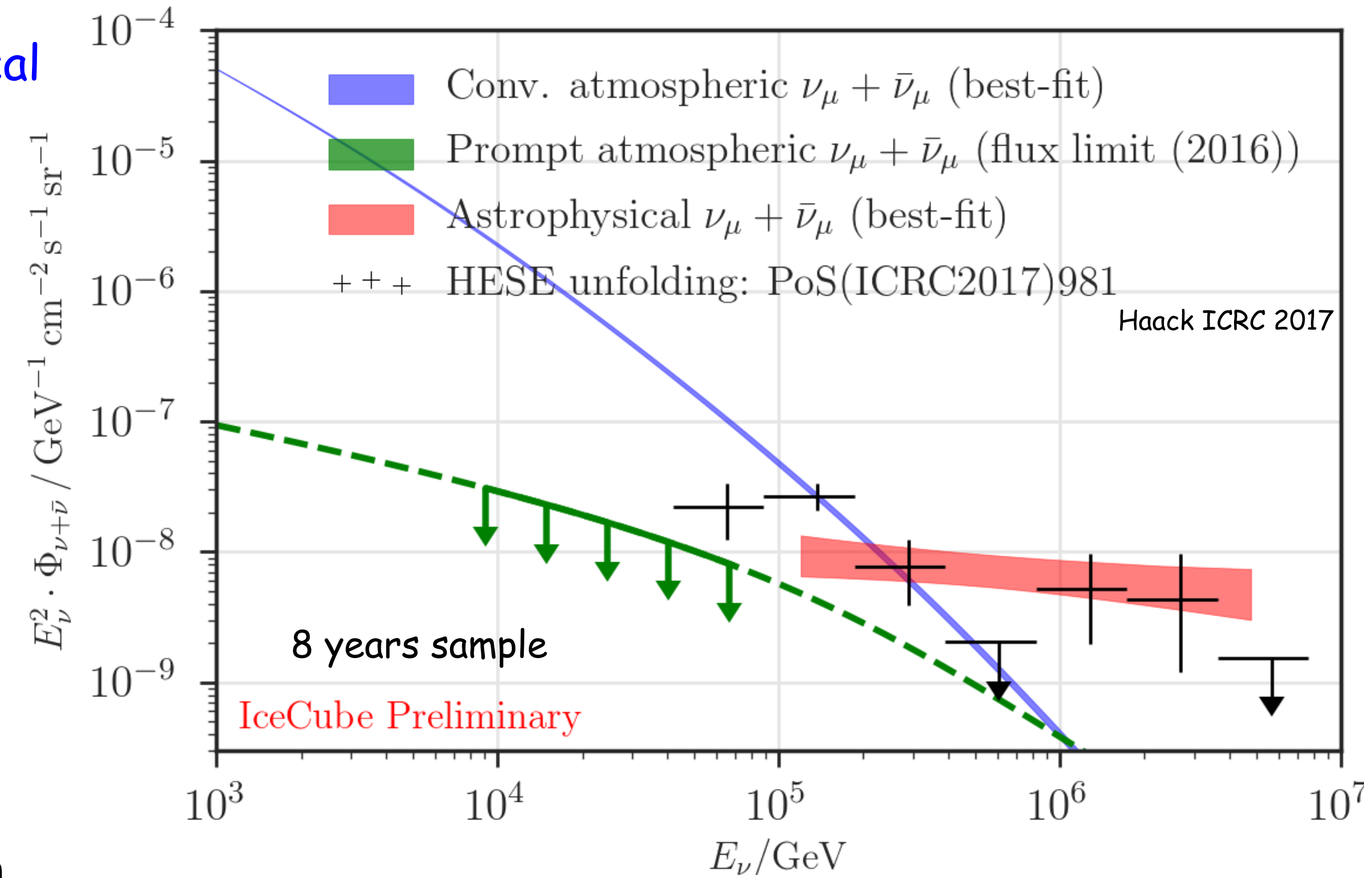
Neutrinos produced in high-energy astrophysical sources

Produced either by a $p-p$ or $p-\gamma$ interaction

No sources detected as of now

Flavor ratio consistent with 1: 1: 1

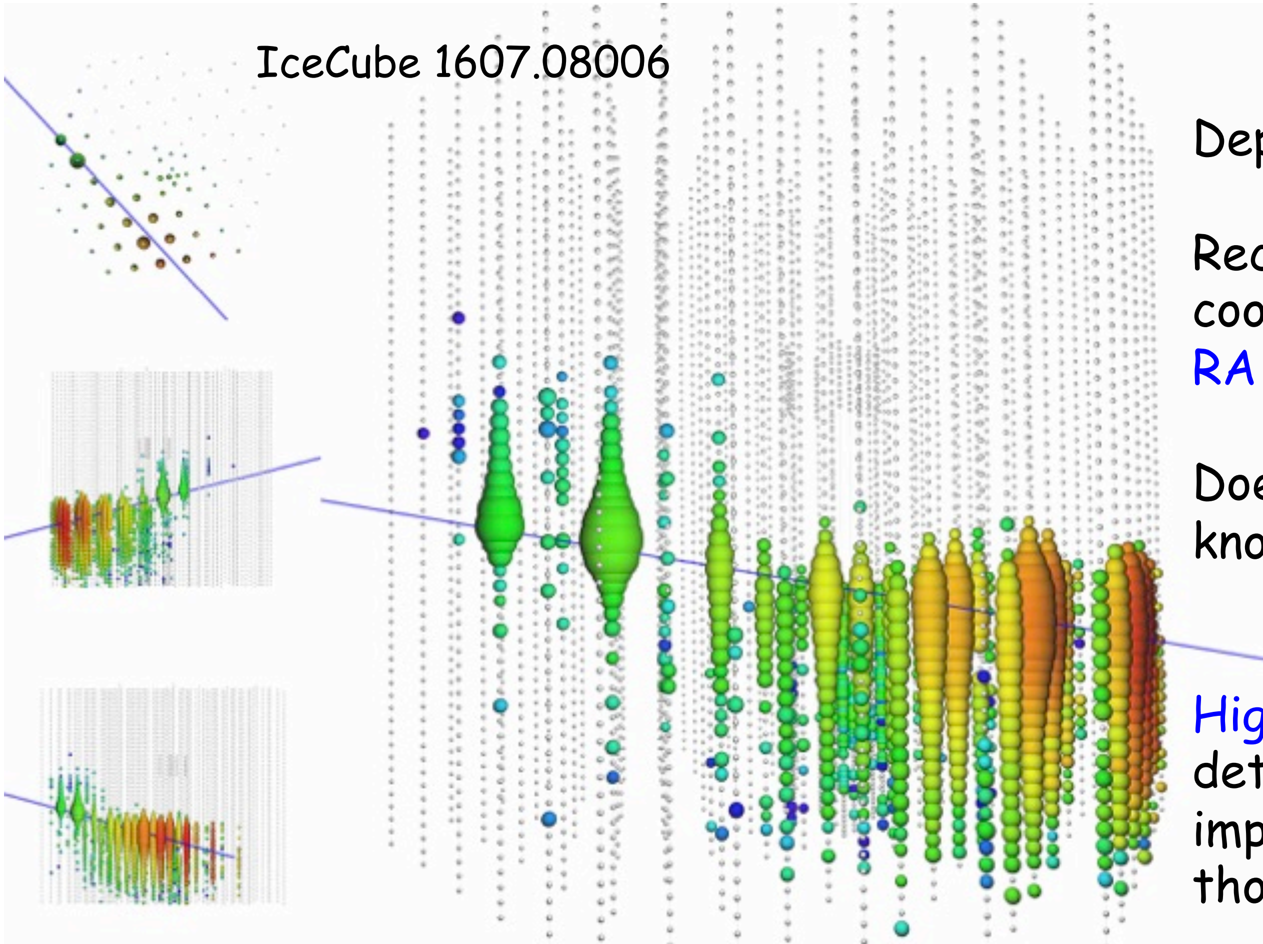
The neutrinos have an isotropic distribution on the sky



Spectral shape between ~E^{-2} and ~$E^{-2.9}$

Intensity of the neutrino flux (one flavor of $\nu + \bar{\nu}$) ~ 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} at 100 TeV

2.6 PeV track event



Deposited energy 2.6 ± 0.3 PeV

Reconstructed equatorial coordinates: decl. 11.42°
RA 110.63°

Does not point towards any known astrophysical source

Highest energy track event detected till date --- very important to analyze it thoroughly

Immediate questions:

1. What flavor of neutrino produces such a track?

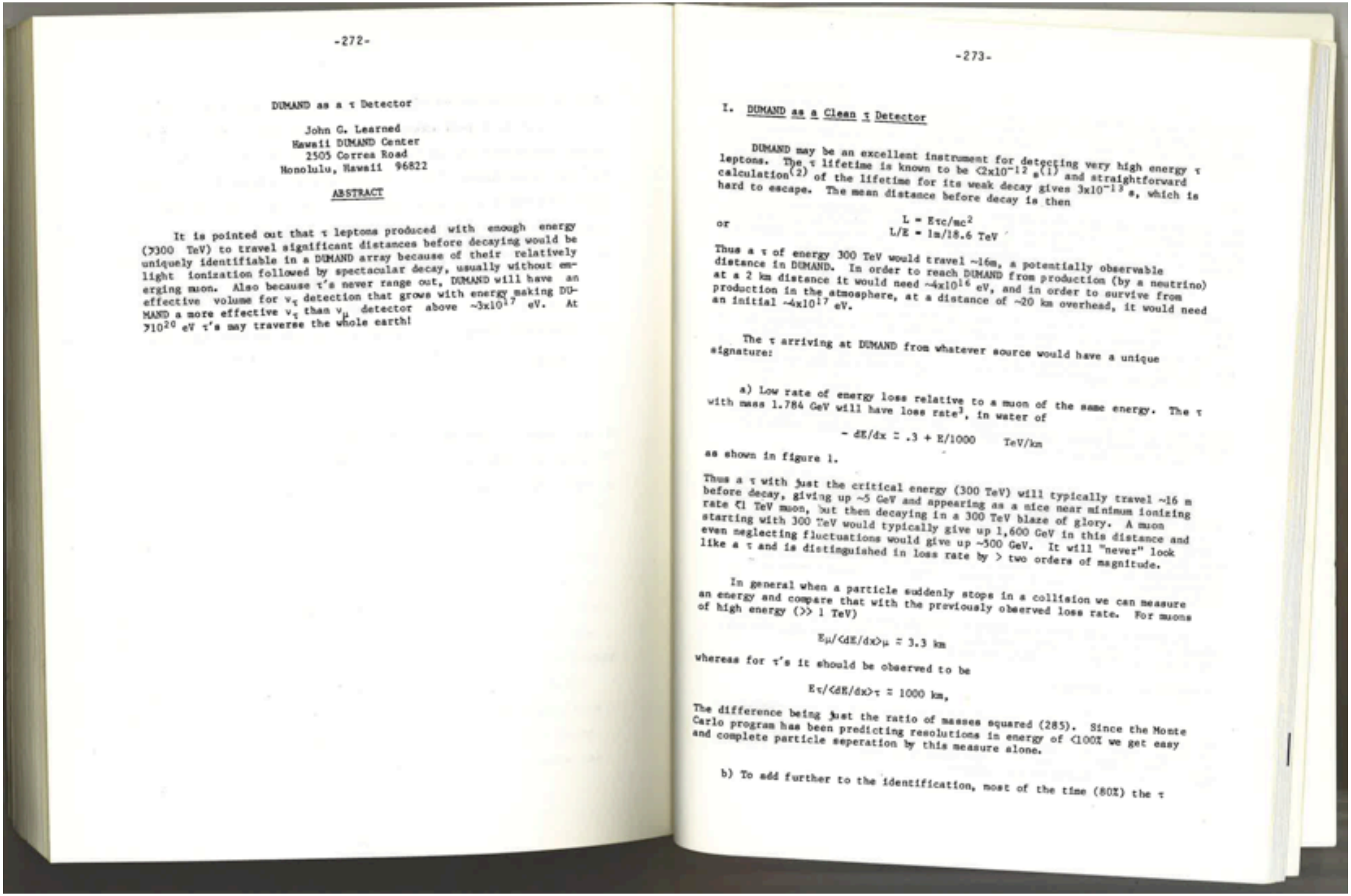
2. What are implications for astrophysical neutrinos in light of prior discoveries?

What neutrino flavor produces a track?

- Muons are assumed to give rise to all through-going track like events
- To deposit 2.6 PeV of energy, the muon typically requires $\gtrsim$ 5 PeV energy at detector entry point --- it is probable that this is a super-Glashow (energy ≥ 6.3 PeV) neutrino
- An overlooked possibility in the literature: very high energy through going taus can also give rise to track-like events
- To deposit 2.6 PeV of energy, the tau requires $\gtrsim$ 50 PeV energy at detector entry point
- Can IceCube individually distinguish a through going tau from a through gong muon?
- We discuss astrophysical scenarios for each of these possibilities

See Kistler and Laha arXiv: 1605.08781 (PRL) for more details

Already mentioned by J. G. Learned in 1980!



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DUMAND as a τ Detector

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Honolulu, Hawaii 96822

ABSTRACT

It is pointed out that τ leptons produced with enough energy (>300 TeV) to travel significant distances before decaying would be uniquely identifiable in a DUMAND array because of their relatively light ionization followed by spectacular decay, usually without emerging muon. Also because τ's never range out, DUMAND will have an effective volume for ν_τ detection that grows with energy making DUMAND a more effective ν_τ than ν_μ detector above $\sim 3 \times 10^{17}$ eV. At $>10^{20}$ eV τ's may traverse the whole earth!

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I. DUMAND as a Clean τ Detector

DUMAND may be an excellent instrument for detecting very high energy τ leptons. The τ lifetime is known to be $< 2 \times 10^{-12}$ s(1) and straightforward calculation(2) of the lifetime for its weak decay gives 3×10^{-13} s, which is hard to escape. The mean distance before decay is then

$$L = E\tau c/mc^2$$

or

$$L/E = 1\text{m}/18.6 \text{ TeV}$$

Thus a τ of energy 300 TeV would travel ~16m, a potentially observable distance in DUMAND. In order to reach DUMAND from production (by a neutrino) at a 2 km distance it would need $\sim 4 \times 10^{16}$ eV, and in order to survive from production in the atmosphere, at a distance of ~20 km overhead, it would need an initial $\sim 4 \times 10^{17}$ eV.

The τ arriving at DUMAND from whatever source would have a unique signature:

a) Low rate of energy loss relative to a muon of the same energy. The τ with mass 1.784 GeV will have loss rate[3], in water of

$$-dE/dx \simeq .3 + E/1000 \quad \text{TeV/km}$$

as shown in figure 1.

Thus a τ with just the critical energy (300 TeV) will typically travel ~16 m before decay, giving up ~5 GeV and appearing as a nice near minimum ionizing rate ≤1 TeV muon, but then decaying in a 300 TeV blaze of glory. A muon starting with 300 TeV would typically give up 1,600 GeV in this distance and even neglecting fluctuations would give up ~500 GeV. It will "never" look like a τ and is distinguished in loss rate by > two orders of magnitude.

In general when a particle suddenly stops in a collision we can measure an energy and compare that with the previously observed loss rate. For muons of high energy (>> 1 TeV)

$$E_\mu/\langle dE/dx\rangle_\mu \simeq 3.3 \text{ km}$$

whereas for τ's it should be observed to be

$$E_\tau/\langle dE/dx\rangle_\tau \simeq 1000 \text{ km},$$

The difference being just the ratio of masses squared (285). Since the Monte Carlo program has been predicting resolutions in energy of <100% we get easy and complete particle seperation by this measure alone.

b) To add further to the identification, most of the time (80%) the τ

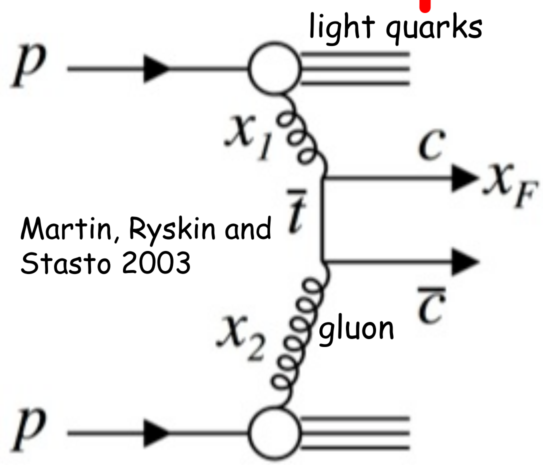
Proceedings of the 1980 International DUMAND Symposium, 2, 272 (1980)

Tracks also arise from through going taus

Intrinsic charm contribution to atmospheric prompt neutrinos

arXiv 1607.08240 (Phys. Rev. D96 2017 no.12, 123002) with Stanley J Brodsky

Prompt atmospheric neutrinos



Martin, Ryskin and Stasto 2003

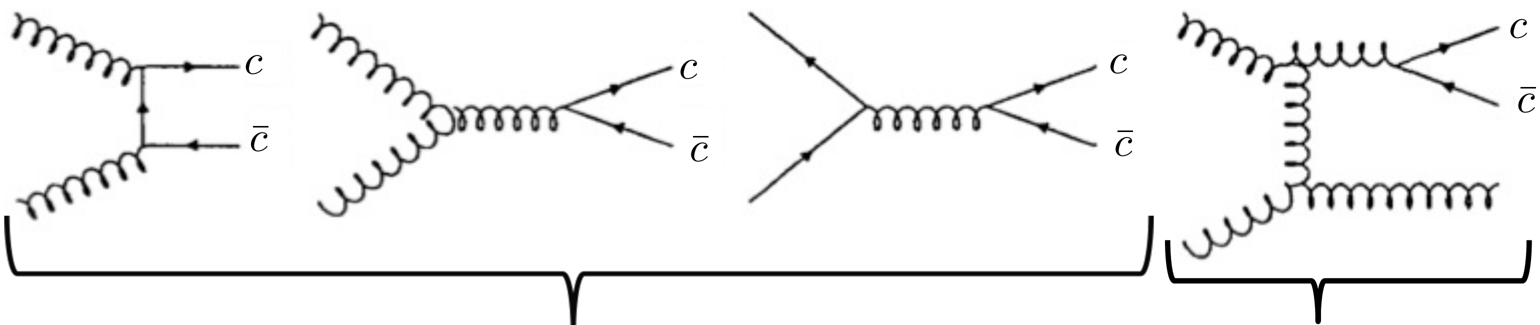
$$p + p \rightarrow c + \bar{c} + X$$

Most calculations are performed in perturbative QCD

Significant uncertainties due to
(i) Charm mass,
(ii) Factorization and renormalization scale, and
(iii) choice of the parton distribution function

Bhattacharya etal., Garzelli etal., Gauld etal., Fedynitch etal., Gaisser, Benzke etal., Jeong etal., PROSA

Additional uncertainty due to the cosmic ray input spectrum



Thunman, Ingelman and Gondolo 1996

leading order

an important next-to-leading order

Sensitive to QCD mechanisms in regions beyond the reach of LHC

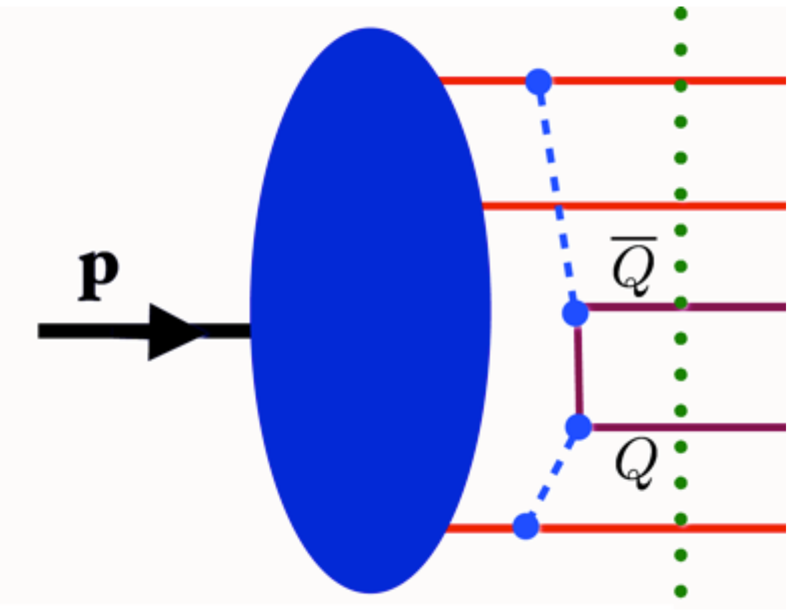
At high s, the interaction is very sensitive to the gluon distribution ($x \sim 10^{-8} - 10^{-4}$)

Intrinsic charm

Brodsky, Hoyer, Peterson, and Sakai 1980

- A rigorous prediction of QCD
- Non-perturbative component
- Flattish $d\sigma/dx_F$ observed at SELEX, ISR
- Dominates at high x_F

$$|p\rangle = A\,|uud\rangle + B\,|uudc\bar{c}\rangle + \ldots$$



Brodsky etal., 1504.06287

Quantum fluctuation of the proton

Probability for the proton to contain an intrinsic charm and anti-charm quark is related to $|B|^2$

During an interaction, the u, d and c quark can combine to form a Λ_c

There are a number of fixed-target experiments like SMOG at LHCb and AFTER@LHC which aim to confirm or constrain the intrinsic charm of the proton

The normalization constant B has to be deduced from experiments

Intrinsic charm contribution

- The measurement of prompt atmospheric neutrinos is a forward measurement $\Rightarrow$ intrinsic charm can play an important role

$$x_F \approx E_c/E$$

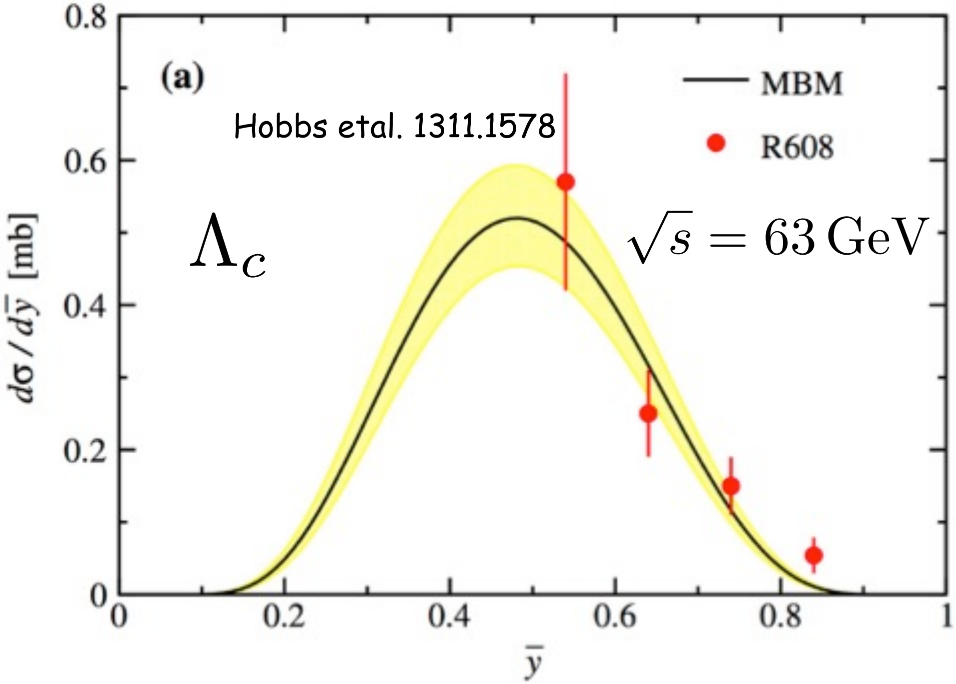
E_c = outgoing charm quark energy

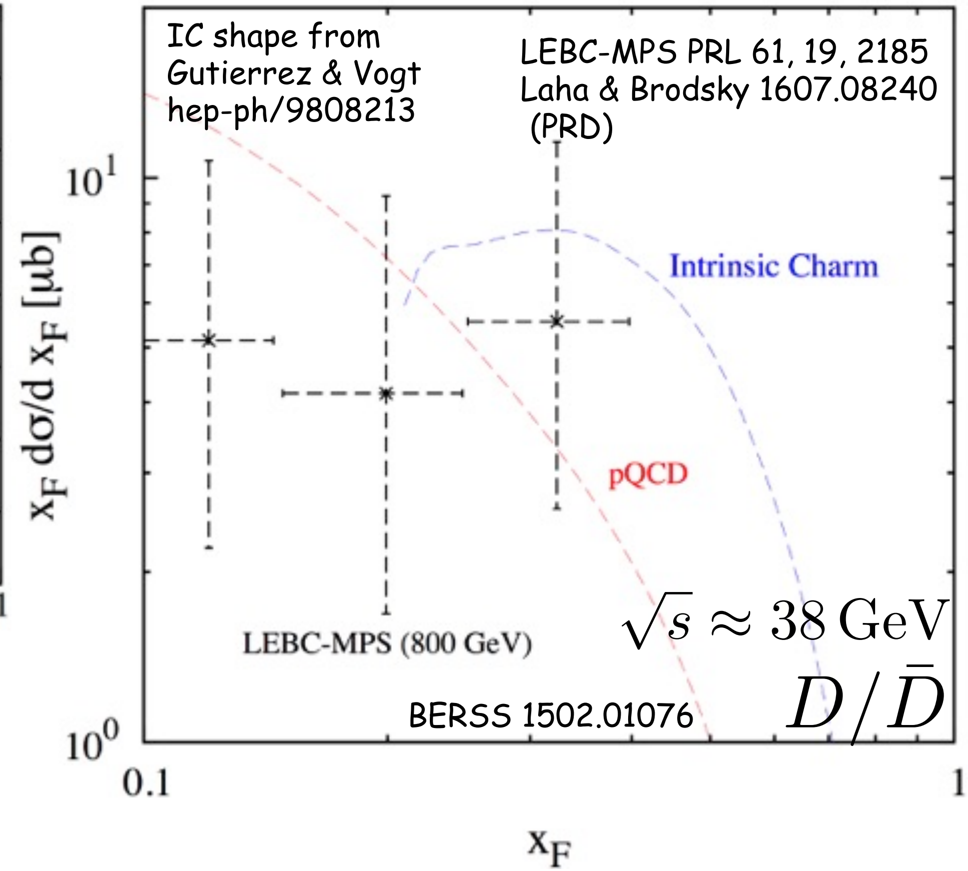
E = incident proton energy

- Intrinsic charm uses the incident proton energy more efficiently. It can play an important role since the cosmic rays have a steeply falling spectrum

- Nuclear dependence ($\sim A^{0.7}$) is important since the atmospheric target is mostly nitrogen

Intrinsic charm cross section normalisation



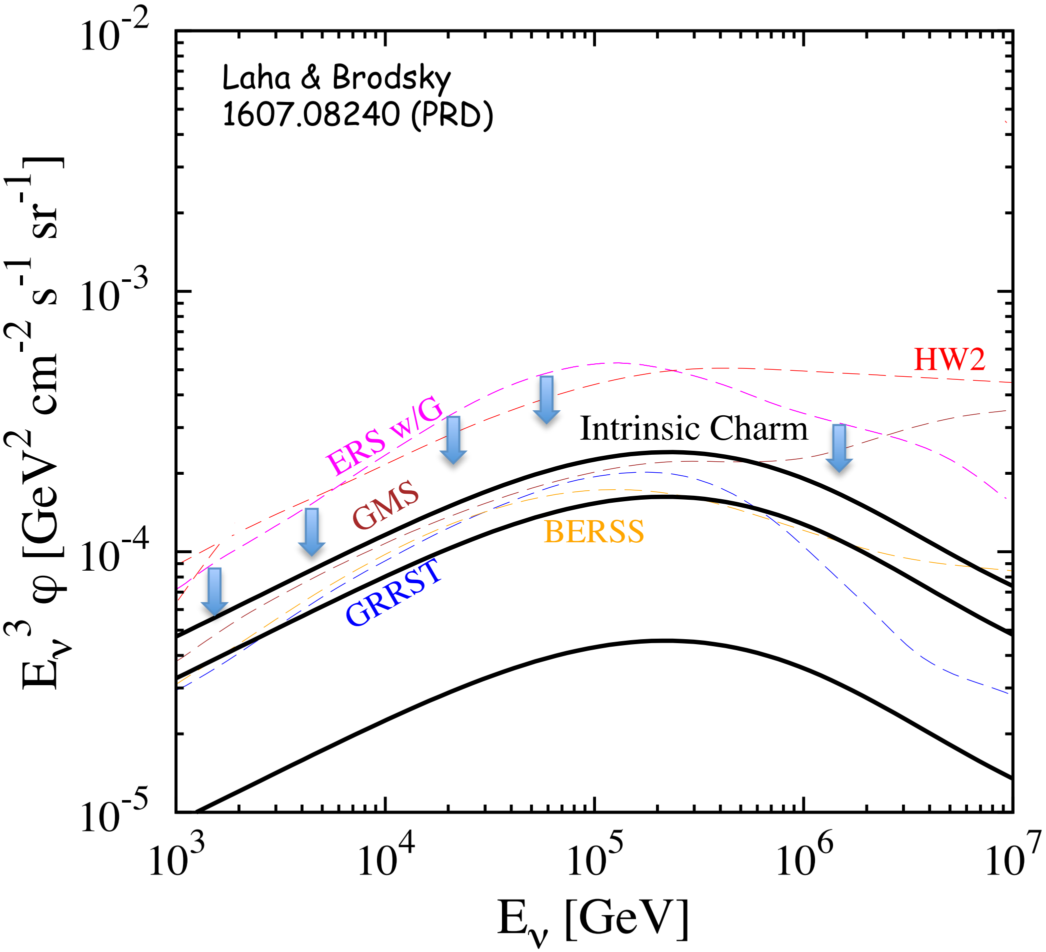


- Substantial uncertainty of pQCD $\Rightarrow$ challenging to find intrinsic charm

- We assume the best-fit pQCD cross section and then use LEBC-MPS data to normalize the D cross sections

- ISR cross section by itself produces too large atmospheric prompt neutrino flux

Prompt atmospheric flux due to intrinsic charm



Depending on the normalization, the contribution due to intrinsic charm can be as large as that due to perturbative QCD.

The important charm hadrons that contribute towards this flux are

$$D^0, \bar{D}^0, D^\pm, D_s^\pm, \Lambda_c$$

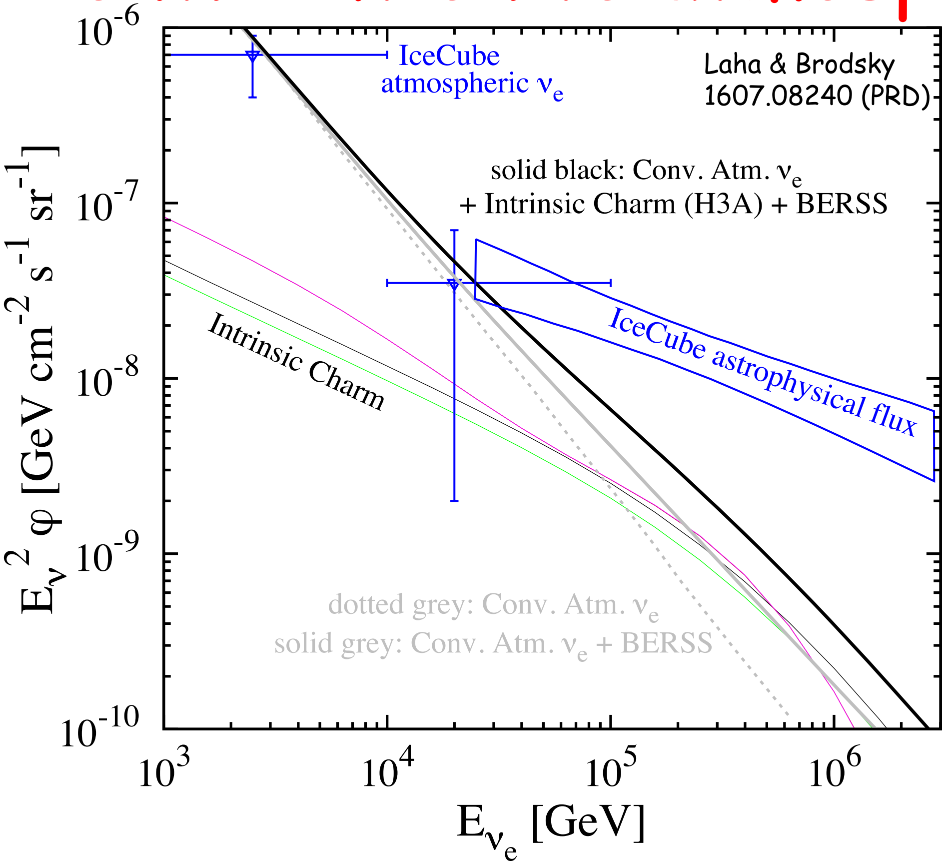
The neutrino flavor ratio is

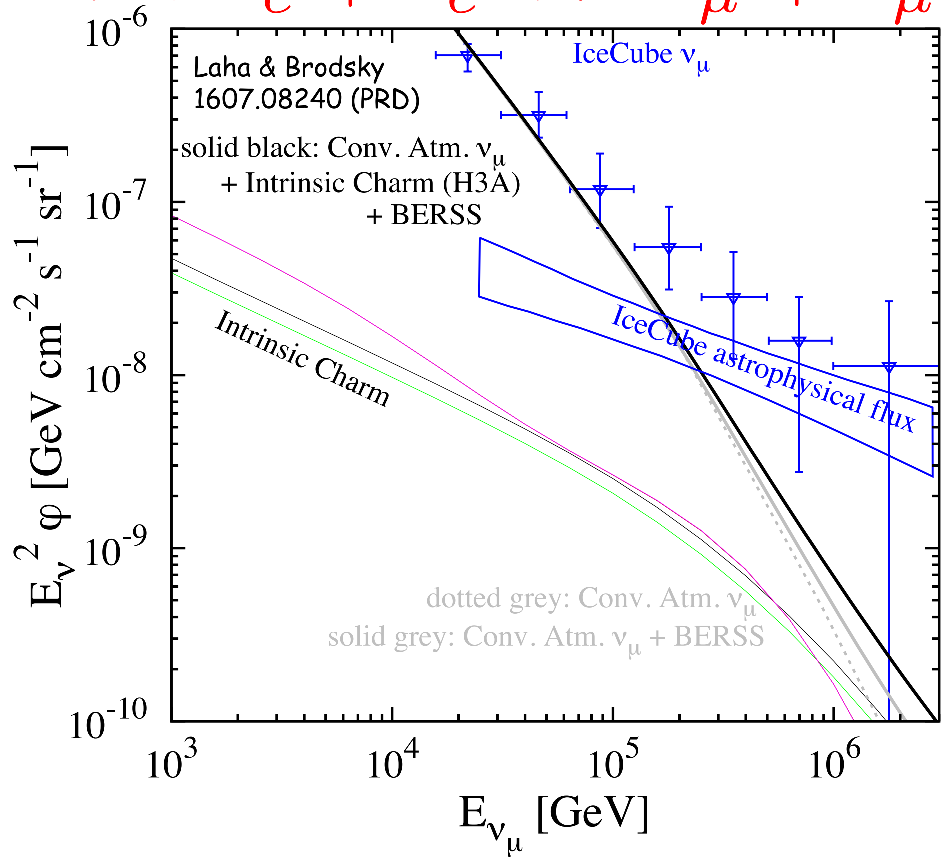
$$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 0.1$$

This is an additional contribution to the prompt atmospheric flux

IceCube upper limits (near ERS w/G flux) are very close to the contribution due to intrinsic charm

Contribution to atmospheric $\nu_e + \bar{\nu}_e$ and $\nu_\mu + \bar{\nu}_\mu$





Conventional atmospheric $\nu_e + \bar{\nu}_e$ flux is lower 🙂 but the statistics are poor 🙁

Conventional atmospheric $\nu_\mu + \bar{\nu}_\mu$ flux is higher 🙁 but the statistics are larger 🙂

Similar calculations by Halzen and Wille. Our results have been confirmed by Giannini etal 1803.01728

Intrinsic charm contribution has been modeled in Sibyll

Conclusions

- Common knowledge: Muons give rise to all through going track events in IceCube ---- incomplete!

- We show for the first time that a through going tau can also give rise to tracks --- a new signal in IceCube ---- needs more research ---- can we distinguish a through going muon track and a through going tau track ?

- We also calculate the contribution of intrinsic charm to prompt atmospheric neutrinos --- a guaranteed contribution

- The intrinsic charm contribution can be as large as the perturbative QCD contribution --- more work needed

Questions: ranjalah@uni-mainz.de