High-energy neutrino interactions: first cross section measurements at TeV and above

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Two seemingly unrelated questions —

1. Where are the most energetic particles coming from?

2. What is the structure of matter at the smallest scales?


ν

Neutrino interactions are weak . . .

. . . but we are persistent

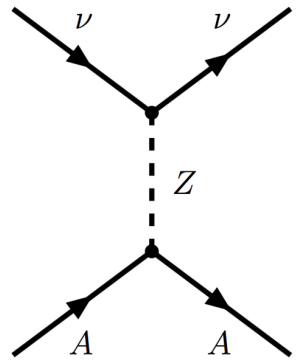
At center-of-mass energy of 1 GeV:

$$\begin{aligned} \sigma_{pp} &\sim 10^{-28}\ \text{cm}^2 \\ \sigma_{\gamma p} &\sim 10^{-29}\ \text{cm}^2 \\ \sigma_{\nu p} &\sim 10^{-38}\ \text{cm}^2 \end{aligned}$$

Neutrino interactions: what we (do not) know

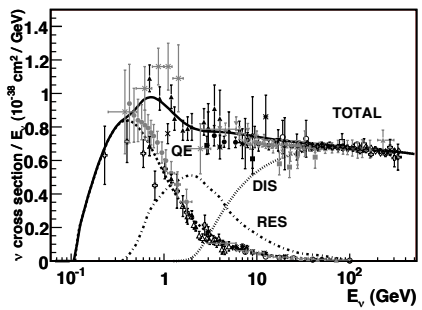
< 1 MeV

Not observed — Coherent neutrino-nucleus scattering (just measured!), capture on radionuclei



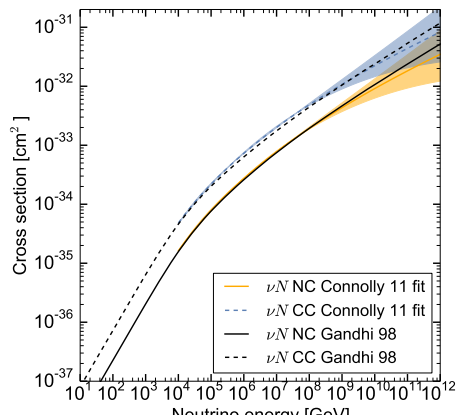
1 MeV – 350 GeV

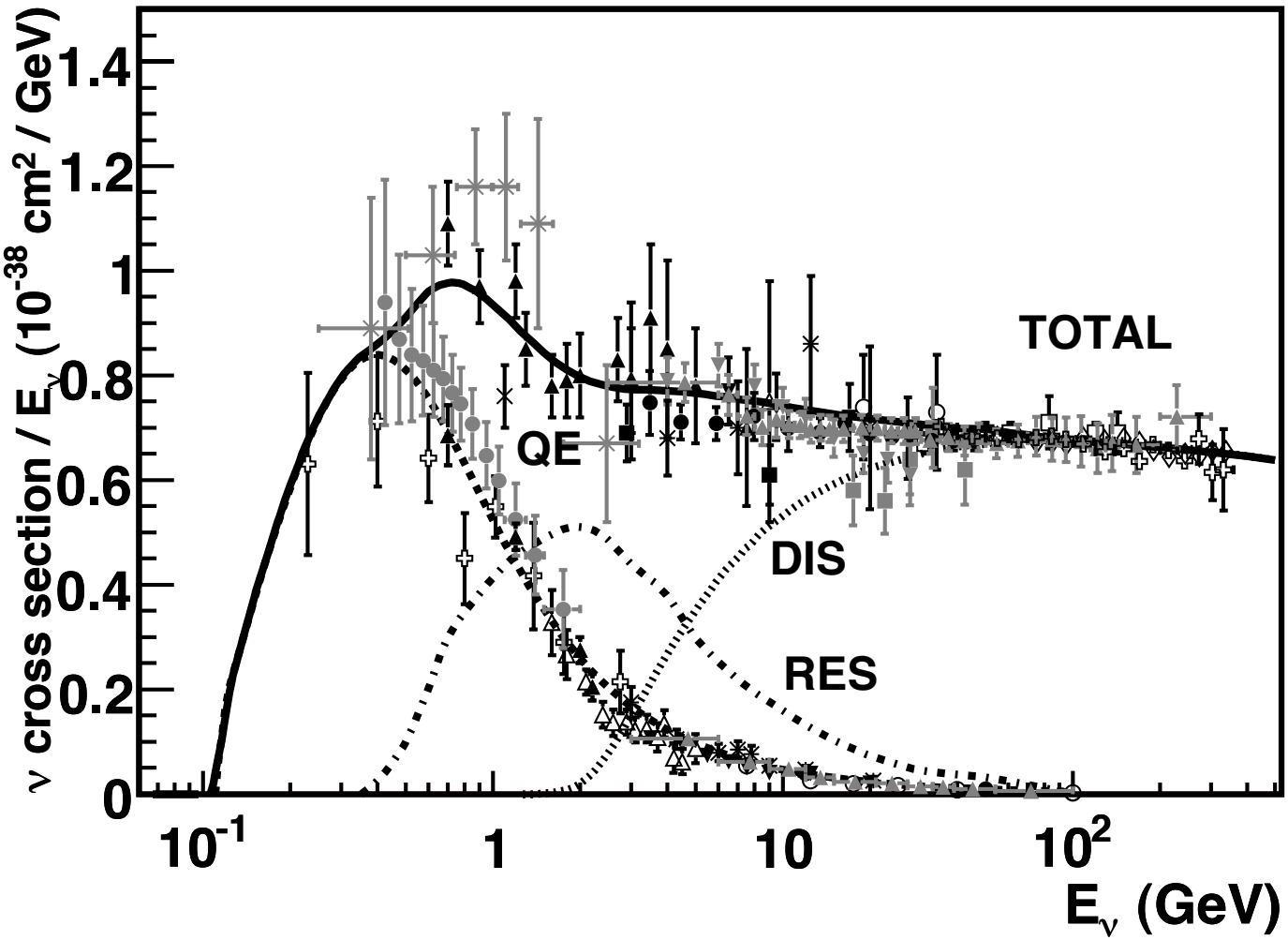
Lots of data — Quasi-elastic scattering, resonance production, deep inelastic scattering

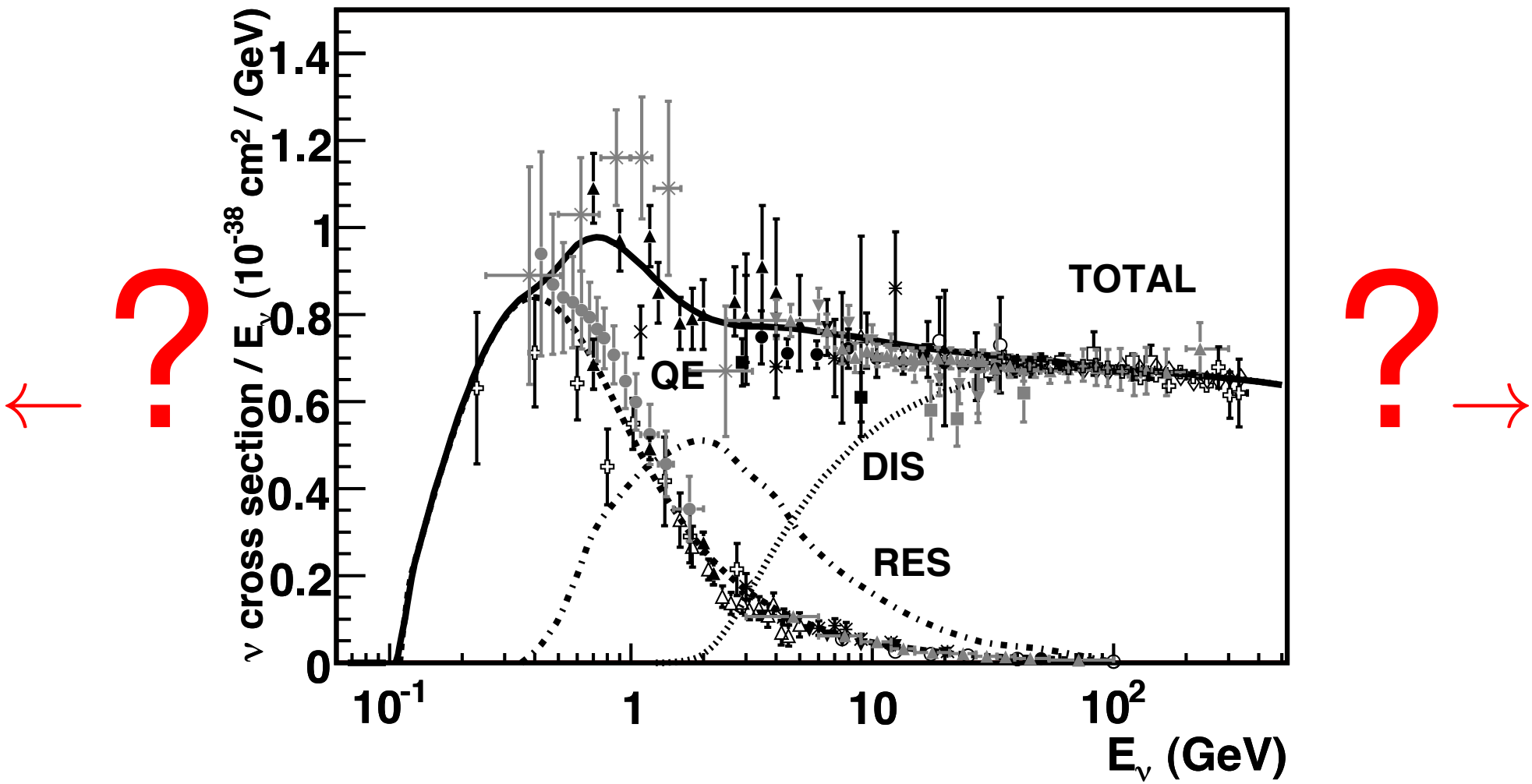


> 350 GeV

Not observed — No high-energy neutrino beam available... til now




ν cross section / E_ν (10^-38 cm^2 / GeV)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^-1
1
10
10^2
E_ν (GeV)
TOTAL
QE
DIS
RES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E_ν (GeV)
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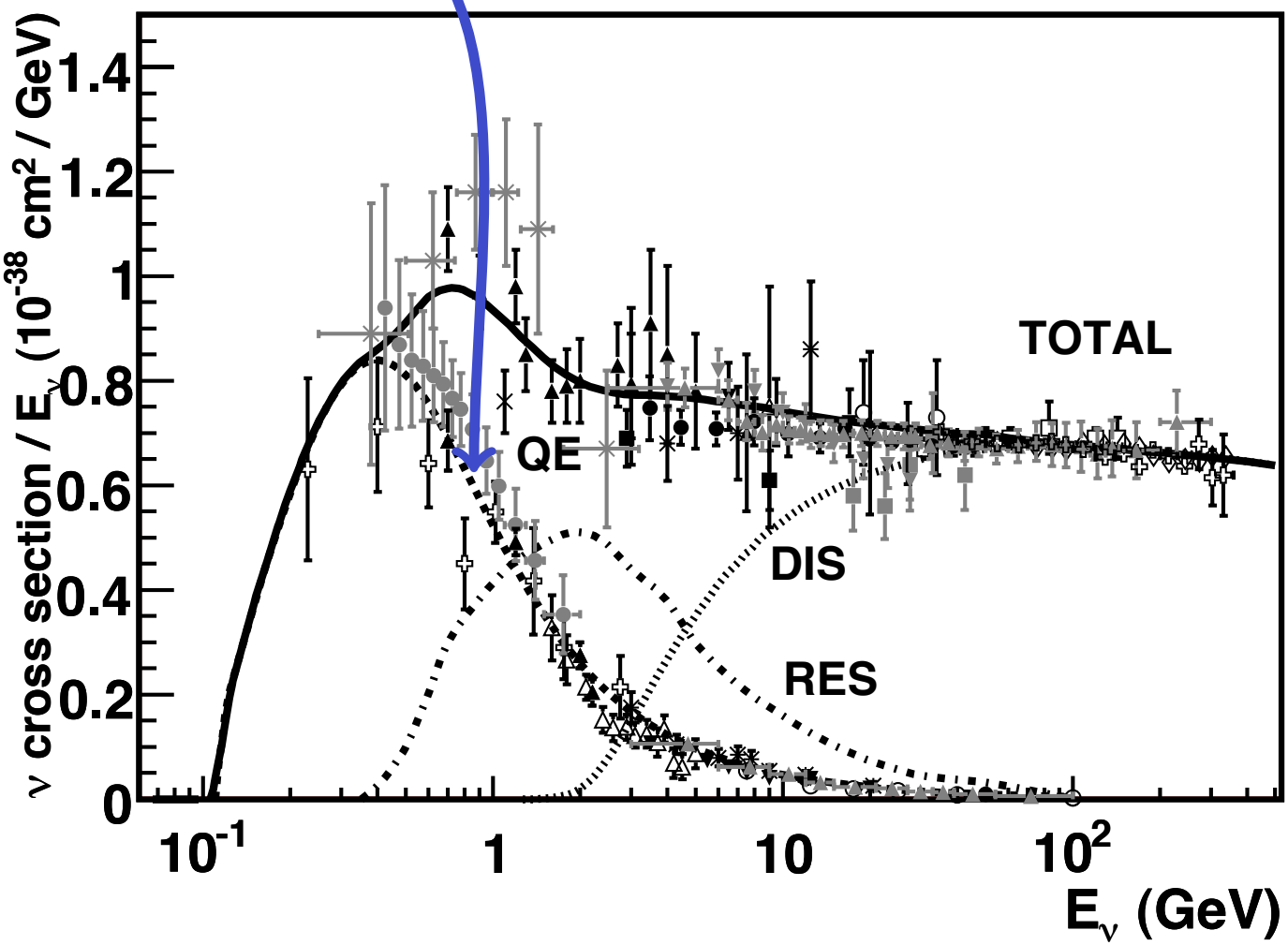
10
10^2

$$\nu_l + n \to l^- + p$$
$$\bar{\nu}_l + p \to l^+ + n$$



$\nu_l + n \to l^- + p$

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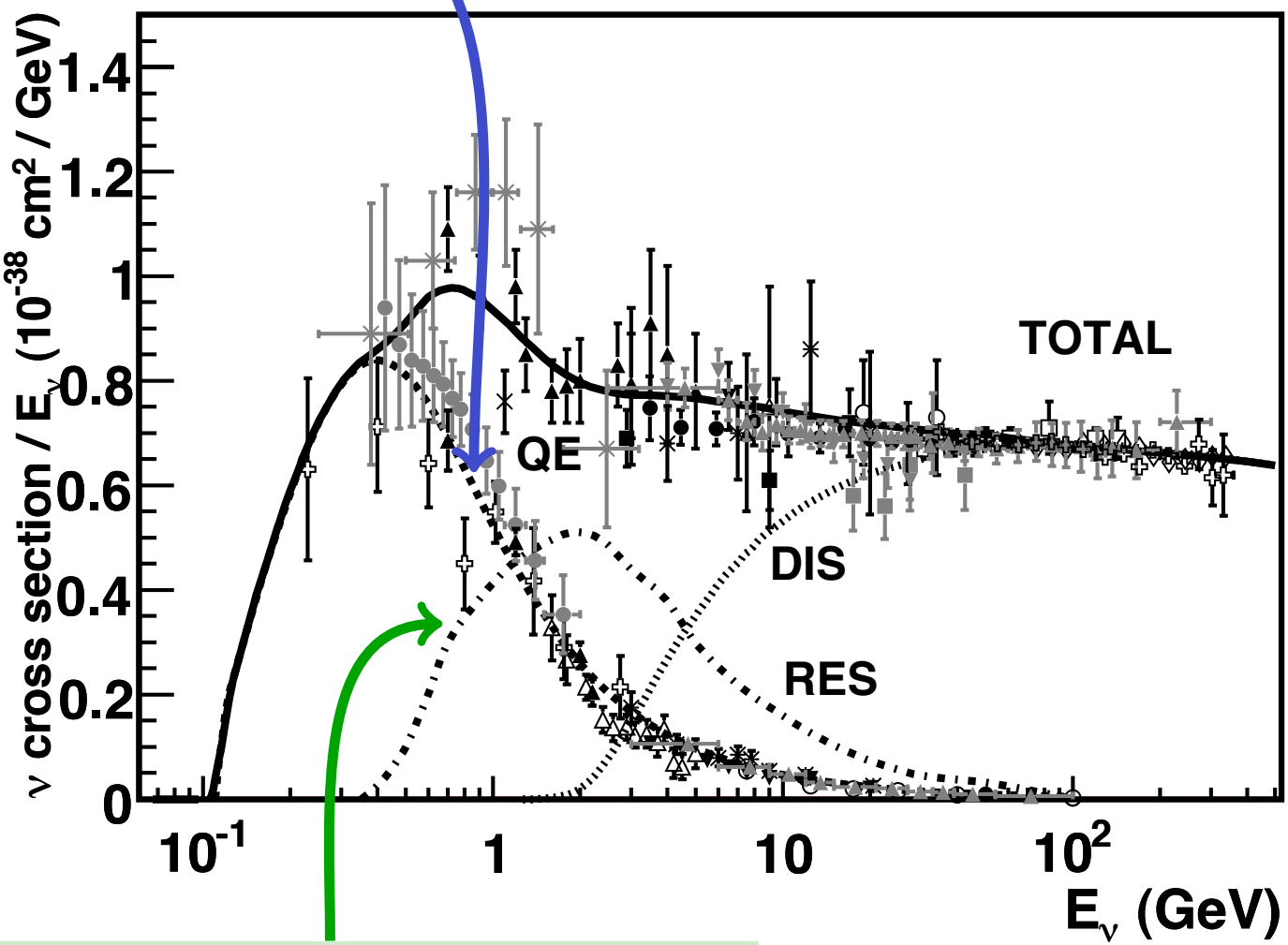
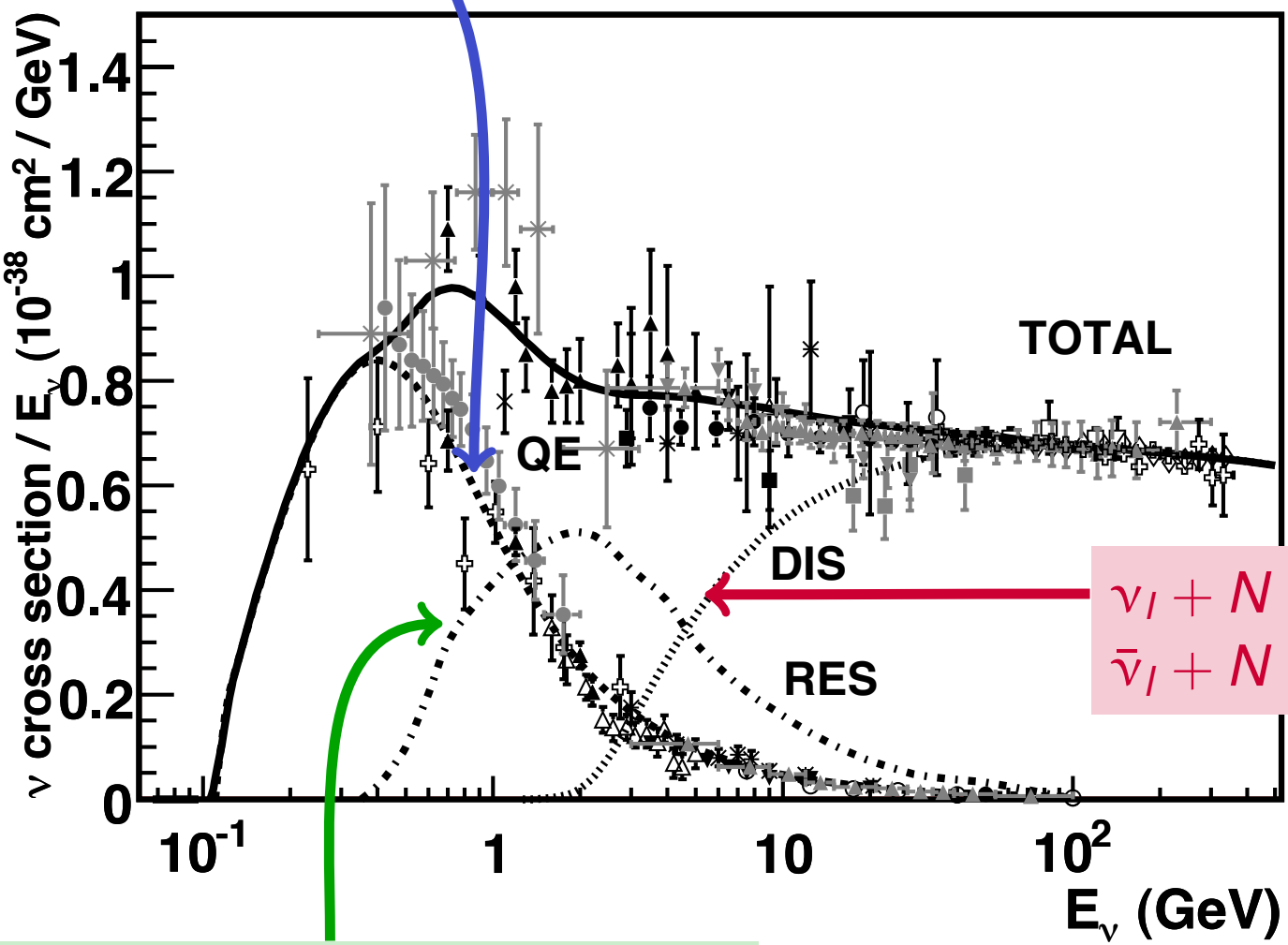


$\nu_l + N \to l^- + N^* \to l^- + \pi + N'$

$\nu_l + n \to l^- + p$
$\bar{\nu}_l + p \to l^+ + n$



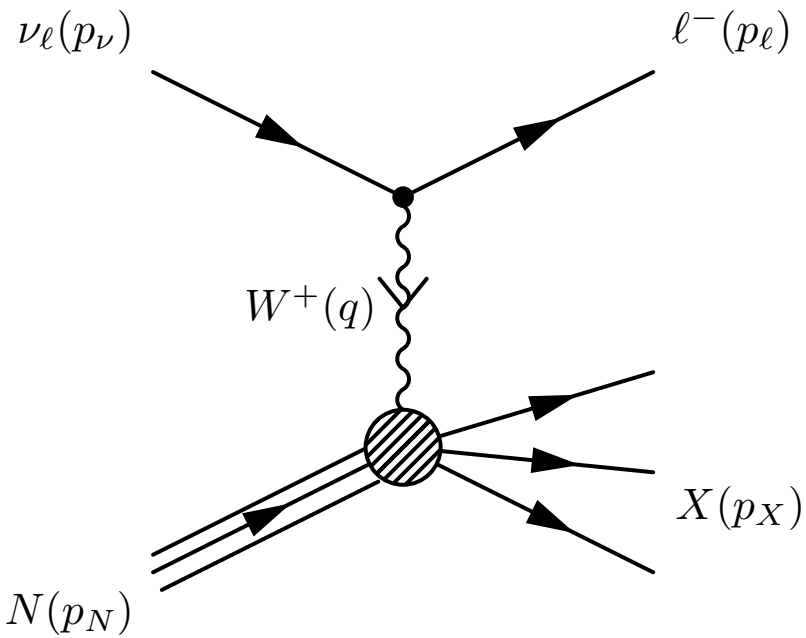
$\nu_l + N \to l^- + X$
$\bar{\nu}_l + N \to l^+ + X$

$\nu_l + N \to l^- + N^* \to l^- + \pi + N'$

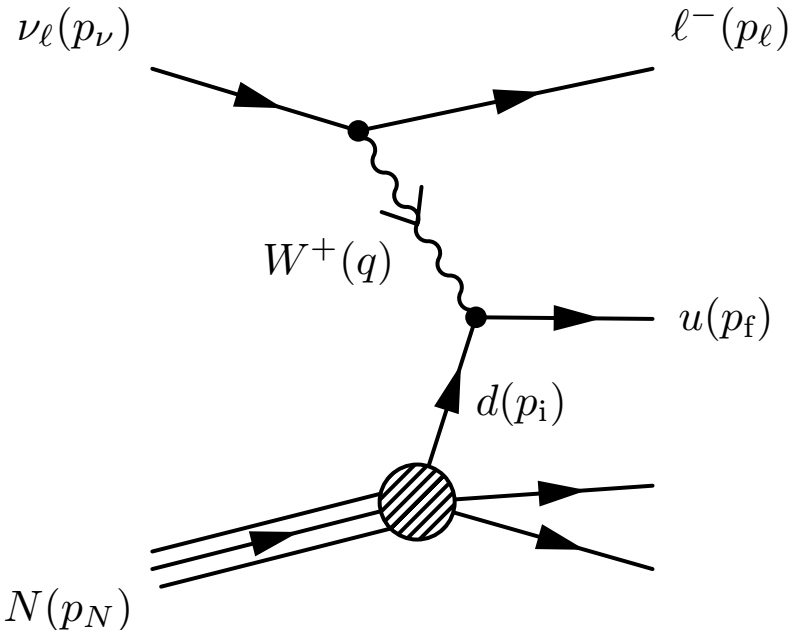
PARTICLE DATA GROUP

How does DIS probe nucleon structure?

What you see

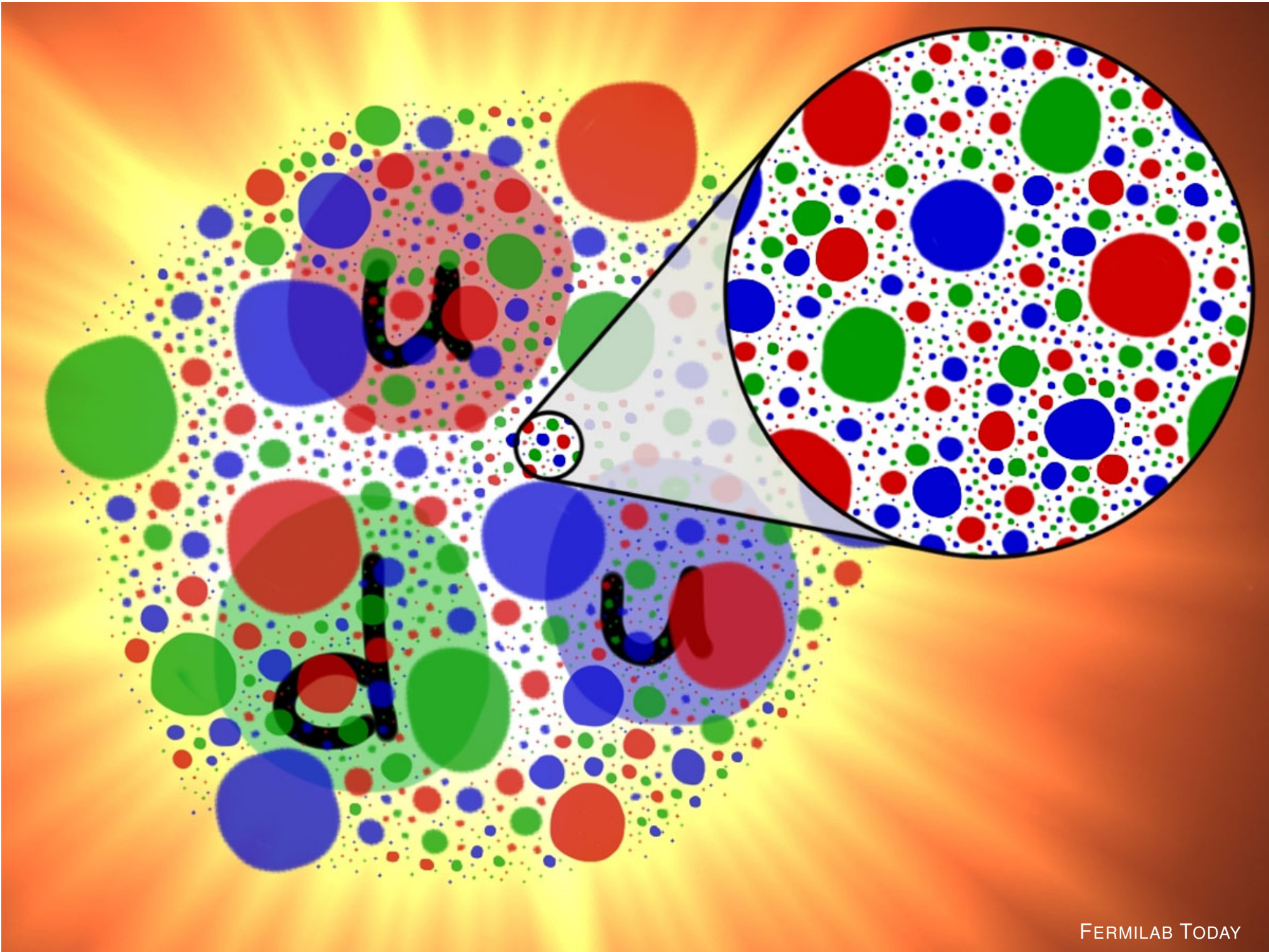


Beneath the hood



Plus the equivalent neutral-current process (Z-exchange)

GIUNTI & KIM, *Fundamentals of Neutrino Physics & Astrophysics*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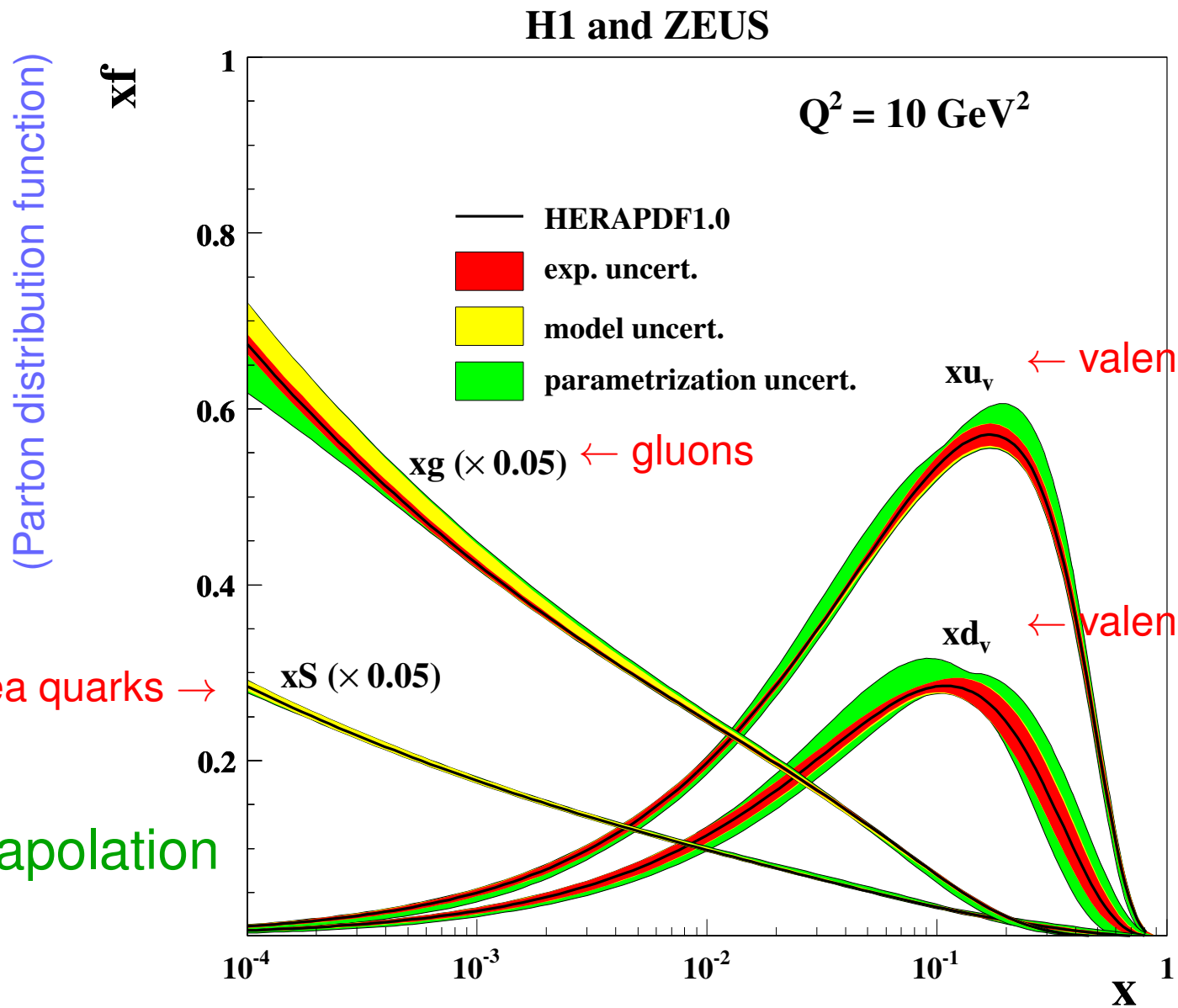
Peeking inside a proton



(Parton distribution function)

← valence up quark

← gluons

← valence down quark

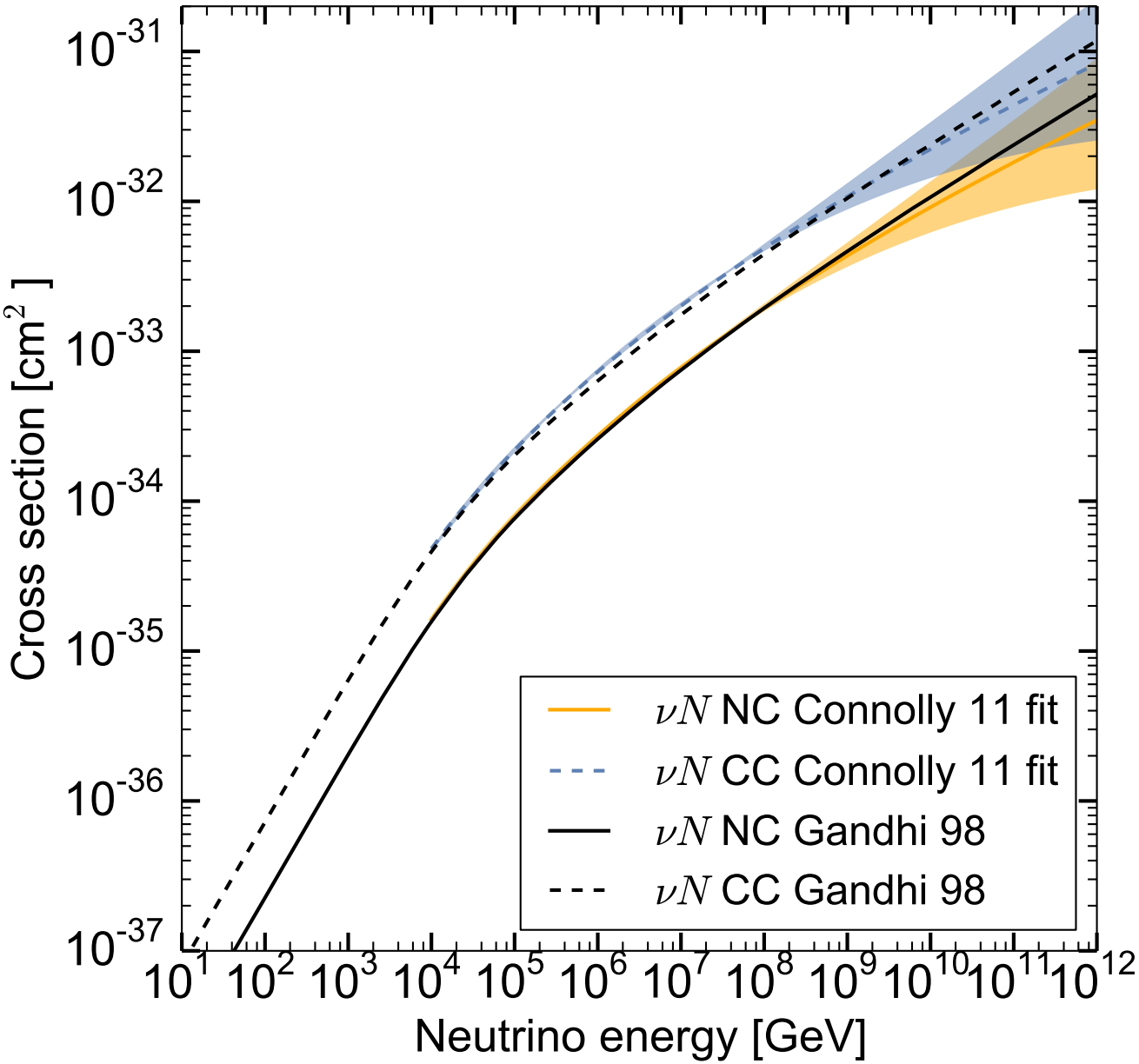
sea quarks →

← Extrapolation

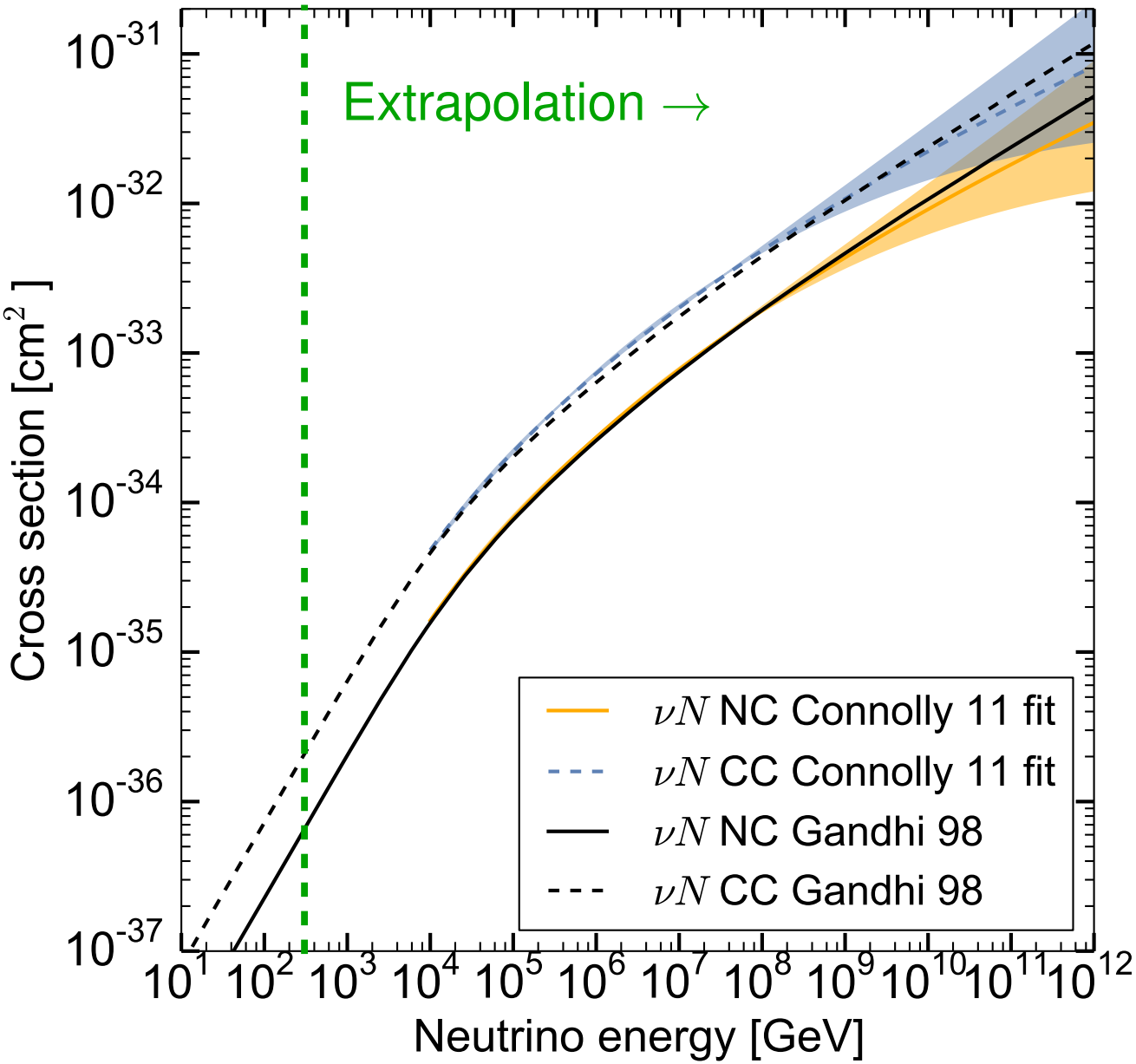
(Fraction of momentum carried by parton)

A. COOPER-SARKAR 2012

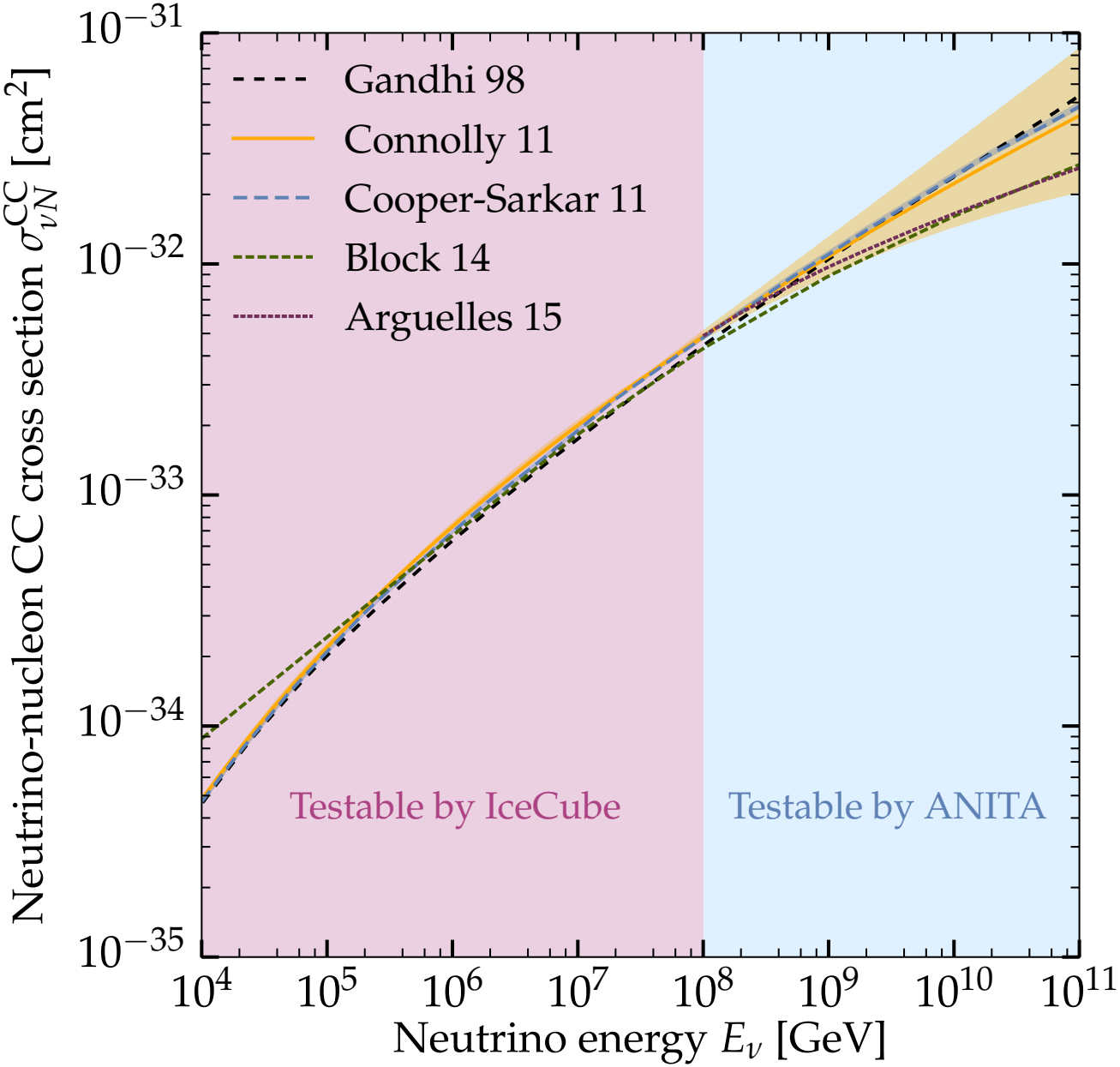
Extrapolating the neutrino cross section



Extrapolating the neutrino cross section



What can IceCube do?



How does IceCube see neutrinos?

Two types of fundamental interactions . . .

Charged-current

$\nu_l + N \rightarrow l + \text{hadrons}$

Neutral-current

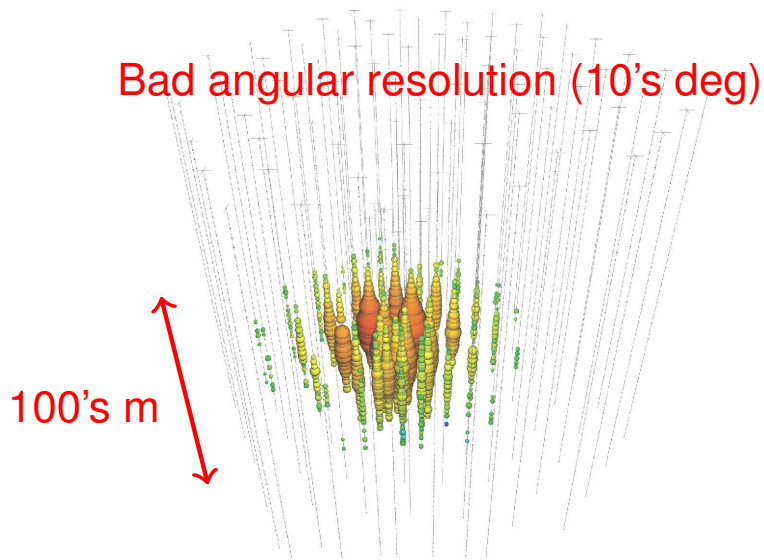
$\nu_l + N \rightarrow \nu_l + \text{hadrons}$

these shower and make light

. . . create two event topologies . . .

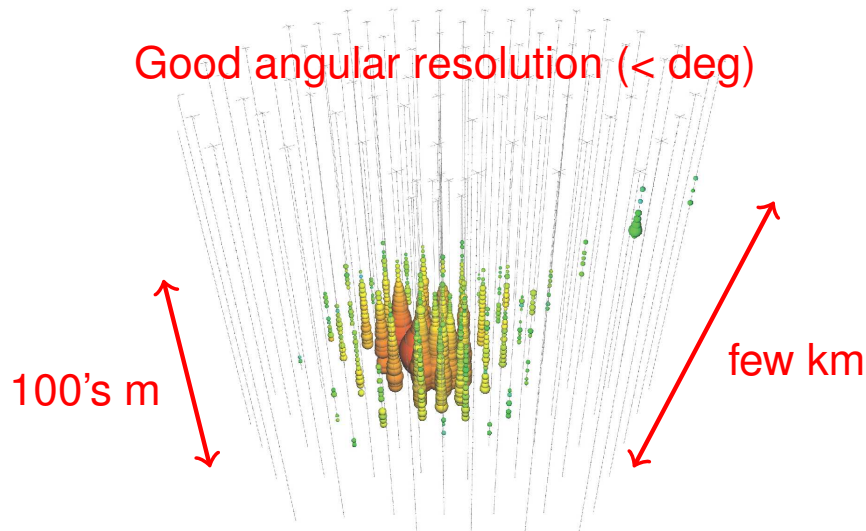
Showers

Made by CC ν_e or ν_τ; or by NC ν_x



Tracks

Made mainly by CC ν_μ



How do we measure the cross section?

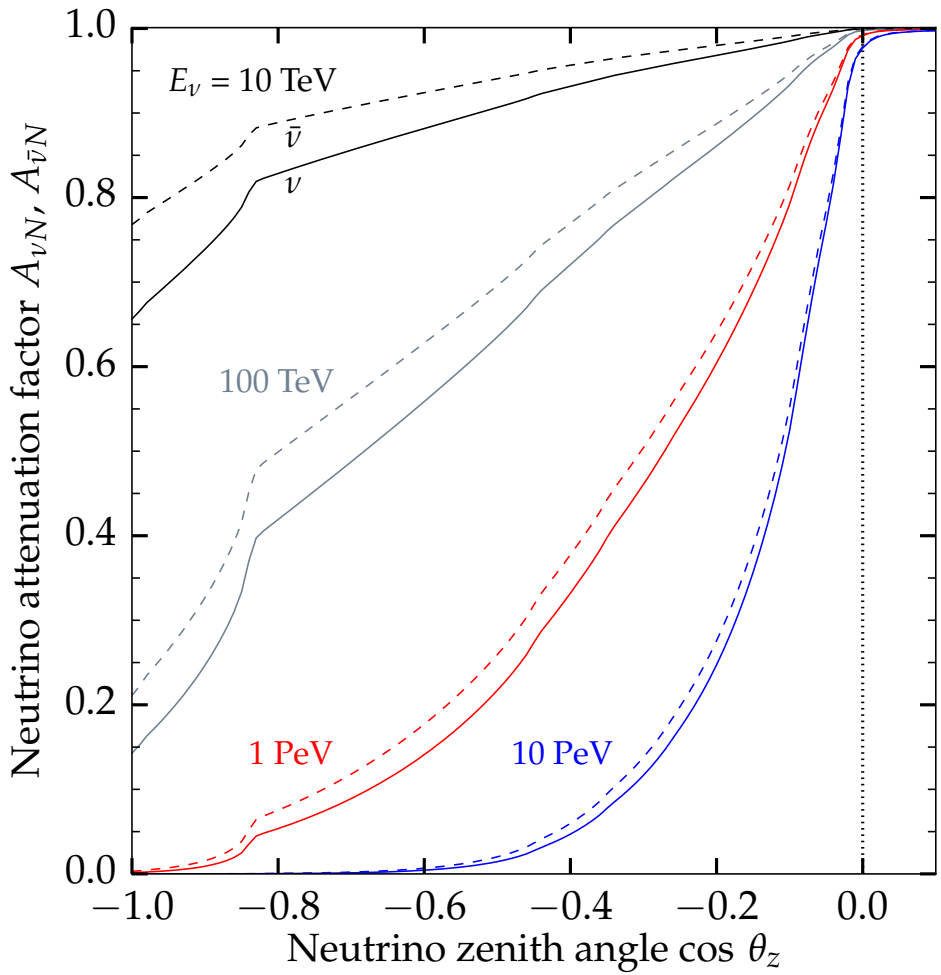
By looking at the angular distribution of events —

- Earth absorbs neutrinos
- Absorption factor:

$$e^{-D(\theta_z)/L_{\rm int}(E_\nu,\theta_z)}$$

- Interaction length:

$$L_{\rm int} = \frac{m_N}{\sigma_{\nu N}^{\rm CC+NC}(E_\nu)\cdot\langle\rho_\oplus(\theta_z)\rangle}$$



Where does the sensitivity to σ come from?

Number of contained events:

$$N \sim \Phi_\nu \cdot \sigma_{\nu N} \cdot e^{-\tau} = \Phi_\nu \cdot \sigma_{\nu N} \cdot e^{-L \sigma_{\nu N} n_N}$$

Downgoing (no matter)

$$N_{\text{dn}} \sim \Phi_\nu \cdot \sigma_{\nu N}$$

Downgoing events fix the product $\Phi_\nu \cdot \sigma_{\nu N}$

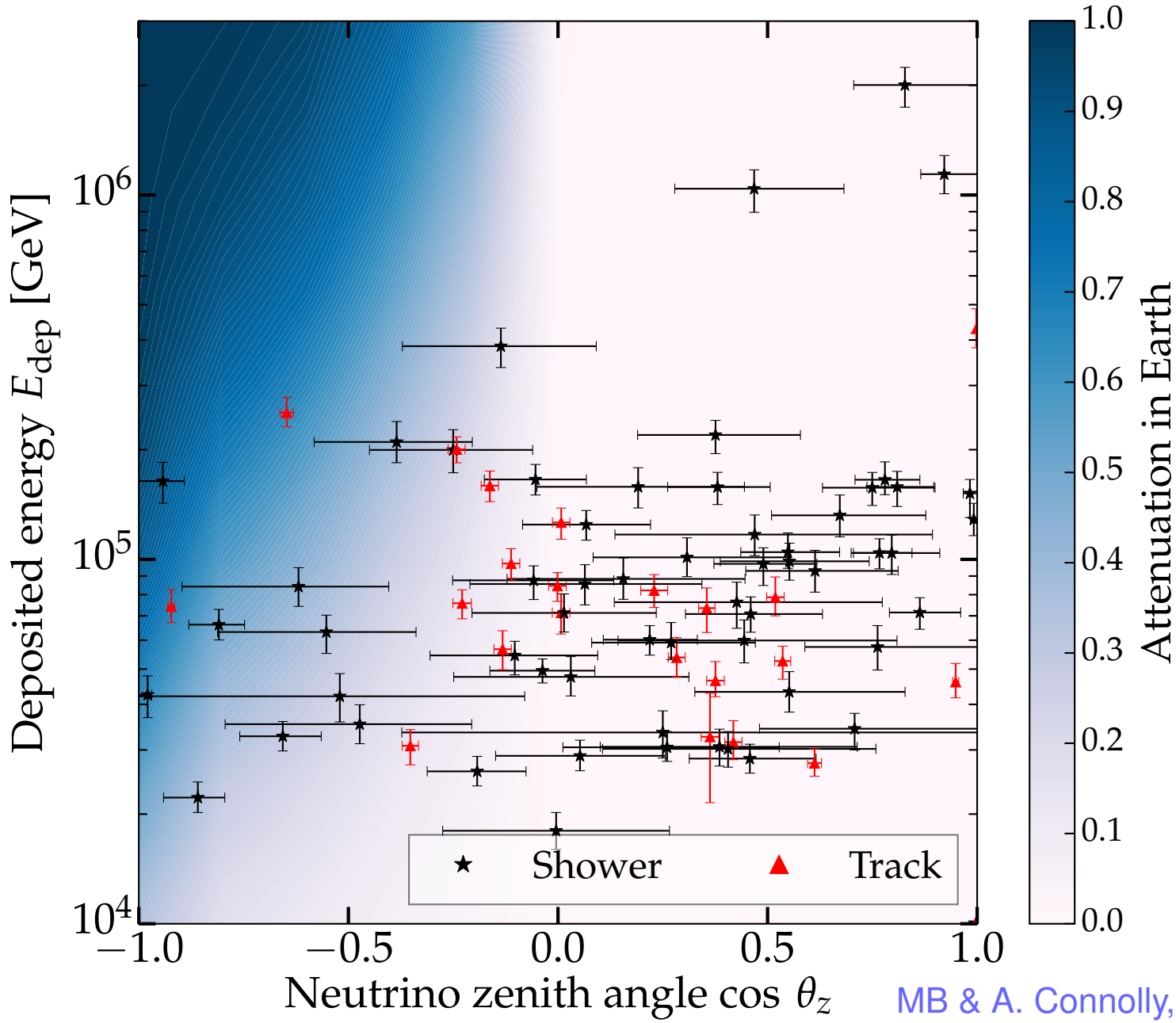
Upgoing (lots of matter)

$$N_{\text{up}} \sim N_{\text{dn}} \cdot e^{-\tau}$$

Upgoing events measure the cross section via τ

Reality check:
Few events (per energy bin), so we are limited by Poissonian statistics

The IceCube HESE sample (6 years)



MB & A. Connolly, *In prep.*

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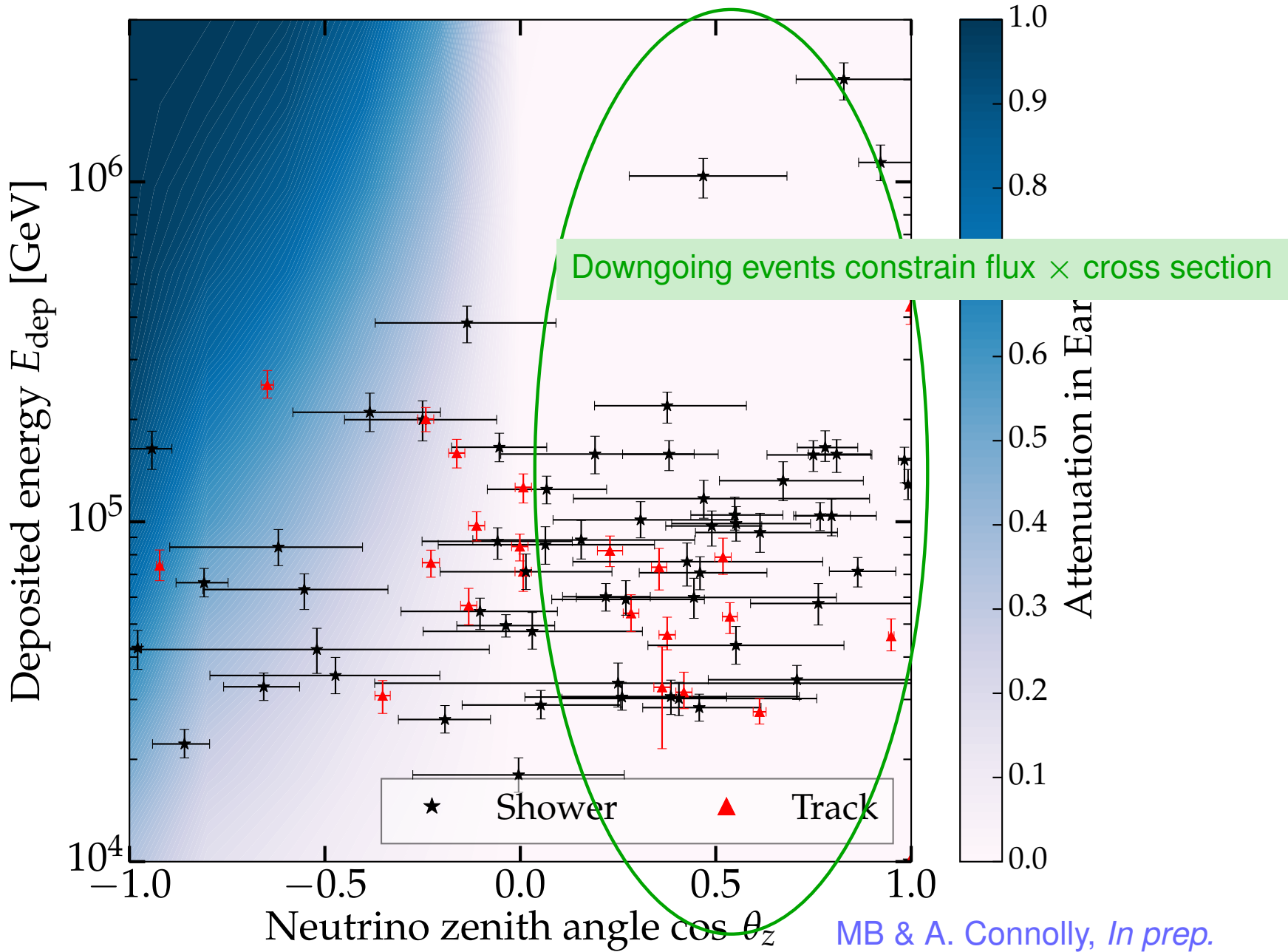

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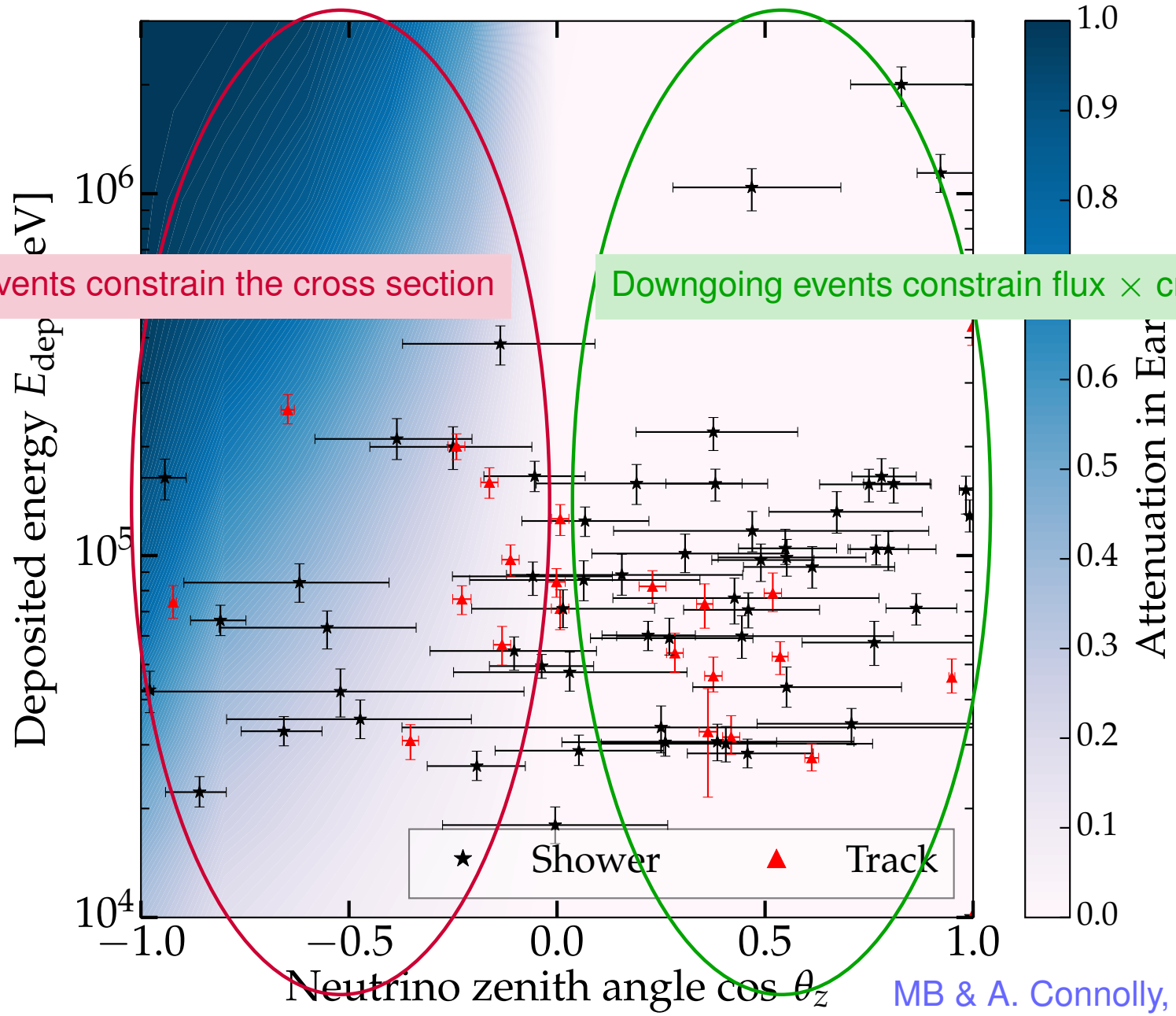

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Flux vs. cross section

In each energy bin:

Downgoing events ($\tau \approx 0$) —

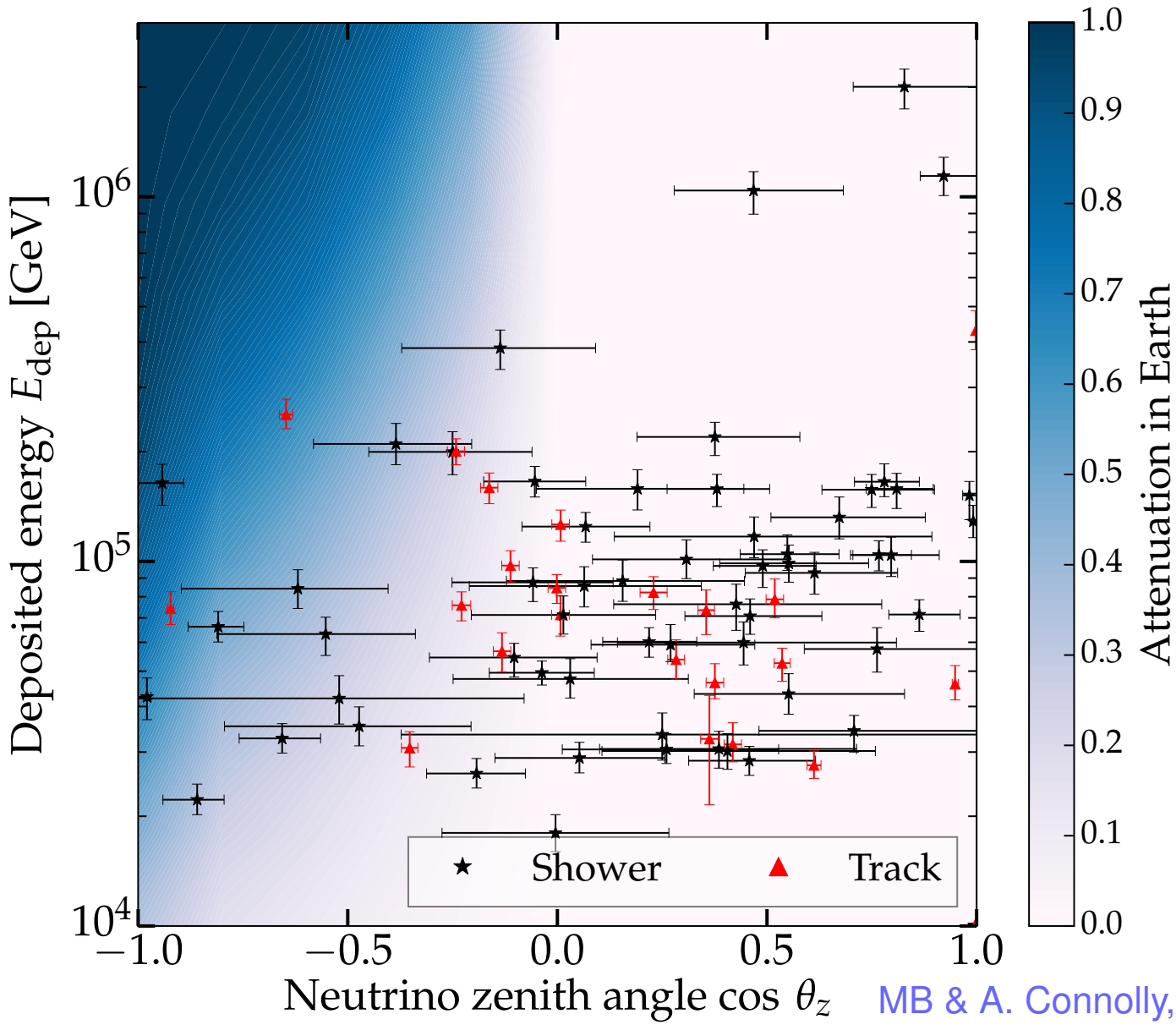
$$N_{\text{down}} \sim \Phi_\nu \, \sigma_{\nu N}$$

Upgoing events ($0 < \tau < 1$) —

$$N_{\text{up}} = N_{\text{down}} \, e^{-\tau} \propto N_{\text{down}} \, e^{-\sigma_{\nu N}}$$

- Comparing N_{down} to N_{up} constrains the cross section
- Sensitivity to $\sigma_{\nu N}$ comes from attenuation, not detection

Where is most of the sensitivity to $\sigma_{\nu N}$?



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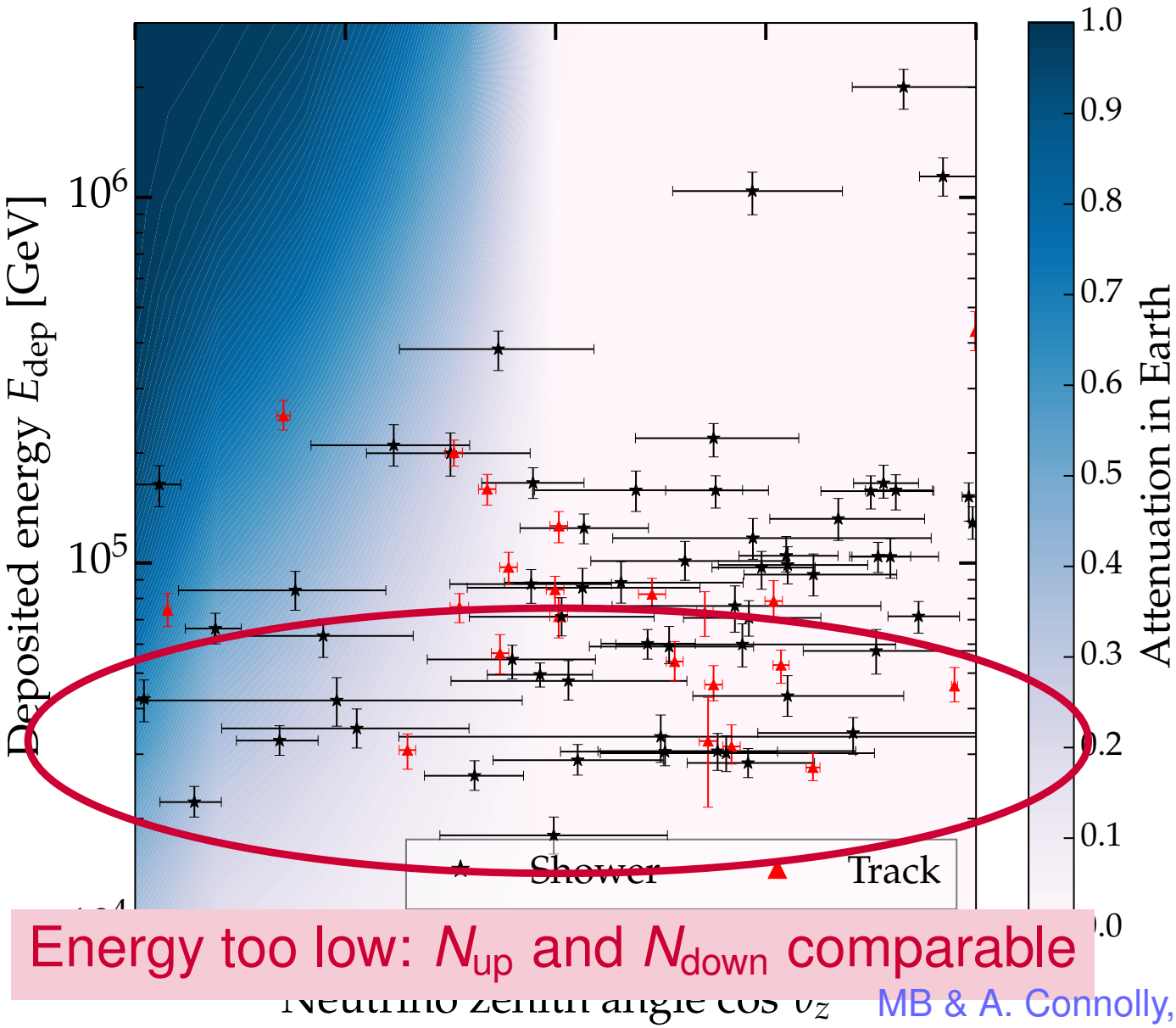

Energy too low: $N_{\rm up}$ and $N_{\rm down}$ comparable

MB & A. Connolly, *In prep.*

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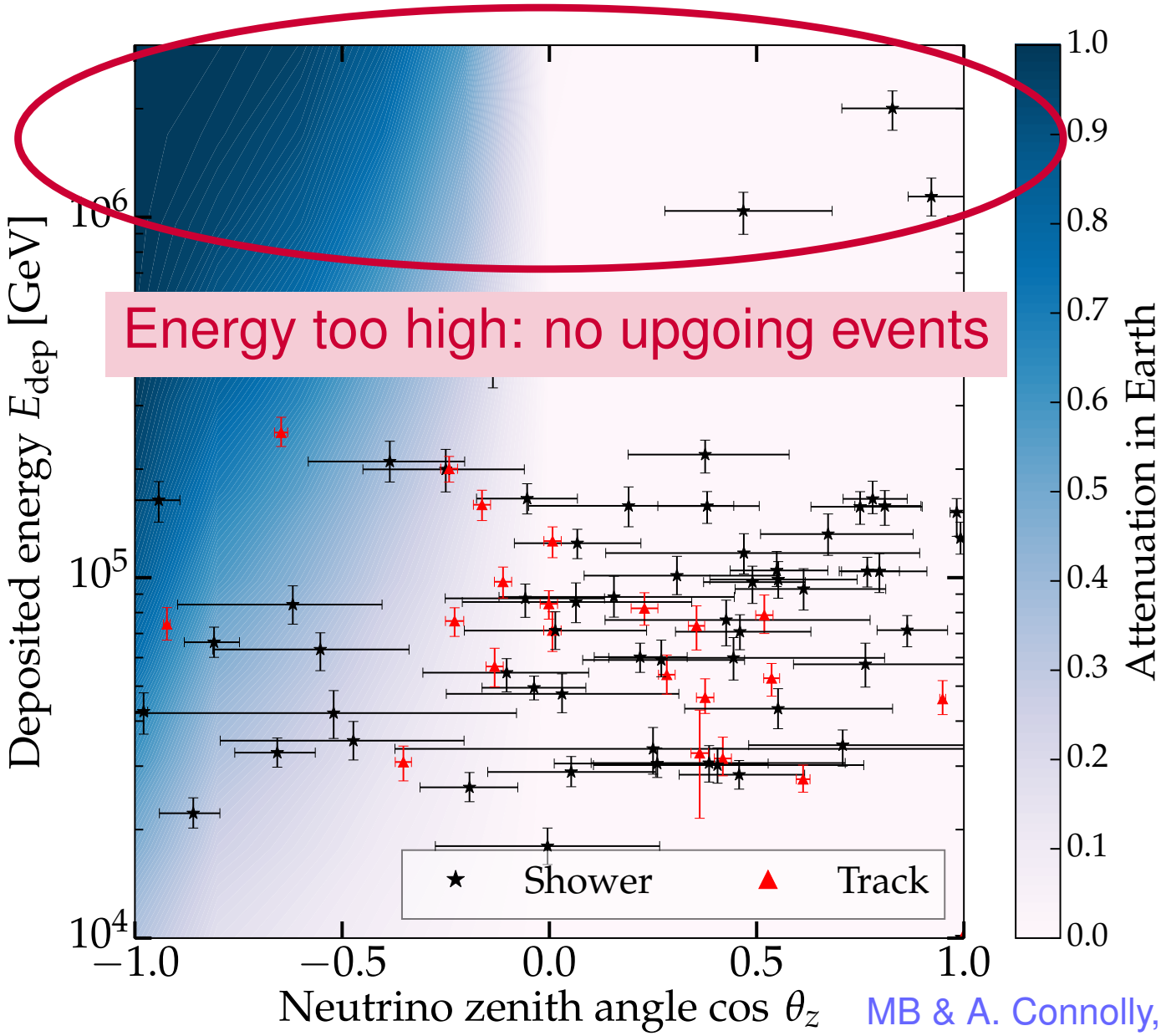

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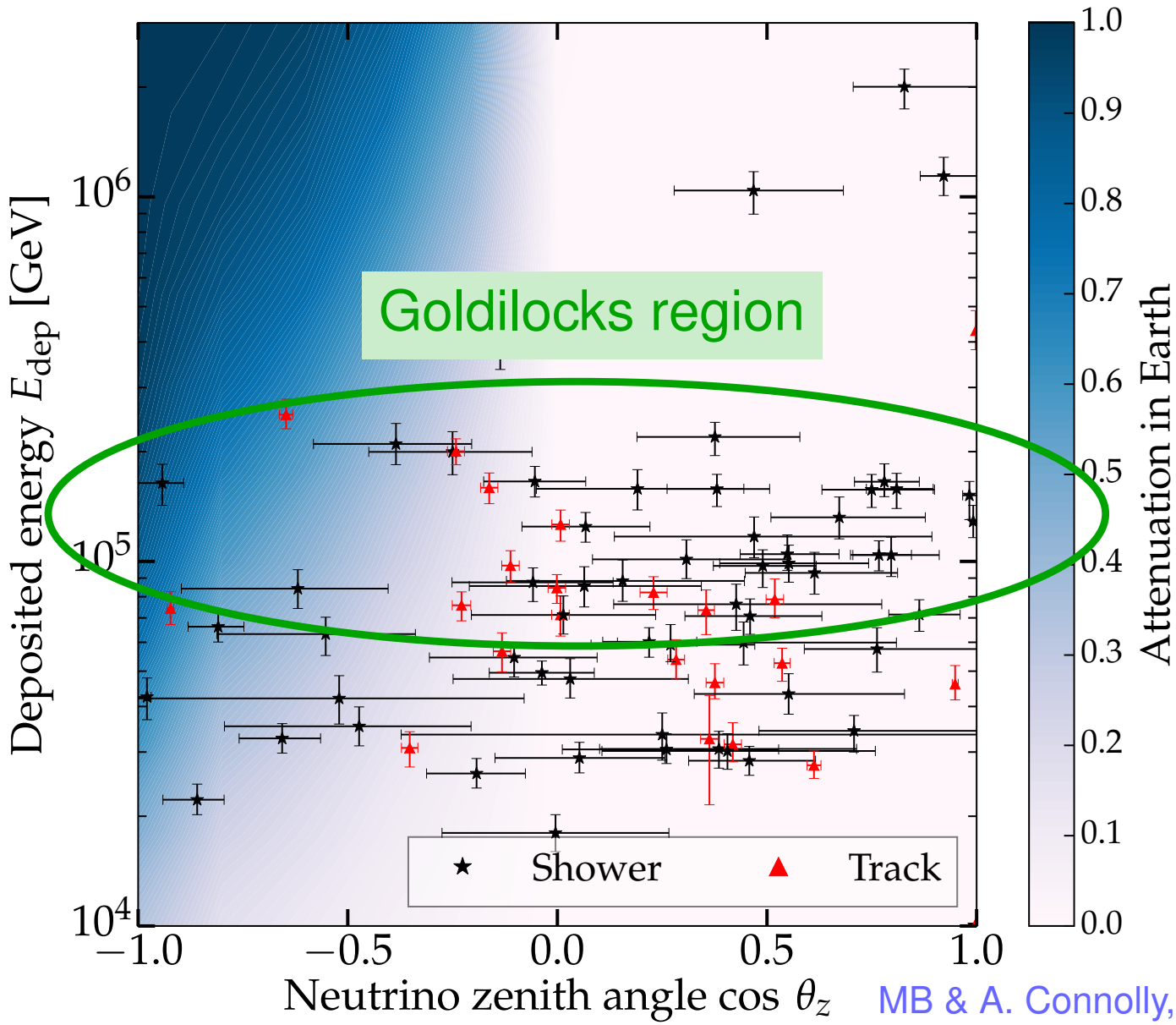

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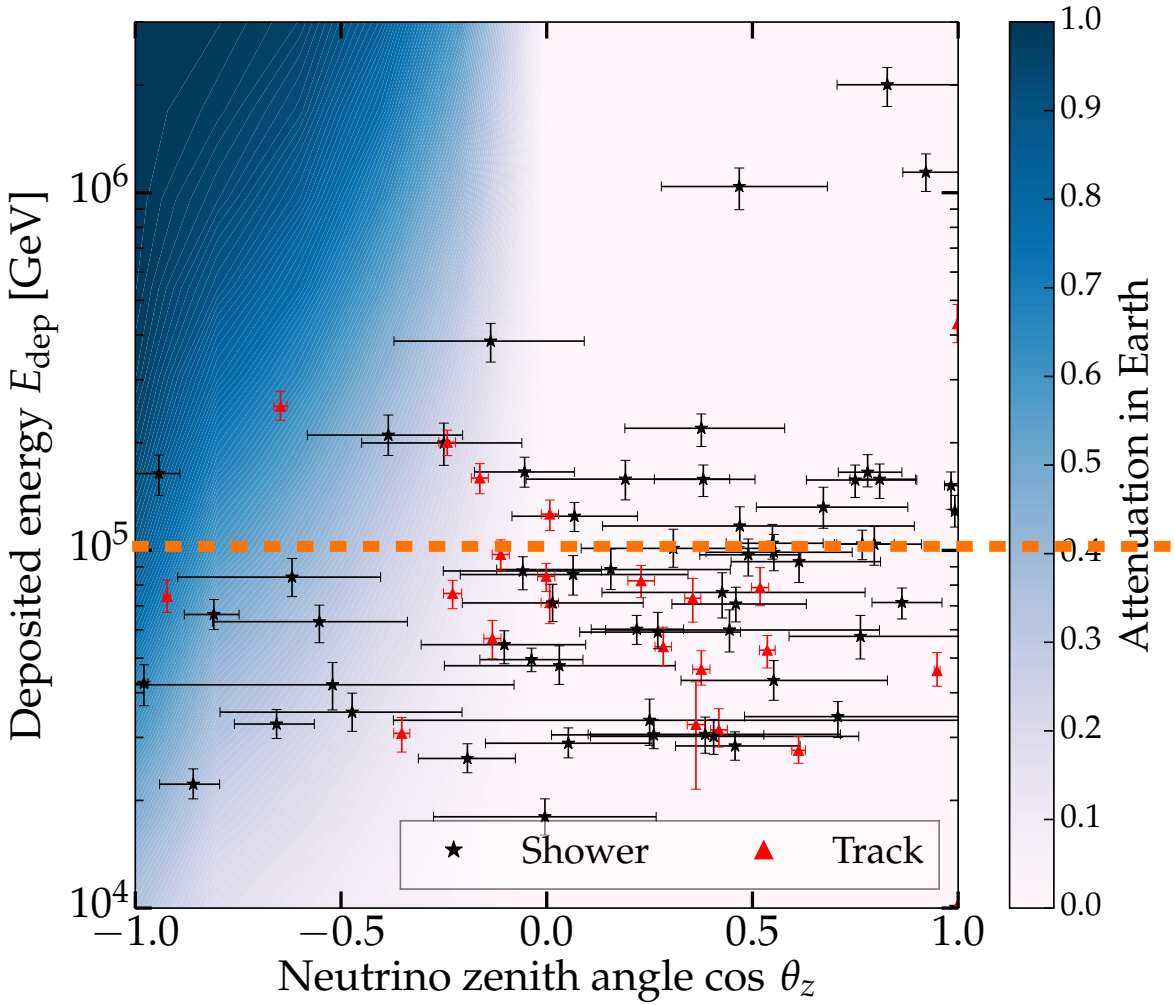
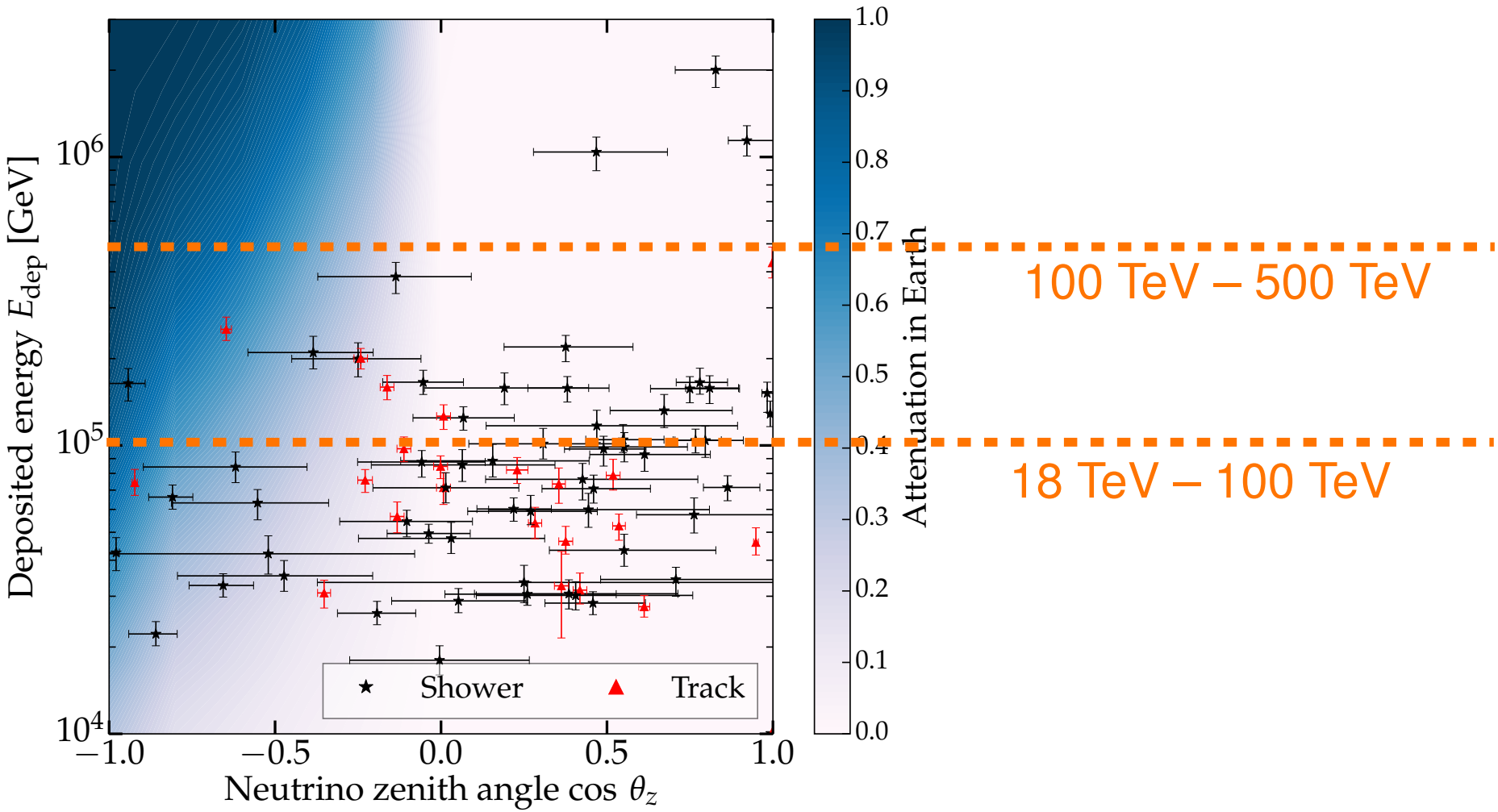
Bin-by-bin analysis



18 TeV – 100 TeV

Bin-by-bin analysis



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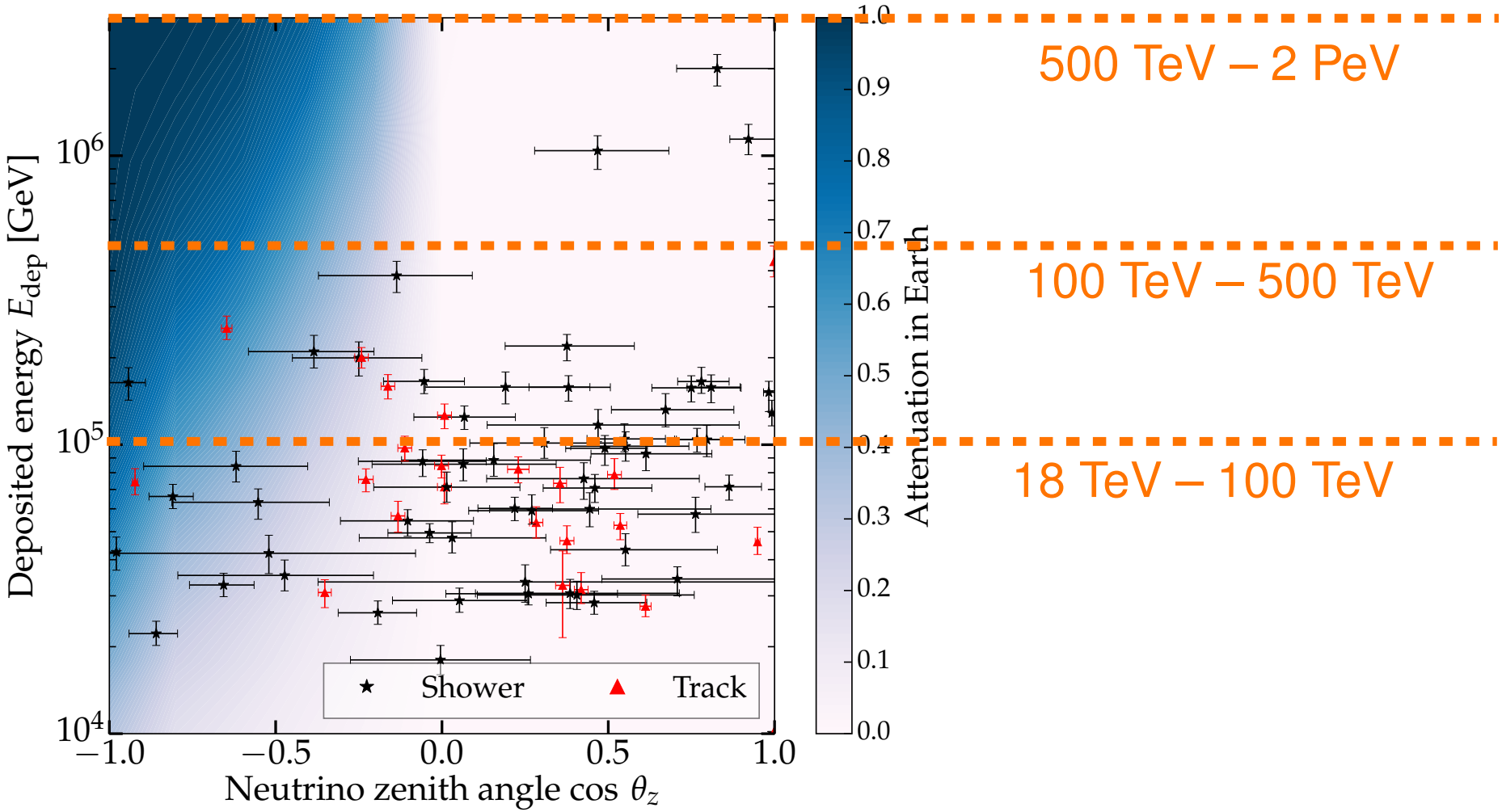


What events do we use?

- $\sigma_{\nu N}$ varies with neutrino energy
- So, we should use events where

  deposited energy $\approx$ neutrino energy
- We use IceCube High-Energy Starting Events (HESE):
  - νN interaction occurs inside the detector
  - ☑ **Showers:** completely contained in the detector ($E_{\text{dep}} \approx E_\nu$)
  - □ **Tracks:** partially contained ($E_{\text{dep}} < E_\nu$)
- We use only 58 HESE showers (ICRC 6-year IceCube HESE sample)

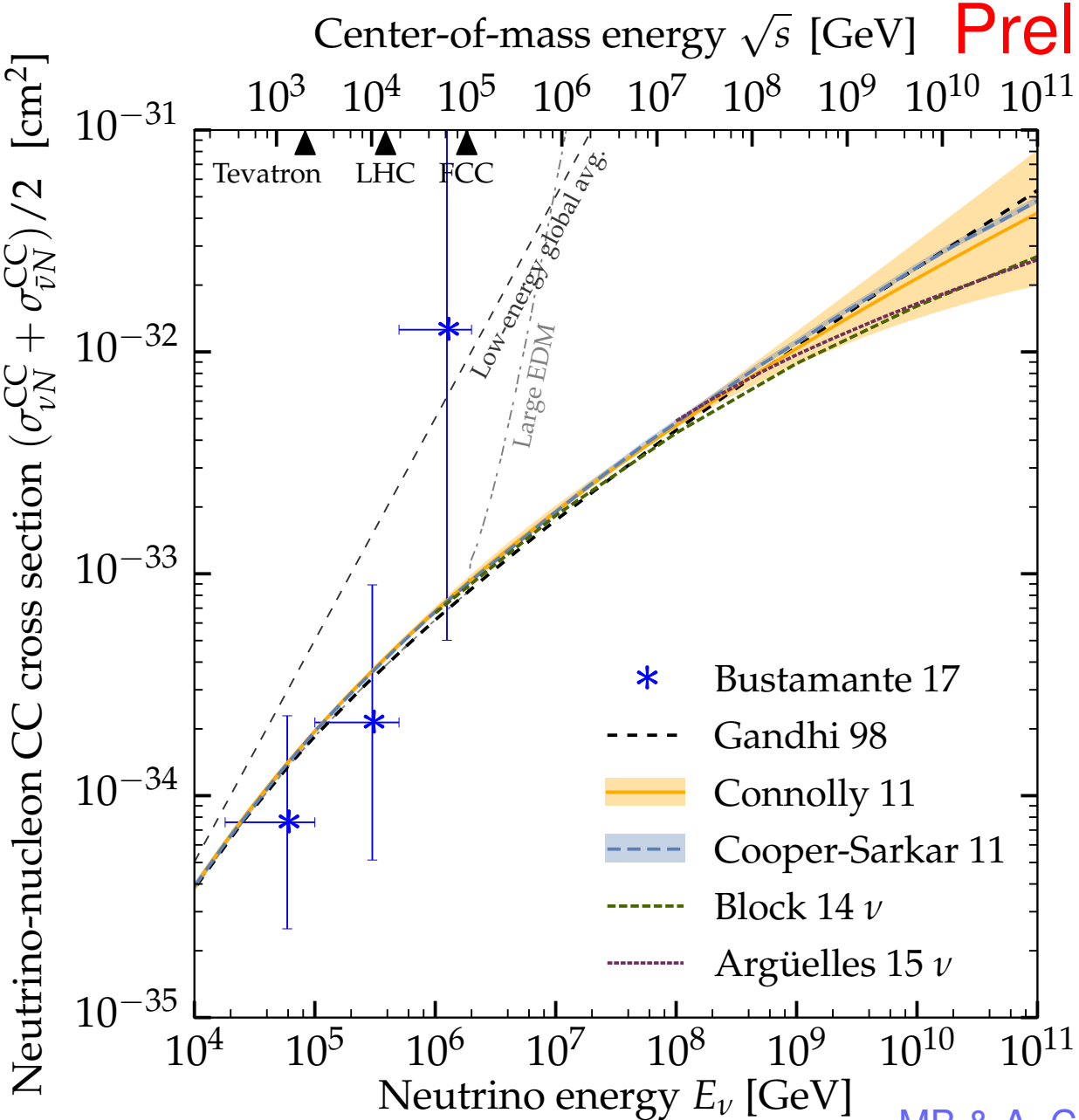
What goes into the (likelihood) mix?

Free parameters varied inside each energy bin:

- $N_{\mathrm{sh}}^{\mathrm{atm}}$ (showers from atmospheric neutrinos)
- $N_{\mathrm{sh}}^{\mathrm{st}}$ (showers from astrophysical neutrinos)
- γ (astrophysical spectral index)
- $\sigma_{\nu N}^{\mathrm{CC}}$ (neutrino-nucleon charged-current cross section)

Neutral-current showers are subdominant — we fix $\sigma_{\nu N}^{\mathrm{NC}} = \sigma_{\nu N}^{\mathrm{CC}}/3$

The result



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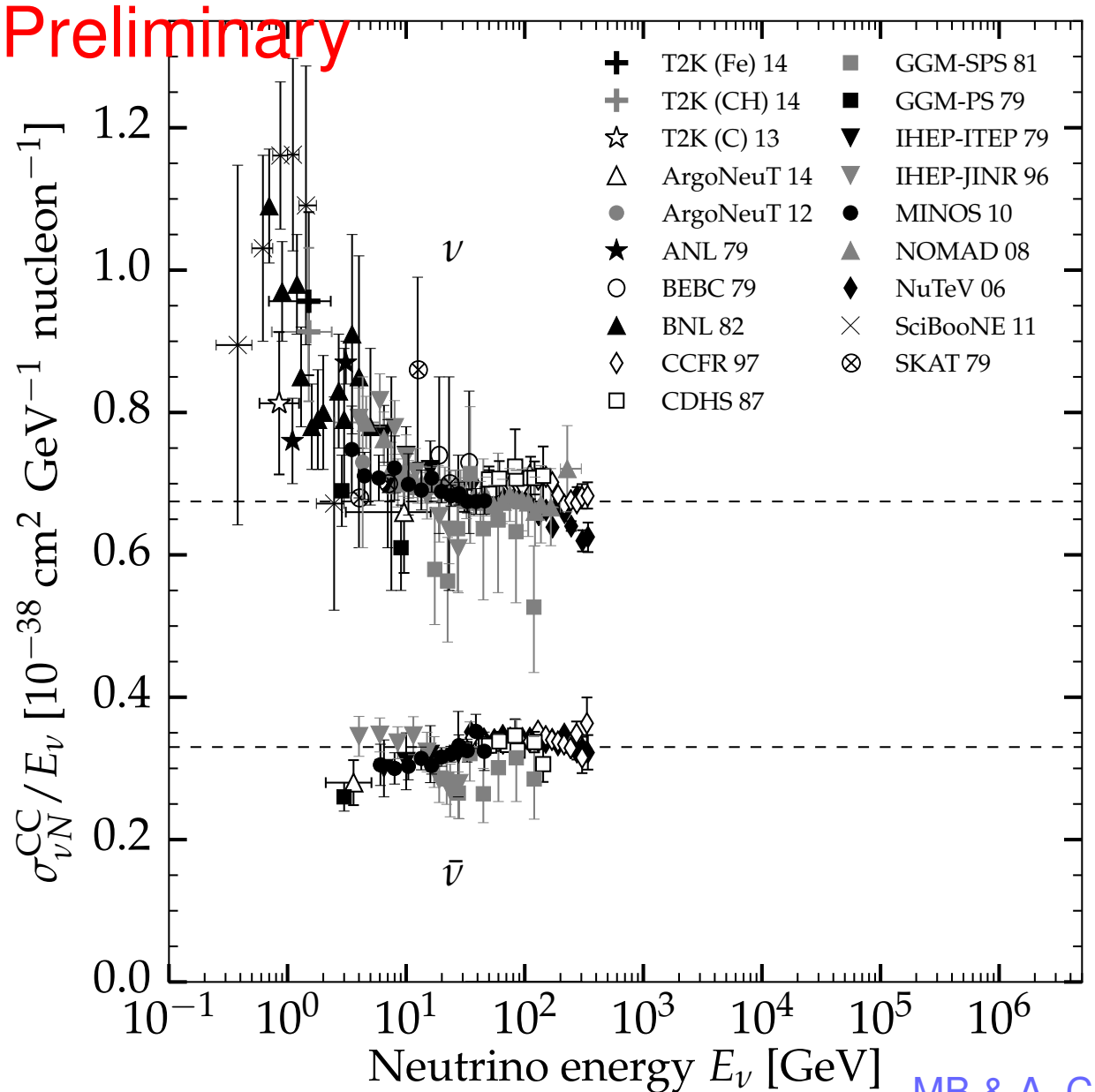
Extending the cross section measurements



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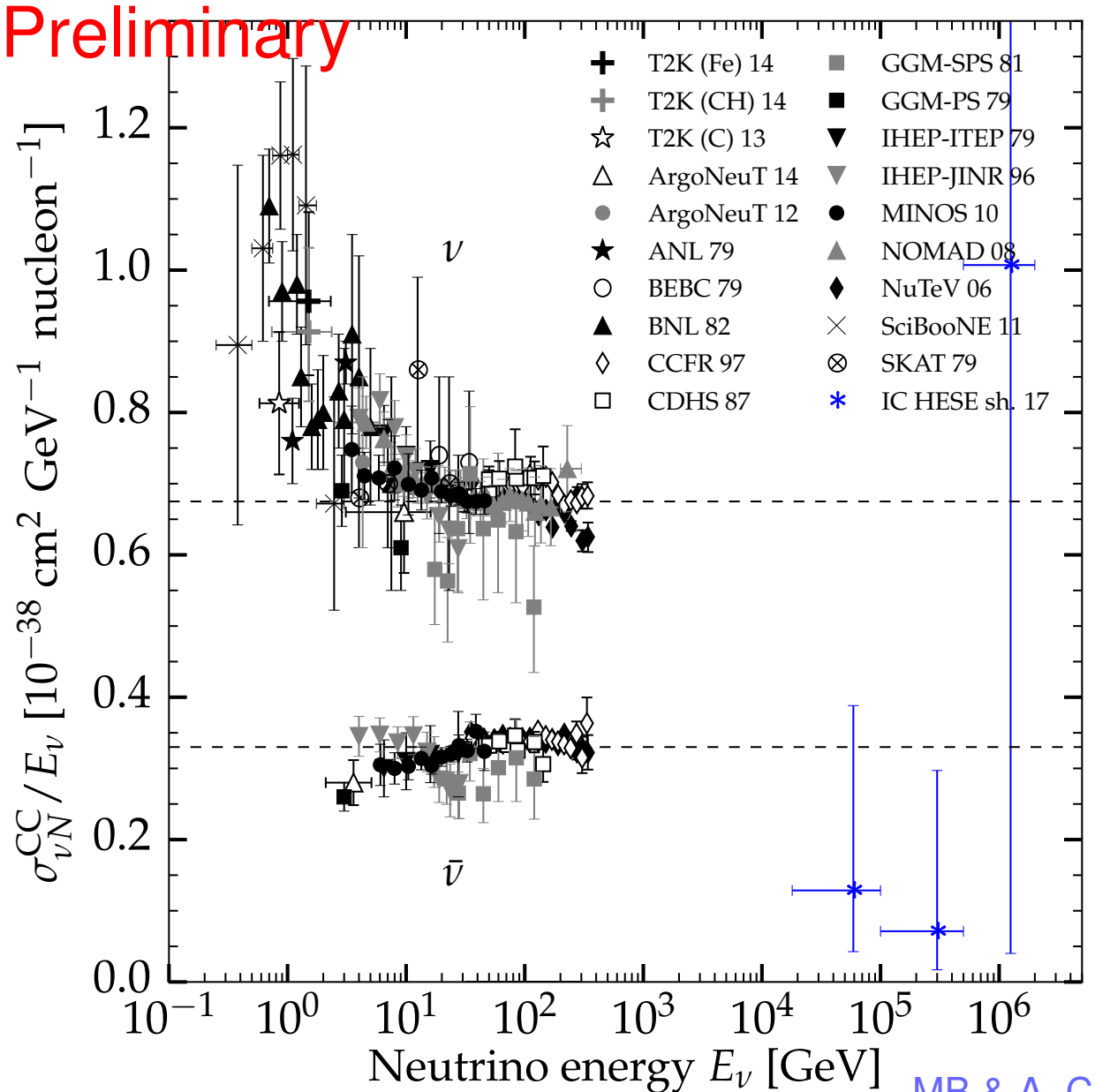

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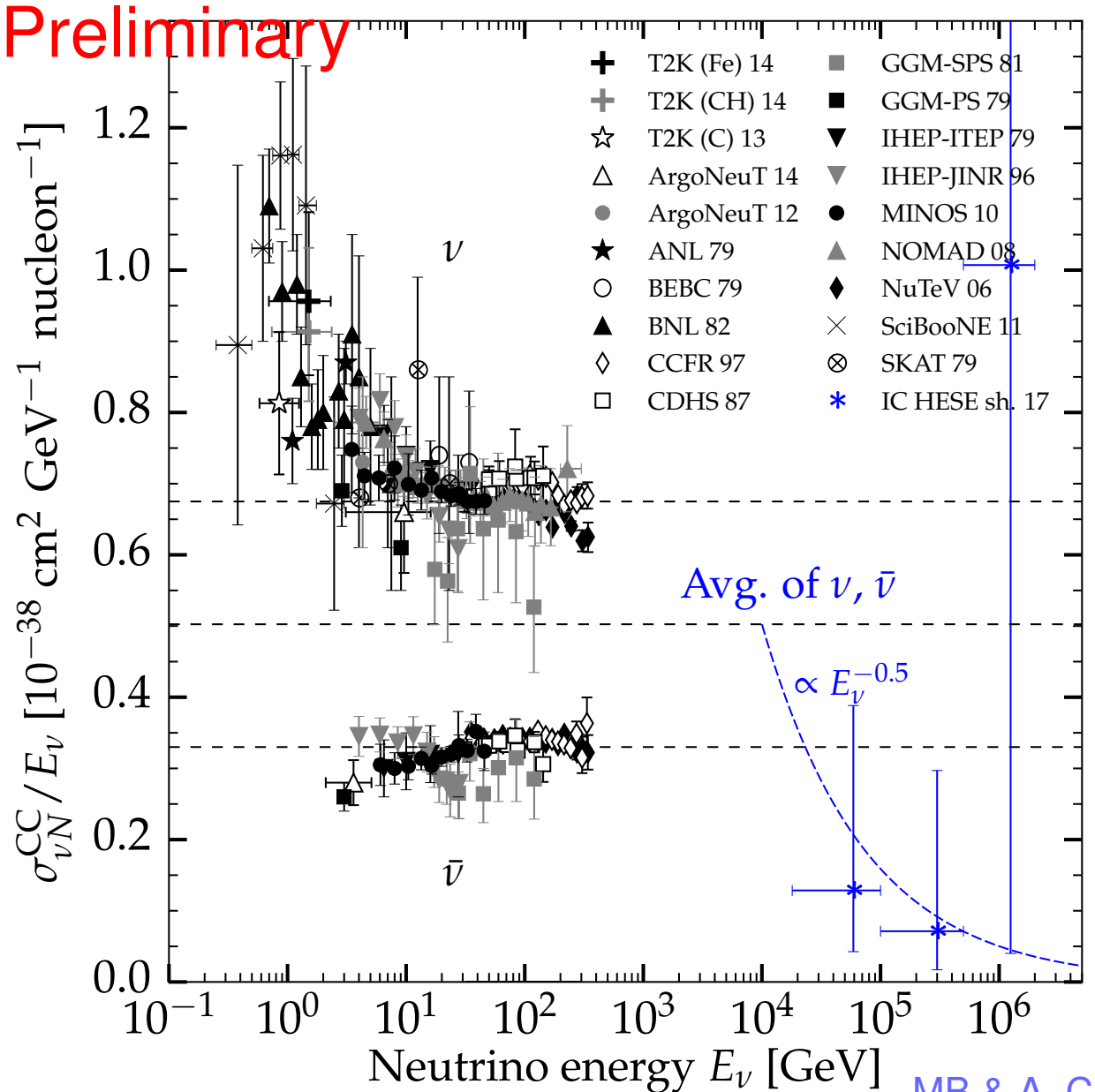

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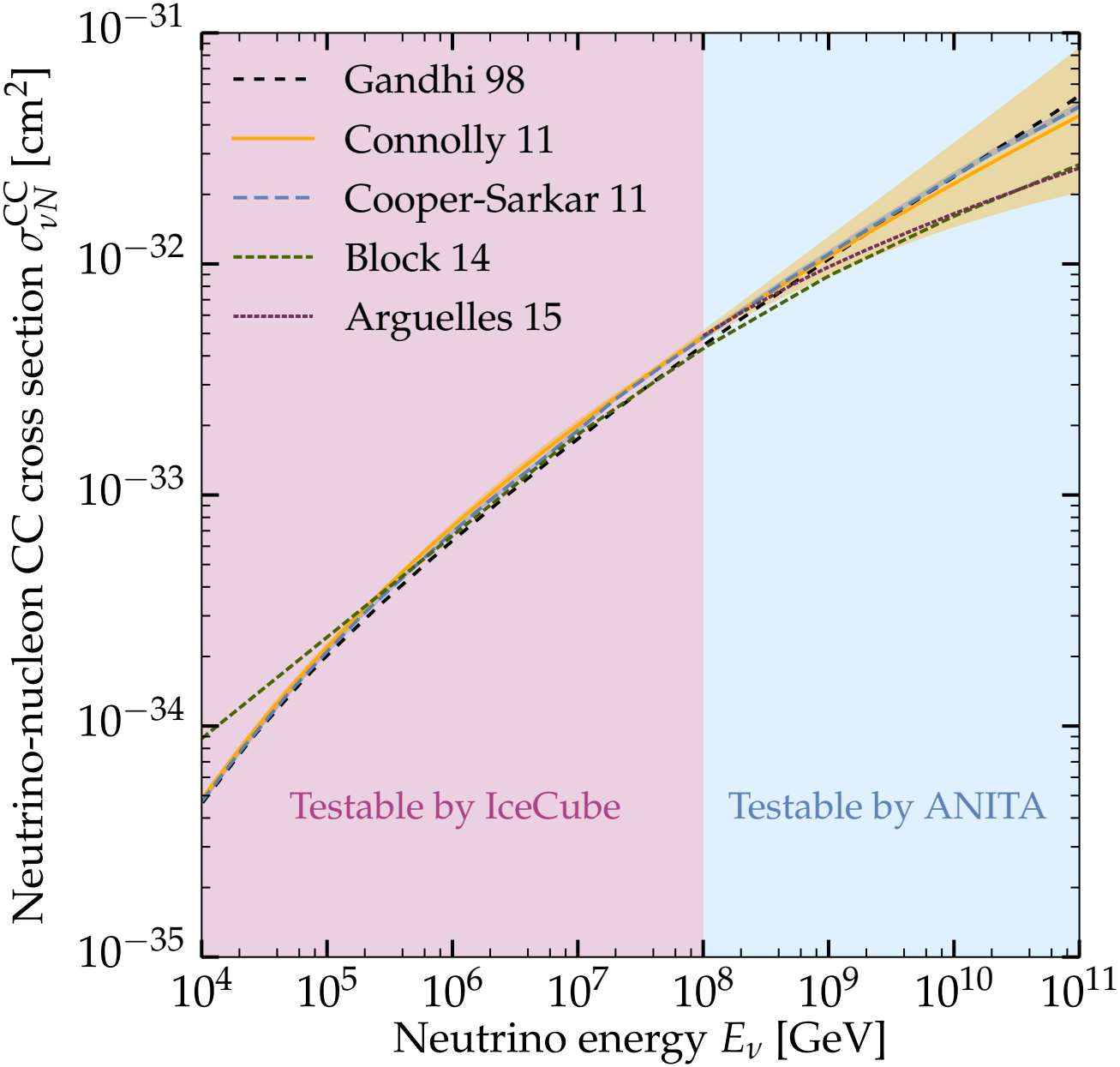
Caveats

- Limited statistics (for now)
  $\longmapsto$ Solvable with more IceCube + IceCube-Gen2 + KM3NeT
- Large errors in arrival directions give errors in attenuation
  $\longmapsto$ Solvable with improvements (talk by Tianlu Yuan) + KM3NeT
- Only constrains charged-current + neutral-current cross section
  $\longmapsto$ Solvable (?) with muon and neutron echoes (Li, MB, Beacom 16)
- Cannot separate ν from $\bar{\nu}$
  $\longmapsto$ Wait for Glashow resonance
- Use starting tracks (easy) + through-going muons (less so)
  $\longmapsto$ Doable now by the Collaboration

Quo vadis: IceCube vs. ANITA/ARA/ARIANNA



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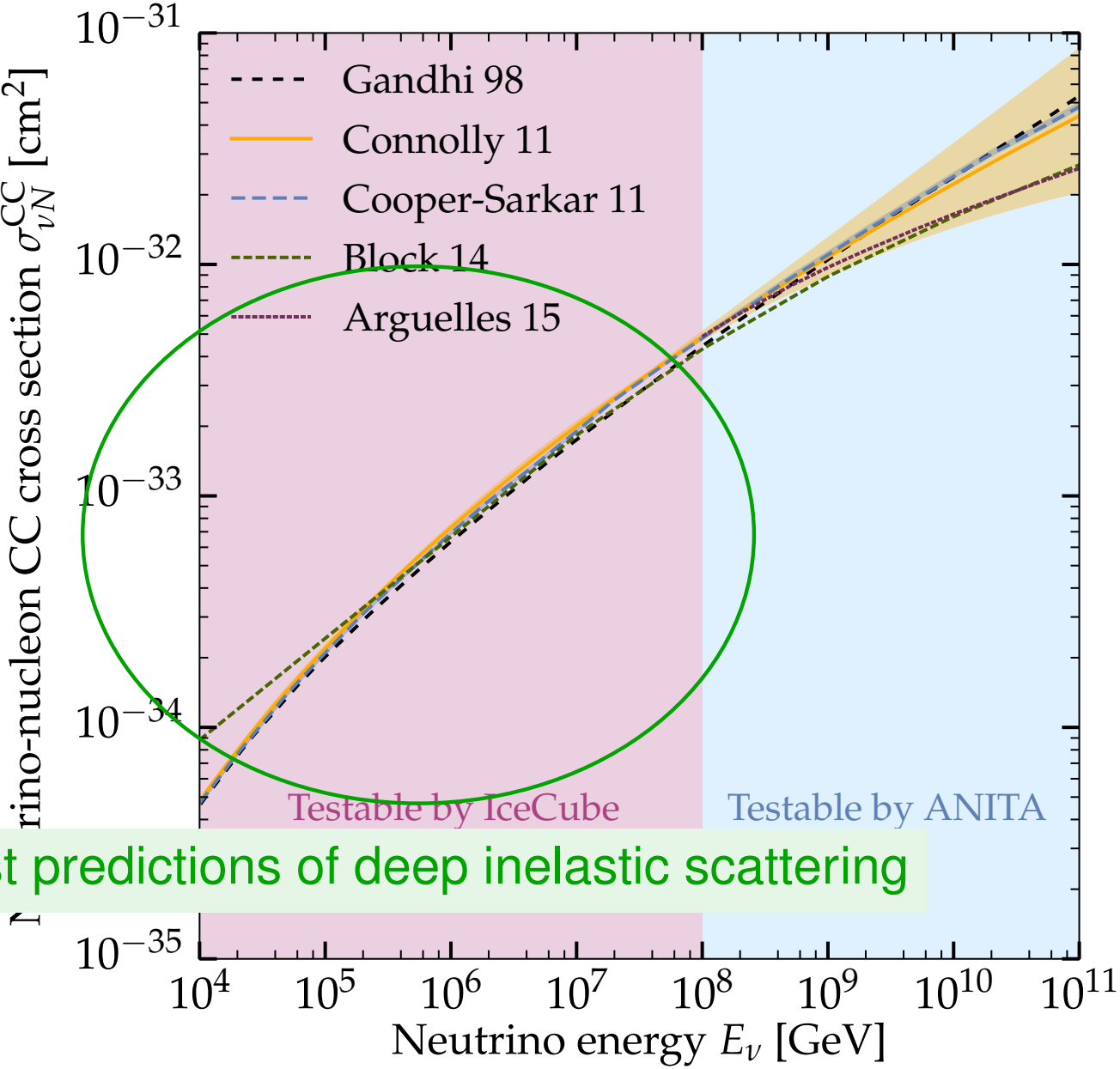
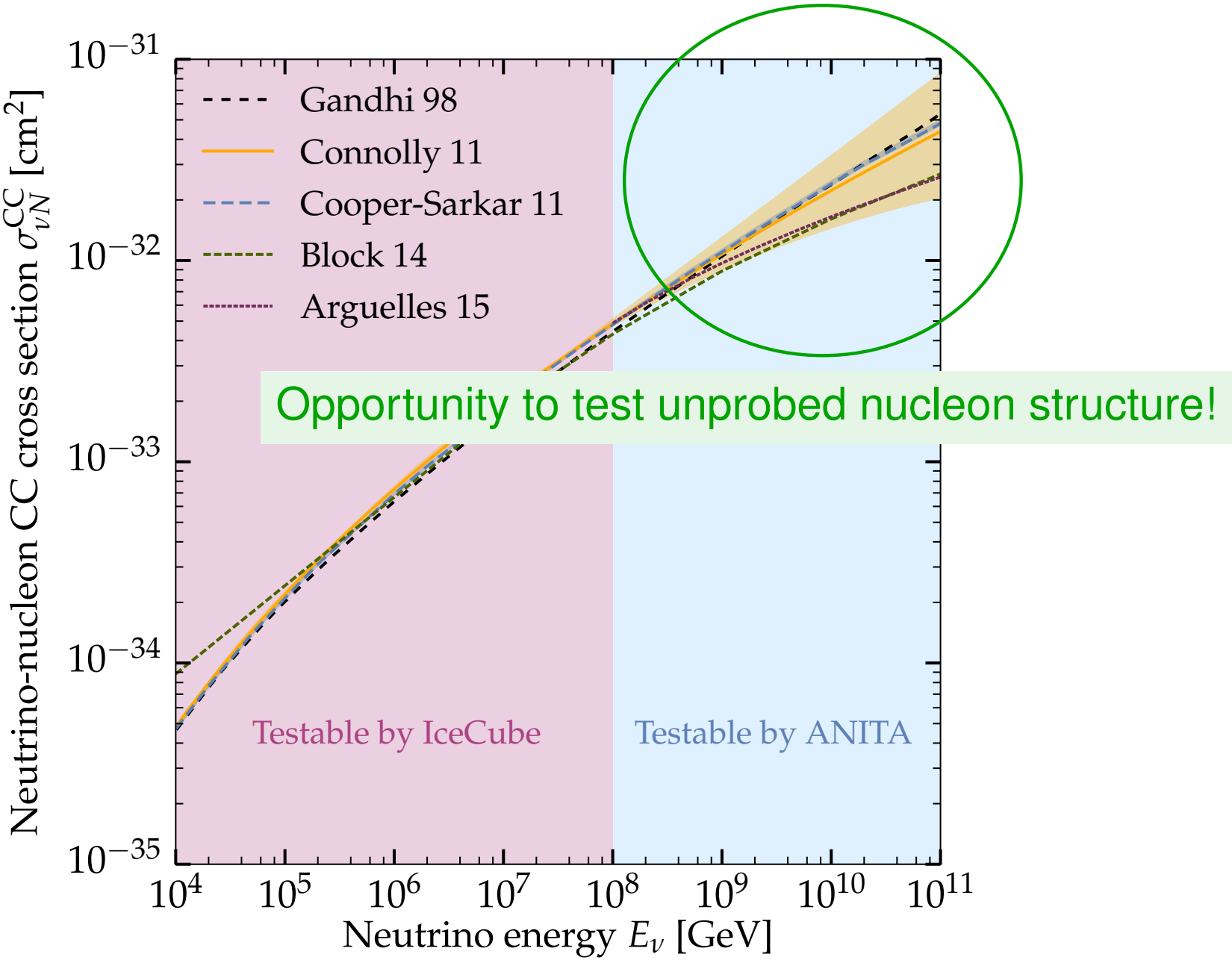


Test predictions of deep inelastic scattering

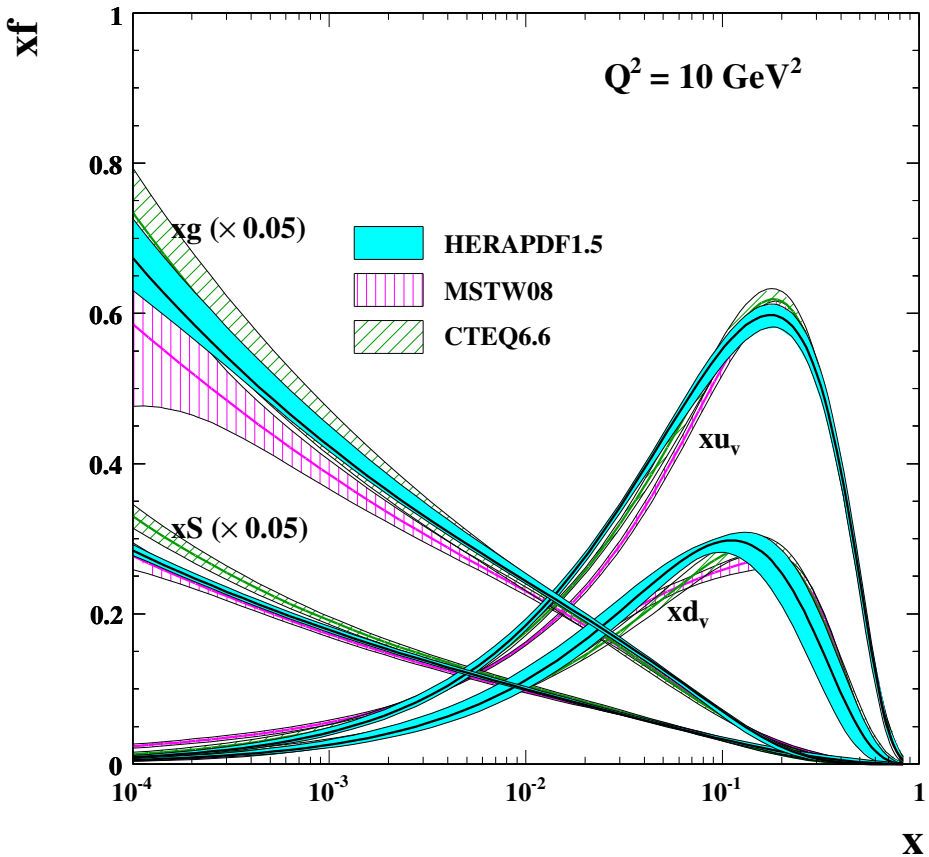
Quo vadis: IceCube vs. ANITA/ARA/ARIANNA



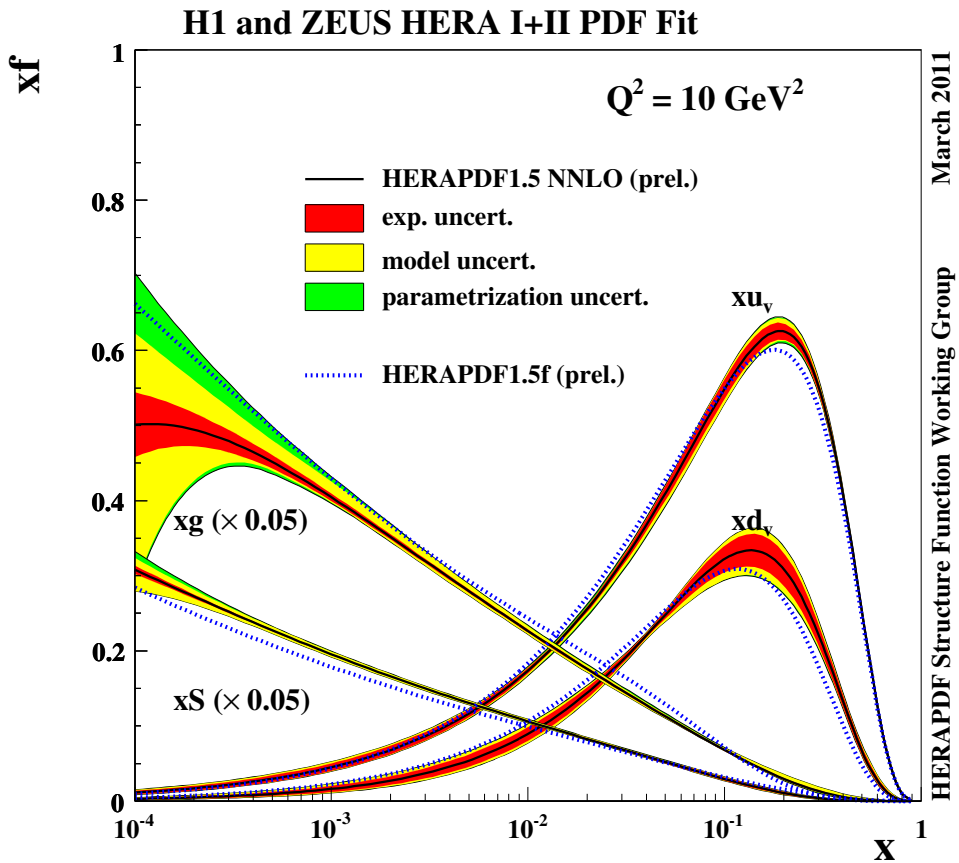
Backup slides

The world of PDFs is messy

Different fitting groups

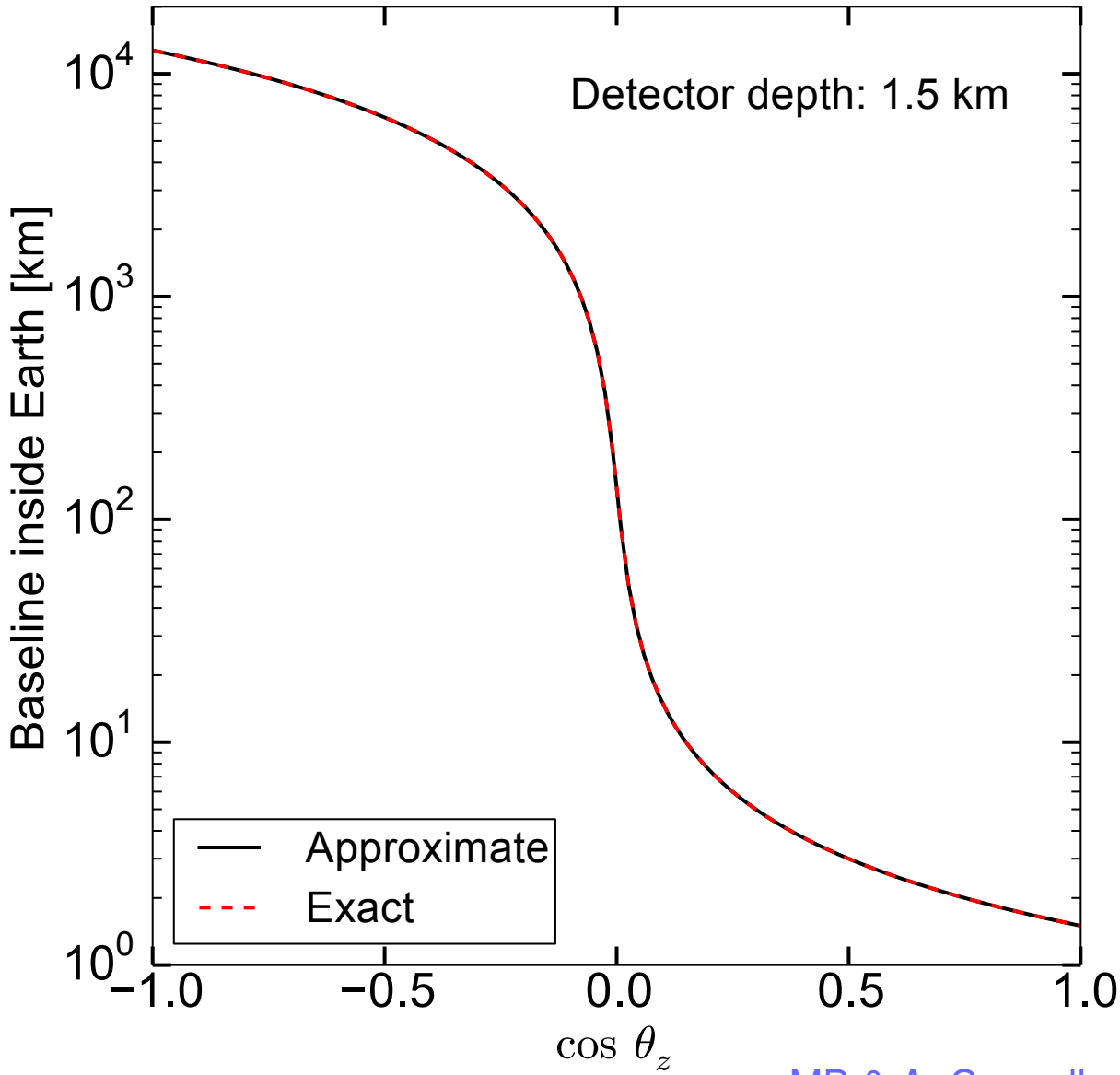


Different QCD prescriptions



A. COOPER-SARKAR 2012

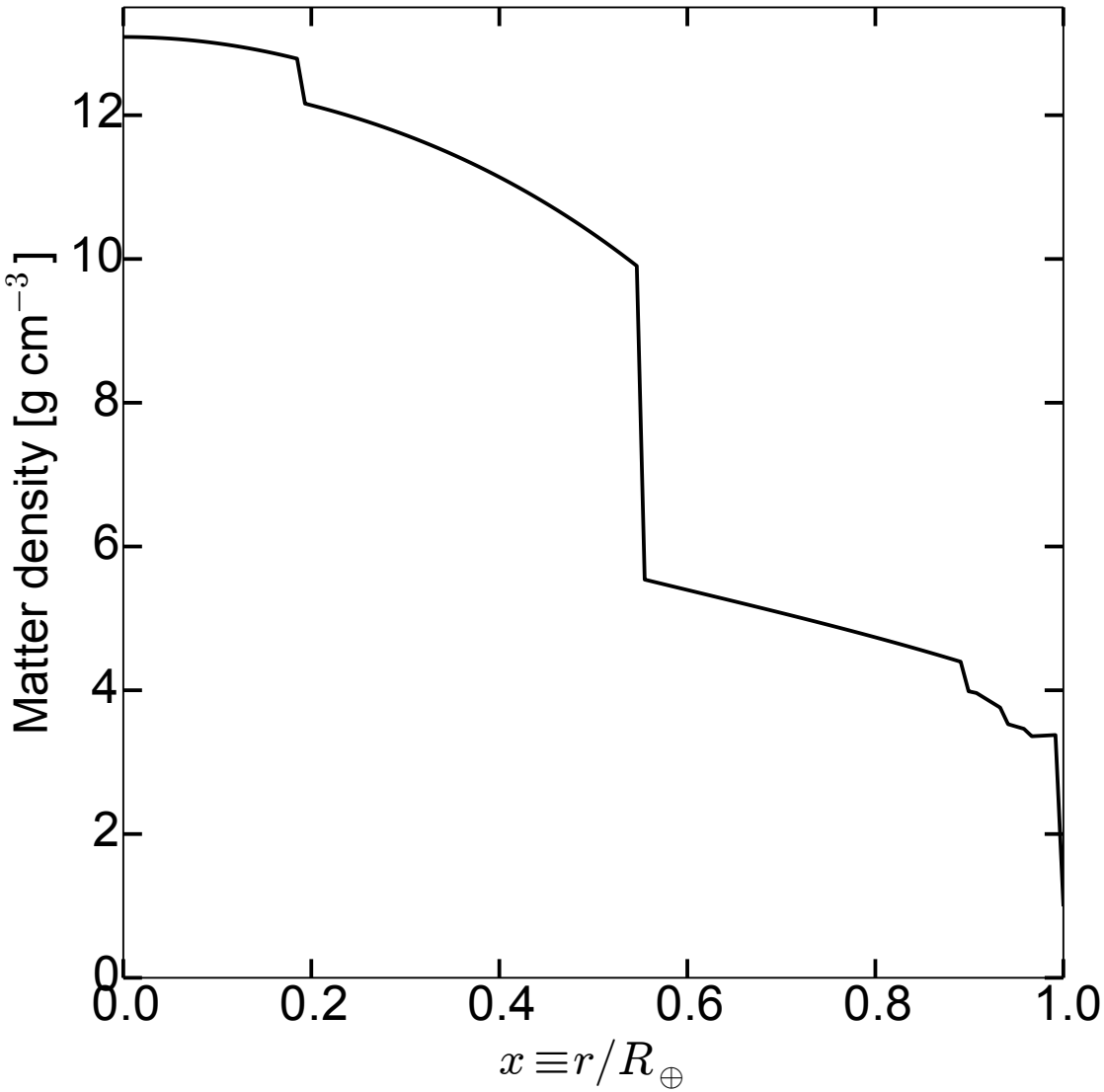
Neutrino baseline inside the Earth



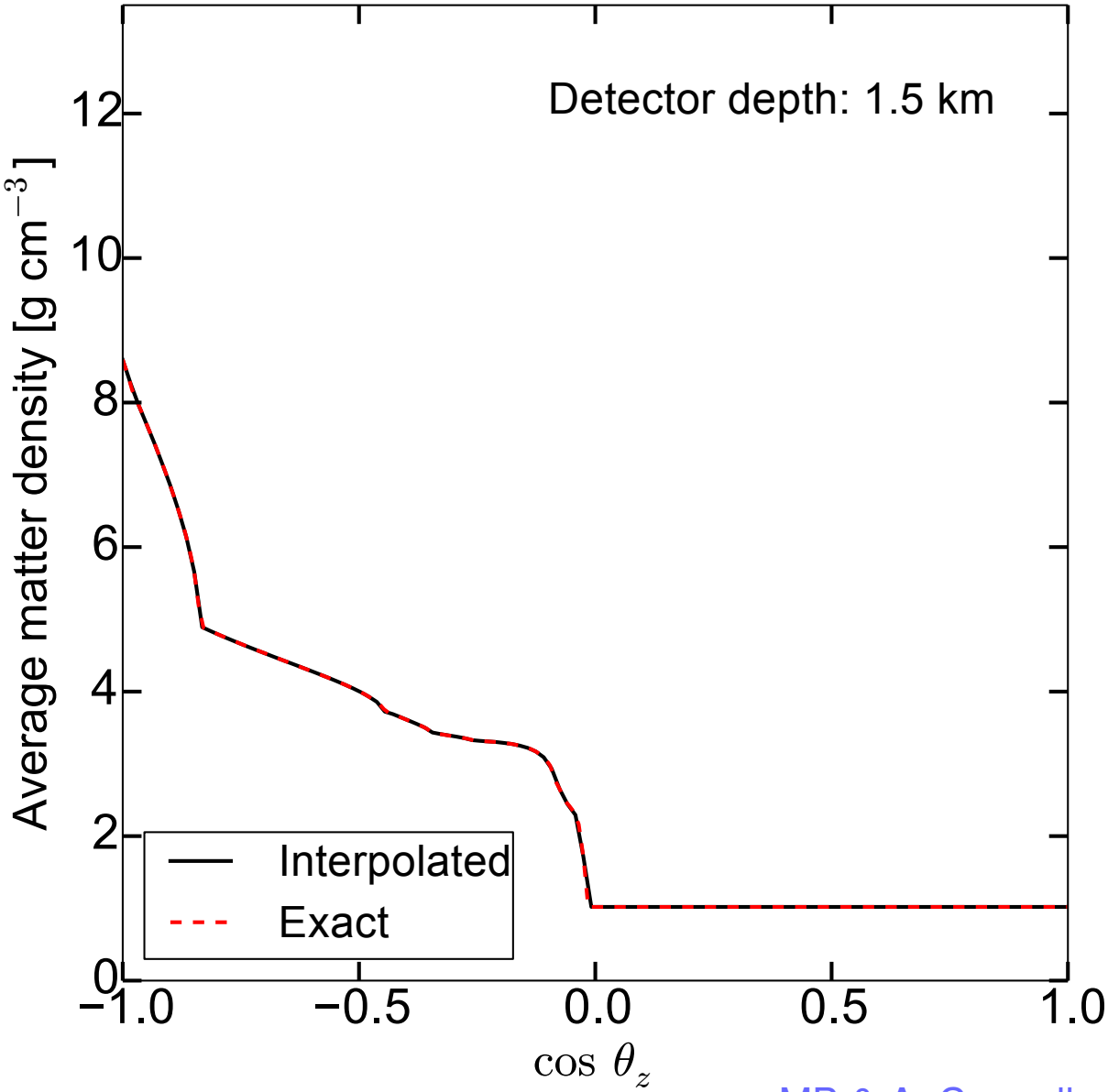
MB & A. Connolly, *In prep.*

Earth density profile

From the Preliminary Reference Earth Model —



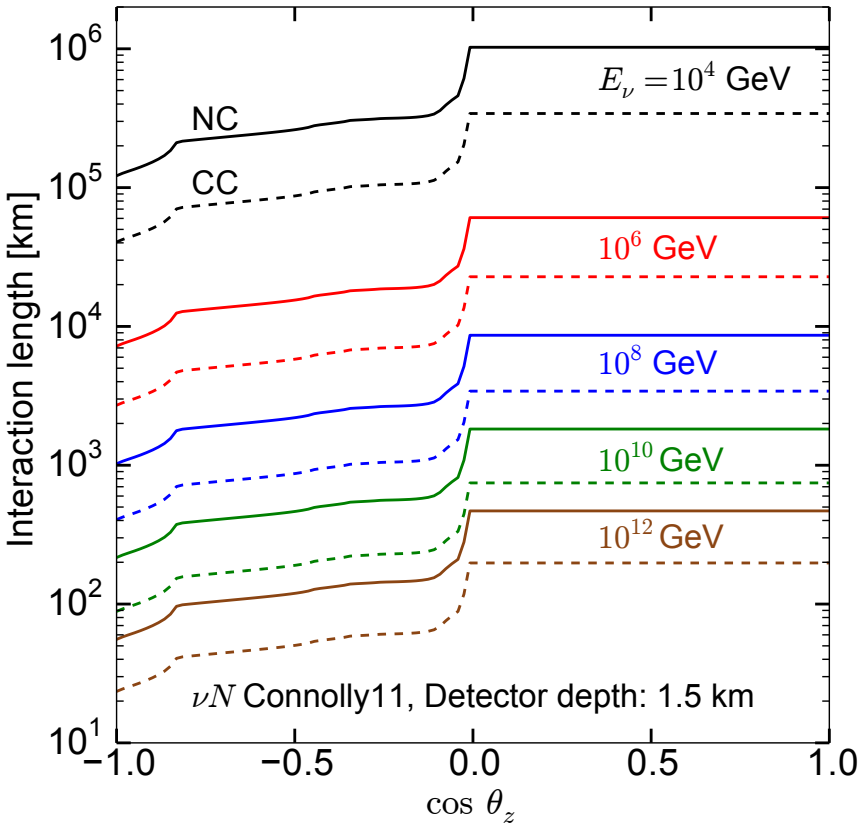
Average Earth density



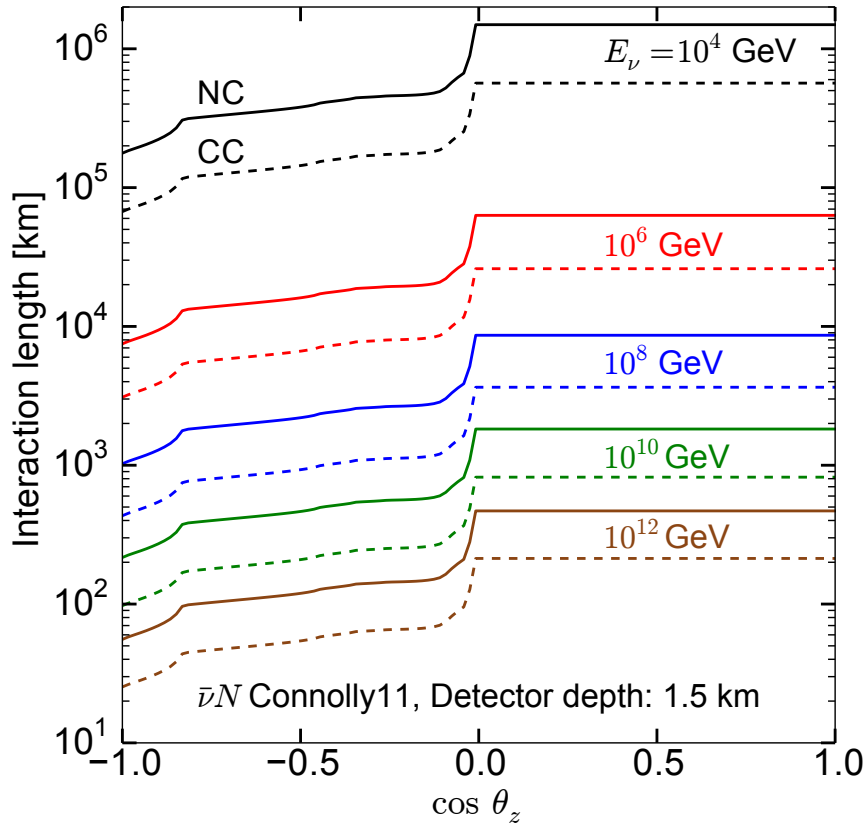
MB & A. Connolly, *In prep.*

Neutrino interaction length inside the Earth

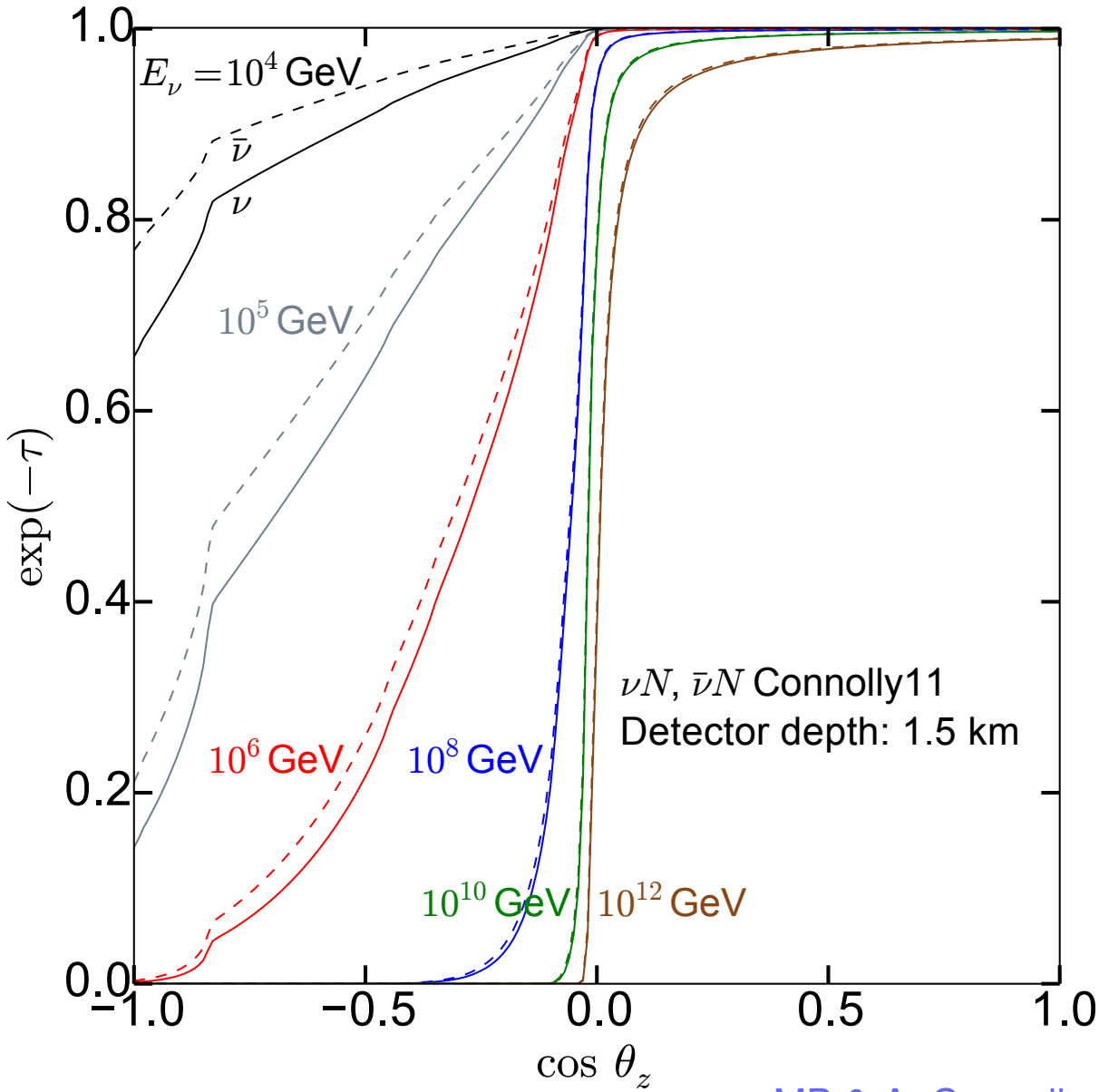
Neutrino



Anti-neutrino



Neutrino absorption in the Earth



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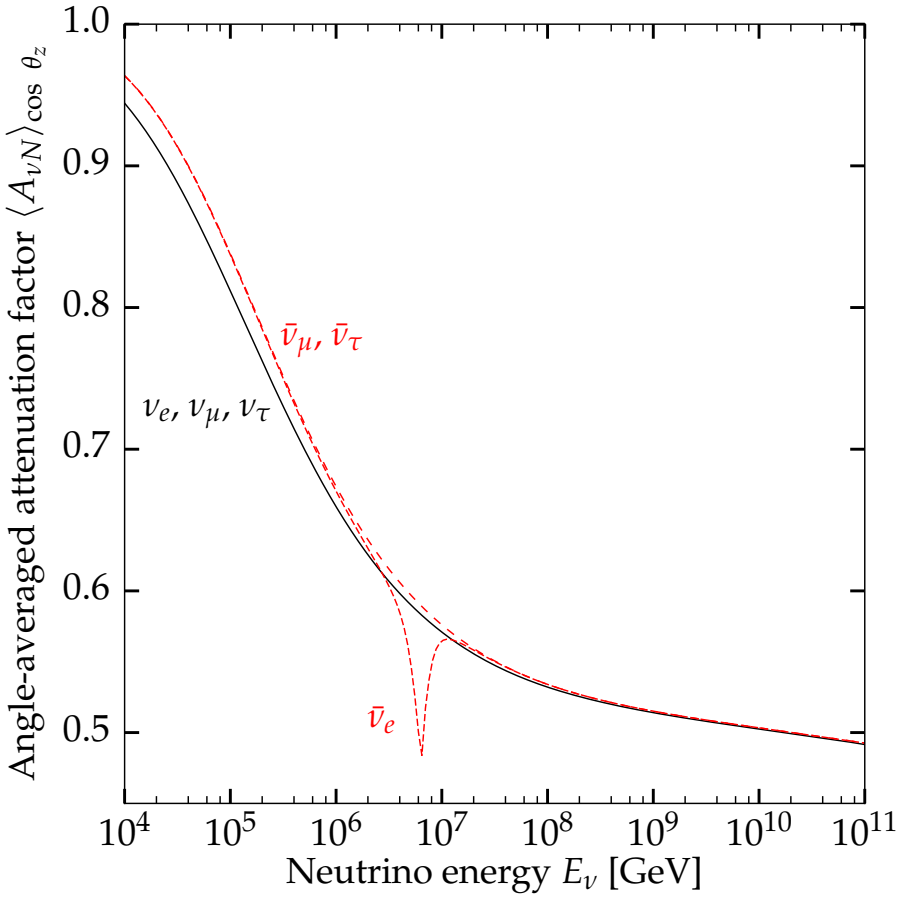
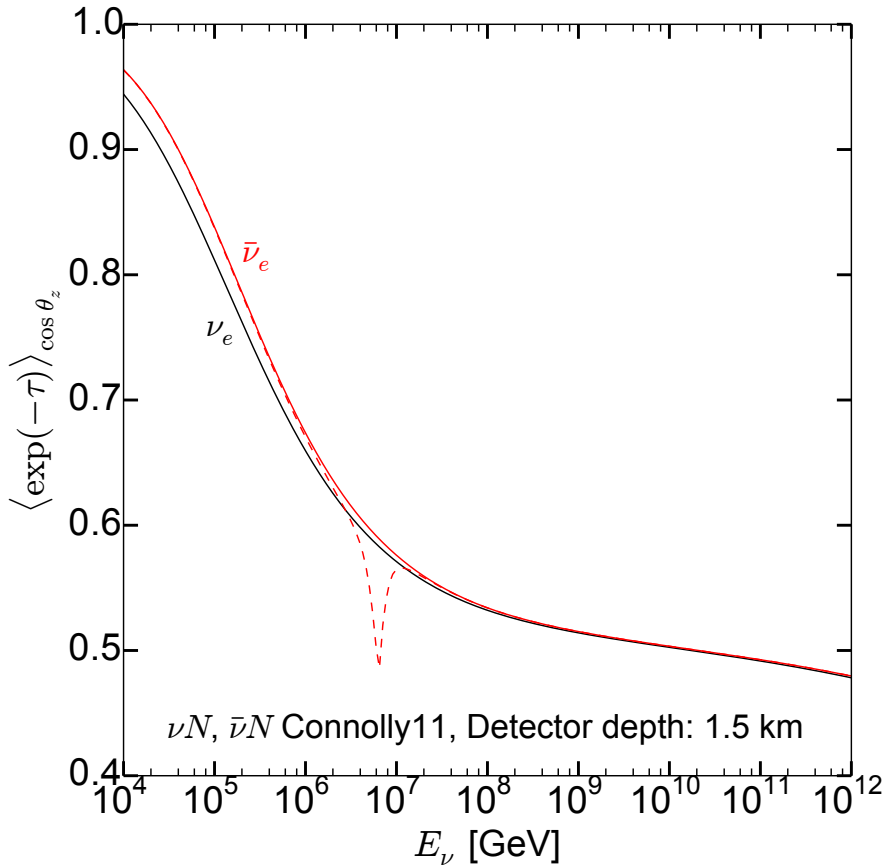
Angle-averaged neutrino absorption in the Earth





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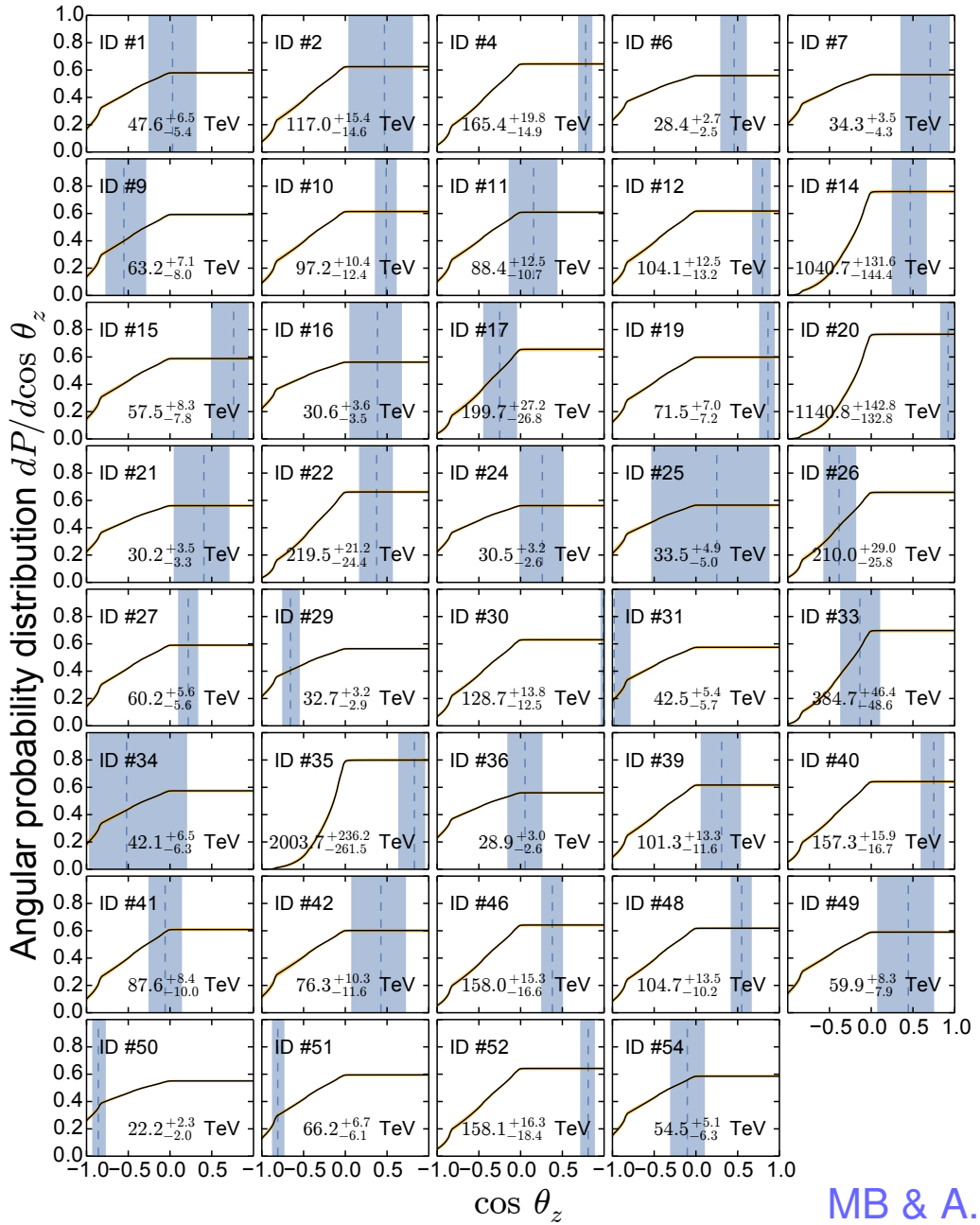
Angular probability distribution for 4-yr HESE events



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