Dimuons in Neutrino Telescopes: New Predictions and First Search in IceCube

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Neutrino telescopes are very important

MeV—GeV ν telescopes

- Solar ν, Nobel prize 2002, 2015, and more to study
- Supernova ν, Nobel prize 2002, and more to study
- Atmospheric ν, Nobel prize 2015, and more to study
- All above have been used to test new physics

High-energy (TeV--PeV) ν telescopes

- Astrophysics:
  - Origin of high-energy cosmic rays (~100-year problem)
  - Gamma ray sources, hadronic vs leptonic (long-term problem)
- Particle physics:
  - Standard model (Glashow resonance, W-boson production)
  - Beyond SM (DM, nu properties, etc.)
    - high-energy, known direction, cosmic distance, extremely high column density (through Earth)

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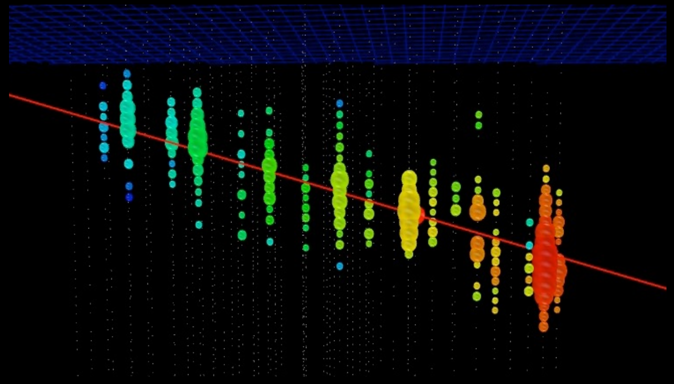
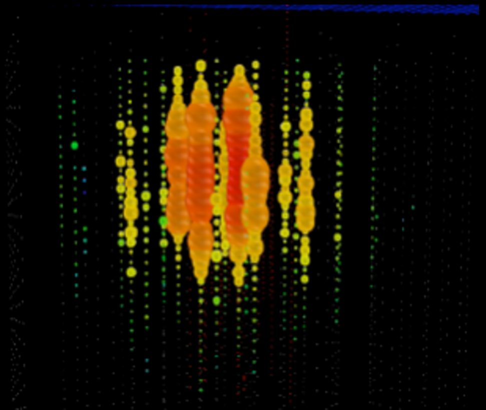
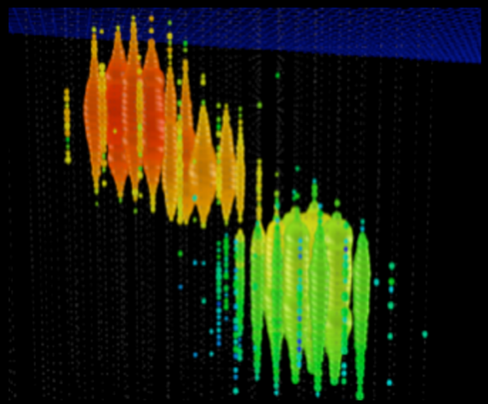
Very important to study new event classes



μ track (ν_μ CC, ν_τCC)



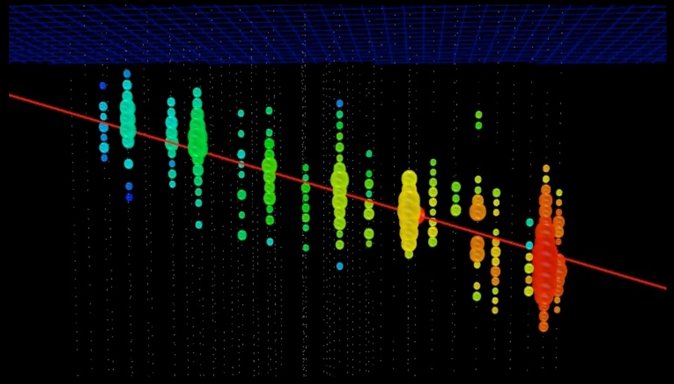
Shower (ν_e CC, ν_τCC, NC)



Double shower/bang (ν_τCC)

- We are having more and more TeV—PeV neutrino detectors
    - IceCube, KM3NeT, BaiKal-GVD, P-ONE, IceCube-Gen2, …
- New event classes are needed to get more physics from the data

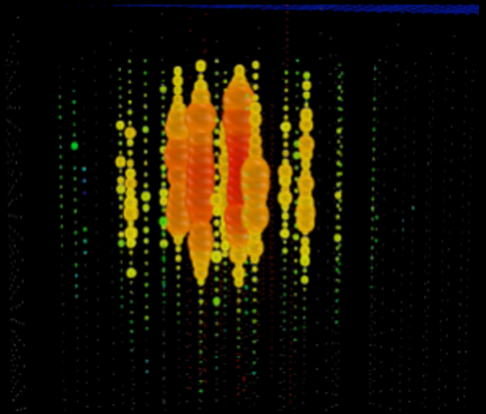
Very important to study new event classes: Dimuon



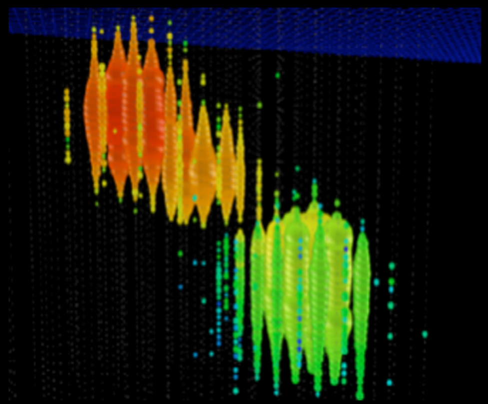
μ track (ν_μ CC, ν_τCC)

Double muons

(Dimuons)



Shower (ν_e CC, ν_τCC, NC)



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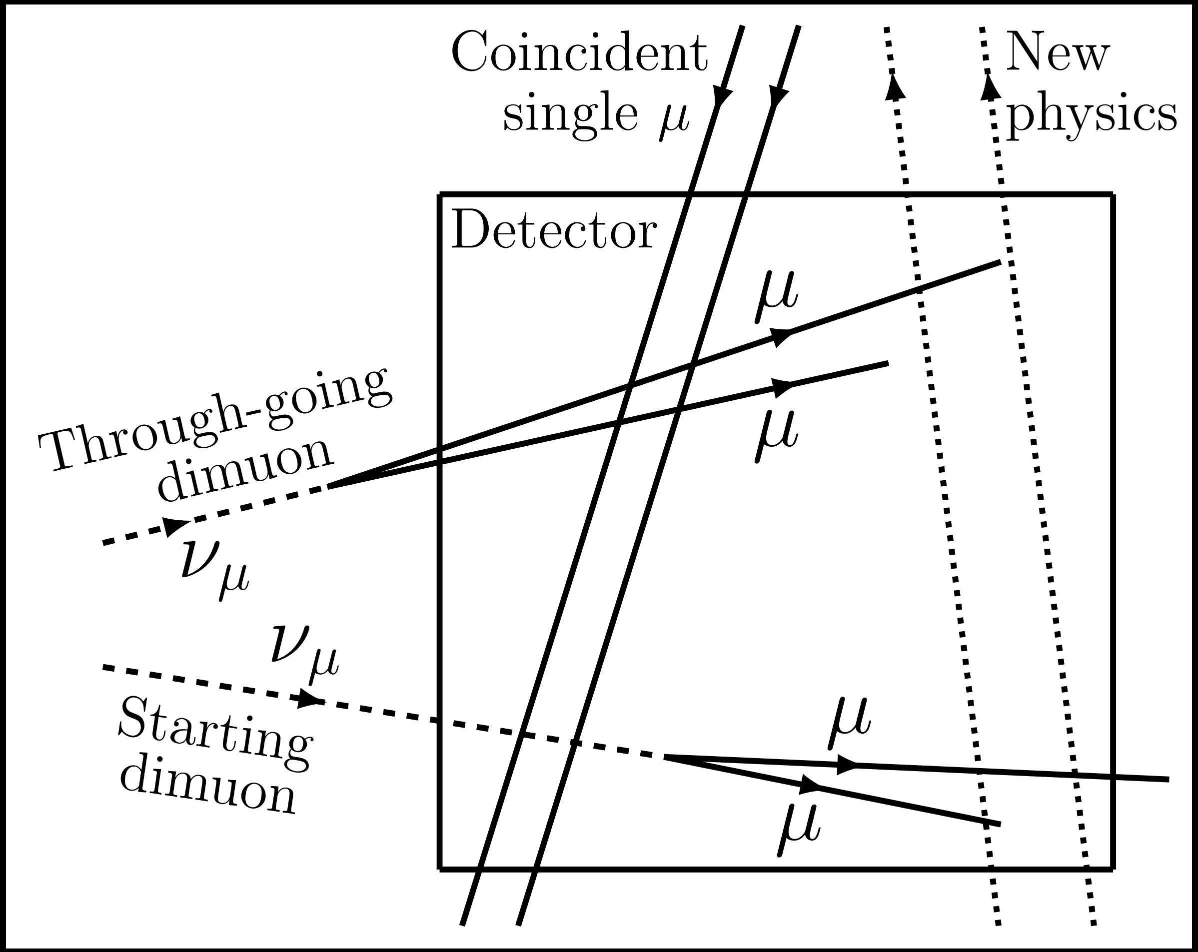
Theoretical work

What is dimuon (double muon)

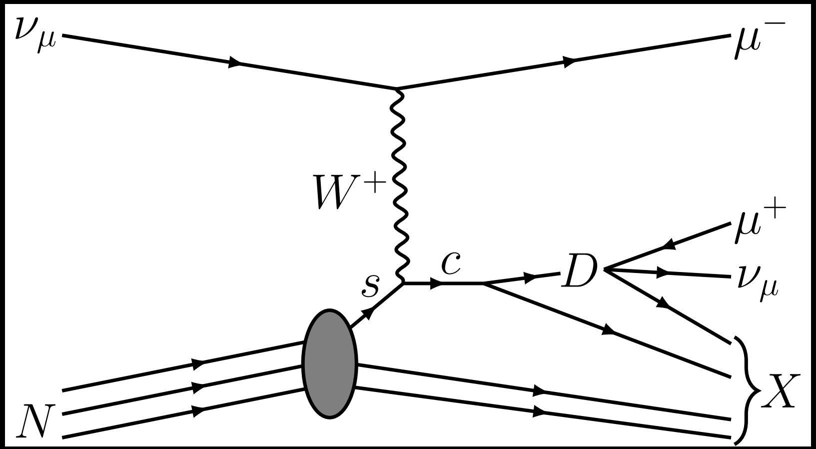


- Coincident single muons
  - background for dimuon,
  - negligible for most cases
- Standard model dimuon
  - Interesting, focus of our work
- BSM dimuon/dimuon-like
  - E.g., double staus from SUSY models
  - More to be studied in this direction

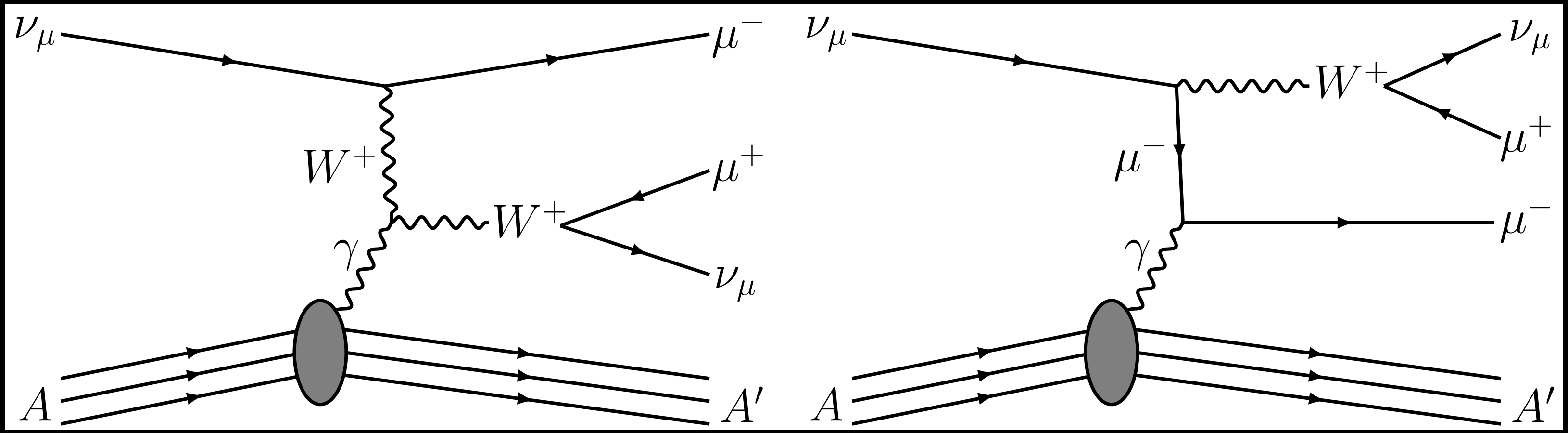
(BZ, Beacom, 2110.02974)

How could one neutrino produce two muons

Deep inelastic scattering (DIS)



(On-shell) W-boson production (WBP)



(BZ, Beacom, 1910.08090, 1910.10720)

DIS is the dominate channel for detecting high-energy neutrinos.

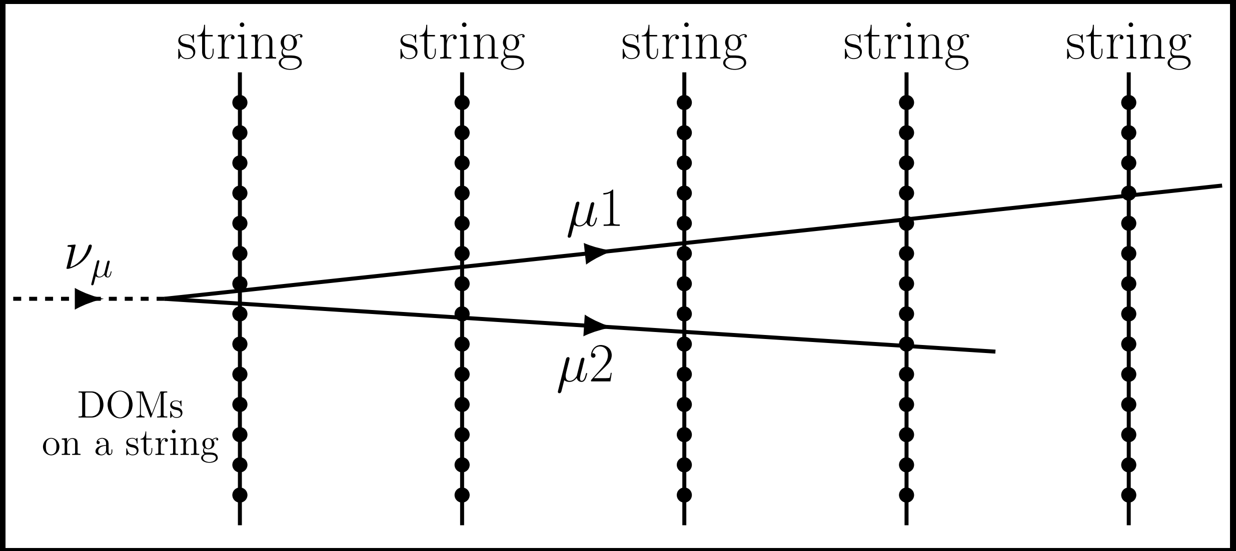
Detected at tens—hundreds GeV, never above a TeV.

WBP is the 2nd most important channel for detecting high-energy neutrinos,

but never identified yet.

How to detect dimuons in TeV--PeV neutrino telescopes

Inside a high-energy neutrino detector



(BZ, Beacom, 2110.02974)

Angular threshold:

$$R_{\mu 2}\theta_{\mu\mu} > 2D_{\mathrm{v}}$$

μ1-μ2 separation

Spacing between adjacent DOMs

Energy Threshold:

100 GeV for IceCube
300 GeV for IceCube-Gen2

First calculational framework for dimu in ν telescopes

(BZ, Beacom, 2110.02974)

Starting dimuons:

$$\frac{dN^{\rm st}_{\mu\mu}}{dE_{\mu1/2}} = N_t T \int_{E_{\rm th}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu}(E_\nu) \frac{d\sigma^{\rm cuts}_{\mu\mu}}{dE'_{\mu1/2}}(E'_{\mu1/2}, E_\nu | E'_{\mu2} > E_{\rm th}) \,,$$

Throughgoing dimuons:

Flux

Interactions

Detector angular threshold

$$\frac{dN^{\rm thr}_{\mu\mu}}{dE_{\mu2}} = \frac{A_{\rm det} T N_A}{\alpha + \beta E_{\mu2}} \int_{E_{\mu2}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu}(E_\nu) \int_{E_{\mu2}}^{E_\nu} dE'_{\mu2} \frac{d\sigma^{\rm cuts}_{\mu\mu}}{dE'_{\mu2}}(E'_{\mu2}, E_\nu) \,, \text{ and}$$

$$\frac{dN^{\rm thr}_{\mu\mu}}{dE_{\mu1}} = \frac{A_{\rm det} T N_A}{\alpha + \beta E_{\mu1}} \int_{E_{\mu1}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu} \int_{E_{\mu1}}^{E_\nu} dE'_{\mu1} \int_{E'_{\mu2,\rm th}}^{E'_{\mu1}} dE'_{\mu2} \frac{d^2\sigma^{\rm cuts}_{\mu\mu}}{dE'_{\mu1} dE'_{\mu2}}(E'_{\mu1}, E'_{\mu2}, E_\nu) \,,$$

Energy losses

Detector energy threshold

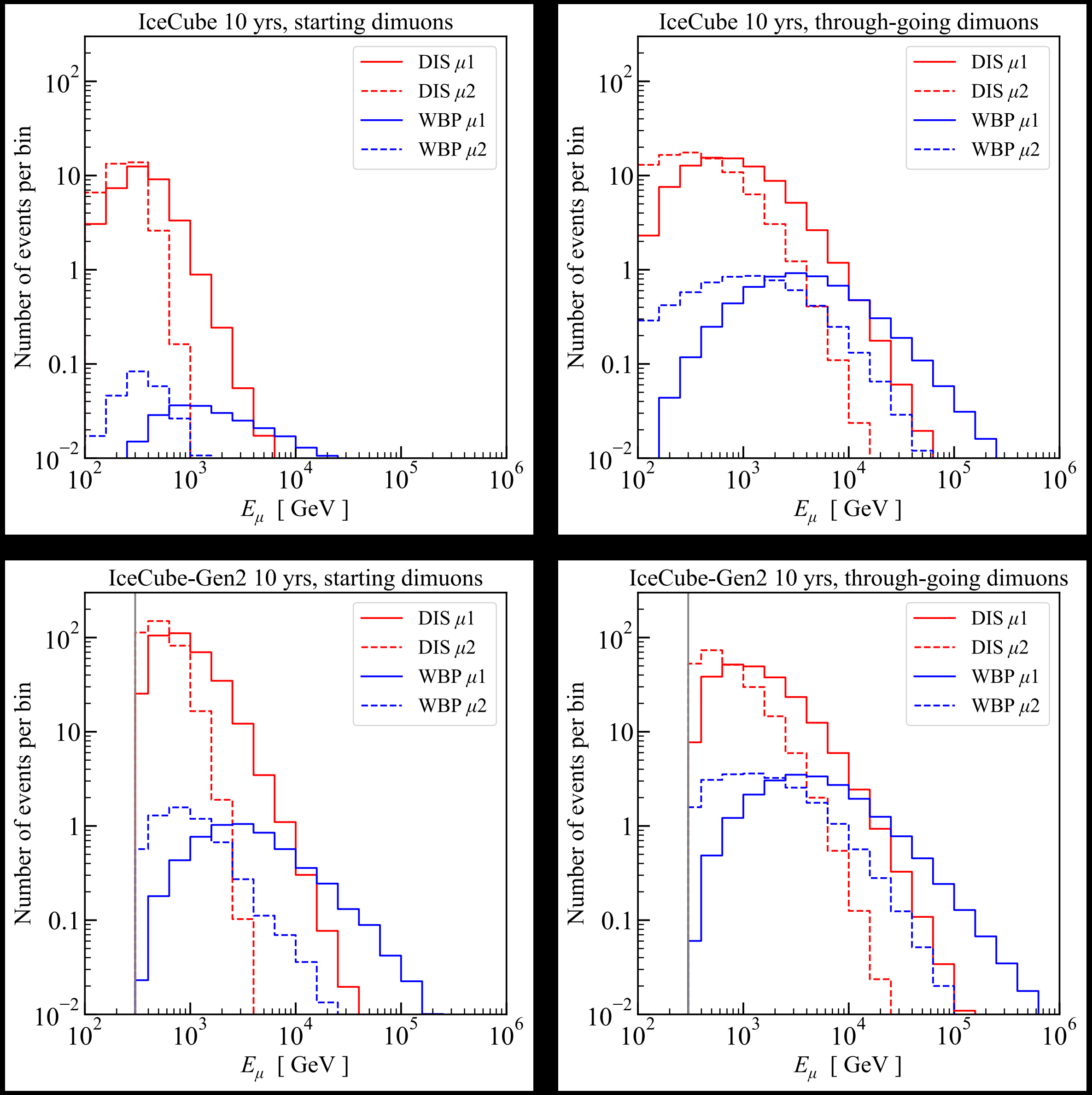
$$E'_{\mu2,\rm th} = \left(\frac{E'_{\mu1} + \epsilon}{E_{\mu1} + \epsilon}\right)(E_{\rm th} + \epsilon) - \epsilon$$

Dimuon rates in IceCube and IceCube-Gen2

Our predicted number of dimuons

	Starting		Throughgoing	
	DIS	WBP	DIS	WBP
IceCube, 10 yrs	37	0.3	85	6.0
IceCube-Gen2, 10 yrs	370	5.8	231	22

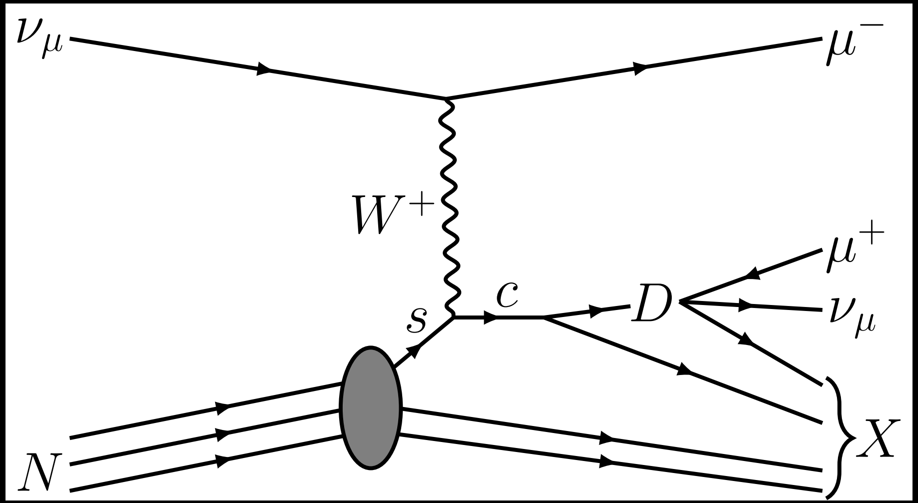
(Note IceCube has run for > 10 years)

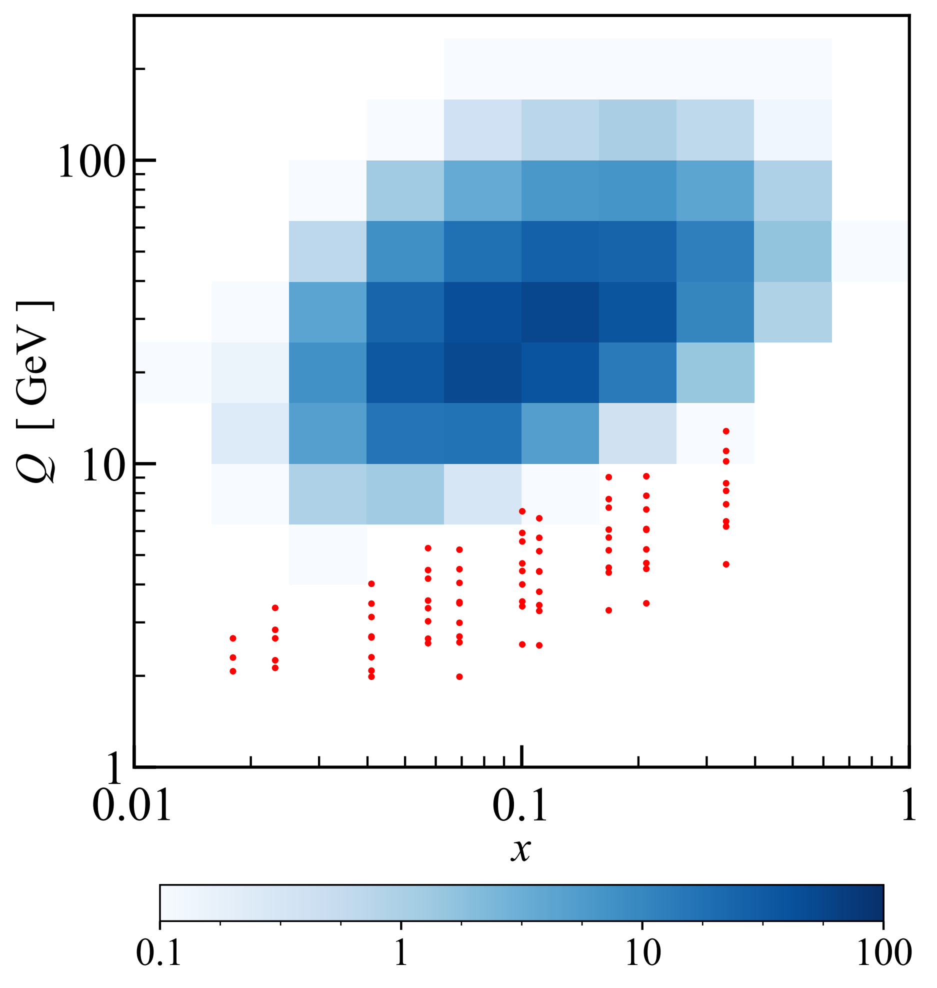


Physics potential: measuring the strange-quark PDF

(Note this measurement can be done with current IceCube data)

Deep inelastic scattering (DIS)



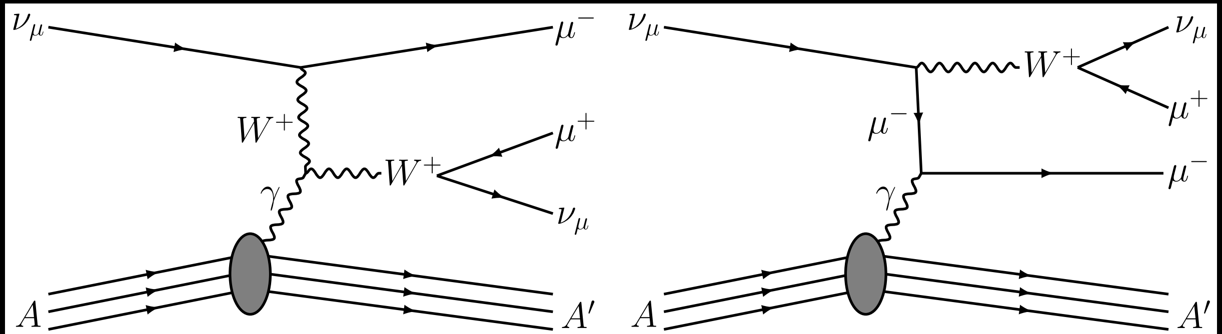


(BZ, Beacom, 2110.02974)

Physics potential: first detection of WBP

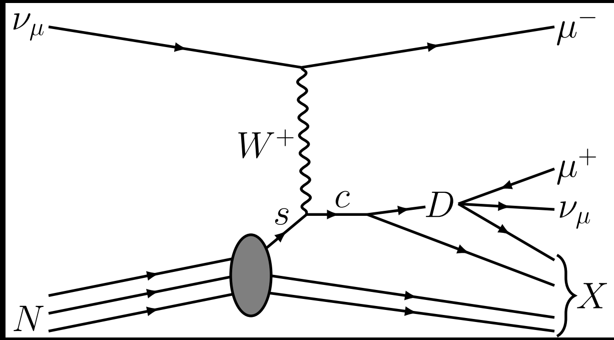
with showerless starting dimuons

Signal: W-boson production (WBP)



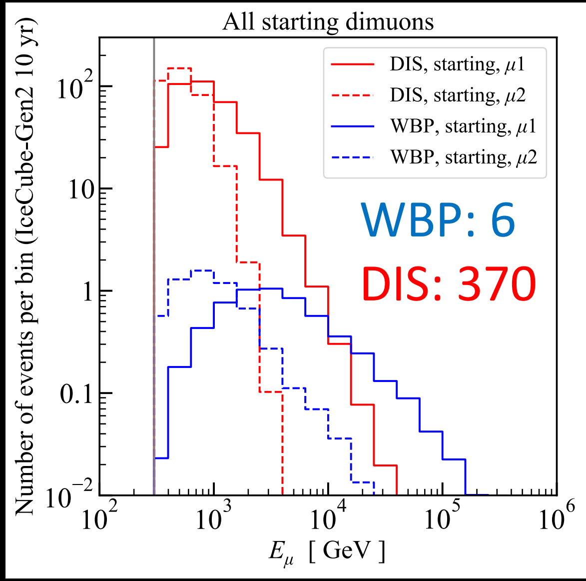
A': No shower

Background: deep inelastic scattering (DIS)

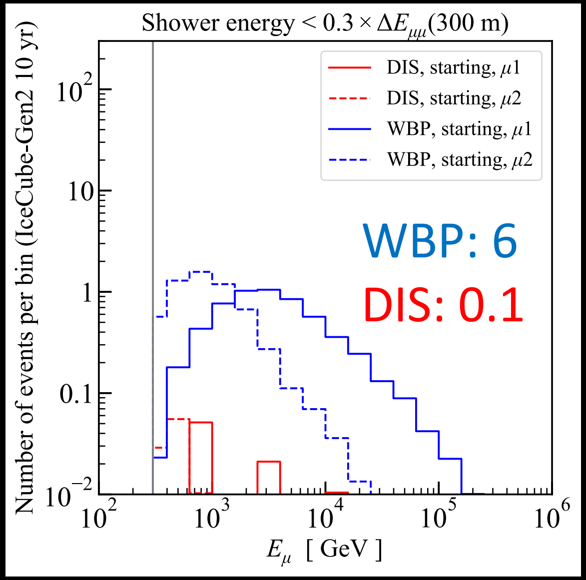


X: Mostly shower

Before shower cut



After shower cut



Other implications

- Better energy measurements for throughgoing dimuons than single muons

- Background for new physics searches
    - E.g., neutrino induced di-staus from some SUSY models

Part 2: observational work

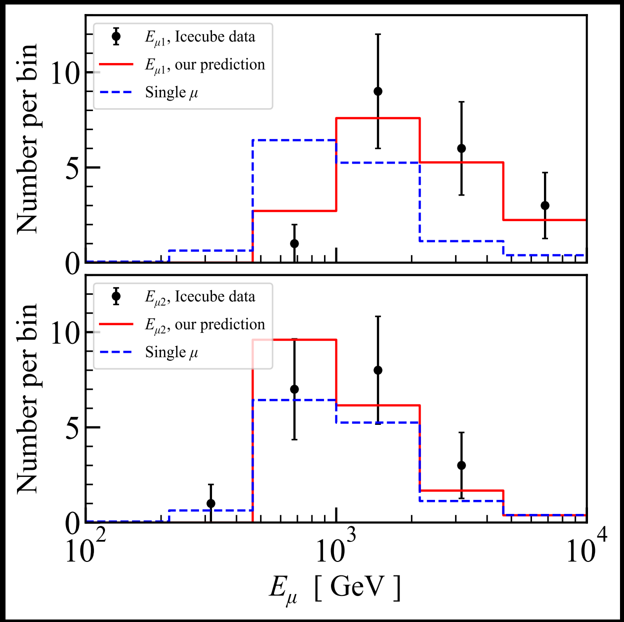
First search for dimuons in a neutrino telescope

- IceCube’s limited public data which have muon neutrino events covering all sky and 10 years.

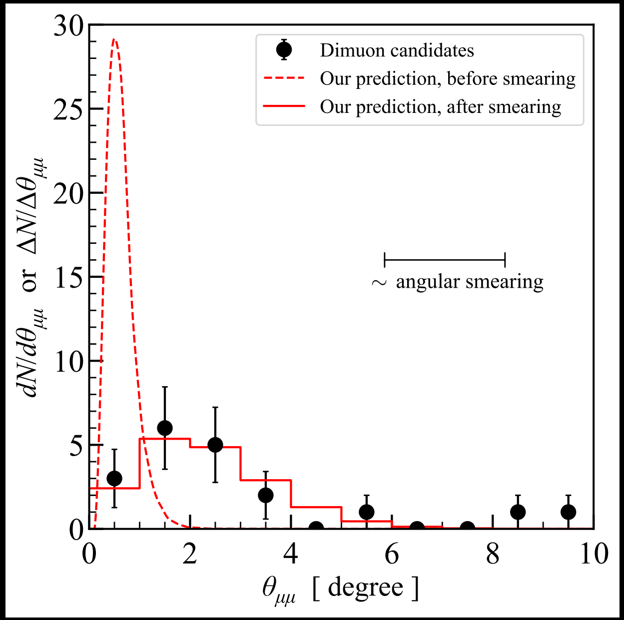
- We analyzed the data and found 19 candidates.

Agrees with our prediction

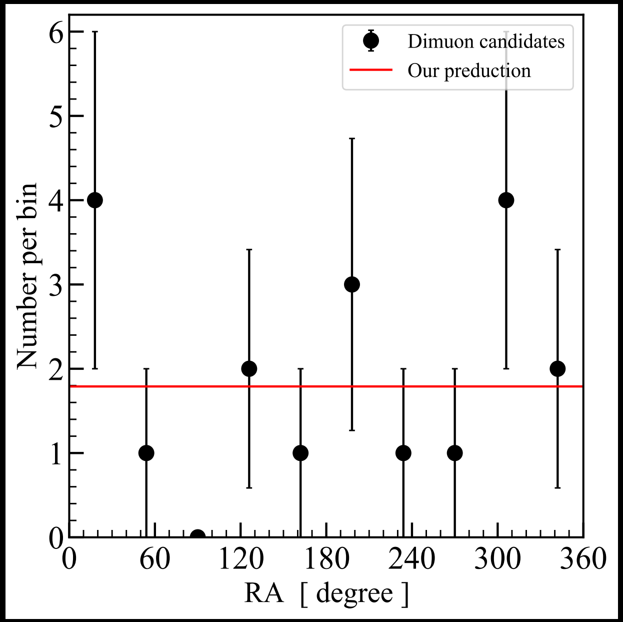
energy distribution



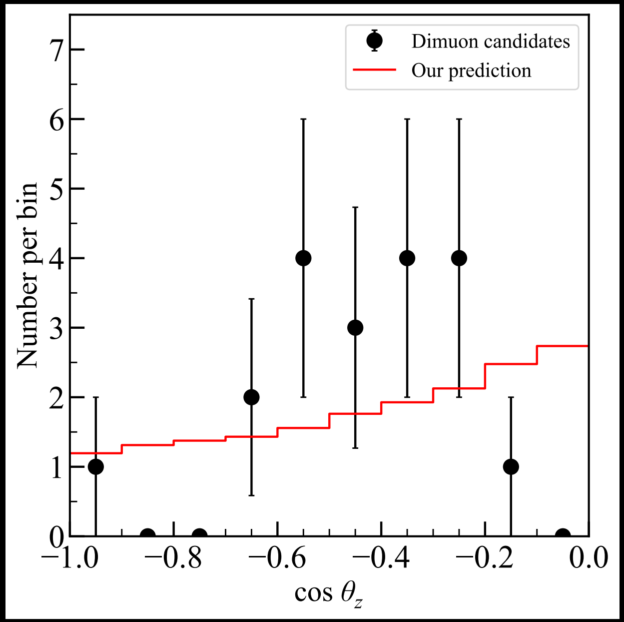
angular distribution



RA distribution



zenith distribution



(BZ, Beacom, 2110.02974)

Outcomes of these candidates

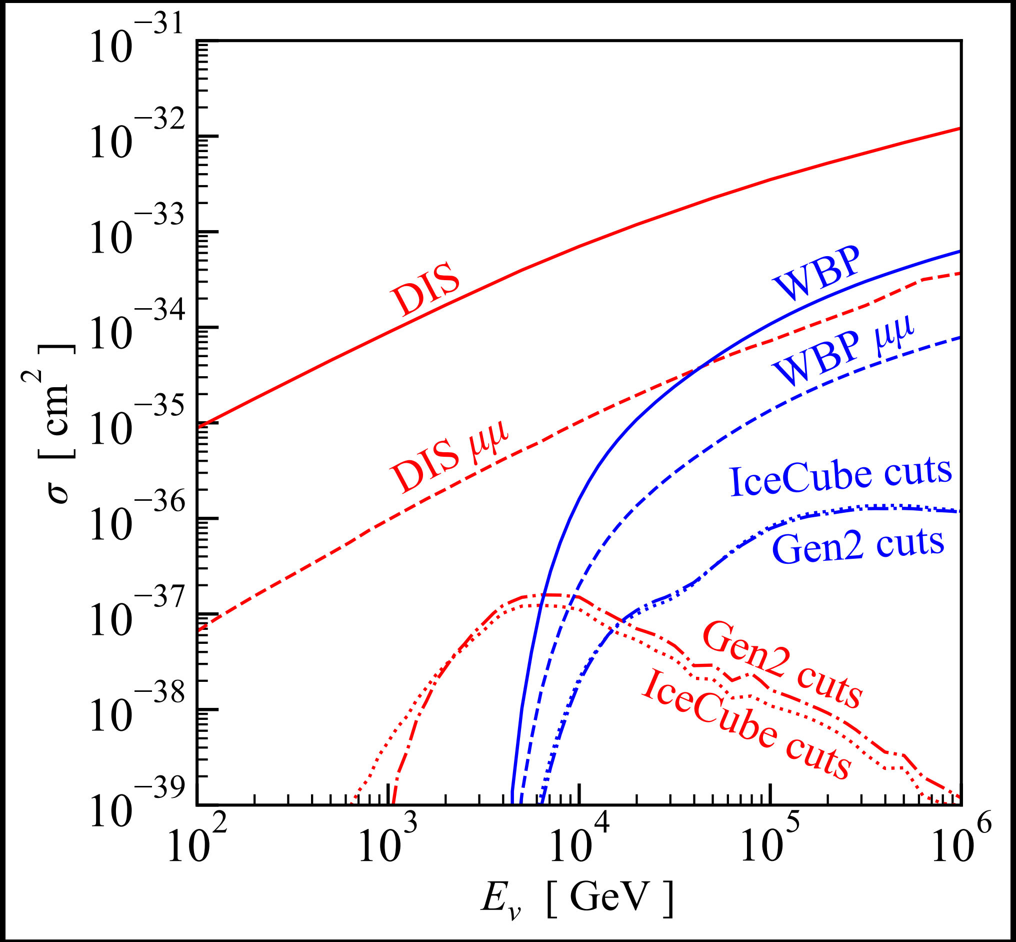
- Subsequent to our paper appearing, IceCube collaboration did a visual inspection to these candidates, and found that they are not real dimuons.
- They are, instead, due to an internal reconstruction error that identifies some single muons crossing the dust layer as two separate muons.
- IceCube has started an analysis searching for dimuons.

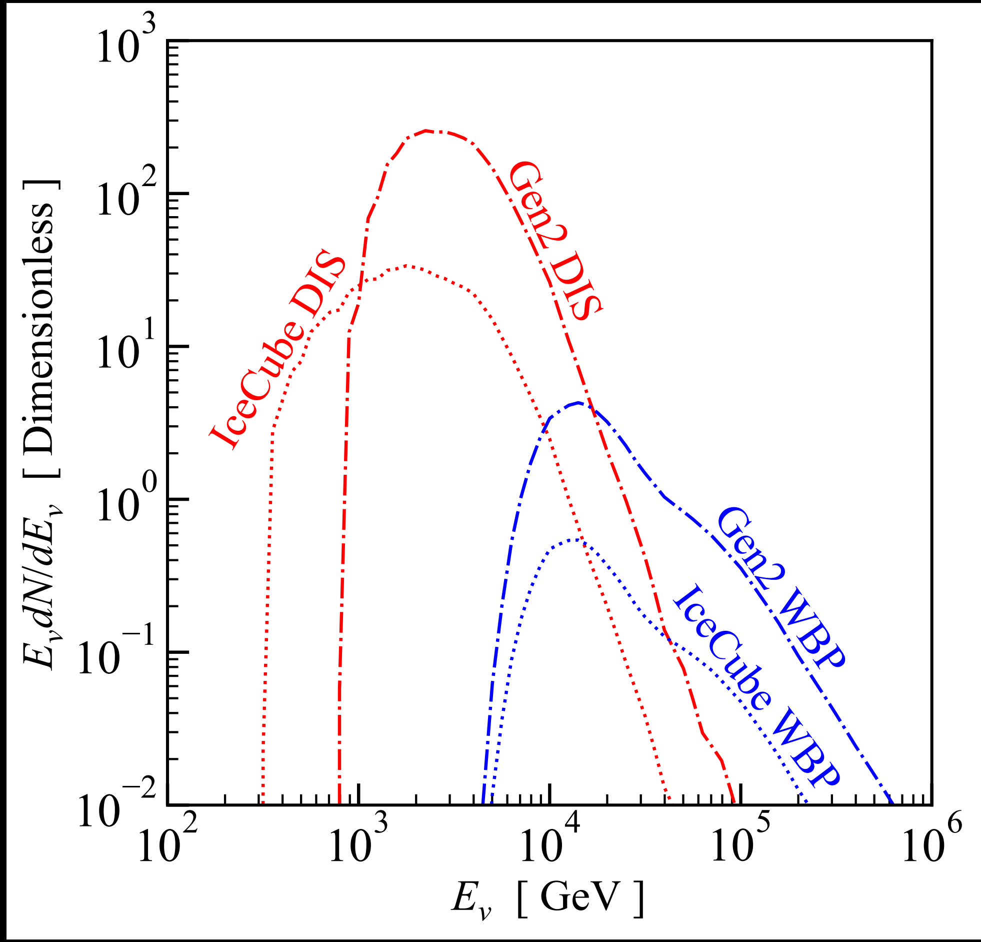
Conclusion

- We studied dimuons as a new event class for high-energy neutrino telescopes
- IceCube has $\simeq$130 events and IceCube-Gen2 will detect $\simeq$620 in 10 years
- They have significant physics potentials
- We did a first search of dimuons with IceCube publica data and found 19 candidates
  - Later they turn out to be misconstruction errors
  - But it doesn’t affect our theoretical studies above
  - IceCube has started their search for dimuons
- Dimuons may be a new direction for high-energy neutrinos

Thanks for your attention!

Dimuon cross sections and parent ν distribution





(BZ, Beacom, 2110.02974)

Physics potential: first detection of WBP

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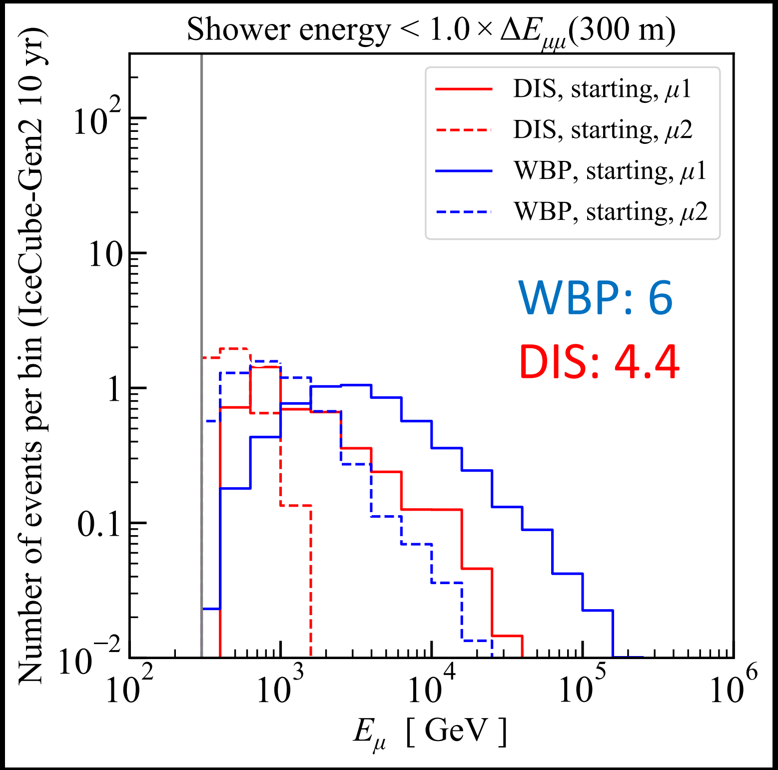
Shower energy threshold

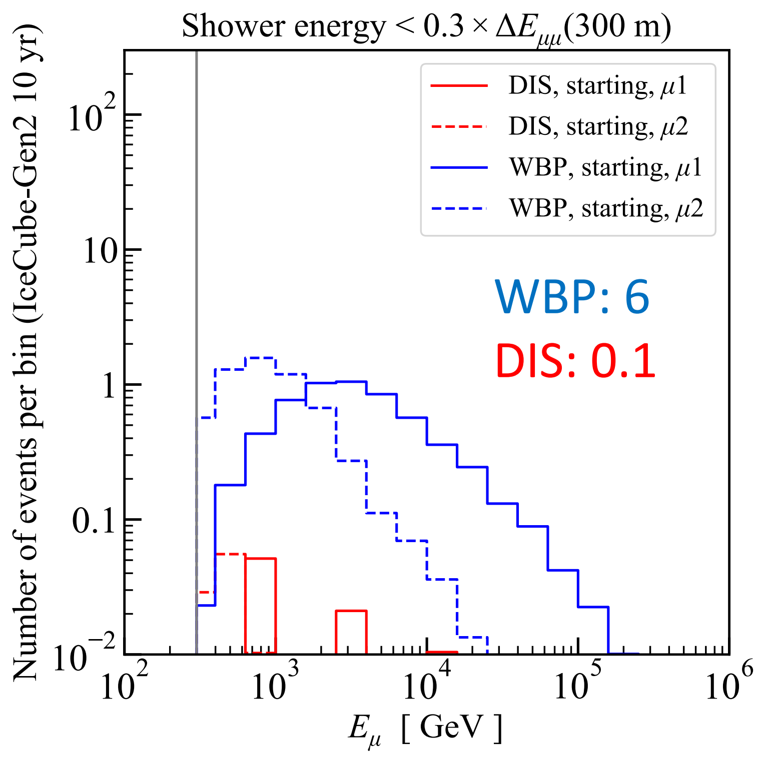
$$E_{\text{shower}} < f \times \Delta E_{\mu\mu}(L)$$

L = 300 m >~ spatial resolution

f ~ energy resolution



f = 1.0

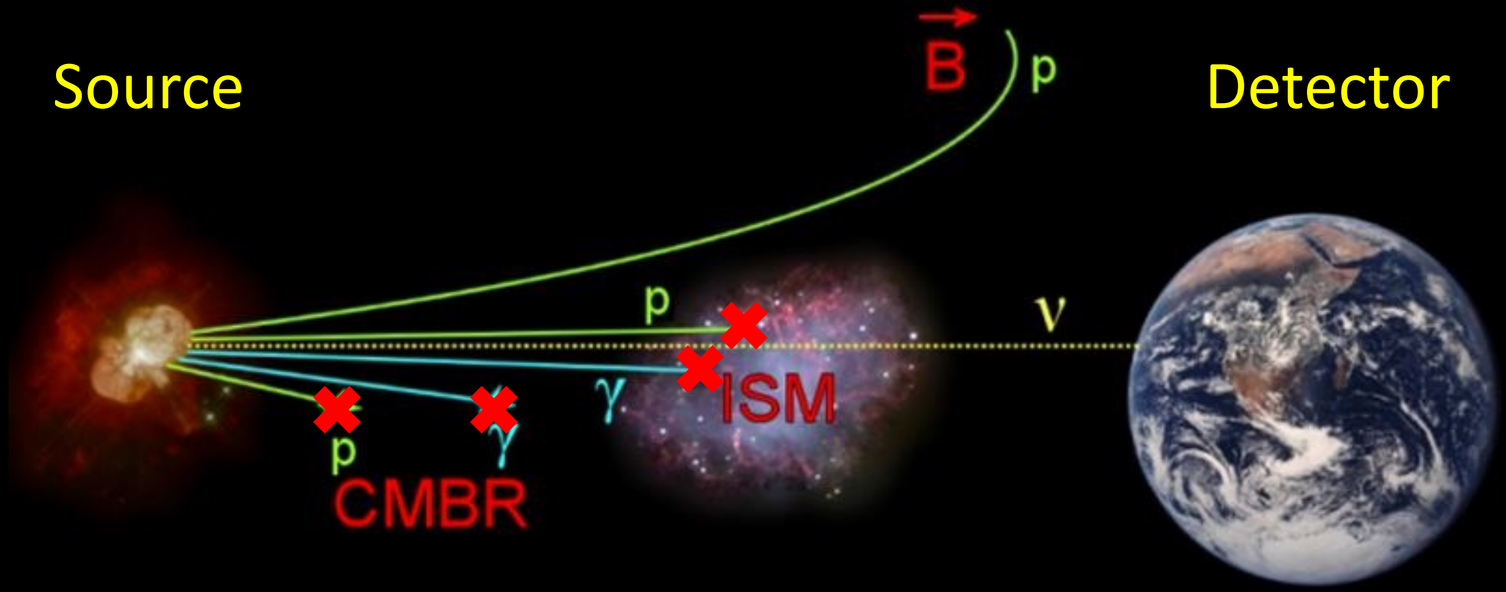


f = 0.3

(BZ, Beacom, 2110.02974)

Why do we detect/study high-energy neutrinos

1. Astrophysics: origin of high-energy cosmic rays (~long-term problem)



   - Particle acceleration mechanisms of those source
2. Gamma ray sources, hadronic vs leptonic (~long-term problem)
3. Particle physics: Neutrino properties, testing new physics (dark matter, etc.)
   - high-energy, known direction, cosmic distance, extremely high column density (through Earth)