COST Action

Rijeka (Croatia)

Quantum gravity with ultra-high-energy neutrinos

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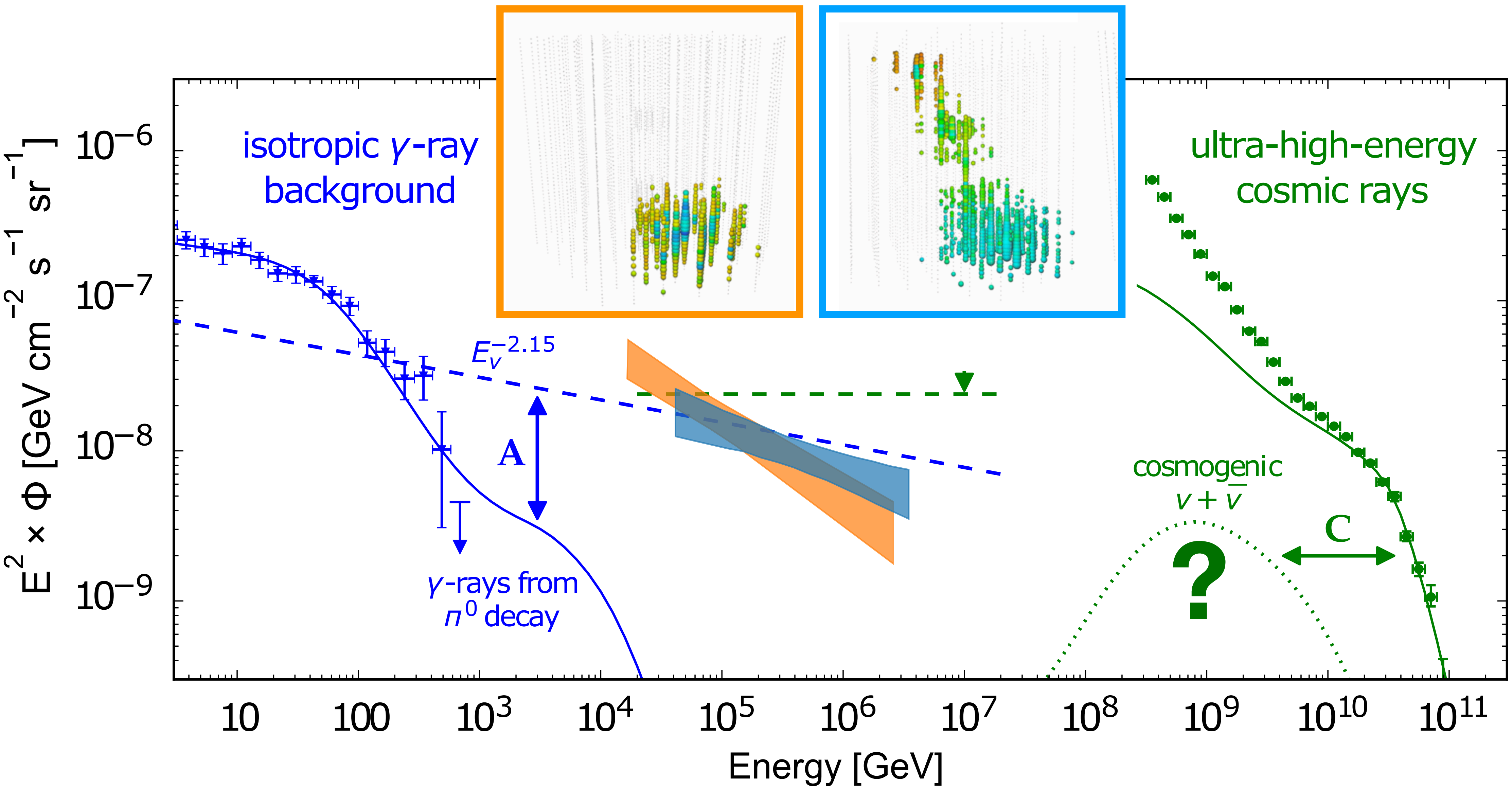
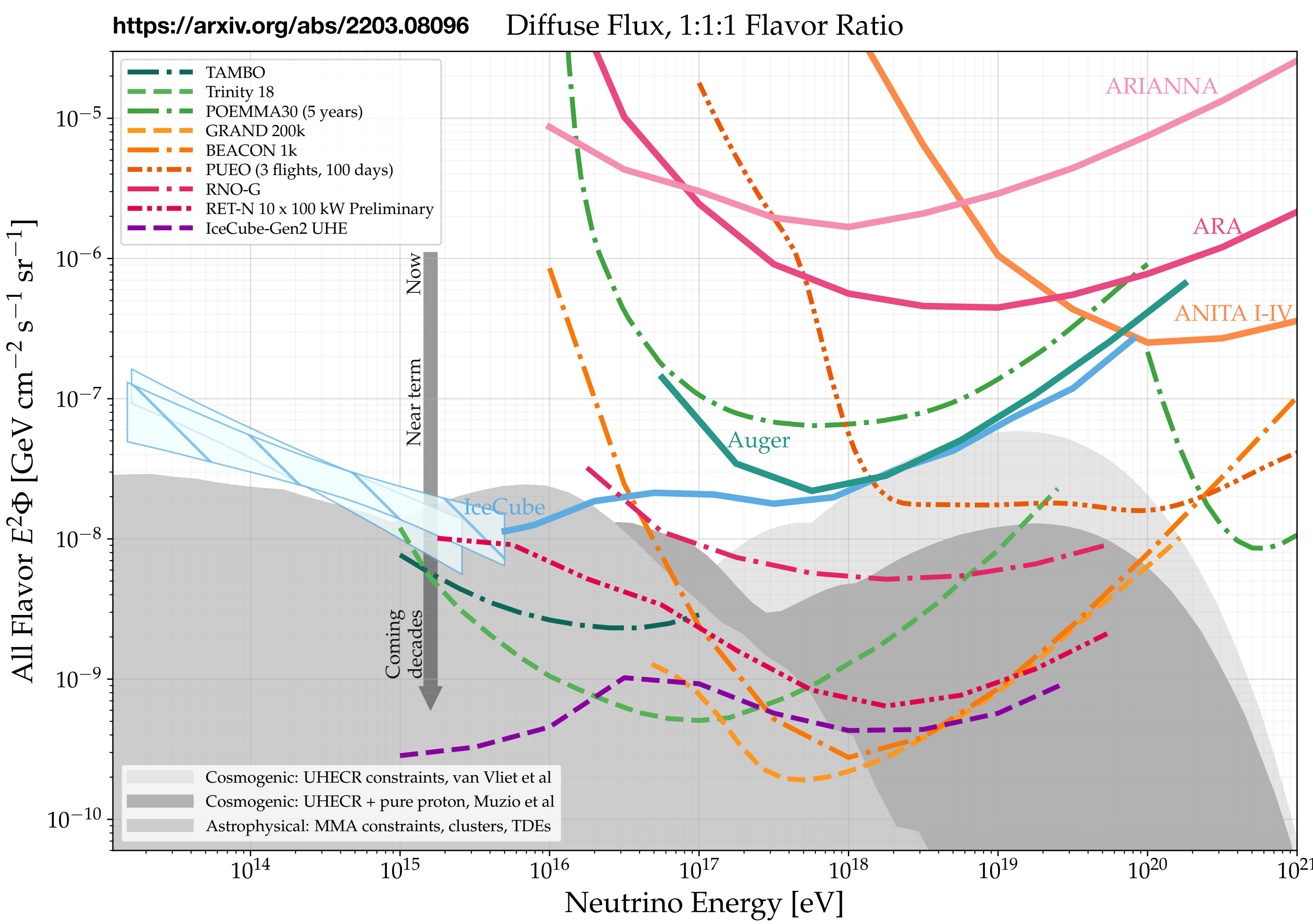
Astrophysical neutrinos

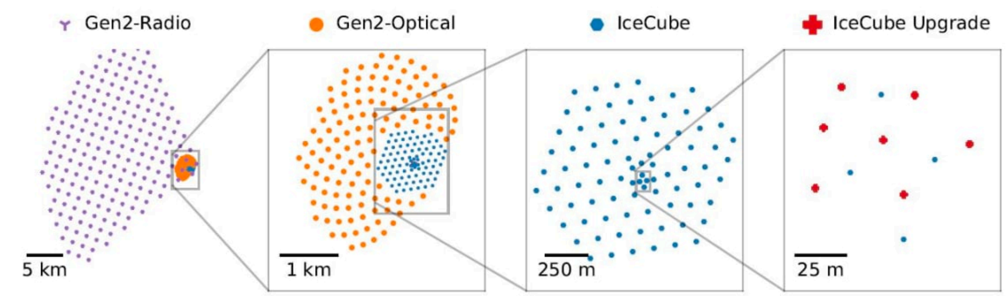
- Origin of cosmic neutrinos remain unclear -> diffuse flux.
- Several IceCube measurements of the spectrum of astrophysical neutrinos.
  - HESE -> High energy showers contained in the detector.
  - Northern tacks -> Long track patterns coming below the horizon.

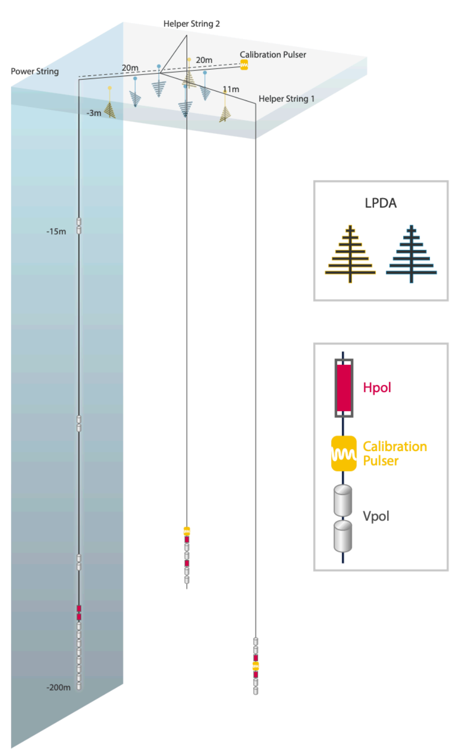


Experimental landscape

- Many proposals to detect ultra-high-energy neutrino
  - Radio technique will allow us to explore E>1 EeV!

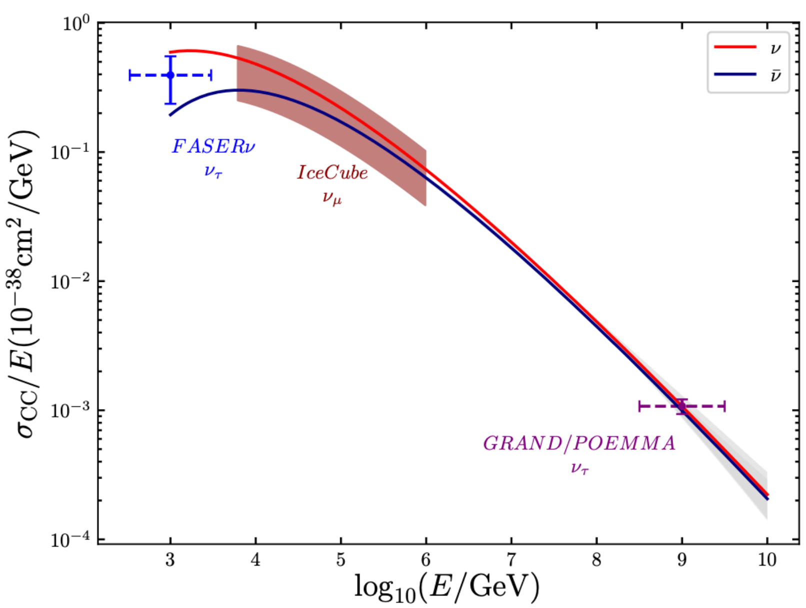




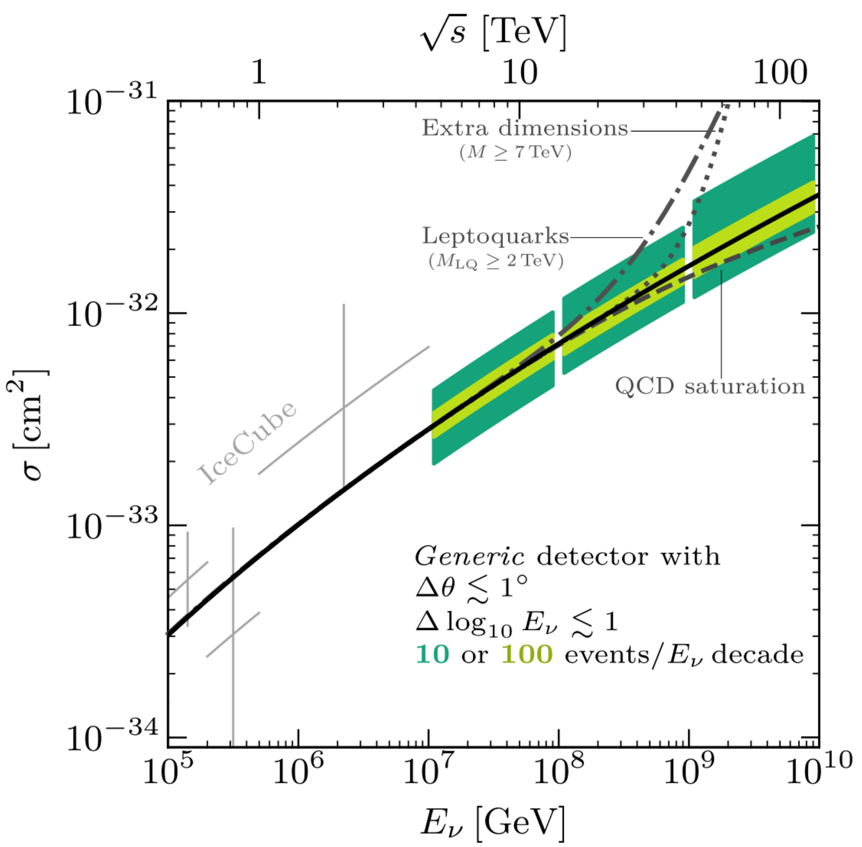


Ultra-high-energy neutrino cross section

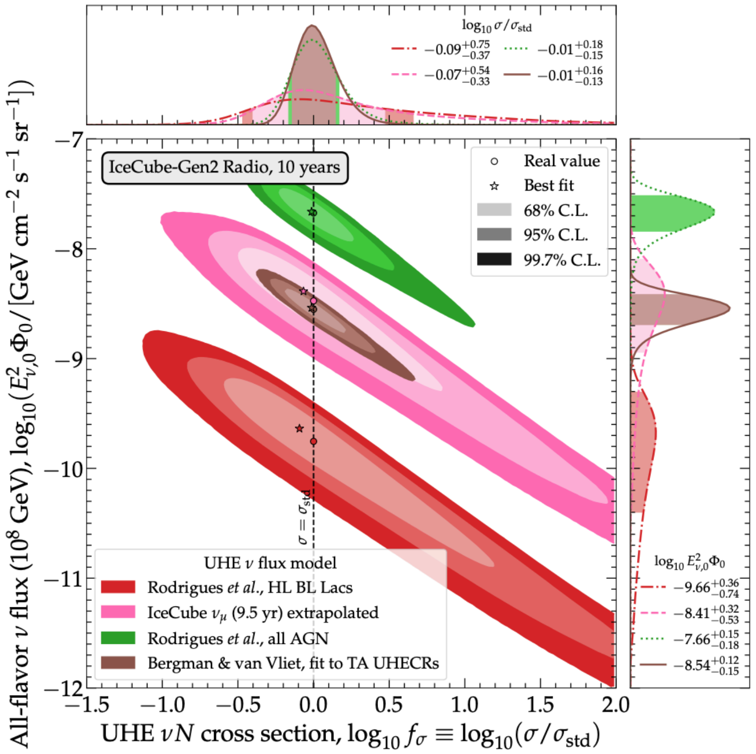
- First studies on the capability to measure neutrino cross section at these energies:
  - Angular resolution (~1deg.) is the key feature to extract the cross section -> breaks degeneracy between flux and cross section.
  - We just need enough events!
- E>2EeV probes CM energies higher than LHC -> Unexplored BSM scenarios!



https://arxiv.org/abs/2007.10334



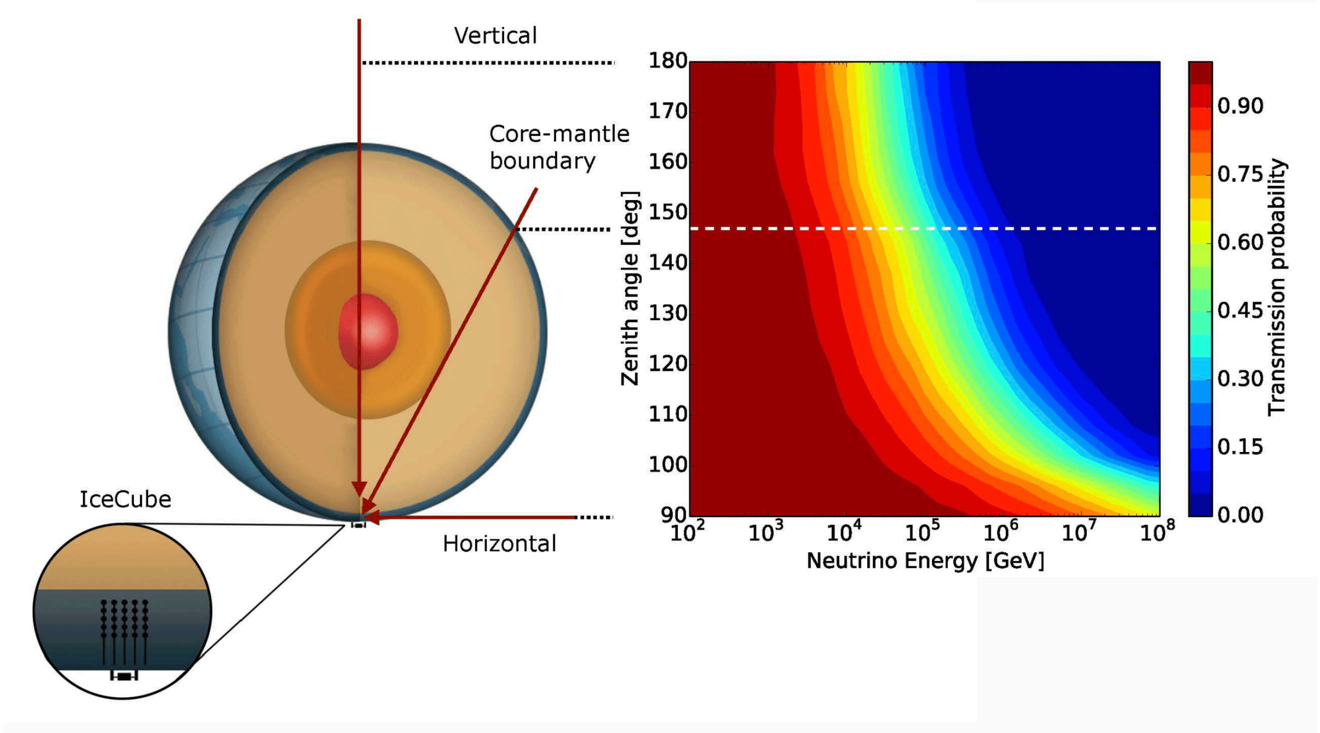
https://arxiv.org/abs/2205.09763



https://arxiv.org/abs/2204.04237

Earth absorption

- How can we disentangle between flux and cross section?
  - Neutrino attenuation becomes relevant at E~10TeV.
  - Attenuation has small dependency on underlying flux -> Att ~ $\exp(-N_{targets}(\theta)\sigma)$
- Method successfully used in IceCube.



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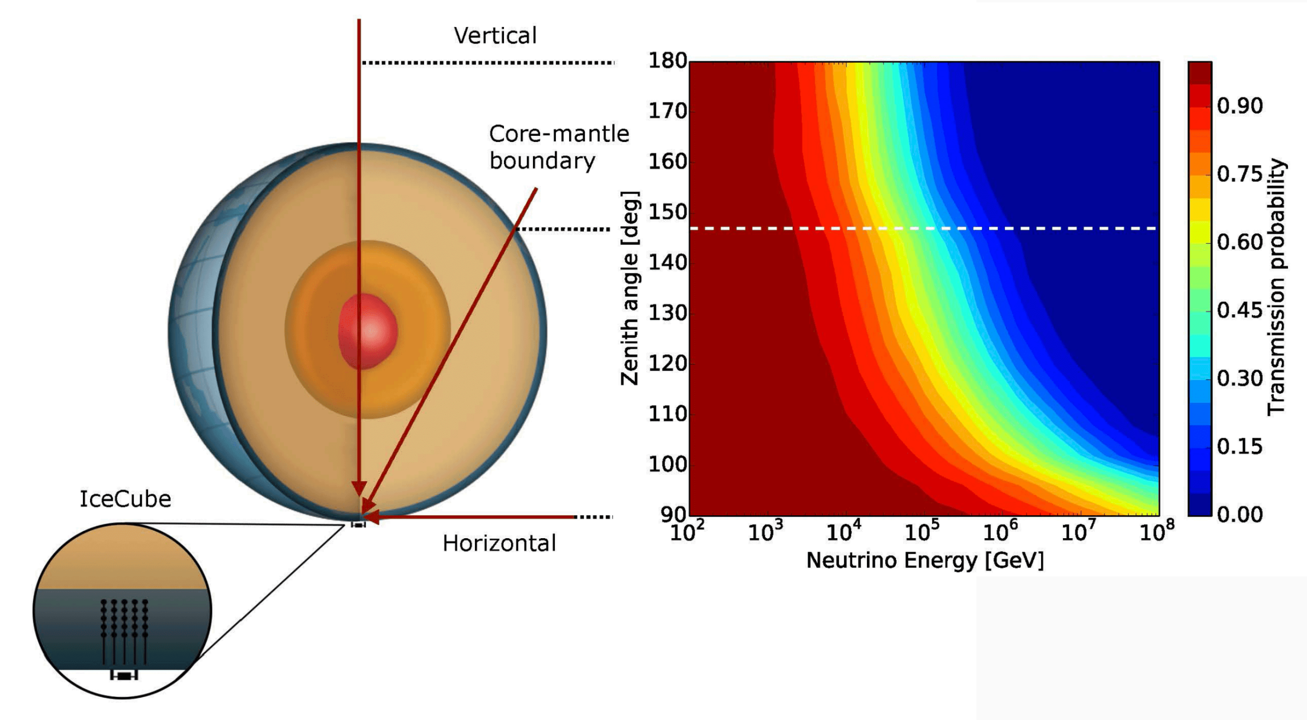

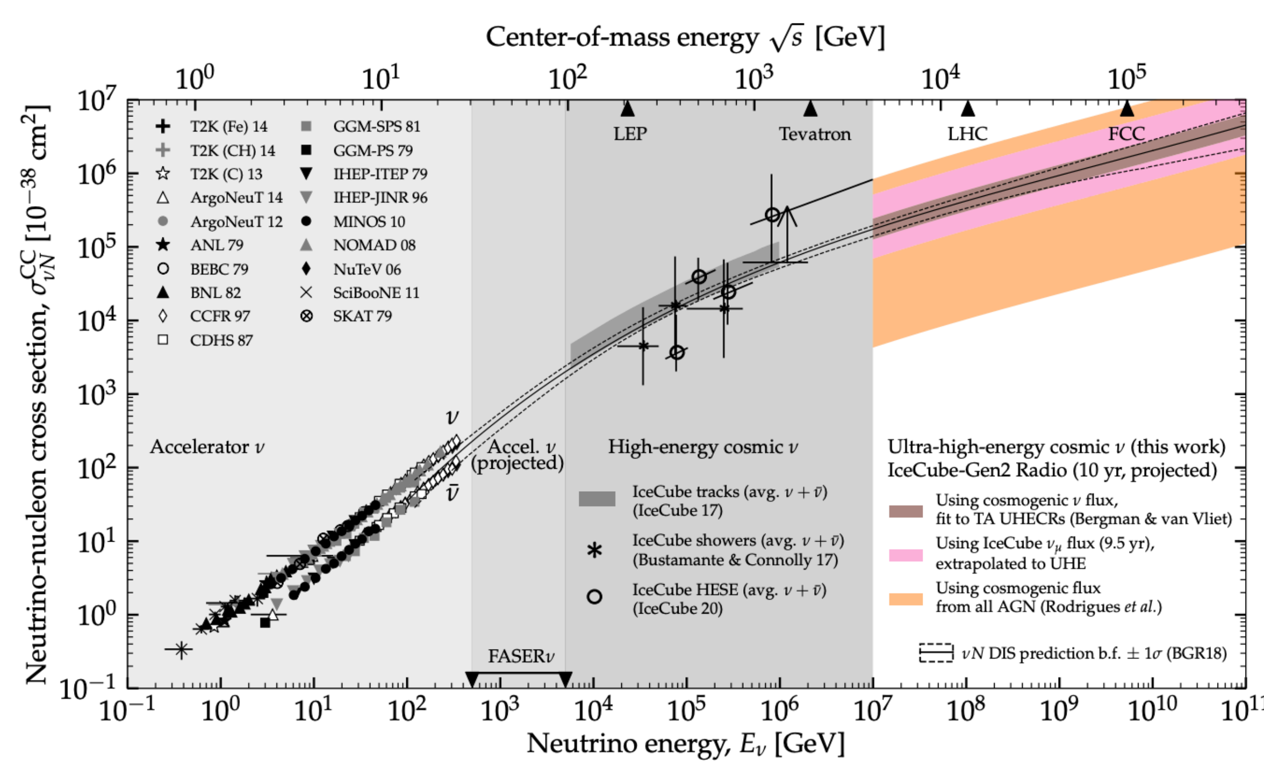

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Quantum gravity

- TeV scale gravity has been thoroughly studied in the context of high-energy neutrinos.
  - Extra dimensions: ADD and Randall-Sundrum.

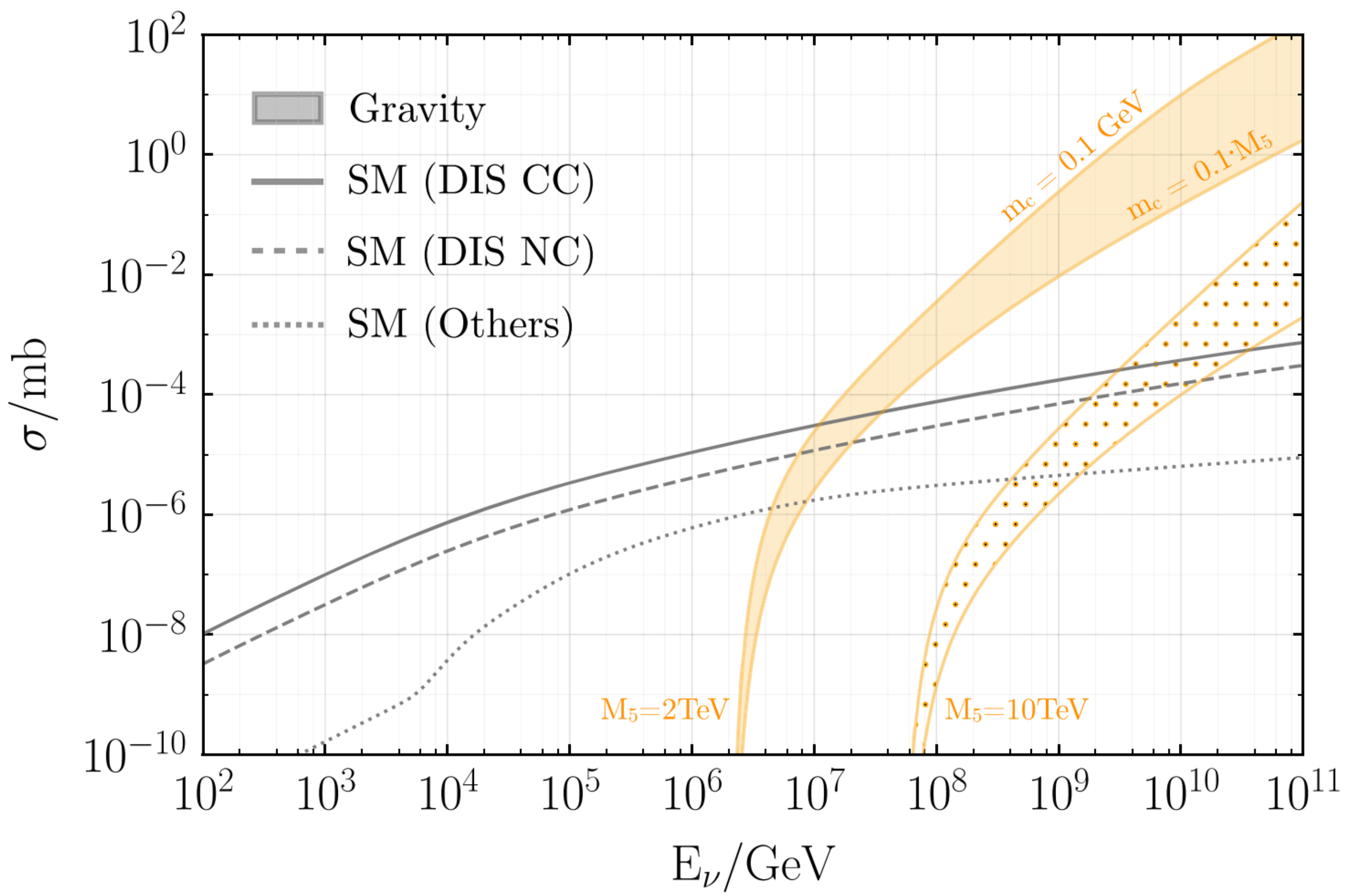
<u>BH formation from neutrinos in air:</u>
L. Anchordoqui and H. Goldberg (2001)
J. L. Feng and A. D. Shapere (2002)
S. Dutta et al (2022)
…

<u>BH formation from neutrinos in ice:</u>
Y. Uehara (2002)
J. Alvarez-Muniz (2002)
M. Kowalski (2002)
L. Anchordoqui et al (2007)
M. Reynoso et al (2013)
N. Arsene et al (2014)
K. J. Mack et al (2020)
…

<u>Eikonal scattering from neutrinos in air/ice:</u>
P. Jain et al (2002)
A.V. Kisselev (2004)
J. Illana (2005) ***Multibang***
…

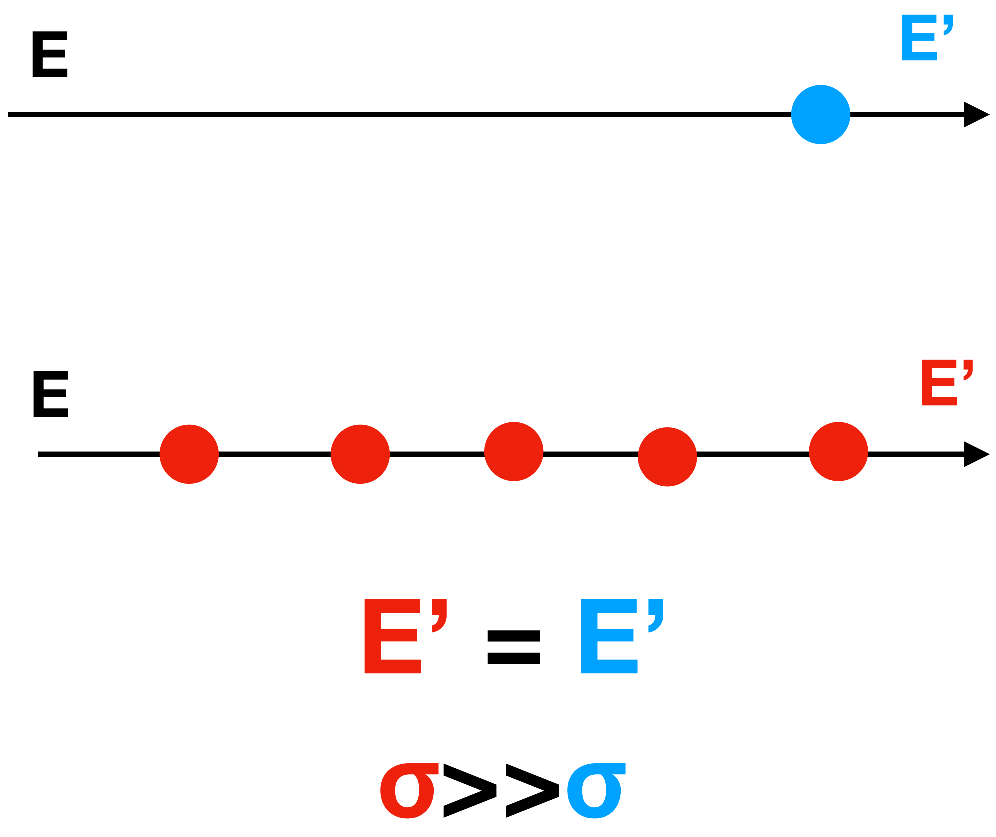
Quantum gravity

- Long distance interactions in the 5-dimensional Randall-Sundrum model
  - M_5 -> Scale where gravity becomes strong (constraints from LHC >2-4TeV).
  - m_c -> Mass of the first Kaluza-Klein excitation (constraints from cosmology >0.05 GeV).
  - Scale M_5 larger than the gap between consecutive KK modes (i.e., $m_c<M_5/10$).
- Total cross section can be significantly larger than SM at 1EeV!
  - Can we constrain this model?



Softness

- Cross section give as an idea of how likely a particle will interact.
- We need to look at the underlying differential cross section to understand how much energy is lost.
  - Different cross section may result in similar energy losses after some distance.



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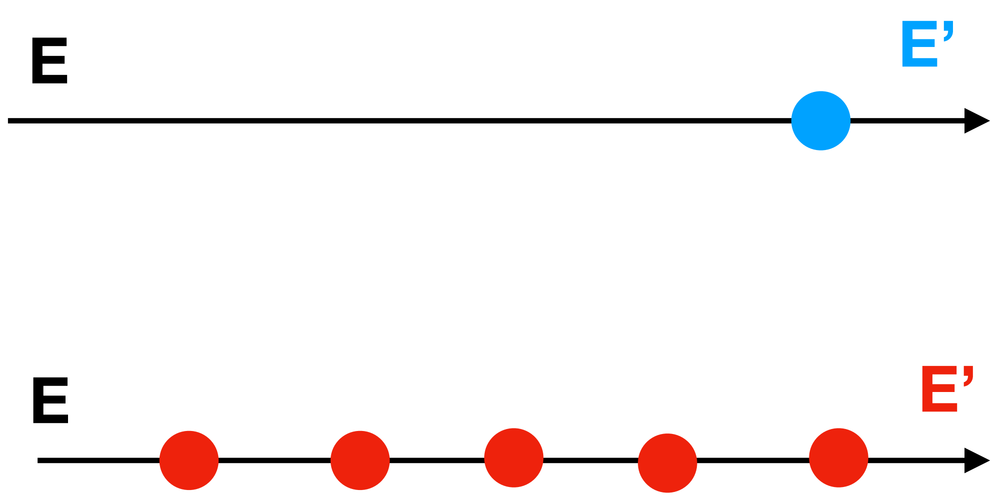
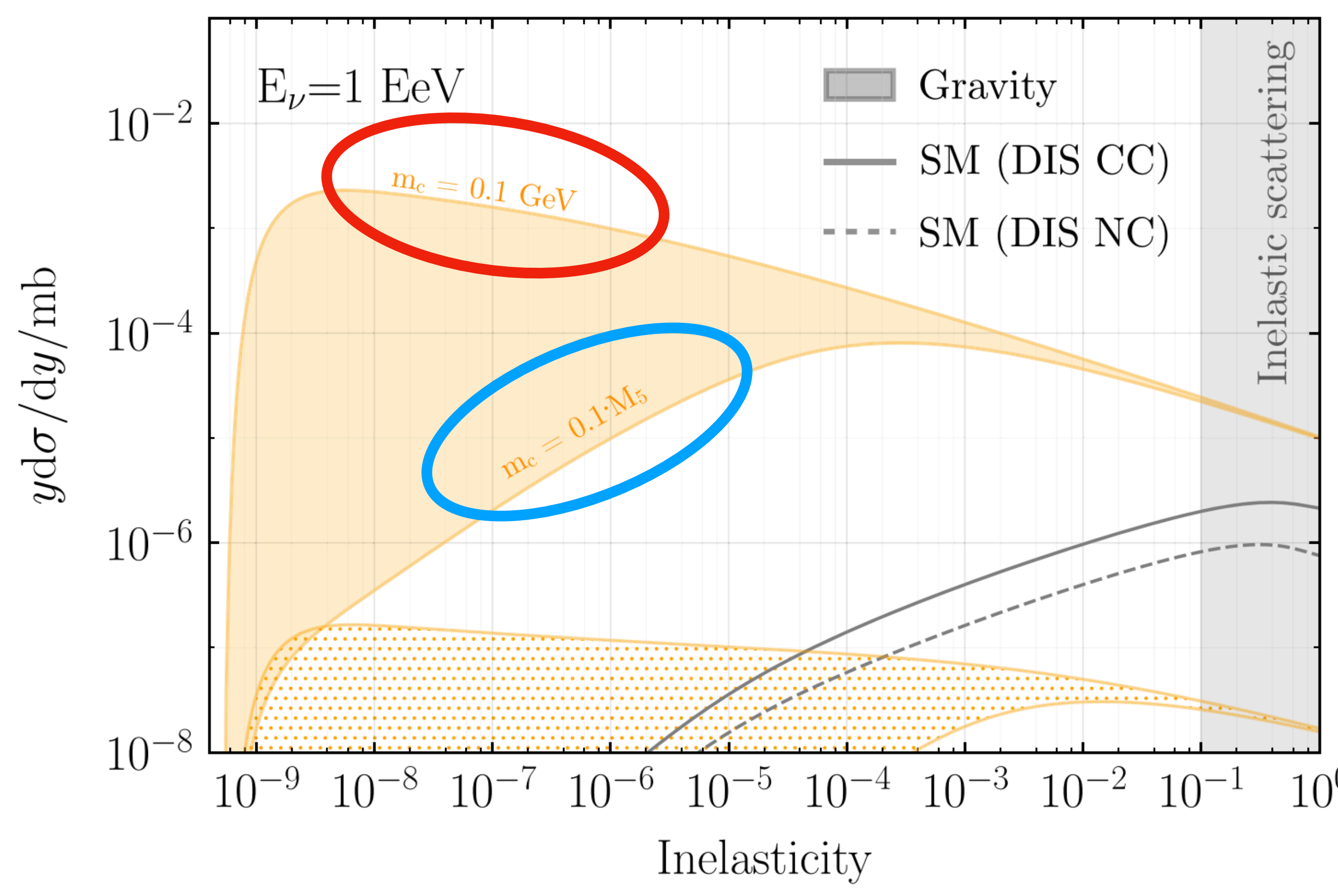


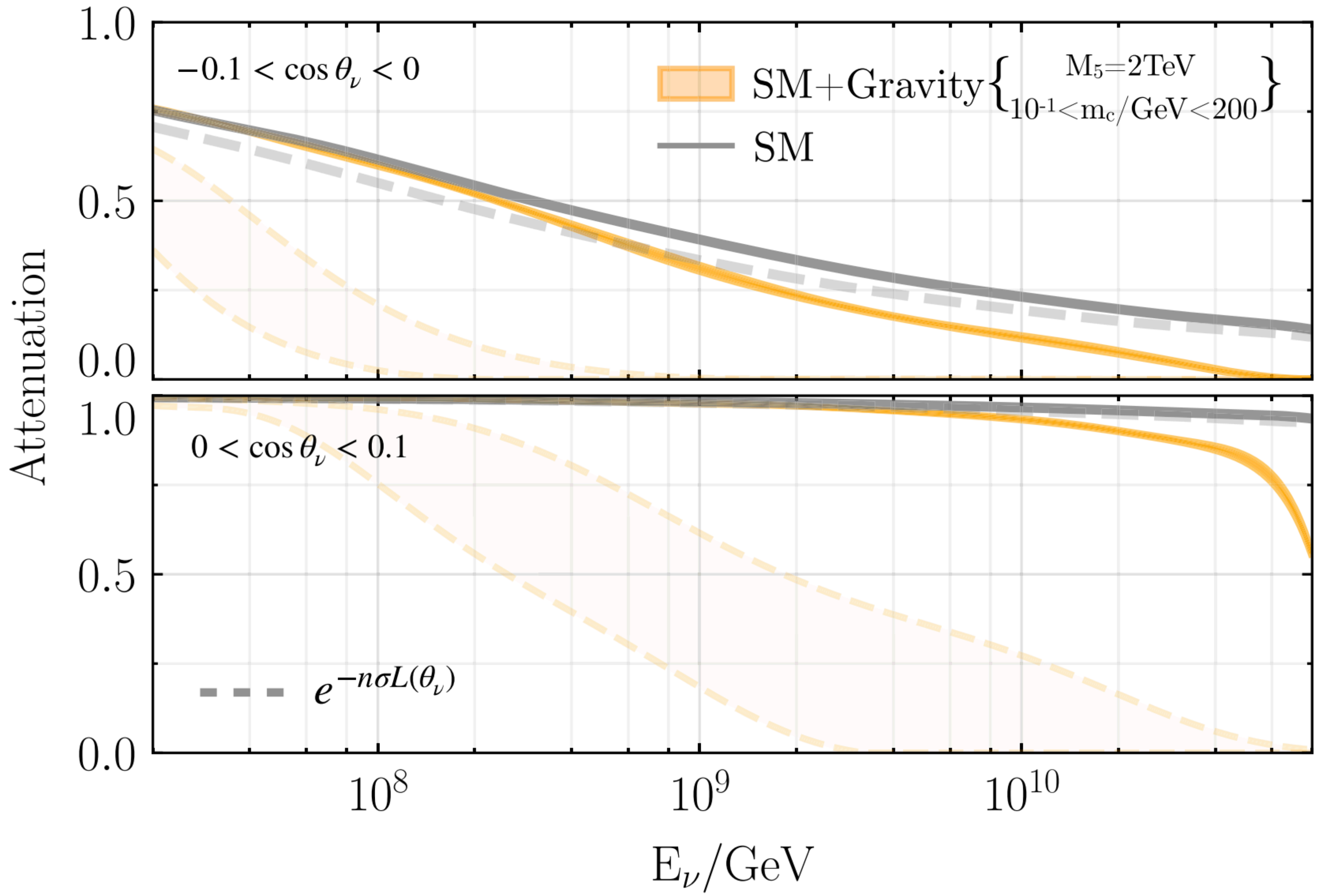
E' = E'

σ>>σ



Earth absorption for elastic scattering

- Attenuation is less affected by elastic interactions.

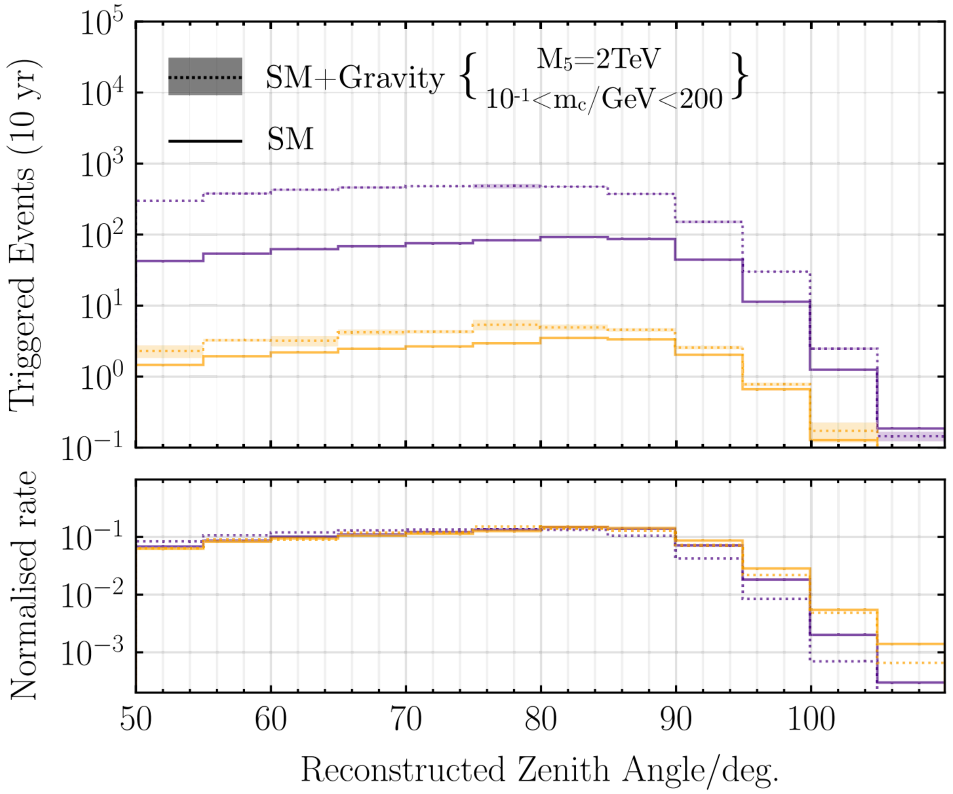


Upgoing

Downgoing

IceCube-Gen2 radio

- Simulate neutrino interactions in IceCube-Gen2 Radio (using NuRadioMC!).
  - Quantum gravity would increase significantly the number of triggered events.
  - Challenging to disentangle SM from SM+Gravity using angular information due to degeneracy with flux.
  - Energy and shower multiplicity can help.



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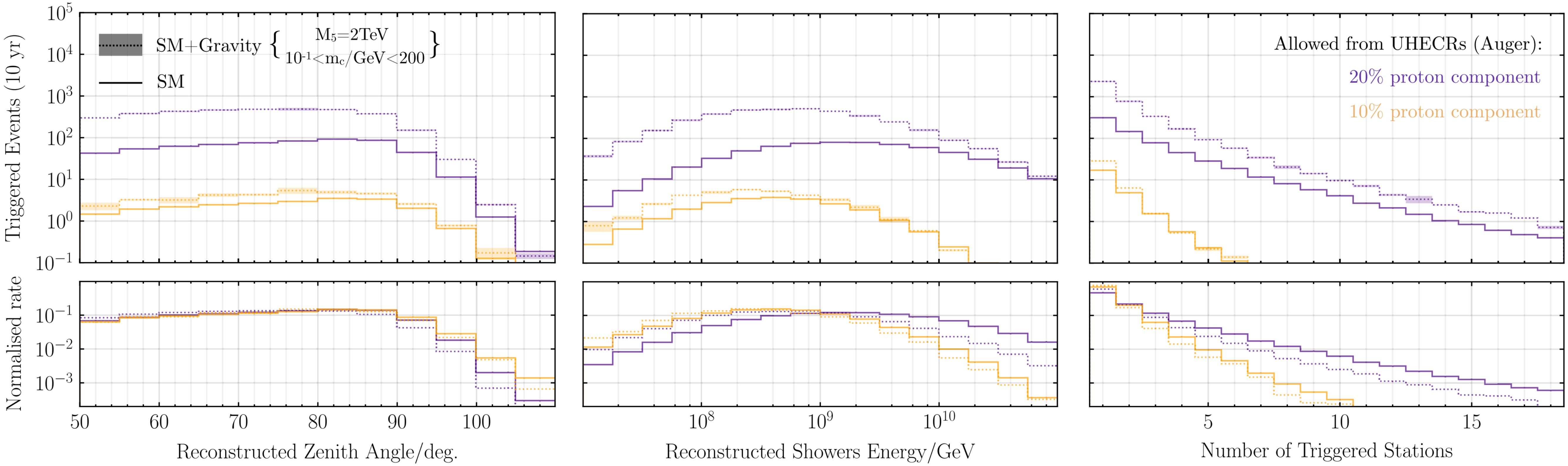

Conclusion

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- Ultra-high-energy neutrino will allow us to probe regions not reachable at LHC.
  - IceCube-Gen2 Radio will be sensitive to BSM scenarios with soft interactions.

- Soft interaction behaves quite differently to the inelastic scattering -> new ideas!
  - Shower multiplicity -> Reduce the energy threshold.

- Reduce uncertainties in the GZK flux.
  - Constraining the shape would help significantly.


Thanks

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101025085.

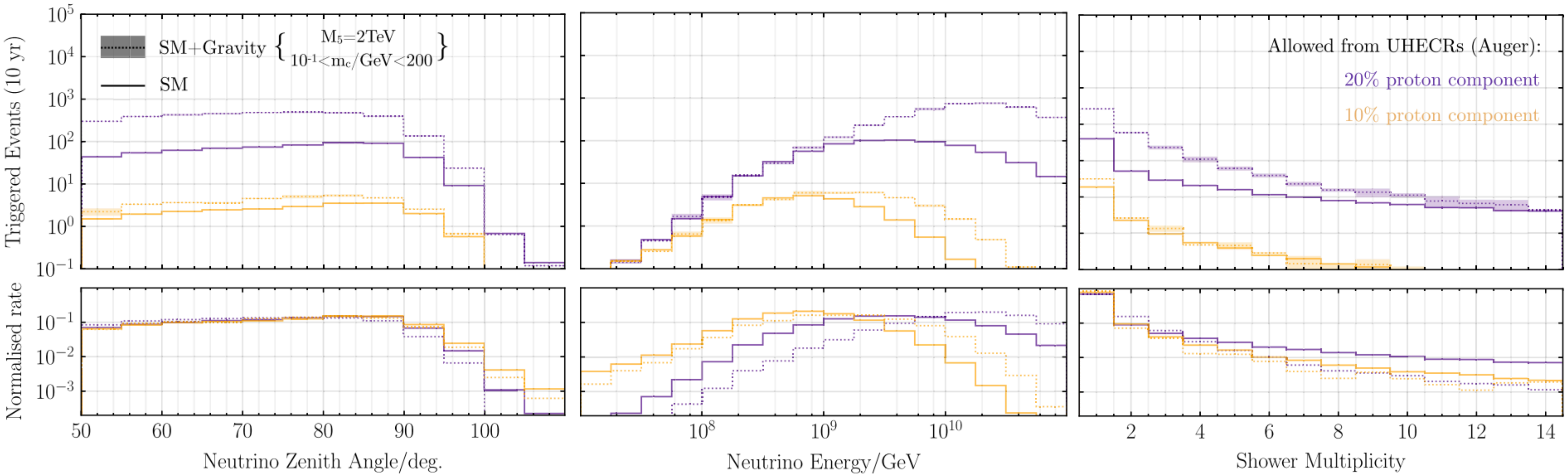
True level

$$\mathcal{A}_{\text{eik}}(s,Q^2) = 4\pi s b_c^2 F_1(b_c Q)\left(\coth\frac{\pi Q}{m_c} - \frac{m_c}{\pi Q}\right)$$

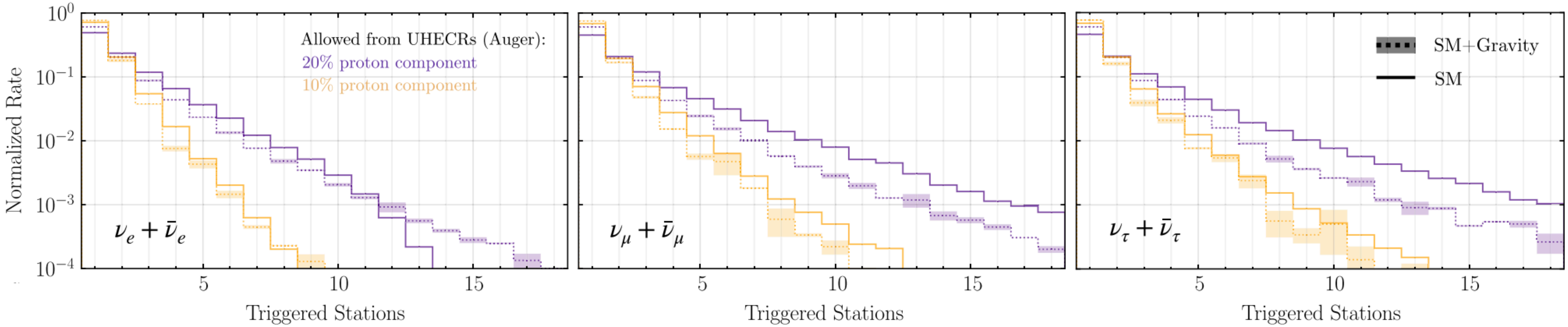
$$\frac{\mathrm{d}\sigma_{\text{eik}}}{\mathrm{d}y} = \int_{M_5/s}^{1} \mathrm{d}x\,\frac{1}{16\pi x s}\,|\mathcal{A}_{\text{eik}}(xs, xys)|^2 \sum_{q,\bar{q},G} f_i(x,\mu)$$

$$|F_1(u)| \simeq 1/\sqrt{1.57u^3 + u^2}$$

$$b_c = s/(2M_5^3),$$



Per flavor



Allowed from UHECRs (Auger):
20% proton component
10% proton component
SM+Gravity
SM
Normalized Rate
Triggered Stations
$\nu_e + \bar{\nu}_e$
$\nu_\mu + \bar{\nu}_\mu$
$\nu_\tau + \bar{\nu}_\tau$