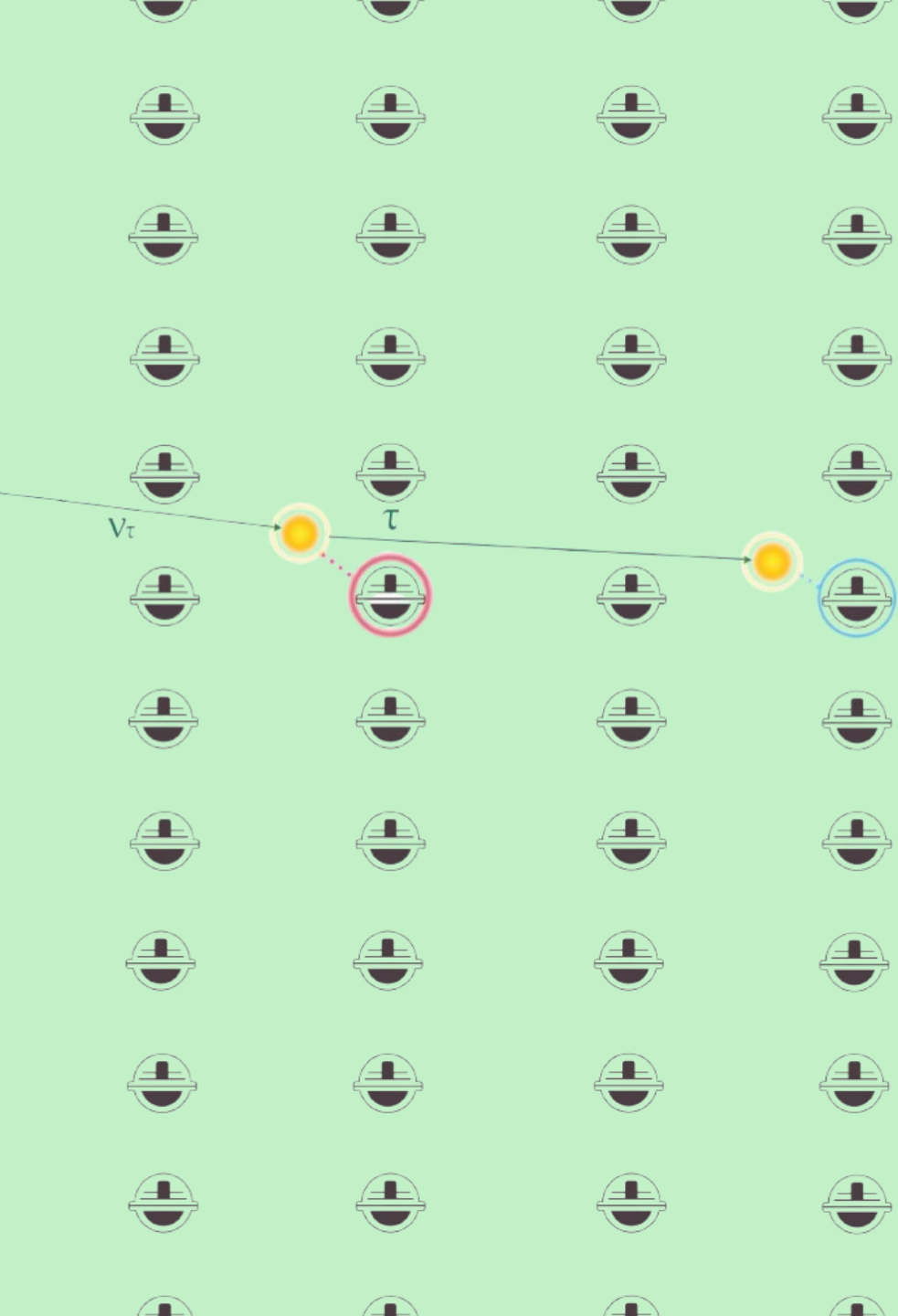




# Tau neutrino reconstruction in IceCube with bright and DeepCore DOMs

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CosPa 2025



# Motivation

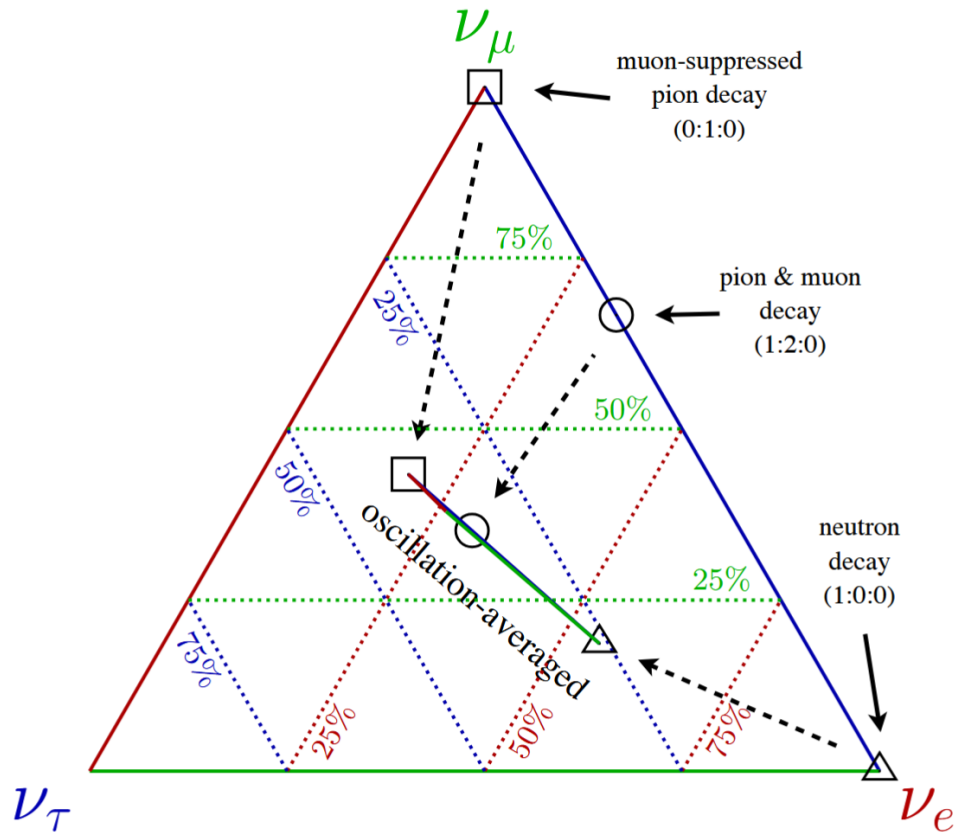


Image: IceCube Collaboration (2014)

- In the main scenarios of neutrino production, the tau neutrino component is zero or negligible at the source
- Significant only after oscillation over long distances
- e.g. pion decay:  
 $(\nu_e : \nu_\mu : \nu_\tau)_s = (1 : 2 : 0) \longrightarrow (\nu_e : \nu_\mu : \nu_\tau)_\oplus \approx (1 : 1 : 1)$
- At the relevant energies, atmospheric neutrinos do not oscillate significantly before detection
- High astrophysical purity for  $\nu_\tau$
- Flavour ratio tells us about sources and oscillation processes

# IceCube

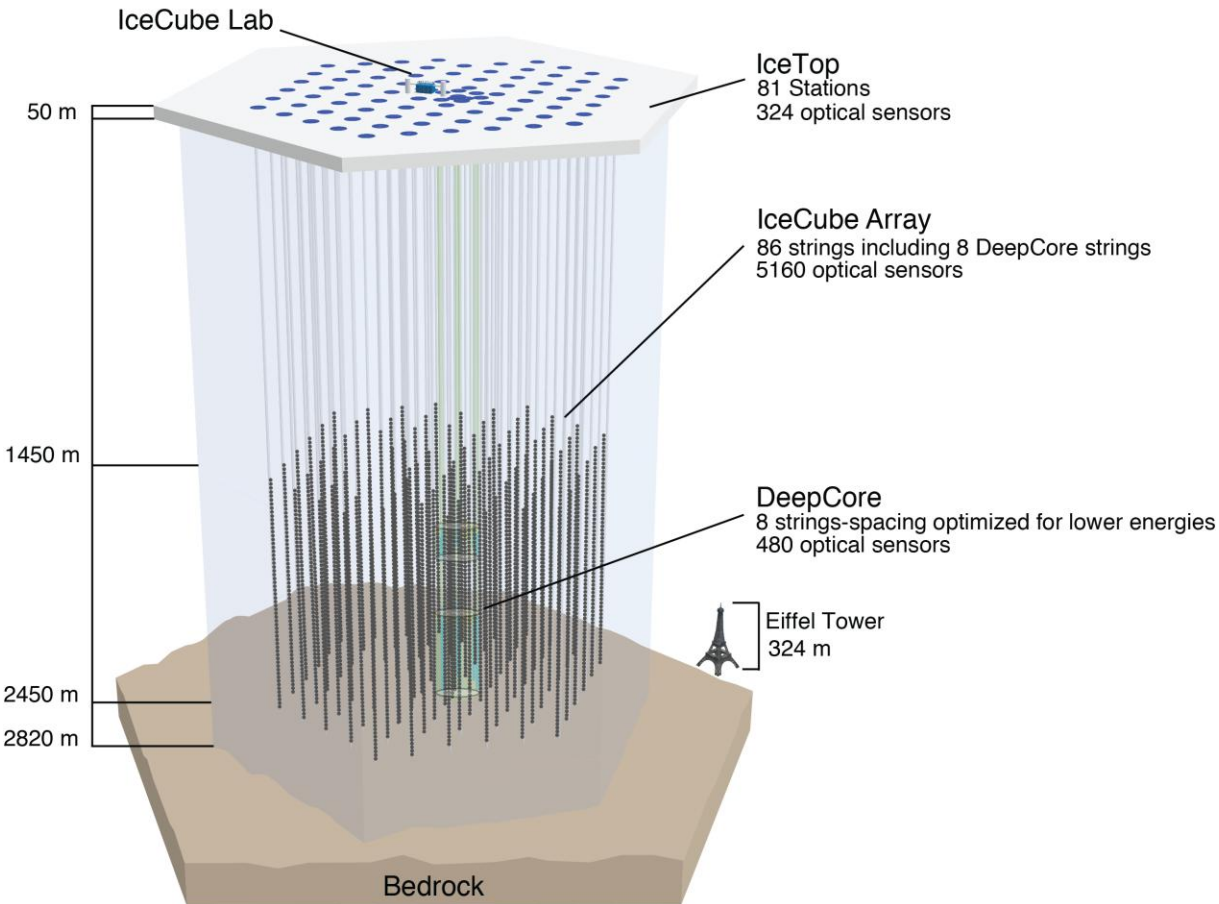
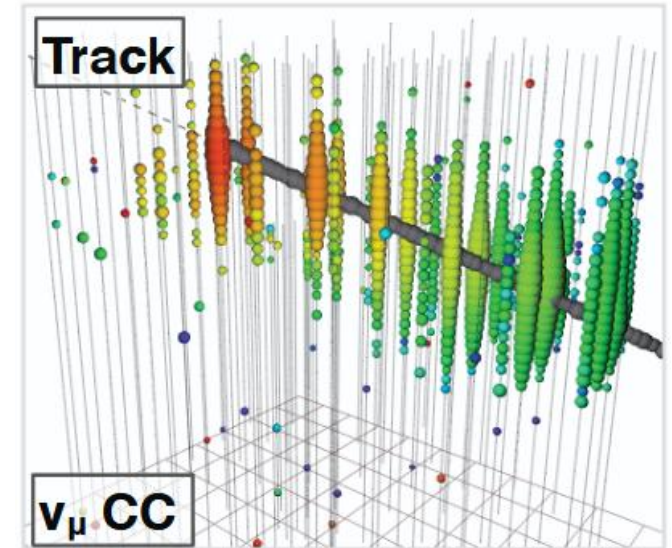
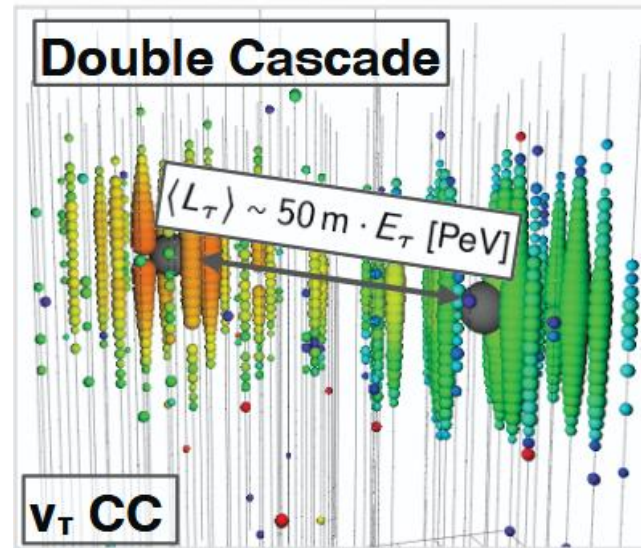
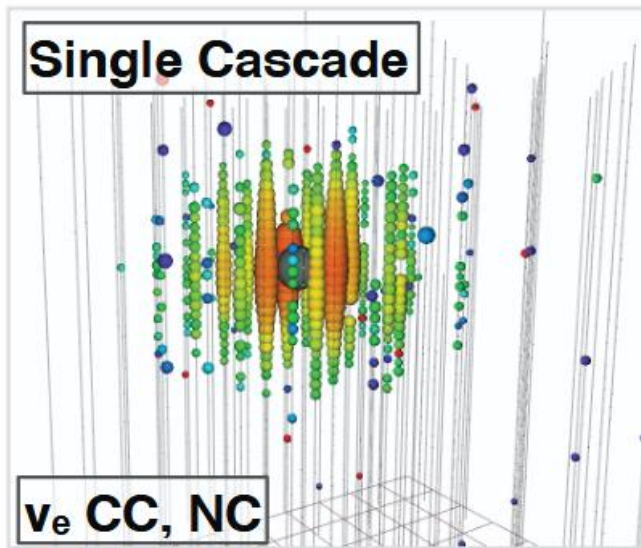


Image: IceCube gallery

- Cubic-kilometre in-ice array plus IceTop surface array and DeepCore
- 5160 digital optical modules (DOMs), each with a photomultiplier tube to detect Cherenkov radiation
- ~125 m between strings, 17 m between DOMs
- Several ongoing IceCube  $\nu_\tau$  analyses covering a range of energies and identification methods
- Astrophysical  $\nu_\tau$  seen at  $5\sigma$  level in 2024 using convolutional neural networks
- This project follows previous studies: Usner (2018), Stachurska (2020), Lad (2025)

# Neutrino interactions in IceCube

- Morphology depends on neutrino flavour and type of interaction
- Main classifications: single cascades, double cascades, tracks
- Double cascades are produced only by  $\nu_\tau$  CC events and relatively rare charm processes
- They are crucial for understanding Tau neutrino reconstruction in IceCube



Images: Usner (2018), Stachurska (2020)

# Event reconstruction

- We reconstruct events using the likelihood-based millipede framework
- Source model depends on the event hypothesis:
  - Single cascade (monopod):  $\vec{h}_{sc} = (x_s, y_s, z_s, t_s, \theta_s, \phi_s, E_s)$
  - Track (mumillipede):  $\vec{h}_t = (x_s, y_s, z_s, t_s, \theta_s, \phi_s, \Delta L, \{E_k\})$
  - Double cascade (taupede):  $\vec{h}_{dc} = (x_s, y_s, z_s, t_s, \theta_s, \phi_s, L, E_1, E_2)$
- Also of interest: energy asymmetry

energy asymmetry

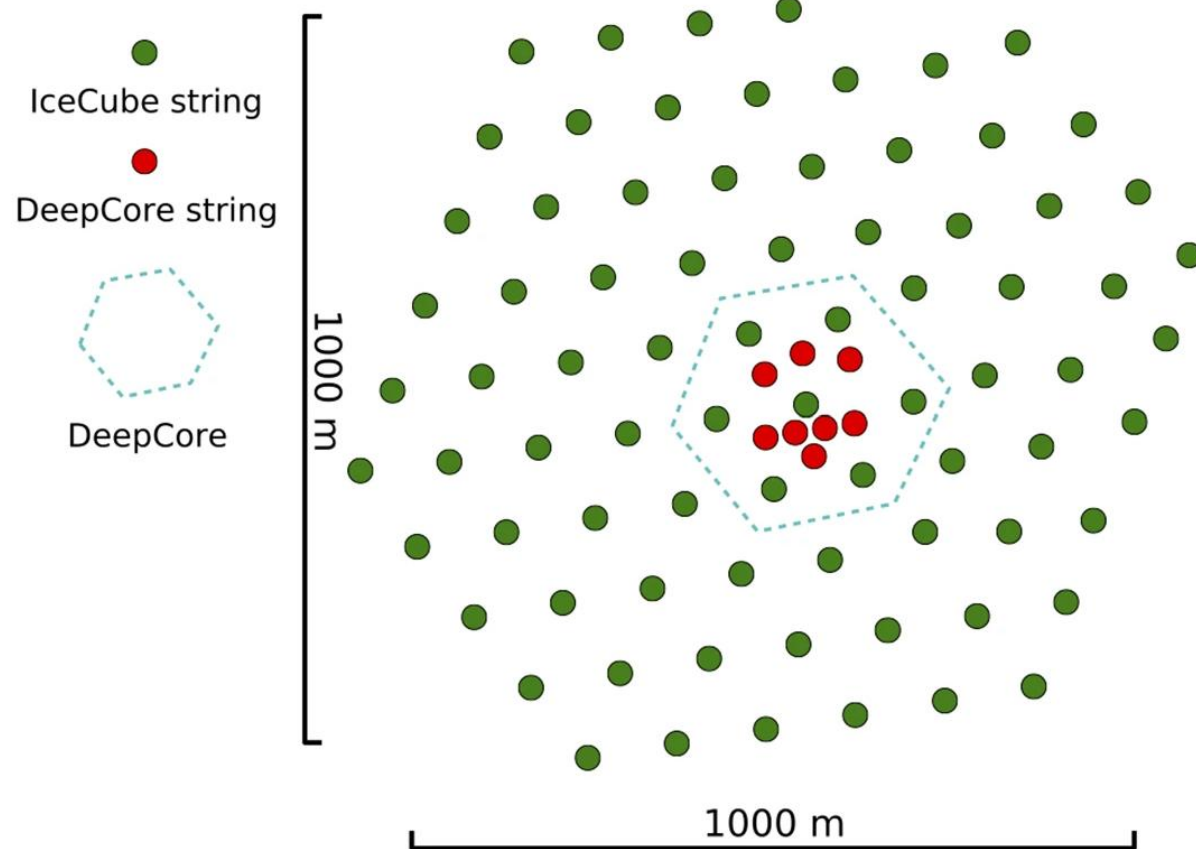
$$E_A = \frac{E_1 - E_2}{E_1 + E_2}$$


The diagram shows two blue circles, one labeled E1 on the left and one labeled E2 on the right. A blue arrow points from E1 to E2, indicating a flow or relationship between the two energy states.

Image: Usner (2018)



# Reconstruction with bright and DeepCore DOMs

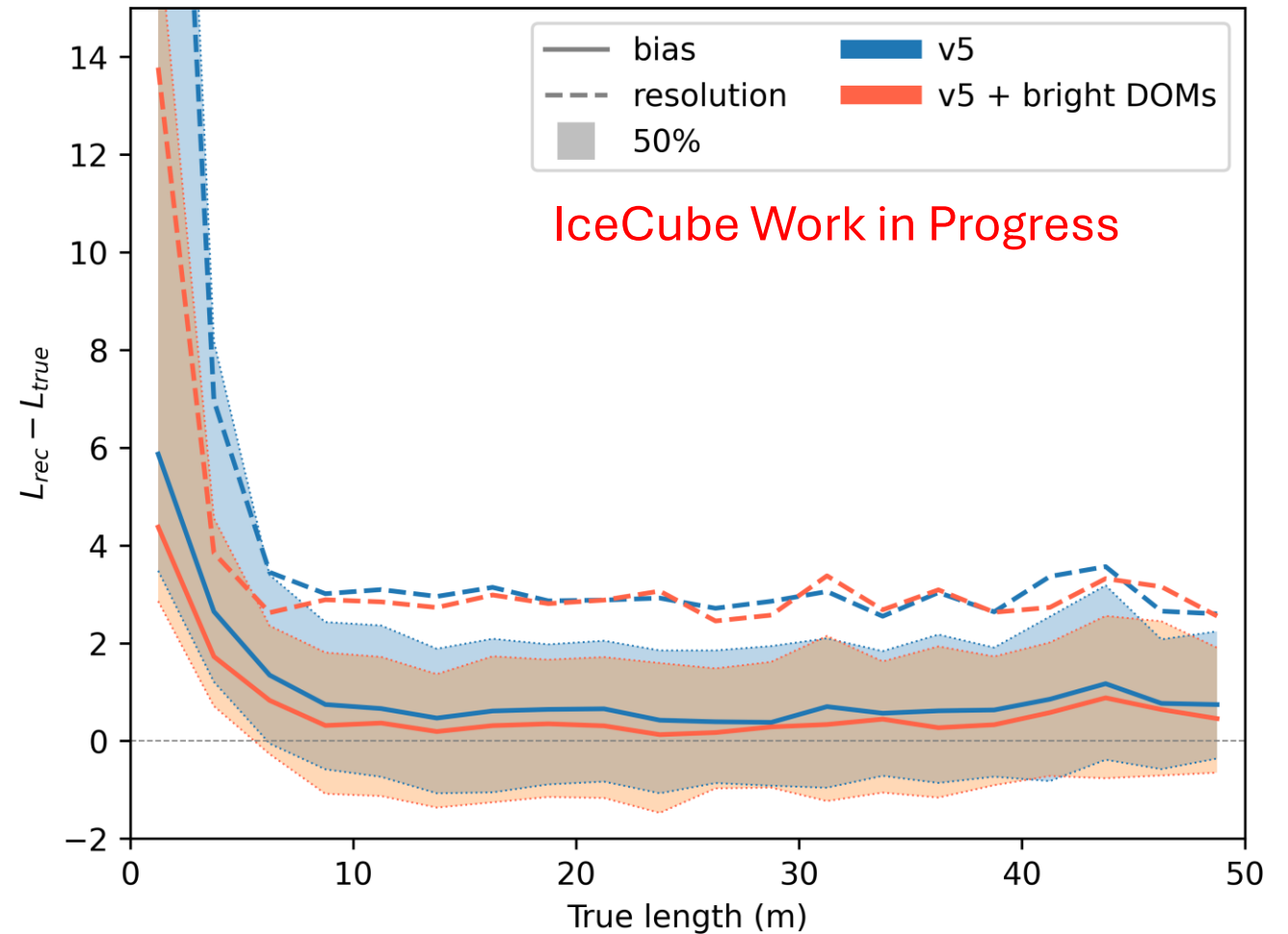


- A DOM is *bright* if the amount of light it collects exceeds the average by a threshold factor
- DeepCore: IceCube sub-array with denser instrumentation and higher quantum efficiency
  - Affects energy estimator
- Bright and DeepCore DOMs both excluded from previous high-energy analyses
- We investigate the effects of their inclusion
- Simulations:  $10^4 - 10^8$  GeV CC  $\nu_\tau$

Image: IceCube Collaboration (2017)

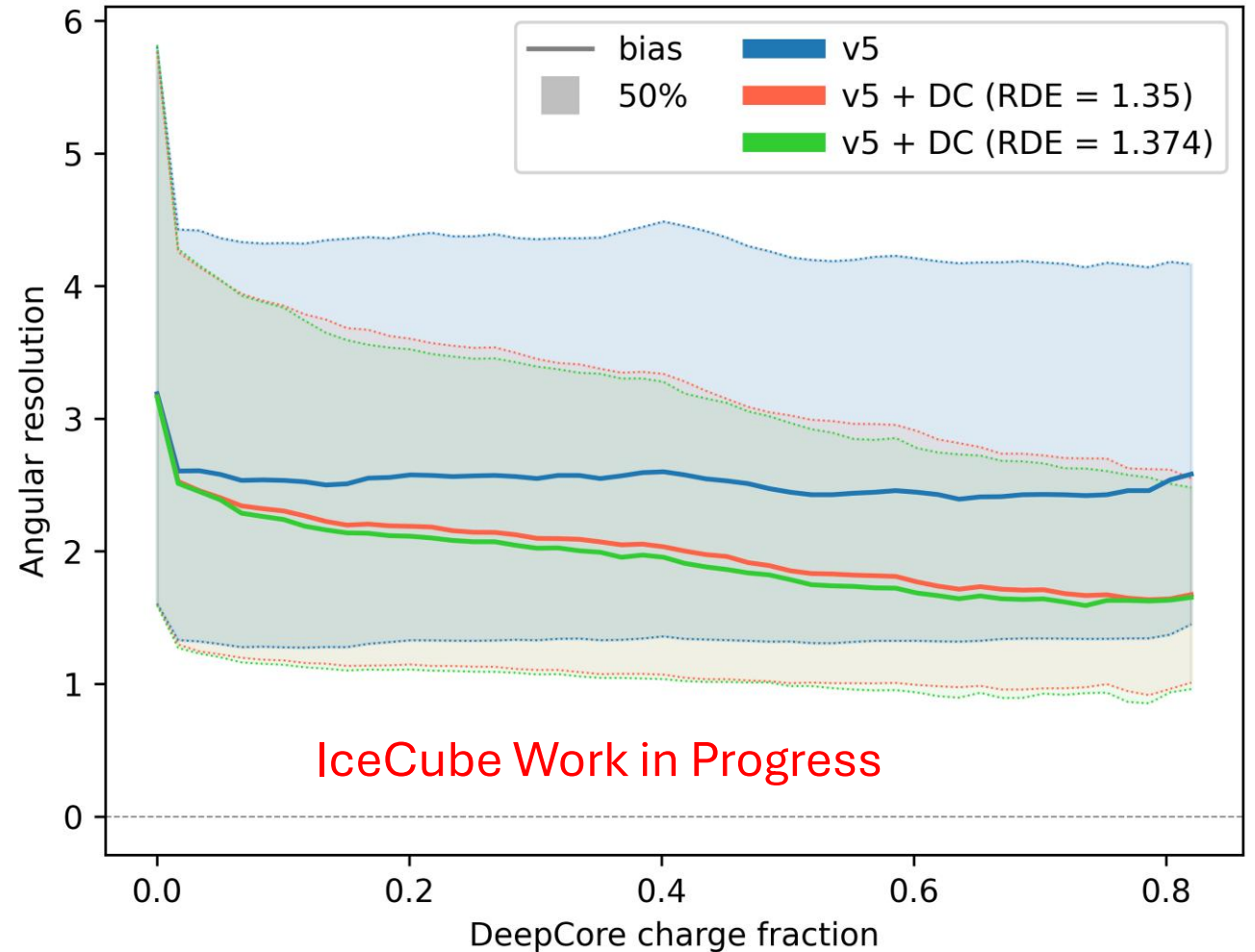
# Bright DOMs: results

- Does not appear to worsen reconstruction for any parameter of interest
- Apparent improvement in length reco



# DeepCore: results

- Energy reconstruction worsened
- All other parameters of interest have better resolution for events with high DeepCore fraction





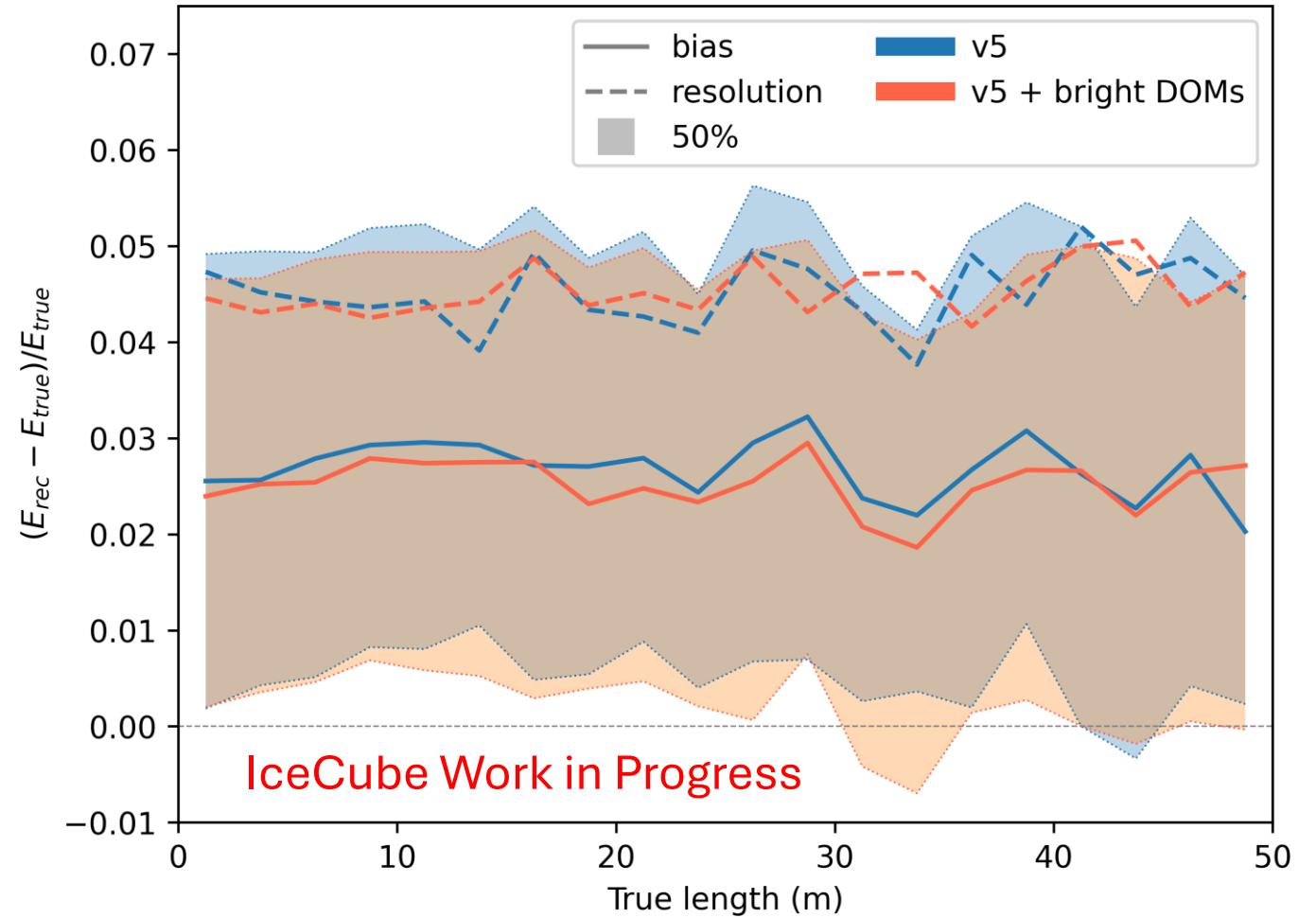
# Conclusions and next steps

- The inclusion of Bright DOMs improved length reconstruction and did not worsen reconstruction for any parameter
- The inclusion of DeepCore worsened energy reconstruction but improved the resolution of all other parameters
- New simulations!
- Once final checks done, start studying improvement of tau-sensitive observables

# Backup

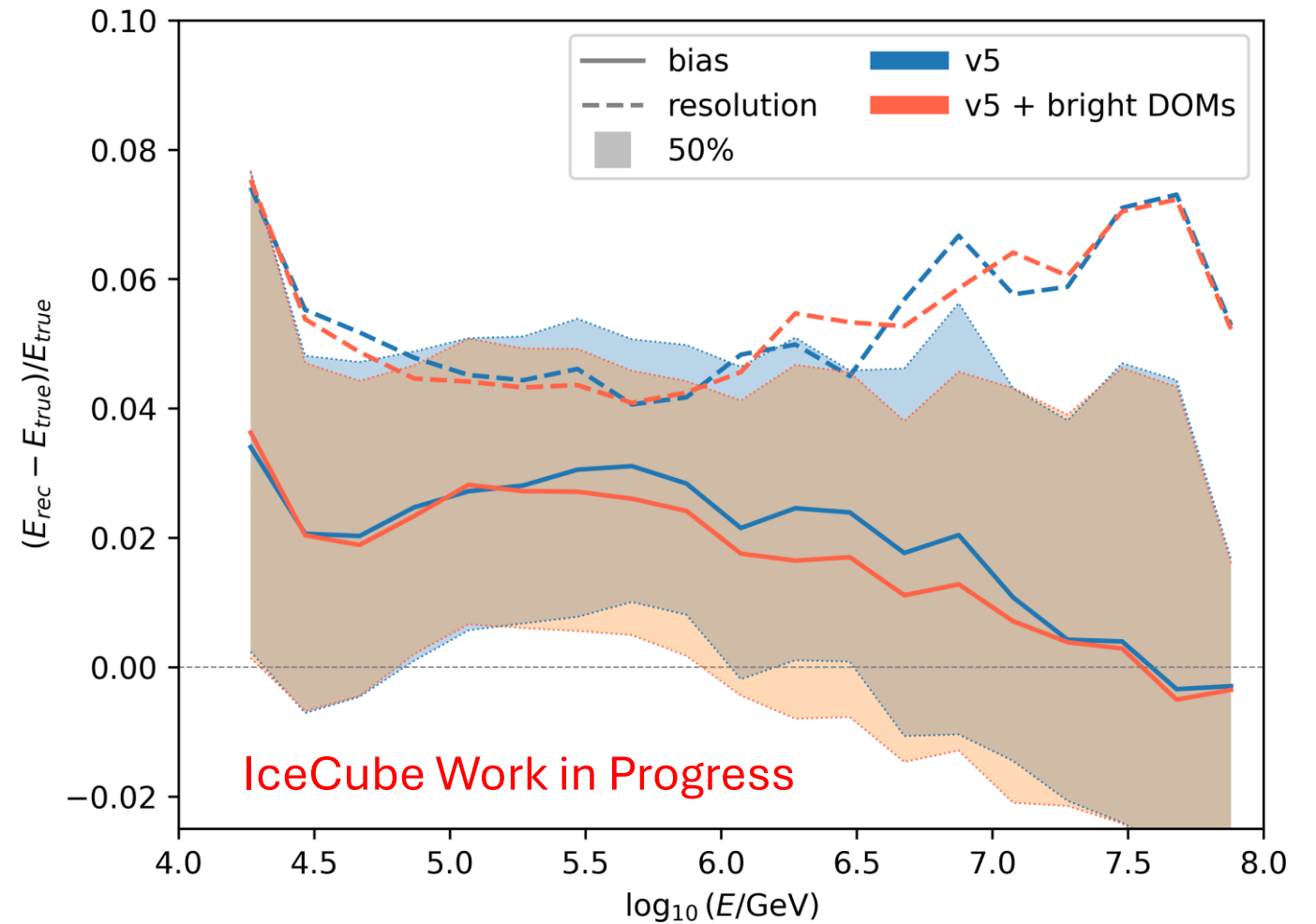
# Bright DOMs: energy

- No significant change



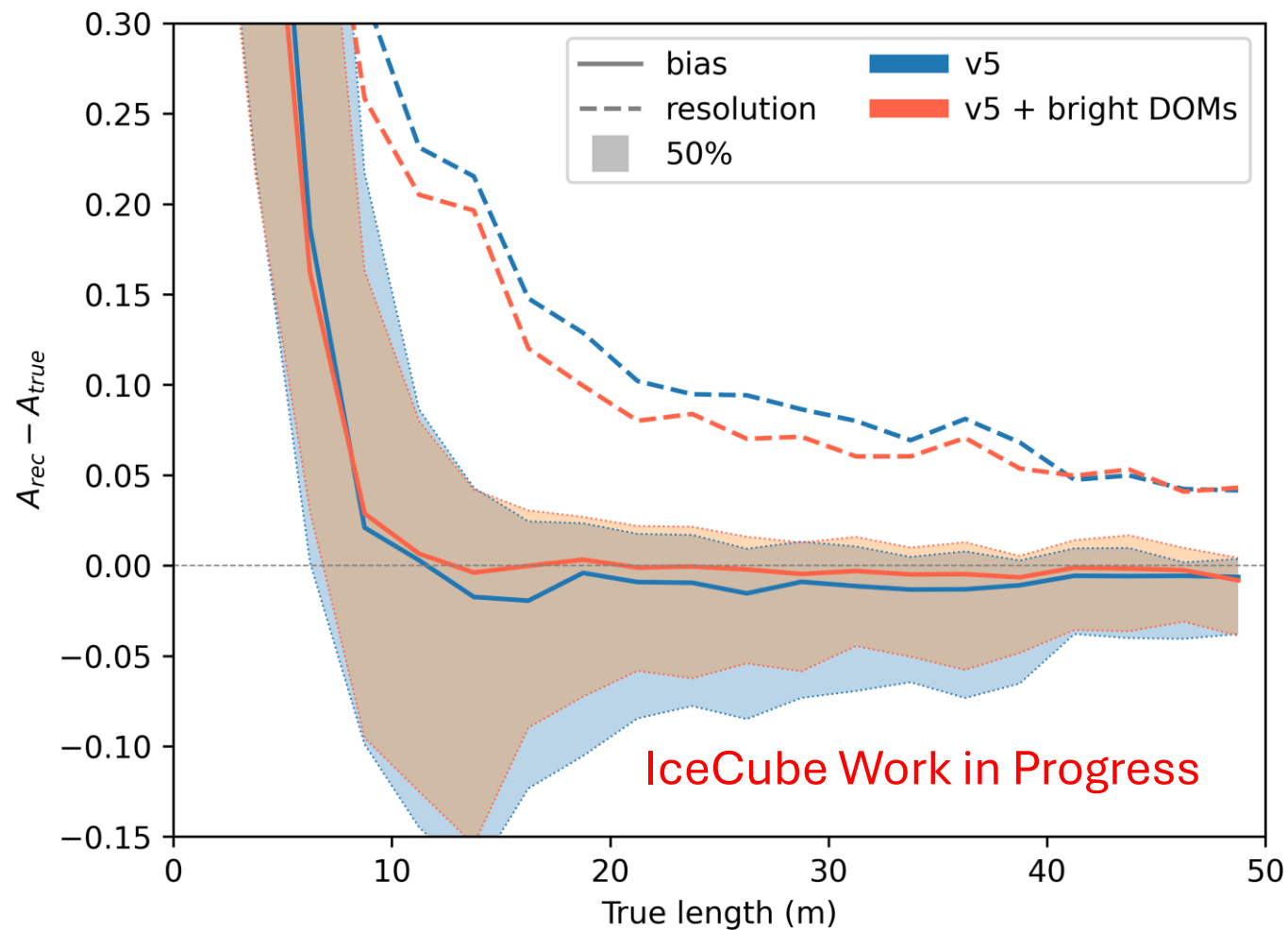
# Bright DOMs: energy

- No significant change



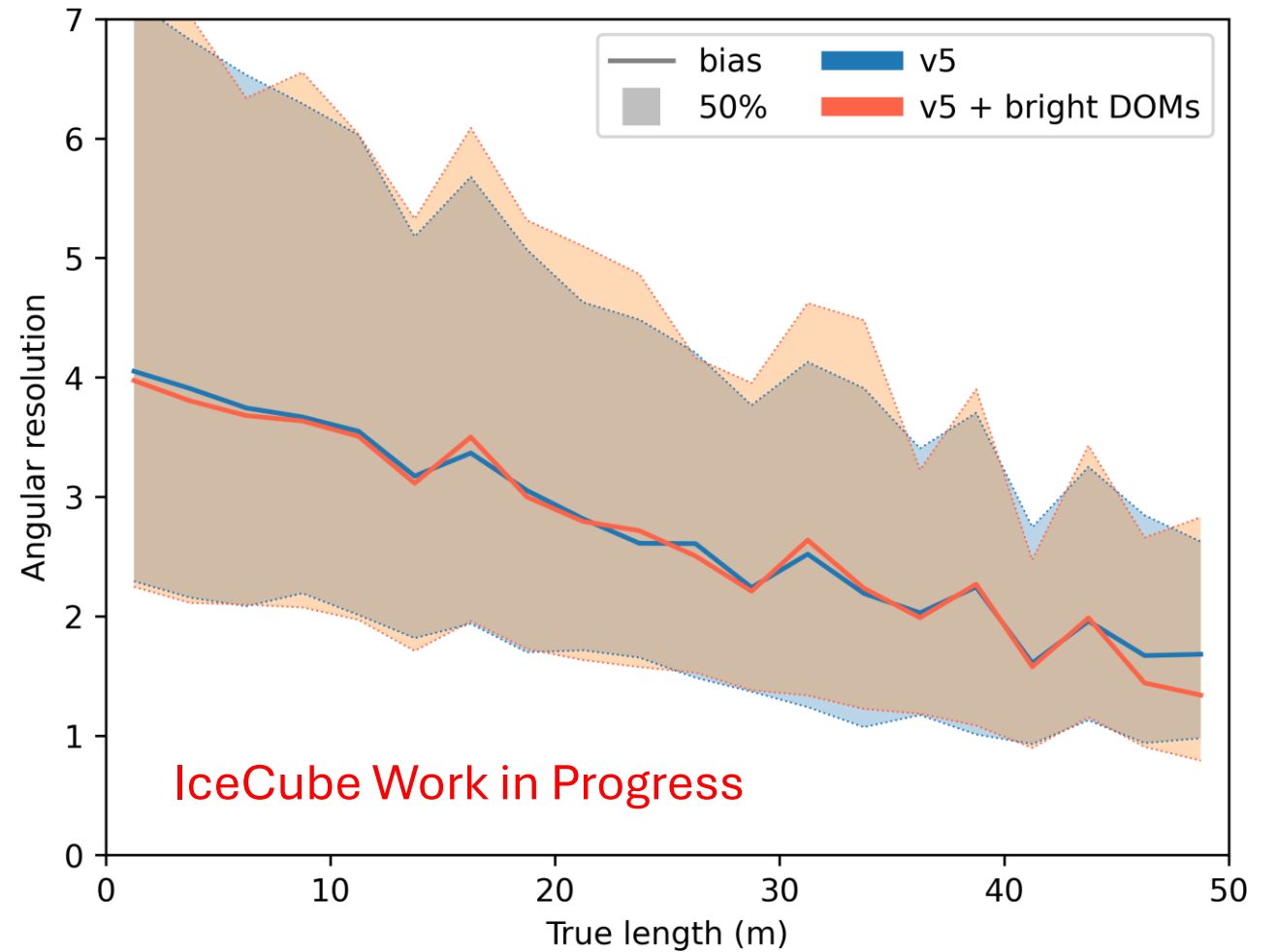
# Bright DOMs: energy asymmetry

- Slight improvement?



# Bright DOMs: angular resolution

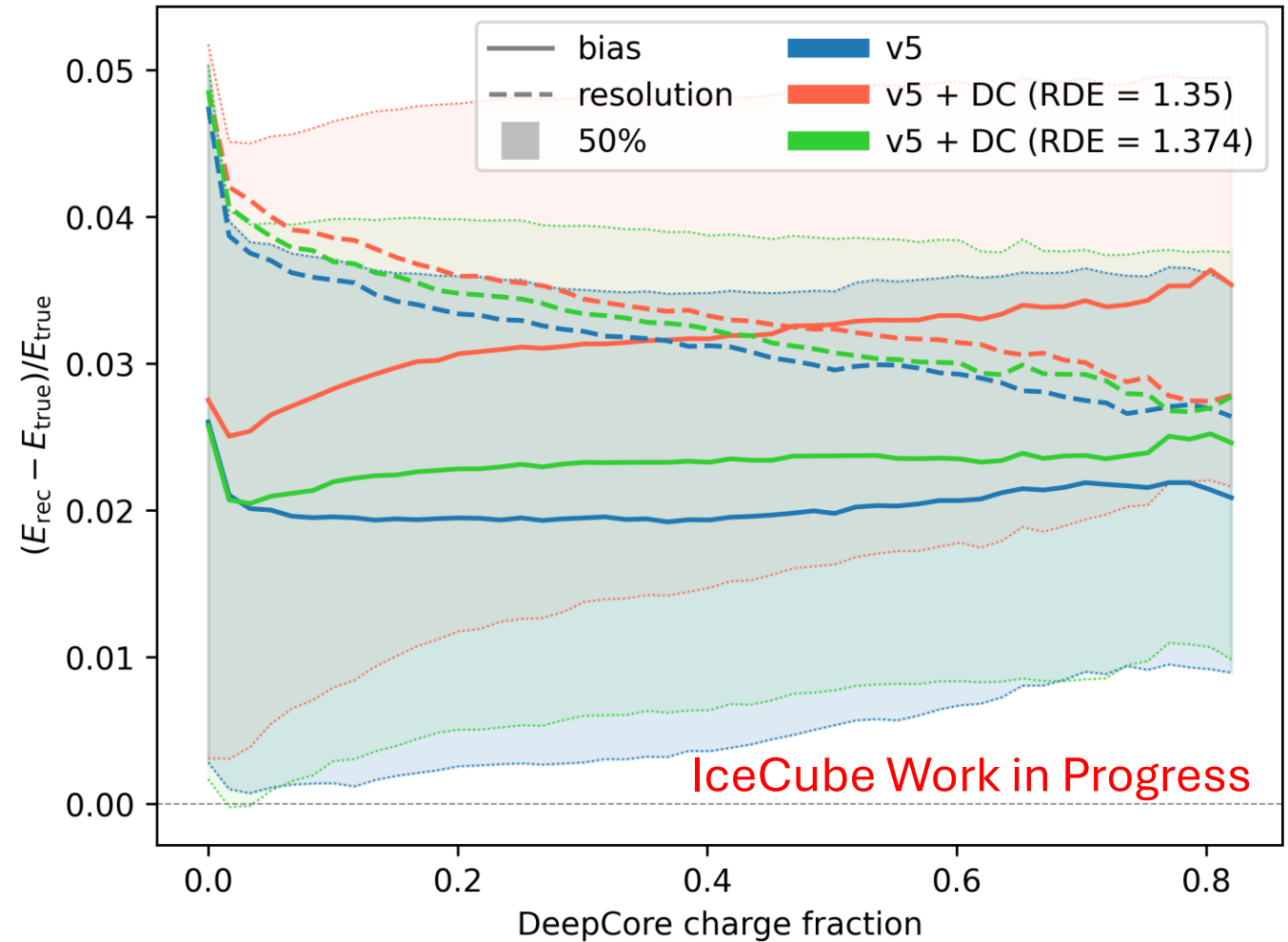
- No significant change





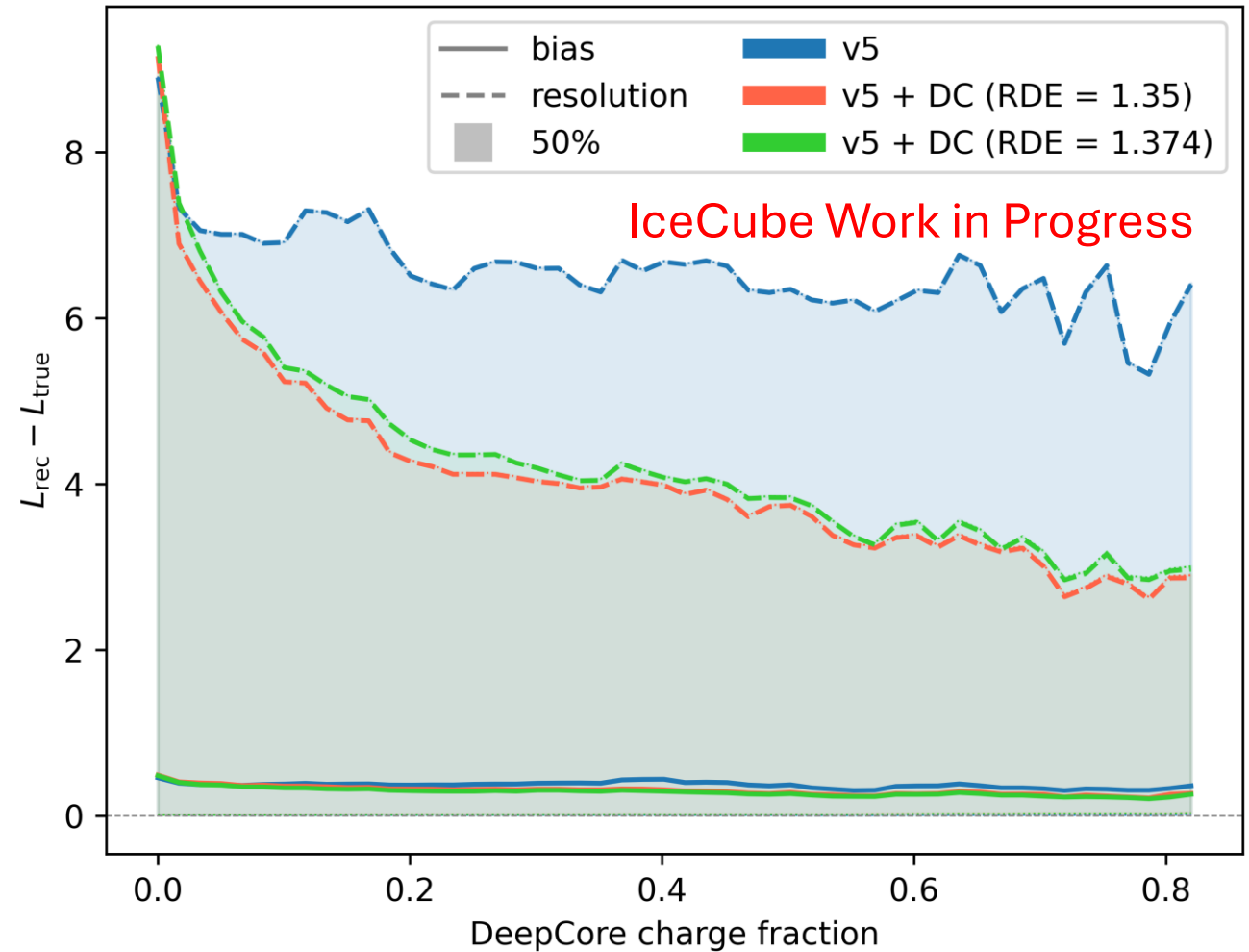
# DeepCore: energy

- Energy reco worsened
- Partially alleviated by changing RDE



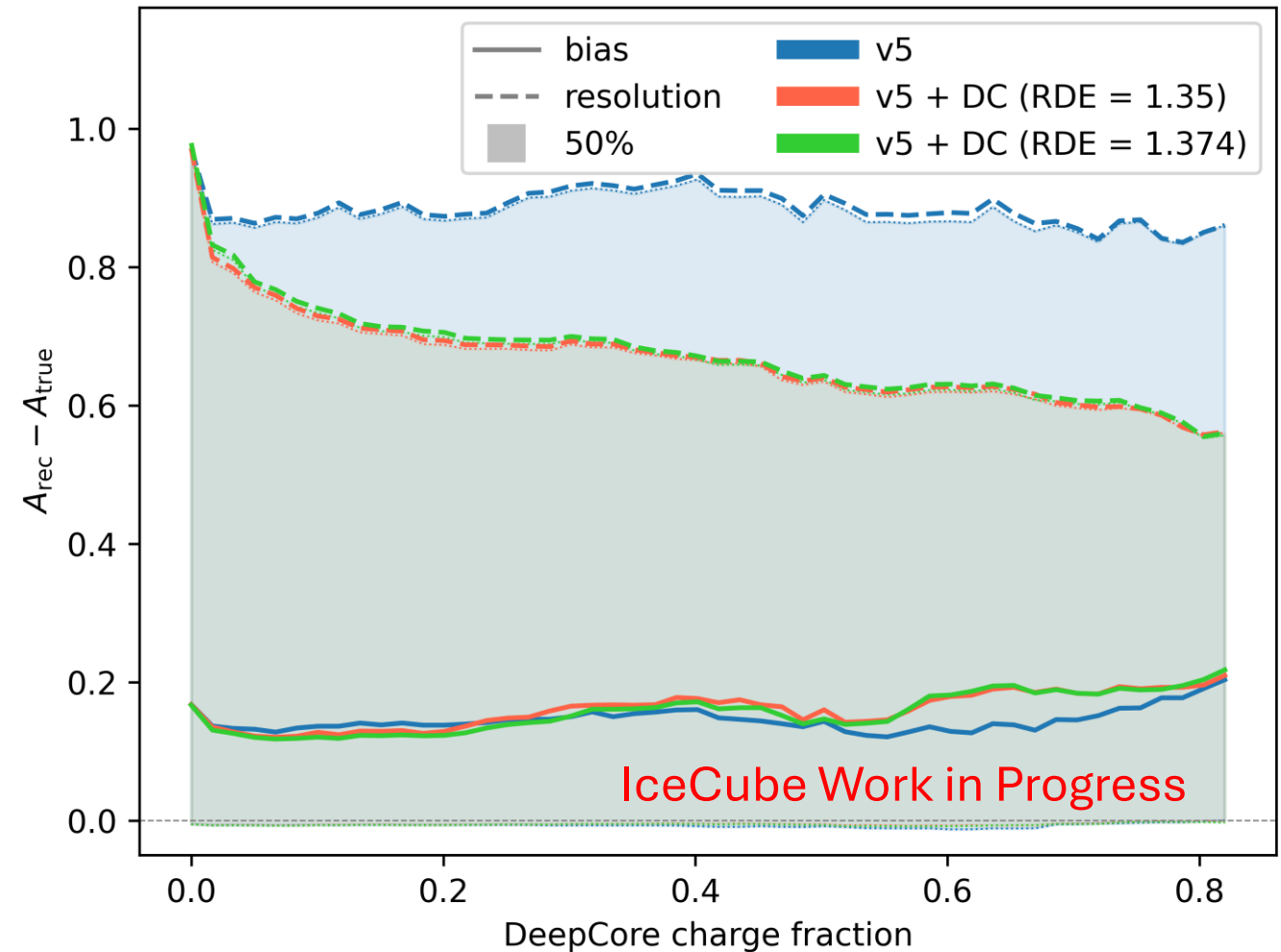
# DeepCore: length

- Length resolution improved

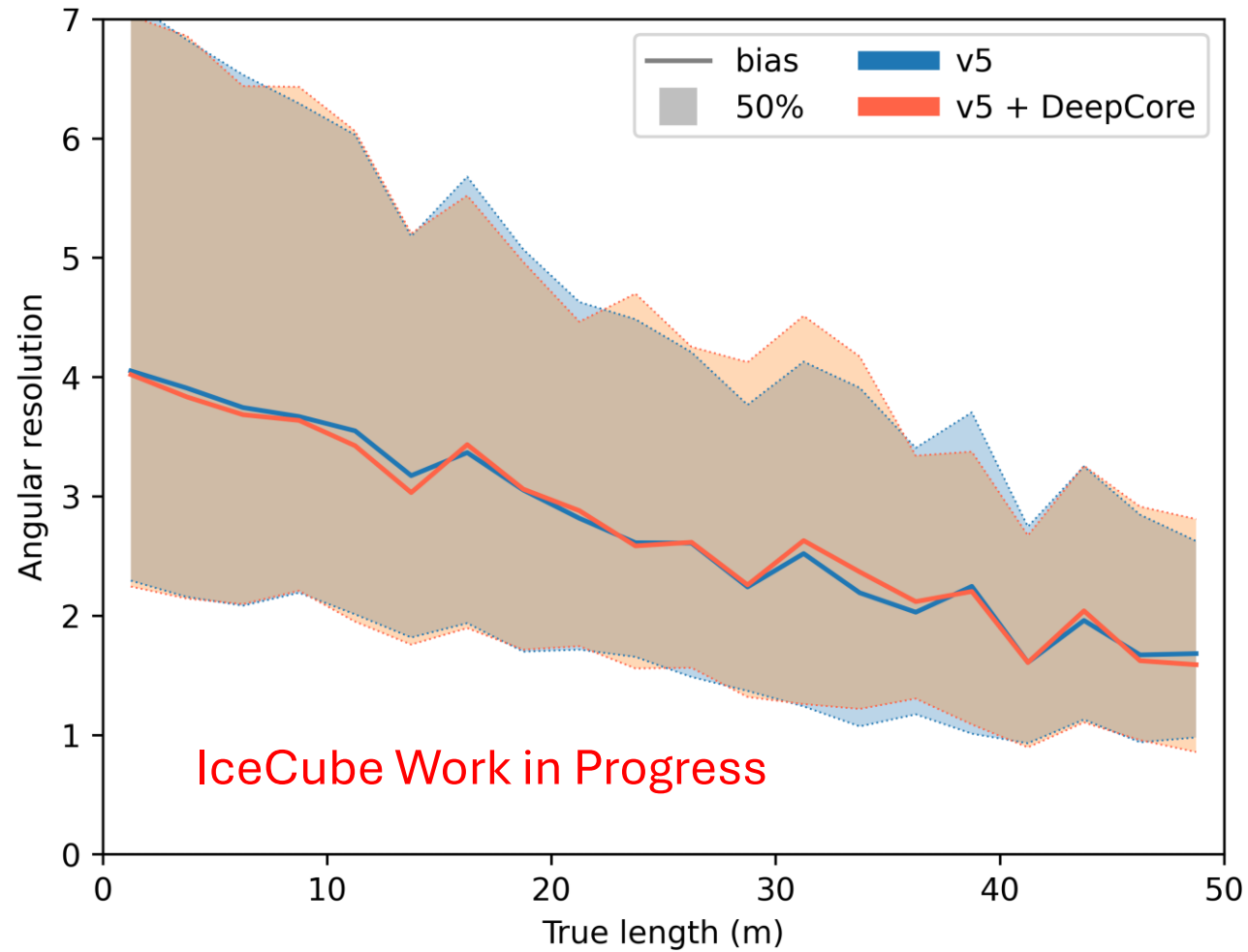


# DeepCore: energy asymmetry

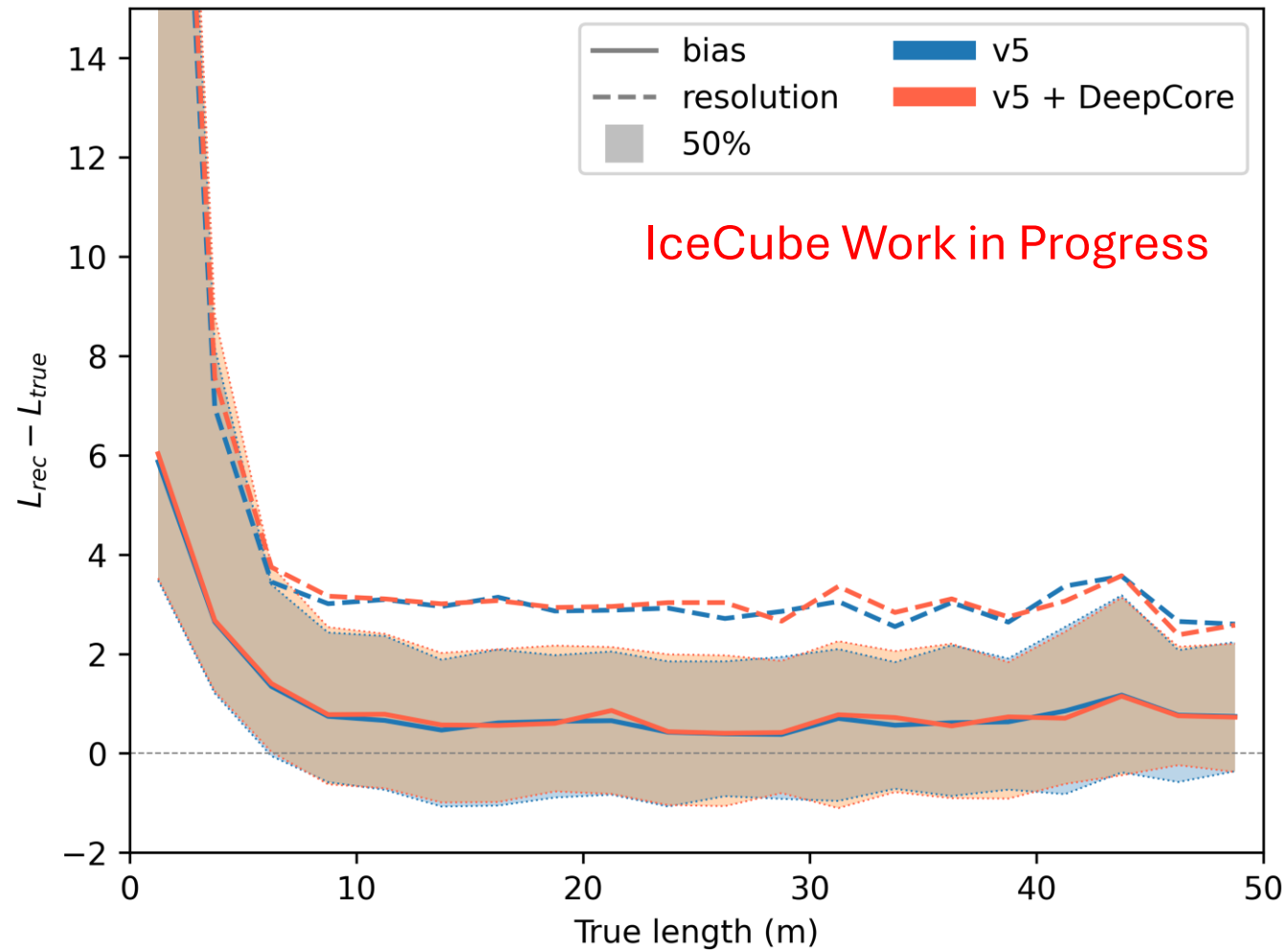
- Energy asymmetry resolution improved



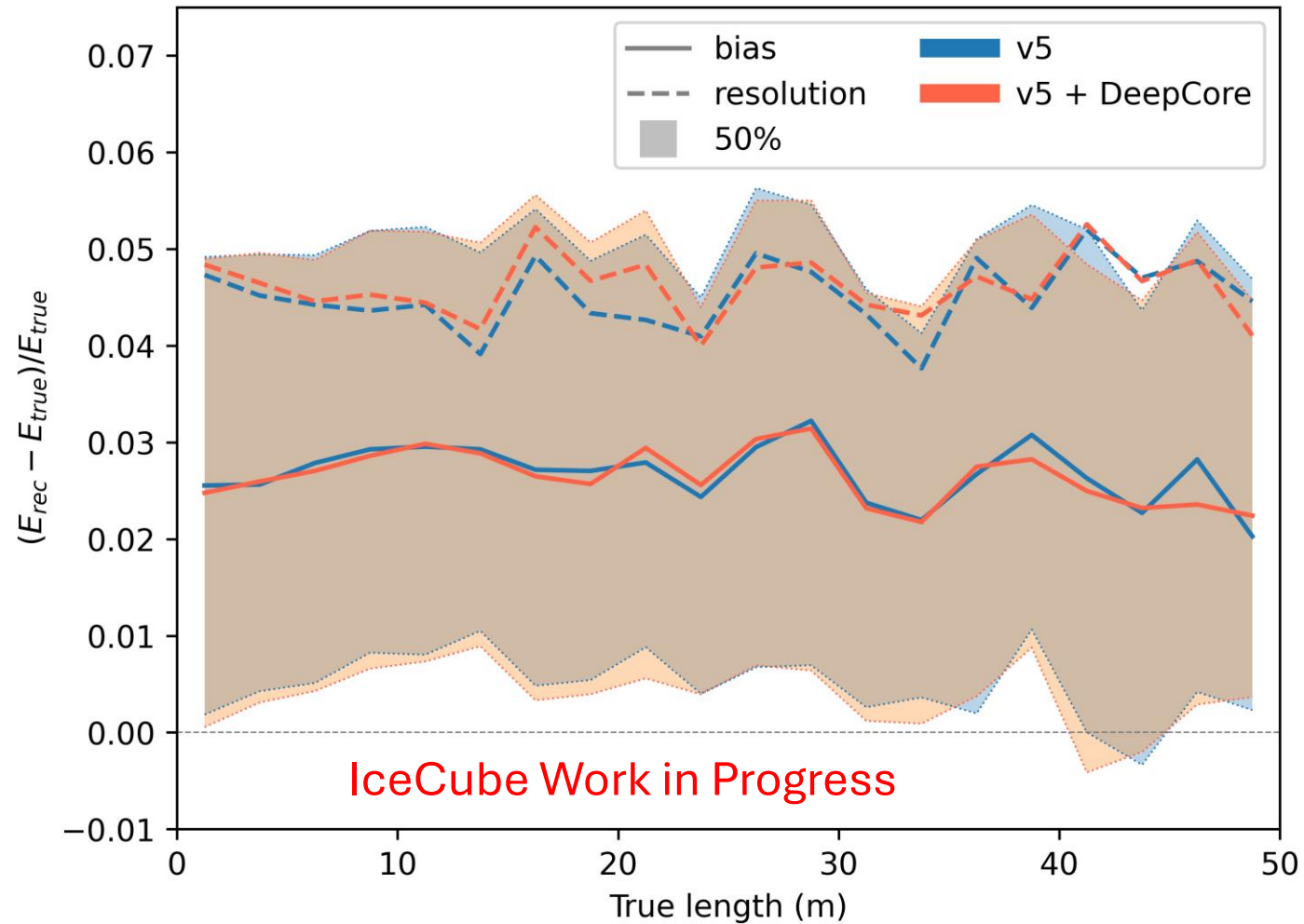
# DeepCore: angular resolution



# DeepCore: length

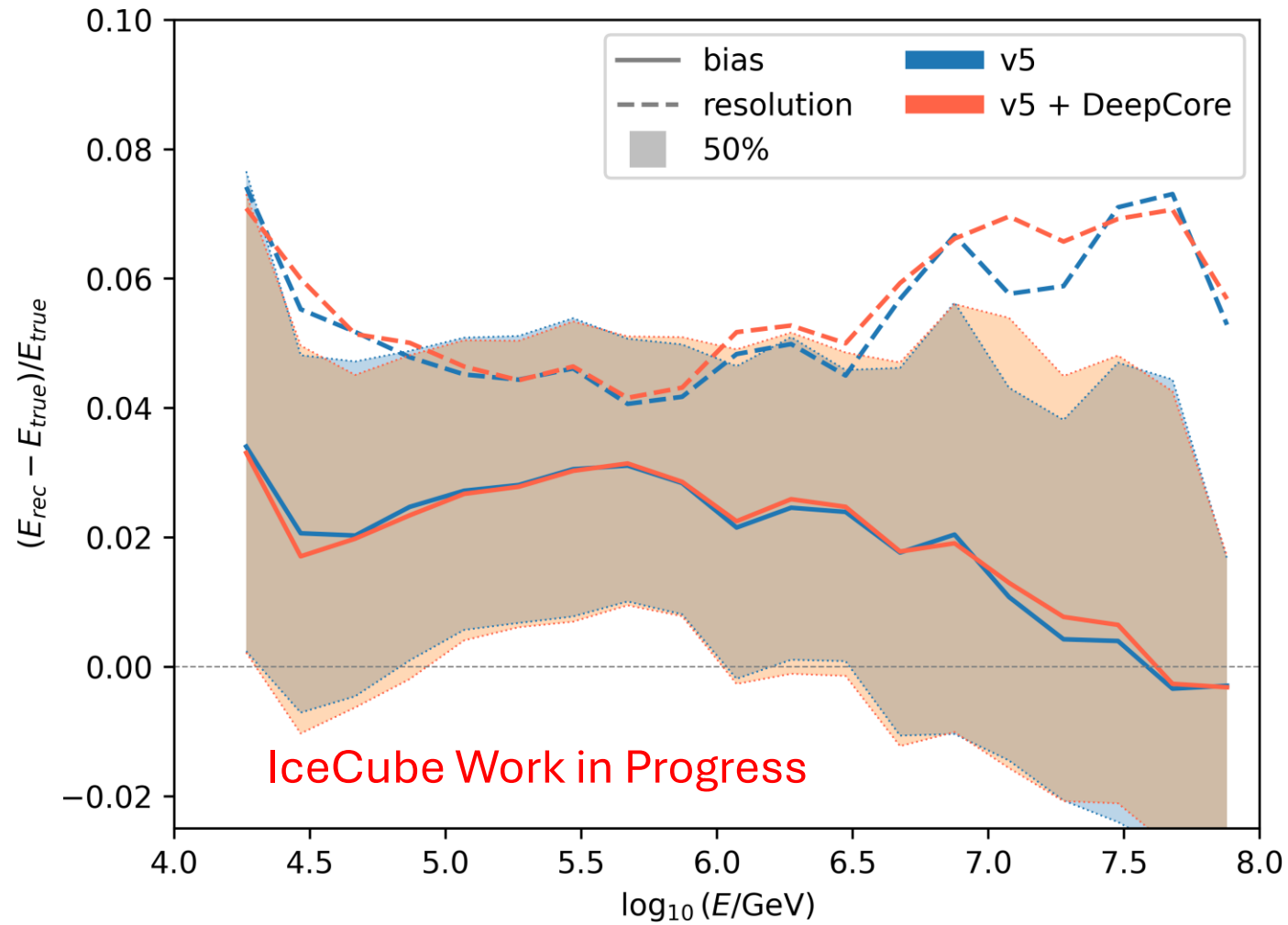


# DeepCore: energy

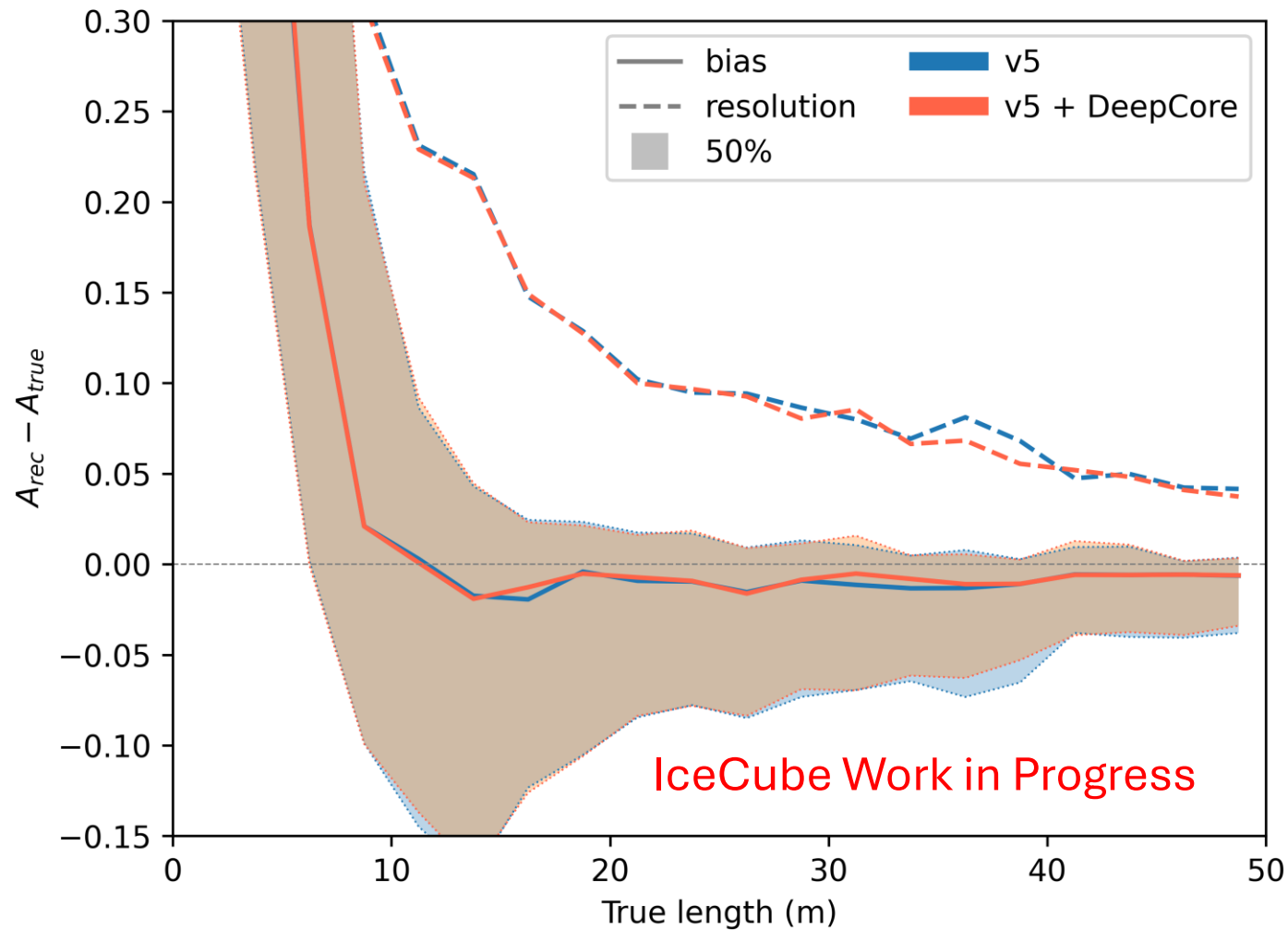




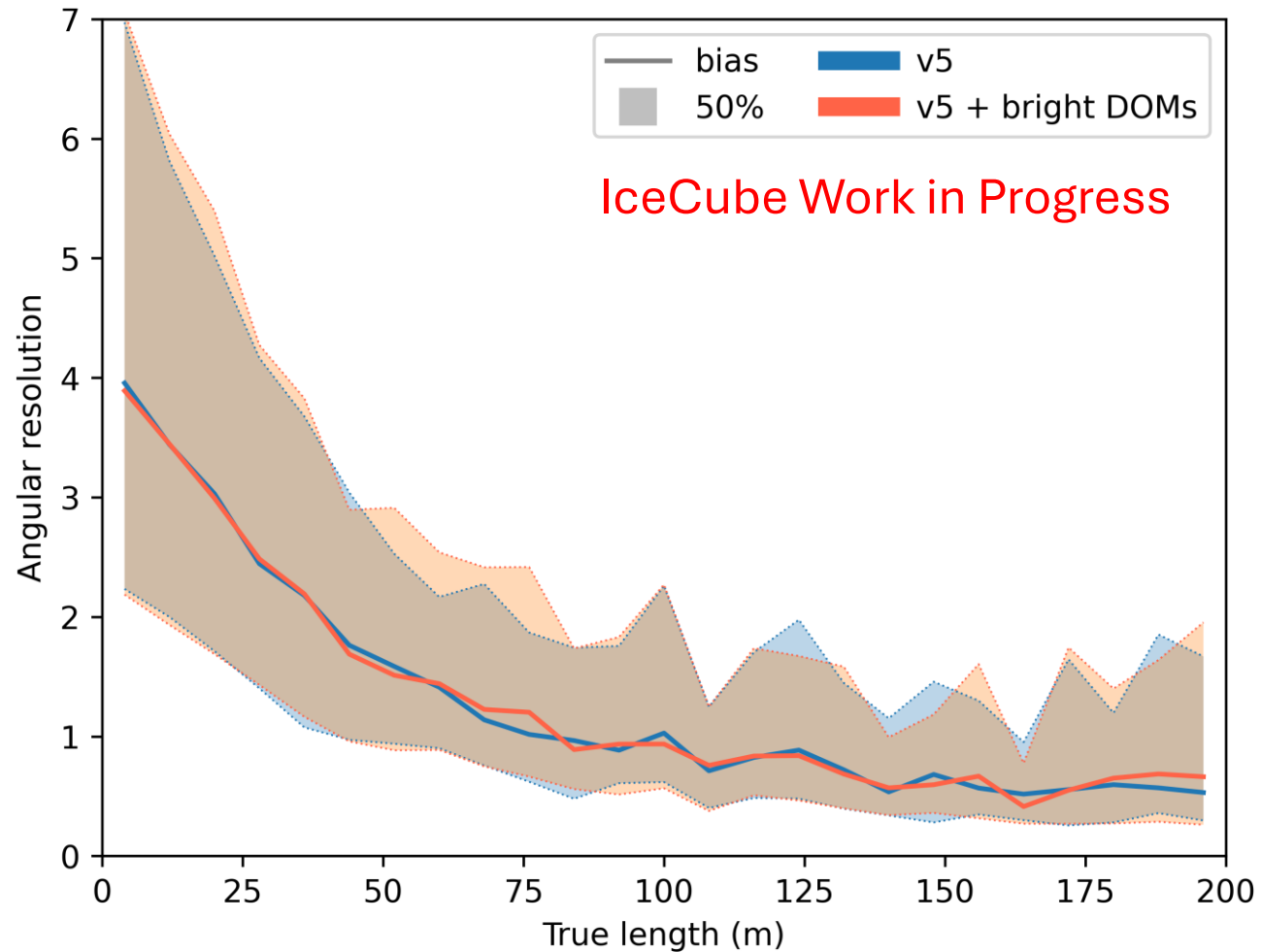
# DeepCore: energy



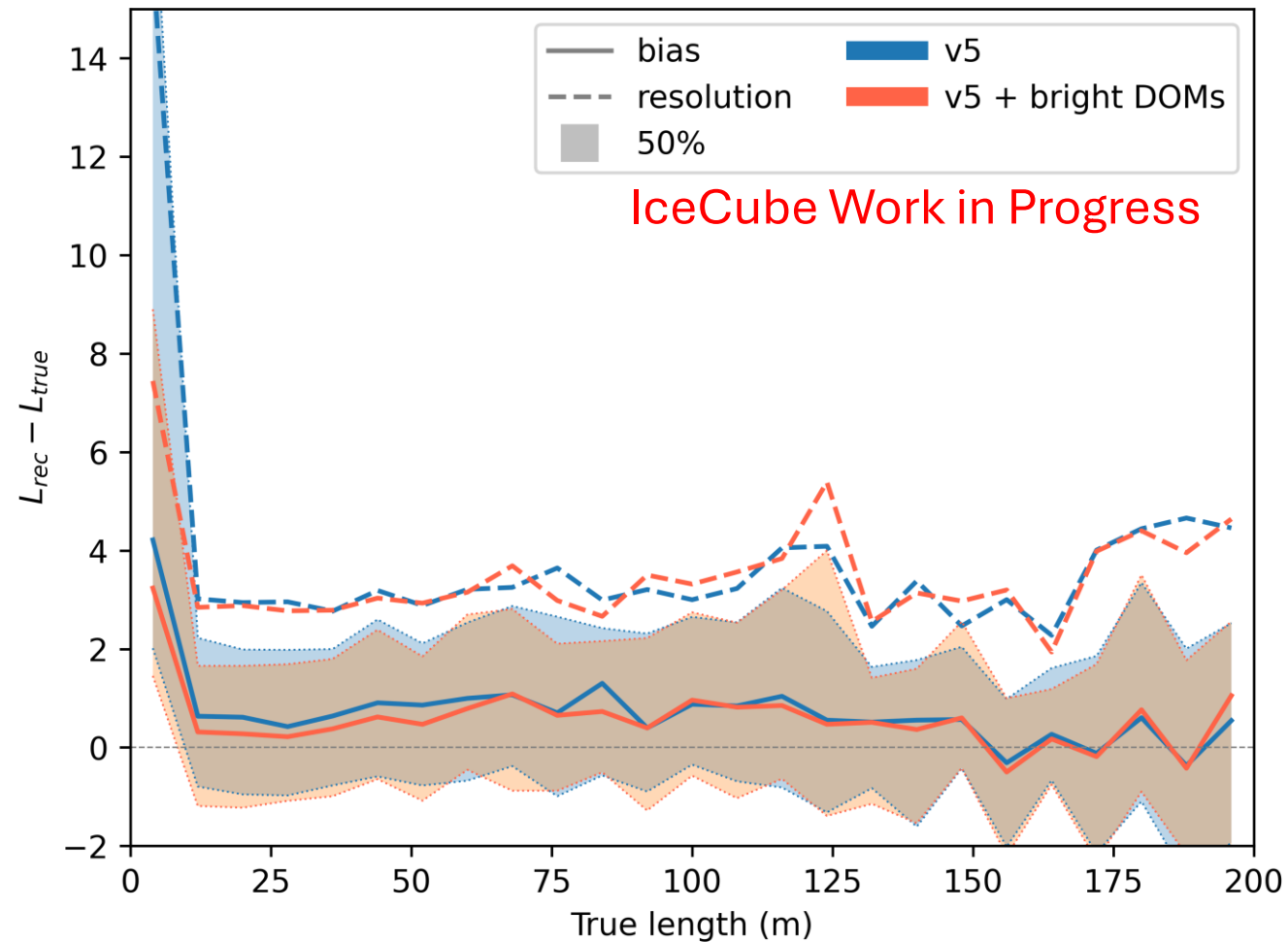
# DeepCore: energy asymmetry



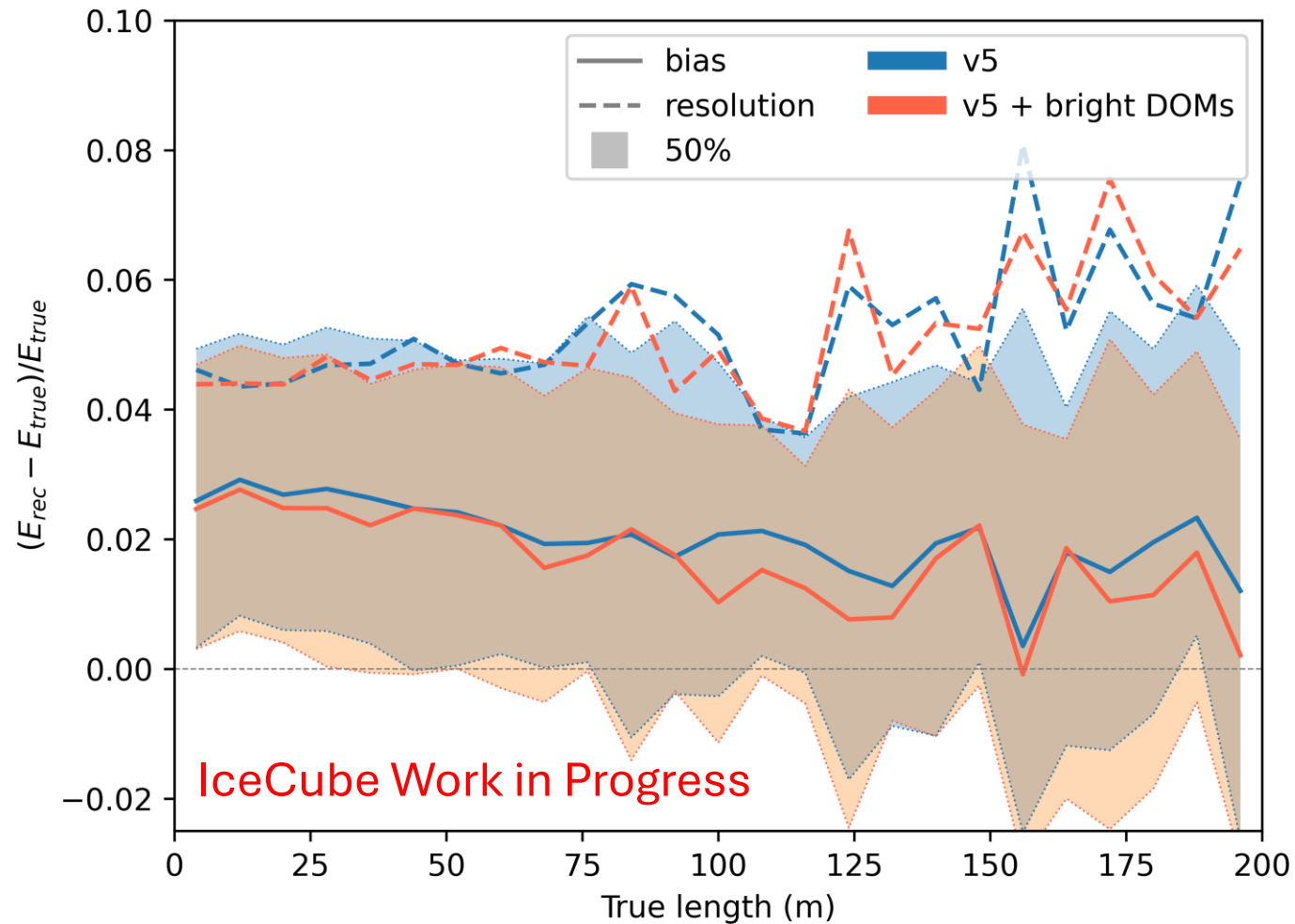
# Bright results to 200m: angular resolution



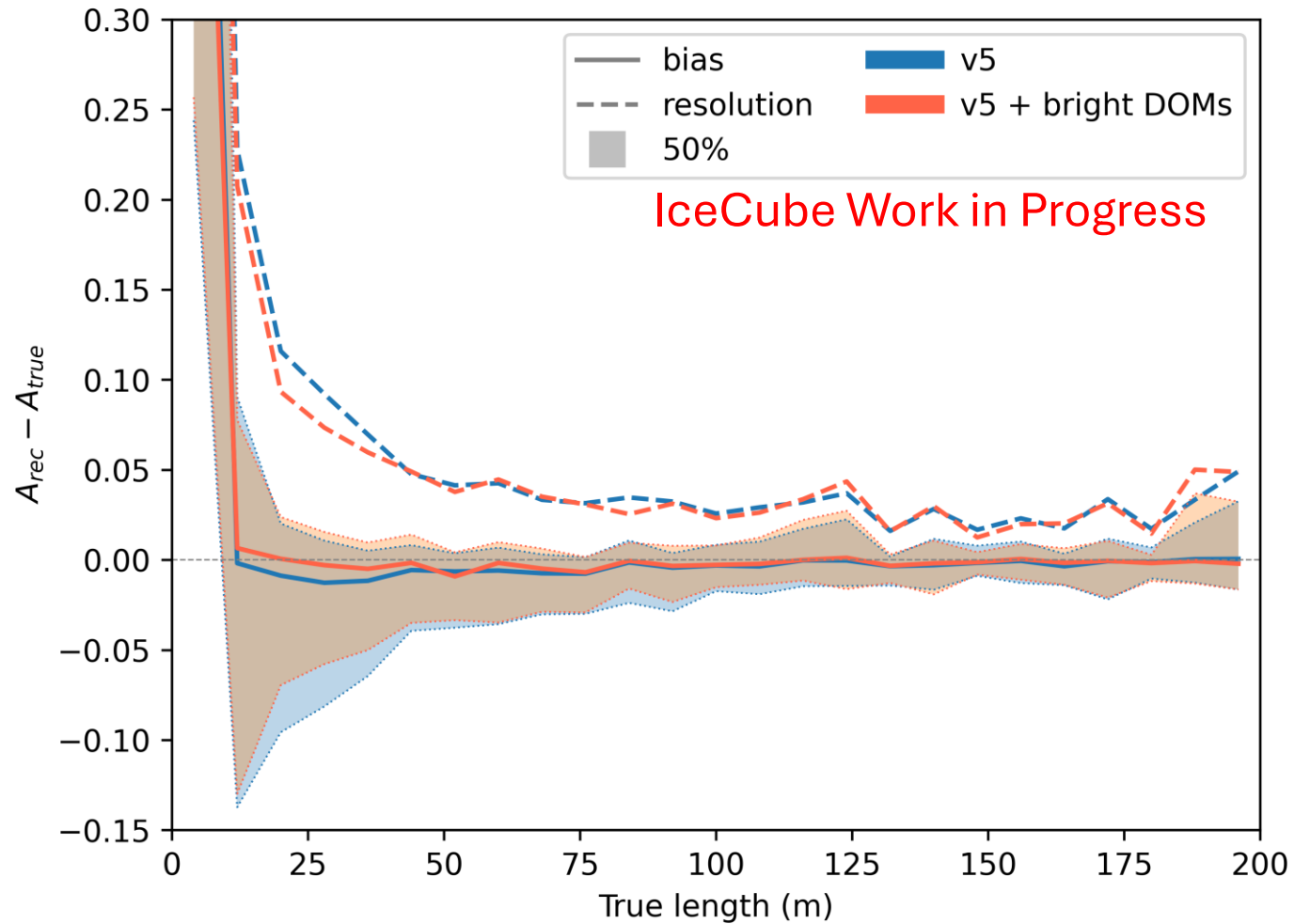
# Bright results to 200m: length



# Bright results to 200m: energy

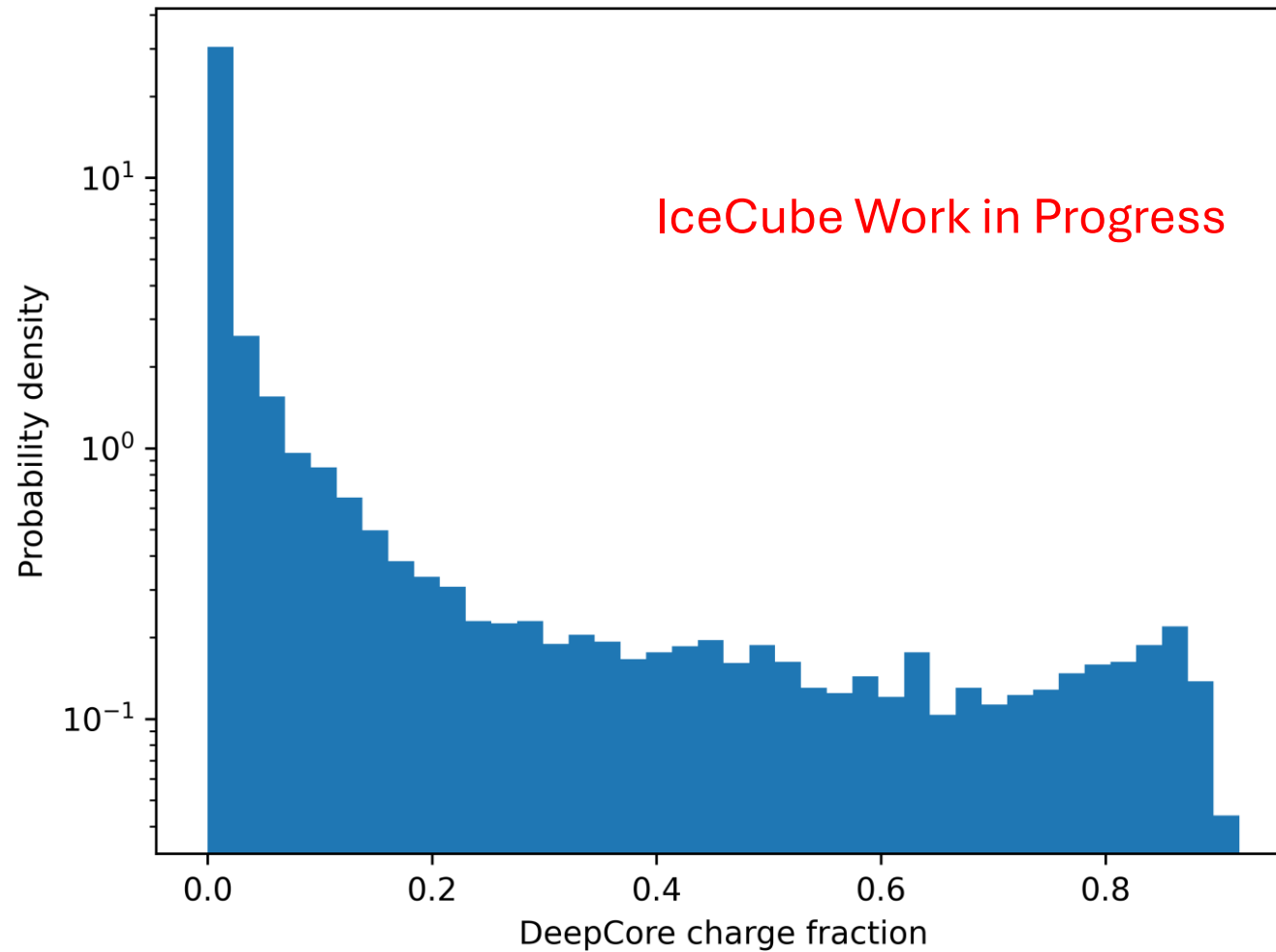


# Bright results to 200m: energy asymmetry





# DeepCore charge fraction distribution



# Classification

