

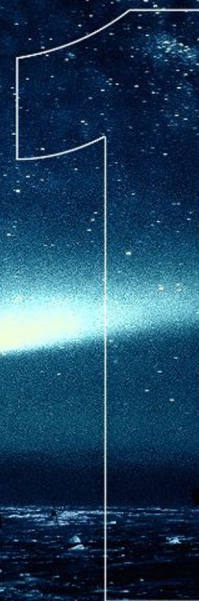


# Searches for astrophysical and cosmological neutrinos

Lu Lu

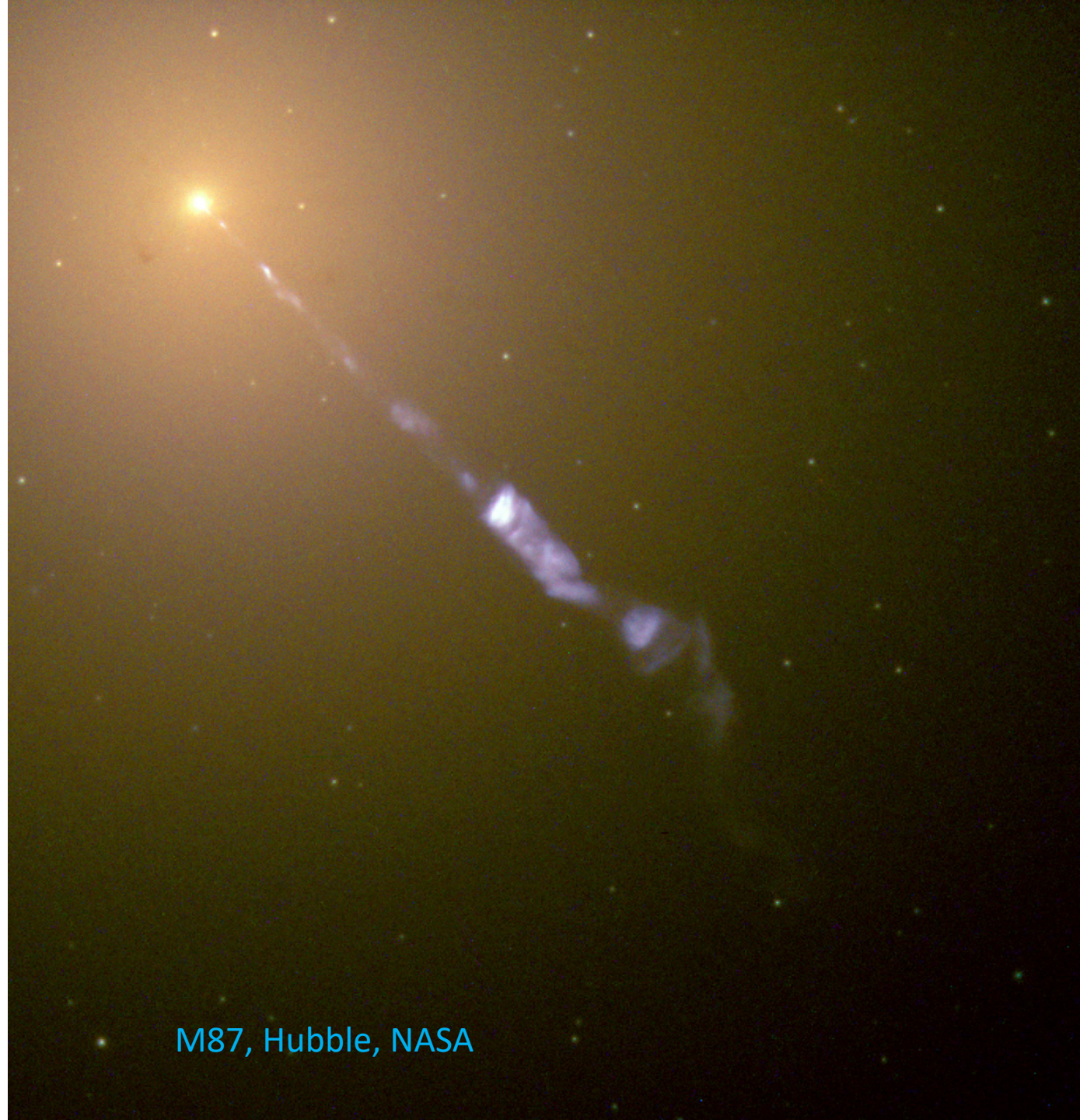
University of Wisconsin-Madison

ICHEP 2024, Prague



# Nature's accelerators

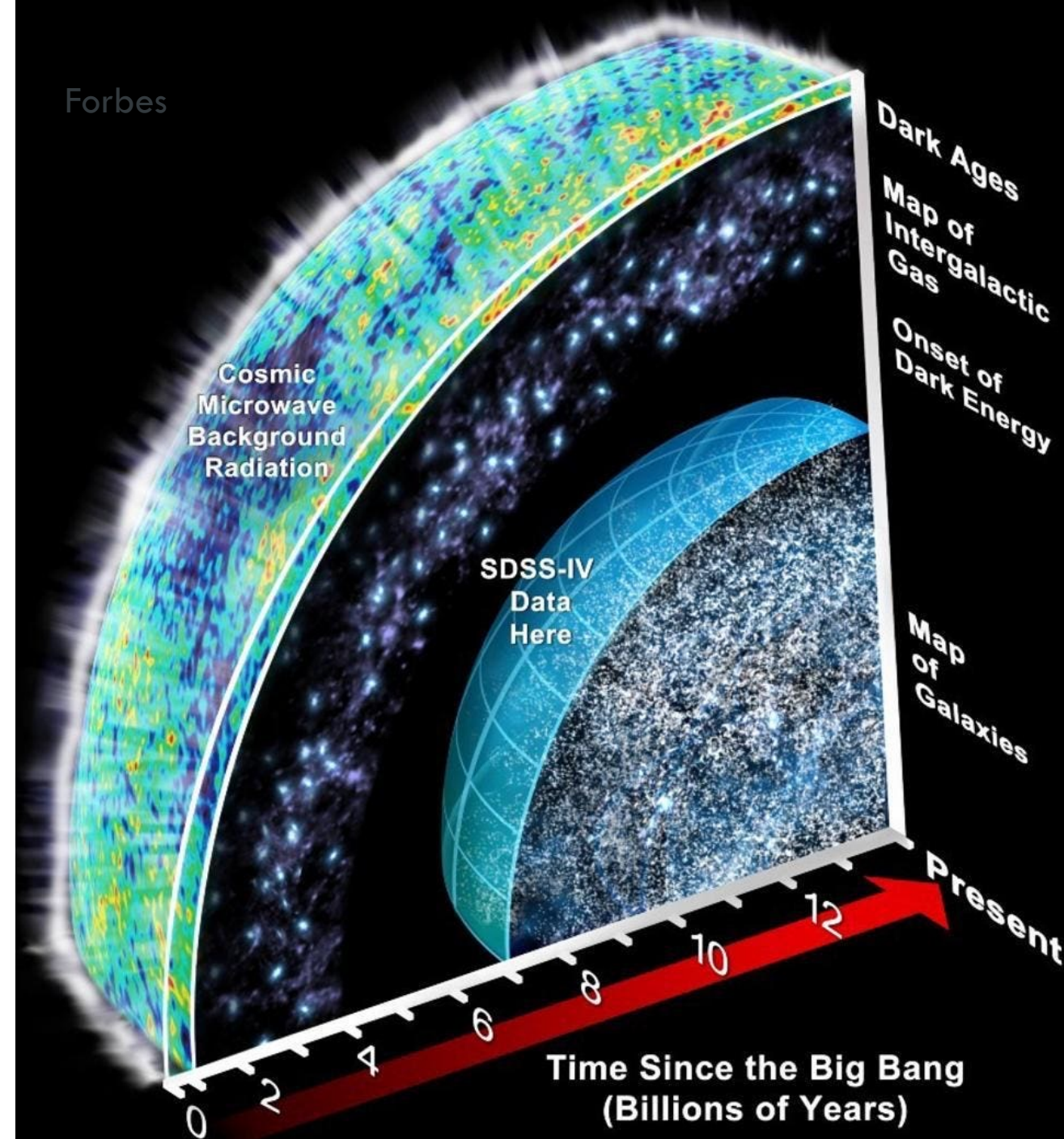
- M87 is 53.5 million light-years away from the Earth.
  - Early primates long before humans existed on Earth
- Jet length: super massive blackhole with a relativistic jet of 5000 light years
  - 3.15 billion times the distance from Earth to the Sun (~ 8 light minute)



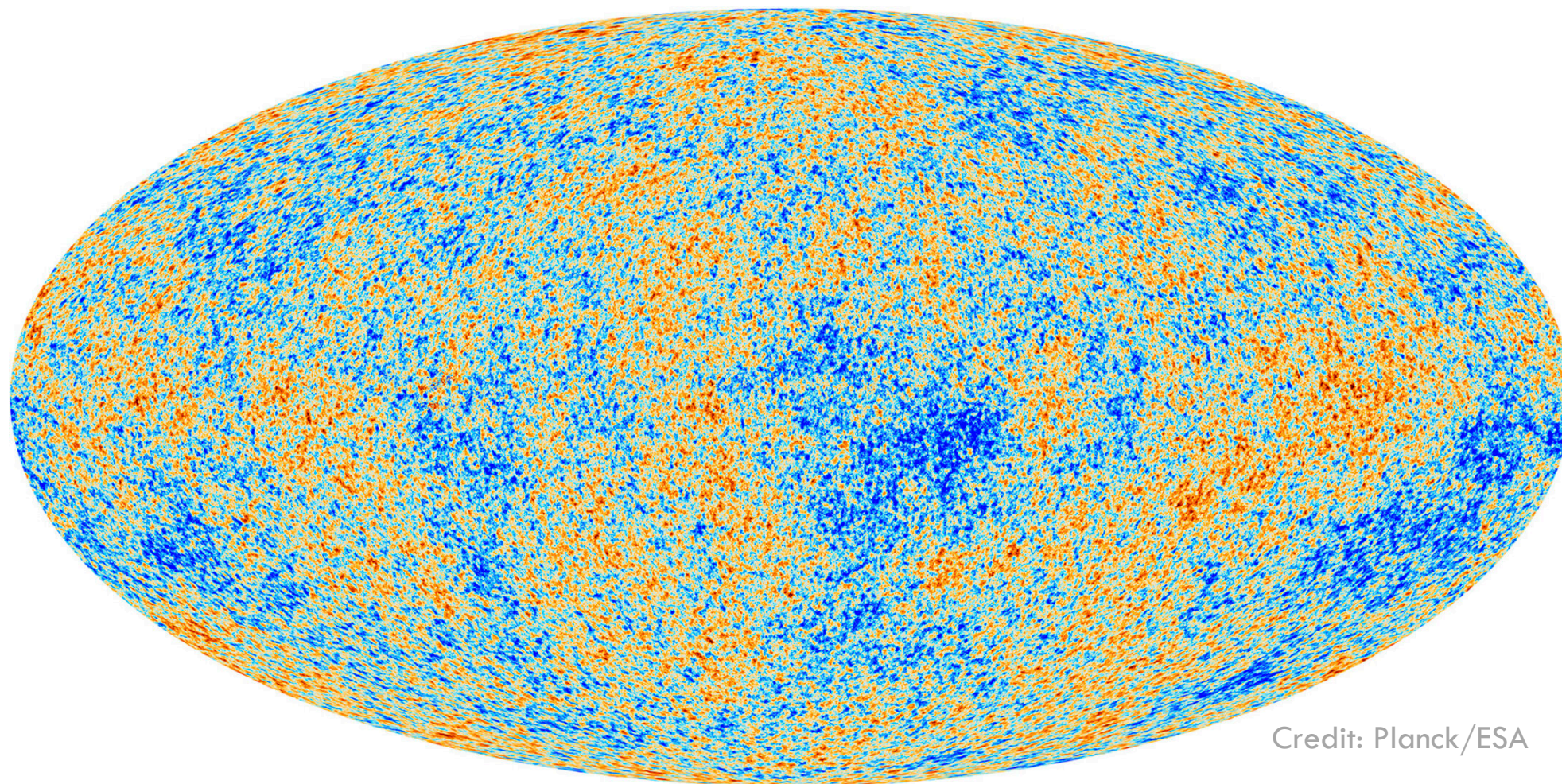
M87, Hubble, NASA

# Particle Astrophysics

LOOKING THROUGH  
HISTORY OF COSMOS  
VIA PARTICLES

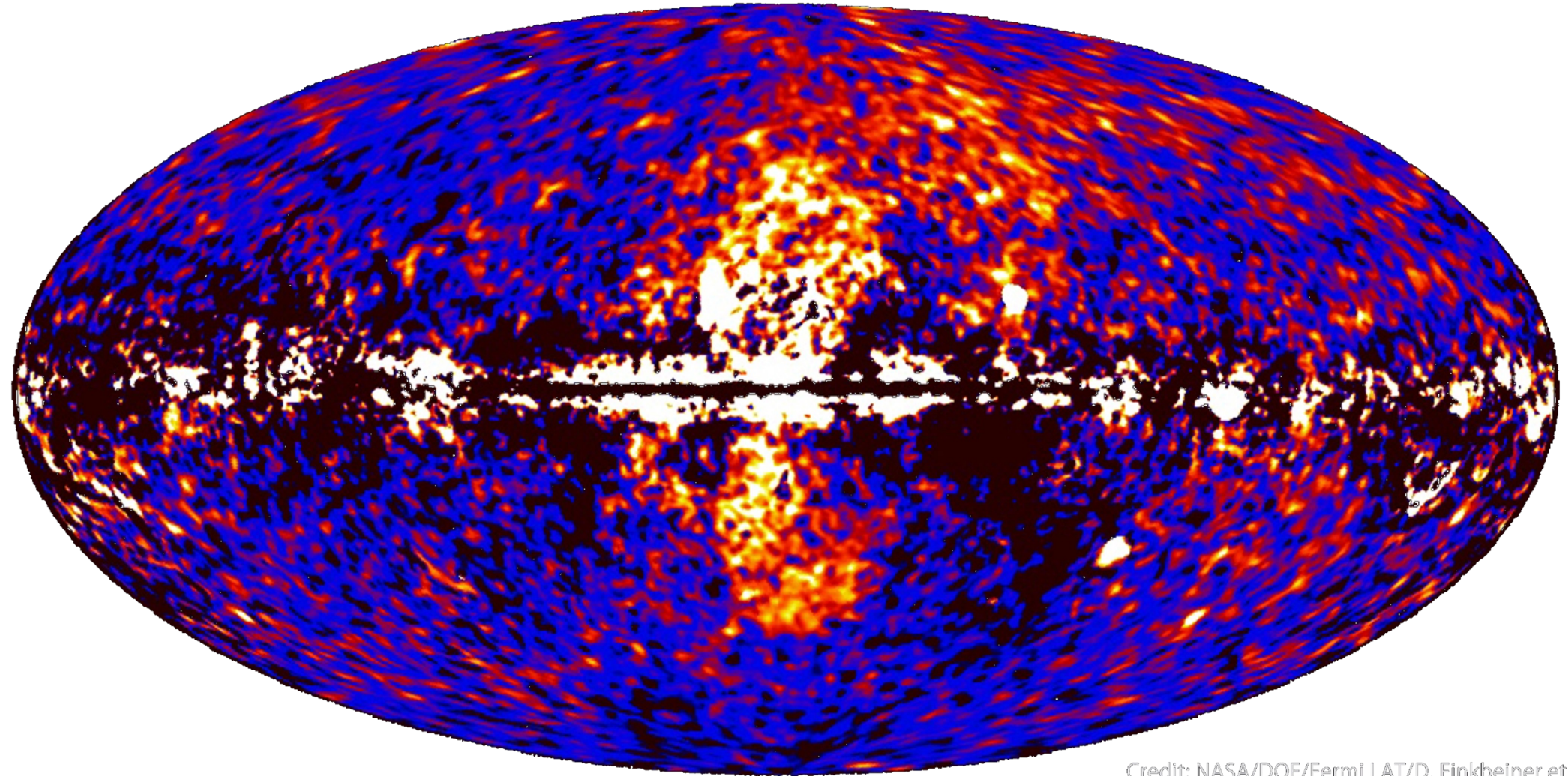


# DIFFUSE MICROWAVE PHOTONS



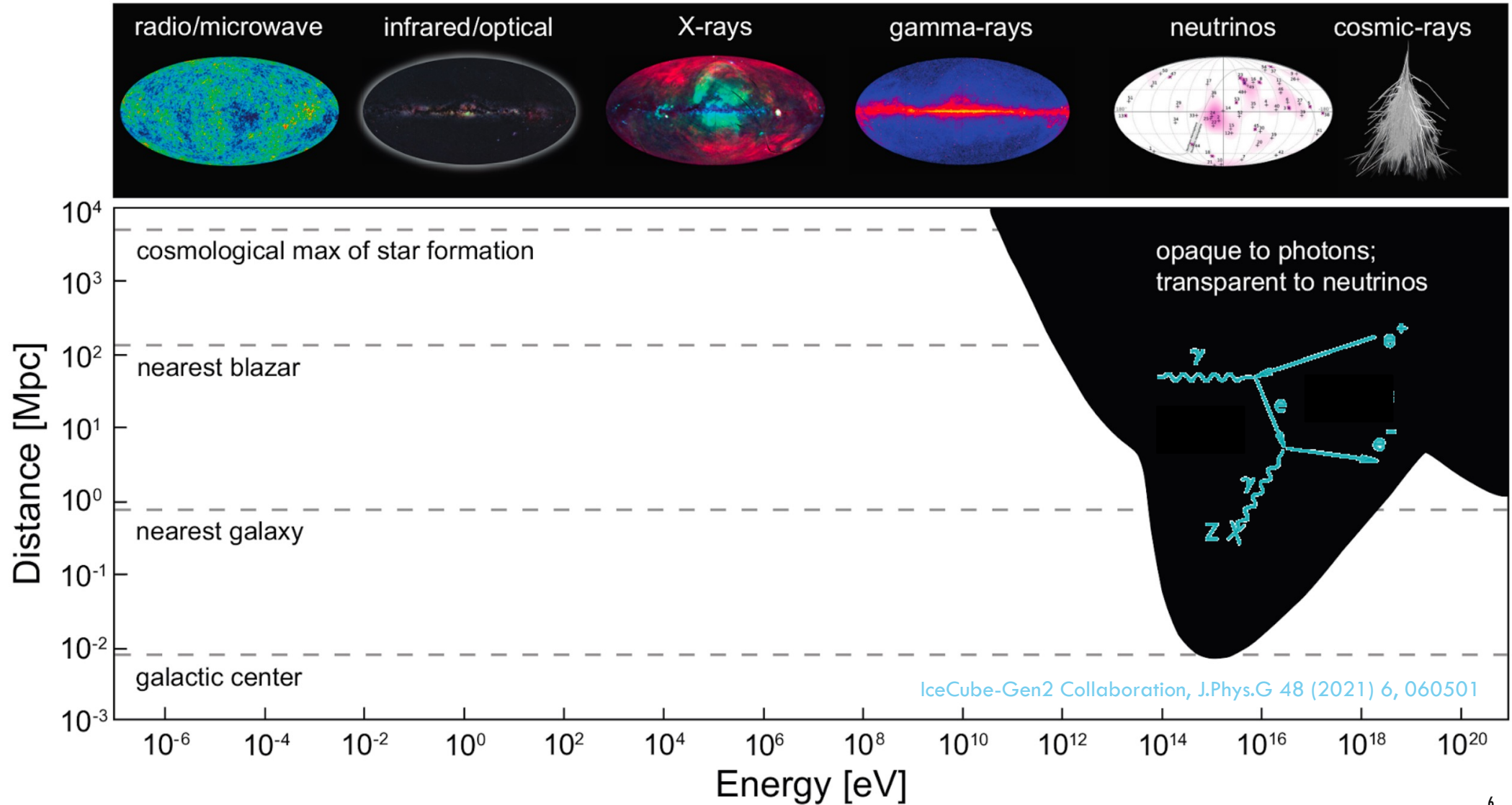
Credit: Planck/ESA

# DIFFUSE GAMMA-RAY PHOTONS



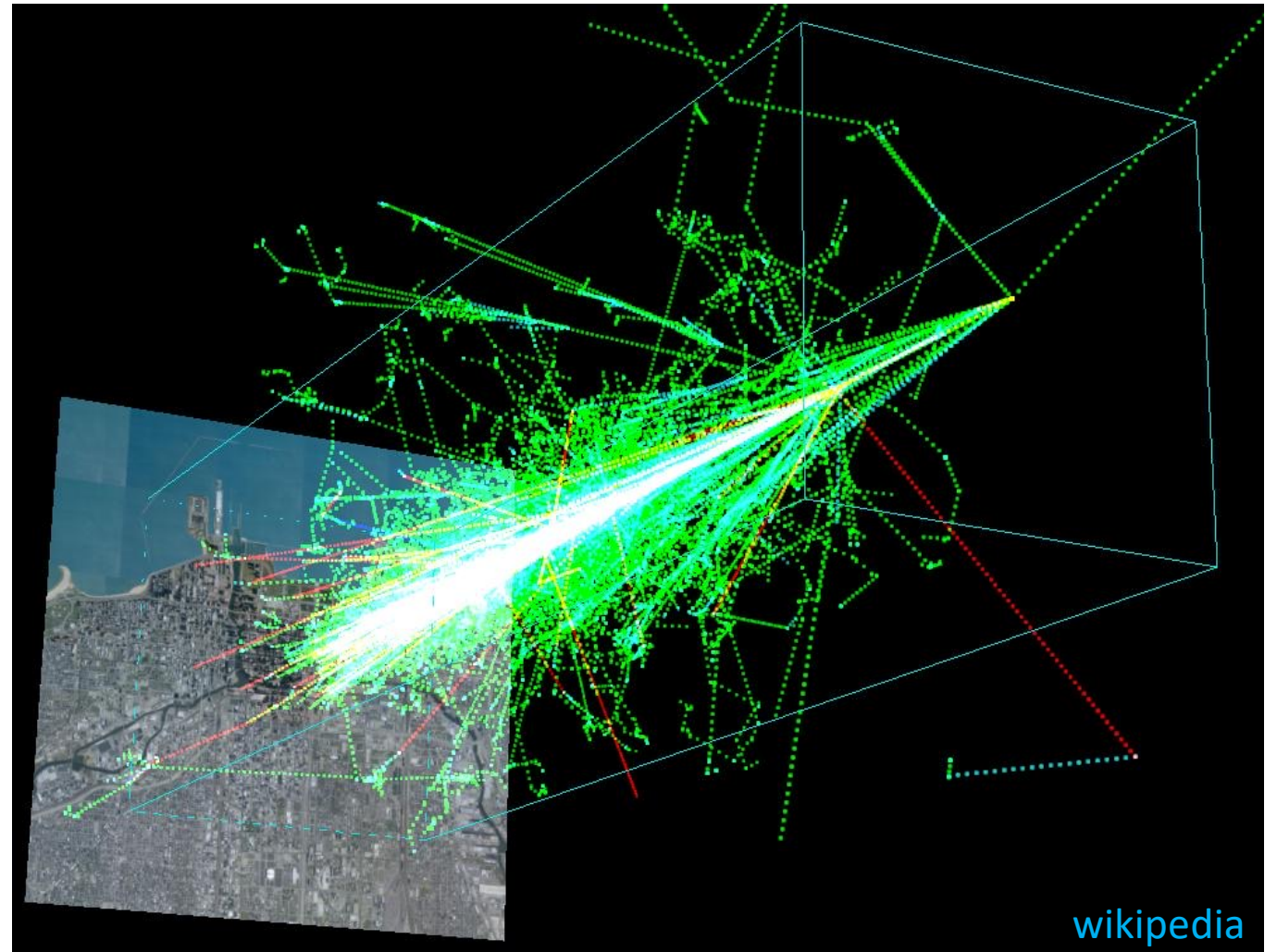
Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

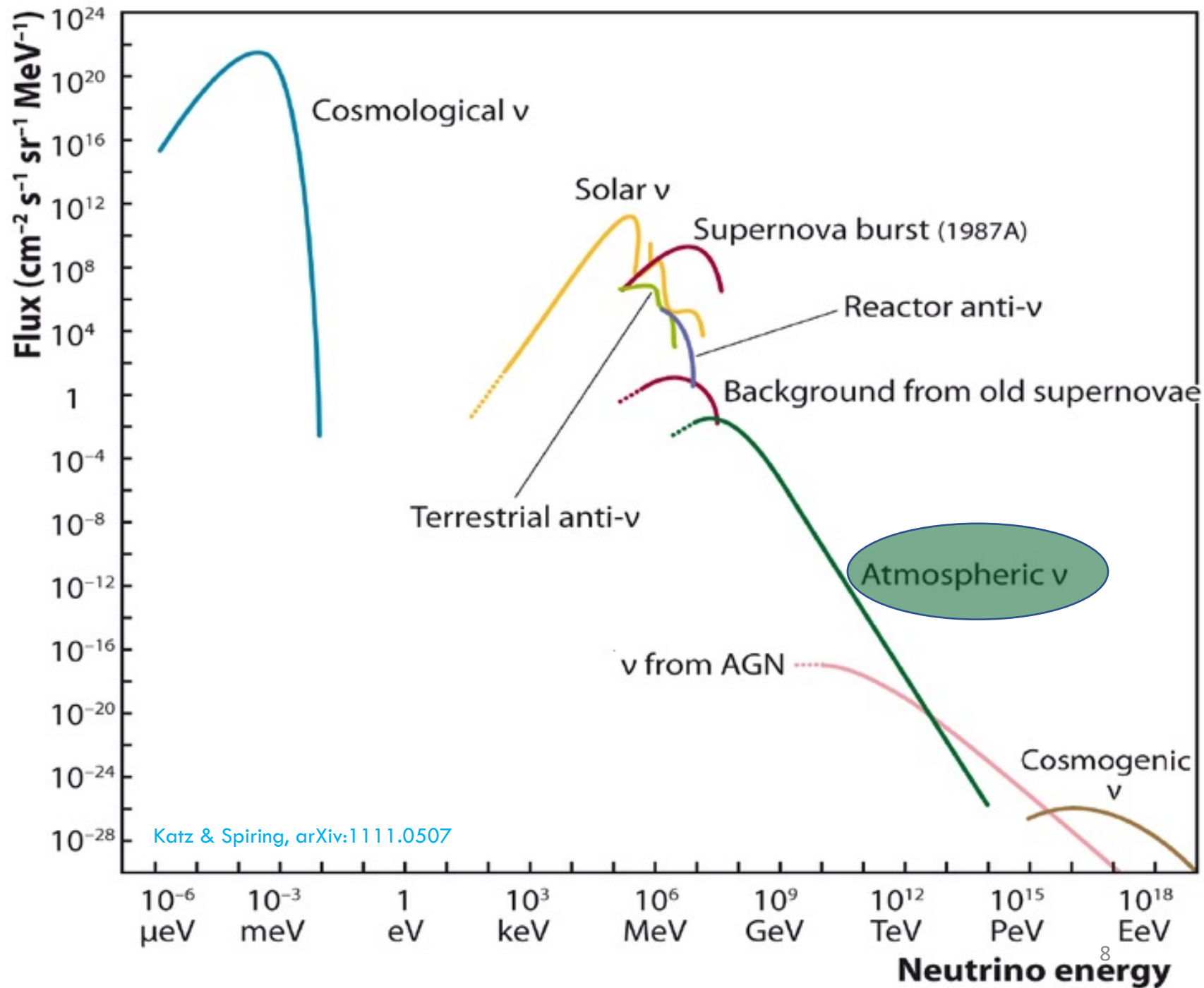
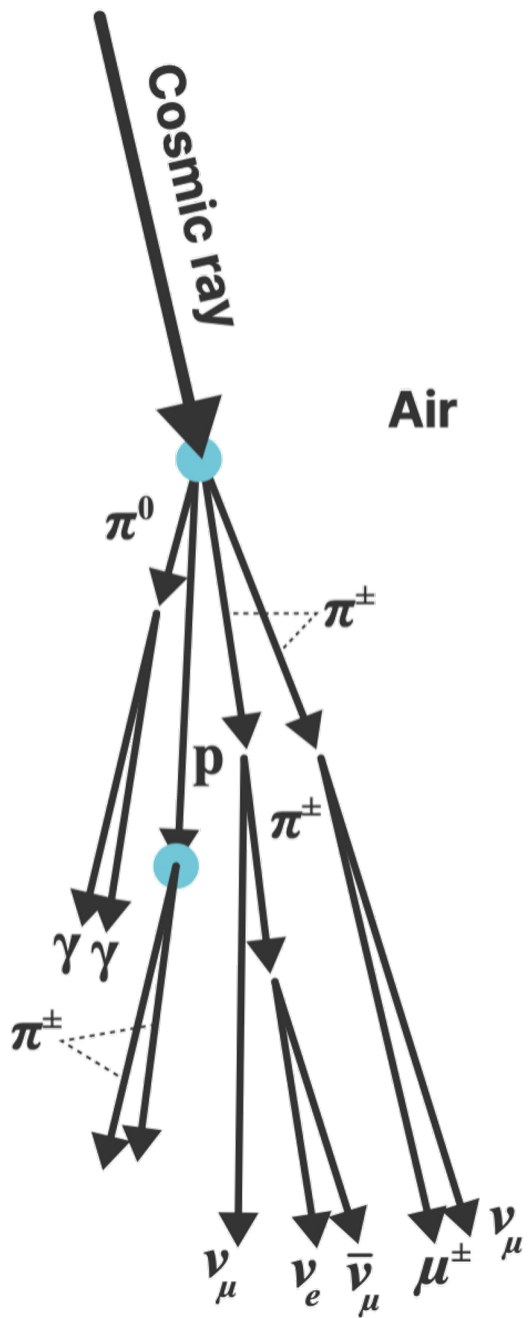
# NEUTRINOS: THE WINDOW TO THE EXTREME UNIVERSE



# FROM CLOUD CHAMBERS TO EXTENSIVE AIR SHOWERS

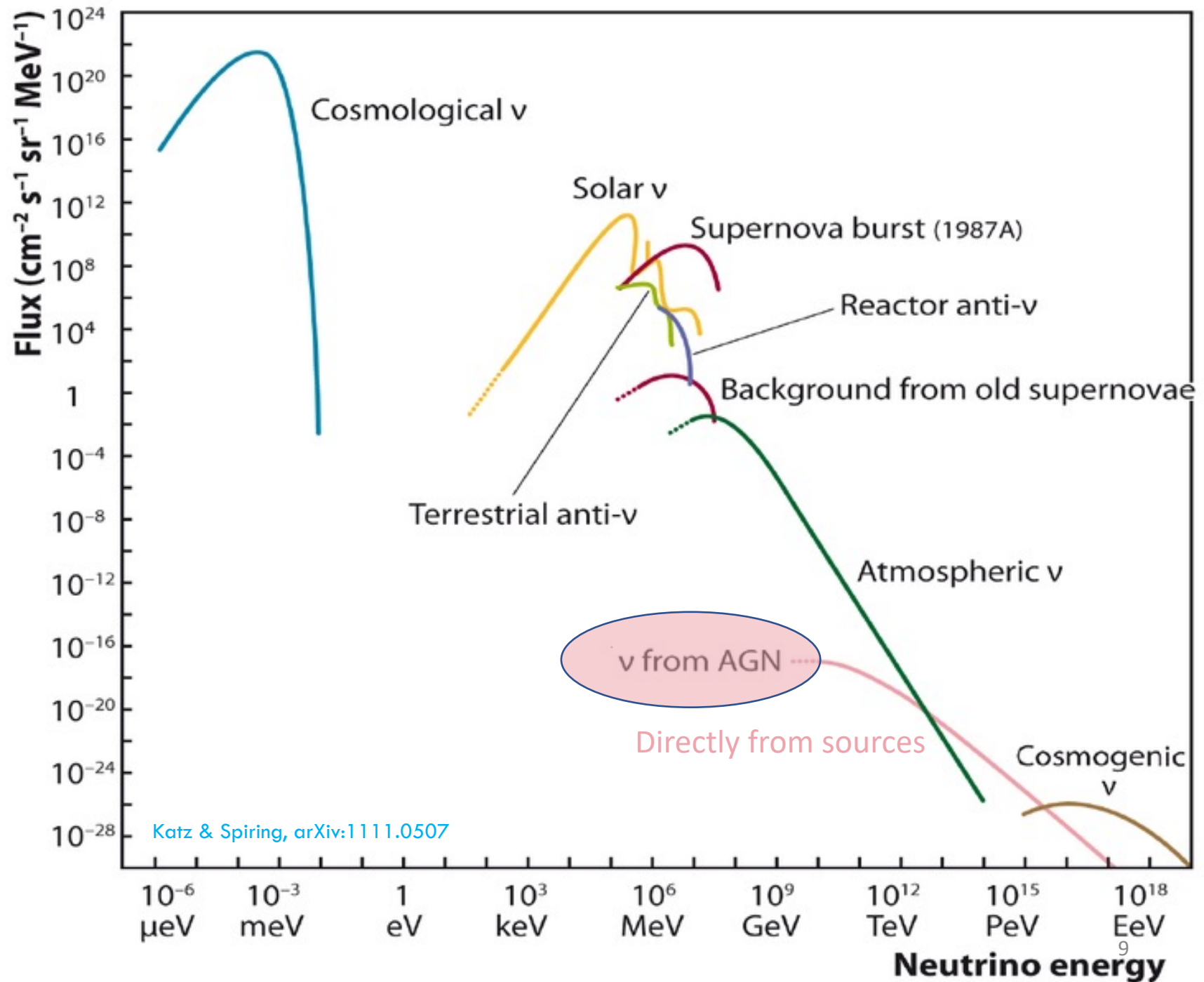
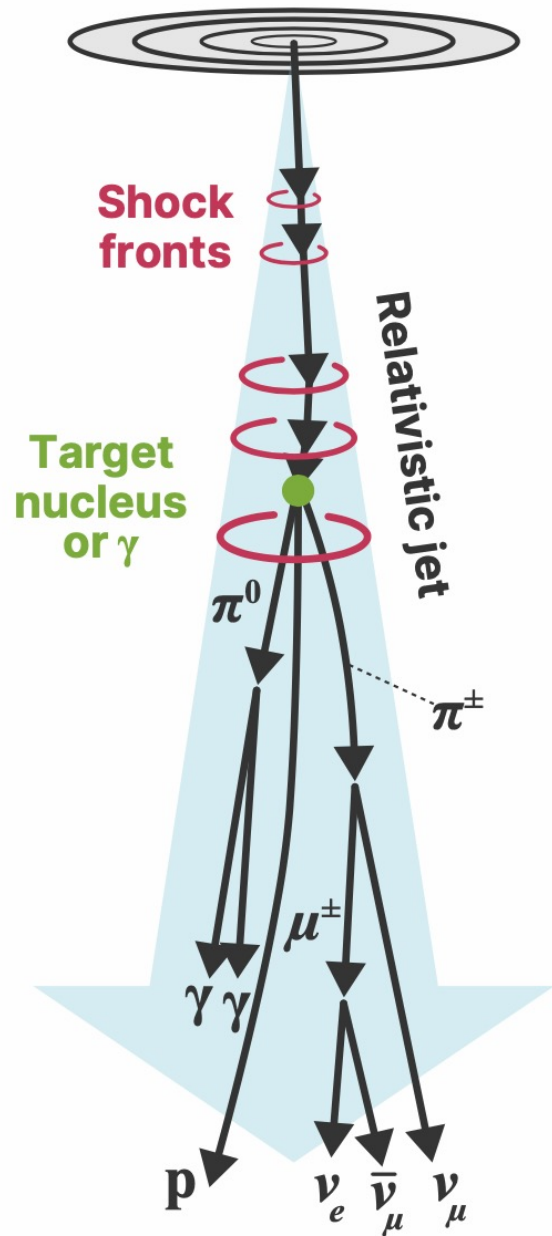
Particle shower universality: fundamental laws at over 10 orders of magnitude in energy

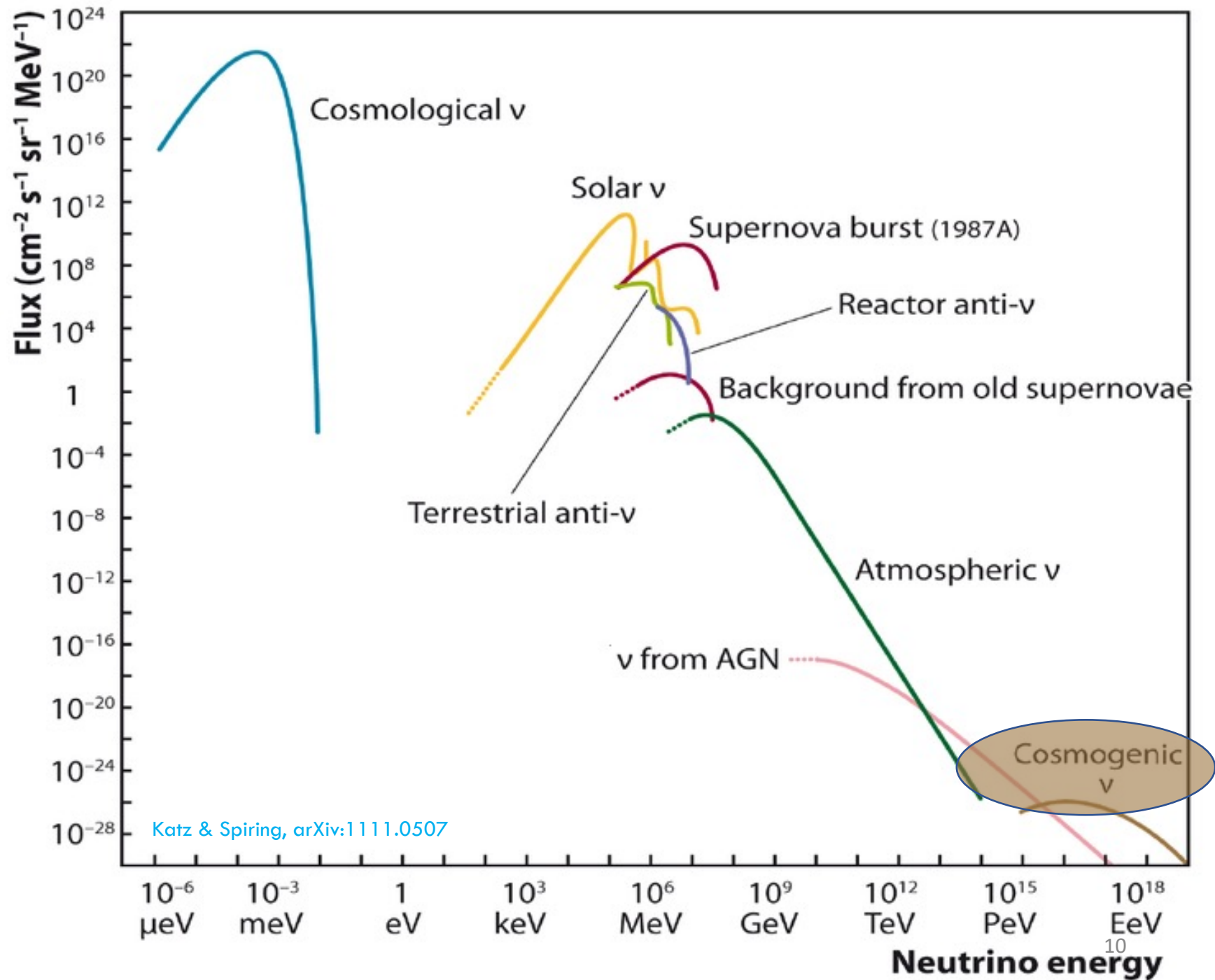
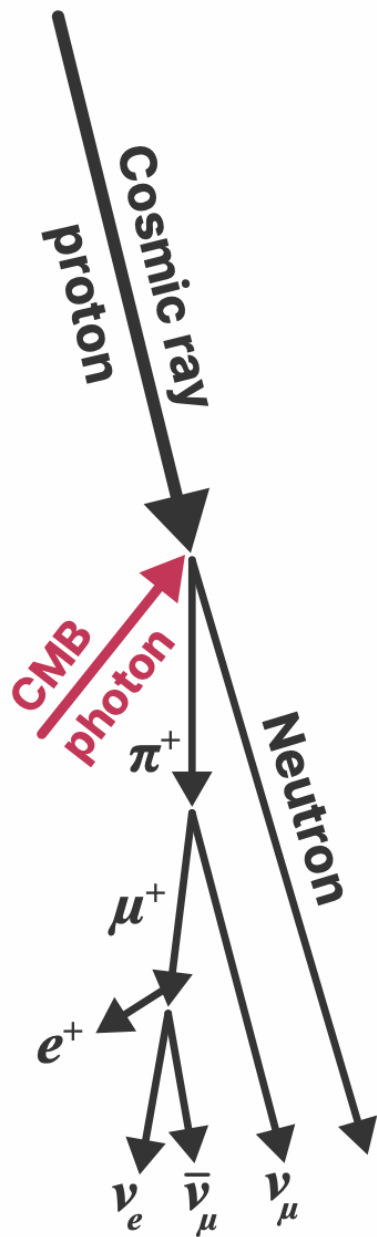




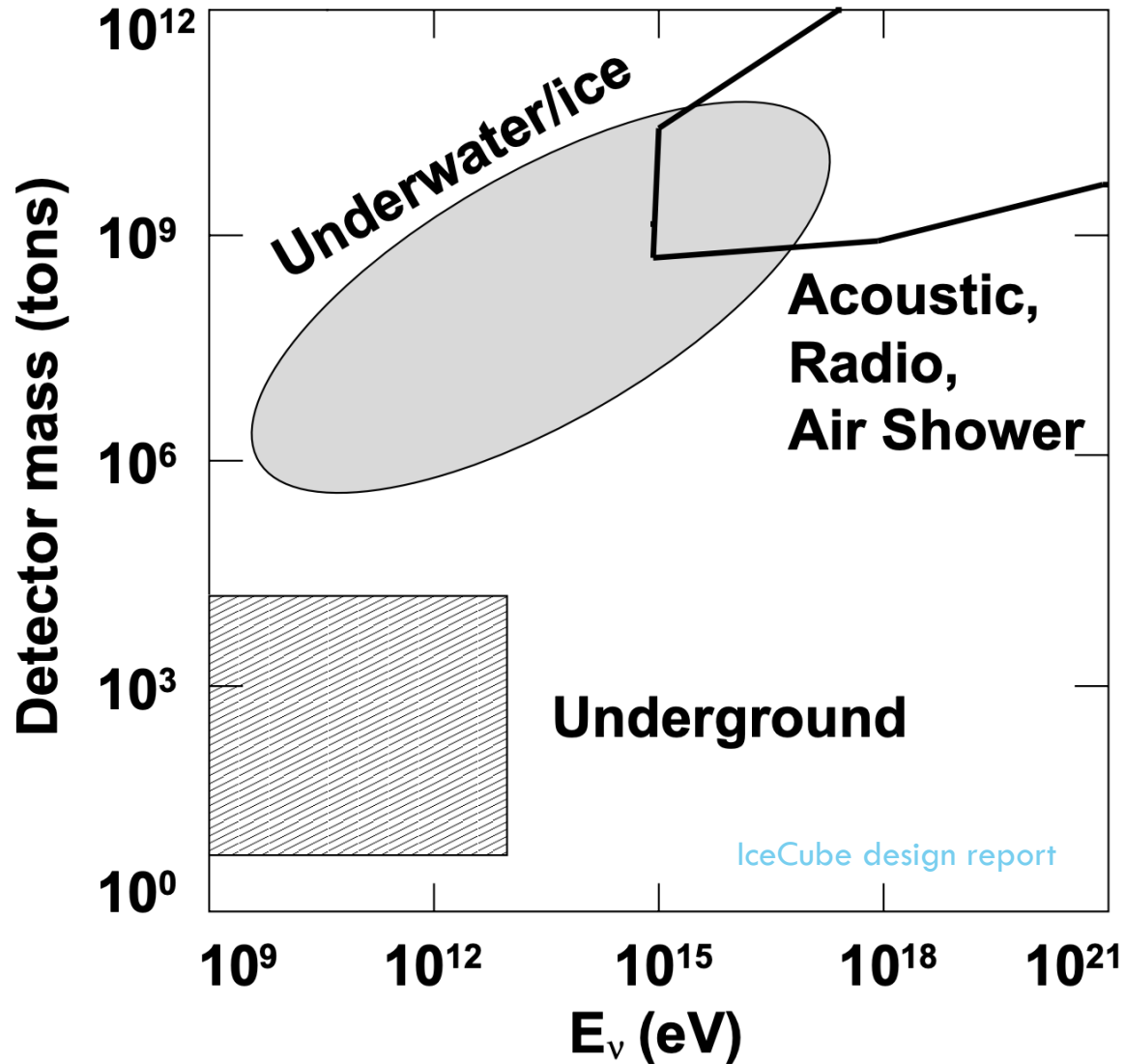


# Active galactic nucleus



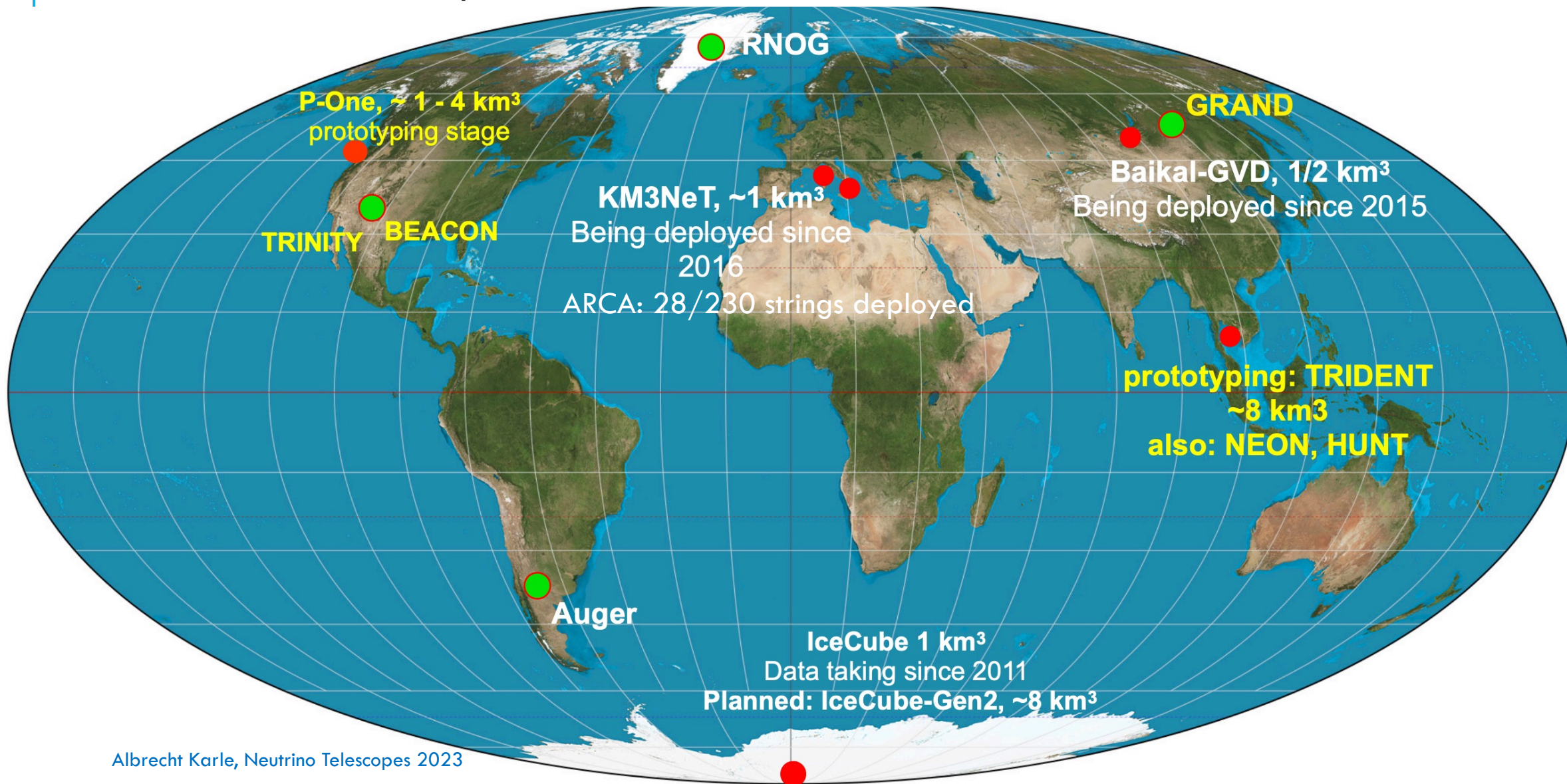


# DETECTING NEUTRINOS FROM GEV TO EEV



- Higher neutrino energy  $\rightarrow$  lower flux  $\rightarrow$  requires a larger instrumentation volume
- $< 1$  TeV: underground Cherenkov detector
- 1 TeV – 50 PeV Under water/ice Cherenkov detector
- $> 50$  PeV: radio, air shower, balloon, space-based, Earth-skimming ...

# UNDER WATER/ICE CHERENKOV LANDSCAPE

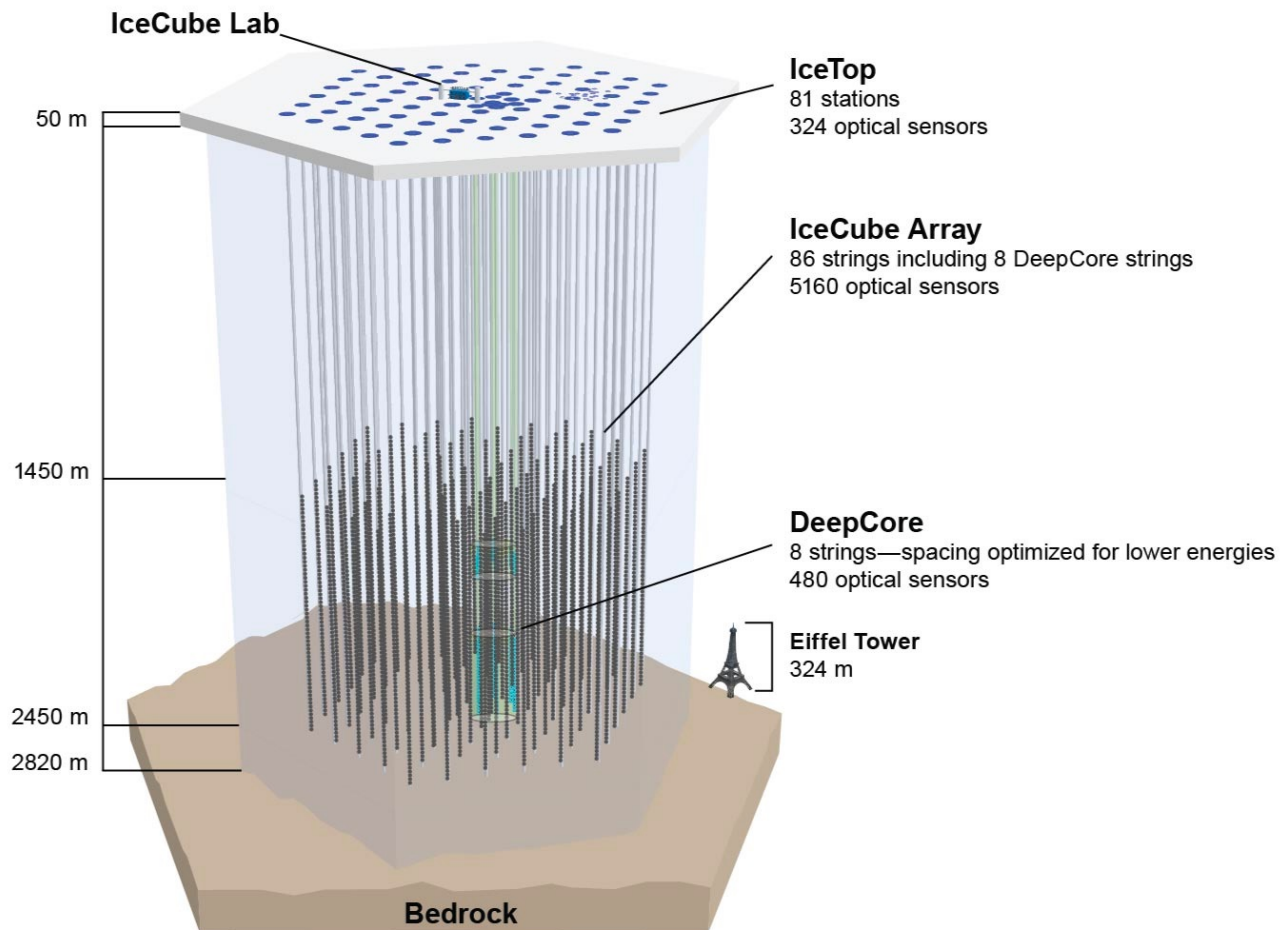


# ICECUBE NEUTRINO OBSERVATORY

South Pole, Antarctica



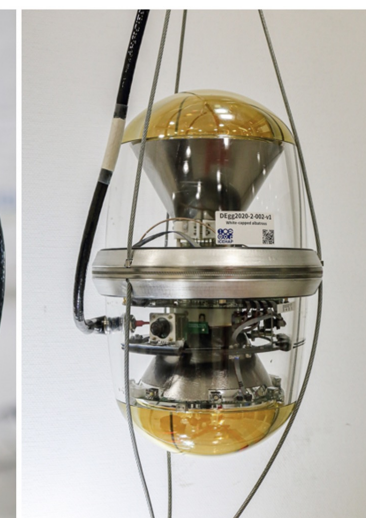
DOM



- Construction completed in 2011
- 86 strings x 60 DOMs per string
- Uptime typically 99.7%-99.9%
- Only 36 DOM failures since commissioning
- IceCube-upgrade underway



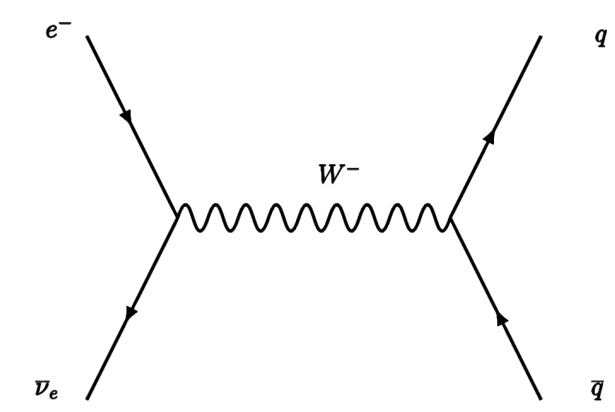
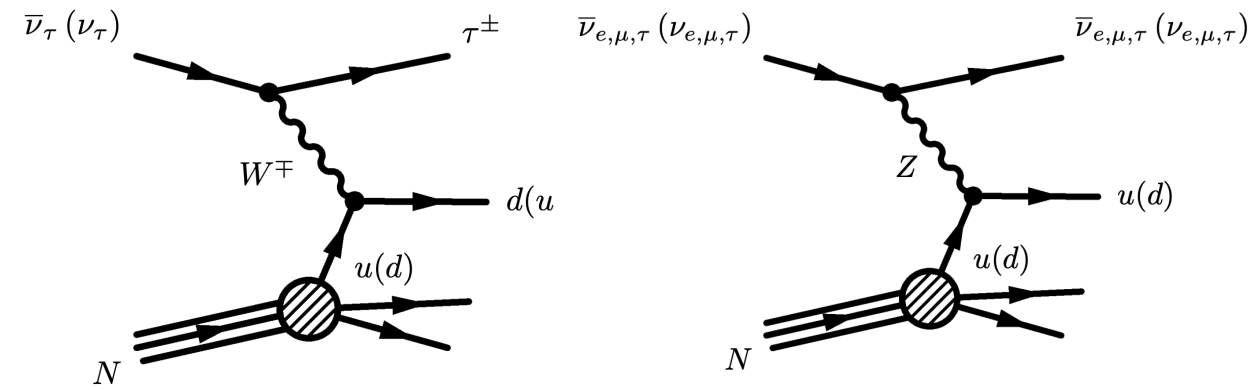
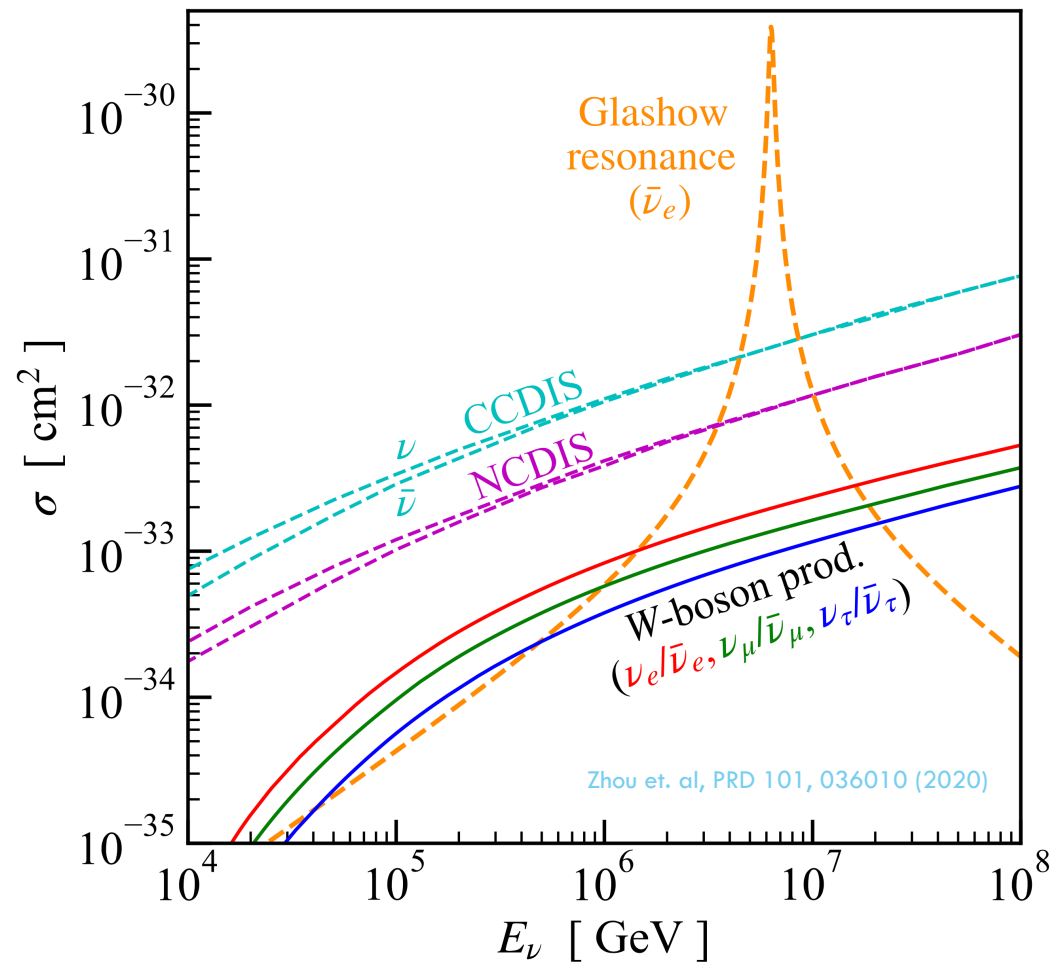
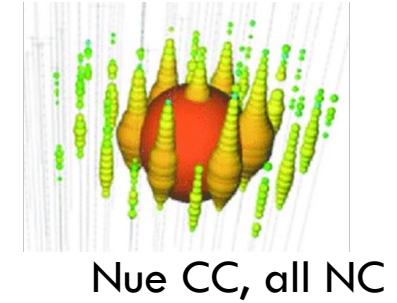
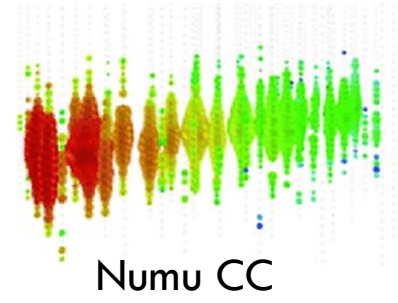
mDOM



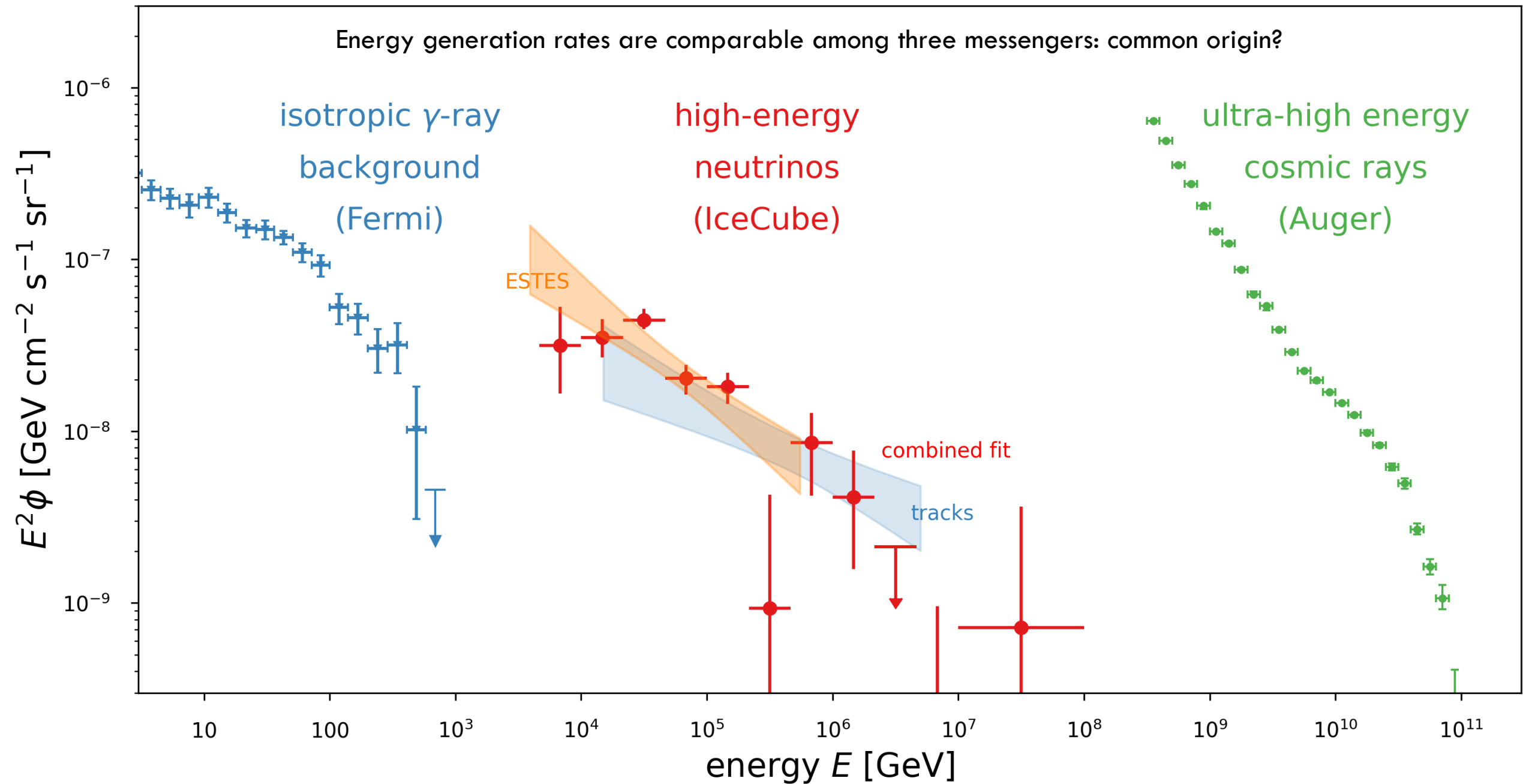
D-Egg

# NEUTRINO INTERACTIONS

Detect Cherenkov radiation from secondary charged particles

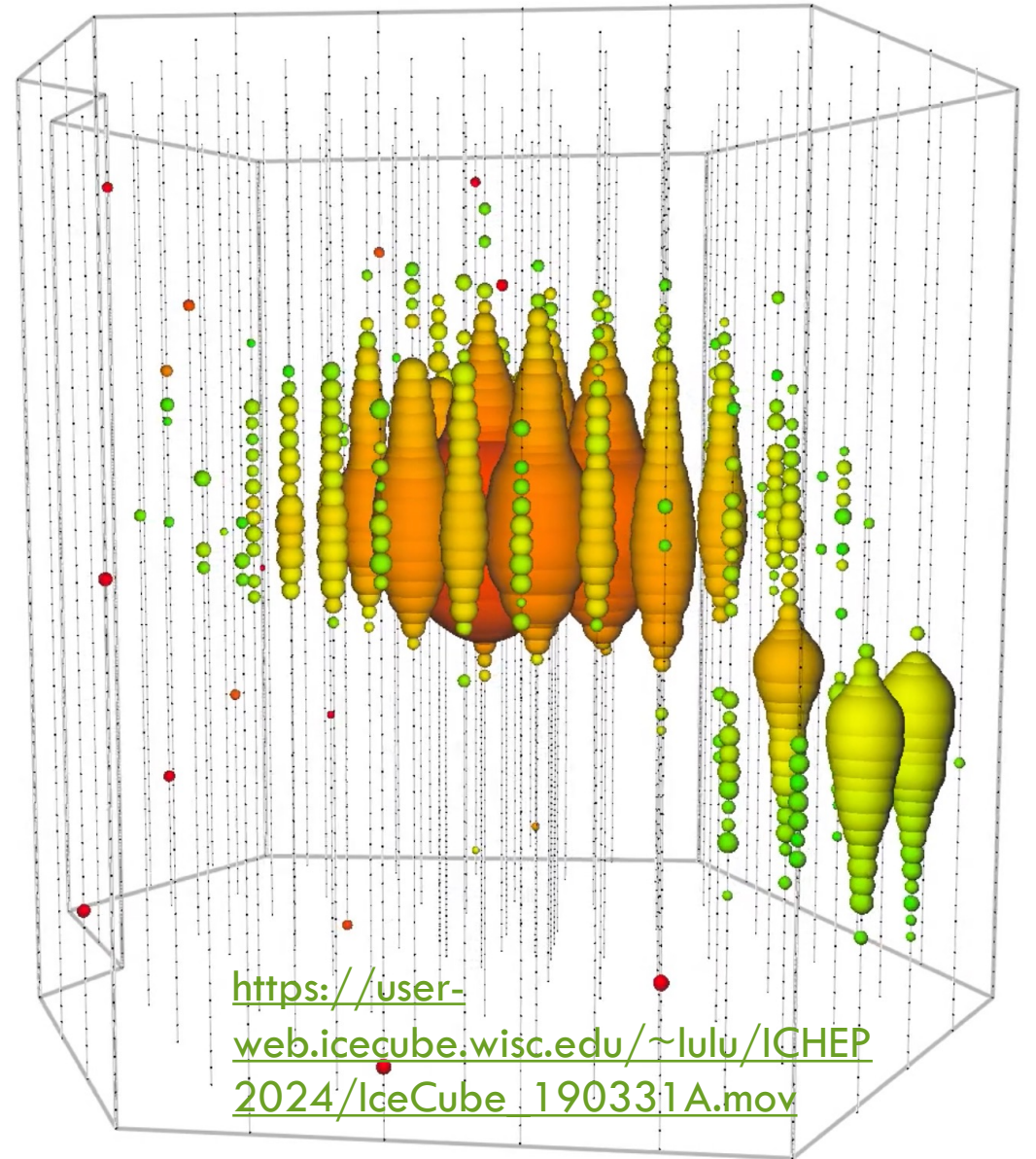


Energy generation rates are comparable among three messengers: common origin?



# ICECUBE'S HIGHEST ENERGY NEUTRINO

- Muon neutrino with contained vertex position
- Deposited energy 4.8 PeV
- $dE/dx \sim 1.125 \text{ TeV/m}$  over last 400m
- Resimulation: **neutrino energy**  
**11.6  $\pm$  2.6 PeV**

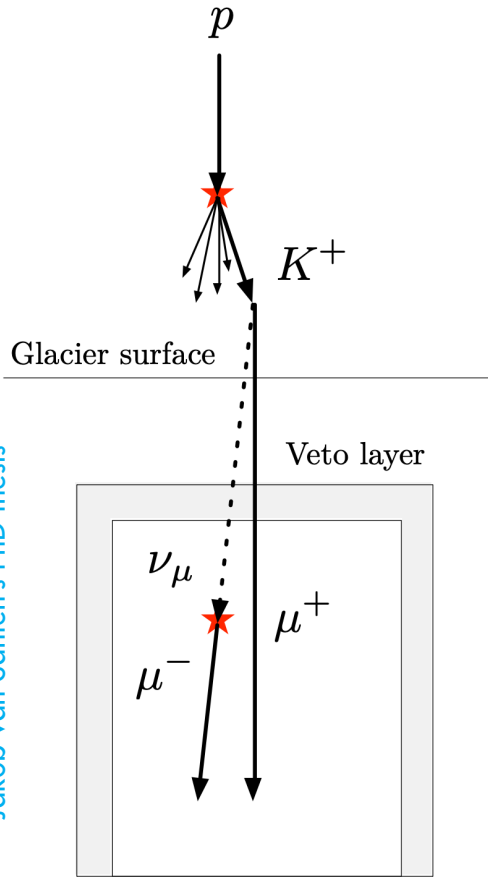


Likely Astrophysical origin instead of cosmogenic

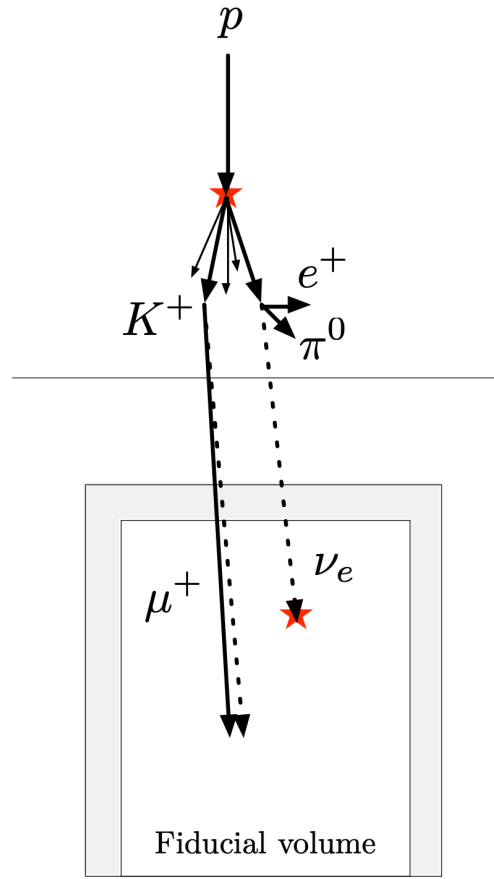


# THE HIGHEST ENERGY EVENT: BACKGROUND REJECTION

Starting event: neutrino selfveto

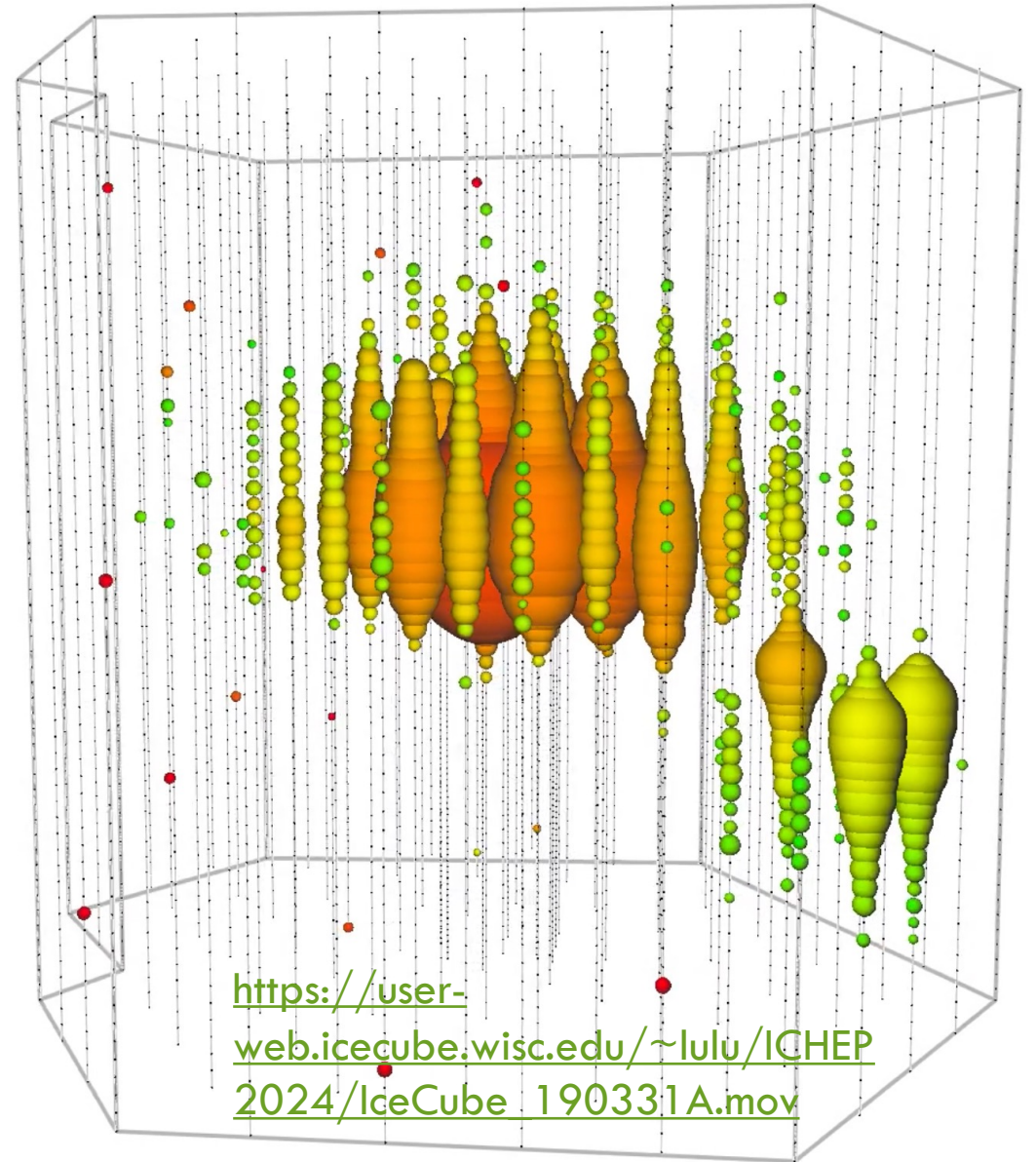


Veto by correlated muon



Veto by uncorrelated muon

Jakob van Santen's PhD thesis

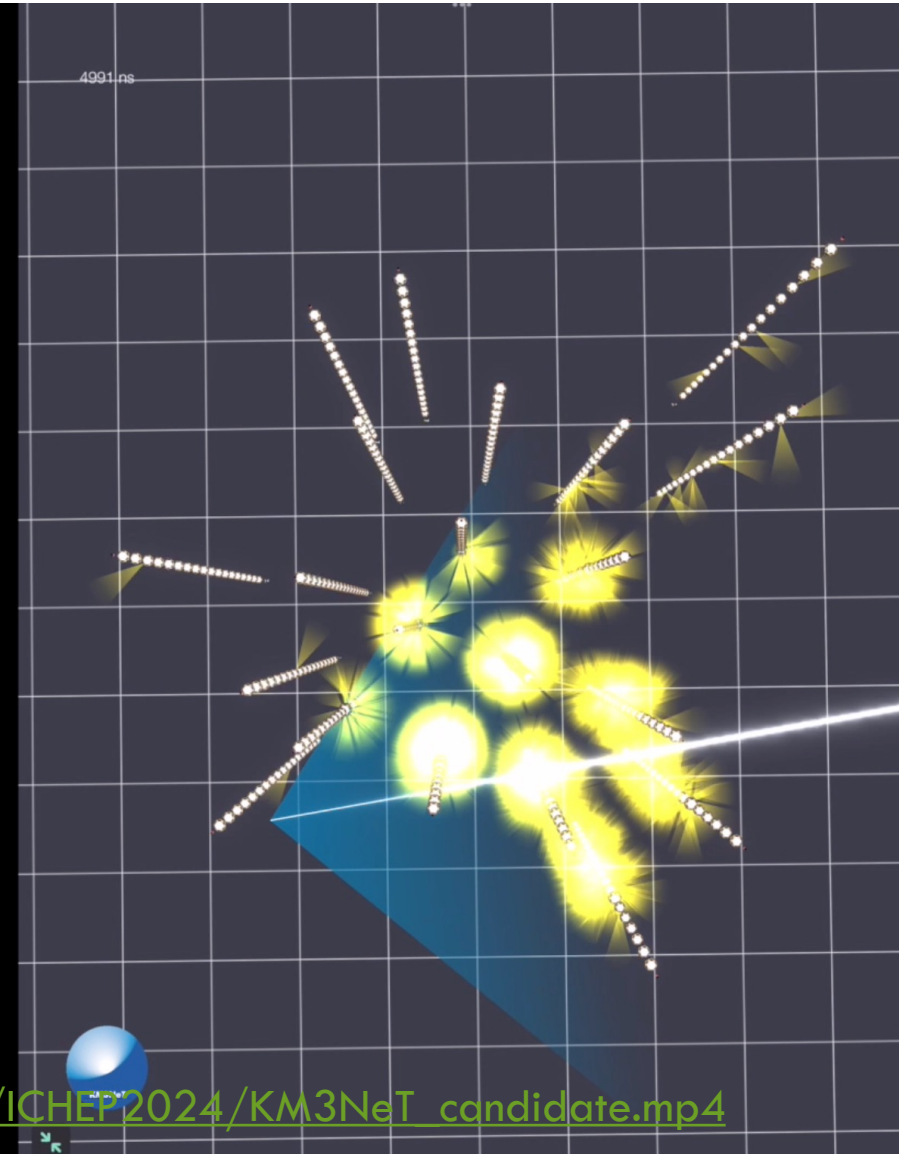
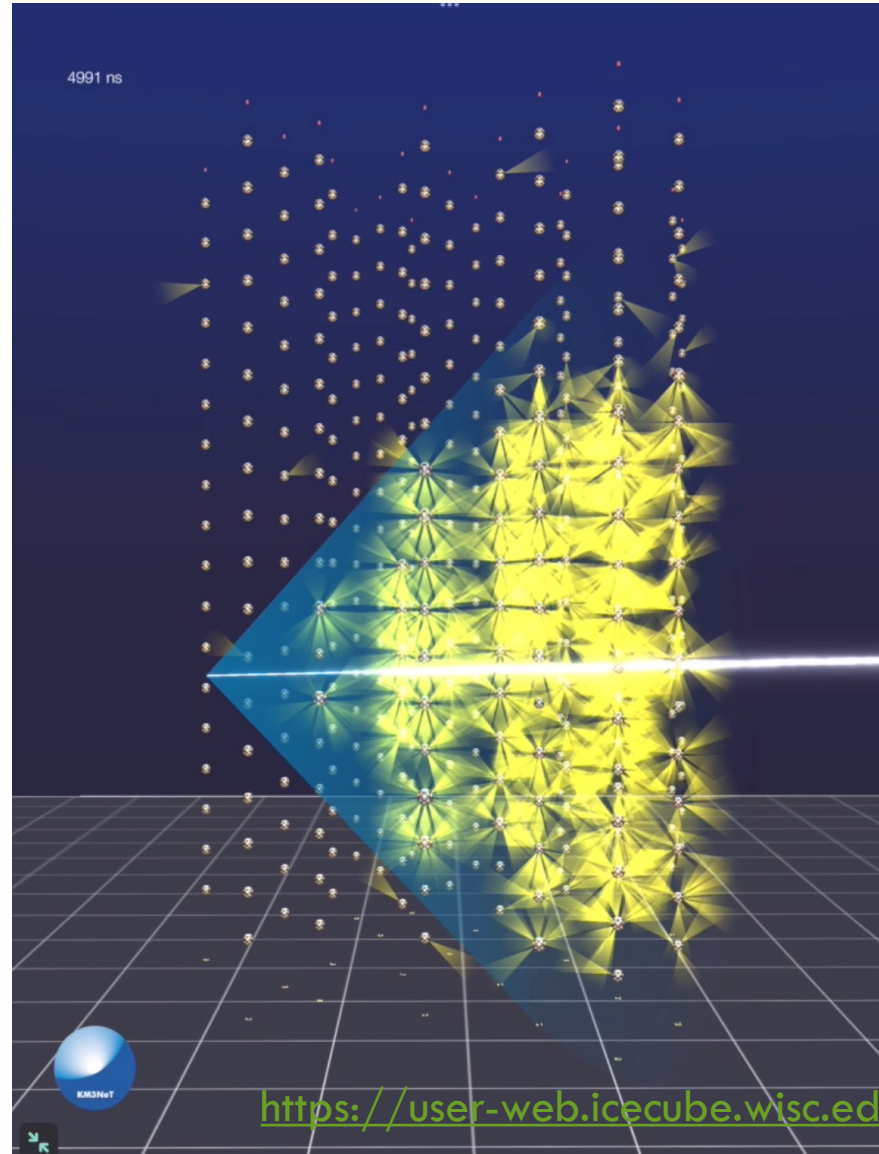
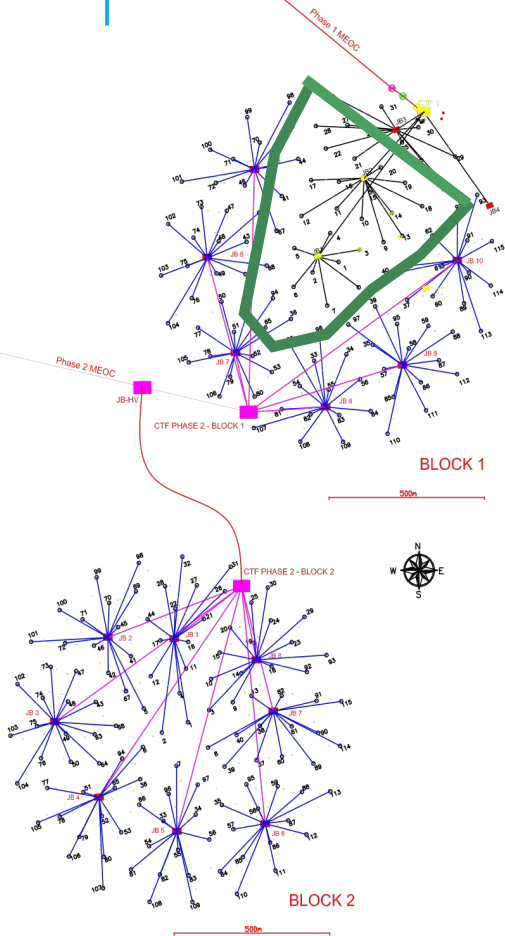


Likely Astrophysical origin instead of Atmospheric

# KM3NET — AN INTRIGUING EVENT

See [talk](#) from Paschal Coyle

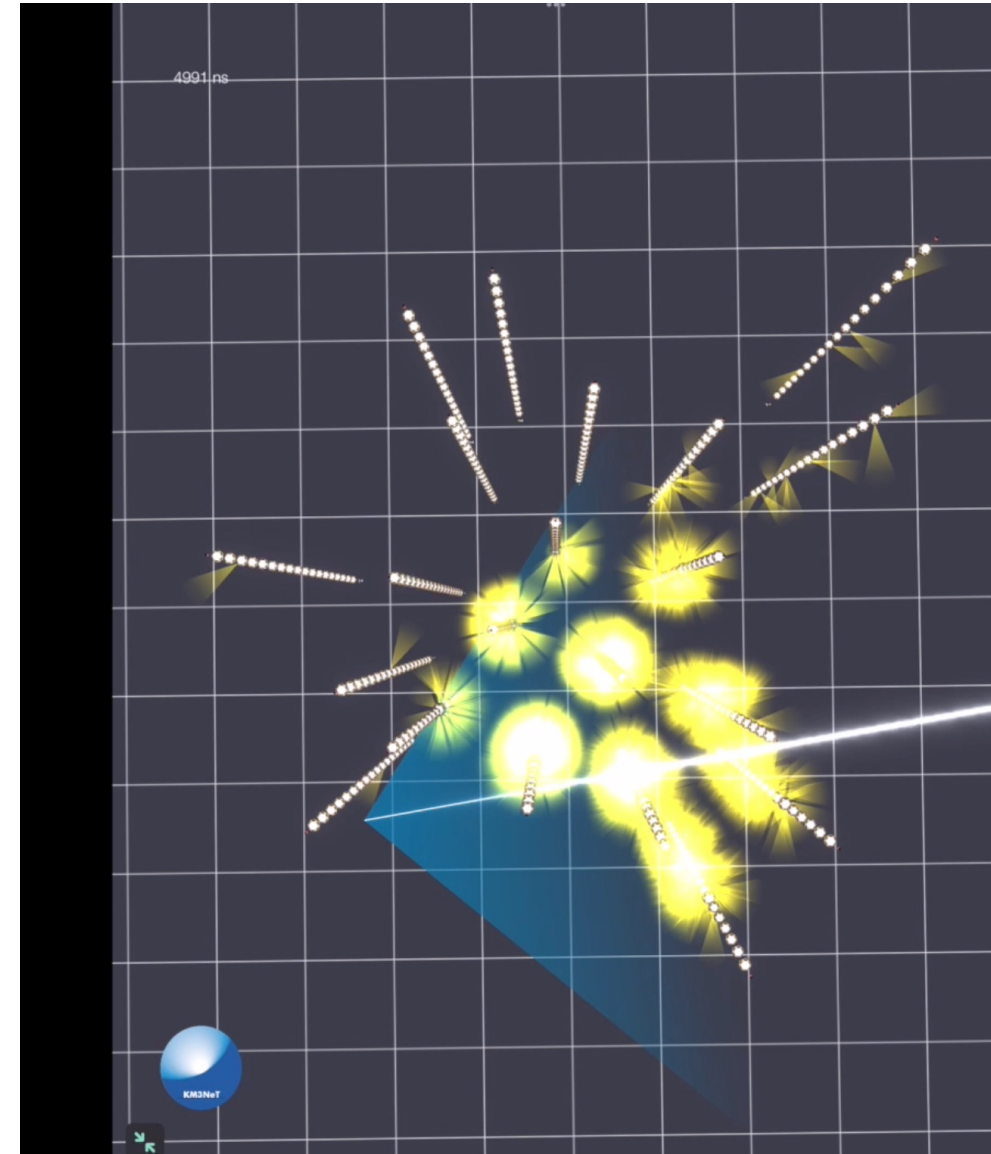
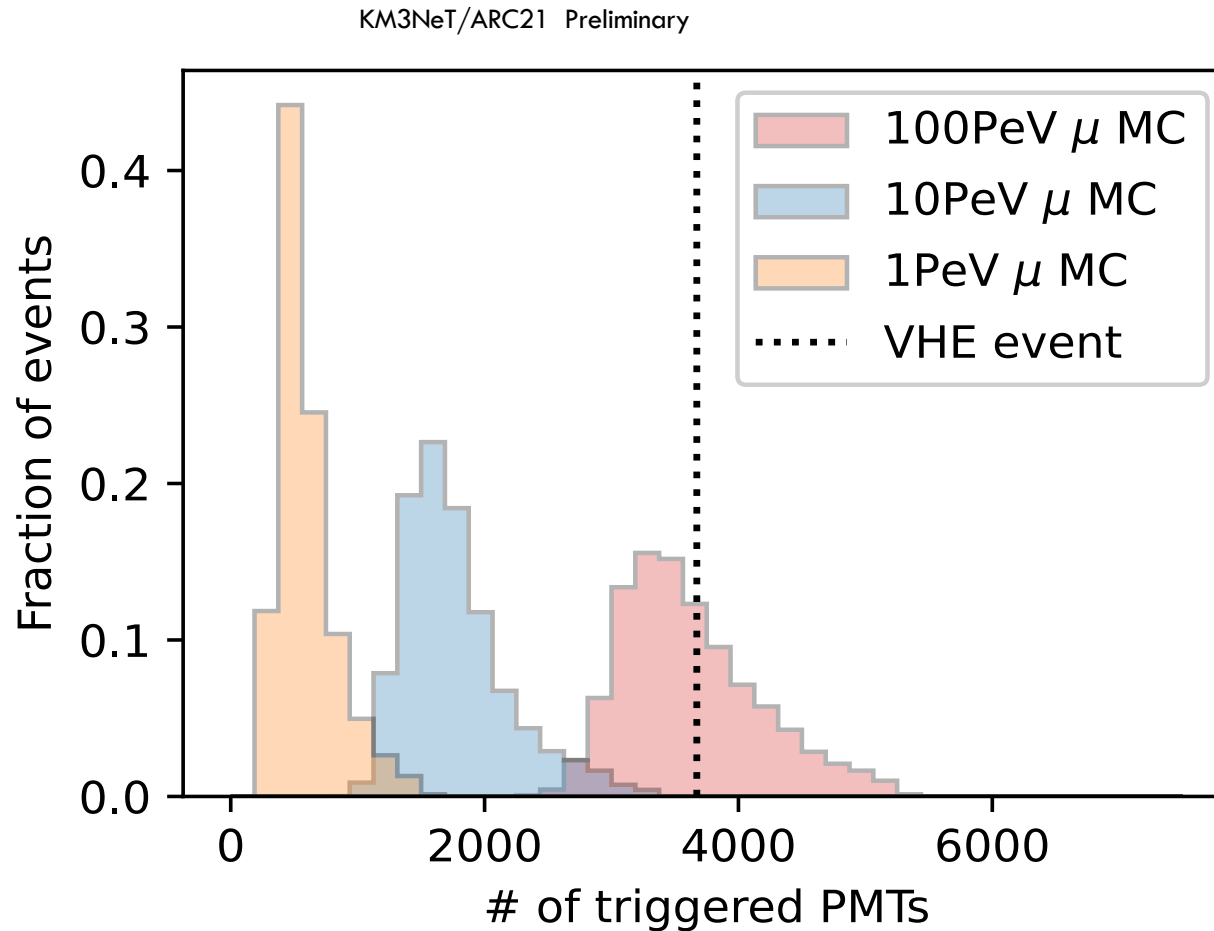
Potentially with muon energy  $\gg 10$  PeV. Background probability, angular and energy uncertainties under study.



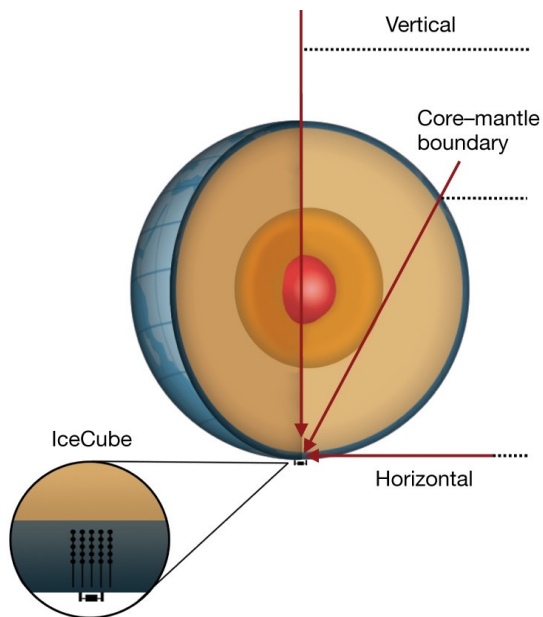
# KM3NET – AN INTRIGUING EVENT

See [talk](#) from Paschal Coyle

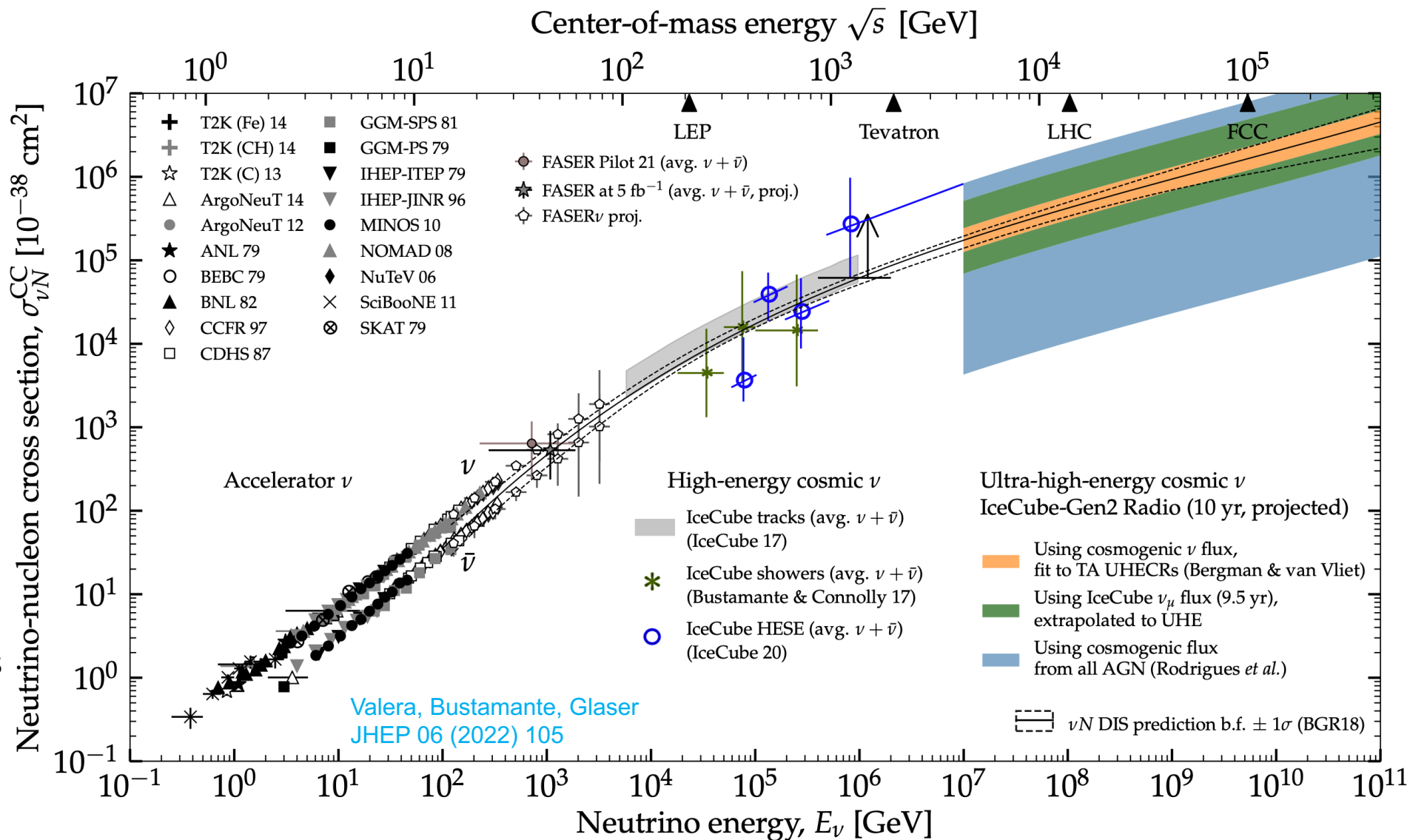
Potentially with muon energy  $\rightarrow$  100 PeV. Background probability, angular and energy uncertainties under study.



# CROSS SECTION WITH EARTH AS THE TARGET



Extending x-section measurements to energies beyond Earth-based accelerators



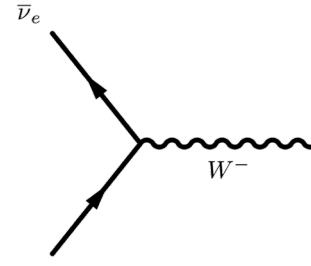
# W BOSON (GLASHOW) RESONANCE

*IceCube Collaboration, Nature 591, 220–224 (2021)*

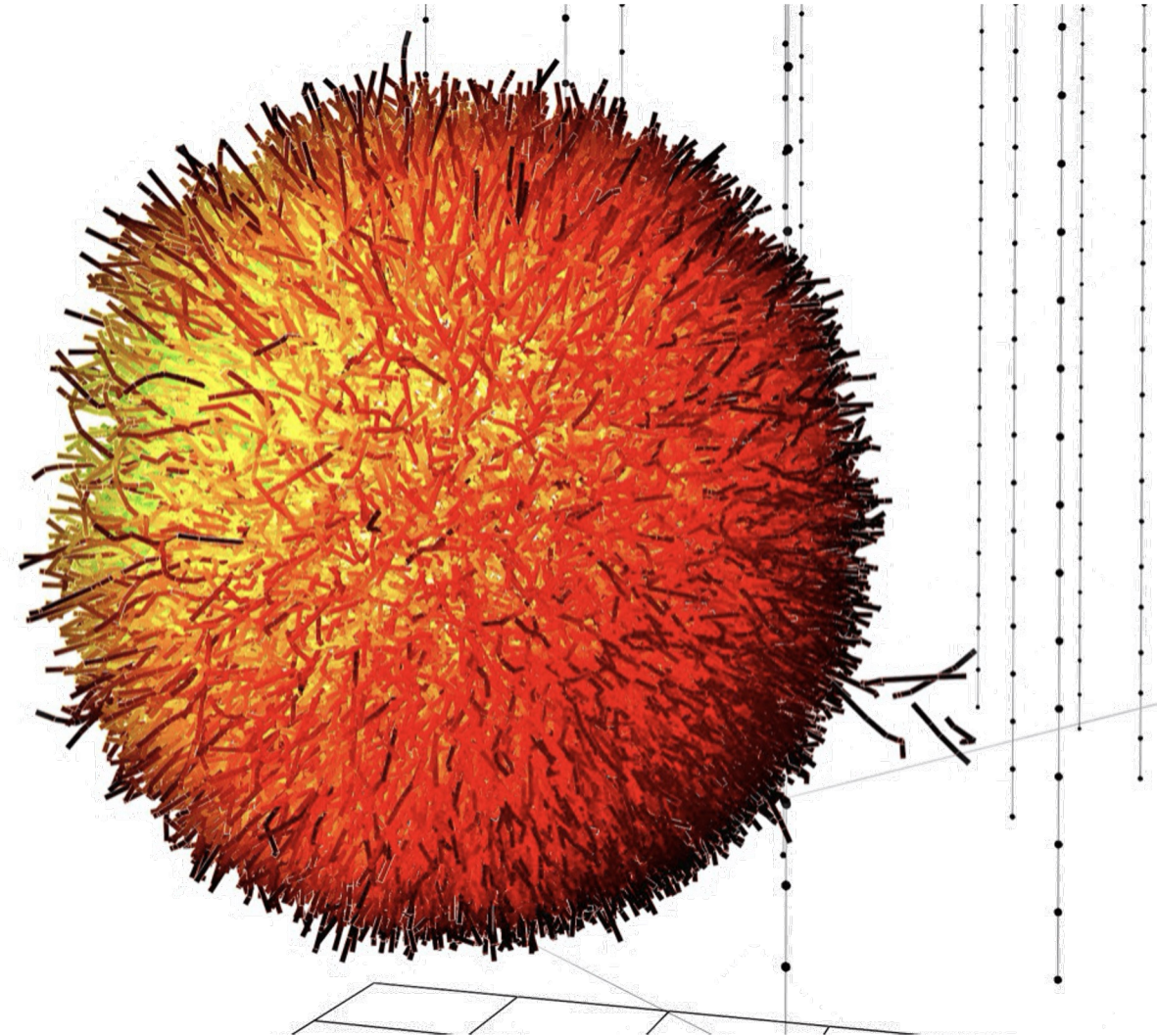
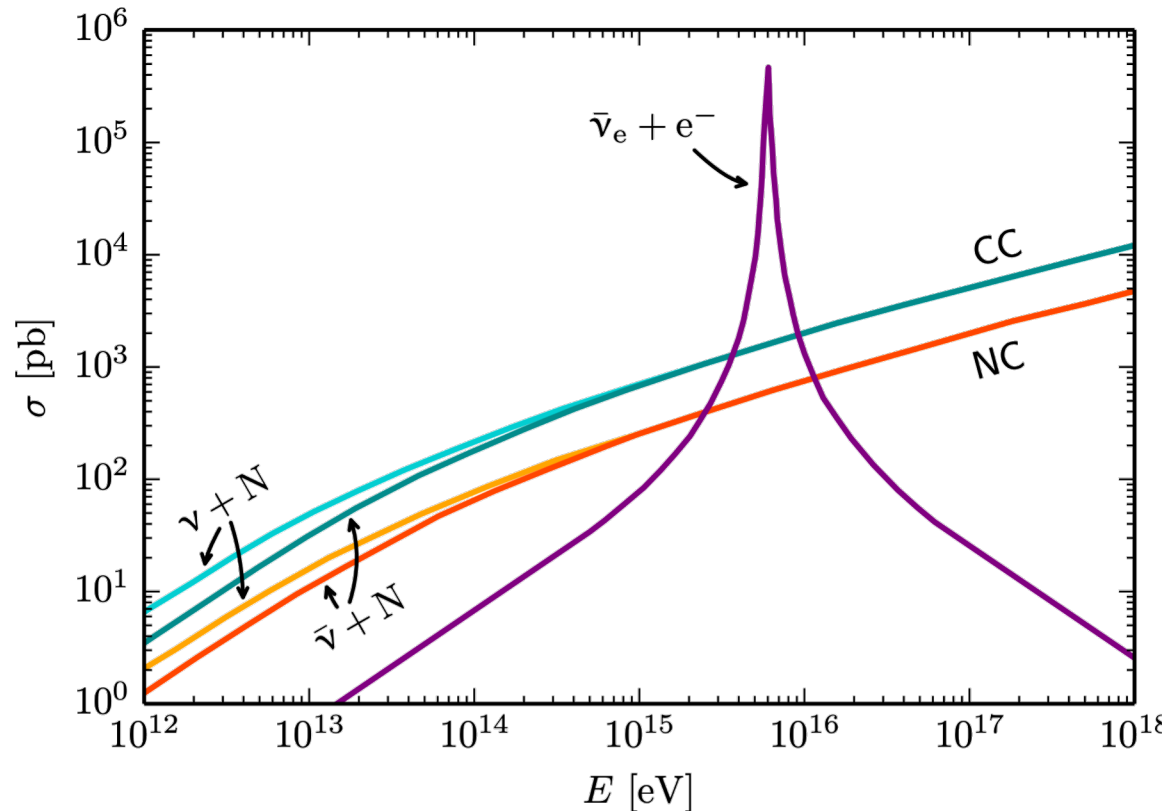
On-shell W-boson resonance production

$$\bar{\nu}_e + e \rightarrow W^- \rightarrow \bar{\nu}_l + l$$

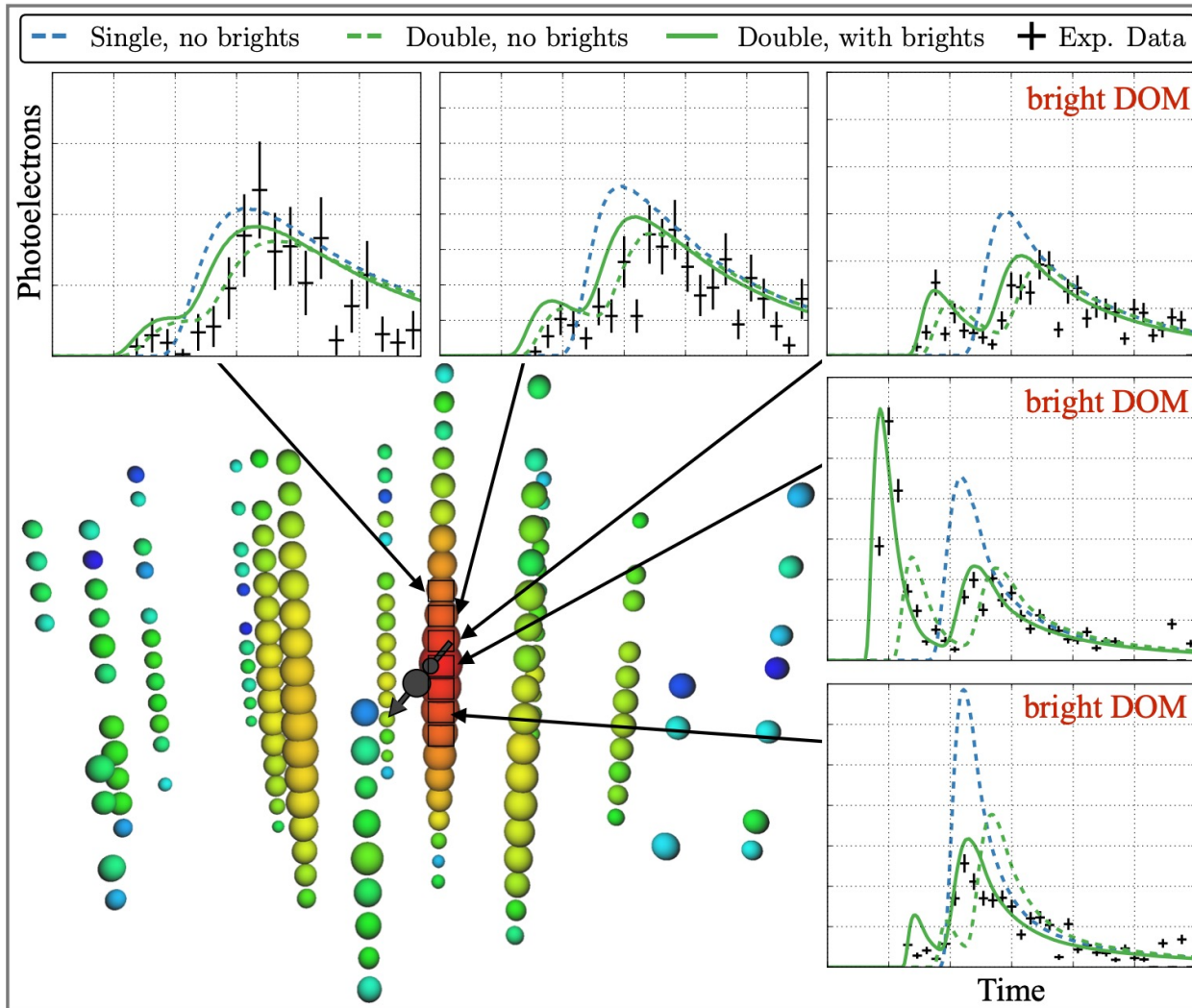
$$\bar{\nu}_e + e \rightarrow W^- \rightarrow X, \quad e^-$$



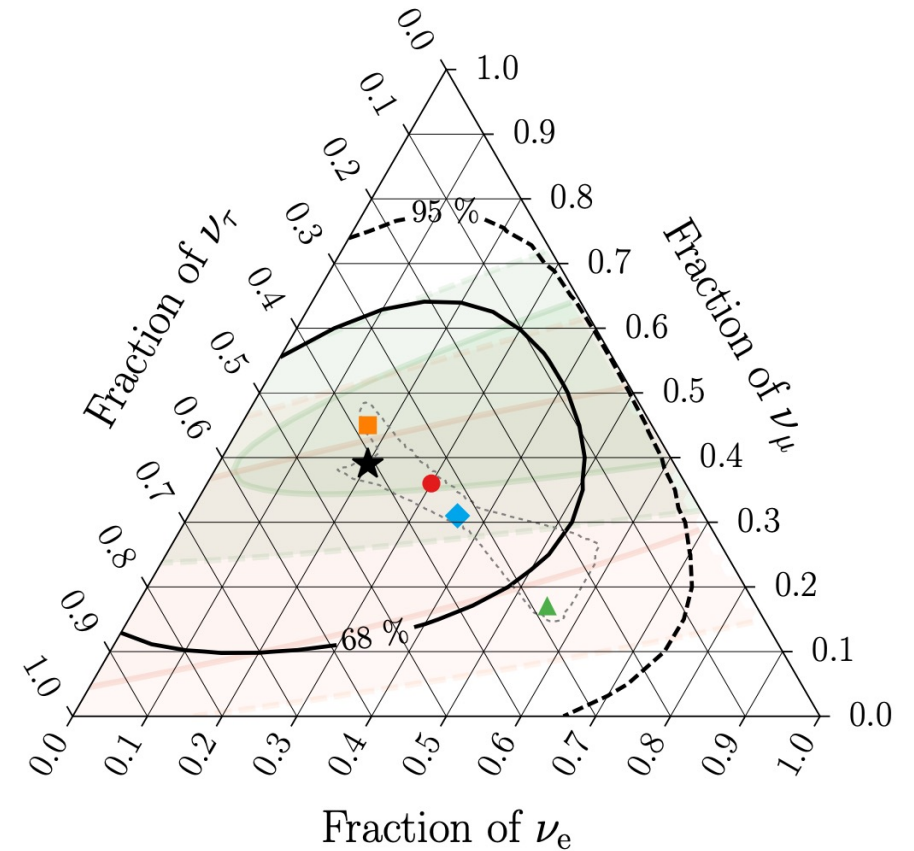
$$E_R = M_W^2 / (2m_e) = 6.32 \text{ PeV}$$



# NEUTRINO OSCILLATIONS AT COSMOLOGICAL BASELINES

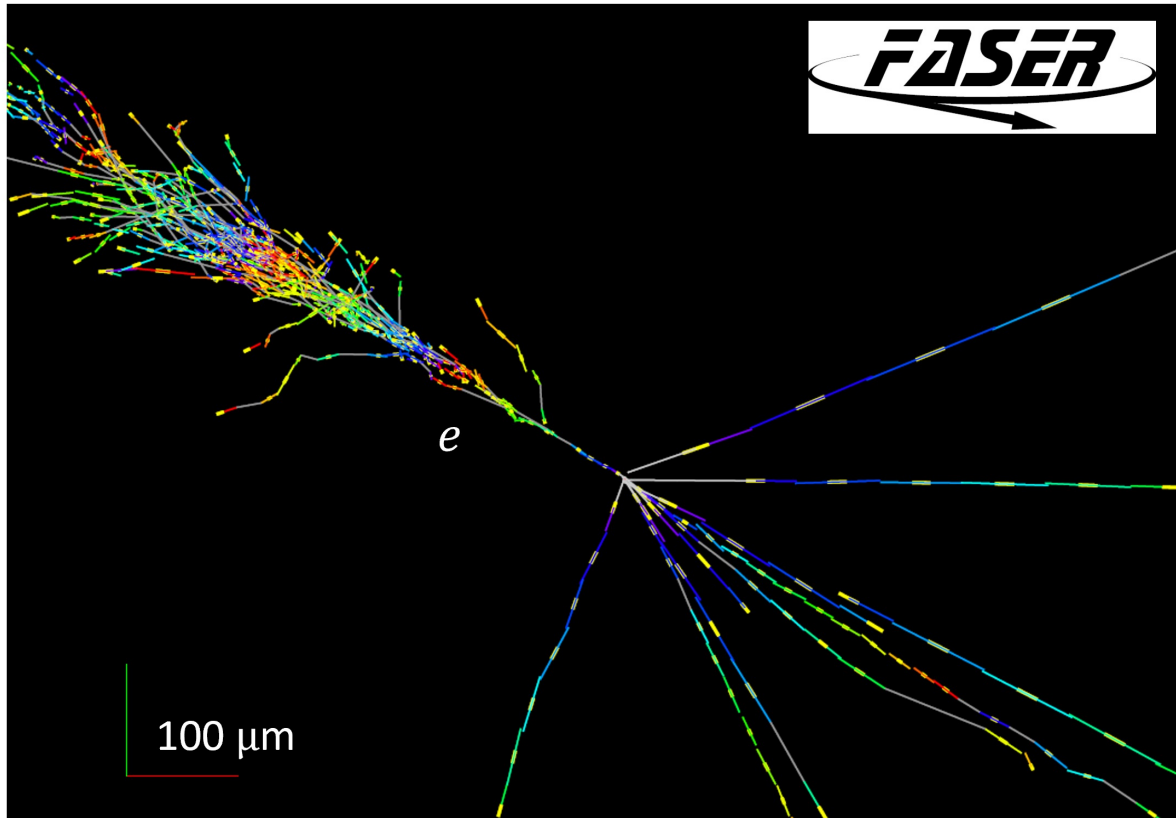


Nutau candidate

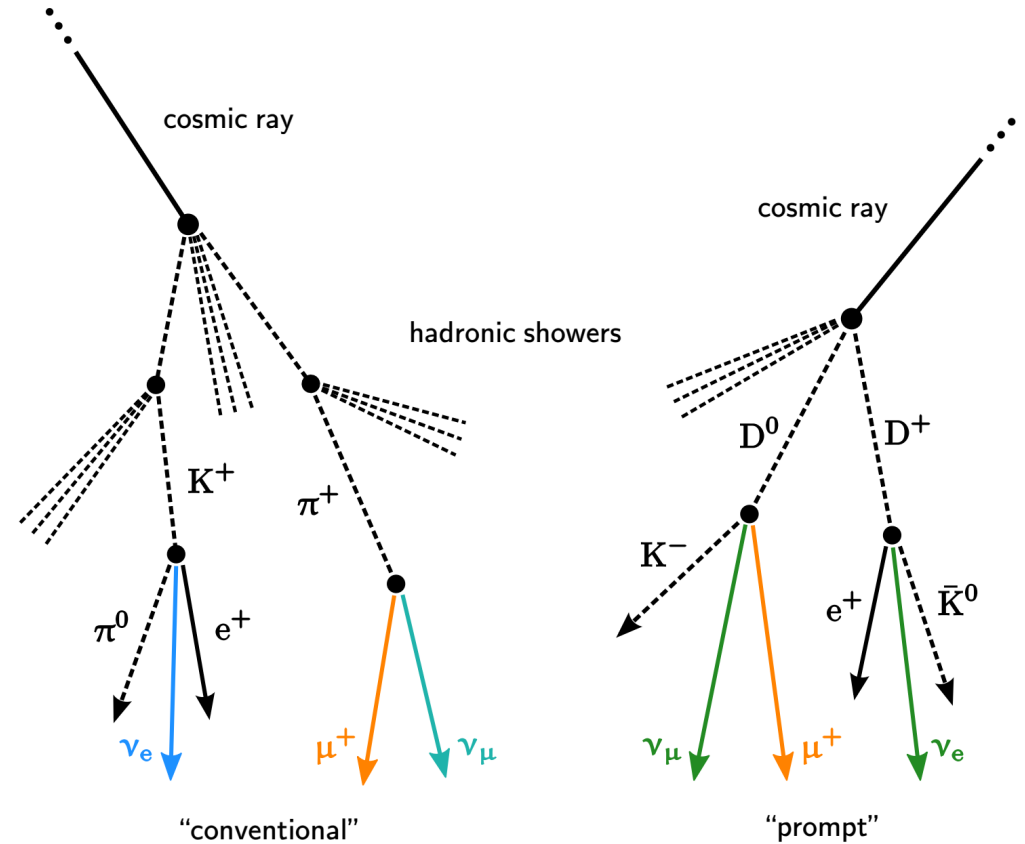


- HESE with ternary topology ID
  - ★ Best fit: 0.20 : 0.39 : 0.42
  - Global Fit (IceCube, APJ 2015)
  - Inelasticity (IceCube, PRD 2019)
  - ⋯ 3ν-mixing 3σ allowed region
- $\nu_e : \nu_\mu : \nu_\tau$  at source → on Earth:
- 0:1:0 → 0.17 : 0.45 : 0.37
  - 1:2:0 → 0.30 : 0.36 : 0.34
  - ▲ 1:0:0 → 0.55 : 0.17 : 0.28
  - ◆ 1:1:0 → 0.36 : 0.31 : 0.33

# FORWARD CHARM MEASUREMENTS



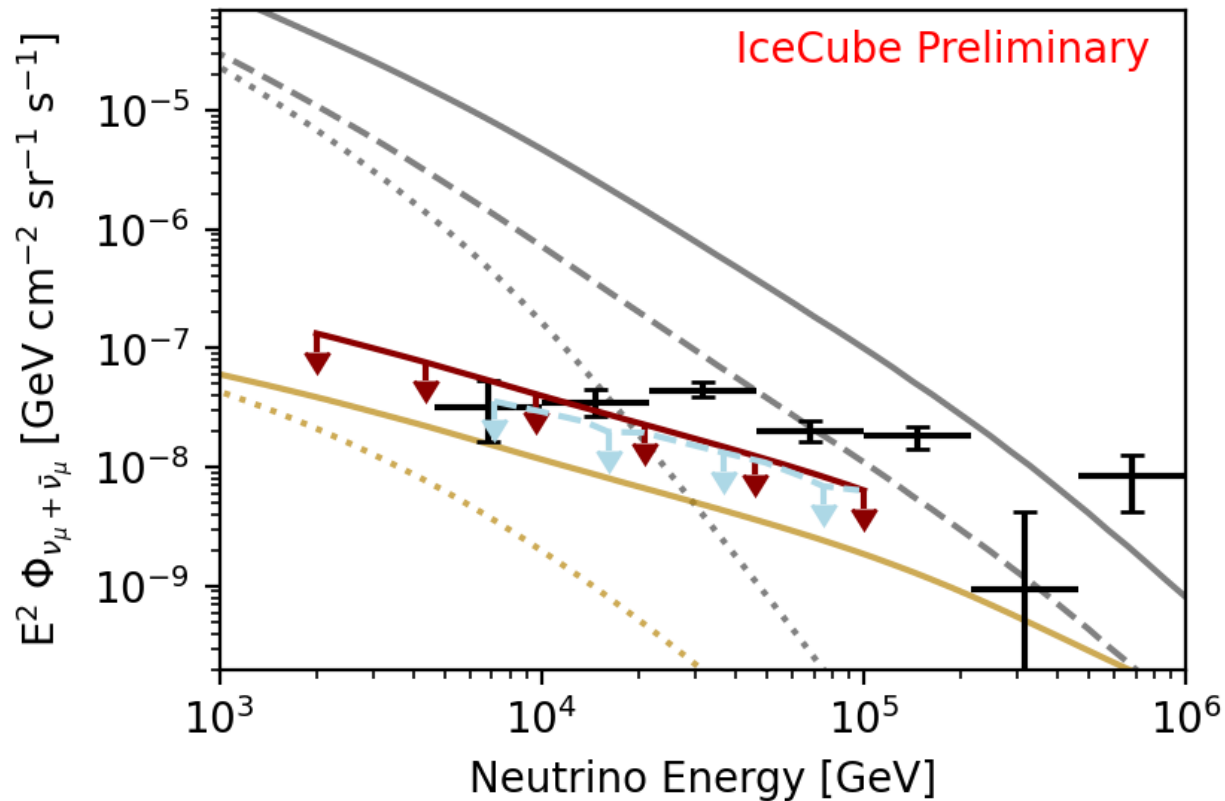
At LHC



Produced in the air shower

# CHARM: PROMPT NEUTRINOS

Prompt neutrino normalization: Constraining forward charm productions in hadronic showers



### Conv. Atmospheric.

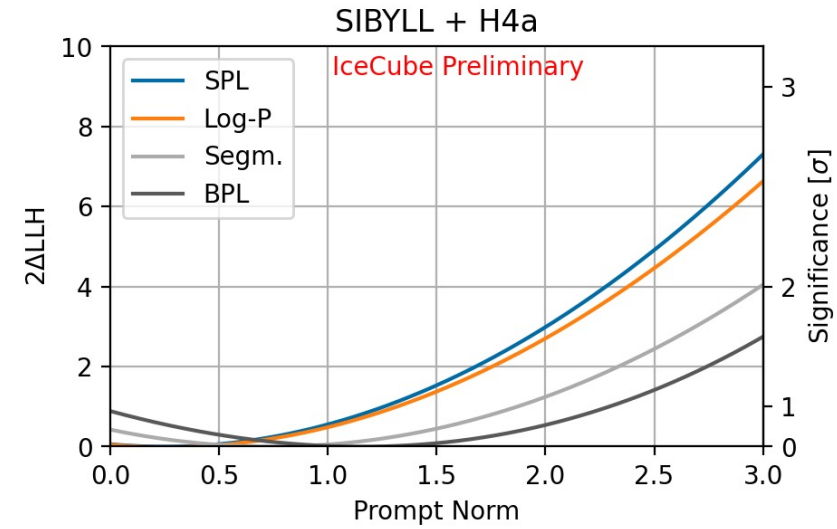
- $\theta = 180^\circ$
- $\theta = 90^\circ$
- .....  $\theta = 0^\circ$  (incl. veto)

### Astrophysical:

- + Combined Fit
- 90% prompt CL:**
- This work
- - - 6y Northern Tracks

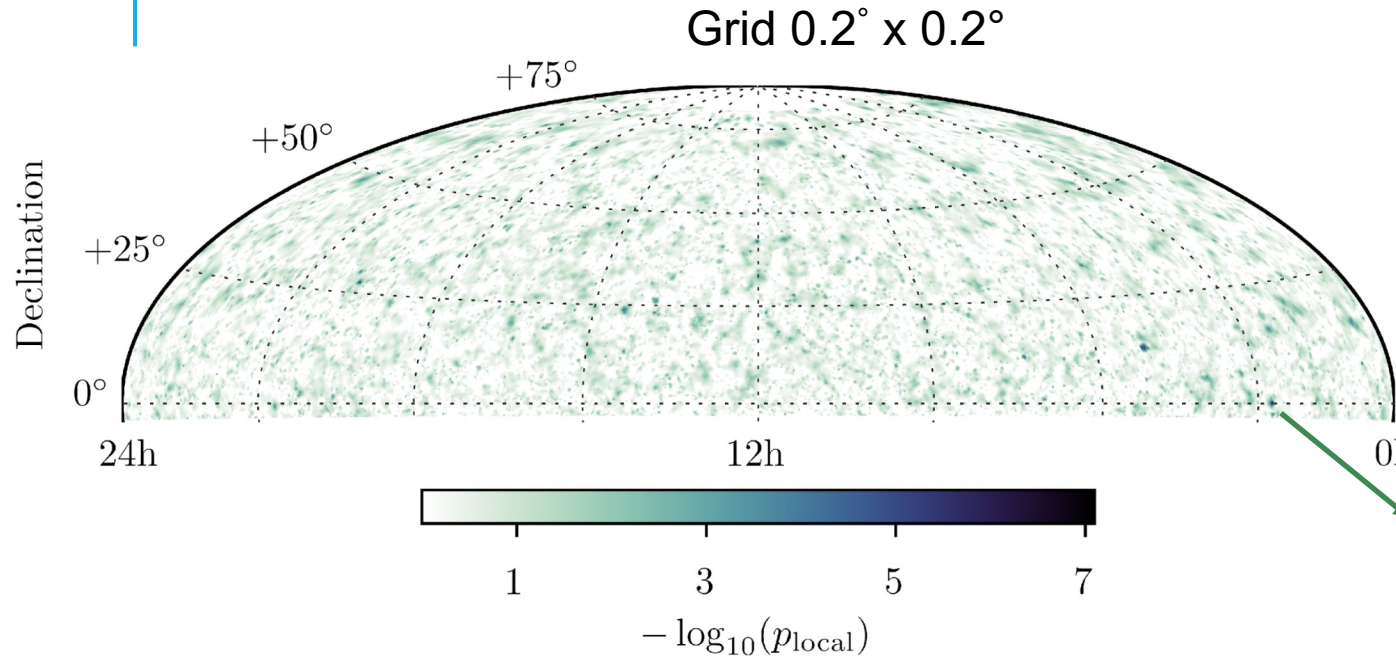
### Best-fit ( $0.65\sigma$ ) prompt:

- $\theta = 90^\circ$
- .....  $\theta = 0^\circ$  (incl. veto)



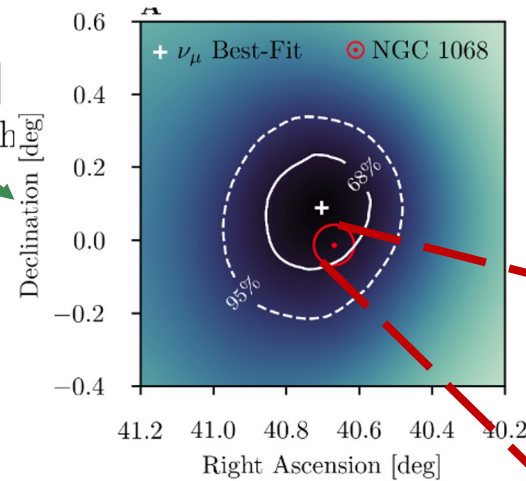


# THE NEUTRINO SKY MAP (ICECUBE 10 YEARS)



NGC1068:  **$4.2\sigma$**

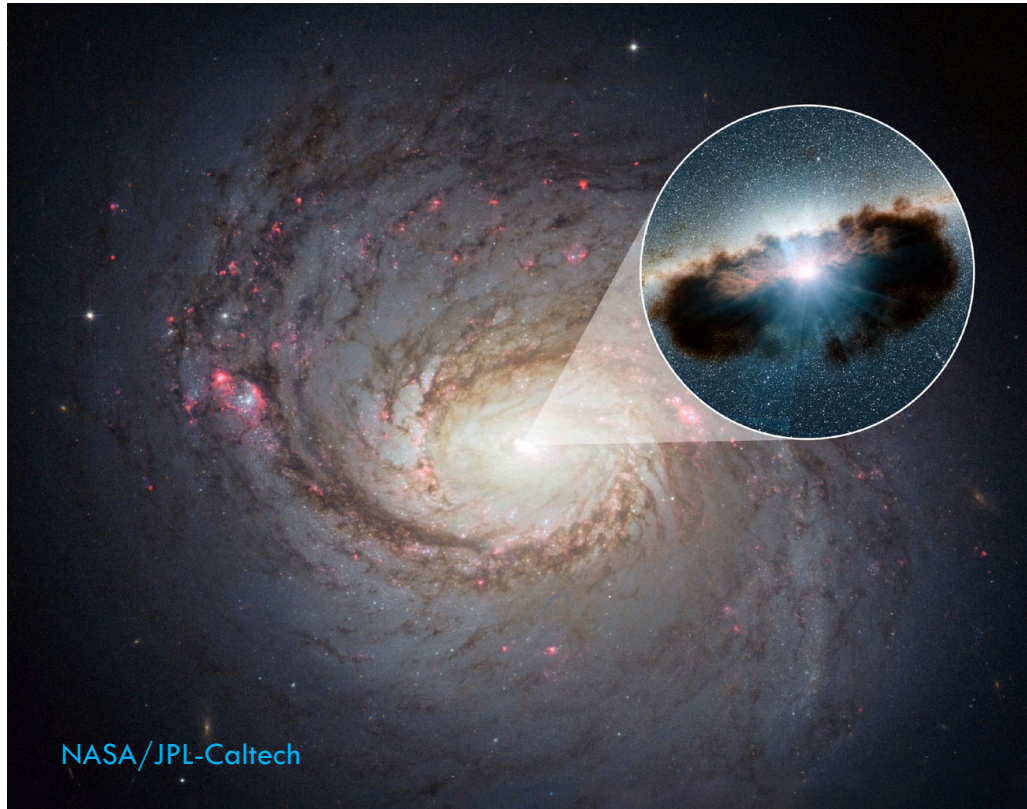
(post trial)



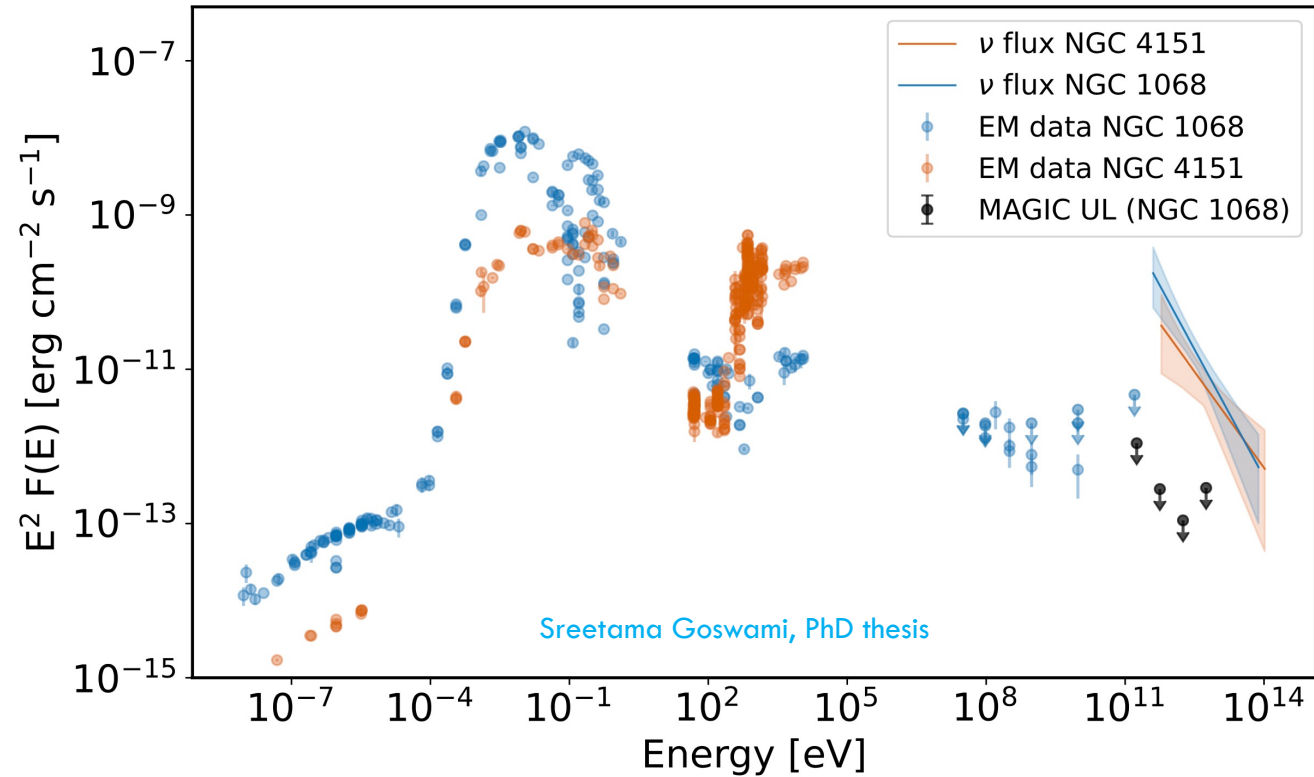
Astrophysical neutrino events =  $79^{+22}_{-20}$   
Spectral index =  $3.2 \pm 0.2$



# COSMIC OBSCURED ACCELERATORS

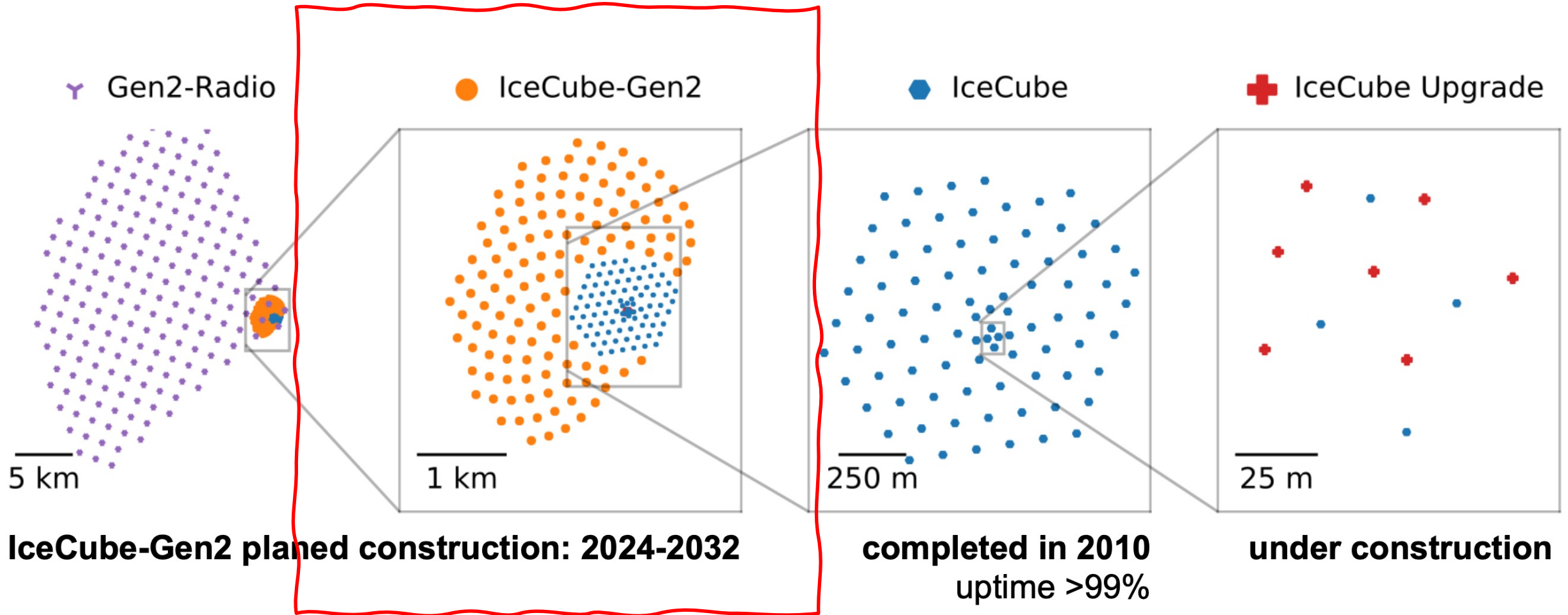


SED for NGC 1068 and NGC4151

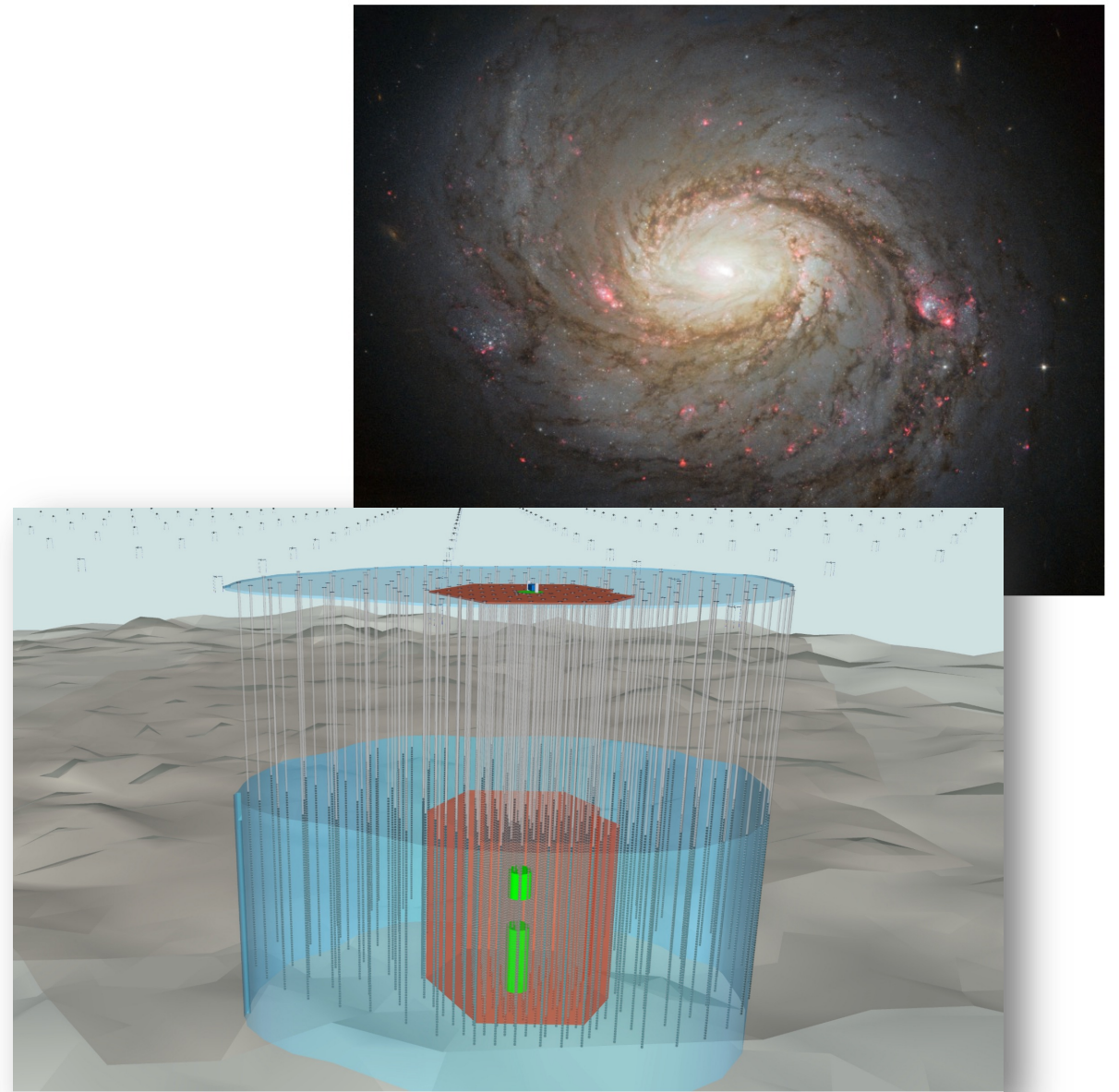
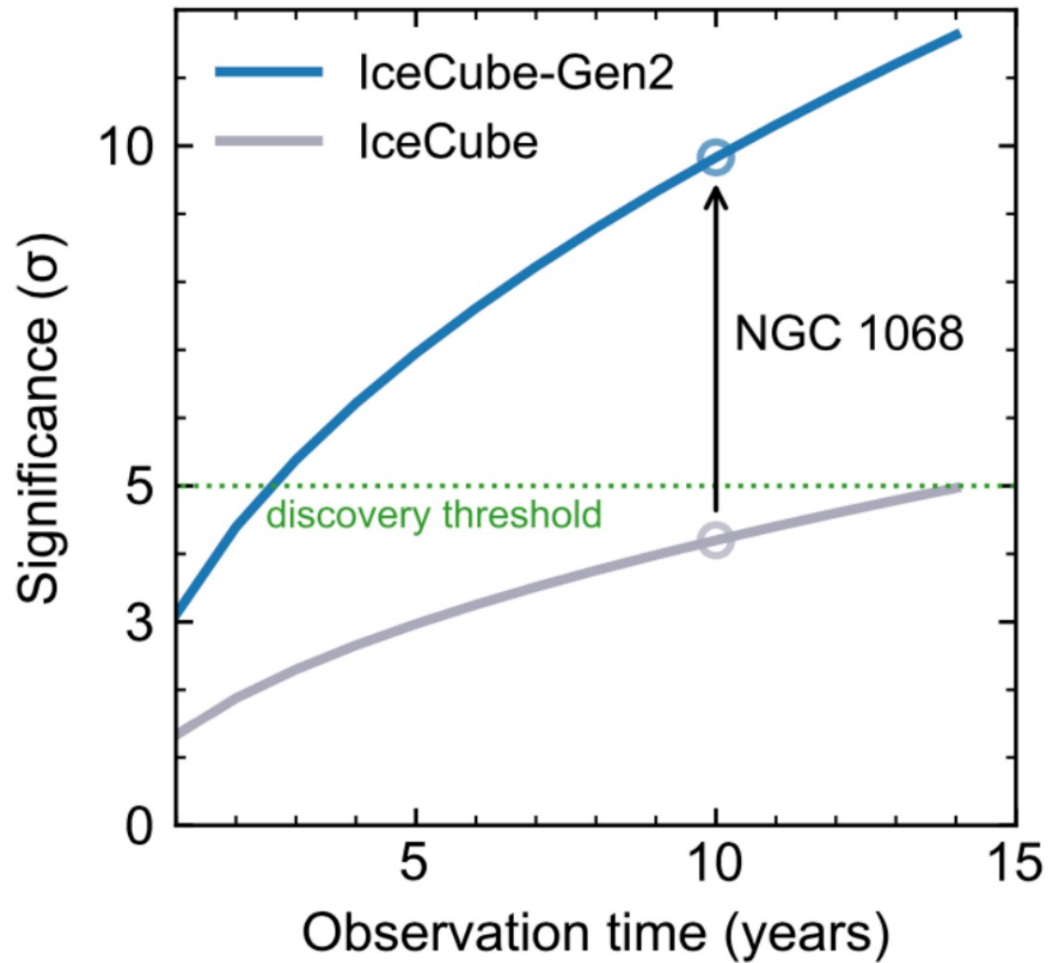


Neutrinos escape dense gas region: excess neutrinos but gamma rays are attenuated / absorbed

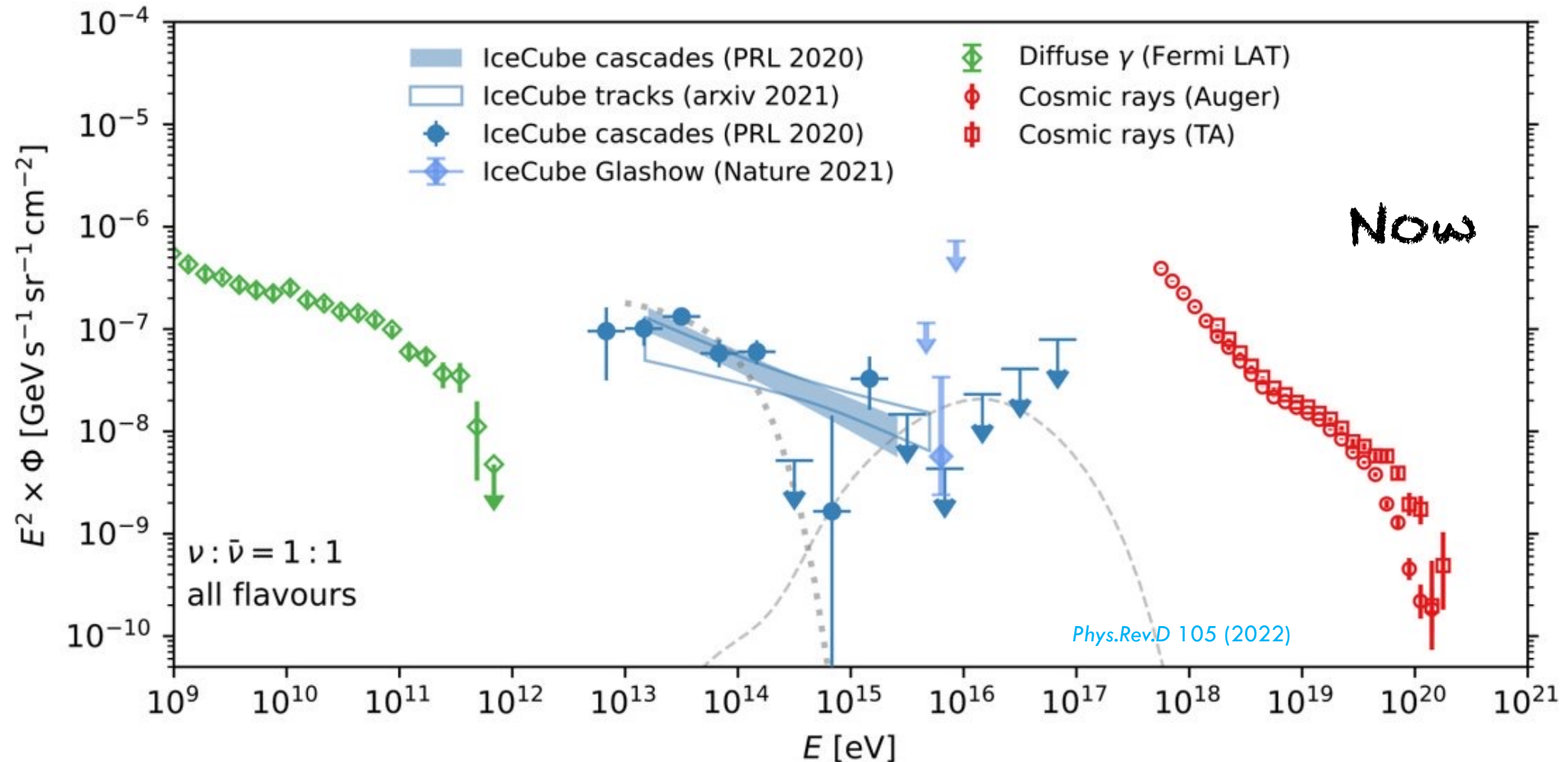
# Future: optimising for from $10^9\text{eV}$ to $10^{19}\text{eV}$



*5 sigma in < 2 years*  
*10 sigma in 10 years.*

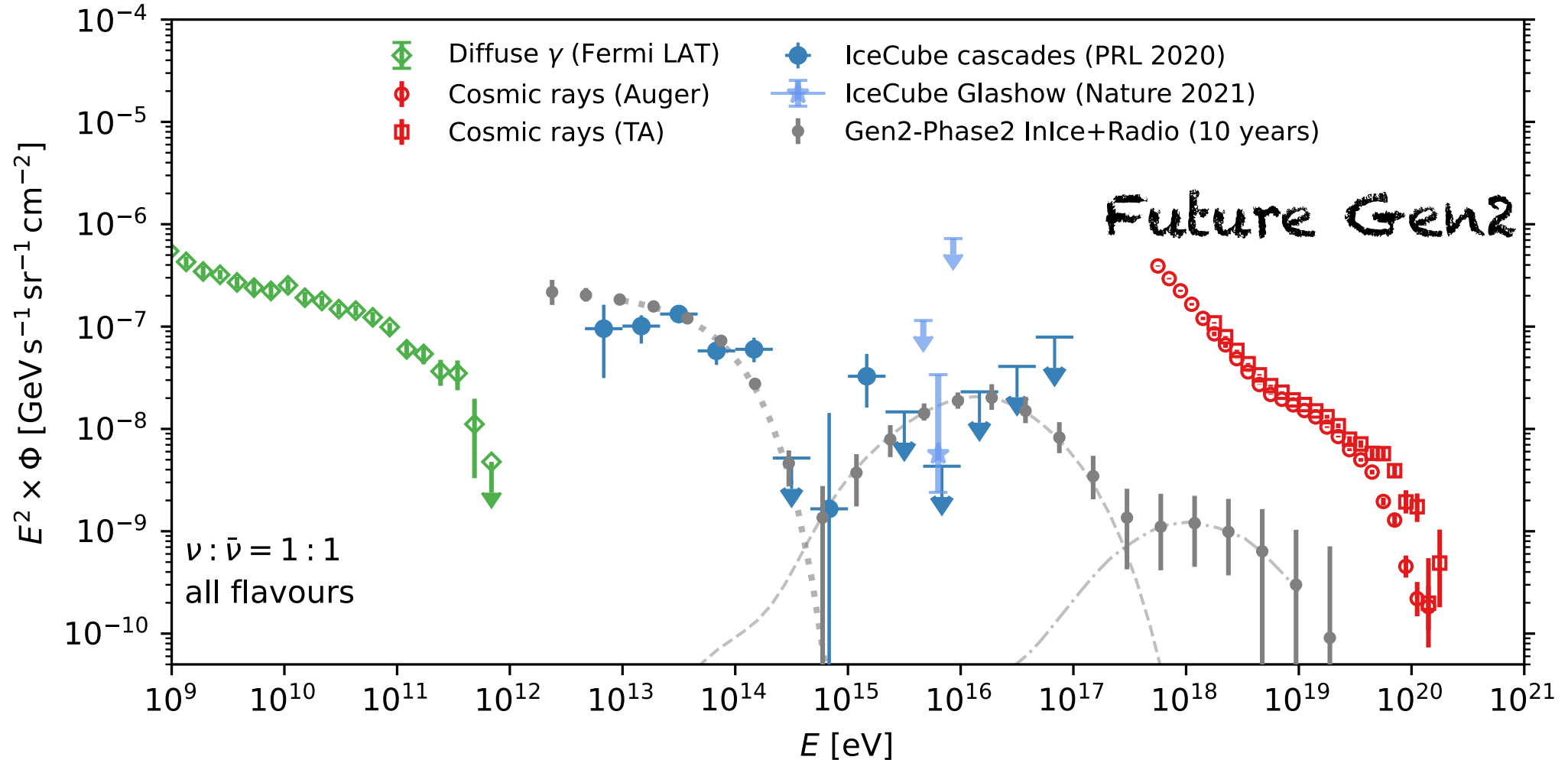


## 10 PEV NEUTRINOS GATEWAY TO $10^{20}$ EV PARTICLES



A common origin with UHECR?

## 10 YEARS OF GEN2 DATA TAKING

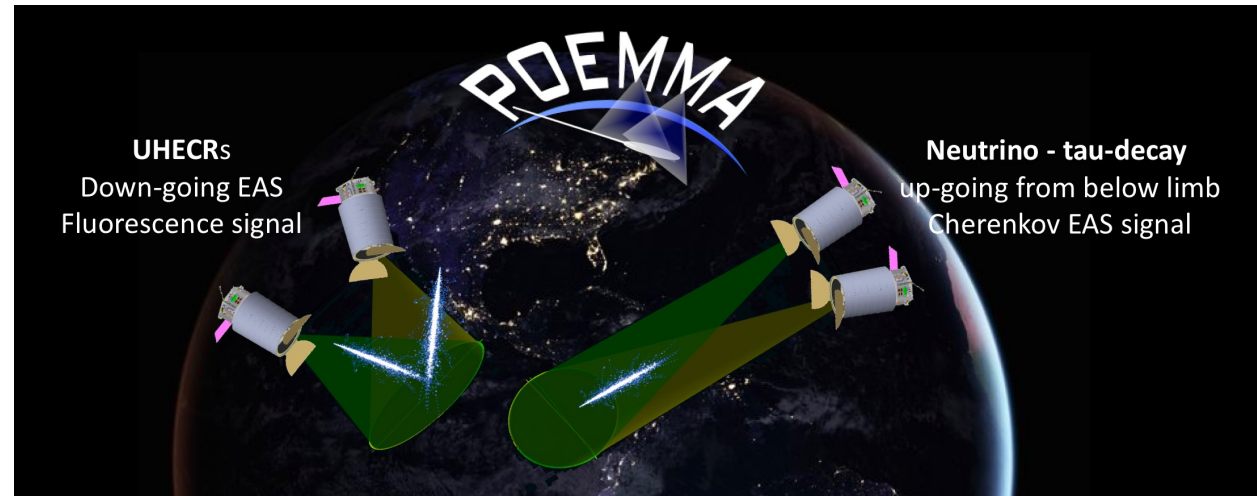
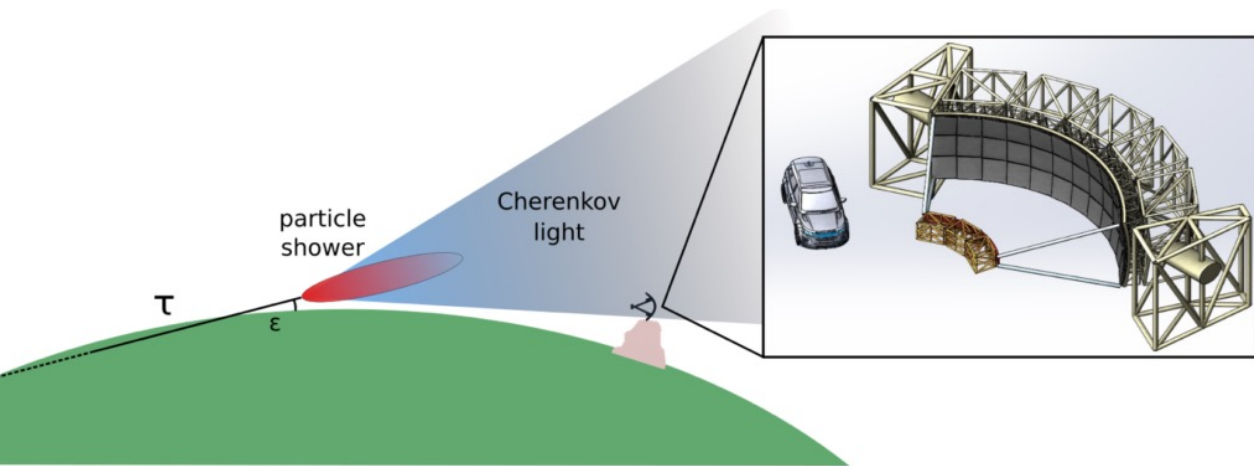
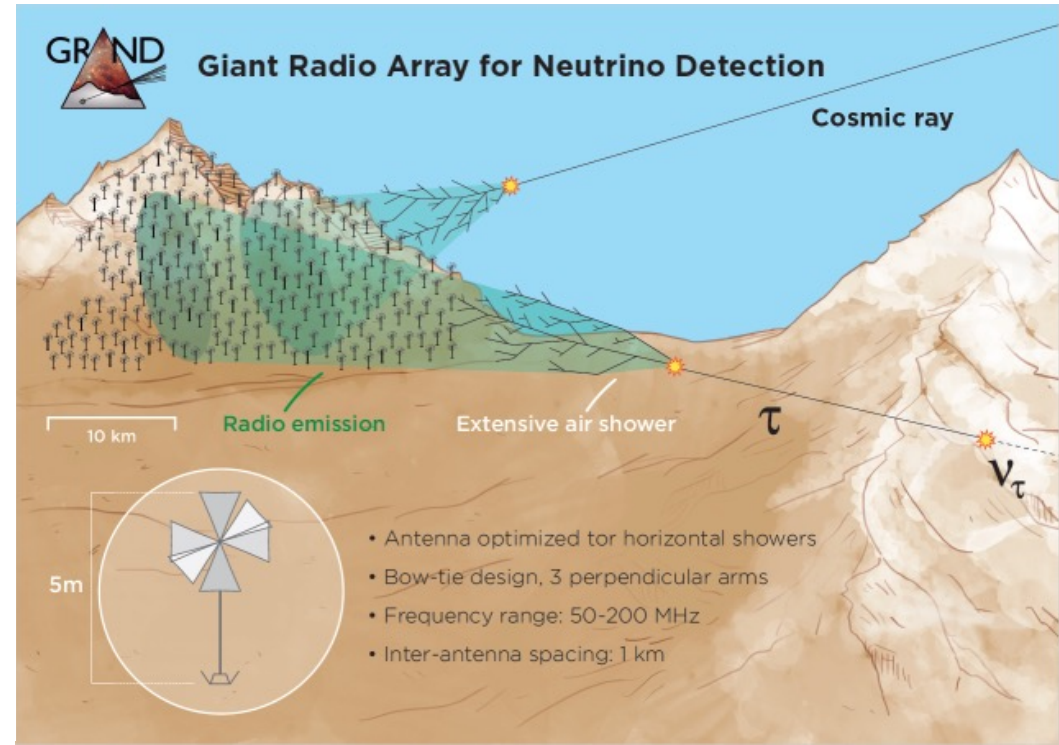
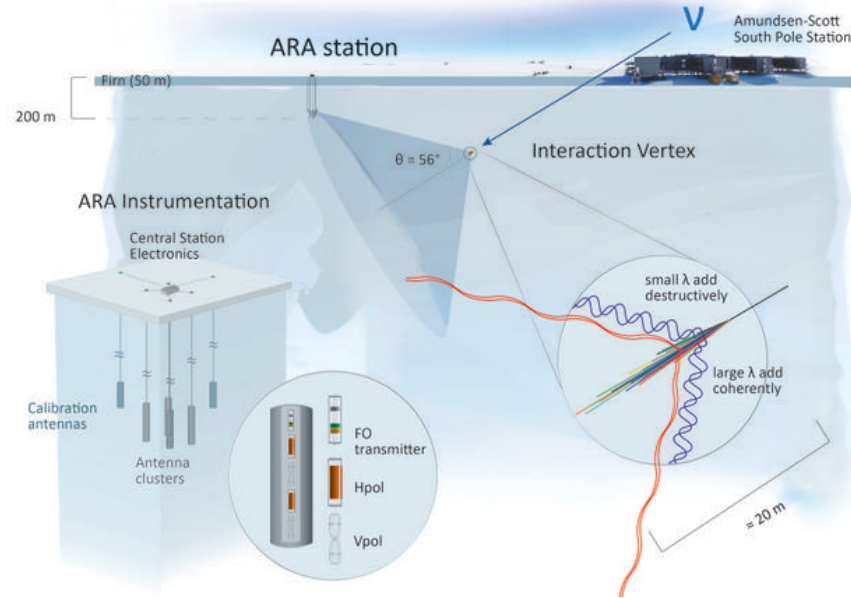


Pin down 10 PeV connection with UHECR

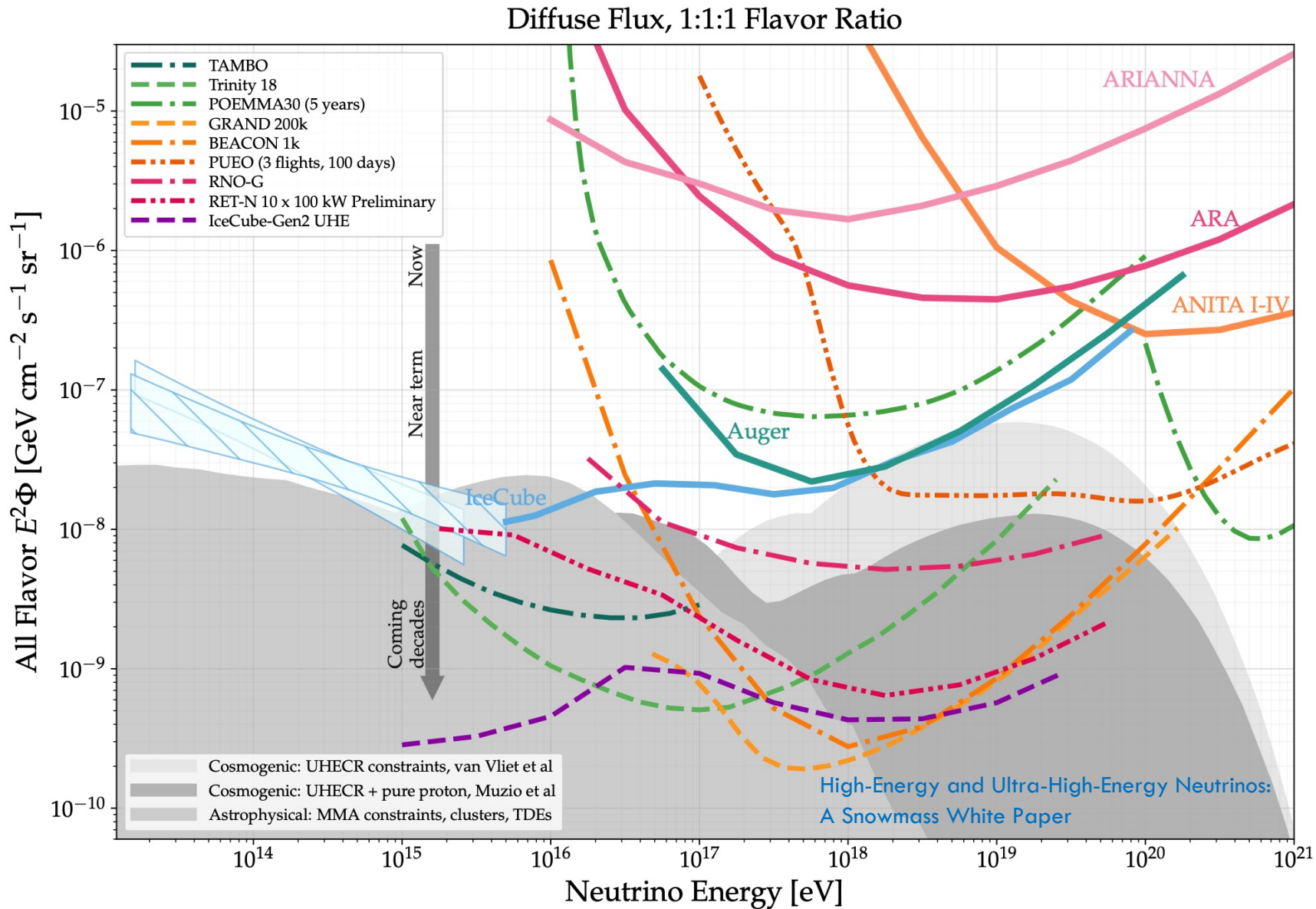
# Ultra-high energy neutrinos



Detection of ultrahigh-energy neutrinos in ARA



# THE RACE FOR THE UHE PUZZLE





# CONCLUSION

Through the past decade, IceCube has achieved

- Discovered astrophysical diffuse neutrino flux
- Established NGC 1068 as a point source obscured in gamma-rays
- Detected a candidate for the Glashow resonance
- Conducted flavor measurements and identified tau neutrino candidates
- Found evidence for neutrinos from the Galactic plane
- Detected neutrinos exceeding 10 PeV

## Unresolved Questions:

- Are high-energy neutrinos linked to ultra-high-energy sources
- When and how will the first cosmogenic neutrino be detected
- What are the primary sources contributing to the IceCube diffuse flux

## Exciting Future:

Many experiments planned or in prototype phase for the coming decades  
Coverage will span from TeV to EeV energies  
Experiments will range from underground detectors to space missions

