Superheavy Supersymmetric Dark Matter for the origin of KM3NeT Ultra-High Energy signal

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> *"I have done a terrible thing: I have postulated a particle that cannot be detected."*
>
> *— Wolfgang Pauli, on neutrinos*

> *"Dark matter is needed to hold galaxies together. Your mind is a Galaxy. More dark than light. But the light makes it worthwhile."*
>
> *— Matt Haig*

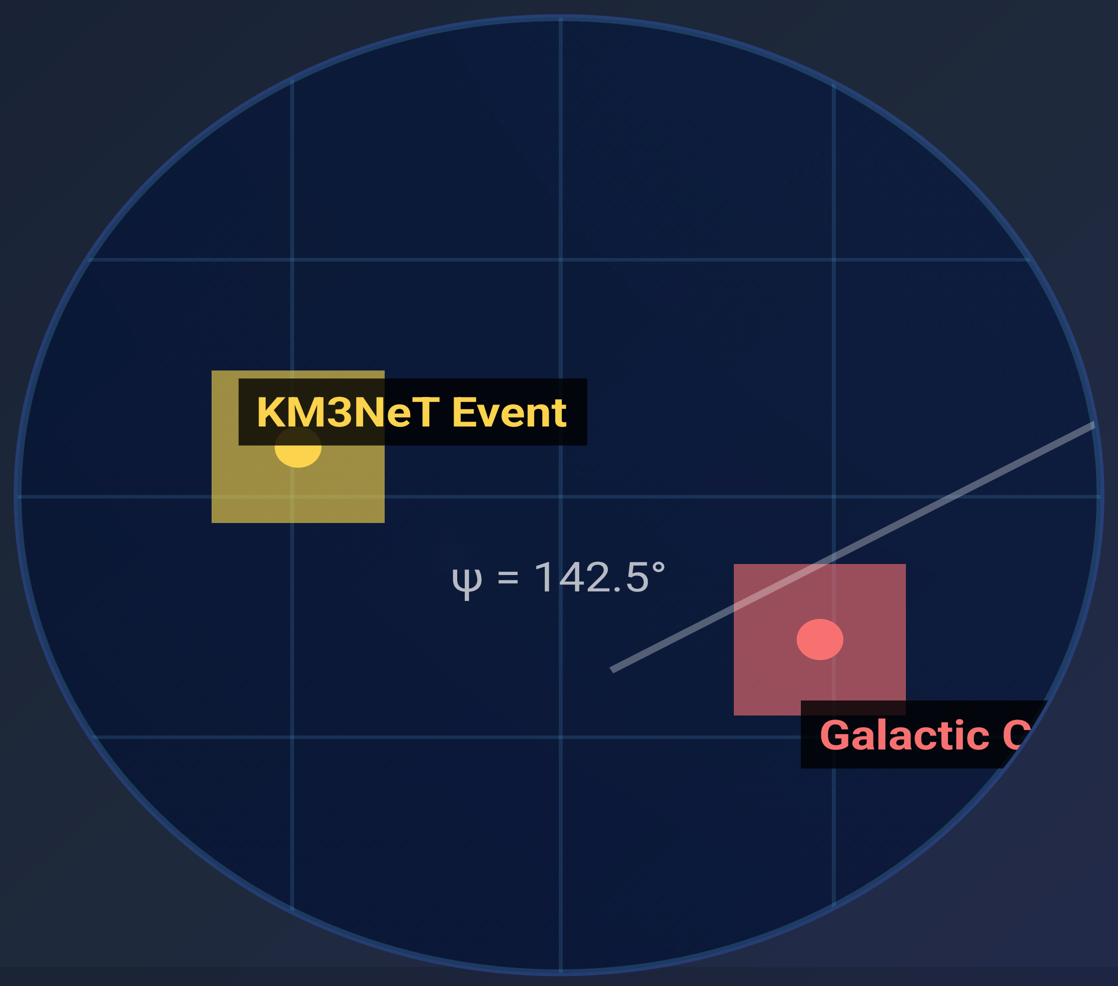
CUBES7 & 구례 based on 2503.18737

KM3NeT Detector and Ultra-High-Energy Neutrino Observation

The KM3NeT Detector

- Deep-sea neutrino telescope in the Mediterranean Sea
- Uses sea water as interaction medium for neutrinos
- Detects Cherenkov light with high-tech optical modules
- Two detectors: ARCA (high-energy) and ORCA (low-energy)
- Designed to detect neutrinos from distant astrophysical sources

Event Direction vs. Galactic Center



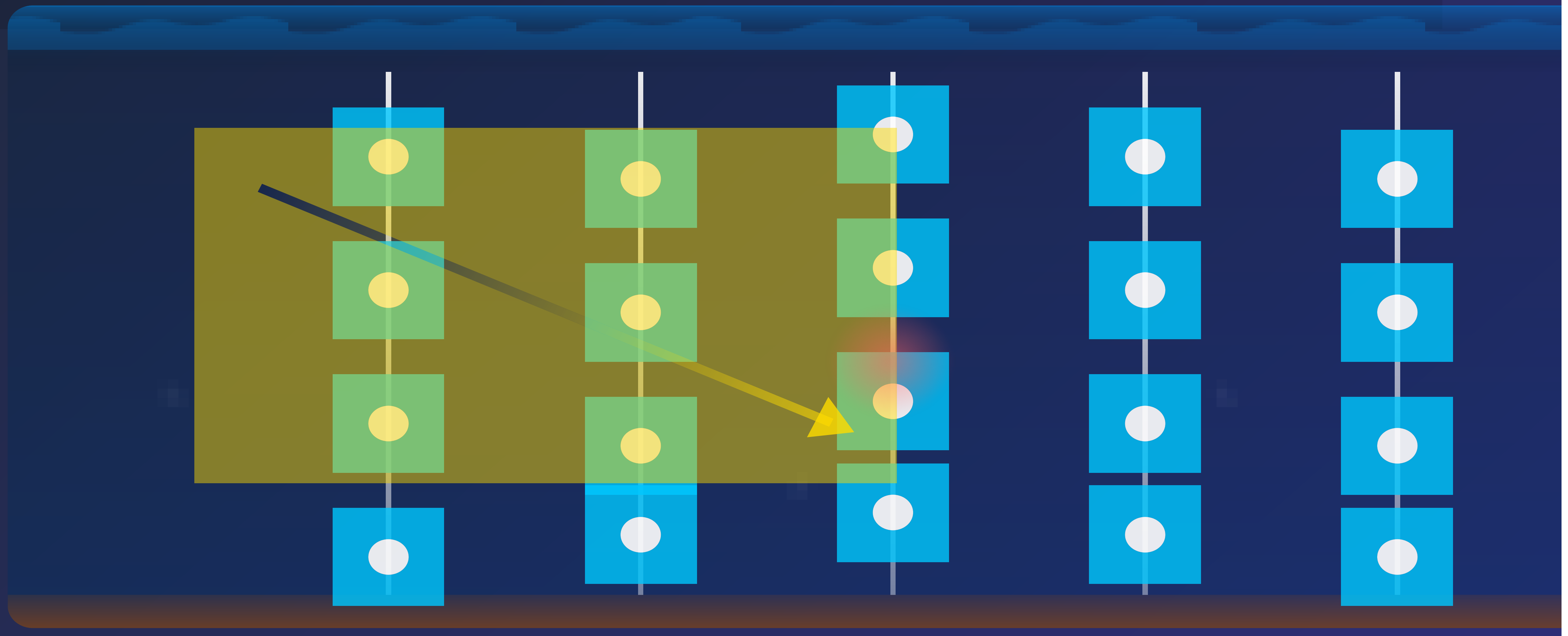
- Event: RA 94.3°, Dec −7.8°
- Galactic Center: RA 266.4°, Dec −29.0°

Ultra-High-Energy Neutrino Event

Event: KM3-230213A

Energy: 220^{+2380}_{-146} PeV

- Most energetic neutrino ever observed
- No definitive associations with particular astrophysical point sources have been established
- Direction nearly opposite to the Galactic Center (angle ψ = 142.5°)



Schematic visualization of the KM3NeT detector arrays and ultra-high-energy neutrino interaction

Conventional Dark Matter Scenarios & Their Limitations

Key Challenges

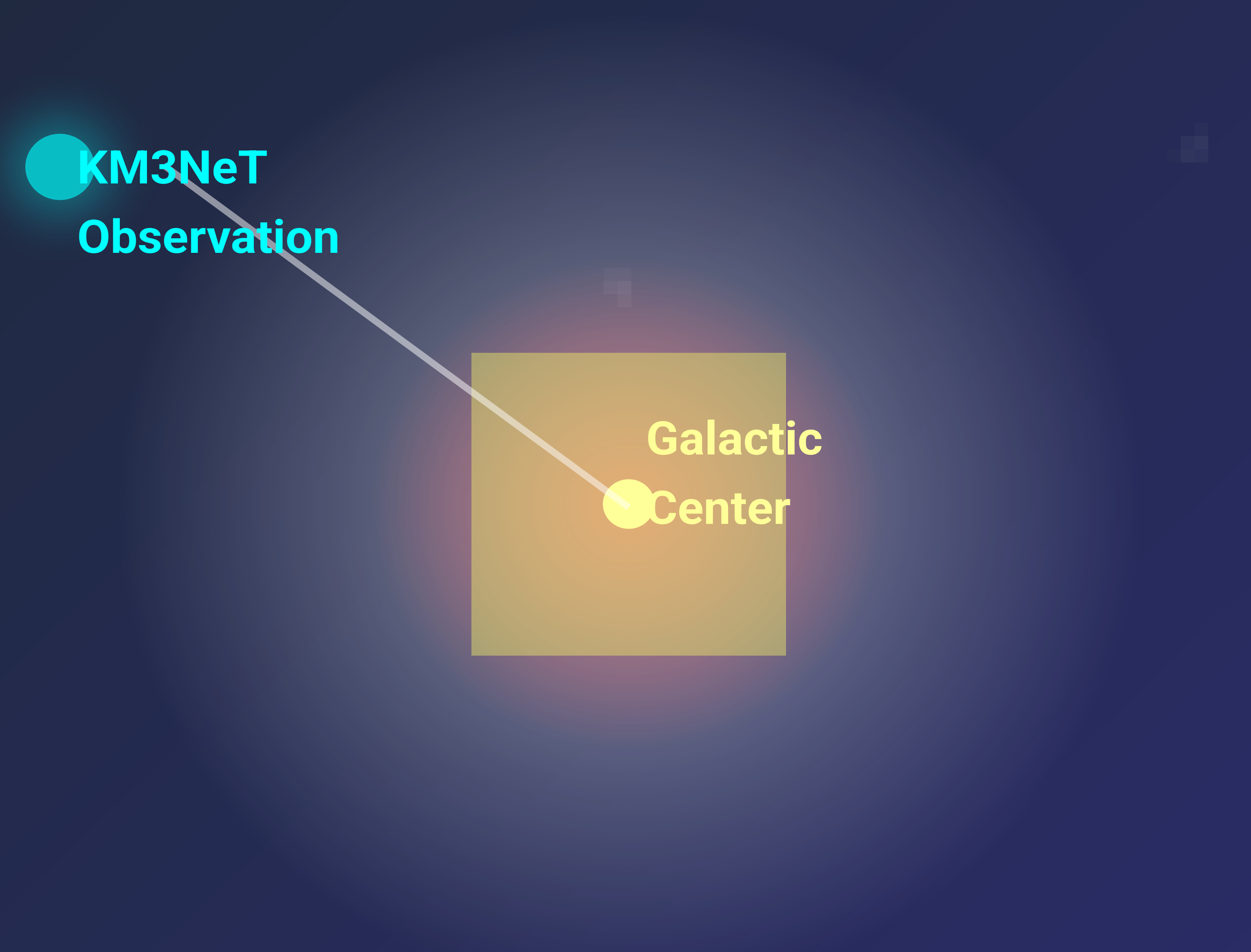
- Conventional decaying DM models predict neutrino flux concentrated around the Galactic Center
- KM3NeT observation points in a direction nearly **opposite** to the Galactic Center (ψKM3NeT = 142.5°)
- Expected flux from Galactic Center should be **5-100 times greater** than from the observed direction

Flux Ratios for Different DM Profiles (P values)

DM Profile	Narrow Energy Window	90% CL Window
NFW(1,3,1.5)	79.6	75.1
NFW(1,3,1)	12.8	9.0
Isothermal	7.9	5.3

Note: P values represent the ratio between energy-integrated fluxes from the Galactic Center versus the KM3NeT observation direction

Galactic Flux Distribution vs. Observation



ψKM3NeT = 142.5° (nearly opposite to Galactic Center)

Key Discrepancy

Conventional decaying DM models cannot easily explain:

1. Why no neutrino signal was observed from the Galactic Center direction
2. Why the UHE neutrino appears to come from a direction nearly opposite to where flux should be concentrated

A new interpretation is needed to explain this directional anomaly

Superheavy Supersymmetric Dark Matter Model

The Multicomponent Framework

- Dark matter exists as multiple components within a **supermultiplet** (X)
- Components include:
  - Fermion component (χ)
  - Two scalar components ($\tilde{\chi}_1$ and $\tilde{\chi}_2$)
- Dominant mass term comes from supersymmetric mass (M)
- SUSY-breaking introduces small mass splitting via F-term

Mass Spectrum & Physics

• Mass splitting determined by SUSY-breaking:

$$M_{\tilde{\chi}1,2} = M \pm F/M, \; M_\chi = M \qquad \Delta M_\chi/M_\chi = F/M^2 \ll 1$$

• Heavier components decay into lighter components:

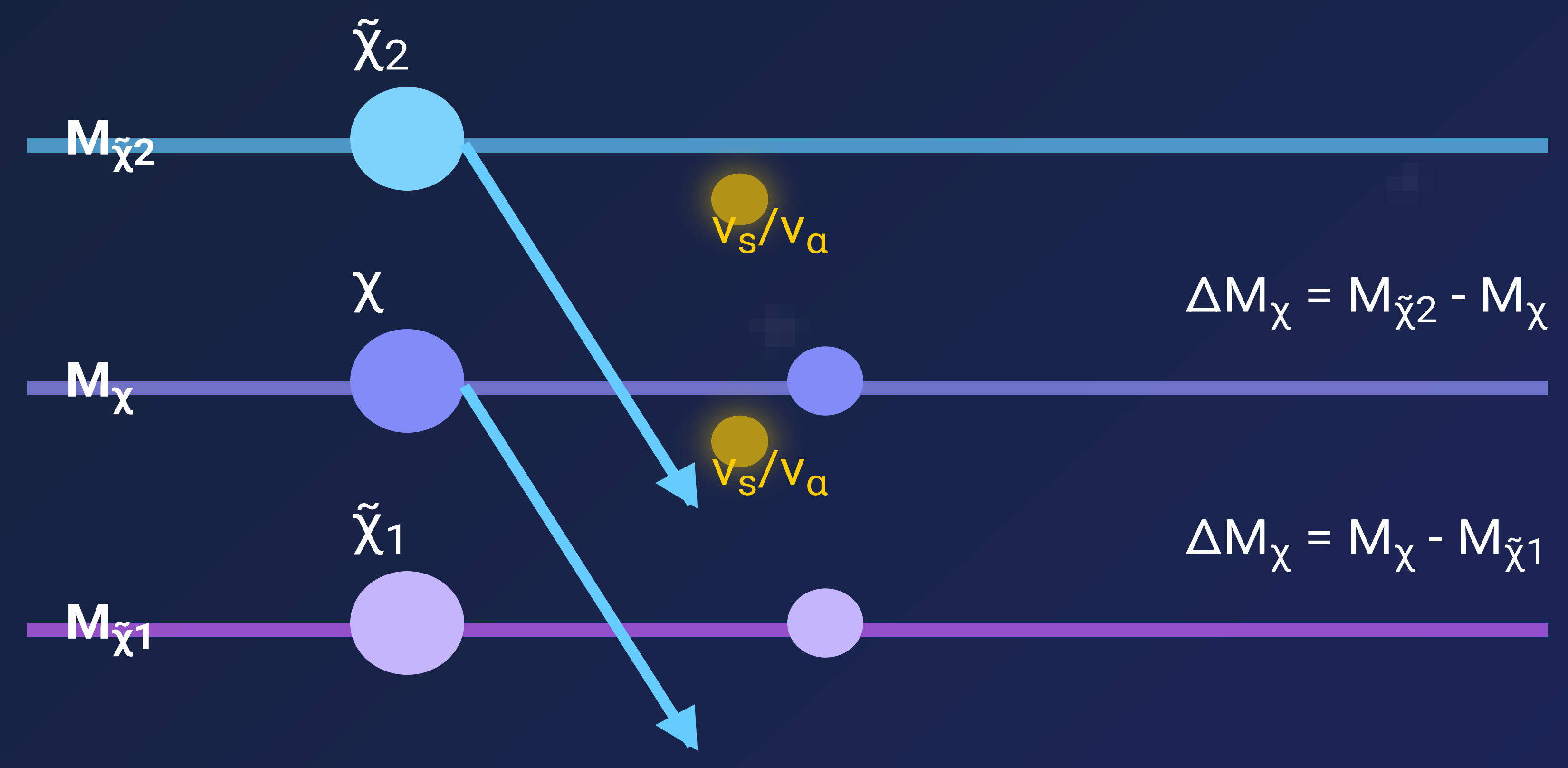
$\chi \rightarrow \tilde{\chi}_1 + \nu_s$ and $\tilde{\chi}_2 \rightarrow \chi + \nu_s$
(ν_s can oscillate to active neutrinos)

• Neutrino energy determined by mass difference:

$$E_\nu \sim \Delta M_\chi \sim 100 \text{ PeV}$$

Key advantage: Decay occurs at cosmological redshift z ~ a few, resulting in isotropic extragalactic signal

Supermultiplet Mass Spectrum & Decay



Neutrino energy $E_\nu \sim \Delta M_\chi \sim 100$ PeV at production

Why This Solves the Directional Anomaly

1. Heavier component's lifetime can be $\tau \lesssim$ age of Universe
2. Decays occur at high redshift (z ~ a few)
3. Results in **isotropic distribution** of signal
4. No concentration of signal at Galactic Center expected
5. Naturally explains extragalactic origin of the KM3NeT UHE neutrino

Two Decay Scenarios and Their Signatures

Scenario I: 3-Body Decay

$\chi_h \longrightarrow \chi_l \; \nu \; h$

$\chi_{heavy} \rightarrow \chi_{light} + \nu_\alpha + h$ (active neutrino + Higgs)

Key Features:

- 3-body decay produces continuous neutrino spectrum
- Higgs decay produces gamma-ray flux
- Parameter example:
  - $M_\chi \approx 10^{16}$ GeV
  - $\Delta M_\chi \approx 3 \times 10^{9}$ GeV
  - $Br_\nu \approx 10^{-2.6}$
- Heavier component's lifetime $\tau_\chi \approx 1$ Gyr ensures extragalactic origin

Scenario II: 2-Body Decay + Oscillation

$\chi_h \longrightarrow \chi_l \; \nu_s$

$\chi_{heavy} \rightarrow \chi_{light} + \nu_s$ (sterile neutrino)

$\nu_s \xrightarrow{\text{oscillation}} \nu_\alpha$

Key Features:

- 2-body decay produces sharper neutrino spectrum
- No significant gamma-ray production
- Parameter example:
  - $M_\chi \approx 6 \times 10^{12}$ GeV
  - $\Delta M_\chi \approx 5 \times 10^{8}$ GeV
  - $Br_\nu \approx 10^{-4} - 10^{-3}$
- Sterile-active mixing angle consistent with existing constraints

WRONG!!

How These Scenarios Explain the KM3NeT Observation

Key Advantages:

- Neutrino energy $E_\nu \approx 100$ PeV determined by small mass difference
- Isotropic signal distribution due to cosmological redshift of $z \gtrsim$ few
- No enhanced signal expected from the Galactic Center

Observational Compatibility:

- Energy scale matches KM3NeT detection (≈ 220 PeV)
- Explains absence of signal from Galactic Center
- Consistent with current gamma-ray constraints
- Predicts potential future detections in similar directions

Model Parameters and Predictions

Key Parameter Values

Parameter	Scenario I: 3-Body Decay	Scenario II: 2-Body Decay
Dark Matter Mass (M_χ)	10^{16} GeV	6×10^{12} GeV
Mass Splitting (ΔM_χ)	3×10^{9} GeV	5×10^{8} GeV
Neutrino Branching Ratio (Br_ν)	$10^{-2.6}$	$10^{-4} - 10^{-3}$
Heavier Component Lifetime (τ_χ)	~ 1 Gyr	
Heavy Component Fraction (f_χ)	~ 0.6	
Decay Scale Parameter	$\Lambda = 1.44 \times 10^{31}$ GeV	$\lambda_s = (1.12 - 3.55) \times 10^{-24}$

Note: The mass splitting parameter directly determines the neutrino energy scale.

Physical Implications

- Mass splitting satisfies $\Delta M_\chi/M_\chi \ll 1$, consistent with radiatively stable SUSY-breaking effects
- Lifetime $\tau_\chi \approx 1$ Gyr ensures:
  - All heavier components have decayed by present time
  - Decays occurred at cosmological redshift $z \gtrsim 1\text{-}2$
  - Resulting in isotropic, extragalactic neutrino flux
- For Scenario II: $\Delta M_\chi/M_\chi \approx 10^{-4}$ satisfies Lyman-α forest constraints on kick velocity

FAKE!!

Observational Compatibility

Neutrino Energy

KM3NeT (observed): 220^{+2380}_{-146} PeV

Model (predicted): ~ 100-300 PeV

Signal Direction

Explanation: Isotropic

Naturally explains lack of directional correlation with Galactic Center

Secondary Signatures

Scenario I: γ-ray flux

Scenario II: minimal γ-rays

Both scenarios consistent with current Fermi-LAT and H.E.S.S constraints

Conclusions and Future Directions

Key Conclusions

- Proposed a **Superheavy Supersymmetric Dark Matter** model to explain the KM3NeT UHE neutrino event
- Supersymmetry naturally produces a nearly degenerate mass spectrum with small splitting $\Delta M_X/M_X \ll 1$
- Decay of heavier components produces UHE neutrinos with energy $E_\nu \sim \Delta M_X \sim 100$ PeV
- Decay at cosmological redshift $z \gtrsim 1$-2 results in **isotropic signal distribution**
- Explains the absence of neutrino signal from the Galactic Center direction

"Dark matter is needed to hold galaxies together. Your mind is a Galaxy. More dark than light. But the light makes it worthwhile."

— Matt Haig

Advantages of This Model

- Resolves the **directional anomaly** of the KM3NeT UHE neutrino observation
- Provides a **natural mechanism** through SUSY for the required energy scale
- Mass degeneracy remains **radiatively stable** due to supersymmetry
- Two implementable scenarios provide different observational signatures
- Consistent with current gamma-ray flux constraints from Fermi-LAT and H.E.S.S.

Future Tests and Directions

Upcoming Observatories

IceCube-Gen2

Expanded neutrino detector with ~10× larger effective area will significantly increase statistics for UHE neutrinos

AugerPrime

Upgraded Pierre Auger Observatory will improve sensitivity to UHE cosmic rays and related neutrinos

KM3NeT (Full Configuration)

Completion of the full detector will increase sensitivity to high-energy neutrinos

Expected Signatures

- Additional UHE neutrino events with isotropic distribution
- Possible directional clustering from large scale structures at high redshift
- For Scenario I: Associated gamma-ray flux near theoretical limits
- For Scenario II: Sharper spectral features in neutrino flux

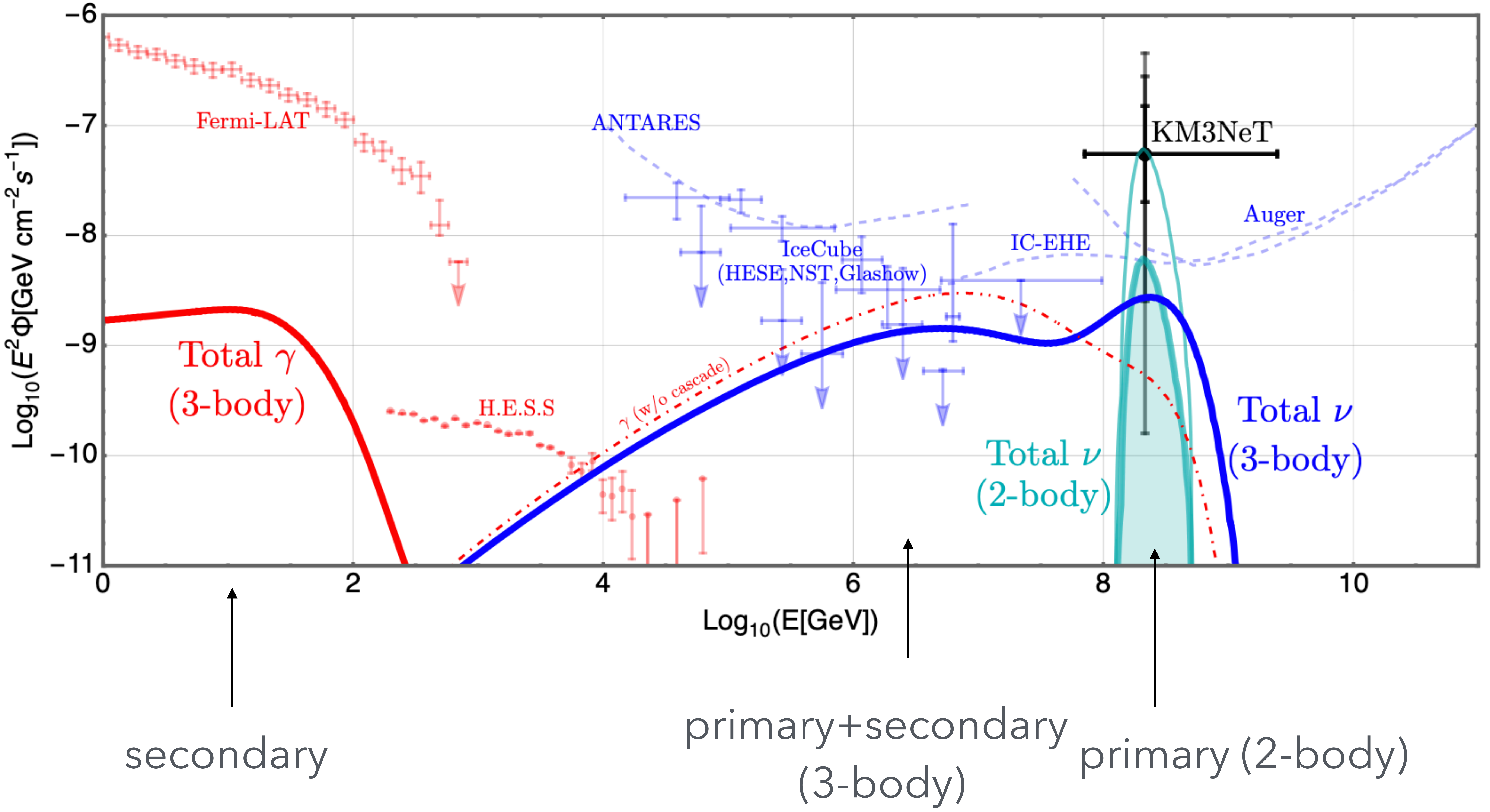
Acknowledgments & Reference

We acknowledge the original work by Yongsoo Jho, Seong Chan Park, and Chang Sub Shin from:

Jho, Y., Park, S.C., & Shin, C.S. (2025). "Superheavy Supersymmetric Dark Matter for the origin of KM3NeT Ultra-High Energy signal." arXiv:2503.18737v1 [hep-ph]

Support provided by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) RS-2022-NR072128, RS-2023-00283129, and RS-2024-00340153.

"With upcoming neutrino and ultra-high-energy cosmic ray observatories, we anticipate that the nature of superheavy dark matter and the origins of ultra-high-energy cosmic particles will be further unveiled in the near future."



- Scenario I ($\chi_h \to \chi_l + \nu + h$)

$$M_\chi = 10^{16}\ \mathrm{GeV},$$
$$\Delta M_\chi = 3\times 10^{9}\ \mathrm{GeV},$$
$$\Lambda = 1.44\times 10^{31}\ \mathrm{GeV}$$

- Scenario II ($\chi_h \to \chi_l + \nu_s$)

$$M_\chi = 6\times 10^{12}\ \mathrm{GeV},$$
$$\Delta M_\chi = 5\times 10^{8}\ \mathrm{GeV},$$
$$\lambda_s = 1.12\times 10^{-22}$$

Finally, my non-AI conclusion

"AI is a powerful tool, but we must use it with caution."

-ChatGPT