Constraints on Antiquark Nuggets from Collisions with the Earth

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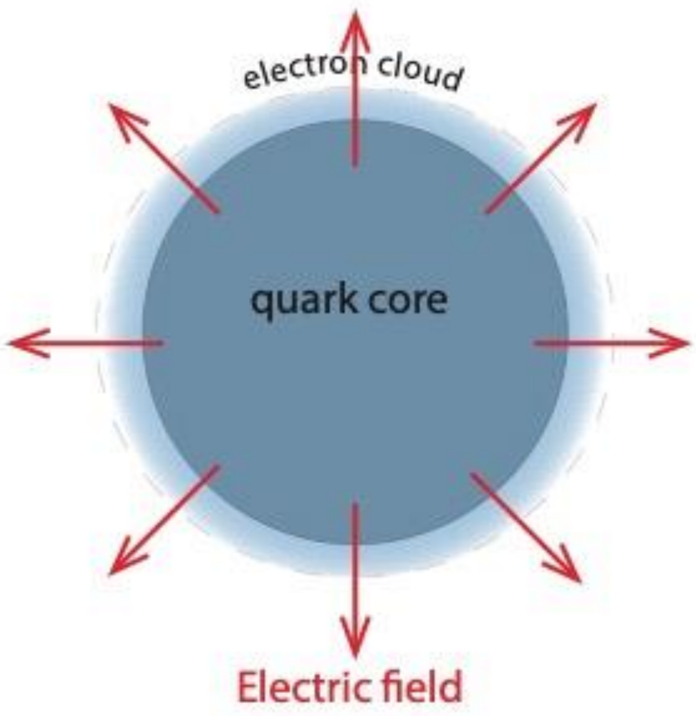
V. V. Flambaum, I. B. Samsonov, and G. K. Vong,
10.48550/arXiv.2405.17775 (2024)

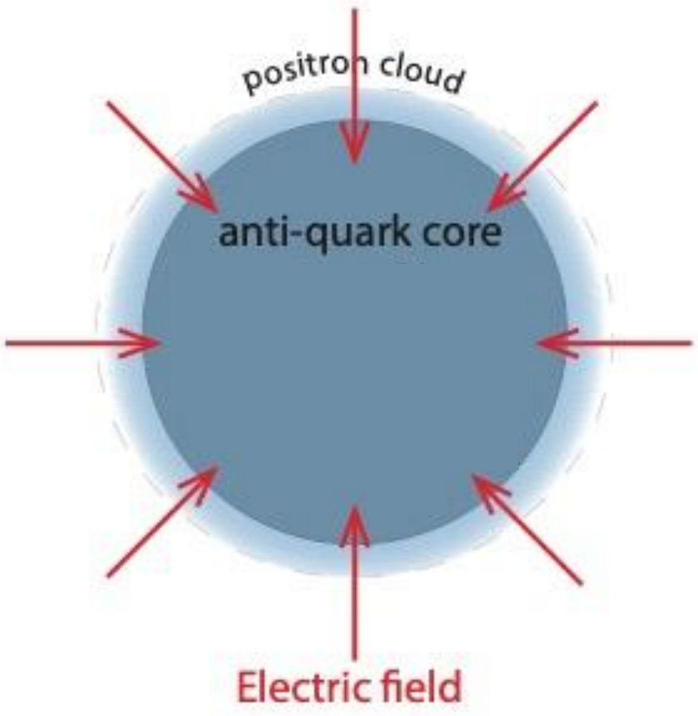
The International Joint Workshop on the Standard Model and Beyond 2024 & 3rd Gordon Godfrey Workshop on Astroparticle Physics

Quark Nugget Dark Matter Model

Quark Nugget



Anti-Quark Nugget



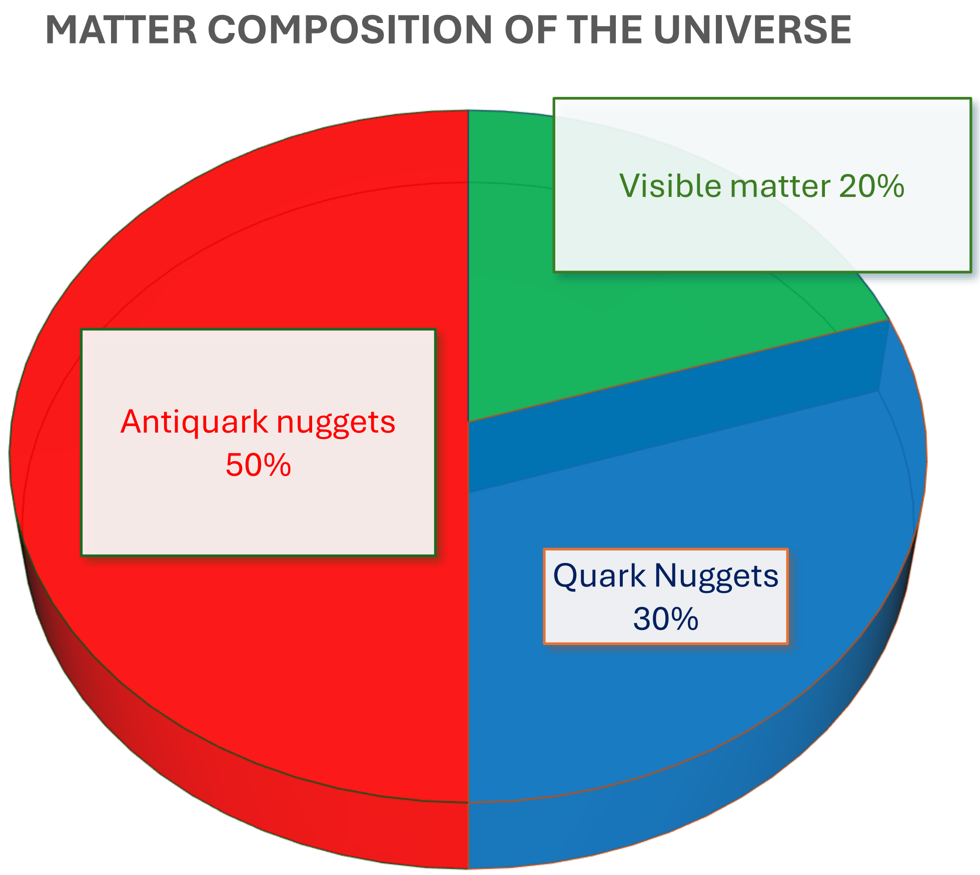
- Small cross section-to-mass ratio
- Extremely small number density in the galaxy: $\sim 10^{-26}$ cm^{-3}
- AntiQNs consist of antimatter
- May be detected when annihilating with visible matter

Adopted from talk by I. Samsonov

Reference: A.Zhnitnitsky, Modern Physics Letters A 2021 36:18

Motivation: Baryon Asymmetry

- All antimatter is hidden in anti-quark nuggets
- Baryon symmetry of the universe is preserved
- Baryogenesis is now a charge segregation process
- No particles beyond SM are required



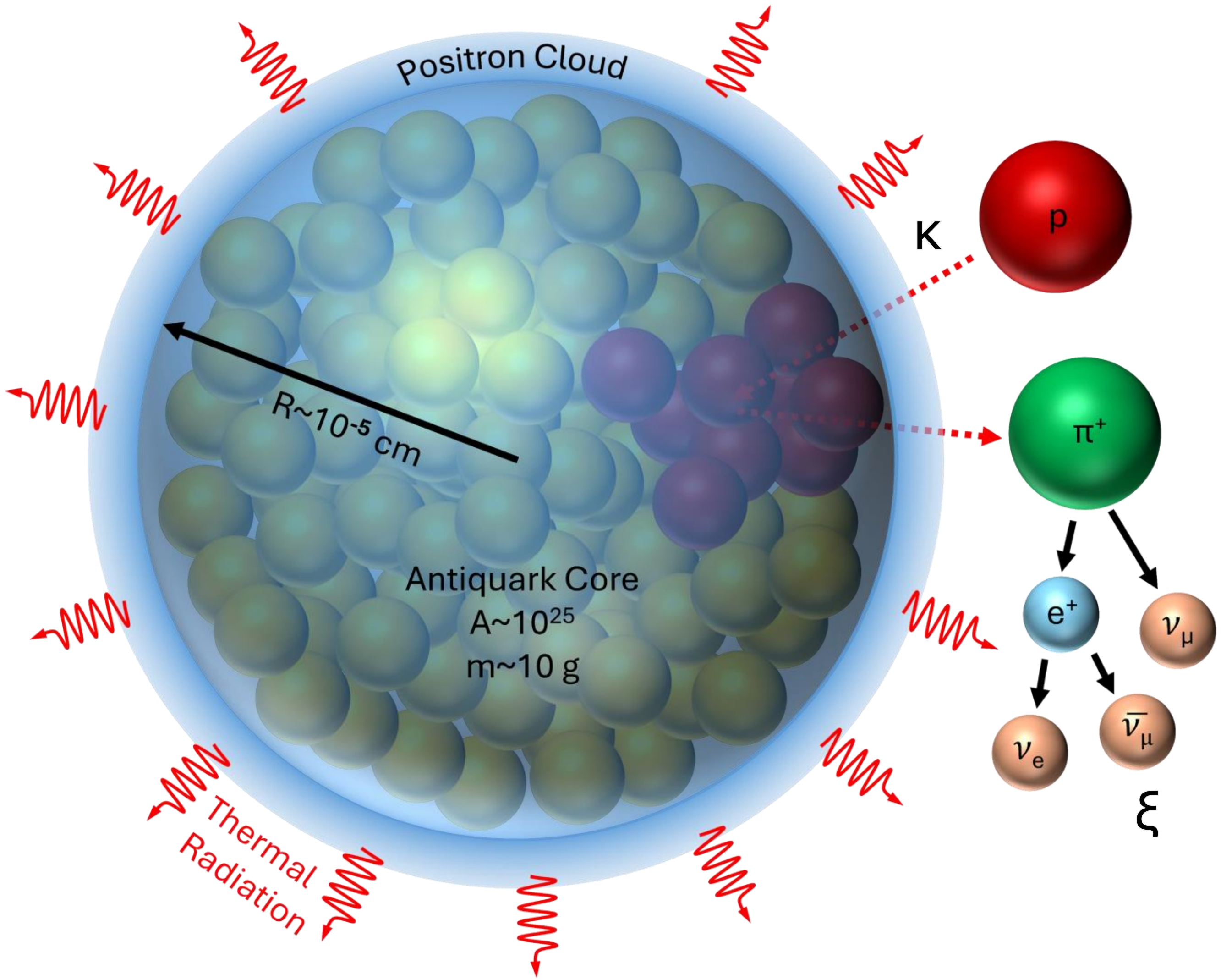
Adopted from talk by I. Samsonov

Radiation from Antiquark Nuggets

Key Parameters

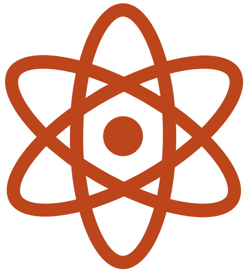
- Mass Number: A=|B|
- Annihilation Efficiency: κ
- Non-Thermalisation: ξ
- Thermal Emissivity: E(ω)

E(ω) studied in V. V. Flambaum, I. B. Samsonov, Phys. Rev. D 105 (2022) 123011

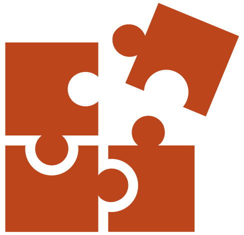


Methodology

Calculate neutrino flux from antiQN annihilation in Sun and Earth



Calculate thermal energy antiQNs deposit into Earth's crust



Use observations to constrain (A,κ,ξ) parameter space

Neutrinos from the Sun

$$\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\overline{\nu_\mu}\nu_\mu$$

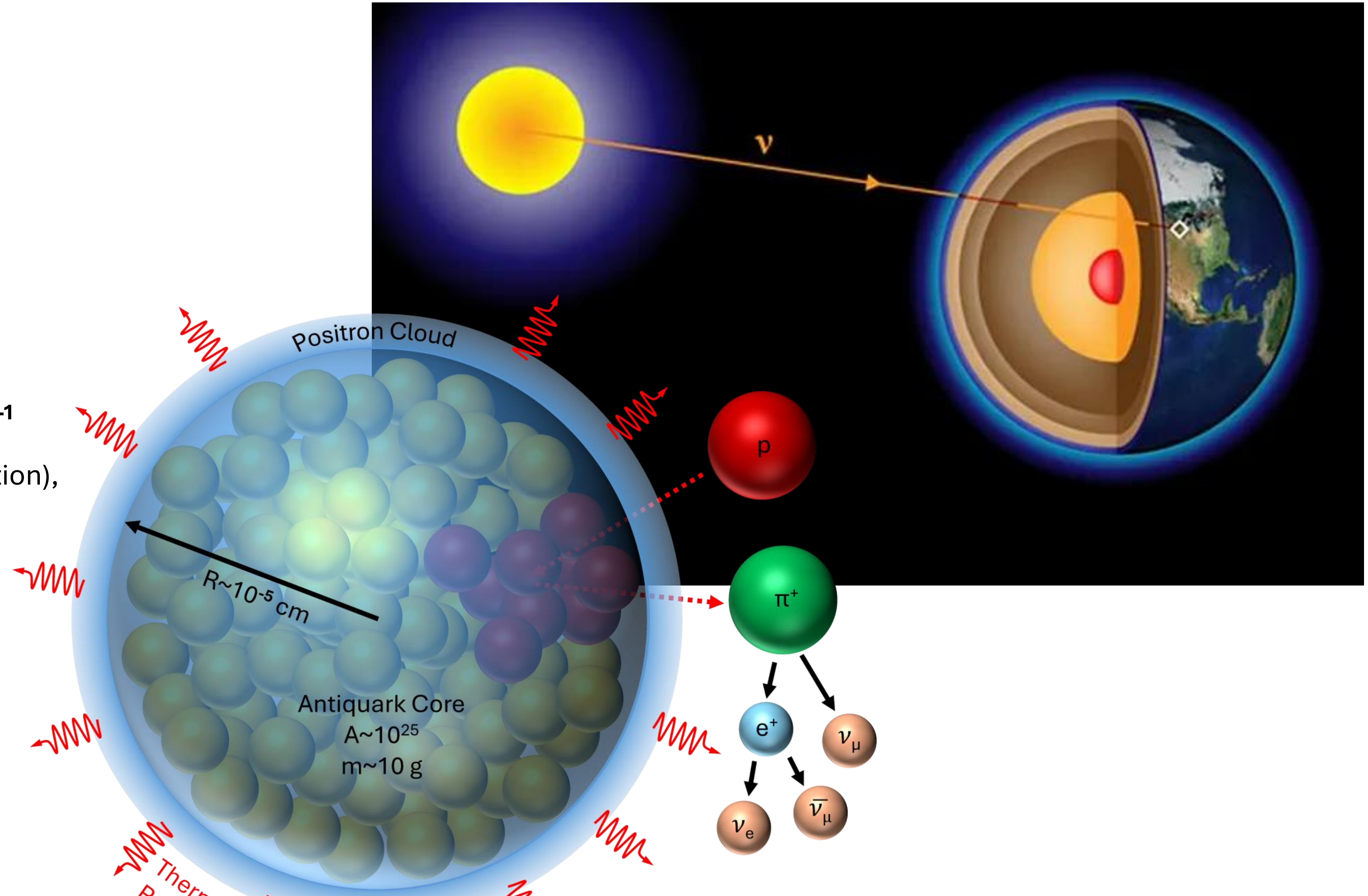
$$\pi^- \rightarrow \mu^-\overline{\nu_\mu} \rightarrow e^-\overline{\nu_e}\nu_\mu\,\nu_\mu$$

$\Phi_{\overline{\nu_e}} \approx 46\xi$ cm^{-2} s^{-1}

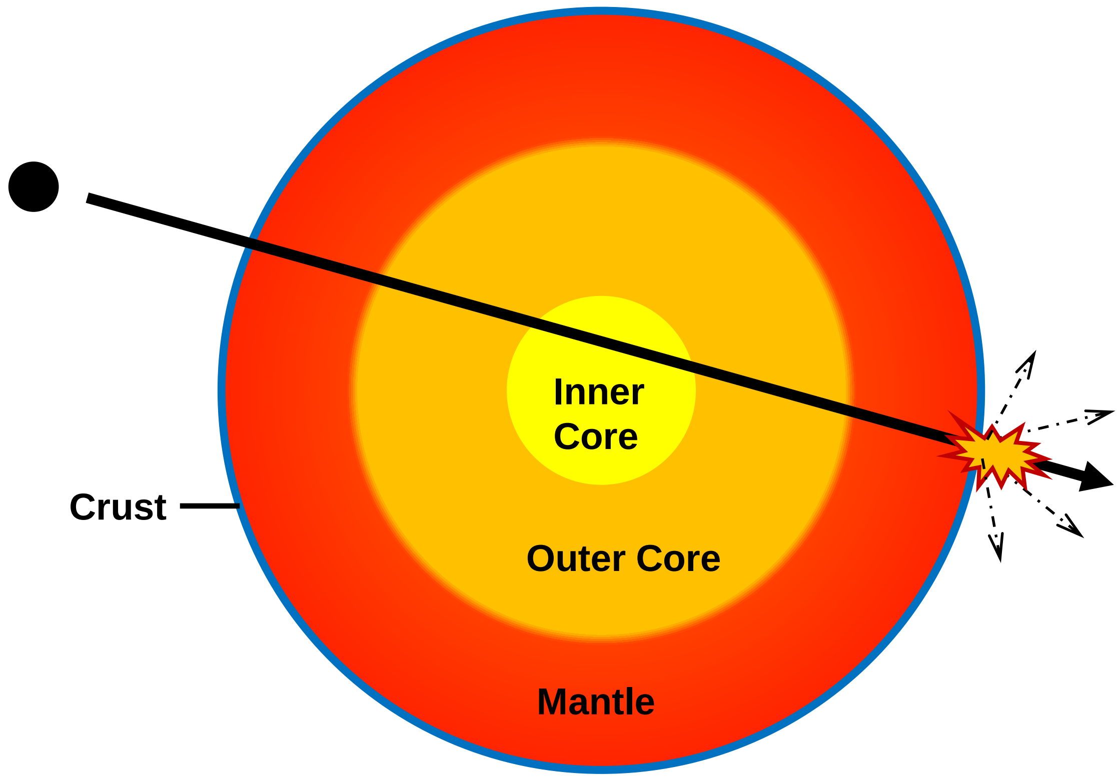
SuperK Upper Limit: $\Phi_{\overline{\nu_e},exp} = 2.7$ cm^{-2} s^{-1}

Abe, K. et al. (Super-Kamiokande Collaboration), Phys. Rev. D 104, 122002 (2021).

ξ < 0.06



Antiquark Nuggets Passing Through the Earth

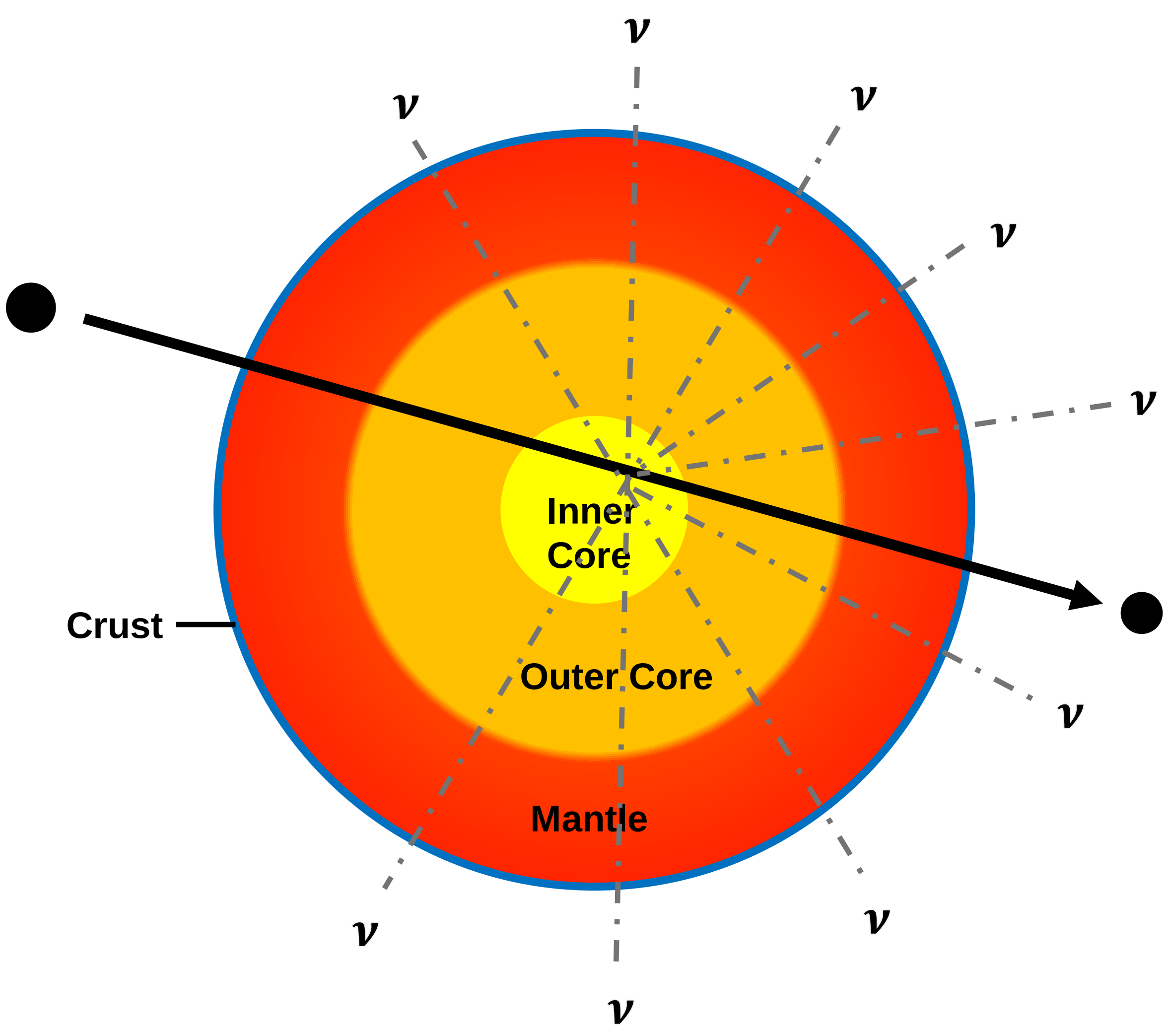


Neutrinos from the Earth

$$\Phi_{\overline{\nu_e}} \approx 3.5 \times 10^{13}\ \xi\kappa A^{-1/3}\ \mathrm{cm^{-2}\,s^{-1}}$$

SuperK Upper Limit: $\Phi_{\overline{\nu_e},exp} = 2.7\ \mathrm{cm^{-2}\,s^{-1}}$

$$\xi\kappa A^{-1} < 7.7 \times 10^{-14}$$



Thermal Radiation Deposited into Crust

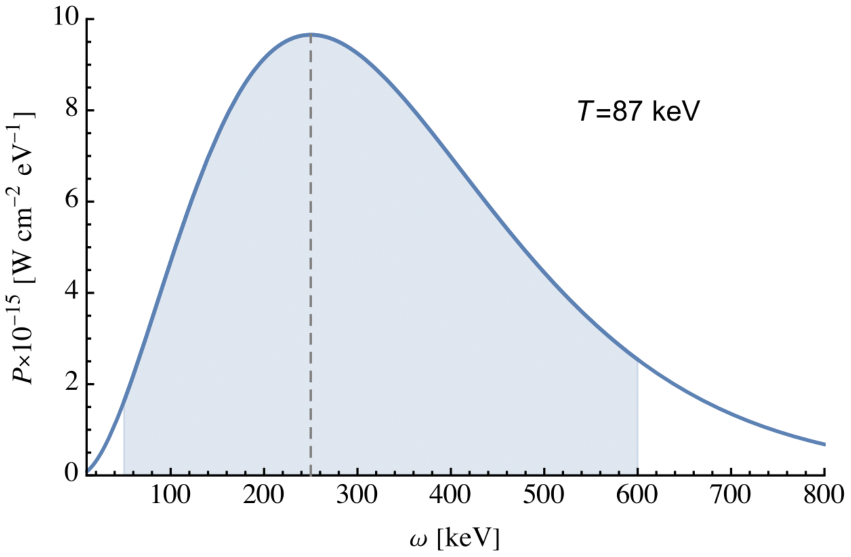
$$P_{thermal} = 4\pi R^2 \varepsilon(T)\sigma_{SB}T^4$$

$$P_{ann} = 2m_p(1-\xi)\sigma_{ann} v n_p$$

$$\sigma_{ann} = \kappa\pi R^2$$

$$\kappa(1-\xi)\rho v = 2\varepsilon(T)\sigma_{SB}T^4$$

V. V. Flambaum, I. B. Samsonov,
Phys. Rev. D 105 (2022) 123011



$A\kappa < 8 \times 10^{24}$

A	E/TJ	TNT equivalent, ton	$\langle\dot{N}\rangle/(100\text{yr})/(0.01\ S_\oplus)$
10^{25}	6.9×10^{-3}	1.7	2×10^7
10^{26}	0.032	7.7	2×10^6
10^{27}	0.15	36	2×10^5
10^{28}	0.7	170	2×10^4
10^{29}	3.2	770	2×10^3
10^{30}	15	3600	200
10^{31}	70	17×10^3	20
10^{32}	320	77×10^3	2
10^{33}	1500	36×10^4	0.2

TABLE I: Energy release E per one kilometer of antiQN trajectory in a rock with density $\rho_{rock} = 2.7\,g/cm^3$ for different baryon charge numbers from $A = 10^{25}$ to $A = 10^{33}$. Here we assume a conservative estimate $\kappa = 0.1$ for the coefficient describing efficiency of annihilation. The TNT energy release equivalent is 4184 J/g. $\langle\dot{N}\rangle$ is mean frequency of antiQN events per 1% of Earth's surface area per a 100-year period.

Results

$\xi < 0.06$

$\xi \kappa A^{-1/3} < 7.7 \times 10^{-14}$

$A\kappa < 8 \times 10^{24}$

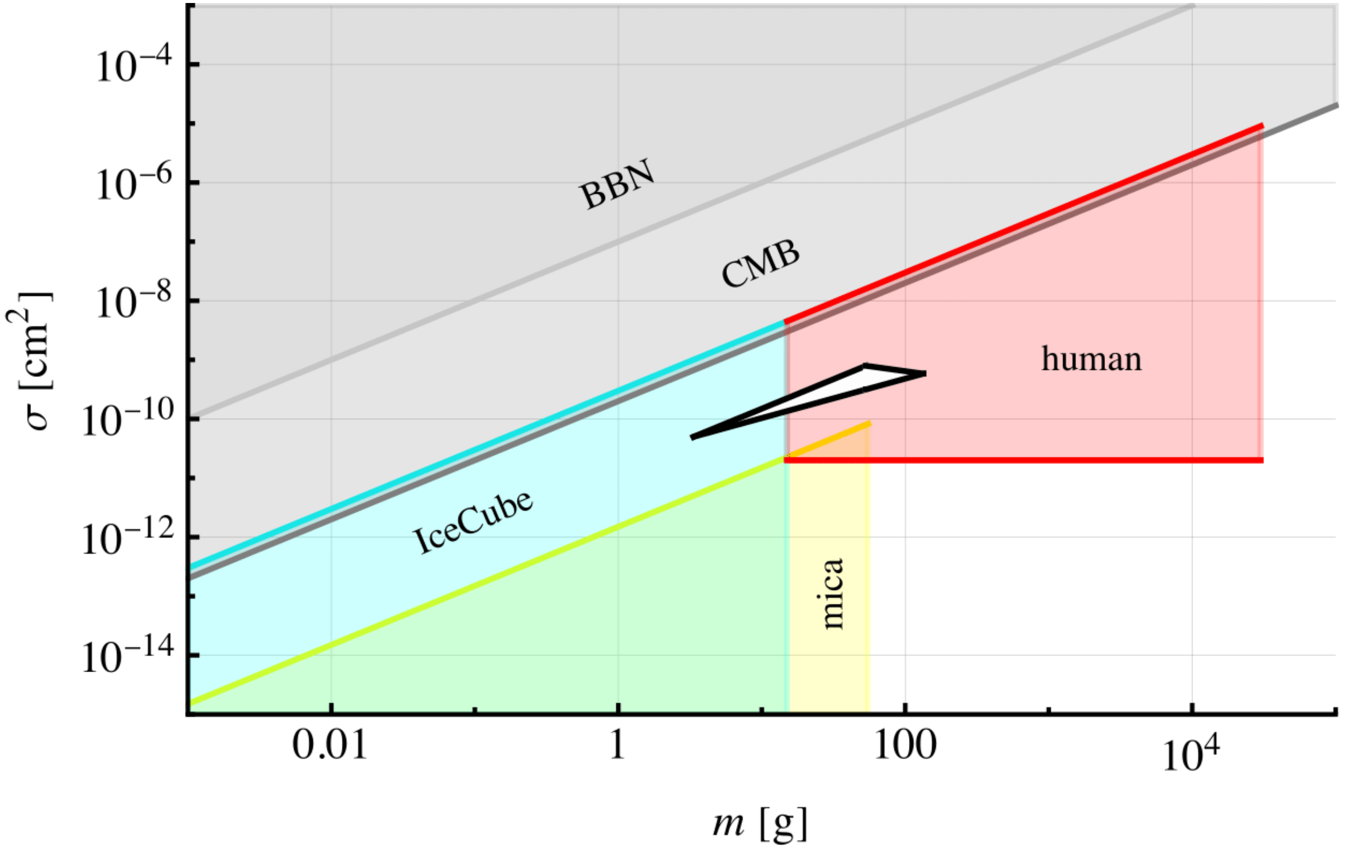
$0.1 \lesssim \kappa \leq 0.25$

$2 \times 10^{24} < A < 8 \times 10^{25}$

$\xi < 3.3 \times 10^{-4}$

Need a more accurate model of quark matter to fully understand annihilation inside core

$\sigma = \kappa \pi R^2$



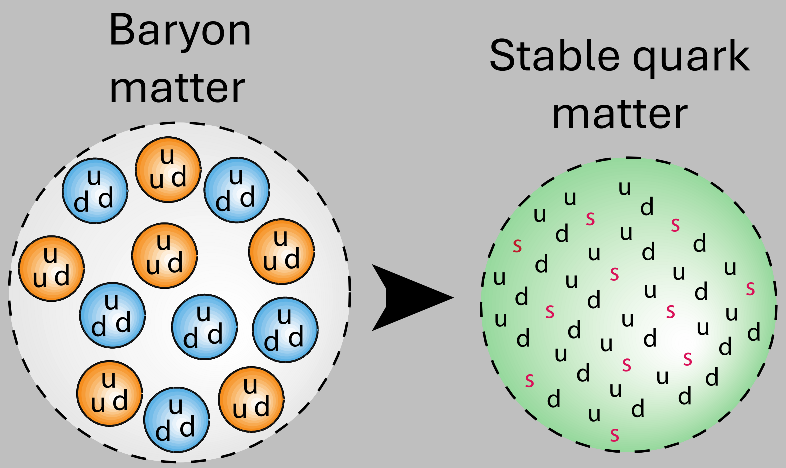
$m = Am_p$

Graph from V. V. Flambaum, I. B. Samsonov, and G. K. Vong, 10.48550/arXiv.2405.17775 (2024)

Thank you!

Strangelet Model

E. Witten, Phys. Rev. D 30, 272 (1984)
E. Farhi and R. L. Jaffe, Phys. Rev. D 30, 2379 (1984)



Axion-Quark nugget model

A. R. Zhitnitsky,
JCAP 2003 (10), 010.
Phys. Rev. D 74, 043515 (2006)
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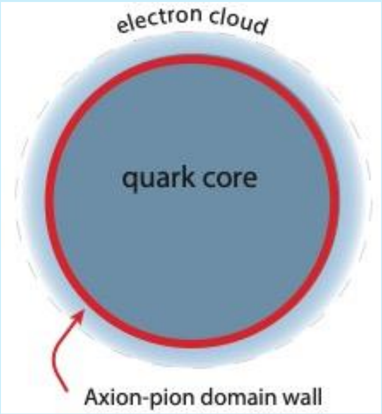
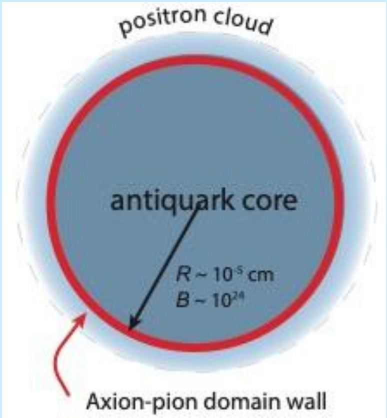
Quark Nugget



Anti-Quark Nugget



Why are Quark Nuggets "dark"?

- Typical **mass number:** $\langle A \rangle \simeq 10^{25}$
- Typical **mass:** $\langle M \rangle = Am_p \simeq 10\ \mathrm{g}$
- Typical **size:** $\langle R \rangle \simeq A^{1/3} \times 1\ \mathrm{fm} = 10^{-5}\mathrm{cm}$

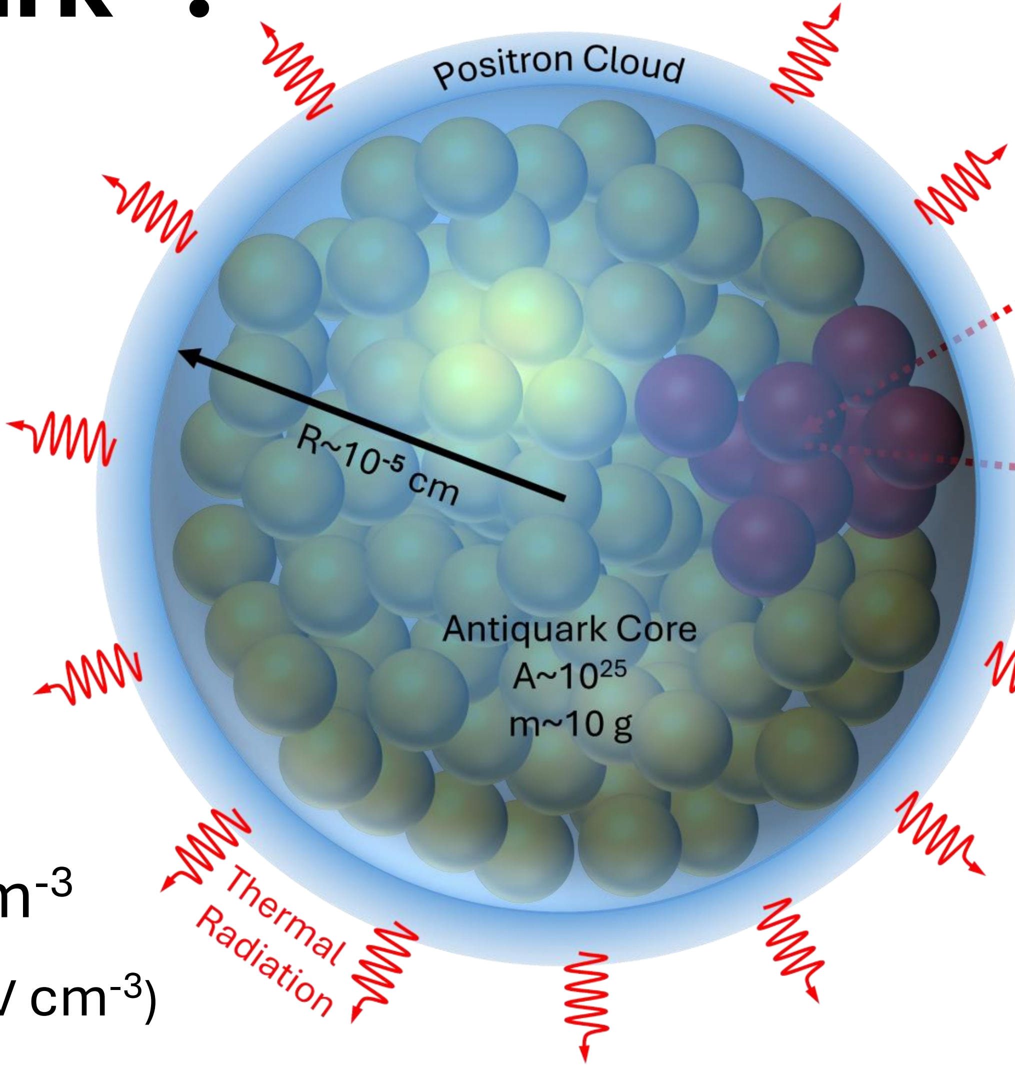
- **Cross-section to mass ratio:**

$$\frac{\sigma}{M} \sim 10^{-9}\ \mathrm{cm^2/g}$$

- **Number density:**

$$\langle n \rangle = \frac{\rho}{\langle M \rangle} \lesssim 10^{-26}\ \mathrm{cm^{-3}}$$

(Local DM density, $\rho = 0.3\ \mathrm{GeV\ cm^{-3}}$)



Quark Nugget Rate on Earth

- Local DM velocity: $v = v_{DM} \simeq 220$ km s^{-1}

- **Rate on Earth:**

$$\frac{\langle \dot{N} \rangle}{4\pi R_{\oplus}^{2}} \simeq 4 \times 10^{-2}\ \mathrm{km}^{2}\ \mathrm{yr}^{-1}$$

Budker, D., Flambaum, V. V., & Zhitnitsky, A. (2022). Infrasonic, Acoustic and Seismic Waves Produced by the Axion Quark Nuggets. *Symmetry*, *14*(3), 459.

Antiquark Nuggets in the Atmosphere

Reference: V. V. Flambaum, I. B. Samsonov and G.K. Vong, Phys. Rev. D 107, 123501

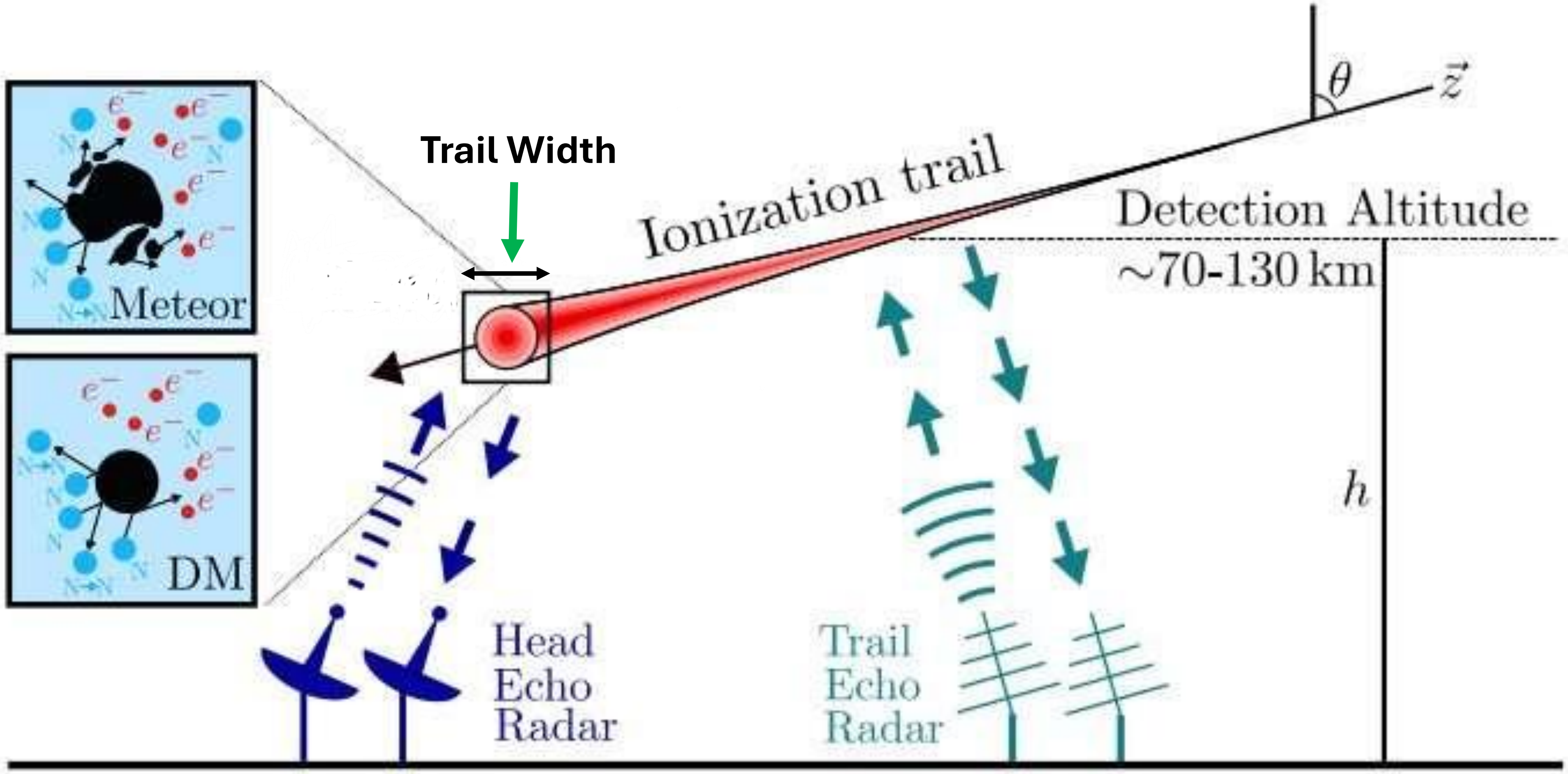


Illustration from P. Dhakal, S. Prohira, C. V. Cappiello, J. F. Beacom, S. Palo, and J. Marino, Phys. Rev. D 107, 043026.

Sample Trajectory of an Antiquark nugget in the Sun