Observational evidence of dark matter within the quark nugget model

Victor Flambaum and Igor Samsonov

V. V. Flambaum, I. S.,
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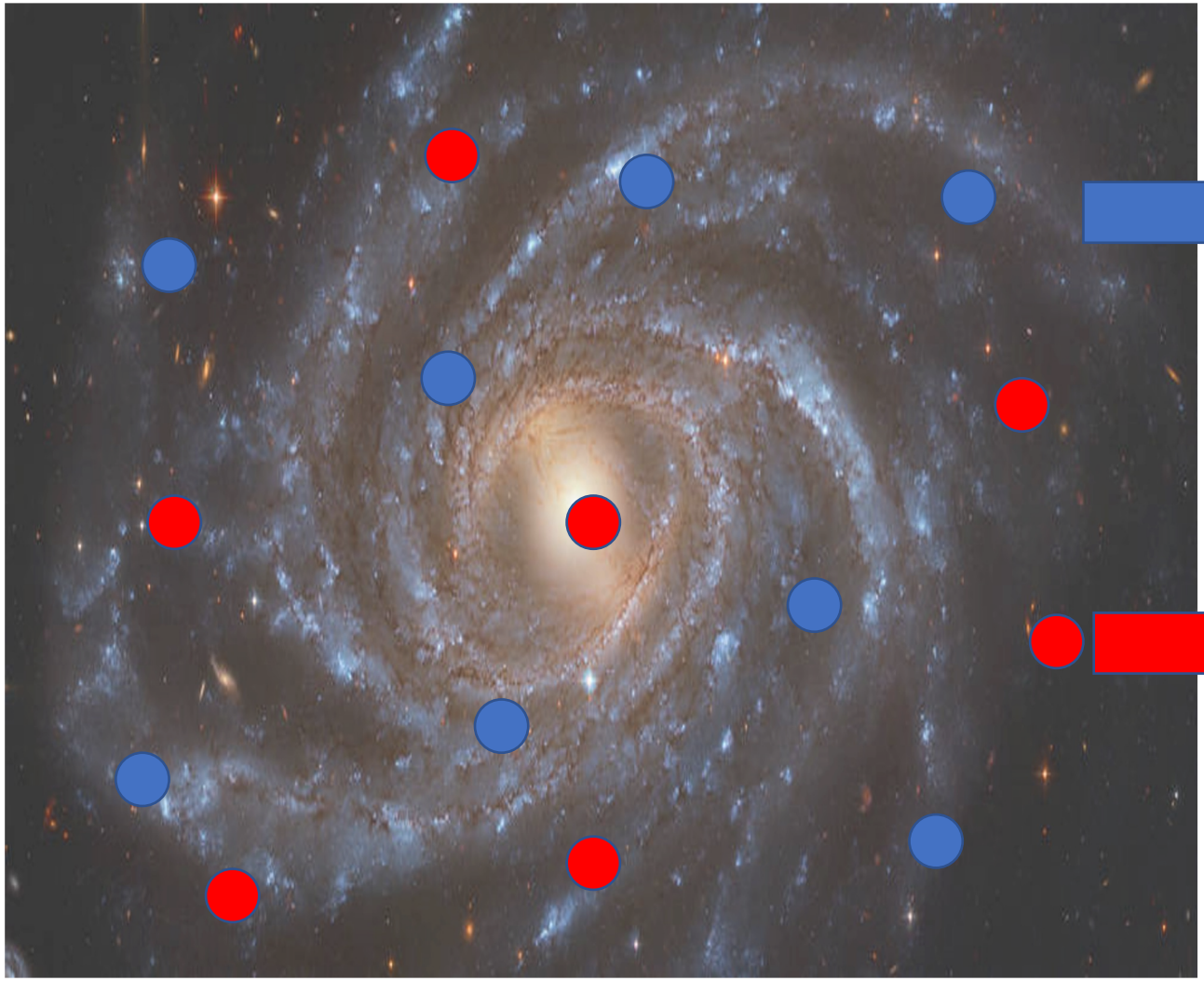
Phys. Rev. D 105 (2022) 123011
Phys. Rev. D 104 (2021), 063042

UNSW SYDNEY

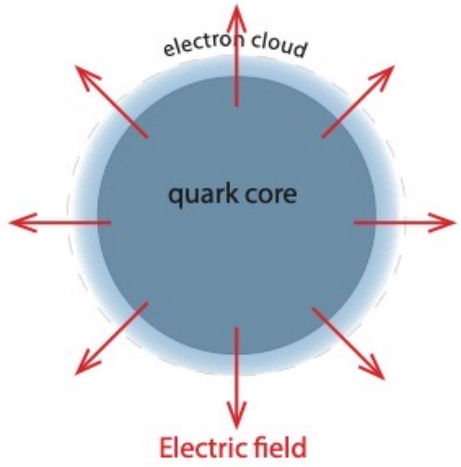
THE MODEL

The quark nugget Dark Matter model

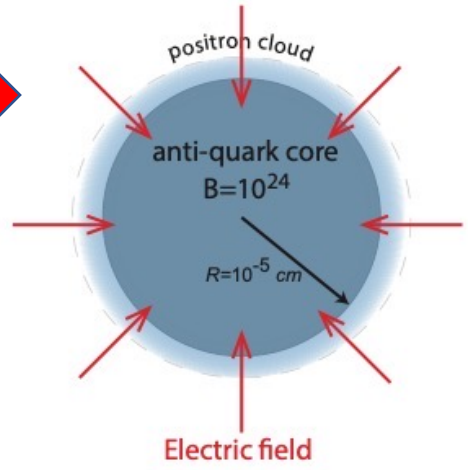
A.R. Zhitnitsky, JCAP 10, 010 (2003).
Phys. Rev. D 74, 043515 (2006)



Quark Nugget

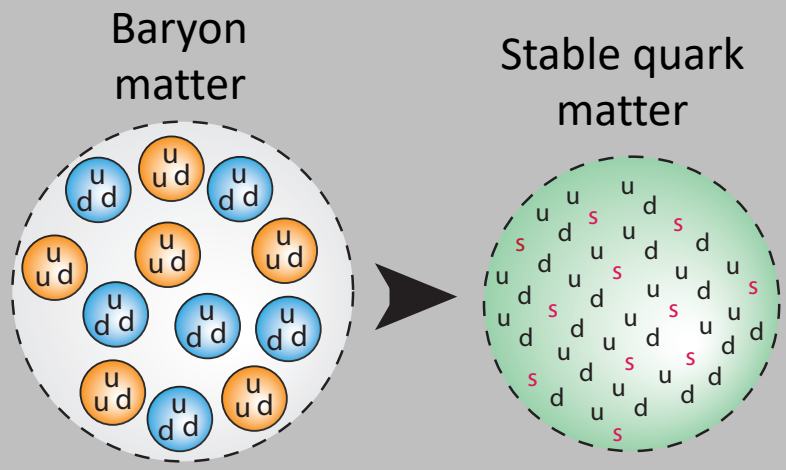


Antiquark Nugget



Strangelet Model

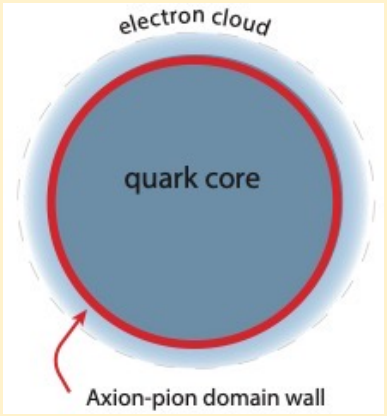
E. Witten, Phys. Rev. D 30, 272 (1984)
E. Farhi and R. L. Jaffe, Phys. Rev. D 30, 2379 (1984)



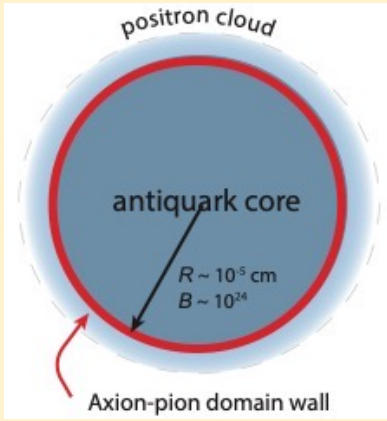
Axion-Quark nugget model

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

Quark Nugget

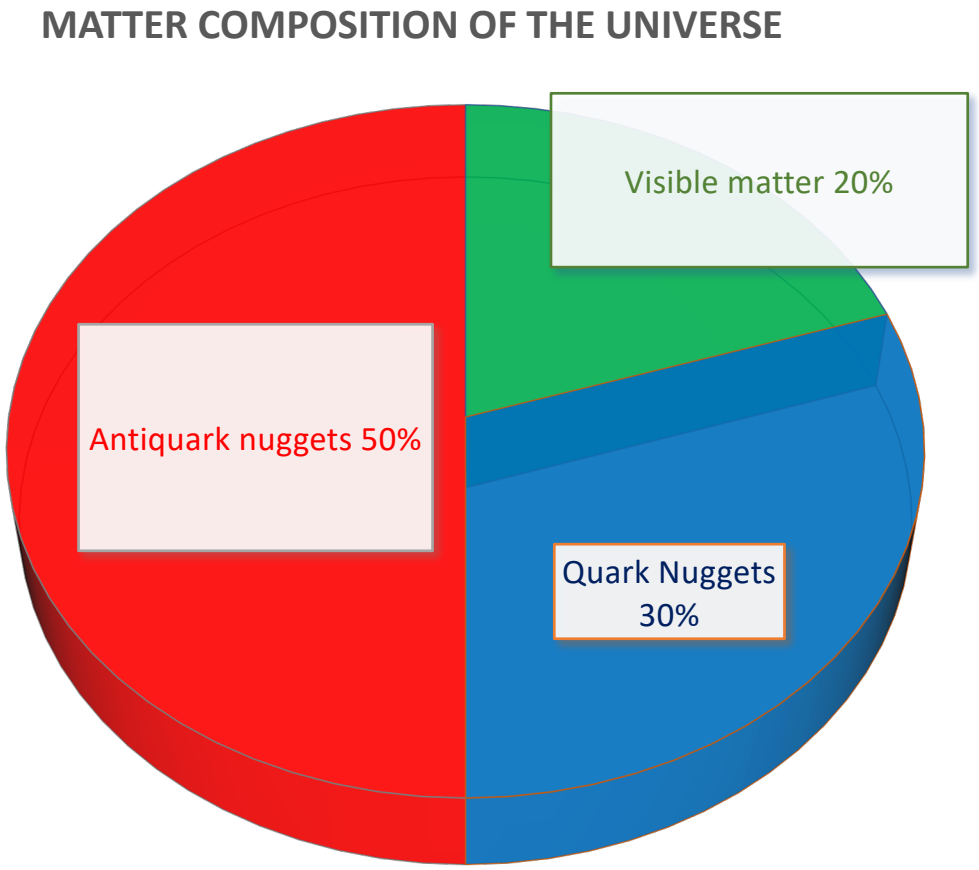


Anti-Quark Nugget



Why two phases?

- Baryon symmetry of the universe is preserved!
- All antimatter is hidden in anti-quark nuggets!
- No particles beyond SM are required!

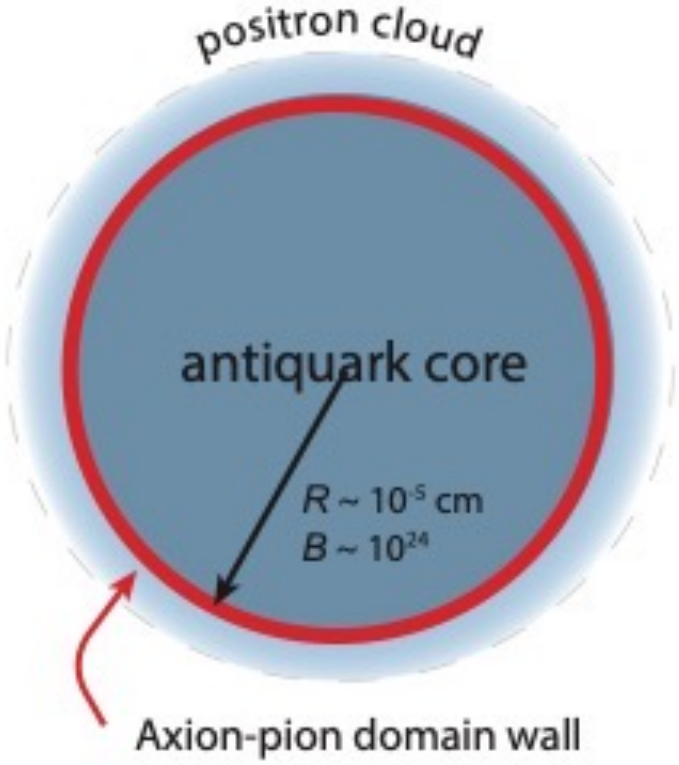


Why are they ``dark?''

- Because of an extremely small cross section-to-mass ratio!

$$\frac{\sigma}{M} \ll 1 \frac{\mathrm{cm}^2}{\mathrm{g}}$$

- Typical (anti)baryon number: B>10^{24}
- Typical size: $R=B^{1/3} * 1$ fm=10^{-5} cm
- Typical mass: $M=B*m_p$=10 g

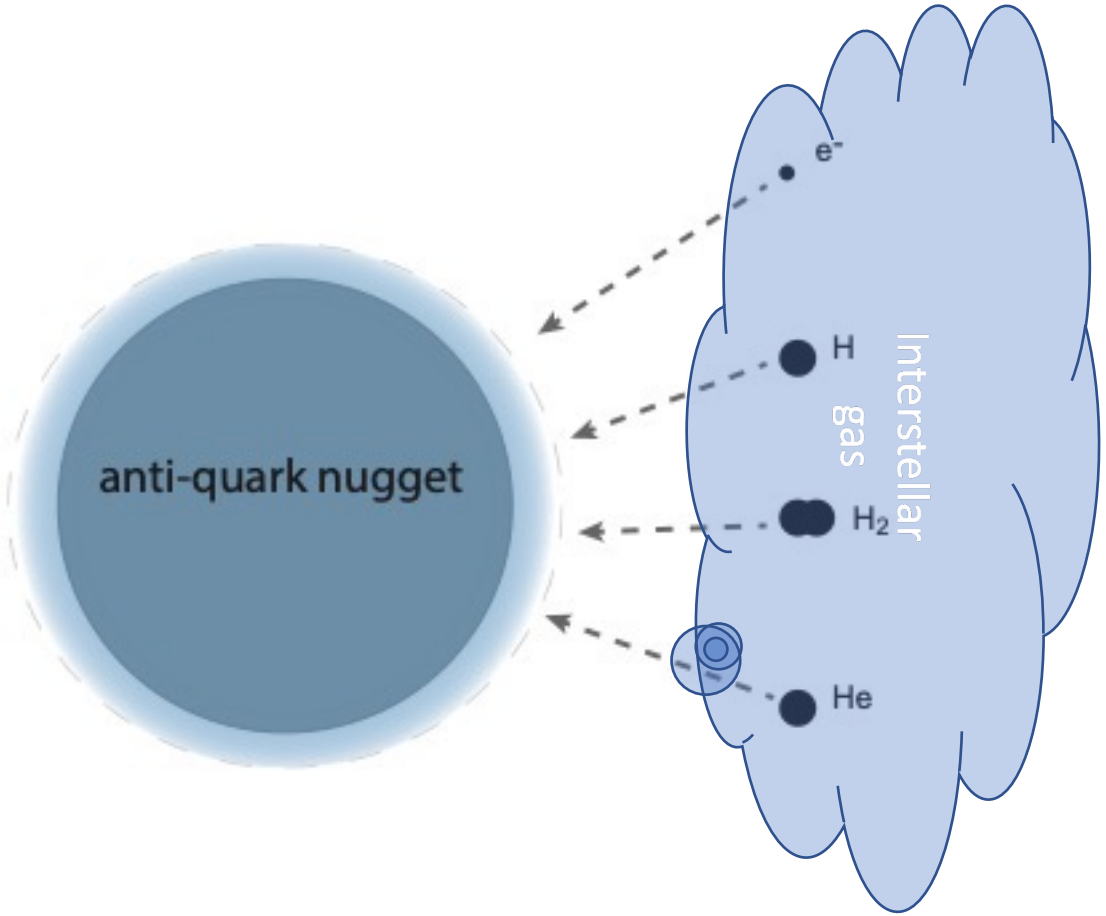


How to detect (anti)quark nuggets?

1. Antiquark nuggets strongly interact with visible matter => have better chances to be detected in contrast with QNs.
2. Anti-QNs hit the Earth and may cause rare seismic (earthquake) and atmospheric (sound waves) events [Budker, Flambaum, Liang, Zhitnitsky, Phys. Rev. D 101, 043012 (2020); Symmetry 14 (2022) 459].
3. Anti-QNs annihilate with gas and dust in Galaxy => look for specific radiation in our Galaxy => In this work!

Possible astrophysical manifestations of antiquark nuggets

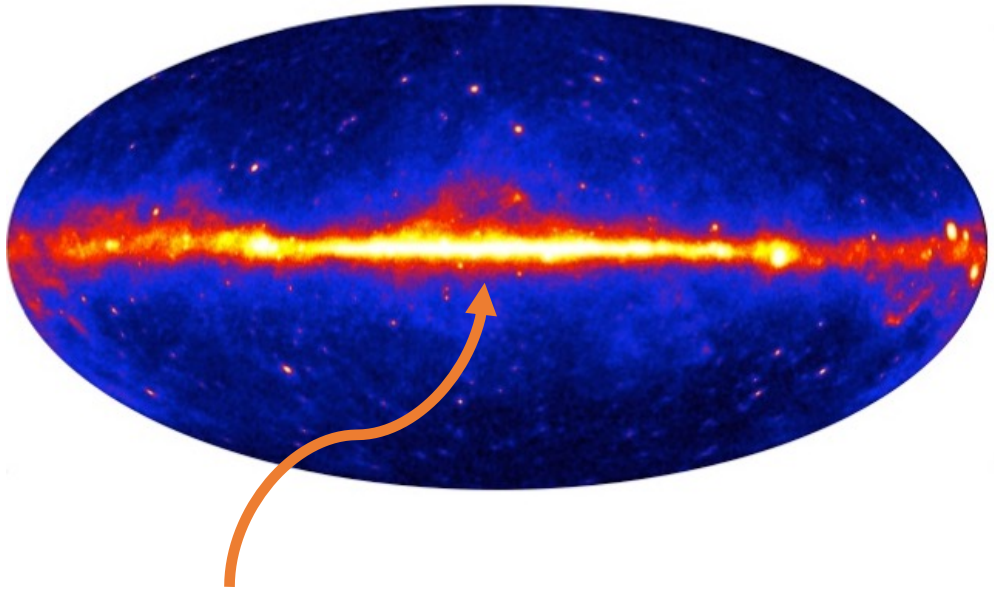
Interstellar gas particles scattering off the anti-quark nuggets



- Particles of the interstellar gas scatter off the antiquark nuggets, annihilate, and create excitations in the antiQN positron cloud.
- The excited antiquark nuggets radiate!
- Thermal radiation from positron cloud
- Non-thermal radiation from matter-antimatter decay products

Proton annihilation in the antiquark nugget

Fermi-LAT gamma-ray image



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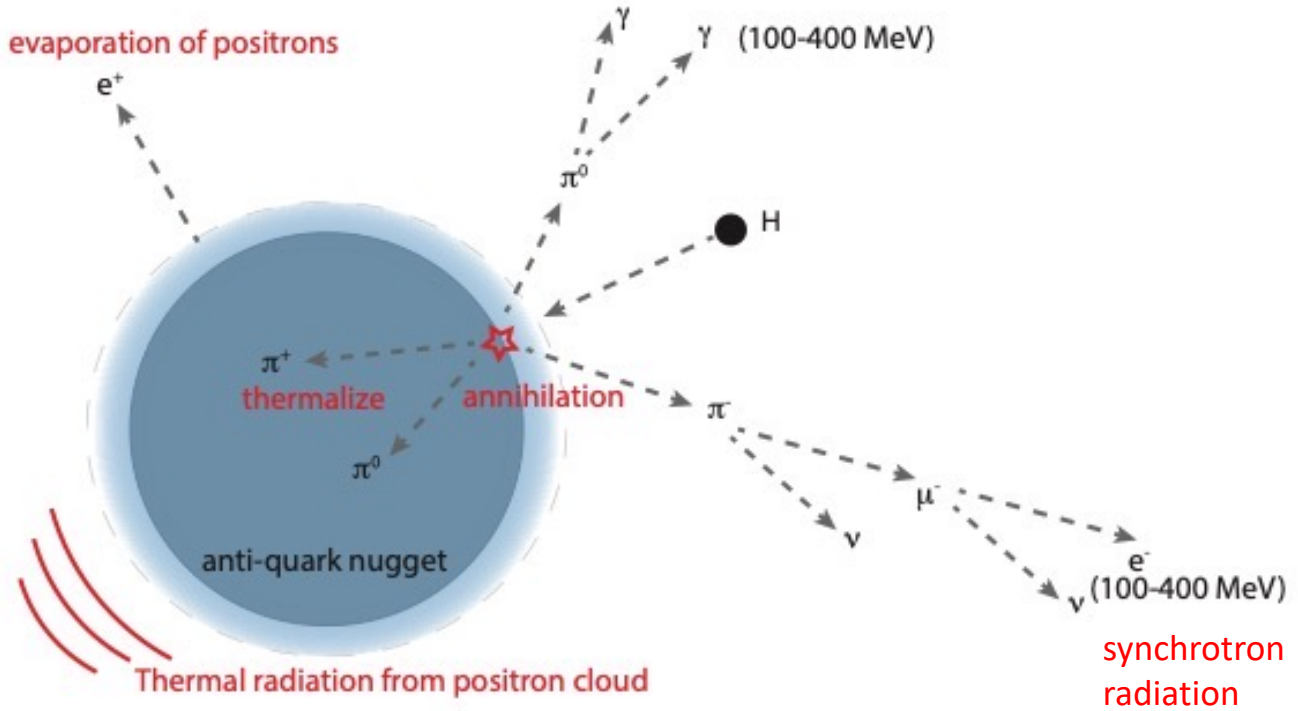
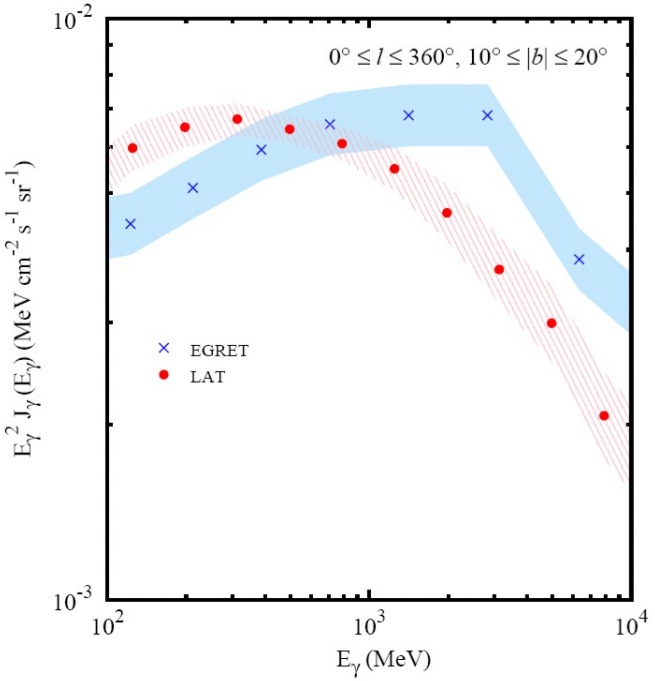


Gamma-rays from neutral π mesons

Observed Fermi-LAT gamma-ray flux



P F Michelson, W B Atwood, S Ritz, Rep. Prog. Phys. 73 (2010) 074901

- Anti-QN annihilation rate with interstellar gas:

$$W = \sigma\, v\, n_{\mathrm{DM}} n_{\mathrm{gas}}$$

$$\sigma = \pi R^2 = \pi B^{2/3}\,\mathrm{fm}^2$$ Annihilation cross section

$$v = 10^{-3} c$$ Velocity of dark matter particles

$$n_{\mathrm{DM}} = \rho_{\mathrm{DM}}/(B\ \mathrm{GeV})$$

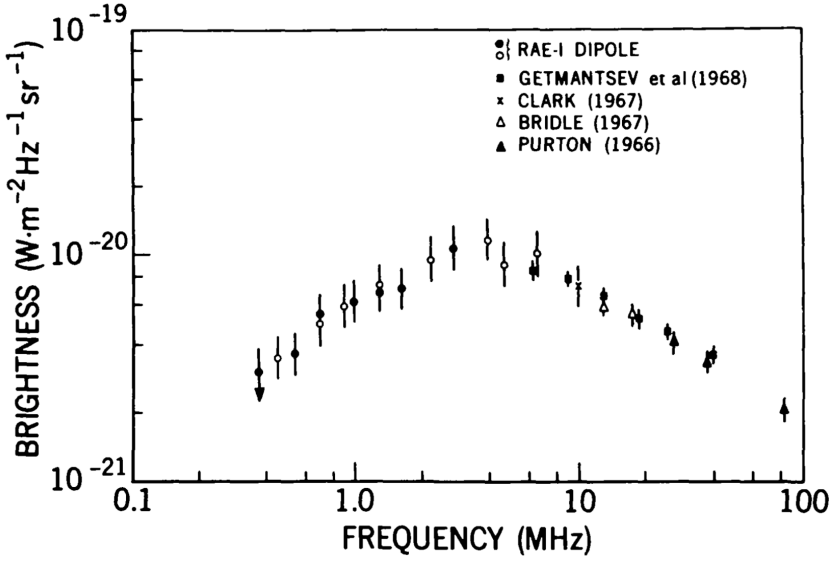
- Photon flux at observation point is given by line-of-sight integral

$$F = \frac{1}{4\pi}\int_l W\, dl = \frac{2\times 10^4}{B^{1/3}}\frac{\mathrm{photons}}{\mathrm{s\ cm^2\ sr}}$$

- Comparing with the Fermi-LAT observation we find that

the flux of Gamma-photons with E>100 MeV may be fully explained within the Quark Nugget model if $B < 2\times 10^{27}$

Synchrotron radiation from emitted electrons/positrons



J. K. Alexander et al, Astrophys. J., Vol. 157, 1969

- Charged Pi-mesons decay into electrons with energy up to 400 MeV
- These electrons produce synchrotron radiation in galaxy when they move in random magnetic fields with H~10 μG
- Maximum of synchrotron radiation at ω=44 MHz
- Intensity of radiation from one such electron

$$I \approx \frac{\sqrt{3}e^3 H}{2\pi\, mc^2} = 3.4\times10^{-28}\,\mathrm{erg\,s^{-1}Hz^{-1}}$$

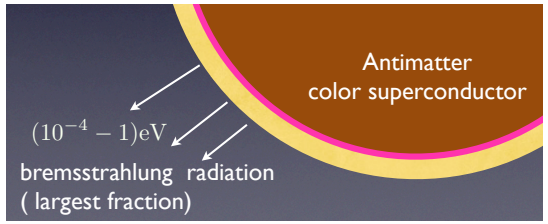
- Radiation power from all such electrons in the galaxy bulge at the observation point on Earth

$$P = \frac{2.7\times10^{-10}}{B^{1/3}}\,\frac{\mathrm{erg}}{\mathrm{s\,cm^2Hz}}$$

- Comparing this with the RAE1 satellite observation, we find that

It is plausible that the observed rf radiation from the galactic bulge is partly produced by charged particles emitted from anti Quark Nuggets with $B < 8\times10^{23}$

Thermal radiation from anti-QNs



- First considered in papers
- [M. M. Forbes and A. R. Zhitnitsky, Phys. Rev. D 78, 083505 (2008)]
- Radiation comes from a gas of positrons on the surface of quark nugget
- Radiation power is estimated as a bremsstrahlung radiation in collisions of positrons in the positron gas. Radiation comes from collisions of individual particles.

$$F_{\rm tot} = \frac{{\rm d}E}{{\rm d}t\,{\rm d}A} = \int_0^\infty {\rm d}\omega\,\frac{{\rm d}F}{{\rm d}\omega}(\omega) \sim \frac{16}{3}\frac{T^4\alpha^{5/2}}{\pi}\sqrt[4]{\frac{T}{m}} \qquad F_{\rm tot} \sim 10^{-6}F_{BB}$$

- This model strongly underestimates the radiation because in macroscopic objects the radiation is a collective effect rather than a two-particle process!

Thermal radiation from anti-QNs

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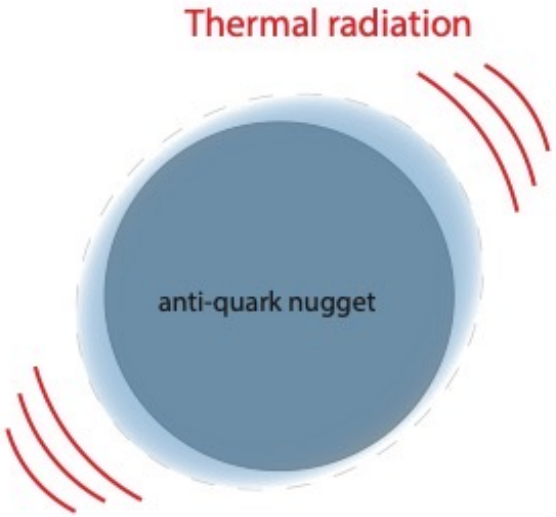
Phys. Rev. D 105 (2022) 123011

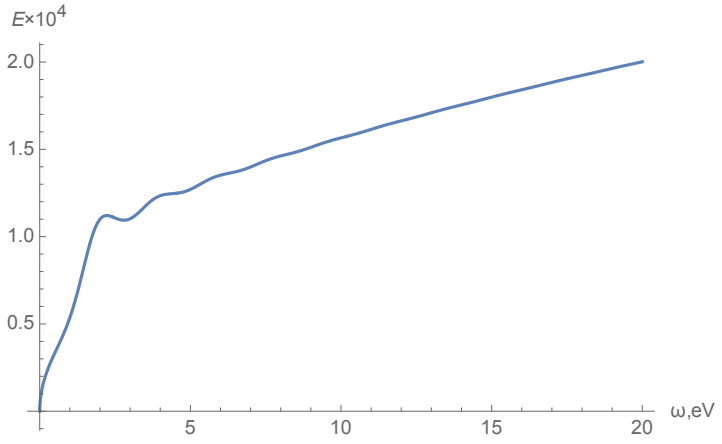


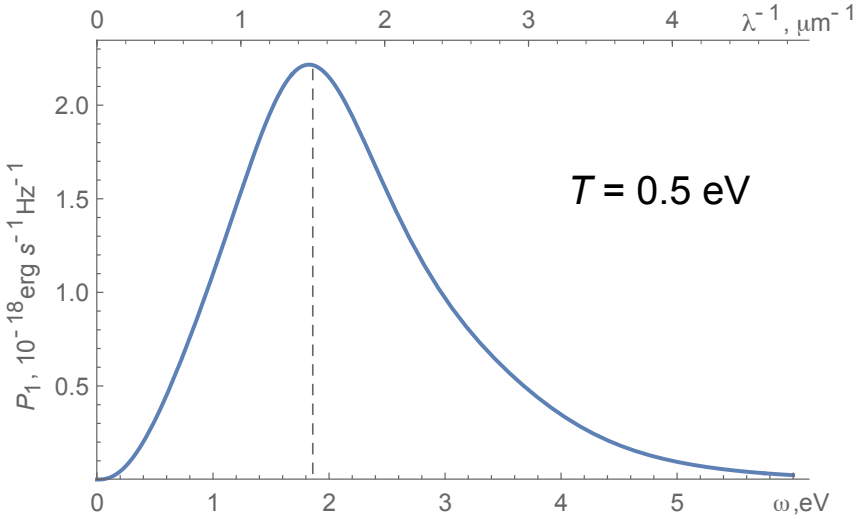
- Thermal radiation is produced by density fluctuations in the positron cloud
- Antiquark nuggets are considered as spherical particles of radius R and with plasma frequency ω_p=2 MeV
- Radiation power from each anti-QN:

$$P(\omega, T) = \pi E(\omega) I_0(\omega, T)$$

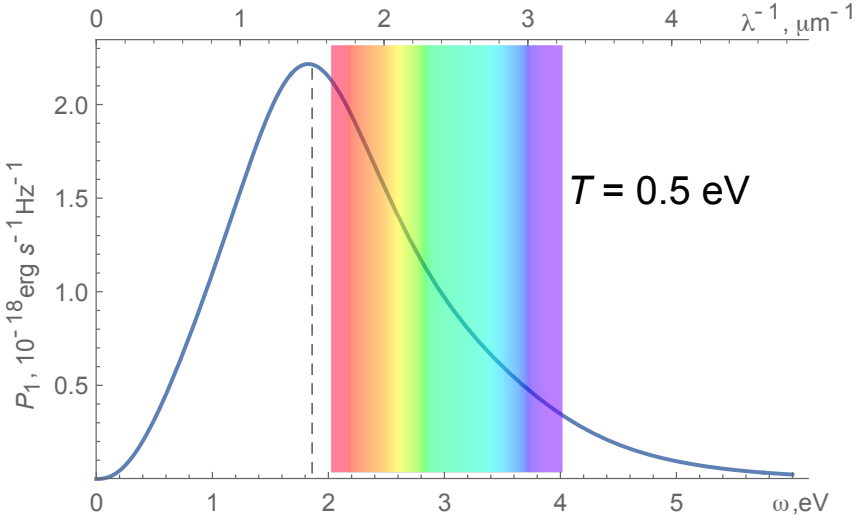
$$I_0 = \frac{\hbar\omega^3}{4\pi^3 c^2} \frac{1}{\exp\left(\frac{\hbar\omega}{k_B T}\right) - 1}$$

- I_0 is the Planck function
- $E(\omega)$ is the thermal emissivity, calculated numerically using Mie theory





Light from Taurus molecular cloud



- Distance to the cloud is L=140 pc
- Gas density n=300 to 1000 cm^{-3}
- Effective QN temperature in the cloud T=0.5eV
- Maximum of the thermal radiation from antiquark nuggets is in near infrared to visible light
- Estimated energy flux at λ=555 nm

$$\Phi = 1.2 \times 10^{-29} \frac{\text{erg}}{\text{s Hz cm}^2}$$

- This corresponds to visible and absolute magnitudes

$$m_{\text{AB}} = -2.5 \log_{10}(\Phi) - 48.6 = 23.2$$
$$M_{\text{AB}} = m_{\text{AB}} - 5 \log_{10} L + 5 = 17.5 .$$

- Hubble Space Telescope can, potentially resolve faint objects with m=31.5. Thus, light from anti-QNs in molecular clouds may be observed if resolved from background.

Summary

- Anti-quark nuggets strongly interact with visible matter and radiate
- Annihilation of gas particles in the interstellar medium on anti-QNs can create an observable flux of ω>100MeV-range photons (Fermi-LAT telescope)
- Charged π mesons decay into ultrarelativistic electrons and positrons, which emit synchrotron radiation when move in the magnetic field in the galaxy. This radiation may represent a significant contribution to the galaxy RF background.
- Positrons from the positron cloud annihilate with atoms in the interstellar gas and produce a flux of 511 keV photons. This flux may be observed by the SPI-INTEGRAL satellite.
- It is predicted that anti-QNs can radiate in cold molecular clouds in visible light which can be detected.

Thank you!

Positron cloud

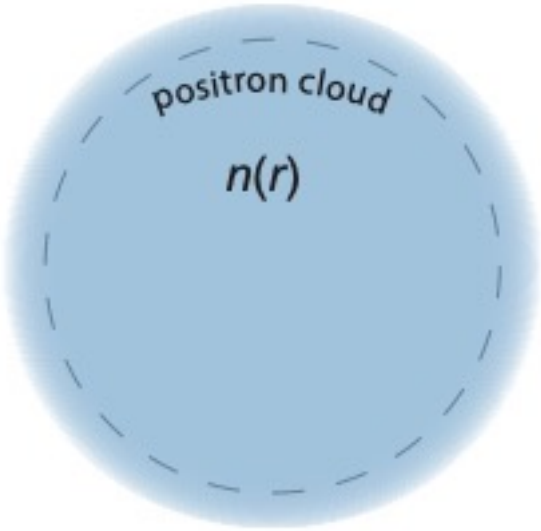
- In the Thomas-Fermi model charge density $n(r)$ which may be found as a solution of Poisson equation with $n_0(r)$ being the quark core charge density

$$\Delta\varphi = 4\pi e[n(r) - n_0(r)]$$

- The positron density, together with the quark core charge density, create the electric field

$$E = -\nabla\varphi$$

- Given the positron density and the electric field, we study the annihilation probability for incident electrons, atoms and molecules.



Quark nuggets and solar corona temperature

- The solar corona temperature is about $T = 10^6$ K that is nearly 100 times higher than that in chromosphere
- A. Zhitnitsky speculates that annihilation of antiquark nuggets in the solar corona is responsible for this high temperature [A. Zhitnitsky, JCAP 2017 (10), 050; N. Raza, L. Van Waerbeke, and A. Zhitnitsky, Phys. Rev.D 98, 103527 (2018)]
- However, plasma density in the solar corona is very low, $n<10^{10}$ cm^{-3}.
- We show that Zhitnitsky *et al* strongly overestimated (~10^8 times) the annihilation cross section of anti-QNs in the solar corona.
- Thus, we show that antiquark nuggets are irrelevant to the solar corona temperature paradox.