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Quark Nugget models of dark matter revisited

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Dark Matter models

Beyond the Standard Model

- WIMS
- Sterile neutrino
- Axion
- Supersymmetric particles
- …

Standard Model based

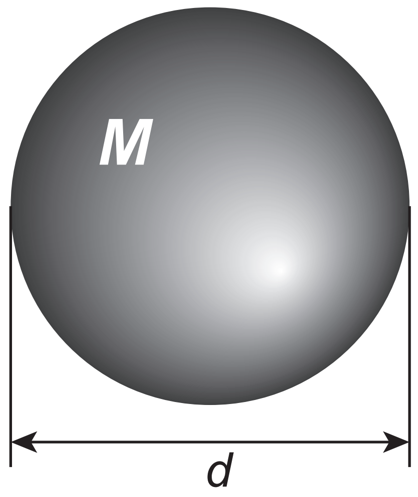
- Black holes
- Strangelets
- Compact Composite objects
- QCD balls
- Axion quark nuggets

Compact composite objects as DM candidates

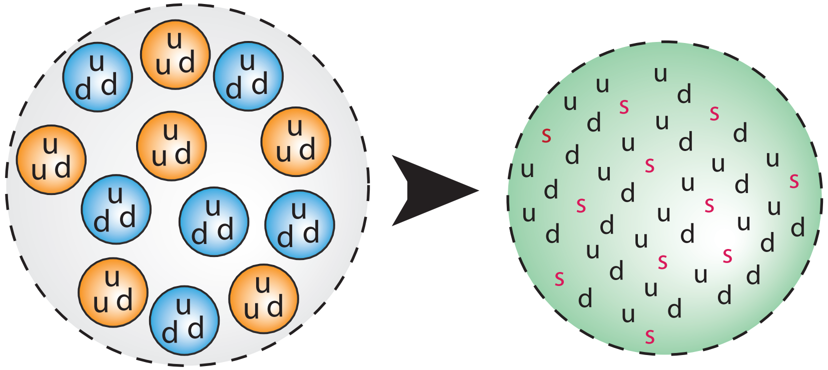
- Can be composed of SM particles (baryons, quarks), do not require new physics
- In spite of strong interaction with visible matter, such objects cannot be detected because of a small ratio of cross section to mass

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

- Such objects are not excluded by any dark matter detecting experiments and cosmological observations



Example: Strangelets



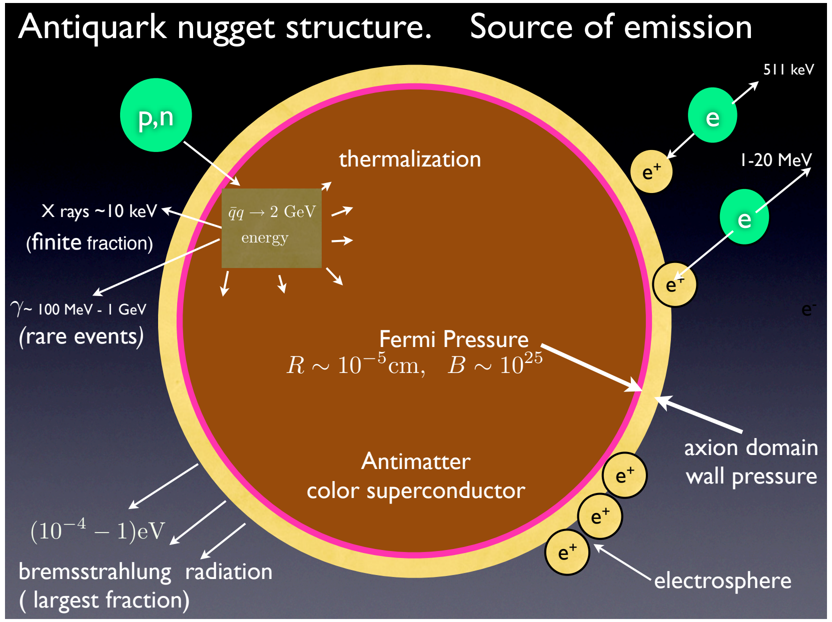
E. Farhi and R. L. Jaffe, Phys. Rev. D 30, 2379 (1984)
E. Witten, Phys. Rev. D 30, 272 (1984)
A. R. Bodmer, Phys. Rev. D 4, 1601 (1971)

- Quark matter: consists of quarks not bound to baryons
- Presence of strange quark can lower the energy of such objects and make them stable
- A stable composite particle which consists of large number of up down and strange quarks – dark matter particle candidate
- Neutron stars could have a quark core with strange quarks (debated)

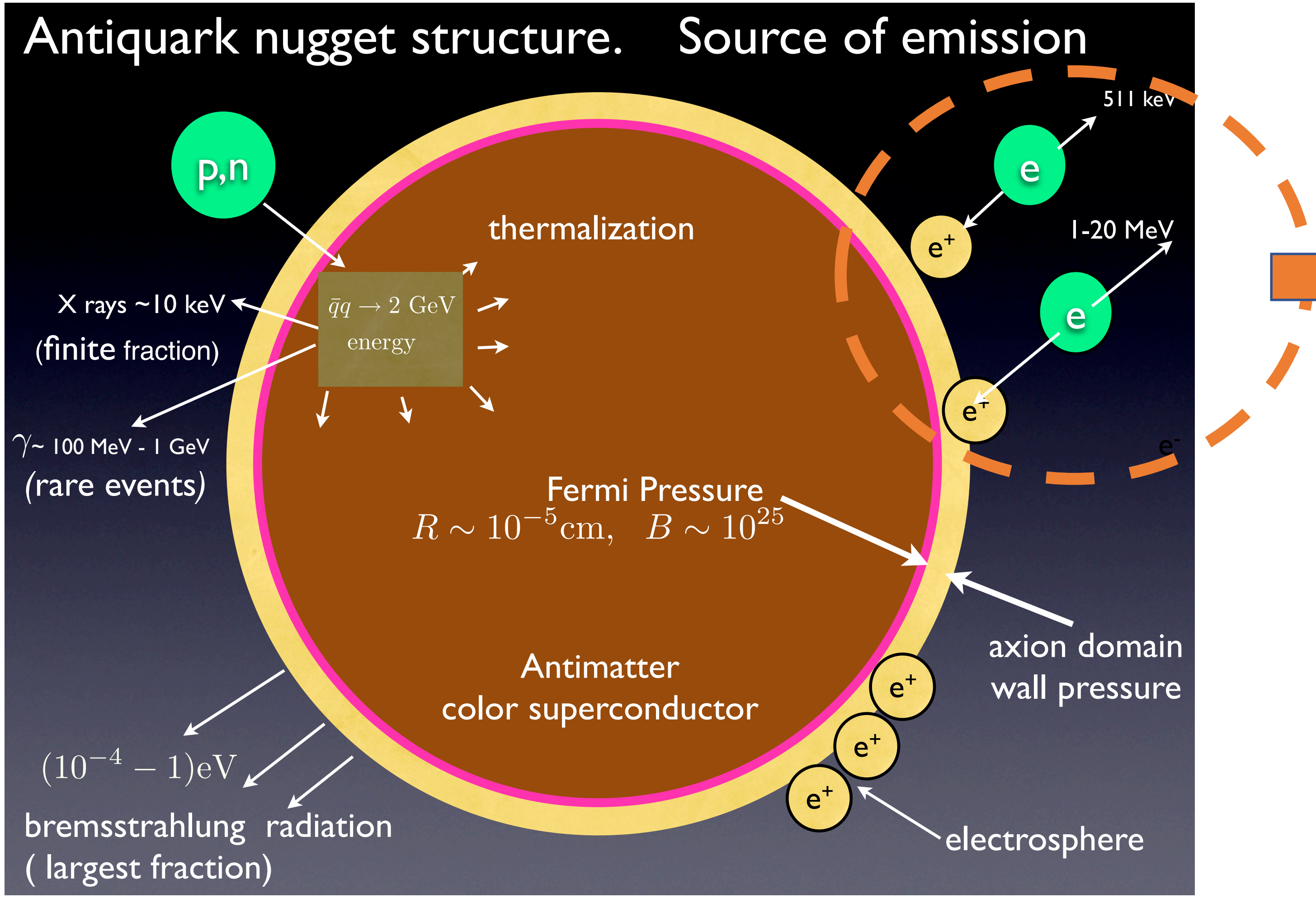
Axion-quark nuggets, QCD balls, Compact composite objects, etc.

- Quark matter nuggets are composed of large number of quarks surrounded by electron cloud
- Anti-quark nugget consist of large number of anti-quarks, surrounded by the positron cloud
- Both quark and anti-quark nuggets amount to Dark Matter
- Assumption on ratio of abundances anti-quark nuggets : quark nuggets : baryonic matter = 3 : 2 : 1
- Explains matter-antimatter asymmetry in nature: anti-matter is hidden in anti-quark nuggets
- Has radiation which may (potentially) be detected

A. R. Zhitnitsky, JCAP10, 010 (2001)
And many subsequent papers



Adopted from the talk by A. Zhitnitsky

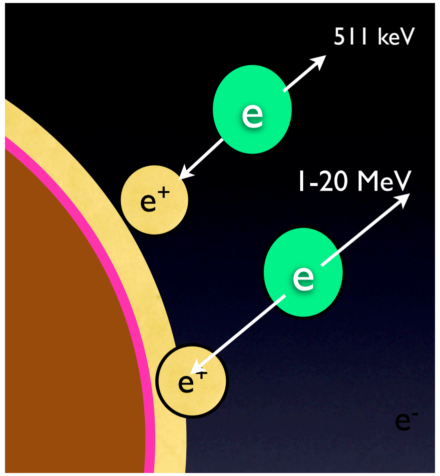


Adopted from the talk by A. Zhitnitsky

- This source of radiation produces very specific 511 keV gamma-photons [D. H. Oaknin and A. Zhitnitsky, Phys. Rev. D 71, 023519 (2005), M. M. Forbes, K. Lawson, A. R. Zhitnitsky, Phys. Rev. D 82, 083510 (2010)]
- Compare with observations of INTEGRAL satellite, B. Teegarden et al., Astrophys. J. 621, 296 (2005).

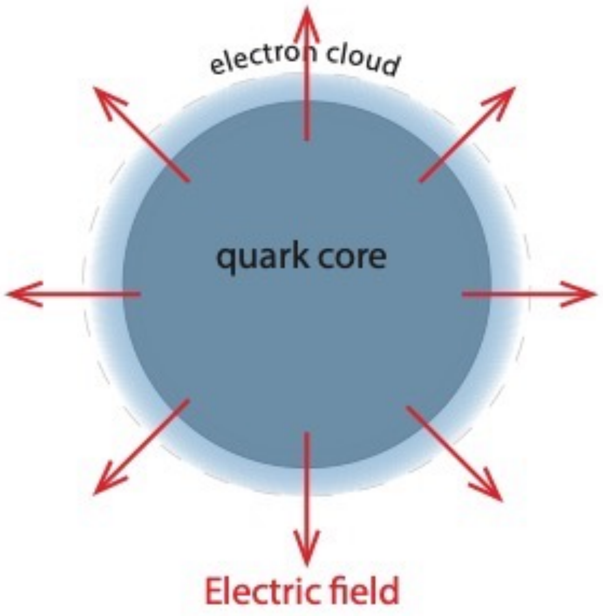
Our goal

- To accurately consider the electron-positron annihilations in collisions of visible matter with anti-quark nuggets
- To study the radiation in such collisions and compare it with satellite observations of the center of our galaxy
- We consider Quark Nugget model which includes AQN as a particular case

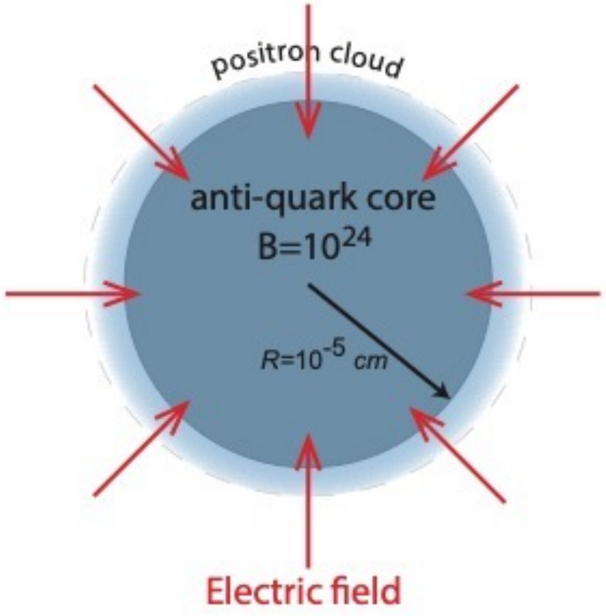


Quark Nugget model

Quark Nugget



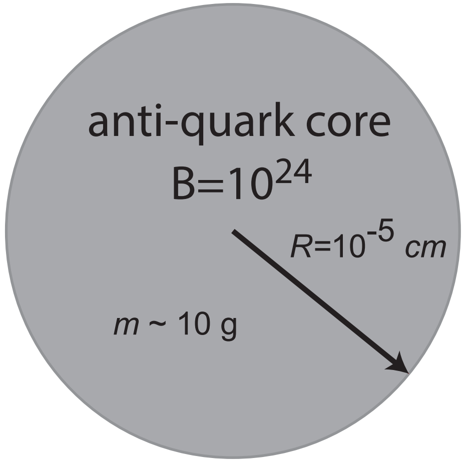
Anti-Quark Nugget



- Anti-QN are 1.5 more abundant
- Consist of anti-matter
- May be detected when collide with visible matter

(anti)Quark core

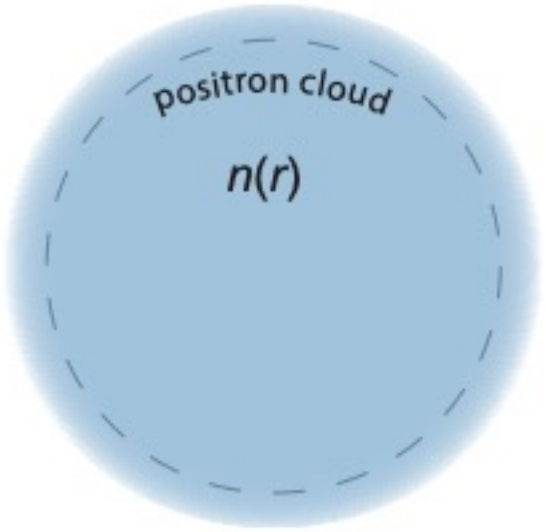
- May be considered as a ball or characteristic radius $R=10^{-5}$ cm
- Characteristic mass is of order 10 g
- Density $n_0(r)$ is 1.5-3 times nuclear matter density
- Baryonic charge varies $10^{23} – 10^{28}$. We adapt $B=10^{24}$.
- Electric charge of quarks Z is unknown. It depends on the equation of state of the quark matter which is not known. If the quarks are in the color-flavor-locked phase, the electric charge is localized at the boundary, $Z=0.3\ B^{2/3}$. If the quarks are in the 2CS phase, $Z \sim 0.001$ B.
- Huge negative charge of anti-quark matter attracts positrons => positron cloud



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

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

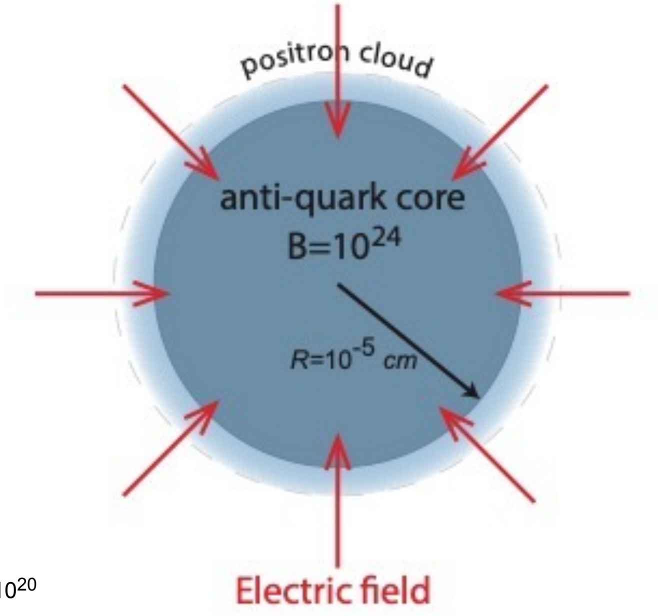


- The positron density, together with the quark core charge density, create the electric field

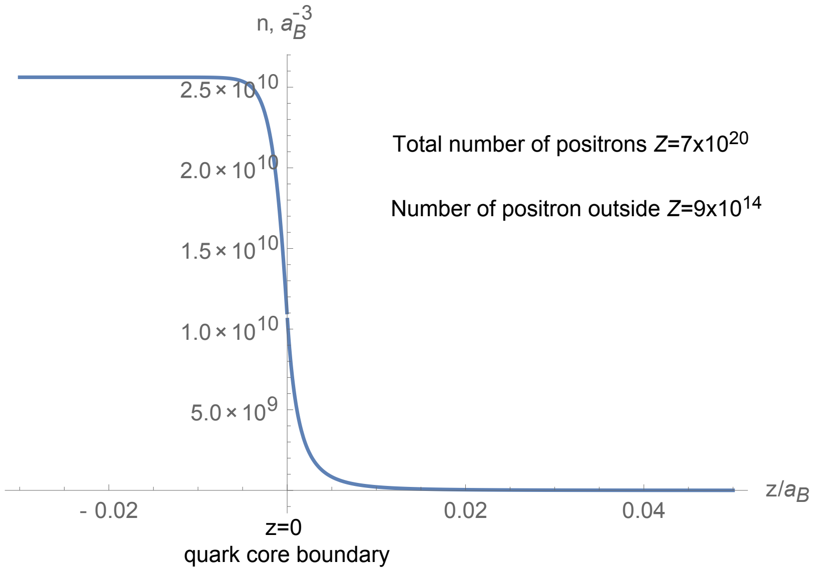
$$E = -\nabla\varphi$$

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

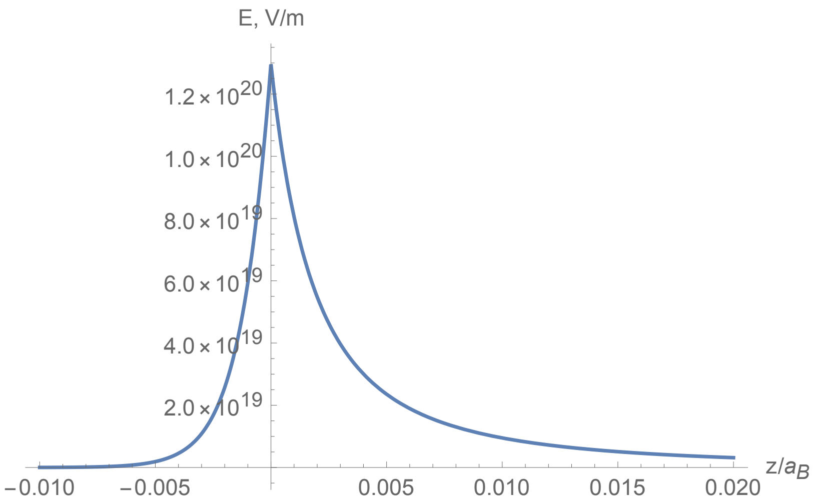
Properties of positron cloud



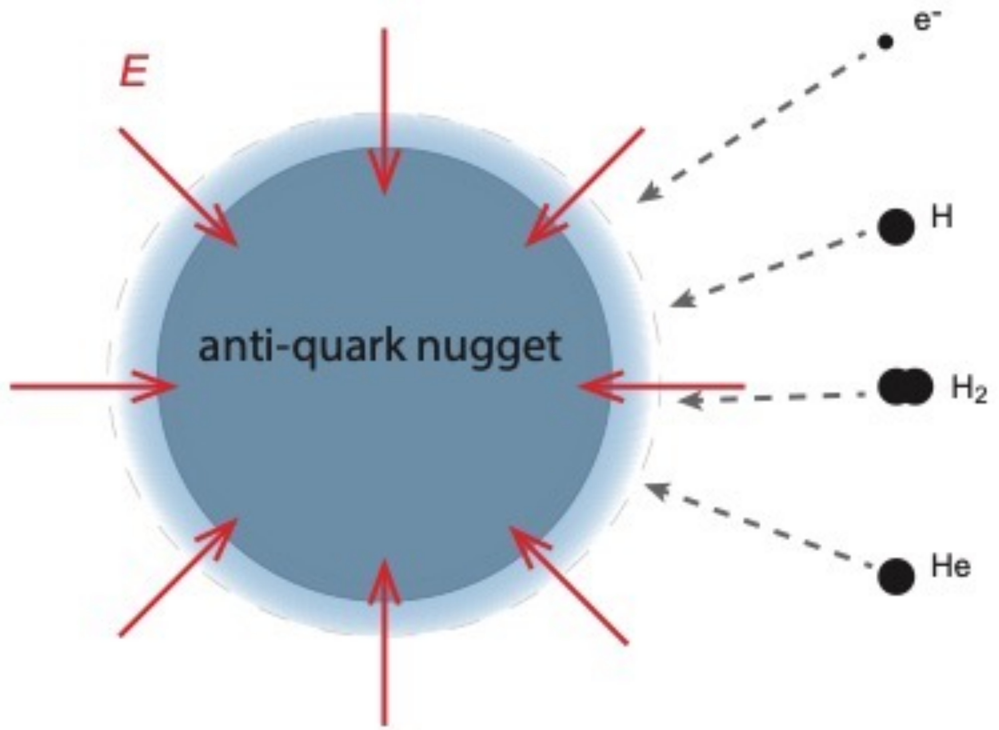
Charge density



Electric field near quark core boundary



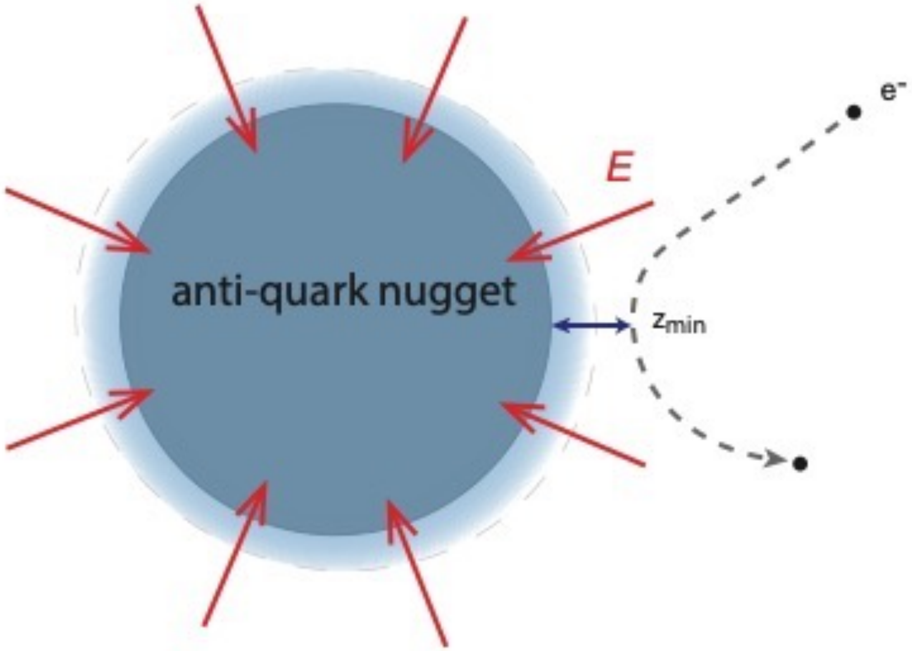
Matter scattering off the Quark Nuggets



- Assume that these particles have characteristic velocities $v=10^{-3}$ c (virial velocities in interstellar medium)

- **Problem:** probability of electron-positron annihilation with emission of 511 keV photons?

Electron scattering



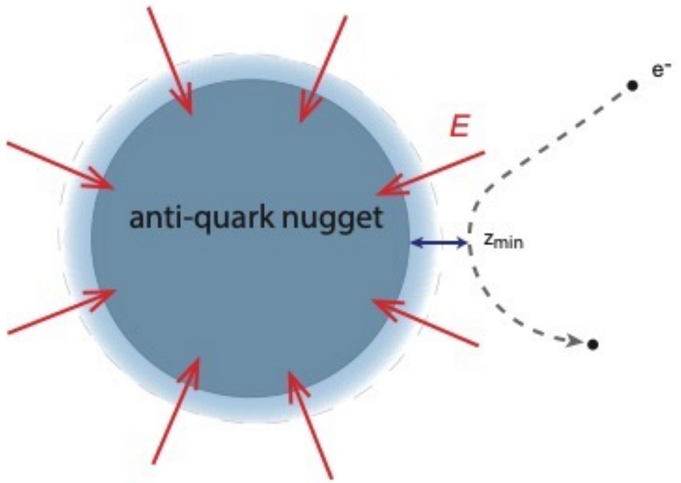
- Electron is repelled by the QN electric field
- Debye screening should be taken into account
- Electron has effective charge when moving through the positron cloud

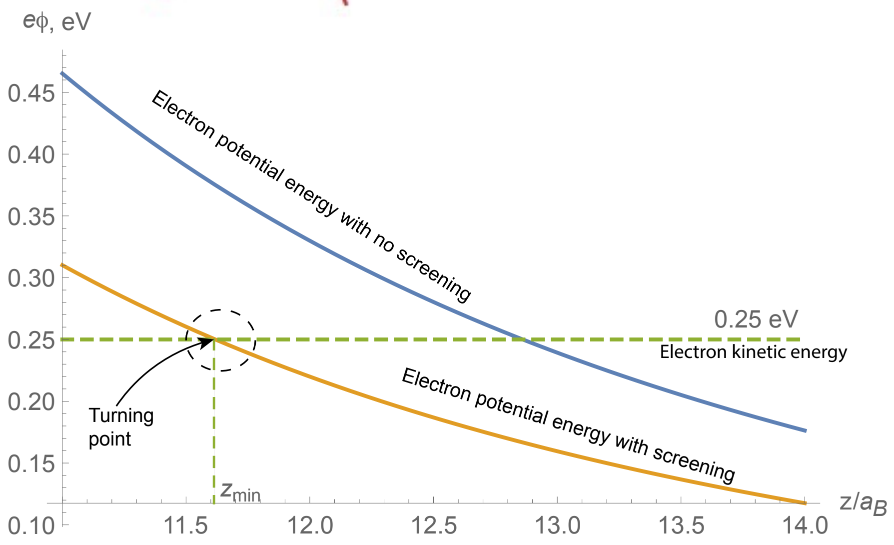
$$q_{\text{eff}} = \frac{1}{3}\frac{e\varphi + 2m}{e\varphi + m}$$

- In the non-relativistic case (far from QN core) $e\varphi \ll m$

$$q_{\text{eff}} = \frac{2}{3}$$

Electron scattering





- Electron can approach QN core to characteristic distance z_{min}=11-12 a_B
- Direct annihilation cross section

$$\sigma \approx \pi r_e^2 c/v$$

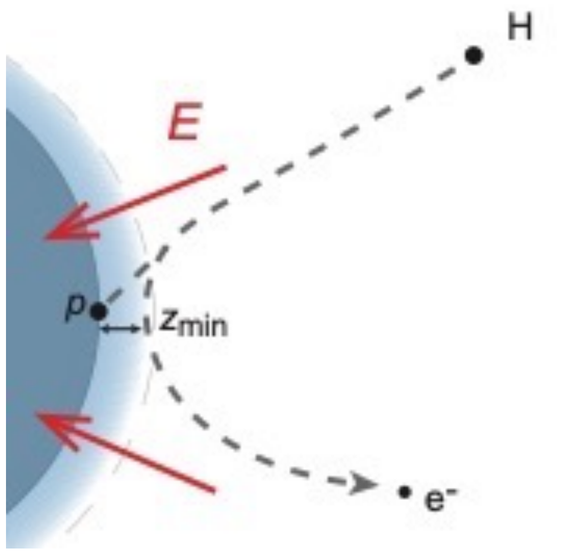
- Annihilation probability

$$P = 1 - \exp\left[-2\sigma \int_{z_{\min}}^{\infty} n(x)dx\right]$$

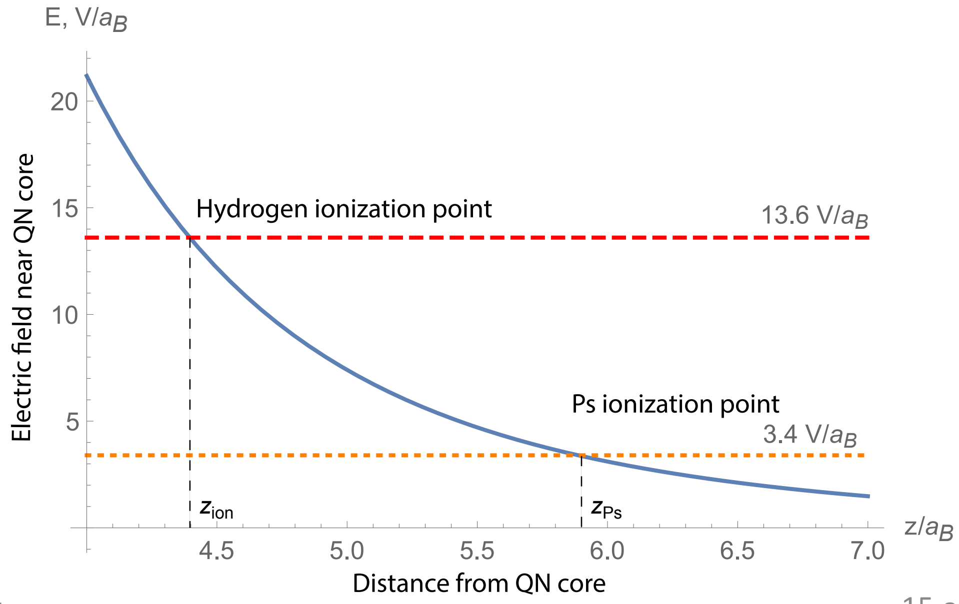
$$P \approx 10^{-9}$$

- Thus, this process plays minor role

Hydrogen & helium scattering



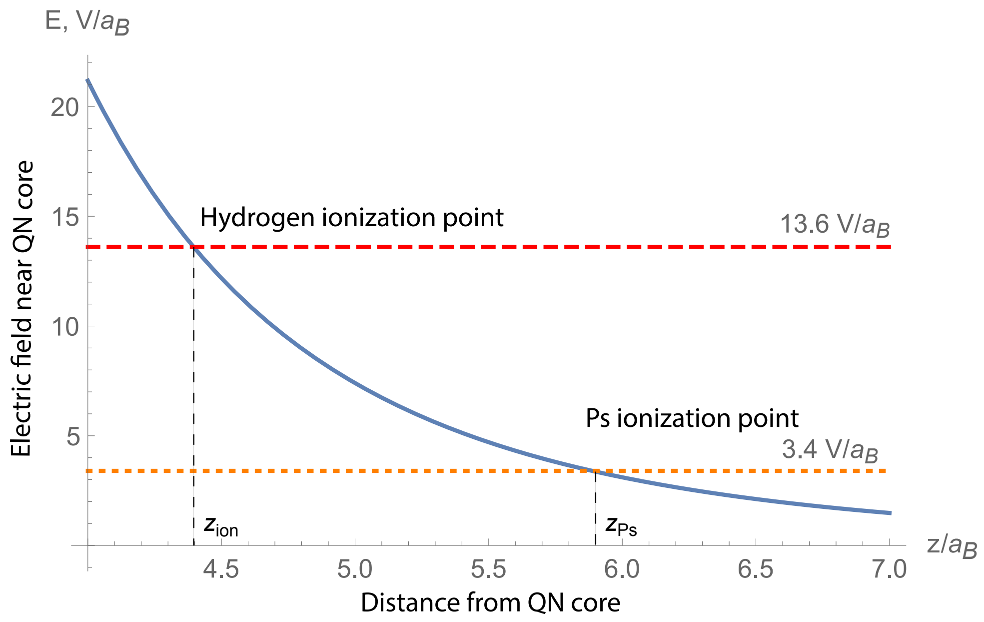
- H, H_2, He or He^+ can approach quark core up to z_{ion}=3-7 a_B.
- Neutral atoms and molecules are attracted due to polarization potential
- Electric field ionizes these atoms and molecules, E=2-30 V/a_B
- Proton falls on the quark core while the electron escapes

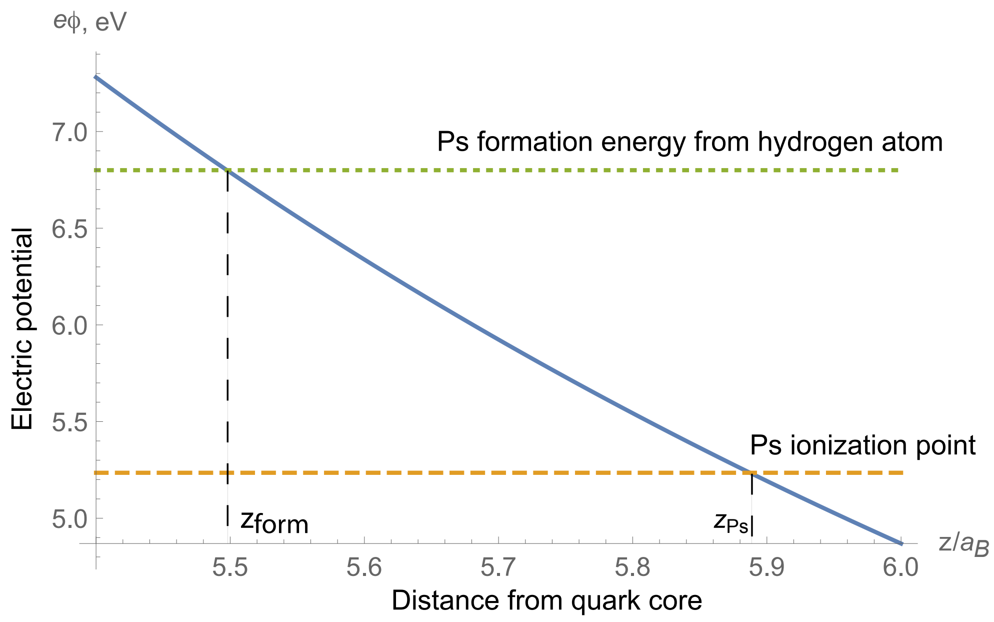


Ps formation in Hydrogen & helium scattering

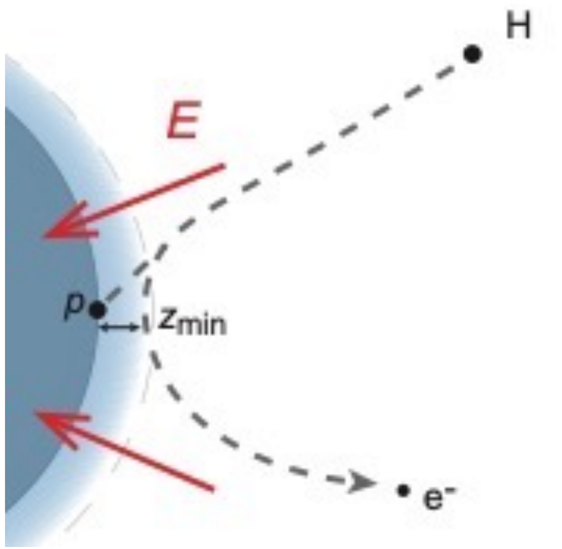
- Positronium is NOT stable at such a strong electric field. In addition, there is strong Pauli blocking at this high positron density. Positronium cannot be formed

$$z_{\text{formation}} < z_{\text{Ps decay}}$$





Direct positron annihilation in Hydrogen & helium



- Cross section of direct positron annihilation on atoms $\sigma \approx Z_{\text{eff}} \pi r_e^2, 4 < Z_{\text{eff}} < 15$
- Probability of direct electron-positron annihilation is

$$P = 1 - \exp\left[-2\sigma \int_{z_{min}}^{\infty} n(x)dx\right]$$

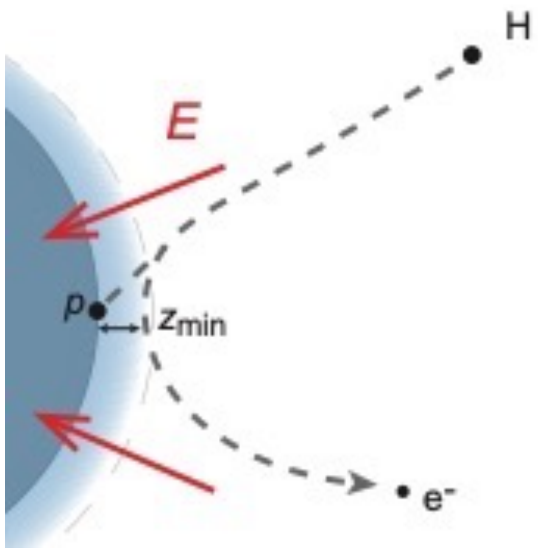
$P \approx 10^{-5}$

- Only photons with 511 keV energy are emitted.
- NO photons with energies 1-20 MeV from electron-positron annihilation since there are no electrons at small z.

Our conclusions:

- Positronium atoms cannot be created in the positron cloud in the vicinity of quark core
- Electron-positron annihilation in the positron cloud cannot produce MeV-energy photons. MeV-range photons may be emitted as the bremsstrahlung radiation of proton falling on the quark core and its annihilation
- A different mechanism of emission of 511 keV photons should be explored

Alternative mechanism



- Proton collides with the quark core and annihilates
- Charge of quark core is reduced
- Temperature of positron cloud rises
- Outer positrons can “evaporate”
- Thus, (anti)quark nuggets are sources of positrons in galaxy center
- These positrons annihilate with atoms and molecules and produce 511 keV photons. Flux of these photons may be compared with INTEGRAL satellite observations.

Summary

- In collisions of Quark Nuggets with atoms and molecules the positronium cannot be created in the positron cloud close to quark core.
- Only direct electron-positron annihilation in atoms is possible, the probability is of order $P = 10^{-5}$.
- Electron-positron and positron-atom collisions cannot produce photons with energies in the MeV range. However, such photons may be produced by bremsstrahlung and proton annihilation.
- However, proton can annihilate in the collision with the quark core. This reduces quark core charge and raises the temperature of the positron gas. This makes the positrons to evaporate.
- Thus, QNs may be a source of positrons which create the excess of 511 keV photons observed in the center of the galaxy.
- More details in forthcoming preprint arXiv:2106.xxxxx.