Quark Nuggets in SK Terry 18/11/16

- Possible dark matter candidates.

- Postulated to freeze out of quark gluon plasma in early universe (E. Witten, Farhi and Jaffe, De Rujula and Glashow).

- They showed that stable states of quark matter could exist with large numbers of quarks and densities of order nuclear density.

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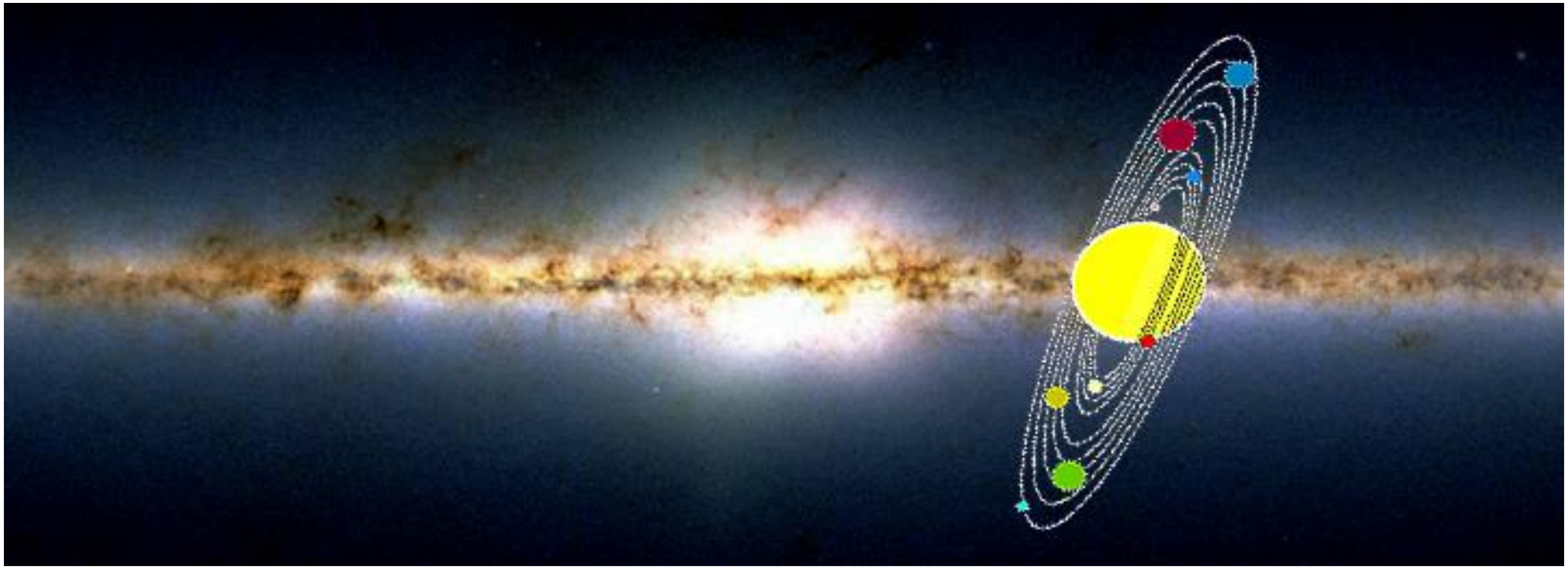
- Masses up to 10^{57}nucleon masses $\sim 10\ M_{\odot}$

Motion of solar system in Galaxy.



Solar System Motion at 230 km/s

N. Hemisphere pointing in
this direction.

Flux of quark nuggets assuming all dark matter is made up of them.

Current local density of dark matter is ~ 0.3 GeV/cm^3 $= 5.4\ 10^{-22}$ kgm/m^3.

So density of QNs is $5.4\ 10^{-22}/M_{QN}$ m^{-3} (mass in Kgm)

So flux hitting Earth is $230000 \cos\theta \frac{5.4\ 10^{-22}}{M_{QN}}$ m^{-2} sec^{-1}

$\sim 10^{-16}/M_{QN}$ m^{-2} sec^{-1} taking $\cos\theta \sim 1$

$\sim 3\ 10^{-7}/M_{QN}$ per year per 100 m^2 (assumed sensitive area of SK).

(where M_{QN} is in Kgm and θ = angle between tangential plane at detector and direction of travel of solar system)

Hence SK is sensitive to masses up to ~10^{-7} kgm.

Magnetic Fields of QNs

(T. Tatsumi PLB 489 (2000) 280)

For quark densities below a critical value Tatsumi believes that QNs of radius r_q with quark density is n_q are ferromagnetic with a huge magnetic moment M_q

$$M_q = \mu_q \cdot (4\pi/3 \cdot r_q^3) n_q$$

Here μ_q= quark magnetic moment which is ~ 1 nuclear magneton.

Putting in the numbers shows that $r_q = (\frac{3}{4\pi}\frac{M_q}{\rho_q})^{\frac{1}{3}} = 6.2\ 10^{-7}\ {M_q}^{1/3}$ m

for $\rho_q = 10^{18}$kgm/m^3 (i.e. nuclear density expected for QN)

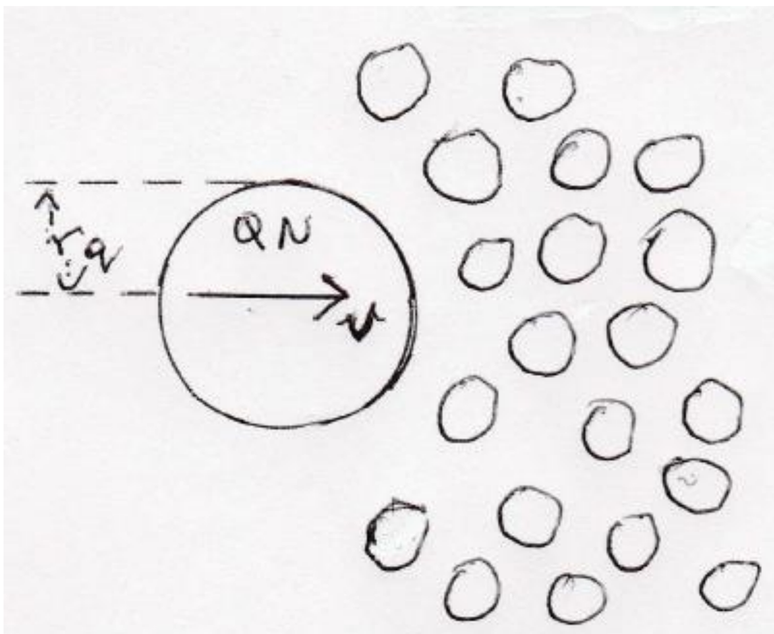
The magnetic field on the surface of a QN $= M_q \mu_0 / 4\pi r_q^3 \sim 10^{12}$T

Tatsumi thinks that nuclear density is below the critical value and will have this large magnetic field. BUT his parameters are guessed. So it is possible that QNs without this large magnetic field could exist.

dE/dx of QNs

QN radius r_q travelling at 230 km/s (β$\sim 0.8\ 10^{-3}$) is too slow to ionize.

Medium of density ρ_w

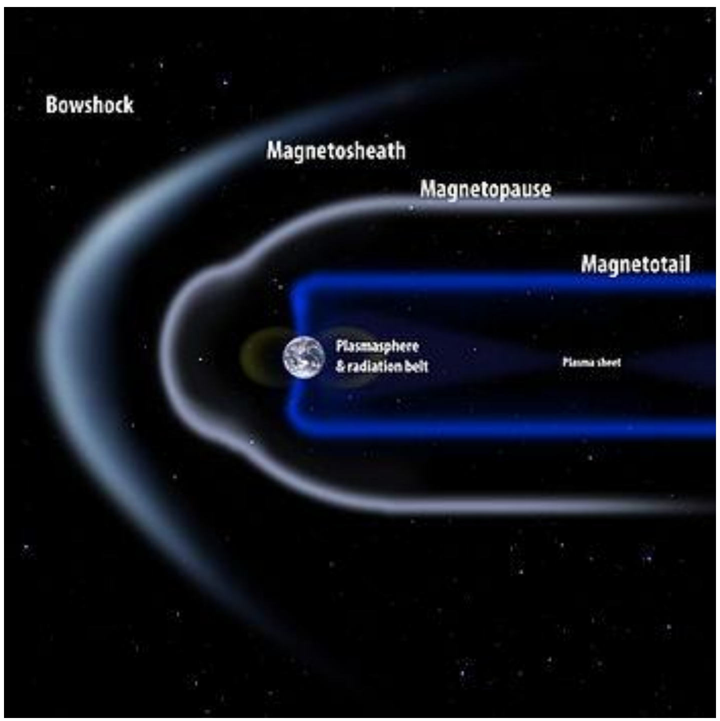


Assume molecules bounce off in random direction with isotropic angular distribution.

From geometry Force = $\frac{dE}{dx} = N_{avog} M_{proton} v^2 \rho_w \pi r^2$ where r is radius of influence of QN (NB *r* is not necessarily the radius of the QN r_q). (NB $N_{avog} M_{proton} = 1$ in SI or cgs units)

3 cases to consider

1. QN without magnetic field and $r_q \gg$ molecular radius
   Radius of influence of the QN is then the radius of the QN, r_q.
2. QN without magnetic field and $r_q \ll$ molecular diameter.
   Radius of influence then becomes the molecular radius.
3. QN with strong magnetic field. Radius of influence is the radius of the magnetopause.



Radius of magnetopause is from plasma physics–

$$r_{MP} = \left(\frac{9B^2 M_q^2}{16\pi^2 \rho_{QN}^2 \mu_0 v^2 \rho_w}\right)^{1/6}$$

NB $r_{MP} \gg r_q$

So QN with strong magnetic field have much larger values of dE/dx i.e. shorter ranges.

Note that r_{MP} is about 3 orders of magnitude bigger than r_q so the value of dE/dx for QNs with a big magnetic field is 6 orders of magnitude bigger than those without.

QNs with large magnetic field will stop in the rock above any underground experiment.

Hence Super Kamiokande is only sensitive to QNs without a magnetic field.

Therefore only treat non-ferromagnetic QNs in what follows.

Non Ferromagnetic QNs

$\frac{dE}{dx} = N_{avog} M_{proton} v^2 \rho_w \pi r_q^2$ for $M_{QN} > 10^{-12}$ Kgm (10^{15}GeV)

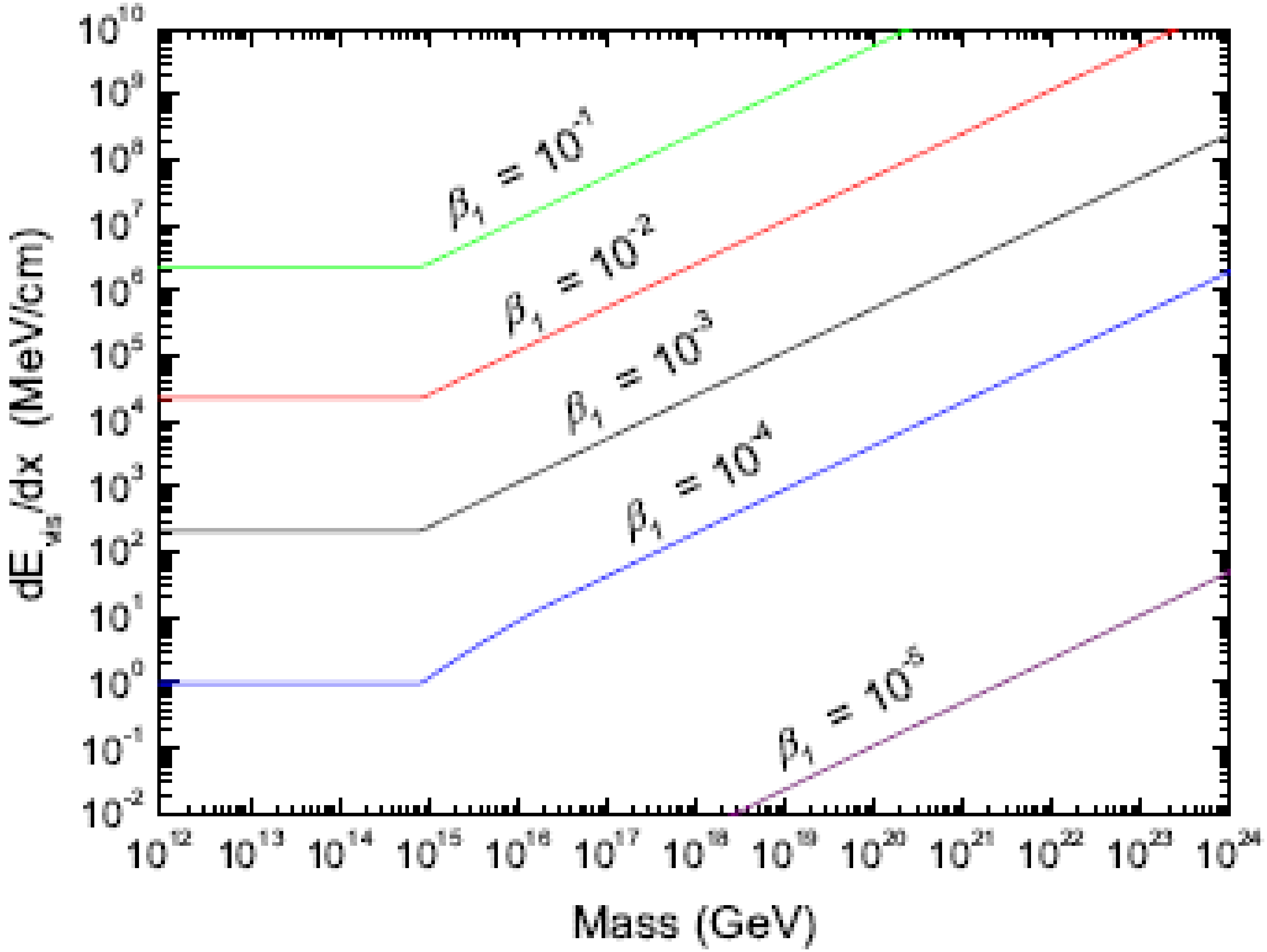
$\frac{dE}{dx} = N_{avog} M_{proton} v^2 \rho_w \pi r_{mol}^2$ for $M_{QN} < 10^{-12}$ Kgm (10^{15}GeV)

(r_q is radius of QN or $r_{mol}$the molecule when $r_q < r_{mol}$)

This energy heats the liquid locally over a column of radius of order the radius of influence which is small i.e. to temperatures of order 10^7K.

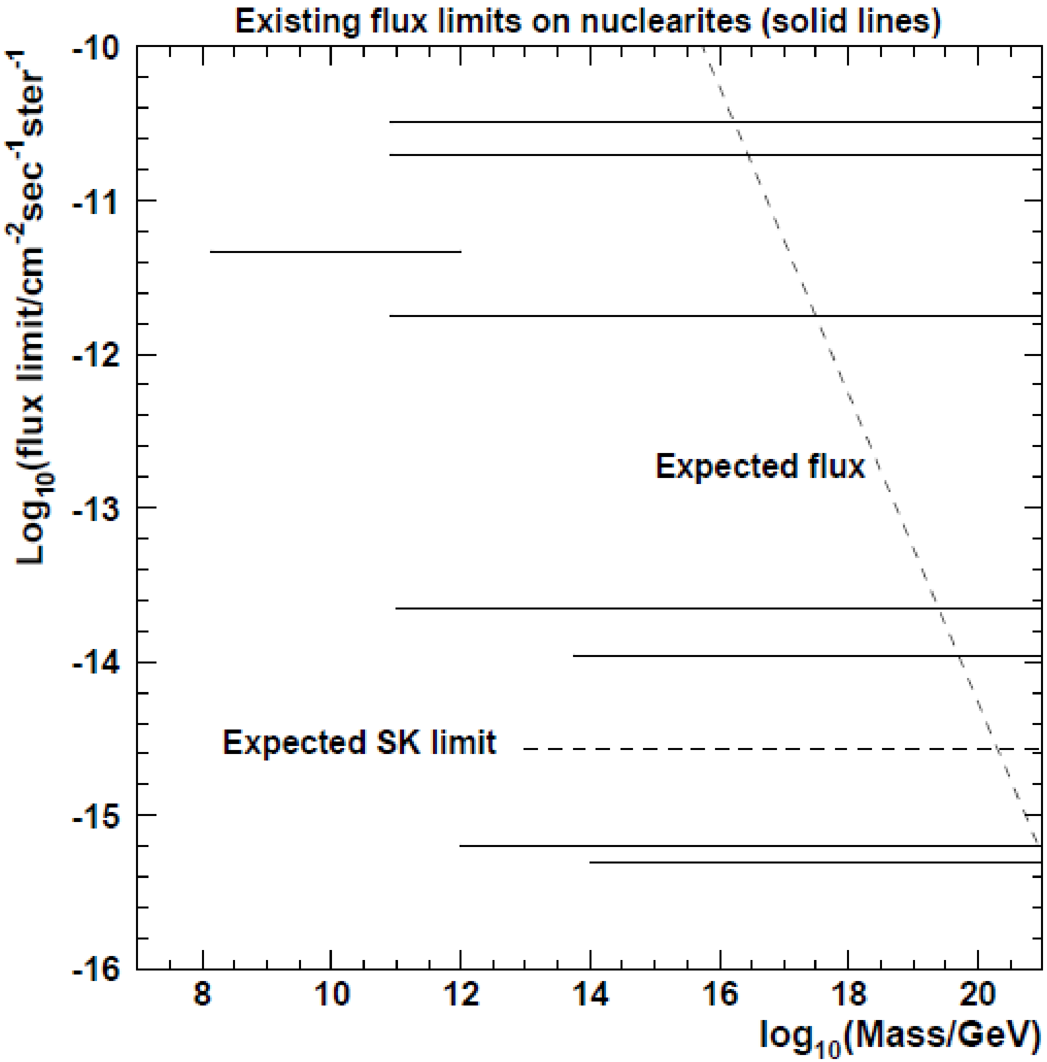
Strong thermal radiation (conduction of heat away is small).

The column glows for times of order tens of nsec finally dying out after of order 1 msec.



Plot from Wan-Lei Guo et al 1611.00166 (proposal to do this in Juno).

NB energy radiated in the visible region where PM tubes are sensitive at the rate of millions of photons per cm of track.



Flux expected if all dark matter is QNs

Expected flux limit for a 1 year search in Super K assuming 10 by 10 m^2 sensitive area.

Lower mass limit set by QNs ranging out in rock overburden.

Conclusions

Could make a search in Super Kamiokande for events in which large numbers of PM tubes light up for a time which dies away in a time of order 1 msec – probably saturating the ADCs.

Are there any backgrounds which could fake such a signal ?

Is it worth doing ? Probably not given that we cannot better present limits, which already say that only a small fraction of dark matter can come from QNs.

But there re no limits for ferromagnetic QNs – needs a surface search to avoid them stopping before they reach an undergraound experiment. Problem for a surface experiment is dE/dx is so large QNs stop in the atmosphere for masses < 10^{24} GeV.

Better in space – AMS, Fermi, Pamela satellite experiments.