Detection of nuclearites in JUNO

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chaired by Zhengguo Zhao (USTC), Xiangdong Ji (Shanghai Jiaotong University), Haijun Yang (Shanghai Jiao Tong University)

from Tuesday, June 19, 2018 at 14:00 to Sunday, June 24, 2018 at 22:00 (Asia/Shanghai)

Outline

- What is the Nuclearites
- How to detect Nuclearites
- JUNO sensitivities to Nuclearites
- Summary

(1) What is the Nuclearites

Strange Quark Matter (SQM):

- ✓ SQM is a hypothetical strongly interacting matter composed of roughly equal numbers of u, d, **s** quarks and a small amount of electrons.
- ✓ 1971, A. Bodmer firstly discussed the SQM, and indicated that SQM is possibly the true ground state of QCD and absolutely stable.
- ✓ 1984, E. Witten argued that SQM is absolutely stable in a large parameter space of QCD theory, and SQM objects have baryon number *A* from a few to 10^57 (neutron stars).
- ✓ 1984, E. Farhi and R. Jaffe got the similar conclusions through the careful calculation in MIT bag and Fermi gas models, and SQM density is about $\boldsymbol{\rho_N = 3.6 \times 10^{14}\,\mathrm{g/cm^3}}$

Nuclearites

SQM classification:

- $A < 10^7$ Strangelet (奇异子)
- $A > 10^7$ Nuclearites (奇异核素) Rujula, Glashow, Nature 1984
- $A \sim 10^{57}$ Strange Star (奇异星)

Nuclearites can be created by：

- hadronization process in the early universe, as Dark Matter
- collision of binary compact stars
- type II supernovae driven by deconfinement phase transition

Nuclearites mass, radius and velocity:

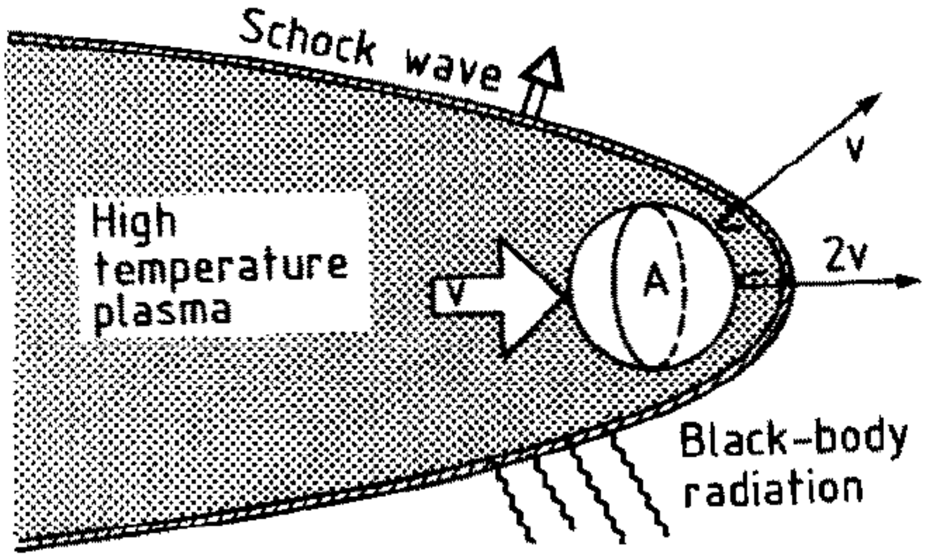
$10^{12}\ \text{GeV} \leq M \leq 10^{24}\ \text{GeV} \rightarrow 0.1\text{Å} \leq R \leq 1000\text{Å}$

$\rho_N = 3.6 \times 10^{14} \text{g/cm}^3$ Atomic radius unit :1 Å = 10^{-10}m

$10^{-5} \leq \beta \leq 10^{-1}$, typical $\beta \sim 10^{-3}$ (galaxy velocity) very slow

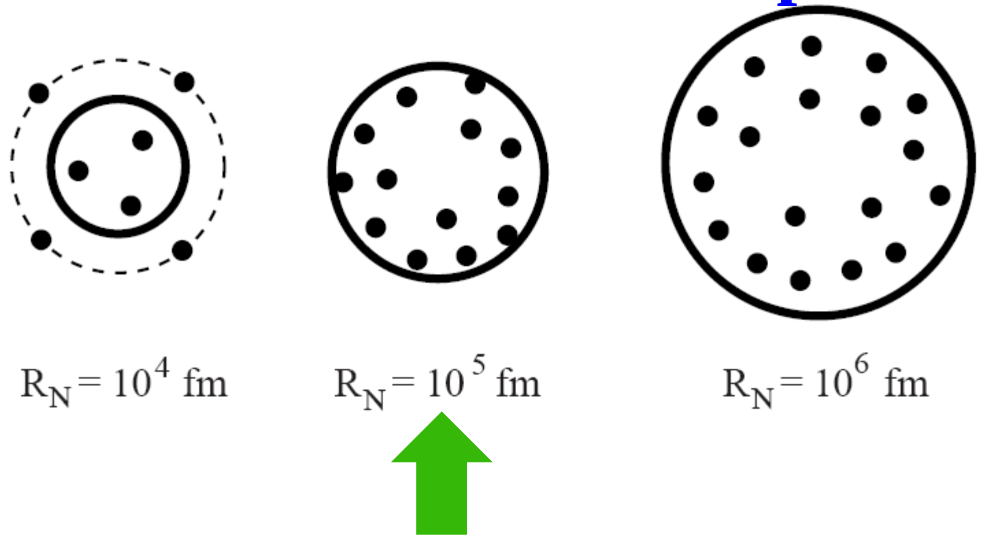
Nuclearite interaction

Interaction picture:



Elastic or quasielastic collisions and electromagnetic interactions

Core and electron atmosphere:



$$\boldsymbol{M = 8.4 \times 10^{14}\ \mathrm{GeV}}$$
$$\boldsymbol{\rightarrow R = 10^5\ \mathrm{fm} = 1\text{Å}}$$

Energy loss rate:

$$\frac{dE}{dx} = -\sigma\rho\beta^2 \qquad \sigma = \begin{cases} \pi R_0^2 = \pi(3M/4\pi\rho_N)^{2/3}; & M \geq 8.4 \times 10^{14}\ \mathrm{GeV} \\ \pi\text{Å}^2 = \pi \times 10^{-16}\ \mathrm{cm}^2; & M < 8.4 \times 10^{14}\ \mathrm{GeV} \end{cases}$$

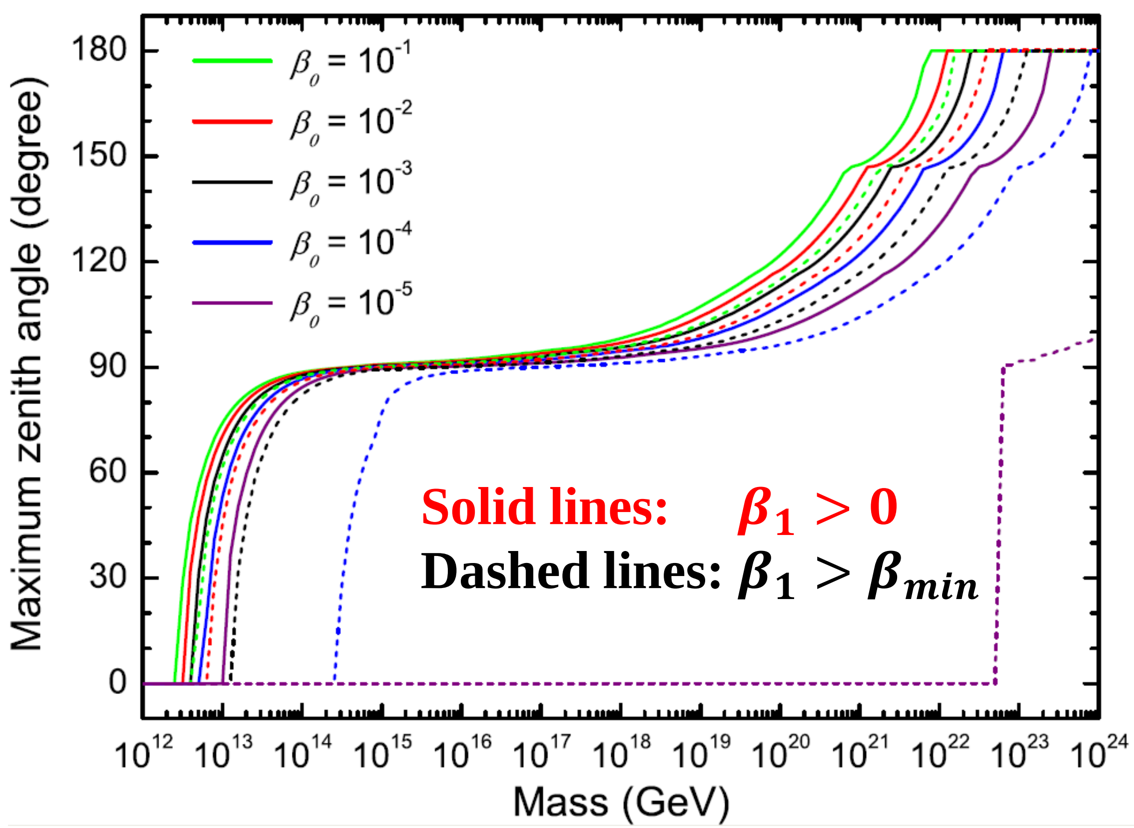
(2) How to detect Nuclearites

Energy loss rate:

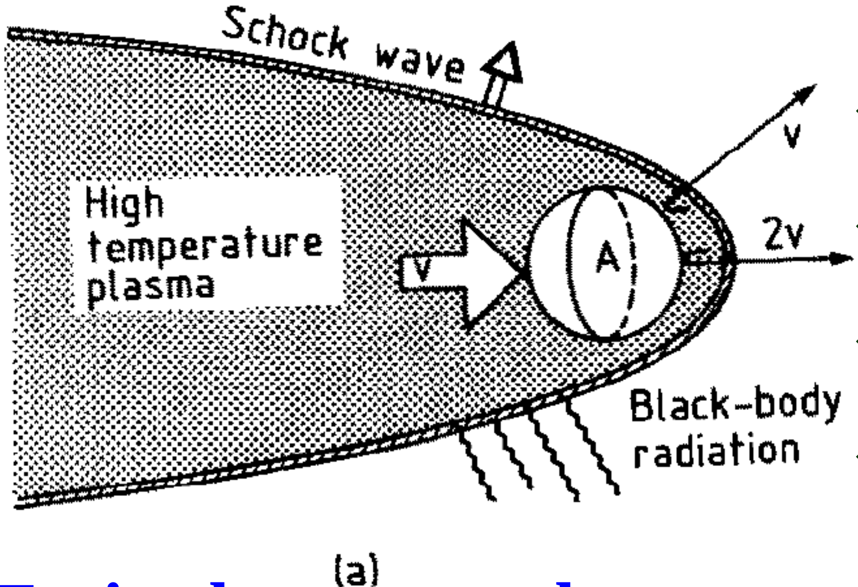
$$\frac{dE}{dx} = -\sigma\rho\beta^2 \qquad \sigma = \begin{cases} \pi R_0^2 = \pi(3M/4\pi\rho_N)^{2/3}; & M \geq 8.4\times10^{14}\ \text{GeV} \\ \pi \text{Å}^2 = \pi\times10^{-16}\ \text{cm}^2; & M < 8.4\times10^{14}\ \text{GeV} \end{cases}$$

Three parameters:

1. **Velocity β:**
   Initial velocity on ground β_0
   Local velocity in JUNO β_1
2. **Mass M**
   $10^{12}\ \text{GeV} \leq M \leq 10^{24}\ \text{GeV}$
3. **Medium density**
   Earth→ PREM model
   LS → 0.859 g/cm^3



Light yield of Nuclearite in JUNO



- Collisions with the ambient atoms
- Further collisions → plasma
- Expanding cylindrical shockwave
- photons from black-body radiation

Emit photon numbers or energy dE_γ/dx ($\omega^2 \to \omega^3$):

$$\frac{dN_\gamma}{dx} = \int d\omega \int dt 2\pi R(t) \frac{dp}{d\omega da}\frac{1}{\omega} = \frac{8^{\frac{1}{4}}}{2\pi}\sqrt{\beta_1 R_0}\int d\omega \int dt t^{\frac{1}{2}}\omega^2 \frac{1}{e^{\omega/T}-1}$$

$$R^2(t) = \sqrt{8}\beta_1 t R_0$$

Radius evolution

$$\frac{dp}{d\omega da} = \frac{\hbar\omega^3}{4\pi^2 c^2}\frac{1}{e^{\hbar\omega/kT}-1}$$

Power spectrum

$\omega = 2\pi c/\lambda$

$$T(t) = m\beta_1 R_0/(\sqrt{8}nt)$$

Temperature evolution

JUNO LAB: $C_6H_5C_kH_{2k+1}$

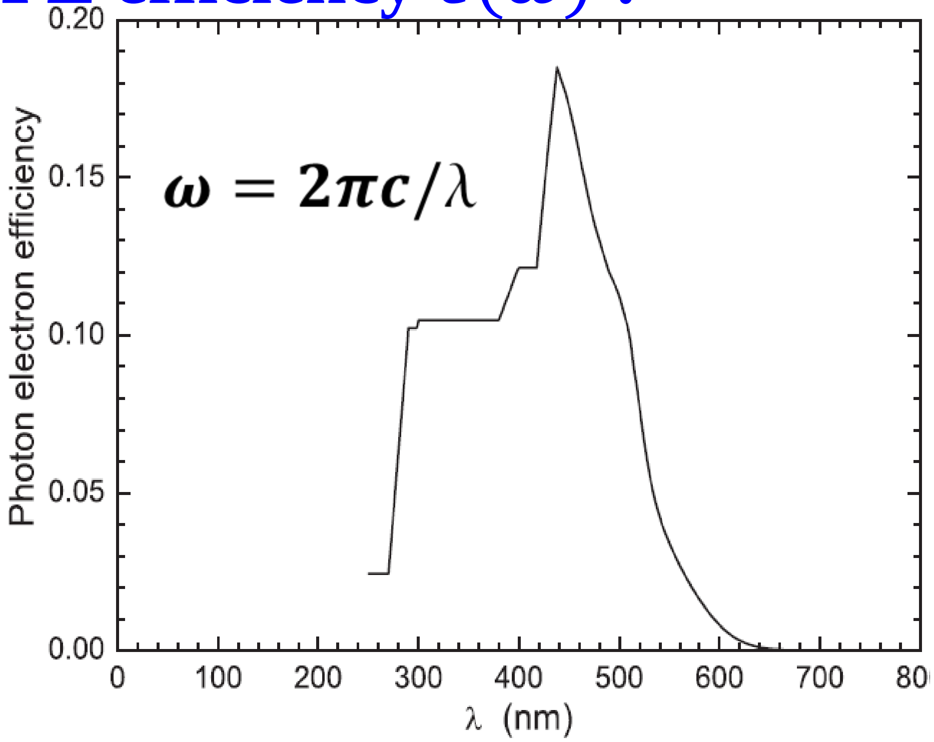
k = 12 → $m = 246, n = 48$

Visible energy of Nuclearites

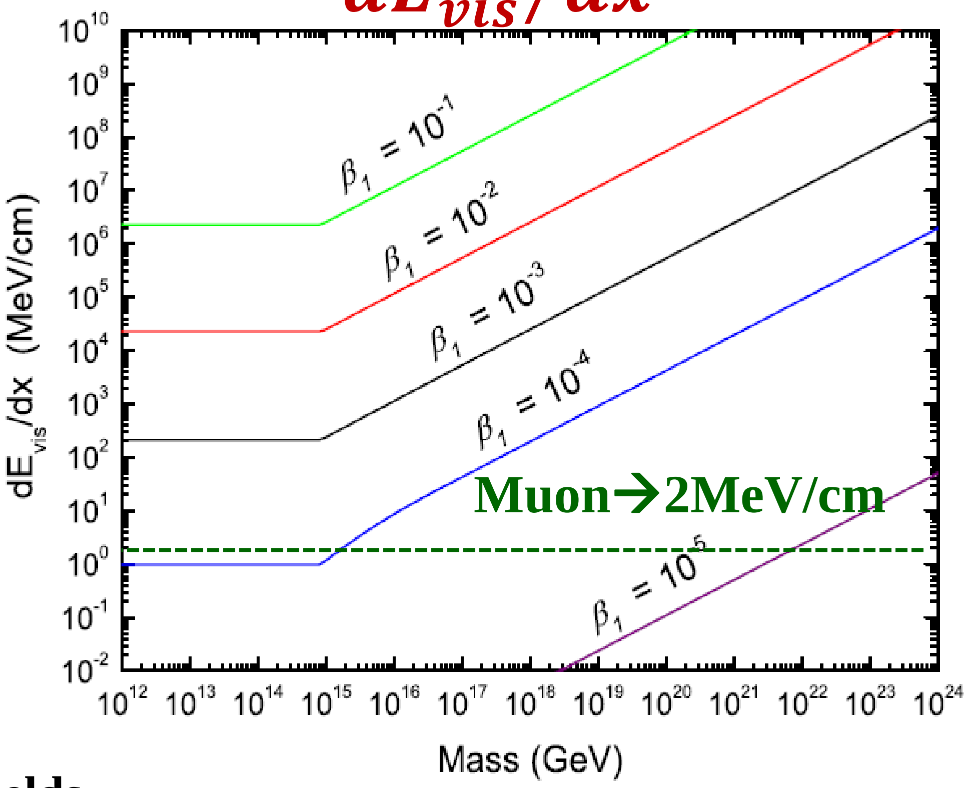
Absorption, reemission, Rayleigh scattering → dE_{vis}/dx

$$\frac{dE_{\rm vis}}{dx} = \frac{\rm MeV}{1200{\rm pe}} \frac{8^{\frac{1}{4}}}{2\pi} \sqrt{\beta_1 R_0} \int d\omega \omega^2 \epsilon(\omega) \int_{t_{\rm min}}^{\infty} dt t^{\frac{1}{2}} \frac{1}{e^{\omega/T} - 1}$$

PE efficiency $\epsilon(\omega)$:



dE_{vis}/dx



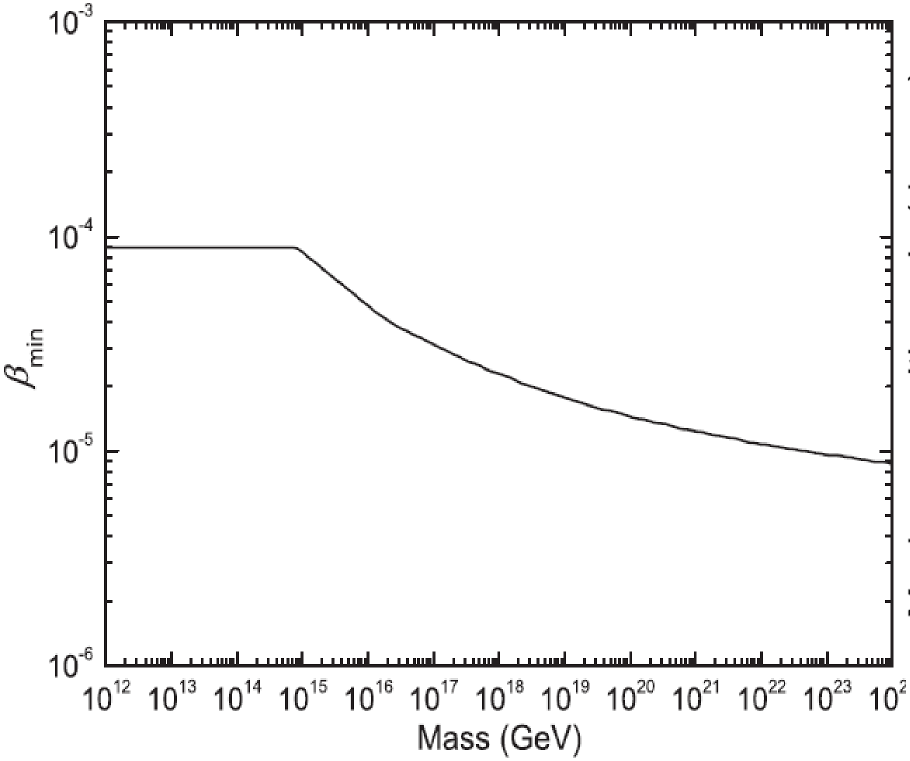
LAB, PPO, bis-MSB fluorescence quantum yields, PMT QE, photocathode coverage, reemitted photons

(3) JUNO sensitivities to Nuclearites

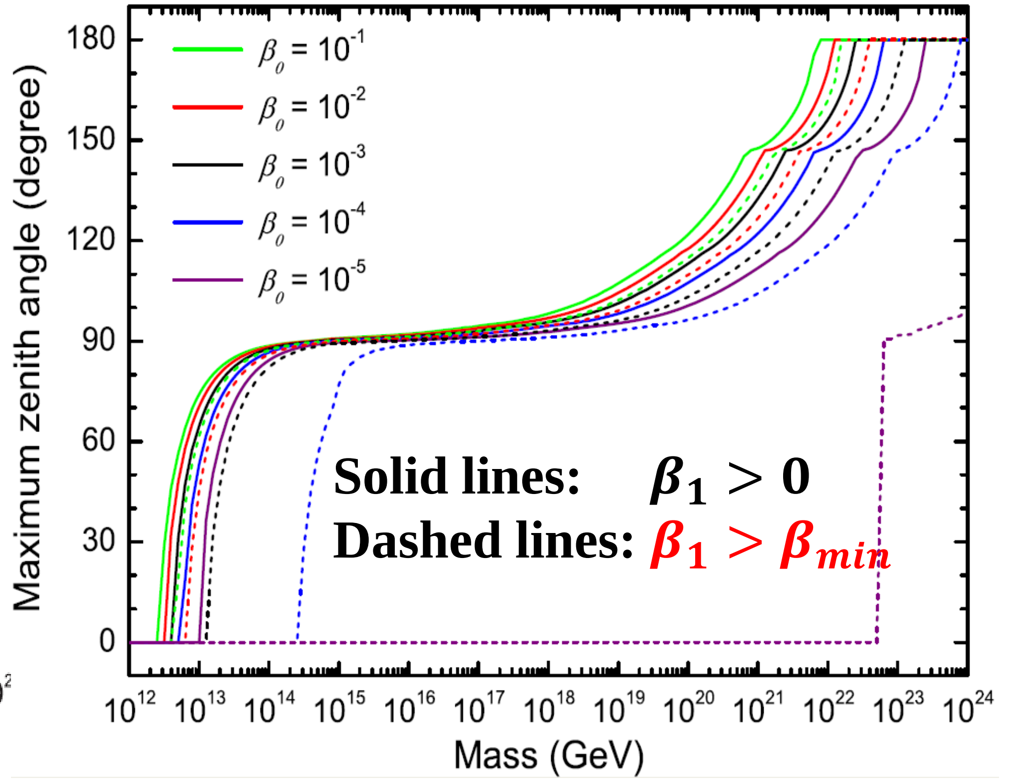
Assume trigger threshold is 0.5MeV within 300ns window:

$$\beta_1 \times 300\ \text{ns} \times \frac{dE_{\text{vis}}}{dx} \geq 0.5\ \text{MeV}$$

Min local velocity β_{min}:



Max zenith angle:



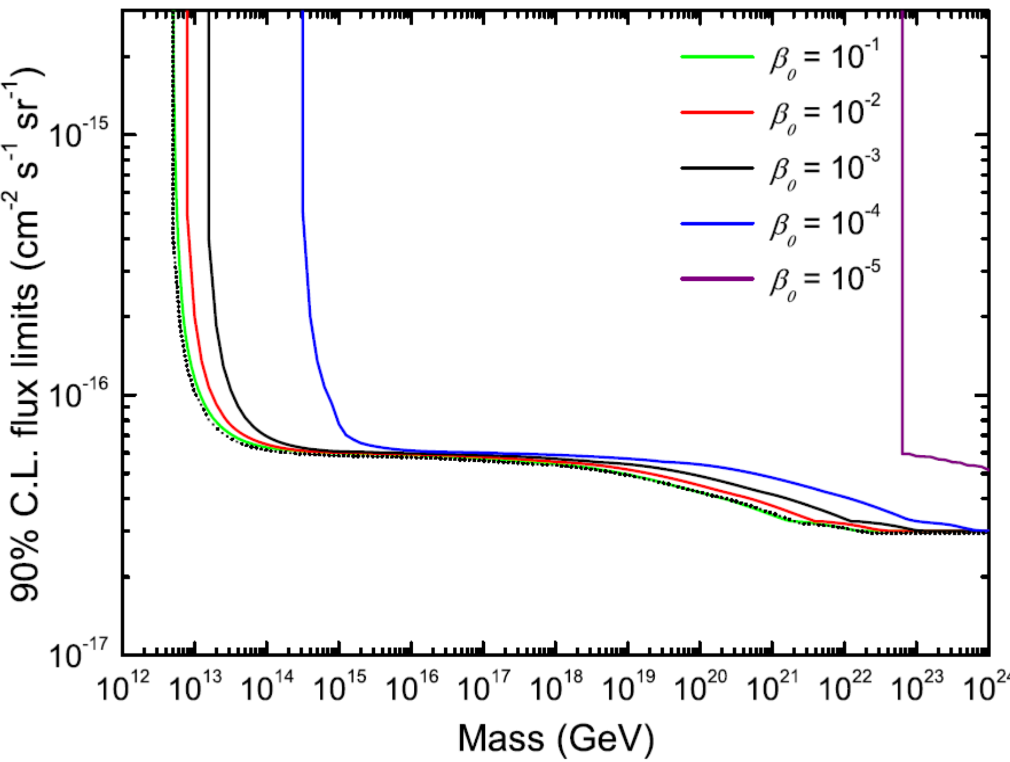
JUNO sensitivities

Expected Nuclearite numbers:

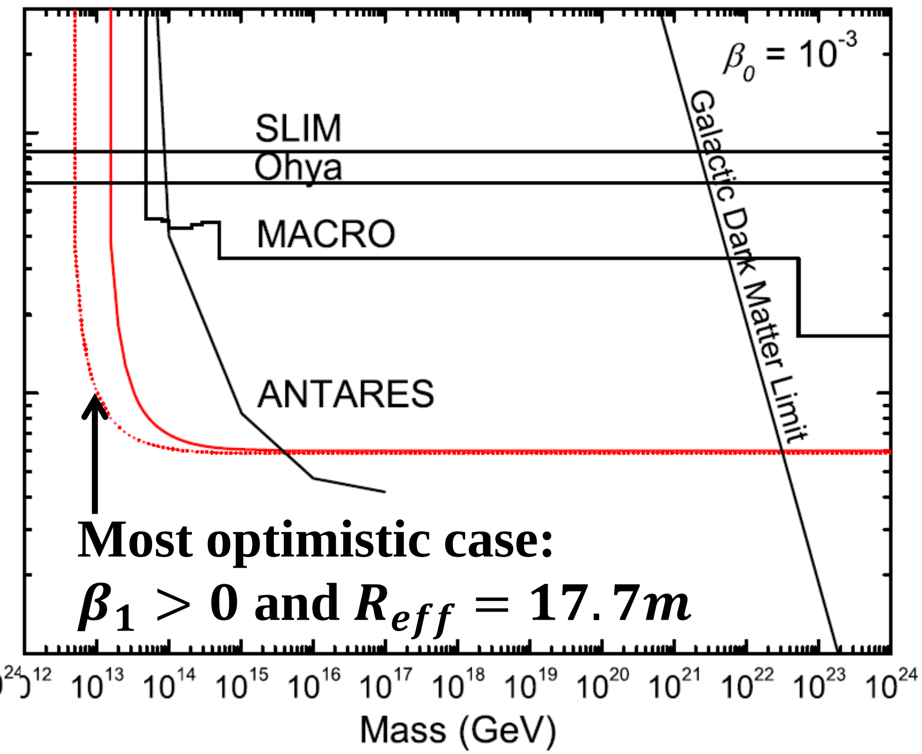
$$N_S = 2\pi(1 - \cos\theta_{\text{max}})\phi T_{\text{run}}\pi R_{\text{eff}}^2$$

$$L > 5\,m \rightarrow R_{eff} = 17.52m$$

JUNO Sensitivities (20 years and $N_{bg} = 0$):



All direction Nuclearites



Downgoing Nuclearites

Summary

- **Nuclearites is a hypothetical strongly interacting matter with a slow velocity and can produce a large visible energy in JUNO through black-body radiation.**

- **JUNO can detect Nuclearites and give the most stringent limits for 1.6×10^{13} GeV $\le M \le 4.0 \times 10^{15}$ GeV and $\beta = 10^{-3}$.**

- **If a Nuclearite is really detected, we can't correctly reconstruct the nuclearite mass because of the incomplete $\epsilon(\lambda)(\lambda < 250\text{nm})$, and JUNO can only give the mass lower bound for very large dE_{vis}/dx because of the PMT saturation problem.**

Thanks !

Backup

- **Central detector**
  - Acrylic sphere with liquid scintillator
  - PMTs in water buffer
  - 78% PMT coverage
- **Water Cherenkov muon veto**
  - 2000 20” PMTs
  - 35 ktons ultra-pure water
  - Efficiency > 95%
  - Radon control → less than 0.2 Bq/m^3