Composition, Structure and Thermal Evolution of Strange Quark Stars

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Compact Star Properties

Some of the stunning properties of a Compact Star:

$N \sim 10^{57}$ baryons

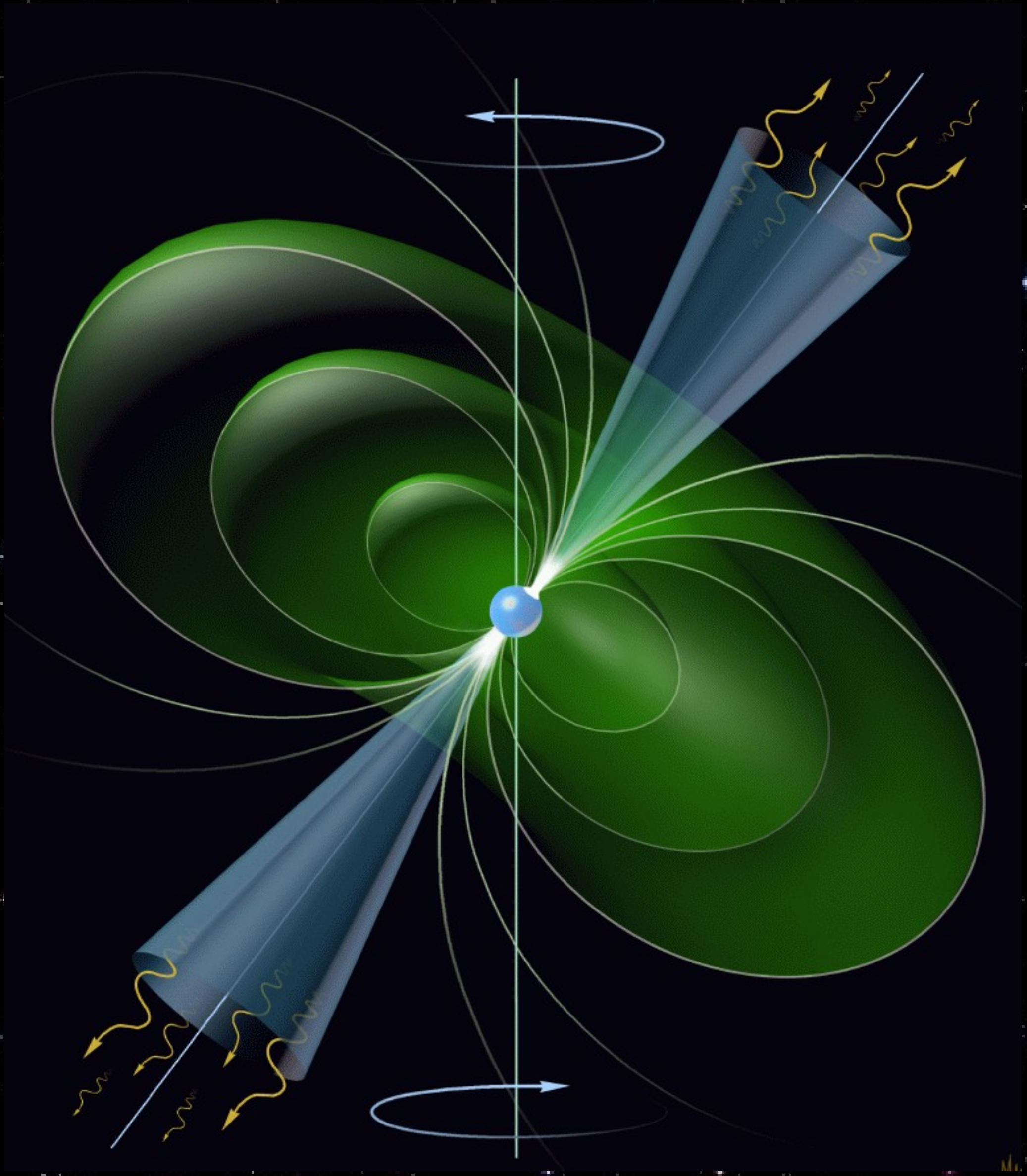
$M \sim 1-2\ M_{sun}$
$R \sim 10-12$ km } $\sim 10^{15} g/cm^3$

$B \sim 10^{8\ \ldots\ 16}$ G, $E \sim 10^{14\text{-}18}$ V/cm

$T \sim 10^{6\ \ldots\ 11}$ K

Total number $\sim 10^9 - 10^{10}$

Currently known ~ 1700



Competing Compositions

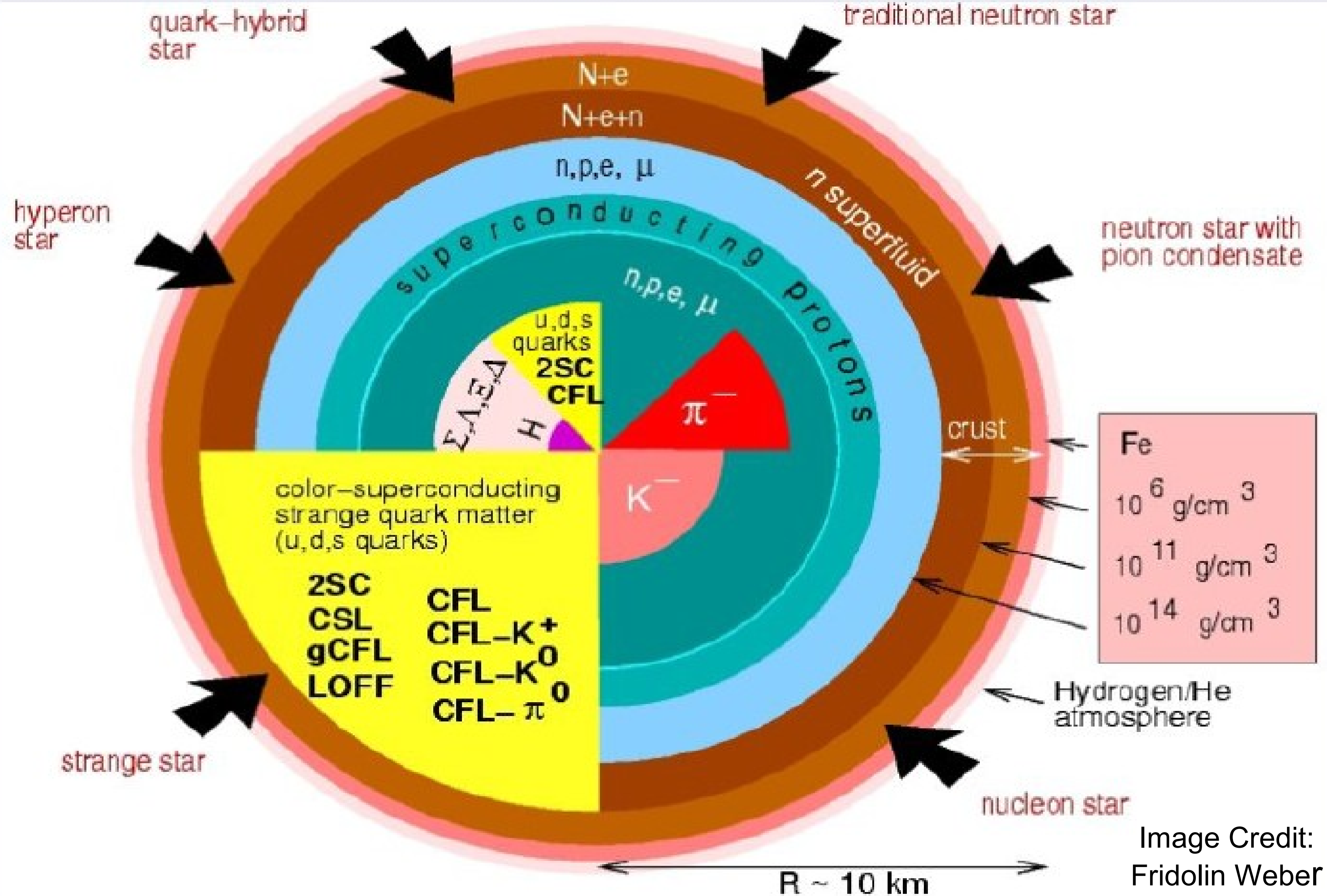
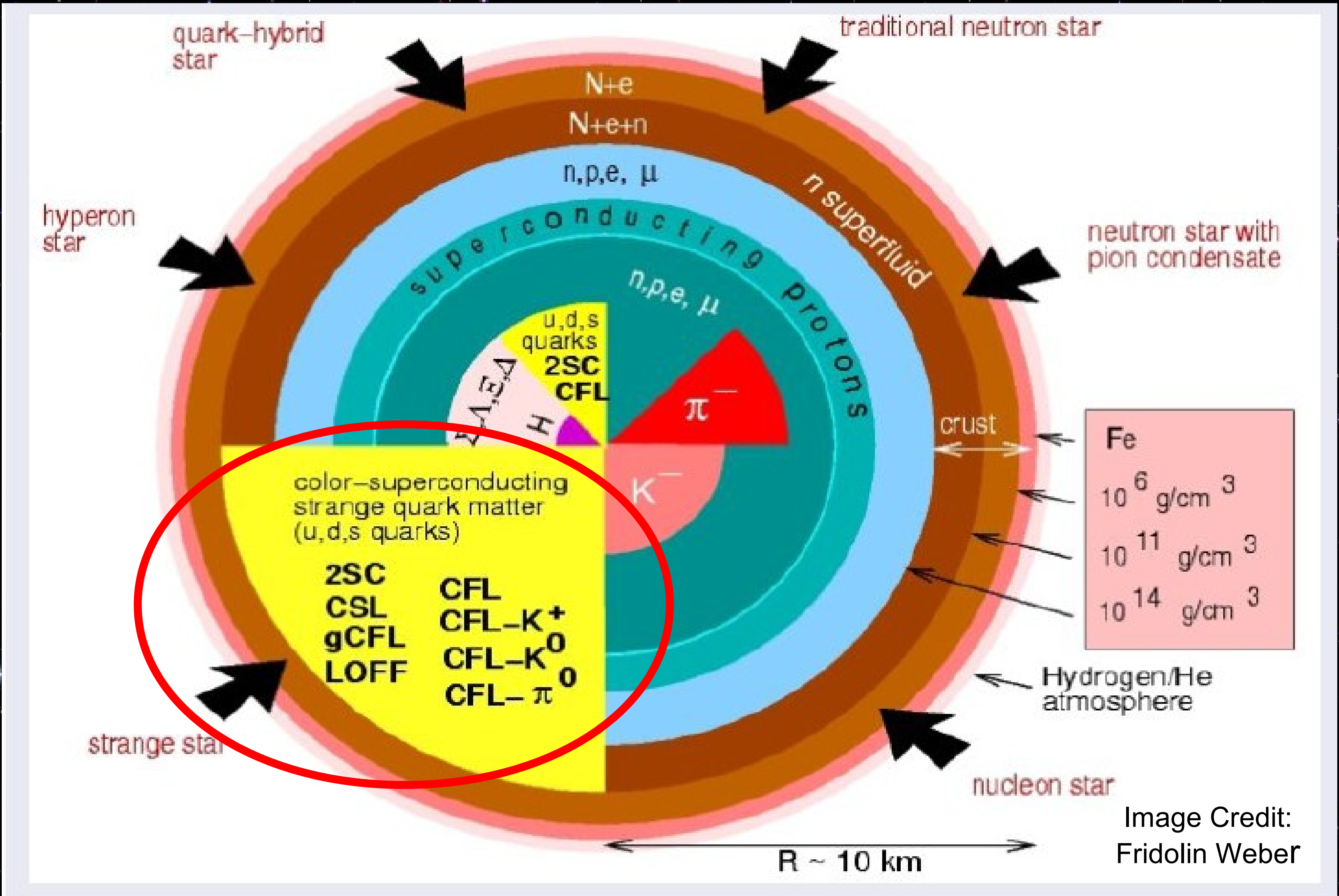


Image Credit:
Fridolin Weber

Competing Compositions



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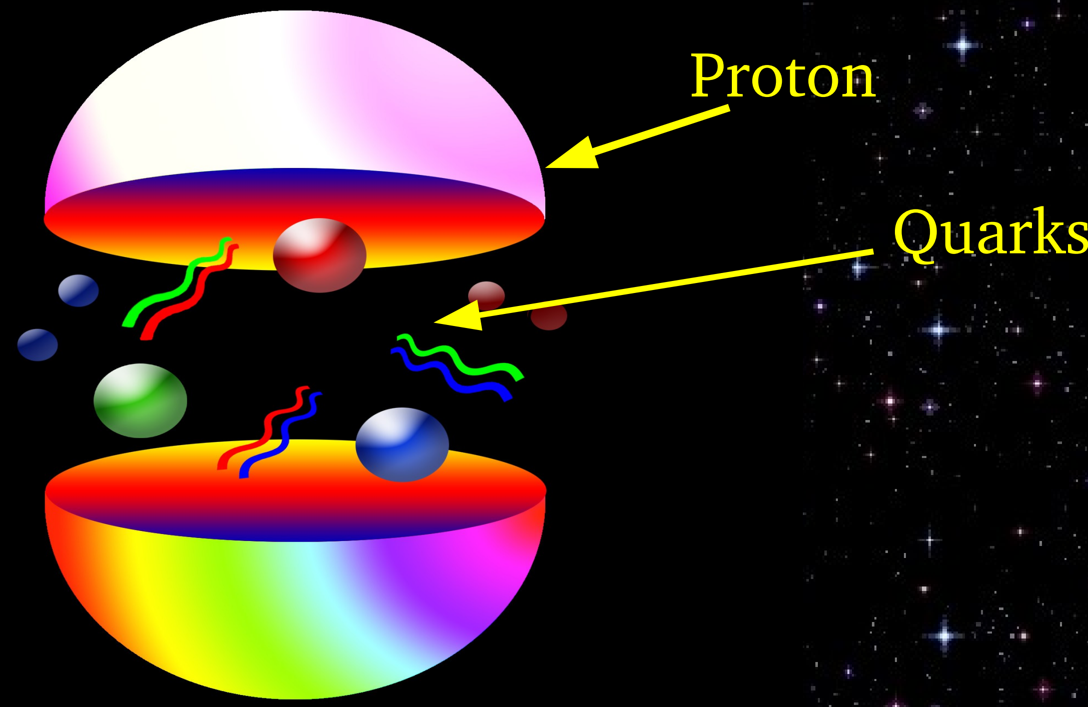
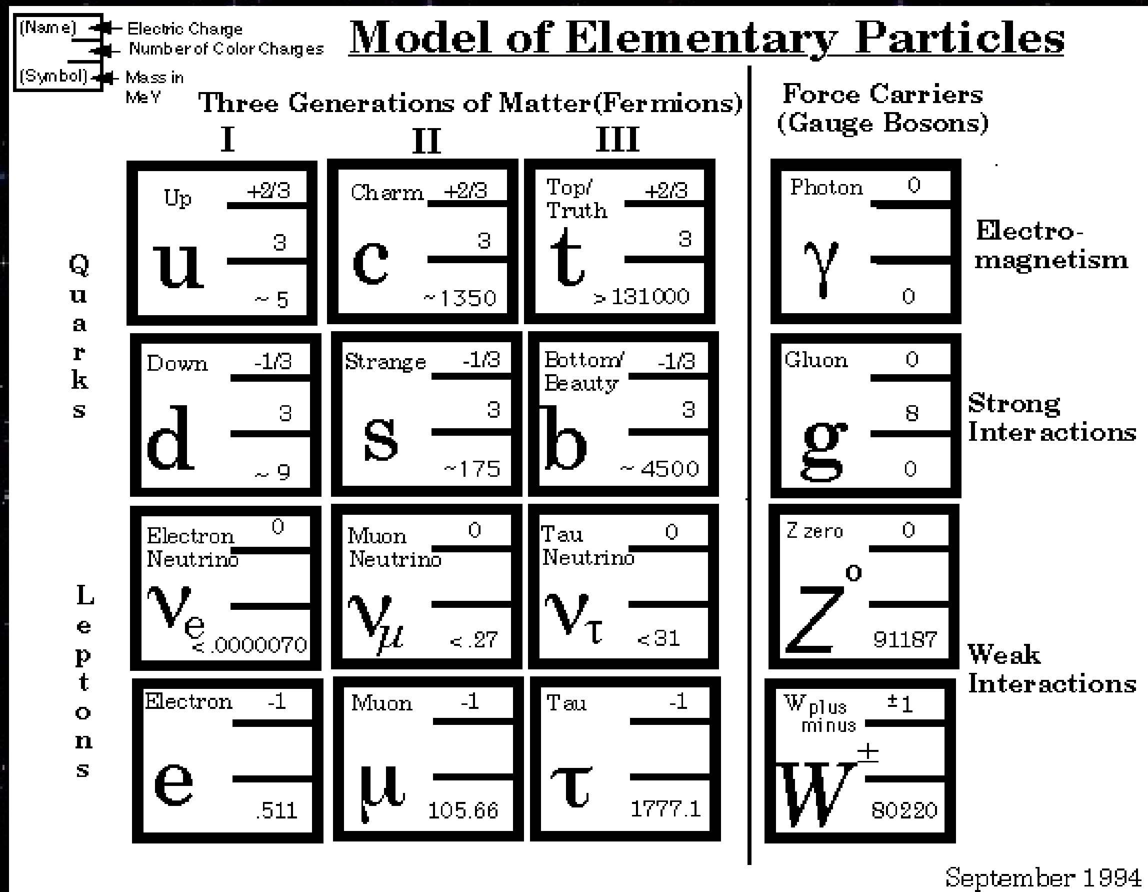
Strange Quark Matter



Quark Matter is a new type of matter that is being searched for at the RHIC (Relativistic Heavy Ion Colliders) at Brookhaven (USA) and at CERN (Europe)

Strange Quark Matter Chemical Equilibrium



Chemical Equilibrium:

$$d \leftrightarrow u + e + \overline{\nu_e},$$

$$s \leftrightarrow u + e + \overline{\nu_e},$$

$$s + u \leftrightarrow u + d.$$

Field Equation for Strange Quark Matter

$$\Omega_u = -\frac{\mu_u^4}{4\pi^2}\left(1-\frac{2\alpha_c}{\pi}\right),$$

$$\Omega_d = -\frac{\mu_d^4}{4\pi^2}\left(1-\frac{2\alpha_c}{\pi}\right),$$

Landau Potentials of Quarks

$$\Omega_e = -\frac{\mu_e^4}{12\pi^2},$$

$$\Omega_s = -\frac{1}{4\pi^2}\{\mu_s\sqrt{\mu_s^2-m_s^2}(\mu_s^2-\frac{5}{2}m_s^2)+\frac{3}{2}m_s^4\ln(\frac{\mu_s+\sqrt{\mu_s^2-m_s^2}}{m_s})$$
$$-\frac{2\alpha_c}{\pi}[3(\mu_s\sqrt{\mu_s^2-m_s^2}-m_s^2\ln(\frac{\mu_s+\sqrt{\mu_s^2-m_s^2}}{m_s}))^2-2(\mu_s^2-m_s^2)^2$$
$$+3m_s^4\ln^2\frac{m_s}{\mu_s}+6\ln\frac{\sigma}{\mu_s}(\mu_s m_s^2\sqrt{\mu_s^2-m_s^2}-m_s^4\ln(\frac{\mu_s+\sqrt{\mu_s^2-m_s^2}}{m_s}))]\}.$$

Chemical equilibrium and charge neutrality condition

$$\mu_d = \mu_s \equiv \mu,$$

$$\mu_u + \mu_e \equiv \mu,$$

$$\rho_i = -\frac{\partial\Omega_i}{\partial\mu_i},$$

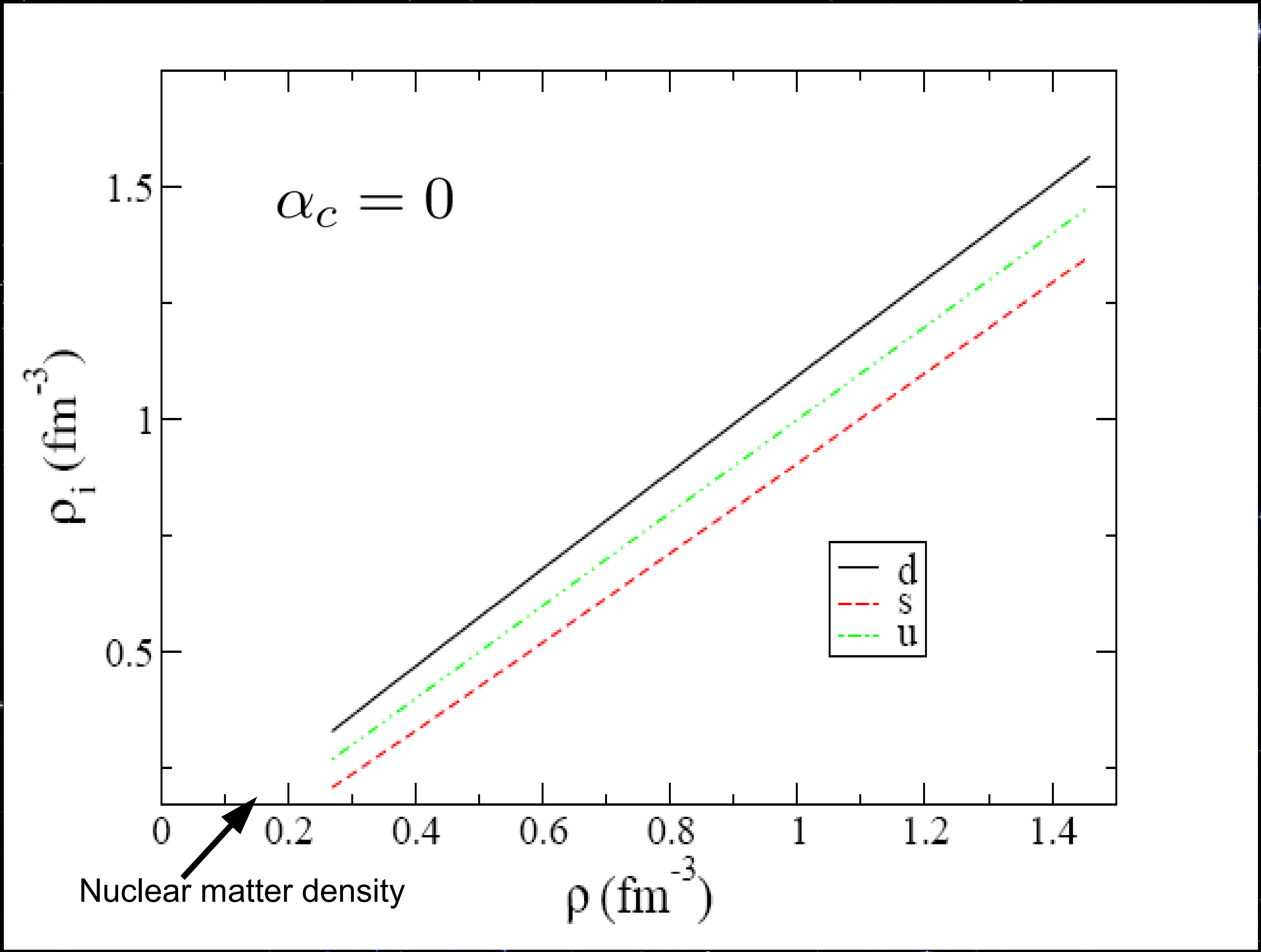
$$\sum_{i=u,d,s,e} q_i\rho_i = 0 = \frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e$$

Equation of State

$$\epsilon = \sum_{i=u,d,s,e}(\Omega_i+\mu_i\rho_i)+B.$$

$$p = -B - \sum_{i=u,d,s,e}\Omega_i.$$

Strange Quark Matter Composition



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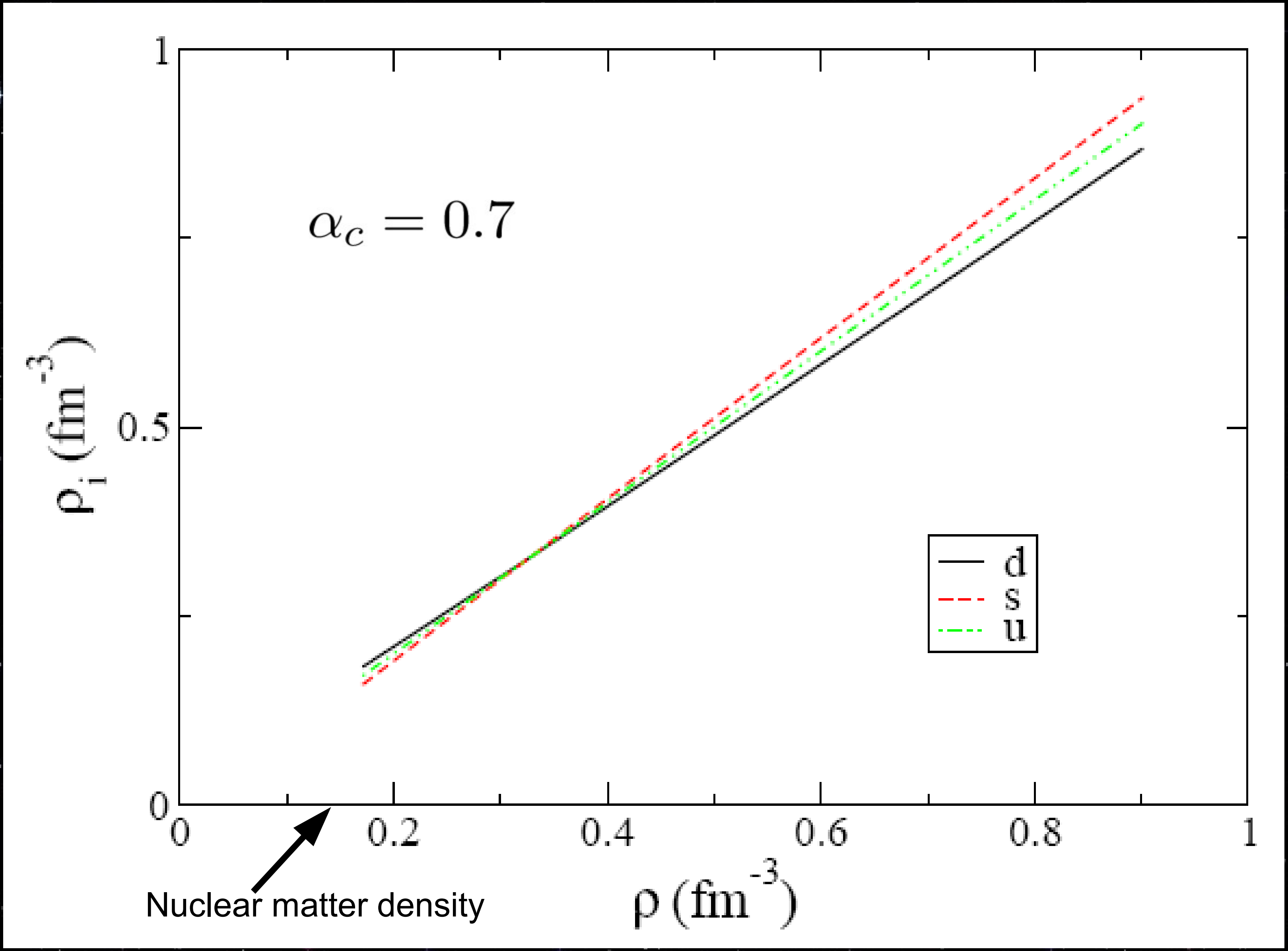

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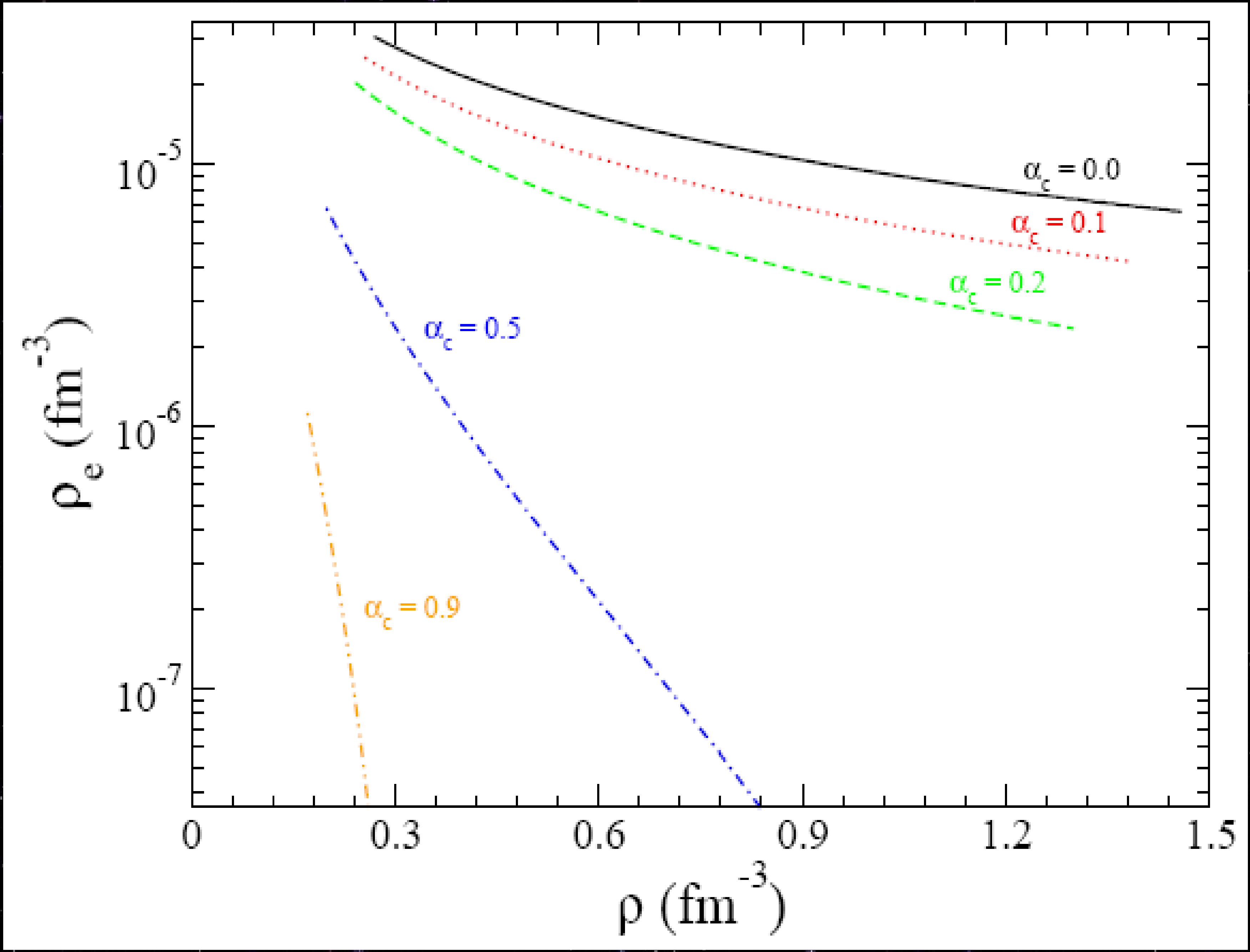
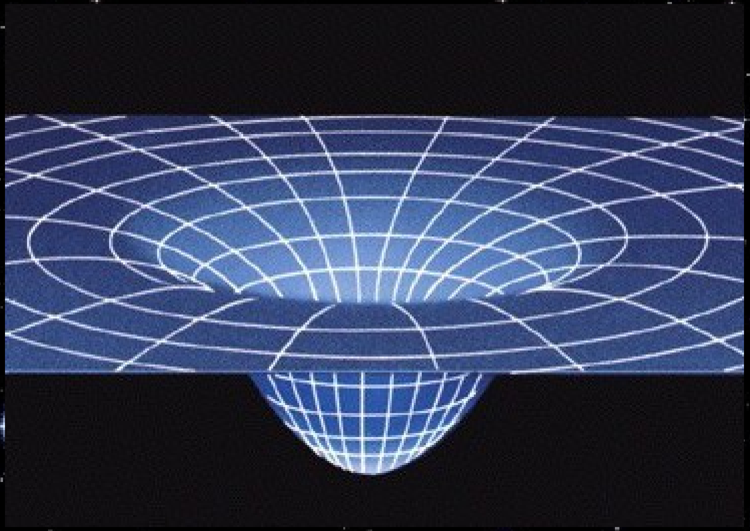


Structure of Quark Stars...

... must be computed in the framework of Einstein's theory of general relativity.



$$ds^2 = e^{\nu(r)}c^2dt^2 - e^{\lambda(r)}dr^2 - r^2(d\theta^2 + sin^2\theta d\phi^2)$$

→ Metric

$$T^{\mu}_{\nu} = (p+\epsilon)u^{\mu}u_{\nu} + p\delta^{\mu}_{\nu}$$

→ Energy-Momentum Tensor (EOS)

$$G_{\nu\mu} = 8\pi T_{\nu\mu}$$

→ Einstein's Equation

$$\frac{dp}{dr} = -\frac{[p(r)+\epsilon(r)][m(r)+4\pi r^3 p(r)]}{r(r-2m(r))}$$

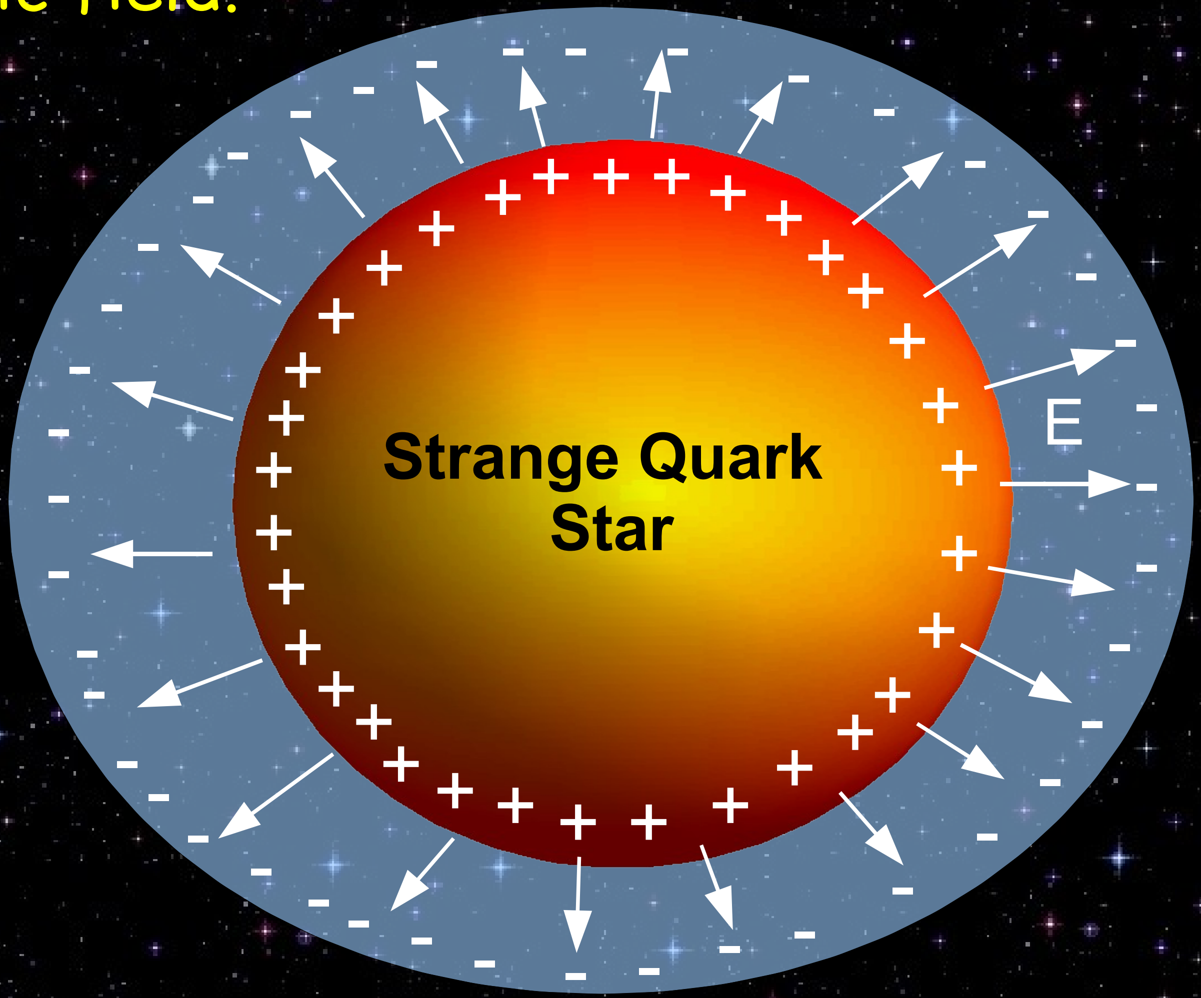
→ TOV equation (General Relativistic Hydrostatic equilibrium)

$$m(r) = 4\pi \int_0^r dr r^2 \epsilon(r)$$

→ Stellar mass

Surface Electric Field

- Depletion of strange quarks near the surface and the screening of electrons generate an ultra high electric field.



Structure of Charged Quark Stars ...

... is modified by the presence of an electric field.

$$T_\nu{}^\mu = (p+\epsilon)u_\nu u^\mu + p\,\delta_\nu{}^\mu + \frac{1}{4\pi}\left(F^{\mu l}F_{\nu l} + \frac{1}{4\pi}\delta_\nu{}^\mu F_{kl}F^{kl}\right)$$

→ Energy-Momentum Tensor (EOS)

$$\frac{dP}{dr} = -\frac{2G\left(m + \frac{4\pi r^3}{c^2}\left(p - \frac{Q^2}{4\pi r^4 c^2}\right)\right)}{c^2 r^2\left(1 - \frac{2Gm}{c^2 r} + \frac{GQ^2}{r^2 c^4}\right)}(p+\epsilon) + \frac{Q}{4\pi r^4}\frac{dQ}{dr}$$

→ TOV equation (General Relativistic Hydrostatic equilibrium)

$$\frac{dm}{dr} = \frac{4\pi r^2}{c^2}\epsilon + \frac{Q}{c^2 r}\frac{dQ}{dr}$$

→ Stellar mass

$$\frac{dQ}{dr} = \frac{r^2\sigma\,\exp\left(-((r-r_g)/b)^2\right)\exp(\Lambda/2)}{2(\sqrt{\pi}b^3/4 + r_g b^2 + \sqrt{\pi}r_g^2 b/2)}$$

→ Relativistic Gauss's Law

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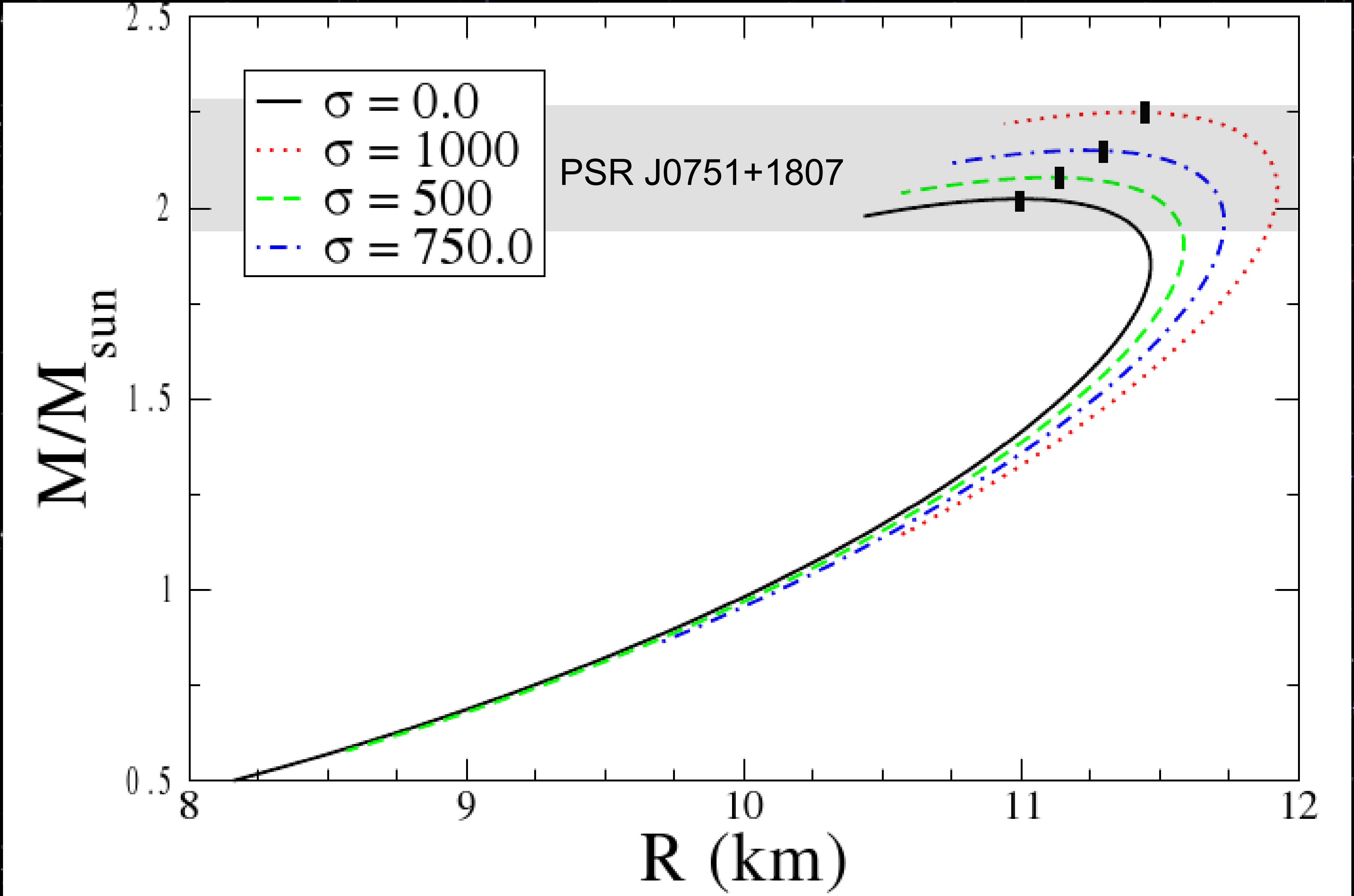
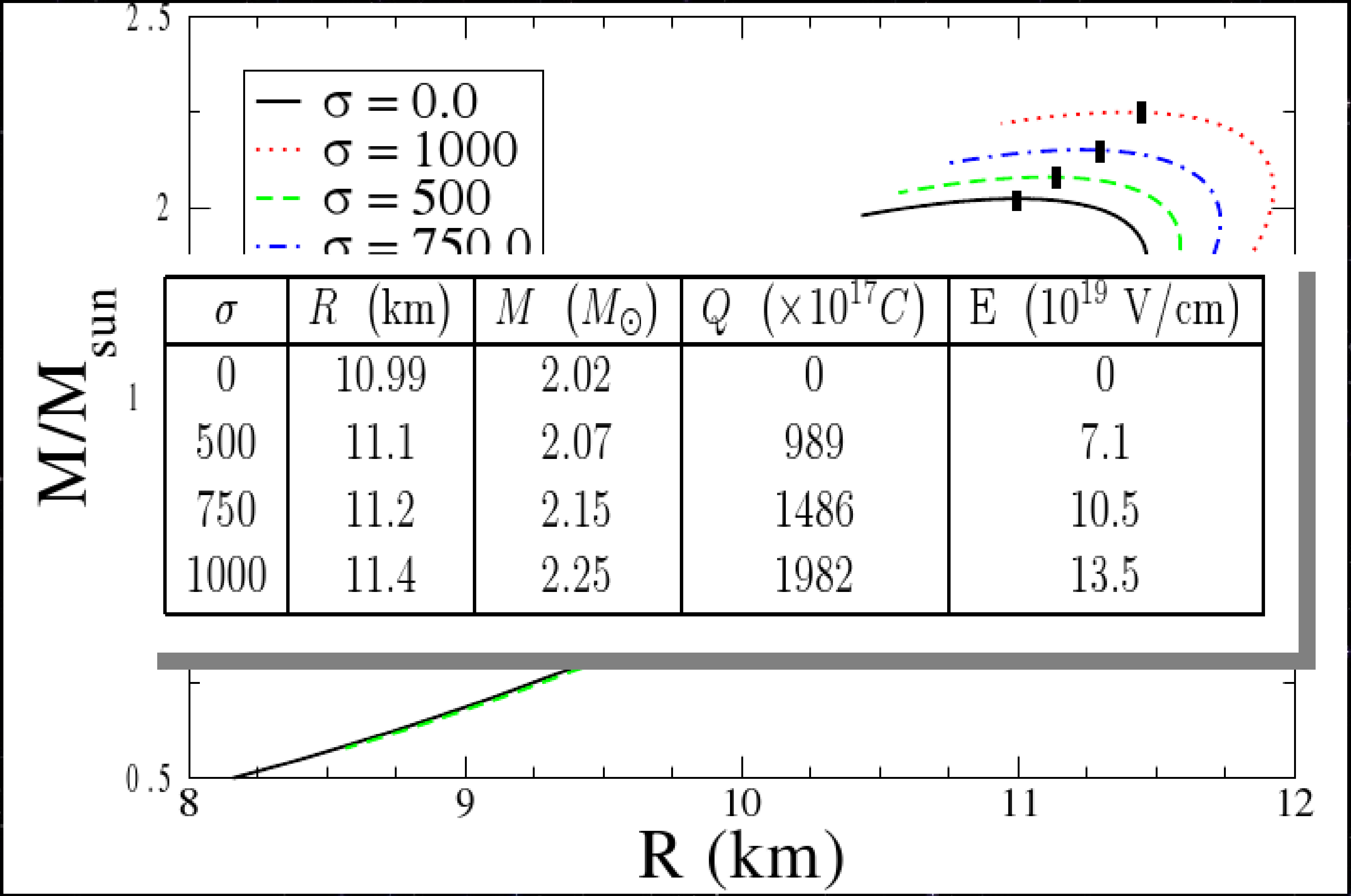
Relativistic Gauss's Law

Stellar Sequences

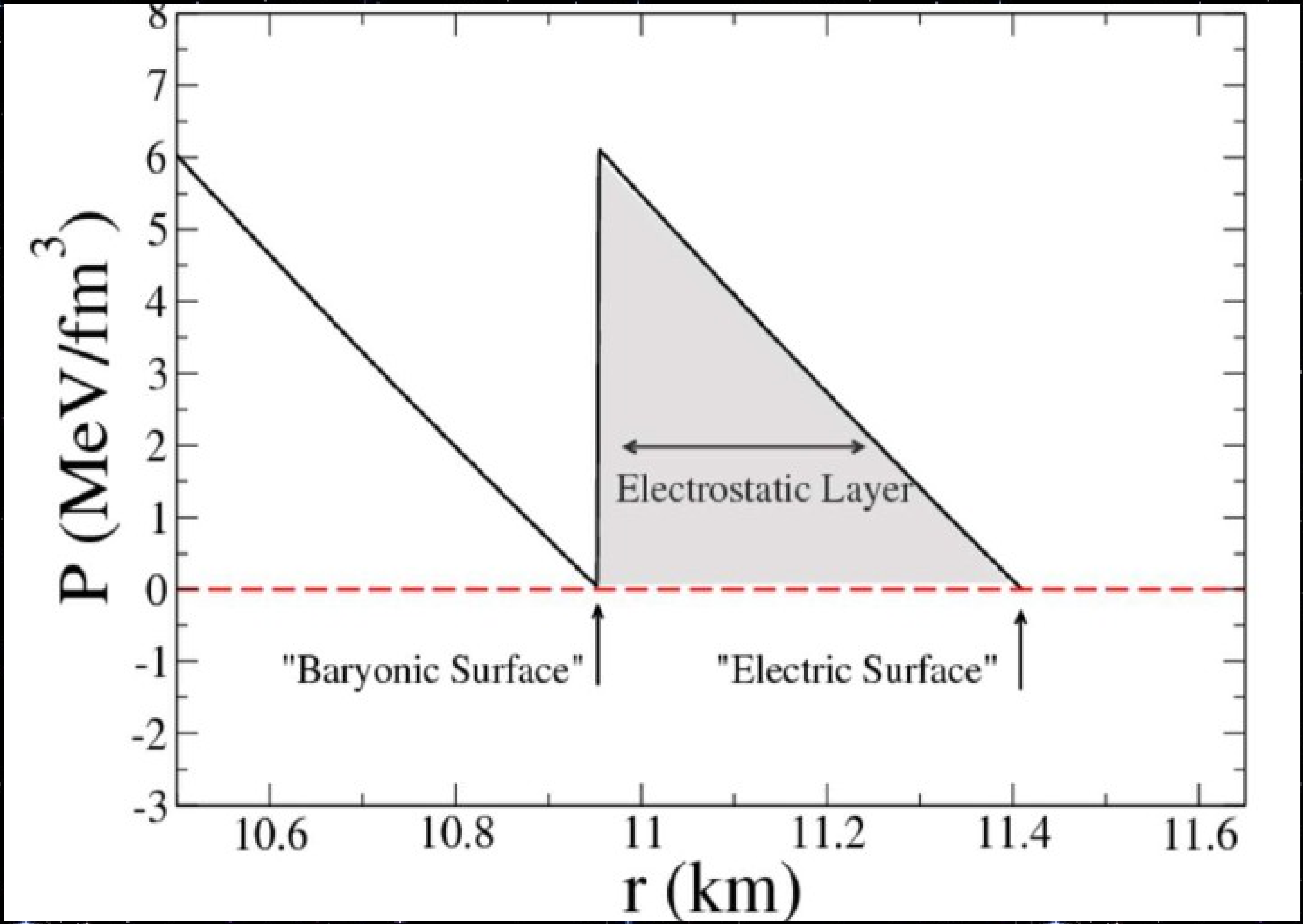


Stellar Sequences

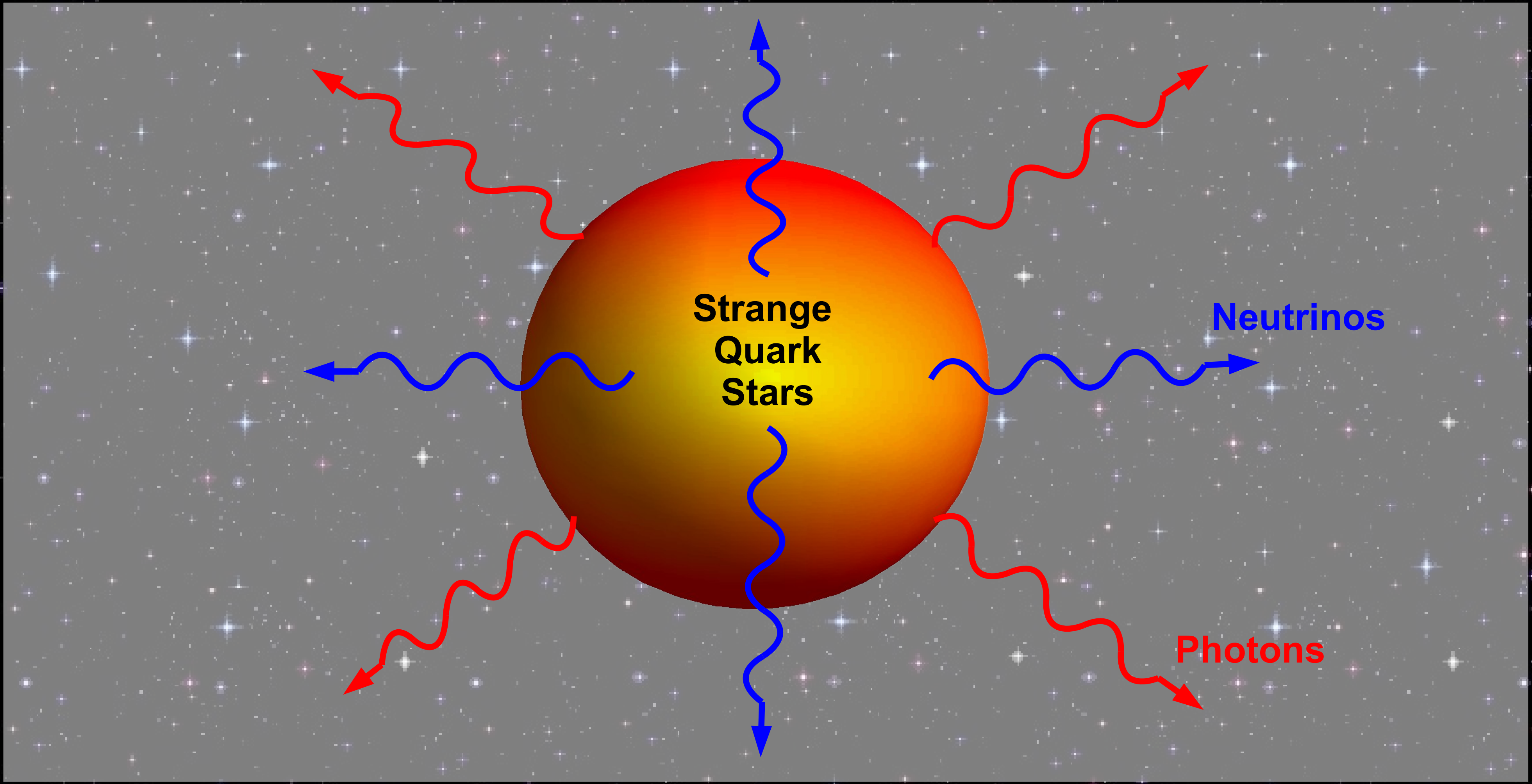


σ	R (km)	M ($M_\odot$)	Q ($\times 10^{17} C$)	E (10^{19} V/cm)
0	10.99	2.02	0	0
500	11.1	2.07	989	7.1
750	11.2	2.15	1486	10.5
1000	11.4	2.25	1982	13.5

How does a superficial electric field change bulk properties of a strange star?



Thermal Evolution...



... is described by general relativistic equation of energy balance and energy transport:

Thermal Evolution Equations

$$\frac{\partial(Le^{2\phi})}{\partial m} = -\frac{1}{\epsilon\sqrt{1-2m/r}}\left(\epsilon_\nu e^{2\phi} + c_v \frac{\partial(Te^{\phi})}{\partial t}\right)$$

$$\frac{\partial(Te^{\phi})}{\partial m} = -\frac{(le^{-\phi})}{16\pi^2 r^4 \kappa\epsilon\sqrt{1-2m/r}},$$

Microscopic input:

Neutrino Emissivity: $\epsilon_\nu(t,\epsilon,T) \propto 10^{26}\ \frac{\mathrm{erg}}{\mathrm{cm^3 s}}$

Specific Heat: $C(t,\epsilon,T) \propto 10^{19}\ \frac{\mathrm{erg}}{\mathrm{cm^3 K}}$

Thermal Conductivity: $\kappa(t,\epsilon,T) \propto 10^{34}\ \frac{\mathrm{erg}}{\mathrm{cm\ K\ s}}$

Equations need to be solved for a timescale of 10^7 years !

Observed Thermal Properties of Compact Stars

Label	Pulsar	Age (years)	$\log_{10}$ (Luminosity (ergs/s))
α	CXOU J232327.9+584843	0.3×10^3	32.94
β	RX J0852.04622	2×10^3	32.83
δ	RX J1713.73946	10×10^3	32.63
ϵ	RX J0822 -4300	2.2×10^3	33.69
ϕ	1E 1207.4-5209	7×10^3	33.39
γ	CXOU J85238.6+004020	9×10^3	33.07

Central Compact Objects

- Compact objects located at the center of supernova remnants.
- Spectrum is very well fit by a one or two component black body model.
- Predicted unusually small radii (0.3 – 5.0 km).

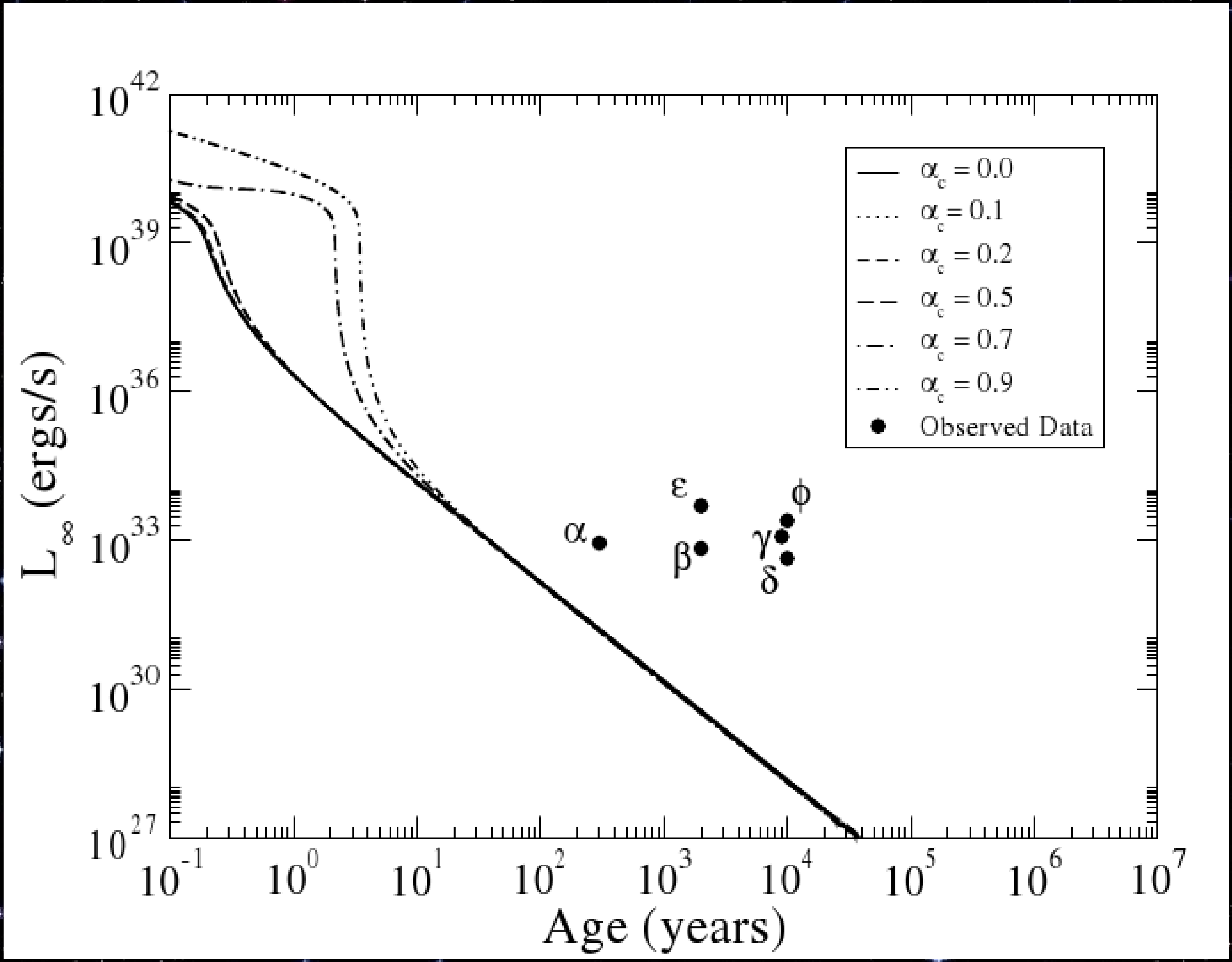
Observed Thermal Properties of Compact Stars

Label	Name	$T \times 10^6$	Age
	(K)	(10^3 years)	
A	SGR 1806-20	$7.56^{+0.8}_{-0.7}$	0.15
B	1E 1048.1-5937	$7.22^{+0.13}_{-0.07}$	2.5
C	CXO J164710.2-455216	7.07	0.5
D	SGR 0526-66	$6.16^{+0.07}_{-0.07}$	1.3
E	1RXS J170849.0-400910	$5.3^{+0.98}_{-1.23}$	6.0
F	1E 1841-045	$5.14^{+0.02}_{-0.02}$	3.0
G	SGR 1900+14	$5.06^{+0.93}_{-0.06}$	0.73
H	CXOU J010043.1-721134	$4.44^{+0.02}_{-0.02}$	4.5
I	XTE J1810-197	$7.92^{+0.22}_{-5.83}$	11.3
J	RX J0720.4-3125	$1.05^{+0.06}_{-0.06}$	1266
L	RBS 1223	$1.00^{+0.0}_{-0.0}$	974

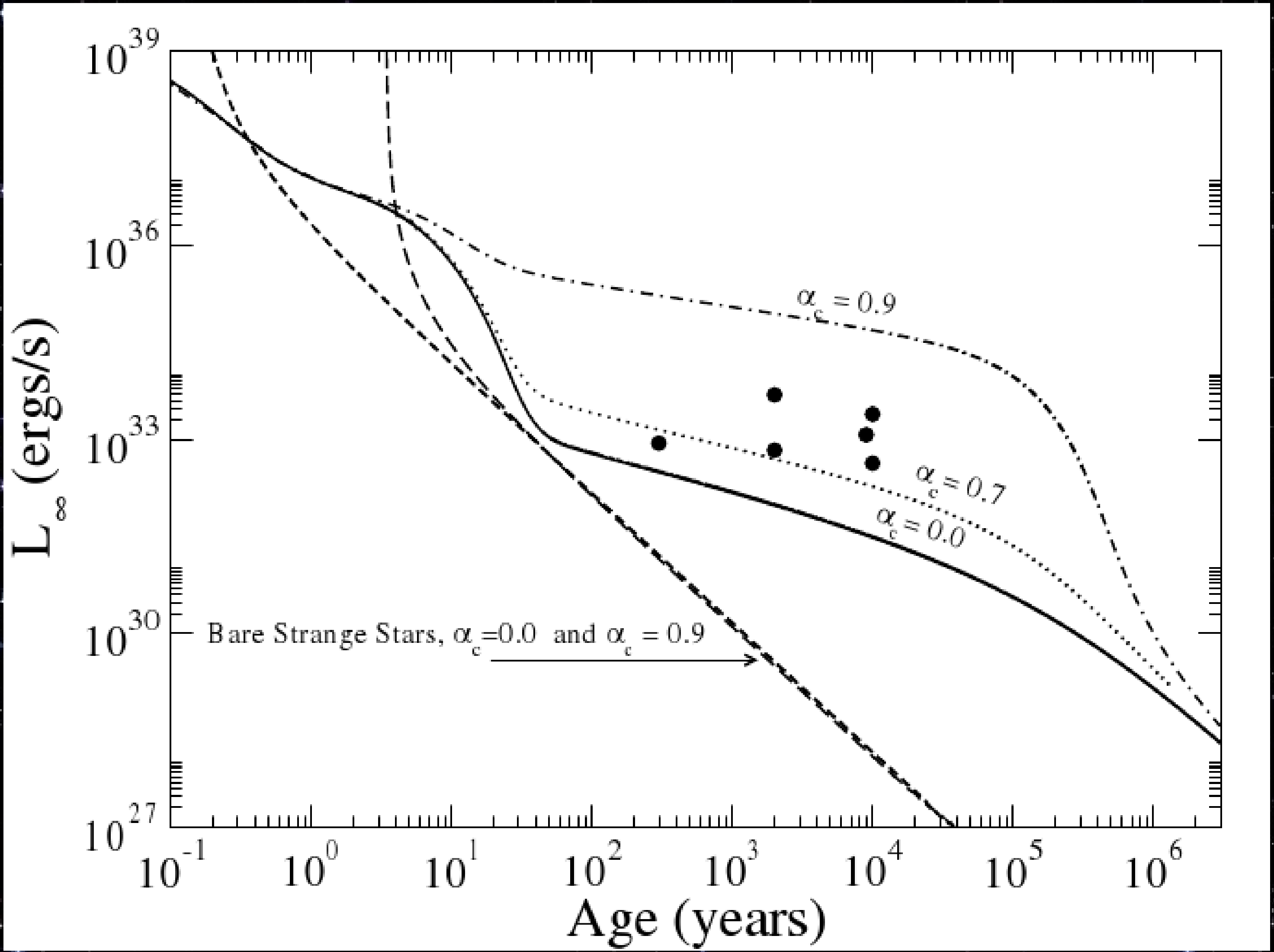
Soft Gamma-Ray Repeaters and Anomalous X-ray pulsars

- Emission of irregular bursts of ultra energetic X-ray and Gamma radiation.
- Very high observed temperatures.

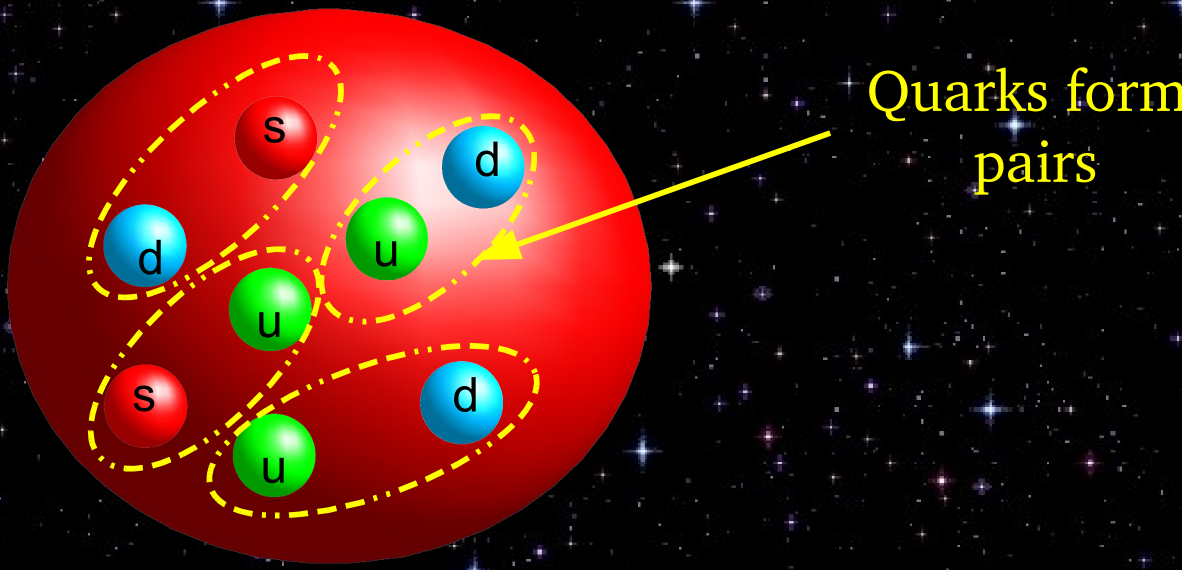
Cooling of Bare Strange Quark Stars



Cooling of Crusted Strange Quark Stars



Superconducting Quark Matter...



... exhibits suppression of neutrino emissivities and a reduction of specific heat

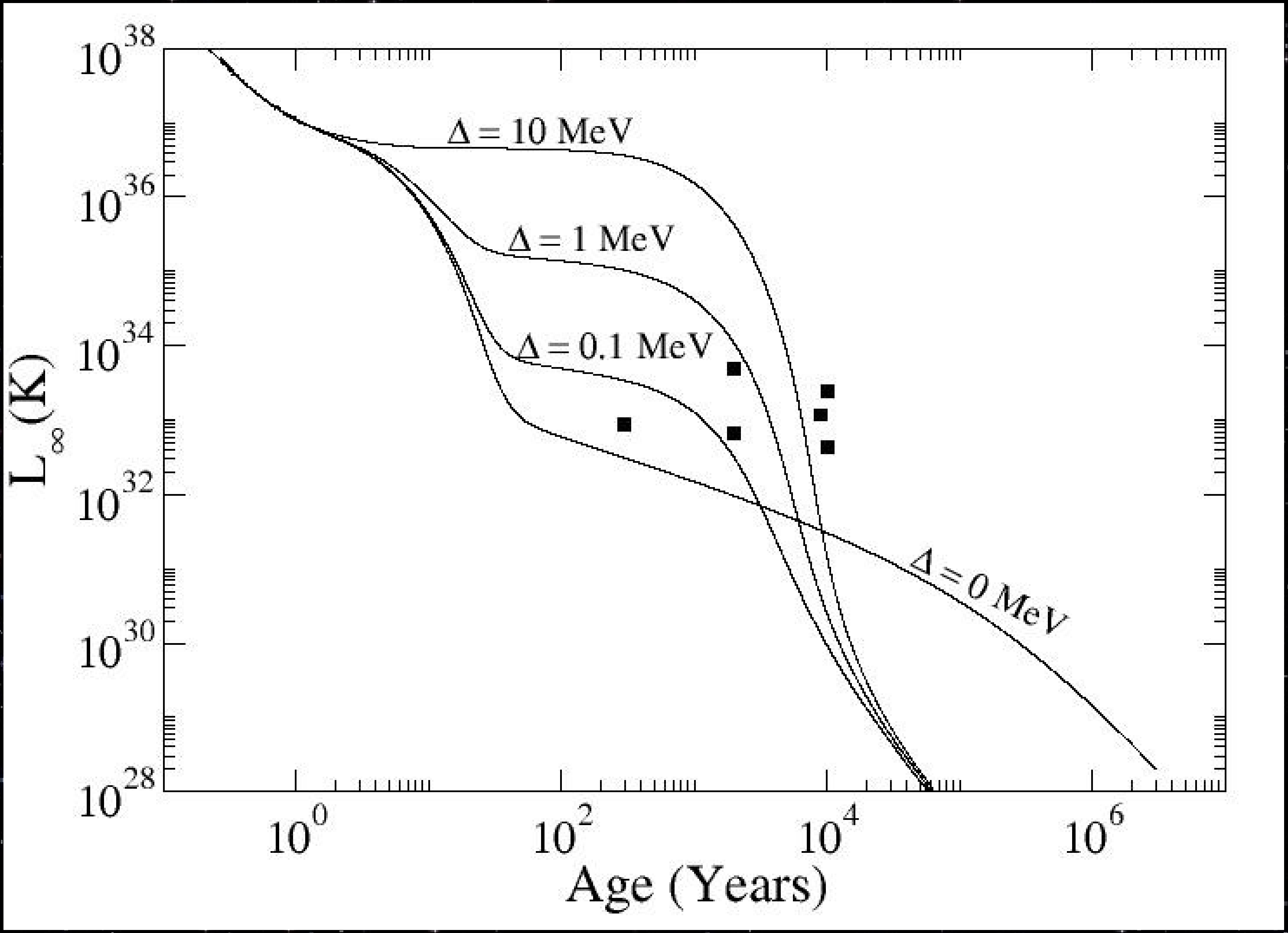
Neutrino emissivities:

$$\epsilon_\nu \longrightarrow \epsilon_\nu \, e^{-(\Delta/kT)}$$

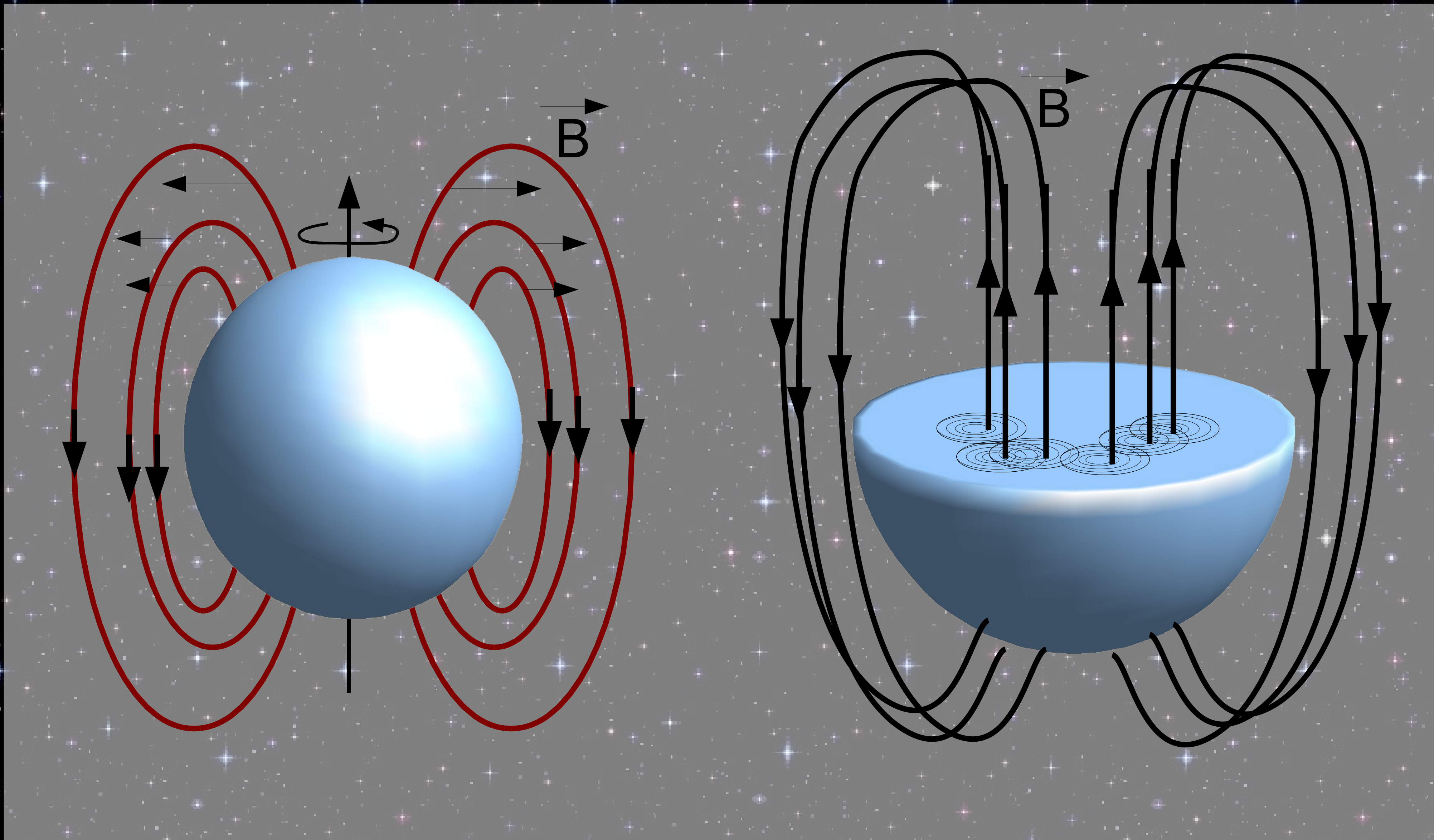
Specific heat:

$$C_{v,\mathrm{CFL,Q}} = 3.2 C_Q \left(\frac{T_c}{T}\right) \times \left[2.5 - 1.7\left(\frac{T}{T_c}\right) + 3.6\left(\frac{T}{T_c}\right)^2\right] e^{-\Delta/(\kappa_B T)}$$

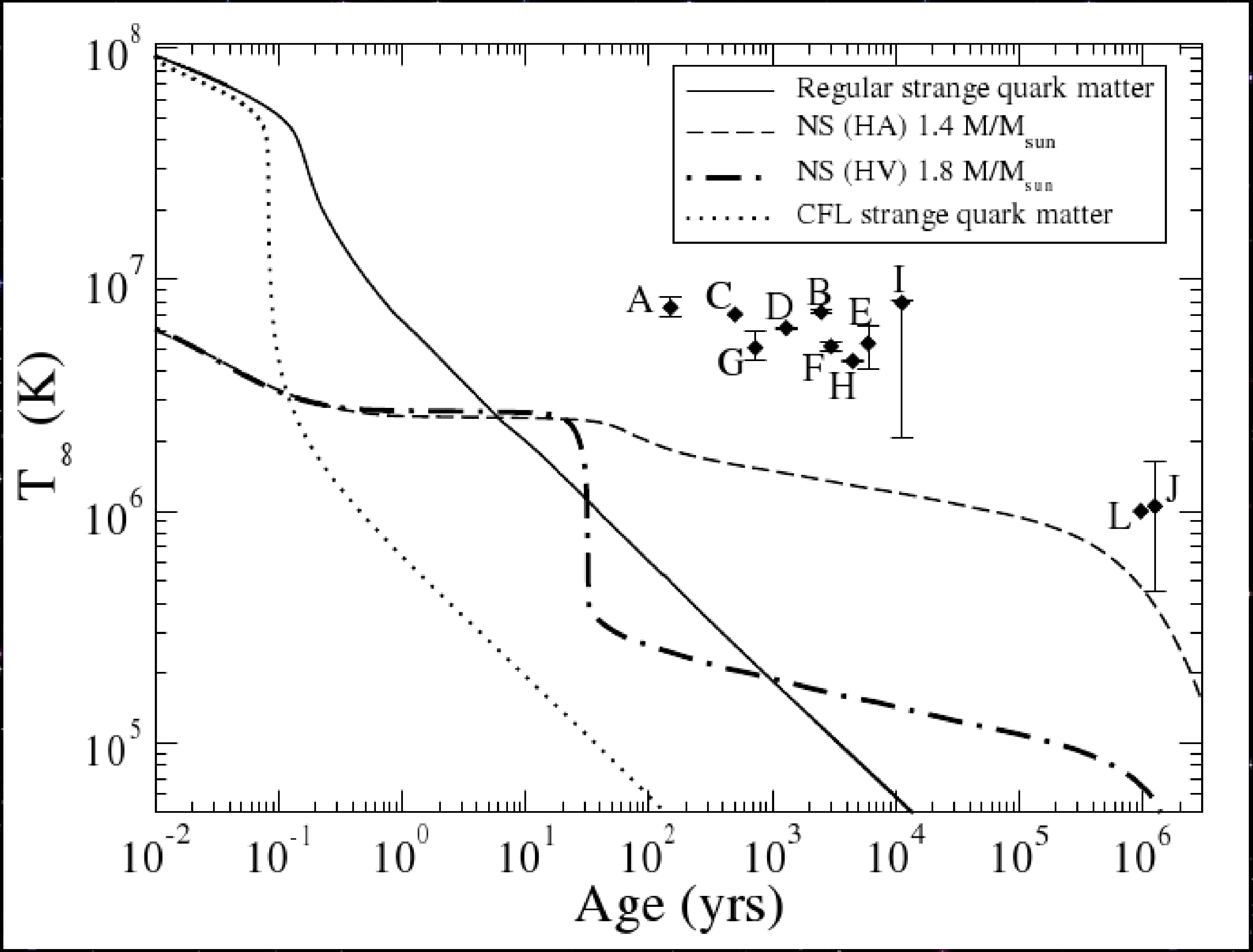
Cooling of Superconducting Strange Quark Stars



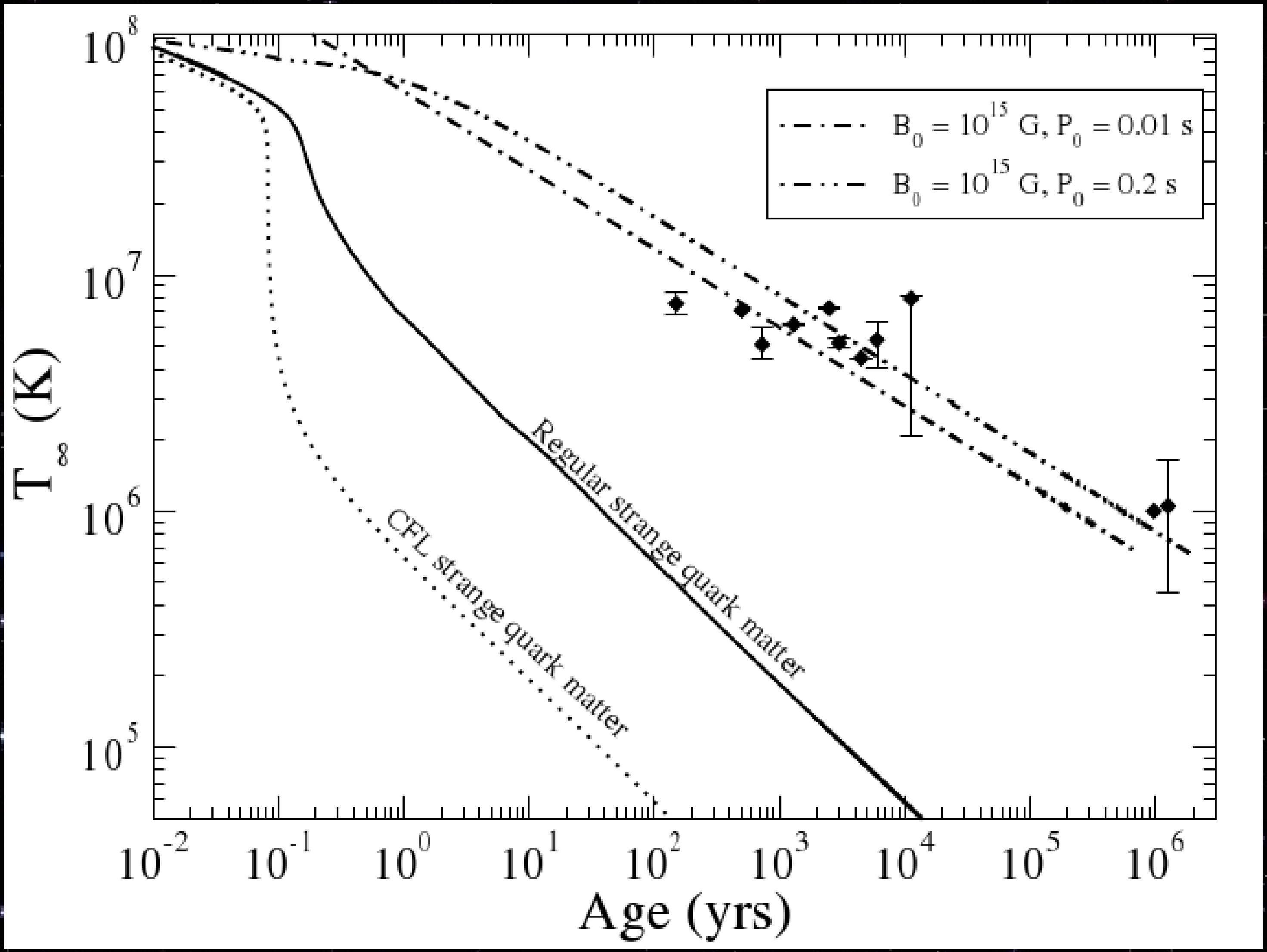
Vortex Expulsion in Superconducting Strange Stars



Very high temperature observed for SGRs and AXPs



Cooling of Superconducting Strange Stars Experiencing Vortex Expulsion



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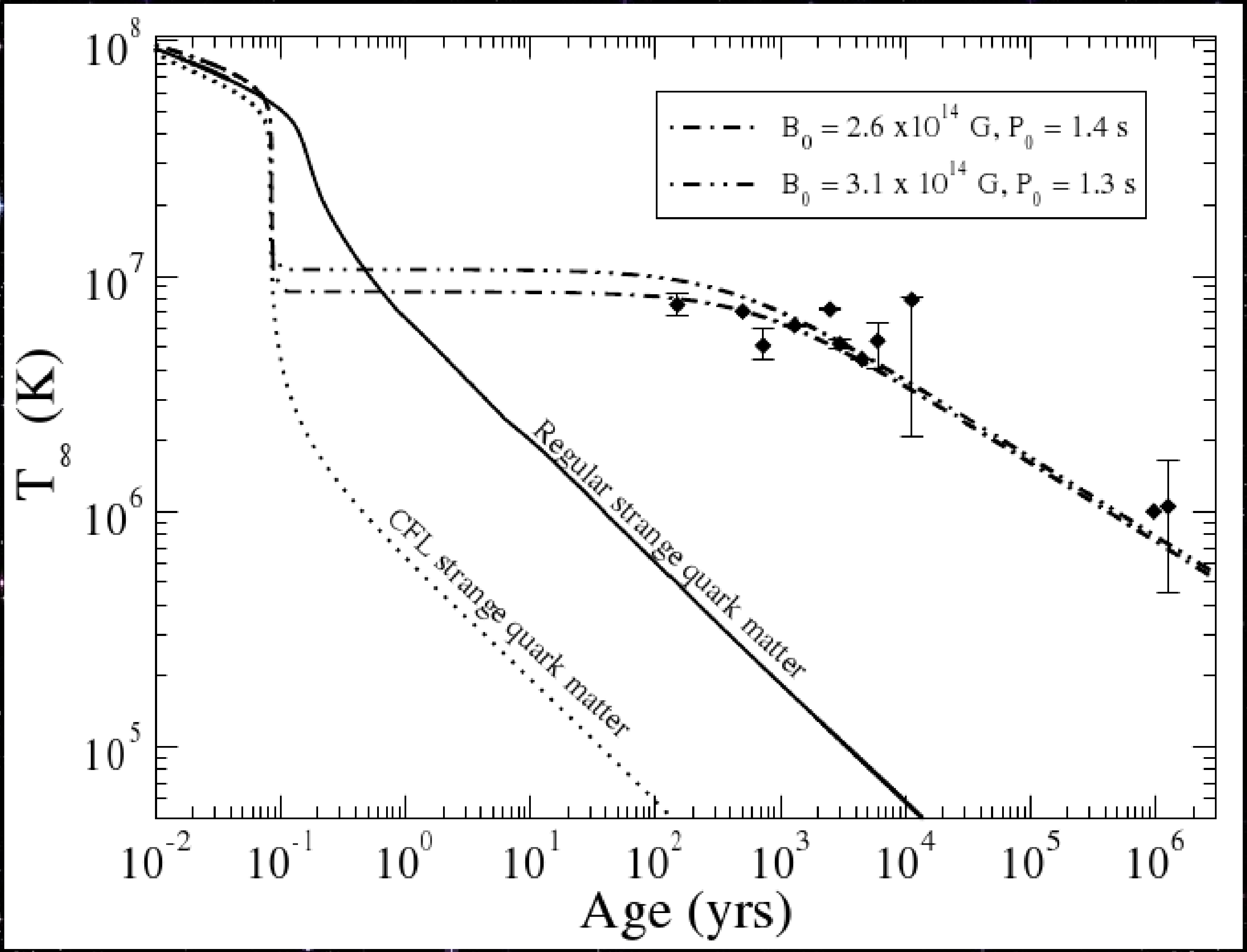

Conclusions

- The bulk properties of strange quark matter strongly depend on the value for the strong coupling constant (α_c).

- The value of α_c and the superconducting gap parameter Δ are very important for the thermal evolution of strange stars.

- The observed temperature of CCO's could be explained by assuming these objects are superconducting strange stars.

- The high temperatures of SGR's and AXP's can be very well modeled by the vortex expulsion mechanism.

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Paper in preparation.