奇异星与中微子

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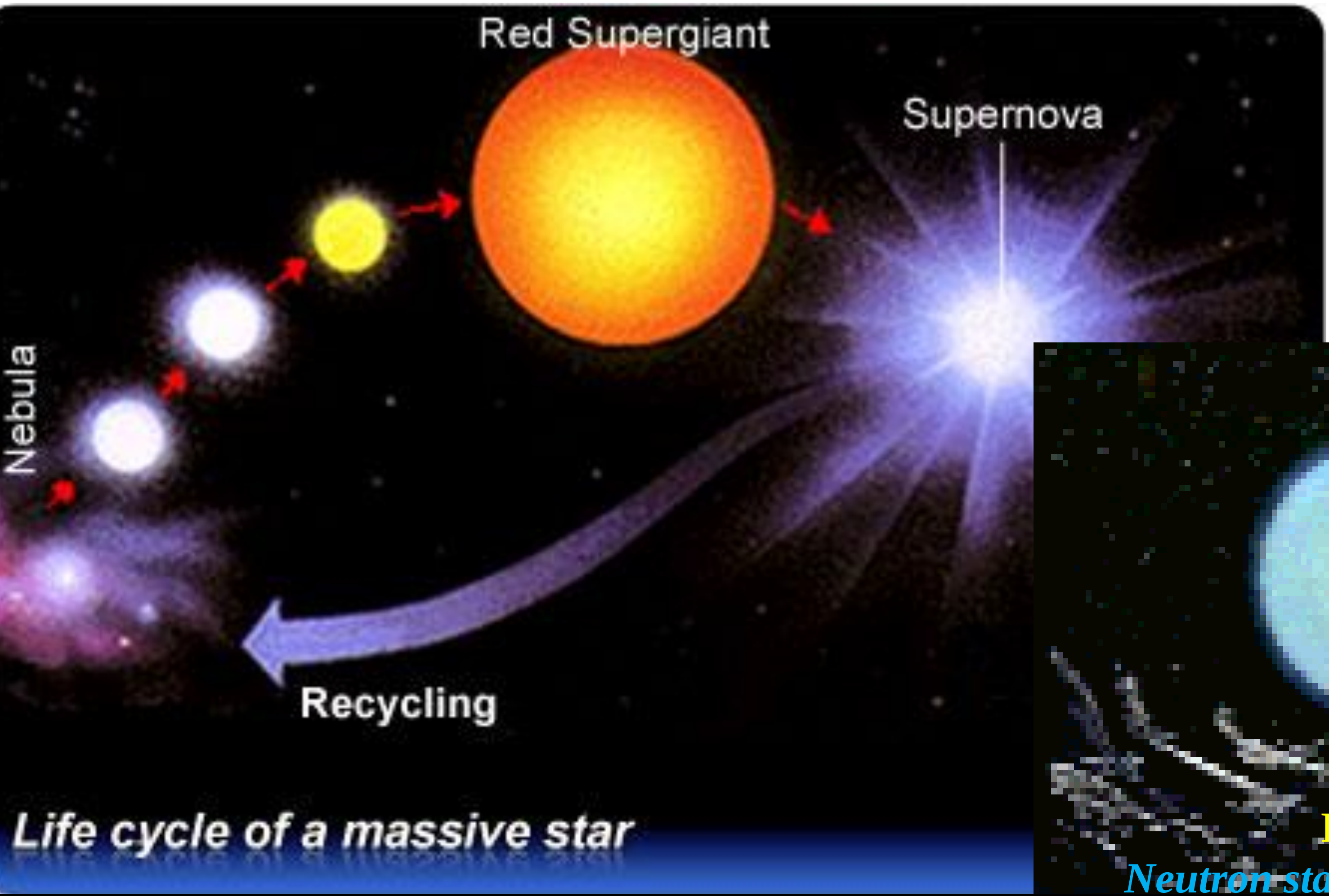
Can ν tell us what the nature is?

- Pulsar is produced inside massive stars after SN



SN occurs due to gravitational energy release when nuclear power cannot stand against gravity.

Summary

- Strange stars: SQS vs. SQcS
- ν-emissivity of strange quark-cluster star
- Conclusions

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- ν-emissivity of strange quark-cluster star
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Millennium Problems | C ×

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Millennium Problems

Yang–Mills and Mass Gap

Experiment and computer simulations suggest the existence of a "mass gap" in the solution to the quantum versions of the Yang-Mills equations. But no proof of this property is known.

Riemann Hypothesis

The prime number theorem determines the average distribution of the primes. The Riemann hypothesis tells us about the deviation from the average. Formulated in Riemann's 1859 paper, it asserts that all the 'non-obvious' zeros of the zeta function are complex numbers with real part 1/2.

P vs NP Problem

If it is easy to check that a solution to a problem is correct, is it also easy to solve the problem? This is the essence of the P vs NP question. Typical of the NP problems is that of the Hamiltonian Path Problem: given N cities to visit, how can one do this without visiting a city twice? If you give me a solution, I can easily check that it is correct. But I cannot so easily find a solution.

Navier–Stokes Equation

This is the equation which governs the flow of fluids such as water and air. However, there is no proof for the most basic questions one can ask: do solutions exist, and are they unique? Why ask for a proof? Because a proof gives not only certitude, but also understanding.

Hodge Conjecture

The answer to this conjecture determines how much of the topology of the solution set of a system of algebraic equations can be defined in terms of further algebraic equations. The Hodge conjecture is known in certain special cases, e.g., when the solution set has dimension less than four. But in dimension four it is unknown.

Poincaré Conjecture

In 1904 the French mathematician Henri Poincaré asked if the three dimensional sphere is characterized as the unique simply connected three manifold. This question, the Poincaré conjecture, was a special case of Thurston's geometrization conjecture. Perelman's proof tells us that every three manifold is built from a set of standard pieces, each with one of eight well-understood geometries.

Solved!

Birch and Swinnerton-Dyer Conjecture

Supported by much experimental evidence, this conjecture relates the number of points on an elliptic curve mod p to the rank of the group of rational points. Elliptic curves, defined by cubic equations in two variables, are fundamental mathematical objects that arise in many areas: Wiles' proof of the Fermat Conjecture, factorization of numbers into primes, and cryptography, to name three.

The ***strong interaction*** at low-energy scale is related to one of the Millennium Problems.

"… The successful use of ***Yang-Mills theory*** to describe the strong interactions of elementary particles depends on a subtle quantum mechanical property called the "***mass gap***": the quantum particles have positive masses, even though the classical waves travel at the speed of light. …"

The nature of "neutron star":

NQCD!

Energy scale **~ 0.4 GeV < 1 GeV**

(~0.5 fm) $pc \sim \hbar c \sim 200$ MeV·fm

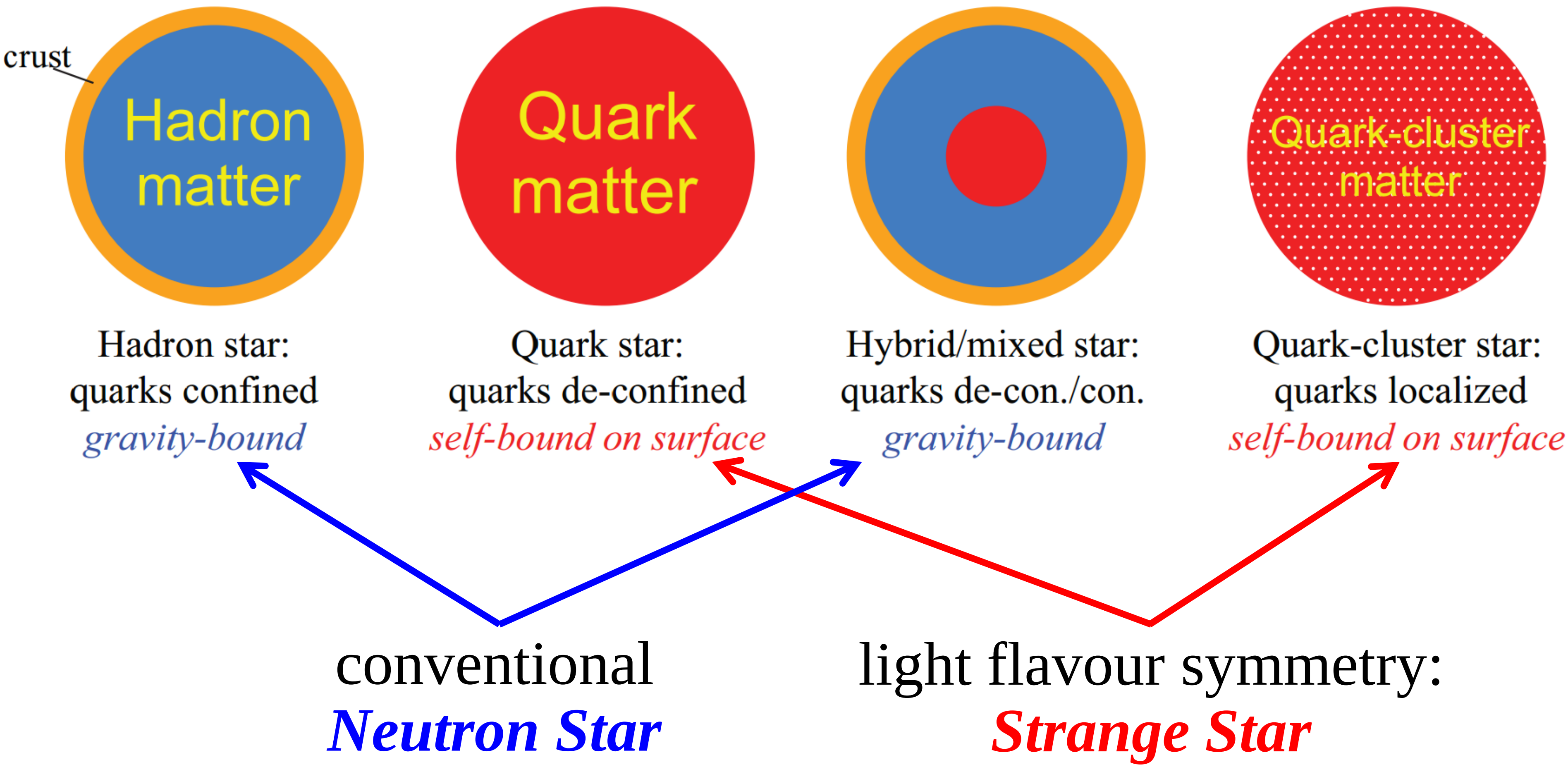
Why our baryonic matter with 2-flavor (rather than ~~1~~- or 3-) symmetry?

Strange Matter

Anthropic principle?

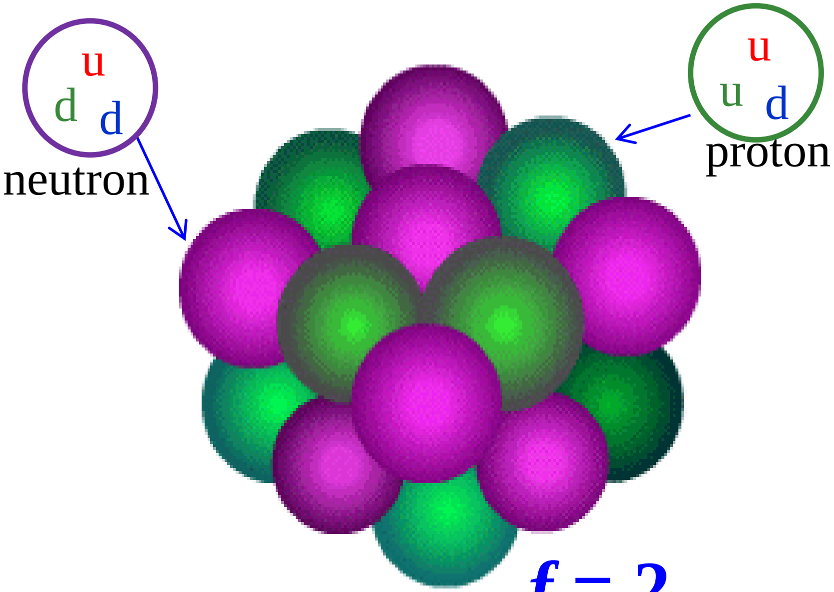
Strange stars: SQS vs. SQcS

- Different models of pulsar's nature in the market



Strange stars: SQS vs. SQcS

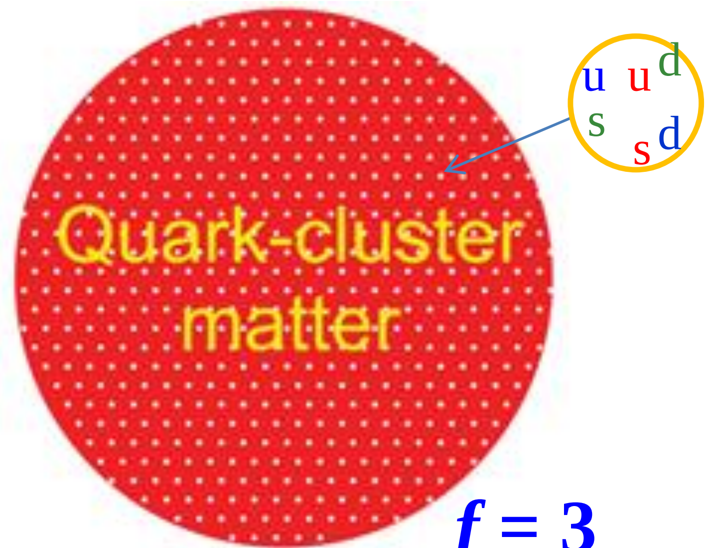
• **2-*f*** micro-nucleus **VS** **3-*f*** macro-nucleus



***f* = 2**

~ fm

Quantum gas/liquid?



***f* = 3**

$> \lambda_c \sim 10^3$fm

Classical solid?!

Macro-nucleus: ***condensed matter*** of quark-clusters!

Strange stars: SQS vs. SQcS

- 通俗：脉冲星就是“三味大原子核”
  - “两味小原子核”：熟知的微观原子核
  - “两味大原子核”：发展成“中子星”
  - “三味大强子”：“奇异夸克星”
  - “三味大原子核”：“奇异夸克集团星”
- 学名：脉冲星是“奇异夸克集团”凝聚体

Strange stars: SQS vs. SQcS

•To ***distinguish*** models by Observations?

Table 1. Neutron stars vs. Quark stars: to explain the observational features of pulsar-like stars in these two kinds of models.

	Phenomena observed	Normal neutron stars	(solid) quark stars	Note
Radio pulsars:	magnetospheric emission	ok?	ok?	$e^{\pm}$ plasma
	normal glitch	vortex (un)pinning	star-quake	to be tested
	slow glitch	???	in low-mass quark star	not in NS model
	(bi)-drifting sub-pulses	binding??	binding!	surface condition
	(free) precession	damped?	no damping	rigid or not
	timing noise	high in msPSRs?	solar or low mass	random torque
AXPs/SGRs*:	energy source	B-field	gravity & strain	magnetar?
	burst with glitch 10^{-6}	?	AISq*	sometimes
	super-flare	high-B magnetar?	giant-quake?	
CCOs*:	age discrepancy	?	quark star with fossil disk	
	erratic timing	?	torque by disk	
DTNs*:	non-atomic feature	high B or Z?	bare quark stars!	
Thermal radii	why small?	polar cap?	low-mass quark stars	local or global
APXPs*:	ADmsPSRs*	ok?	low-mass quark star?	spin up & down
XRBs*:	bursts	nuclear power	crusted quark star?	
Sub-msPSR*:	spuper-Kepler spin	no!	possible	prediction (QS)
Others:	supernova	ν-driven??	γ-driven?	not successful
	MACHOs*	?	(low-mass) quark stars?	
	UHECRs*	?	strangelets?	

*AXPs/SGRs: anomalous X-ray pulsars/soft γ-ray repeaters; CCOs: compact central objects; DTNs: dim thermal "neutron stars"; APXPs: accretion-powered X-ray pulsars; XRBs: X-ray bursters; Sub-msPSRs: sub-millisecond pulsars; MACHOs: massive compact halo objects; UHECRSs: ultra-high energy cosmic rays; AISq: accretion-induced star-quake.

Xu (2008)

Strange stars: SQS vs. SQcS

To *test* SQcS models by SN neutrinos

- Questions related to neutrino of JUNO
  - ✓ Can one reproduce SN1984A's ν with SQcS?
  - ✓ What's the difference?
  - ✓ ν-observational test: CCSN? DSNB?

Summary

- Strange stars: SQS vs. SQcS

✓ ν-emissivity of strange quark-cluster star

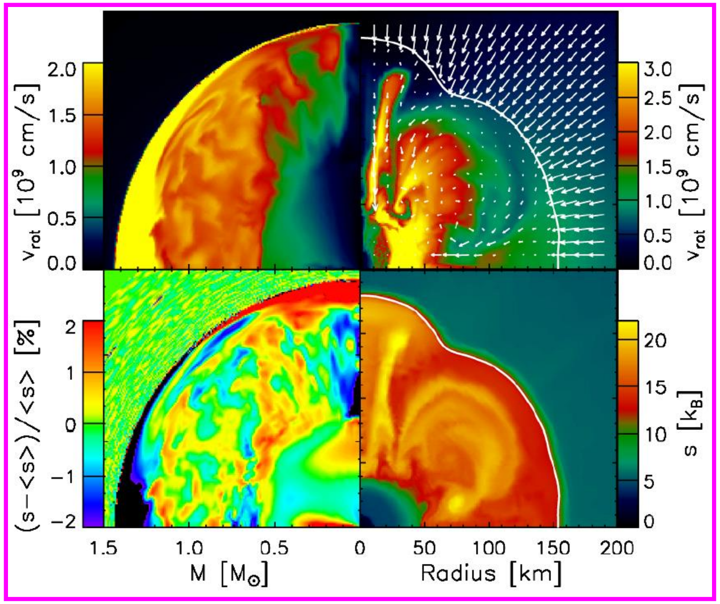
- Conclusions

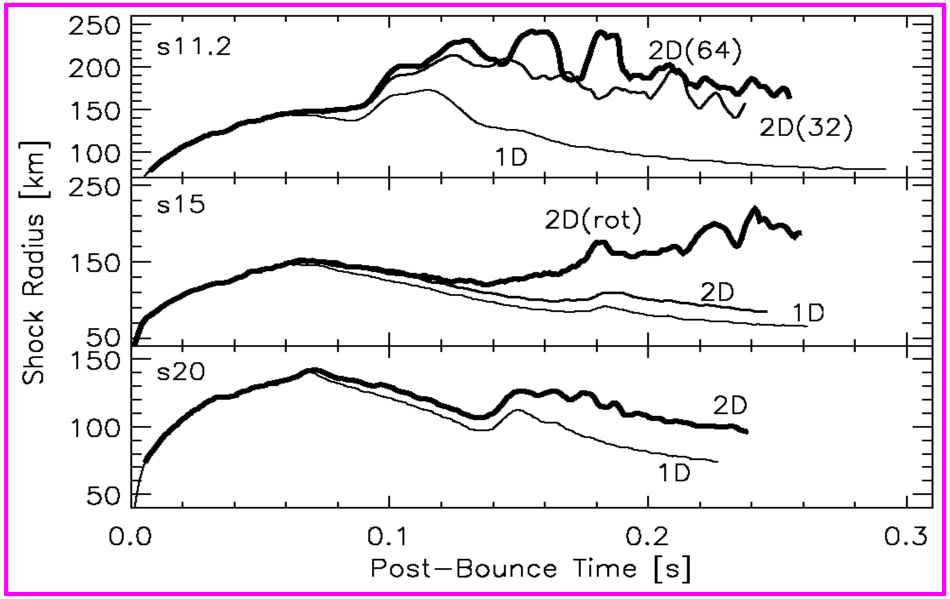
R. Buras, M. Rampp, H.-Th. Janka, K. Kifonidis, 2003, PRL90, 241101

Improved Models of Stellar Core Collapse and Still No Explosions: What Is Missing?

R. Buras, M. Rampp, H.-Th. Janka, and K. Kifonidis
Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, D-85741 Garching, Germany
(Received 7 March 2003; published 19 June 2003)

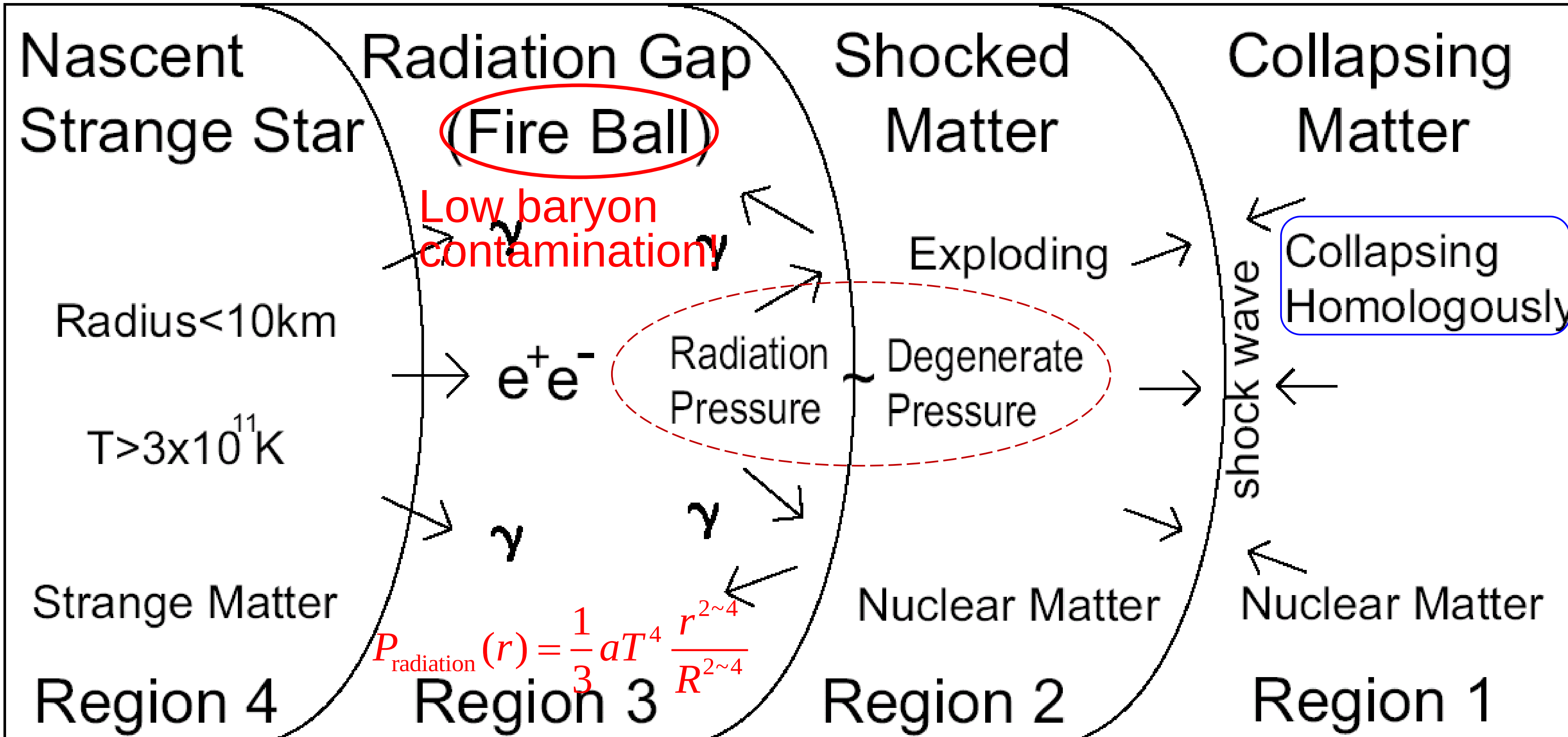
Two-dimensional hydrodynamic simulations of stellar core collapse are presented which for the first time were performed by solving the Boltzmann equation for the neutrino transport including a state-of-the-art description of neutrino interactions. Stellar rotation is also taken into account. Although convection develops below the neutrinosphere and in the neutrino-heated region behind the supernova shock, the models do not explode. This suggests missing physics, possibly with respect to the nuclear equation of state and weak interactions in the subnuclear regime. However, it might also indicate a fundamental problem with the neutrino-driven explosion mechanism.





ν-emissivity of strange quark-cluster star

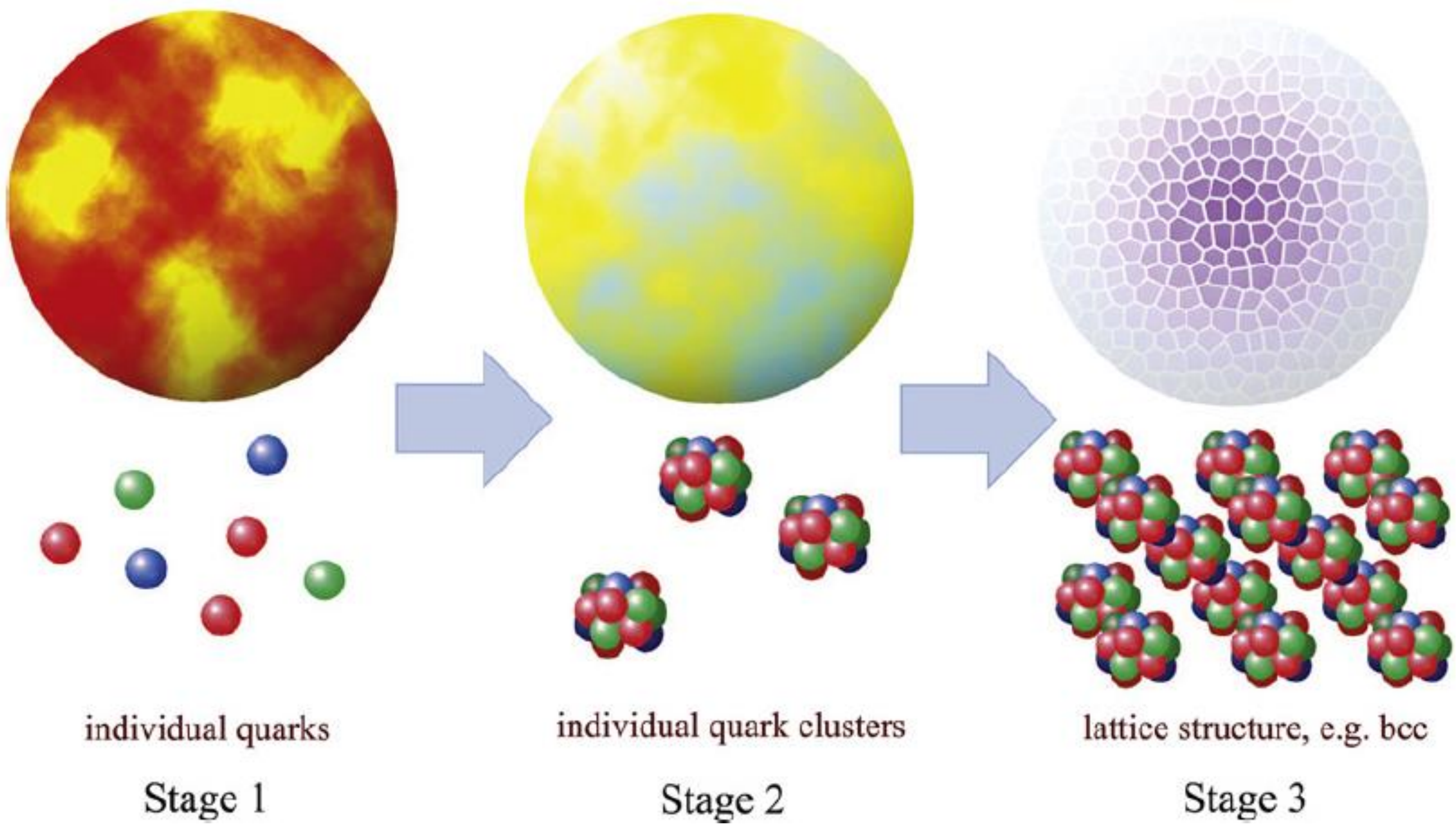
- Photon-driven supernova in strange star model?



Chen, Yu & Xu (2007, ApJ, 668, L55)

ν-emissivity of strange quark-cluster star

- Thermal evolution of strange quark-cluster star



Yu & Xu (2011, APh, 34, 439)

$$C_v^{e} \sim N_e \cdot \frac{k_B T_s}{E_F} \cdot k_B, \quad c_v^{l} = \frac{12\pi^4}{5} k_B \left(\frac{T_s}{\theta_D}\right)^3$$

ν-emissivity of strange quark-cluster star

- Total inner energy U of an SQcS:

$$U = (U_{\gamma+\nu} + U_{\rm sc} + U_e + U_\pi) \sim 10^{53}\,{\rm erg}$$

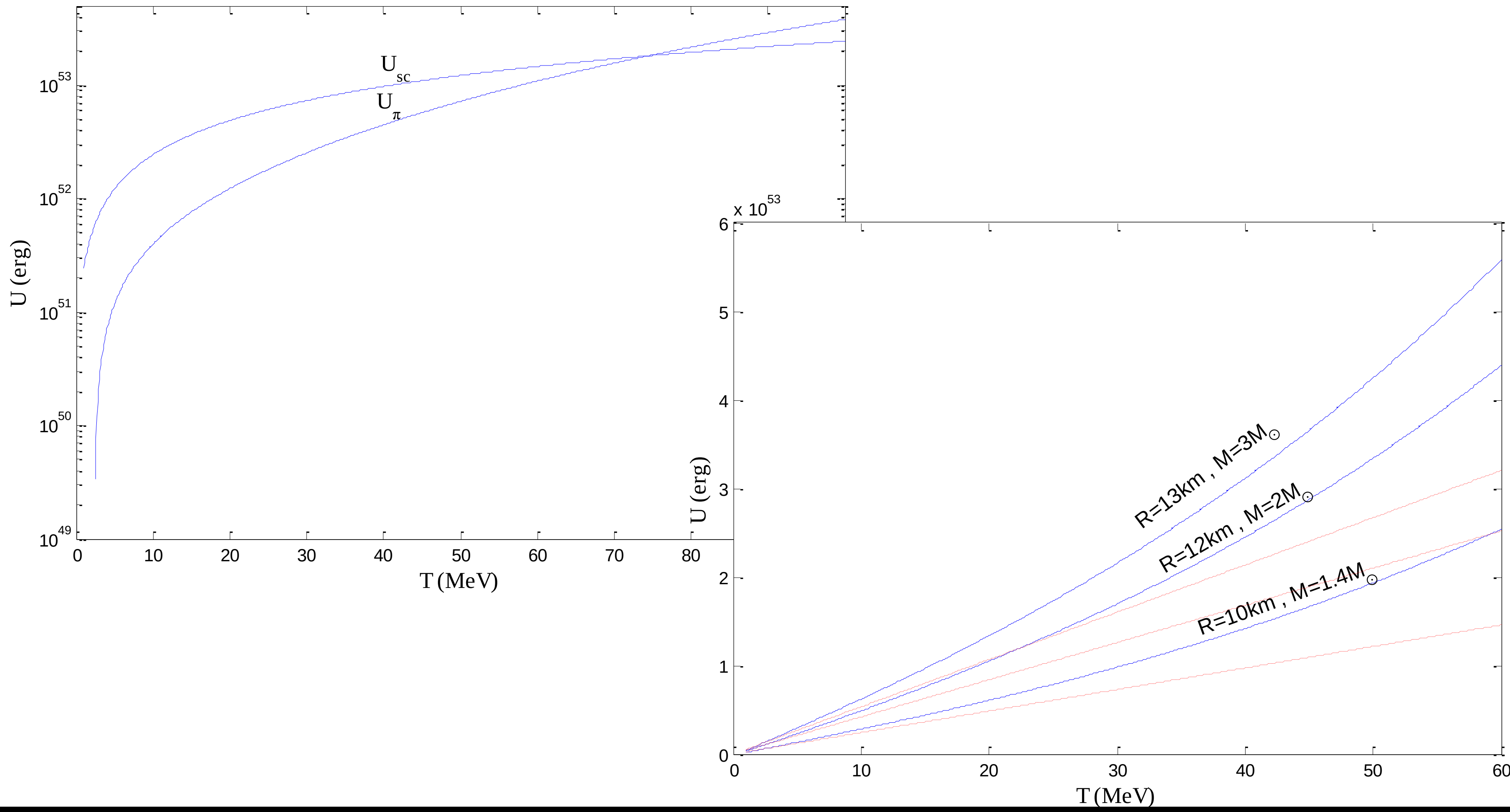
对于光子γ和中微子ν，在原奇异星内部，其能量密度近似于黑体谱形式，分别为$\frac{4\sigma_\gamma}{c}T^4$和$\frac{4\sigma_\nu}{c}T^4$，取奇异星半径$10^6$cm，初始温度$10^{11}K$，量级上可以估算出$U_{\gamma+\nu}\sim 10^{48}$erg，该项对星体内能贡献也可以忽略。

$$U_\pi = 3\int_0^\infty \frac{4\pi V}{h^3} p^2 \frac{\varepsilon}{e^{\frac{\varepsilon-\mu}{kT}} - 1} dp$$

$$U_{\rm sc} = N_{\rm sc}\frac{3}{2}kT$$

ν-emissivity of strange quark-cluster star

- Comparison between U_{sc} and U_{π}



ν-emissivity of strange quark-cluster star

- Neutrino emissivity of an SQcS

$$L = L_{\nu.s} + L_{\nu.b} + L_{\gamma}$$

$L_{\nu.s} = 4\pi R^2 \sigma_{\nu} T^4$是热辐射的中微子光度，表现出黑体辐射特性，因此用黑体辐射计算处理：

$$\epsilon_{\nu} = s \cdot \frac{8\pi \nu^2}{c^3} \cdot \frac{h\nu}{e^{\frac{h\nu}{kT}} + 1}$$

对全部中微子， $s = 6$

$$R_{\nu} = \left(\frac{c}{4}\right) \epsilon_{\nu}$$

$$R = \int_0^{\infty} R_{\nu} d\nu$$

$$\sigma_{\nu} = 14.88 \mathrm{W/(cm^2 \cdot s \cdot k^4)}$$

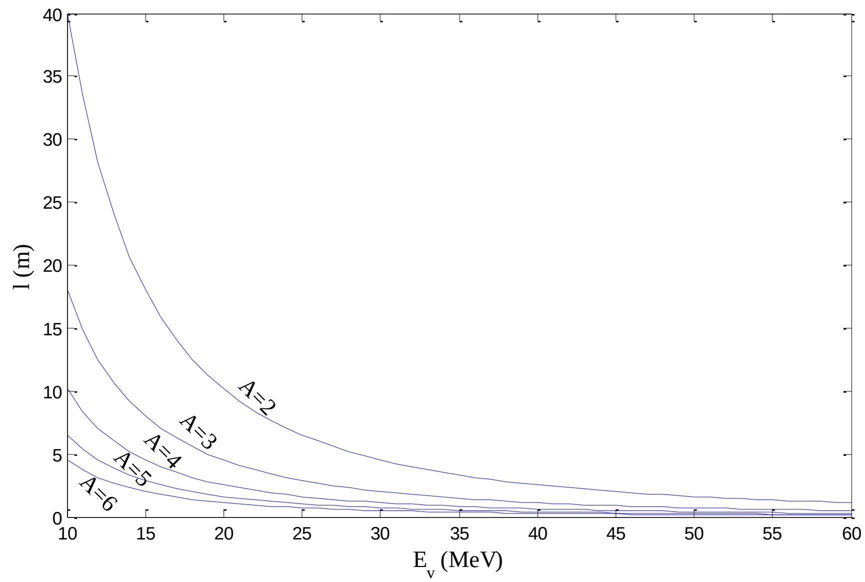
P. J. Walsh &C. F. Gallo在1980年的一篇文章“**Thermodynamic laws of neutrino and photon emission**”也有类似的处理。

ν-emissivity of strange quark-cluster star

$L_{v.b} = 4\pi R^2 l \cdot Q_v$，$l$是中微子在星体内部不透明的平均自由程，计算过程中，粑粒子——奇异粒子采用重核模型处理（Tubbs.D.L, ApJ,1975）。Q_v是中微子在高温下对反应产生的出射率，引用Itoh et.al (1989)的计算结果。其中l计算过程为

$$\sigma(v.sc) = \frac{1}{32}\sigma_0 A^2 \left(\frac{E_v}{m_e c^2}\right)^2$$

奇异粒子A可取2—6，$l = \frac{1}{n_{sc} \cdot \sigma(v.sc)} \sim 10^3\text{cm}$



ν-emissivity of strange quark-cluster star

- Cooling of strange quark-cluster star

固化之前： $-\frac{dU}{dt} = L_{\nu.s} + L_{\nu.b} + L_\gamma$

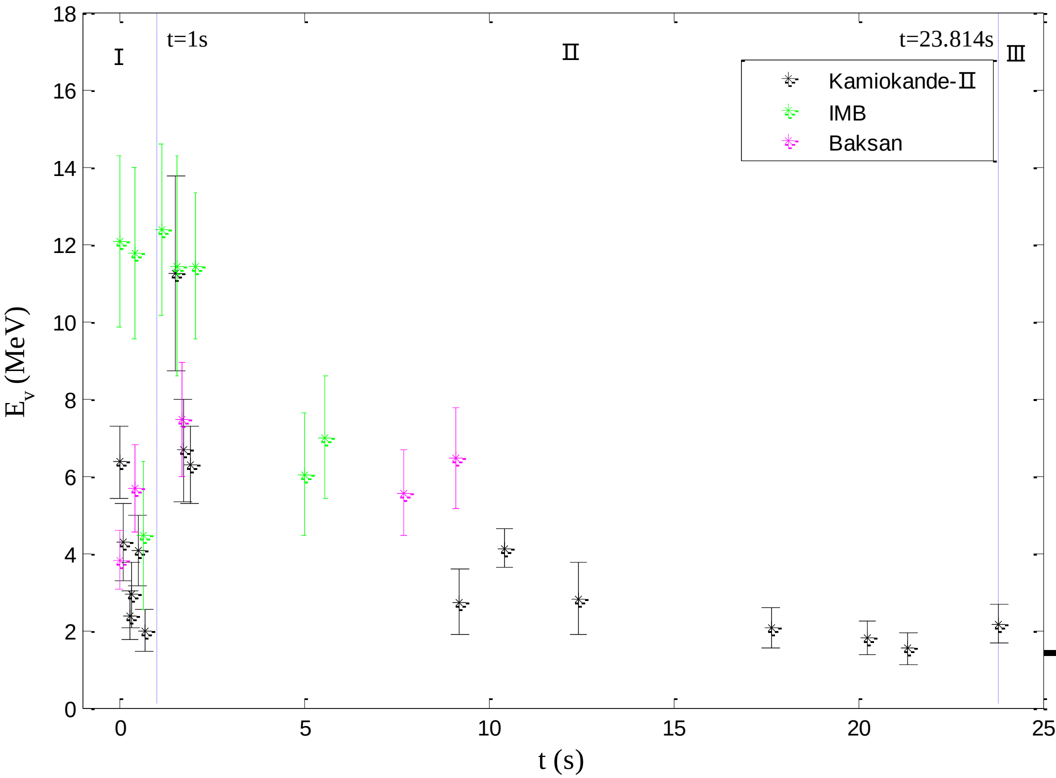
液固相变： $(L_\nu + L_\gamma)\cdot t = U(T_m)$， T_m： 溶解温度

固化之后： $-C_v\frac{dT}{dt} = L_{\nu.s} + L_{\nu.b} + L_\gamma$

注意：演化后期冷却过程主要由奇异夸克集团热容主导，因此C_v代表结晶固化后的奇异夸克集团晶格热容，采用德拜模型计算。

ν-emissivity of strange quark-cluster star

- Supernova neutrino burst: SN1987A



Stage Ⅰ: rapid cooling
Stage Ⅱ : slow cooling
Stage Ⅲ : cut off

对于超新星中微子，平均能量与温度对应关系为

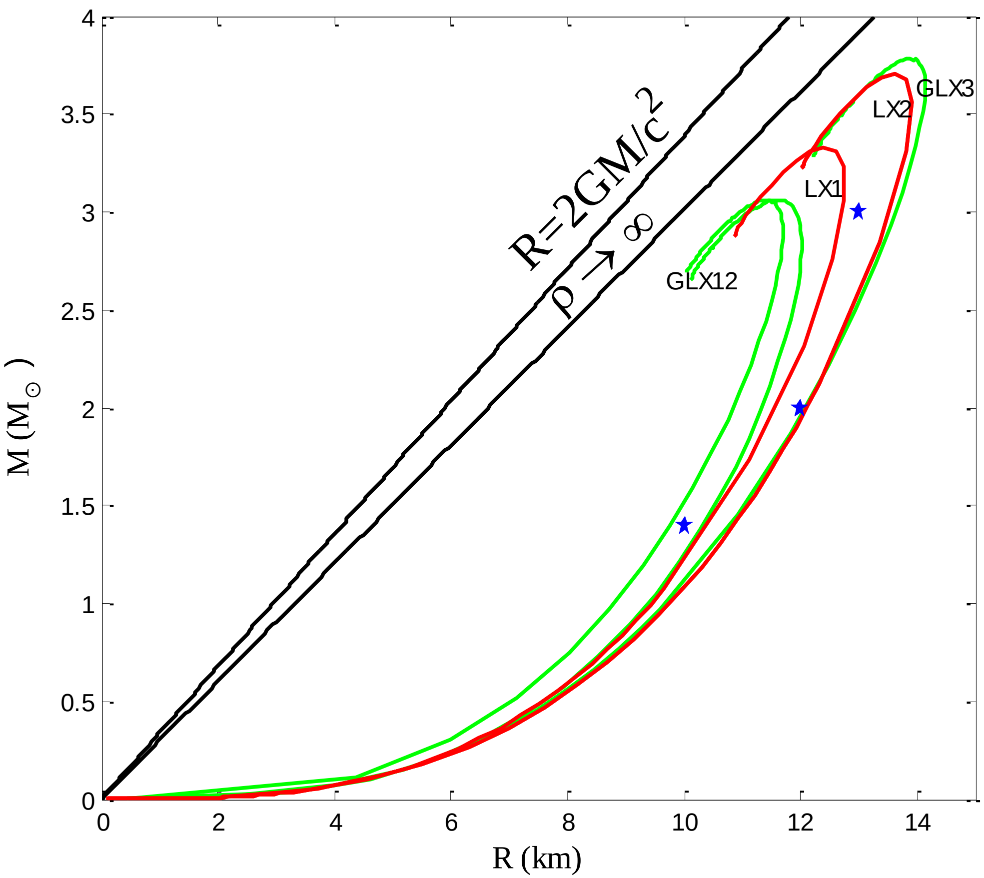
$$\langle E_\nu \rangle = 3.15T$$

	N_p (10^{32})	E_{min} (MeV)	Background events in 30 s	σ_{stat} (MeV)	σ_{syst} (MeV)
Kamiokande-II	1.4	7.5	0.55	1.27	1.0
“	“	4.5	5.6	“	“
IMB	4.6	15	0.01	3.0	0.4
Baksan	0.2	10	1.0	0.0	2.0

(Vissani F,J.Phys.G:Nucl.Part.Phys,2014)

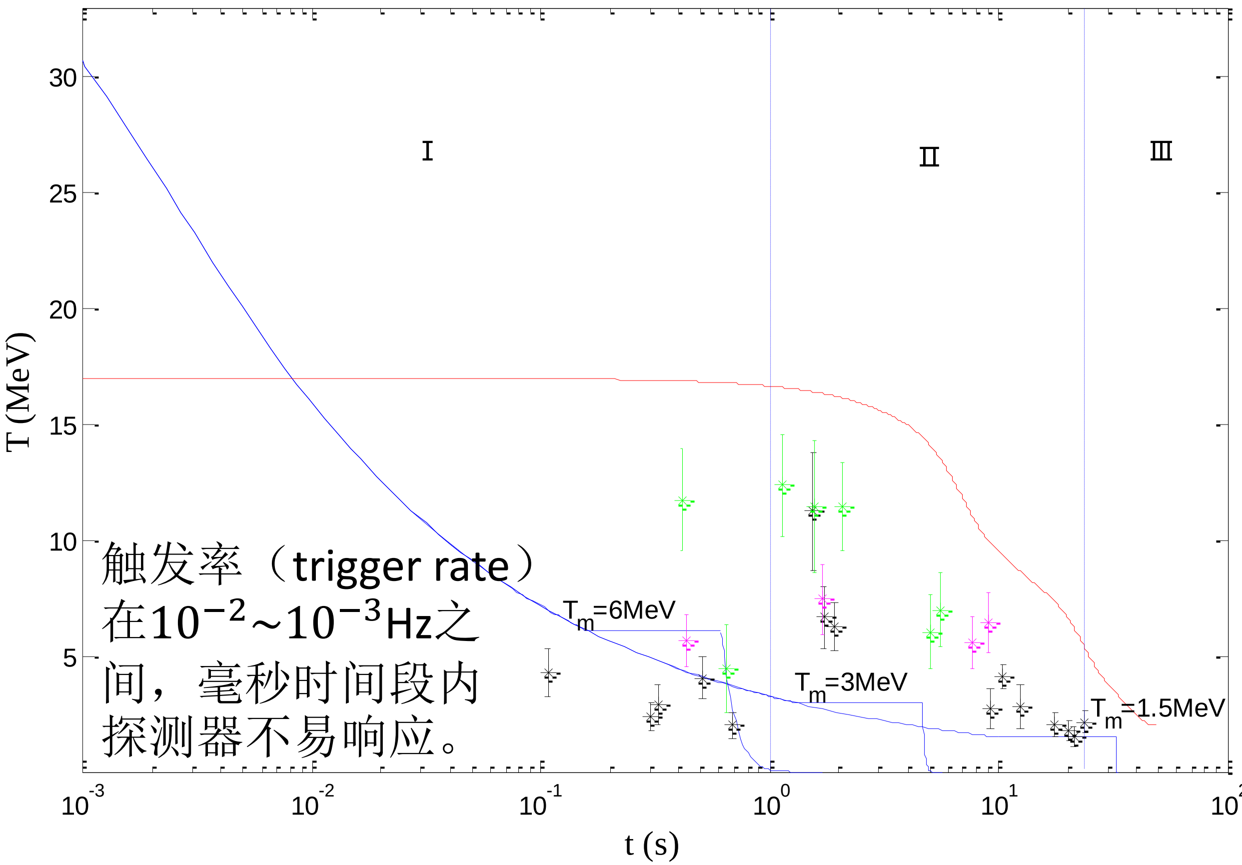
ν-emissivity of strange quark-cluster star

- Can one reproduce SN1987A in SQcS model?



$$M_1 = 1.4M_\odot, \quad R_1 = 10\text{km}$$
$$M_2 = 2M_\odot, \quad R_2 = 12\text{km}$$
$$M_3 = 3M_\odot, \quad R_3 = 13\text{km}$$

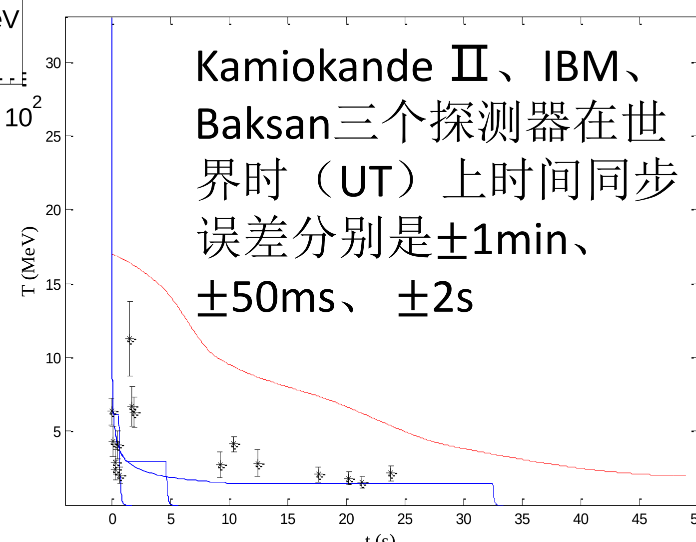
ν-emissivity of strange quark-cluster star



红线表示的是Pons.J.A,Reddy.S在1999年的计算的普通中子星模型初期的热演化过程，具体参考“Evolution of proto-neutron stars”（Pons.J.A,Reddy.S ,Ap J,1999）

$M_1 = 1.4M_\odot$，$R_1 = 10\text{km}$

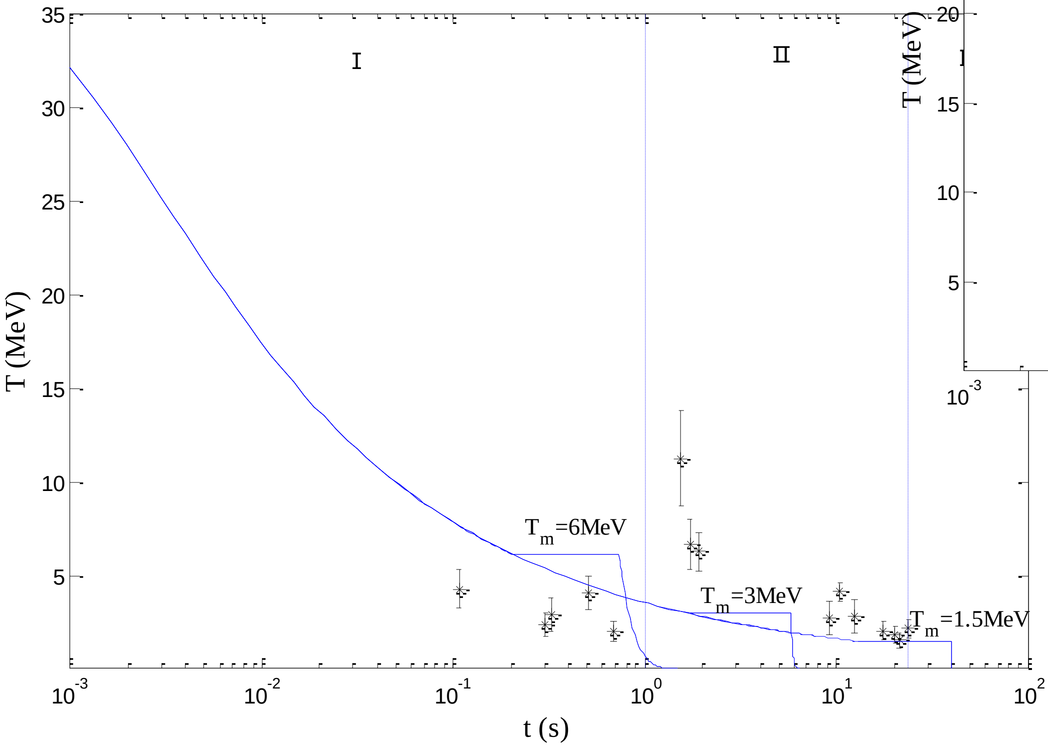
其中Ⅰ、Ⅱ 、Ⅲ分别对应中微子暴的三个阶段。$T_0 = 40$ MeV.

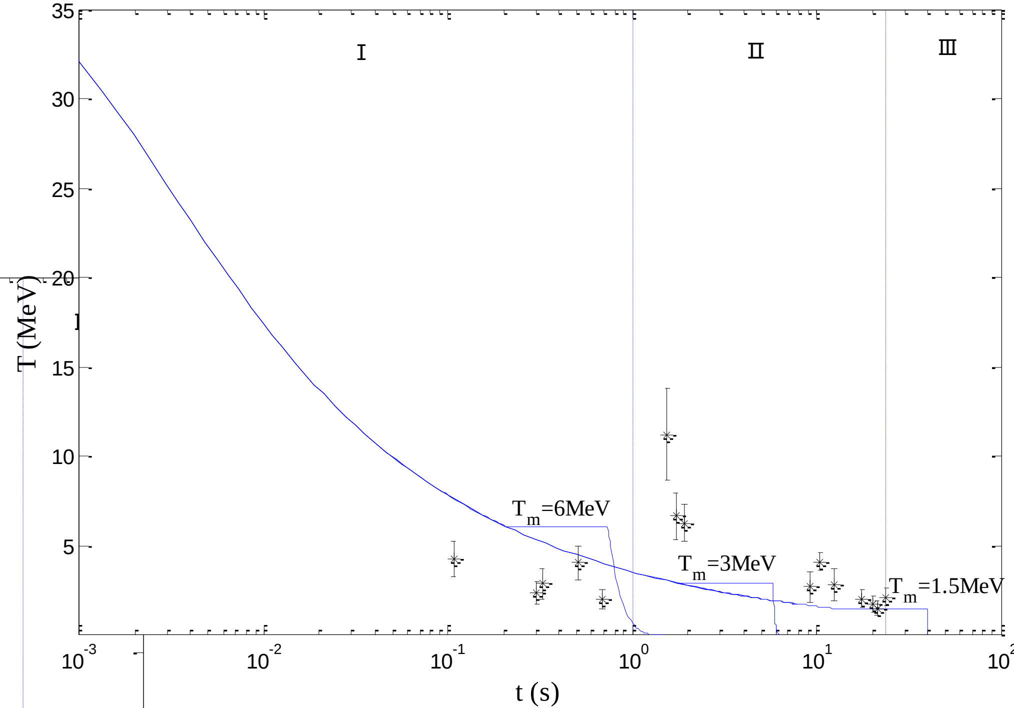


ν-emissivity of strange quark-cluster star

- Can one reproduce SN1987A in SQcS model?

$M_2 = 2M_{\odot}$, $R_2 = 12\text{km}$





$M_3 = 3M_{\odot}$, $R_3 = 13\text{km}$

Summary

- Strange stars: SQS vs. SQcS
- ν-emissivity of strange quark-cluster star

✓ Conclusions

Conclusions

- We can ***reproduce*** SN1987A's neutrino burst in SQcS model.
- There is a neutrino ***cutoff*** in our model, relevant to the ***melting temperature*** of SQcS, that could be tested by either CCSN or DSNB with future advanced neutrino observatories.

THANKS!

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