Probing Quark Matter in Neutron Stars

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- Quark matter in neutron star interiors may have distinctive signatures in basic observables such as

(1) masses and radii,

(2) surface temperatures versus spin-down age,

(3) spin-down rates of milli-second pulsars, and

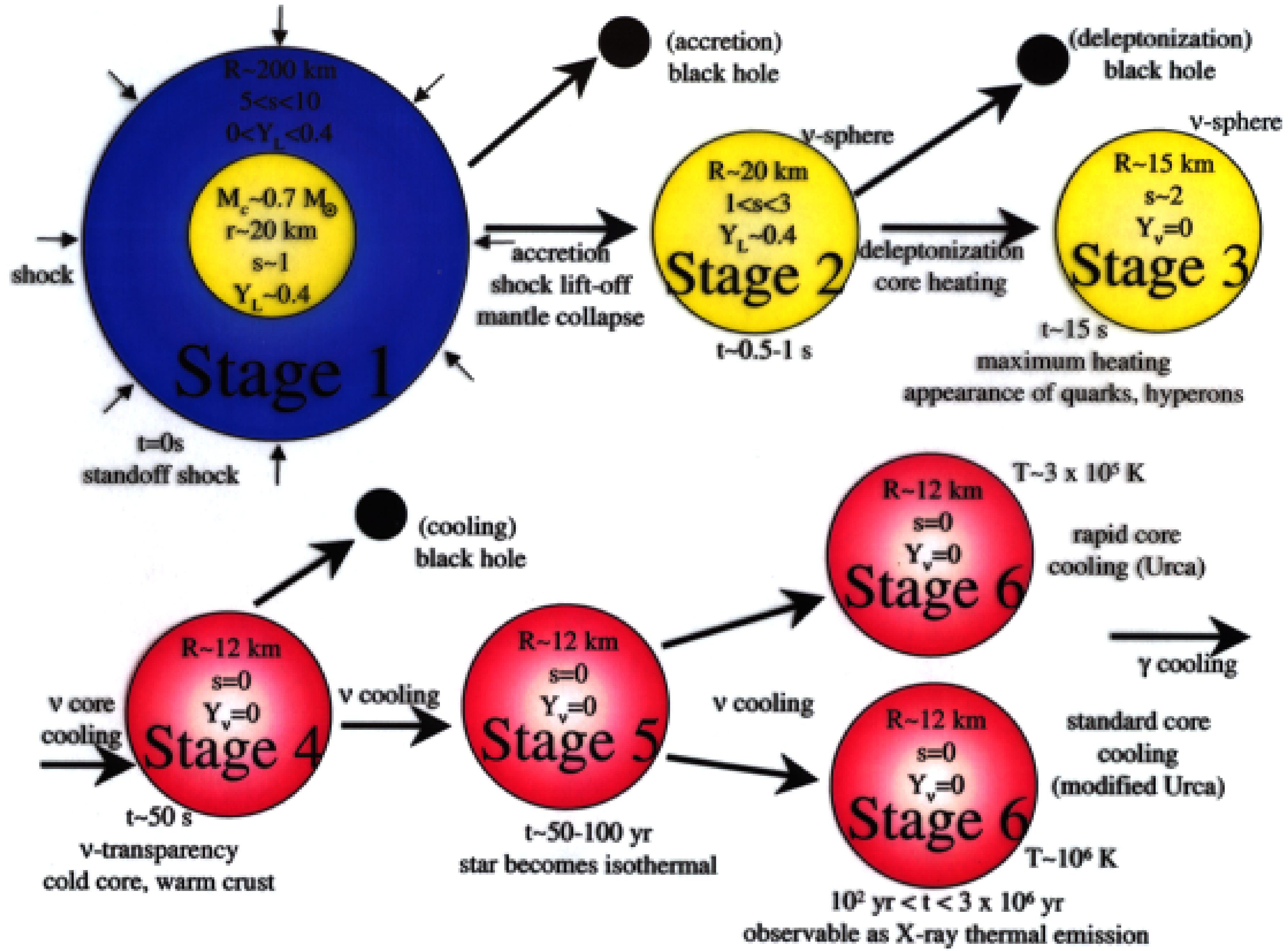
(4) $\nu-$luminosities from core collapse supernovae.

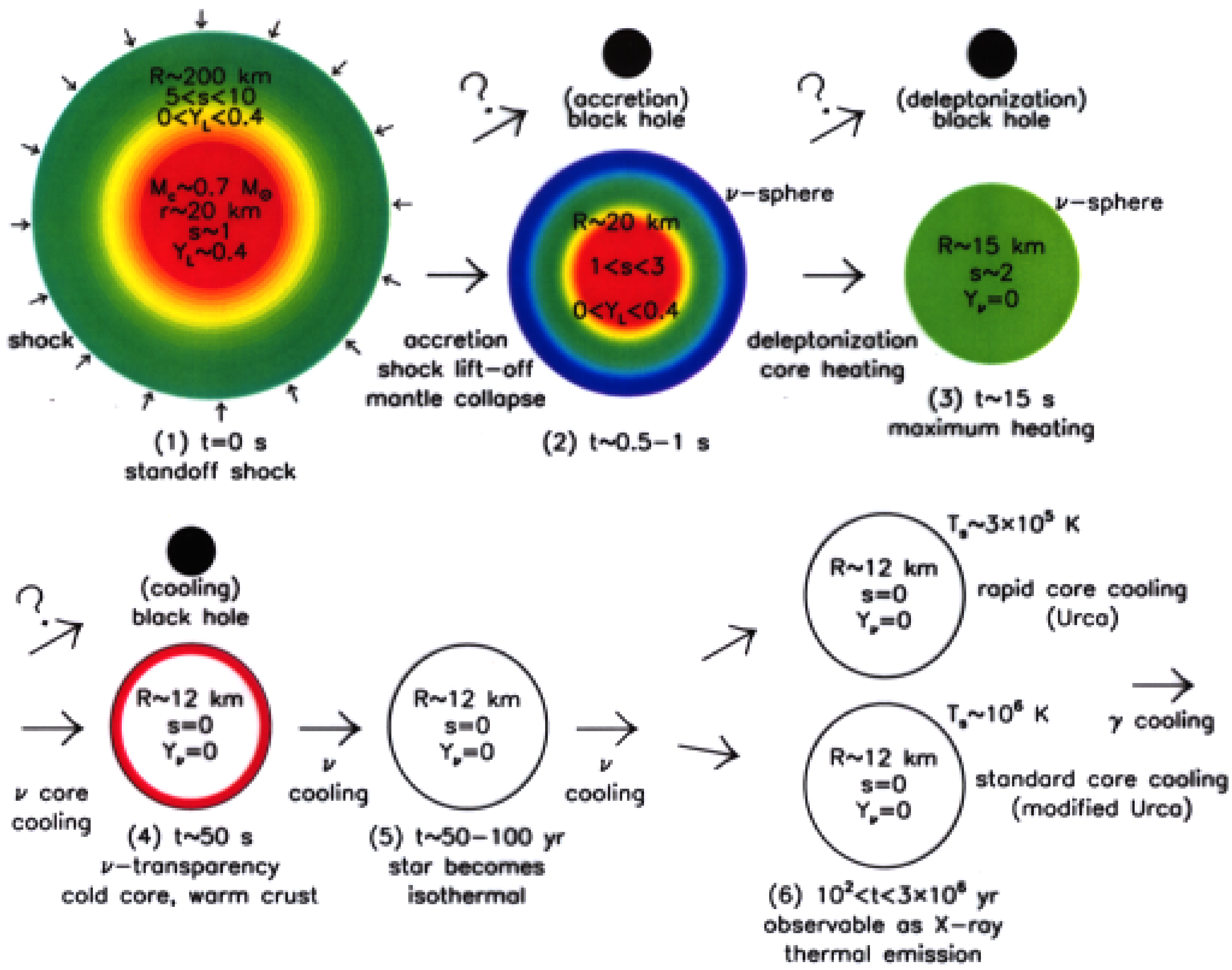
- What are the prospects of detecting quarks through observations

→ in X-ray, UV, optical, and radio frequencies with the HST, Chandra, XMM *etc.*, and,

→ of supernova neutrinos from detectors such as the SuperK, SNO, and others including UNO?

- Gains: Delineation of QCD at finite baryon density in addition to the composition, structure, and evolution of both newly-born and old neutron stars.


R~200 km
5<s<10
0<Y_L<0.4
M_c~0.7 M_⊙
r~20 km
s~1
Y_L~0.4
Stage 1
shock
t=0s
standoff shock
(accretion)
black hole
accretion
shock lift-off
mantle collapse
ν-sphere
R~20 km
1<s<3
Y_L~0.4
Stage 2
t~0.5-1 s
(deleptonization)
black hole
deleptonization
core heating
ν-sphere
R~15 km
s~2
Y_ν=0
Stage 3
t~15 s
maximum heating
appearance of quarks, hyperons
(cooling)
black hole
ν core
cooling
R~12 km
s=0
Y_ν=0
Stage 4
t~50 s
ν-transparency
cold core, warm crust
ν cooling
R~12 km
s=0
Y_ν=0
Stage 5
t~50-100 yr
star becomes isothermal
ν cooling
T~3 x 10⁵ K
R~12 km
s=0
Y_ν=0
Stage 6
rapid core
cooling (Urca)
γ cooling
R~12 km
s=0
Y_ν=0
Stage 6
standard core
cooling
(modified Urca)
T~10⁶ K
10² yr < t < 3 x 10⁶ yr
observable as X-ray thermal emission



R~200 km
5<s<10
0<Y_L<0.4
M_c~0.7 M_⊙
r~20 km
s~1
Y_L~0.4
shock
(1) t=0 s
standoff shock
?
accretion
shock lift−off
mantle collapse
(accretion)
black hole
ν−sphere
R~20 km
1<s<3
0<Y_L<0.4
(2) t~0.5−1 s
?
deleptonization
core heating
(deleptonization)
black hole
ν−sphere
R~15 km
s~2
Y_ν=0
(3) t~15 s
maximum heating
?
(cooling)
black hole
ν core
cooling
R~12 km
s=0
Y_ν=0
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cold core, warm crust
ν
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R~12 km
s=0
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(5) t~50−100 yr
star becomes
isothermal
ν
cooling
T_s~3×10^5 K
R~12 km
s=0
Y_ν=0
rapid core cooling
(Urca)
T_s~10^6 K
R~12 km
s=0
Y_ν=0
standard core cooling
(modified Urca)
γ cooling
(6) 10^2<t<3×10^6 yr
observable as X−ray
thermal emission

The Basic Equations

Structure : (TOV)

$$\frac{\partial P}{\partial r} = -(\rho + P)\frac{e^{2\Lambda}}{r^2}(m + 4\pi r^3 P)$$

$$\frac{\partial \mu}{\partial r} = 4\pi r^2 n_B e^{\Lambda}$$

$$\frac{\partial m}{\partial r} = 4\pi r^2 \rho$$

Transport :

$$\frac{dY_\nu}{d\tau} + e^{-\phi}\frac{\partial(e^{\phi}4\pi r^2 F_\nu)}{\partial \mu} = \frac{S_N}{n_B}$$

$$\frac{dY_e}{d\tau} = -\frac{S_N}{n_B}$$

$$\frac{dE}{d\tau} + P\frac{d(\frac{1}{n_B})}{d\tau} + e^{-2\phi}\frac{\partial(e^{2\phi}4\pi r^2 H_\nu)}{\partial \mu} = 0$$

metric:

$$ds^2 = -\ e^{2\phi}dt^2 + e^{2\Lambda}dr^2 + r^2 d\theta^2 + r^2\sin^2\theta d\varphi^2$$

$$e^{\phi} = \sqrt{-g_{00}} \quad e^{2\Lambda} = \frac{1}{(1 - 2Gm/rc^2)} \qquad \frac{d}{d\tau} = e^{-\phi}\frac{d}{dt}$$

n_B:= baryon density
m:= enclosed mass
F_ν:=Lepton Flux
S := source term
μ := enclosed rest mass
ρ :=mass-energy density
H_ν:= Energy Flux
τ :=proper time

Evolution of Protoneutron Stars

- Physical Inputs (Dense Matter EOS & $\nu-$Opacities)

1. Stiffness of nucleonic EOS
2. Effects of composition (strangeness) & phase transitions
3. $\nu-$opacities consistent with the EOS

- Neutrino Transport (Diffusion Approximation)

1. Allows comparision to earlier works
2. Connections between microphysical ingredients & global characteristics of $\nu-$emission
3. Multigroup approach required for precise $\nu-$ spectra

- Neutrino Signals (Sensitivity)

1. Baseline simulations
2. Vary initial conditions & remnant mass
3. Vary composition and physical state of matter
4. Metastable neutron stars

- remnant mass, composition & EOS of dense matter
- ν_x- mass, magnetic moment, oscillations, . . .
- . . . .

NEUTRINO TRAPPED STARS
(Newborn neutron stars)

- Entropy/baryon $\sim 1-2$
- Leptons/baryons $Y_{L\ell} = Y_\ell + Y_{\nu\ell}$, ($\ell = e, \mu$ and τ) conserved on dynamical timescales of collapse
- Neutrinos trapped !
- Chemical equilibrium

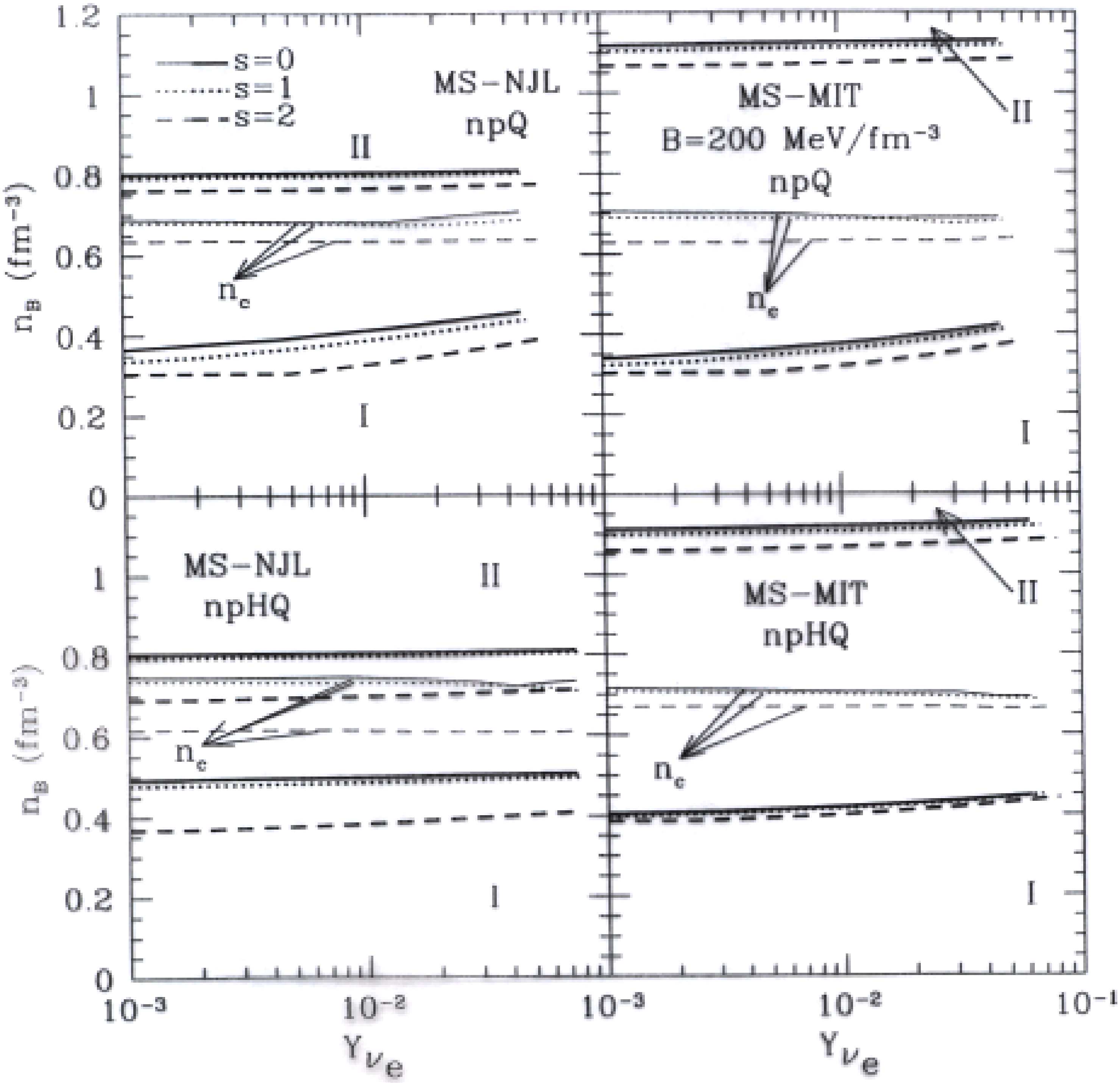
$$\Rightarrow \boxed{\mu_i = b_i\mu_n - q_i(\mu_\ell - \mu_{\nu\ell})}$$

b_i : baryon #
q_i : baryon charge
$\mu_{\nu\ell}$: neutrino chemical potential

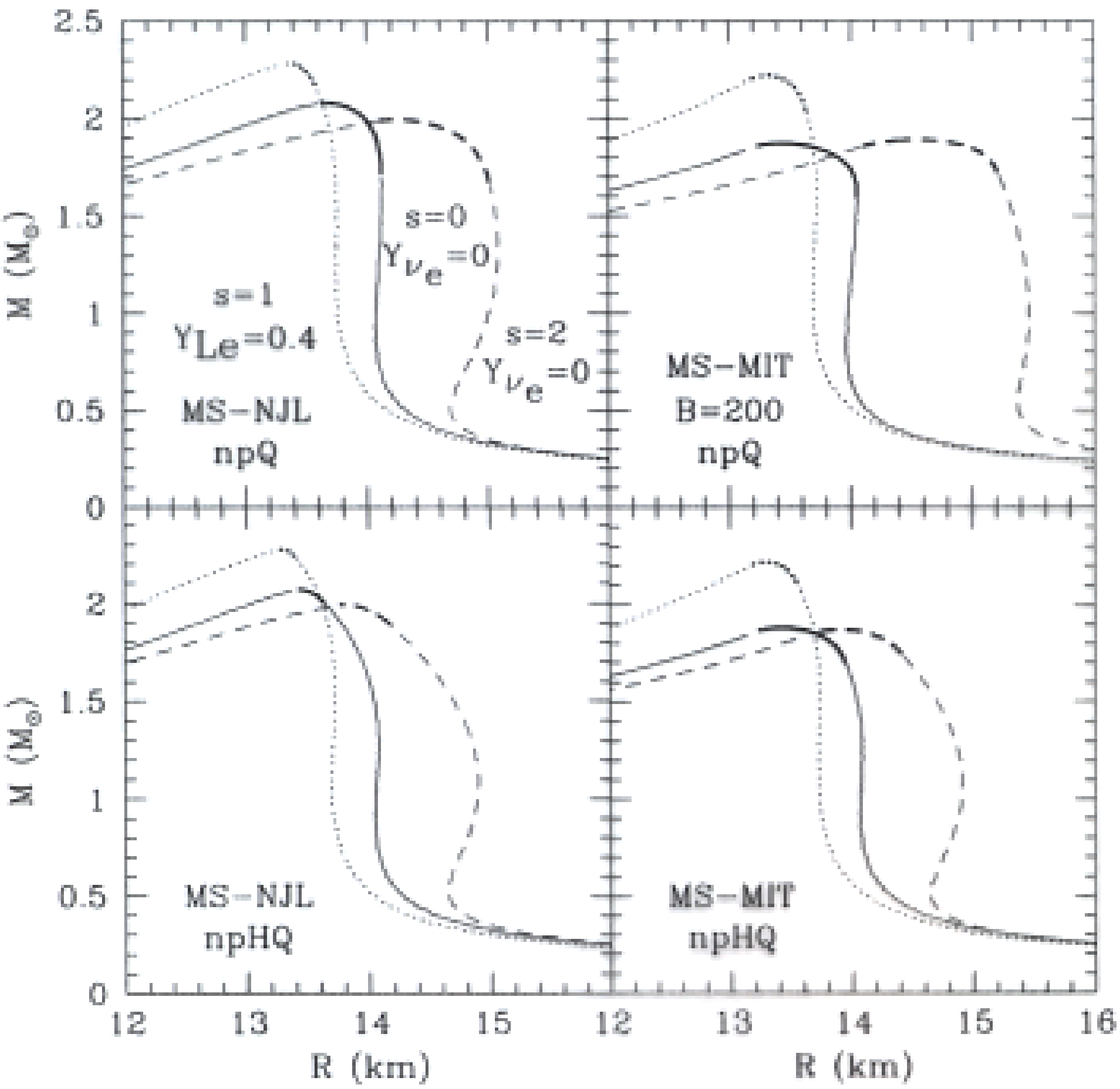
- Collapse calculations

$$\Rightarrow Y_{Le} = Y_e + Y_{\nu_e} \simeq 0.4$$
$$Y_{L\mu} = Y_\mu + Y_{\nu_\mu} \simeq 0.0$$

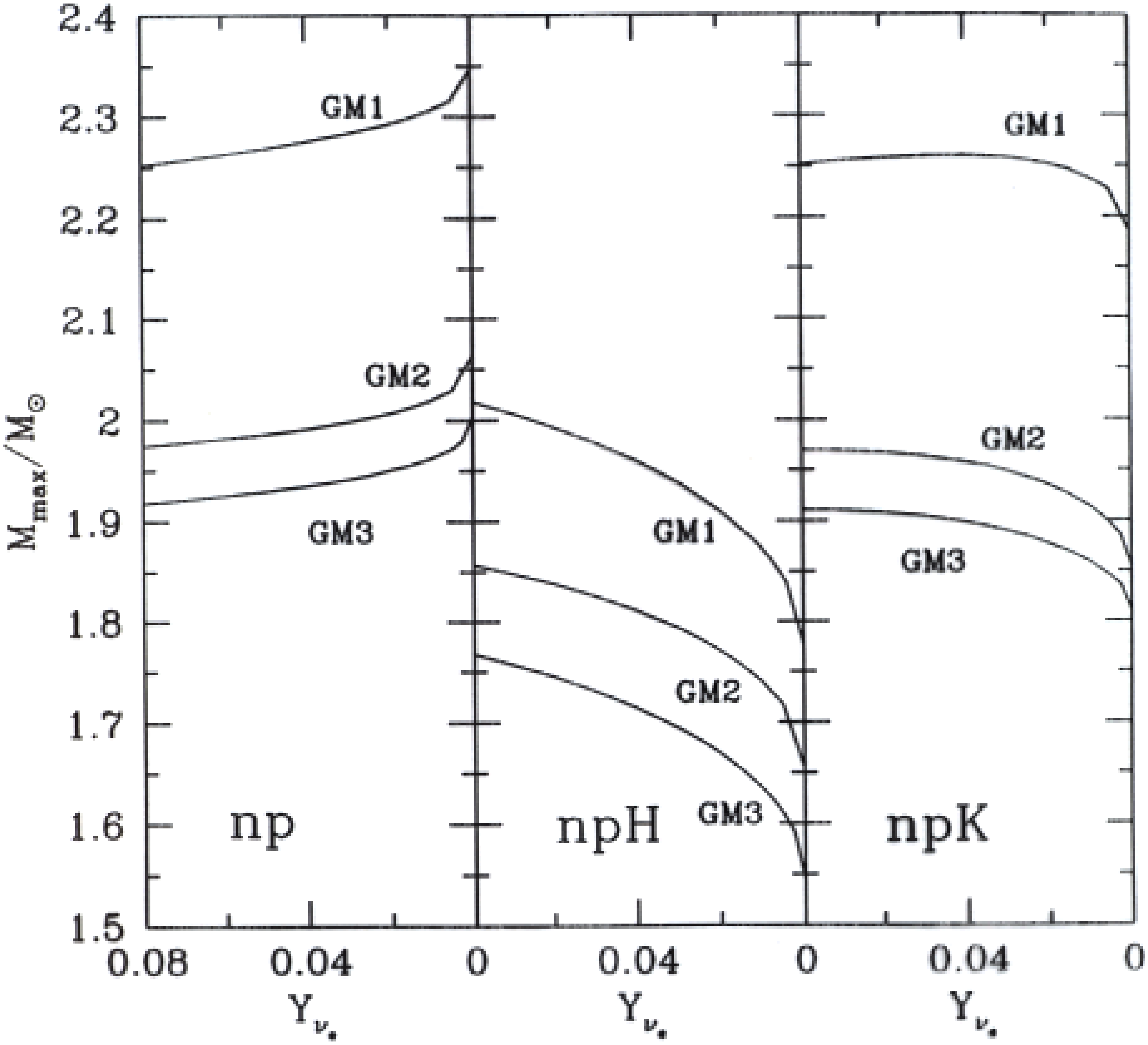
Phase Diagram



Metastability

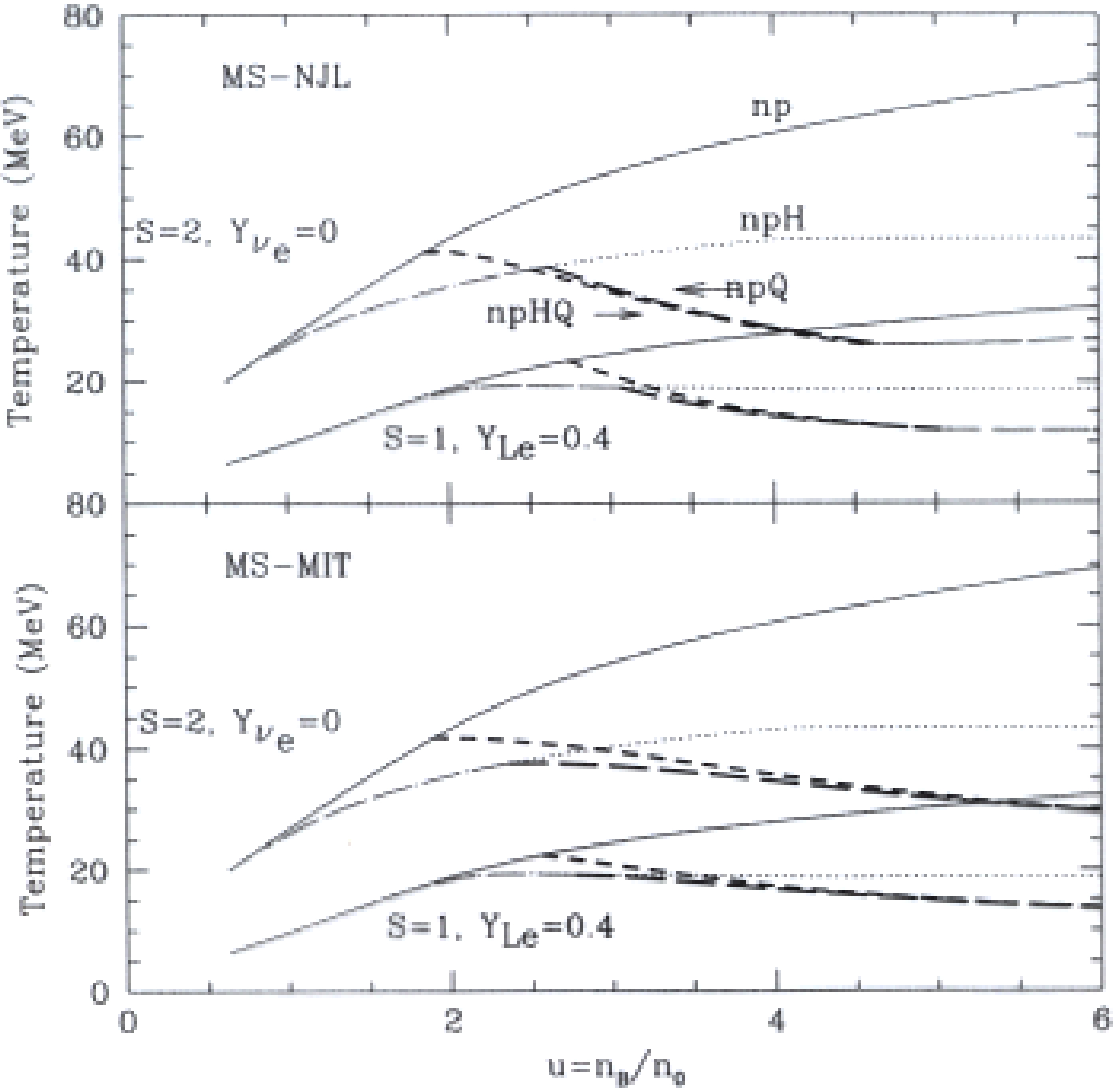


- Neutrino trapping creates metastable configurations in all models - The maximum mass decreases upon deleptonization



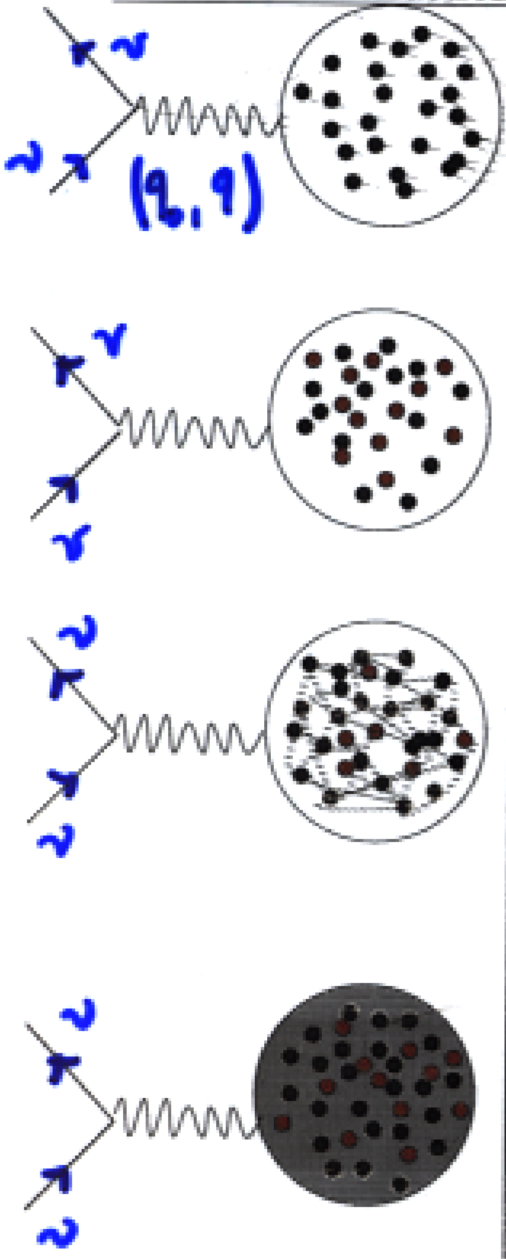
$$Y_{\nu_e} = \frac{n_{\nu_e}}{n_b}$$

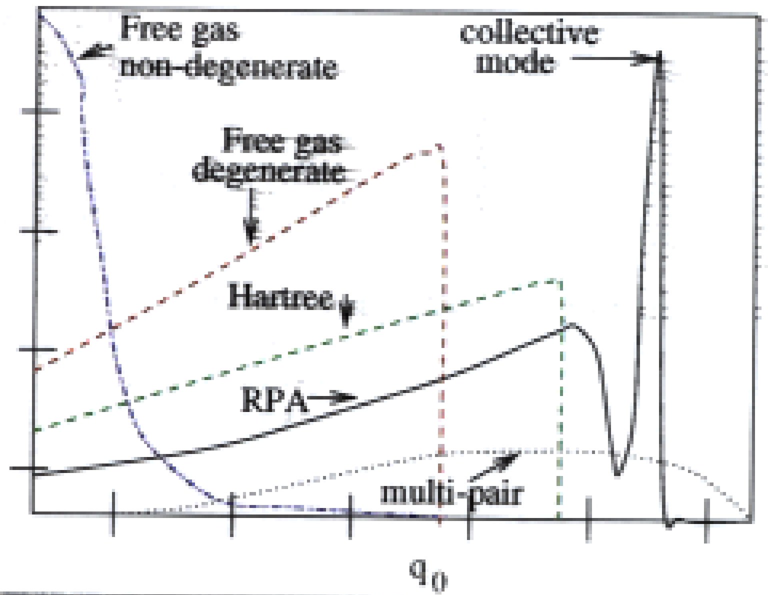
Temperature

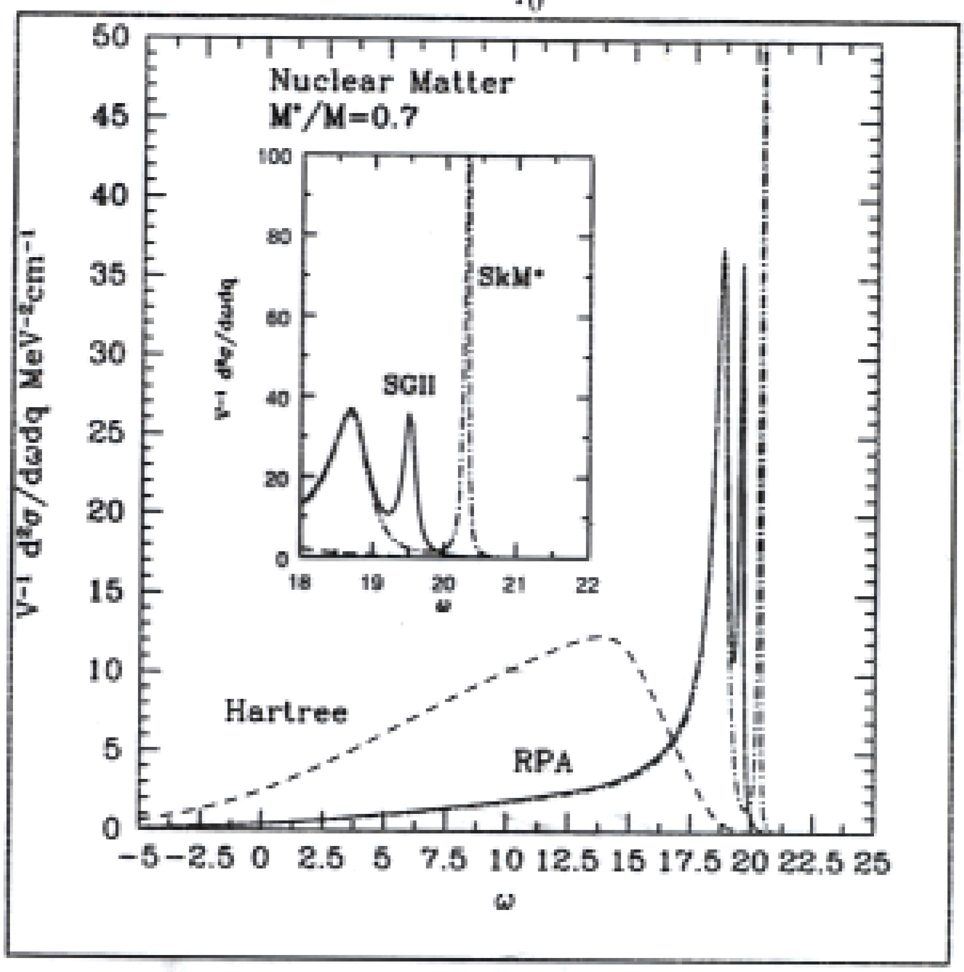


- Temperature decreases along an adiabat as a function of density in the mixed phase
- This may have an observable effect on neutrino spectra - Lower temperature tends to decrease the neutrino energies and increase the neutrino mean free paths

Neutrino Interactions







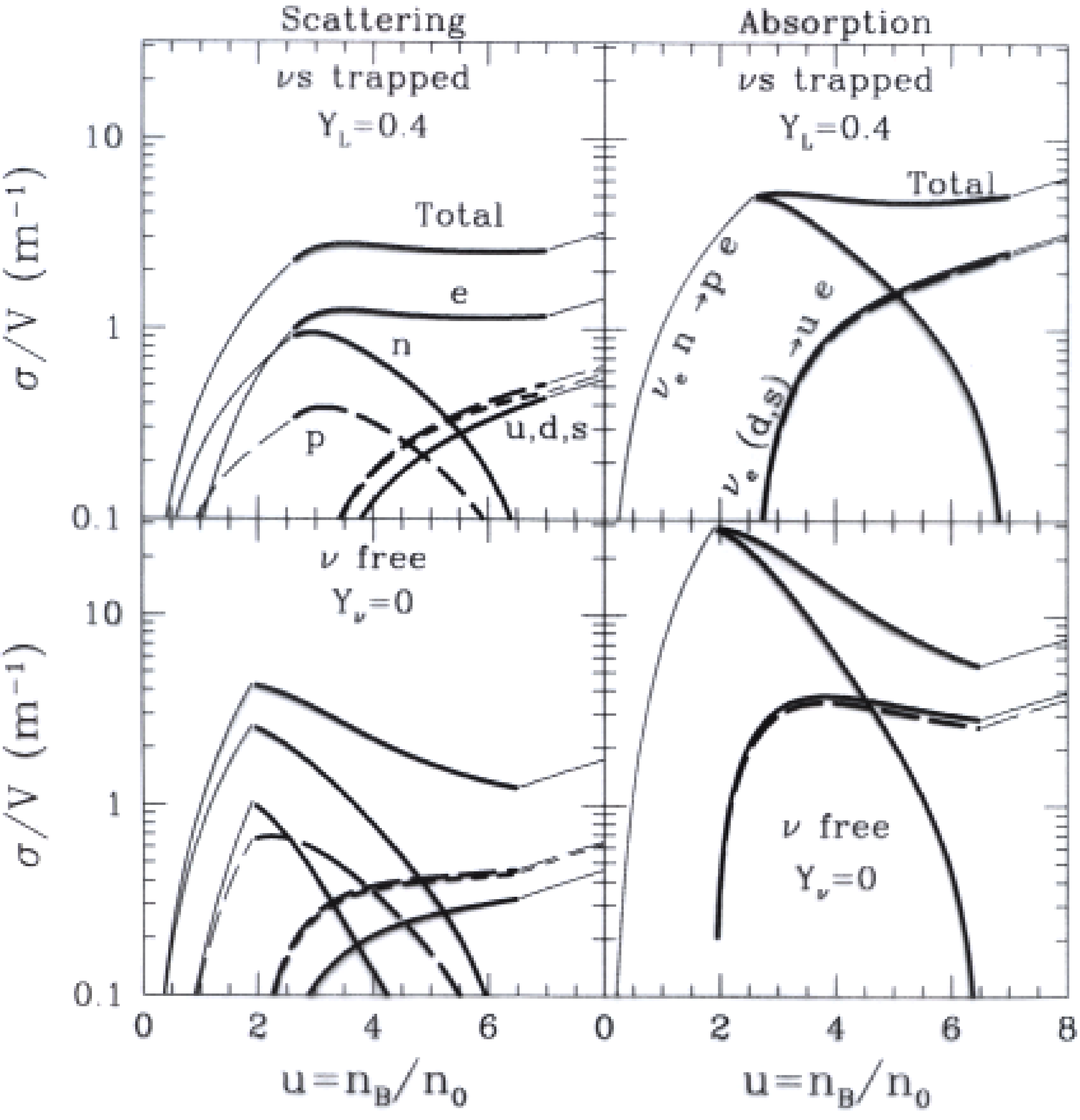
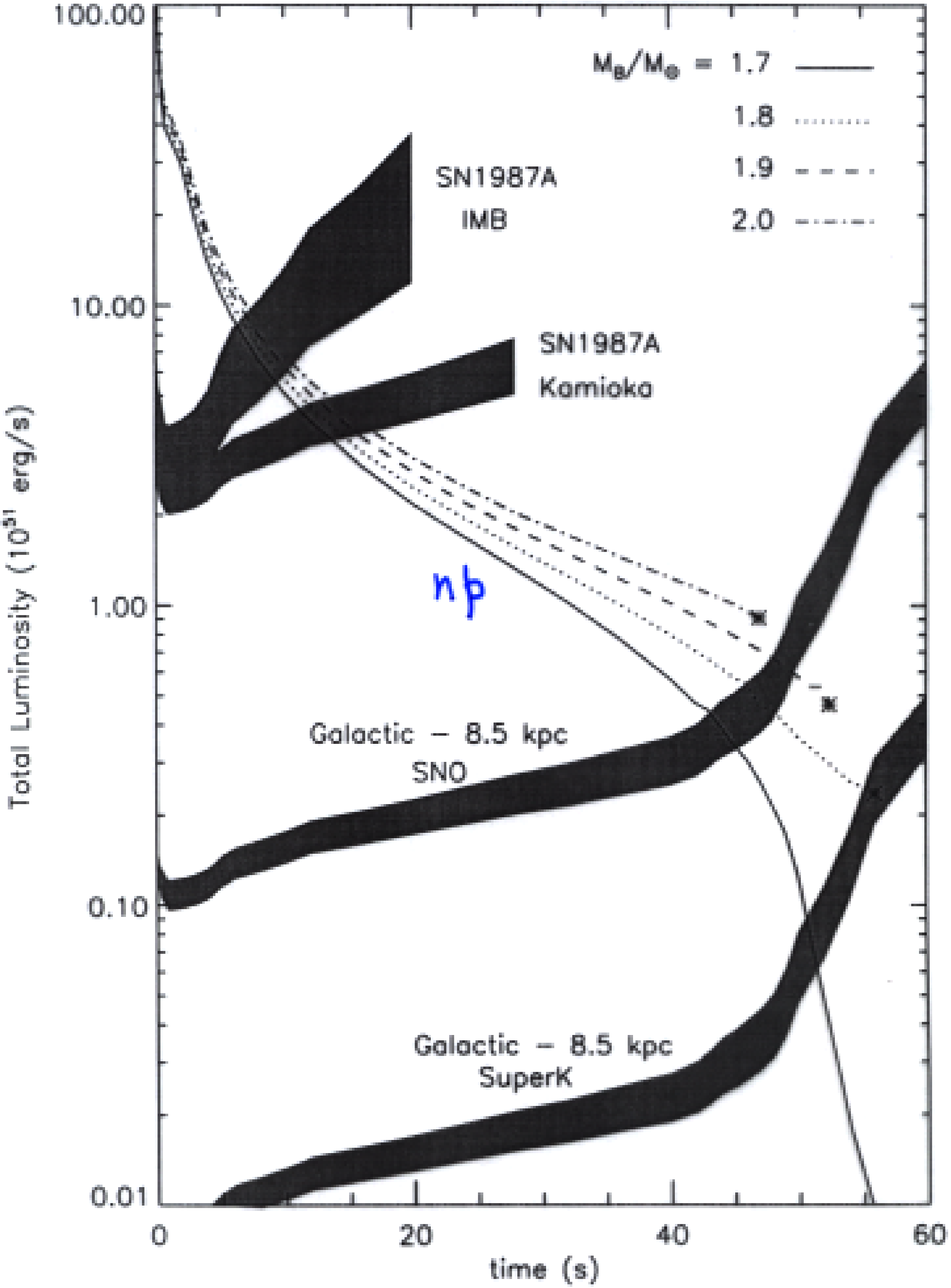


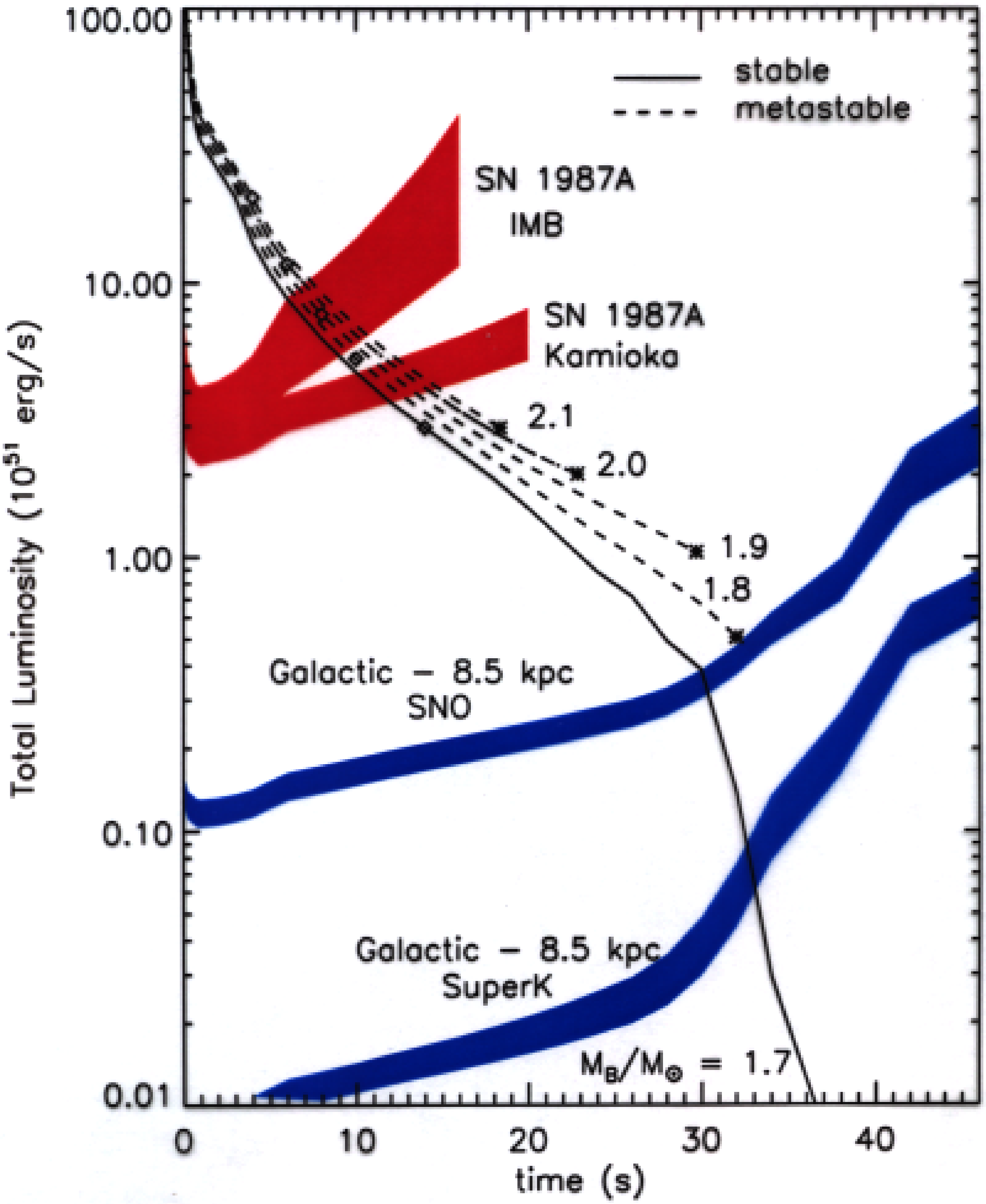
Figure 3: ν_e cross sections with various particles as a function of baryon density ($n_0 = 0.16$ fm^{-3}) in the mixed phase. The upper panels correspond to Stage 2 in Fig. 1 and the lower panels correspond to Stage 3. Thick lines show the mixed phase region. Color designation: hadrons-red, quarks-green, leptons-blue, and total-black.

npk
H
Q

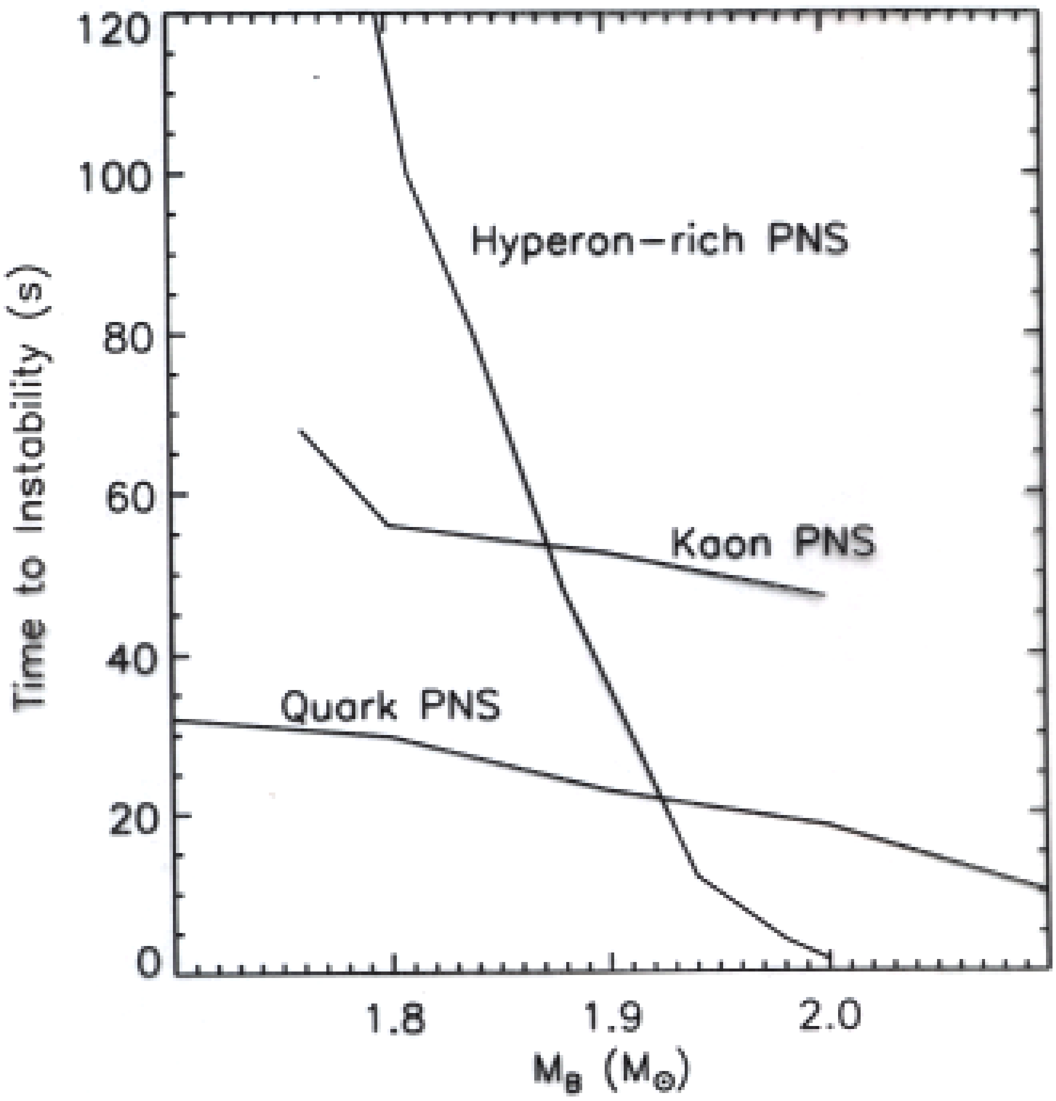


Total Luminosity (10^{51} erg/s)
time (s)
$M_B/M_\odot$ = 1.7
1.8
1.9
2.0
SN1987A
IMB
SN1987A
Kamioka
np
Galactic – 8.5 kpc
SNO
Galactic – 8.5 kpc
SuperK

Fig. 10.—



stable
metastable
SN 1987A
IMB
SN 1987A
Kamioka
2.1
2.0
1.9
1.8
Galactic – 8.5 kpc
SNO
Galactic – 8.5 kpc
SuperK
$M_B/M_\odot$ = 1.7
Total Luminosity (10^{51} erg/s)
100.00
10.00
1.00
0.10
0.01
0
10
20
30
40
time (s)



Hyperon-rich PNS
Kaon PNS
Quark PNS
Time to Instability (s)
M_B ($M_\odot$)
0
20
40
60
80
100
120
1.8
1.9
2.0

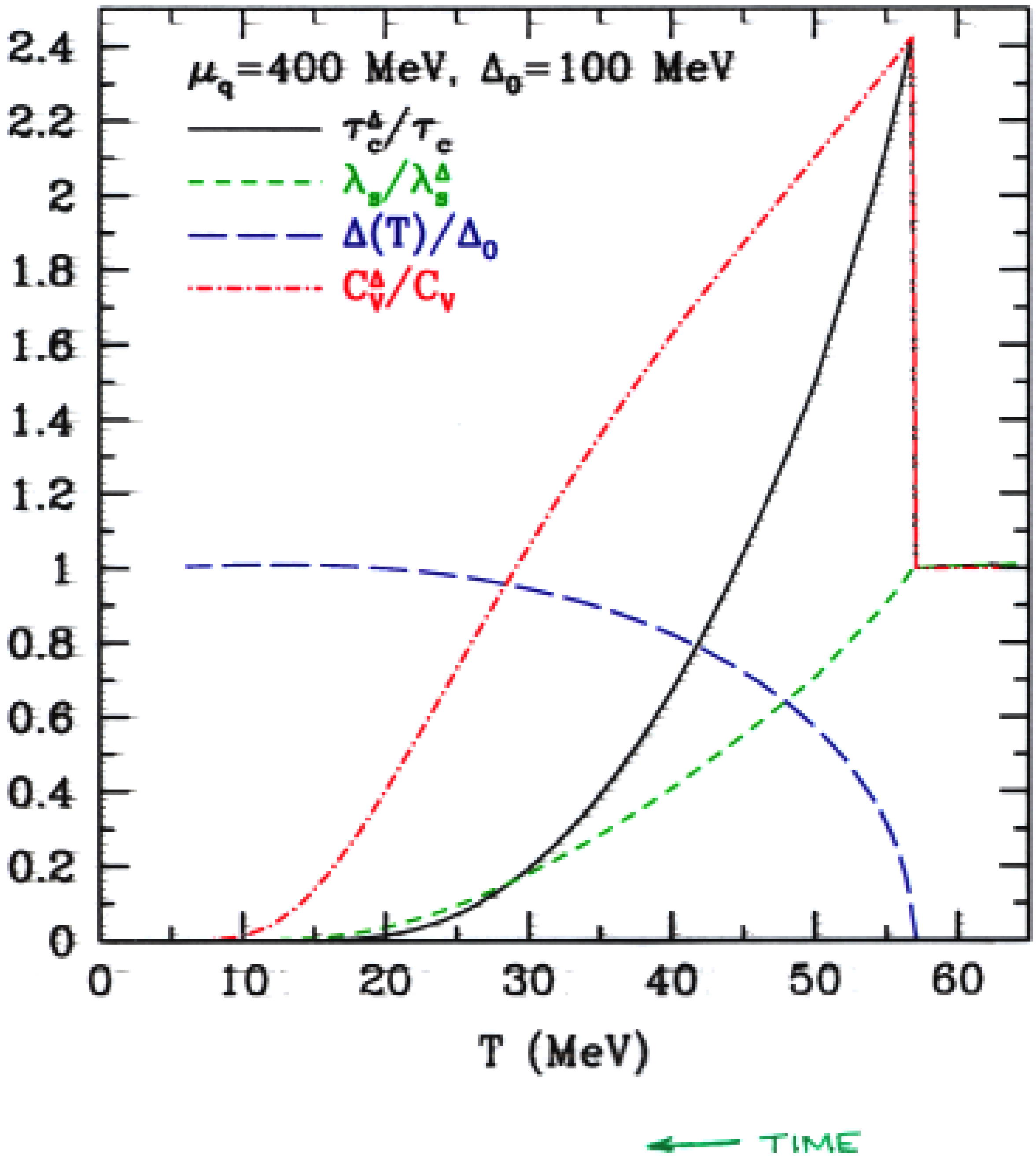
CONCLUSIONS - II

1. Appearance of hyperons, bosons and/or quarks is delayed to higher density in neutrino-trapped (lepton-rich) matter

2. Nascent neutron stars, with negatively charged strongly interacting particles, have larger maximum masses than their cold catalyzed counterparts; a reversal in behavior from matter containing only neutrons, protons and leptons

3. Above permits existence of metastable young stars that could collapse to black holes during deleptonization

4. In all cases, effects of entropy (of order 1 or 2) on the maximum mass are small in comparison to effects of neutrino trapping



μq=400 MeV, Δ0=100 MeV
τcΔ/τc
λs/λsΔ
Δ(T)/Δ0
CVΔ/CV
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10
20
30
40
50
60
T (MeV)
← TIME

Tasks for Better Predictions

→ Treat semi-transparent regions using multi-group neutrino transport to determine $< E_\nu >_i$, $(dN/dE_\nu)_i$ & $(dN/dt)_i$.

→ Couple convection with neutrino transport as large regions are convectively unstable.

→ Include self-consistent hydrodynamical models with accretion, which adds mass and contributes significantly to L_ν.

• Simulations with Bose condensates or quarks could provide contrasts with hyperons, since feedbacks involving the specific heat and $\nu-$opacities are different.

Note:

→ Crucial for early time signals

• Relevant for late time signals

CONCLUSIONS

- From observations of neutron star cooling,

$\rightarrow$ one could constrain the smaller of the $n-$ or $\Lambda-$ pairing gaps and the star's mass;

$\rightarrow$ deducing the sizes of quark gaps will be difficult;

$\rightarrow$ large $q-$gaps render quarks invisible; &

$\rightarrow$ vanishing $q-$gaps lead to cooling behaviors which are indistinguishable from those of np or npH stars.

HOWEVER,

Think This Titillating Thought !

- The observation of a neutron star

  older than 10^6 y & hotter than $\sim 10^7$ ^{o}K

  signals quarks with large gaps in neutron stars !!