Neutrino Effects in Stellar Cooling

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Strange Pathways for Black Hole Formation

- Cores of neutron stars (NS) may contain hyperons, a kaon condensate, or strange quarks

→ *Can* observations of NS structure (M, R & B.E.) & its evolution (age, P, $\dot{P}$, T_s & B) *confirm* the presence of strangeness?

- Neutron stars implicated in X-ray & γ-ray bursters, pulsars, black holes, etc.

→ *Observational programs:*

HST, CHANDRA, XMM, ASTROE ... (γ's)
SK, SNO, LVDs, AMANDA ... (ν's)
LIGO, VIRGO ... (gravity waves)

- Neutrino observations

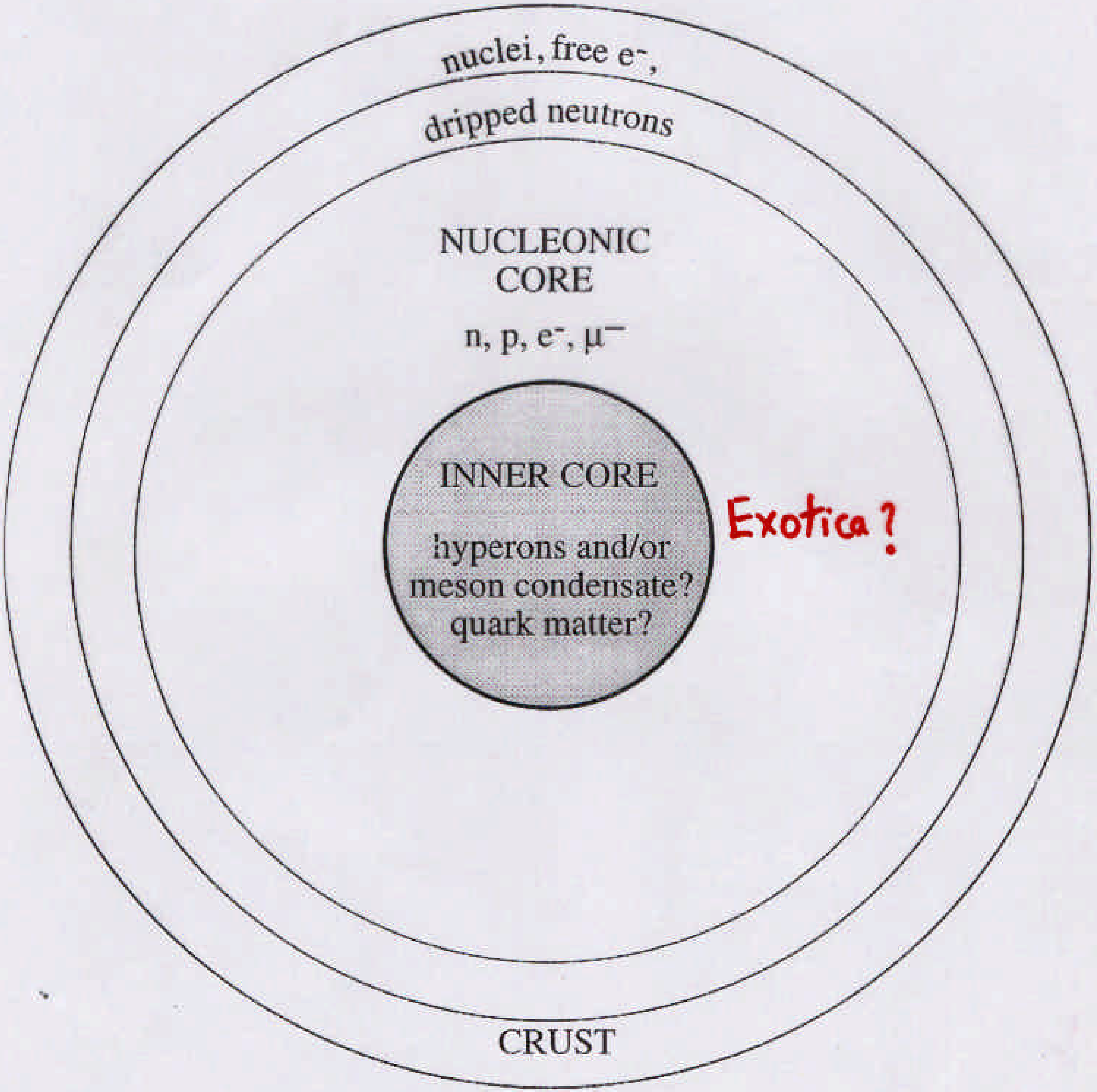
→ Presence of strangeness permits metastable NS ending up as a BH after deleptonization–

→ Detectable in late–time ν–signals.

→ Need a Galactic type-II supernova to go off!

$M : \sim (1-2)\, M_\odot \,; \quad M_\odot \sim 2 \times 10^{33}\, g$

$R : \sim 10$ km



COMPOSITION OF DENSE STELLAR MATTER

- CRUSTAL SURFACE :

electrons, nuclei, dripped neutrons, $\cdots$ set in a lattice
new phases with lasagna, sphagetti, $\cdots$ like structures

- LIQUID (SOLID?) CORE :

$n, p, \Delta, \cdots$ leptons: $e^{\pm}, \mu^{\pm}, \nu_e' s, \nu_\mu' s$
$\Lambda, \Sigma, \Xi, \cdots$
$K^-, \pi^-, \cdots$ condensates
$u, d, s, \cdots$ quarks

- CONSTRAINTS :

1. $n_b = n_n + n_p + n_\Lambda + \cdots$: baryon # conservation
2. $n_p + n_{\Sigma^+} + \cdots = n_e + n_\mu$: charge neutrality
3. $\mu_i = b_i \mu_n - q_i \mu_\ell$: energy conservation

$\Rightarrow$

$$\mu_\Lambda = \mu_{\Sigma^0} = \mu_{\Xi^0} = \mu_n$$
$$\mu_{\Sigma^-} = \mu_{\Xi^-} = \mu_n + \mu_e$$
$$\mu_p = \mu_{\Sigma^+} = \mu_n - \mu_e$$

$\Rightarrow$

$$\mu_{K^-} = \mu_e = \mu_\mu = \mu_n - \mu_p$$

$\Rightarrow$

$$\mu_d = \mu_u + \mu_e = \mu_s = (\mu_n + \mu_e)/3$$
$$\mu_u = (\mu_n - 2\mu_e)/3$$

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 $\tau)$ 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

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

• NP

• Concentrations $Y_i = n_i/n_b$

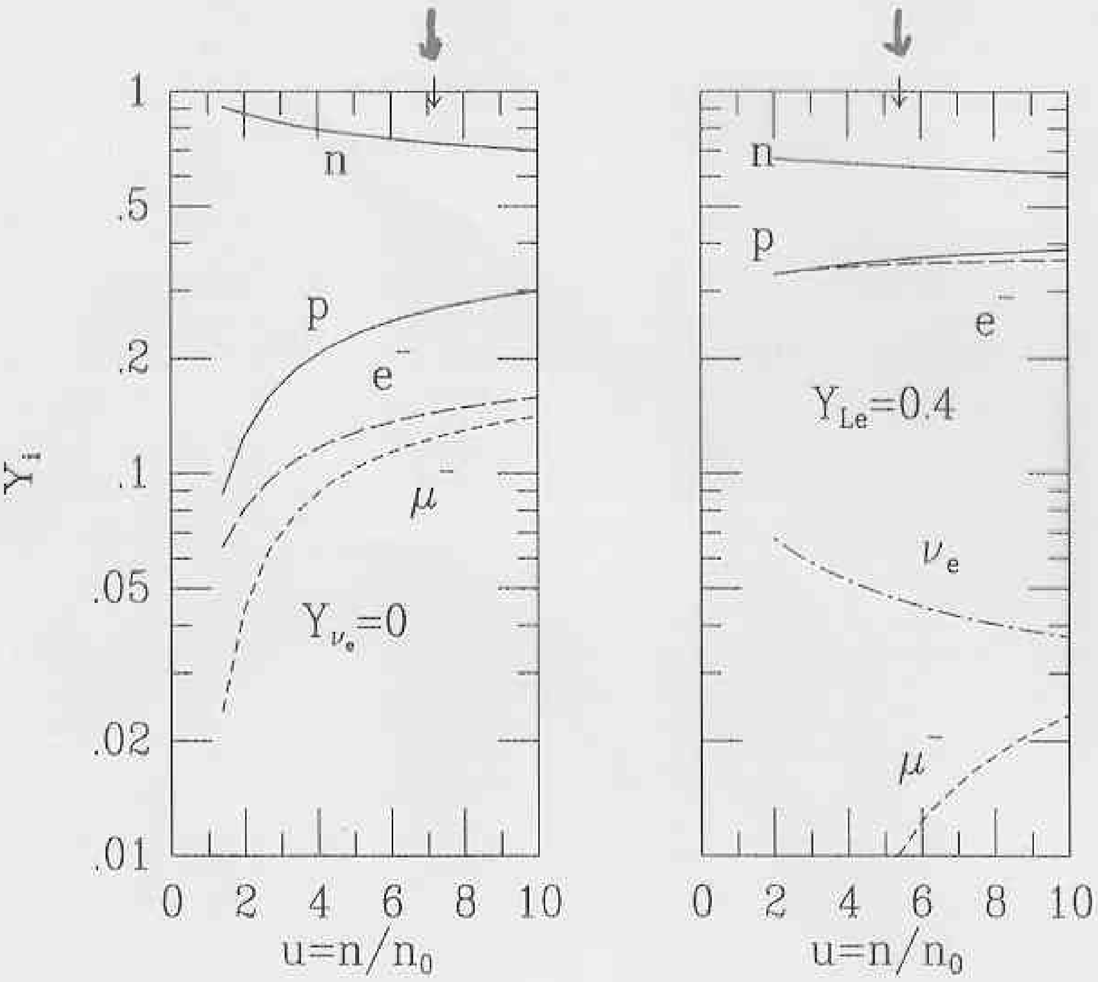


Figure 1:

$$\mu = \mu_e - \mu_{\nu_e} \Big)_{\text{trapped}} < \mu = \mu_e \Big)_{\nu\text{-free}}$$

$$\Rightarrow Y_e \simeq Y_p \Big)_{\nu\text{-trapped}} > Y_e + Y_\mu = Y_p \Big)_{\nu\text{-free}}$$

• NPH

• Concentrations $Y_i = n_i/n_b$

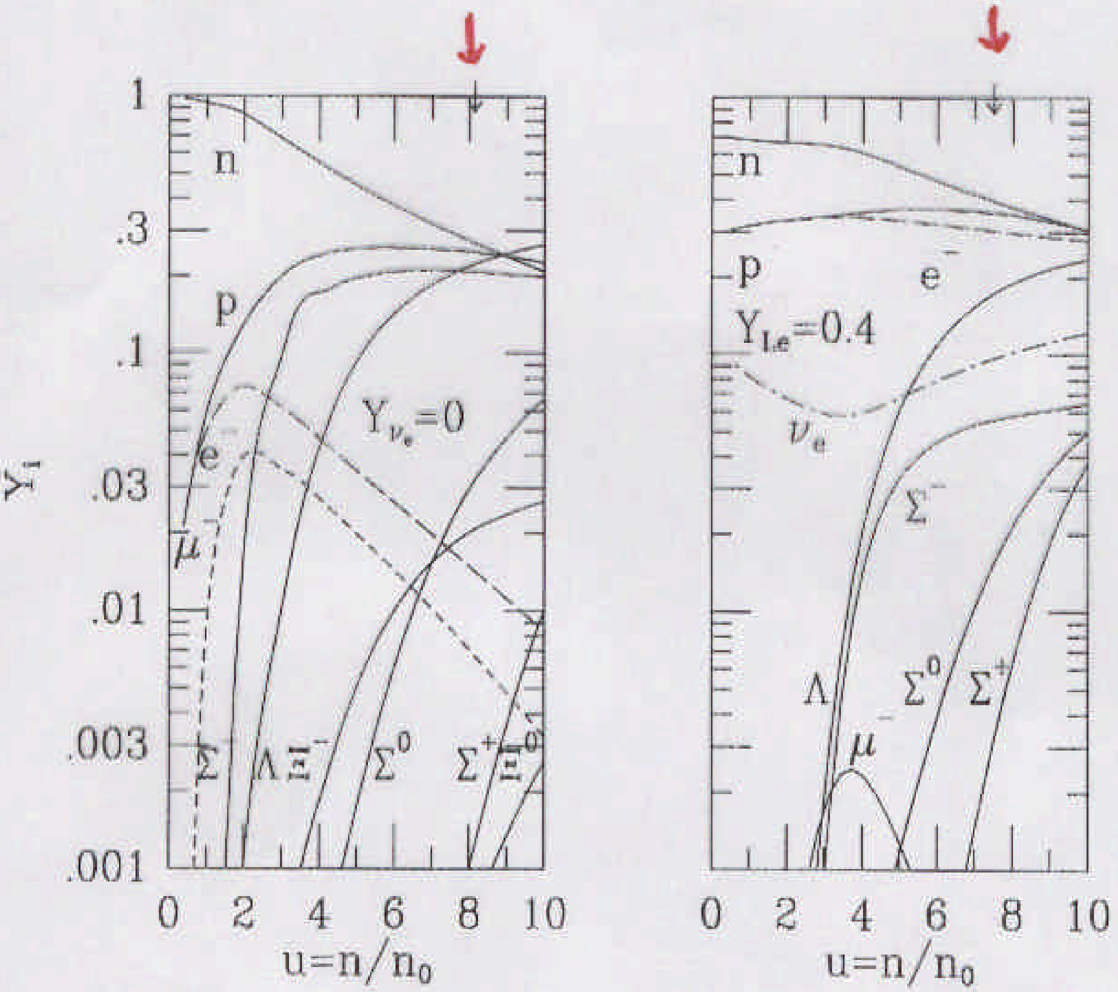


Figure 2:

Concentrations $Y_i = n_i/n_b$

npK

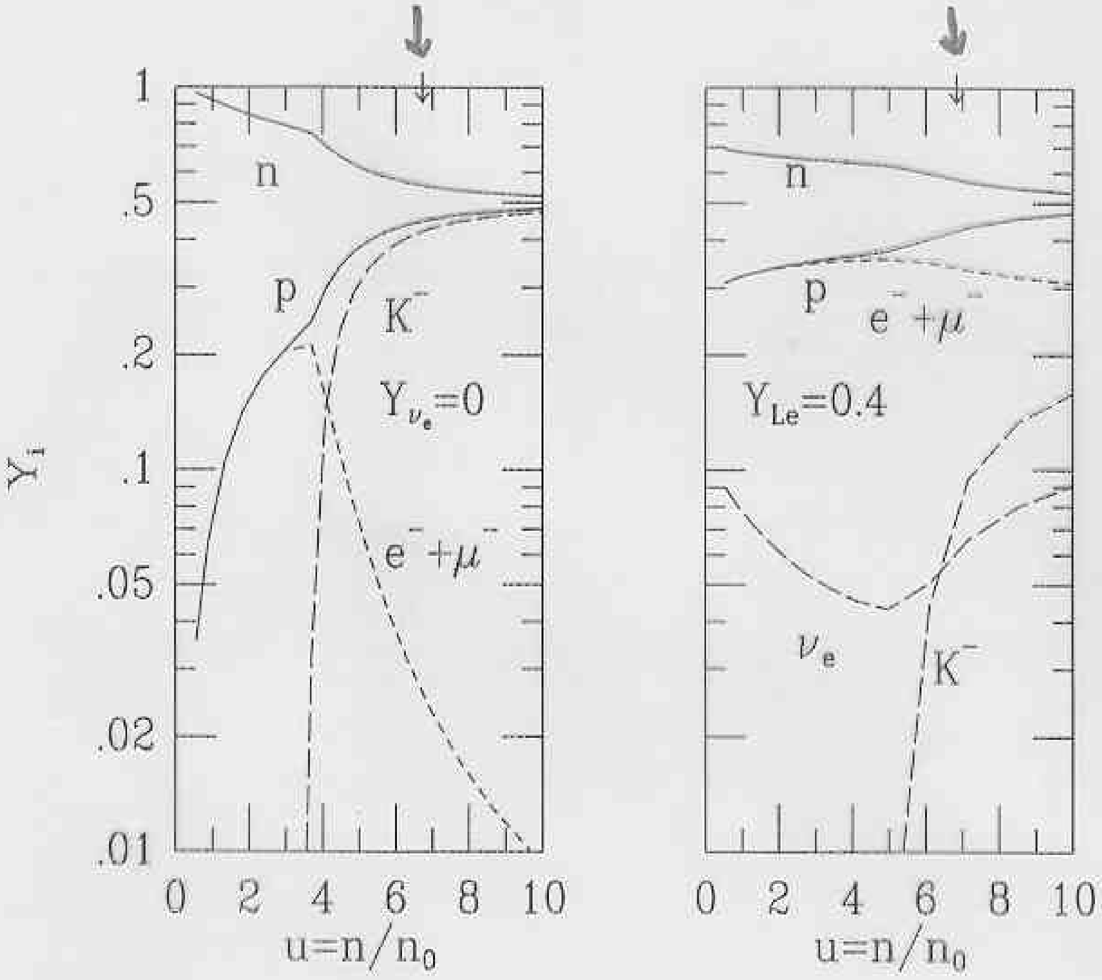
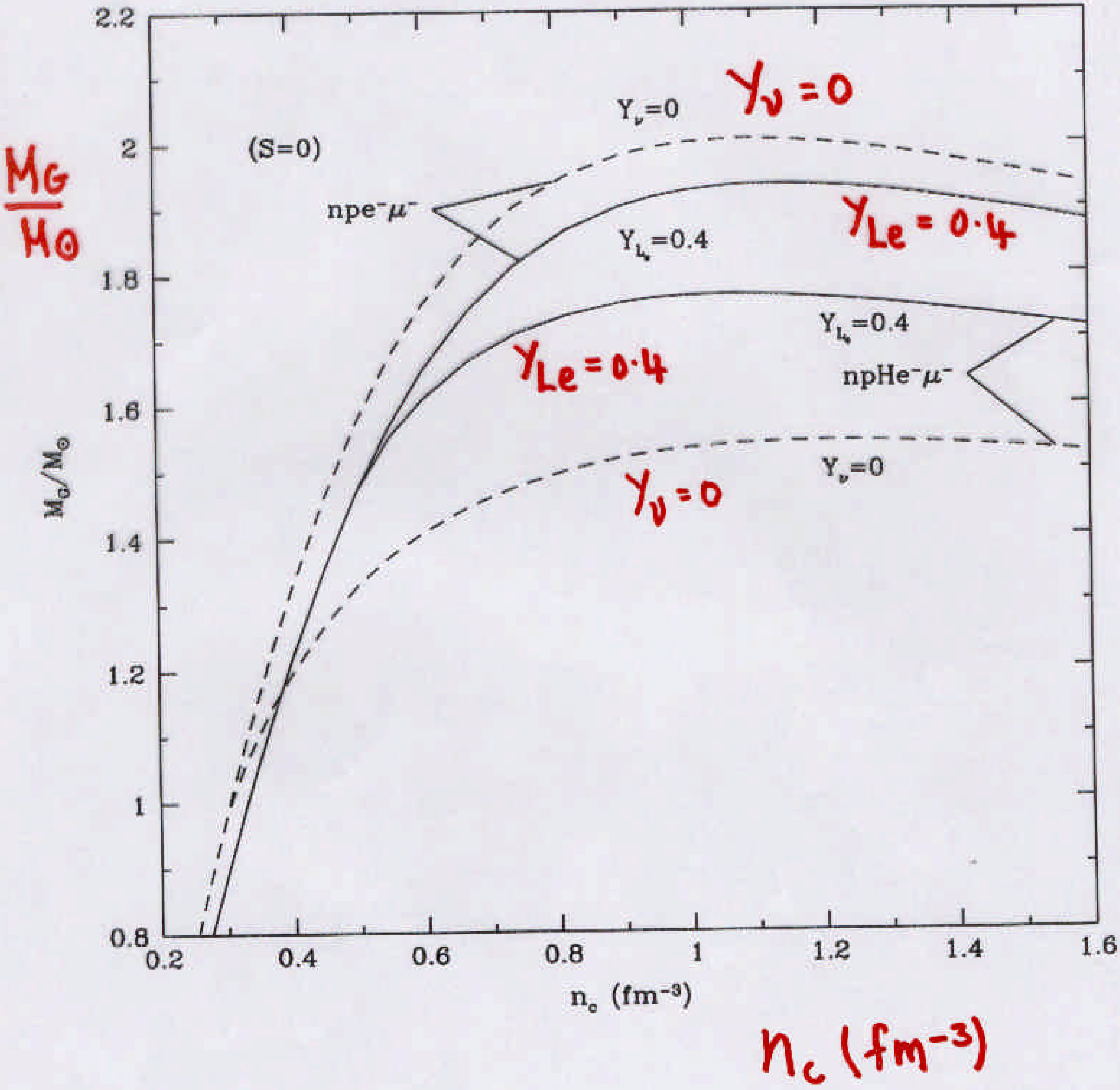
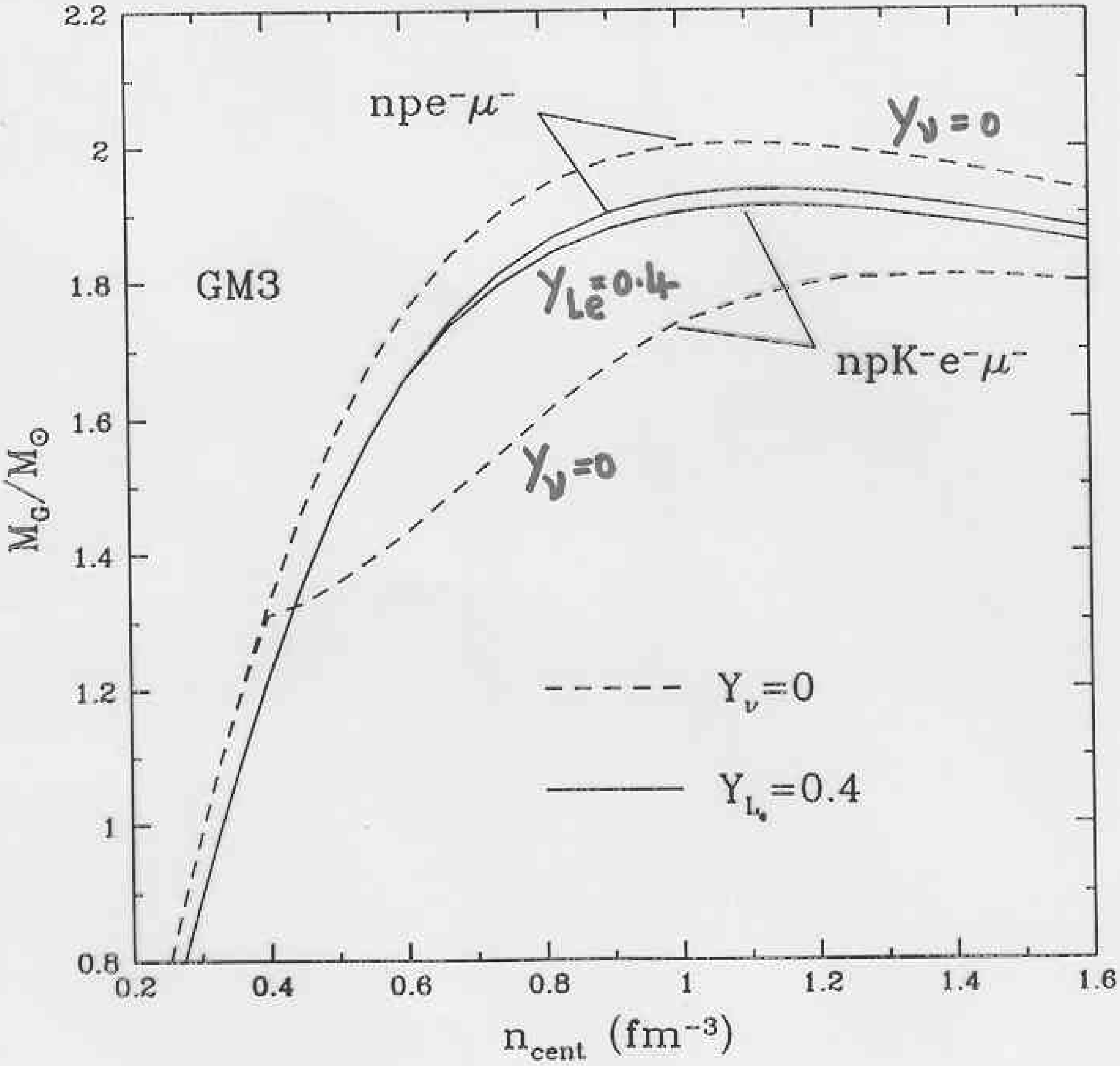


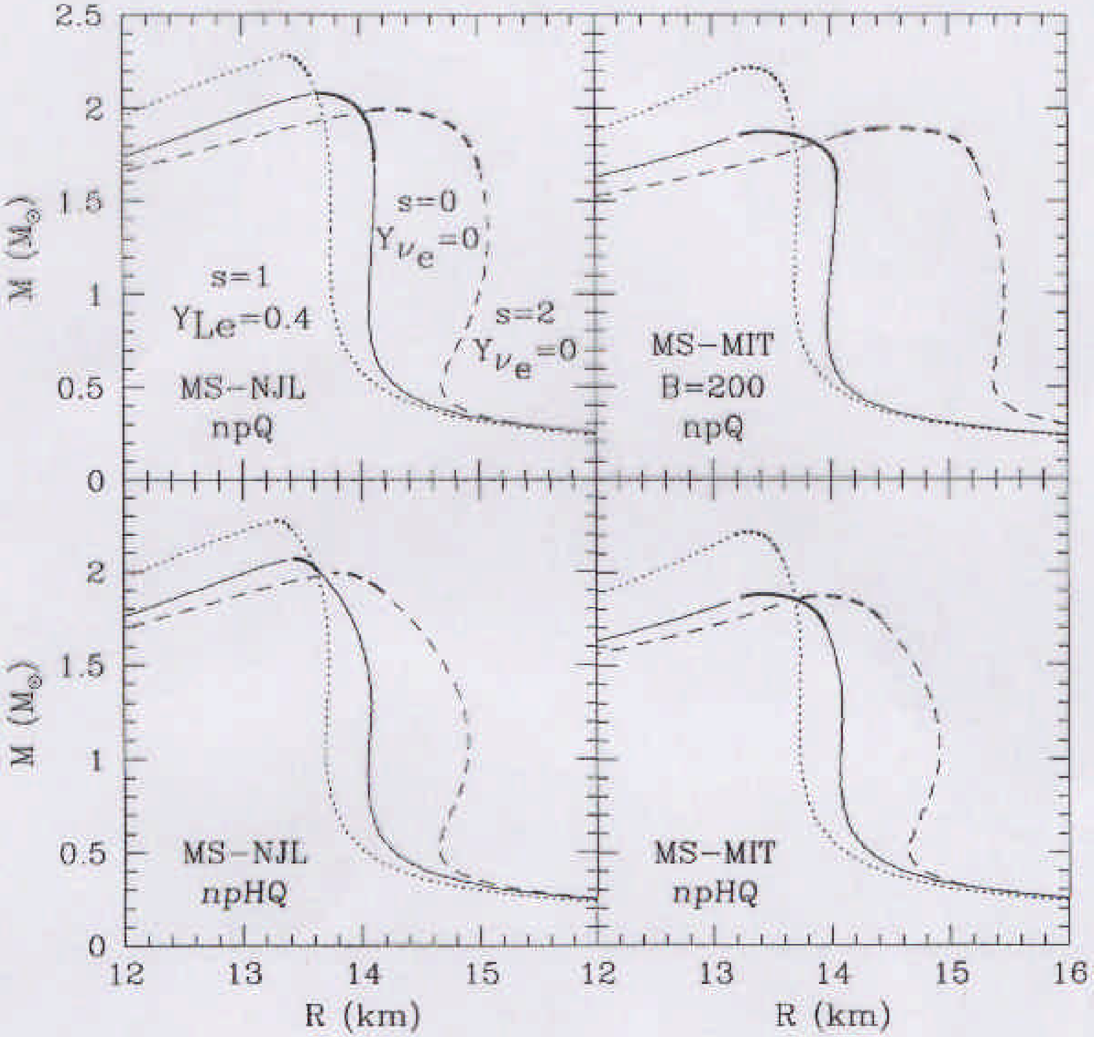
Figure 3:

$$Y_i = \frac{n_i}{n_b}$$

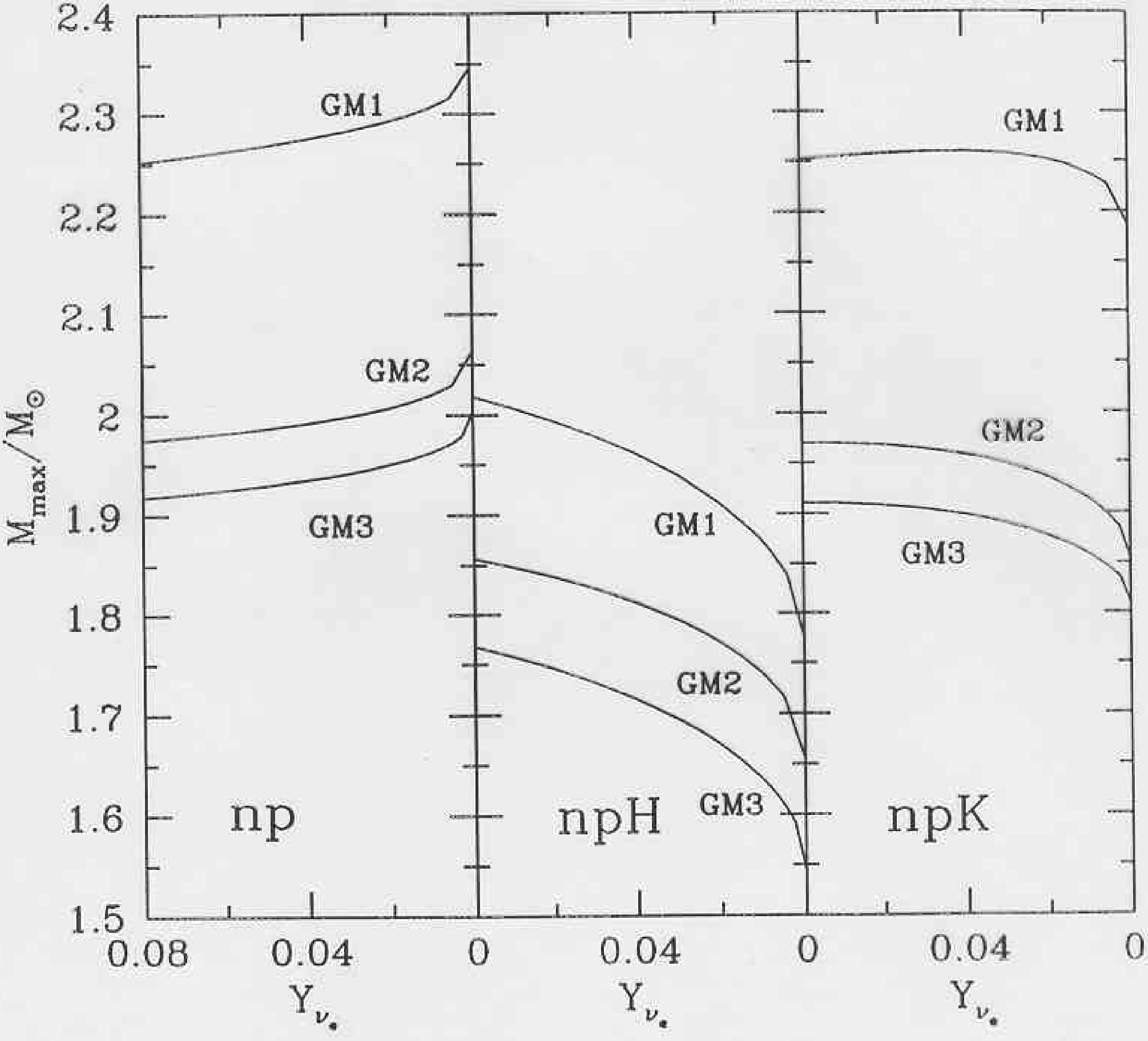

2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
$M_G/M_\odot$
n_c (fm^{-3})
(S=0)
Y_ν=0
$Y_\nu = 0$
npe$^-\mu^-$
Y_{L_e}=0.4
$Y_{Le} = 0.4$
Y_{L_e}=0.4
$Y_{Le} = 0.4$
npHe$^-\mu^-$
Y_ν=0
$Y_\nu = 0$
$\frac{M_G}{M_\odot}$
n_c (fm^{-3})


npe⁻μ⁻
Yν=0
GM3
YLe=0.4
npK⁻e⁻μ⁻
Yν=0
Yν=0
YLe=0.4
M_G/M_⊙
n_cent (fm⁻³)
0.8
1
1.2
1.4
1.6
1.8
2
2.2
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

Metastability



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



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

CONCLUSIONS - II

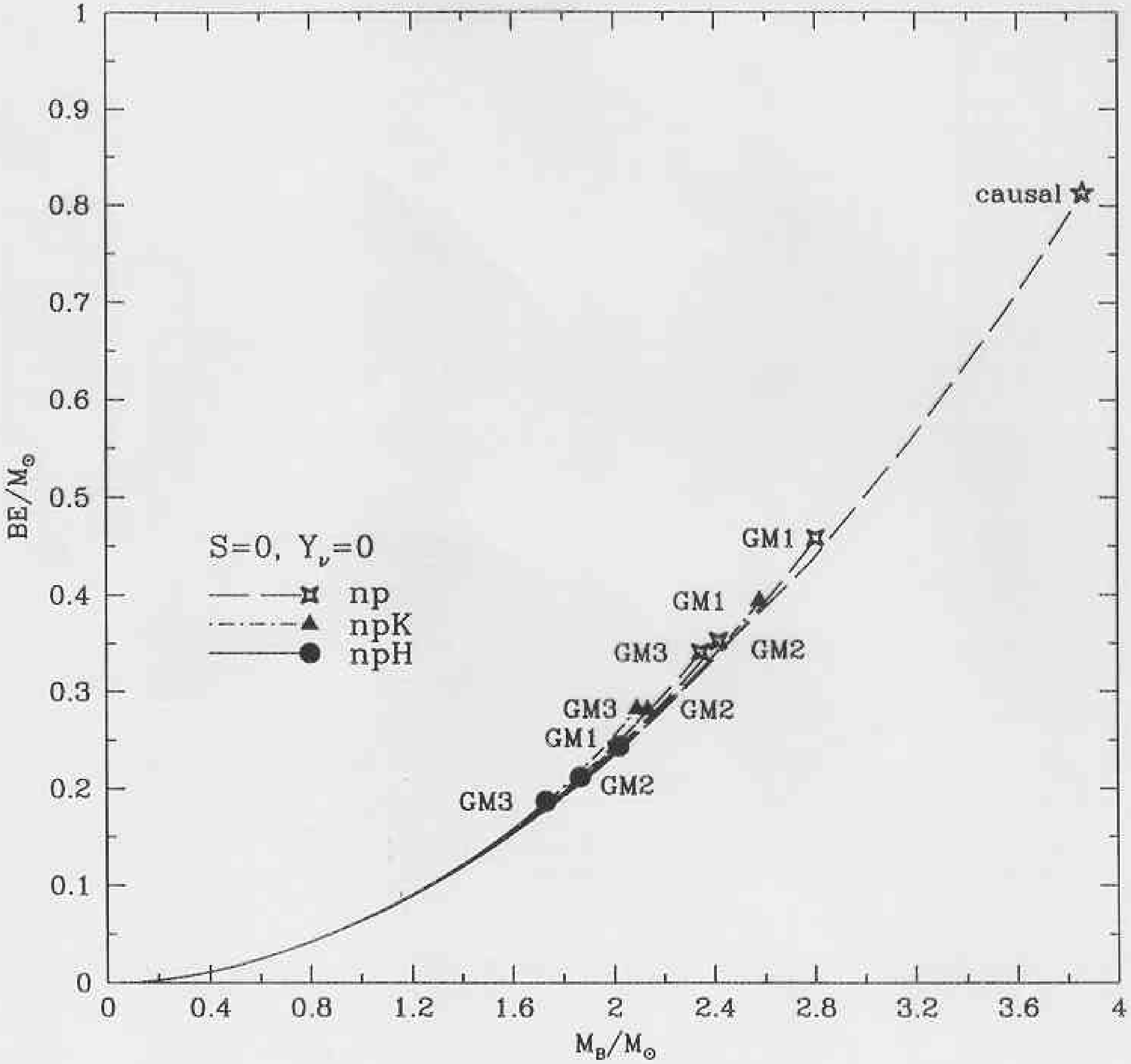
1. Appearance of hyperons, bosons and/or quarks is delayed to higher density in neutrino-trapped (lepton-rich) matter

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

$$B.E = (M_B - M_G)c^2 \simeq (0.065 \pm 0.01)\left(\frac{M_B}{M_\odot}\right)^2 M_\odot$$



- Accurate measurement of total ν-energy
  ⇒ A good estimate of remnant mass
- Not a good discriminant of the EOS

FUTURE DETECTIONS

- In an optimistic scenario, about 10,000 neutrinos will be seen from a typical galactic supernova in a single detector. Crucial question is whether the statistical uncertainty in a time-dependent signal can be small enough to adequately differentiate models.

Among the interesting features that could be sought are:

1. Possible cessation of a neutrino signal due to black hole formation.
2. Possible burst or light curve feature associated with the onset of negatively-charged hadrons near the end of deleptonization, whether or not a black hole is formed.
3. Identification of the deleptonization/cooling epochs by changes in luminosity evolution or in neutrino flavor distribution.
4. Determination of a radius-mean free path correlation from the luminosity decay time or the onset of neutrino transparency.
5. Determination of the neutron star mass from the universal binding energy–mass relation.

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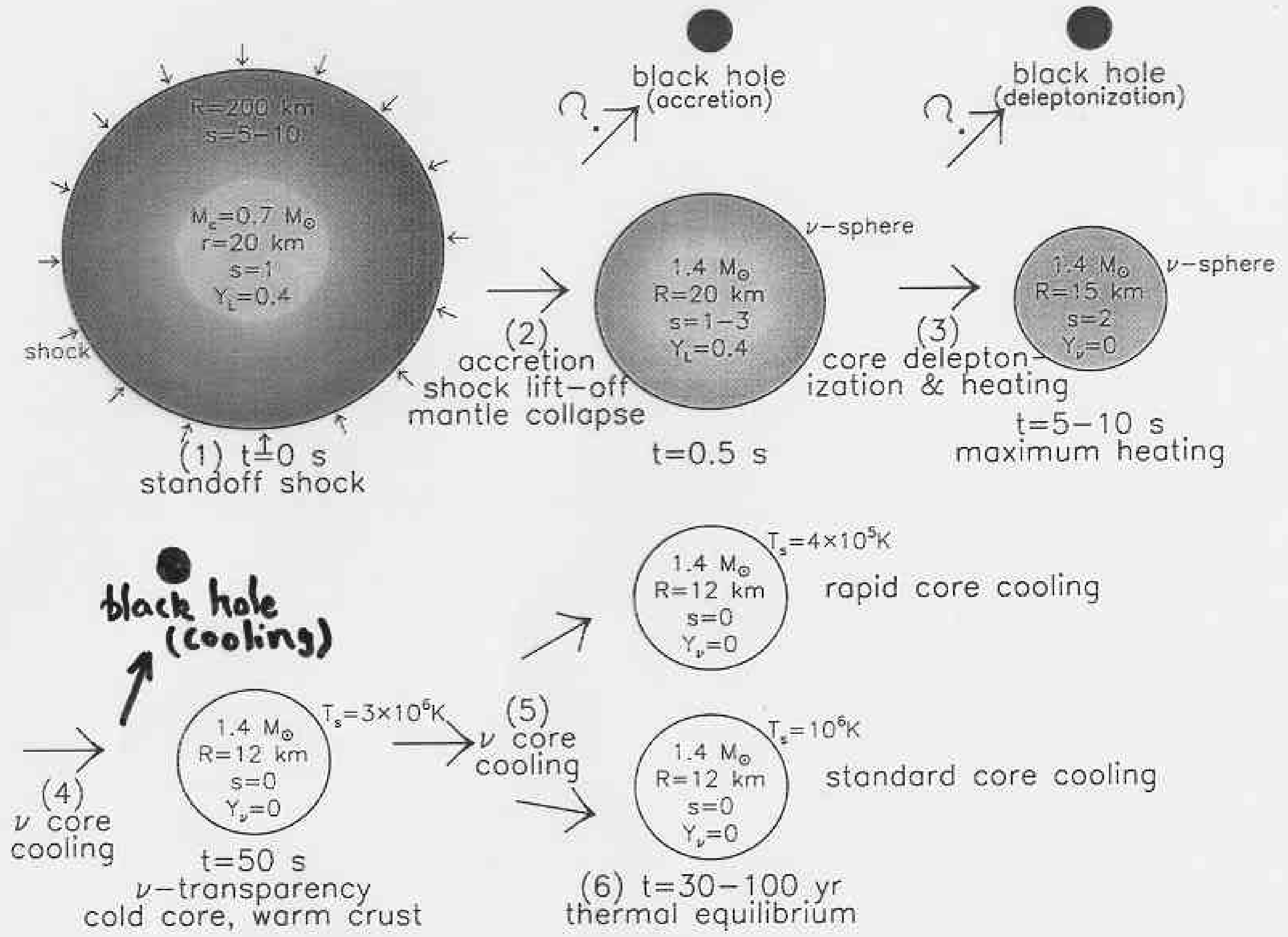

R=200 km
s=5−10
M_c=0.7 $M_\odot$
r=20 km
s=1
Y_L=0.4
shock
(1) t$\overset{+}{-}$0 s
standoff shock
(2)
accretion
shock lift−off
mantle collapse
black hole
(accretion)
?
1.4 $M_\odot$
R=20 km
s=1−3
Y_L=0.4
ν−sphere
t=0.5 s
(3)
core delepton-
ization & heating
black hole
(deleptonization)
?
1.4 $M_\odot$
R=15 km
s=2
Y_ν=0
ν−sphere
t=5−10 s
maximum heating
black hole
(cooling)
(4)
ν core
cooling
1.4 $M_\odot$
R=12 km
s=0
Y_ν=0
T_s=3×10^{6}K
t=50 s
ν−transparency
cold core, warm crust
(5)
ν core
cooling
1.4 $M_\odot$
R=12 km
s=0
Y_ν=0
T_s=4×10^{5}K
rapid core cooling
1.4 $M_\odot$
R=12 km
s=0
Y_ν=0
T_s=10^{6}K
standard core cooling
(6) t=30−100 yr
thermal equilibrium

The Basic Equations

Structure :
(TOV)

$$\begin{aligned}\frac{\partial P}{\partial r} &= -(\rho+P)\frac{e^{2\Lambda}}{r^2}(m+4\pi r^3 P)\\ \frac{\partial \mu}{\partial r} &= 4\pi r^2 n_B e^{\Lambda}\\ \frac{\partial m}{\partial r} &= 4\pi r^2 \rho\end{aligned}$$

Transport :

$$\begin{aligned}\frac{dY_\nu}{d\tau} + e^{-\phi}\frac{\partial(e^{\phi}4\pi r^2 F_\nu)}{\partial \mu} &= \frac{S_N}{n_B}\\ \frac{dY_e}{d\tau} &= -\frac{S_N}{n_B}\\ \frac{dE}{d\tau} + P\frac{d(\frac{1}{n_B})}{d\tau} + e^{-2\phi}\frac{\partial(e^{2\phi}4\pi r^2 H_\nu)}{\partial \mu} &= 0 \cdot\end{aligned}$$

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

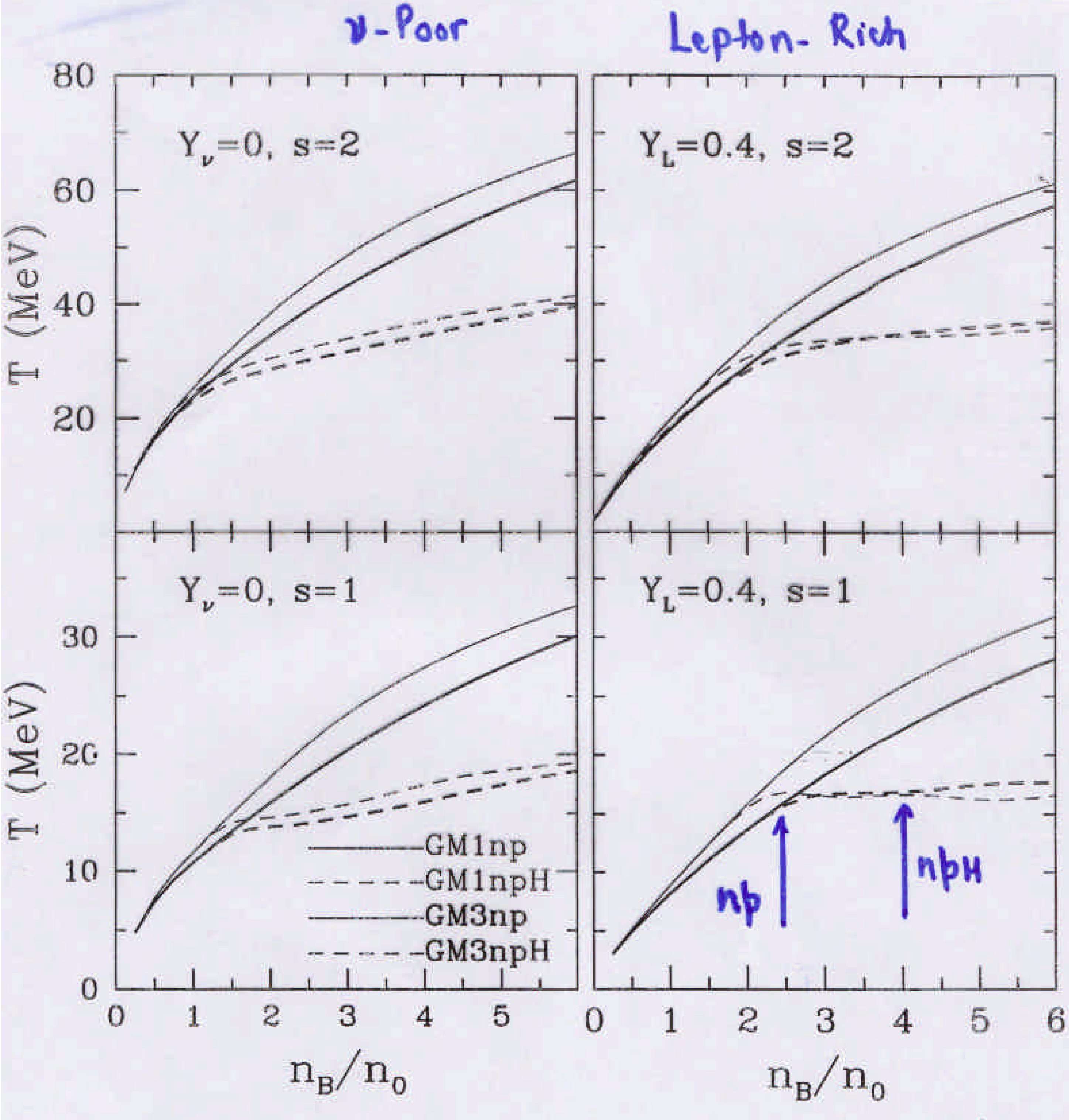
- Neutrino Transport (Diffusion Approximation)

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-mass, magnetic moment, oscillations, . . .
- . . . .



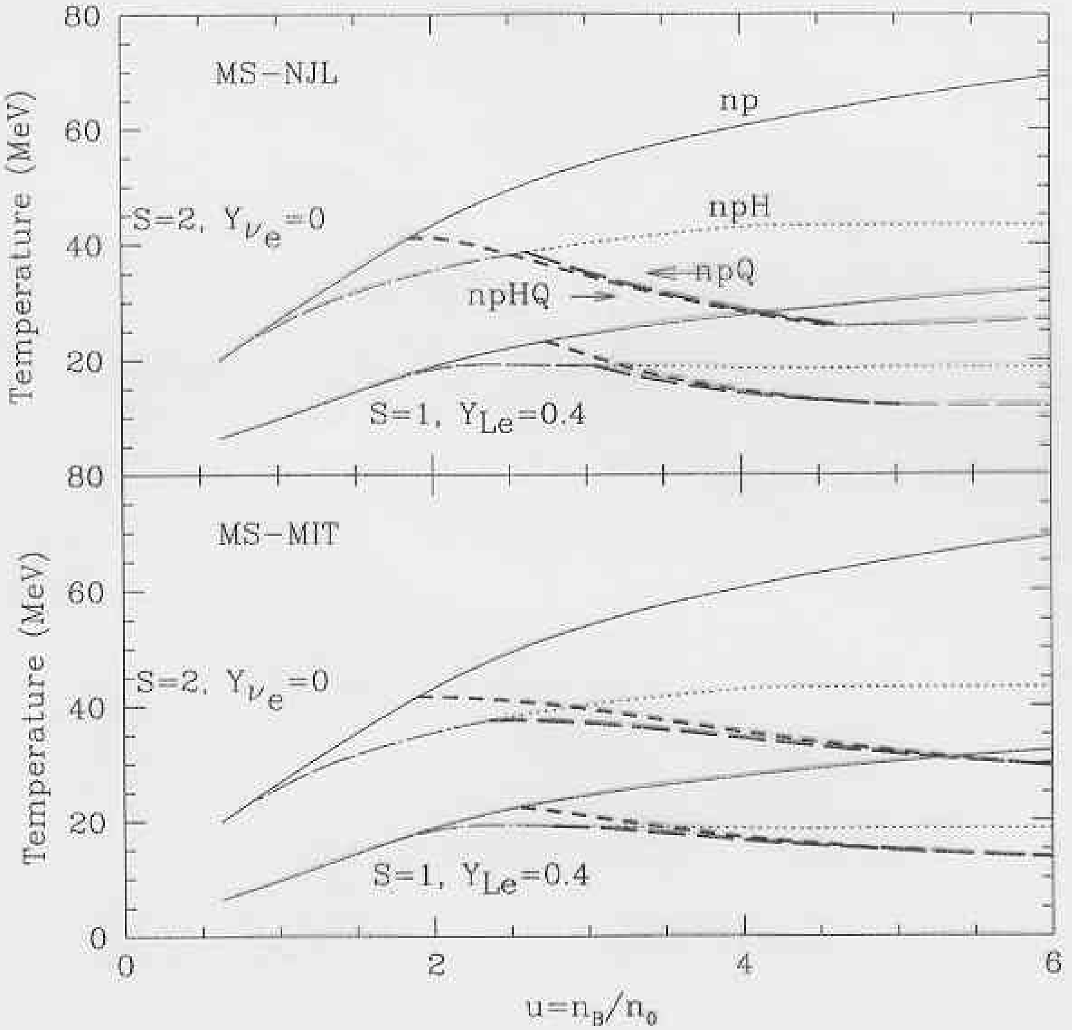
- Feedbacks

- Temperatures

$$\frac{\pi^2 T}{s} = \frac{(3\pi^2 n_B)^{2/3}}{\sum_i Y_i^{1/3}\sqrt{M_i^{*2}+k_{F_i}^2}} \quad , \quad Y_i = \frac{n_i}{n_B}$$

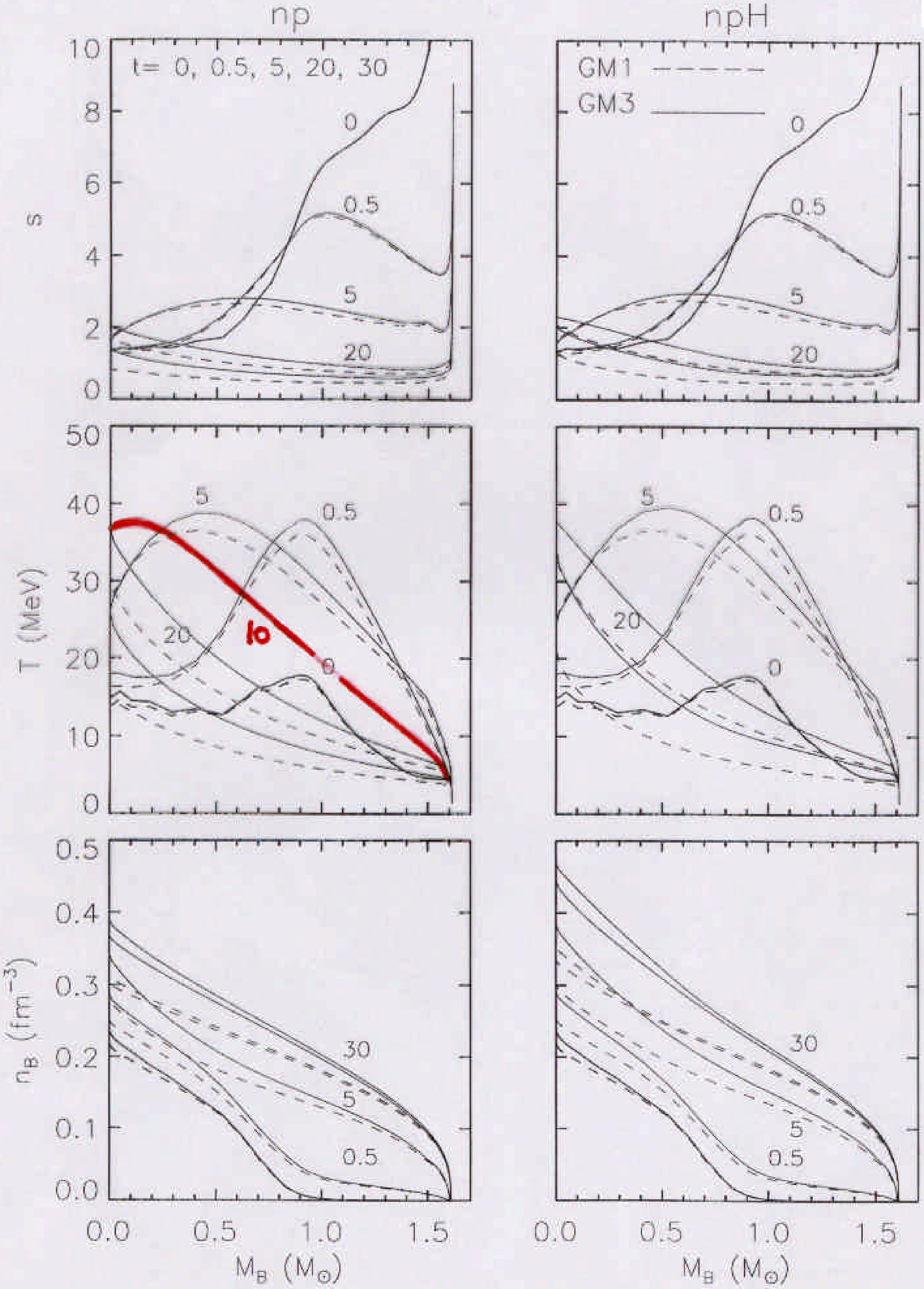
3

Temperature

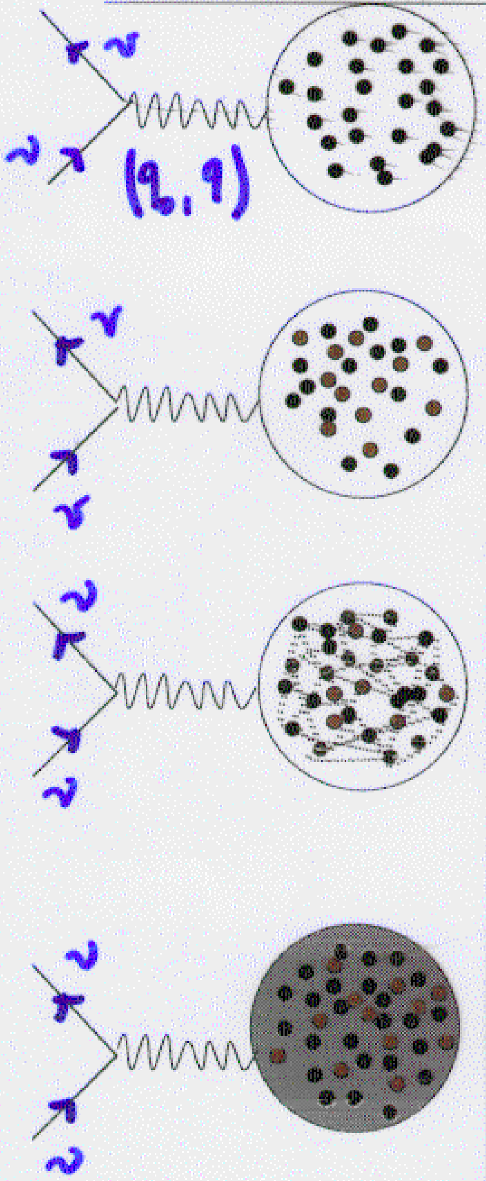


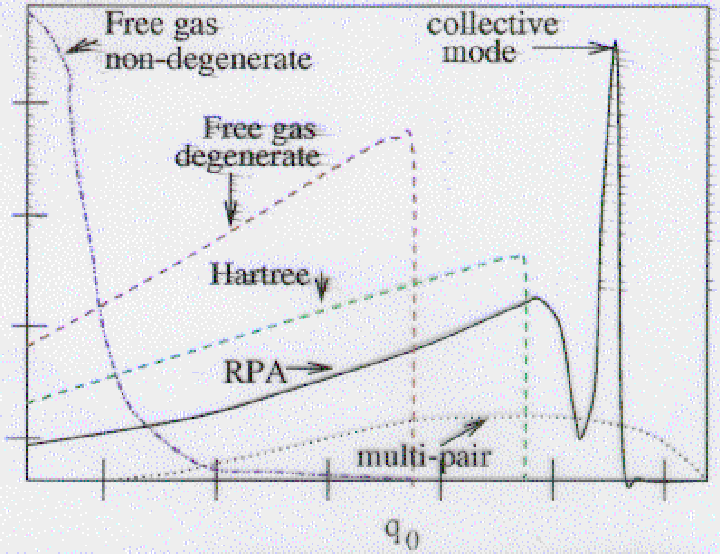
- Temperature decreases along an adiabat as a function of density in the mixed phase
- This may have an observable effect on neutrino spectra - Lower temperature tends to decrease the neutrino energies and increase the neutrino mean free paths

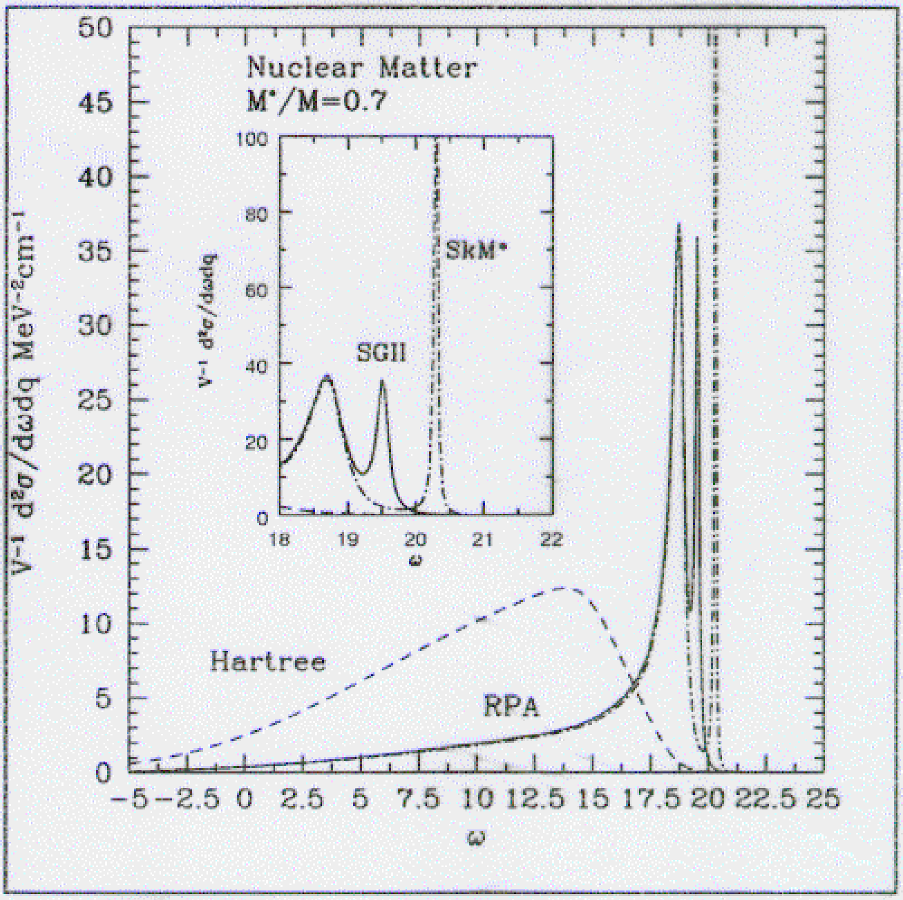
THERMAL FEATURES



Neutrino Interactions

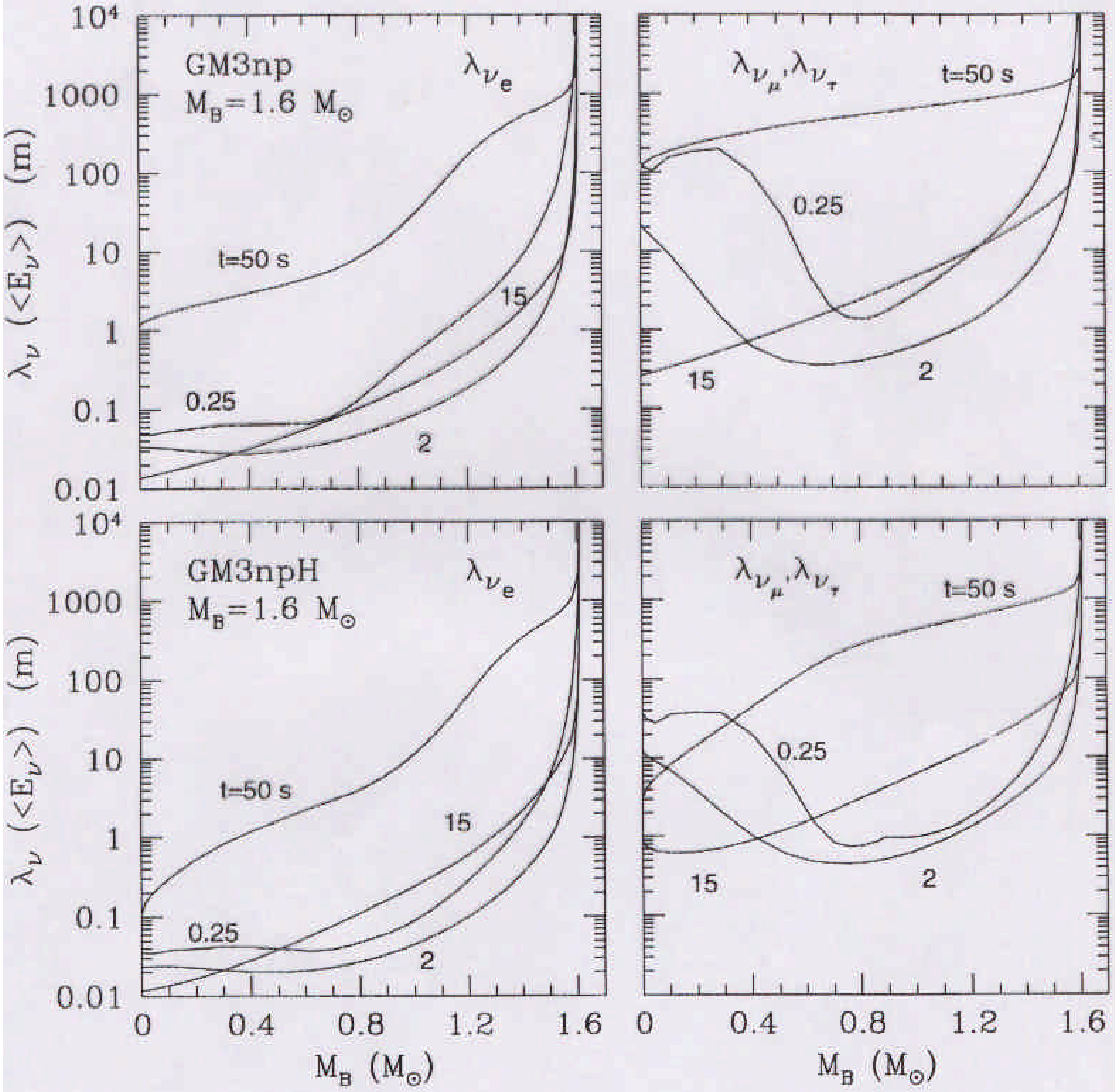




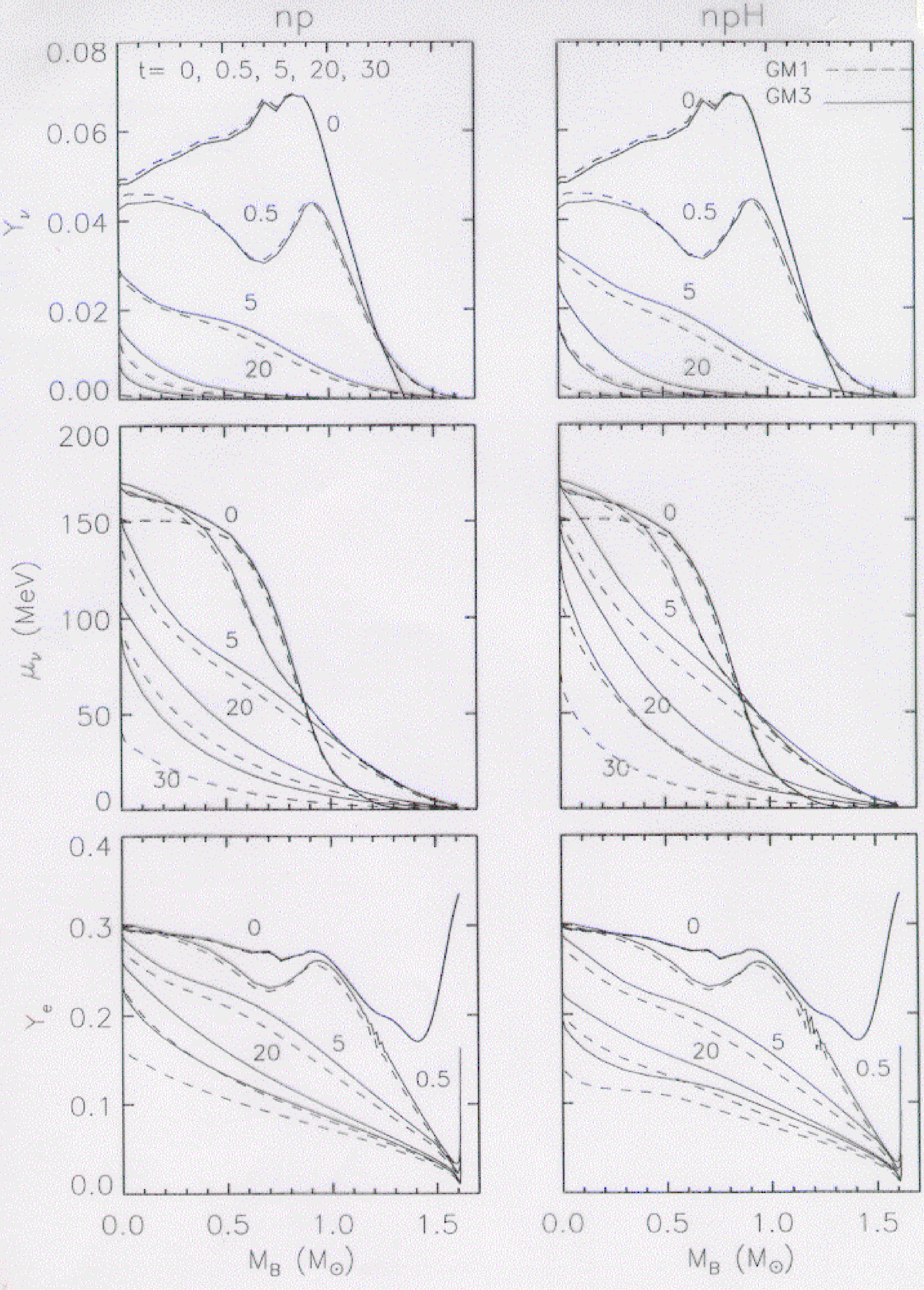


- Typical ν-mfp's

$\langle E_{\nu_e}\rangle = \mu_{\nu_e} + \pi T$ $\langle E_{\nu_{\mu,\tau}}\rangle = \pi T$



LEPTON CONTENT



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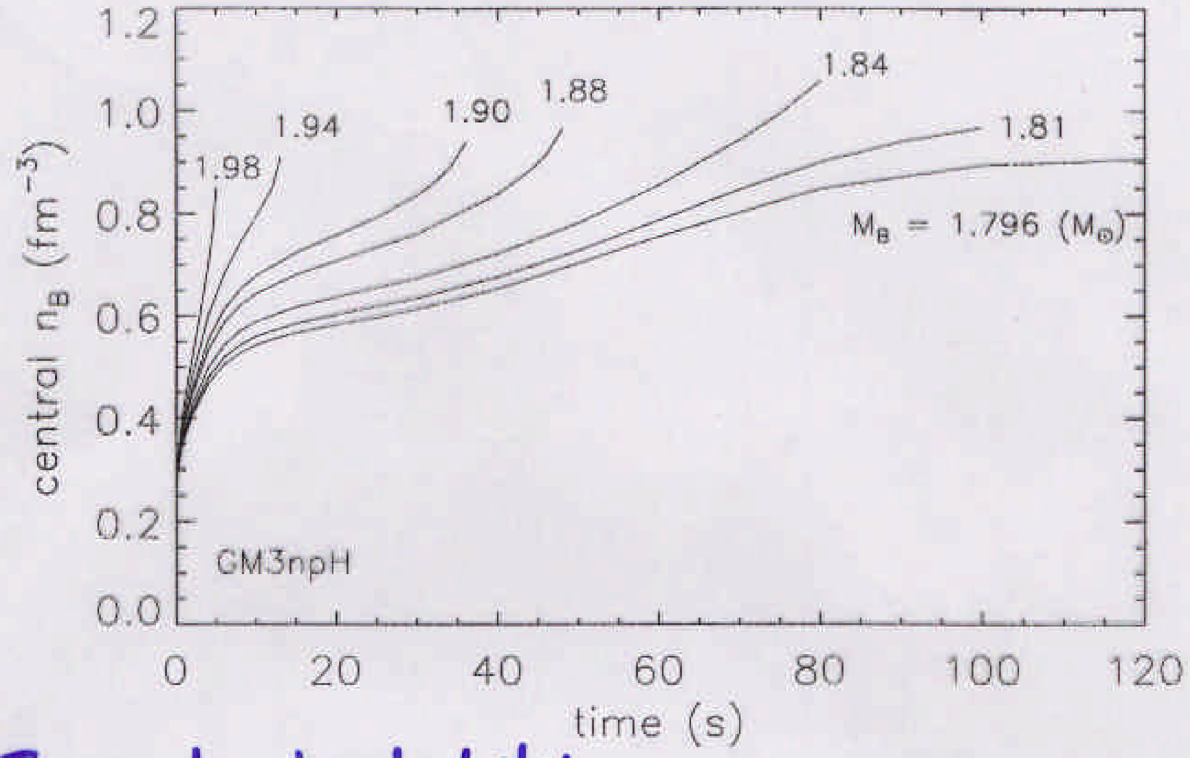
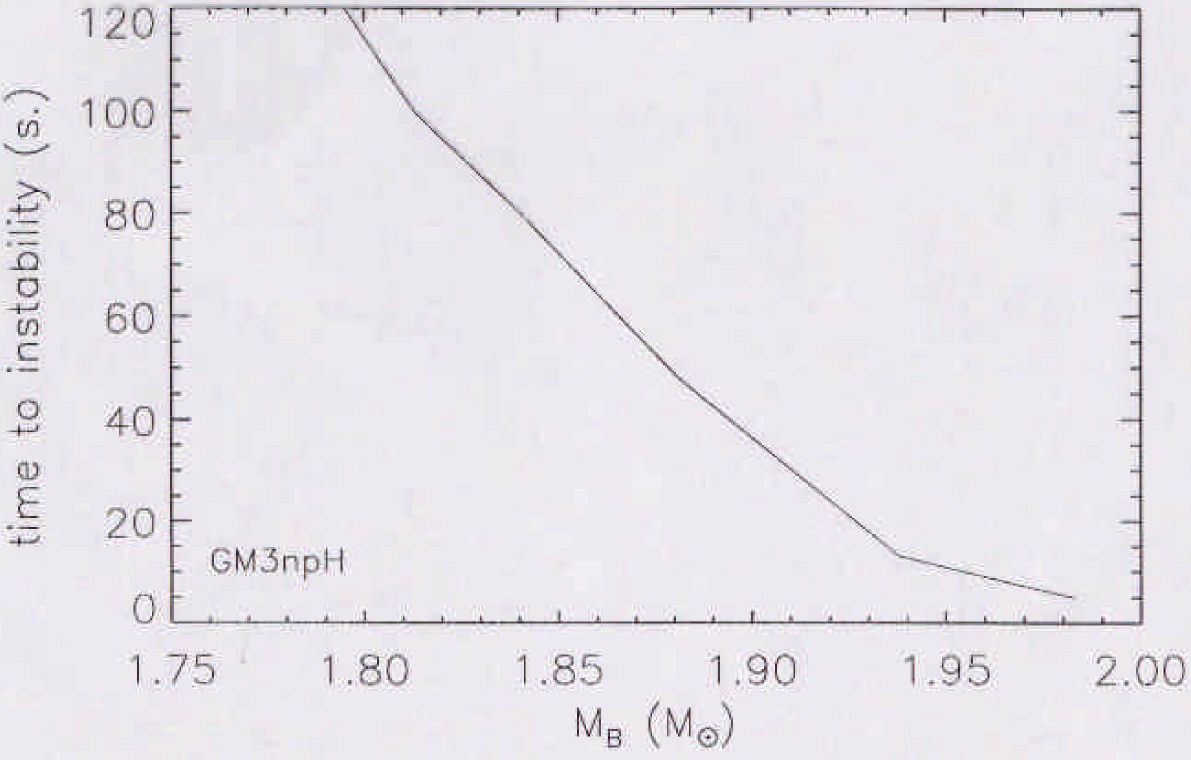
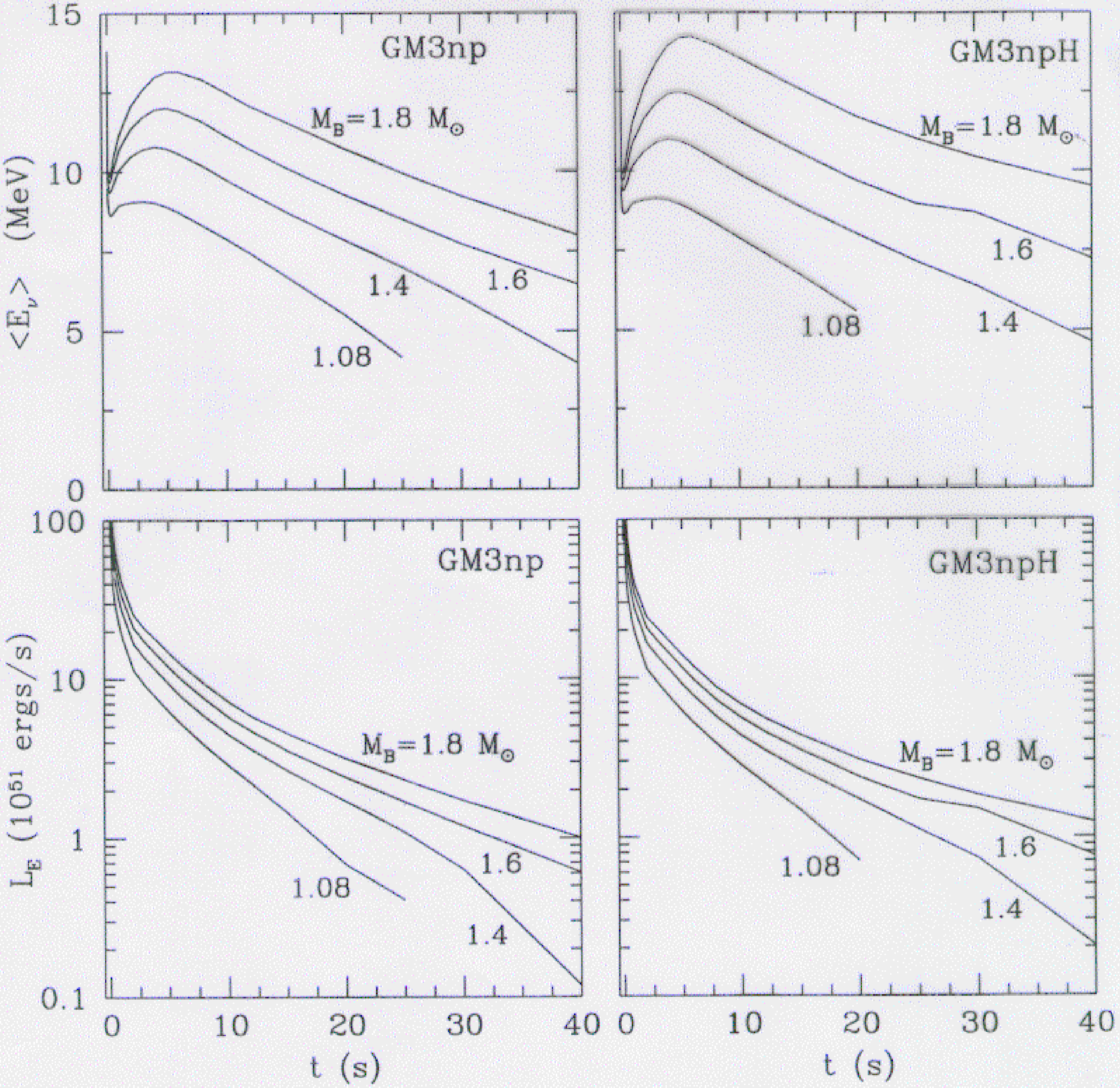
- Evolution of metastable stars



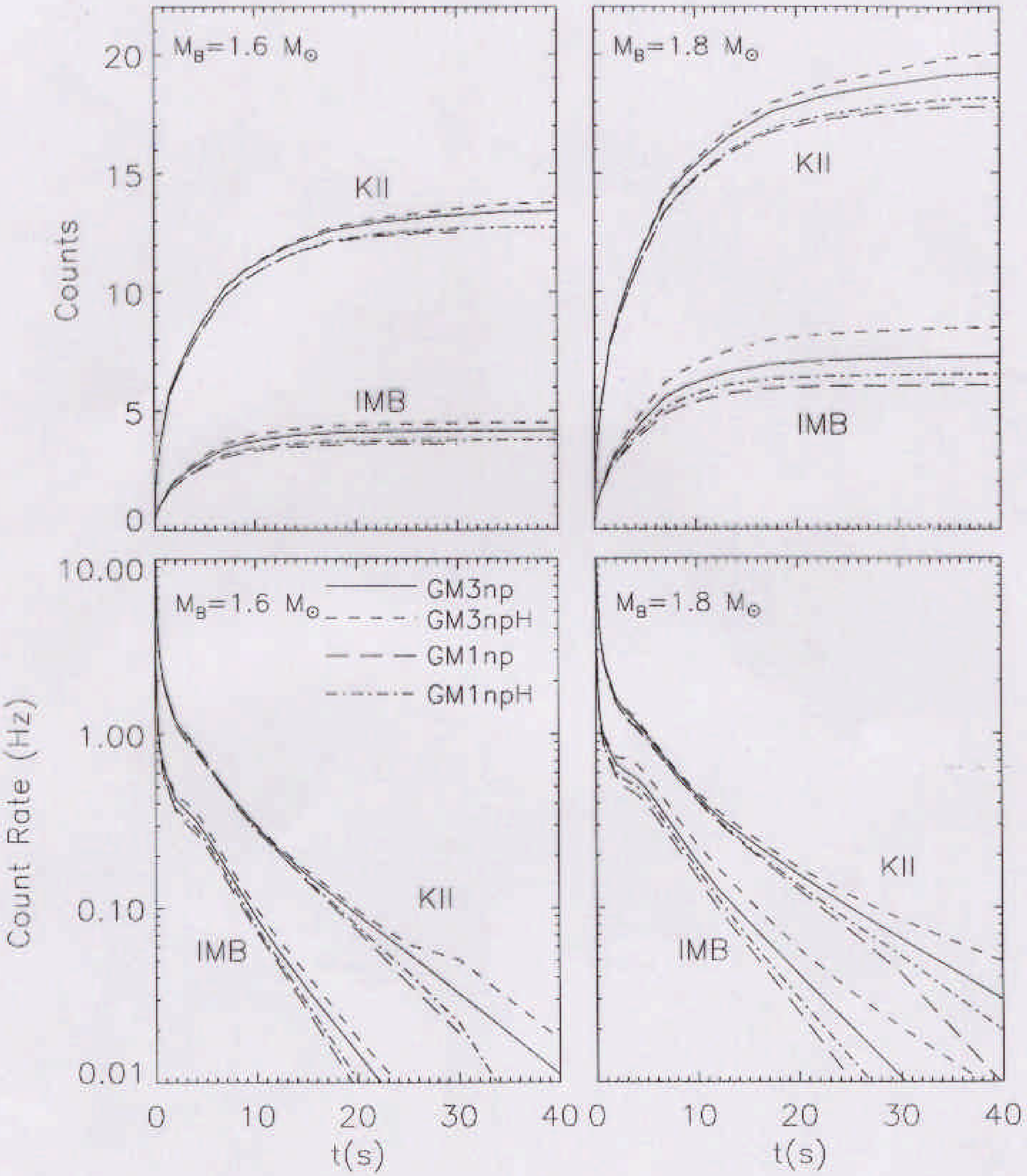
- Time to instability



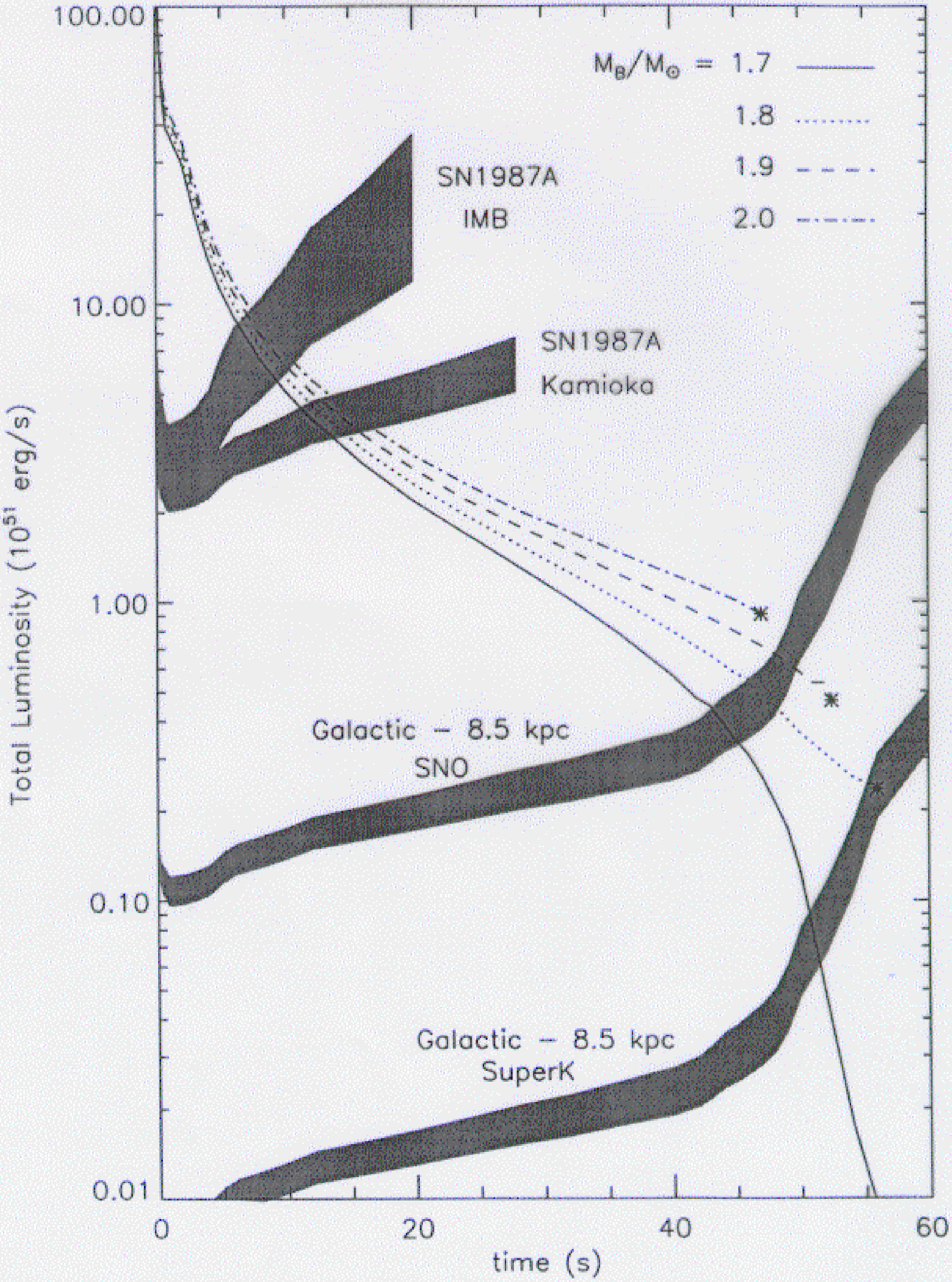
- Mass dependence of $\langle E_\nu \rangle$ & L_E



- Signals in detectors



npk



100.00
10.00
1.00
0.10
0.01
0
20
40
60
time (s)
Total Luminosity (10^{51} erg/s)
$M_B/M_\odot$ = 1.7
1.8
1.9
2.0
SN1987A
IMB
SN1987A
Kamioka
Galactic – 8.5 kpc
SNO
Galactic – 8.5 kpc
SuperK

Fig. 10.—

Summary of Findings

1. For ***relatively early*** times ($t < 10$ s), predicted L_ν & $< E_\nu >$ *do not* greatly depend upon the initial entropy & lepton profiles or the high-density EOS, provided $\nu-$opacities are consistent with the EOS.
2. The same holds true in matter containing hyperons, ***except*** when the initial mass is significantly larger than the maximum mass for cold, catalyzed (i.e. $\nu-$poor) matter.
3. For $t > 10$ s, and prior to $\nu-$transparency, L_ν decays exponentially with a time constant determined by the high-density EOS.
4. $< E_\nu >$ increases during the first 5 s, and then decreases nearly linearly with time.
5. Increasing the protoneutron star mass increases L_ν & $< E_\nu >$, as well as the overall evolutionary time scale.
6. The influence of hyperons or variations in the dense matter EOS is increasingly important at later times ($t > 15 - 20$ s).
7. Metastable stars, those with hyperons which are unstable to collapse upon deleptonization, have evolution times which increase the nearer the mass is to the maximum mass supported by a cold, deleptonized star.
8. Strong & electromagnetic many-body correlations, axial-charge renormalization, and multi-pair excitations have little effect on neutrino fluxes or signals during early times ($t < 10$ s).

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

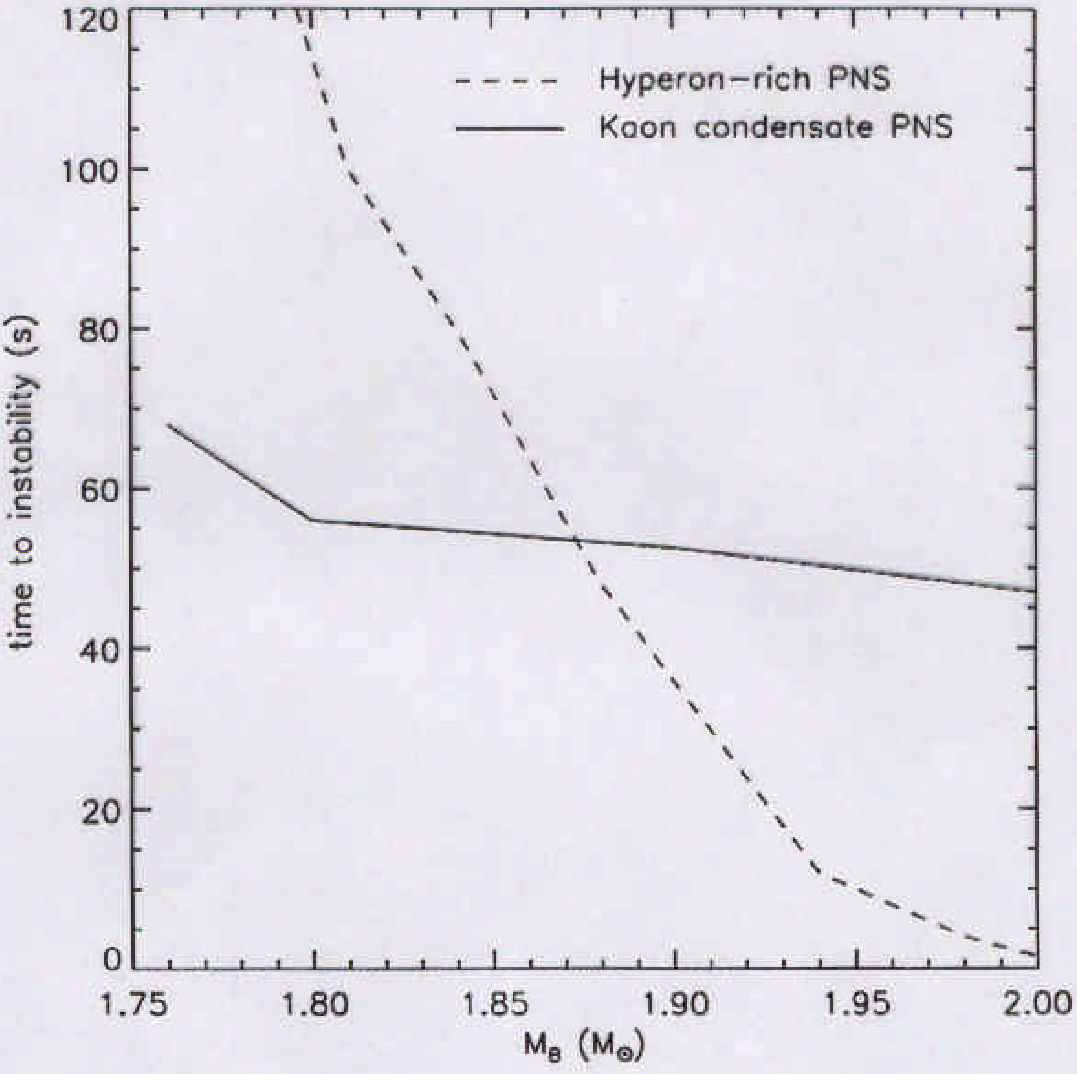

120
100
80
60
40
20
0
time to instability (s)
1.75
1.80
1.85
1.90
1.95
2.00
M_B ($M_\odot$)
Hyperon–rich PNS
Kaon condensate PNS

Fig. 12.—

- What could a Super-Duper-Kamioknande } do?
  Super-SNO }

  - A titillating thought !

    ν- Interferometry
    (HBT- typeanalysis)
    to determine R_ν, the radius
    of the neutrinosphere.

- What could accelerators do ?

  - ν-reactions on heavy nuclei

    Probes directly M.E. of the axial current
    in nuclear matter

    Detect (μ^+ or e^+) in

    $$(\text{Gev or so}) \quad \bar{\nu} + x \rightarrow \mu^+ \ (\text{or } e^+) + \pi^- \ (\text{or } K^-) + X$$

    Kinematically possible when
    in-medium π^- or (K^-) dispersion relation
    finds support in space-like regions

- References

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PRD 52 (1995) 661
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22 (1996) 63

→ Equation of State: Phys. Rep. 280 (1997) 1
PRC (~~1999~~) ?
2000

→ $\nu-$ opacities: PRD 58 (1998) 013009-1-27
PRC 59 (1999) 2888
PLB (~~1999~~) ~~in press~~
(2000) 475, 1

→ Evolution: ApJ 513 (1999) 780