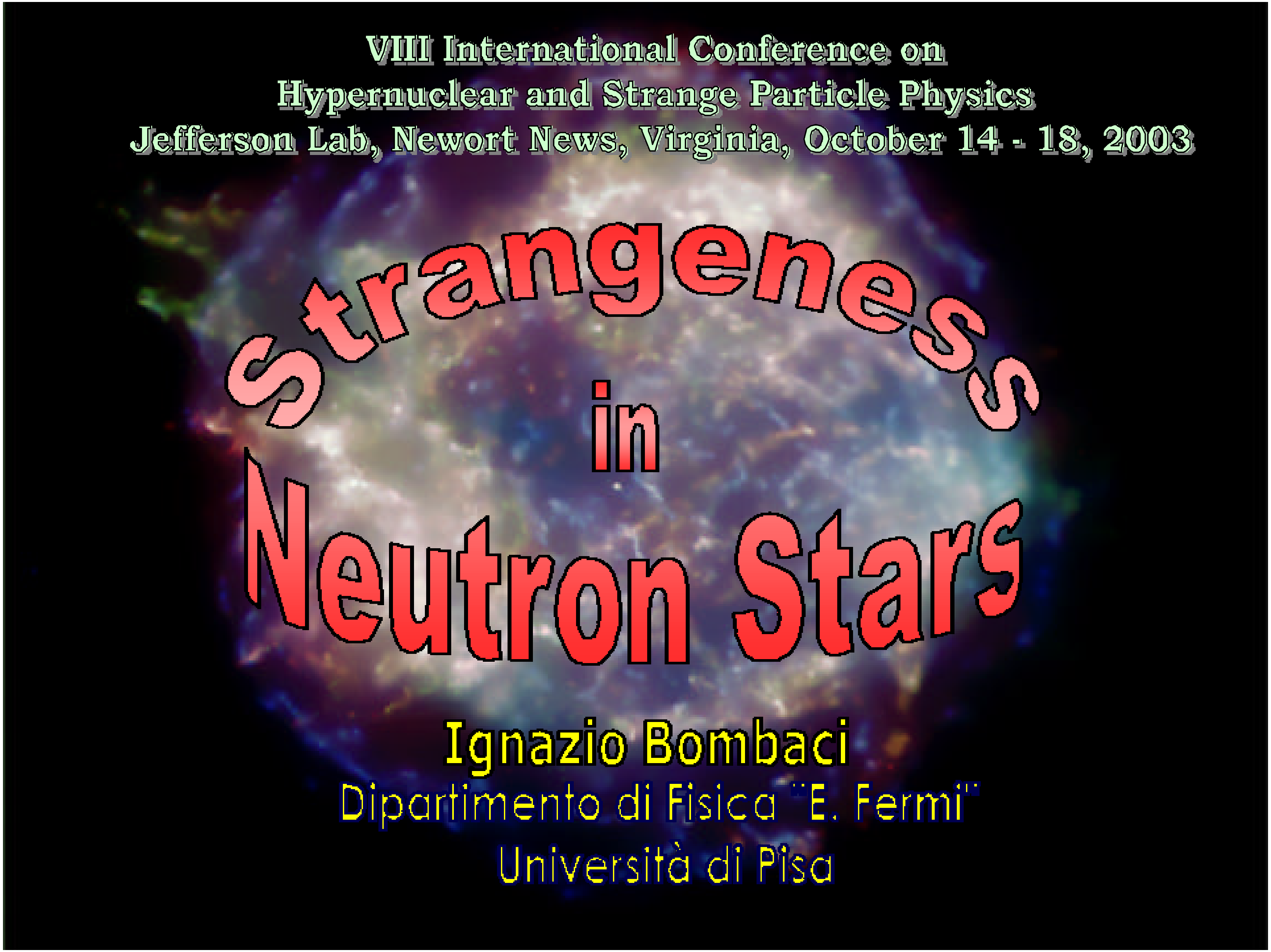


VIII International Conference on
Hypernuclear and Strange Particle Physics
Jefferson Lab, Newort News, Virginia, October 14 - 18, 2003

Strangeness in Neutron Stars

Ignazio Bombaci
Dipartimento di Fisica "E. Fermi"
Università di Pisa

Plan of the talk

- **Why strangeness is expected in "Neutron stars"(compact stars) ?**

  Confined form of strangeness: **Hyperons, Kaons**
  Deconfined form of strangeness: **Strange Quark Matter**

- **Role of strangeness on the bulk properties of Neutron Stars**

- **Astrophysical implications of strangeness in Compact Stars**

  Possible ***new family of compact stars***: **Strange Stars**

  Quark-Deconfinement Nova ➔ possible **"engine" for GRBs**

Neutron Stars or Hyperon Stars

Why is it very likely to have hyperons in the core of a Neutron Star?

(1) The central density of a Neutron Star is “high”

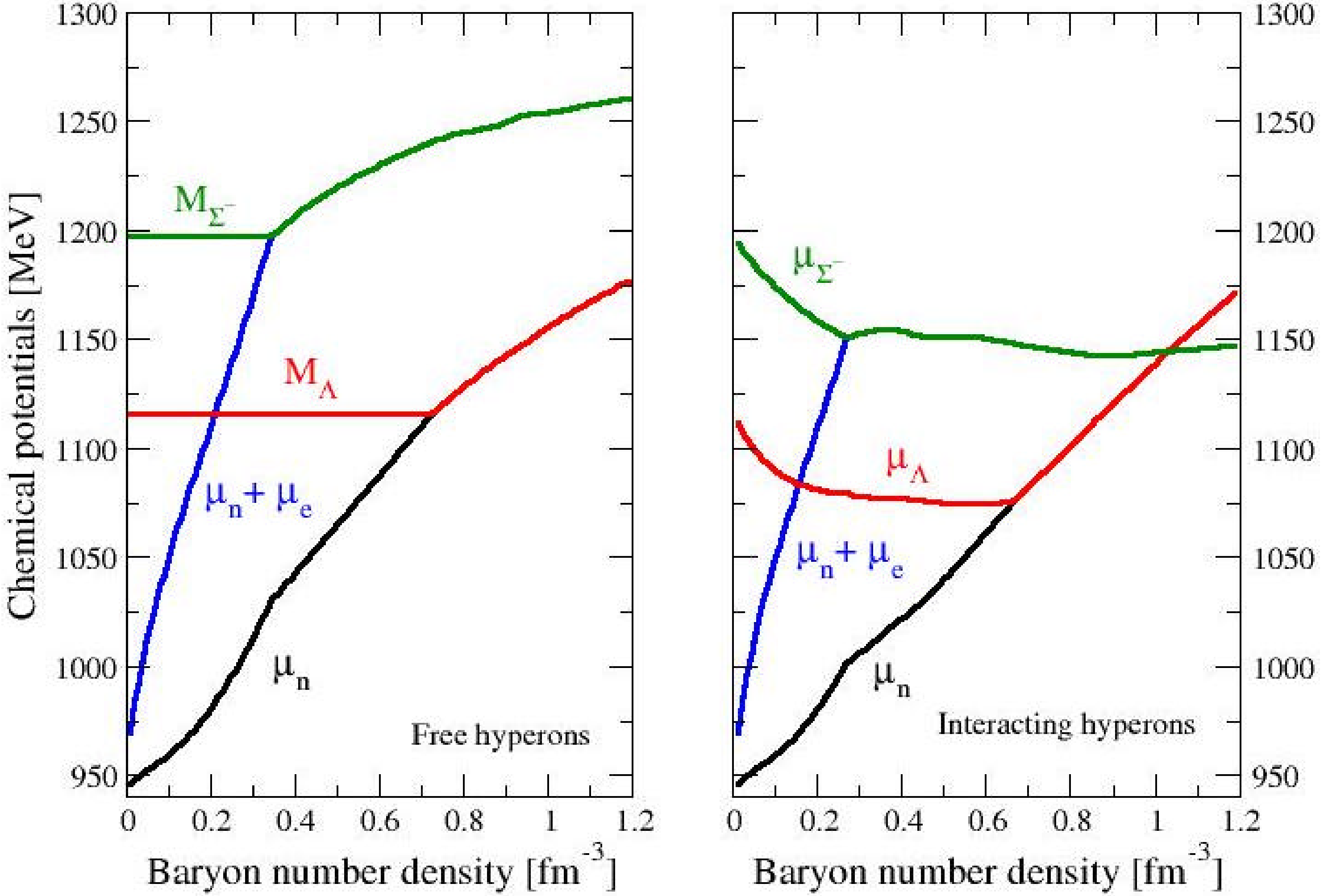
$\mathbf{r_c}$ **» (4 – 8)** $\mathbf{r_0}$ ($\rho_0 = 0.17\ \text{fm}^{-3}$)

(2) The nucleon chemical potentials increase very rapidly as function of density.

⇨ Above a threshold density ($\mathbf{r_c}$ **» (2 – 3)** $\mathbf{r_0}$) hyperons are created in the stellar interior.

A. Ambarsumyan, G.S. Saakyan, (1960)
V.R. Pandharipande (1971)

Baryon chemical potentials in dense hyperonic matter



I. Vidaña, Ph.D. thesis (2001)

Microscopic EOS for hyperonic matter: extended Brueckner theory

$$G(\omega)_{B_1B_2\,B_3B_4} = V_{B_1B_2B_3B_4} + \sum_{B_5B_6} V_{B_1B_2\,B_5B_6} \frac{Q_{B_5B_6}}{\omega - e_{B_5} - e_{B_6}} G(\omega)_{B_5B_6B_3B_4}$$

$$e_{B_i}(k) = M_{B_i}c^2 + \frac{\hbar^2 k^2}{2M_{B_i}} + U_{B_i}(k)$$

$$U_{B_i}(k) = \sum_{B_j} \sum_{k' \le k_{F\,B_j}} \langle \vec{k}\vec{k}' |\, G_{B_iB_j\,B_i\,B_j}(\omega = e_{B_i} + e_{B_j}) \,|\, \vec{k}\vec{k}' \rangle$$

V is the **baryon--baryon interaction for the baryon octet (n, p, L, s$^-$, s^0, s$^+$, x $^-$, x ^{0}) (e.g. the Nijmegen potential).**

- **Energy per baryon in the BHF approximation**

$$E/N_B = 2 \sum_{B_i} \int_0^{k_F[B_i]} \frac{d^3k}{(2\pi)^3} \left\{ M_{B_i}c^2 + \frac{\hbar^2 k^2}{2M_{B_i}} + \frac{1}{2} U^N_{B_i}(k) + \frac{1}{2} U^Y_{B_i}(k) \right\}$$

Baldo, Burgio, Schulze, Phys.Rev. C61 (2000) 055801;
Vidaña, Polls, Ramos, Engvik, Hjorth-Jensen, Phys.Rev. C62 (2000) 035801;
Vidaña, Bombaci, Polls, Ramos, Astron. Astrophys. 399, (2003) 687.

b-stable hadronic matter

☐ **Equilibrium with respect to the weak interaction processes**

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

$$\mu_n = \mu_{\Sigma^0} = \mu_{\Xi^0} = \mu_\Lambda$$

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

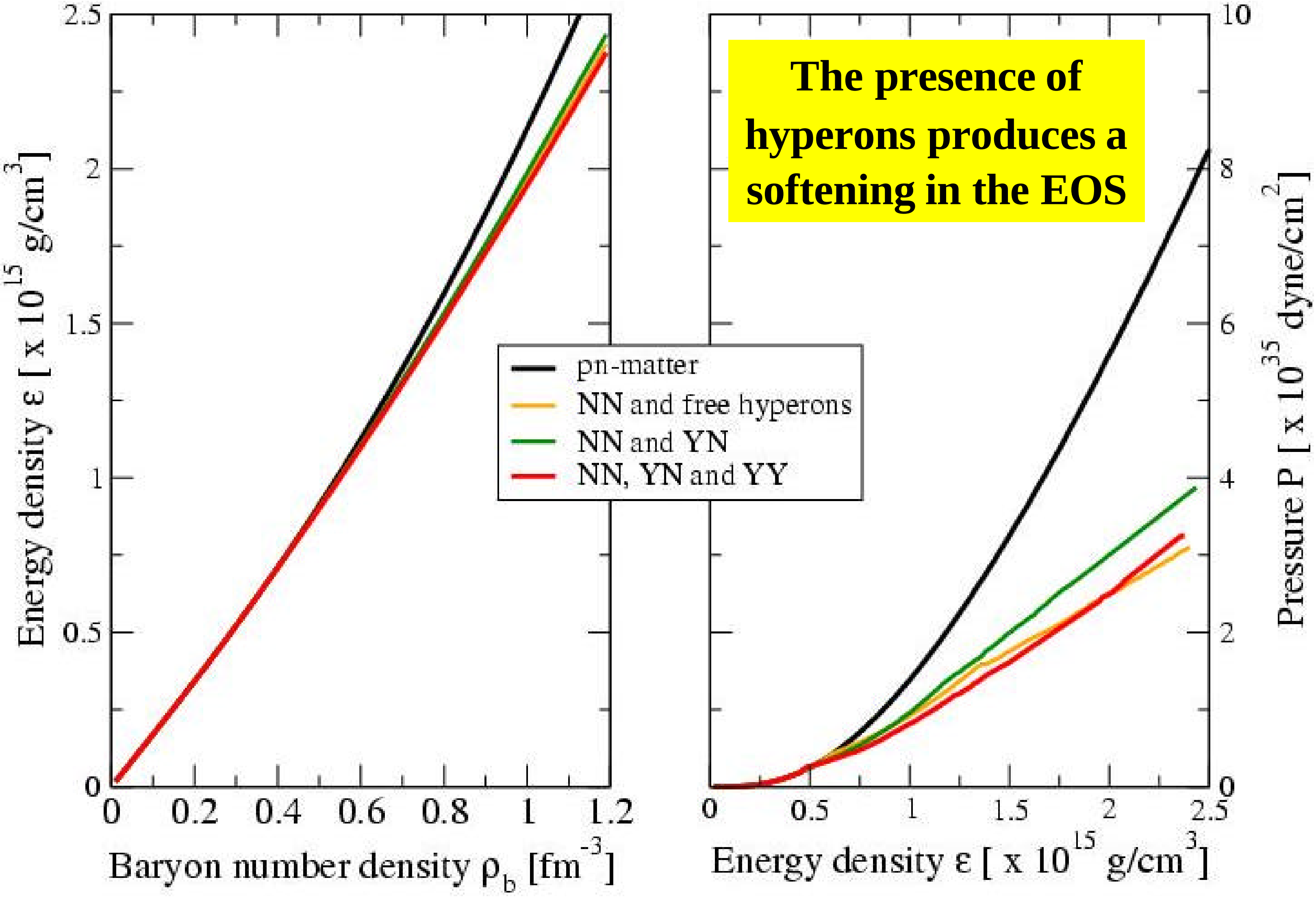
$$\mu_\mu = \mu_e$$

☐ **Charge neutrality**

$$n_p + n_{\Sigma^+} = n_e + n_\mu + n_{\Sigma^-} + n_{\Xi^-}$$

For any given value of the total baryon number density n_B

The Equation of State of Hyperonic Matter



The presence of hyperons produces a softening in the EOS

NSC97e

I. Vidaña et al., Phys. Rev: C62 (2000) 035801

Structure equations for compact stars

Hydrostatic equilibrium in General Relativity:

Tolman – Oppenheimer – Volkov equations (TOV)

$$\frac{dP}{dr} = -G\frac{m(r)\rho(r)}{r^2}\left(1+\frac{P(r)}{c^2\rho(r)}\right)\left(1+4\pi\frac{r^3P(r)}{c^2}m(r)\right)\left[1-\frac{2Gm(r)}{c^2r}\right]^{-1}$$

$$\frac{dm}{dr} = 4\pi r^2\rho(r)$$

Boundary conditions:

$$m(r=0) = 0$$

$$P(r=R) = P_{surf}$$

R = stellar radius

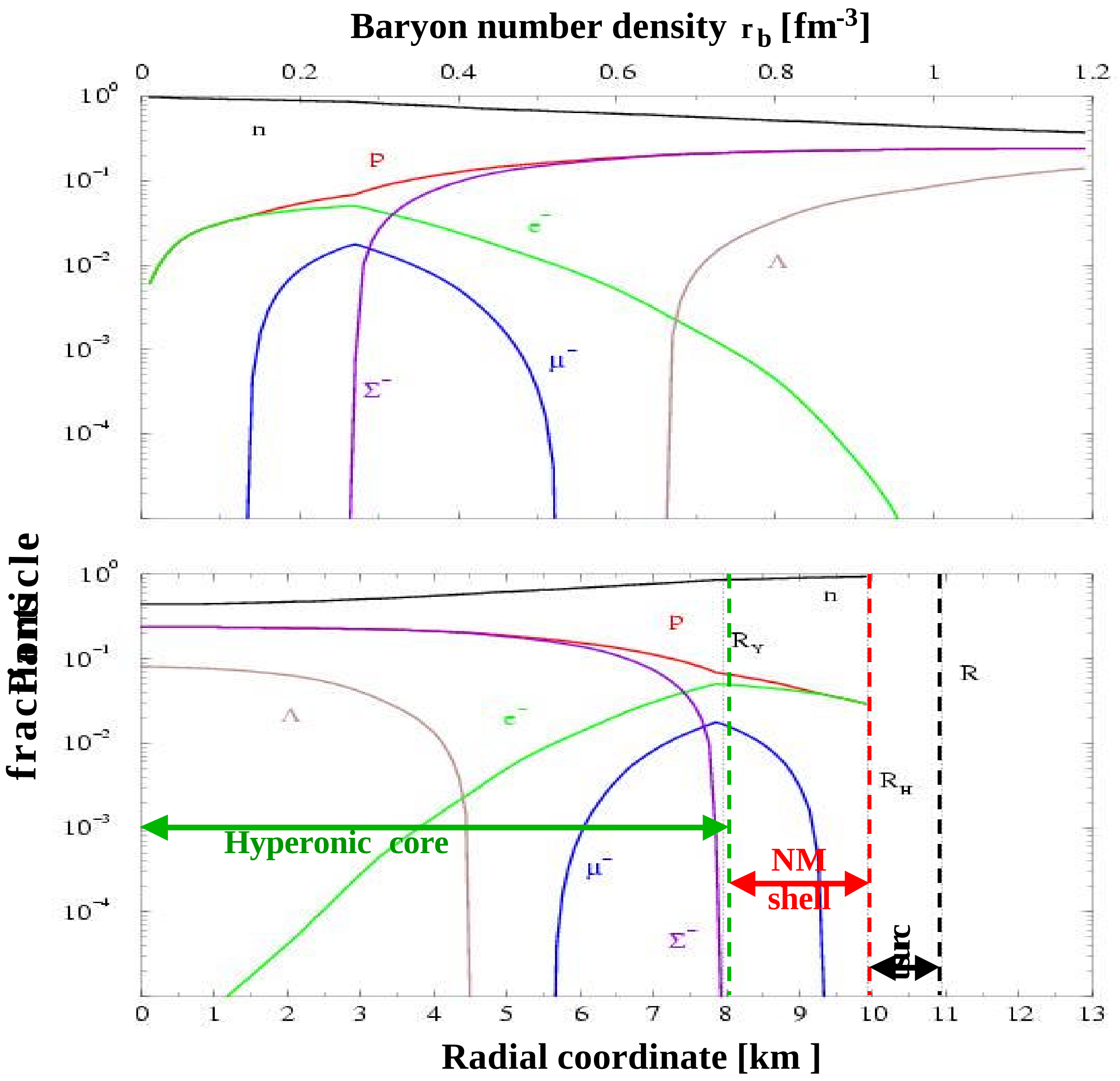
$$P = P(r, \rho_c)$$

$$m = m(r, \rho_c)$$

The solutions of the TOV eq.s depend parametrically on the central density

$$\rho_c = \rho(r=0)$$

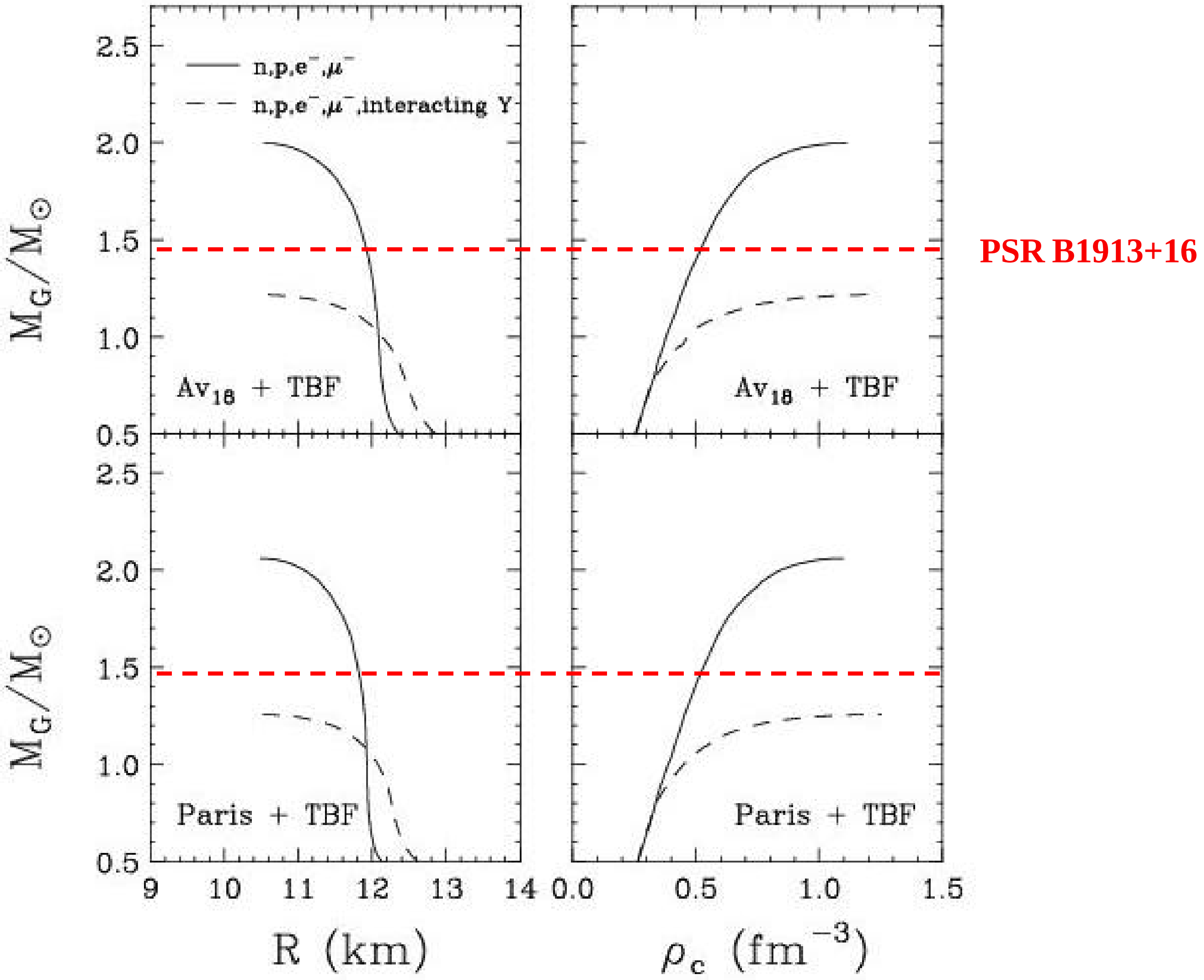
Composition of hyperonic beta-stable matter



Hyperonic Star

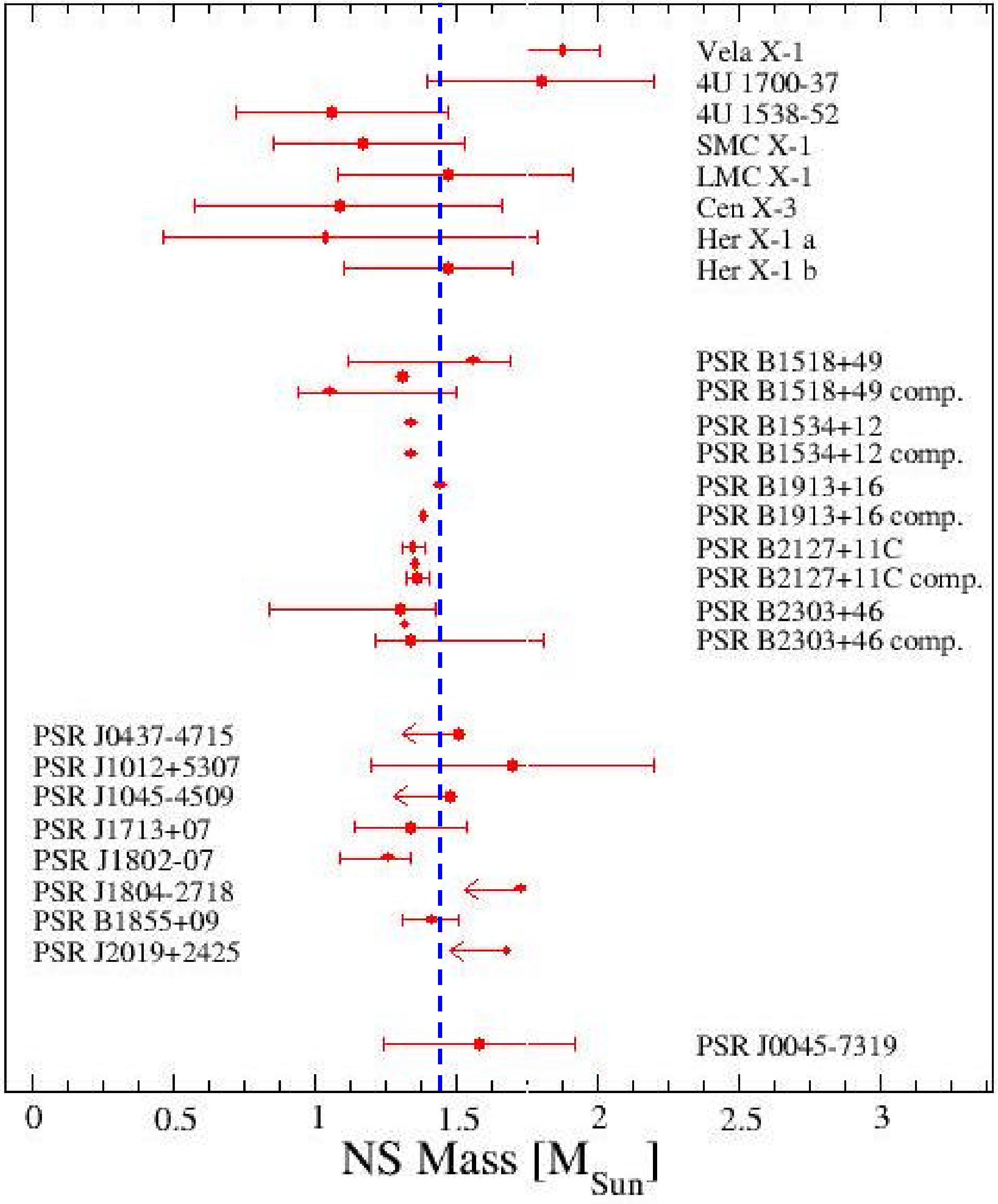
$M_B = 1.34\ M_\odot$

I. Vidaña, I. Bombaci,
A. Polls, A. Ramos,
Astron. and Astrophys.
399 (2003) 687



M. Baldo, G.F. Burgio, H.-J. Schulze, Phys.Rev. C61 (2000)

Measured Neutron Star Masses



M_{max} ³ $1.44\ M_{\odot}$

“very soft” EOS
are ruled out

Hyperons in Neutron Stars: implications for the stellar structure

The presence of hyperons reduces the maximum mass of neutron stars: $\mathrm{D}M_{max}$ **»** $(0.5 – 0.8)\ M_{\odot}$

Therefore, **to neglect hyperons always leads to an overestimate of the maximum mass of neutron stars**

Microscopic EOS for hyperonic matter:

“very soft” EOS non compatible with measured NS masses.

→ **Need for extra pressure at high density**

- **Improved NY, YY two-body interaction**
- **Three-body forces: NNY, NYY, YYY**

Strange quark matter in Neuron Stars

QCD

Ultra-Relativistic Heavy Ion Collisions

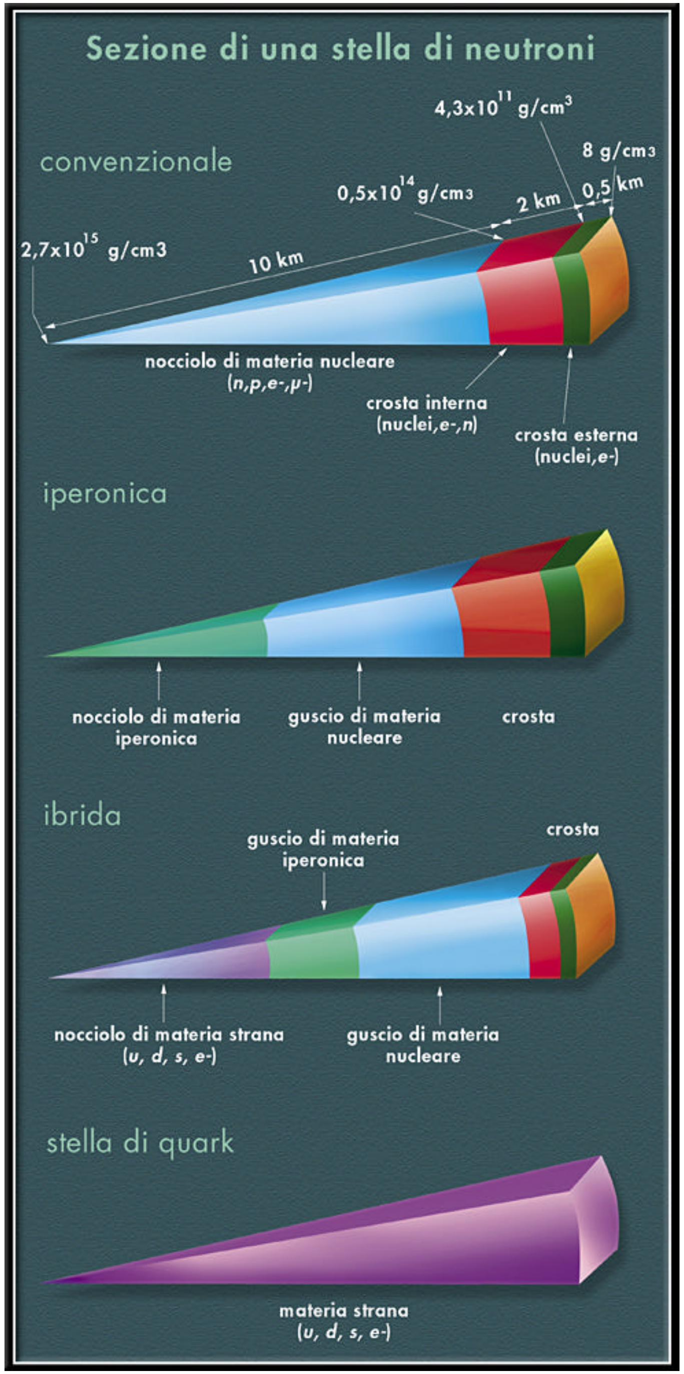
Quark-deconfinement phase transition expected at

r_c » **(3 – 5)** r_0

The core of the most massive neutron stars is one of the best candidates in the Universe where such a deconfined phase of quark matter can be found

- **Hybrid Neutron Stars**
- **Strange Stars** (Bodmer-Witten hypotesis for SQM)

Compact stars



"Conventional" Neutron Stars

Hyperon Stars

} **Hadronic Stars**

Hybrid Stars

Strange Stars

The Strange Matter hypothesis

Bodmer (1971), Terazawa (1979), Witten (1984)

Three-flavor *u,d,s* quark matter, in equilibrium with respect to the weak interactions, could be the true ground state of strongly interacting matter, rather than ^{56}Fe

$$E/A|_{SQM} \quad \text{£} \quad E(^{56}Fe)/56 \sim 930\ MeV$$

Stability of Nuclei with respect to u,d quark matter

The success of traditional nuclear physics provides a clear indication that **quarks in the atomic Nucleus are confined within protons and neutrons**

$$E/A|_{ud} \quad {}^{3} \quad E(^{56}Fe)/56$$

The X-ray burster SAX J1808.4-3658

- **Discovered in Sept. 1996 by Beppo SAX**
- **Type-I X-ray burst source (DT < 30 sec.)**
- **Transient X-ray source (XTE J1808-369) detected with the proportional counter array on board of the Rossi X-ray Timing Explorer (RXTE) (1998)**
- **Millisecond PSR: Coerent pulsation with P = 2.49 ms**
- **Member of a LMXB: P_{orb} = 2.01 hours**

SAXJ1808.4-3658 is the first of the (so far) 3 discovered accreting X-ray millisecond PSRs.

XTE J1751-305 : P = 2.297 ms, P_{orb} = 42.4 min [2002]
XTE J0929-314 : P = 5.405 ms, P_{orb} = 43.6 min [2002]

▶ **millisecond X-ray PSRs were expected from theoretical models on the genesis of millisecond radio pulsars.**

The Mass-Radius relation for SAX J1808.4-3658

(i) In the course of RXTE observation in April – May 1998, the 3—150 keV X-ray luminosity of the source decreased by a factor of ~100.

(ii) X-ray pulsation was observed over this range of X-ray luminosity.

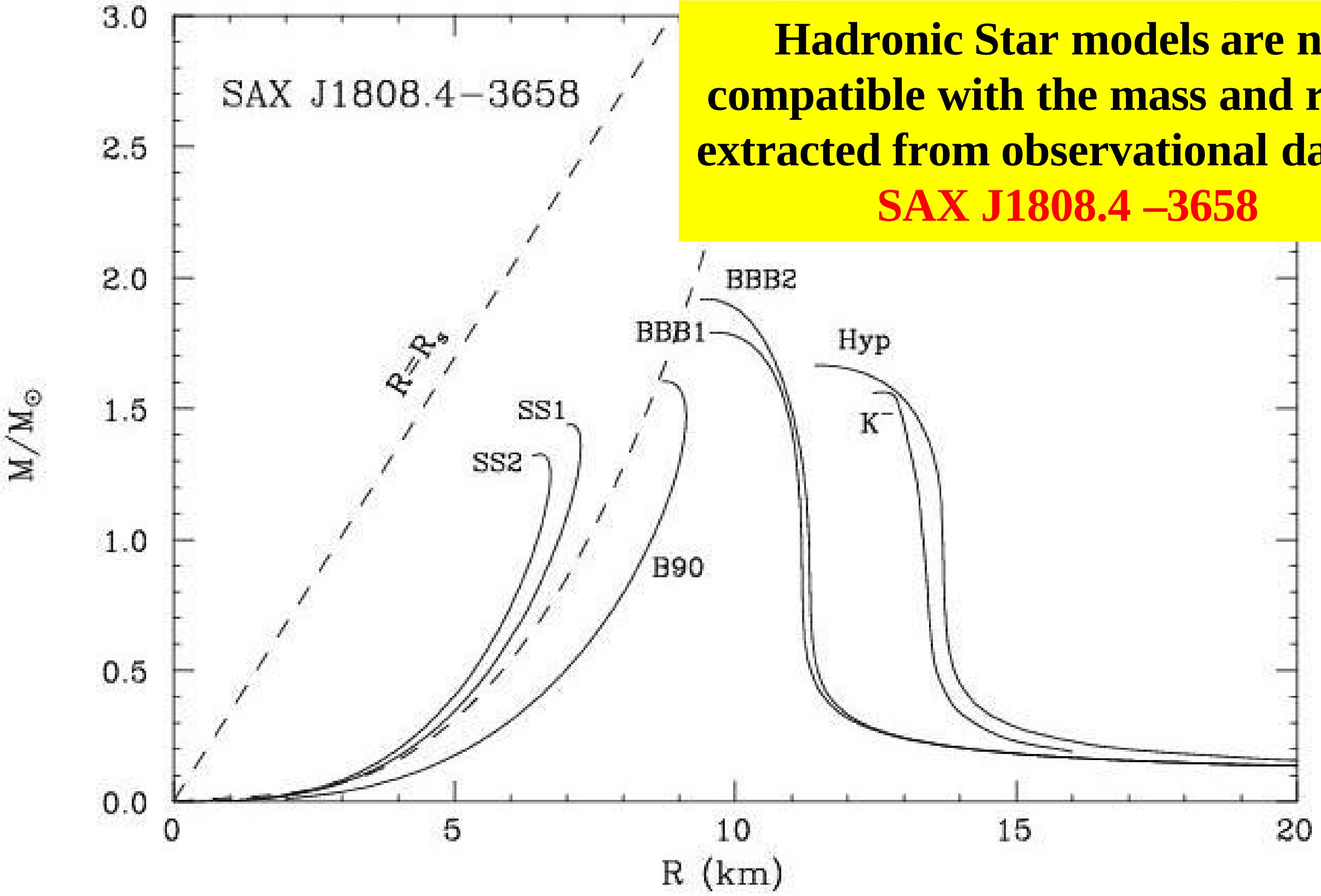
- From (i) and (ii) the following firm upper limit for the radius of the compact object can be derived (X.-D. Li, I. Bombaci, M. Dey, J. Dey, E.P.J. Van den Heuvel, Phys. Rev. Lett. 83, (1999), 3776)

$$R < (F_{min} / F_{max})^{2/7} (GM_{\odot} / 4p^2)^{1/3} P^{2/3} (M / M_{\odot})^{1/3}$$

F_{min}= X-ray flux measured during the “low state” of the source
F_{max}= X-ray flux measured during the “high state” of the source

$F_{max} / F_{min} \sim 100$

A strange star candidate: SAX J1808.4 –3658



Hadronic Star models are not compatible with the mass and radius extracted from observational data for SAX J1808.4 –3658

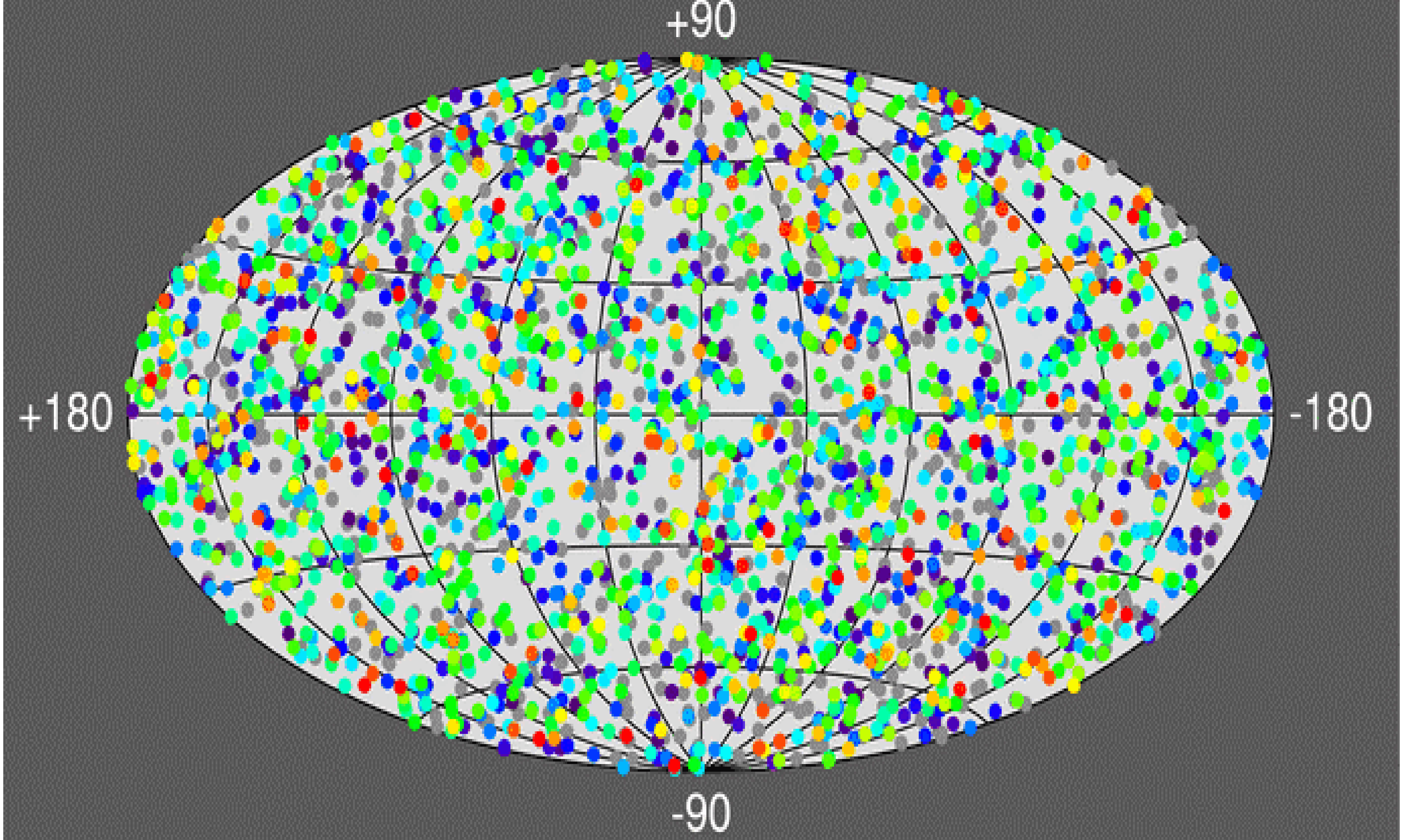
X.-D. Li, I. Bombaci, M. Dey, J. Dey, E.P.J. Van den Heuvel, Phys. Rev. Lett. 83, (1999), 3776

Strange Quark Matter in compact stars and Gamma Ray Bursts

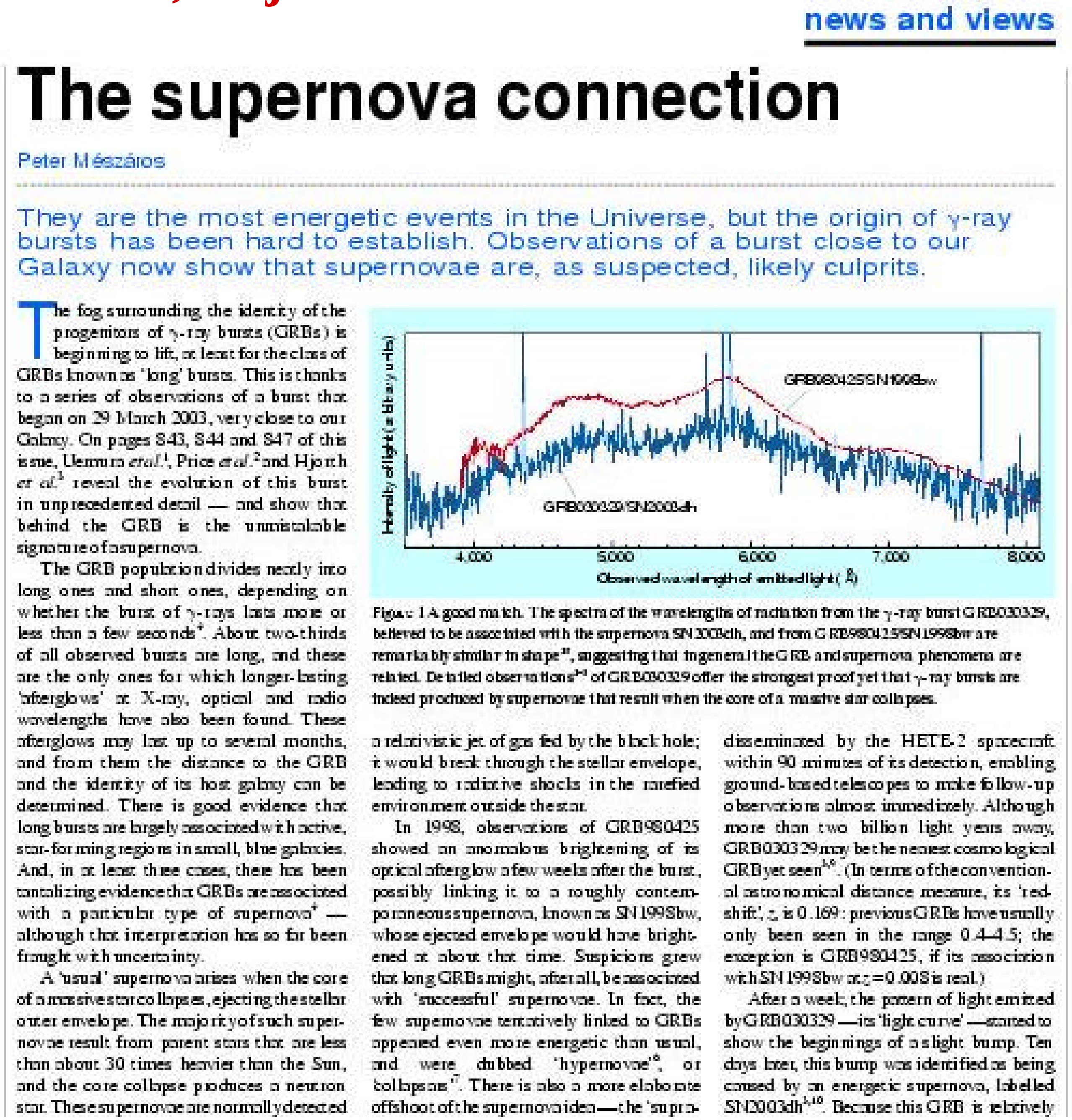
Gamma Ray Bursts (GRBs)

- **Spatial distribution:** isotropic
- **Distance:** "cosmological" d = (1 – 10) 10^{9} ly
- **Energy range:** 100 keV – a few MeV
- **Emitted energy:** ~ 10^{51} erg (beamed / jets)
- **Duration:** 1 – 300 s

2704 BATSE Gamma-Ray Bursts



NATURE, vol. 423, 19 june 2003



news and views

The supernova connection

Peter Mészáros

They are the most energetic events in the Universe, but the origin of γ-ray bursts has been hard to establish. Observations of a burst close to our Galaxy now show that supernovae are, as suspected, likely culprits.

The fog surrounding the identity of the progenitors of γ-ray bursts (GRBs) is beginning to lift, at least for the class of GRBs known as 'long' bursts. This is thanks to a series of observations of a burst that began on 29 March 2003, very close to our Galaxy. On pages 843, 844 and 847 of this issue, Uemura *et al.*[1], Price *et al.*[2] and Hjorth *et al.*[3] reveal the evolution of this burst in unprecedented detail — and show that behind the GRB is the unmistakable signature of a supernova.

The GRB population divides neatly into long ones and short ones, depending on whether the burst of γ-rays lasts more or less than a few seconds[4]. About two-thirds of all observed bursts are long, and these are the only ones for which longer-lasting 'afterglows' at X-ray, optical and radio wavelengths have also been found. These afterglows may last up to several months, and from them the distance to the GRB and the identity of its host galaxy can be determined. There is good evidence that long bursts are largely associated with active, star-forming regions in small, blue galaxies. And, in at least three cases, there has been tantalizing evidence that GRBs are associated with a particular type of supernova[4] — although that interpretation has so far been fraught with uncertainty.

A 'usual' supernova arises when the core of a massive star collapses, ejecting the stellar outer envelope. The majority of such supernovae result from parent stars that are less than about 30 times heavier than the Sun, and the core collapse produces a neutron star. These supernovae are normally detected

Figure 1 A good match. The spectra of the wavelengths of radiation from the γ-ray burst GRB030329, believed to be associated with the supernova SN2003dh, and from GRB980425/SN1998bw are remarkably similar in shape[3], suggesting that in general the GRB and supernova phenomena are related. Detailed observations[1-3] of GRB030329 offer the strongest proof yet that γ-ray bursts are indeed produced by supernovae that result when the core of a massive star collapses.

a relativistic jet of gas fed by the black hole; it would break through the stellar envelope, leading to radiative shocks in the rarefied environment outside the star.

In 1998, observations of GRB980425 showed an anomalous brightening of its optical afterglow a few weeks after the burst, possibly linking it to a roughly contemporaneous supernova, known as SN1998bw, whose ejected envelope would have brightened at about that time. Suspicions grew that long GRBs might, after all, be associated with 'successful' supernovae. In fact, the few supernovae tentatively linked to GRBs appeared even more energetic than usual, and were dubbed 'hypernovae'[6], or 'collapsars'[7]. There is also a more elaborate offshoot of the supernova idea — the 'supra-

disseminated by the HETE-2 spacecraft within 90 minutes of its detection, enabling ground-based telescopes to make follow-up observations almost immediately. Although more than two billion light years away, GRB030329 may be the nearest cosmological GRB yet seen[3,8]. (In terms of the conventional astronomical distance measure, its 'redshift', z, is 0.169: previous GRBs have usually only been seen in the range 0.4–4.5; the exception is GRB980425, if its association with SN1998bw at $z = 0.008$ is real.)

After a week, the pattern of light emitted by GRB030329 — its 'light curve' — started to show the beginnings of a slight bump. Ten days later, this bump was identified as being caused by an energetic supernova, labelled SN2003dh[3,10]. Because this GRB is relatively

SN – GRB connection

❖ **GRB990705** **DT ~ 10 yr**

ΔT = time delay between the SN expl. and the GRB

Amati et al., Science 290 (2000) 953

❖ **GRB011211** **DT ~ 4 days**

Reeves et al. , Nature (2002)

A two-stages scenario

1st explosion : **Supernova** **(birth of a NS)**

2nd "explosion" **(ass. with the NS) : central engine of the GRB**

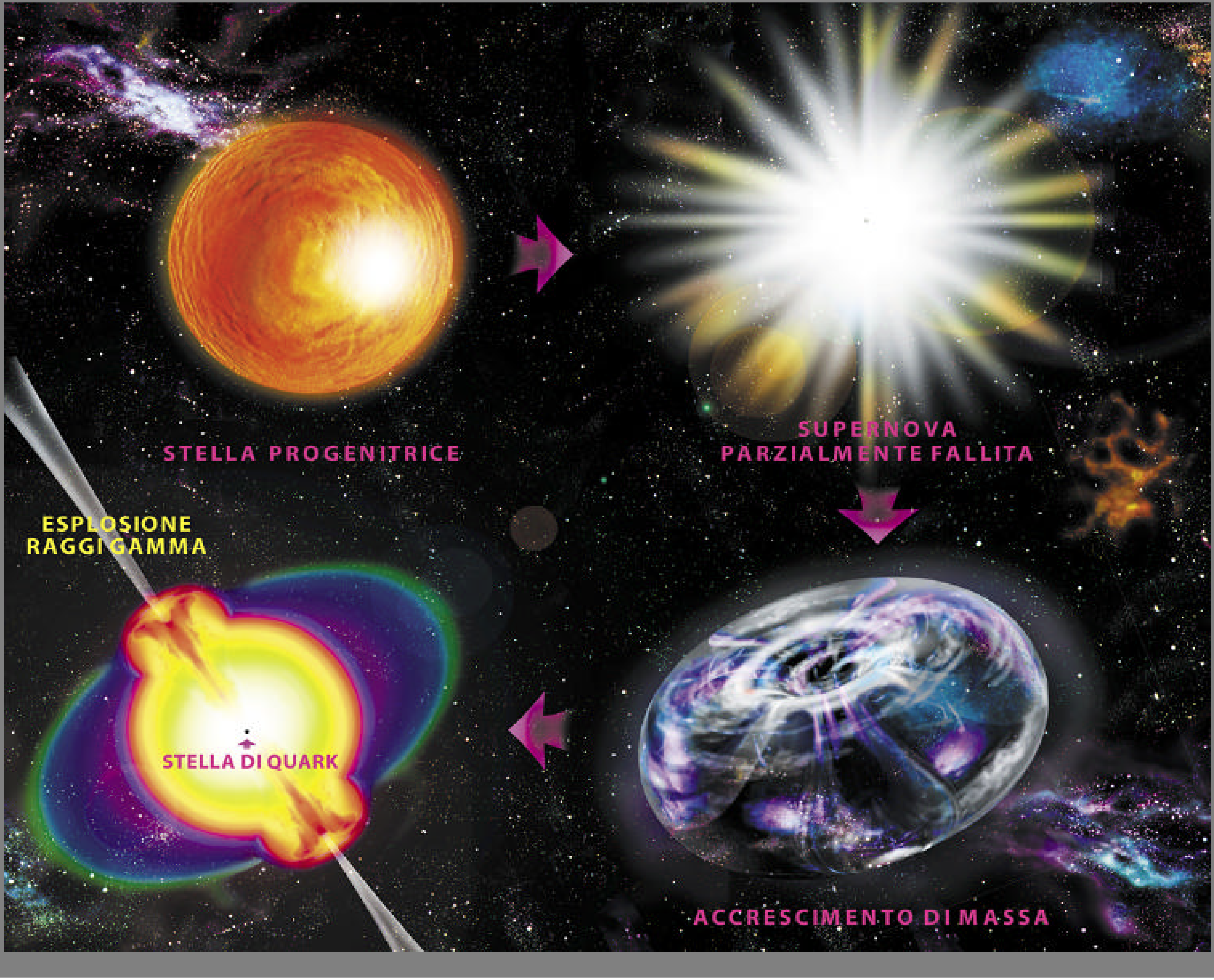
Questions

- What is the origin of the 2nd "explosion" ?
- How to explain the long time delay between the two events?

Delayed collapse of an Hadronic Star to a Quark Star

- pure Hadronic Star ⟶ Hybrid Star or Quark Star
- The conversion process can be delayed due to the effects of the surface tension between the HM phase and the QM phase.
- The nucleation time depends dramaticaly on the central pressure of the Hadronic Star
- As a critical-size drop of QM is formed the HS is converted to a QS or a HyS
- The conversion process liberates **$E_{conv} \sim 10^{52}$ -- 10^{53} erg**
- Central engine for a GRB.

Supernova-GRB connection: the Quark-Deconfinement Nova model



Hadron-Quark phase transition in bulk matter

- **Multicomponent system**: two conserved “charges” (electric charge and baryon number)
- In bulk matter the H-Q phase transition begins at the *static transition point* defined according to the **Gibbs’ criterion for phase equilibrium**

$$\mu_H = \mu_Q \equiv \mu_0 \, ; \qquad P(\mu_H) = P(\mu_Q) \equiv P(\mu_0)$$

$T_H = T_Q \equiv T$ (T= 0, we consider cold matter)

$$\mu_H = \frac{\varepsilon_H + P_H}{n_{b,H}} \qquad \mu_Q = \frac{\varepsilon_Q + P_Q}{n_{b,Q}}$$

Finite size effects on the H-Q phase transition

- The formation of a **critical-size drop** of QM is not immediate:

$$DP = P - P_0$$

overpressure with respect to the static transition point P_0

- Oscillation time of a virtual drop in the potential energy well:

n_0^{-1} » 10^{-23} sec. $<<$ t_{weak}

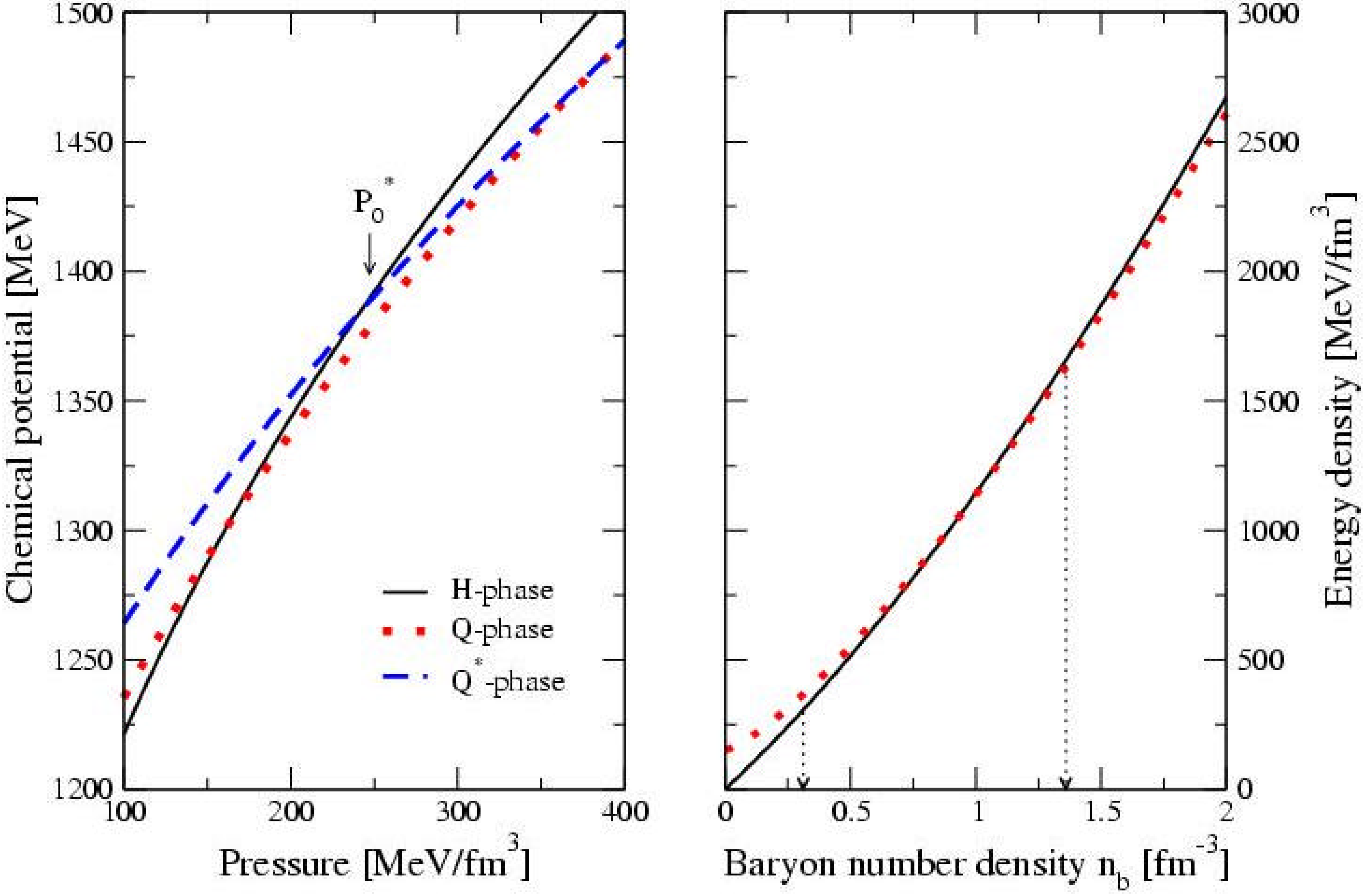
→ Quark-flavor must be conserved in the early stage of deconfinement

Q*-phase: flavor content is equal to that of beta-stable HM at the same pressure

- **Q-phase:** beta-stable SQM.

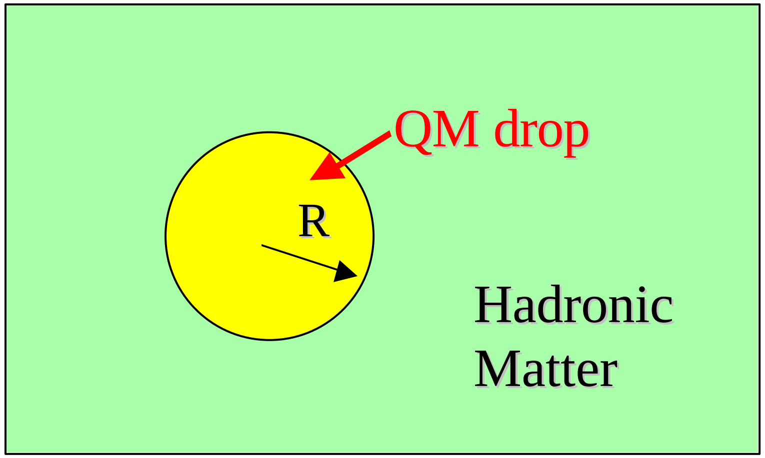
Soon afterwards a critical-size drop of QM is formed,

the weak interaction re-establish beta-equilibrium


Chemical potential [MeV]
1500
1450
1400
1350
1300
1250
1200
100
200
300
400
Pressure [MeV/fm^3]
P_0^*
H-phase
Q-phase
Q^*-phase
Energy density [MeV/fm^3]
3000
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
Baryon number density n_b [fm^{-3}]

Quantum nucleation theory

Quantum fluctuation of a virtual drop of QM in HM

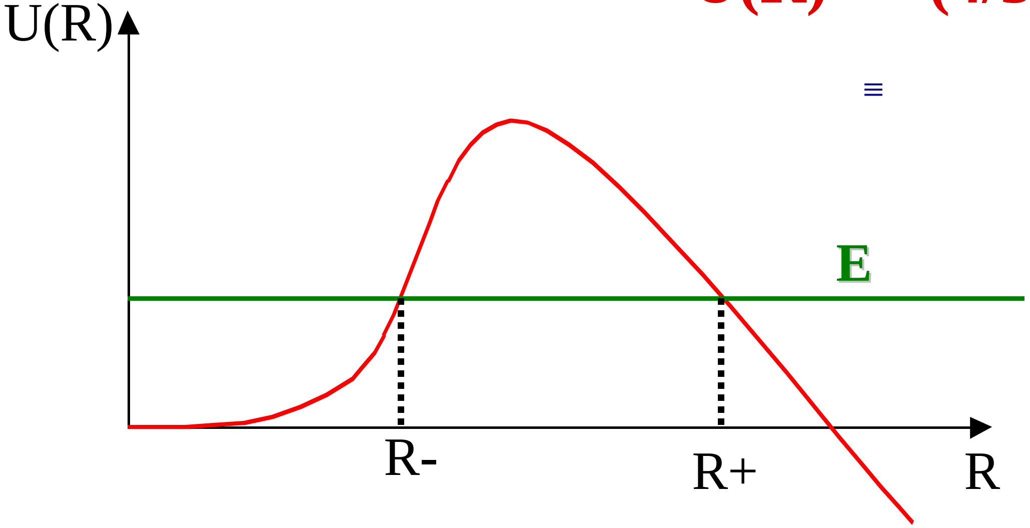


$$L = \frac{1}{2} M(R)\dot{R}^{2} - U(R)$$

$$M(R) = 4\pi\rho_H \ (1 - n_Q/n_H)^2$$

$$\mathbf{U(R) = (4/3)p\, R^3\, n_Q\, (m_Q - m_H) + 4p\, s\, R^2}$$

$$\equiv \quad a_v R^3 \quad + \quad a_s R^2$$



As $R > R_C$ the drop grows with no limitation.

$R_C \equiv$ radius of the critical size drop

Probability of tunneling

Oscillation frequency of the virtual drop inside the potential well

$$\boxed{\nu_0 = (dI/dE)^{-1} \quad \text{for } E = E_0}$$

$$I(E_0) = \frac{2}{3}\pi\ \hbar$$

$$I(E) = 2\int_0^{R_-} dR\,\sqrt{2M(R)[E - U(R)]}$$

Action of the zero point oscillations

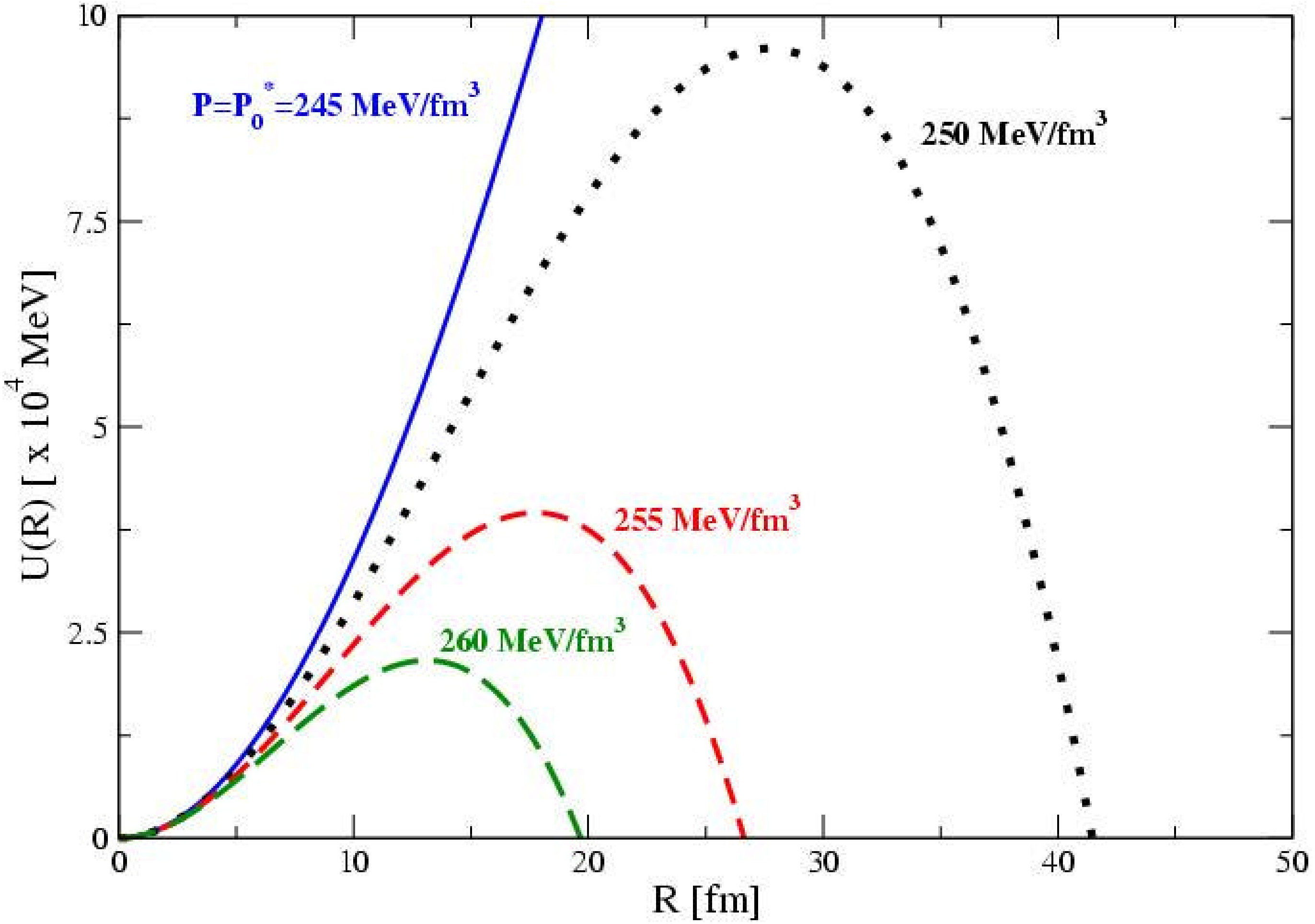
Penetrability of the potential barrier (WKB appox.)

$$\boxed{p_0 = \exp\left[-\frac{A(E_0)}{\hbar}\right]}$$

$$A(E) = 2\int_{R_-}^{R_+} dR\,\sqrt{2M(R)[U(R) - E]}$$

Nucleation time $\boxed{\tau = (\nu_0 p_0 N_c)^{-1}}$

$N_c \sim 10^{48}$
numb. of nucleation
centers in the star core

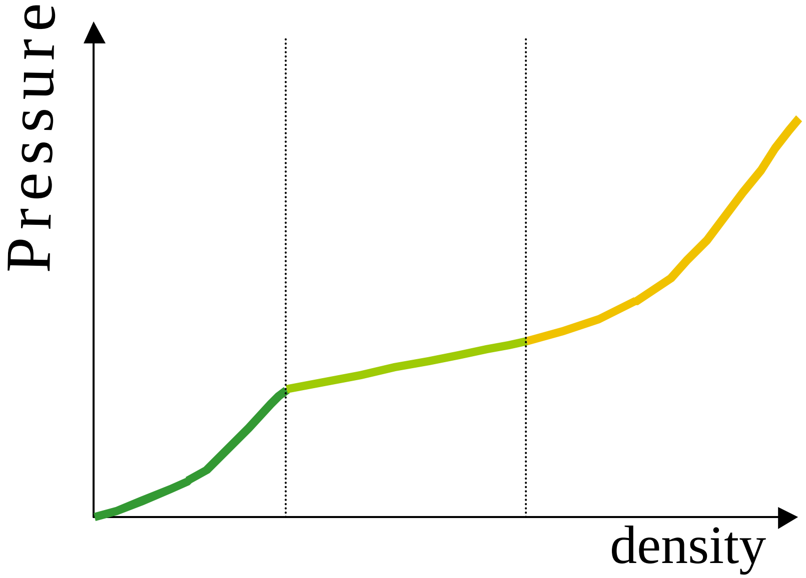

P=P$_0^*$=245 MeV/fm^3
250 MeV/fm^3
255 MeV/fm^3
260 MeV/fm^3
U(R) [x 10^4 MeV]
R [fm]
0
2.5
5
7.5
10
0
10
20
30
40
50

The EOS of dense matter

∗ **Hadronic phase :** **Relativistic Mean Field Theory of hadrons interacting via meson exch.** [e.g. Glendenning, Moszkowsky, PRL 67(1991)]

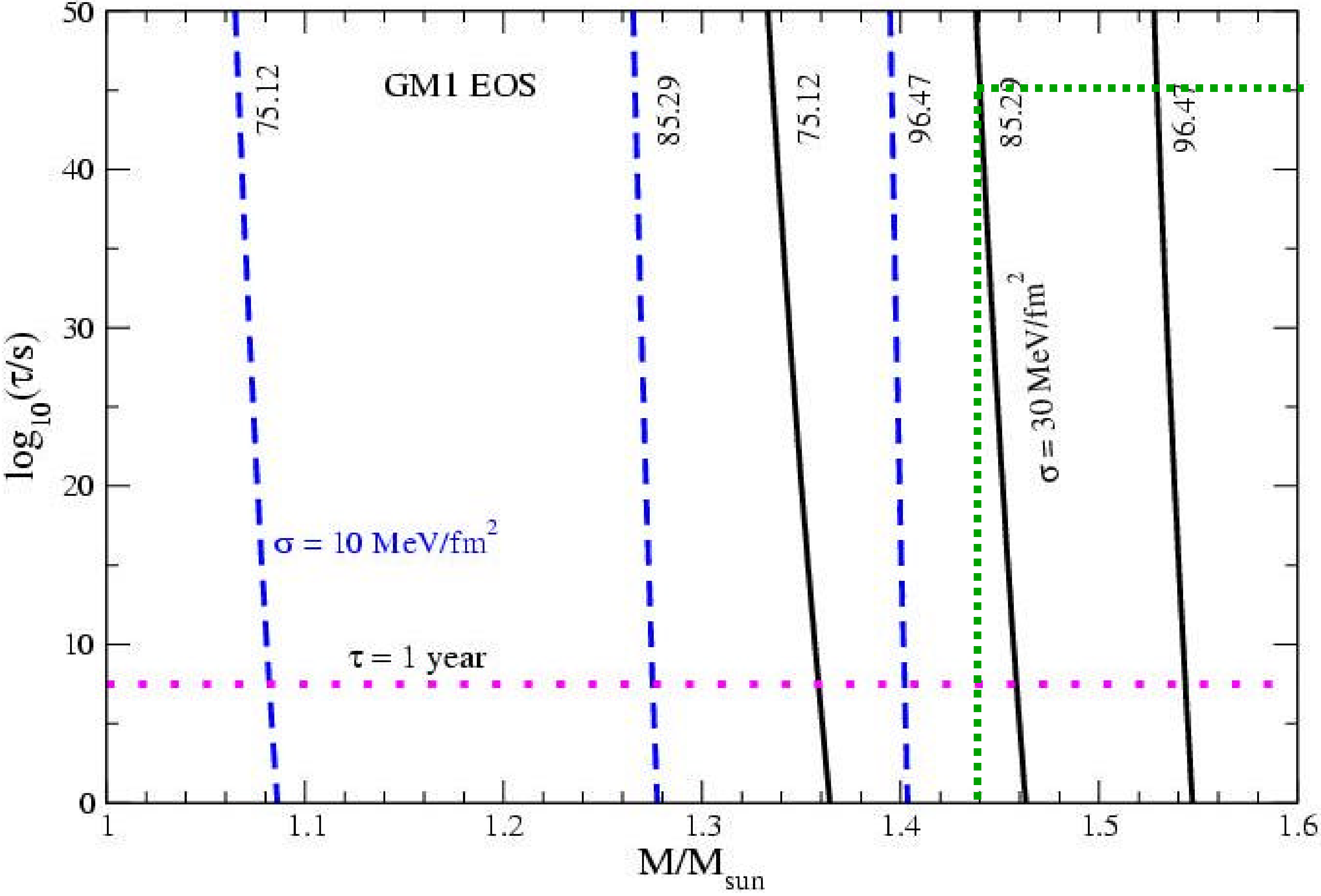
∗ **Quark phase :** **EOS based on the MIT bag model for hadrons.** [Farhi, Jaffe, Phys. Rev. D46(1992)]

∗ **Mixed phase :** **Gibbs construction for a multicomponent system with two conserved "charges".** [Glendenning, Phys. Rev. D46 (1992)]



$$P = P(r)$$

Hadronic Star mean-life time



In our scenario:

- Pure Hadronic Stars having a central pressure larger than the static transition pressure for the formation of the Q*-phase are **metastable** to the "decay" (conversion) to a more compact stellar configuration in which deconfined quark matter is present (HyS or SS).

- These metastable HS have a *mean-life time* which is related to the nucleation time to form the first critical-size drop of deconfined matter in their interior.

The critical mass of metastable Hadronic Stars

Def.: $M_{cr} = M_{HS}(t=1yr)$

- HS with $M_{HS} < M_{cr}$ are metastable with $t = 1$ yr – ¥

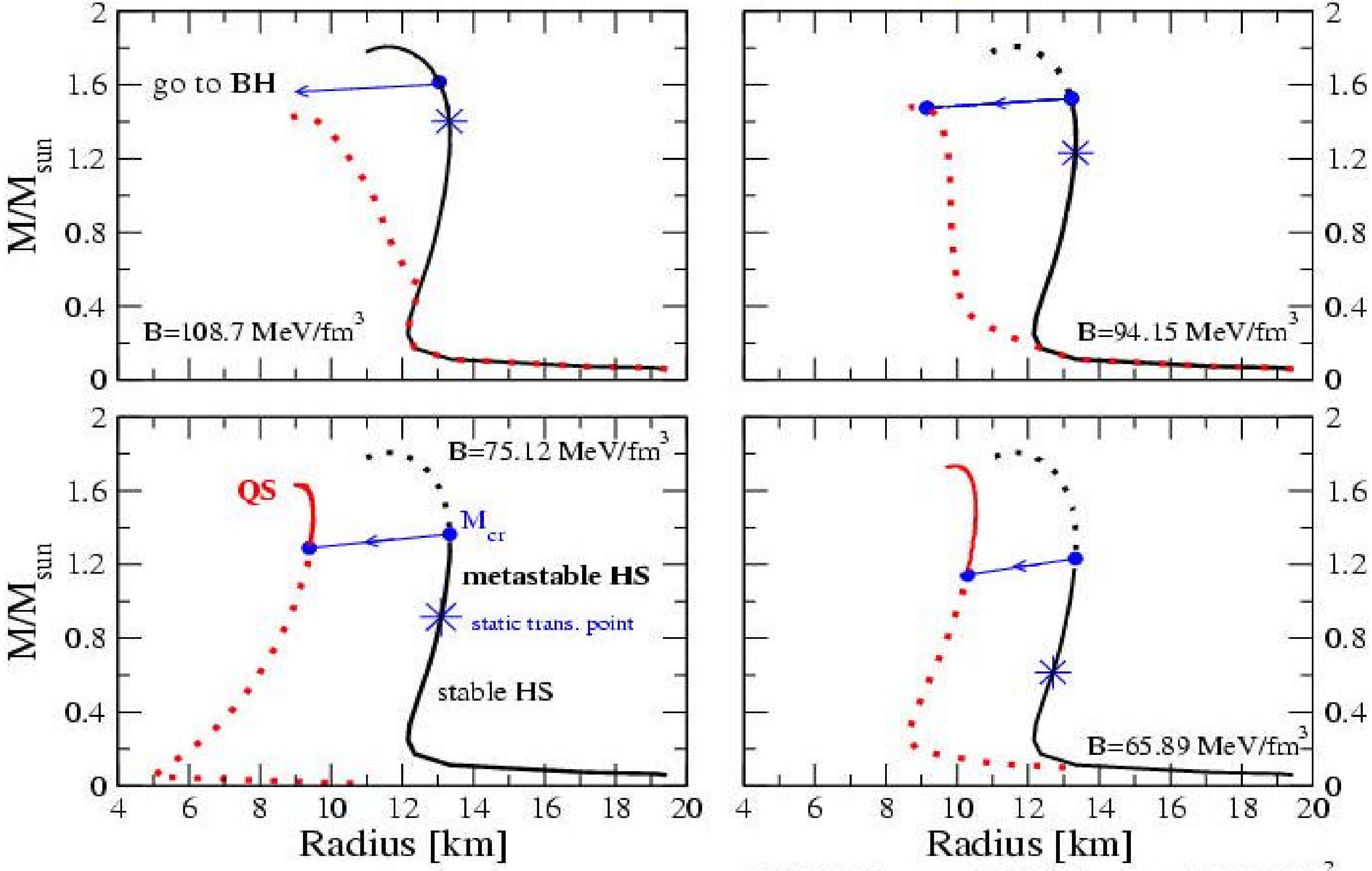
- The accretion of M_{accr} » $0.01\ M_{\odot}$ reduces the HS *mean-life time*

  t >> age of the Universe → t » a few years

- HS with $M_{HS} > M_{cr}$ are very unlikely to be observed

- The critical mass M_{cr} plays the role of an ***effective maximum mass*** for the hadronic branch of compact stars

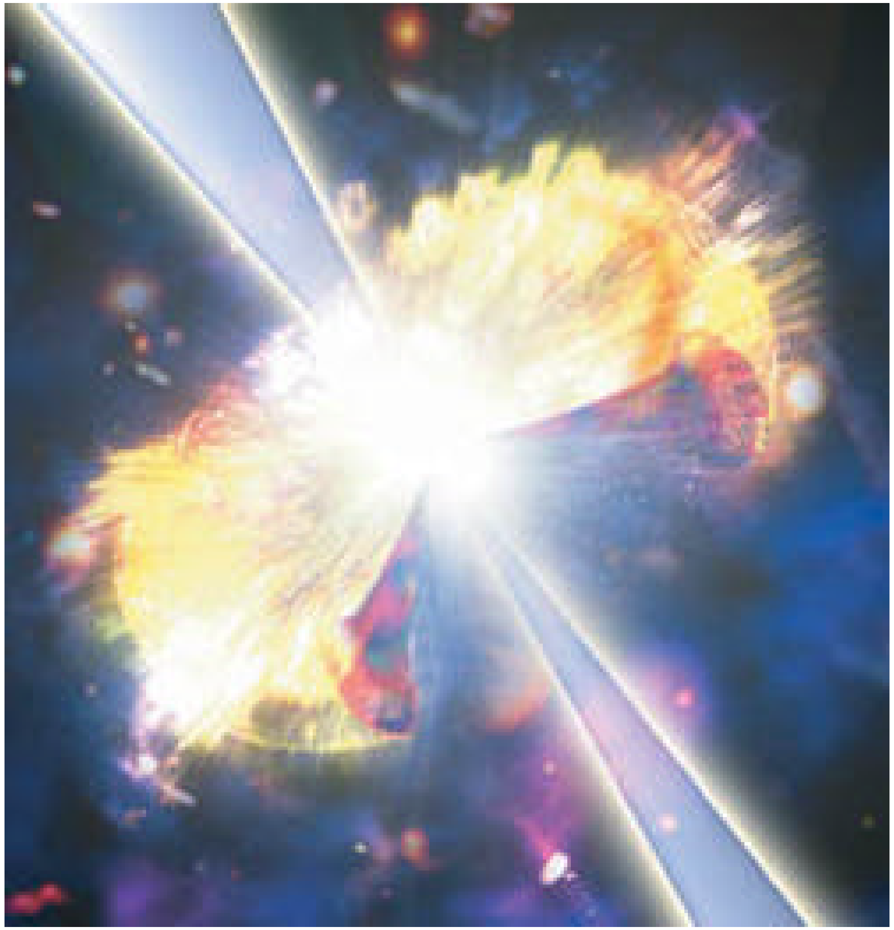
The two families of Compact Stars



GM1 EOS, $m_s = 150$ MeV, $\sigma = 30$ MeV/fm^2

Hadronic Stars: nucleons + hyperons

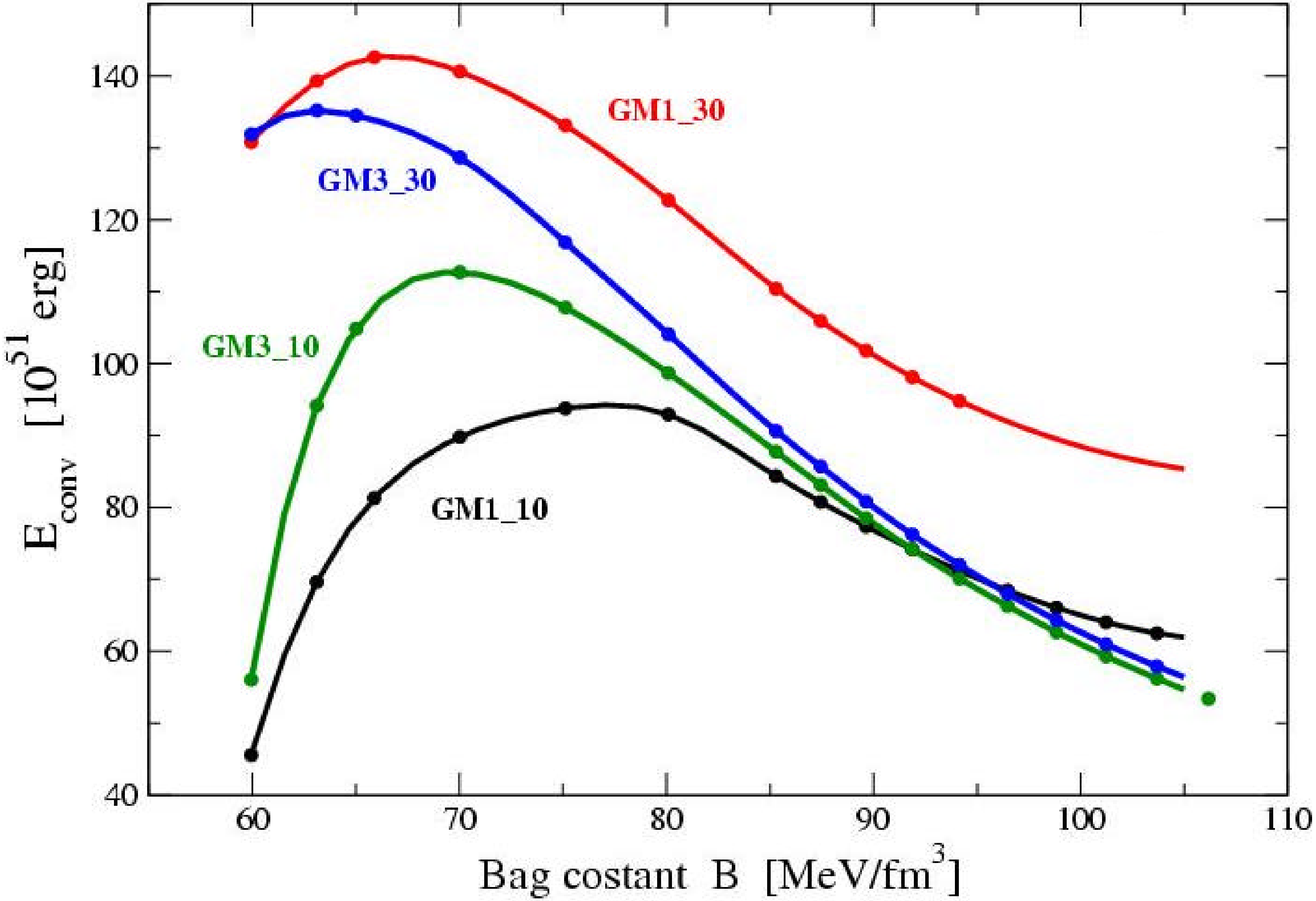
Total energy released in the stellar conversion



Assuming that the stellar baryonic mass is conserved during the stellar conversion the total energy released in the process is :

$$E_{conv} = M_{cr} - M_{QS}(M^{b}_{cr})$$

Total energy released in the stellar conversion



Production of gamma-rays

Total energy released from the QDN: $10^{52} – 10^{53}$ erg

$$n + \bar{n} \longrightarrow e^{+} + e^{-} \longrightarrow 2\ g$$

$$E_{g} = h\ E_{conv}$$

(1) Ignoring strong gravit. effects on the cross section

$$h = h_{Newt} \sim 0.01$$

(2) In a strong gravitational field

(Salmonson and Wilson, ApJ 517,(1999))

$$h_{GR} = (10 – 30)\ h_{Newt}$$

at $r \sim R_{n} \sim R \sim (1.5 – 2.0)\ 2GM/c^{2}$

$$E_{g} = 10^{51} — 10^{52}\ \text{erg}$$

Effects of hyperons with respect to the pure nucleonic case

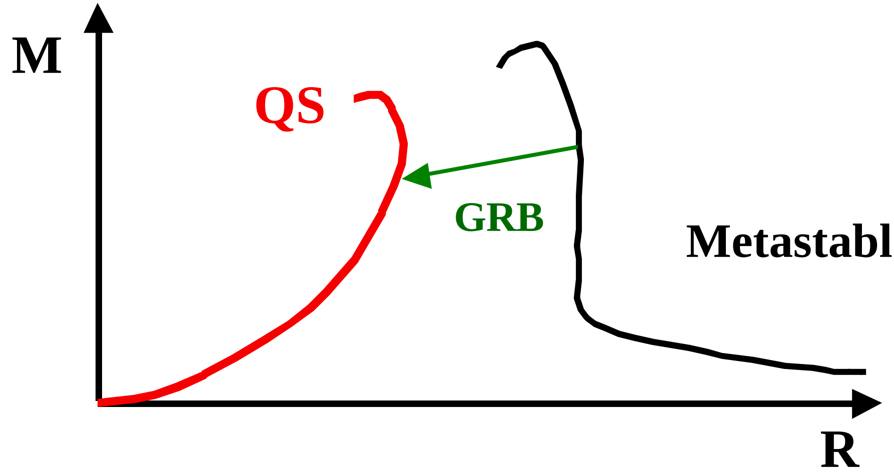
on the:

(1) Hadronic star critical mass

(2) Energy released in the stellar conversion

See talk by Isaac Vidaña,
Parallel session 2,
this afternoon

Conclusions (of the last part of the talk)



- "Neutron stars" (HS) are **metastable** to

  HS → QS or to **HS → HyS**

the **HS *mean-life time*** range within: **t >> age univ. — t ~ yr-days**

- $E_{conv} \sim 10^{52} - 10^{53}$ erg ⇒ **GRBs**

- Our model explains the SN-GRB connection and
  the time delay **DT(SN-GRB) ~ a few years**
  inferred for **GRB990705**

- **Implications of our scenario:**
  existence of two different families of compact stars:

(1) pure Hadronic Stars (metastable)

which could have "large" radii (R ~ 12 – 15 km),
as *e.g.*, 1E 1207.4-5209

(2) Strange Stars or Hybrid Stars

with "small" radii (R ~ 7 – 9 km),
as *e.g.*, SAX J1808.4-3658 or 4U 1728-34