Quark deconfinement in compact stars:

connection with GRB

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Skopelos, Hellas
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Summary

- Short overview on Gamma-Ray Bursts (GRBs)
- Delayed nucleation of Quark Matter
- How to generate Gamma-Ray Bursts from deconfinement
- Conclusions

Gamma-Ray Bursts (GRBs)

Spatial distribution: isotropic

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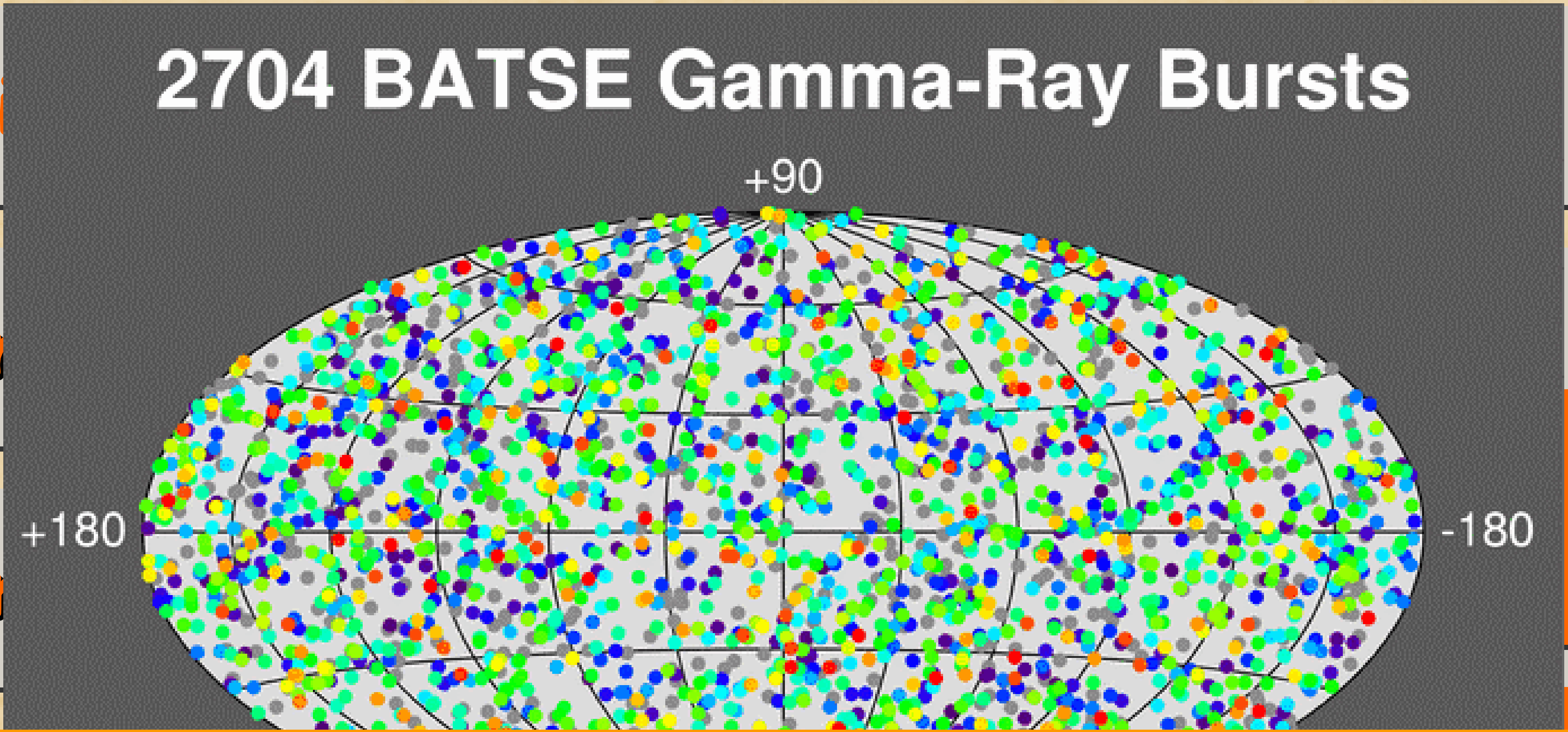
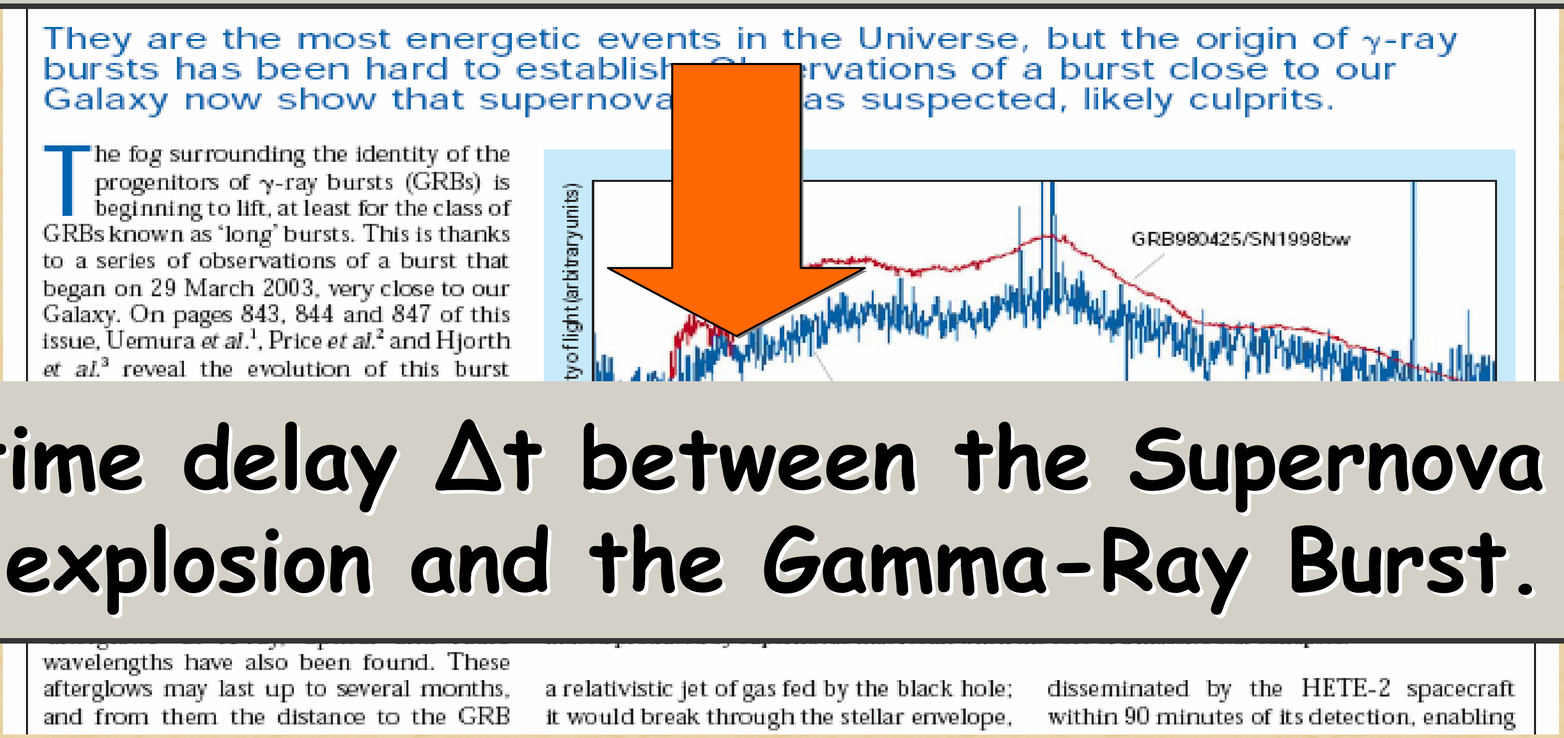


J.S. Bloom, D.A. Frail, S.R. Kulkarni, ApJ 594, 2003

GRB and supernovae

Connection between GRB and Supernovae

Evidence for atomic lines in the spectra of the X-ray afterglow



They are the most energetic events in the Universe, but the origin of γ-ray bursts has been hard to establis
ervations of a burst close to our
Galaxy now show that supernova
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

wavelengths have also been found. These afterglows may last up to several months, and from them the distance to the GRB

a relativistic jet of gas fed by the black hole; it would break through the stellar envelope,

disseminated by the HETE-2 spacecraft within 90 minutes of its detection, enabling

time delay Δt between the Supernova explosion and the Gamma-Ray Burst.

Time delay from SN to GRB

GRB 990705 → $\Delta T \approx 10$ yr

Amati et al., Science 290, 2000, 953

GRB 011211 → $\Delta T \approx 4$ days

Watson et al., ApJ 595, 2003, L29

GRB 030227 → $\Delta T \approx 3\text{-}80$ days

Reeves etal. , Nature 2002

A two-stages scenario

1^{st} explosion:

SUPERNOVA

(birth of a NS)

2^{nd} "explosion":

CENTRAL ENGINE OF THE GRB

(ass. with the NS)

open questions

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

Delayed collapse of a HS to a QS

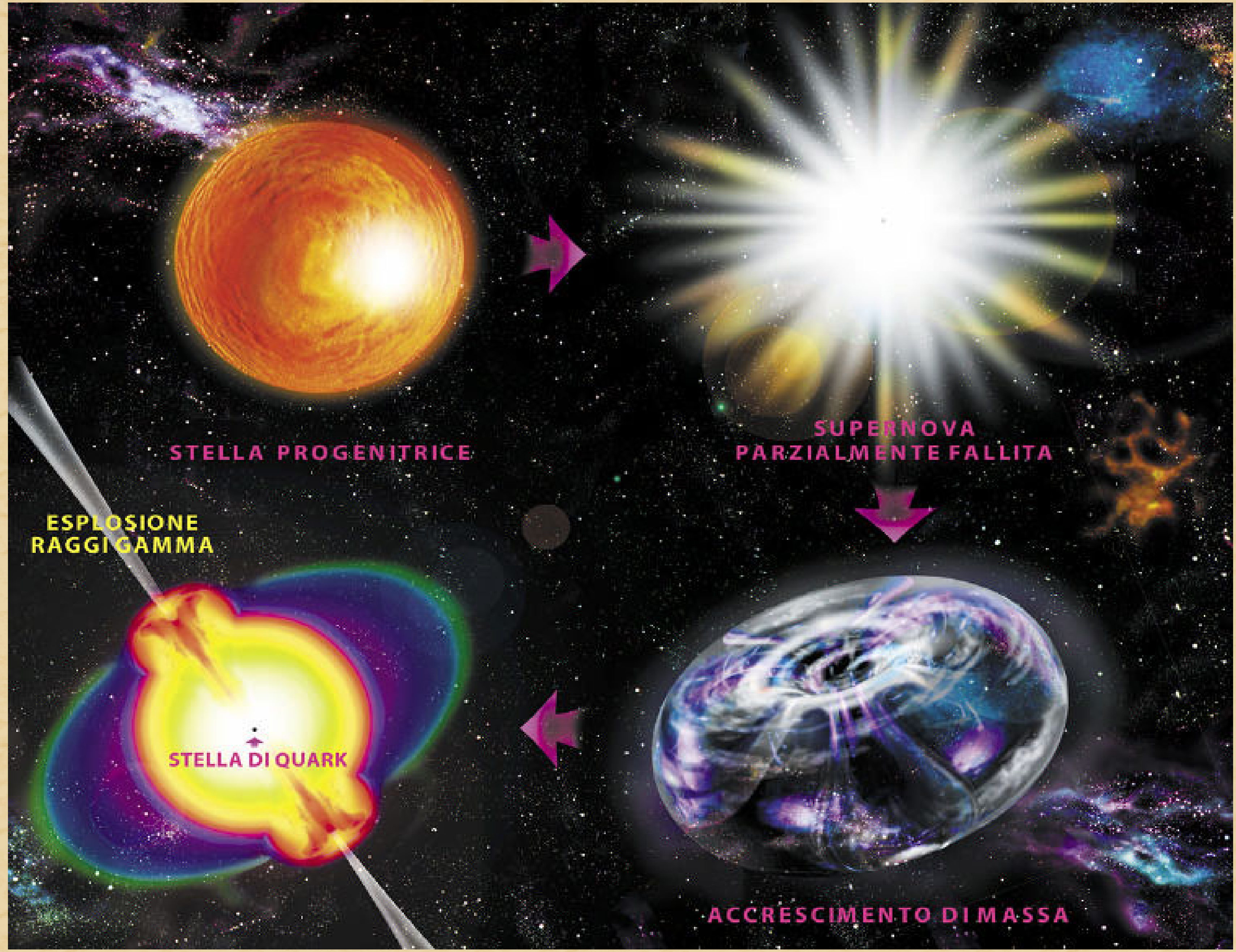
Z. Berezhiani, I. Bombaci, A. Drago, F. Frontera and A. Lavagno ApJ. 586 (2003) 1250

Pure HS ⟹ Hybrid Star or Quark Star

- The co version proces can be ayed due to the effects of the sur tensi tw ase and the QM phase.
- The nuc on the central pressure of
- As a critical-siz the HS is converted to a QS or HyS.
- The conversion proces releases $E_{conv.} \approx 10^{52} - 10^{53}$ erg

Possible central engine for GRB

The Quark-Deconfinement Nova model



Finite-size effects

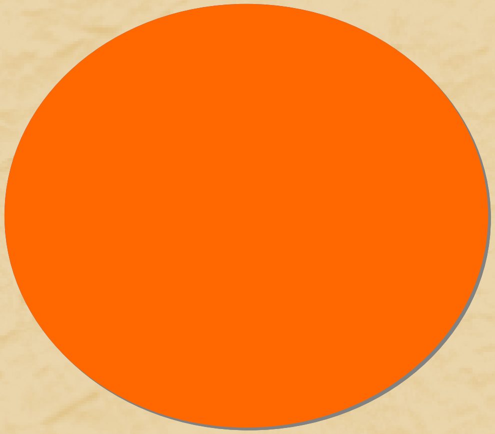
- The formation of a critical-size drop of QM is not immediate.
It's necessary to have an **overpressure** to form a droplet having a size large enough to overcome the effect of the surface tension.

- A virtual droplet moves back and forth in the potential energy well on a time scale:

$$v_0^{-1} \sim 10^{-23}\ \mathrm{s} \ll \tau_{weak}$$

quark-flavor must be conserved during the deconfinement transition.

Quark deconfinement



real droplet of
strange matter

The drop grows with no limitation.

β-stable hadronic system at the same pressure.
We call it: Q*-phase.

Soon afterwards the weak interactions change the quark flavor fraction to lower the energy.

Equation of State

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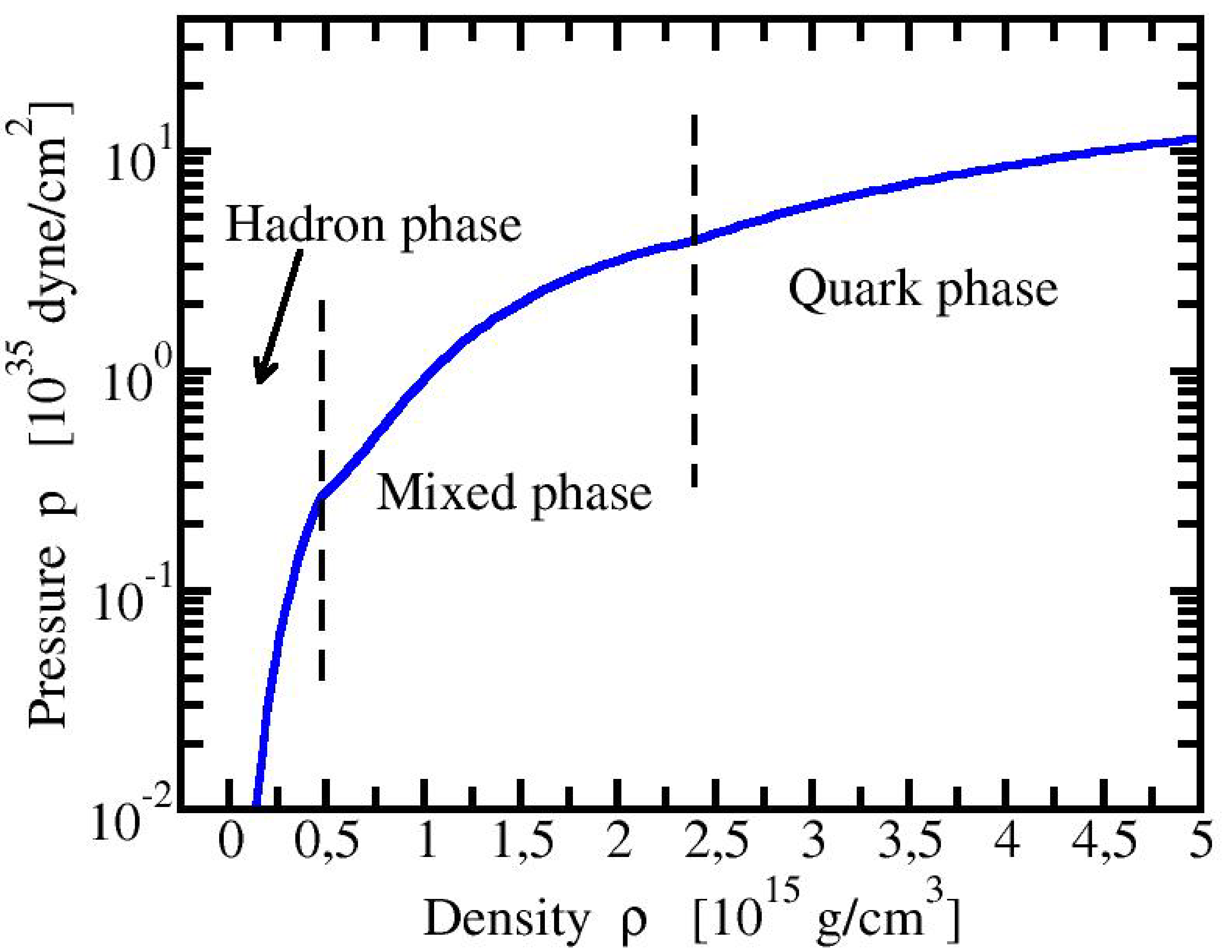


Quantum nucleation theory

I.M. Lifshitz and Y. Kagan, Sov. Phys. JETP 35 (1972) 206
K. Iida and K. Sato, Phys. Rev. C58 (1998) 2538

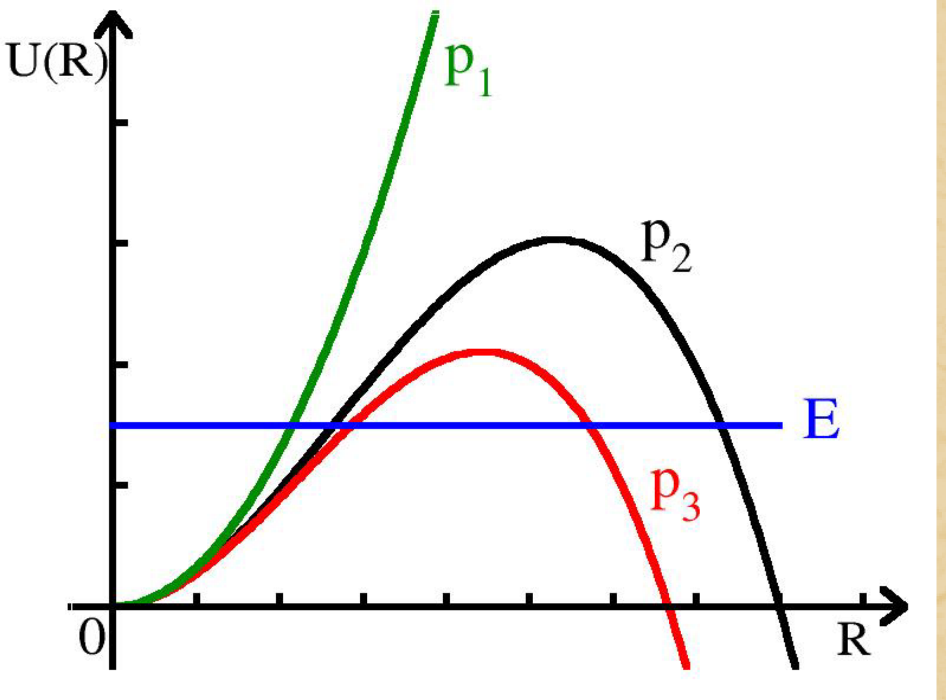
Droplet potential energy:

$$U(R) = \frac{4}{3}\pi n_{Q^*}\left(\mu_{Q^*} - \mu_H\right)R^3 + 4\pi\sigma R^2 = a_V R^3 + a_s R^2$$

n_{Q^*} baryonic number density in the Q*-phase at a fixed pressure P.

μ_{Q^*}, μ_H chemical potentials at a fixed pressure P.

σ surface tension (=10,30 MeV/fm^2)



Nucleation time

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a critical … atter.
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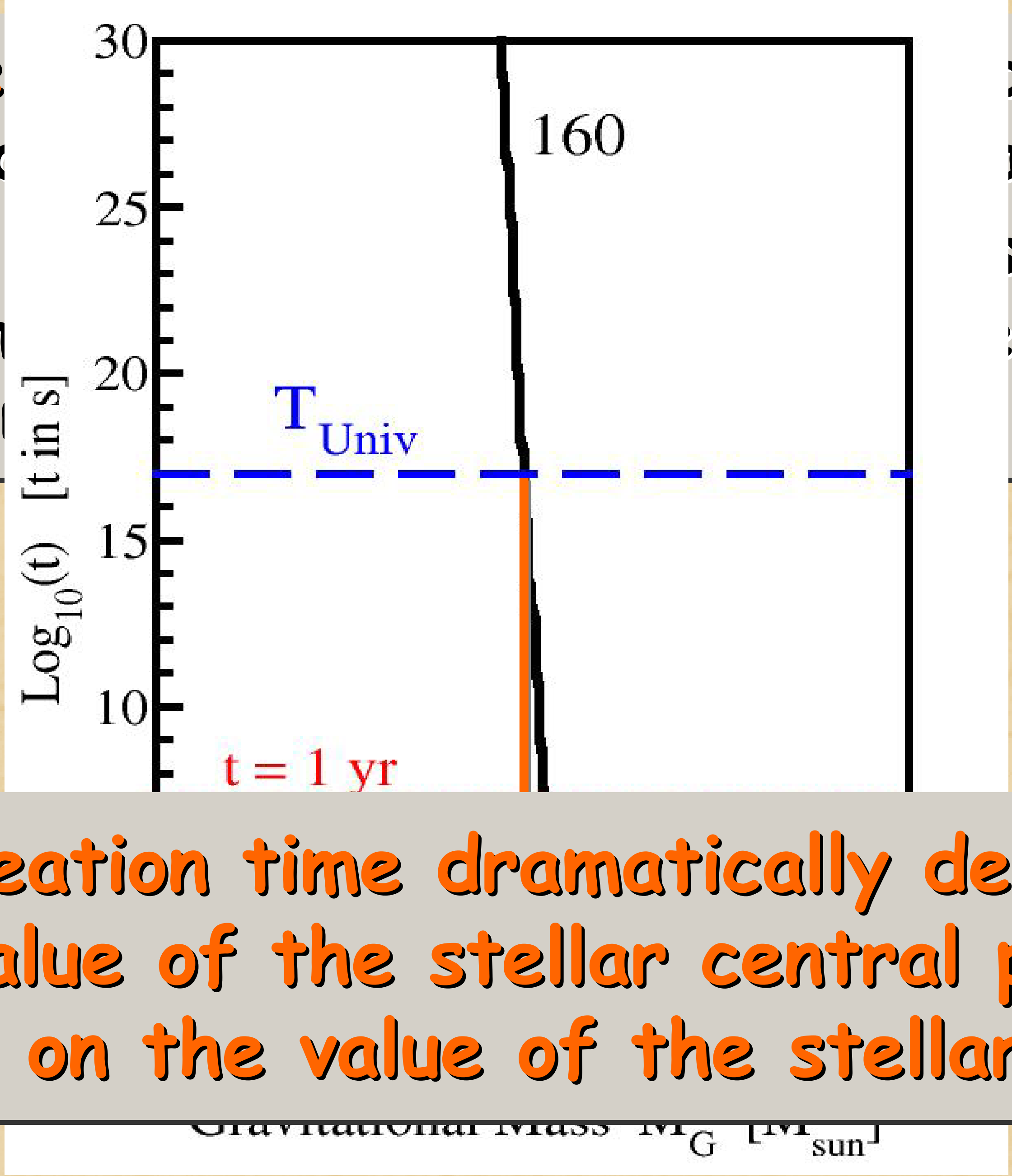


The nucleation time dramatically depends on the value of the stellar central pressure and then on the value of the stellar mass.

The critical mass of metastable HS

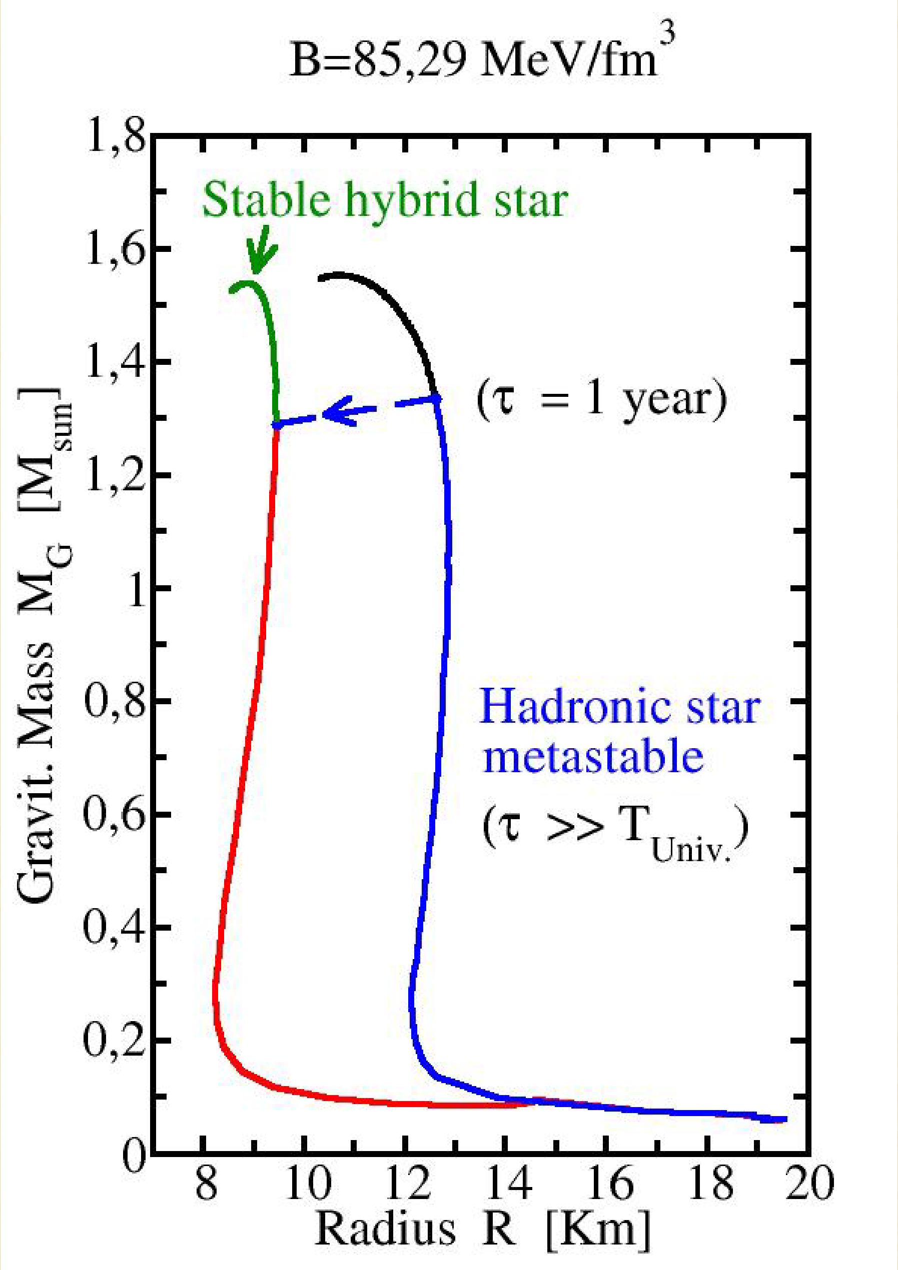
- We fixed the time of nucleation at 1 yr.
- The gravitational mass corresponding to this nucleation time is called critical mass:

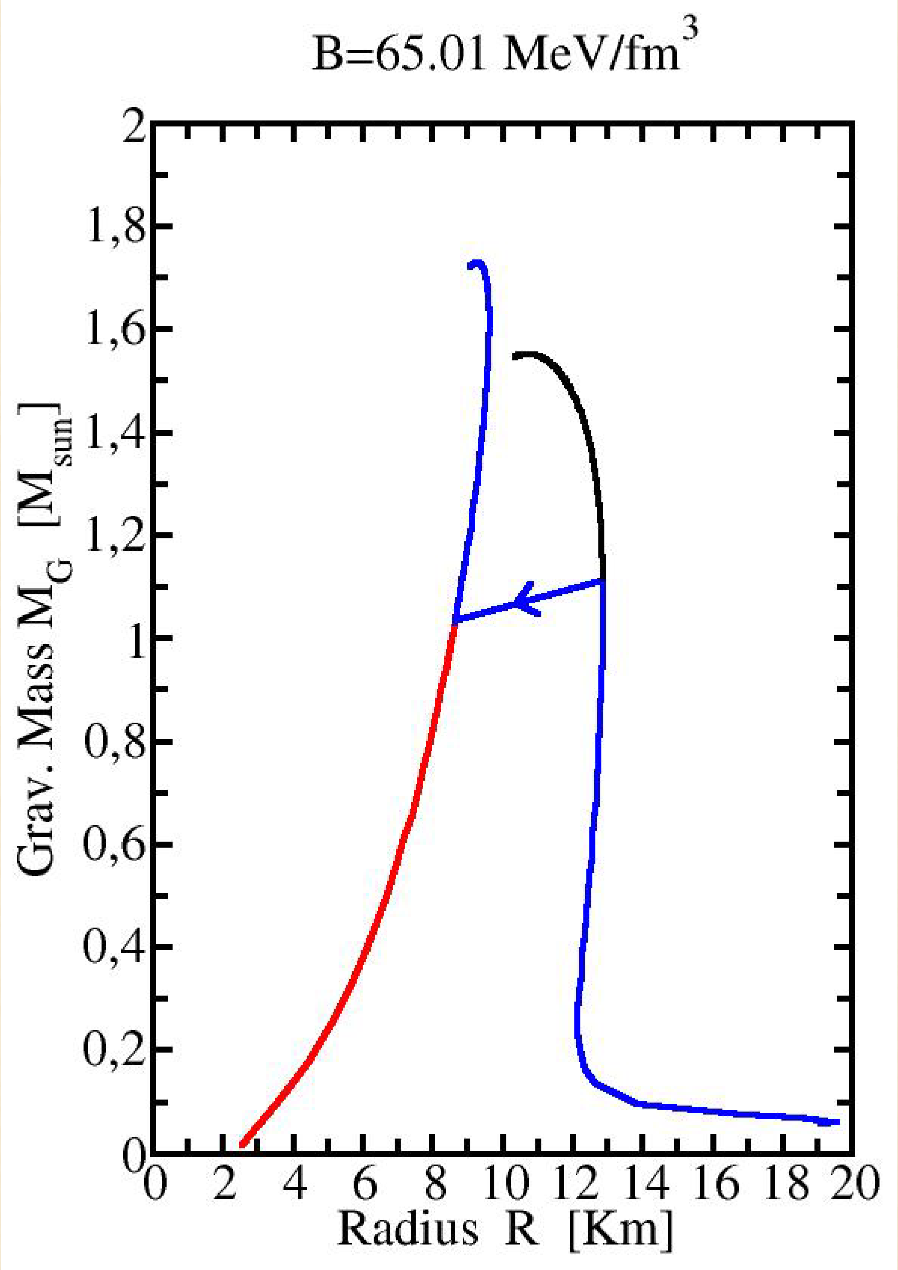
$$\boxed{M_{cr} = M_{HS}(\overline{\tau} = 1\ \mathrm{yr})}$$

We assume that during the stellar conversion process the total numbers of baryons in the star (and then the baryonic mass) is conserved. [I. Bombaci and B. Datta, ApJ. 530 (2000) L69]

➡ The gravitational mass of the final star is taken to be the mass in the stable configuration corresponding to that baryonic mass.

Two families of compact stars

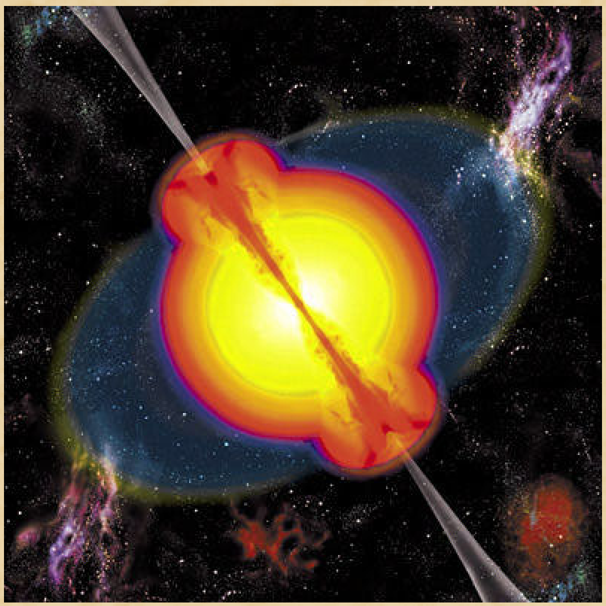


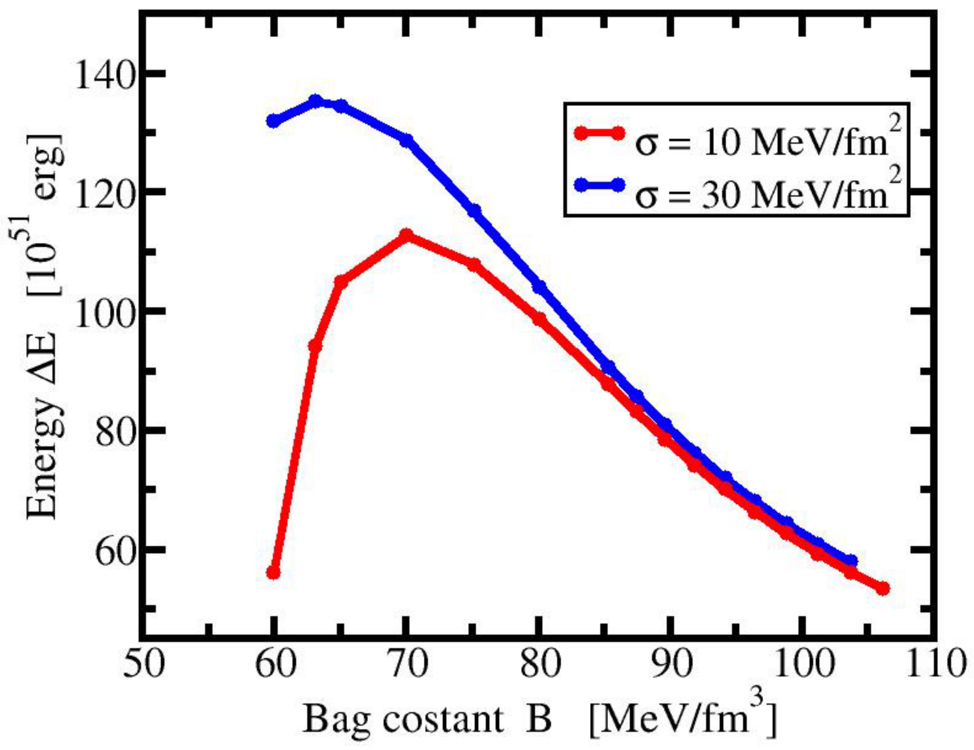


Energy released

The total energy released in the stellar conversion is given by the difference between the gravitational mass of the initial hadronic star ($M_{in}=M_{cr}$) and the mass of the final hybrid or strange stellar configuration ($M_{fin}=M_{QS}(M^b_{cr})$):

$$E_{conv} = (M_{in} - M_{fin})c^2$$





How to generate GRBs

The energy released is carried out by pairs of neutrinos - antineutrinos.

The reaction that generate gamma-ray is:

$$\boxed{\nu + \bar{\nu} \rightarrow e^{+} + e^{-} \rightarrow 2\gamma}$$

The efficence of this reaction in a strong gravitational field is: $\boxed{\eta \approx 10\%}$

[J. D. Salmonson and J. R. Wilson, ApJ 545 (1999) 859]

$$\boxed{E_{\gamma} = \eta\, E_{conv} \approx 10^{51} - 10^{52}\, erg}$$

Conclusions

- Neutron stars (HS) are **metastable** to HS —> QS or to HS —> HyS
- $E_{conv} \approx 10^{52} - 10^{53}$ erg → **GRBs**
- Our model explains the connection and the time delay between SN and GRBs.
- possible existence of two different families of compact stars:
  - **pure Hadronic Stars**
  - **Hybrid stars** or **Strange Stars**

Collaborators

- **Dr. Ignazio Bombaci**
- **Dr. Isaac Vidaña**

University of Pisa

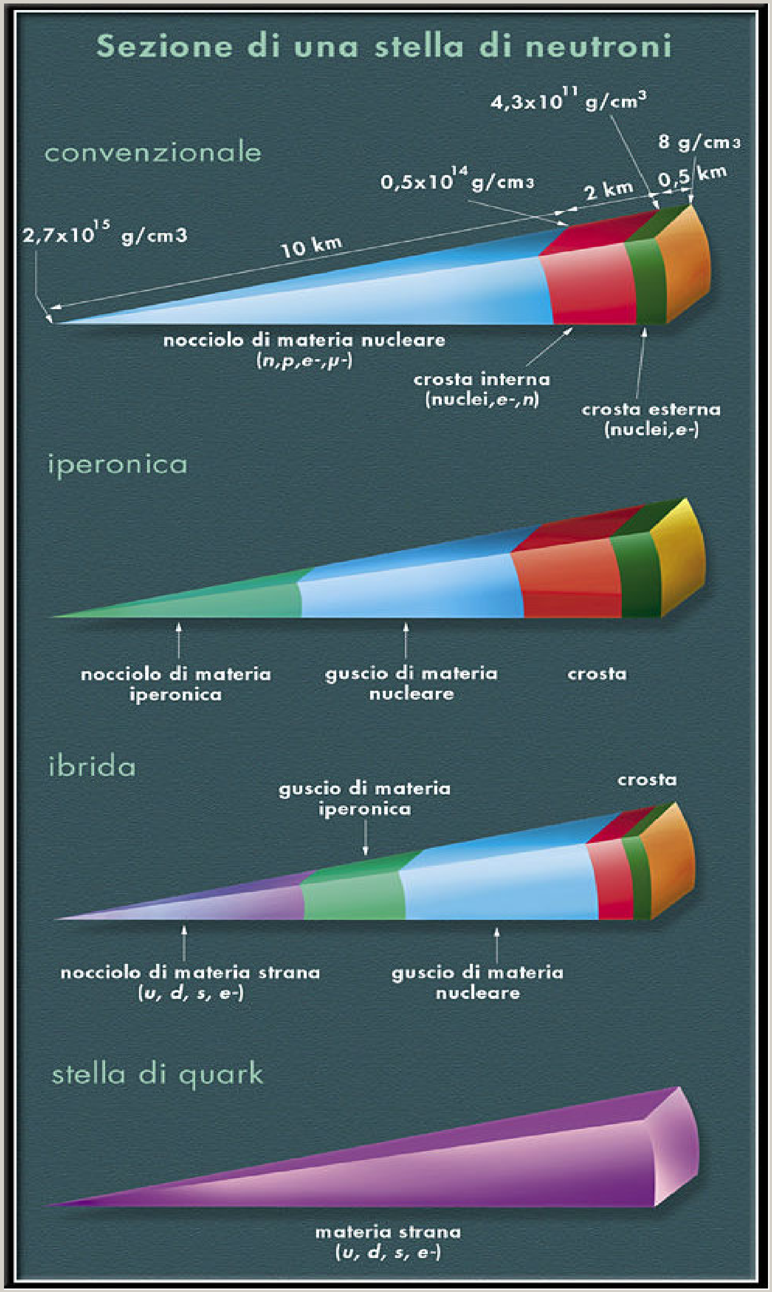
INFN of Pisa

Ref: I. Bombaci, I. P., I. Vidaña
arXiv:astro-ph/0402404

Appendix

Compact stars

- **HADRONIC STARS (HS)**
  - conventional neutron stars
  - hyperon stars
- **HYBRID STARS (HyS)** →
- **STRANGE STARS (SS or QS)** →



Probability of tunneling

Oscillation frequency of the virtual drop inside the potential well:

$$\nu_0 = \left(\frac{dI}{dE}\right)^{-1}\Bigg|_{E=E_0}$$

Penetrability of the potential barrier:

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

Nucleation time:

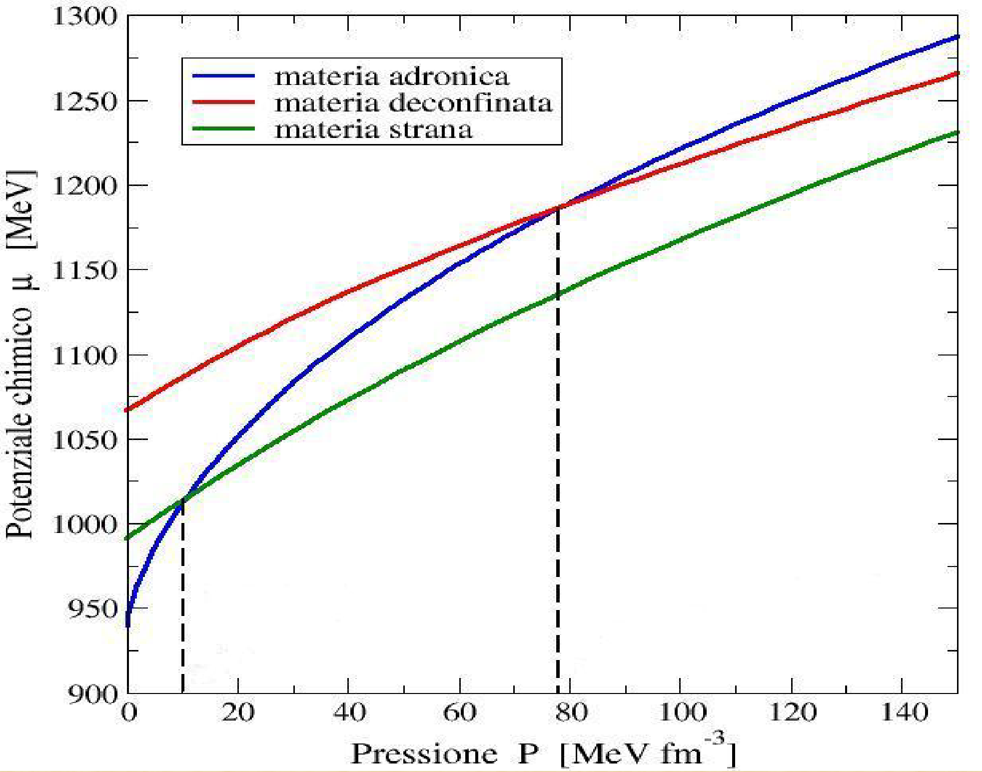
$$\tau = \left(\nu_0 p_0 N_C\right)^{-1}$$

Nc=number of nucleation centers in the star core

Matter in the droplet

Flavor fractions are the same of the β-stable hadronic system at the same pressure:

$$\begin{pmatrix} Y_u \\ Y_d \\ Y_s \end{pmatrix} = \begin{pmatrix} 2 & 1 & 1 & 2 & 1 & 0 & 1 & 0 \\ 1 & 2 & 1 & 0 & 1 & 2 & 0 & 1 \\ 0 & 0 & 1 & 1 & 1 & 1 & 2 & 2 \end{pmatrix} \begin{pmatrix} Y_p \\ Y_n \\ Y_\Lambda \\ Y_{\Sigma^+} \\ Y_{\Sigma^0} \\ Y_{\Sigma^-} \\ Y_{\Xi^0} \\ Y_{\Xi^-} \end{pmatrix}$$



The pressure needed for phase transition is more larger than that without flavor conservation.