Theoretical Research on the

Nuclear Astrophysics of Dense Stars

at the **University of Milano**

Why is the level density parameter of exotic nuclei relevant for Supernova explosions?

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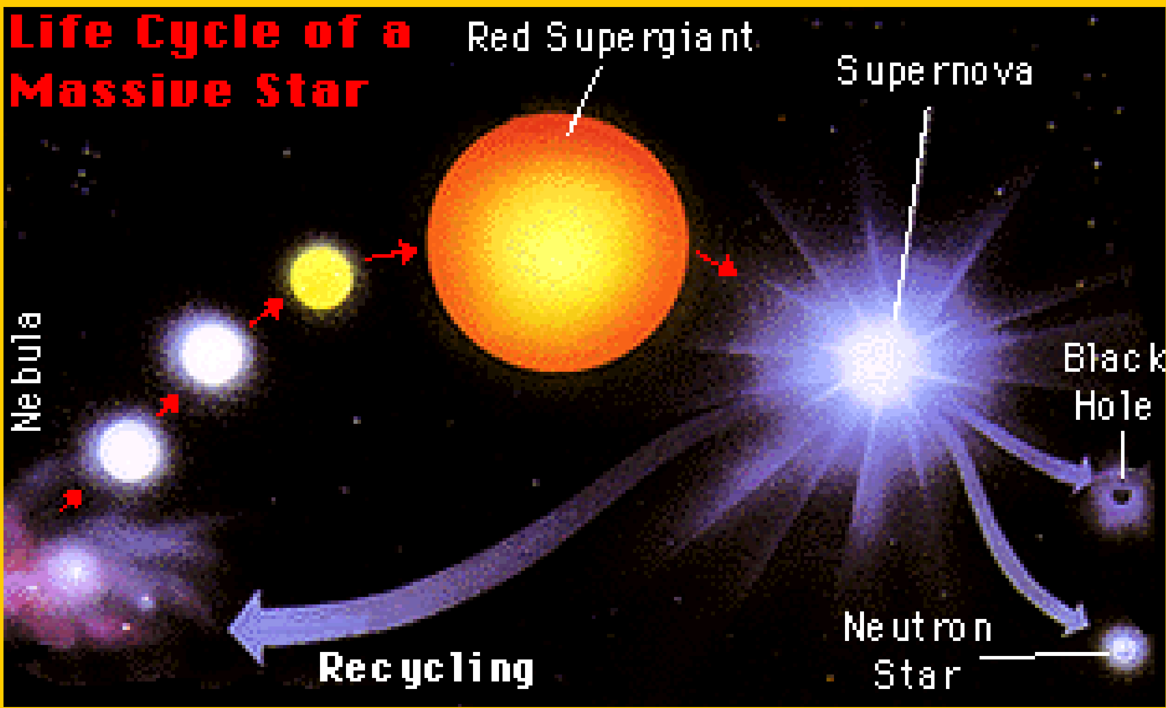

AGATA workshop, 22-24 March 2004

Stable exotic nuclei in Nature

- ***The rationale for* stable *exotic nuclei***

'n–p–e' system $\rightarrow$ n $\rightleftarrows$ p + e

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At *equilibrium* $\rightarrow$ $\mu_n = \mu_p + \mu_e$ $\rightarrow$ fixes n/p

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Increase of μ_e $\rightarrow$ increase of n/p (neutronization)

- ***How to increase*** μ_e

Degenerate & relativistic electrons $\rightarrow$ $\mu_e \propto \rho^{1/3}$

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Neutrons *appear* if $\mu_e \geq 1.29$ MeV $\rightarrow$ $\rho \geq 1.2 \times 10^7$ g/cm^3

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Higher ρ $\Rightarrow$ neutronization

- **Where to find *stable* exotic nuclei**

Only *dense* objects in Nature $\rightarrow$ "compact stars"

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1) White dwarfs $\rightarrow$ $\rho_{max} \cong 10^7$ g/cm^3 $\rightarrow$ normal

2) Neutron stars $\rightarrow$ $\rho_{max} \cong 10^{15}$ g/cm^3 $\rightarrow$ *very exotic*

3) Pre-supernova cores $\rightarrow$ $\rho > 10^9$ g/cm^3 $\rightarrow$ *quite exotic*

- ***Astrophysical* relevance of n-rich nuclei**

NS $\rightarrow$ thermal effects (observable surface cooling)
mechanical effects (vortex pinning and observable Pulsar glitches)

Collapsing SN core $\rightarrow$ nuclear effects (electron capture)

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Exotic nuclei $\Rightarrow$ strength of SN explosion

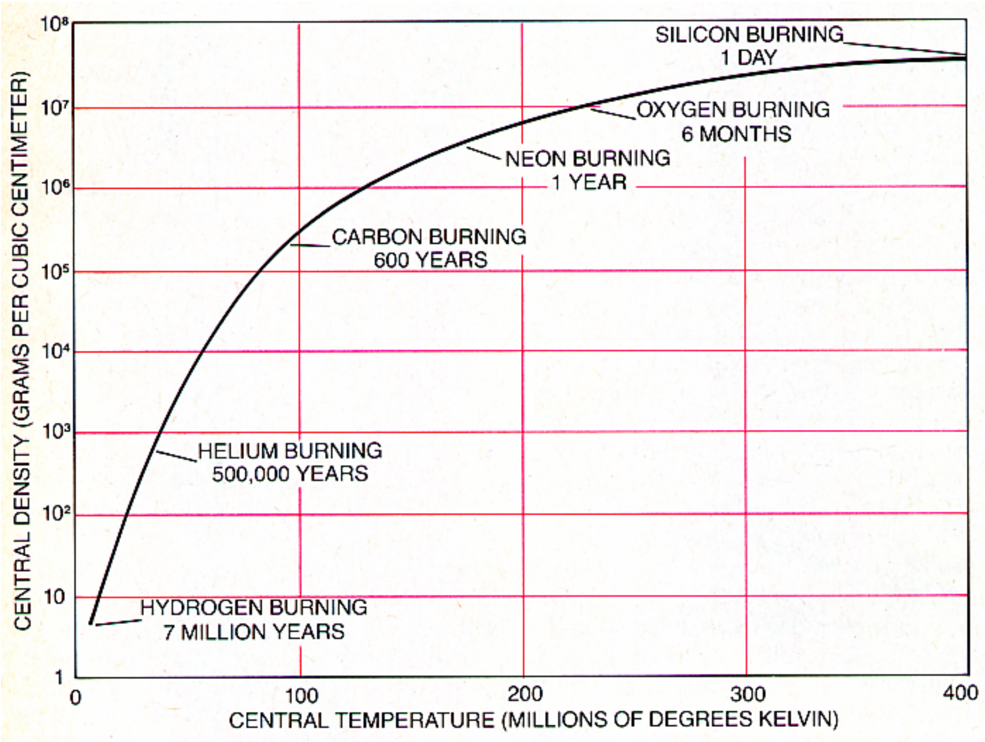
Death of a massive star: overview

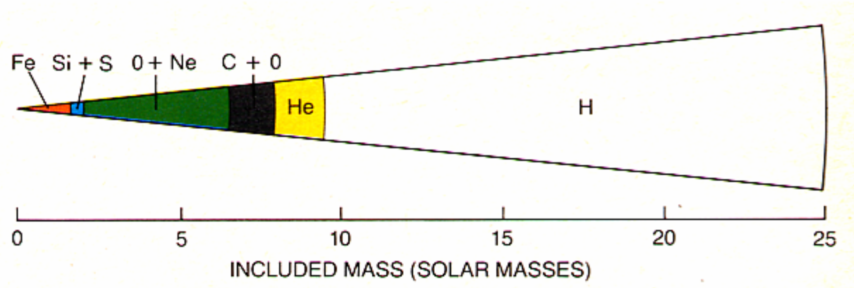
- ***Stellar evolution (nuclear burning)***

$$^{1}H \rightarrow {}^{4}He \rightarrow {}^{12}C \rightarrow {}^{20}Ne \rightarrow {}^{16}O \rightarrow {}^{28}Si \rightarrow {}^{56}Fe$$

$$\Downarrow$$

Onion-like structure → ‘Fe core’ + extended H\He envelope





Onset of collapse (initial conditions)

Nuclear burning in the core stops at ^{56}Fe

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Gravitational instability of 'Fe core'

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$Y_{ini} \approx 0.42$ $(Y = n_{lep} / n_B)$

$\rho_{ini} \approx 3.7 \times 10^9$ g/cm^3

$T_{ini} \approx 0.7$ MeV

Supernova explosion: 3 phases

1) Gravitational collapse of 'Fe core' (implosion)

2) Bounce of 'homologous core' (shock wave formation)

3) Shock wave propagation (explosion)

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1) Gravitational collapse

Determines position of shock formation

Controlled by lepton fraction Y and s (EOS of *low density* nuclear matter)

2) Core bounce

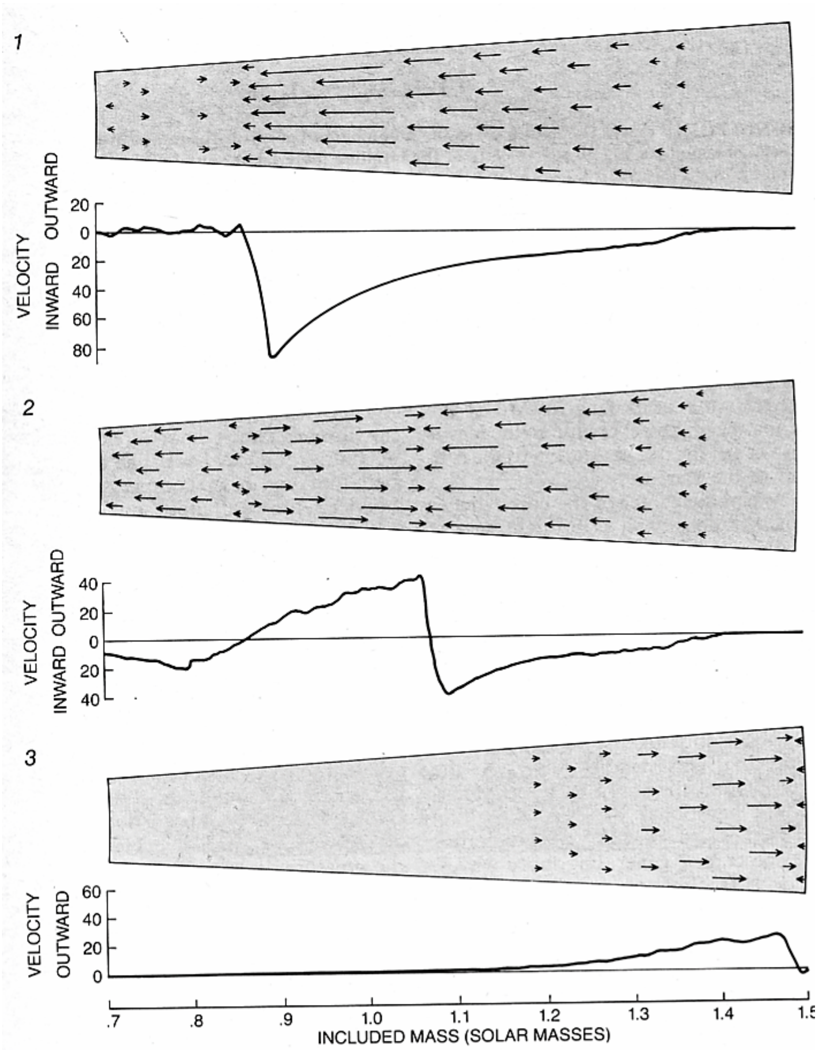
Determines strength of shock wave

Controlled by EOS of *dense* nuclear matter (Γ and K)

3) Shock propagation

Hindered by shock energy dissipation

Controlled by shock position and strength, and by neutrino production and transport



Outcome of explosion

If shock not *stalled* by energy losses $\rightarrow$ type II Supernova

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Explosive nucleosynthesis of heavy elements

Ejection of H\He envelope $\rightarrow$ electromagnetic display

Formation of neutron star or black hole from collapsed core

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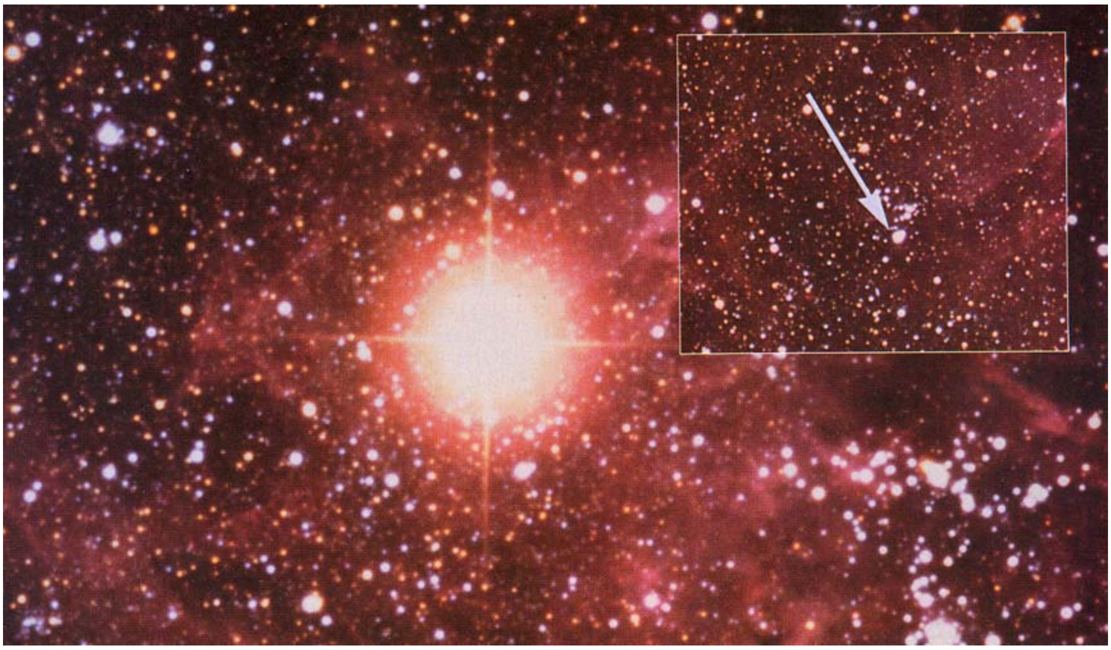
Stronger shock $\Rightarrow$ successful explosion



SN 1987A

Neutronization and shock position

- ***Neutronization of the 'Fe core'***

Nuclear burning ends inside \`Fe' $\rightarrow$ core collapses

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density increases $\rightarrow$ μ_e increases

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shift of β-equilibrium $\rightarrow$ electron capture *driven* by ρ

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if $\rho < \rho_{trap}$ $\rightarrow$ escape of neutrinos

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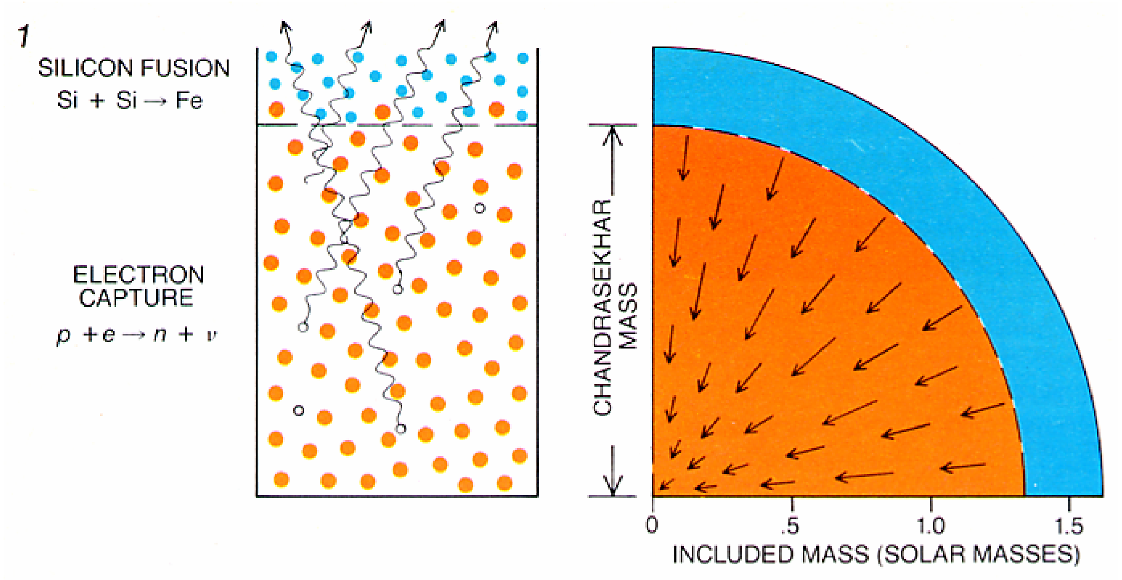
Decrease of lepton fraction Y & Formation of exotic nuclei



- ***Neutrino trapping (final conditions)***

Diffusion time ~ collapse time $\rightarrow$ neutrinos trapped

$$\rho > \rho_{trap} \approx 5\times10^{11}\ \mathrm{g/cm^3}$$

Lepton fraction Y is constant after ν-trapping

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$$Y_{fin} = Y_{trap}$$

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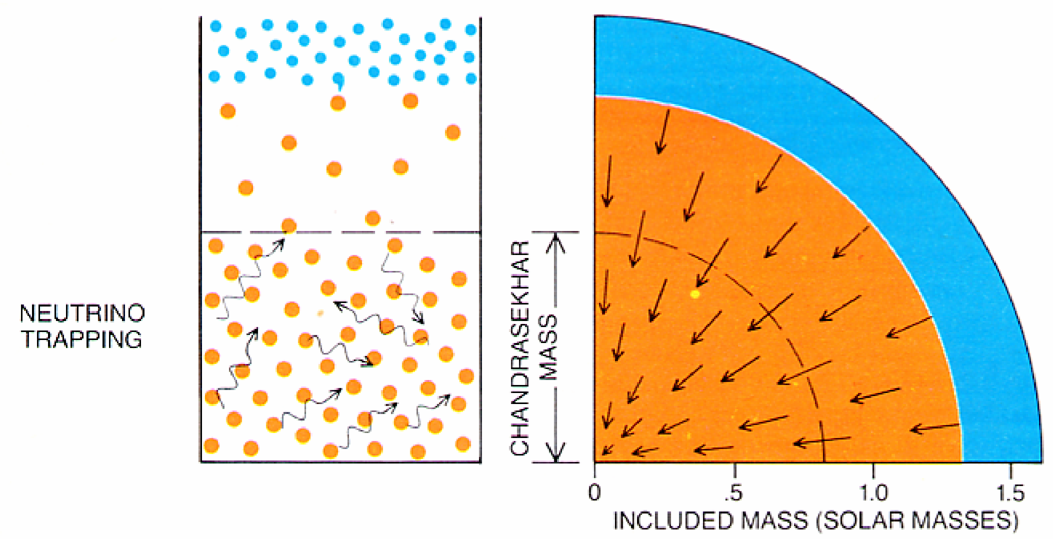

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Y *decreases* from Y_{ini} to Y_{trap}

- ***Position of shock formation***

'homologous core' $\rightarrow$ inner region of 'Fe core'
(collapses and rebounds as a whole)

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Shock forms at edge of 'homologous core'

- ***The Chandraseckhar mass***

Maximum mass supported by degenerate lepton pressure

$M_{ch}(Y)$ depends only on lepton fraction Y

Mass of 'Fe core'

$Y_{ini} \rightarrow$ mass of collapsing 'Fe core'

$M_{Fe} = M_{ch}(Y_{ini})$

Mass of 'homologous core'

$Y_{trap} \rightarrow$ mass of rebounding 'homologous core'

$M_{hom} = M_{ch}(Y_{trap})$

Dissipation of shock energy

- ***Mass crossed by shock***

Shock forms at the edge of 'homologous core' and crosses the rest of 'Fe core'

Mass crossed $\rightarrow$ $\Delta M = M_{Fe} - M_{hom}$

- ***Iron dissociation by shock***

$$^{56}Fe \rightarrow 13\ ^{4}He + 4\ n$$

$$\Delta E/\Delta M \approx 17 \times 10^{51} \ \ erg/M_{sun}$$

- ***Energy lost by shock***

Energy dissipated $\rightarrow$ $E_{diss} \propto (\, Y_{ini}^{2} - Y_{trap}^{2} \,)$

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Larger Y_{trap} $\rightarrow$ less energy dissipation

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Less neutronization $\Rightarrow$ stronger shock

Rate of electron capture

- **Capture on protons (free and bound)**

$$p + e \rightarrow n + \nu_e$$

$$\Downarrow$$

Capture rate *depends* on $\hat{\mu} = \mu_n - \mu_p$

(e.g.: fraction of free protons $\rightarrow \frac{Y_p}{Y_n} = e^{-\hat{\mu}/T}$)

$$\Downarrow$$

Larger $\hat{\mu}$ $\rightarrow$ less neutronization

- ***Symmetry energy***

n–p energy difference is related to symmetry coefficient

$$\hat{\mu} \propto b_{sym} + \ldots$$

where

$$E_{sym} = b_{sym} \cdot (1 - 2x)^2$$

is symmetry term in E_{bind}/A for nucleus with $x = Z/A$

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Larger b_{sym} $\Rightarrow$ less neutronization

The role of *hot exotic* nuclei

- ***Which exotic nuclei?***

Collapsing ‘Fe’ core $\rightarrow$ e-capture on nuclei *driven* by ρ

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Very neutron-rich *equilibrium* nuclides $\rightarrow$ $0.3 < Z/A < 0.42$

(from EOS of nuclear matter below neutron drip)

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^{84}Se ^{82}Ge ^{80}Zn ^{78}Ni ^{76}Fe ^{124}Mo

$^{120,122}Sr$ $^{86,118}Kr$

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b_{sym} of exotic nuclei $\Rightarrow$ neutronization rate

- ***The role of temperature (from theory*)***

Collective excitations of nuclei (surface vibrations)

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$b_{sym} = b_{sym}(T)$ is temperature-dependent

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$b_{sym}(T)$ found to increase in the range $T = 0–2$ MeV

Effects of temperature-dependence (*)

Range of temperature up to ν-trapping: 0.7 → 1.5 MeV

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i) Follow core collapse up to ν-trapping

ii) Evaluate *decrease* of neutronization with T-dependence

iii) Evaluate *gain* in shock energy with T-dependence

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Gain in shock energy → $\delta(E_{shock}) \approx 0.5\text{–}0.7 \times 10^{51}$ erg

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Typical SN energy (*SN1987A***) → $E_{expl} \approx 1.5 \times 10^{51}$ erg

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T-dependence of b_{sym} ⇒ stronger explosion

(*) **P. Donati et al., PRL 72 (1994) 2835**
Temperature dependence of the nucleon effective mass and the physics of stellar collapse

(**) **H. Bethe & P. Pizzochero, ApJ Letters 350 (1990) L33**
Mass-energy relation for SN1987A from observations

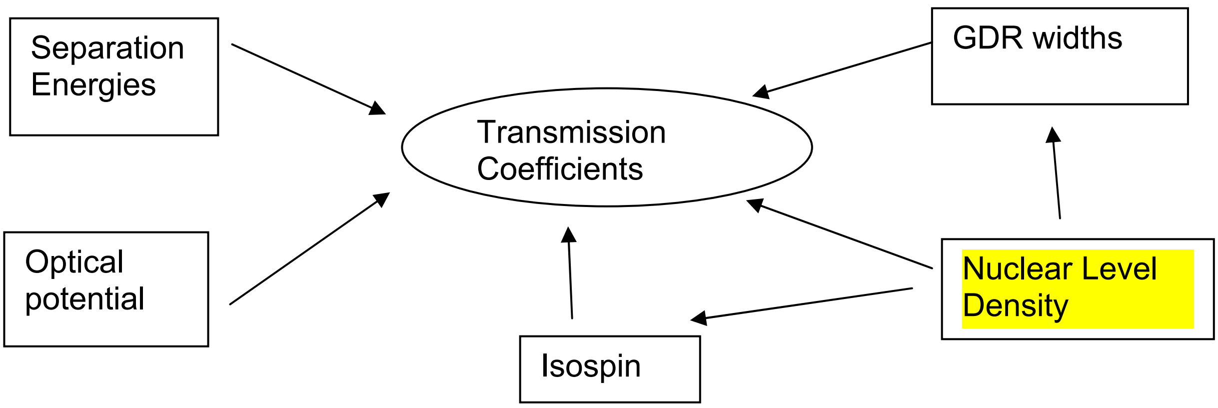
What should we measure?

- ***Nuclear reactions in Astrophysics***

Average cross section for given channel:

$$\sigma_i = \sigma_{form} \times b_i = \sigma_{form} \times \Gamma_i / \Gamma_{tot}$$

partial widths Γ ↔ transmission coefficients T
(statistical model of Hauser-Feshbach)



- ***Nuclear level density (NLD)***

NLD expressed in terms of parameter ***a***

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Level density parameter ***a*** depends on energy and isospin

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E-dependence of ***a*** ⇒ T-dependence of b_{sym}

The role of AGATA in Supernova theory

Oslo cyclotron group

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Extract NLD from primary γ-spectra

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S. Siem: "Possibility to measure level densities as a function of spin using AGATA" (Wednesday 24, 14:10)

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Measure energy and spin dependence of NLD for exotic nuclei (e.g. ^{110}Mo)