Convective Urca Process and cooling in dense stellar matter

M. Schoenberg:
The name Urca was given by us to the process which accompanies the emission of neutrino in supernova because of the following curious situation: In Rio de Janeiro, we went to play at the Casino-da-Urca and Gamow was very impressed with the table in which there was a roulette, in which money disappeared very quickly. With a sense of humor, he said: ‘Well, the energy is being lost in the centre of supernova with almost the same rapidity as money does from these tables!’

(from Grib, Novello: “Gamow in rio and the discovery of the URCA process”, Astronom & Astrophys. Trans. 2000, Vol 19)

Feb 10 2010, Advisor-Seminar WS09/10 by Fabian Miczek

Urca reactions

Urca pairs consist of mother (*M*) and daughter (*D*) nuclei

Urca reactions

- beta decay: $^{A}_{Z+1}M \rightarrow {}^{A}_{Z}D + e^{-} + \overline{\nu}_{e}$
- electron capture: $^{A}_{Z}D + e^{-} \rightarrow {}^{A}_{Z+1}M + \nu_{e}$

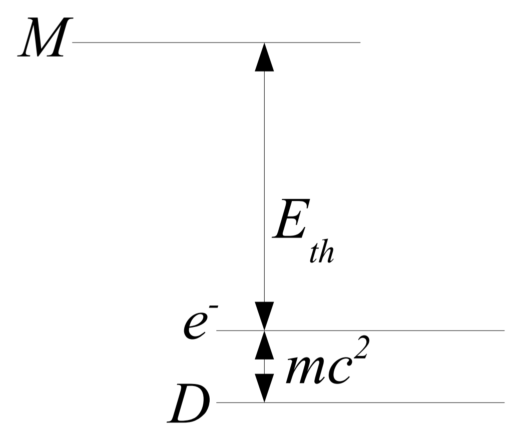
Central questions:

Is a continuous cycling between mother and daugter possible?

Both reactions emit a neutrino => possible cooling mechanism?

electron captures require a threshold energy $E_{th} = E_{M} - E_{D} - m_{e} c^{2}$

beta decays release the threshold energy



We're interested in **degenerate stellar matter**

(ideal gas of ions, Fermi gas of electrons)

threshold energy can be provided by

the Fermi energy of the electrons

Example (E_{th} = 4.4 MeV) $^{23}Na \rightarrow {}^{23}Ne + e^{-} + \overline{\nu}_{e}$

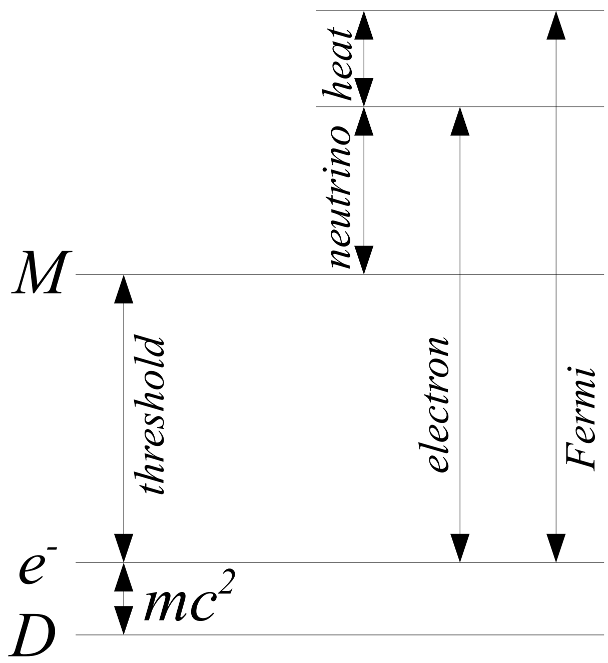
$$^{23}Ne + e^{-} \rightarrow {}^{23}Na + \nu_{e}$$

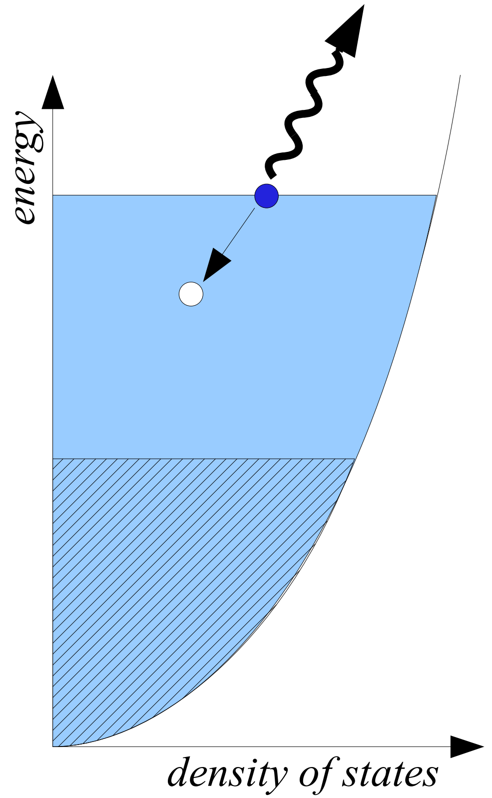
Electron captures in degenerate matter

Fermi energy > threshold energy

assume zero temperature ($kT << E_F$)

$${}^{A}_{Z}D + e^- \rightarrow {}_{Z+1}^{A}M + \nu_e$$





energy source: 'Fermi energy', electron rest mass

energy deposit: heat, neutrino $\quad E_{neutrino} \approx 3\, E_{heat}$

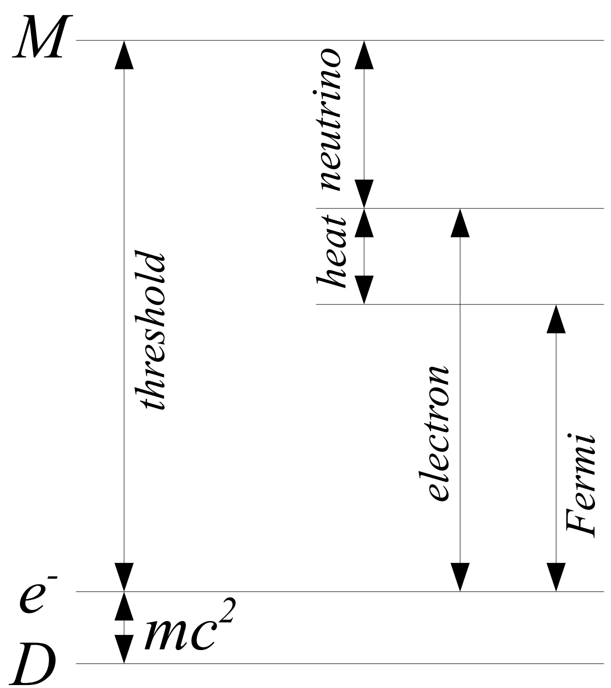
=> electron captures heat up degenerate matter

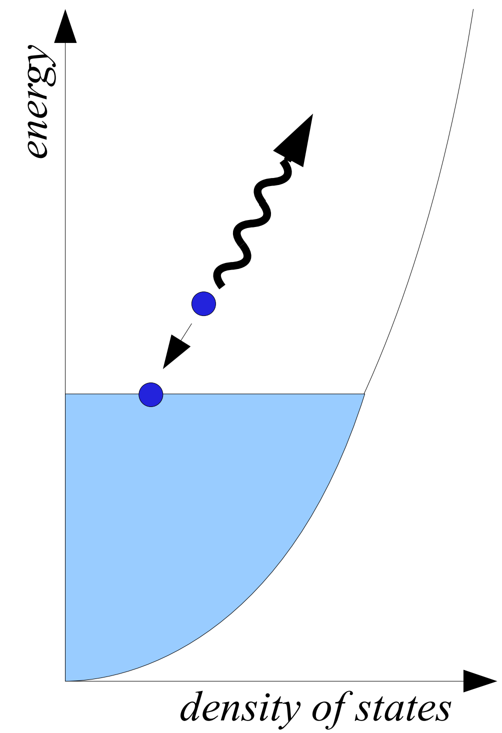
Beta decay in degenerate matter

Fermi energy < threshold energy

assume zero temperature ($kT << E_F$)

$${}^{A}_{Z+1}M \rightarrow {}^{A}_{Z}D + e^- + \overline{\nu}_e$$





energy source: rest mass

energy deposit: heat, neutrino $E_{neutrino} \approx 3\, E_{heat}$

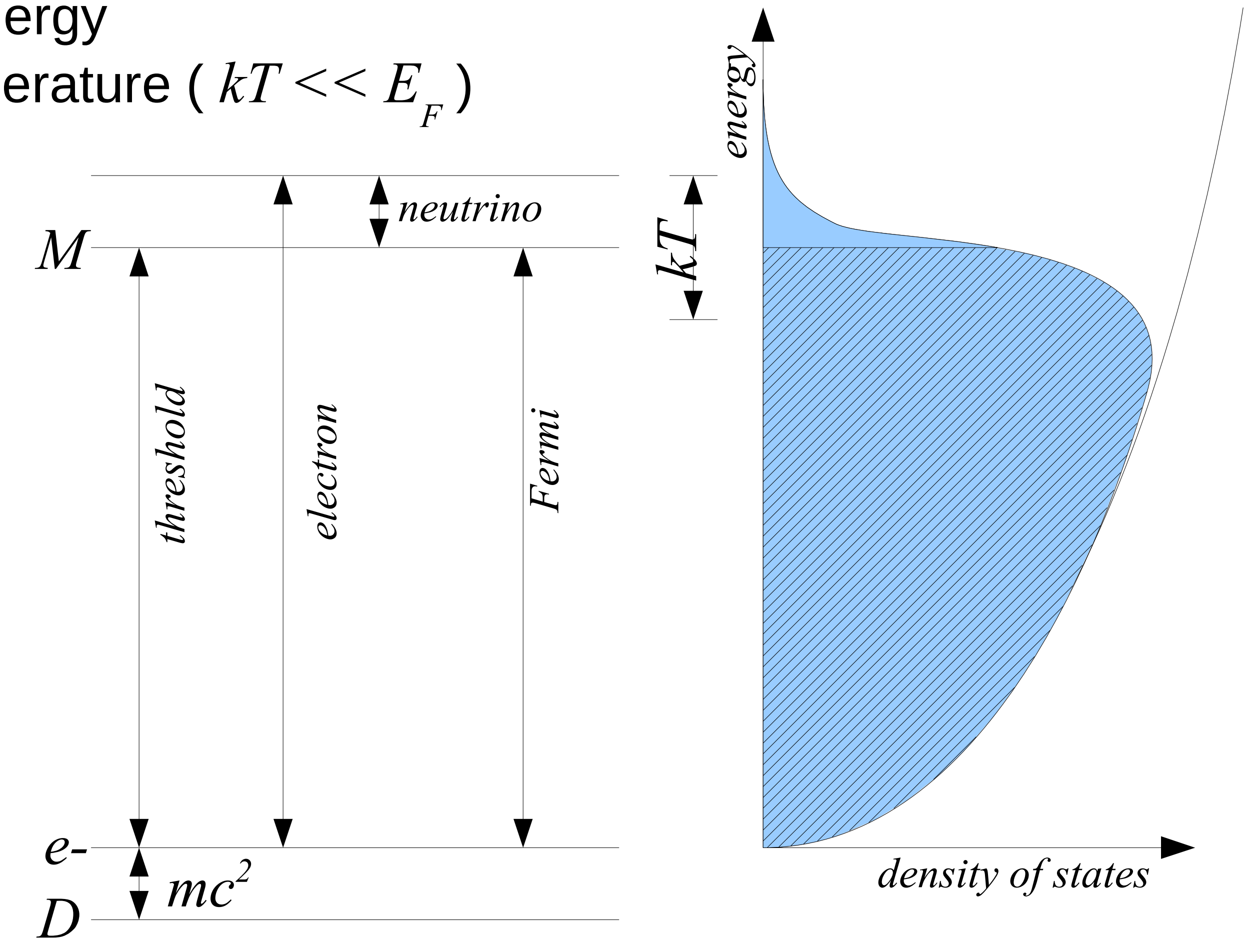
=> beta decays heat up degenerate matter

Electron captures in degenerate matter

Fermi energy = threshold energy

assume small nonzero temperature ($kT << E_F$)

$${}^{A}_{Z}D + e^- \rightarrow {}^{A}_{Z+1}M + \nu_e$$



electron captured from the 'hot side' of the electron distribution (evaporation like)

=> net cooling

energy source: thermal energy

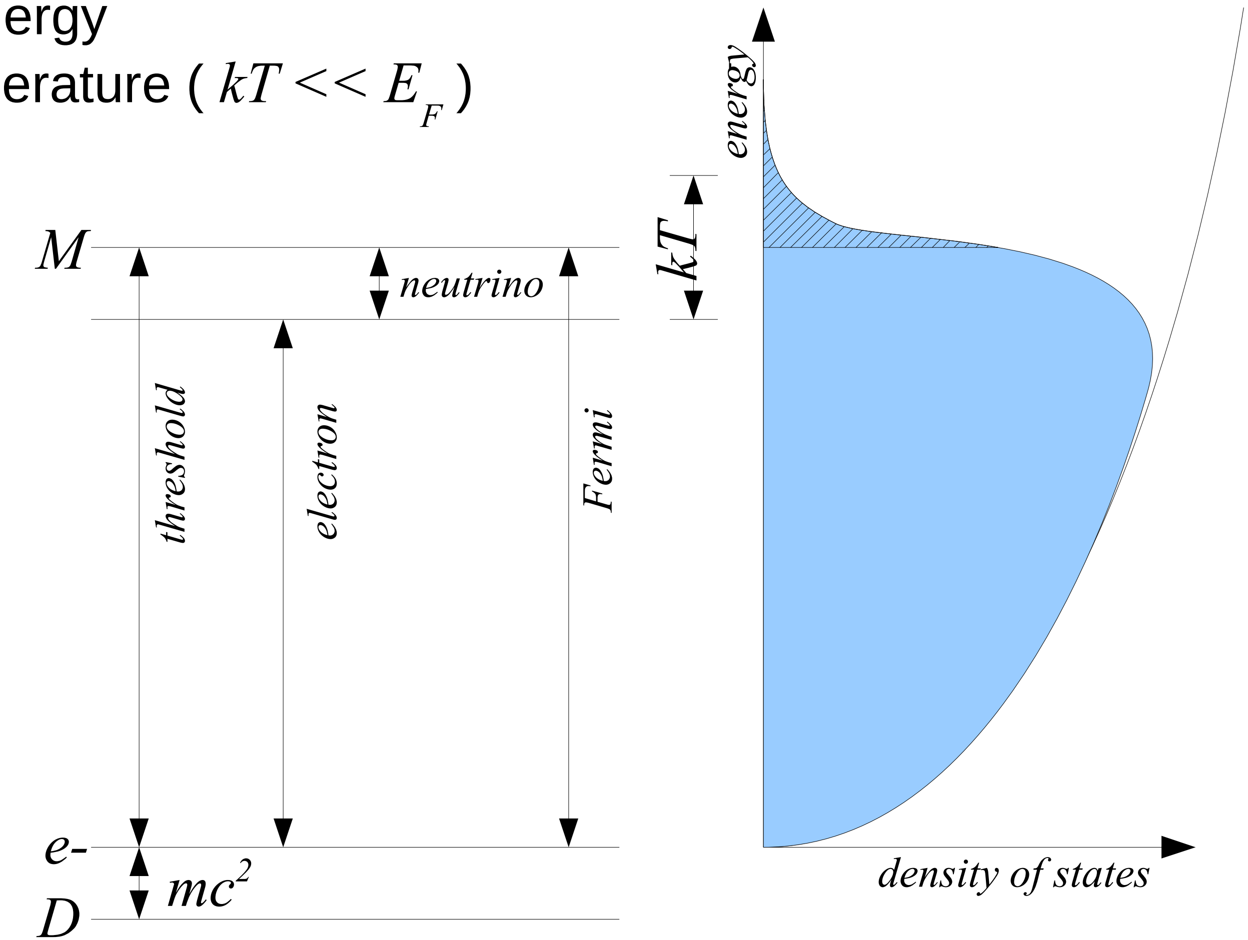
energy deposit: neutrino

Beta decay in degenerate matter

Fermi energy = threshold energy

assume small nonzero temperature ($kT << E_F$)

$${}^{A}_{Z+1}M \rightarrow {}^{A}_{Z}D + e^- + \bar{\nu}_e$$



beta decay produces electrons on the 'cold side' of the energy distribution

=> net cooling

energy source: thermal energy

energy deposit: neutrino

Urca processes

Fermi energy	< threshold en.	= threshold en.	> threshold en.
electron capture	not possible	cooling	heating
beta decay	heating	cooling	not possible

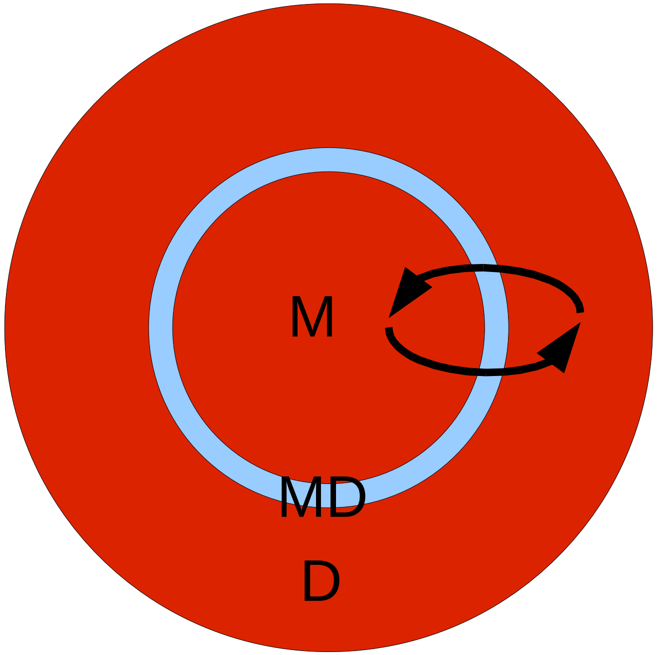
consider degenerate stellar matter, i.e. a white dwarf enriched with Urca matter
density and Fermi energy decrease outwards

Fermi energy = threshold energy defines the **Urca shell**

Thermal Urca process: cooling at the Urca shell

inside Urca shell: lowered electron fraction
outside Urca shell: increased electron fraction

Idea of **Convective Urca process**:
use Urca matter as working fluid for a heat engine
driven by convection through the Urca shell



Open question: Do we get a heating system or a refrigerator?

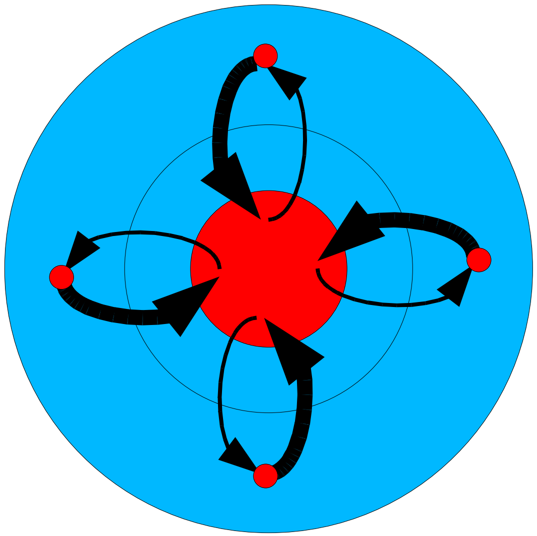
Convective Urca process

- heat source at the center -> superadiabatic temperature gradient -> convection
- assume matter contains some fraction of Urca pairs
- assume convection crosses Urca shell
- energy loss: 2 neutrinos per cycle and nuclei

outside Urca shell: fraction of electrons increases by beta decays
inside Urca shell: fraction of electrons decreases by electron captures
-> additional work needed to transport the electrons downwards
-> convection slowed down?

heat release from beta decays may flatten the superadiabatic temperature gradient

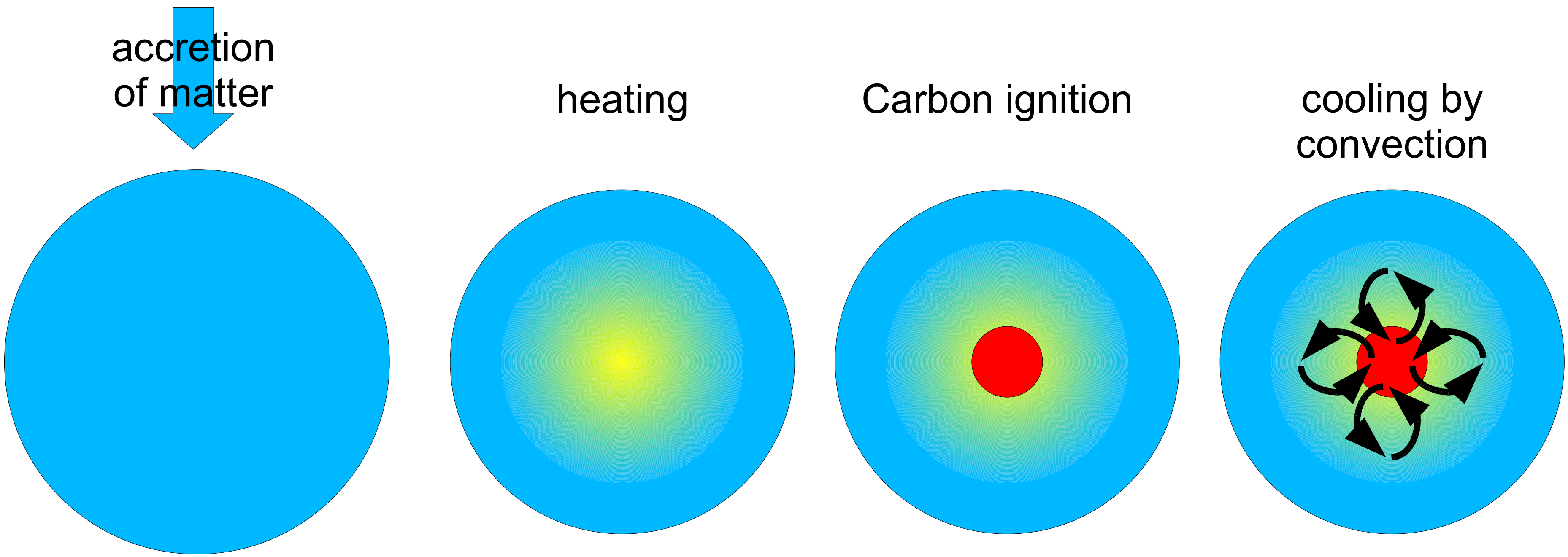
=> Convective Urca process alters the convection pattern
no self consistent solution found yet!
global heat flux unclear!



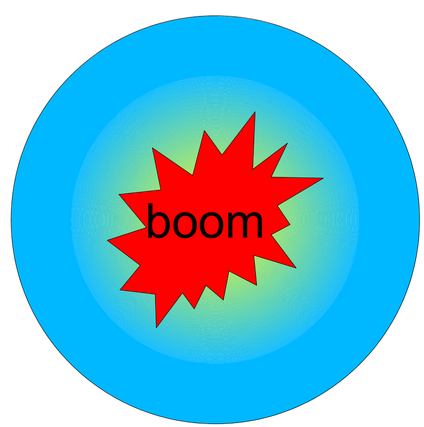
Solution may critically depend on:
- number density of Urca pairs
- Urca reaction rates
- thermal Urca process?

Exploding white dwarfs (in a nutshell)

Consider CO white dwarf, close to Chandrasekhar mass



heating by Carbon burning
overwhelms cooling
-> thermal runaway
-> type Ia supernova explosion



=> Convective Urca process
may drastically alter the
conditions for runaway

Convective Urca process in CO white dwarfs

convection is driven by heat release of Carbon burning
heat is transfered to kinetic energy

relevant time scales:

- dynamical time scale: ~1s
- convective time scale: $\sim 10^5$ s (days)
- nuclear time scale: $\sim 10^{11}$ s (10,000 years)

Urca reactions time scale:	between convective and nuclear time sc.
time from Carbon ignition to runaway:	nuclear time scale
time for runaway to take plae:	dynamical time scale

up to ~30 relevant Urca nuclei, including:

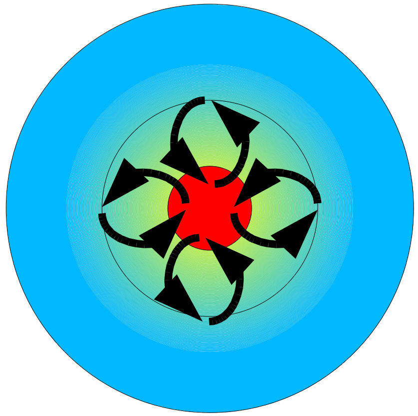
.	E_{th} / MeV	ρ_{th} / (10^9 g/cm^3)	
^{21}Ne / ^{21}F	5.7	3.4	
^{23}Na / ^{23}Ne	4.4	1.7	^{12}C+^{12}C -> ^{24}Mg -> {^{23}Na + p, ...}
^{25}Mg / ^{25}Na	3.8	1.2	further reaction of CNO elements
^{55}Mn / ^{55}Cr	2.5	0.4	

-> many Urca shells, Urca pairs partly generated by Carbon burning

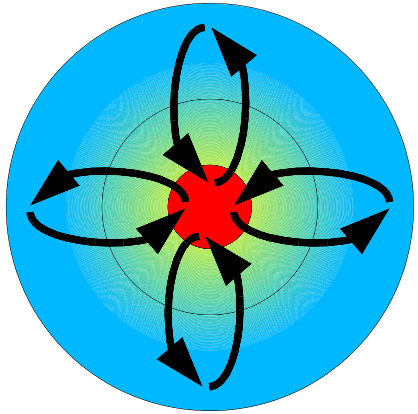
Convective Urca process in CO white dwarfs

possible scenarios:

- convection is stopped by an Urca shell
  beta decays beyond an Urca shell flatten the temperature gradient
  Carbon burning energy is confined
  less efficient cooling -> runaway earlier



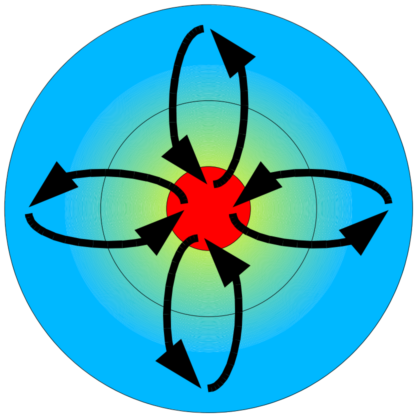
- convection is stimulated by Urca shells
  runaway is postponed, if not eliminated
  runaway occurs at higher densities



Numerical simulations of convective Urca processes

Stellar evolution codes:
- include Urca processes in mixing length theories
- simulation of long time scales possible
- based on assumptions on global statistical equilibrium (uncertain)

Hydrodynamical simulations:
- convective motion << sound speed → low Mach number code
- need to simulate many turnover times
- artificial dissipation of kinetic energy
- artificial diffusion of Urca matter



Summary & Literature

- Urca reactions: electron capture, beta decay in degenerate matter
- Thermal Urca process: cooling at the Urca shell
- Convective Urca process
    complicated interaction between convection and nuclear reactions
    net effect unclear
- Important for the understanding of Carbon ignition in white dwarfs
    (also stellar cores)
- Challenging simulations, even for state-of-the art codes

Literature:

Paczynski: “Carbon ignition in degenerate stellar cores”
Astrophys. Lett. 1972, Vol. 11, pp. 53

Regev, Shaviv: “On the interaction between the Urca process and convection”
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Barkat, Wheeler: “The convective Urca mechanism”
ApJ 1990, Vol. 355, pp. 602

Stein, Barkat, Wheeler: “The role of kinetic energy flux in the convective Urca process”
ApJ 1999, Vol. 523, pp. 381

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MNRAS 2005, Vol. 356, pp. 131