

Nuclear liquid-gas phase transition and supernovae evolution

Neutrino propagation in dense matter

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Working on:

Nuclear inputs for SN collapse:

- Temperature effects:
 - nucleon masses in the medium,
 - symmetry energy
 - electron capture rates (Fueller model)
- Full self-consistent nuclear models:
 - EoS (HF at finite T, pairing correlations, ... with WS approx.)
 - Electron capture rates (cf. Langanke & Martinez-Pinedo)

Tested in 1D
multigroup model

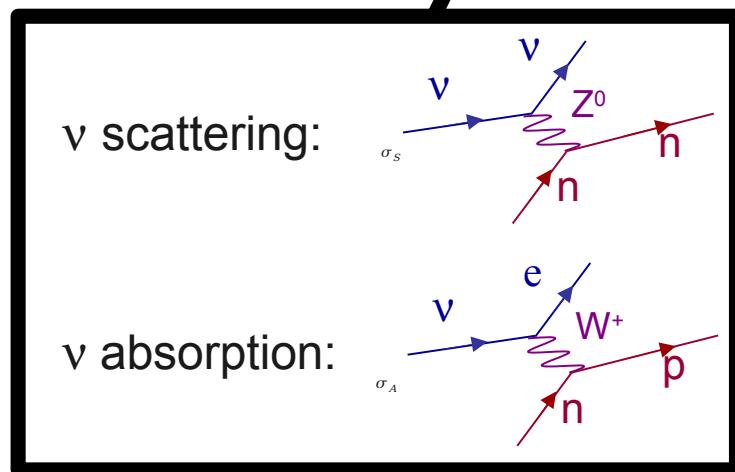
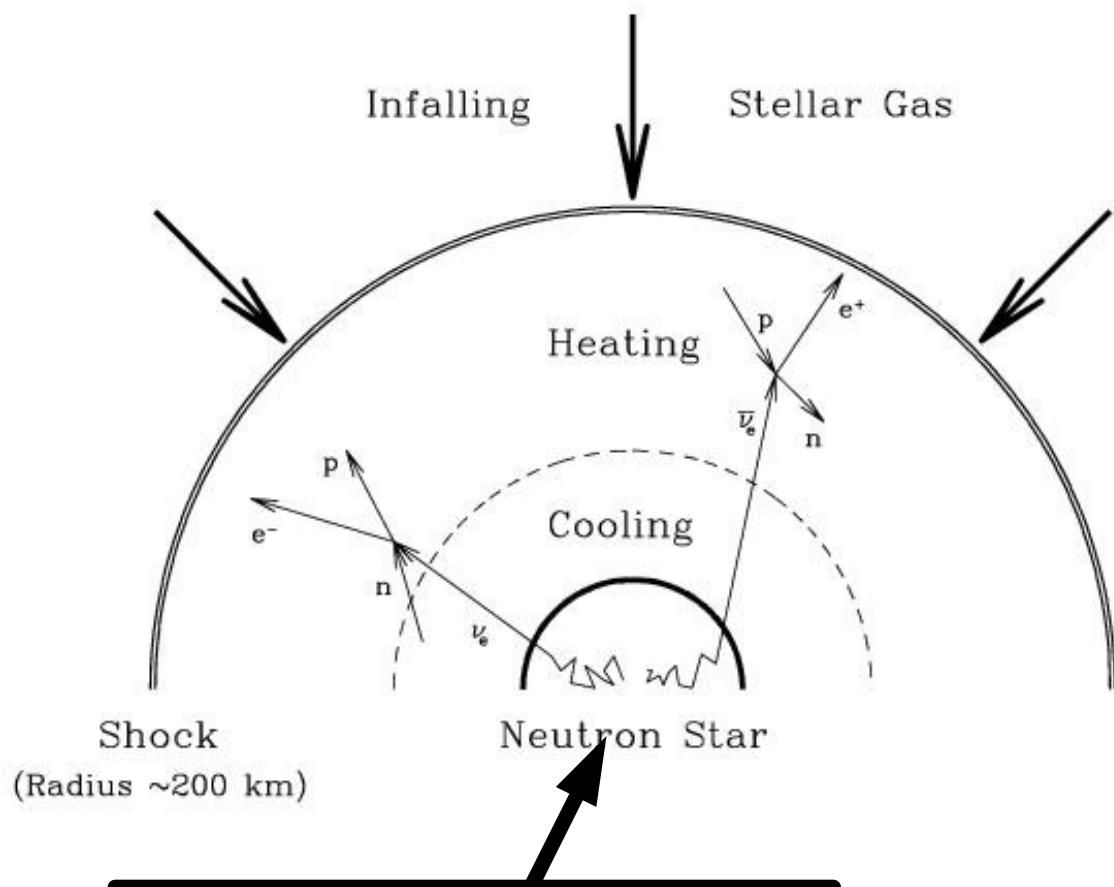
Correlations in uniform matter:

- In medium nuclear interaction (effective interactions, G-matrix, ...)
- Response function (HF+RPA) -> neutrino mean free path.

Neutron star: ...

v propagation in dense matter

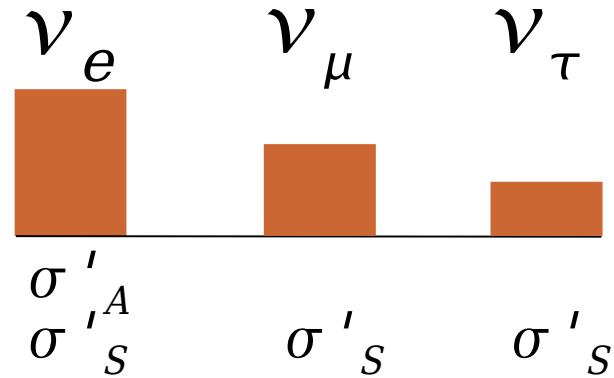
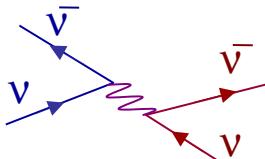
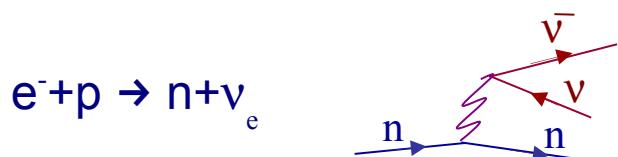
ν trapping, ν wind & Shock wave heating



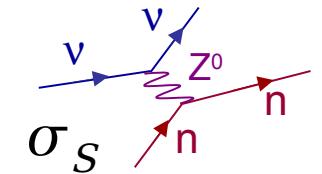
Sawyer, Phys. Rev. D 11, 2740 (1975)
Iwamoto & Pethick, Phys. Rev. D 25, 313 (1982)

Density fluctuations couple to neutrinos

In the dense core:
production of all neutrino flavors



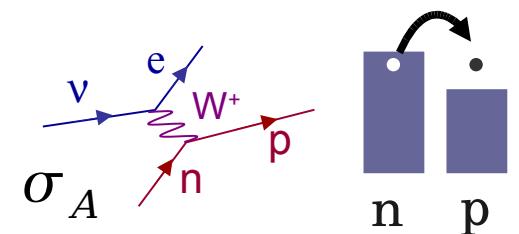
Neutral currents are modified by density fluctuations
involve all neutrino flavours



$$S(q=0) = \frac{1}{N} \left\{ \langle \hat{N}^2 \rangle - \langle \hat{N} \rangle^2 \right\}$$

1974 R. Sawyer: scattering of neutrinos is sensible to density fluctuations in pure neutron star (neutral currents).

Charge currents are not modified by density fluctuations
but by isospin flip density fluctuation

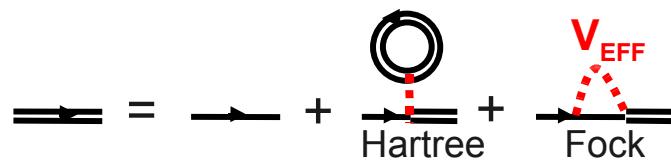


Response to an external probe

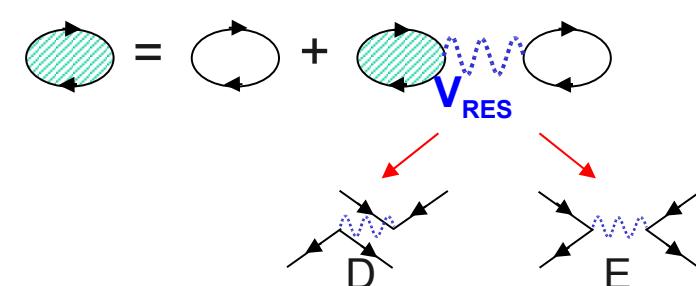
Response Fonction

Hartree-Fock

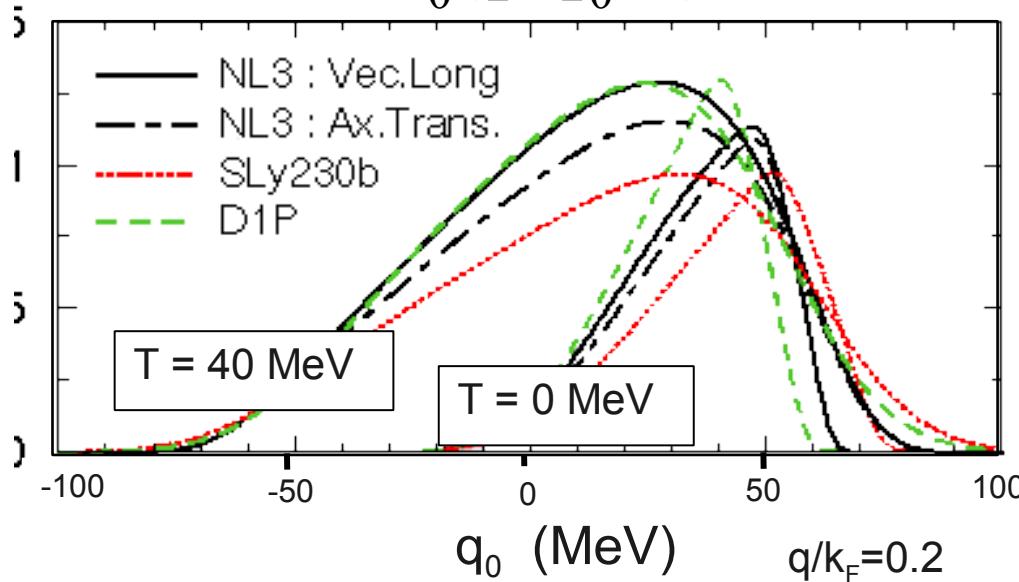
Hartree-Fock + RPA



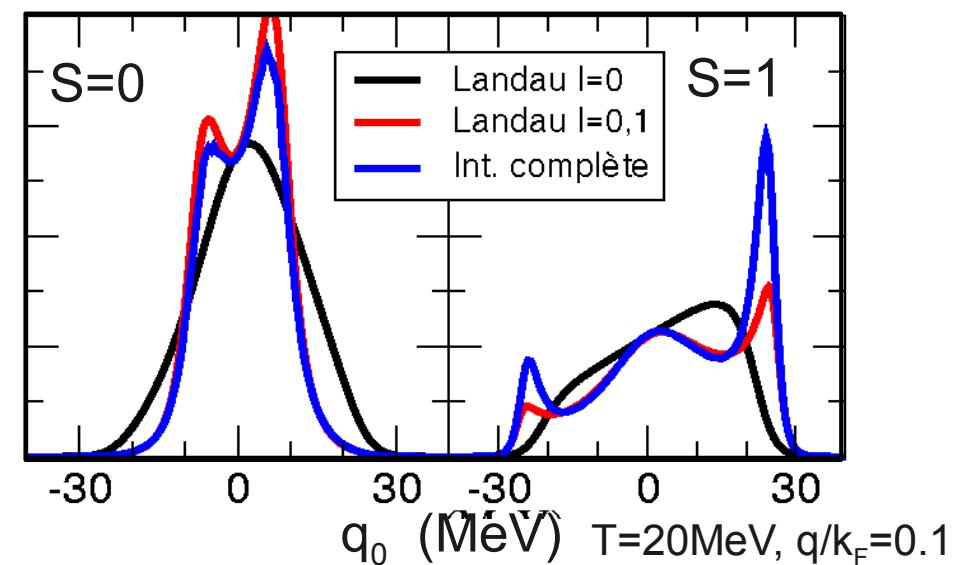
$\rightarrow \left\{ \begin{array}{l} \text{single particle} \\ \text{energy : } e^*(k) \end{array} \right.$



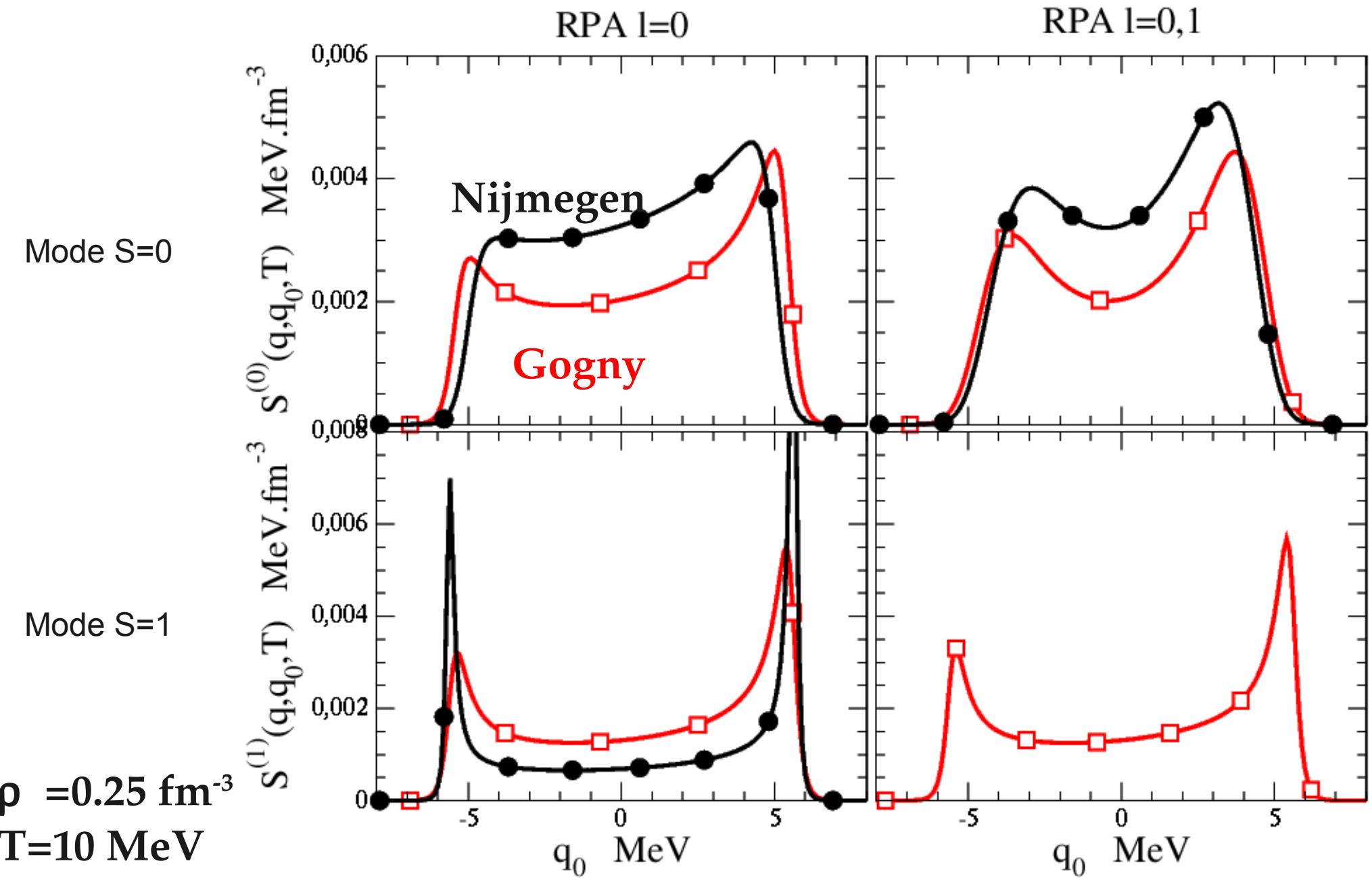
$S_0(q, q_0, T)$



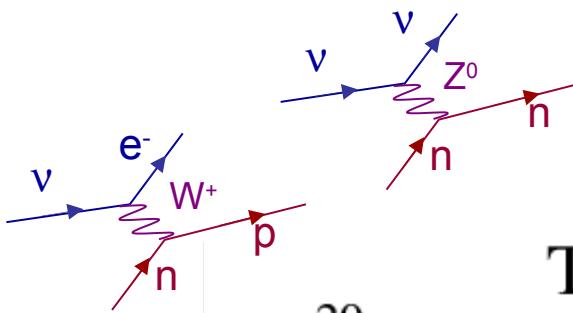
$S_{\text{RPA}}^{(S)}(q, q_0, T)$



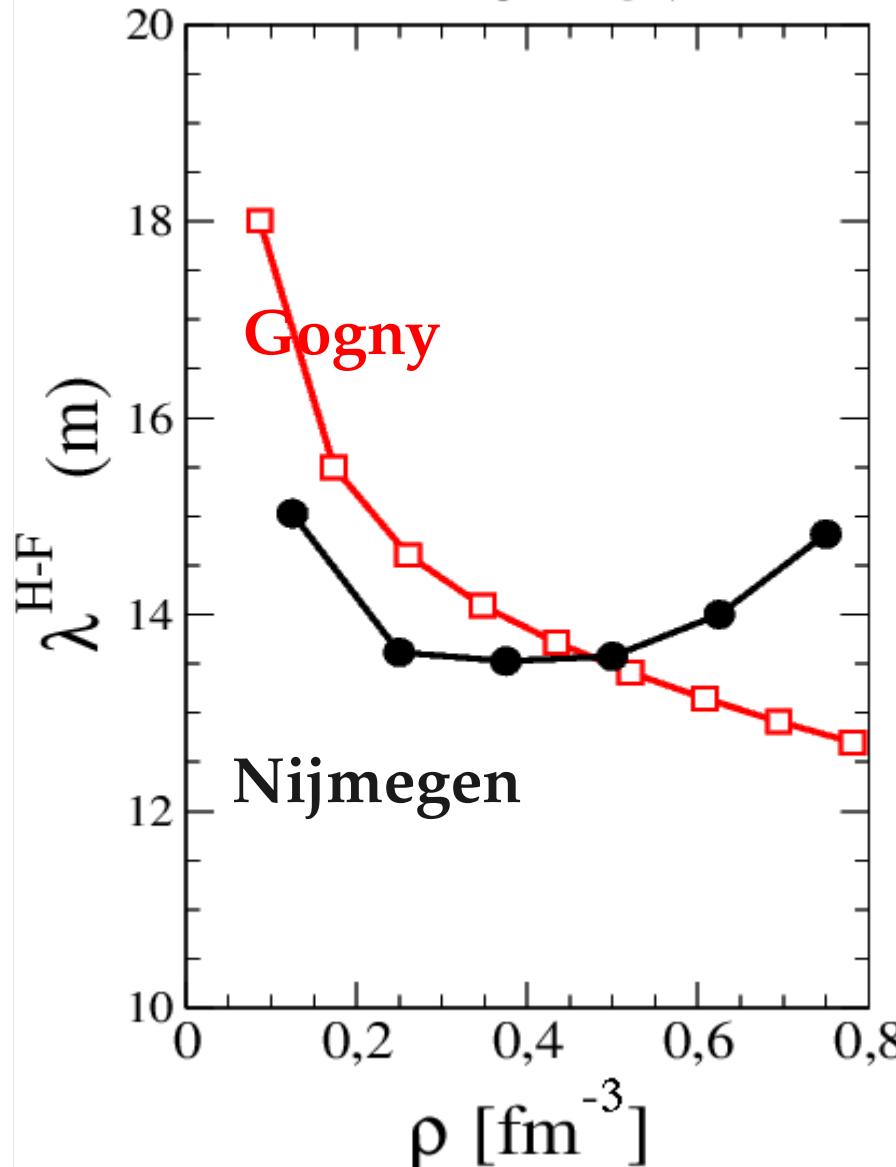
Response function (HF+RPA)



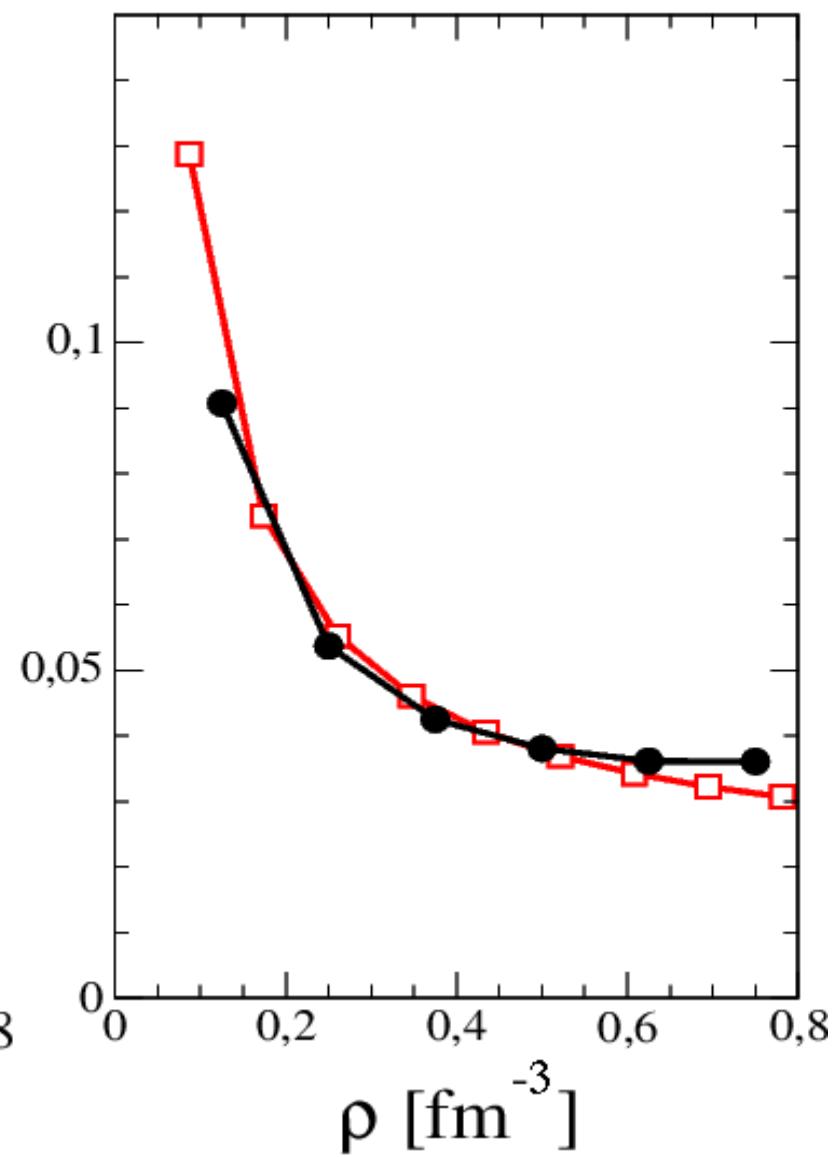
Neutrino mean free path in pure neutron matter



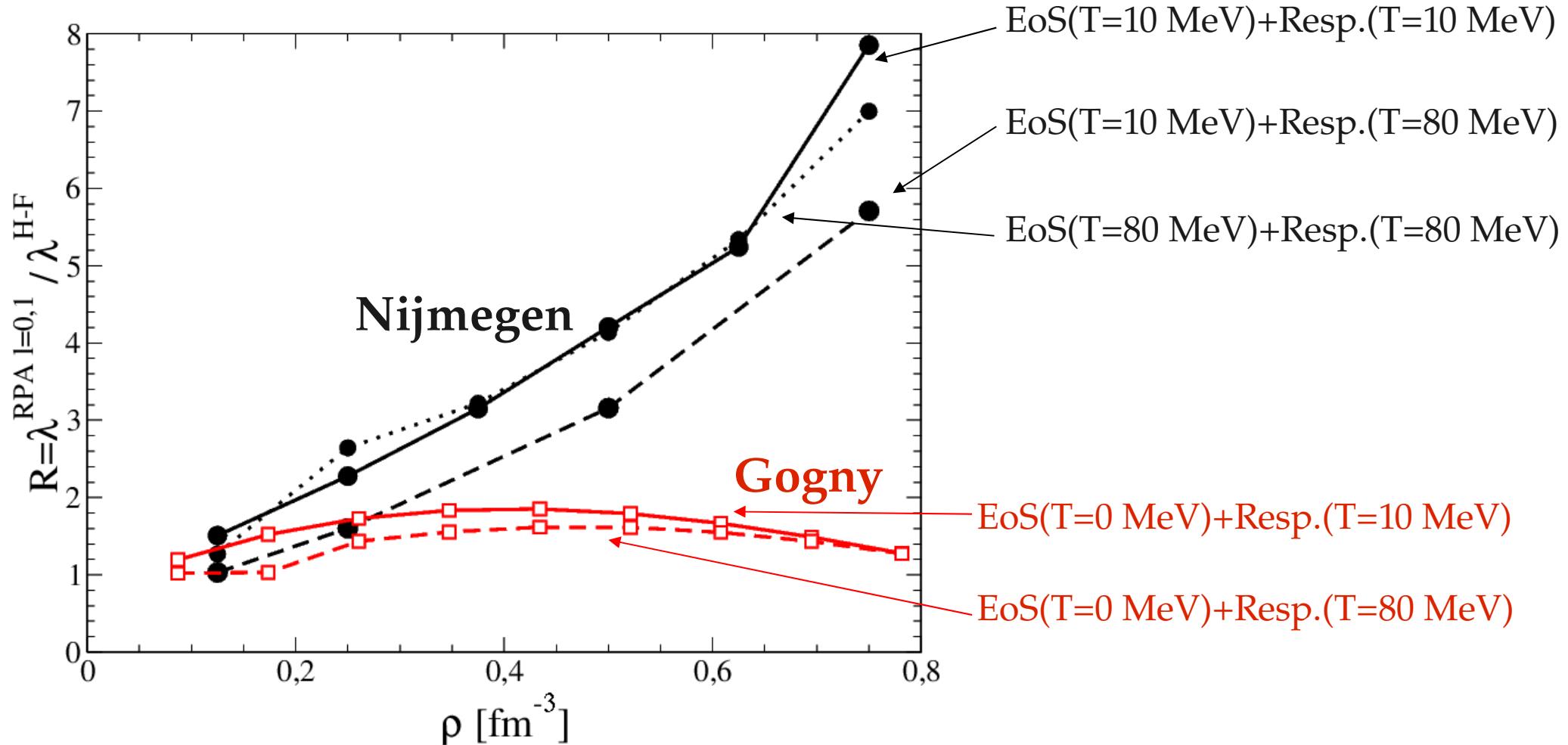
$T = 10 \text{ MeV}$



$T = 80 \text{ MeV}$



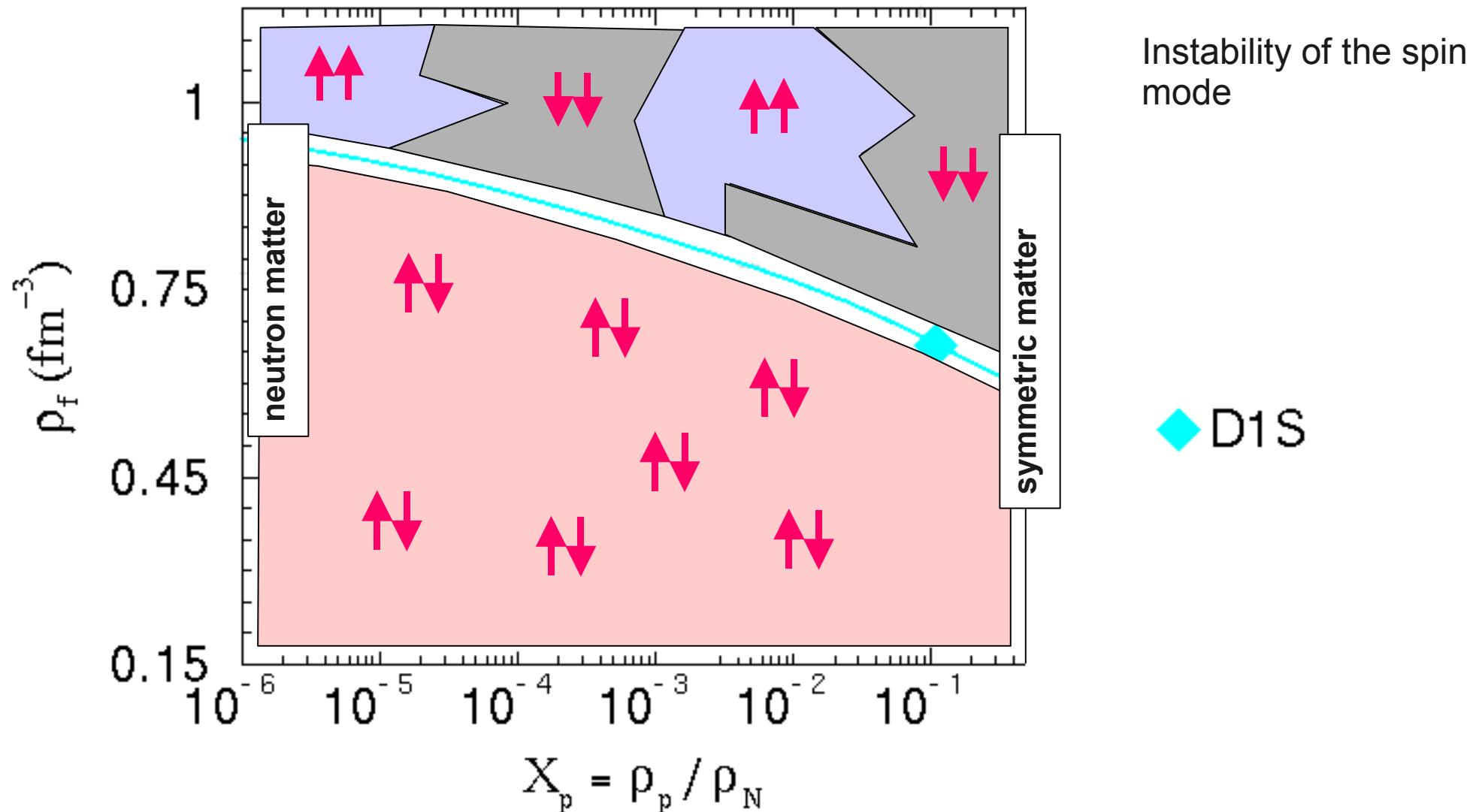
Effect of RPA correlations



Temperature effect ~ 2
Landau parameters ~ 10 at large densities

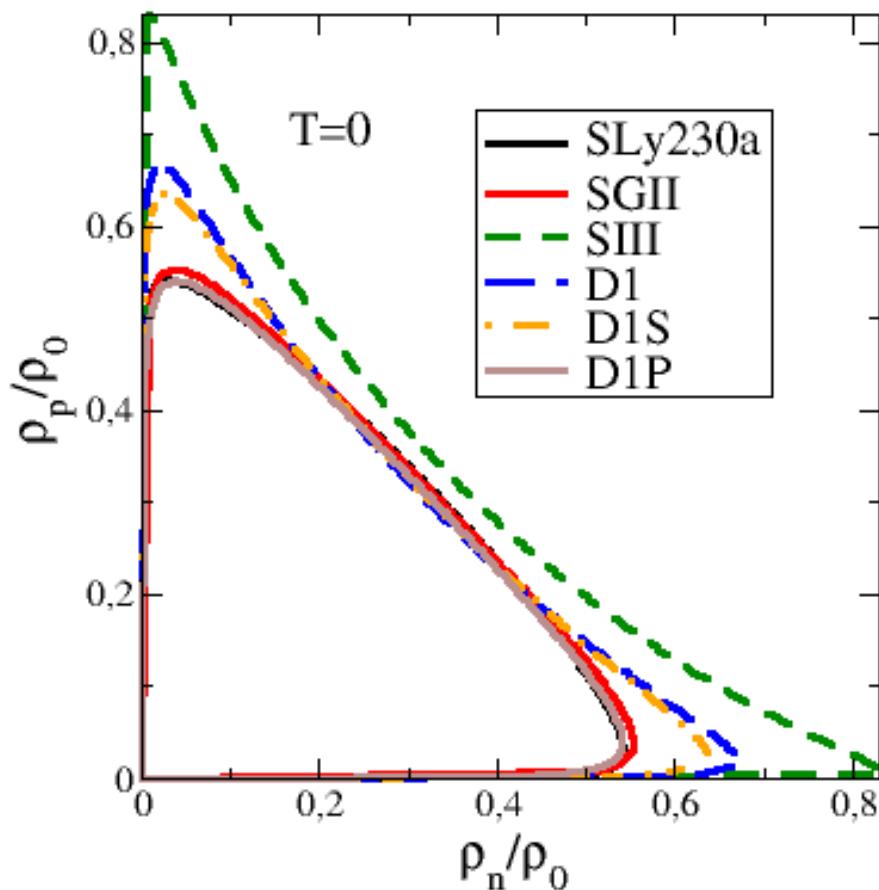
Mean-field instabilities

Ferromagnetic phase diagram

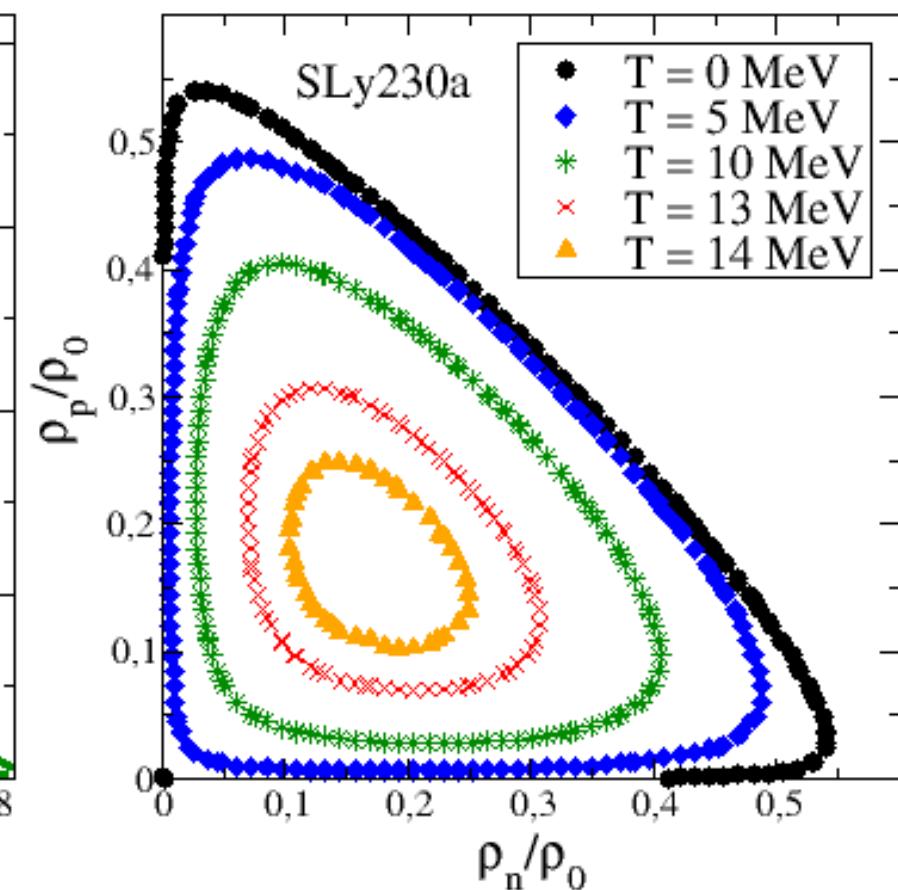


Liquid-gas phase transition in uniform matter below saturation density

Changing the interaction



Increasing the temperature

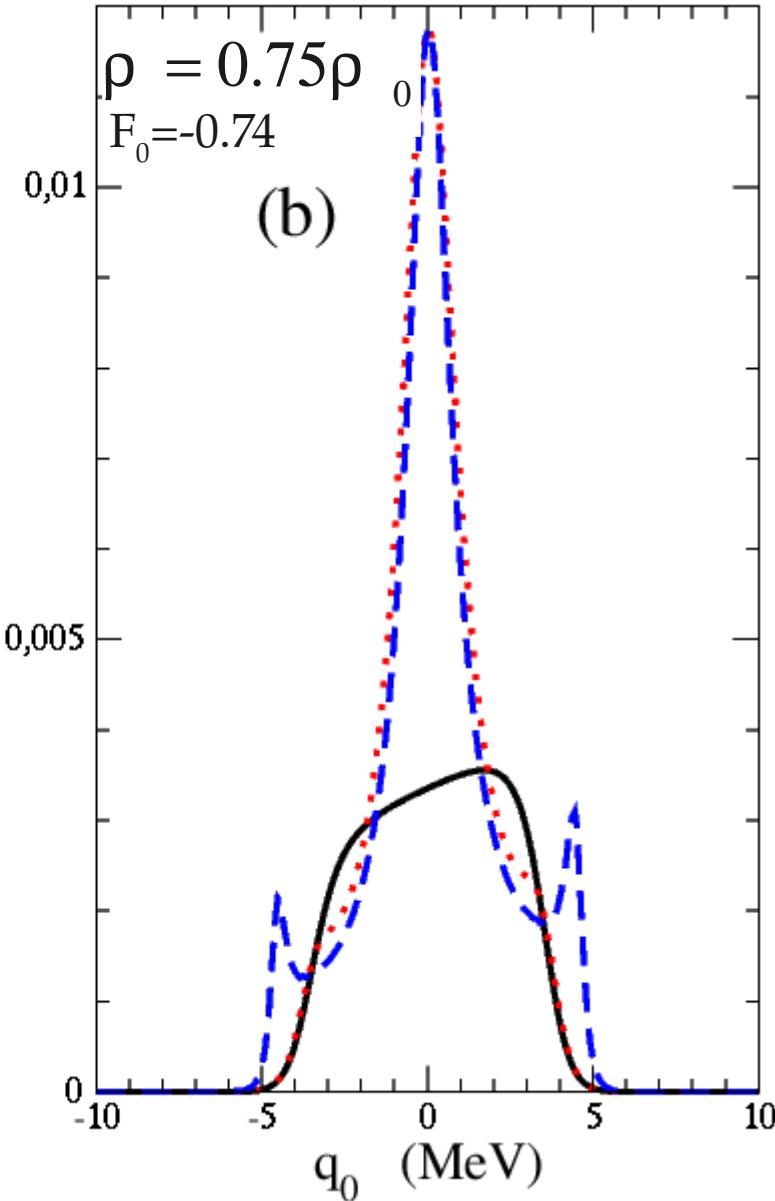
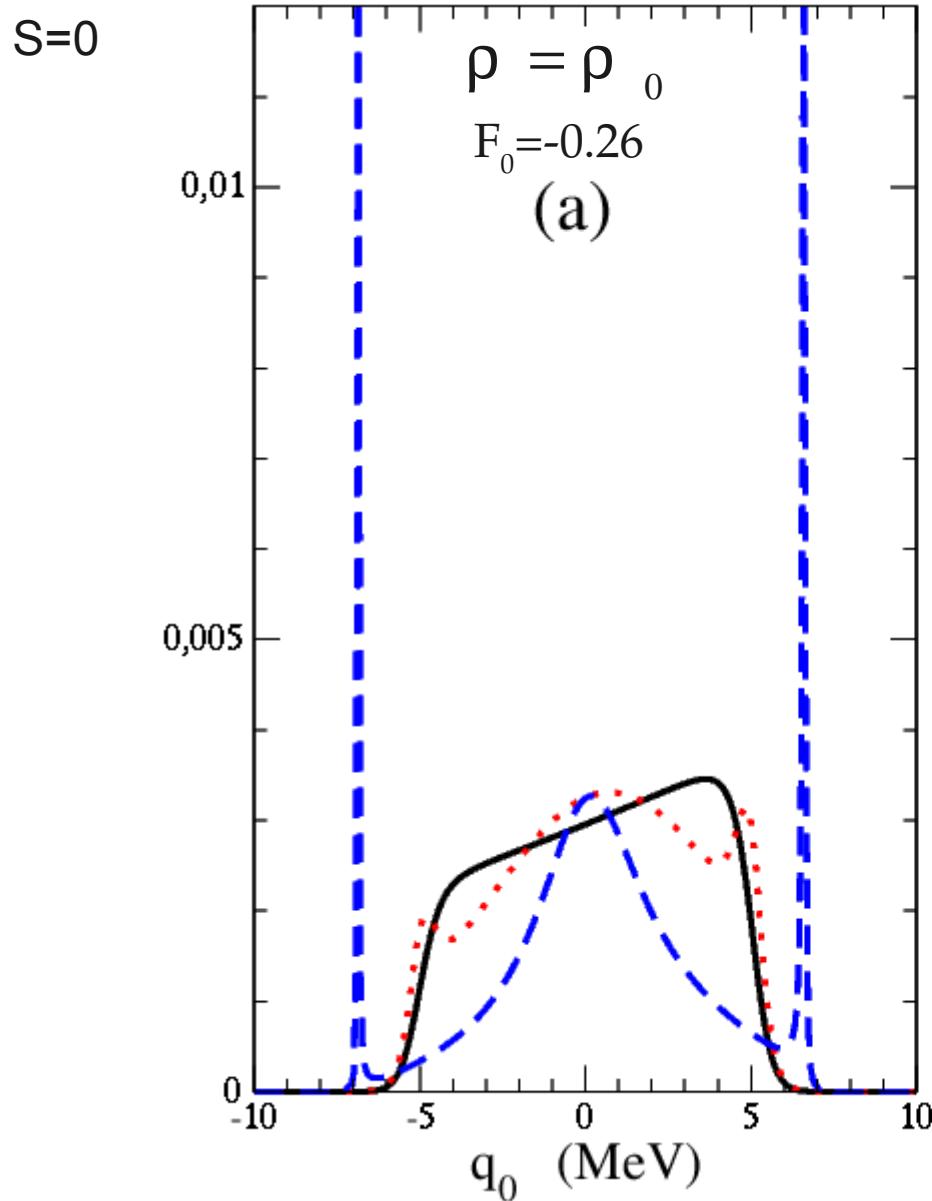


Effect on the response function

Density fluctuations at low density

T=10 MeV

q=10 MeV



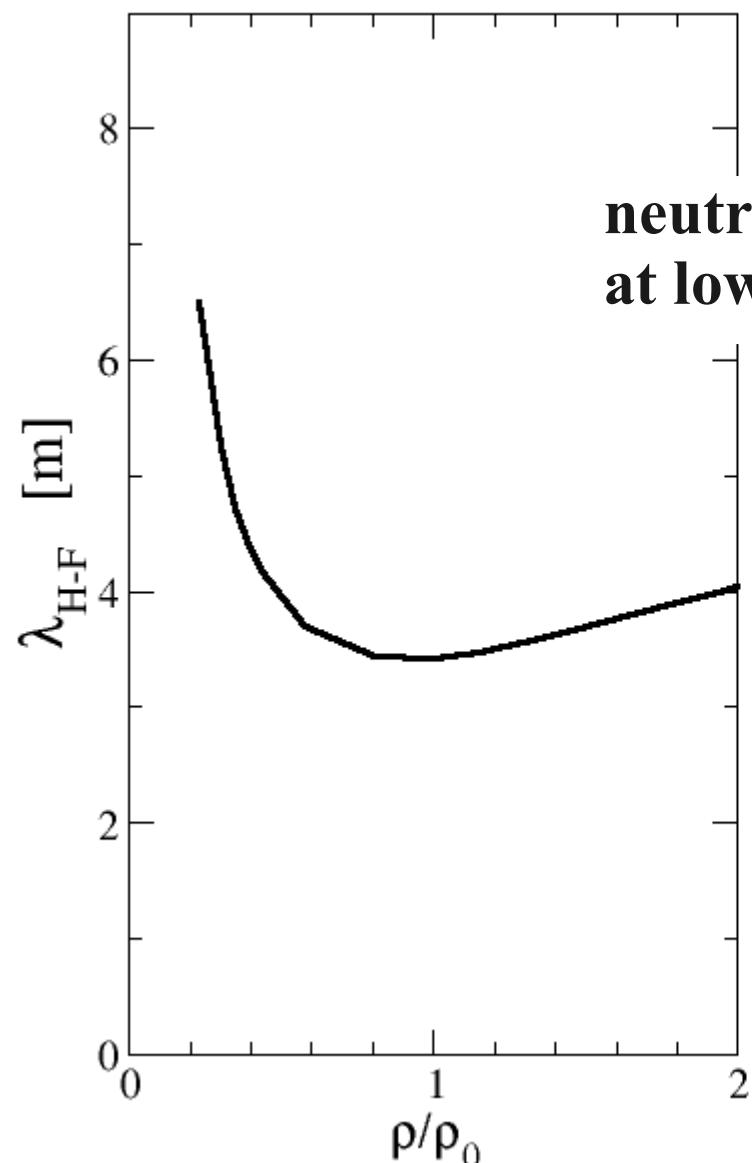
Consequences for the ν mean free path

Gogny interaction

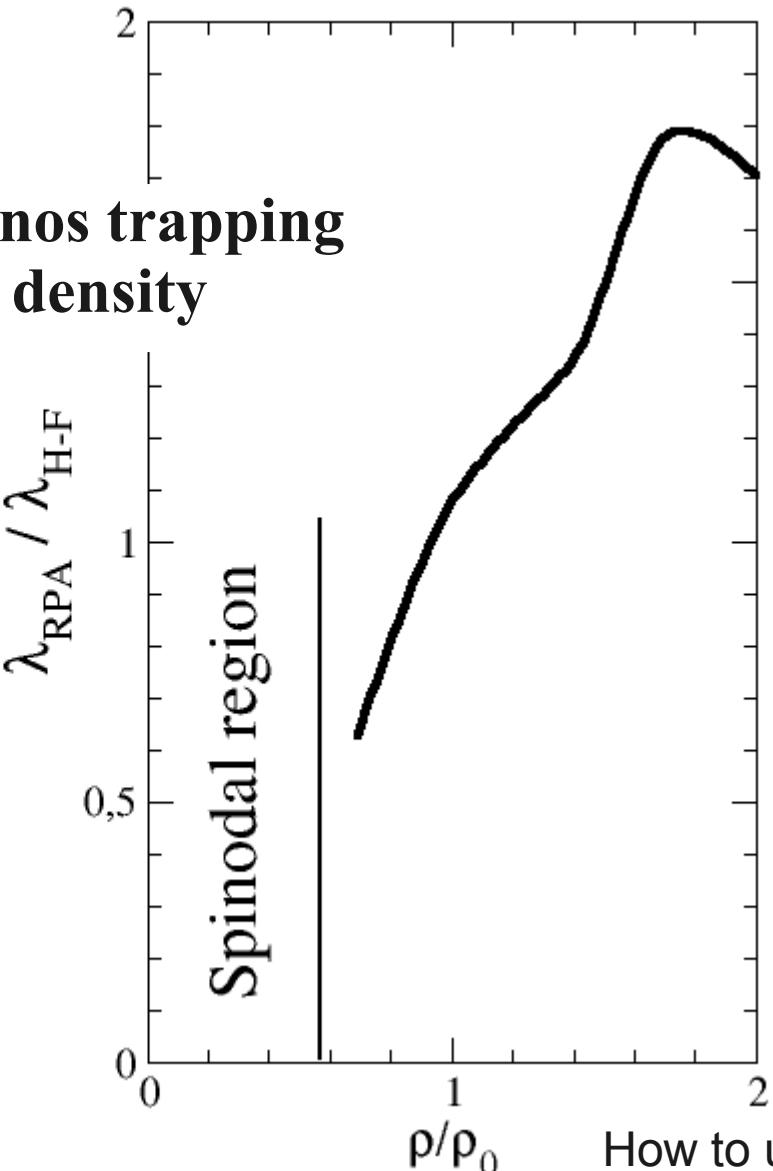


T=10 MeV

$x_p = 0.3$



neutrinos trapping
at low density



Spinodal region

How to understand
this effect ?

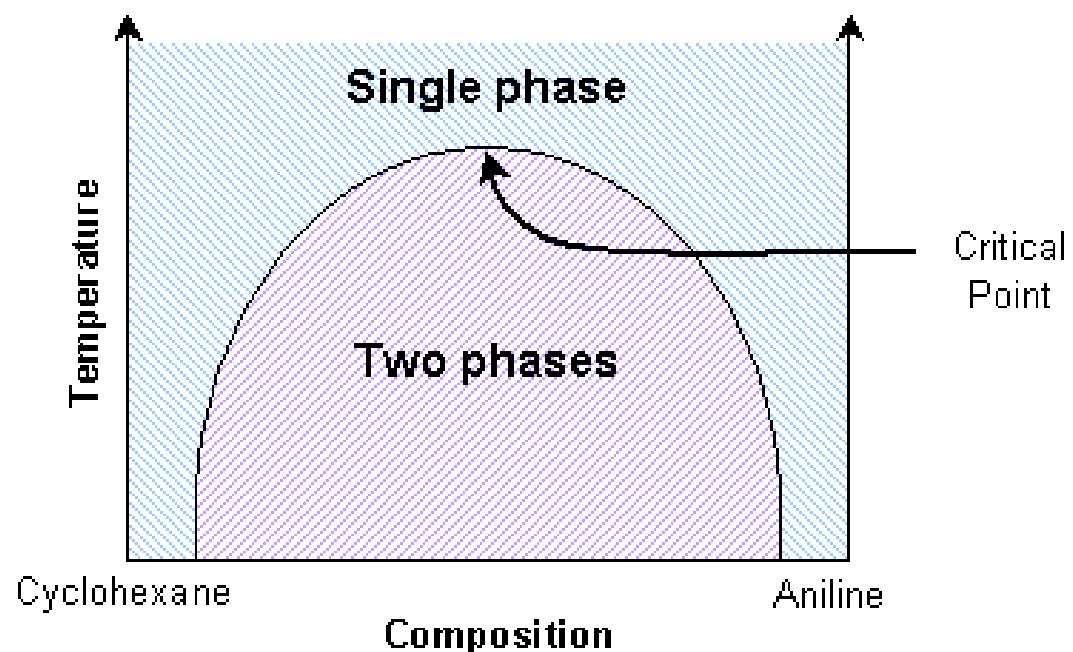
Critical opalescence in laboratory experiments

Opalescence in fluids

It arises in the region of a continuous, or 2nd order, phase transition.

1869: Discovered by Thomas Andrews for the liquid-gas transition in Carbon Dioxide.

Binary Fluids: water & triethylamine, aniline & cyclohexane, methanol & cyclohexane



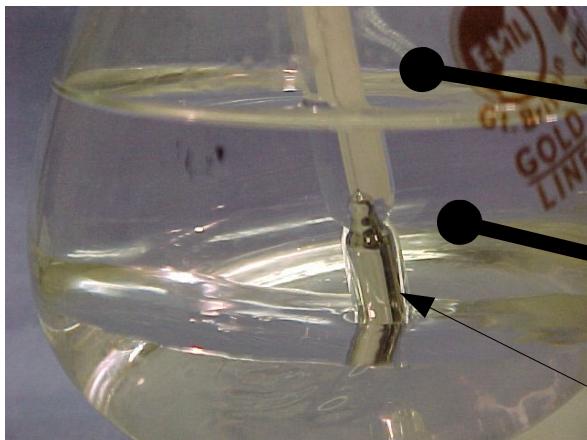
A significant point occurs when the distinction between the two coexisting phases reduces to zero. Here the domains present in the mixture can switch easily between aniline-rich and cyclohexane-rich. **The composition variance is on such a scale as to interfere with light passing through it.** Light will scatter in proportion to the squared difference in n , the index of refraction, of the two phases. Therefore light scatters more as the number of domain interfaces increases. Hence light is scattered strongly by the mixture across a small temperature range around the transition temperature.

The domains demonstrate some interesting properties, such as fractal shapes, and there is a peak in the heat capacity.

hexane and methanol binary fluid

<http://www.physicsofmatter.com/NotTheBook/CriticalOpal/Opal.html>

T = 18 °C



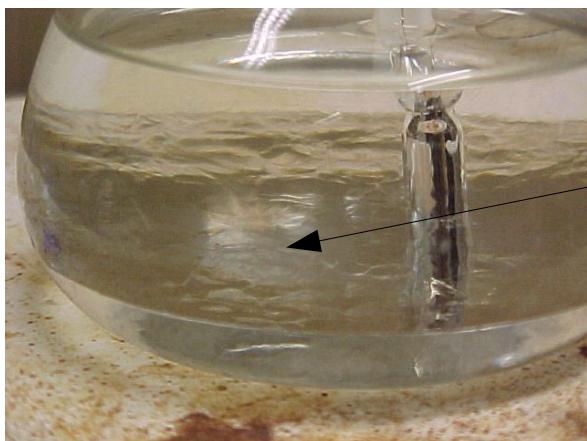
hexane-rich phase

methanol-rich phase

thermometer

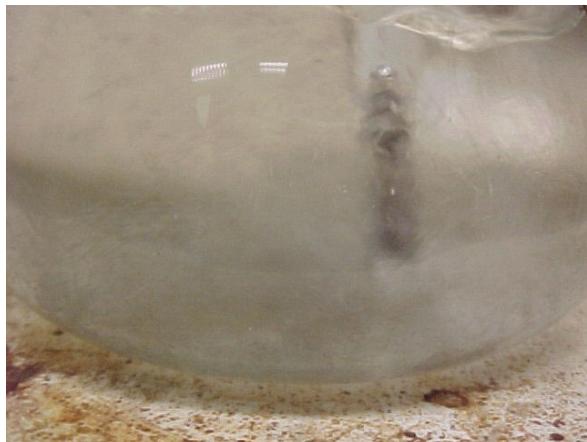
Capillary waves at the interface between the two fluids: very persistent and move slowly around the container giving a "slow motion" effect.

T = 30 °C



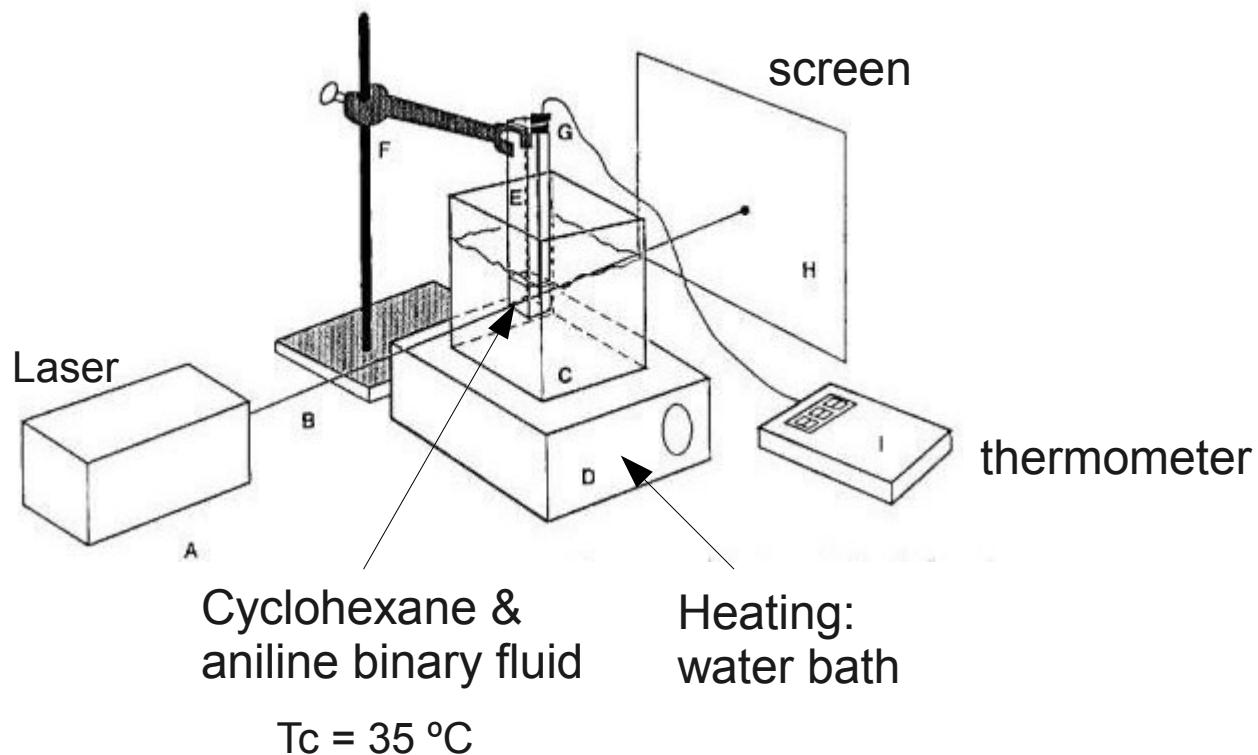
cloudy or milky white -> Opalescence

T = 45 °C



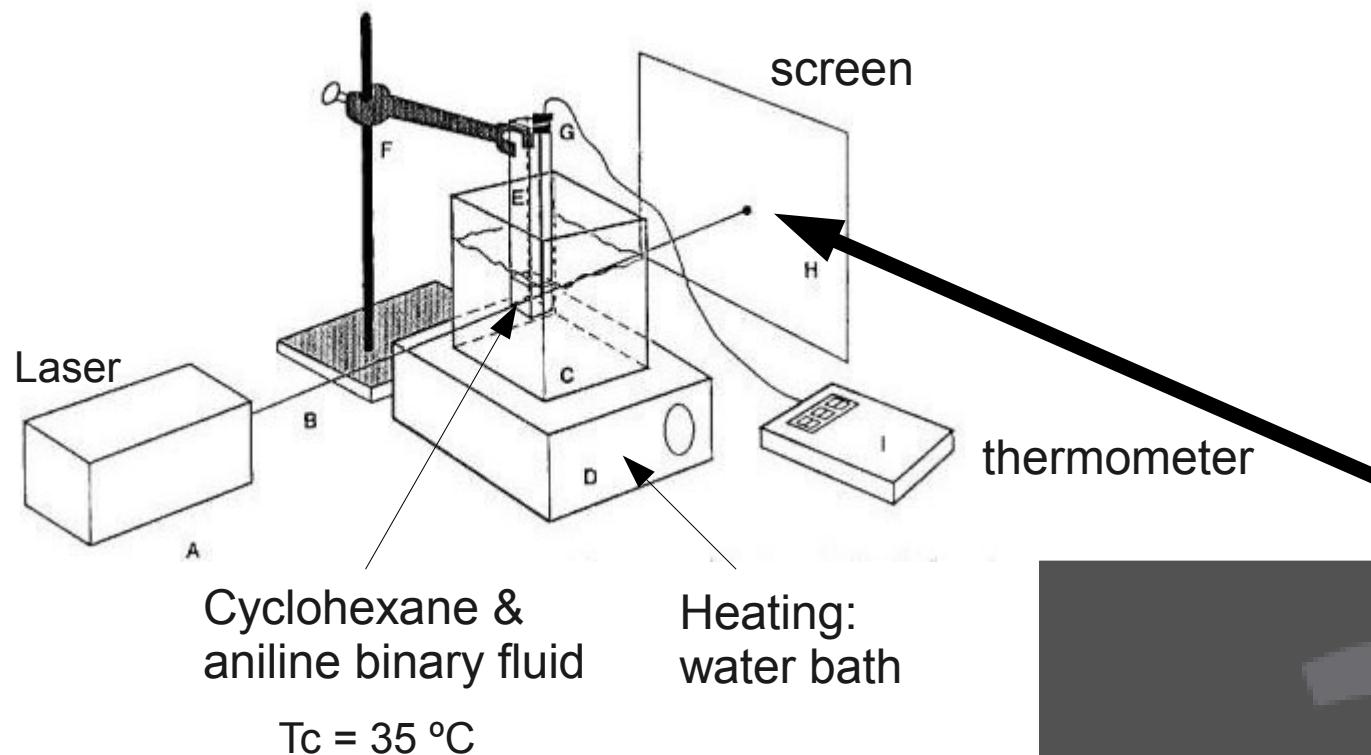
One phase is "boiling" into the other. Small jets of the lower (hotter) methanol-rich phase could be seen exploding into the other!

Demonstration of critical opalescence



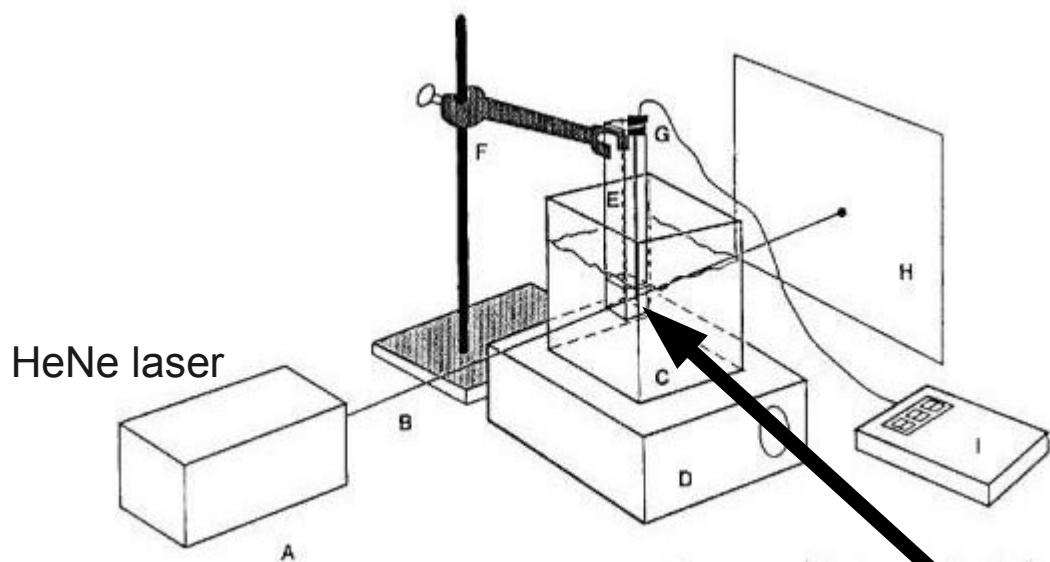
<http://www.msm.cam.ac.uk/doitpoms/tlplib/solid-solutions/demo.php>
<http://www.ucl.ac.uk/~uccaata/work/opalescence/opalescence.html>

Demonstration of critical opalescence



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<http://www.ucl.ac.uk/~uccaata/work/opalescence/opalescence.html>

Demonstration of critical opalescence

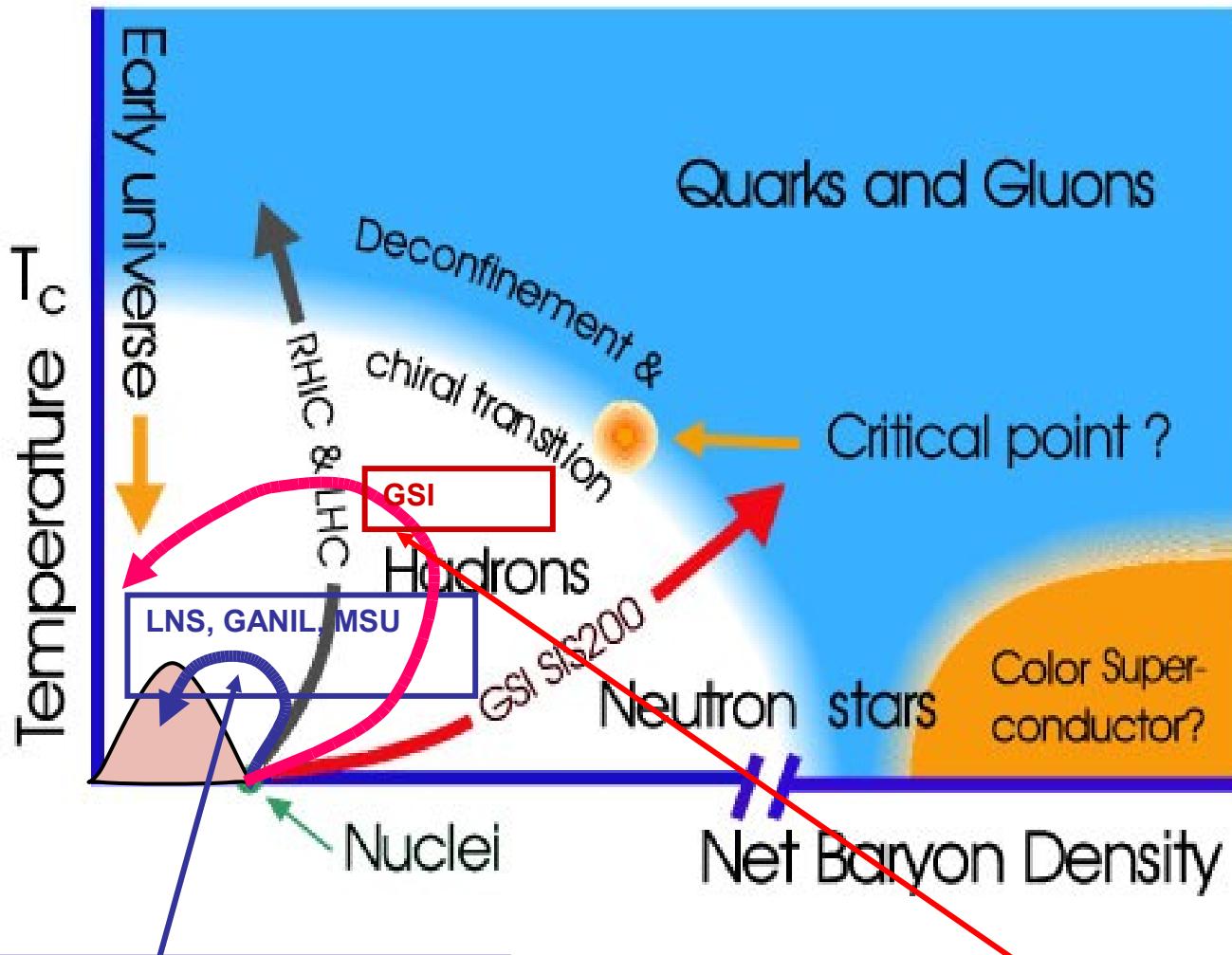


<http://www.msm.cam.ac.uk/doitpoms/tlplib/solid-solutions/demo.php>

<http://www.ucl.ac.uk/~uccaata/work/opalescence/opalescence.html>

Liquid-gas phase transition in nuclear physics

Heavy Ion Collisions



Low energy (Fermi regime):

Fragmentation, liquid-gas phase transition,

Deep inelastic

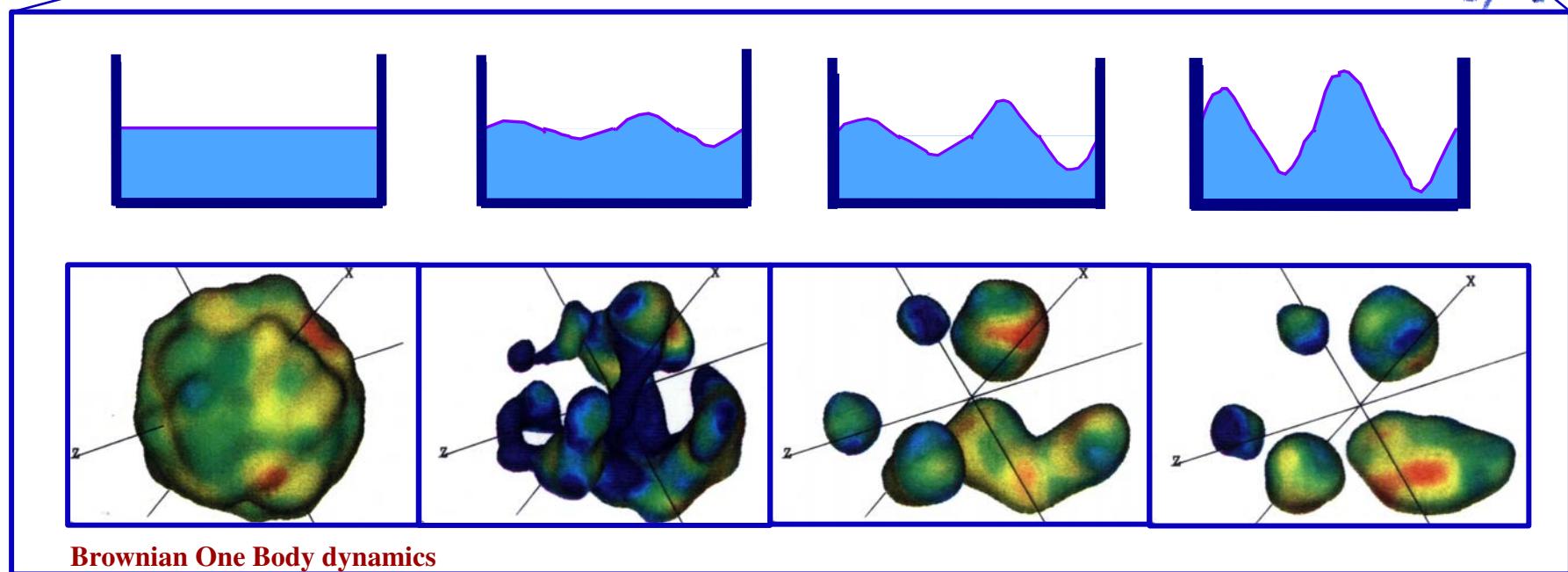
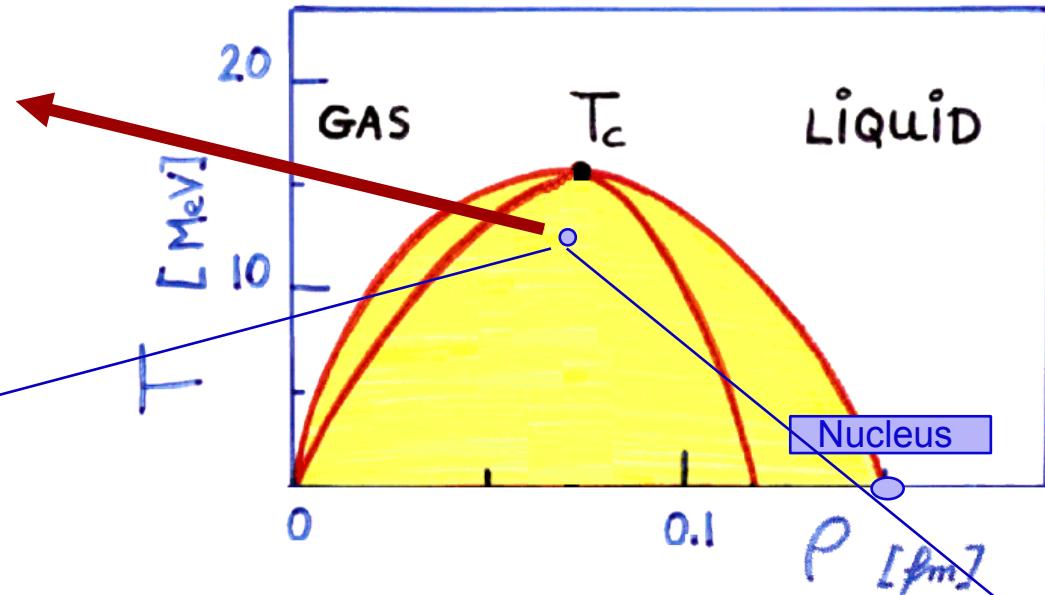
High energy (relativistic):

Compression, particle production,
temperature.

Modification of hadron properties

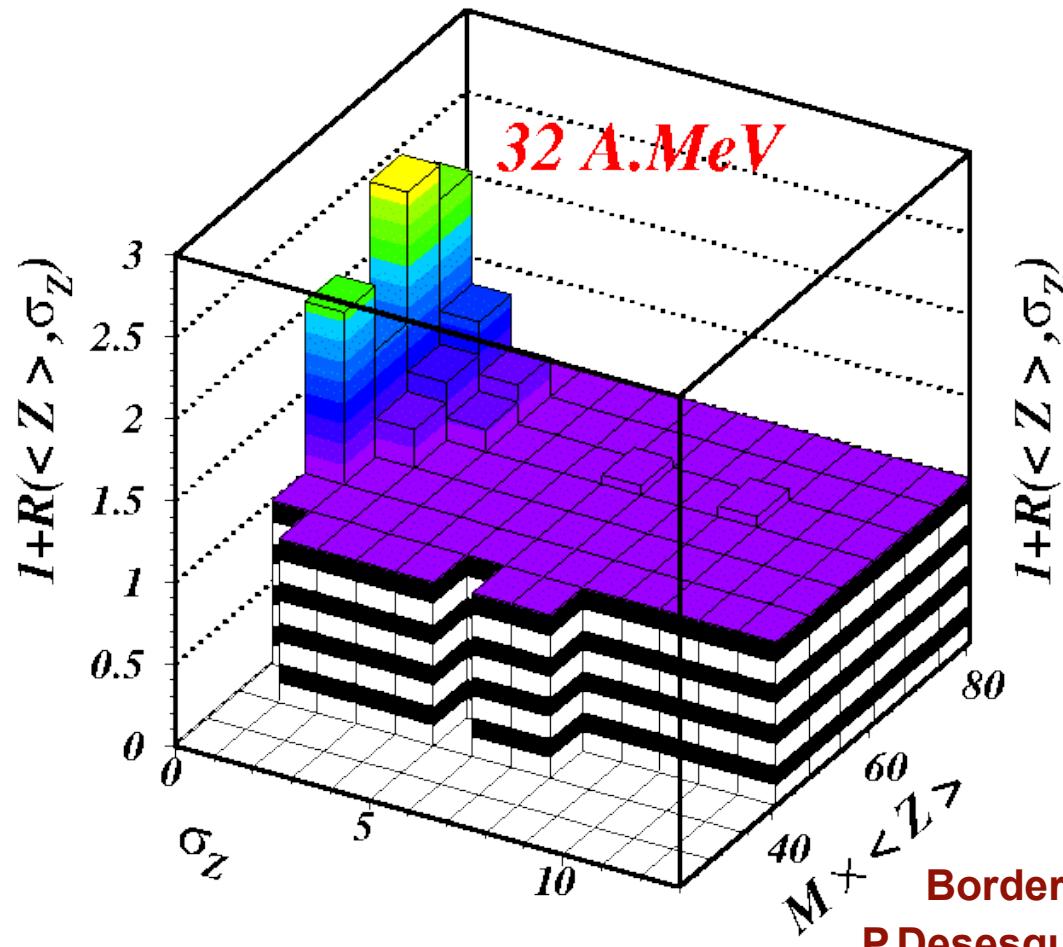
Experimental status : multifragmentation

Spinodal
Decomposition



Spinodal decomposition

A possible experimental signal for liquid-gas phase transition

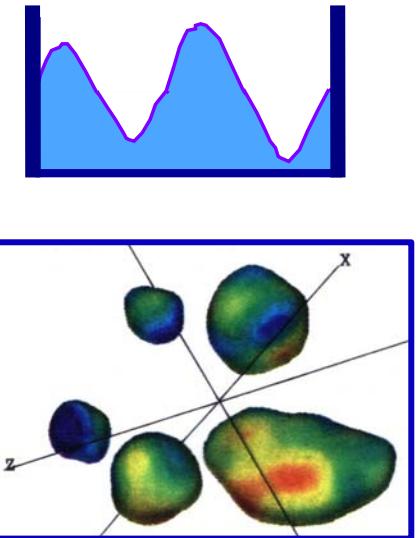


$I+R(\langle Z \rangle, \sigma_Z)$

Borderie et al, PRL 86 (2001) 3252

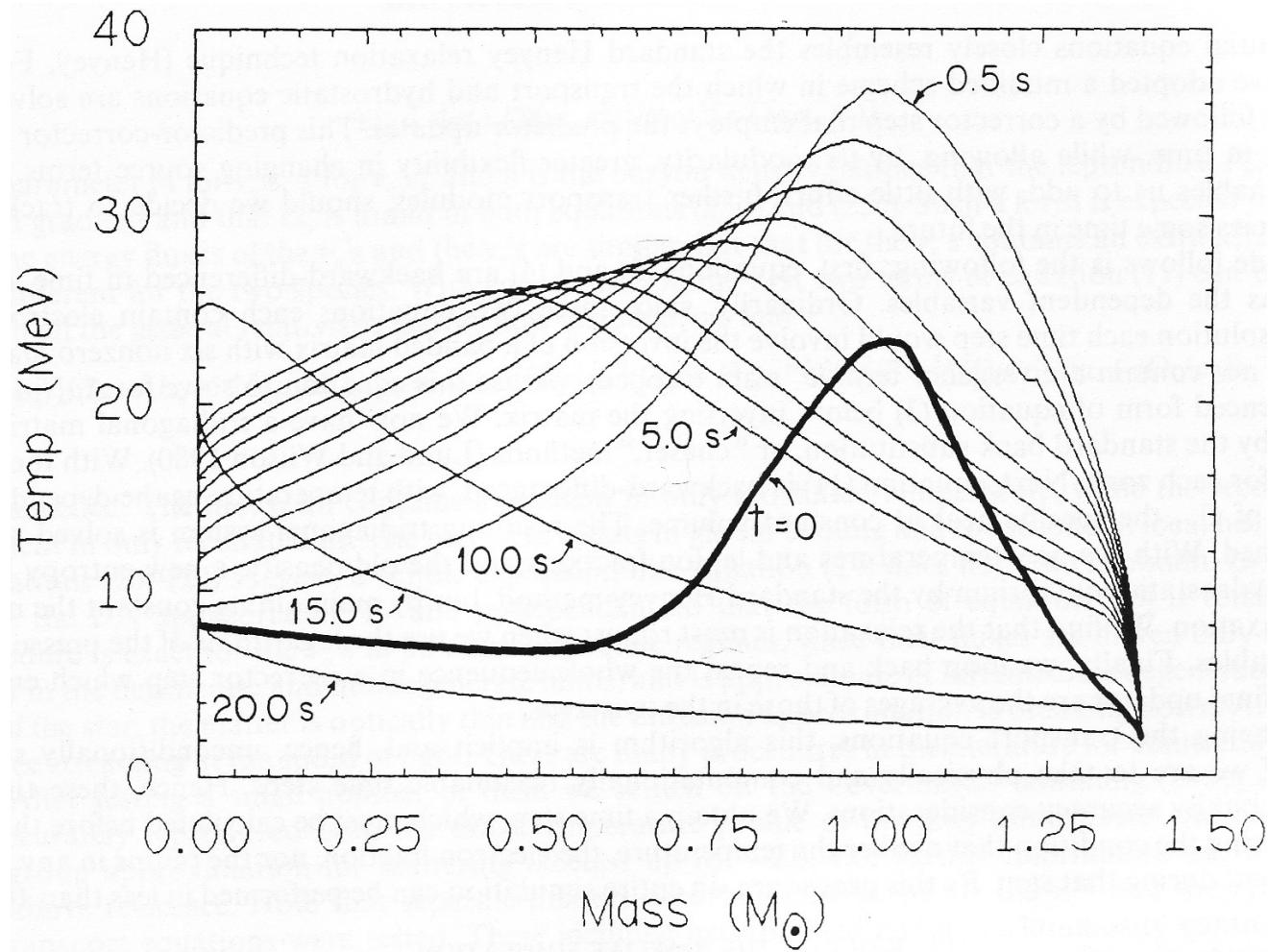
P.Desesquelles, PRC 65 (2002) 34604

Tabacaru et al., EPJ, nucl-ex/0212018



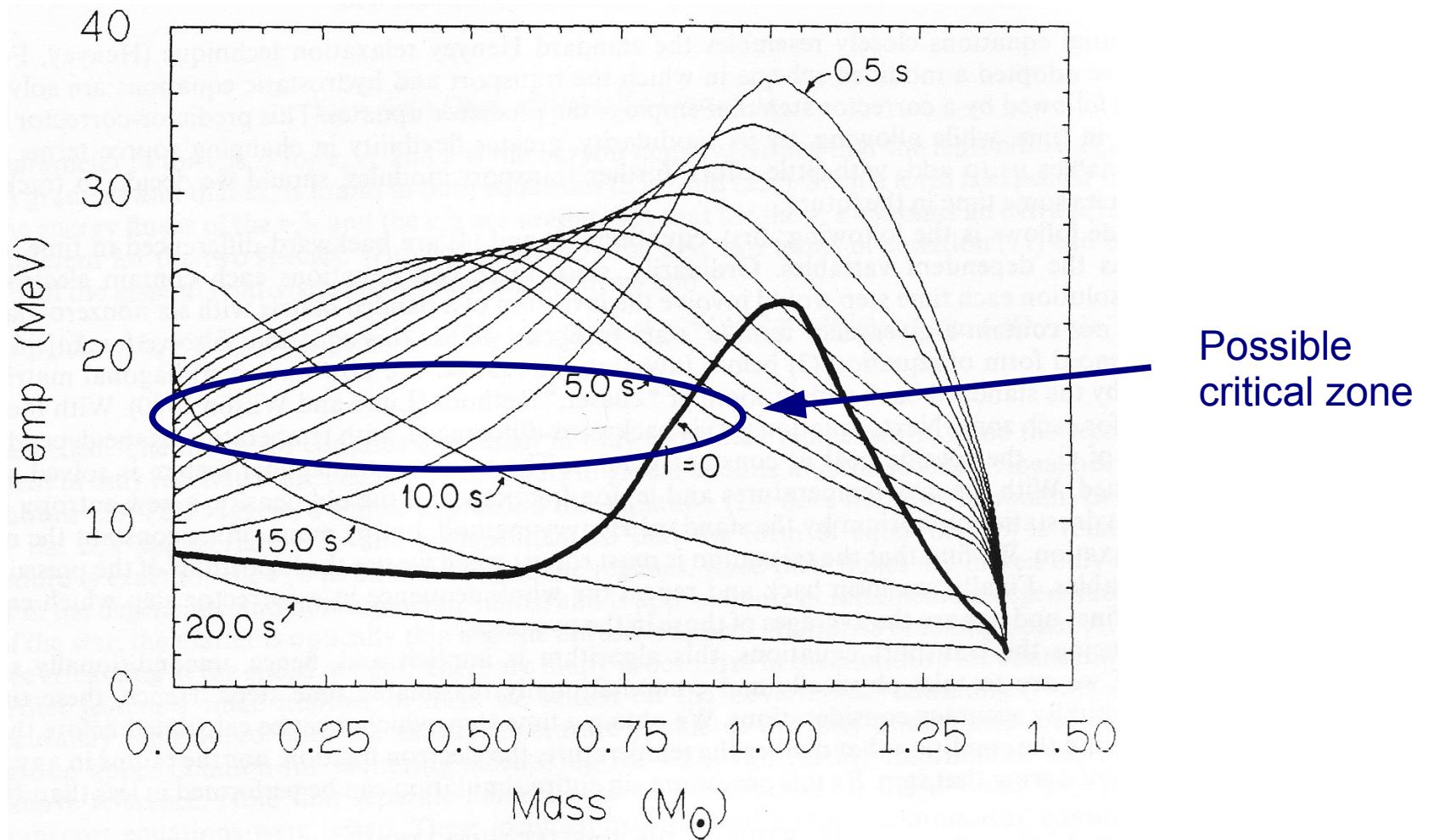
Is there a critical point in proto-neutron star ?

The birth of neutron stars



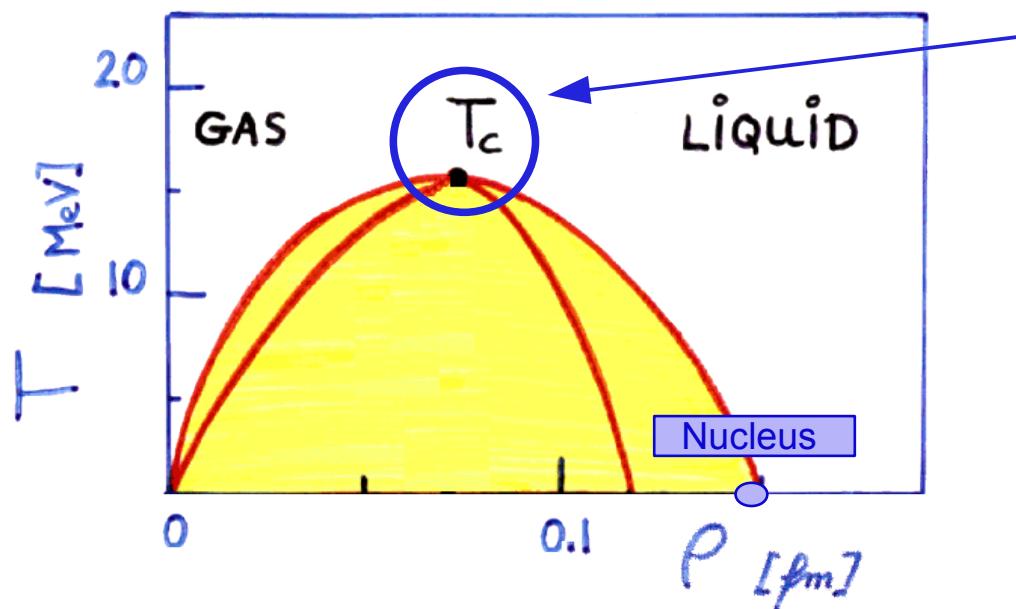
Burrows & Lattimer, *Astrophys. J.* 307 (1986) 178

The birth of neutron stars

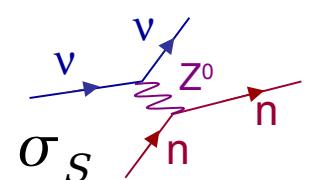


Burrows & Lattimer, *Astrophys. J.* 307 (1986) 178

Critical opalescence in the “pasta phases”



Strong density fluctuations
→ modify neutral currents
(for all neutrino flavours)



$$S(q=\cdot) = \frac{1}{N} \left\{ \langle \hat{N} \rangle - \langle \hat{N} \rangle^{\dagger} \right\}$$

Consequences: neutrino over-trapped

But proto-neutron star have electrons !!

Unstability in (n, p, e) space, e highly incompressible !!!

The presence of electrons washes out the instability:

- RPA response function:

Ducoin, Chomaz, Gulminelli, NPA 789 (2007) 403

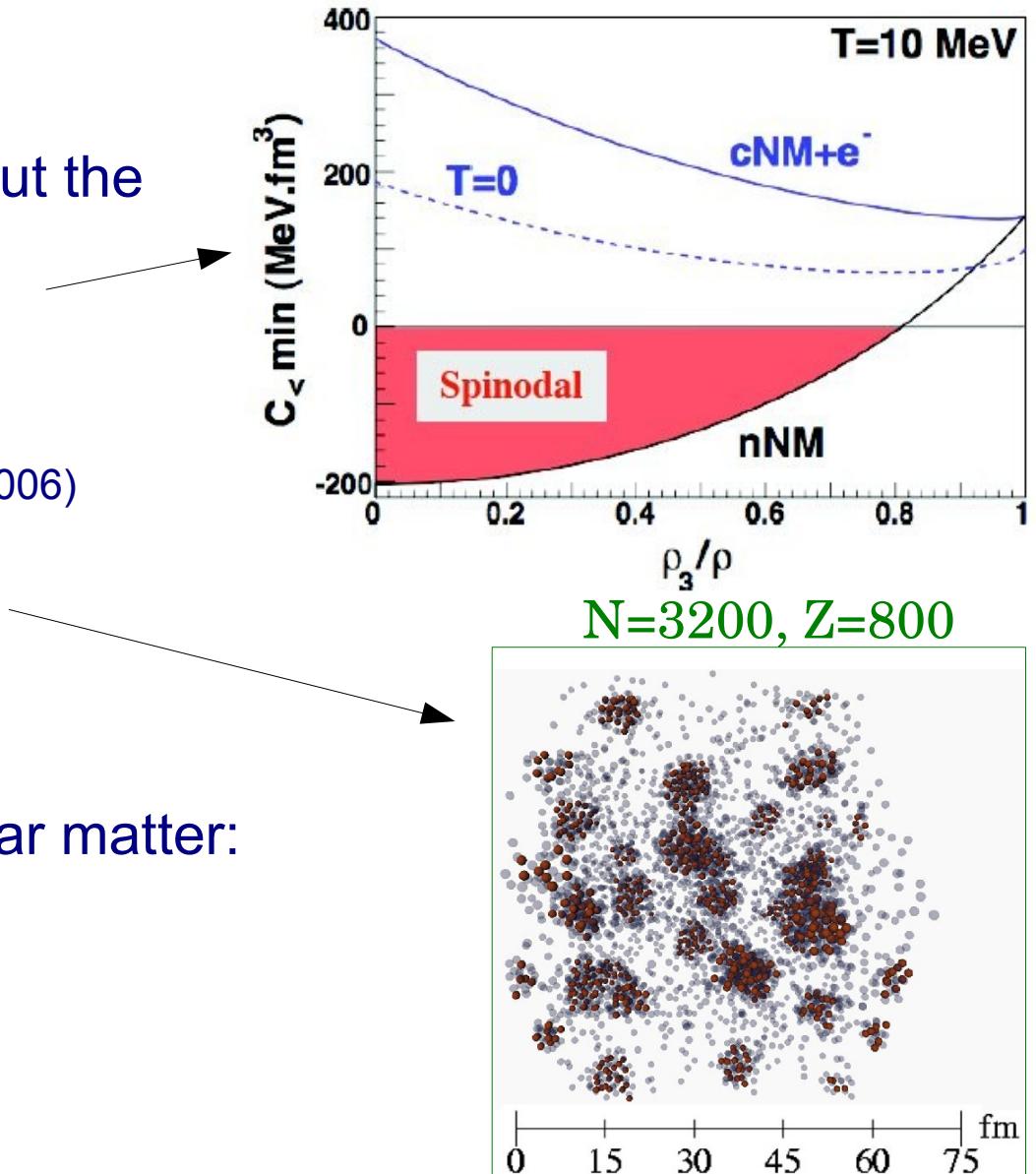
Da Providencia et al., Phys. Rev. C 74, 045802 (2006)

- Molecular dynamics:

Horowitz et al., Phys. Rev. C 72, 035801 (2005)

- Ising model analogue to neutron star matter:

P. Napolitani, Phys. Rev. Lett. 98, 131102 (2007)

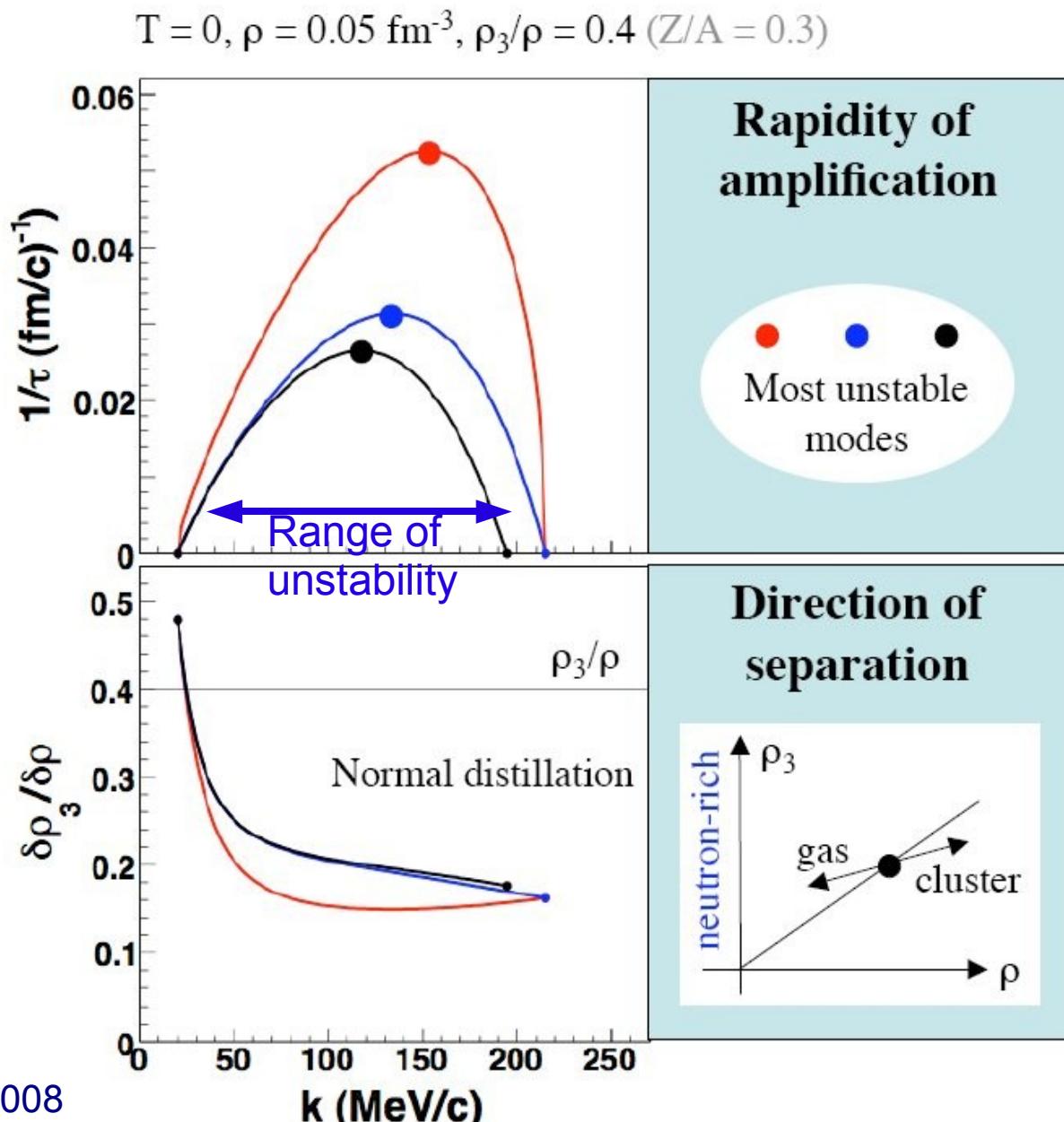


But still...

RPA response become unstable in an interval of k
 (momentum exchanged)
 \rightarrow given scale $1/k$

It is not a critical point
 (instability at any scale $1/k$)

But it could potentially trap neutrino



Conclusions

From a micro-physics point of view:

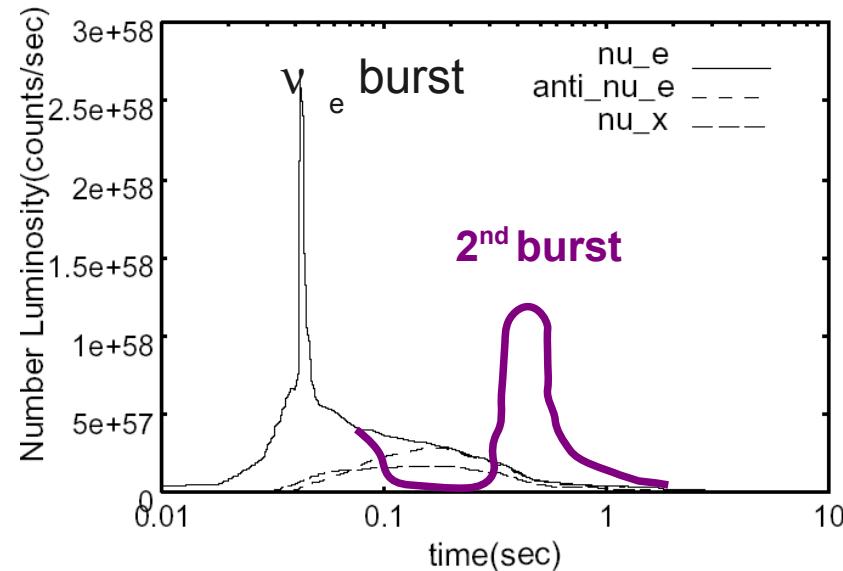
- There is an atypical (interesting) response of compact-star matter below saturation density
- RPA correlation could be very strong below saturation density and overtrap neutrinos

From an astrophysicists point of view:

- Could it influence neutrino transport after the bounce ?

Possible consequences

neutrino emission spectrum



If strong trapping ...

