Elementary excitations in superfluid Neutron Star matter

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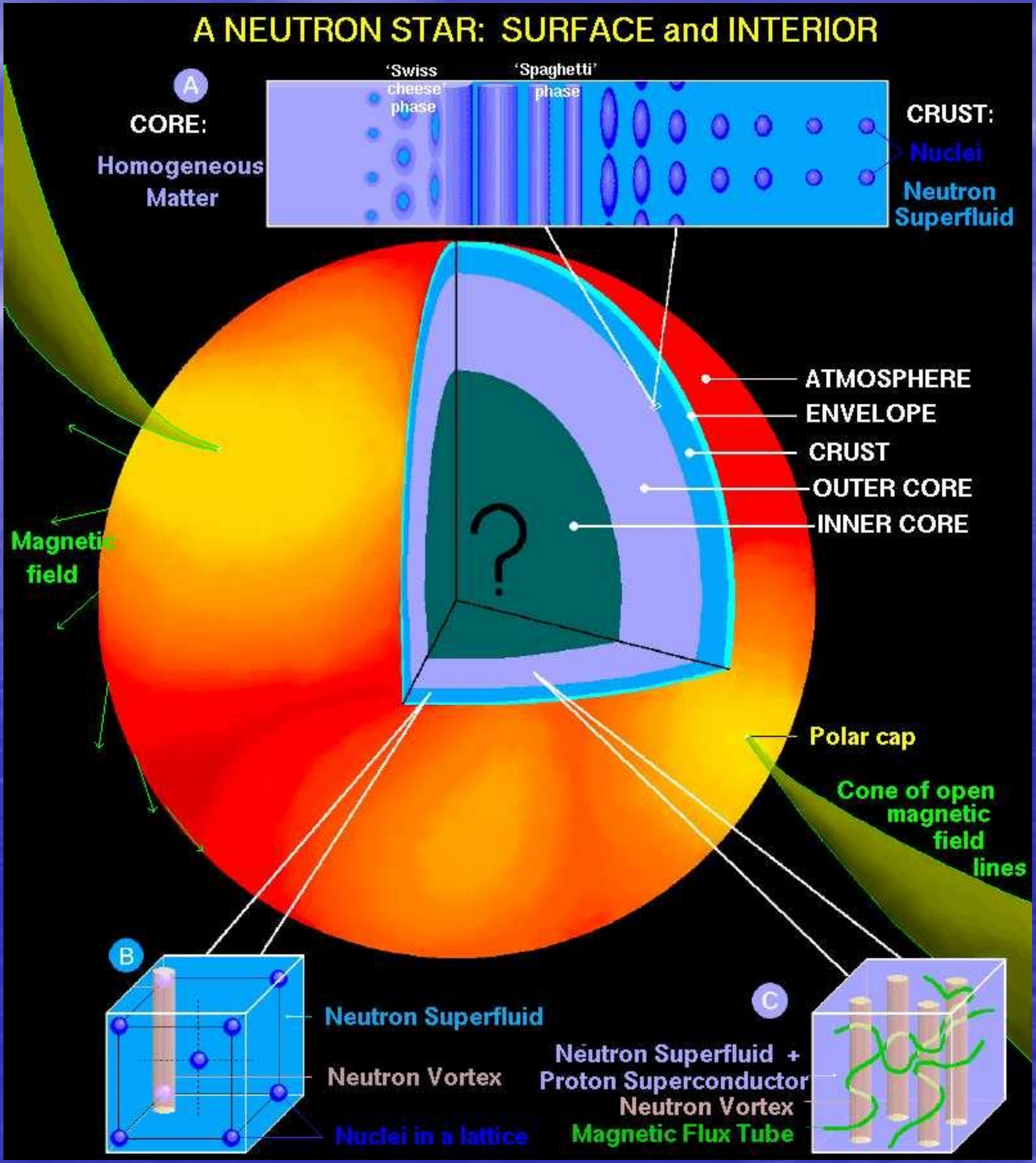
A section (schematic) of a neutron star



MOTIVATIONS

. Neutrino emission from the superfluid matter

. Neutrino mean free path

. Heat capacity

. Thermal and electrical conductivity

. Transport coefficients (e.g. shear viscosity)

Possible physical processes

Neutrino emission

A collective mode with energy linear in momentum cannot decay into a neutrino-antineutrino pair. It is essential to know the strength function

Vertex renormalization of the response function

Neutrino mean free path

Scattering from the Goldstone mode or collective modes in general

Heat capacity

Counting correctly the effective degrees of freedom

Transport coefficients

#Direct contribution of the superfluid phonons

(Tolos et al. PRC 90, 055803 (2014), PRD 84, 123007 (2011))

Some references

J. Kundu and S. Reddy, PRC 70, 055803 (2004)

L.B. Leinson and A. Perez, PLB 638, 114 (2006)

A. Sedrakian, H. Muether and P. Schuck, PRC 76, 055805 (2007)

A.W. Steiner and S. Reddy, PRC 79, 015802 (2009)

L.B. Leinson, PRC 79, 045502 (2009)

E. Kolomeitsev and D. Voskresenky, PRC 81, 065801 (2010)

M.B. and C. Ducoin, PRC 84, 035806 (2011); PRC96, 025811 (2017)

N. Martin and M. Urban, PRC 90, 065805 (2014)

We will include neutron, proton and electron components

Some questions to be answered

. How much protons and neutrons decouple ?

. How efficient is the electron screening ?

. How much neutron modes are affected by protons ?

. Are the phonon damped ? How much ?

Basic equation for the strength functions

$$\Pi_{ik}(t,t') = \Pi^0_{ik}(t,t') + \sum_{jl} \Pi^0_{ij}(t,\overline{t_1}) v_{j,l} \Pi_{lk}(\overline{t_1},t')$$

$$S_k = -Im(\Pi_{kk})$$

Linear response including electrons and protons only

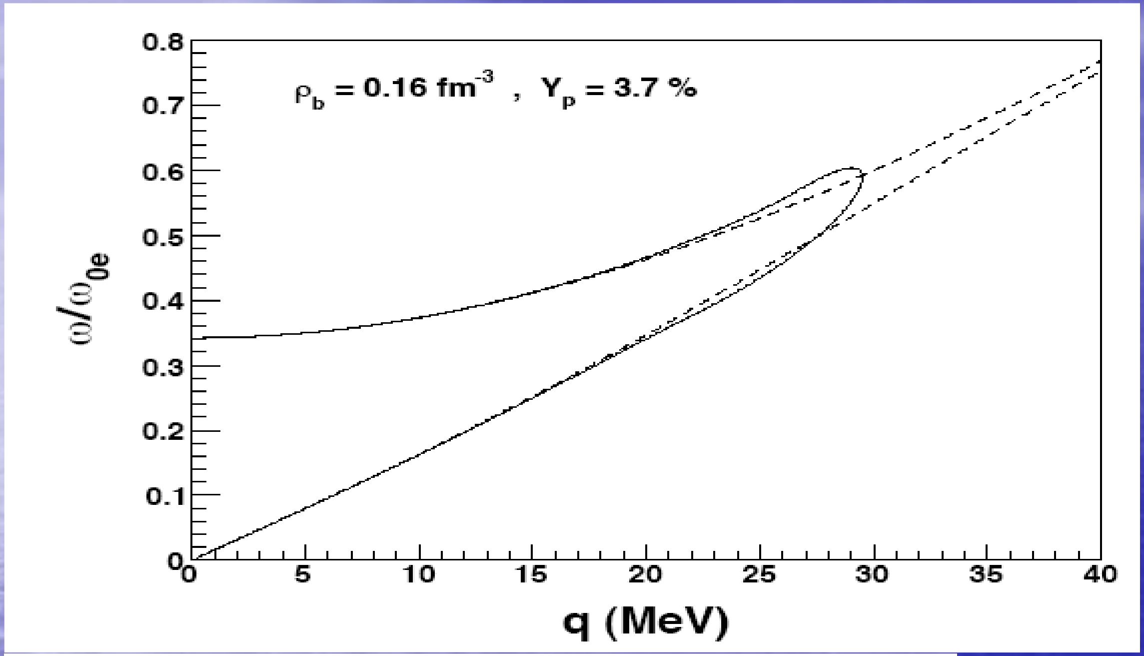
$$
\begin{aligned}
X^{ph}_{GG}(q) &= \frac{1}{i}\int \frac{dk}{(2\pi)^4} G(k)G(k+q) \;\; ; \;\; X^{ph}_{GG}(-q) = X^{ph}_{GG}(q) \\
X^{pp}_{GG}(q) &= \frac{1}{i}\int \frac{dk}{(2\pi)^4} G(k)G(-k+q) \\
X^{pp}_{GG}(-q) &= \frac{1}{i}\int \frac{dk}{(2\pi)^4} G(k)G(-k-q) \\
X_{GF}(q) &= \frac{1}{i}\int \frac{dk}{(2\pi)^4} G(k)F(k+q) \\
X_{GF}(-q) &= \frac{1}{i}\int \frac{dk}{(2\pi)^4} G(k)F(k-q) \\
X_{FF}(q) &= \frac{1}{i}\int \frac{dk}{(2\pi)^4} F(k)F(k+q) \;\; ; \;\; X_{FF}(-q) = X_{FF}(q)
\end{aligned}
$$

$$
\begin{aligned}
\Pi^{(+)} &= \frac{1}{2}\left(\Pi_{11;\alpha\beta} + \Pi_{-1-1;\alpha\beta}\right) \\
\Pi^{(-)} &= \frac{1}{2}\left(\Pi_{11;\alpha\beta} - \Pi_{11;\alpha\beta}\right) \\
\Pi^{(ph)} &= \Pi_{-11;\alpha\beta}
\end{aligned}
$$

$$
\begin{aligned}
X^{pp}_{\pm} &= \frac{1}{2}\left[X^{pp}_{GG}(q) + X^{pp}_{GG}(-q)\right] \pm X_{FF}(q) \\
X^{ph}_{\pm} &= X^{ph}_{GG}(q) \pm X_{FF}(q) \\
X^{\pm}_{GF} &= X_{GF}(q) \pm X_{GF}(-q)
\end{aligned}
$$

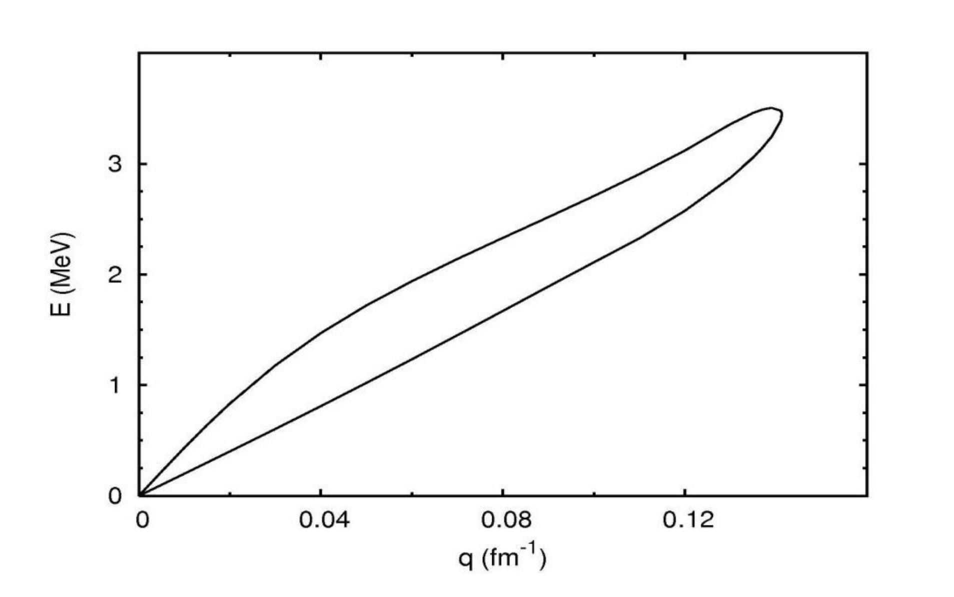
$$
\begin{pmatrix}
1 + X^{pp}_{+} U_{pair} & -2X^{-}_{GF} v_c & 2X^{-}_{GF} v_c \\
-X^{-}_{GF} U_{pair} & 1 - 2X^{ph}_{-} v_c & 2X^{ph} v_c \\
0 & 2X^{e} v_c & 1 - 2X^{e} v_c
\end{pmatrix}
\begin{pmatrix}
\Pi^{(+)}_{S} \\
\Pi^{(ph)}_{S} \\
\Pi^{(ee)}_{S}
\end{pmatrix}
=
\begin{pmatrix}
\Pi^{(+)}_{0,S} \\
\Pi^{(ph)}_{0,S} \\
\Pi^{(ee)}_{0,S}
\end{pmatrix}
$$

NORMAL SYSTEM. Electron screening effect. From the proton plasmon to the sound mode



Static electron background

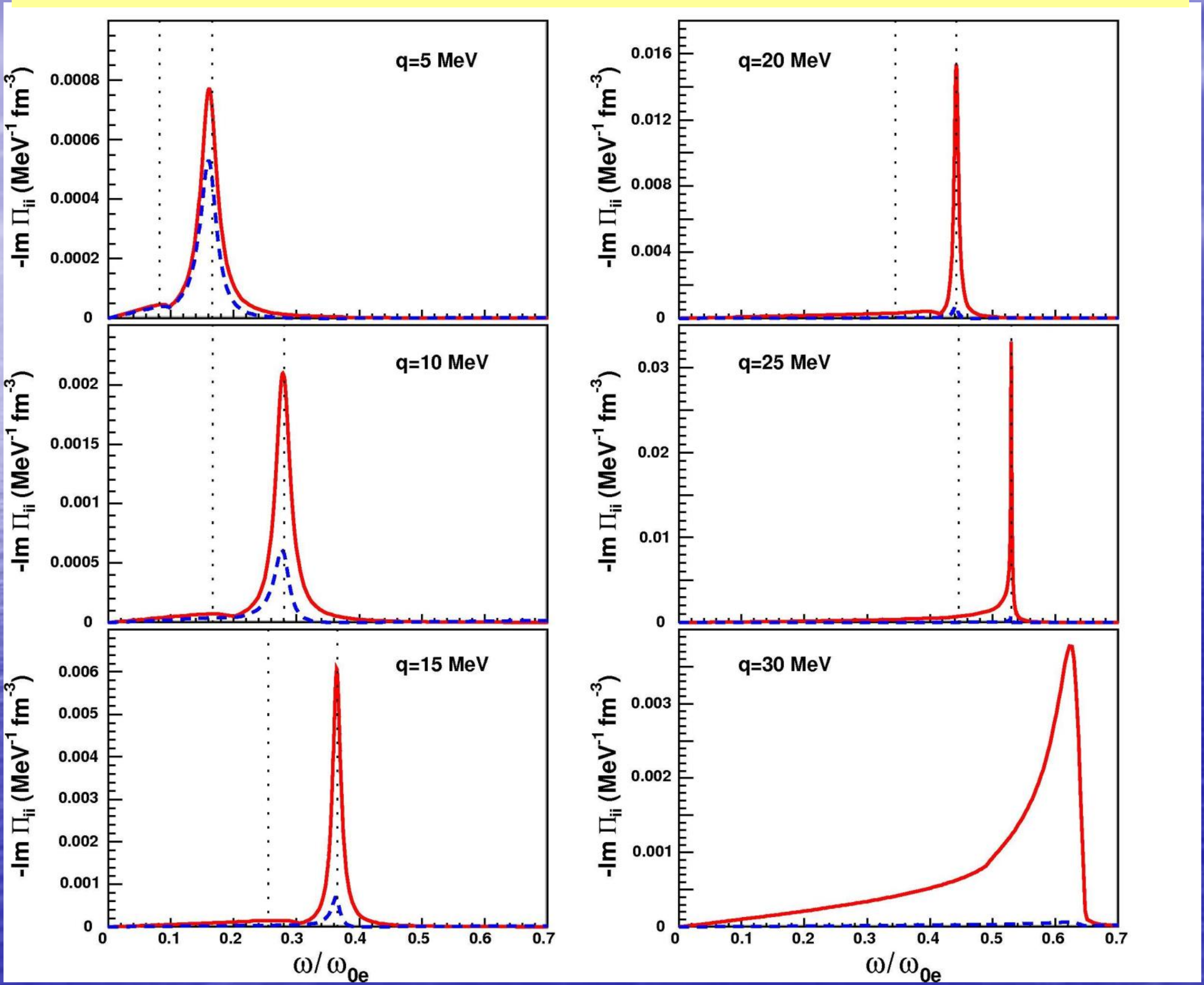
Plasmon mode



With screening

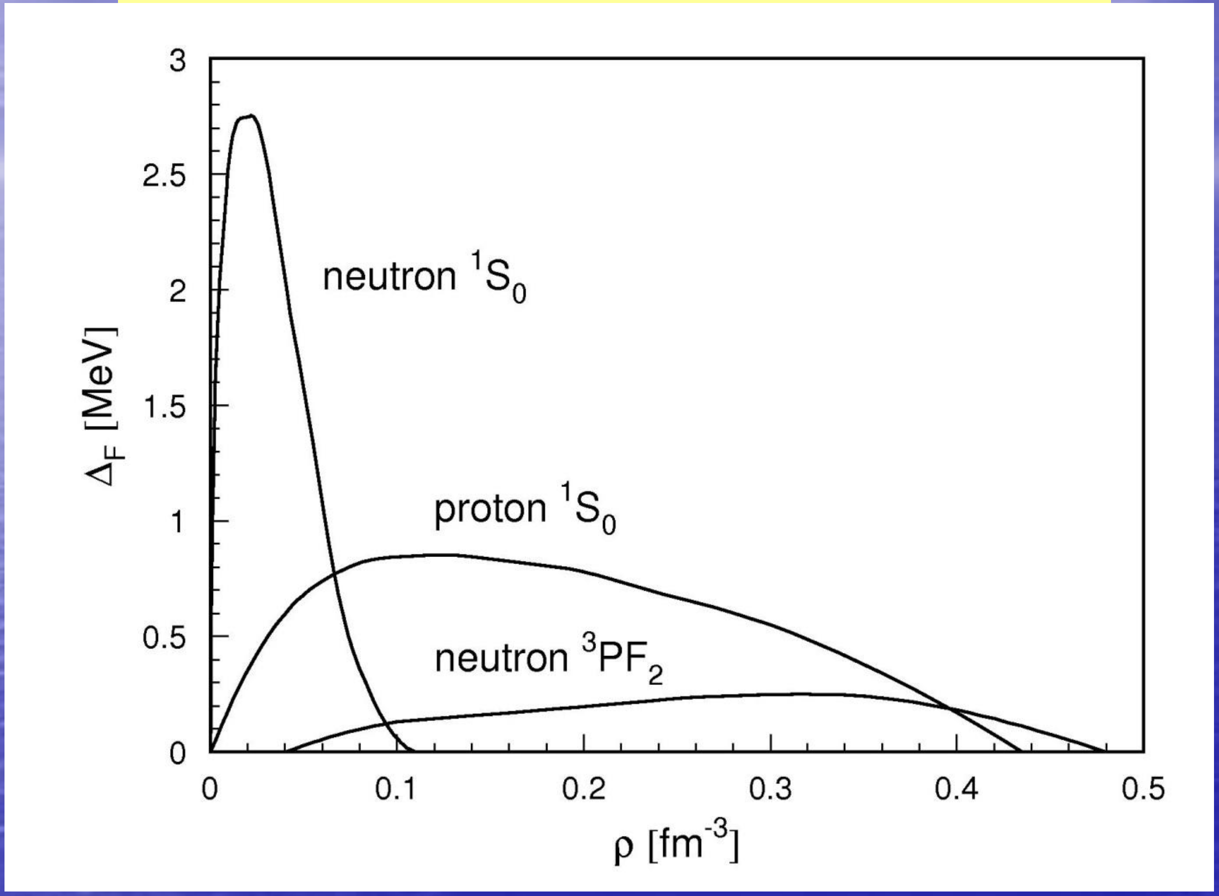
Sound mode

Proton and electron spectral functions. Normal system



M.B. and C. Ducoin , PRC79, 035901 (2009)

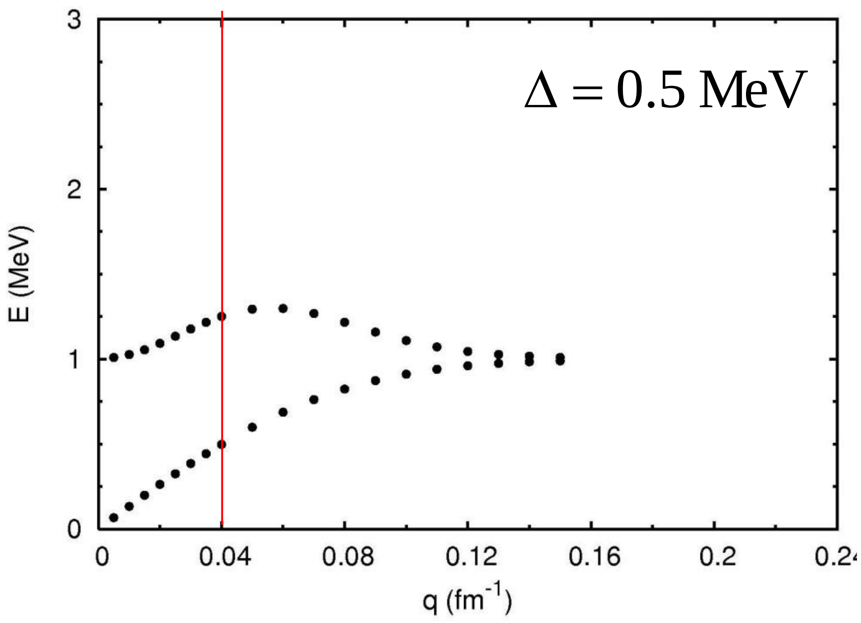
Overview of superfluid gaps in homogeneous matter



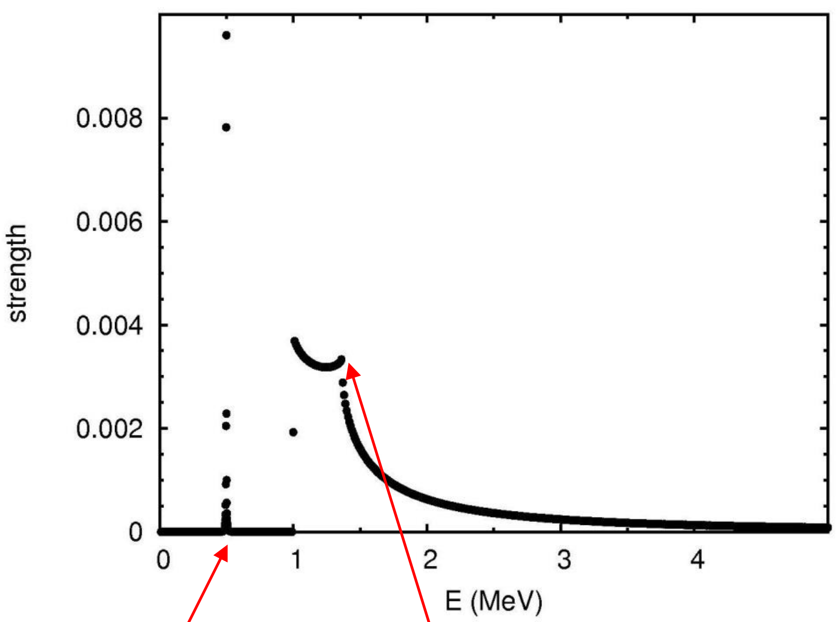
Since the gaps are largely unknown, they will be treated as parameters

Pairing interaction only

Spectrum



Strength function



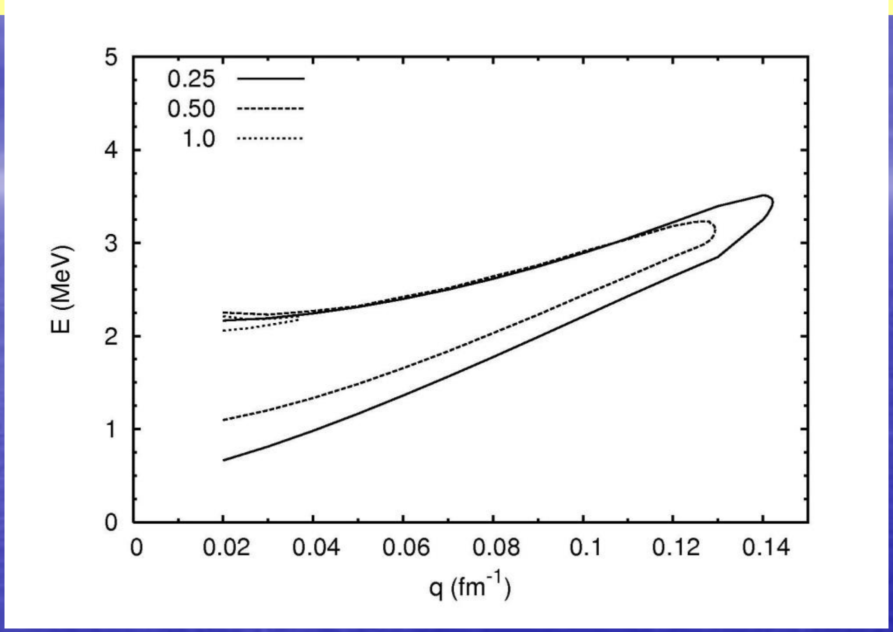
Goldstone mode

$s_G \approx v_F / \sqrt{3}$

Pair-breaking mode

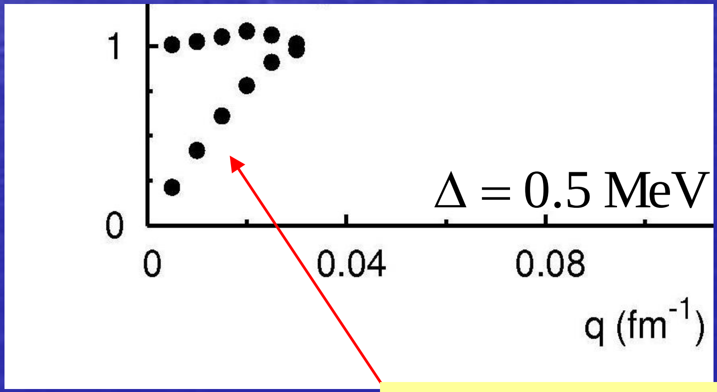
Including the Coulomb interaction

Death and resurrection of the Goldstone mode



Static electrons

Proton plasmons



Including electrons

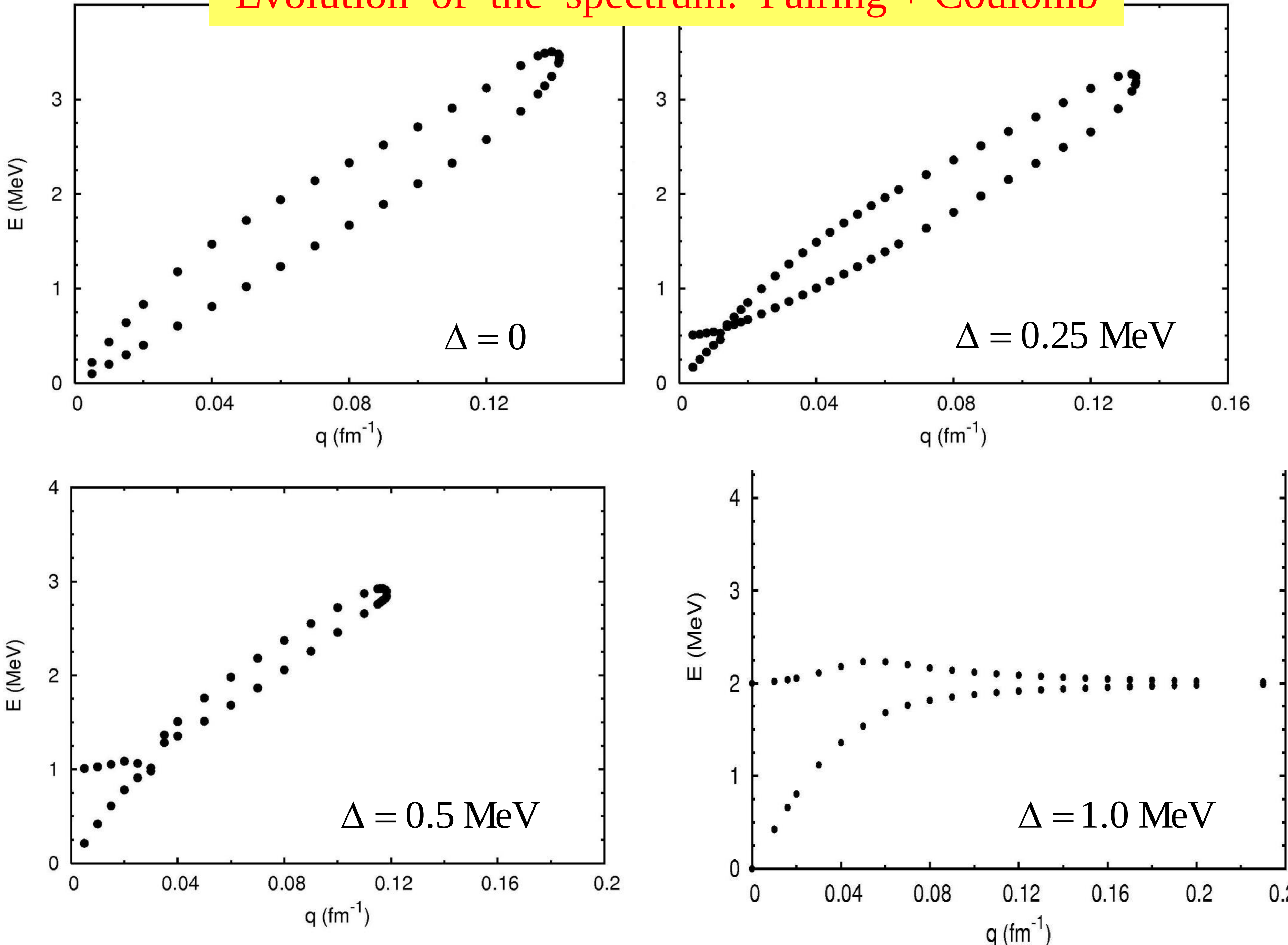
"Pseudo-Goldstone" mode

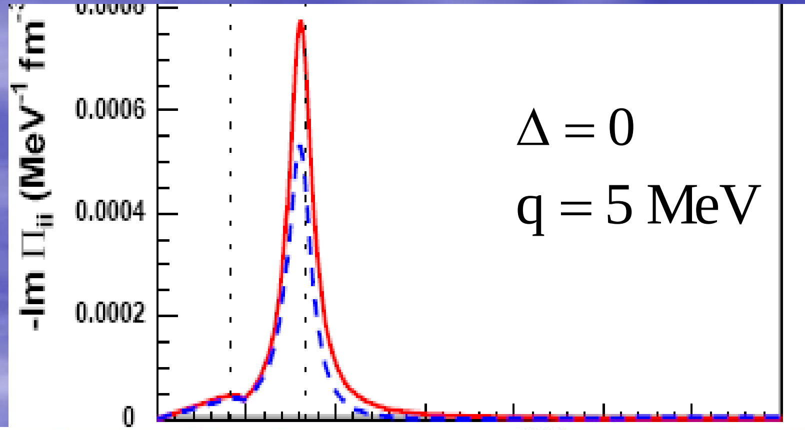
$$\gamma = \Delta / E_F$$

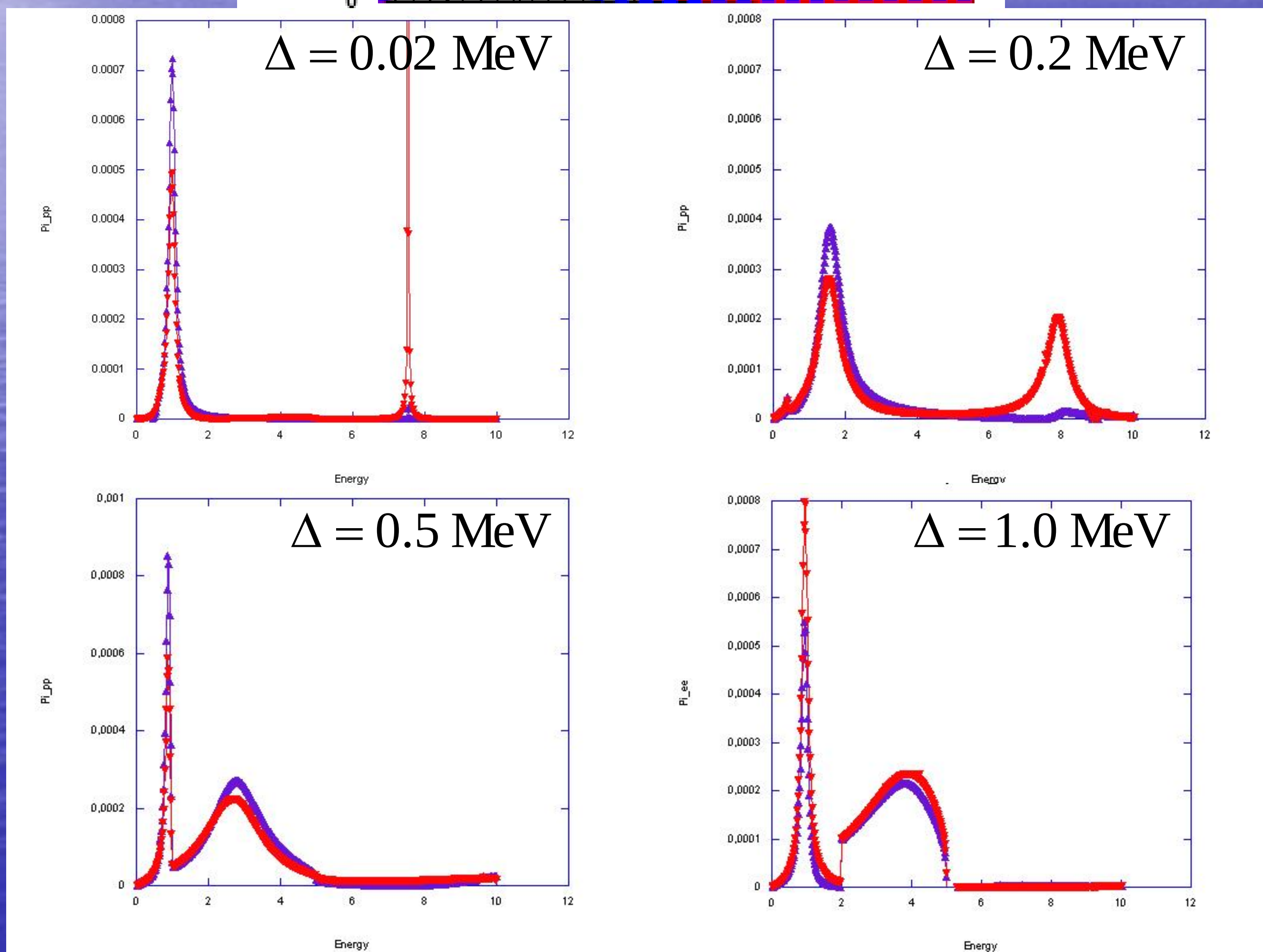
$$v_{PG}^2 = v_G^2 \left[1 + \frac{N_p}{N_e} (1 - \frac{\gamma^2}{4}) \right]$$

$$v_{PG} \approx 3\, v_G$$

Evolution of the spectrum. Pairing + Coulomb

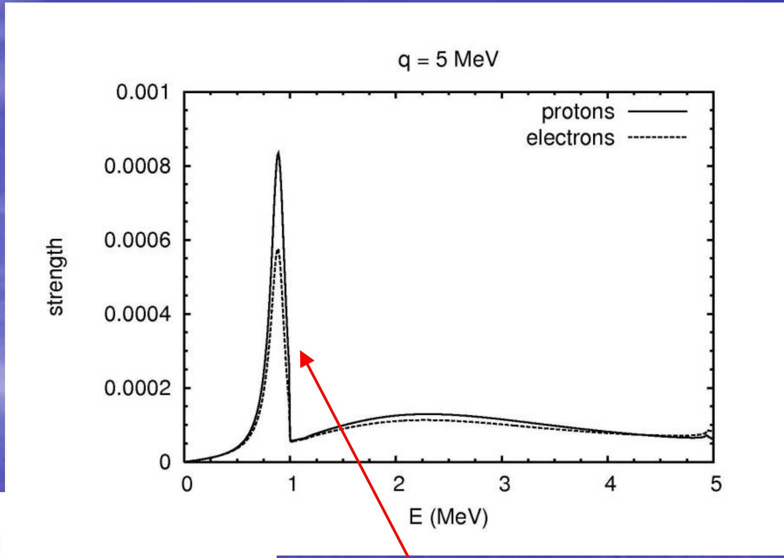


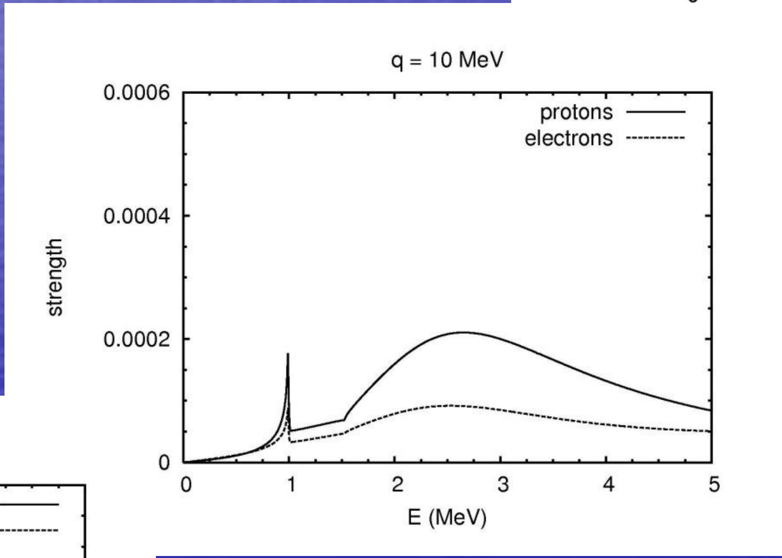

$\Delta = 0$
$q = 5$ MeV
-Im Π_{ii} (MeV^{-1} fm^{-3})
0.0006
0.0004
0.0002
0

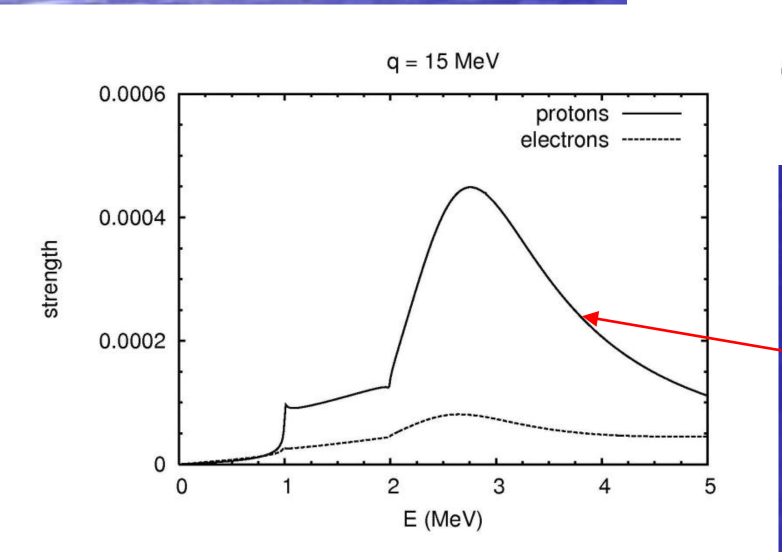

$\Delta = 0.02$ MeV
$\Delta = 0.2$ MeV
$\Delta = 0.5$ MeV
$\Delta = 1.0$ MeV
Pi_pp
Pi_ee
Energy

From the pseudo-Goldstone
to
the sound mode

$\Delta = 0.5$ MeV



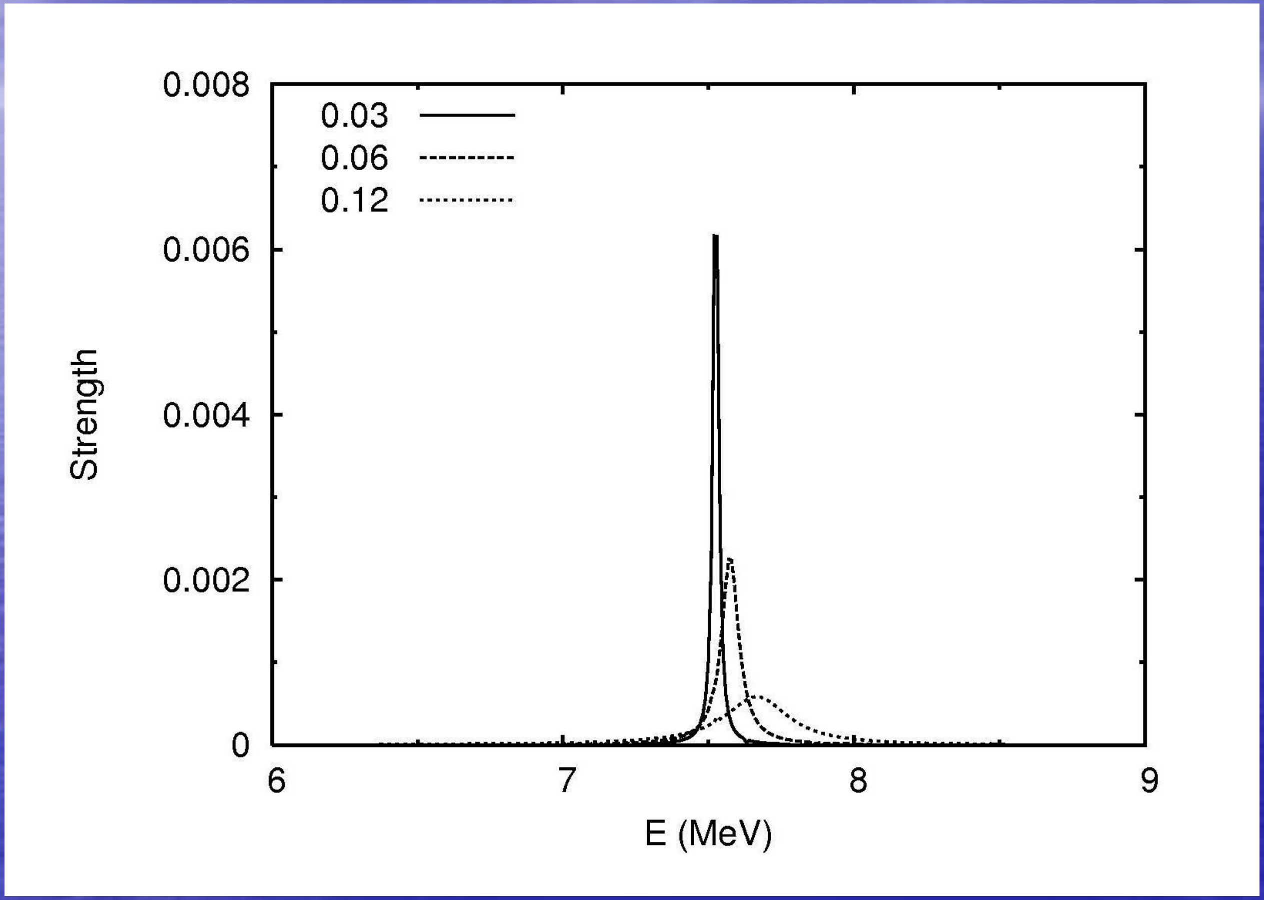




Pseudo-
Goldstone

Sound mode

The electron plasmon damping



Including the nuclear interaction and neutrons in the normal phase

$$\begin{pmatrix} 1-X_+^{pp}U_{\rm pair} & -2X_{GF}^{-}v_{pp} & 2X_{GF}^{-}v_c & -2X_{GF}^{-}v_{pn} \\ X_{GF}^{-}U_{\rm pair} & 1-2X_-^{ph}v_{pp} & 2X^{ph}v_c & -2X^{ph}v_{pn} \\ 0 & 2X^e v_c & 1-2X^e v_c & 0 \\ 0 & 2X^n v_{np} & 0 & 1-2X^n v_{nn} \end{pmatrix} \begin{pmatrix} \Pi_S^{(+)} \\ \Pi_S^{(ph)} \\ \Pi_S^{(ee)} \\ \Pi_S^{(nn)} \end{pmatrix} = \begin{pmatrix} \Pi_{0,S}^{(+)} \\ \Pi_{0,S}^{(ph)} \\ \Pi_{0,S}^{(ee)} \\ \Pi_{0,S}^{(nn)} \end{pmatrix}$$

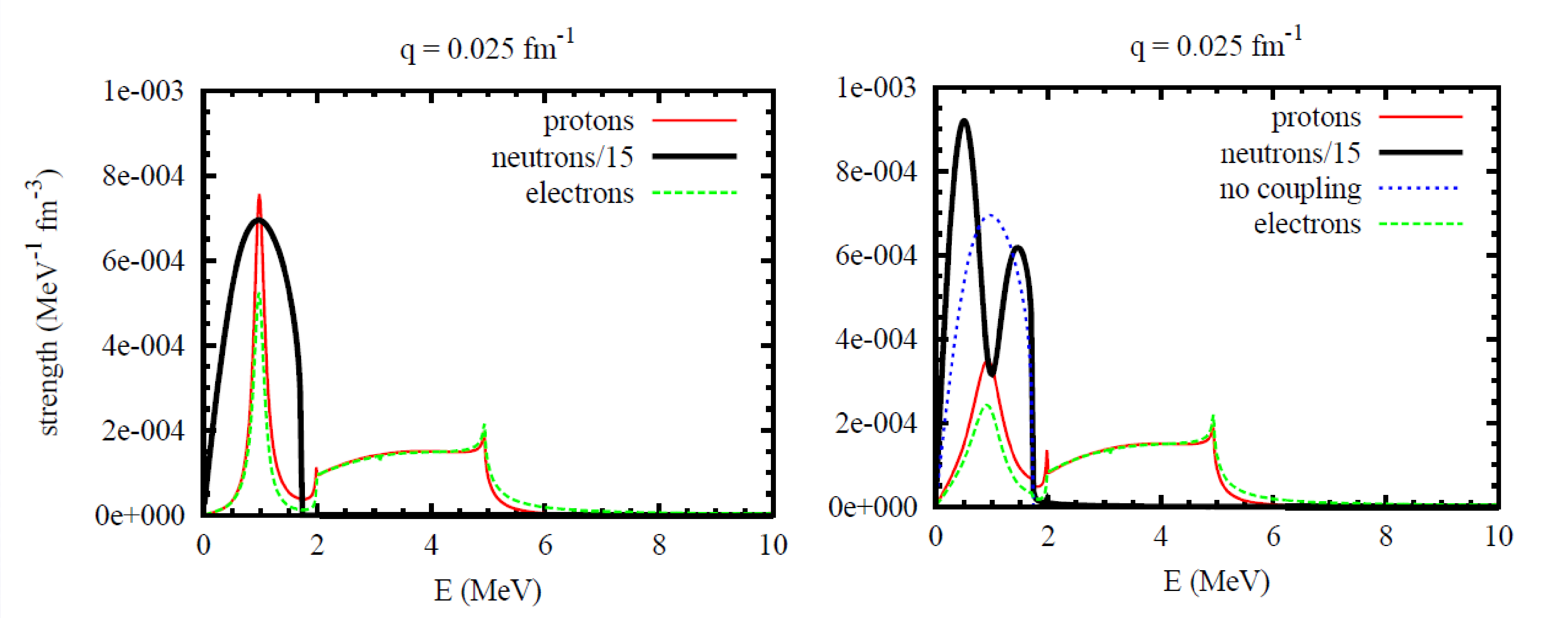
Nuclear interaction from BHF as Skyrme-like functional

$$v_{\rm res}^{ij} = \left(\frac{\delta U_i}{\delta \rho_j}(k_{{\rm F}i}, \rho_n, \rho_p) \right)_{k,\rho_i = {\rm cst}} .$$

monopolar approximation

A comparison

$$\Delta = 1\,MeV$$



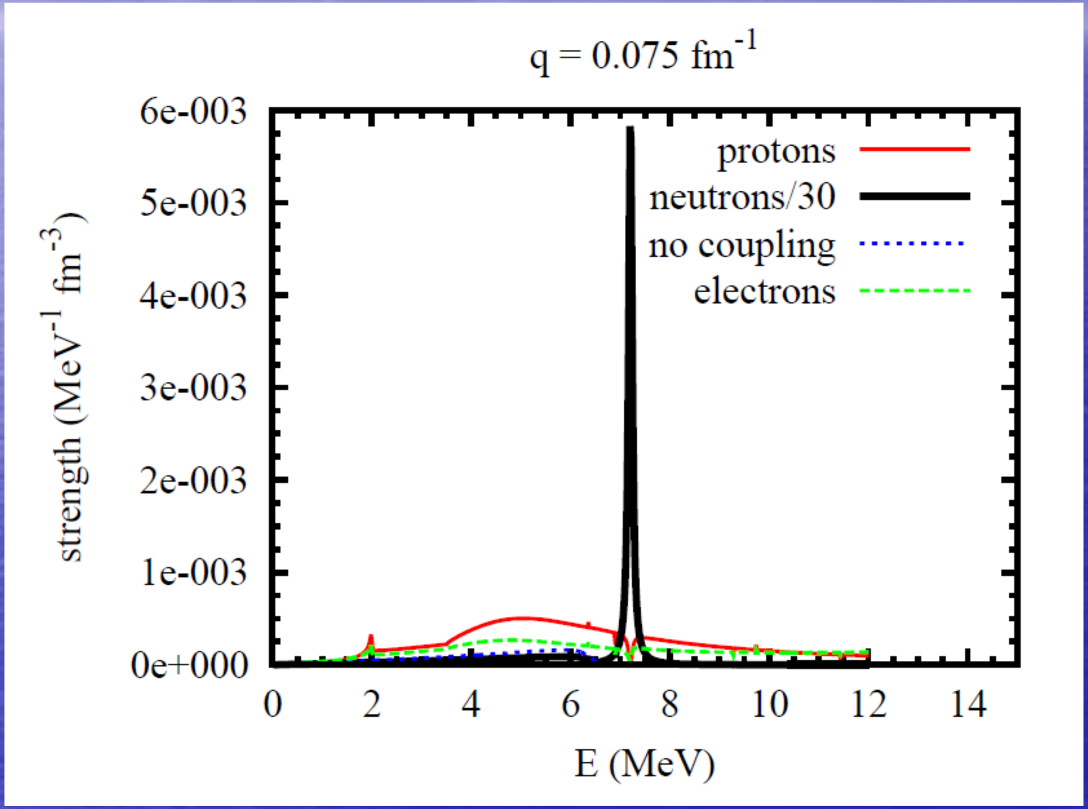
No np coupling

With np coupling

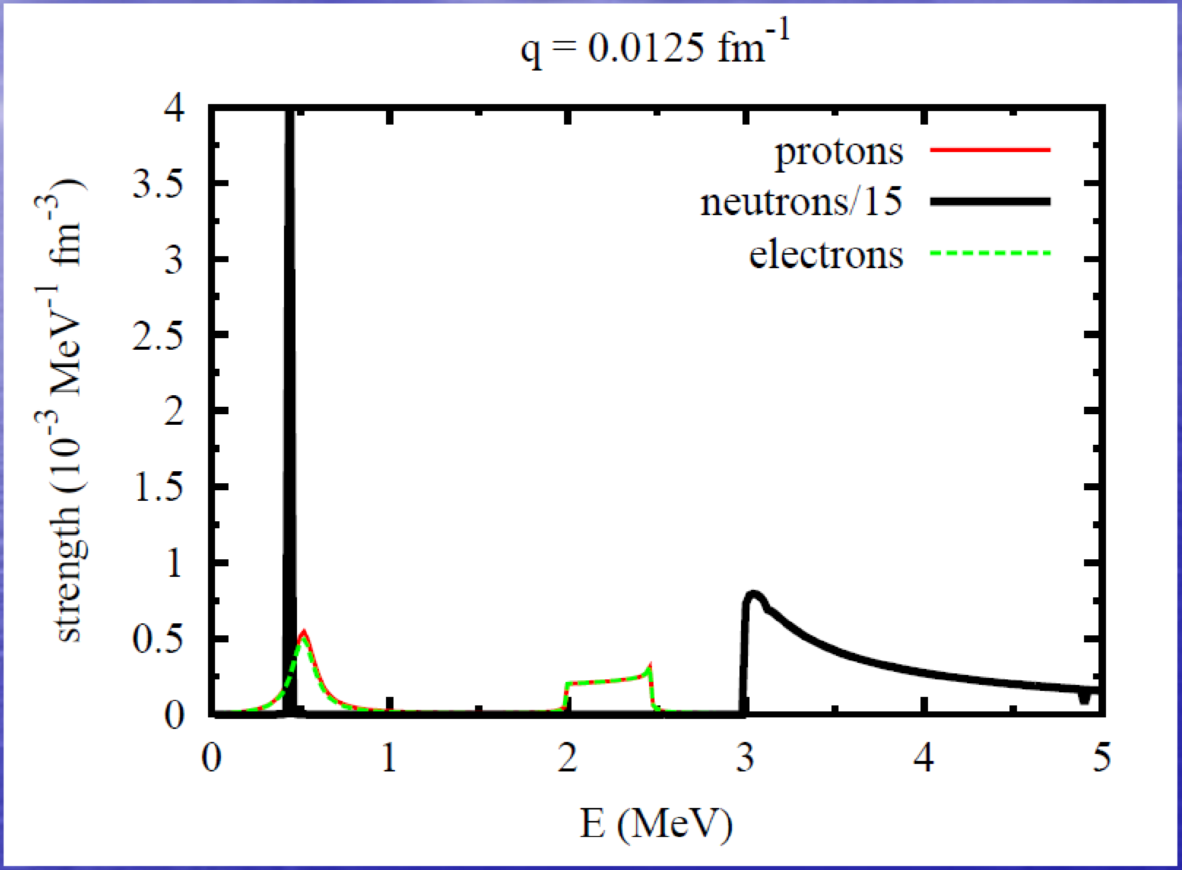
Notice : no sound mode for the neutron gas
(attractive nn particle-hole effective interaction)

Two times saturation density

$\Delta = 1\, MeV$

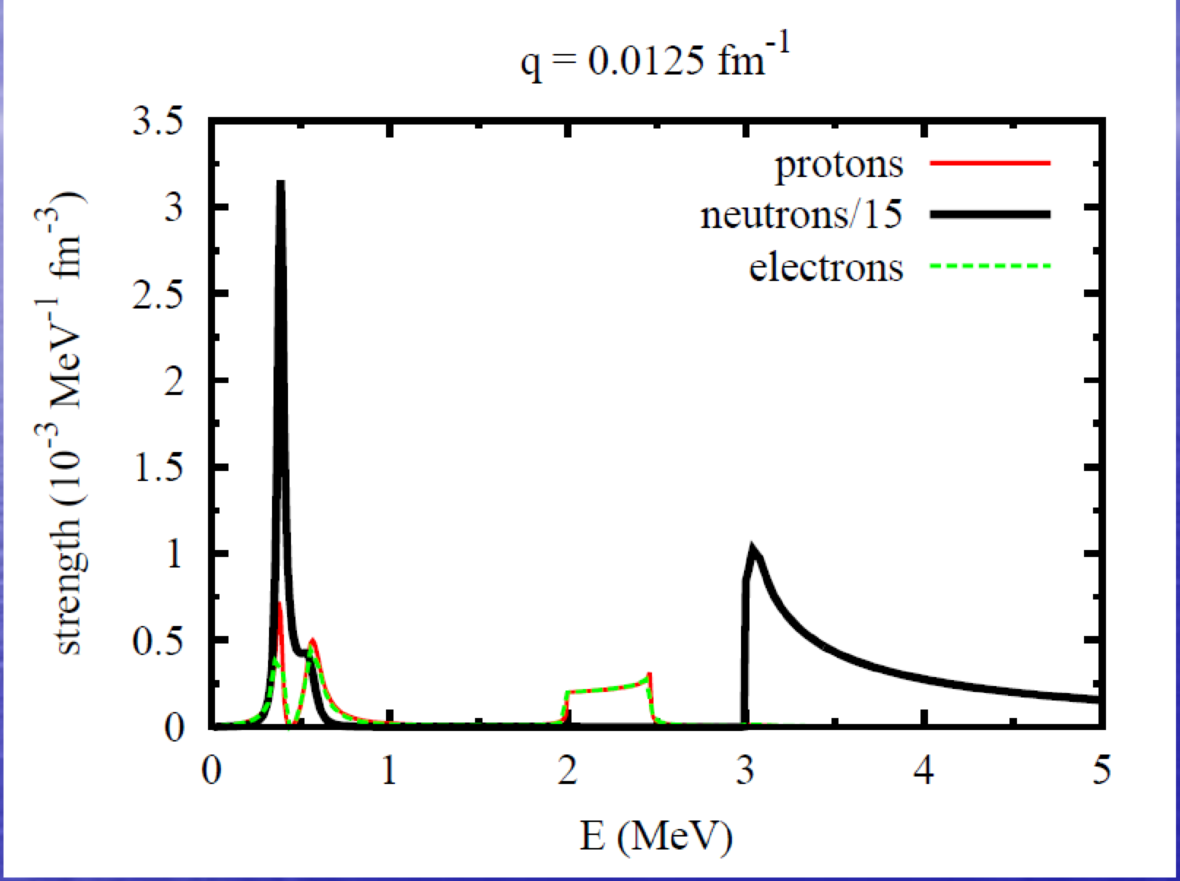


Both proton and neutron superfluid
(work in progress)



Proton gap = 1 Mev, neutron gap = 1.5 MeV
Saturation density. No pn interaction

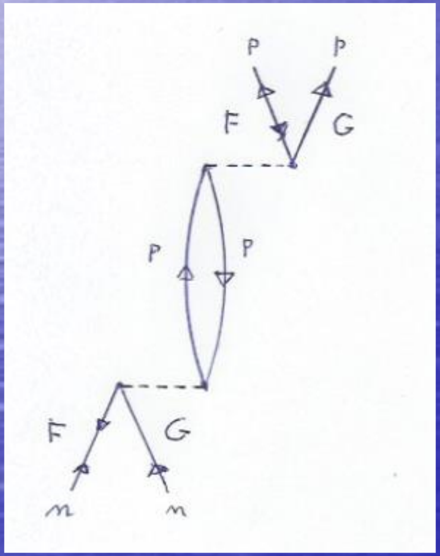
Introducing proton-neutron coupling



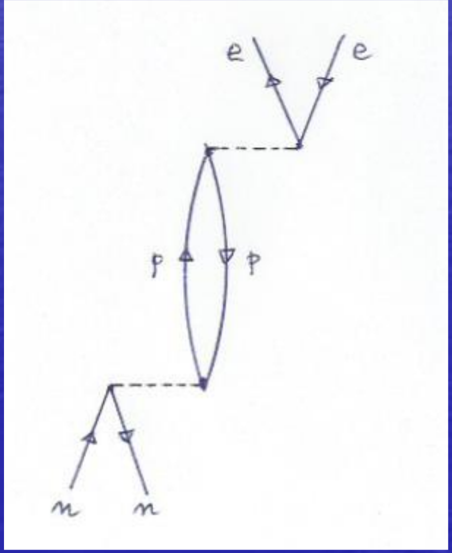
Proton gap = 1 Mev, neutron gap = 1.5 MeV
Saturation density

Introducing proton-neutron coupling

Neutron-proton pair vibrations

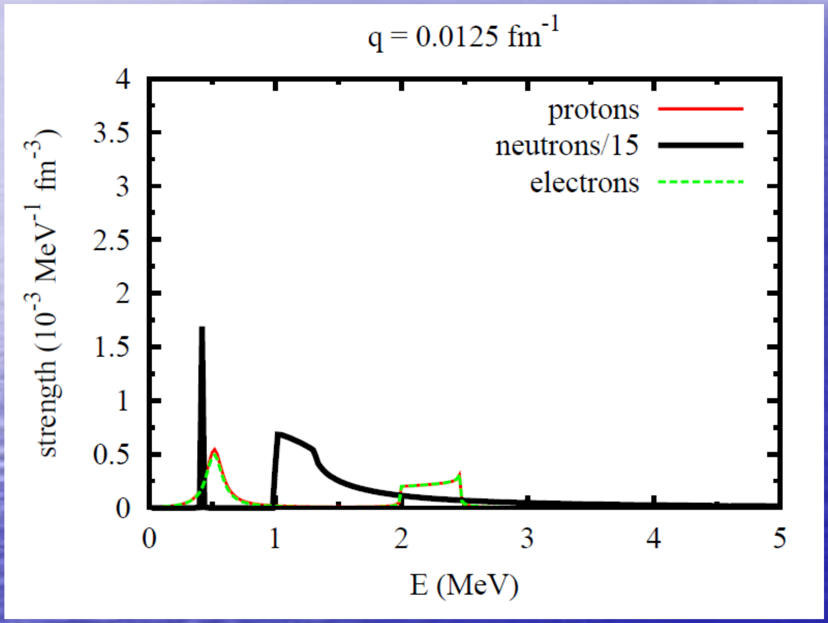


Neutron-electron coupling

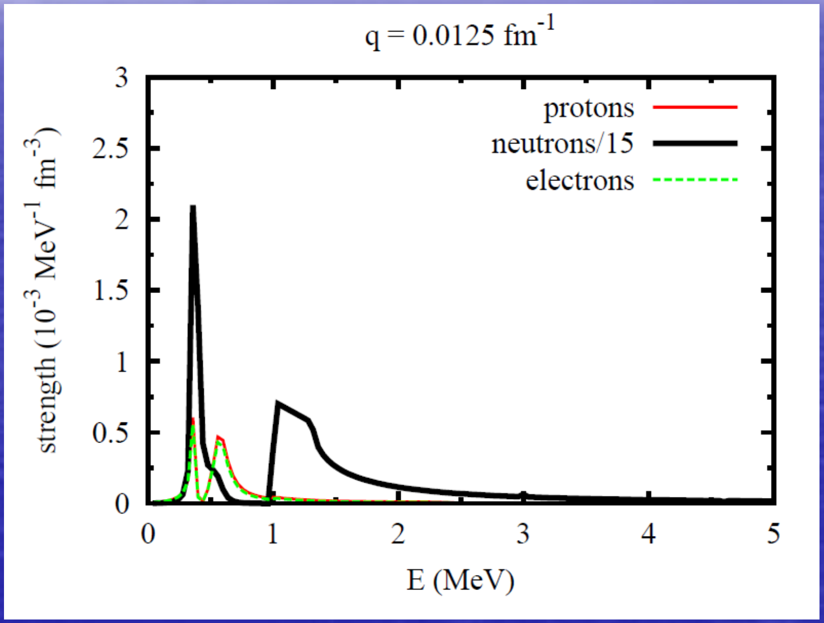


Smaller neutron gap

No p-n interaction



With p-n interaction

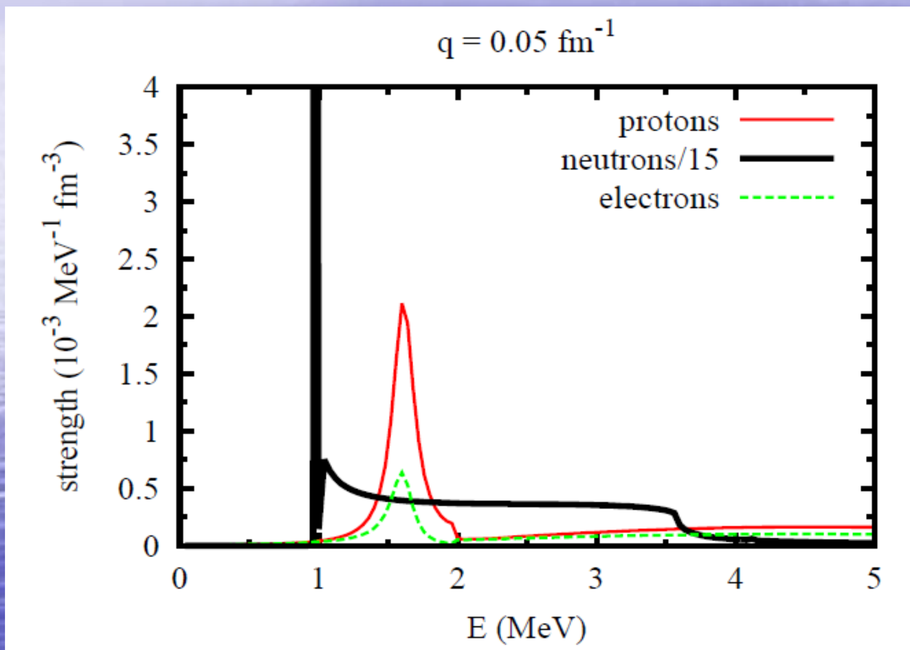


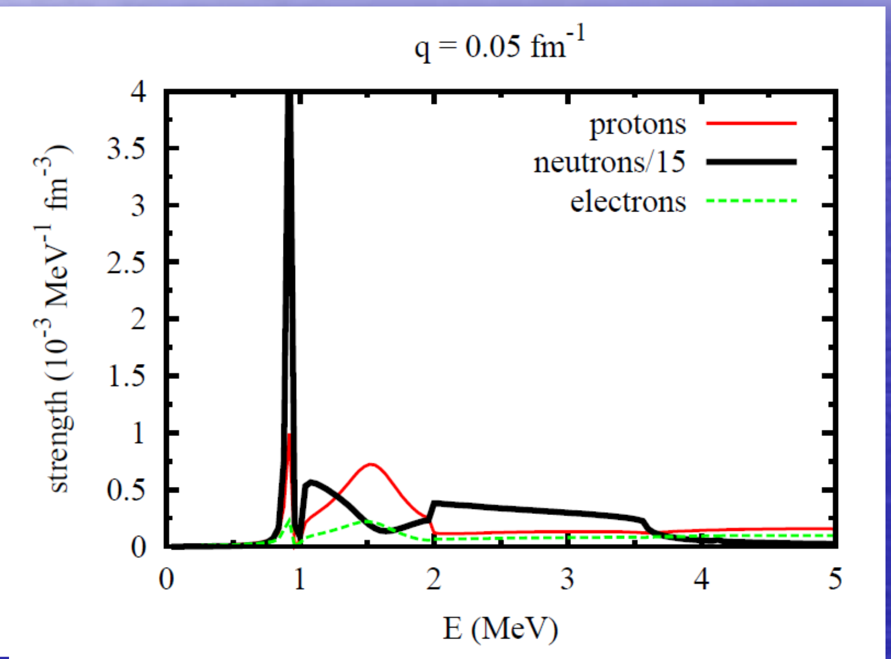
Proton gap = 1.0 Mev, neutron gap = 0.5 MeV
Saturation density

Higher momentum

No p-n interaction

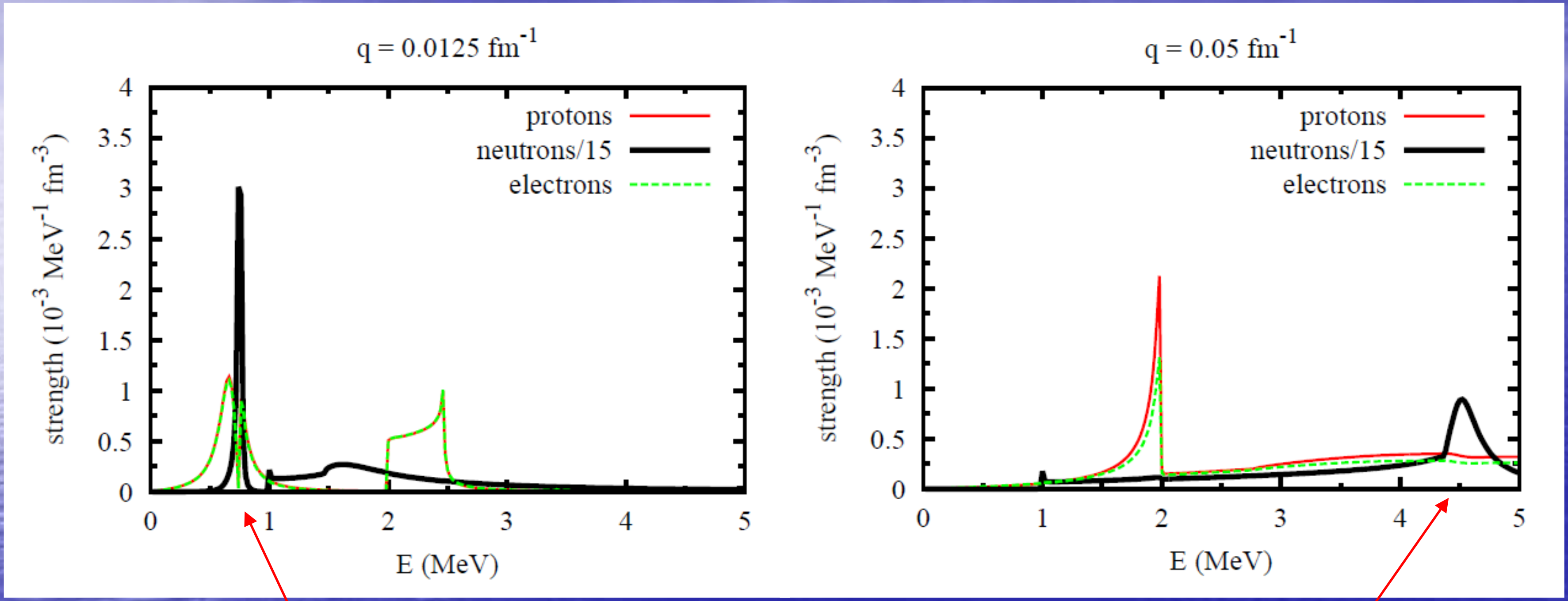
With p-n interaction





Proton gap = 1.0 Mev, neutron gap = 0.5 MeV
Saturation density

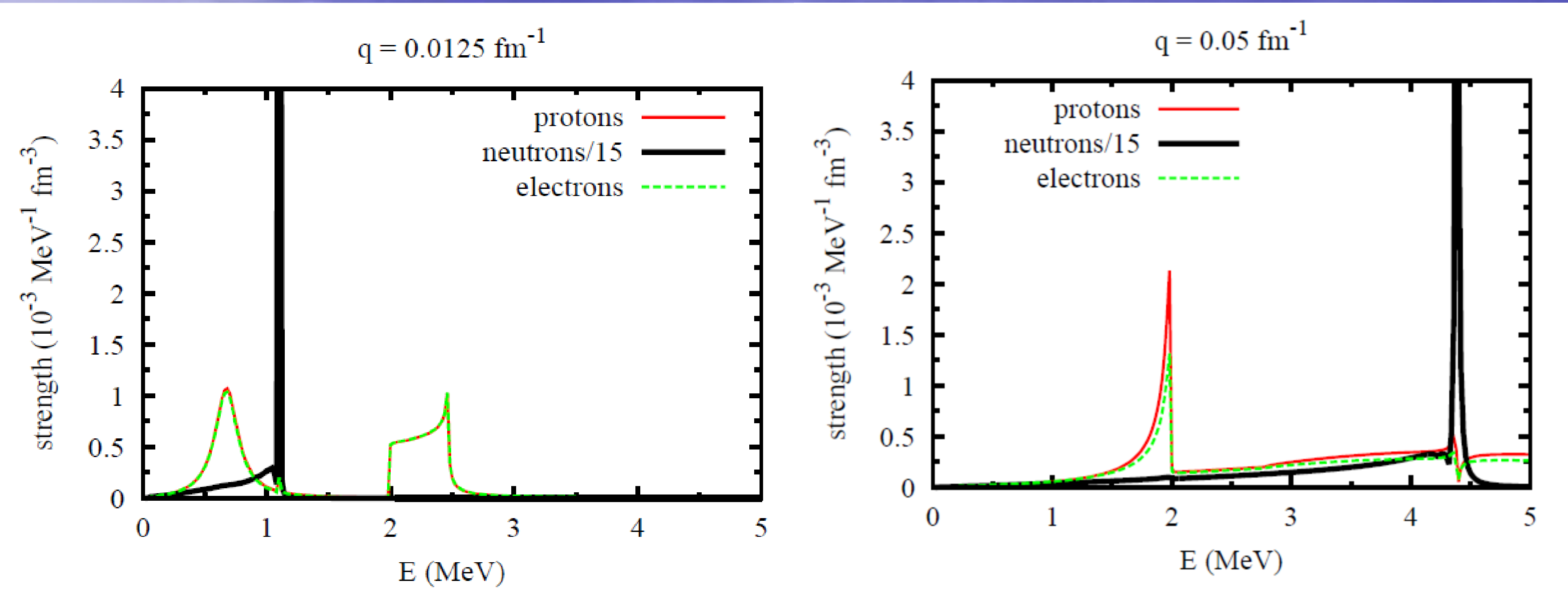
At twice saturation density



Neutron pseudo-Goldstone

Neutron sound mode

At twice saturation density



No neutron superfluidity. Sharp neutron sound mode

CONCLUSIONS

. The electron screening suppresses the proton plasmon mode which is converted into a sound mode above $2\triangle$

. The proton component has relevan effect on the spectral functions.

. At increasing value of the superfluid proton gap the electron plasmon is rapidily suppressed.

. Each superfluid component is characterized by a pseudo-Goldstone mode below $2\triangle$ and a pair-breaking mode above $2\triangle$, which merges into a sound mode at increasing momentum.

. The possible proton pseudo-Goldstone mode is damped by the coulomb coupling with the electrons.

. If one includes the neutron-proton interaction the pseudo-Goldstone mode becomes a neutron-proton mode and it is damped.

. The overall spectral function is distorted by the neutron-proton interaction.

. If the neutrons are in the normal phase, the sound mode can undergo Landau damping, depending on the interaction at the different densities

OUTLOOK

. Extend the analysis to the 3P2 superfluidity.
(Bedaque et al. Phys. Rev. C92, 035809 (2015))

. Extend the analysis to the vector channel.

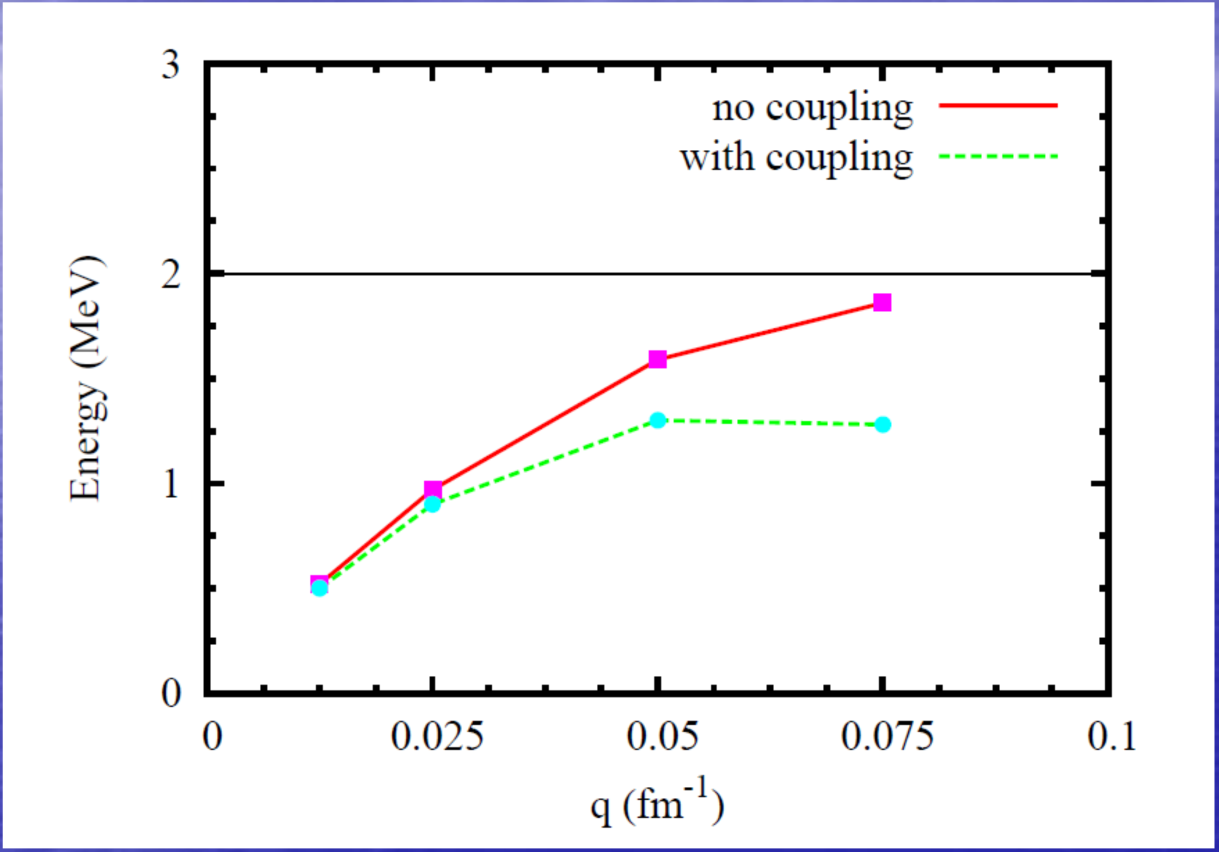
. Relevance of the phonons on different phenomena,
e.g. cooling.

. Relevance of the phonon damping on the different
physical processes.

. Lepton-lepton collisions mediated by proton phonons.
(Shternin, PRD 98, 063015 (2018))

. Establish the scenario of Neutron Star matter superfludity
(where proton and neutron superfluidity are present ?)

Position of the centroid of the peak in the proton spectral function



$\Delta = 1\,MeV$