Cooling of neutron stars within ''nuclear medium cooling scenario''

Yerevan 2017

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Plan

- Neutrino reaction rates in normal nuclear matter, in superfluid nuclear matter.

"Standard" scenario.
"Minimal" cooling scenario.
"Nuclear medium cooling" scenario.

Cooling of neutron stars

After passing a minute after formation, during 10^5 years a neutron star cools down by neutrino emission, then by photon emission from the surface

$$\lambda_\nu \gg R \simeq 10\mathrm{km}$$

White-body radiation problem (at low $T<T_{\mathrm{opac}}$ ~1-few MeV) -- direct reactions

Neutrinos bring information straight from the dense interior

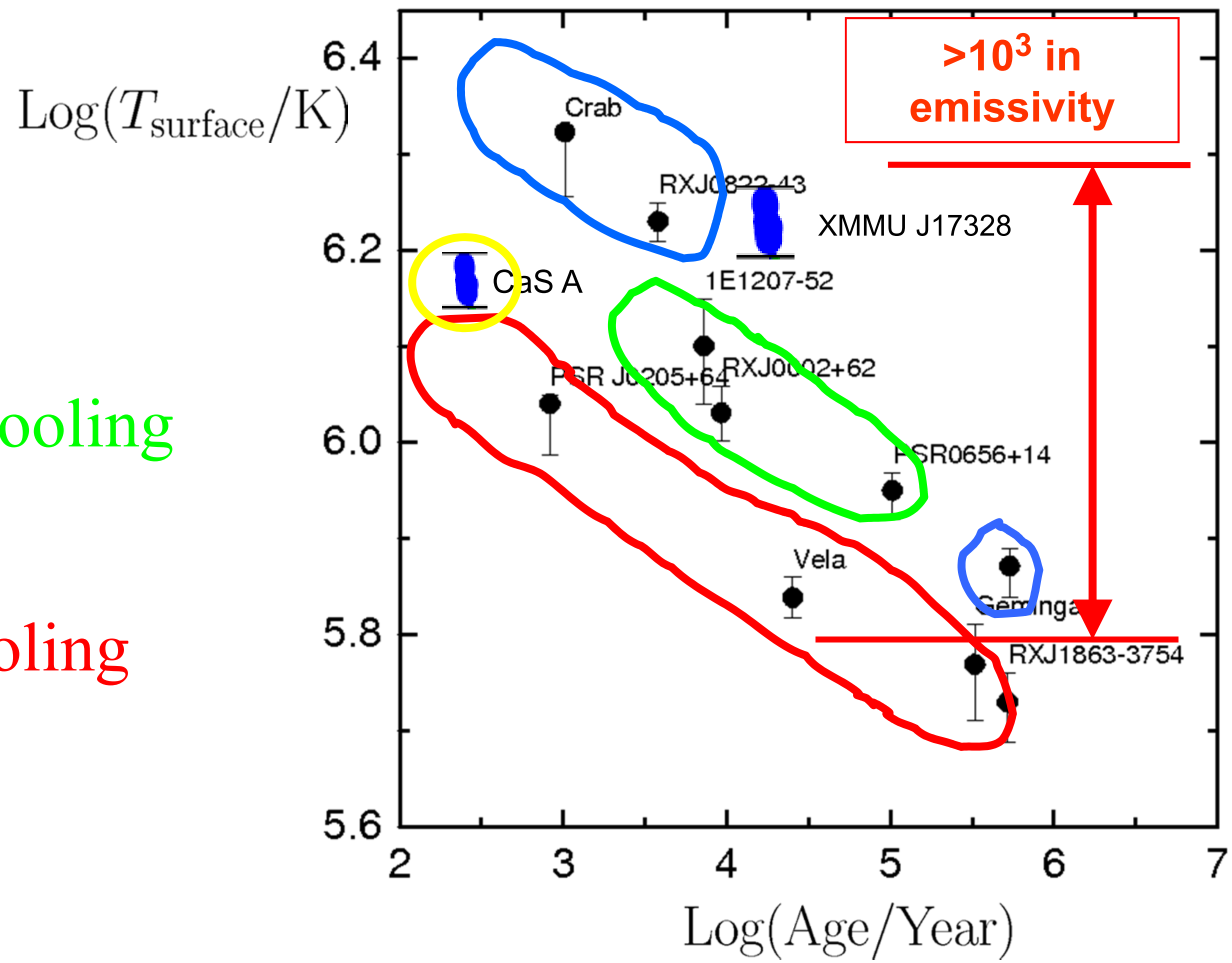
NS cooling data

3 groups+Cas A:

slow cooling

intermediate cooling

rapid cooling



How to describe all groups within one cooling scenario?

Heat transport and neutrino radiation

For $T<T_{opac}\sim$ MeV neutron star is transparent for neutrino

$$\frac{\partial}{\partial t}\left(T\mathrm{e}^{\phi}\right) = -\frac{\epsilon_\nu}{c_V}\mathrm{e}^{2\phi} + \frac{\mathrm{e}^{\lambda}}{c_V r^2}\frac{\partial}{\partial r}\left(\kappa\, r^2 \mathrm{e}^{\phi} +\lambda \frac{\partial}{\partial r}\left(T\mathrm{e}^{\phi}\right)\right)$$

c_V - specific heat density,

ε_ν – neutrino emissivity,

Φ, λ – metric coefficients

κ- heat conductivity

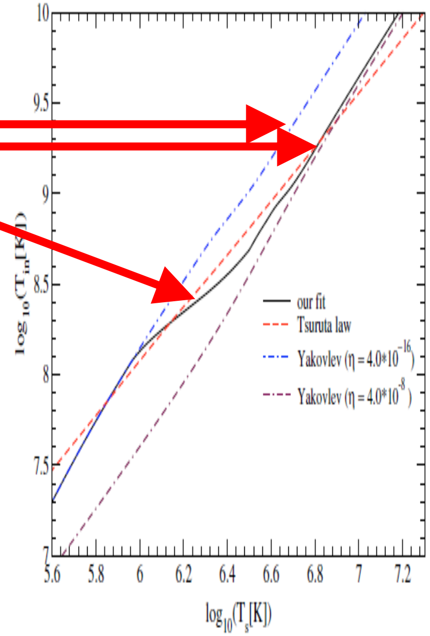
for t>300-500 yr -- isothermal stage

$$\boxed{C_V \frac{\mathrm{d}T}{\mathrm{d}t} = -L}$$

C_V – specific heat,
L-luminosity

Yakovlev et al., Page et al.

Blaschke,Grigorian, D.V.



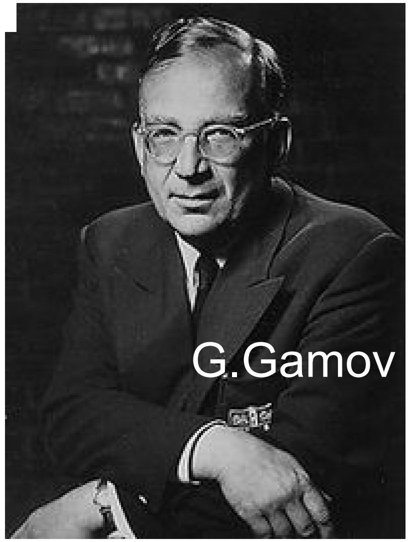
Within an EoS:

Strategy: Emissivity $\epsilon(T_{in})$, specific heat C_V, thermal cond. κ from calcul., $\rightarrow T_{in}(t)$ from transport calcul., $T_s = f(T_{in})$ from calcul., $\rightarrow T_s(t) \rightarrow$ compare with $T_s(t)$ known from observations.

Direct reactions in standard scenario

- **1965** S. Tsuruta, A. Cameron, and J. Bahcall, R. Wolf: First scenario for NS cooling.

Cooling: crust is light and interior is massive



→ most important are reactions in dense interior

(where baryon density $n \gtrsim n_0$ n_0 is the nuclear saturation density)

Phase-space separation

one-nucleon reactions: $n \to p + e + \bar{\nu}$ direct Urca (DU)

URCA "Unrecordable Cooling Agent" (by Gamov 1941)

Casino da Urca in Brazil-waist of money;
pilferer, thief in Odessa

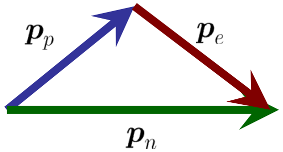
two-nucleon reactions: $n + n \to n + p + e + \bar{\nu}$ modified Urca (MU)

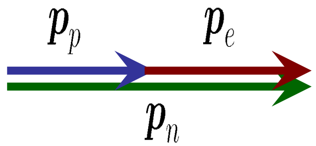
$n + n \to n + n + \nu + \bar{\nu}$ nucleon bremsstrahlung (NB)
(less important)

NS cooling

- **1965** S. Tsuruta, A. Cameron, and J. Bahcall, R. Wolf: First scenario for NS cooling.

DU process $$n \longrightarrow p + e + \bar{\nu}$$





momentum conservation: $p_{Fn} \geq 2p_{Fp}$.

$$n_p = n_e \,, \quad p_{F,p} = q_{F,e}$$

For the gas of free quasiparticles

$$\mu_n = E_{F,n} \simeq \frac{p_{F,n}^2}{2m_N^*} \,, \quad \mu_p = E_{F,p} \simeq \frac{p_{F,p}^2}{2m_N^*} \,, \quad \mu_e = E_{F,e} \simeq q_{F,e}$$

$n_{c,DU} \approx 30\, n_0$ ➡ **one concluded that DU process is forbidden in NS**

Standard scenario

Tsuruta, S. 1979, Phys. Rep., 56

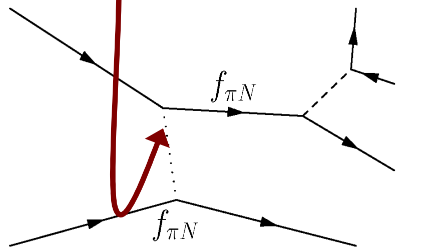
Shapiro, S., & Teukolsky, S. A. 1983, Black Holes, White Dwarfs and Neutron Stars: The Physics of Compact Objects (New York: Wiley), Chap. 11

Main permitted process is MU: $n + n \rightarrow n + p + e + \bar{\nu}$

1979 Friman and Maxwell computed MU in FOPE model

$$D_\pi^{-1} = \omega^2 - m_\pi^2 - k^2$$

+ simple T_s –T_{in} relation (Tsuruta law $T_s^{Tsur} = (10\ T_{in})^{2/3}$)

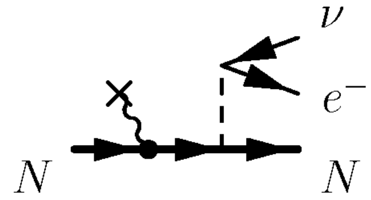


➡ scenario for slow cooling of NS

Standard + exotics (pi-cond.) scenario

1977 Maxwell, O., Brown, G. E., Campbell, D. K., Dashen, R. F., Manassah, J. T. 1977, ApJ, 216

added process on pion condensate



➡ **scenario for rapid cooling**

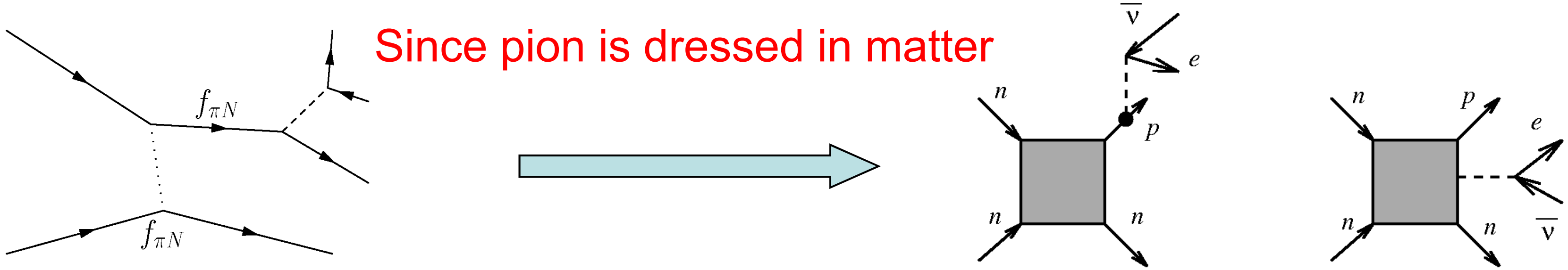
that time most of researches believed that all NS have the very same masses ≈1.4 M_{sol}

so, only slow coolers either rapid ones could be explained

Nuclear medium cooling

- D.V., A. V. Senatorov JETP Lett.1984, JETP 1986 found strong density (NS mass) dependence of emissivity of

$n + n \to n + p + e + \bar{\nu}$ process (called Medium MU process)

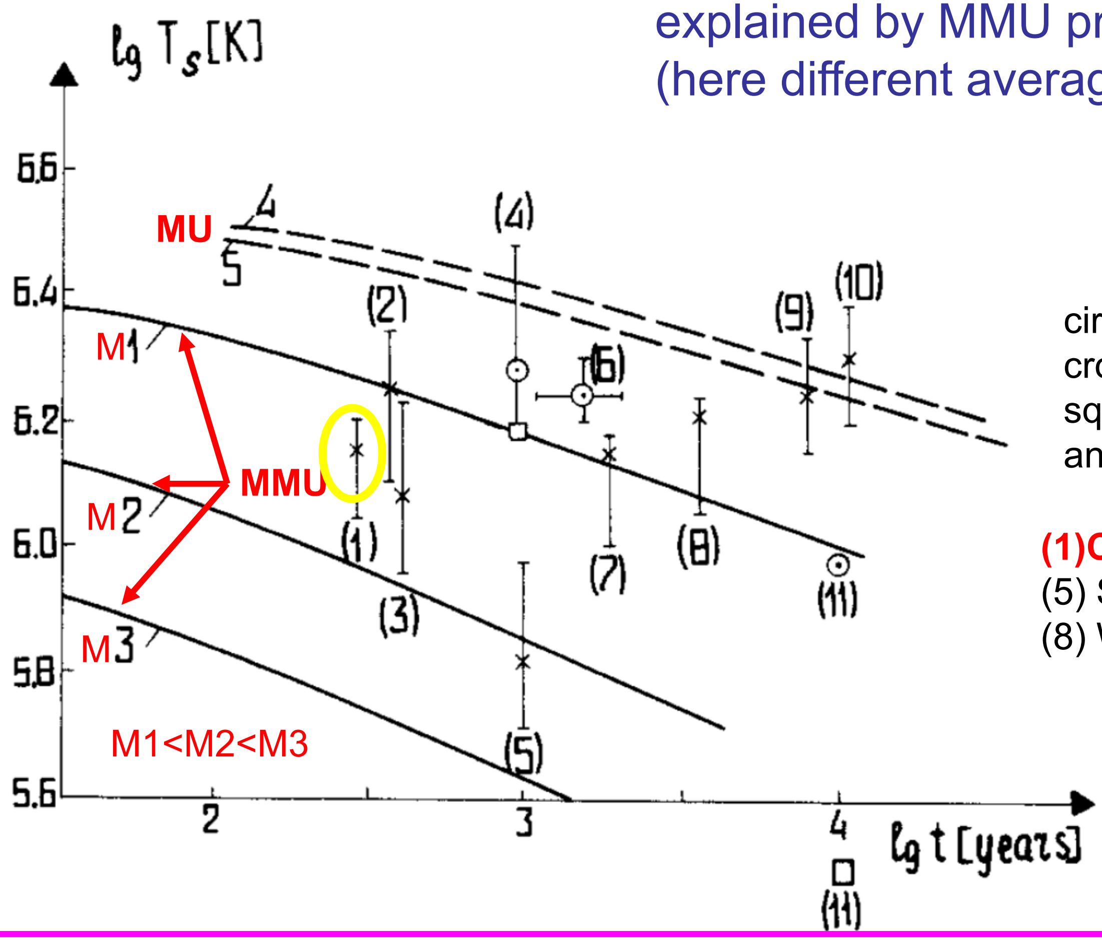


and suggested that NS (might be seen in soft X rays)

have essentially different masses.

Heavier NS cool down substantially faster!

D.V., Senatorov JETP **1986:** all the data (upper limits to T_s known to that time) were explained by MMU process assuming different masses (here different average densities) of NS



circles: observed sources (not temperatures!),
crosses: upper limits,
squares: T_s of Crab and Vela, adjusted from an analysis of their frequency glitches

(1)Cas A, (2) Kepler, (3) Tycho, (4) Crab, (5) SN 1006, (6) RCW 103, (7) RCW 86, (8) W28, (9) G350, 018, (10) G22, 7-02, (11) Vela

JETP 1986: If in the future central sources are discovered in supernova remnants with low values of T_s (see Fig. 6), then they could be associated with neutron stars having a denser internal region than other neutron stars with higher T_s

New data: masses are essentially different

Pulsar J1614-2230

$$\mathrm{M} = (1.97 \pm 0.04)\ \mathrm{M}_{\mathrm{sol}}$$

P.Demorest et al., Nature 467 (2010)

Measured Shapiro delay with high precision

Corrected as (1.928±0.017), by Fonseca et al. (2016)

Pulsar J0348-04232

$$\mathrm{M} = (2.01 \pm 0.04)\ \mathrm{M}_{\mathrm{sol}}$$

J. Antoniadis et al., Science (2013)

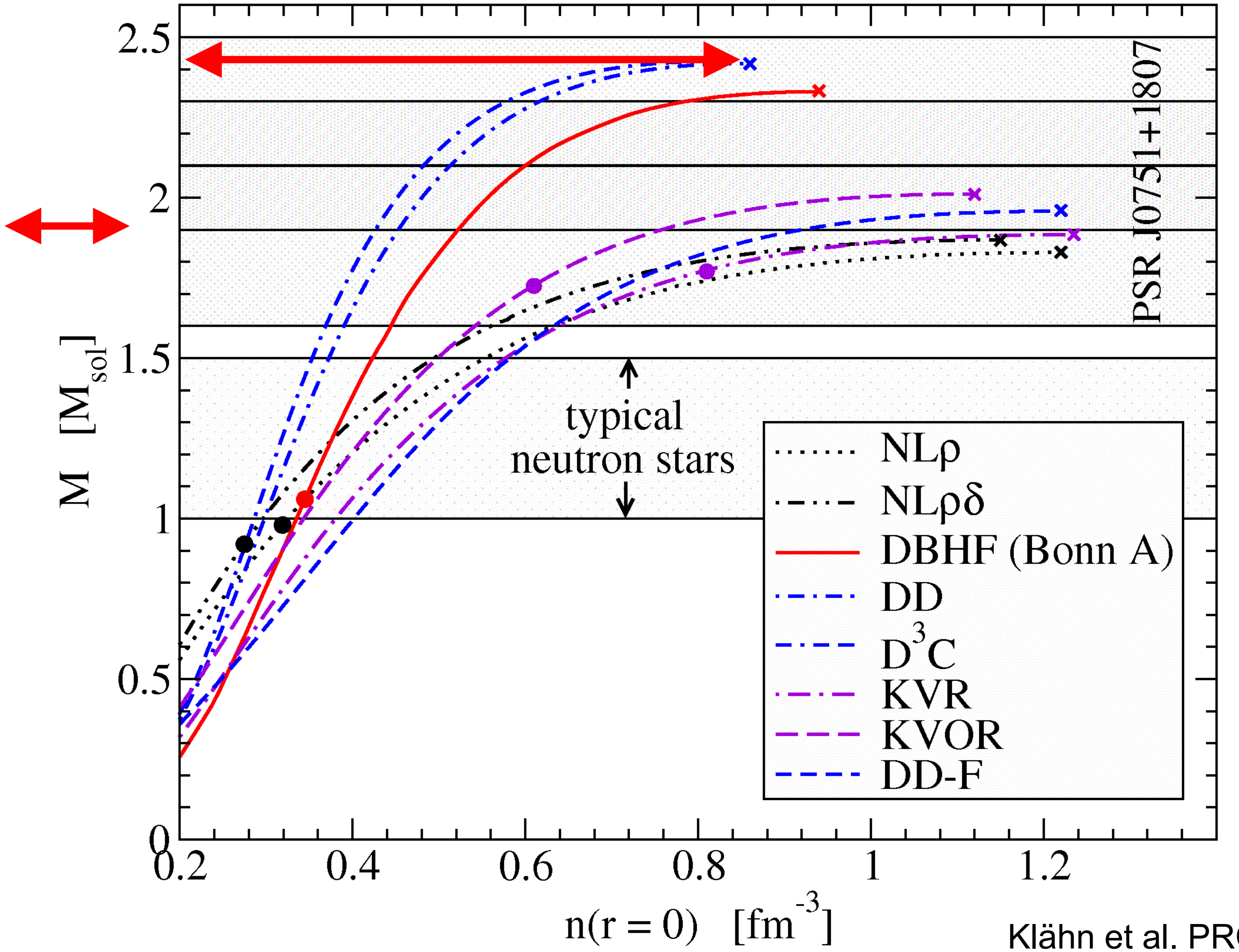
Highest well-known masses of NS

there are heavier, but far less precisely measured candidates)

$2.44^{+0.27}_{-0.27}\ M_\odot$ for 4U 1700-377,

Lightest NS PSR J1807-2500B: $M=1.2064 \pm 0.0020\ M_{sol}$

EoS: NS mass-central density diagram



Klähn et al. PRC 74, 035802 (2006)

If M>2.4 M_{sol} ( ) were observed, all these EoS would be invalid!

Central densities in various NS are different! Studying cooling of NSs we may test density dependences of EoS and NN interaction

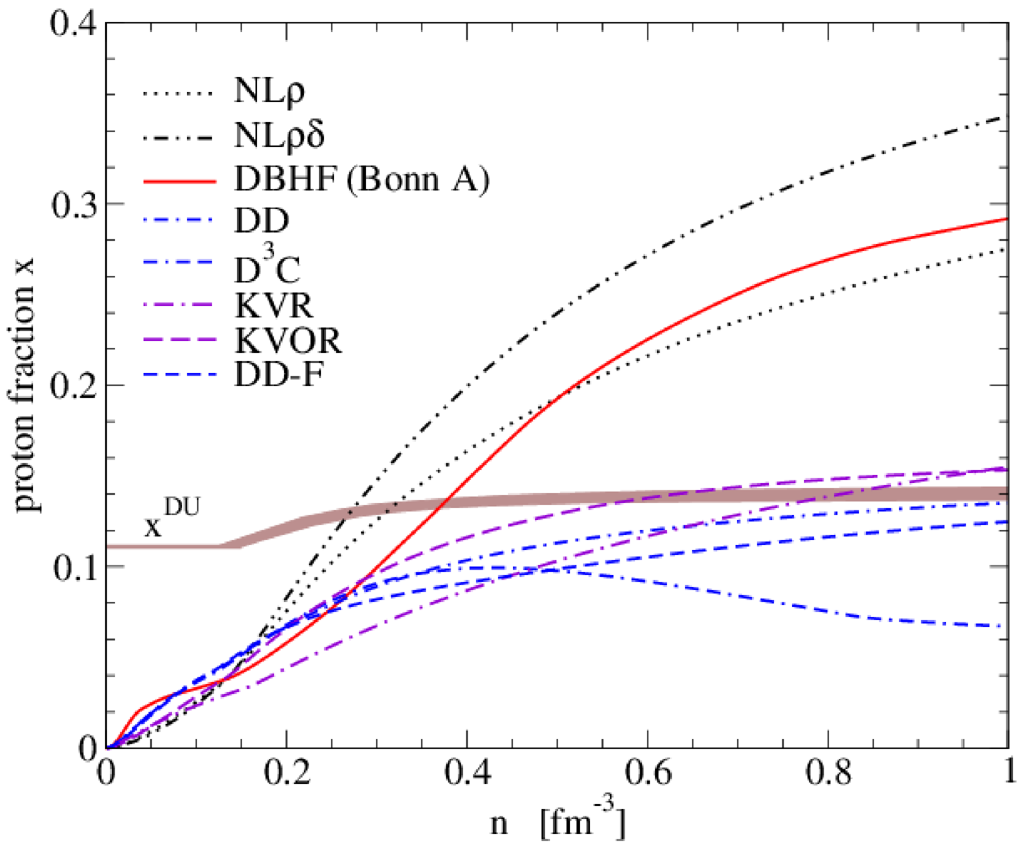
Back to DU

For realistic EoS DU threshold m.b. decreased!

Suggested by Boguta, Bodmer NPA 1977 in RMF model, new life of DU: Lattimer, Prakash, Pethick, Haensel, PRL 1991

$$\mu_i = \frac{\partial E}{\partial n_i}$$

Not as for ideal Fermi gas !



Klähn et al. PRC 74, 035802 (2006)

Calculation of processes. Suppressed medium effects.

$$L^{\rm int} = \frac{G}{\sqrt{2}} j_\mu l^\mu \qquad G = 1.16 \cdot 10^{-5}\ {\rm GeV}^{-2}$$ the weak interaction constant

lepton current $$l_\mu = \bar{u}(q_1)\,\gamma_\mu(1-\gamma_5)\,u(q_2) \qquad \sum_{spin} u(q)\,\bar{u}(q) = \gamma_\mu\, q^\mu$$

nucleon current $$< N|j_\mu|N > \;=\; V_\mu^{NN} - A_\mu^{NN} = \bar{g}_V\,(\bar{N}\,\gamma_\mu N) - \bar{g}_A(\bar{N}\,\gamma_\mu\,\gamma_5 N)$$

$$V_\mu^{np} \approx g_V\,\chi_p^\dagger(p')\big(1, \boldsymbol{v}\big)\chi_n(p)$$

$$V_\mu^{nn} \approx -\frac{g_V}{2}\,\chi_n^\dagger(p')\big(1, \boldsymbol{v}\big)\chi_n(p)$$

$$V_\mu^{pp} \approx +\frac{g_V}{2}\,\mathbf{c_V}\chi_p^\dagger(p')\big(1, \boldsymbol{v}\big)\chi_p(p)$$

$$g_V = 1 \qquad \boldsymbol{v} = \frac{\boldsymbol{p}+\boldsymbol{p}'}{2\,m_N}$$

$$\mathbf{c_V} = 1 - 4\sin^2\theta_W \simeq \mathbf{0.08}$$

$$\begin{aligned} A_\mu^{np} &= -2\,A_\mu^{pp} = -2\,A_\mu^{nn} \\ &\approx g_A\,\chi_p^\dagger(p')\big(\boldsymbol{\sigma}\cdot\boldsymbol{v}, \boldsymbol{\sigma}\big)\chi_n(p) \end{aligned}$$

$$g_A \simeq 1.26$$

~v (Fermi velocity)
corrections are important

Note 1/2 in neutral channel,
since *Z* boson is neutral and *W* is charged!

Two types of perturbative calcul. of neutrino rates

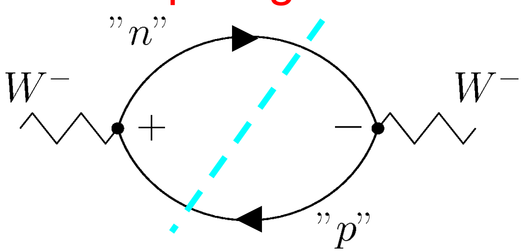
In quantum mechanics: **Born amplitude** $$d\sigma = \frac{m^2}{4\pi^2\hbar^4}\left|\int U e^{-i\mathbf{qr}}\, dV\right|^2 do.$$

Optical theorem $$\sigma_{\rm tot} = \frac{4\pi}{k}{\rm Im}F(0) \longleftarrow$$ forward scattering amplitude.

$${\rm Im}F(\boldsymbol{k}',\boldsymbol{k}) = \frac{k}{4\pi}\int F(\boldsymbol{k}',\boldsymbol{k}')\,F^*(\boldsymbol{k}'',\boldsymbol{k})\,d\Omega''$$

we may calculate cross-sections as an integral of $|M|^2$ over the phase space
or as an imaginary part of W$^-$ boson self-energy

In non-eq. diagram tech.



using relation $$i\,\Pi^{-+} = -\frac{2\,{\rm Im}\Pi^R}{e^{\omega/T}-1}$$

perturbative expansion: **second-order term in weak coupling**
and **zeroth-order** term in strong coupling

In general case terms of higher order in strong coupling must be included! There are no free asymptotic states in matter! Only optical theorem formalism yields correct result

$\Pi_0^{-+} \longrightarrow \Pi^{-+}$ D.V., Senatorov, Sov, J. Nucl. Phys. 45 (1987), Knoll, D.V., Ann. Phys. 249 (1996)

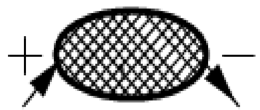
General consideration: Knoll, D.V. Ann. Phys. 249 (1996)

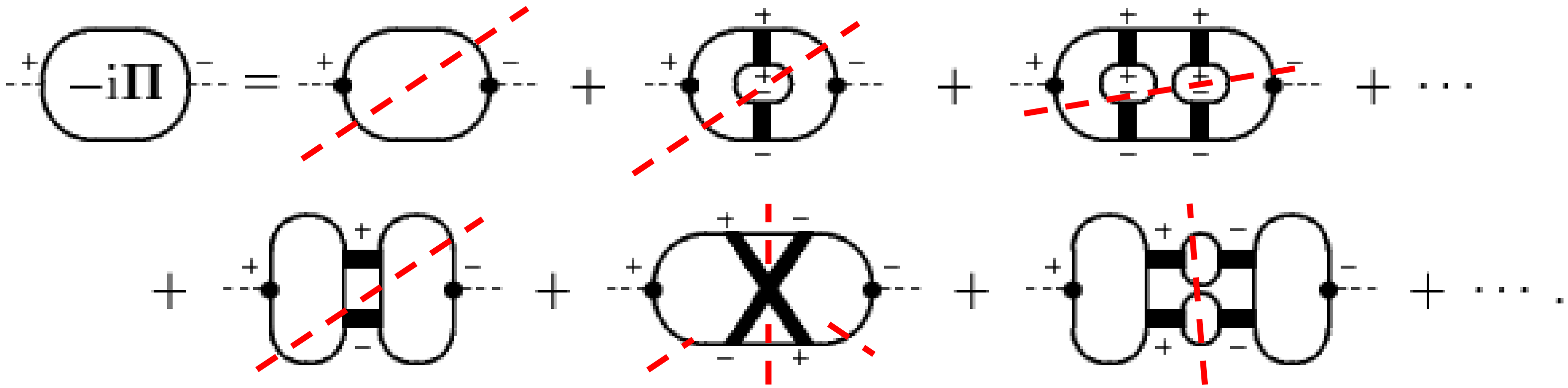
white body radiation problem in closed non-eq. diagram technique (optical theorem formalism)

Direct reactions from piece of matter (ν in NS, e+e-, γ, K⁺ in HIC)

expansion in full non-equilibrium G^{-+}

$$\frac{dW}{d^3q/[(2\pi)^3 2\omega_q]} = -i\Pi^{-+} =$$



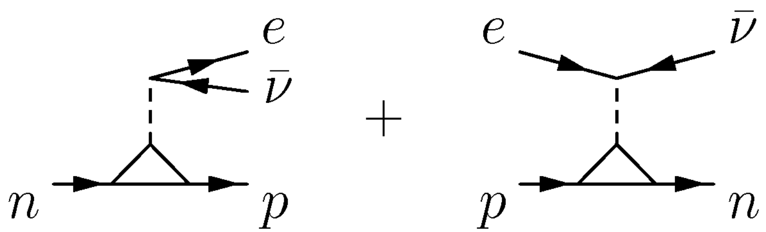


For low T<<ε_F, quasiparticle approximation is valid D.V., Senatorov Yad.Fiz.(1987) (each G^{-+} yields T^2, allows to cut diagrams over G^{-+})
For soft radiation: semiclassics (all graphs in first line are of the same order):LPM effect: Knoll,D.V (1996), A.Sedrakian,Dieperink (1999), Fortmann et al. (2006),…

One-nucleon processes (DU). No medium effects

For $n > n_c^{\mathrm{DU}}$ $(M > M_c^{\mathrm{DU}})$

emissivity (Fermi golden rule):



bare vertices !

$$\epsilon_\nu^{\mathrm{DU}} = 2\int \frac{d^3p_n}{(2\pi)^3} f_n \int \frac{d^3p_p}{(2\pi)^3}(1-f_p) \int \frac{d^3q_e}{2\omega_e(2\pi)^3}(1-f_e) \int \frac{d^3q_{\bar\nu}\,\omega_{\bar\nu}}{2\omega_{\bar\nu}(2\pi)^3}(2\pi)^4\delta^{(4)}(P_f-P_i)\sum_{\mathrm{spins}}|M|^2$$

Counting powers of T:

each external nucleon and electron line ~T

neutrino phase space × neutrino energy ~T^3

$\Rightarrow$ $\epsilon_\nu^{\mathrm{DU}} \sim T^6$

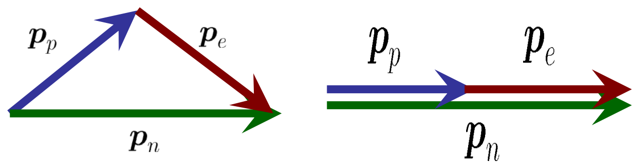
$$\epsilon_\nu^{\mathrm{DU}} \simeq 4\cdot 10^{27}\,(n_e/n_0)^{1/3}\,T_9^6\,\Theta(2p_{\mathrm{F},p}-p_{\mathrm{F},n})\,\frac{\mathrm{erg}}{\mathrm{cm}^3\cdot\mathrm{s}}$$

$T_9 = T/10^9\,\mathrm{K}$

$n_0 \simeq 0.17\ \mathrm{fm}^{-3}$

- one-nucleon phase-space volume (» 10^{27}-10^{28} factor)
- T^6 dependence
- threshold behavior ($n>n_c^{DU}$, n_c^{DU} depends on EoS)
- very moderate density dependence

$|\boldsymbol{p}_p| = |\boldsymbol{p}_e|$

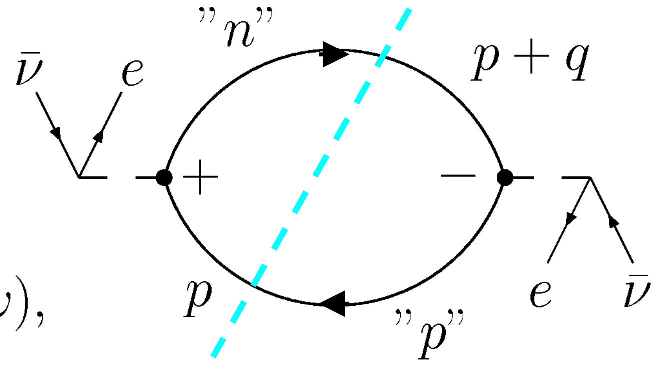


Optical theorem in non-equilibrium diagram technique

Perturbative analysis

self-energy with free non-equilibrium Green's functions

$$-i\,\Pi_0^{-+} =$$



$$-i\,\Pi_0^{-+} = 2\,n_{\rm bos}(\omega)\,{\rm Im}\,\Pi^R(\omega),$$

$$-i\Pi_0^{-+} \;=\; \frac{G^2}{2}{\rm Tr}\{l_1^\mu l_2^\nu\}\int\frac{d^4p}{(2\pi)^4}\,{\rm Tr}\{(-iJ_\mu)\,iG_n^{-+}(p+q)\,(+iJ_\nu)\,iG_p^{+-}(p)(-1)\}$$

$$\epsilon_\nu^{\rm DU} = 2\int\frac{d^3q_e}{2\omega_e(2\pi)^3}(1-f_e)\,\frac{d^3q_{\bar\nu}}{2\,\omega_{\bar\nu}\,(2\pi)^3}\,\omega_{\bar\nu}\,[-i\Pi_0^{-+}(q_e+q_{\bar\nu})]$$

$$G_0^{-+} = \pm 2\,\pi\,i\,f(E)\,\delta(E+\mu-E_p) \quad G_0^{+-} = -2\,\pi\,i\,(1\mp f(E))\,\delta(E+\mu-E_p)$$

Cut of the diagram means removing of dE integration due to δ-function

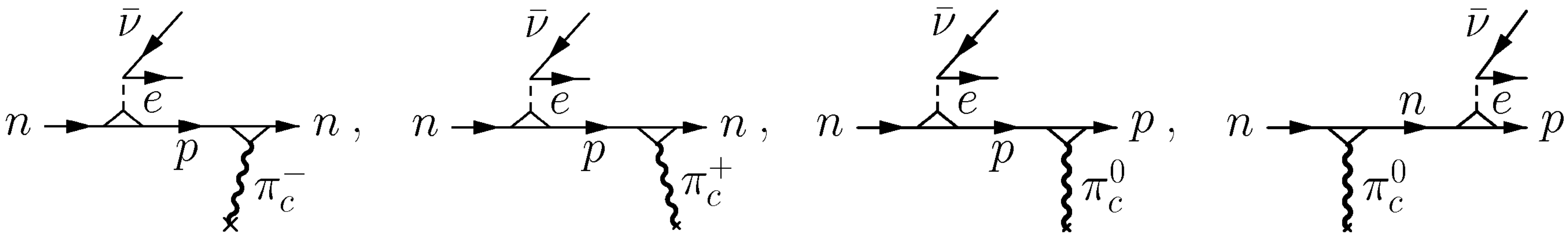
$$\epsilon_\nu^{\rm DU} = 2\int\frac{d^3q_e}{2\omega_e(2\pi)^3}(1-f_e)\,\frac{d^3q_{\bar\nu}}{2\,\omega_{\bar\nu}\,(2\pi)^3}\,\omega_{\bar\nu}\,[-i\Pi_0^{-+}(q_e+q_{\bar\nu})]$$

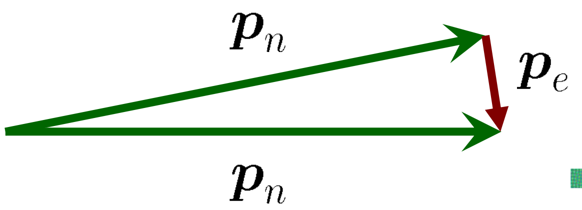
Convenient formalism in QP approx. :
expansion in loops (G^{-+} G^{+-}) is expansion in $(T/\varepsilon_{FN})^2$ D.V., Senatorov Yad.Fiz.(1987)

Pion Urca processes

PU is also one-nucleon process (if the model permits pion condensation)

For $n > n_c^{\rm PU}$ $(M > M_c^{\rm PU})$ pion Urca (PU) processes:





neutrons in both initial and final states

energy-momentum conservation is easily fulfilled

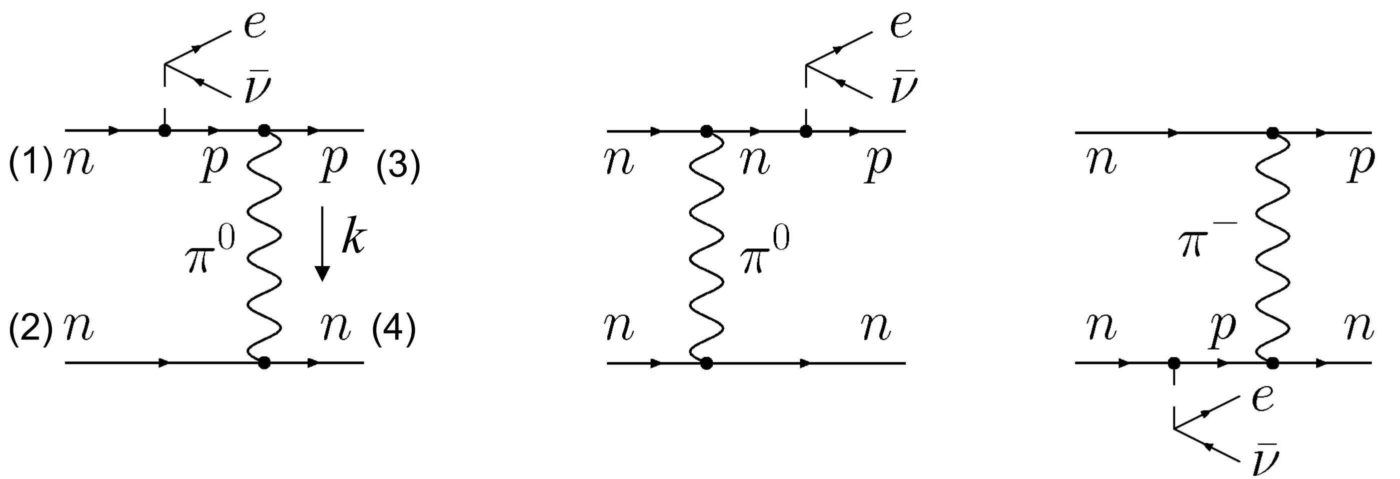
with bare vertices: $\epsilon_\nu \sim 10^{26}\ T_9^6 (n/n_0)^{1/3}\ \dfrac{\rm erg}{\rm cm^3\ sec}$

All “exotic” one-nucleon processes start only when the density exceeds some <u>critical density</u>

Two-nucleon process (Modified Urca)

Friman & Maxwell AJ (1979) $n + n \rightarrow n + p + e + \bar{\nu}$

FOPE model of NN interaction (no medium effects)



Additionally one should take into account exchange reactions (identical nucleons)

FOPE model continues to be used by different groups,
e.g. by Page et. al., Yakovlev et al.

Two-nucleon process (Modified Urca)

no medium effects included

Emissivity:

$$\epsilon_\nu^{\rm MU} = \prod_{i=1}^{4} \int \left[\frac{d^3 p_i}{(2\pi)^3}\right] f_1\, f_2\, (1-f_3)\,(1-f_4)\, \frac{d^3 q_e\,(1-f_e)}{2\,\omega_e\,(2\pi)^3}$$
$$\times\ \frac{d^3 q_{\bar\nu}}{2\,\omega_{\bar\nu}\,(2\pi)^3}\, \omega_{\bar\nu}\,(2\,\pi)^4\,\delta^{(4)}(P_f - P_i)\,\frac{1}{s}\sum_{spins} |M|^2,$$

$s=2$ is symmetry factor. Reactions with the electron in an initial state yield extra factor 2.

Finally

$$\epsilon_\nu^{\rm MU} = \frac{11513}{60480\,\pi}\, G^2\, g_A^2\, f_{\pi NN}^4\, m_n^3\, m_p\, p_{{\rm F},e}\, T^8\, 1.3 \simeq 8 \cdot 10^{21}\, (n_p/n_0)^{1/3}\, T_9^8 \times \frac{\rm erg}{{\rm cm}^3 \cdot {\rm s}}$$

only axial-vector term contributes

due to exchange reactions

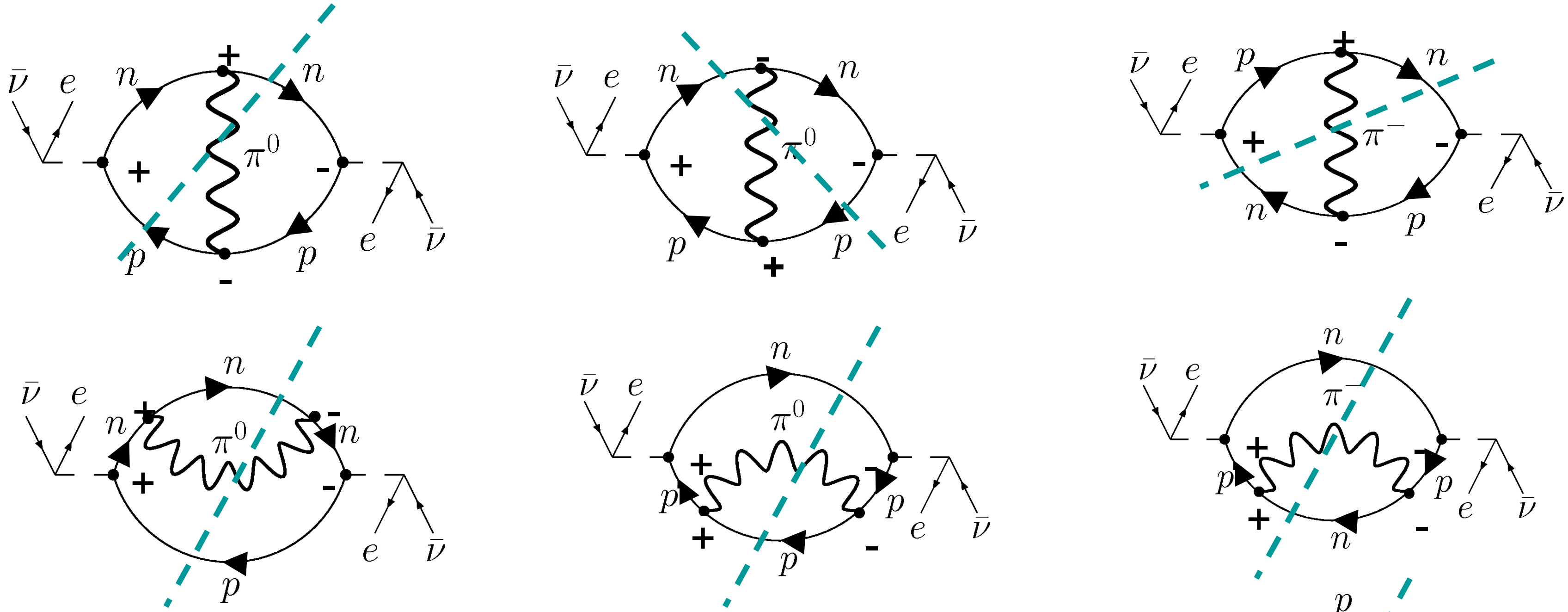
✔ T^8 dependence of the emissivity

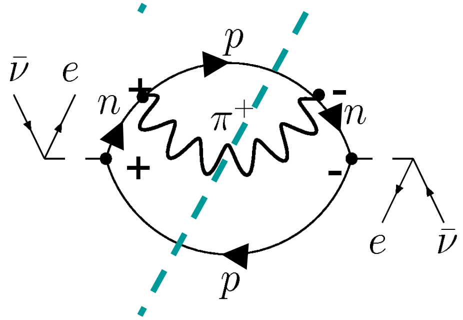
(5 fermions $\Rightarrow \sim T^5$, $\quad \omega_{\bar\nu}\,\delta(\omega_{\bar\nu} + \ldots)\,\omega_{\bar\nu}^2\, d\omega_{\bar\nu}$ $\quad\Rightarrow T^3$)

Optical theorem for modified URCA reactions

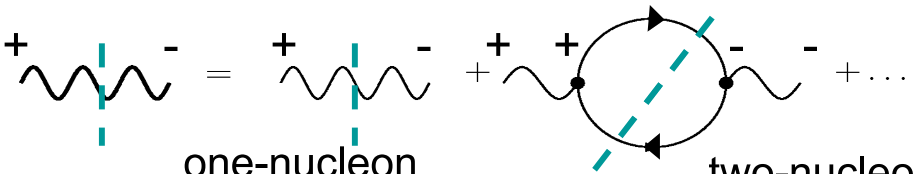
Perturbative analysis

$$\epsilon_\nu^{\mathrm{MU}} = \int \frac{d^3 q_e\,(1-f_e)}{2\,\omega_e\,(2\,\pi)^3}\,\frac{d^3 q_{\bar\nu}}{2\,\omega_{\bar\nu}\,(2\,\pi)^3}\,\omega_{\bar\nu}\,[-i\Pi^{-+}_{\mathrm{MU}}(q_e+q_{\bar\nu})]$$





thick pion line (here up to 2nd order!):

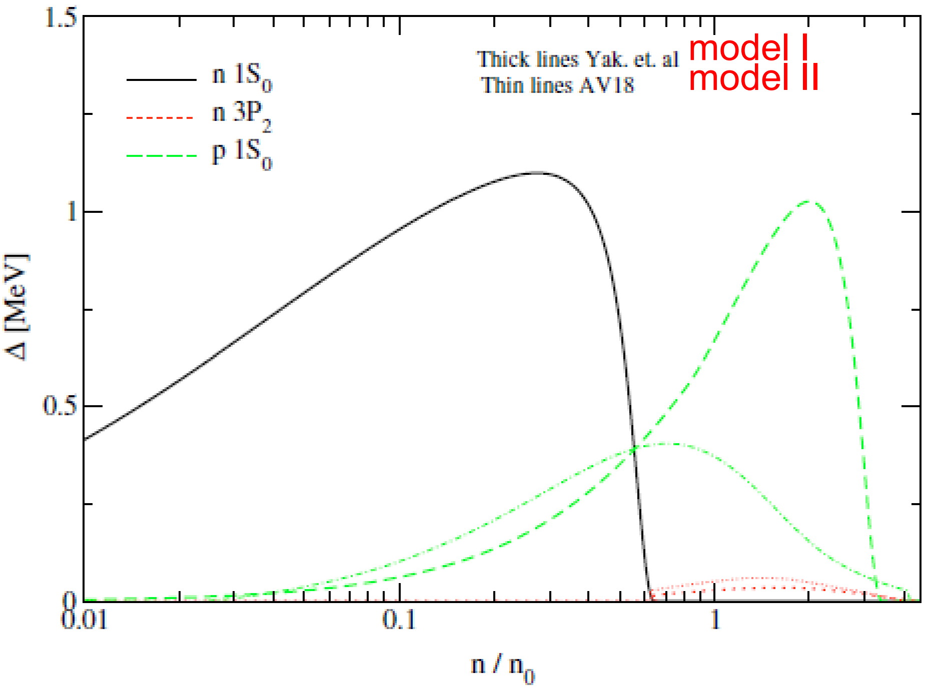


one-nucleon process with pion

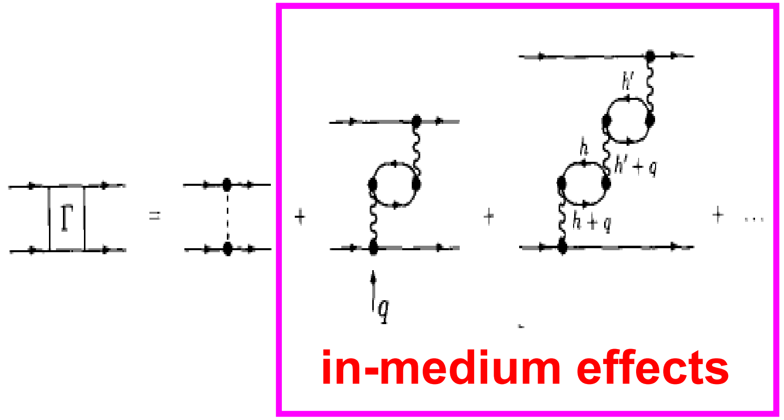
two-nucleon process

Pairing in NS matter

A.B.Migdal (1959)



$$\Delta \simeq 2E_F \exp(-1/(NV)), \quad N = m^* p_F/\pi^2,$$



U. Lombardo and H.-J. Schulze (2000)

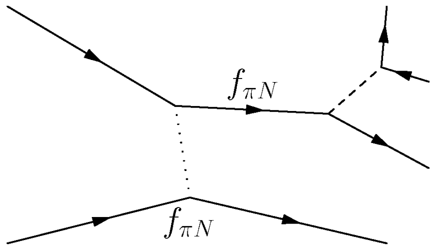
- **NS cooling is most sensitive to pairing in dense matter (to $3P_2$ nn and $1S_0$ pp gaps)**
- Gaps are very sensitive to inclusion of **in-medium effects**
- gaps drop above ~$4n_0$

Schwenk, Friman, PRL (2004) triplet paring is supperessed by medium-induced spin-orbit interaction, $3P_2$ gap <10 keV, **we** *(*Blaschke,Grigorian, D.V. (2004), Grigorian,D.V. (2005)...) *exploit this result*, **others** (Page et al. (2004), Yakovlev et al. (2004)...) use BCS-based estimates of $\Delta(3P_2)$ ~0.1 MeV

Standard scenario + exotics

standard $\qquad T < T_{\rm opac} \sim 10^{-1} \div 10^{0}$ MeV

MU:



$$10^{21} \times \left(\frac{m_N^*}{m_N}\right)^4 T_9^8 \left(\frac{n_e}{n_0}\right)^{\frac{1}{3}} \frac{\rm erg}{\rm cm^3\, s} \times e^{-2\Delta/T}$$

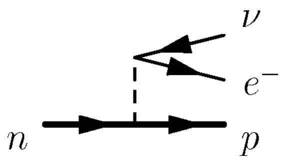
more correctly

$\exp[-(\Delta_n + \Delta_p)/T]$

exotics

All "exotic" processes start only for n > n cr (for M>M cr)

DU:



$$10^{27} \times T_9^6 \left(\frac{n_e}{n_0}\right)^{\frac{1}{3}} \frac{\rm erg}{\rm cm^3\, s} \times e^{-\Delta/T}$$

allowed if $n > n_c^{\rm DU}$

Standard + exotics

standard scenario (MU+pairing)

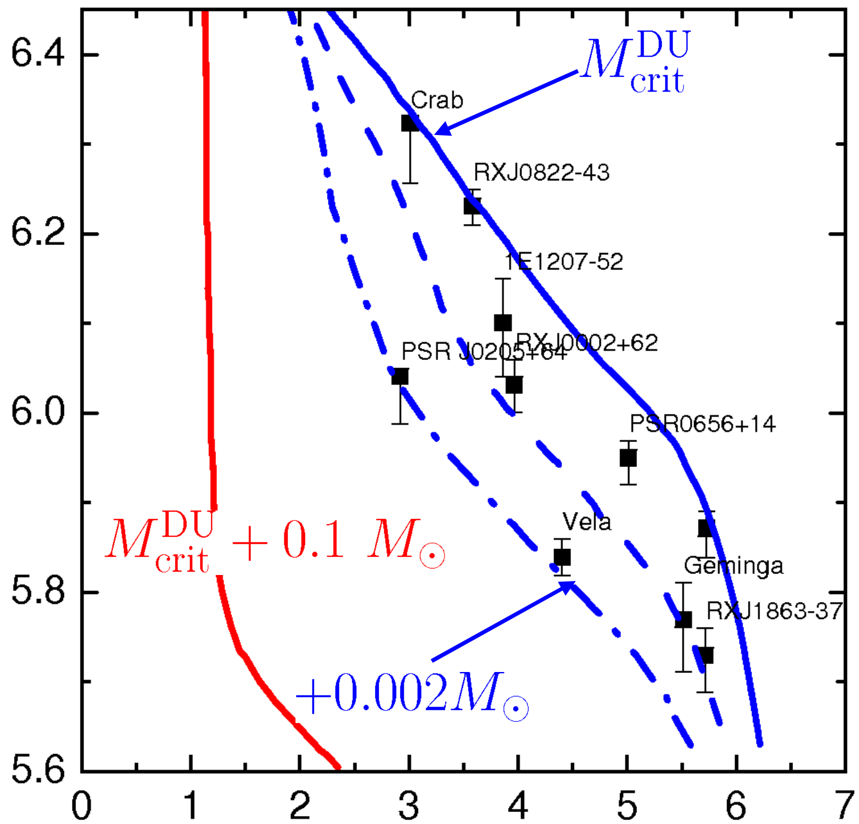
only "slow" and "intermediate" cooling can be described

Direct-Urca scenario

NS masses close to M^{DU}_{crit} ≈1.36 M_{sol}

cf. D. Page, ApJ (1994), Levenfish,Yakovlev Astroph.L. (1996) ,

since that time most of researches believed that all NS have approximately the same masses ≈1.35-1.4 M_{sol}



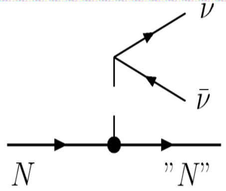
contradics to that masses of NS, as now is known, are essentially different

Kolomeitsev, D.V. NPA 2005, Klahn et al. PRC 2006 formulated **DU constraint**, M_{cr} >1.35-1.5 M_{sol}

Either EoS with low DU threshold should be rejected (Blaschke,Grigorian, D.V. 2004)
or m.b. pp- gap should be very large (see in Taranto et al. 2016)

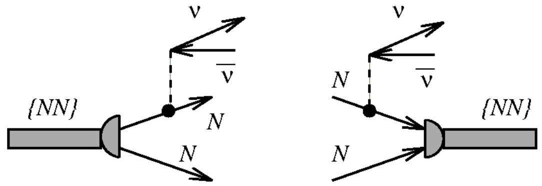
Next step! **Breaking and Formation of Cooper pairs (PBF)**

In normal matter one-nucleon processes



are forbidden

In superfluid $(T<T_c<0.1\text{-}1\ \mathrm{MeV})$



are allowed

Flowers, Ruderman, Sutherland, APJ (1976)

$$\epsilon_\nu \sim 10^{20} T_9^7\ \xi_{nn}^2$$

Δ_{nn} is neutron gap, $\xi_{nn}=\exp(-\Delta_{nn}/T)$

computed in matrix element formalism for PBF on neutrons without inclusion of medium effects

D.V., Senatorov Sov J. Nucl. Phys.(1987)

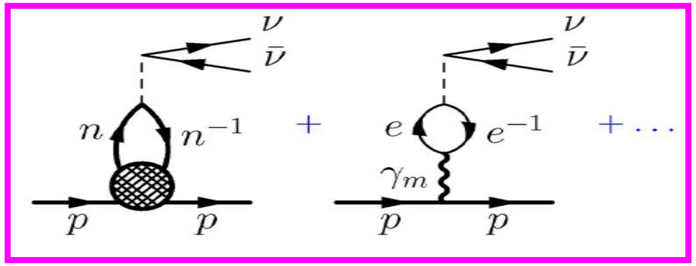
calculated in optical theorem formalism

$$10^{28} \times \left(\frac{\Delta}{\mathrm{MeV}}\right)^7 \left(\frac{T}{\Delta}\right)^{\frac{1}{2}} e^{-2\Delta/T}\ \frac{\mathrm{erg}}{\mathrm{cm}^3\,\mathrm{s}}$$

pre-factor Δ^7_{nn} rather than T^7 !

PBF both on neutrons and on protons:

with incl. of in-medium effects PBF on p is efficient:



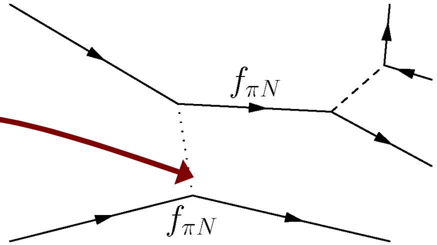
Incl. in code in Schaab, D.V., A. Sedrakian, Weber, Weigel 1996

Now PBF processes are incorporated in all existing scenarios of NS cooling

Minimal cooling paradigm D.Page et al. 2004, D.G. Yakovlev et al. 2004

Reactions in presence of pairing

MU:



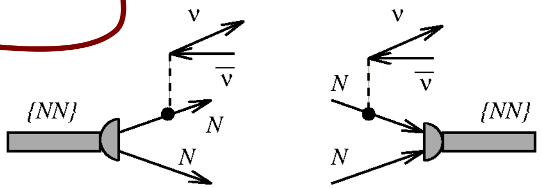
FOPE, i.e. no medium effects included

$$10^{22} \times \left(\frac{m_N^*}{m_N}\right)^4 T_9^8 \left(\frac{n_e}{n_0}\right)^{\frac{1}{3}} \frac{\mathrm{erg}}{\mathrm{cm^3\,s}} \times e^{-2\Delta/T}$$

more correctly

$$\exp[-(\Delta_n + \Delta_p)/T]$$

PBF:



$$\epsilon_\nu \sim 10^{20} T_9^7\, \xi_{nn}^2$$

$$\xi_{nn} = \exp(-\Delta_{nn}/T)$$

attempts to fit cooling data by using different T_s-T_{in} for different NS

They state that ***info on internal neutrino emission is distinguished by unknown composition of heat blanket*** (T_s-T_{in})

and fitting Δ (n) dependencies

imposible to fit all the data

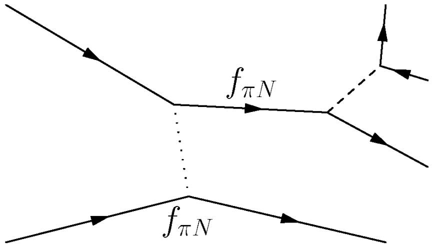
Minimal (+exotics) scenario

Neutrino emission reactions

for T<T$_c$

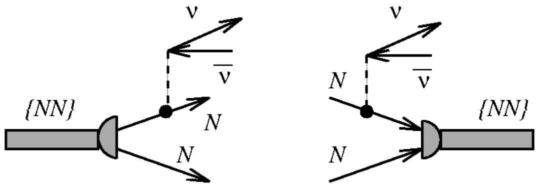
minimal

MU:



$$10^{22}\times\left(\frac{m_N^*}{m_N}\right)^4 T_9^8\left(\frac{n_e}{n_0}\right)^{\frac{1}{3}}\ \frac{\mathrm{erg}}{\mathrm{cm}^3\,\mathrm{s}}\quad \times e^{-2\Delta/T}$$

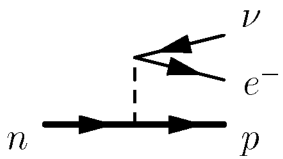
PBF:



$$\epsilon_\nu \sim 10^{20} T_9^7\ \xi_{nn}^2$$

Exotics resolves problem with rapid coolers

DU:

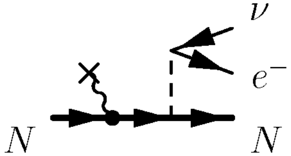


$$10^{27}\times T_9^6\left(\frac{n_e}{n_0}\right)^{\frac{1}{3}}\ \frac{\mathrm{erg}}{\mathrm{cm}^3\,\mathrm{s}}\quad \times e^{-\Delta/T}$$

allowed if $n > n_c^{\mathrm{DU}}$

Sometimes one includes P -wave PU

PU:



$$10^{27}\times T_9^6\ \frac{|\varphi_c|^2}{m_\pi^2}\ \frac{\mathrm{erg}}{\mathrm{cm}^3\,\mathrm{s}}\quad \times e^{-\Delta/T}$$

allowed if $n > n_c^{\mathrm{PU}}$

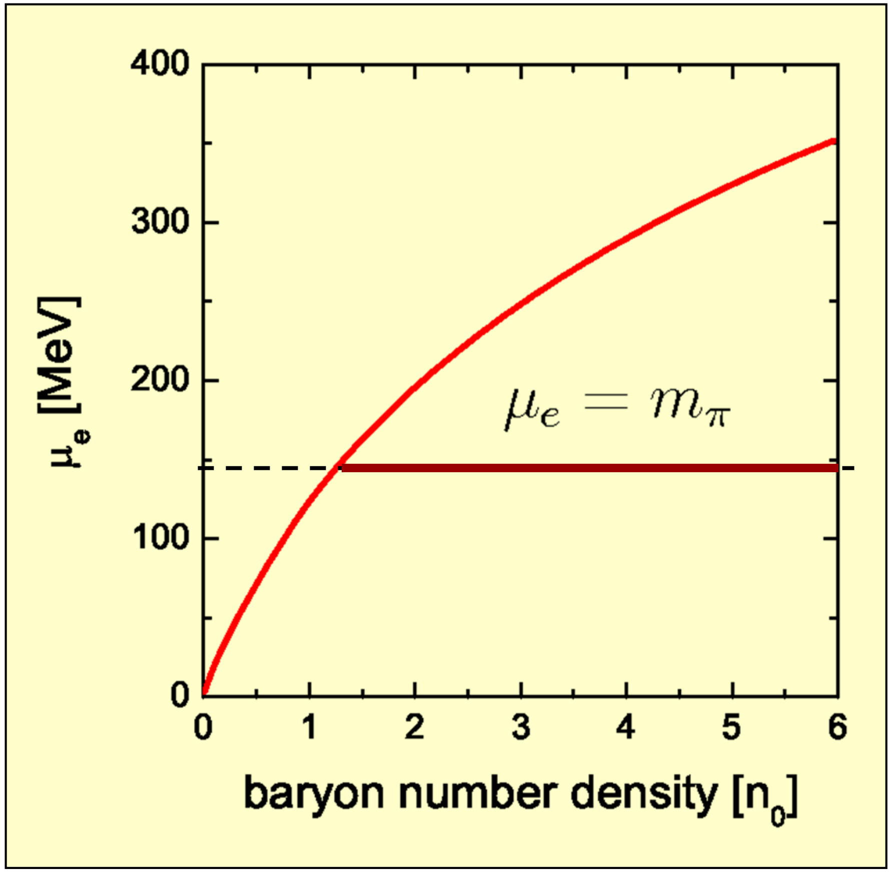
But P-wave pion condensation does not appear in FOPE model!

Theoretical inconsistencies of minimal cooling model

If no medium effects in pion propagator:

pionization (Bose-Einstein cond.)

G.Saakyan 1977



Weak reactions start

$$e^- \longrightarrow \pi^- + \nu_e$$

In Minimal Cooling Scenario one silently ignores pionization!
But within their concept (ussage of FOPE-free pion) it must be included! If were included pionization would result in a very rapid cooling for all NS.

Repulsive π^- N interaction in S-wave

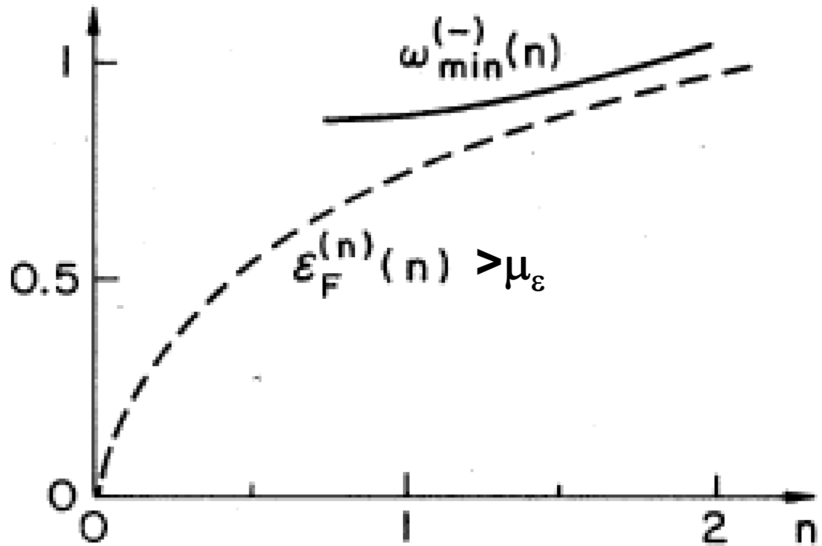
$$\Pi_S(\omega) = -T^{(-)}(\omega)\,(\rho_p - \rho_n) - T^{(+)}(\omega)\,(\rho_p + \rho_n)$$

repulsive in neutron reach matter

repulsive for $\omega > m_\pi$

$$T^{(-)}(\omega) = \frac{\omega}{2\,f_\pi^2}\left(1 + C\,\frac{\omega^2}{8\,\pi^2\,f_\pi^2}\right) \qquad T^{(+)}(\omega) = \frac{\sigma_{\pi N}}{f_\pi^2}\left(1 - \frac{\omega^2}{m_\pi^2}\right)$$

$$C > 0$$

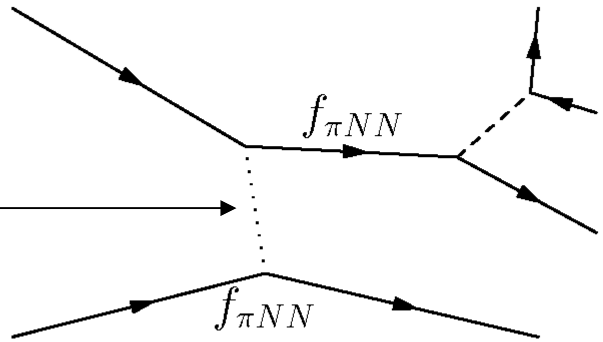


No S-wave pion condensation (Migdal 1973) Pionization does not occur! Only P-wave pion condensation is allowed!

Inconsistencies of FOPE model

The only diagram in FOPE model which contributes to the MU and NB is

Free one-pion exchange



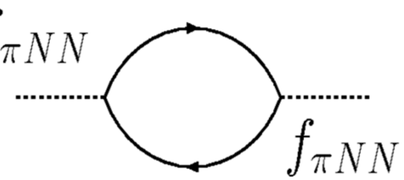
For consistency one needs to calculate corrections of the second-order in $f_{\pi NN}$ in other values. Otherwise -- problems with unitarity.

Pion polarization operator in dispersion relation at order $f_{\pi NN}^2$:

$$D^{-1}(\omega, k) = \omega^2 - m_\pi^2 - k^2 - \Pi_0^R(\omega, k, n) = 0$$

$$-D^{-1}(0, k_m \simeq p_{\mathrm{F}}) =: \omega^{*\,2}(k_m) < 0$$

measure of pion softening



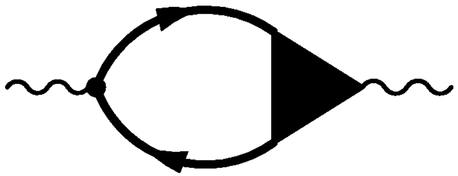
Pion condensation in ISM already at $n>0.3\ n_0$

But there is no pion condensation in atomic nuclei

Solution of the puzzle

One should replace FOPE by the full NN interaction,
essential part of which is due to MOPE
with vertices corrected by NN correlations.

NN^{-1} part of the pion polarization operator is



$$\approx \Pi_0^R(\omega, k, n)\,\gamma(g', \omega, k, n)$$

suppressed by the factor $\gamma(g', \omega = 0, k \simeq p_F, n \simeq n_0) \simeq 0.35 \div 0.45.$

in isospin-symmetric matter no pion condensation at $n \lesssim n_0$

but it may appear at higher n

“Nuclear medium cooling” scenario uses

Fermi liquid approach based on separation of long-range
and short-range strong interactions

Long-range (nucleon-nucleon hole, Delta-isobar-nucleon hole, pion)
processes are taken into account explicitly

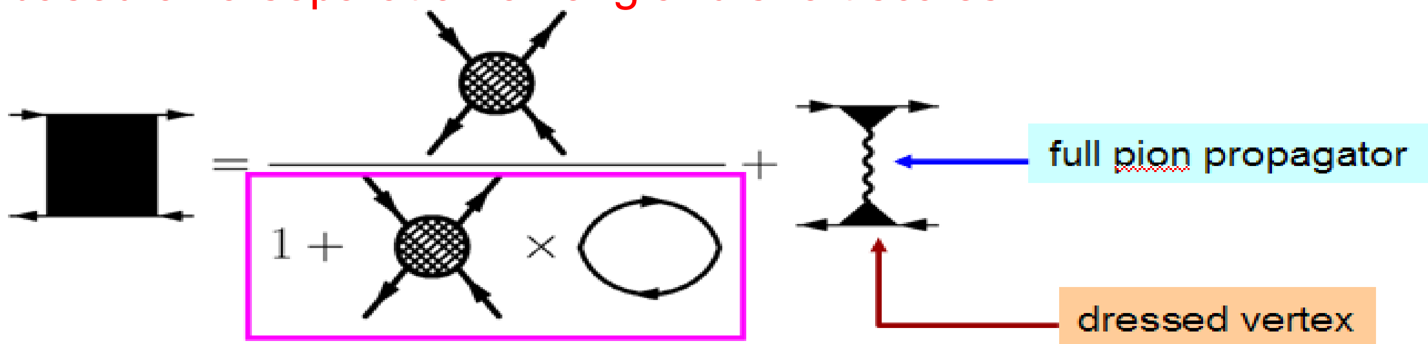
Short-range processes are incorporated
with the help of Landau-Migdal parameters

For review see in Migdal, Saperstein,Troitsky,D.V. Phys.Rep.1990

Low energy excitations in nuclear Fermi liquid (Landau-Migdal appr.)

Resummed NN interaction

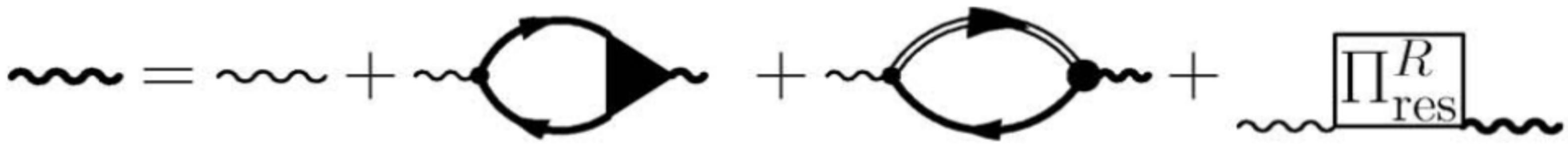
based on a separation of long and short scales



$= C_0\,(f_{12} + g_{12}\boldsymbol{\sigma_1}\boldsymbol{\sigma_2})$

Info. on short-range interact. Is extracted from analysis of atomic nuclei exp.

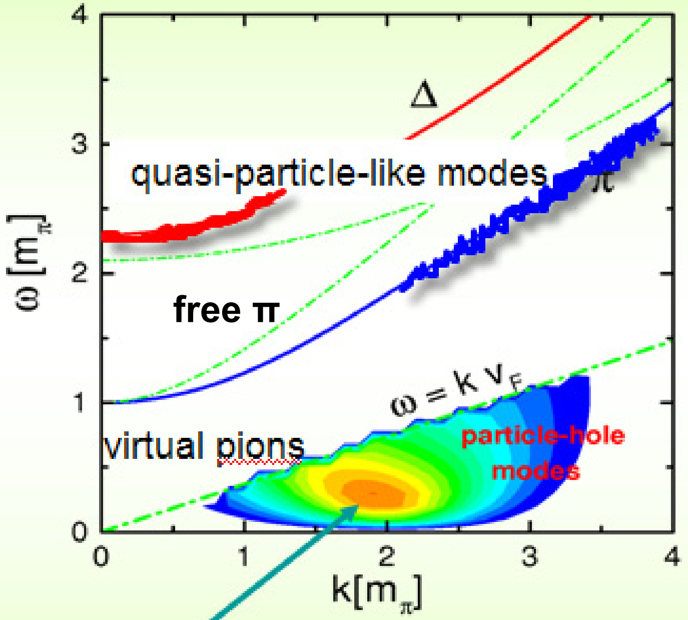
Poles yield zero-sound modes in scalar and spin channels



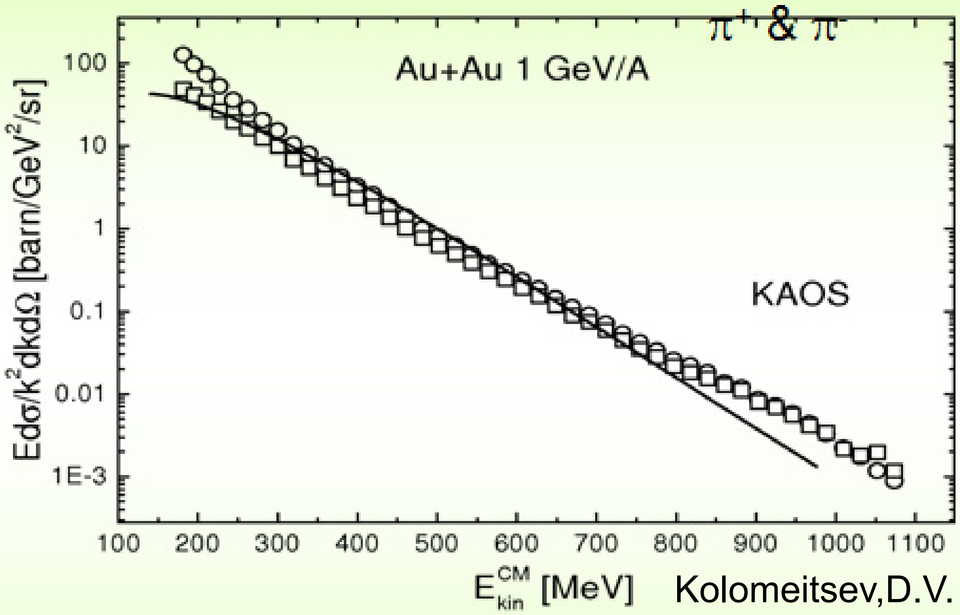
"Pion degrees of freedom in nuclear matter",
A.B.Migdal,E.Saperstein,M.Troitsky,D.V. Phys.Rep.190 (1990).

Pion spectra in nuclear matter N=Z

Pion spectrum in nuclear matter at saturation.
similar for π^0 in neutron matter



Pion production in Au+Au collision with energy 1 GeV per nucleon



Kolomeitsev,D.V. (1996)

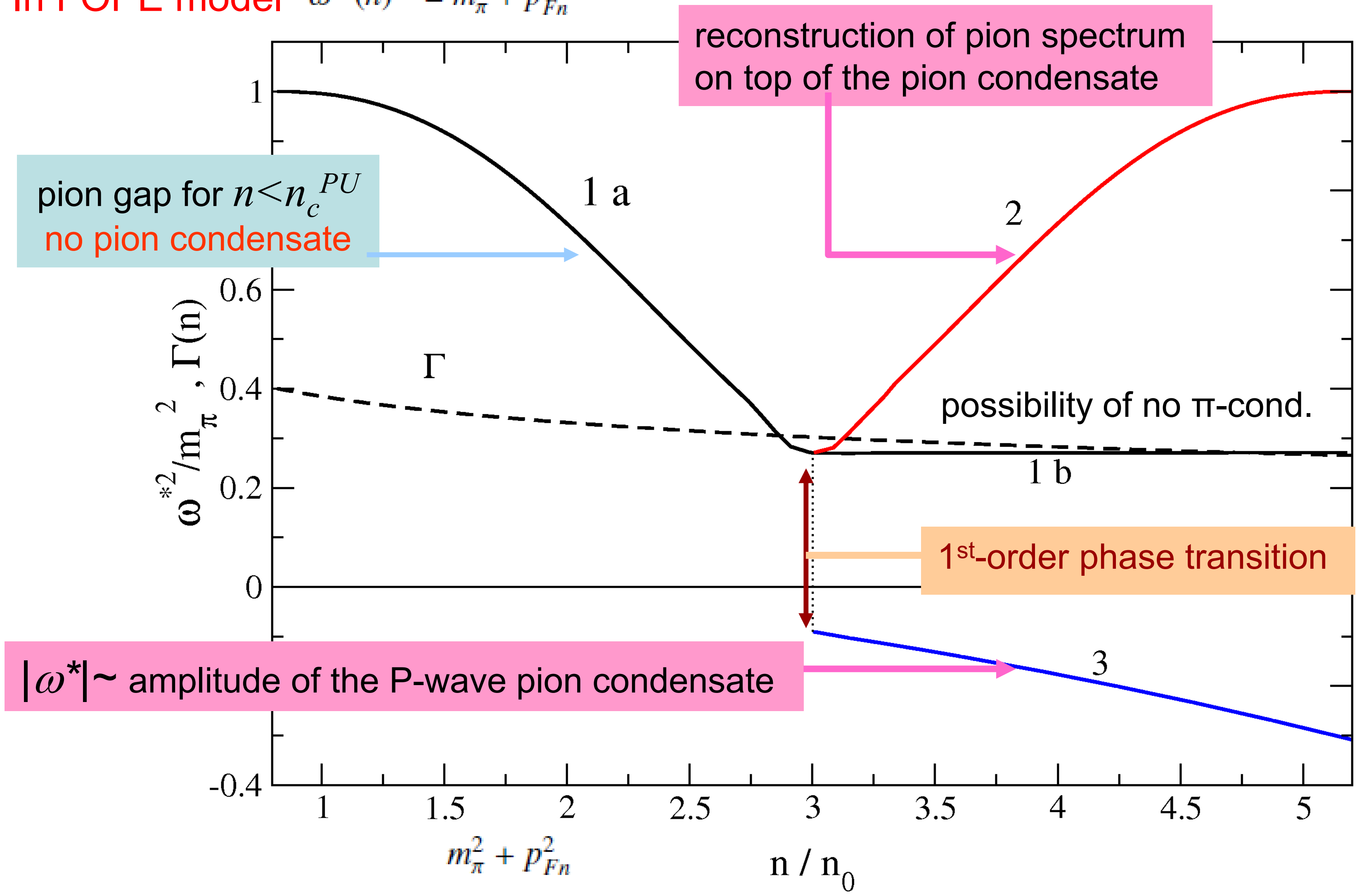
Pions have short mean-free path and are radiated at freeze-out
the smaller collision energy, the larger is in-medium effect

Possibility of the P-wave pion condensation in dense NS interiors : $\omega^2<0$ for $n>n_{cr}$
A.B. Migdal ZhETF (1971)

Pion softening with increase of the density

$\omega^{*2}(n) \approx -D^{-1}(\omega = 0, k = p_{Fn}, n)$ (at minimum over k, $k_m \approx p_F$)

In FOPE model $\omega^{*2}(n) = m_\pi^2 + p_{Fn}^2$

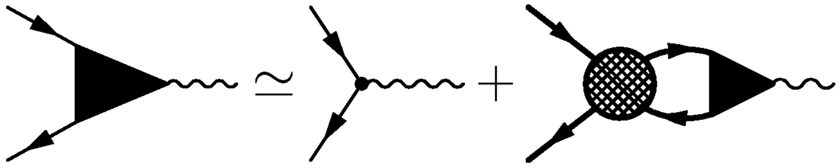


Γ –vertex suppression factor

From the cooling fit $n_c > 1.5\text{-}2\ n_0$ for stiff EoS

Re-summed weak interaction

The weak coupling vertex is renormalized in medium:



wavy line corresponds to weak current

For the β-decay:

$$V_\beta = \frac{G}{\sqrt{2}} \left[\widetilde{\gamma}(f')\, l_0 - g_A\, \widetilde{\gamma}(g')\, \boldsymbol{l\sigma}\right]$$

For processes on the neutral currents $N_1 N_2 \to N_1 N_2 \nu \bar{\nu}$

$$V_{nn} = -\frac{G}{2\sqrt{2}} \left[\gamma(f_{nn})\, l_0 - g_A\, \gamma(g_{nn})\, \boldsymbol{l\sigma}\right]$$

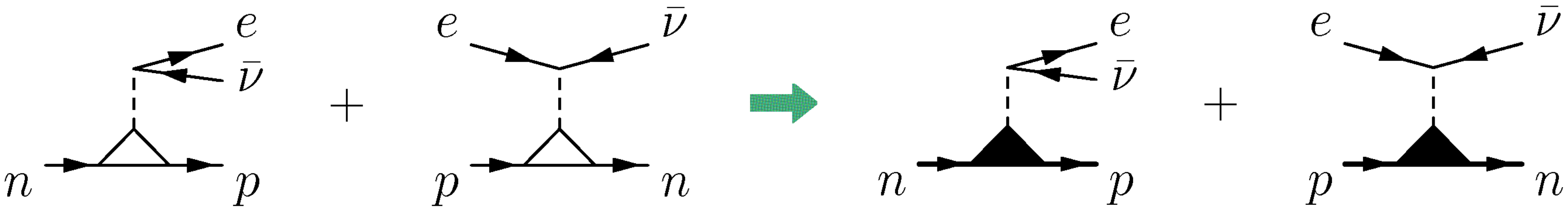
$$V_{pp}^N = \frac{G}{2\sqrt{2}} \left[\kappa_{pp}\, l_0 - g_A\, \gamma_{pp}\, \boldsymbol{l\sigma}\right]$$

with the correlation functions

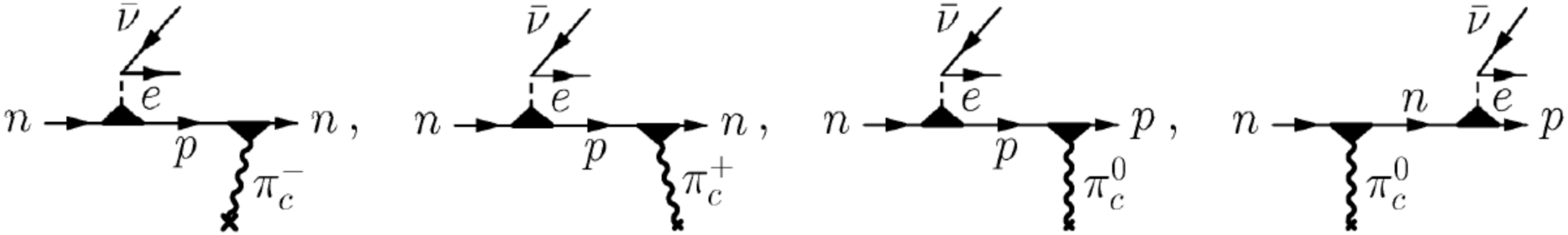
$$\kappa_{pp} = c_V - 2 f_{np}\, \gamma(f_{nn})\, C_0\, L_{nn},\;\; \gamma_{pp} = (1 - 4\, g\, C_0\, L_{nn})\; \gamma(g_{nn}),$$

[D.V., Senatorov, Sov. J. Nucl. Phys. 45 (1987)]

Proper DU processes



Due to full vertices ➡ a factor $\Gamma^2_{\mathrm{w-s}}$ in emissivity.
(rather minor modification, since $\omega \simeq p_{\mathrm{F},e} \gg q \sim T$).

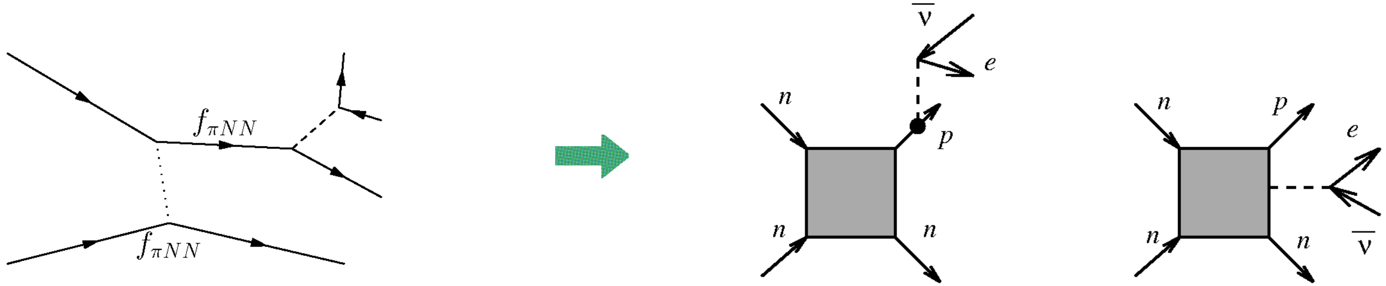


with full vertices: $\epsilon_\nu \sim 10^{26} \Gamma_s^2 \Gamma^2_{\mathrm{w-s}}\, T_9^6 (n/n_0)^{1/3}\, \frac{\mathrm{erg}}{\mathrm{cm^3\ sec}}$

➡ $\Gamma_s^2 \Gamma^2_{\mathrm{w-s}} \sim 10^{-1} - 10^{-2}$

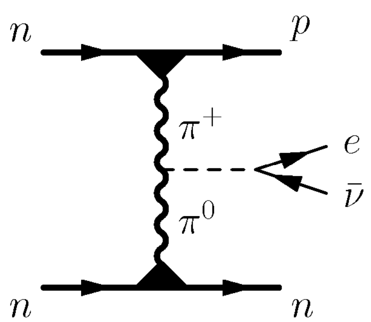
Medium effects in two-nucleon processes

MU(FOPE) :

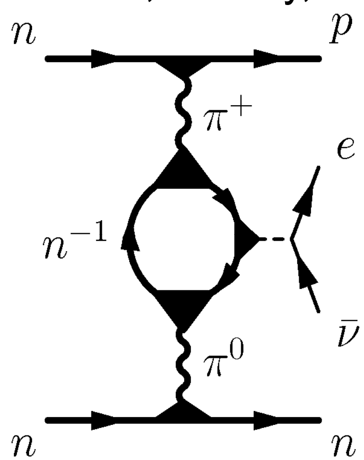


D.V., Senatorov (1986), Migdal, Saperstein,Troitsky,D.V. Phys.Rep.1990

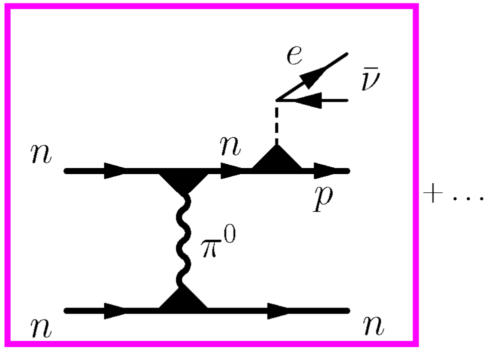
MOPE



$+$



$+$



$+\dots$

Straight generalization of MU

emissivity: larger → smaller

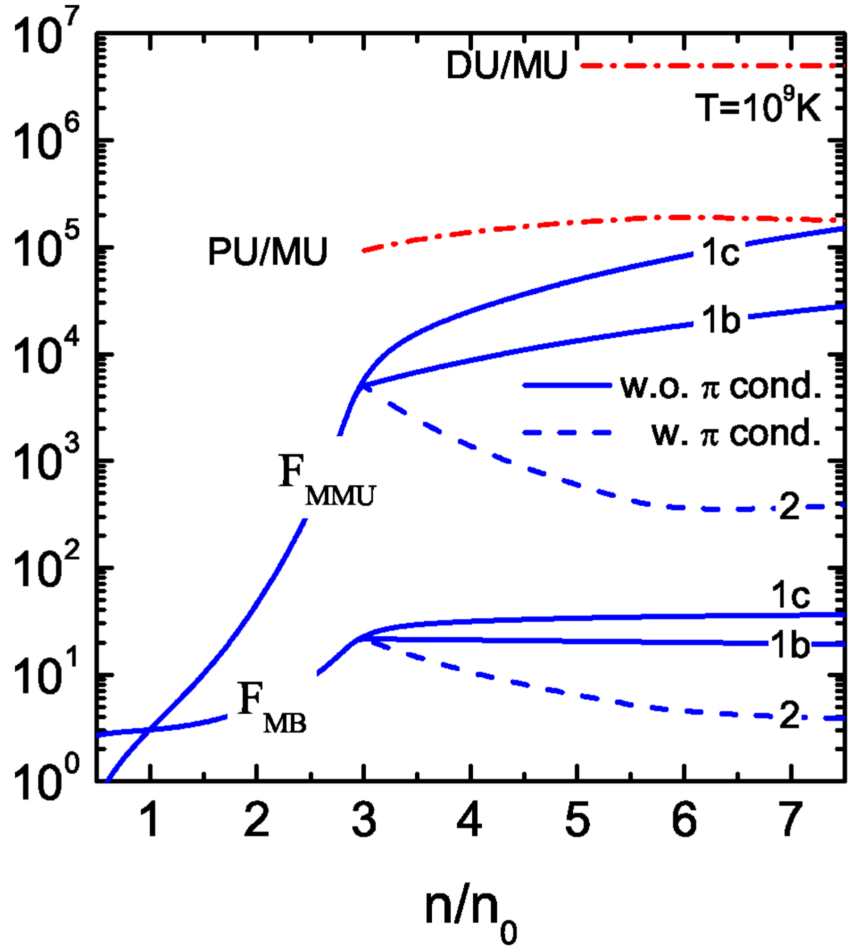
Very important in our scenario!

$$F_{MMU} = \frac{\epsilon_\nu[\mathrm{MMU}]}{\epsilon_\nu[\mathrm{MU}]} \sim 3\left(\frac{n}{n_0}\right)^{10/3} \frac{[\Gamma(n)/\Gamma(n_0)]^6}{[\omega^*(n)/m_\pi]^8}$$

Very strong density dependence

enhancement factor ~10^3 -- 10^5 for n~(1.5-4) n_0

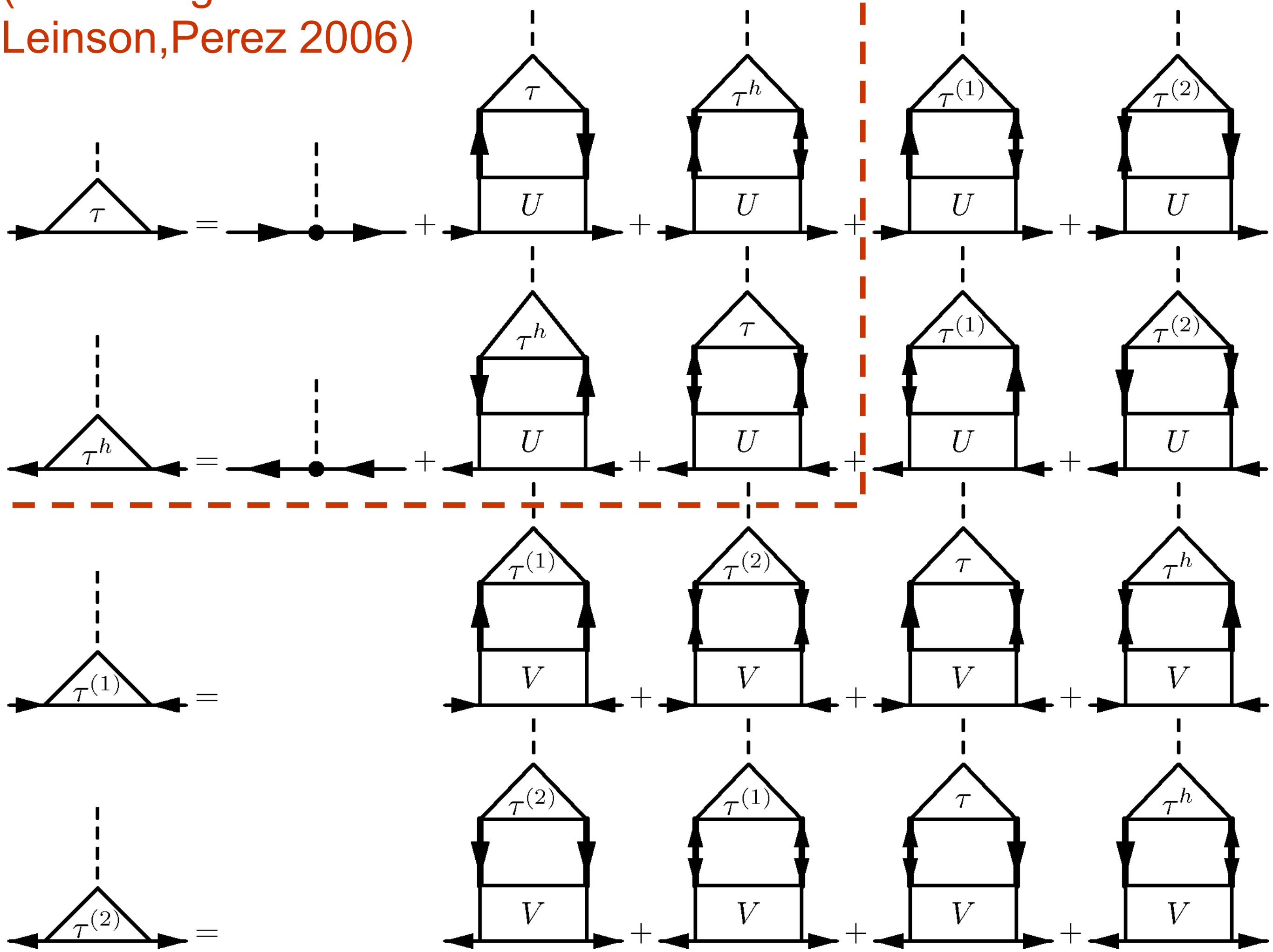
F-factors with HDD (similar to APR) EoS



Larkin-Migdal equations for superfl. matter

PBF processes: Flowers, Ruderman, Sutherland 1976 used free vertices

taken into account in D.V.,Senatorov 1987
(not enough for vector cur. conserv.:
Leinson,Perez 2006)



Cannot be written in matrix form in Nambu-Gor'kov space since U ≠ V

Back to PBF

$$\epsilon^{(n)}_{\nu\nu,A} \simeq \left(1+\frac{11}{21}-\frac{2}{3}\right) v^2_{\mathrm{F},n}\, \epsilon^{(0n)}_{\nu\nu,A}$$

moderate suppression

Kolomeitsev,D.V. PRC(2008,2010)

$$\epsilon^{(n)}_{\nu\nu,V} \simeq \frac{4}{81} v^4_{\mathrm{F},n}\, \epsilon^{(0n)}_{\nu\nu,V}$$

strong suppression

Leinson,Perez (2006),Kolomeitsev,D.V. (2008)

with free vertices

$$\epsilon^{(0n)}_{\nu\nu} = \frac{4\rho_n\, G^2 \Delta^7_n}{15\,\pi^3} I\left(\frac{\Delta_n}{T}\right) \qquad I(z) = \int_1^\infty \frac{\mathrm{d}y\, y^5}{\sqrt{y^2-1}} e^{-2zy}\,,$$

$$R(\mathrm{nPFB}) = \frac{\epsilon^{\mathrm{nPBF}}_{\nu\nu}}{\epsilon^{(0n)}_{\nu\nu}} \simeq \frac{\epsilon^{\mathrm{nPBF}}_{\nu\nu,A}}{\epsilon^{(0n)}_{\nu\nu}} \simeq \frac{6}{7} g^{*\,2}_A\, v^2_{\mathrm{F},n} = F_n\, v^2_{\mathrm{F},n}\,.$$

$$\epsilon^{p\mathrm{PBF}}_{\nu\nu,A} \simeq \epsilon^{(0p)}_{\nu\nu}\, \tfrac{6}{7} g^{*\,2}_A\, v^2_{\mathrm{F},p}.$$

Main contribution is due to the axial current. Kolomeitsev,D.V. (2008)

Suppression of the result with free vertices is ~0.1

Purely in-medium effect!

Medium effects in thermal conductivity

loops included everywhere !!!

Important to describe young objects like Cas A Blaschke, Grigorian, D.V. 2013

lepton term
with inclusion of
Landau damping
(ee^{-1} loops)

Shternin,Yakovlev (2007)

$$\kappa_e = 8.5 \cdot 10^{21} \left(\frac{p_{\mathrm{F},e}}{\mathrm{fm}^{-1}} \right)^2 f_e \,\mathrm{ergs\ s^{-1} cm^{-1} K^{-1}}, \quad (3)$$

$$f_e \simeq \frac{2.7}{e^{1.3T/T_{cp}} - 1},$$ yields suppression of previous Baiko result

for $T < T_{cp}$ and $f_e = 1$ for $T > T_{cp}$. For simplicity a contribution of muons is neglected.

nn- term with inclusion
of pion softening

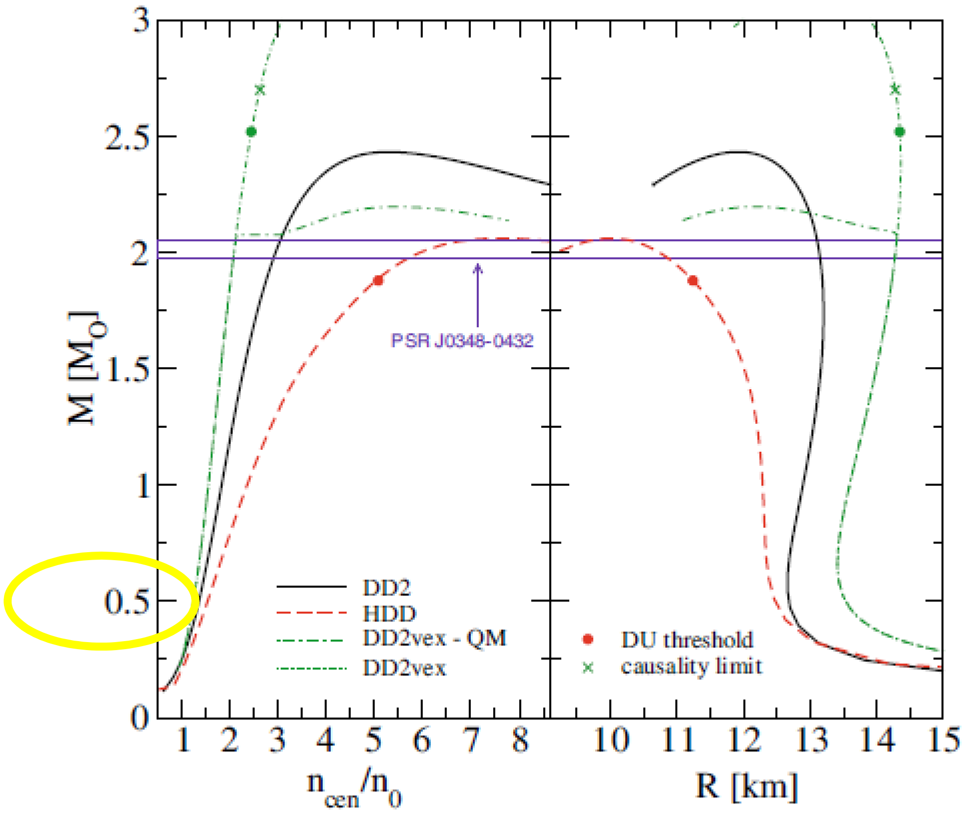
$$\kappa_b = \kappa_b^{\mathrm{SY}} \left(\omega^*(n)/m_\pi\right)^3 \left(\Gamma(n_0)/\Gamma(n)\right)^4 n_0/n$$

Blaschke, Grigorian, D.V. 2004,2013

One more inconsistency of minimal cooling model: includes now medium effects in lepton thermal conductivity but ignores them in many other relevant effects

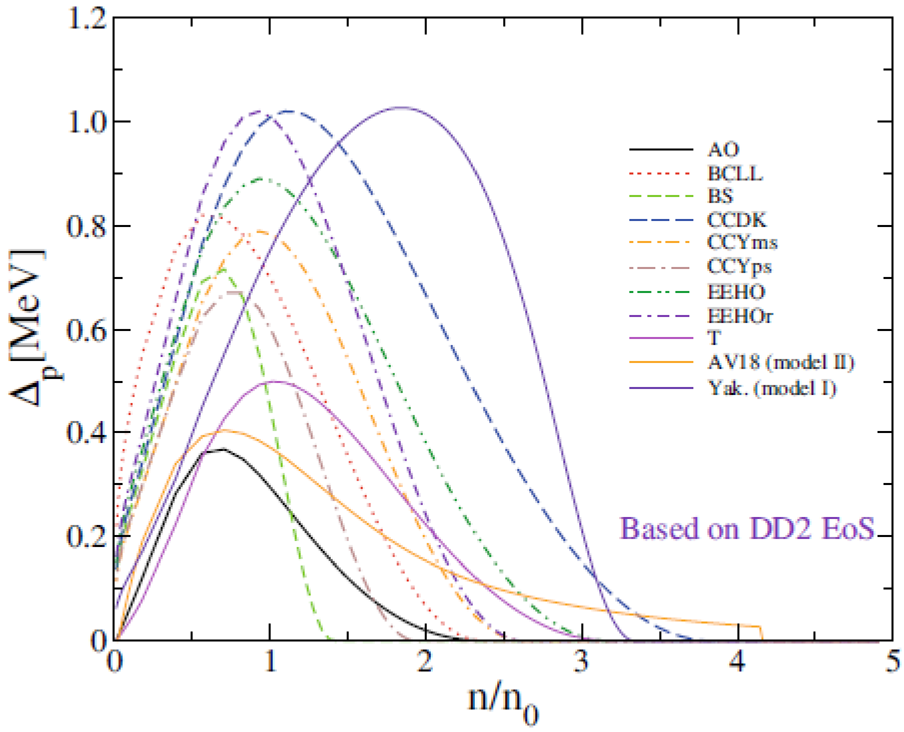
NS Mass-central density plot for EoSs that we use

Blaschke, Grigorian, D.V. 2013



We incorporated excluded volume effect: HDD EoS is very close to KVOR, APR EoS for n<4 n_0 (thus we satisfy the HIC-flow constraint) but EoS stiffens for n>4n_0 increasing M_{max}. DD2 does not fulfil the flow constraint.

$1S_0$ proton pairing gap models



Nuclear medium cooling scenario

Blaschke, Grigorian, D.V. 2013,2016

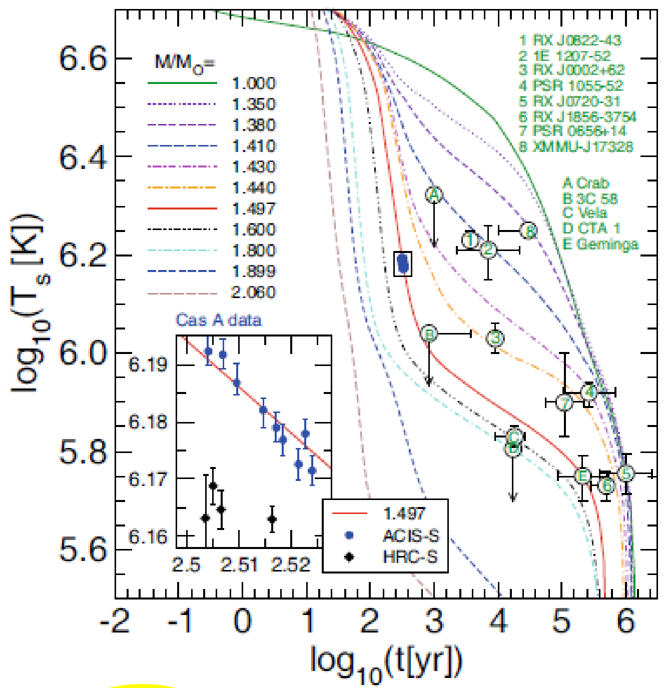
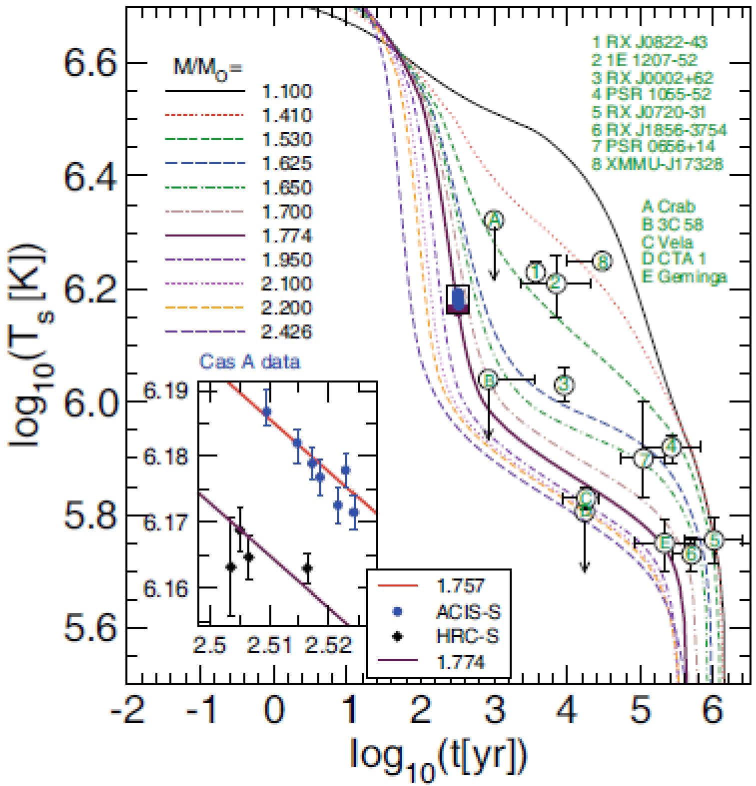


Fig. 4. Cooling curves for a NS sequence according to the hadronic HDD EoS: T_s is the redshifted surface temperature, t is the NS age. The effective pion gap is given by the solid curve 1a+1b in fig. 2, $n_c^\pi = 3n_0$. The $1S_0$ pp pairing gap corresponds to model I. The mass range is shown in the legend. Comparison with Cas A ACIS-S and HRC-S data is shown in the inset. Cooling ACIS-S data for Cas A are explained with a NS mass of $M = 1.497 M_\odot$.



An example for DD2 EoS of S. Typel

Cooling of NS can be explained within “Nuclear medium cooling scenario”, i.e., taking into account pion softening and other medium effects on neutrino emissivity.

Research was supported by RNF grant No. 17-12-01427,
visit to Yerevan was also supported by Helmholtz International Center