Surprising pairing properties around the drip line and in the crust of neutron stars

J. Margueron, IPN Lyon, France.

I- Superfluidity and neutron stars

II- Surprising features of superfluidity

In collaboration with :

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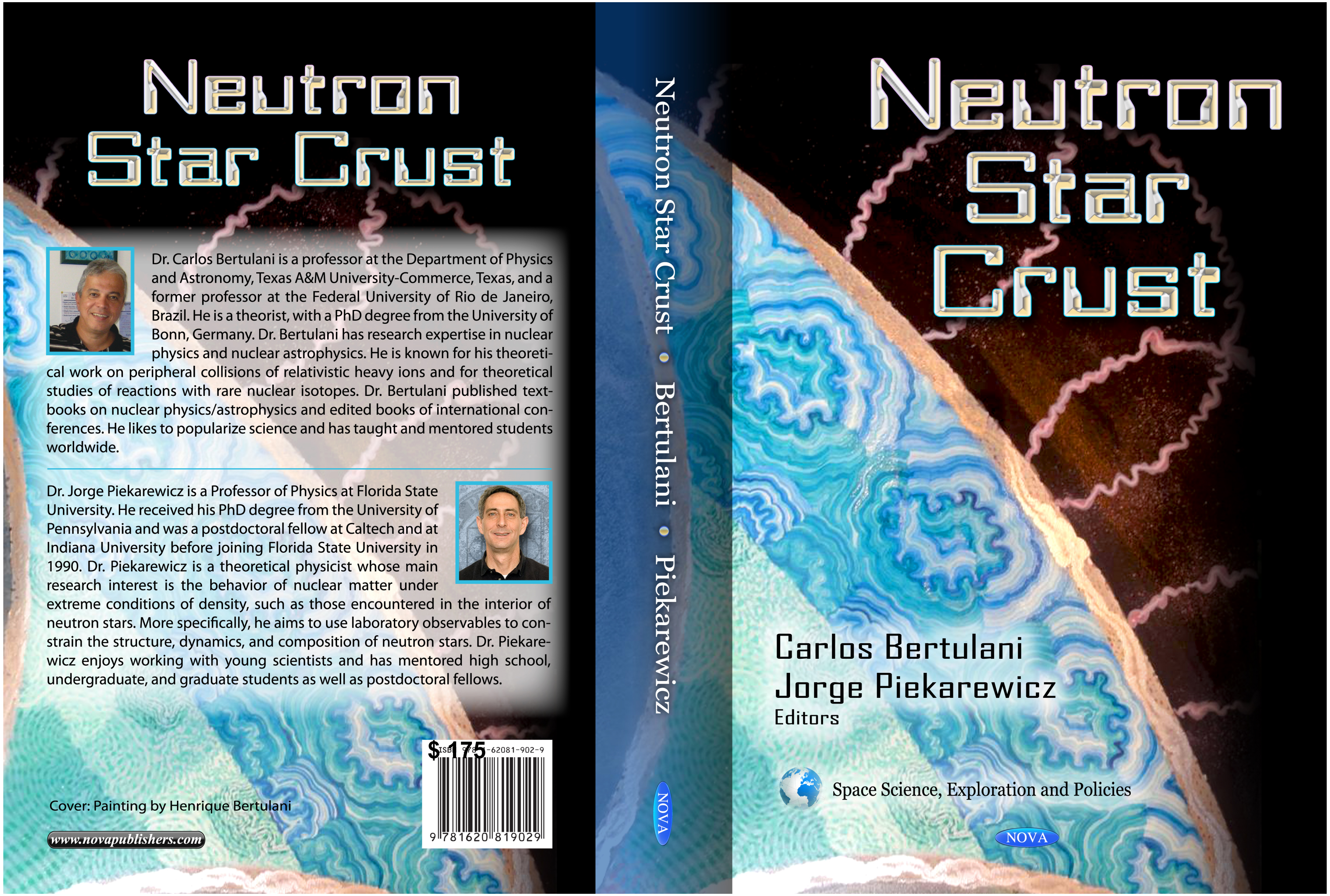
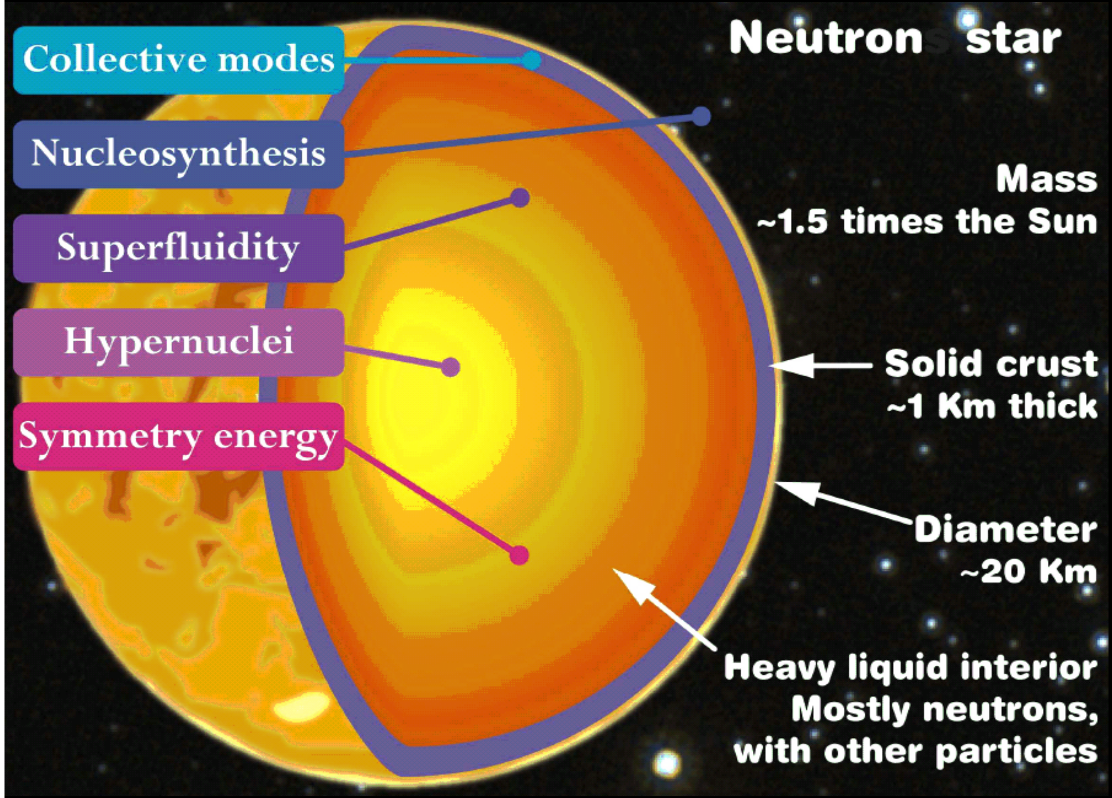
A. Pastore (IAA Bruxelles),
N. Sandulescu (NIPNE Bucharest),
P. Schuck (IPN Orsay),
X. Vinas (Univ. of Barcelona).

What is a neutron star? What is the crust of neutron stars?



Exploring foundamental physics with neutron stars

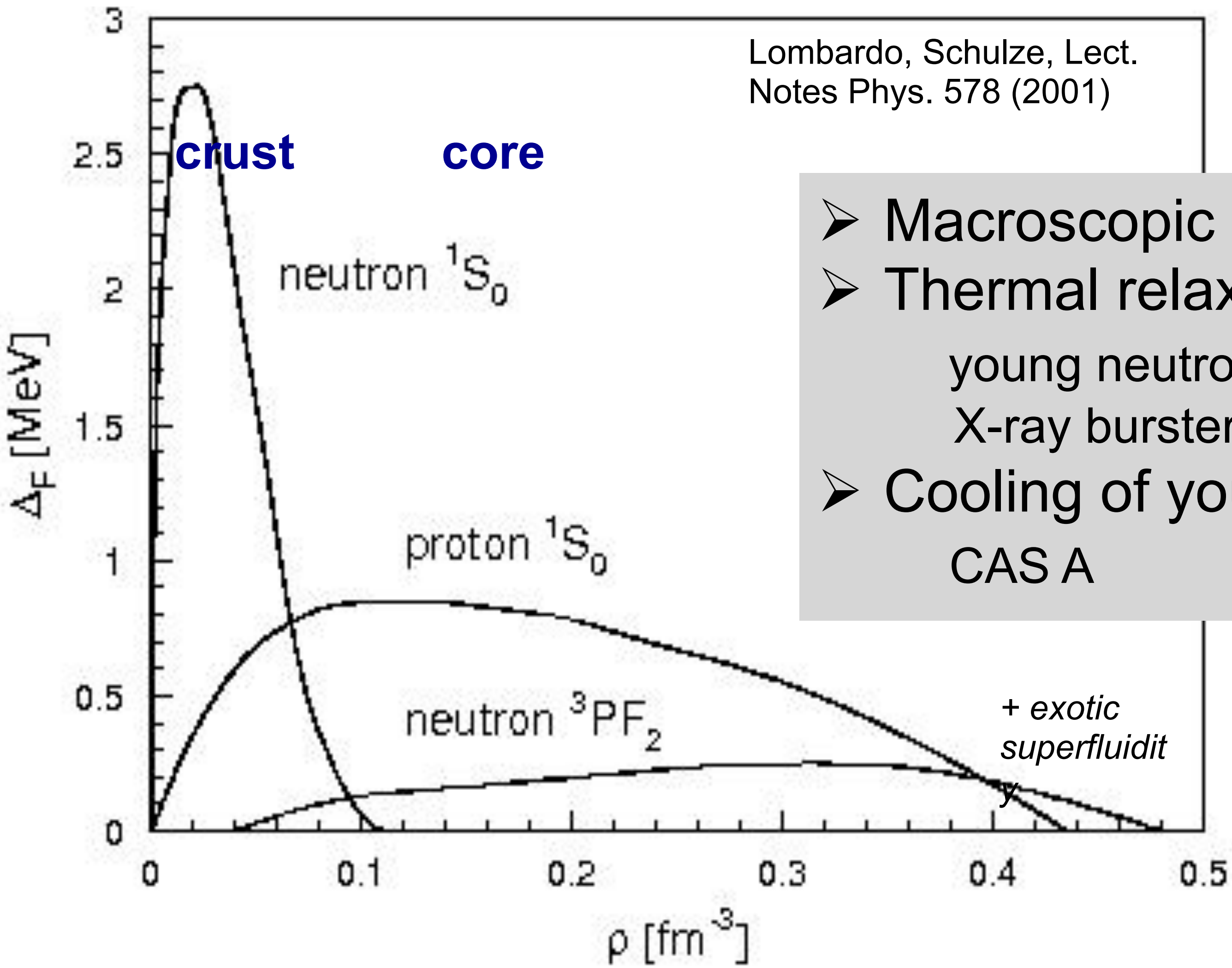


Neutron star is a laboratory to study matter under *extreme conditions* (density, temperature, ...)

Interdisciplinary **field: nuclear and particle physics, condensed matter and plasma physics, astrophysics, ...**

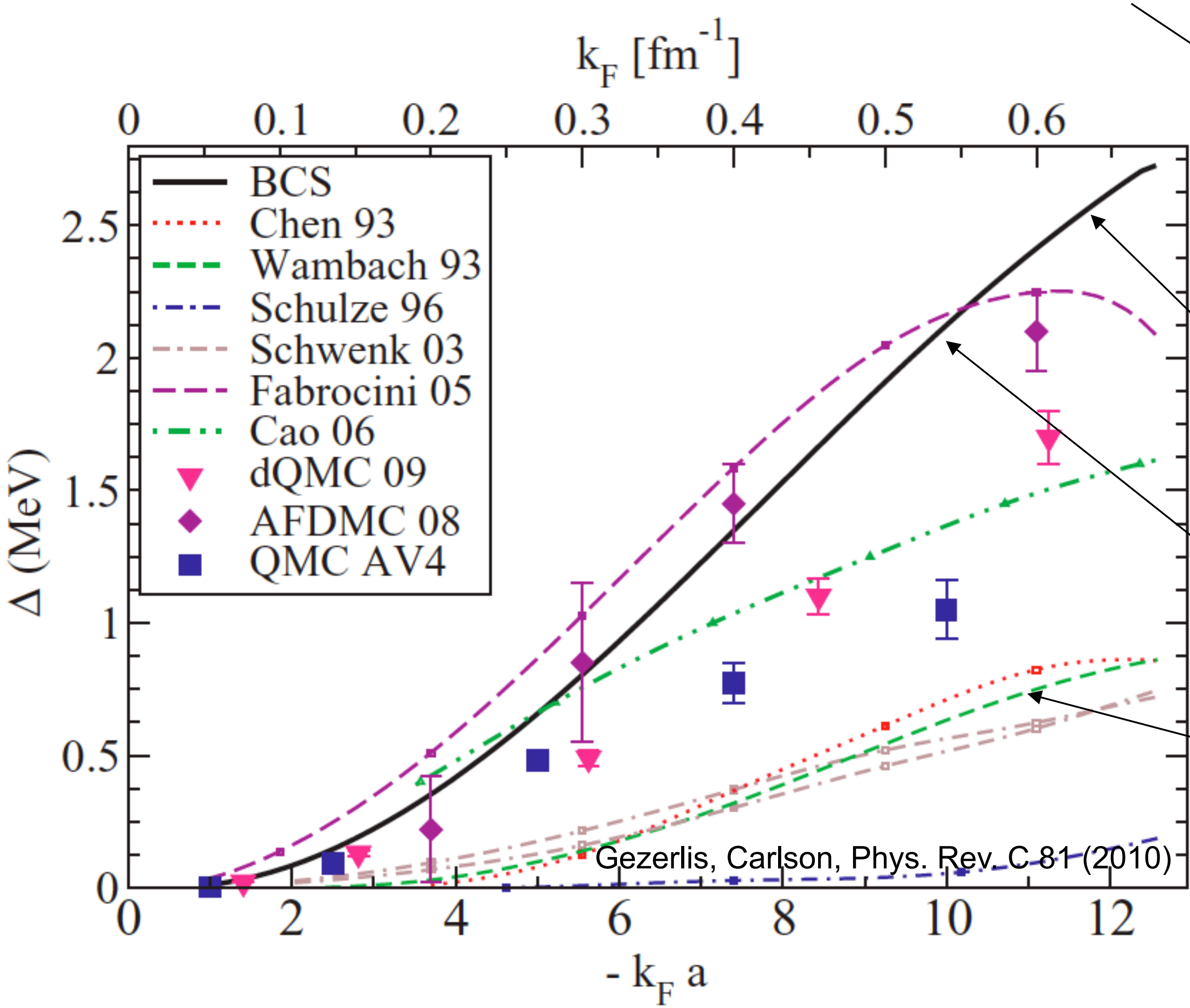
Neutron stars are macroscopic superfluids

Superfluidity & Neutron stars



- Macroscopic Glitches
- Thermal relaxation of the crust
  - young neutron stars
  - X-ray bursters
- Cooling of young neutron star
  - CAS A

$^1S_0$ Pairing in uniform matter : large "theoretical errorbars"



Needs for observational constraints

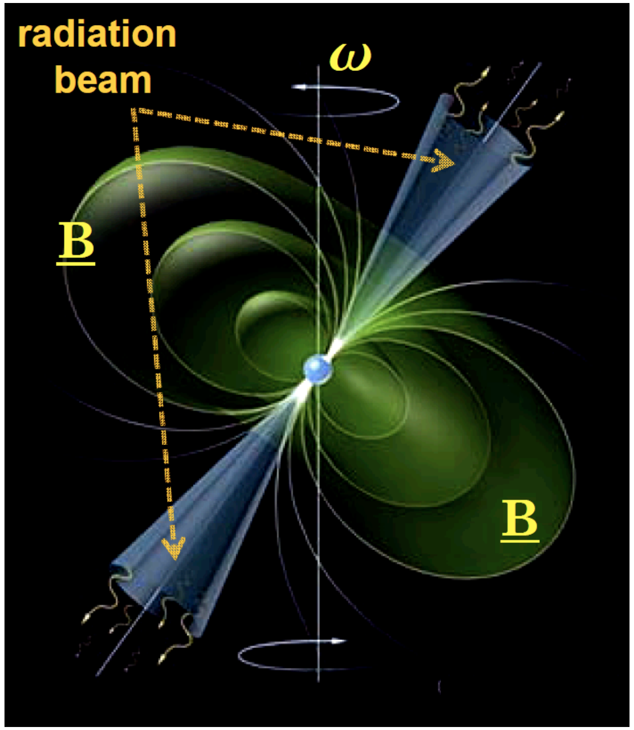
BCS

Strong
(max at 3 MeV),

Weak
(max at 1 MeV).

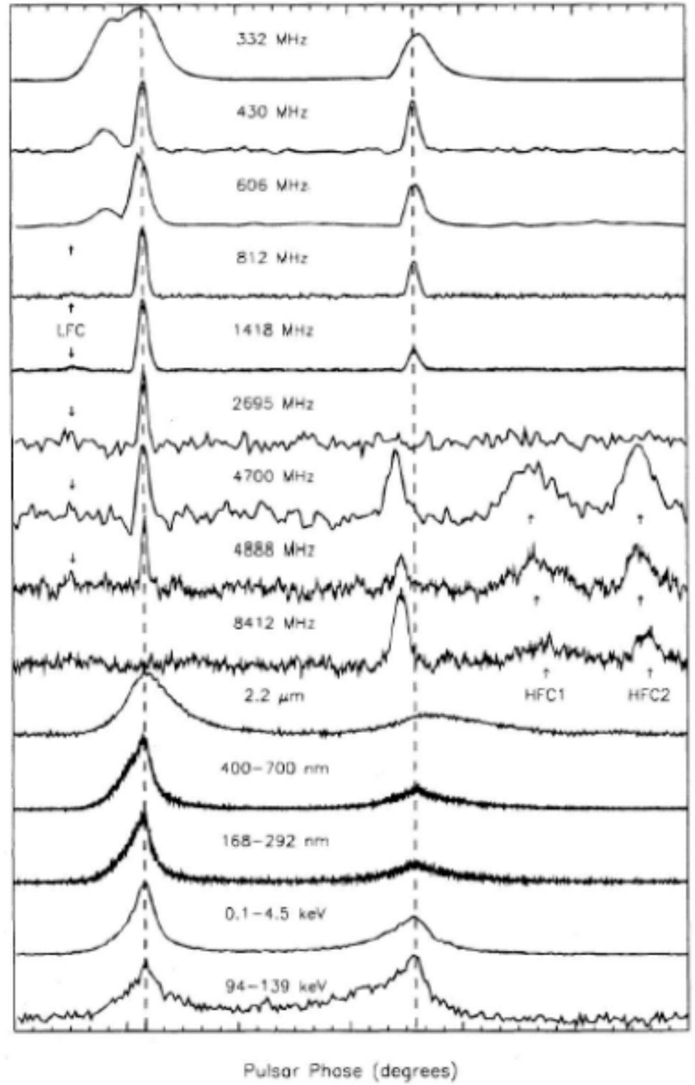
Superfluidity and rotation of neutron stars

Lighthouse model



Period ~ few s to few ms

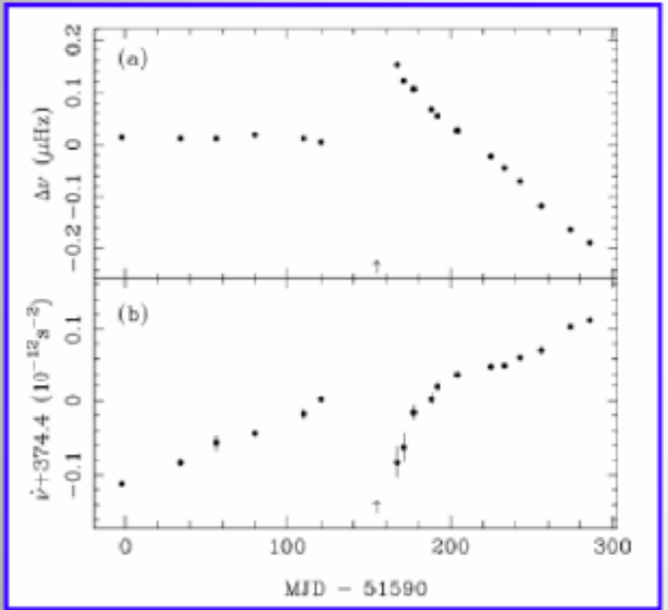
Observed pulse of Vela

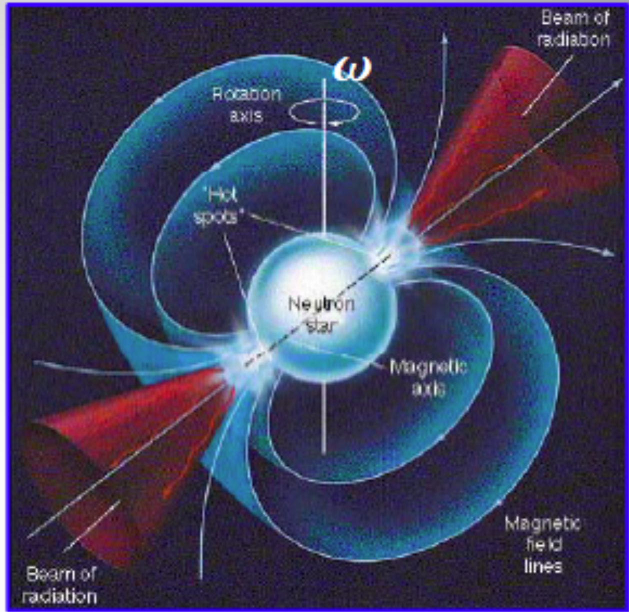


Slides from P. Pizzochero, Univ. of Milano

Pulsar glitches

Steady rotational slow-down of Pulsar due to emission of e.m. and gravitational waves

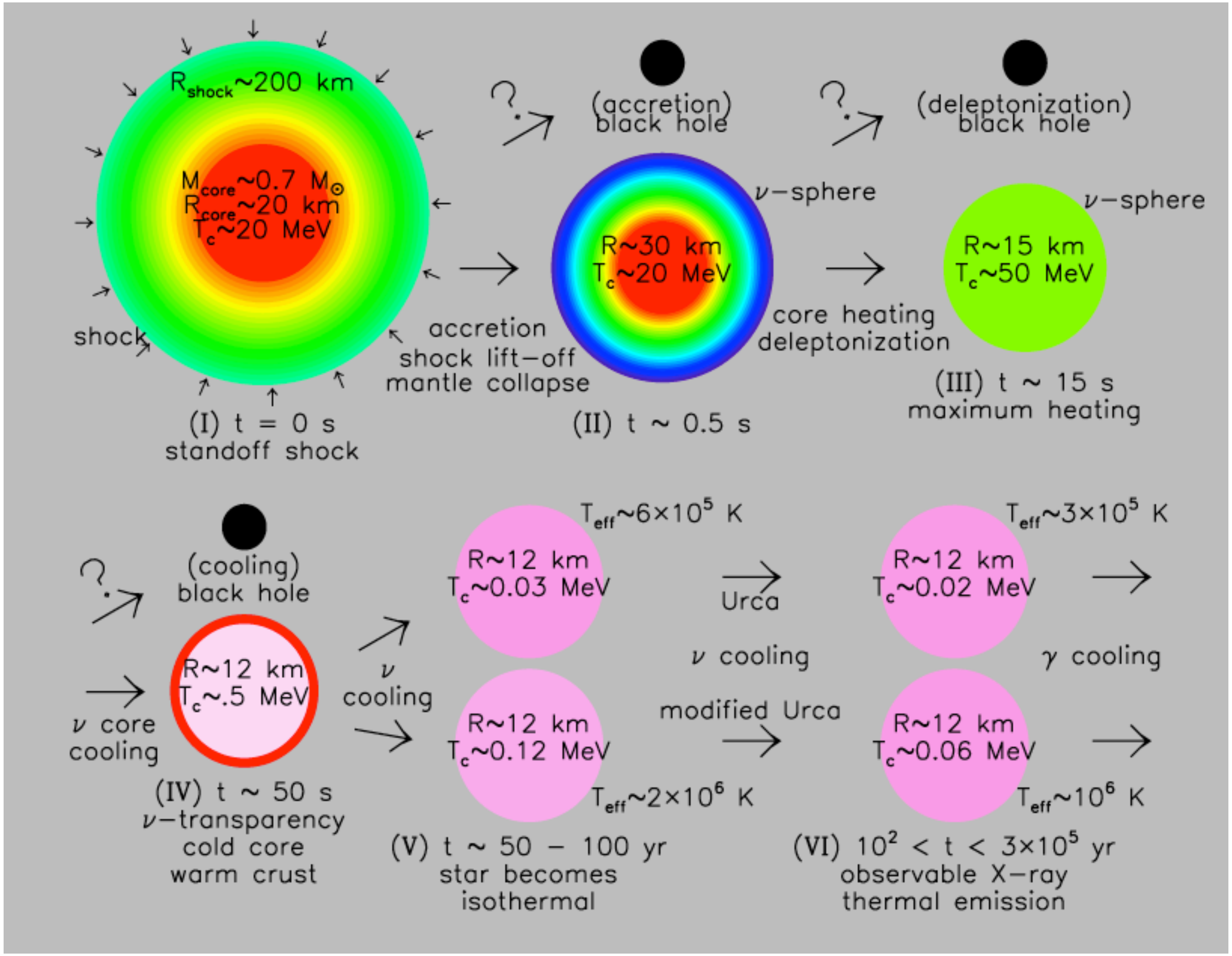


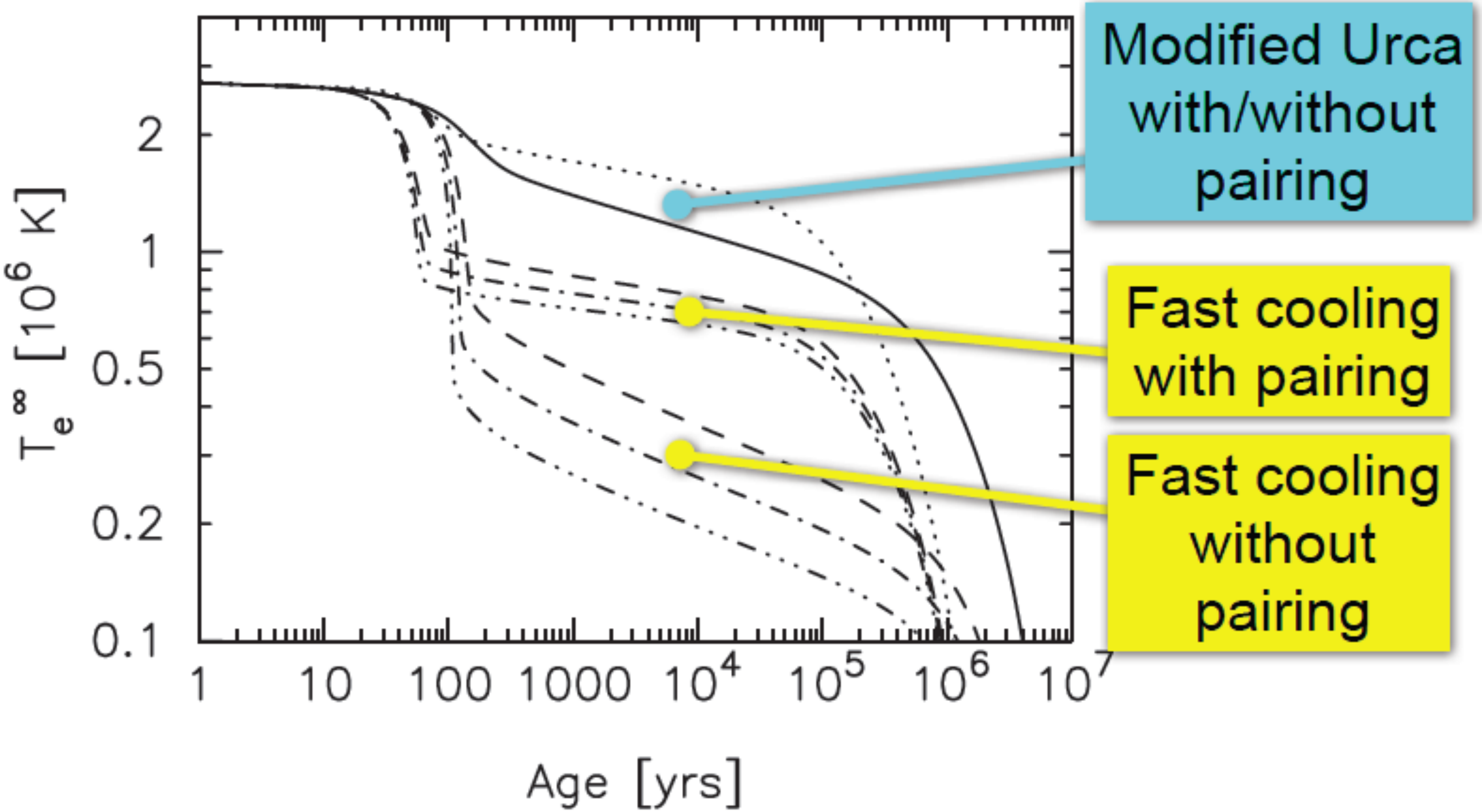


Pulsar glitches are recurrent spin-ups of rotational frequency ($\Delta\omega \sim 10^{-8}$- $10^{-6}\,\omega$) without external forces

Glitches as direct observational evidence of the existence of macroscopic (km-sized) **nucleon superfluidity** inside NS

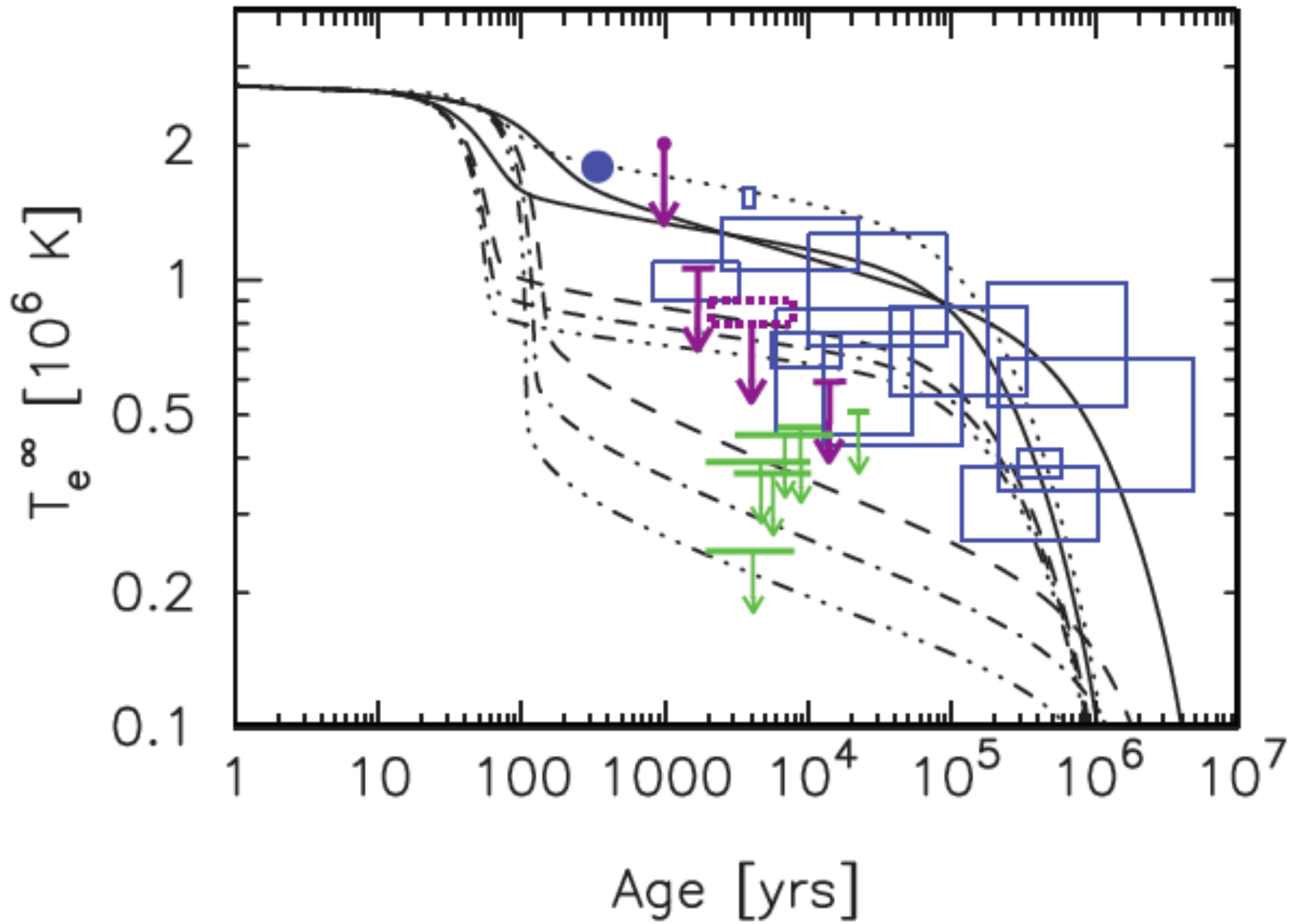
Superfluidity and cooling of neutron stars





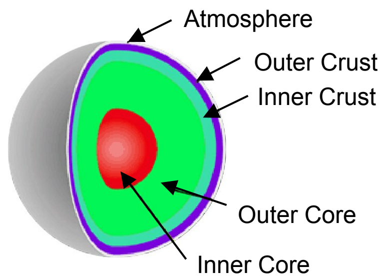
D. Page, CompStar2012, Tahiti

Data versus model



D. Page, CompStar2012, Tahiti

Thermal relaxation of Neutron stars

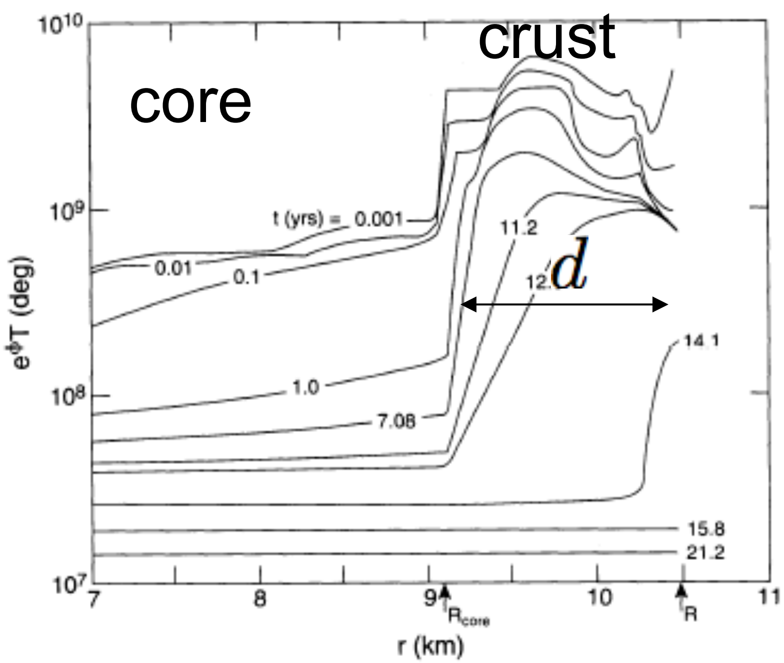


Fast cooling of the core:

→ after ~1 year: Tcore << Tcrust ~0.5 MeV,
→ next ~10-100 years: **thermalisation** of the crust:

$$\tau \propto \frac{d^2}{D}$$

with $$D = \frac{K}{\sum_i C_{v,i} \approx C_{v,n}}$$



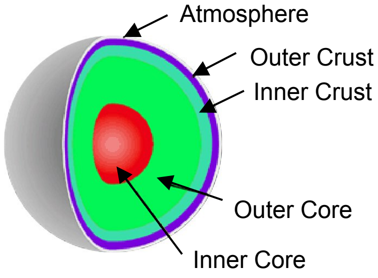
Lattimer et al., APJ 425 (1994)

K, conductivity

$C_{v,n}$ neutron specific heat

} depend on the cluster structure

Thermal relaxation of Neutron stars



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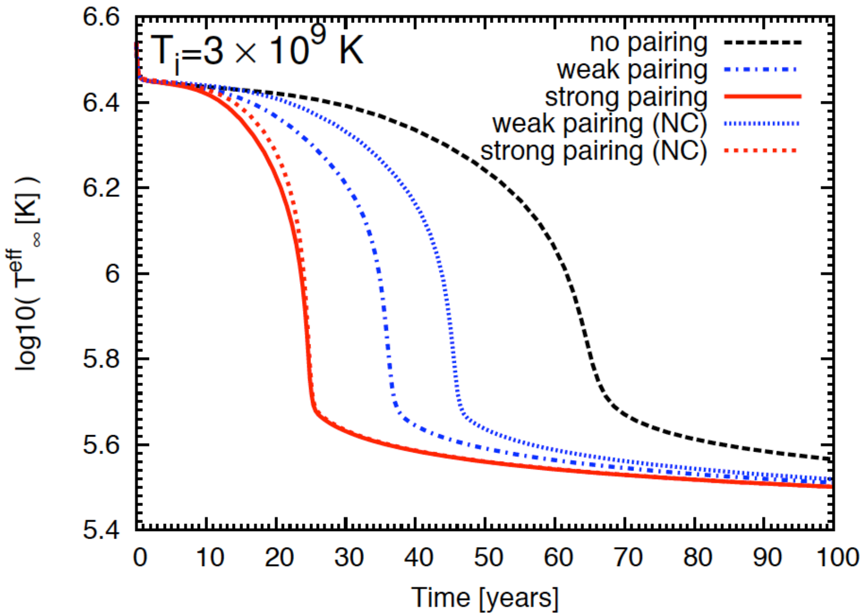

Fortin, Grill, J.M., Page, Sandulescu, PRC 88 (2010)

K, conductivity

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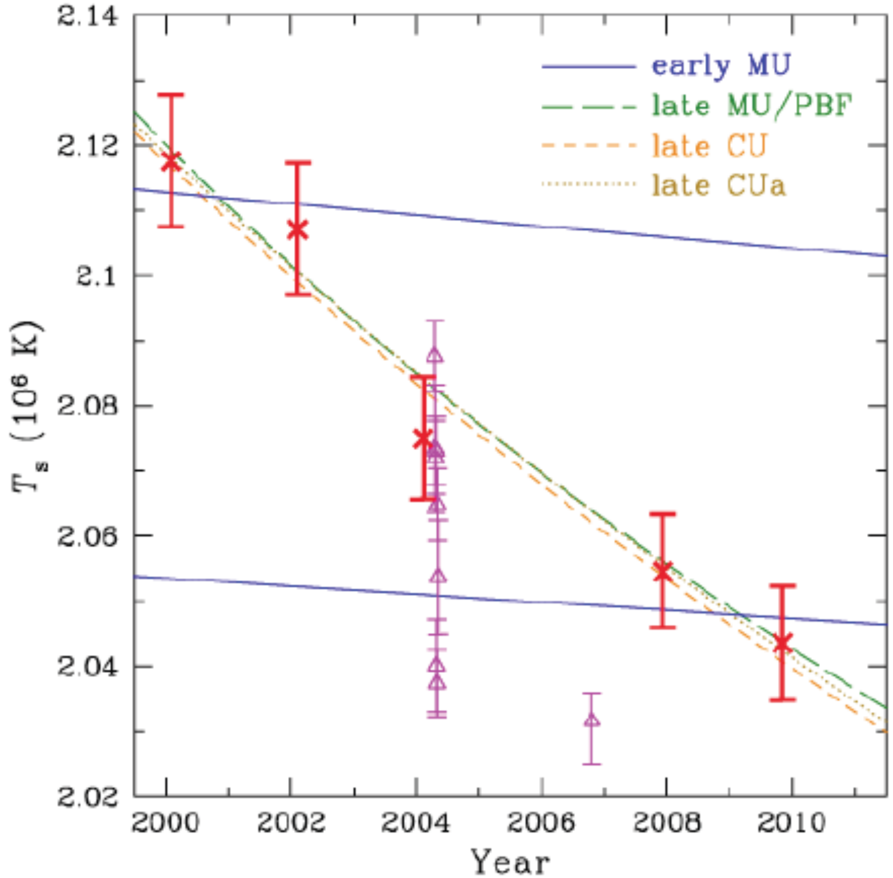
} depend on the cluster structure

Rapid cooling of Cas A

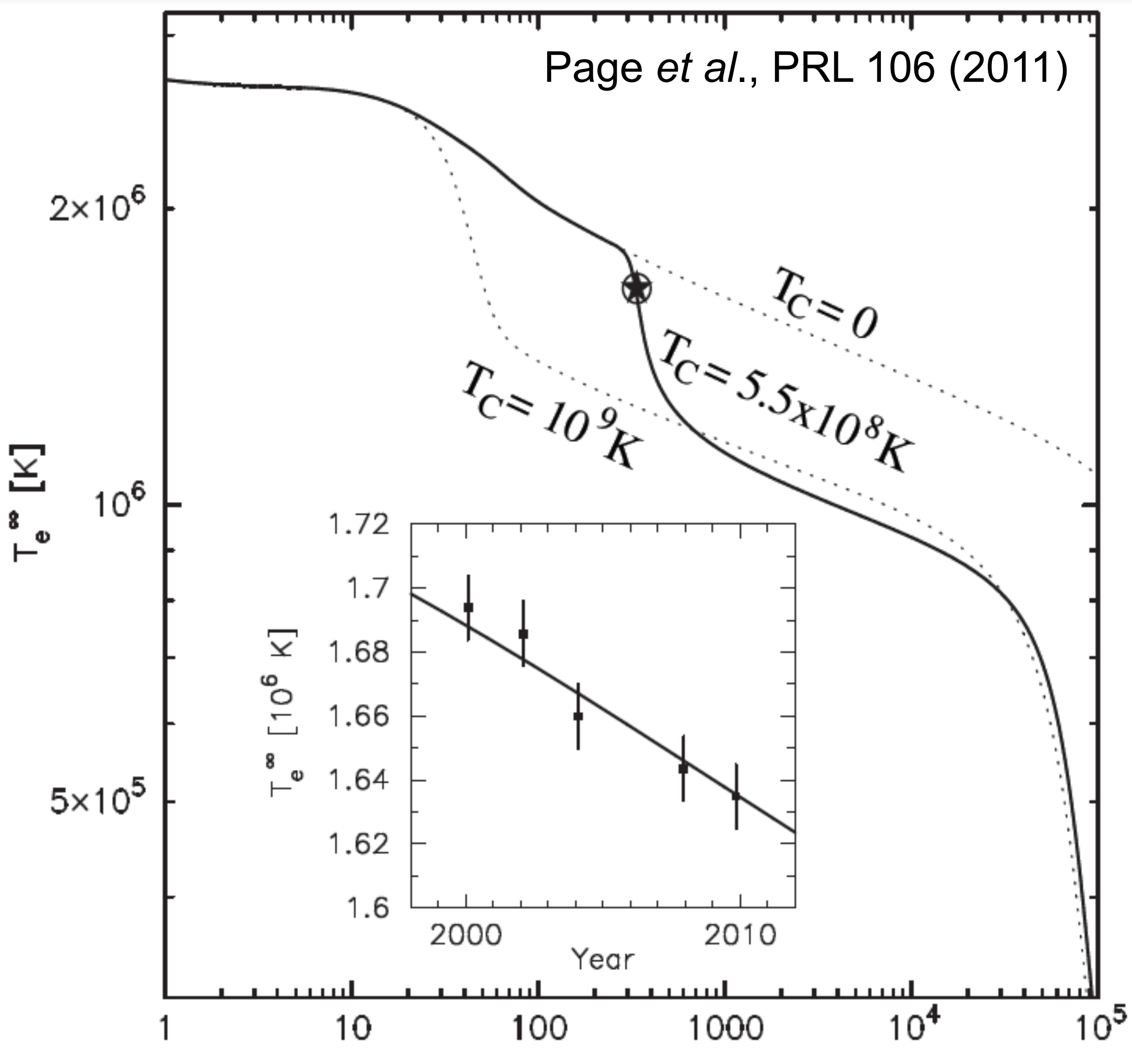
4% decrease in T_e
20% decrease in L_γ



Direct Observation of the Cooling of the Cassiopeia A Neutron Star
Heinke, Craig O.; Ho, Wynn C. G. 2010ApJ...719L.167H

D. Page, CompStar2012, Tahiti

Rapid cooling of Cas A

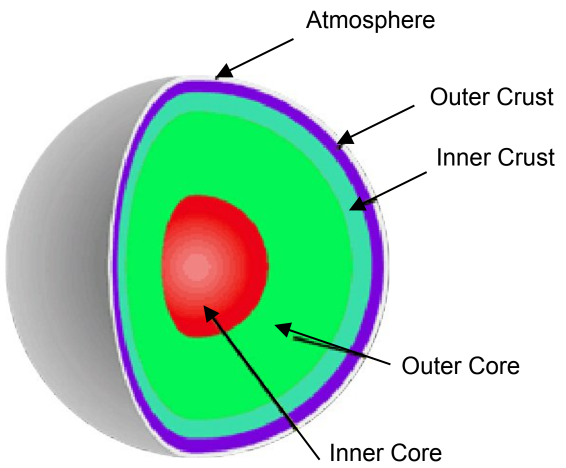


Constrain on 3P2 neutron and 1S0 proton pairing.

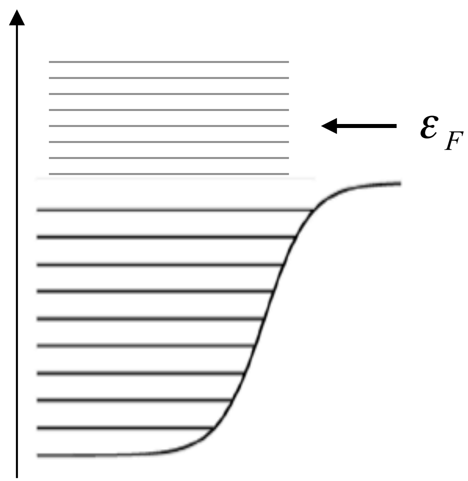
First direct observation of superfluidity in the core of neutron stars.

Part II:

Surprising features of superfluidity



Transition outer / inner crust



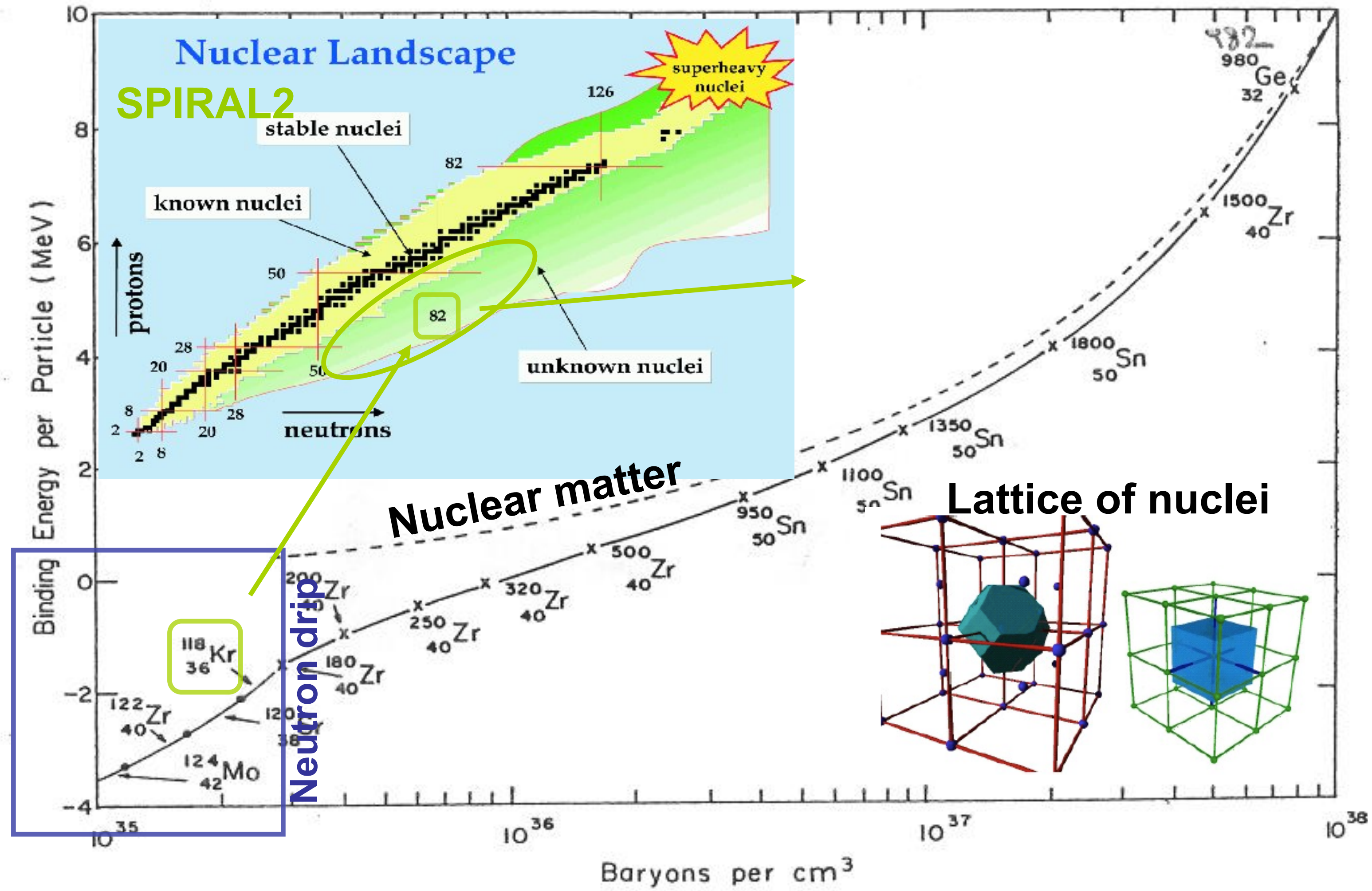
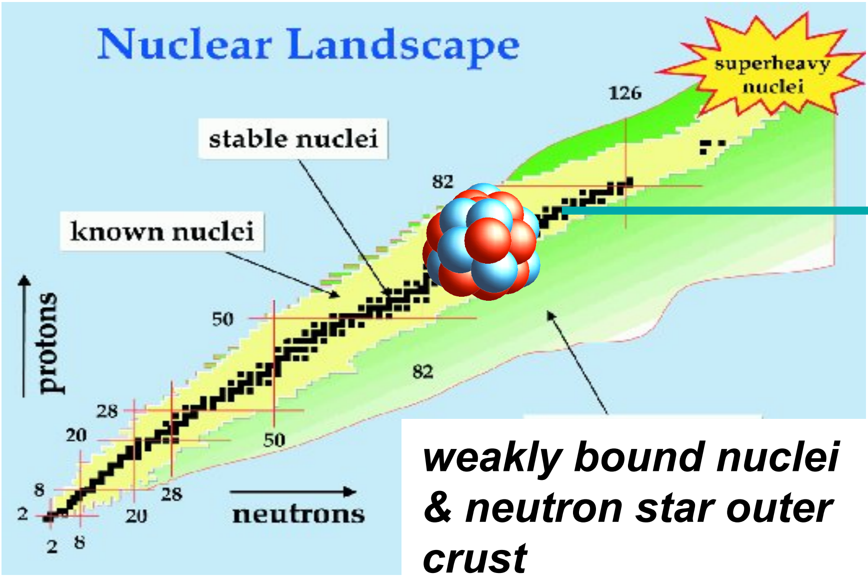


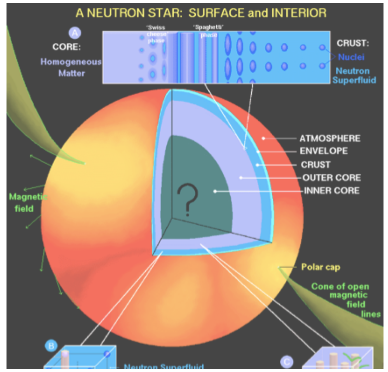
Fig. 2. Energy per particle versus baryon density.

From stable nuclei to nuclear matter



Increasing number of neutrons
Or increasing density

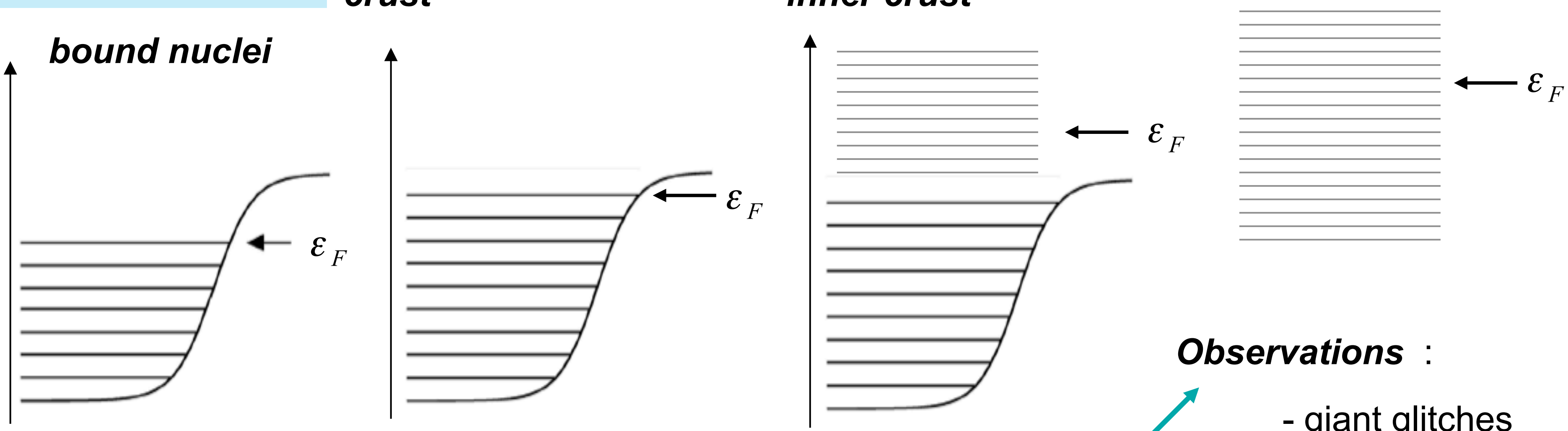
$$e + p \rightarrow n + \nu$$



weakly bound nuclei & neutron star outer crust

Finite temperature nuclei & neutron star inner crust

Uniform matter



Observations :

- giant glitches
- cooling

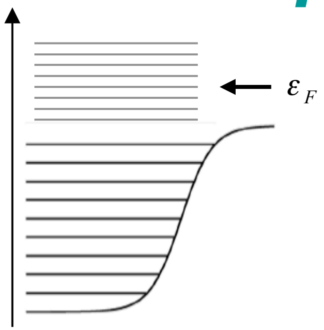
Measurements

- binding (e.g., neutron skins and halos)
- quasi-particle excitations

Nuclear density functional approach

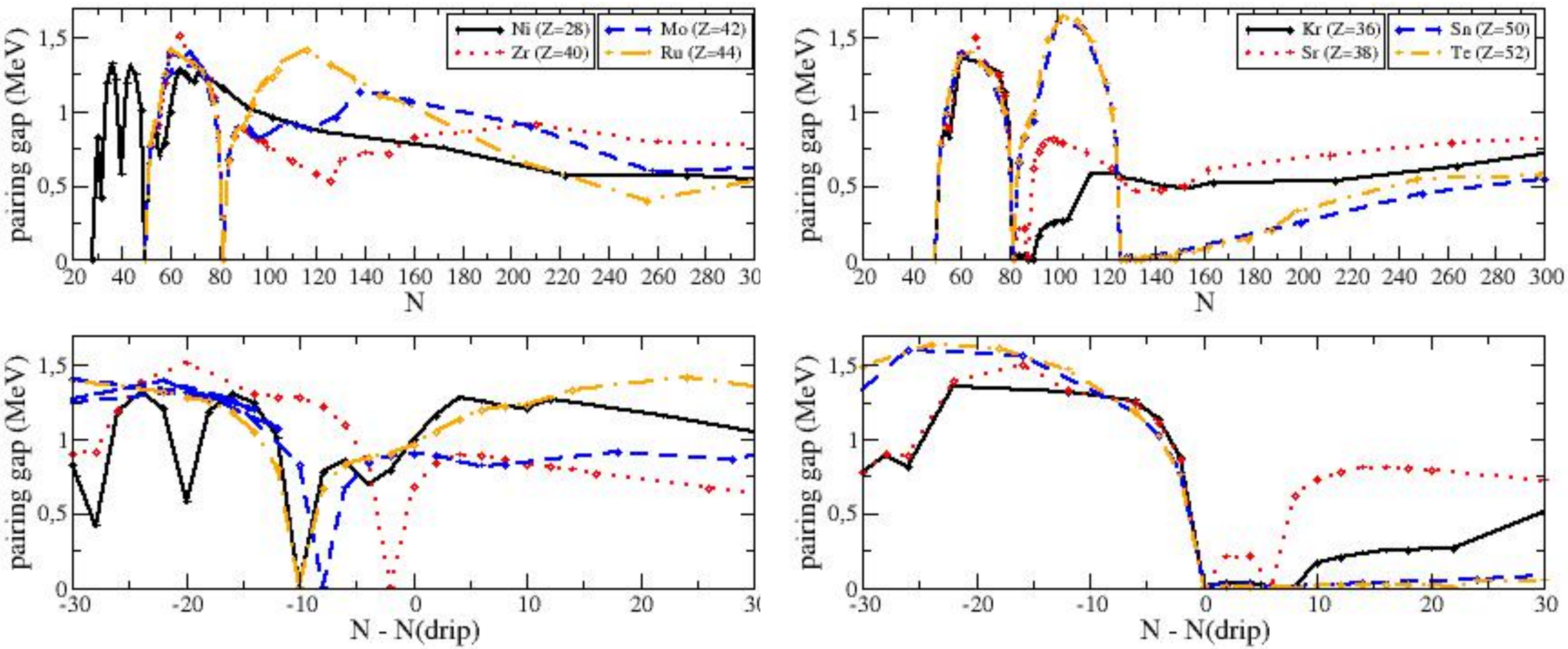
A systematic study based on 8 isotopes with 28<Z<50

Nucleus	Z	N_{drip}	group	N_{res}
Ni	28	60	$\mathcal{A}_1$	3.0
Kr	36	82	$\mathcal{A}_2$	0.0
Sr	38	82	$\mathcal{A}_2$	0.0
Zr	40	84	$\mathcal{A}_1$	2.2
Mo	42	90	$\mathcal{A}_1$	8.0
Ru	44	92	$\mathcal{A}_1$	3.0
Sn	50	126	$\mathcal{A}_2$	0.0
Te	52	126	$\mathcal{A}_2$	0.0



Suppression or persistence of pairing upon overflowing neutrons.

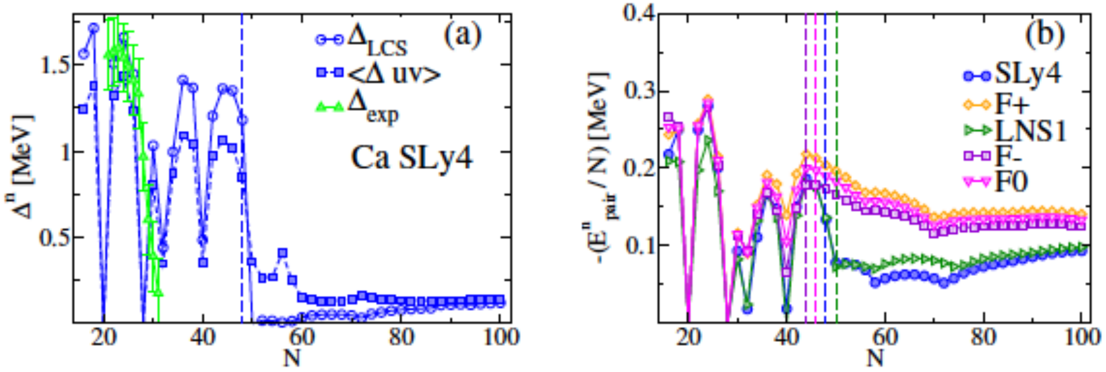
group $\mathcal{A}_1$ group $\mathcal{A}_2$



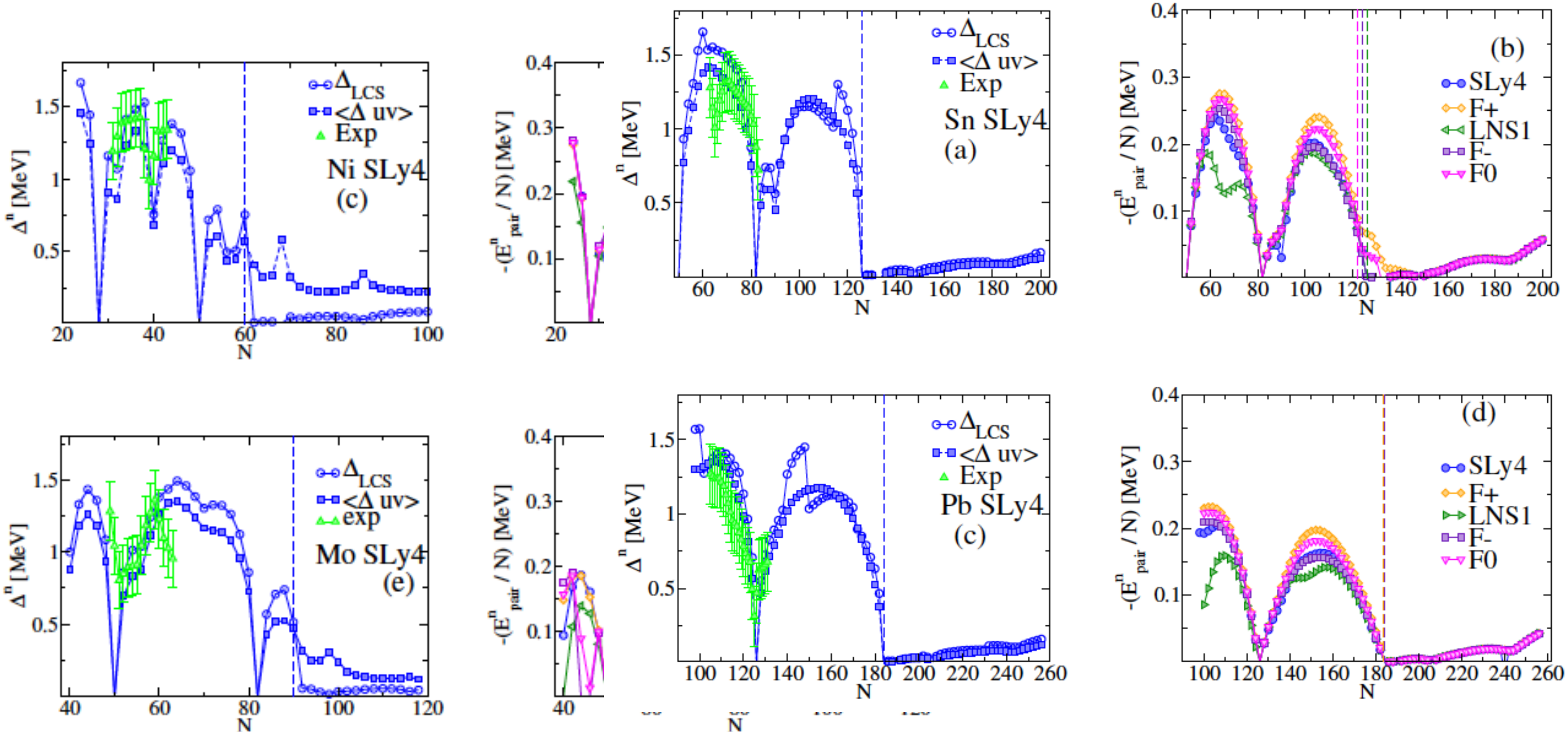
J.M. & Khan, PRC 2012

Weak dependence on the model

Group A_1



Group A_2



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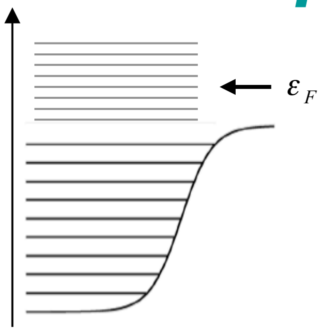
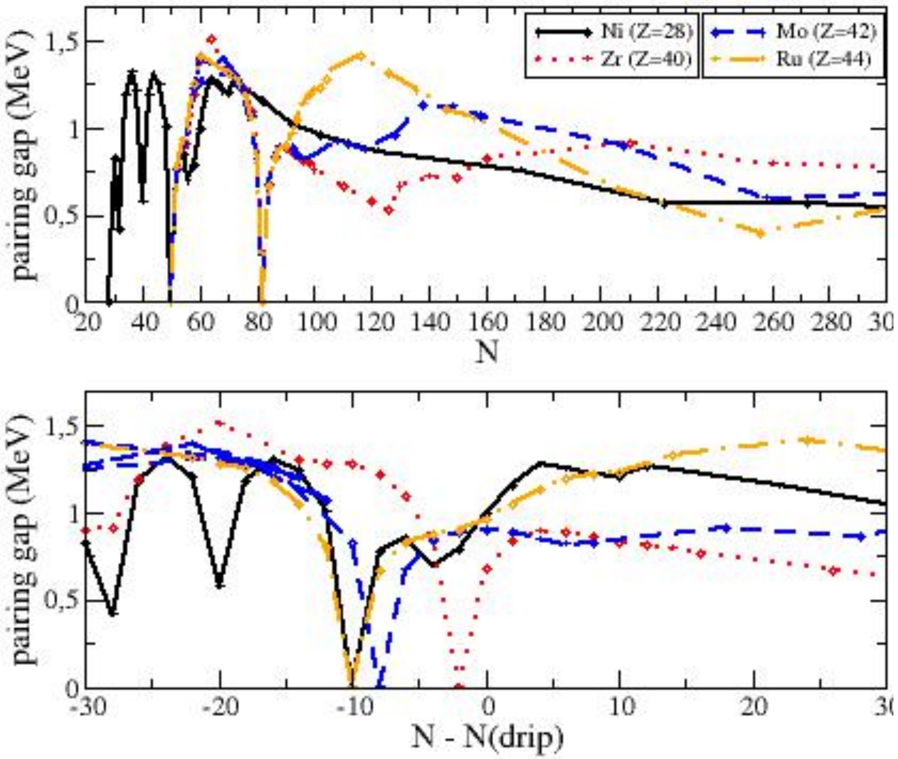
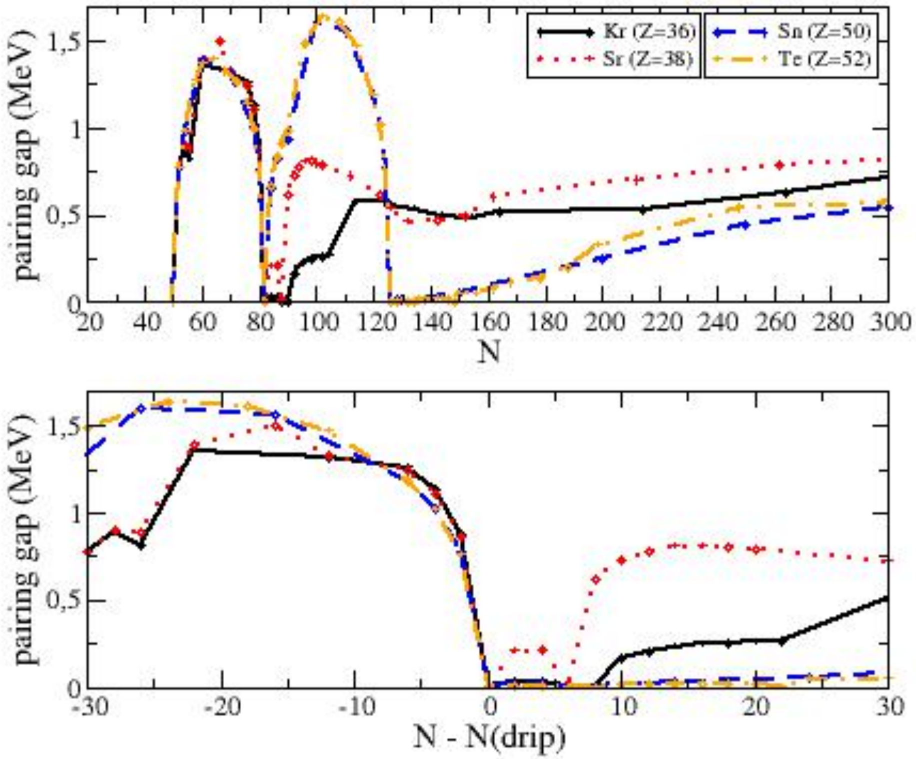


Pairing is suppressed in the absence of occupied resonant states at the drip-line.

group $\mathcal{A}_1$

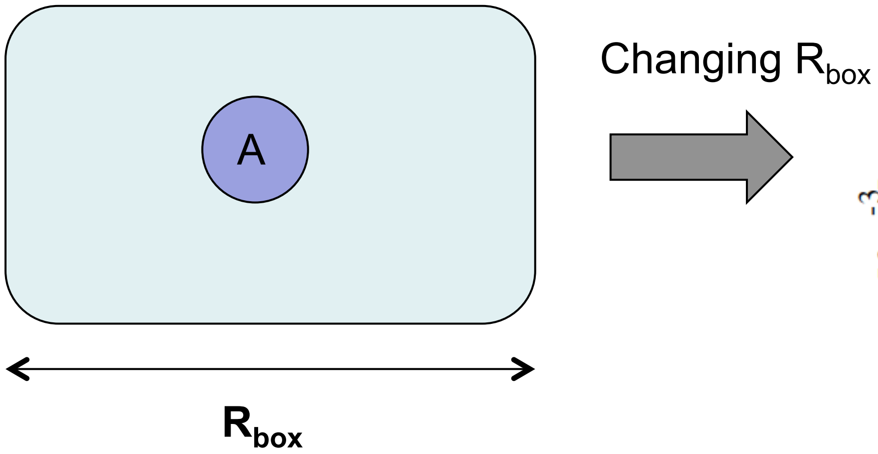


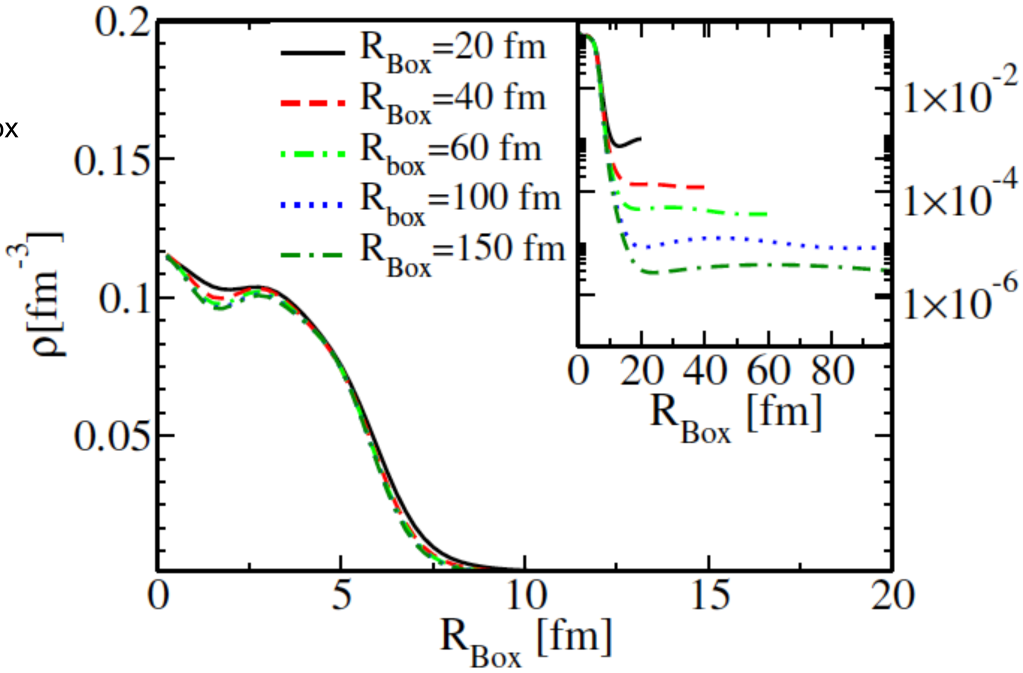
group $\mathcal{A}_2$



J.M. & Khan, PRC 2012

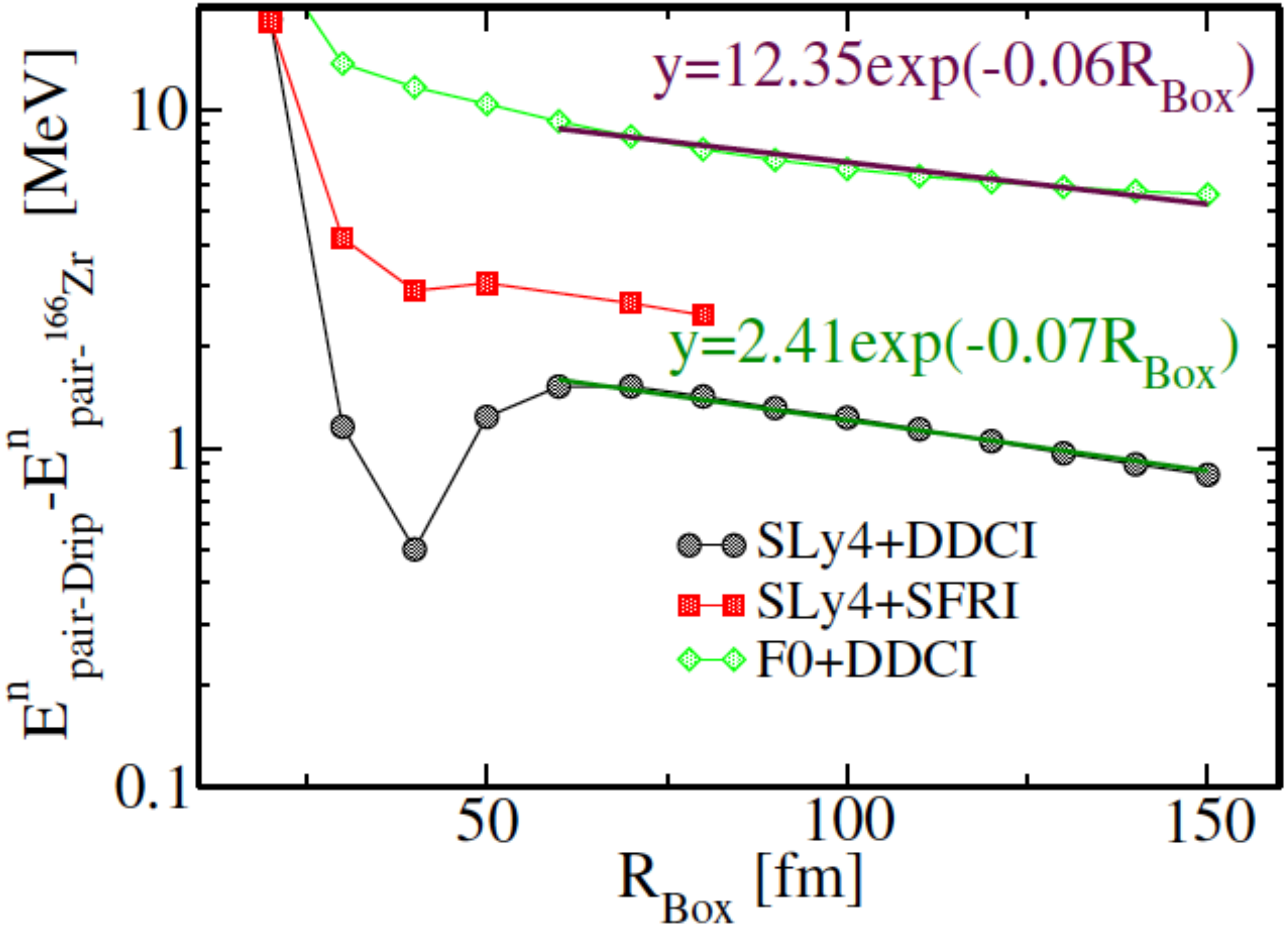
Interaction of a shallow gas with a nucleus





How does the pairing energy changes with R_{box}?

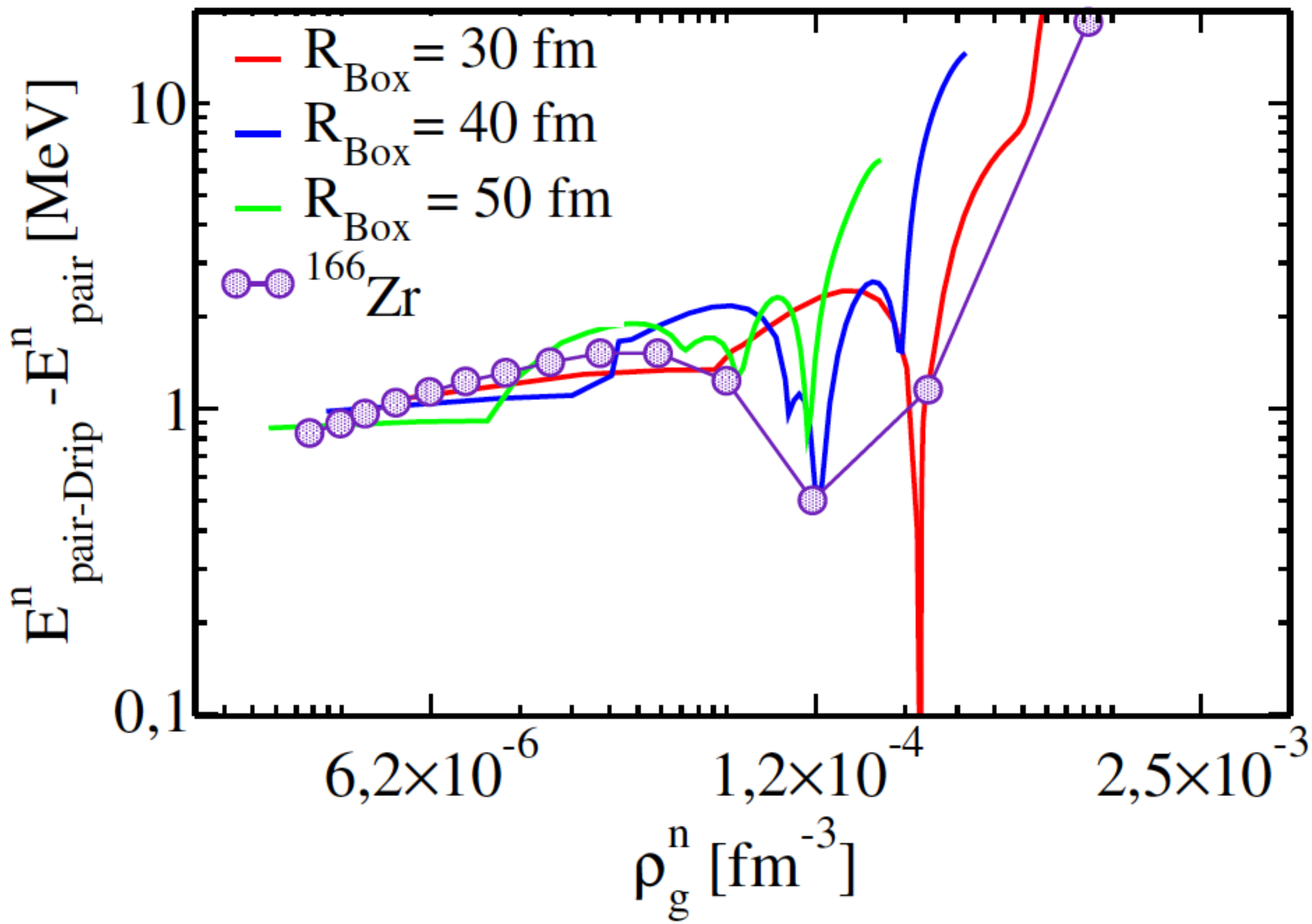
Interaction of a shallow gas with a nucleus



Pastore, JM, Schuck, Vinas, to be submitted

Interaction of a shallow gas with a nucleus

Fix Rbox, and decrease the total number of neutrons



Pastore, JM, Schuck, Vinas, to be submitted

Temperature effects on superfluidity

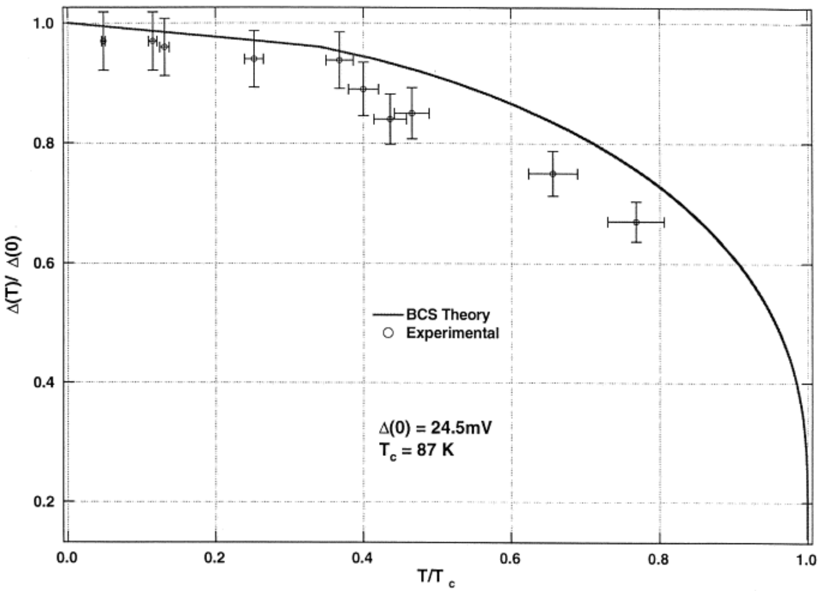
Text-book features of BCS

B

C

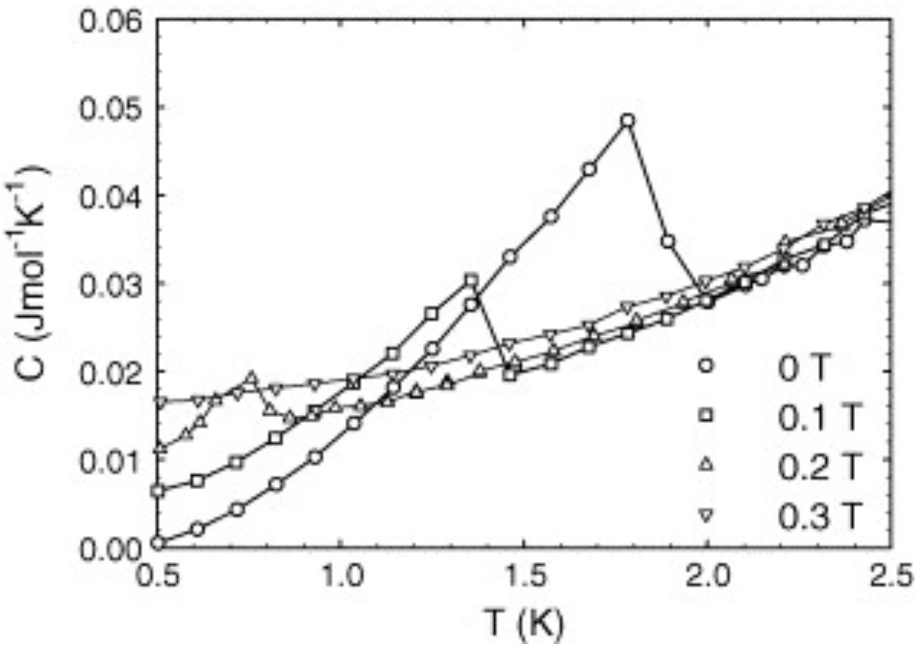
S

pairing gap



T/T_c

Specific heat

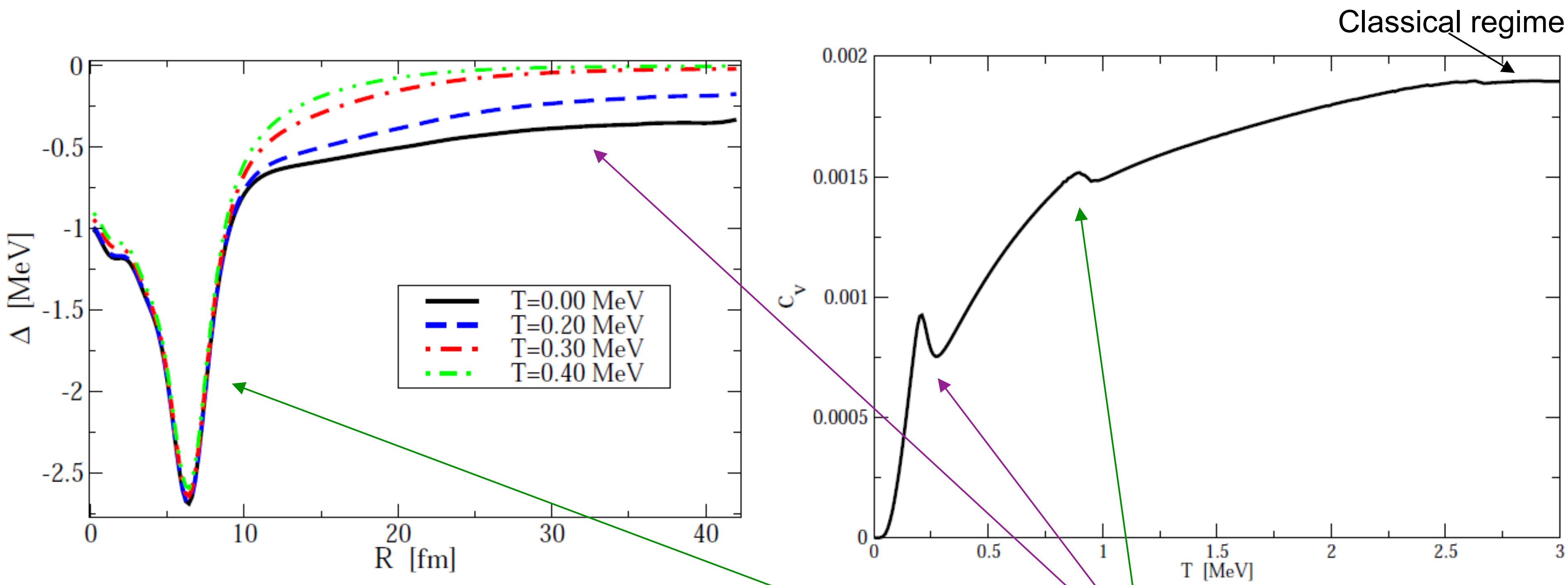


Neutrons specific heat in ^{500}Zr

N=460, Z=40

Pairing field profile
at various temperatures:

Neutron specific heat:



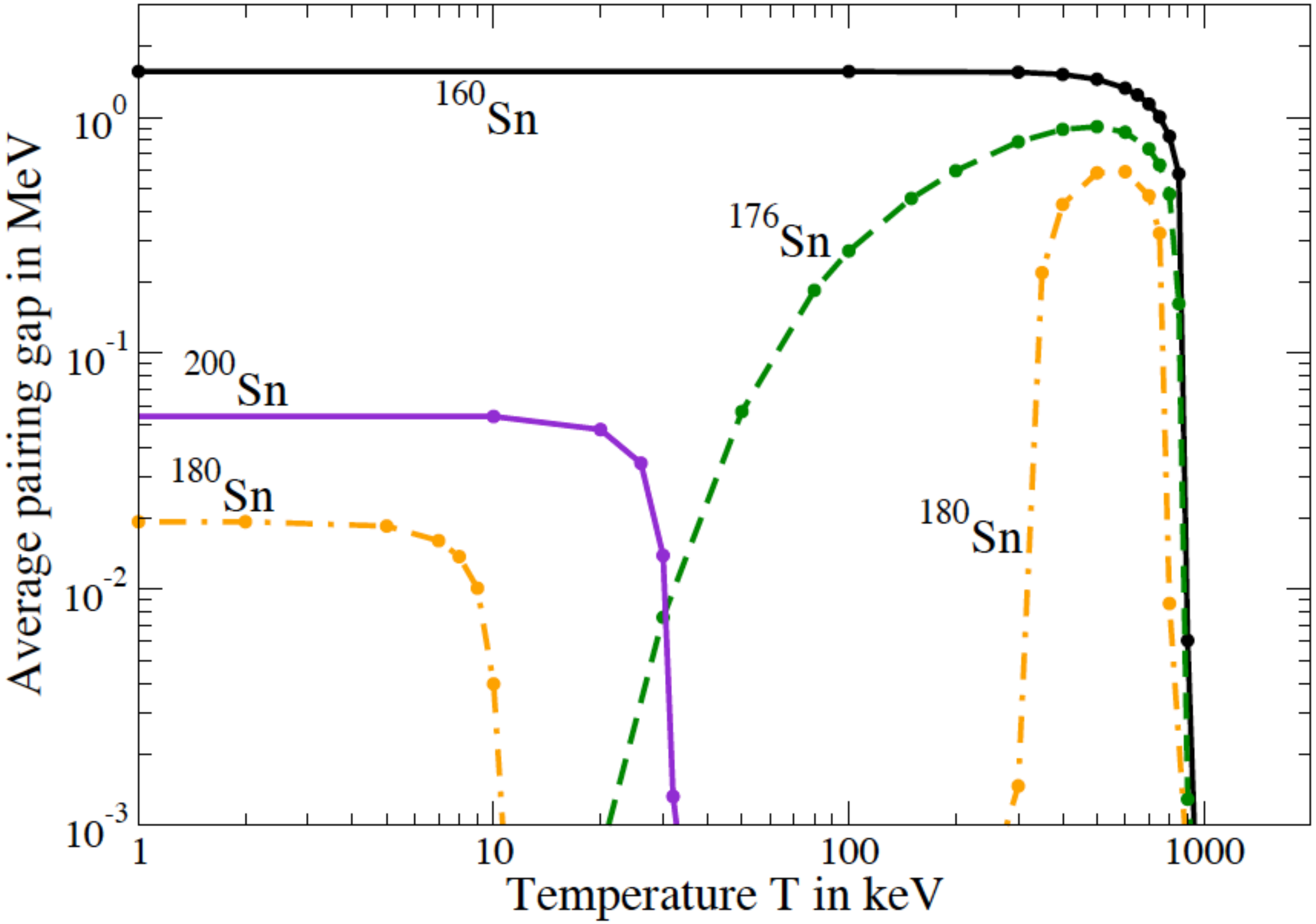
Disappearance of superfluidity

in the neutron gas

in the cluster

Fortin, Grill, J.M., Page, Sandulescu, PRC 88 065804 (2010)

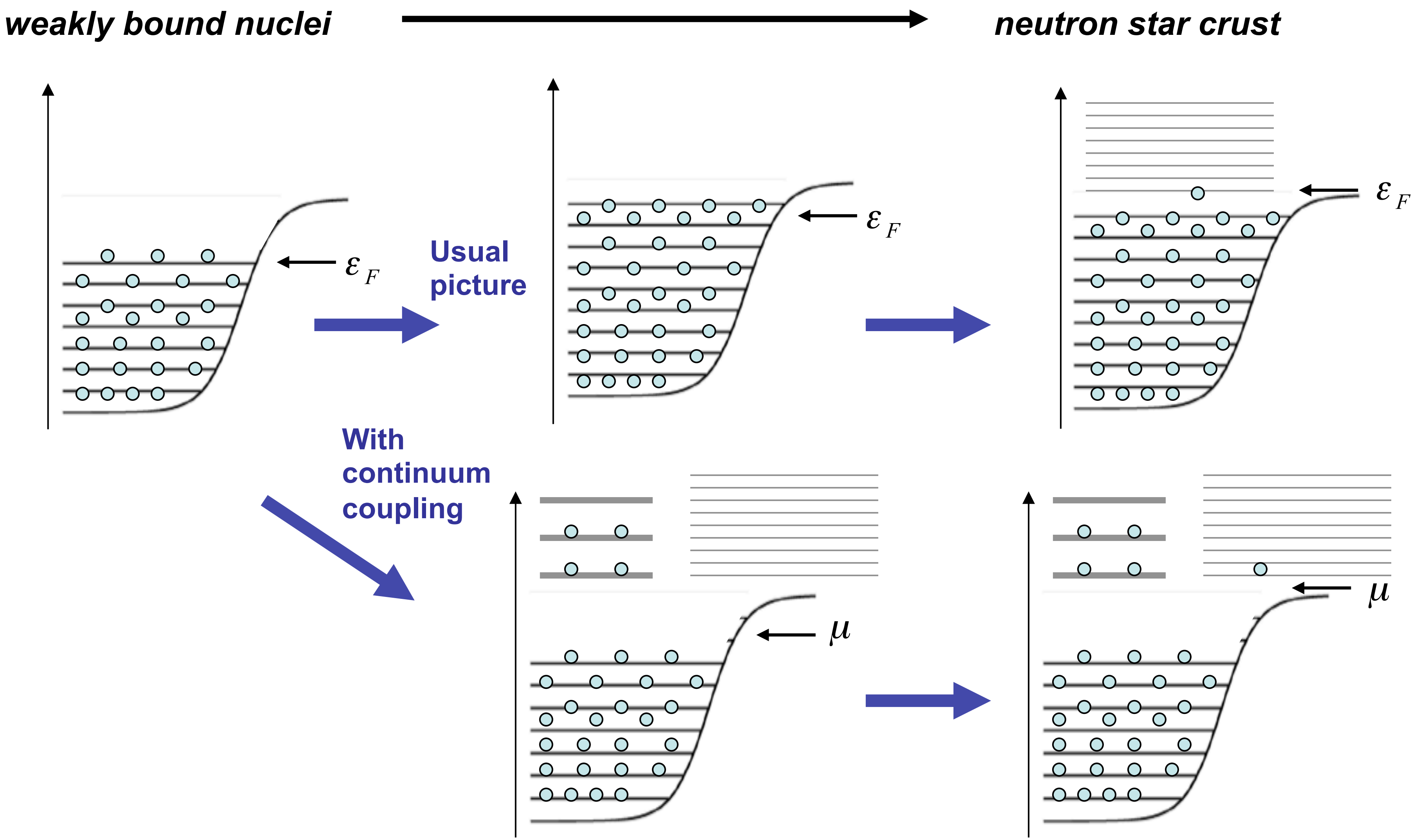
Pairing reentrance phenomenon in Sn at the drip



Temperature populates excited states:
1- kinetic energy cost induces a quenching of pairing,
2- in some cases, pairing occurs among thermally occupied excited states.

J.M. & Khan, PRC 2012

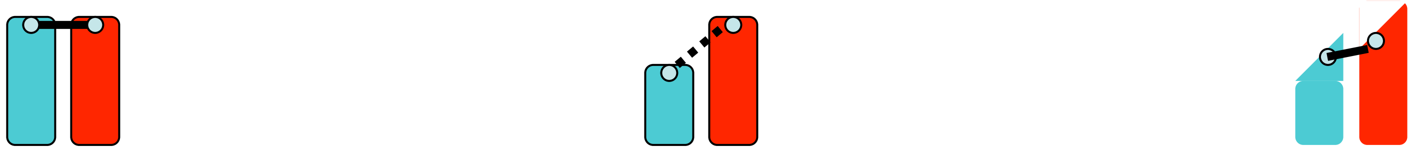
Towards a better understanding of the neutron drip (line and -ing)



Pairing reentrance phenomenon

Superfluidity is destroyed by increasing the temperature…
But a bit of temperature sometimes helps in restoring superfluidity !

Pairing reentrance in asymmetric systems:



Pairing in symmetric systems

Asymmetry detroys pairing

Temperature in asymmetric systems restore superfluidity

In nuclear matter: pairing in the T=0 (deuteron) channel

Sedrakian, Alm, Lombardo, PRC 55, R582 (1997)

In spin-asymmetric cold atom gas

Castorina, Grasso, Oertel, Urban, Zappala, PRA 72, 025601 (2005)
Chien, Chen, He, Levin, PRL 97, 090402 (2006)

In higly polarized Liquid ^{3}He, ^{4}He

Frossati, Bedell, Wiegers, Vermeulen, PRL 57 (1986)

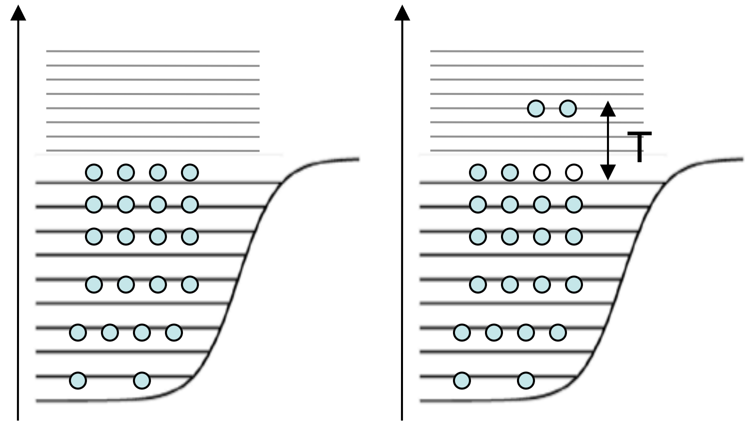
Pairing in heated rotating nuclei

Dean, Langanke, Nam, and Nazarewicz, PRL105, 212504 (2010).

Pairing reentrance in finite systems:

In magic nuclei, the presence of low-energy resonances, populated at low temperature, can help superfluidity to appear.

J.M., Khan, PRC 2012



Conclusions:

cold systems are fun !

Conclusions:

- The transition between the outer / inner crust offers a fascinating playground to apply and test pairing theories.
- Since two superfluids overlap (gas+nucleus), surprising features occurs.
- Resonant states (existing because of nuclei) play a crucial role in understanding these features.

These non-trivial features of superfluidity are interesting for:

- Models for the crust including pairing shall be revised,
- Better understanding of the phenomenology of pairing, and possible application in other fields (cold atoms).