Pairing correlations around the drip-line of finite systems, and beyond, ESNT, may 2013

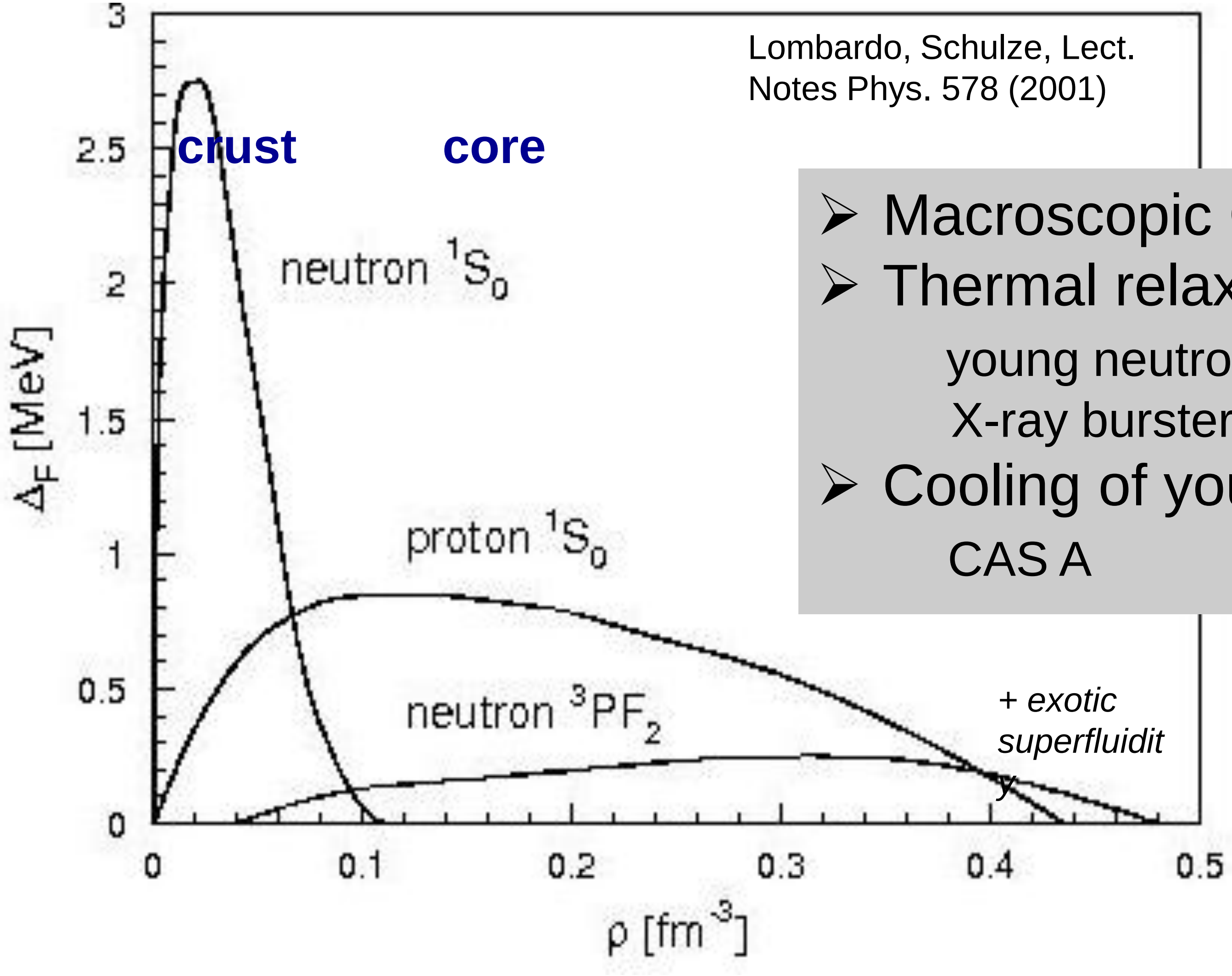
Superfluidity and Neutron stars

J. Margueron, IPN Lyon, France.

I- Superfluidity and neutron stars

II- Pairing properties and the role of resonance states

Pairing gaps through the star



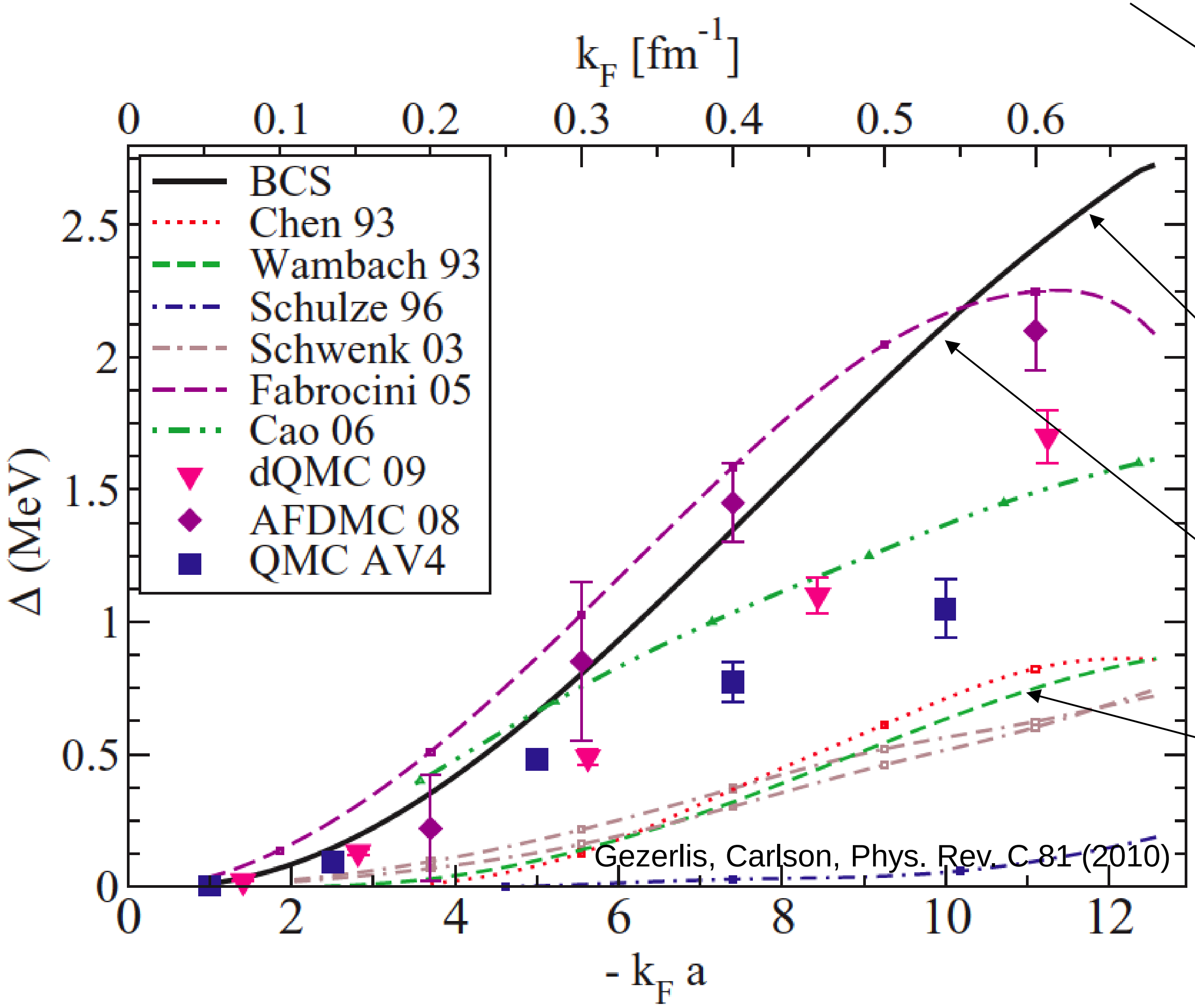
crust **core**

Lombardo, Schulze, Lect. Notes Phys. 578 (2001)

+ exotic superfluidity

- ➢ 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"



Gezerlis, Carlson, Phys. Rev. C 81 (2010)

Needs for observational constraints

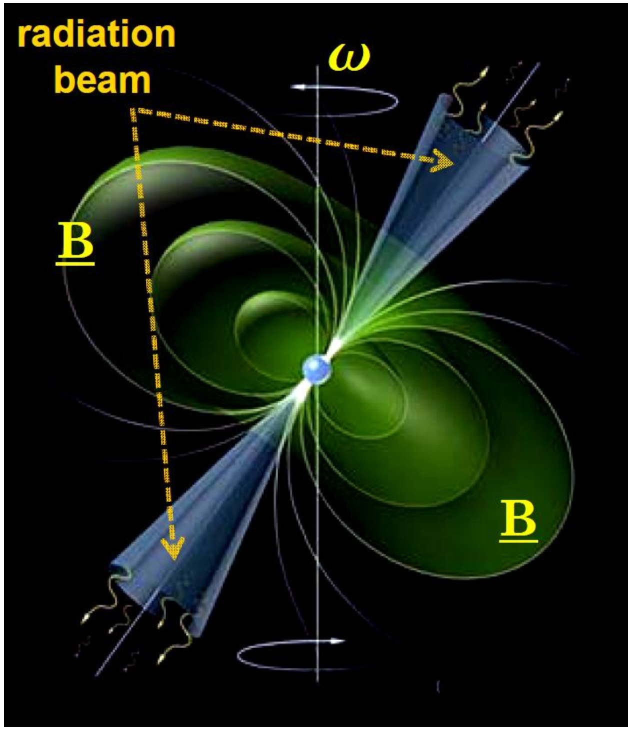
BCS

Strong (max at 3 MeV),

Weak (max at 1 MeV).

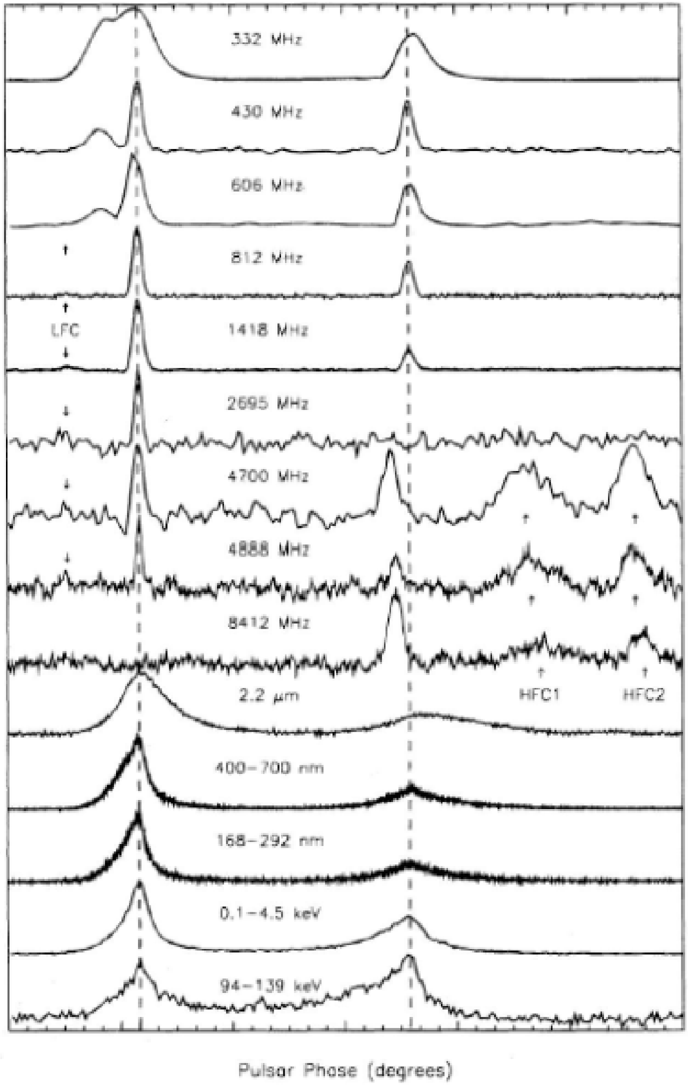
Superfluidity and rotation of neutron stars

Lighthouse model



Period ~ few s to few ms

Observed pulse of Vela

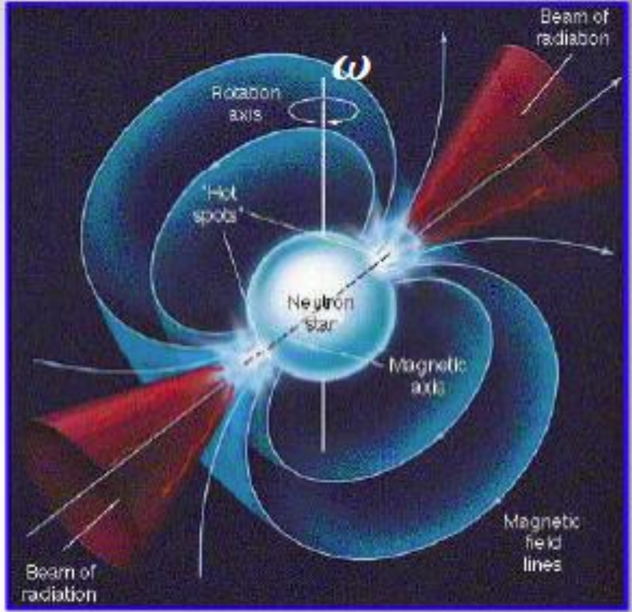


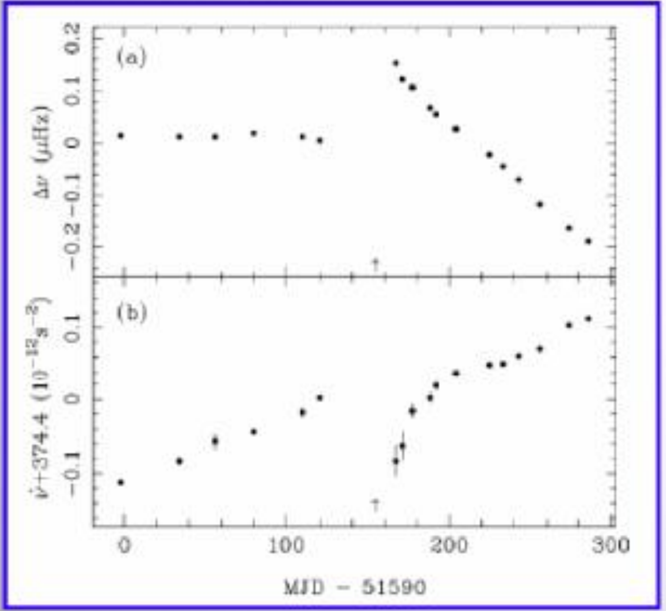
The “sound” – pulses - of the Vela pulsar
http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html

Slides from
P. Pizzochero,
Univ. of Milano

Pulsar glitches

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



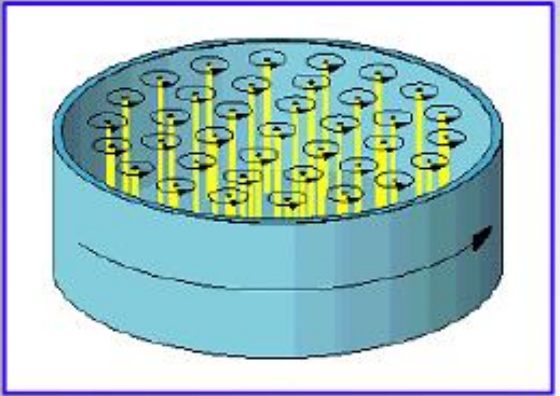


Pulsar glitches are recurrent spin-ups of rotational frequency ($\Delta\omega \sim 10^{-8}$- $10^{-6}\,\omega$) without external forces

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

Slides from
P. Pizzochero,
Univ. of Milano

Vortex theory of glitches



Collective vortex depinning
by hydrodynamical forces

⇓

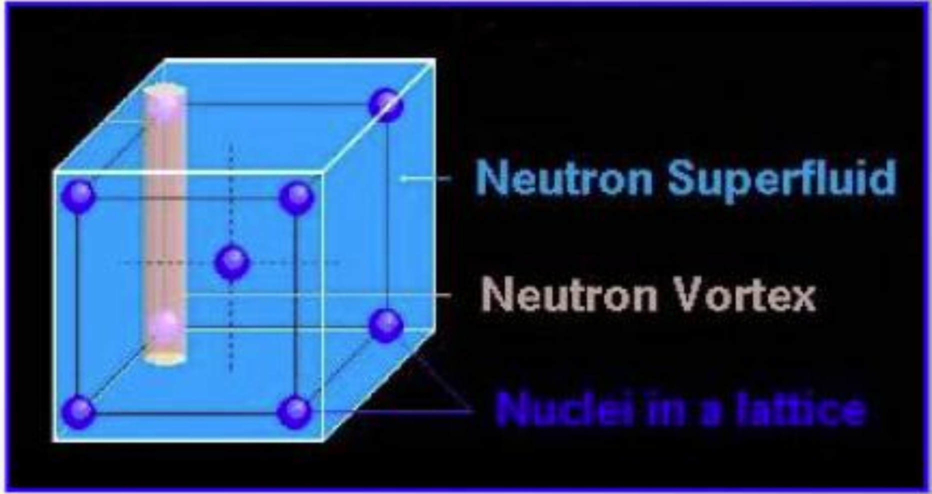
Transfer of angular
momentum from superfluid
to star surface

⇓

Glitch in rotational
frequency

Microscopic input
pinning energy

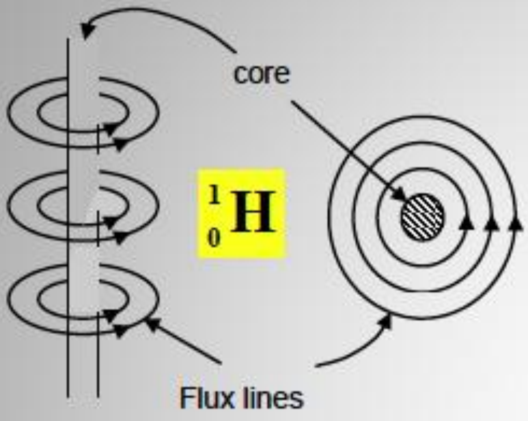
Angular momentum of rotating
neutron superfluid is quantized
in parallel array of vortex lines



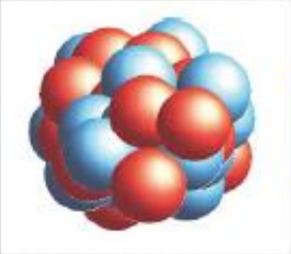
Vortices in the Inner Crust pin
to lattice of exotic nuclei ⇒
angular momentum of neutron
superfluid is frozen

Slides from
P. Pizzochero,
Univ. of Milano

Vortex-nucleus interaction

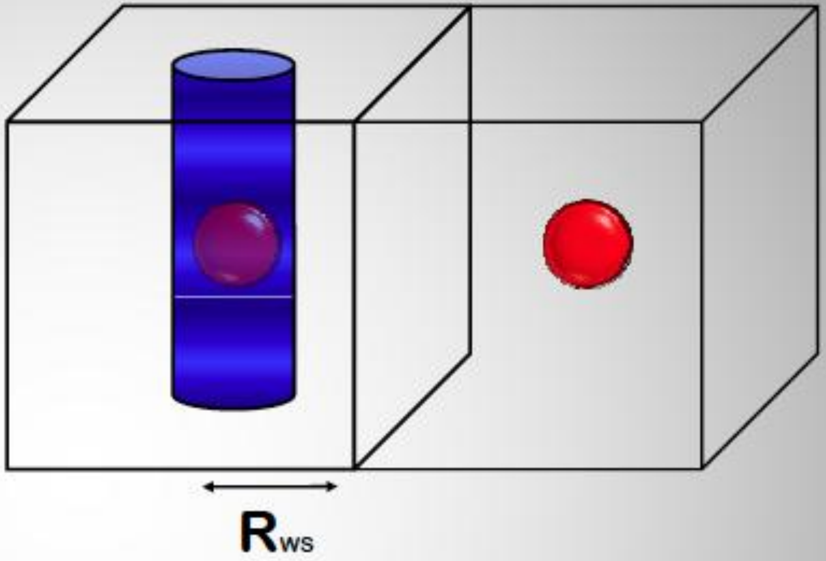


$^{1}_{0}\mathrm{H}$

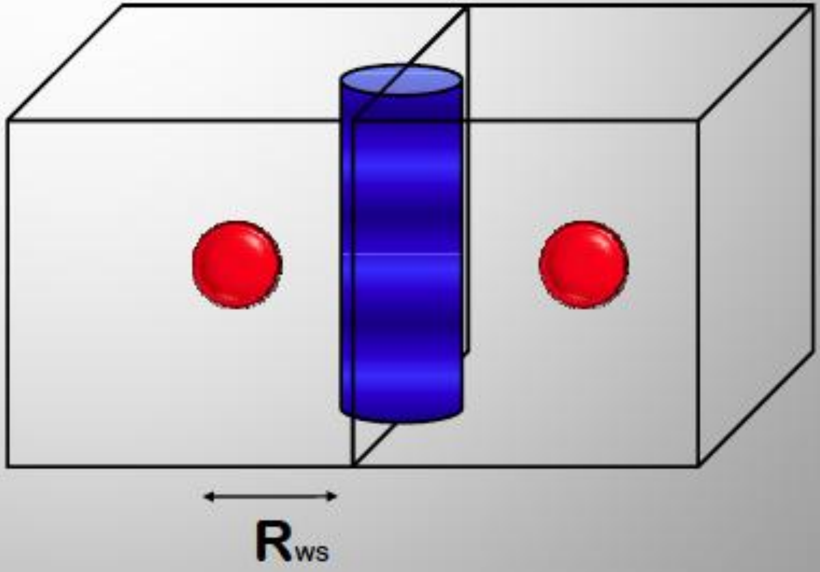


$^{1800}_{50}\mathrm{Sn}$

$$E_{pin} = E_{NP} - E_{IP}$$



E_{NP}



E_{IP}

Deducing NS radii from Glitches

Crustal fraction of the moment of inertia:

$$\frac{\Delta I}{I} \simeq \frac{8\pi}{3c^2}\frac{R^4 \boxed{p_t}}{M^2}\left[\alpha^{-1} f(\beta)^{-1} - 2\beta\right]\exp\left(-\frac{6\gamma}{2\gamma-1}\frac{\Delta}{\boxed{R}}\right)$$

Pressure at the
core-crust transition

radius

J.M. Lattimer and M. Prakash, Phys. Rep. 442, 109 (2007).

Can be measured from
pulsar glitches

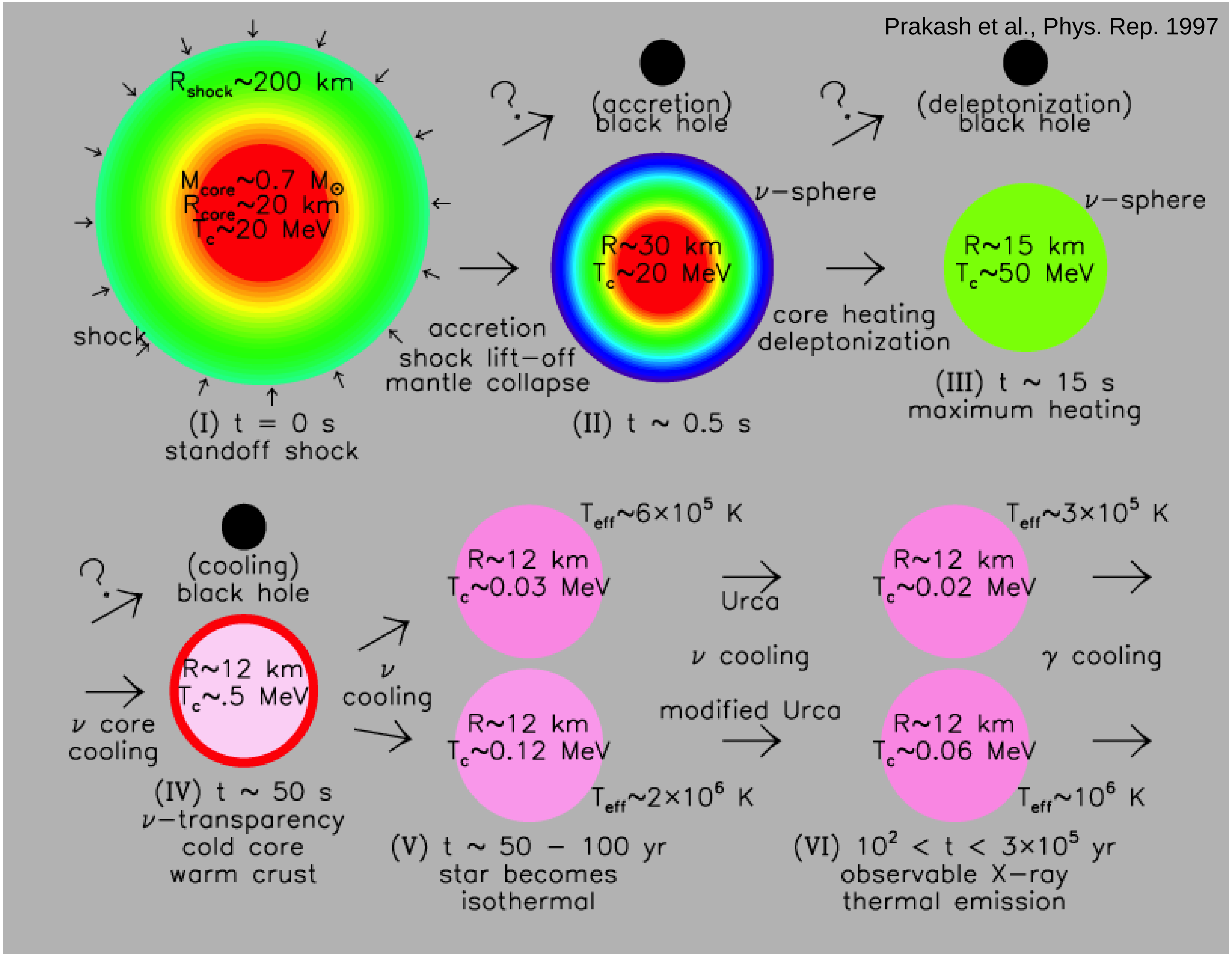
B. Link et al., PRL 83, (1999)

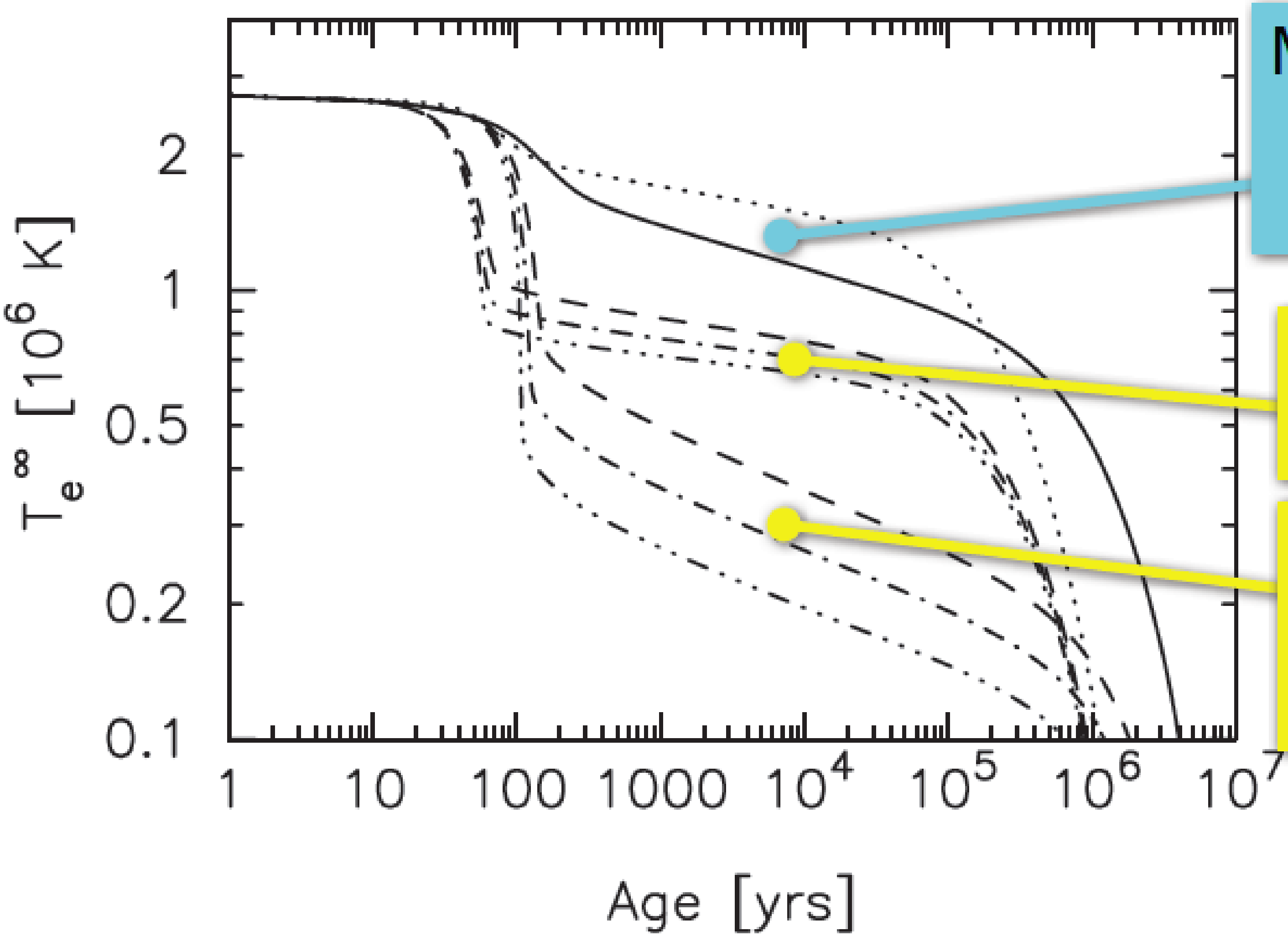
Puts constraints on the NS
radius; ex: Vela pulsar

The pressure p_t can be related to nuclear parameters, e.g. J, L, ...

Bao-An Li, Phys. Rep. 464, 113 (2008)
Ducoin et al., EPL 2010, PRC 2011

Superfluidity and cooling of neutron stars





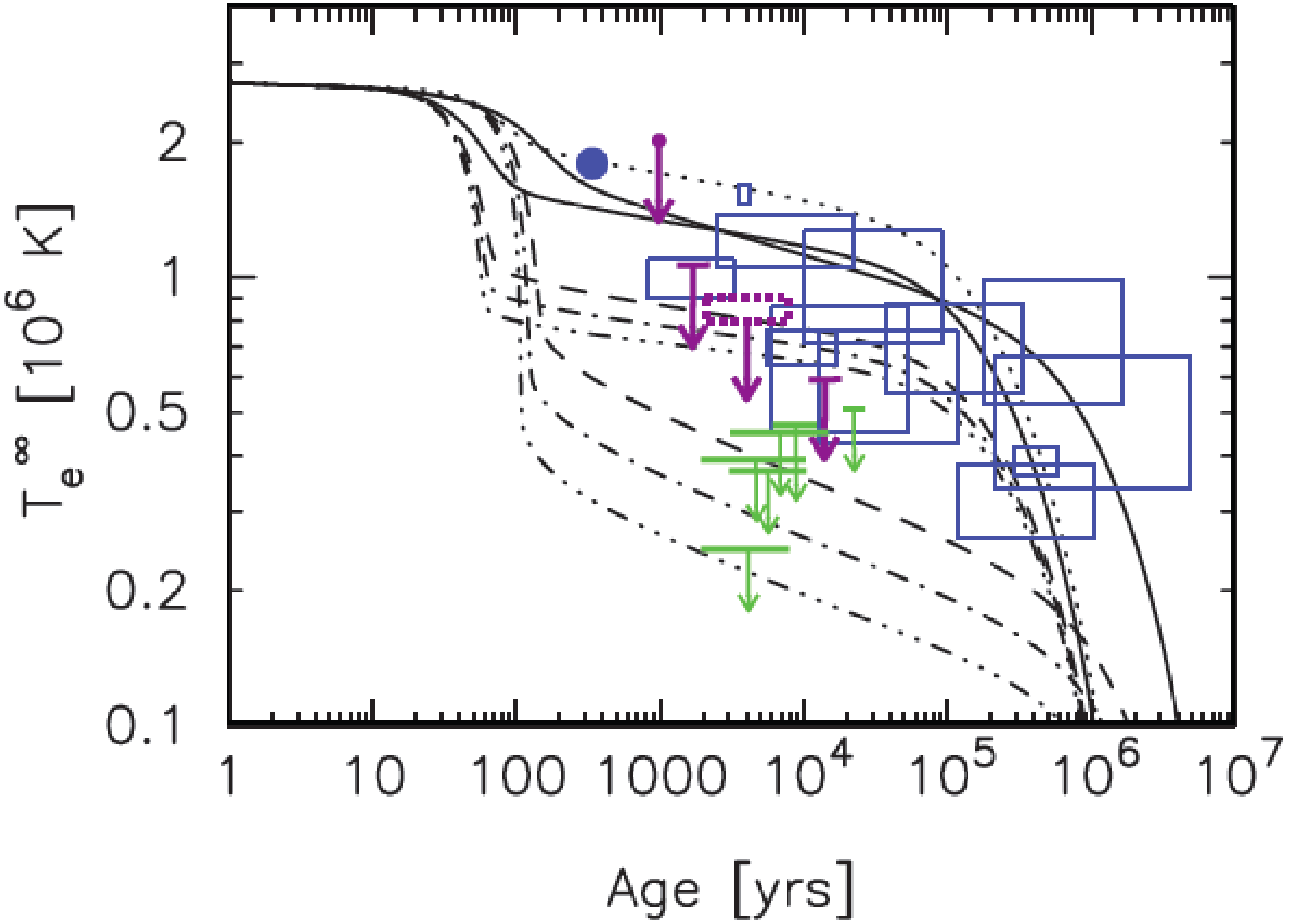
Modified Urca with/without pairing

Fast cooling with pairing

Fast cooling without pairing

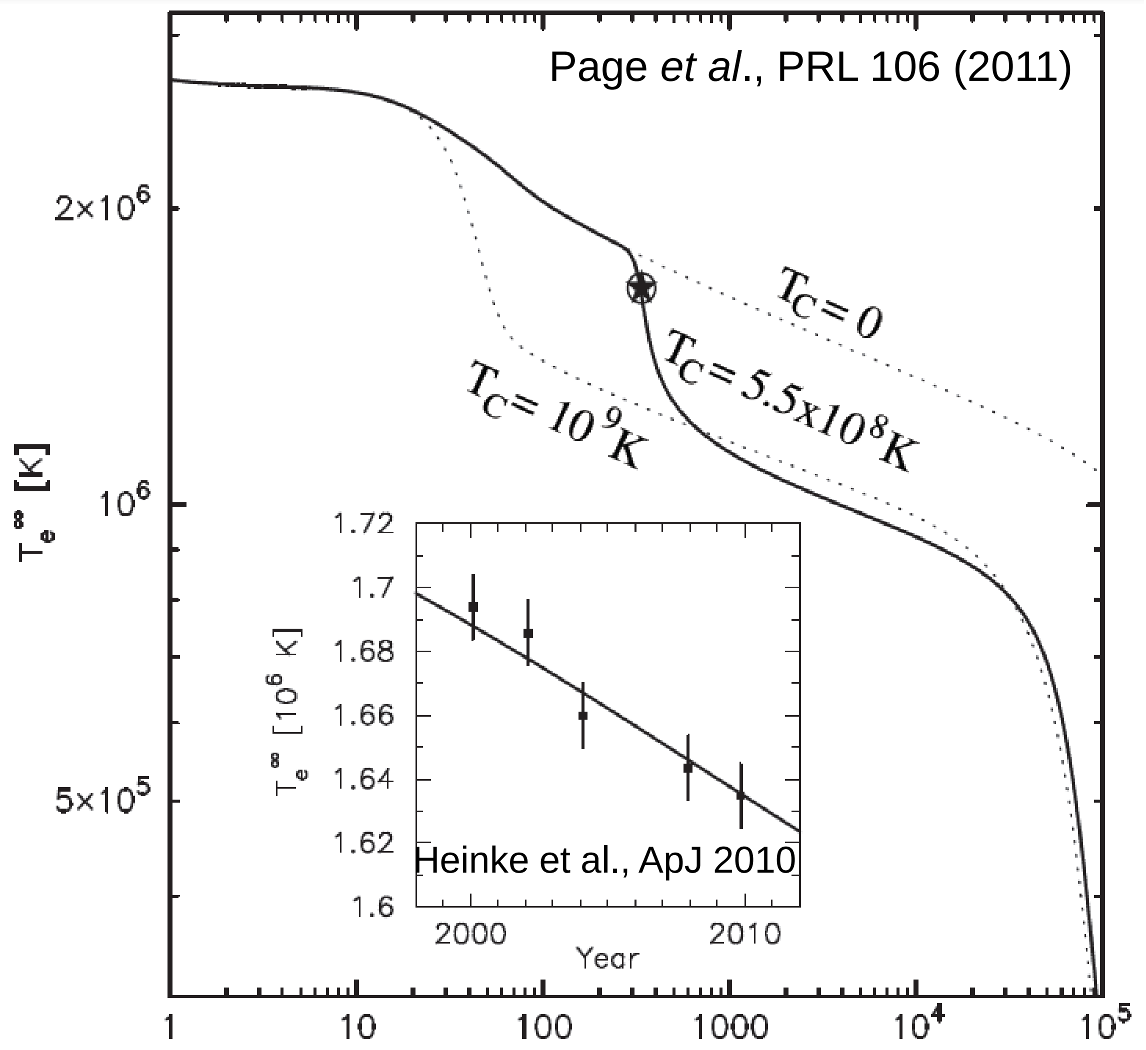
D. Page, CompStar2012, Tahiti

Data versus model



D. Page, CompStar2012, Tahiti

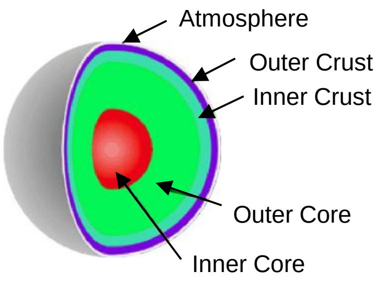
Rapid cooling of Cas A



Constrain on $^3P_2$ neutron and $^1S_0$ proton pairing.

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

Thermal relaxation of Neutron stars

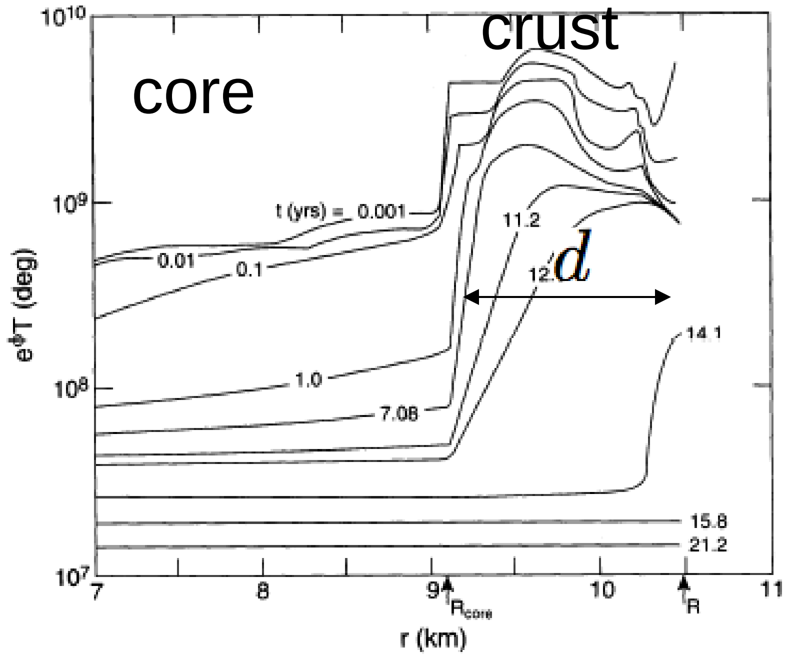


Fast cooling of the core:

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

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

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



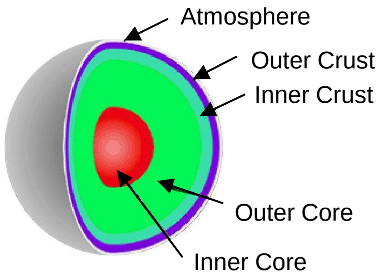
Lattimer et al., APJ 425 (1994)

K, conductivity

$C_{v,n}$ neutron specific heat

depend on the cluster structure
In the neutron star crust

Thermal relaxation of Neutron stars



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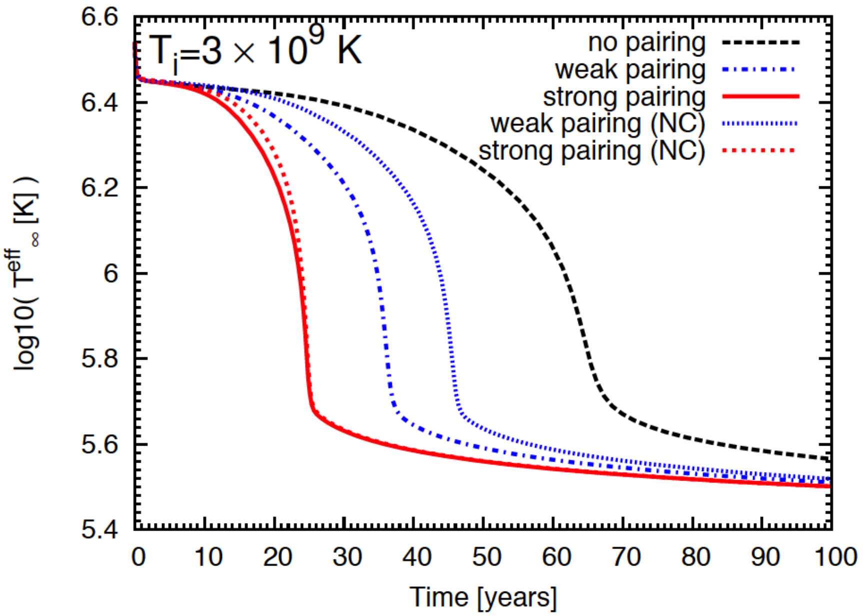


Fortin et al., PRC 88 (2010)

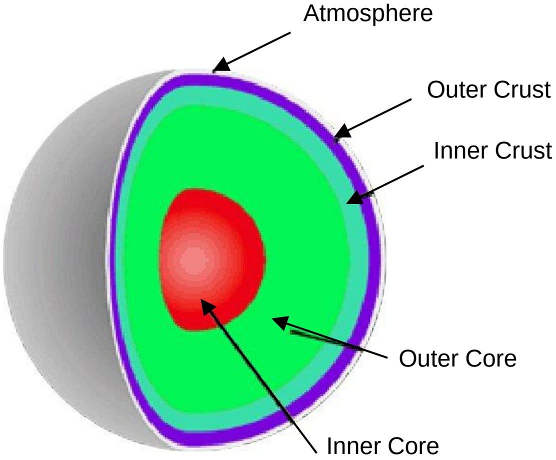
K, conductivity

$C_{v,n}$ neutron specific heat

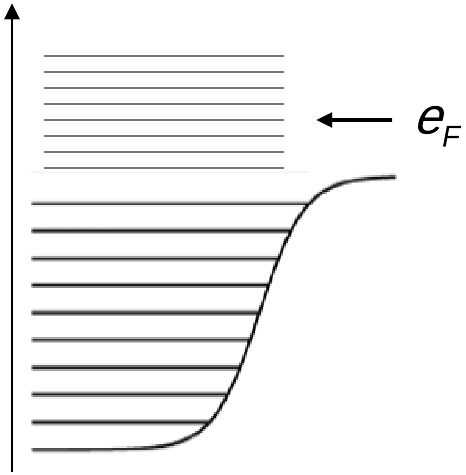
} depend on the cluster structure

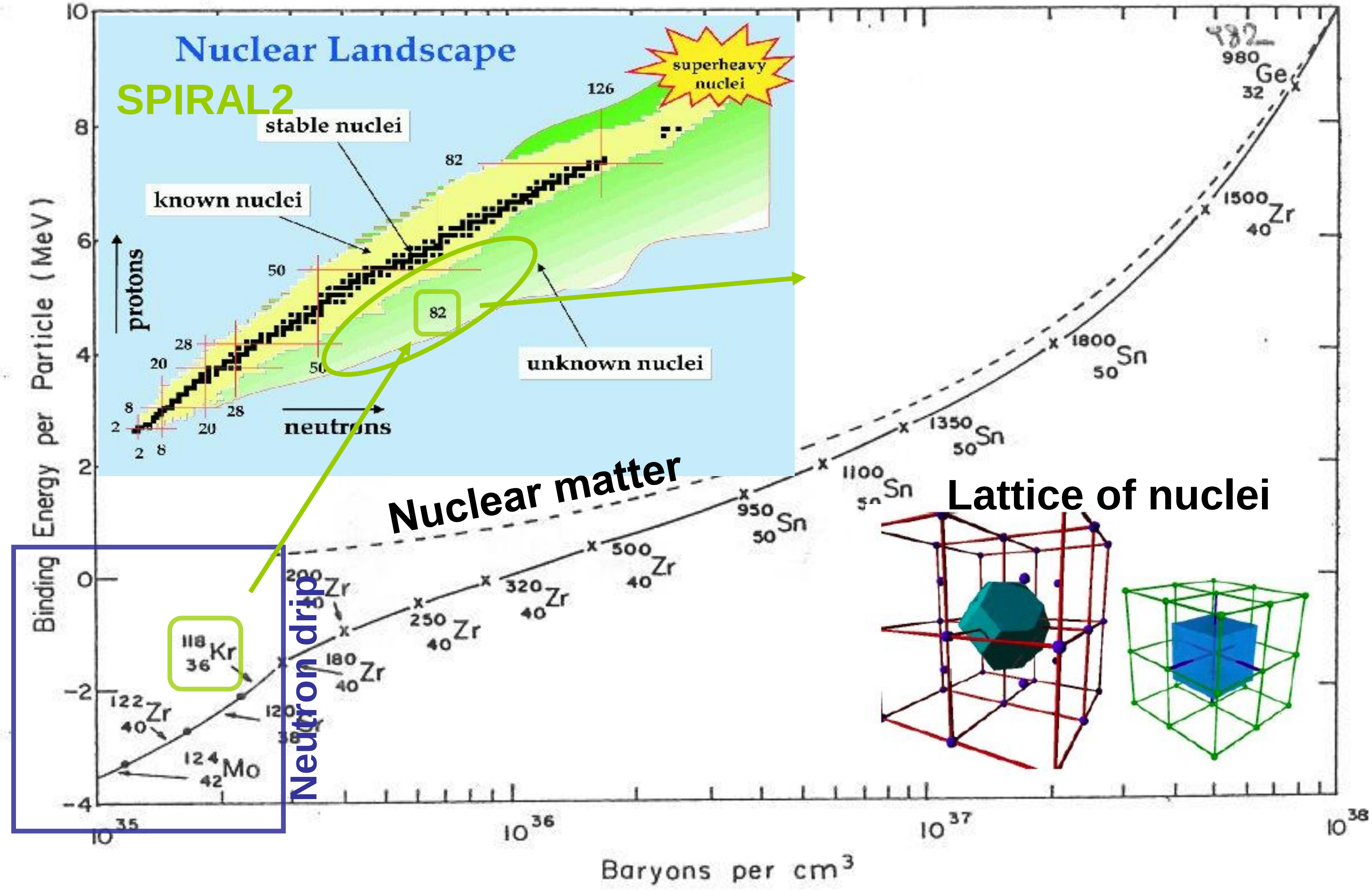
Part II:

Important role of resonance states in the crust superfluidity



Transition outer / inner crust





SPIRAL2

Nuclear matter

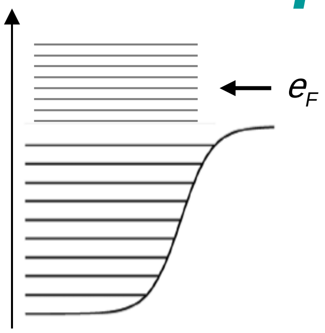
Lattice of nuclei

Neutron drip

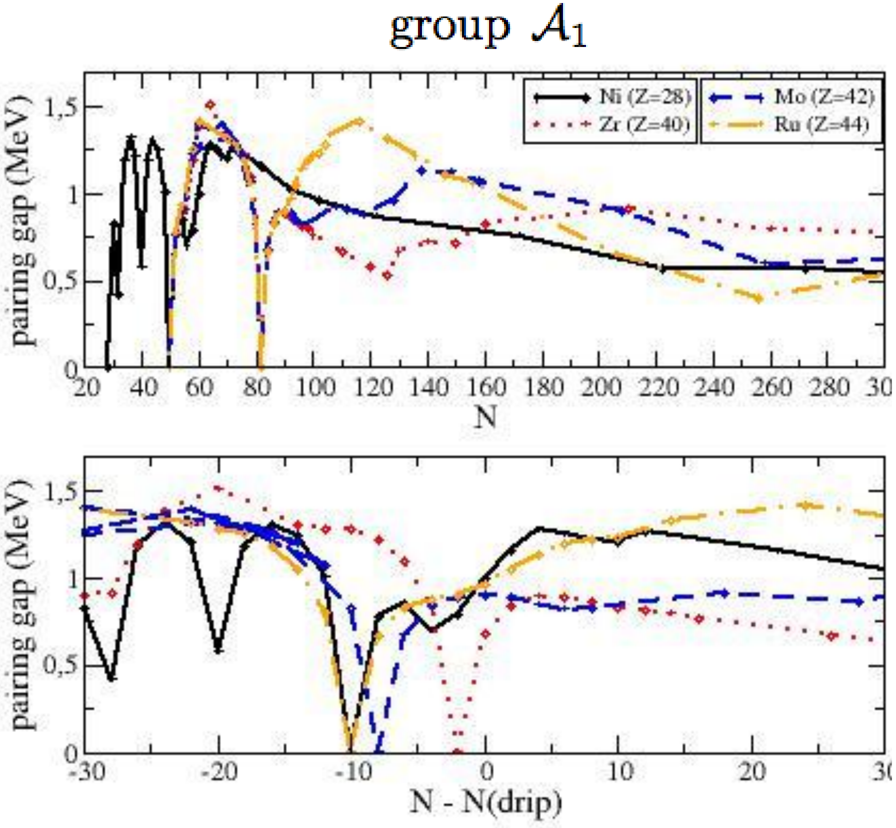
Fig. 2. Energy per particle versus baryon density.

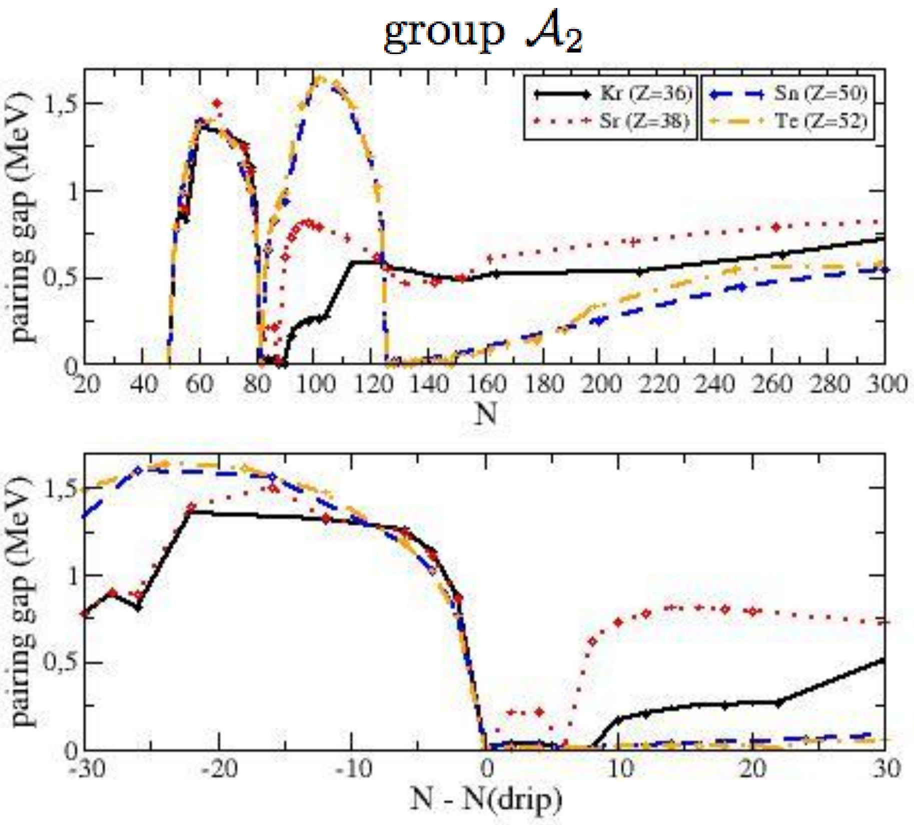
A systematic study based on 8 isotopes with 28<Z<50

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



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

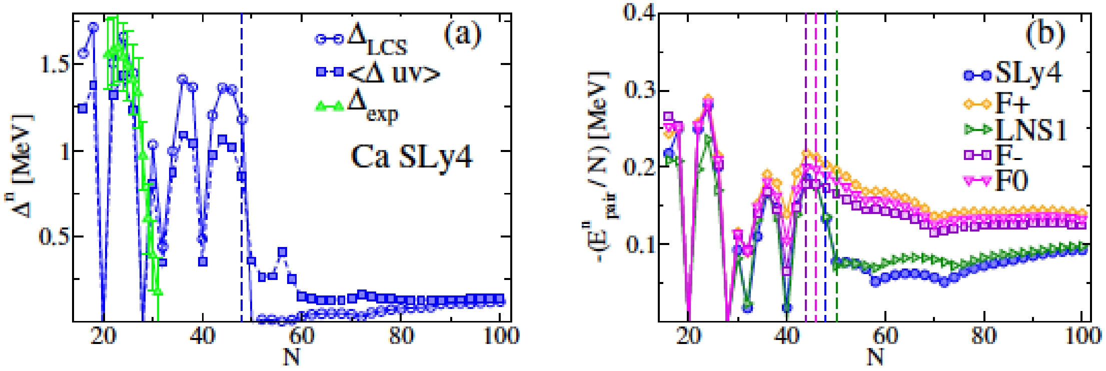

group $\mathcal{A}_1$


group $\mathcal{A}_2$

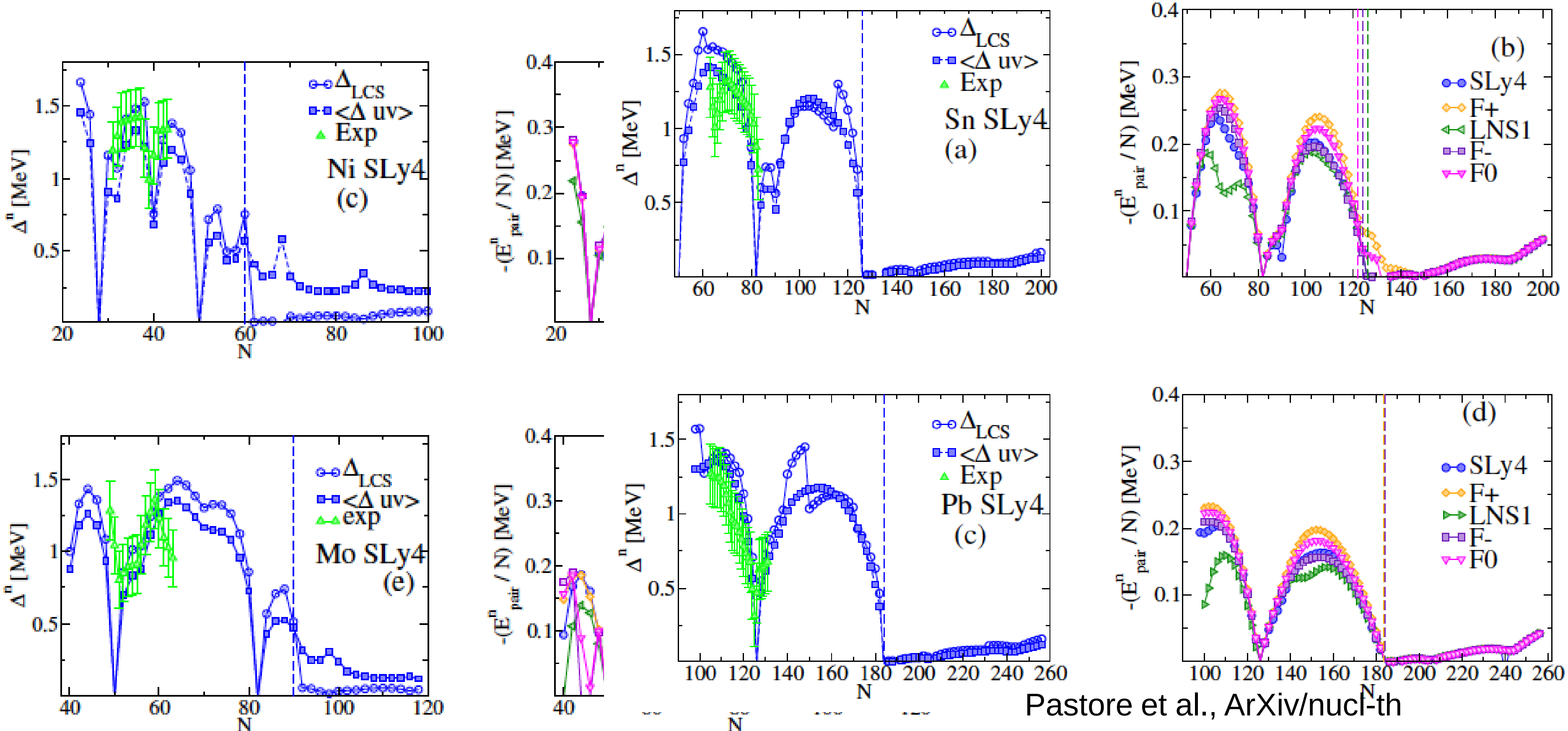
J.M. & Khan, PRC 2012

Weak dependence on the model

Group A_1

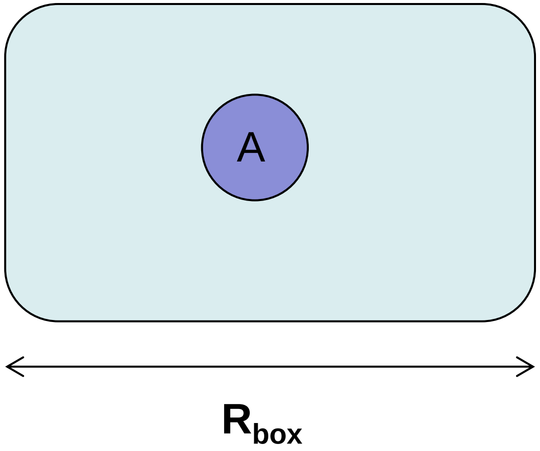


Group A_2

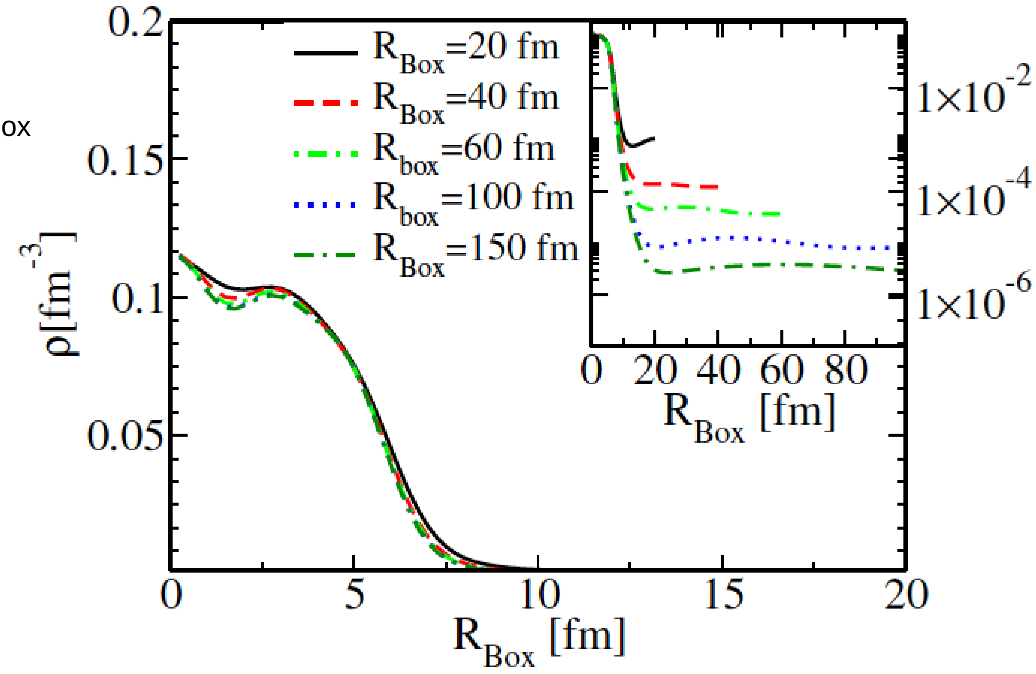


Pastore et al., ArXiv/nucl-th

Interaction of a shallow gas with a nucleus

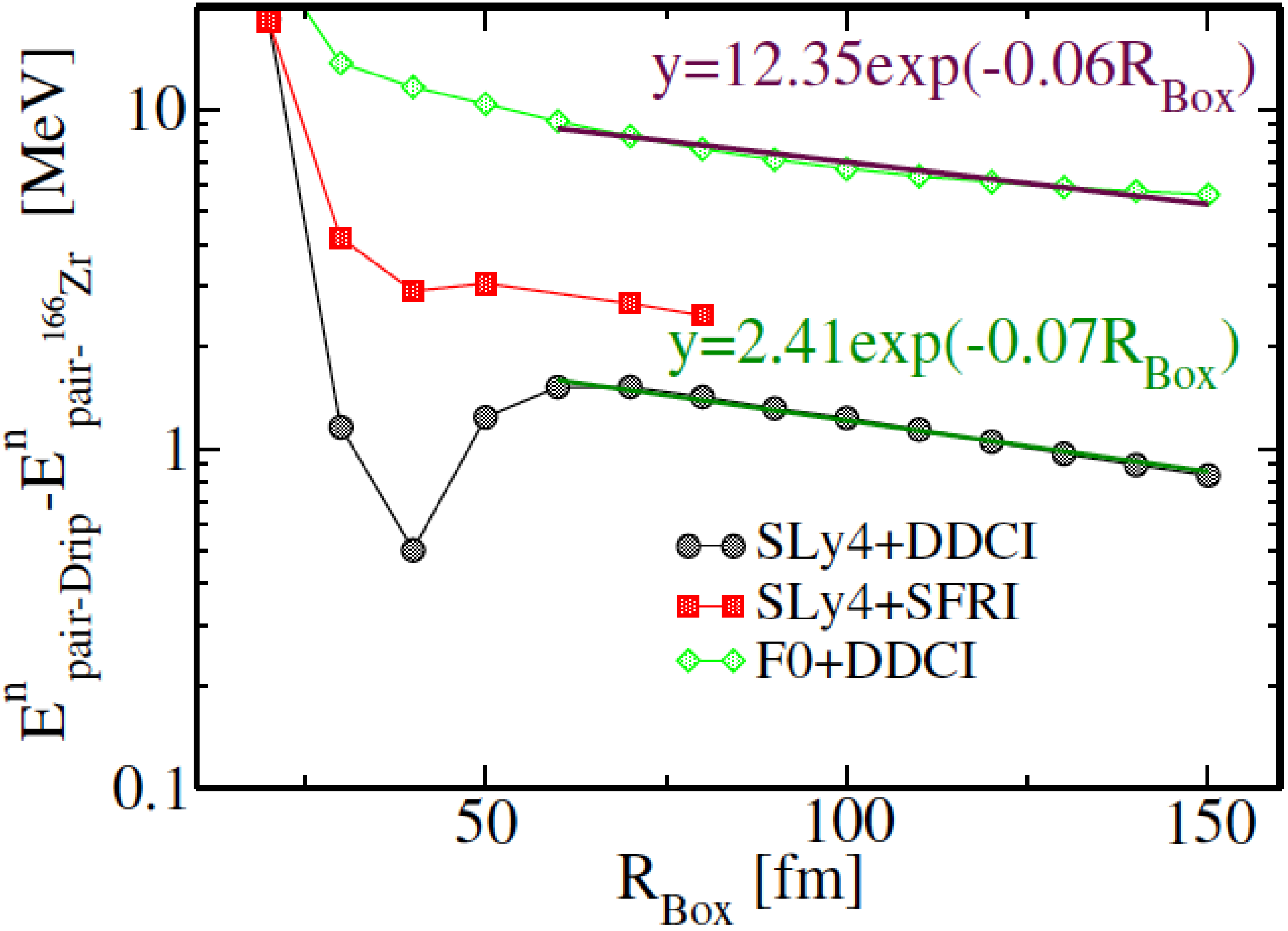


Changing R_{box}



How does the pairing properties changes with ρ_{gas}?

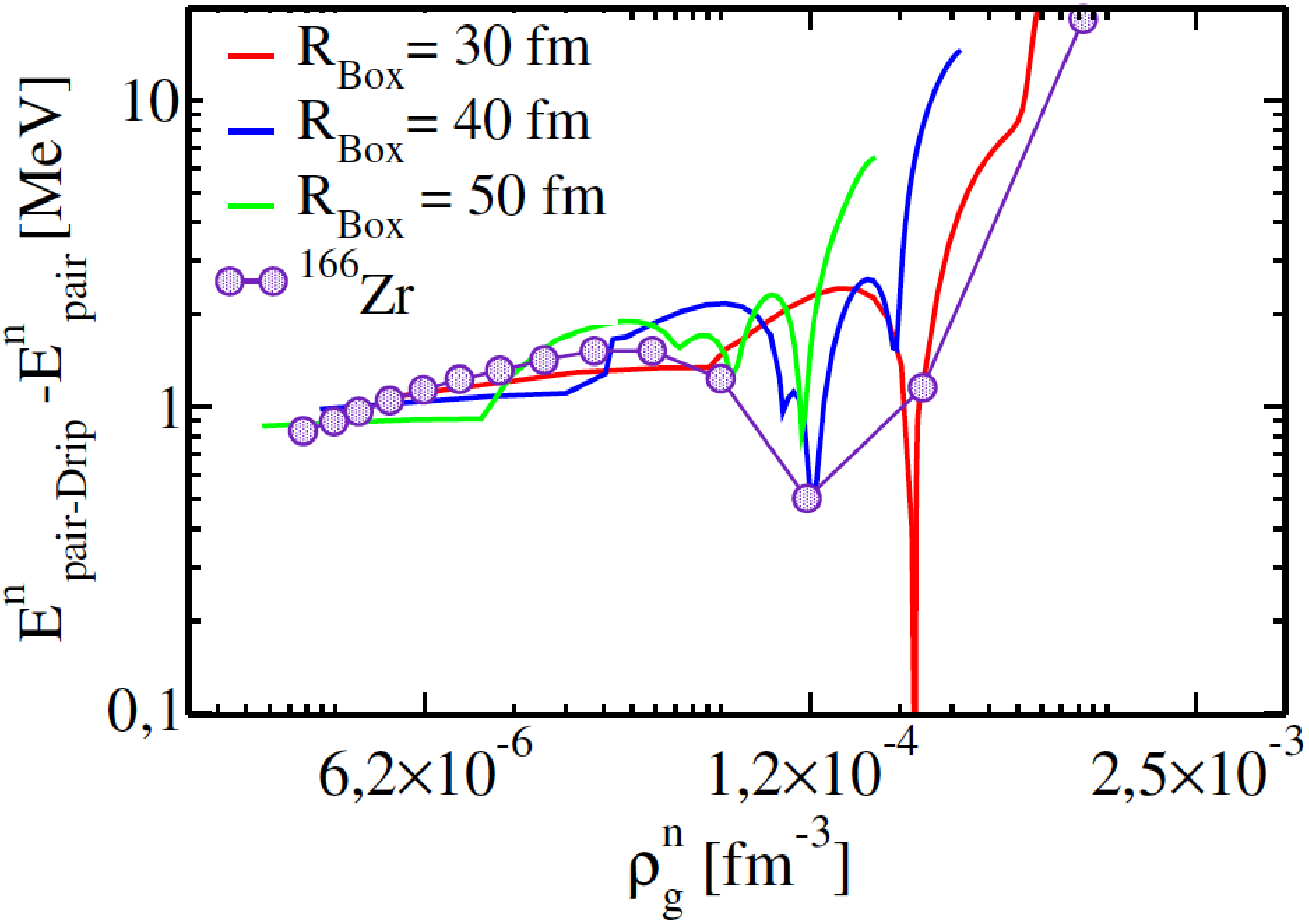
Interaction of a shallow gas with a nucleus



Pastore et al., ArXiv/nucl-th

Interaction of a shallow gas with a nucleus

Fix Rbox, and decrease the total number of neutrons

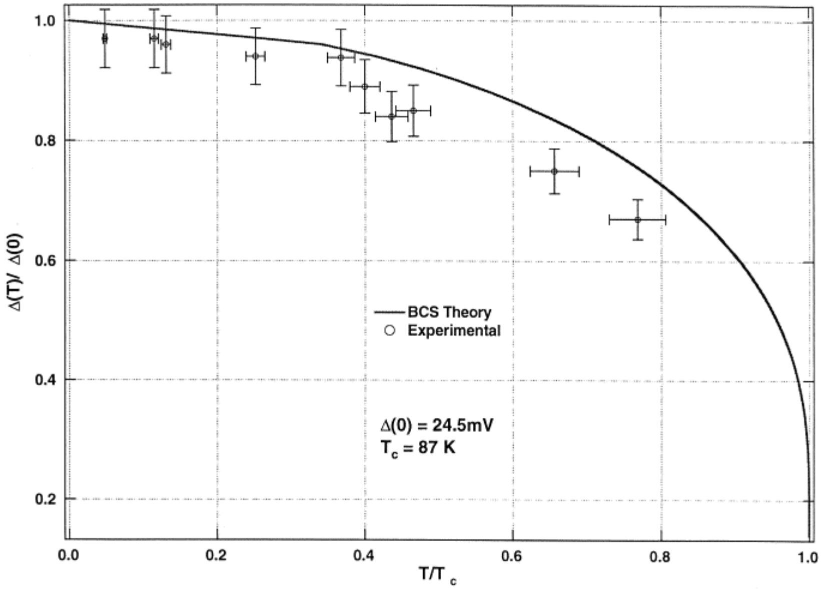


Pastore et al., ArXiv/nucl-th

Temperature effects on superfluidity

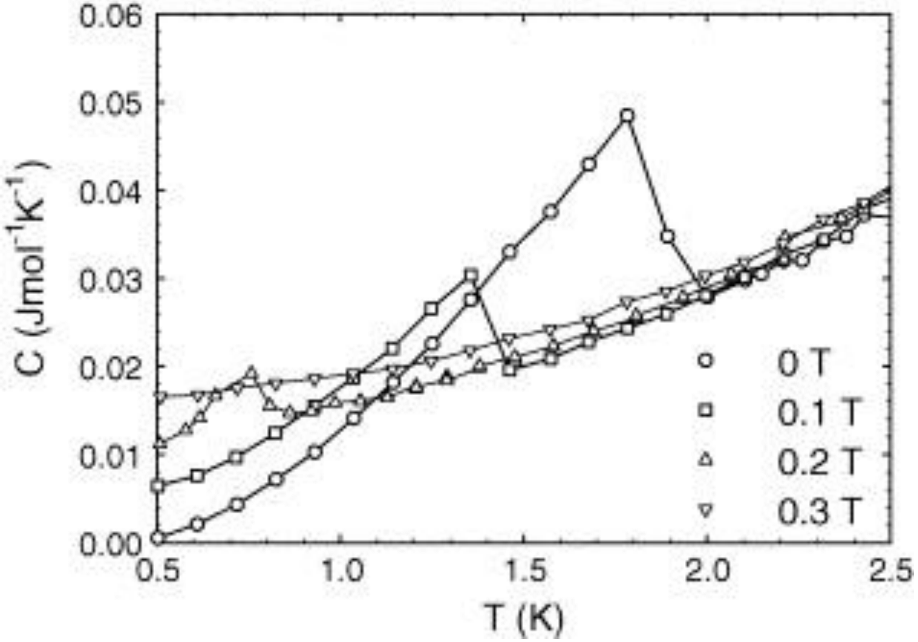
Text-book features of BCS

pairing gap



T/T$_c$

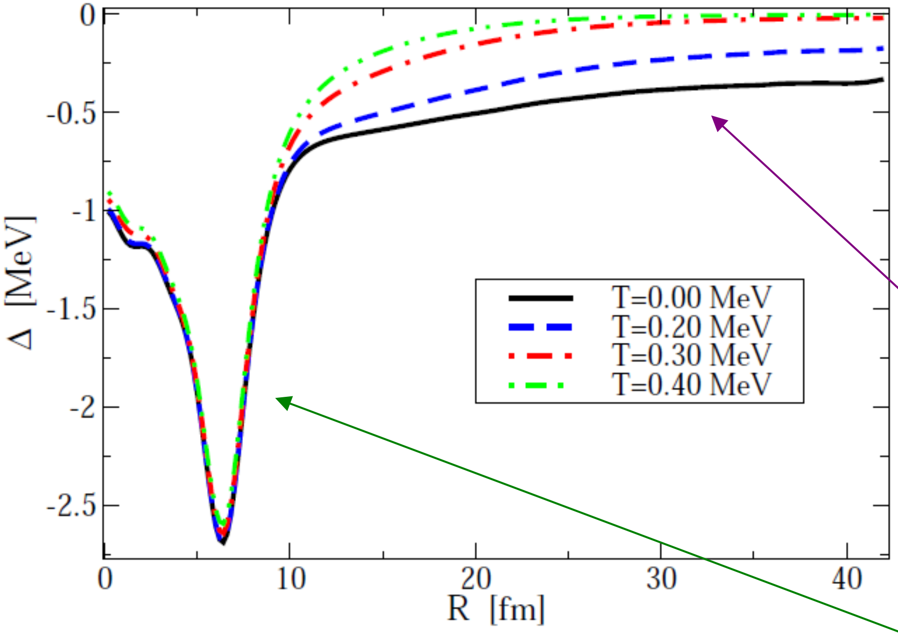
Specific heat



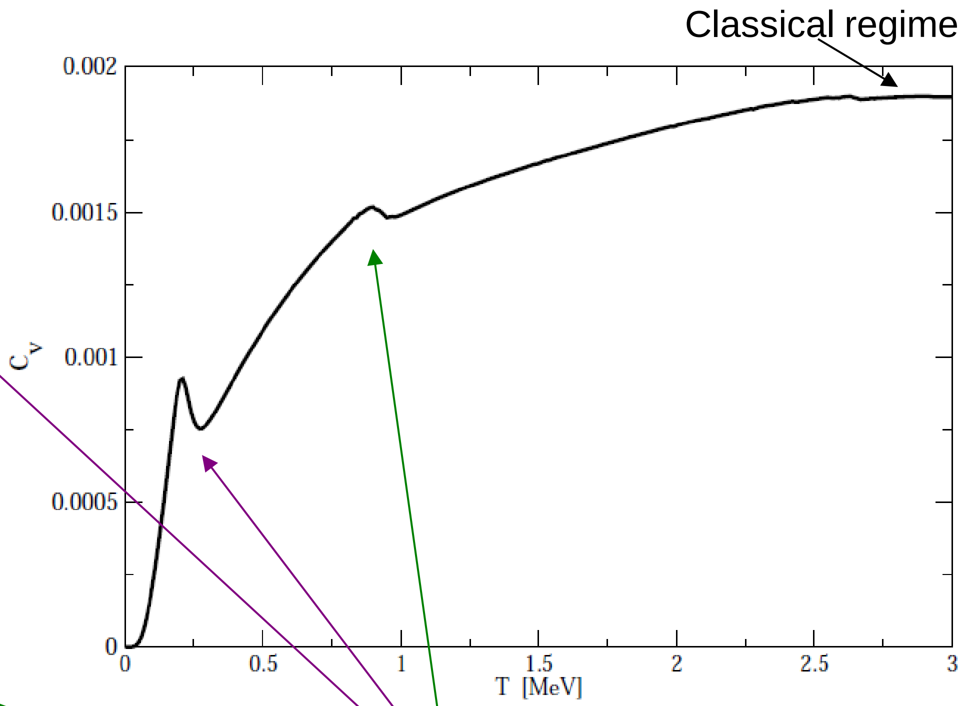
Neutrons specific heat in ^{500}Zr

N=460, Z=40

Pairing field profile
at various temperatures:



Neutron specific heat:



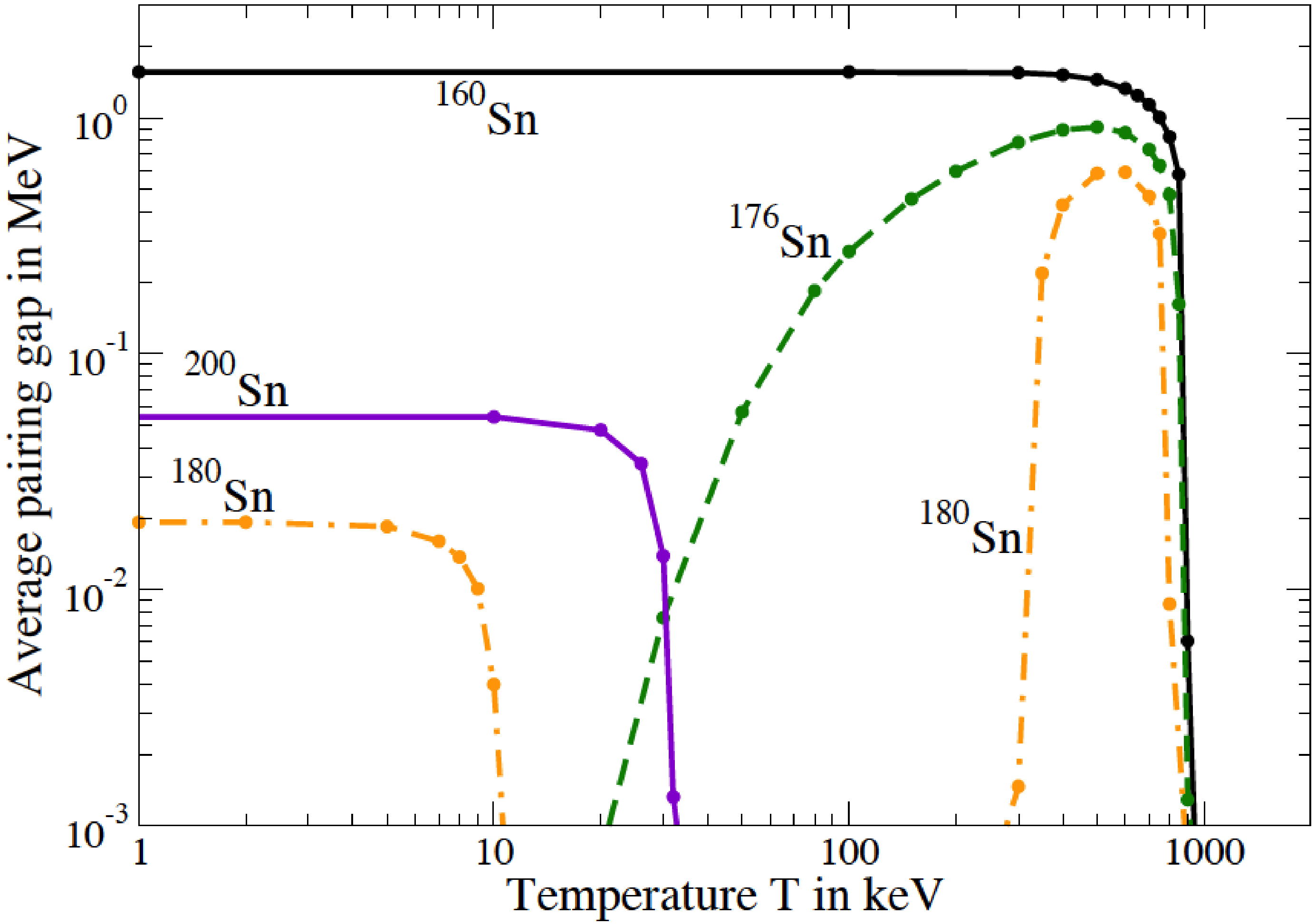
Disappearance of superfluidity

in the neutron gas

in the cluster

Fortin et al., PRC 88 065804 (2010)

Pairing reentrance phenomenon in Sn at the drip



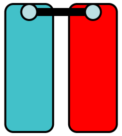
Temperature populates excited states:
1- kinetic energy cost induces a quenching of pairing,
2- in some cases, pairing occurs among thermally occupied excited states.

J.M. & Khan, PRC 2012

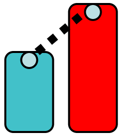
Pairing reentrance phenomenon

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

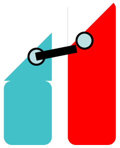
Pairing reentrance in asymmetric systems:



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)

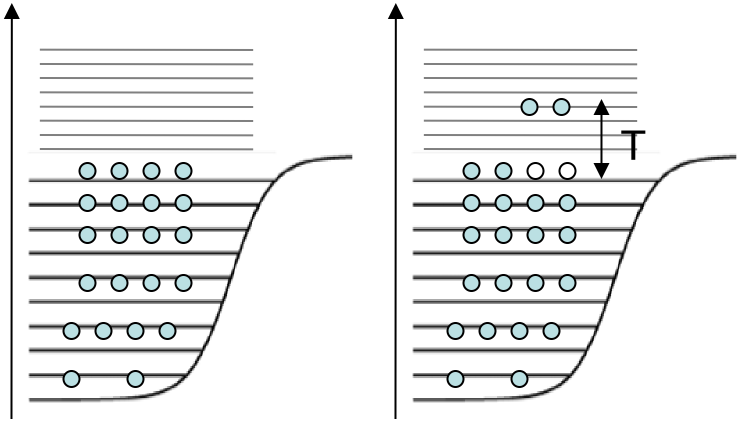
Pairing in heated rotating nuclei

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

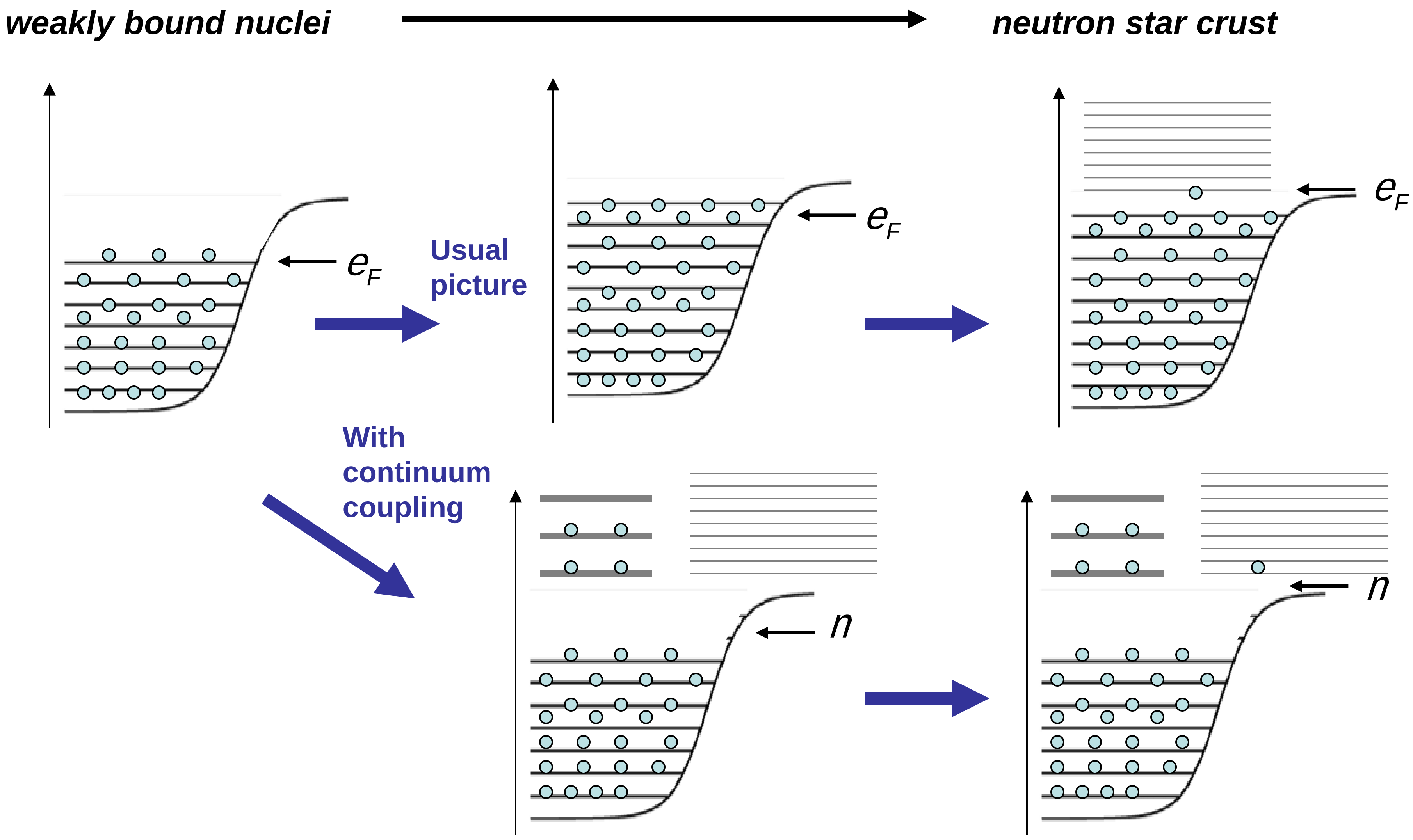
Pairing reentrance in finite systems:

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

J.M., Khan, PRC 2012



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



weakly bound nuclei

neutron star crust

Usual picture

With continuum coupling

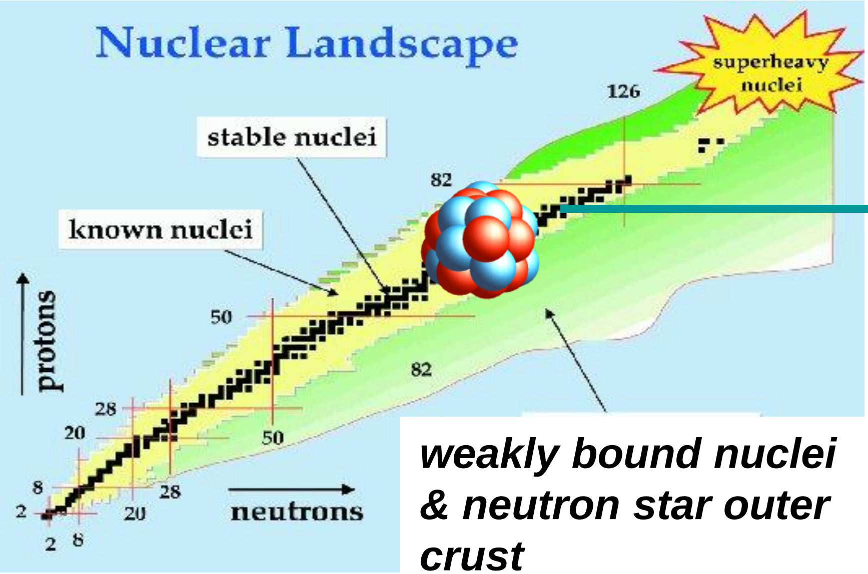
Conclusions:

- 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:

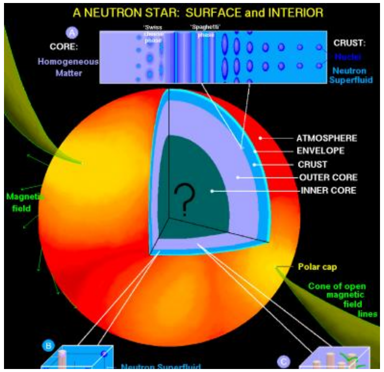
- Models for the crust including pairing shall be revised,
- Better understanding of the phenomenology of pairing, and possible application in other fields (cold atoms).

From stable nuclei to nuclear matter



Increasing number of neutrons
Or increasing density

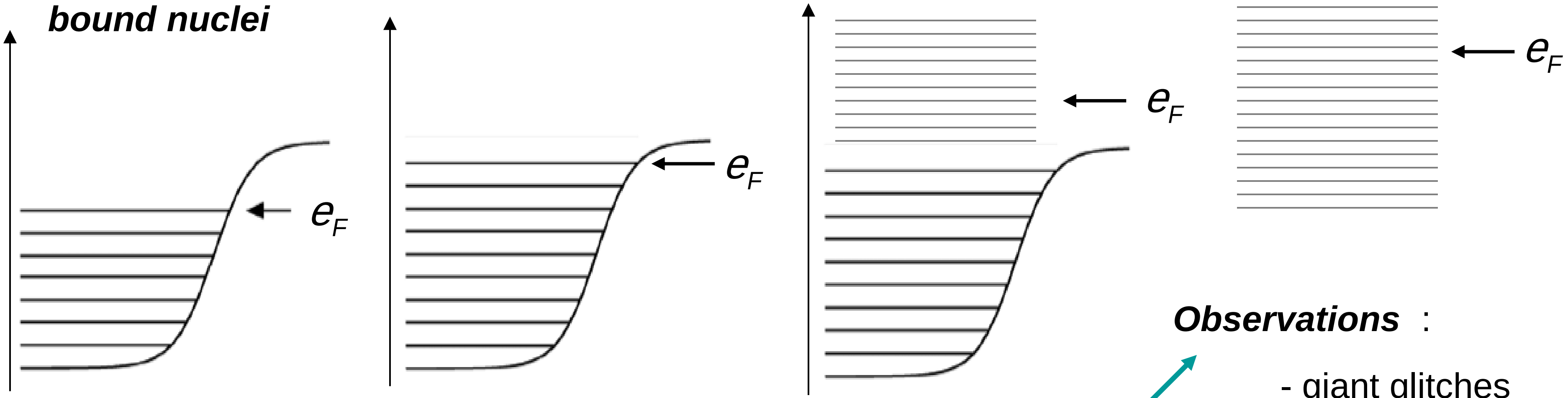
$$e + p \rightarrow n + \nu$$



weakly bound nuclei & neutron star outer crust

Finite temperature nuclei & neutron star inner crust

Uniform matter



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

Nuclear density functional approach

Observations :

- giant glitches
- cooling

Nucleus	Z	N_{drip}	group	N_{res}
Ni	28	60	$\mathcal{A}_1$	3.0
Kr	36	82	$\mathcal{A}_2$	0.0
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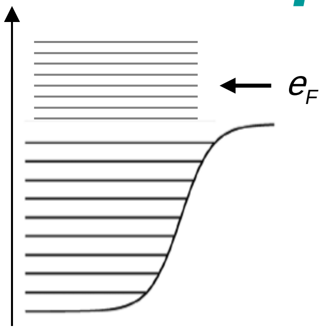
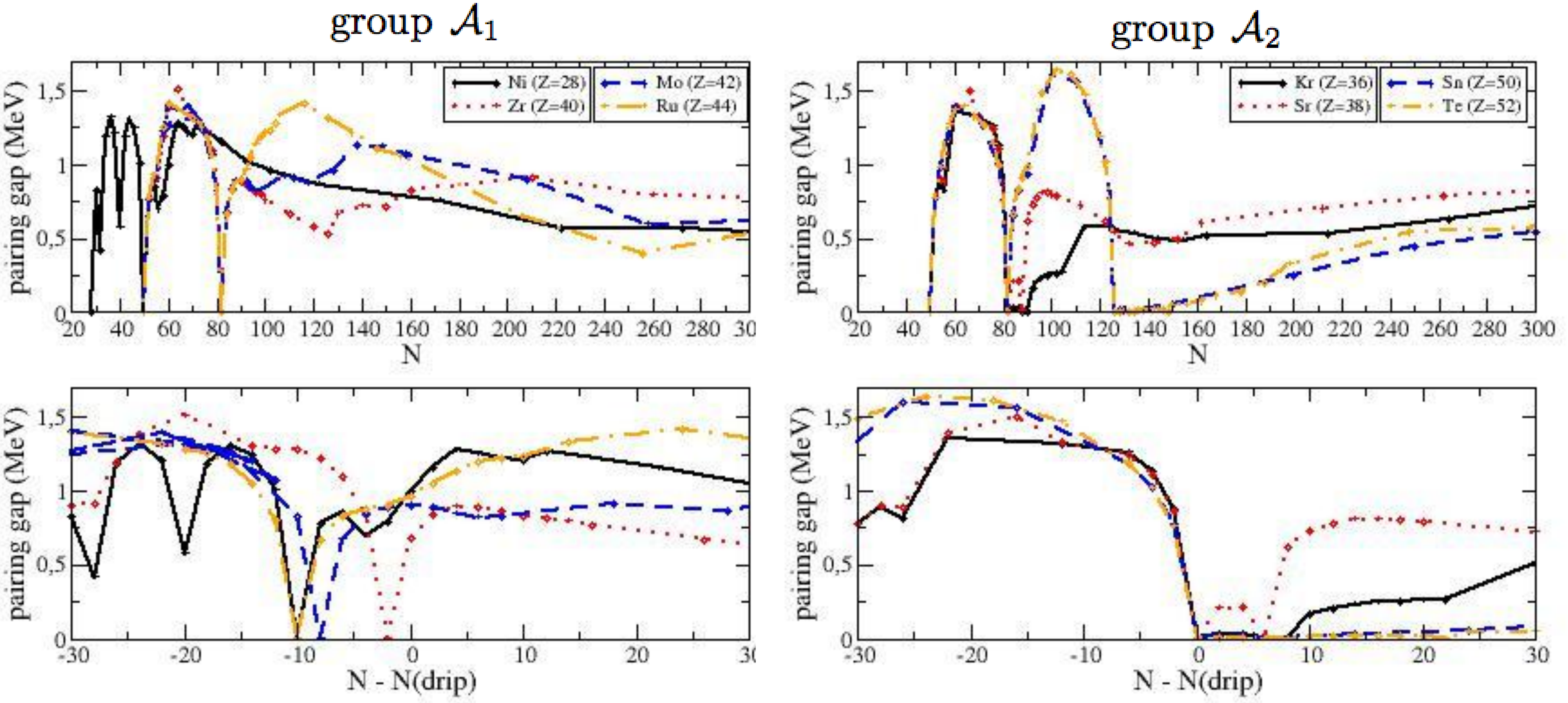
A systematic study based on 8 isotopes with 28<Z<50



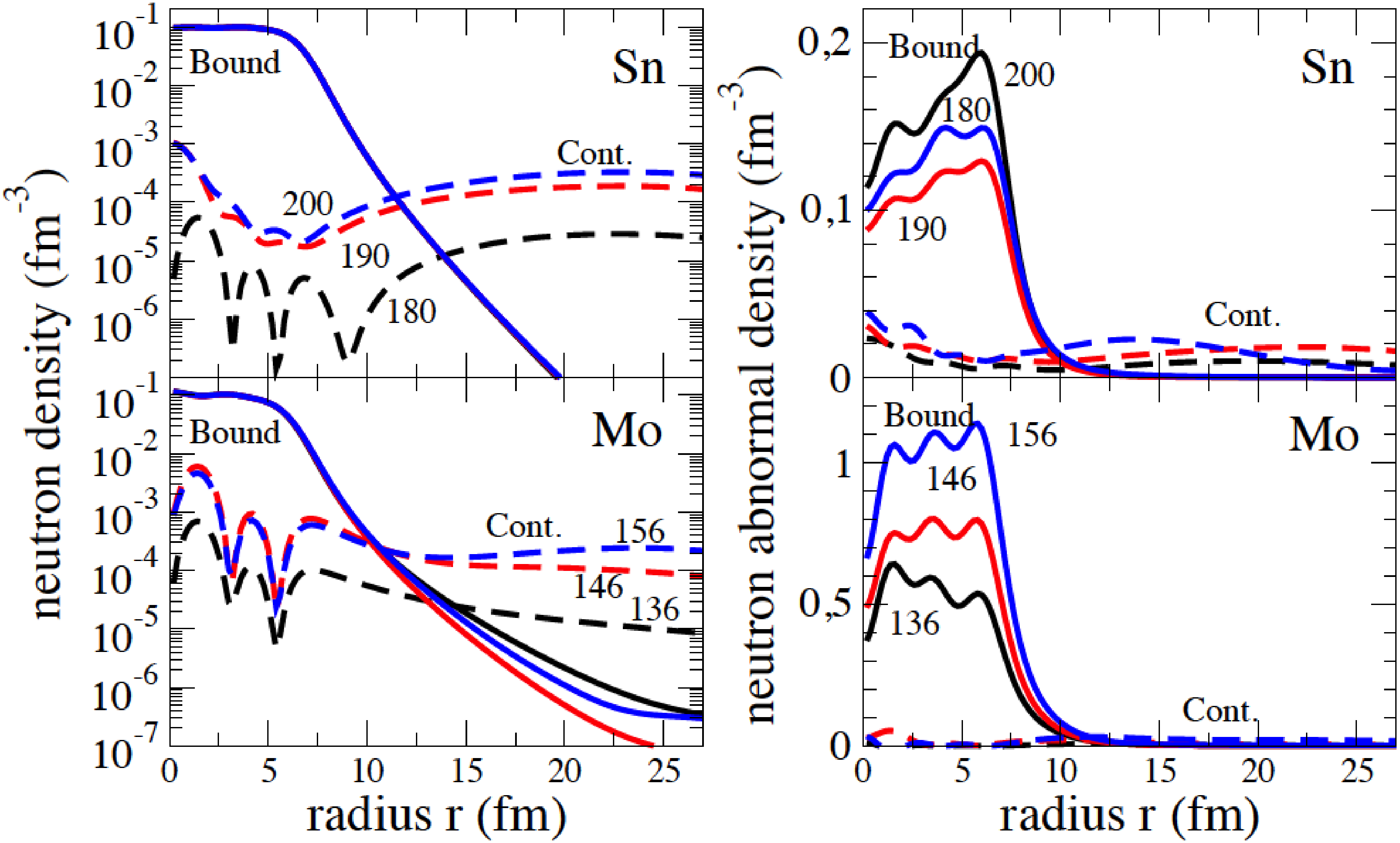
Suppression or persistence of pairing upon overflowing neutrons.


group $\mathcal{A}_1$

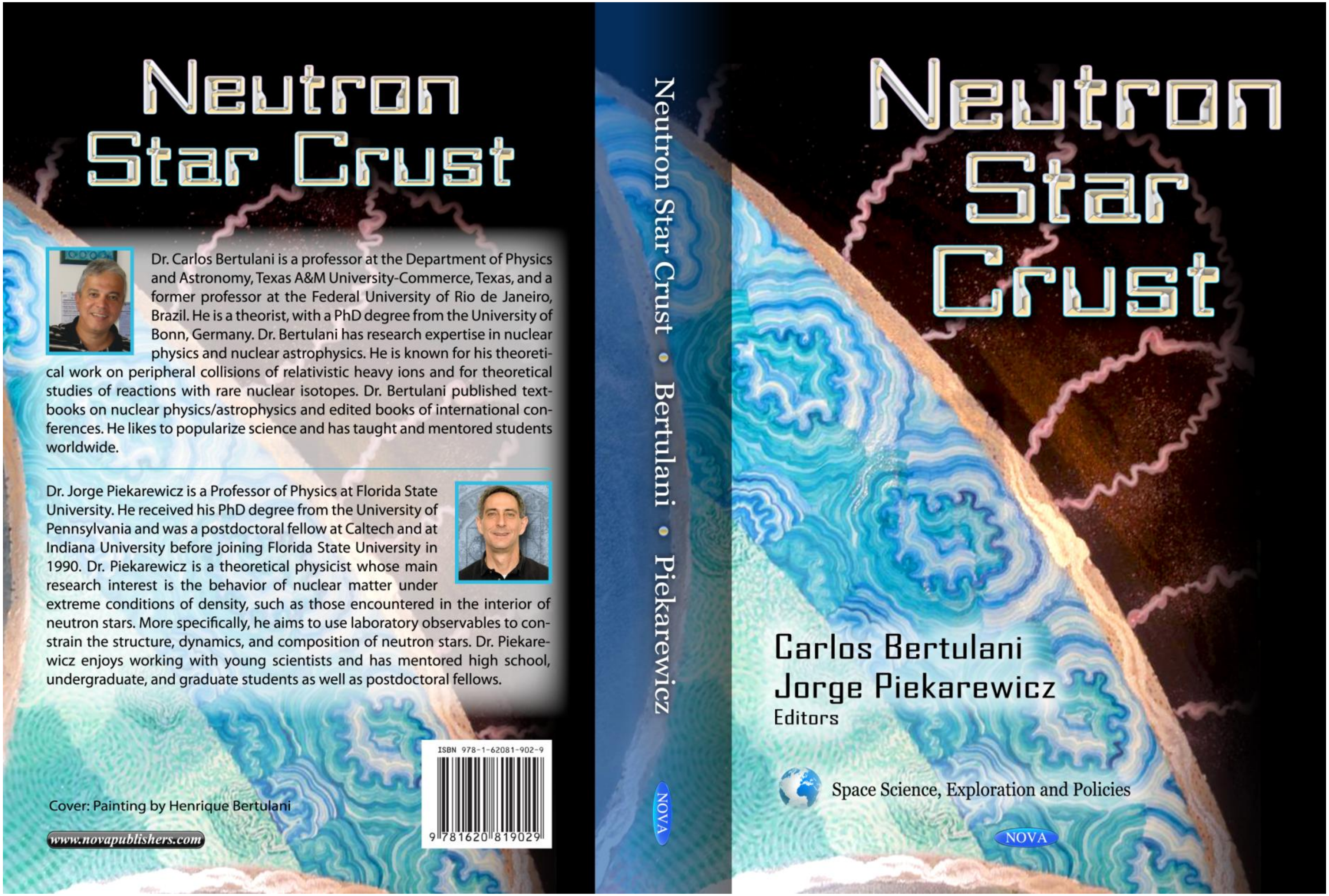
group $\mathcal{A}_2$

J.M. & Khan, PRC 2012

Bound and unbound densities



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



Neutron Star Crust

Dr. Carlos Bertulani is a professor at the Department of Physics and Astronomy, Texas A&M University-Commerce, Texas, and a former professor at the Federal University of Rio de Janeiro, Brazil. He is a theorist, with a PhD degree from the University of Bonn, Germany. Dr. Bertulani has research expertise in nuclear physics and nuclear astrophysics. He is known for his theoretical work on peripheral collisions of relativistic heavy ions and for theoretical studies of reactions with rare nuclear isotopes. Dr. Bertulani published textbooks on nuclear physics/astrophysics and edited books of international conferences. He likes to popularize science and has taught and mentored students worldwide.

Dr. Jorge Piekarewicz is a Professor of Physics at Florida State University. He received his PhD degree from the University of Pennsylvania and was a postdoctoral fellow at Caltech and at Indiana University before joining Florida State University in 1990. Dr. Piekarewicz is a theoretical physicist whose main research interest is the behavior of nuclear matter under extreme conditions of density, such as those encountered in the interior of neutron stars. More specifically, he aims to use laboratory observables to constrain the structure, dynamics, and composition of neutron stars. Dr. Piekarewicz enjoys working with young scientists and has mentored high school, undergraduate, and graduate students as well as postdoctoral fellows.

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Neutron Star Crust

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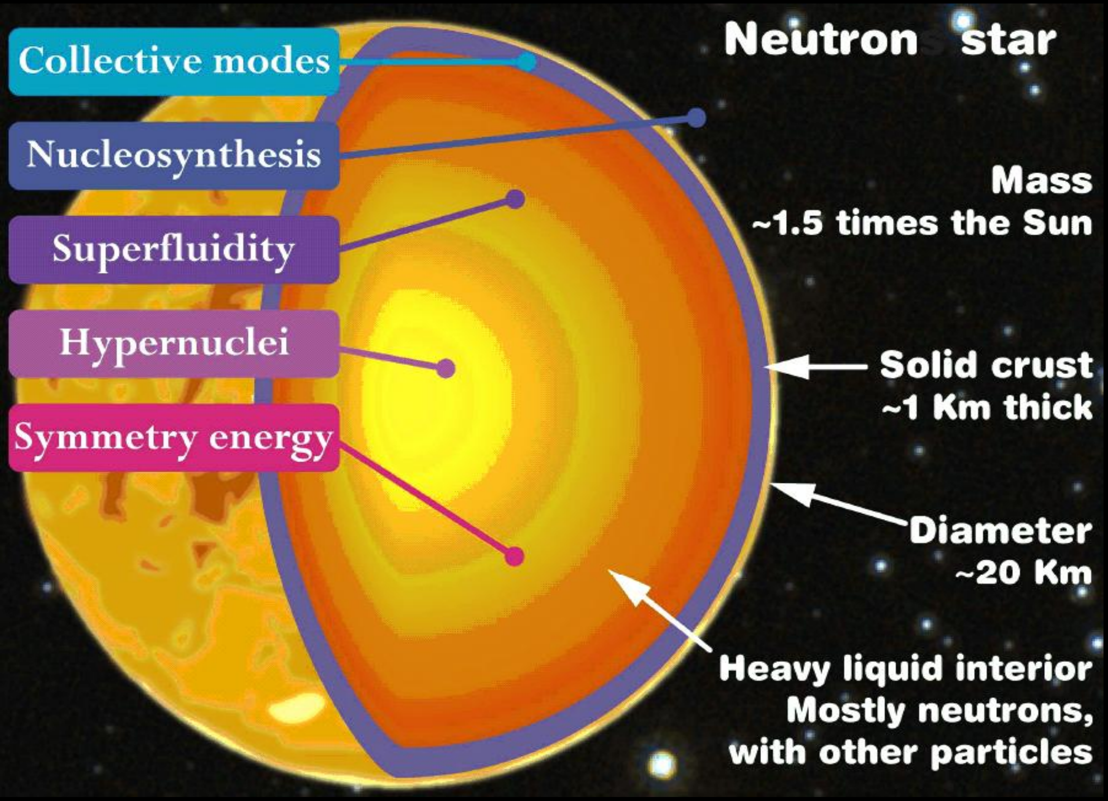
Exploring foundamental physics with neutron stars



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

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