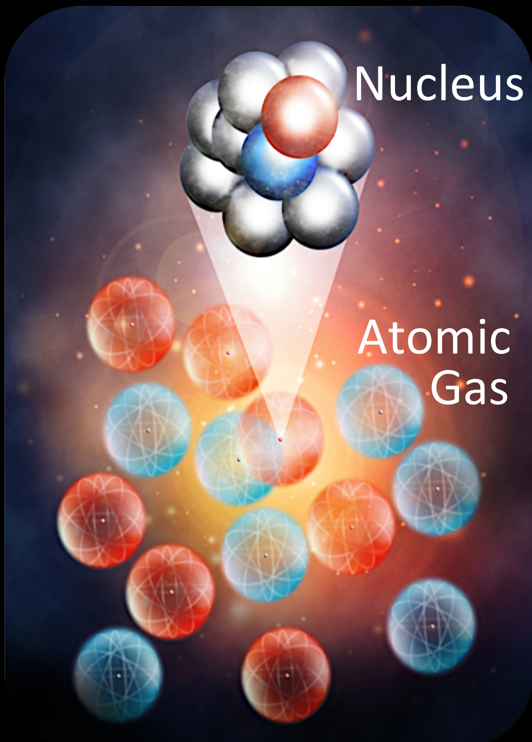
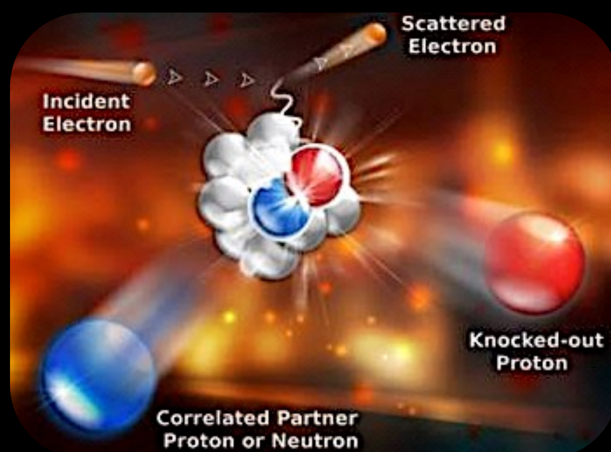
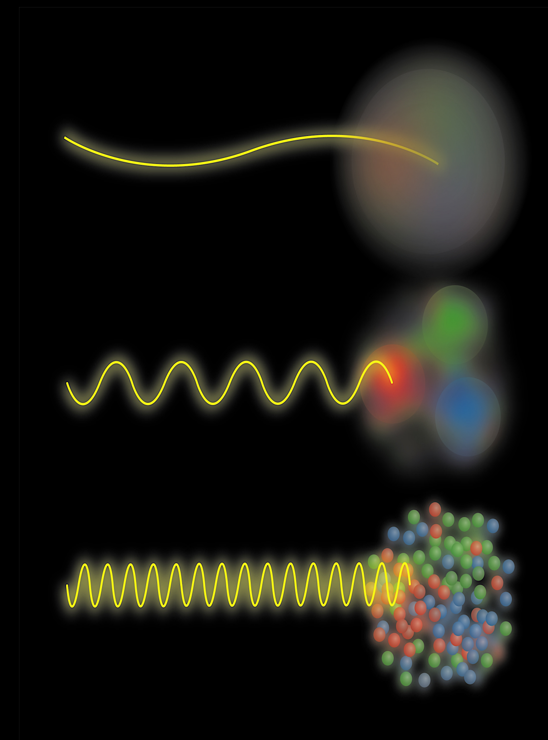
Contact Interactions and the Nuclear Symmetry Energy



Or Hen

Tel-Aviv (-> MIT)





EMMI Workshop, GSI, Germany (October 14th 2015)

Two-component interacting Fermi systems

The contact term

Please forget about nuclear physics for a moment

The Contact and Universal Relations

A concept developed for a ***dilute*** two-component Fermi systems with a short-range interaction.

Scattering length

$$\text{dilute} \equiv r_{eff} << a, d$$

Distance between fermions

S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

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These systems have a high-momentum tail:

$$n(k) = C / k^4 \quad \text{for} \quad k > k_F$$

C is the contact term

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Tan's Contact term:

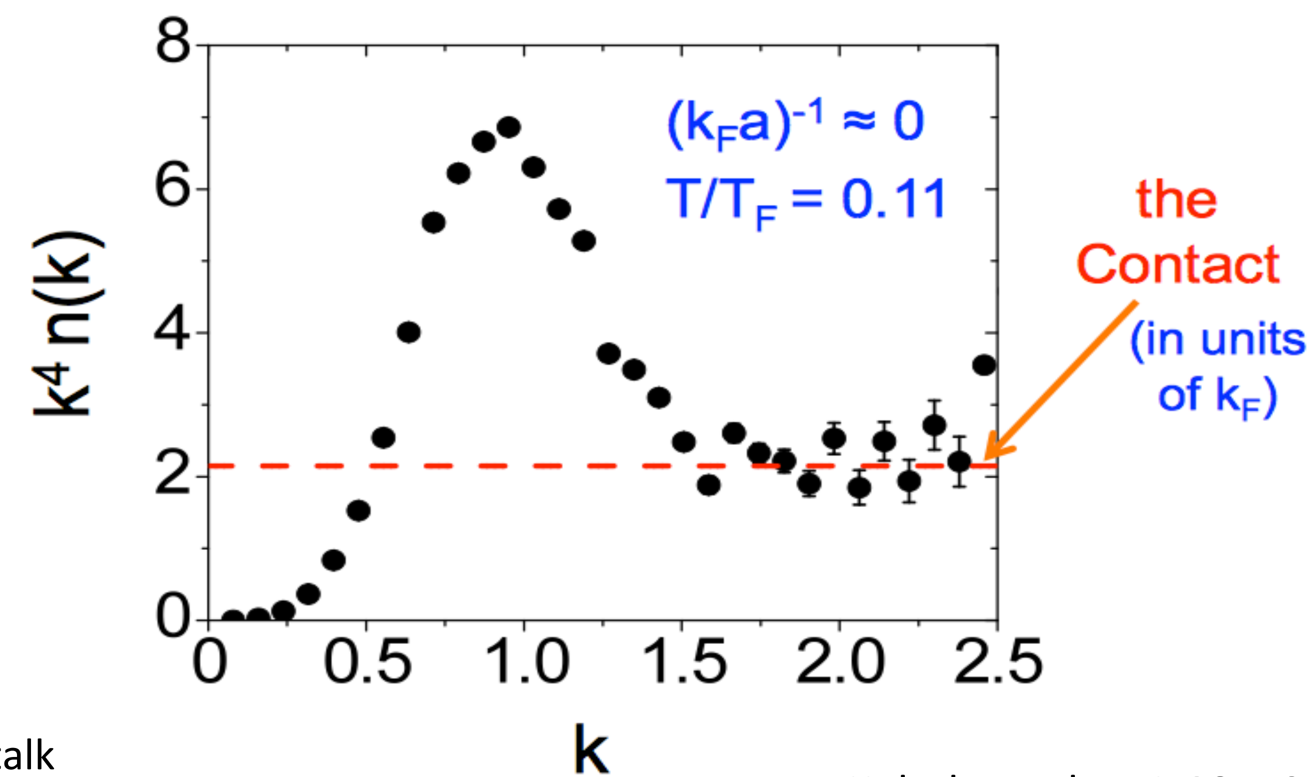
1. Measures the number of SRC different fermion pairs.
2. Determines the thermodynamics through a series of universal relations.

S. Tan Annals of Physics 323 (2008) 2952, ibid 2971, ibid 2987

Experimental Validation

Two spin-state mixtures of ultra-cold ^{40}K and ^{6}Li atomic gas systems.

=> extracted the contact and verified the universal relations



Adapted from a talk by Debbie Jin (JILA)

Kuhnle et al. PRL **105**, 070402 (2010)

Experimental Validation

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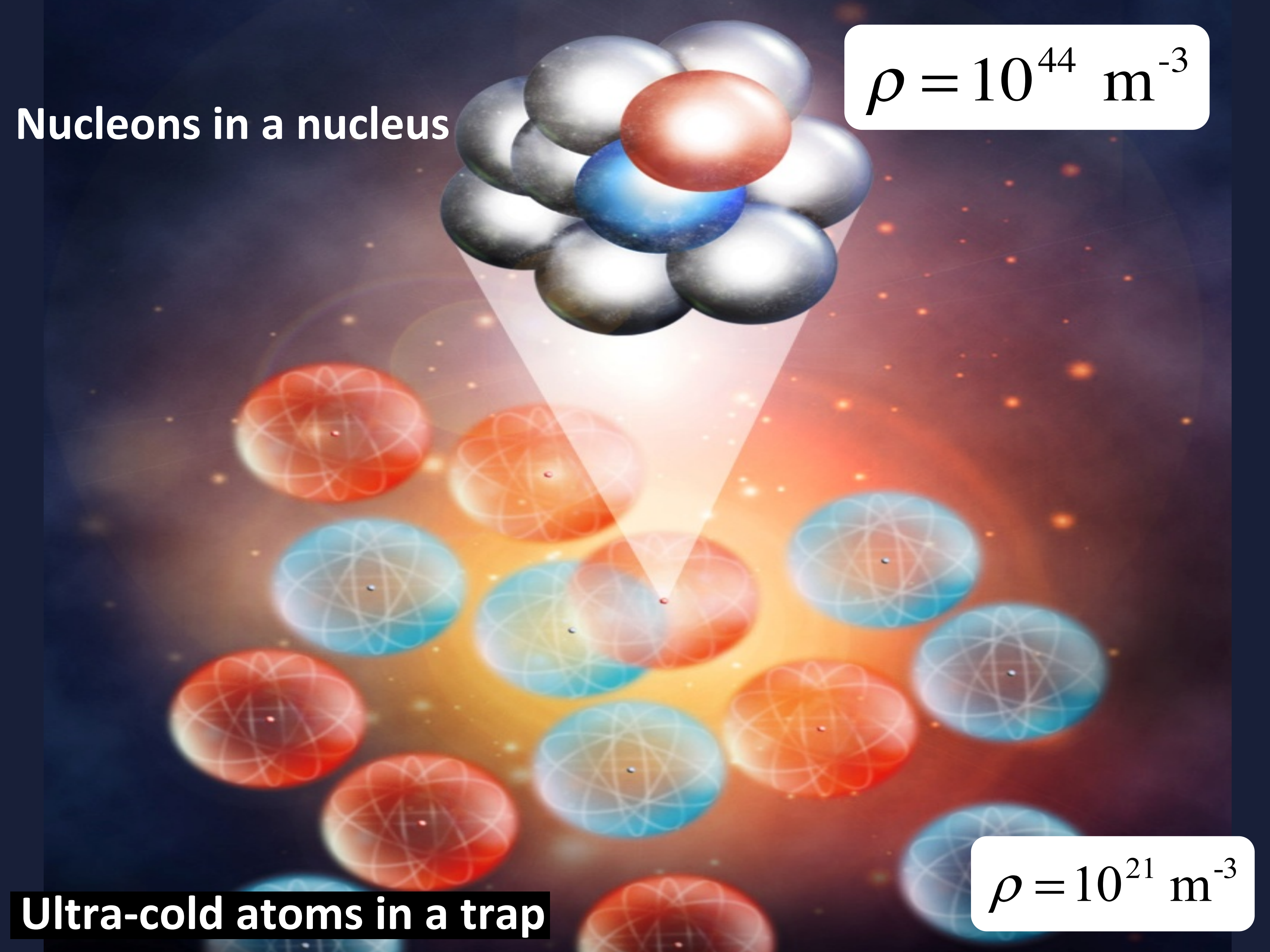
What About
a *Nuclear*
Contact ?

Adapted from a talk
by Debbie Jin (JILA)

105, 070402 (2010)



Nucleons in a nucleus
$\rho = 10^{44}\ \mathrm{m}^{-3}$
$\rho = 10^{21}\ \mathrm{m}^{-3}$
Ultra-cold atoms in a trap

$$\sigma_1 \approx 1 \ \text{person/m}^2$$

$$\sigma_1 \approx 1 \ \text{person/m}^2$$

$$\sigma_2 \approx 1 \ \text{person/km}^2$$

$$\sigma_1 / \sigma_2 \approx 10^6$$

A Nuclear Contact?

Are nuclei dilute? (i.e. $r_{eff} << a,d$)

$$d = \left(\rho/2\right)^{-1/3} \approx 2.3 \text{ fm}$$

$$r_{eff} \approx \frac{\hbar}{2 \cdot m_\pi \cdot c} \approx 0.7 \text{ fm}$$ **[Tensor force]**

$$a\left({}^3S_1\right) = 5.42 \text{ fm}$$

[The high-momentum tail is predominantly ${}^3S_1$ (${}^3D_1$)]

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$$a\left({}^3S_1\right) = 5.42 \text{ fm}$$

$$r_{eff}(0.7 \text{ fm}) < d(2.3 \text{ fm}), a(5.4 \text{ fm})$$

Is there $1/k^4$ scaling regardless?

$$1.5k_F < k < 3k_F$$

$$n_A(k) = a_2(A/d) \cdot n_d(k)$$

Constant

Deuteron Momentum Distribution

A Nuclear Contact?

Is there $1/k^4$ scaling regardless? YES!

$$1.5k_F < k < 3k_F$$

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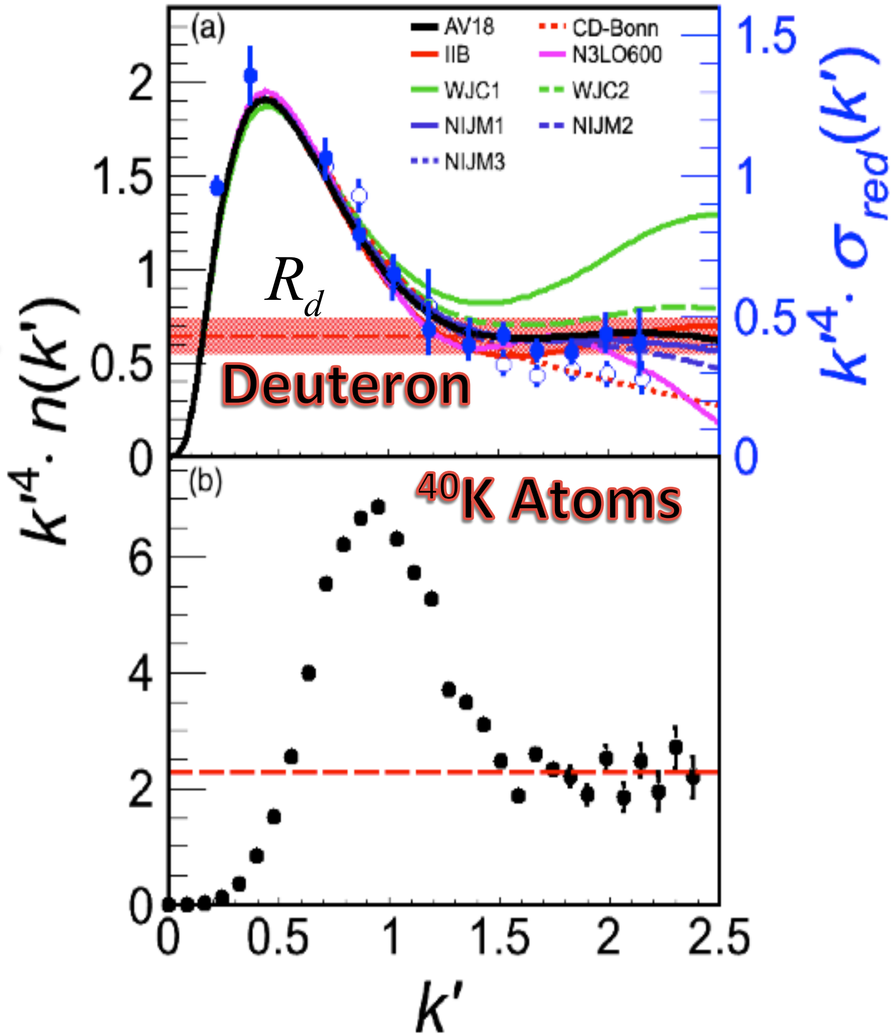

O. Hen et al. Phys. Rev. C, In-Print (2015)

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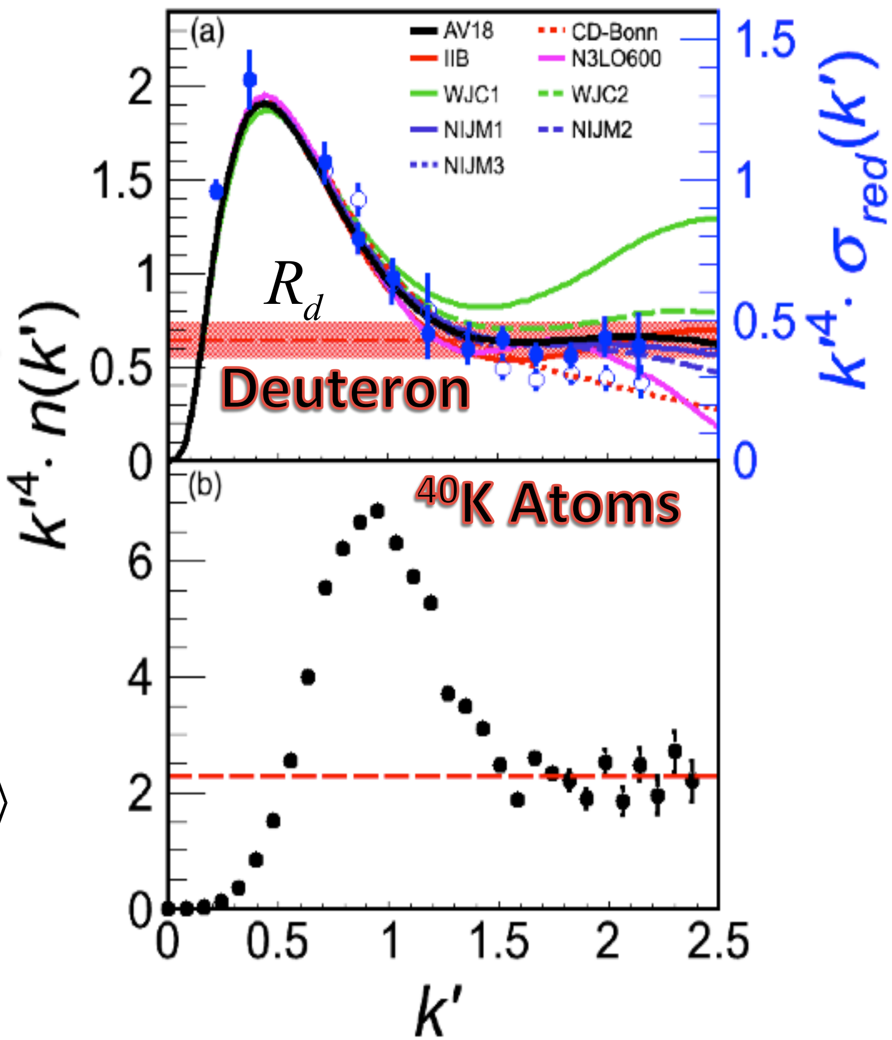

Why $1/k^4$?

Effect of the one pion exchange (OPE) contribution to the tensor potential acting in second order

$$(-B - H_0)|\Psi_D\rangle = V_T|\Psi_S\rangle$$

$$V_{00} = V_T(-B - H_0)^{-1} V_T$$

O. Hen et al. Phys. Rev. C, In-Print (2015)

A Nuclear Contact?

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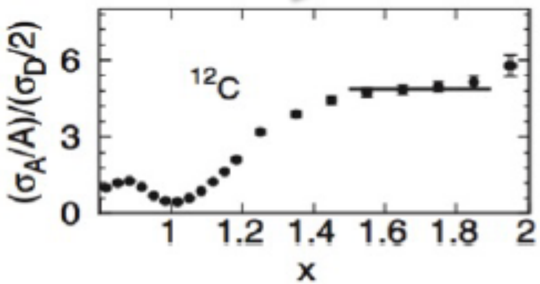

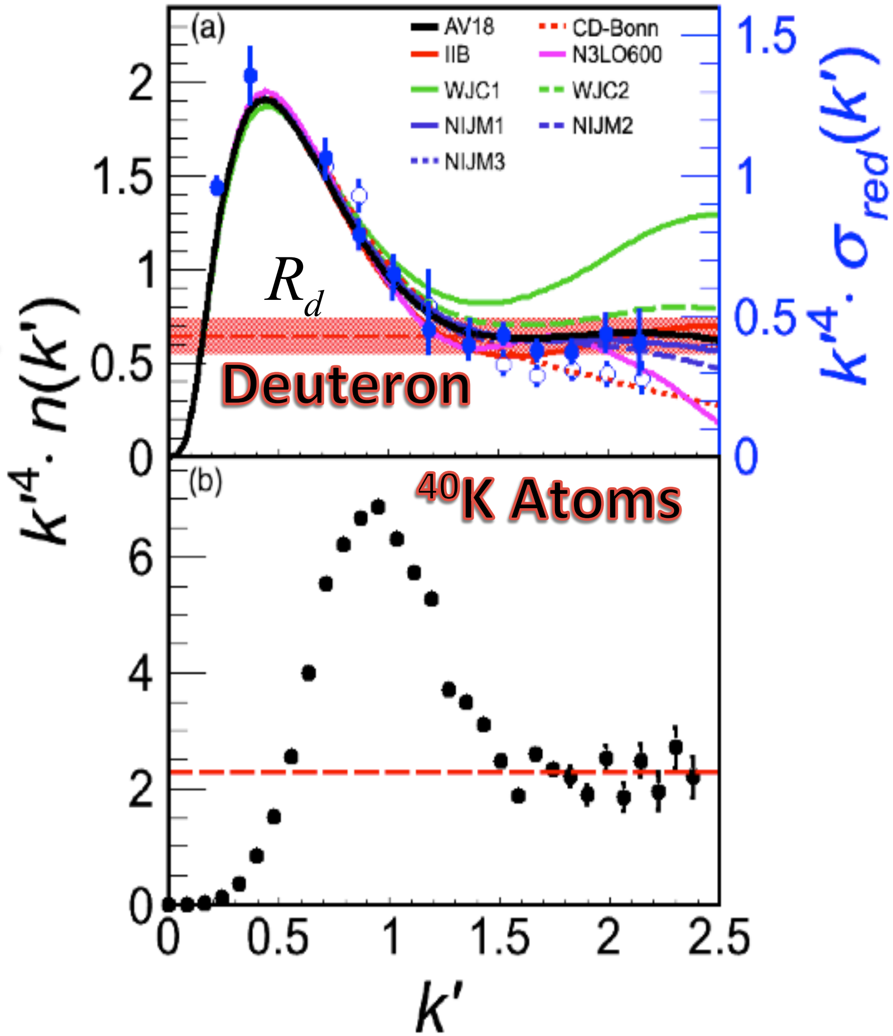

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A Nuclear Contact?

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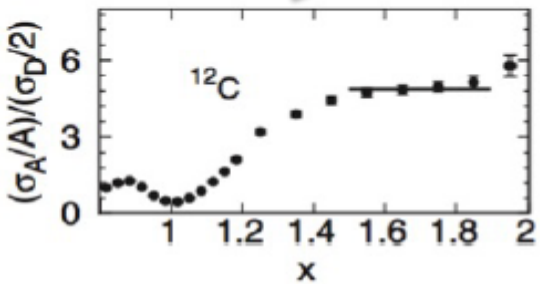
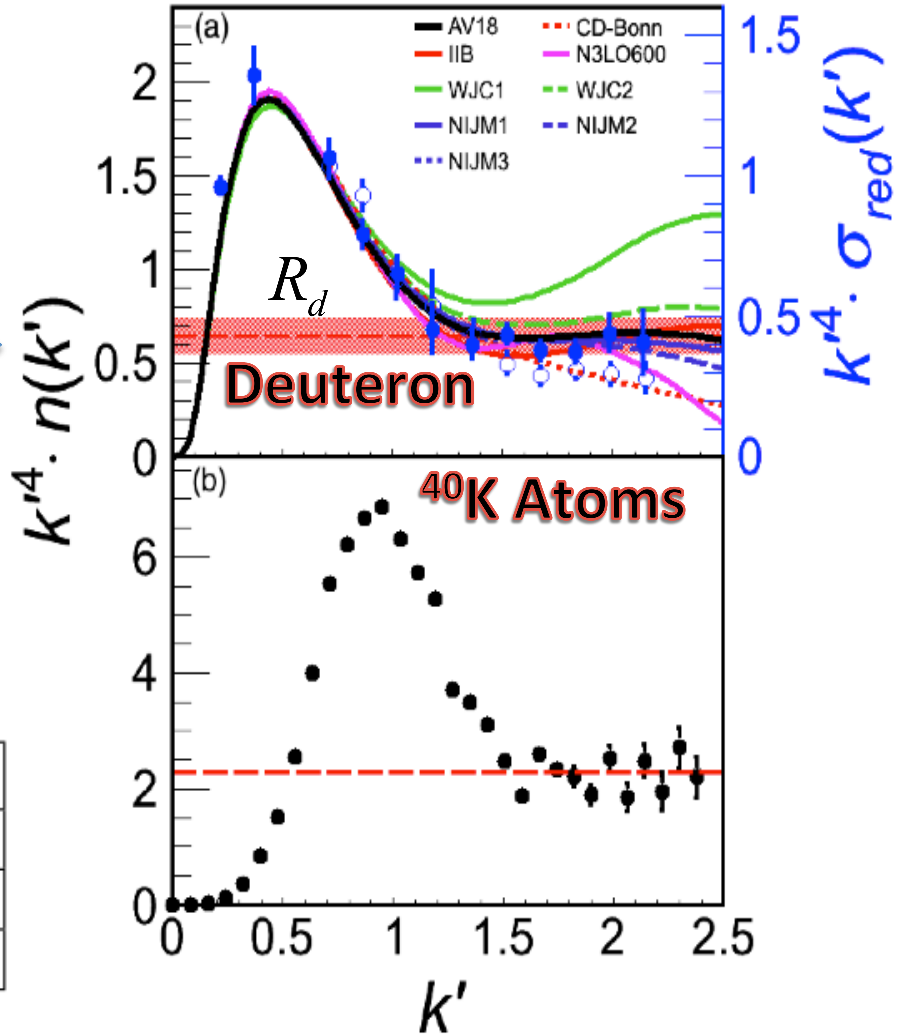


$$\frac{C}{k_F \cdot A} = a_2(A) \cdot R_d$$

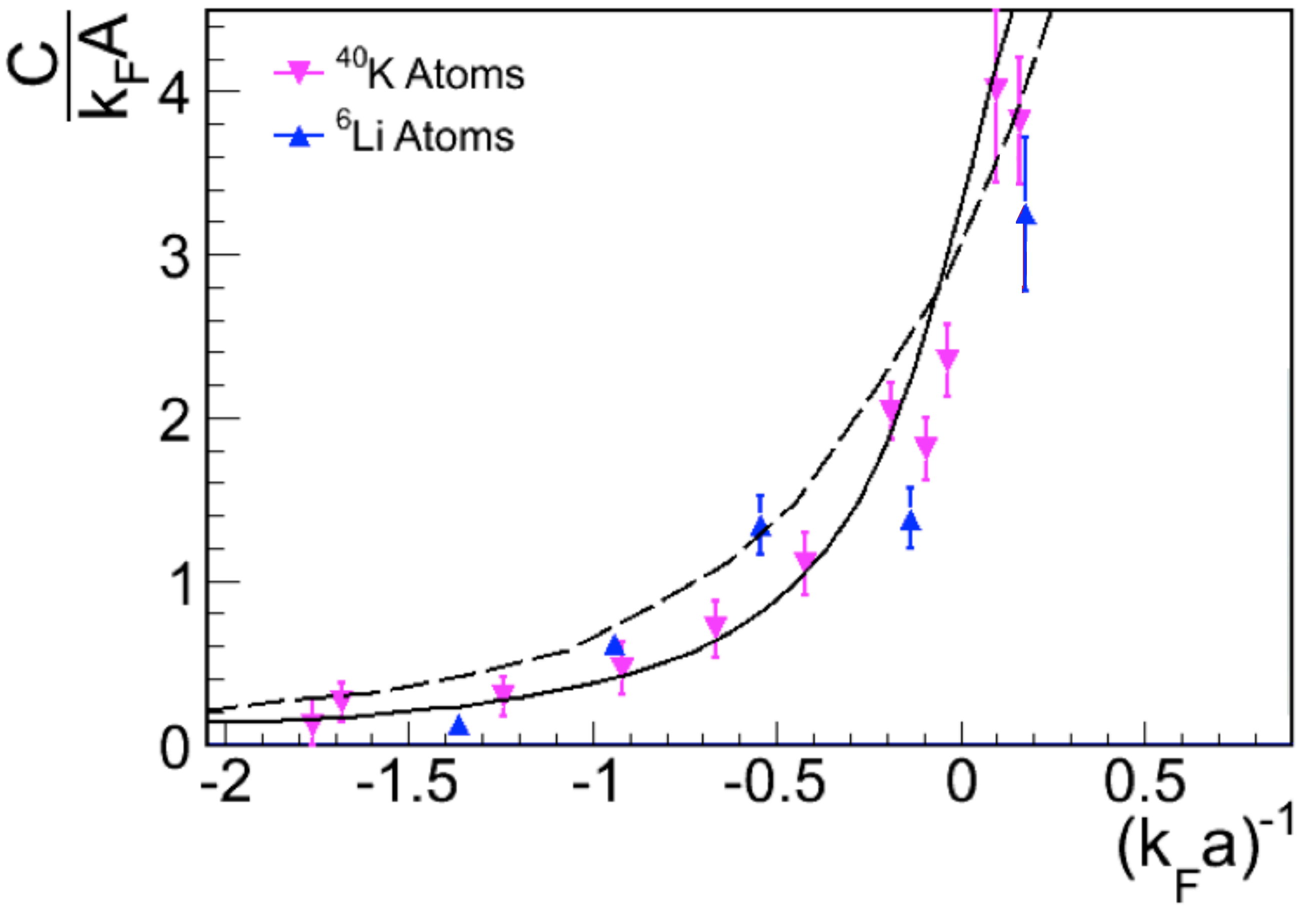
Nucleus	$a_2(A)$	$\frac{C}{k_F A}$
^{12}C	4.75 ± 0.16	3.04 ± 0.49
^{56}Fe	5.21 ± 0.20	3.33 ± 0.54
^{197}Au	5.16 ± 0.22	3.30 ± 0.53



O. Hen et al. Phys. Rev. C, In-Print (2015)

Comparing with atomic systems

Finding the same *dimensionless* interaction strength



Stewart et al. Phys. Rev. Lett. **104**, 235301 (2010)
Kuhnle et al. Phys. Rev. Lett. **105**, 070402 (2010)

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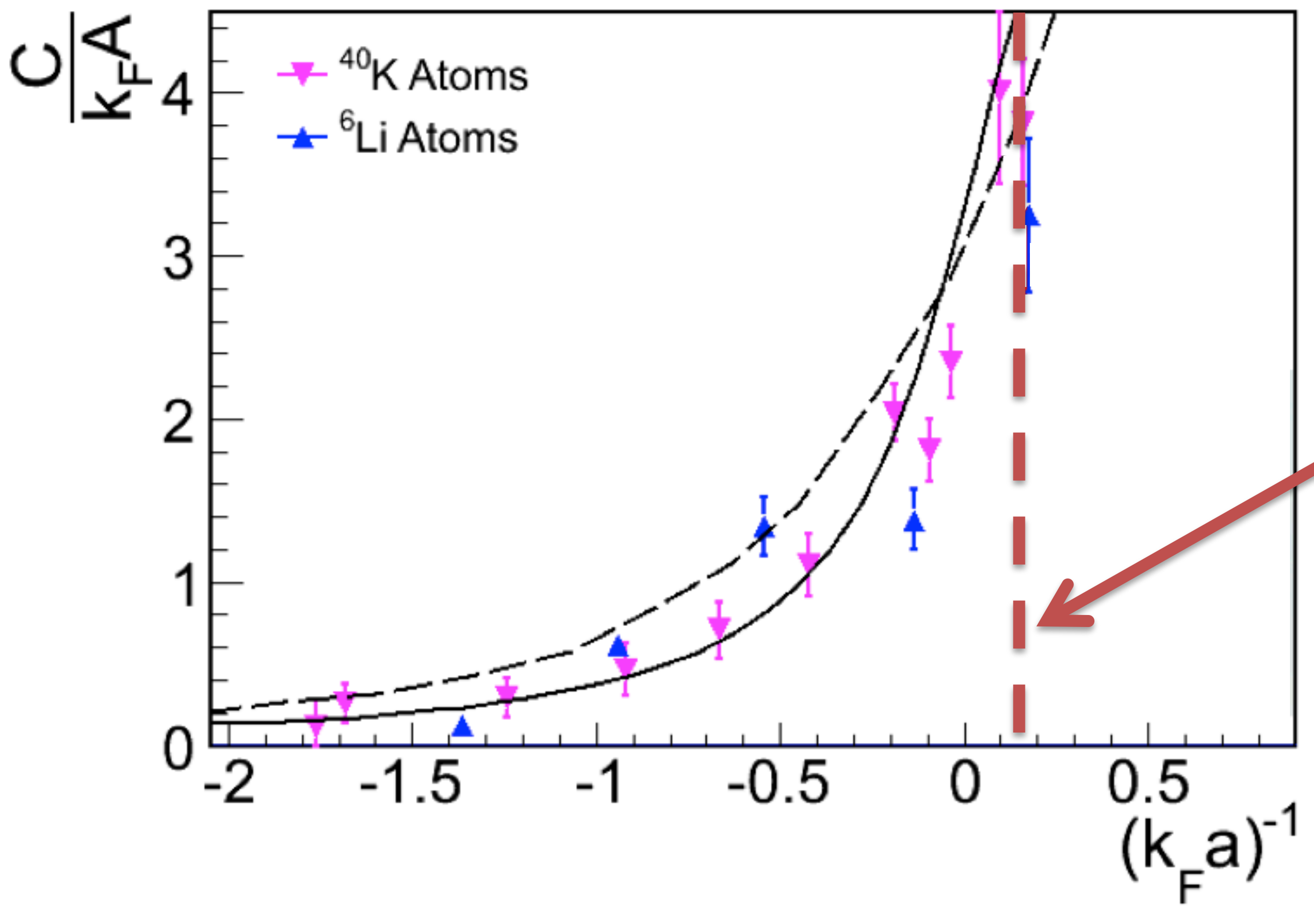

<u>For Nuclei:</u>

$k_F \approx 1.27\ \mathrm{fm}^{-1}$

$a \approx 5.4\ \mathrm{fm}$

=> $(k_F a)^{-1} \approx 0.15$

Stewart et al. Phys. Rev. Lett. **104**, 235301 (2010)
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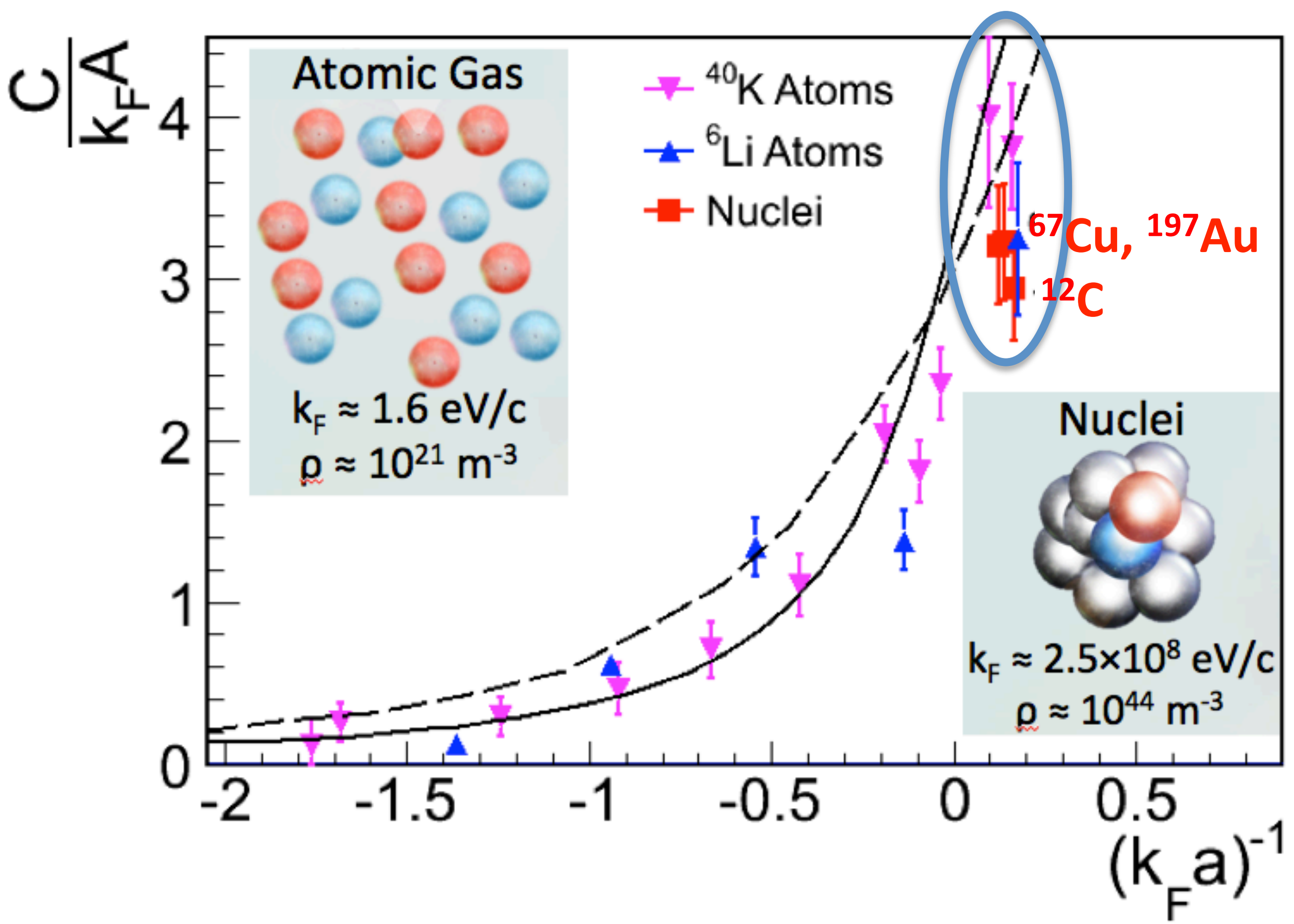
Comparing with atomic systems

Equal contacts for equal interactions strength!



For Nuclei:

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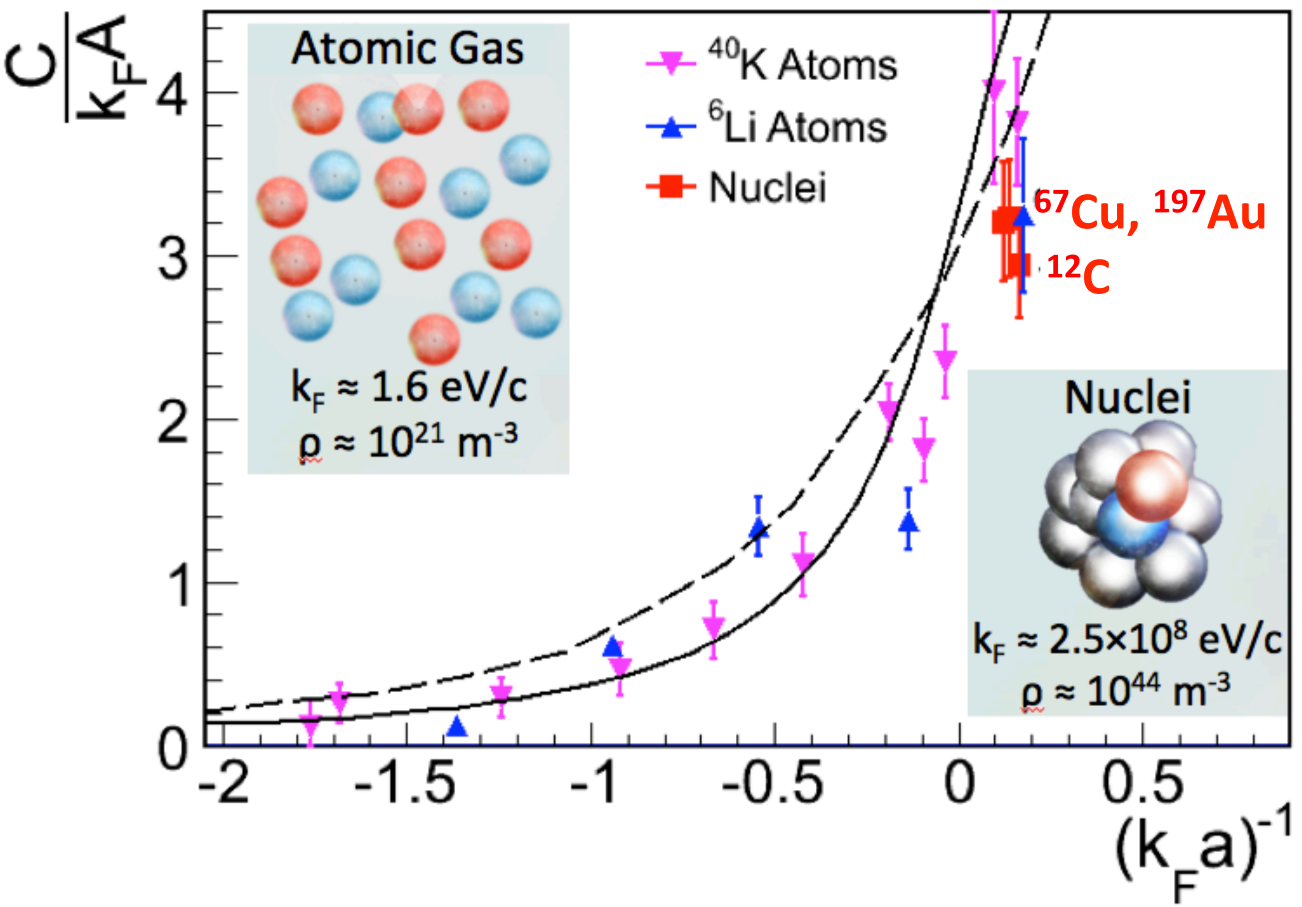
Comparing with atomic systems



At unitary (i.e. $(k_F a)^{-1} \approx 0$) the SRC probability is ~20% for both systems

O. Hen et al. Phys. Rev. C, In-Print (2015)
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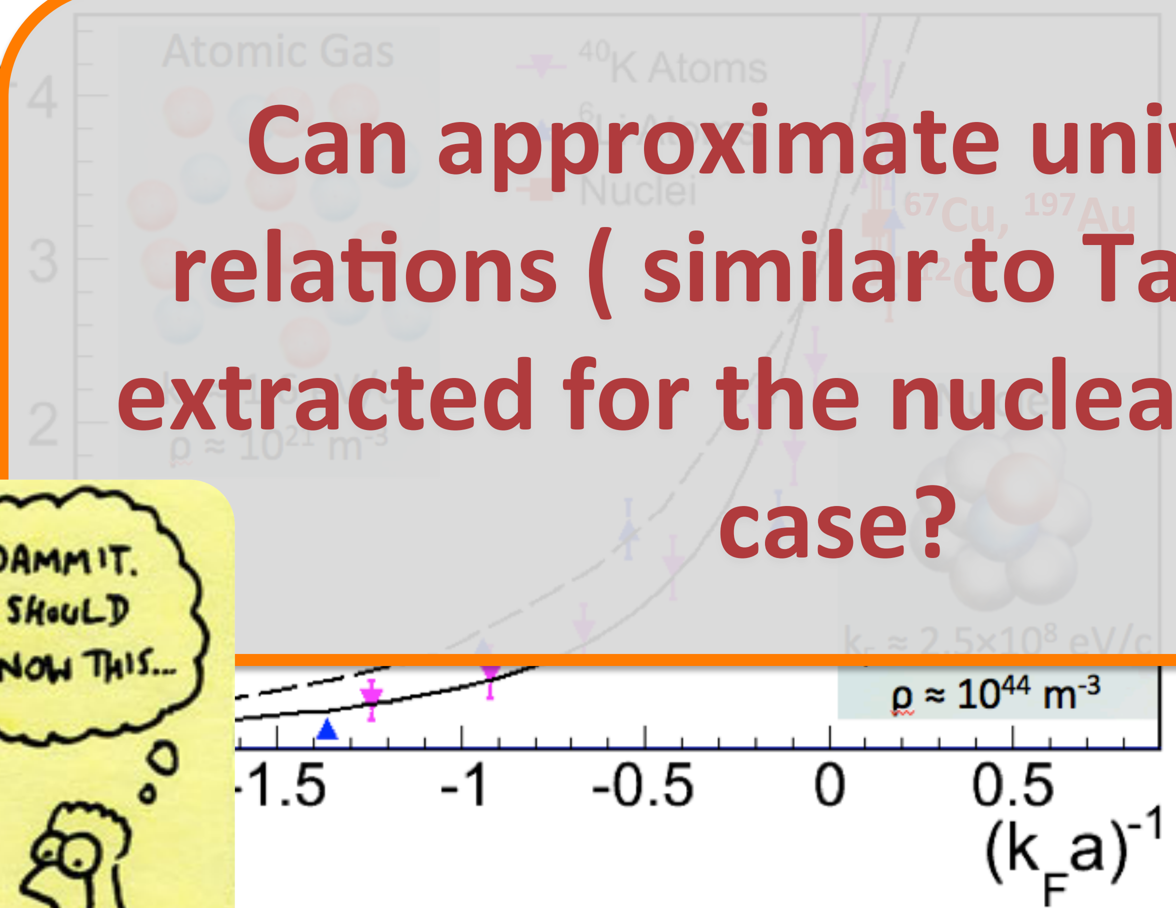
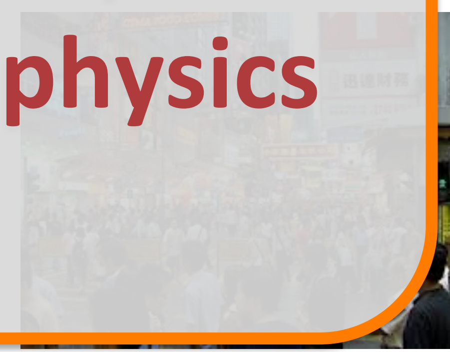


Can approximate universal relations (similar to Tan's) be extracted for the nuclear physics case?



Rev. C, In-Print (2015)
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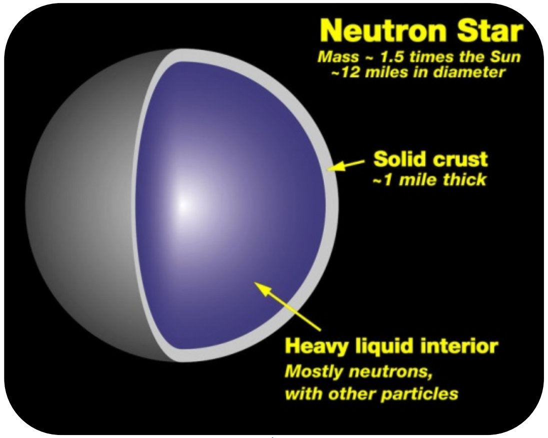
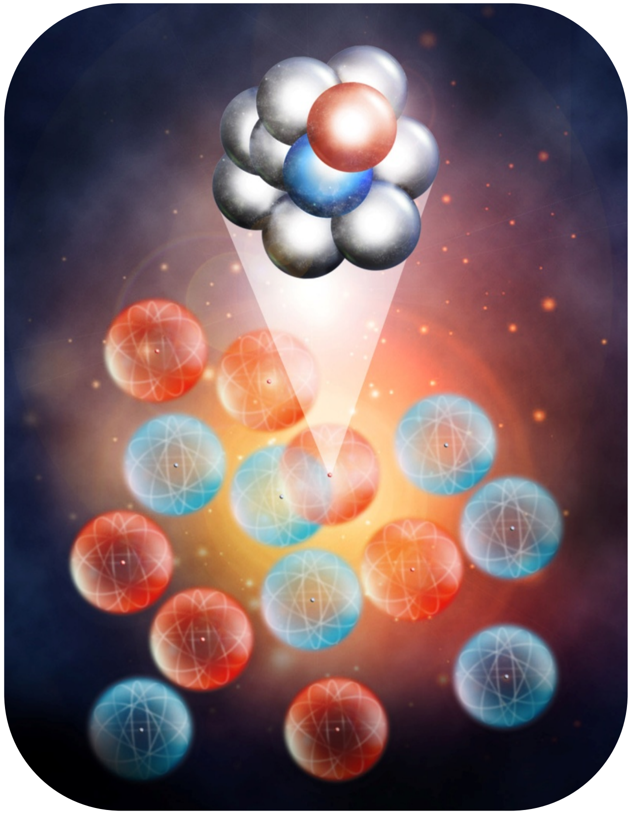


$$(2-3)\cdot\rho_0$$

?

$$\rho_0$$



$$10^{-25}\cdot\rho_0$$

Nuclear Symmetry Energy

Energy of *asymmetric* nuclear matter:

$$E(\rho_n, \rho_p) = E_0(\rho_n = \rho_p) \quad E_{sym}(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + O(\delta^4)$$

Energy of *symmetric* nuclear matter

symmetry energy

Isospin asymmetry (δ)

Nuclear Symmetry Energy

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symmetry energy

$$E_{sym}(\rho) \approx E(\rho)_{\mathrm{PNM}} - E(\rho)_{\mathrm{SNM}}$$

Relates to the energy change when replacing n with p

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Relates to the energy change when replacing n with p

- equation-of-state of neutron stars
- heavy-ion collisions
- r-process nucleosynthesis
- core-collapse supernovae
- more…

Thomson Research Fronts 2013

ASTRONOMY AND ASTROPHYSICS

RANK	RESEARCH FRONTS	CORE PAPERS	CITATIONS	MEAN YEAR OF CORE PAPERS
1	Galileon cosmology	34	1,584	2010.7
2	Probing extreme redshift galaxies in the Hubble Ultra Deep Field	31	2,415	2010.3
3	Sterile neutrinos at the eV scale	41	2,472	2010.2
4	Herschel Space Observatory and initial performance	9	1,456	2010.2
5	Kepler Mission and the search for extra-solar planets	47	4,211	2010.0
6	Neutron star observations and nuclear symmetry energy	18	1,536	2009.9
7	Evolution of massive early-type galaxies	18	1,724	2009.6
8	Gamma-ray sources detected by the Fermi Large Area Telescope	8	1,531	2009.5
9	Data from Hinode (Solar-B) Solar Optical Telescope and Solar Dynamics Observatory (SDO)	24	3,023	2009.4
10	Supernova Type Ia light curves and dark energy	19	5,920	2009.2

Source: Thomson Reuters Essential Science Indicators

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symmetry energy

$$E_{sym}(\rho) \approx E(\rho)_{PNM} - E(\rho)_{SNM}$$

np-SRC exist in SNM but not in PNM

$$\Rightarrow E_{sym}(\rho) = E_{PNM}(\rho) - E_{SNM}(\rho)$$

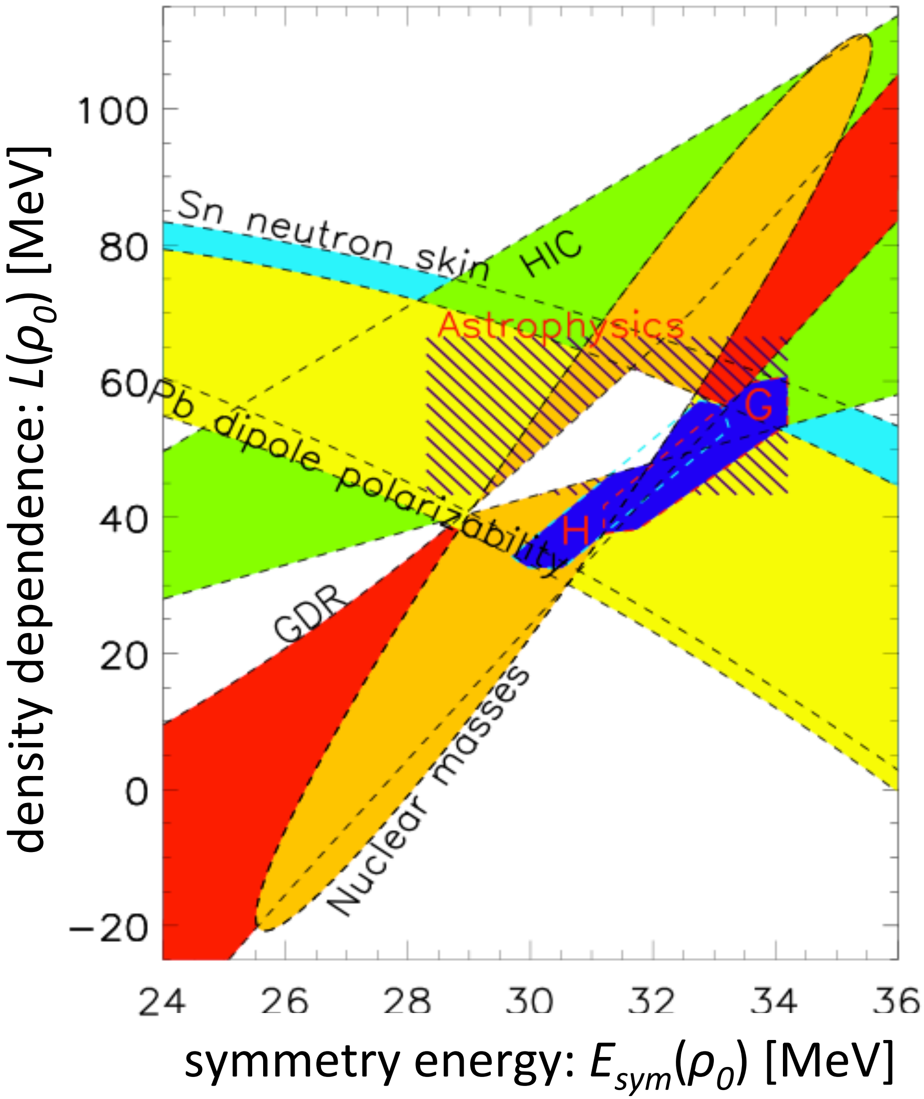
Could change drastically

Relates to the energy change when replacing n with p

[SNM: Symmetric Nuclear Matter, PNM: Pure Neutron Matter]

- neutron stars
- heavy-ion collisions
- ...nucleosynthesis
- core-collapse supernovae
- more…

Symmetry Energy @ Saturation Density



Global analysis of world data:

$28.9 \leq E_{sym}(\rho_0) \leq 34.1$

$42.4 \leq L(\rho_0) \leq 74.4$

$^{*}L(\rho_0) = 3\rho[dE/d\rho]|_{\rho 0}$

Constraining the Symmetry Energy

$$E_{sym}\left(\rho\right)=E_{sym}^{kin}\left(\rho_0\right)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha}+E_{sym}^{pot}\left(\rho_0\right)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

***$E_{sym}(\rho)$* requires separate knowledge of the kinetic and potential parts.**

<u>Fermi-Gas Model:</u> a common approximation for the kinetic term

M.B. Tsang et al., Phys. Rev. Lett **102**, 122701 (2009)
A.W. Steiner, J.M. Lattimer, and E.F. Brown, Astrophys. J. **722**, 33 (2010).

Constraining the Symmetry Energy

[Fermi-Gas Picture]

$$E_{sym}(\rho) = E_{sym}^{kin}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha} + E_{sym}^{pot}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

<u>Fermi-Gas Model</u>

$$E_{sym}^{kin}(\rho) = \frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3}$$

Constraining the Symmetry Energy

[Fermi-Gas Picture]

$$\underbrace{E_{sym}(\rho) = E_{sym}^{kin}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha}}_{\text{Fermi-Gas Model}} + E_{sym}^{pot}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

Fermi-Gas Model

$$E_{sym}^{kin}(\rho) = \frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3}$$

☑ $\alpha = 2/3$

☑ $E_{sym}^{kin}(\rho_0) = 12.5\ \text{MeV}$

Constraining the Symmetry Energy

[Fermi-Gas Picture]

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Constraining the Symmetry Energy

[Fermi-Gas Picture]

$$E_{sym}(\rho) = \underbrace{E_{sym}^{kin}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha}}_{\text{Fermi-Gas Model}} + E_{sym}^{pot}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

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Only unknown is γ_i probed in HI collision measurements and neutron stars observations

Constraining the Symmetry Energy

[With SRCs]

$$E_{sym}(\rho) = \underbrace{E_{sym}^{kin}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\alpha}}_{} + E_{sym}^{pot}(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

Fermi-Gas Model + Correlations

$$E_{sym}^{kin}(\rho) = \frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3} + \Delta_{SRC}(\rho)$$

- ☑ $\alpha = 2/3$
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Fermi-Gas Model + Correlations

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Constraining the Symmetry Energy

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~~**<u>Only unknown is γ_i</u>** probed in HI collision measurements and neutron stars observations~~

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Constraining the Symmetry Energy

[With SRCs]

$$E_{sym}(\rho) = E^{kin}_{sym}(\rho_0)\left(\frac{\rho}{\rho_0}\right)^{\alpha} + E^{pot}_{sym}(\rho_0)\left(\frac{\rho}{\rho_0}\right)^{\gamma_i}$$

Adding np-SRCs breaks the Fermi-Gas picture

=> Need a correlated Fermi-Gas Model

Fermi-Gas Model + Correlations

$$E^{kin}_{sym}(\rho) = \frac{1}{3}E_F(\rho_0)\cdot\left(\frac{\rho}{\rho_0}\right)^{2/3} + \Delta_{SRC}(\rho)$$

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☑ $\alpha = \cancel{2/3}$

☑ $E^{kin}_{sym}(\rho_0) = \cancel{12.5}$ MeV

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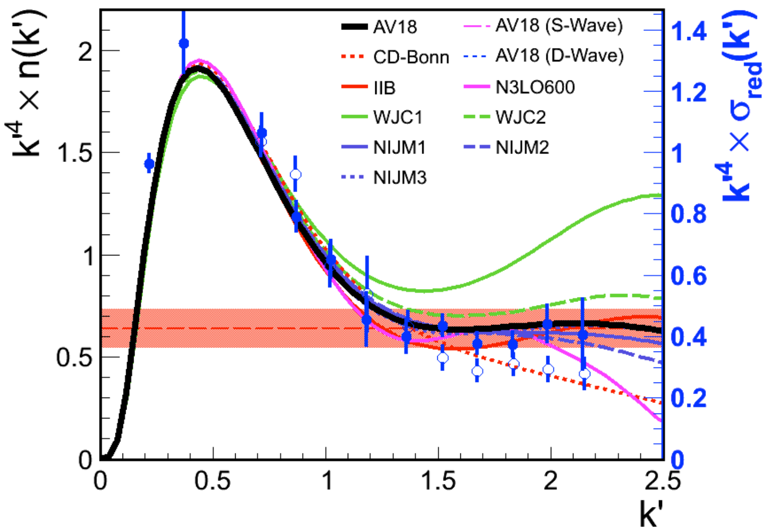
Correlated Fermi-Gas Model (CFG)

[Fermi-Gas with an SRC tail]

$$n_{CFG}(k) = \begin{cases} & \text{SNM} & & \text{PNM} & \\ & A_0 & , & A_1 & k < k_F \\ & C_\infty / k^4 & , & 0 & k_F < k < \lambda k_F^0 \\ & 0 & , & 0 & 0k > \lambda k_F^0 \end{cases}$$

C/k^4 is a good parameterization of the high-momentum tail:



O. Hen et al., Phys. Rev. C 91, 025803 (2015).

Correlated Fermi-Gas Model (CFG)

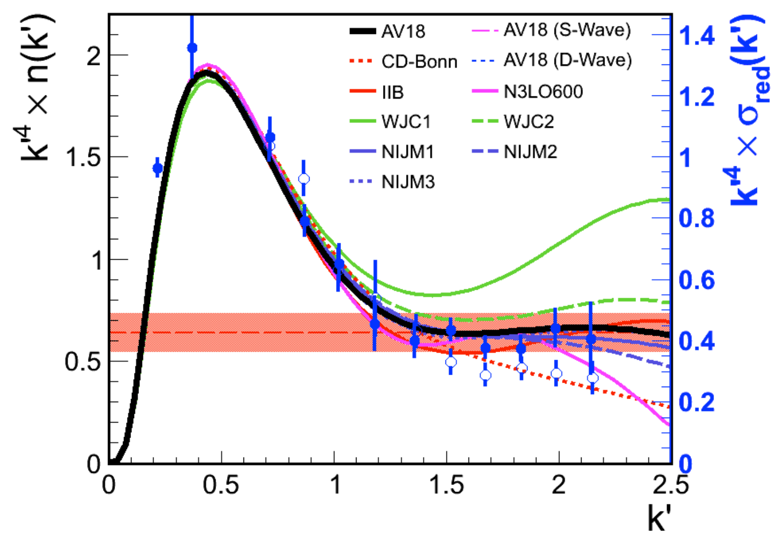
[Fermi-Gas with an SRC tail]

$$n_{CFG}(k) = \begin{cases} \boxed{\begin{matrix} \text{SNM} \\ A_0 \\ C_\infty / k^4 \\ 0 \end{matrix}} & \begin{matrix} \text{PNM} \\ , \quad A_1 \\ , \quad 0 \\ , \quad 0 \end{matrix} & \begin{matrix} \\ k < k_F \\ k_F < k < \lambda k_F^0 \\ 0 k > \lambda k_F^0 \end{matrix} \end{cases}$$

<u>SNM Model:</u>

- Depleted Fermi Distribution (A_0)
- High-Momentum tail (C/k^4)
- Momentum cutoff (λ)

C/k^4 is a good parameterization of the high-momentum tail:



O. Hen et al., Phys. Rev. C 91, 025803 (2015).

Correlated Fermi-Gas Model (CFG)

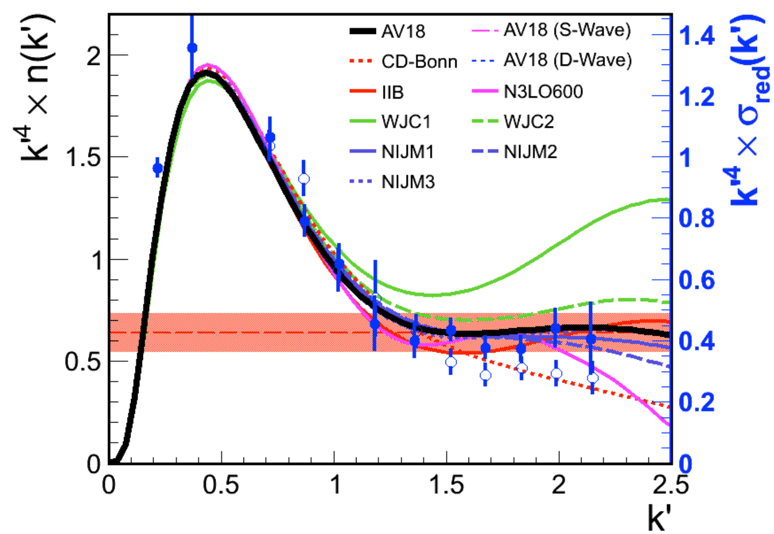
[Fermi-Gas with an SRC tail]

$$
n_{CFG}(k) = \left\{ \begin{array}{cccc} \text{SNM} & & \boxed{\text{PNM}} & \\ A_0 & , & A_1 & k < k_F \\ C_\infty / k^4 & , & 0 & k_F < k < \lambda k_F^0 \\ 0 & , & 0 & 0k > \lambda k_F^0 \end{array} \right.
$$

<u>PNM Model:</u>

- Free Fermi Gas

C/k[4] is a good parameterization of the high-momentum tail:

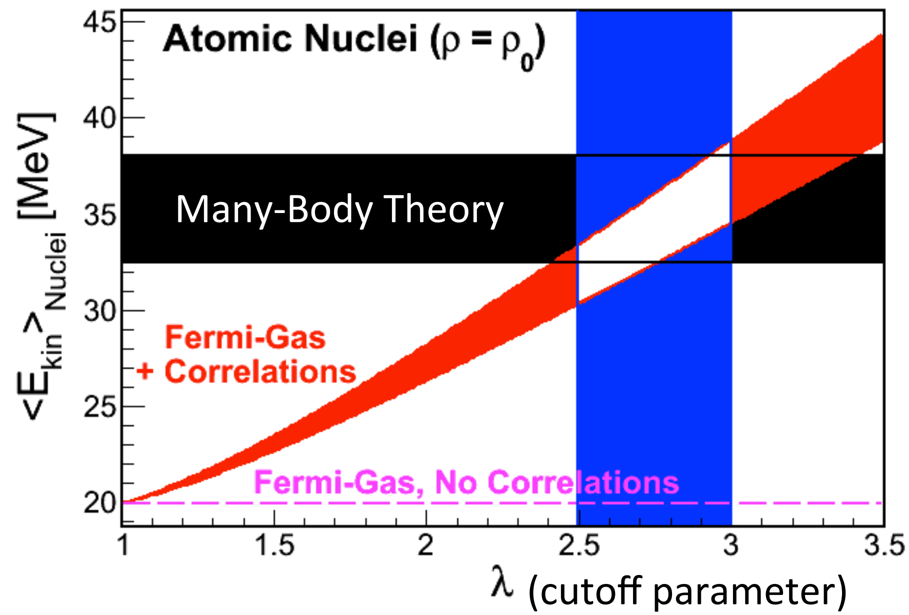


O. Hen et al., Phys. Rev. C 91, 025803 (2015).

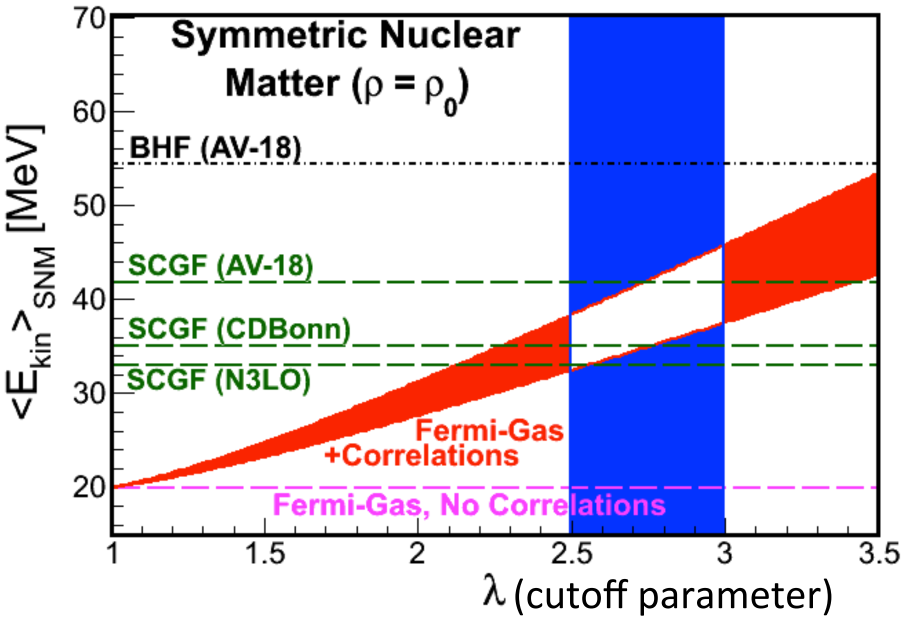
Benchmark Against Microscopic Calculations

$$E_{kin} = \frac{4\pi}{(2\pi)^3} \int_0^\infty \frac{\hbar^2 k^2}{2m} n(k) k^2 dk.$$

Average kinetic energy - Nuclei



Average kinetic energy – SNM



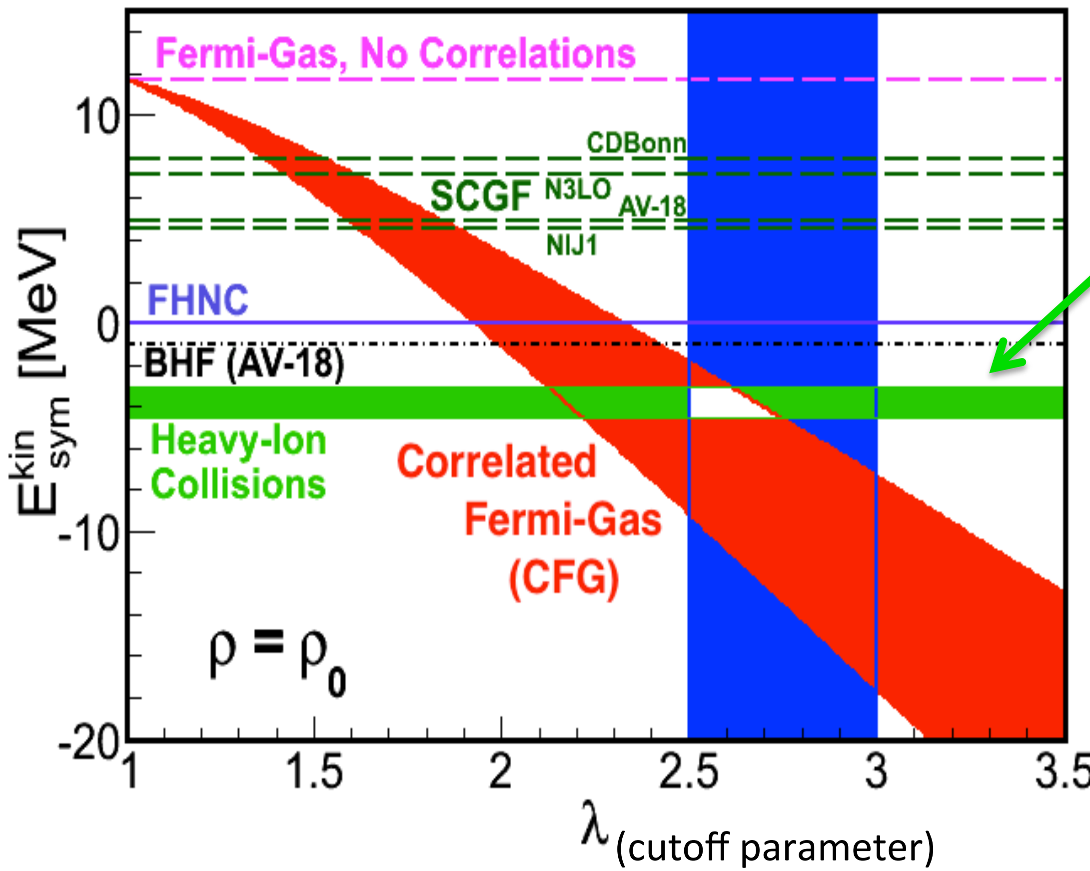
$a_2(A) = 5.0 \pm 0.3$

$a_2(\infty) = 7.0 \pm 1.0$

O. Hen et al., Phys. Rev. C 91, 025803 (2015).

Extracting the Kinetic Symmetry Energy

Kinetic symmetry energy

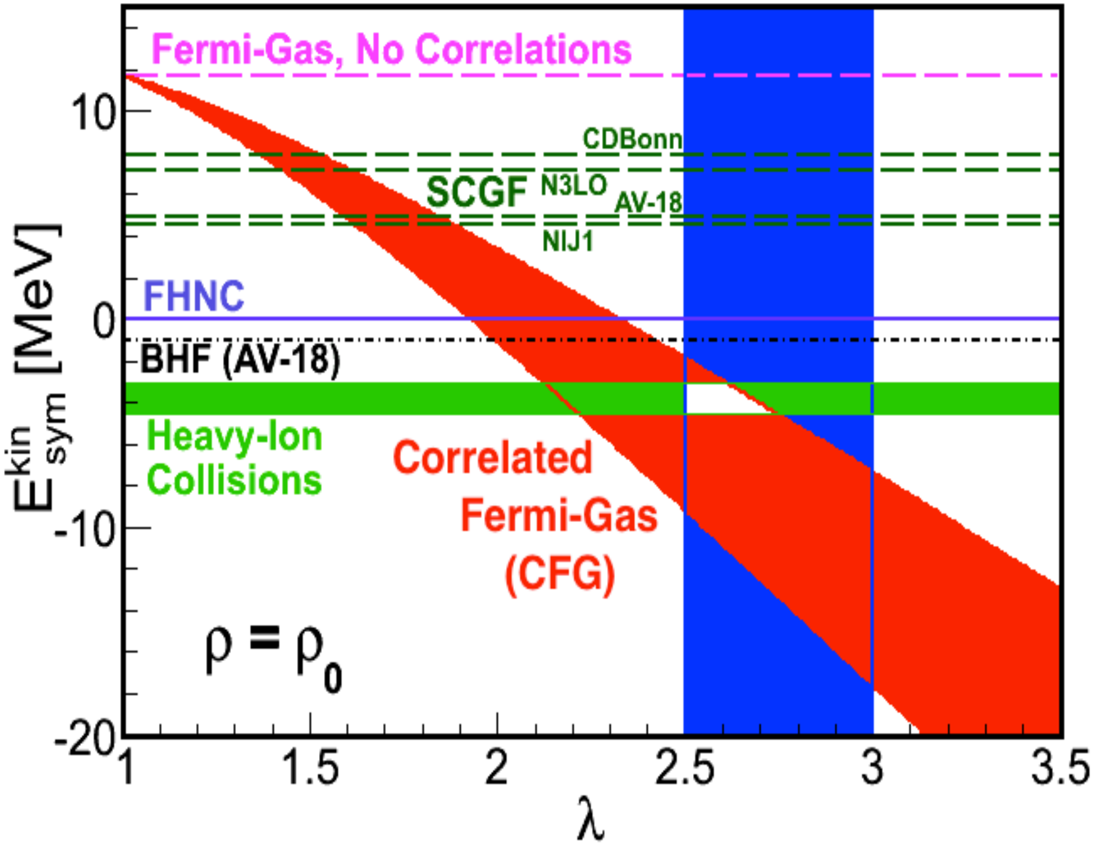


Transport calculation of $^{124}Sn+^{124}Sn$ and $^{112}Sn+^{112}Sn$ collisions also yield reduced kinetic symmetry energy

O. Hen et al., Phys. Rev. C 91, 025803 (2015).

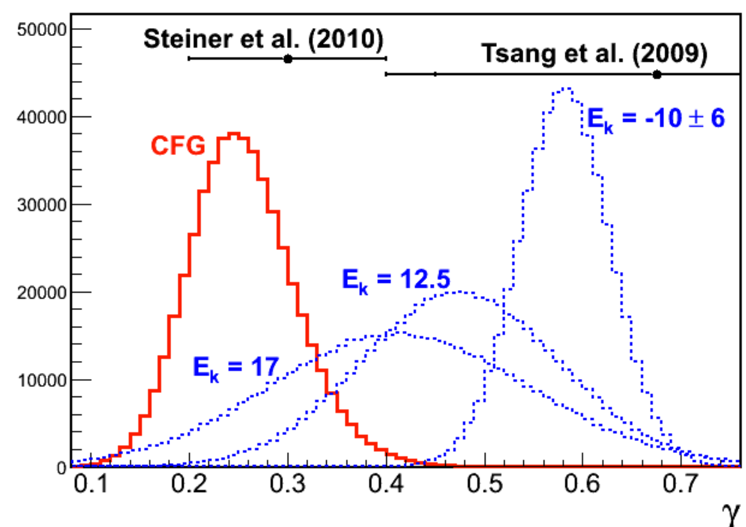
Extracting the Kinetic Symmetry Energy

Kinetic symmetry energy



SRCs reduce the kinetic symmetry energy

[Enhance the potential symmetry energy and alter its density dependence]



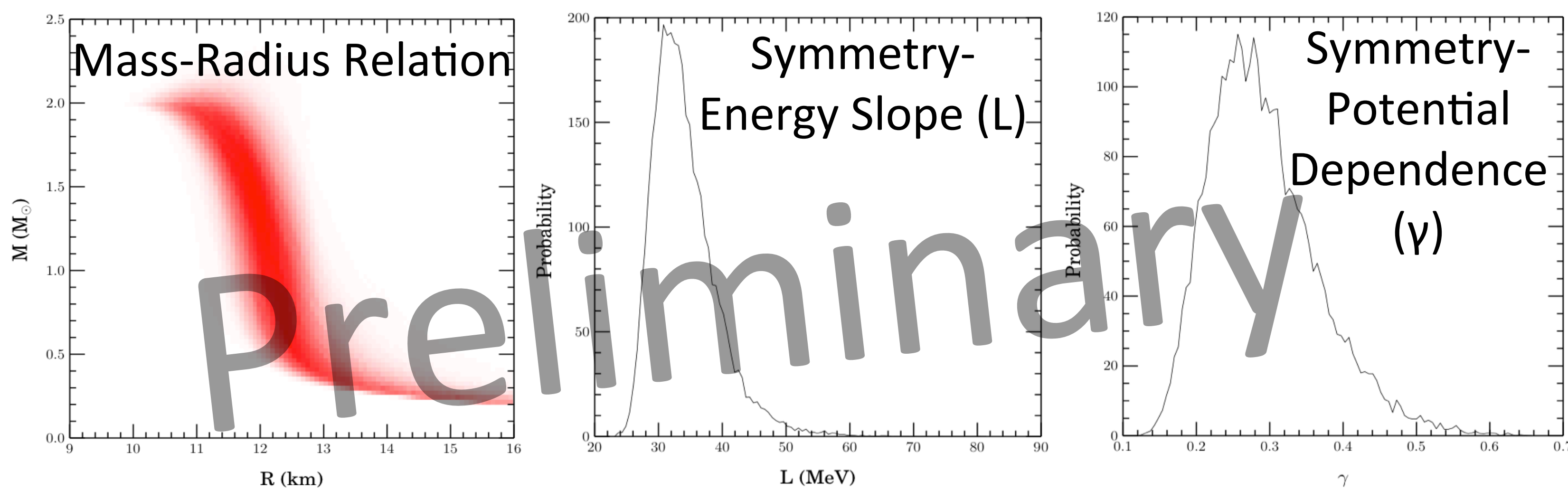
O. Hen et al., Phys. Rev. C 91, 025803 (2015).

Next Step – Incorporating CFG model into:

- neutron stars equation-of-state fits
- Transport models for HI collision analysis

Next (*ongoing*) Step – Incorporating CFG model into:

- **neutron stars equation-of-state fits**
- **Transport models for HI collision analysis**



O. Hen, A.W. Steiner, and E. Piasetzky, In-Preparation (2015)

Thank You!

(again)

Questions?