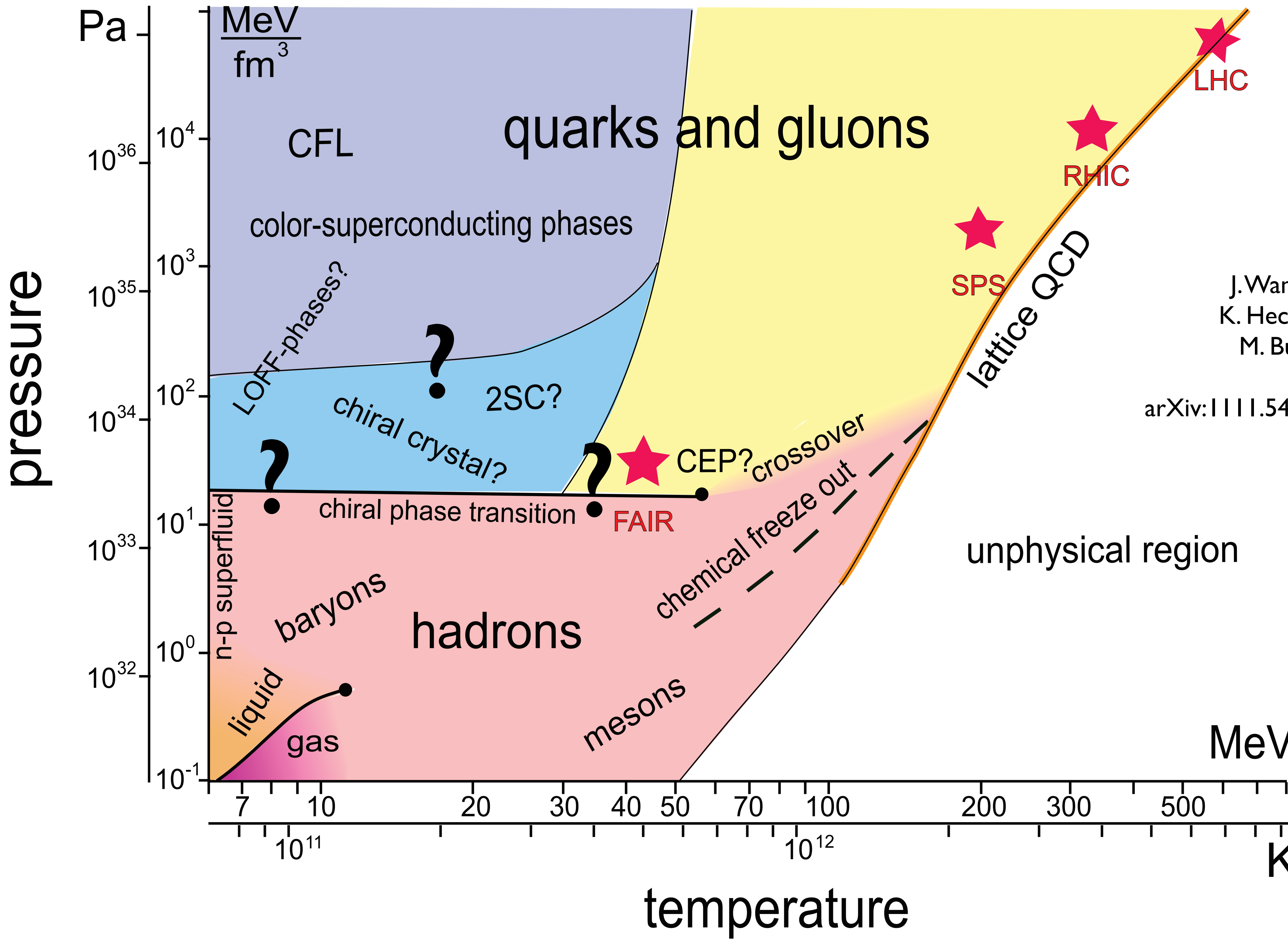
CHIRAL DYNAMICS and NUCLEAR MATTER

Wolfram Weise

ECT* Trento and Technische Universität München

- **Chiral EFT approaches to nuclear many-body systems**
- Beyond mean field:
  fluctuations and **Functional Renormalisation Group**
- **Nuclear matter, neutron matter** and **neutron stars**
- **Pion mass** in the **nuclear medium**
- Thermodynamics of the **chiral order parameter**
- Outlook:
  Chiral **SU(3)** dynamics and **hypernuclear matter**

PHASES and STRUCTURES of QCD
- facts and visions -



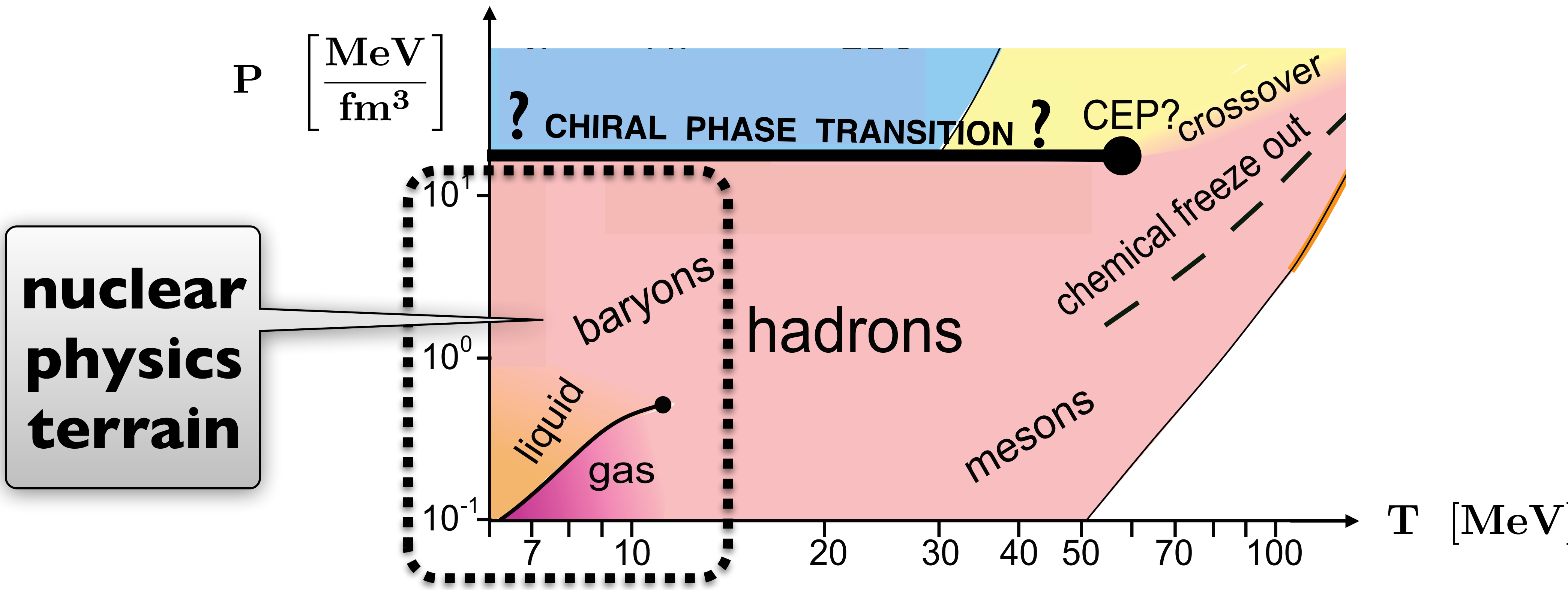
J. Wambach, K. Heckmann, M. Buballa

arXiv:1111.5475v2 [hep-ph]

CHIRAL SYMMETRY RESTORATION

from **Nambu-Goldstone** to
Wigner-Weyl Realisation of **Chiral Symmetry**

- **PHASE TRANSITION** or smooth **CROSSOVER ?**



- **Chiral first-order phase transition** and **critical point ?**

. . . based on chiral quark models which do not respect **nuclear physics** constraints

- Needed: systematic approach to **nuclear thermodynamics**

PIONS, NUCLEONS and NUCLEI in the context of LOW-ENERGY QCD

- CONFINEMENT of quarks and gluons in hadrons
- Spontaneously broken CHIRAL SYMMETRY
- LOW-ENERGY QCD with light (u,d) quarks: Effective Field Theory of (weakly) interacting Nambu-Goldstone Bosons (pions)

- Chiral EFT represents QCD at energy/momentum scales

$$\mathrm{Q} << 4\pi\,\mathrm{f}_\pi \sim 1\,\mathrm{GeV}$$

- **Strategies** at the interface between **QCD and nuclear physics** :

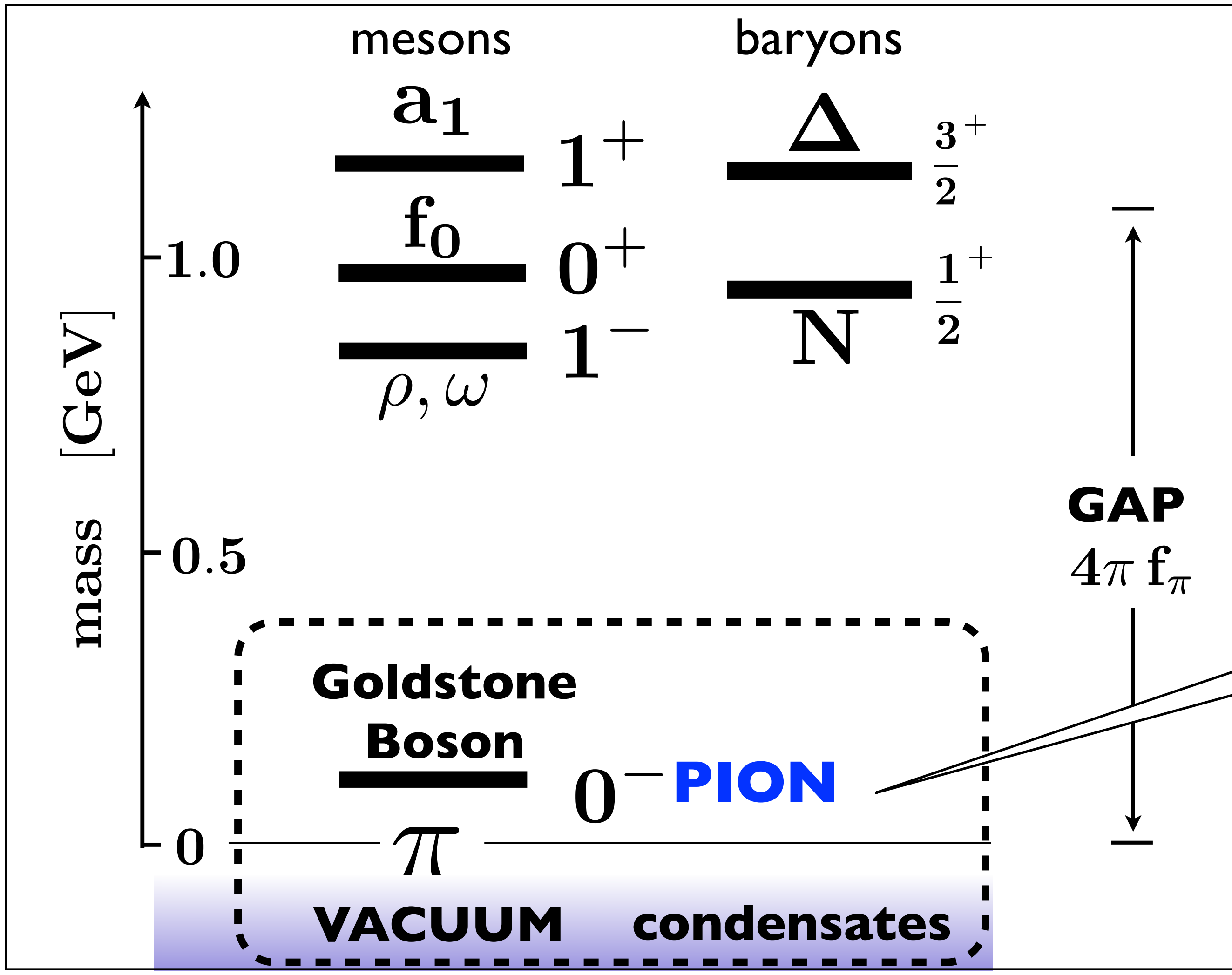
In-medium Chiral Perturbation Theory based on **non-linear sigma model** (with inclusion of nucleons)

expansion of free energy density in powers of Fermi momentum

Chiral Nucleon-Meson model based on **linear sigma model**

non-perturbative Renormalization Group approach

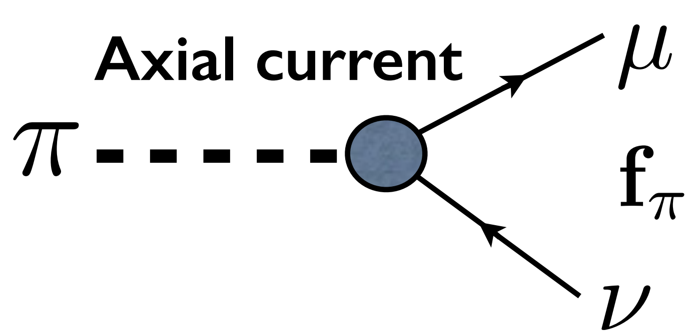
Spontaneously Broken CHIRAL SYMMETRY



Triplet
of
NAMBU - GOLDSTONE BOSONS:
$\pi^+, \ \pi^0, \ \pi^-$

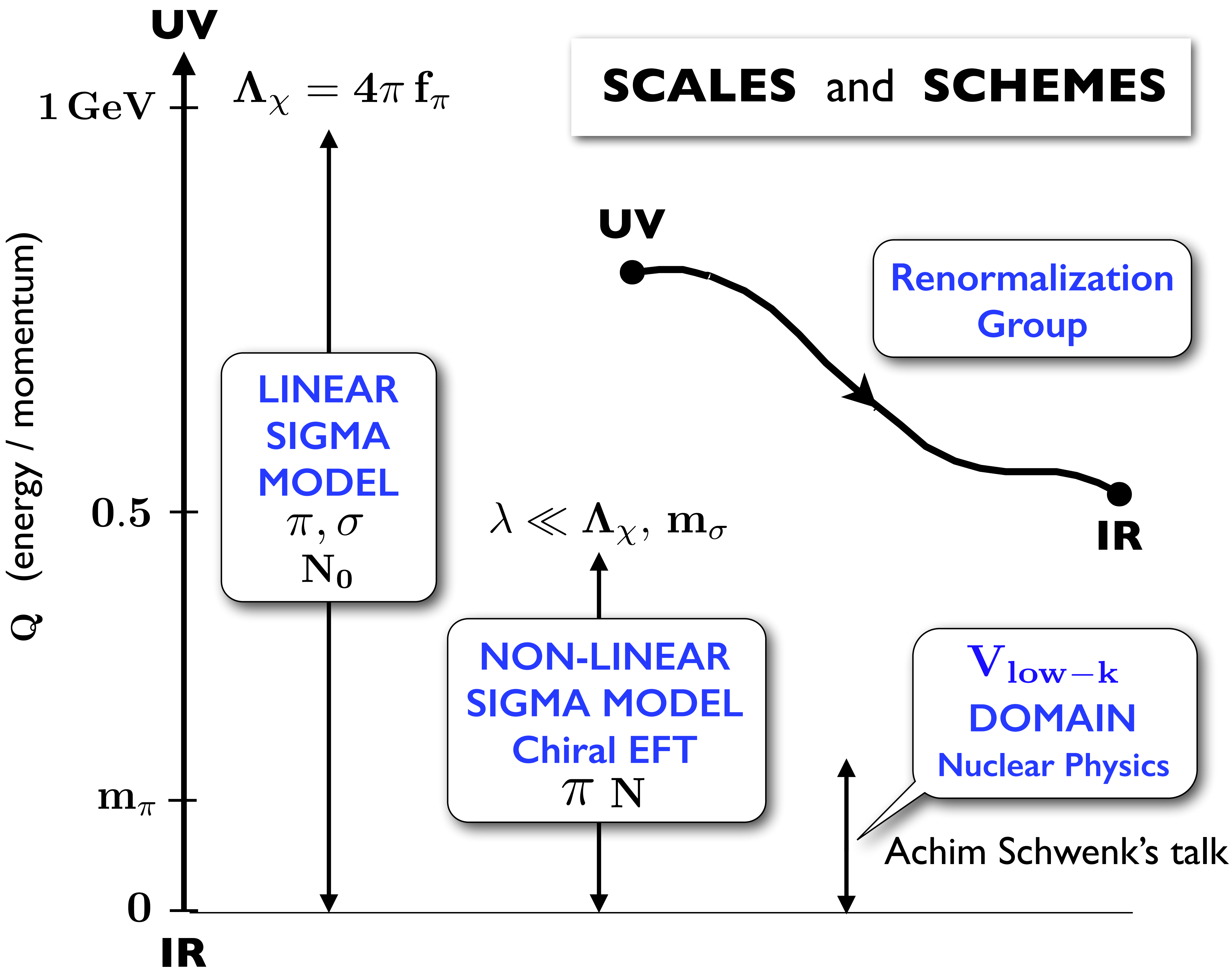
Characteristic Symmetry Breaking SCALE:
$4\pi\, f_\pi \sim 1 \text{ GeV}$

- **PION DECAY CONSTANT**



$$f_\pi = 92.2 \pm 0.2 \text{ MeV}$$

SCALES and SCHEMES



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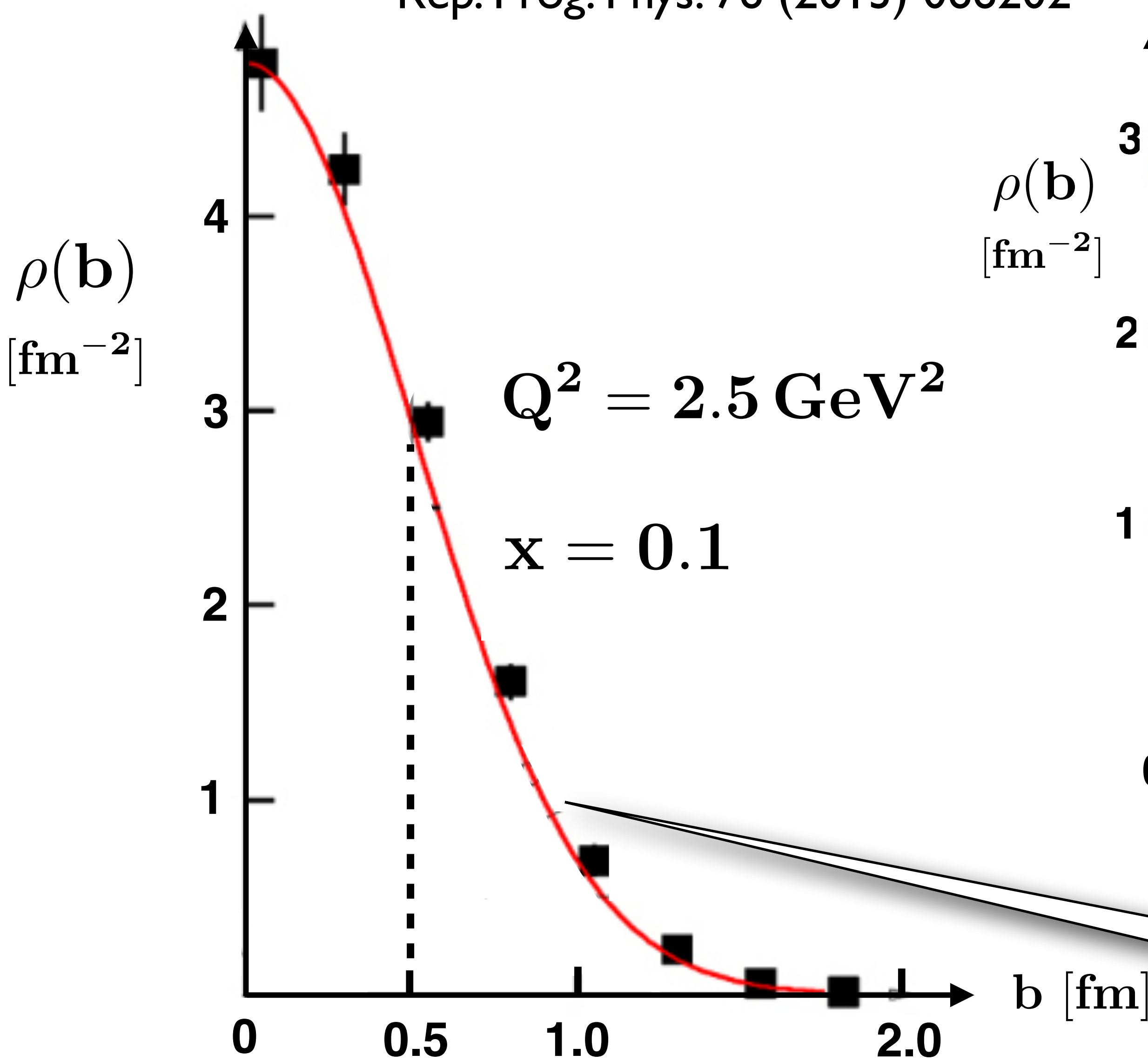
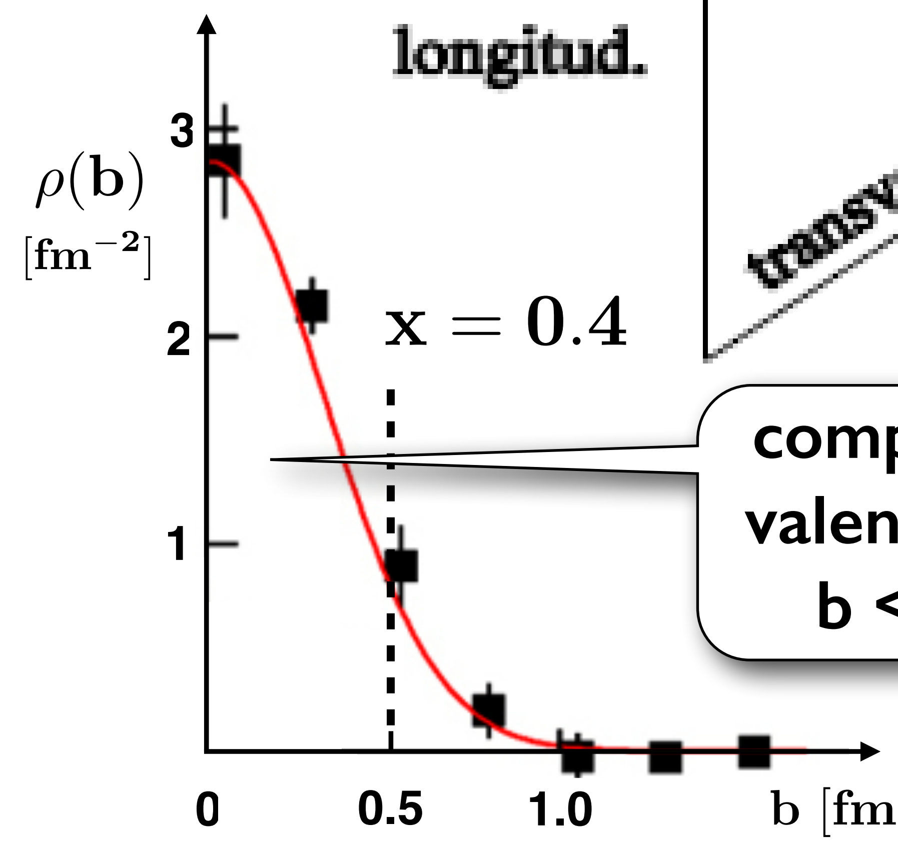
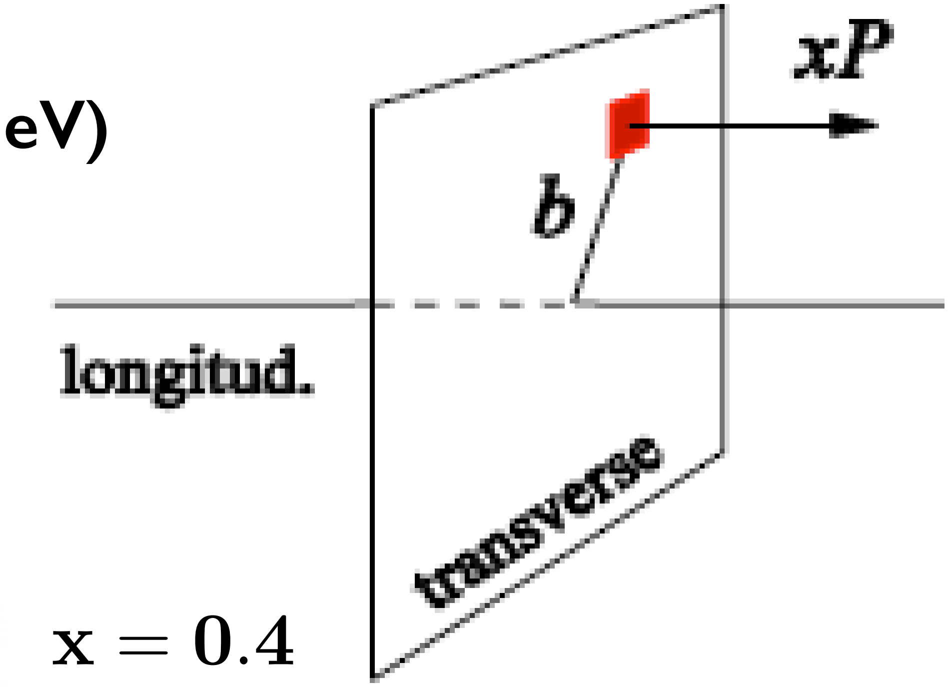
Transverse distributions of **quarks** in the **proton**
core - plus - cloud structure ?

Deeply Virtual Compton Scattering
(expectations for DVCS @ JLab - 12 GeV)

M. Guidal, H. Moutarde, M. Vanderhaeghen
Rep. Prog. Phys. 76 (2013) 066202







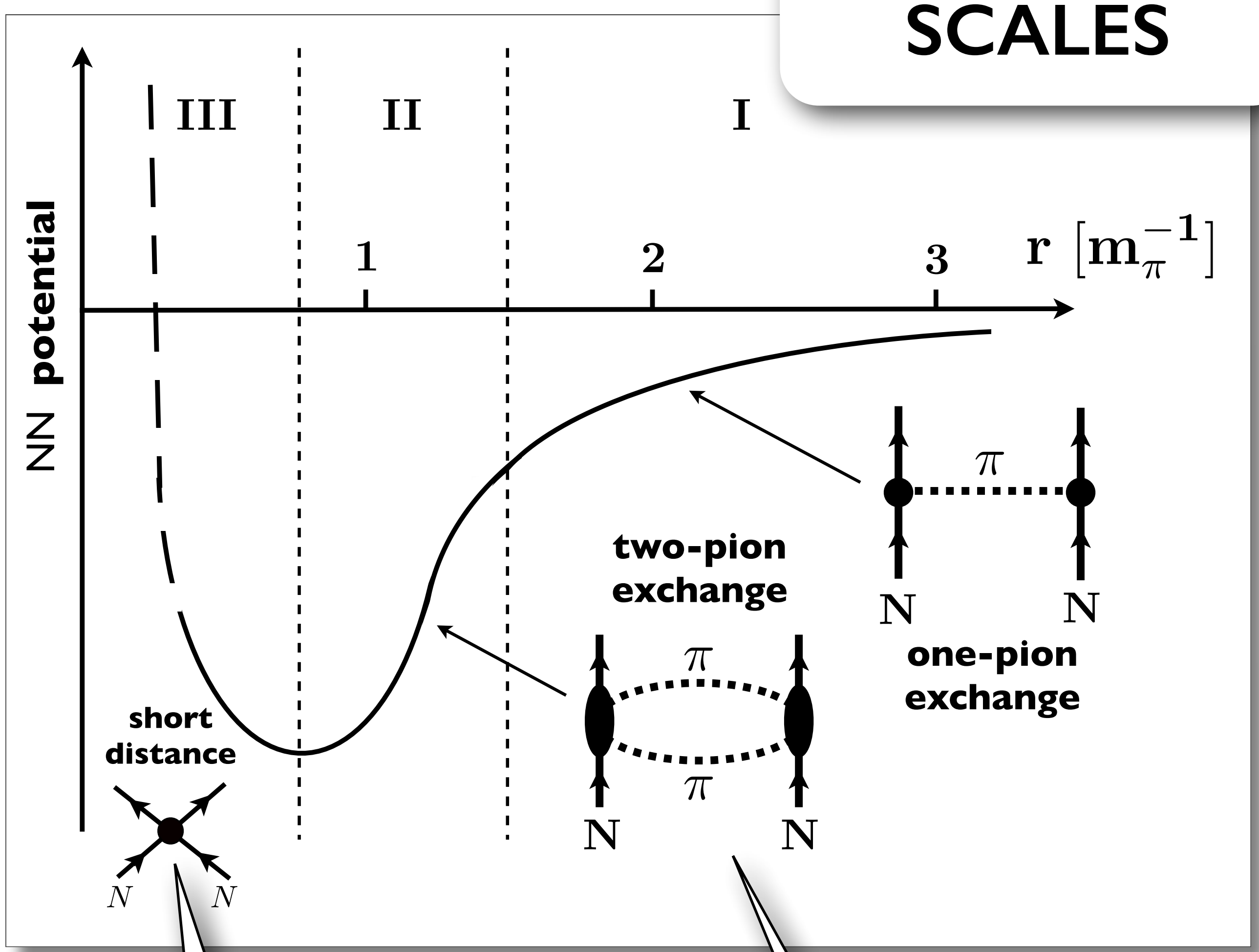
compact core:
valence quarks
b < 0.5 fm

valence + sea quarks
(core + (pion) cloud)

NN Interaction

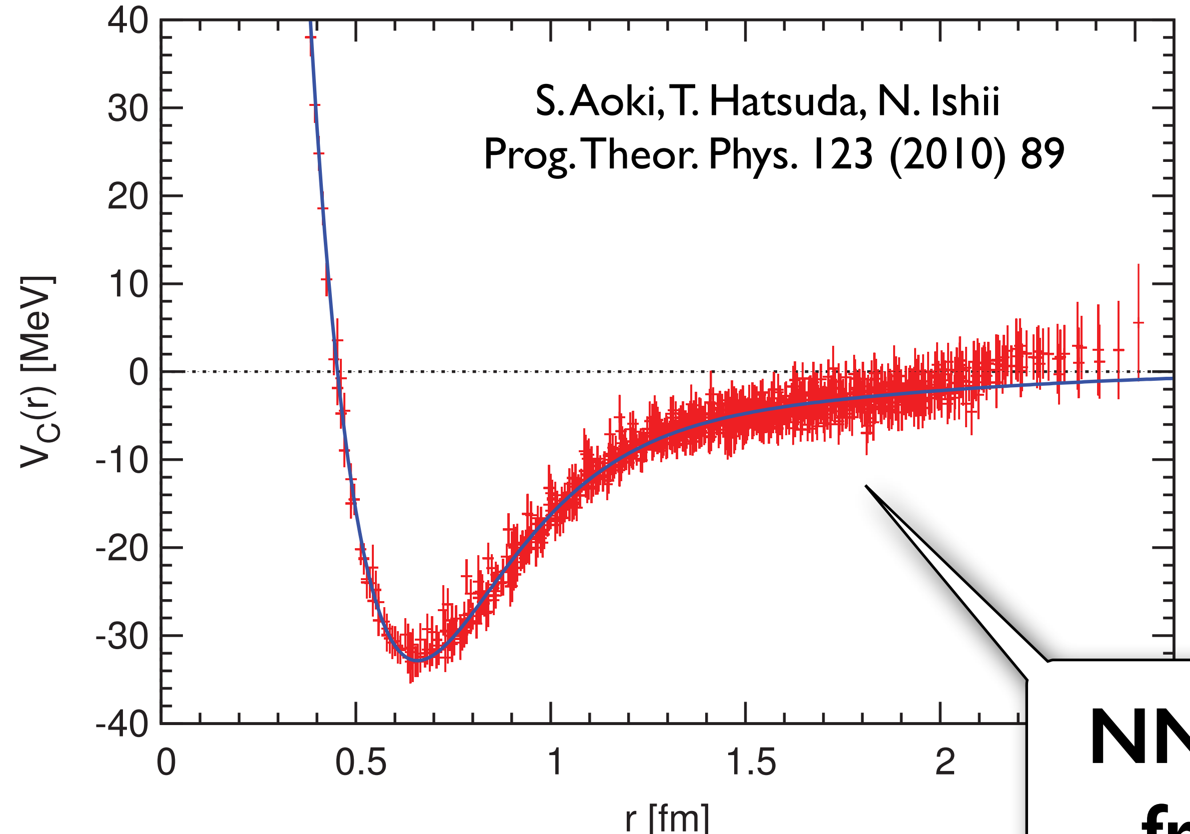
Chiral Effective Field Theory & Lattice QCD

Hierarchy of SCALES



contact terms

explicit treatment of two-pion exchange



NN Central Potential from Lattice QCD

CHIRAL EFFECTIVE FIELD THEORY

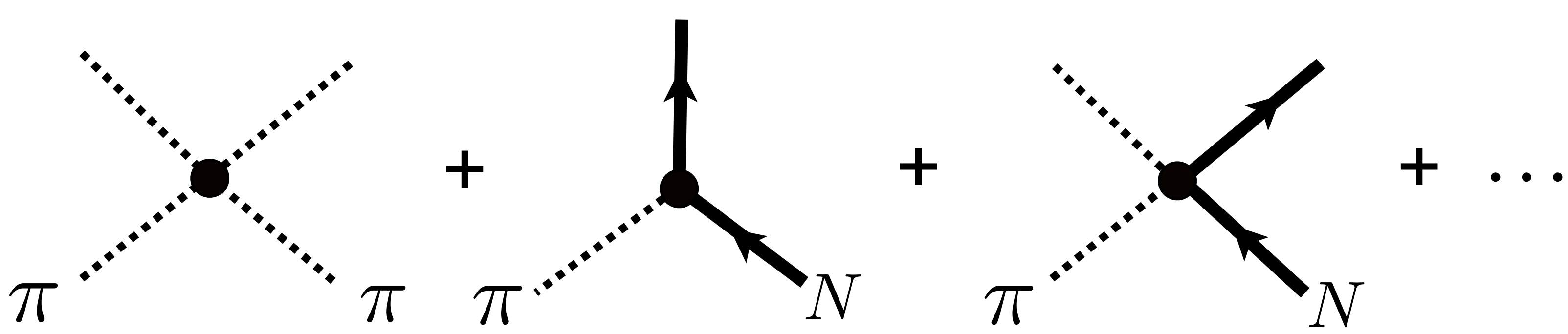
- Realization of **Low-Energy QCD**
  based on **Non-Linear Sigma Model** plus (heavy) baryons

- Interacting systems of
  PIONS (light / fast) and **NUCLEONS** (heavy / slow):

$$\mathcal{L}_{eff} = \mathcal{L}_\pi(U, \partial U) + \mathcal{L}_N(\Psi_N, U, ...)$$

$$U(x) = exp[i\tau_a \pi_a(x)/f_\pi]$$

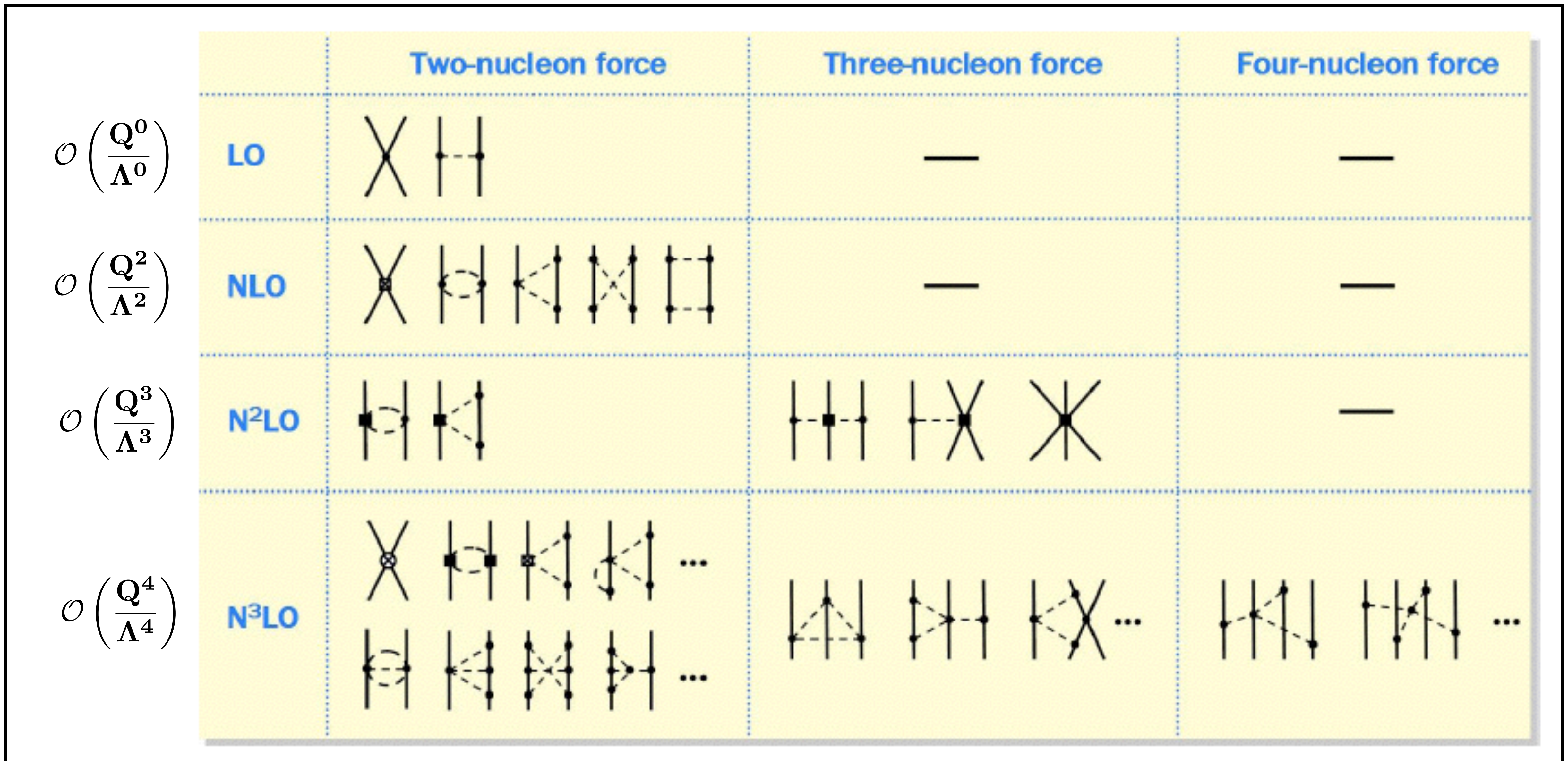
- Construction of Effective Lagrangian: **Symmetries**



short distance dynamics: **contact terms**

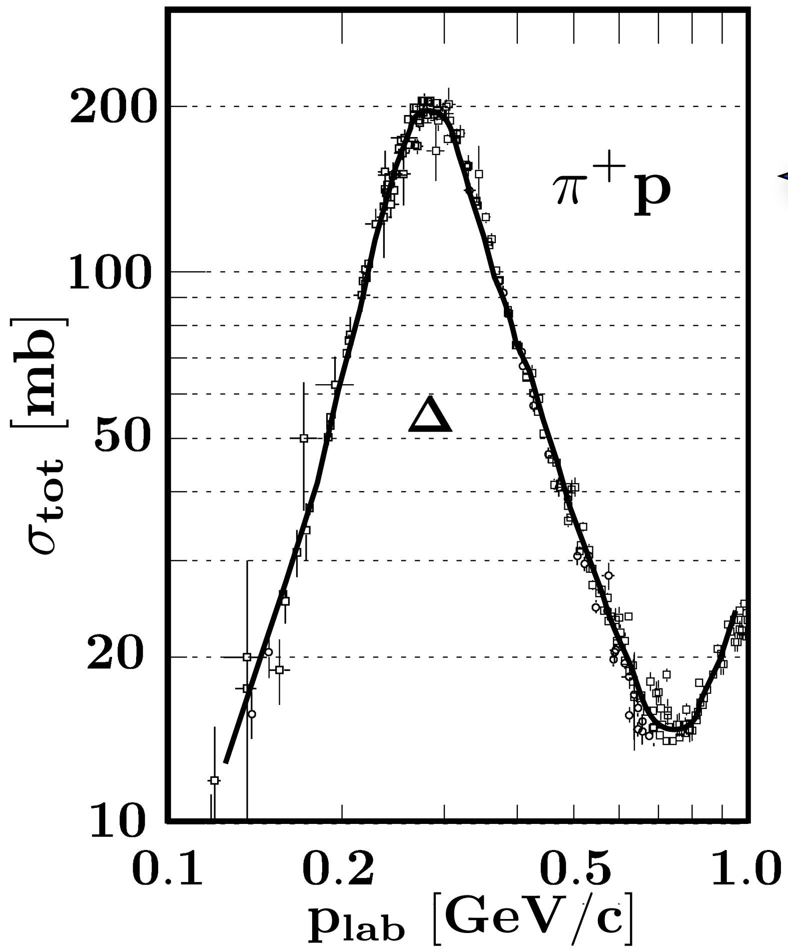
NUCLEAR INTERACTIONS from CHIRAL EFFECTIVE FIELD THEORY

Weinberg   Bedaque & van Kolck   Bernard, Epelbaum, Kaiser, Meißner; . . .



- Systematically organized HIERARCHY

Explicit $\Delta(1230)$ DEGREES of FREEDOM



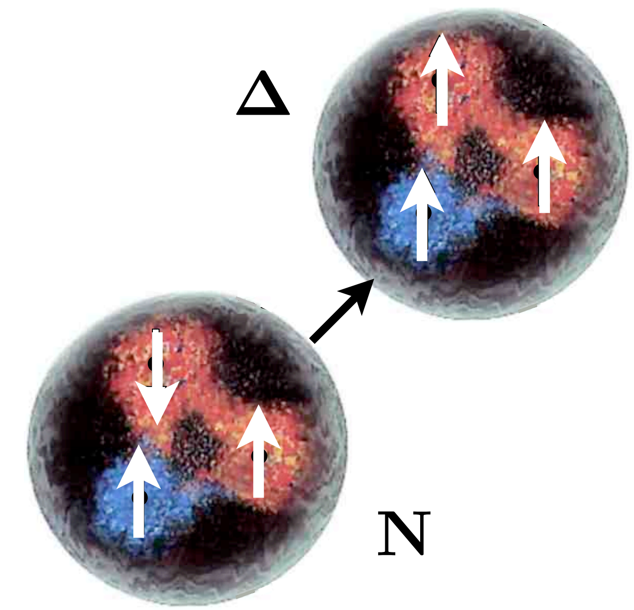
- **Large spin-isospin polarizability** of the Nucleon

◀ Dominance of $\Delta(1230)$ in pion-nucleon scattering

$$\beta_\Delta = \frac{g_A^2}{f_\pi^2 (M_\Delta - M_N)} \sim 5\,\mathrm{fm}^3$$

$$M_\Delta - M_N \simeq 2\, m_\pi << 4\pi\, f_\pi$$

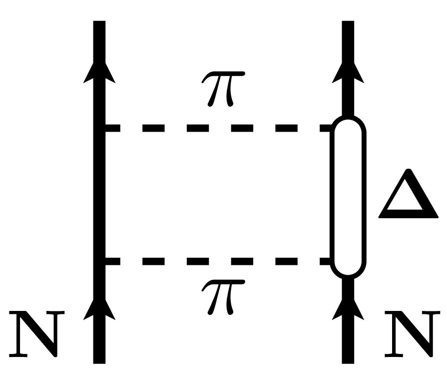
(small scale)



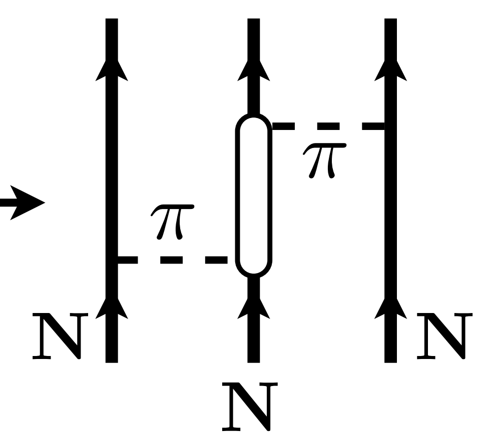
- **Pionic Van der Waals -** type intermediate range central potential

N. Kaiser, S. Gerstendörfer, W.W., NPA637 (1998) 395

N. Kaiser, S. Fritsch, W.W., NPA750 (2005) 259



$$V_c(r) = -\frac{9\, g_A^2}{32\pi^2 f_\pi^2}\, \beta_\Delta\, \frac{e^{-2m_\pi r}}{r^6}\, P(m_\pi r) \longleftrightarrow$$

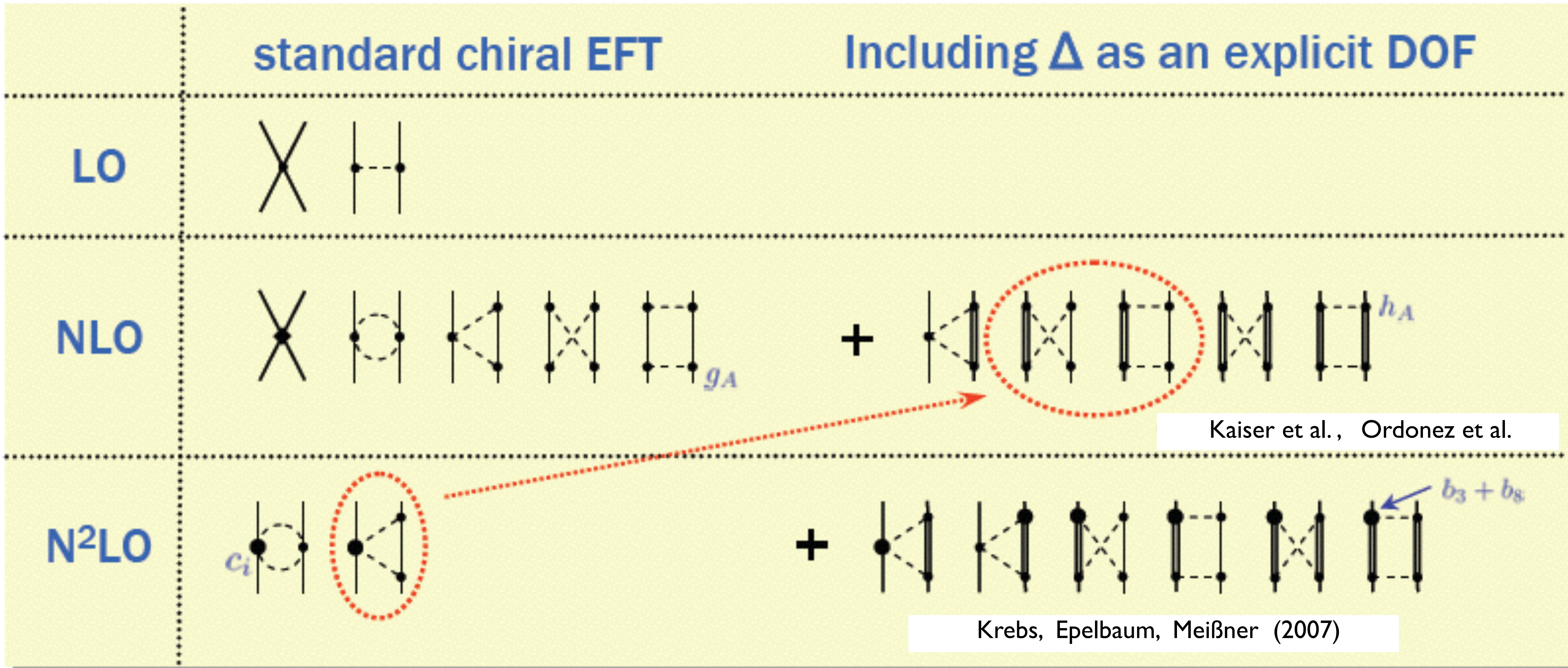


strong 3-body interaction

J. Fujita, H. Miyazawa (1957)

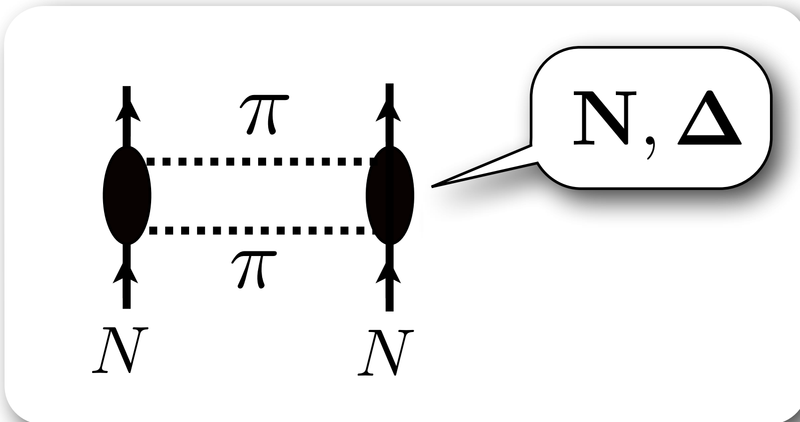
Pieper, Pandharipande, Wiringa, Carlson (2001)

Explicit $\Delta(1230)$ DEGREES of FREEDOM (contd.)



- Important physics of $\Delta(1230)$ promoted to **NLO**
- **Improved** convergence

Important :
Explicit treatment of two-pion exchange dynamics



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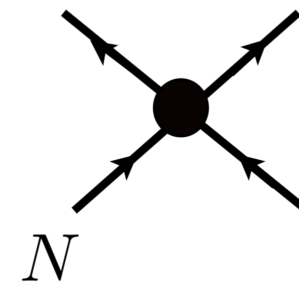


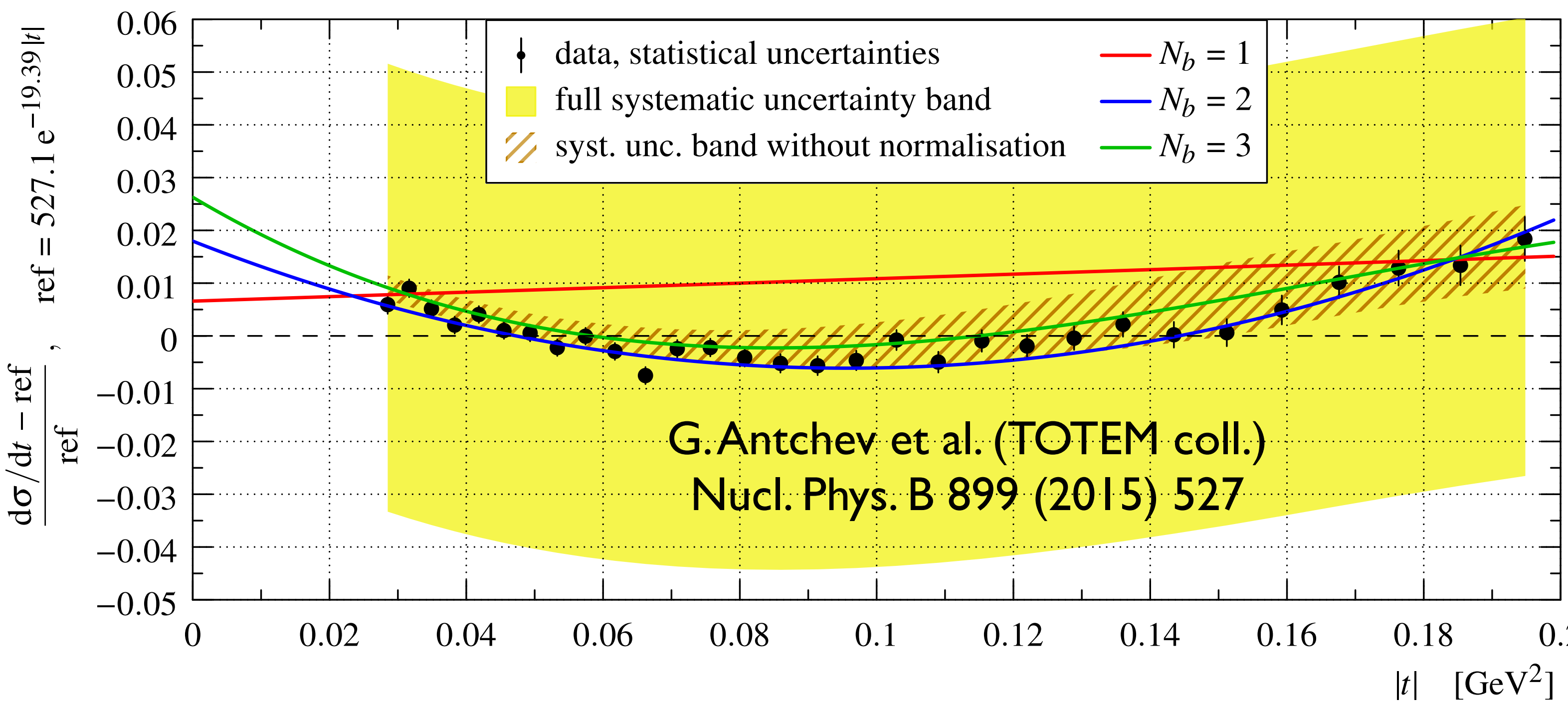
contact terms

+ 3-body forces

- **Short digression:**

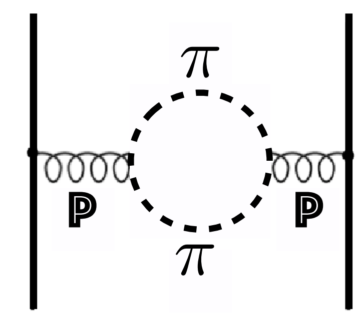
  "Discovery" of two-pion exchange at LHC: elastic pp scattering at $\sqrt{s} = 8\,\text{TeV}$

  deviation from standard exponential behaviour $\frac{d\sigma}{dt} \propto e^{bt}$



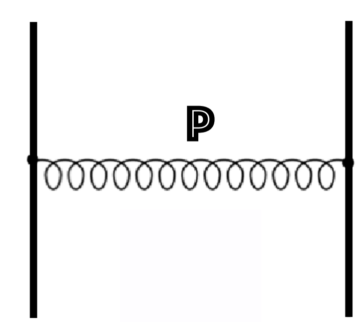
G. Antchev et al. (TOTEM coll.)
Nucl. Phys. B 899 (2015) 527

V.A. Khoze, A.D. Martin, M.G. Ryskin
J. Phys. G 42 (2015) 025003



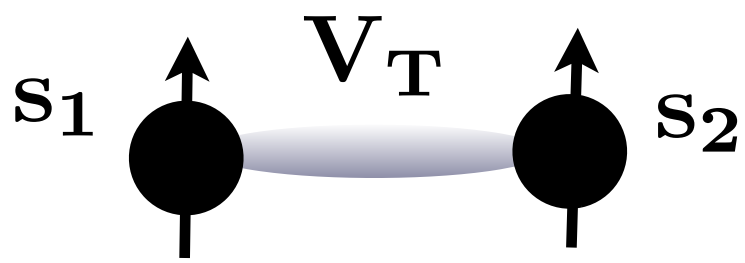
+

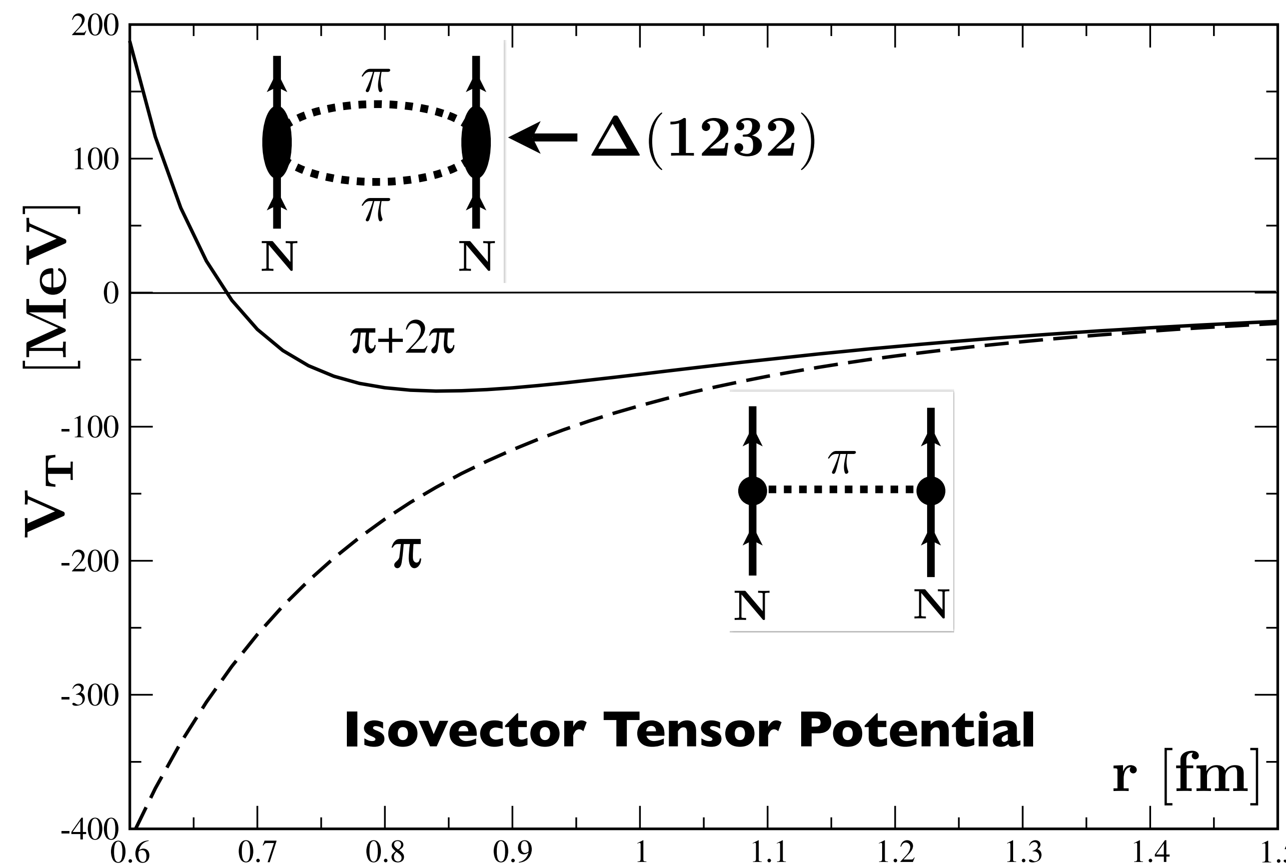
L. Jenkovszky, A. Lengyel
Acta Phys. Pol. B 46 (2015) 863



Important pieces of the
CHIRAL NUCLEON-NUCLEON INTERACTION

- **ISOVECTOR TENSOR FORCE**

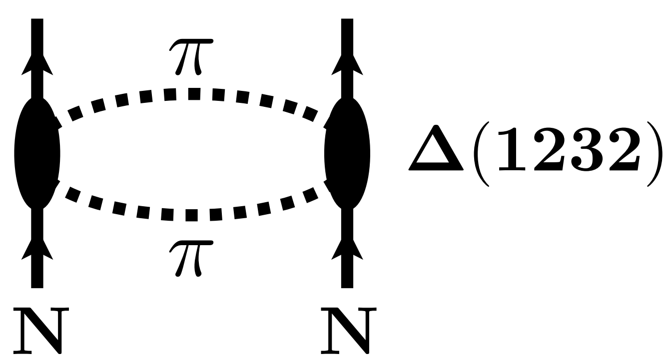




N. Kaiser, S. Gerstendörfer, W.W.: Nucl. Phys. A 637 (1998) 395

- note: **no** ρ meson

- **CENTRAL ATTRACTION** from **TWO-PION EXCHANGE**



- note: **no** σ boson

Van der WAALS - like force:

$$\mathbf{V_c(r)} \propto -\frac{\exp[-\mathbf{2m_\pi r}]}{\mathbf{r^6}}\mathbf{P(m_\pi r)}$$

... at intermediate and long distance

IN-MEDIUM CHIRAL PERTURBATION THEORY

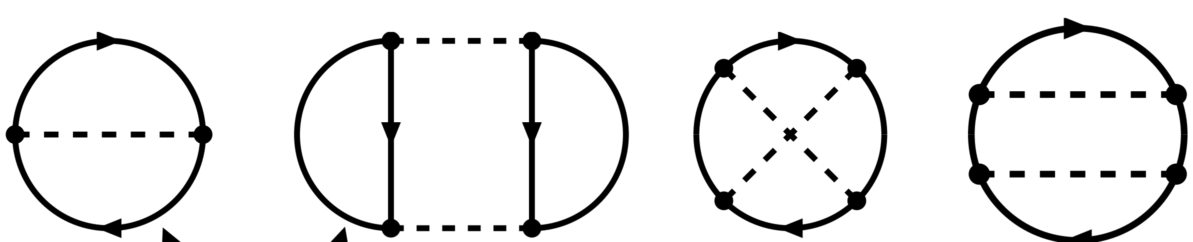
- **Small scales:** energy, momentum, m_π, $k_F << 4\pi f_\pi \sim 1\,\mathrm{GeV}$

- "Medium insertion" in the nucleon propagator:

$$(\gamma_\mu p^\mu + M_N)\left[\frac{i}{p^2 - M_N^2 + i\varepsilon} - 2\pi\,\delta(p^2 - M_N^2)\,\theta(p^0)\,\theta(k_F - |\vec{p}|)\right]$$

Loop expansion of (In-Medium) **Chiral Perturbation Theory**
⟷ Expansion of **ENERGY DENSITY** $\mathcal{E}(k_F)$ in **powers of Fermi momentum** [modulo functions $f_n(k_F/m_\pi)$]

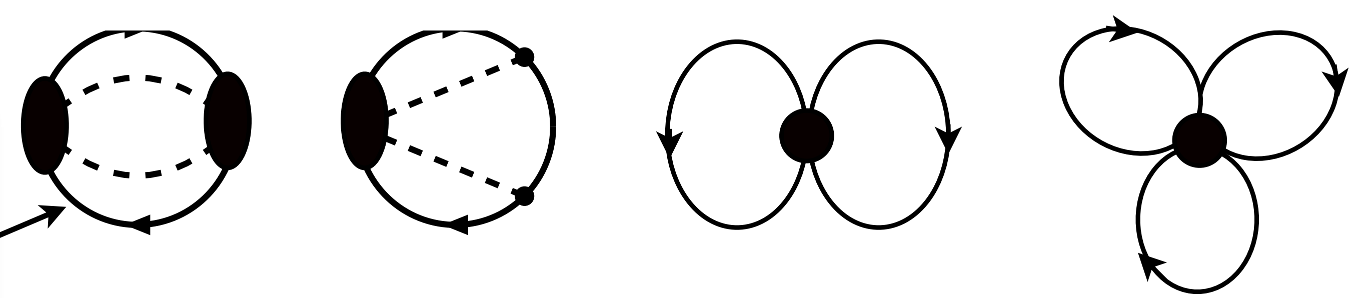
Nuclear **thermodynamics**: compute **free energy density**



(3-loop order)

N. Kaiser, S. Fritsch, W.W. (2002-2004)

in-medium nucleon propagators incl. **Pauli blocking**



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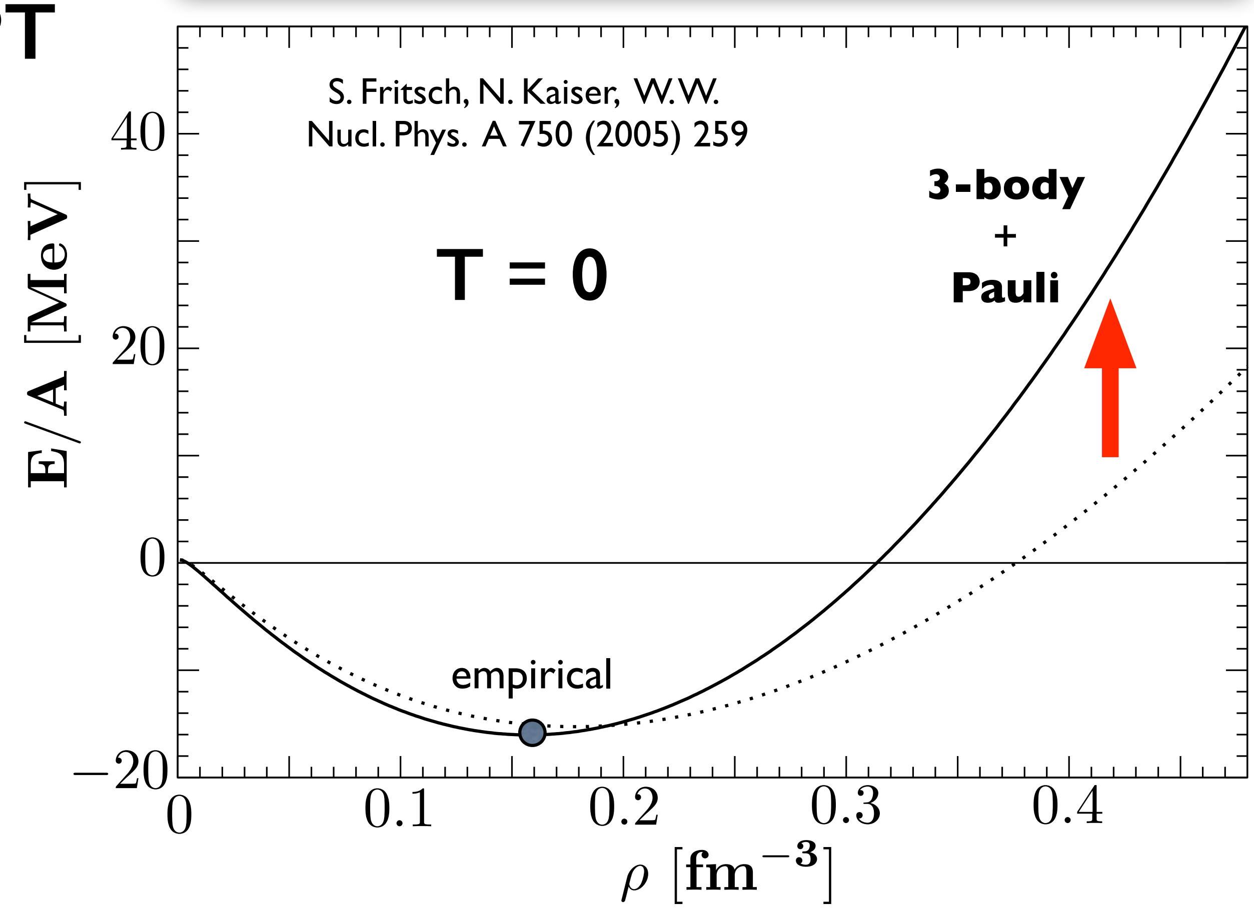
NUCLEAR MATTER

- **In-medium ChPT**
  3-loop $(\pi, \mathbf{N}, \mathbf{\Delta})$
- **Input** parameters:
  few contact terms
- basically:
  analytic calculation



- **Binding, saturation**
- **Asymmetry energy**
- **Nuclear thermodynamics: liquid-gas phase transition**

- **Realistic** (complex, momentum dependent) **single-particle potential**
  ... satisfying **Hugenholtz - van Hove** and **Luttinger** theorems (!)

- **Fermi Liquid Theory**:
  Quasiparticle interaction and Landau parameters

J.W. Holt, N. Kaiser, W.W.
(2011 - 2013)

- **Nuclear Energy Density Functional** and finite nuclei

C. Wellenhofer, J.W. Holt,
N. Kaiser, W.W.
Phys. Rev. C 89 (2014) 064009

Recent reviews:

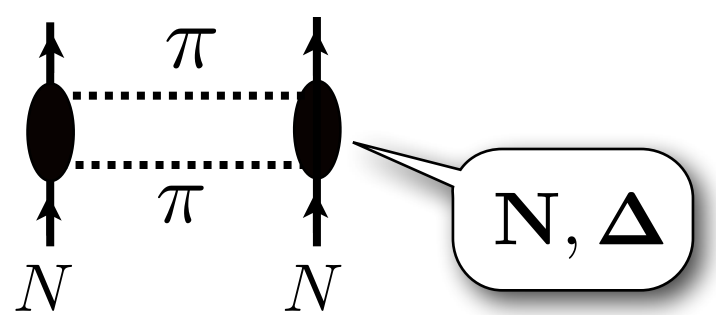
J.W. Holt, N. Kaiser, W.W. Prog. Part. Nucl. Phys. 73 (2013) 35
J.W. Holt, M. Rho, W.W. arXiv:1411.6681, Phys. Reports (2015)

NUCLEAR THERMODYNAMICS

NUCLEAR
CHIRAL (PION) DYNAMICS

BINDING & SATURATION:

Van der Waals + Pauli



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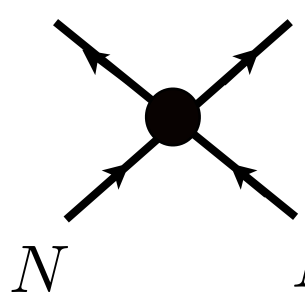
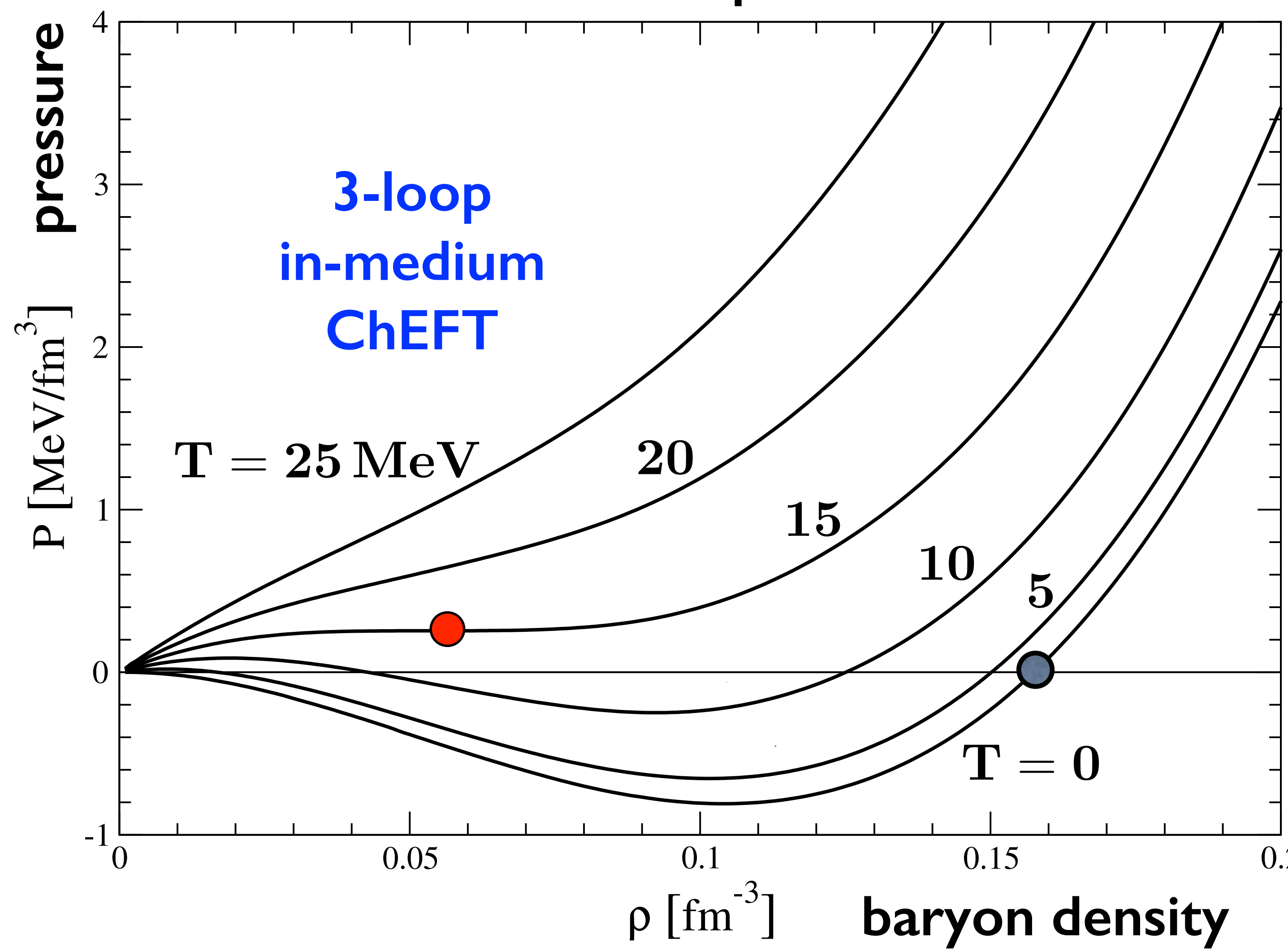


+ 3-body forces

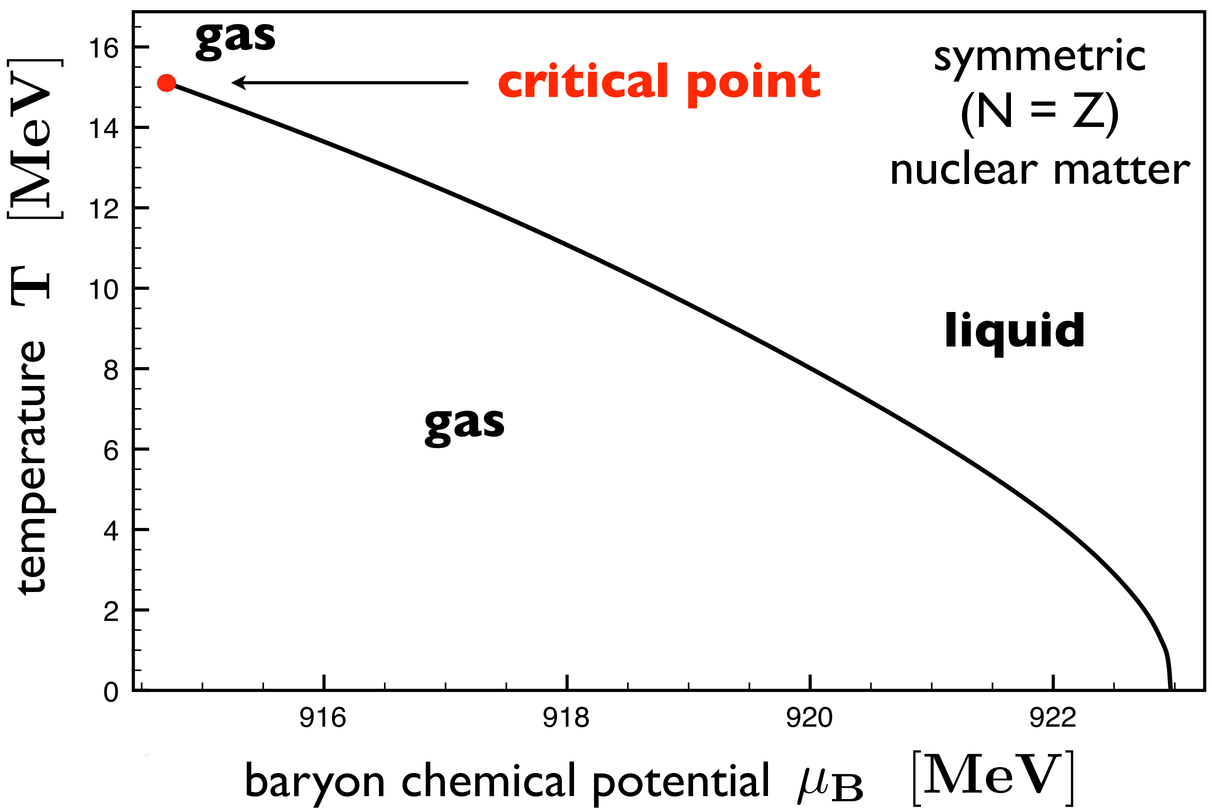
contact terms

nuclear matter: equation of state



Liquid - Gas Transition at
Critical Temperature T_c = 15 MeV
(empirical: T_c = 16 - 18 MeV)

PHASE DIAGRAM of NUCLEAR MATTER

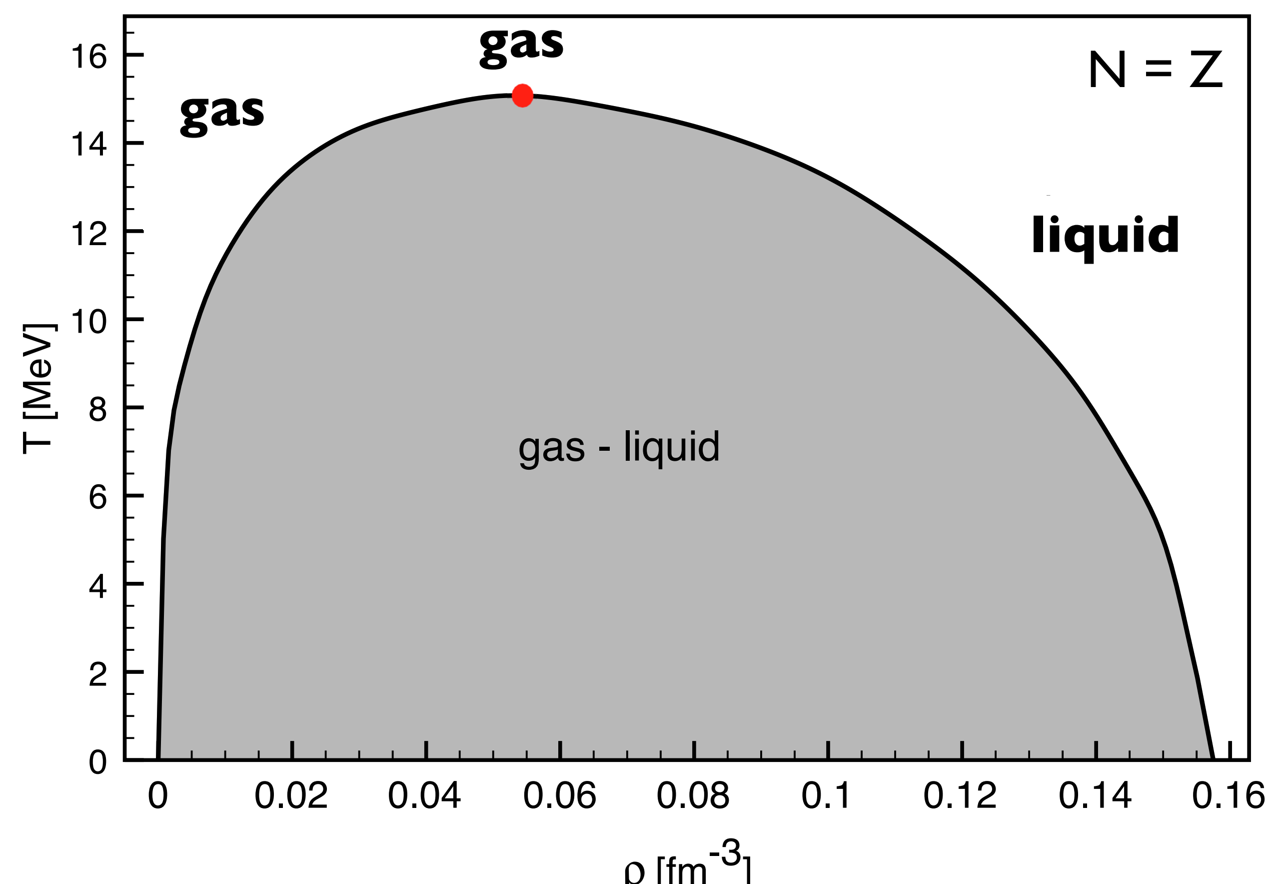


- In-medium
  chiral effective field theory
  (3-loop calculation of free energy density)

S. Fritsch, N. Kaiser, W.W.
Nucl. Phys. A 750 (2005) 259

S. Fiorilla, N. Kaiser, W.W.
Nucl. Phys. A 880 (2012) 65

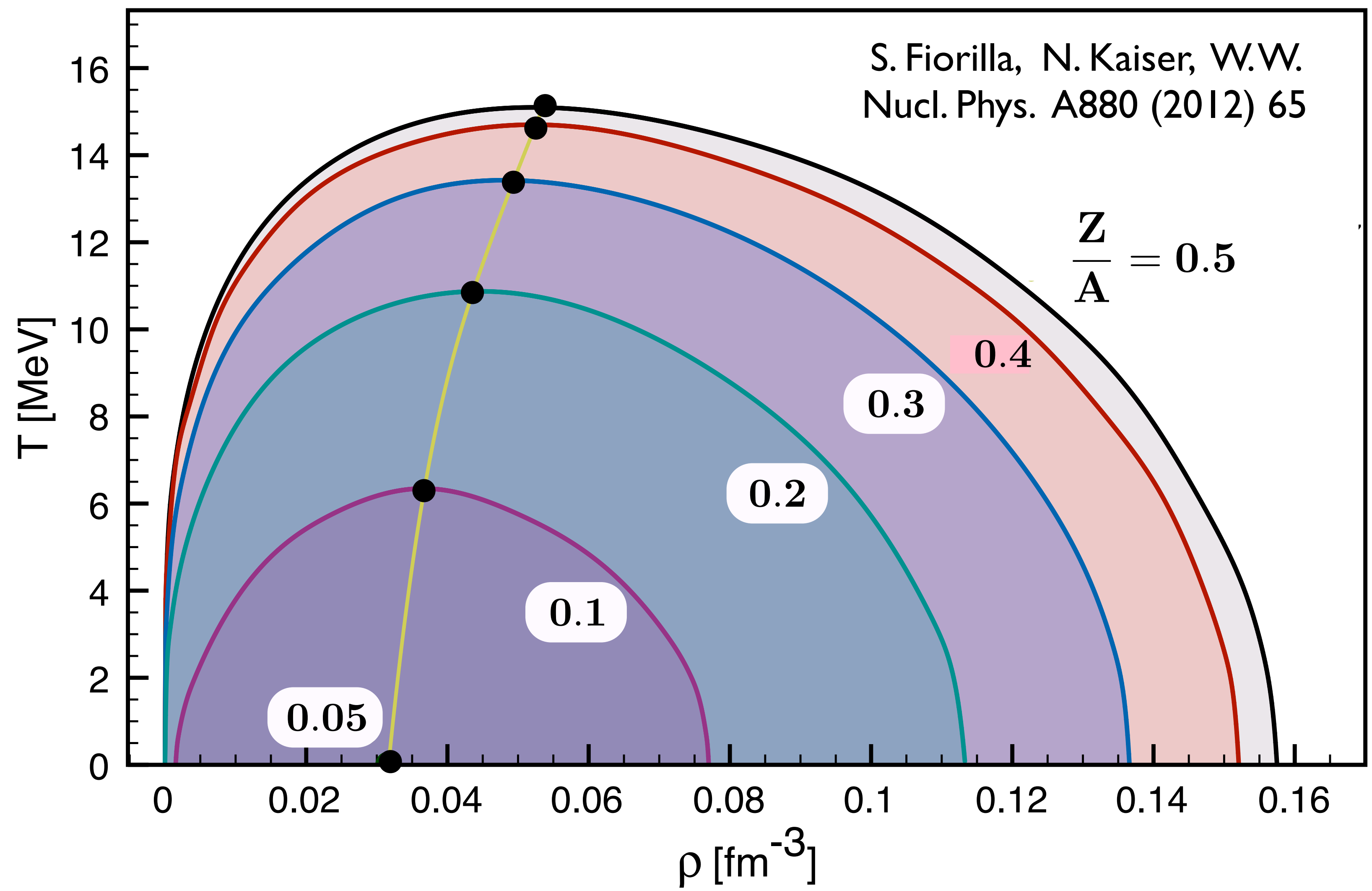
- Pion-nucleon dynamics including delta isobars
- Short-distance NN contact terms
- Three-body forces



PHASE DIAGRAM of NUCLEAR MATTER

- **Trajectory of CRITICAL POINT for asymmetric matter**

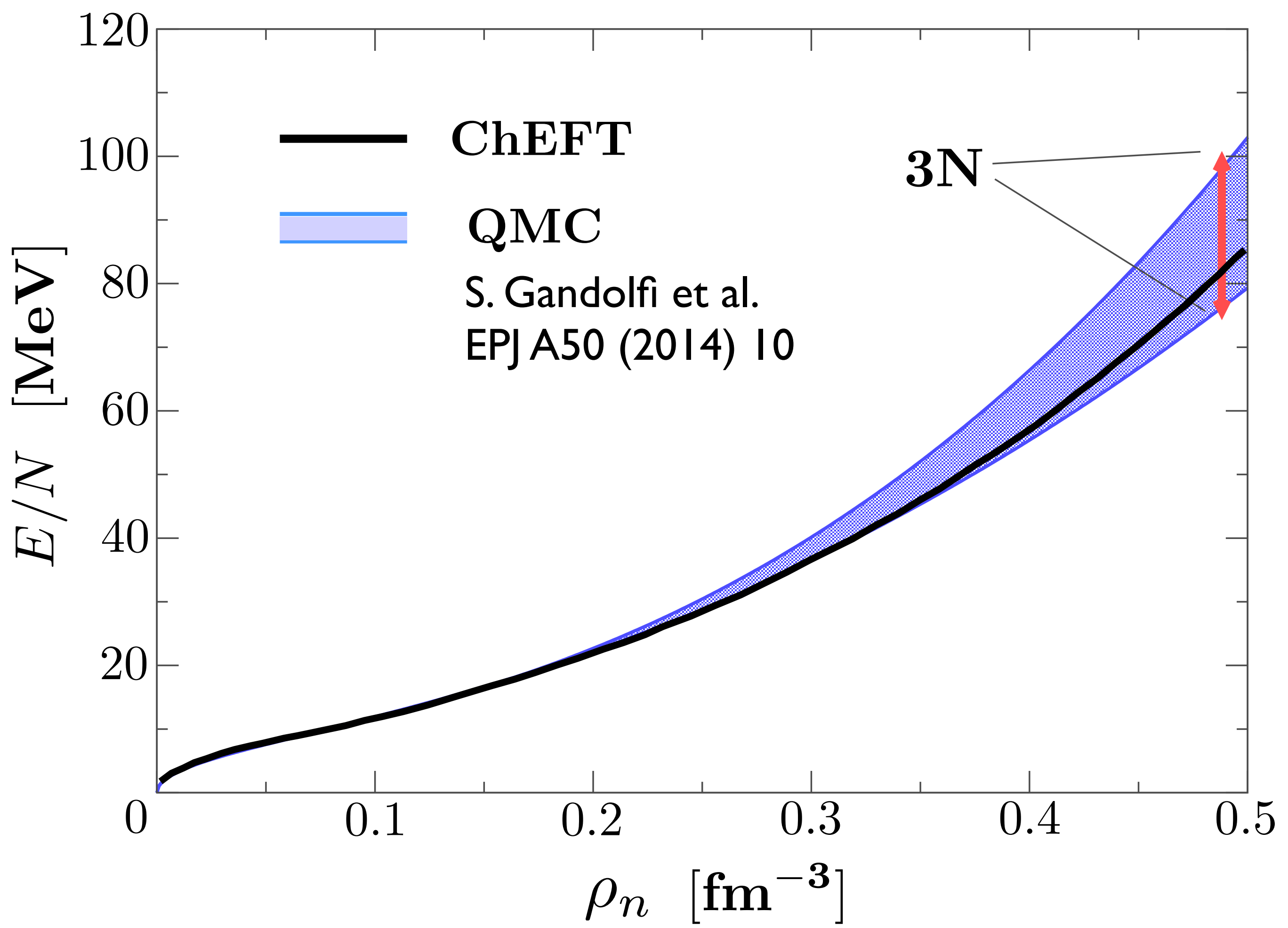
as function of proton fraction Z/A



. . . determined almost completely by
isospin dependent (one- and two-) pion exchange dynamics

NEUTRON MATTER

- In-medium chiral effective field theory (3-loop) with resummation of short distance contact terms (large nn scattering length, $a_s = 19$ fm)



- Neutron matter behaves almost (but not quite) like a unitary Fermi gas
- Bertsch parameter

$$\xi = \frac{\bar{E}}{E_{\text{Fermi gas}}} \simeq 0.5$$

J.W. Holt, N. Kaiser, W.W.
Phys. Rev. C 87 (2013) 014338

- **agreement with sophisticated many-body calculations**

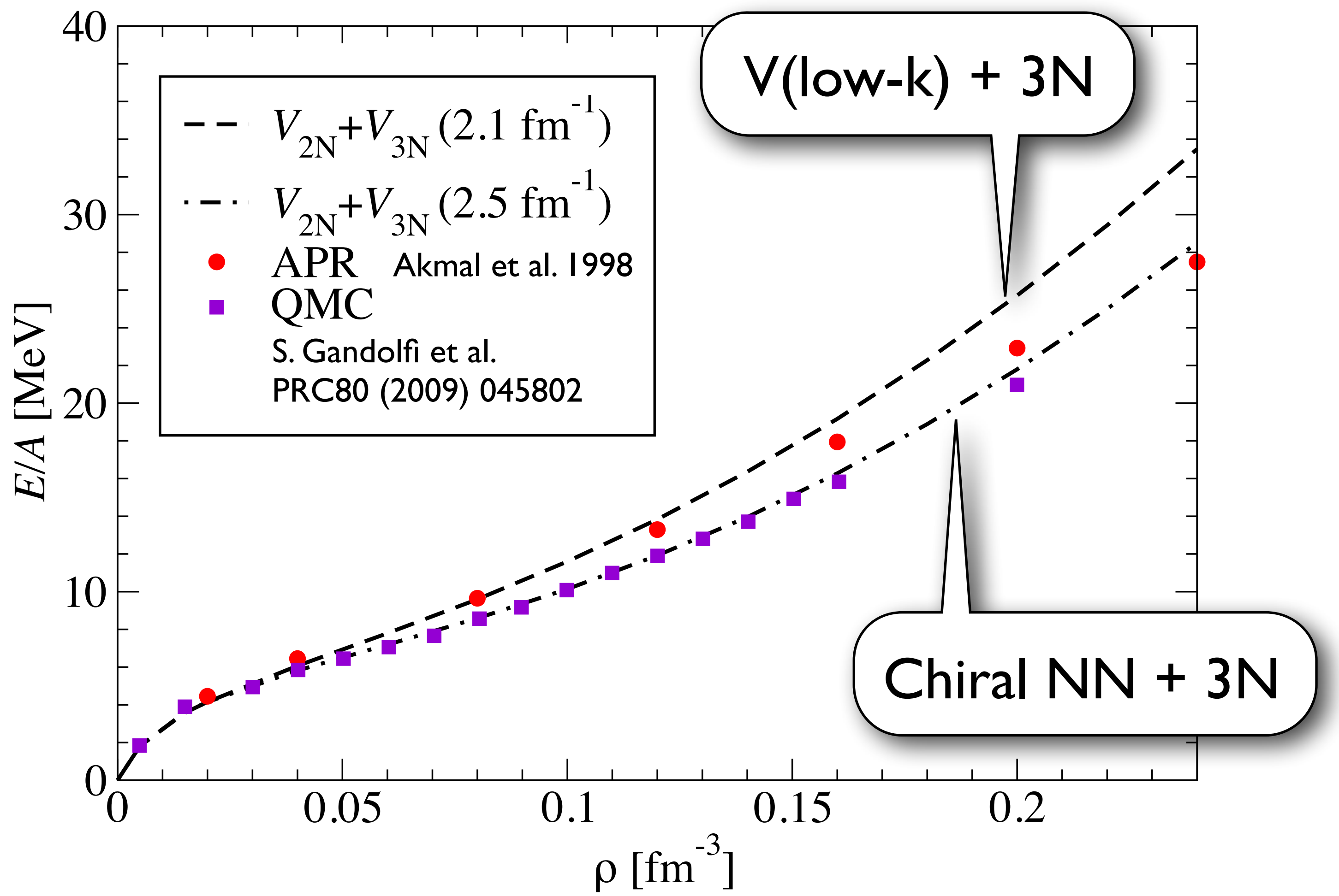
(e.g. recent **Q**uantum **M**onte **C**arlo computations)

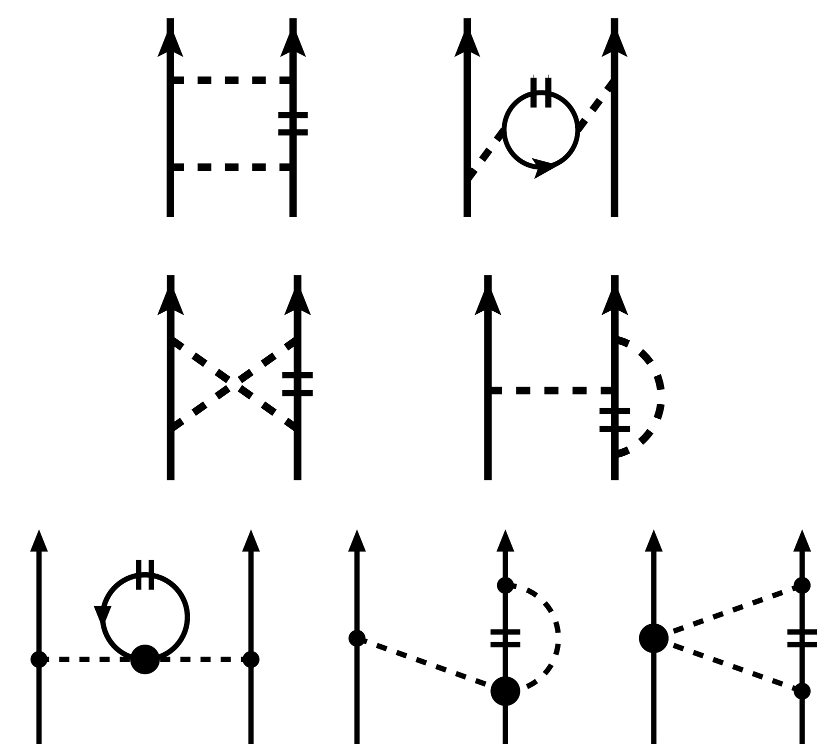
Chiral Fermi Liquid Approach to Neutron Matter

- **Quasiparticle interaction** based on accurate **NNLO** chiral nucleon-nucleon interaction including three-body forces:

$$\delta\mathcal{E} = \sum_{\vec{p}st} \epsilon_{\vec{p}}\, \delta n_{\vec{p}st} + \frac{1}{2} \sum_{\substack{\vec{p}_1 s_1 t_1 \\ \vec{p}_2 s_2 t_2}} \mathcal{F}(\vec{p}_1 s_1 t_1; \vec{p}_2 s_2 t_2)\, \delta n_{\vec{p}_1 s_1 t_1} \delta n_{\vec{p}_2 s_2 t_2} + \cdots ,$$

$$\mathcal{F}(\vec{p}_1, \vec{p}_2) = f(\vec{p}_1, \vec{p}_2) + g(\vec{p}_1, \vec{p}_2)\vec{\sigma}_1 \cdot \vec{\sigma}_2 + h(\vec{p}_1, \vec{p}_2) S_{12}(\hat{q}) + \ \ldots$$





J.W. Holt, N. Kaiser, W.W.
Phys. Rev. C 87 (2013) 014338

- **Q**uantum **M**onte **C**arlo calculations with ChEFT Interactions exhibit **systematic order-by-order convergence**

A. Gezerlis et al.
Phys. Rev. Lett. 111 (2013) 032501

Chiral Nucleon-Meson Model

(based on Linear Sigma Model)

and

Functional Renormalization Group

Mesons, Nucleons, Nuclear Matter
and
Functional Renormalization Group

- **Chiral nucleon - meson model** $\psi = (\psi_p, \psi_n)^T$

$$\mathcal{L} = \bar{\psi} i\gamma_\mu \partial^\mu \psi + \frac{1}{2}\partial_\mu \sigma\, \partial^\mu \sigma + \frac{1}{2}\partial_\mu \boldsymbol{\pi} \cdot \partial^\mu \boldsymbol{\pi}$$
$$- \bar{\psi}\Big[g(\sigma + i\gamma_5\, \boldsymbol{\tau}\cdot\boldsymbol{\pi}) + \gamma_\mu(g_\omega\, \omega^\mu + g_\rho \boldsymbol{\tau}\cdot\boldsymbol{\rho}^\mu)\Big]\psi$$
$$- \frac{1}{4}F^{(\omega)}_{\mu\nu}F^{(\omega)\mu\nu} - \frac{1}{4}\boldsymbol{F}^{(\rho)}_{\mu\nu}\cdot\boldsymbol{F}^{(\rho)\mu\nu}$$
$$+ \frac{1}{2}m_V^2\,(\omega_\mu\omega^\mu + \boldsymbol{\rho}_\mu\cdot\boldsymbol{\rho}^\mu) - \mathcal{U}(\sigma, \boldsymbol{\pi})$$

- **Effective potential** constructed to reproduce standard nuclear thermodynamics around equilibrium

- **Mean field** calculations

  S. Floerchinger, Ch. Wetterich : Nucl. Phys. A 890-891 (2012) 11

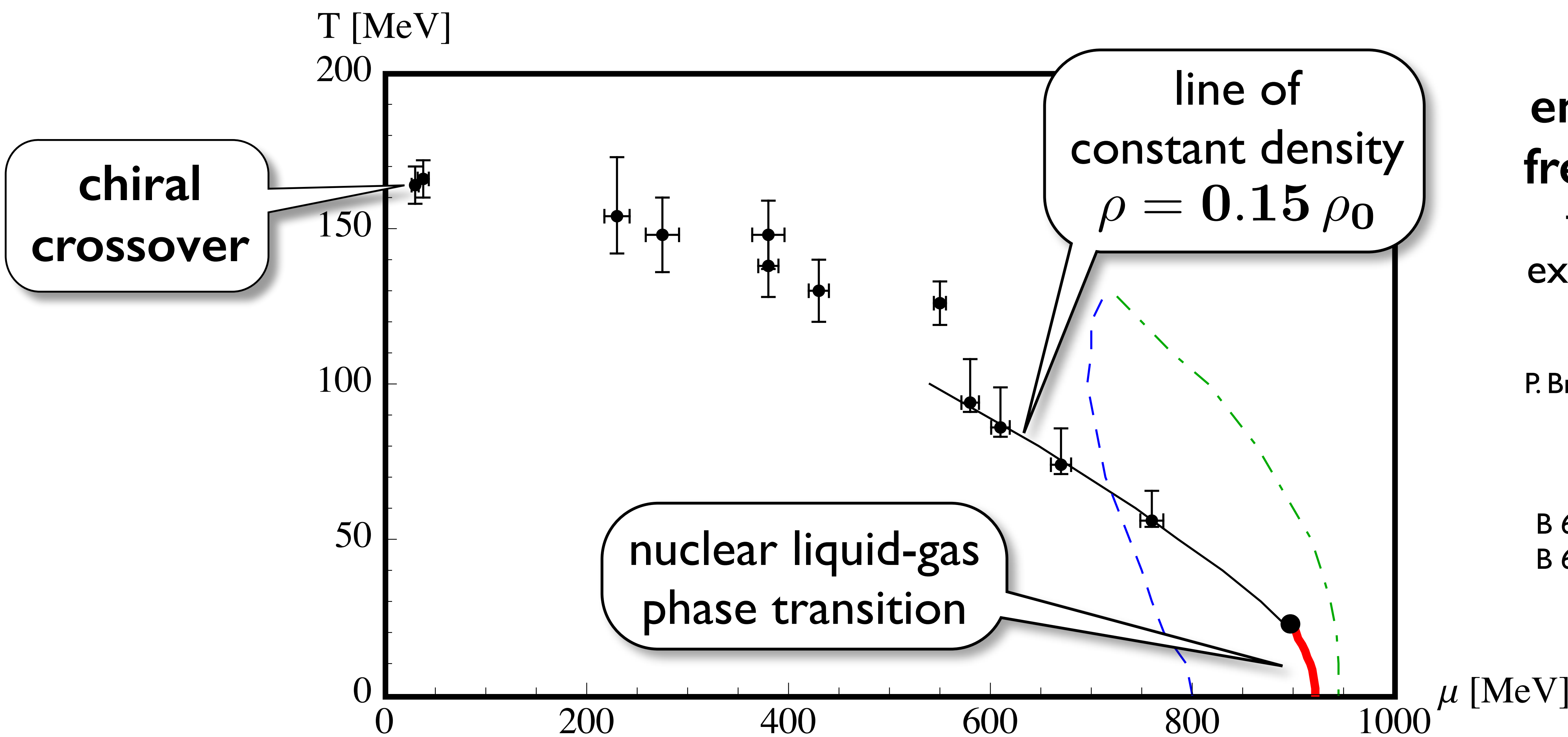
- **Mesonic** and **nucleonic particle-hole** fluctuations treated non-perturbatively using **FRG**

  M. Drews, T. Hell, B. Klein, W.W. Phys. Rev. D88 (2013) 096011
  M. Drews, W.W. Phys. Lett. B738 (2014) 187 Phys. Rev. C91 (2015) 035802

CHEMICAL FREEZE-OUT

S. Floerchinger, Ch. Wetterich : Nucl. Phys. A 890-891 (2012) 11

- **Chiral nucleon - meson model** in mean-field approximation



empirical freeze-out from HI experiments

A. Andronic, P. Braun-Munzinger, J. Stachel

Phys. Lett. B 673 (2009) 142
B 678 (2009) 516

- **Chemical freeze-out in baryonic matter at T < 100 MeV is not associated with (chiral) phase transition or rapid crossover**

Fixing the input: some comments

- **Potential** $\mathcal{U}(\sigma, \boldsymbol{\pi}) = \mathcal{U}_0(\chi) - m_\pi^2 f_\pi(\sigma - f_\pi)$

  chiral invariant part
  parametrized in powers of $\chi = \frac{1}{2}(\sigma^2 + \boldsymbol{\pi}^2)$

  explicit chiral symmetry breaking

- **Scalar** (“sigma”) **field**
  has **mean-field** (chiral **order parameter**) and **fluctuating** pieces.
  σ mass: **NOT** to be identified with “$\sigma(500)$” pole in I = 0 s-wave pion-pion T matrix

  Nucleon mass: $m_N^2 = 2g\,\chi$ … in vacuum: $m_N = g\,f_\pi$

- **Vector fields** encode short-distance NN dynamics,
  self-consistently determined background **mean fields** (non-fluctuating)
  (**NOT** to be identified with physical ω and ρ mesons)

  Effective chemical potentials $\mu_{n,p}^{\text{eff}} = \mu_{n,p} - g_\omega\,\omega_0 \pm g_\rho\,\rho_0^3$

  Relevant quantities: $G_\rho = \frac{g_\rho^2}{m_V^2}\,,\; G_\omega = \frac{g_\omega^2}{m_V^2}$ $\longleftrightarrow$ **contact terms** in **ChEFT**

- **Parameters:** 2 coefficients in $\mathcal{U}_0$, $\mathbf{m_\sigma \simeq 0.8\,GeV}\,,\; \mathbf{G_\rho \sim G_\omega/4 \simeq 1\,fm^2}$
  determined by nuclear matter properties and symmetry energy

Renormalization Group strategies
Chiral nucleon-meson model beyond mean-field

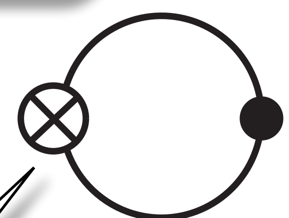
M. Drews, T. Hell, B. Klein, W.W. Phys. Rev. D 88 (2013) 096011

- **Fluctuations:** Wetterich's RG flow equations

effective action

full propagator

$$k \frac{\partial \Gamma_k}{\partial k} =$$



$$= \frac{1}{2} \,\mathrm{Tr}\, \frac{k \frac{\partial R_k}{\partial k}}{\Gamma_k^{(2)} + R_k}$$

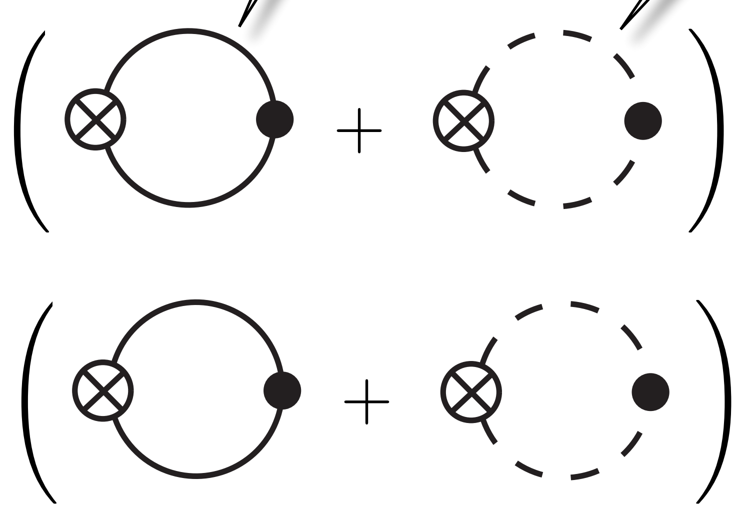
scale regulator: $R_k(\boldsymbol{p}^2) = (k^2 - \boldsymbol{p}^2)\,\theta(k^2 - \boldsymbol{p}^2)$

- **Thermodynamics:**

nucleons

pions

$$k\,\partial_k \bar{\Gamma}_k(T,\mu) =$$



$\Big|_{T,\,\mu_p,\,\mu_n}$ $-\,(\ldots)\Big|_{T=0,\,\mu=\mu_0\,(=m_N - E_0/A)}$

C. Wetterich:
Phys. Lett. B 301 (1993) 90

Non-perturbative treatment of

- **multi-pion exchange** processes
- **nucleon-hole** excitations
- **multi-nucleon** correlations

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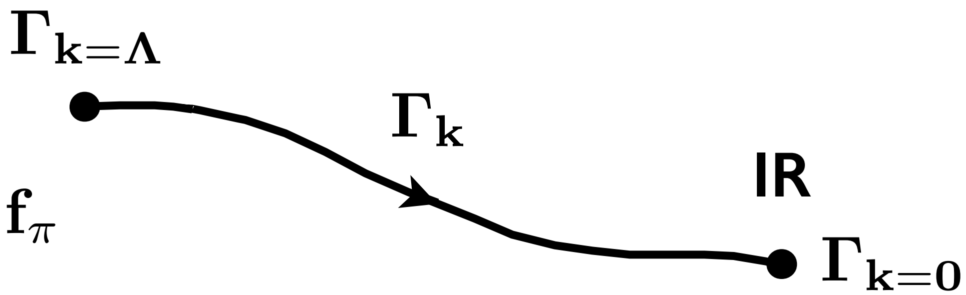
Flow equations in practice



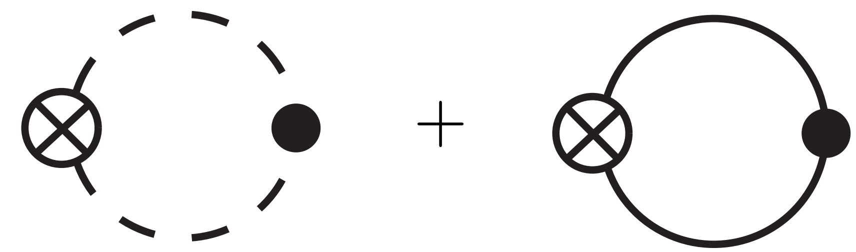
UV scale:

$\mathbf{\Lambda \simeq \Lambda_\chi = 4\pi\, f_\pi}$

"full" effective action

effective potential $\mathbf{U_{k=0}}$

$$k\frac{\partial U_k}{\partial k}(T,\mu_p,\mu_n,\chi,\omega_0,\rho_0^3) =$$



$$= \frac{k^5}{12\pi^2}\left\{\frac{1+2n_{\rm B}(E_\sigma)}{E_\sigma} + \frac{3\left[1+2n_{\rm B}(E_\pi)\right]}{E_\pi} - 4\sum_{i=n,p}\frac{1 - n_{\rm F}(E_{\rm N} - \mu_{i,\rm eff})}{E_{\rm N}}\right\}$$

$$E_\pi^2 = k^2 + U_k'(\chi)\,,\;\; E_\sigma^2 = k^2 + U_k'(\chi) + 2\chi\, U_k''(\chi)\,,$$

$$U_k'(\chi) = \frac{\partial U_k(\chi)}{\partial\chi}\,,\quad E_{\rm N}^2 = k^2 + 2g^2\chi\,,$$

$$\mu_{n,p}^{\rm eff}(k) = \mu_{n,p} - g_\omega\,\omega_0(k) \pm g_\rho\,\rho_0^3(k)\,,$$

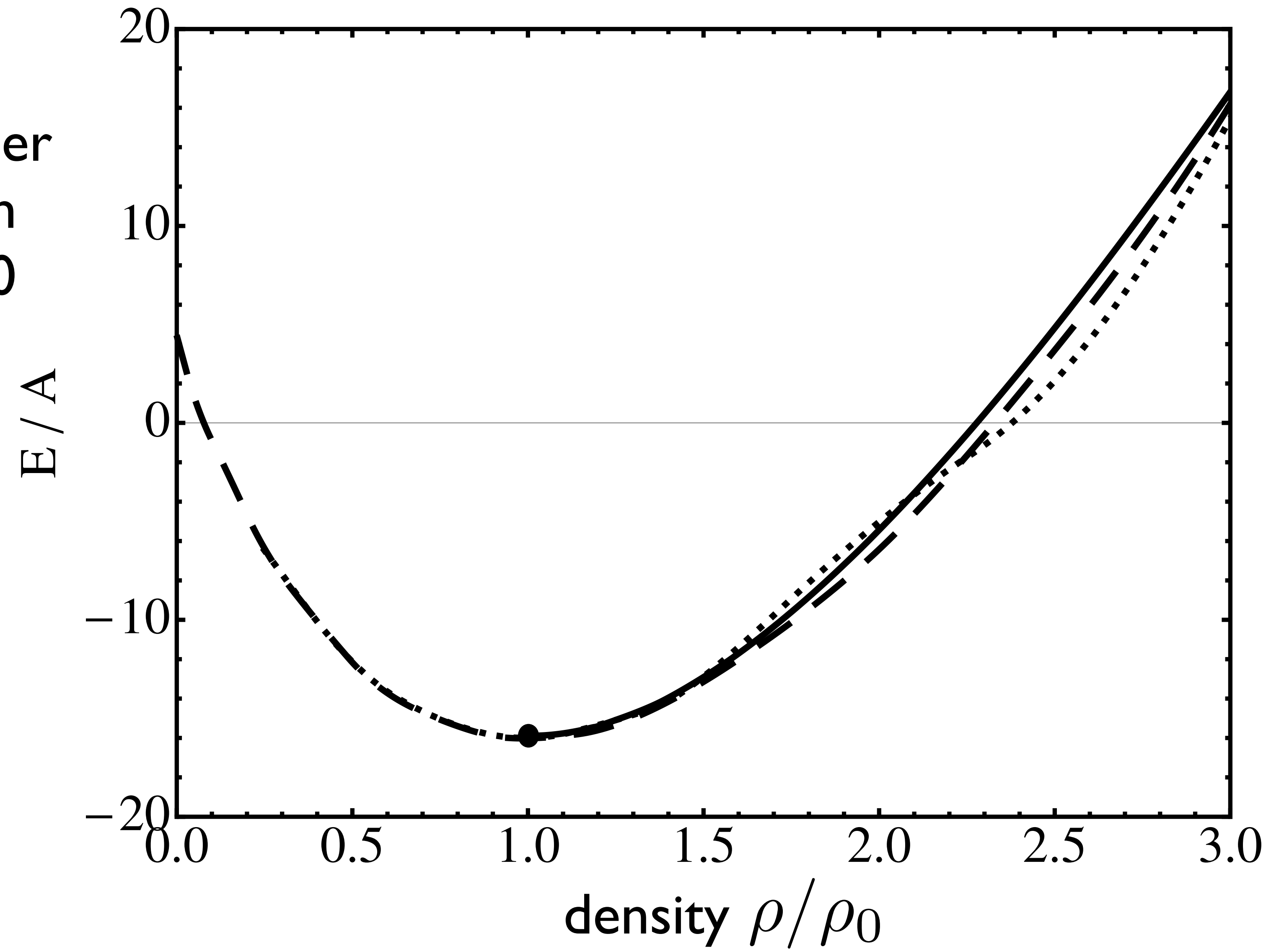
$$n_{\rm B}(E) = \frac{1}{{\rm e}^{E/T} - 1}\,,$$

$$n_{\rm F}(E) = \frac{1}{{\rm e}^{E/T} + 1}\,.$$

... plus vector field equations, then full system of equations solved on a grid.

Symmetric nuclear matter in the **chiral FRG approach**

energy per nucleon at T = 0



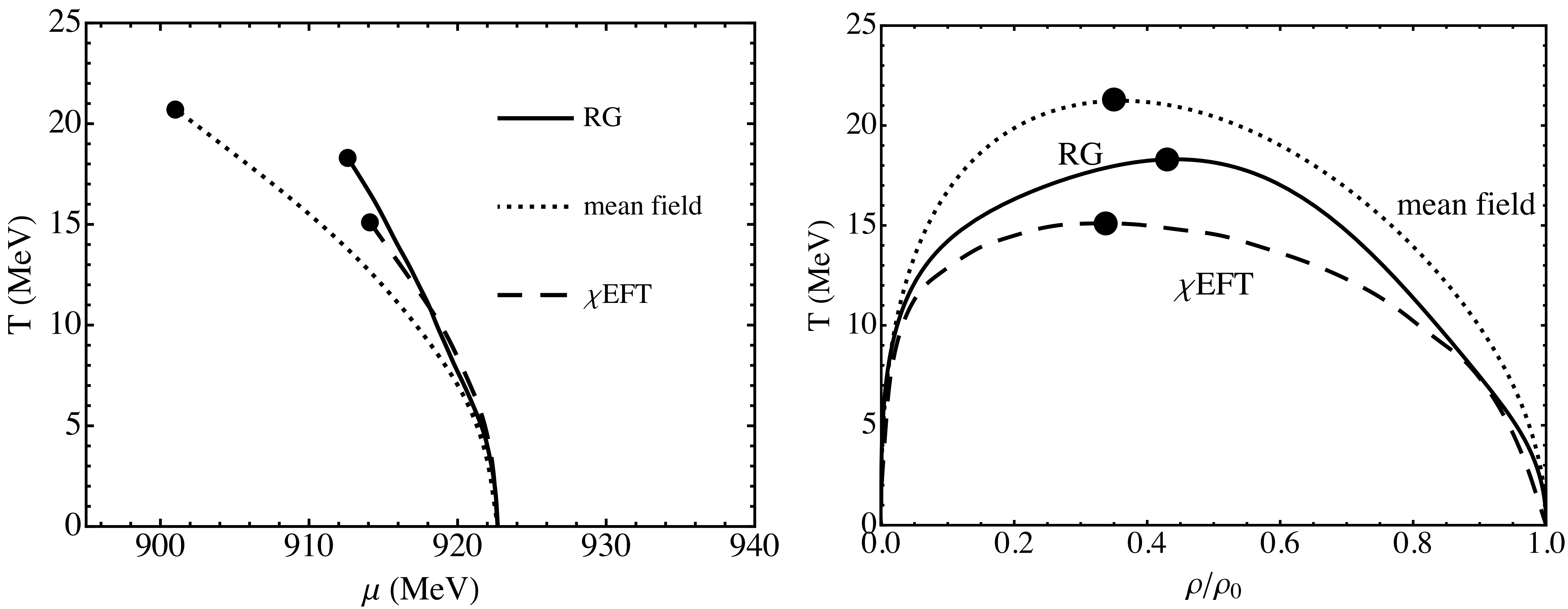
M. Drews, T. Hell, B. Klein, W.W.
Phys. Rev. D 88 (2013) 096011

- **FRG-Nucleon-Meson-Model** (solid curve) in comparison with advanced many-body (variational and QMC) computations

Results : Liquid - Gas Transition

- symmetric nuclear matter -

M. Drews, T. Hell, B. Klein, W.W.
Phys. Rev. D 88 (2013) 096011



- close correspondence between **(perturbative) in-medium ChEFT** and **(non-perturbative) FRG** results

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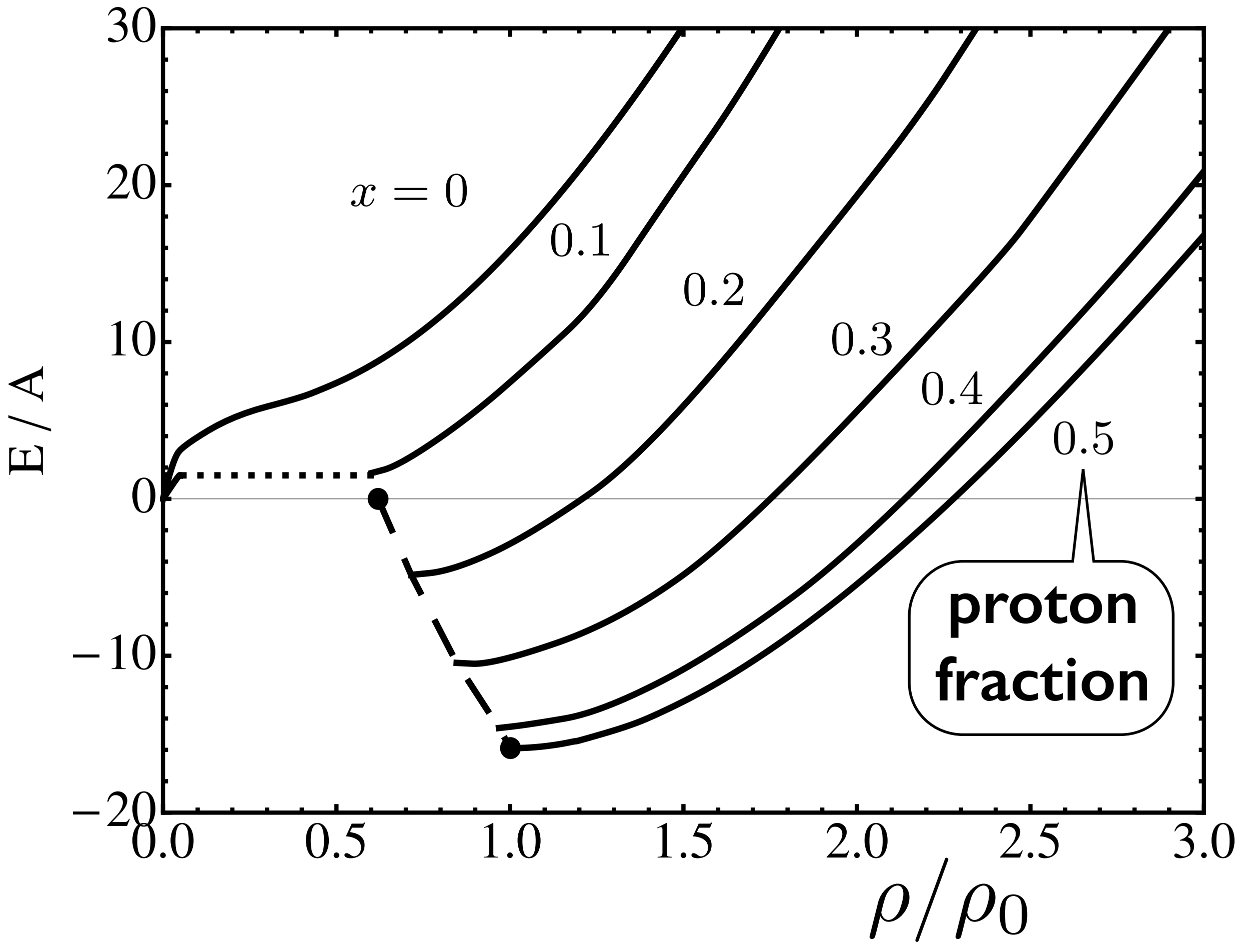
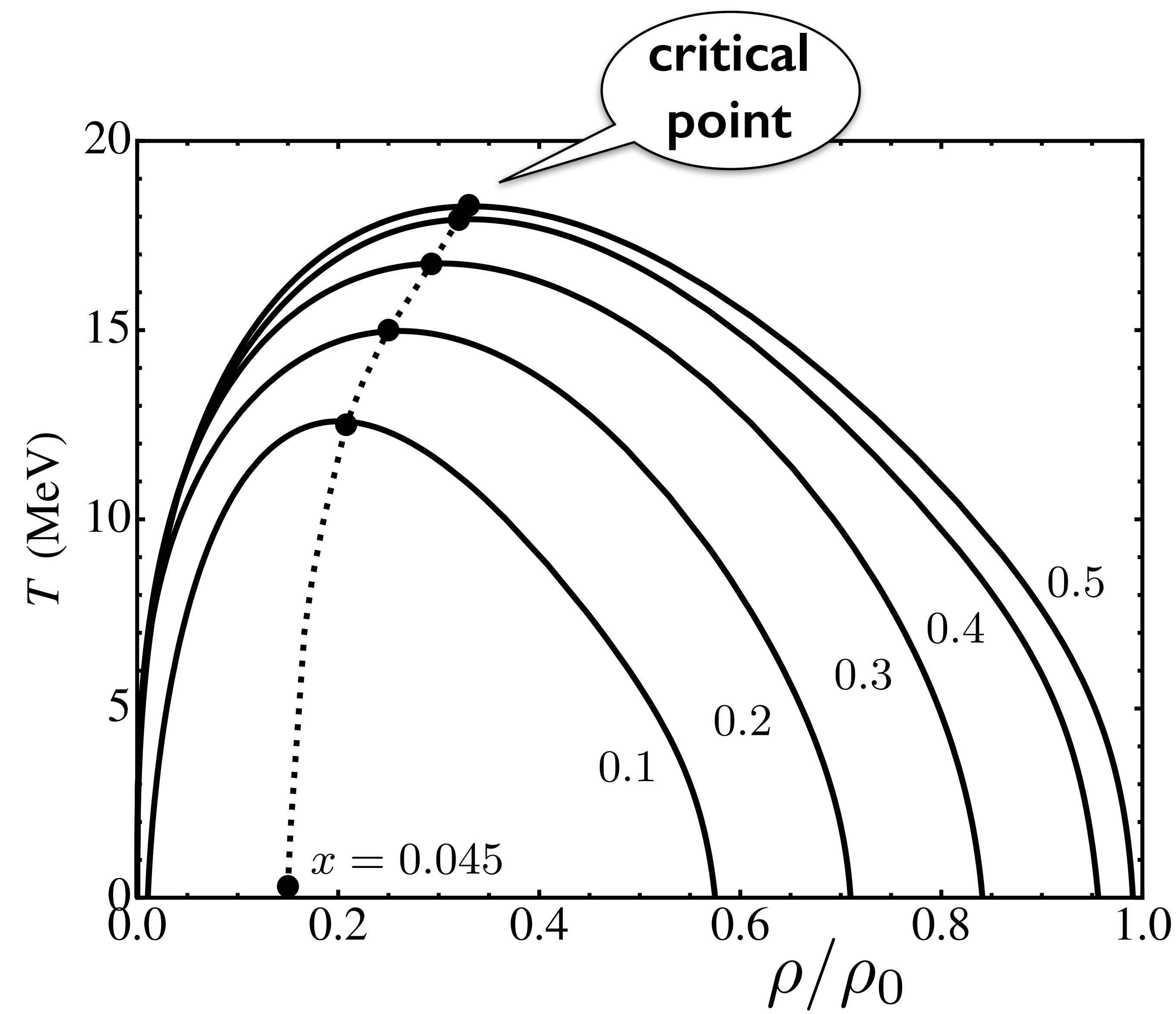
Asymmetric nuclear matter in the chiral FRG approach

M. Drews, W.W. Phys. Lett. B738 (2014) 187 Phys. Rev. C91 (2015) 035802



Liquid-gas phase transition:

evolution of coexistence regions from symmetric to asymmetric nuclear matter



- **FRG results (non-perturbative)** are remarkably similar to **(perturbative)** in-medium **Chiral EFT calculations**

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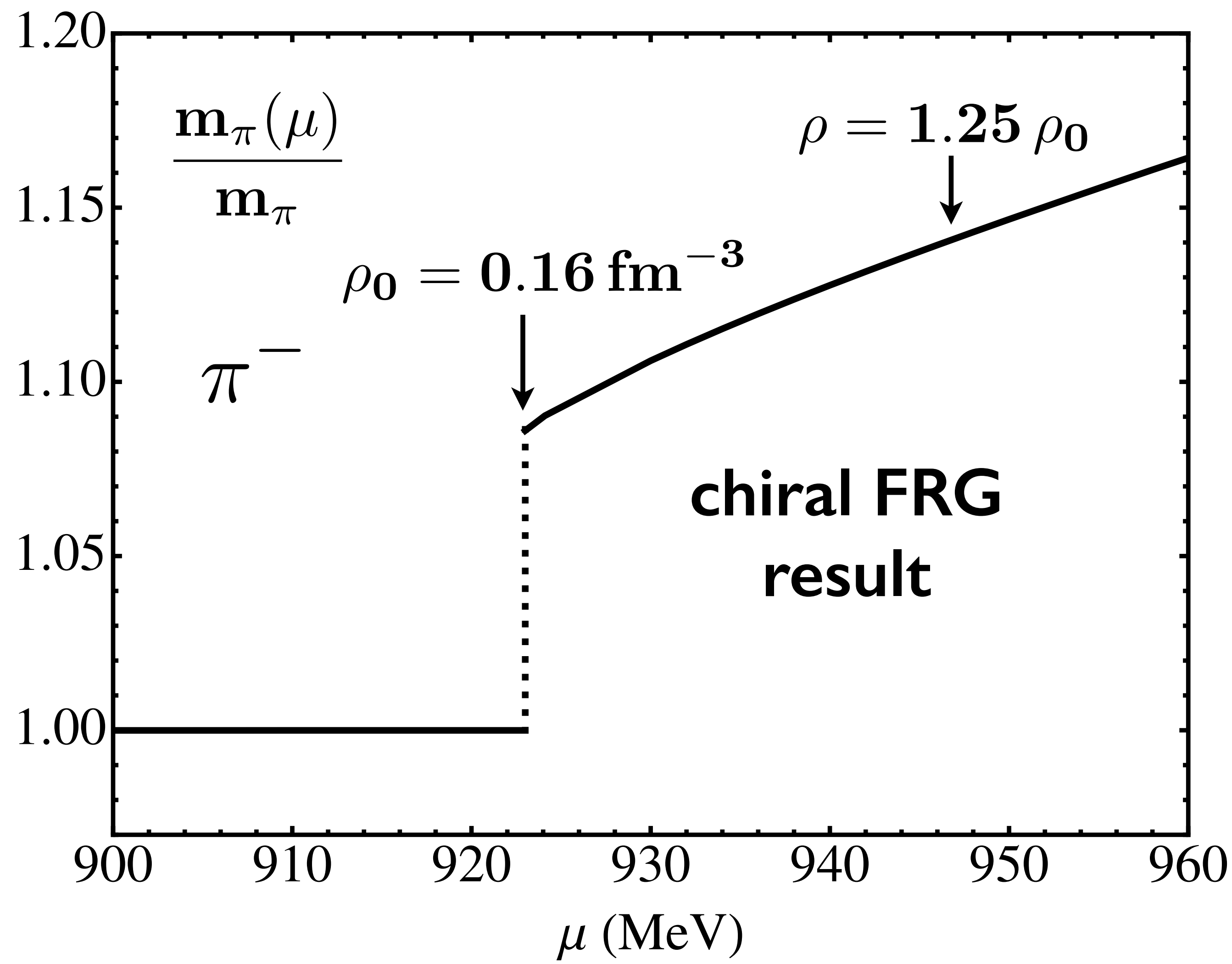
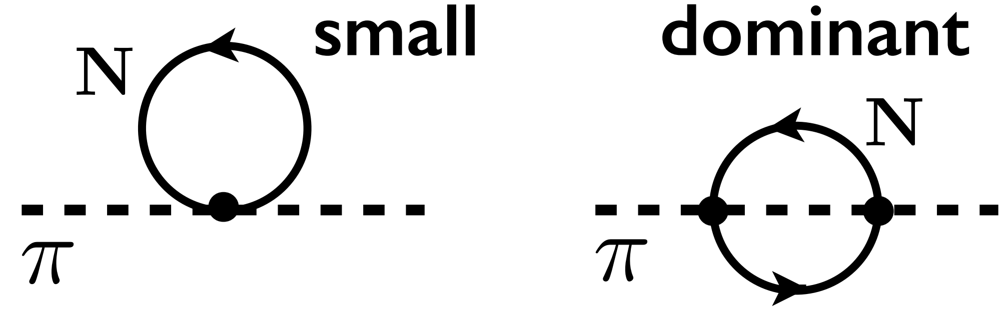
In-medium pion mass

- Test case and contact with phenomenology :
  compare with **s-wave pion-nuclear optical potential** from **pionic atoms**



phenomenology:



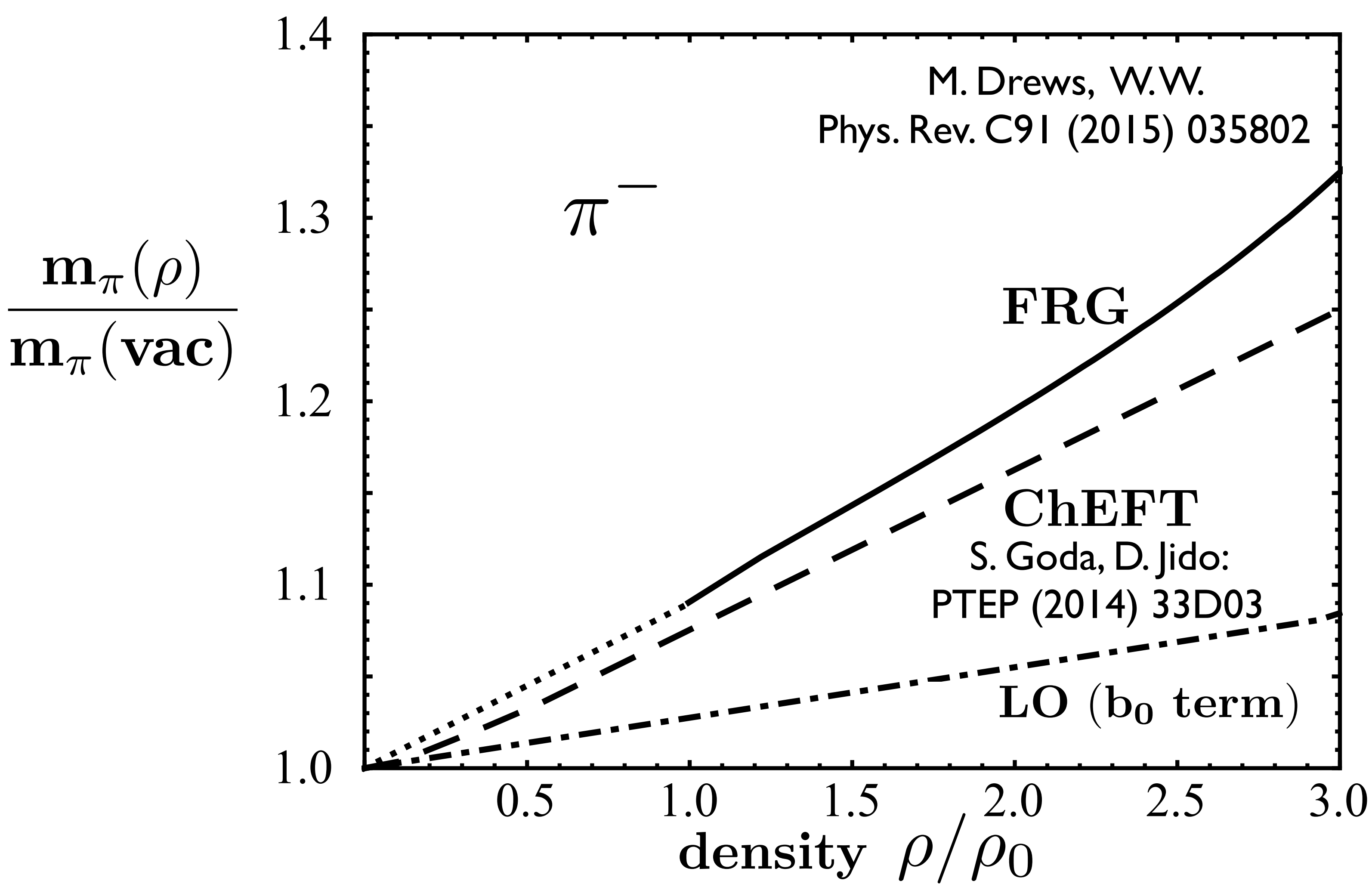
$$U(\rho) = -\frac{2\pi}{m_\pi}\left[b_o - (b_0^2 - 2b_1^2)\left\langle\frac{1}{r}\right\rangle\right]\rho$$

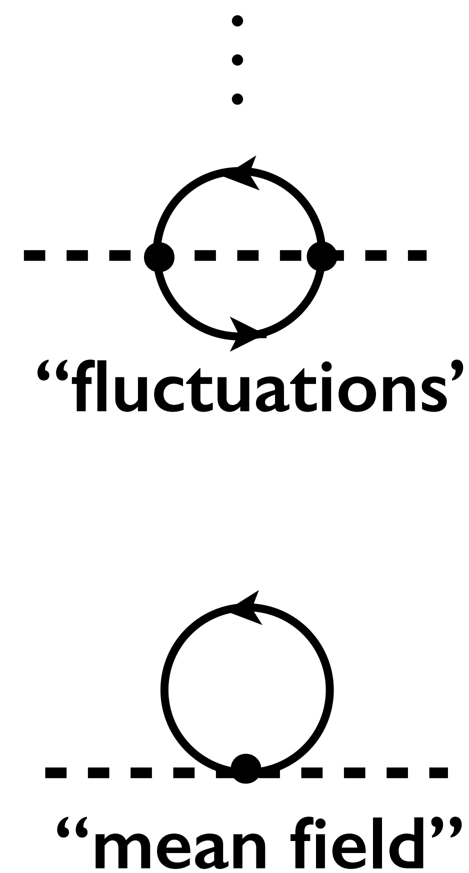
$$\frac{m_\pi(\rho)}{m_\pi} \simeq 1 + \frac{U(\rho)}{m_\pi} \simeq 1.1\,\frac{\rho}{\rho_0}$$

- Good agreement of **FRG** calculation with empirical
  in-medium pion mass shift, both in sign and magnitude

In-medium pion mass (contd.)

- **Non-perturbative FRG** result in comparison with in-medium **Chiral Perturbation Theory**





- in-medium ChEFT (NLO):

$$m_\pi^* = m_\pi \left\{1 + \rho\frac{b^+}{2m_\pi^2} - \frac{g_A^2 k_F^4}{24\pi^4 f_\pi^4}F(\frac{m_\pi}{2k_F}) + \left[\frac{1}{8} + m_\pi^2\left(\frac{b^+}{2m_\pi^2} - \frac{g_A^2}{8m_N}\right)^2\right]\frac{2k_F^4}{\pi^4 f_\pi^4}\right\}$$

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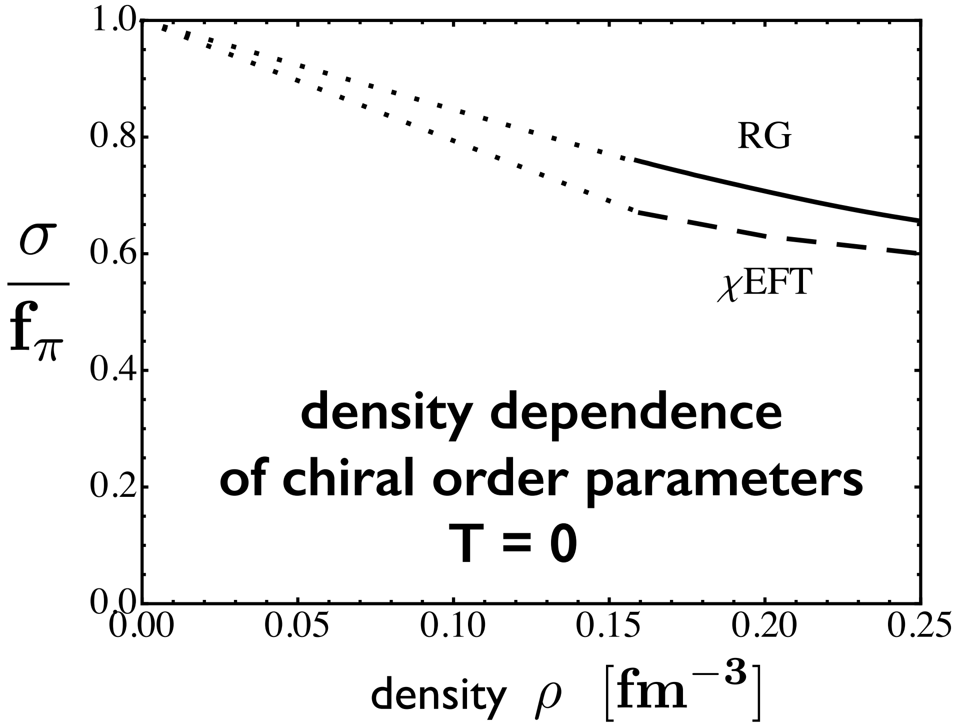
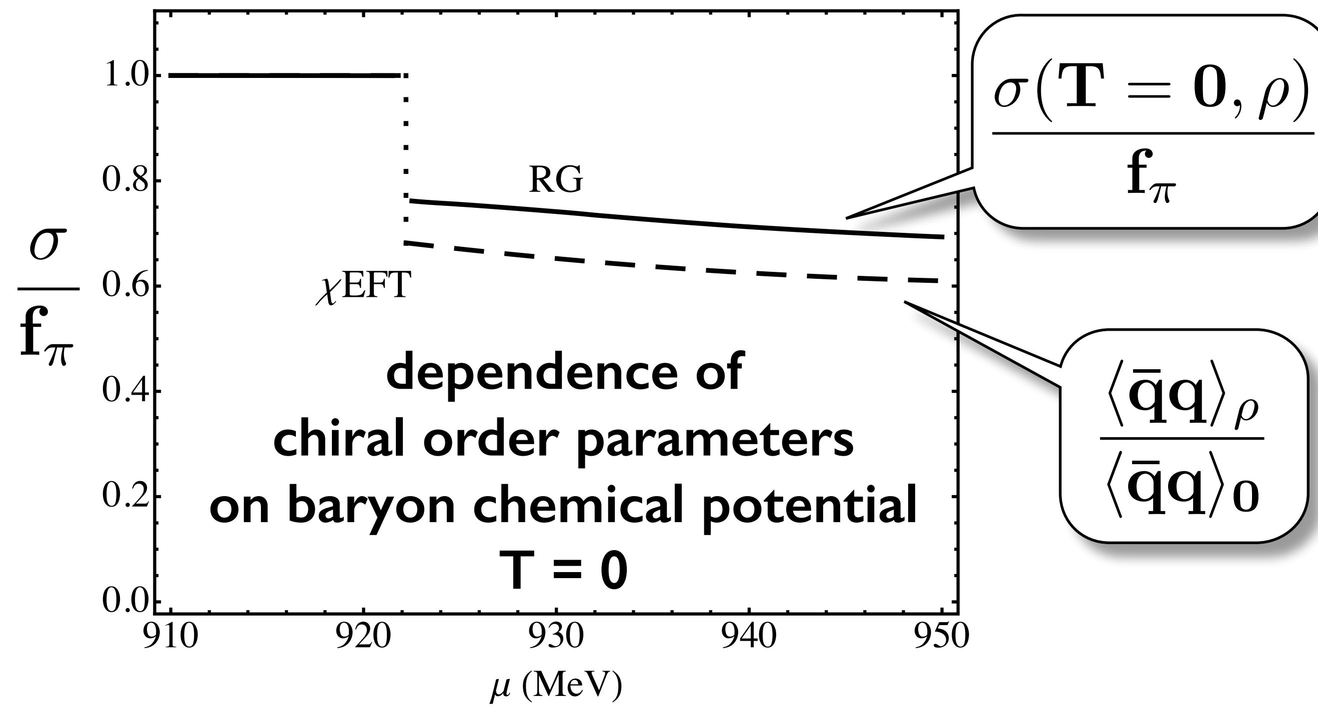
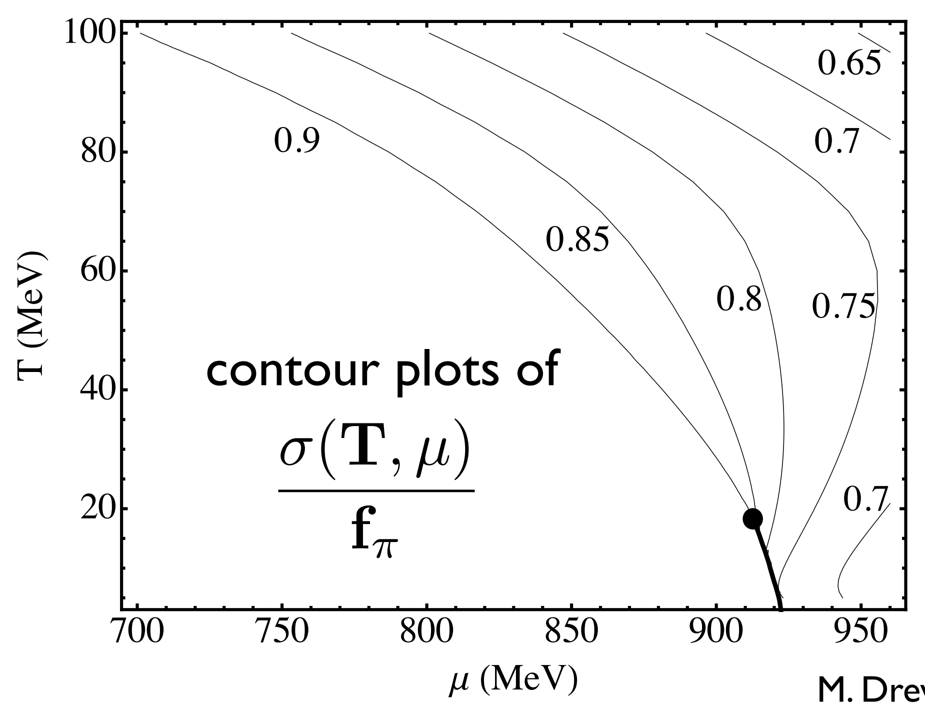
Chiral Order Parameters

- Comparison of **chiral effective field theory** and **NM-FRG** results







- **No** tendency towards
chiral phase transition
for baryon chemical potentials
$\mu \lesssim 1\ \mathbf{GeV}$
and temperatures
$\mathbf{T} \lesssim 100\ \mathbf{MeV}$

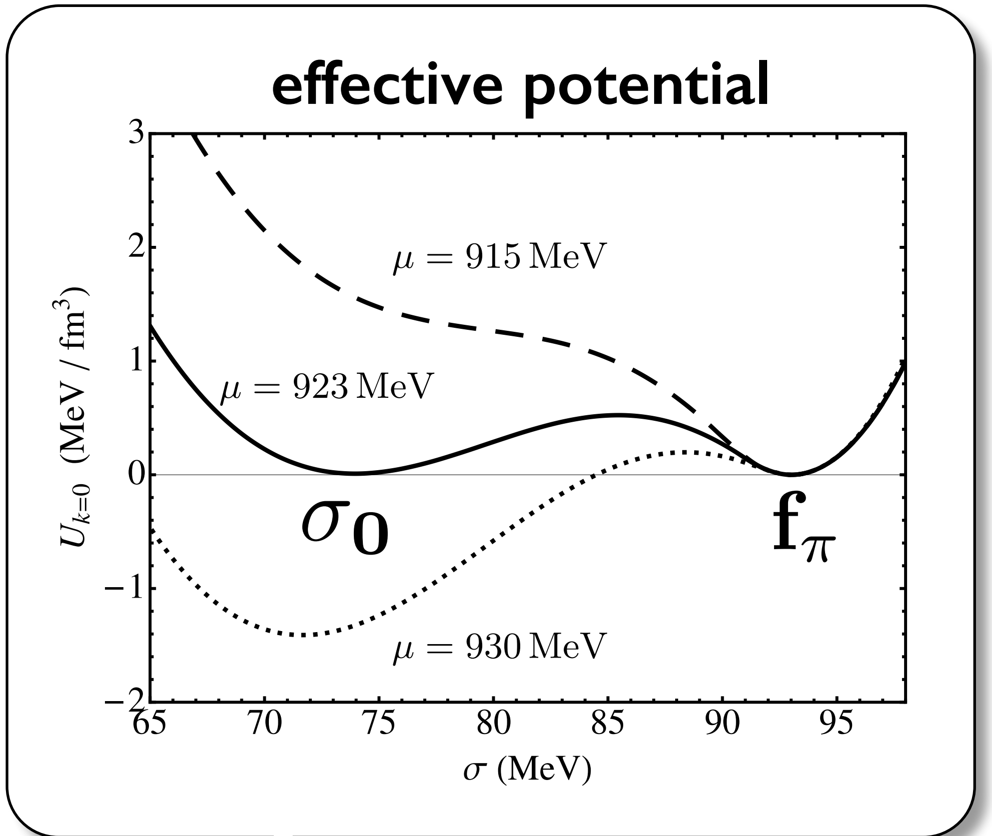
M. Drews, T. Hell, B. Klein, W.W.
Phys. Rev. D 88 (2013) 096011

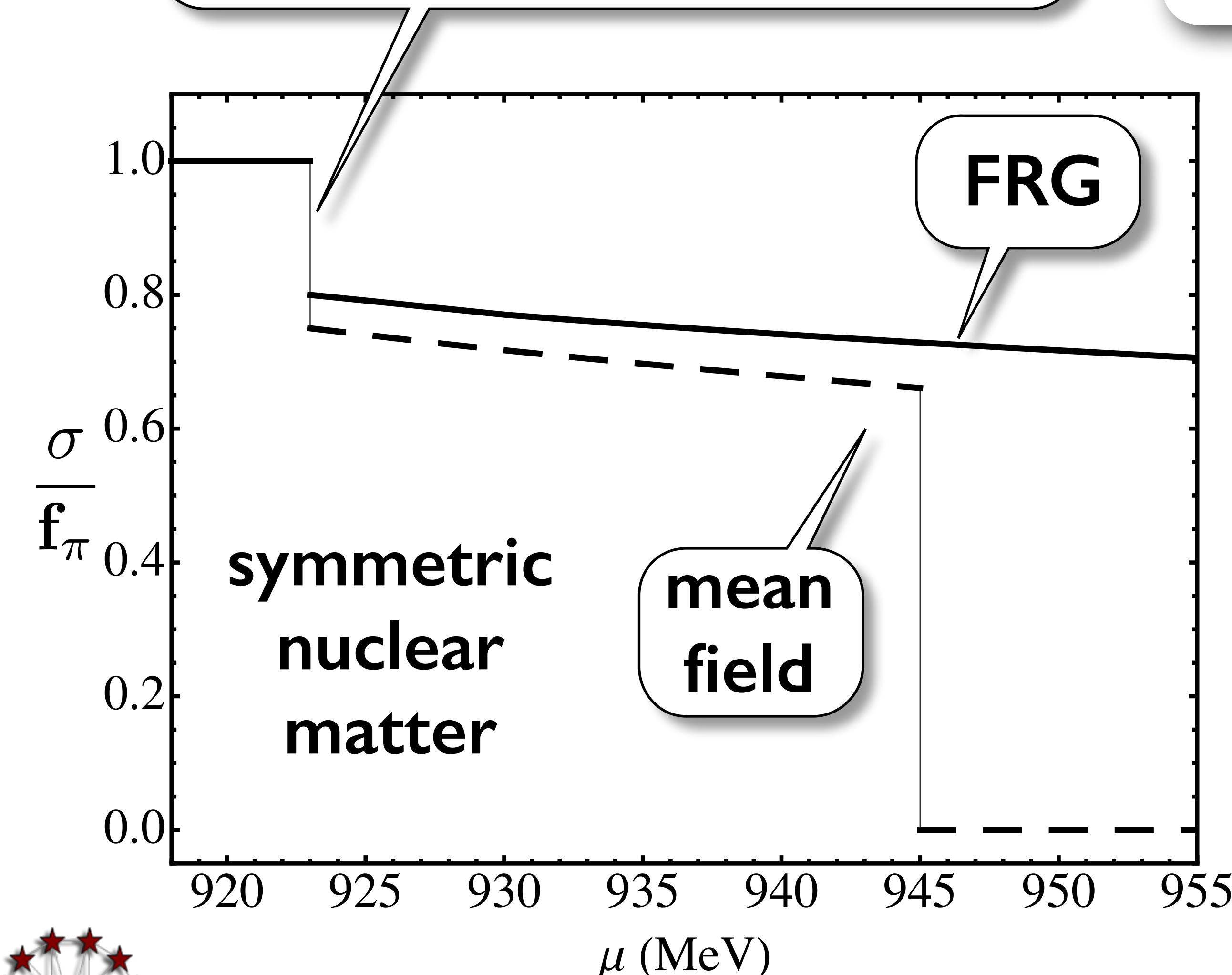
Chiral Order Parameter

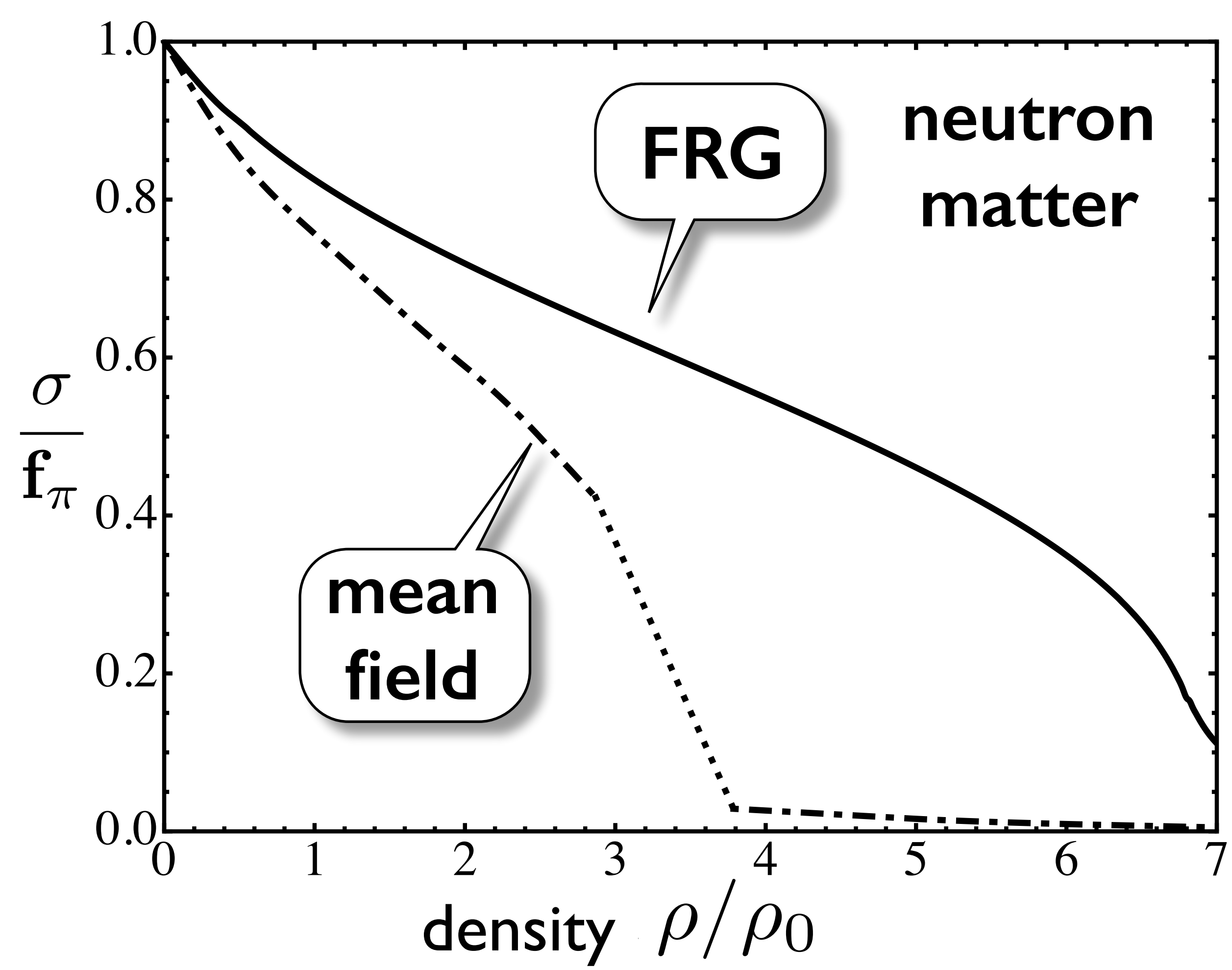
M. Drews, W.W.
Phys. Rev. C91 (2015) 035802

important role of **fluctuations** beyond mean-field approximation:

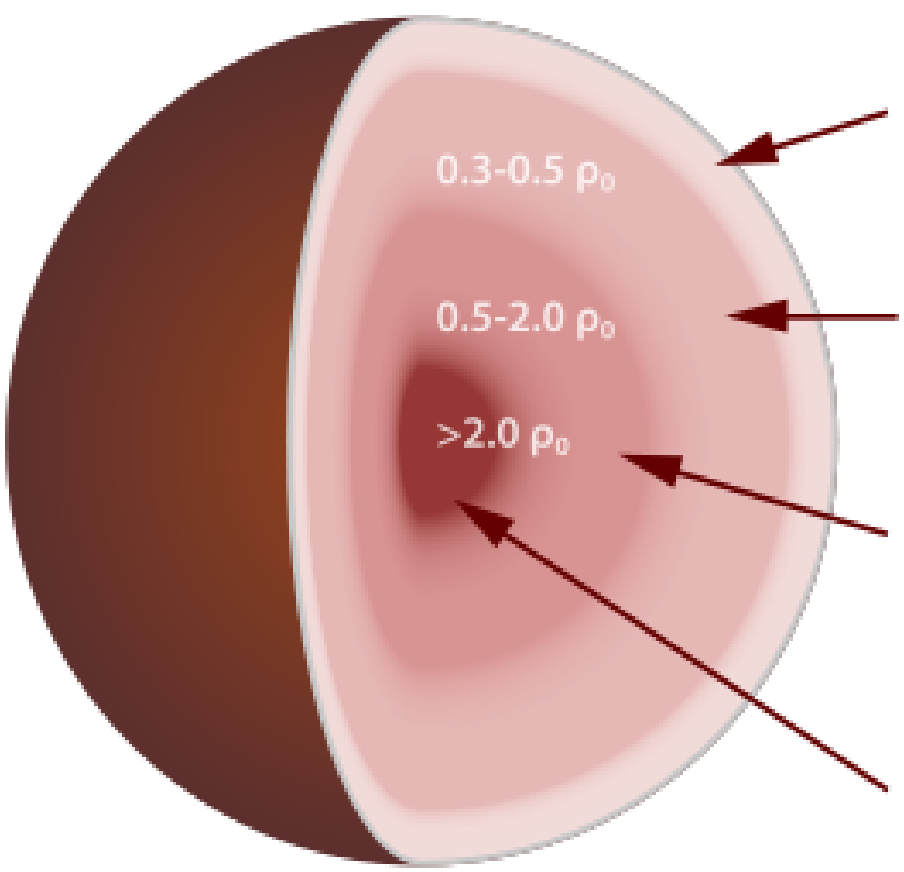
DISAPPEARANCE of first-order chiral phase transition







News from NEUTRON STARS



outer crust 0.3-0.5 km
ions, electrons

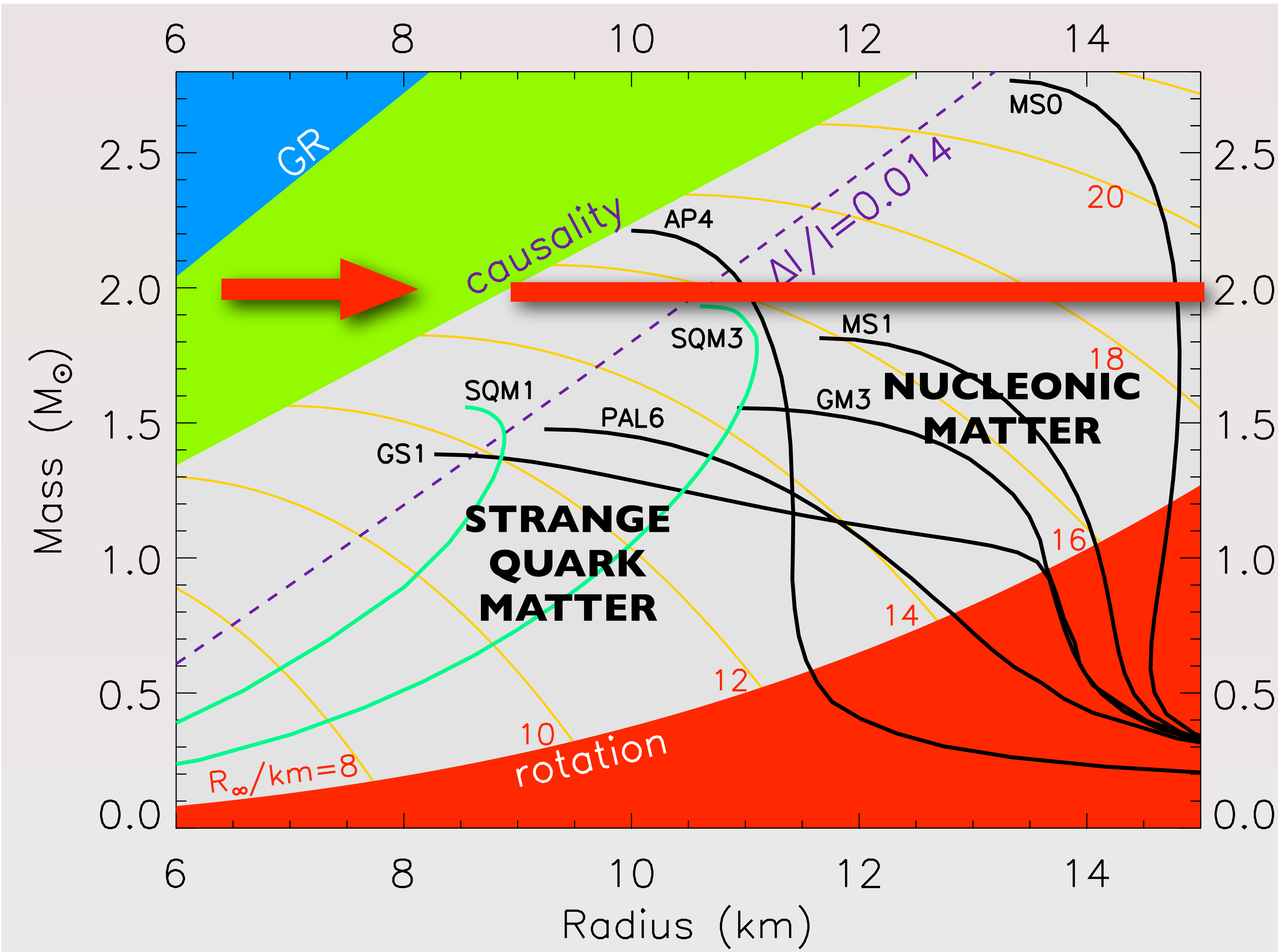
inner crust 1-2 km
electrons, neutrons, nuclei

outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas

inner core 0-3 km

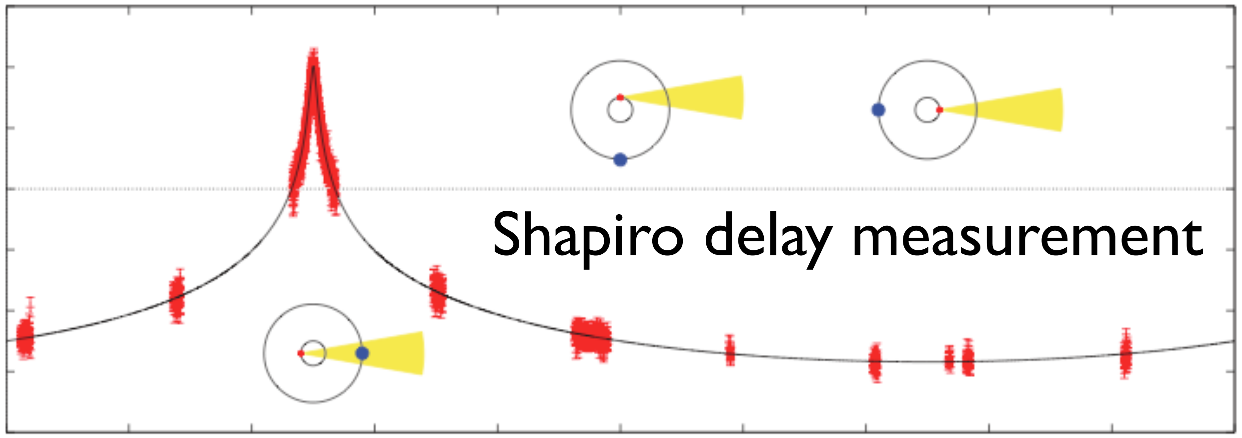
quark matter ??

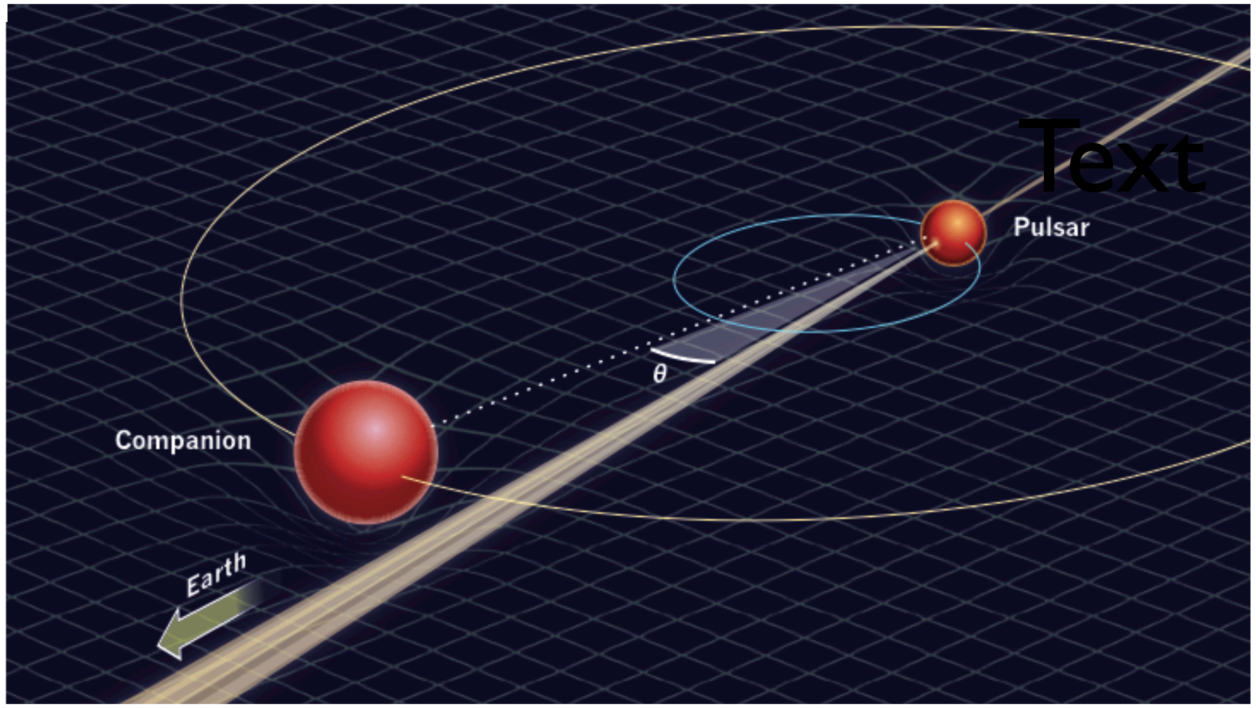
New constraints
from **2-solar-mass NEUTRON STARS**



New constraints from NEUTRON STARS

P.B. Demorest et al.
Nature 467 (2010) 1081

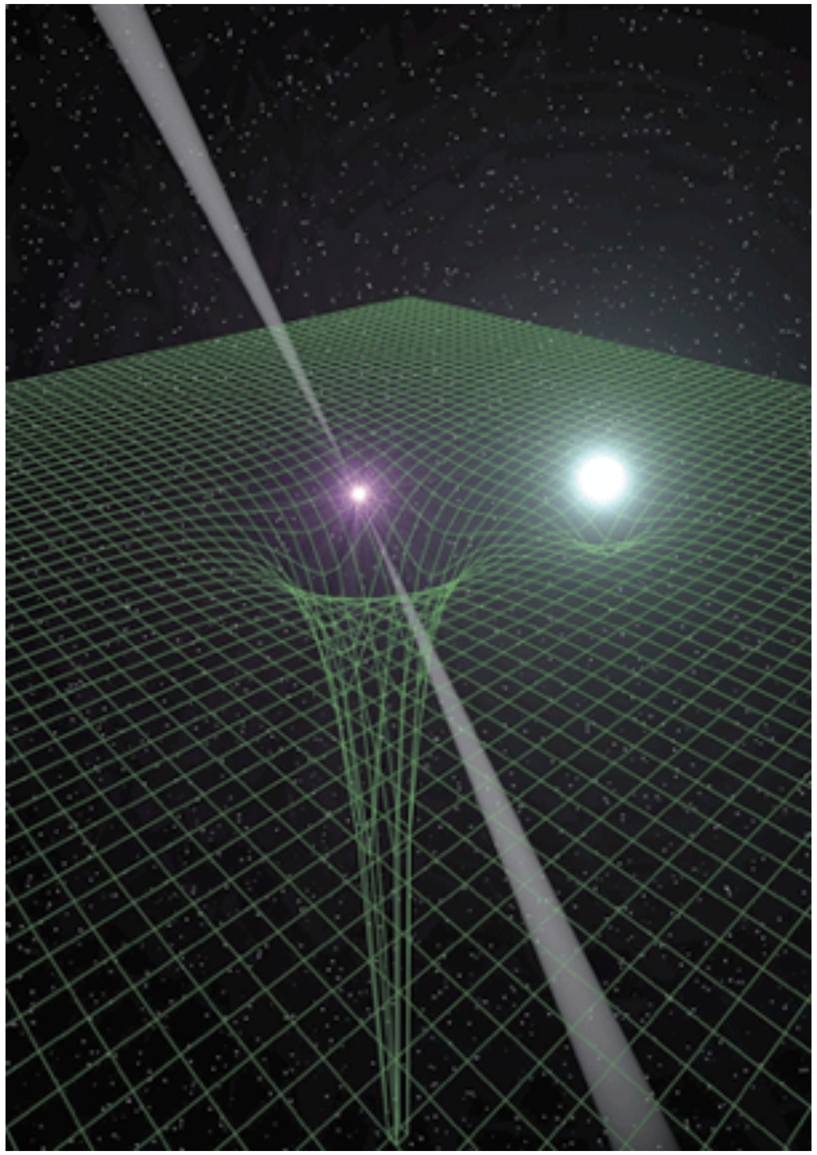




PSR J1614+2230

$$\mathrm{M} = 1.97 \pm 0.04\ \mathrm{M}_\odot$$

J. Antoniadis et al.
Science 340 (2013) 6131



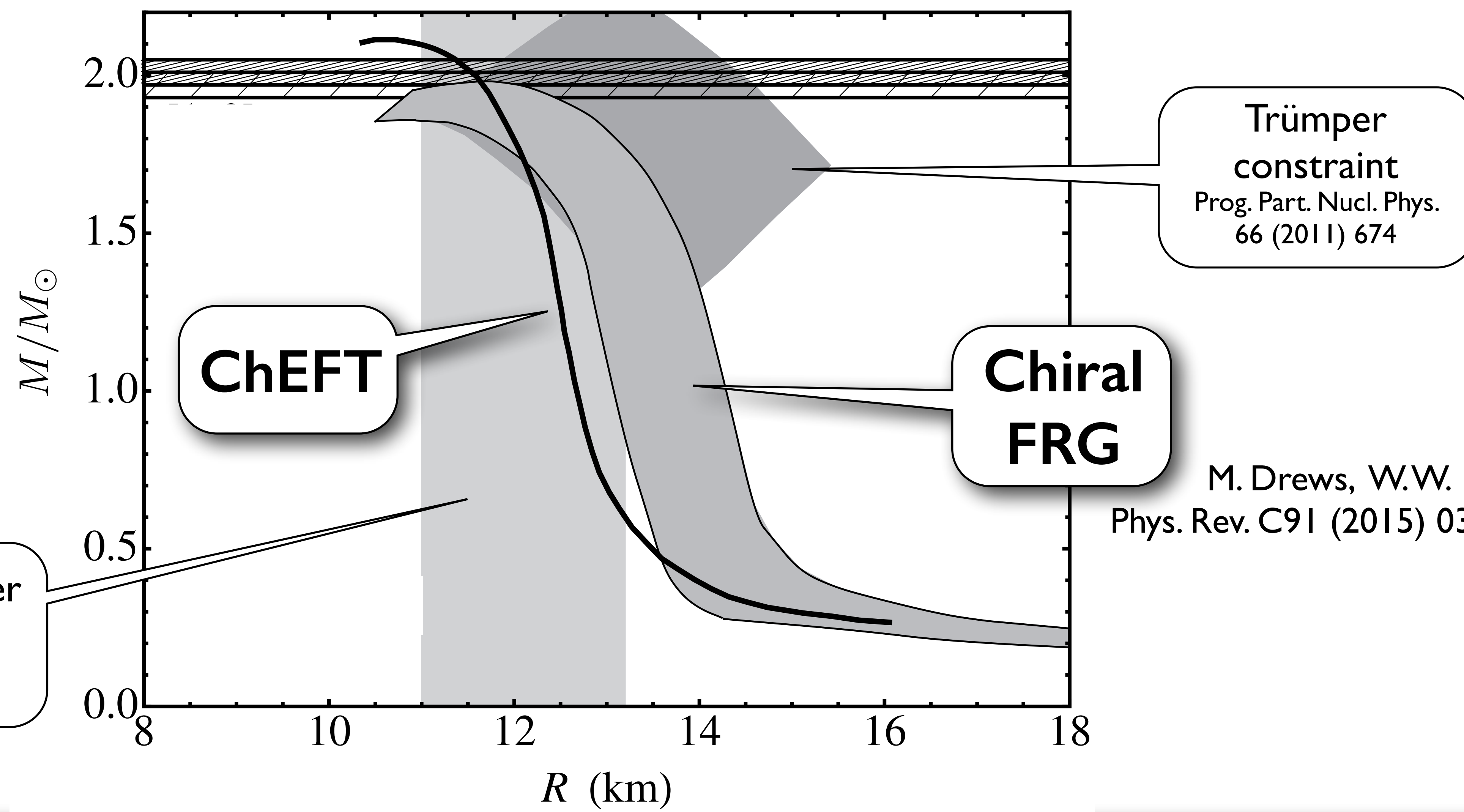
PSR J0348+0432

$$\mathrm{M} = 2.01 \pm 0.04\ \mathrm{M}_\odot$$

NEUTRON STAR MATTER
from Chiral Nucleon-Meson Approach and **FRG**

- **Neutron matter plus proton admixture (beta equilibrium)**
- **Symmetry energy range: 30 - 37 MeV**

T. Hell, W.W.
Phys. Rev.
C90 (2014) 045801



M. Drews, W.W.
Phys. Rev. C91 (2015) 035802

- **Chiral many-body dynamics using "conventional" (pion & nucleon) degrees of freedom is consistent with neutron star constraints**

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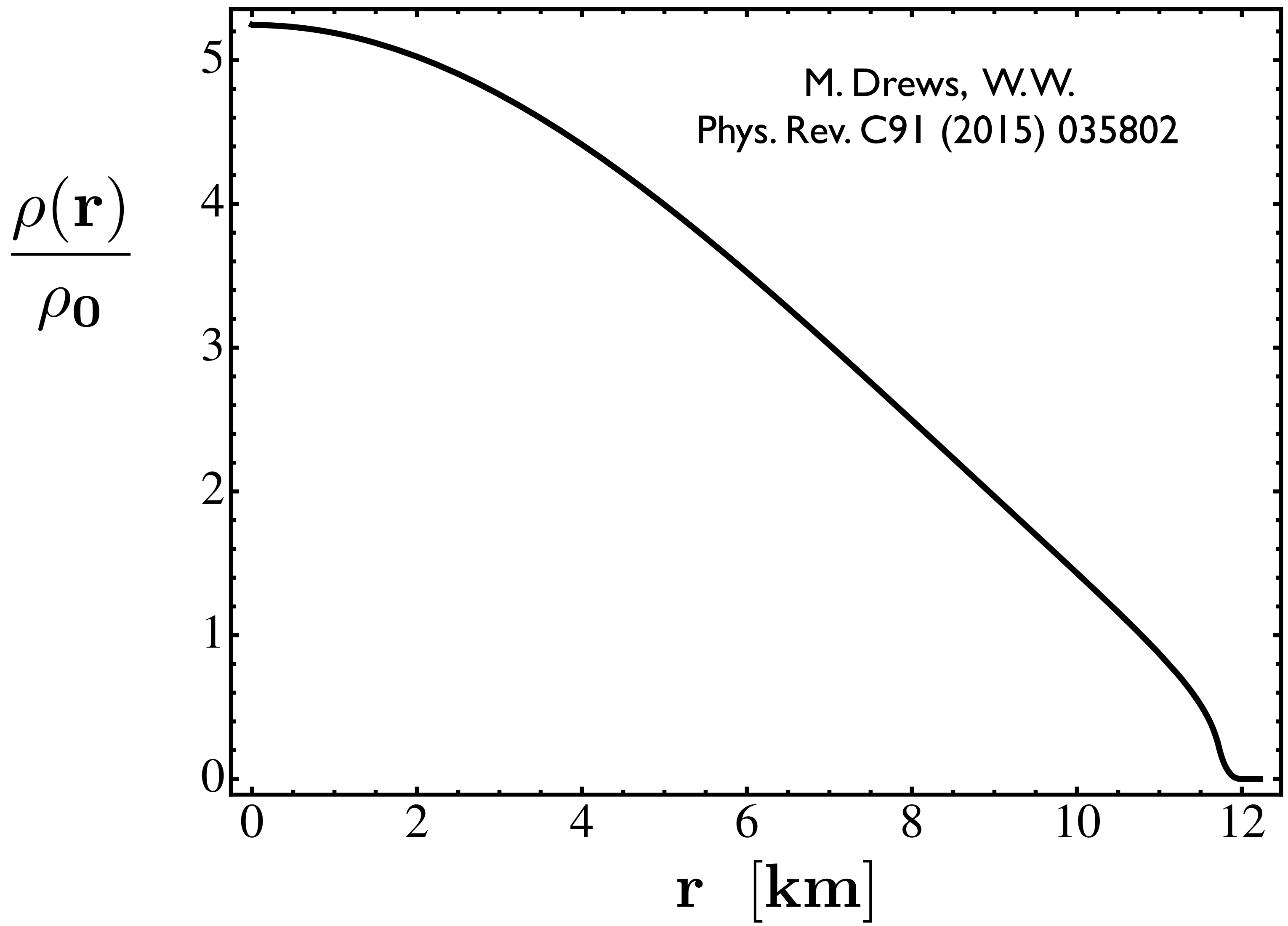
Density profile of two-solar-mass neutron star



Chiral FRG calculation

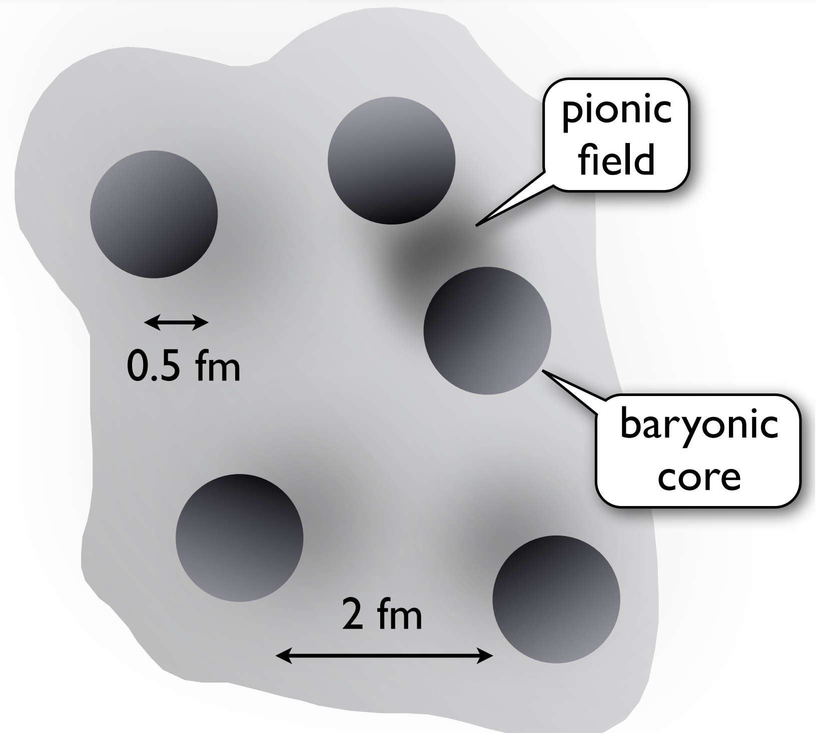
maximum n-star core density:

$$\rho_{\mathbf{max}} \sim \mathbf{5}\,\rho_{\mathbf{0}}$$

$$(\rho_{\mathbf{0}} = \mathbf{0.16\ fm^{-3}})$$

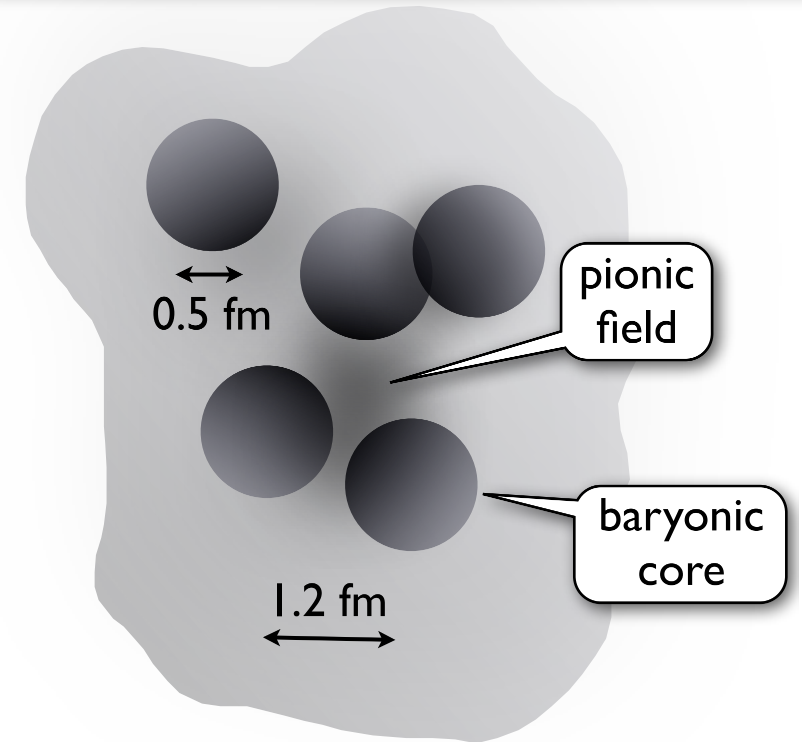
- **No ultrahigh densities in the neutron star core**

Densities and **Scales** in **Compressed Baryonic Matter**



$\rho_B = 0.15 \text{ fm}^{-3}$

normal nuclear matter: dilute

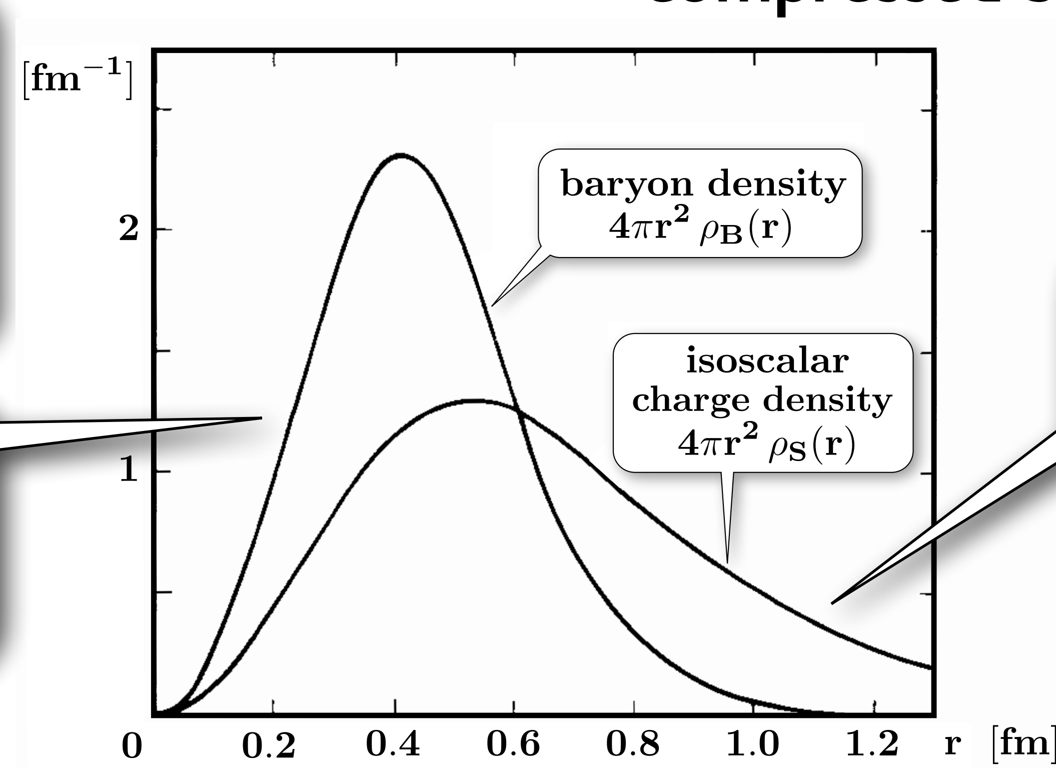


$\rho_B = 0.6 \text{ fm}^{-3}$

neutron star core matter:
compressed but **not superdense**

chiral
(soliton)
model
of the nucleon

compact
baryonic core
$\langle r^2 \rangle_B^{1/2} \simeq 0.5 \text{ fm}$



N. Kaiser, U.-G. Meißner, W.W.
Nucl. Phys. A 466 (1987) 685

mesonic cloud
$\langle r^2 \rangle_{E,\text{isoscalar}}^{1/2} \simeq 0.8 \text{ fm}$

in-medium pion field
treated properly
in chiral EFT

SUMMARY

- **Chiral Effective Field Theory** and **Functional Renormalization Group:**
  Nuclear Chiral Dynamics and **Thermodynamics**
  from symmetric to asymmetric nuclear matter and neutron (star) matter
  - **Fluctuations beyond mean field** include important multi-pion exchange mechanisms and low-energy nucleonic particle-hole excitations
  - 1st order phase transition: Fermi liquid $\leftrightarrow$ interacting Fermi gas
- **No** indication of **first-order chiral phase transition**
  - **Fluctuations work against early restoration of chiral symmetry**
- **New** constraints from **neutron stars** for the **equation-of-state** of **dense & cold baryonic matter**:
  - Mass - radius relation: **stiff equation of state** required !
    No ultrahigh densities $(\varrho_{\mathbf{max}} \sim \mathbf{5}\, \varrho_{\mathbf{0}})$
  - **Conventional** (nucleon-meson, "non-exotic") **EoS** meets constraints
    Issue of **strangeness: suppression of hyperons in neutron stars** ?)

Appendix:

HYPERONS
in
NEUTRON STARS

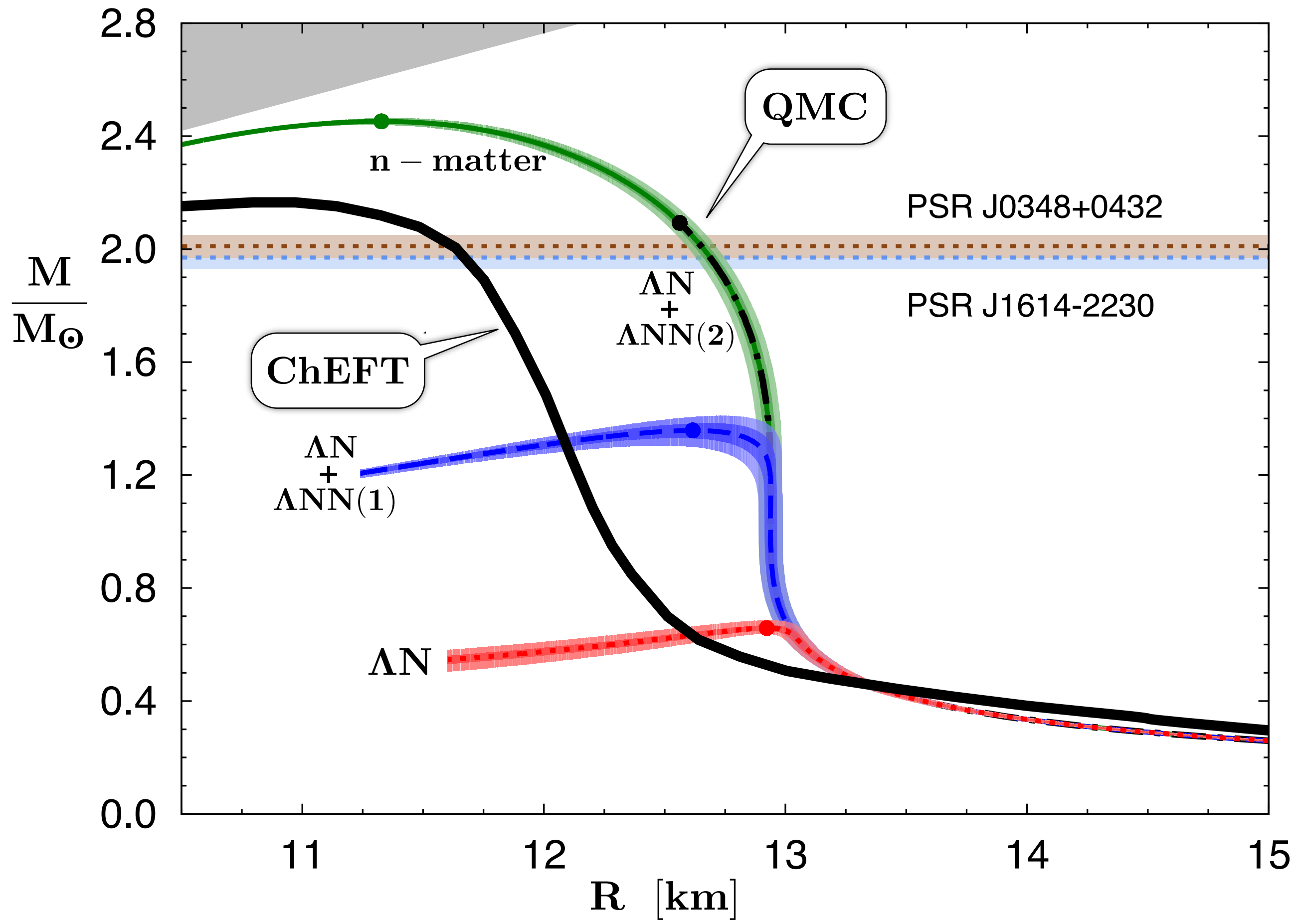
NEUTRON STAR MATTER including HYPERONS

New **Q**uantum **M**onte **C**arlo **calculations** using phenomenological hyperon-nucleon and hyperon-NN **three-body** interactions constrained by **hypernuclei**

Mass - radius relation of neutron stars

ChEFT calculations (“conventional” n-star matter):

T. Hell, W.W.
PRC90 (2014) 045801



QMC computations (hyper-neutron matter):

D. Lonardoni,
A. Lovato,
S. Gandolfi,
F. Pederiva
Phys. Rev. Lett.
114 (2015) 092301

with inclusion of **hyperons**: EoS **too soft** to support 2-solar-mass star unless strong short-range **repulsion** in YN and / or YNN interactions

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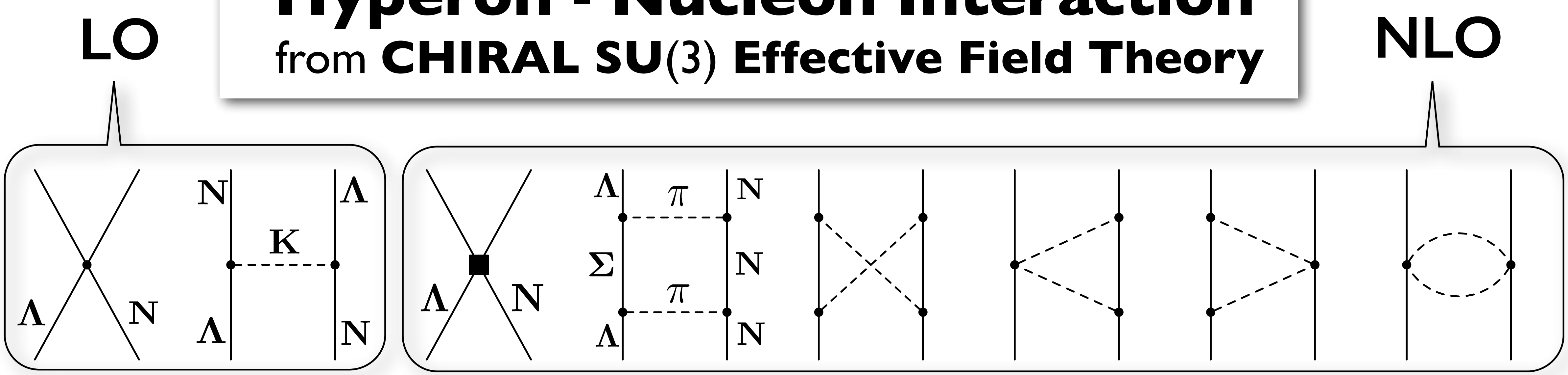
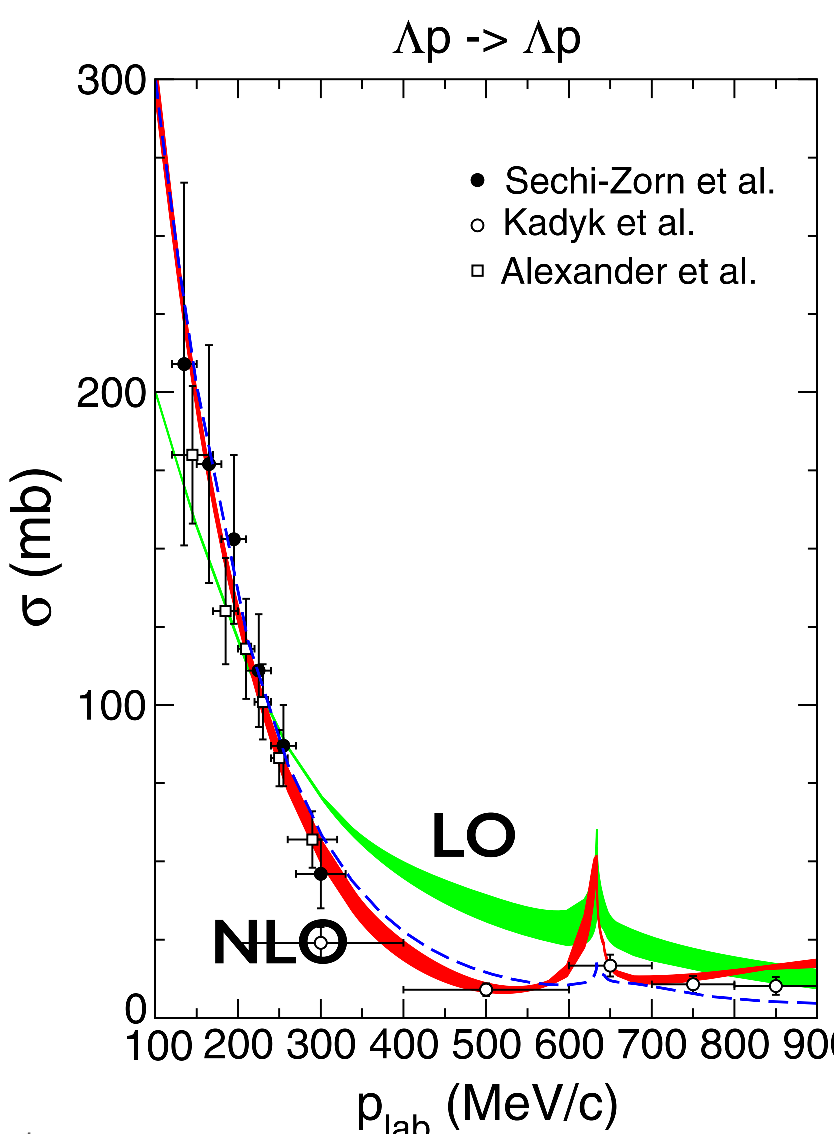
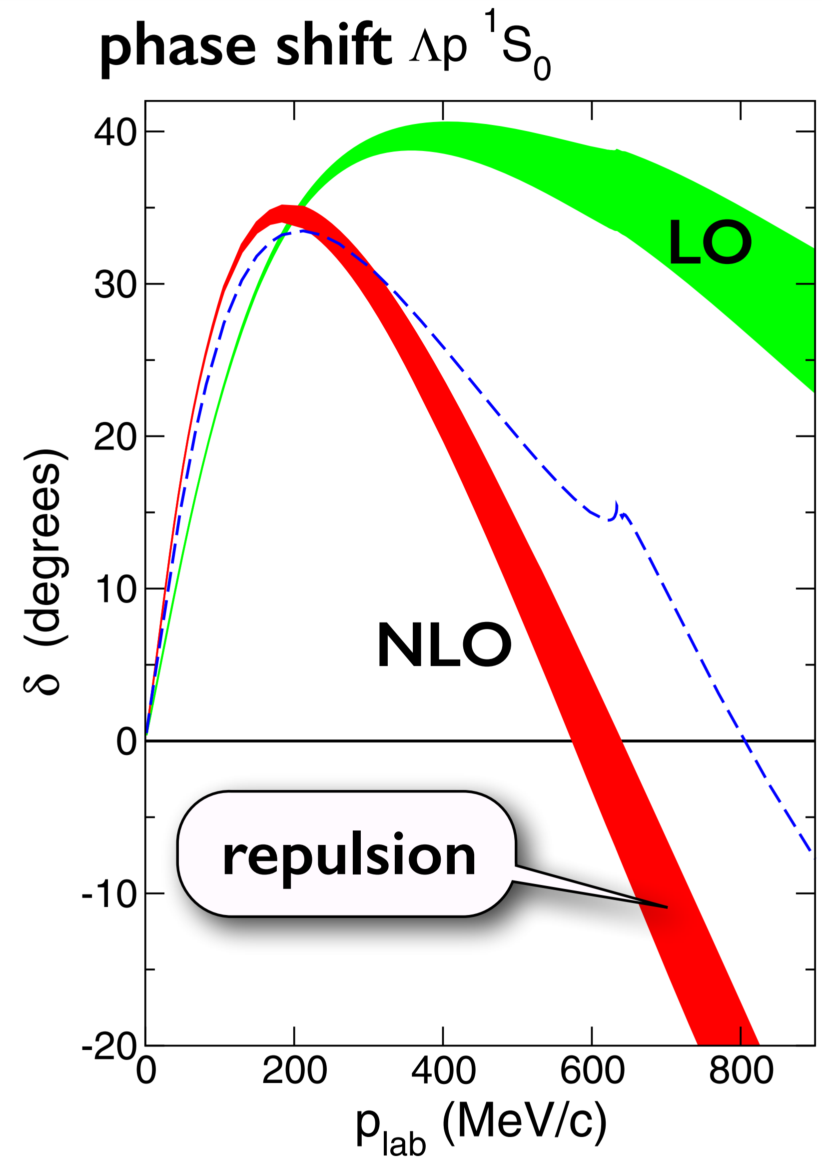
Technische Universität München TUM

Hyperon - Nucleon Interaction
from **CHIRAL SU(3) Effective Field Theory**







- **moderate attraction** at low momenta
  - → relevant for **hypernuclei**
- **strong repulsion** at higher momenta
  - → relevant for **dense baryonic matter**

J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W.W.
Nucl. Phys. A 915 (2013) 24

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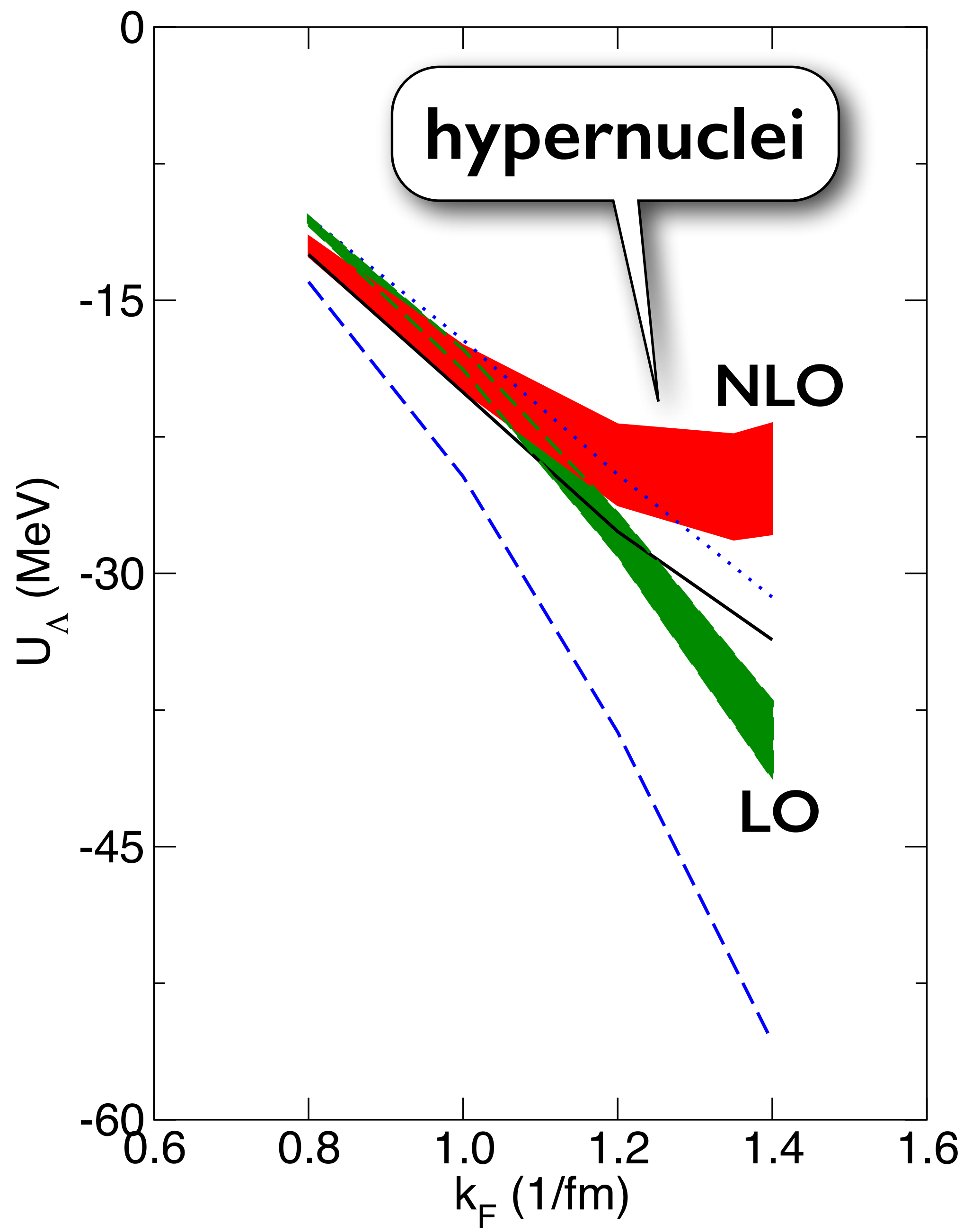
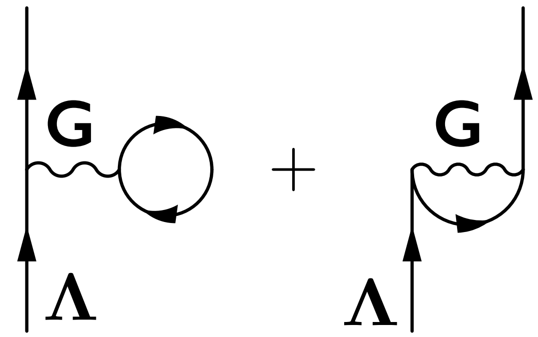
Density dependence of Λ single particle potential

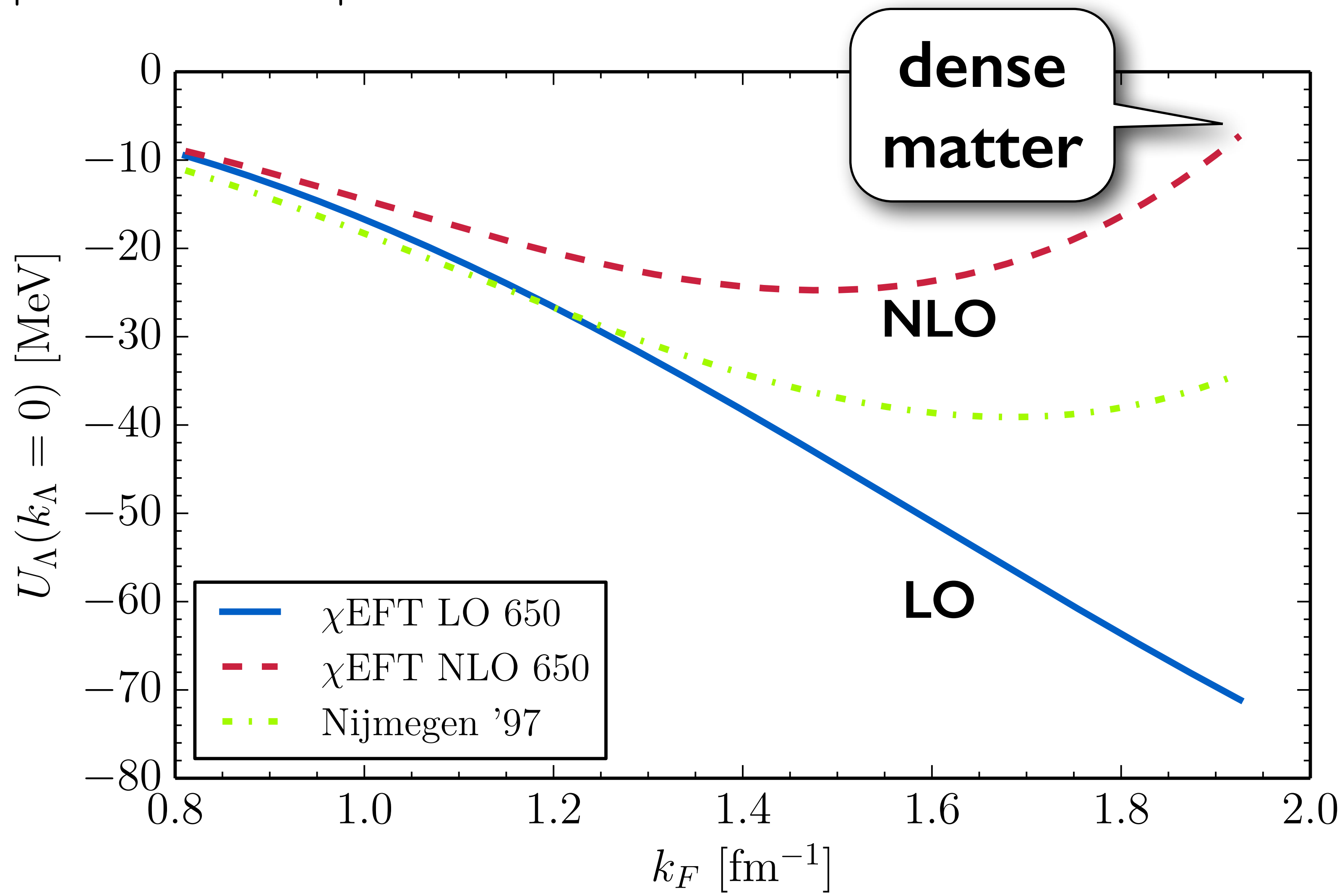
Brueckner calculations
using chiral SU(3) interaction



J. Haidenbauer, U.-G. Meißner, Nucl. Phys. A 936 (2015) 29



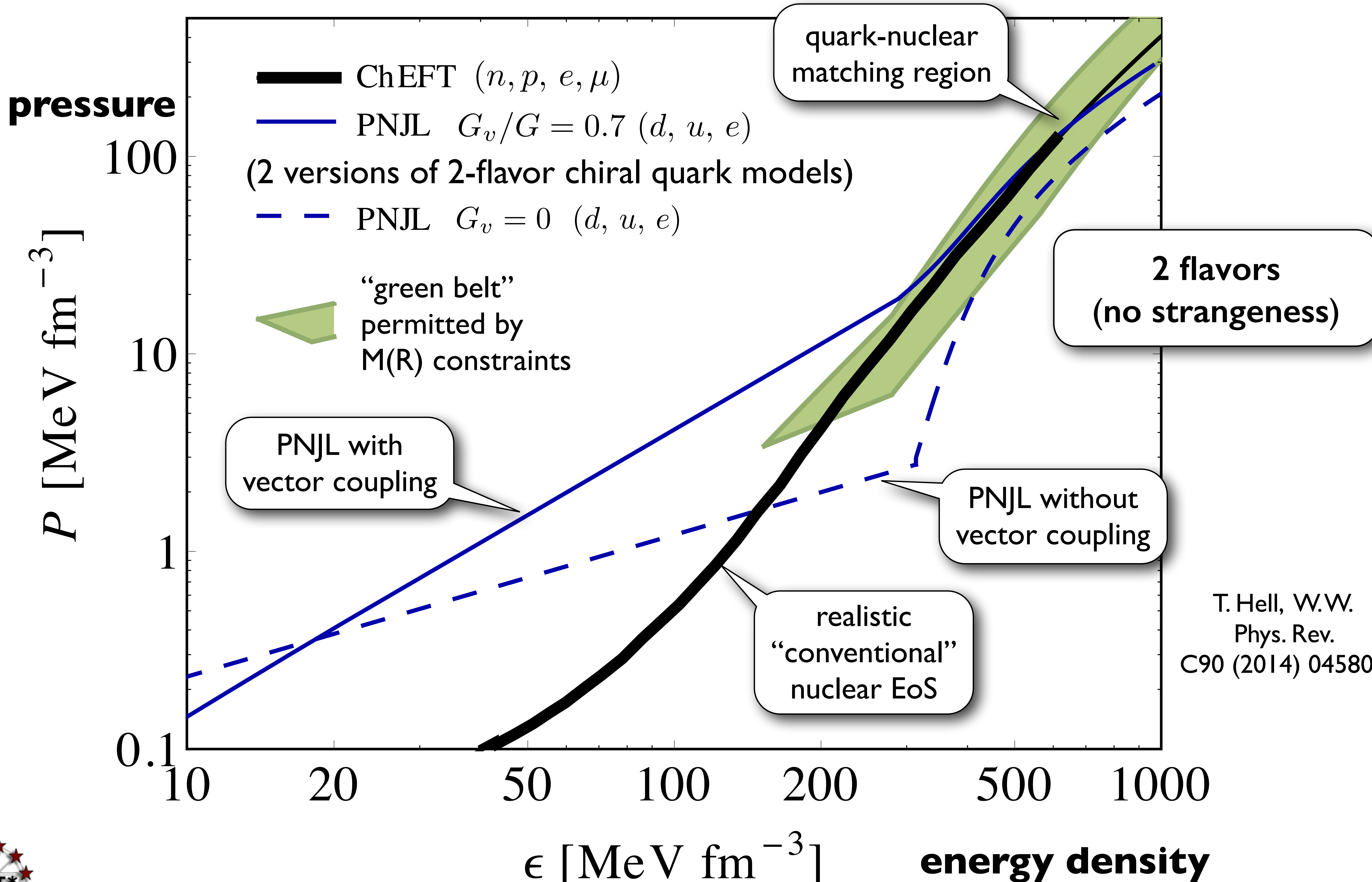
$$G(\omega) = V + V \frac{Q}{e(\omega) + i\epsilon} G(\omega)$$



S. Petschauer, J. Haidenbauer, N. Kaiser, U.-G. Meißner, W.W.
EPJA (2015) ; arXiv:1507.08808 [nucl-th]

Supplementary Materials

NEUTRON STAR Equation of State



T. Hell, W.W.
Phys. Rev.
C90 (2014) 045801

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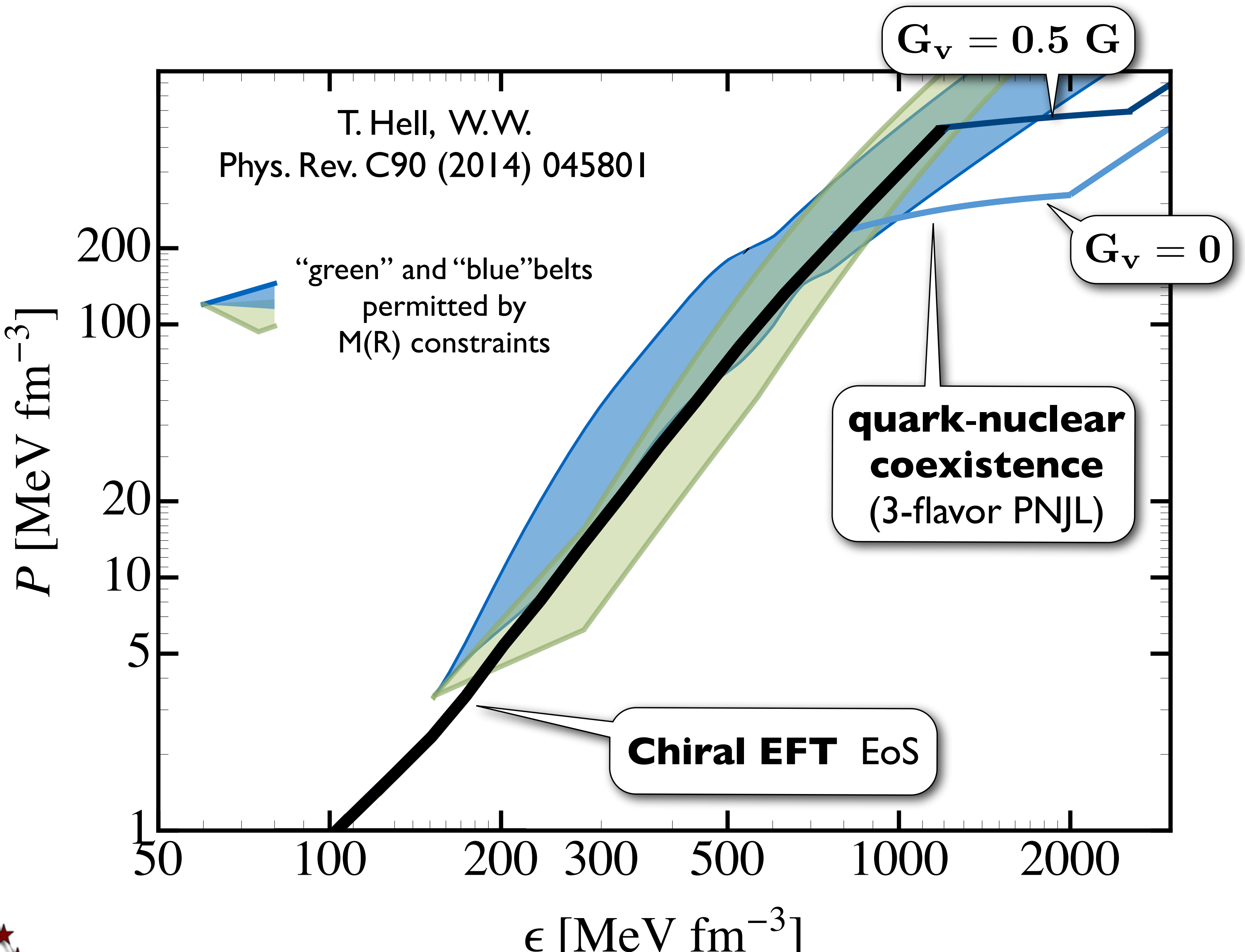
NEUTRON STAR MATTER
Equation of State

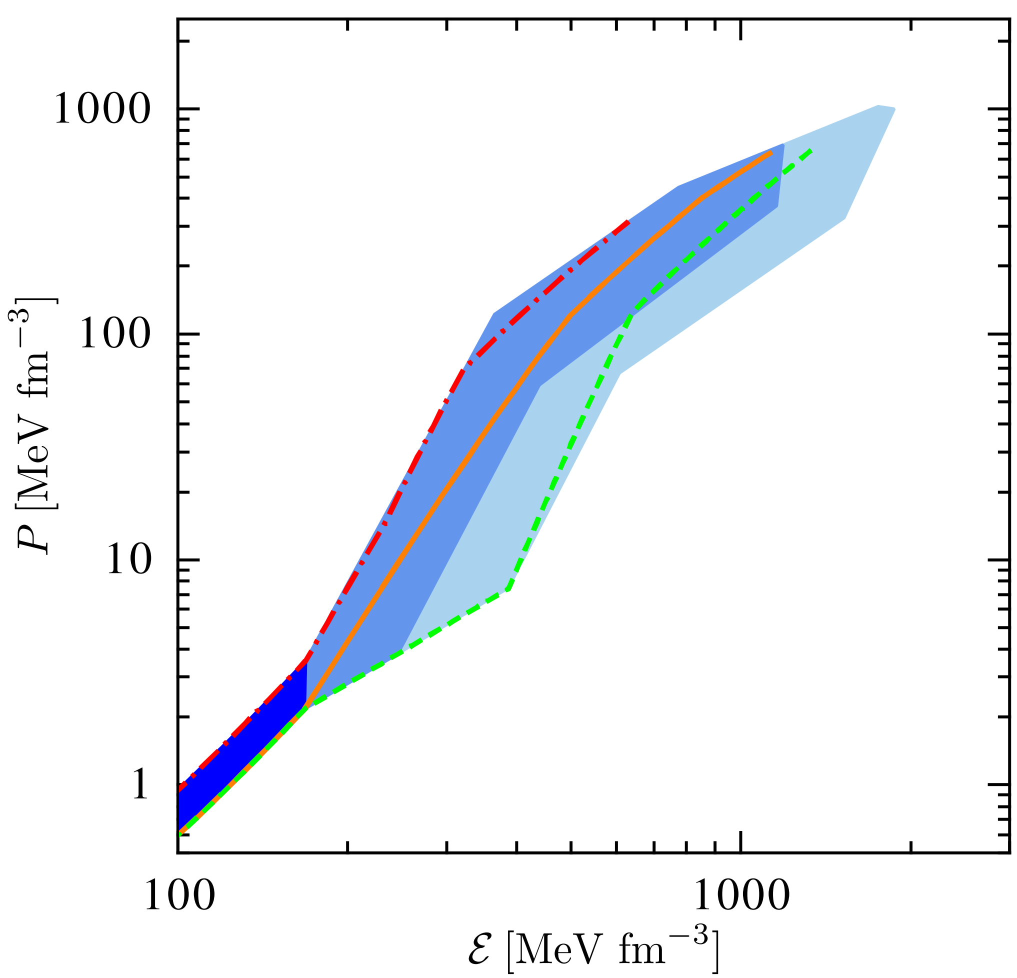
- In-medium **Chiral Effective Field Theory** up to 3 loops
  (reproducing thermodynamics of normal nuclear matter)
- **3-flavor PNJL** model at high densities (incl. **strange** quarks)

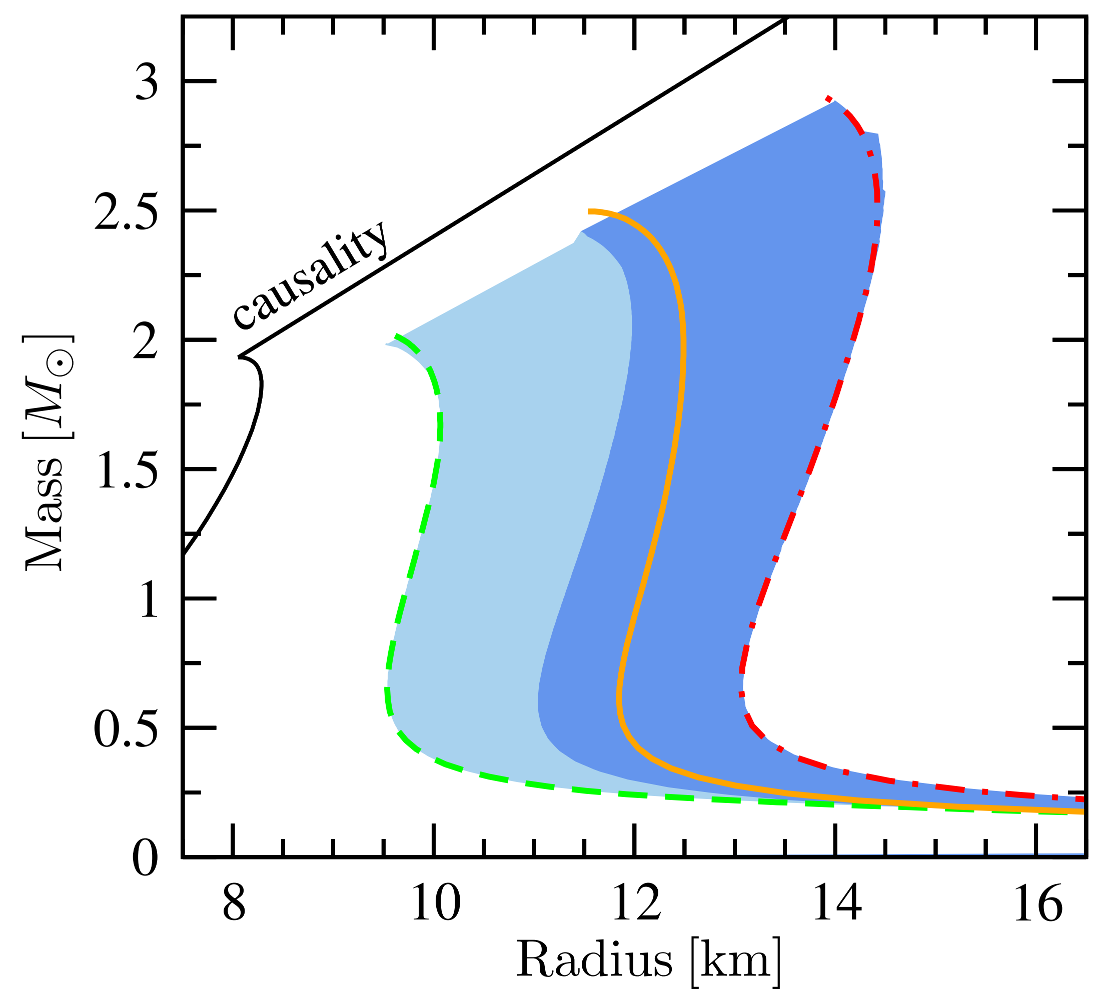


- beta equilibrium
  $\mathbf{n} \leftrightarrow \mathbf{p} + e, \mu$
- charge conservation
- coexistence region:
  Gibbs conditions
- **quark-nuclear**
  coexistence occurs
  (if at all)
  at baryon densities
  $\rho > \mathbf{5}\ \rho_0$

NEUTRON STAR MATTER
Equation of State

- Further independent analysis of new constraints from n-stars
  (Chiral EFT EoS and polytrope extrapolation)





K. Hebeler, J.M. Lattimer, C.J. Pethick, A. Schwenk   Astrophys. J. 773 (2013) 11