BARYONIC MATTER and RENORMALIZATION GROUP

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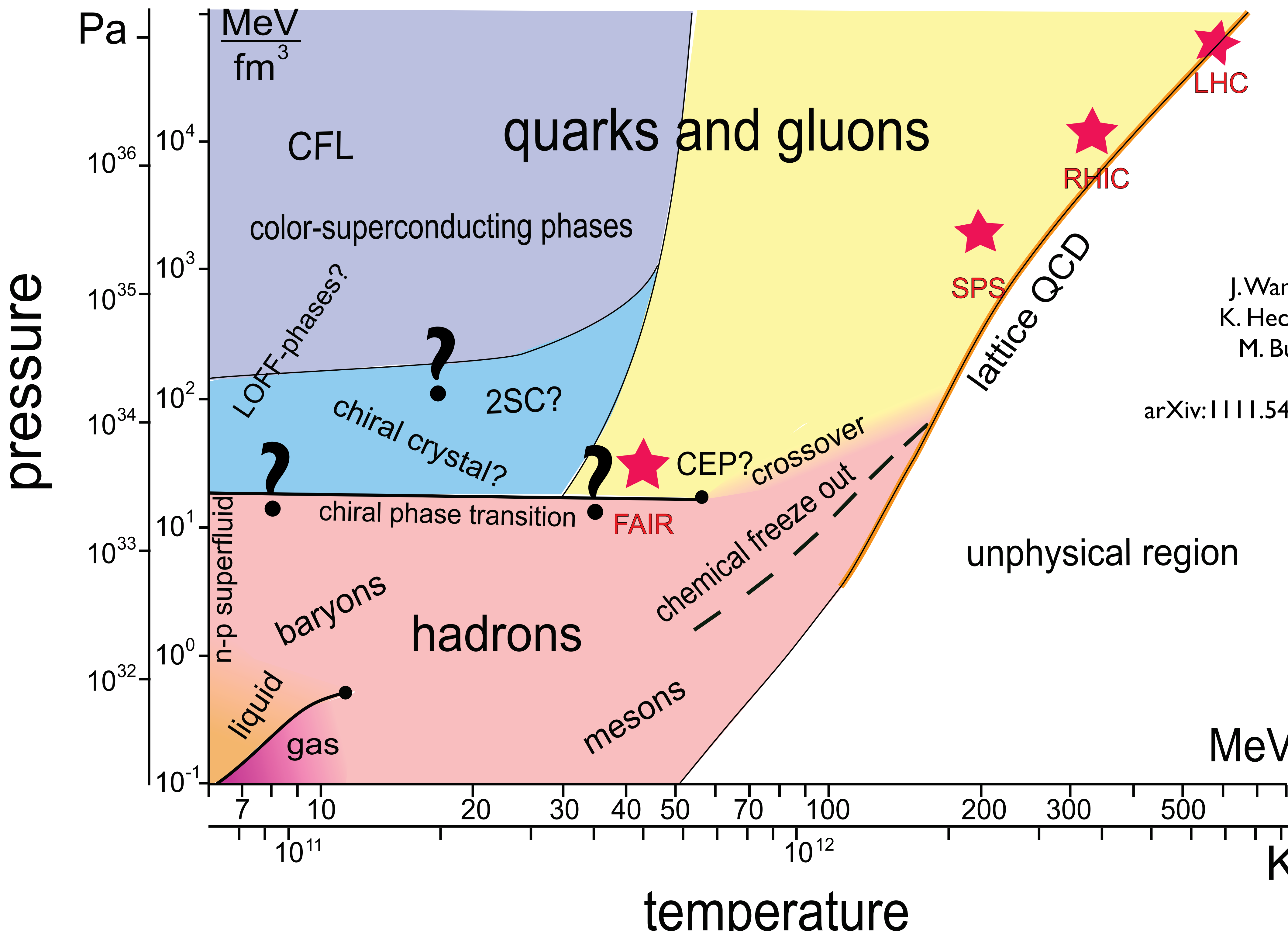
PHYSIK DEPARTMENT

- **Chiral EFT** approaches to **nuclear thermodynamics**
- Beyond mean field:
  Fluctuations and **Functional Renormalization Group**
- **Nuclear matter, neutron matter** and **neutron stars**
- **Pion mass** in the **nuclear medium**
- **Chiral symmetry restoration** ?
  Thermodynamics of the **chiral order parameter**
- Outlook:
  Chiral SU(3) dynamics and **hyper-nuclear matter**

PHASES and STRUCTURES of QCD
- facts and visions -



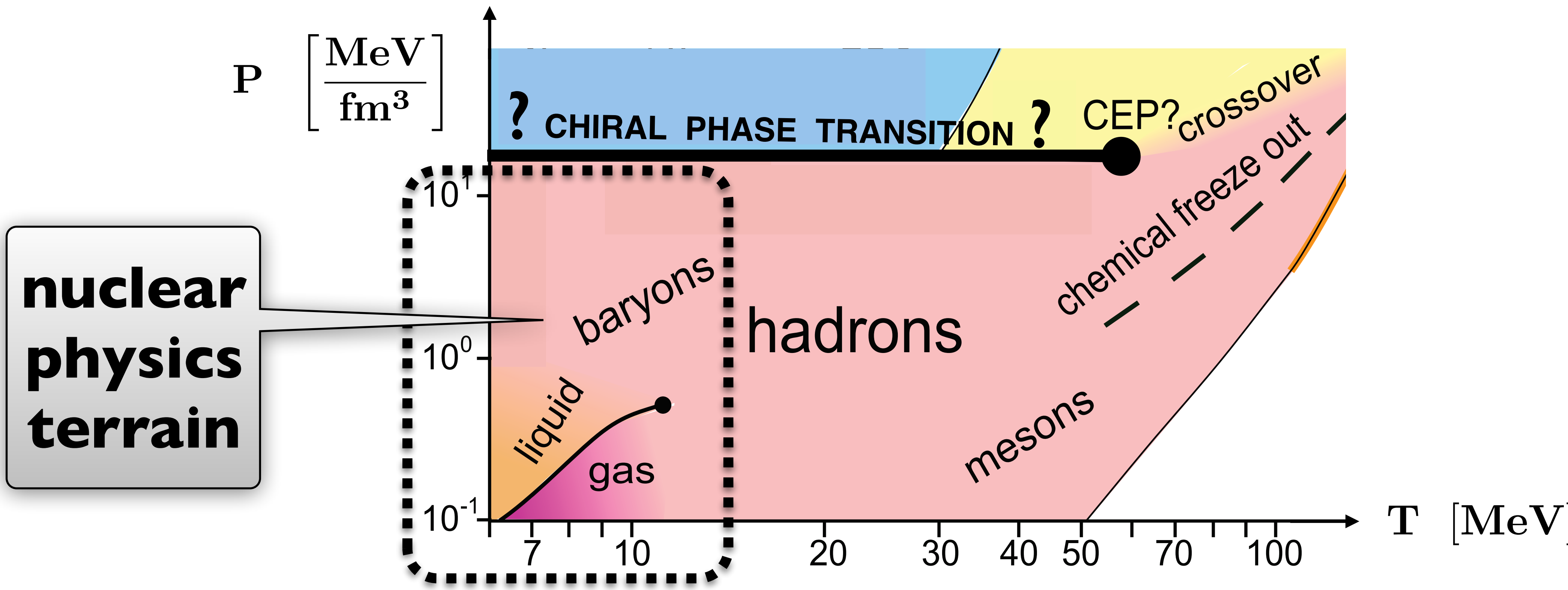
J. Wambach,
K. Heckmann,
M. Buballa

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 beyond mean-field** approximation

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: **E**ffective **F**ield **T**heory of (weakly) interacting **Nambu-Goldstone Bosons** (pions)

- **Chiral EFT** represents QCD at energy/momentum scales

$$\mathbf{Q << 4\pi\, f_\pi \sim 1\, GeV}$$

- **Strategies** at the interface of Low-Energy **QCD** and **nuclear physics** :

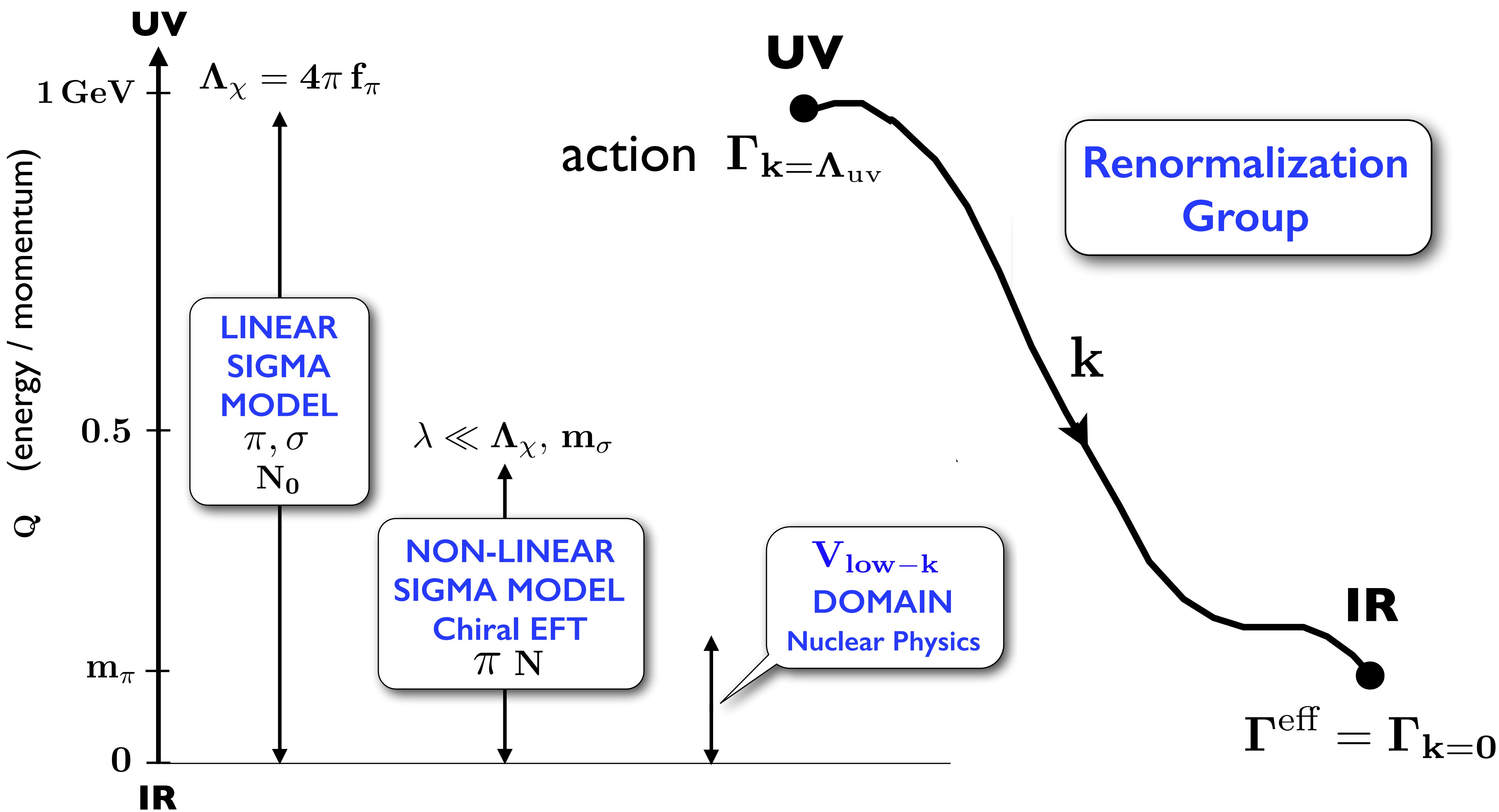
In-medium **C**hiral **P**erturbation **T**heory
based on **non-linear sigma model**
+ nucleons (+ Δ(1230))

expansion of free-energy density
in powers of Fermi momentum

Chiral Nucleon-Meson model
based on **linear sigma model**
(with non-linear chiral potential)

non-perturbative
Renormalization Group approach

SCALES and SCHEMES



CHIRAL EFFECTIVE FIELD THEORY

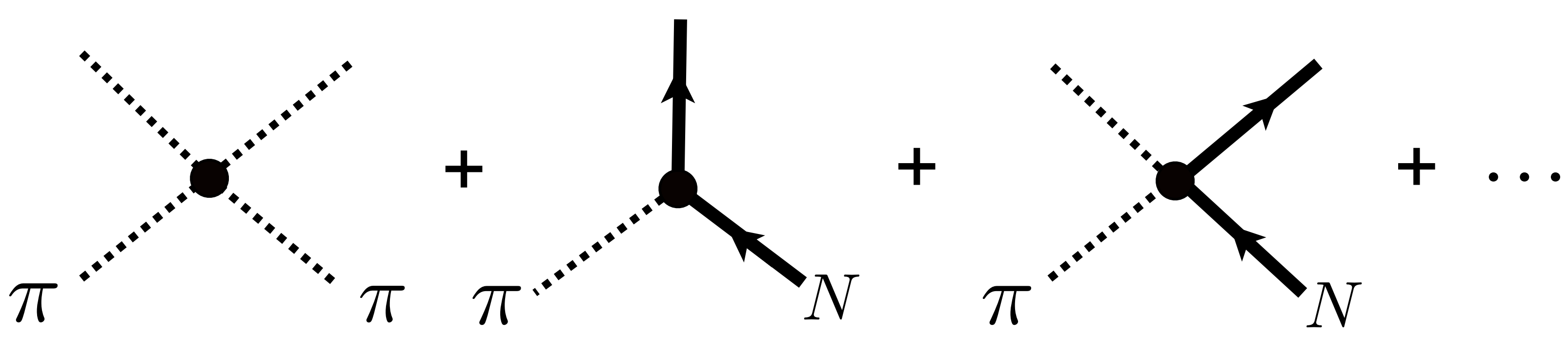
- Realization of **Low-Energy QCD** based on **Non-Linear Sigma Model** plus (heavy) baryons

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

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

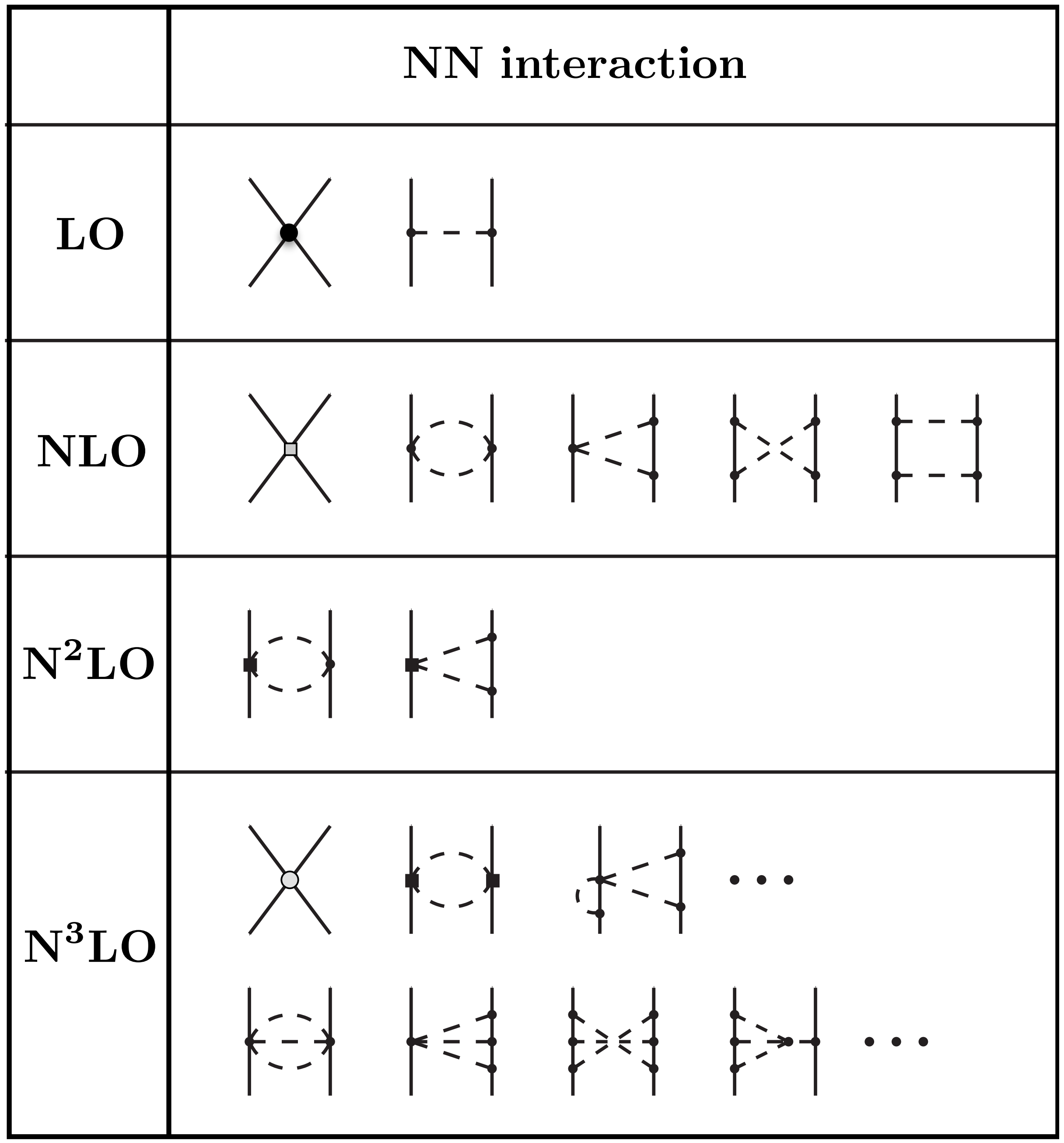
$$U(x) = exp[i\tau_a \pi_a(x)/f_\pi]$$

- Construction of Effective Lagrangian: **Symmetries**



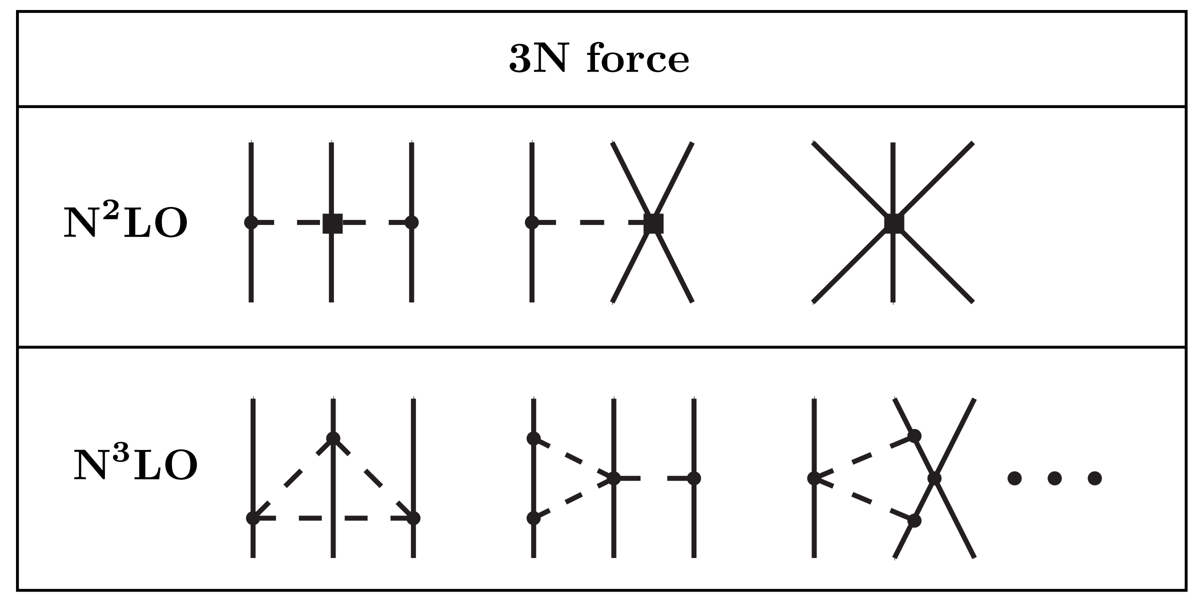
short distance dynamics: **contact terms**

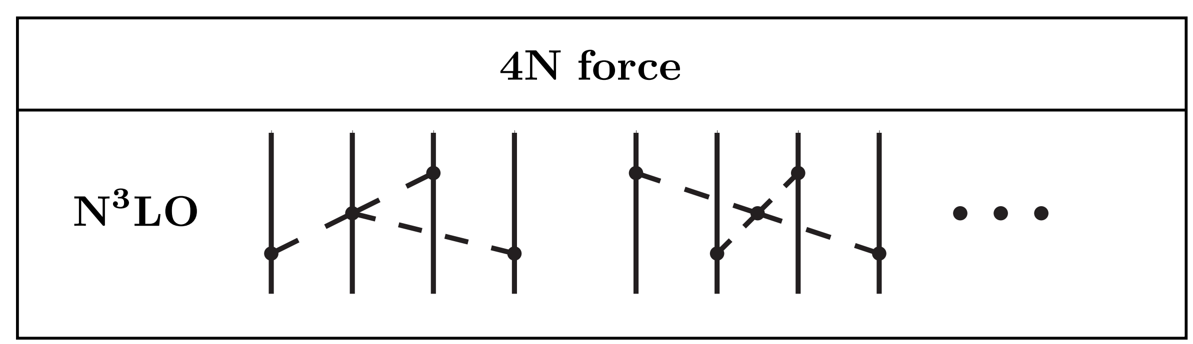
NUCLEAR INTERACTIONS from CHIRAL EFFECTIVE FIELD THEORY



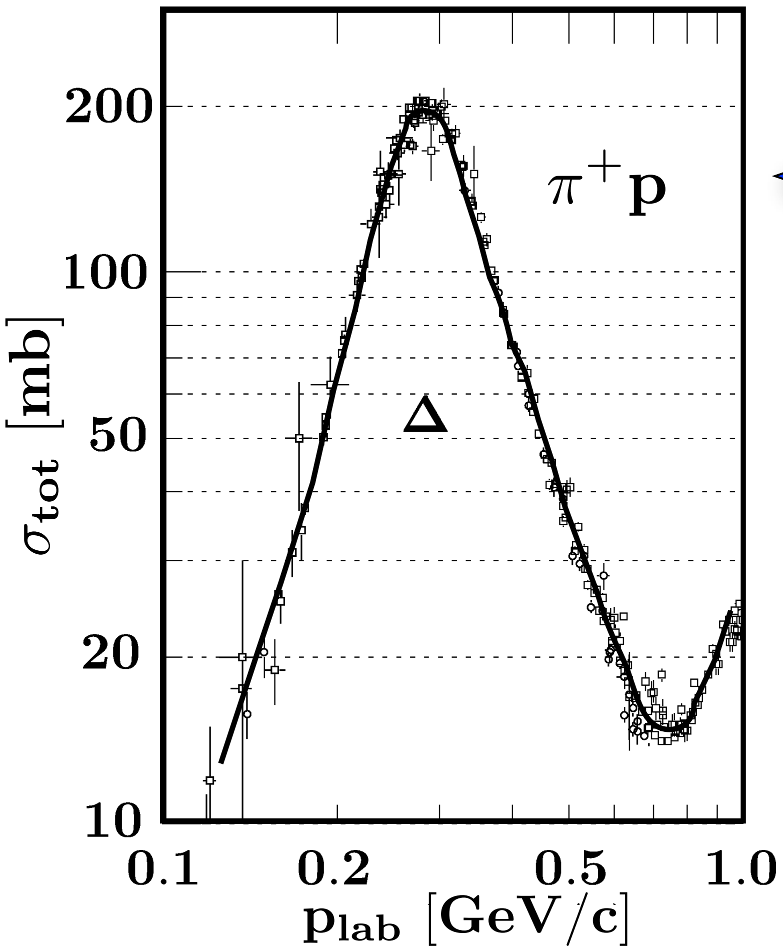
- Systematically organized hierarchy in powers of $\frac{Q}{\Lambda}$

  (Q: momentum, energy, pion mass)





Explicit $\Delta(1230)$ DEGREES of FREEDOM

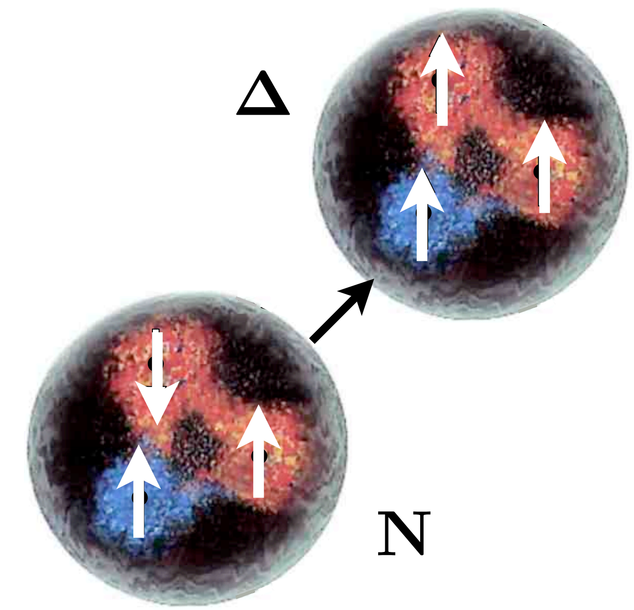


- **Large spin-isospin polarizability** of the **nucleon**
  - Dominance of $\Delta(1230)$ in pion-nucleon scattering

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

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

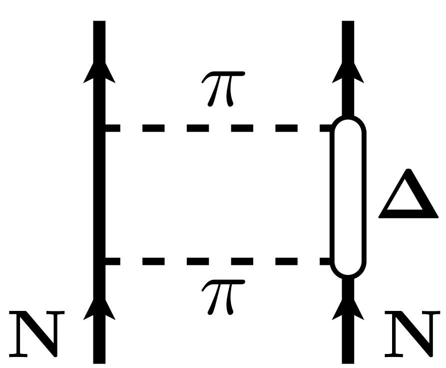
(small scale)



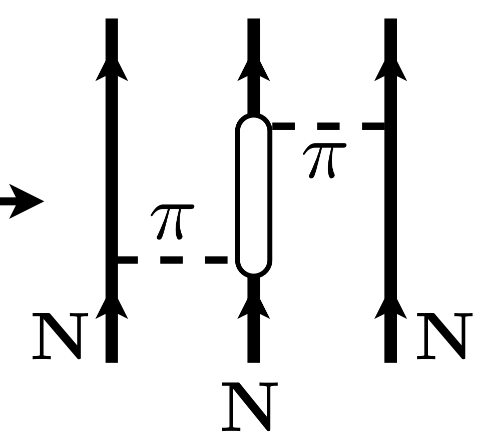
- **Pionic Van der Waals** - type intermediate range central potential

N. Kaiser, S. Gerstendörfer, W.W., NP A637 (1998) 395

N. Kaiser, S. Fritsch, W.W., NP A750 (2005) 259



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

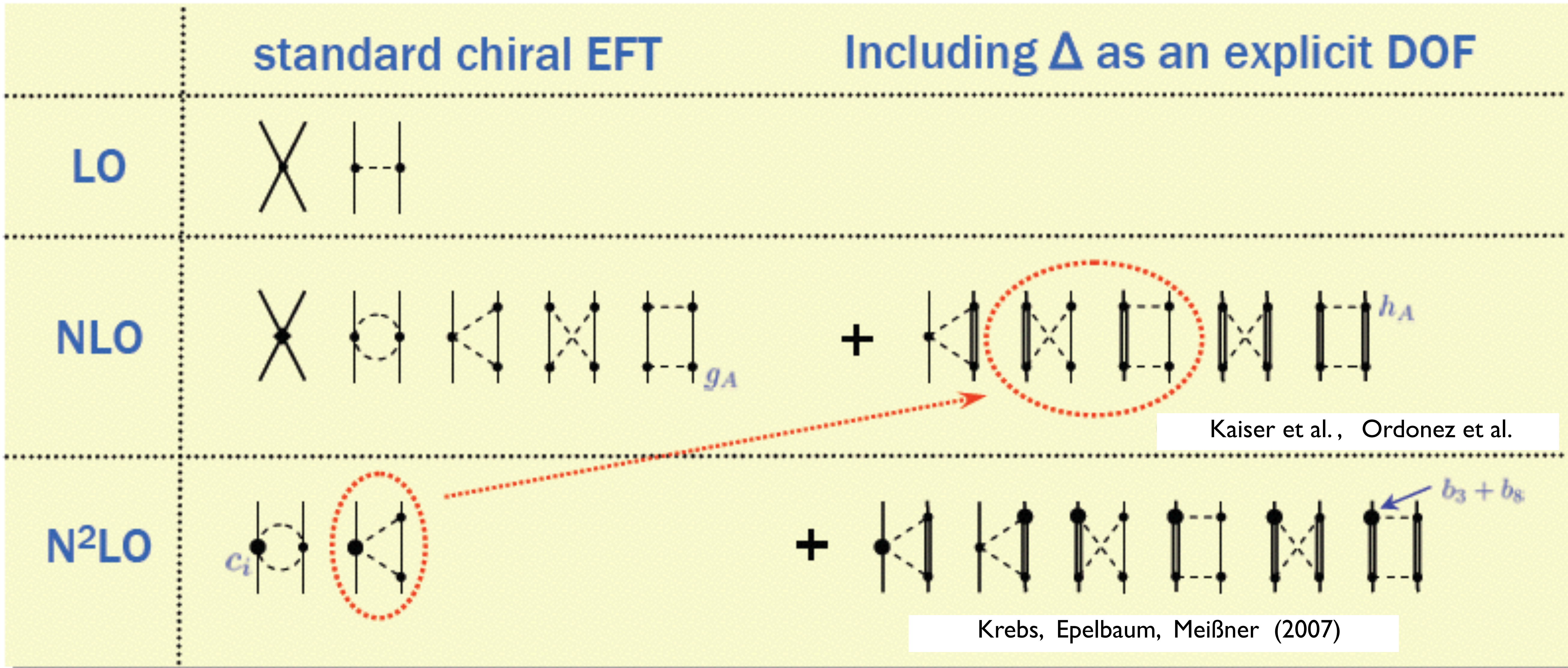


strong 3-body interaction

J. Fujita, H. Miyazawa (1957)

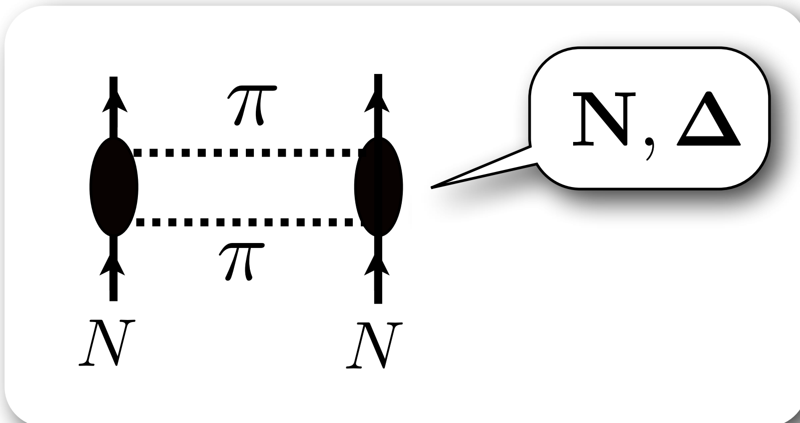
Pieper, Pandharipande, Wiringa, Carlson (2001)

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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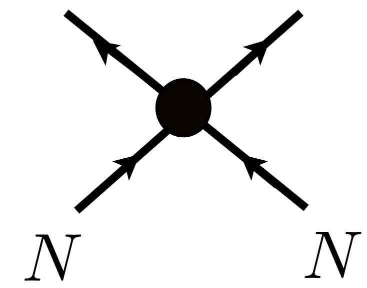


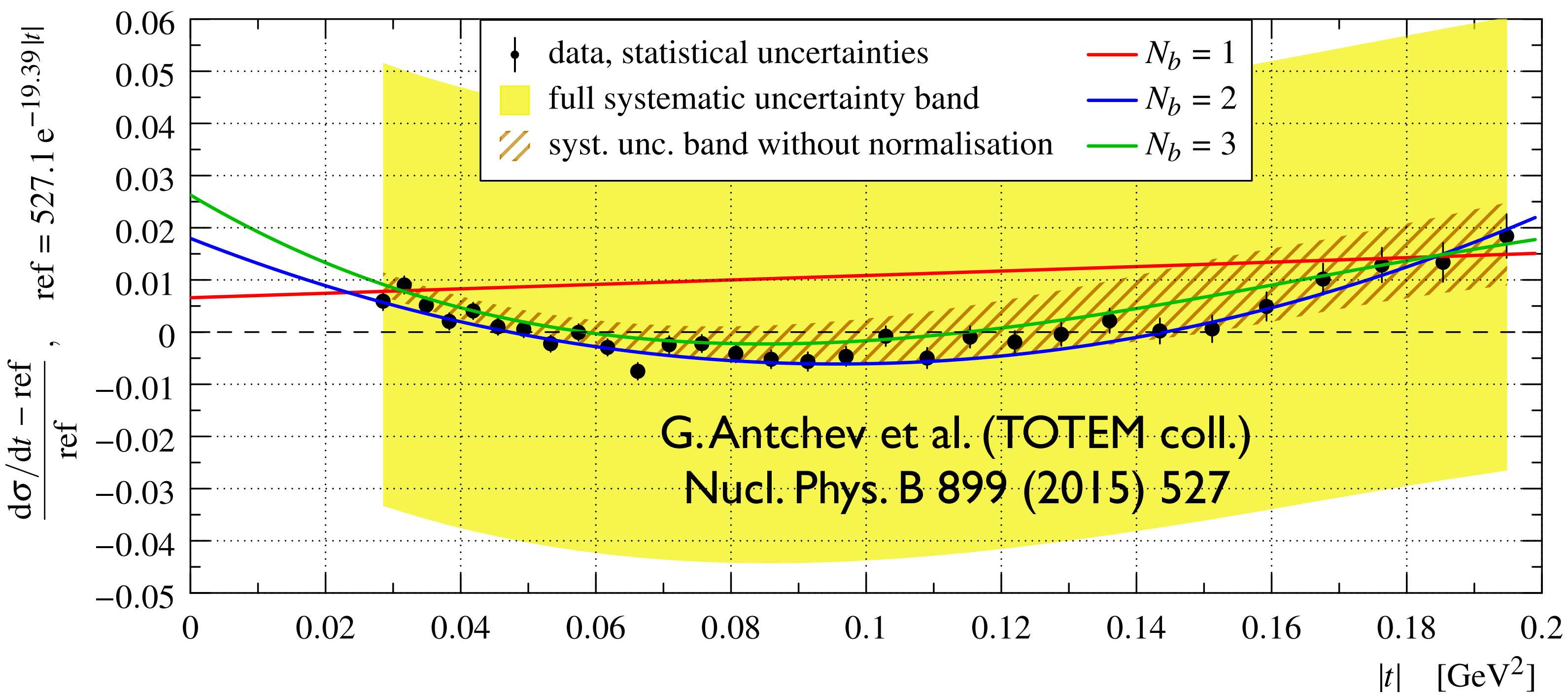
contact terms

+ 3-body forces

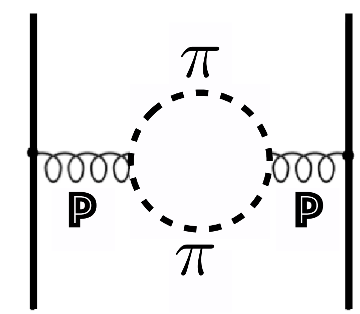
- **Short digression:**

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

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

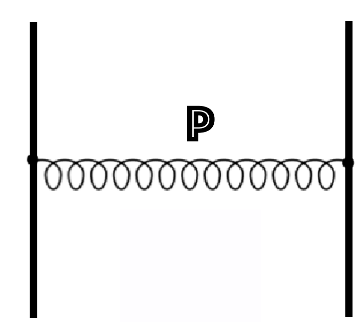


V.A. Khoze, A.D. Martin, M.G. Ryskin
J. Phys. G 42 (2015) 025003



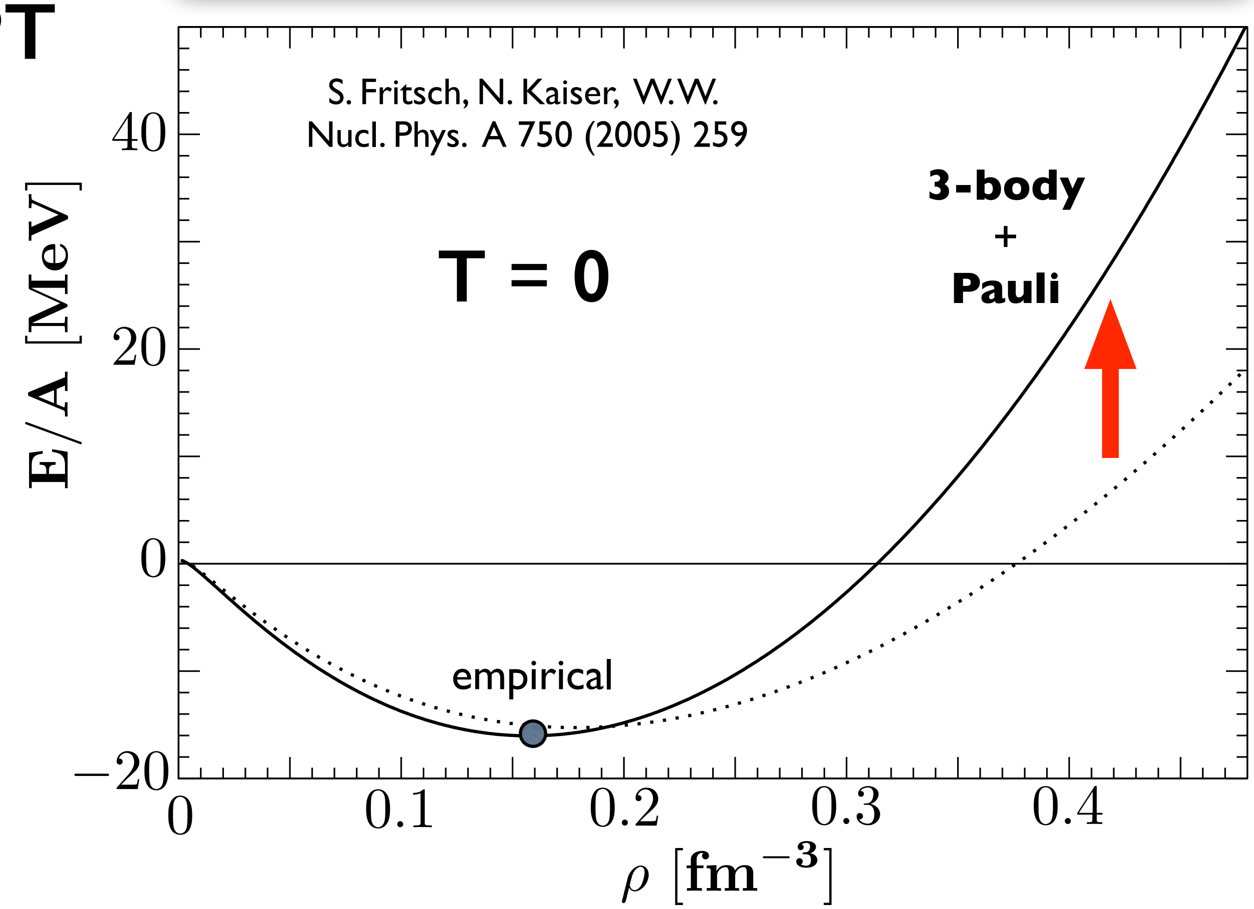
+

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



NUCLEAR MATTER

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



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

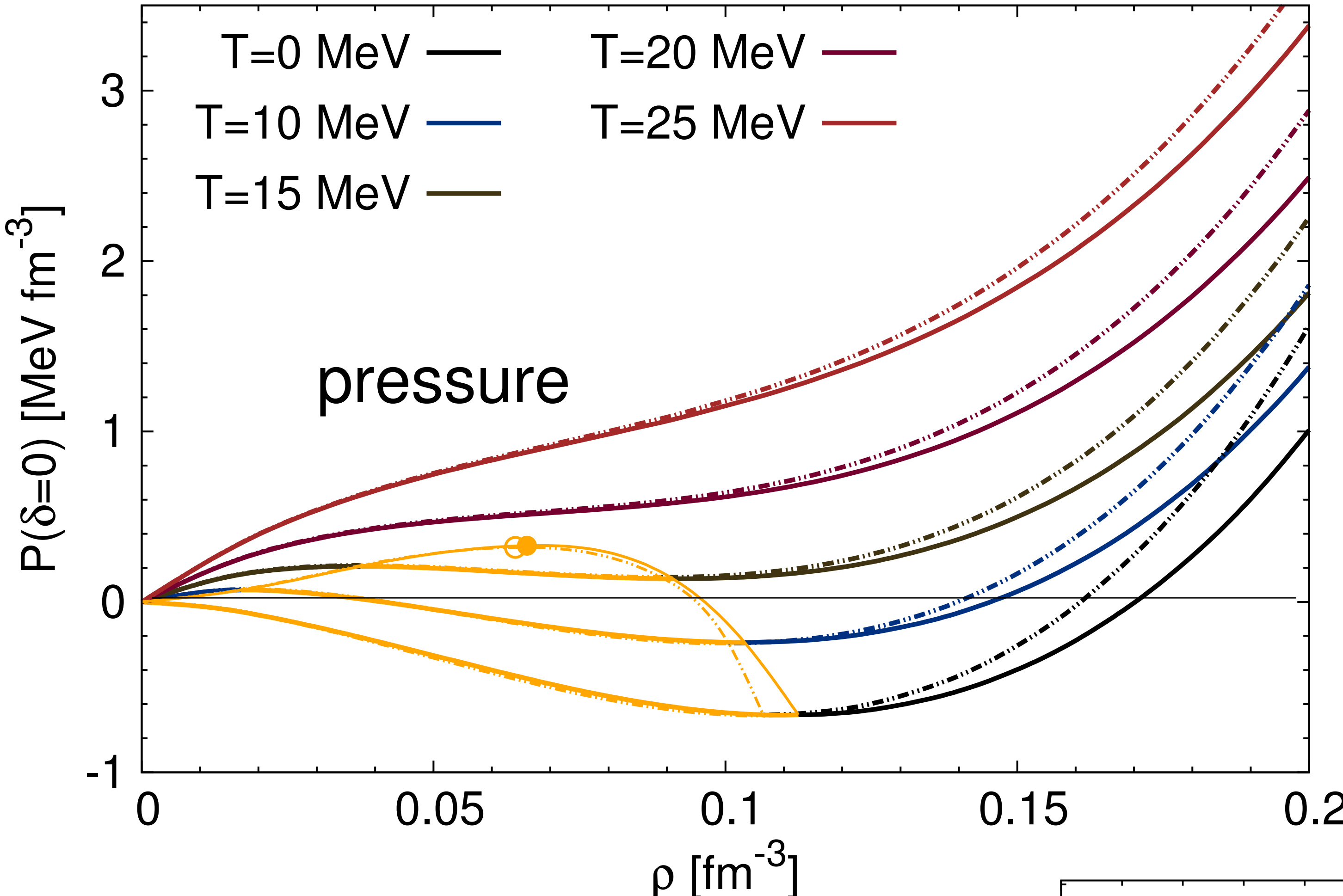
- **Realistic** (complex, momentum dependent) **single-particle potential**
  ... satisfying **Hugenholtz - van Hove** and **Luttinger** theorems (!)
- **Fermi Liquid Theory**:
  Quasiparticle interaction and Landau parameters
- **Nuclear Energy Density Functional** and finite nuclei

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

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. : Physics Reports 621 (2016) 2

Nuclear Thermodynamics from Chiral EFT

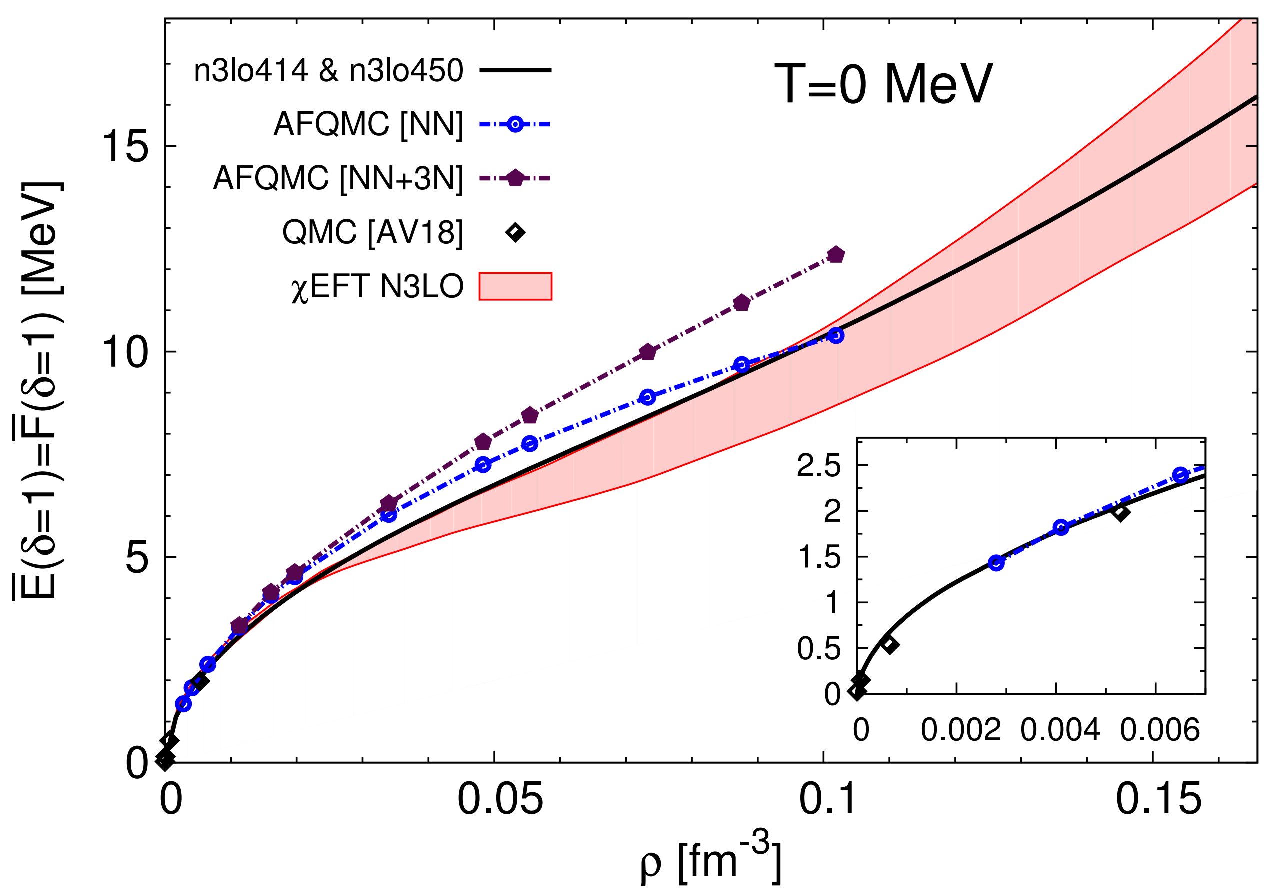


Symmetric nuclear matter: liquid - gas phase transition

C. Wellenhofer, J.W. Holt, N. Kaiser
Phys. Rev. C92 (2016) 015801

Neutron matter

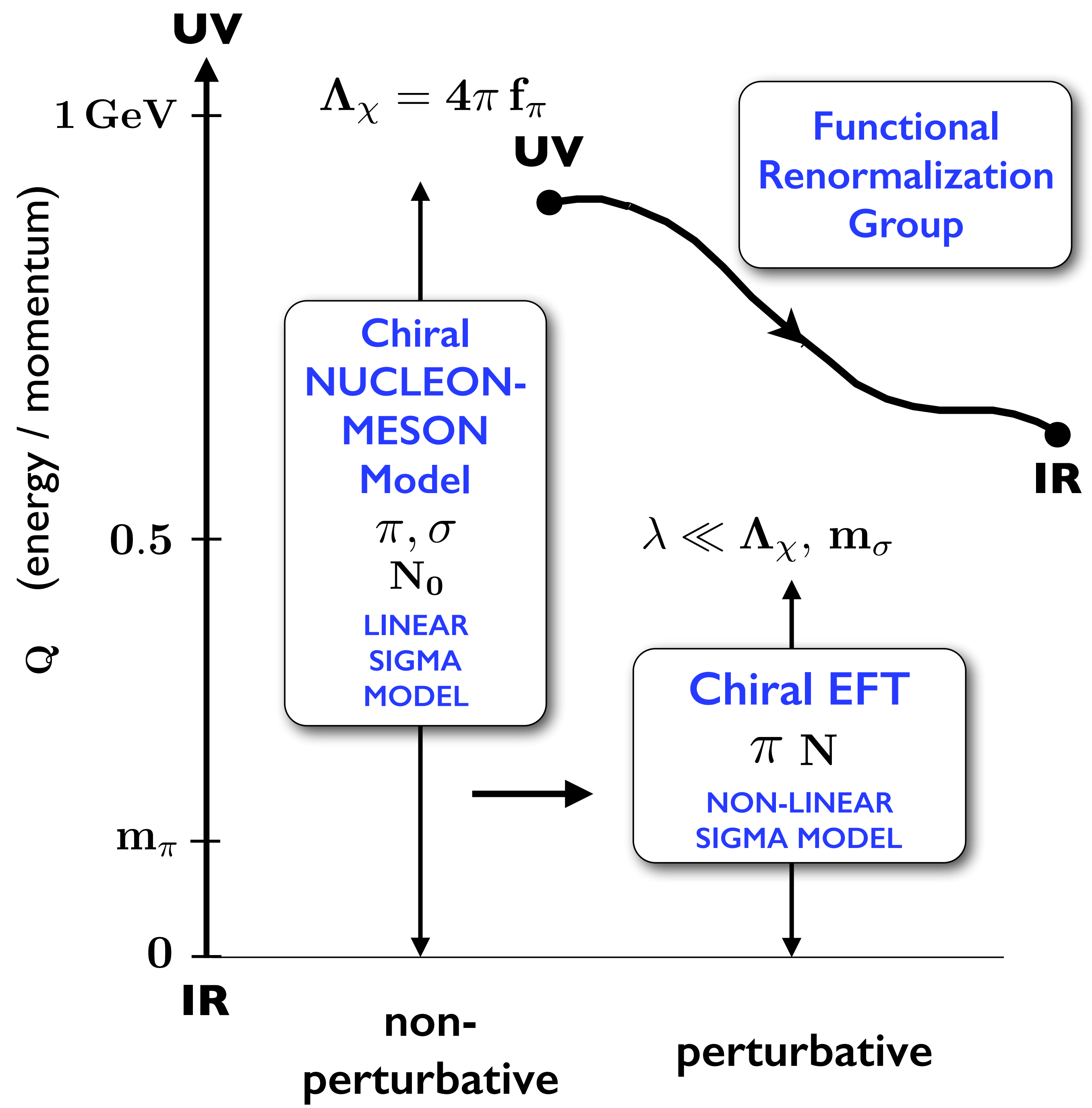
N3LO Chiral EFT
in comparison with
QMC calculations



Chiral Nucleon-Meson Model

and

Functional Renormalization Group



Mesons, Nucleons, Nuclear Matter
and
Functional Renormalization Group

- **Chiral nucleon - meson model** $\mathbf{\Psi} = (\psi_\mathbf{p}, \psi_\mathbf{n})^\top$

$$\mathcal{L} = \bar{\mathbf{\Psi}}\, i\gamma_\mu \partial^\mu \mathbf{\Psi} + \frac{1}{2}\left(\partial_\mu \sigma \partial^\mu \sigma + \partial_\mu \boldsymbol{\pi} \cdot \partial^\mu \boldsymbol{\pi}\right)$$
$$- \bar{\mathbf{\Psi}}\left[g(\sigma + i\gamma_5\, \boldsymbol{\tau} \cdot \boldsymbol{\pi}) + \gamma_\mu\left(g_v\, v^\mu + g_\tau\, \boldsymbol{\rho}^\mu\right)\right]\mathbf{\Psi}$$
$$- \boldsymbol{\mathcal{U}}(\sigma, \pi) + \frac{1}{2}\, m_V^2\left(v_\mu v^\mu + \boldsymbol{\rho}_\mu \boldsymbol{\rho}^\mu\right)$$
$$- \frac{1}{4}\left[F^{(v)}_{\mu\nu} F^{(v)\mu\nu} + \boldsymbol{F}^{(\rho)}_{\mu\nu} \cdot \boldsymbol{F}^{(\rho)\mu\nu}\right]$$

- **Effective potential** $\boldsymbol{\mathcal{U}}(\sigma, \boldsymbol{\pi})$ constructed to reproduce standard nuclear thermodynamics around equilibrium

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

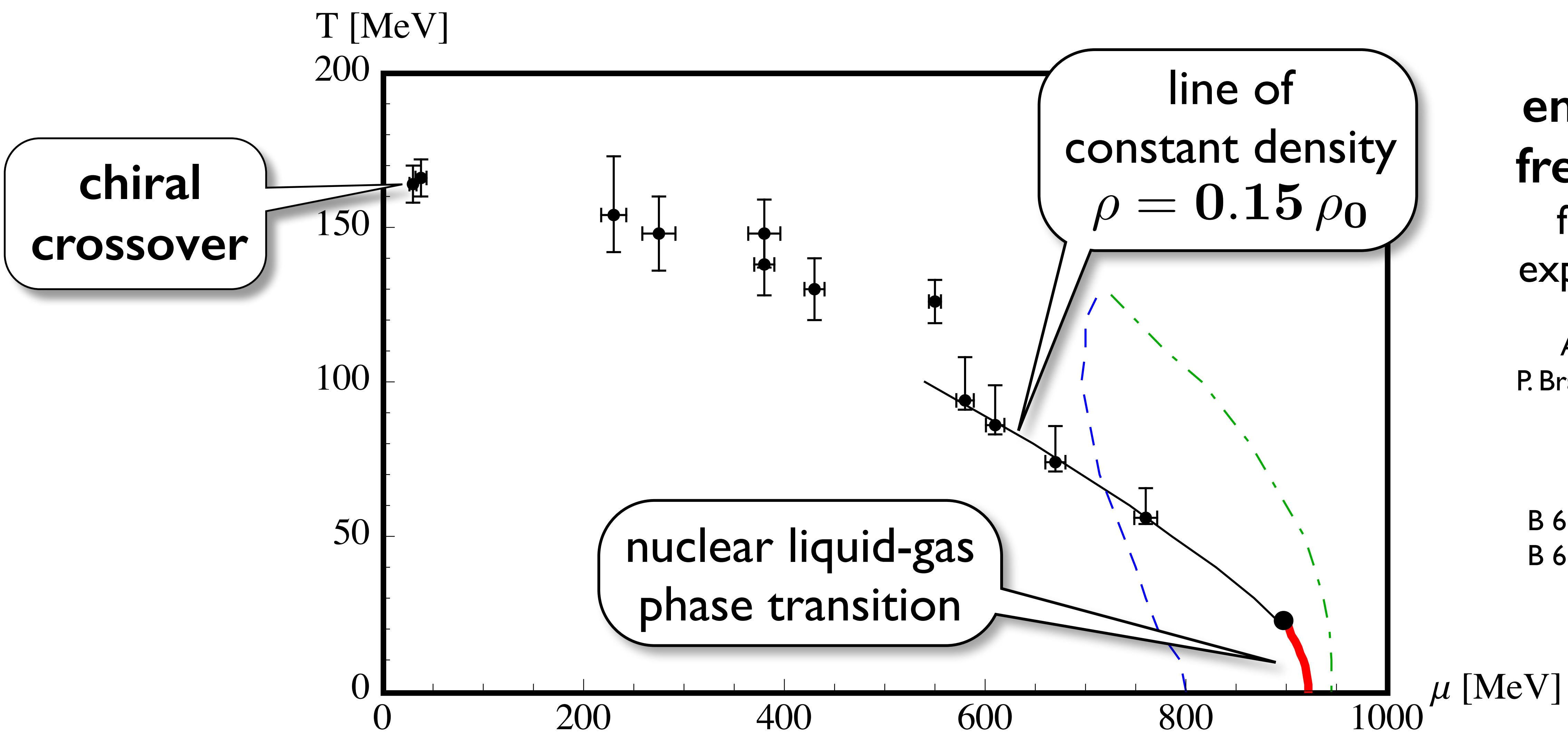
- **Mesonic** and **nucleonic particle-hole** fluctuations treated non-perturbatively using **FRG**

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

- **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 "$\sigma(\mathbf{500})$" 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 $\mu_{\mathbf{n,p}}^{\rm eff} = \mu_{\mathbf{n,p}} - g_v\,v_0 \pm g_\tau\,\rho_0^3$

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

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

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

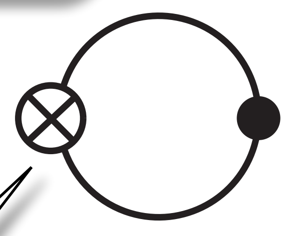
M. Drews, T. Hell, B. Klein, W.W. Phys. Rev. D 88 (2013) 096011

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

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

k-dep. action **full propagator**

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

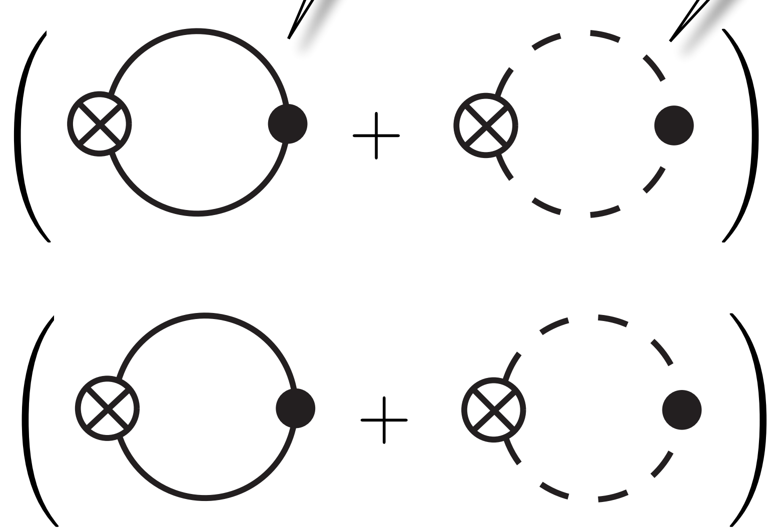


$$= \frac{1}{2} \mathrm{Tr} \frac{k \frac{\partial R_k}{\partial k}}{\Gamma_k^{(2)} + R_k}$$

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

- **Thermodynamics:** **nucleons** **pions**

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



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

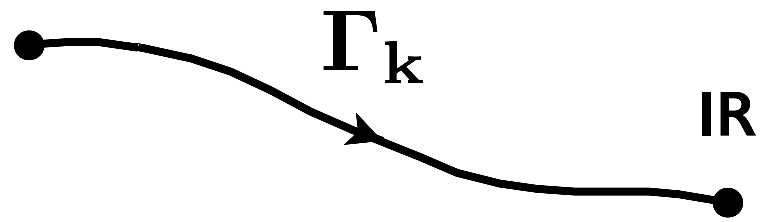
Non-perturbative treatment of

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

Flow equations in practice

UV scale: **action** $\Gamma_{\mathbf{k}=\mathbf{\Lambda}}$

$\mathbf{\Lambda} \simeq \mathbf{\Lambda}_\chi = 4\pi\, \mathrm{f}_\pi$



"full" effective action $\Gamma_{\mathbf{k}=\mathbf{0}}$

- Simplifying assumptions: **derivative expansion & no "running" of Yukawa coupling**

k-dependent potential:

$$k\frac{\partial \mathcal{U}_k}{\partial k}(T, \mu_\mathrm{p}, \mu_\mathrm{n}, \chi, v_0, \rho_0^3) =$$

$$= \frac{k^5}{12\pi^2}\left\{\frac{1+2n_B(E_\sigma)}{E_\sigma} + \frac{3+2n_B(E_\pi)}{E_\pi} - 4\sum_{i=n,p}\frac{1-n_F(E_N-\mu_i^{\mathrm{eff}})}{E_N}\right\}$$

$$E_\pi^2 = k^2 + \mathcal{U}_k'(\chi)\,, \quad E_\sigma^2 = k^2 + \mathcal{U}_k'(\chi) + 2\chi\,\mathcal{U}_k''(\chi)\,, \qquad \chi = \frac{1}{2}(\sigma^2 + \boldsymbol{\pi}^2)$$

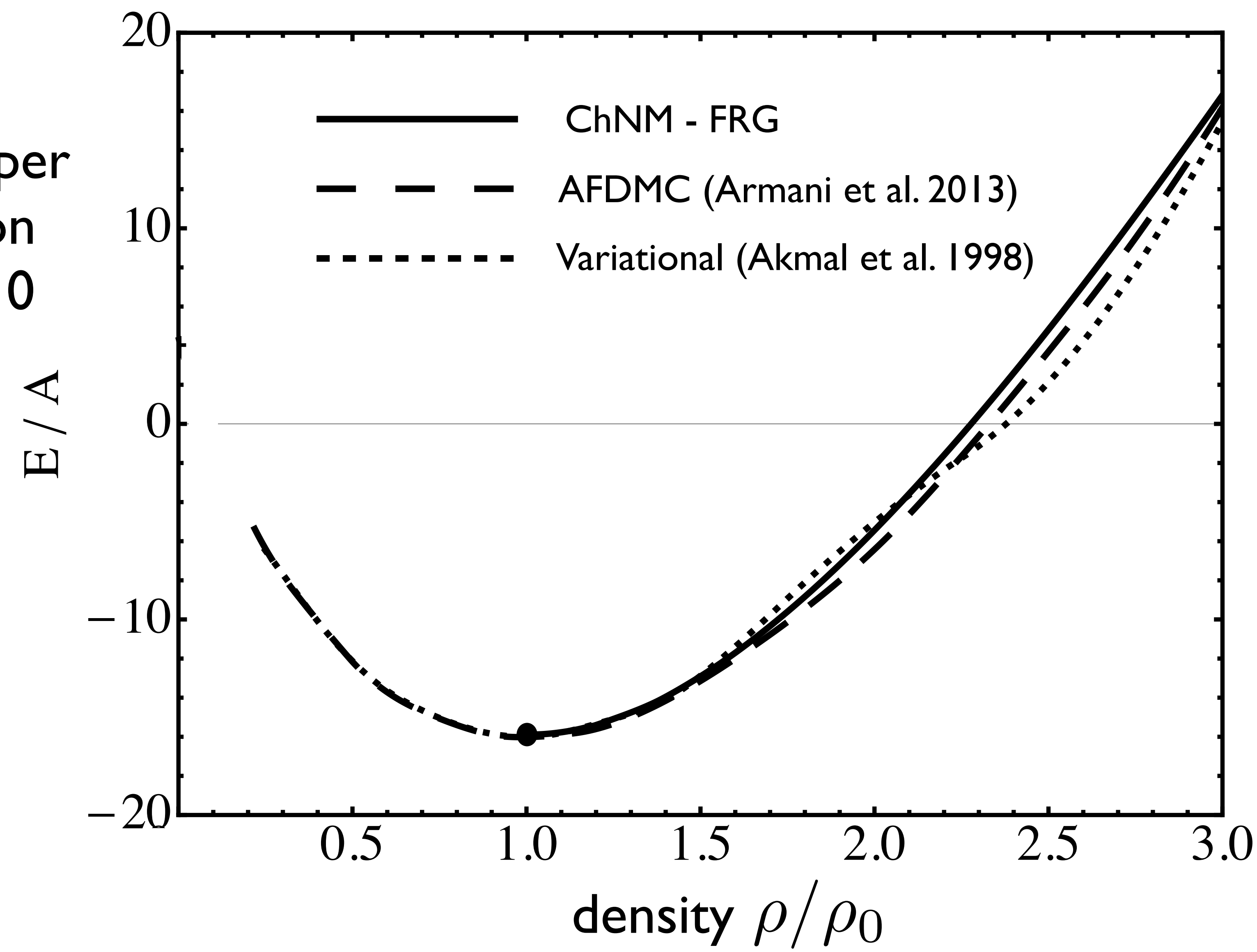
$$\mathcal{U}_k'(\chi) = \frac{\partial \mathcal{U}_k(\chi)}{\partial \chi}\,, \quad E_N^2 = k^2 + 2g^2\chi\,, \qquad n_\mathrm{B}(E) = \frac{1}{\mathrm{e}^{E/T}-1}\,,$$

$$\mu_{\mathbf{n},\mathbf{p}}^{\mathrm{eff}} = \mu_{\mathbf{n},\mathbf{p}} - g_v\, v_0 \pm g_\tau\, \rho_0^3 \qquad n_\mathrm{F}(E) = \frac{1}{\mathrm{e}^{E/T}+1}\,.$$

. . . 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



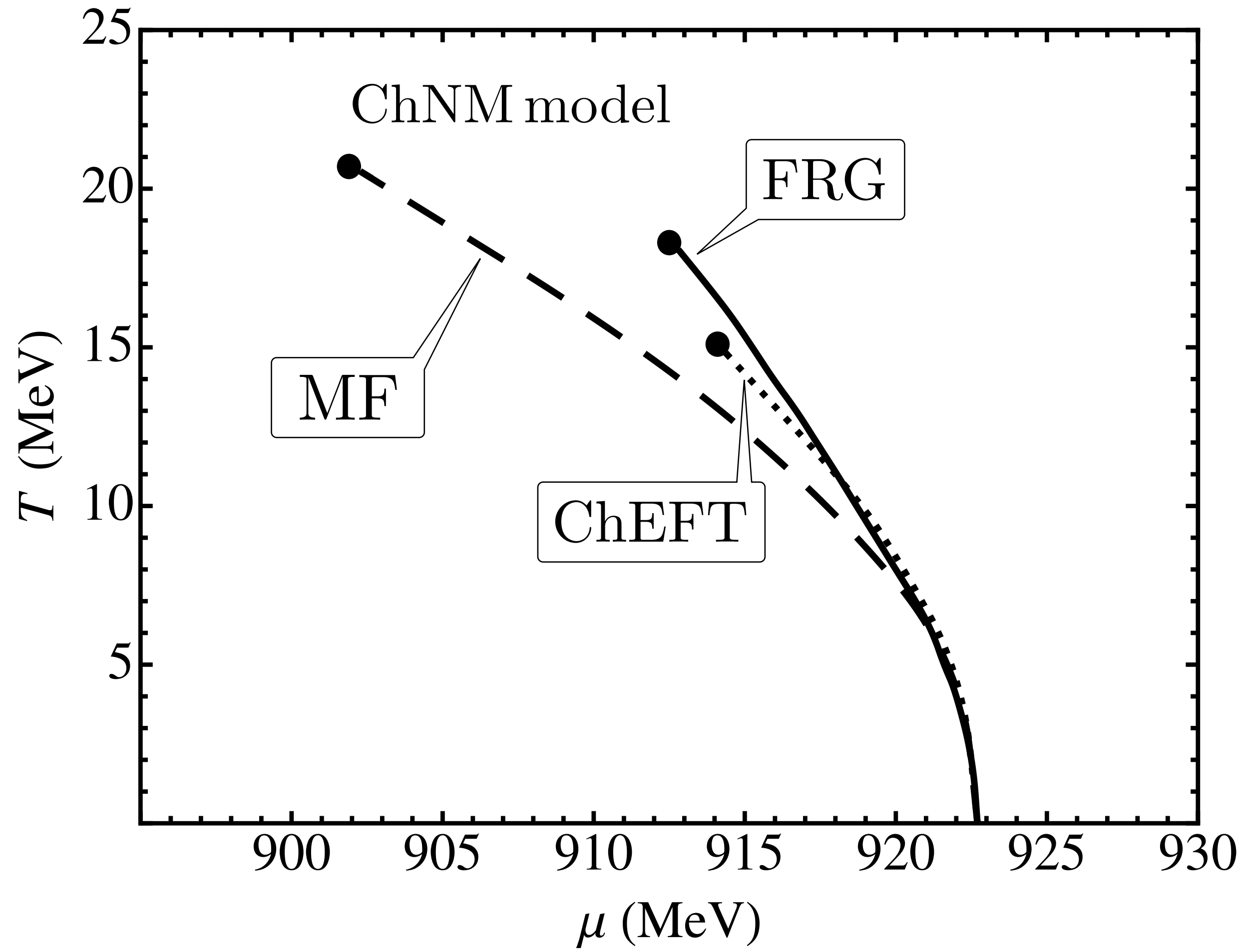
M. Drews, T. Hell, B. Klein, W.W.
Phys. Rev. D 88 (2013) 096011

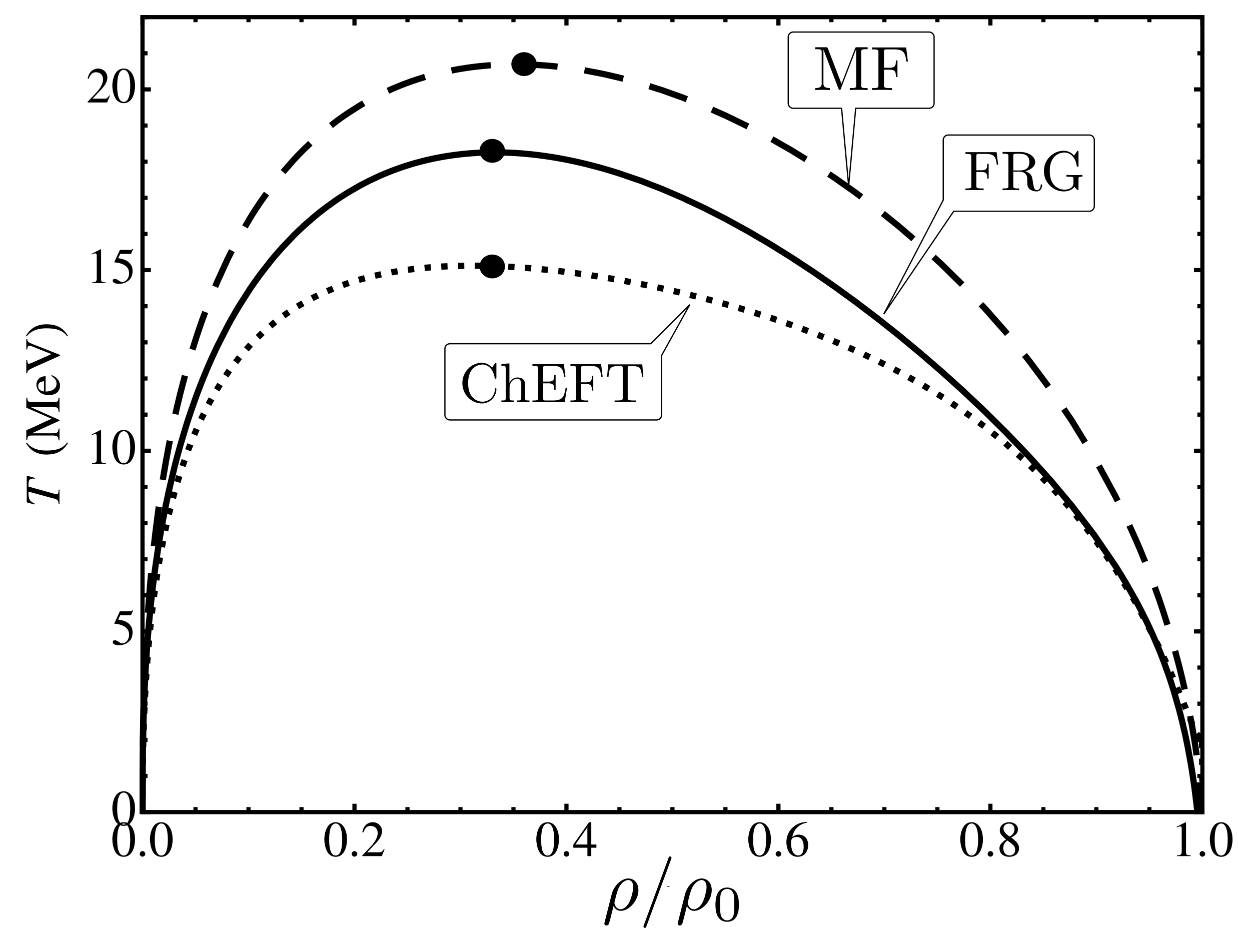
- **FRG-Nucleon-Meson-Model** (solid curve) in comparison with “ab-initio” many-body (variational and QMC) computations

Results : Liquid - Gas Transition

- symmetric nuclear matter -

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

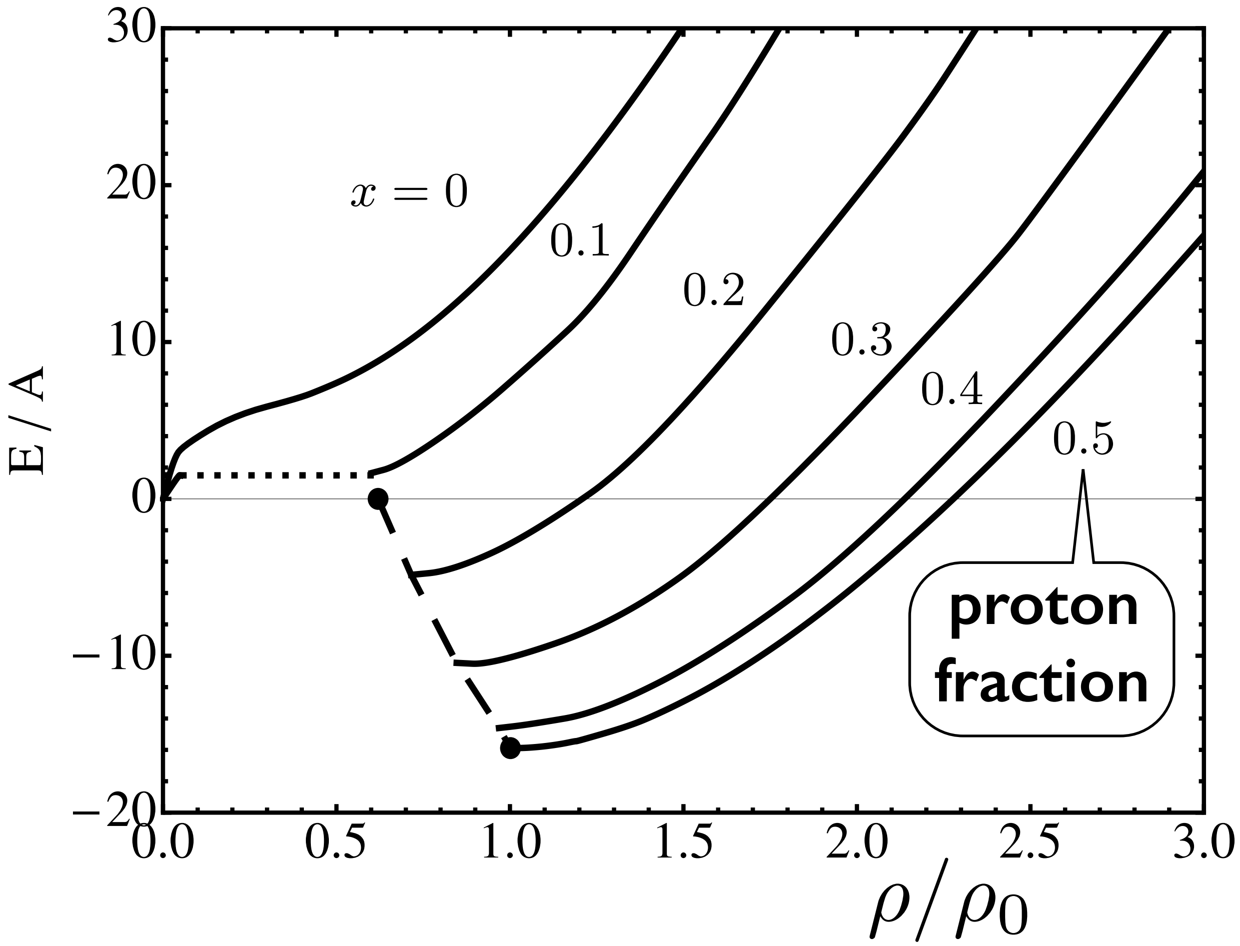




- note similarity between **(perturbative) in-medium ChEFT** and **(non-perturbative) FRG** results

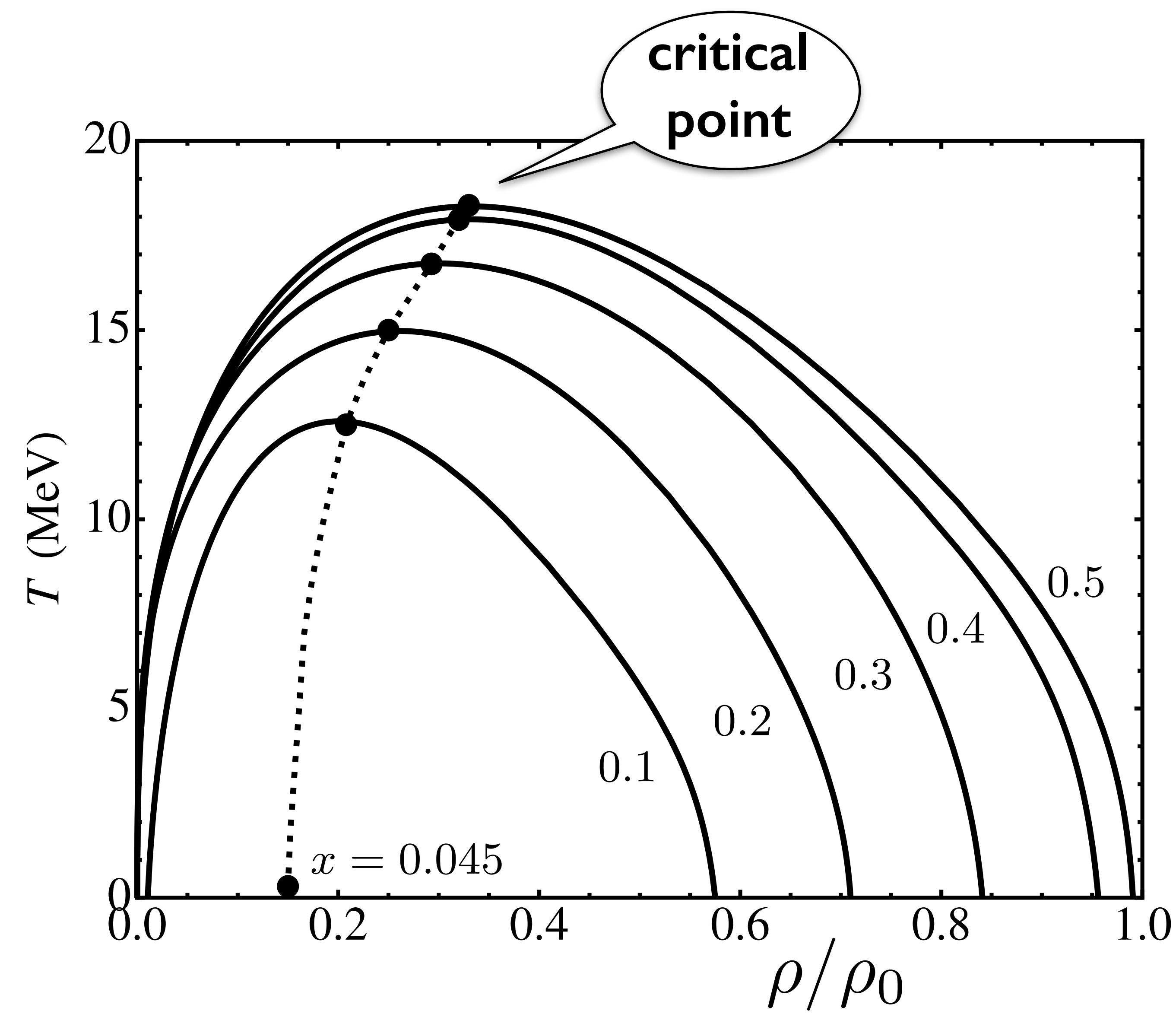
Asymmetric nuclear matter in the chiral FRG approach

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



Liquid-gas phase transition:

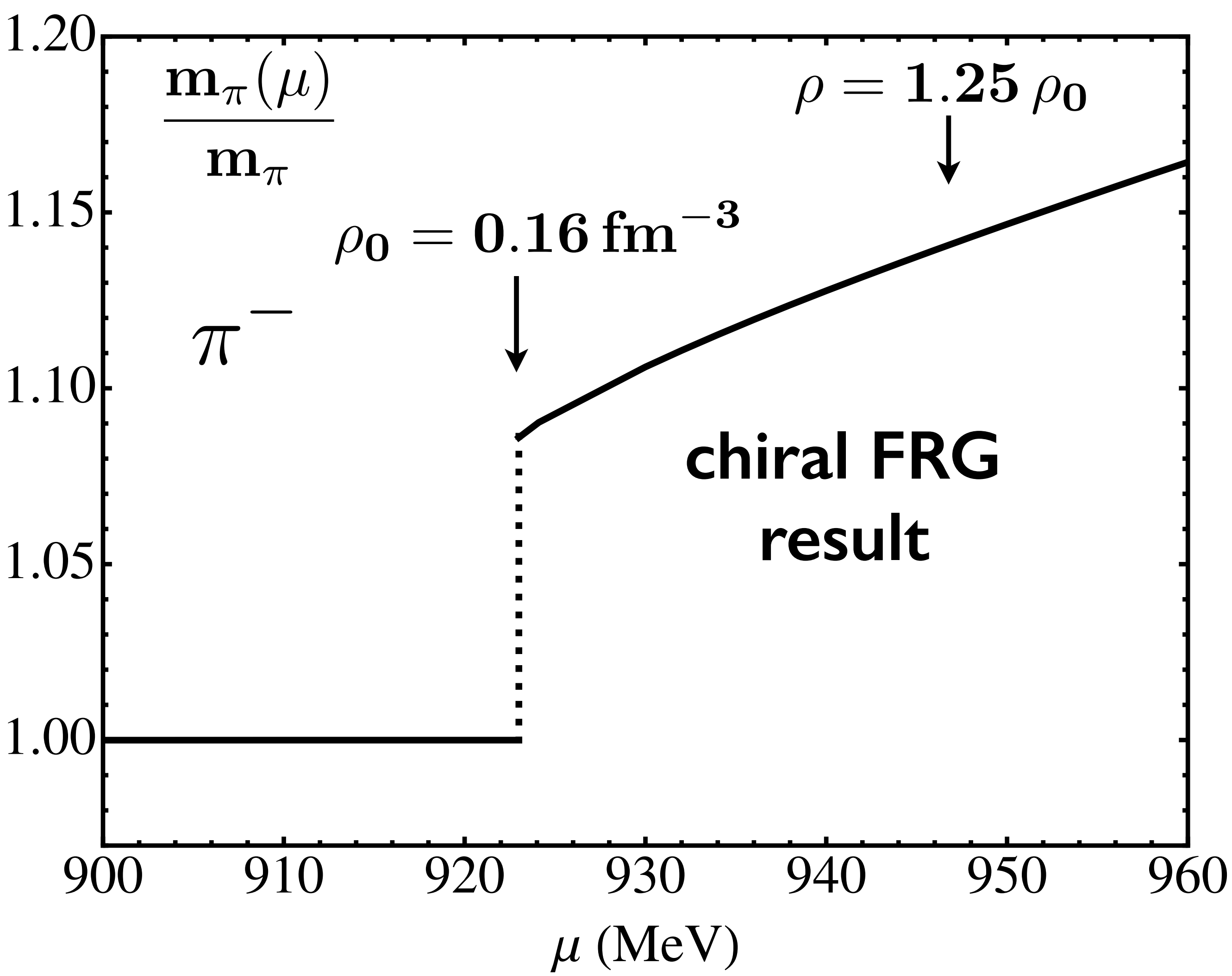
evolution of coexistence regions from symmetric to asymmetric nuclear matter



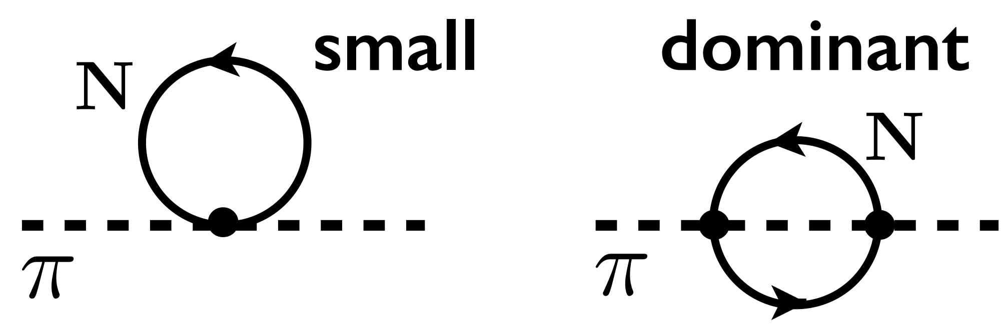
- **FRG results (non-perturbative)** are similar to **(perturbative)** in-medium **Chiral EFT calculations**

In-medium pion mass

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



phenomenology:



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

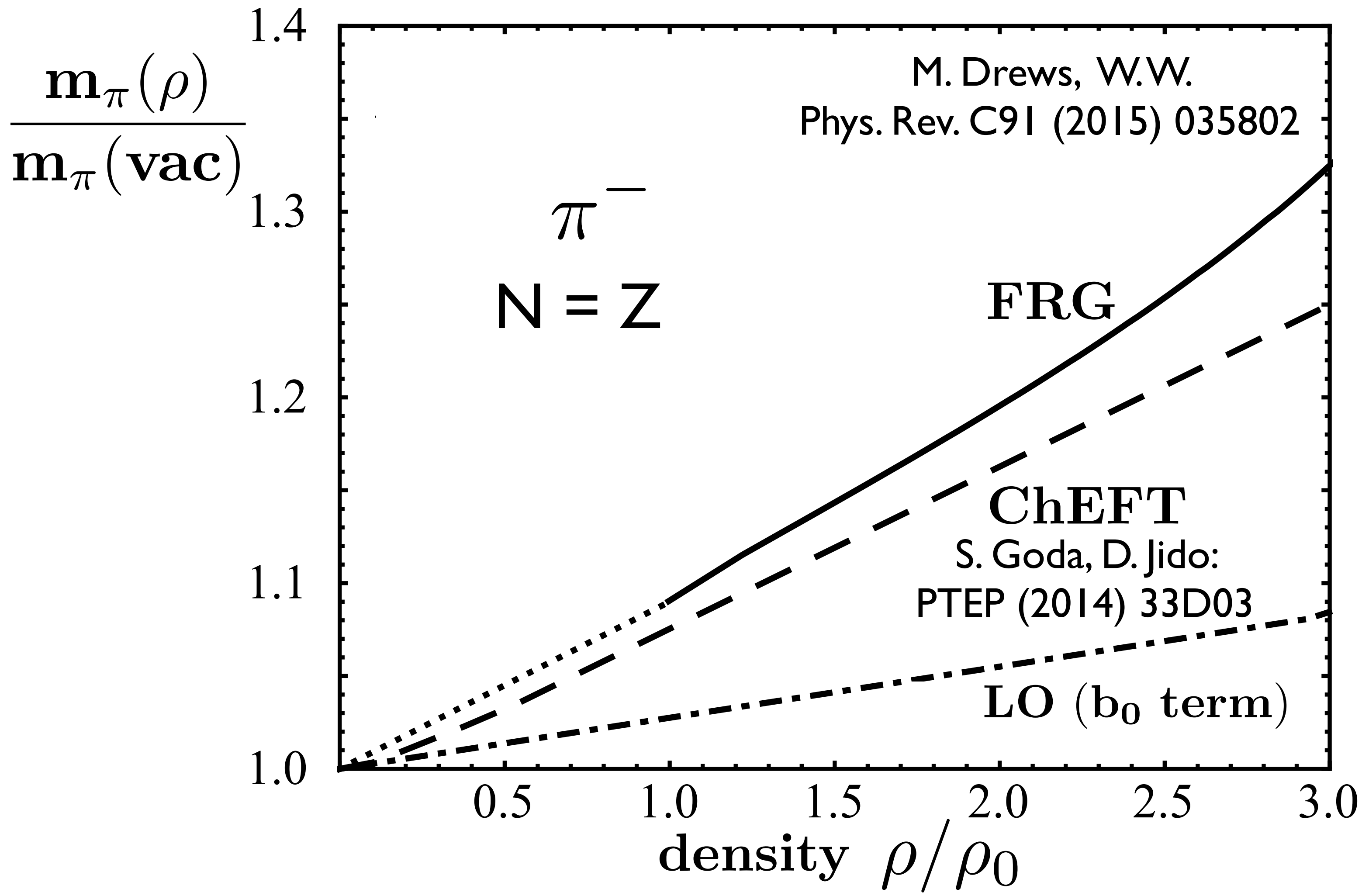
$$\frac{m_\pi(\rho)}{m_\pi} \simeq 1 + \frac{U(\rho)}{m_\pi} \simeq 1.1\,\frac{\rho}{\rho_0}$$

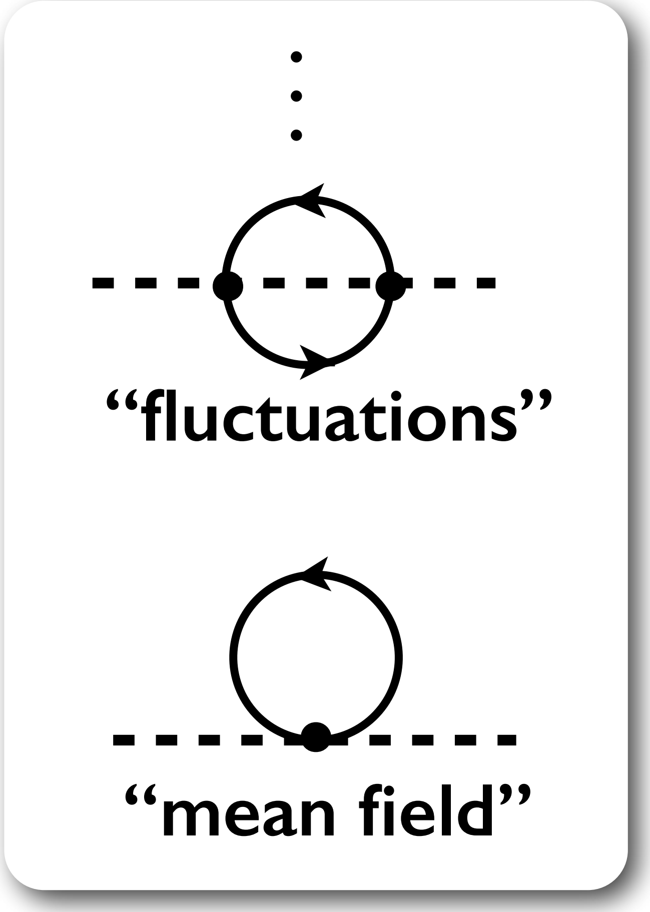
- Good agreement of **FRG** calculation with empirical
  in-medium pion mass shift, both in sign and magnitude

In-medium pion mass (contd.)

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

$$m_\pi^2 = \frac{\partial \mathcal{U}_{k=0}}{\partial \chi}$$





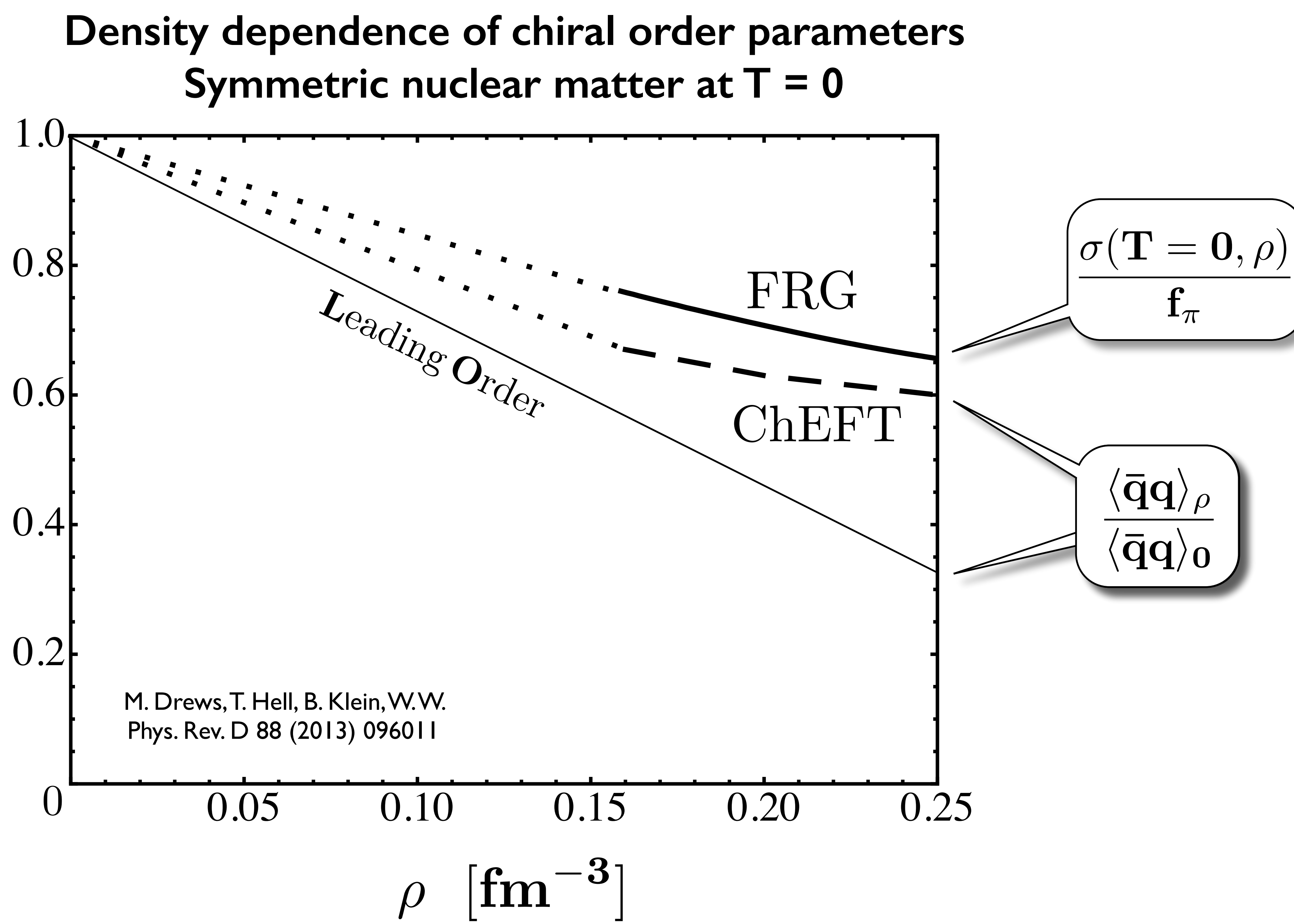
- in-medium **ChEFT (NLO)**:

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

Technische Universität München

Chiral Order Parameters

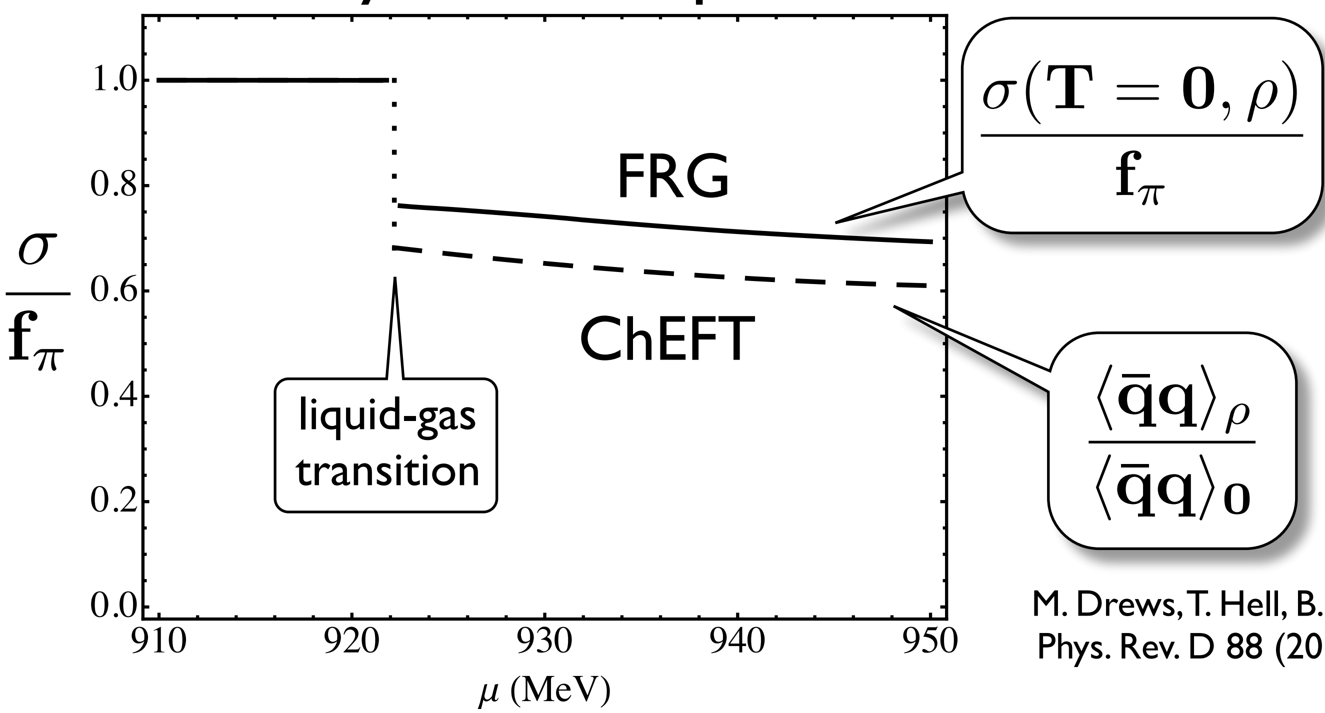
- Comparison of **chiral effective field theory** and **ChNM-FRG** results



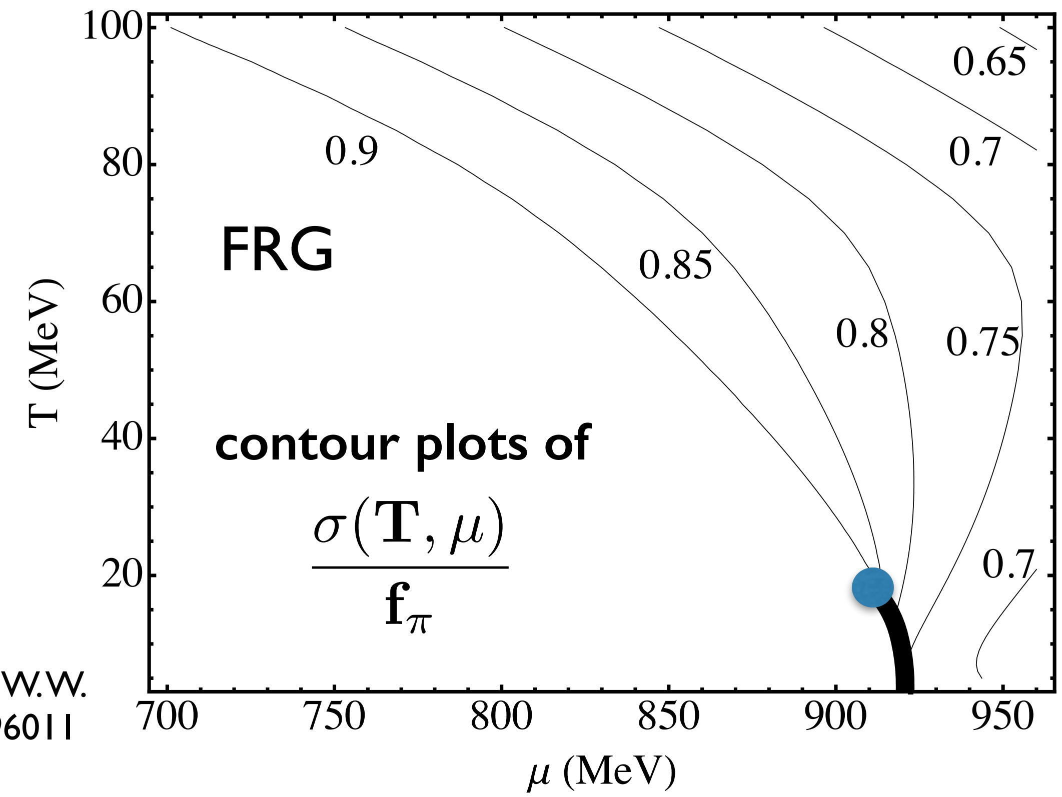
Chiral Order Parameters
(contd.)

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

Chiral order parameters vs. baryon chemical potential



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



- **No** tendency towards **chiral phase transition** for baryon chemical potentials and temperatures

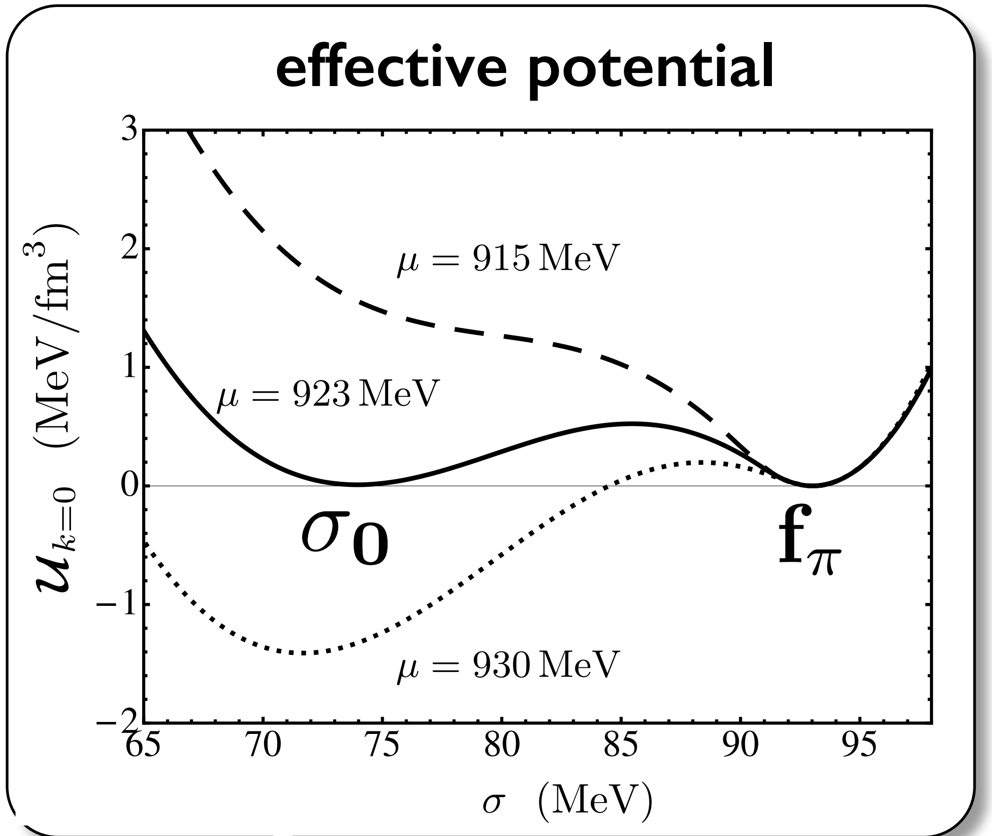
$$\mu \lesssim 1\ \mathrm{GeV} \qquad T \lesssim 100\ \mathrm{MeV}$$

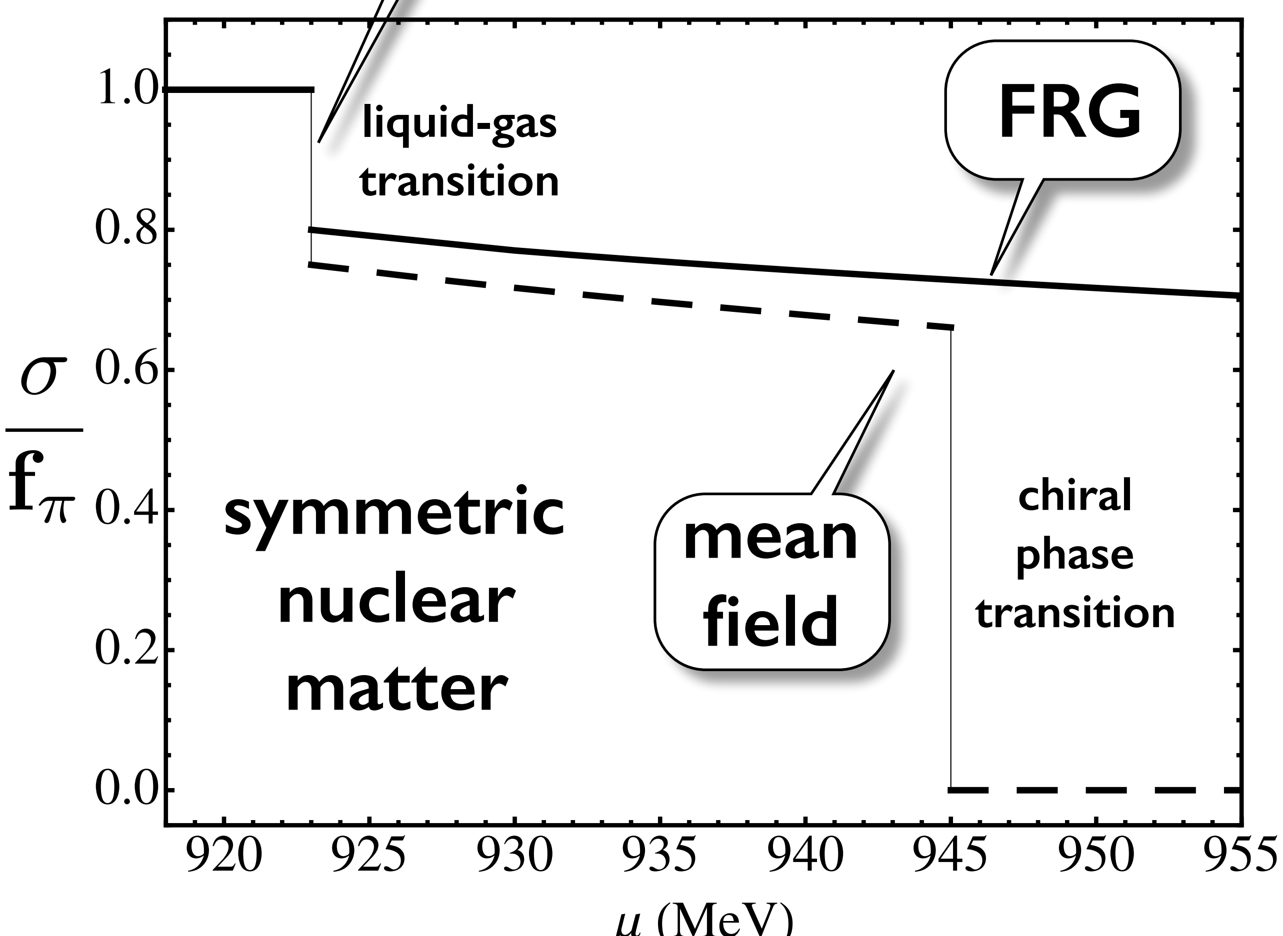
Chiral Order Parameter

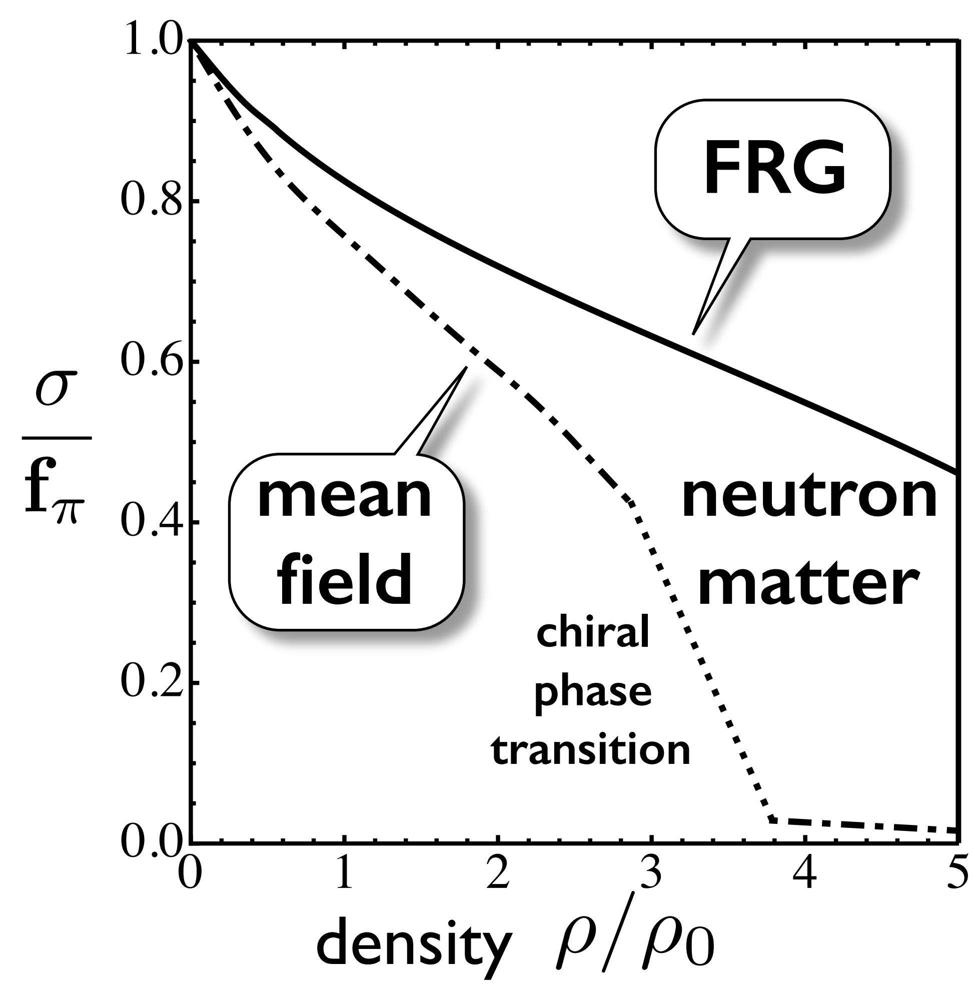
M. Drews, W.W.
Phys. Rev. C91 (2015) 035802

important role of fluctuations
beyond mean-field approximation:

DISAPPEARANCE of
first-order chiral phase transition

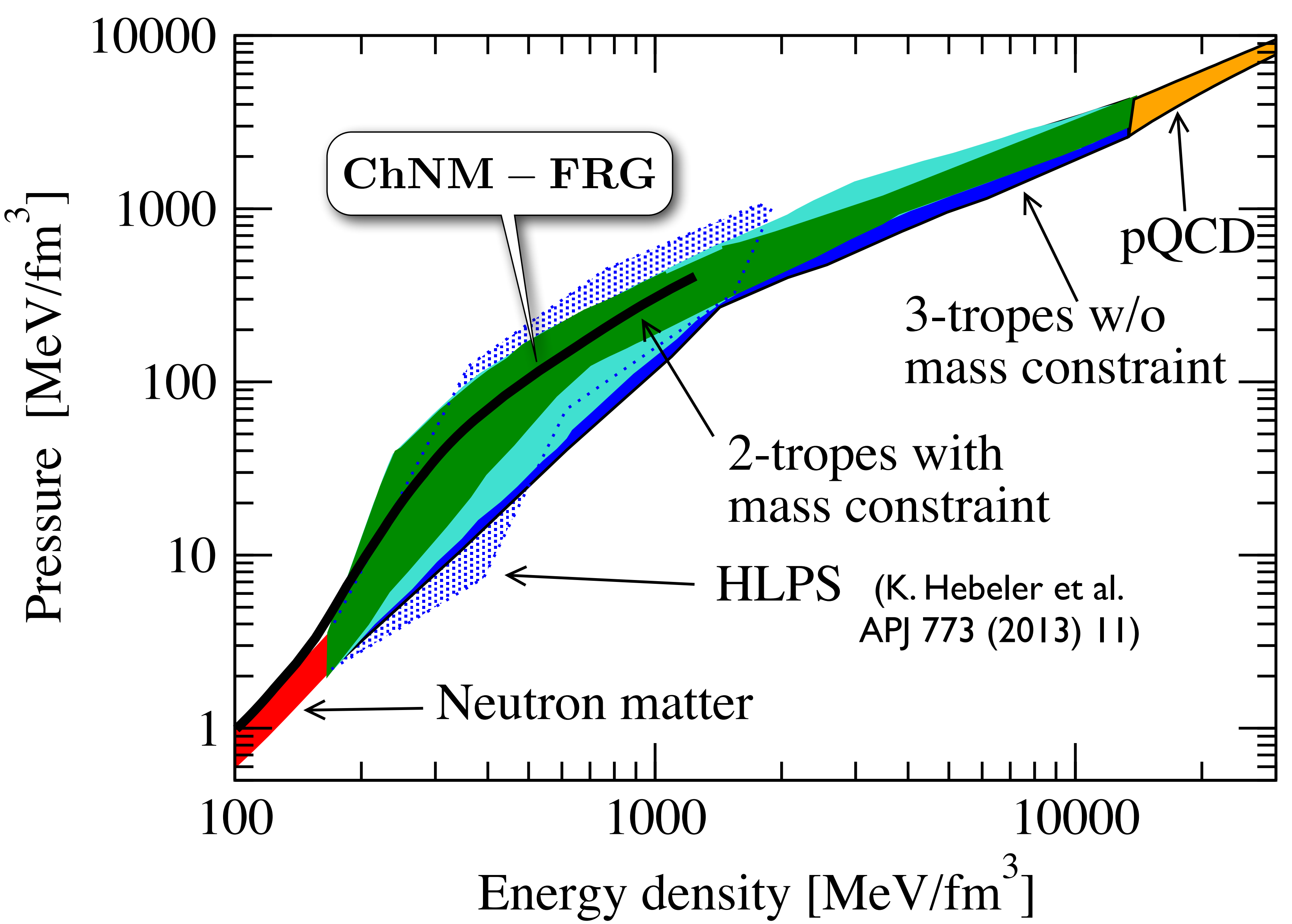






NEUTRON STAR MATTER
Equation of State

. . . and extrapolation to PQCD limit



A. Kurkela et al.
Astroph. J.
789 (2014) 127

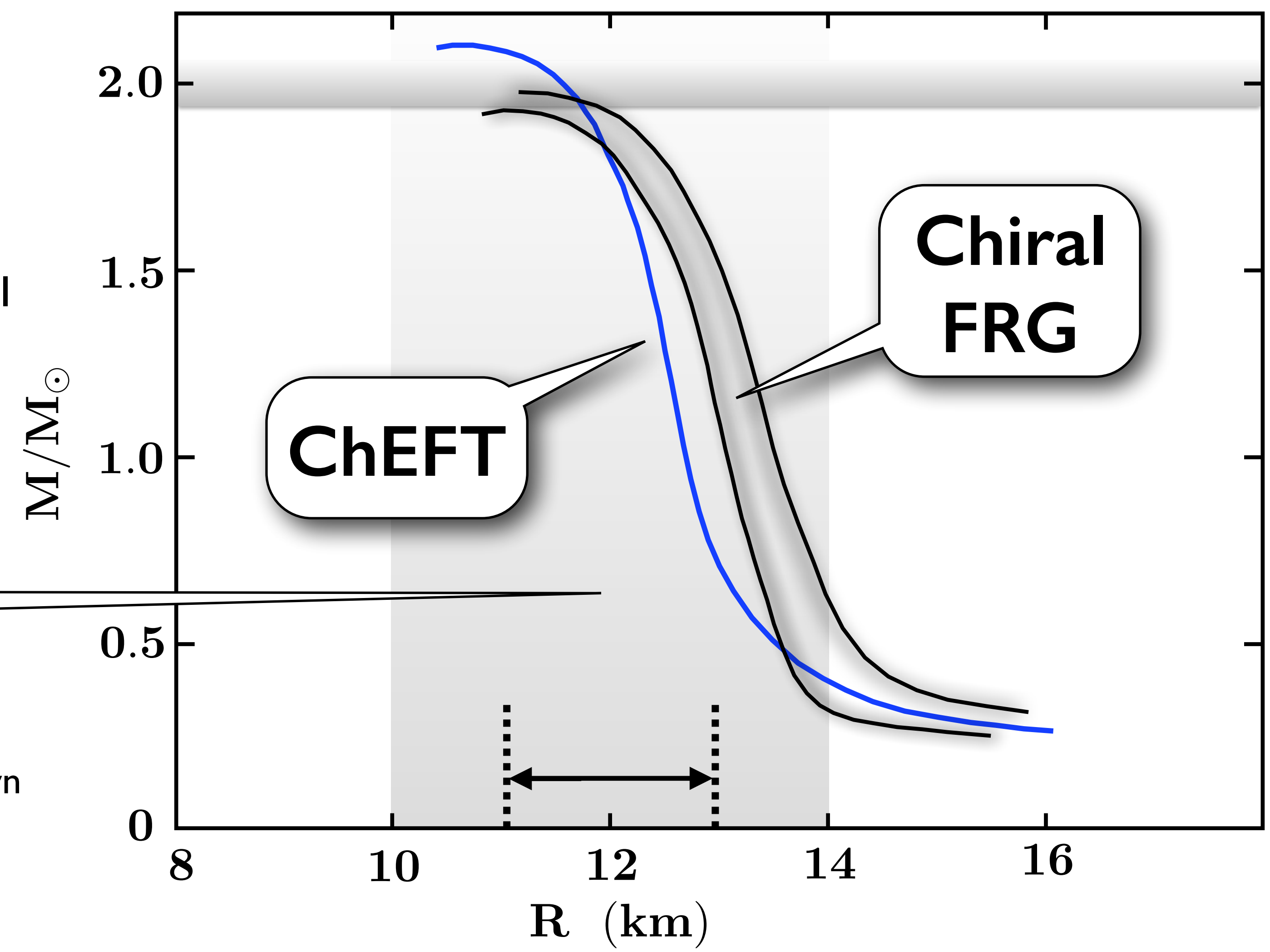
ChNM - FRG:

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

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

- **Neutron matter plus proton admixture (beta equilibrium)**
- **Symmetry energy range: 30 - 35 MeV**

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

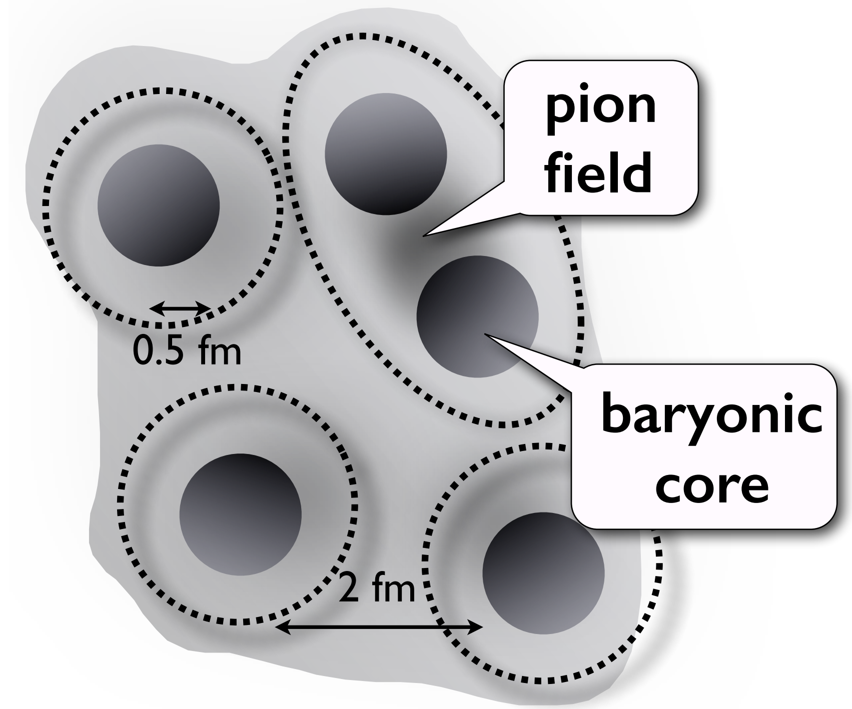


M. Drews, W.W.
Phys. Rev.
C91 (2015) 035802

A.W. Steiner,
J.M. Lattimer, E.F. Brown
EPJ A52 (2016) 18

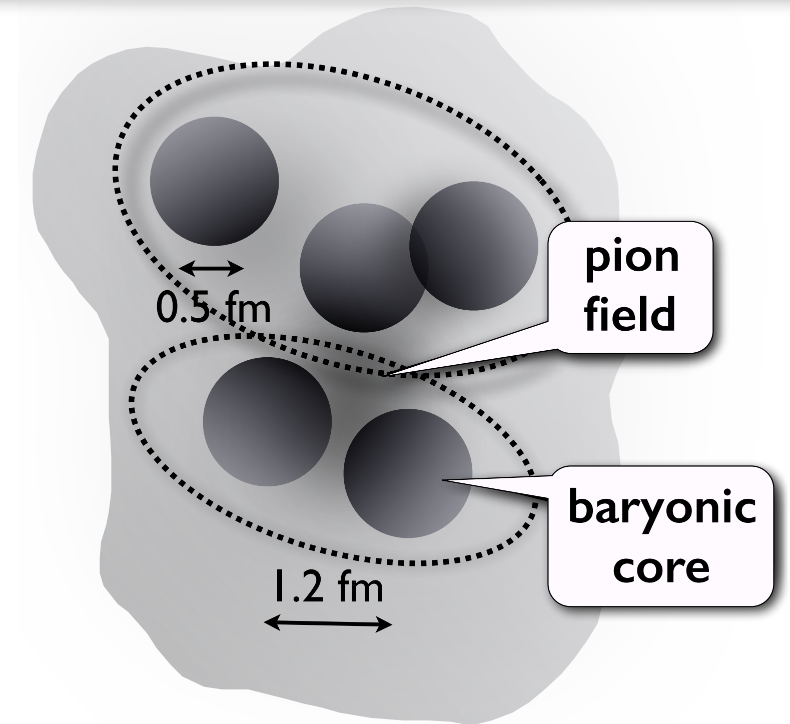
- **Chiral many-body dynamics using "conventional" (pion & nucleon) degrees of freedom is consistent with neutron star constraints**

Densities and Scales in Compressed Baryonic Matter



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

normal nuclear matter: dilute

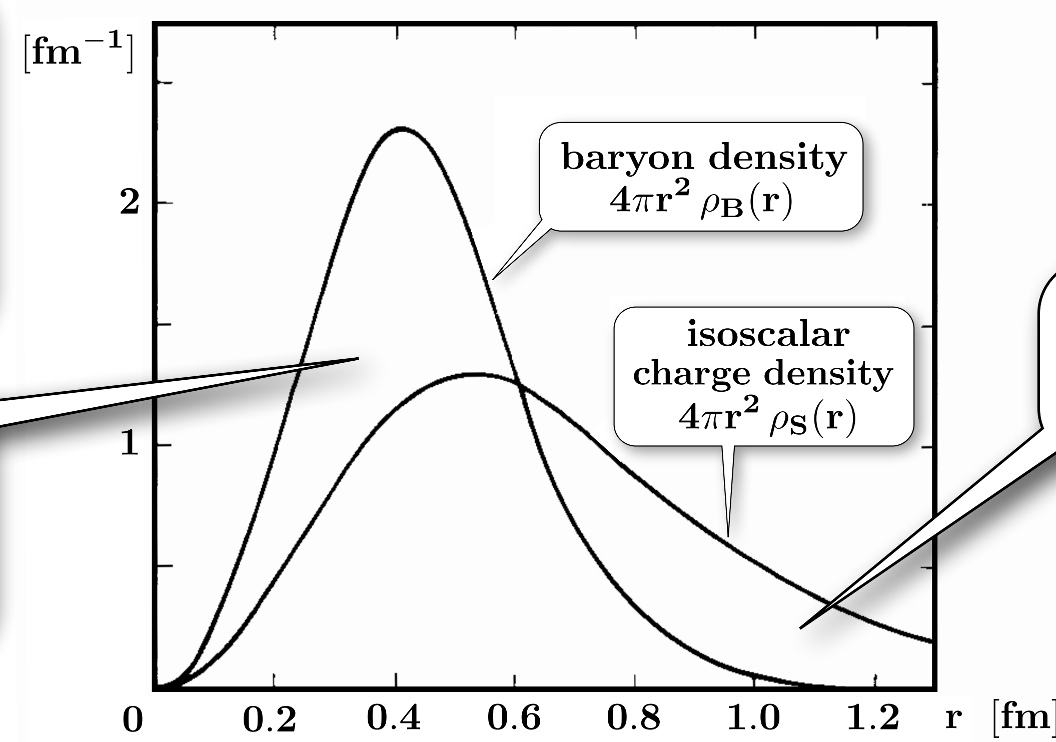


$\rho_B = 0.6\ \mathrm{fm}^{-3}$

neutron star core matter: compressed but not superdense

● **chiral (soliton) model** of the nucleon

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



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

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

. . . treated properly in Chiral EFT

Outlook:

about

HYPERONS

in

NEUTRON STARS

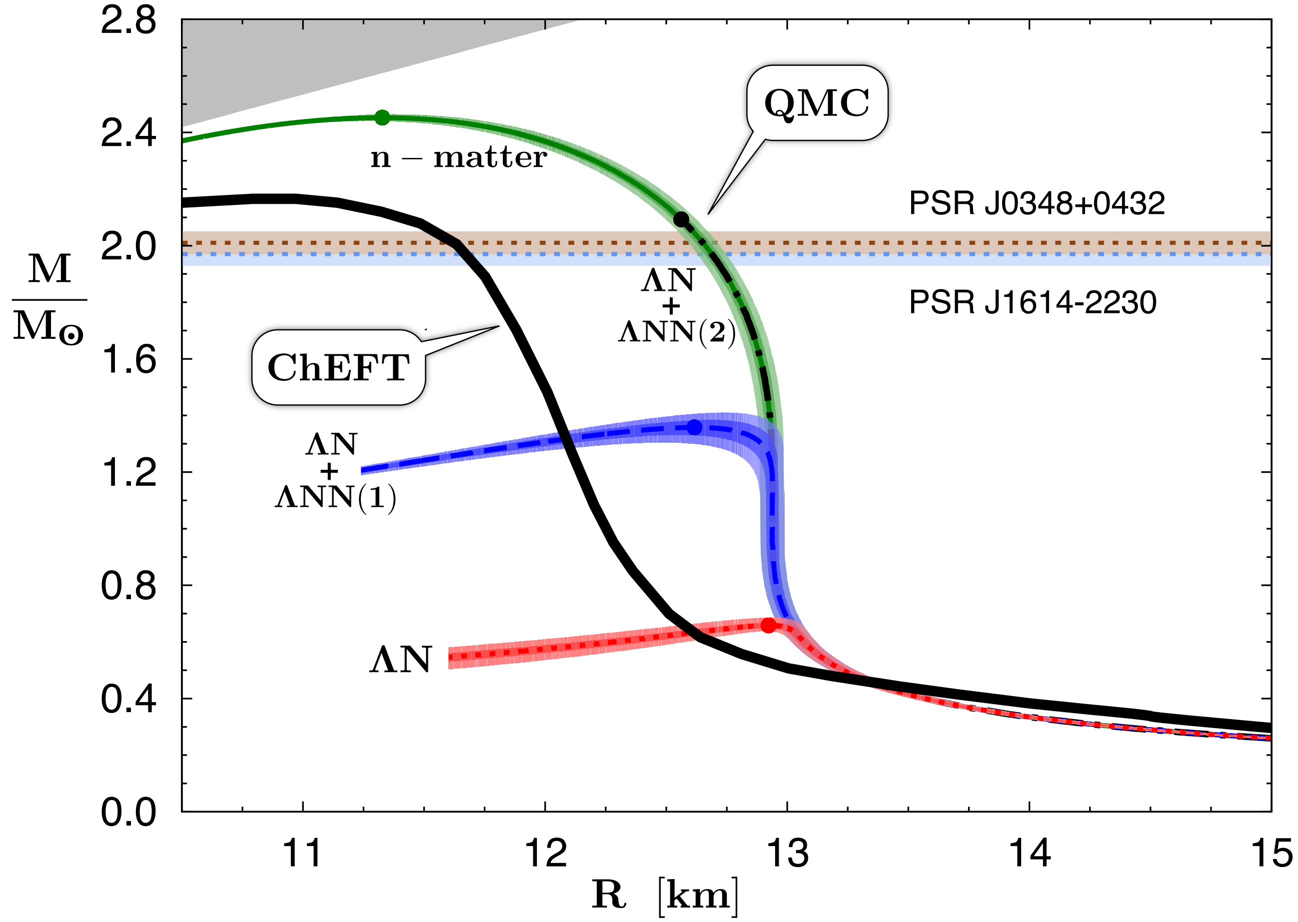
NEUTRON STAR MATTER including HYPERONS

Quantum Monte Carlo calculations using phenomenological hyperon-nucleon and hyperon-NN three-body interactions constrained by hypernuclei

ChEFT calculations "conventional" n-star matter

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

Mass - radius relation of neutron stars



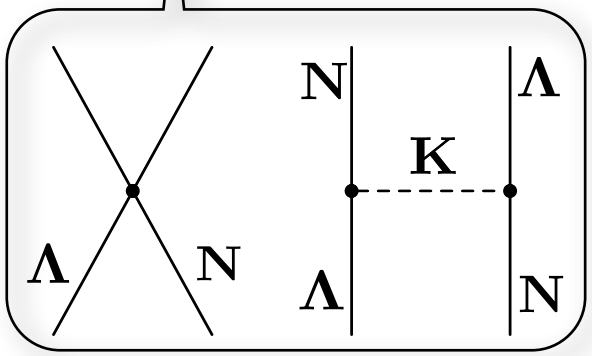
QMC computations (hyper-neutron matter):

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

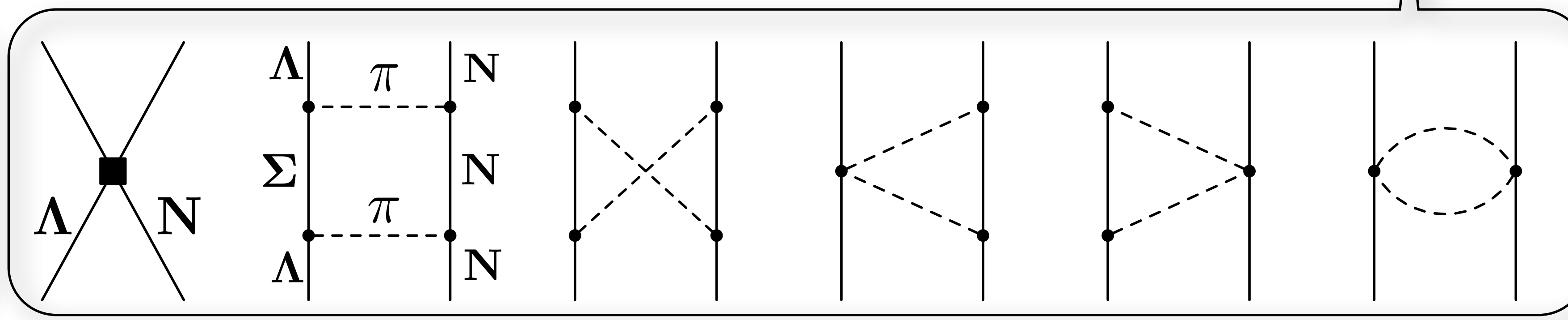
with inclusion of **hyperons**: EoS **too soft** to support 2-solar-mass star unless: strong short-range **repulsion** in YN and / or YNN interactions

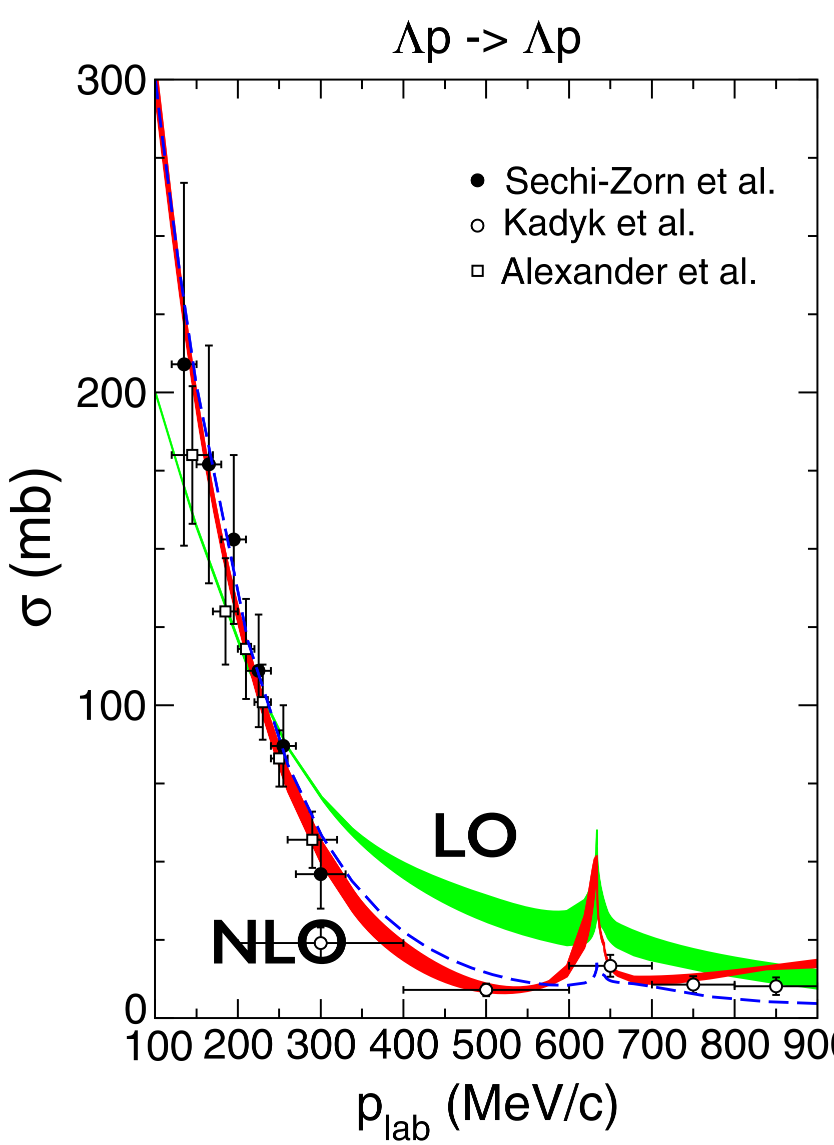
Hyperon - Nucleon Interaction
from **CHIRAL SU(3) Effective Field Theory**

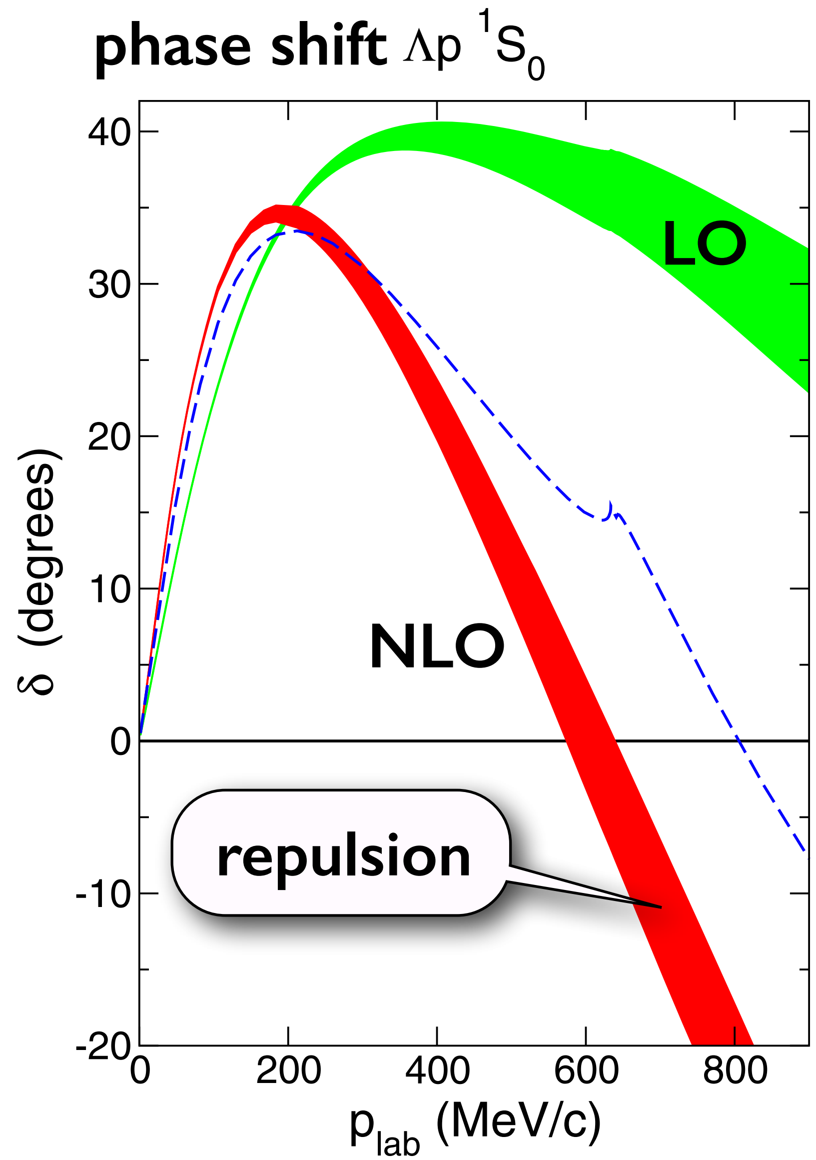
LO



NLO







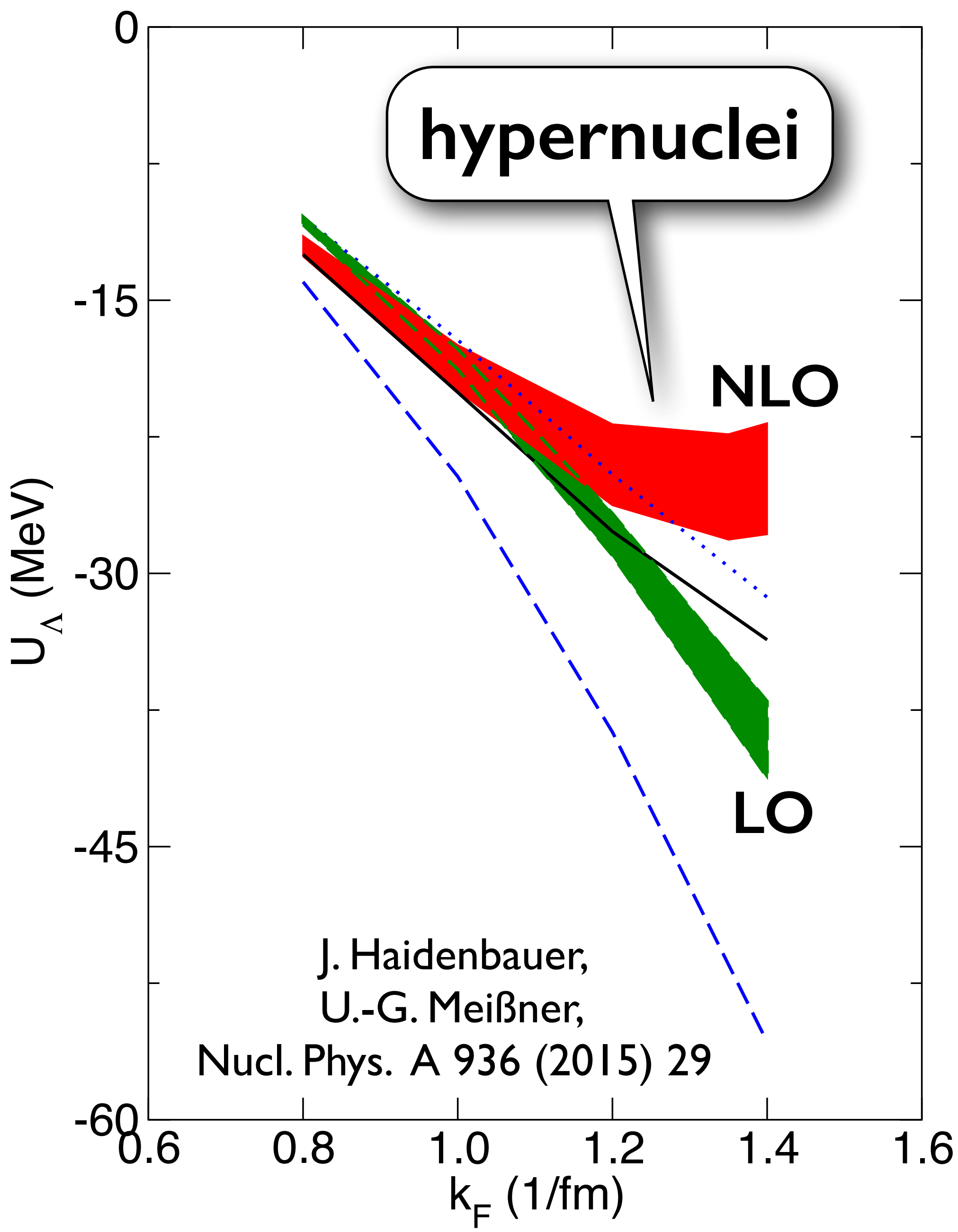
- **moderate attraction** at low momenta
  - → relevant for **hypernuclei**
- **strong repulsion** at higher momenta
  - → relevant for **dense baryonic matter**

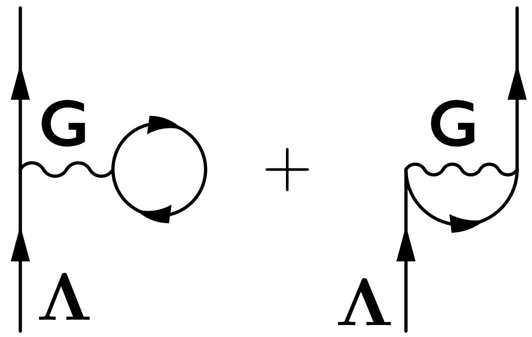
J. Haidenbauer, S. Petschauer, N. Kaiser,
U.-G. Meißner, A. Nogga, W.W.
Nucl. Phys. A 915 (2013) 24

Density dependence of Λ single particle potential

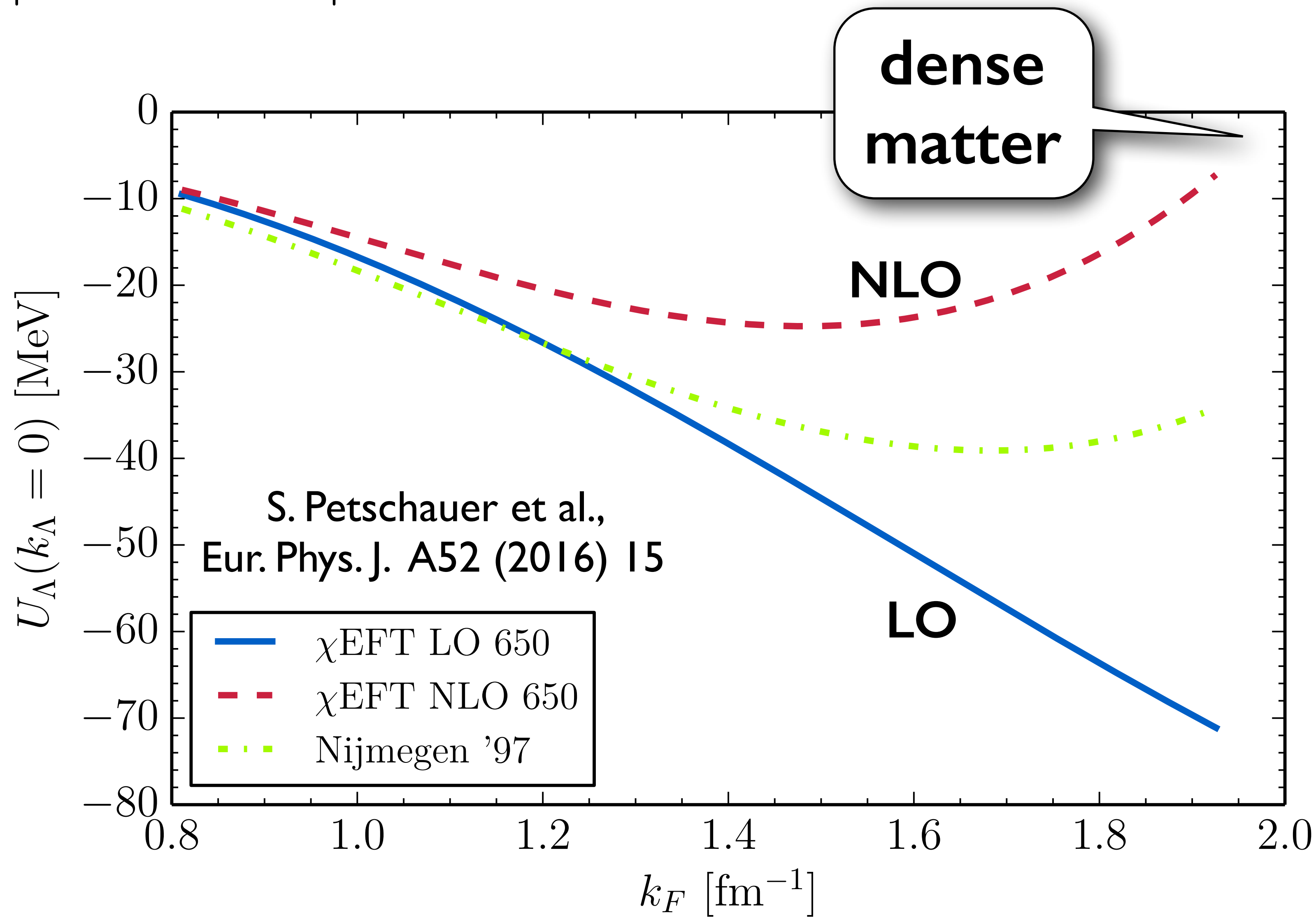
Brueckner calculations

using chiral SU(3) interaction





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



- plus additional repulsion at high density from ΛNN three-body forces

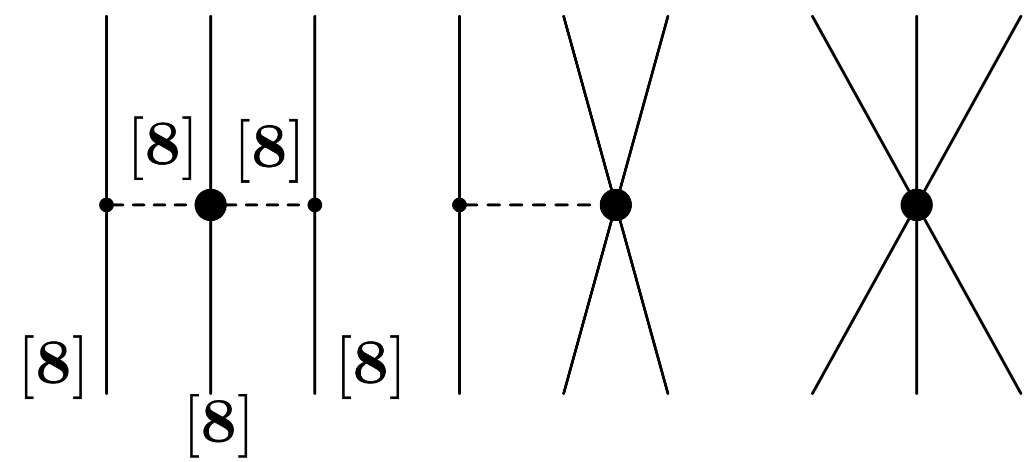
HYPERON - NUCLEON - NUCLEON THREE-BODY FORCES from CHIRAL SU(3) EFT

S. Petschauer et al. arXiv:1607.04307

- Chiral SU(3) Effective Field Theory:
  interacting pseudoscalar meson & baryon octets + contact terms

3-baryon sector:

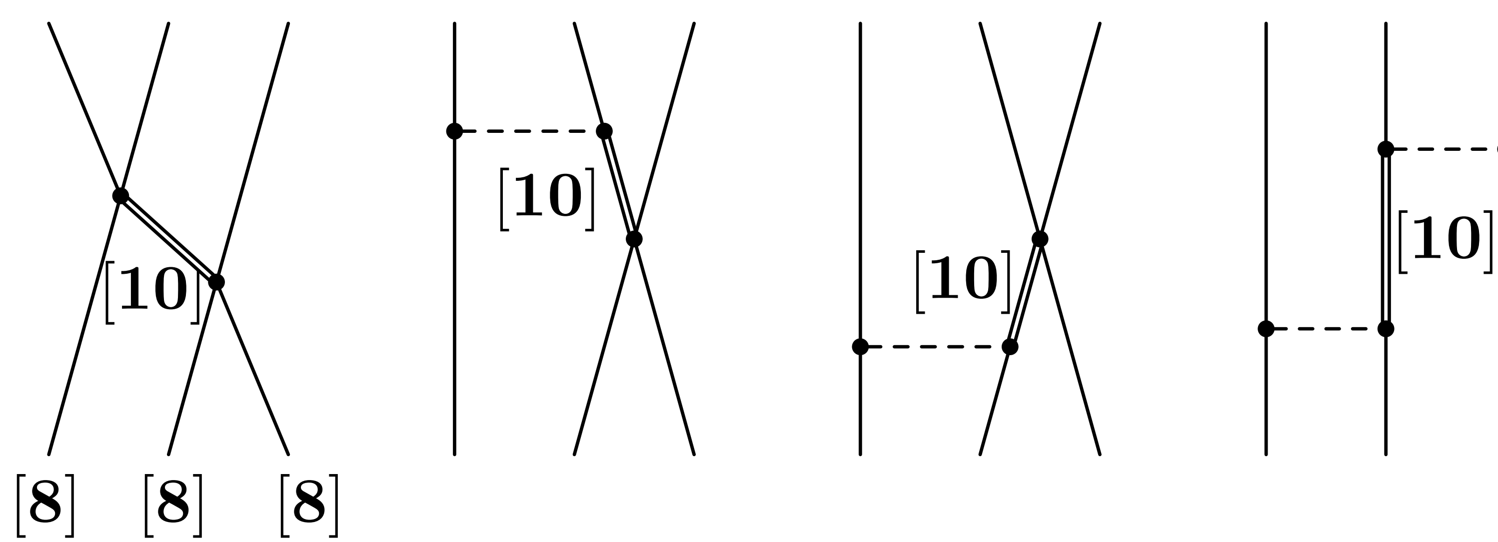
NNLO:



- Chiral SU(3) Effective Field Theory with explicit decuplet baryons:

explicit **baryon decuplet** :

promotion to **NLO**



Density-dependent effective baryon-baryon interaction from chiral three-baryon forces

Stefan Petschauer,[1,*] Johann Haidenbauer,[2] Norbert Kaiser,[1] Ulf-G. Meißner,[2,3] and Wolfram Weise[1]

[1] *Physik Department, Technische Universität München, D-85747 Garching, Germany*
[2] *Institute for Advanced Simulation and Jülich Center for Hadron Physics, Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany*
[3] *Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany*

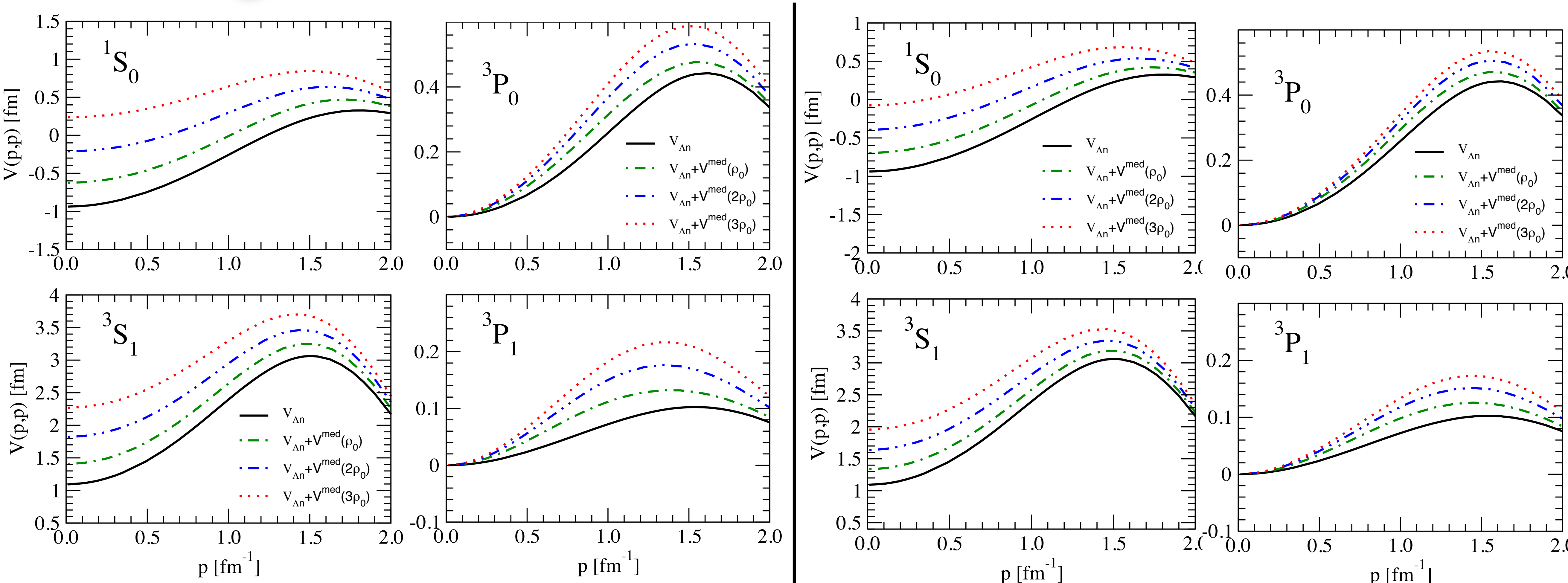
(Dated: July 14, 2016)

arXiv:1607.04307

- **ΛNN**

three-body force transformed into density-dependent effective two-body interaction

- **momentum-space potentials:** increasing **repulsion** $\propto \rho$



Λ in symmetric nuclear matter

Λ in neutron matter

SUMMARY

Nuclear Chiral Dynamics and Thermodynamics

- From (perturbative) **ChEFT** to (non-pertubative) **Functional RG:**
  - From symmetric to asymmetric nuclear matter and neutron matter
  - **Fluctuations beyond mean field:** important **multi-pion exchange** mechanisms and low-energy nucleonic **particle-hole excitations**
  - 1st order phase transition: Fermi **liquid** ↔ interacting Fermi **gas**
- **Fluctuations** (repulsive many-body forces, Pauli effects, . . .):
  - **. . . work against early restoration of chiral symmetry**
  - **No** indication of **first-order chiral phase transition** (within $\rho \lesssim 3\rho_0,\ \mathrm{T} \lesssim 100\,\mathrm{MeV}$ for nucl. matter, $\rho \lesssim 5\rho_0$ for n-matter)
- **Neutron star equation-of-state:** sufficiently stiff to support $2\,\mathrm{M}_\odot$ stars
  - $\mathrm{R} \gtrsim 12\,\mathrm{km}$ and **no ultrahigh core densities** $(\rho_{\mathrm{max}} \sim 5\,\rho_0)$
  - **Strangeness** issues: **Repulsive correlations** and **suppression** of **hyperons** in **neutron stars** ?