STRANGENESS in LOW-ENERGY QCD
and
DENSE BARYONIC MATTER

Wolfram Weise

ECT* Trento and Technische Universität München

- **Role** of **strange quarks**
  Chiral symmetry breaking patterns in QCD

- **Antikaon** interactions with **nucleons** and **nuclei**
  Antikaon-nucleon **threshold observables**

- **Baryonic interactions** with **strangeness**
  Short-range repulsions from **Lattice QCD**

- **Strangeness** in **dense baryonic matter**
  New **constraints** from **neutron stars**

BASIC ISSUES

- **Strange quarks** are intermediate between "**light**" and "**heavy**":
  - Interplay between
    spontaneous and **explicit chiral symmetry breaking**
    in low-energy QCD
- Testing ground: high-precision **antikaon-nucleon** threshold physics
  - Strongly **attractive** low-energy $\bar{K}N$ interaction
- Nature and structure of $\Lambda(1405)$ $(B = 1,\ \ S = -1,\ \ J^P = 1/2^-)$
  - **Three-quark** valence structure vs.
    "**molecular**" meson-baryon system ?
- Quest for quasi-bound **antikaon-nuclear** systems ?
- Role of **strangeness** in dense baryonic matter
  - **Kaon condensation** ?
    Strange quark matter in **neutron stars** ?

Part I.

LOW-ENERGY QCD
with
STRANGE QUARKS:

Chiral SU(3) Dynamics

Hierarchy of **QUARK MASSES** in **QCD**

$$\mathbf{m_u \simeq 2-3\ MeV}$$
$$\mathbf{m_u/m_d \sim 0.4-0.6}$$
$$\mathbf{m_s = 95 \pm 5\ MeV}$$
$$(\mu \simeq \mathbf{2\ GeV})$$

PDG Phys. Rev. D 86 (2012)

- **LOW-ENERGY QCD: CHIRAL EFFECTIVE FIELD THEORY**
- **expansion in $\mathrm{m_q}$ and in powers of low momentum**

$$\mathbf{m_c \simeq 1.25\ GeV}$$
$$m_b \simeq 4.2\ GeV$$
$$m_t \simeq 174\ GeV$$

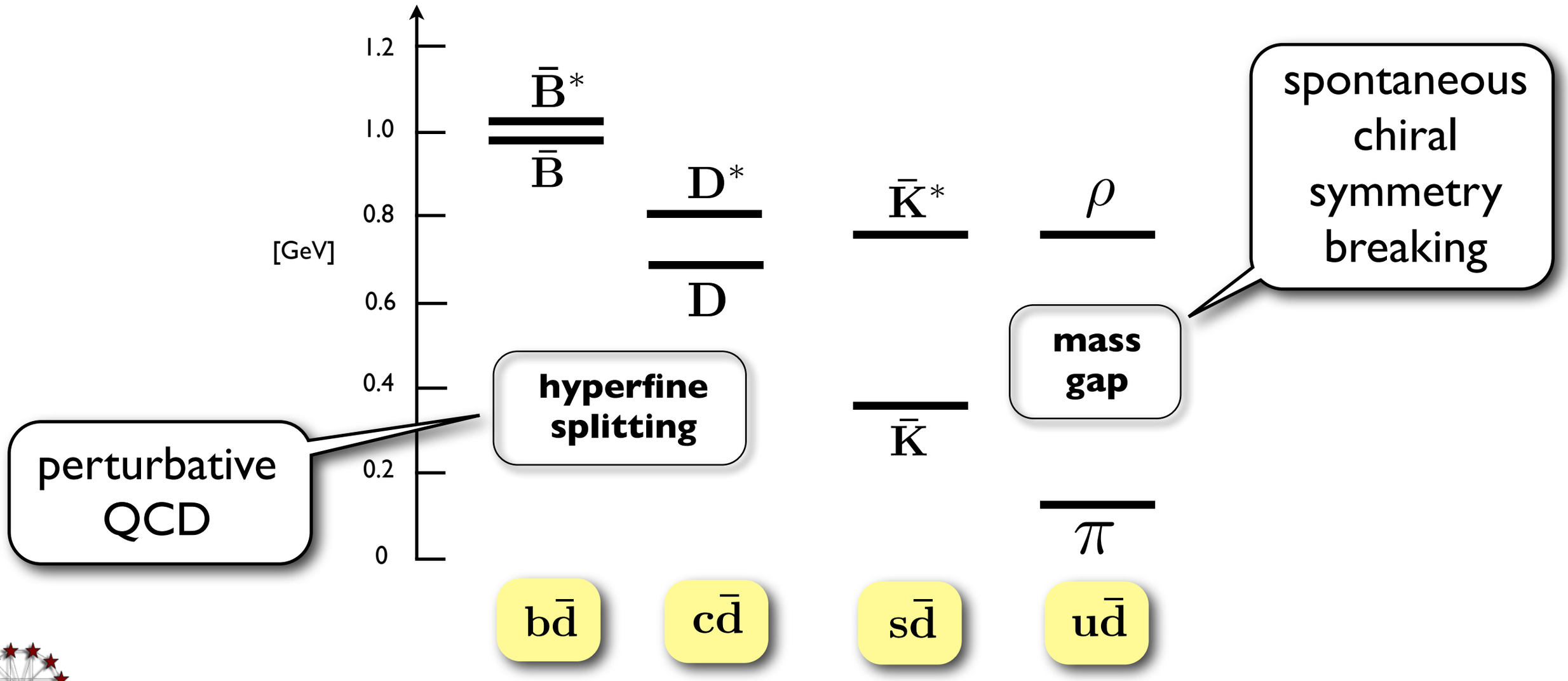
- **Non-Relativistic QCD: HEAVY QUARK EFFECTIVE THEORY**
- **expansion in powers of $1/\mathrm{m_Q}$**

MASS SPLITTINGS in SINGLET and TRIPLET Quark-Antiquark States

$[\mathrm{Q}\,\bar{\mathrm{q}}]_{1S_0}$ $[\mathrm{Q}\,\bar{\mathrm{q}}]_{3S_1}$

Spectroscopic patterns: **LIGHT** versus **HEAVY**

$\mathrm{M_{meson}} - \mathrm{m_Q} - \mathrm{m_q}$



Spontaneously Broken
CHIRAL $\mathrm{SU(3)_L \times SU(3)_R}$ SYMMETRY

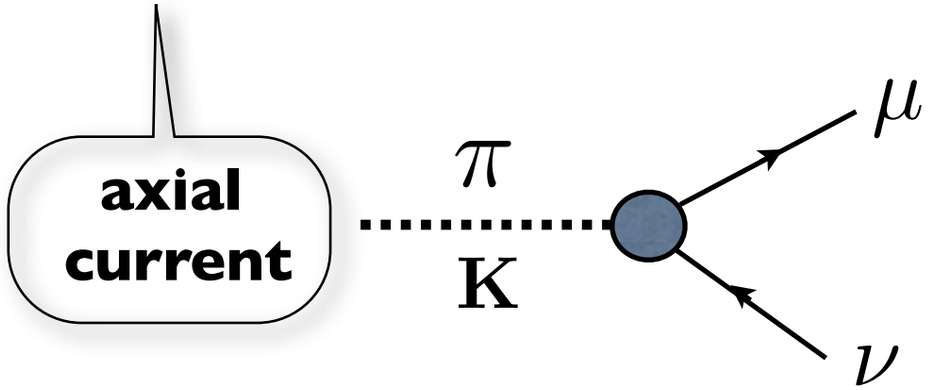
- **NAMBU - GOLDSTONE BOSONS**:

  Pseudoscalar SU(3) meson octet $\quad \{\phi_a\} = \{\pi,\, \mathbf{K},\, \bar{\mathbf{K}},\, \eta_8\}$

- **ORDER PARAMETERS**: **DECAY CONSTANTS**

$$\langle 0|\mathbf{A}_a^\mu(0)|\phi_b(p)\rangle = i\delta_{ab}\, p^\mu\, \mathbf{f}_b$$

(chiral limit: $\mathbf{f = 86.2\ MeV}$)



$$\mathbf{f_\pi = 92.4 \pm 0.3\ MeV}$$
$$\mathbf{f_K = 110.0 \pm 0.9\ MeV}$$

- **G**ell-Mann, **O**akes, **R**enner relations

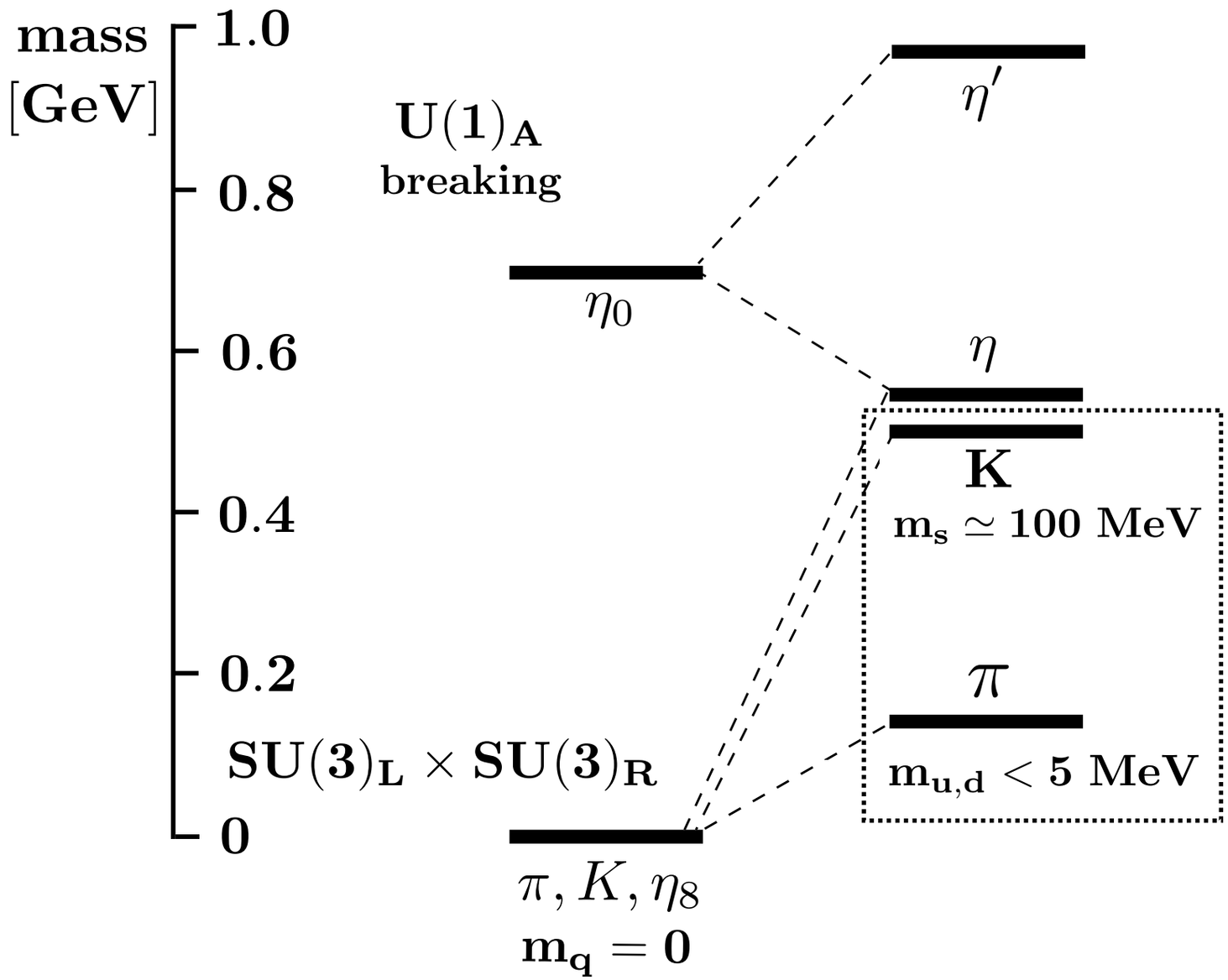
$$\mathbf{m_\pi^2\, f_\pi^2} = -\frac{\mathbf{m_u + m_d}}{\mathbf{2}}\langle \bar{\mathbf{u}}\mathbf{u} + \bar{\mathbf{d}}\mathbf{d}\rangle$$

$$\mathbf{m_K^2\, f_K^2} = -\frac{\mathbf{m_u + m_s}}{\mathbf{2}}\langle \bar{\mathbf{u}}\mathbf{u} + \bar{\mathbf{s}}\mathbf{s}\rangle$$

\+ higher order corrections

SYMMETRY BREAKING PATTERN

PSEUDOSCALAR MESON SPECTRUM



Calculation: **N**ambu & **J**ona-**L**asinio model with $N_f = 3$ quark flavors

S. Klimt, M. Lutz, U. Vogl, W. W.
Nucl. Phys. A 516 (1990) 429

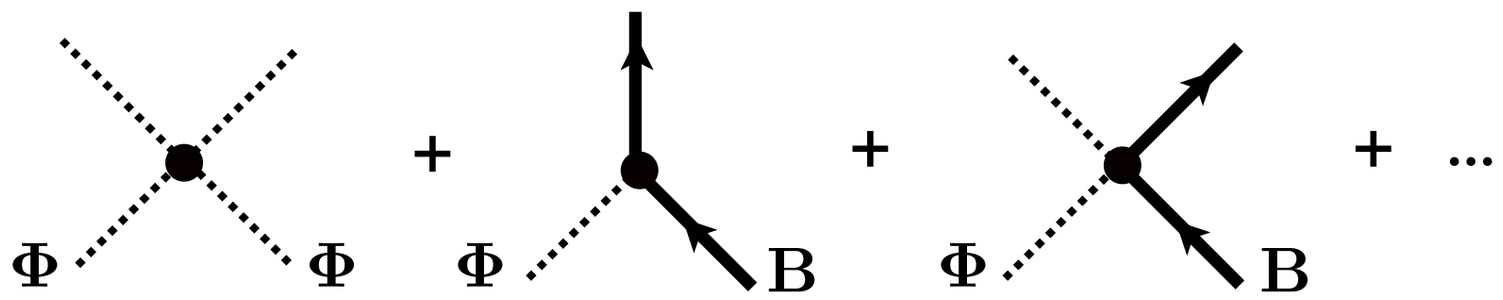
U. Vogl, W. W.
Prog. Part. Nucl. Phys. 27 (1991) 195

CHIRAL SU(3) EFFECTIVE FIELD THEORY

- Interacting systems of **NAMBU-GOLDSTONE BOSONS** (Φ) (**pions**, **kaons**) coupled to **BARYONS** (B)

$$\mathcal{L}_{eff} = \mathcal{L}_{mesons}(\Phi) + \mathcal{L}_{B}(\Phi, \Psi_B)$$

- Leading **DERIVATIVE** couplings (involving $\partial^\mu \Phi$) determined by spontaneously broken **CHIRAL SYMMETRY**



higher orders with additional low-energy constants

- Low-Energy Expansion: **CHIRAL PERTURBATION THEORY**

"small parameter": $\dfrac{\mathrm{p}}{4\pi\,\mathrm{f}_\pi} \sim \dfrac{\text{energy / momentum}}{1\ \mathrm{GeV}}$

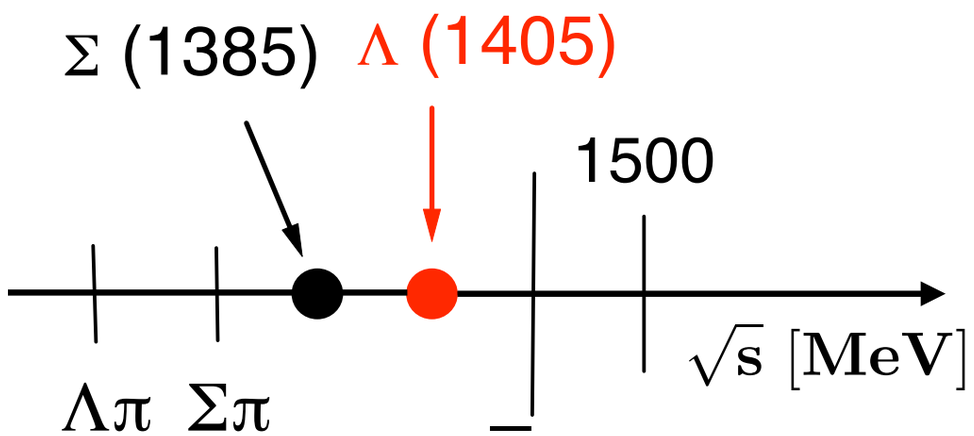
- works well for low-energy **pion-pion** and **pion-nucleon** interactions

▶ ... but **NOT** for systems with **strangeness** $\mathrm{S} = -1$ $(\bar{\mathrm{K}}\mathrm{N},\ \pi\Sigma,\ \ldots)$

Low-Energy $\bar{K}$ N Interactions

- Chiral Perturbation Theory **NOT** applicable:

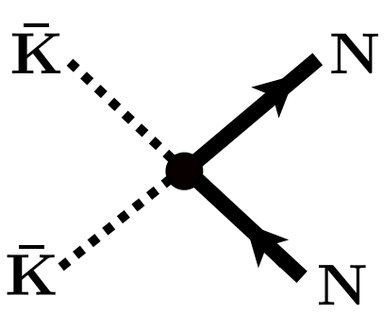
  $\Lambda(1405)$ resonance 27 MeV below $K^- p$ threshold

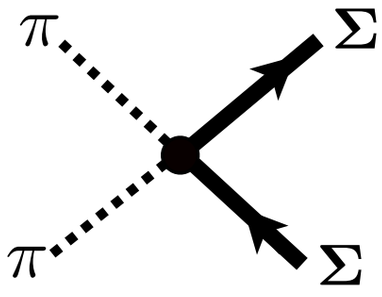


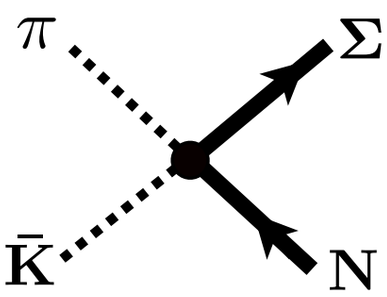
Non-perturbative
Coupled Channels
approach based on
Chiral SU(3) Dynamics

N. Kaiser, P. Siegel, W.W. (1995)
E. Oset, A. Ramos (1998)

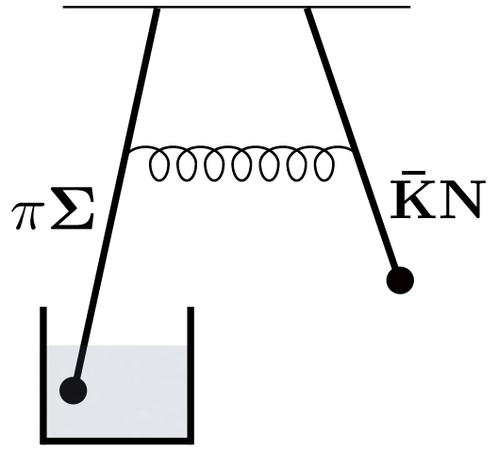
- Leading s-wave I = 0 meson-baryon interactions (Tomozawa-Weinberg)



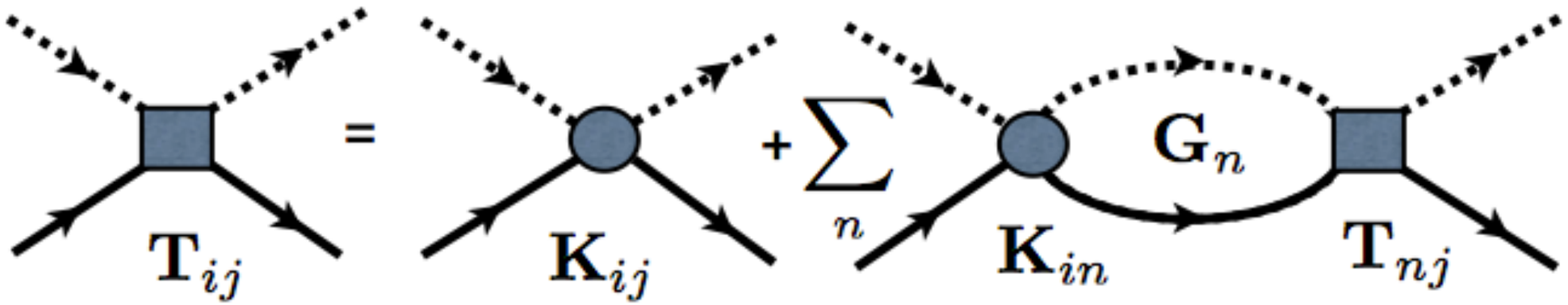




channel coupling



CHIRAL SU(3) COUPLED CHANNELS DYNAMICS



$$\mathbf{T_{ij}} = \mathbf{K_{ij}} + \sum_{\mathbf{n}} \mathbf{K_{in}}\, \mathbf{G_n}\, \mathbf{T_{nj}}$$

input from chiral SU(3) meson-baryon effective Lagrangian

loop functions (dim. regularization) with subtraction constants encoding short distance dynamics

- **coupled channels**:

$$\mathbf{K^- p},\ \mathbf{\bar{K}^0 n},\ \mathbf{\pi^0 \Sigma^0},\ \mathbf{\pi^+ \Sigma^-},\ \mathbf{\pi^- \Sigma^+},\ \mathbf{\pi^0 \Lambda},\ \mathbf{\eta \Lambda},\ \mathbf{\eta \Sigma^0},\ \mathbf{K^+ \Xi^-},\ \mathbf{K^- \Xi^0}$$

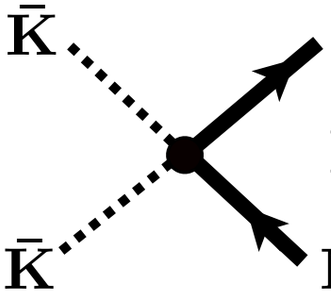
CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

$$\mathbf{T_{ij} = K_{ij} + \sum_n K_{in}\, G_n\, T_{nj}}$$

- Leading s-wave I = 0 meson-baryon interactions (Tomozawa-Weinberg)

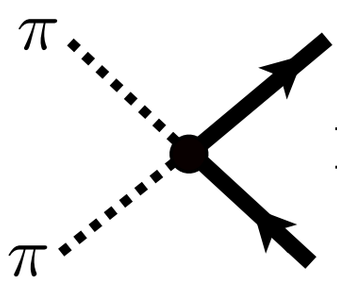
  Note: **ENERGY DEPENDENCE** characteristic of Nambu-Goldstone Bosons

$|1\rangle = |\bar{K}N, I=0\rangle$



$$\mathbf{K_{11} = \frac{3}{2\, f_K^2}(\sqrt{s} - M_N)}$$

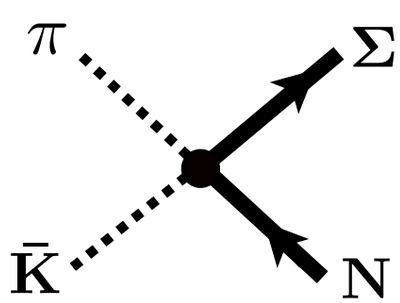
$|2\rangle = |\pi\Sigma, I=0\rangle$



$$\mathbf{K_{22} = \frac{2}{f_\pi^2}(\sqrt{s} - M_\Sigma)}$$

- driving interactions individually **strong** enough to produce
  - $\bar{K}N$ **bound state**
  - $\pi\Sigma$ **resonance**

- **strong** channel coupling $12 \leftrightarrow 21$:

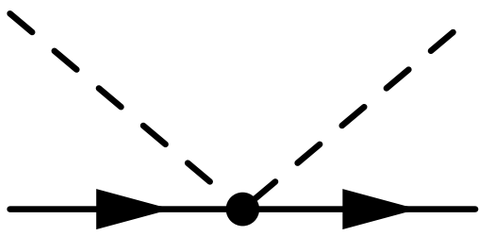


$$\mathbf{f_\pi = 92.4 \pm 0.3\ MeV}$$
$$\mathbf{f_K = 110.0 \pm 0.9\ MeV}$$

$$\mathbf{K_{12} = \frac{-1}{2\, f_\pi\, f_K}\sqrt{\frac{3}{2}}\left(\sqrt{s} - \frac{M_\Sigma + M_N}{2}\right)}$$

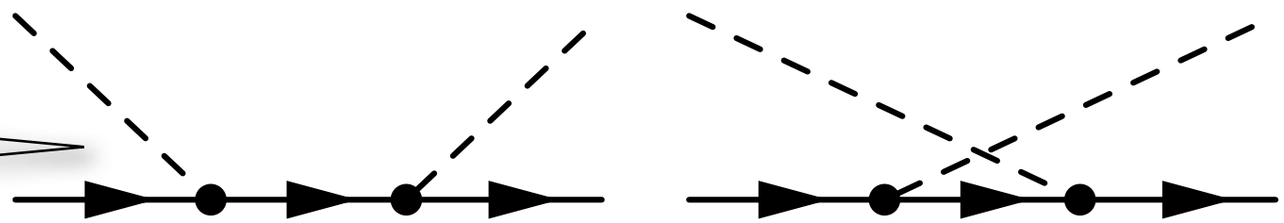
CHIRAL SU(3) COUPLED CHANNELS DYNAMICS:

- NLO hierarchy of driving terms -



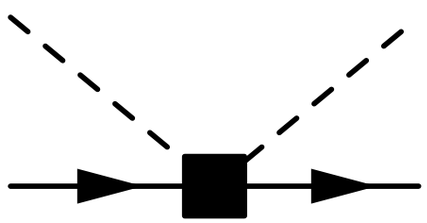
leading order (**W**einberg-**T**omozawa) terms
input: physical pion and kaon decay constants

direct and crossed **Born terms**
input: axial vector constants
D and F from hyperon beta decays



$$g_A = D + F = 1.26$$

$$\mathcal{L}_1^{MB} = \mathrm{Tr}\left(\frac{D}{2}(\bar{B}\gamma^\mu\gamma_5\{u_\mu, B\}) + \frac{F}{2}(\bar{B}\gamma^\mu\gamma_5[u_\mu, B])\right)$$

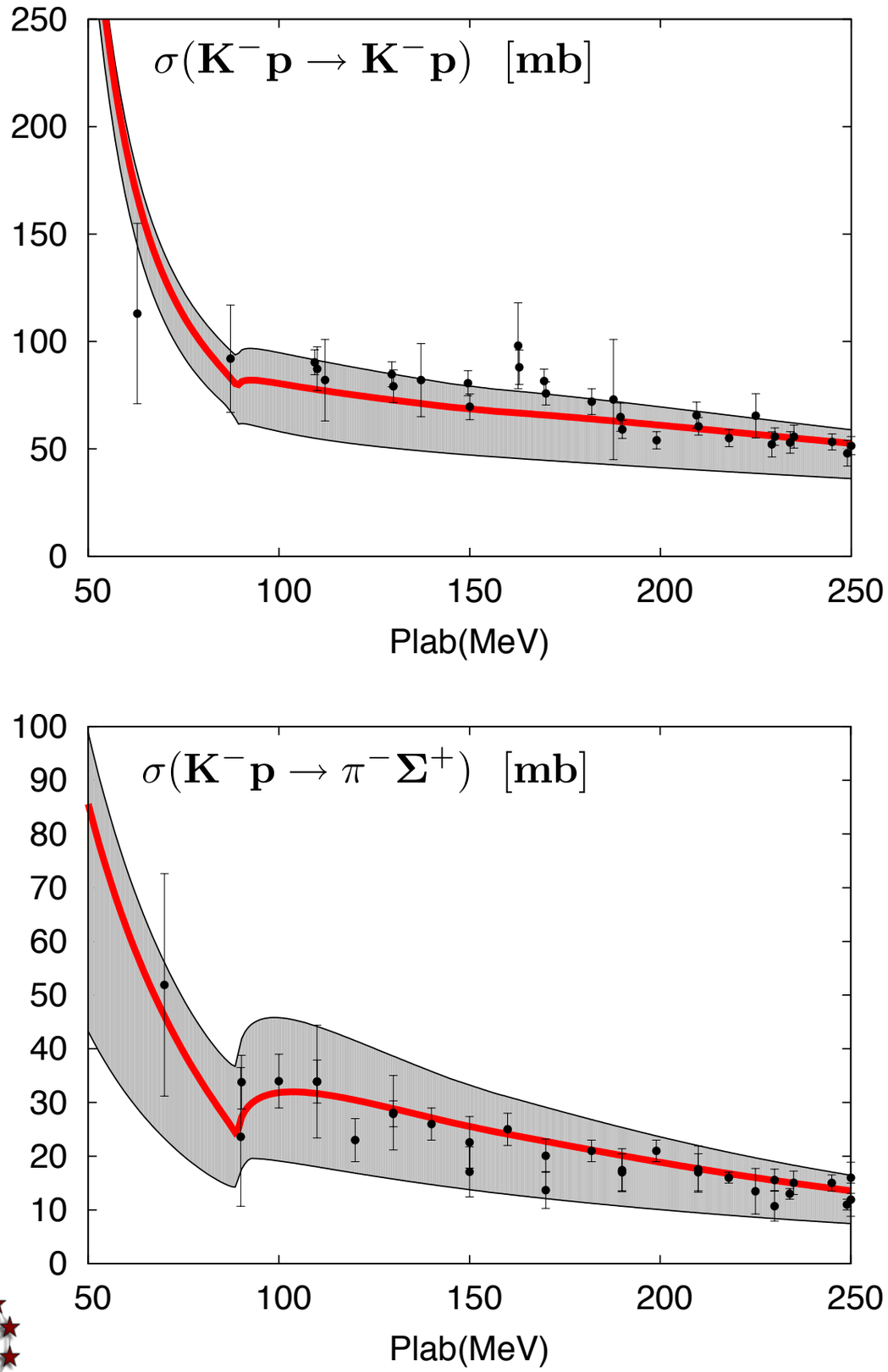


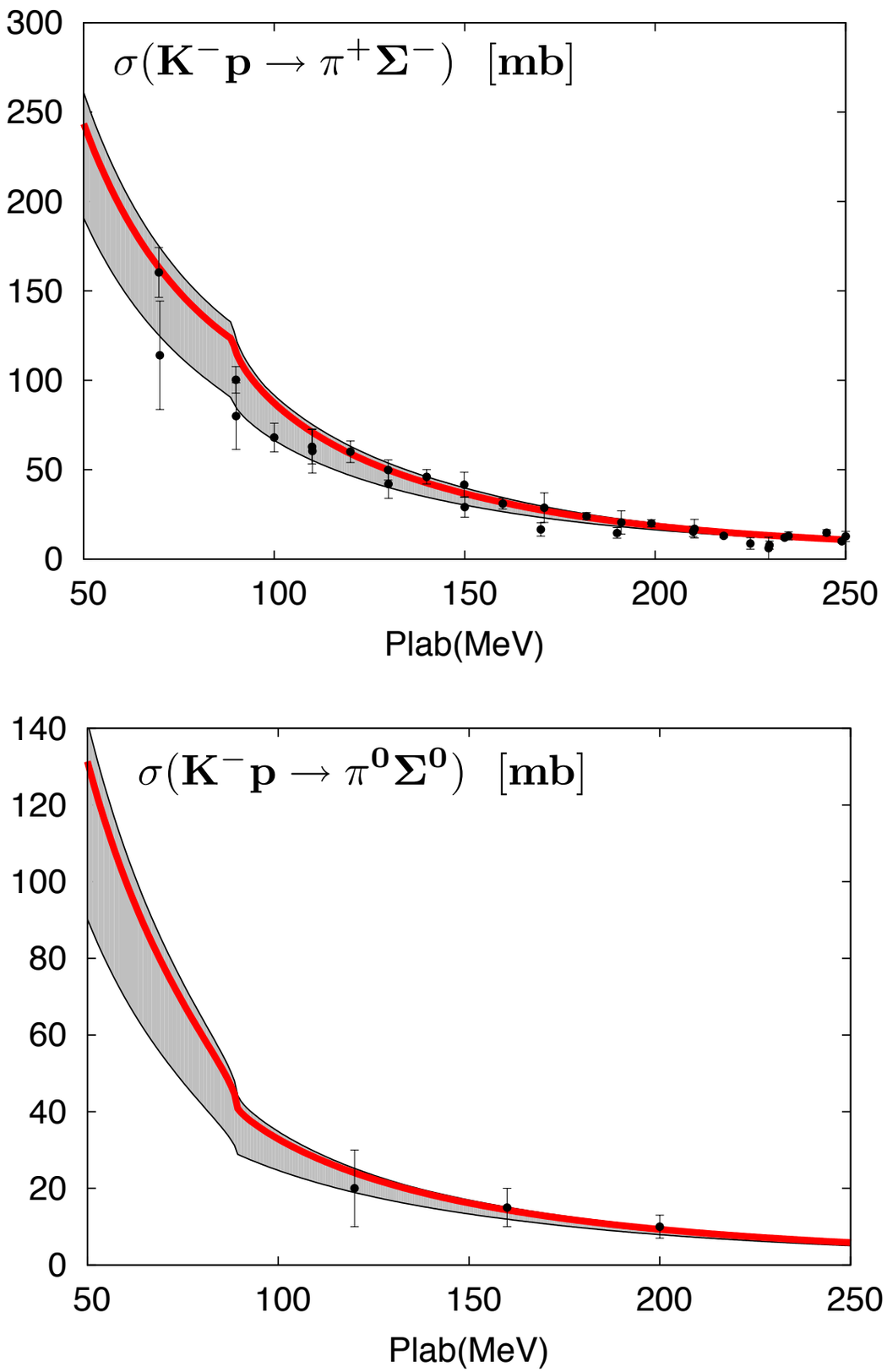
next-to-leading order (**NLO**)
input: 7 low-energy constants

$\mathcal{O}(p^2)$

$$\begin{aligned}\mathcal{L}_2^{MB} =& b_D \mathrm{Tr}\big(\bar{B}\{\chi_+, B\}\big) + b_F \mathrm{Tr}\big(\bar{B}[\chi_+, B]\big) + b_0 \mathrm{Tr}(\bar{B}B)\mathrm{Tr}(\chi_+) \\ &+ d_1 \mathrm{Tr}\big(\bar{B}\{u^\mu, [u_\mu, B]\}\big) + d_2 \mathrm{Tr}\big(\bar{B}[u^\mu, [u_\mu, B]]\big) \\ &+ d_3 \mathrm{Tr}(\bar{B}u_\mu)\mathrm{Tr}(u^\mu B) + d_4 \mathrm{Tr}(\bar{B}B)\mathrm{Tr}(u^\mu u_\mu),\end{aligned}$$

UPDATED ANALYSIS of K^-p LOW-ENERGY CROSS SECTIONS





ECT*

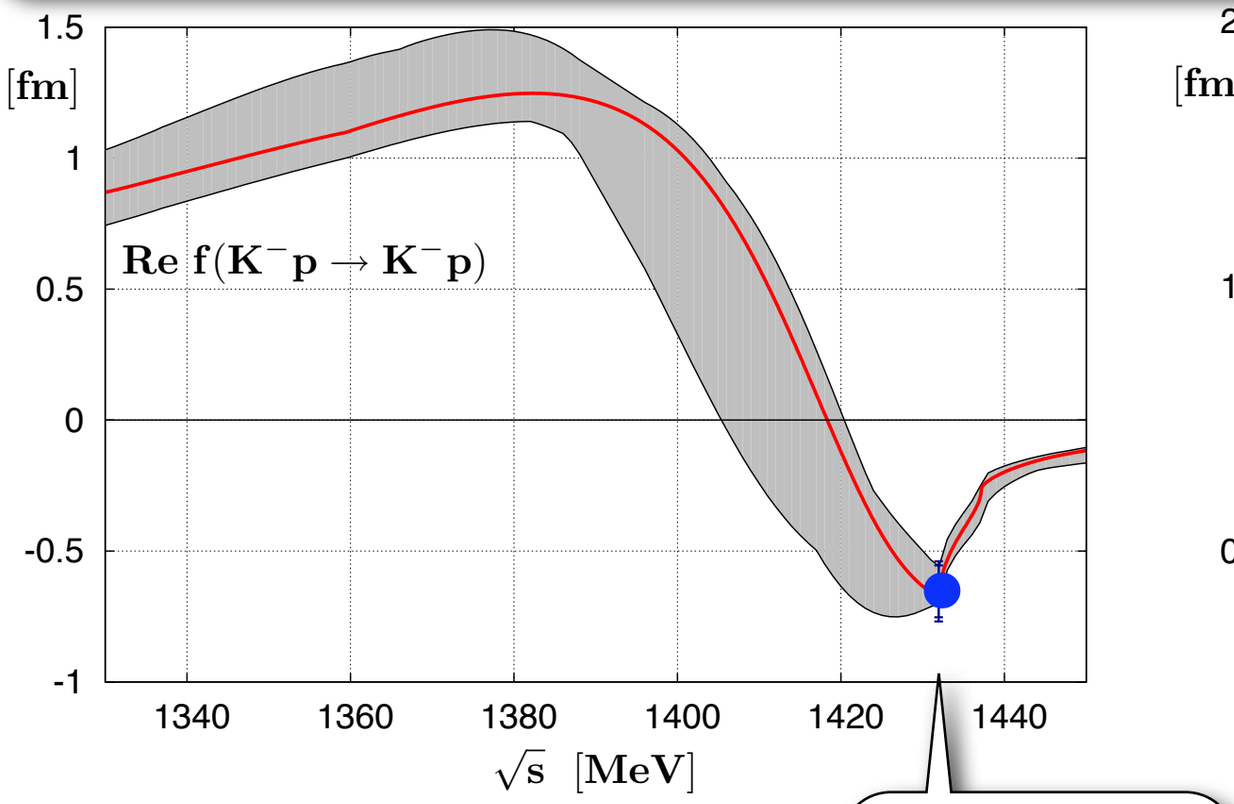
$\mathrm{K^-p}$ SCATTERING AMPLITUDE

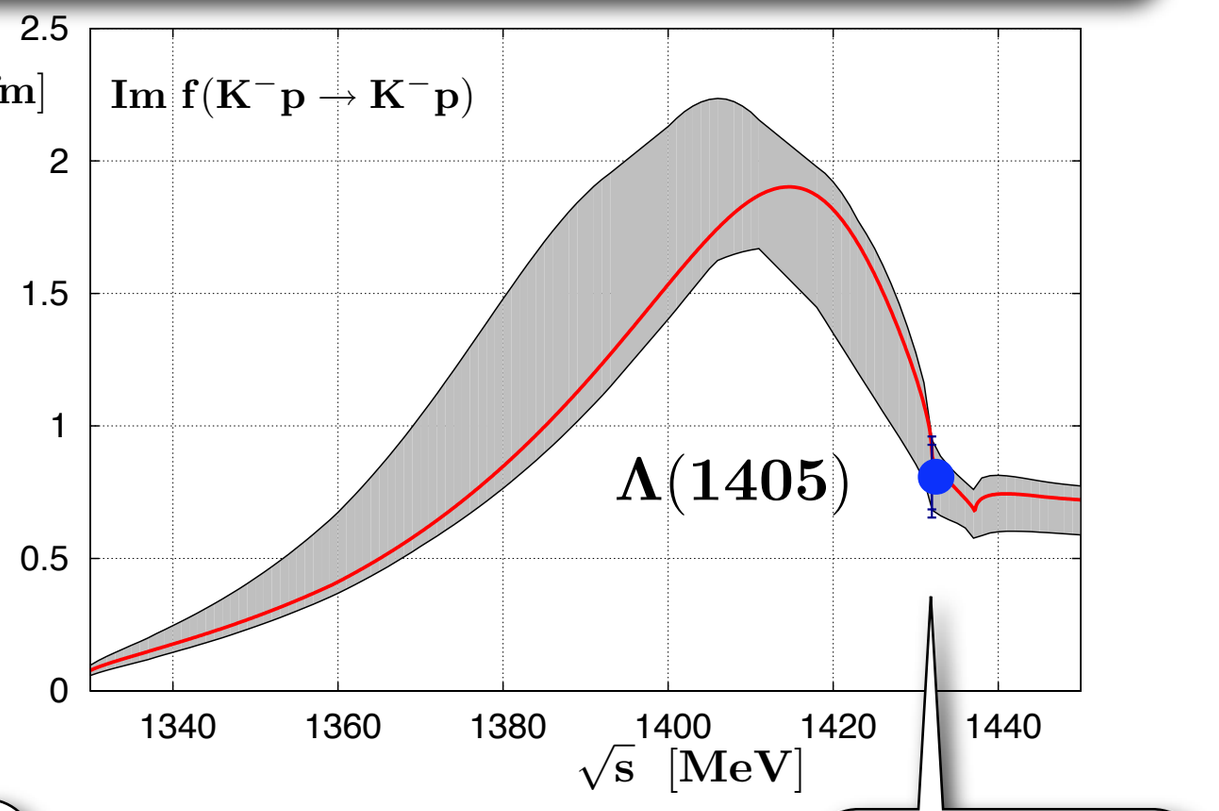
$$\mathrm{f(K^-p) = \frac{1}{2}\left[f_{\bar{K}N}(I=0) + f_{\bar{K}N}(I=1)\right]}$$

Y. Ikeda, T. Hyodo, W. W.
PLB 706 (2011) 63
NPA881 (2012) 98

- threshold region and subthreshold extrapolation:

$\Lambda(1405)$: $\bar{\mathrm{K}}\mathrm{N}$ $(\mathrm{I}=0)$ **quasibound state** embedded in the $\pi\Sigma$ continuum





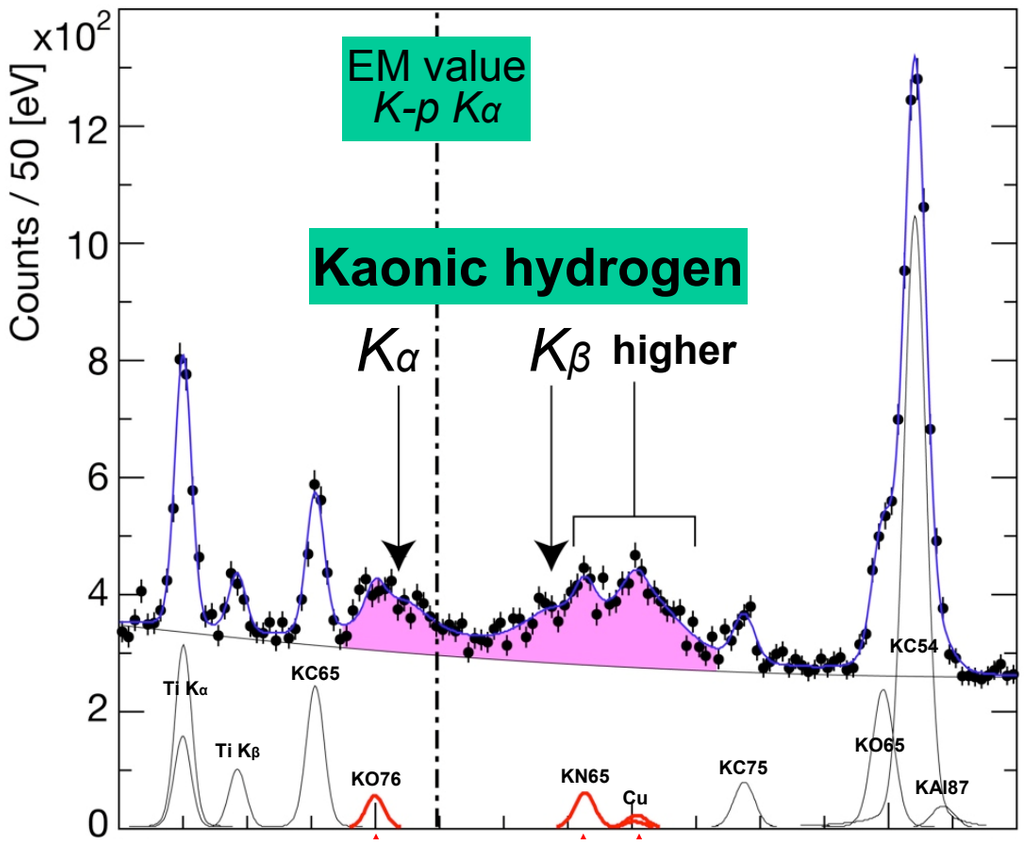
- complex scattering length (including Coulomb corrections)

$$\mathrm{Re\ a(K^-p) = -0.65 \pm 0.10\ \ fm}$$

$$\mathrm{Im\, a(K^-p) = 0.81 \pm 0.15\ \ fm}$$

CONSTRAINTS from SIDDHARTA

- **Kaonic hydrogen** precision data

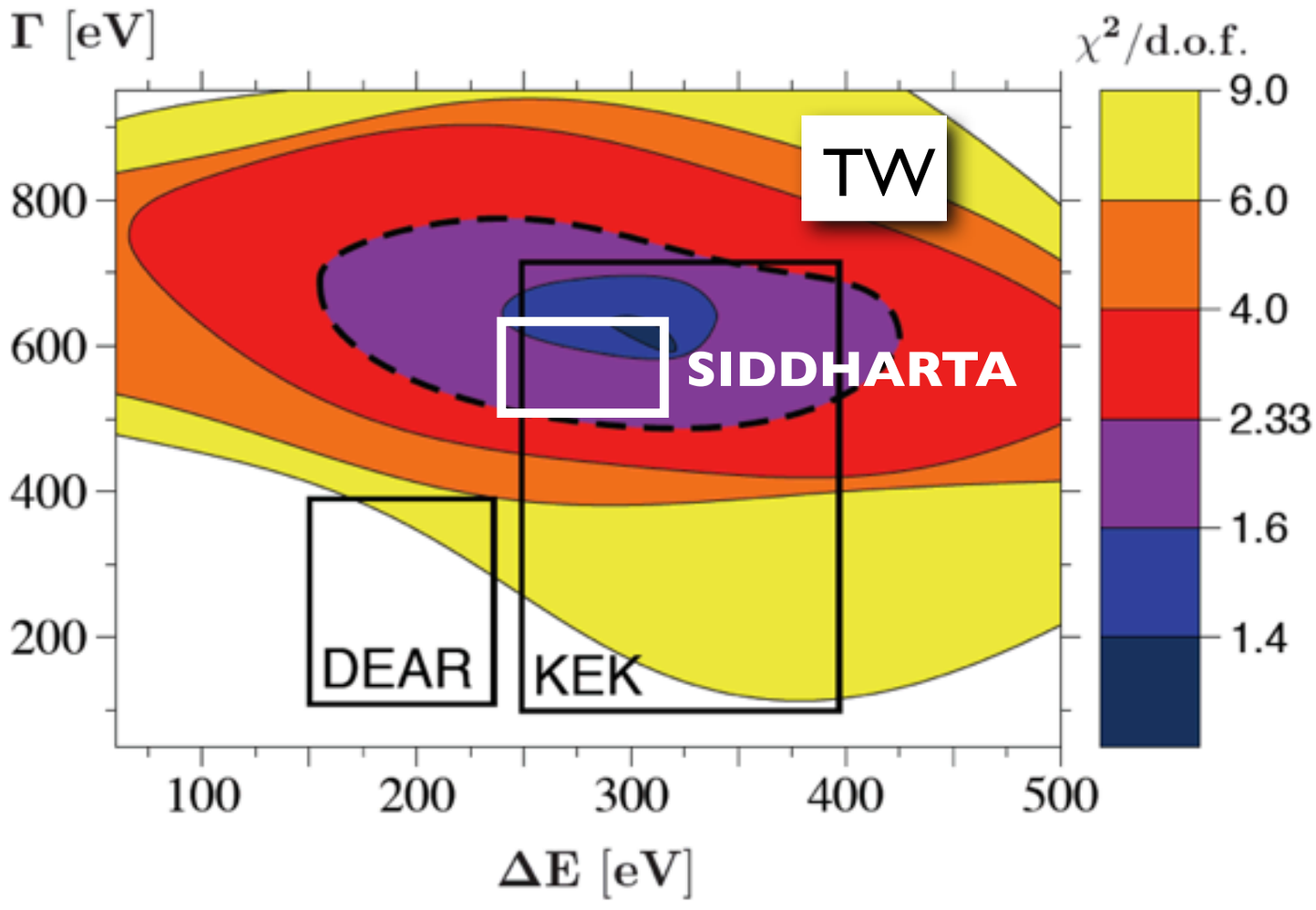


M. Bazzi et al. (SIDDHARTA)
Phys. Lett. B 704 (2011) 113

- strong interaction shift and width:

$$\Delta E = 283 \pm 36\,(stat) \pm 6\,(syst) \quad \text{eV}$$

$$\Gamma = 541 \pm 89\,(stat) \pm 22\,(syst) \quad \text{eV}$$



- Theory:
  leading order
  (Tomozawa - Weinberg)

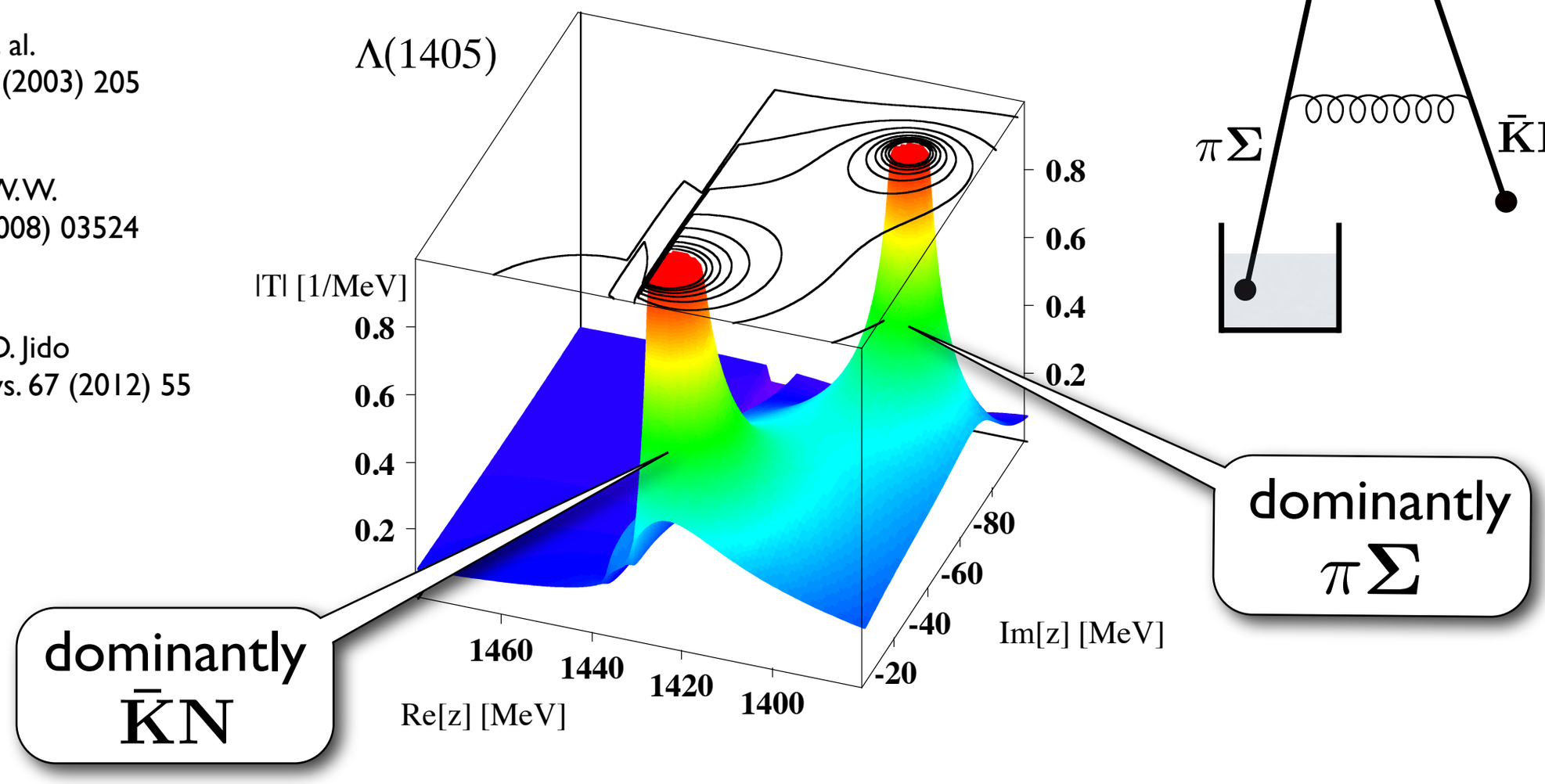
B. Borasoy, R. Nißler, W.W. Eur. Phys. J. A25 (2005) 79
B. Borasoy, U.-G. Meißner, R. Nißler PRC74 (2006) 055201

The TWO POLES scenario

D. Jido et al.
Nucl. Phys. A723 (2003) 205

T. Hyodo, W.W.
Phys. Rev. C 77 (2008) 03524

T. Hyodo, D. Jido
Prog. Part. Nucl. Phys. 67 (2012) 55



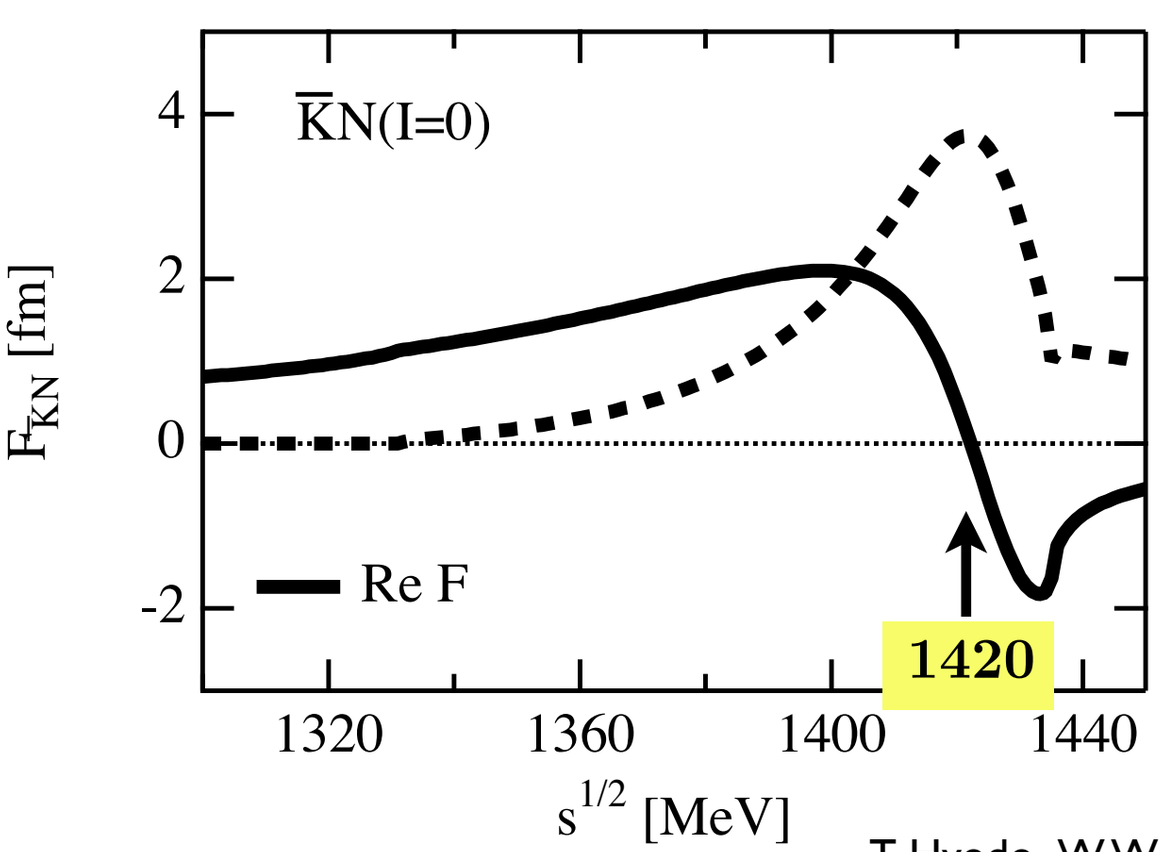
- Pole positions from **chiral SU(3) coupled-channels calculation** with **SIDDHARTA** threshold constraints:

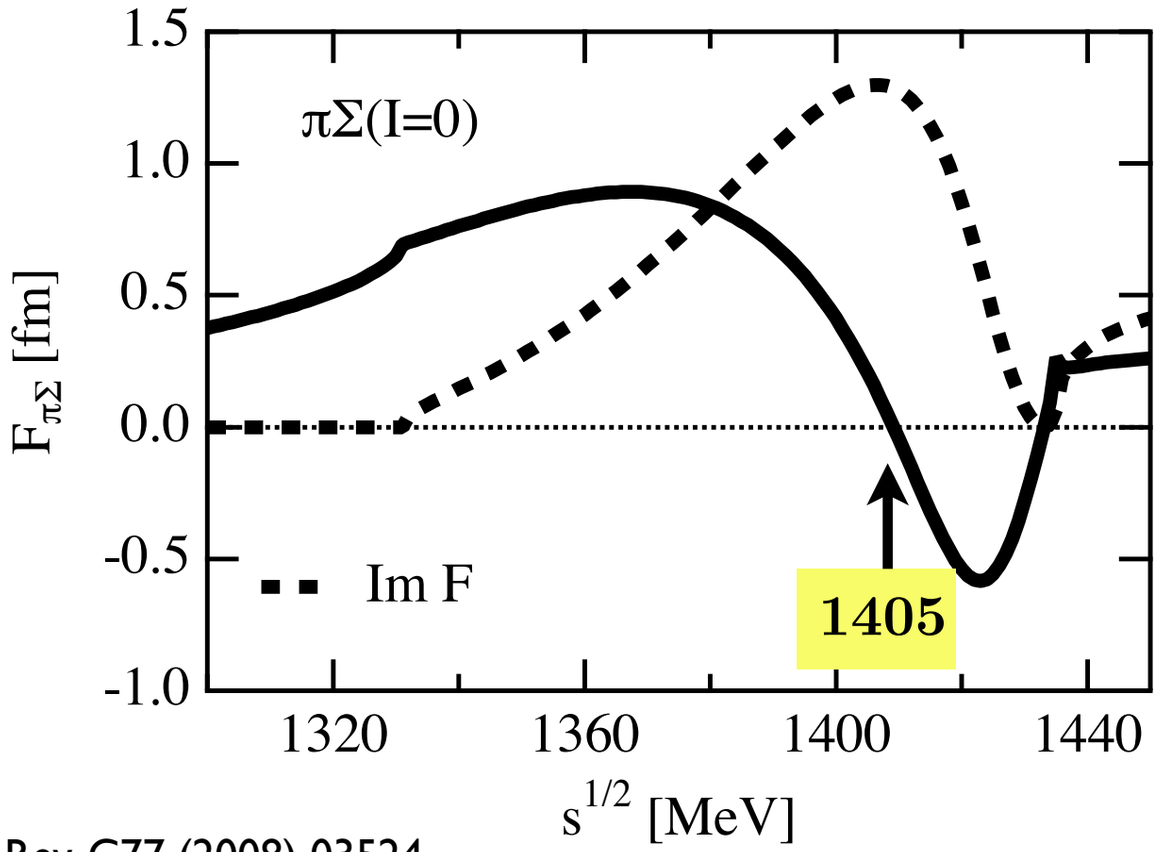
$$\mathbf{E_1 = 1424 \pm 15\ MeV} \qquad \mathbf{E_2 = 1381 \pm 15\ MeV}$$
$$\mathbf{\Gamma_1 = 52 \pm 10\ MeV} \qquad \mathbf{\Gamma_2 = 162 \pm 15\ MeV}$$

Y. Ikeda, T. Hyodo, W.W.: Nucl. Phys. A 881 (2012) 98

The TWO POLES scenario (contd.)

- $\bar{K}N$ and $\pi\Sigma$ amplitudes





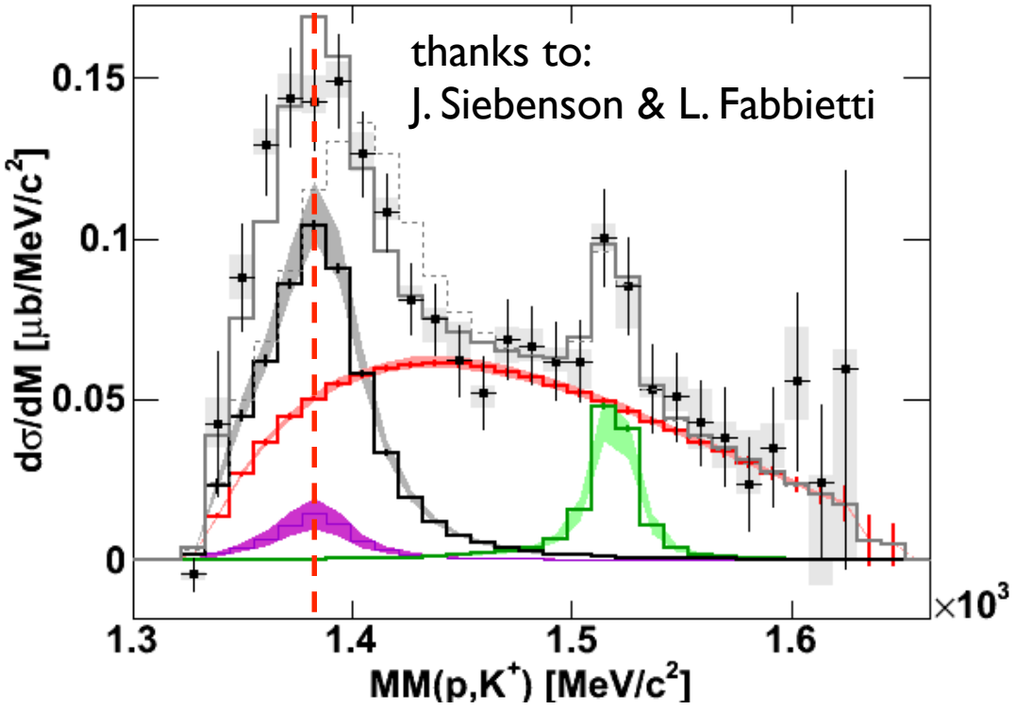
T. Hyodo, W.W.: Phys. Rev. C77 (2008) 03524

- **Note difference** in spectral maxima of $\bar{K}N$ and $\pi\Sigma$

D. Jido et al., NP A725 (2003) 263

PRODUCTION of $\Lambda(1405)$ in $p\ p \rightarrow K^+ p\ \pi^{\pm}\Sigma^{\mp}$

$\Sigma^+\pi^-$ + $\Sigma^-\pi^+$ channel

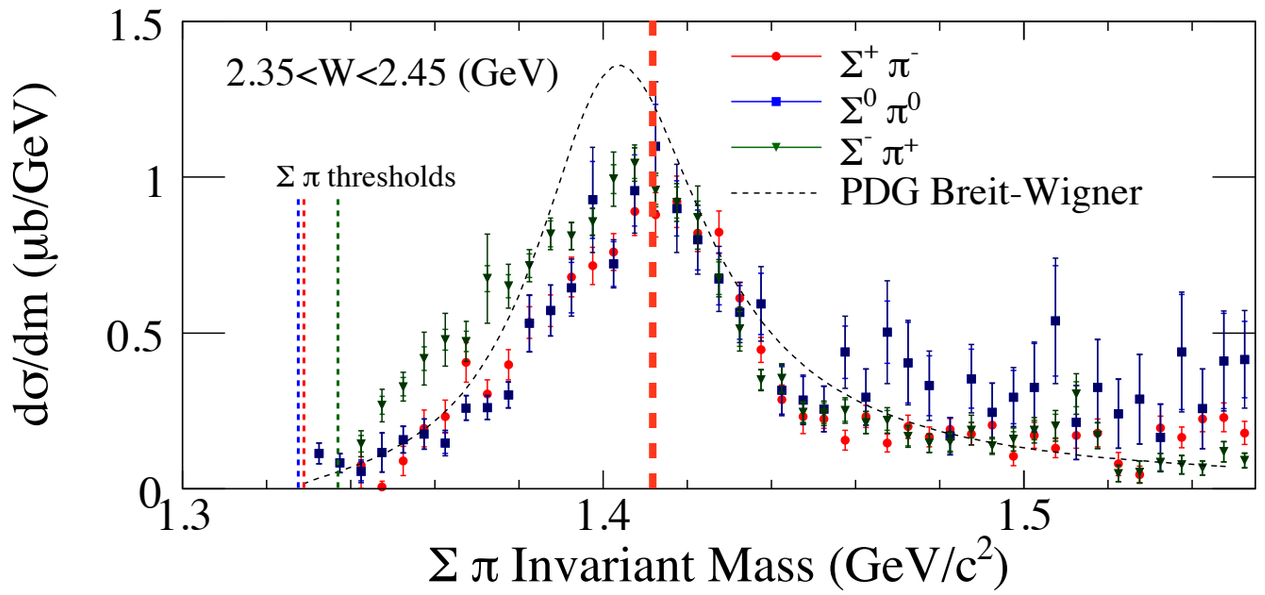


HADES collaboration
arXiv:1208.0205
Nucl. Phys. A 881 (2012) 178

p+p → $\Lambda(1405)+p+K^+$
$\Sigma(1385)^0+p+K^+$
$\Lambda(1520)+p+K^+$
$\Sigma^{+/-}+\pi^{-/+}+p+K^+$

PHOTOPRODUCTION of $\Lambda(1405)$ at JLAB $\gamma\ p \rightarrow K^+\ \pi\Sigma$

- **Note difference** in spectral maxima for **photoproduction** vs. **proton-induced** production

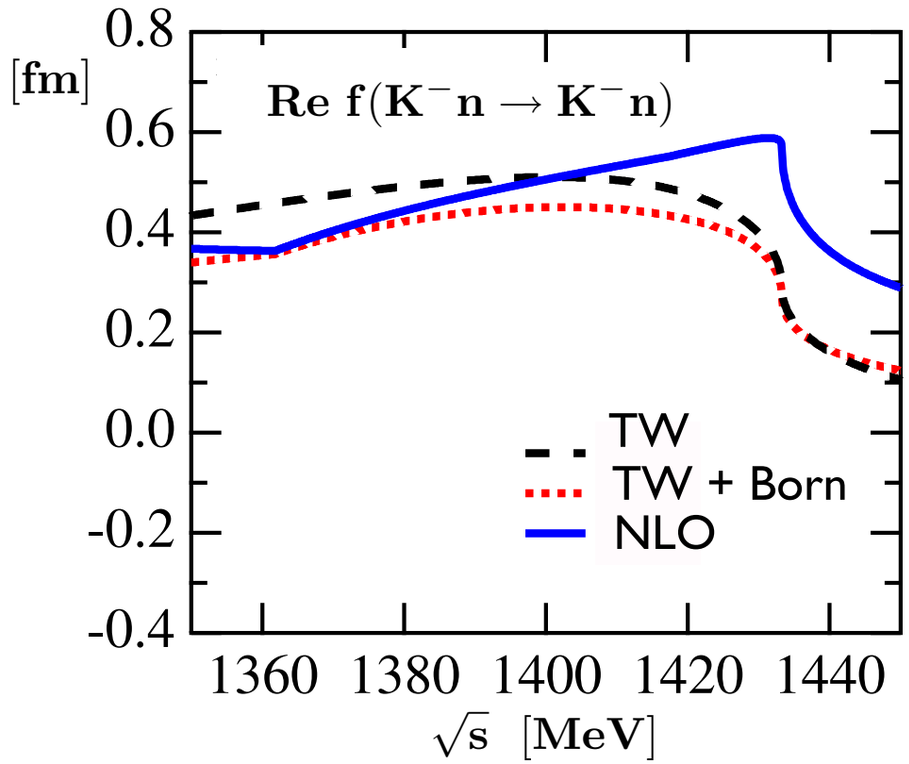


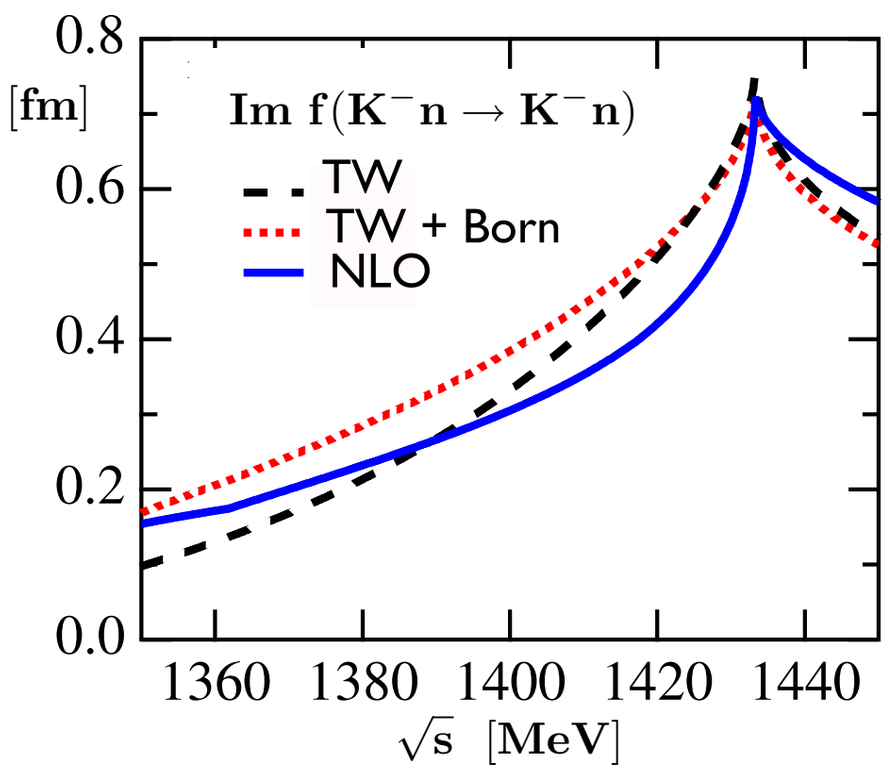
CLAS collaboration
arXiv:
1301.5000

CHIRAL SU(3) COUPLED CHANNELS DYNAMICS

- Predicted **antikaon-neutron** amplitudes at and below threshold

Y. Ikeda, T. Hyodo, W. Weise : Phys. Lett. B 706 (2011) 63 , Nucl. Phys. A 881 (2012) 98





$$a(K^- n) = 0.57^{+0.04}_{-0.21} + \mathrm{i}\, 0.72^{+0.26}_{-0.41} \quad \mathrm{fm}$$

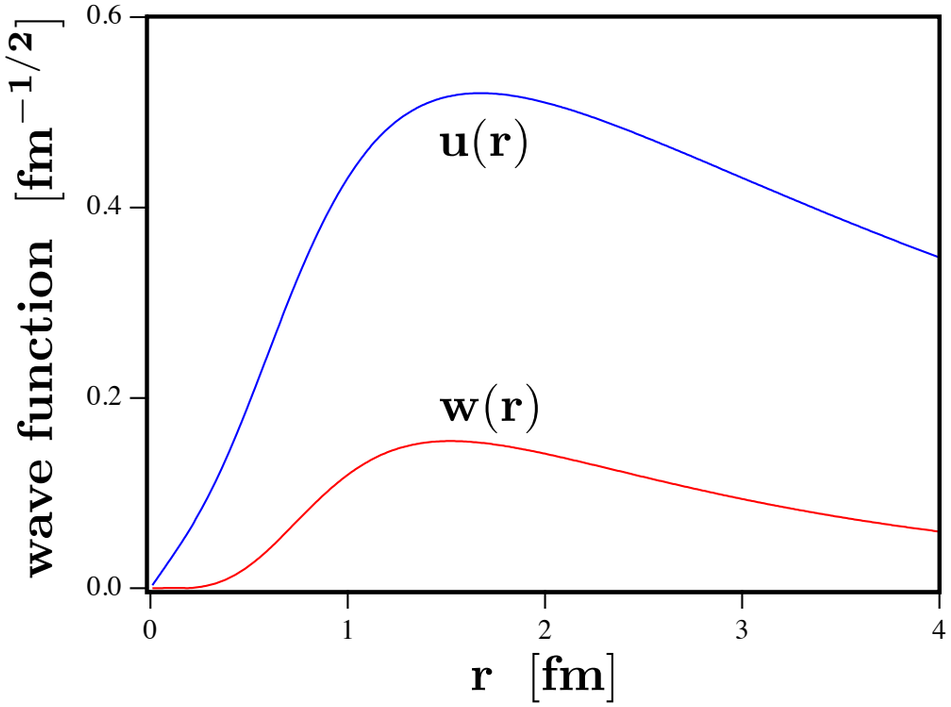
- **Needed**: accurate constraints from **antikaon-deuteron** threshold measurements
  - **complete** information for both isospin $\mathrm{I} = 0$ and $\mathrm{I} = 1$ $\bar{\mathrm{K}}\mathrm{N}$ channels
  - plus potentially important information about **K-NN absorption**

ANTIKAON - DEUTERON THRESHOLD PHYSICS

… looking forward to **SIDDHARTA 2**

- **Strategies**: Multiple scattering (MS) theory vs. three-body (Faddeev) calculations with Chiral SU(3) Coupled Channels input
- **MS approach** (fixed scatterer approximation): $\mathbf{K^- d}$ **scattering length**

S.S. Kamalov, E. Oset, A. Ramos: Nucl. Phys. A 690 (2001) 494

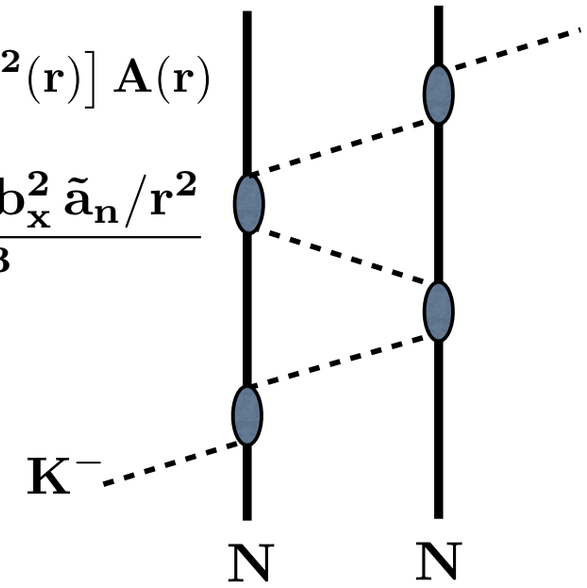


$$\mathbf{a(K^- d)} = \left(1 + \frac{\mathbf{m_K}}{\mathbf{M_d}}\right)^{-1} \int_0^\infty \mathbf{dr}\left[\mathbf{u^2(r)} + \mathbf{w^2(r)}\right] \mathbf{A(r)}$$

$$\mathbf{A(r)} = \frac{\tilde{\mathbf{a}}_\mathbf{p} + \tilde{\mathbf{a}}_\mathbf{n} + (\mathbf{2}\,\tilde{\mathbf{a}}_\mathbf{p}\,\tilde{\mathbf{a}}_\mathbf{n} - \mathbf{b_x^2})/\mathbf{r} - \mathbf{2}\,\mathbf{b_x^2}\,\tilde{\mathbf{a}}_\mathbf{n}/\mathbf{r^2}}{\mathbf{1} - \tilde{\mathbf{a}}_\mathbf{p}\,\tilde{\mathbf{a}}_\mathbf{n}/\mathbf{r^2} + \mathbf{b_x^2}\,\tilde{\mathbf{a}}_\mathbf{n}/\mathbf{r^3}}$$

$$\tilde{\mathbf{a}}_\mathbf{p} = \left(1 + \frac{\mathbf{m_K}}{\mathbf{M_N}}\right) \mathbf{a(K^- p \to K^- p)}$$

$$\tilde{\mathbf{a}}_\mathbf{n} = \left(1 + \frac{\mathbf{m_K}}{\mathbf{M_N}}\right) \mathbf{a(K^- n \to K^- n)}$$



$\mathbf{b_x}$ incorporates $\mathbf{K^- p \to \bar{K}_0\, n}$ and $\mathbf{\bar{K}_0\, n \to \bar{K}_0\, n}$

- Using IHW input scattering lengths constrained by SIDDHARTA kaonic hydrogen:

$\mathbf{a(K^- d)}$ [fm]	
full MS	$-1.54 + i1.64$
no charge exchange	$-1.04 + i1.34$
impulse approximation	$-0.13 + i1.81$

T. Hyodo, Y. Ikeda, W.W. (2012) preliminary

ANTIKAON - DEUTERON SCATTERING LENGTH

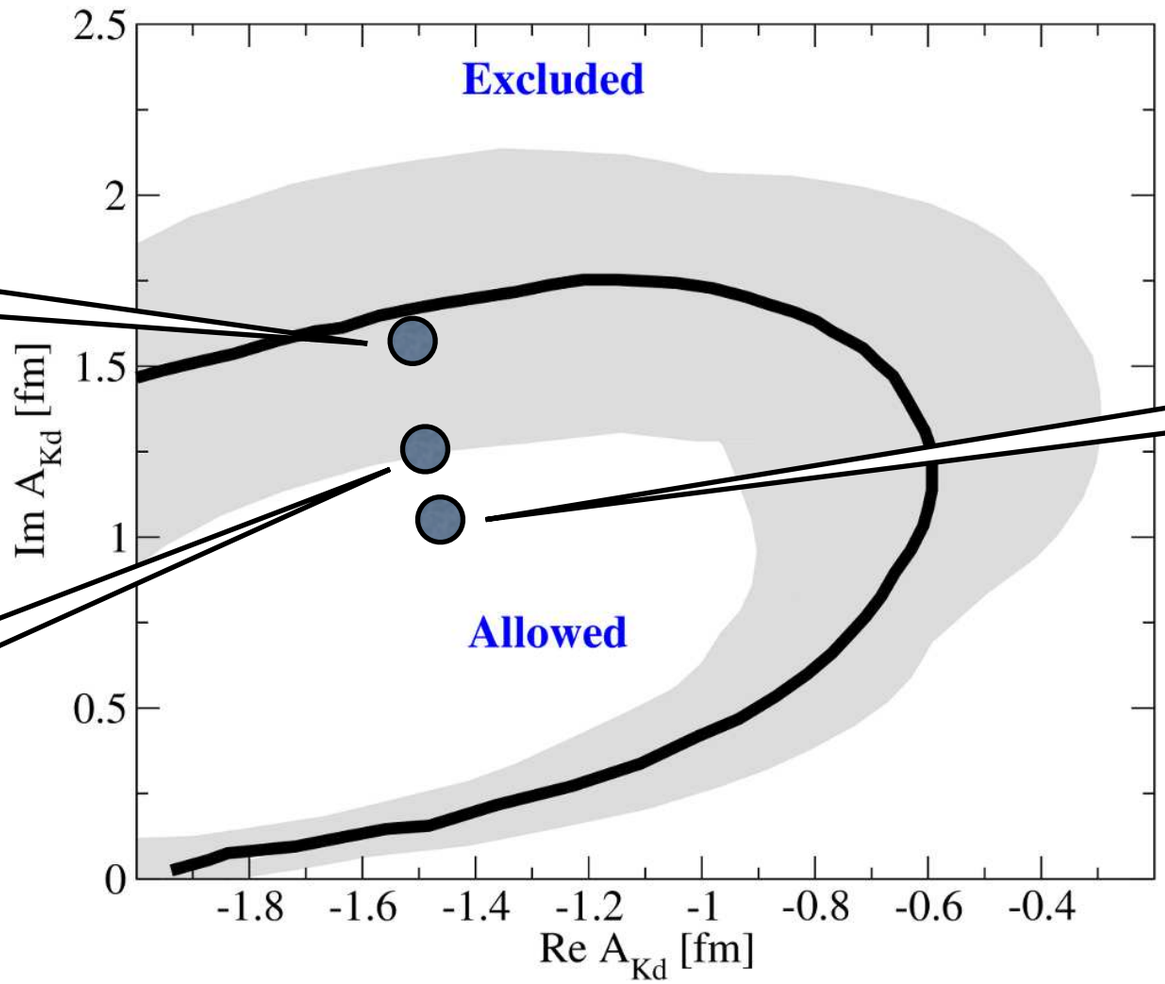
- Recent calculations using SIDDHARTA - constrained input

Multiple scattering using IHW scattering lengths

T. Hyodo, Y. Ikeda, W.W. (2012-13) preliminary

Faddeev calculation separable "chiral" amplitudes

N.V. Shevchenko
NPA 890-891 (2012) 50



Non-relativistic effective field theory

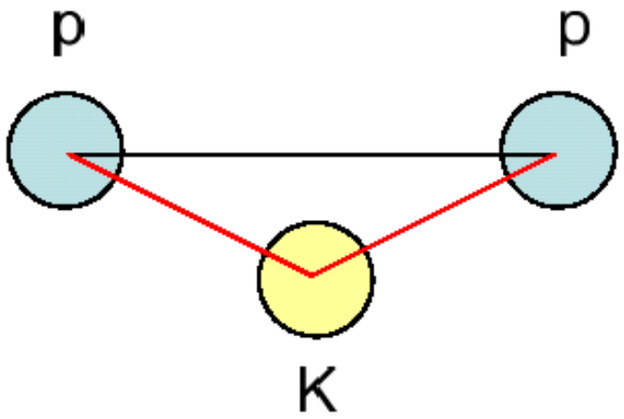
M. Döring, U.-G. Meißner
Phys. Lett. B 704 (2011) 663

- Primary theoretical uncertainties from $\mathbf{K^- n}$ amplitude
- Predicted energy **shift** and **width** of kaonic deuterium (Faddeev calculation):

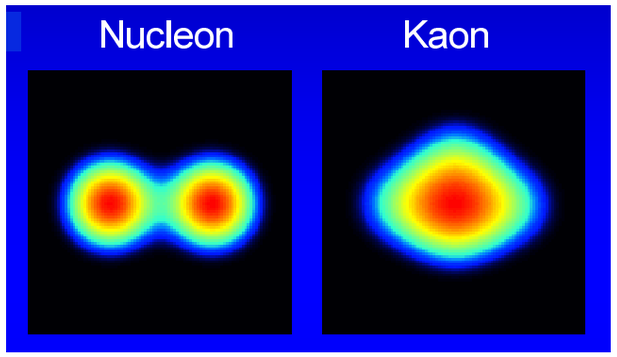
$$\mathbf{\Delta E_{1s} = -794\ eV} \qquad \mathbf{\Gamma_{1s}(K^- d) = 1012\ eV}$$

- Not included: $\mathbf{K^- d \to YN}$ absorption

UPDATE on QUASIBOUND K^-pp



3-Body (Faddeev) calculations



Variational calculations

- . . . now consistently using amplitudes from **Chiral SU(3) coupled-channels** dynamics including **energy dependence** in subthreshold extrapolations

- Calculated **binding energy** and **width** (in MeV) of the K^-pp system

modest binding
large width

	[1]	[2]	[3]
B	16	17–23	9–16
Γ	41	40–70	34–46

remarkable degree of consistency

[1] Variational (hyperspherical harmonics): N. Barnea, A. Gal, E.Z. Livets ; Phys. Lett. B 712 (2012) 132

[2] Variational (Gaussian trial wave functions): A. Doté, T. Hyodo, W.W. ; Phys. Rev. C 79 (2009) 014003

[3] Faddeev: Y. Ikeda, H. Kamano, T. Sato ; Prog. Theor. Phys. 124 (2010) 533

Part II.

STRANGENESS
in
BARYONIC MATTER
and
NEWS from NEUTRON STARS

Brief History, Part I

Kaons and Antikaons in Nuclear Matter

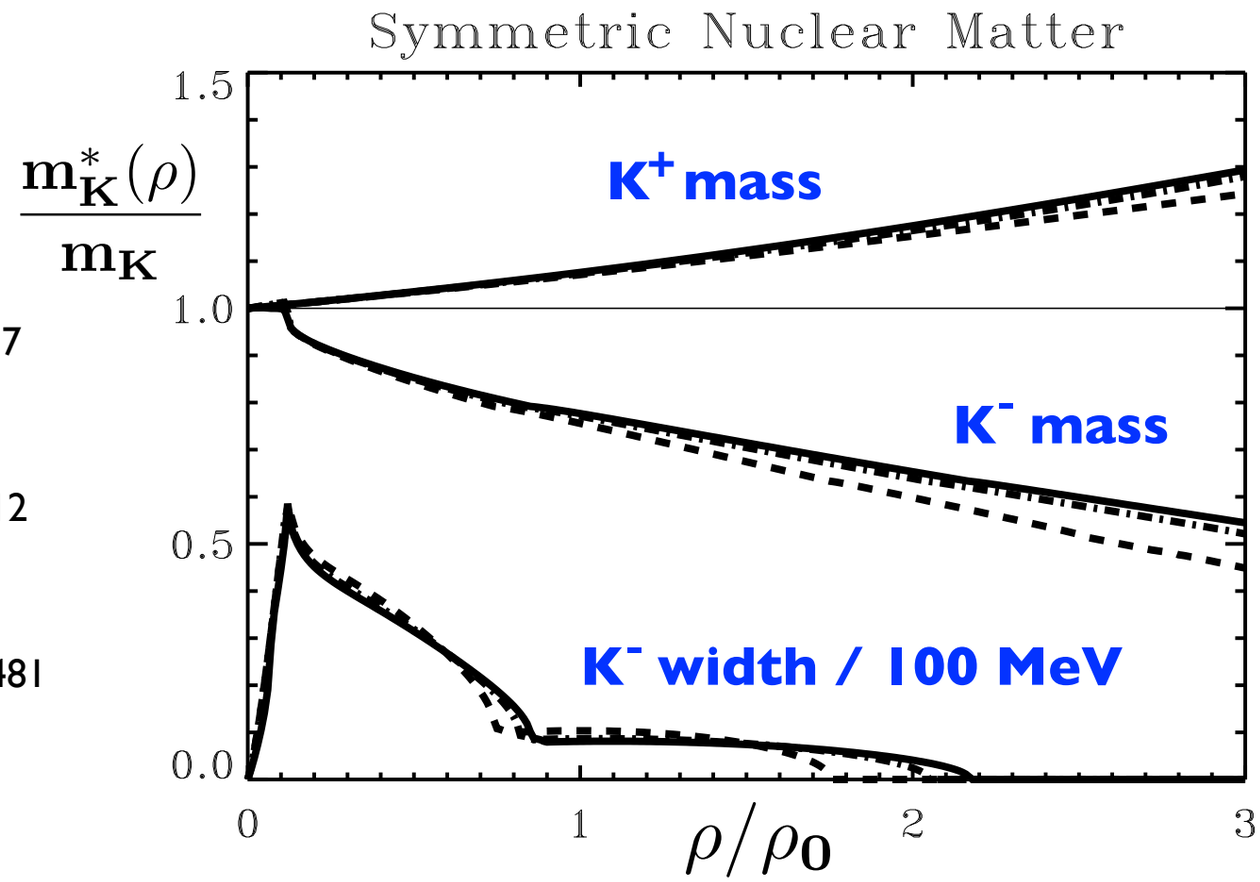
In-medium Chiral SU(3) Dynamics with Coupled Channels

- **Kaon spectrum in matter** determined by:

$$\omega^2 - \vec{q}^{\,2} - m_K^2 - \Pi_K(\omega, \vec{q}; \rho) = 0$$

$$\Pi_{K^-} = 2\omega U_{K^-} = -4\pi \left[f_{K^- p}\, \rho_p + f_{K^- n}\, \rho_n \right] + \ldots +$$

Pauli blocking, Fermi motion, 2N correlations



V. Koch
Phys. Lett. B 337 (1994) 7

M. Lutz
Phys. Lett. B 426 (1998) 12

A. Ramos, E. Oset
Nucl. Phys. A 671 (2000) 481

T. Waas, N. Kaiser, W. W.:
Phys. Lett. B 379 (1996) 34

T. Waas, W. W.:
Nucl. Phys. A 625 (1997) 287

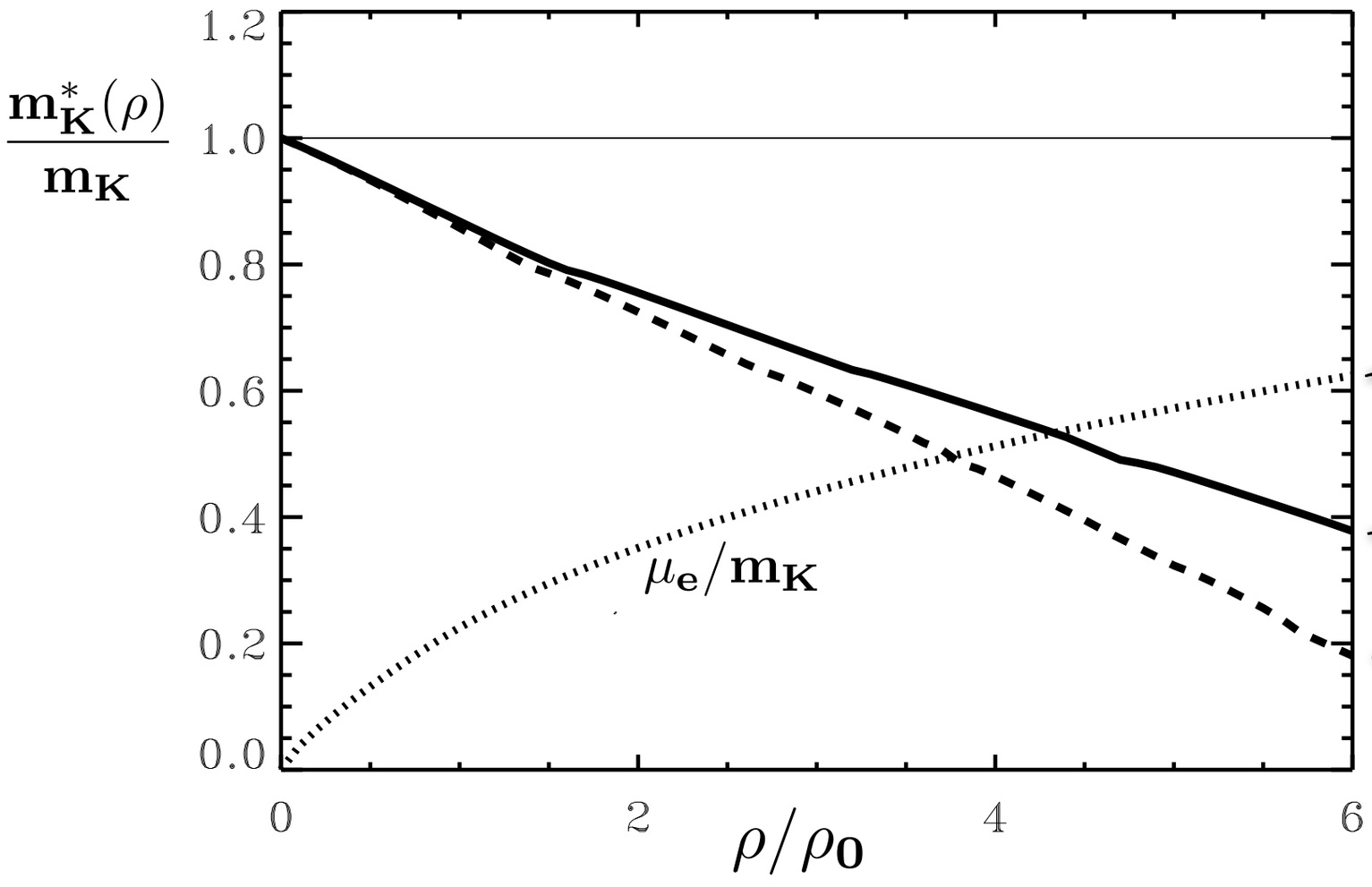
M. Lutz, C.L. Korpa, M. Möller
Nucl. Phys. A 808 (2008) 124

- Note: In-medium $\bar{K}$ width drops when mass falls below $\pi\Sigma$ threshold

Brief History, Part II

Kaon Condensation in Neutron Star Matter ?

- first suggested by D. Kaplan, A. Nelson (1985) on the basis of **attractive K^-N Tomozawa - Weinberg term**
- at high density, energetically favourable to condense K^- ?



T. Waas, M. Rho, W. W. :
Nucl. Phys. A 617 (1997) 449

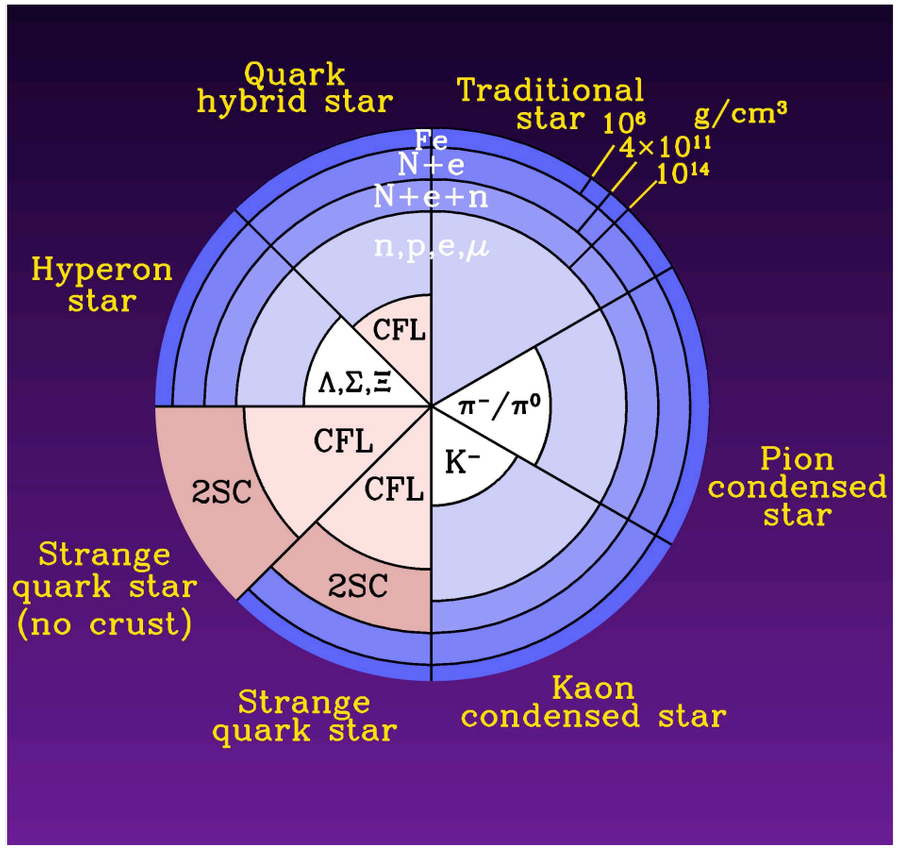
electron chemical potential

including **NN correlations**

in-medium chiral SU(3) dynamics

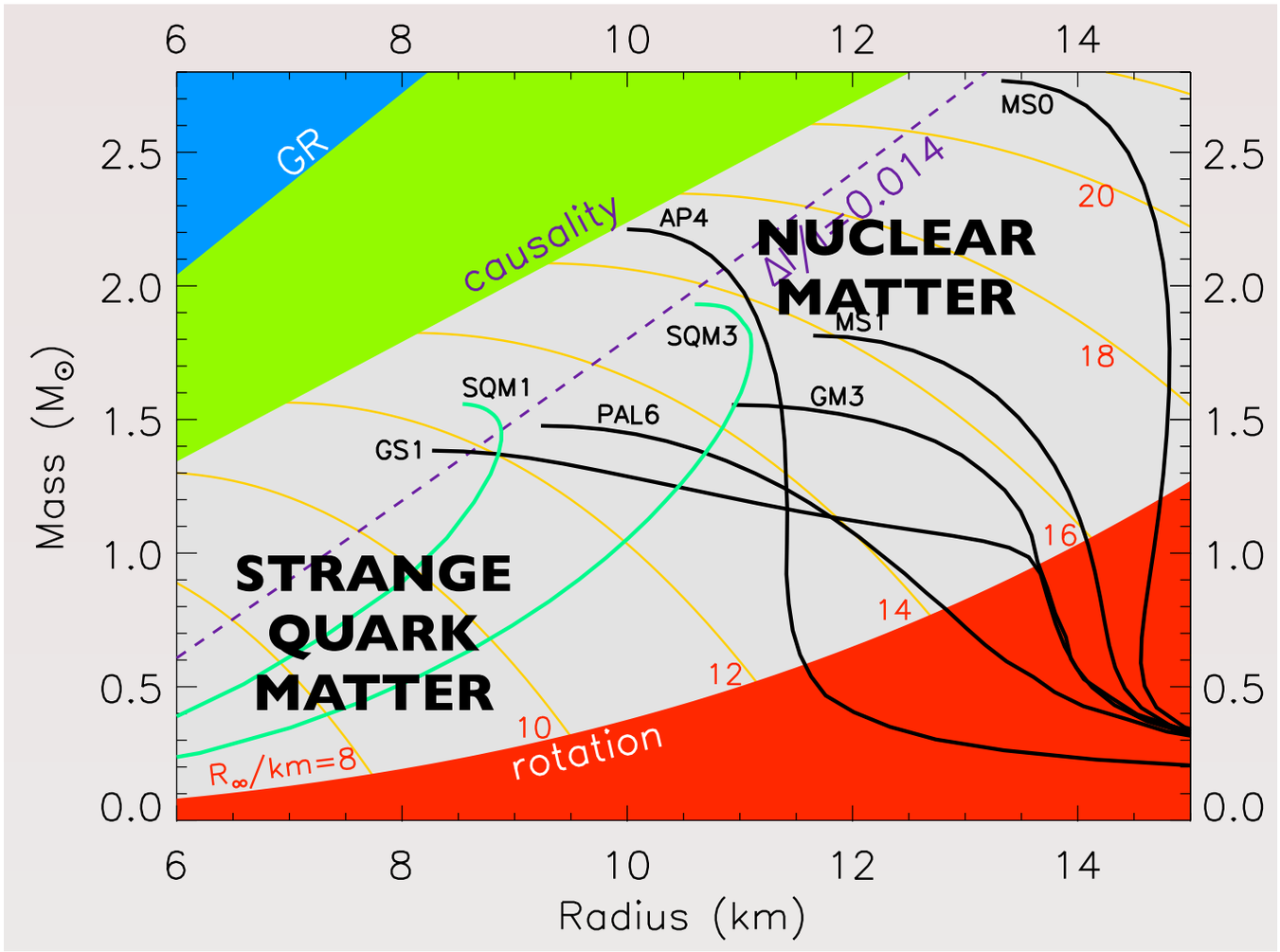
- ... **but**: conversion of kaons to hyperons via $K^-NN \to YN$!

NEUTRON STARS and the EQUATION OF STATE of DENSE BARYONIC MATTER



J. Lattimer, M. Prakash: Astrophys. J. 550 (2001) 426
Phys. Reports 442 (2007) 109

- **Mass-Radius Relation**



- **Neutron Star Scenarios**
- **T**olman-**O**ppenheimer-**V**olkov equations

$$\frac{dP}{dr} = -\frac{G}{c^2}\frac{(M + 4\pi P r^3)(\mathcal{E} + P)}{r(r - GM/c^2)}$$

$$\frac{dM}{dr} = 4\pi r^2 \frac{\mathcal{E}}{c^2}$$

New constraints from NEUTRON STARS

A two-solar-mass neutron star measured using Shapiro delay

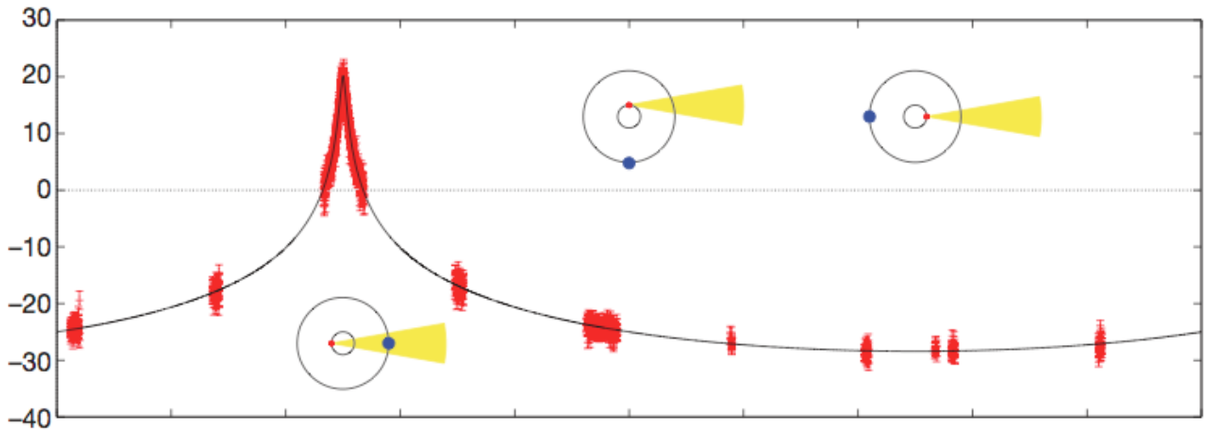
P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

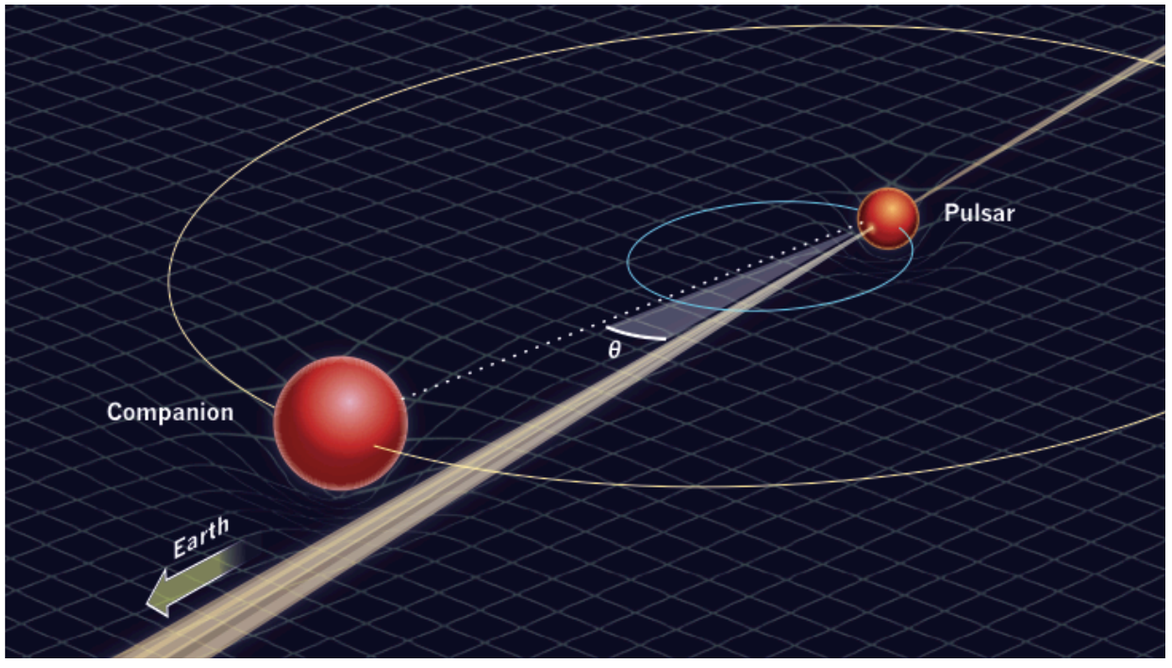
Nature, Oct. 28, 2010

direct measurement of neutron star mass from increase in travel time near companion

J1614-2230
most edge-on binary pulsar known (89.17°)
+ massive white dwarf companion (0.5 M_{sun})

heaviest neutron star with 1.97±0.04 M_{sun}





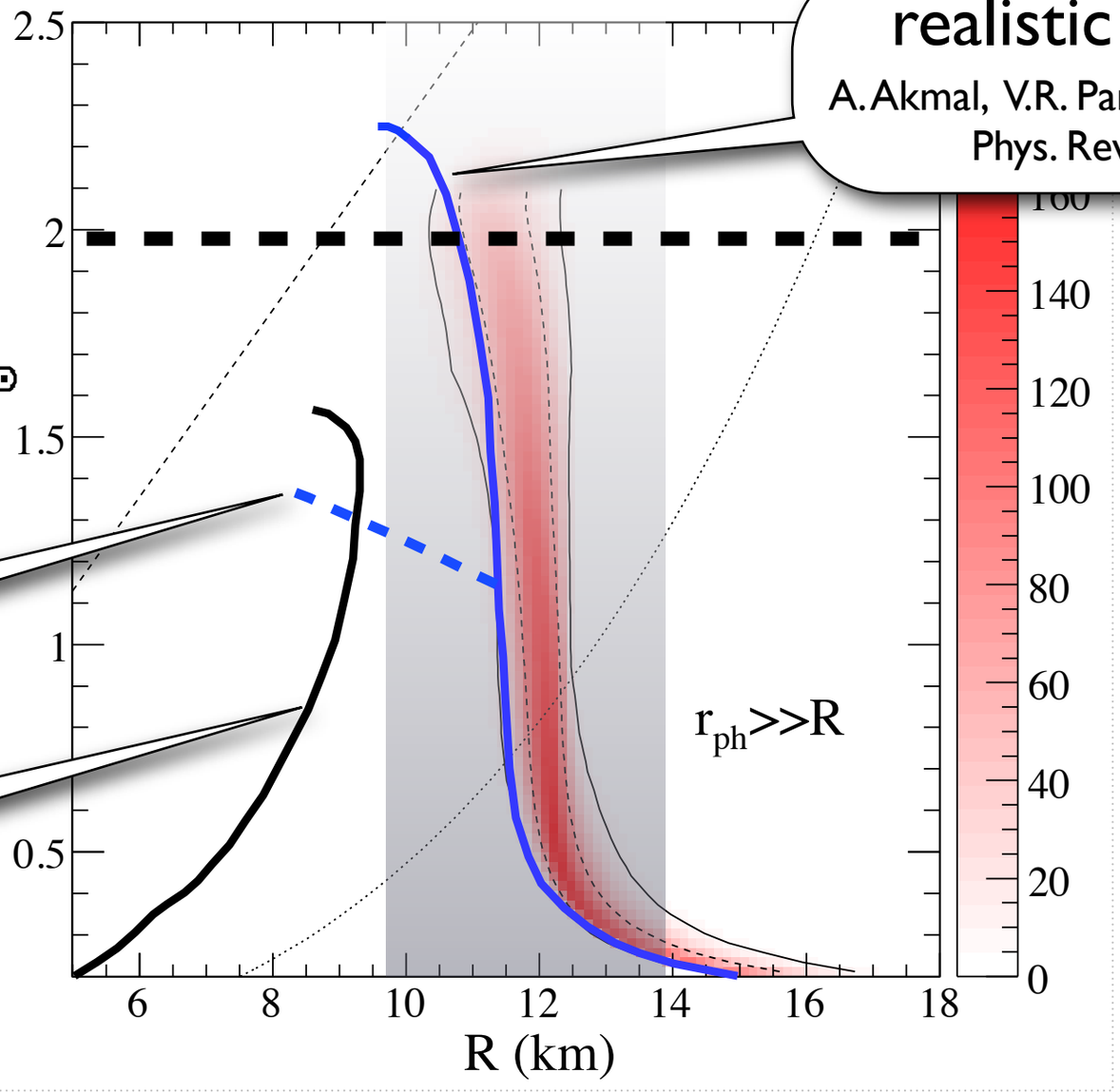
News from NEUTRON STARS

- Constraints from **neutron star observables**

A.W. Steiner, J. Lattimer, E.F. Brown
Astroph. J. 722 (2010) 33

K. Hebeler, J. Lattimer, C. Pethick, A. Schwenk
PRL 105 (2010) 161102

realistic "nuclear" EoS
A. Akmal, V.R. Pandharipande, D.G. Ravenhall
Phys. Rev. C 58 (1998) 1804



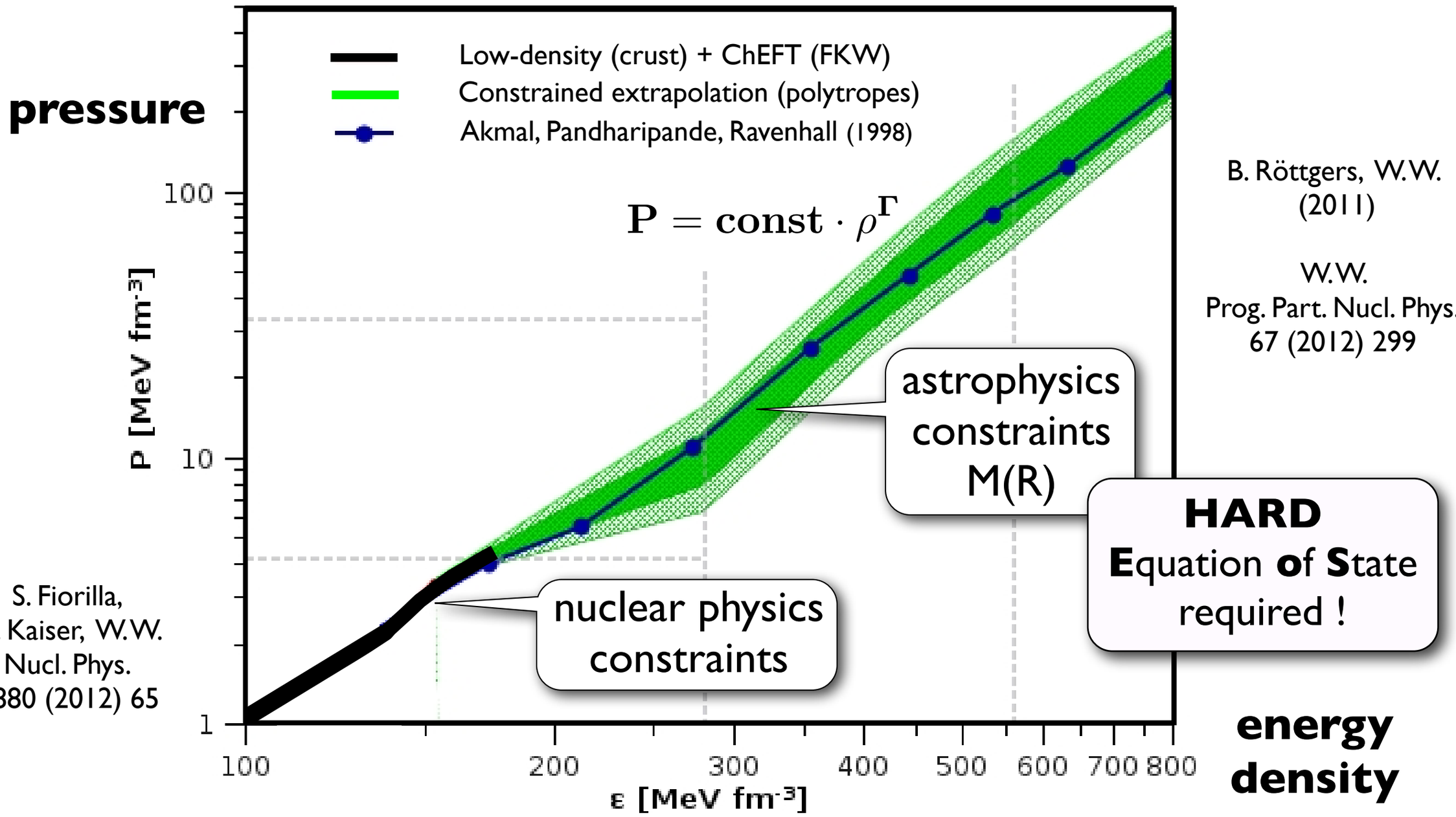
kaon condensate

quark matter

- "**Exotic**" equations of state ruled out ?

NEUTRON STAR MATTER

Equation of State



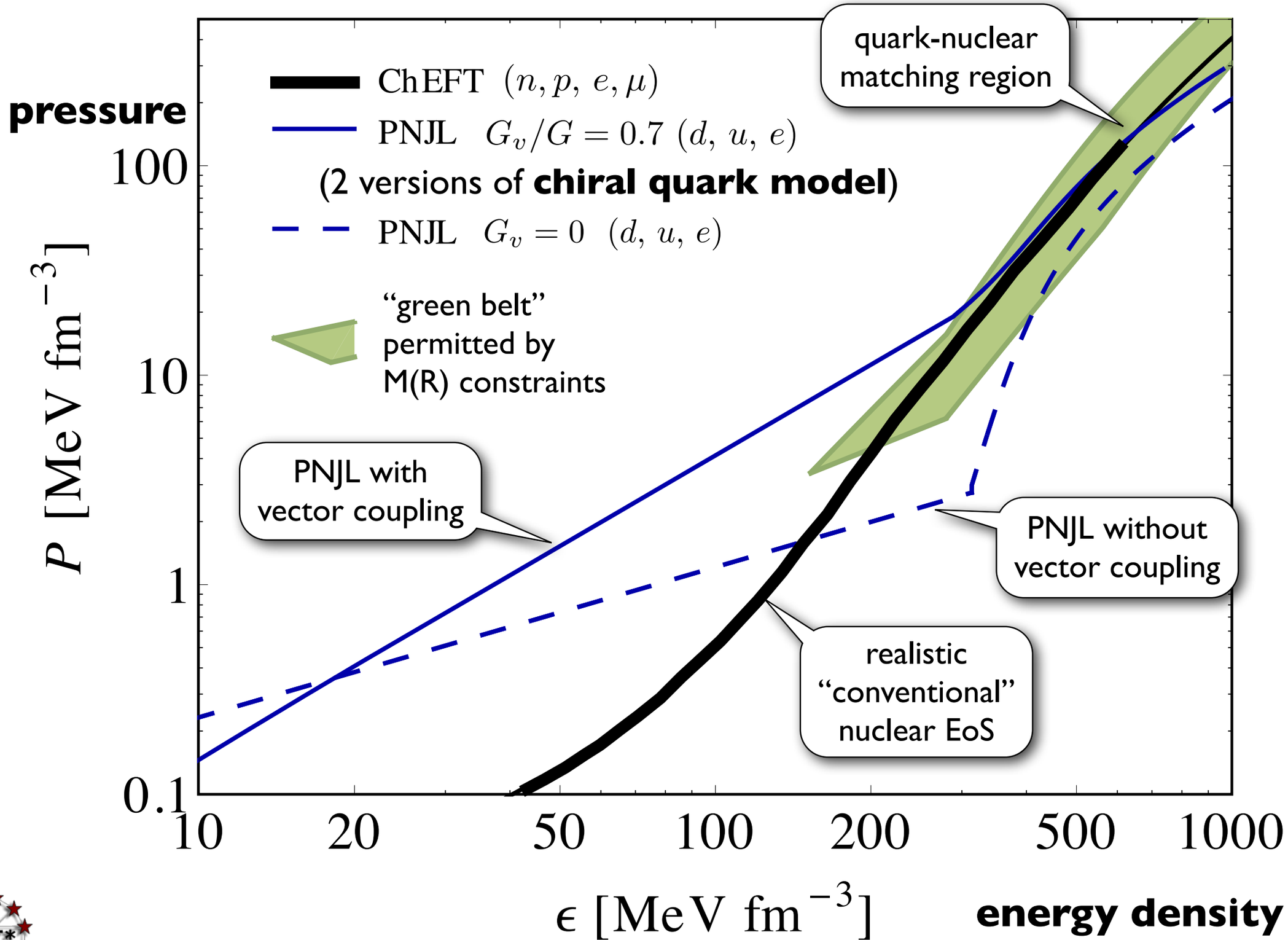
B. Röttgers, W.W. (2011)

W.W. Prog. Part. Nucl. Phys. 67 (2012) 299

S. Fiorilla, N. Kaiser, W.W. Nucl. Phys. A880 (2012) 65

- Including new neutron star constraints plus **C**hiral **E**ffective **F**ield **T**heory at lower density

NEUTRON STAR Equation of State



T. Hell,
B. Röttgers,
S. Schultess,
N. Kaiser
W.W.
(2012-13)

see also:

K. Masuda,
T. Hatsuda,
T.Takatsuka
Astroph. J.
764 (2013) 12

ECT*

NEUTRON STAR MATTER

Mass - Radius relation

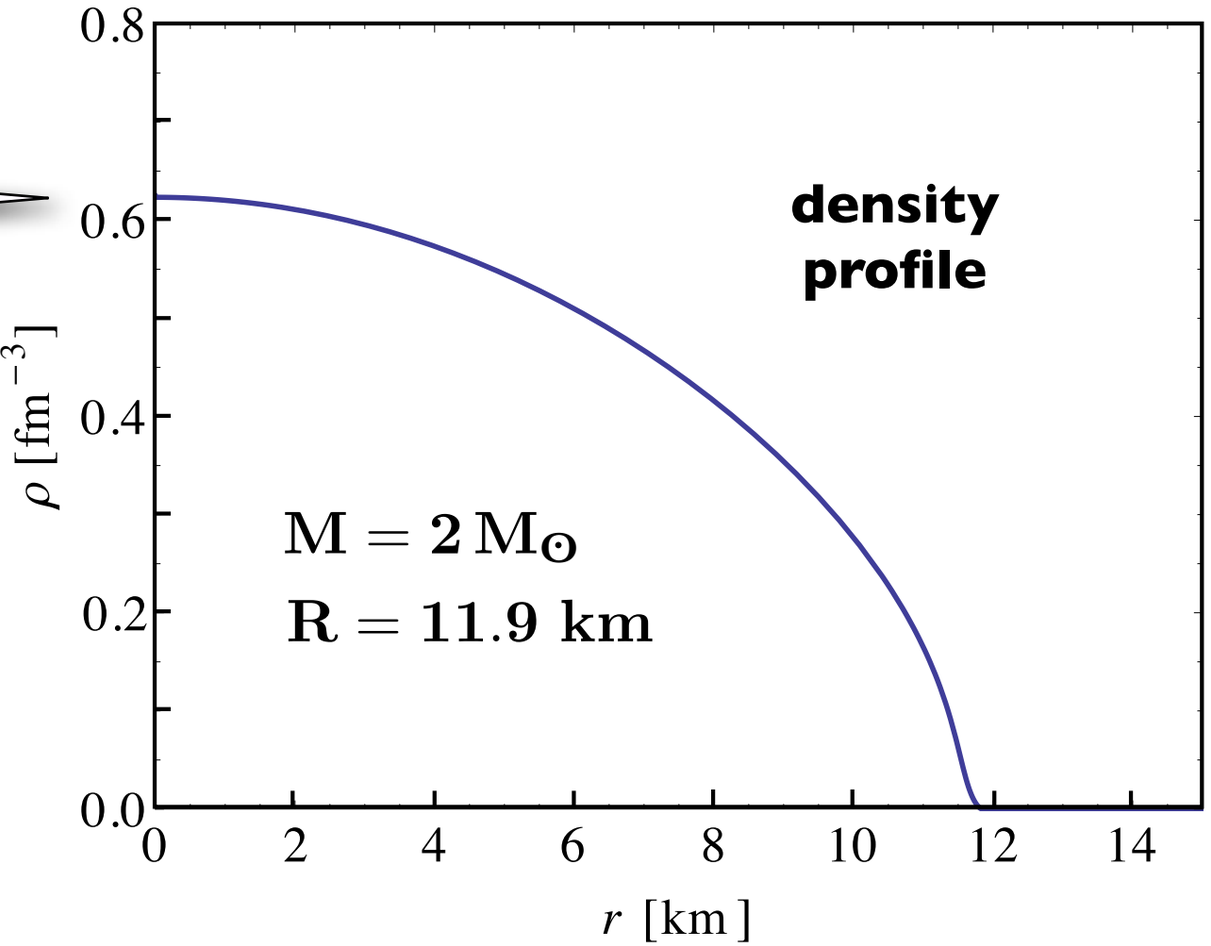
- Conventional hadronic (**baryonic** + **mesonic**) degrees of freedom

- In-medium **C**hiral **E**ffective **F**ield **T**heory up to 3 loops (reproducing thermodynamics of normal nuclear matter) including beta equilibrium $\mathbf{n} \leftrightarrow \mathbf{p} + e, \mu$

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

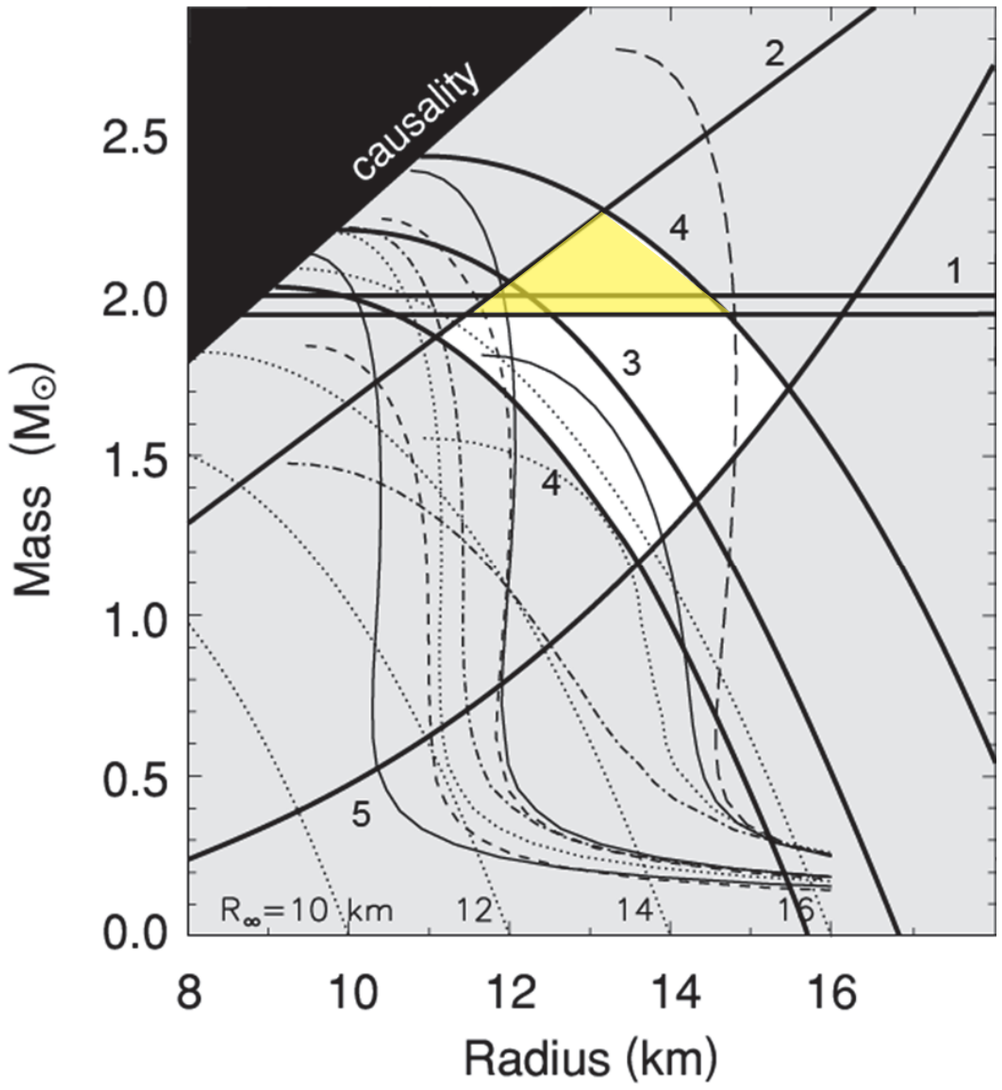
neutron star core density is less than four times ρ_0

$\rho_0 = 0.16\ \mathrm{fm}^{-3}$
(density of normal nuclear matter)



T. Hell, B. Röttgers, S. Schultess, N. Kaiser, W.W. (2012-13)

NEUTRON STARS:
MASS and RADIUS constraints



from:
J. Trümper

Irsee
Symposium
2012

HARD
Equation **o**f **S**tate
required !!

1 Largest mass J1614 - 2230
(Demorest et al. 2010)

2 Maximum gravity XTE 1814 – 338
(Bhattacharyya et al. 2005)

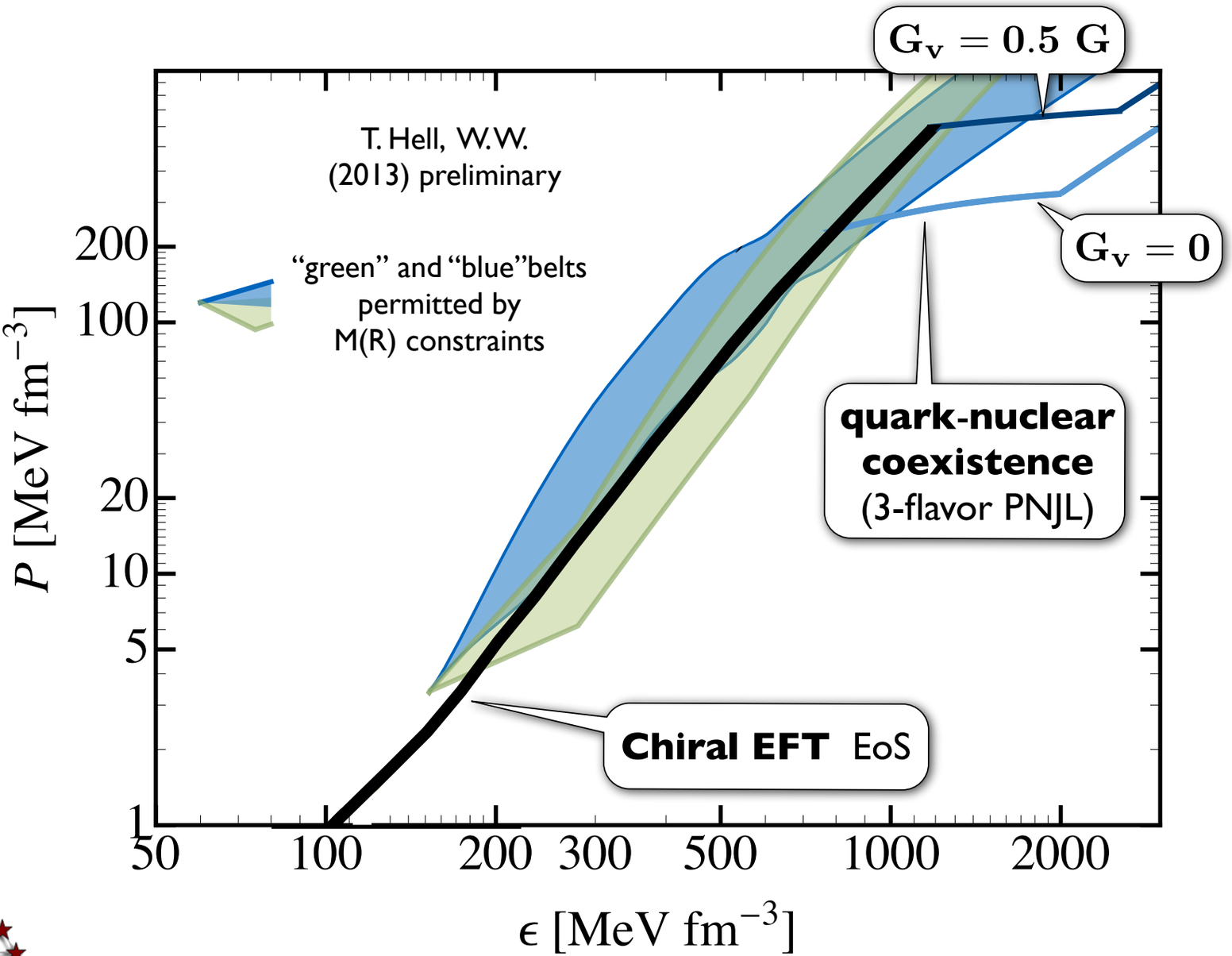
3 Minimum radius RXJ1856 - 3754
(Trümper et al. 2004)

4 Radius, 90% confidence limits LMXB 47 Tuc
(Heinke et al. 2006)

5 Largest spin frequency J1748 – 2446
(Hessels et al. 2006)

NEUTRON STAR MATTER
Equation of State

- In-medium **C**hiral **E**ffective **F**ield **T**heory up to 3 loops
  (reproducing thermodynamics of normal nuclear matter)
- **3**-flavor **PNJL** model at high densities (incl. **strange** quarks)



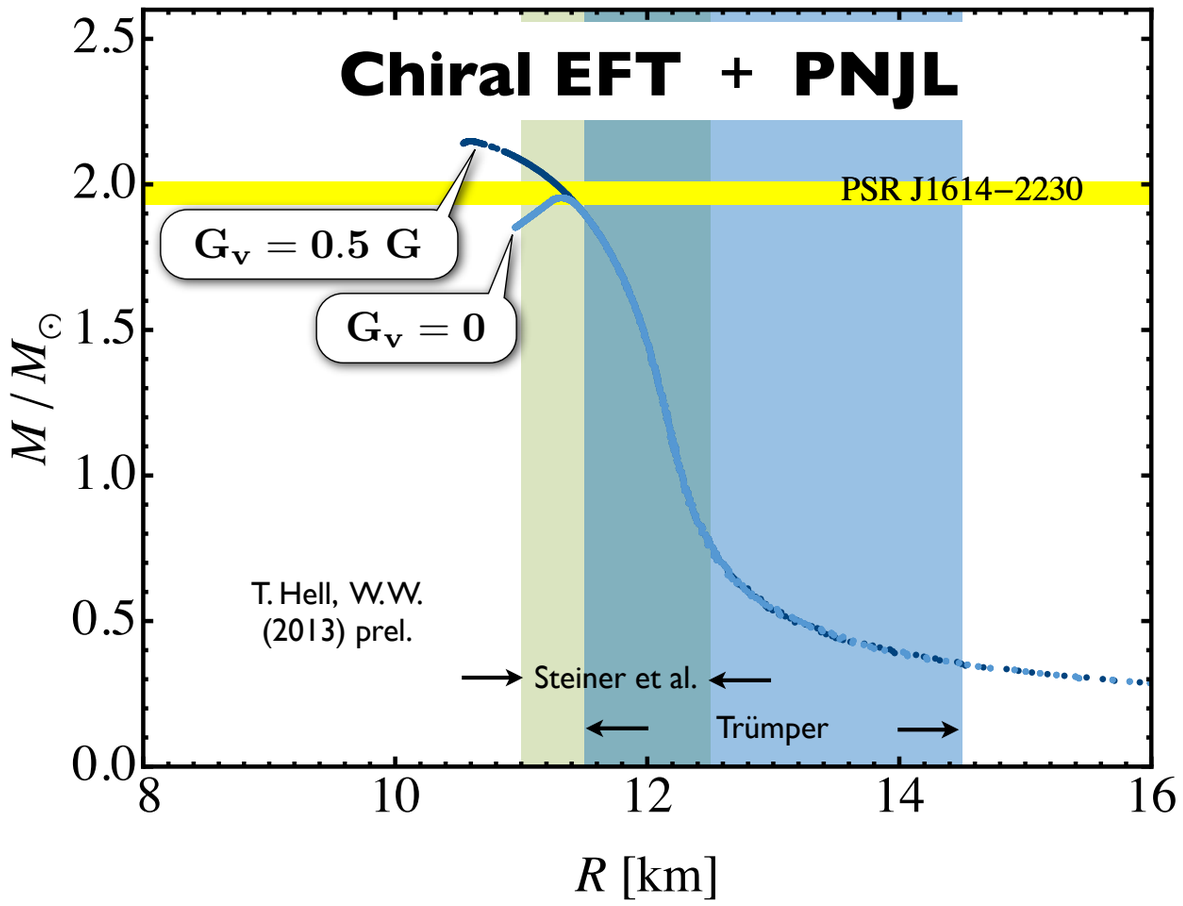
- beta equilibrium
  $\mathbf{n} \leftrightarrow \mathbf{p} + e, \mu$
- charge conservation
- coexistence region:
  Gibbs conditions

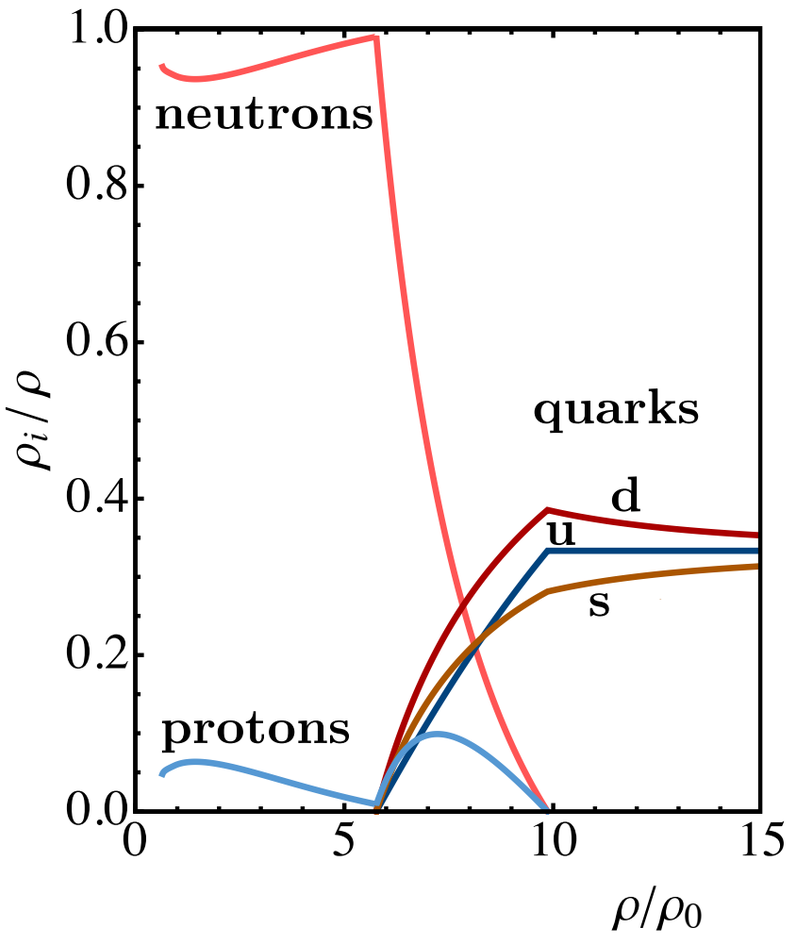
- **quark-nuclear**
  coexistence occurs
  (if at all)
  at baryon densities
  $\rho > 5\ \rho_0$

NEUTRON STAR MATTER

Mass - Radius Relation and Composition

- In-medium **C**hiral **E**ffective **F**ield **T**heory + 3-flavor **PNJL** model





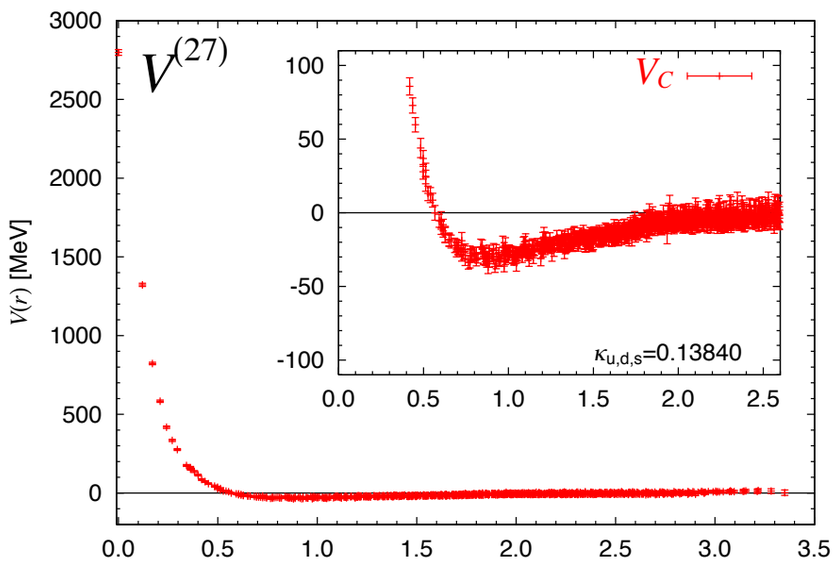
- **Strangeness**: small admixtures of Λ hyperons possible at $\rho > 3\,\rho_0$

but: strong hyperon-nucleon short-range **repulsion**
and/or ΛNN **3-body forces** required

Hyperon - Nucleon Potentials from Lattice QCD

S. Aoki et al. (HAL QCD Collaboration),

PTEP 2012 (2012) 01A105 ; arXiv: 1206.5088 [hep-lat]



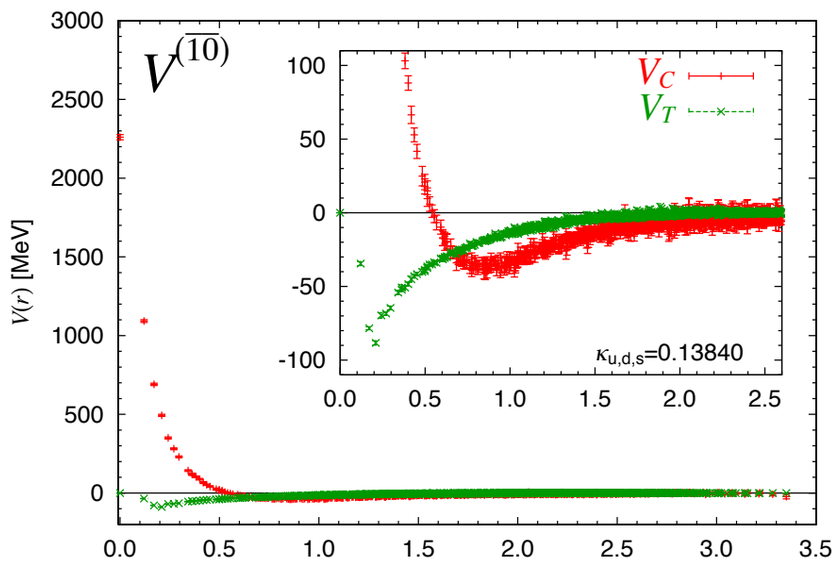
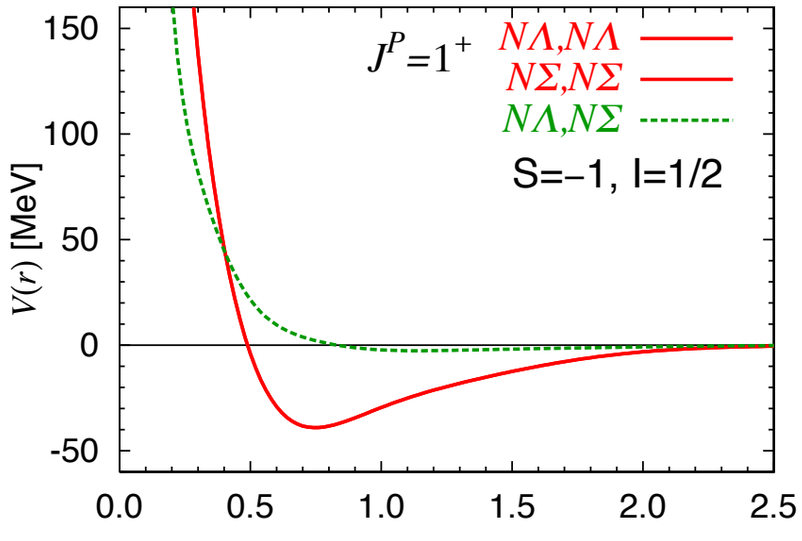


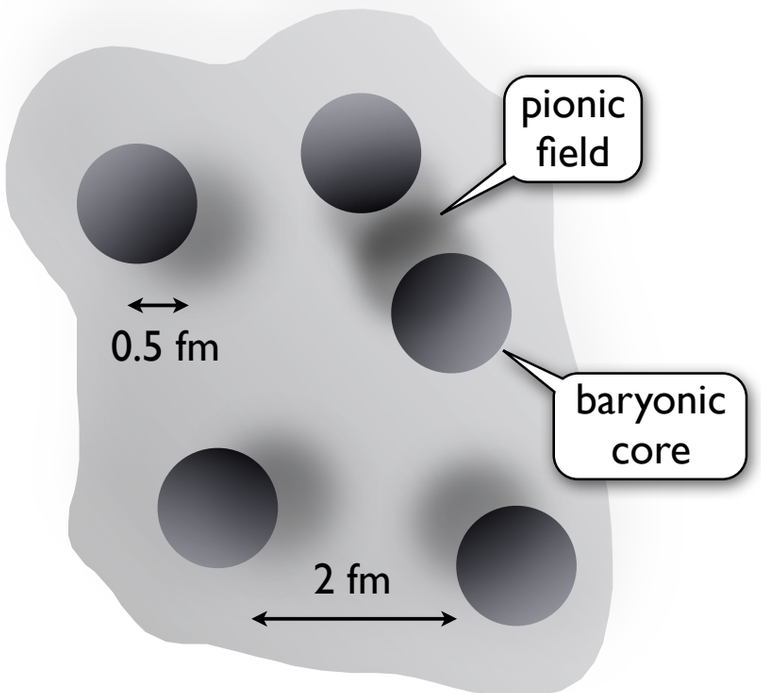
Fig. 13. The BB potentials in **27** (Left) and $\overline{\mathbf{10}}$ (Right) representations extracted from the lattice QCD simulation at $M_{\rm ps} = 469$ MeV. Taken from Ref. 56).

$$\mathbf{8} \otimes \mathbf{8} = \underbrace{\mathbf{27} \oplus \mathbf{8} \oplus \mathbf{1}}_{\text{symmetric}} \oplus \underbrace{\overline{\mathbf{10}} \oplus \mathbf{10} \oplus \mathbf{8}}_{\text{anti-symmetric}},$$



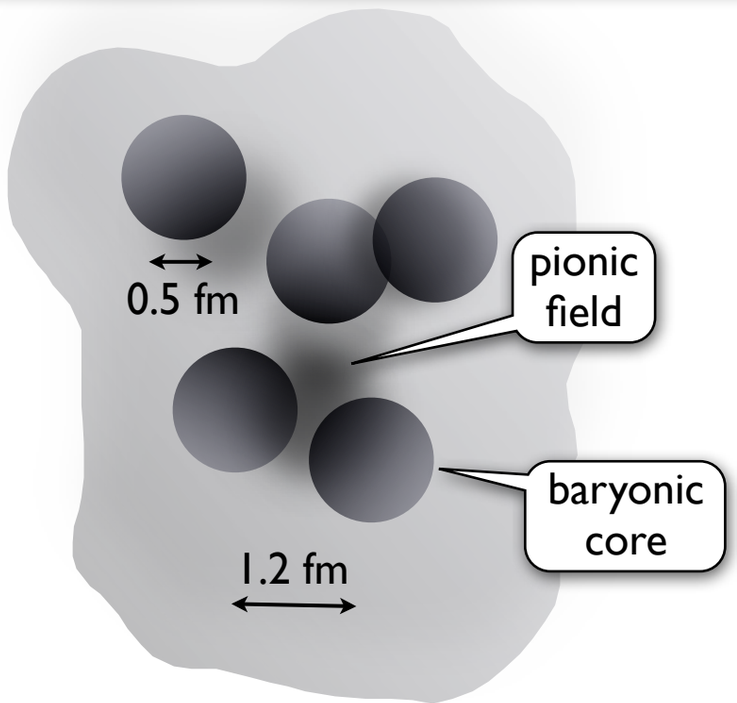
- **Strong repulsion** at short distances
- works against superdense **strange matter**

Densities and Scales in Compressed Baryonic Matter



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

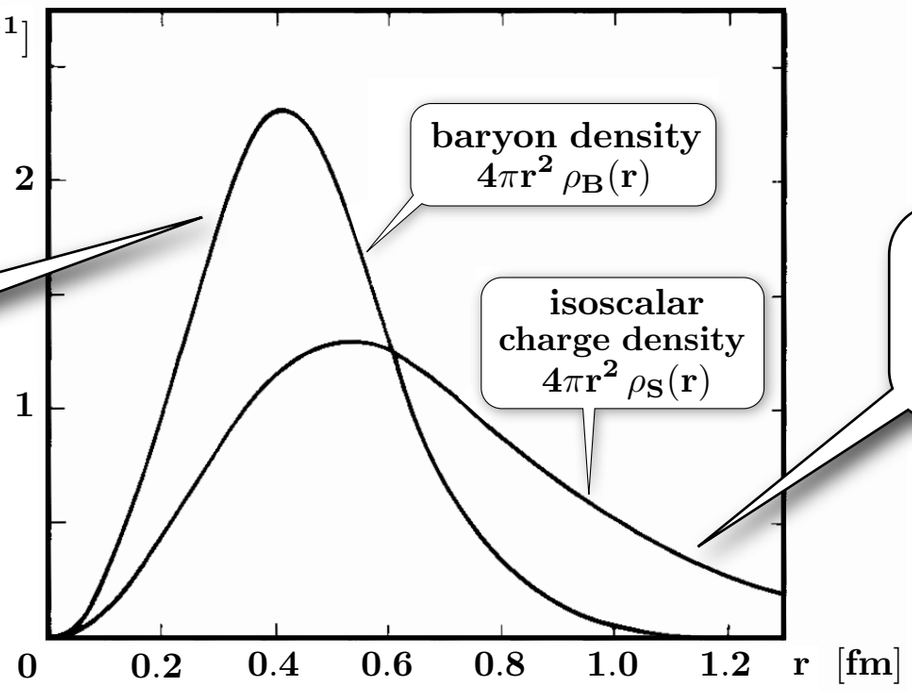
normal nuclear matter: dilute



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

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

- recall: chiral (soliton) model of the nucleon



compact baryonic core

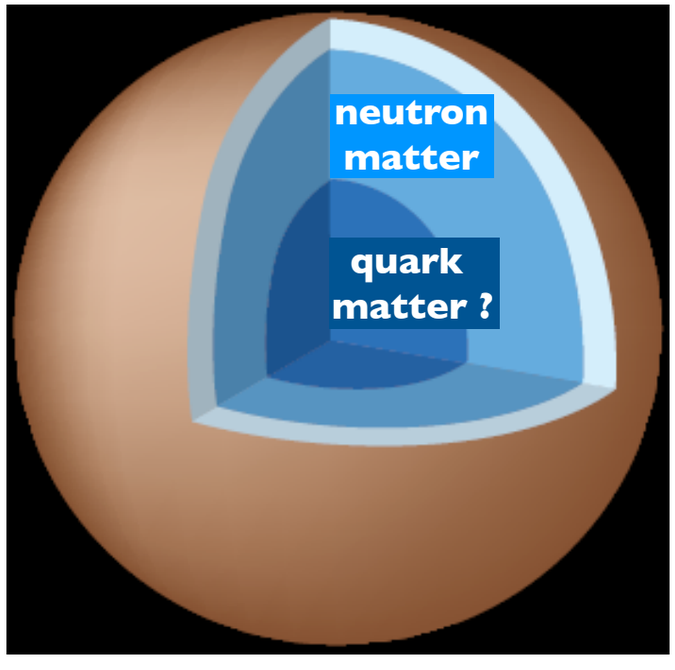
$\langle r^2 \rangle_B^{1/2} \simeq 0.5\ \mathrm{fm}$

mesonic cloud

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

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

. . . treated properly in chiral EFT



Two-solar-mass neutron star sets strong constraints:

"Stiff" equation-of-state required

- **"Conventional" EoS works best**
  (nuclear physics + effective field theory + advanced many-body methods)
- **Central baryon densities** in neutron stars are not extreme
  (do not exceed 4 - 5 times the density of normal nuclear matter)
- **Change of paradigm ?**
  "Exotic" forms of matter (**kaon condensates**, **quark matter** with **first-order phase transition**, . . .) unlikely to exist in n-star cores
- **Strangeness and hyperons in dense baryonic matter ?**
  Small admixtures still possible, but only with strongly repulsive short-range hyperon-nucleon and hyperon-hyperon interactions (⟶ see Lattice QCD)

SUMMARY

- Chiral SU(3) Coupled-Channels approach based on symmetry breaking pattern of Low-Energy QCD

  . . . is now a well established framework:

  - antiK-nucleon & antiK-deuteron **scattering lengths**
  - Remarkable consistency of variational and Faddeev **K-pp** calculations: **weak binding**, **large width**

- **K-deuteron** threshold physics: predictions now available
  - . . . looking forward to **kaonic deuterium** (SIDDHARTA 2)

- New **dense** & **cold matter** constraints from **neutron stars**:
  - Mass - radius relation; observation of **2-solar-mass n-star**
  - "Non-exotic" stiff equation-of-state works best !
  - **Kaon condensation** ruled out
  - **Hyperon admixtures** still possible but with requirement of strongly **repulsive short-range YN interactions** (► Lattice QCD)

The End

thanks to :

Tetsuo Hyodo Yoichi Ikeda

Salvatore Fiorilla Thomas Hell Jeremy Holt
Norbert Kaiser Bernhard Röttgers Sebastian Schultess