YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

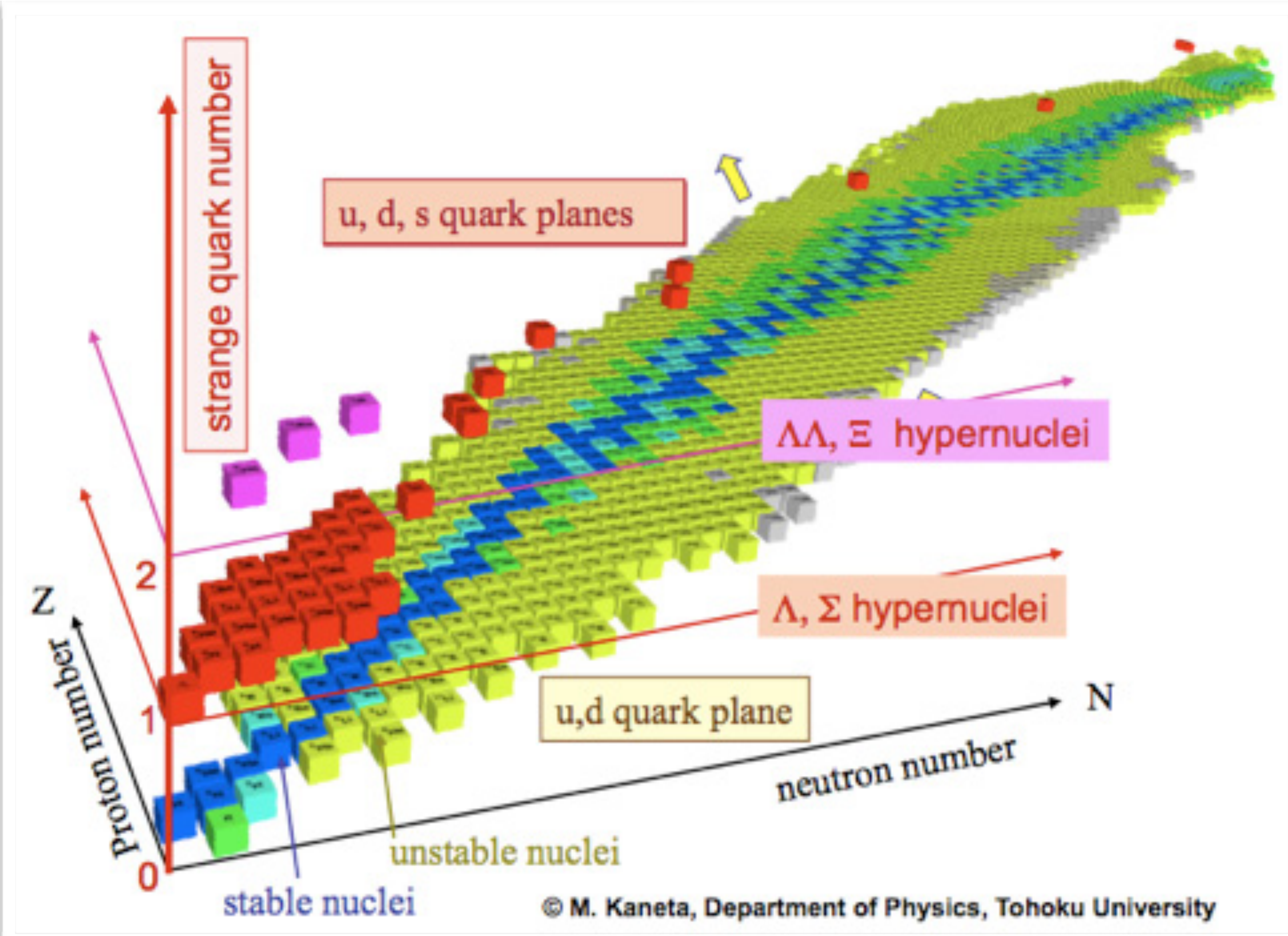
Kyoto, 17 May 2017

LAMBDA-NUCLEAR INTERACTION and HYPERON PUZZLE in NEUTRON STARS

Wolfram Weise
Technische Universität München
PHYSIK DEPARTMENT

- Equation of State of dense baryonic matter : constraints from massive neutron stars
- Hyperon-nucleon interactions from SU(3) chiral effective field theory
- Hyperon-NN three-body forces
- Emerging repulsions : suppression of hyperons in dense neutron matter

Stefan Petschauer, Johann Haidenbauer, et al. :
Eur. Phys. J. **A** (2017) (arXiv: 1612.03758 [nucl-th]); Nucl. Phys. **A 957** (2017) 347;
Phys. Rev. **C93** (2016) 014001; Eur. Phys. J. **A52** (2016)15; Nucl. Phys. **A915** (2013) 24



strange quark number
u, d, s quark planes
ΛΛ, Ξ hypernuclei
Λ, Σ hypernuclei
u,d quark plane
Z
Proton number
N
neutron number
0
1
2
unstable nuclei
stable nuclei
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Part I: Prologue

Constraints on Equations of State

from

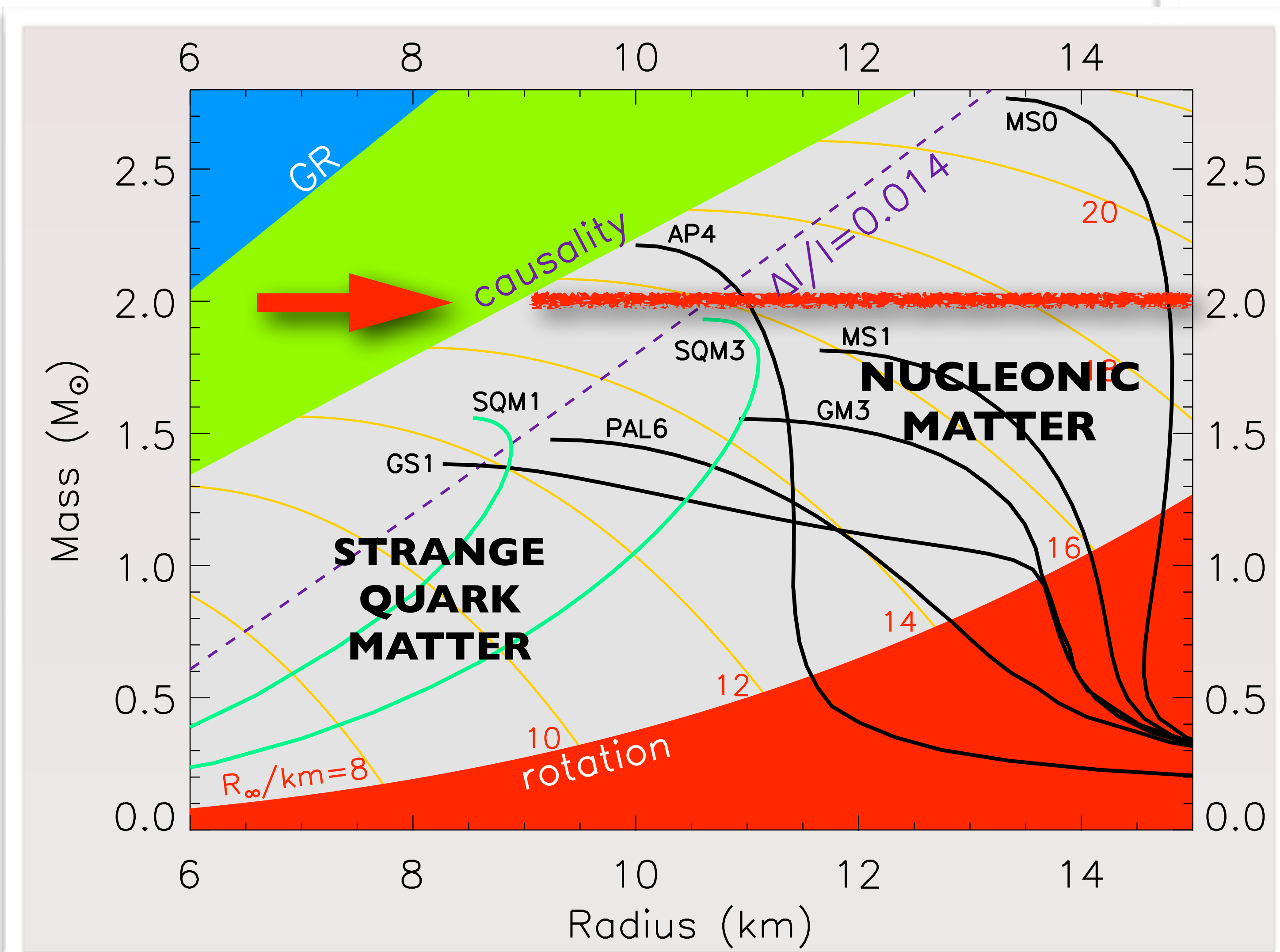
massive Neutron Stars

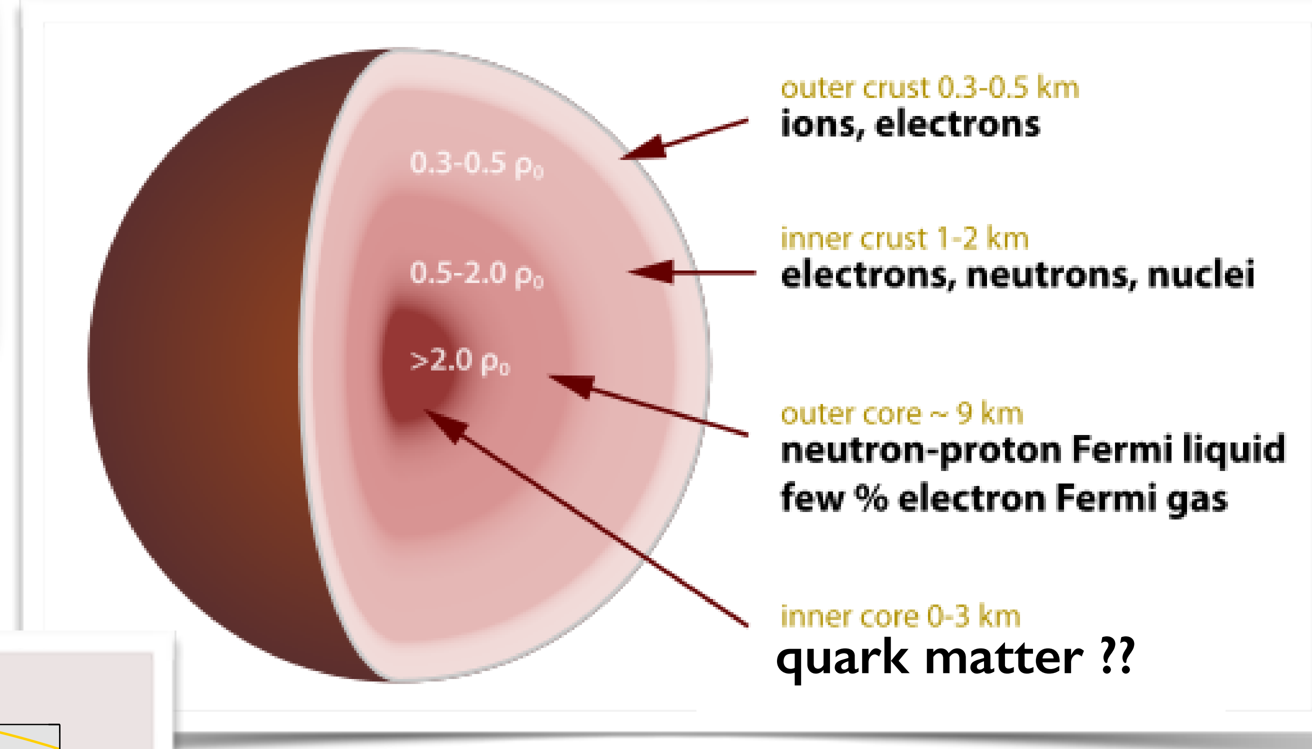
NEUTRON STARS and the EQUATION OF STATE of DENSE BARYONIC MATTER

J. Lattimer, M. Prakash

Phys. Reports 442 (2007) 109 Phys. Reports 621(2016) 127

Mass-Radius Relation





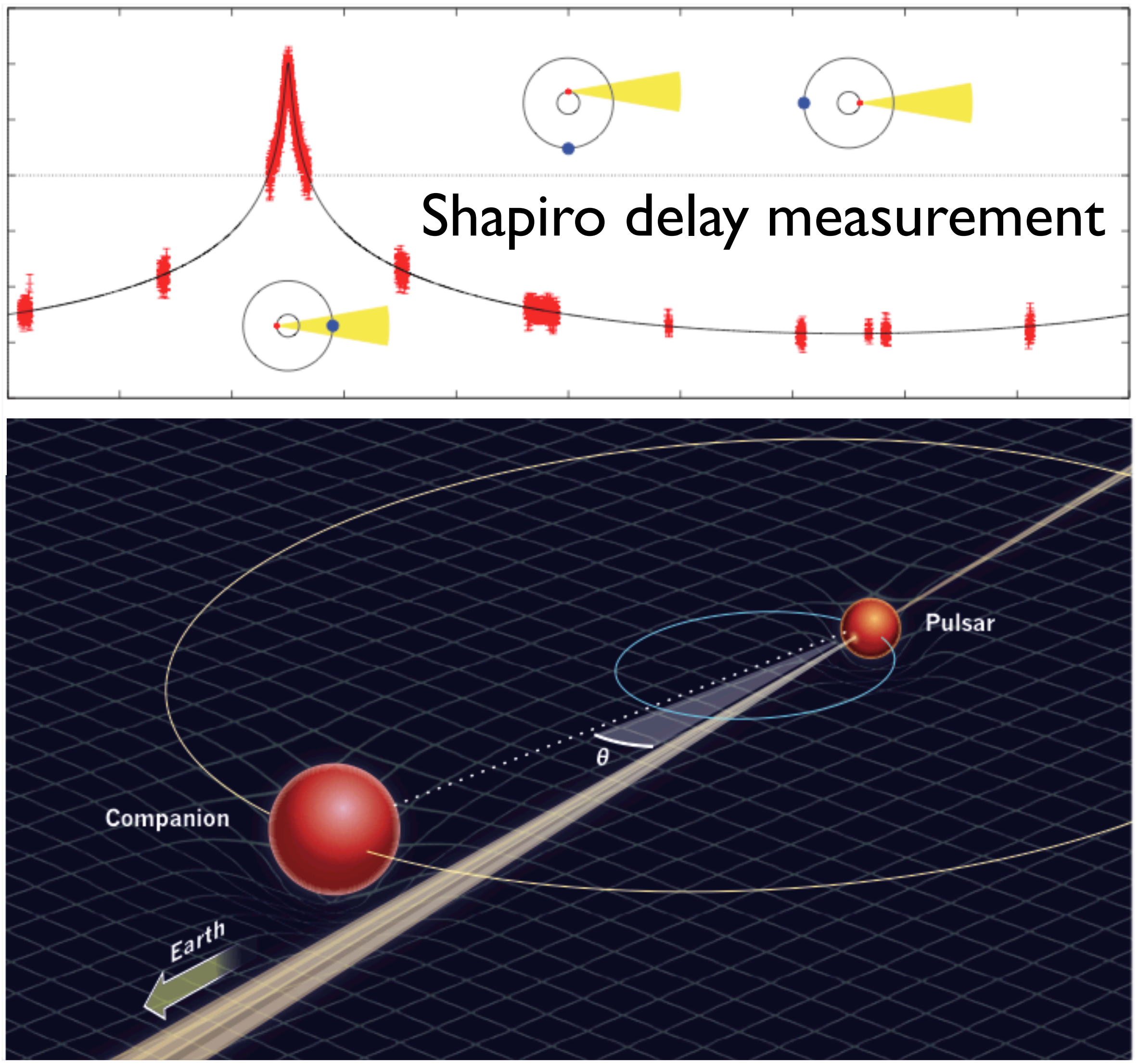
- Tolman-Oppenheimer-Volkov Equations

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

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

Constraints from massive NEUTRON STARS

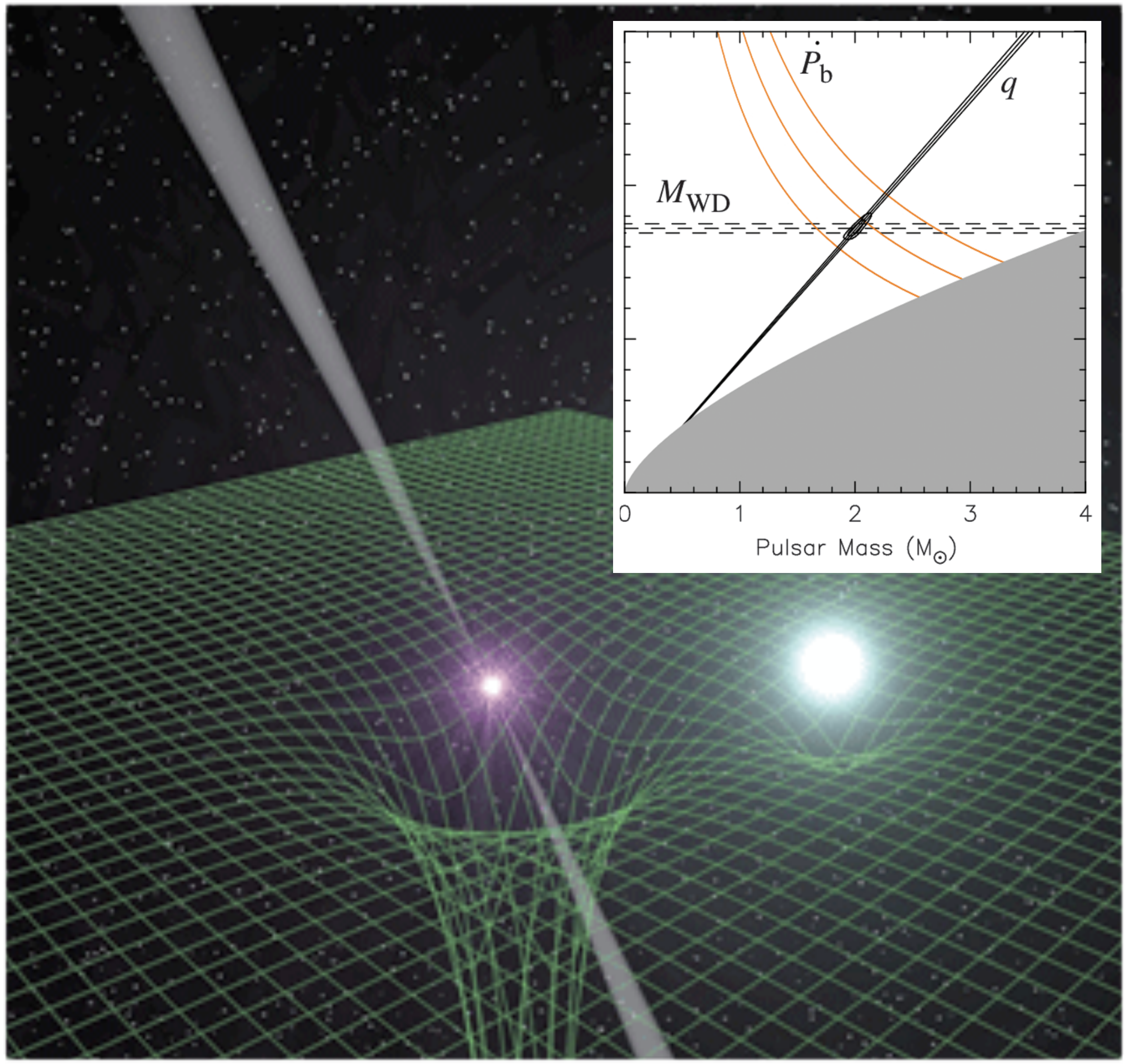
P.B. Demorest et al.
Nature 467 (2010) 1081



PSR J1614+2230

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

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

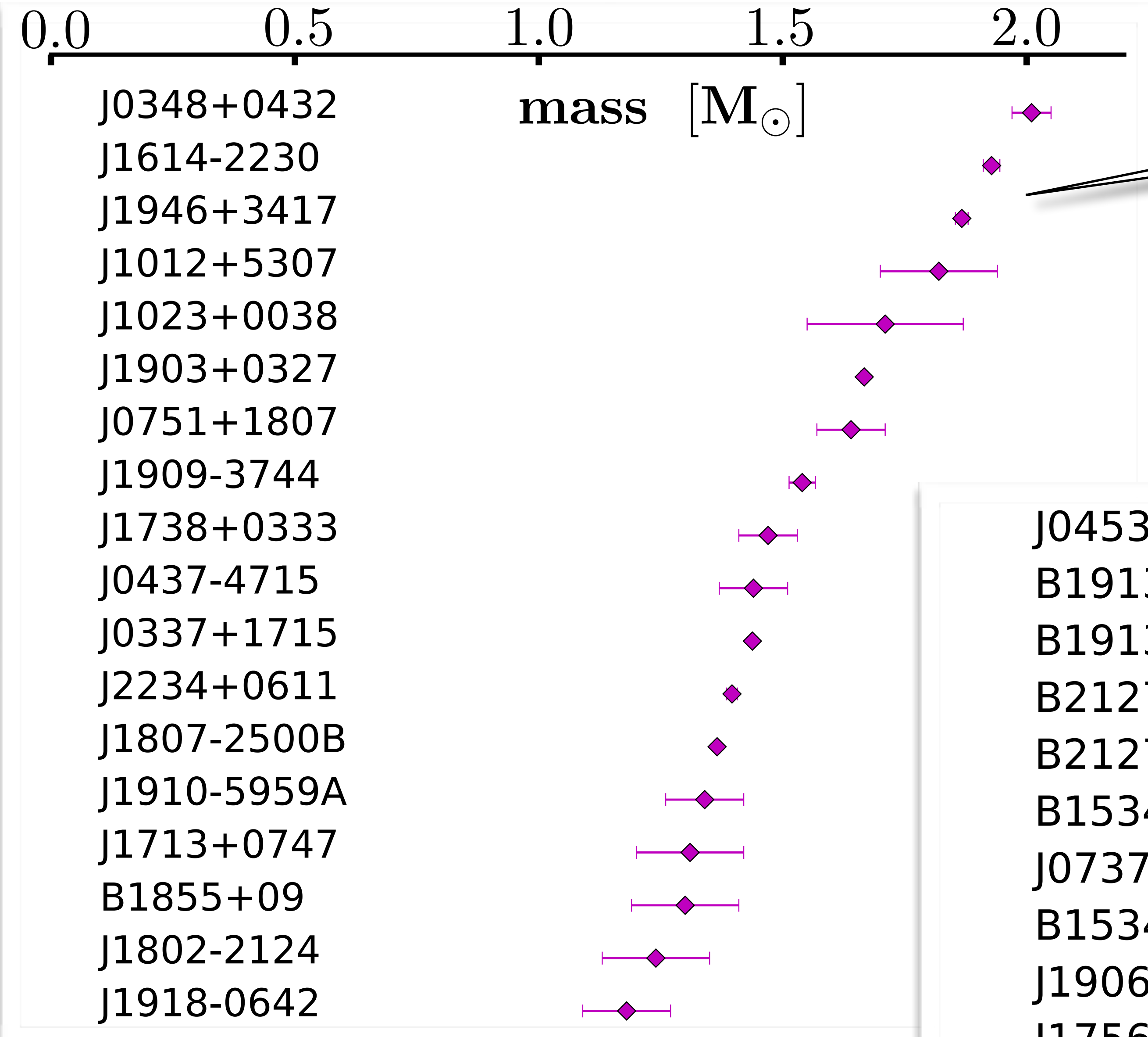


PSR J0348+0432

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

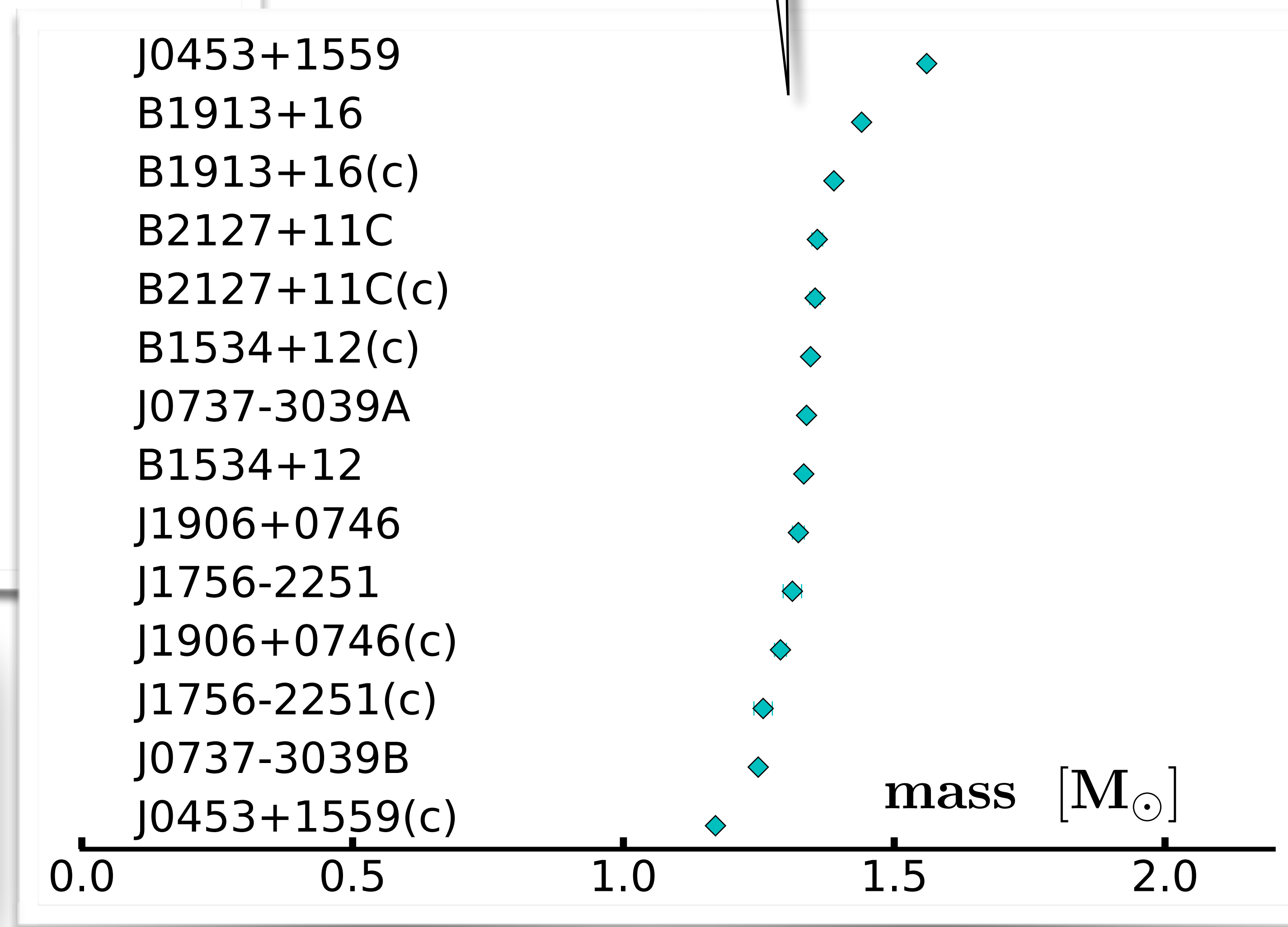
Population of MILLISECOND PULSARS

J.Antoniadis et al. arXiv:1605.01665



ms pulsars in binaries
e.g. with white dwarfs

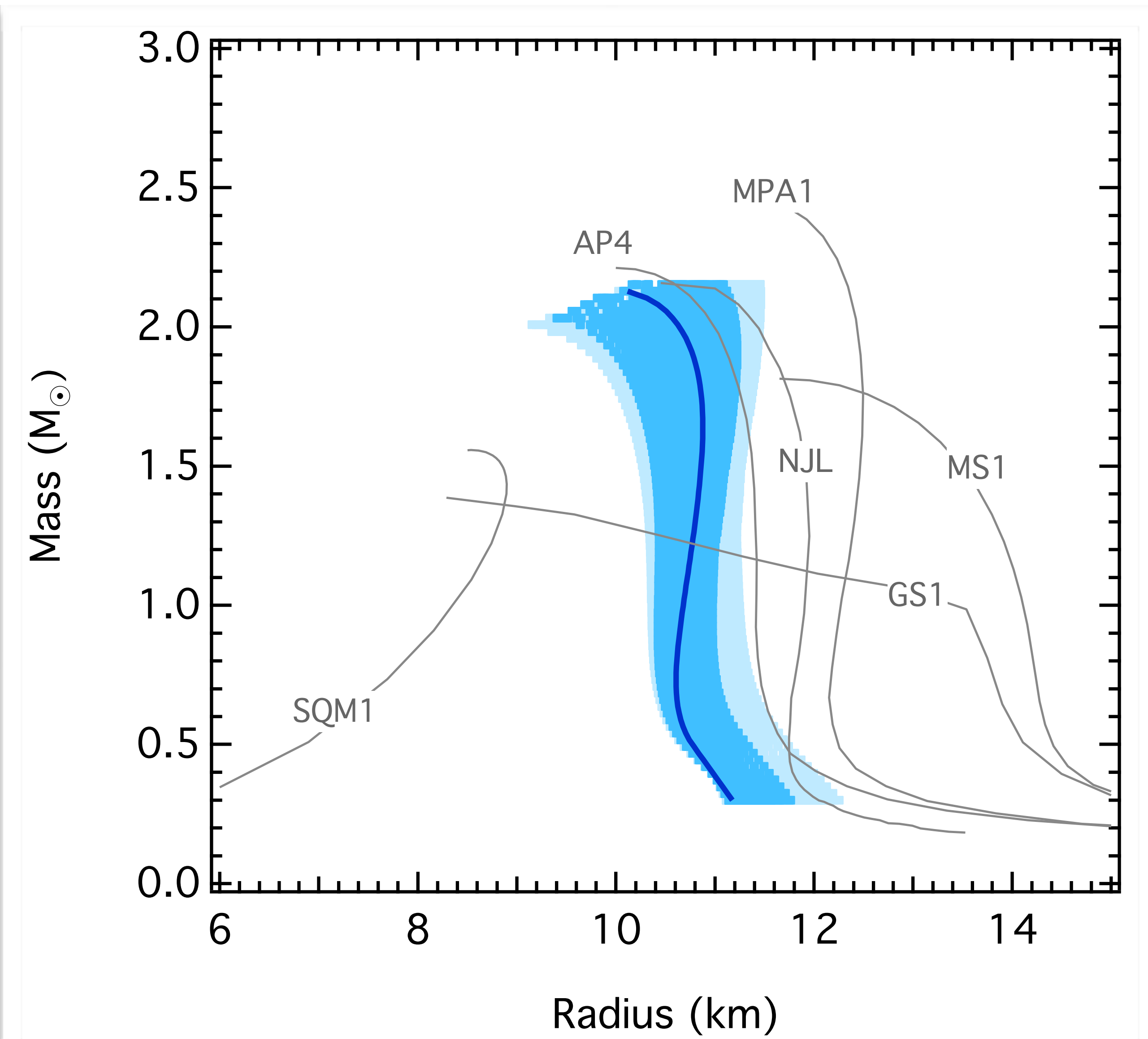
double neutron stars



Note:
about **25%** of population are
massive n-stars $(M > 1.5\, M_\odot)$

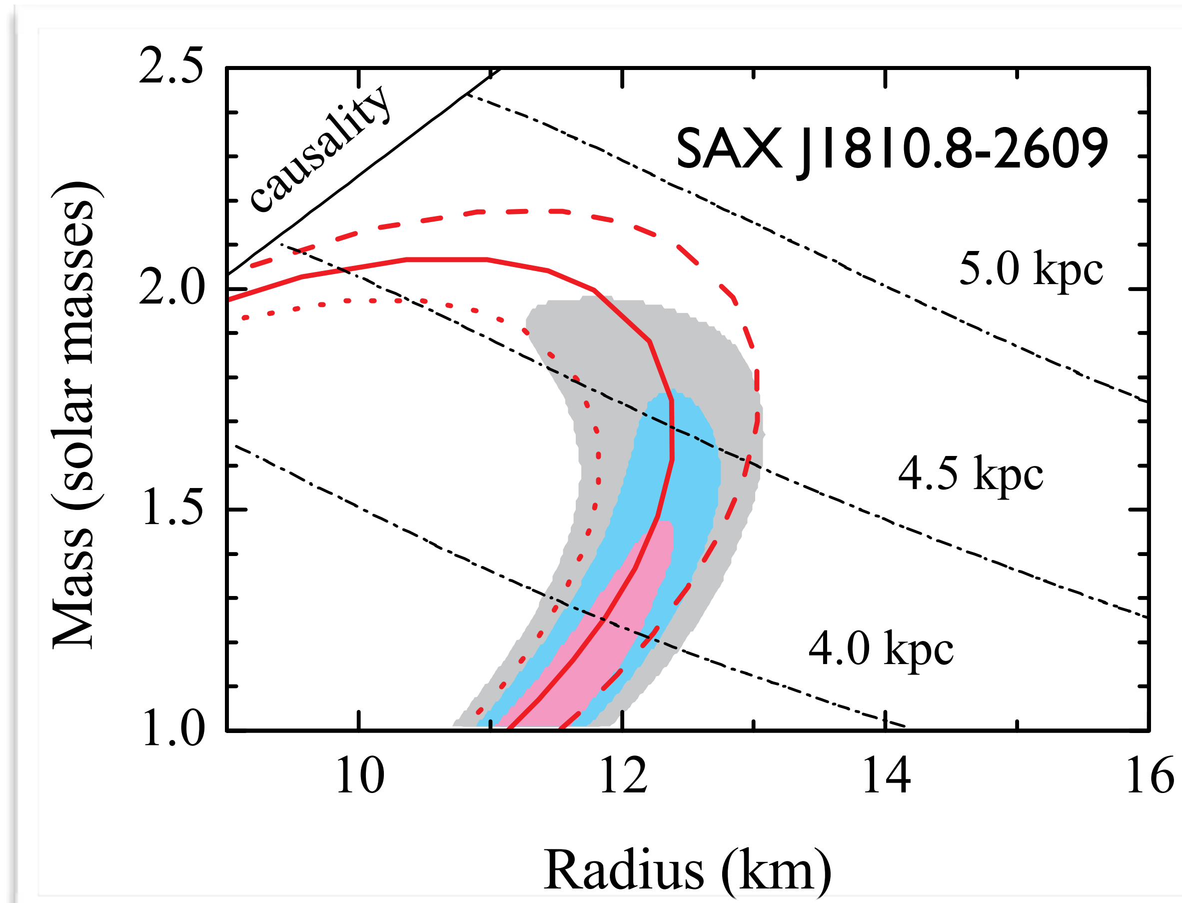
CONSTRAINTS from NEUTRON STARS
(contd.)

- Comprehensive analysis of 12 selected neutron stars



F. Özel, D. Psaltis, T. Güver, G. Baym, C. Heinke, S. Guillot
Astroph. J. 820 (2016) 28

- Atmosphere model fits of X-ray bursts



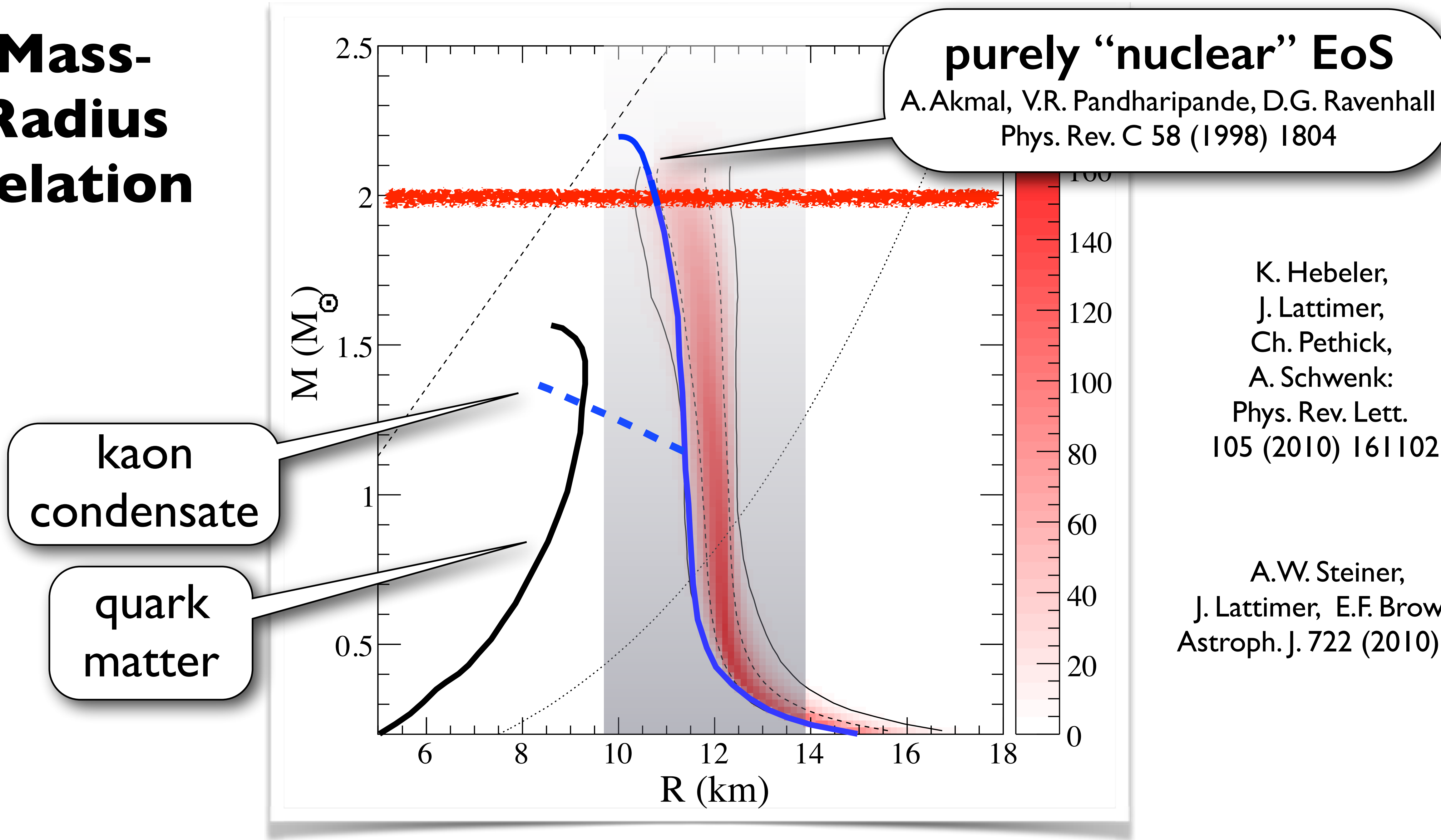
$$\mathbf{R = (11.5 - 13.0)\,km}$$
$$(\mathbf{M = 1.3 - 1.8\ M}_{solar})$$

J. Nättilä et al.: Astron. Astroph. 591 (2016) A25
V.F. Suleimanov et al.: arXiv:1611.09885

CONSTRAINTS from NEUTRON STARS

F. Özil, D. Psaltis: Phys. Rev. D80 (2009) 103003
F. Özil, G. Baym, T. Güver: Phys. Rev. D82 (2010)101301

Mass-Radius Relation



K. Hebeler,
J. Lattimer,
Ch. Pethick,
A. Schwenk:
Phys. Rev. Lett.
105 (2010) 161102

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

- “Exotic” equations of state ruled out ?

NEUTRON STAR MATTER
from **Chiral EFT** and **FRG**

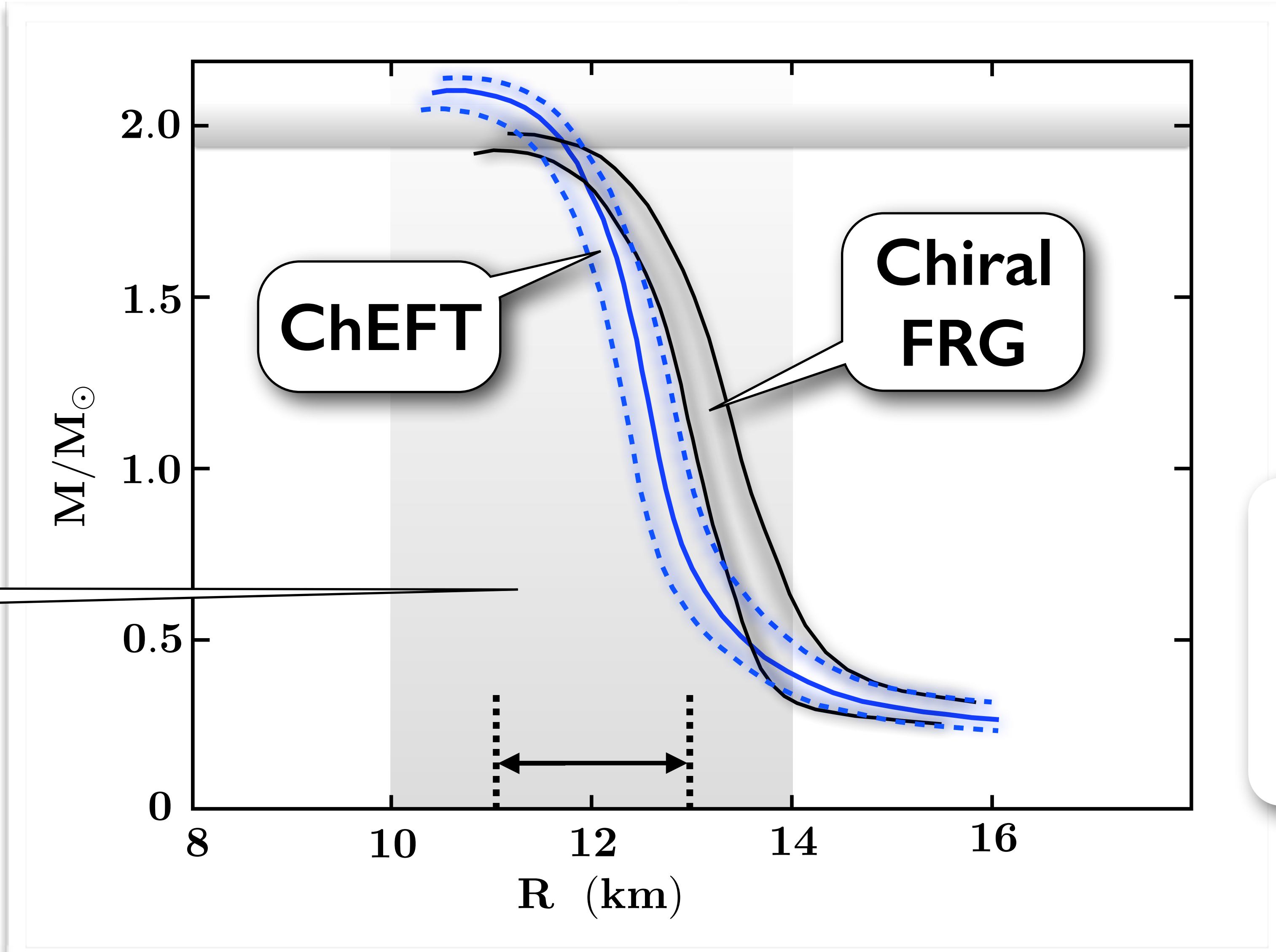
- **Symmetry energy range: 30 - 35 MeV**
- **Crust: SLy EoS**

M. Drews, W.W.

Phys. Rev. C91 (2015) 035802

Prog. Part. Nucl. Phys. 93 (2017) 69

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



Radius window

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

- **Central core density**

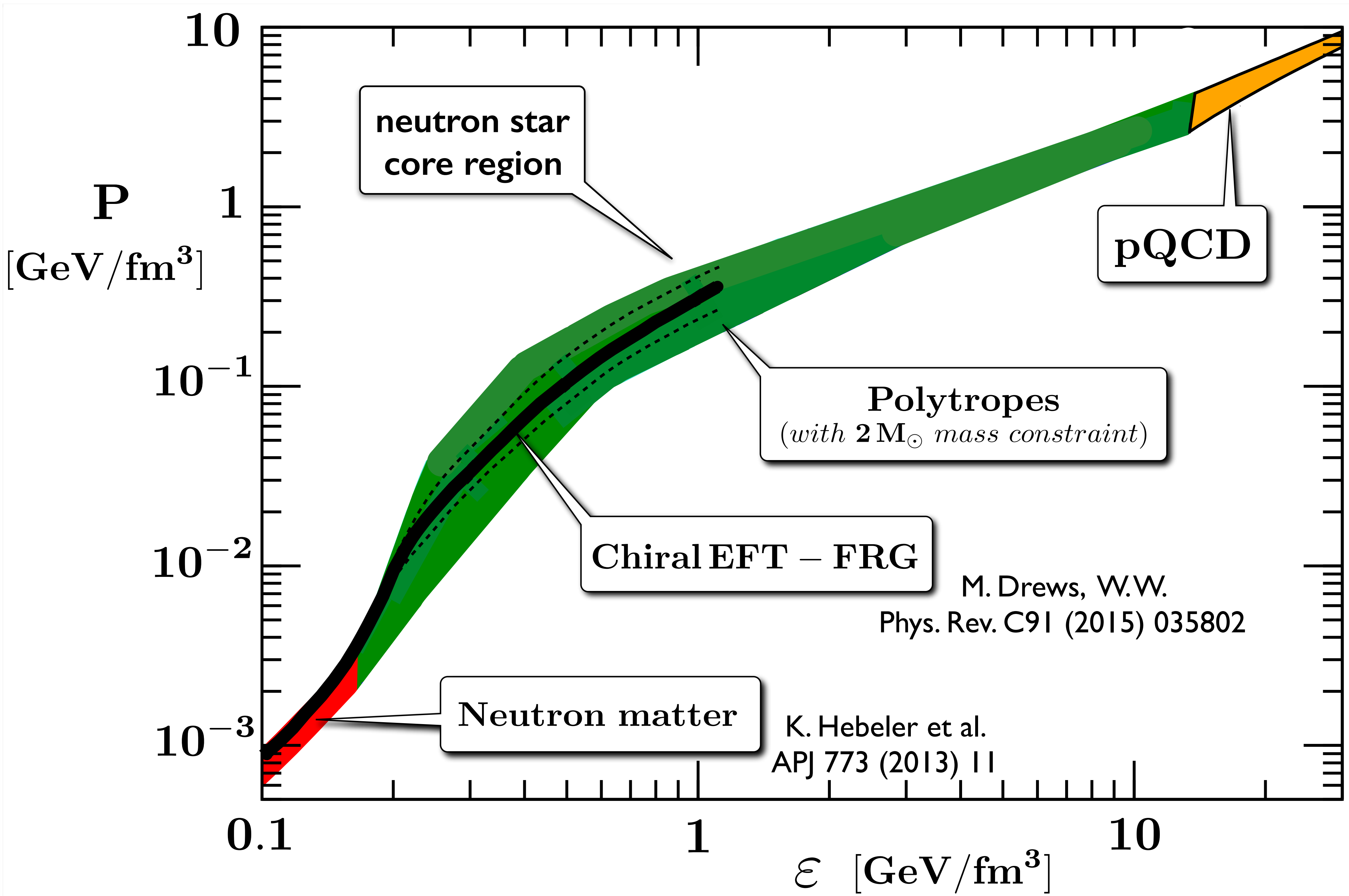
$$\rho_c \lesssim 5\,\rho_0$$

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

NEUTRON STAR MATTER
Equation of State

… and extrapolation to PQCD limit

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

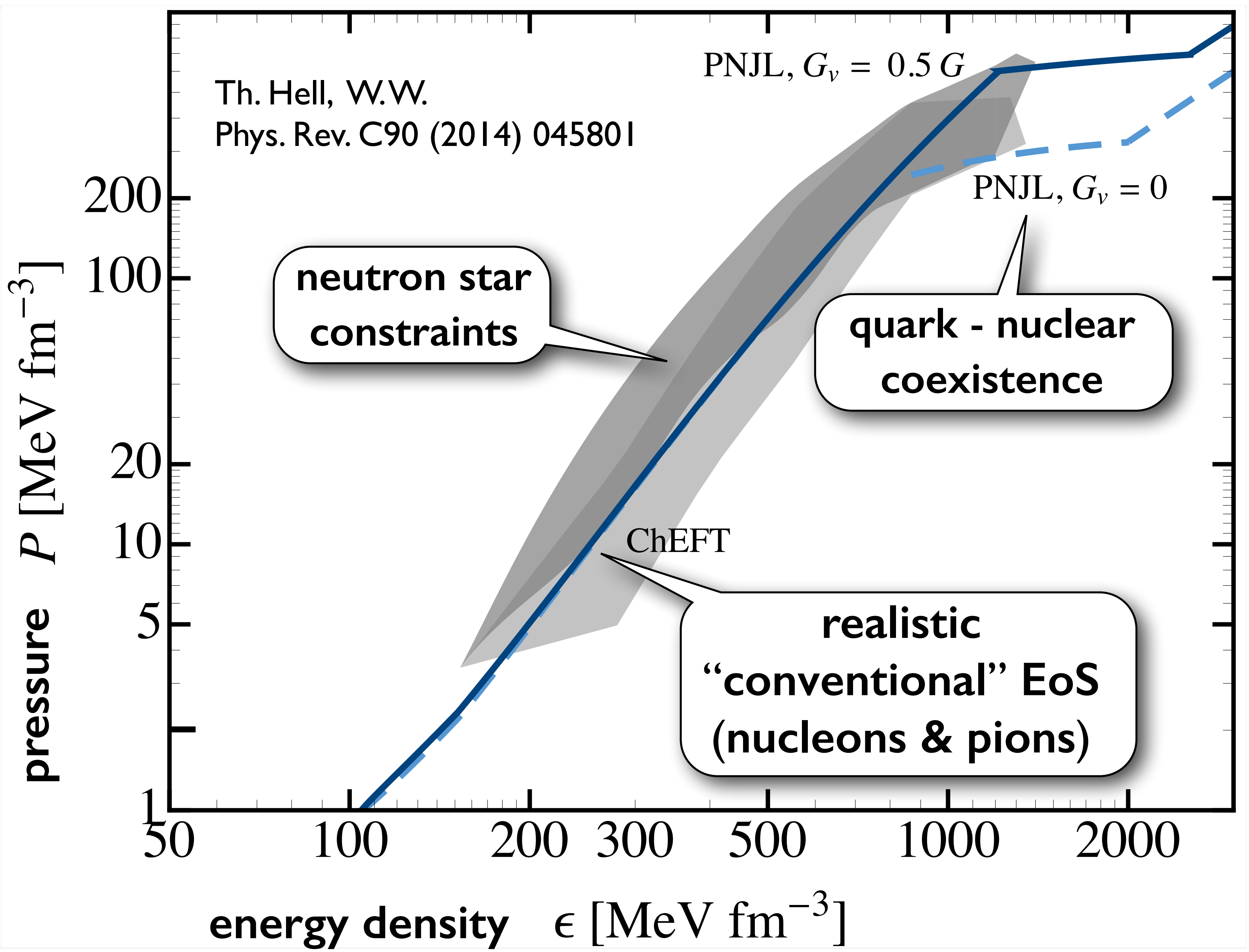


M. Drews, W.W.
Phys. Rev. C91 (2015) 035802

K. Hebeler et al.
APJ 773 (2013) 11

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 (chiral quark) model at high densities (incl. **strange** quarks)



- conventional **(hadronic)** equation of state seems to work
- **quark-nuclear** coexistence can occur at baryon densities

$$\rho > 5\,\rho_0$$
$$(\rho_0 = 0.16\,\mathrm{fm}^{-3})$$

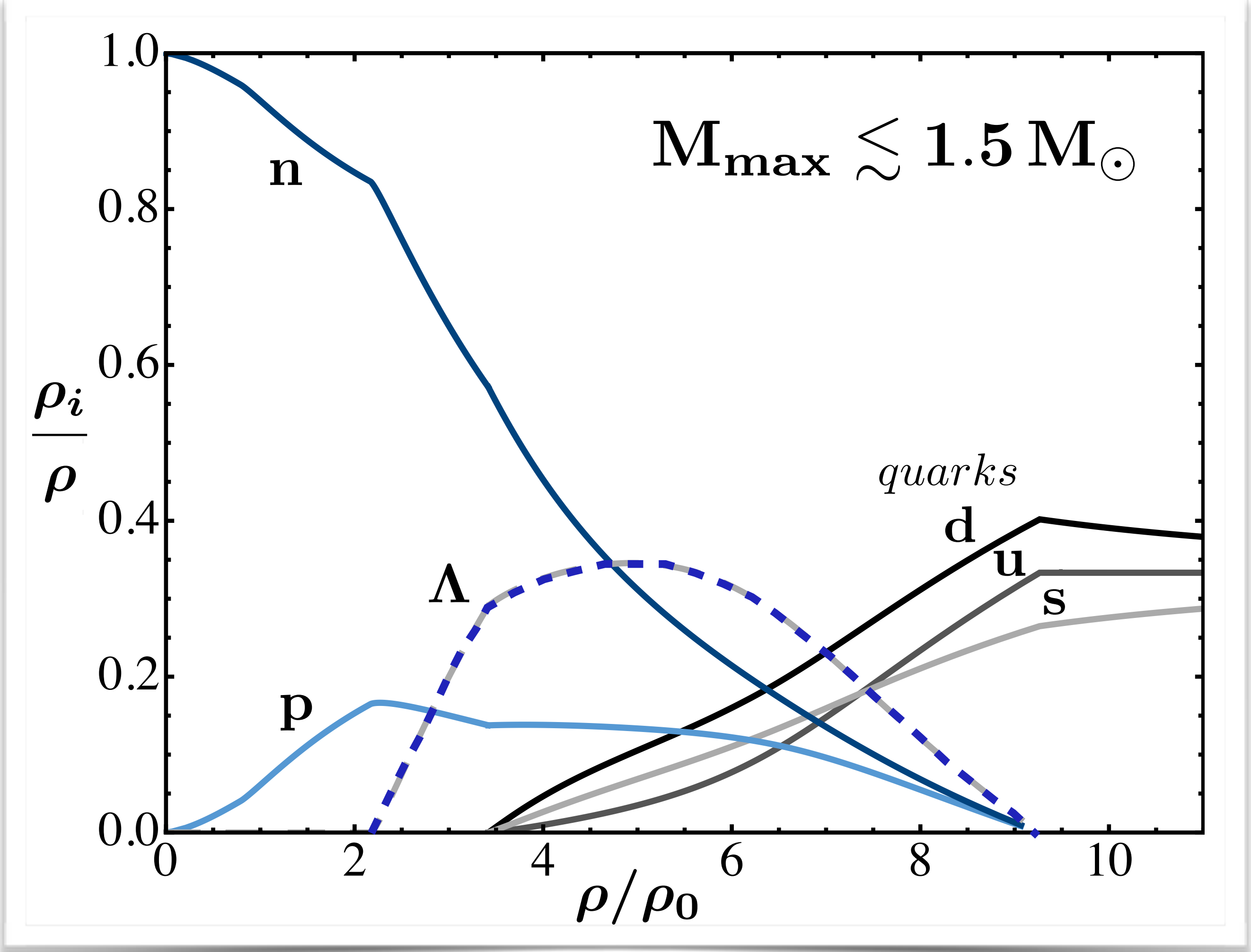
see also:
K. Masuda, T. Hatsuda, T. Takatsuka
PTEP (2013) 7, 073D01

NEUTRON STAR MATTER including HYPERONS

- In-medium **Chiral Effective Field Theory** (3-loops)
  plus Λ hyperons (incl. potential consistent with hypernuclei)
- 3-flavor **PNJL** model at high densities (incl. **strange** quarks)

Particle composition:

Fraction of particle species as function of baryon density

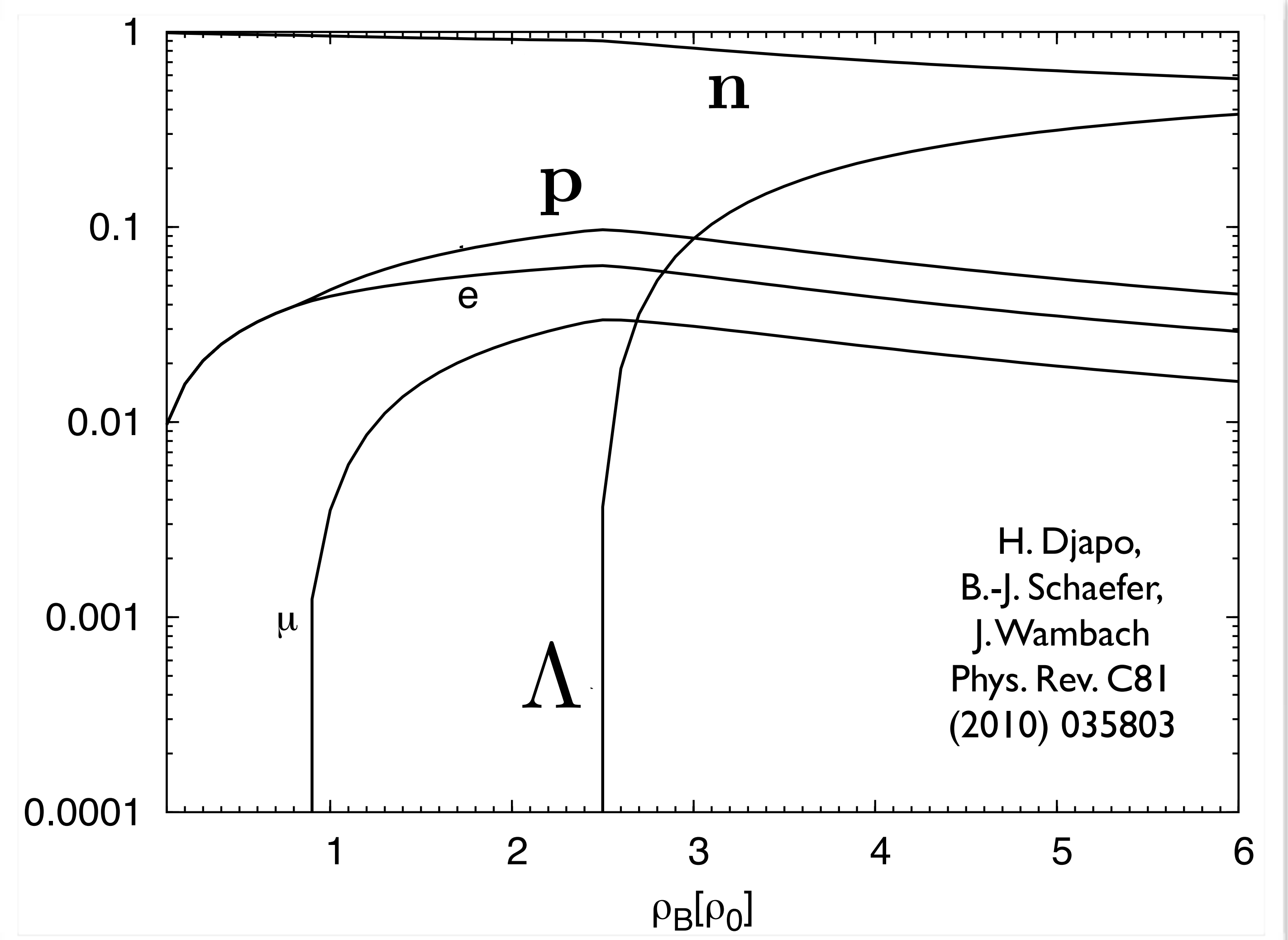


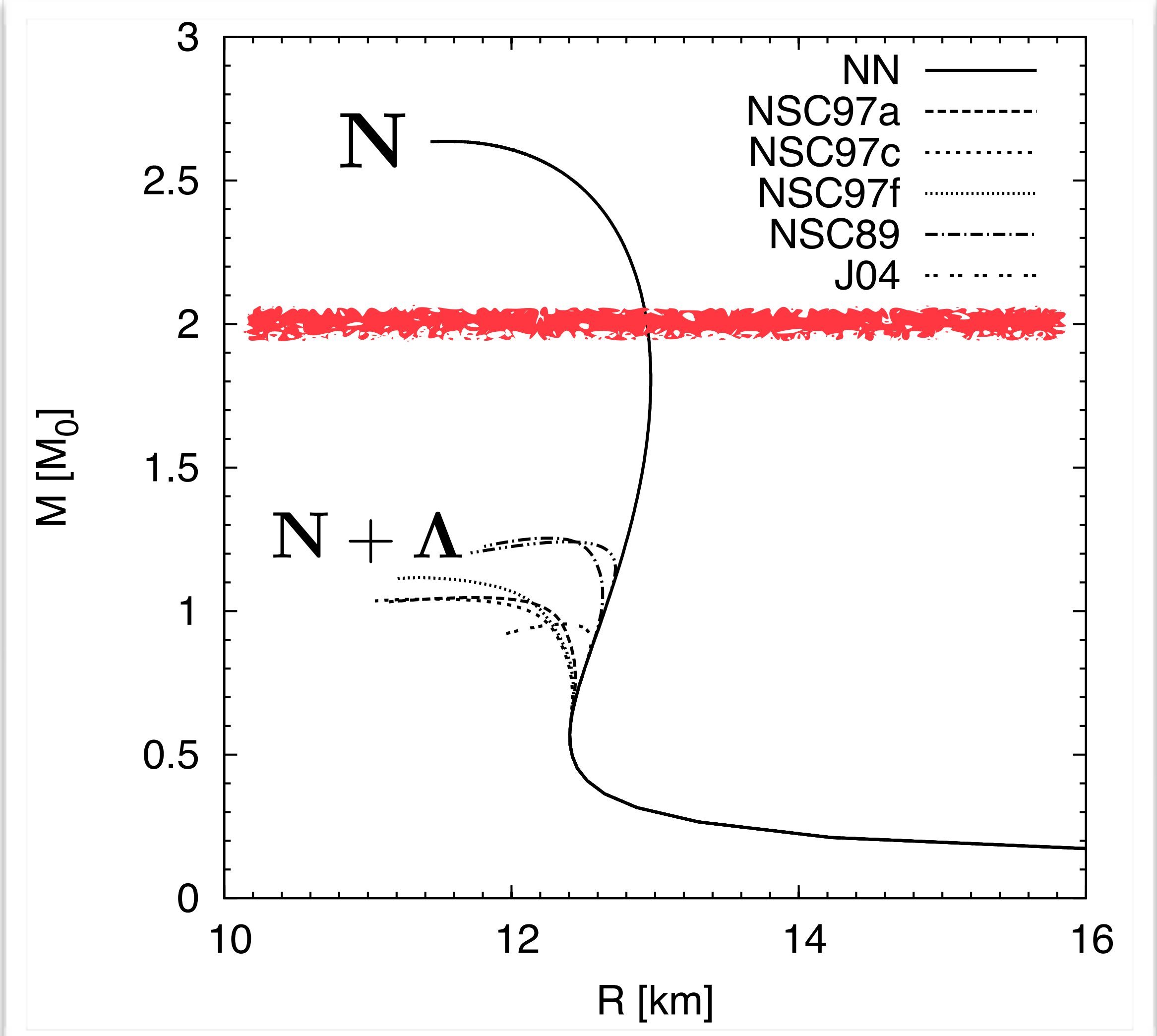
T. Hell, W.W.
Phys. Rev. C90 (2014) 045801

occurrence of Λ hyperons
$\mu_n = \mu_\Lambda$

- **Equation of state too soft :** maximum neutron star mass **too low**

NEUTRON STAR MATTER including HYPERONS





- Adding **hyperons**: equation of state far **too soft**

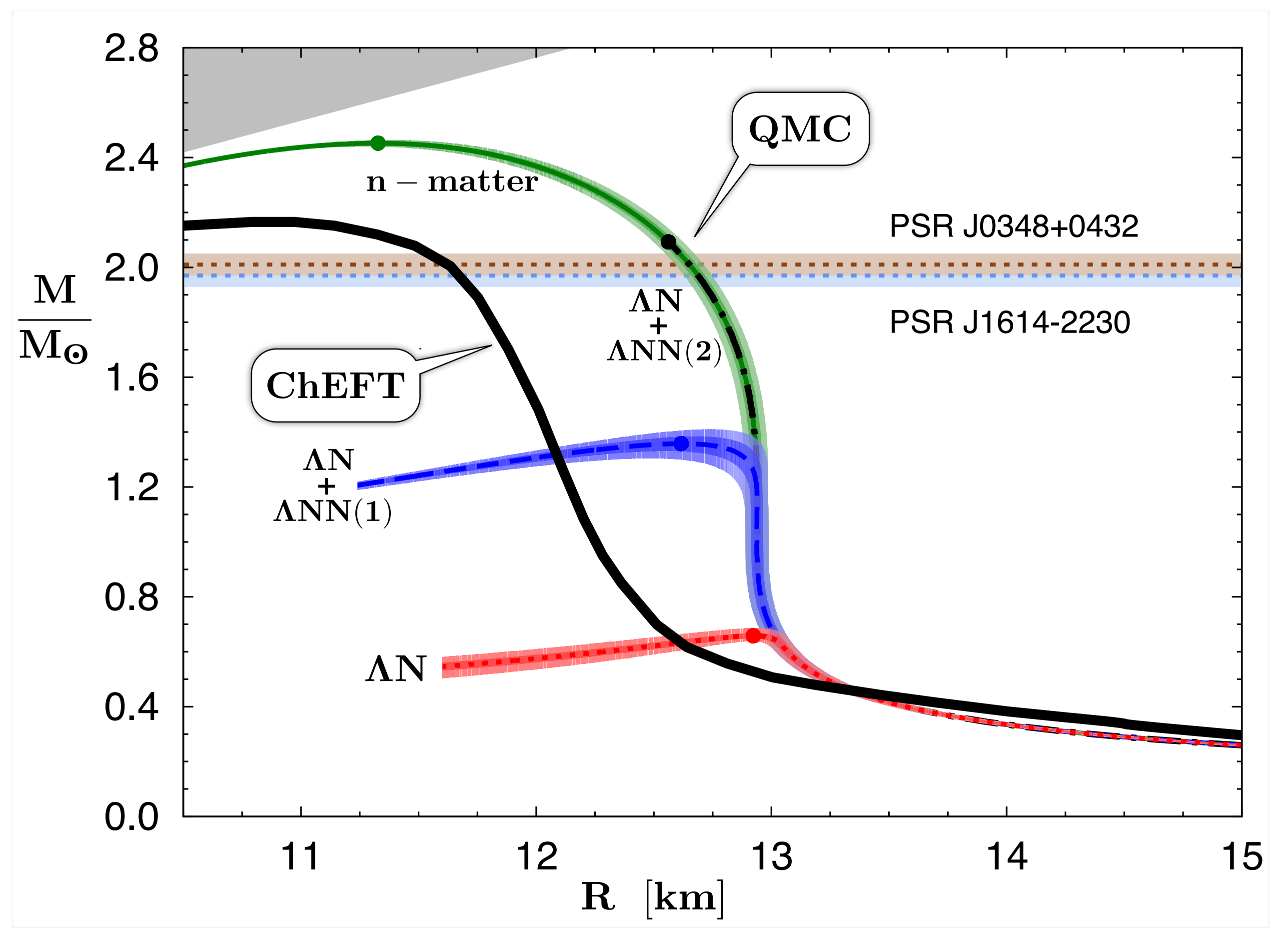
"Hyperon Puzzle"

NEUTRON STAR MATTER including HYPERONS

Quantum **M**onte **C**arlo **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



QMC computations (hyper-neutron matter):

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

Inclusion of **hyperons**: EoS **too soft** to support 2-solar-mass n-stars unless: **strong repulsion** in **YN** and **YNN** … interactions

Part II

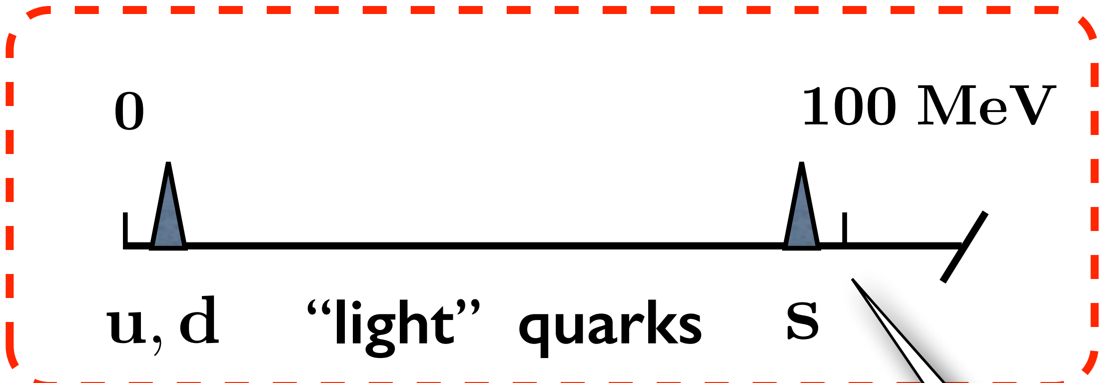
Hyperon - Nucleon Interactions

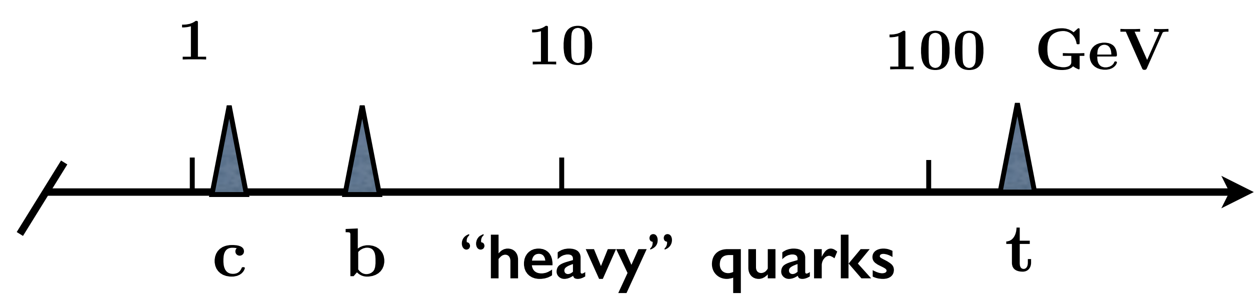
from

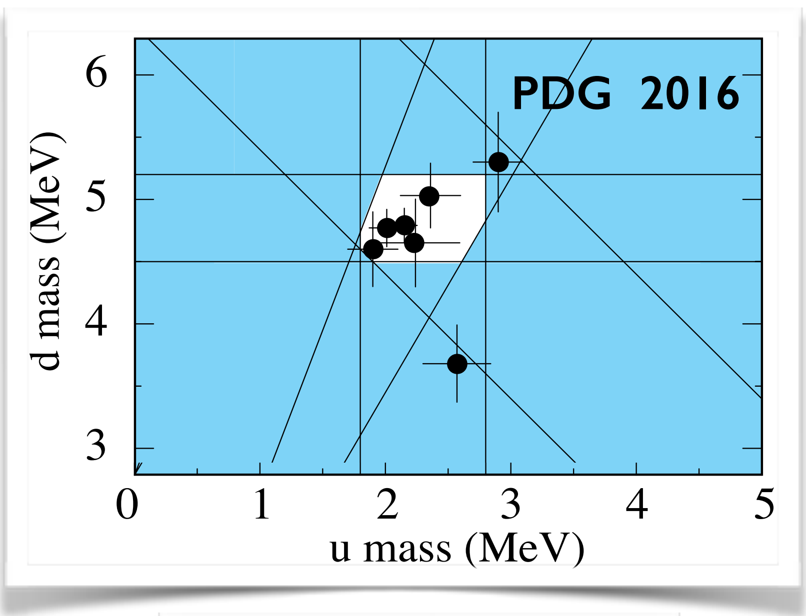
Chiral SU(3) Effective Field Theory

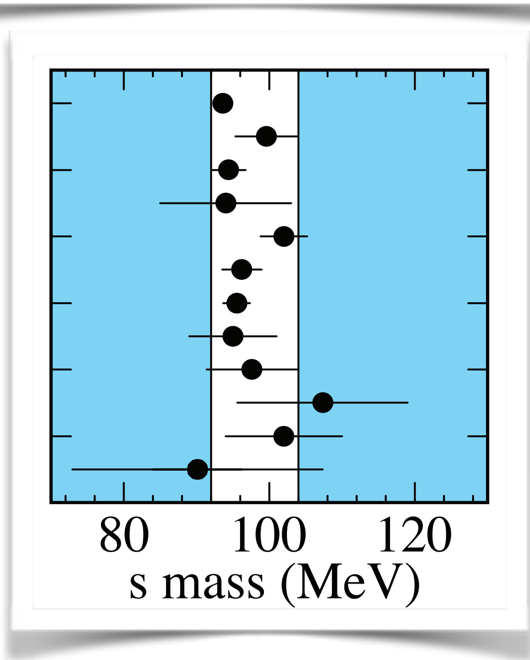
Hierarchy of **QUARK MASSES** in **QCD**

- Separation of Scales -









Basic principles of

LOW-ENERGY QCD :

Confinement of quarks & gluons in hadrons

Chiral Symmetry

$$SU(3)_L \times SU(3)_R$$

Spontaneously broken (QCD dynamics)

Explicitly broken by non-zero quark masses

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

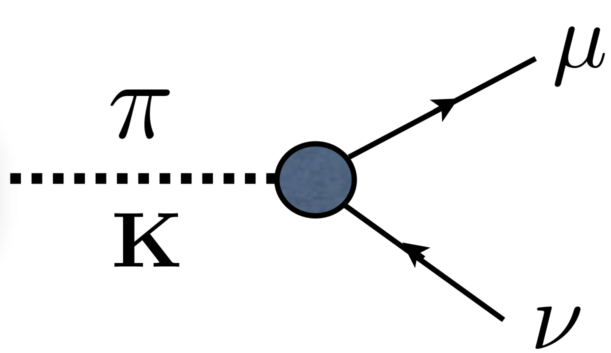
- **NAMBU - GOLDSTONE BOSONS**:

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

- **DECAY CONSTANTS**:

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

  axial current



Chiral limit: $\mathbf{f} = 86.2\ \mathrm{MeV}$

Order parameter :

$4\pi\,\mathbf{f} \sim 1\ \mathrm{GeV}$

$$\mathbf{f}_\pi = 92.21 \pm 0.16\ \ \mathrm{MeV}$$

$$\mathbf{f}_\mathbf{K} = 110.5 \pm 0.5\ \ \mathrm{MeV}$$

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

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

$$\mathbf{m}_\mathbf{K}^2\, \mathbf{f}_\mathbf{K}^2 = -\frac{\mathbf{m_u} + \mathbf{m_s}}{2}\langle \bar{\mathbf{u}}\mathbf{u} + \bar{\mathbf{s}}\mathbf{s}\rangle$$

+ higher order corrections

Chiral $\mathbf{SU(3)_L \times SU(3)_R}$ Effective Field Theory

- Realization of **Low-Energy QCD** for energies / momenta

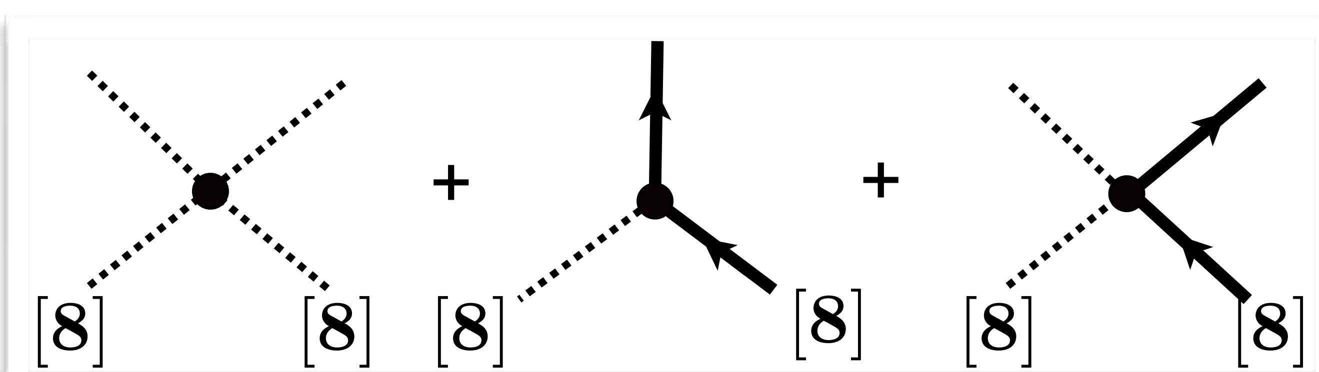
$$\mathbf{Q < 4\pi\, f \sim 1\, GeV}$$

- based on SU(3) **Non-Linear Sigma Model** plus (heavy) **baryons**

- **Pseudoscalar meson octet** of $\mathbf{SU(3)_L \times SU(3)_R}$
  Nambu-Goldstone bosons coupled to **baryon octet**

$$P = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix} \qquad B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ -\Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

meson-baryon interaction vertices



+ . . .

short distance dynamics: **contact terms**

Chiral $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ Effective Field Theory

- Starting point: **Meson-Baryon Lagrangian** (chiral limit)

$$\mathcal{L}_{MB} = \mathrm{tr}\left(\bar{B}\left(\mathrm{i}\gamma^\mu D_\mu - M_0\right)B\right) - \frac{D}{2}\,\mathrm{tr}\left(\bar{B}\gamma^\mu\gamma_5\{u_\mu, B\}\right) - \frac{F}{2}\,\mathrm{tr}\left(\bar{B}\gamma^\mu\gamma_5[u_\mu, B]\right)$$

$$P = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix} \qquad B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ -\Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

- Chiral covariant derivative: $D_\mu B = \partial_\mu B + [\Gamma_\mu, B]$

$$\Gamma_\mu = \tfrac{1}{2}(u^\dagger\partial_\mu u + u\partial_\mu u^\dagger) \qquad u_\mu = \mathrm{i}(u^\dagger\partial_\mu u - u\partial_\mu u^\dagger)$$

- Chiral (pseudoscalar Nambu-Goldstone boson) field :

$$\boldsymbol{U}(x) = \boldsymbol{u}^2(x) = \exp\left(i\frac{\sqrt{2}P(x)}{f}\right)$$ transforms as $\boldsymbol{U} \rightarrow \boldsymbol{R}\,\boldsymbol{U}\,\boldsymbol{L}^\dagger$

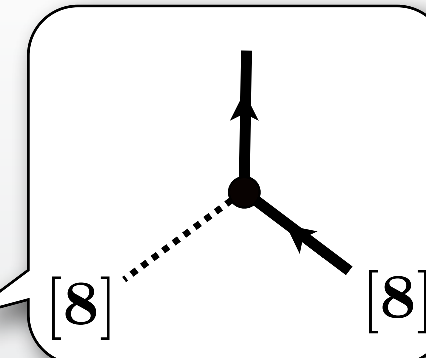
$\boldsymbol{R} \in \boldsymbol{SU(3)}_R \quad \boldsymbol{L} \in \boldsymbol{SU(3)}_L$

Chiral $\mathbf{SU(3)_L \times SU(3)_R}$ Effective Field Theory

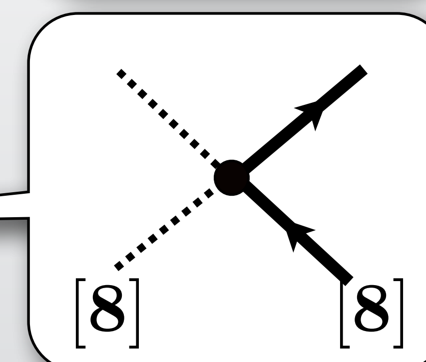
- **Interaction Lagrangian:** expand in powers of meson fields P(x)

$$\mathcal{L}_{int} = \mathcal{L}_1 + \mathcal{L}_2 + \ldots + \text{ mass terms}$$

$$\mathcal{L}_1 = -\frac{\sqrt{2}}{2f}\,\mathrm{tr}\big(D\bar{B}\gamma^\mu\gamma_5\{\partial_\mu P, B\} + F\bar{B}\gamma^\mu\gamma_5[\partial_\mu P, B]\big)$$



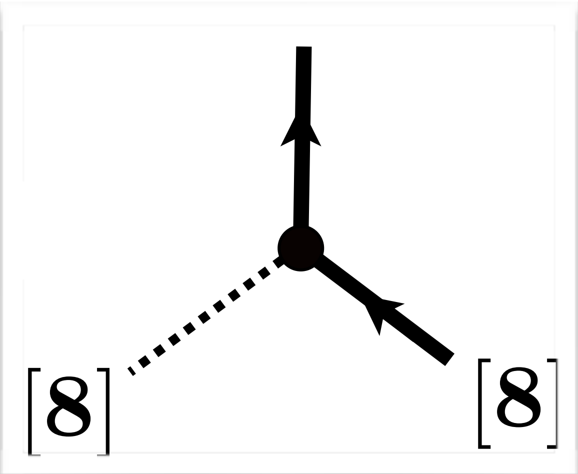
$$\mathcal{L}_2 = \frac{1}{4f^2}\,\mathrm{tr}\big(\mathrm{i}\bar{B}\gamma^\mu\big[[P, \partial_\mu P], B\big]\big)$$



- **Input** : $F = 0.46 \quad D = 0.81$ $\quad f = 0.09\,GeV$
  $(g_A = F + D = 1.27)$

- **Physical** meson and baryon masses (SU(3) breaking)

Chiral $\mathrm{SU(3)_L \times SU(3)_R}$ Effective Field Theory : meson-baryon vertices



$$
\begin{aligned}
\mathcal{L}_1 \;=\; & -f_{NN\pi}\bar{N}\gamma^\mu\gamma_5\boldsymbol{\tau}N\cdot\partial_\mu\boldsymbol{\pi} + i f_{\Sigma\Sigma\pi}\bar{\boldsymbol{\Sigma}}\gamma^\mu\gamma_5\times\boldsymbol{\Sigma}\cdot\partial_\mu\boldsymbol{\pi}\\
& -f_{\Lambda\Sigma\pi}\left[\bar{\Lambda}\gamma^\mu\gamma_5\boldsymbol{\Sigma}+\bar{\boldsymbol{\Sigma}}\gamma^\mu\gamma_5\Lambda\right]\cdot\partial_\mu\boldsymbol{\pi} - f_{\Xi\Xi\pi}\bar{\Xi}\gamma^\mu\gamma_5\boldsymbol{\tau}\Xi\cdot\partial_\mu\boldsymbol{\pi}\\
& -f_{\Lambda NK}\left[\bar{N}\gamma^\mu\gamma_5\Lambda\partial_\mu K + \text{h.c.}\right] - f_{\Xi\Lambda K}\left[\bar{\Xi}\gamma^\mu\gamma_5\Lambda\partial_\mu\overline{K} + \text{h.c.}\right]\\
& -f_{\Sigma NK}\left[\bar{N}\gamma^\mu\gamma_5\boldsymbol{\tau}\partial_\mu K\cdot\boldsymbol{\Sigma} + \text{h.c.}\right] - f_{\Sigma\Xi K}\left[\bar{\Xi}\gamma^\mu\gamma_5\boldsymbol{\tau}\partial_\mu\overline{K}\cdot\boldsymbol{\Sigma} + \text{h.c.}\right]\\
& -f_{NN\eta_8}\bar{N}\gamma^\mu\gamma_5N\partial_\mu\eta - f_{\Lambda\Lambda\eta_8}\bar{\Lambda}\gamma^\mu\gamma_5\Lambda\partial_\mu\eta\\
& -f_{\Sigma\Sigma\eta_8}\bar{\boldsymbol{\Sigma}}\cdot\gamma^\mu\gamma_5\boldsymbol{\Sigma}\partial_\mu\eta - f_{\Xi\Xi\eta_8}\bar{\Xi}\gamma^\mu\gamma_5\Xi\partial_\mu\eta\;.
\end{aligned}
$$

$$
\begin{aligned}
f_{NN\pi} &= G & f_{NN\eta_8} &= \tfrac{1}{\sqrt{3}}(4\alpha-1)\,G & f_{\Lambda NK} &= -\tfrac{1}{\sqrt{3}}(1+2\alpha)\,G\\
f_{\Xi\Xi\pi} &= -(1-2\alpha)G & f_{\Xi\Xi\eta_8} &= -\tfrac{1}{\sqrt{3}}(1+2\alpha)G & f_{\Xi\Lambda K} &= \tfrac{1}{\sqrt{3}}(4\alpha-1)\,G\\
f_{\Lambda\Sigma\pi} &= \tfrac{2}{\sqrt{3}}(1-\alpha)\,G & f_{\Sigma\Sigma\eta_8} &= \tfrac{2}{\sqrt{3}}(1-\alpha)\,G & f_{\Sigma NK} &= (1-2\alpha)\,G\\
f_{\Sigma\Sigma\pi} &= 2\alpha G & f_{\Lambda\Lambda\eta_8} &= -\tfrac{2}{\sqrt{3}}(1-\alpha)G & f_{\Xi\Sigma K} &= -\,G
\end{aligned}
$$

$$G = \frac{g_A}{2f} \simeq 7\,GeV^{-1} \simeq 1.4\,fm \qquad \alpha = \frac{F}{F+D} = 0.36$$

Chiral SU(3) Effective Field Theory and Hyperon-Nucleon Interactions

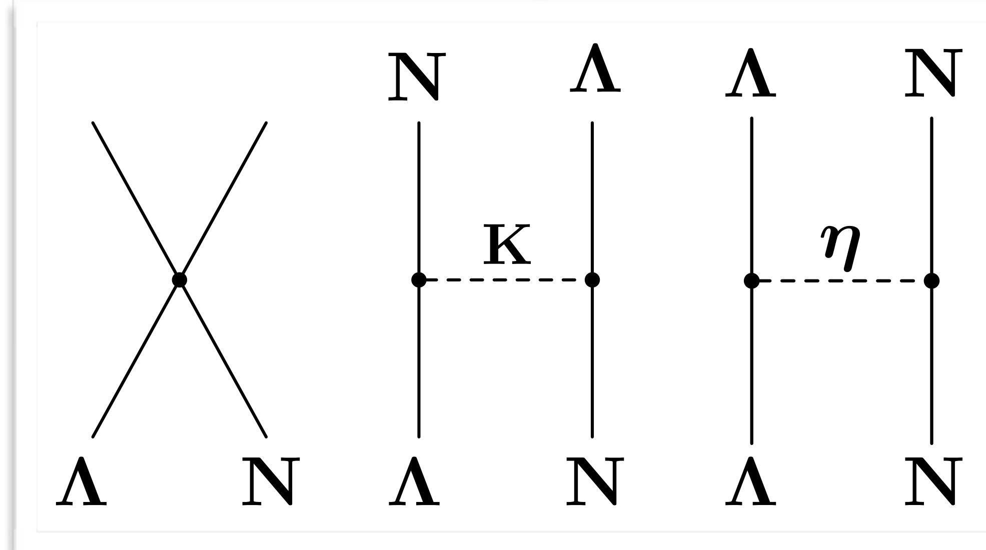
J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W.W.: Nucl. Phys. A 915 (2013) 24

Example:

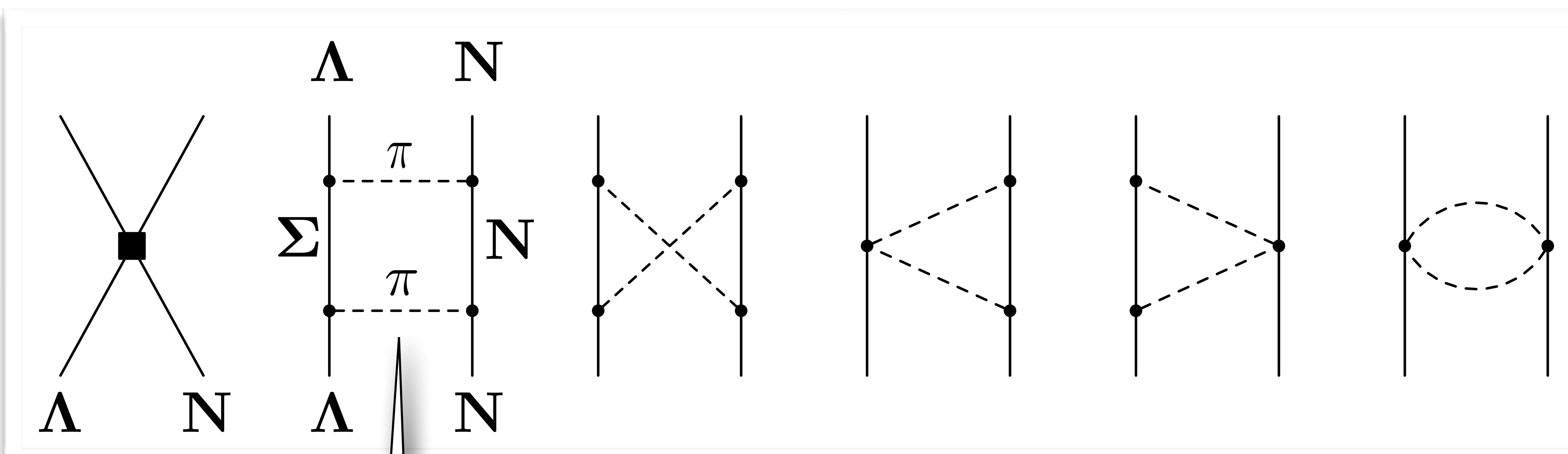
Λ N

interaction

- **Leading order (LO)**

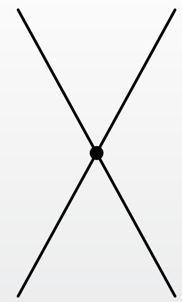


- **Next-to-leading order (NLO)**

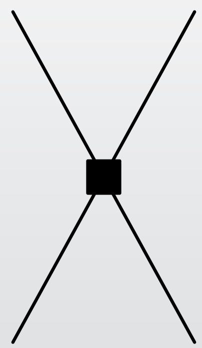


2nd order tensor force

Hyperon - Nucleon Interaction
Contact Terms



$$V^{(0)}_{BB\to BB} = C_S + C_T \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$$



$$V^{(2)}_{BB\to BB} = C_1 \mathbf{q}^2 + C_2 \mathbf{k}^2 + \left(C_3 \mathbf{q}^2 + C_4 \mathbf{k}^2\right)\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 + \frac{\mathrm{i}}{2} C_5 (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\cdot(\mathbf{q}\times\mathbf{k})$$
$$+ C_6 (\mathbf{q}\cdot\boldsymbol{\sigma}_1)(\mathbf{q}\cdot\boldsymbol{\sigma}_2) + C_7 (\mathbf{k}\cdot\boldsymbol{\sigma}_1)(\mathbf{k}\cdot\boldsymbol{\sigma}_2) + \frac{\mathrm{i}}{2} C_8 (\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2)\cdot(\mathbf{q}\times\mathbf{k})$$

- **SU(3) symmetry** reduces number of independent constants

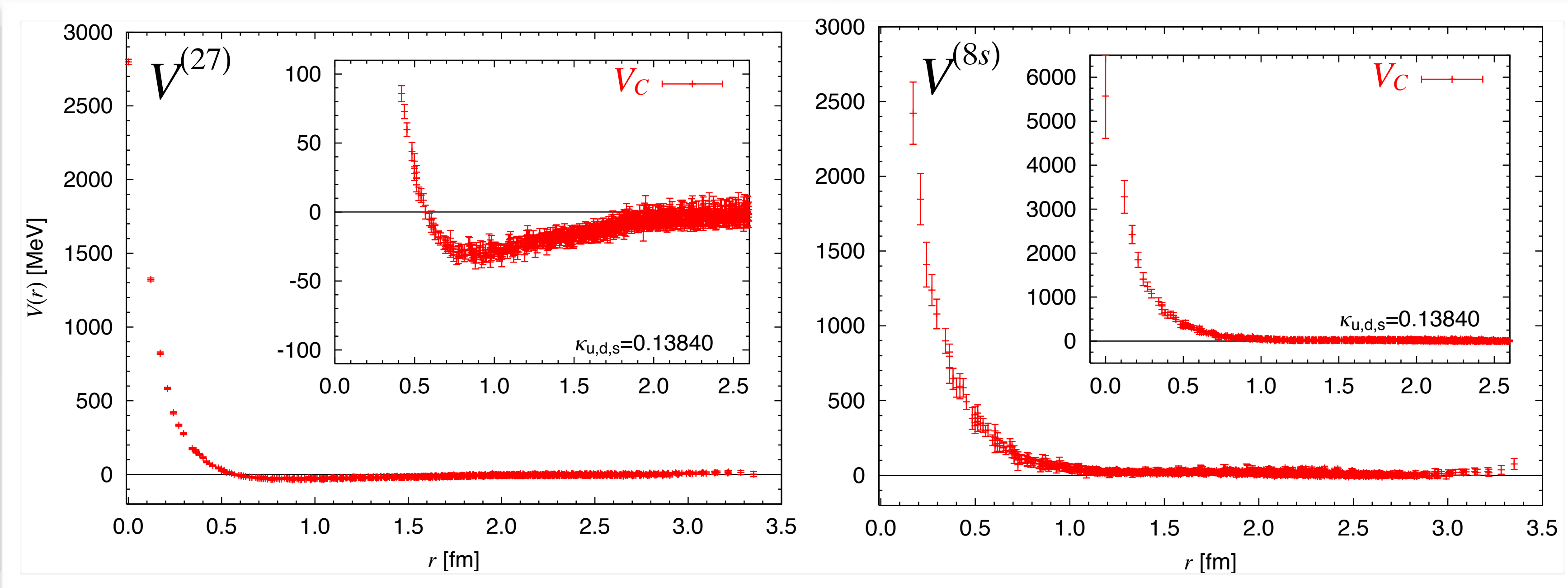
$$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} \oplus \mathbf{8_s} \oplus \mathbf{1} \oplus \mathbf{10} \oplus \mathbf{10}^* \oplus \mathbf{8_a}$$

S	Channel	I	$V_{^1S_0,\,^3P_0,\,^3P_1,\,^3P_2}$	$V_{^3S_1,\,^3S_1\text{-}^3D_1,\,^1P_1}$
0	$NN \to NN$	0	–	C^{10^*}
	$NN \to NN$	1	C^{27}	–
−1	$\Lambda N \to \Lambda N$	$\frac{1}{2}$	$\frac{1}{10}\left(9C^{27} + C^{8_s}\right)$	$\frac{1}{2}\left(C^{8_a} + C^{10^*}\right)$
	$\Lambda N \to \Sigma N$	$\frac{1}{2}$	$\frac{3}{10}\left(-C^{27} + C^{8_s}\right)$	$\frac{1}{2}\left(-C^{8_a} + C^{10^*}\right)$
	$\Sigma N \to \Sigma N$	$\frac{1}{2}$	$\frac{1}{10}\left(C^{27} + 9C^{8_s}\right)$	$\frac{1}{2}\left(C^{8_a} + C^{10^*}\right)$
	$\Sigma N \to \Sigma N$	$\frac{3}{2}$	C^{27}	C^{10}

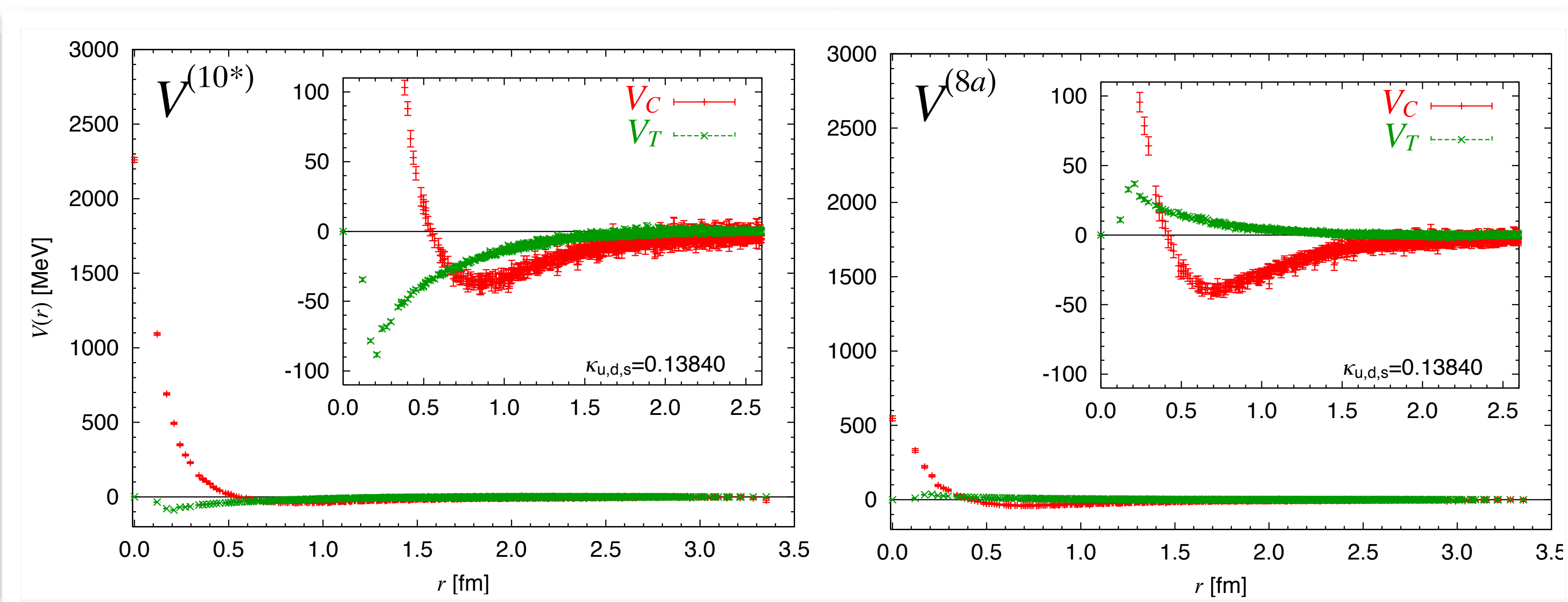
S. Petschauer,
N. Kaiser
Nucl. Phys.
A 916 (2013) 1-29

Hyperon - Nucleon Interactions from Lattice QCD

$$\Lambda N(^1S_0) = \frac{9}{10}[\mathbf{27}] + \frac{1}{10}[\mathbf{8_s}]$$



$$\Lambda N(^3S_1) = \frac{1}{2}[\mathbf{10^*}] + \frac{1}{2}[\mathbf{8_a}]$$



$$m_{ps} = 0.47\,\text{GeV}$$

T. Inoue et al.

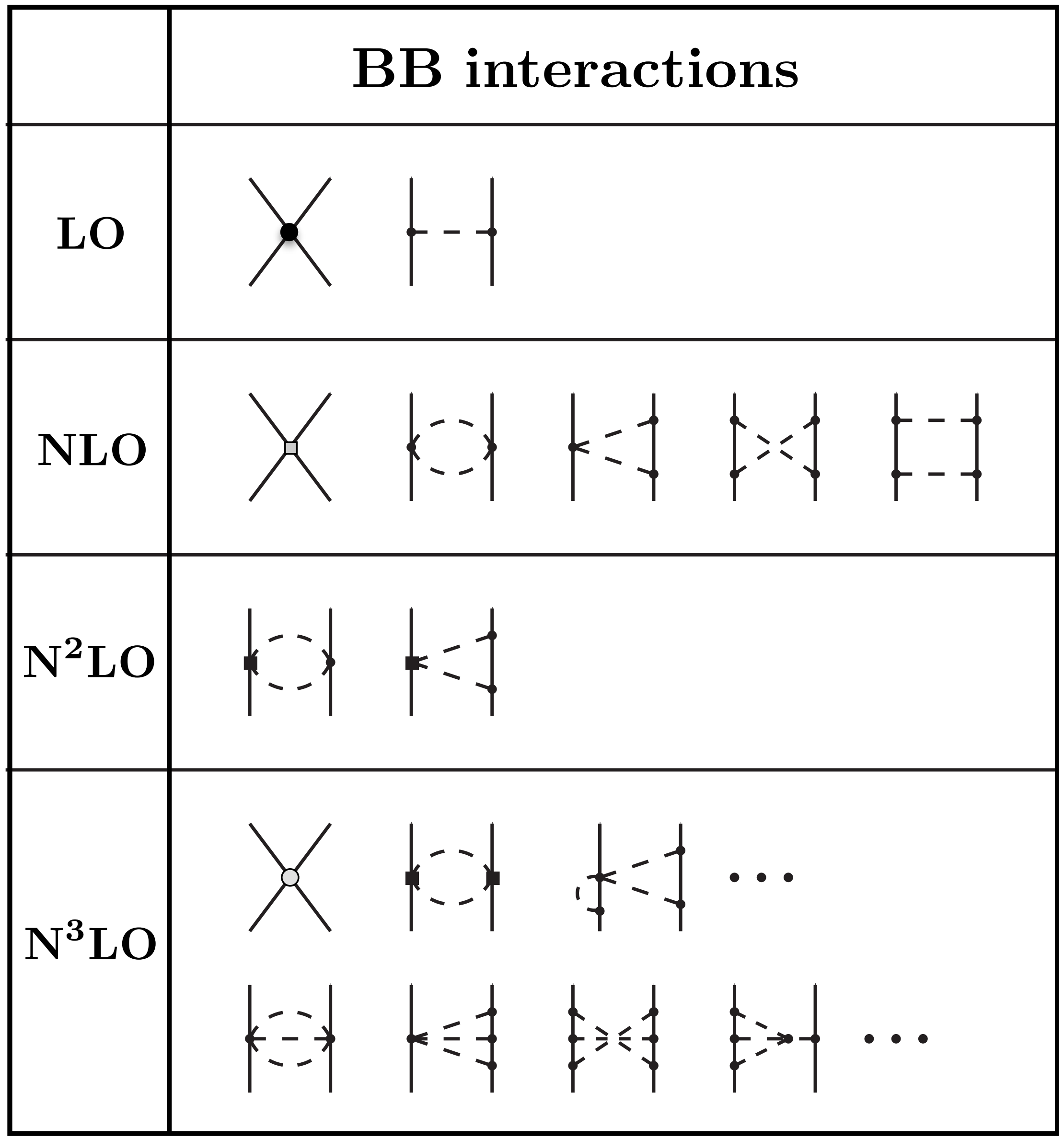
(HAL QCD)
PTP 124 (2010) 591

Nucl. Phys.
A881 (2012) 28

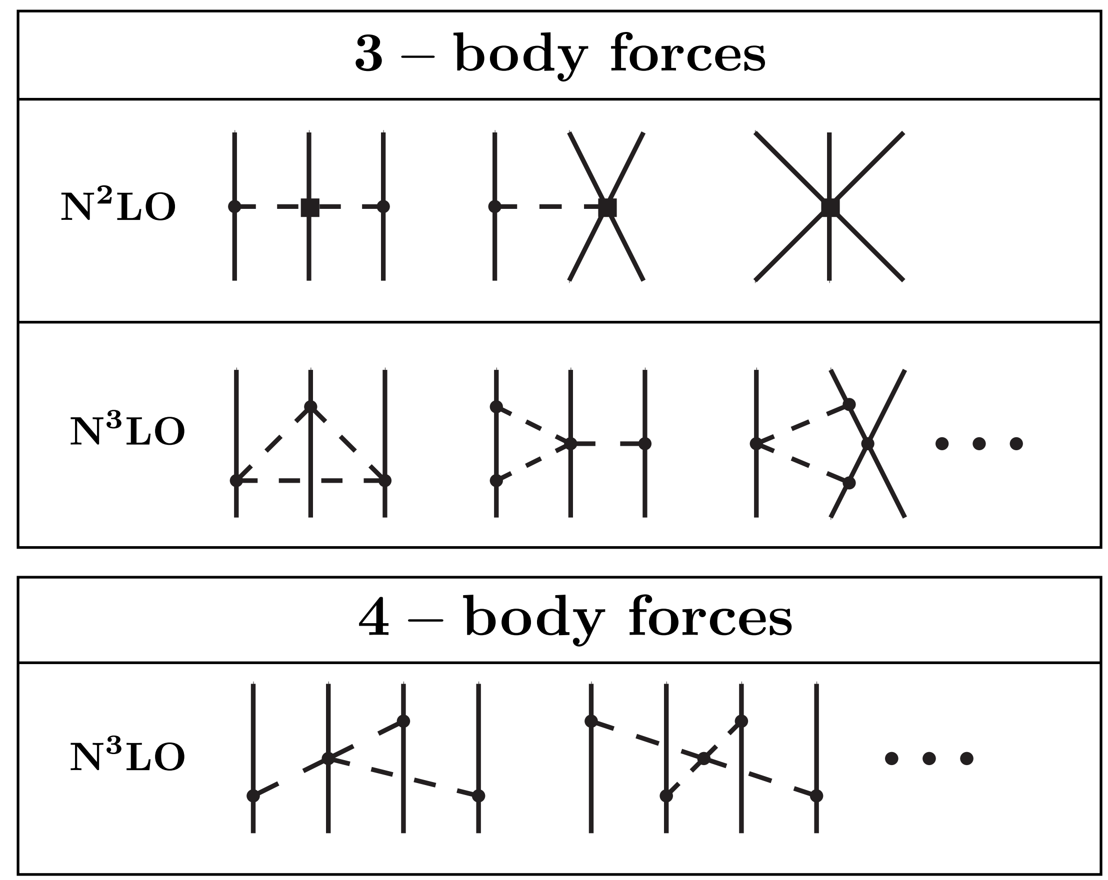
towards physical quark masses

- note: **strong short-distance repulsive interaction**

BARYON-BARYON INTERACTIONS from CHIRAL EFFECTIVE FIELD THEORY

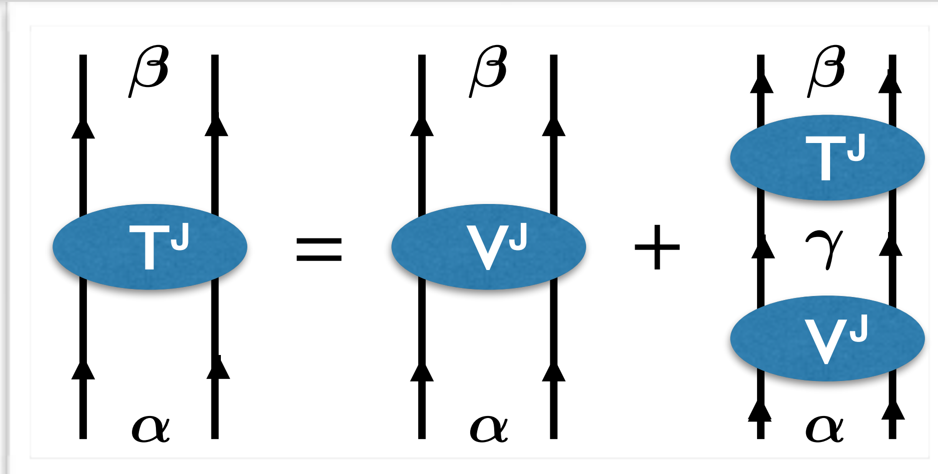


- Systematically organized hierarchy in powers of $\frac{Q}{\Lambda}$
(Q: momentum, energy, pion mass)



- NN interaction state-of-the-art: N^4LO plus convergence tests at N^5LO
- **YN** interaction (limited data base): NLO plus three-body forces

Coupled-Channels Lippmann-Schwinger Equation



- Partial waves (LS)J , baryon-baryon channels α, β

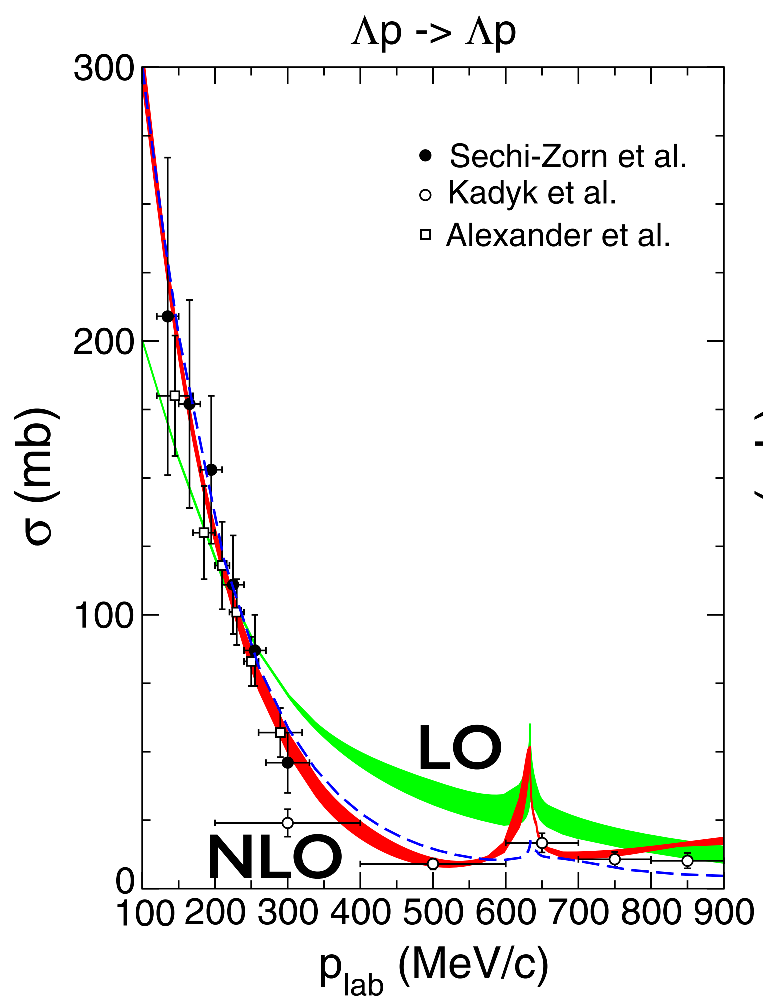
$$\mathbf{T}^J_{\beta\alpha}(p_f, p_i; \sqrt{s}) = \mathbf{V}^J_{\beta\alpha}(p_f, p_i) + \sum_\gamma \int_0^\infty \frac{dp\, p^2}{(2\pi)^3} \mathbf{V}^J_{\beta\gamma}(p_f, p) \frac{2\mu_\gamma}{p_\gamma^2 - p^2 + i\varepsilon} \mathbf{T}^J_{\gamma\alpha}(p, p_i; \sqrt{s})$$

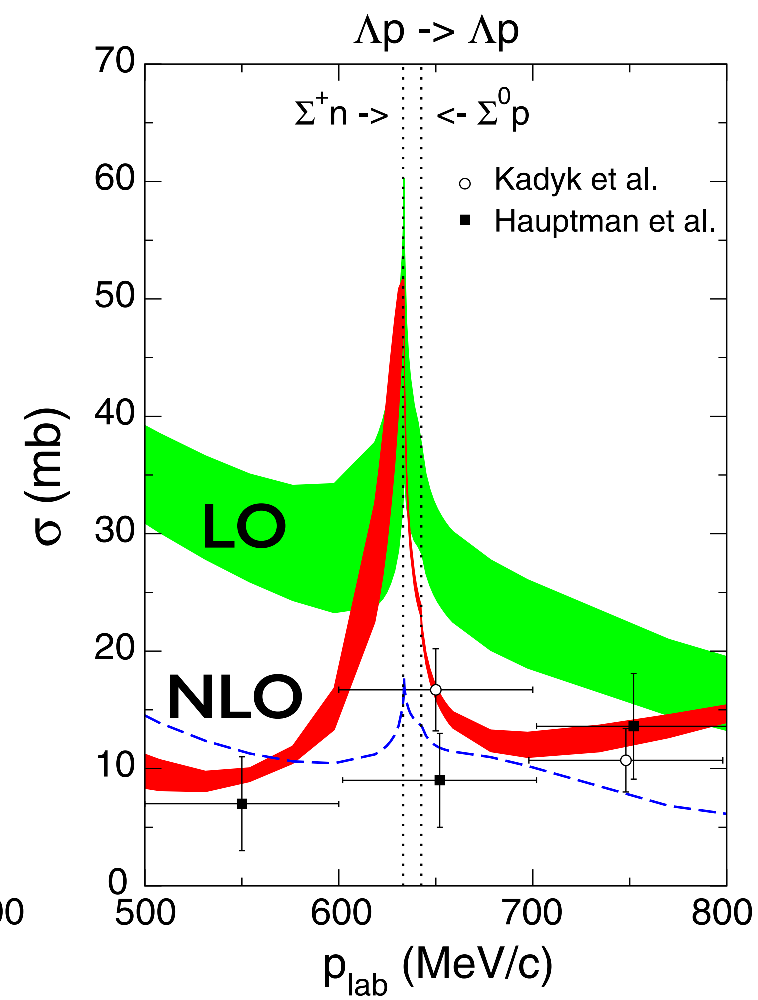
- On-shell momentum of intermediate channel γ determined by :

$$\sqrt{s} = \sqrt{M^2_{\gamma,1} + p^2_\gamma} + \sqrt{M^2_{\gamma,2} + p^2_\gamma}$$

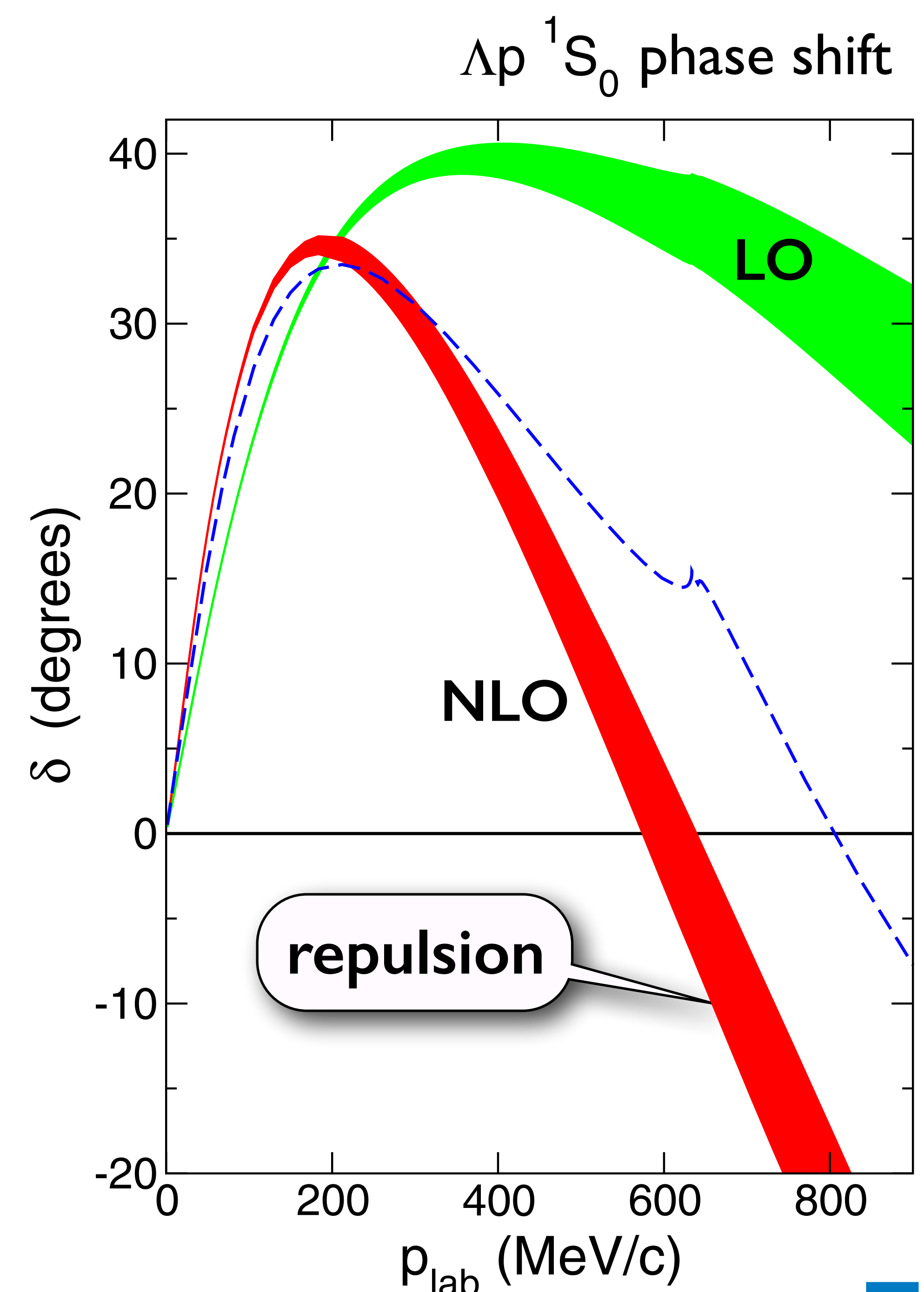
- Relativistic kinematics relating lab. and c.m. momenta

Hyperon - Nucleon Interaction
from Chiral SU(3) EFT





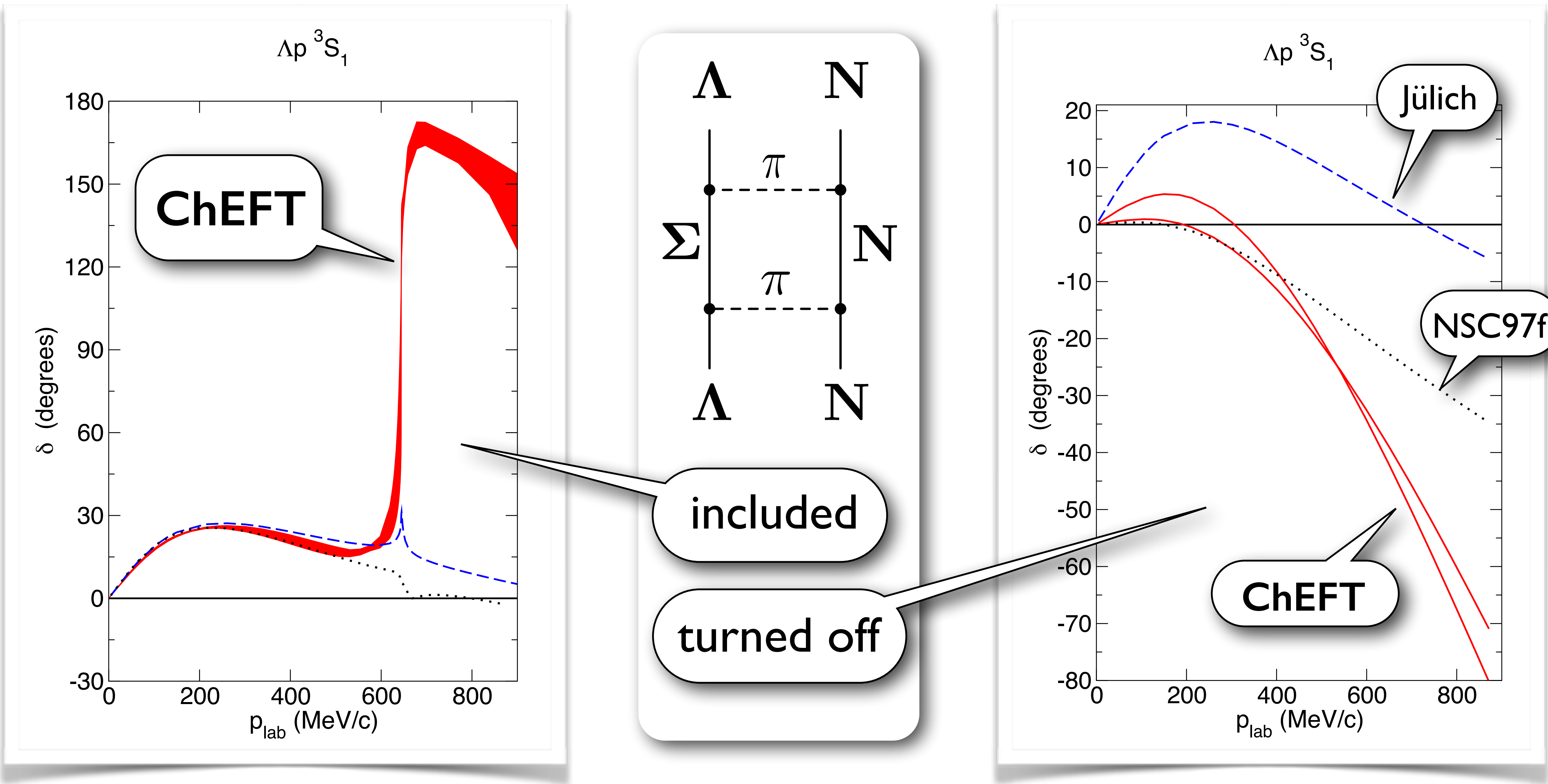
J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W.W.
Nucl. Phys. A 915 (2013) 24



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

Hyperon - Nucleon Interaction (contd.)

- Triplet-S channel and $\Lambda N \leftrightarrow \Sigma N$ **coupling** (2nd order tensor force)



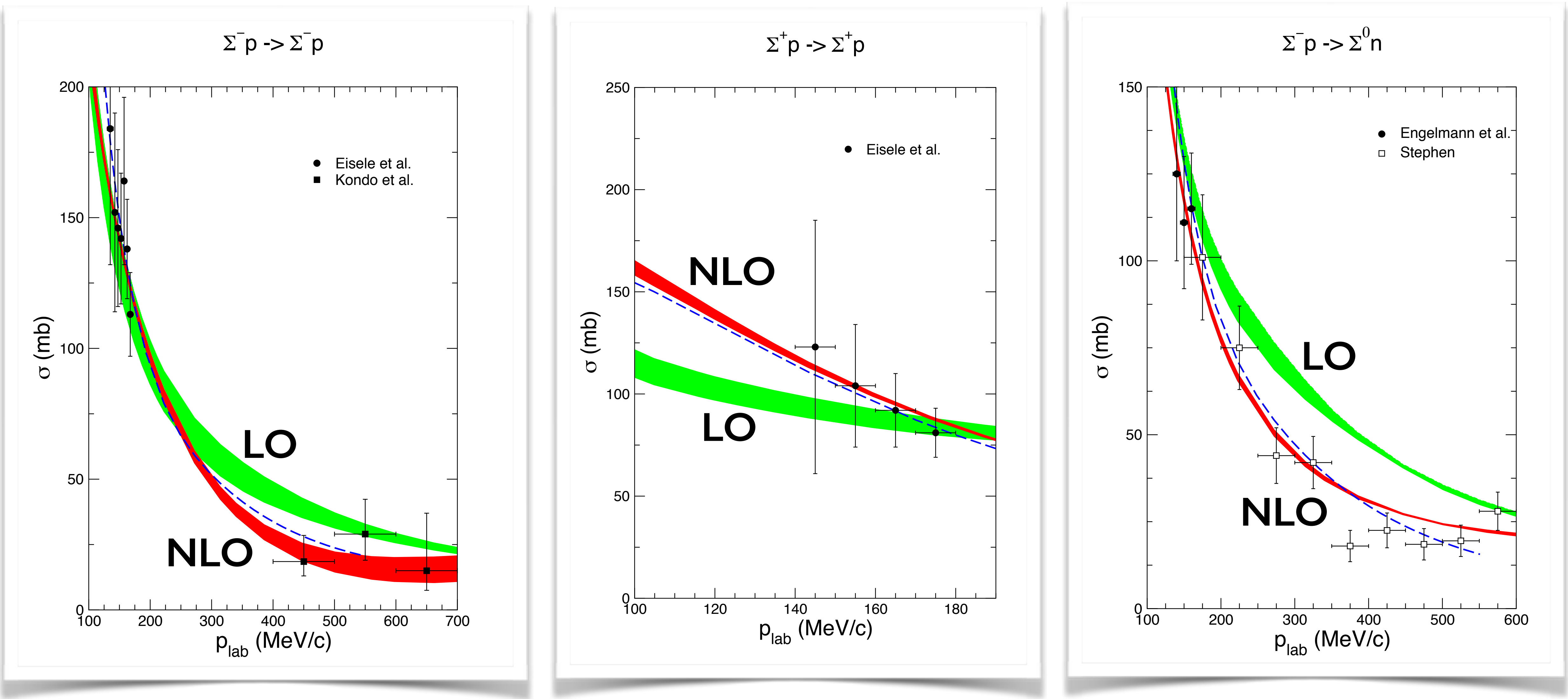
- In-medium (Pauli) **suppression** of $\Lambda N \leftrightarrow \Sigma N$ **coupling :**

  increasing repulsion with rising density

Hyperon - Nucleon Interaction (contd.)

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

- ΣN elastic and charge exchange scattering

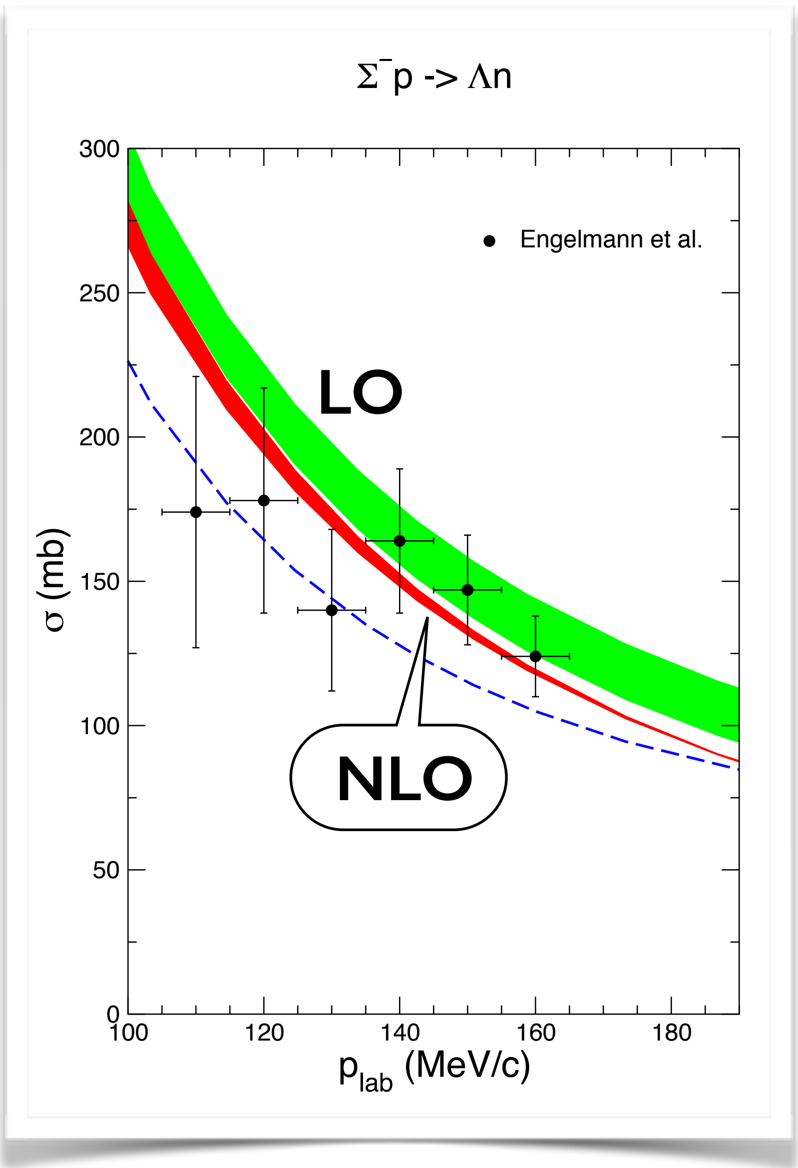


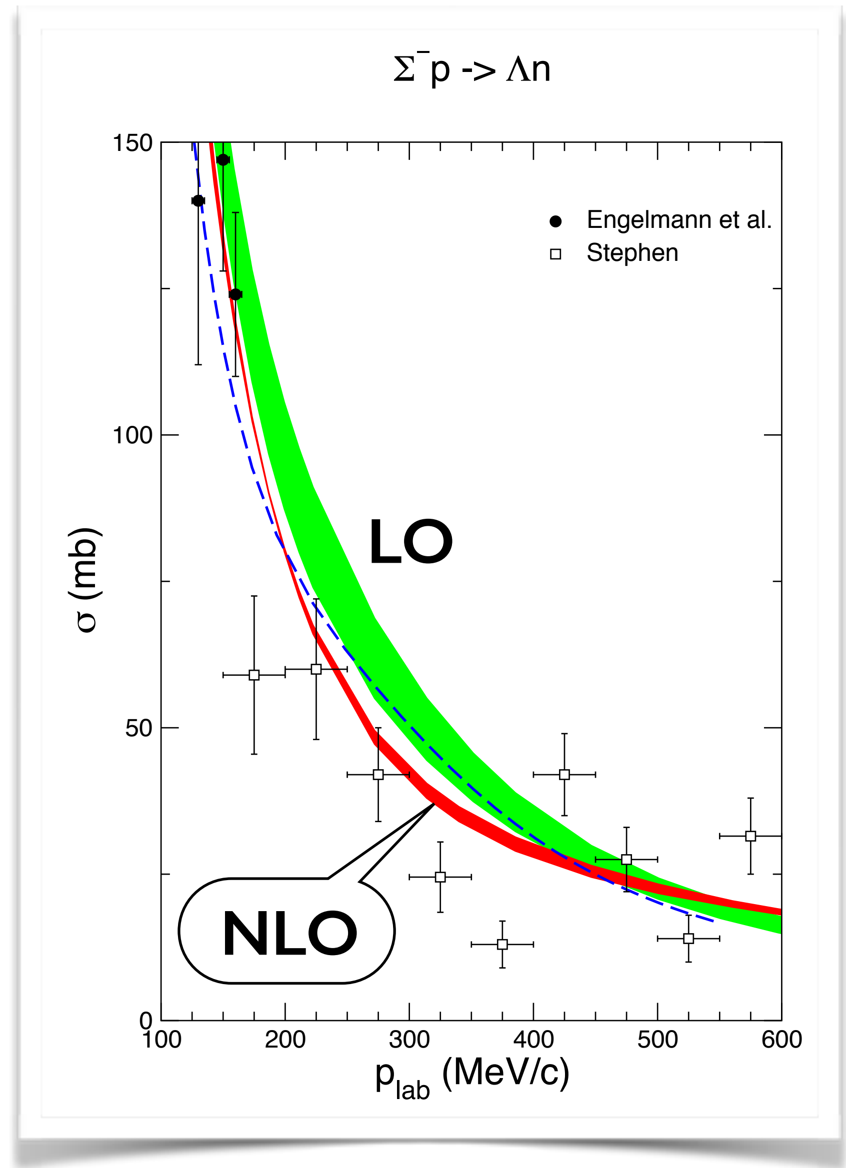
- **Quest for much improved hyperon-nucleon scattering data base !**

Hyperon - Nucleon Interaction (contd.)

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

- $\Sigma N \rightarrow \Lambda N$ **reaction**





- **Quest for much improved hyperon-nucleon scattering data base !**

Part III

Hyperon Interactions

in

Nuclear and Neutron Matter

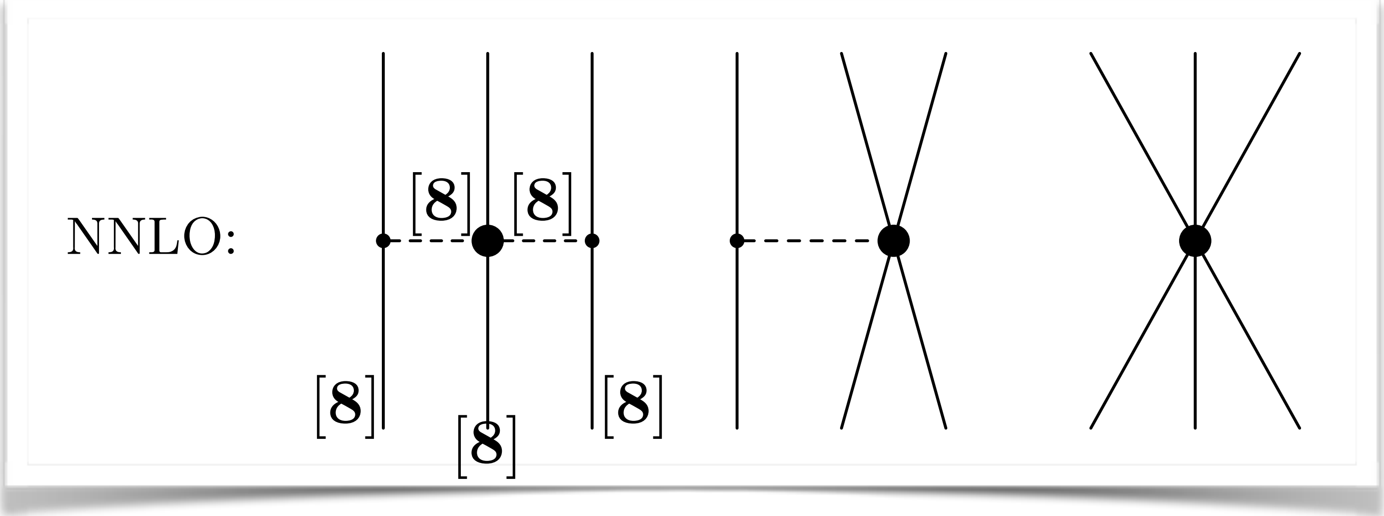
- **YNN three-body forces** from **Chiral SU(3) EFT**
- **Density dependence** of
  Λ-nuclear single particle potential
- Towards a **solution** of the
  "hyperon puzzle" in **neutron stars ?**

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

S. Petschauer et al. Phys. Rev. C93 (2016) 014001

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

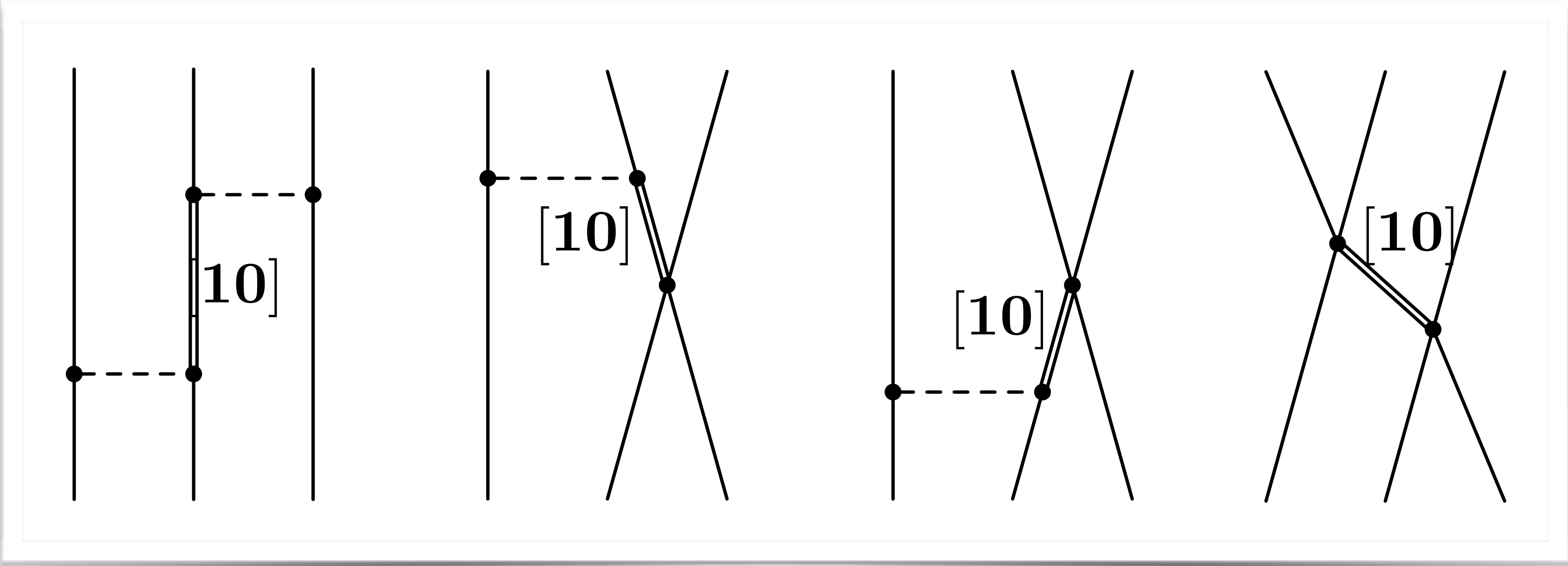
3-baryon sector:



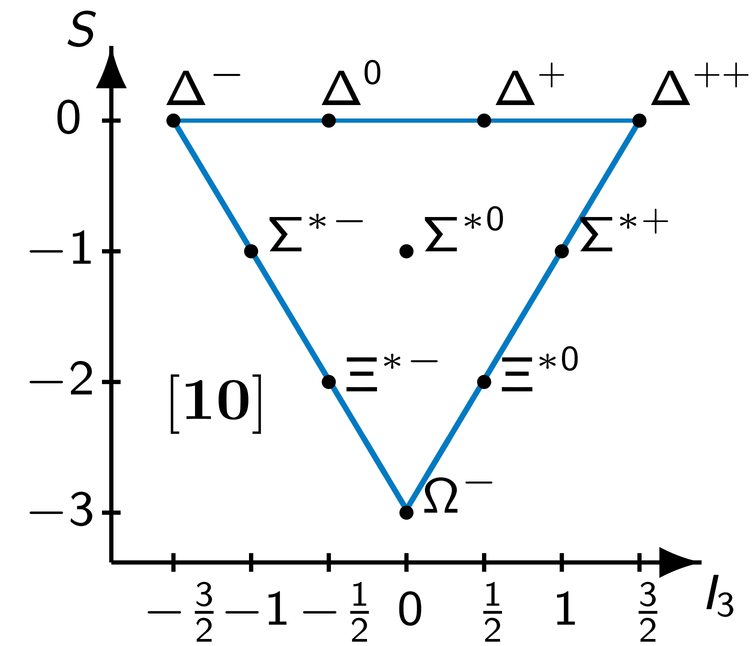
- Chiral SU(3) Effective Field Theory with **explicit decuplet baryons:**

explicit
baryon decuplet :

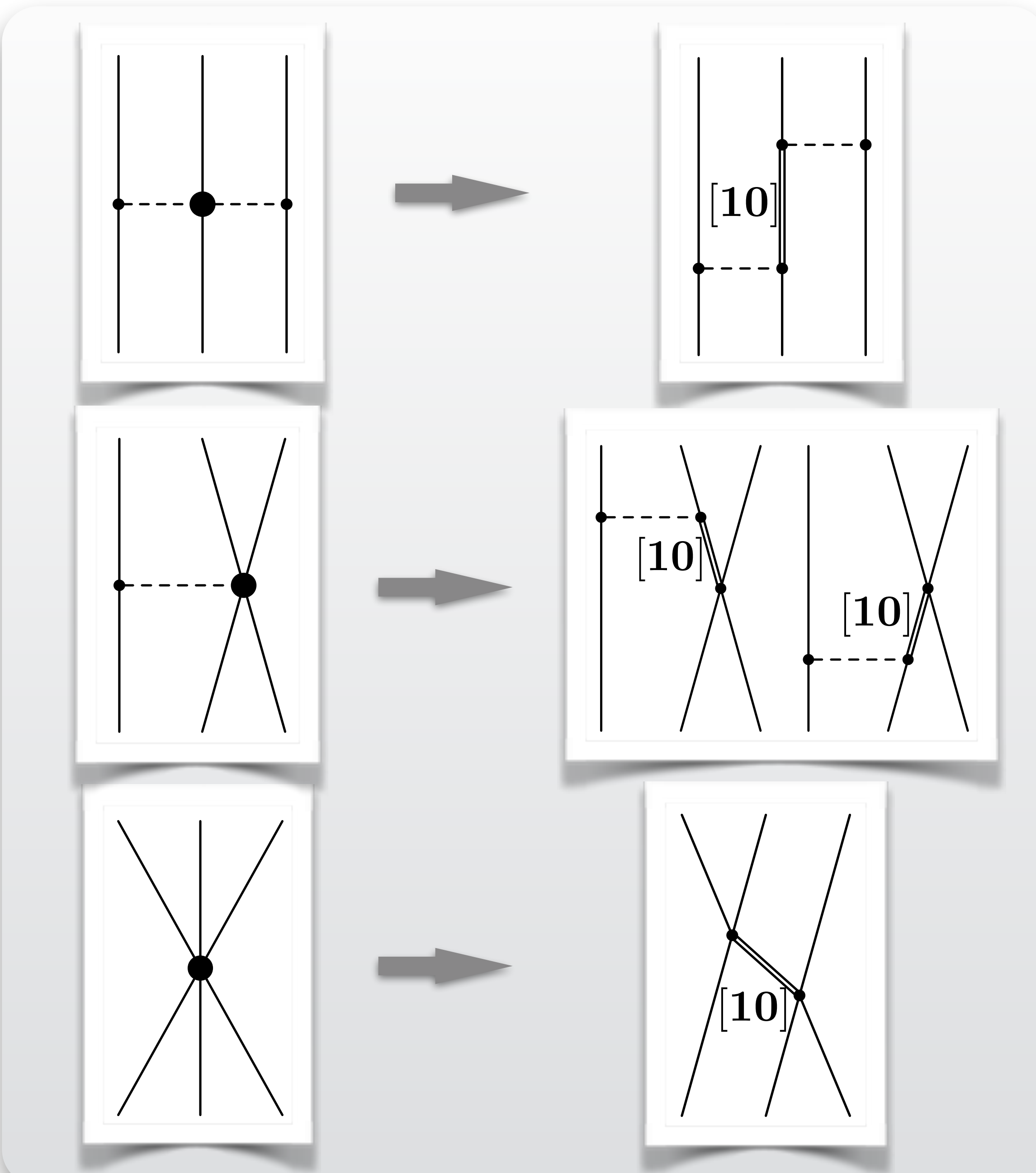
promotion to **NLO**



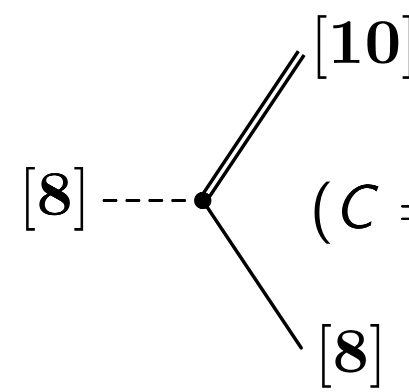
Decuplet Dominance
in YNN three-body forces



- Estimates of YNN 3-body interactions assuming dominant decuplet (Σ^*, Δ) intermediate states

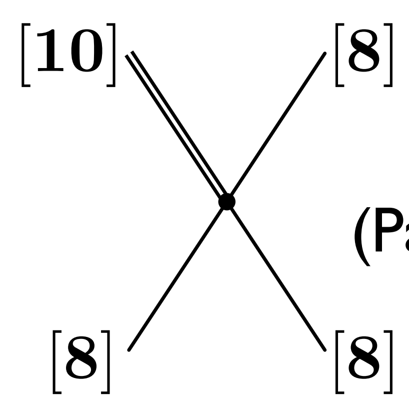


- … much reduced set of parameters
  basic vertices :



one constant

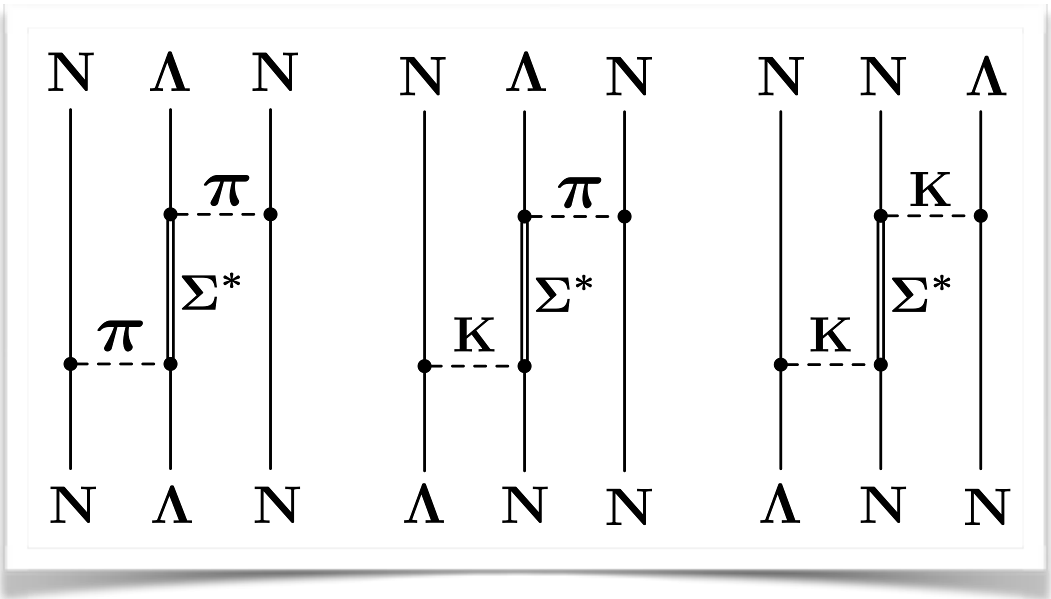
($C = \frac{3}{4} g_A \approx 1$ from $\Delta \rightarrow N\pi$)

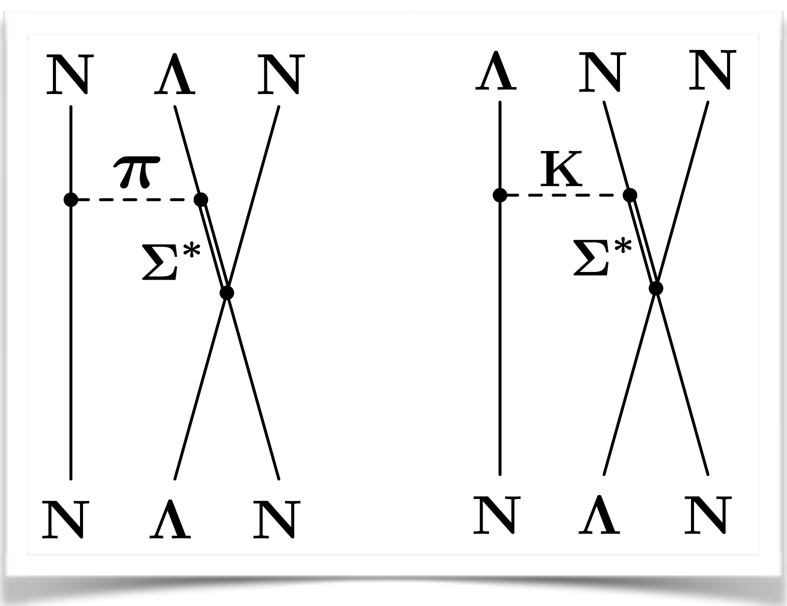


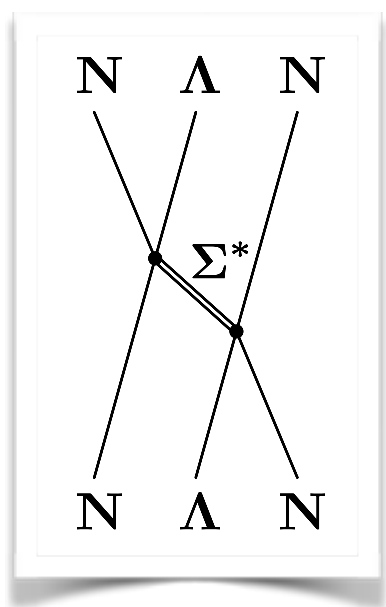
two constants

(Pauli-forbidden in NN sector)

Example :
ΛNN three-body interactions





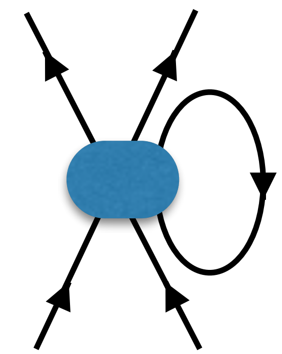


transition	type	B^*
$NNN \to NNN$	$\pi\pi$	Δ
	$\pi\pi$	Σ^*
	πK	Σ^*
	KK	Σ^*
$\Lambda NN \to \Lambda NN$	π	Σ^*
	K	Σ^*
	ct	Σ^*
	$\pi\pi$	Δ, Σ^*
	πK	Δ, Σ^*
	$\pi\eta$	Σ^*
	KK	Σ^*
$\Lambda NN \leftrightarrow \Sigma NN$	$K\eta$	Σ^*
	π	Δ, Σ^*
	K	Σ^*
	η	Σ^*
	ct	Σ^*

Density-dependent EFFECTIVE HYPERON - NUCLEON INTERACTION from CHIRAL THREE-BARYON FORCES

S. Petschauer, J. Haidenbauer, N. Kaiser, U.-G. Meißner, W.W. Nucl. Phys. A957 (2017) 347

$$V_{12} = \sum_B \mathrm{tr}_{\sigma_3} \int_{|\vec{k}|\leq k_f^B} \frac{\mathrm{d}^3 k}{(2\pi)^3} V_{123}$$



- Λn density-dependent effective interaction

$$V_{\Lambda n}^{\mathbf{eff},\pi\pi} = \frac{C^2 g_A^2}{2f^4\,\Delta}\,[\rho_n + 2\rho_p] + \mathcal{F}(k_F^p, k_F^n; p, q)$$ **repulsive**

$$V_{\Lambda n}^{\mathbf{eff},\pi} = \frac{CH\,g_A}{9f^2\,\Delta}\,[\rho_n + 2\rho_p] + \mathcal{G}(k_F^p, k_F^n; p, q)$$ **+/-**

$$V_{\Lambda n}^{\mathbf{eff},ct} = \frac{H^2}{18\Delta}\,[\rho_n + 2\rho_p]$$ **repulsive**

- **Decuplet-octet mass difference** $\Delta = M_{[10]} - M_{[8]} = 270\,MeV$
- **Coupling parameters :** $C = \frac{3}{4} g_A \simeq 1$ $\quad -\frac{1}{f^2} \lesssim H \lesssim +\frac{1}{f^2}$ (dim. arguments natural size)

Density-dependent EFFECTIVE HYPERON - NUCLEON INTERACTION from CHIRAL THREE-BARYON FORCES

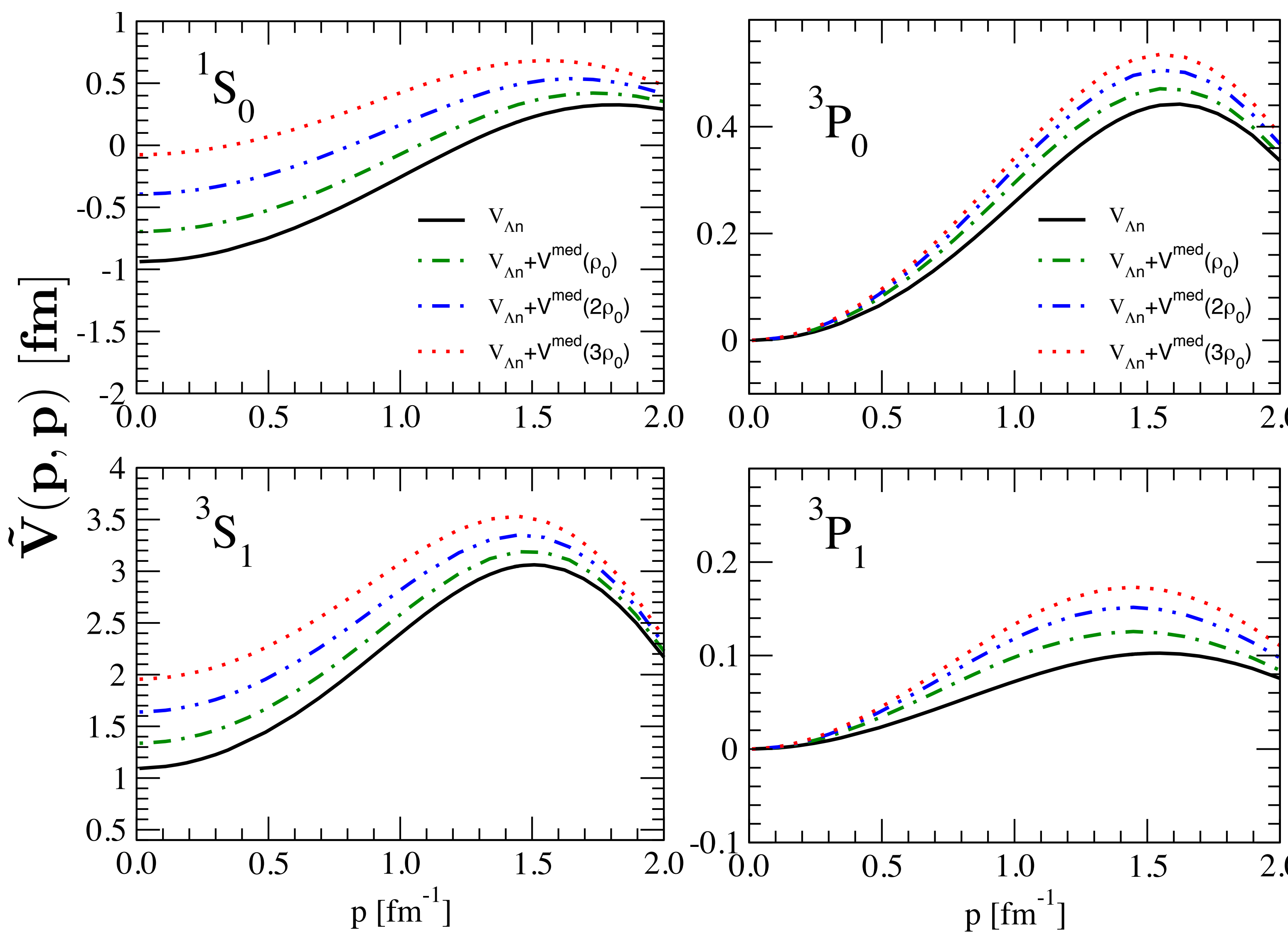
S. Petschauer, J. Haidenbauer, N. Kaiser, U.-G. Meißner, W.W.
NP A957 (2017) 347

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

- Λn **effective interaction in neutron matter**

- **Momentum-space potentials** $(H = +\frac{1}{f^2})$

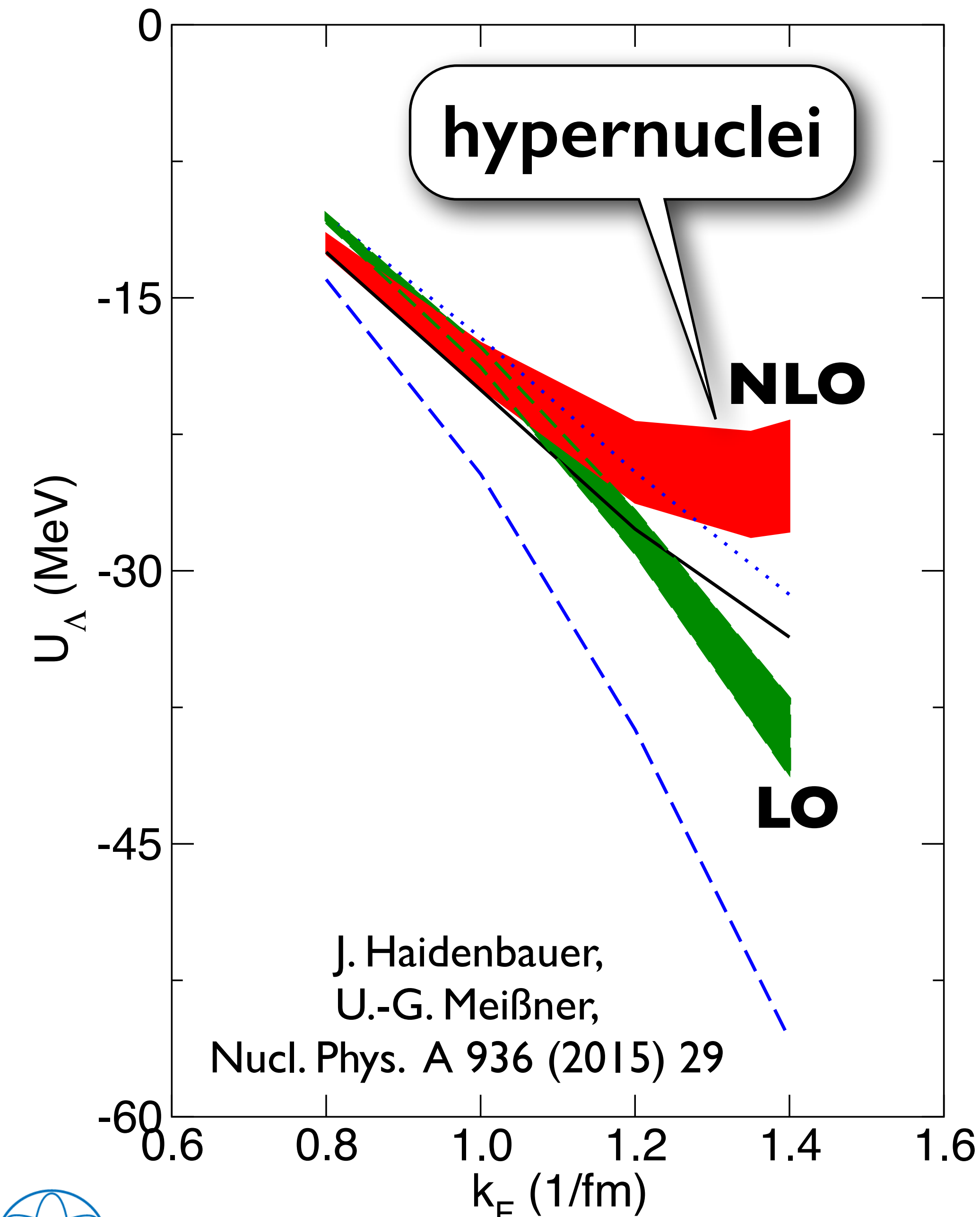
increasing **repulsion ~ proportional to density**

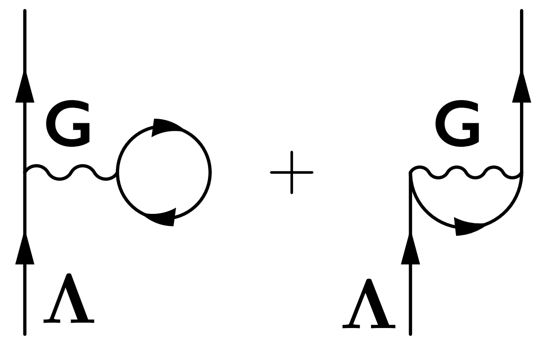


Density dependence of Λ single particle potential

Λ in symmetric nuclear matter - **YN two-body interactions only**

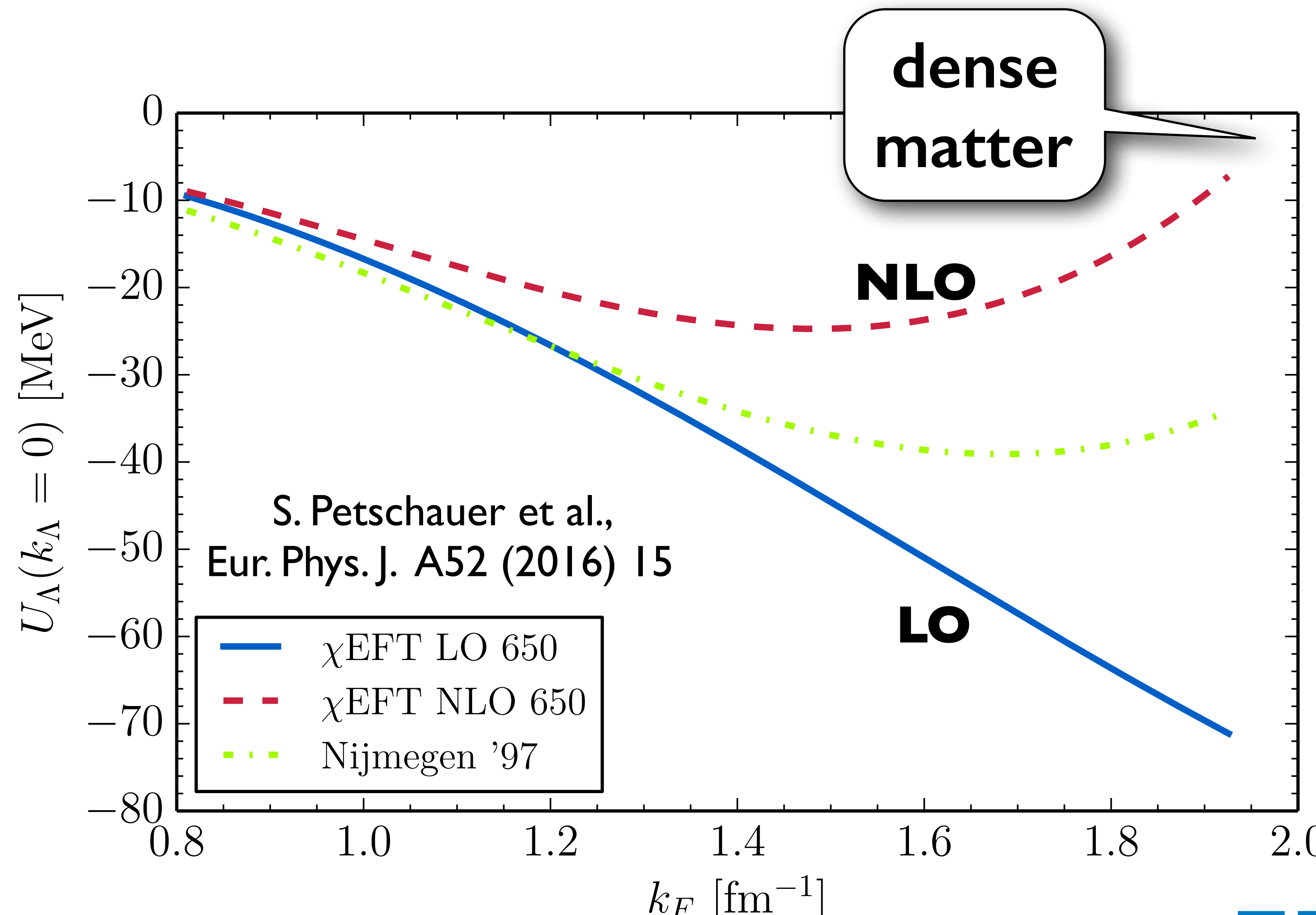
Brueckner calculations
using chiral SU(3) interaction





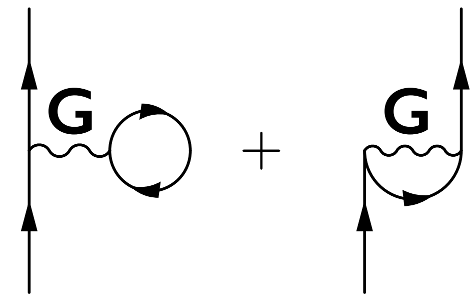
$$\mathbf{G}(\omega) = \mathbf{V} + \mathbf{V}\frac{\mathbf{Q}}{\mathbf{e}(\omega) + \mathbf{i}\epsilon}\mathbf{G}(\omega)$$

("continuous choice")

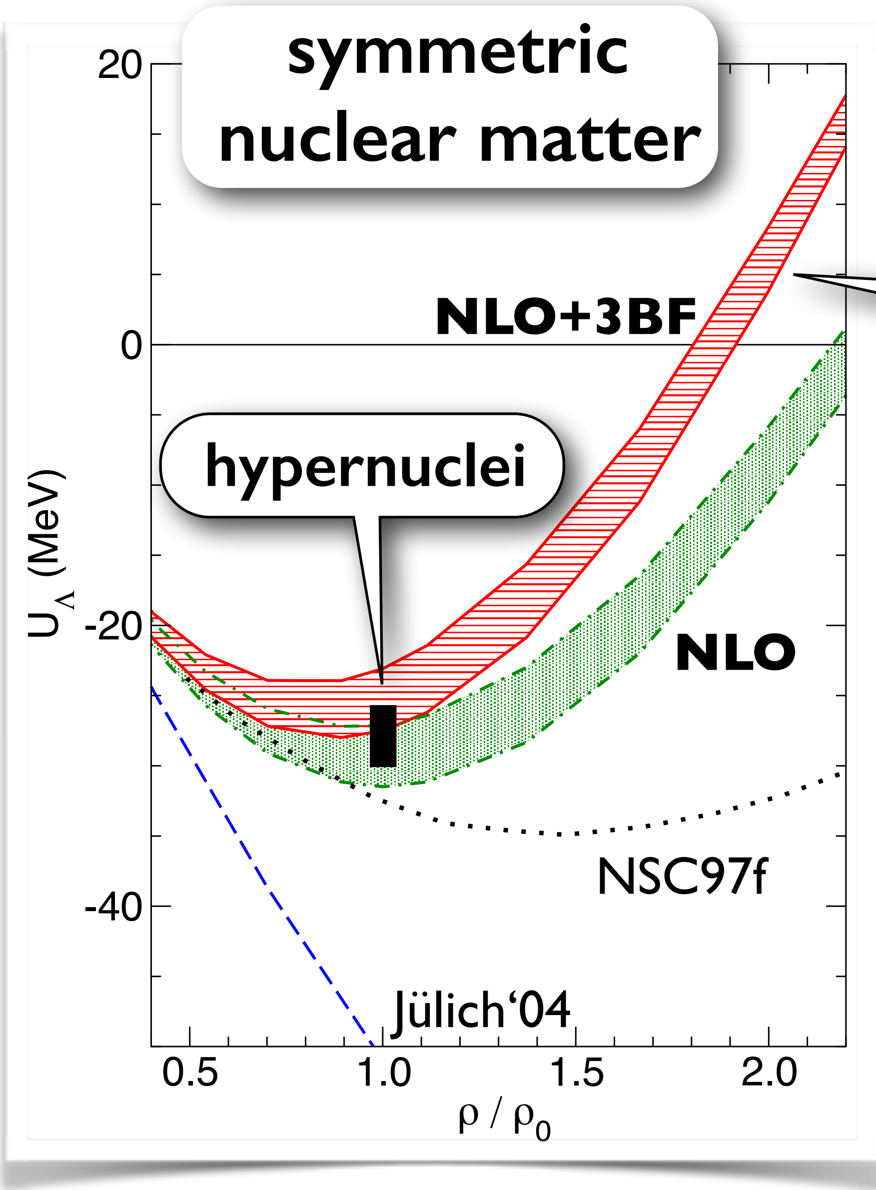


Density dependence of Λ single particle potential

- **Brueckner calculations**
  using
  chiral SU(3) interactions

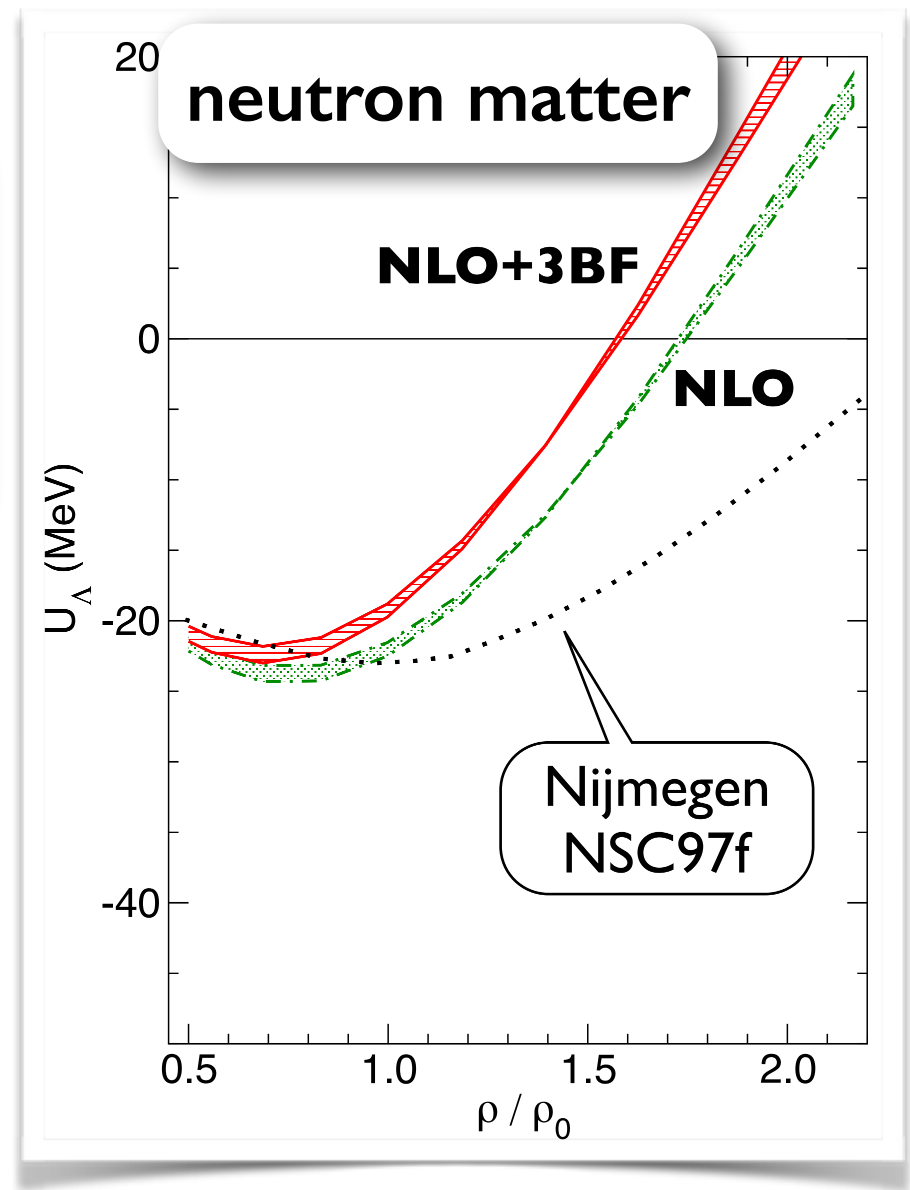


$$\mathbf{G}(\omega) = \mathbf{V} + \mathbf{V}\,\frac{\mathbf{Q}}{\mathbf{e}(\omega) + \mathbf{i}\epsilon}\,\mathbf{G}(\omega)$$



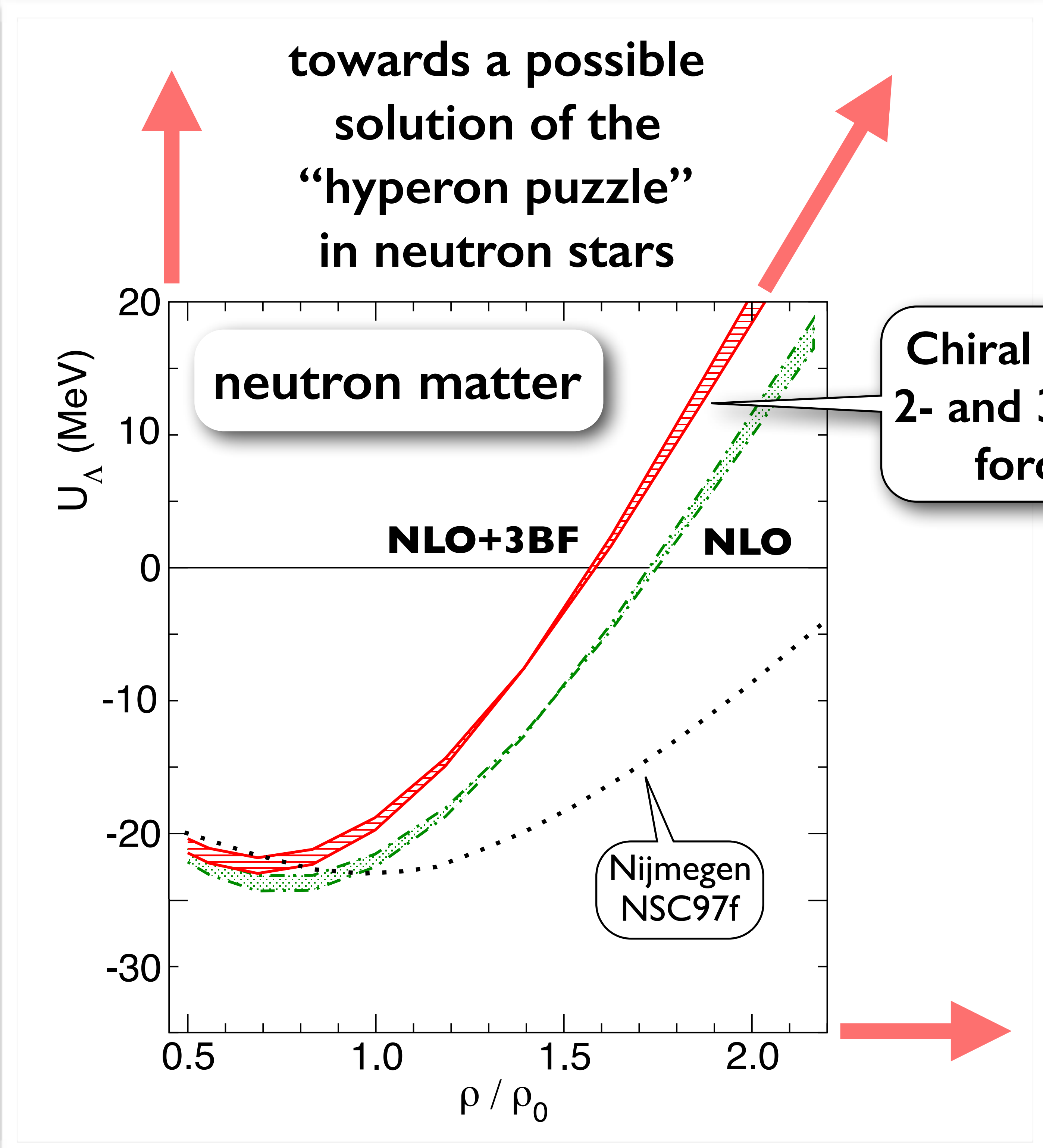
Chiral SU(3) 2- and 3-body forces
$(H = -\frac{1}{f^2})$

J. Haidenbauer,
U.-G. Meißner,
N. Kaiser,
W.W.
arXiv:1612.03758
EPJA (2017)
to appear



- **… towards a possible solution of the "hyperon puzzle"**

Hyperons in the core of neutron stars ?



Chiral SU(3) 2- and 3-body forces

- Quick estimate

$$\mathcal{E} = (E_n + E_\Lambda)\rho$$

$$E_\Lambda \simeq \frac{3\,(k_F^\Lambda)^2}{10\,M_\Lambda^*} + U_\Lambda(\rho)$$

If E_Λ grows as fast as

$$\mu_n = \frac{\partial \mathcal{E}}{\partial \rho_n}$$

with increasing density:
no hyperons
in n-star matter

SUMMARY

- **Constraints on dense baryon matter equation-of-state from neutron stars :**
  - **very stiff EoS** required !
  - **"non-exotic" EoS (nuclear chiral dynamics)** seems to work
  - **hyperon puzzle:**
    naively adding hyperons implies **far too soft EoS**
- **Progress in constructing hyperon-nuclear interactions from Chiral SU(3) Effective Field Theory**
  - **YN two-body interactions** at **NLO**
  - **importance of** $\Lambda N \leftrightarrow \Sigma N$ (2nd order pion exchange tensor force)
  - **YNN three-body forces**
- **Single particle potential of a** Λ in **nuclear** and **neutron matter**
  - **moderately attractive** at low density (hypernuclei)
  - **strongly repulsive** at high density
    . . . towards solution of **"hyperon problem"** in neutron stars