Hypernuclear Physics at the SUPER-FRS

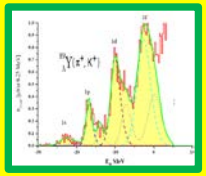
H. Lenske

Institut für Theoretische Physik

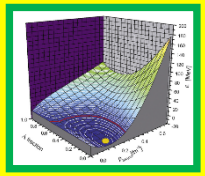
JLU Giessen

Why Hypernuclear Physics?

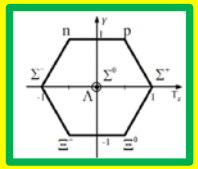
- **Hyperons as Probes for Nuclear Structure**



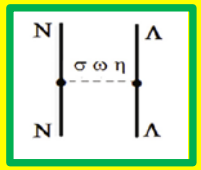
- **Nuclear matter → Baryonic Matter**



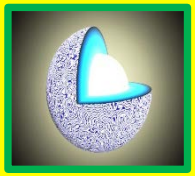
- **Limits of Stability: Isospin → Strangeness**



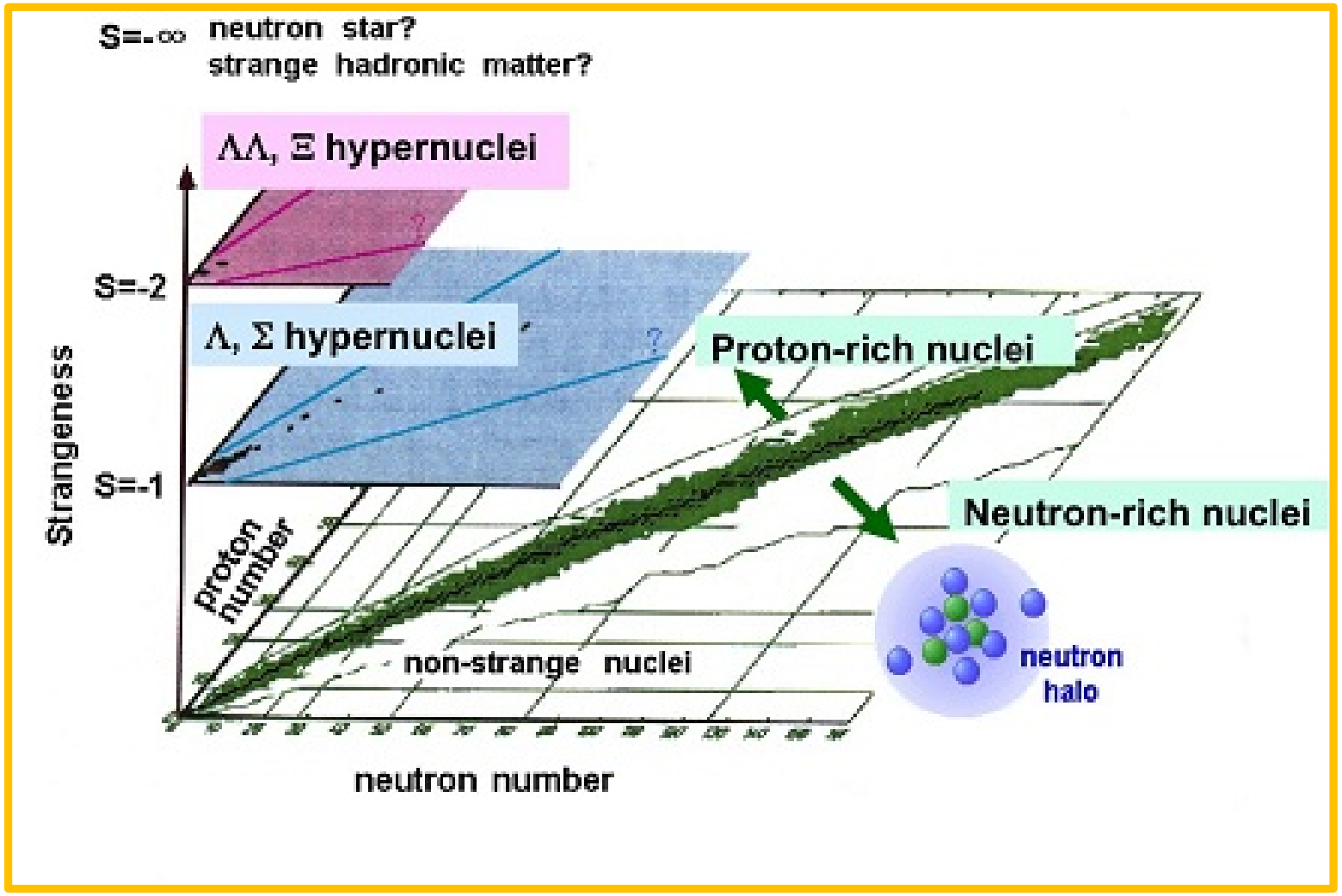
- **Flavor Structure of Nuclear Interactions**



- **Neutron Star Physics**



…Completing Nuclear Physics:

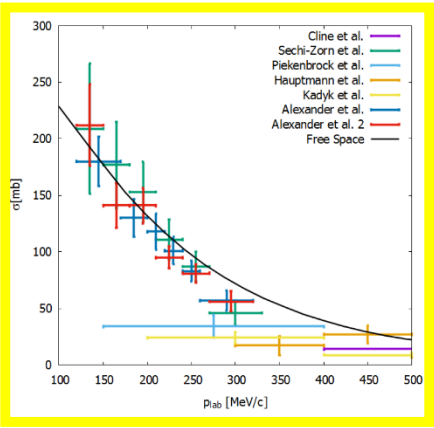


Agenda

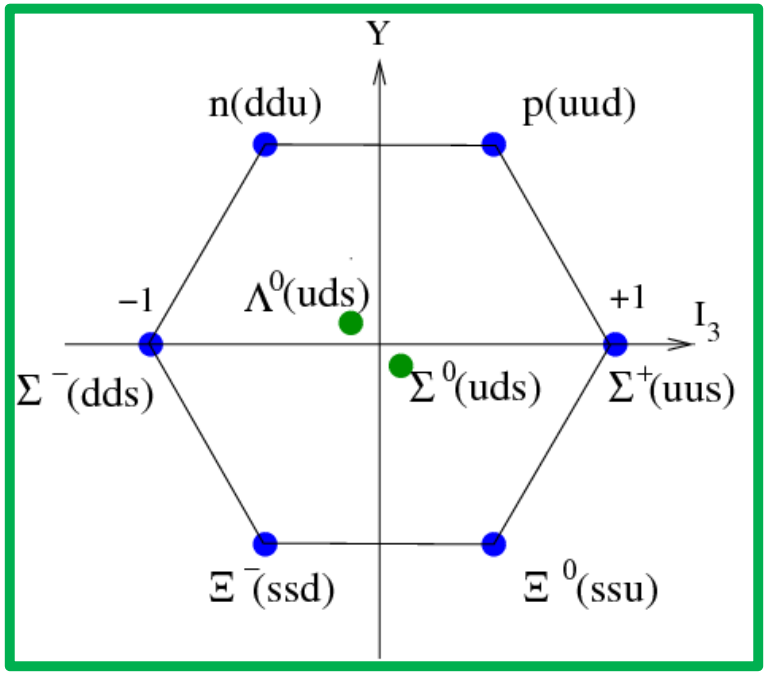
- **SU(3) approach to nucleon and hyperon interactions**
- **Hypermatter and hypernuclei**
- **Hyperons in neutron stars**
- **Hypernuclear production at the FRS and Super-FRS**
- **Summary and Outlook**

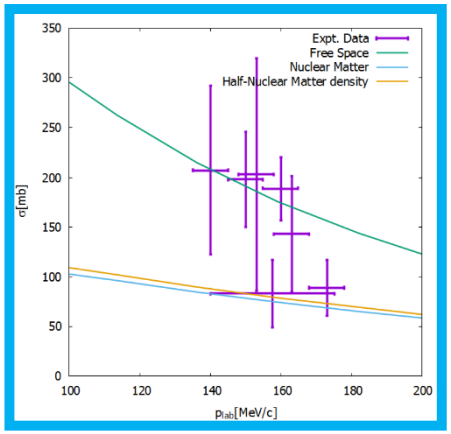
…see H. Lenske et al., Prog.Part.Nucl.Phys 98 (2018) 119-206;
H. Lenske, M. Dhar, Lect.Notes 948 (2018) 161-253

Interactions in the SU(3) Baryon Octet



$\Lambda + p \rightarrow \Lambda + p$





$\Sigma^+ + p \rightarrow \Sigma^+ + p$

SU(3) Representation of Interactions

$$\mathcal{L}^{\mathbf{x}}_{\mathbf{int}} = -\mathbf{g_x}\alpha_{\mathbf{x}}\mathbf{Tr}\left(\left[\mathbf{B},\bar{\mathbf{B}}\right]\phi_{\mathbf{x}}\right) + \mathbf{g_x}(\mathbf{1}-\alpha_{\mathbf{x}})\mathbf{Tr}\left(\left\{\mathbf{B},\bar{\mathbf{B}}\right\}\phi_{\mathbf{x}}\right)$$

Baryon Matrix:

$$\mathcal{B} = \sum_{i=1\cdots 8}\lambda_i B_i = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ -\Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}.$$

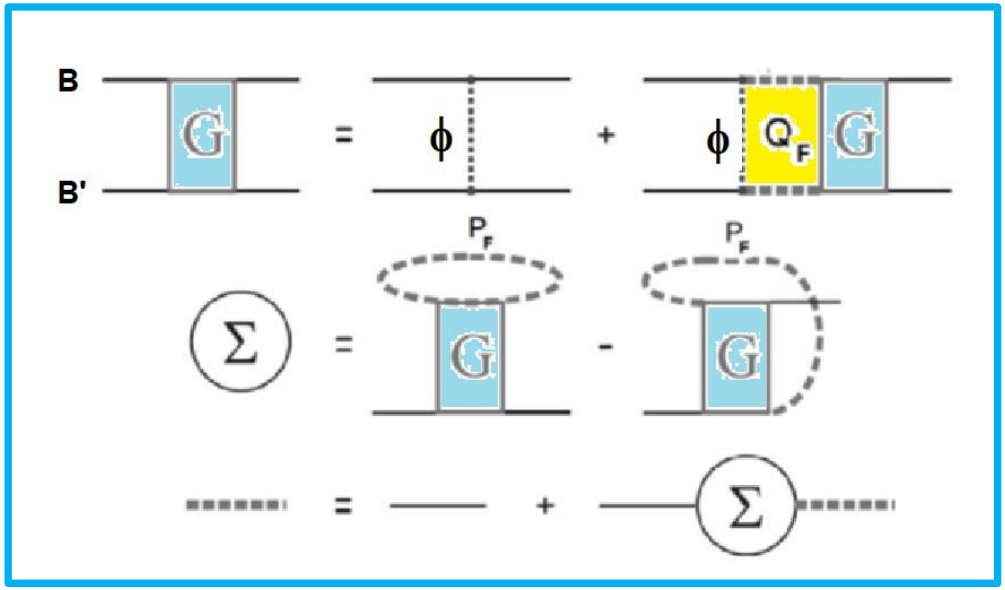
ϕ_x= pseudoscalar (π,η,K), vector (ω,ρ,K*), scalar (σ,δ,κ) Mesons

→ 6 independent coupling constants:
3 of g_x and 3 of α_x type

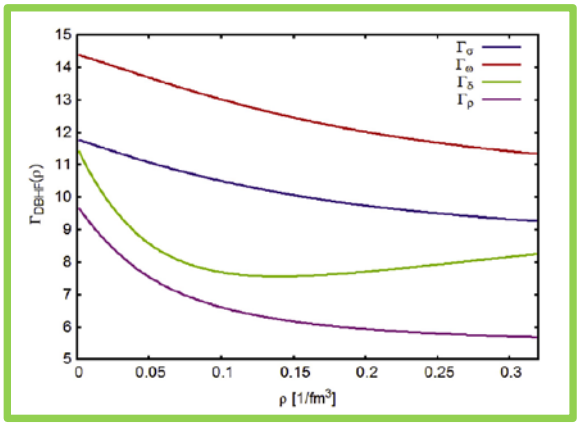
Example: BB'π couplings – $g_8 \equiv g_{PS}$

$$g_{NN\pi} = g_8, \quad g_{\Lambda\Sigma\pi} = \frac{2}{\sqrt{3}} g_8 \left(1-\alpha_{ps}\right), \quad g_{\Sigma\Sigma\pi} = 2 g_8 \alpha_{ps}, \quad g_{\Xi\Xi\pi} = -g_8\left(1-2\alpha_{ps}\right)$$

Bethe-Salpeter Equation and Brueckner G-Matrix



g_x , $\alpha_x \rightarrow g_x(\rho)$, $\alpha_x(\rho)$

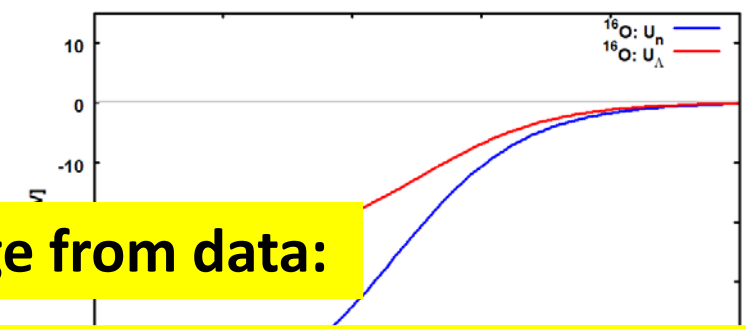


„Standard Form“ of BB‘ Interactions: Non-relativistic Reduction

$$G_{BB'} \rightarrow V_{BB'} = V_0 + V_\tau \tau_B \cdot \tau_{B'} + V_\sigma \quad {}_B \cdot \quad {}_{B'} \qquad {}_{ls} \ell_{BB'} \cdot (\quad {}_B \qquad {}_{B'})$$

$$V_{BB'} = V_{BB'}(\quad g_{ps}, g_v, g_s) = V_{BB'}(\quad g_8)$$

$$\Psi_B = \Psi_B \alpha_8 \quad \rightarrow U_B(\quad g_8, \quad \sim U_{0B} f_{WS}(\quad r, R_B, a_B \ldots)$$

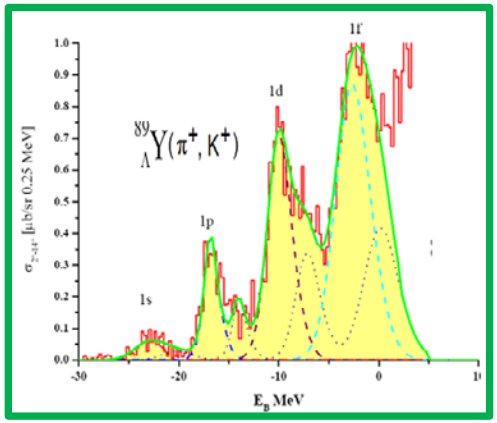


…the message from data:

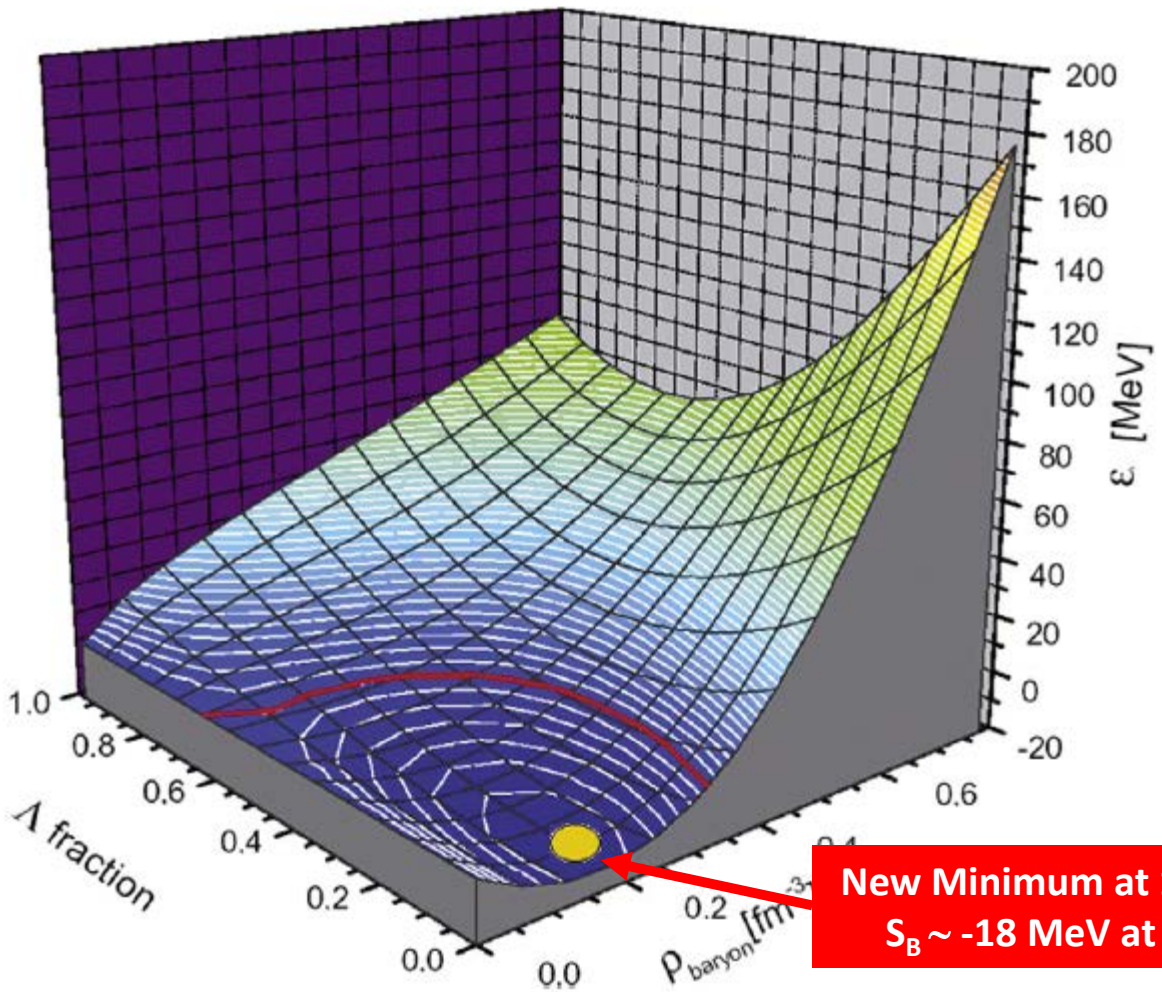
$$U_\Lambda^{\mathrm{Exp}}(0) \simeq -30, \quad U_\Xi(0)^{\mathrm{Exp}} \simeq -10\,?, \quad U_\Sigma^{\mathrm{Exp}}(0) \geq +20\,? \quad [\mathrm{MeV}]$$

attraction attraction repulsion

Hypermatter and Hypernuclei



„EoS“ of Hypermatter: DBHF Results for npΛ Matter



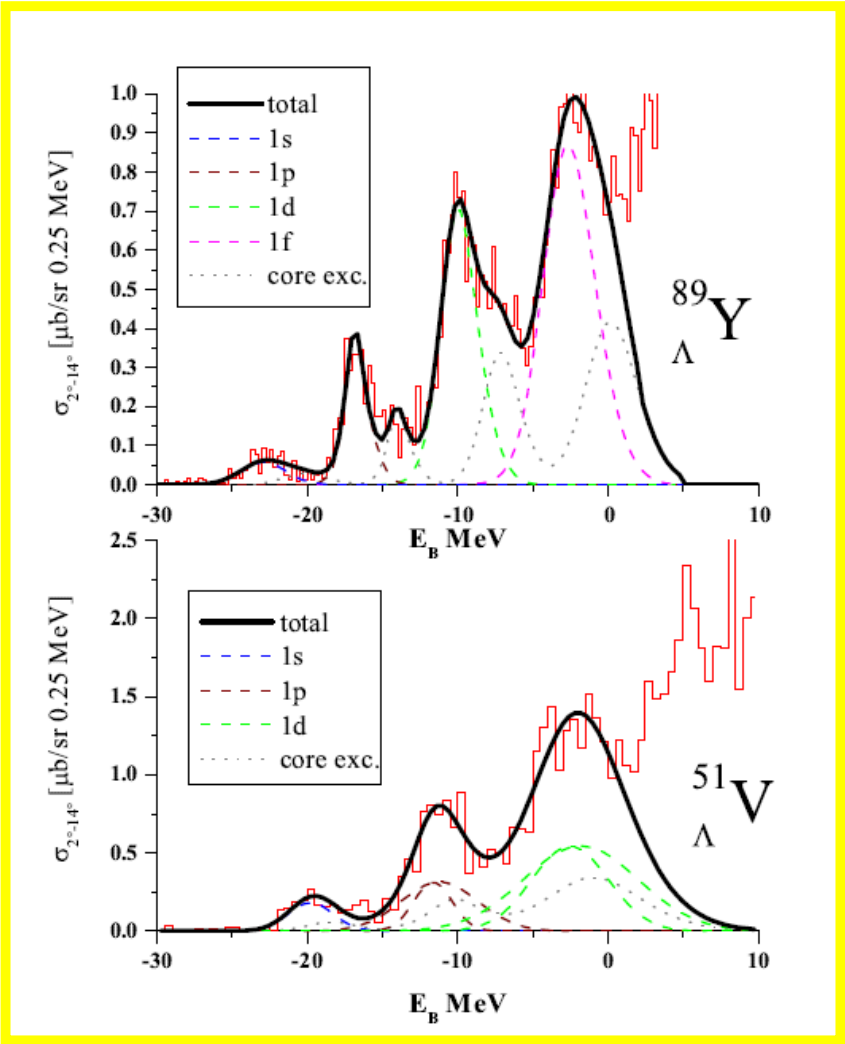
Prog.Part.Nucl.Phys. 98 (2018) 119

Application to (π^+,K^+) KEK-Data: Giessen Resonance Model plus DFT

(KEK Data: Hotchi et al.)

Λ-States in ^{89}Y:

	$^{89}_{\Lambda}$Y
$1s_{1/2}$	-22.94 ± 0.64 MeV
$1p_{3/2}$	-17.02 ± 0.07 MeV
$1p_{1/2}$	-16.68 ± 0.07 MeV
$1d_{5/2}$	-10.26 ± 0.07 MeV
$1d_{3/2}$	-9.71 ± 0.07 MeV
$1f_{7/2}$	-3.04 ± 0.11 MeV
$1f_{5/2}$	-2.26 ± 0.11 MeV

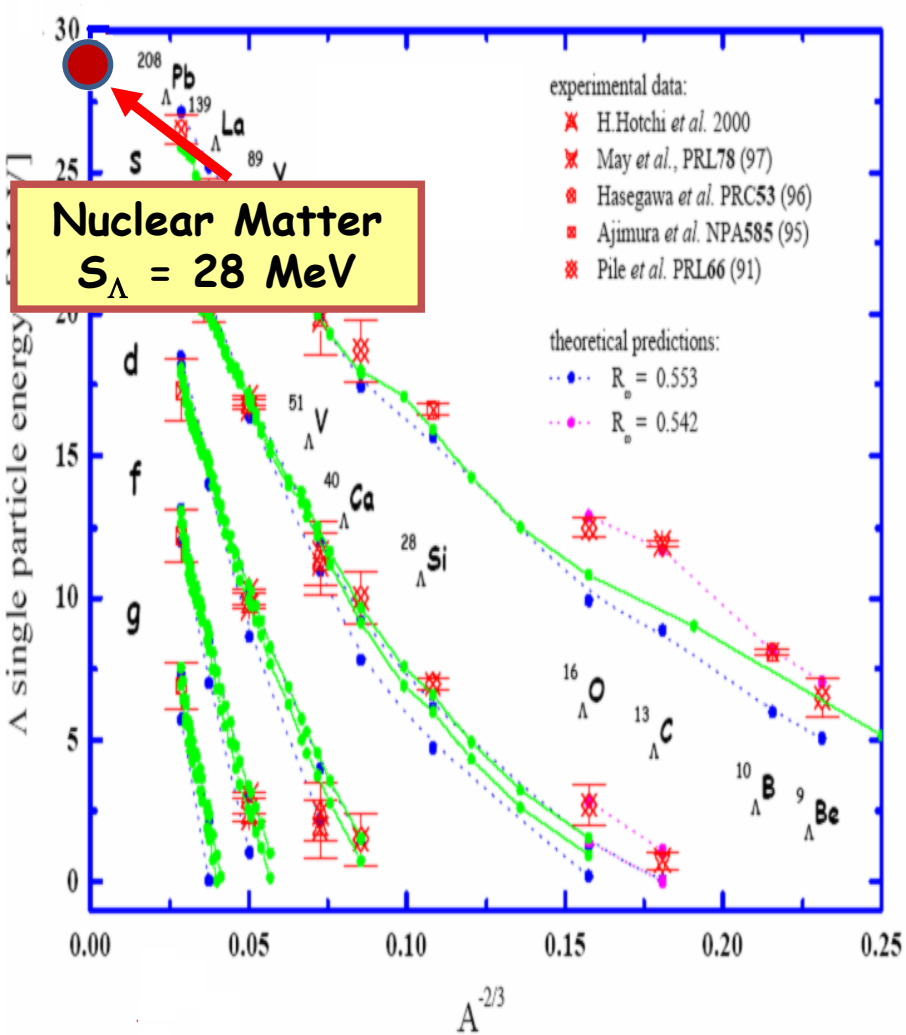


Λ-States in ^{51}V:

	$^{51}_{\Lambda}$V
$1s_{1/2}$	-19.8 ± 1.4 MeV
$1p_{3/2}$	-11.8 ± 1.3 MeV
$1p_{1/2}$	-11.4 ± 1.3 MeV
$1d_{5/2}$	-2.7 ± 1.2 MeV
$1d_{3/2}$	-1.9 ± 1.2 MeV

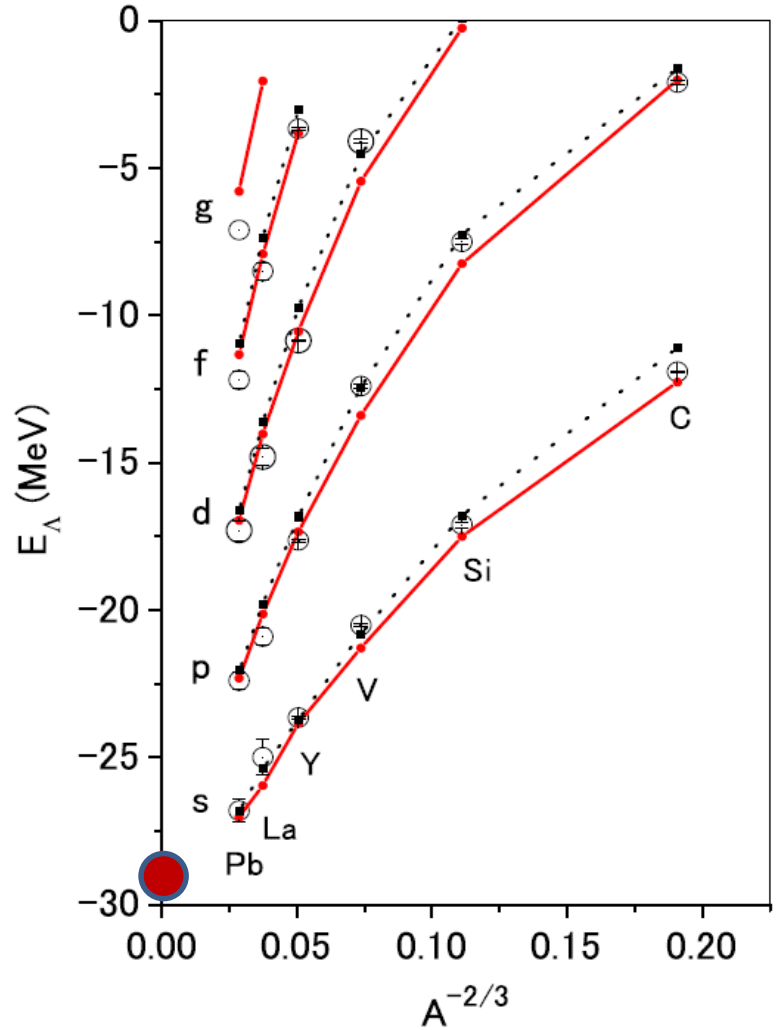
S. Bender, R. Shyam, HL, Nucl. Phys. A 839:51 (2010)

Giessen DBHF



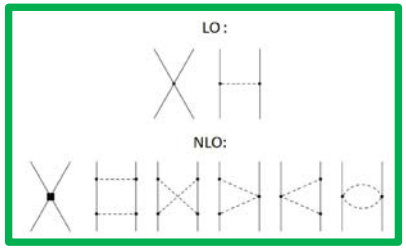
Relativistic DFT
DDRH Vertex Functionals

ESC08+MPP

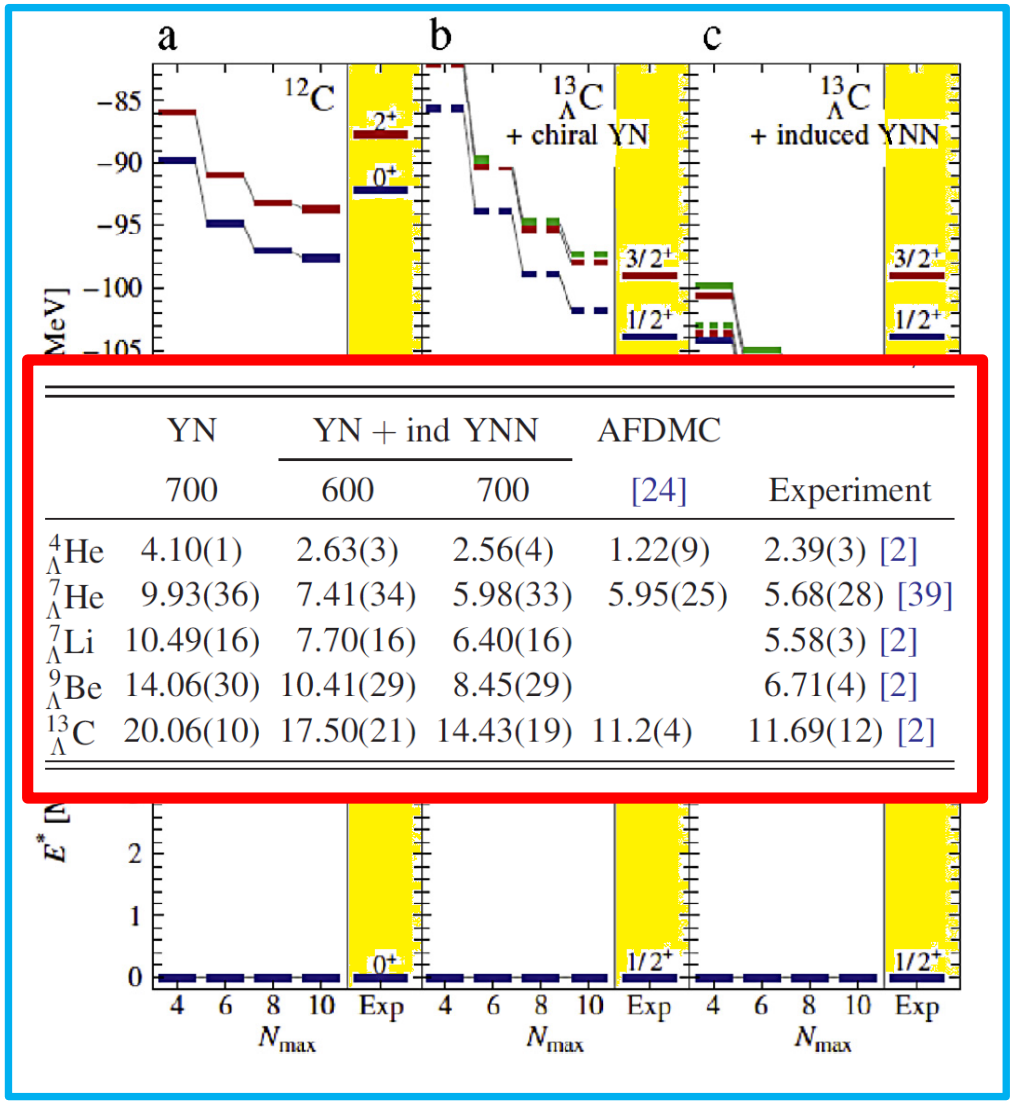


Nijmegen Folding Approach
YNN by Multi-Pomeron Forces +TBA

No-Core Shell Model Results for Chiral Interactions



…and for the first time: NCSM with chiral YNN forces



	YN	YN + ind YNN		AFDMC	
	700	600	700	[24]	Experiment
$^{4}_{\Lambda}$He	4.10(1)	2.63(3)	2.56(4)	1.22(9)	2.39(3) [2]
$^{7}_{\Lambda}$He	9.93(36)	7.41(34)	5.98(33)	5.95(25)	5.68(28) [39]
$^{7}_{\Lambda}$Li	10.49(16)	7.70(16)	6.40(16)		5.58(3) [2]
$^{9}_{\Lambda}$Be	14.06(30)	10.41(29)	8.45(29)		6.71(4) [2]
$^{13}_{\Lambda}$C	20.06(10)	17.50(21)	14.43(19)	11.2(4)	11.69(12) [2]

R. Wirth, R. Roth, Phys. Rev. Lett. 117 (2016) 182501

…recent reviews on hypernuclear physics:

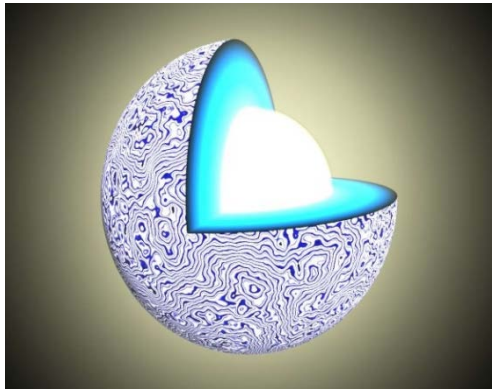
- ***Strangeness in nuclear physics*, A. Gal, E. V. Hungerford, and D. J. Millener, Rev. Mod. Phys. 88 (2016) 035004**

- ***Recent Progress in Strangeness and Charm Hadronic and Nuclear Physics*, Special issue Nucl. Phys. A 954, eds. A. Gal and J. Pochodzalla**

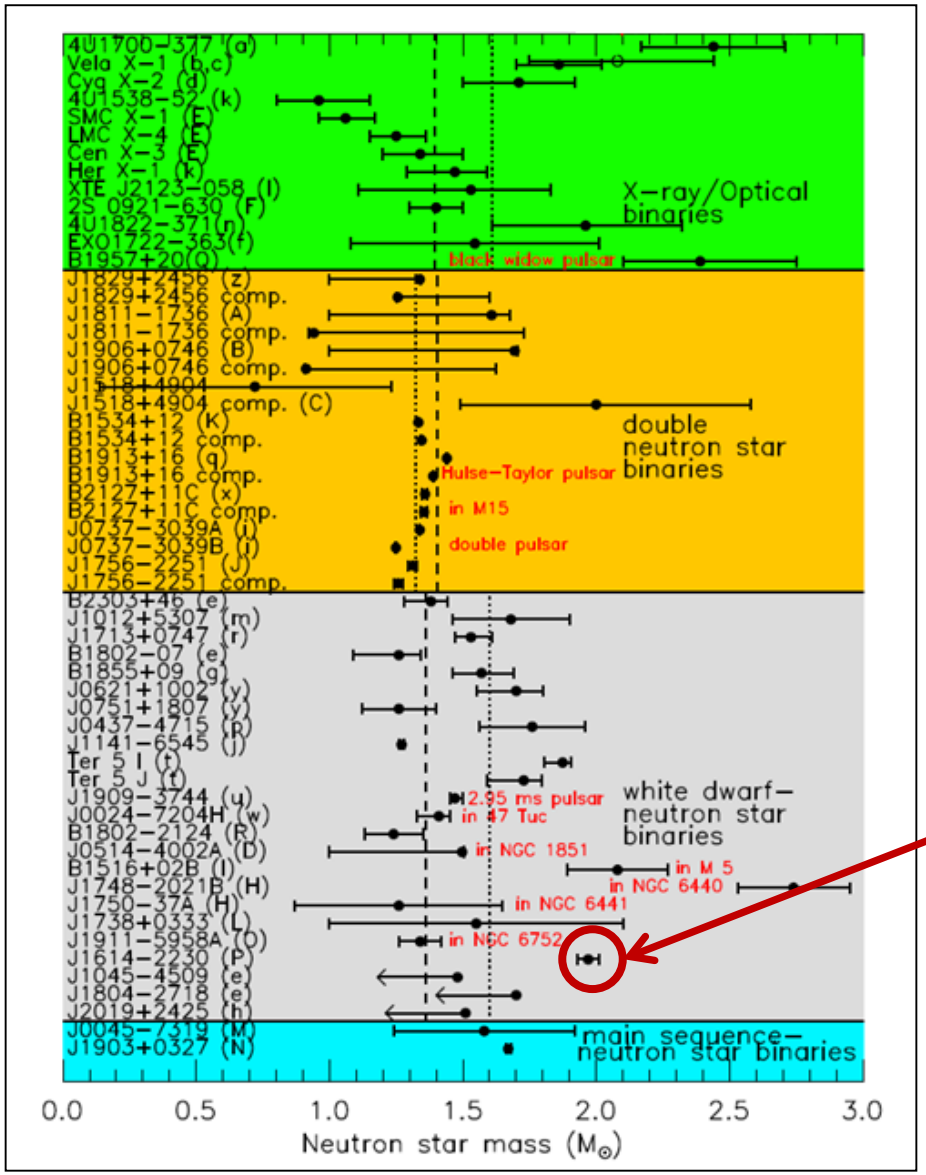
- **HYP2018: *13th International Conference on Hypernuclear and Strange Particle Physics* (Norfolk VA./USA, July 2018)**

- ***Topical issue on exotic matter in neutron stars*, Eur. Phys. J. A 52 (2016), eds. D. Blaschke, J. Schaffner-Bielich, and H.-J. Schulze**

Hyperons in Neutron Stars



Observed Neutron Star Mass Distribution



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

J1614-2230

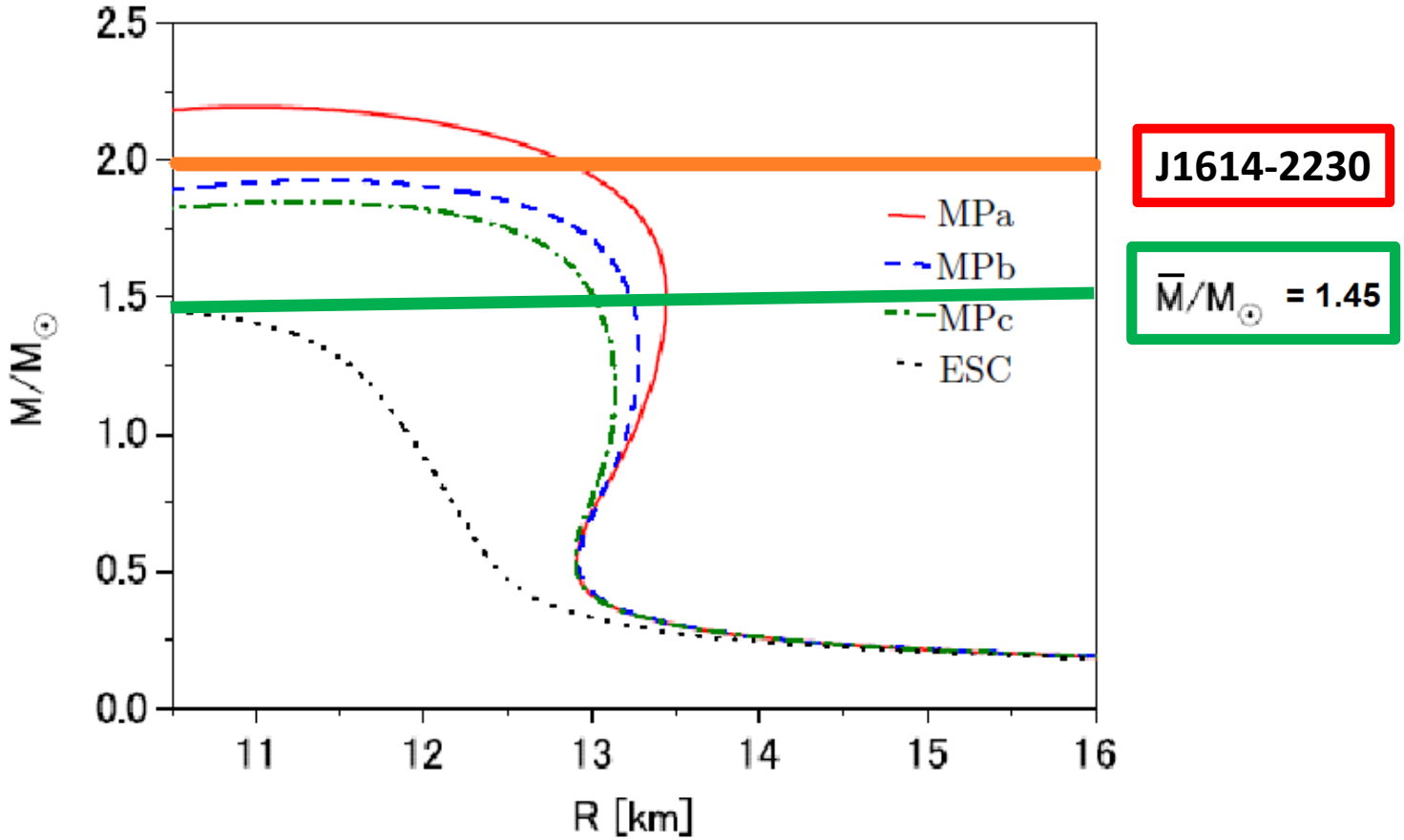
$$M = 1.97 \pm 0.04 M_{\odot}$$

J. Lattimer
Annu. Rev. Nucl. Part. Sci. 62, 485 (2012)

Neutron Star Mass-Radius Relation

Nijmegen ESC08

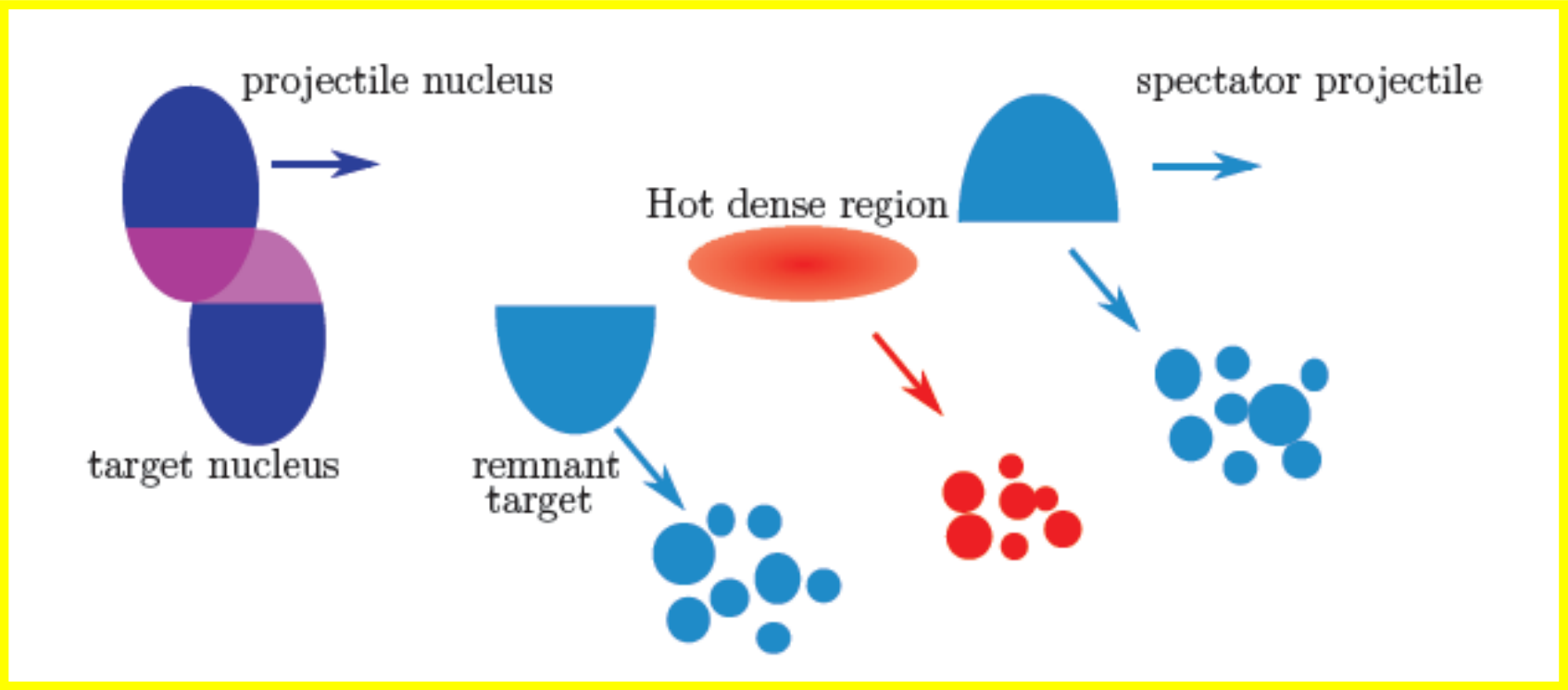
TBA and TBR YNN & YNNN from MultiPomeron (MP) Exchange



Y. Yamamoto, T. Furumoto, N. Yasutake, Th.A. Rijken, Phys.Rev. C90 (2014) 04580, arxiv:1406.4332

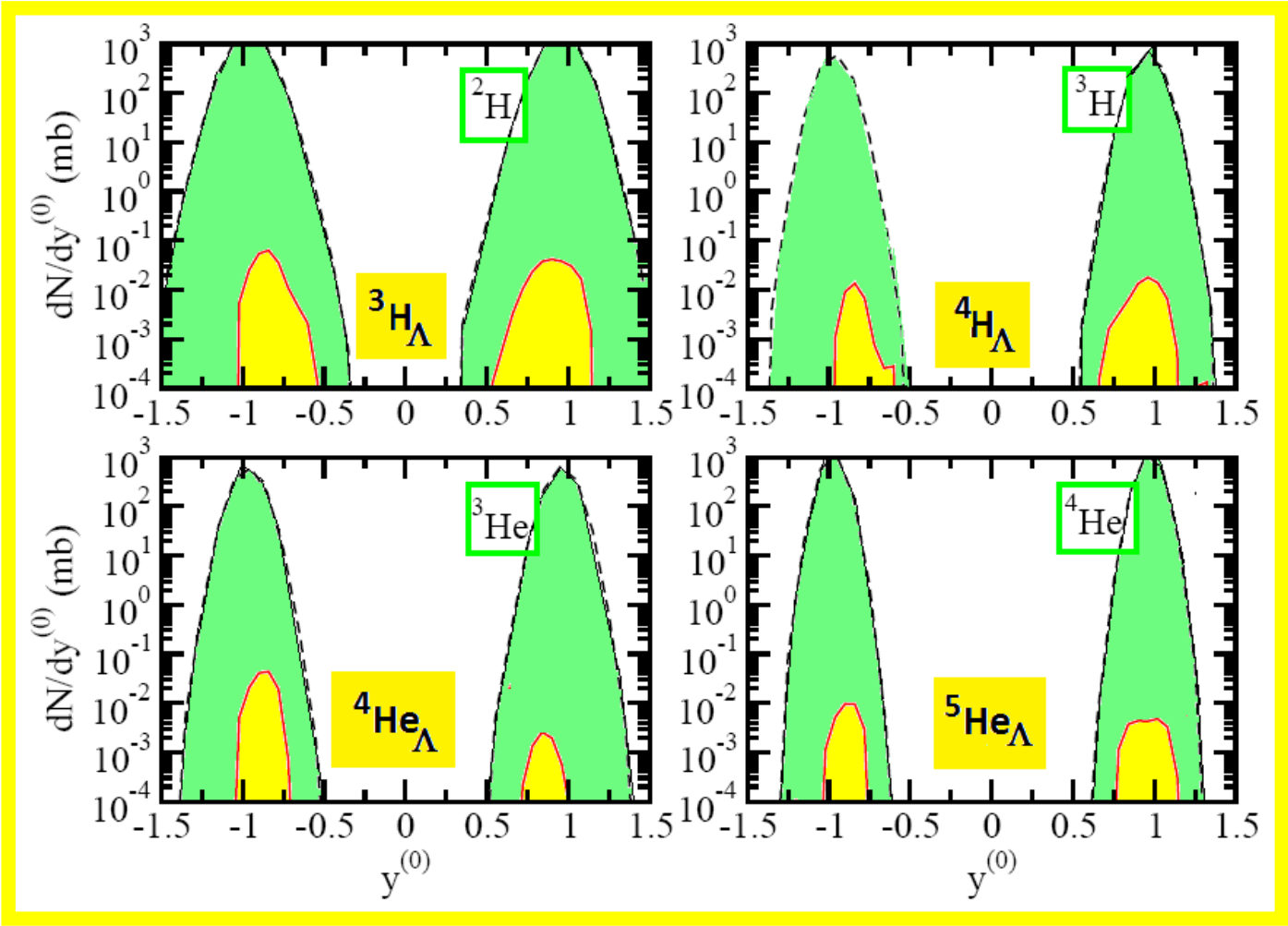
Hypernuclear Production
at
FRS and SUPER-FRS

Fragmentation Scenario
(T_{lab}>1 AGeV)



→ Transport Theory plus Statistical Multi-Fragmentation Model ←

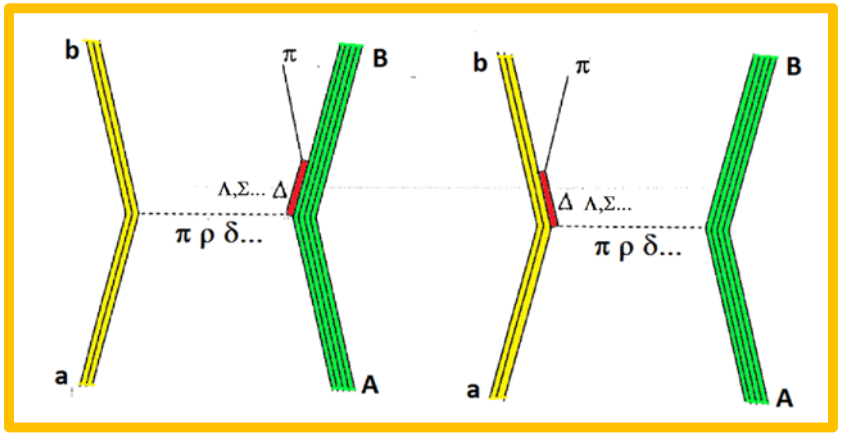
Production of Light Hypernuclei in $^{12}C+^{12}C$@2AGeV



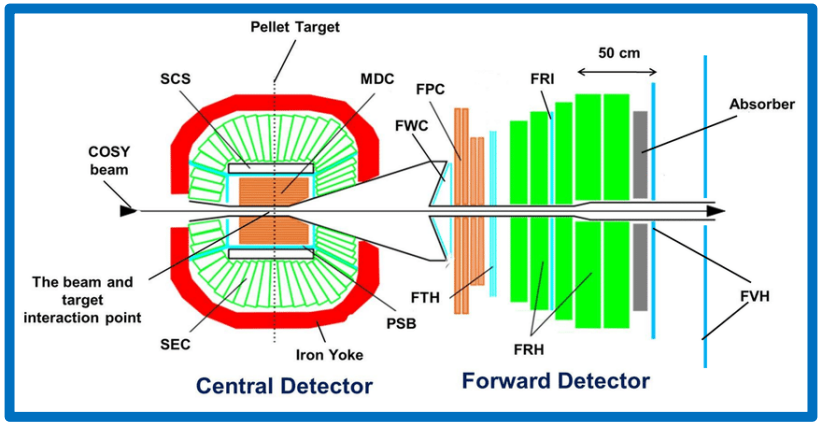
Th. Gaitanos, HL, Phys. Lett. B 675, 297 (2009), NPA (2012), NPA (2016)…

Decay Spectroscopy

…see Prog.Part.Nucl.Phys. 98:119 (2018)



…and in addition multi-pion decay of higher N* and Y*



WASA@COSY → WASA@FAIR
→ Contribution by T. Saito

Summary and Outlook

- **Nucleon and hyperon interactions**
- **Λ single particle states in medium and heavy mass hypernuclei**
- **Hyperons in neutron stars**
- **Hypernuclei by fragmentation reactions**
- **Decay spectroscopy: WASA@SUPER-FRS**
- ***N* resonances in nuclear matter***
- ***The NNΛ problem***

…further reading:
H. Lenske, M. Dhar, Th. Gaitanos, Xu Cao, Prog.Part.Nucl.Phys. 98:119 (2018)
H. Lenske, M. Dhar, Lect.Notes .Phys. 948:161 (2018)
…and special credits to
A. Larionov, R. Shyam, and I. Vidana

(supported by DFG, BMBF, GSI, and HIC for FAIR)