Strange Hadrons and Neutrons Stars

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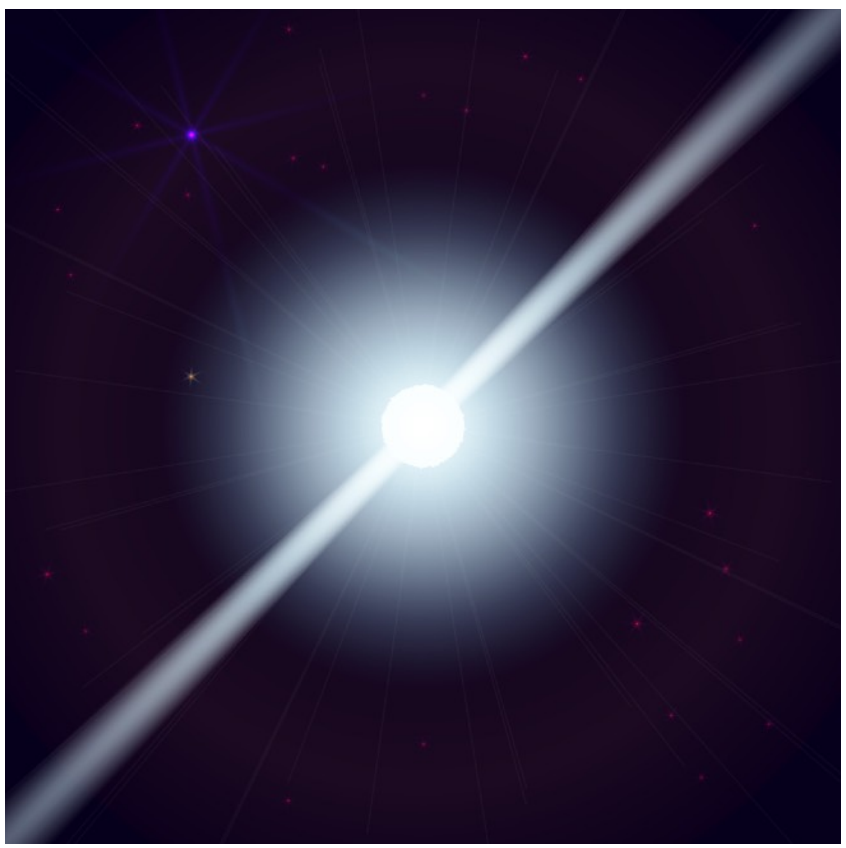
E62 – Dense and Strange Matter

Outline

- Hyperon Puzzle in Neutron Stars
- How to evaluate a correct Equation of State for dense hadronic matter with strange content
- (strange) Hadron interactions: what is known and what needs to be measured
- pp collisions and CATS

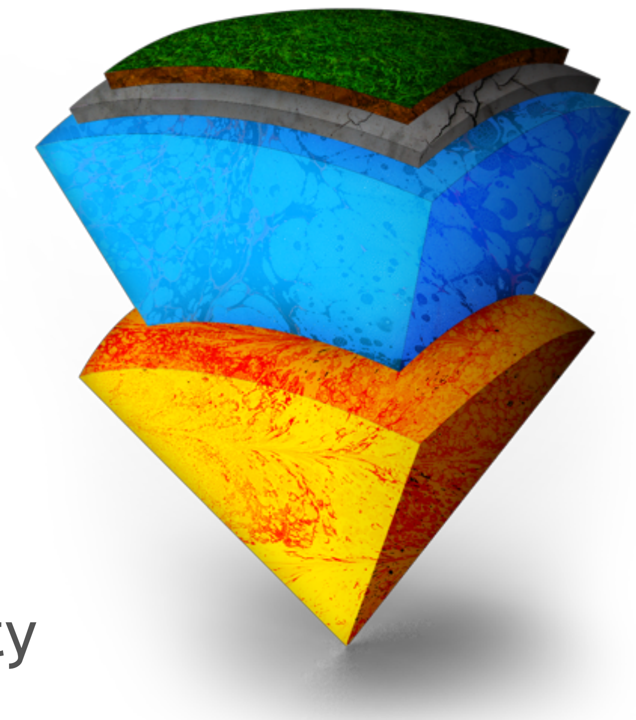
Neutron Stars

$$R \approx 10 - 15\ Km$$
$$M \approx 1.5 - 2\ M_{\odot}$$



Courtesy of Shutterstock

density



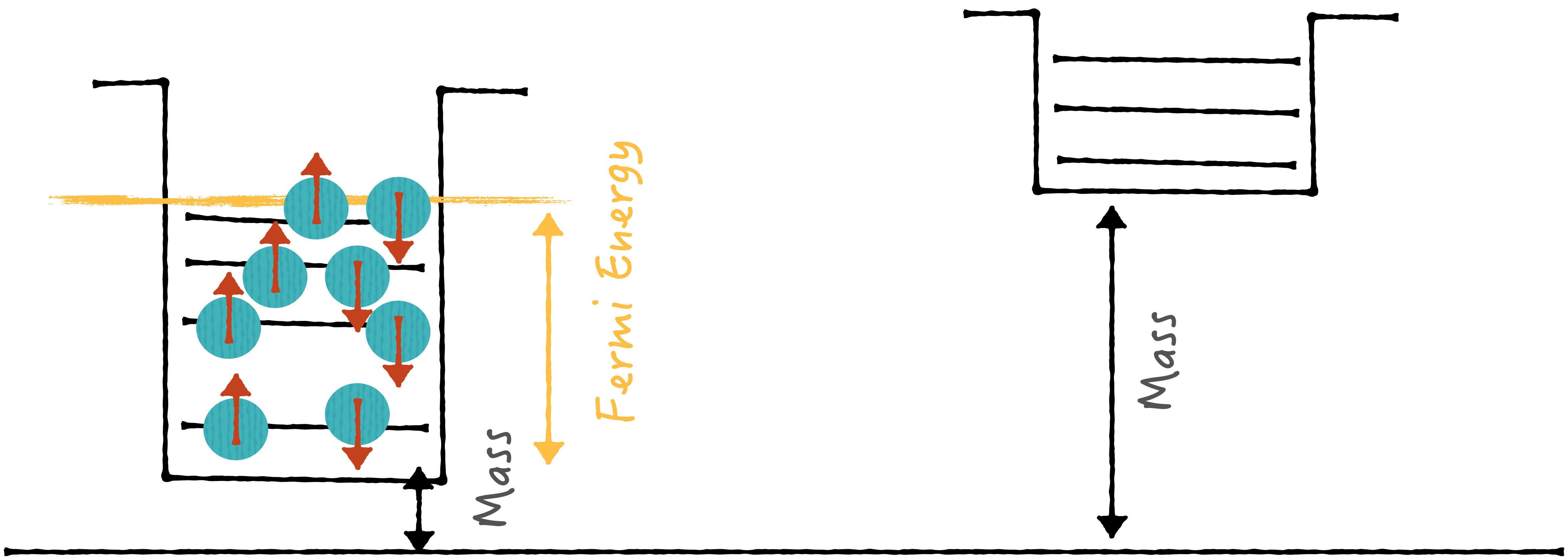
<u>Outer Crust:</u>
Ions, electrons Gas, Neutrons

<u>Inner Core: ??</u>
Neutrons ?? Protons ??
Hyperons ??
Quark Matter ??

- Very high density in the interior
- Rotating object emitting Synchrotron radiation in Radio-Frequency (Pulsar character)
- Mass measured in binary systems with White Dwarfs (Shapiro Delay, WD Spectroscopy)
- Radius Measurement very difficult

What is inside Neutron Stars??

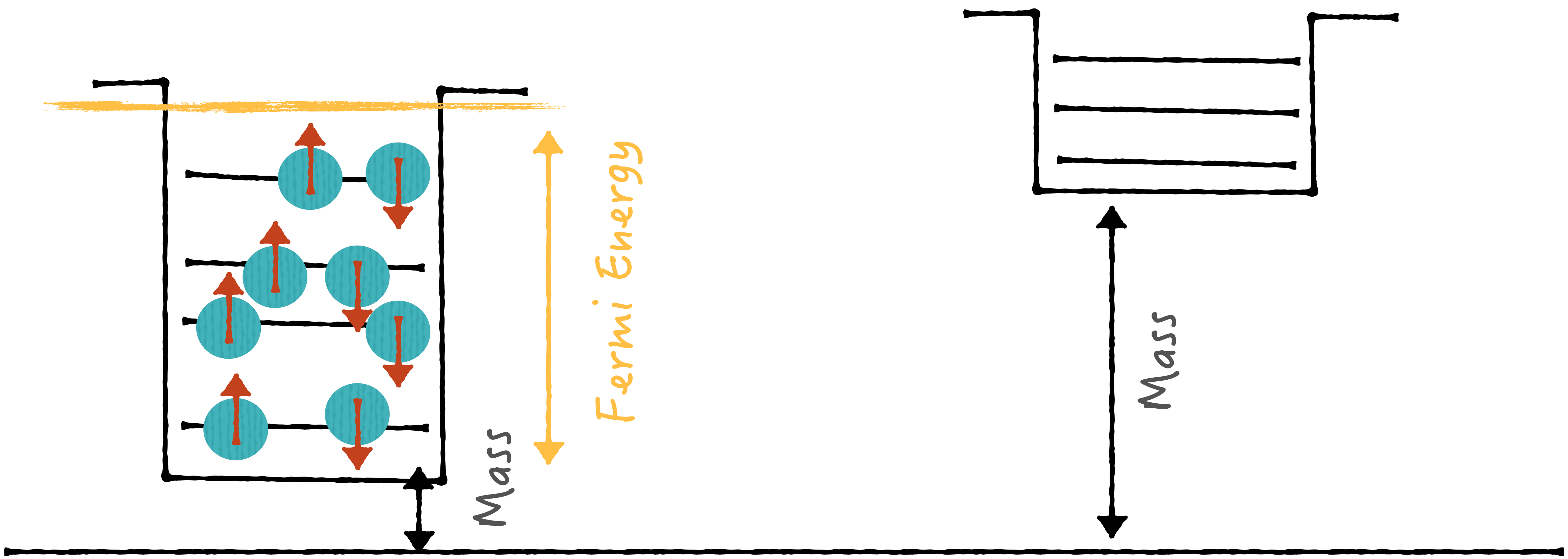
Neutrons (uud, m= 938 MeV) **Λ Hyperons (uds, m= 1115 MeV)**



Chemical Potential $\mu = E_F + mass$

If the density increases also the Fermi Energy increases and hence the chemical potential

Neutrons (uud, m= 938 MeV) Λ **Hyperons (uds, m= 1115 MeV)**



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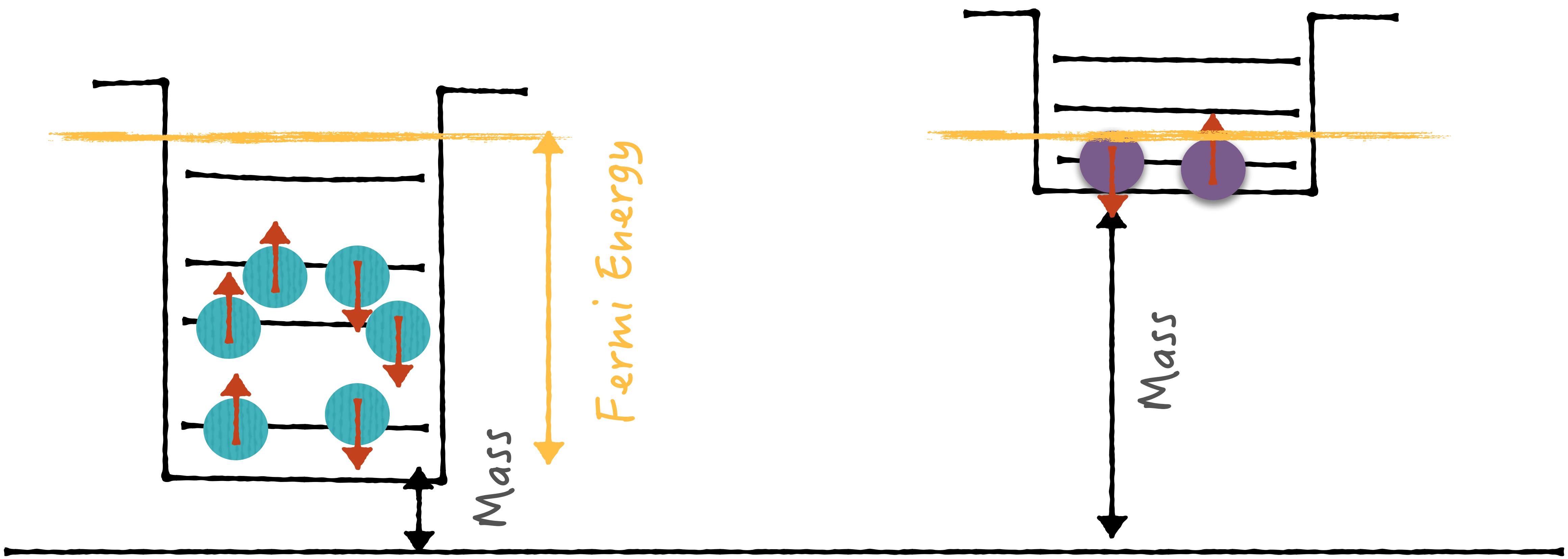


$$n + n \rightarrow \Lambda + n$$

$$p + e^{-} \rightarrow \Lambda + \nu_{e^-}$$

$$n + n \rightarrow \Sigma^{-} + p$$

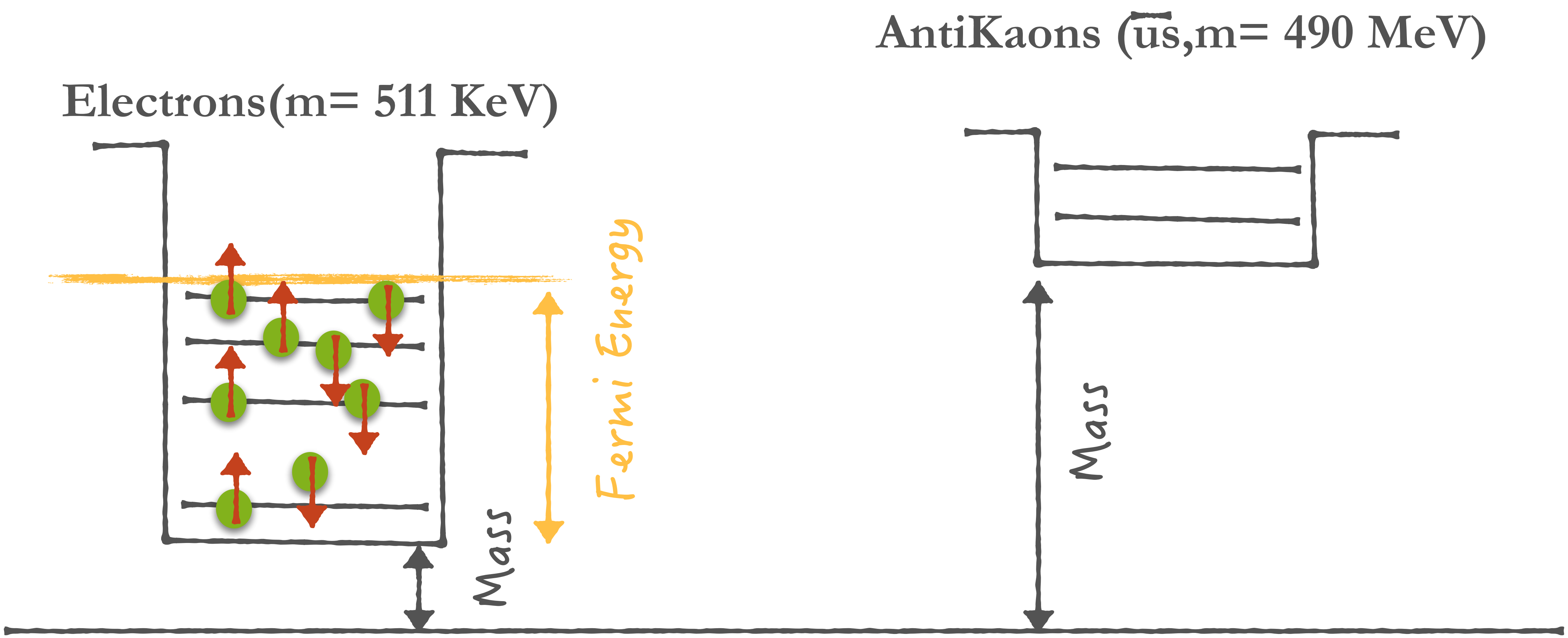
$$\Lambda + \Lambda \rightarrow \Xi + N$$

$$n + \Lambda \rightarrow \Xi + N$$

In order to have chemical equilibrium $\mu_{neutron} = \mu_{\Lambda}$

If the Y-nucleon interaction is attractive the processes is even more likely

$$n \rightarrow p + e^{-} + \bar{\nu_e}$$



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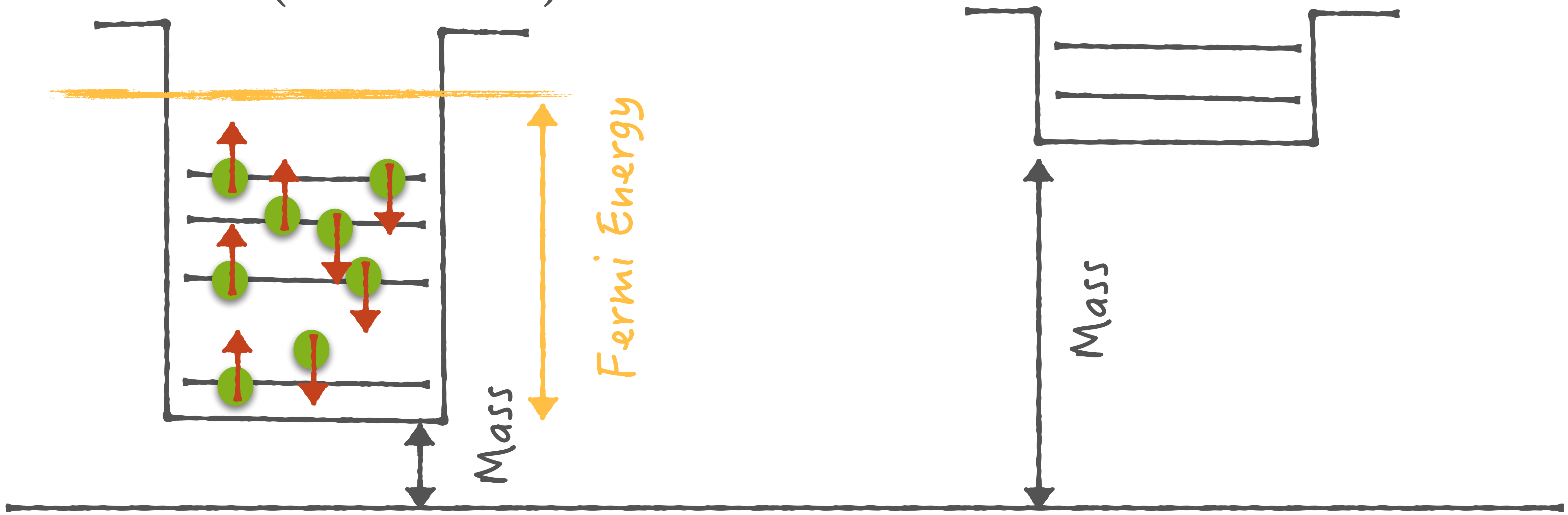
AntiKaons ($\overline{u}s$,m= 490 MeV)

Electrons(m= 511 KeV)



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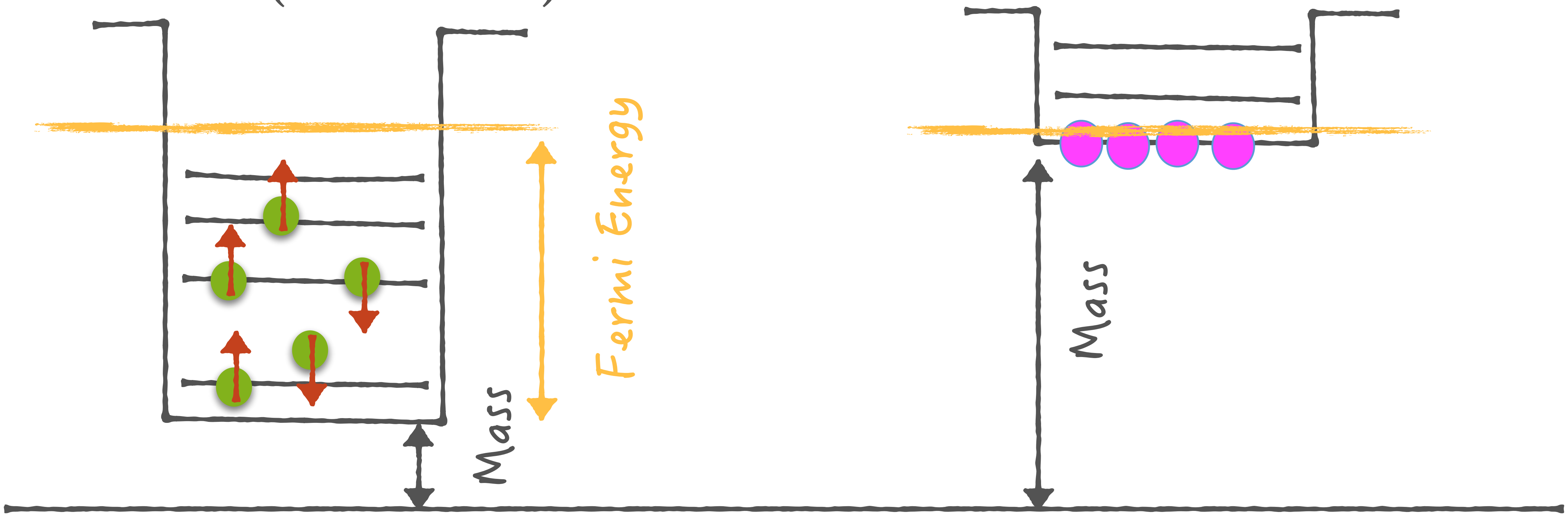


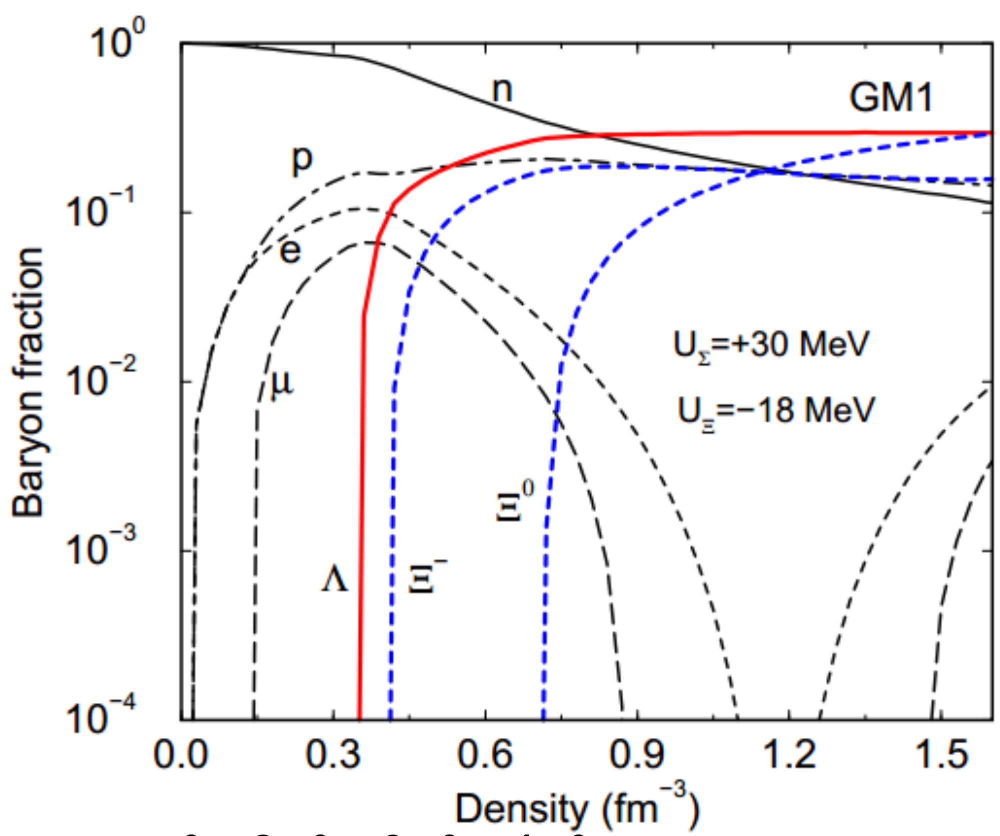
Chemical Potential $\mu = E_F + mass$

If $m^{*}_{K^-} < \mu_{e^-}$ $\Rightarrow$ $e^{-} \rightarrow K^{-} + \nu_e$ $\Rightarrow$ $K^{-} + n \rightarrow \Lambda + \pi^{-}$

$$K^{-} + n \rightarrow \Sigma^{-}$$

The Hyperon Puzzle in Neutron Stars

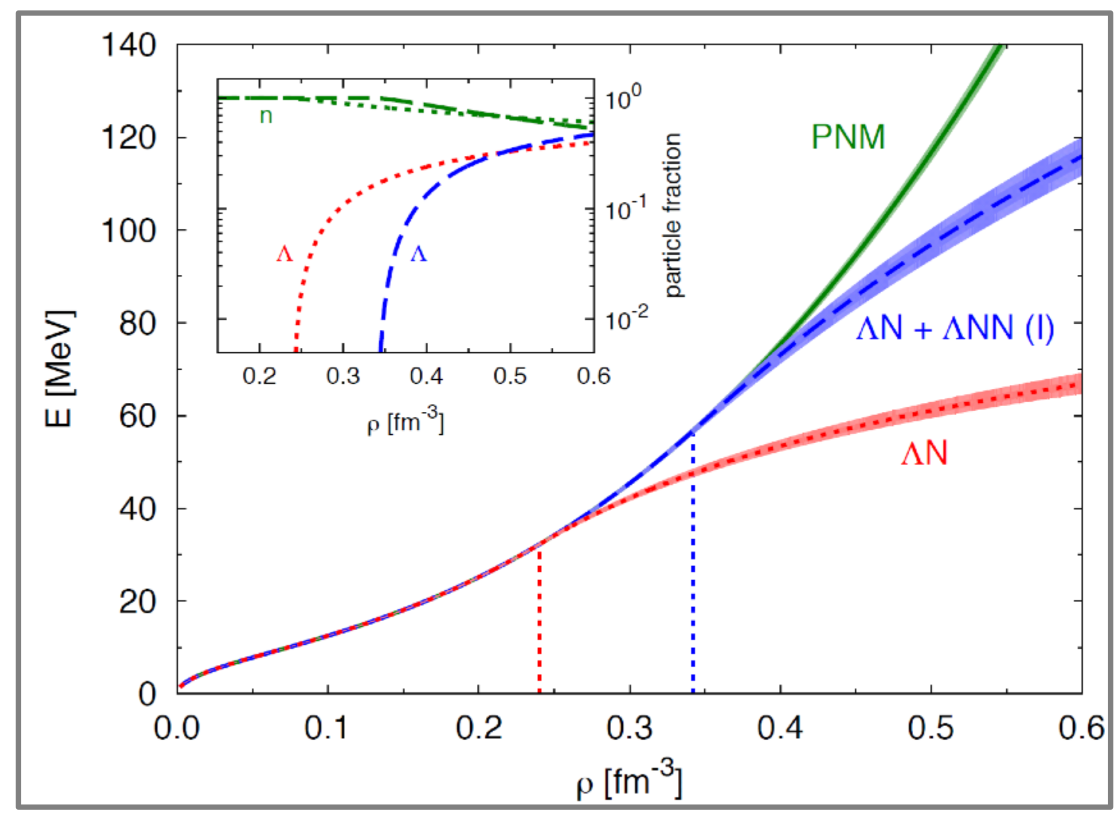
Hyperons should appear in dense neutron-rich matter starting from moderate large densities
Threshold depends on the Y-N interaction



ϱ0 2ϱ0 3ϱ0 4ϱ0 …..

J. Schaffner-Bielich, NPA 804 (2008)

The appearance of Hyperons softens the EoS



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

The Hyperon Puzzle in Neutron Stars

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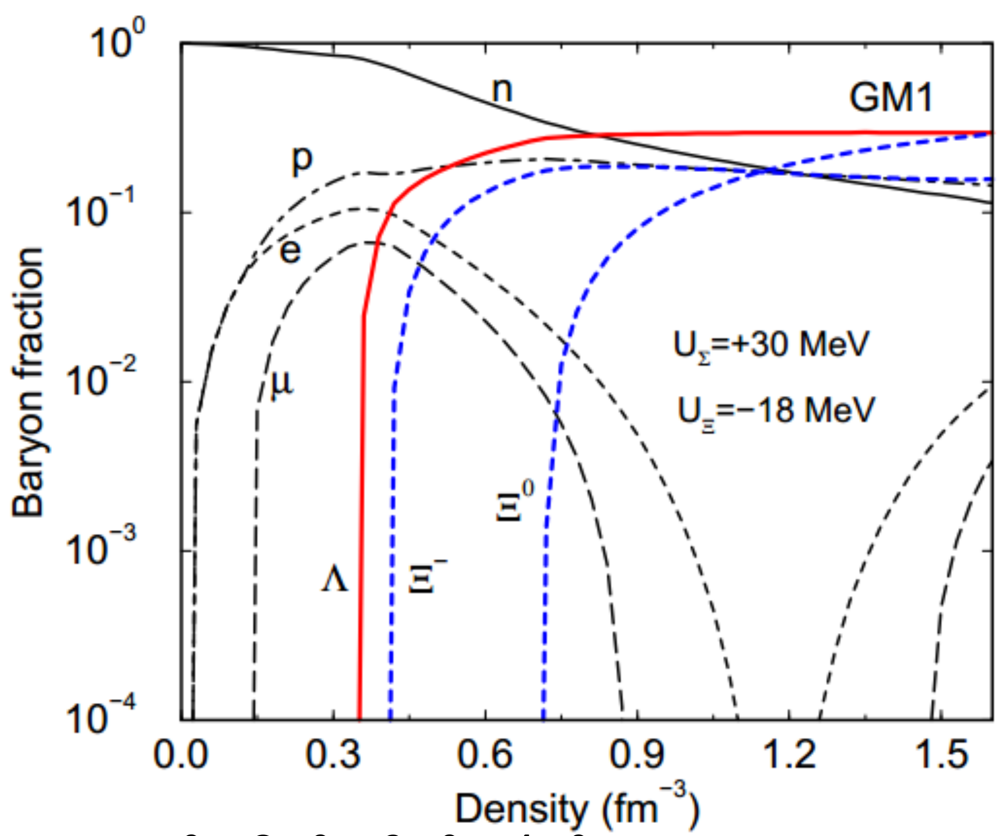
Threshold depends on the Y-N interaction

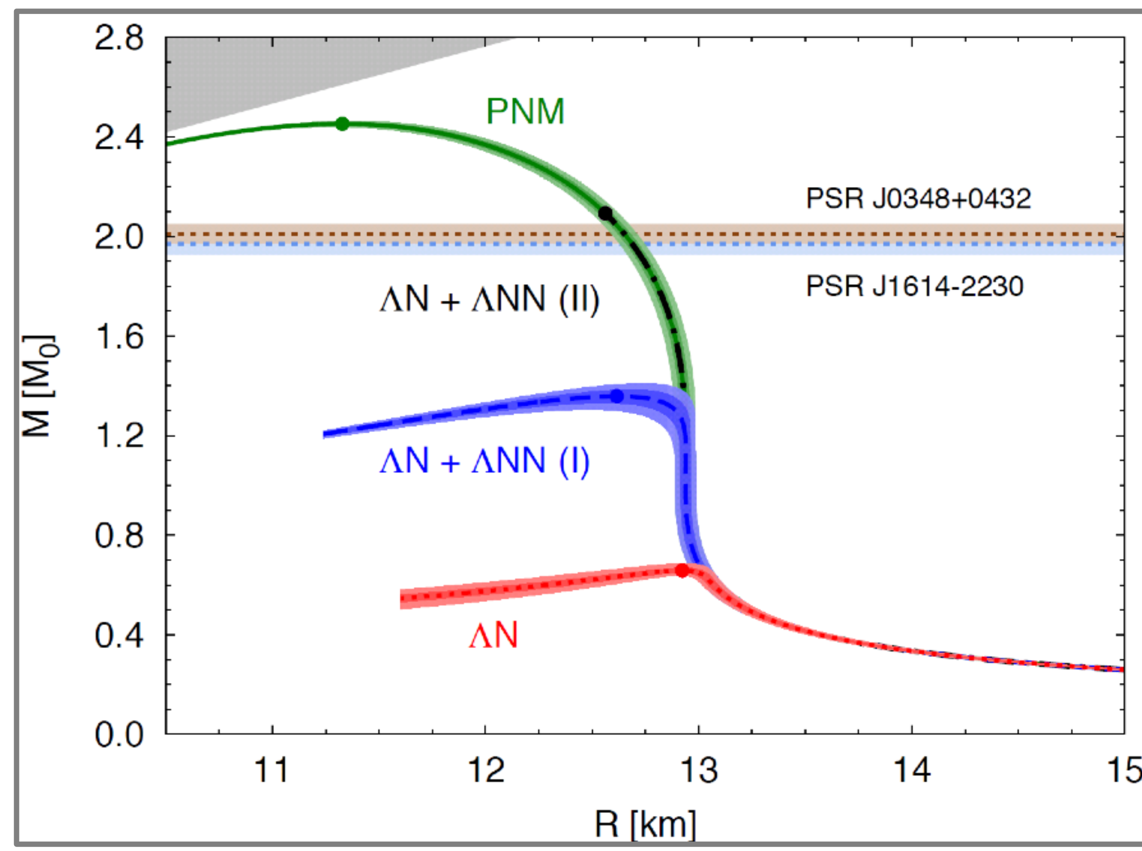
The appearance of Hyperons softens the EoS

⇨ <u>Maximum NS masses get smaller</u>



ϱ_0 $2\varrho_0$ $3\varrho_0$ $4\varrho_0$ .....

J. Schaffner-Bielich, NPA 804 (2008)



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

These predictions are only qualitative to this end

Equation of State in Quantum Montecarlo

AFDMC Hamiltonians

$$H = \sum_i \frac{p_i^2}{2m_N} + \sum_{i<j} v_{ij} + \sum_{i<j<k} v_{ijk}$$

2B: NN scattering + deuteron

3B: nuclei + nuclear matter

Equation of State in Quantum Montecarlo

- nucleon-nucleon phenomenological interaction: Argonne & Urbana
- hyperon-nucleon phenomenological interaction: Argonne & Urbana like

$$H = \sum_i \frac{p_i^2}{2m_N} + \sum_{i<j} v_{ij} + \sum_{i<j<k} v_{ijk}$$

$$+ \sum_\lambda \frac{p_\lambda^2}{2m_\Lambda} + \sum_{\lambda,i} v_{\lambda i} + \sum_{\lambda,i<j} v_{\lambda ij}$$

2B: Λp scattering + $A = 4$ CSB*

3B: no unique fit!!

Idea: use QMC to fit the 3-body hypernuclear force on available experimental data

lambda separation energy: $B_\Lambda = E(^{A-1}Z) - E(^A_\Lambda Z)$

$E(^{A-1}Z)$ → core nucleus

$E(^A_\Lambda Z)$ → hypernucleus

What is needed to pin down the EoS of matter with strange hadrons

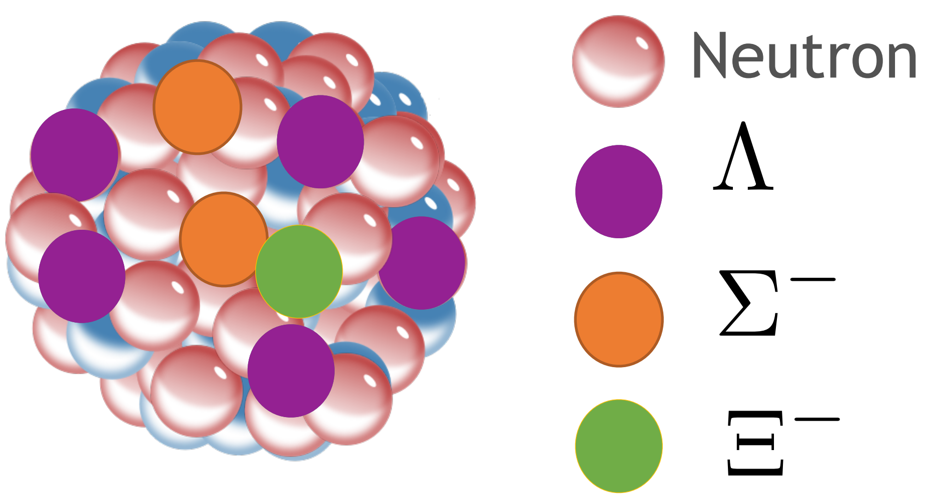
- Hyperon-Nucleon, Hyperon-Hyperon and Kaon-nucleon, Kaon-hyperon interactions in vacuum

$pp,\ p\Lambda,\ \Lambda\Lambda,\ pK^{-},\ pK^{+},\ p\Xi^{-},\ p\Omega$

$p\Sigma^{0}$

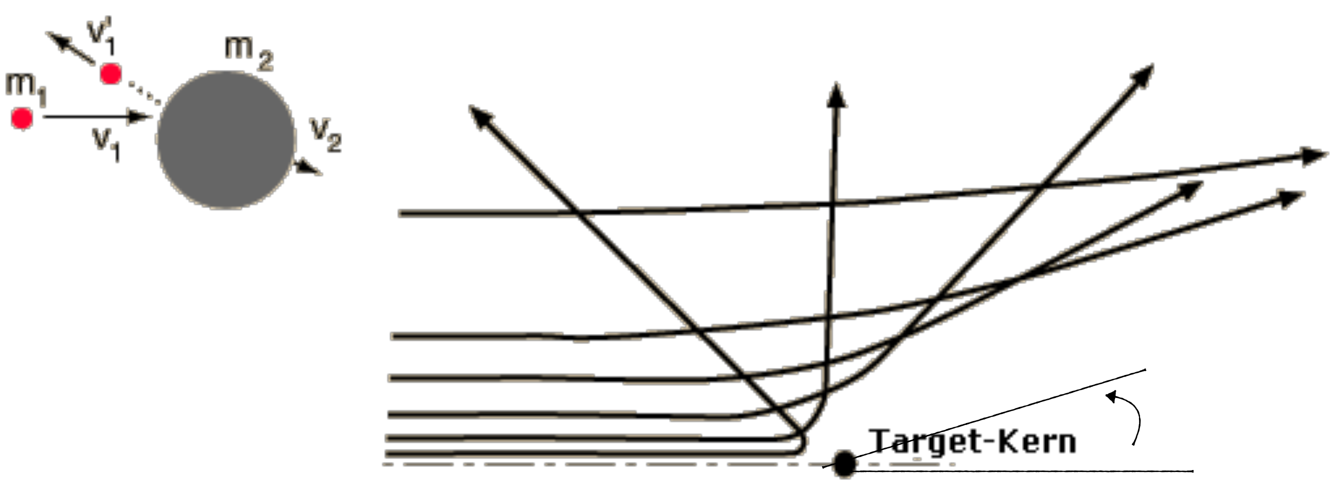
$p\Sigma^{+},\ p\Sigma-,\ p\Xi^{+}$

- extrapolations to dense baryonic matter OR short distances !!
- EoS which includes all the relevant degrees of freedom!



Scattering Data and Interaction Parameters

Scattering experiments -> Extraction of the differential cross section



$$\longrightarrow \quad \frac{d\sigma}{d\Omega}$$

Partial Wave Expansion:

$$\sigma = \frac{4\pi}{k^2} \sum_l (2l+1) \sin^2(\delta_l).$$

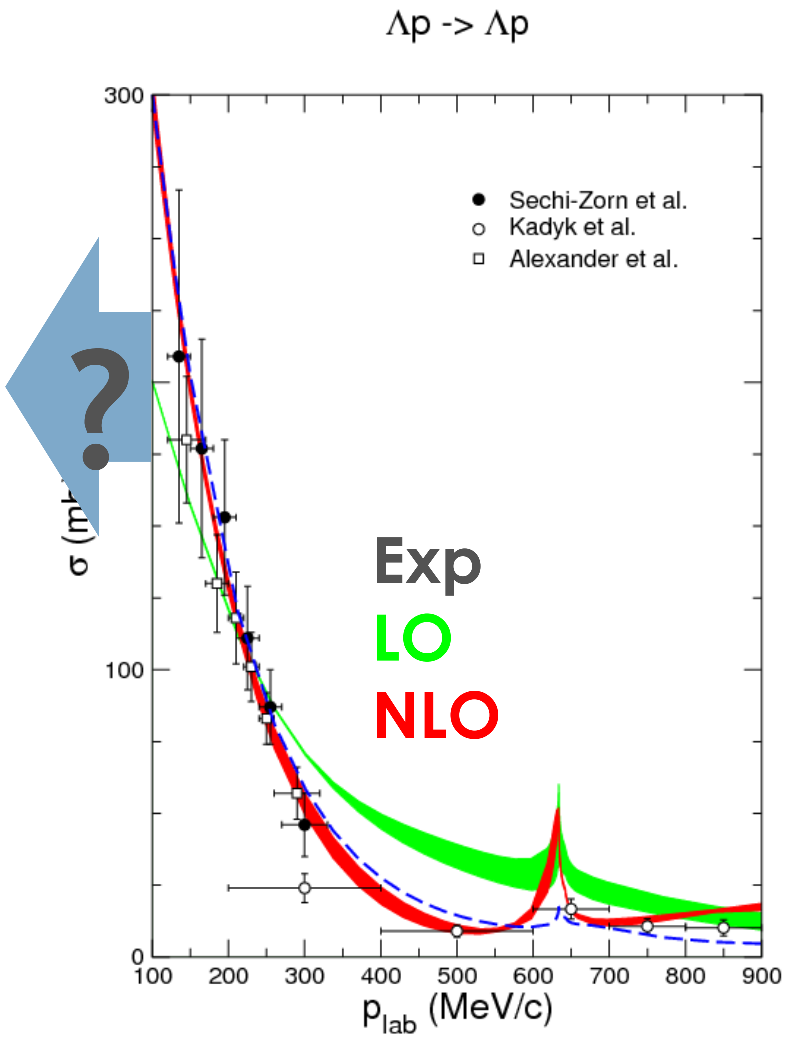
δ_l = phase shifts

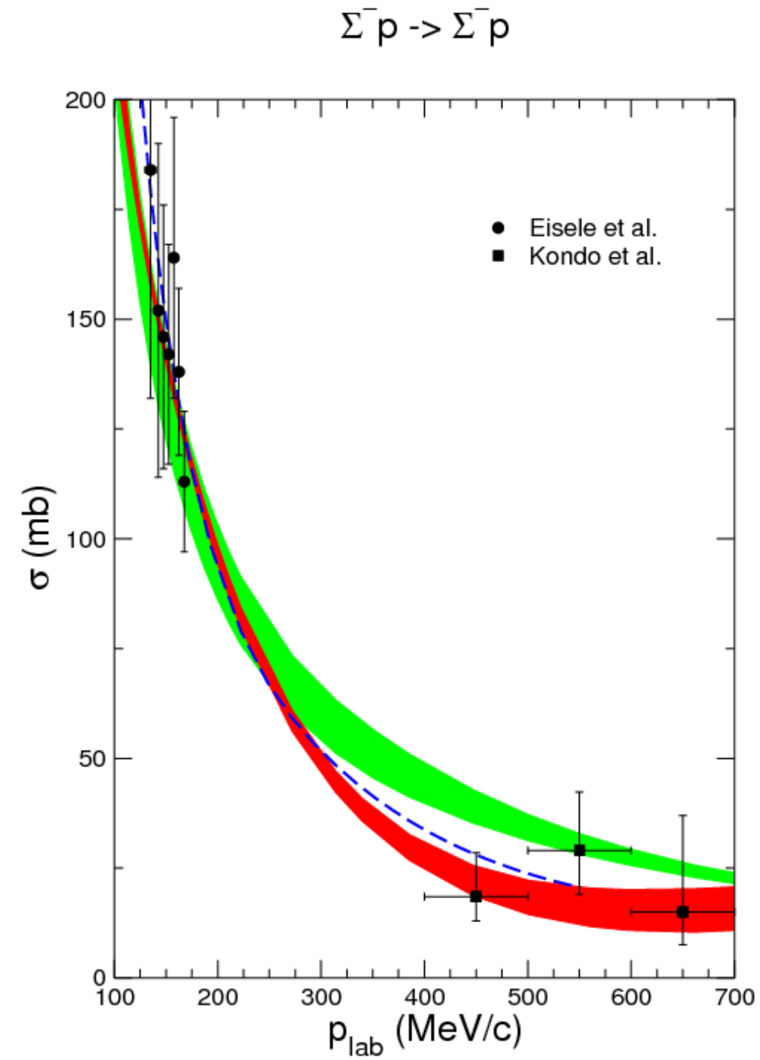
Scattering Length

$$f_0 = -\lim_{k \to 0} \frac{1}{k} \tan \delta_0(k)$$

l=0, s-wave Only!

Hyperon-Nucleon Scattering





LO: H. Polinder, J.H., U. Meißner, NPA 779 (2006) 244
NLO: J.Haidenbauer., N.Kaiser, et al., NPA 915 (2013) 24

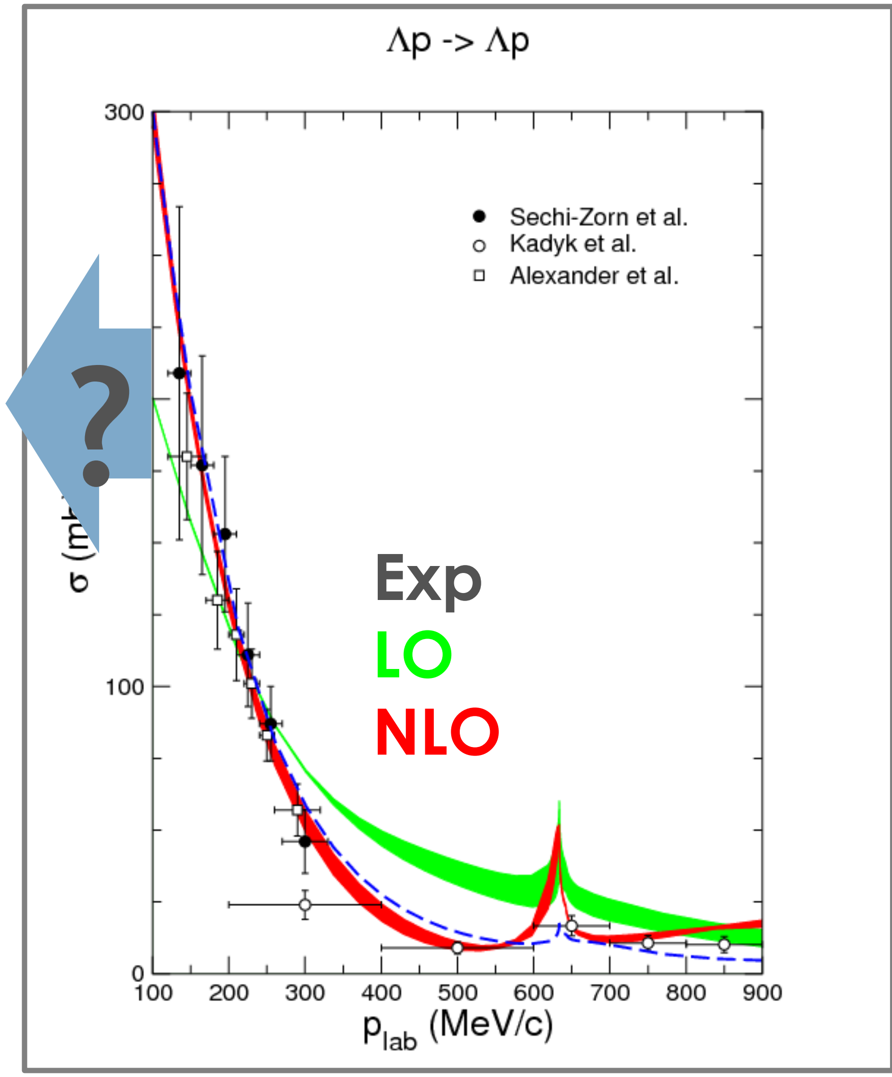
Data from scattering experiments and bubble chambers detectors from 1968 and 1971

$K^- + p \rightarrow \Sigma^0 + \pi^0,\ \Sigma^0 \rightarrow \Lambda + \gamma$

$K^- + p \rightarrow \Sigma^- + \pi^+ \ldots$

Production Threshold for $\Lambda's:\ p \geq 100\, MeV$

Hyperon-Nucleon Scattering



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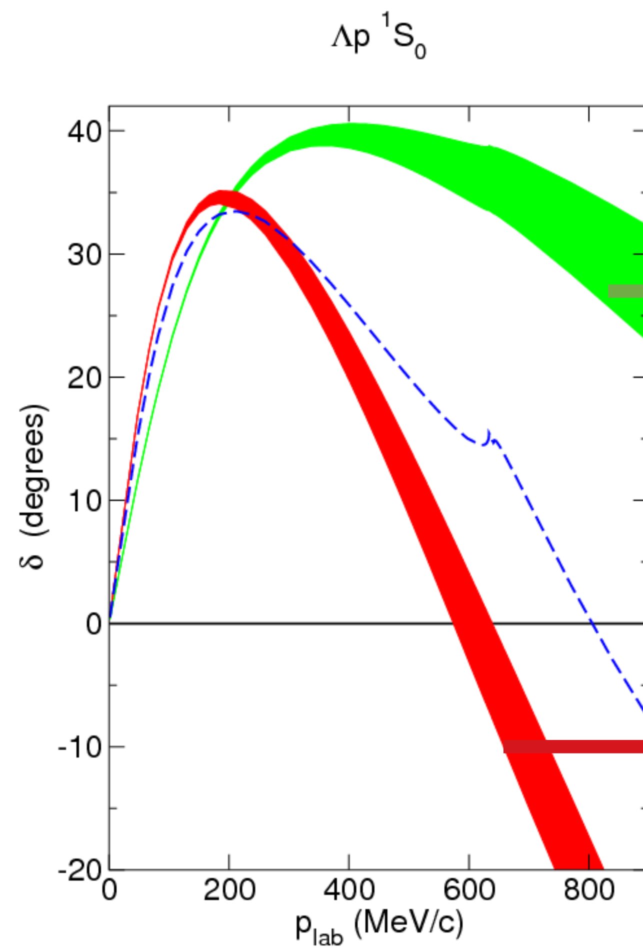
NLO: J.Haidenbauer., N.Kaiser, et al., NPA 915 (2013) 24

LO less attractive than NLO

$a^1S_0 = -1.91\, fm$

$a^1S_0 = -2.91\, fm$



Interaction always attractive

Interaction becomes repulsive
Repulsive core of the interaction

Data from scattering experiments and bubble chambers detectors from 1968 and 1971

$$K^- + p \rightarrow \Sigma^0 + \pi^0,\ \Sigma^0 \rightarrow \Lambda + \gamma$$

$$K^- + p \rightarrow \Sigma^- + \pi^+ ...$$

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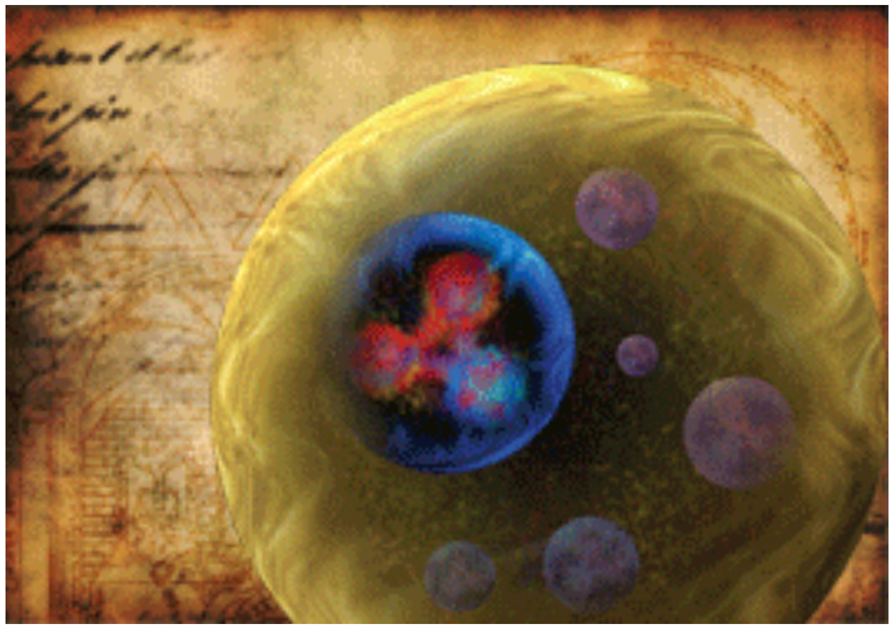
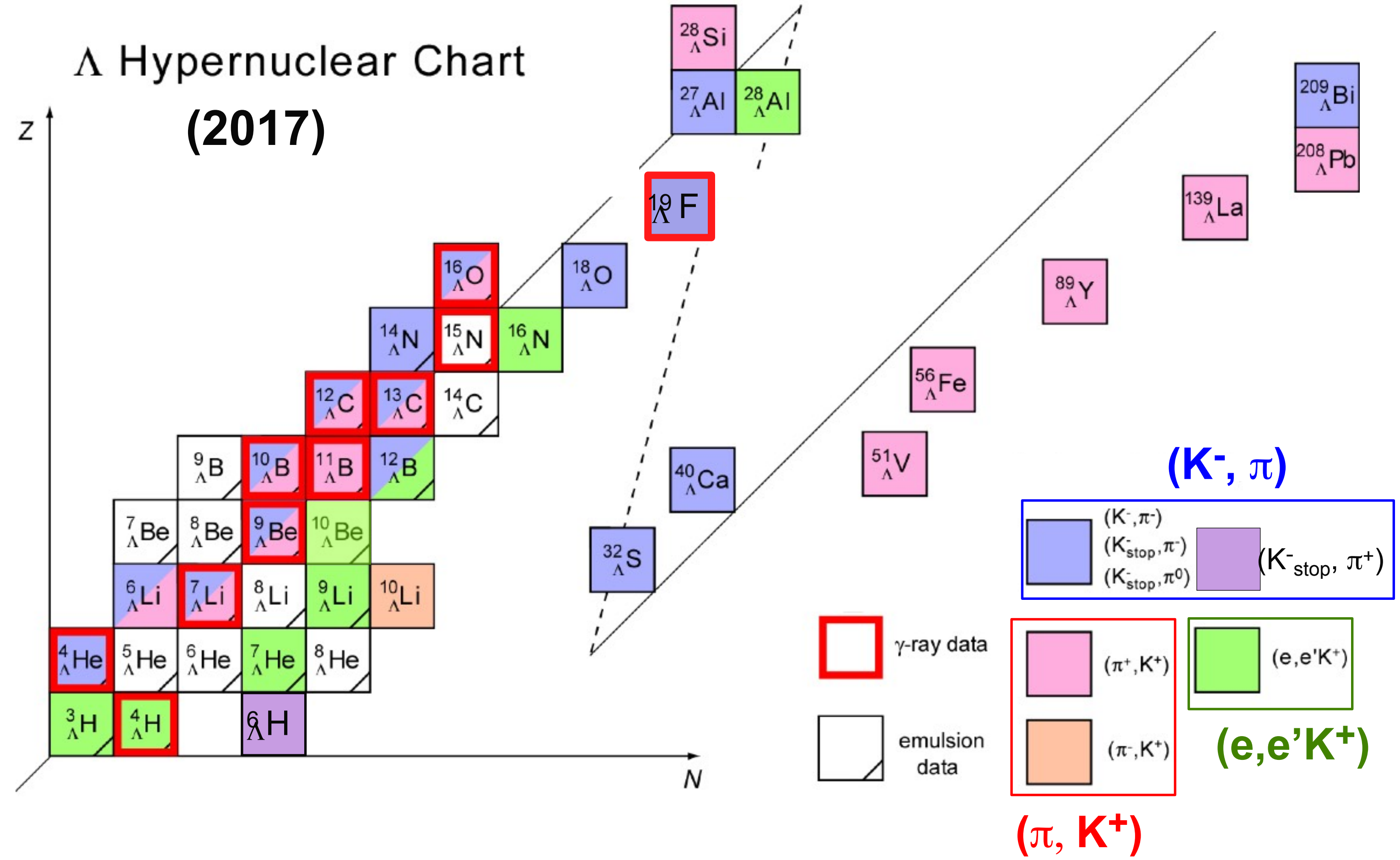
Hypernuclei

http://eaae-astronomy.org/blog/?cat=254





Hypernuclei can be produced

Binding Energy of Λ to nucleus = 30 MeV

O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

Wirth and Roth Phys.Rev.Lett. 117 (2016) 182501

Hypernuclei

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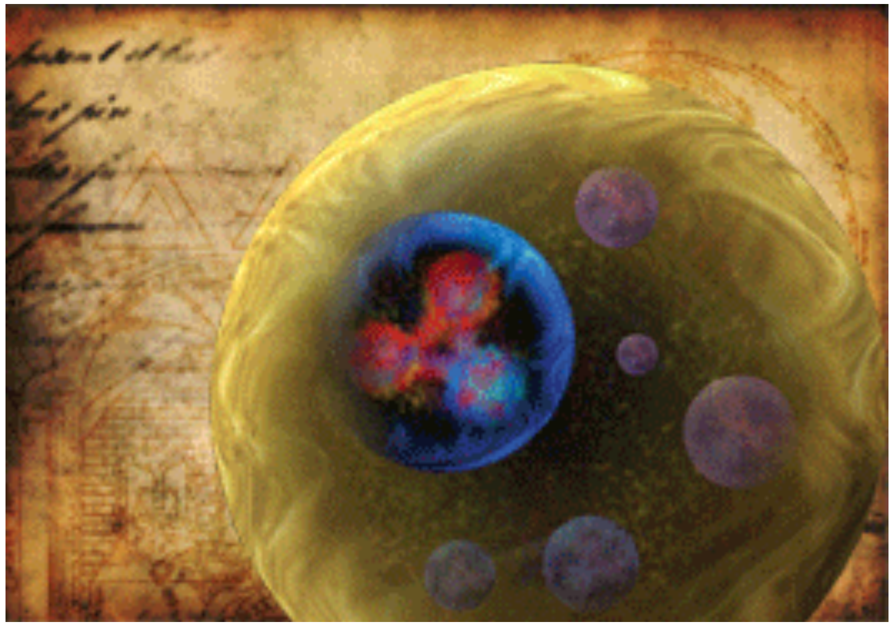

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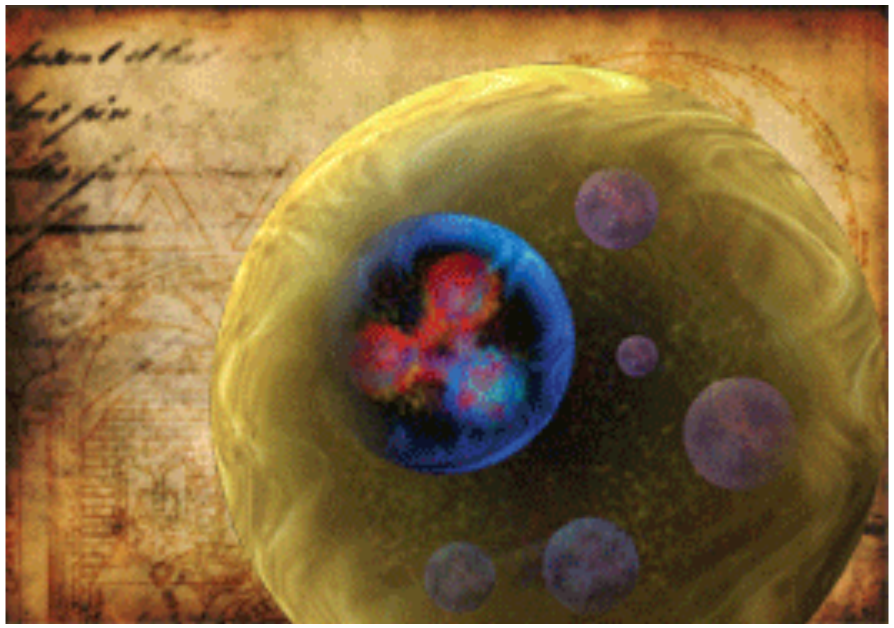
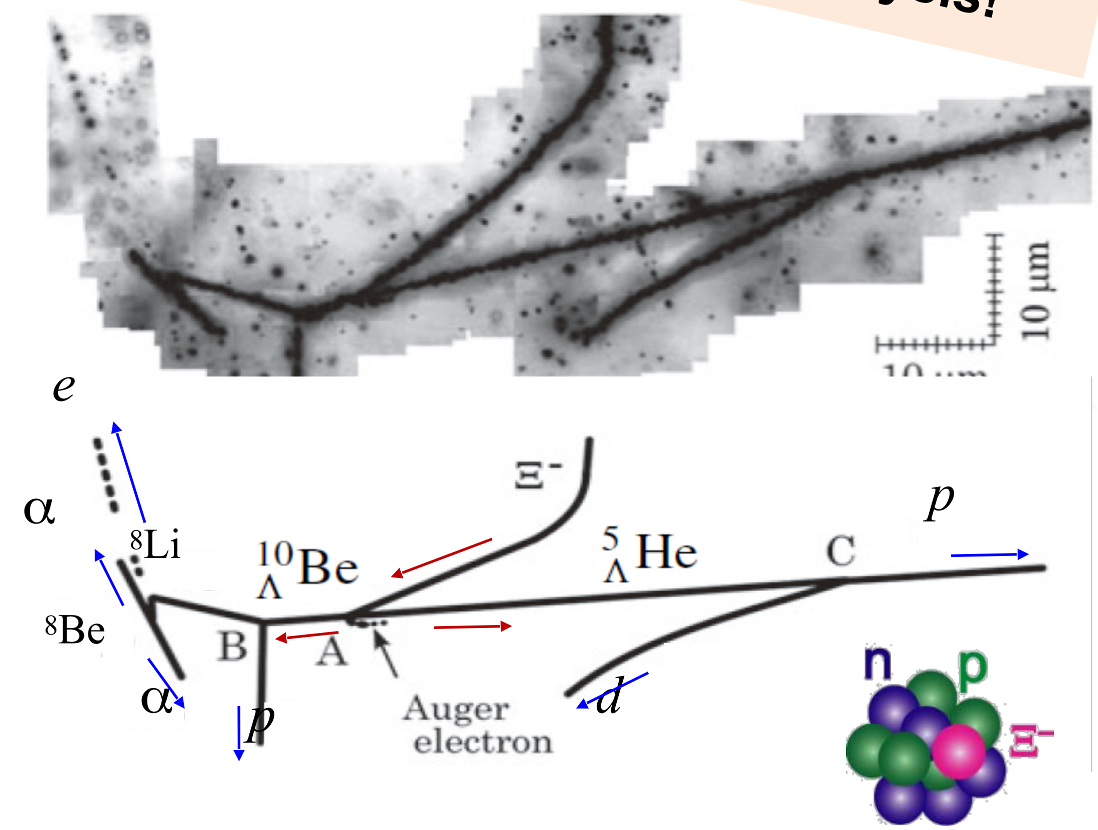


Courtesy H. Tamura, Bormio Winter Meeting 2018

New analysis!

Kiso event



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Binding Energy of Λ to nucleus = 30 MeV

Nothing is known about Σ - hypernuclei

Ξ - Hypernucleus shows a shallow attractive interaction

$$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$$

The first clear Ξ hypernucleus

$$B_{\Xi^-} = 4.38 \pm 0.25\ \mathrm{MeV},$$
$$1.11 \pm 0.25\ \mathrm{MeV}$$

K. Nakazawa et al. PTEP 2015, 033D02

Hypernuclei

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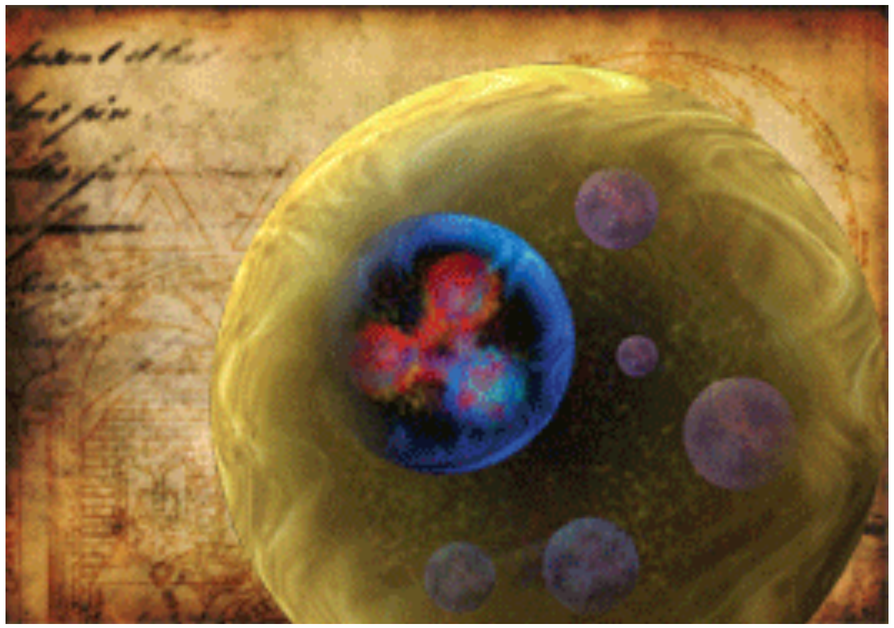


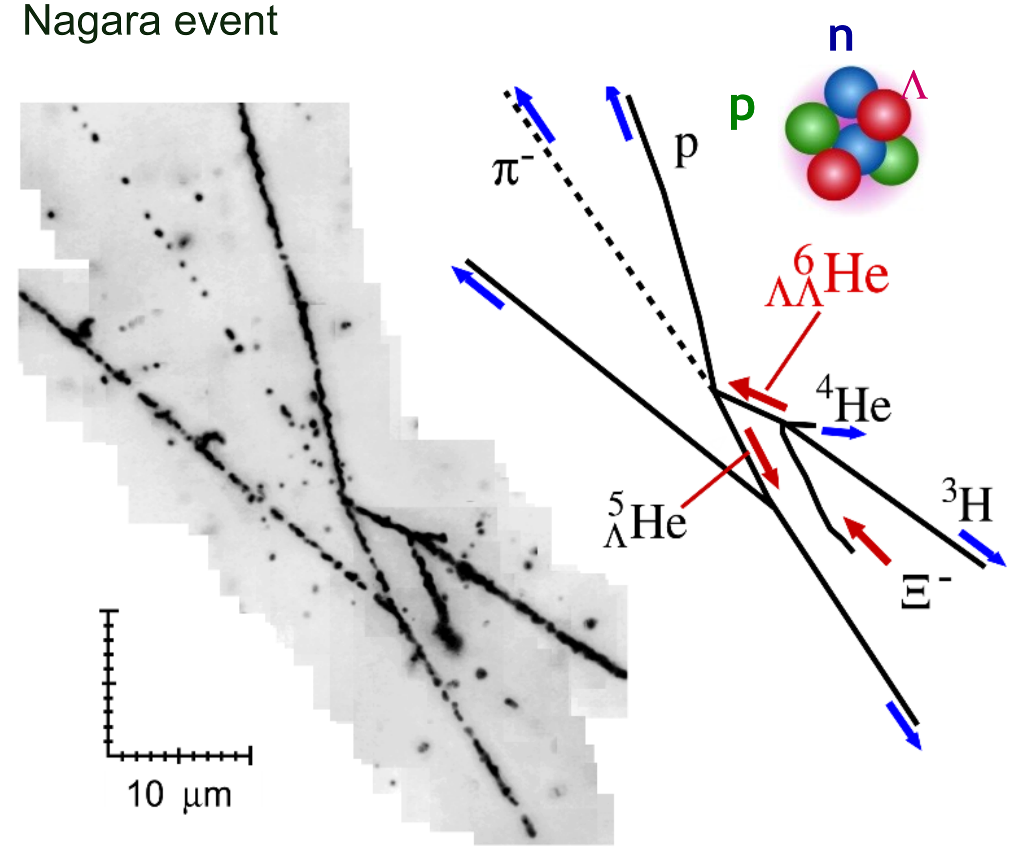
Hypernuclei can be produced
Binding Energy of Λ to nucleus = 30 MeV

Nothing is known about Σ - hypernuclei

Ξ - Hypernucleus shows a shallow attractive interaction

Even $\Lambda\Lambda$-hypernuclei exist

Nagara event



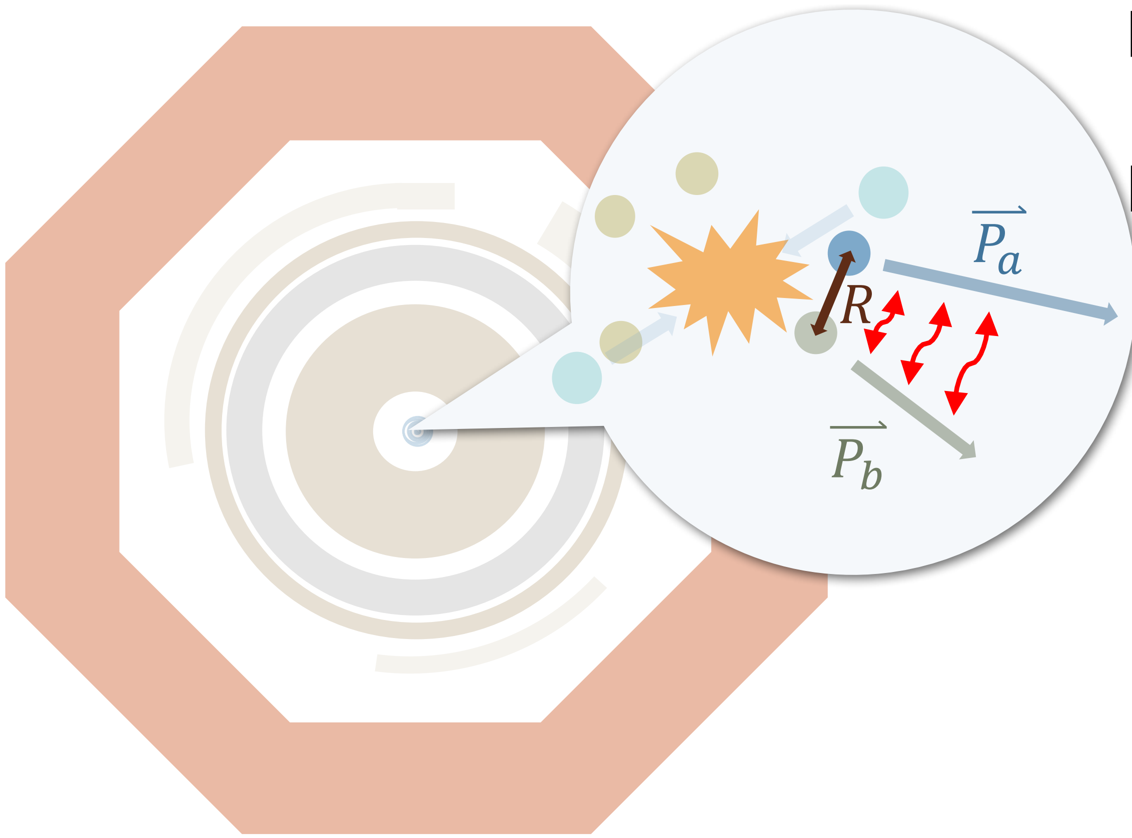
$^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^{-}$

$\Delta B_{\Lambda\Lambda}$= 0.67±0.17 MeV

H. Takahashi et al., PRL 87 (2001) 212502

Λ-Λ is weakly attractive

The ALICE Data Set used in our Analyses



We measure **pp**, **pΛ**, **ΛΛ**, **pΞ, pK, p**Σ, **p**Ω

Proton and Pion identification with TPC and TOF

Reconstruction of hyperons

$\Lambda \rightarrow p\pi^-$ (BR ~ 64%)

$\Xi^- \rightarrow \Lambda\ \pi^-$ (BR ~ 100%)

$\Omega^- \rightarrow \Lambda K^- (BR\ 68\%)$

Datasets:

- pp 7 TeV: $3.4 \cdot 10^8$ MB Events
- pp 5 TeV: $10 \cdot 10^8$ MB Events
- pp 13 TeV: $15 \cdot 10^8$ MB Events
- p-Pb 5.02 TeV: $6.0 \cdot 10^8$ MB Events
- pp 13 TeV: $15 \cdot 10^8$ HM Events (0-0.072% INEL)

The Correlation Function

The correlation function:

$$C(k^*) = \frac{P(\boldsymbol{p}_a, \boldsymbol{p}_b)}{P(\boldsymbol{p}_a)P(\boldsymbol{p}_b)},$$

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$$C(k^*) = \boldsymbol{\mathcal{N}} \frac{N_{Same}(k^*)}{N_{Mixed}(k^*)}$$

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Given by:

$$C(k^*) = \int S(\boldsymbol{r}, k^*) |\psi(\boldsymbol{r}, k^*)|^2 \, d\vec{\boldsymbol{r}}$$

$\xrightarrow{k^* \to \infty} 1$

Source → $S(\boldsymbol{r}, k^*)$

Relative Wave Function → $\psi(\boldsymbol{r}, k^*)$

$$k^* = \frac{|\boldsymbol{p}_a^* - \boldsymbol{p}_b^*|}{2} \text{ and } \boldsymbol{p}_a^* + \boldsymbol{p}_b^* = 0$$

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Source

Relative Wave Function

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Assumption of a **common source** with **Gaussian shape*** for the **pp, pΛ, pΞ**, $\Lambda\Lambda$, pK, pΣ and pΩ Correlation Function

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Σ Ω

$k^* \rightarrow \infty$ 1

Source

Relative Wave Function

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Strong constraint

Assumption of a **common source** with **Gaussian shape*** for the **pp, pΛ, pΞ**, $\Lambda\Lambda$, pK, pΣ and pΩ Correlation Function

The Correlation Function

(D.L.Mihaylov et al. Eur.Phys.J. C78 (2018) no.5,394)

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$k^* \to \infty$ → 1

Source

Relative Wave Function

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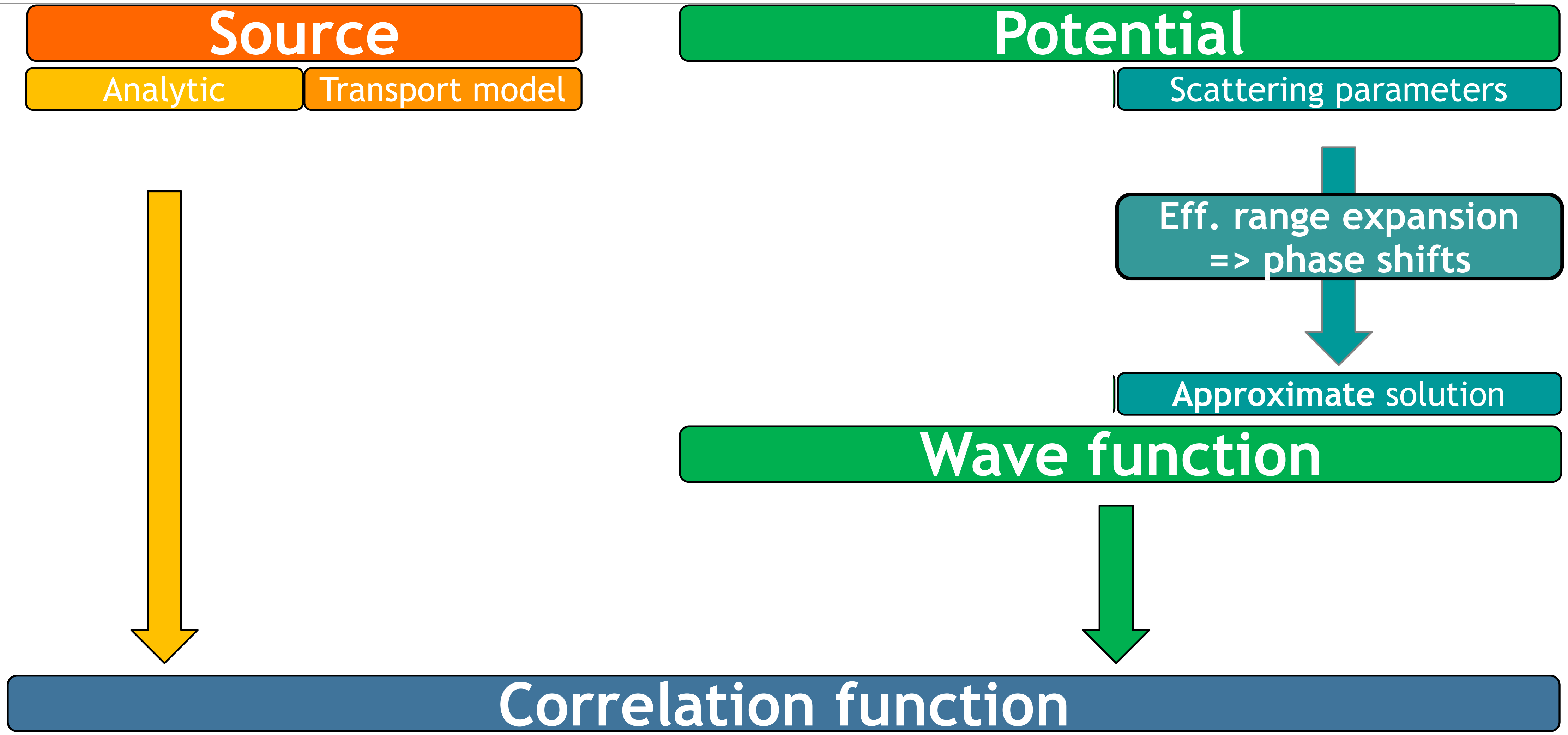
Assumption of a **common source** with **Gaussian shape*** for the **pp, p**Λ**, p**Ξ, $\Lambda\Lambda$, pK, pΣ and pΩ Correlation Function

Strong constraint

correlations functions allow to study the interactions

Lednicky Model

R. Lednicky and V. L. Lyuboshits, Sov. J. Nucl. Phys. **35**, 770 (1982), [Yad. Fiz.35,1316(1981)].

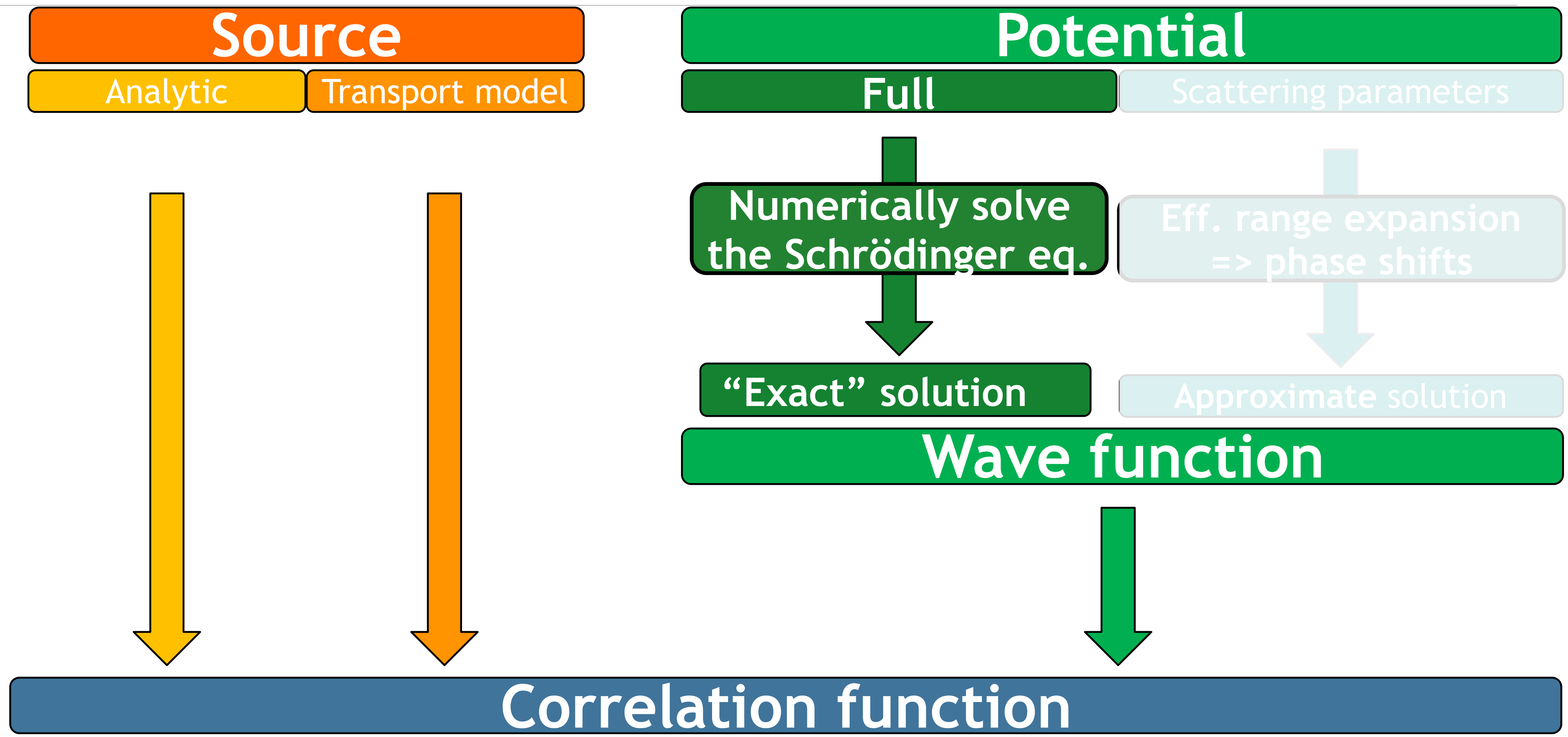


$$C(k) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k)}{R_G^{\Lambda p}} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} R_G^{\Lambda p}} \right) + 2 \frac{\mathcal{R} f^S(k)}{\sqrt{\pi} R_G^{\Lambda p}} F_1(Q R_G^{\Lambda p}) - \frac{\mathcal{I} f^S(k)}{R_G^{\Lambda p}} F_2(Q R_G^{\Lambda p}) \right]$$

might locally break down for small sources

CATS – Correlation Analysis Tool Using the Schrödinger Equation

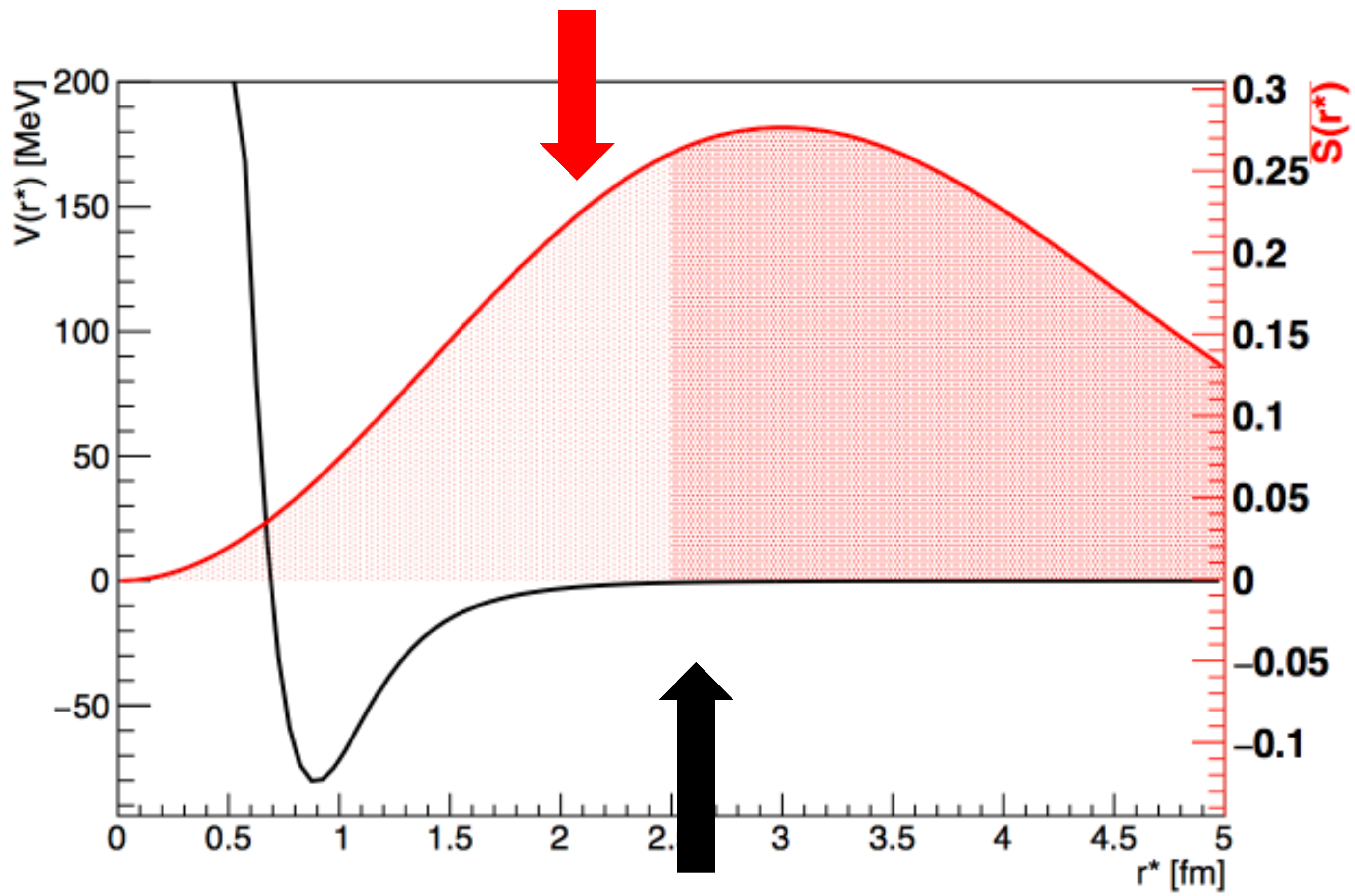
(D.L.Mihaylov et al. Eur.Phys.J. C78 (2018) no.5,394)



$$C(k) = \int S(\vec{r},k)\,|\psi(\vec{r},k)|^2\, d\vec{r} \xrightarrow{k\to\infty} 1$$

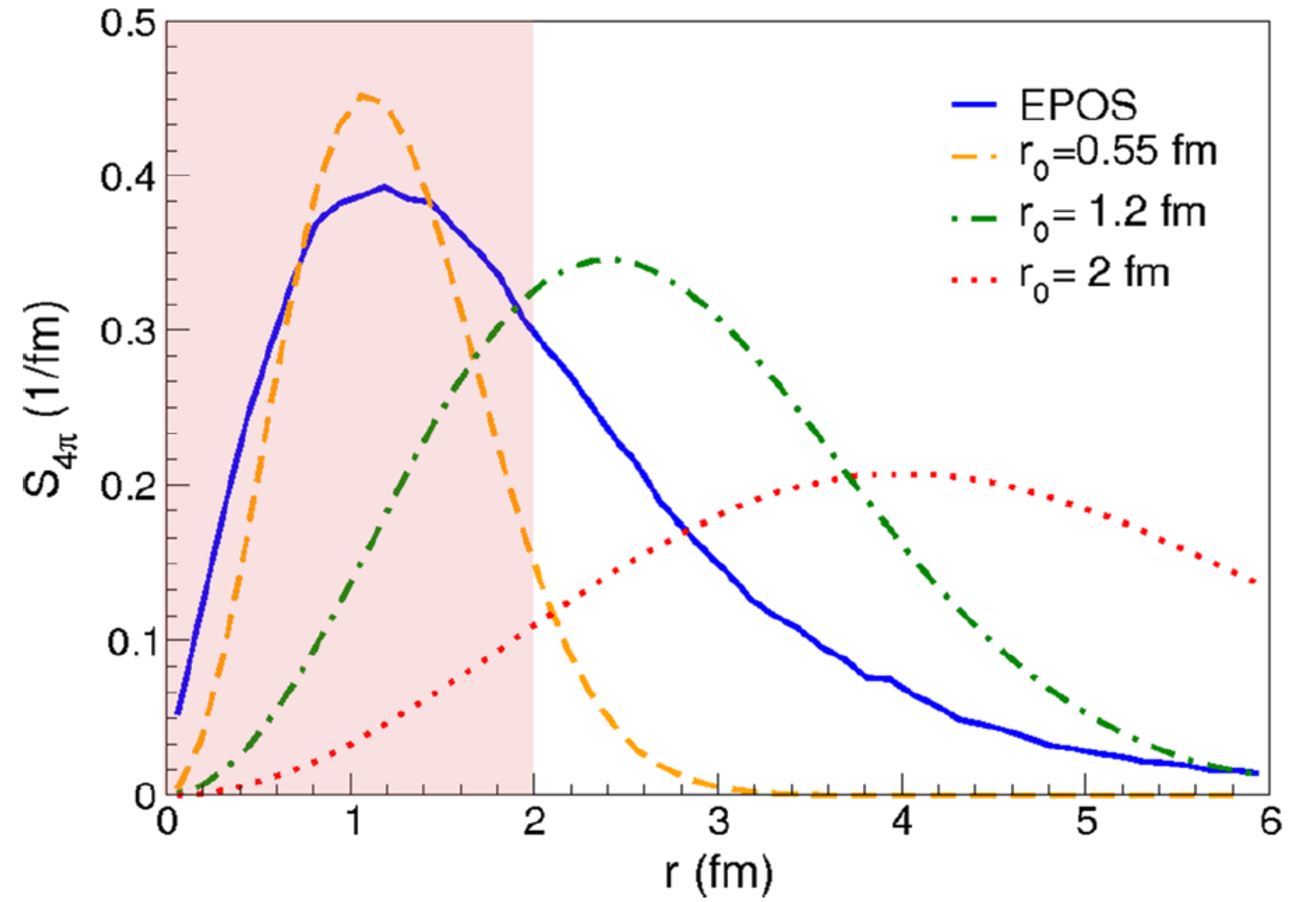
Small sources I: Small colliding systems and small distances

Pdf for a Gaussian Source Function (R_G = 1.5 fm)



Typical short range nuclear potential for pp

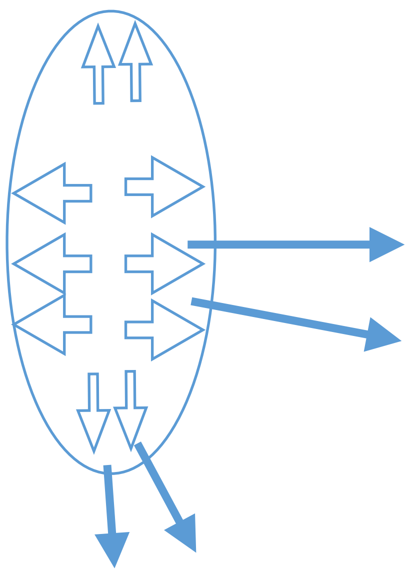
(D.L.Mihaylov et al. Eur.Phys.J. C78 (2018) no.5,394)



Small Radii provided by pp Collisions at the LHC (r ~ 1.2 fm)

Small sources II: Collective Effects and Strong Resonances

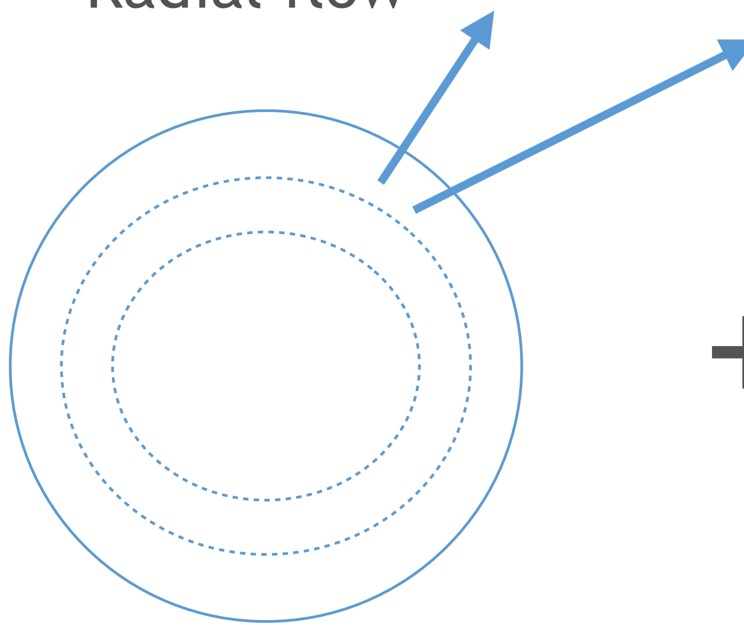
Elliptic flow



anisotropic pressure gradients within the source

+

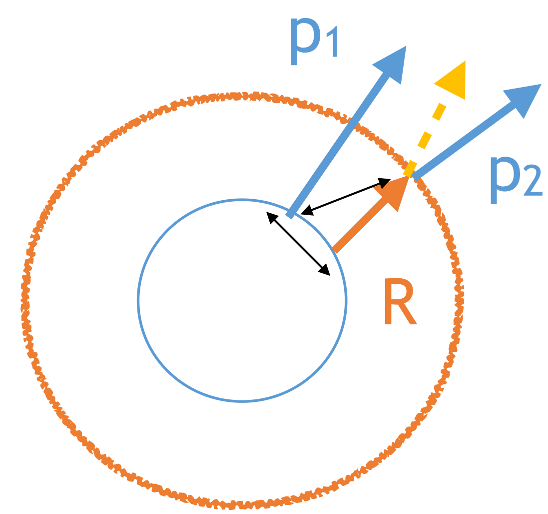
Radial flow



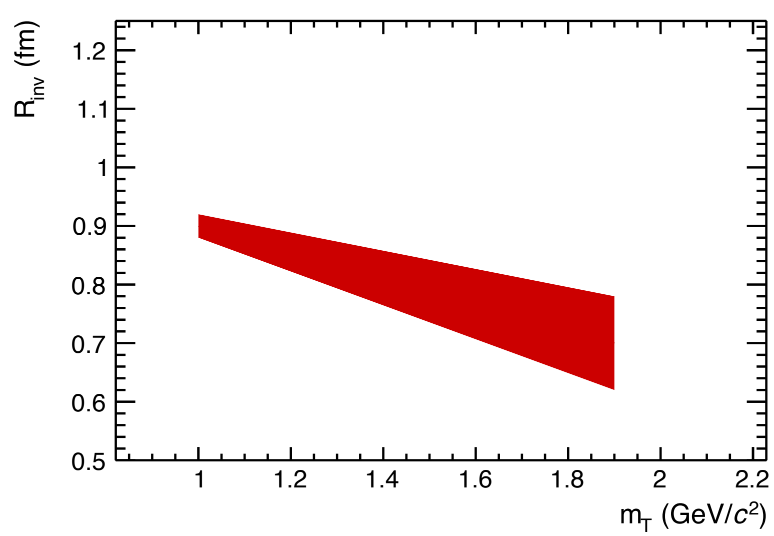
Expanding source with constant velocity
different effect on different masses

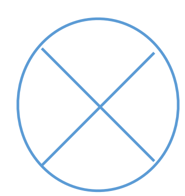
+

Strong decays of broad resonances



$p,\ \Lambda,\ \Xi,\ K$ are 'fed' by resonances with different masses and lifetimes





Strong decays of Specific resonances

CATS – Correlation Analysis Tool Using the Schrödinger Equation

(D.L.Mihaylov et al. Eur.Phys.J. C78 (2018) no.5,394)

$$\psi_k(\mathbf{r}) = \sum_{l=0}^{l_{max}} i^l (2l+1) R_{k,l}(r) P_l(\cos\theta) \qquad u_{k,l}(r) = r R_{k,l}(r)$$

$$\frac{\mathrm{d}^2 u_{k,l}(r)}{\mathrm{d}r^2} = \left[\frac{2\mu V_{I,s,l,j}(r)}{\hbar^2} + \frac{l(l+1)}{r^2} - k^2\right] u_{k,l}(r).$$

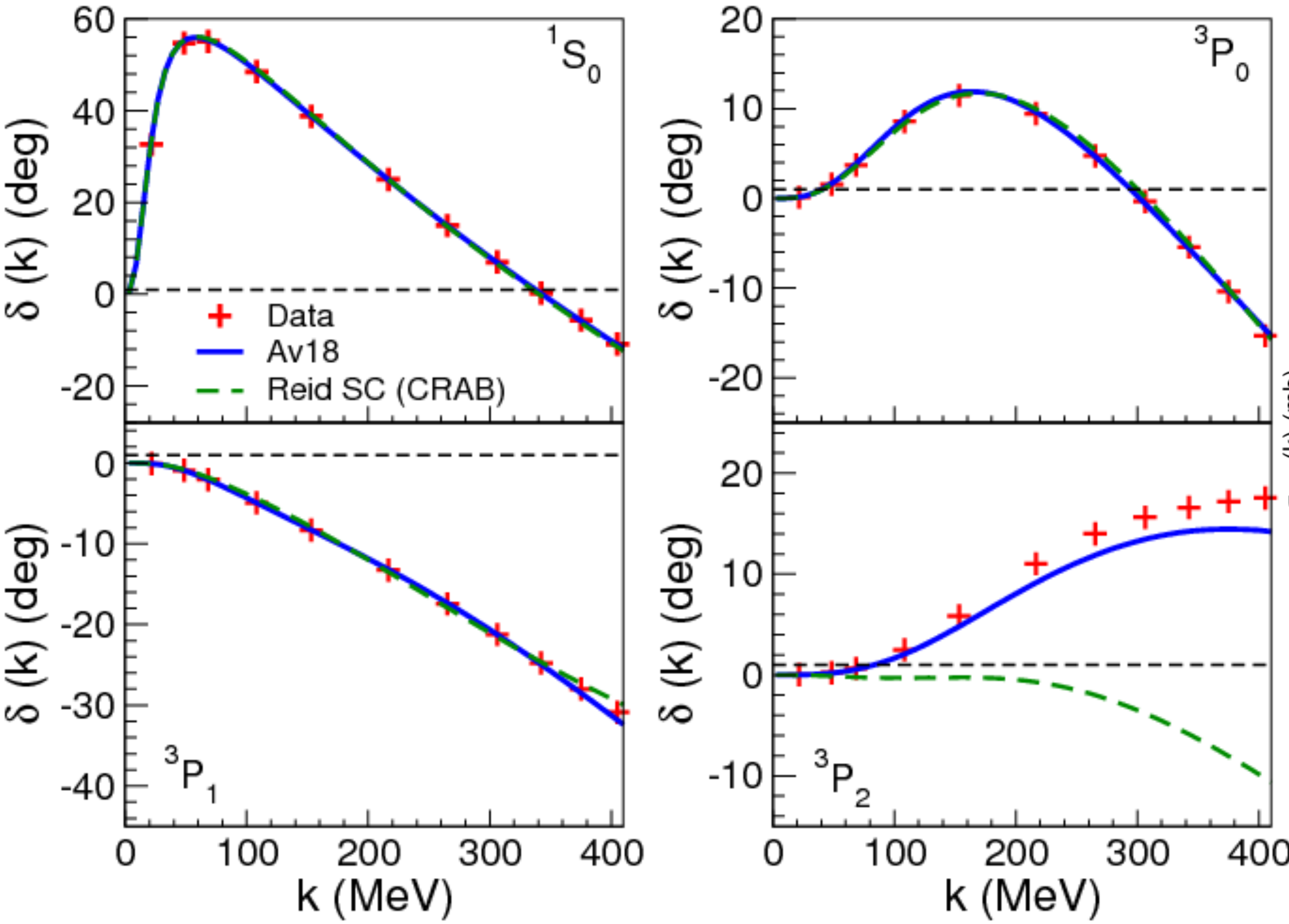
Solutions in bins of k

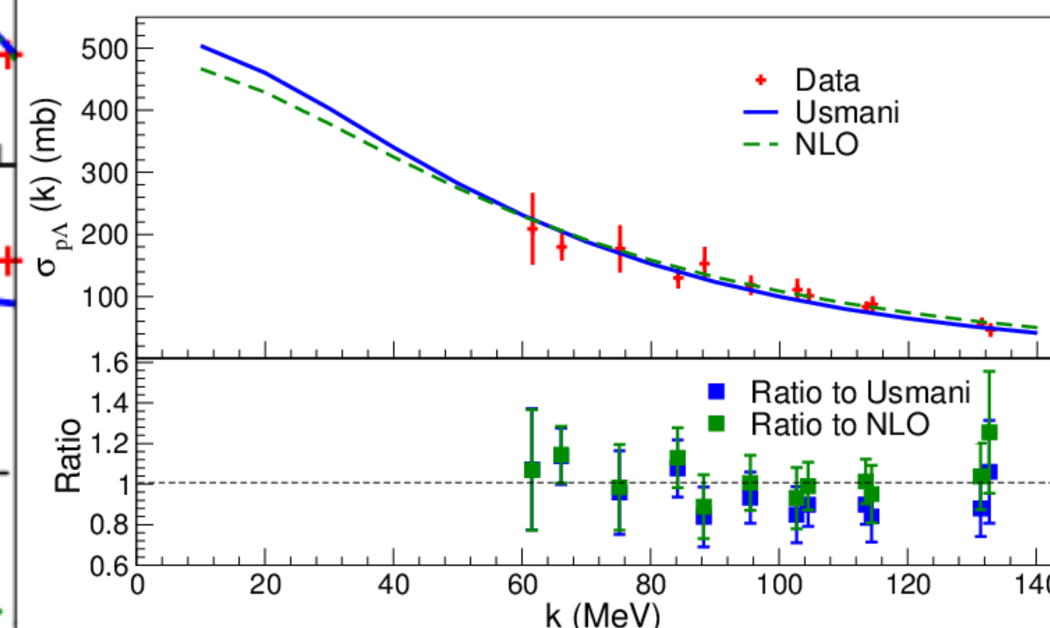
Different solutions with fixed quantum numbers I, s, l and j

Shift can be extracted and compared to existing scattering data for pp (benchmark)

CATS – Correlation Analysis Tool Using the Schrödinger Equation

(D.L.Mihaylov et al. Eur.Phys.J. C78 (2018) no.5,394)





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Solutions in bins of k

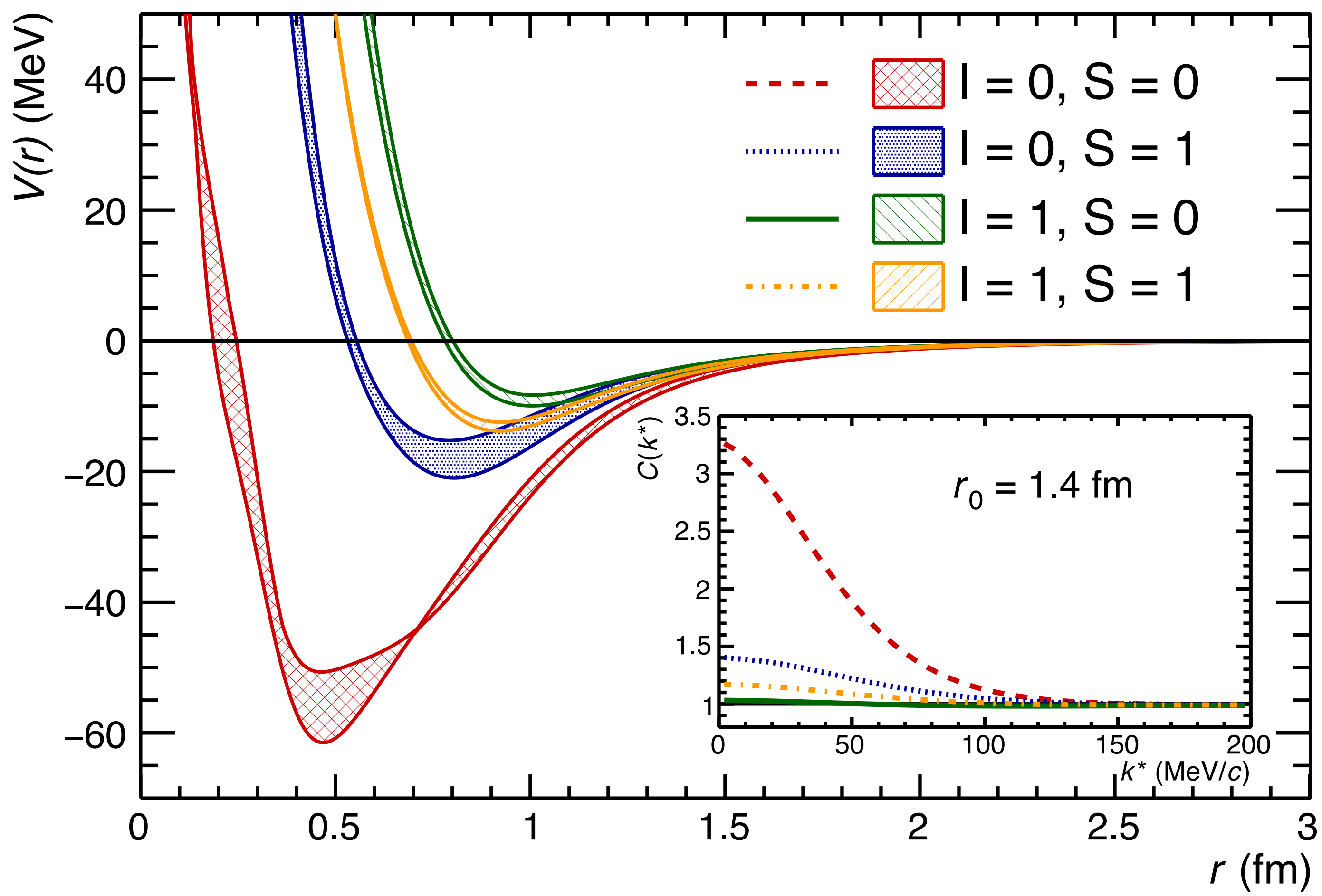
Different solutions with fixed quantum numbers I, s, l and j are combined via Clebtsch-Gordon coefficients

CATS – Correlation Analysis Tool Using the Schrödinger Equation

(D.L.Mihaylov et al. Eur.Phys.J. C78 (2018) no.5,394)

Example:

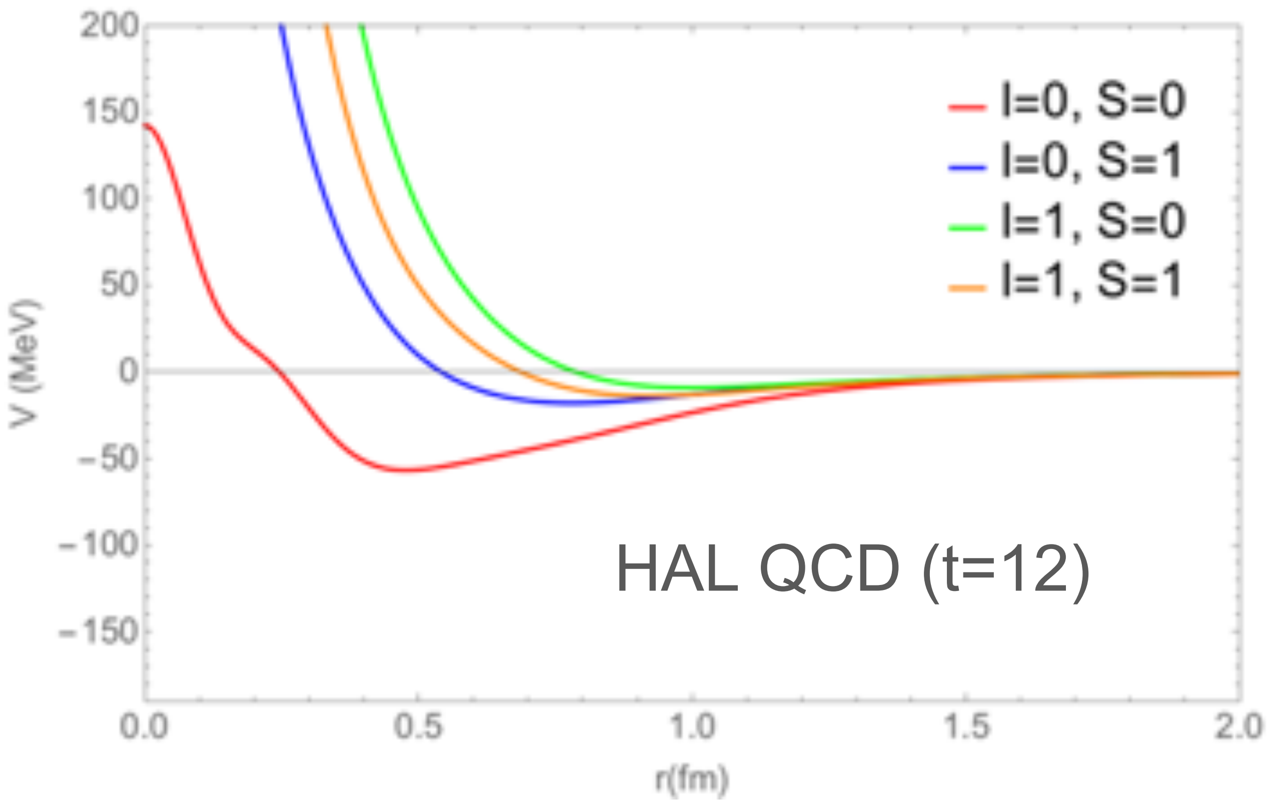
(Potential from Hatsuda et al., NPA967 (2017) 856, PoS Lattice2016 (2017) 116)

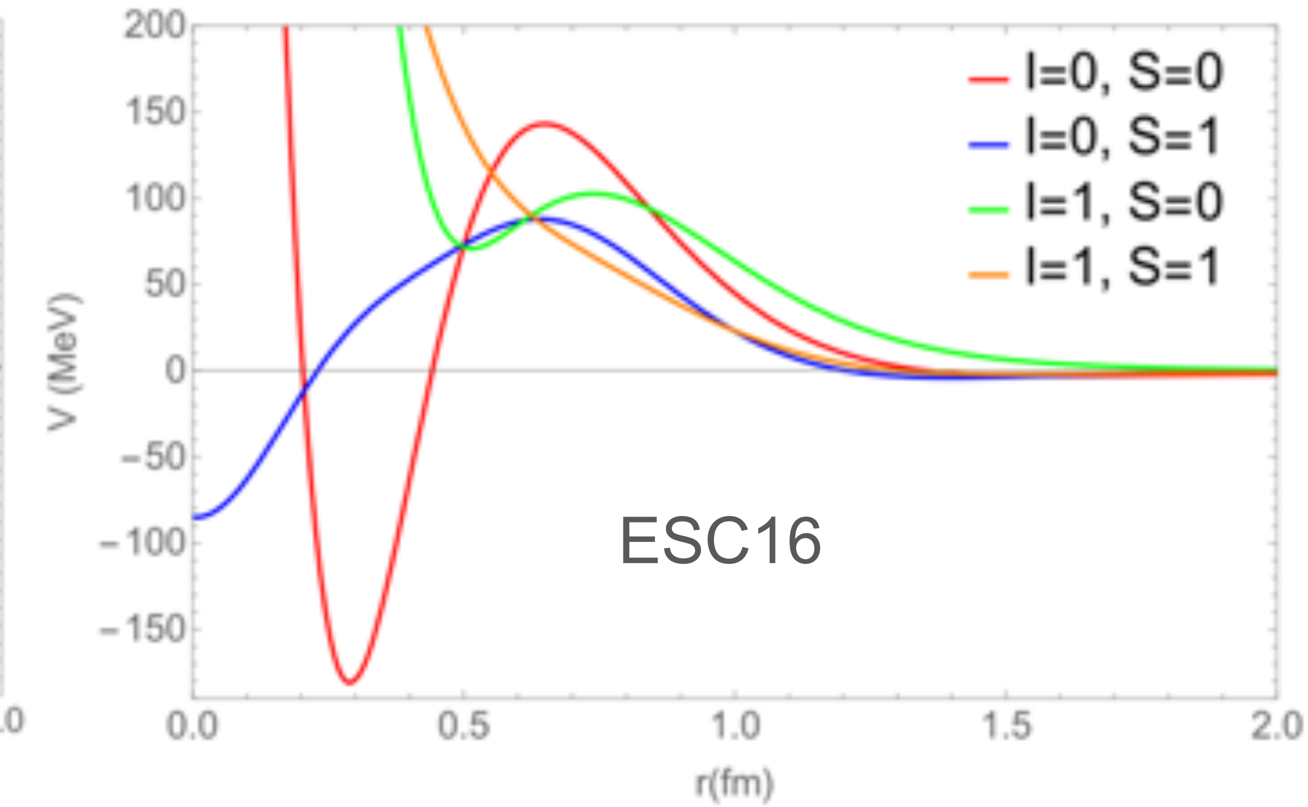


Each Potential can be converted in a correlation function via CATS

$$C(k^*) = \frac{1}{8}\left(C_{I=0}^{S=0} + C_{I=1}^{S=0}\right) + \frac{3}{8}\left(C_{I=0}^{S=1} + C_{I=1}^{S=1}\right)$$

A look into different potentials

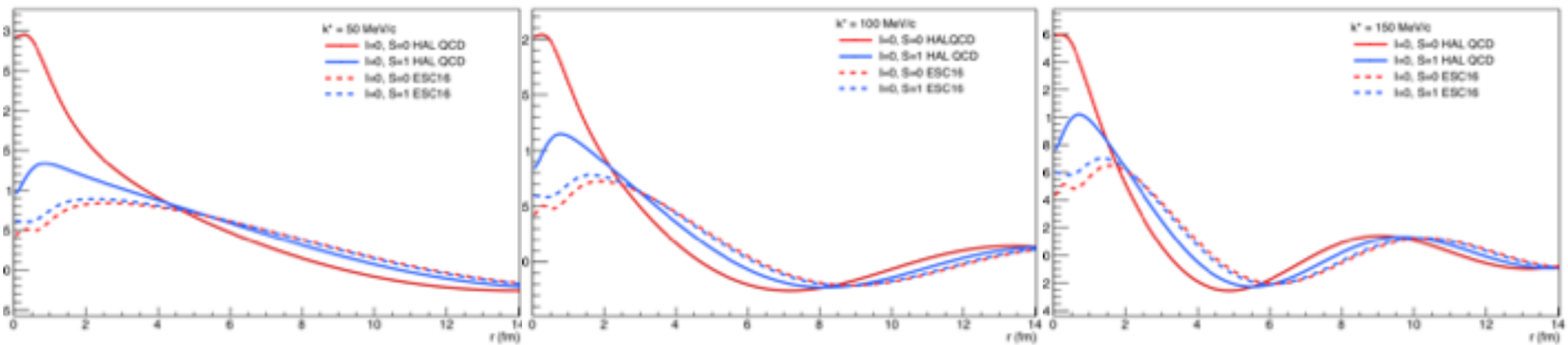




Huge different behaviour in the I=0 sector ->we do expect large differences in the WFs

Comparison of HAL-QCD and ESC016 ($p\Xi^-$, I=0)

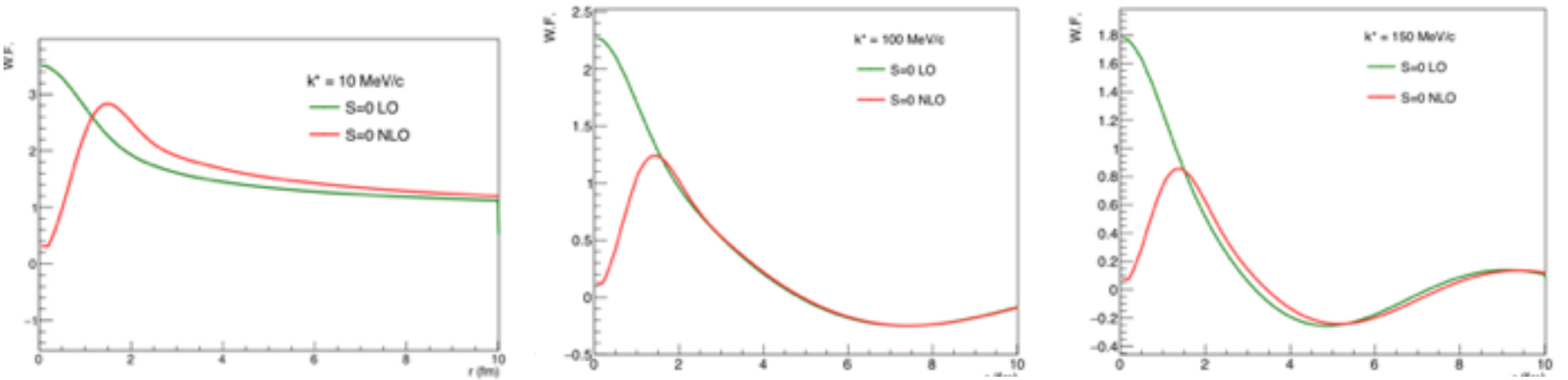
k* increasing



- Increasing k* -> approaching the same oscillating free wfs for both models
- HAL QCD potential shows in this channel more attraction -> wfs always larger than ESC16
- ESC16 wfs suppressed at small and intermediate (~ 2 fm) ranges due to the overall repulsion

Comparison of the LO and NLO wave functions for $p\Lambda$ (S=0)

k* increasing



- The 1S0 channel is the one who has the most difference as expected
- Clearly seen the NLO repulsive core -> wfs suppressed at small r
- the huge difference between LO and NLO occurs below 2 fm where our pdf sources (roughly peaking at 2-3 fm) are not sensitive BUT at small k* (1st panel left) this is exactly what we see in the correlation function -> NLO more attractive than LO

Table of applications (pp and pPb collisions, 7,5 13 TeV)

Channel	Potential	Wave Function	Model
pp	AV18		CATS
$p\Lambda$			
$\Lambda\Lambda$			Lednicky (Exclusion Plot) CATS
pK^+		Jülich Model	CATS
pK^-		Hyodo Model Jülich Model	CATS
$p\Sigma^0$		Jülich Model ESC16 Model	Lednicky CATS
$p\Xi^-$	Lattice ESC16 Jülich Model		CATS
$p\Omega^-$	Lattice Kyoto Model		CATS

Summary

- EoS for Neutron stars with hyperons content can be built starting from 2- and 3-body interactions
- ALICE delivered new results with unprecedented high statistics for many 2-body interaction (YN, YY, Kaon-N..)
- The 3-body problem should be attacked in the next future

So far:

1)- Mihaylov, D.L. *et al*. Eur.Phys.J. C78 (2018) no.5, 394

2) ALICE Coll., ‘pp,p-Lambda and Lambda-Lambda correlations studied via femtoscopy in pp reactions at 7 TeV’, Phys.Rev. C99 (2019) no.2, 024001.

3) ALICE Coll.’ First observation of an attractive interaction between a proton and a multi-strange baryon’, (submitted to PRL), arXiv:1904.12198.

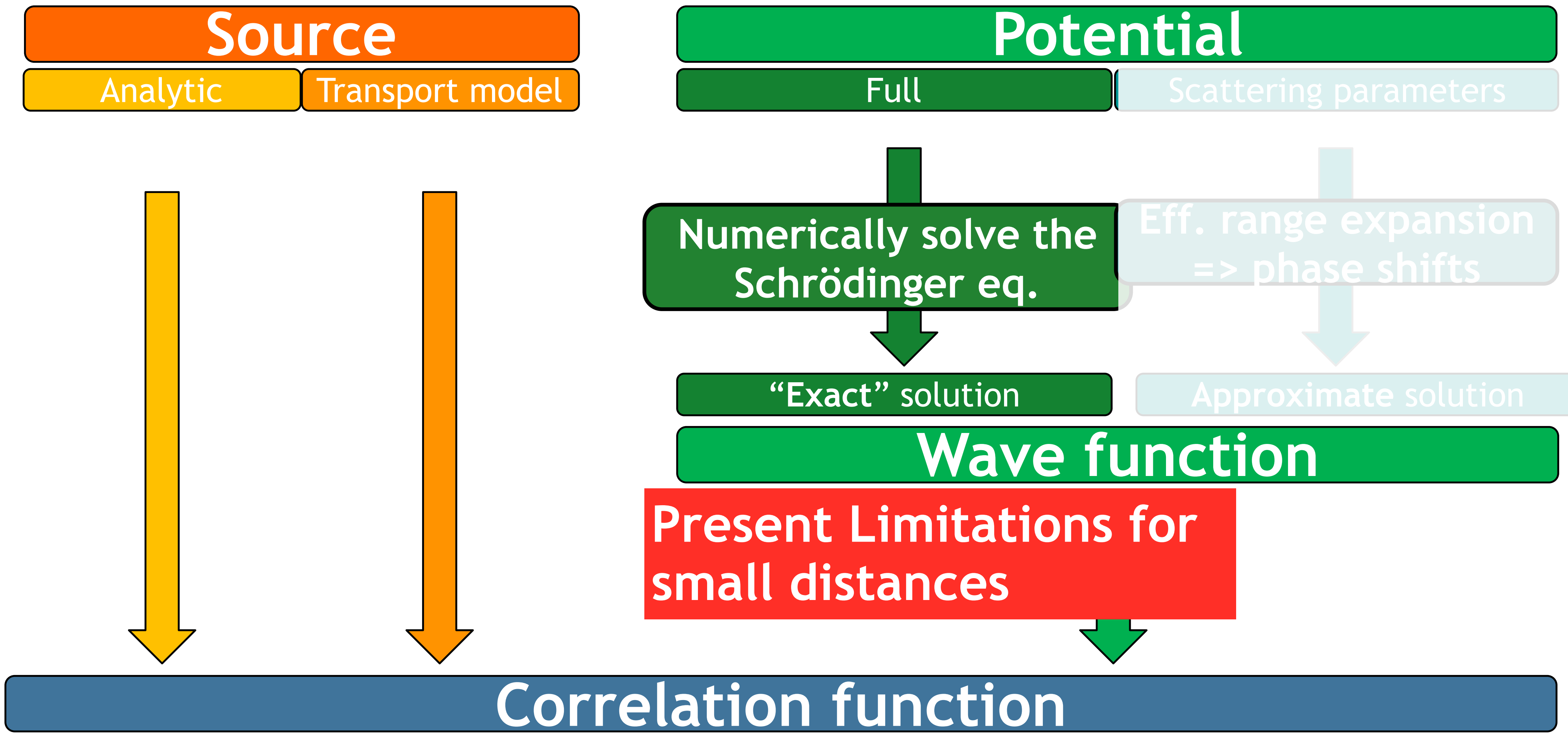
4) ALICE Coll., ‘ Study of the Lambda-Lambda interaction with femtoscopy correlations in pp and p-Pb collisions at the LHC’, (submitted to PLB), arXiv:1905.07209.

5)ALICE Coll., ‘Scattering studies with low-energy kaon-proton femtoscopy in proton-proton collisions at the LHC’, (submitted to PRL), arXiv:1905.13470

CRAB – Correlation After Burner

http://www.pa.msu.edu/~pratts/freecodes/crab/home.html

$$C(k) = \int S(\vec{r}, k) |\psi(\vec{r}, k)|^2 \, d\vec{r} \xrightarrow{k \to \infty} 1$$



Unconventional Femto-Gang@DUBNA

XIV Workshop on Particle Correlations and Femtoscopy, Dubna 2019