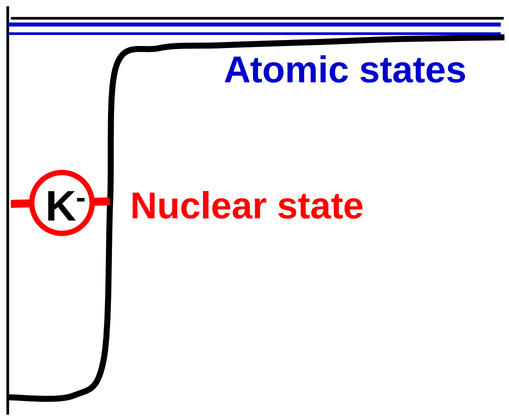
RIKEN Lecture
January 6, 2006

Deeply Bound $\bar{K}$ Nuclei

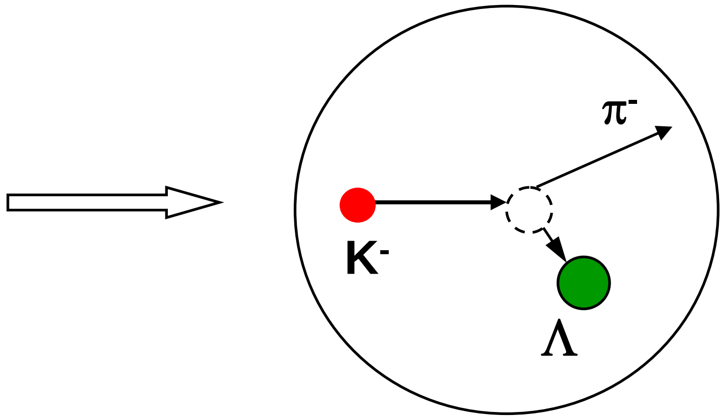


Yoshinori AKAISHI and Toshimitsu YAMAZAKI

Production of hypernuclei

$$K^- + n \rightarrow \Lambda + \pi^-$$

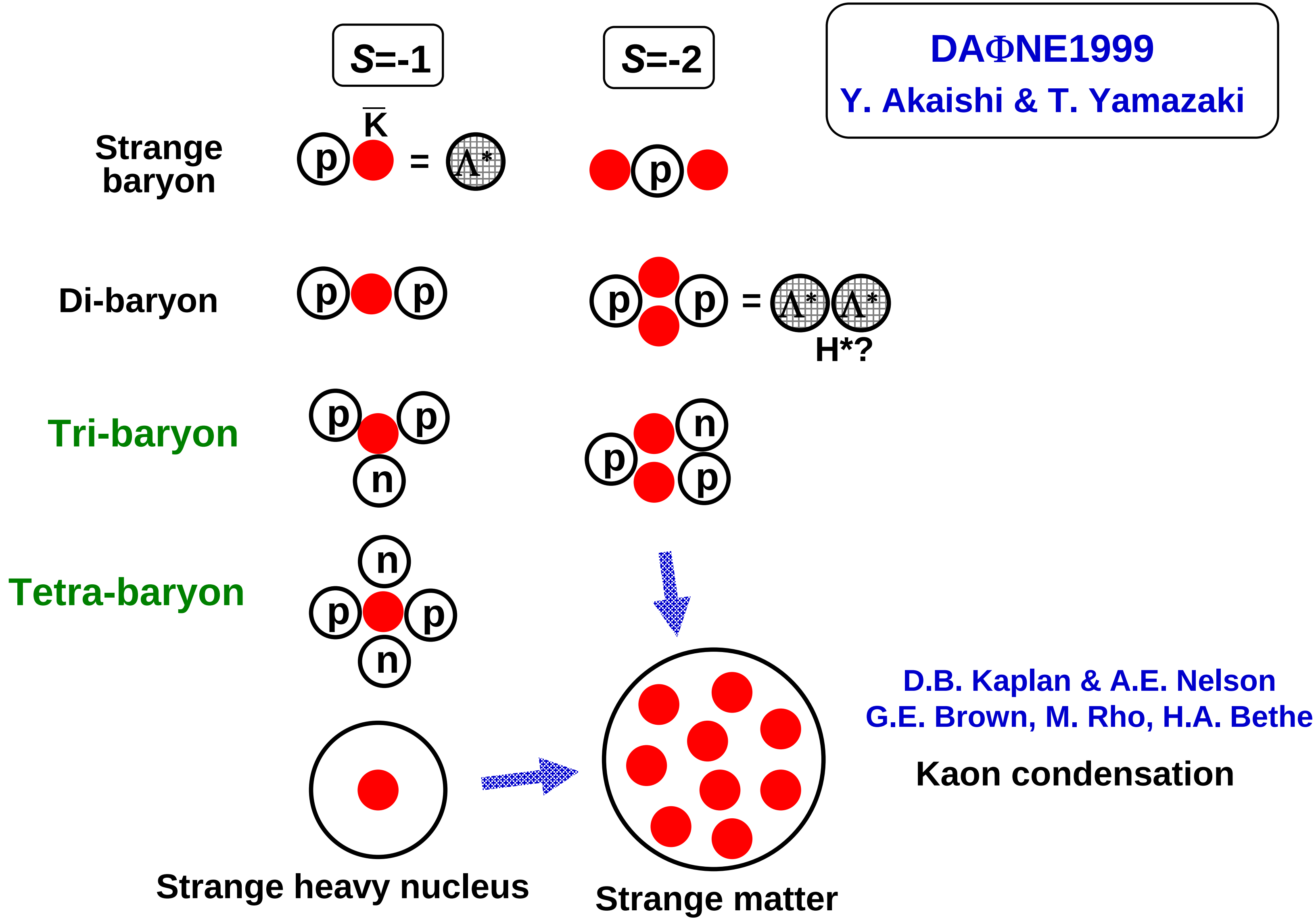
K^-	n	Λ	π^-
($\bar{u}$s)	(udd)	(uds)	($\bar{u}$d)
T=1/2	*T*=1/2	*T*=0	*T*=1



K^-	$\bar{u}s$	$493.65\ \mathrm{MeV}/c^2$	1.24×10^{-8} sec
$\bar{K}^0$	$\bar{d}s$	$497.67\ \mathrm{MeV}/c^2$	(K_S^0 0.89E-10, K_L^0 5.18E-8 sec)
K^0	$d\bar{s}$	$497.67\ \mathrm{MeV}/c^2$	
K^+	$u\bar{s}$	$493.65\ \mathrm{MeV}/c^2$	1.24×10^{-8} sec

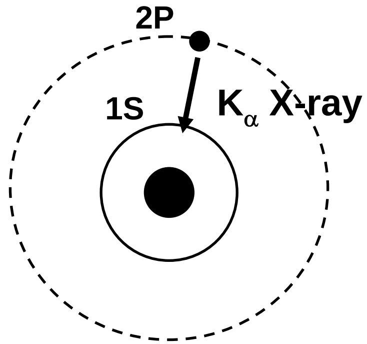
$$\Lambda\ \ \mathrm{uds}\ \ T=0\ \ \ 1115.63\ \mathrm{MeV}/c^2\ \ \ 2.63\times10^{-10}\ \mathrm{sec}$$

Few-body $\bar{K}N$ systems



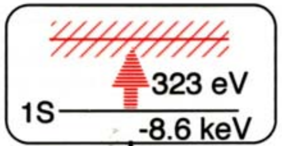
$$(-323 \pm 63 \pm 11) + i(407 \pm 208 \pm 100)\ \mathrm{eV}$$
$$(-193 \pm 37 \pm 6) + i(249 \pm 111 \pm 30)\ \mathrm{eV}$$

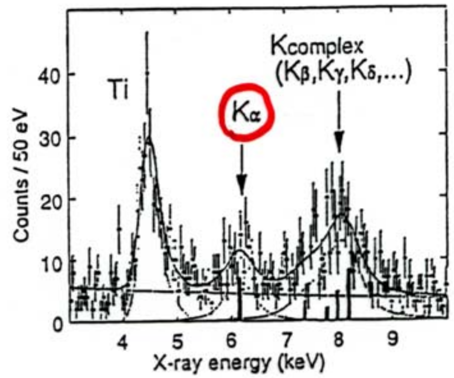
DEAR @ DAΦNE



K⁻p atom

M. Iwasaki et al., Phys. Rev. Lett. **78** (1997) 3067.
T.M. Ito et al., Phys. Rev. C **58** (1998) 2366.





$$\varepsilon + \tfrac{i}{2}\Gamma = 2\alpha^3 \mu\, a_{K^-p}$$

$$a_{K^-p} = (-0.78 \pm 0.15 \pm 0.03) + i(0.49 \pm 0.25 \pm 0.12)\ \mathrm{fm}$$

$$a_{K^-p} = (-0.66 \pm 0.05) + i(0.64 \pm 0.04)\ \mathrm{fm}$$ Martin

$$a_{K^-p} = \tfrac{1}{2}a^{T=0} + \tfrac{1}{2}a^{T=1}$$

$\bar{K}$N scattering length

$$a^{T=0} = (-1.70 \pm 0.07) + i(0.68 \pm 0.04)\ \mathrm{fm}$$
$$a^{T=1} = (\ 0.37 \pm 0.09) + i(0.60 \pm 0.07)\ \mathrm{fm}$$

A.D. Martin,
Nucl. Phys. B179 (81) 33.

$$a_0 = \tfrac{1}{4}a^{T=0} + \tfrac{3}{4}a^{T=1} = -0.15 + i\,0.62\ \mathrm{fm}$$

$\bar{K}$-nucleus optical potential

$$U^{opt}(r_K) = -\frac{2\pi\hbar^2}{\mu_K}\left(1 + \frac{m_K}{M_N}\right) a\, \rho(r_K)$$

$$\Rightarrow +19 - i\,80\ \ \mathrm{MeV}\ \ \text{at}\ \ r_K = 0$$

Repulsive!

$\bar{K}N$ interaction

$$V^T_{\bar{K}N}(r) = V^T_D \exp(-(r/0.66)^2)$$

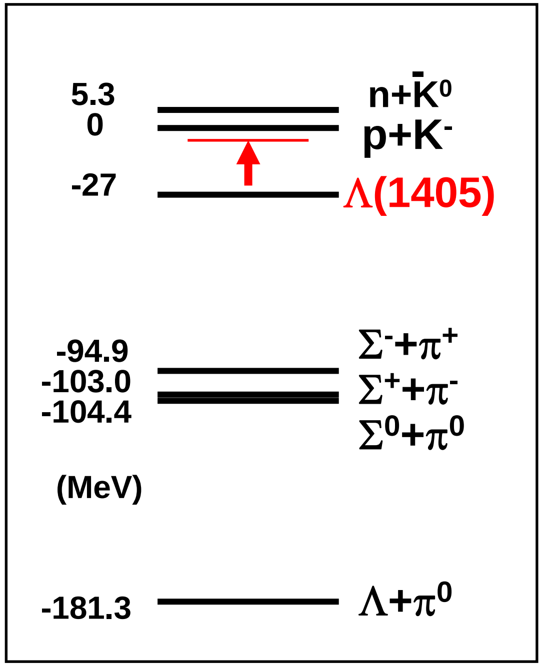
$$V^T_{\bar{K}N,\pi\Sigma}(r) = V^T_{C_1} \exp(-(r/0.66)^2)$$

$$V^T_{\bar{K}N,\pi\Lambda}(r) = V^T_{C_2} \exp(-(r/0.66)^2)$$

$$V^T_{\pi\Sigma}(r) = V^T_{\pi\Lambda} = 0$$

$V^{T=0}_D$ = -436 MeV
$V^{T=0}_{C_1}$ = -412 MeV
$V^{T=0}_{C_2}$ = none

$V^{T=1}_D$ = -62 MeV
$V^{T=1}_{C_1}$ = -285 MeV
$V^{T=1}_{C_2}$ = -285 MeV



Martin (1981)

$$a^{T=0} = (-1.70 \pm 0.07) + i(0.68 \pm 0.04)\ \text{fm}$$

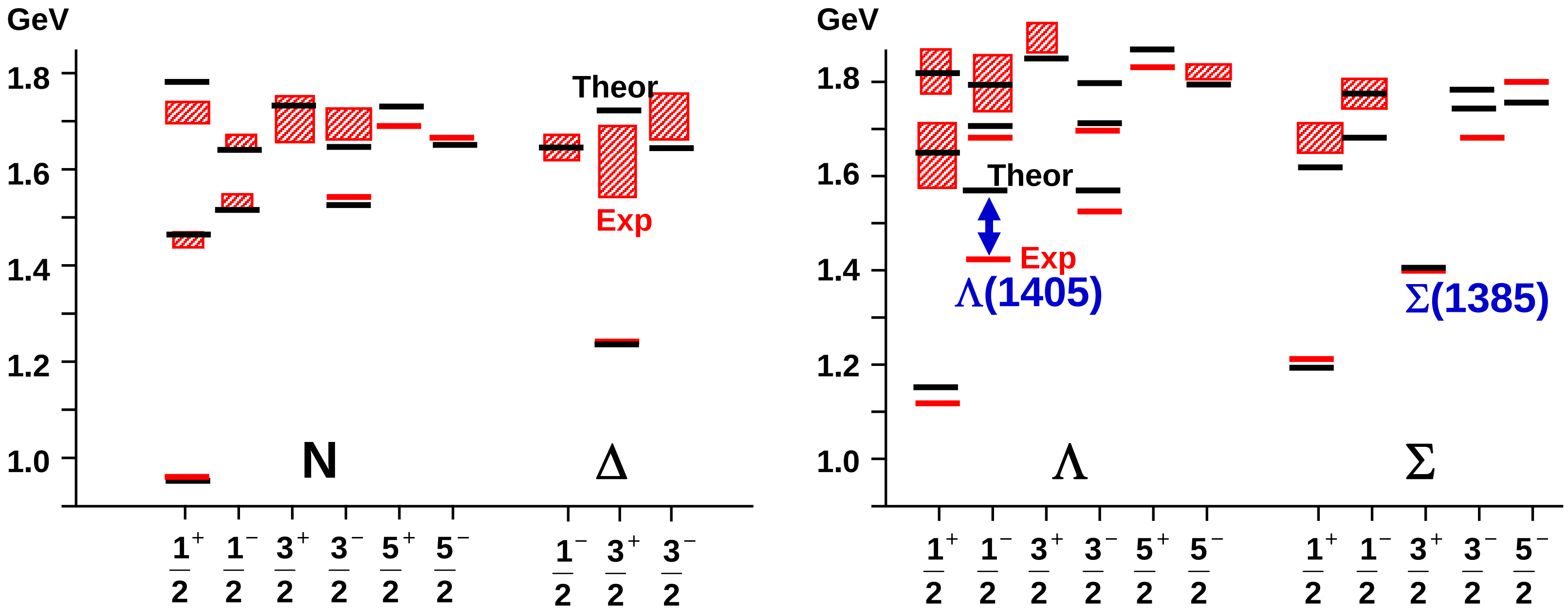
$$a^{T=1} = 0.37 + i\,0.60\ \text{fm}$$

KpX Iwasaki et al. (1997)

$$a_{K^-p} = (-0.78 \pm 0.15 \pm 0.03) + i(0.49 \pm 0.25 \pm 0.12)\ \text{fm}$$

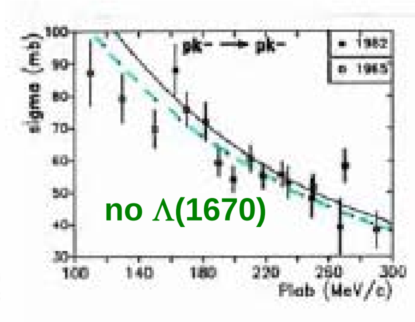
A chiral constituent-quark model

L.Ya. Glozman, W. Plessas, K. Varga & R.F. Wagenbrunn,
Phys. Rev. D 58 (1998) 094030.



Lattice QCD quenched to
3Q: H. Suganuma et al.
$M(3Q, 1/2^-) \approx 1.7$ GeV
5Q: N. Ishii et al.

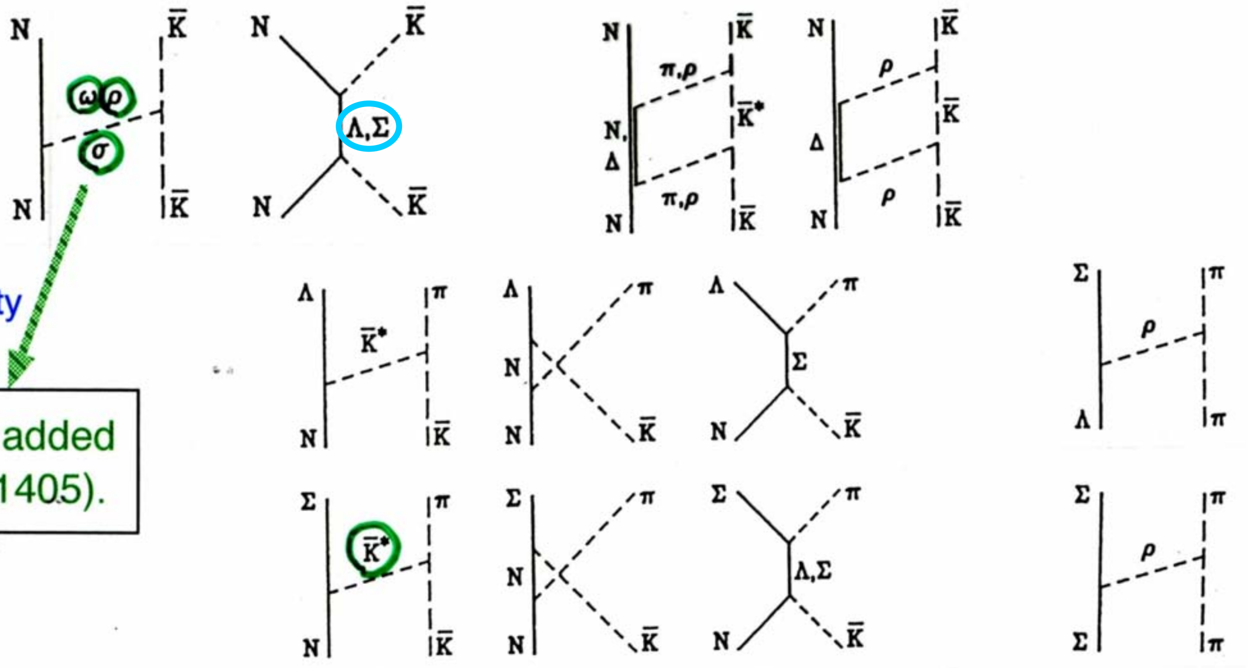
Jülich $\bar{K}N$ Quasi-potential



A. Müller-Groeling, K. Holinde & J. Speth, Nucl. Phys. **A513** (1990) 557.

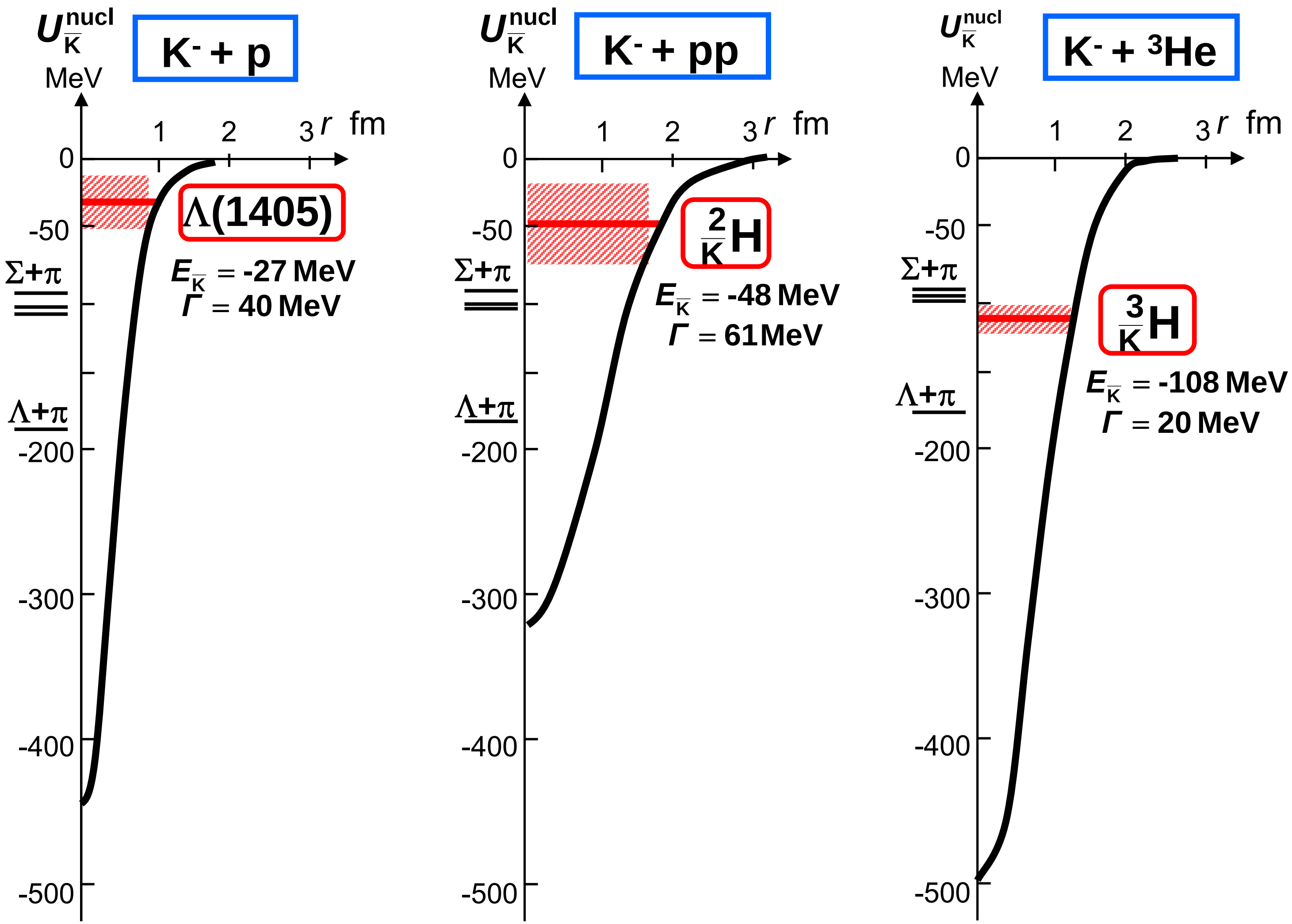
$$p_{\bar{K}}^{\text{lab.}} = 60 \sim 300\ \text{MeV}/c$$

Dominant Minor



G-parity

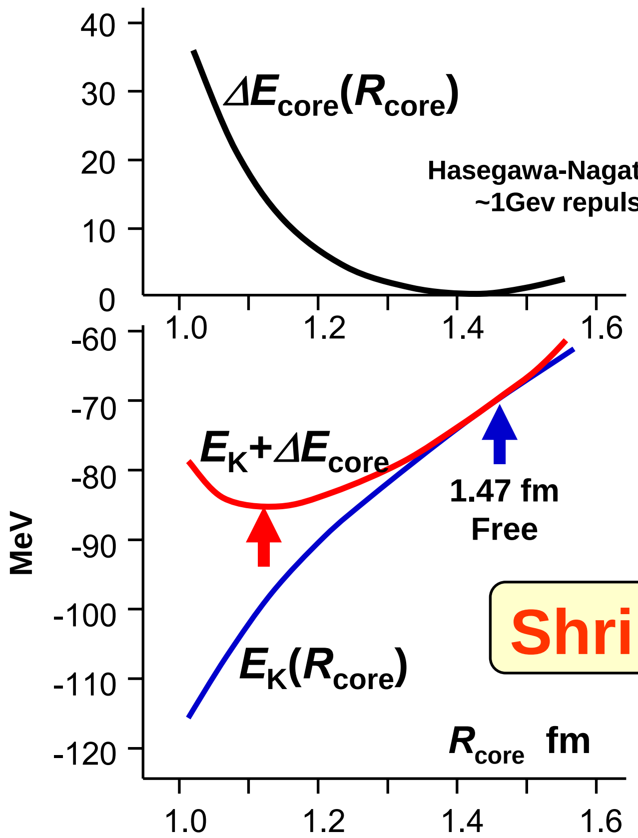
Coherently added to form Λ(1405).

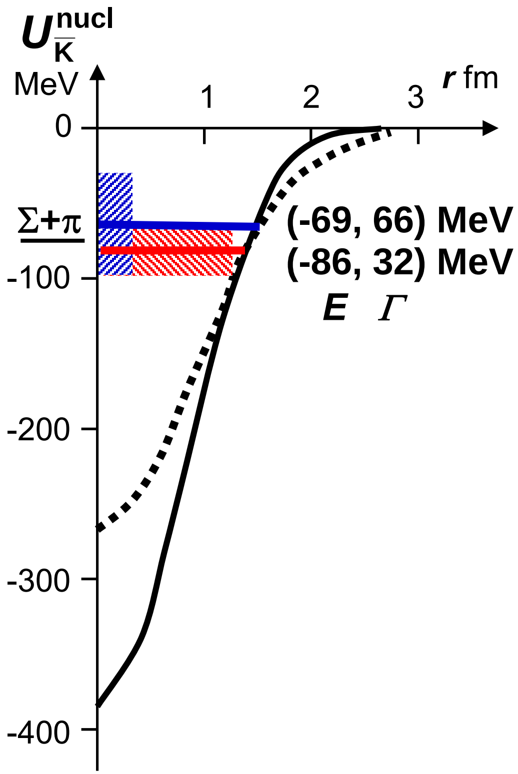


Y. Akaishi & T. Yamazaki, Phys. Rev. C 65 (2002) 044005

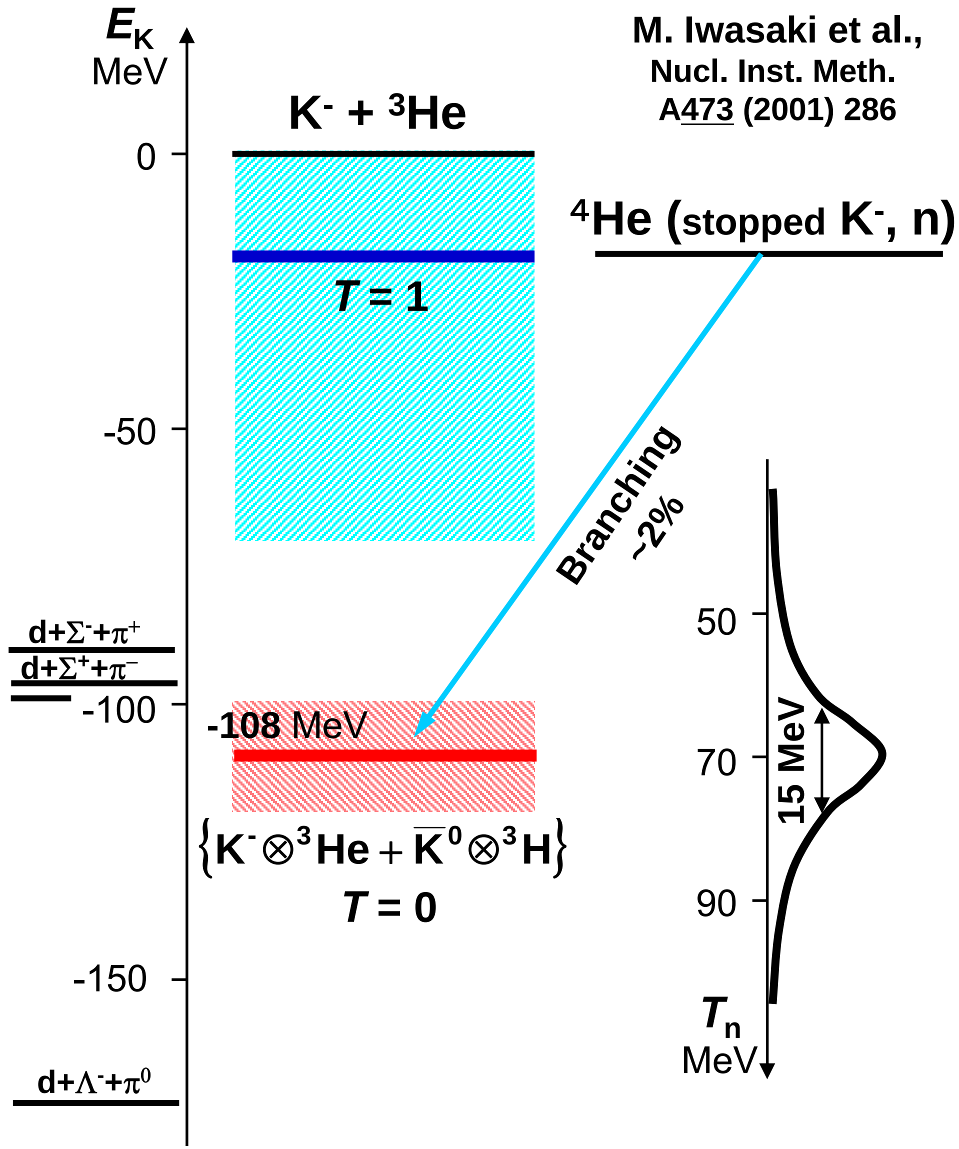
Nuclear ${}^{4}_{\bar{K}}H$ bound state

$[K^- \otimes {}^4He]_{T=1/2}$





Shrinkage !



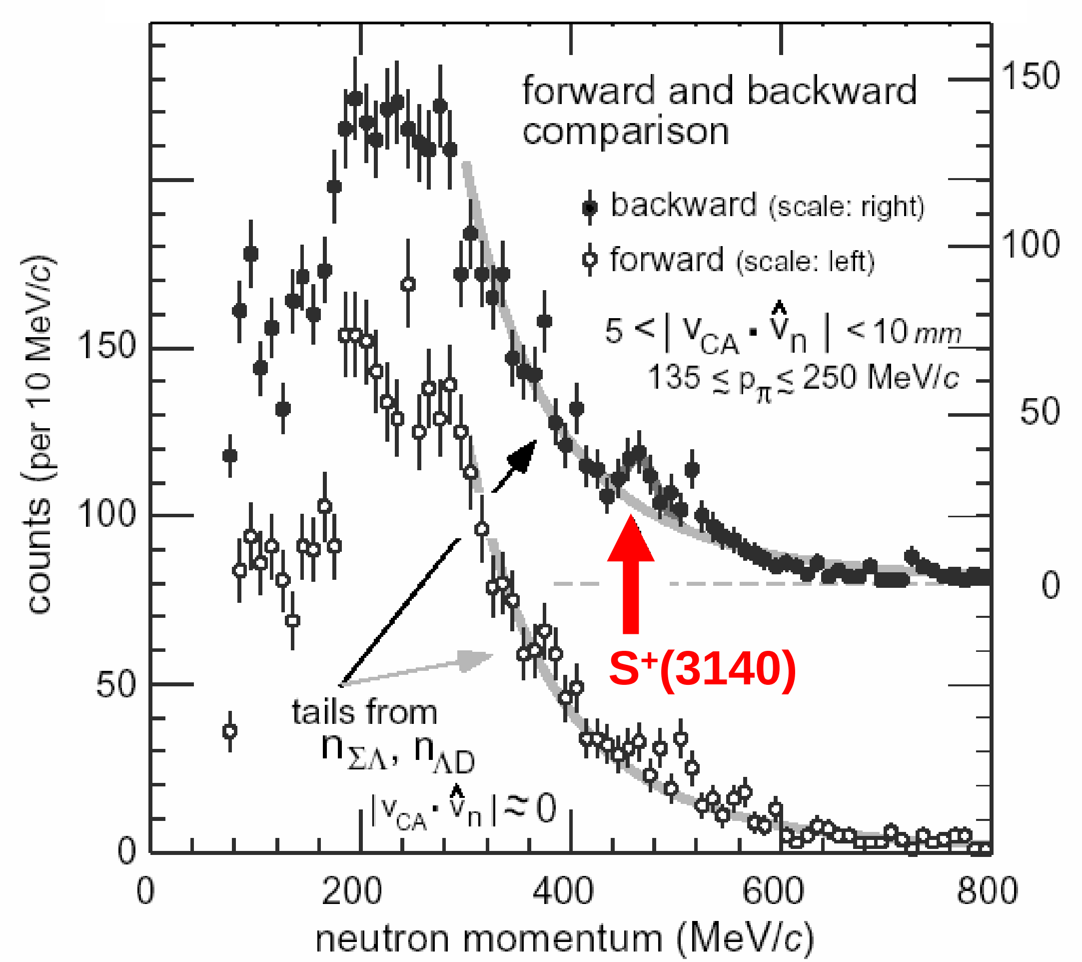
E_K
MeV
M. Iwasaki et al.,
Nucl. Inst. Meth.
A473 (2001) 286
$K^- + {}^3He$
0
^4He (stopped K^-, n)
$T = 1$
-50
Branching
~2%
50
$d+\Sigma^-+\pi^+$
$d+\Sigma^++\pi^-$
-100
-108 MeV
15 MeV
70
$\{K^- \otimes {}^3He + \bar{K}^0 \otimes {}^3H\}$
$T = 0$
90
-150
T_n
MeV
$d+\Lambda+\pi^0$

Evidence for K^-ppn

from ^4He(stopped K^-,n)

Oct.16, 2003 M. Iwasaki et al.

nucl-ex/0310018



M. Iwasaki
T. Suzuki
H. Bhang
G. Franklin
K. Gomikawa
R.S. Hayano
T. Hayashi
K. Ishikawa
S. Ishimoto
K. Itahashi
T. Katayama
Y. Kondo
Y. Matsuda
T. Nakamura
S. Okada
H. Outa
B. Quinn
M. Sato
M. Shindo
H. So
T. Sugimoto
P. Strasser
K. Suzuki
S. Suzuki
D. Tomono
A.M. Vinodkumar
E. Widmann
T. Yamazaki
T. Yoneyama

$$\hbar\omega = \frac{\hbar^2}{M} a \approx 55\ \mathrm{MeV}$$

$$\rho(r) = \rho(0)\exp\left(-\frac{3}{2} a r^2\right)$$

$$\rho(0) = 3\left(\frac{3a}{2\pi}\right)^{3/2}$$

$$\bar{\rho} = \int d\vec{r}\, \rho(r)\{\rho(r)/3\} = \sqrt{\frac{1}{8}}\,\rho(0),$$

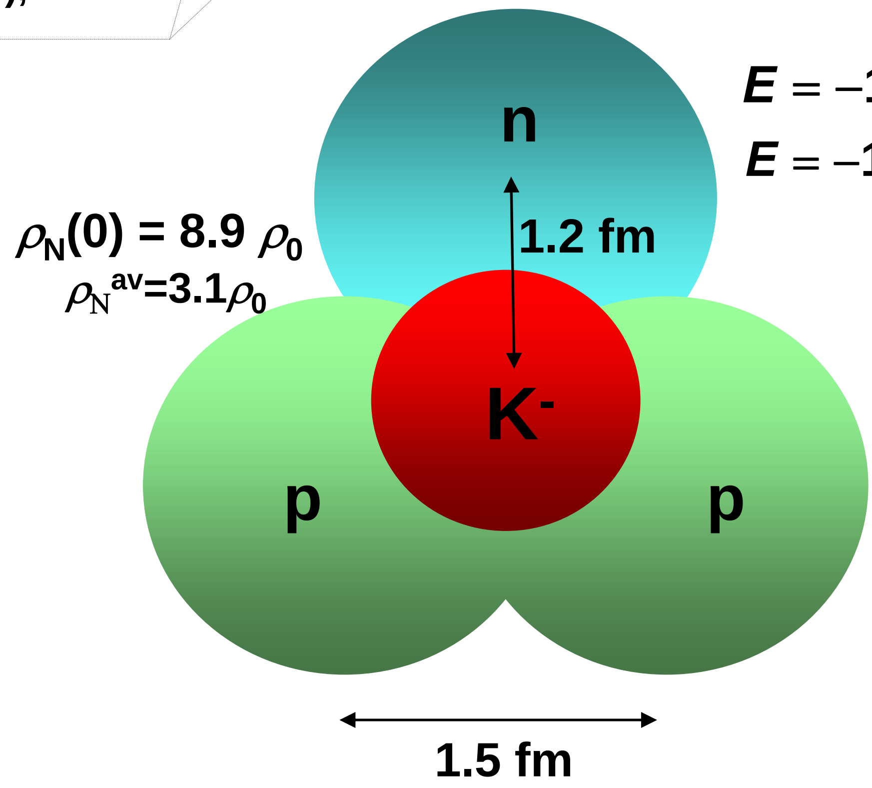
ppnK$^-$

Meson-baryon ?

$E = -111\ \mathrm{MeV},\quad \Gamma = 20\ \mathrm{MeV}$

$E = -169 \pm 6\ \mathrm{MeV},\quad \Gamma \le 25\ \mathrm{MeV}$

Exp.



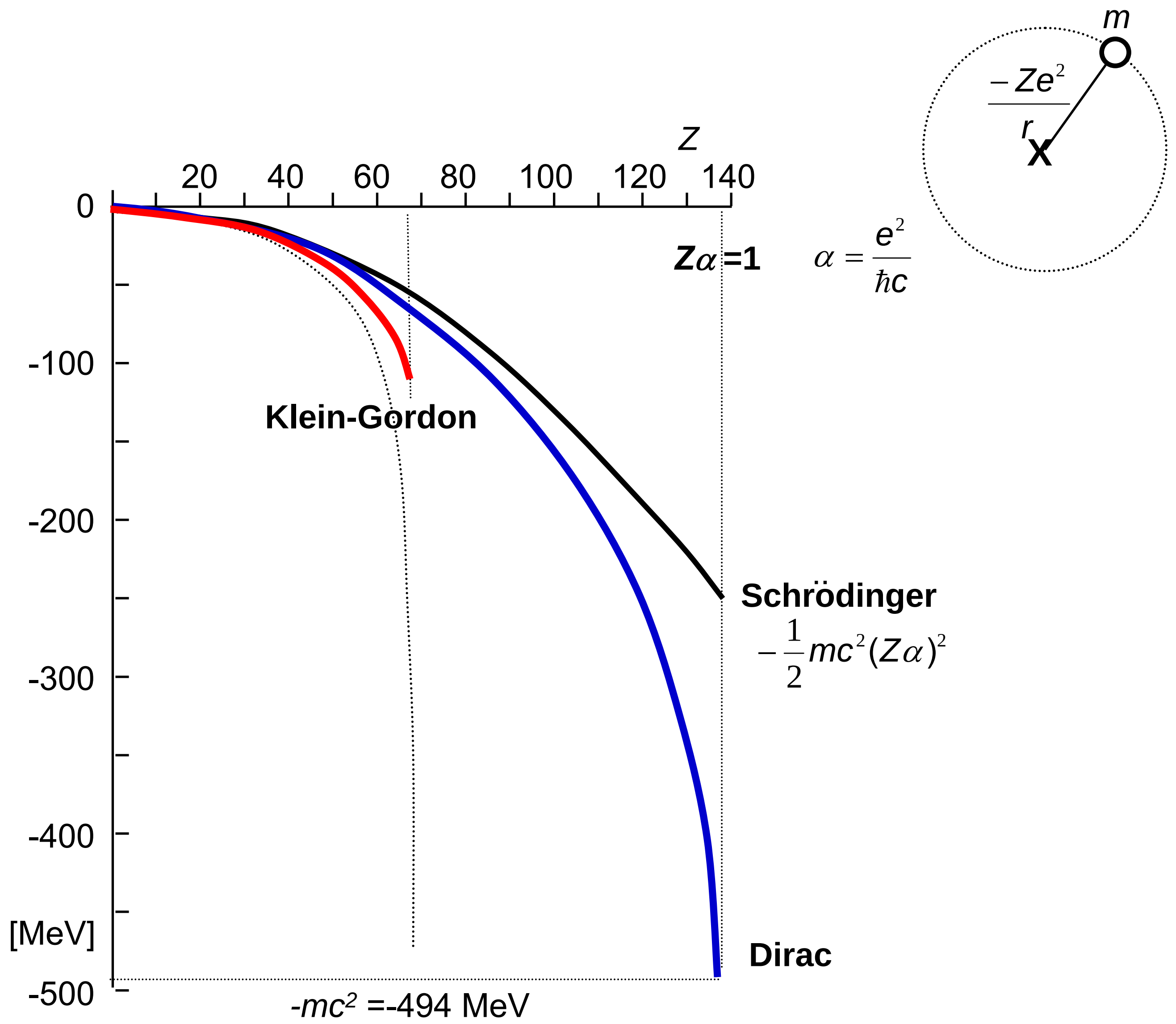
$\Delta B_{th\text{-}ex} \sim 60\ \mathrm{MeV}$

Chiral restoration ?

m_K / f^2

Relativistic effect ?

Atomic systems by point-Coulomb interaction



Klein-Gordon equation

$$(E - V_C - U_v)^2 = \vec{p}^2 c^2 + (m^2 c^4 + 2mc^2 U_S)$$

$$\Downarrow \quad E = \varepsilon + mc^2$$

$$\left\{\varepsilon + \frac{\varepsilon^2}{2mc^2}\right\} = \frac{\vec{p}^2}{2m} + \left\{\left(1 + \frac{\varepsilon}{mc^2}\right)V_C - \frac{V_C{}^2}{2mc^2}\right\} + \underbrace{\left\{U_s + \left(1 + \frac{\varepsilon}{mc^2}\right)U_v - \frac{U_v{}^2}{2mc^2}\right\}}_{\equiv U_{opt}}$$

Atomic state

$$\varepsilon \approx \frac{\vec{p}^2}{2m} + \left\{V_C - \frac{V_C{}^2}{2mc^2}\right\} + U_{opt}$$

$$\left\{-\hbar^2 c^2 \vec{\nabla}^2 - 2mc^2\varepsilon + 2mc^2\left(U_{opt} + V_C\right) - V_C{}^2\right\}\Psi = 0$$

Deeply bound state

$$\left\{-\frac{\hbar^2}{2m}\vec{\nabla}^2 + U_{opt}\right\}\Psi \approx \underbrace{\left\{\varepsilon + \frac{\varepsilon^2}{2mc^2}\right\}}_{\equiv \varepsilon_S}\Psi$$

$$\varepsilon = mc^2\left\{\sqrt{1 + \frac{2\varepsilon_S}{mc^2}} - 1\right\}$$

Relativistic effect

$$\Delta\varepsilon_{RC} \equiv \varepsilon - \varepsilon_S = \frac{\varepsilon^2}{2mc^2}$$

$$\Delta\varepsilon_{RC} = mc^2\sqrt{1+\frac{2\varepsilon_S}{mc^2}} - (mc^2 + \varepsilon_S)$$

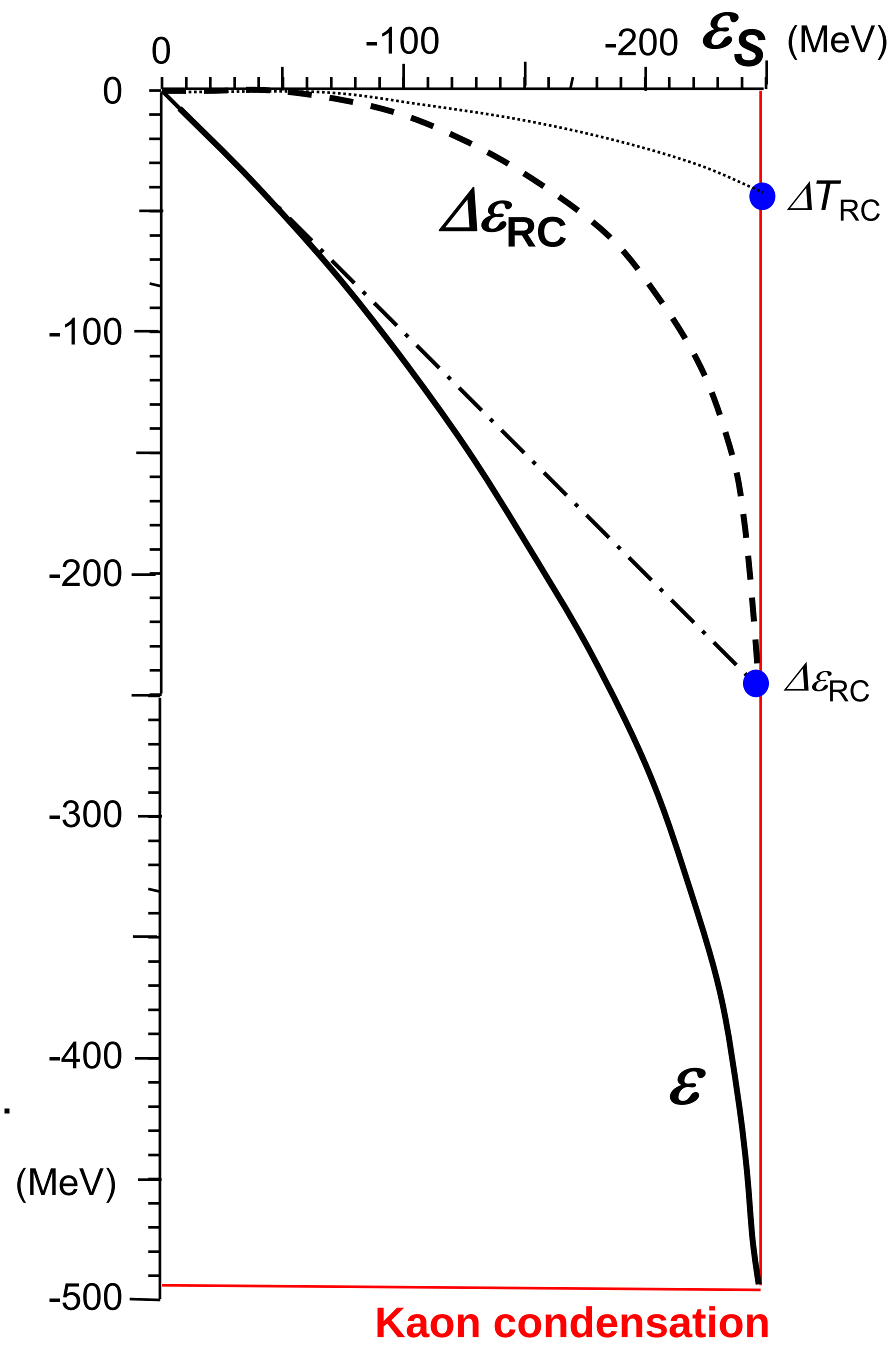
$$\Delta T_{RC} = mc^2\sqrt{1+\frac{2T_S}{mc^2}} - (mc^2 + T_S)$$

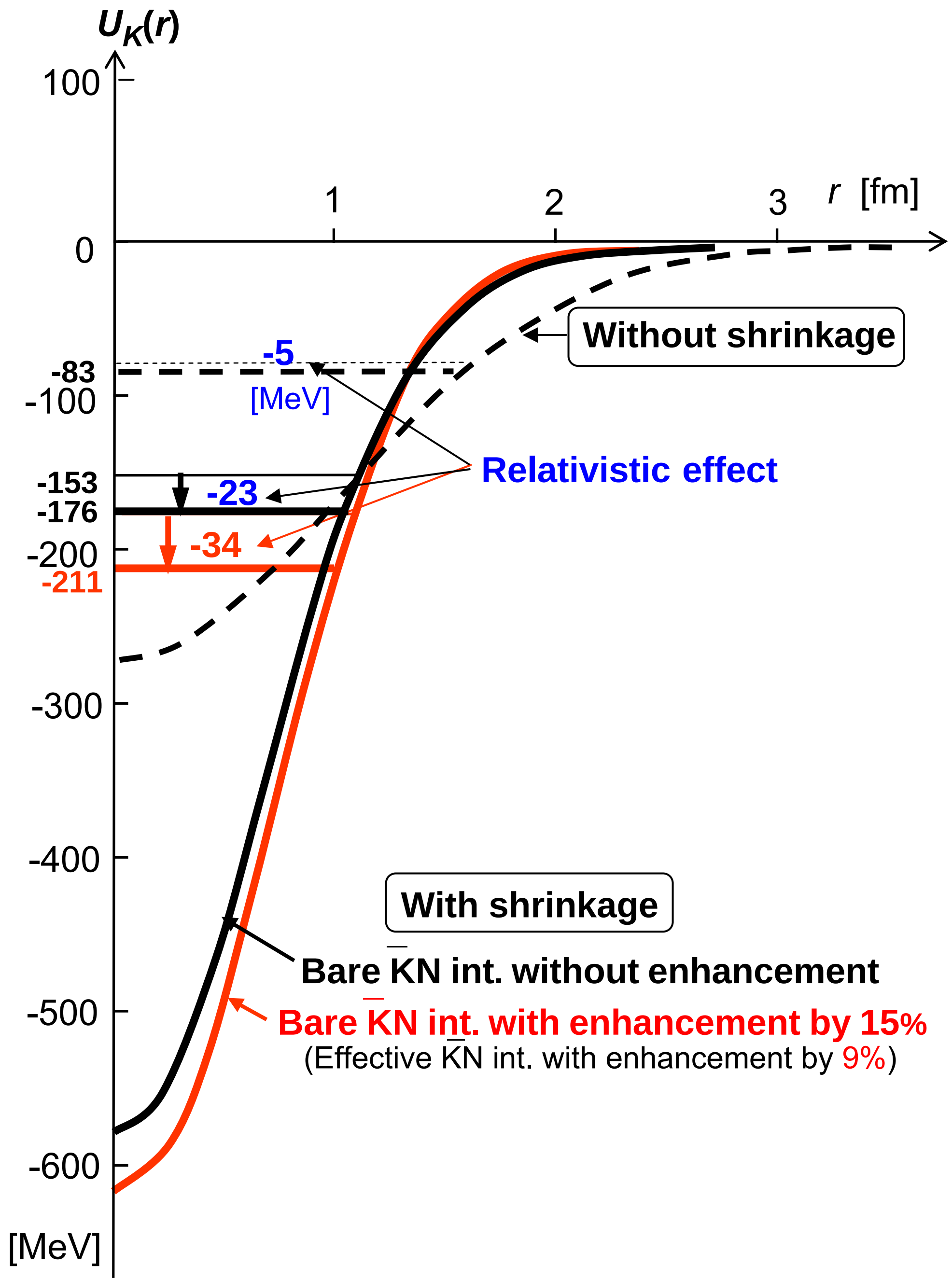
$$= \sqrt{m^2c^4 + \vec{p}^2c^2} - \left(mc^2 + \frac{\vec{p}^2}{2m}\right)$$

$$-\frac{1}{2mc^2}T_S^2 + \frac{1}{2m^2c^4}T_S^3 - \frac{5}{8m^3c^6}T_S^4 + \frac{7}{8m^4c^8}T_S^5 + ..$$

$$-\frac{1}{2mc^2}\varepsilon_S^2 + \frac{1}{2m^2c^4}\varepsilon_S^3 - \frac{5}{8m^3c^6}\varepsilon_S^4 + \frac{7}{8m^4c^8}\varepsilon_S^5 + ..$$

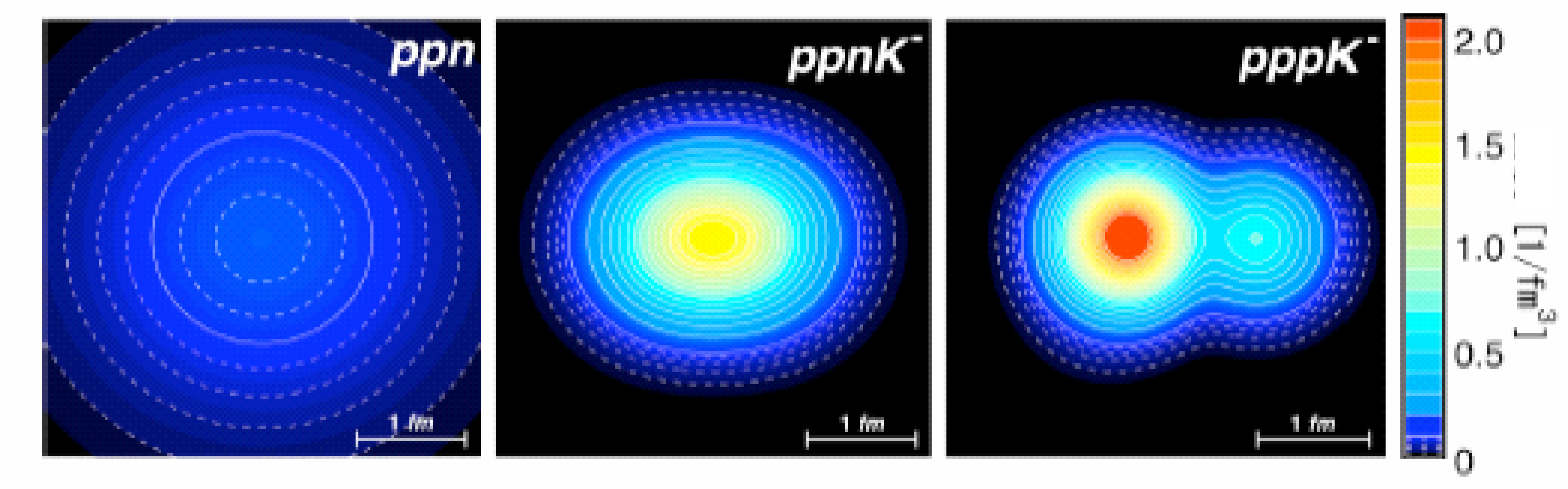
$T_S \approx -\varepsilon_S$ (Virial)

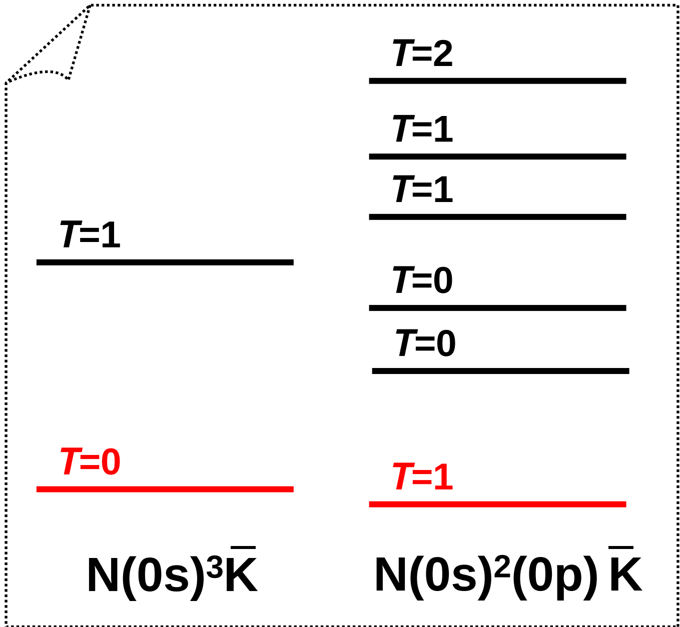




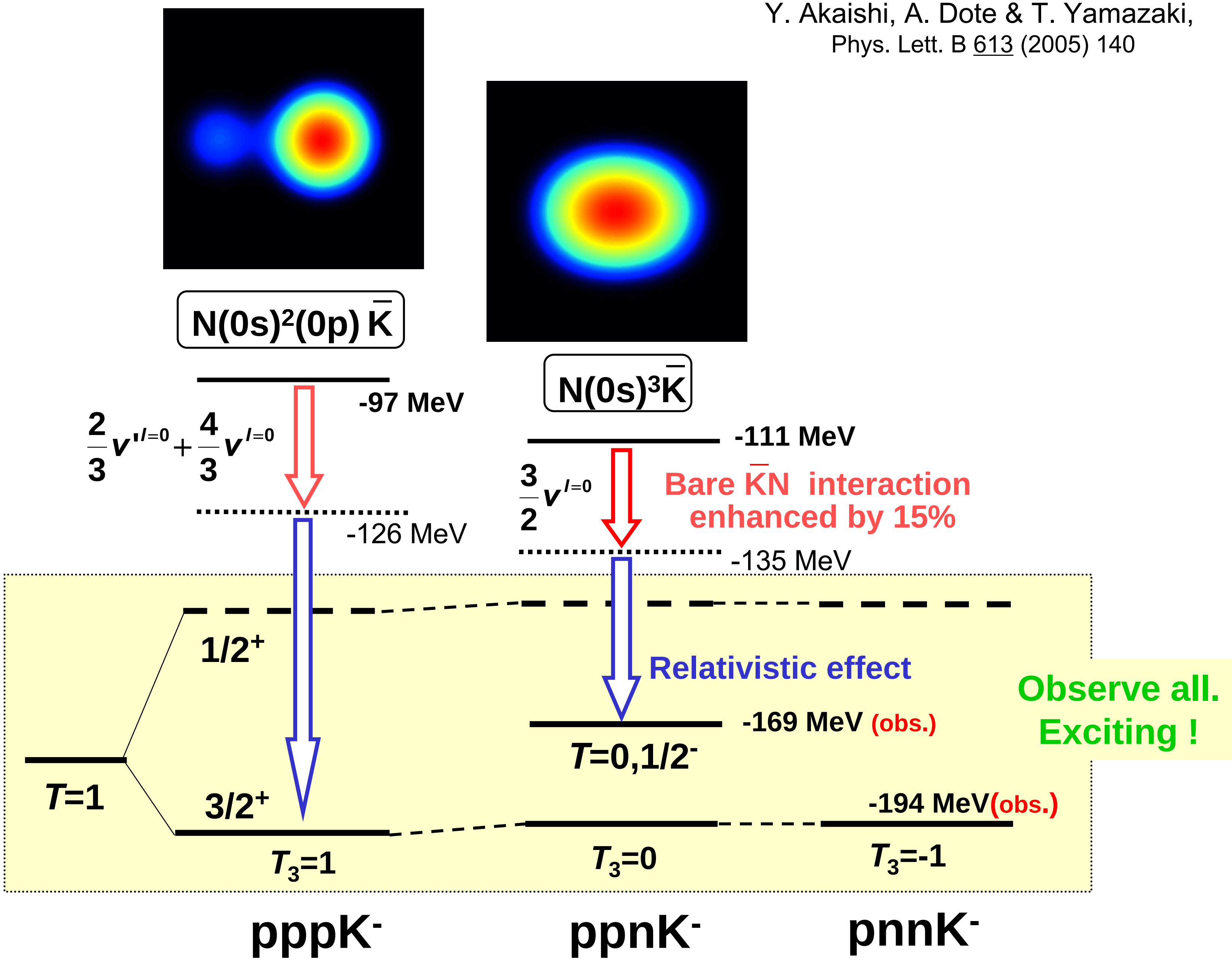
$U_K(r)$
100
0
-83
-100
-153
-176
-200
-211
-300
-400
-500
-600
[MeV]
1
2
3
r [fm]
-5
[MeV]
Without shrinkage
Relativistic effect
-23
-34
With shrinkage
Bare $\bar{K}N$ int. without enhancement
Bare $\bar{K}N$ int. with enhancement by 15%
(Effective $\bar{K}N$ int. with enhancement by 9%)

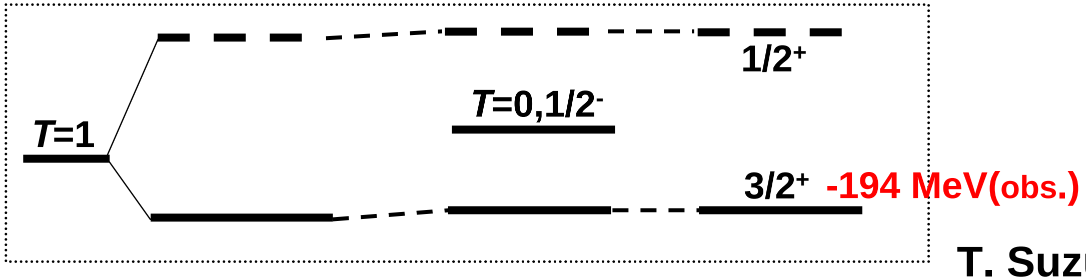
A. Dote et al.,
Phys. Rev. C70 (2004) 044313





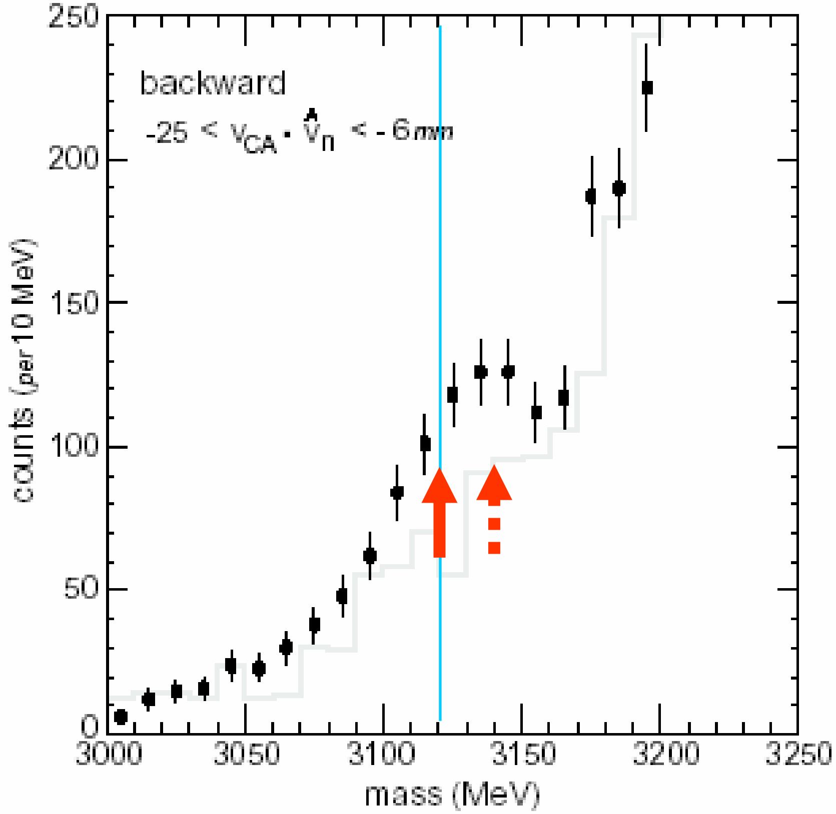
Y. Akaishi, A. Dote & T. Yamazaki,
Phys. Lett. B 613 (2005) 140





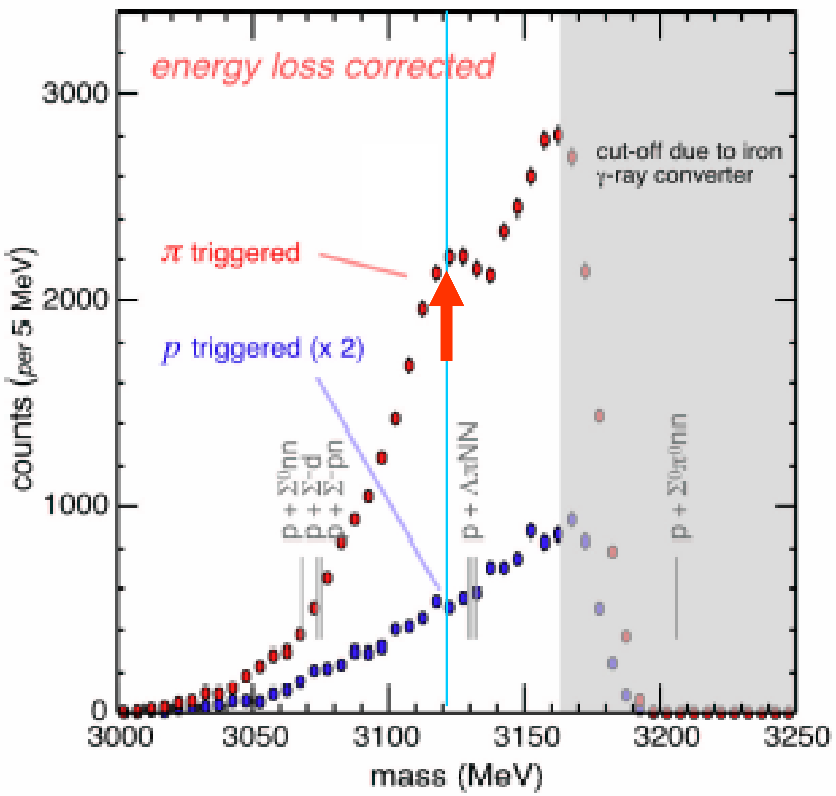
T. Suzuki et al.,
Phys. Lett. B597 (2004) 263

^{4}He(stopped K$^-$, n)



S^0(3115)?
S$^+$(3140)?

^{4}He(stopped K$^-$, p)

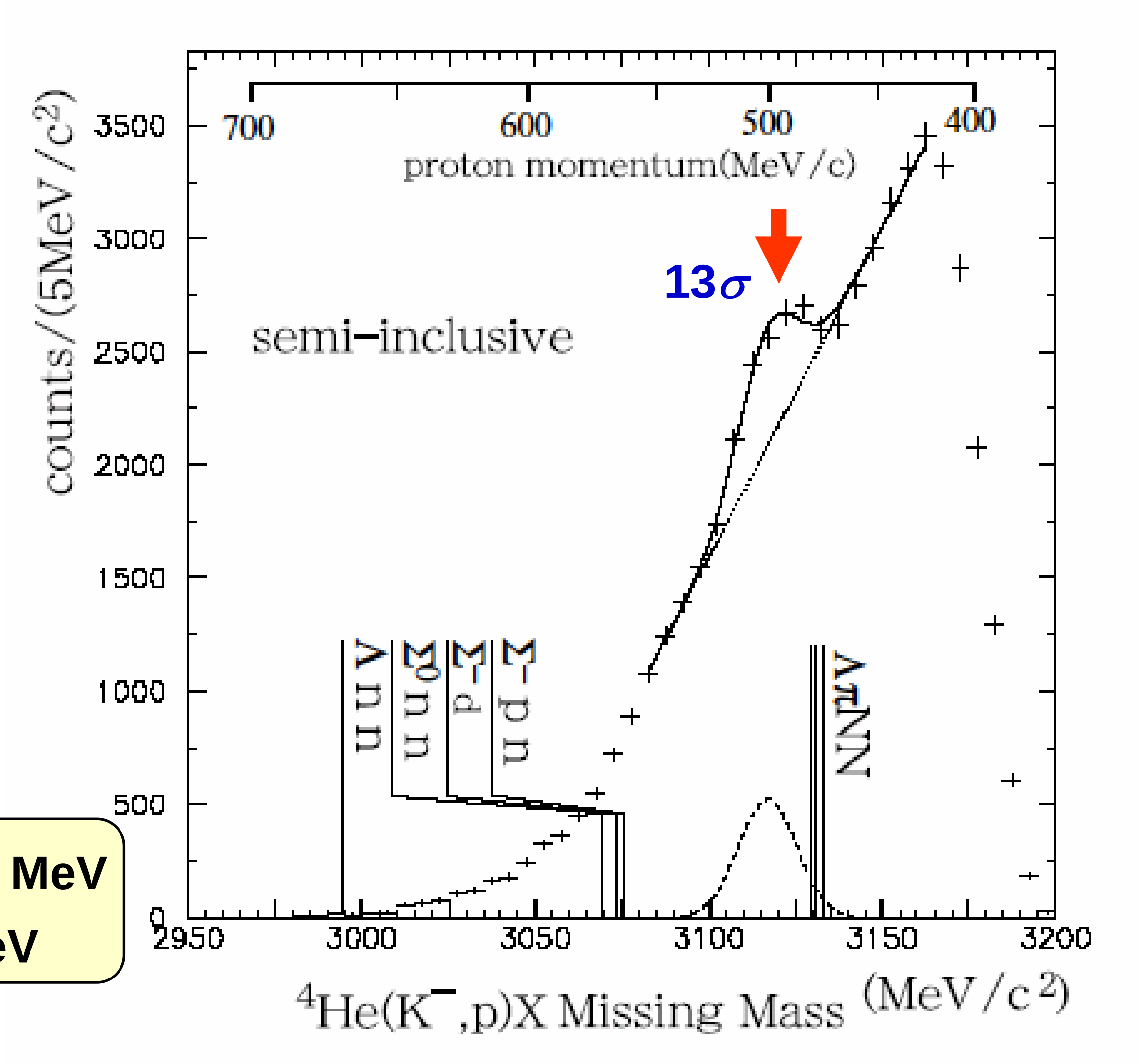


S^0(3115)

Discovery of $S^0(3115)$

in ^4He(stopped K^-,p)K^-pnn

Phys. Lett. B597 (2004) 263



$E = -193^{+1.5}_{-4.4}$ **MeV**

$\Gamma \leq 21$ **MeV**

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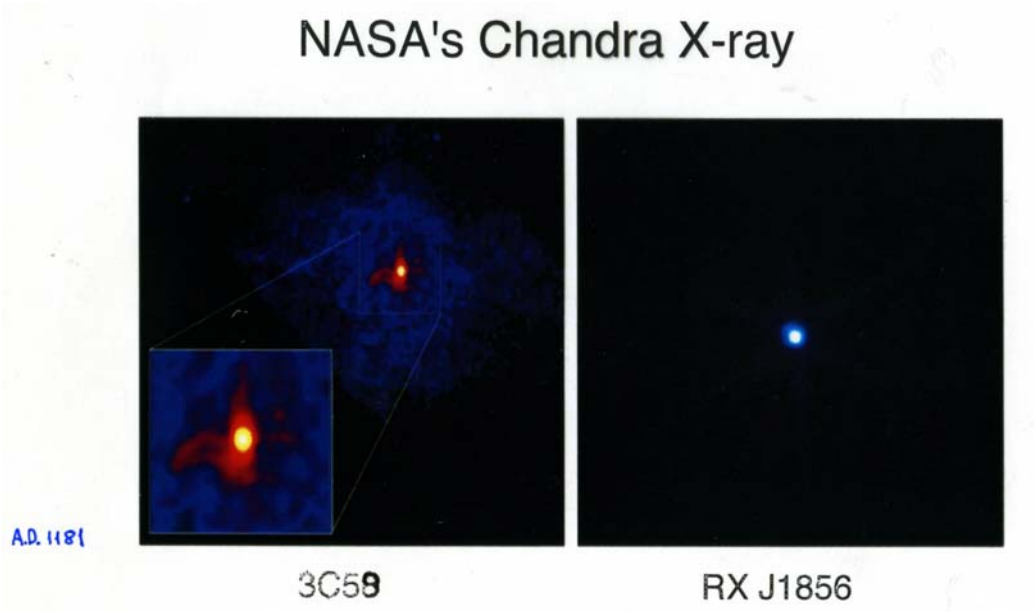
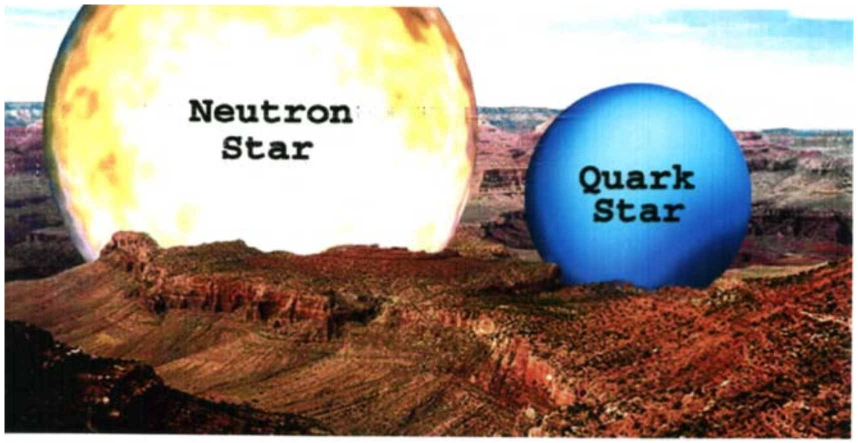
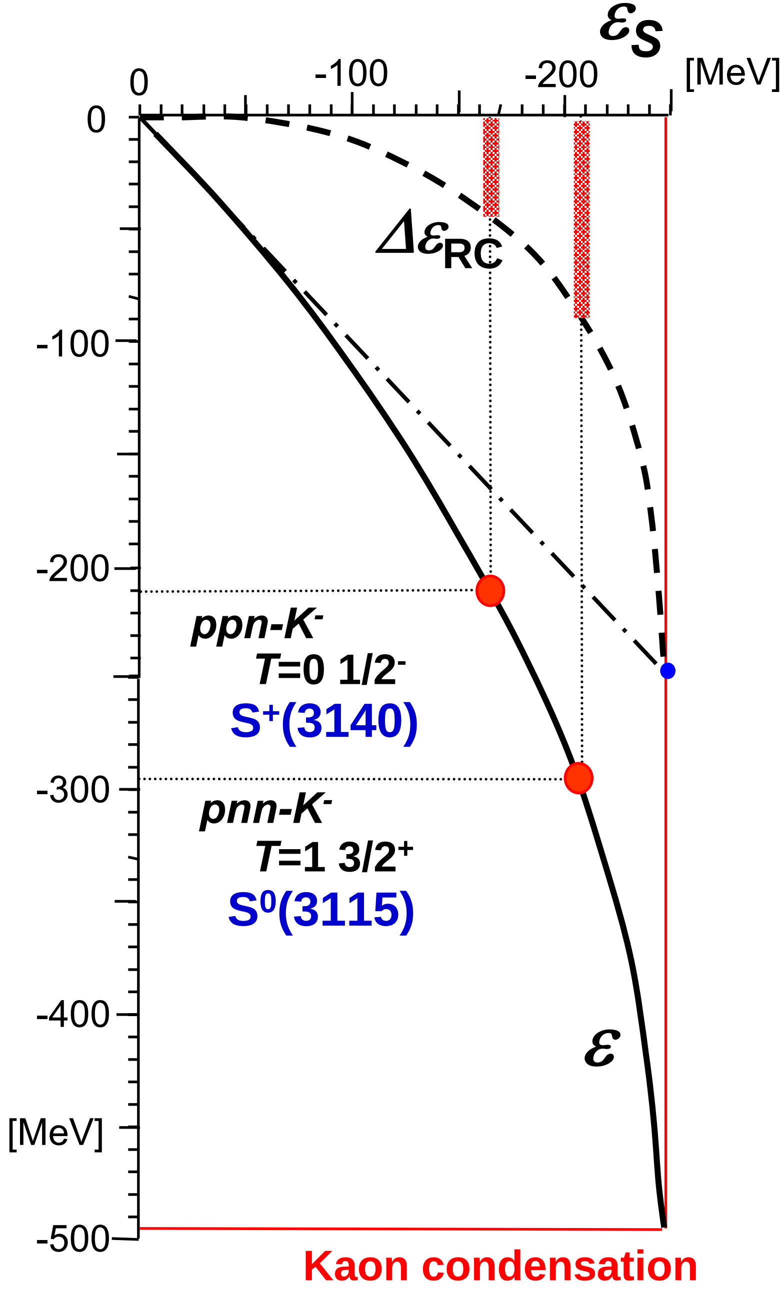


NASA's Chandra X-ray
A.D. 1181
3C58
RX J1856



Neutron Star
Quark Star



ε_S
0
-100
-200
[MeV]
0
-100
-200
-300
-400
[MeV]
-500
$\Delta\varepsilon_{RC}$
ppn-K⁻
T=0 1/2⁻
S⁺(3140)
pnn-K⁻
T=1 3/2⁺
S⁰(3115)
ε
Kaon condensation

@high densities

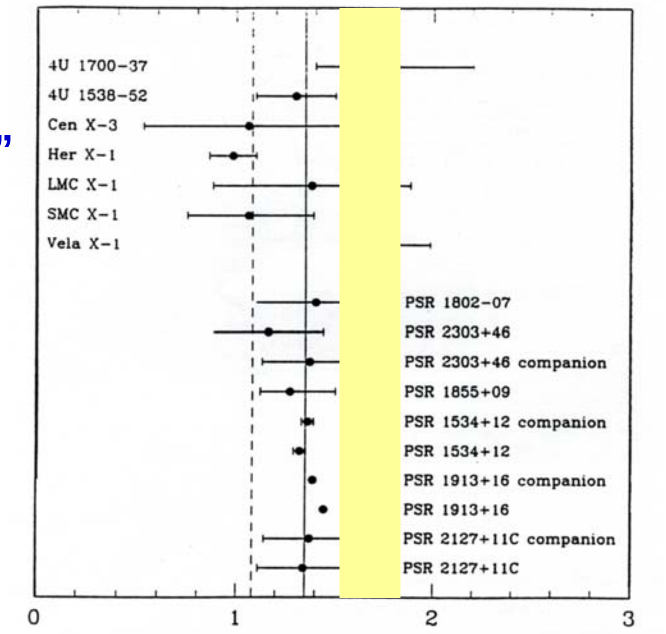
$e^- + p + n \longrightarrow \nu + n + n$ "Neutron star"

~$3\rho_0$

$\nu + K^- + p + n$

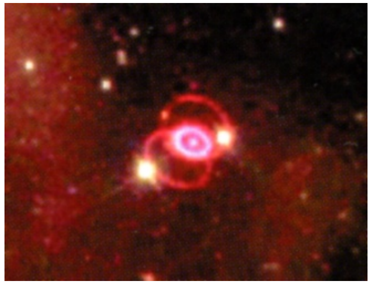
Strong attraction

"Nucleon star"
with kaon condensation



"Low-mass black hole"
1.5~1.8 $M_\odot$

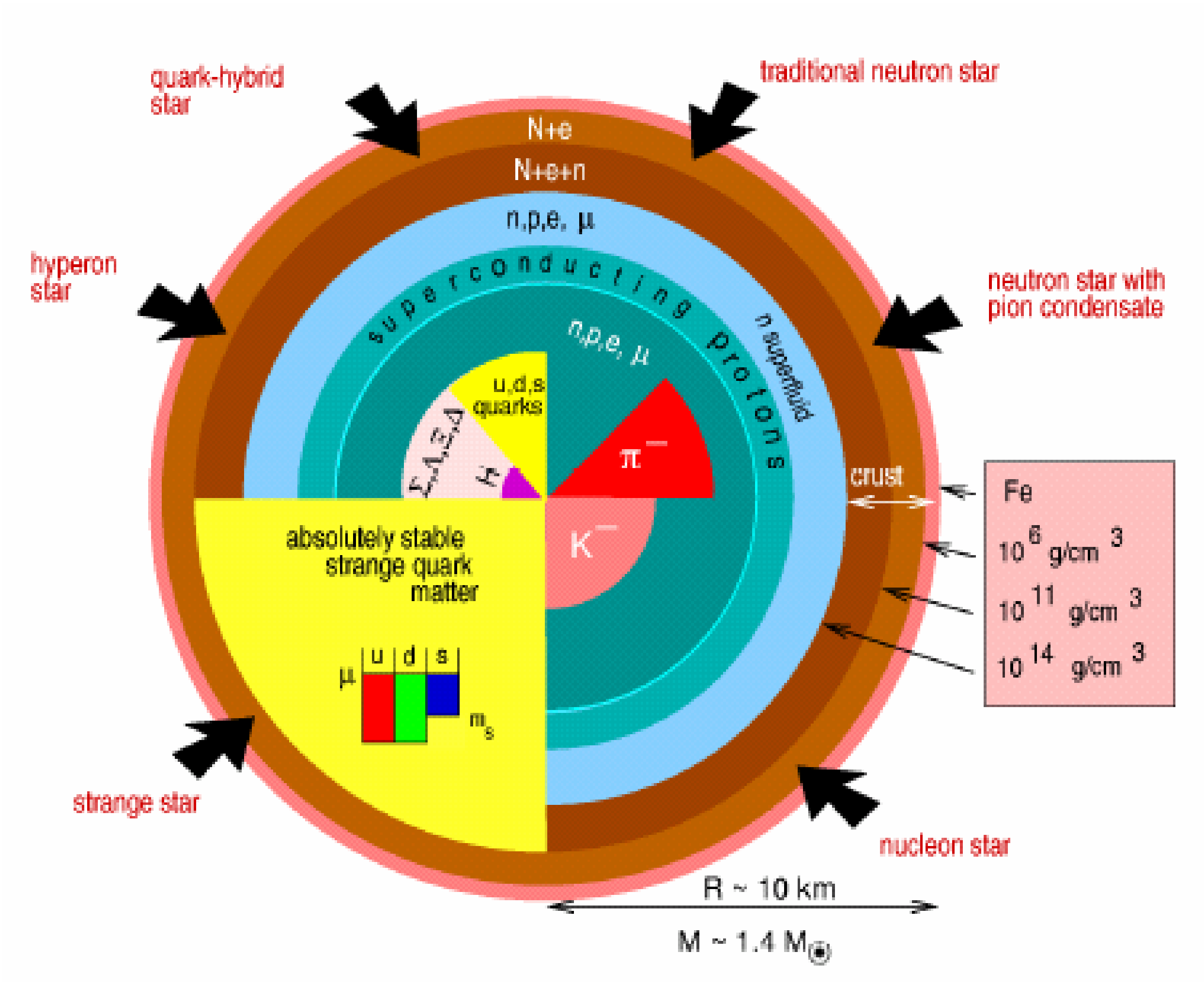
SN1987A ?



G.E. Brown, Nucl. Phys. A574 (1994) 217c.

G.E. Brown & H.A. Bethe, Astrophys. J. 423 (1994) 659.

G.E. Brown & M. Rho, Phys. Rev. Lett. 66 (1991) 2720,
"BR scaling"
C.H. Lee, G.E. Brown, D.P. Min & M. Rho, Nucl. Phys. A585 (1995) 401


quark-hybrid star
traditional neutron star
hyperon star
neutron star with pion condensate
strange star
nucleon star
N+e
N+e+n
n,p,e, μ
superconducting protons
n superfluid
n,p,e, μ
u,d,s quarks
Σ,Λ,Ξ,Δ
H
π⁻
K⁻
absolutely stable strange quark matter
μ
u
d
s
m_s
crust
Fe
10^6 g/cm^3
10^11 g/cm^3
10^14 g/cm^3
R ~ 10 km
M ~ 1.4 M_⊙

X. ????

Nona-quark states

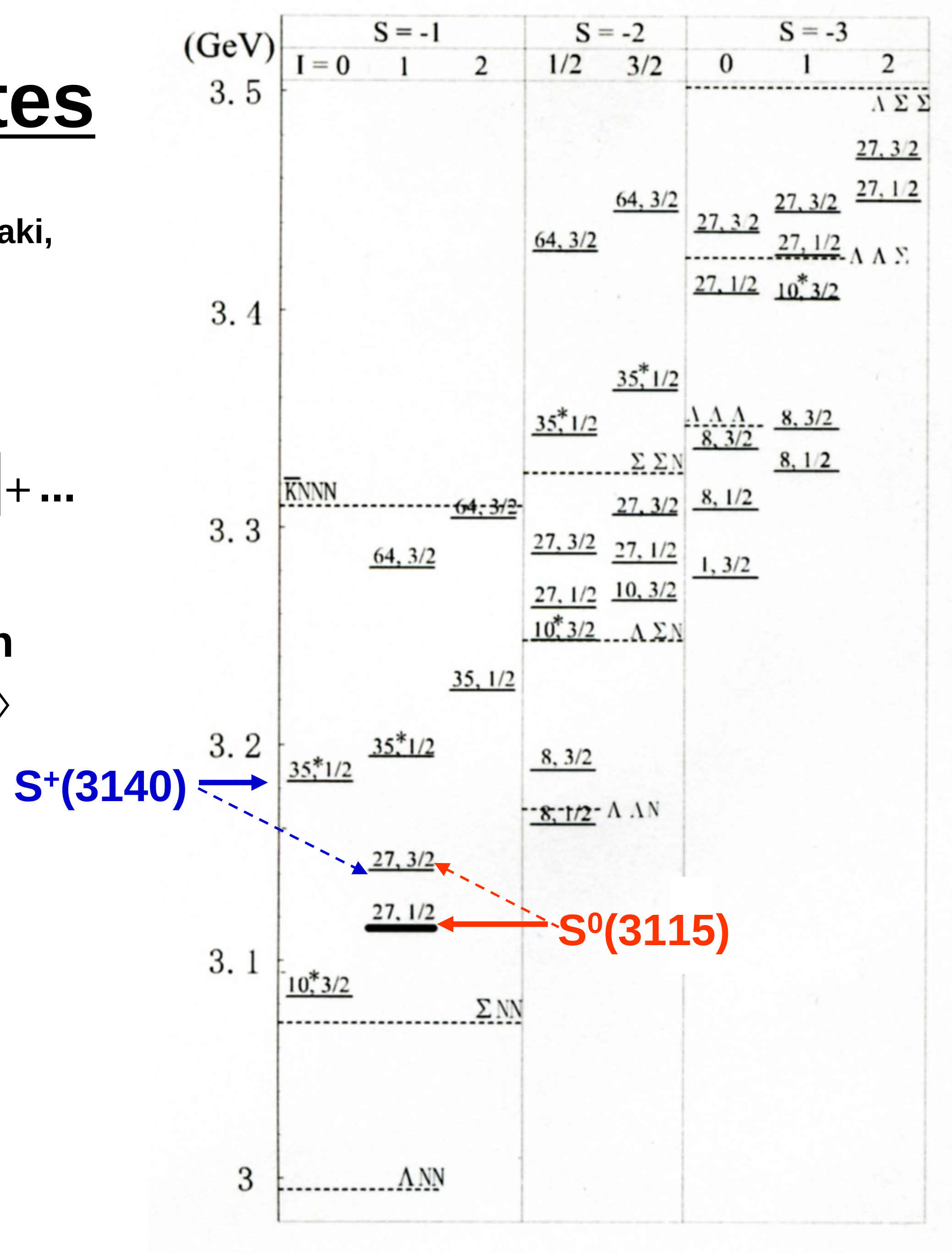
Y. Maezawa, T. Hatsuda & S. Sasaki,
Hep-ph/0412025

$$H = a_0 + a_2 Y + a_1\left[C_3(F) + \tfrac{1}{3}\vec{J}^2\right] + \ldots$$

Color-magnetic interaction

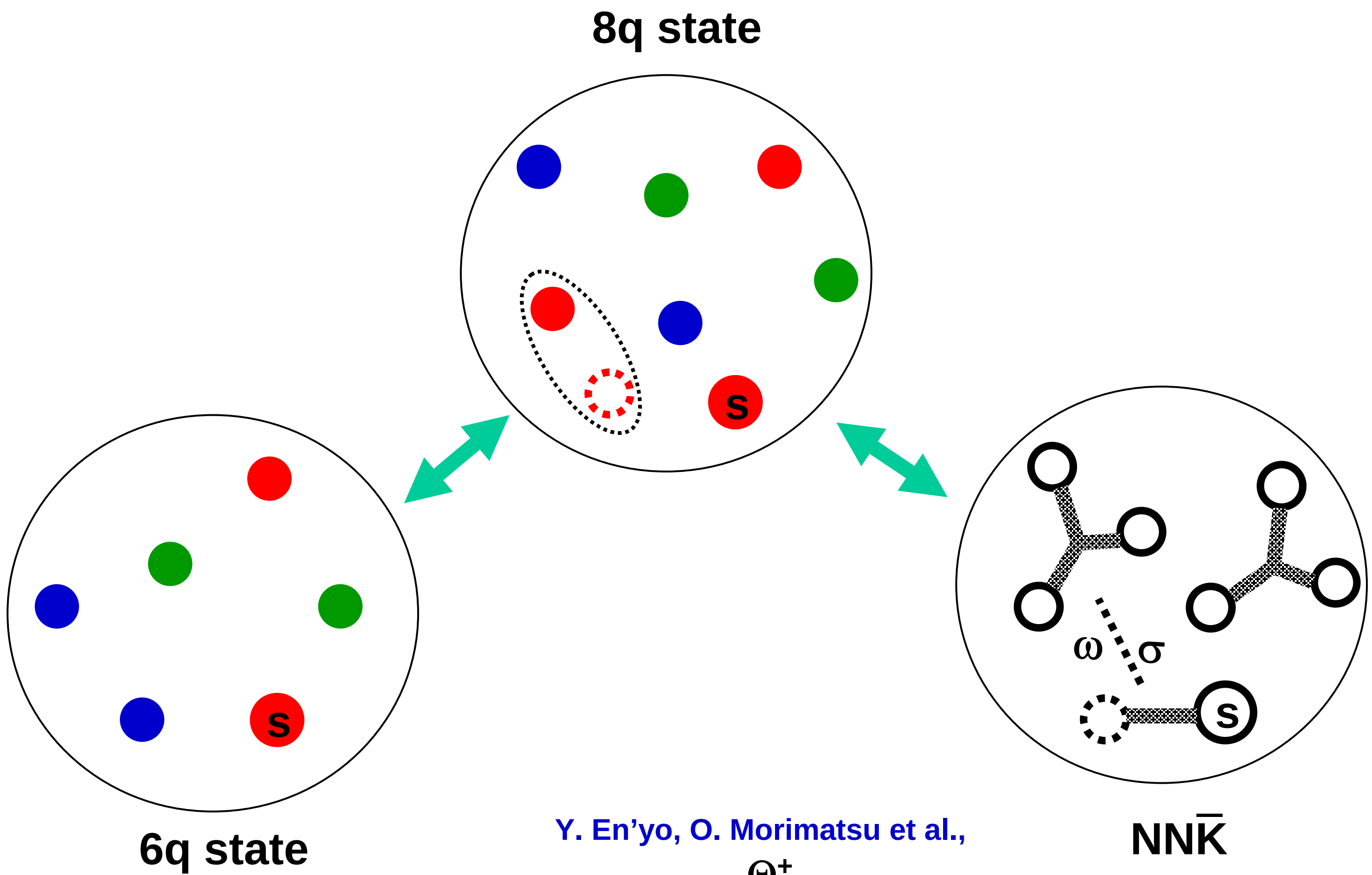
$$\alpha_s^{\mathrm{eff}} = 2.0 \rightarrow 1.0 \;\Rightarrow$$

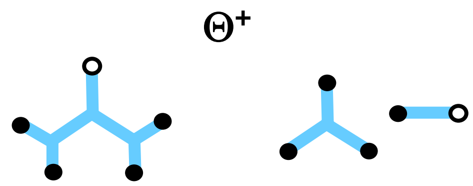
MIT bag: R_9=1.3 fm



$M_{\Delta} - M_{N} \approx 300\ \mathrm{MeV}/c^2$

Phase transition of ppK$^-$

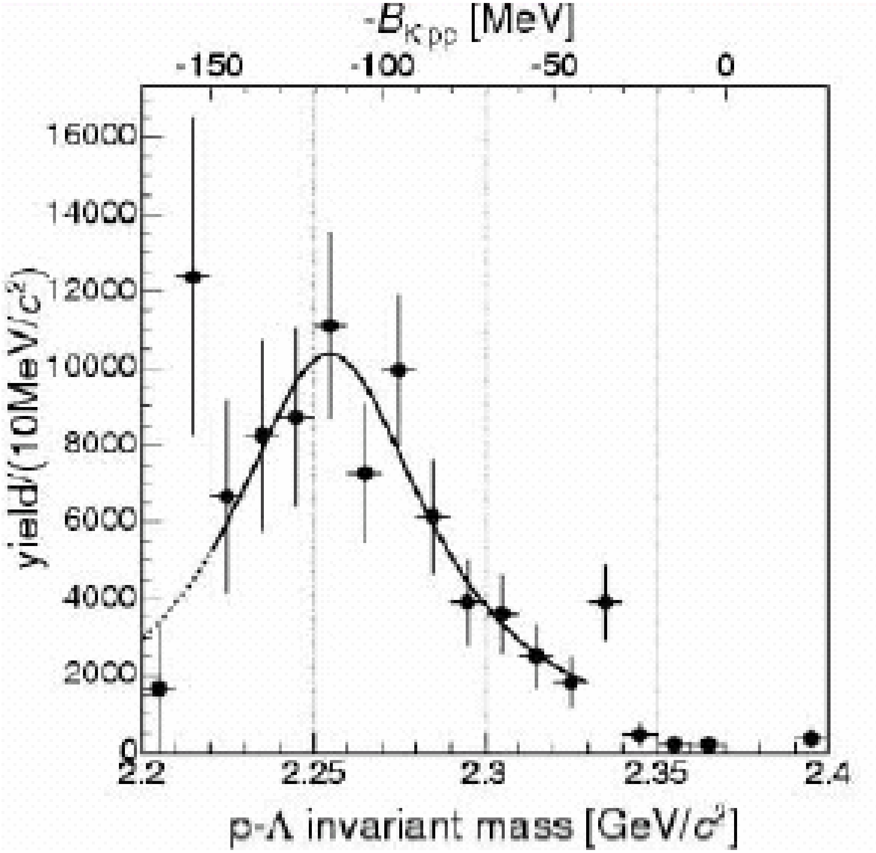




Challenging problem !

Observation of ppK$^-$

M. Agnello, H. Fujioka et al., Phys. Rev. Lett. 94 (2005) 212303



FINUDA@DAΦNE

$$\boldsymbol{B} = 115\,^{+6+3}_{-5-4}\ \text{MeV}$$

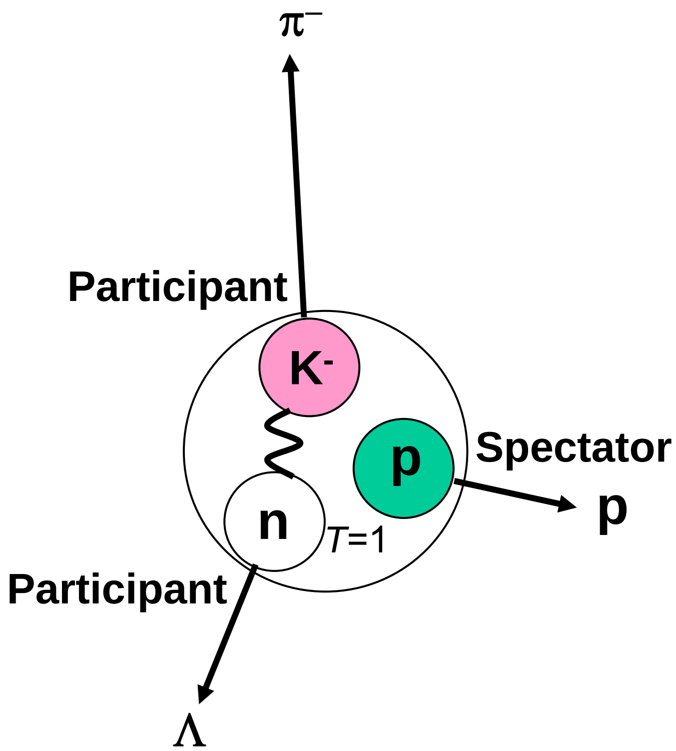
$$\Gamma = 67\,^{+14+2}_{-11-3}\ \text{MeV}$$

15% enhanced $\bar{K}N$ interaction

B **= 48 MeV → 86 MeV**

Invariant masses of pnK$^-$ decay

P. Kienle, Y. Akaishi & T. Yamazaki



All are detectable !

Invariant mass

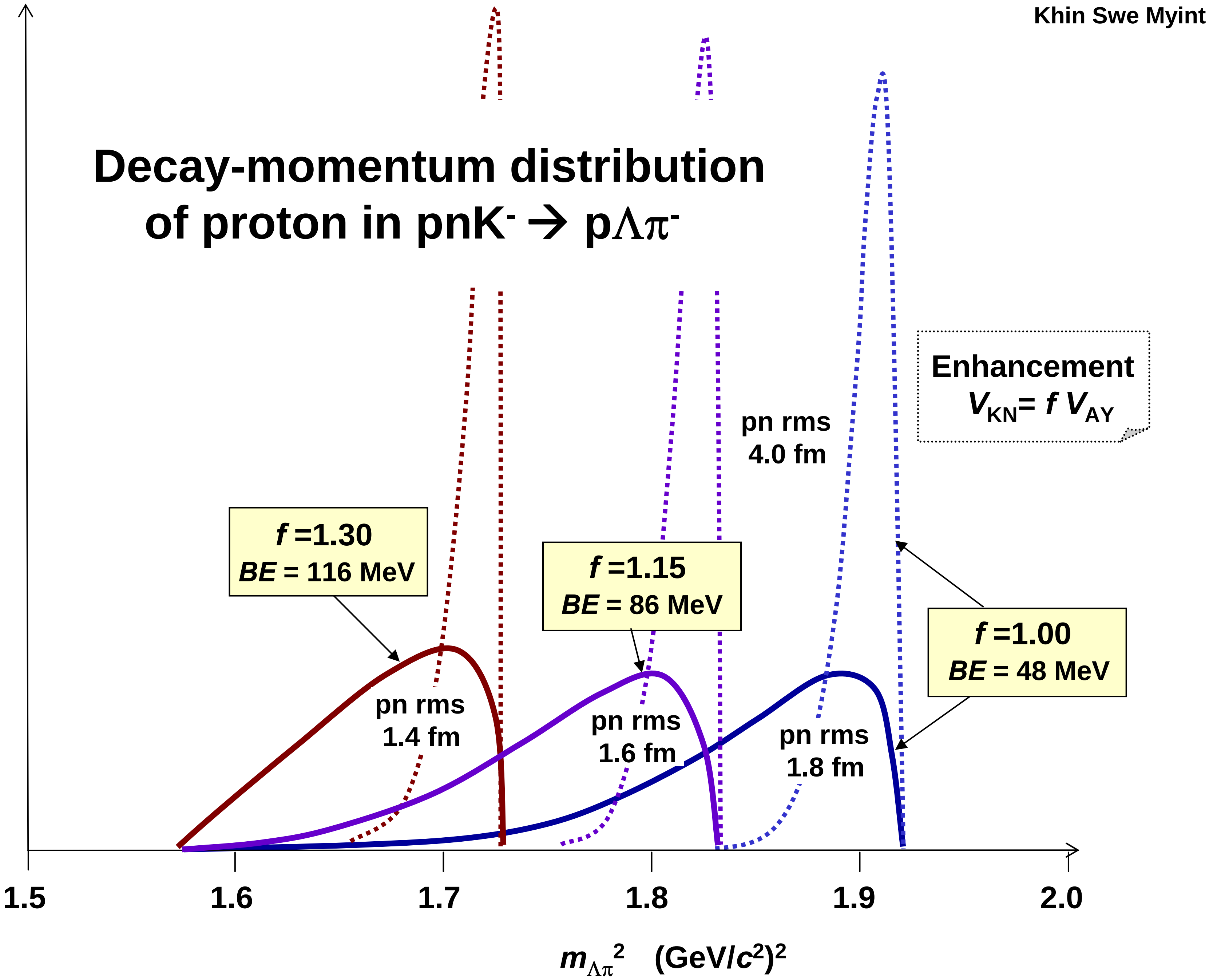
$$M_{pnK}^2=(E_p+E_\pi+E_\Lambda)^2-(\boldsymbol{p}_p+\boldsymbol{p}_\pi+\boldsymbol{p}_\Lambda)^2$$

Partial invariant mass

Dalitz's variable

$$m_{\Lambda\pi}^2=(E_\pi+E_\Lambda)^2-(\boldsymbol{p}_\pi+\boldsymbol{p}_\Lambda)^2 \quad \text{: Any frame}$$

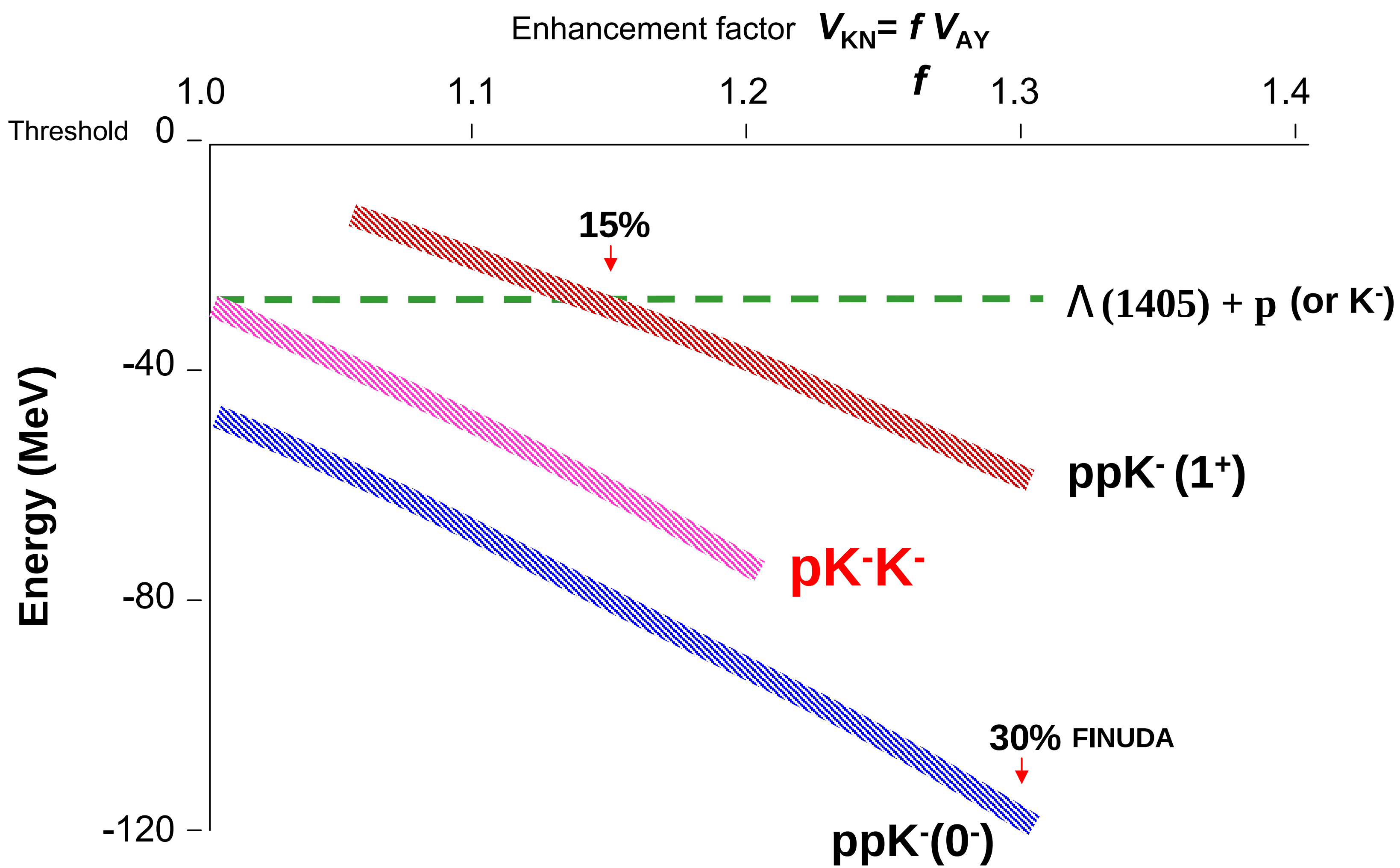
$$=(M_{pnK}-E_p)^2-\boldsymbol{p}_p^2 \quad \text{: Rest frame of pnK}^-$$



Khin Swe Myint
Decay-momentum distribution
of proton in pnK⁻ → pΛπ⁻
Enhancement
V_KN = f V_AY
pn rms
4.0 fm
f =1.30
BE = 116 MeV
f =1.15
BE = 86 MeV
f =1.00
BE = 48 MeV
pn rms
1.4 fm
pn rms
1.6 fm
pn rms
1.8 fm
1.5
1.6
1.7
1.8
1.9
2.0
m_Λπ^2 (GeV/c^2)^2

Energy of three-body kaonic nuclei

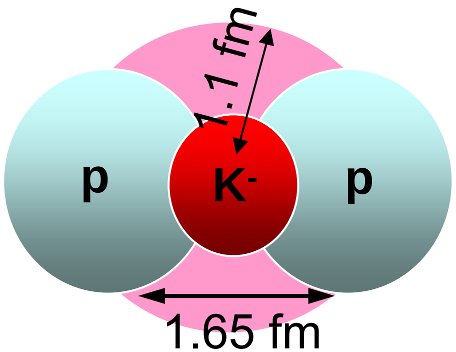
Khin Swe Myint

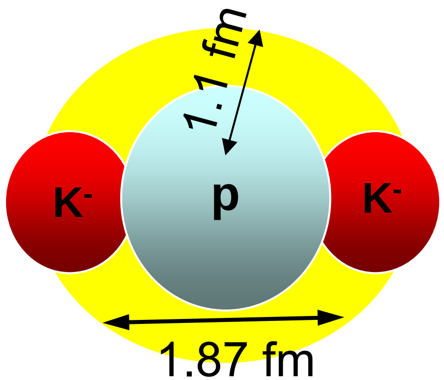


ppK^-

pK^-K^-

15% enhancement





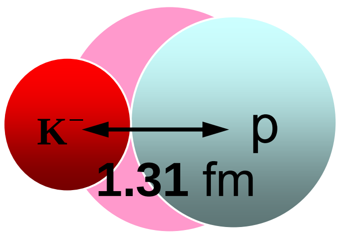
rms d (fm)

p-p = 1.65

K^--p = 1.37

K^--(pp) = 1.10

⇦



⇨

rms d (fm)

K^-- K^- = 1.87

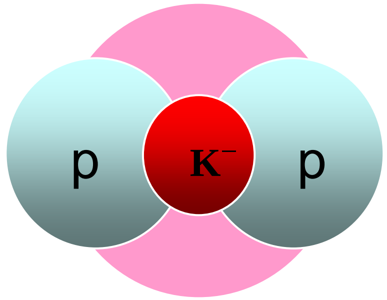
K^--p = 1.42

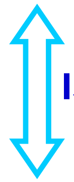
p-(K^-K^-) = 1.10

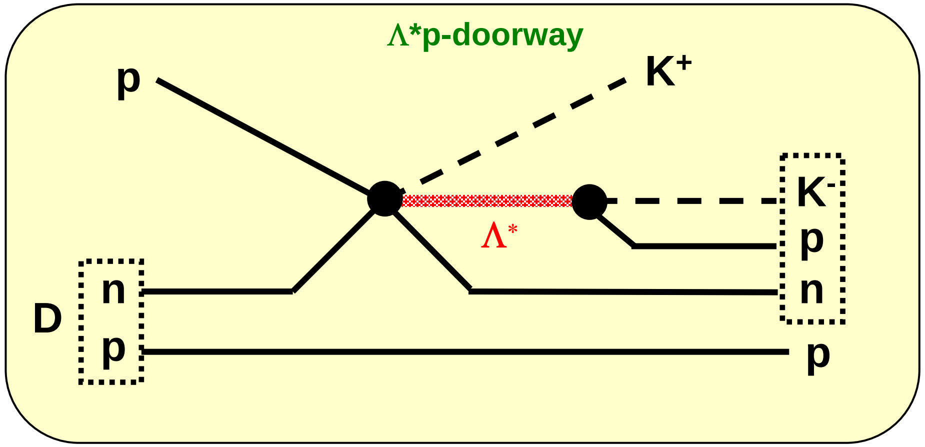
Λ(1405)

Λ(1405)-doorway process

T. Yamazaki & Y. Akaishi, Phys. Lett. B535 (2002) 70.





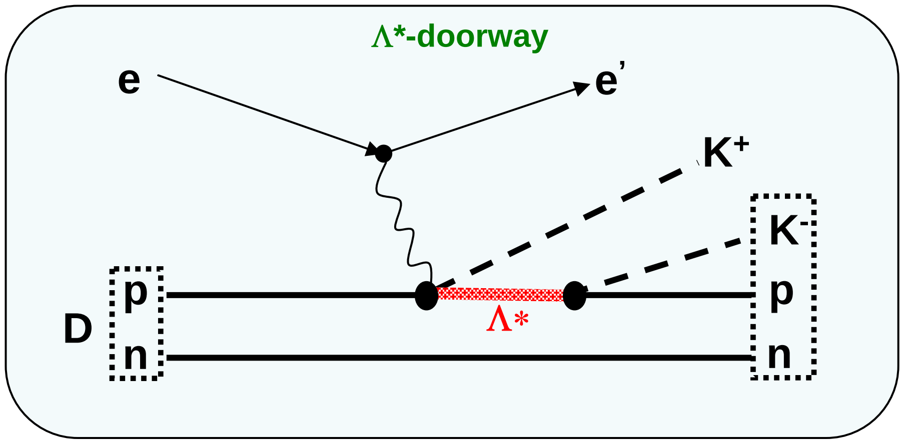


T=1

D(p,p'K⁺)pnK⁻

(p,K⁺) S⁺(3140)

Missing mass spectroscopy



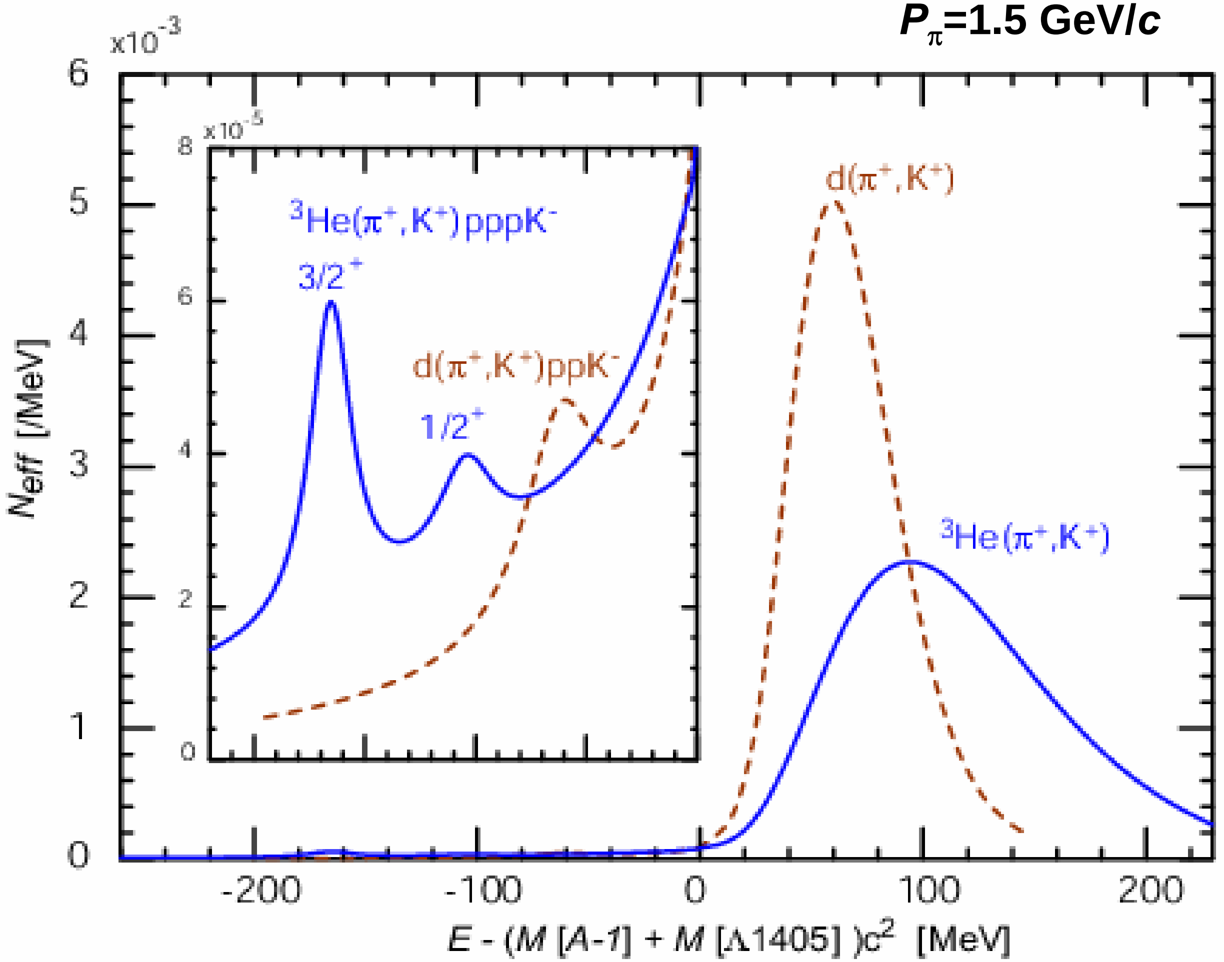
T=1

D(e,e'K⁺)pnK⁻

(γ,K⁺)

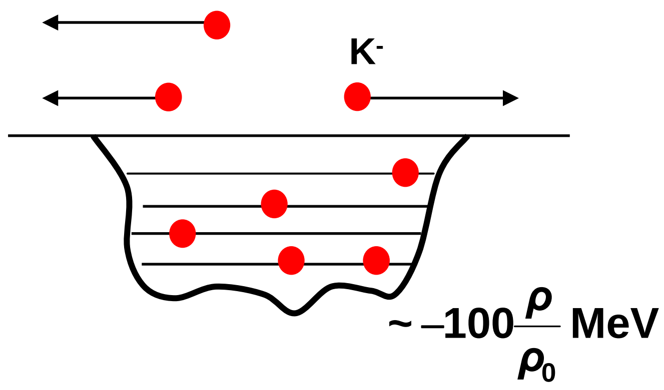
Green's function method
O. Morimatsu & K. Yazaki, Nucl. Phys. A435 (1985) 727

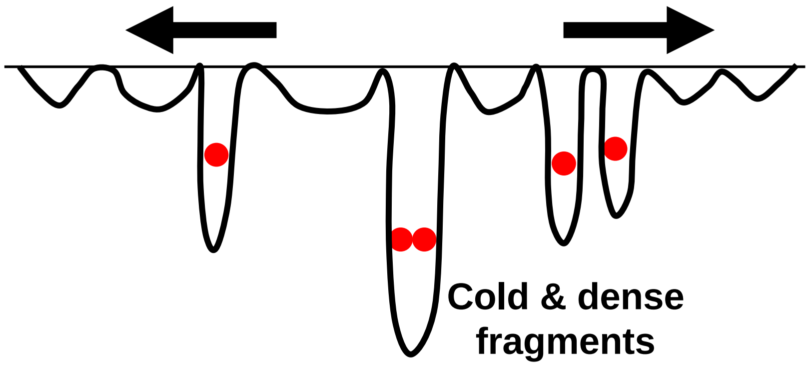
Spectra from (π^+,K$^+$) reaction

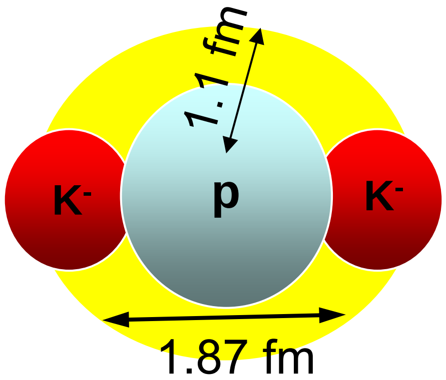


Heavy-ion reaction ~10*A* GeV

High-density environment provided by HI fireball







Invariant mass spectroscopy

$ppnK^- \rightarrow \Lambda + d$

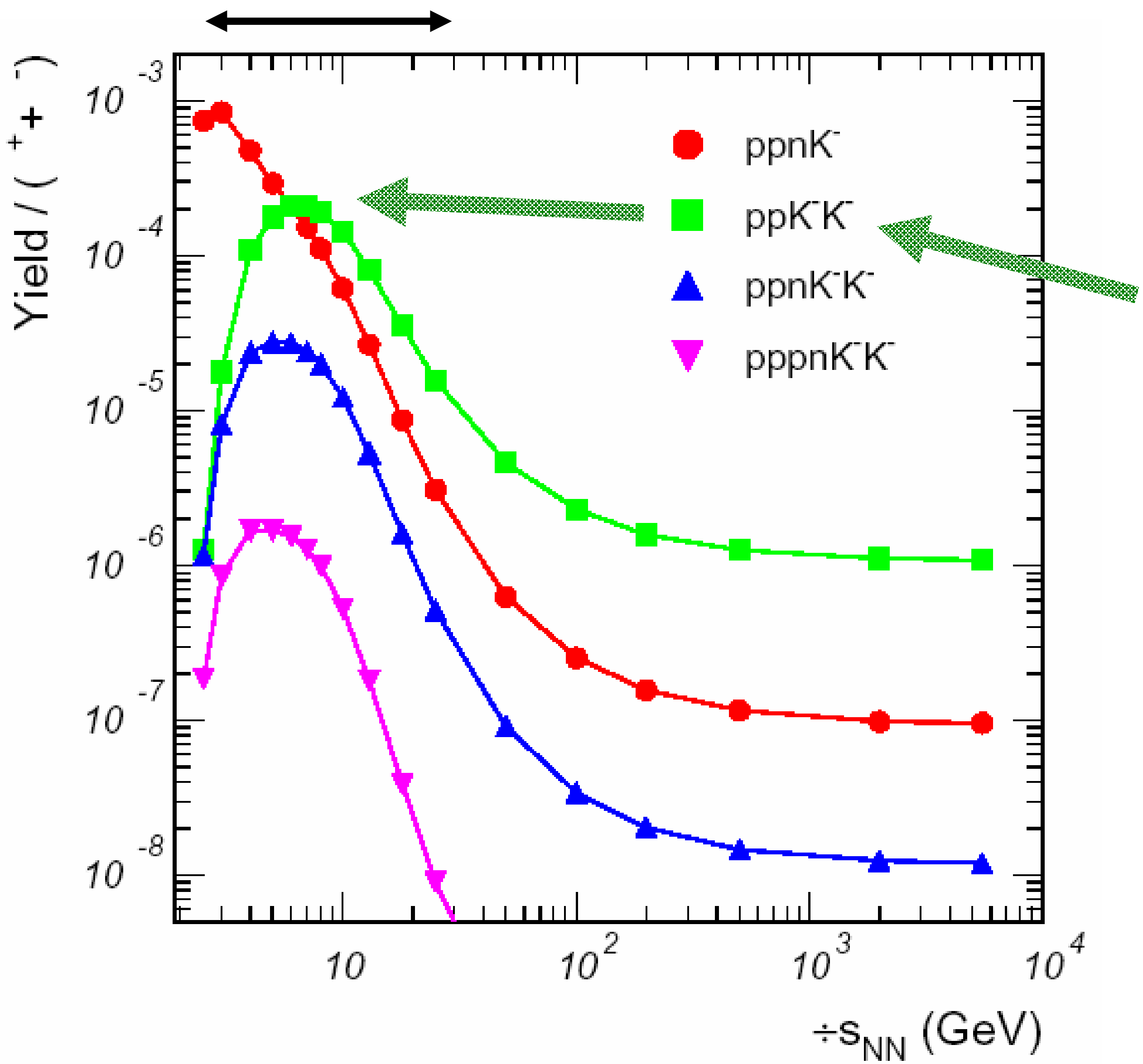
$ppK^- \rightarrow \Lambda + p$

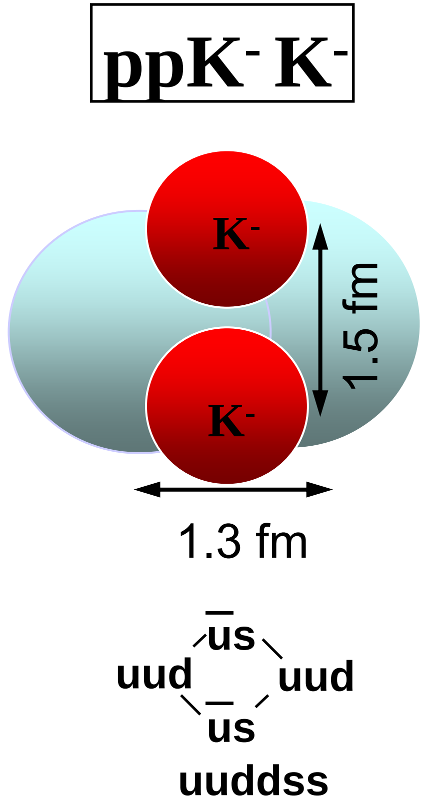
$pK^-K^- \rightarrow \Lambda + K^-$

N. Herrmann , T. Yamazaki

A. Andronic and P. Braun-Munzinger, priv.comm., 2003

GSI SIS100/300





Excited H*
di-baryon?

Remarks

Nuclear $\bar{K}$ bound state

Mini strange matter

$\bar{K}$ plays a role of "contractor".

A new means to investigate
hadron dynamics in dense&cold matter

Production-/Decay-channel spectroscopies

Missing-mass/Invariant-mass

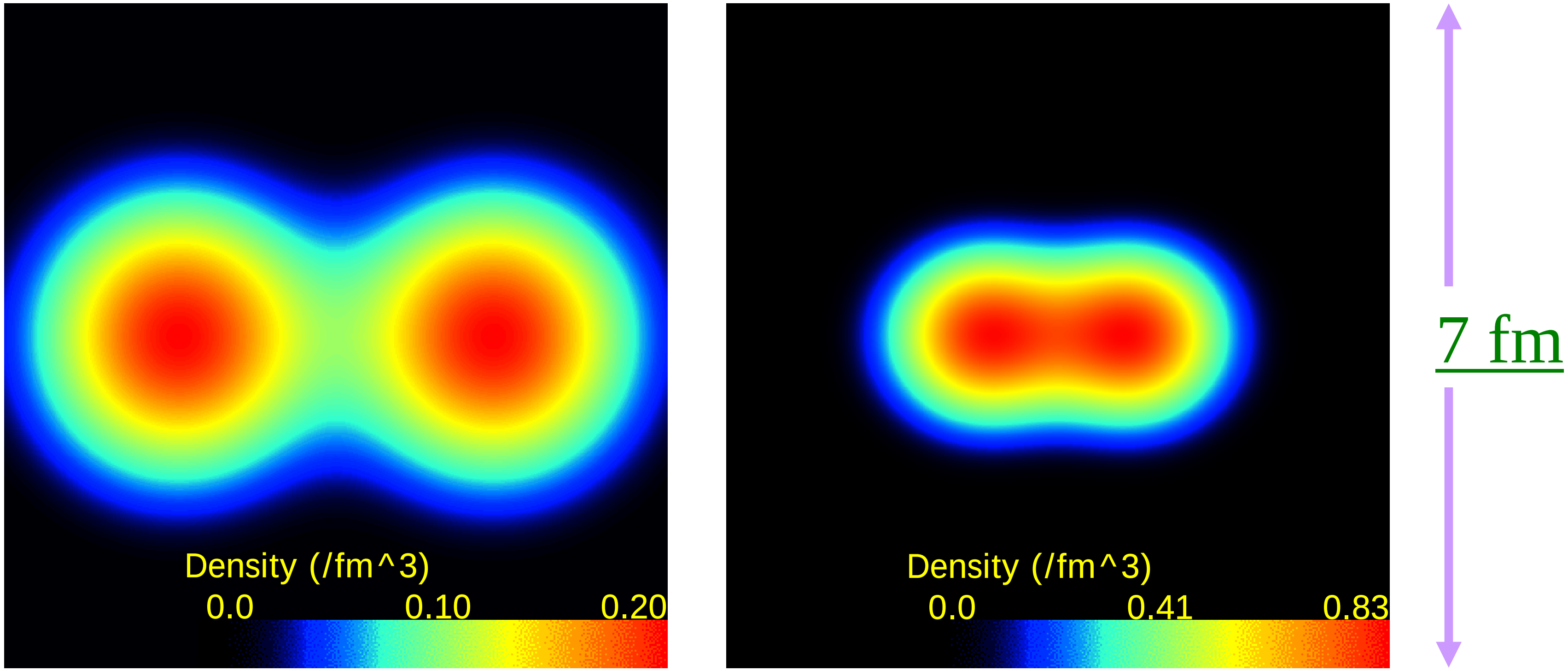
Ψ/J

Chiral restoration?
Color superconductivity?
Kaon condensation?
Strange hadronic/quark matter?

KEK
DAΦNE
SPring-8
GSI
J-Lab
J-PARC

Few-body $\bar{K}$ nuclear systems would provide experimental data of fundamental importance for hadron physics with strangeness.

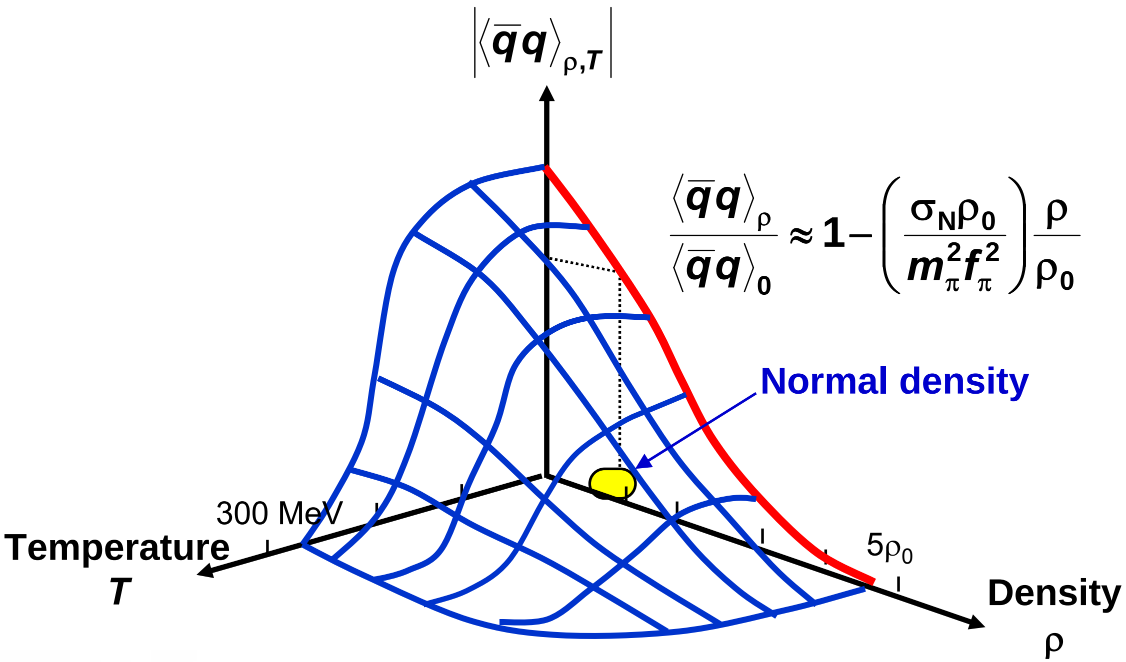
^{8}Be $^{8}BeK^{-}$

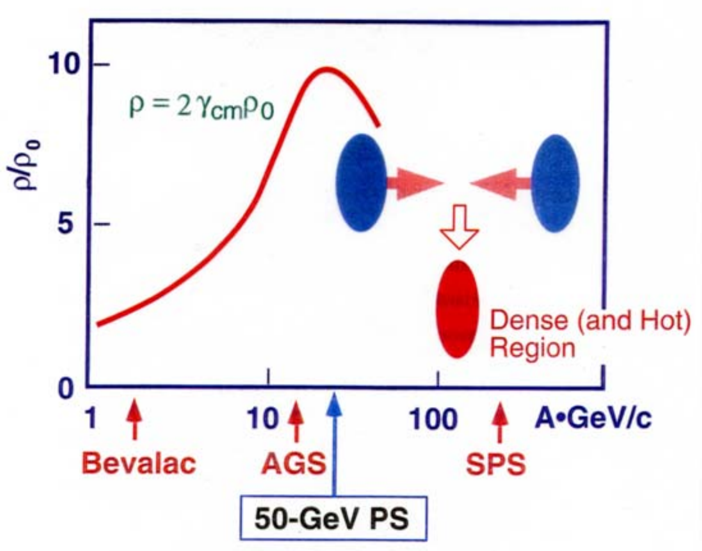


Dense & Cold

AntisymmetrizedMolecularDynamics calculation

A. Dote, H. Horiuchi, Y. Akaishi & T. Yamazaki, Phys. Lett. B590 (2004) 51.

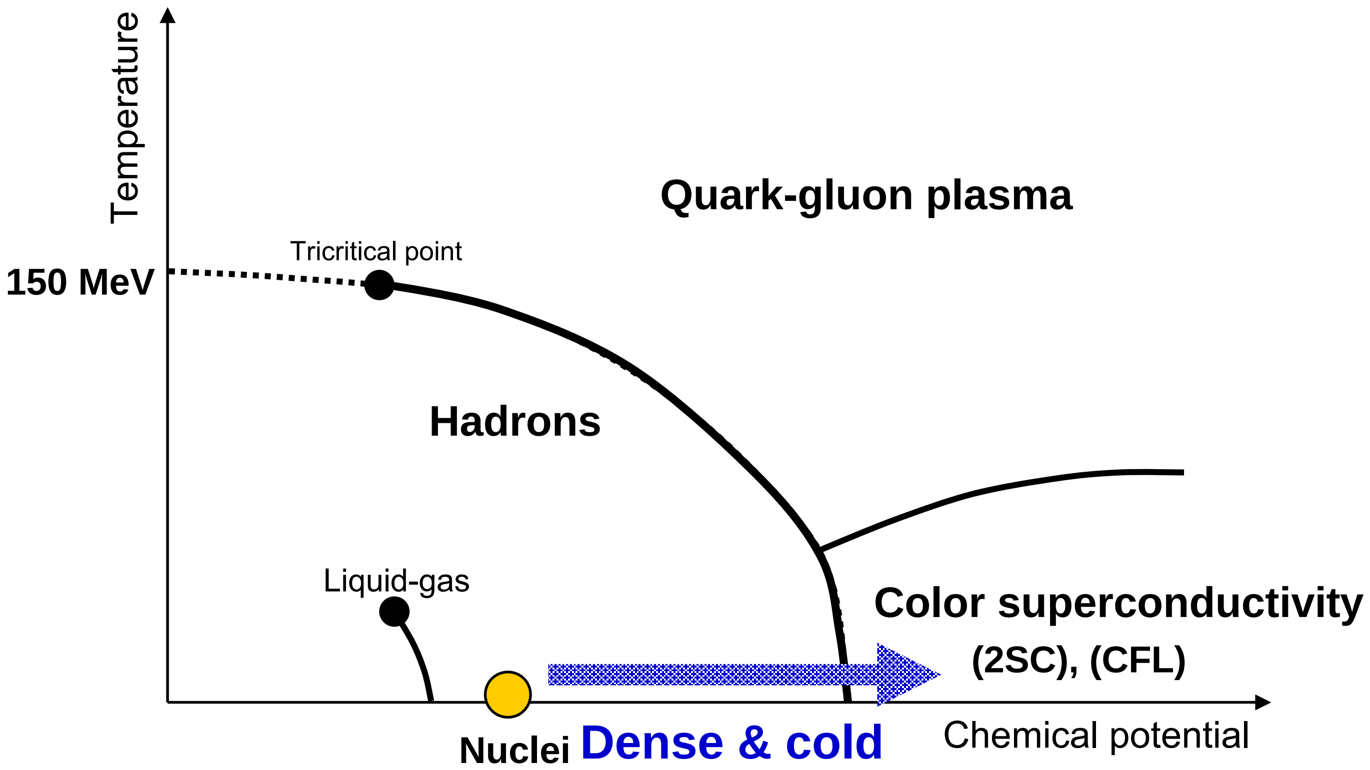




T. Hatsuda & T. Kunihiro,
Phys. Rev. Lett. 55 (1985) 158.

M. Lutz, S. Klimt & W. Weise,
Nucl. Phys. A542 (1992) 52.
W. Weise, Nucl. Phys. A553 (1993) 59c.

Nuclear phase diagram



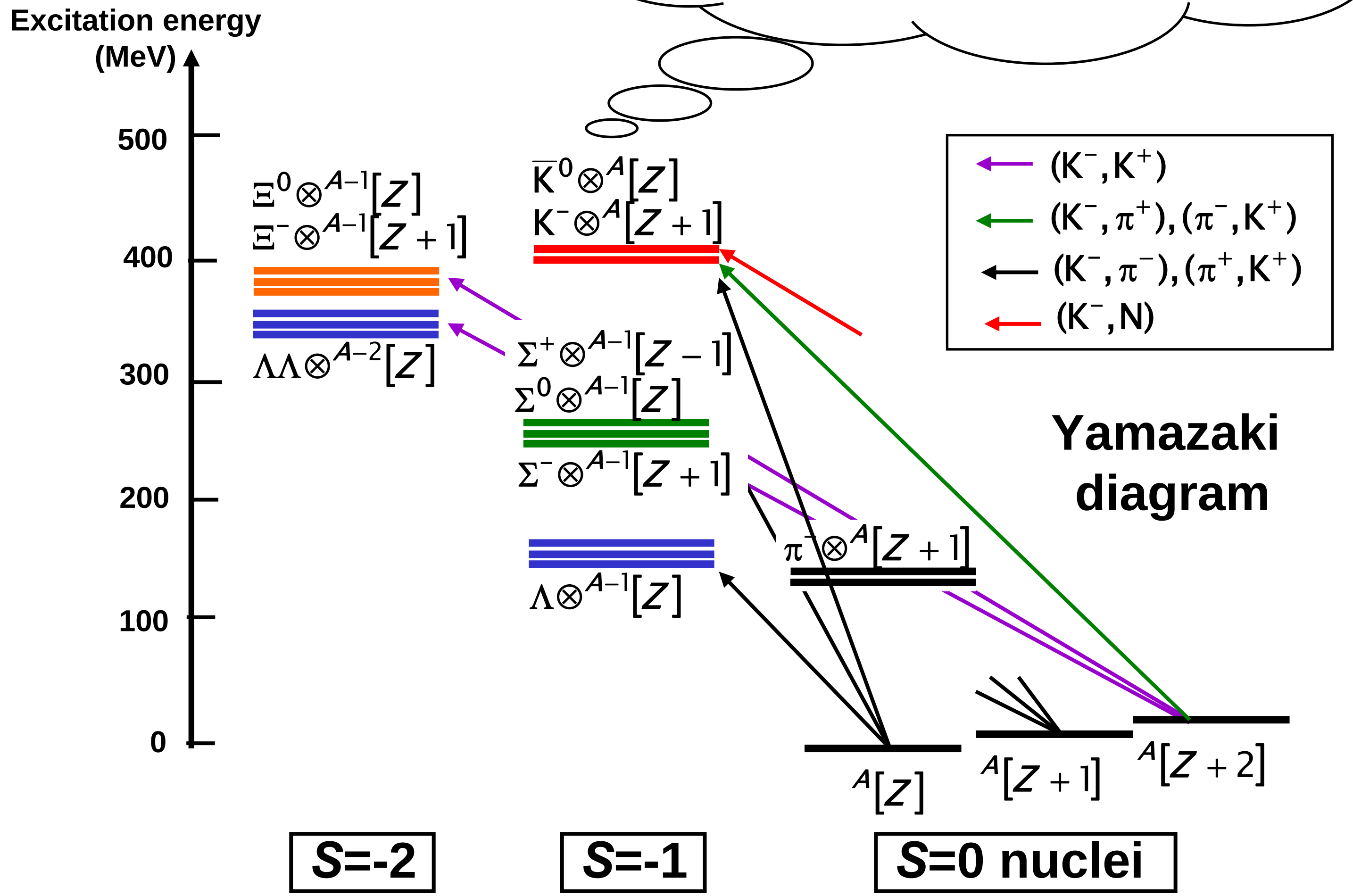
T. Hatsuda & T. Kunihiro,
Phys. Rev. Lett. 55 (1985) 158

An epoch-making milestone has been obtained by T. Suzuki, M. Iwasaki et al.

A new paradigm of Nuclear Physics

Nuclei of 2nd generation

The $s\bar{u}$ quark plays a leading role in forming a dense and cold nucleus.



原子核は豊かである。

Thank you very much!