Exploring Strange Matters

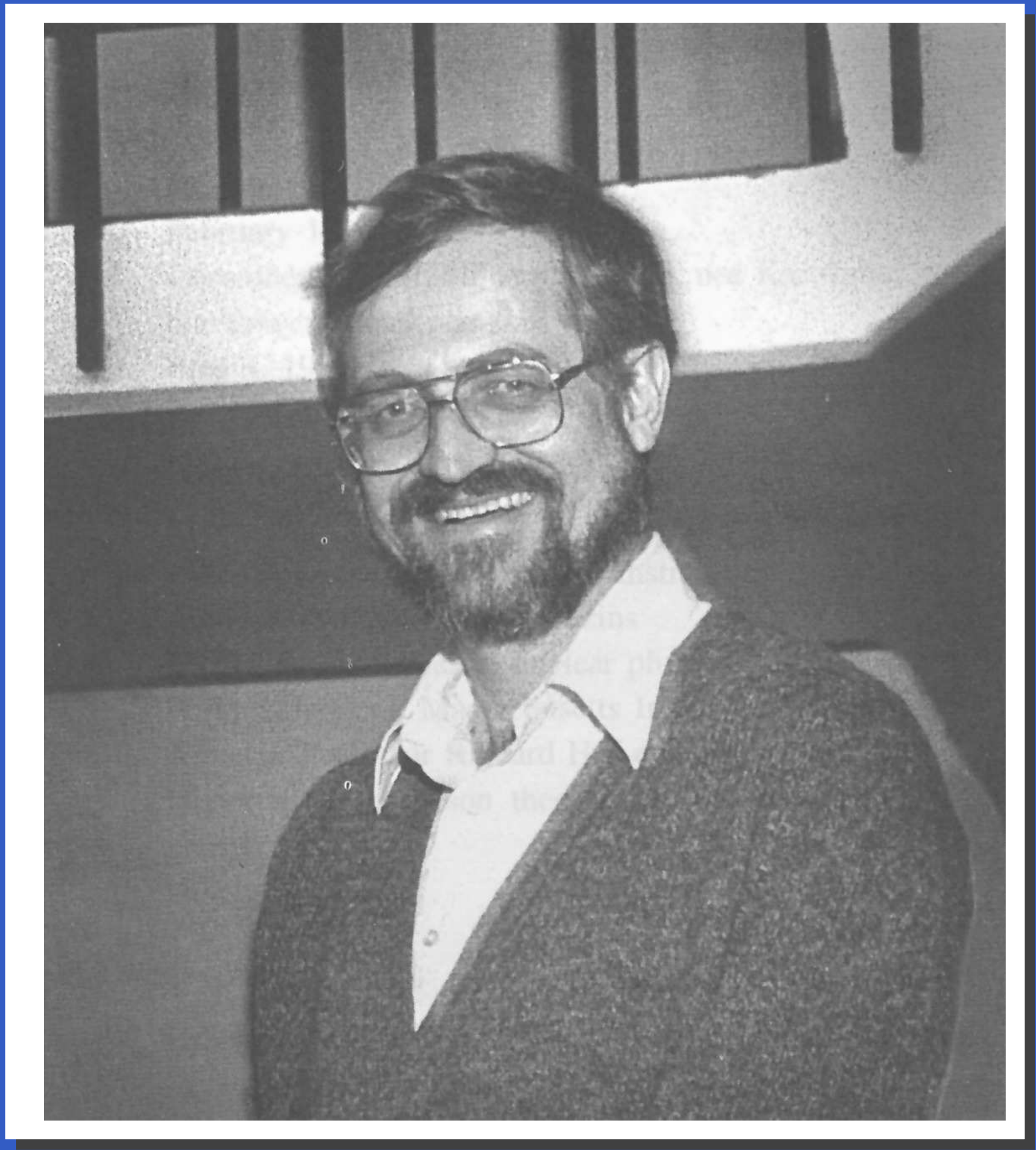
Jürgen Schaffner-Bielich

Institute for Theoretical Physics and
Heidelberg Graduate School for Fundamental Physics and
ExtreMe Matter Institute EMMI

Carl Dover Memorial Lecture

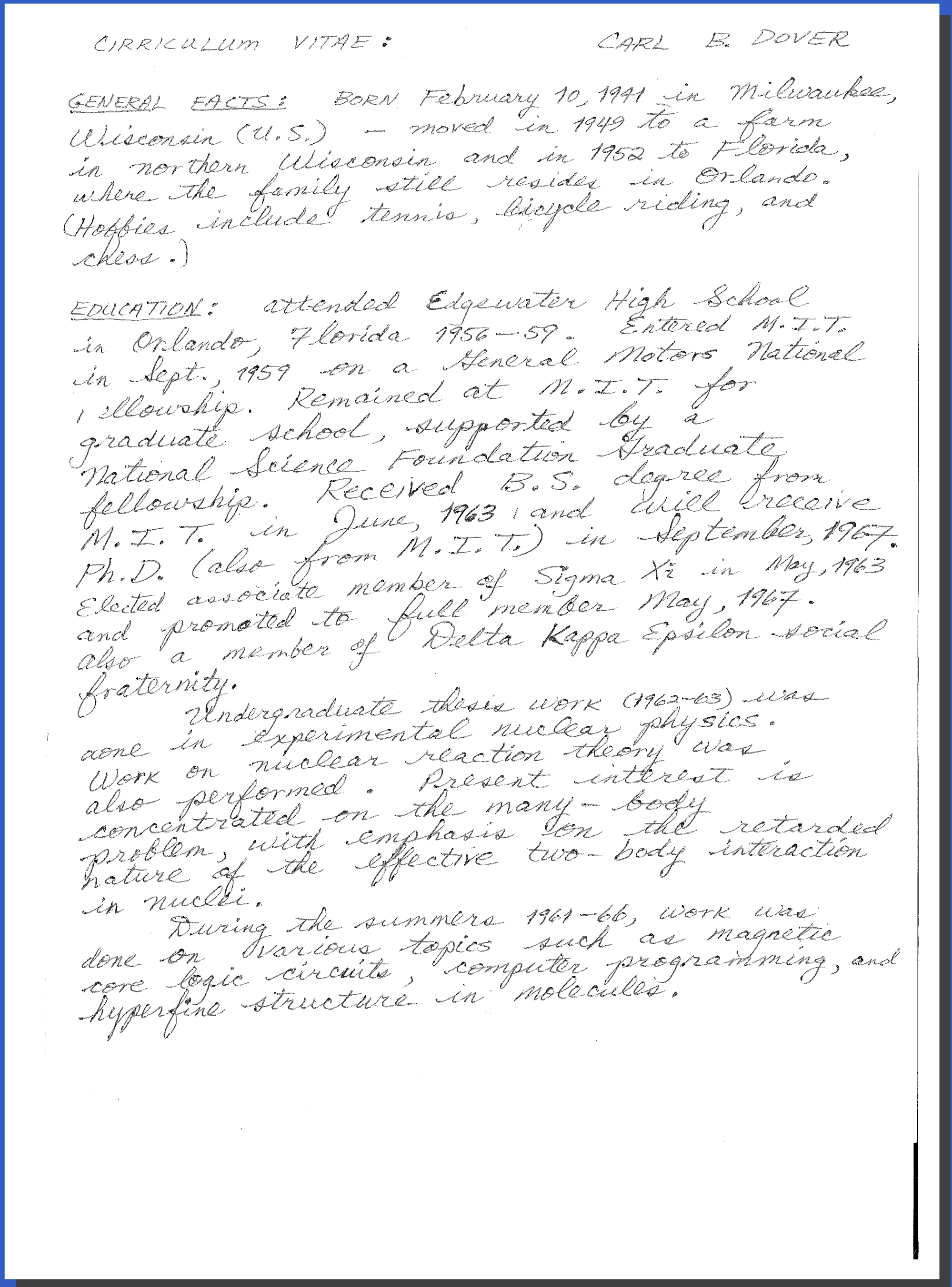
Brookhaven National Laboratory, New York, USA, March 1, 2012

Carl B. Dover 1941–1996



(from Carl Dover memorial issue, Nucl. Phys. A 625 (1997))

Carl B. Dover: curriculum vitae



CIRRICULUM VITAE: CARL B. DOVER

GENERAL FACTS: BORN February 10, 1941 in Milwaukee, Wisconsin (U.S.) — moved in 1949 to a farm in northern Wisconsin and in 1952 to Florida, where the family still resides in Orlando. (Hobbies include tennis, bicycle riding, and chess.)

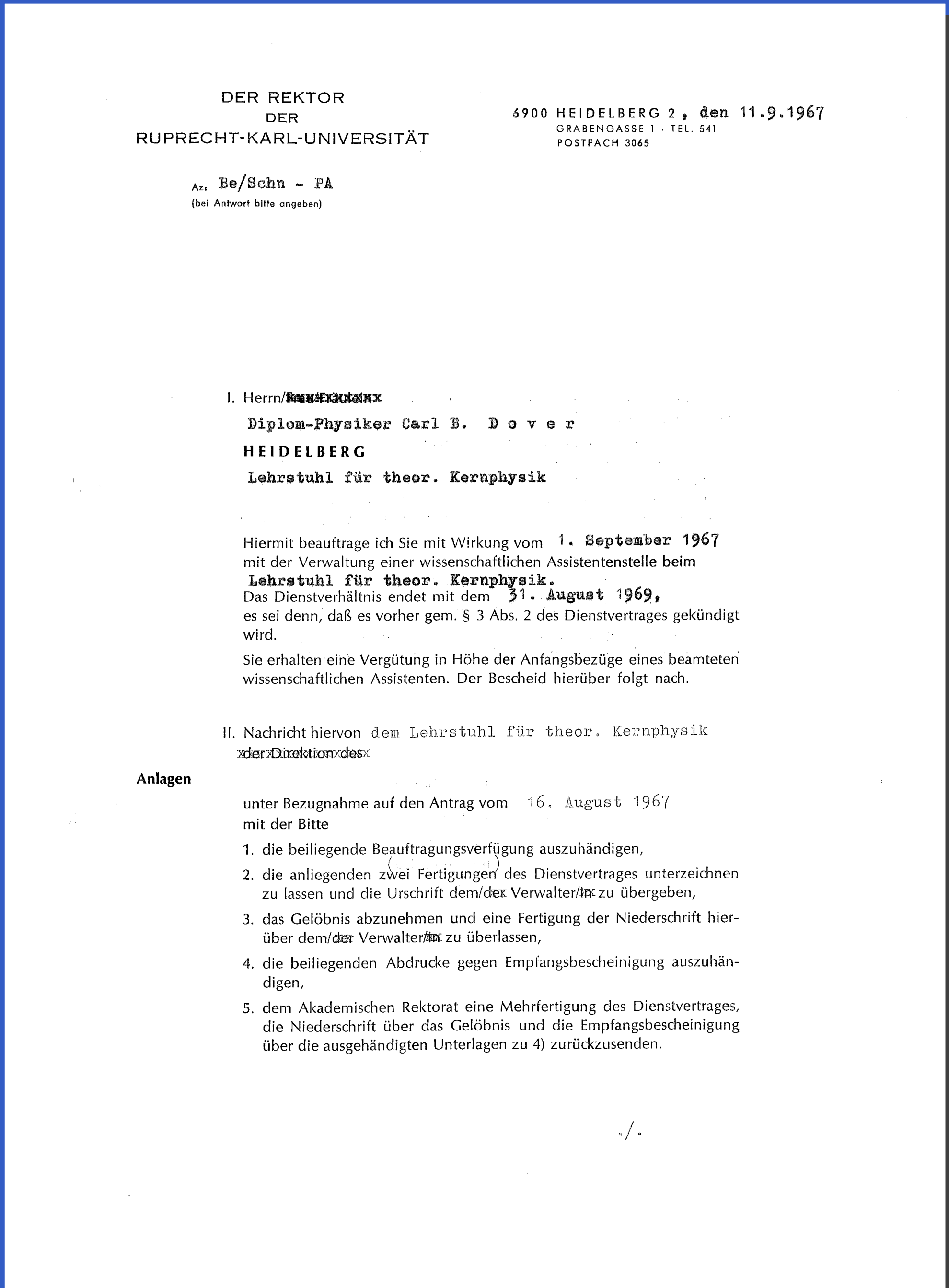
EDUCATION: attended Edgewater High School in Orlando, Florida 1956—59. Entered M.I.T. in Sept., 1959 on a General Motors National Fellowship. Remained at M.I.T. for graduate school, supported by a National Science Foundation Graduate fellowship. Received B.S. degree from M.I.T. in June, 1963, and will receive Ph.D. (also from M.I.T.) in September, 1967. Elected associate member of Sigma Xi in May, 1963 and promoted to full member May, 1967. also a member of Delta Kappa Epsilon social fraternity.

Undergraduate thesis work (1962–63) was done in experimental nuclear physics. Work on nuclear reaction theory was also performed. Present interest is concentrated on the many-body problem, with emphasis on the retarded nature of the effective two-body interaction in nuclei.

During the summers 1961–66, work was done on various topics such as magnetic core logic circuits, computer programming, and hyperfine structure in molecules.

- hand-written cv for the post-doc position in Heidelberg
- bachelor of science in experimental physics!
- PhD at MIT in 1967 (advisor: Prof. Richard Lemmer)

Carl B. Dover: first post-doc in Heidelberg



DER REKTOR
DER
RUPRECHT-KARL-UNIVERSITÄT

6900 HEIDELBERG 2, den 11.9.1967
GRABENGASSE 1 · TEL. 541
POSTFACH 3065

Az: Be/Schn - PA
(bei Antwort bitte angeben)

I. Herrn/xxxxxxxxx

Diplom-Physiker Carl B. D o v e r
HEIDELBERG
Lehrstuhl für theor. Kernphysik

Hiermit beauftrage ich Sie mit Wirkung vom 1. September 1967 mit der Verwaltung einer wissenschaftlichen Assistentenstelle beim Lehrstuhl für theor. Kernphysik.
Das Dienstverhältnis endet mit dem 31. August 1969, es sei denn, daß es vorher gem. § 3 Abs. 2 des Dienstvertrages gekündigt wird.

Sie erhalten eine Vergütung in Höhe der Anfangsbezüge eines beamteten wissenschaftlichen Assistenten. Der Bescheid hierüber folgt nach.

II. Nachricht hiervon dem Lehrstuhl für theor. Kernphysik
~~der Direktion des~~

Anlagen

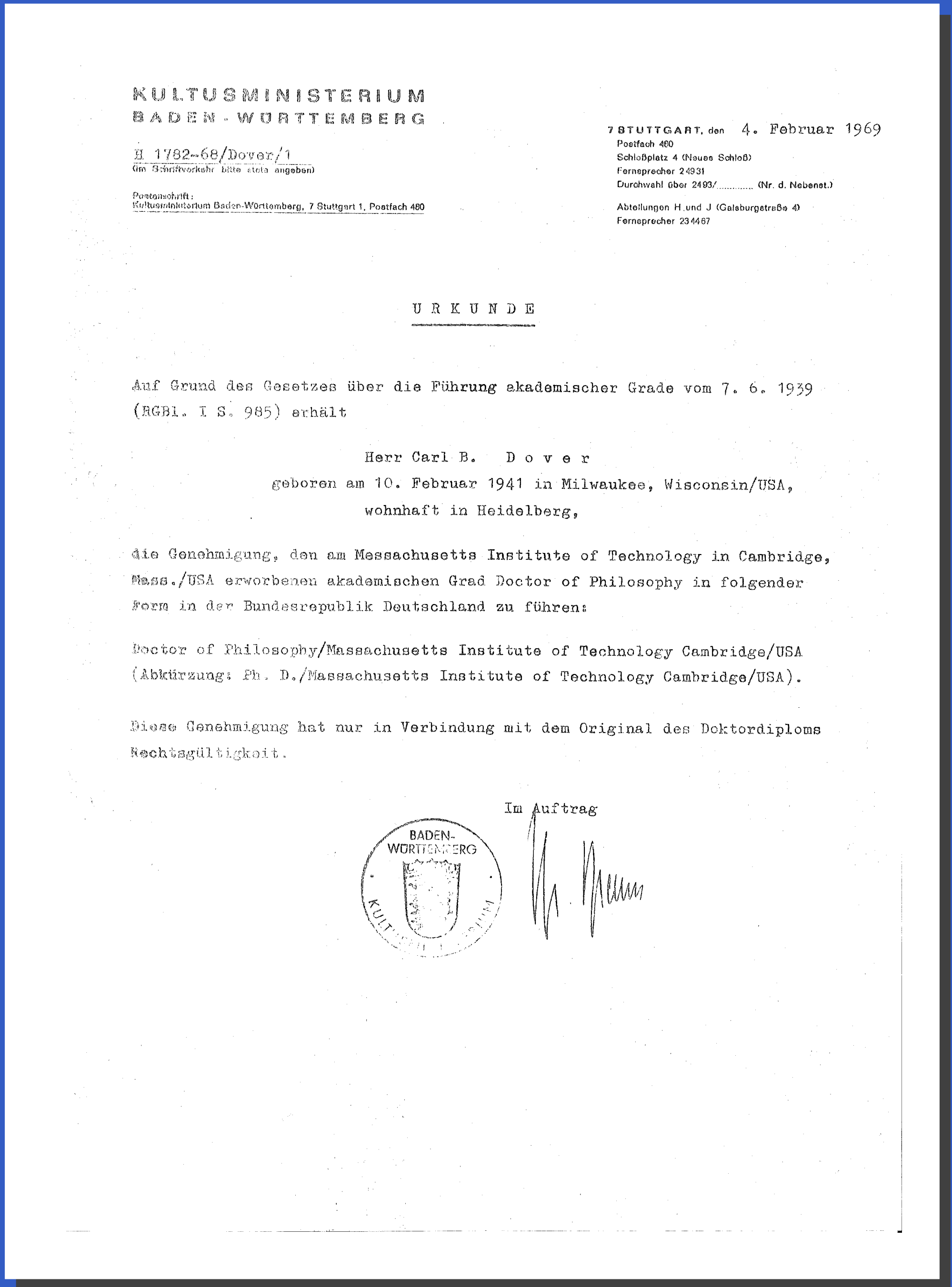
unter Bezugnahme auf den Antrag vom 16. August 1967
mit der Bitte

1. die beiliegende Beauftragungsverfügung auszuhändigen,
2. die anliegenden zwei Fertigungen des Dienstvertrages unterzeichnen zu lassen und die Urschrift dem/der Verwalter/in zu übergeben,
3. das Gelöbnis abzunehmen und eine Fertigung der Niederschrift hierüber dem/der Verwalter/in zu überlassen,
4. die beiliegenden Abdrucke gegen Empfangsbescheinigung auszuhändigen,
5. dem Akademischen Rektorat eine Mehrfertigung des Dienstvertrages, die Niederschrift über das Gelöbnis und die Empfangsbescheinigung über die ausgehändigten Unterlagen zu 4) zurückzusenden.

./.

- first post-doc positions in Heidelberg 1967-1970
- 'Verwalter einer wissenschaftlichen Assistentenstelle' 1967-1969
- 'Planmäßiger Wissenschaftlicher Assistent' 1969-1970

Carl B. Dover: PhD title in Germany



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7 STUTTGART, den 4. Februar 1969
Postfach 480
Schloßplatz 4 (Neues Schloß)
Fernsprecher 24931
Durchwahl über 2493/............ (Nr. d. Nebenst.)

Abteilungen H und J (Gaisburgstraße 4)
Fernsprecher 234467

U R K U N D E

Auf Grund des Gesetzes über die Führung akademischer Grade vom 7. 6. 1939 (RGBl. I S. 985) erhält

Herr Carl B. D o v e r
geboren am 10. Februar 1941 in Milwaukee, Wisconsin/USA,
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Diese Genehmigung hat nur in Verbindung mit dem Original des Doktordiploms Rechtsgültigkeit.

Im Auftrag

BADEN-WÜRTTEMBERG KULTUSMINISTERIUM

- german ministry grants Carl Dover permission for bearing the title PhD in Germany

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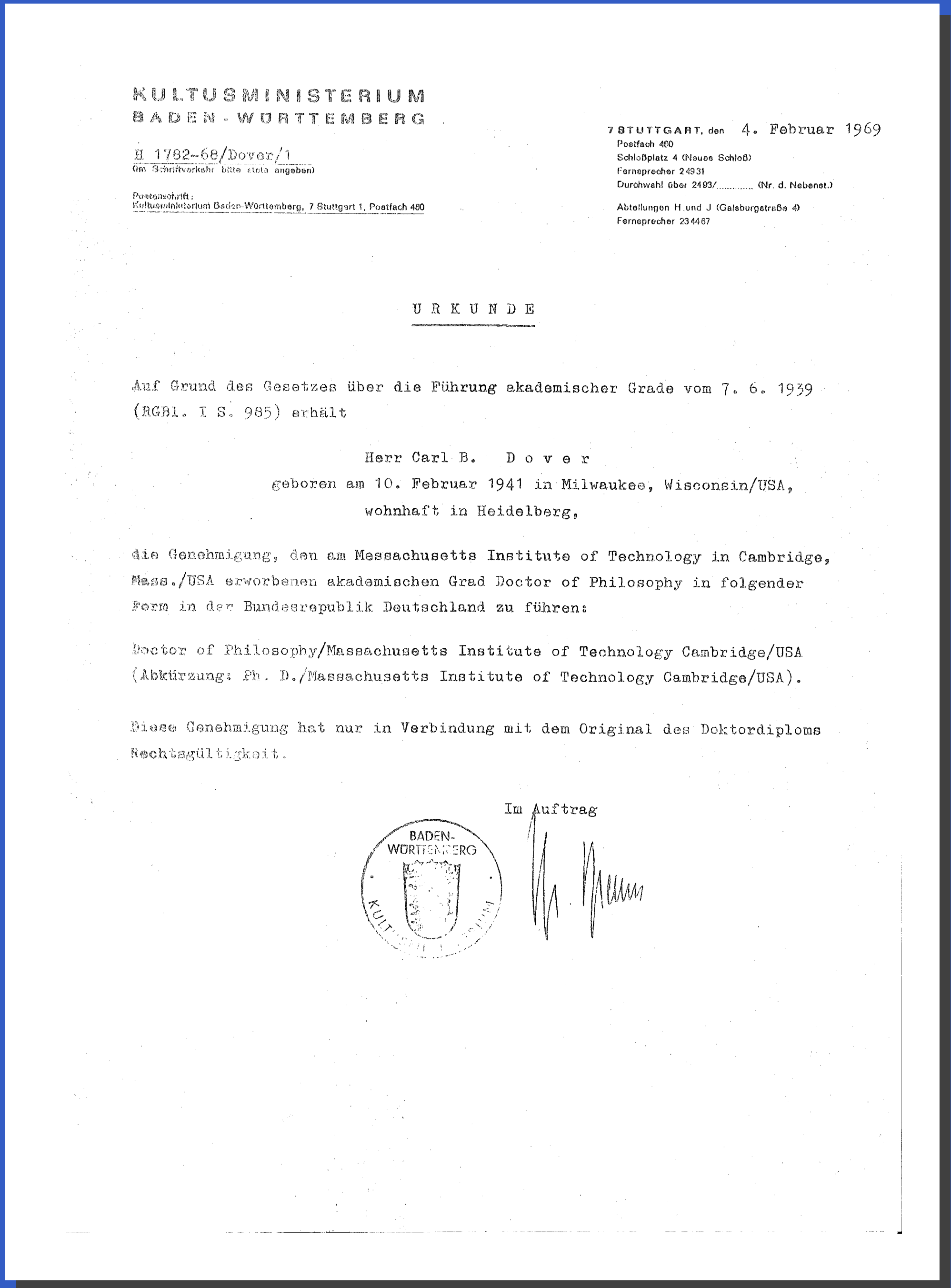

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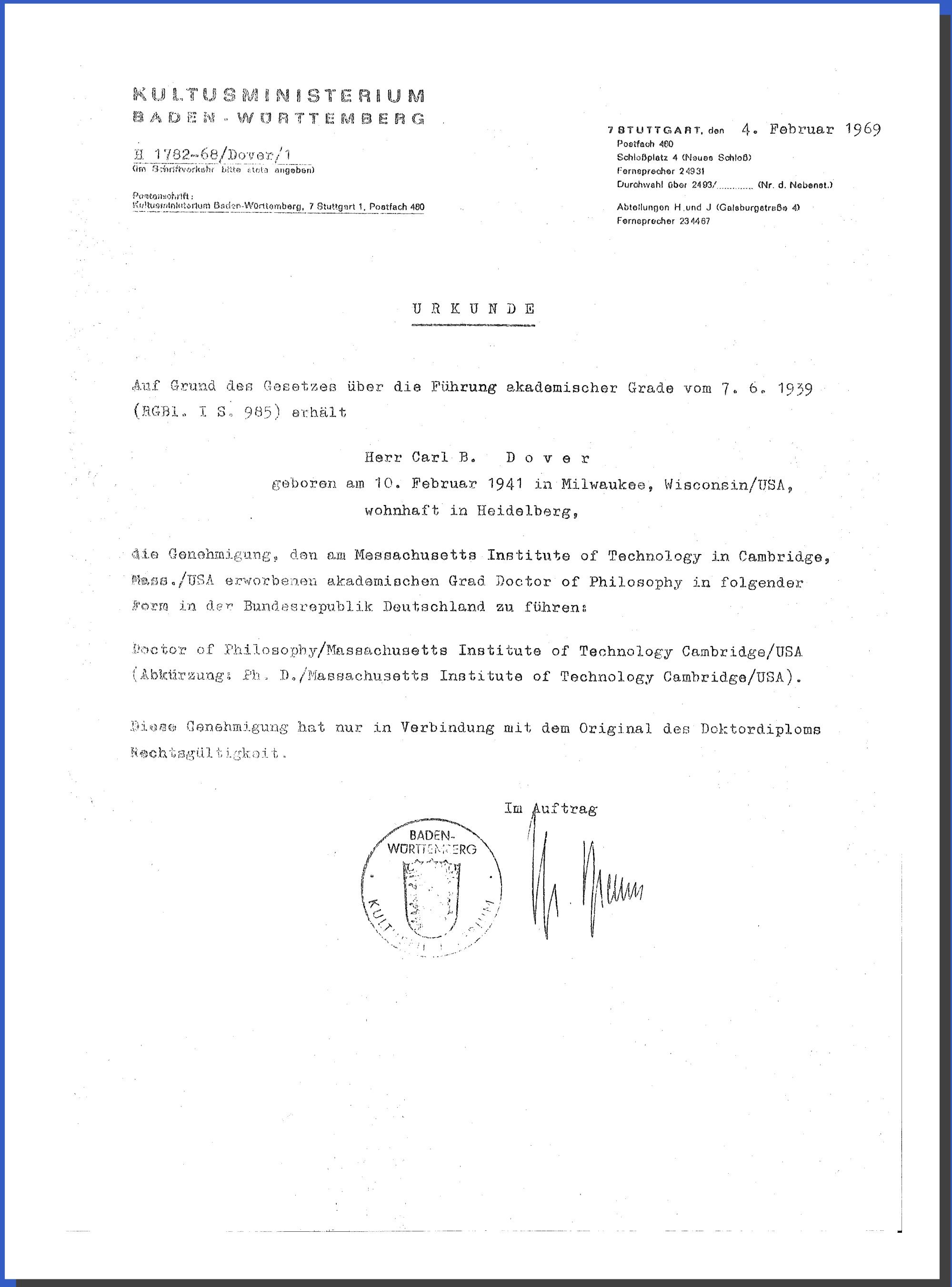

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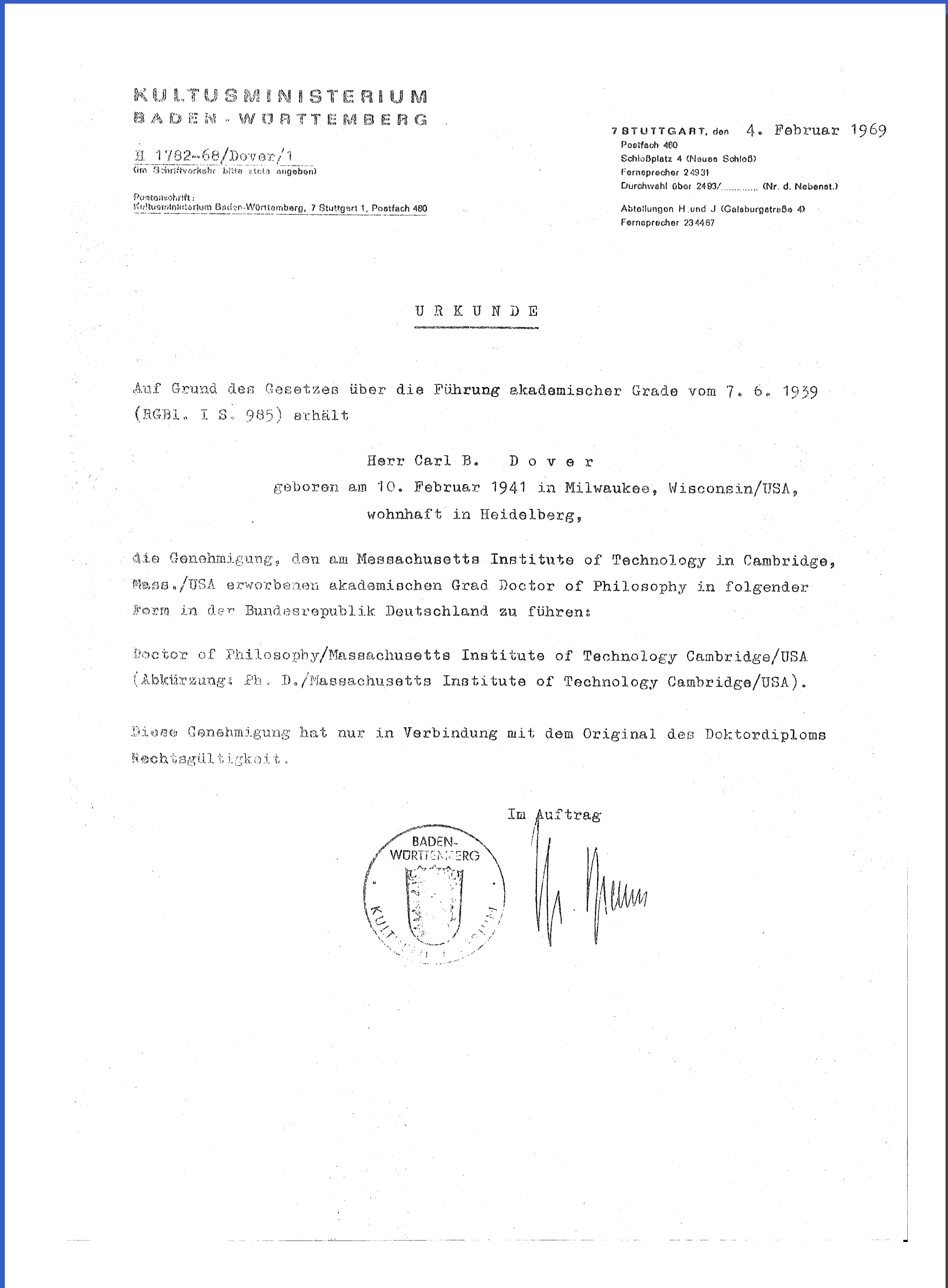

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- . . . and asks for an administrative fee of DM 80 (in a separate letter)

Carl B. Dover: CV part II (abridged)

- 1970-71: University of Paris, Orsay, Institut de Physique Nucléaire, Chercheur Associé au CNRS
- 1971-present: Brookhaven National Laboratory, Upton, NY
  Assistant Physicist (1971-1973)
  Associate Physicist (1973-1975)
  Physicist (1975-1982)
  Senior Physicist (1982-present)
  Group Leader of Nuclear Theory (1990-present)
- 1989-1993 Humboldt Senior Scientist Award
  1991 Appointed Adjunct Professor, Yale University
  1993 Appointed Adjunct Professor, SUNY/Stony Brook

more than 200 publications, 14 posthumously!
(2 in Dover memorial issue, 12 with E864 collaboration)

Carl B. Dover and Strange Hadronic Matter (abridged)

- his first talk ever on dibaryons:
  first hypernuclear meeting in Heidelberg 1982

  (Avraham Gal, private communication)

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- organizing the summer program on strangeness in Seattle 1992 (where we first met)

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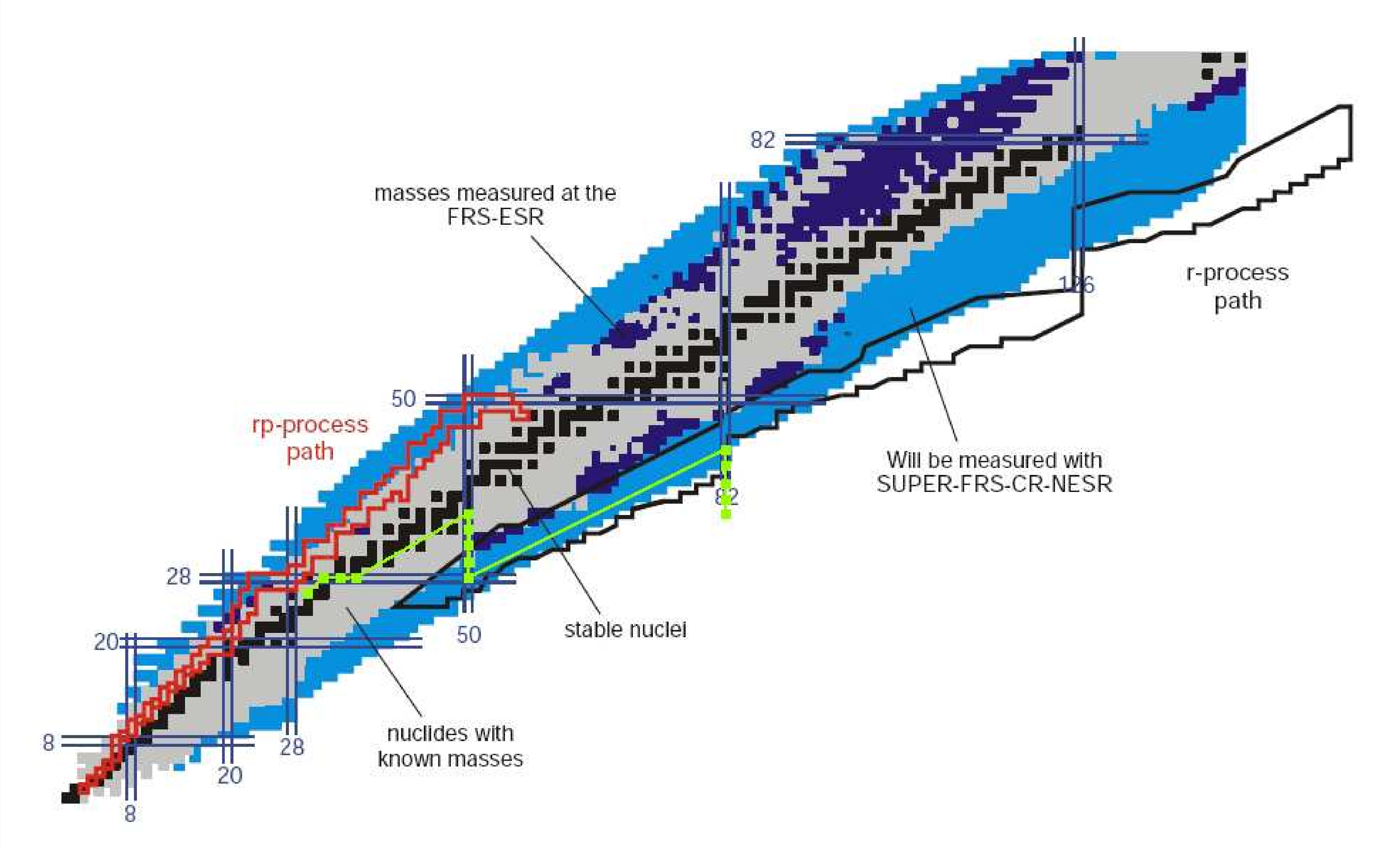
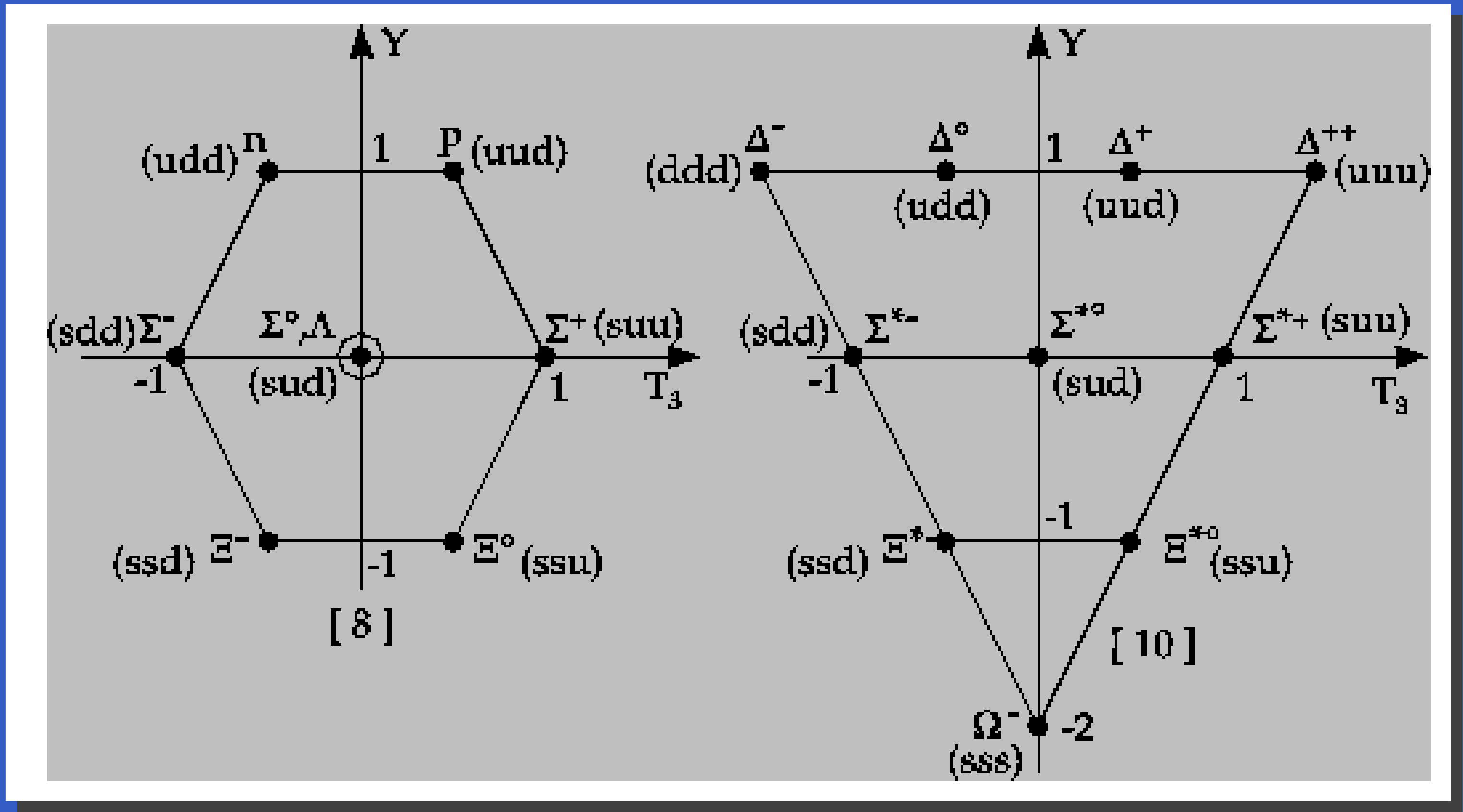
- work on production of dibaryons in heavy-ion collisions (1989 with P. Koch and M. May)
- organizing the summer program on strangeness in Seattle 1992 (where we first met)
- joint work on strange hadronic matter 1993, 1994 (with Gal, Millener, C. Greiner, Stöcker and myself)

Nuclei with hyperons: hypernuclei

Nuclear chart

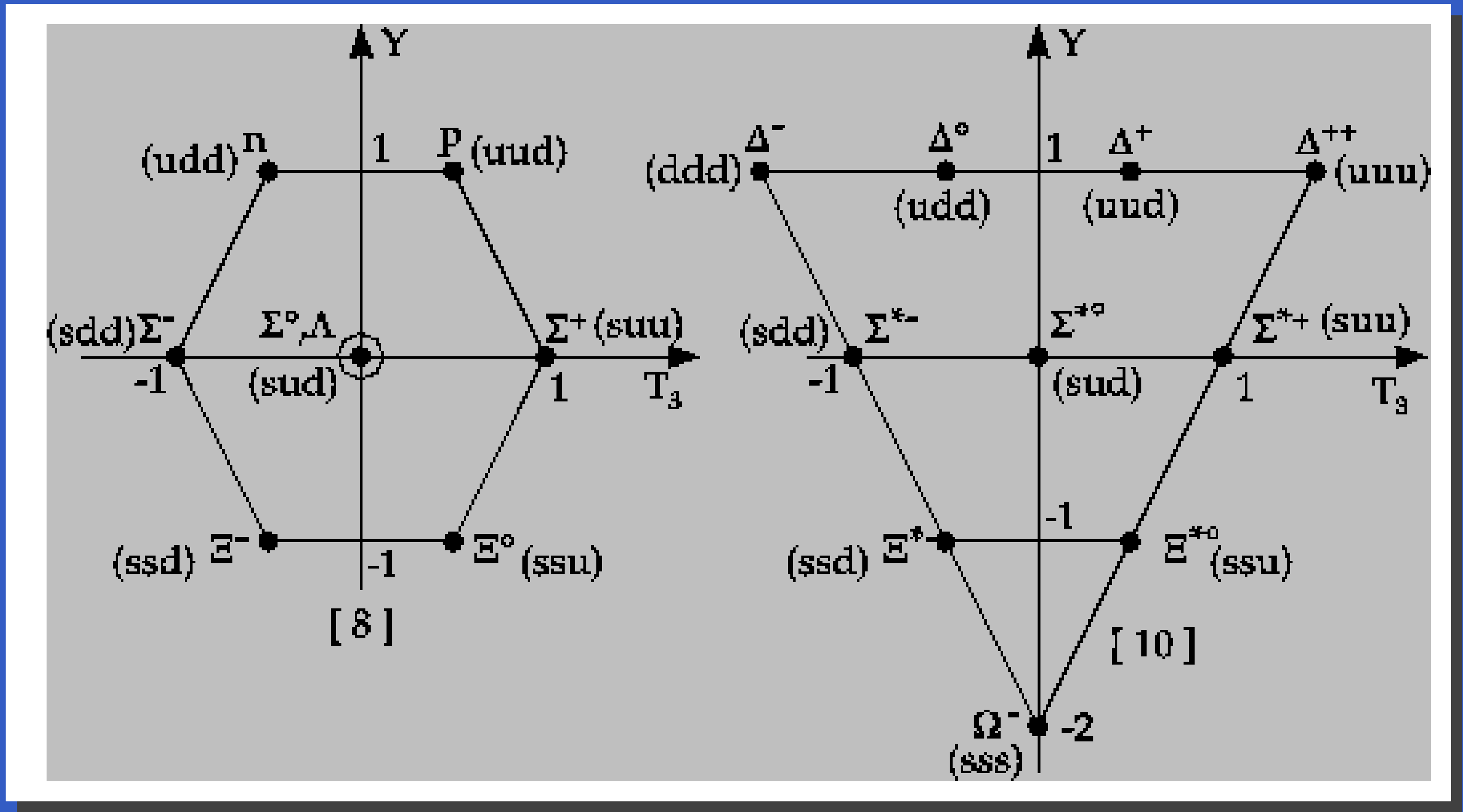


Baryon octet and decuplet



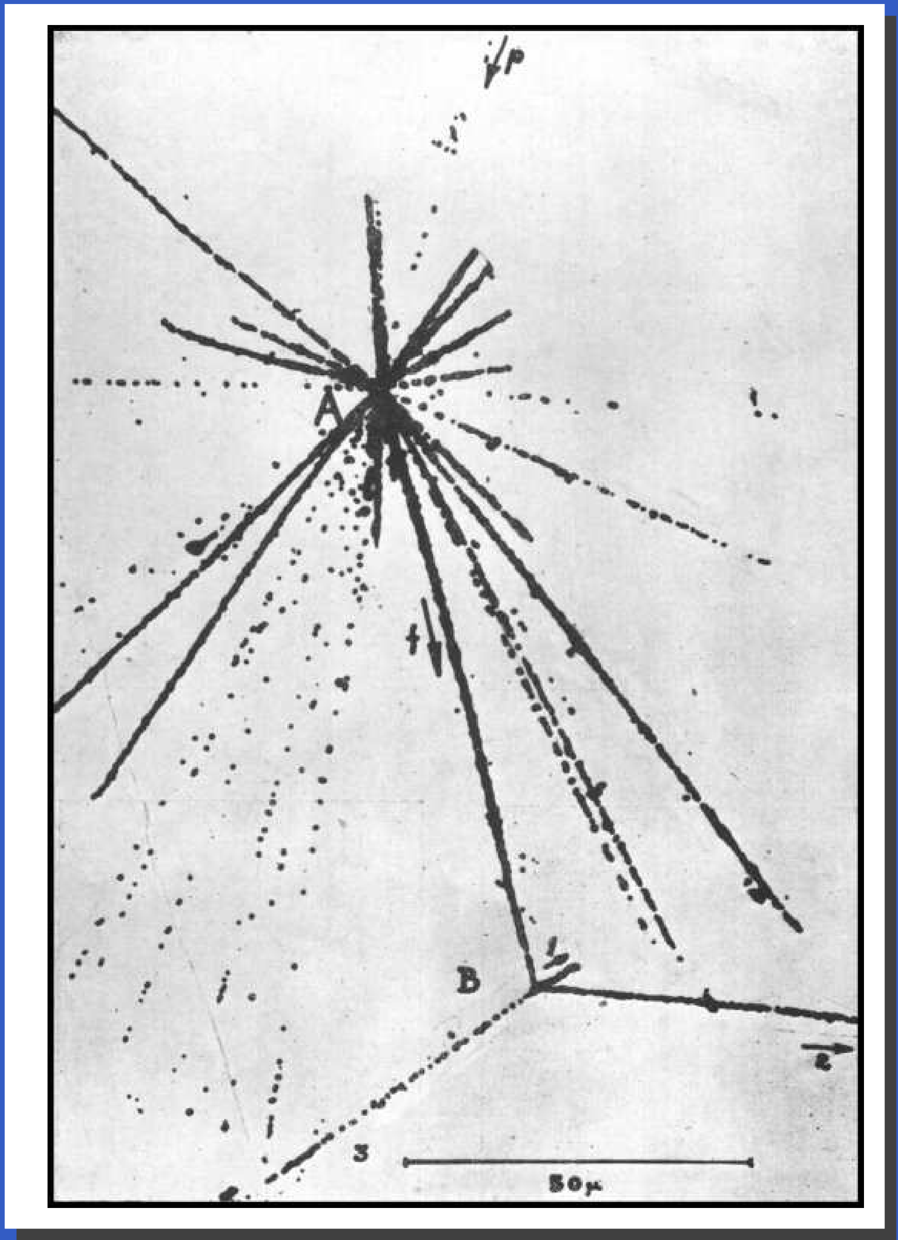
- eightfold way: baryons have three quarks
- lowest multiplets: octet (spin 1/2) and decuplet (spin 3/2)
- baryon mass increases with number of strange quarks (strangeness)
- nucleon (no s-quark): $m_N = 940$ MeV $\rightarrow$ nuclear chart

Baryon masses



- hyperons with one s-quark: $m_\Lambda = 1116$ MeV, $m_{\Sigma^+} = 1189$ MeV, $m_{\Sigma^0} = 1193$ MeV, $m_{\Sigma^-} = 1197$ MeV
- hyperons with two s-quarks: $m_{\Xi^0} = 1314$ MeV, $m_{\Xi^-} = 1321$ MeV
- hyperon with three s-quarks: $m_{\Omega^-} = 1672$ MeV (spin 3/2, Pauli principle!)
- bound system with nucleons and hyperons: hypernuclei!

First hypernuclear event

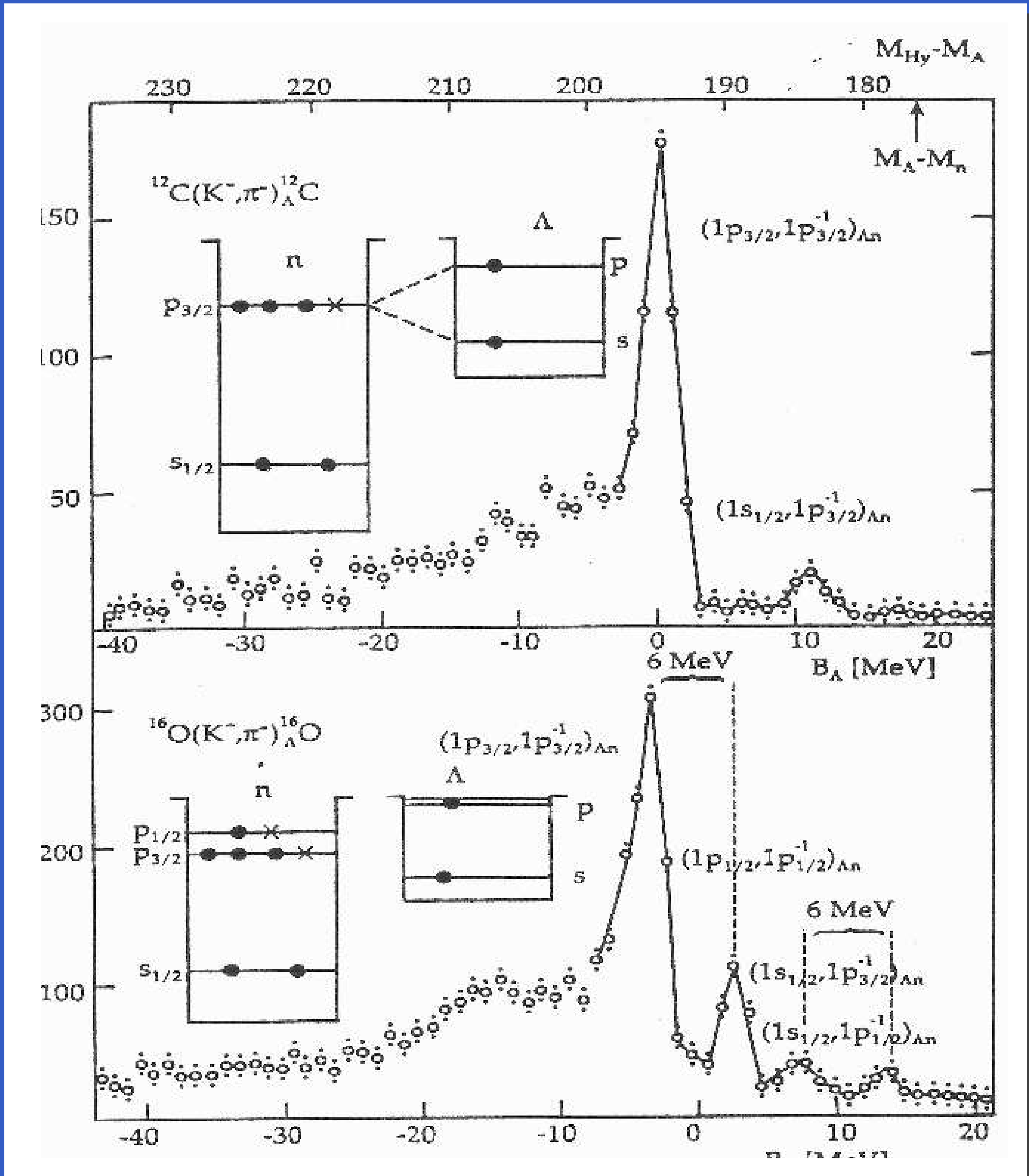


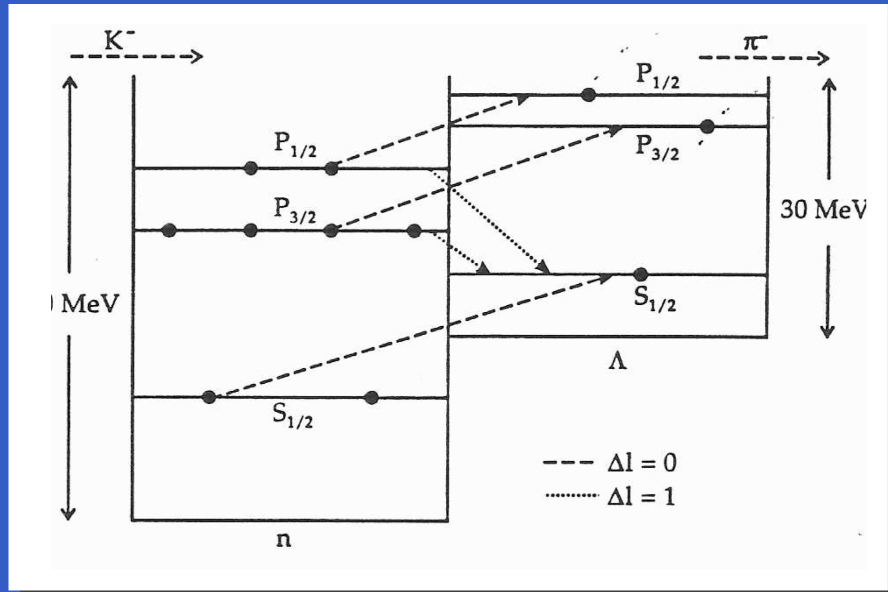
- first hypernuclear measurement: 1953 by Danysz and Pniewski from cosmic ray emulsion event
- unique double-star feature on emulsion plate: one from hypernuclear production, one from hypernuclear decay!

Danysz and Pniewski

Polish postcard commemorating Danysz and Pniewski (check out the stamp!)

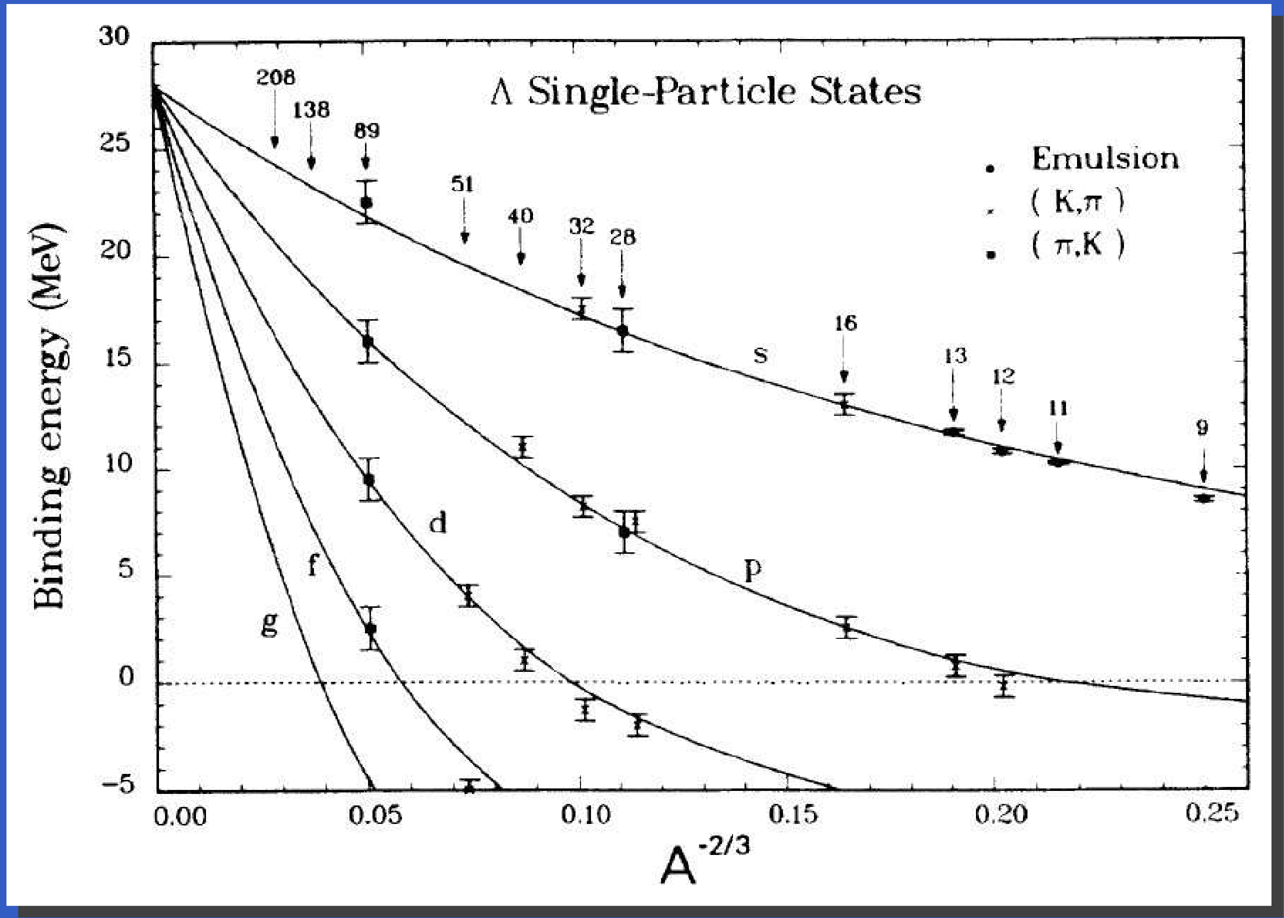
Hypernuclear spectra and levels





- peak structure in pion spectra
- related to single-particle levels of hypernucleus!
- first surprise: tiny spin-orbit splitting for $^{16}_{\Lambda}$O !

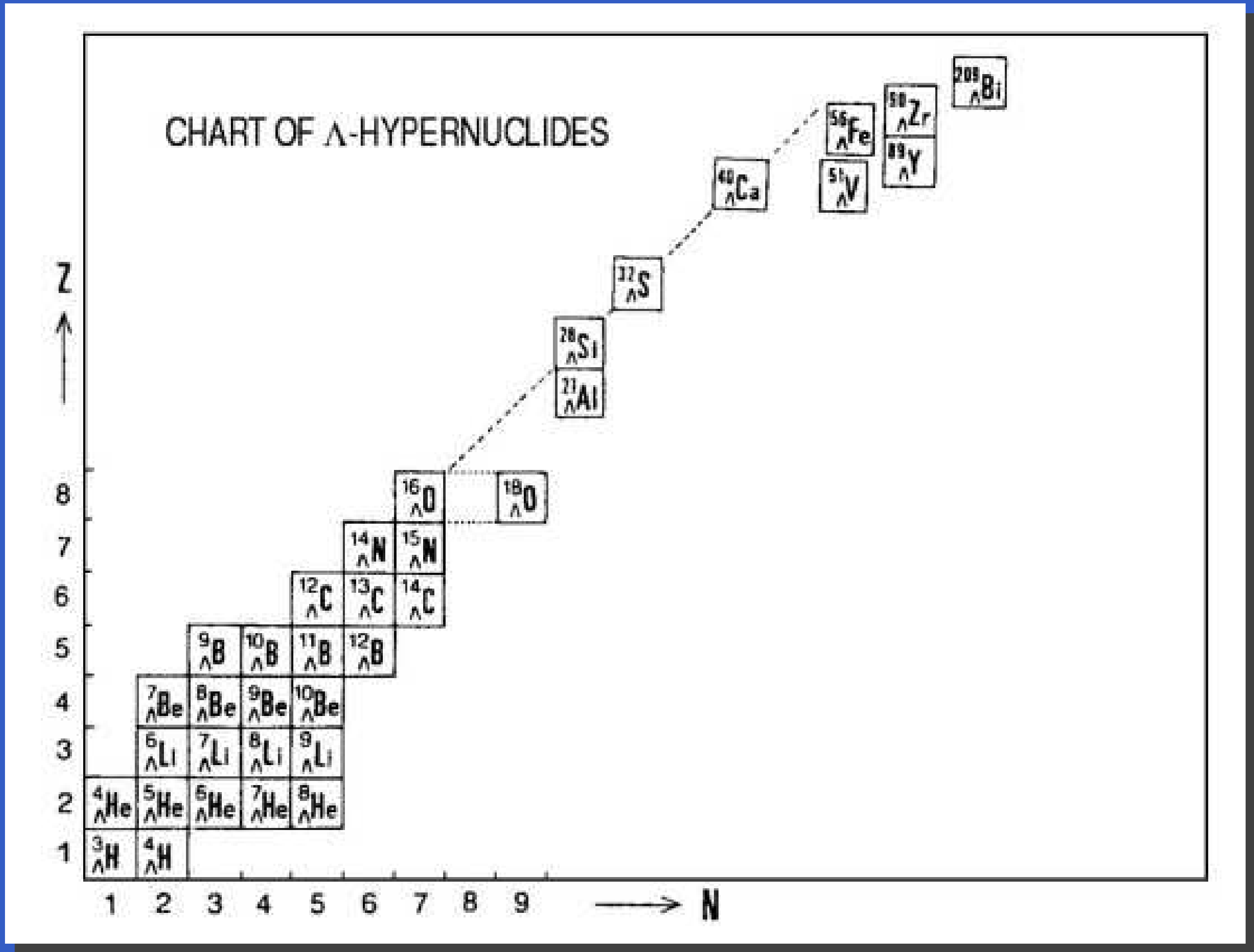
Λ Single–Particle Energies



(Millener, Dover, Gal 1988)

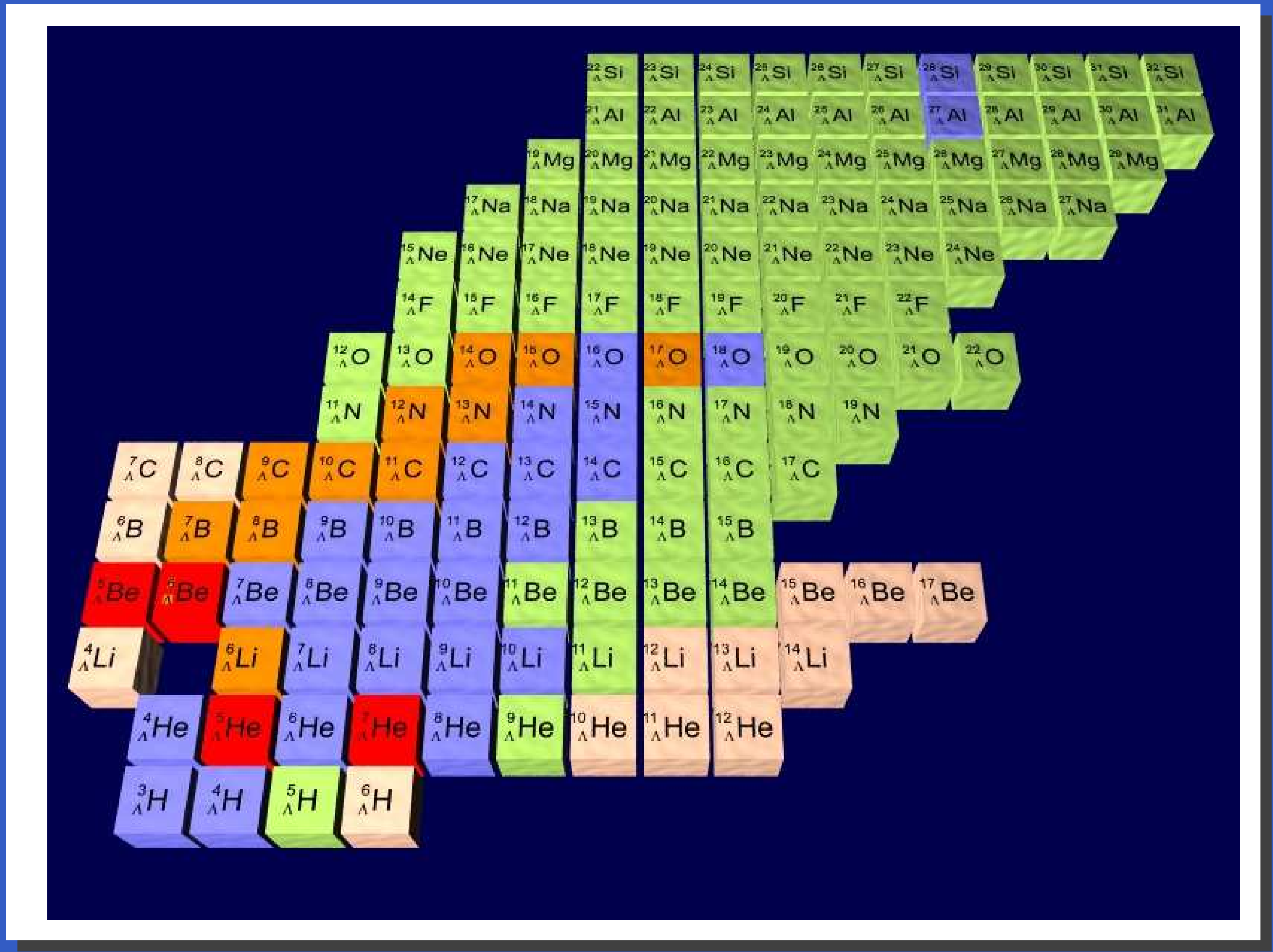
- measured in (π^+, K^+) and (K^-, π^-) reactions
- fit to single particle energies: $U_\Lambda = -28$ MeV for $A \to \infty$
- 'textbook' example for single-particle structure in nuclear physics

Hypernuclear chart (Bando 1990)



- many light hypernuclei observed in emulsion experiments (up to A=15)
- heavier systems measured spectroscopically

HypHI program at GSI (Take Saito et al.)



- exploration of the whole hypernuclear chart for light systems!
- determination of the hypernuclear drip-line
- note: hyperons stabilize nuclei, ^{8}Be is unbound, but $^{9}_{\Lambda}$Be is bound!
- evidence for $^{6}_{\Lambda}$H by FINUDA collaboration (2012)!

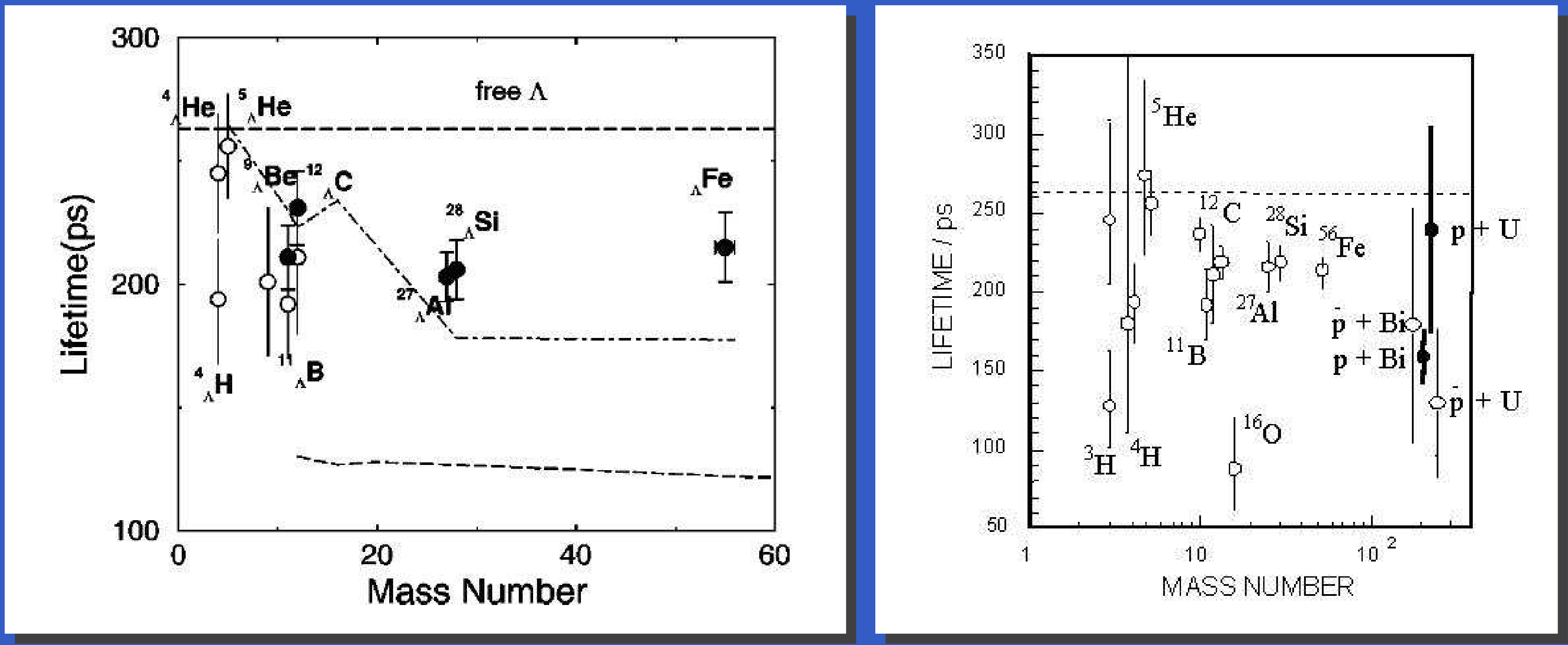
Hyperon decays

Hyperons decay mainly by weak interactions: conserves baryon number and charge but changes strangeness by one unit

- $\Lambda \to p + \pi^-(64\%), \quad n + \pi^0(36\%)$
- $\Sigma^+ \to p + \pi^0(52\%), \quad n + \pi^+(48\%)$
- $\Sigma^0 \to \Lambda + \gamma$ (electromagnetic)
- $\Sigma^- \to n + \pi^-$
- $\Xi^0 \to \Lambda + \pi^0$
- $\Xi^- \to \Lambda + \pi^-$

typical lifetime: $\tau \approx 10^{-10}$ seconds

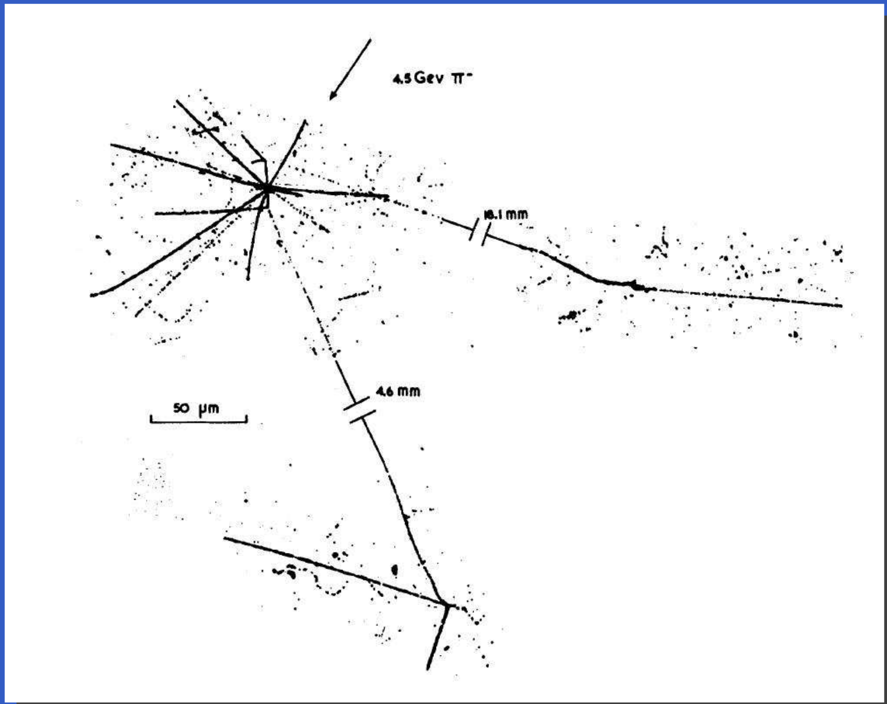
Hypernuclear decays



(Park et al., PRC61 (2000) 054004)

- Hyperons in the medium can also decay non-mesonically:
- $\Lambda + N \to N + N, \quad \Sigma + N \to N + N$
- $\Xi + N \to \Sigma + N$ or $\Lambda + N, \quad \Lambda + \Lambda \to \Sigma + N$ or $\Lambda + N \dots$
- nonmesonic decay dominates already for moderate mass number!
- hypernuclear lifetime saturates around 200 ps

Xi hypernuclei (Dover and Gal 1983)



Hypernucleus	B_{Ξ^-} [MeV]	B_{Ξ^0} [MeV]
${}^{8}_{\Xi}$He	$8.1^* \pm 1.2$	14.2 ± 1.8
${}^{11}_{\Xi}$B	9.2 ± 2.2	0.4 ± 2.8
${}^{13}_{\Xi}$C	18.1 ± 3.2	-4.3 ± 3.8
${}^{15}_{\Xi}$C	16.0 ± 4.7	11.1 ± 5.3
${}^{17}_{\Xi}$O	16.0 ± 5.5	-4.5 ± 6.1
${}^{28}_{\Xi}$Al	23.2 ± 6.8	13.3 ± 7.4

- first bound Ξ hypernucleus seen in 1959
  (Wilkinson, Lorant, Robinson, Lokanathan, PRL 3 (1959) 397)
- incoming pion beam produces first star
- two short tracks towards south and north: two hypernuclei emitted!
- interpretation: ${}^{8}_{\Xi}$B with $B_\Xi = 8.1 \pm 1.2$ (corrected for modern value of m_Ξ)
- Ξ reacts via $\Xi + N \rightarrow \Lambda + \Lambda$ to form two hypernuclei

$\Lambda\Lambda$ Hypernuclei

1963 Danysz et al.: $^{10}_{\Lambda\Lambda}$Be$\rightarrow ^{9}_{\Lambda}Be+\mathrm{p}+\pi^-$, $\triangle B_{\Lambda\Lambda} = 4.3 \pm 0.4$ MeV

1966 Prowse: $^{6}_{\Lambda\Lambda}$He$\rightarrow ^{5}_{\Lambda}He+\mathrm{p}+\pi^-$, $\triangle B_{\Lambda\Lambda} = 4.7 \pm 0.6$ MeV

1991 E176 (KEK): $^{13}_{\Lambda\Lambda}$B$\rightarrow ^{13}_{\Lambda}C+\pi^-$, $\triangle B_{\Lambda\Lambda} = 4.8 \pm 0.7$ MeV

(Dover, Millener, Gal, Davis 1991)

2001 E373 (KEK): $^{6}_{\Lambda\Lambda}$He$\rightarrow ^{5}_{\Lambda}He+\mathrm{p}+\pi^-$, $\triangle B_{\Lambda\Lambda} = 1.0 \pm 0.2$ MeV!

2001 E906 (BNL): $^{4}_{\Lambda\Lambda}$H$\rightarrow ^{4}_{\Lambda}He+\pi^-$ or $^{7}_{\Lambda\Lambda}$Li (Randeniya and Hungerford 2007)

- $\Lambda\Lambda$ interaction is weakly attractive
- total binding energy of two Λ's: $B_{\Lambda\Lambda}(^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}(^{A}_{\Lambda\Lambda}Z) + B_{\Lambda}(^{A-1}_{\Lambda}Z)$
- additional bond energy: $\triangle B_{\Lambda\Lambda}(^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}(^{A}_{\Lambda\Lambda}Z) - 2B_{\Lambda}(^{A-1}_{\Lambda}Z)$

Updated world data on $\Lambda\Lambda$ hypernuclei (2011)

$B_{\Lambda\Lambda}$: theory vs. KEK experiments

event	$^{A}_{\Lambda\Lambda}Z$	$B^{\rm exp}_{\Lambda\Lambda}$	$B^{\rm CM}_{\Lambda\Lambda}$	$B^{\rm SM}_{\Lambda\Lambda}$
E373-Nagara	$^{6}_{\Lambda\Lambda}$He	6.91 ± 0.16	6.91 ± 0.16	6.91 ± 0.16
E373-DemYan	$^{10}_{\Lambda\Lambda}$Be	14.94 ± 0.13	14.74 ± 0.16	14.97 ± 0.22 †
E176-G2	$^{11}_{\Lambda\Lambda}$Be	17.53 ± 0.71	18.23 ± 0.16	18.40 ± 0.28
E373-Hida	$^{11}_{\Lambda\Lambda}$Be	20.83 ± 1.27	18.23 ± 0.16	18.40 ± 0.28
E373-Hida	$^{12}_{\Lambda\Lambda}$Be	22.48 ± 1.21	–	20.72 ± 0.20
E176-E2	$^{12}_{\Lambda\Lambda}$B	20.02 ± 0.78	–	20.85 ± 0.20
E176-E4	$^{13}_{\Lambda\Lambda}$B	23.4 ± 0.7	–	23.21 ± 0.21

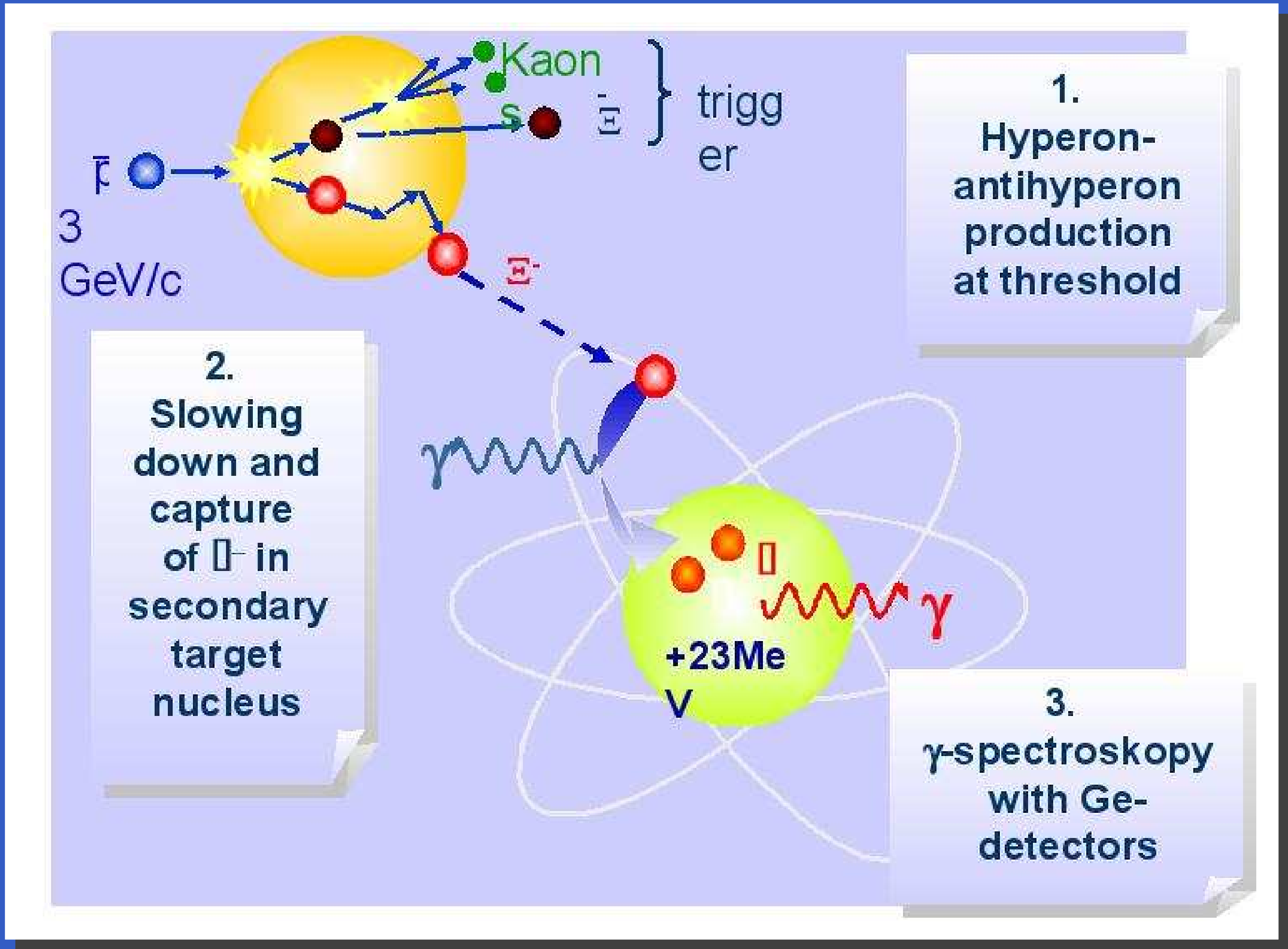
† $B^{\rm SM}_{\Lambda\Lambda}(^{10}_{\Lambda\Lambda}{\rm Be}) = 2\,\overline{B}_{\Lambda}(^{9}_{\Lambda}{\rm Be}) + 4\,[\overline{V}(^{9}_{\Lambda}{\rm Be}) - \overline{V}_{\rm average}] + < V_{\Lambda\Lambda} >_{\rm SM}$.

- All E176 entries refer to a single event, see NPA 828 (2009) 191.
- Hida-event [K. Nakazawa, H. Takahashi, PTPS 185 (2010) 335] interpretations are dubious.

(Gal and Millener 2011)

- three modern events, comparison to shell model and cluster model calculations
- only uniquely identified double Λ hypernucleus: $^{6}_{\Lambda\Lambda}$He !

PANDA at GSI: Measurement of double Λ hypernuclei



- production of Ξ via antiproton beam on nuclei
- capture of Ξ in another nucleus
- γ-spectroscopy of produced double-Λ hypernucleus

Summary of Hypernuclear Systems

NΛ: attractive $\rightarrow$ Λ-hypernuclei for $A = 3 - 209$

$U_\Lambda = -30$ MeV at $n = n_0$

NΣ: ${}^4_\Sigma$He hypernucleus bound by isospin forces

Σ^- atoms: potential is repulsive

NΞ: attractive $\rightarrow$ 7 Ξ hypernuclear events

$U_\Xi = -28$ MeV at $n = n_0$

quasi-free production of Ξ: $U_\Xi = -18$ MeV

$\Lambda\Lambda$: attractive $\rightarrow$ 5 $\Lambda\Lambda$ hypernuclear measurements

YY: Y$= \Lambda, \Sigma, \Xi$, unknown!

hypernuclear programs at:

DaΦne, JLab, J-PARC, MAMI, and PANDA, HYPHI @FAIR!

Metastable Exotic Multihypernuclear Objects (MEMOs)

Classification of strange hadronic matter: doublets

$-S\backslash Z$	-2	-1	0	+1	+2
0			nn	np	pp
1		Σ^-n	Λ n	Λ p	Σ^+p
2	$\Sigma^-\Sigma^-$	Ξ^-n	$\Lambda\Lambda$	Ξ^0p	$\Sigma^+\Sigma^+$
3	$\Xi^-\Sigma^-$	$\Xi^-\Lambda$	$\Xi^0\Lambda$	$\Xi^0\Sigma^+$	
4	$\Xi^-\Xi^-$	$\Xi^0\Xi^-$	$\Xi^0\Xi^0$		
5	$\Xi^-\Omega^-$	$\Xi^0\Omega^-$			
6	$\Omega^-\Omega^-$				

(JS, C.Greiner, Stöcker 1992, JSB, Dover, Gal, Millener, C.Greiner, Stöcker 1993, 1994)

ordering according to lowest sum of vacuum masses for given strangeness S and charge Z

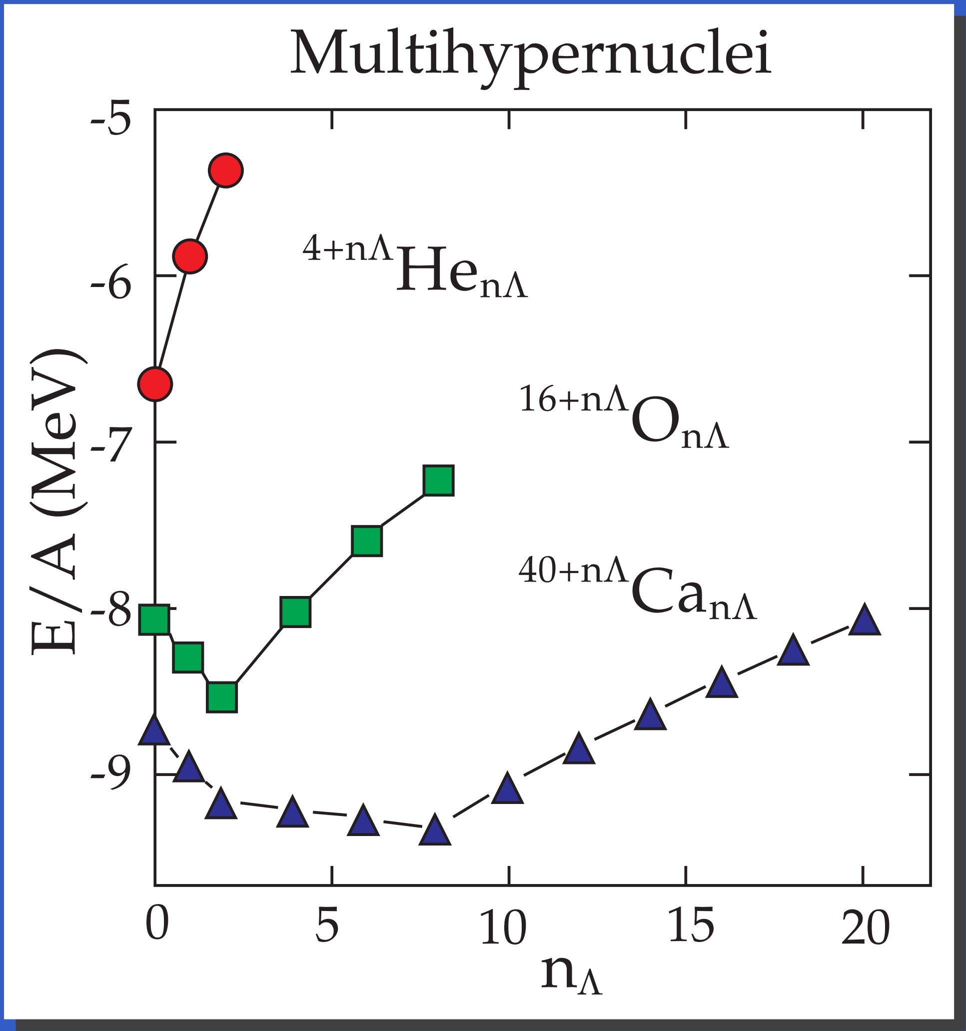
Classification of strange hadronic matter: triplets

$-S\backslash Z$	-2	-1	0	+1	+2
1				Λnp	
2					
3	$\Xi^-\Sigma^-$n	$\Xi^-\Lambda$n		$\Xi^0\Lambda$ p	$\Xi^0\Sigma^+$p
4					
5		$\Xi^-\Xi^0\Lambda$			
6					
7	$\Omega^-\Xi^-\Xi^0$				

(JS, C. Greiner, Stöcker 1992, JSB, Dover, Gal, Millener, C. Greiner, Stöcker 1993, 1994)

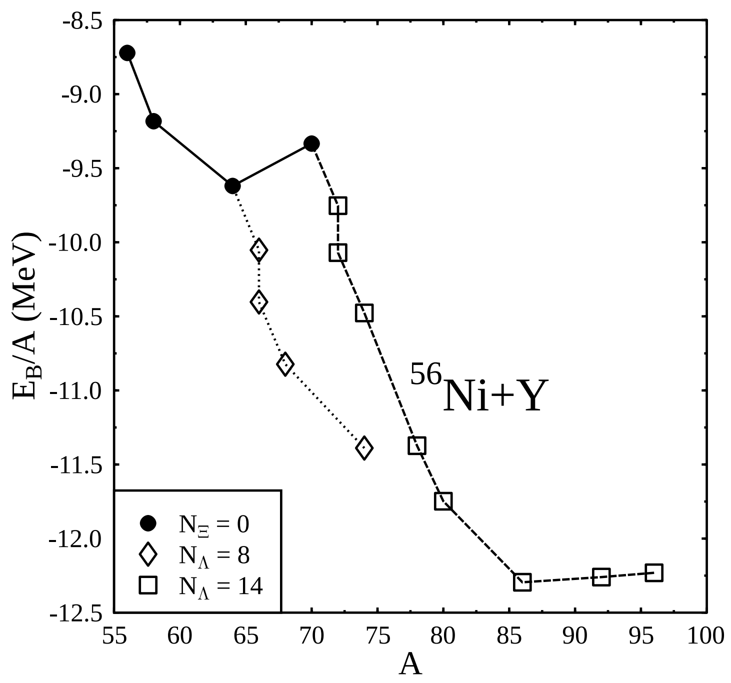
more than three different baryons: system not stable against strong decay in vacuum

Stability of multi-Λ hypernuclei



- total binding energy becomes smaller for light systems
- binding energy increase for heavier systems
- maximum binding energy for some (magic) number of Λ's

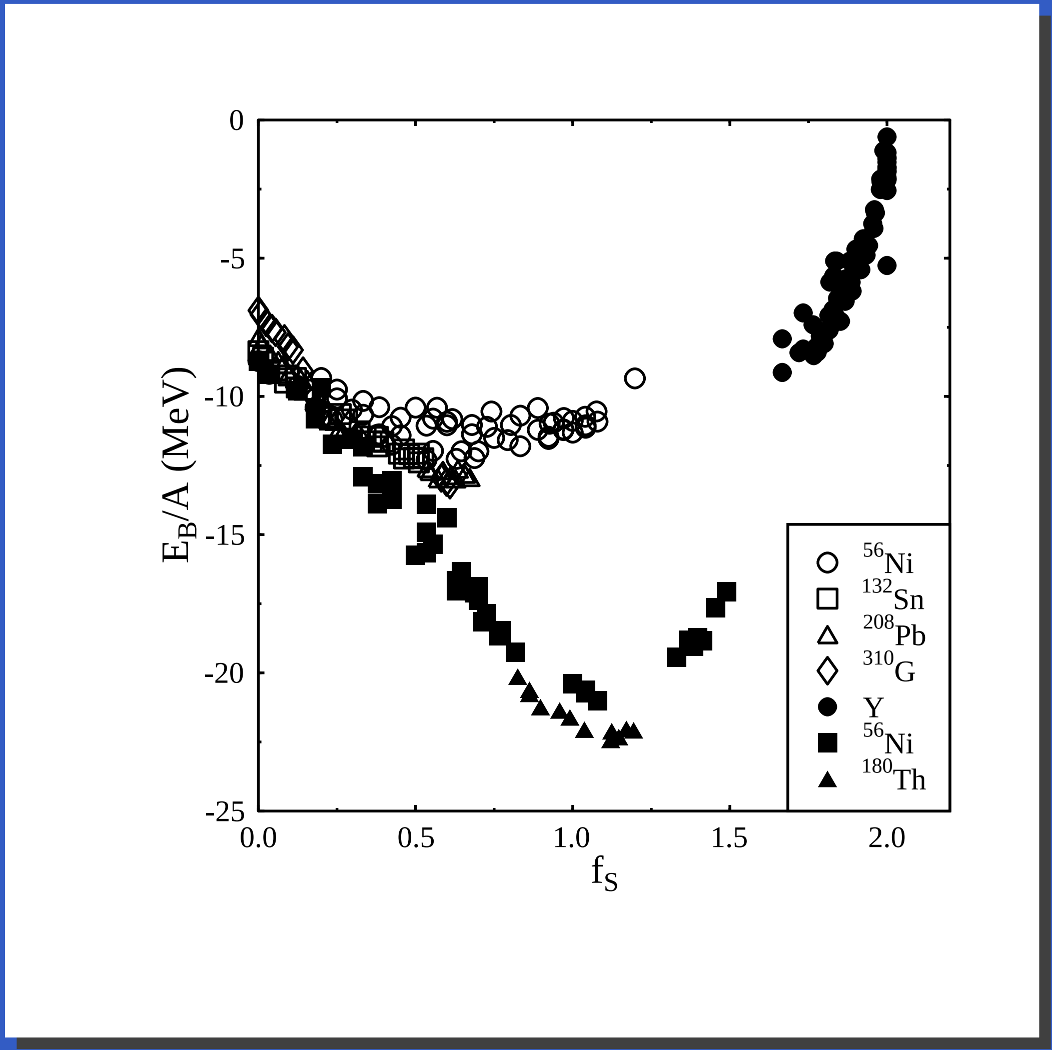
Systems of Nucleons and Hyperons



(JS, Dover, Gal, Greiner, Stöcker (1993))

- Pauli–blocking of the reactions: $\Lambda + \Lambda \leftrightarrow \Xi + N$, $Q \approx -25$ MeV
- Σs are not stable: $\Sigma + N \to \Lambda + N$, $Q \approx -80$ MeV
- nuclear binding energy with Λs and Ξs increases to $E/A = -12$ MeV!

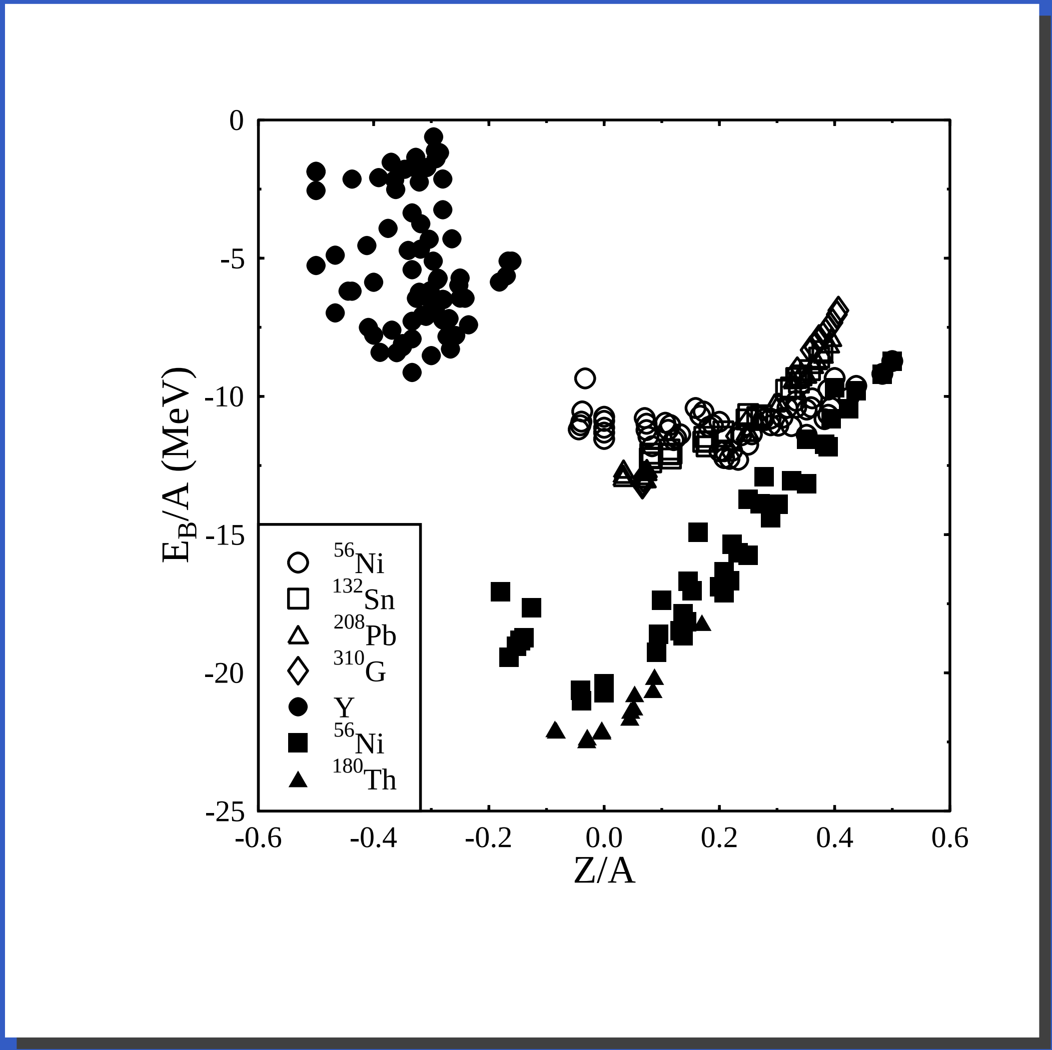
Binding energy of multistrange nuclei



(JS, Dover, Gal, Greiner, Stöcker (1993))

- sizable increase of the binding energy to $E/A = -21$ MeV
- large strangeness fraction of $f_s = |S|/A = 0.6$ up to $f_s = 1.1$

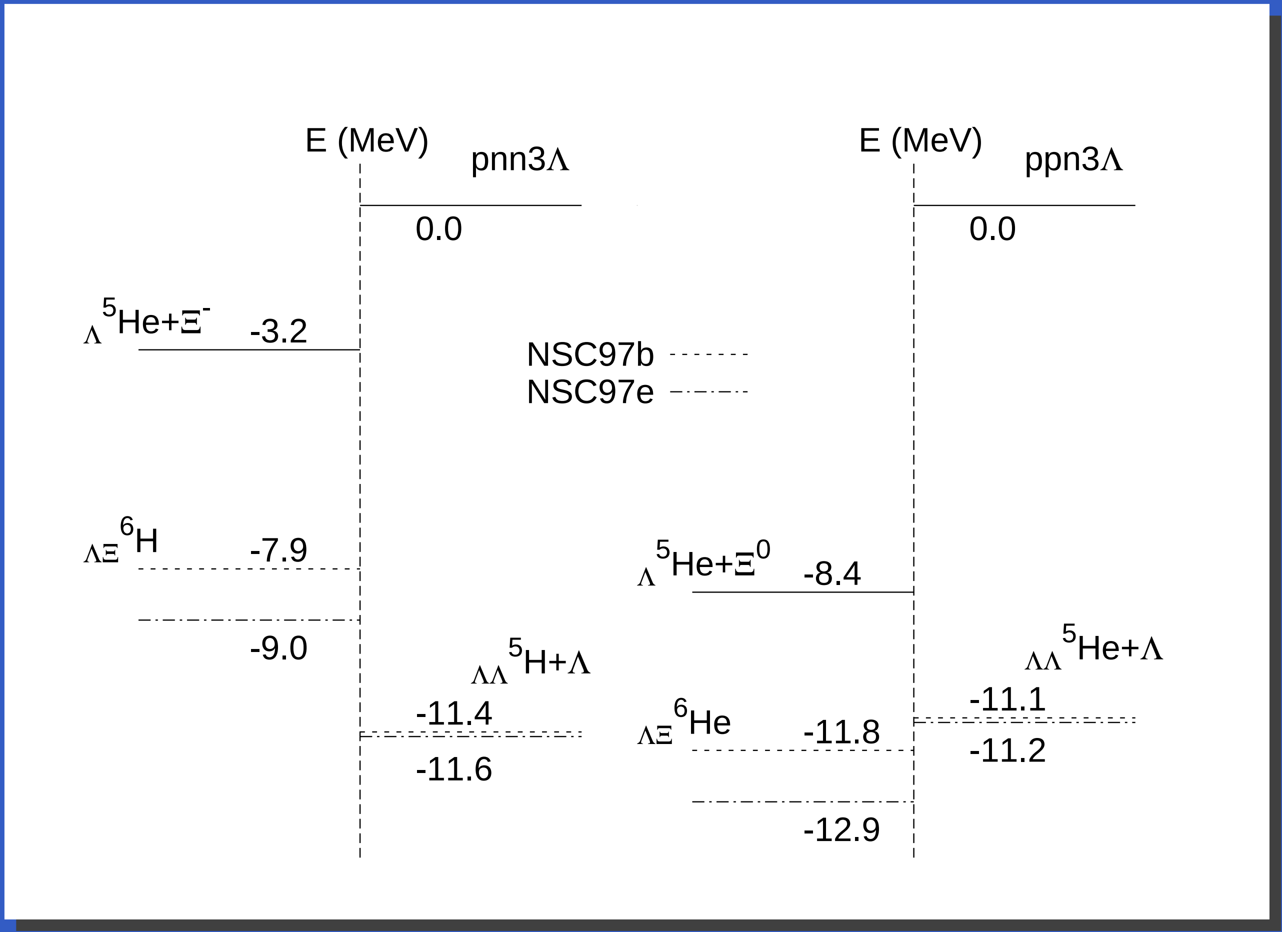
Charge of multistrange nuclei



(JS, Dover, Gal, Greiner, Stöcker (1993))

- negatively charged nuclei possible (with positive baryon number)!
- purely hyperonic nuclei exist for $f_s = 1.8$ and $Z/A \approx -0.3$

Lightest MEMO candidate: ${}^{6}_{\Lambda\Xi}$He



(Filikhin and Gal 2002)

- binding energy for different light systems with an α core plus three units of strangeness within a Fadeev calculation
- possibly the lightest MEMO: ${}^{6}_{\Lambda\Xi}$He where $\Xi + N \to \Lambda + \Lambda$ is Pauli-blocked

Dibaryons

Multi-Quark States: Some History (incomplete)

- multi-quark states already mentioned by Gell-Mann in 1964
- strange four-quark states ($qs\bar{q}\bar{s}$): Jaffe 1977
- strange six-quark states ($qqqqss$: H-dibaryon): Jaffe 1978
- heavy tetraquarks ($QQ\bar{q}\bar{q}$): Ader, Richard, Taxil 1982
- pentaquarks with charm ($qqqs\bar{c}$): Lipkin 1987 and Gignoux, Silvestre-Brac, Richard 1987
- . . .
- light pentaquark ($qqqq\bar{s}$) in chiral soliton model: Diakonov, Petrov, Polyakov 1997
- light pentaquark in diquark model: Jaffe and Wilczek 2003

News from Lattice Data on Dibaryons

- HALQCD collaboration (Inoue et al. 2011):
  bound H-dibaryon with $B_H = 20 - 50$ MeV (for $m_{ps} = 469 - 1171$ MeV)
- NPLQCD collaboration (Beane et al. 2011):
  bound H-dibaryon with $B_H = 13.2(1.8)(4.0)$ MeV and bound $(\Xi^-\Xi^-)_b$ state with $B_{\Xi\Xi} = 14.0(1.4)(6.7)$ MeV (for $m_\pi = 390$ MeV)
- Shanahan, Thomas, Young 2011:
  H unbound by 13 ± 14 MeV at physical pion mass
- Haidenbauer and Meißner 2011:
  either $\Lambda\Lambda$ is unbound (HALQCD) or
  a resonant state 5 MeV below ΞN threshold (NPLQCD)

Baryon-baryon potentials: SU(3) symmetry

TABLE XIII. SU(3) content of the different interaction channels. S is the total strangeness and I is the isospin. The upper half refers to the space-spin symmetric states $^3S_1$, $^1P_1$, ^3D, ..., while the lower half refers to the space-spin antisymmetric states $^1S_0$, ^3P, $^1D_2$, ...

S	I	Channels	SU(3) irreps
		Space-spin symmetric states	
0	0	NN	$\{10^*\}$
−1	1/2	ΛN, ΣN	$\{10^*\}$, $\{8\}_a$
	3/2	ΣN	$\{10\}$
−2	0	ΞN	$\{8\}_a$
	1	ΞN, $\Sigma\Sigma$	$\{10\}$, $\{10^*\}$, $\{8\}_a$
		$\Sigma\Lambda$	$\{10\}$, $\{10^*\}$
−3	1/2	$\Xi\Lambda$, $\Xi\Sigma$	$\{10\}$, $\{8\}_a$
	3/2	$\Xi\Sigma$	$\{10^*\}$
−4	0	$\Xi\Xi$	$\{10\}$
		Space-spin antisymmetric states	
S	I	Channels	SU(3) irreps
0	1	NN	$\{27\}$
−1	1/2	ΛN, ΣN	$\{27\}$, $\{8\}_s$
	3/2	ΣN	$\{27\}$
−2	0	$\Lambda\Lambda$, ΞN, $\Sigma\Sigma$	$\{27\}$, $\{8\}_s$, $\{1\}$
	1	ΞN, $\Sigma\Lambda$	$\{27\}$, $\{8\}_s$
	2	$\Sigma\Sigma$	$\{27\}$
−3	1/2	$\Xi\Lambda$, $\Xi\Sigma$	$\{27\}$, $\{8\}_s$
	3/2	$\Xi\Sigma$	$\{27\}$
−4	1	$\Xi\Xi$	$\{27\}$

(Stoks and Rijken 1999)

- classify states according to SU(3)
- coupling of two octets: $8 \times 8 = 1 + 8 + 8 + 10 + 10^* + 27$
- NN has bound state in $^3S_1 - ^3D_1$ (deuteron) $\rightarrow \{10^*\}$
- NN has quasi-bound state in $^3S_0$ ($E = +90$ keV) $\rightarrow \{27\}$
- SU(3) symmetry: bound states in all pure $\{10^*\}$
- broken SU(3): quasi-bound states become bound as hyperons are heavier than nucleons

Baryon-baryon potentials: Nijmegen soft-core models

- Nijmegen soft core model NSC97a-f (newer versions of extended soft-core model: ESC04-08)
- one-boson exchange model for pseudoscalar, scalar, and vector mesons
- uses SU(3) flavour symmetry
- fitted to NN and NY scattering data
- predictions for dibaryons (Stoks, Rijken 1999):

Baryon-baryon potentials: Nijmegen soft-core models

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- uses SU(3) flavour symmetry
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- predictions for dibaryons (Stoks, Rijken 1999):

Σ^+p, Σ^-n:	quasibound state
$\Sigma^+\Sigma^+$, $\Sigma^-\Sigma^-$:	$E_b = -1.5$ to -3.2 MeV
$\Xi^0\Sigma^+$, $\Xi^-\Sigma^-$:	$E_b = -2$ to -17 MeV
$\Xi^0\Xi^0$, $\Xi^0\Xi^-$:	$E_b = +1$ to -16 MeV
$\Xi^-\Xi^-$:	less bound by ≈ 1 MeV

Baryon-baryon potentials: Quark-meson models

- quark-meson exchange model
- uses confinement potential for quarks
- SU(3) symmetry for quark-meson coupling constants
- describes light hypernuclei
- predictions for dibaryons
  (Fujiwara, Suzuki, Nakamoto 2007):

Baryon-baryon potentials: Quark-meson models

- quark-meson exchange model
- uses confinement potential for quarks
- SU(3) symmetry for quark-meson coupling constants
- describes light hypernuclei
- predictions for dibaryons
  (Fujiwara, Suzuki, Nakamoto 2007):

no bound states

Baryon-baryon potentials: chiral effective models

- one-boson exchange of pseudoscalar mesons plus contact terms
- uses SU(3) symmetry, low-energy constants
- fixed to NN and NY scattering data
- predictions for dibaryons
  (Haidenbauer and Meißner 2010):

Baryon-baryon potentials: chiral effective models

- one-boson exchange of pseudoscalar mesons plus contact terms
- uses SU(3) symmetry, low-energy constants
- fixed to NN and NY scattering data
- predictions for dibaryons (Haidenbauer and Meißner 2010):

$\Xi^0\Lambda$:	$E_b = -0.43$ MeV or quasibound
$\Xi^0\Sigma^+$:	$E_b = -2.23$ to -6.15 MeV
$\Xi\Xi$:	$E_b = -2.56$ to -7.28 MeV

results depend on cutoff

SU(3) model for hyperon weak decays

Matrix element of mesonic decay $B \to B' + \pi$:

$$\mathcal{M} = \bar{u}_f (A + B\gamma_5) u_i \cdot \phi_\pi$$

SU(3) flavour symmetry for weak interaction vertex of two baryons and one pseudoscalar meson

$$\begin{aligned} \mathcal{L} &= D \mathrm{Tr} \bar{B} B \left[P, \lambda_6\right] + F \mathrm{Tr} \bar{B} \left[P, \lambda_6\right] B \\ &\quad + G \mathrm{Tr} \bar{B} P \gamma_5 B \lambda_6 + H \mathrm{Tr} \bar{B} \lambda_6 \gamma_5 B P + J \mathrm{Tr} \bar{B} \{P, \lambda_6\} \gamma_5 B \end{aligned}$$

B: baryon octet, P: pseudoscalar nonet.
Parameters: $D = 4.72$ and $F = -1.62$ for A amplitudes and $G = 40.0$, $H = 47.8$, and $J = -7.1$ for the B amplitudes in units of 10^{-7}

(JSB, Mattiello, Sorge 2000)

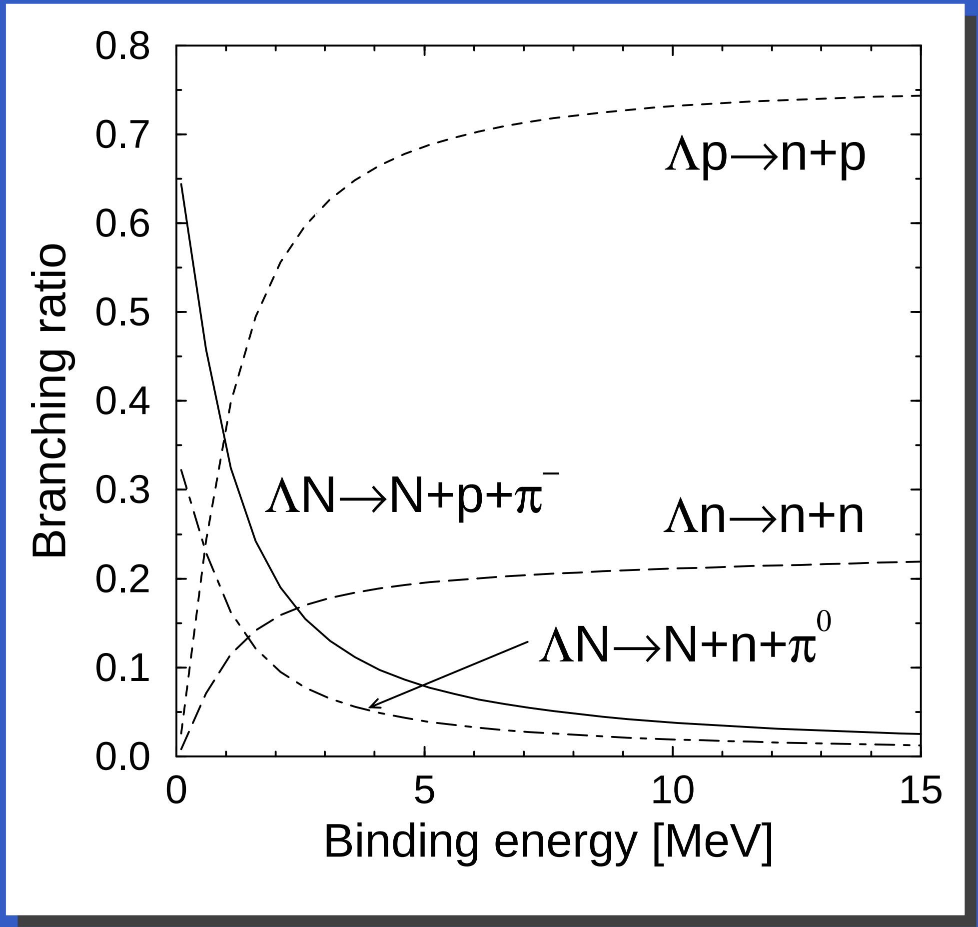
SU(3) model for nonmesonic decay

model the nonmesonic decay

$$(B_1 B_2) \to B_1' + B_2'$$

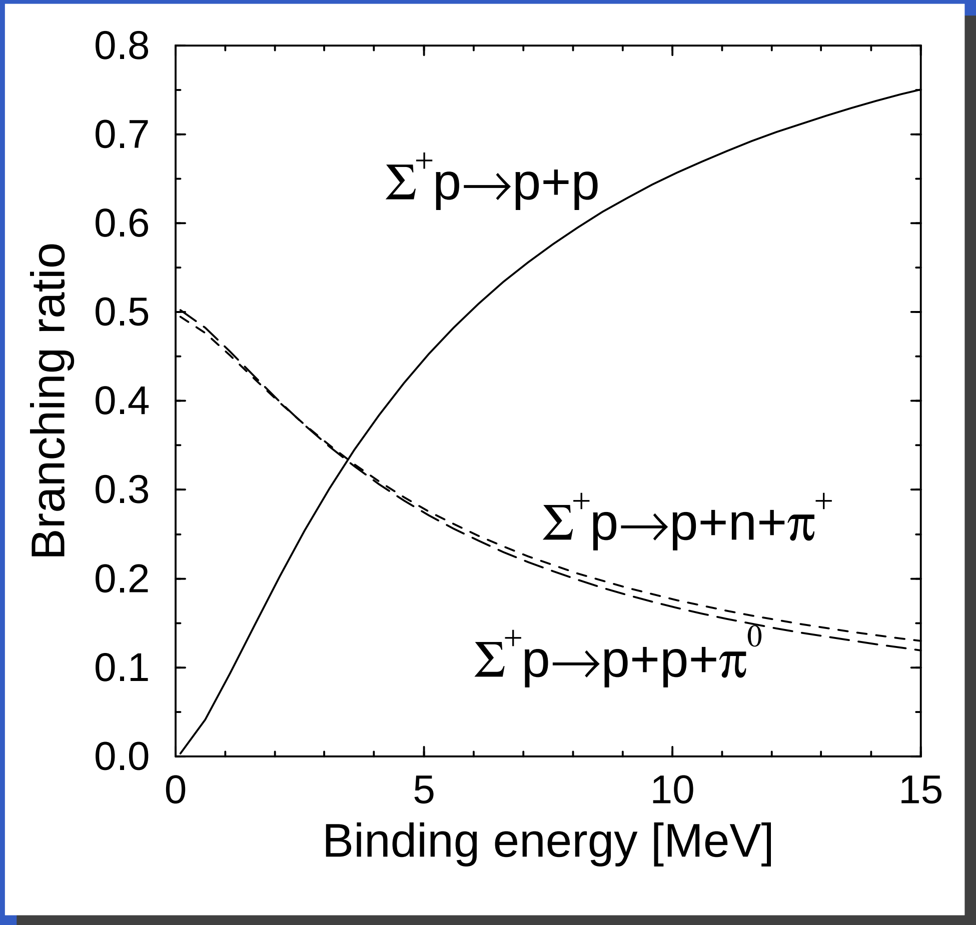
- meson exchange model: strong vertex from one-boson exchange model
- weak vertex from weak hyperon decay
- use parameterized deuteron-like wavefunction (Krivoruchenko and Shchepkin 1982)
- one parameter: binding energy of dibaryon system

Weak decays of bound ΛN systems



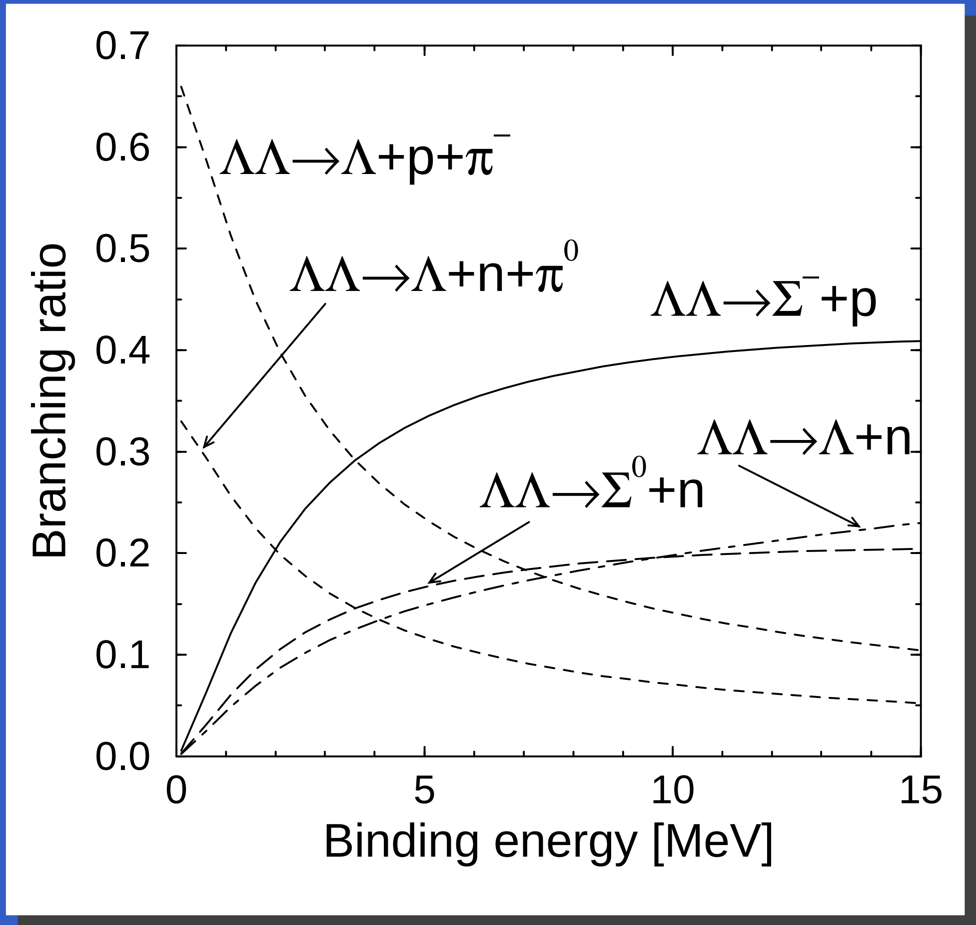
- mesonic decay dominates for small binding energies
- dominant decay mode is the nonmesonic one for larger binding energies
- $\Delta I = 1/2$ rule favours nonmesonic decays with protons

Dibaryon Σp



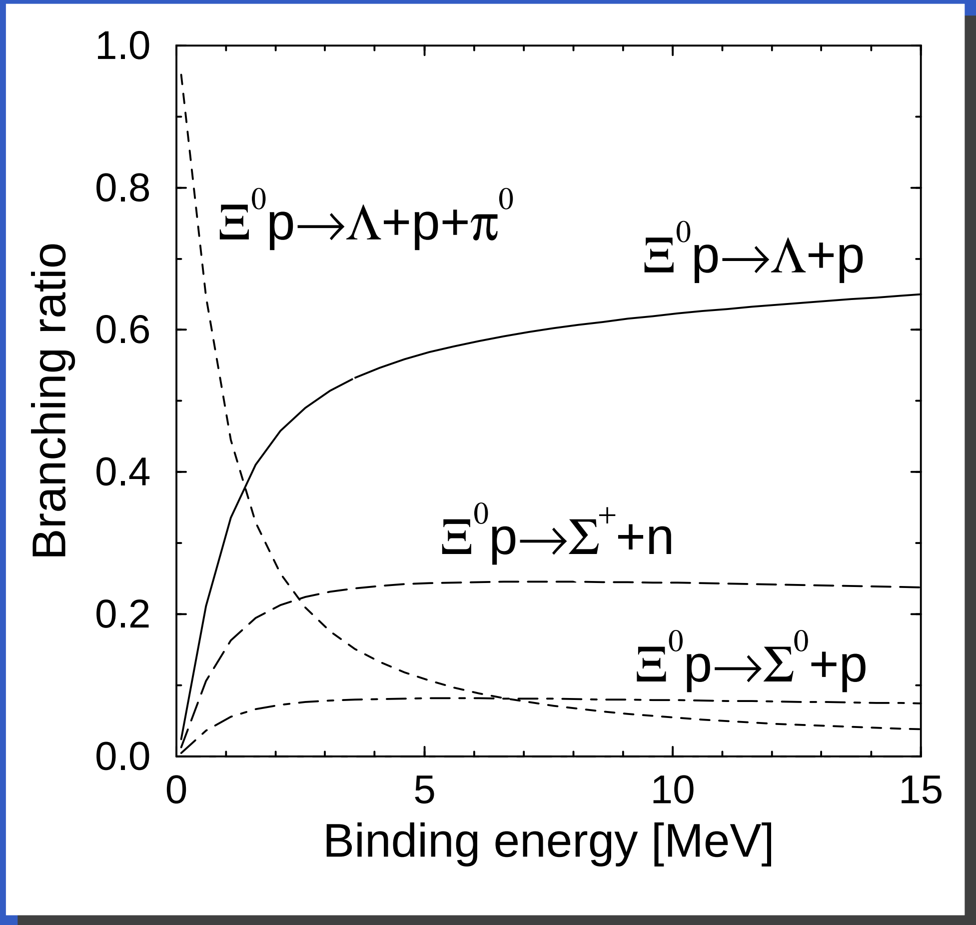
- Σ^+p has charge +2 !
- only one nonmesonic decay channel possible to two protons
- a bound state should show up in invariant pp-spectrum at $M = 2.128$GeV $- E_b$

Weak Decays of Dibaryon $\Lambda\Lambda$



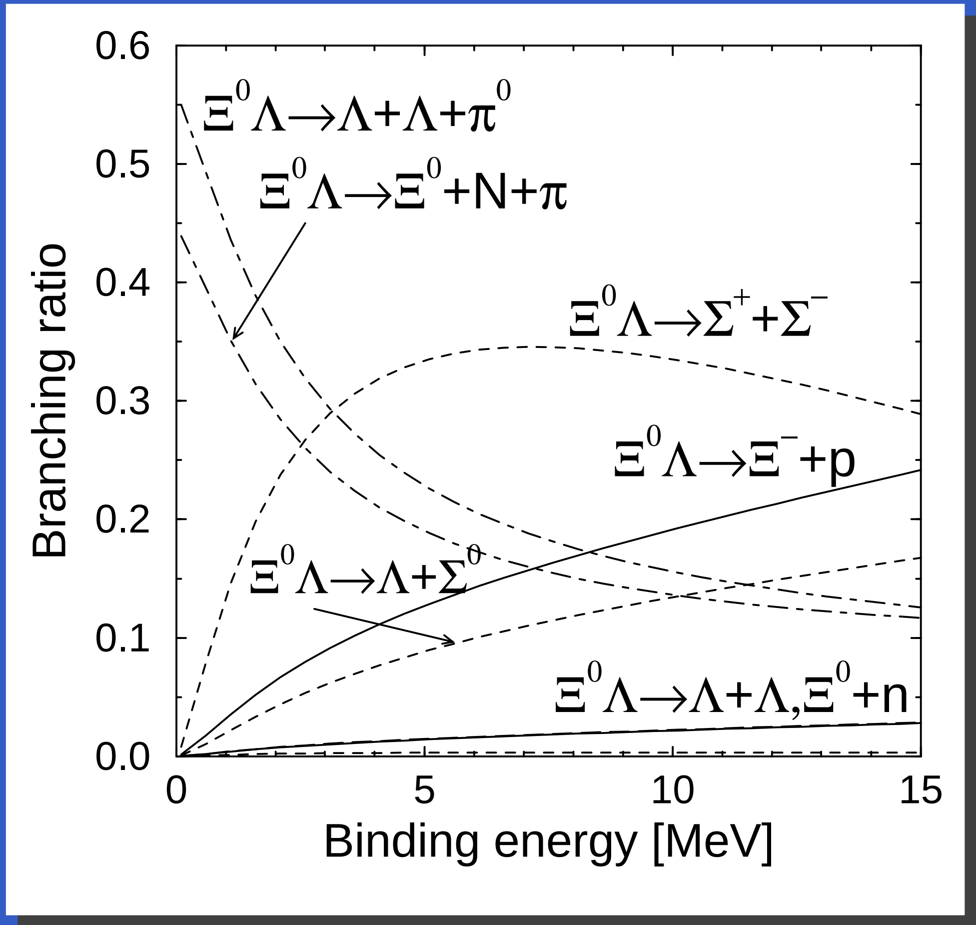
- dominant decay mode of the dihyperon is $(\Lambda\Lambda)_b \rightarrow \Sigma^- + \mathrm{p}$
- similar to the H-dibaryon $H \rightarrow \Sigma^- + \mathrm{p}$

Weak Decays of Dibaryon Ξ^0p



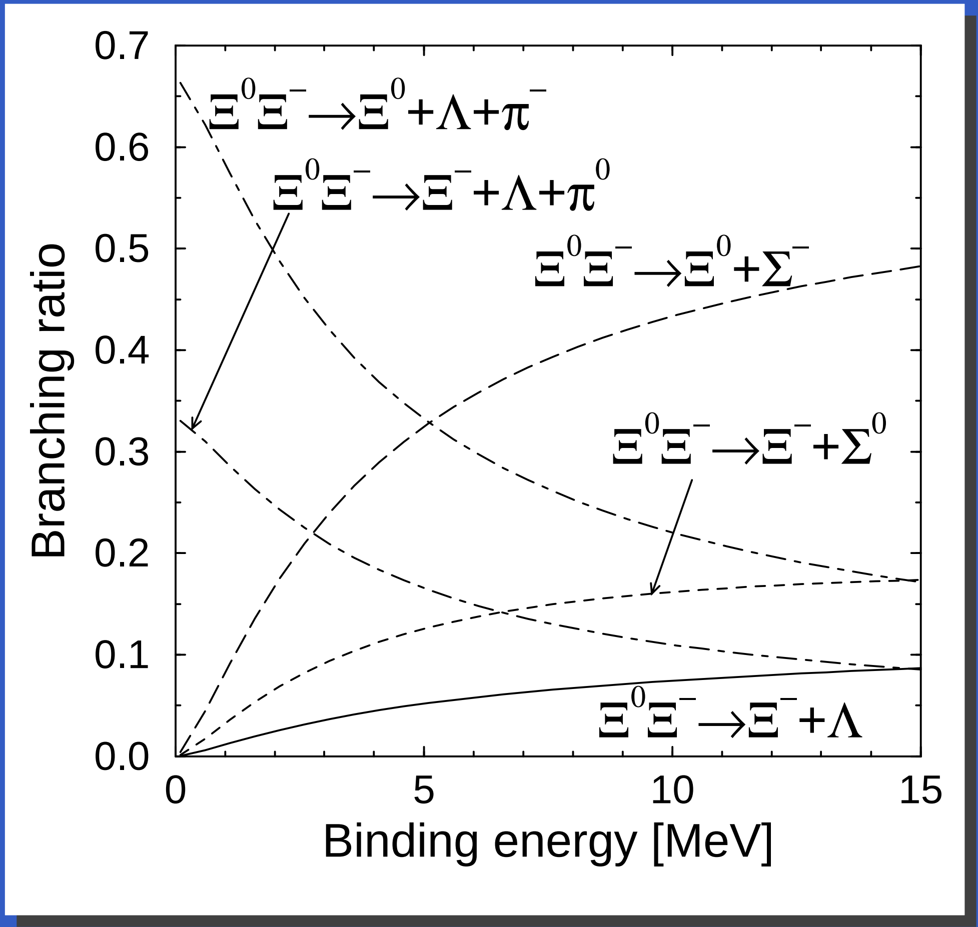
- decay $(\Xi^0 \mathrm{p})_b \to \Lambda + \mathrm{p}$ dominates for $E_b > 1.5$ MeV
- can be seen in Λp mass spectrum
- weak decay has the same decay topology as $\Xi^- \to \Lambda + \pi^-$ and $\Omega^- \to \Lambda$K$^-$

Weak Decays of Dibaryon $\Xi^0\Lambda$



- $(\Xi^0\Lambda)_b$ decays to $\Lambda + \Lambda$ or $\Xi^- + \mathrm{p}$
- look at $\Lambda\Lambda$ and Ξ^-p invariant mass spectrum
- reconstruction of two Λs in a single event possible (AGS: E896, SPS: WA97, RHIC: STAR, CERN:ALICE)

Weak Decays of Dibaryon $\Xi^0\Xi^-$

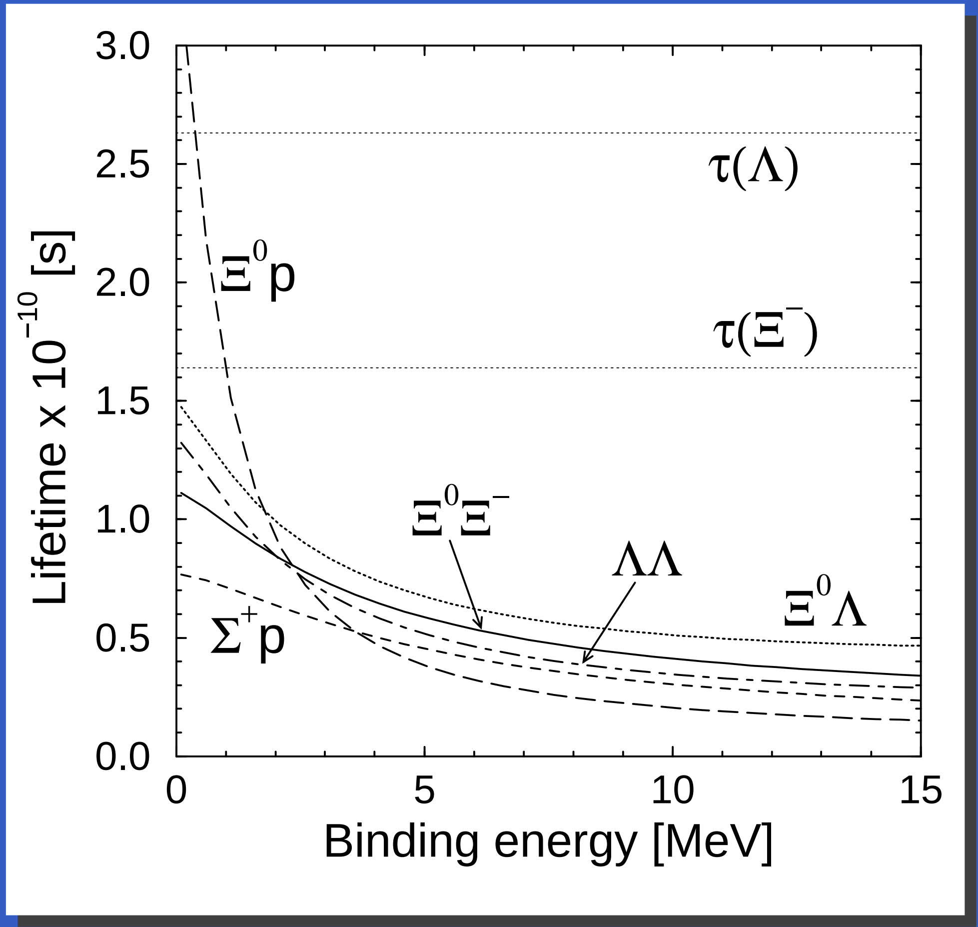


- predicted to be bound by Nijmegen model NSC97 and Chiral EFT
- can be seen by $(\Xi^0\Xi^-)_b \rightarrow \Xi^- + \Lambda$ in $\Xi^-\Lambda$ mass plots
- branching ratio is only a few percent

Doubly Charged Dibaryons

- $(\Sigma^-\Sigma^-)_b \rightarrow \Sigma^- + n + \pi^-$ (the only decay channel!)
- $$\begin{aligned}(\Sigma^-\Xi^-)_b &\rightarrow \Sigma^- + \Sigma^- \\ &\rightarrow \Sigma^- + \Lambda + \pi^- \\ &\rightarrow \Xi^- + n + \pi^-\end{aligned}$$
- $$\begin{aligned}(\Xi^-\Xi^-)_b &\rightarrow \Xi^- + \Sigma^- \\ &\rightarrow \Xi^- + \Lambda + \pi^-\end{aligned}$$
- all decays have a unique decay prong (one track splits to two)!
- experimental problem: neutral particles and/or three-body decay, hard to measure

Lifetime of dibaryons



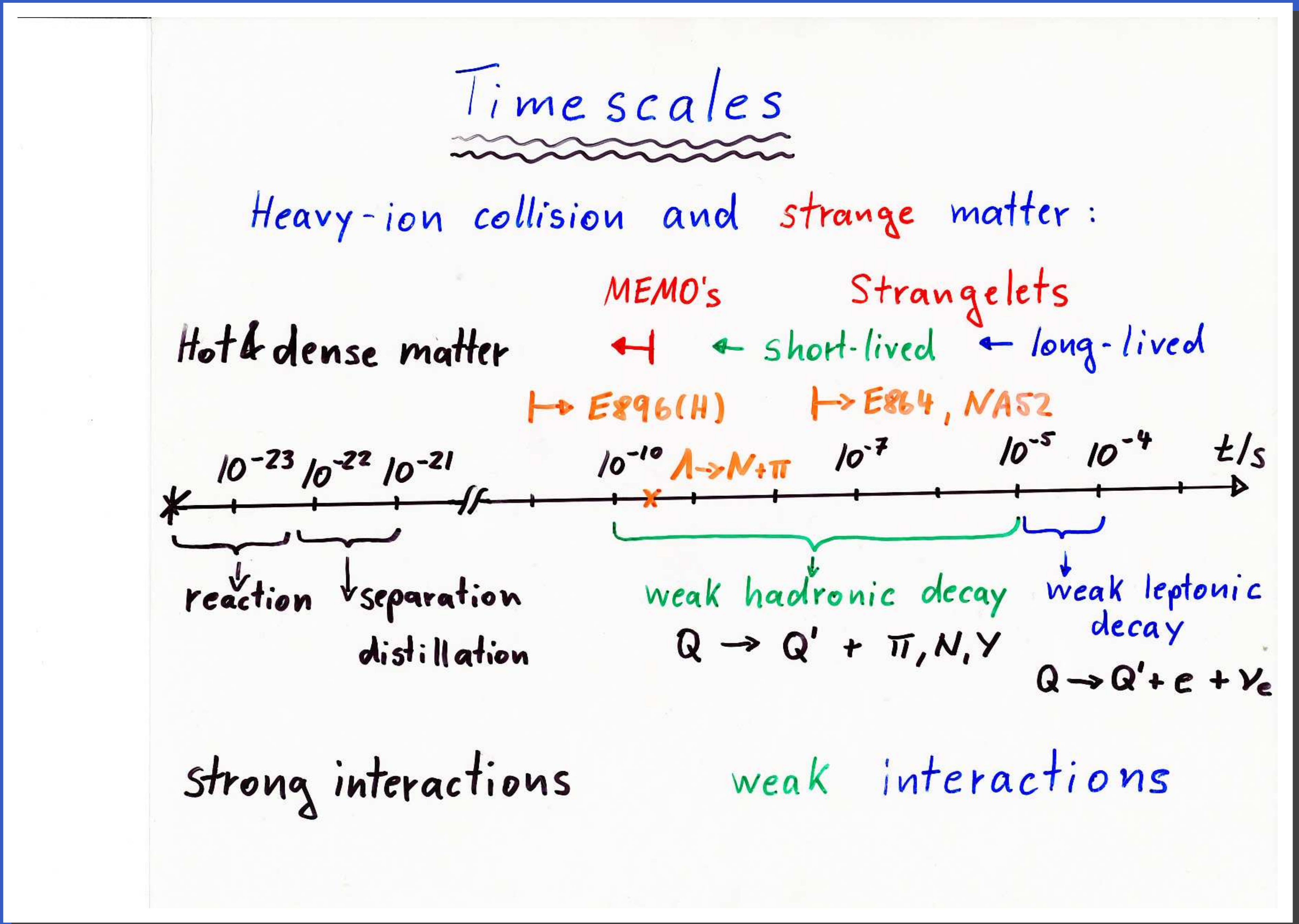
- bound dibaryons have just a smaller decay length than hyperons $c\tau = 1 - 5$ cm
- lifetime decreases with the binding energy as baryons are sitting closer together

Meson assisted strange dibaryons

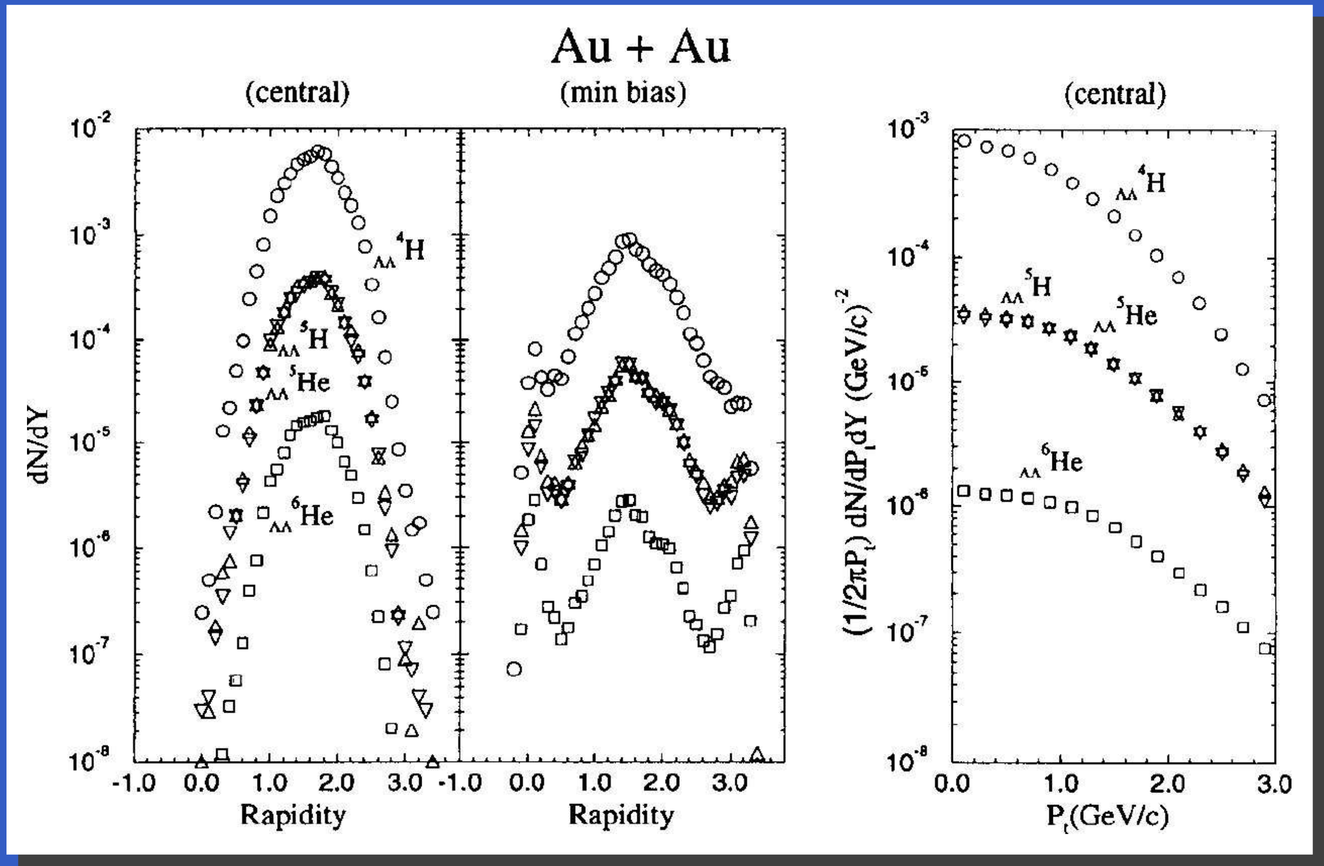
- proposed by Gal and Garcilazo (2008, 2010)
- bound states of mesons and two baryons
- maximum isospin, attractive p-wave channel for mesons
- candidates: $\pi N \Xi$, $\pi \Lambda \Xi$
- charmed analog: $\pi N \Lambda_c$
  (can only decay weakly if bound!)

Finding exotic matter

Timeline for strange matter detection



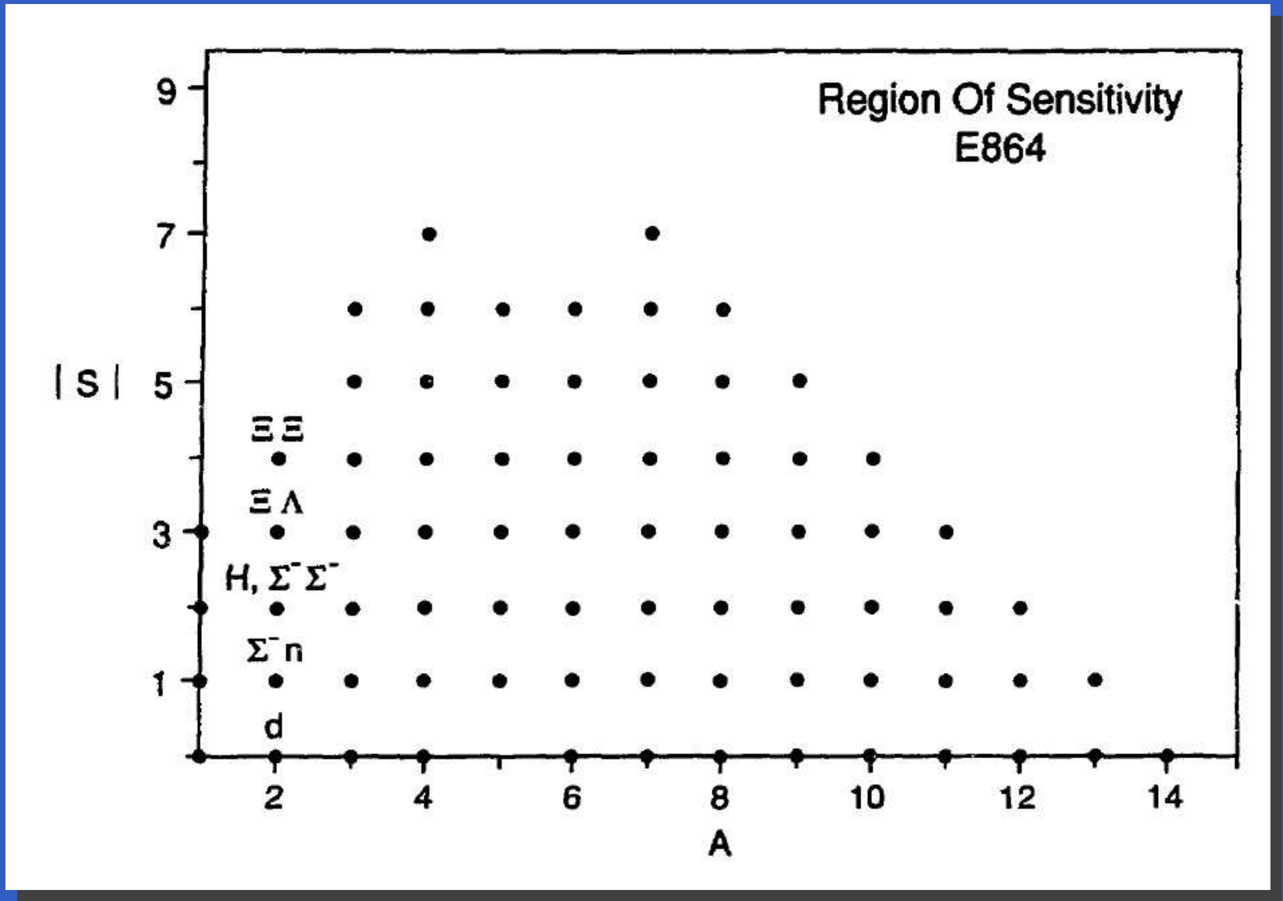
Double hypernuclei production at the AGS



(Baltz, Dover, Kahana, Pang, Schlegel, Schnedermann 1994)

- coalescence model within a relativistic transport model
- first full phase-space model calculation for hypernuclear production in heavy-ion collisions
- includes (significant) production rates for double Λ hypernuclei

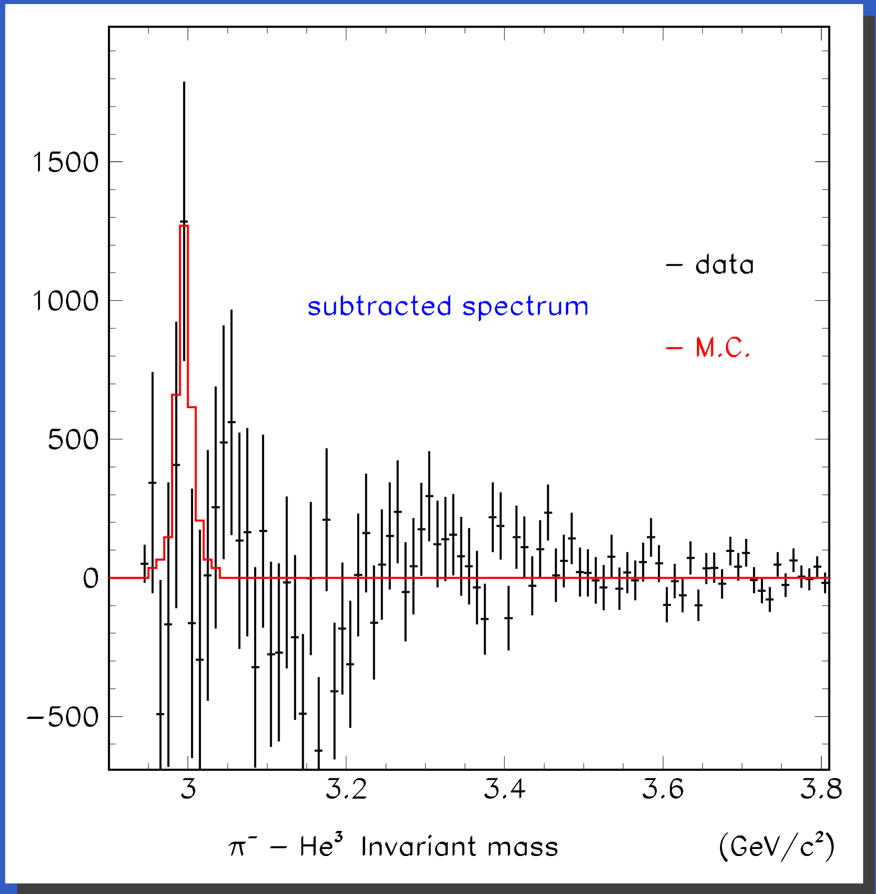
Sensitivity range for detecting strange matter

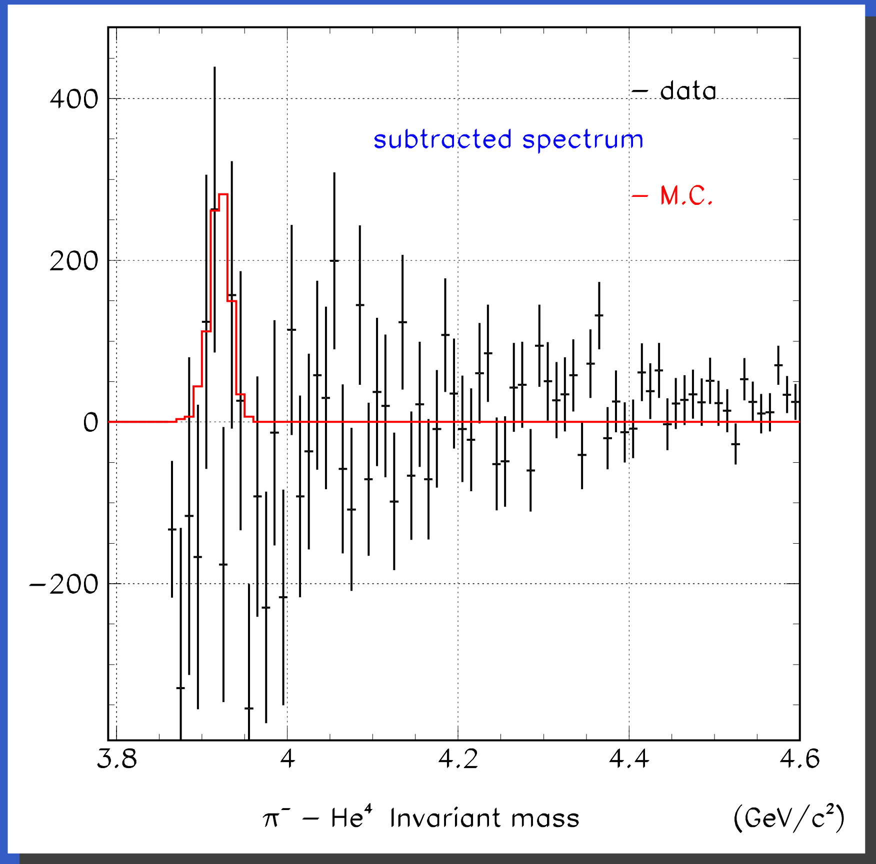


(Dover, talk given at PANIC meeting 1991, preprint BNL-46322)

- rough coalescence estimate: production $\propto q^A \cdot \lambda^{|S|}$, $q = N_d/N_p$, $\lambda = N_Y/N_N$
- for a sensitivity of the experiment of 10^{-n}: $|S| + A \leq n + 3$
- includes (stable) dibaryon states!

Production of hypernuclei in heavy-ion collisions

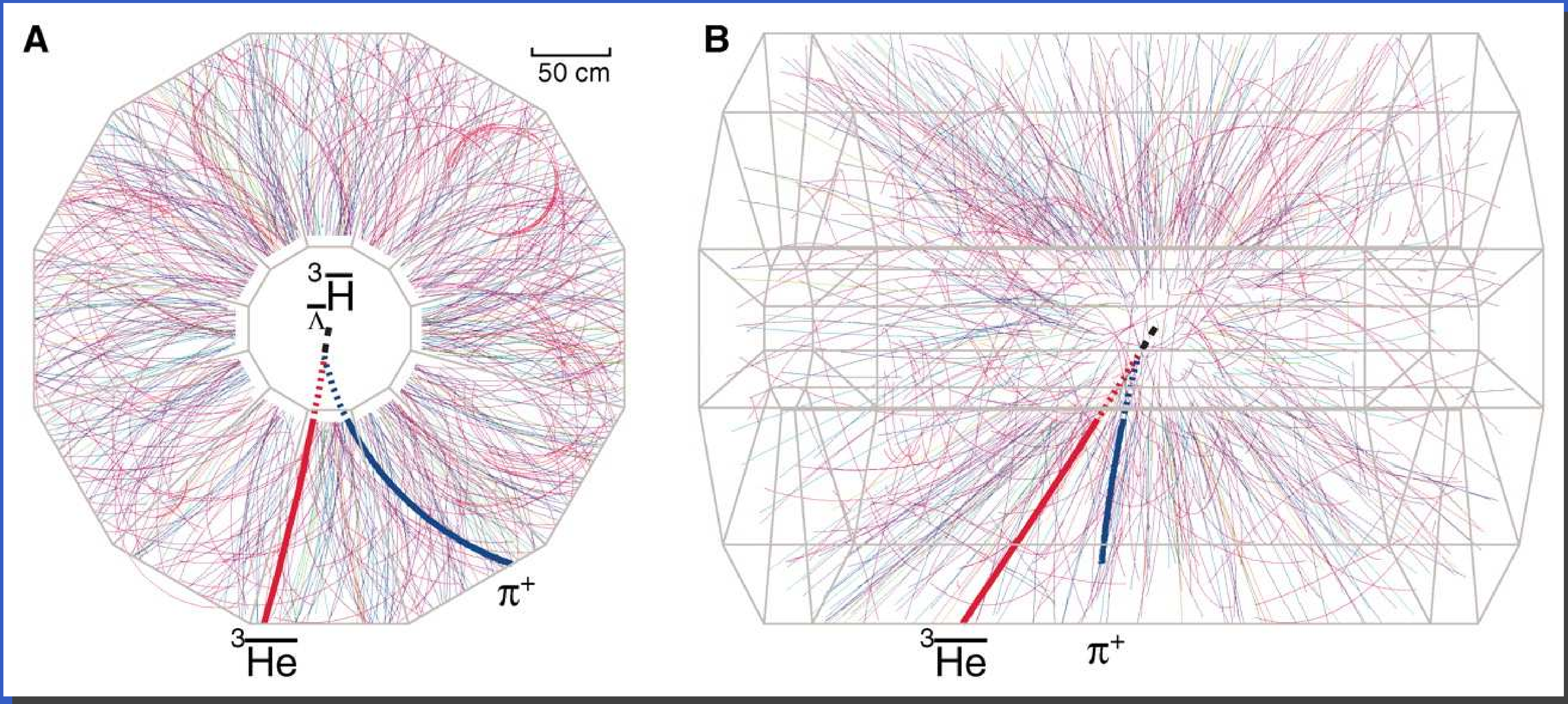




(Armstrong, Dover et al. (E864 collaboration) 2004)

- production of ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H seen!
- decay modes: ${}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^{-}$, ${}^{4}_{\Lambda}\mathrm{H} \to {}^{4}\mathrm{He} + \pi^{-}$
- last paper of Carl Dover!

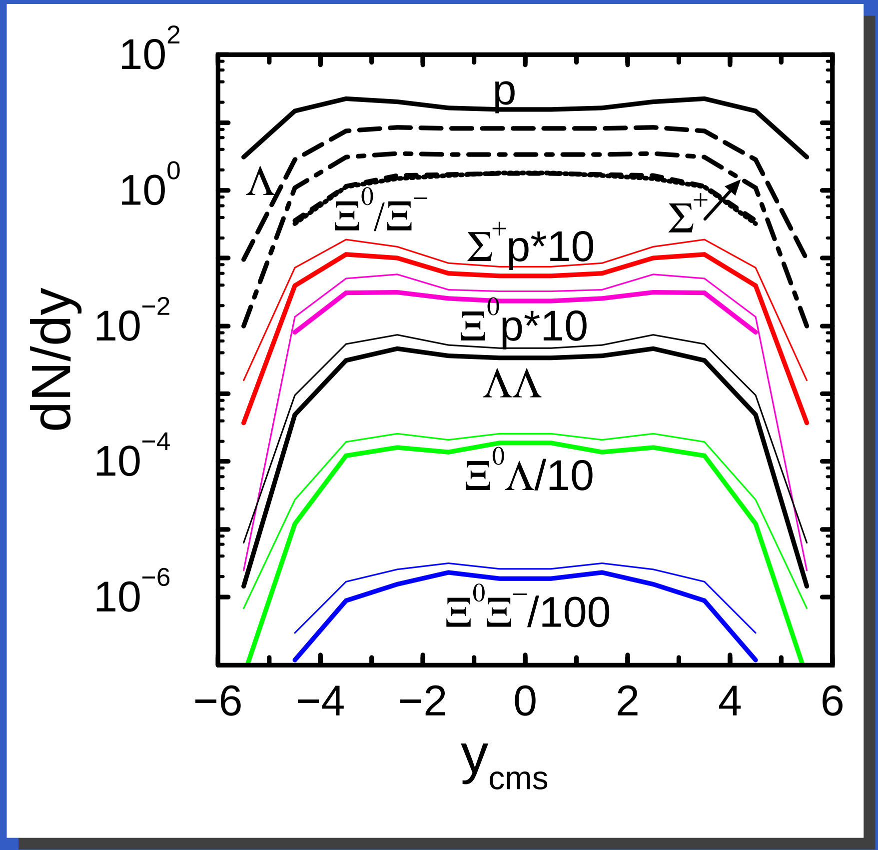
Fishing hypernuclei out of the QGP at RHIC



(STAR collaboration, Science 2010)

- production of $^{3}_{\Lambda}$H and its antiparticle seen
- measurement of invariant mass spectrum of π^{-} and ^{3}He
- initiated follow-up experiments at GSI (FOPI) and LHC (ALICE)!

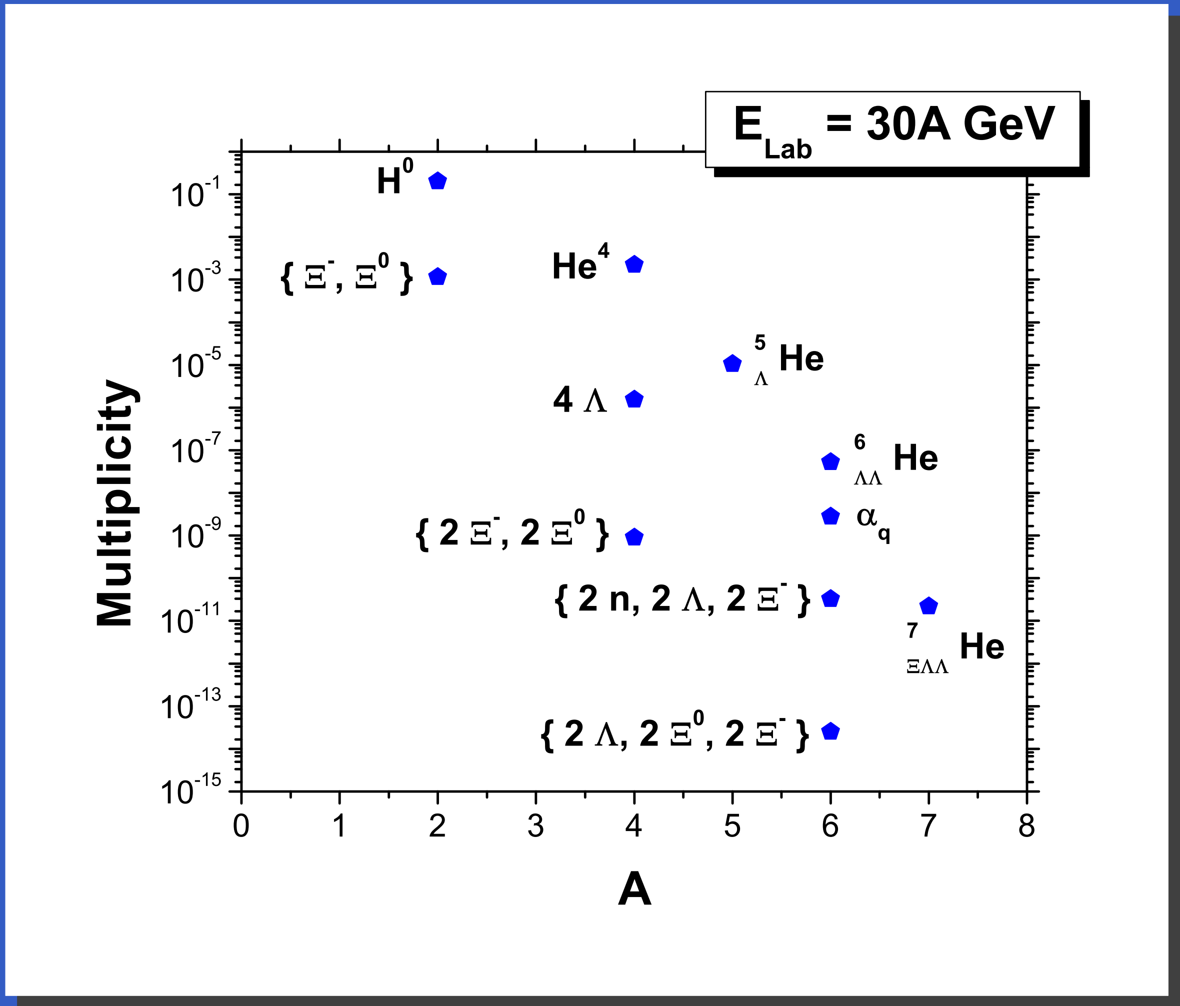
Dibaryon production rates at RHIC



(JSB, Mattiello, Sorge 2000)

- assuming coalescence, phase-space overlap
  (a QGP or a chiral phase will enhance rates)
- production rates for dihyperons are between 10^{-2} and 10^{-4} per event
- flat rapidity distribution, detection at forward/backward rapidity likely

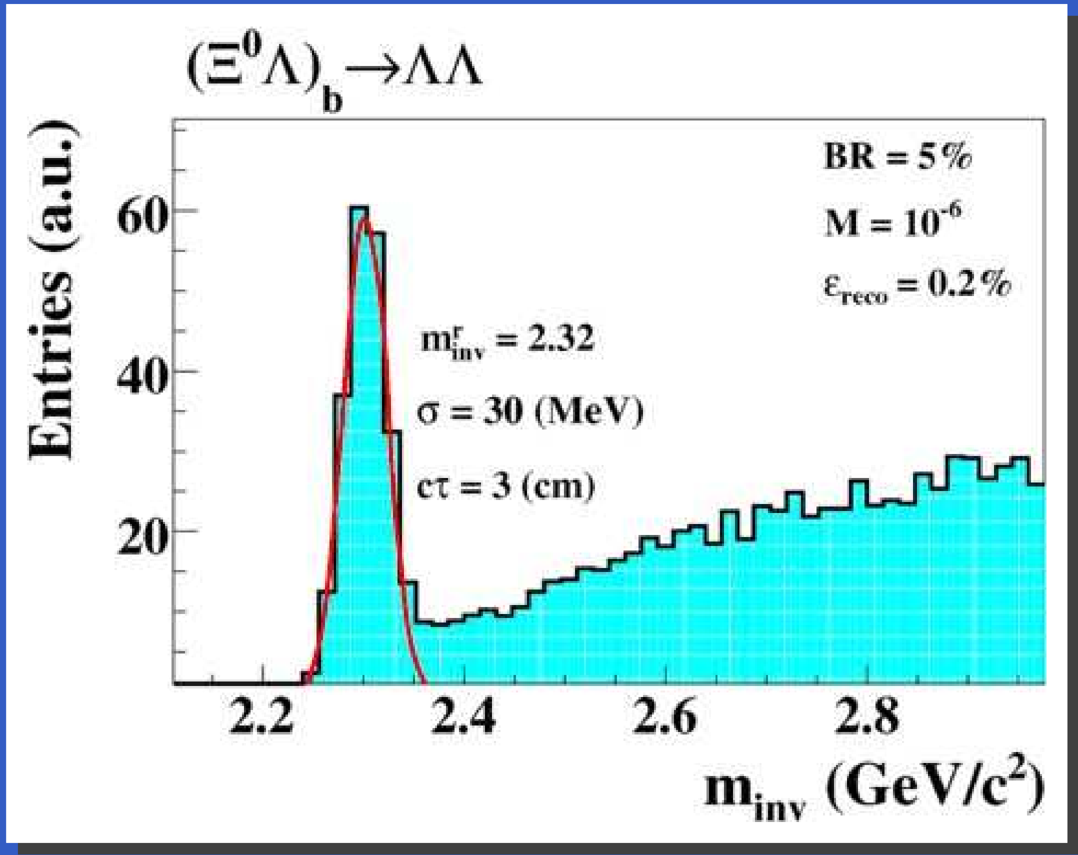
MEMO production at future GSI's FAIR machine



(Steinheimer et al. 2009)

- coalescence estimate within a hybrid model: UrQMD plus Hydro 3D code
- CBM experiment is sensitive to all these extremely strange objects!

Dibaryon feasibility study for FAIR energies



(Steinheimer et al. 2010)

- UrQMD event generator for Au+Au at 25 AGeV heavy-ion collisions
- mock data within UrQMD event of bound $(\Xi^0\Lambda)_b$ dibaryon states
- look at invariant mass spectrum of two Λ's
- peak clearly visible over background

The charming world of exotic states

- talk given by Carl at the HIPAGS meeting 1990 (BNL-44520) on: 'Production of rare composite objects in relativistic heavy-ion collision'
- discusses antimatter, hypernuclei, strangelets, H-dibaryon, charmed pentaquark and tetraquark state with bottom quark
- probability for forming charmed states at RHIC à la Car:l

$$P(A,C) \approx \left(\frac{\sigma_{c\bar{c}}}{\sigma_{total}}\right)^{|C|} \times \left(\frac{N_N}{N_\pi}\right)^{A} \times N_\pi \approx 10^{3-2|C|-2A}$$

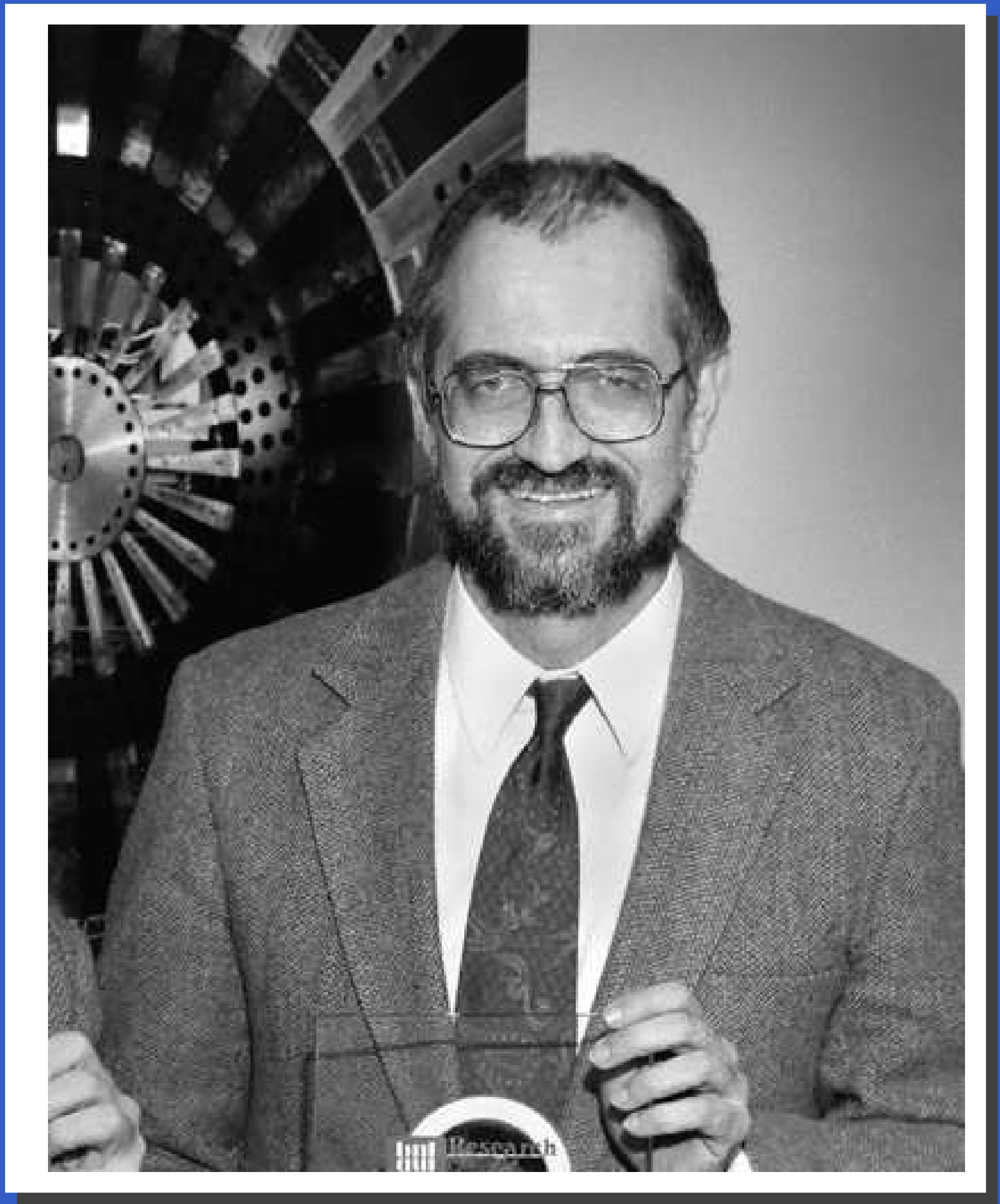
- gives about 0.1 deuterons, 0.1 Λ_c, 10 D-mesons
- for a sensitivity of 10^{-n}: $2A + 2|C| < 3 + n$
- able to find charmed hexaquark states?

(JSB and Vischer 1998)

How to detect strange matter?

- unique opportunity to produce and study them in heavy-ion collisions
- tracking down strange dibaryons by:
  - (A) a direct look: exotic decay tracks in TPC
  - (B) backtracking: invariant mass spectra for bound dibaryons
  - (C) correlations: resonances seen in correlation functions, reveals interaction potential
- poised for discoveries!

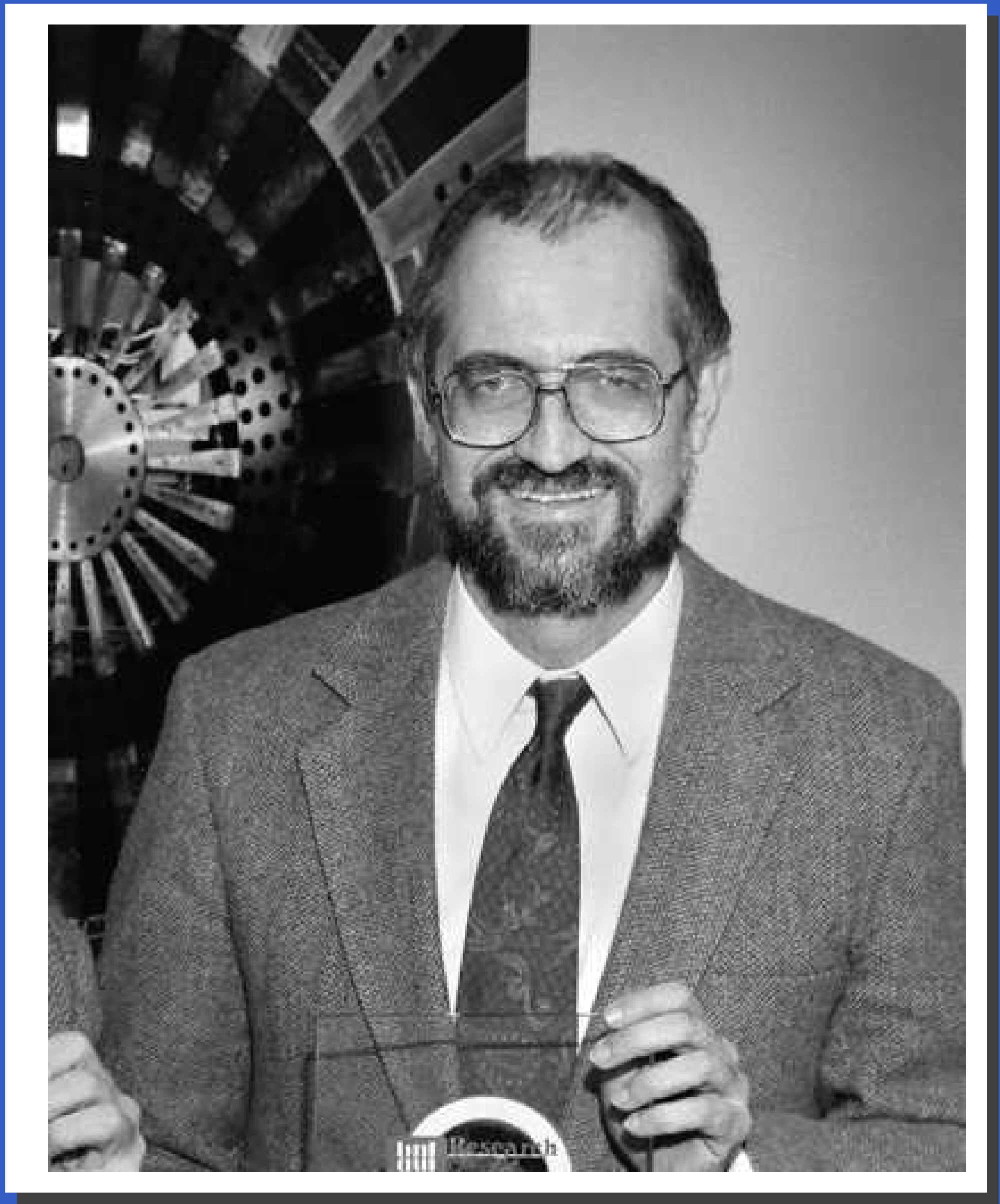
The heritage of Carl B. Dover



(BNL Science and Technology Award 1994, courtesy: Tony Baltz)

- the exploration of strange matter lives on

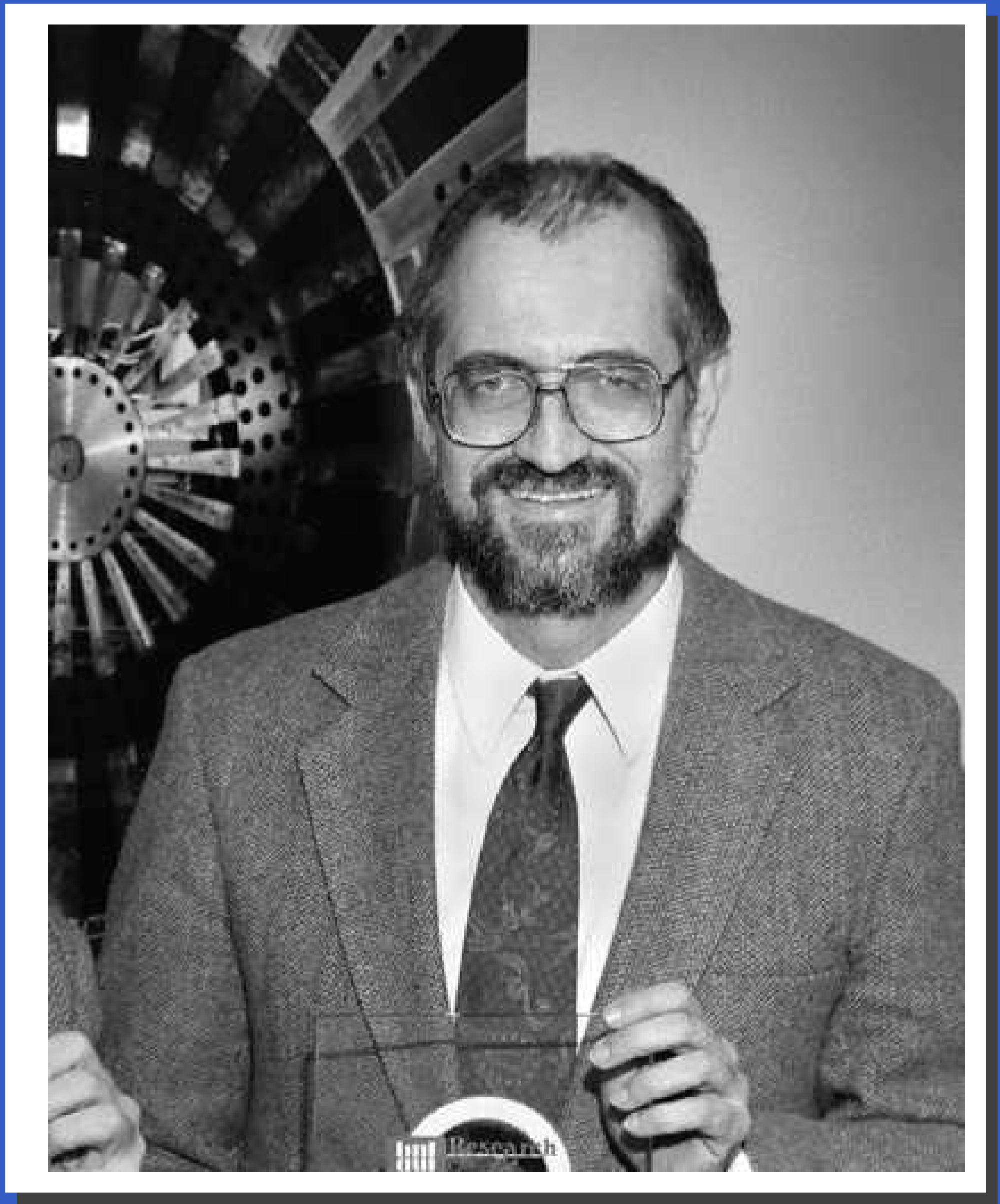
The heritage of Carl B. Dover



(BNL Science and Technology Award 1994,
courtesy: Tony Baltz)

- the exploration of strange matter lives on
- the scientific heritage of Carl!

The heritage of Carl B. Dover



(BNL Science and Technology Award 1994, courtesy: Tony Baltz)

- the exploration of strange matter lives on
- the scientific heritage of Carl!
- thanks Carl!