Strangeness Nuclear Physics at the J-PARC era

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- Brief history of Strangeness Nuclear Physics
- J-PARC status
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  - Kaonic Nuclei
- Summary

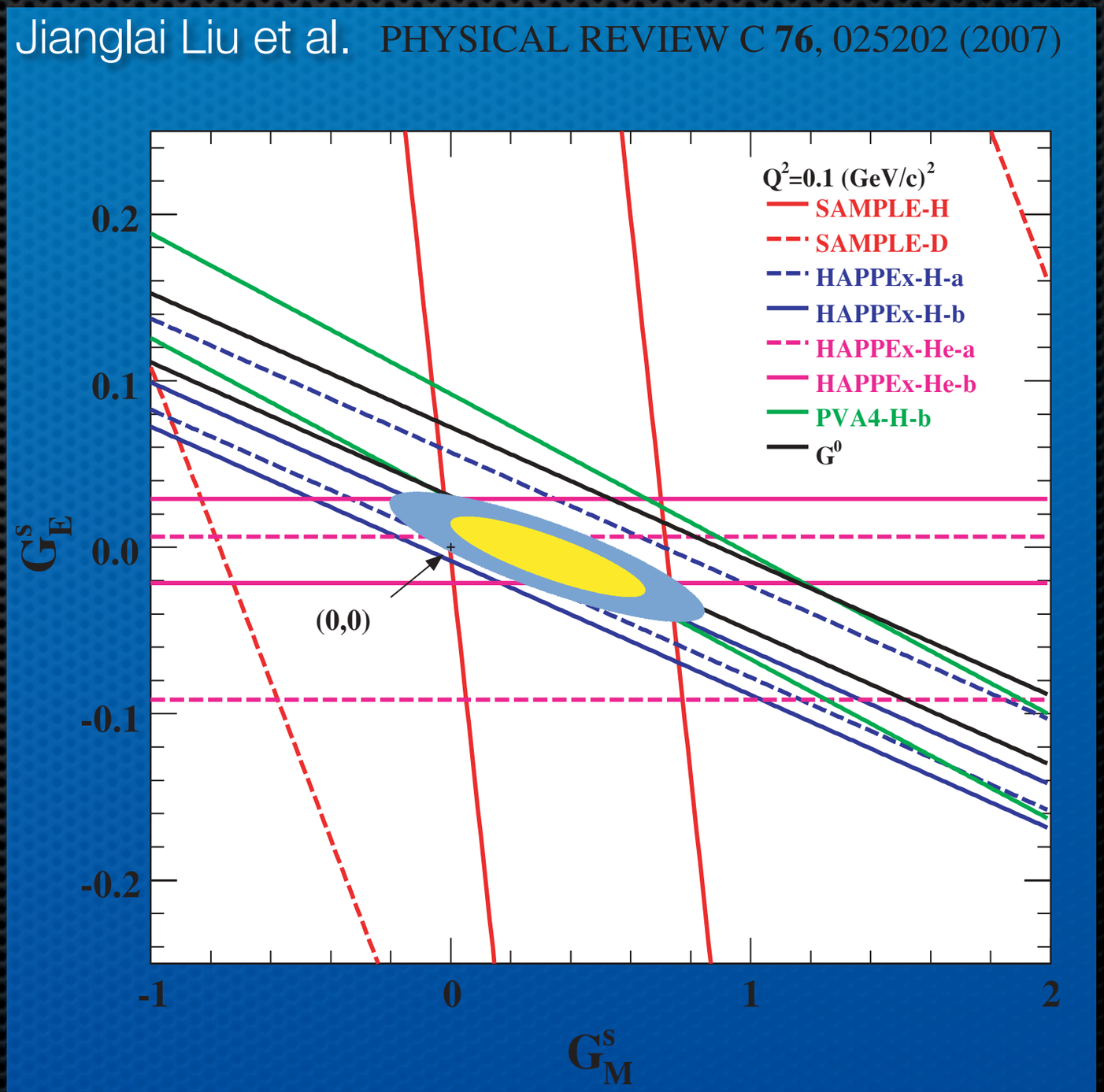
Strangeness in Nuclear Physics

- Strangeness in Nucleons
  - Strange Form Factors
  - Strange Quark Contents
- QCD Phase Transition
  - at High-Temperature
  - at High-Density

Nucleon Strange Form Factors

- Parity-violating electron elastic scattering
  - SAMPLE, PVA4, HAPPEx, G0
    - G^s_E=-0.008±0.016
    - G^s_M=0.29±0.21

Jianglai Liu et al. PHYSICAL REVIEW C **76**, 025202 (2007)



Strange quark contents in Nucleon

- Lattice QCD

$$y \equiv \frac{2\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u + \bar{d}d|N\rangle}$$

y=0.2±0.2 ?

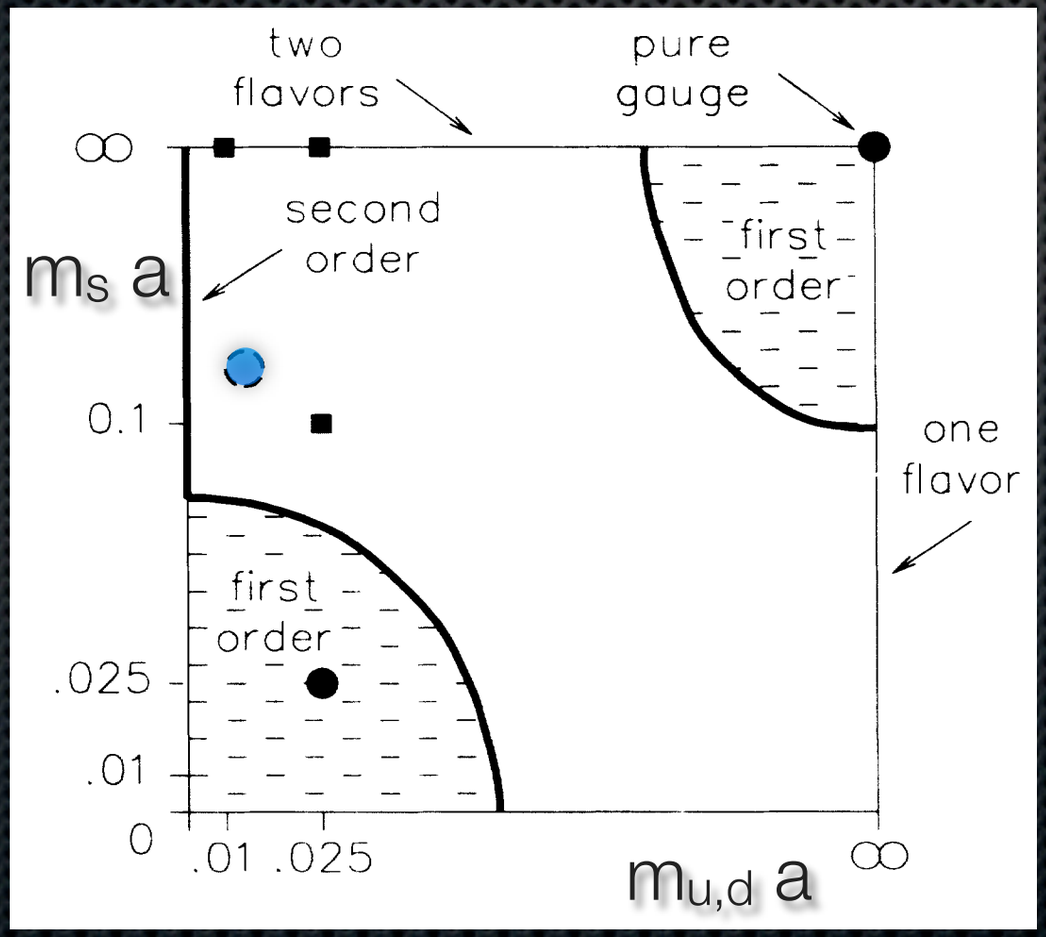
- JLQCD: $y = 0.030(16)_{\mathrm{stat}}(+6,-8)_{\mathrm{extrap}}(+1,-2)_{\mathrm{ms}}$
  - H. Ohki et al., Phys. Rev. D78, 054502 (2008)

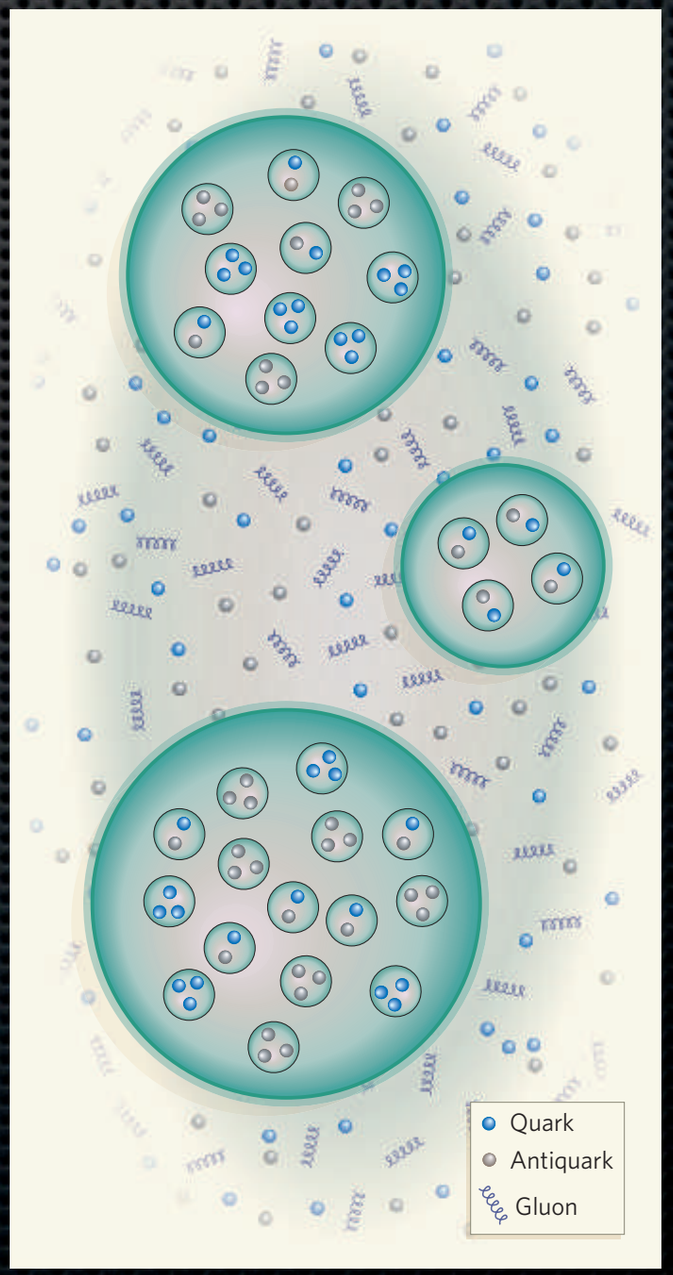
QCD Phase Transition at High-Temperature

$\Lambda_{QCD} \sim m_s$

- Two (u,d) flavors: 2nd order

- Three (u,d,s) flavors: Cross-over

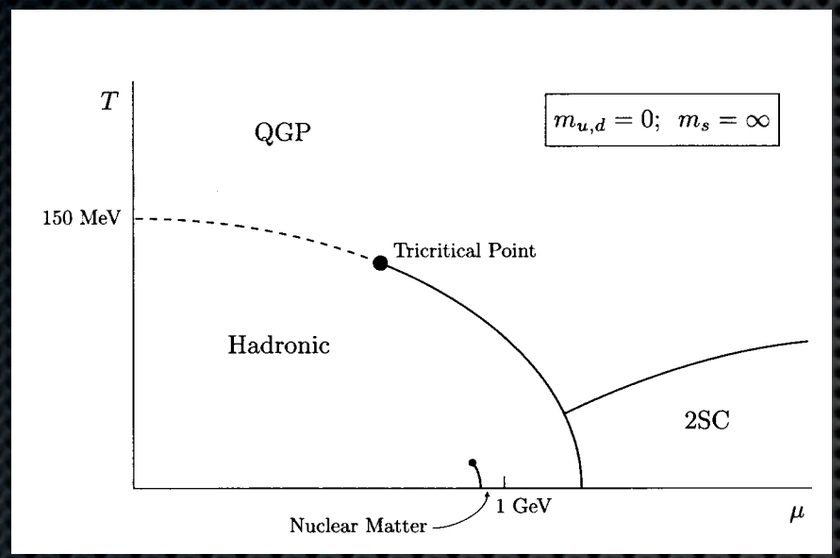


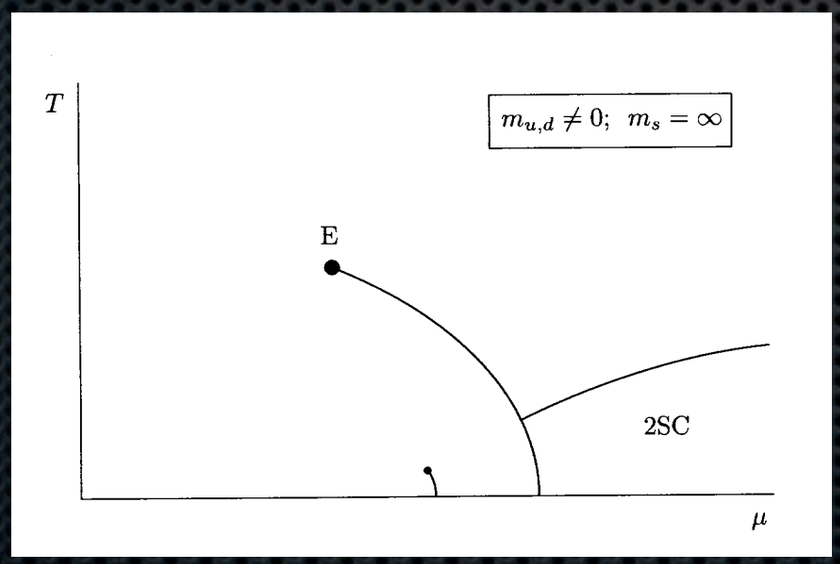


Lattice QCD
F.R. Brown et al., PRL65, 2491-2494 (1990)

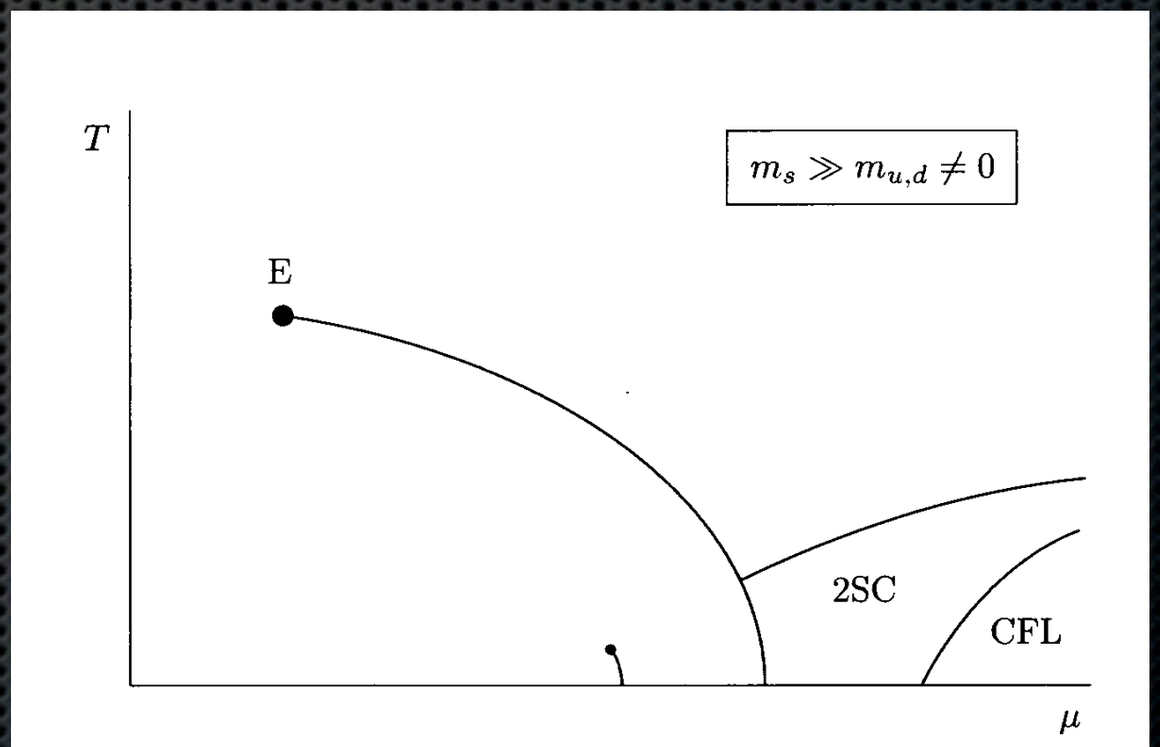
QCD Phase Transition at High-Density

- Two Flavors

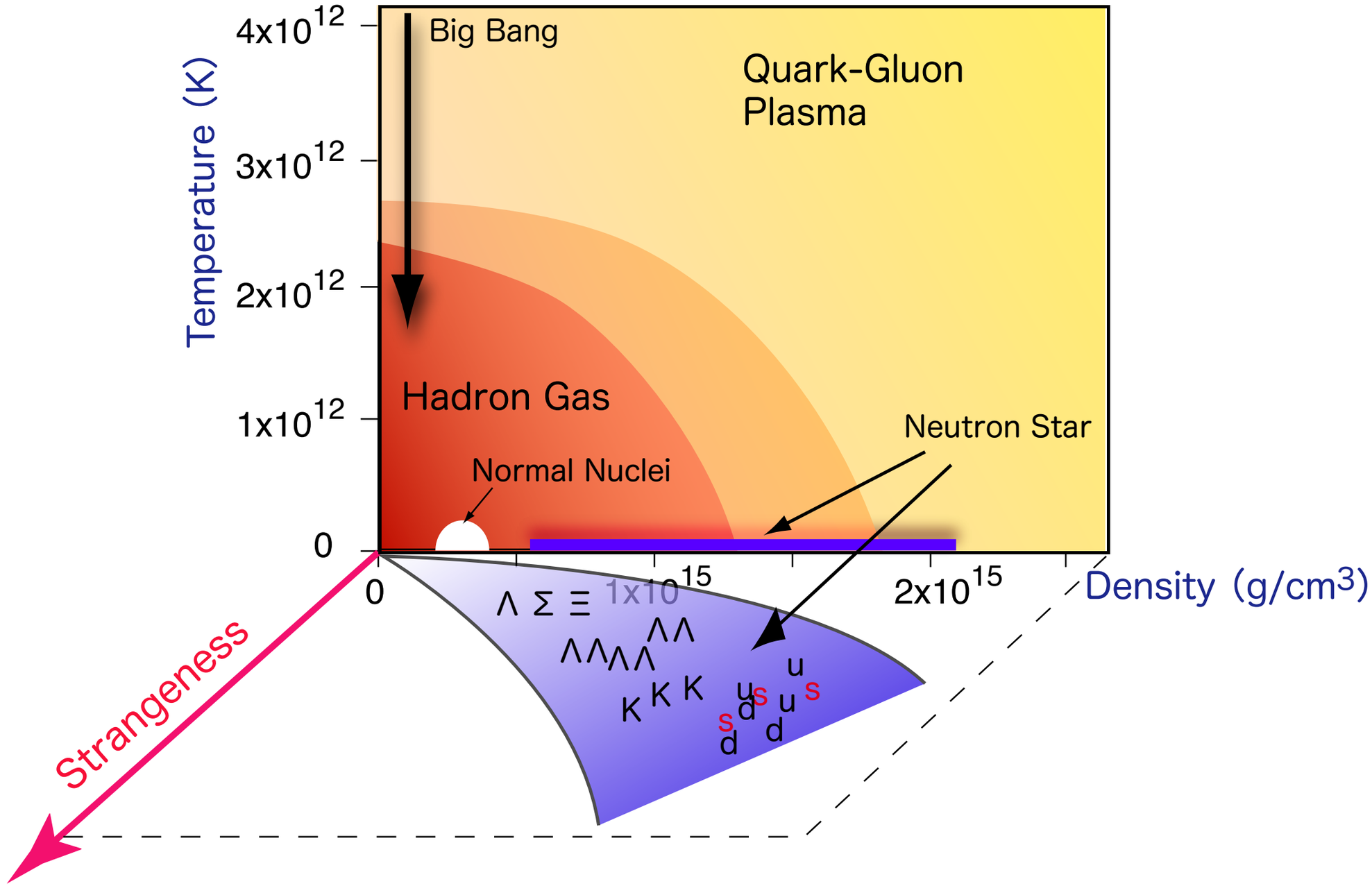


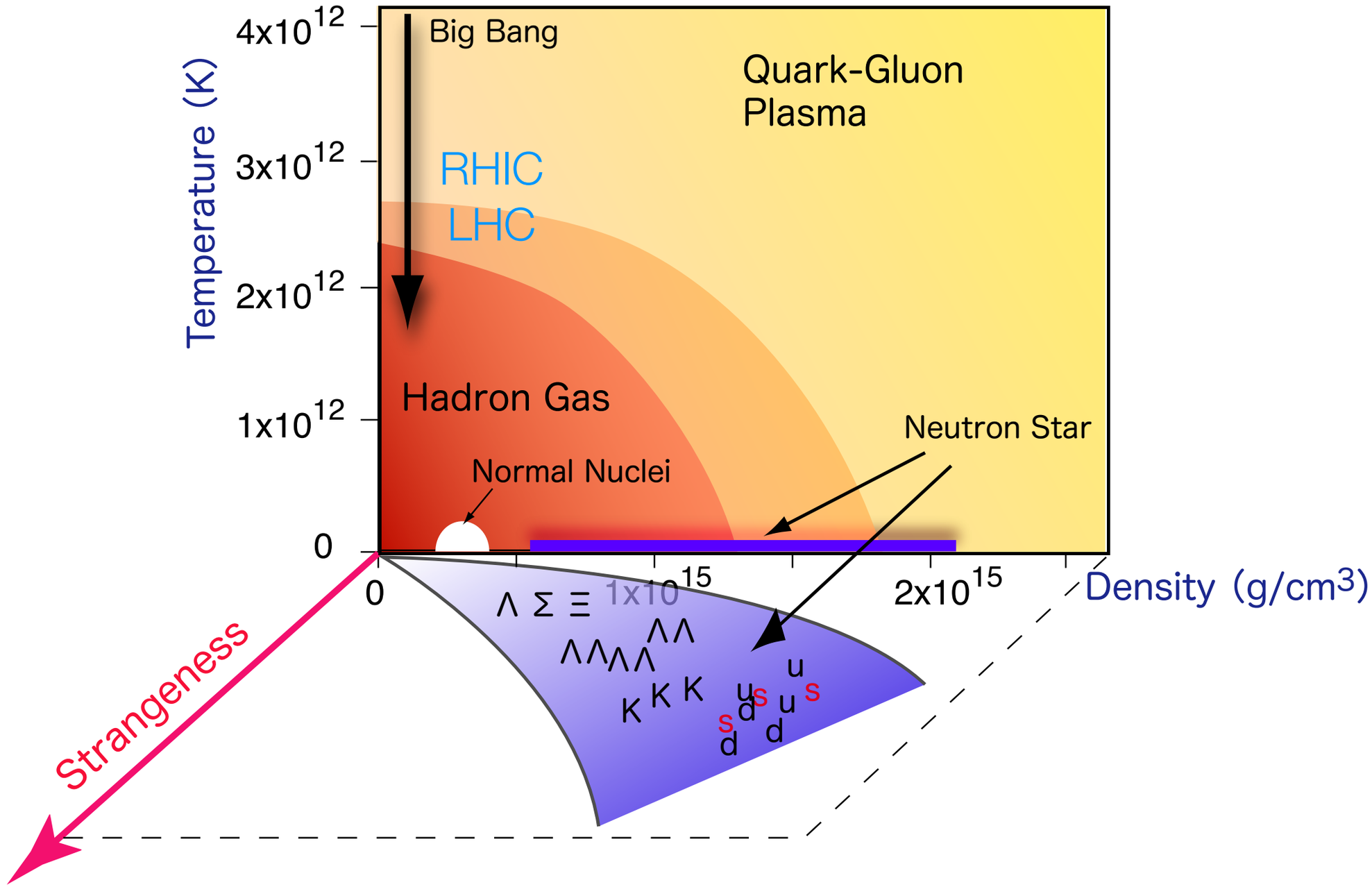


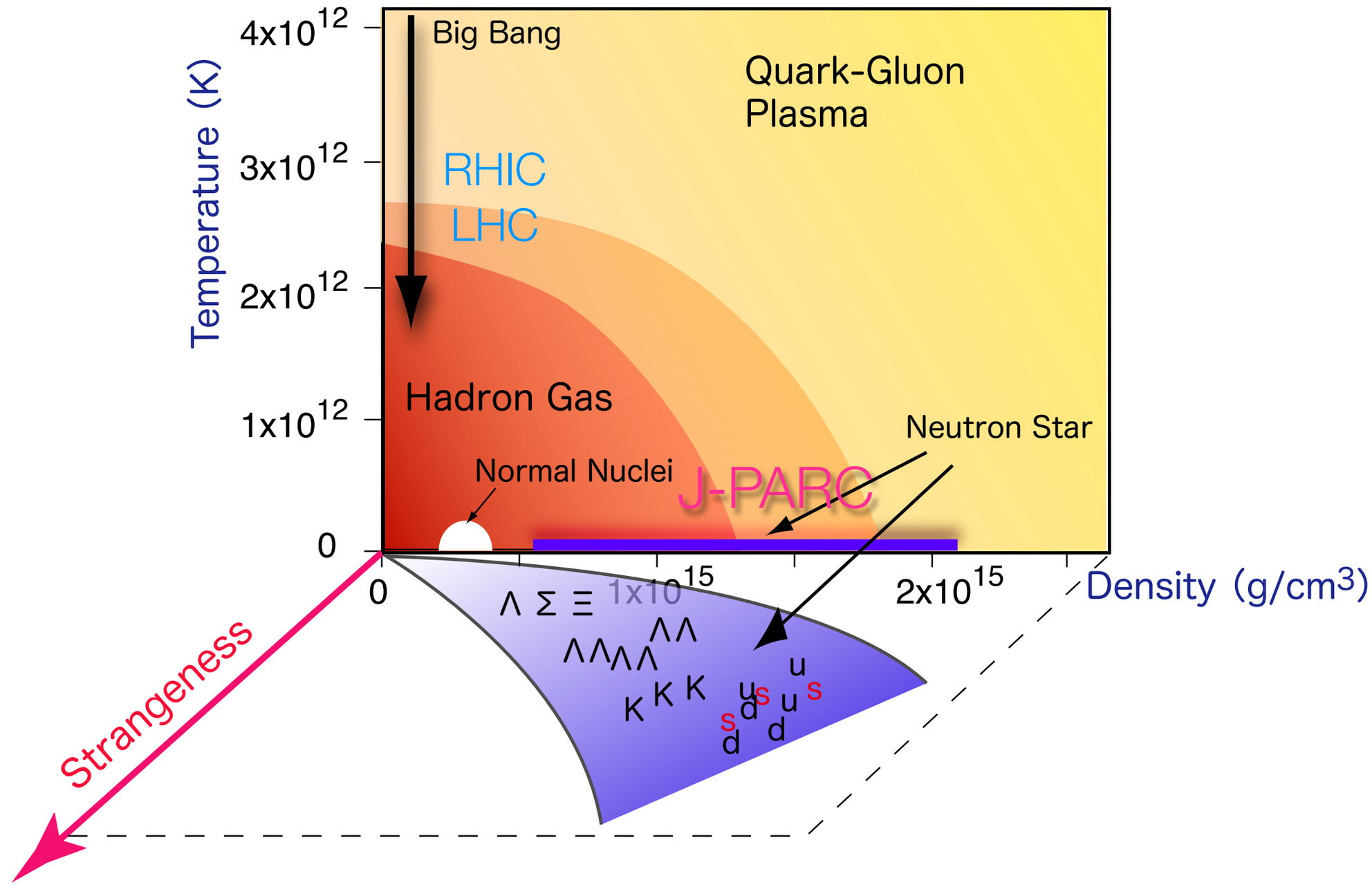
Three Flavors



Color-Flavor Locked Phase ?

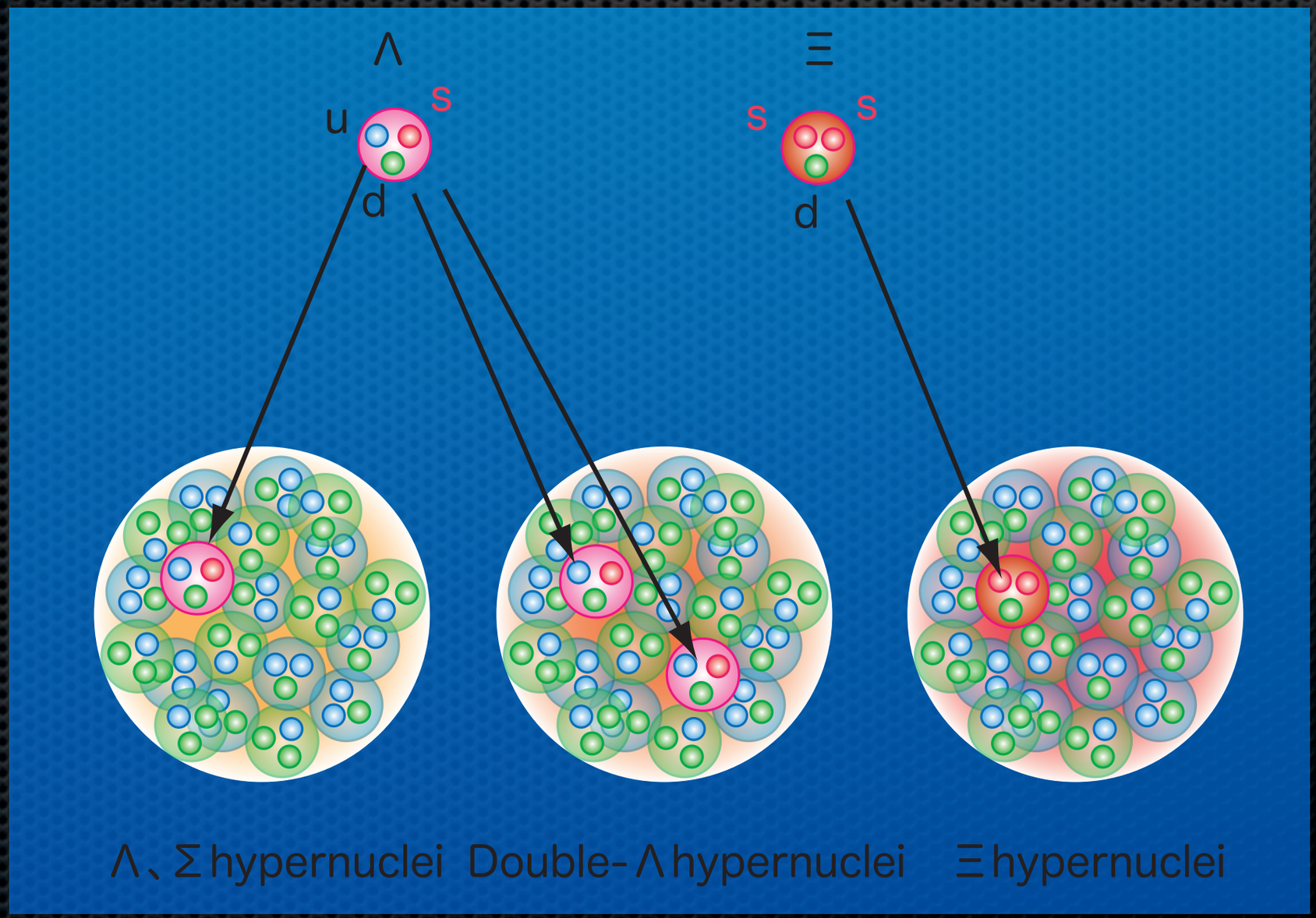

4x10^12
3x10^12
2x10^12
1x10^12
0
Temperature (K)
Big Bang
Quark-Gluon
Plasma
Hadron Gas
Normal Nuclei
Neutron Star
0
1x10^15
2x10^15
Density (g/cm3)
Strangeness
Λ Σ Ξ
ΛΛ
ΛΛΛ
K K K
u
s
d


4x10^12
3x10^12
2x10^12
1x10^12
0
Temperature (K)
Big Bang
Quark-Gluon Plasma
RHIC
LHC
Hadron Gas
Neutron Star
Normal Nuclei
0
1x10^15
2x10^15
Density (g/cm3)
Strangeness
Λ Σ Ξ
ΛΛ
ΛΛΛ
K K K
u s u s
s d d d


4x10^12
3x10^12
2x10^12
1x10^12
0
Temperature (K)
Big Bang
Quark-Gluon Plasma
RHIC
LHC
Hadron Gas
Neutron Star
Normal Nuclei
J-PARC
0
1x10^15
2x10^15
Density (g/cm3)
Strangeness
Λ Σ Ξ
ΛΛ
ΛΛΛ
K K K
u s u s
s d d

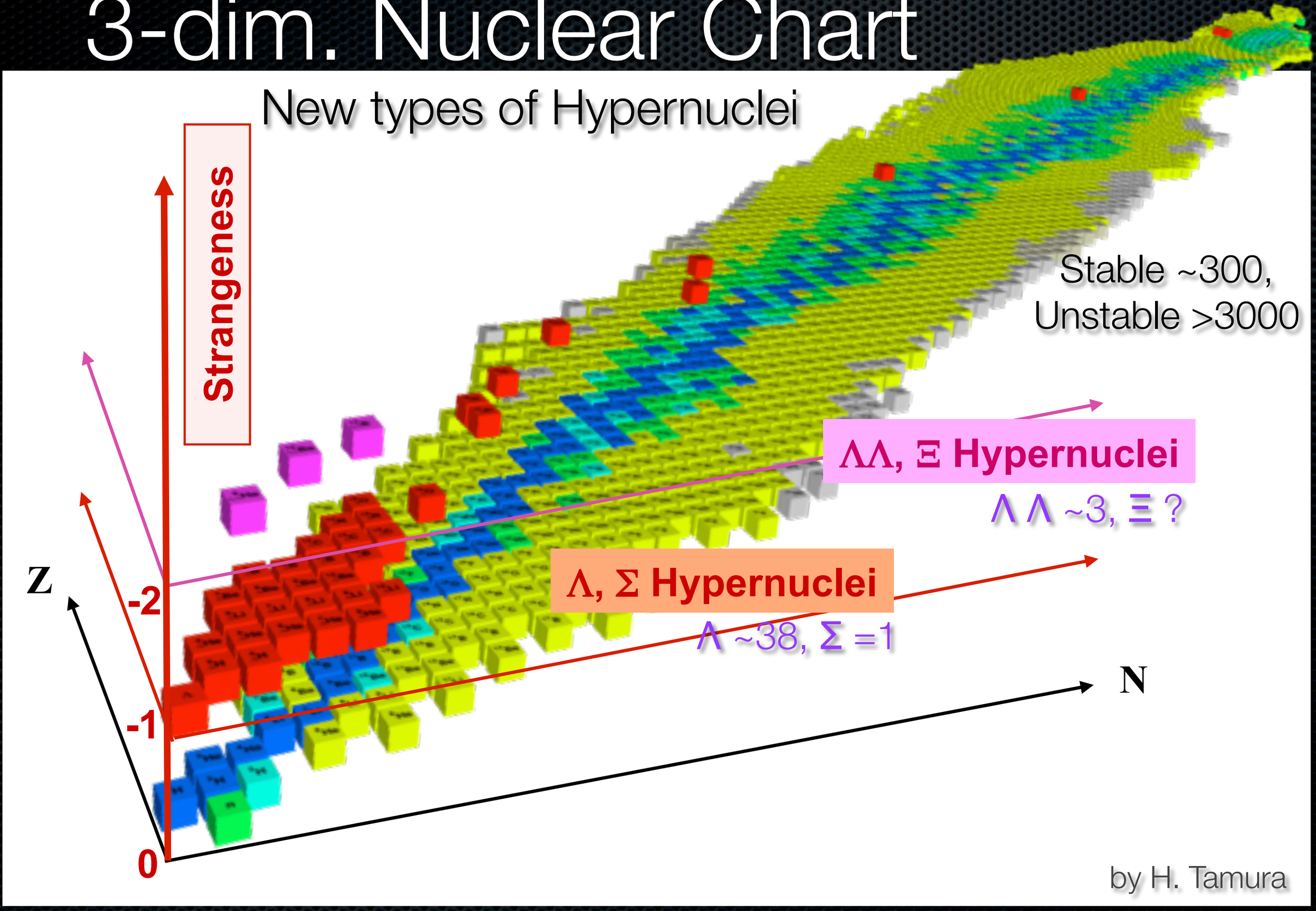
Hadron Many-Body Systems with Strangeness

- Hypernuclei : Hyperons(Λ, Σ, Ξ) in Nuclei



3-dim. Nuclear Chart

New types of Hypernuclei



by H. Tamura

From 1974 Nobel Lecture by A. Hewish , “Pulsars and High Density Physics”,

- At yet deeper levels the neutron-neutron interaction may result in the creation of a solid neutron lattice, although this possibility is under debate, and finally there is the question of a material composed of stable hyperons

Strangeness nuclear physics can have an answer

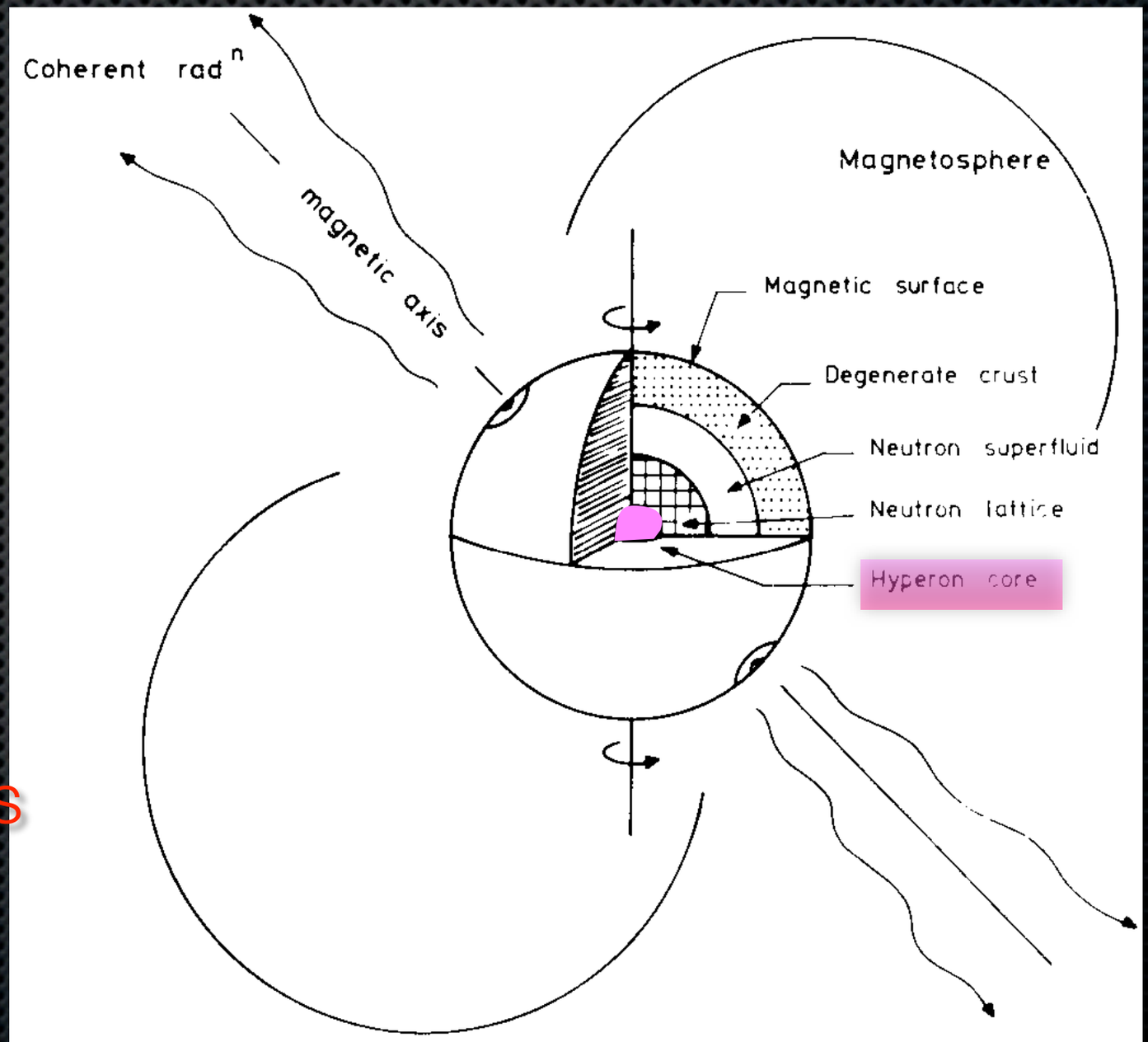
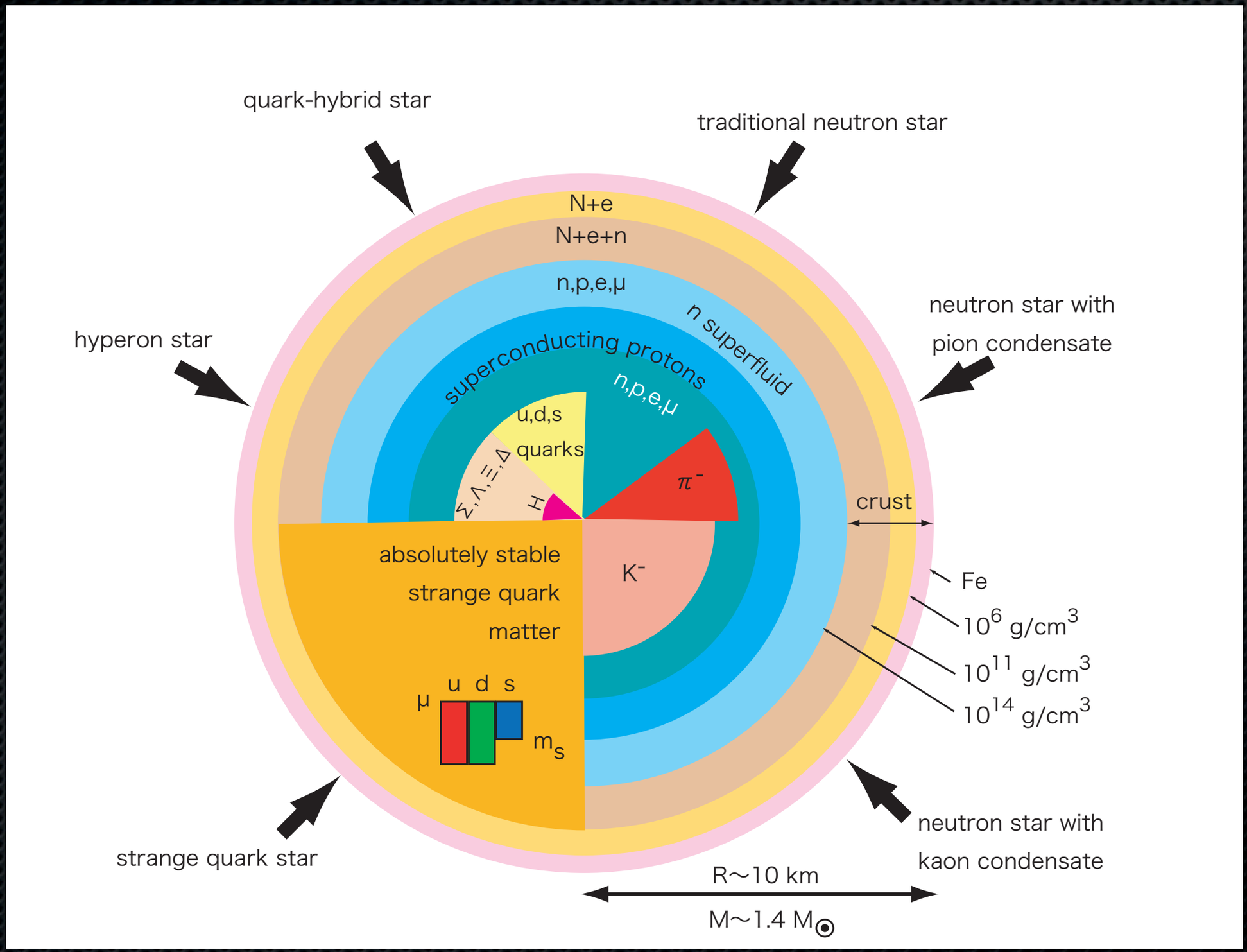


Fig. 5. Model of a neutron star

What's in the Neutron Star Core ?

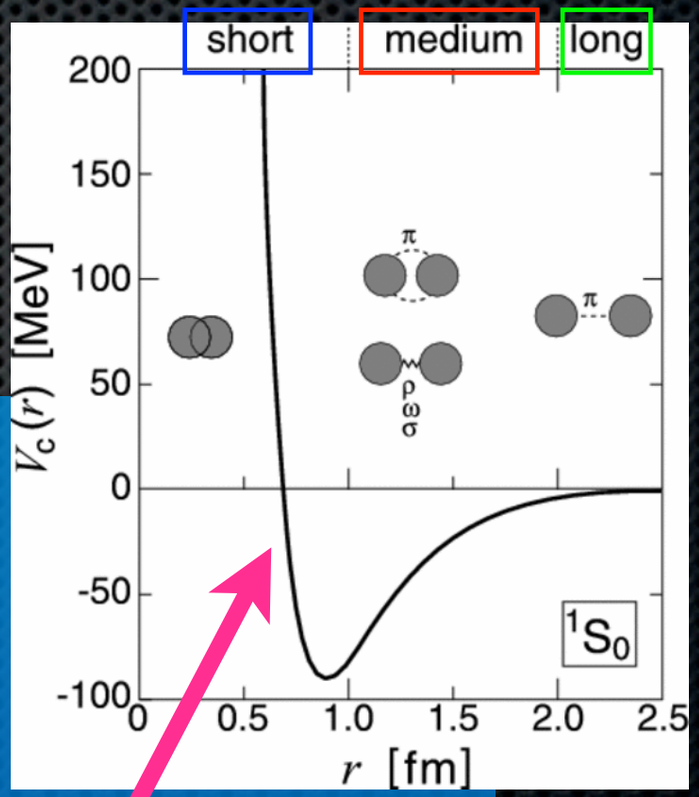


By F. Weber

→EA0002: T. Hatsuda

Modern Picture of Baryon-Baryon Interactions

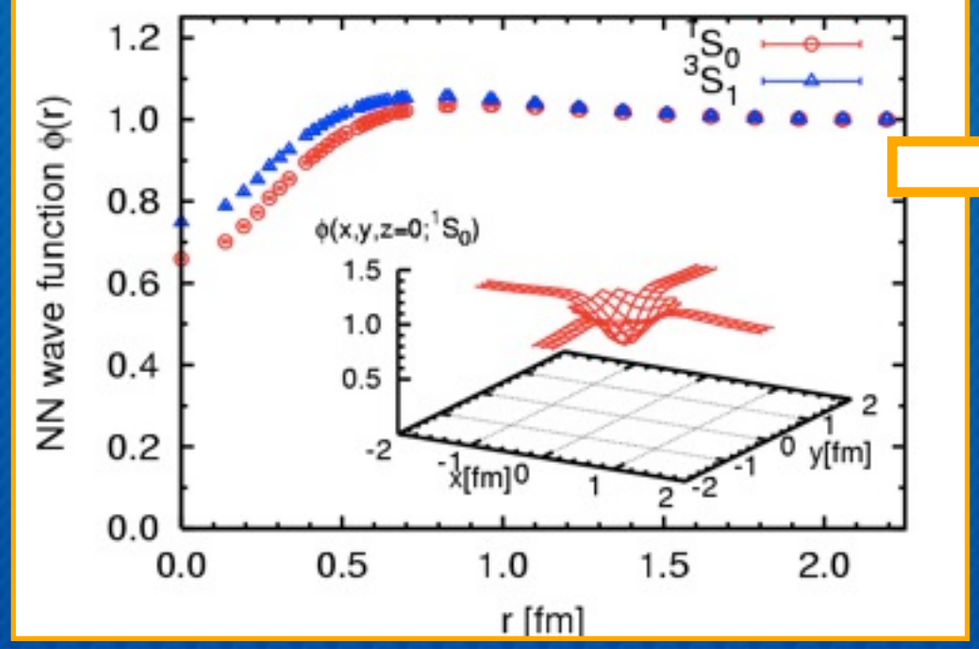
- Nuclear Force from Lattice QCD



Long-range attraction
+
Repulsive Hard-core

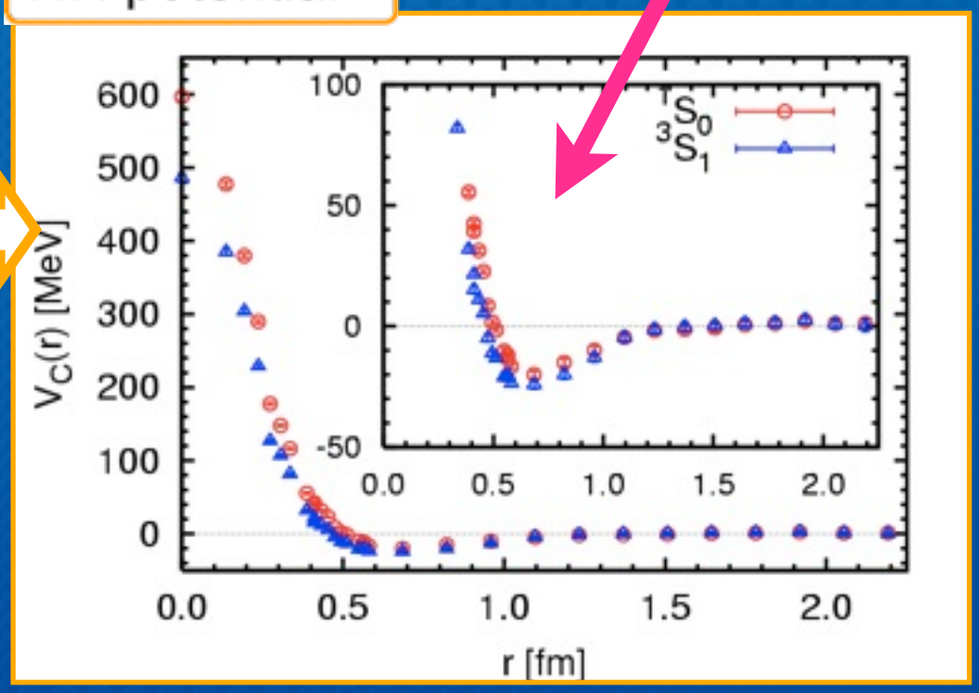
lattice QCD

wave function



Schrodinger Eq.

NN potential

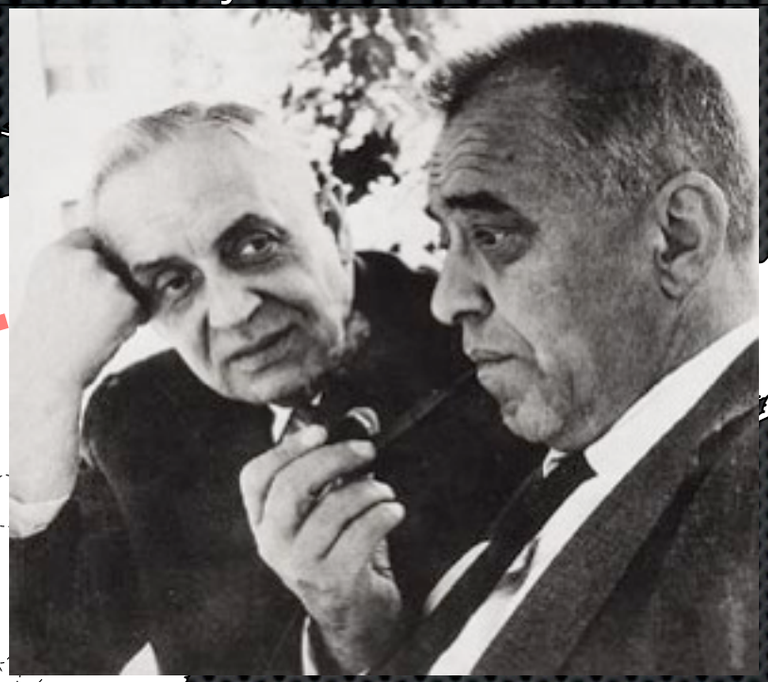


N.Ishii, S.Aoki, T.Hatsuda, Phys.Rev.Lett.99,022001 (2007).

First Hyperfragment in 1953

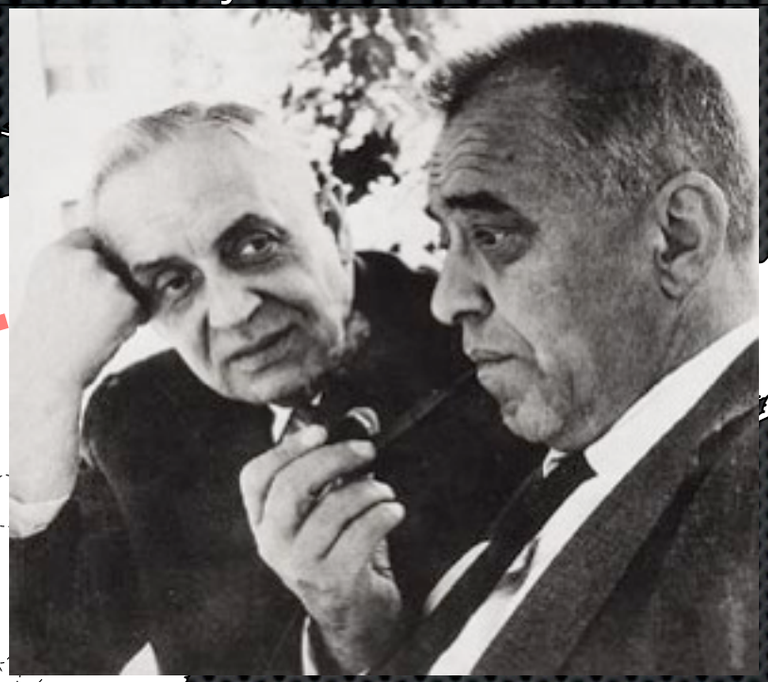
First Hyperfragment in 1953

M. Danysz and J. Pniewski

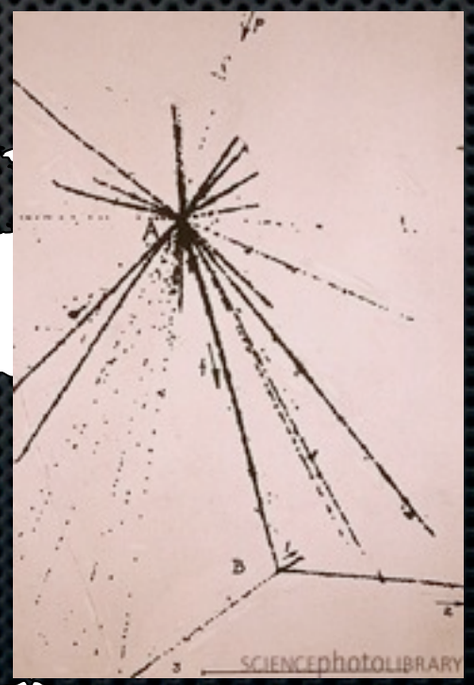


First Hyperfragment in 1953

M. Danysz and J. Pniewski



Stopped K^-



First Hyperfragment in 1953

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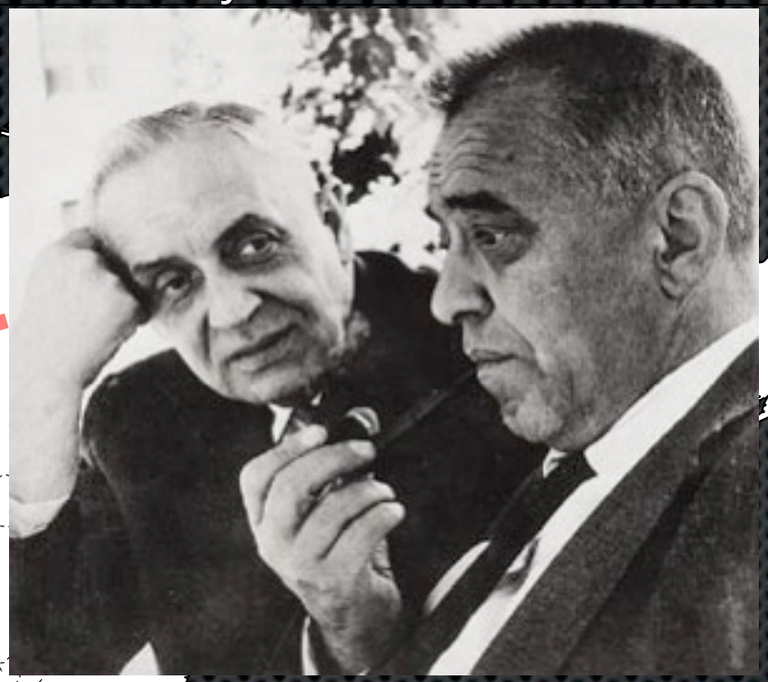
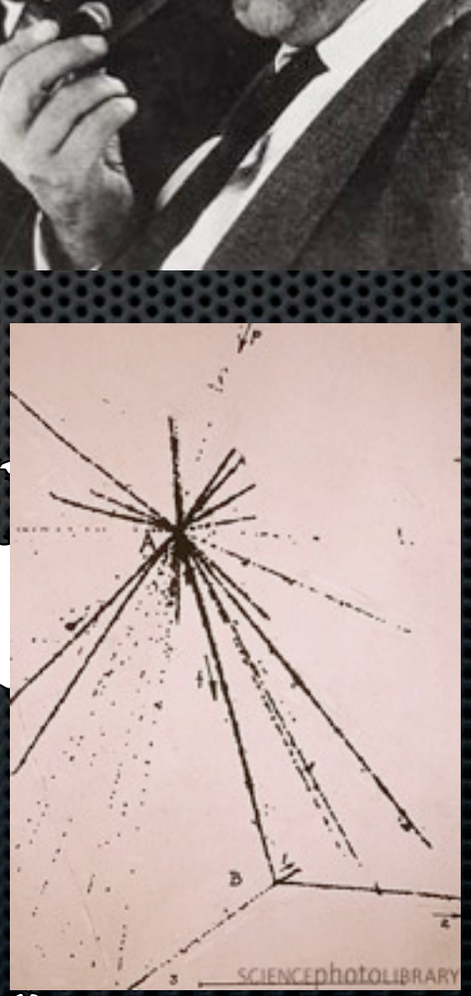


Stopped K^-



Nuclear Emulsion

Ground states of Light Λ hypernuclei

1970s - 1985

1970s - 1985

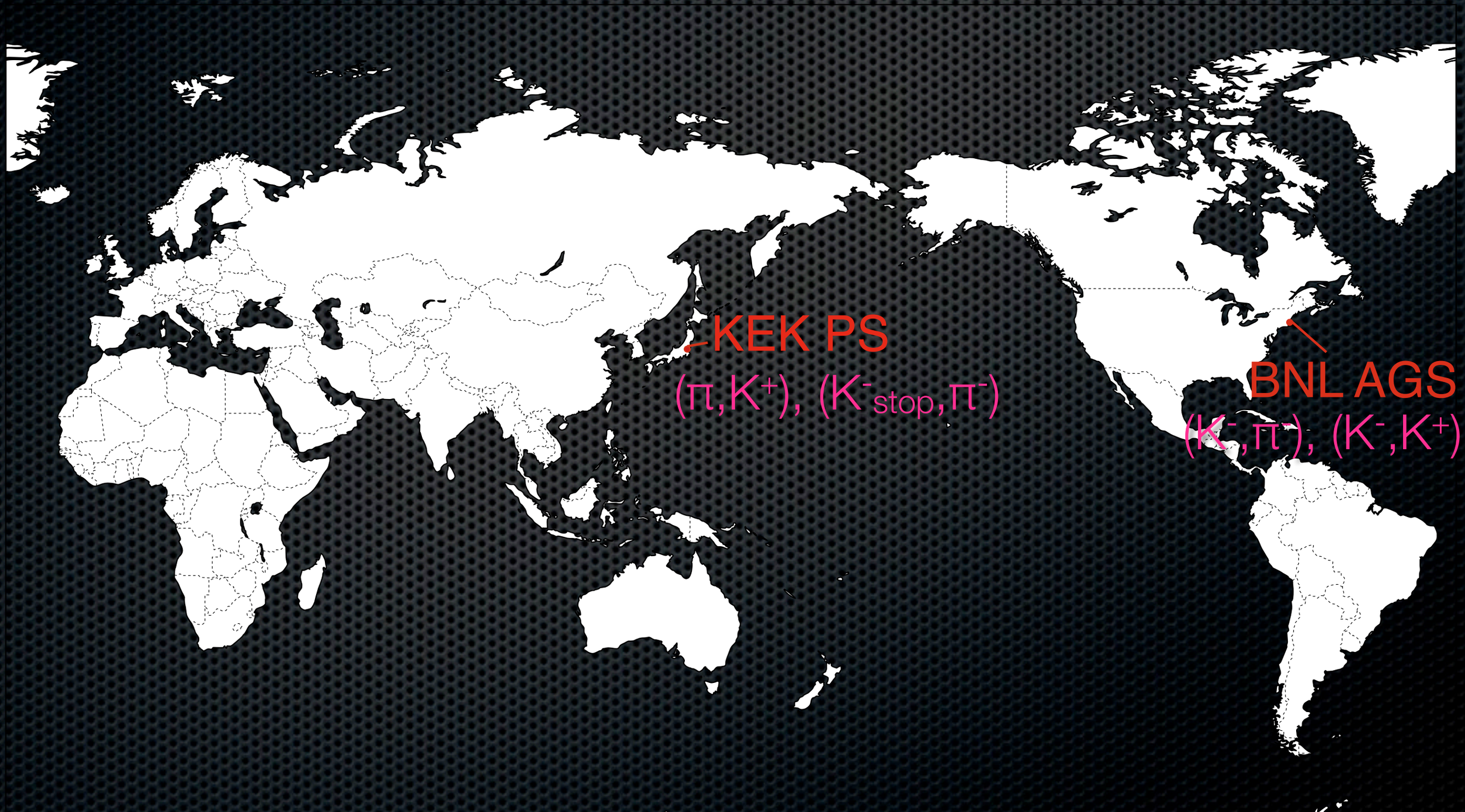
1970s - 1985


CERN PS
(K⁻,π⁻)
Recoil-less Method
Excited Levels of Λ hypernuclei
Σ hypernuclei Puzzle

Mid 80’s - 2000

Mid 80's - 2000

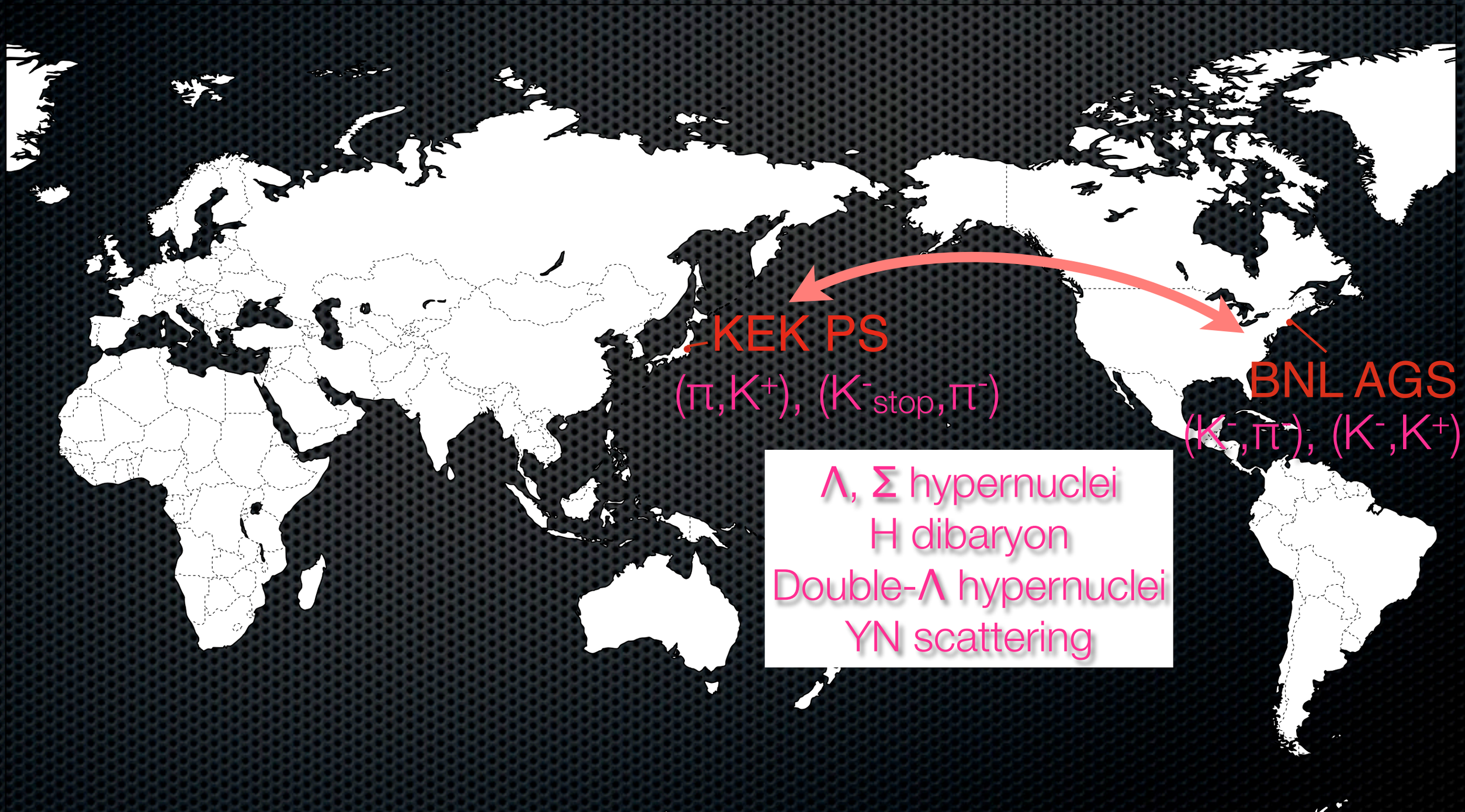
Mid 80’s - 2000



Mid 80's - 2000


KEK PS
(π,K+), (K-stop,π-)
BNL AGS
(K-,π-), (K-,K+)
Λ, Σ hypernuclei
H dibaryon
Double-Λ hypernuclei
YN scattering

Mid 80's - 2000


KEK PS
(π,K+), (K-stop,π-)
BNL AGS
(K-,π-), (K-,K+)
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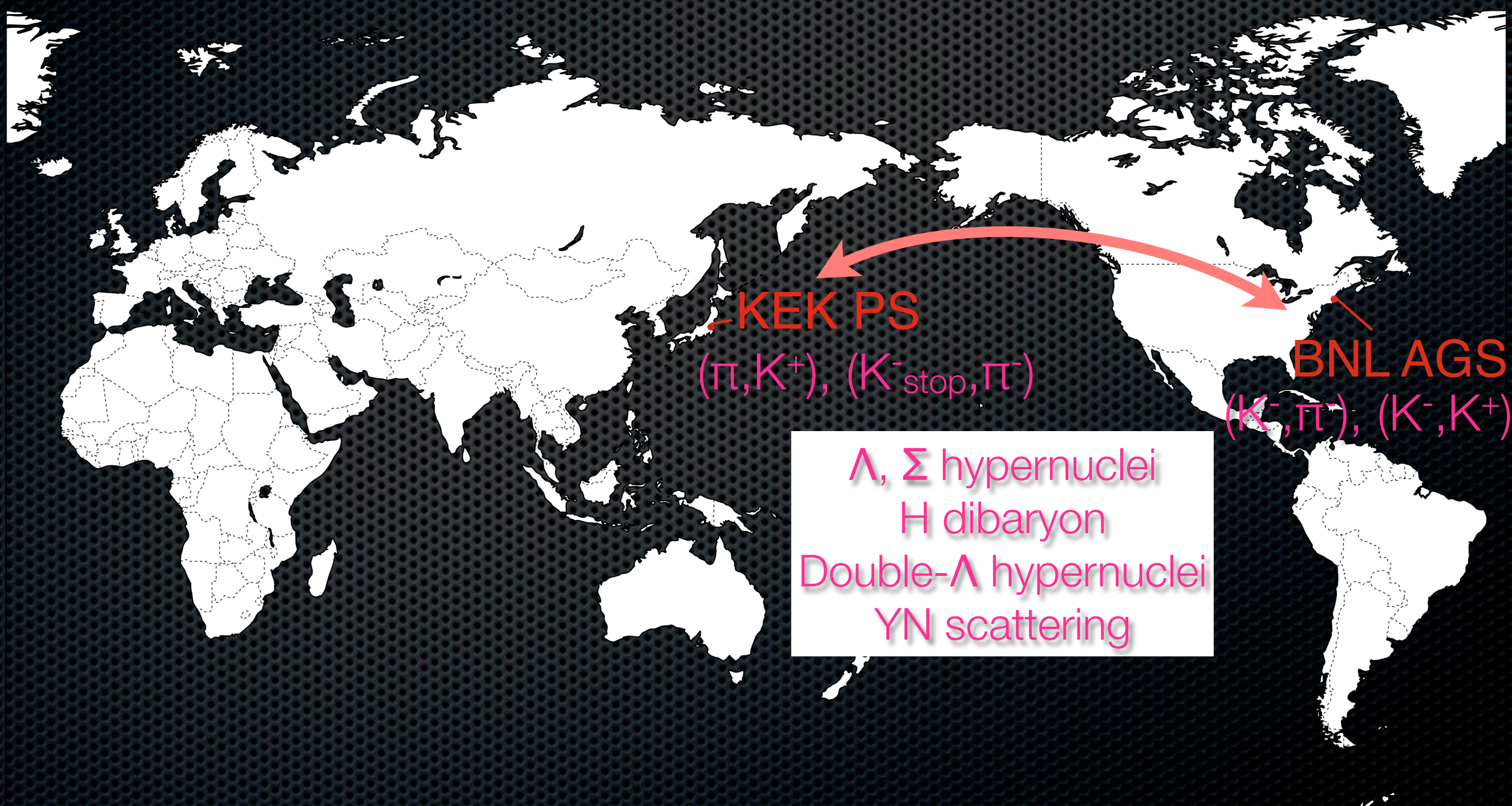
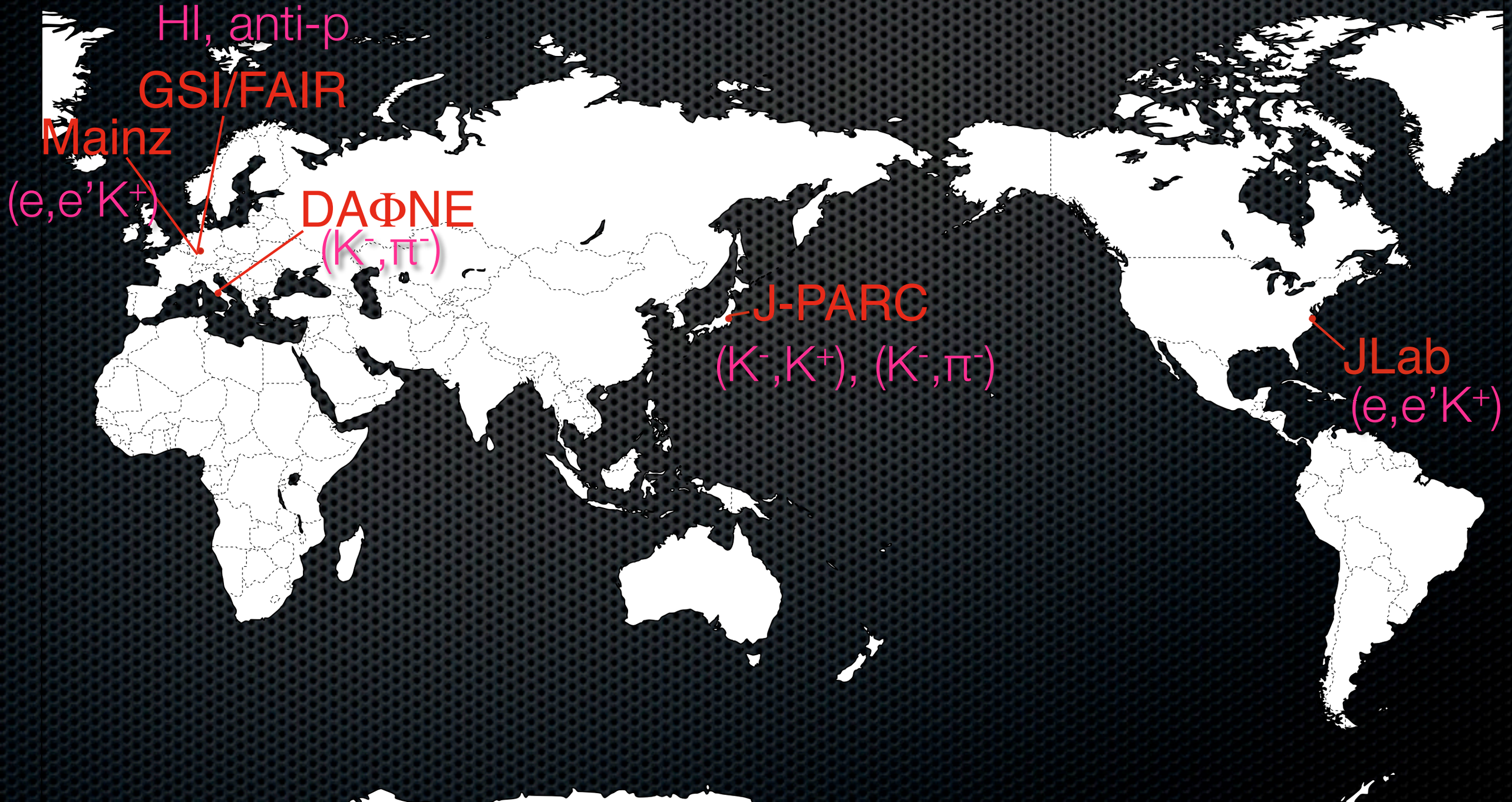
H dibaryon
Double-Λ hypernuclei
YN scattering

Mid 80's - 2000

Hypernuclear Physics → Strangeness Nuclear Physics

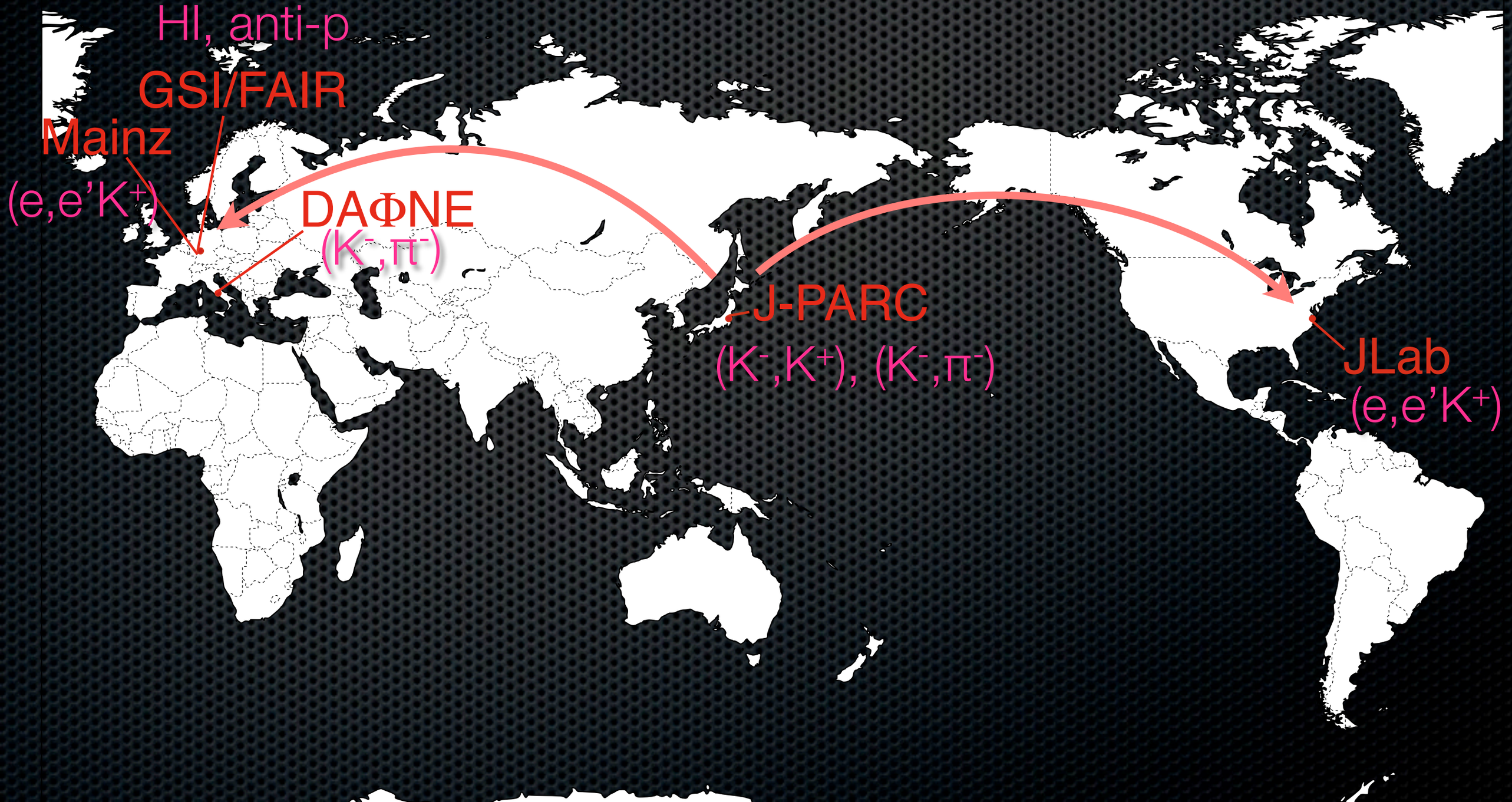


World Facilities in the 21st Century

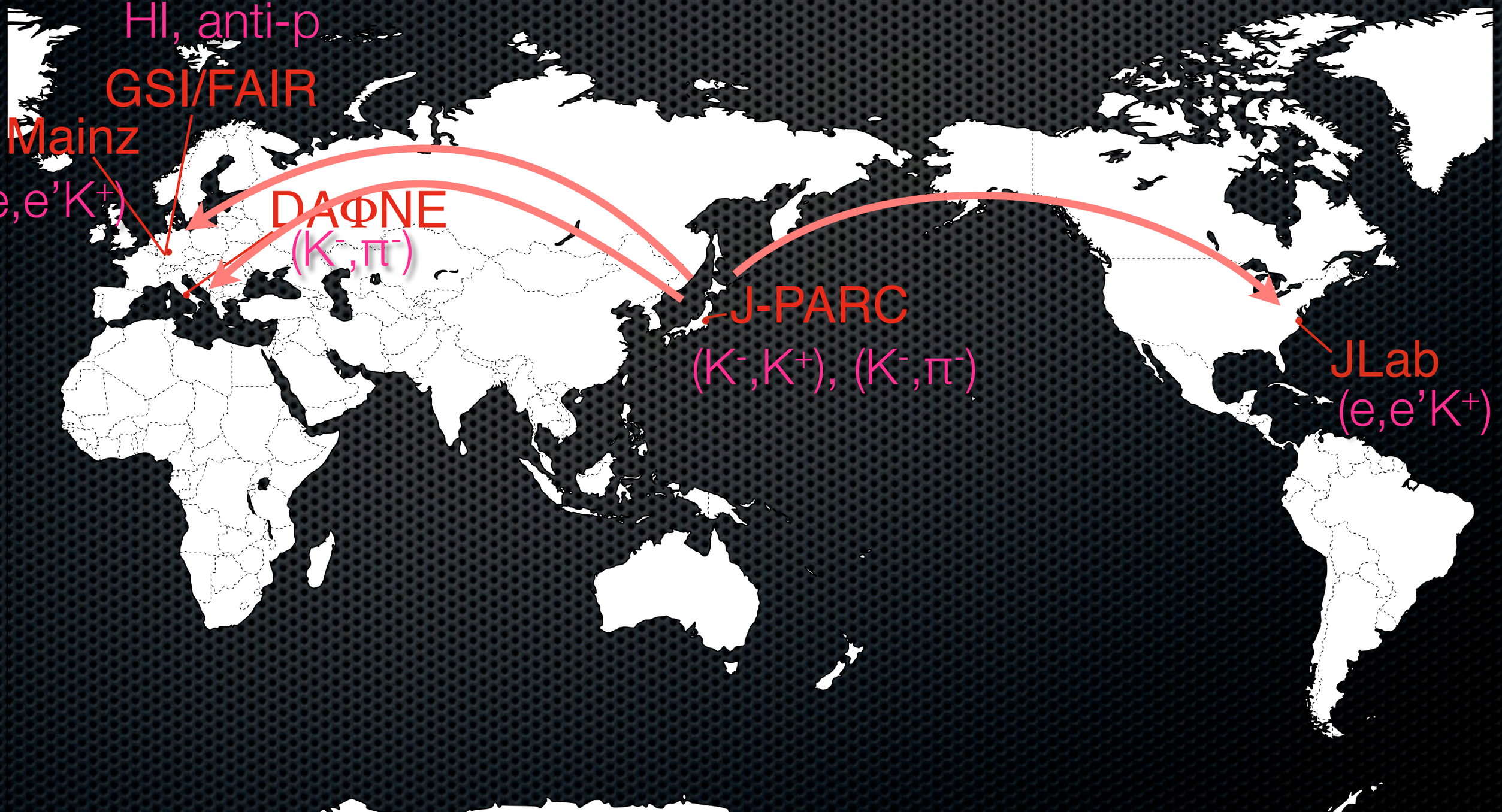


World Facilities in the 21st Century

World Facilities in the 21st Century



World Facilities in the 21st Century



World Facilities in the 21st Century

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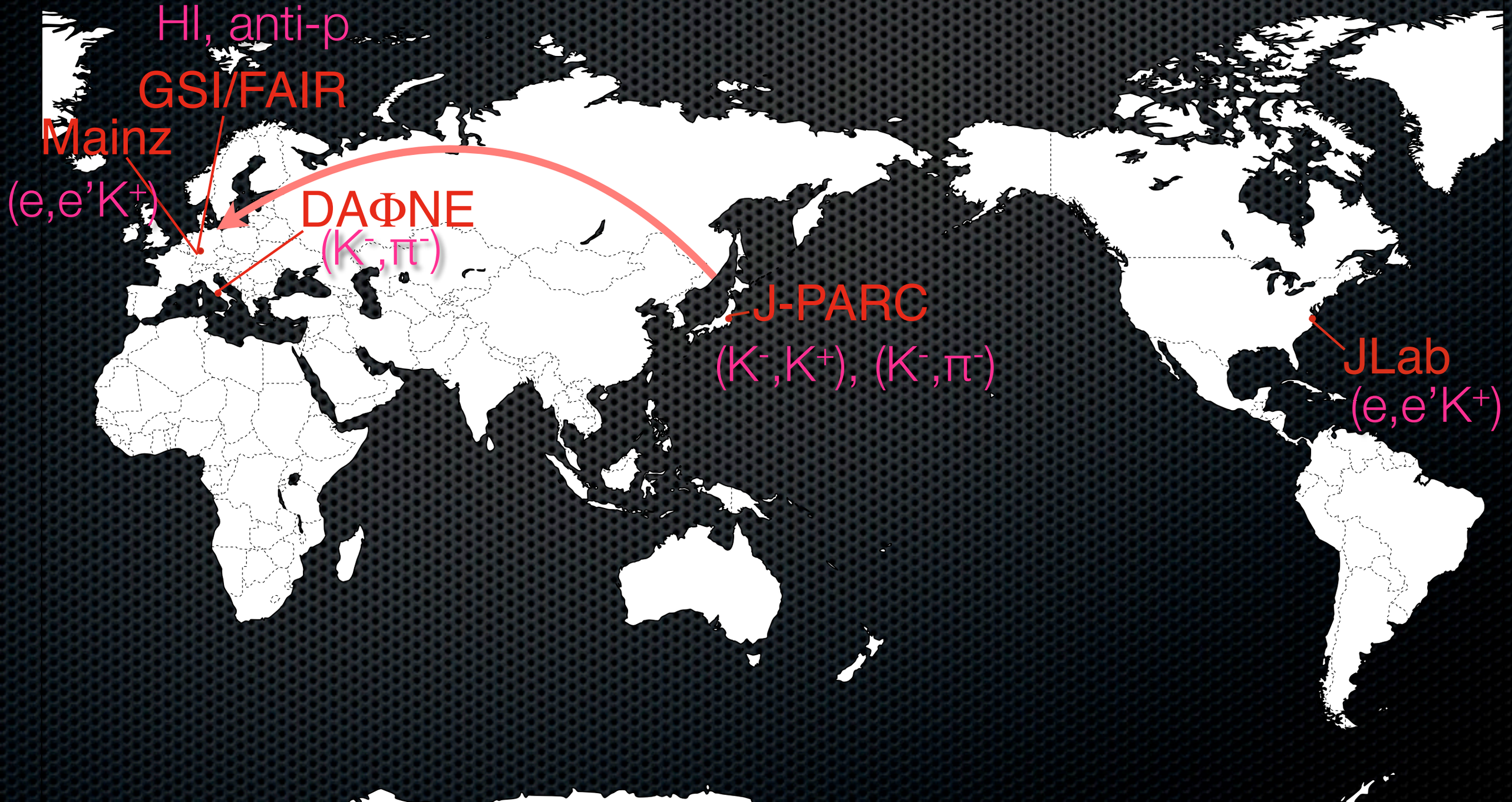
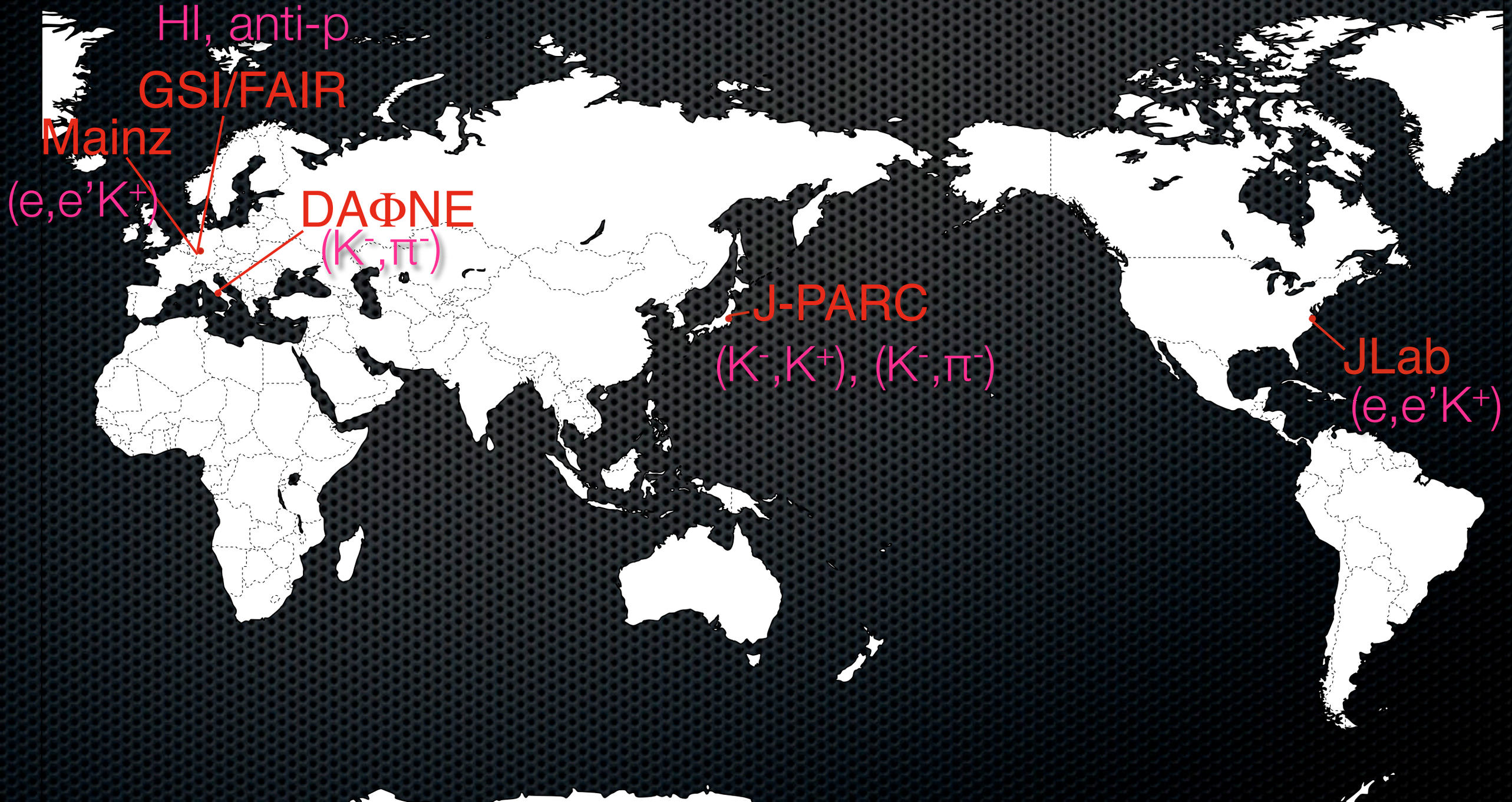


World Facilities in the 21st Century



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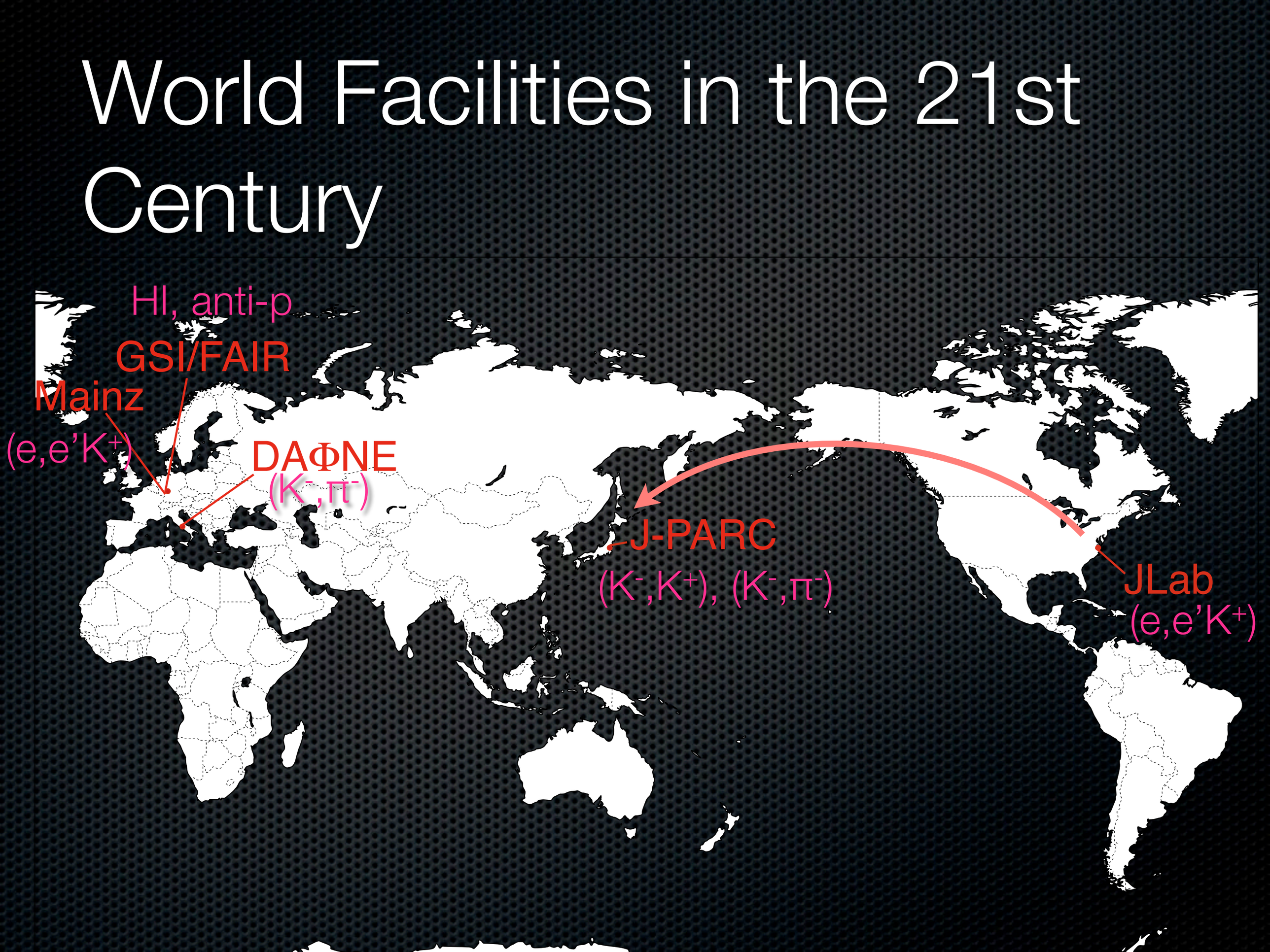
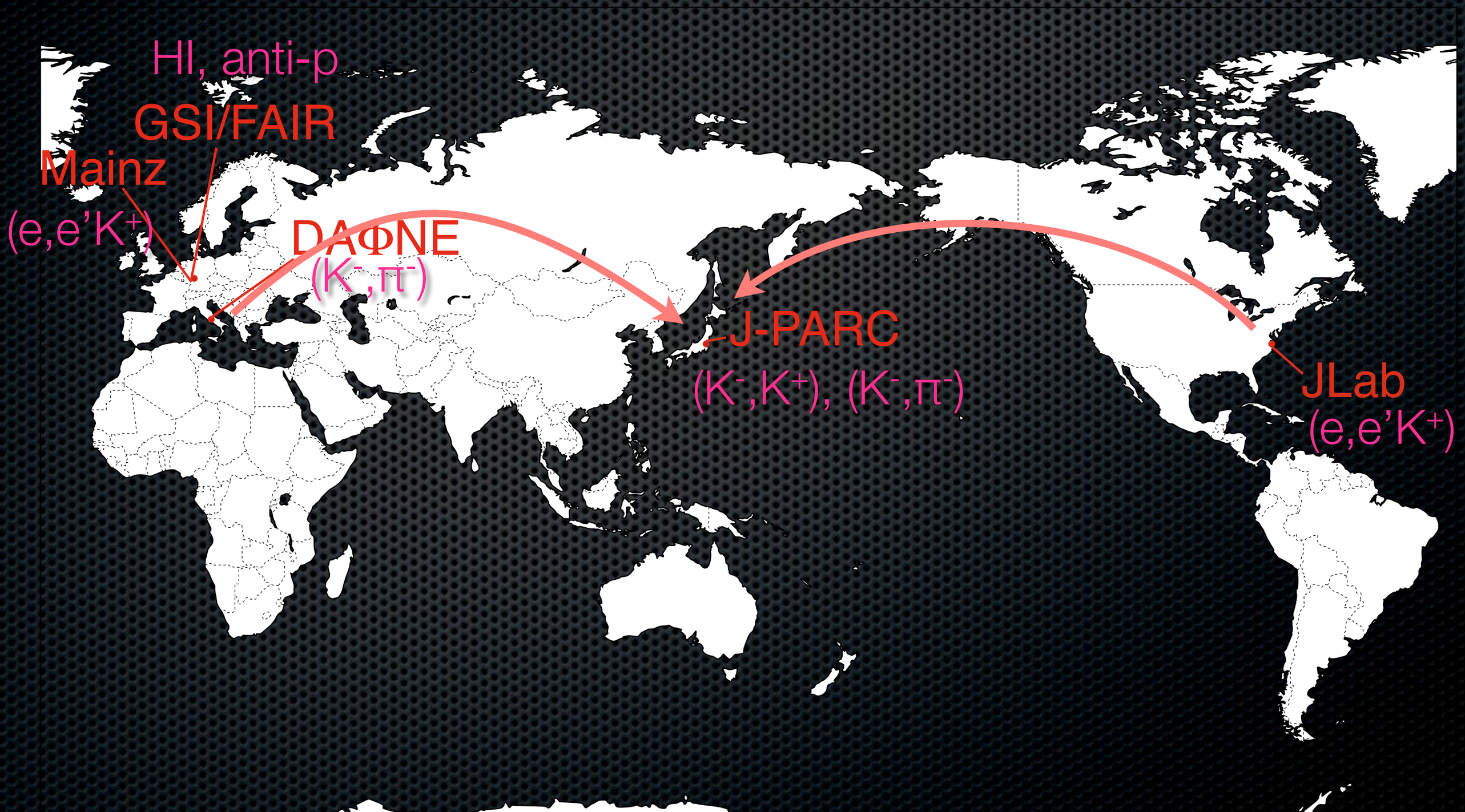


World Facilities in the 21st Century

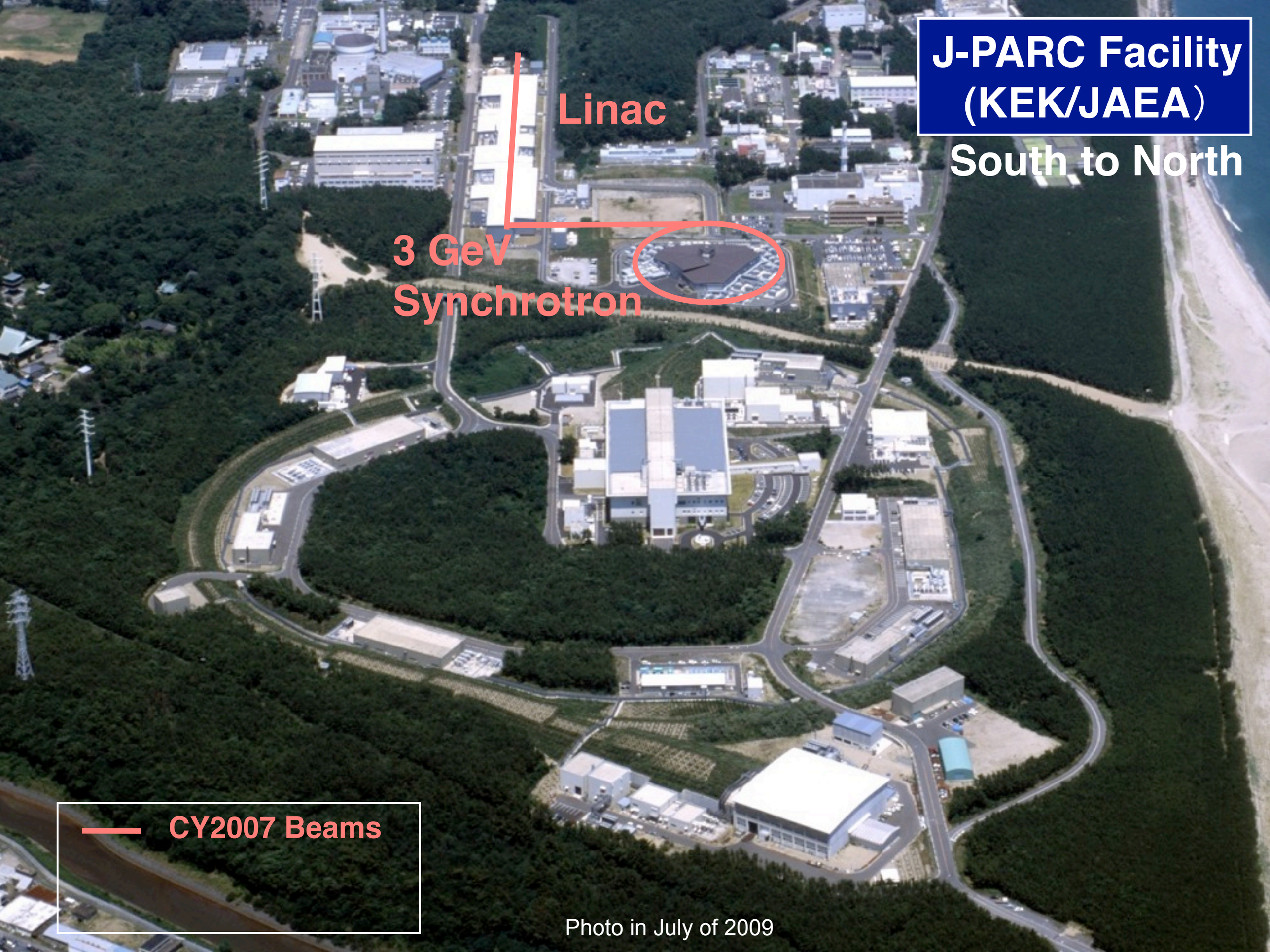


World Facilities in the 21st Century

J-PARC Facility (KEK/JAEA)

South to North

Photo in July of 2009


J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
CY2007 Beams
Photo in July of 2009

J-PARC Facility (KEK/JAEA)

South to North

Linac

3 GeV Synchrotron

50 GeV Synchrotron

Materials and Life Experimental Facility

Hadron Exp. Facility

CY2007 Beams

JFY2008 Beams

Photo in July of 2009

J-PARC Facility (KEK/JAEA)

South to North

Linac

3 GeV Synchrotron

Neutrino Beams (to Kamioka)

50 GeV Synchrotron

Materials and Life Experimental Facility

Hadron Exp. Facility

CY2007 Beams
JFY2008 Beams
JFY2009 Beams

Photo in July of 2009

Inauguration Ceremony on July 6, 2009

Beam Extraction at Hadron Exp. Hall: Jan. 27, 2009

Hadron Experimental Hall

World highest intensity Kaon beams !

60m x 56m

First beam in Feb. 2009

30~50 GeV
Primary Beam

K1.8

K1.8BR

KL

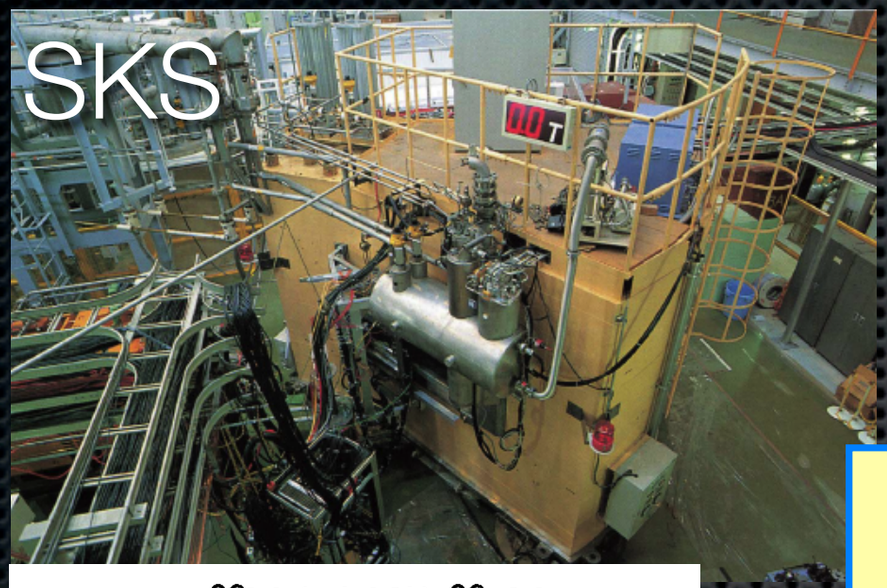
Production
target (T1)

K1.1

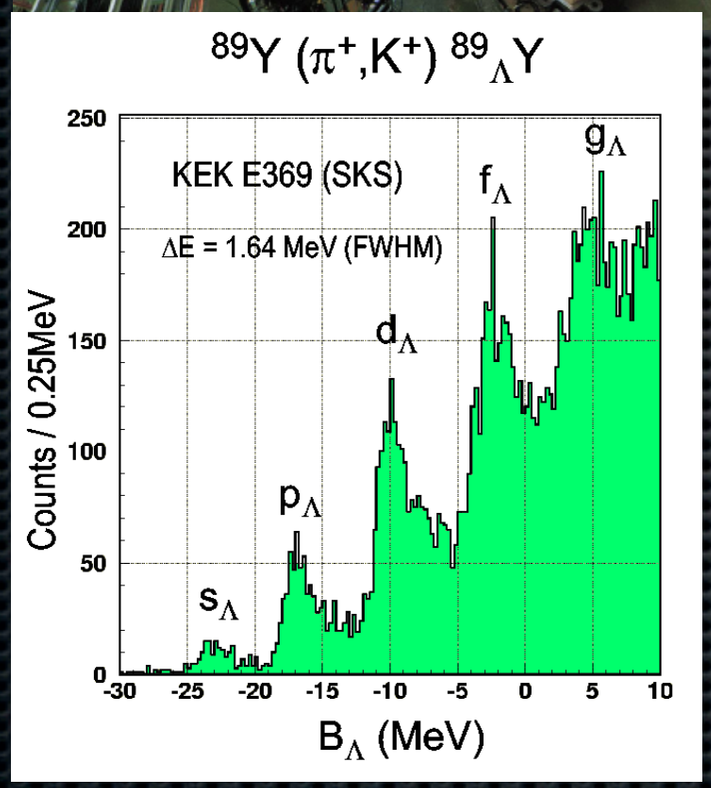
K1.1BR

S=-1 Baryon Systems

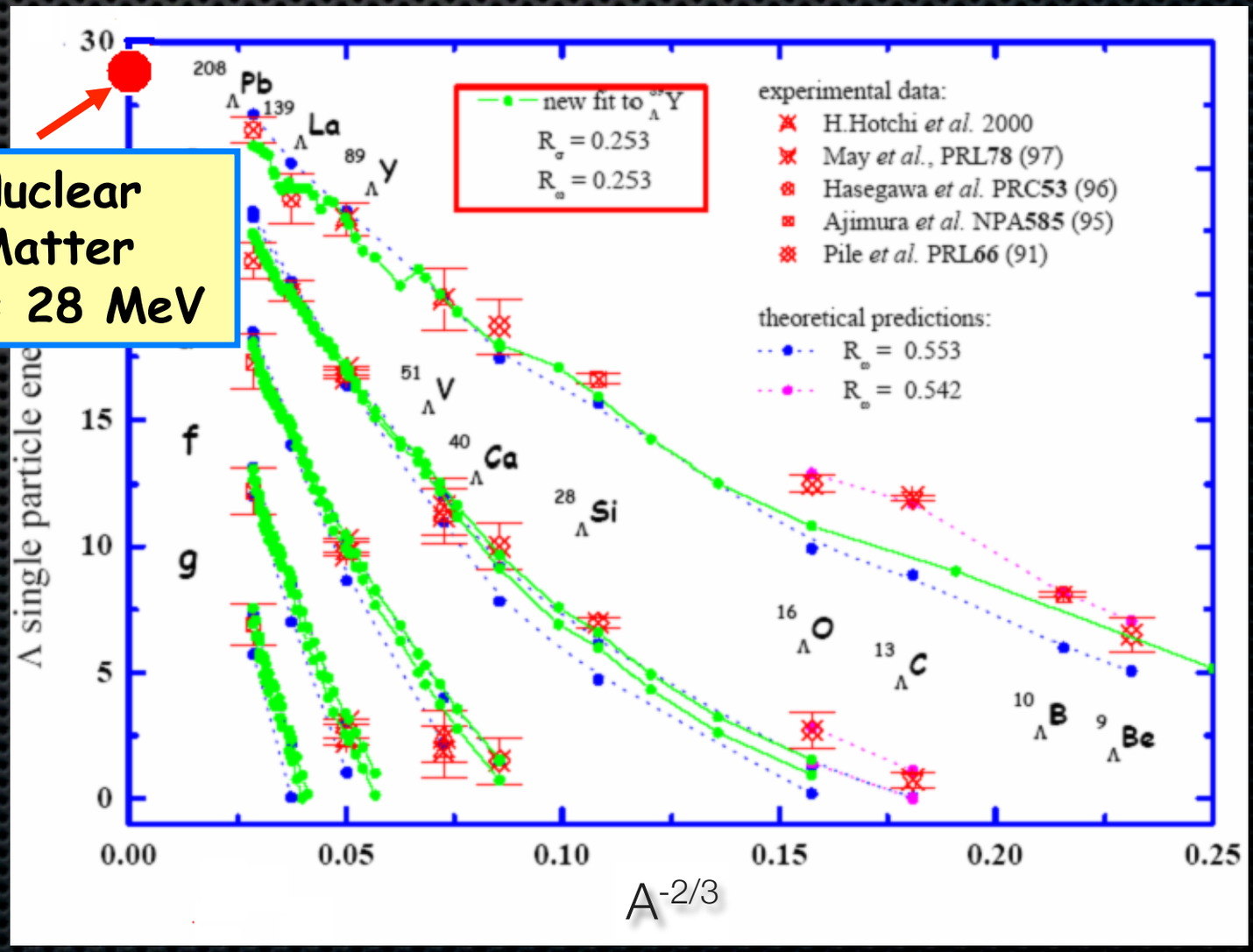
Success of (π^+,K^+) Spectroscopy



- Λ single-particle energy
  → U_Λ=28 MeV



Nuclear Matter S_Λ = 28 MeV

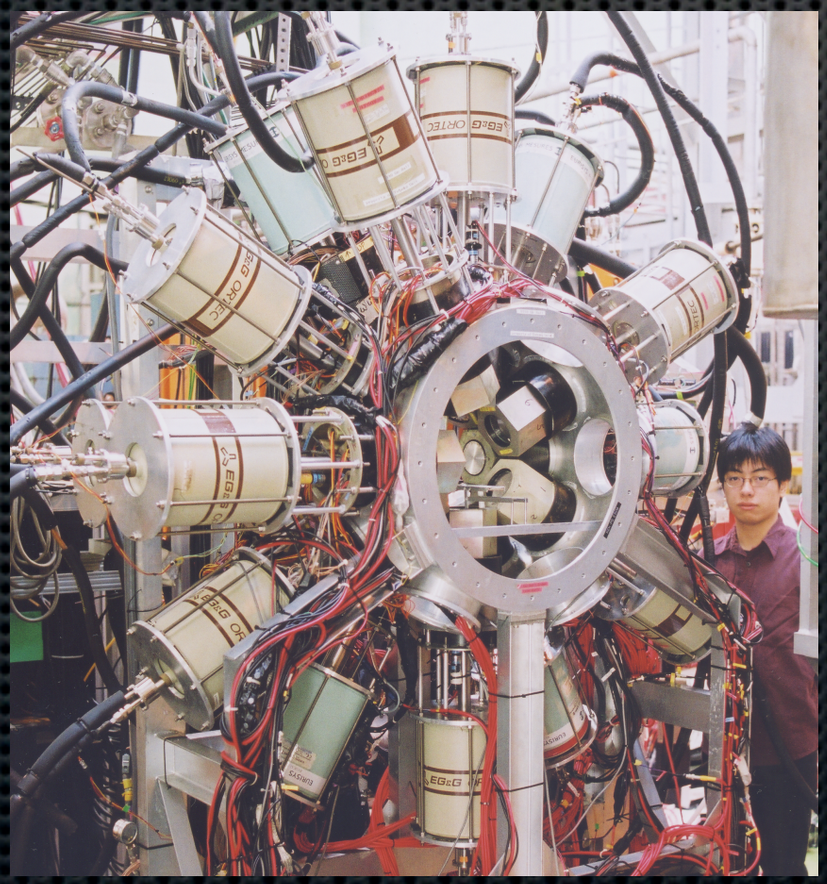


H.Hotchi et al., PRC 64, 044302(2001)

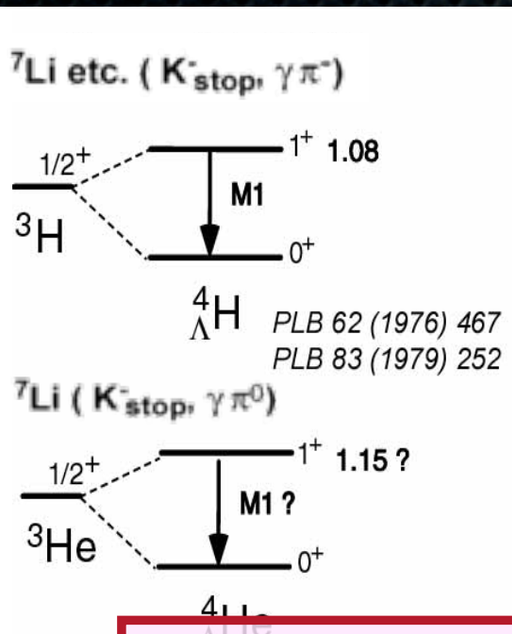
→BJ0001: H. Tamura

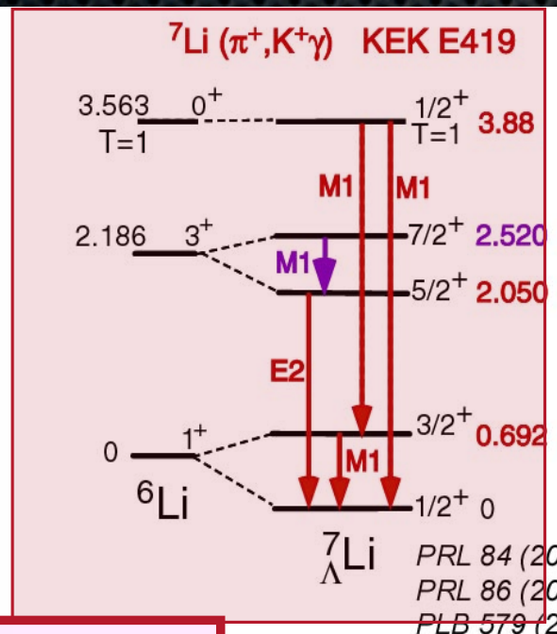
Success of Hypernuclear Gamma-Ray Spectroscopy

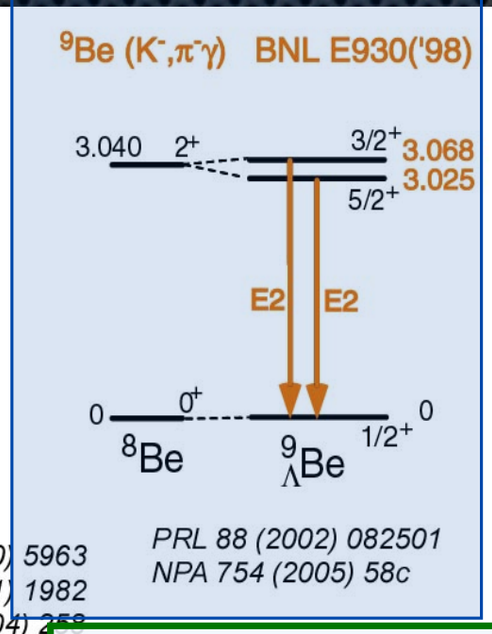
- Hyperball : Tohoku/KEK/Kyoto in 1998
  - 14 Ge(r.e.60%);
    Ω~15%, ε~3% at 1 MeV
  - BGO suppressor

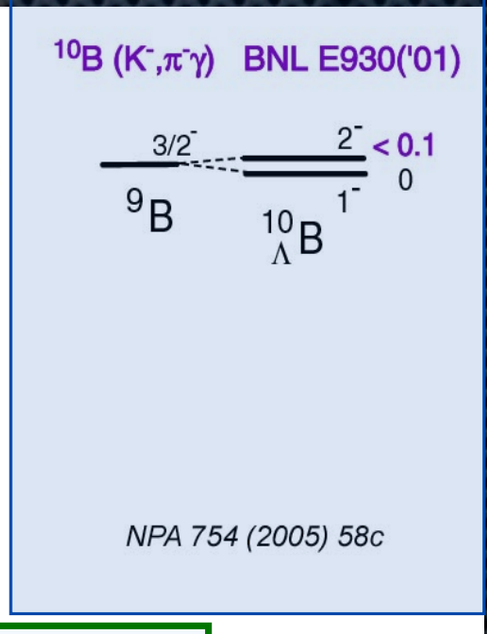


Hypernuclear Gamma-rays



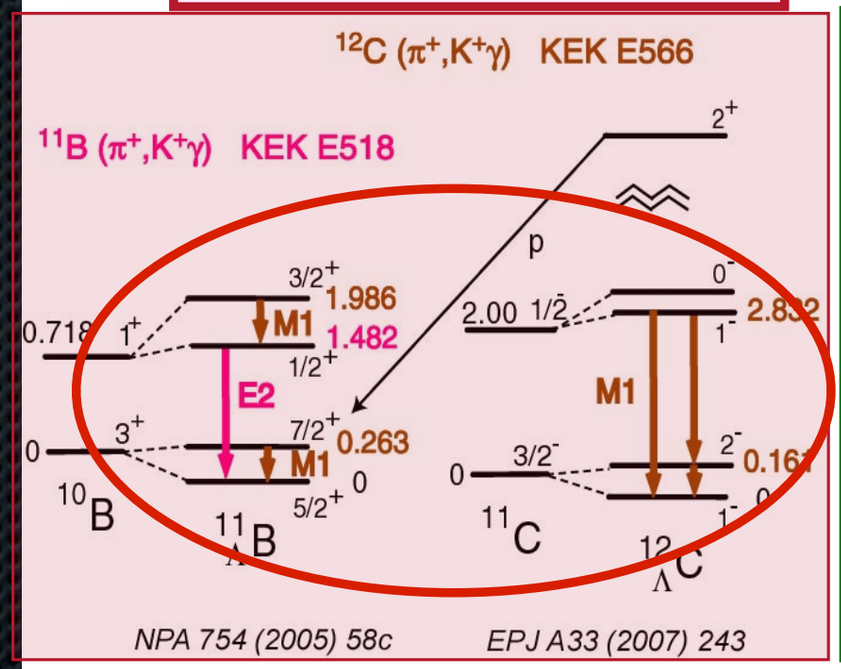


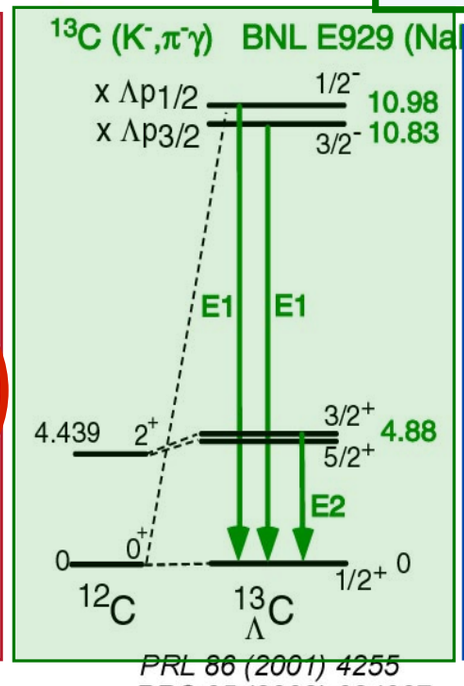


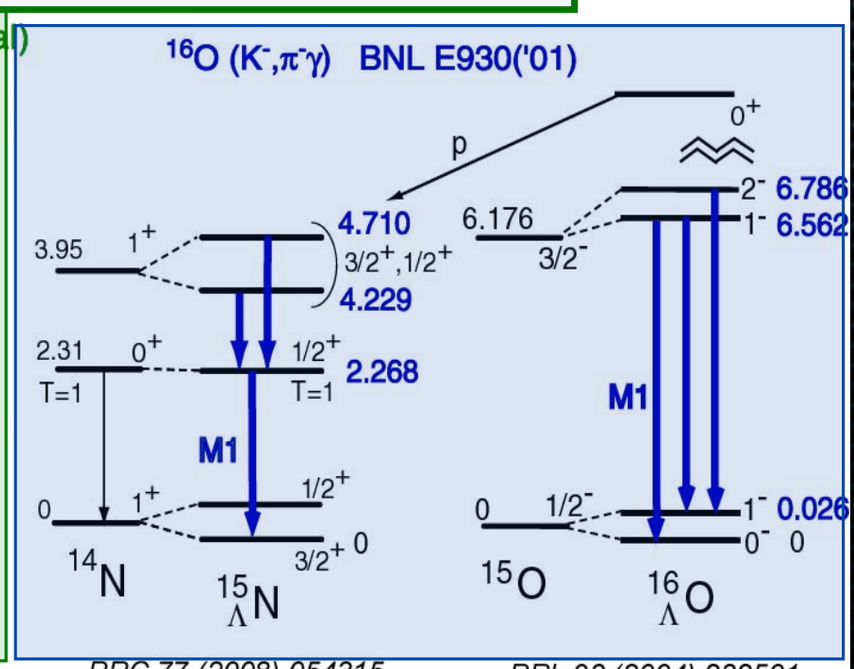


$(\pi^+,K^+\gamma)$ at KEK-PS

$(K^-,\pi^-\gamma)$ at BNL-AGS







by H. Tamura

ΛN Effective Interaction

$$V_{\Lambda N}^{eff} = V_0(r) + V_\sigma(r)\vec{s_\Lambda}\vec{s_N} + V_\Lambda(r)\vec{\ell}_{\Lambda N}\vec{s_\Lambda} + V_N(r)\vec{\ell}_{\Lambda N}\vec{s_N} + V_T(r)S_{12}$$

Δ S_Λ S_N T

Parameters in MeV

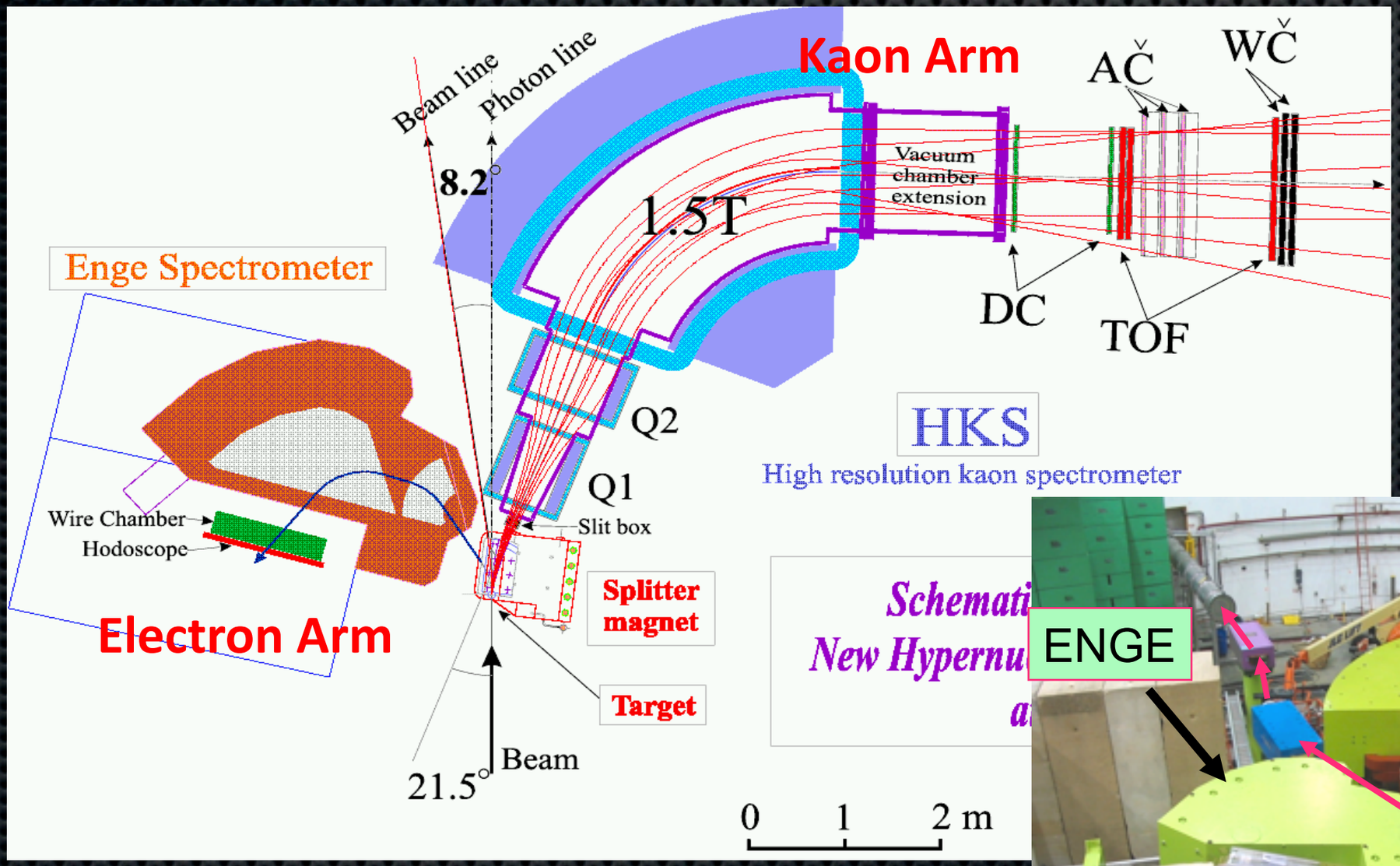
	Δ	S_Λ	S_N	T
$A = 7-$?	0.430	−0.015	−0.390	0.030
$A = 11 - 16$	0.330	−0.015	−0.350	0.024

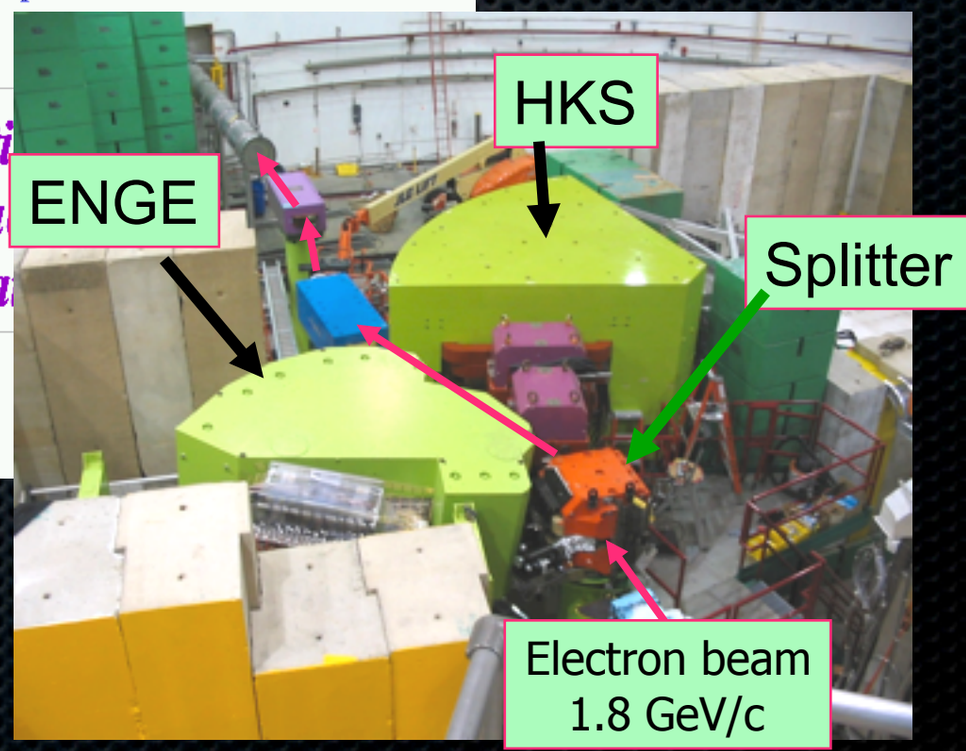
Very small LS

by D.J. Millener

→EA0001: L. Tang

JLab E01-011: (e,e'K+)



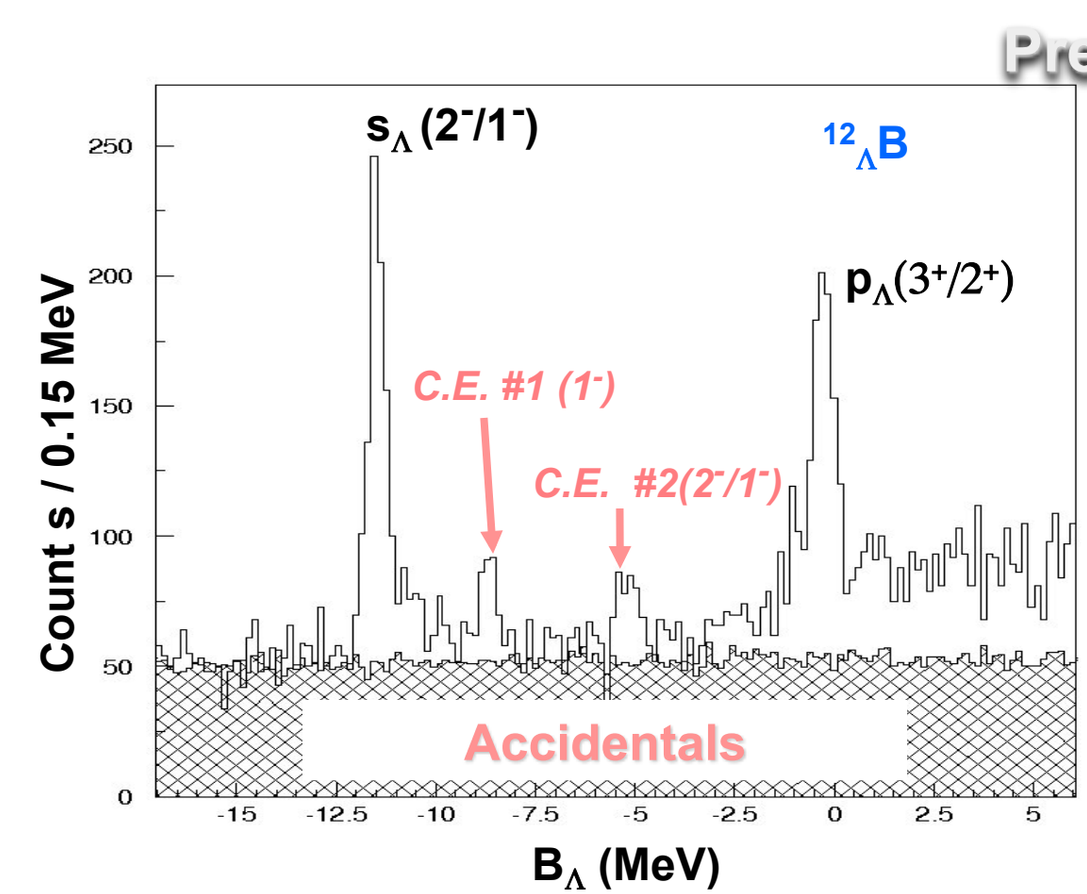


High-resolution Spectrometer in Hall-A & -C

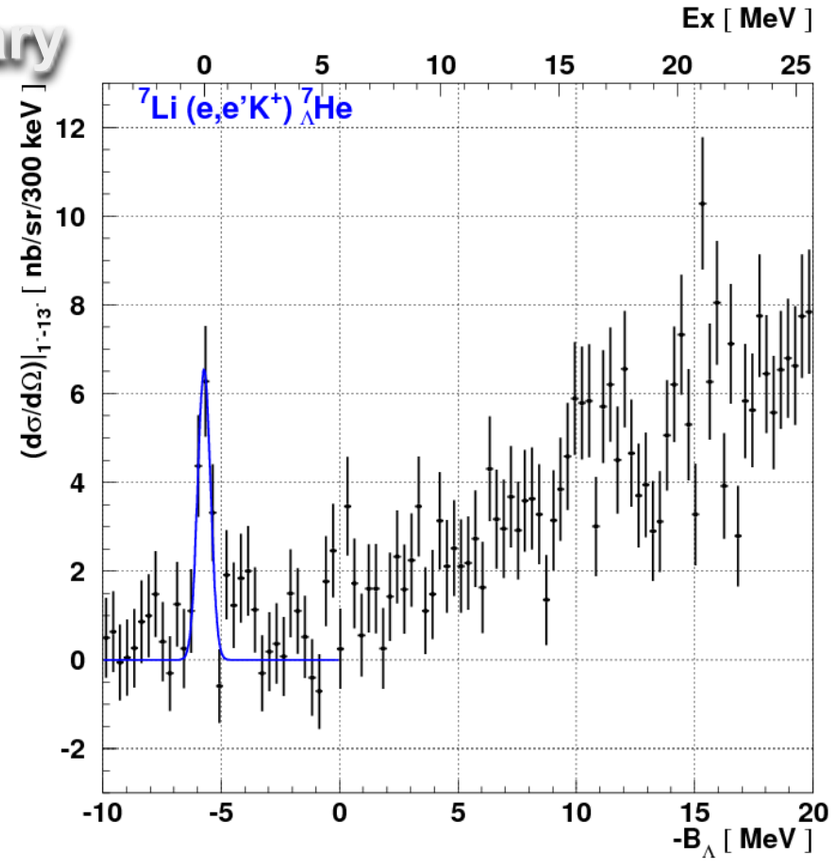
→BJ0005: A. Matsumura

$^{12}_{\Lambda}$B

$^{7}_{\Lambda}$He



- $^{12}_{\Lambda}$B Ground state resolution: 465 keV FWHM

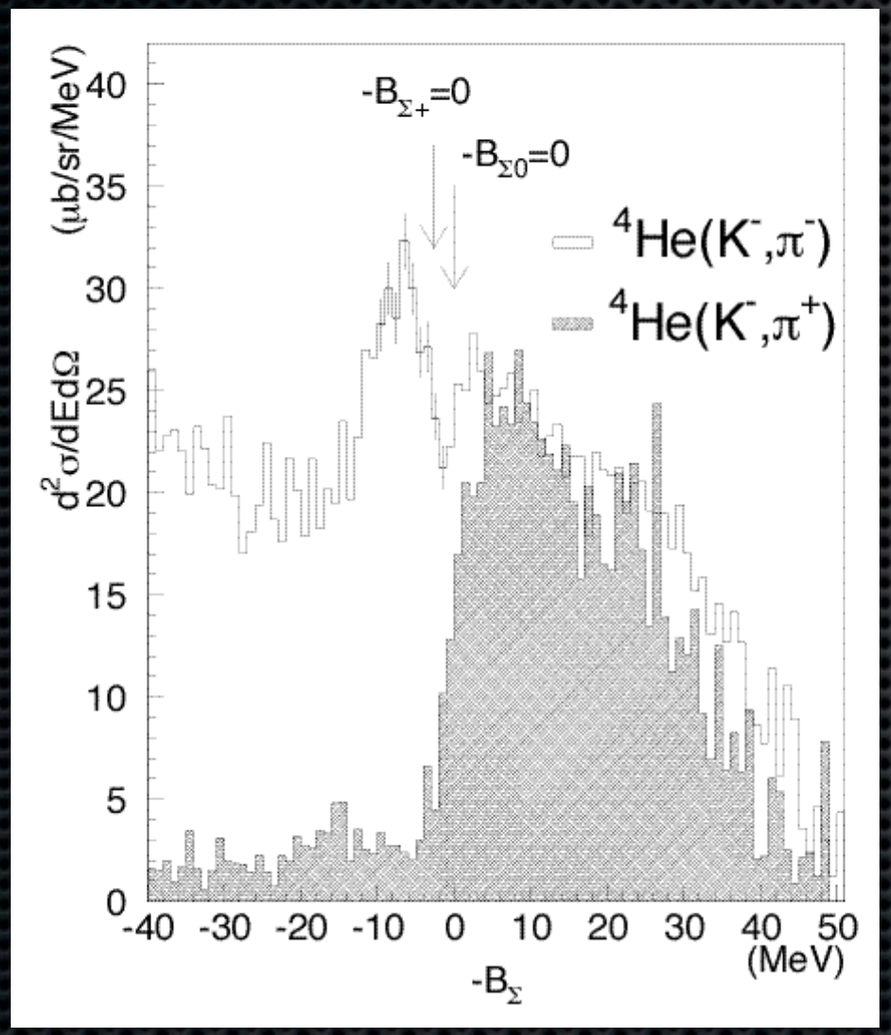


Resolution : ~510 keV (FWHM) for g.s.
Data taking : ~30 hours w/ 30 μA

O. Hashimoto @ Hyp-X

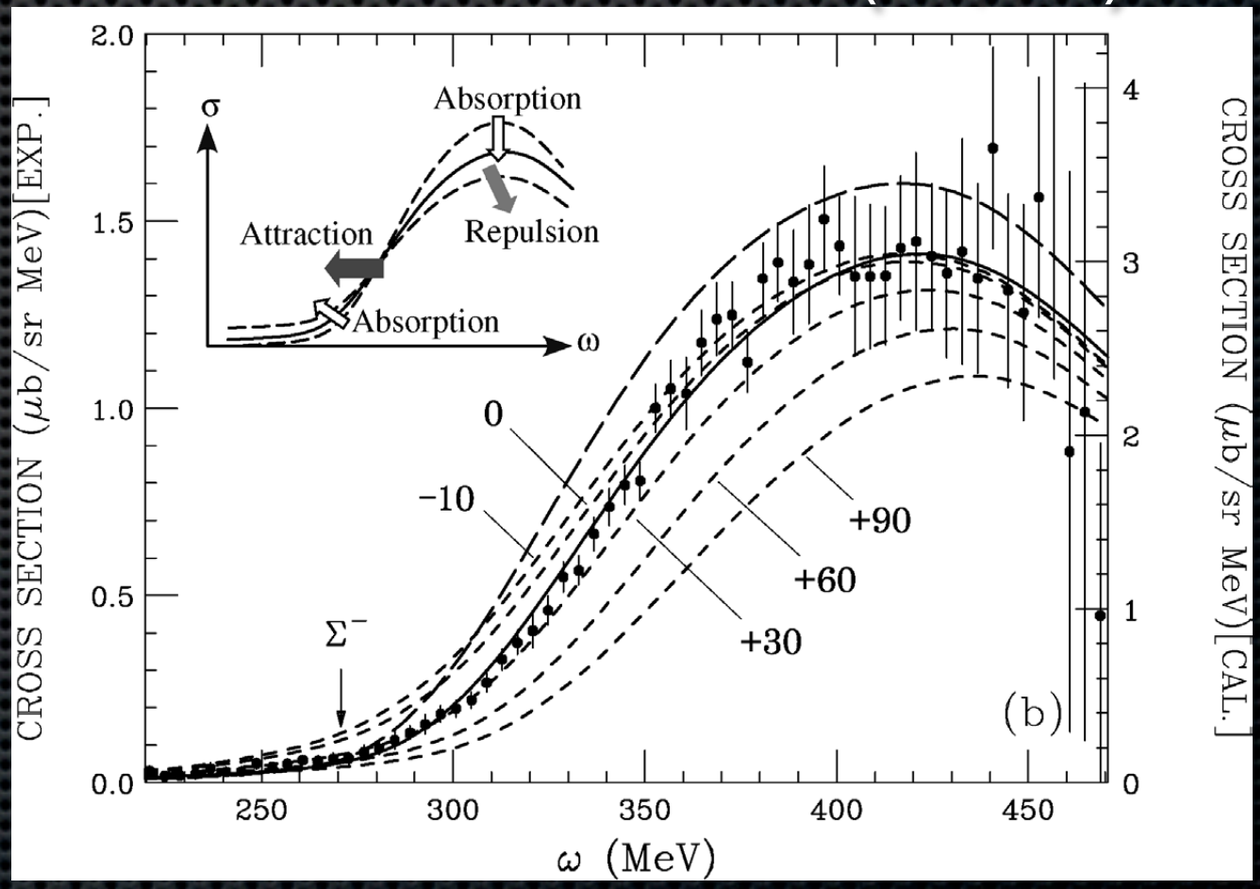
Σ -Hypernuclei

- One bound state observed: $^{4}_{\Sigma}$He



T. Nagae et al., PRL 80 (1998) 1605.

^{28}Si(π$^-$,K$^+$)



Σ^--Nucleus potential: Repulsive

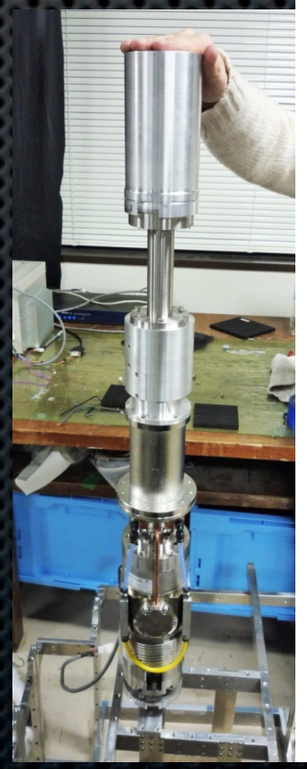
Gamma-ray Spectroscopy of Light Hypernuclei

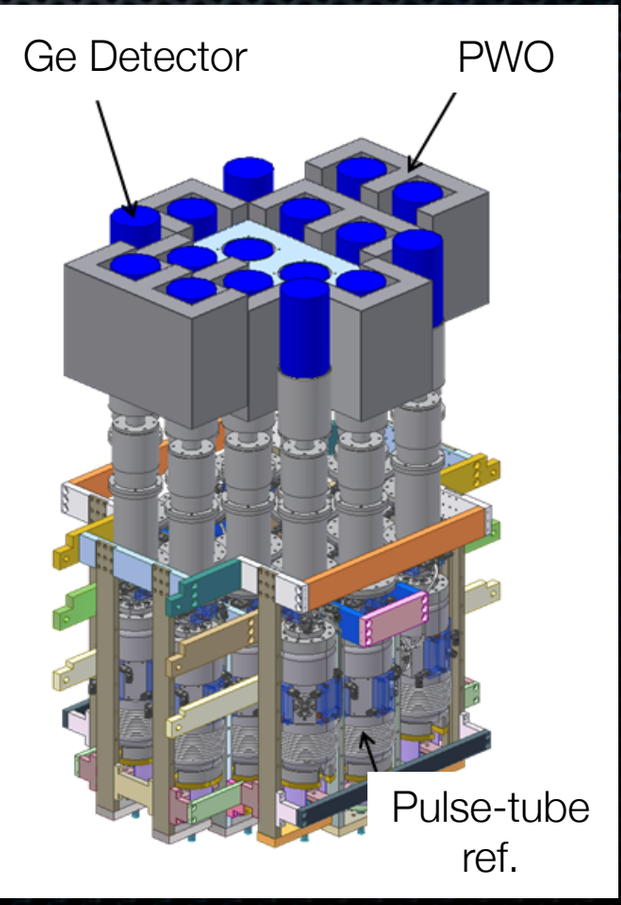
J-PARC E13
H. Tamura et al.

- Spin-flip B(M1) measurement for g_Λ in nuclei
  - ^{7}Li($K^-,\pi^-\gamma$)$^{7}_{\Lambda}$Li at 1.5 GeV/c: M1($3/2^+ \rightarrow 1/2^+$)

Hyperball-J

- ΛN interaction in sd-shell hypernuclei
  - $^{19}_{\Lambda}$F: easiest in sd-shell
- ΛN interaction in p-shell hypernuclei
  - $^{10}_{\Lambda}$B
- etc.





Ge x32; ε~5.8% at 1 MeV
→ γ-γ coincidence

Neutron-rich Hypernuclei with (π^-,K^+) reaction

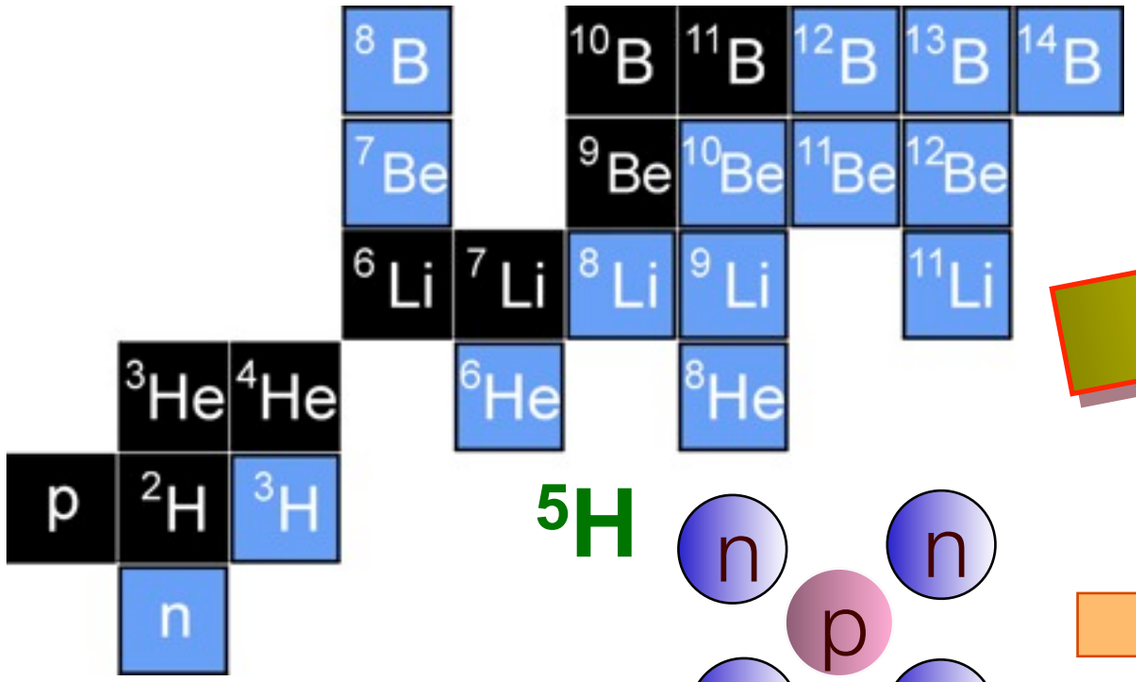
J-PARC E10
A. Sakaguchi et al.

NCX: (K^-,π^-), (π^+,K^+) reaction

SCX: $(e,e'K^+)$, (K^-,π^0), (π^-,K^0) reaction

DCX: (K^-,π^+), (π^-,K^+) reaction

ordinary nuclei



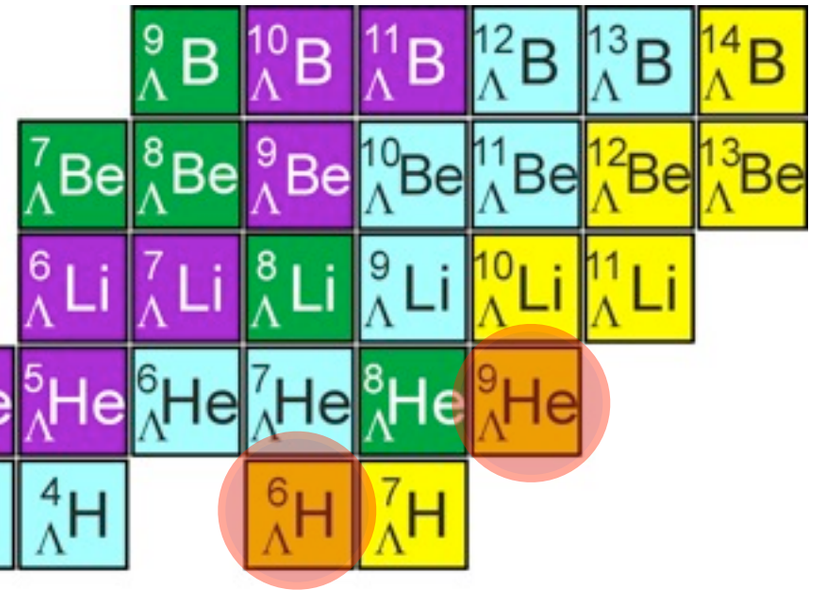
NCX

SCX

DCX

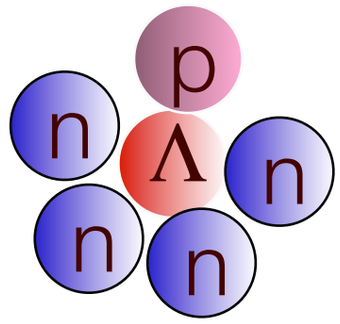
Λ

Λ-hypernuclei



^{5}H

unbound



$^6_\Lambda$H

Akaishi:
Glue-like role of Λ
(B_Λ=4.4 MeV)
+
ΛNN coherent coupling (+1.4 MeV)

"Hyperheavy hydrogen": deeply bound

S=-2 Baryon Systems

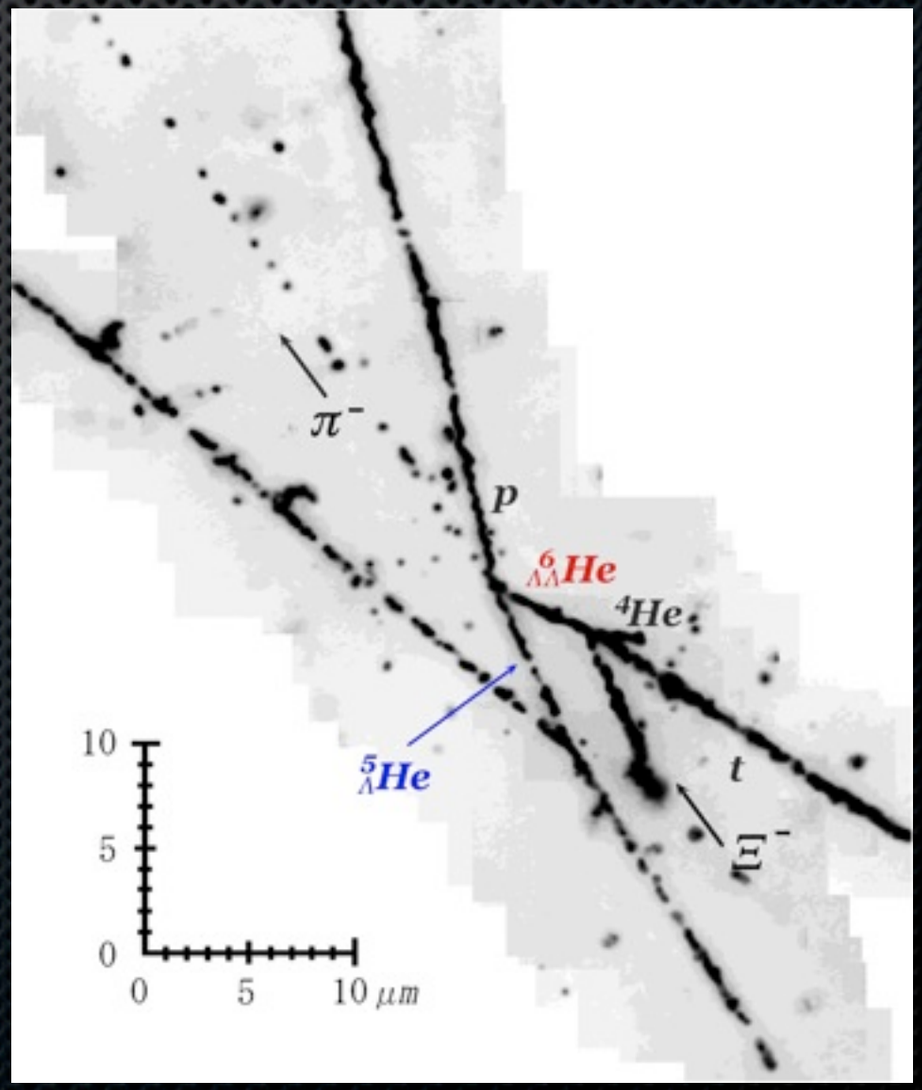
Double-Λ Hypernuclei

- "Nagara" event; ${}^{\Lambda\Lambda}{}^{6}\mathrm{He}$
  - Uniquely identified
  - $\Delta B_{\Lambda\Lambda}$=1.01±0.02+0.18/-0.11 MeV

0.67 MeV
(updated by Nakazawa@Hyp-X)

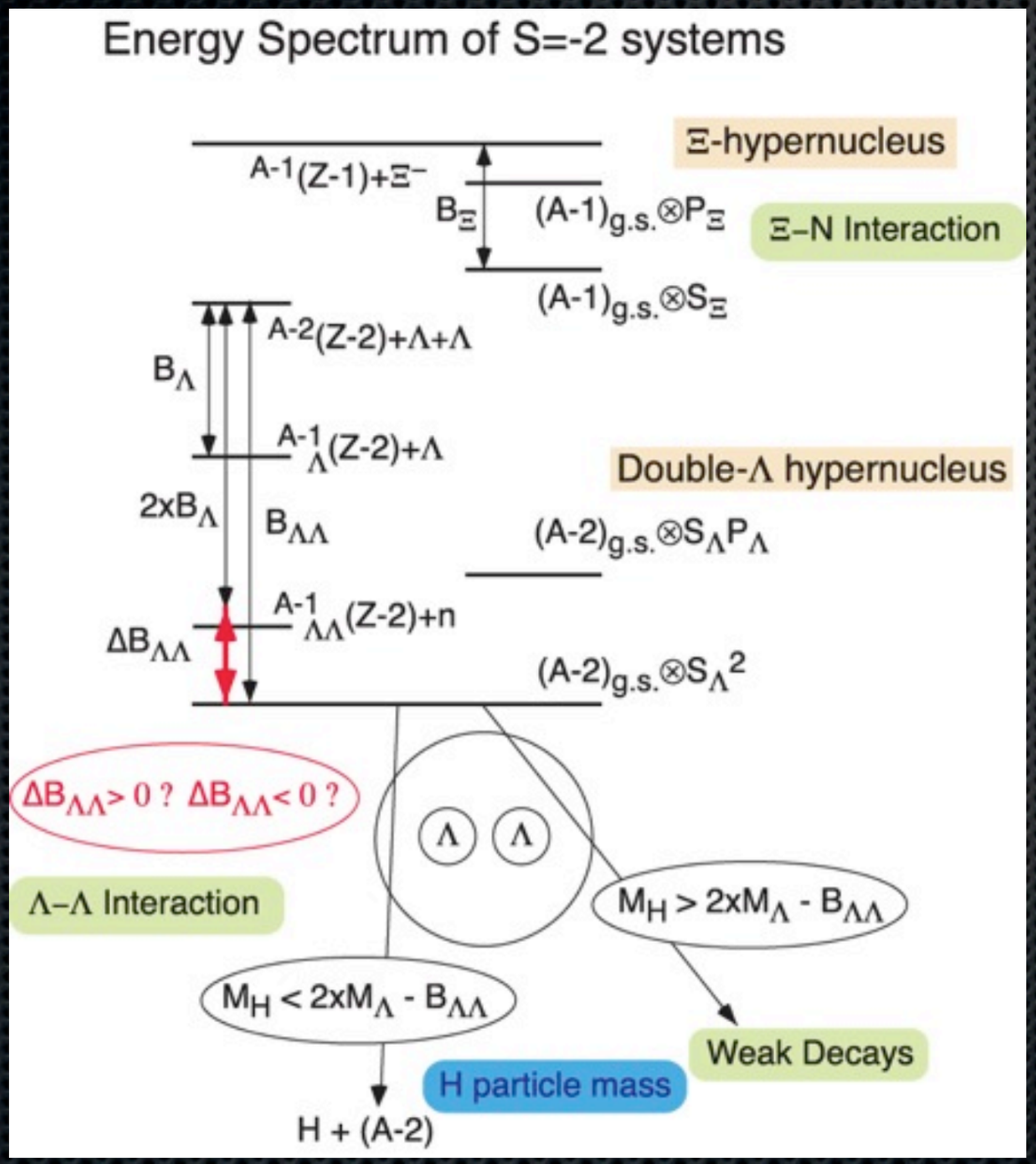
  - smaller than before (~4 MeV)

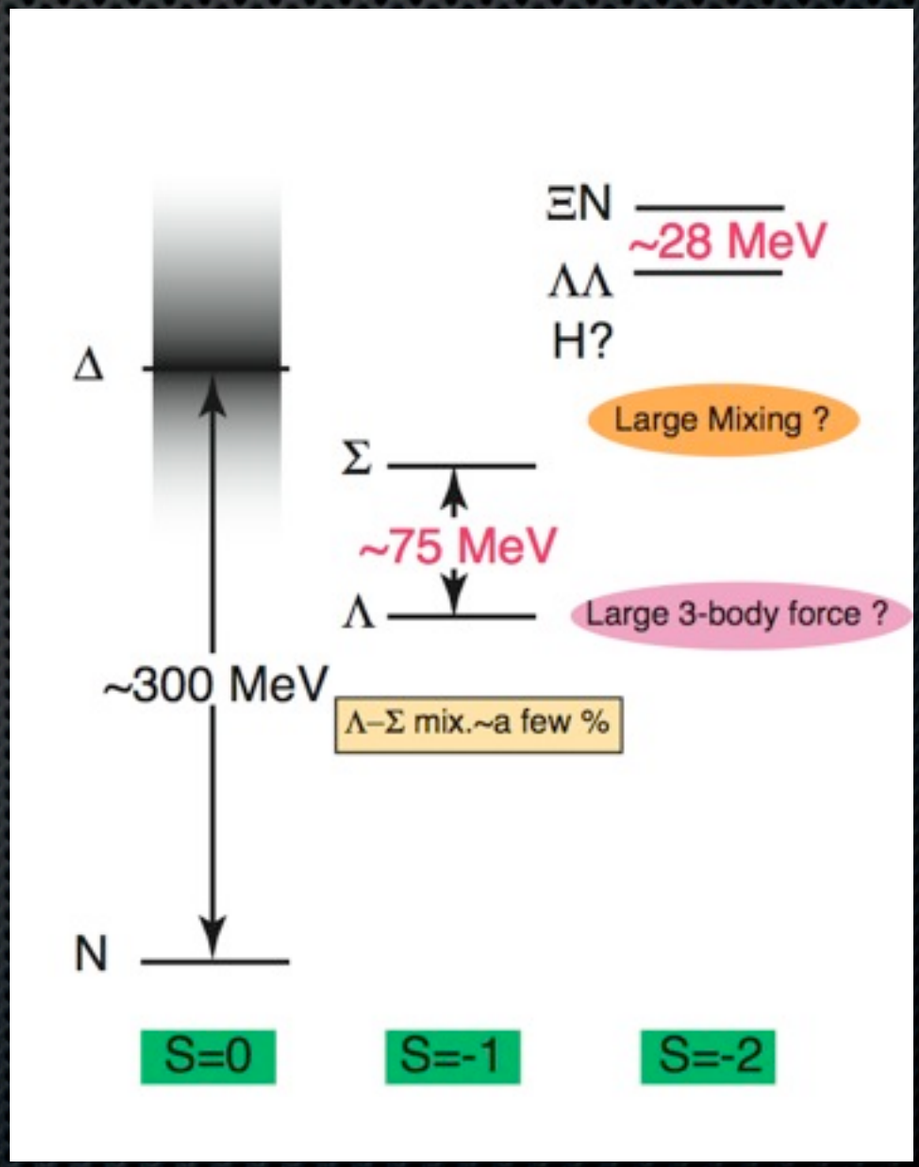
KEK E373



H. Takahashi et al., PRL87, (2001) 212502.

S=-2 World


Energy Spectrum of S=-2 systems
Ξ-hypernucleus
A-1(Z-1)+Ξ⁻
BΞ
(A-1)g.s.⊗PΞ
Ξ–N Interaction
(A-1)g.s.⊗SΞ
A-2(Z-2)+Λ+Λ
BΛ
A-1Λ(Z-2)+Λ
Double-Λ hypernucleus
2xBΛ
BΛΛ
(A-2)g.s.⊗SΛPΛ
A-1ΛΛ(Z-2)+n
ΔBΛΛ
(A-2)g.s.⊗SΛ2
ΔBΛΛ> 0 ? ΔBΛΛ< 0 ?
Λ Λ
Λ–Λ Interaction
MH > 2xMΛ - BΛΛ
MH < 2xMΛ - BΛΛ
Weak Decays
H particle mass
H + (A-2)

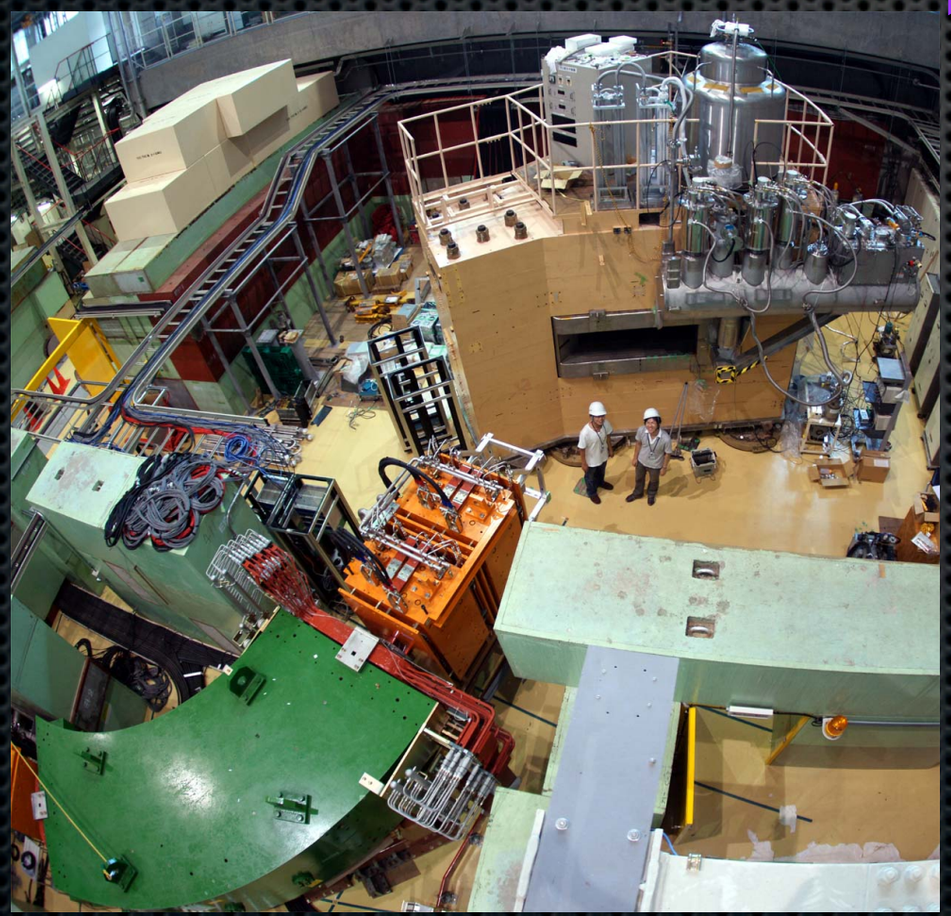

ΞN
ΛΛ
H?
~28 MeV
Large Mixing ?
Δ
Σ
~75 MeV
Λ
Large 3-body force ?
~300 MeV
Λ–Σ mix.~a few %
N
S=0
S=-1
S=-2

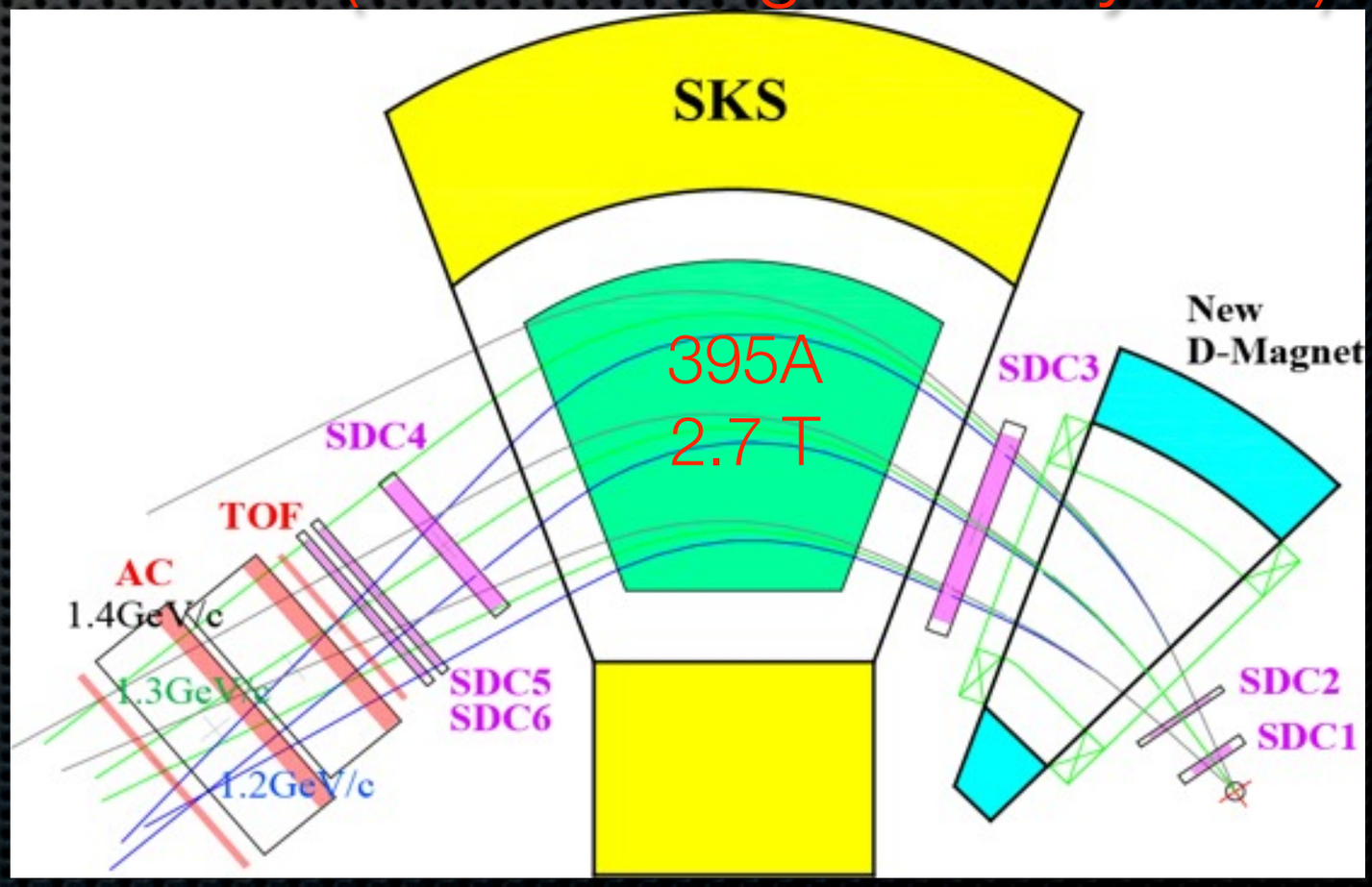
Spectroscopic Study of Ξ-Hypernucleus, $^{12}_{\Xi}$Be, via the ^{12}C(K^-,K^+) Reaction

J-PARC E05
T. Nagae et al.

- Discovery of Ξ-hypernuclei
- Measurement of Ξ-nucleus potential depth and width

of $^{12}_{\Xi}$Be S=-1 → S=-2 (Multi-Strangeness System)

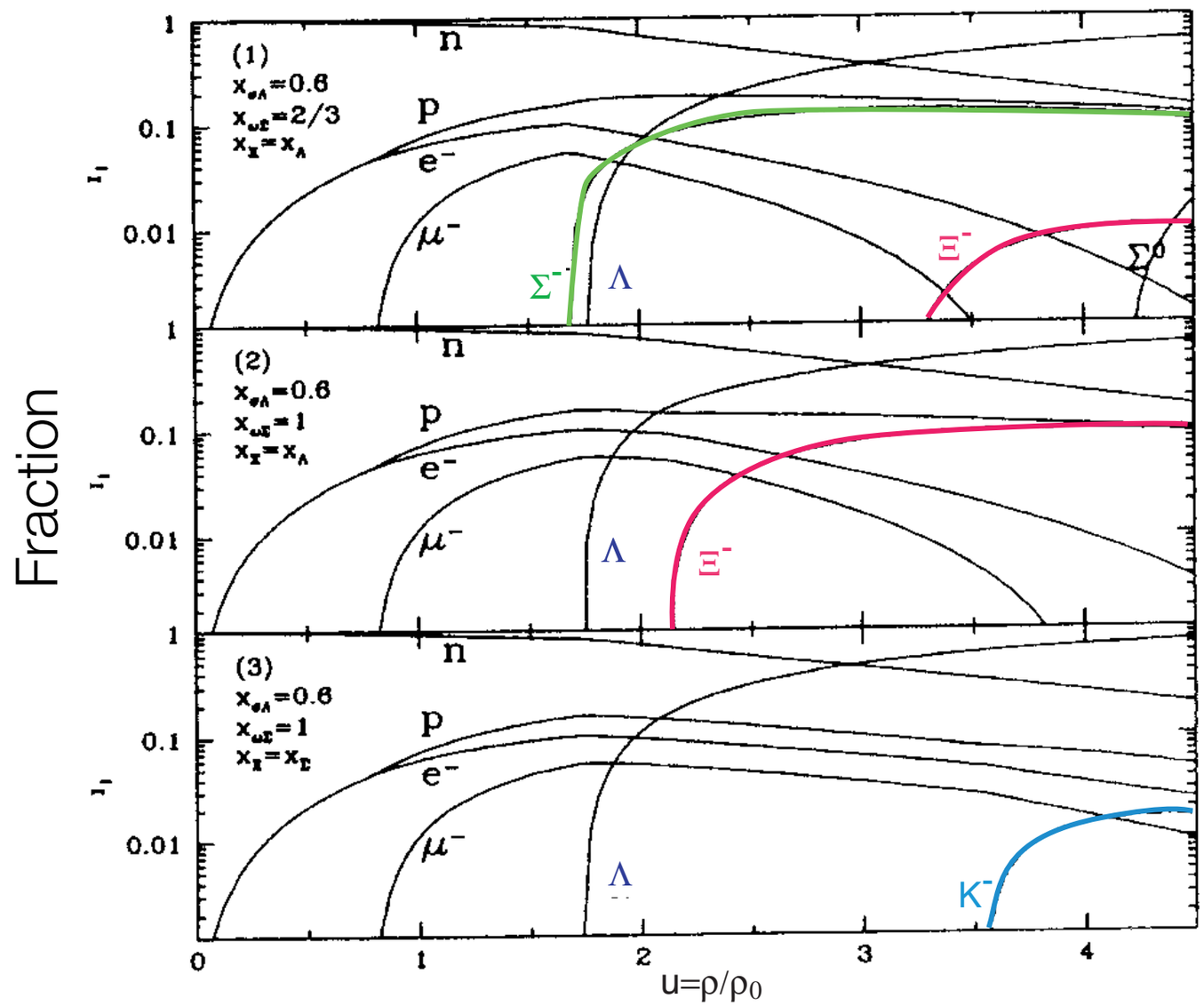




Ξ -Nucleus potential ?

- Chemical Potential:

$$\mu_B = m_B + \frac{k_F^{\,2}}{2m_B} + U(k_F)$$



$U_\Sigma < 0,\ U_\Xi < 0$

$U_\Sigma > 0,\ U_\Xi < 0$

$U_\Sigma > 0,\ U_\Xi > 0$

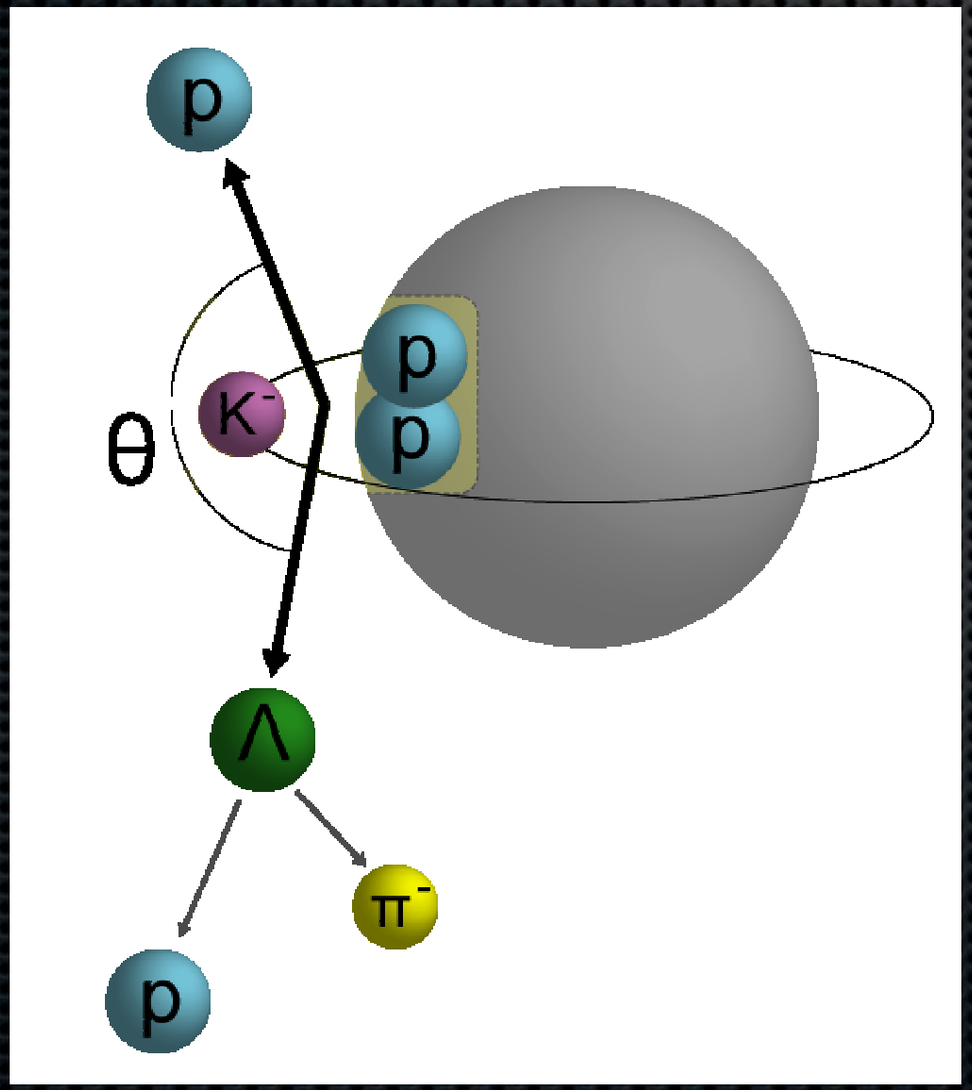
Kaonic Nuclei

→EA0003: H. Fujioka

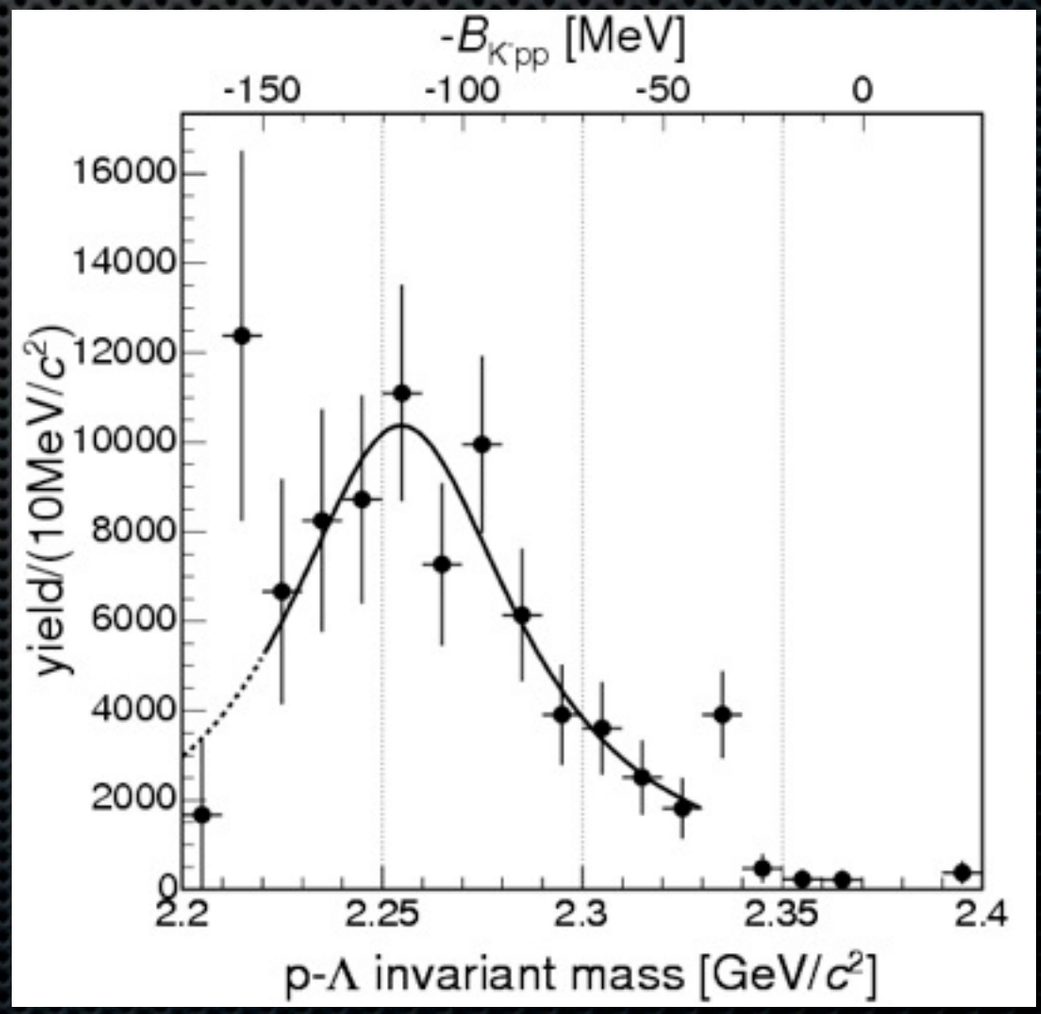
Evidence for K^-pp in FINUDA

- Back-to-back Λ-p pairs in Stopped K^- absorption

$$K^- + \text{“}pp\text{”} \rightarrow \Lambda + p$$



B=115+6/-5+3/-4 MeV
Γ= 67+14/-11+2/-3 MeV



M. Agnello et al., PRL94, (2005) 212303

→CD0008: A. Dote

Theoretical work on K^-pp

- K^-pp does exist !!

...but maybe broad (consistent with FINUDA)

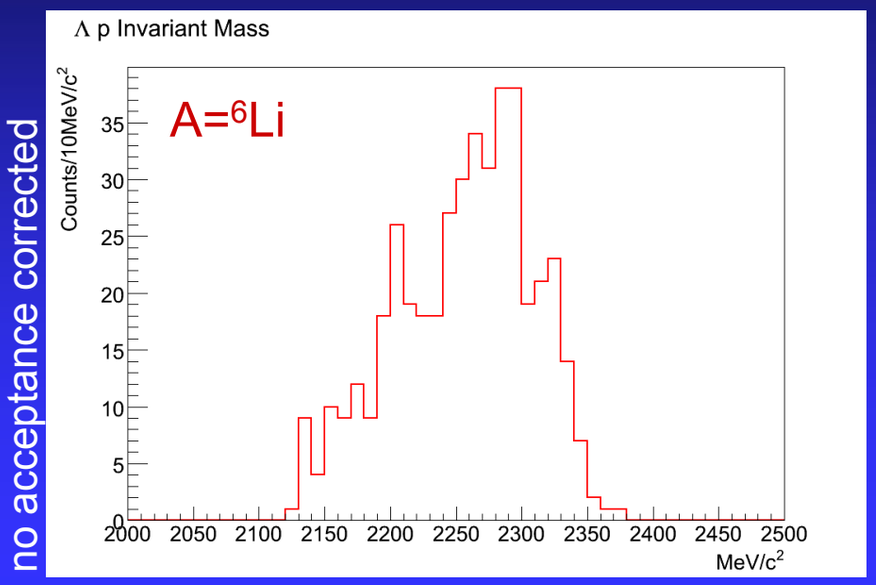
(MeV)	ATMS Yamazaki & Akaishi, PLB535 (2002) 70.	Variational Dote, Hyodo, Weise, PRC79 (2009) 014003.	Faddeev Shevchenko, Gal, Mares, PRL98 (2007) 082301.	Faddeev Ikeda & Sato, PRC79 (2009) 035201.	Variational Wycech & Green, PRC79 (2009) 014001.
B	48	17-23	50-70	60-95	40-80
Γ	61	40-70	90-110	45-80	40-85

New FINUDA data on K^-pp

- First evidence of K^-pp with ^{6}Li+^{7}Li+^{12}C

- Confirmed for ^{6}Li only, with better statistics

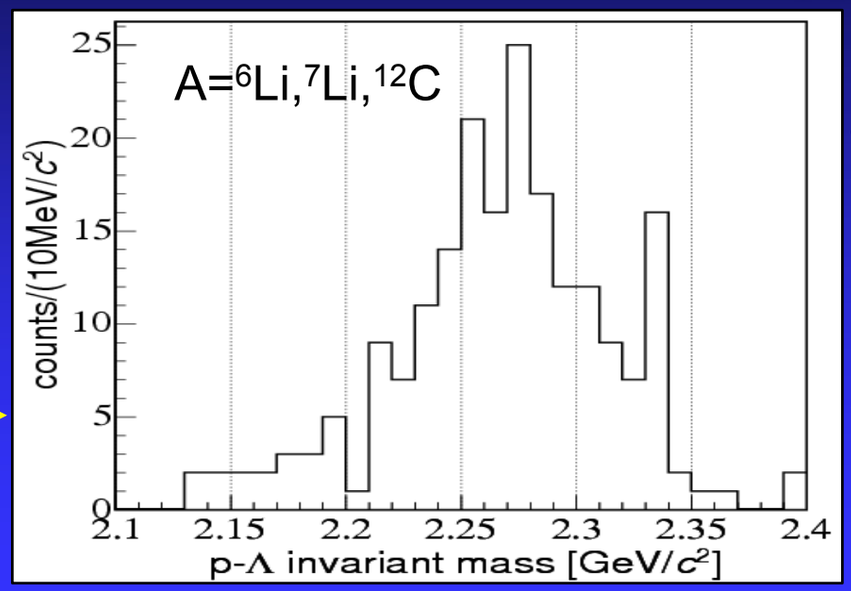
S. Piano@Hyp-X



New
inv mass spectra
compatible with
published one

New data ⟷ Old data

Same cuts applied



FINUDA Coll., PRL 94(2005)212303

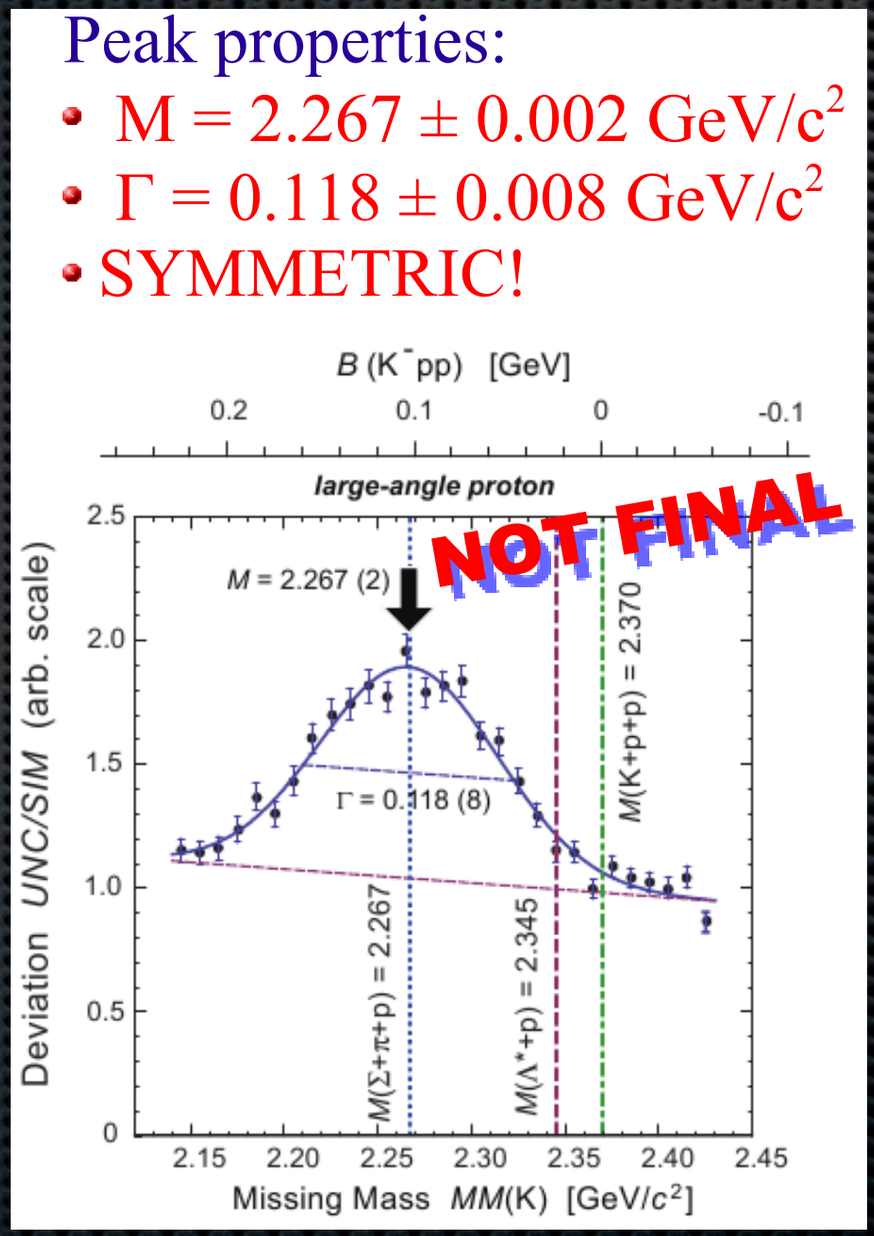
FSI, ΣN→ΛN conversion cannot explain the new data

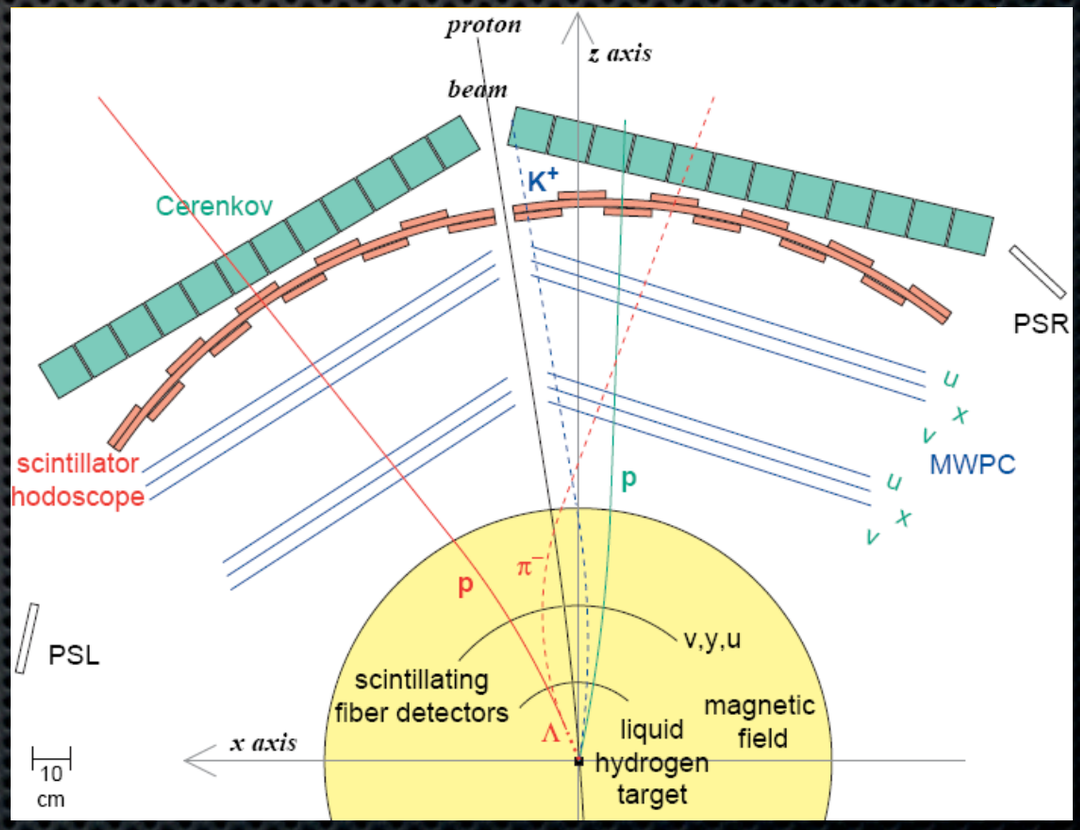
DISTO data on K^-pp

- p+p→K^-pp + K^+ at 2.85 GeV

Peak properties:

- M = 2.267 ± 0.002 GeV/c^2
- Γ = 0.118 ± 0.008 GeV/c^2
- SYMMETRIC!

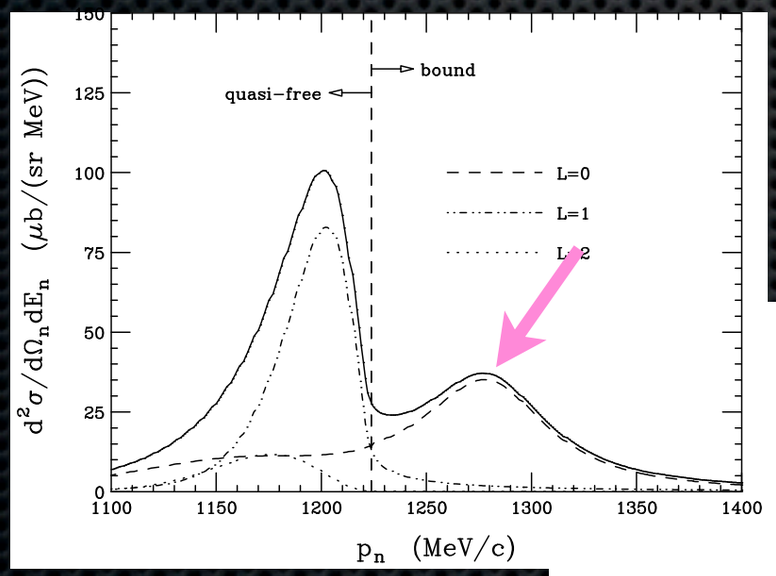




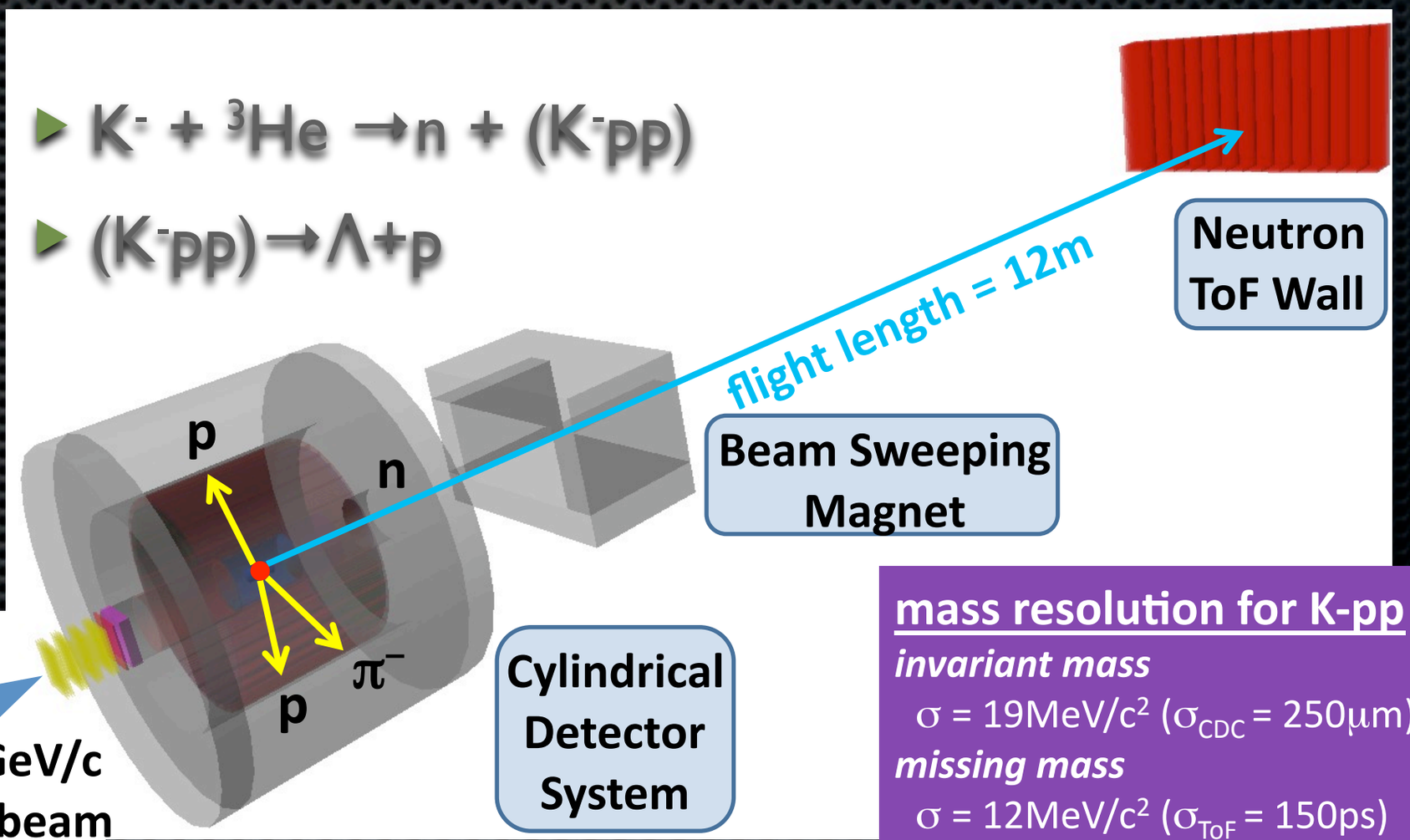
M. Maggiora @Hyp-X

In-flight (K^-,n) reaction on ^{3}He

J-PARC E15
M. Iwasaki, T. Nagae et al.



- $K^- + {}^3He \rightarrow n + (K^-pp)$
- $(K^-pp) \rightarrow \Lambda + p$



mass resolution for K-pp

invariant mass

σ = 19MeV/c^2 (σ_{CDC} = 250μm)

missing mass

σ = 12MeV/c^2 (σ_{ToF} = 150ps)

Summary

- J-PARC; construction completed.
  - will open a new era for Strangeness Nuclear Physics.
- Day-1 Experiments are about to run.
  - Ξ hypernuclear Spectroscopy
  - Hypernuclear γ-ray Spectroscopy
  - Search for Kaonic Nuclei
  - Neutron-rich hypernuclei
  - and more ...

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Join us !!