OVERVIEW and **PERSPECTIVES** in **NUCLEAR PHYSICS**

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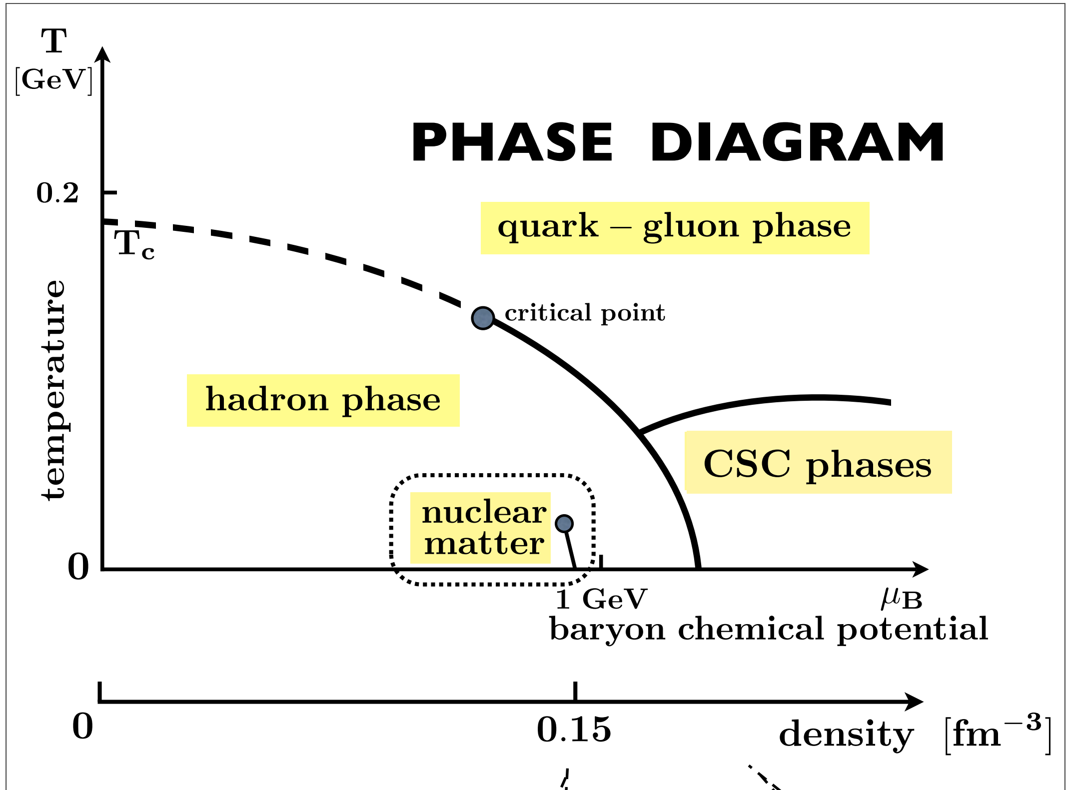
From **Yukawa**'s **Meson** ...

... via the **Phases** and **Structures** of **QCD** ...

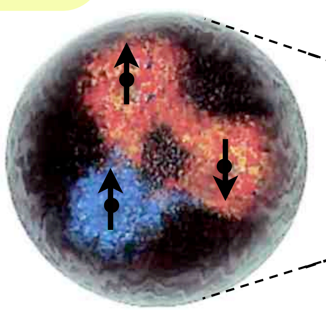
... to **Supernovae** and **Neutron Stars**

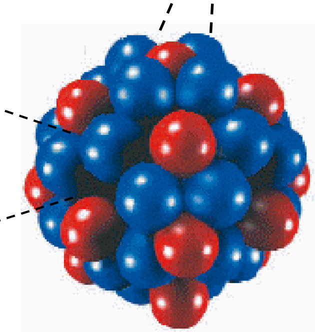
NUCLEAR PHYSICS :
exploring the **PHASES** and **STRUCTURES** of **QCD**



nucleon

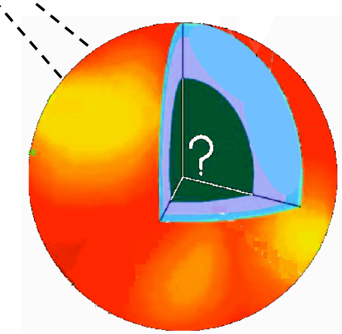
1 fm





10 fm

nuclei



20 km

neutron stars

I.

The **Beginnings**

Nucleon-Nucleon Interaction

M. Taketani, S. Nakamura, M. Sasaki
Prog. Theor. Phys. **6** (1951) 581

M. Taketani, Suppl. Prog. Theor. Phys. (1956)

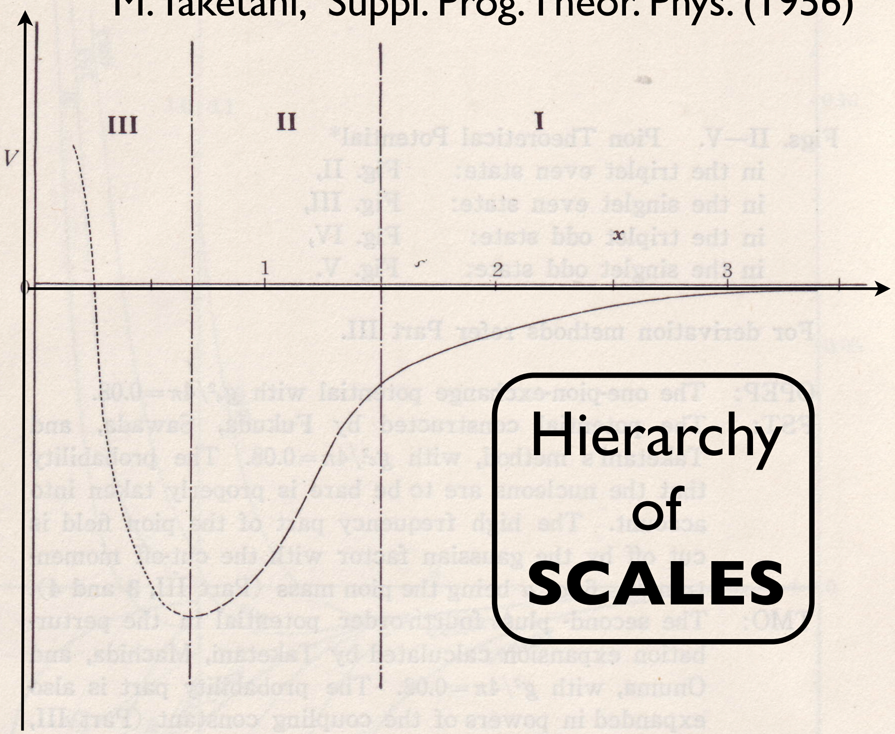


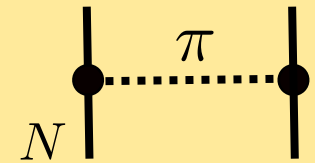
Fig. I. Three Regions of Nuclear Potential.*

Region I. *Classical region*, $r \lesssim 1.5\kappa^{-1}$, ($\kappa^{-1}$ is the pion Compton wave length) where the one-pion-exchange potential dominates and the quantitative behavior of the potential has been established.

Region II. *Dynamical region*, $0.7\kappa^{-1} \lesssim r \lesssim 1.5\kappa^{-1}$, where the two-pion-exchange potential competes with and exceeds the one-pion-exchange potential. The recoil effect is also appreciable in this region. The qualitative behavior, however, has been clarified.

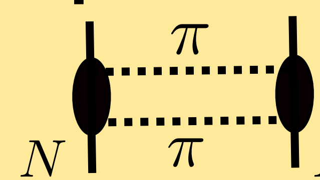
Region III. *Phenomenological region*, $r \lesssim 0.7\kappa^{-1}$, where exist so many complicated effects, e.g., the relativistic effect, the isobar effect, the effect of new particles, etc., that at present we may have no means but some phenomenological treatment to fit with experiments.

region I
long distance:
one-pion exchange



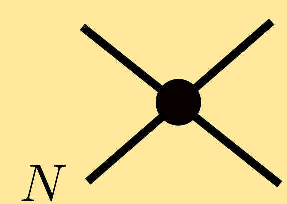
H. Yukawa (1935)

region II
intermediate distance:
two-pion exchange



H. Miyazawa et al. (1957)

region III
short distance: unresolved



II.

Yukawa's Pion
and
Low-Energy QCD:

Guiding Principles

QCD

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}\,(i\gamma_\mu \mathcal{D}^\mu - \mathbf{m})\,\psi - \frac{1}{4}\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}$$

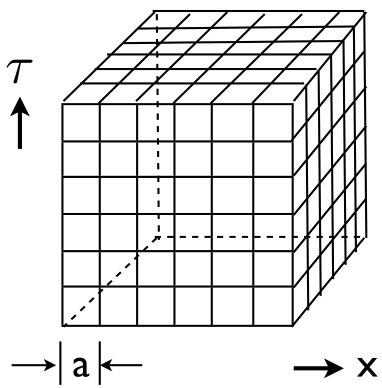
BASIC CONCEPTS and **STRATEGIES**

- “**HIGH - Q**” (> several GeV) $\leftrightarrow$ **SHORT DISTANCE** (< 0.1 fm)

  ➡ Theory of WEAKLY INTERACTING QUARKS and GLUONS

- **LATTICE QCD**

  ➡ Large-scale computer simulations on EUCLIDEAN SPACE-TIME Lattices



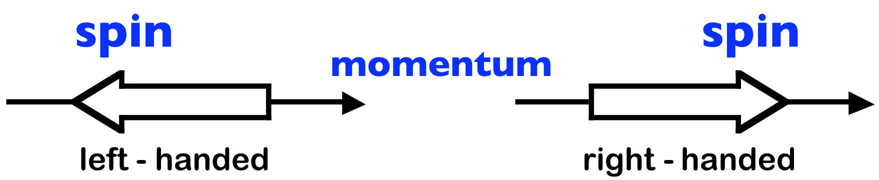
- “**LOW - Q**” (<< 1 GeV) $\leftrightarrow$ **LONG DISTANCE** (> 1 fm)

  ➡ **SPONTANEOUS** (CHIRAL) **SYMMETRY BREAKING**

  ➡ Effective Field Theory of WEAKLY INTERACTING **PIONS** as **NAMBU-GOLDSTONE BOSONS**

Low-Energy QCD : CHIRAL SYMMETRY

- **QCD** with (almost) **MASSLESS u-** and **d-QUARKS** ($N_f = 2$)



$$\mathbf{SU(2)_L \times SU(2)_R}$$

$$\psi = (\mathbf{u}, \mathbf{d})$$

pseudoscalar isovector

$$\pi^a \leftrightarrow \bar{\psi}\,\gamma_5\,\mathbf{t}^a\,\psi$$

$$\mathbf{J}^\pi = \mathbf{0}^- \qquad \mathbf{I} = \mathbf{1}$$

PION

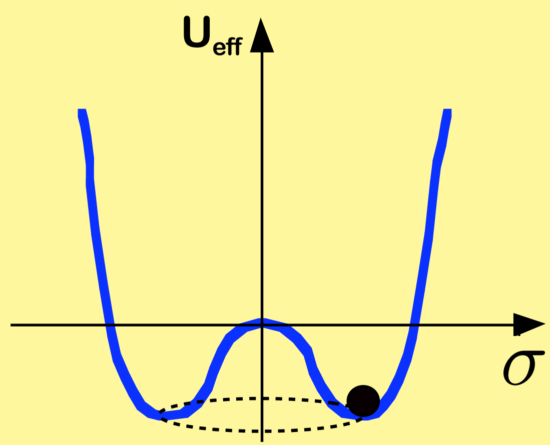
scalar isoscalar

$$\sigma \leftrightarrow \bar{\psi}\,\psi$$

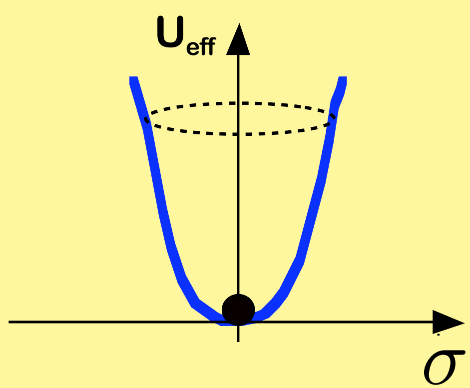
$$\mathbf{J}^\pi = \mathbf{0}^+ \qquad \mathbf{I} = \mathbf{0}$$

- **SPONTANEOUS SYMMETRY BREAKING**
  (Nambu - Goldstone)

LOW T



HIGH T



- **CHIRAL** (QUARK) **CONDENSATE**

$$\langle \bar{\mathbf{q}}\mathbf{q} \rangle \neq \mathbf{0} \qquad\qquad \langle \bar{\mathbf{q}}\mathbf{q} \rangle = \mathbf{0}$$

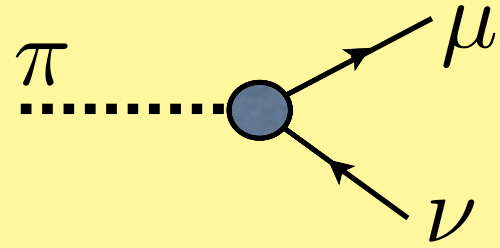
Spontaneously Broken CHIRAL SYMMETRY

- **NAMBU - GOLDSTONE BOSON**: **PION**

- **ORDER PARAMETER**: **PION DECAY CONSTANT**

$$\langle 0|\mathbf{A}^a_\mu(0)|\pi^b(p)\rangle = i\delta^{ab}\, p_\mu\, \mathbf{f}_\pi$$

Axial current



$$\mathbf{f}_\pi = \mathbf{92.4\,MeV}$$

- **SYMMETRY BREAKING SCALE ⟷ MASS GAP**

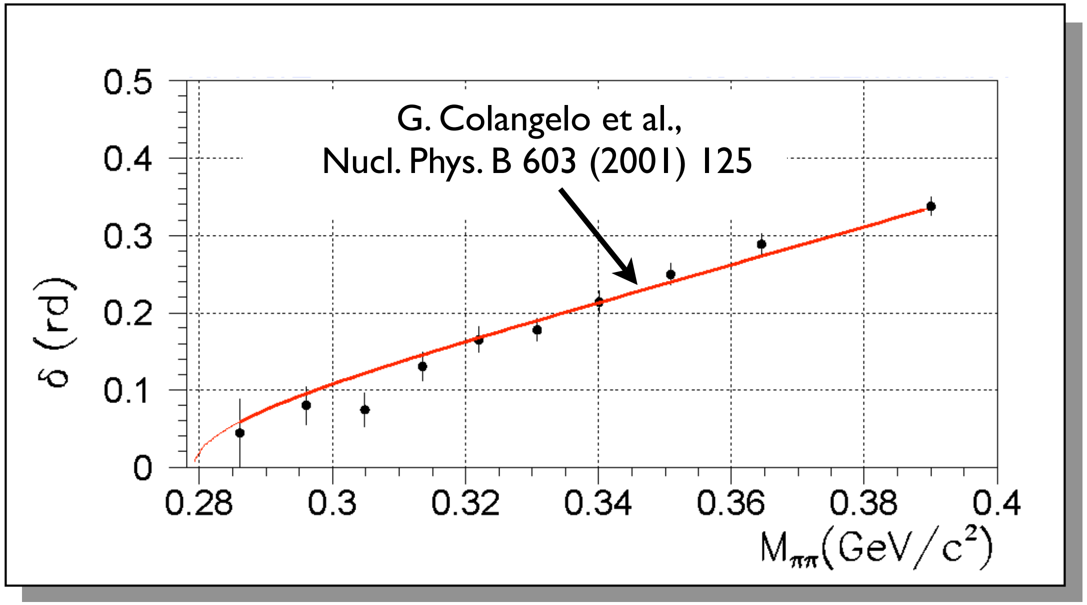
$$\mathbf{\Lambda}_\chi = \mathbf{4}\pi\,\mathbf{f}_\pi \sim \mathbf{1\,GeV}$$

- **PCAC**: $$\mathbf{m}_\pi^{\mathbf{2}}\,\mathbf{f}_\pi^{\mathbf{2}} = -\mathbf{m_q}\,\langle\bar\psi\psi\rangle + \mathcal{O}(m_q^2)$$

Gell-Mann - Oakes - Renner Relation

Tests of the **Chiral Symmetry Breaking Scenario**

low-energy $\pi\pi$ phase shifts from $K \rightarrow \pi\pi e\nu$



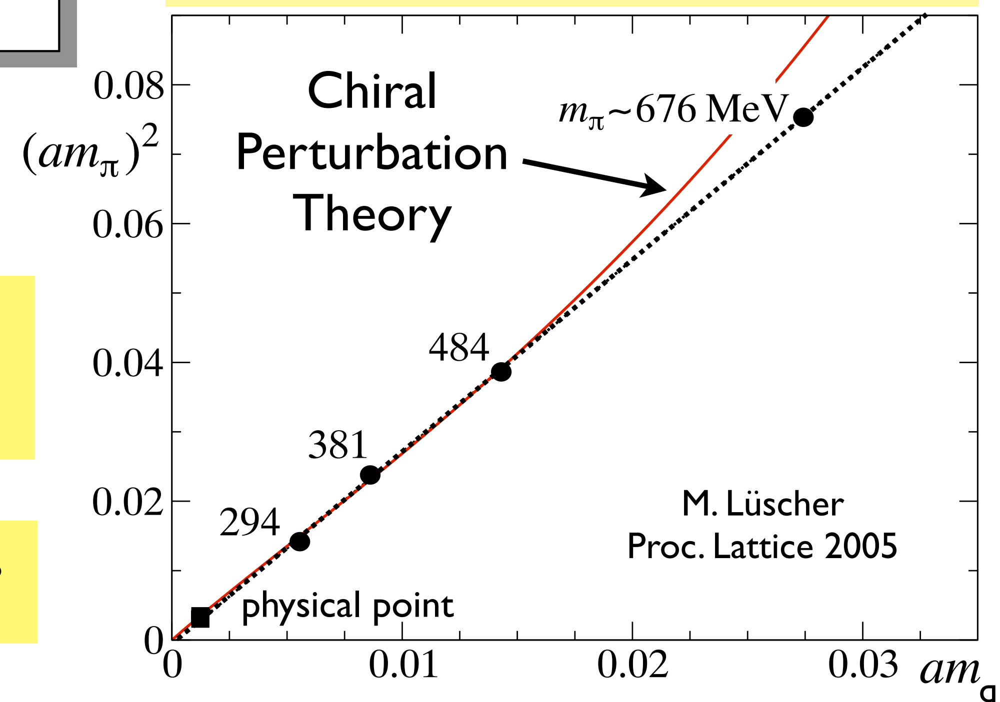
confirmation of "standard" spontaneous symmetry breaking with **Pion** as **Nambu-Goldstone Boson** and **Strong Quark Condensate**

- perfect consistency with leading order Gell-Mann - Oakes - Renner relation

$$m_\pi^2 = -\frac{m_u + m_d}{\mathbf{f}_\pi^2}\langle \bar{\mathbf{q}}\mathbf{q}\rangle + \mathcal{O}(m_q^2)$$

$$|\langle \bar{\mathbf{q}}\mathbf{q}\rangle| \simeq (\mathbf{0.23\,GeV})^3 \simeq \mathbf{1.5\ fm^{-3}}$$

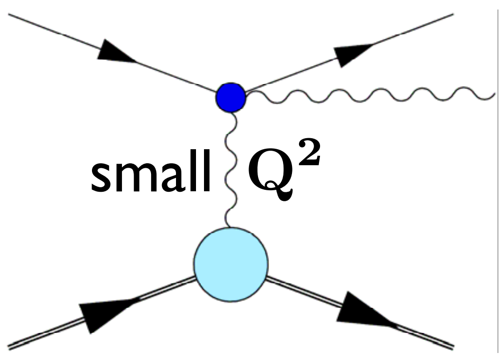
PION from **LATTICE QCD**



Tests of the **Chiral Symmetry Breaking Scenario** (part II)

- **Electromagnetic Polarizability** of the **PION**

pion beam
(190 GeV)

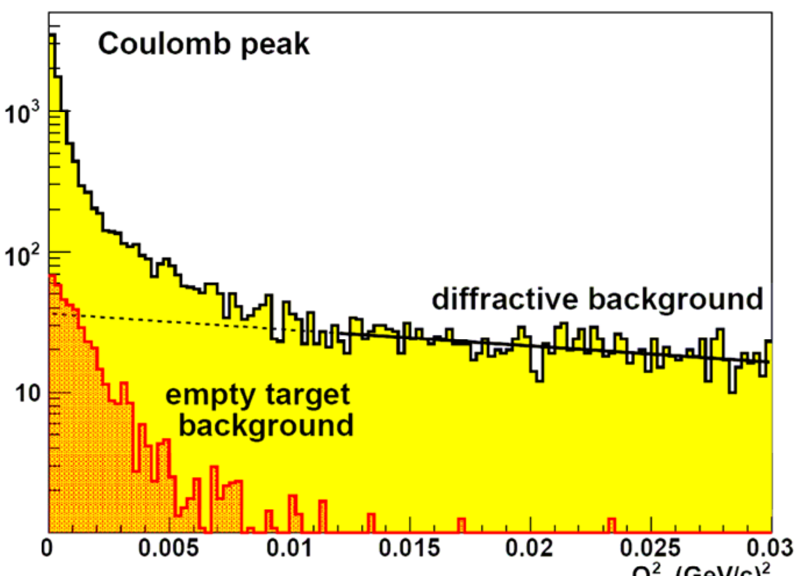


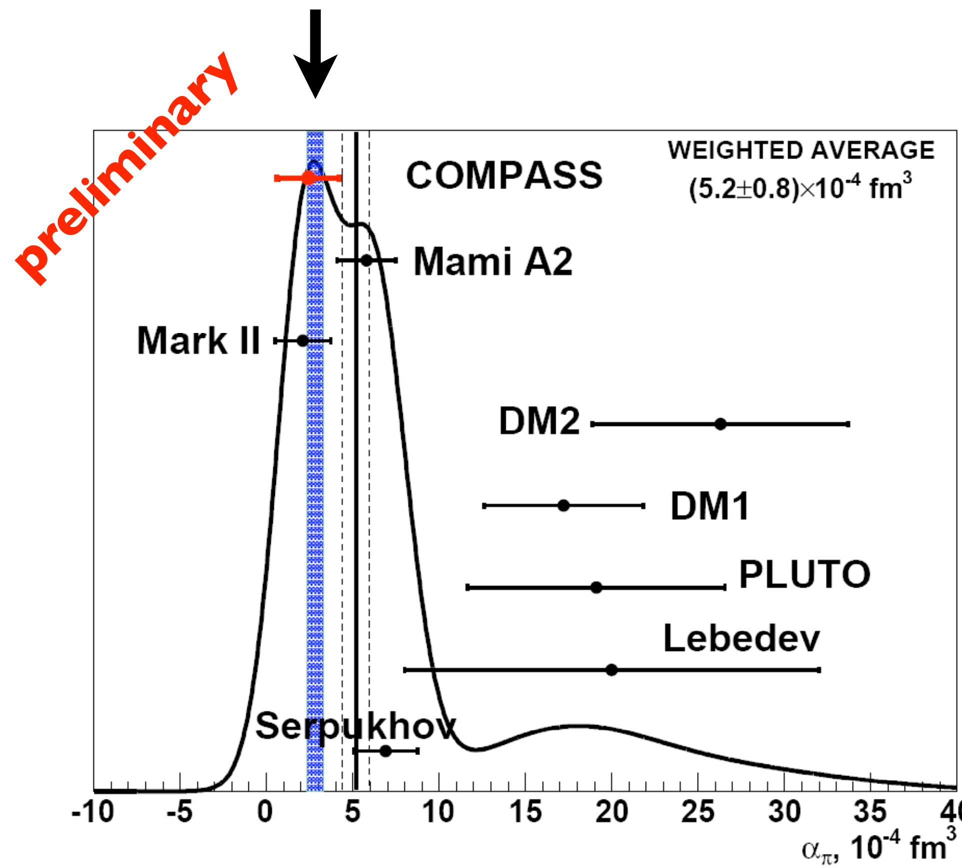
nuclear
target

$$\alpha_\pi = -\beta_\pi = (\mathbf{2.5} \pm \mathbf{1.7}_{\mathbf{stat}}) \cdot \mathbf{10^{-4}\ fm^3}$$

consistent with
Chiral Perturbation Theory

Primakoff Reaction @ **COMPASS**

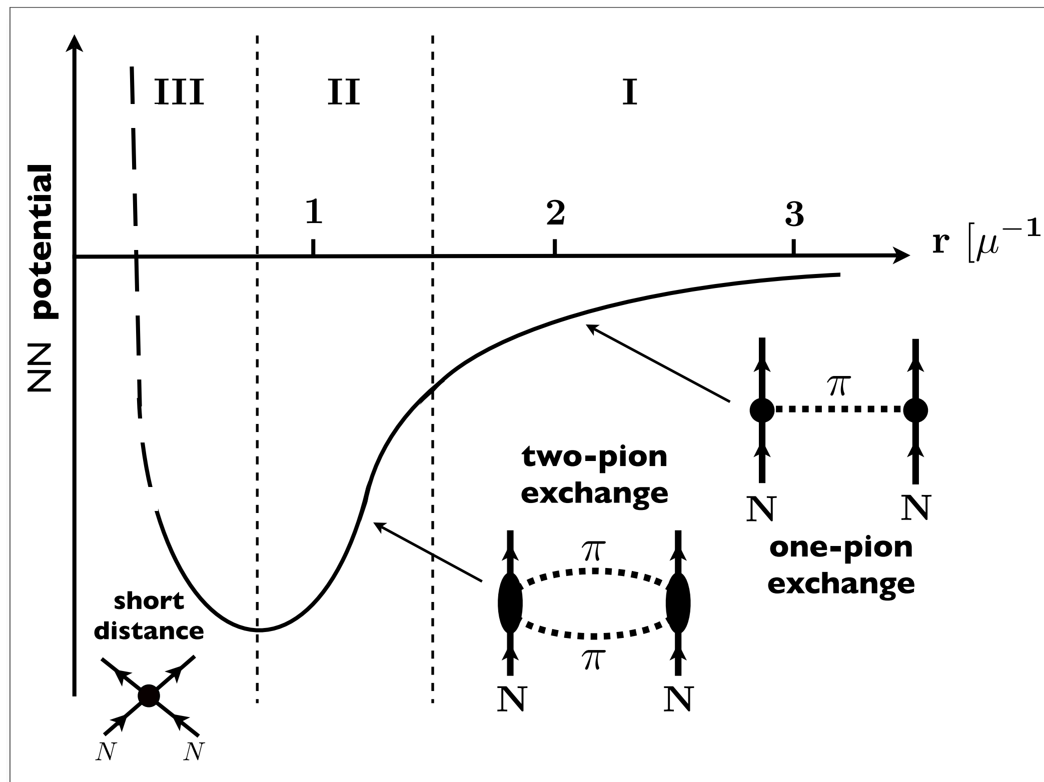




III.

NN and **NNN**
Interactions

Modern
Developments



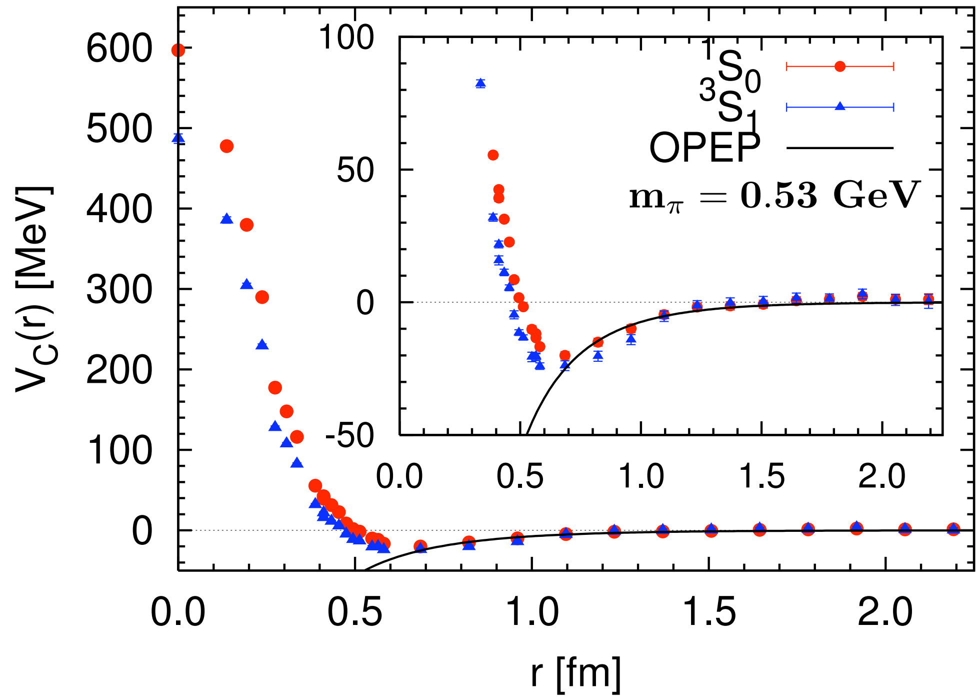
NN POTENTIAL from LATTICE QCD

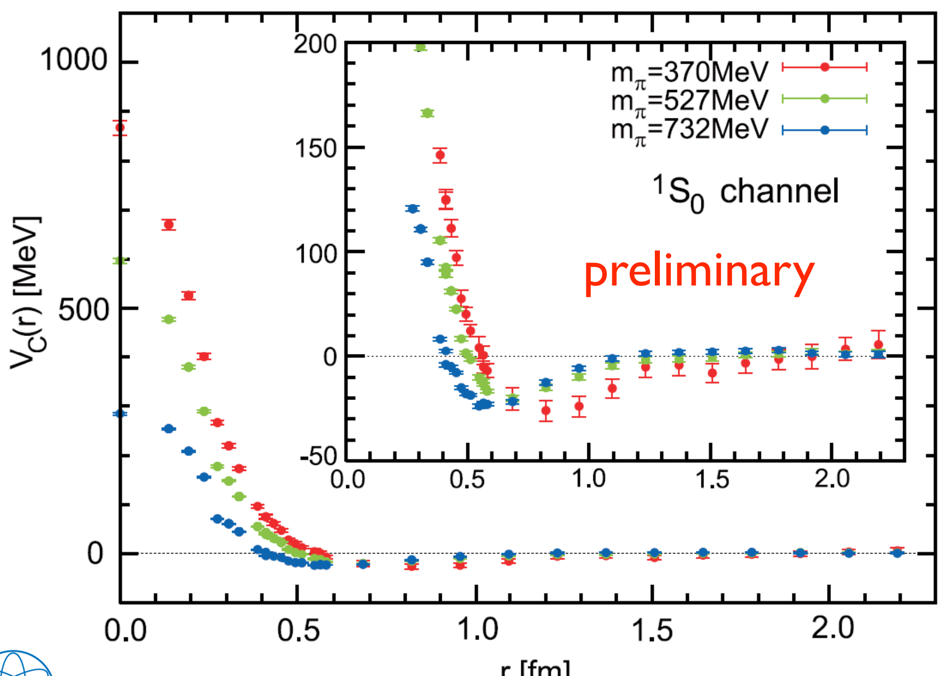
Ishii, Aoki, Hatsuda: hep-lat/0611096 (PRL 2007)

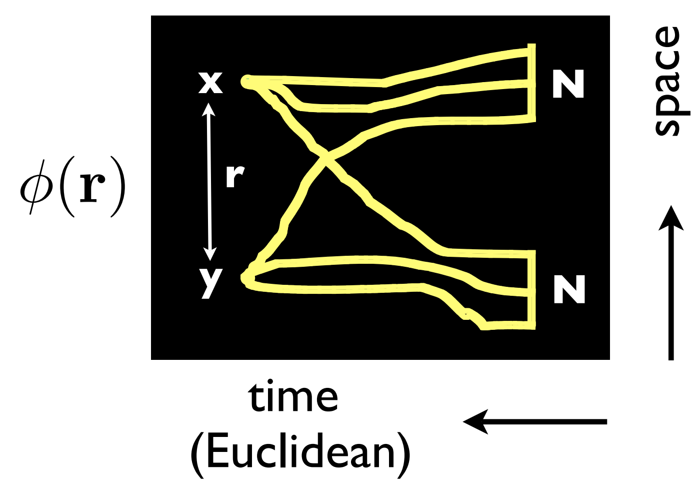
- Reconstruct potential from wave function:

$$\mathbf{V_C(r)} = \mathbf{E} + \frac{\nabla^2 \phi(\mathbf{r})}{2\mu\ \phi(\mathbf{r})}$$

- **Repulsive core** from Lattice QCD







quenched QCD

"large" quark/pion masses

NUCLEAR INTERACTIONS from CHIRAL EFFECTIVE FIELD THEORY

... inward bound:

- Separation of Scales

  $\mathrm{Q} << 4\pi\, f_\pi \sim 1\,\mathrm{GeV}$

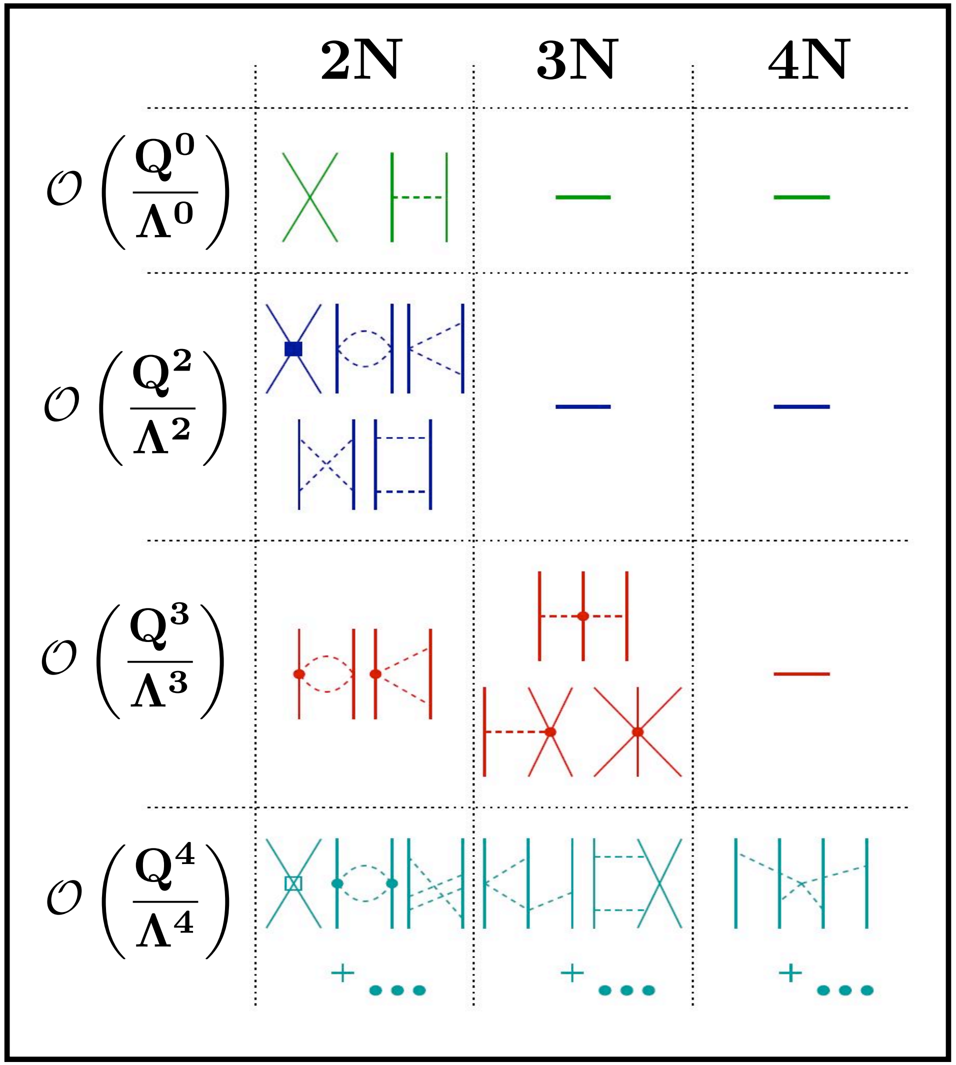
- **Nambu-Goldstone Bosons**

  (light / fast)

  coupled to

  Baryons

  (heavy / slow)



Weinberg; Bedaque & van Kolck

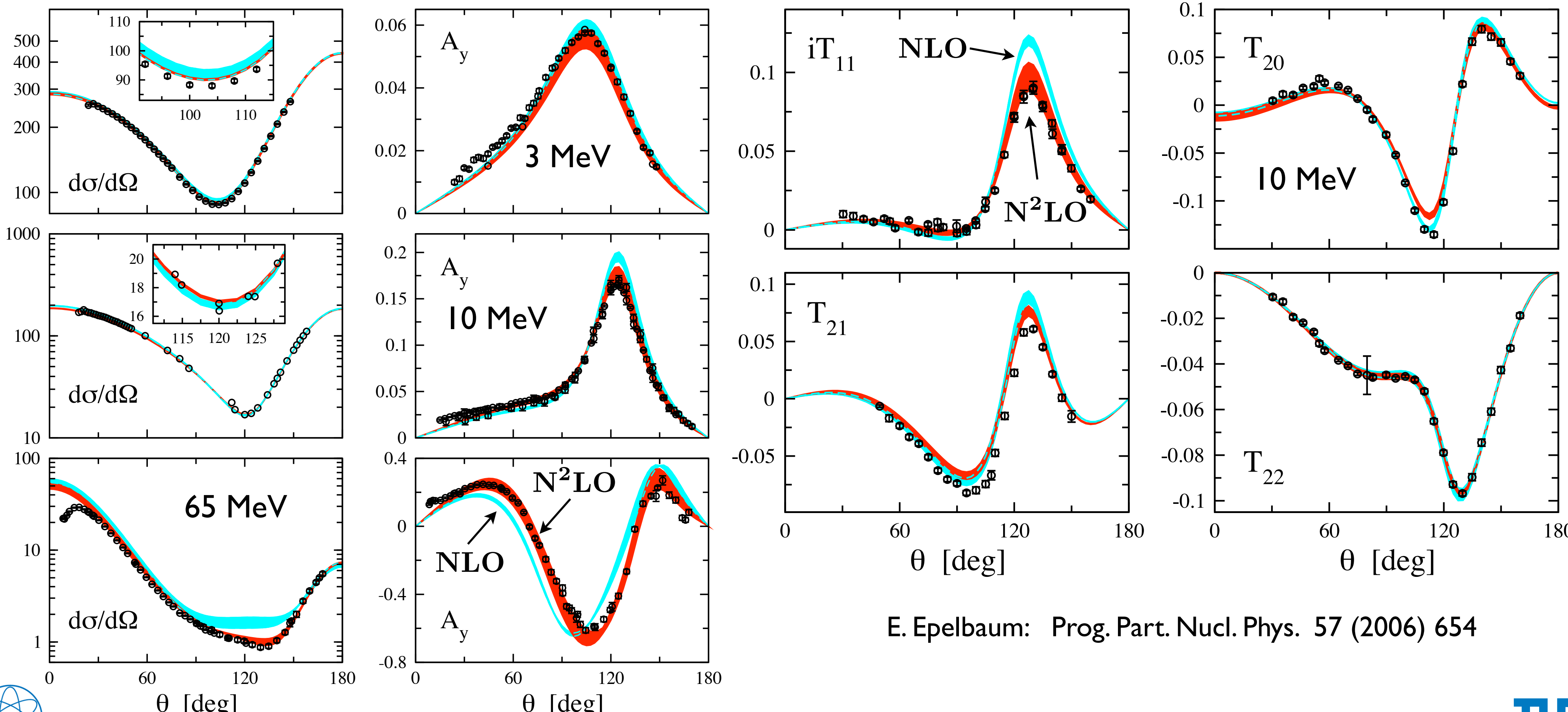
CHIRAL EFFECTIVE FIELD THEORY
at work in nuclear few-body systems

- example: elastic **nd** scattering

differential cross sections [mb/sr]

vector analysing power

tensor analysing power



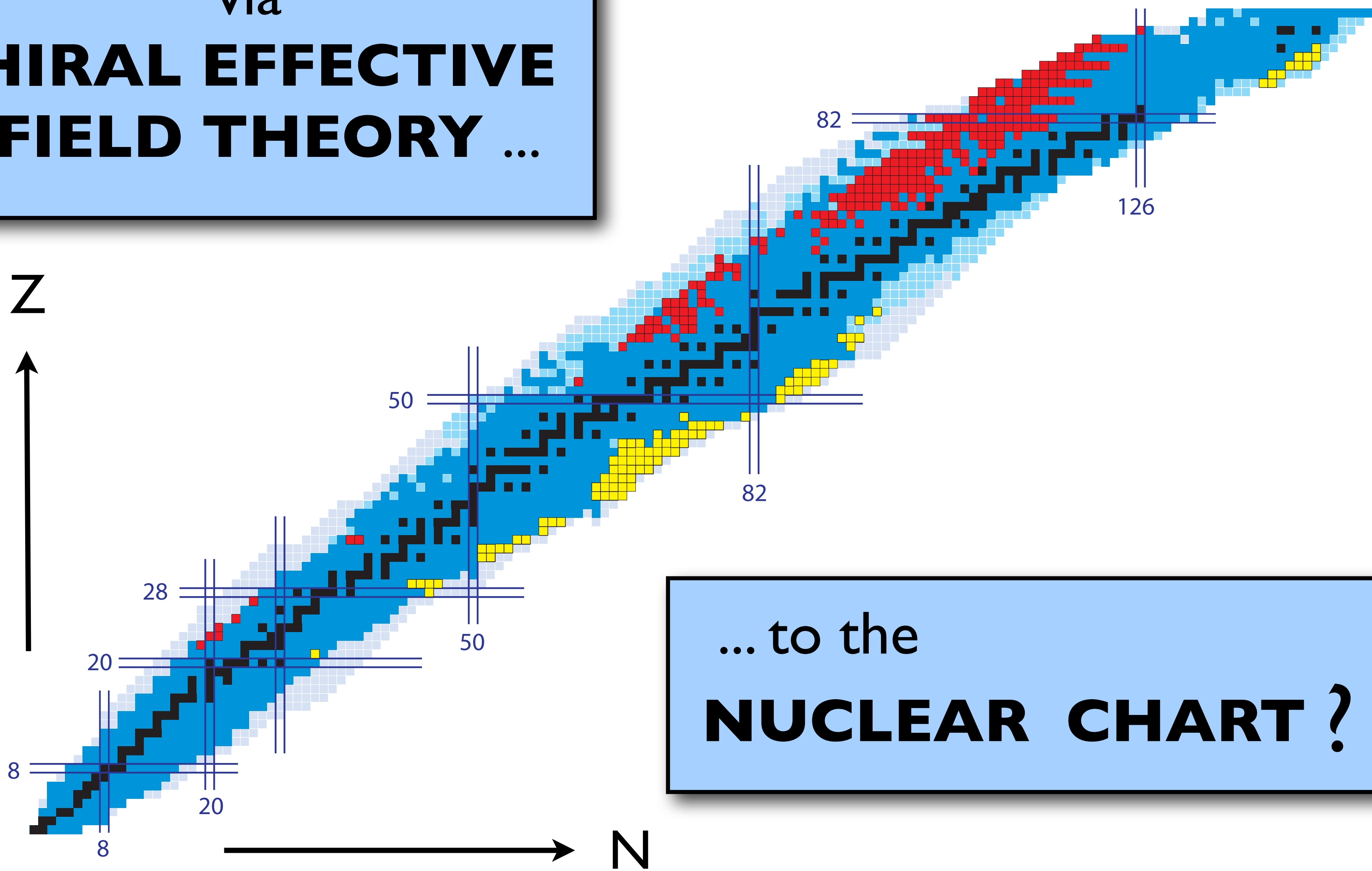
E. Epelbaum: Prog. Part. Nucl. Phys. 57 (2006) 654

IV.

... from **QCD**

via

CHIRAL EFFECTIVE FIELD THEORY ...

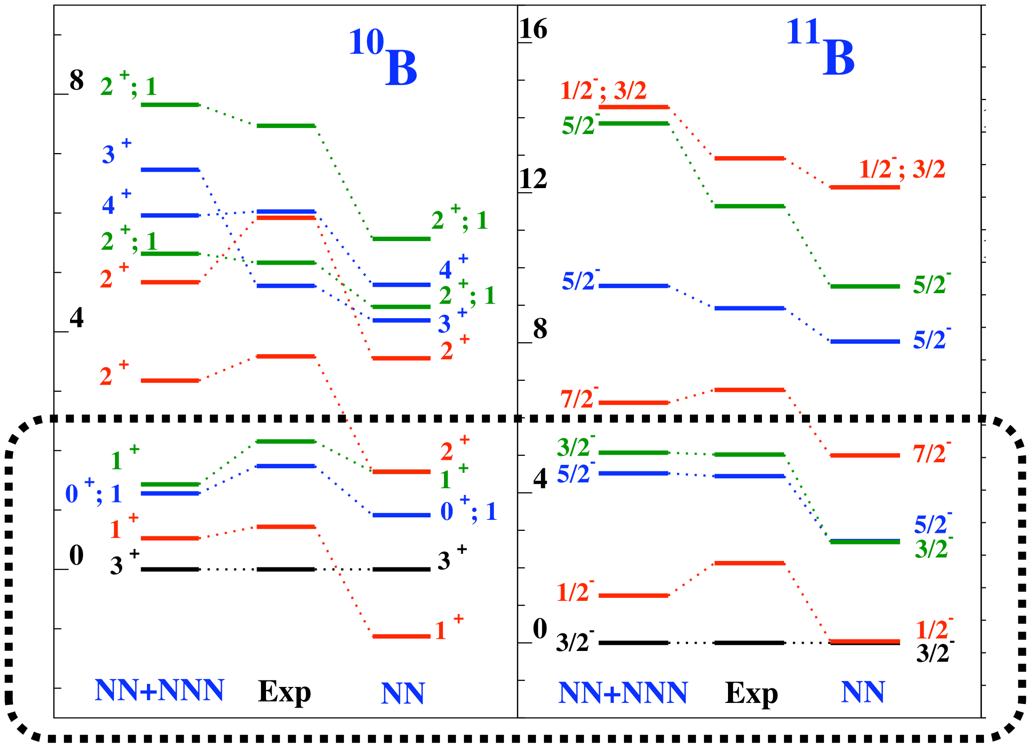


... to the

NUCLEAR CHART ?

Example: P-SHELL NUCLEI

- NC Shell Model calculations
- NN and NNN interactions from Chiral Effective Field Theory



P. Navrátil et al., nucl-th/0701038

- → **importance of 3N force**

V. J. Pandharipande, R. Wiringa et al.

CHIRAL DYNAMICS and the NUCLEAR MANY-BODY PROBLEM

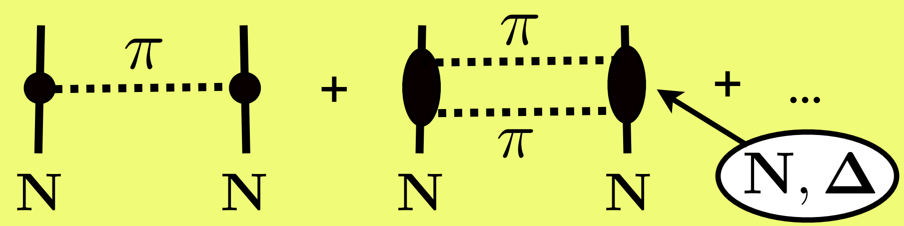
- additional relevant scale: **Fermi momentum** $\mathbf{p_F}$

  "small" scales: $\mathbf{p_F \sim 2\,m_\pi \sim M_\Delta - M_N << 4\pi\, f_\pi}$

- **PIONS** (and **DELTA** isobars) as **explicit** degrees of freedom

- **IN-MEDIUM CHIRAL PERTURBATION THEORY**

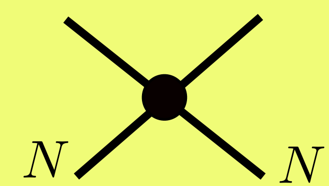
  ➡ pion exchange in presence of filled Fermi sea



  " in medium"

  2nd order TENSOR force + nucleon's SPIN-ISOSPIN polarizability

  ➡ short-distance dynamics: contact interactions



- Expansion of **ENERGY DENSITY**

  in powers of Fermi momentum

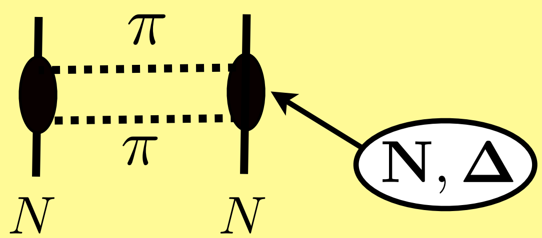
NUCLEAR THERMODYNAMICS

NUCLEAR CHIRAL (PION) DYNAMICS

Yukawa

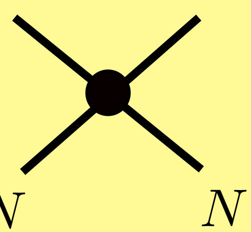
+ Van der Waals

+ Pauli



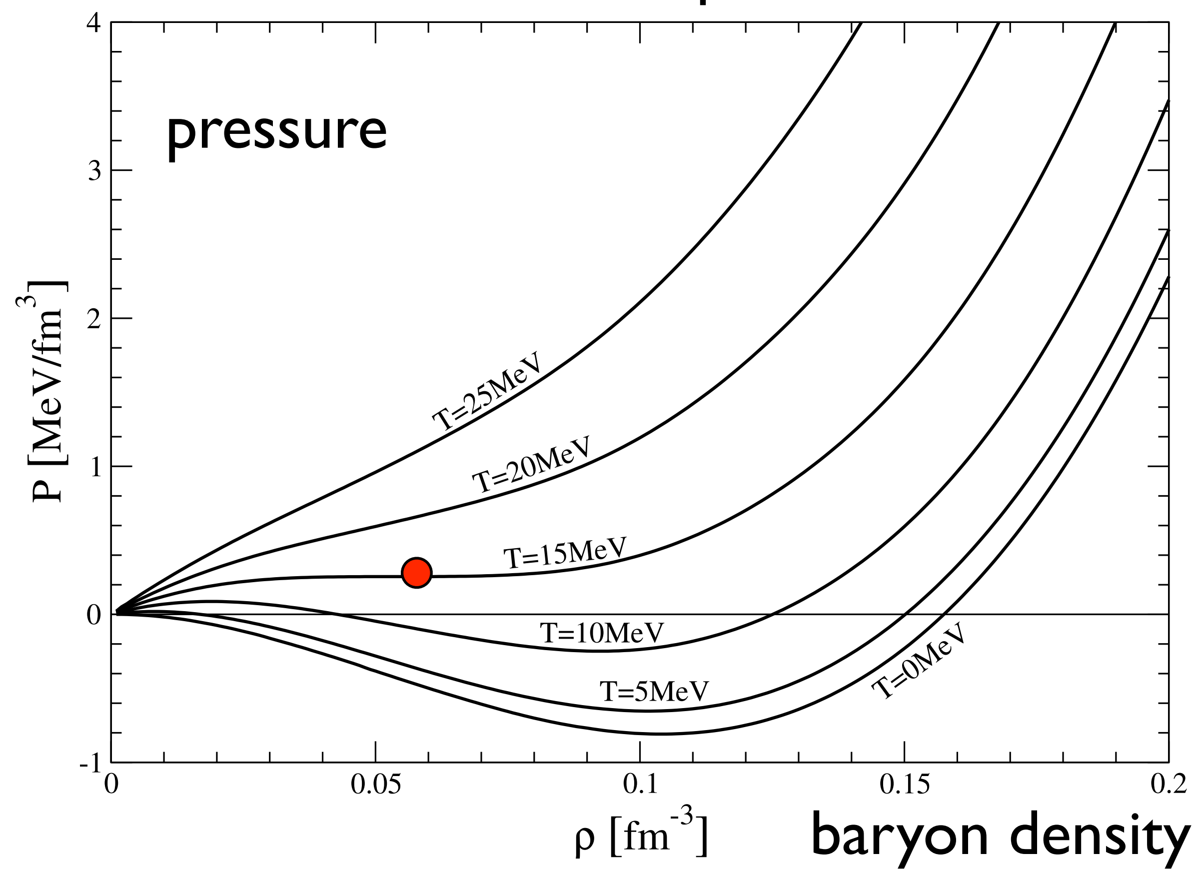
$$\mathbf{V(r) \sim -\frac{e^{-2m_\pi r}}{r^6} P(m_\pi r)}$$

+



... plus contact terms

nuclear matter: equation of state



Liquid - Gas Transition at

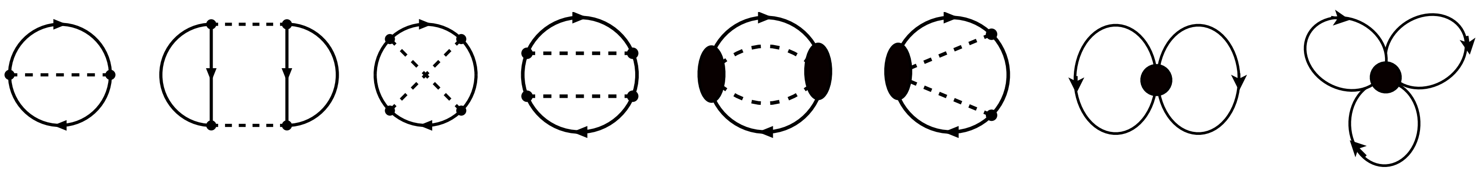
Critical Temperature T_c = 15 MeV

(empirical: T_c = 16 - 18 MeV)

DENSITY FUNCTIONAL STRATEGIES

... constrained by **symmetry breaking pattern** of **Low-Energy QCD**

$$\mathbf{E}[\rho] = \mathbf{E_{kin}} + \int \mathbf{d^3x}\,[\mathcal{E}^{(\mathbf{0})}(\rho) + \mathcal{E}_{\mathbf{exc}}(\rho)] + \mathbf{E_{coul}}$$



- $\mathcal{E}_{\mathbf{exc}}(\rho)$ from in-medium Chiral Perturbation Theory (”**Pionic fluctuations**”)
- $\mathcal{E}^{(\mathbf{0})}(\rho)$ strong **SCALAR** and **VECTOR** mean fields generated by IN-MEDIUM changes of QCD CONDENSATES

Examples (part I)

- Strategy :

➡ Calculate physics at **long** and **intermediate** distances using nuclear **chiral effective field theory**

➡ Fix **short** distance constants (contact interactions) e.g. in Pb region

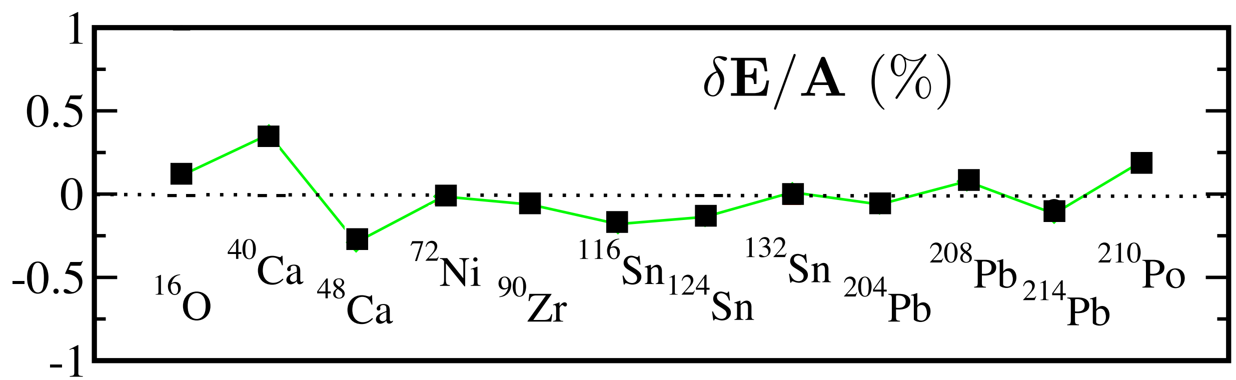
➡ Predict **systematics** for all other nuclei

deviations (in %) between calculated and measured

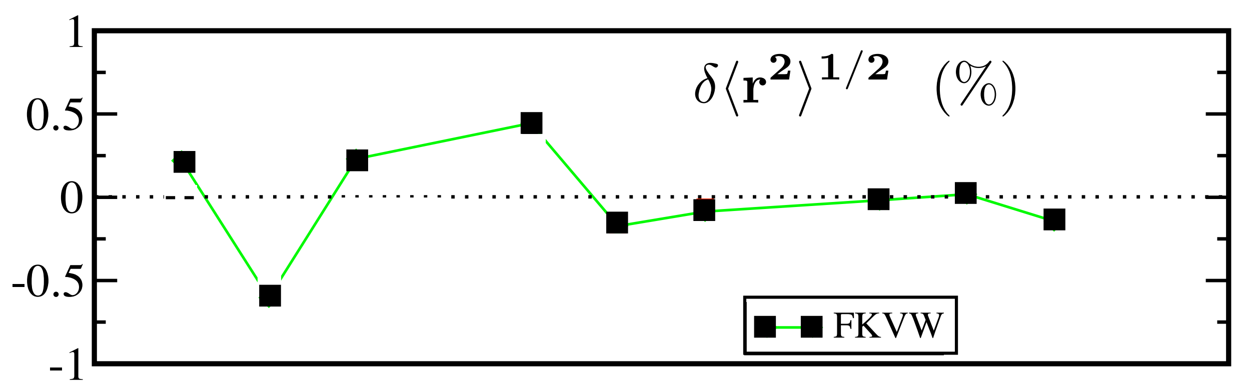
binding energies per nucleon ...

... and charge radii

P. Finelli et al., Nucl. Phys. A770 (2006) 1



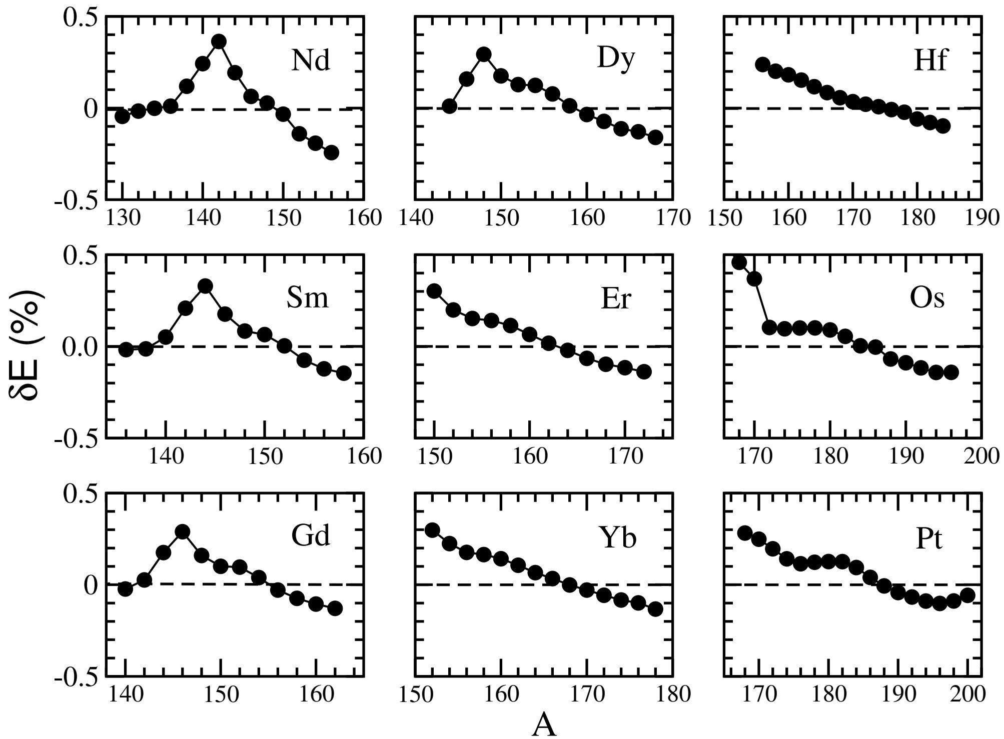
P. Finelli et al.: Nucl. Phys. A770 (2006) 1

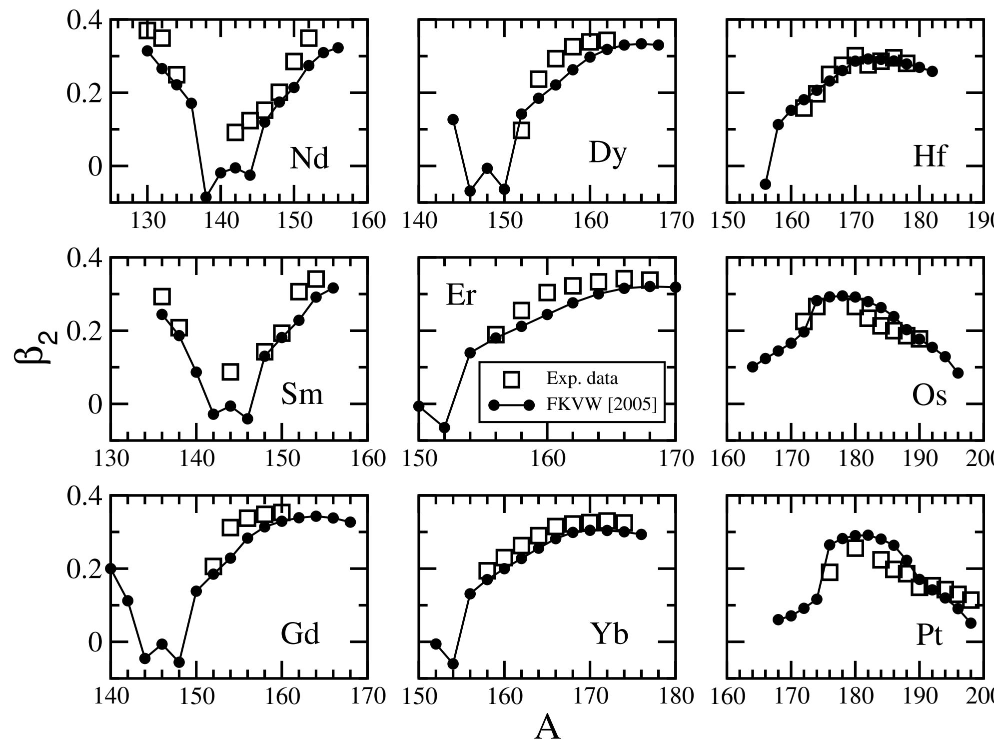


Examples (part II): **DEFORMED NUCLEI**

deviations (in %) between
calculated and measured binding energies

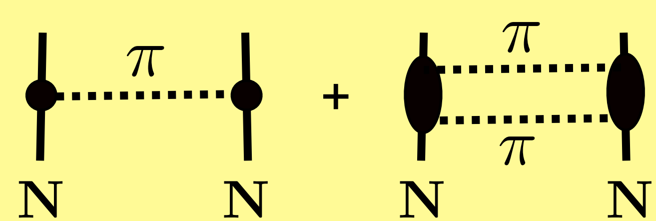
Ground state deformations





P. Finelli et al., Nucl. Phys. A770 (2006) 1

Systematics through **isotopic chains**
governed by
isospin dependent forces
from **chiral pion dynamics**



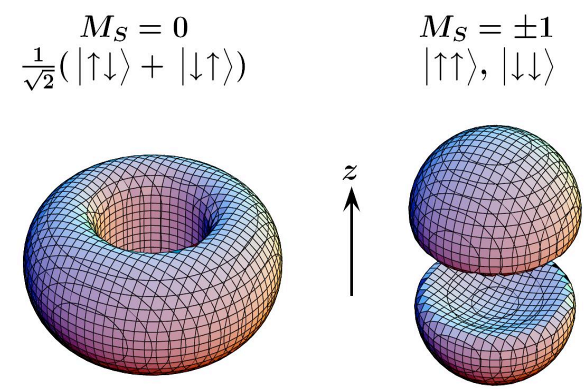
TENSOR force

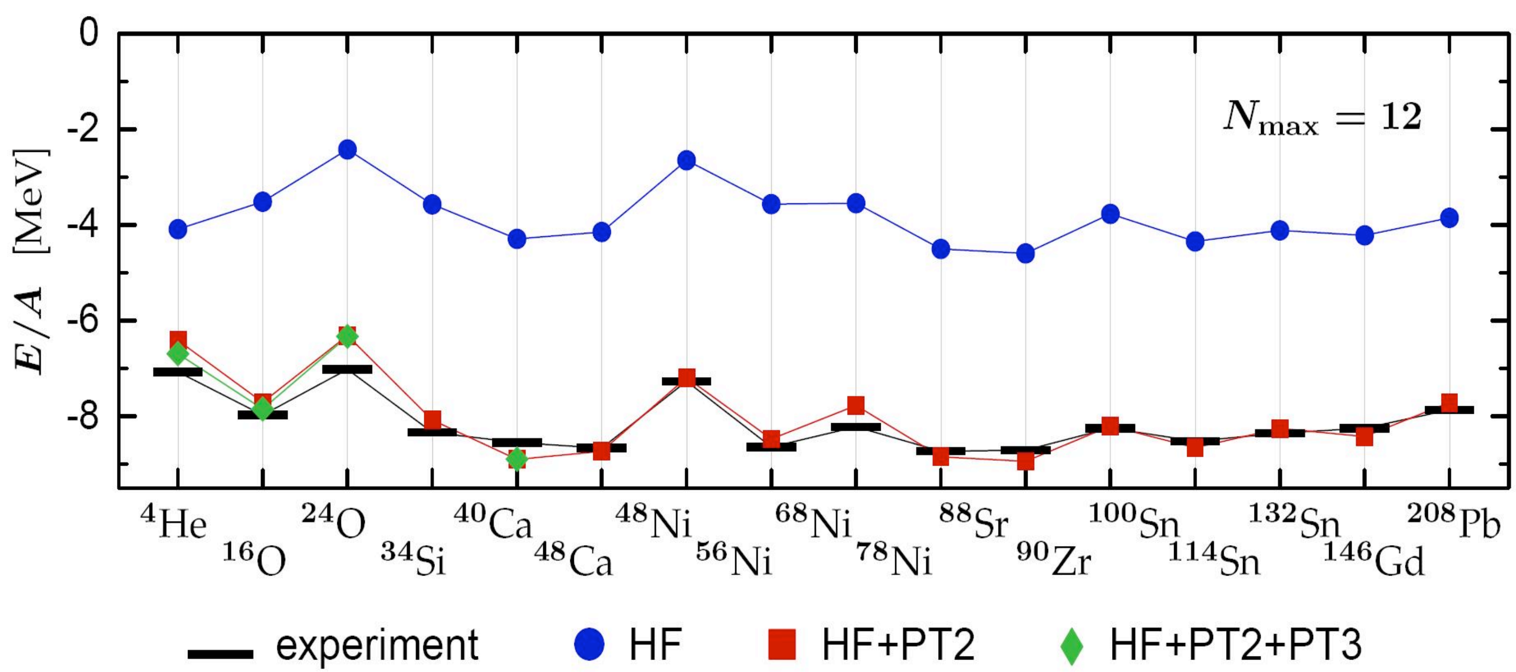
Examples (part III):
Unitary Correlation Operator Method

Roth, Paar, Papaconstantinou (2006)

$$|\tilde{\Psi}\rangle = \exp[-\mathrm{i}G]\,|\Psi\rangle$$

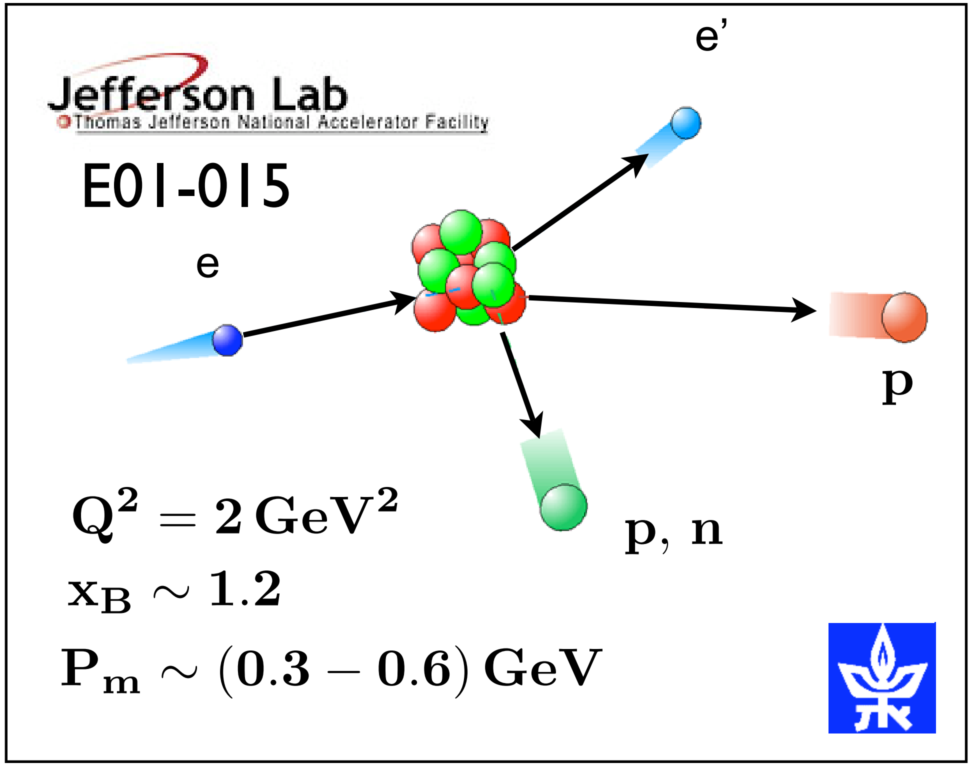
- important role of **tensor correlations** (as in deuteron)

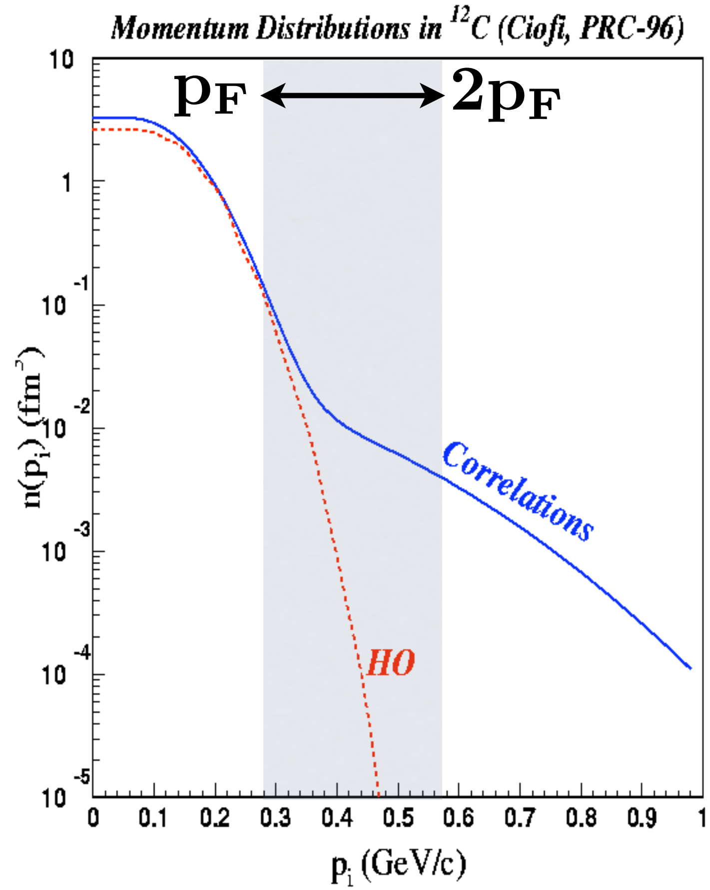




... much more info: $\longrightarrow$ talk by D.J. Dean

Short Range NN Correlations, revisited





preliminary

$$\frac{^{12}C(e,e'\,pn)}{^{12}C(e,e'\,pp)} = 9.1 \pm 2.5$$

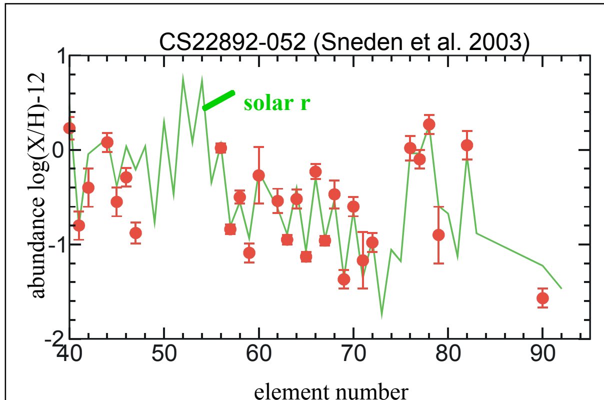
- dominance of **tensor correlations**

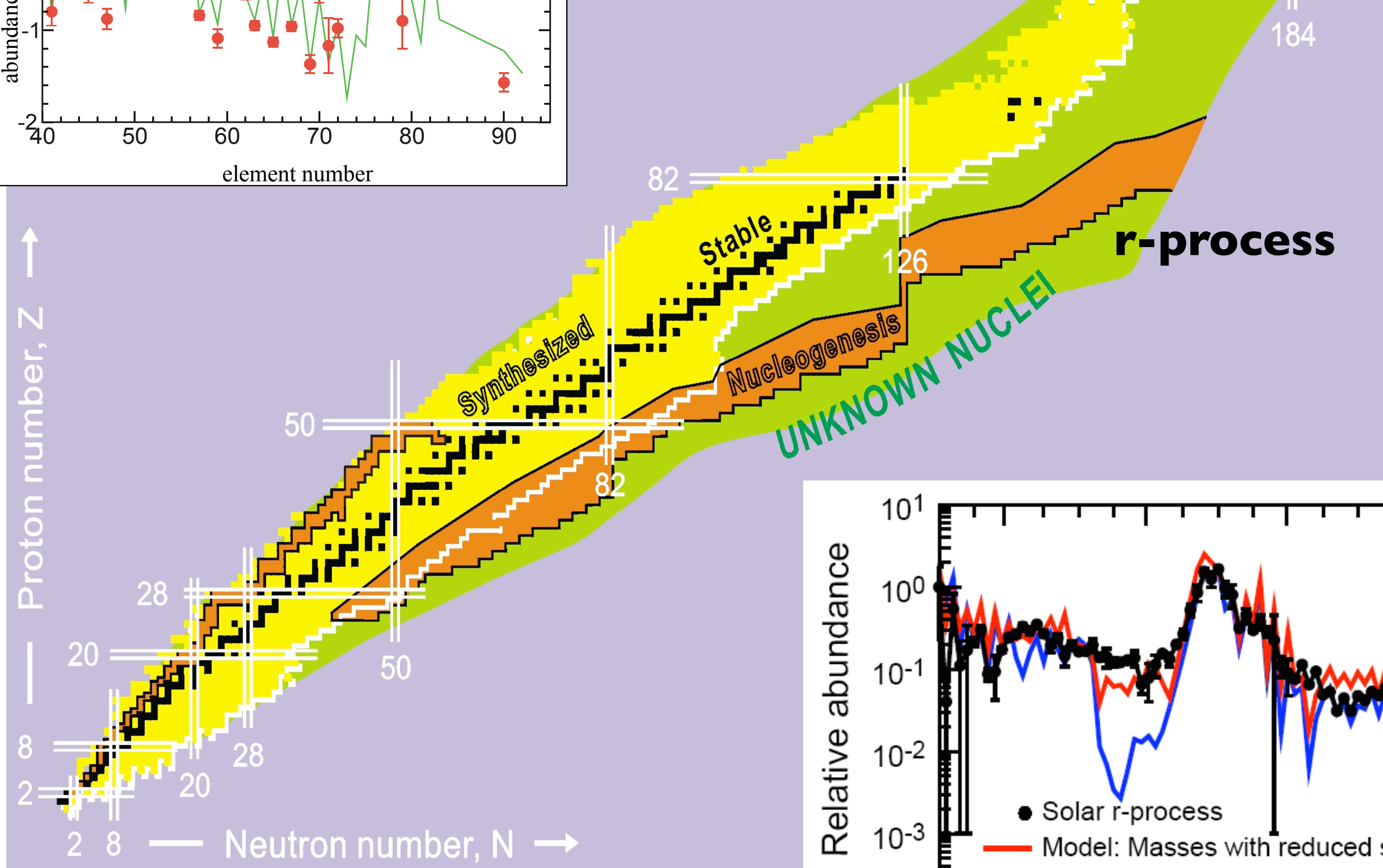
Subedi, Shneor, Piasetzky et al. (2007)

C. Ciofi, L. Frankfurt, M. Strikman, et al.

Extrapolations into Unknown Territory

- ... require detailed knowledge of **isospin** (and spin) dependent interactions





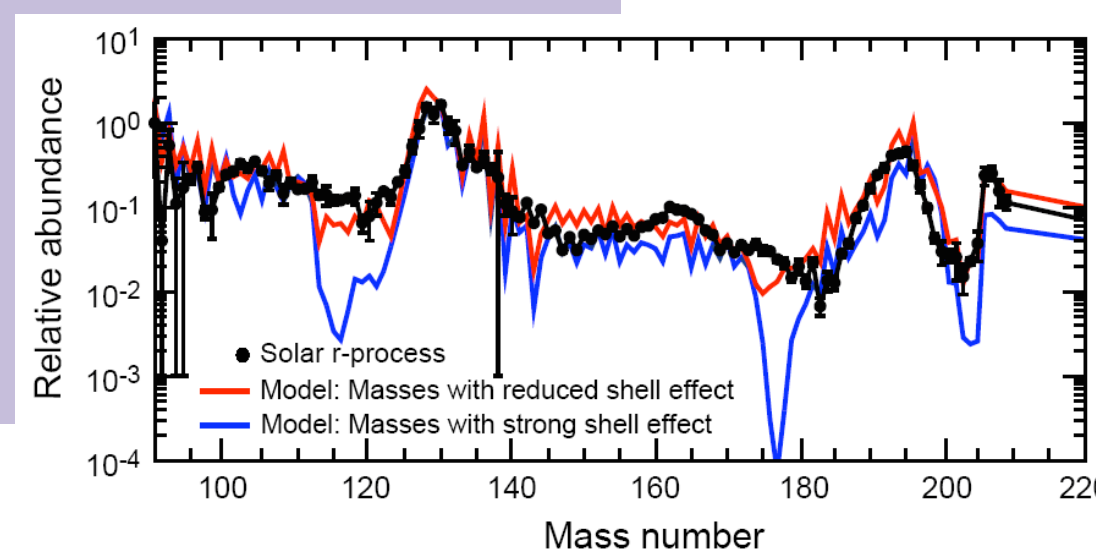
- guidance from:

Yukawa's **Pion**

+

Symmetry Breaking Pattern

(**Chiral** EFTh)



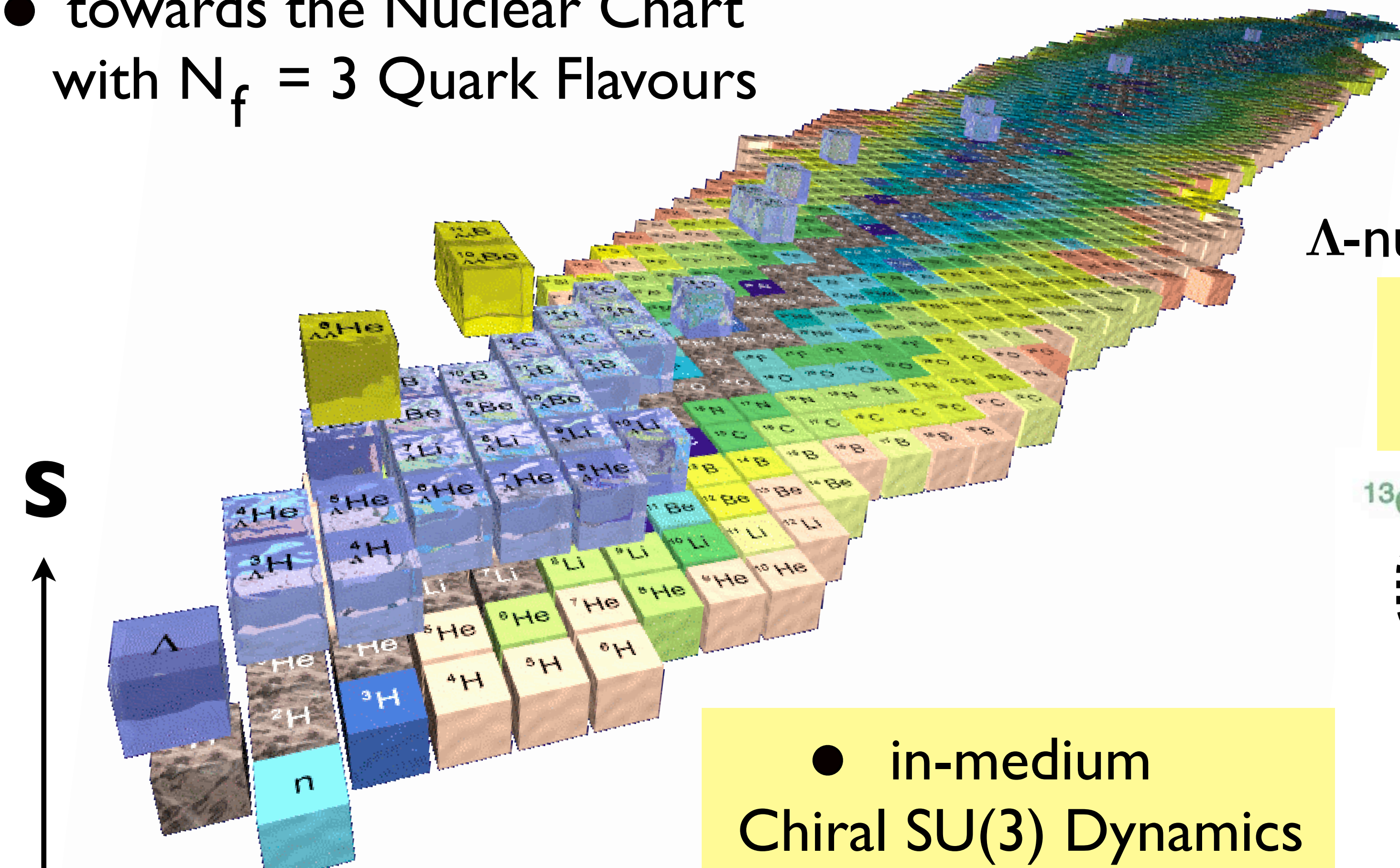
→ talk by T. Otsuka

Strangeness and **HYPERNUCLEI**

... the 3rd dimension:

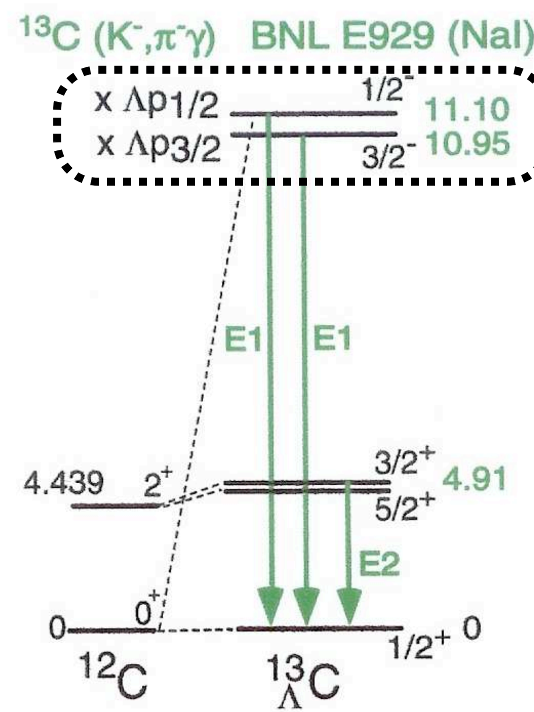
KEK, FINUDA, → J-PARC

- towards the Nuclear Chart with N_f = 3 Quark Flavours



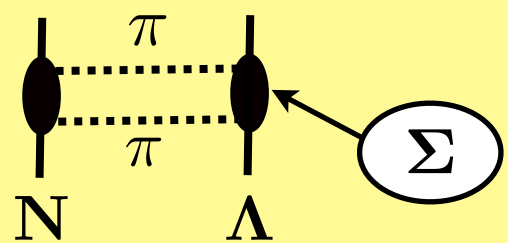
- key issue: weakness of the Λ-nuclear spin-orbit force

$$\delta \mathbf{E}(\mathbf{p}_{3/2} - \mathbf{p}_{1/2}) = (\mathbf{150} \pm \mathbf{90})\,\mathbf{keV}$$



PRL 86 (2001) 4255

- in-medium Chiral SU(3) Dynamics



N. Kaiser et al., Phys. Rev. C71 (2005) 015203

V.

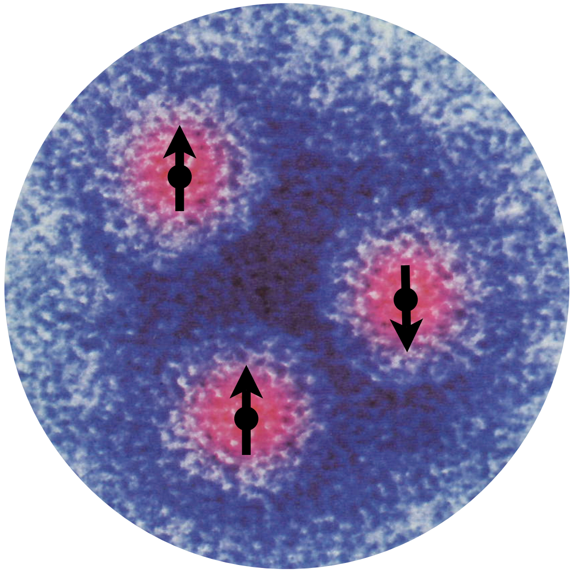
The

NUCLEON

... a QCD

many-body system

full of surprises



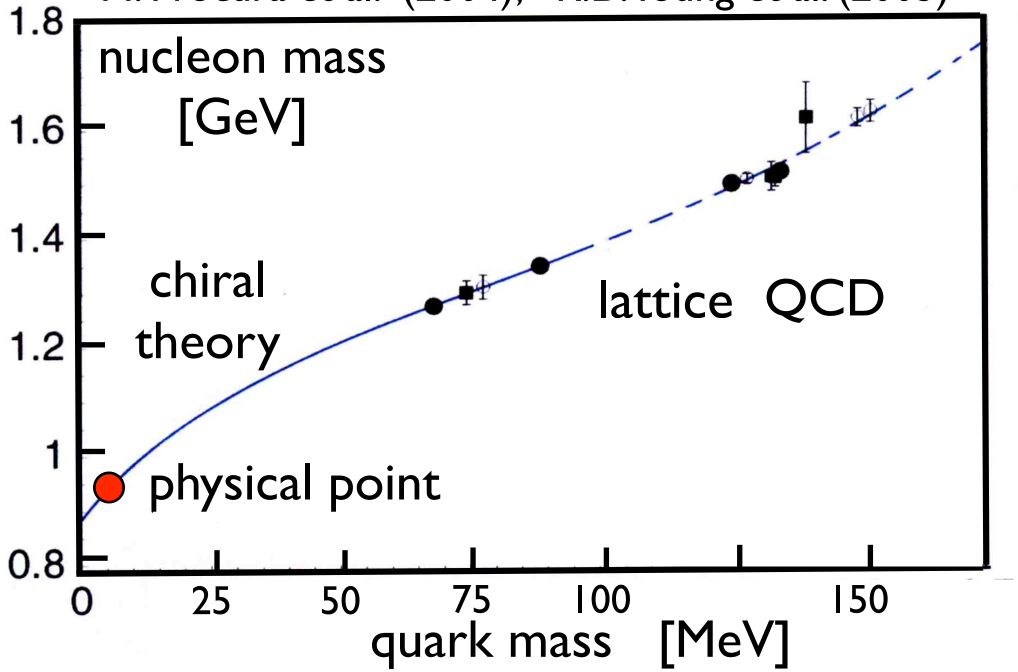
Origin of the **NUCLEON MASS**

$$\mathbf{m_u \simeq 3\,MeV \quad m_d \simeq 6\,MeV}$$
$$\mathbf{u + u + d = proton}$$
$$\mathbf{mass: \quad 3 + 3 + 6 \neq 938\,!}$$

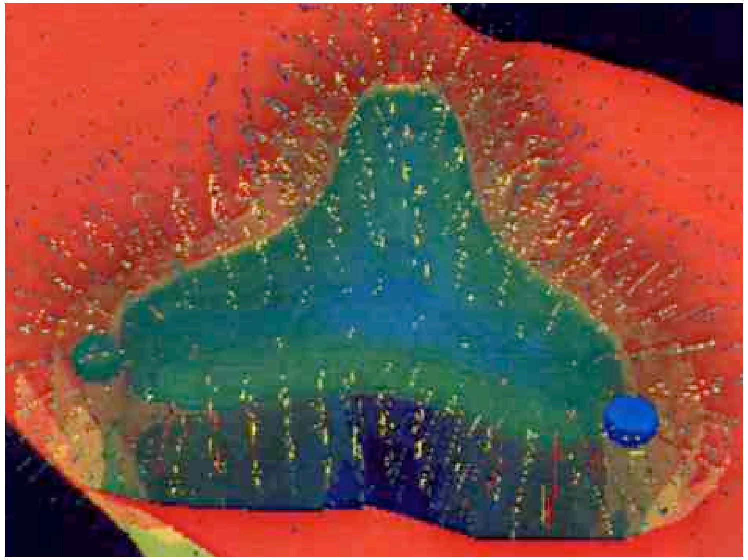
... mostly **GLUONS**

$$\mathbf{M = E/c^2}$$

M. Procura et al. (2004); R.D.Young et al. (2003)



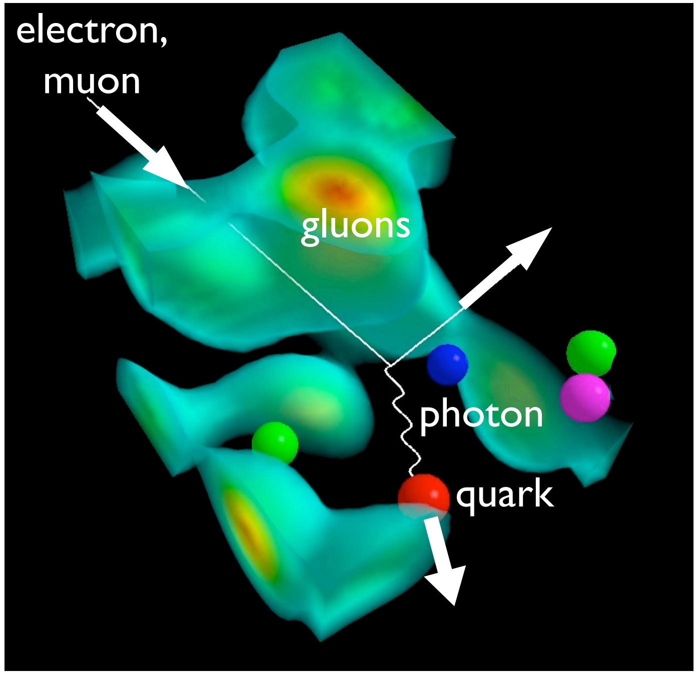
D. B. Leinweber et al. 2004



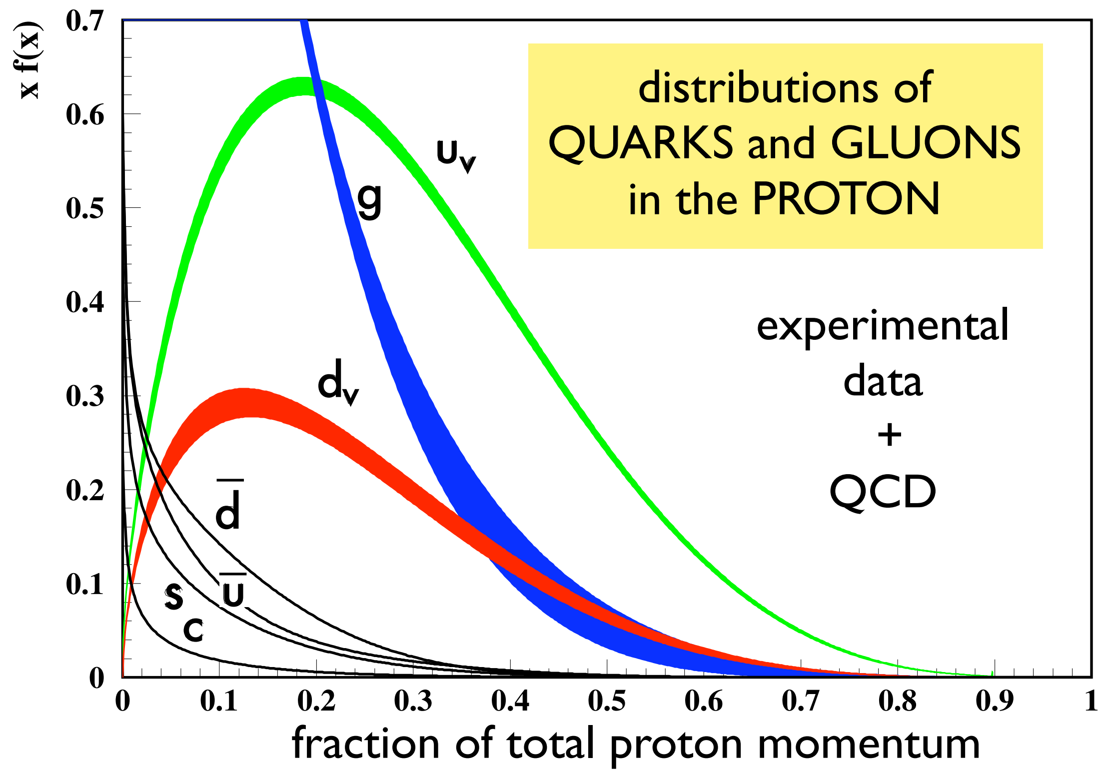
Lattice QCD

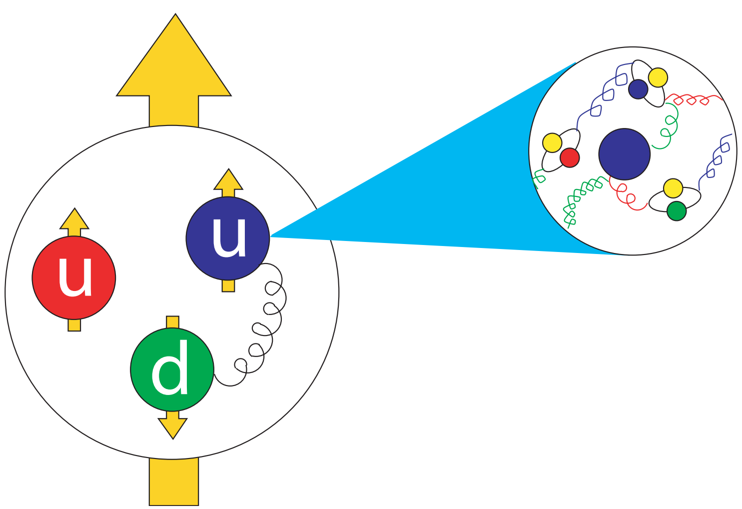
- **CONFINEMENT** of quarks → **spontaneous** (dynamical) **CHIRAL SYMMETRY BREAKING**

SNAPSHOTS of the NUCLEON´S INTERIOR



Deep **I**nelastic **S**cattering



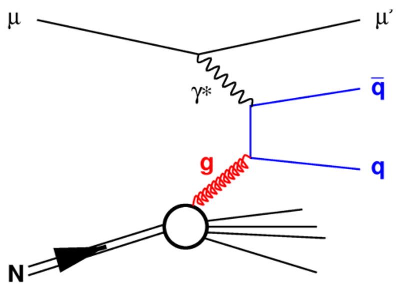


Quarks in the nucleon carry :

- ... only **1/2** of the nucleon's total **momentum**
- ... less than **1/3** of the nucleon's **spin**

Surprises (part I) :
Gluon contribution to **Nucleon Spin**

Photon-Gluon-Fusion



PGF tag: hadronic final state in SIDIS

Open charm: q=c
+ clean
- low statistics

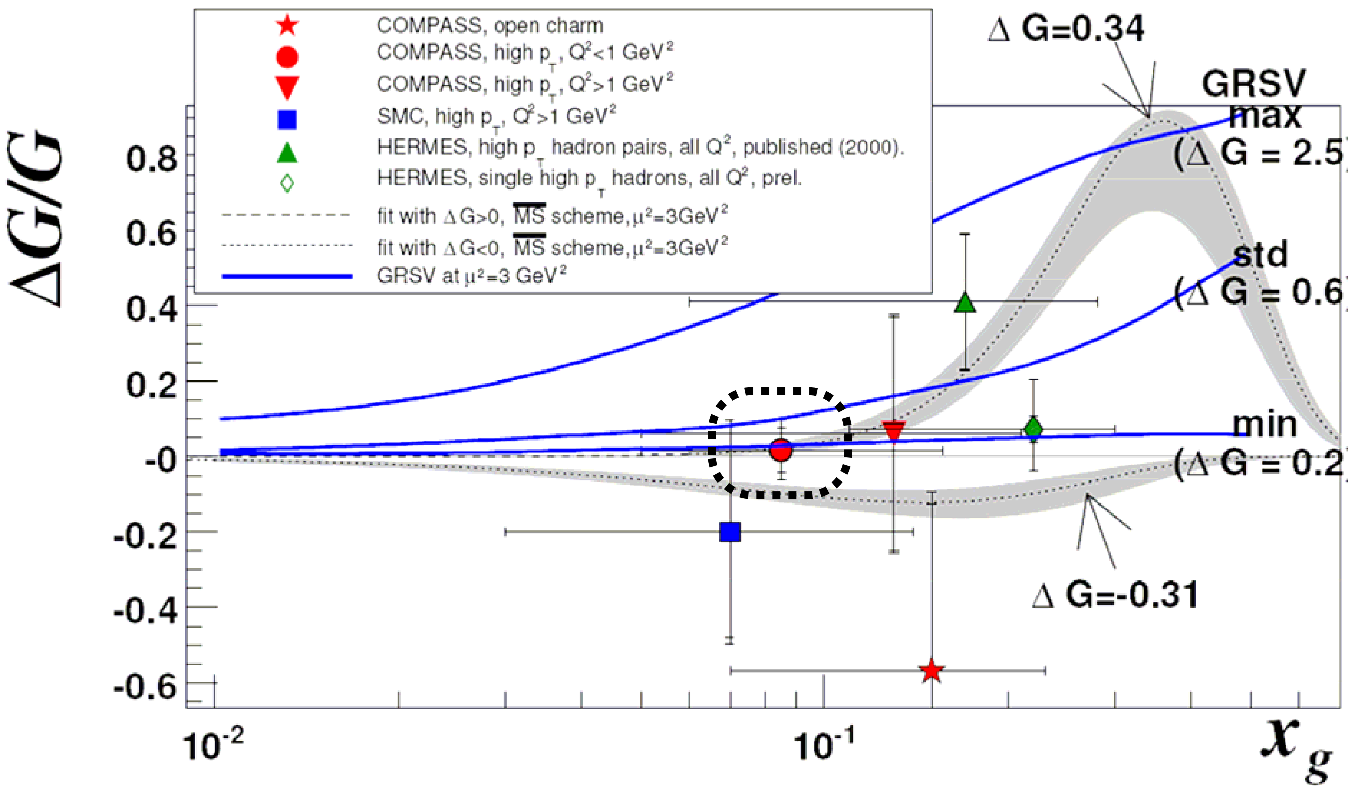
High-p_T hadron pairs: q=u,d(,s)
+ high statistics
- background processes

COMPASS experiment

- ... favours **small**
  $\Delta G/G$
  at $x_g \sim 0.1$

- ... where are the remaining portions of the **nucleon spin** ?

- **orbital** angular momentum ?

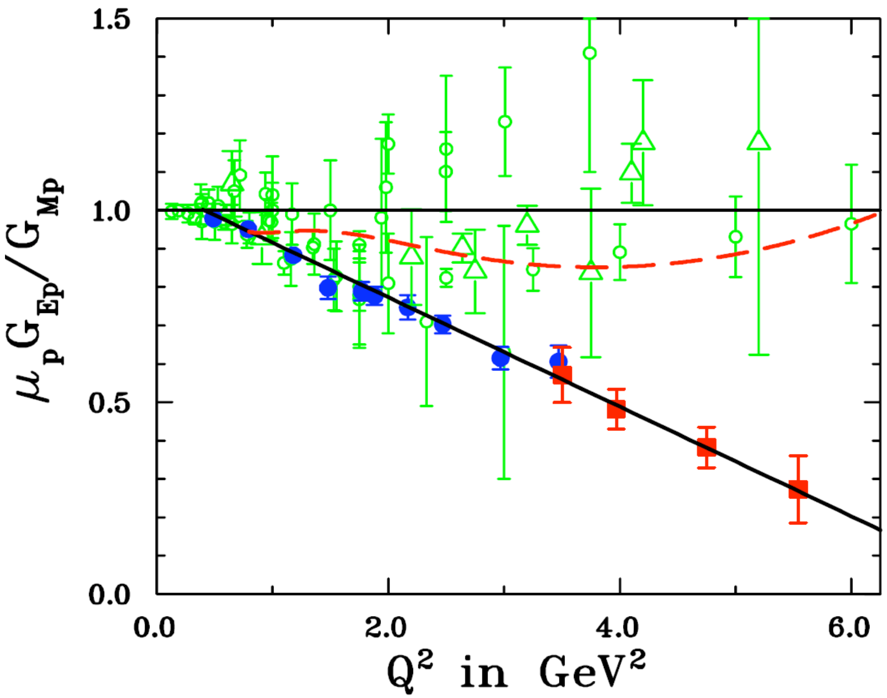


Surprises (part II) :
Electromagnetic FORM FACTORS of the **PROTON**

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Polarization Transfer $\vec{e} + p \rightarrow e + \vec{p}$

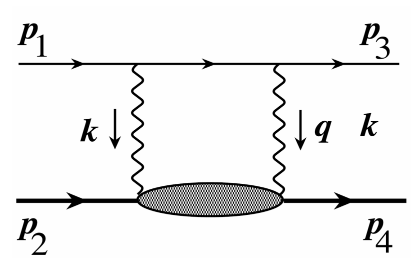
$$R = -\mu \frac{E+E'}{2m} \tan\frac{\theta_e}{2} \frac{P_x}{P_z} \equiv \mu \frac{G_E}{G_M}$$

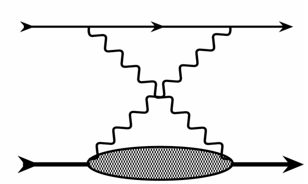


courtesy of
G. Ron
E. Piasetzky

TEL AVIV UNIVERSITY

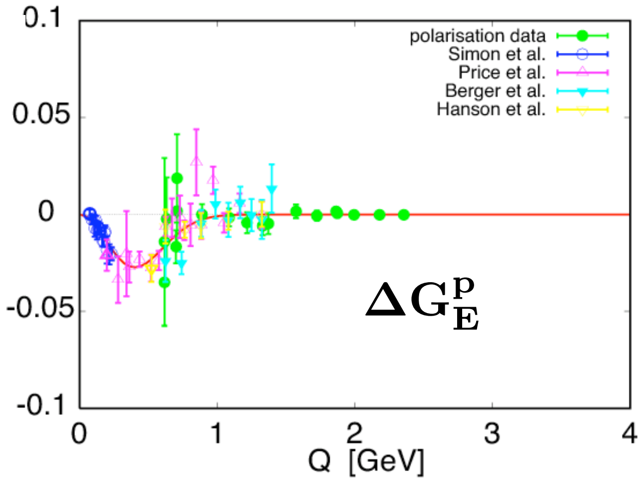
- Possible resolution with the inclusion of two photon effects in the Rosenbluth analysis which have a minor influence on the polarization analysis.
- Removes ~50% of the discrepancy.

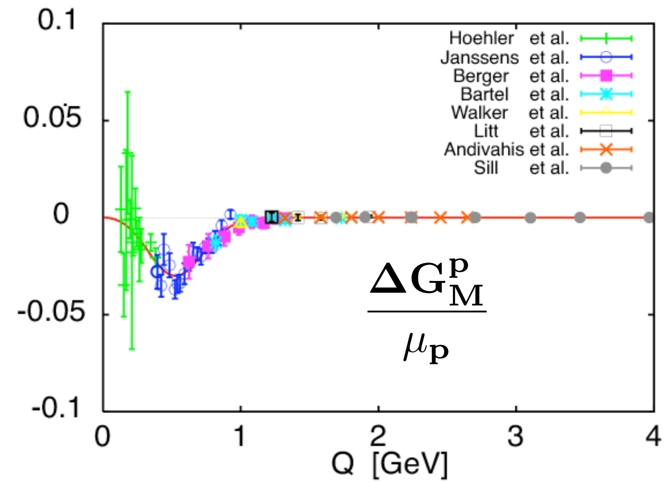




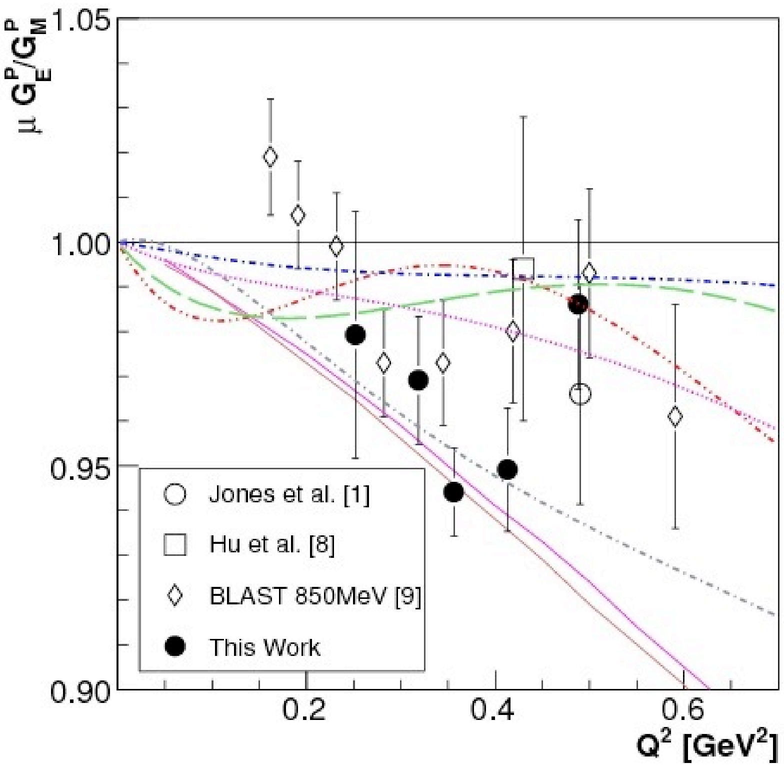
Guichon et al. (2003); Blunden et al. (2003); Afanasev et al. (2005)

Surprises (part III) :
Electromagnetic FORM FACTORS of the **PROTON** (LOW Q)





Friedrich
&
Walcher



PION CLOUD
of the
NUCLEON ?

Jefferson Lab
Thomas Jefferson National Accelerator Facility

preliminary

VI.

HADRONS

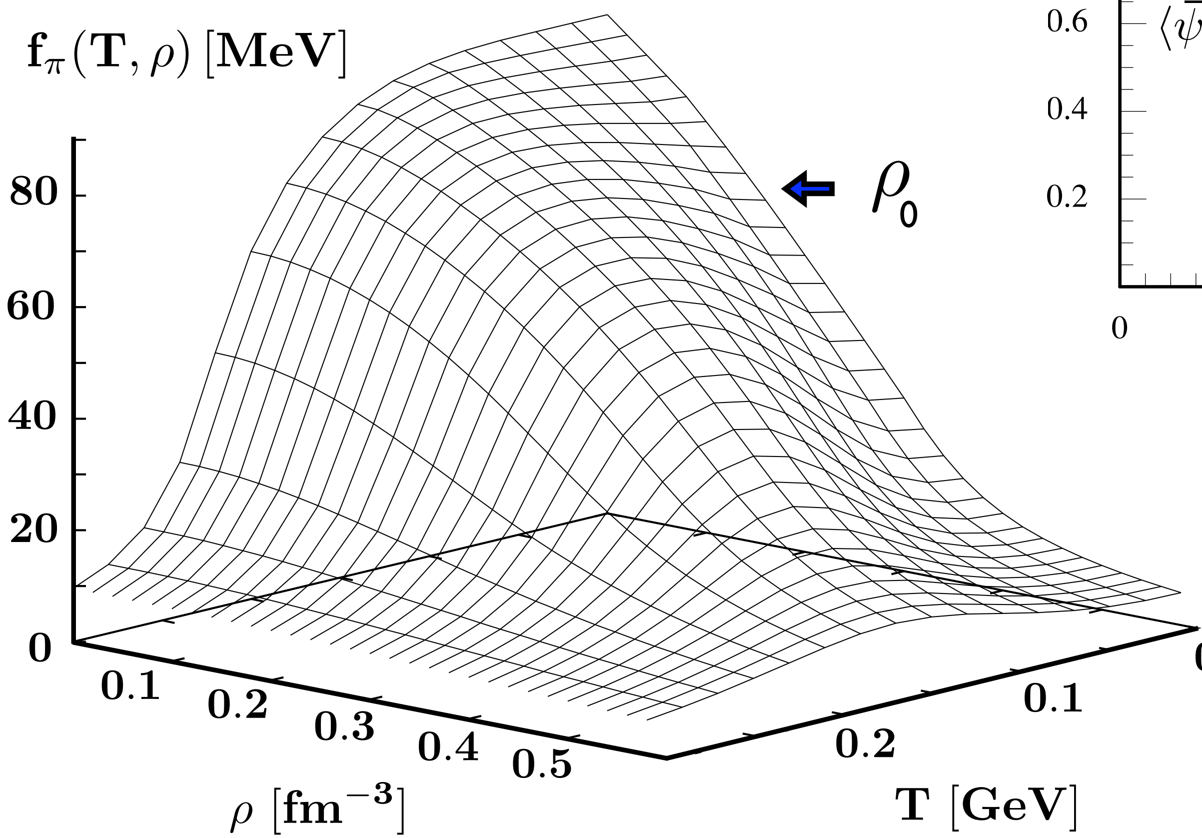
in

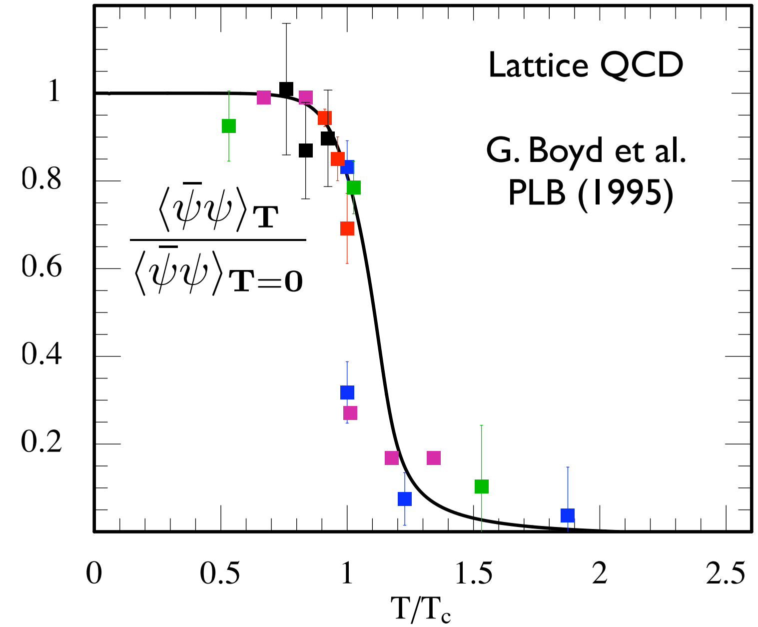
MATTER

CHIRAL ORDER PARAMETER

- **Pion decay constant** and **Chiral Condensate**

dependence on
temperature and baryon density
$(\rho_0 \simeq 0.16\,\mathrm{fm}^{-3})$





S. Klimt et al.
PLB (1990)

$$\frac{f_\pi^2(T,\rho)}{f_\pi^2(0)} \sim \frac{\langle\bar{q}q\rangle_{T,\rho}}{\langle\bar{q}q\rangle_0} = 1 - \frac{T^2}{8\,f_\pi^2} - \frac{\sigma_N}{m_\pi^2\,f_\pi^2}\,\rho + \;\ldots$$

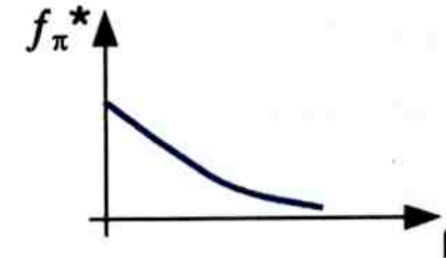
nucleon "sigma" term
$\sigma_N \simeq 45\,\mathrm{MeV}$

GOLDSTONE BOSONS in MATTER

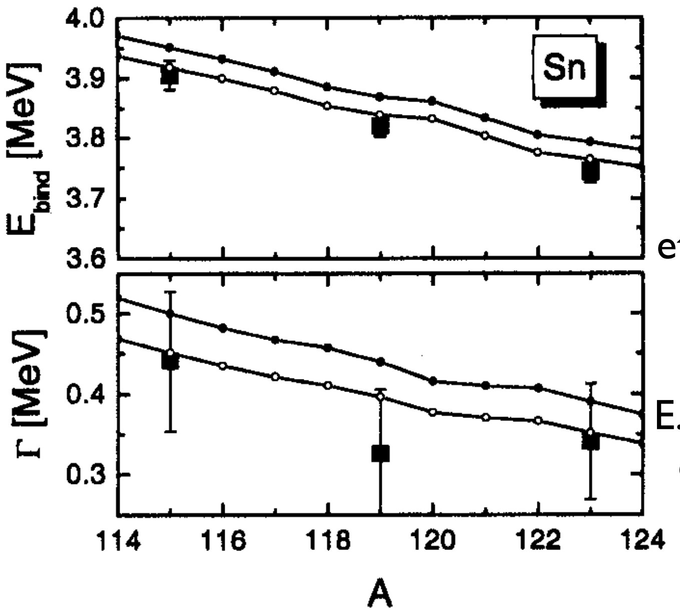
- Chiral Symmetry:

$$\mathbf{U}_{strong}(\pi^{\pm}\mathbf{A}) = \pm\frac{\rho_\mathbf{p} - \rho_\mathbf{n}}{4\,\mathbf{f}_\pi^2} + \dots$$

$$\mathbf{f}_\pi \rightarrow \mathbf{f}_\pi^*(\rho)$$



Deeply Bound States of **Pionic Atoms**

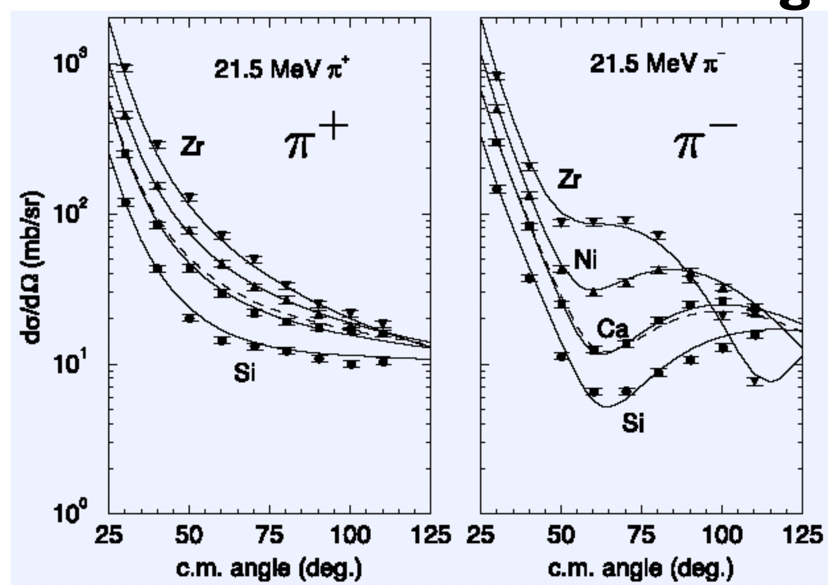


GSI

exp.: K. Suzuki et al. (2004)

theory: E. Kolomeitsev et al. (2003)

Low Energy **Pion-Nucleus Scattering**



PSI

E. Friedman et al. (2004)

E. Friedman, A. Gal arXiv 0705.3965

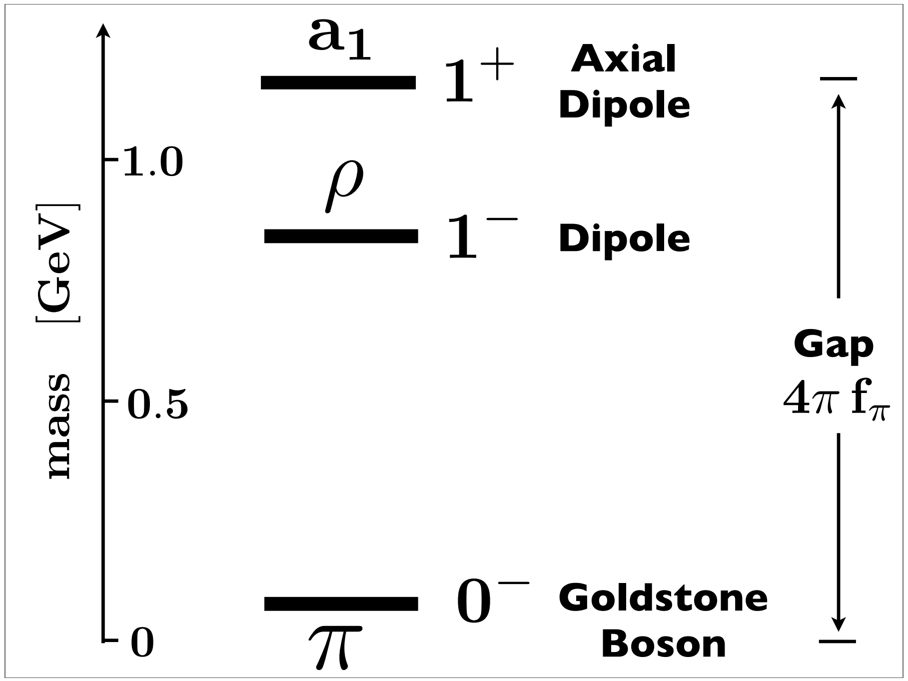
$$\mathbf{f}_\pi^*(\rho_\mathbf{0}) \simeq \mathbf{0.8}\,\mathbf{f}_\pi \sim 1 - \frac{\sigma_N}{2\,\mathbf{m}_\pi^2\,\mathbf{f}_\pi^2}\,\rho_0$$

deduced from exp.

theory pred. $(\sigma_\mathbf{N} \simeq \mathbf{50\,MeV})$

"Fingerprints of CHIRAL SYMMETRY RESTORATION ?"

VECTOR MESONS, QCD VACUUM and Spontaneous CHIRAL SYMMETRY breaking



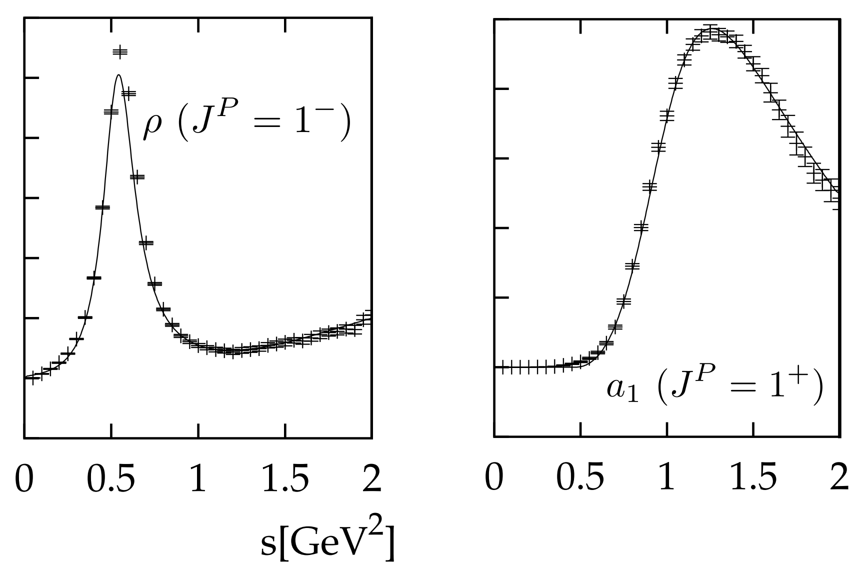
- Current Algebra Weinberg Sum Rules

$$\mathbf{m_{a_1} = \sqrt{2}\, m_\rho = 4\pi\, f_\pi}$$

- KSFR Relation

$$\mathbf{m_\rho^2 = 2\, g^2\, f_\pi^2 \quad (g = 2\pi)}$$

- Change of **MASS GAP** with varying **THERMODYNAMIC conditions** (density, temperature) ?



In-Medium Spectral Functions of VECTOR MESONS

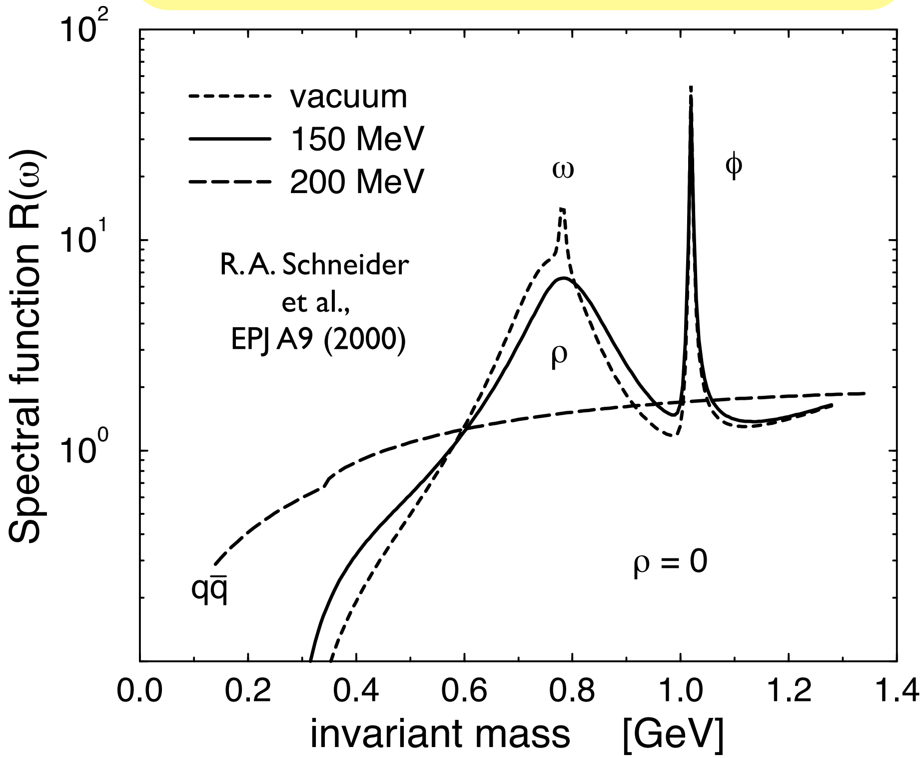
- Brown-Rho Scaling
  (1991)
- Review: R. Rapp, J. Wambach, Adv. Nucl. Phys. 25 (2000)

- In-Medium QCD Sum Rules

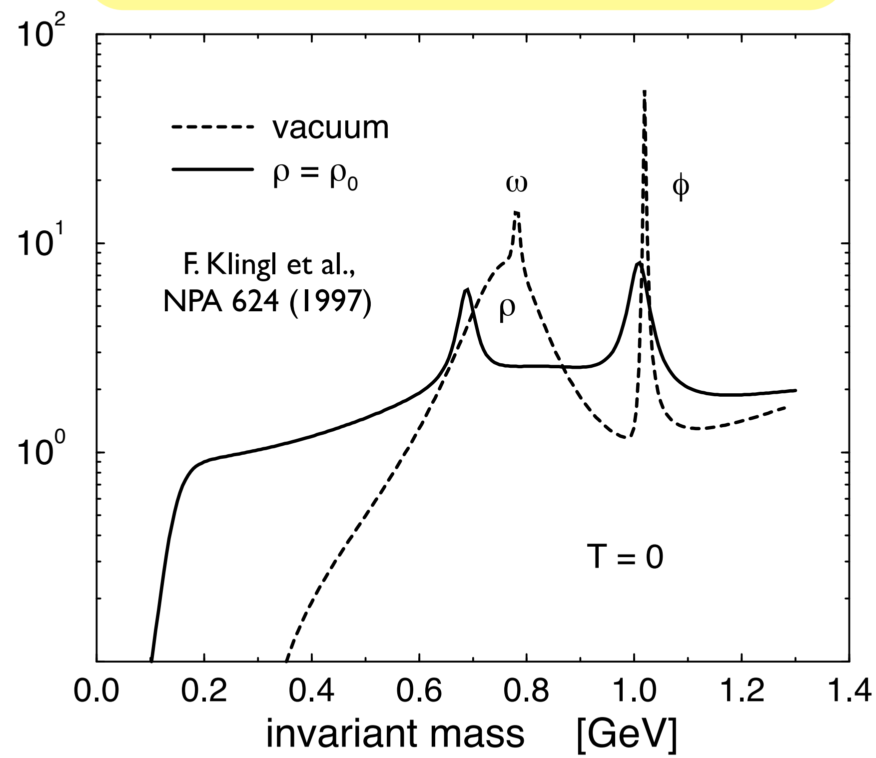
T. Hatsuda, S.H. Lee
Phys. Rev. C 46 (1992)

F. Klingl, N. Kaiser, W.W.
Nucl. Phys. A 624 (1997)

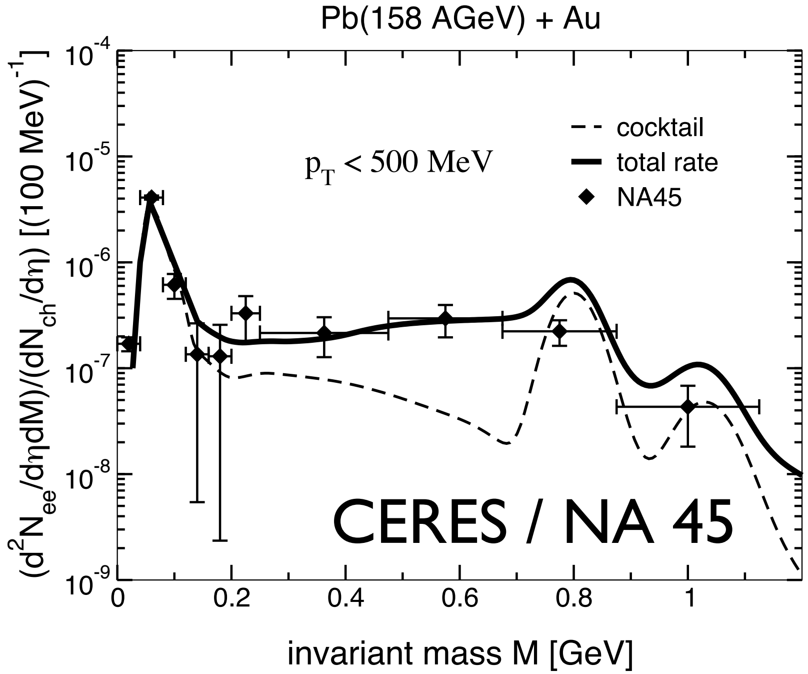
temperature dependence



density dependence



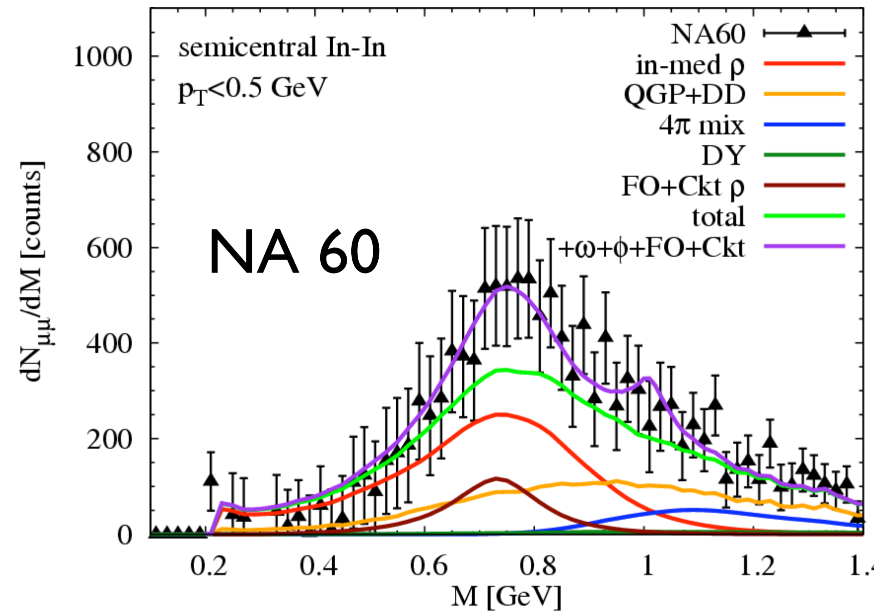
DILEPTONS from HEAVY - ION COLLISIONS, PROTON- and PHOTON-NUCLEUS REACTIONS



R. Rapp, J. Wambach (2000)

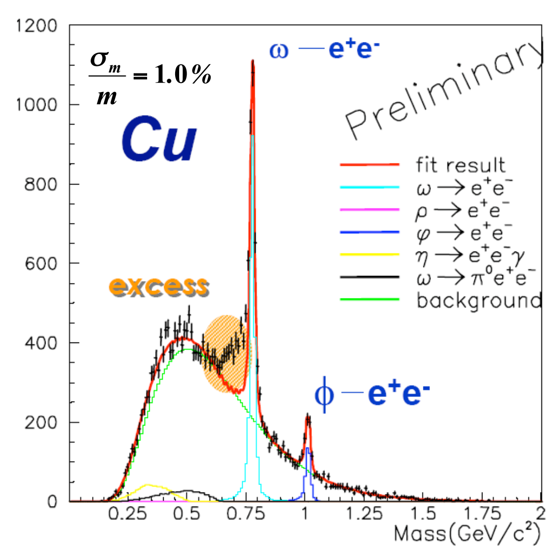
T. Renk, R.A. Schneider, W.W. (2002)

J. Ruppert, T. Renk EPJ C49 (2007)

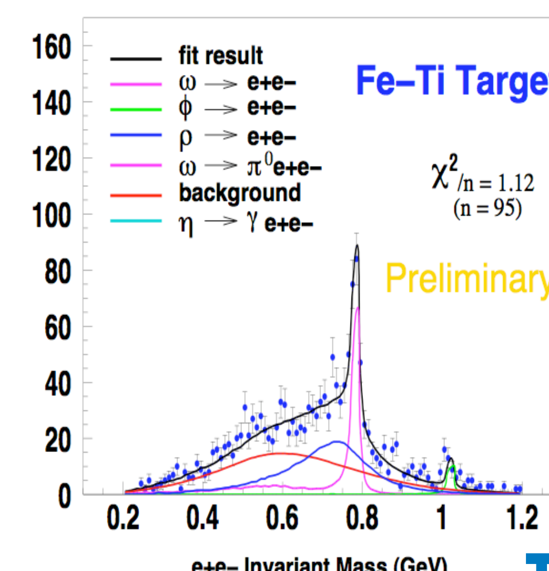


ENHANCED SPECTRAL STRENGTH at low mass

KEK-E325: p (12 GeV) A→ ρ, ω +X



JLAB – CLAS : G7 $\gamma A \to e^+e^- + X$

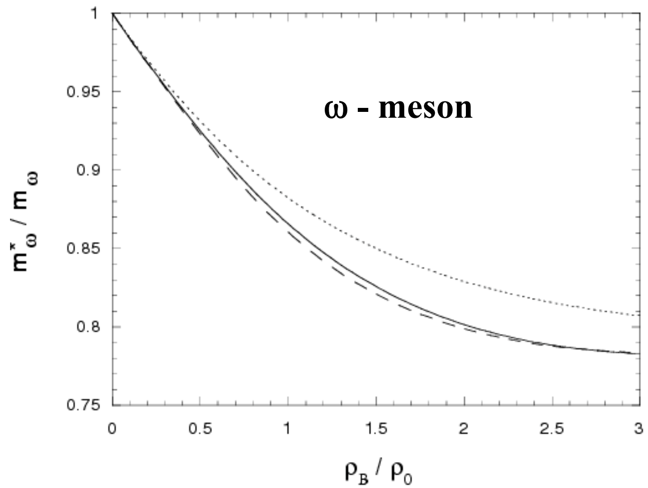


Technische Universität München

The ω MESON in MATTER

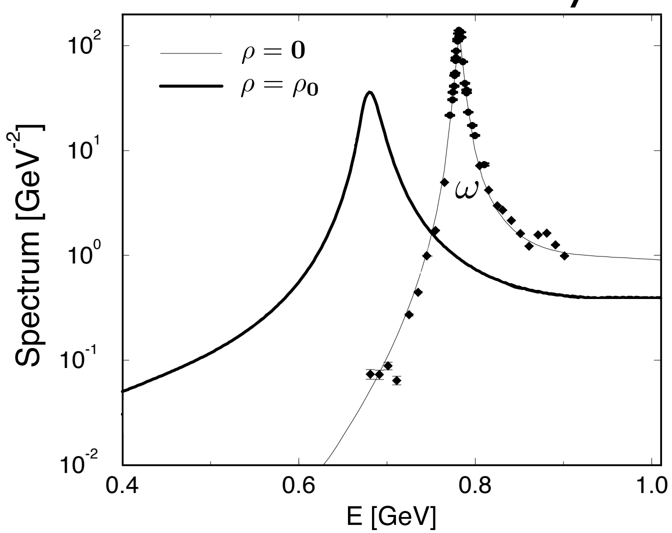
• Predictions from theory:

quark-meson coupling model



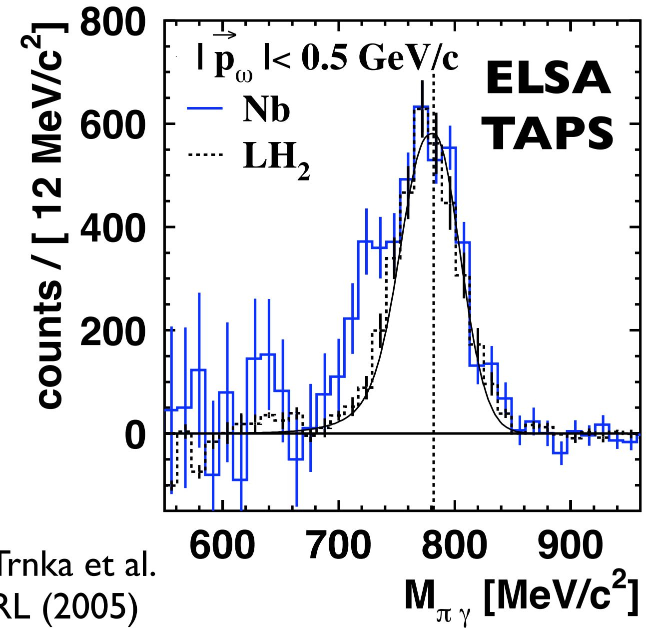
K. Saito, K. Tsushima, A.W. Thomas PRC (1997)

chiral effective field theory + vector mesons + baryons

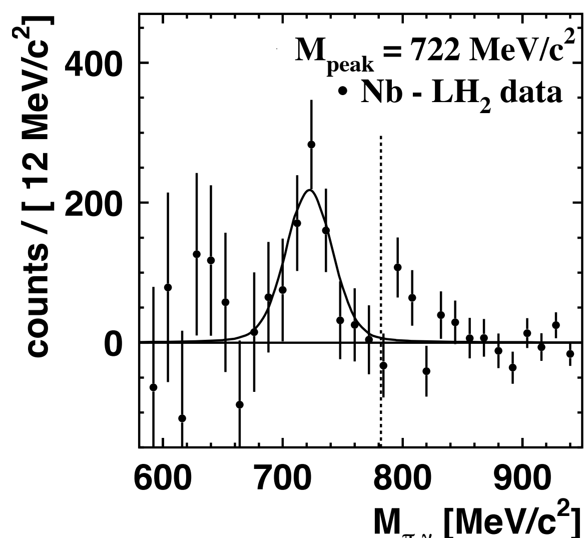


F. Klingl, N. Kaiser, W.W. NPA (1997)

• Experiment: Photoproduction of ω mesons



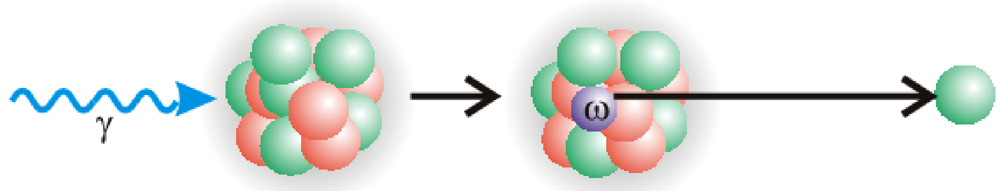
D. Trnka et al. PRL (2005)



QUASIBOUND ω MESON - NUCLEAR STATES ?

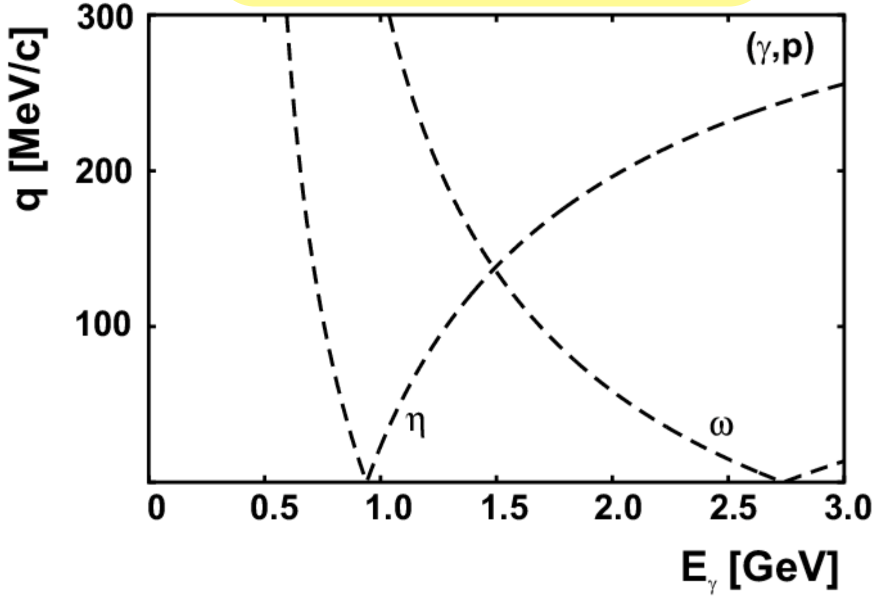
$$\gamma\, \mathbf{A} \rightarrow \omega(\mathbf{A}-\mathbf{1}) + \mathbf{N}$$

- **ω A attraction strong enough to allow for ω bound states??**

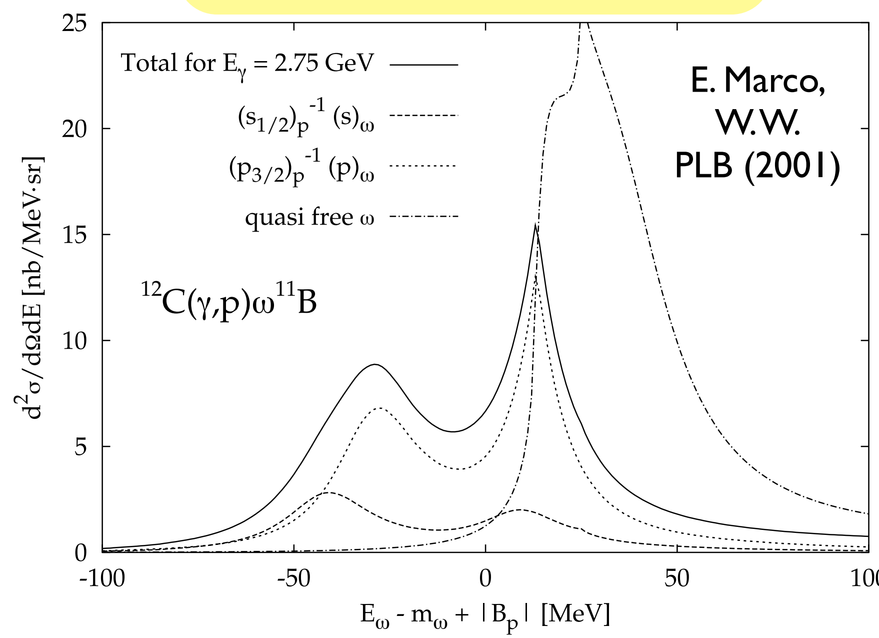


forward going nucleon takes over photon momentum

no-recoil kinematics:



prediction from theory:



magic incident energies **η: $E_\gamma \approx$ 930 MeV**
ω: $E_\gamma \approx$ 2750 MeV

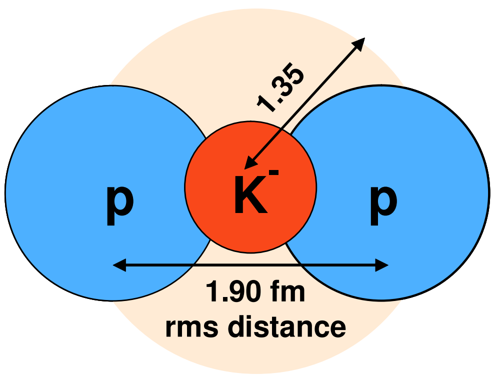
experiment: data analysis ongoing
(ELSA - TAPS)

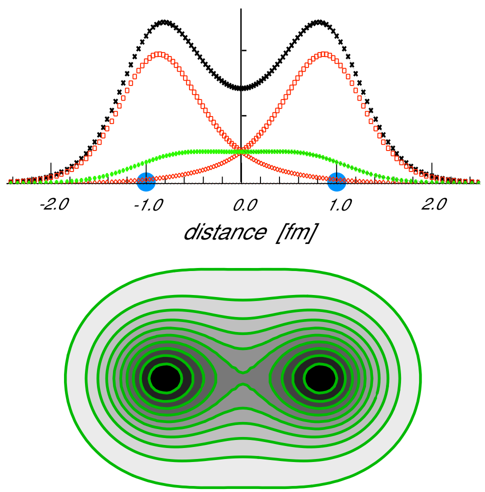
DEEPLY BOUND $\bar{\mathrm{K}}$- NUCLEAR STATES ?

- Strongly attractive $\bar{\mathrm{K}}\mathrm{N}$ I = 0 s-wave interaction close to threshold
- $\Lambda(1405)$ as $\bar{\mathrm{K}}\mathrm{N}$ quasibound state embedded in $\pi\Sigma$ continuum
  (R. Dalitz et al. (1960's))
- Chiral SU(3) Dynamics with coupled channels (P. Siegel et al. NPA (1995))
- Deeply Bound $\bar{\mathrm{K}}$- NUCLEAR CLUSTERS ?

Y. Akaishi, T. Yamazaki PLB (2002)

prototype example:

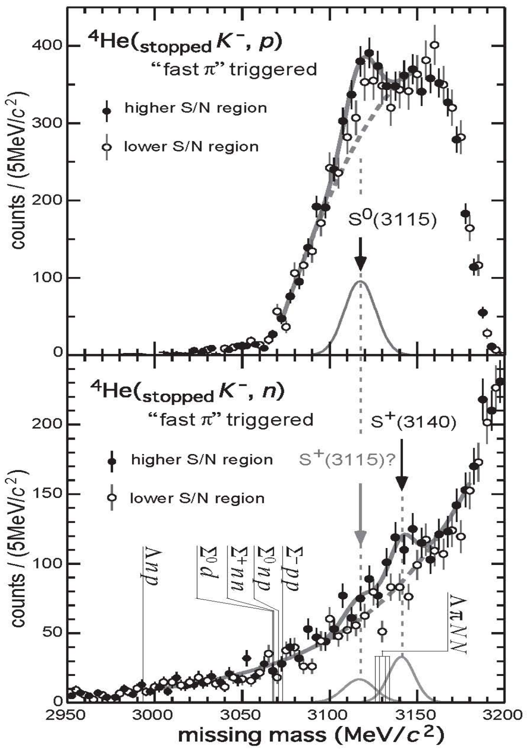




- Fadeev coupled channels calculation: binding, but large width
  (Shevchenko, Mares, Gal (2006))

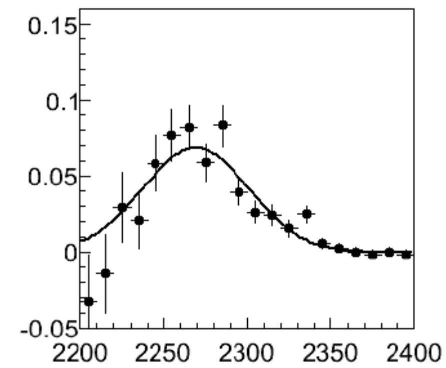
KEK / E471

FINUDA

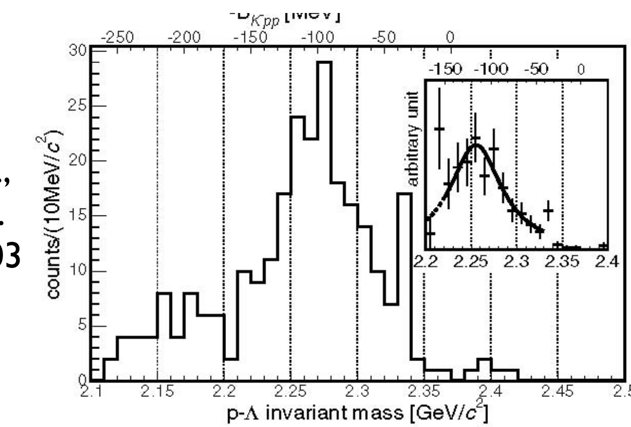


T. Suzuki et al.,
Phys. Lett. B 597 (2004) 263

M. Iwasaki et al.,
nucl-ex/0310018



^{12}C
(prel.)



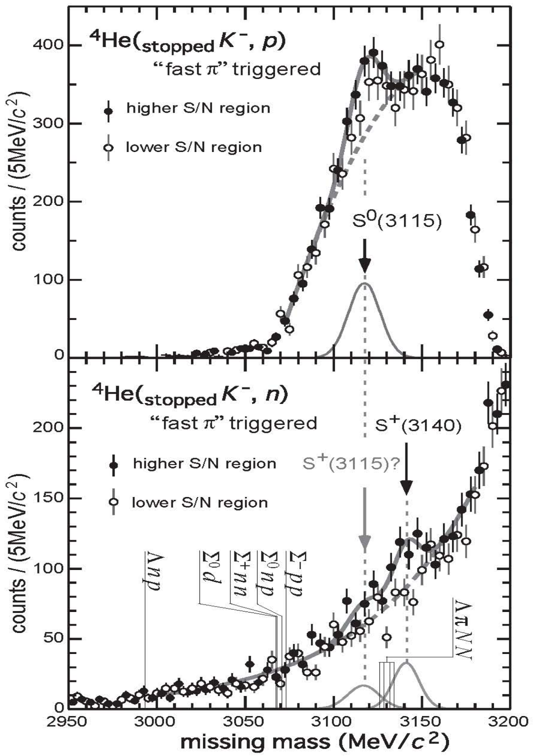
M. Agnello et al.,
Phys. Rev. Lett.
94 (2005) 212303

$$\mathbf{B(K^-ppn) \simeq 169\,MeV}$$
$$\mathbf{B(K^-pnn) \simeq 194\,MeV}$$
$$\mathbf{\Gamma < 21\,MeV \quad (!)}$$

$$\mathbf{(^6Li,\ ^7Li,\ ^{12}C)}$$
$$\mathbf{B(K^-pp) = (115 \pm 9)\,MeV}$$
$$\mathbf{\Gamma = (67 \pm 16)\,MeV}$$

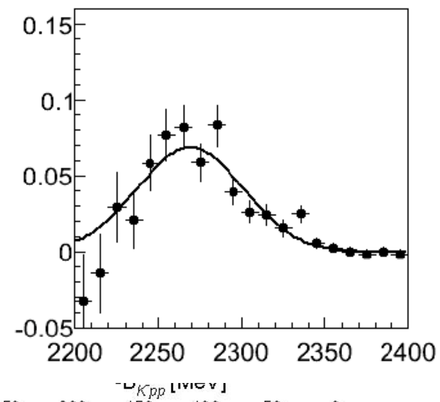
KEK / E471

FINUDA



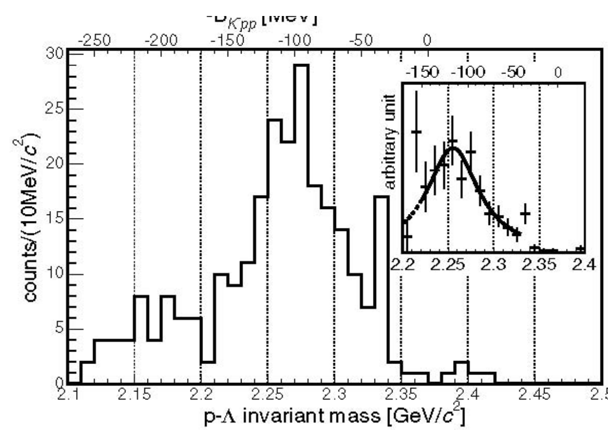
T. Suzuki et al.,
Phys. Lett. B 597 (2004) 263

M. Iwasaki et al.,
nucl-ex/0310018



^{12}C
(prel.)

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



?

$$({}^6\mathrm{Li},\ {}^7\mathrm{Li},\ {}^{12}\mathrm{C})$$

$$\mathbf{B(K^-pp) = (115 \pm 9)\ MeV}$$

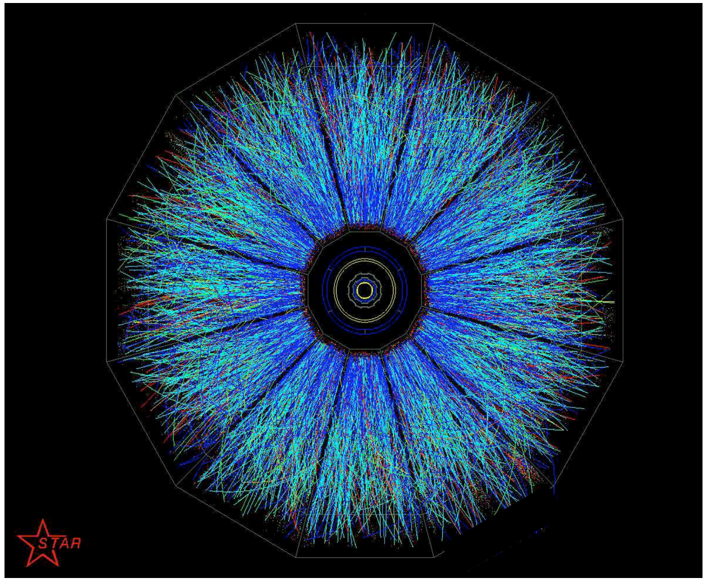
$$\mathbf{\Gamma = (67 \pm 16)\ MeV}$$

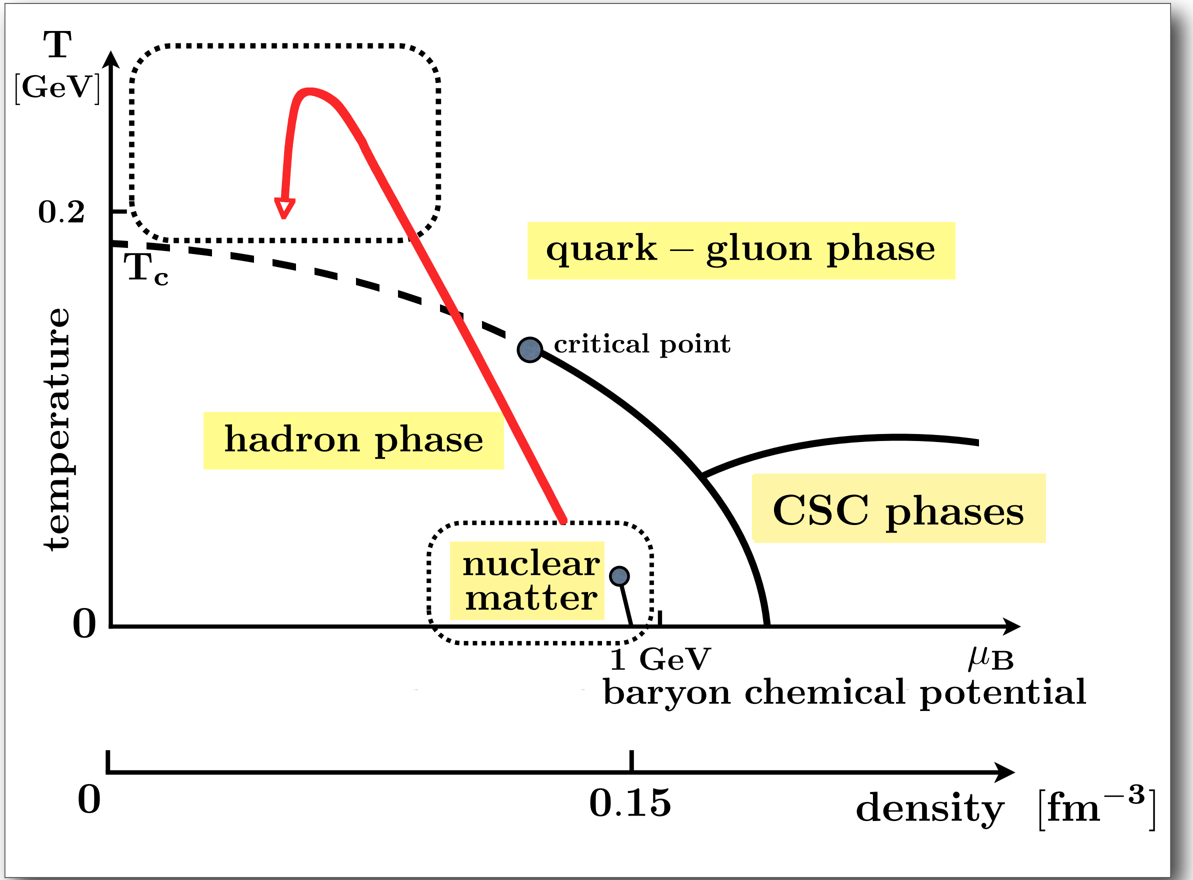
- present situation unclear
  new analysis ongoing

- interpretation under dispute

VII.

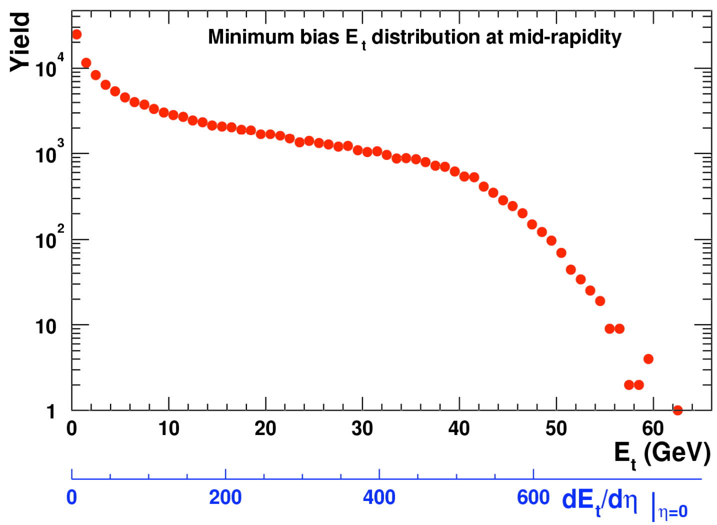
MATTER
under
EXTREME CONDITIONS



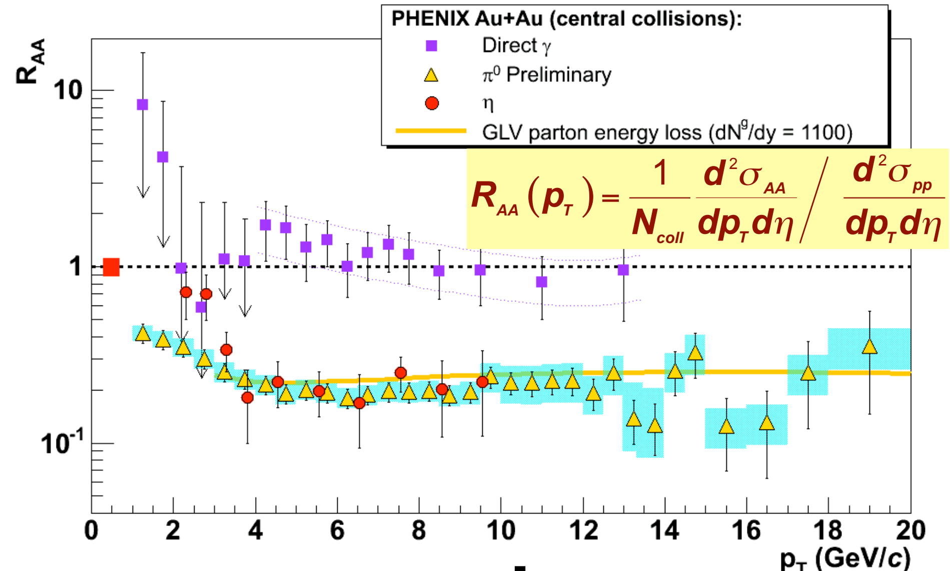


QUARK-GLUON MATTER produced at RHIC

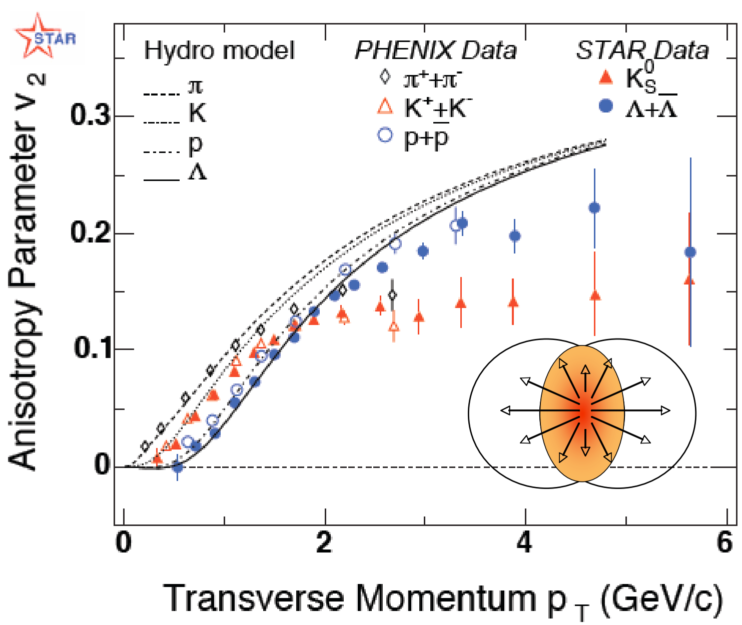
- TRANSVERSE ENERGY



- JET QUENCHING



- FLOW / HYDRODYNAMICS



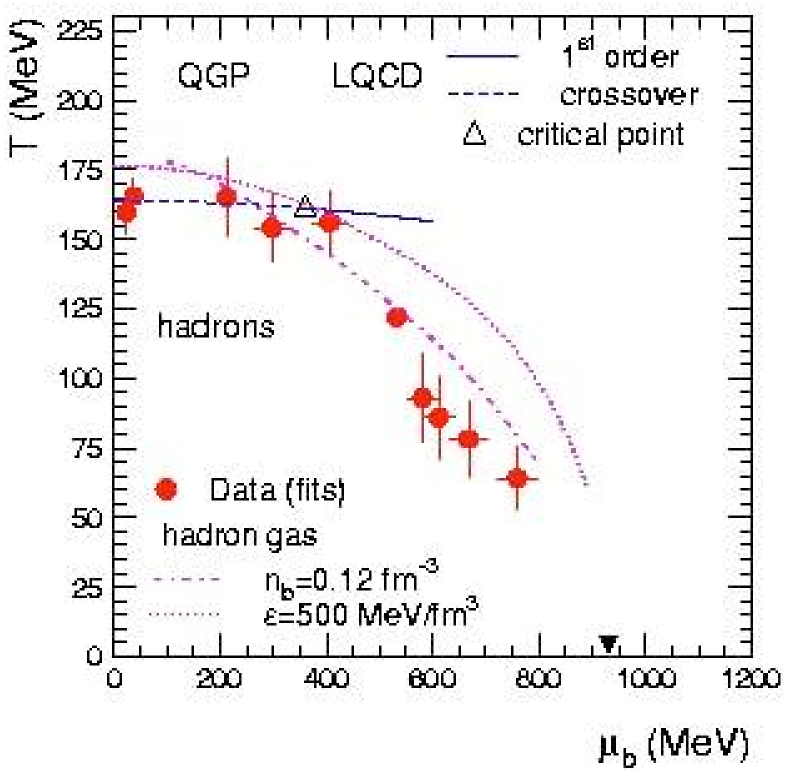
- **initial energy density**

$$\mathcal{E} \sim (10-20)\,\mathrm{GeV\,fm^{-3}}$$

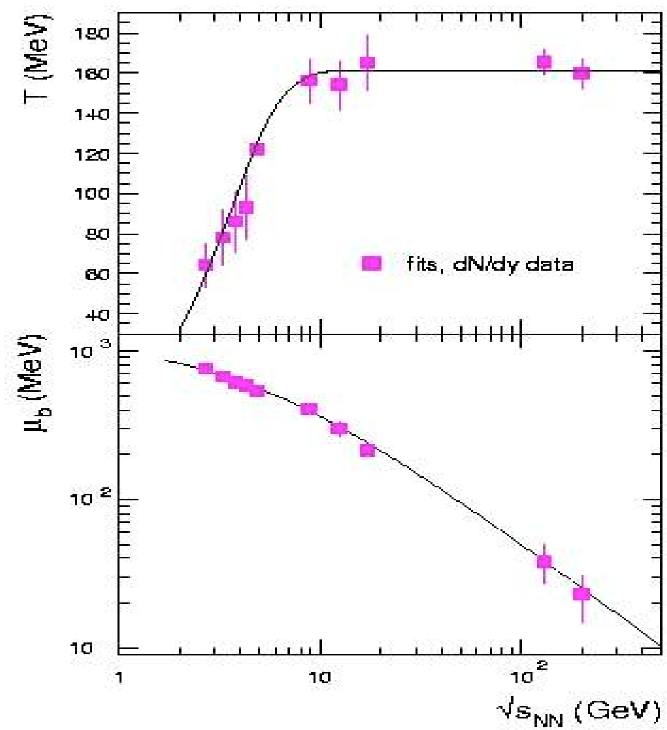
- **strongly coupled** (opaque) **quark-gluon matter**
- **nearly perfect liquid**

CHEMICAL FREEZE-OUT

- Thermal (grand canonical) description of hadron yields works well
- Fast equilibration
- ... relation to QCD phase boundary at small chemical potential ?



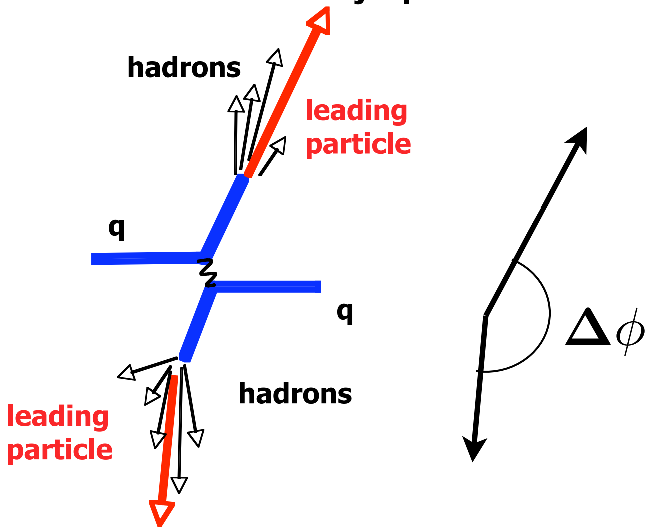
A. Andronic, P. Braun-Munzinger, J. Stachel
NPA 772 (2006) 167

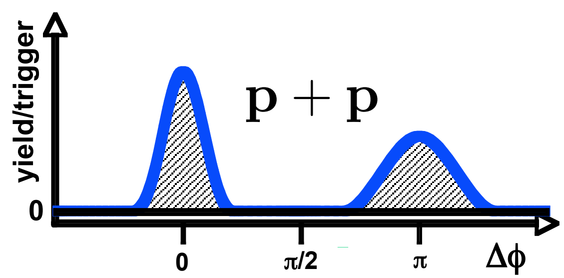


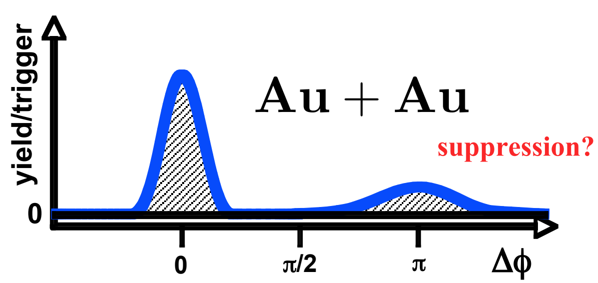
- Limiting Temperature
  $$\mathbf{T}_{lim} \simeq \mathbf{160\,MeV}$$

CORRELATIONS:
towards a more detailed understanding of
MATTER produced at RHIC

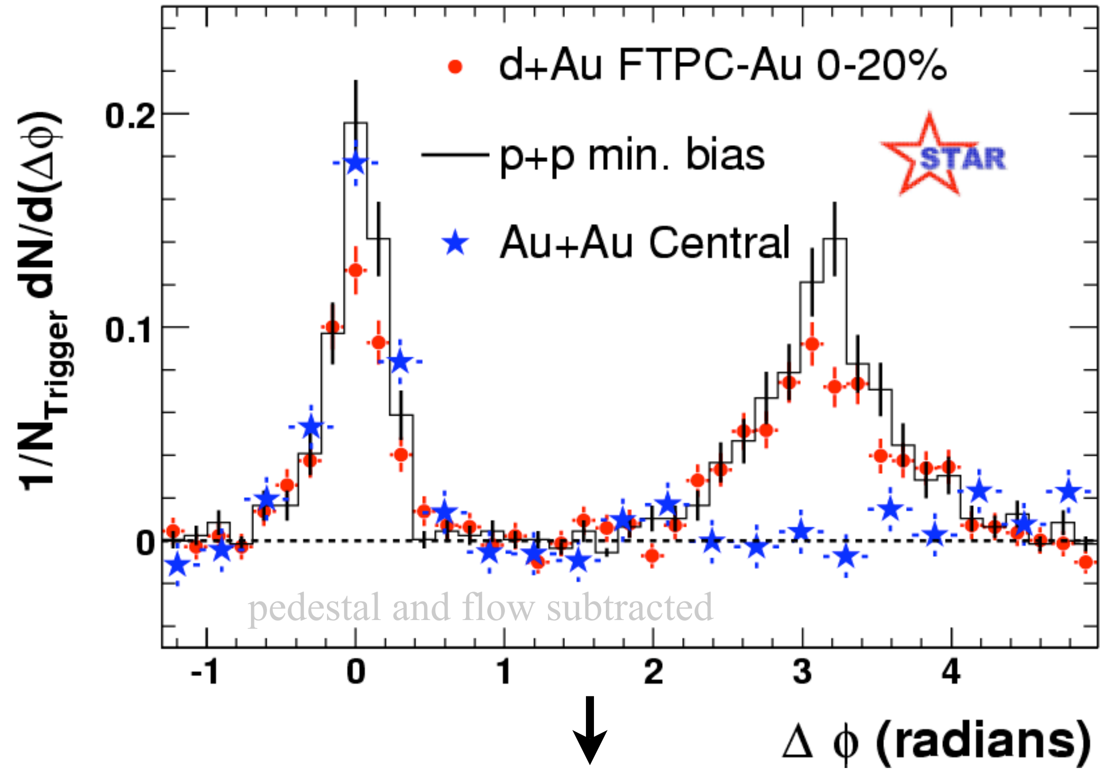
schematic view of jet production







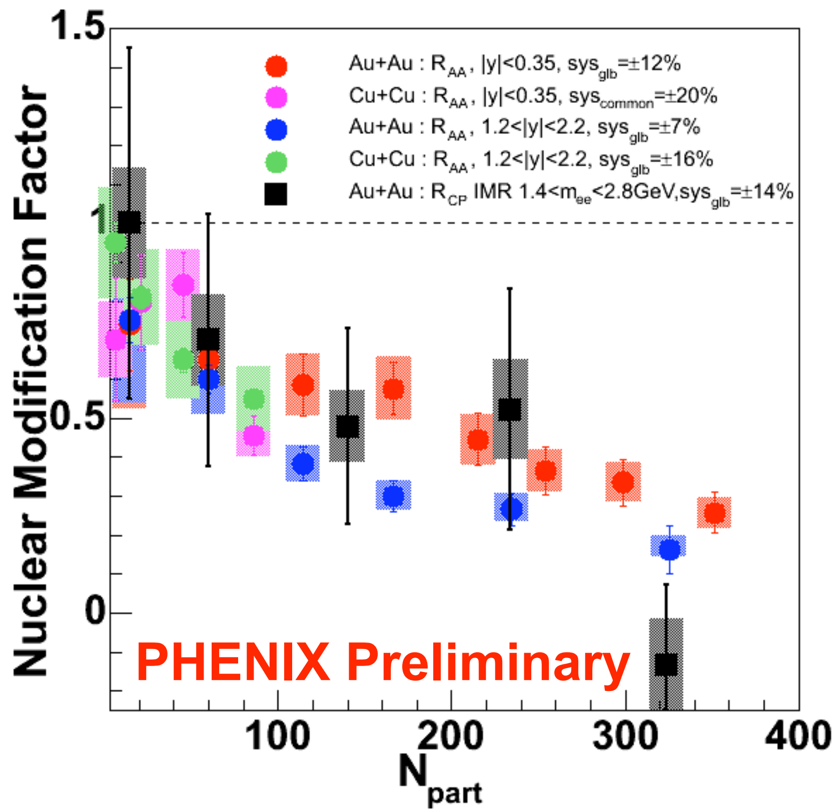
"near" "away" side

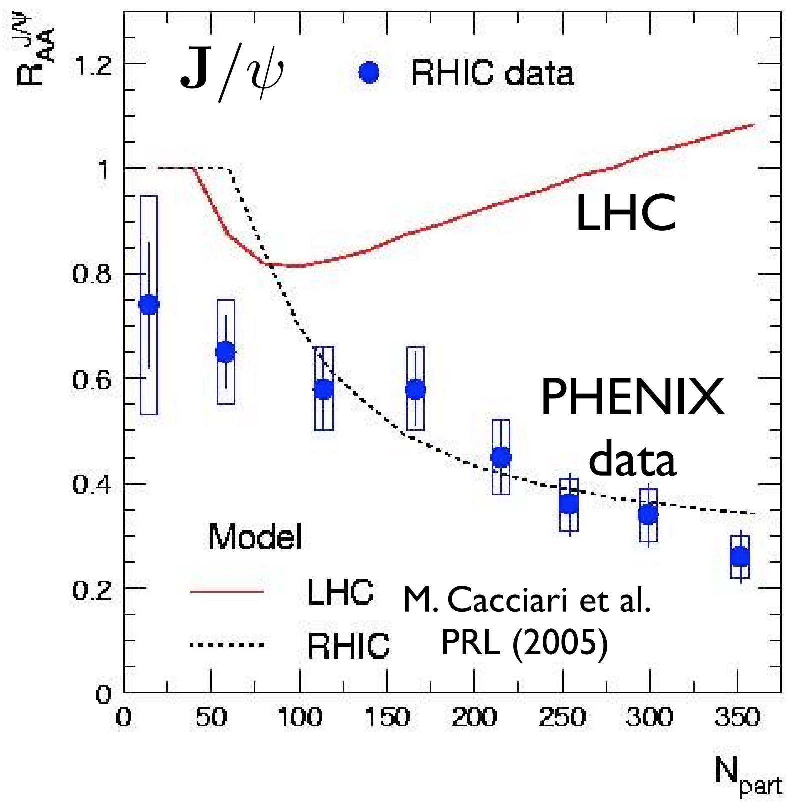


- learn about jet **transport** through **quark-gluon matter**

- PHENIX:
  direct photon - jet correlations

CHARM PRODUCTION



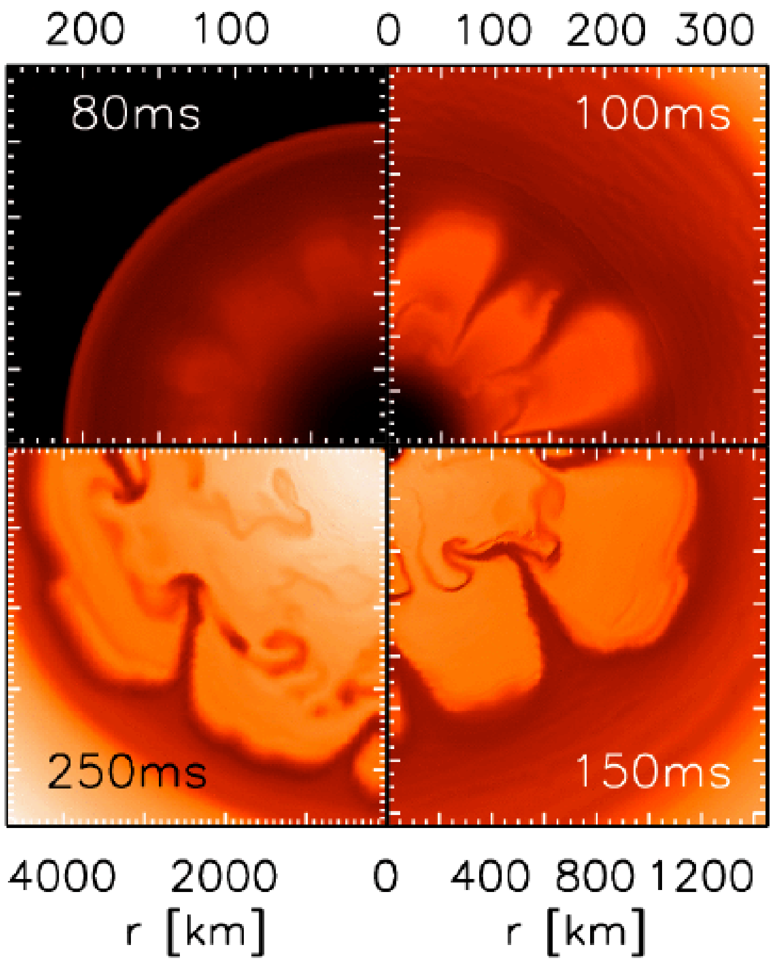


- suppression not only for J/ψ but also for "intermediate mass" quark-antiquark pairs

- J/ψ suppression may turn into J/ψ enhancement at **LHC**

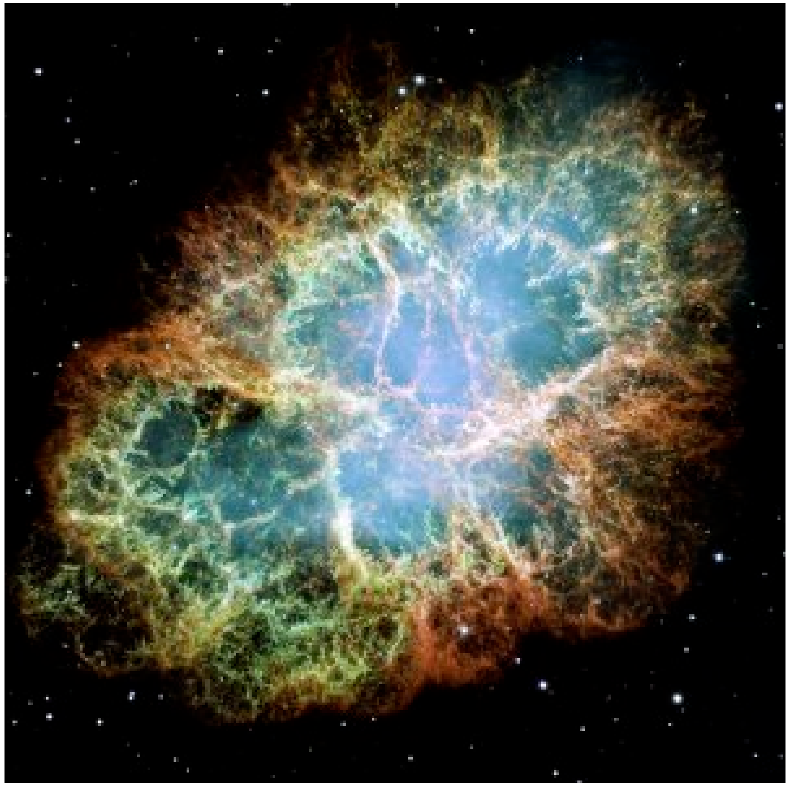
- reminder: CHARMONIUM RENAISSANCE
  many interesting new states "embedded in the continuum" above open charm thresholds

VIII. MATTER under EXTREME CONDITIONS: SUPERNOVAE and NEUTRON STARS

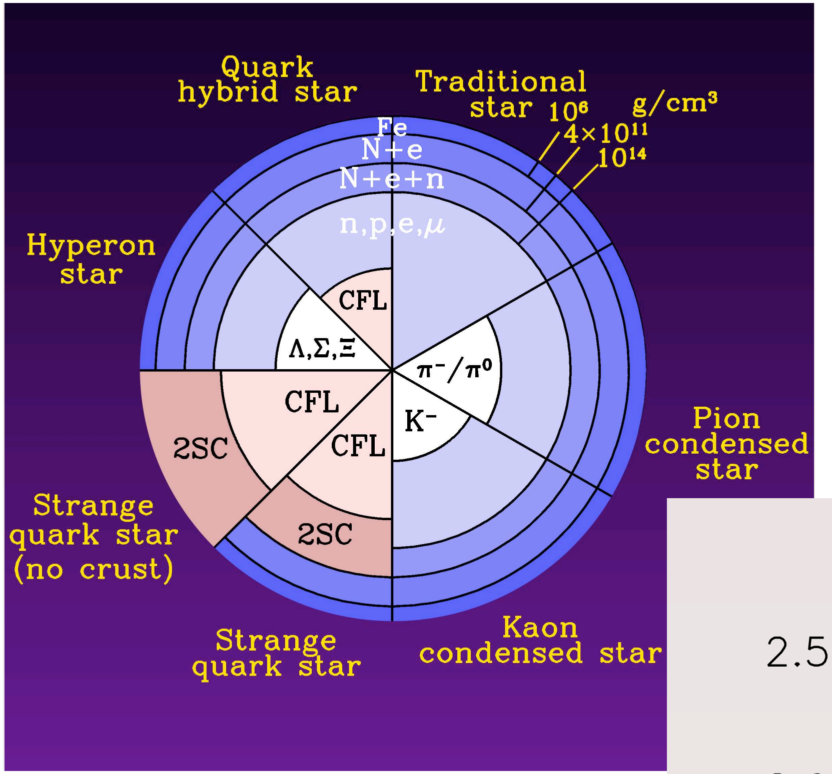


- Progress in
  2D Hydrodynamics Simulations of
  Core Collapse Supernovae

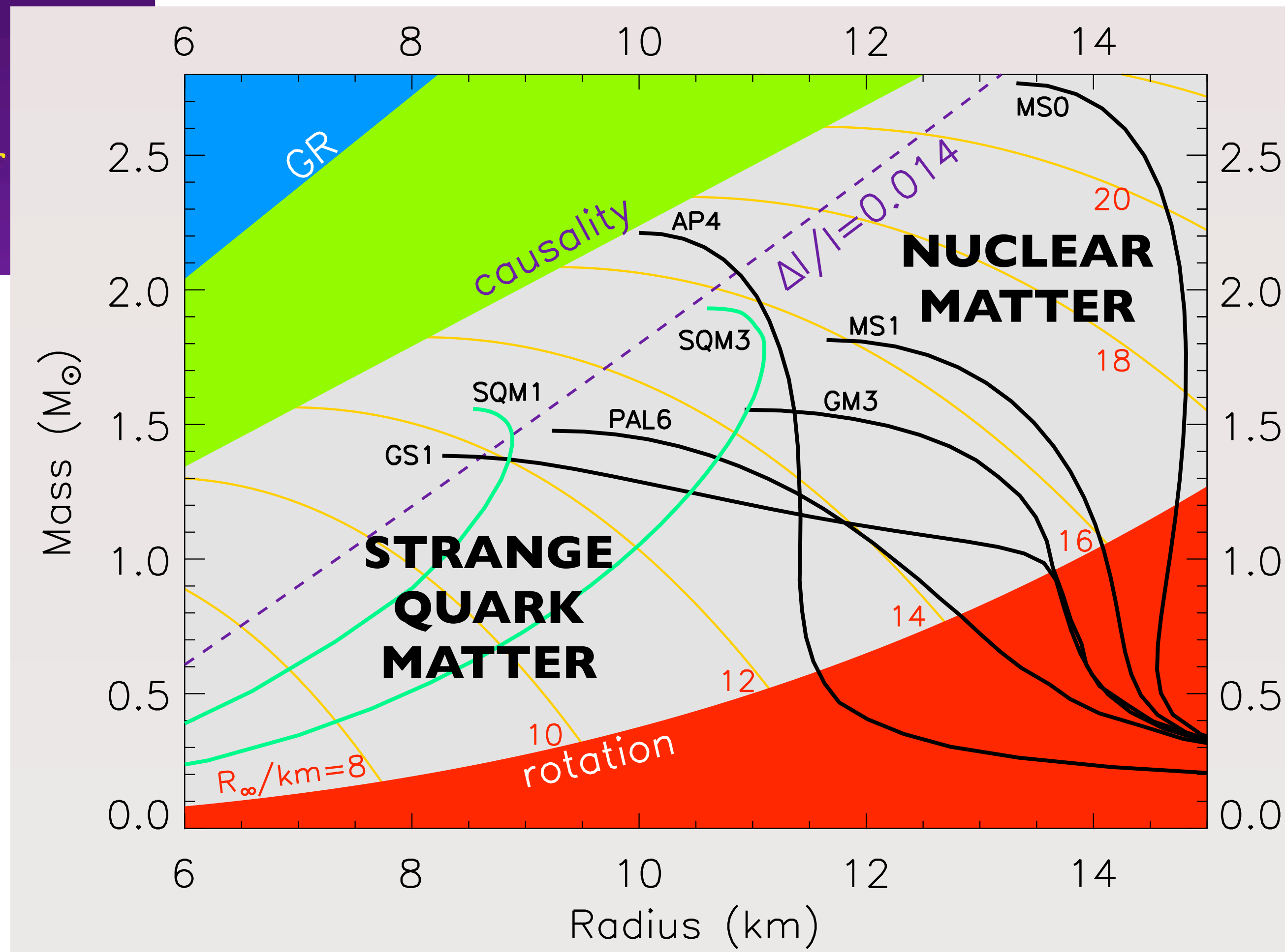
Th. Janka et al.
(2006)



NEUTRON STARS
and the
EQUATION OF STATE
of
DENSE BARYONIC MATTER



Neutron Star Scenarios



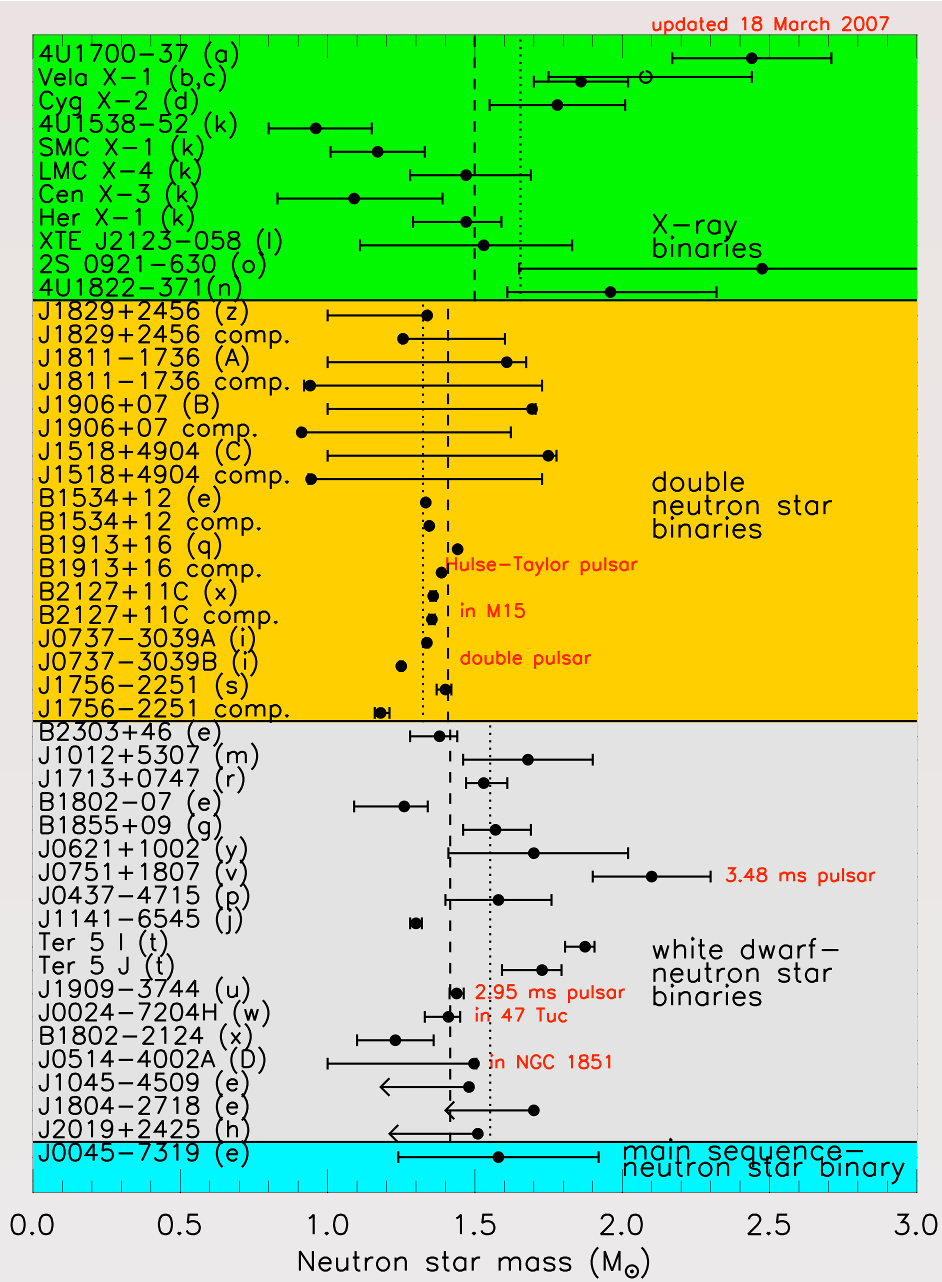
Mass-Radius Relation

J. Lattimer, M. Prakash

ApJ (2001)

Science (2004)

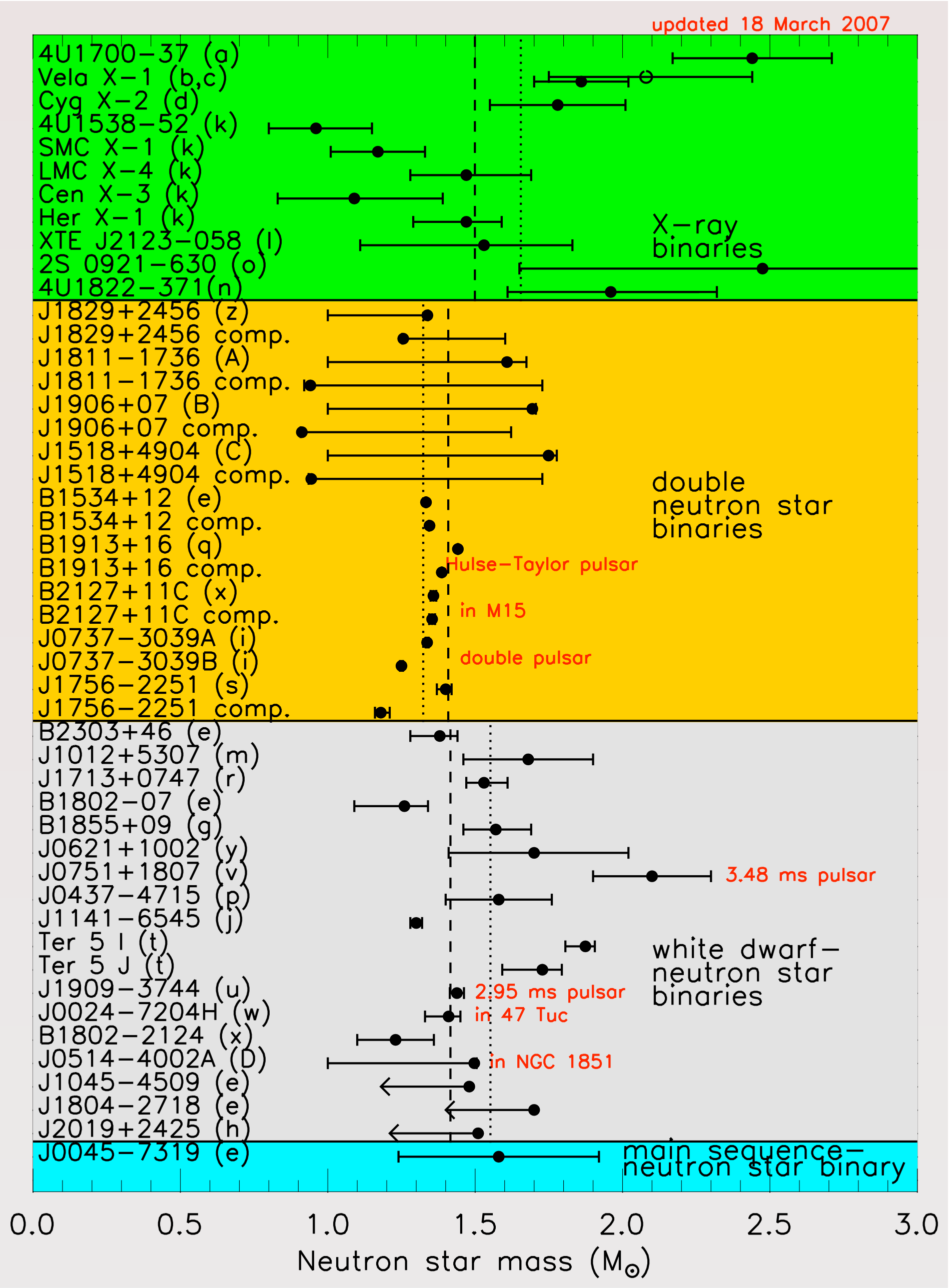
MEASUREMENTS of NEUTRON STAR MASSES and RADII



Object	R (km)	Ref
Omega Cen Chandra	13.5 ± 2.1	Rutledge et al. ('02)
Omega Cen (XMM)	13.6 ± 0.3	Gendre et al. ('02)
M13 (XMM)	12.6 ± 0.4	Gendre et al. ('02)
47 Tuc X7 (Chandra)	$14.5^{+1.6}_{-1.4}$ ($1.4\ M_\odot$)	Rybicki et al. ('05)
M28 (Chandra)	$14.5^{+6.9}_{-3.8}$	Becker et al. ('03)
EXO 0748-676 (Chandra)	13.8 ± 1.8 ($2.10 \pm 0.28\ M_\odot$)	Ozel ('06)

- ... would this make "exotic" neutron star scenarios unlikely ??

NEUTRON STAR MASSES and RADII



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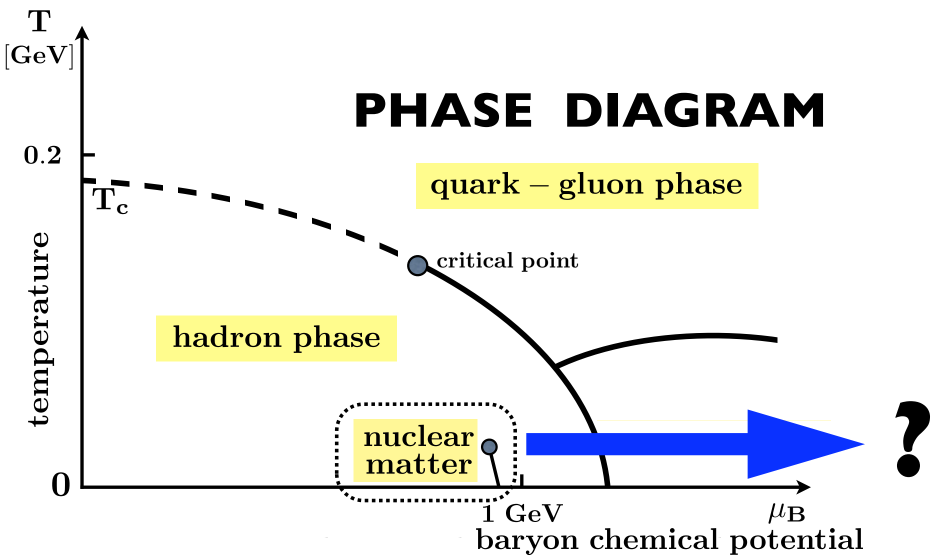
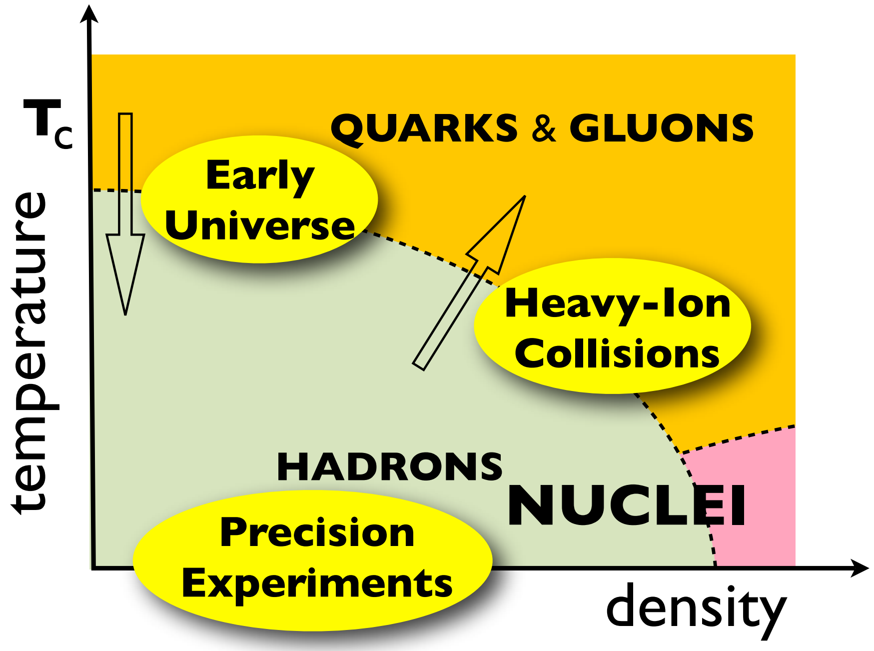


Keyword Summary : passing through **PHASE BOUNDARIES**



- **Confinement** of **Quarks** and **Gluons** in (composite) **Hadrons**

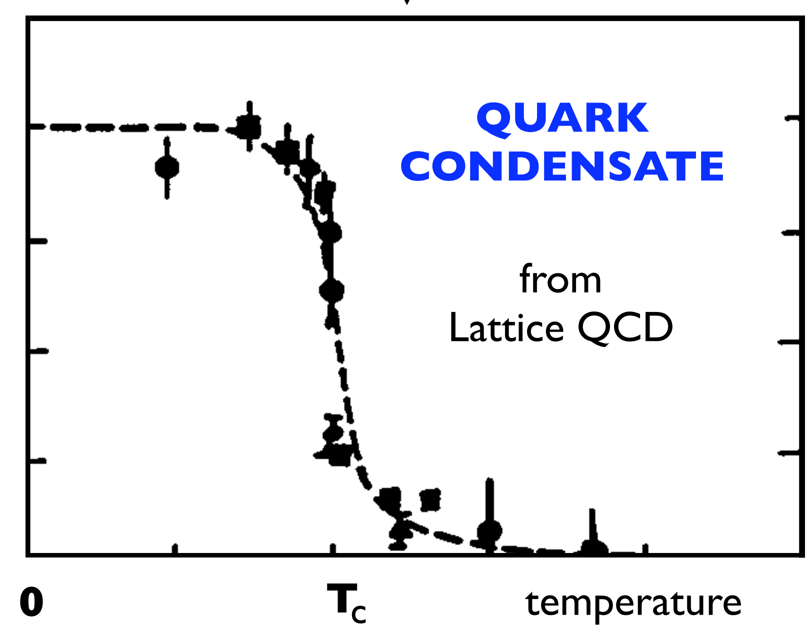
↓

- **Vacuum Structure** : **Condensation** of **Quarks** and **Gluons**

↕

- **Spontaneous (Chiral) Symmetry Breaking**

↔



↓

- **Nambu-Goldstone Bosons: Pions**

↓

- **Nuclear Masses and Forces**