Nuclear equation of state phase transitions, and their astrophysical implications

Evgeni Kolomeitsev

BLTP JINR, Dubna
Matej Bel University, Slovakia

...per collisionis ad astra …

Why do we collide heavy nuclei?

QCD in action

Phase diagrams of nuclear matter

Giant nuclei in space – neutron stars

The Standard model. The QCD

<u>Degrees of freedom for strong interaction</u>:

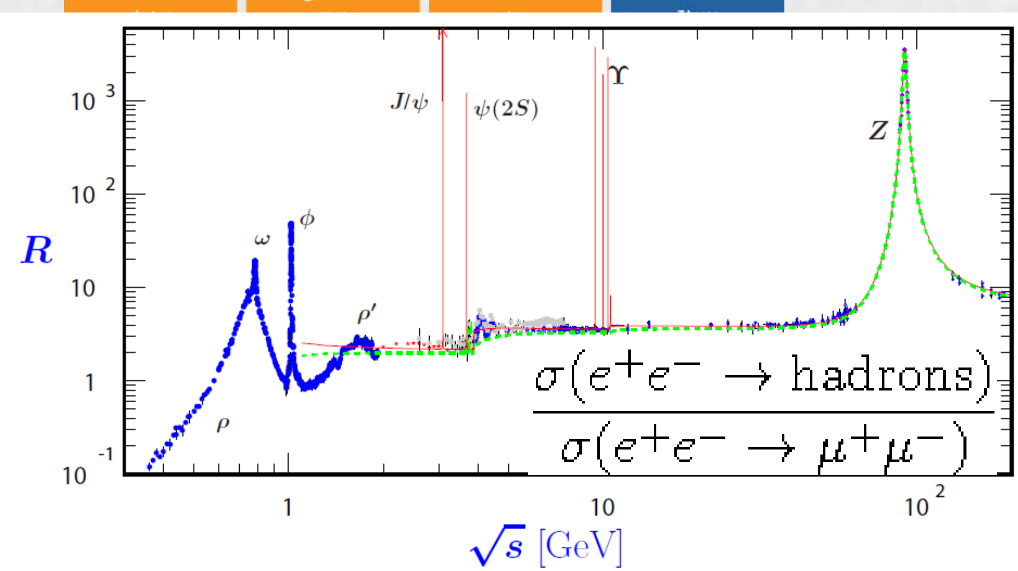
fermions: **quarks**

bosons: **gluons**

SU(3) gauge symmetry (color)

- QCD: symmetries

Gell-Mann, Ne'eman "Eightfold way"
flavour SU(3) and chiral symmetry
(accidential symmetries)
small masses of u,d,s quarks
Georgi, Manohar Large N_c counting (3>>1)



- QCD: dynamics

Fritzsch, Gel-Mann, Leutwyler
hadron currents vs. quark currents

Jets, DIS, pp, p-bar-p,
parton distribution functions

QCD with light quarks

✔ **quarks** $q_L(x) = \frac{1+\gamma_5}{2} \begin{pmatrix} u(x) \\ d(x) \\ s(x) \end{pmatrix}$ ✔ **gluons** $G^a(x) \longleftarrow$ SU(N_c) gauge bosons

$D_\mu(G) = \partial_\mu - i\,\frac{g}{2}\,G^a_\mu(x)\,\lambda_a$

$$\mathcal{L}_{\rm QCD}(x) = \bar q_L(x)\, i\,\gamma^\mu D_\mu(G) q_L(x) + \bar q_R(x)\, i\,\gamma^\mu D_\mu(G) q_R(x) - \frac{1}{4}\sum_{a=1}^{N_c^2-1} G^{\mu\nu}_a(x)\, G_{\mu\nu,a}(x)$$

$$- \bar q_L(x) \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix} q_R(x) - \bar q_R(x) \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix} q_L(x)$$

Accidental symmetries

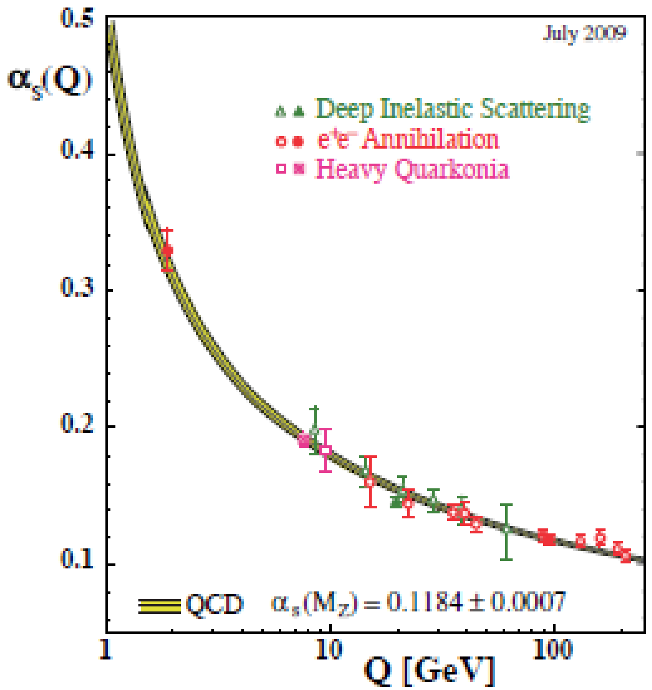
✔ consider $m_{u,d,s}$ to be small

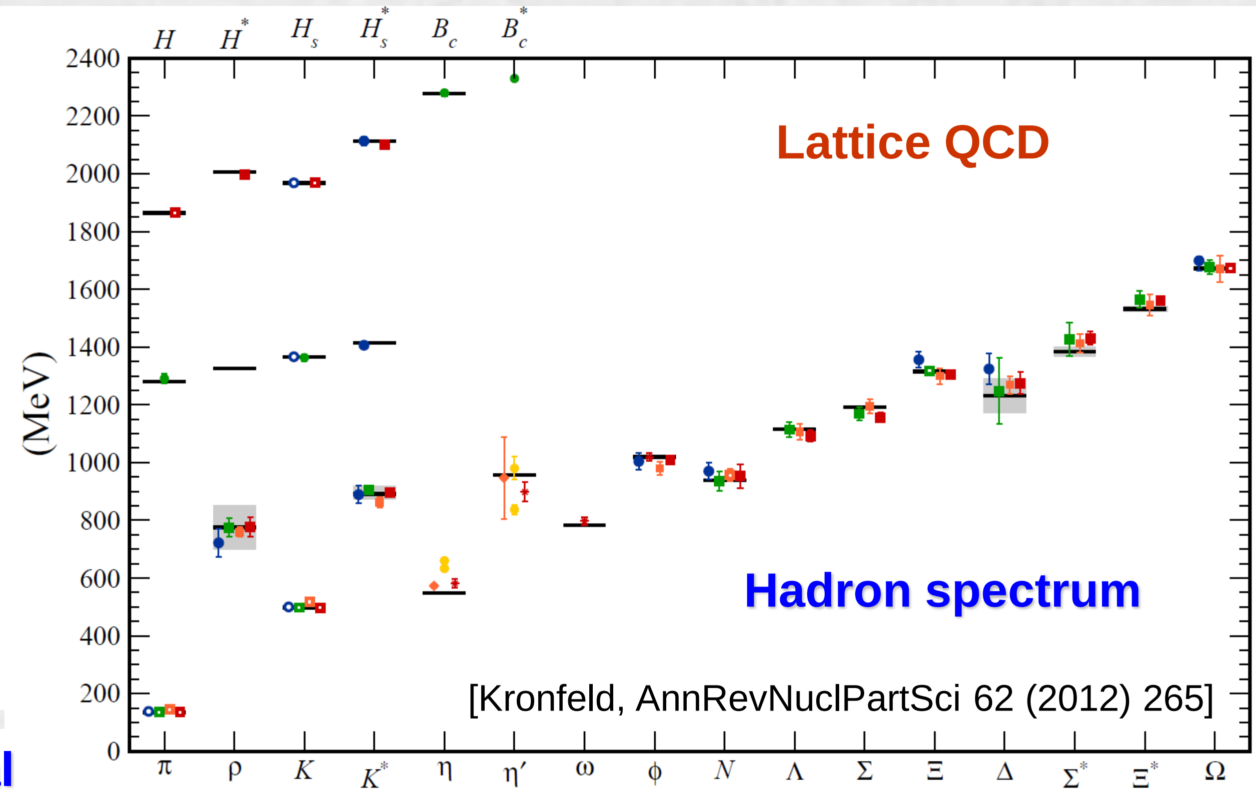
- approximate $SU(3)_L \otimes SU(3)_R$ chiral symmetry
- parity doublets in hadron spectrum (if not broken spontaneously !)

✔ consider number of colors $N_c = 3$ to be large: assume $g \sim N_c^{-1}$

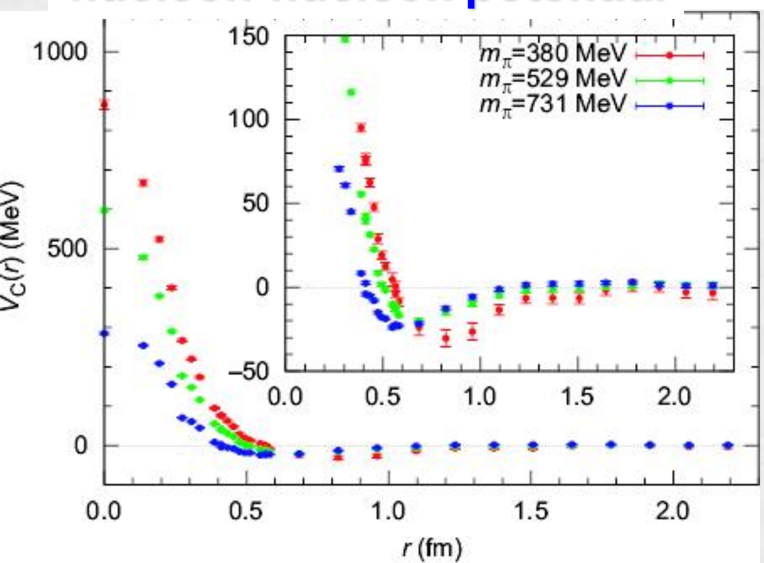
- contracted spin-flavor symmetry SU(6)

Running coupling constant → soft QCD is nonperturbative

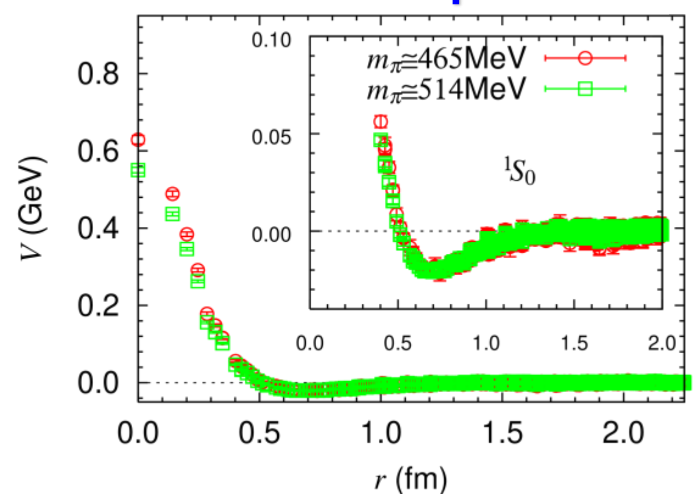




nucleon-nucleon potential



Lambda-nucleon potential



Does the success of perturbative and nonperturbative QCD mean that we know everything about strong interaction?

2005

FAIR-Discussion among H. Fritzsch, M. Gell-Mann (HEP community) and hadron-physics community in Germany

New facets of the QCD:

hadron spectroscopy
decay patterns
new ‘exotic states’;
Hadrogenesis – hadron moleculs.

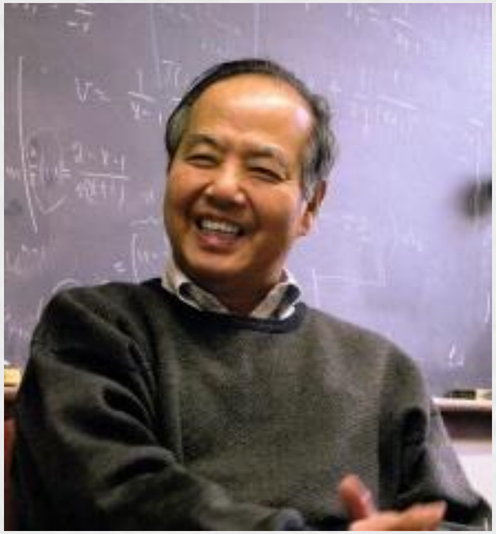
QCD phase diagrams
New phases (signals?)
Critical points (signals?)

equation of state
T=0 compact star physics constrraints
T=/=0 thermal excitation of relevant d.o.f

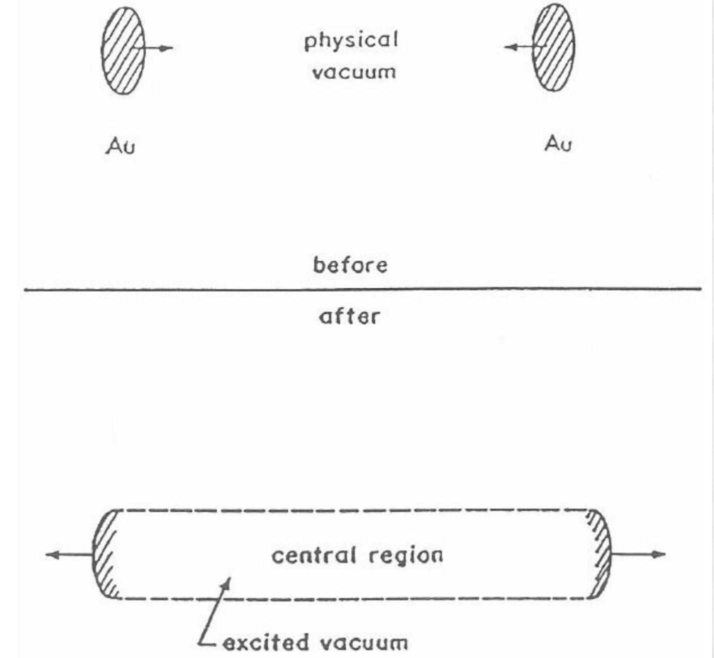
We have a beautiful piece of art and we are very curios how is it made?

We suspect some structures and hidden elements under the covers?

We want to try to rebuild it and study it properties.



Tsung-Dao Lee



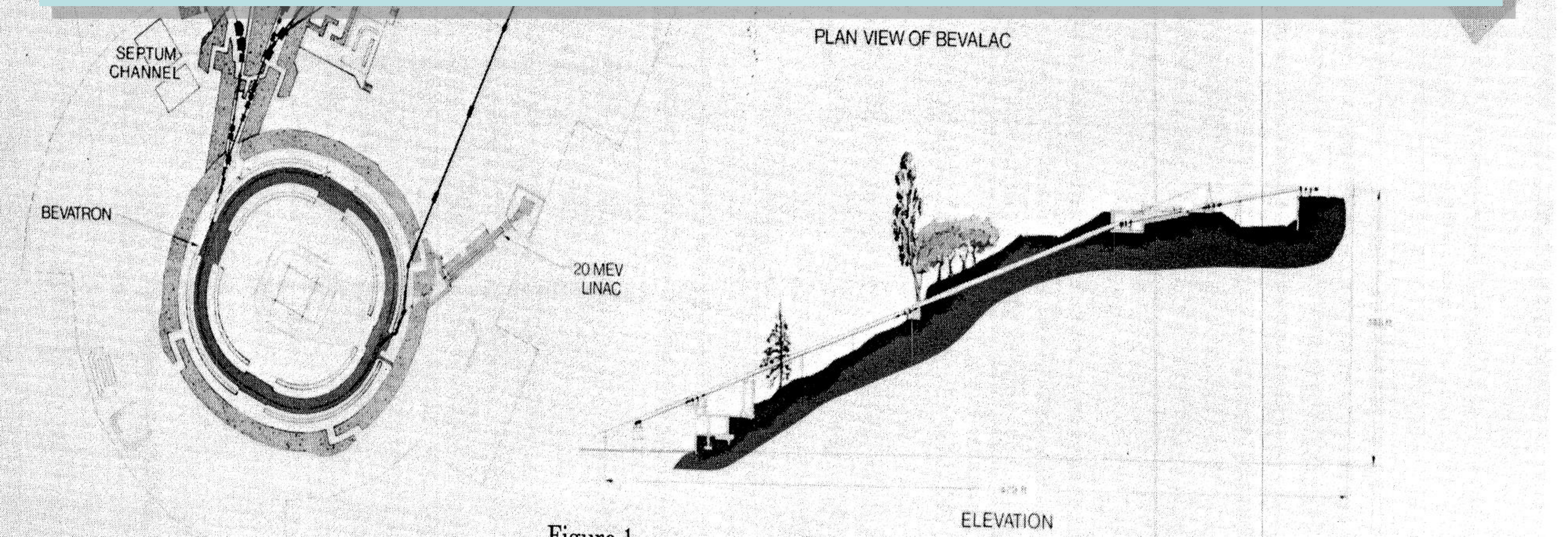
The most crucial questions in an ultra-relativistic heavy ion collision are:

1. Can extended objects of very high energy densities
   (>> energy density inside a proton) be produced?

2. If produced, how can they be detected and how can we analyze their properties?

[in *Symmetry in Particle Physics*,1984]

The early 1974 Workshop at Bear Mountain, just north of New York City, on *BeV/nucleon collisions of heavy ions,* was a pivotal event in the conception of heavy ion physics, since after this workshop physicists began to take seriously the possibility of using heavy ion collisions as a tool to study the properties of matter under extreme conditions of high energy and baryon densities, to ask whether was there a "nuclear world quite different from the one we have learned to accept as familiar and stable?" [Gordon Baym, NPA956(2016) 1]



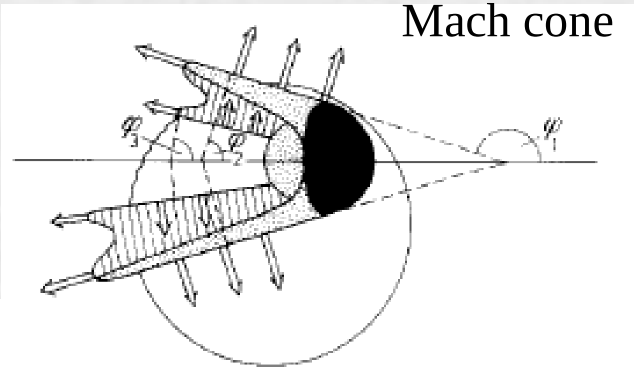
Shock waves and nuclear compression

What happens when two nuclei collide? Interpenetration? Bounce?

Z. Physik 226, 364—394 (1969)

Quasimolecular Nuclear Optical Potentials*

WERNER SCHEID and WALTER GREINER
Institut für Theoretische Physik der Universität Frankfurt (Main), Germany



PHYSICAL REVIEW D VOLUME 8, NUMBER 12

Highly Excited Nuclear Matter*

G. F. Chapline, M. H. Johnson, E. Teller, and M. S. Weiss
Lawrence Livermore Laboratory, University of California, Livermore, California 94550

Baumgardt et al 75

Nuclear Physics A251 (1975) 502 – 529

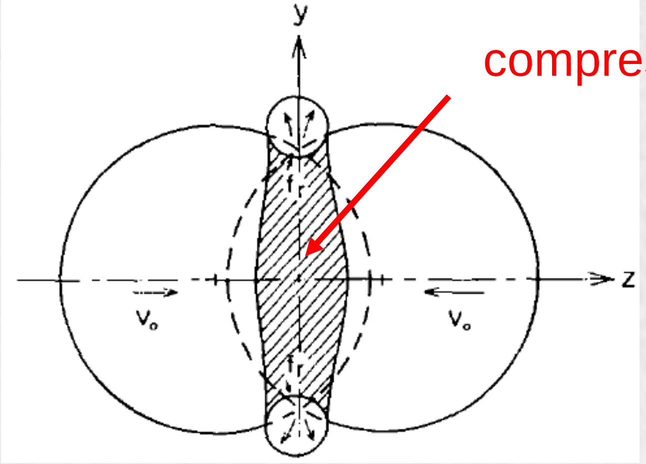
SHOCK WAVES IN COLLIDING NUCLEI

MICHAEL I. SOBEL†
Nordita, Copenhagen

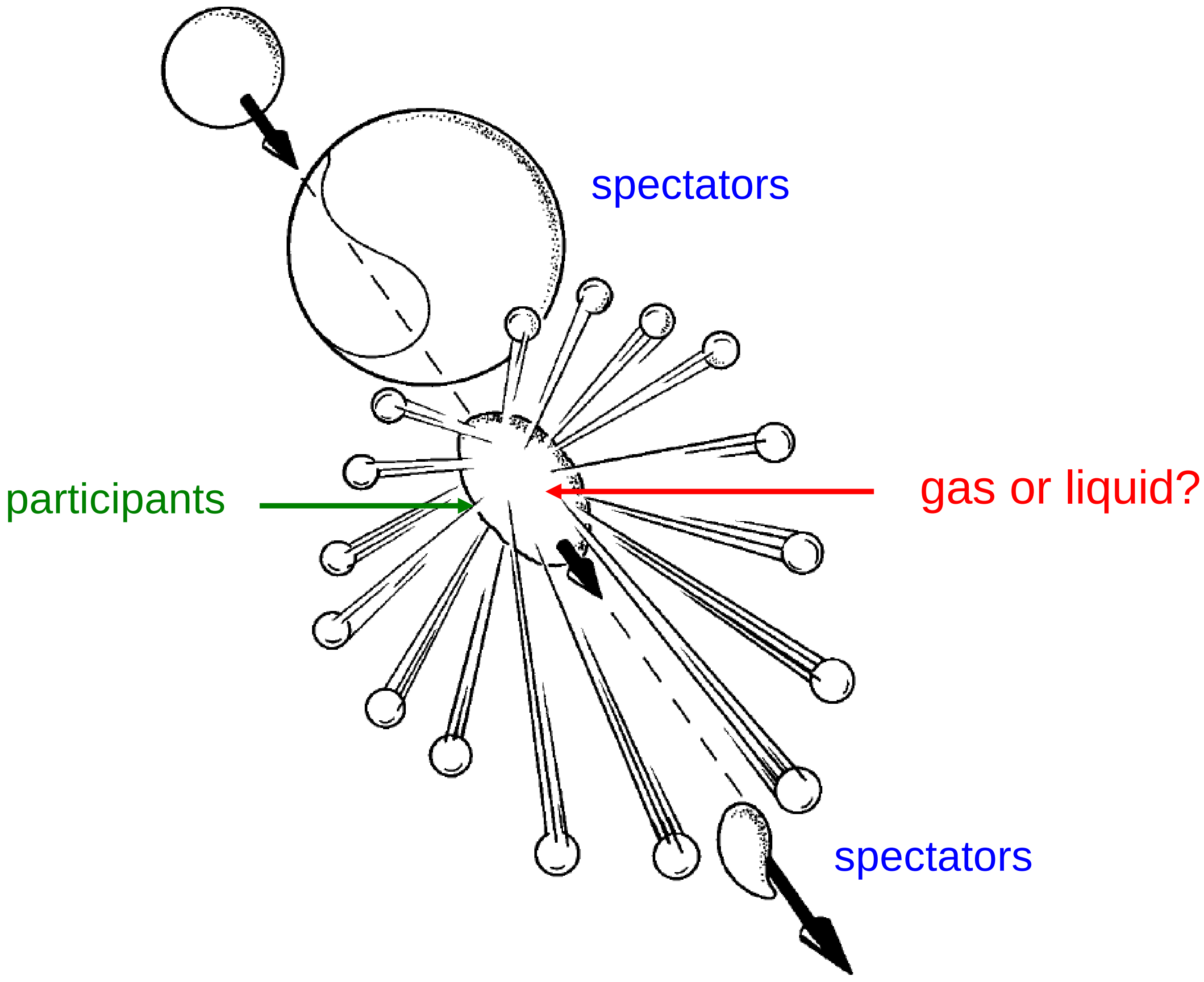
PHILIP J. SIEMENS and JAKOB P. BONDORF
The Niels Bohr Institute, Copenhagen

and

H. A. BETHE††
Nordita, Copenhagen



Collectivity



Sigma model

$\psi = \begin{pmatrix} p \\ n \end{pmatrix}$ [baryons: protons and neutrons] $\frac{1}{2}^+$

[mesons]

$\boldsymbol{\pi} = (\pi_1, \pi_2, \pi_3)$ pions 0^-

σ sigma-meson 0^+

$$\mathcal{L} = \bar{\psi}\gamma_\mu \partial^\mu \psi + \frac{1}{2}\partial_\mu \boldsymbol{\pi}\partial^\mu \boldsymbol{\pi} + \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma + \bar{\psi}\left[\gamma_5(\boldsymbol{\tau}\,\boldsymbol{\pi}) + \sigma\right]\psi + U(\boldsymbol{\pi}^{\,2} + \sigma^2)$$

massless nucleons and mesons

Invariant under two transformations

vector transform.

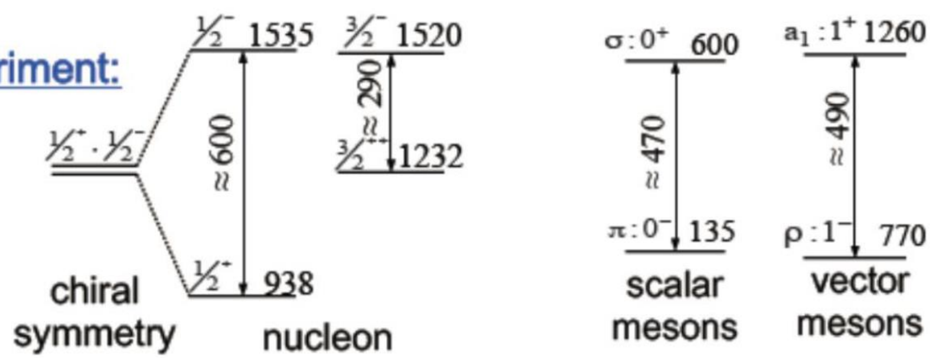
$$\psi \to (1 - i\frac{\boldsymbol{\tau}}{2}\boldsymbol{\Theta})\psi$$
$$\boldsymbol{\pi} \to \pi + \boldsymbol{\Theta} \times \boldsymbol{\pi}$$
$$\sigma \to \sigma$$

axial transform.

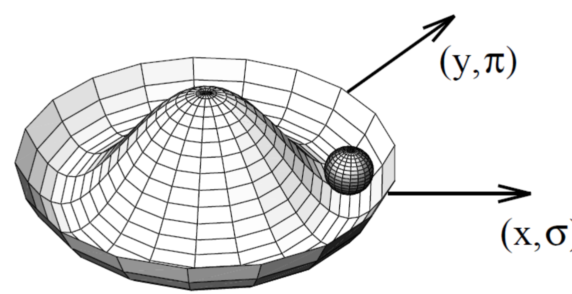
$$\psi \to (1 - i\gamma_5\frac{\boldsymbol{\tau}}{2}\boldsymbol{\Theta})\psi$$
$$\boldsymbol{\pi} \to \boldsymbol{\pi} + \boldsymbol{\Theta}\sigma$$
$$\sigma \to \sigma + \boldsymbol{\Theta}\boldsymbol{\pi}$$

mixes states with different parities

experiment:



Symmetry should be spontaneously broken



massive nucleons, σ mesons, almost **massless** pions

+small explicit symmetry breaking

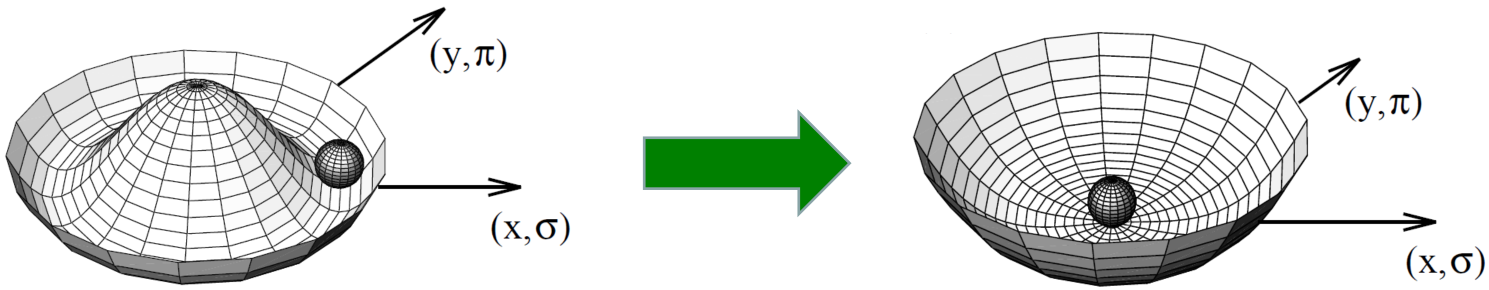
Goldstone modes

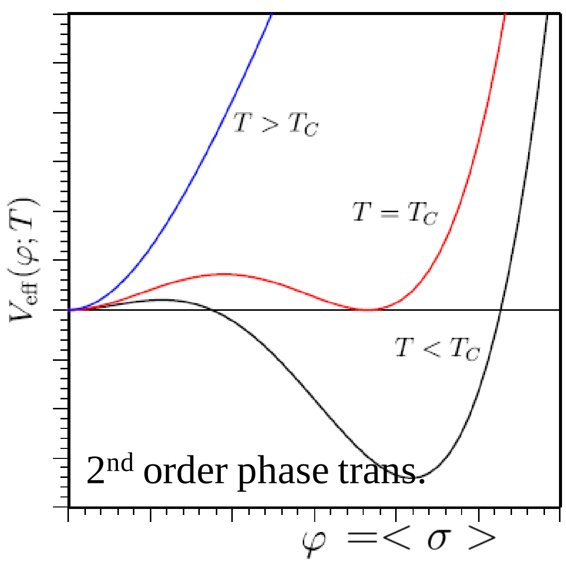
Medium = hot and/or dense hadron matter

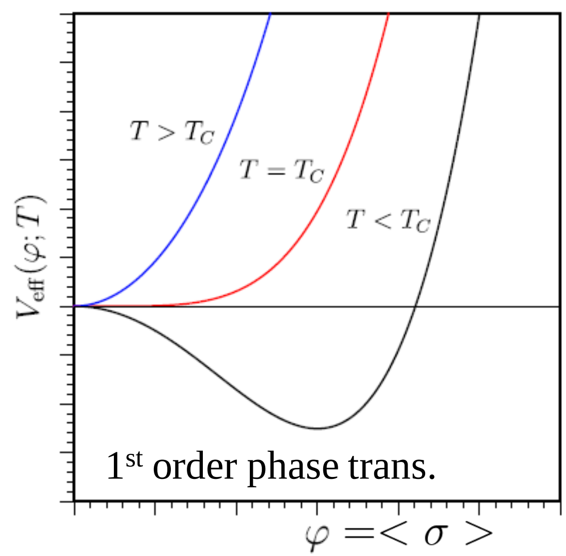
$$U(\boldsymbol{\pi}^2+\sigma^2) \to U_{\text{eff}}(\boldsymbol{\pi},\sigma;T,n_{\text{B}}) = U(\boldsymbol{\pi}^2+\sigma^2) + Loops(\text{medium})$$

1971 Migdal
1972 Kirzhnits, A. Linde
1974 Weinberg, Dolan, Jackiw,
....

Chiral symmetry restoration





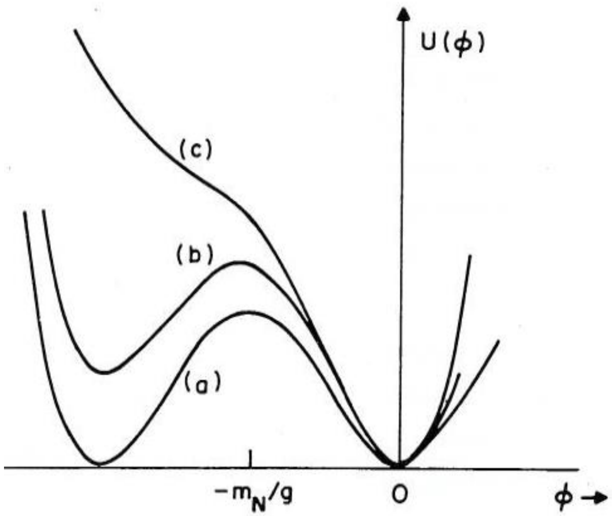


[Senaha, Symmetry **2020**, *12*(5), 733]

"Abnormal Nuclear States"

T.D. Lee, G.C Wick

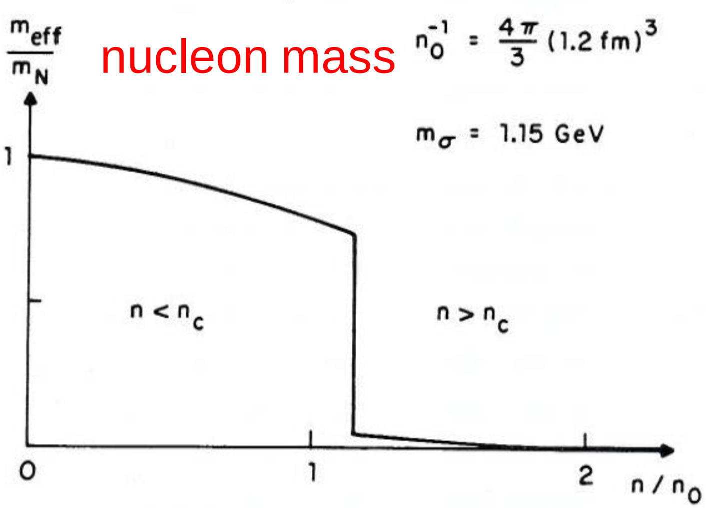
scalar field rearrangement

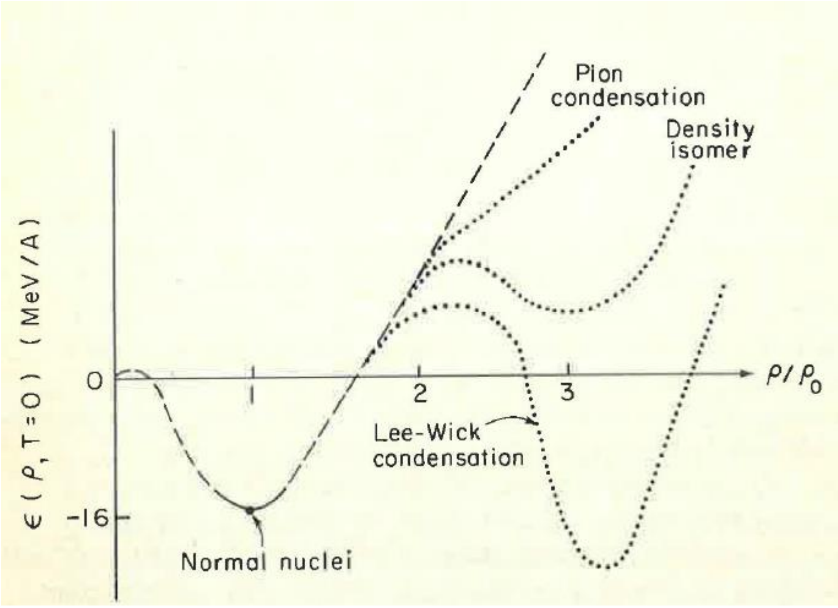


Tsung-Dao Lee

Gian Carlo Wick

nucleon mass





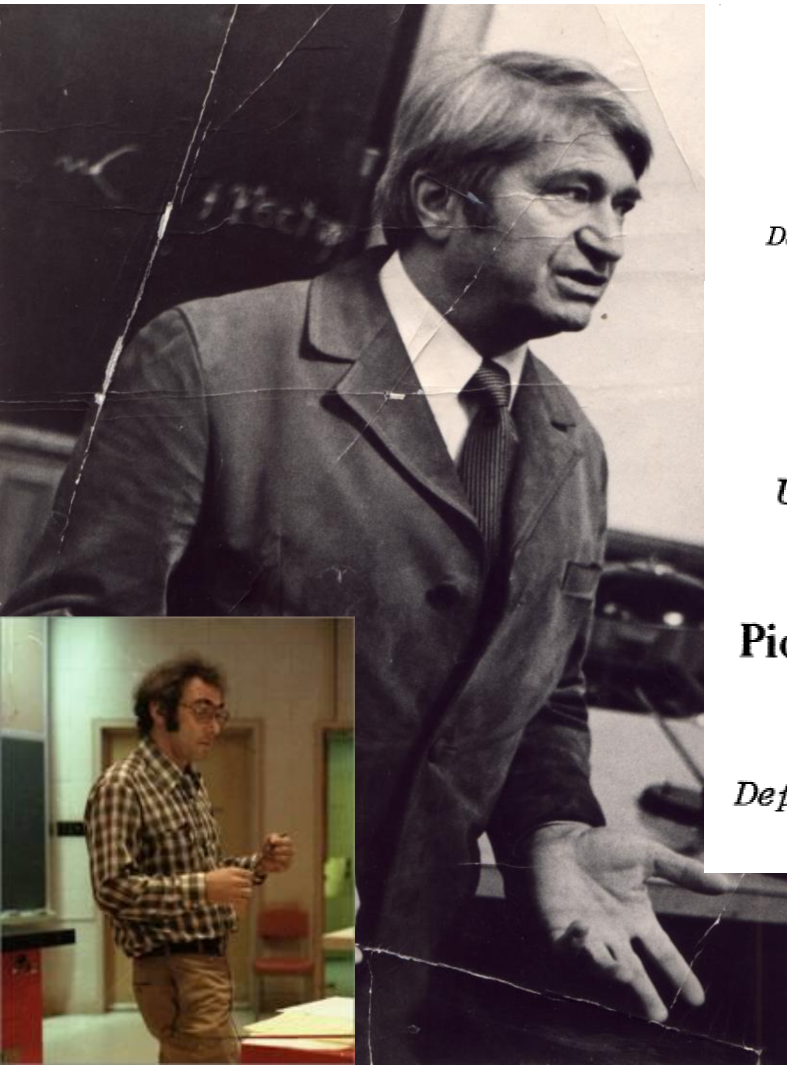
Stability of Vacuum and Limiting Fields

A. B. Migdal

L. D. Landau Institute of Theoretical Physics, USSR Academy of Sciences

Submitted June 21, 1971

Zh. Eksp. Teor. Fiz. **61**, 2209–2224 (December, 1972)



Condensed π^- Phase in Neutron-Star Matter*

R. F. Sawyer

Department of Physics, University of California, Santa Barbara, California 93106

(Received 29 March 1972)

π^- Condensate in Dense Nuclear Matter*

D. J. Scalapino

University of California, Santa Barbara, California 93106

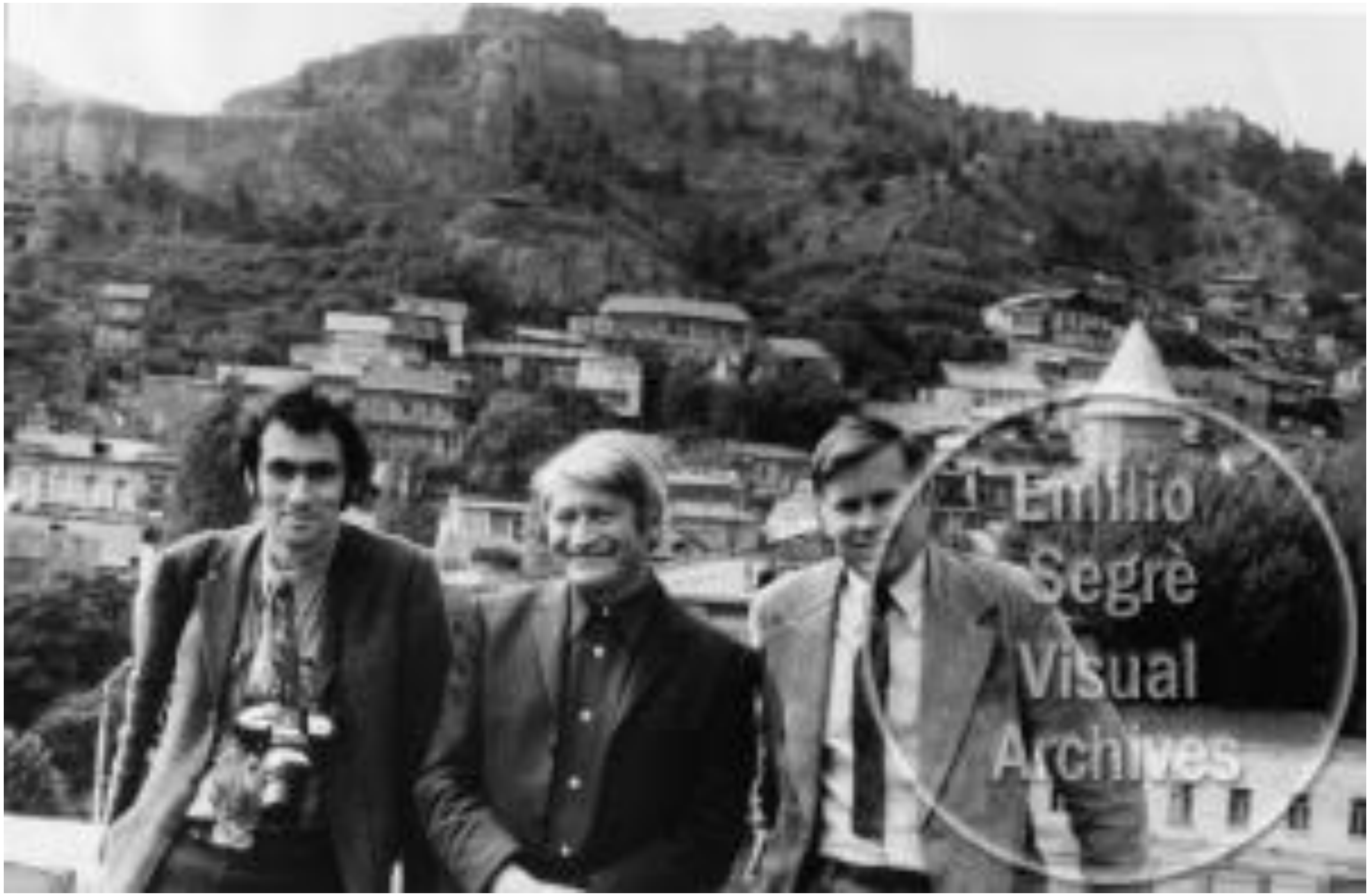
(Received 17 April 1972)

Pion Condensation in Nuclear and Neutron Star Matter*

Gordon Baym

Department of Physics, University of Illinois, Urbana, Illinois 61801

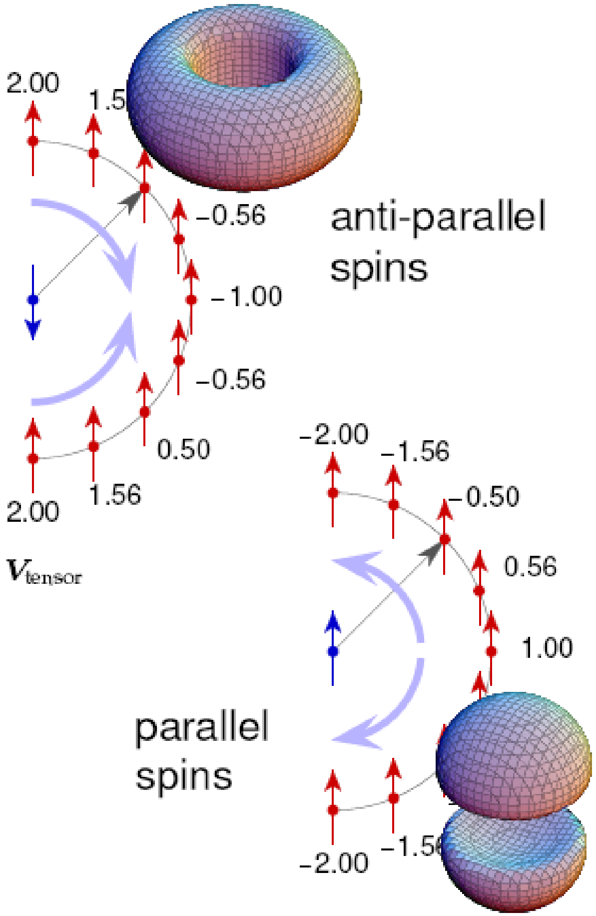
(Received 13 April 1973)

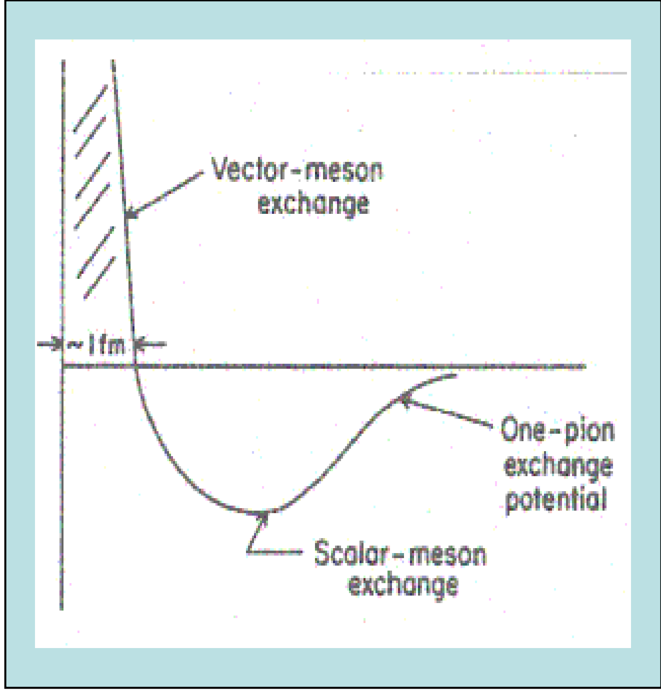


Baym Migdal Scalapino

1974 Tbilisi

Tensor forces in NN interaction





$$V_{\text{tensor}} = V_t(r) \left(3 \frac{(\boldsymbol{\sigma}_1 \boldsymbol{r})(\boldsymbol{\sigma}_2 \boldsymbol{r})}{r^2} - \boldsymbol{\sigma}_1 \boldsymbol{\sigma}_2 \right)$$

Resummed, enhanced pion exchange

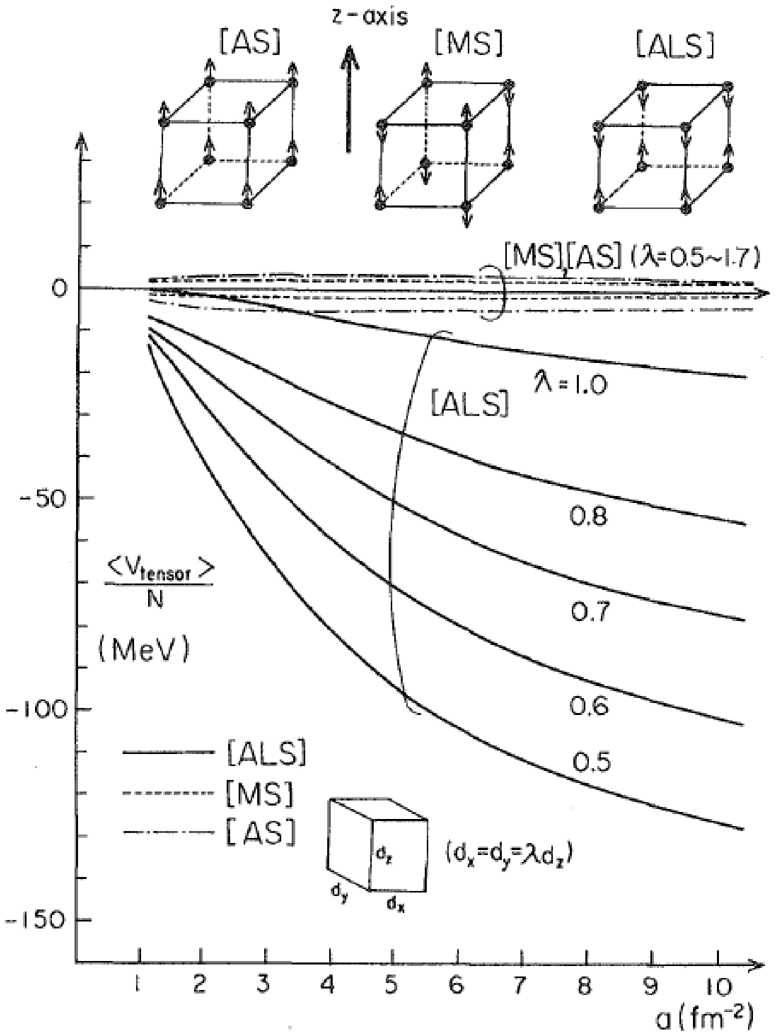
nucleon arrangement

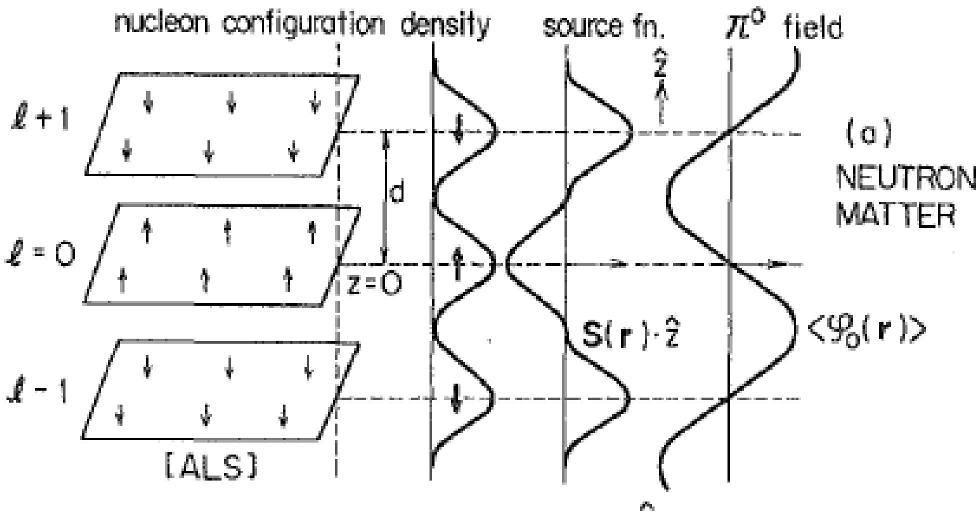
Alternating-layer-spin configurations

Ryozo Tamagaki

Tatsuyuki Takatsuka

1972'-73'

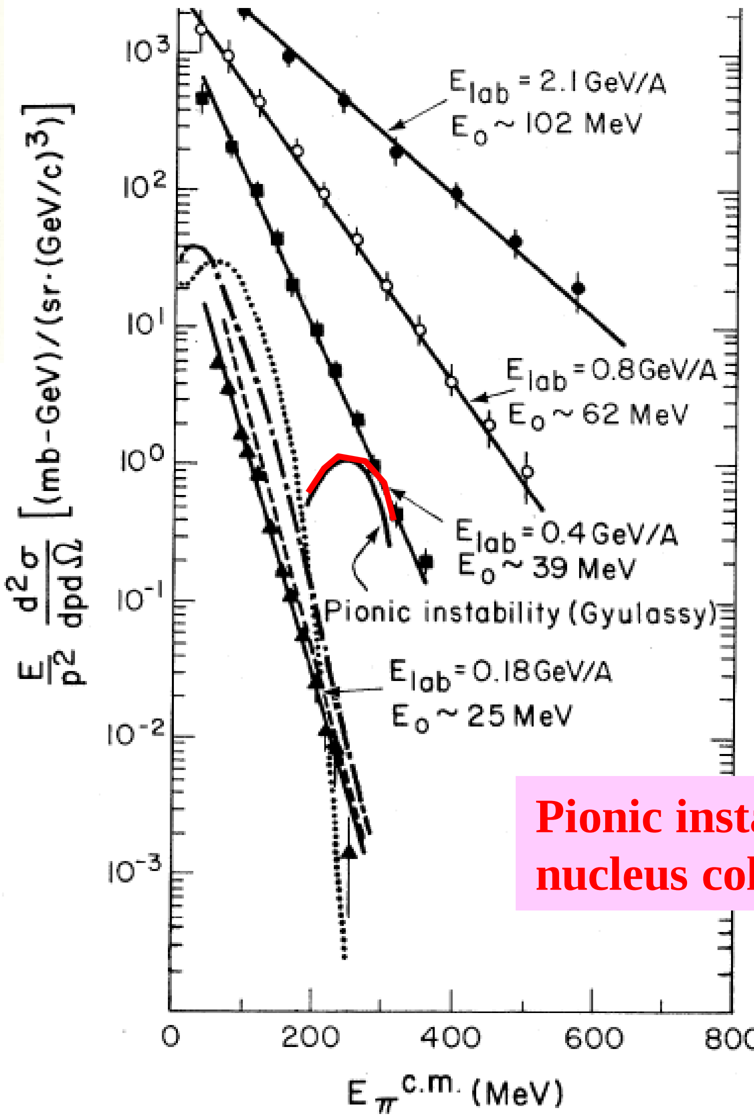




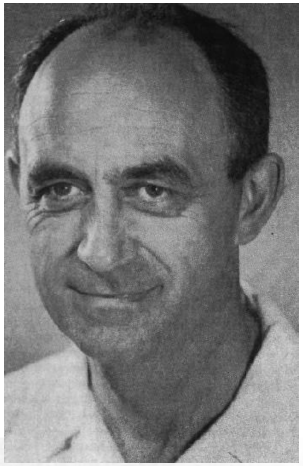
π^0 condensate

Pion condensation

A.B. Migdal, and D. Scalapino, R. Sawyer



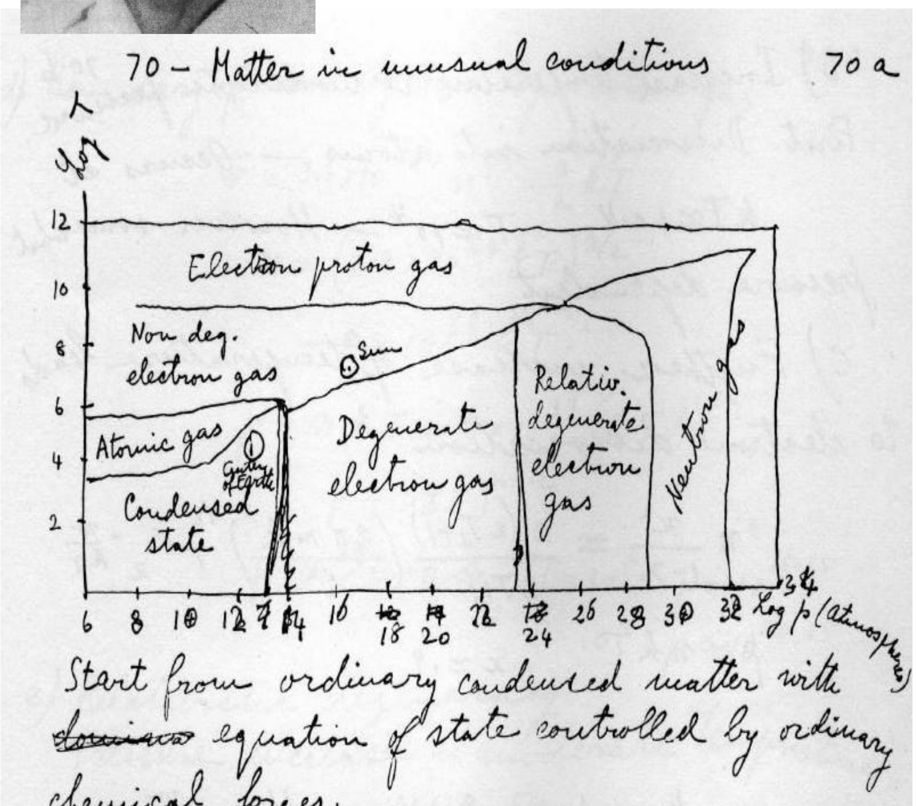
Pionic instability in nucleus collisions

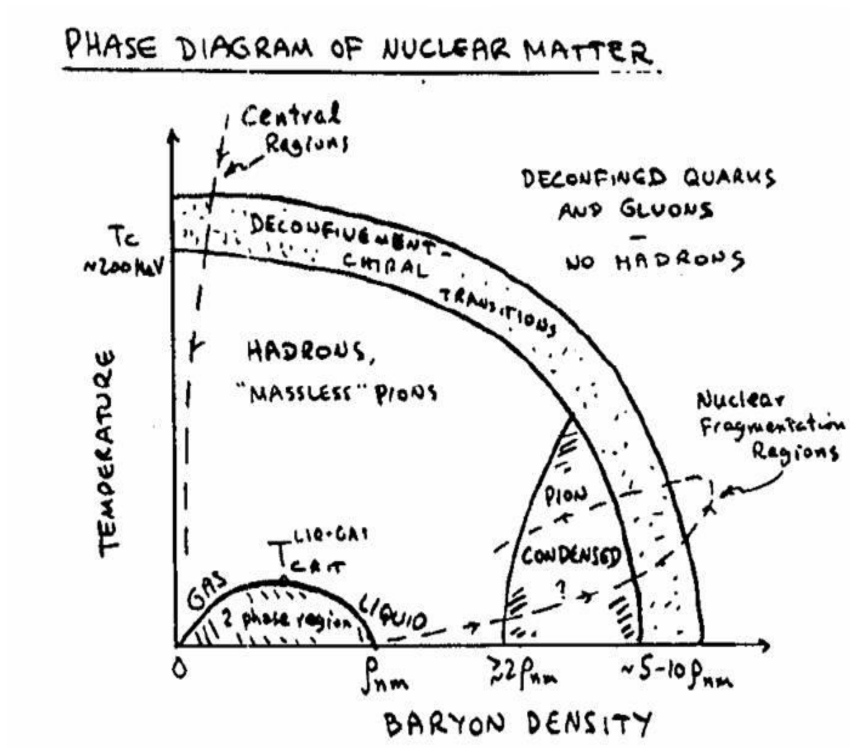


Phase diagrams

E.Fermi: Notes on themodymamics and statistics, 1953

G.Baym: Nucl. Phys. A**418** (1984) 433c





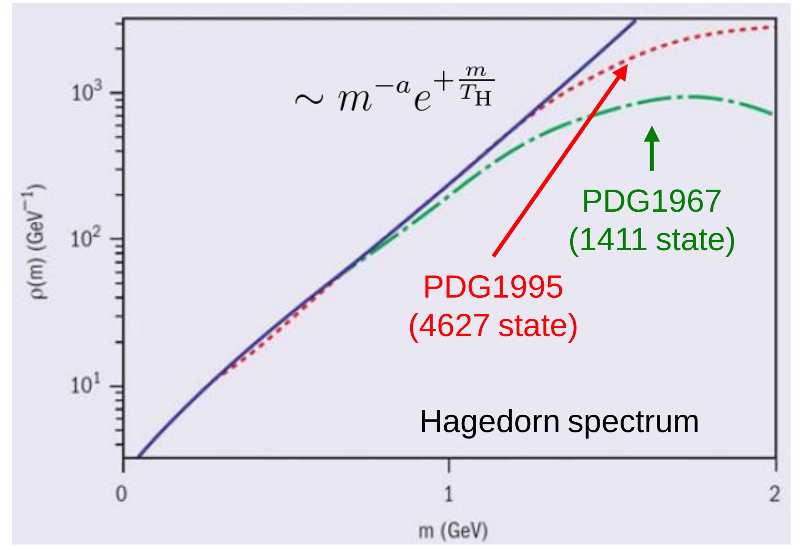
Condensed matter

Nuclear matter

Limiting hadronic temperature

PDG book → mass spectrum of hadronic states

$$\rho(m) \sim m^{-a} e^{+\frac{m}{T_\mathrm{H}}} \qquad a \simeq 3$$



<u>Partition function of a hadron-resonance gas</u>

$$\log Z = \sum_i \frac{VTm_i^2}{2\pi^2} \rho(m_i) K_2(m_i/T) \simeq \frac{VT}{2\pi^2} \int^{\infty} \mathrm{d}m\, m^2 \rho(m) K_2(m/T) \sim V \left[\frac{T}{2\pi}\right]^{3/2} \int^{\infty} \frac{\mathrm{d}m}{m^{3/2}} e^{-\left(\frac{m}{T} - \frac{m}{T_\mathrm{H}}\right)}$$

changes sign if $T > T_\mathrm{H}$

energy density $\quad \epsilon(T) = -\frac{1}{V} \frac{\partial \log Z}{\partial (1/T)}$ diverges if $T \to T_\mathrm{H}$ ← Hagedorn temperature

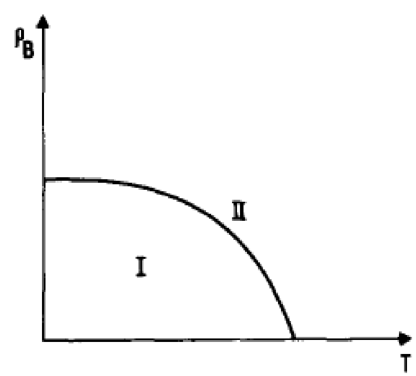
T_H is the highest possible temperature of matter: it would require an infinite energy to reach it.

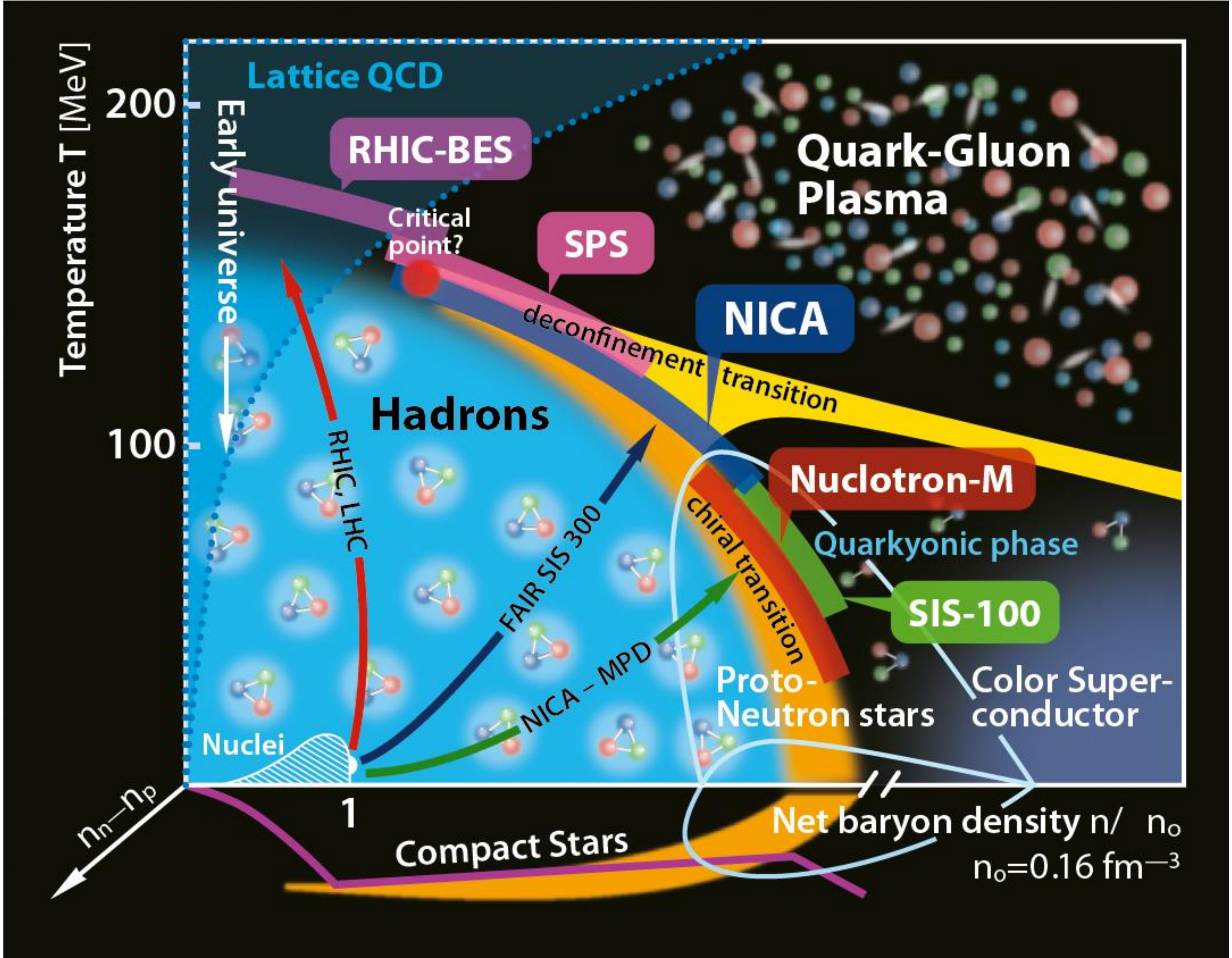
EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO
Istituto di Fisica, Università di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

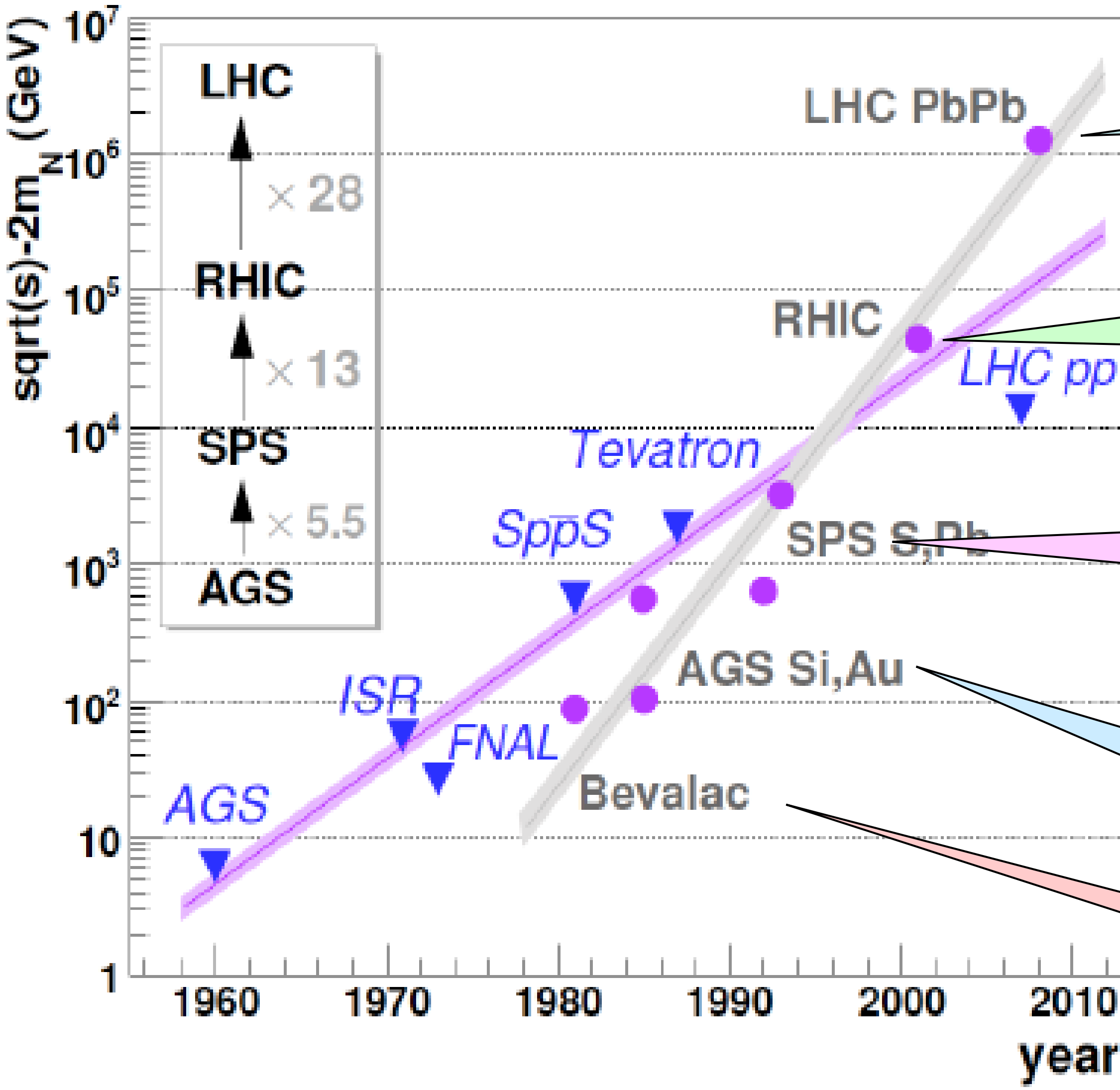
Received 9 June 1975





Temperature T [MeV]
200
100
Lattice QCD
Early universe
RHIC-BES
Critical point?
SPS
Quark-Gluon Plasma
NICA
deconfinement transition
Hadrons
Nuclotron-M
chiral transition
Quarkyonic phase
SIS-100
RHIC, LHC
FAIR SIS 300
NICA – MPD
Proto-Neutron stars
Color Super-conductor
Nuclei
1
Compact Stars
Net baryon density n/ n₀
n₀=0.16 fm⁻³
nₙ–nₚ

Citius, Altius, Fortius!



Big QGP

Perfect liquid!
Jet suppression..

Quark liberation!
J/Ψ suppression

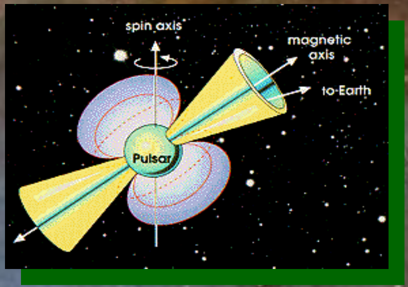
soft point, flow
soft kaons (low pT)

pion condensate
abnormal state

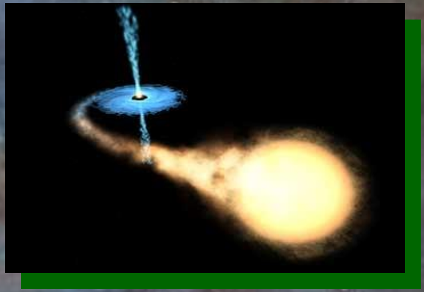
[Pasechnik, Šumbera Universe 2017,3,7]

Neutron Star Zoo

>2000 neutron stars in isolated rotation-powered pulsars
~ 30 millisecond pulsars



>100 neutron stars in accretion-powered X-ray binaries
~ 50 x-ray pulsar
intense X-ray bursters (thermonuclear flashes)



short gamma-ray bursts
neutron star -- neutron star,
neutron star -- black-hole mergers

soft gamma-ray repeaters – magnetars
(super-strong magnetic fields)

Measuring pulsar mass

Pulsar mass can be measured only in binary systems

$$\frac{(M_1 \sin i)^3}{(M_1 + M_2)^2} = \left(\frac{2\pi}{P_b}\right)^2 \frac{(a_1 \sin i)^3}{G}$$

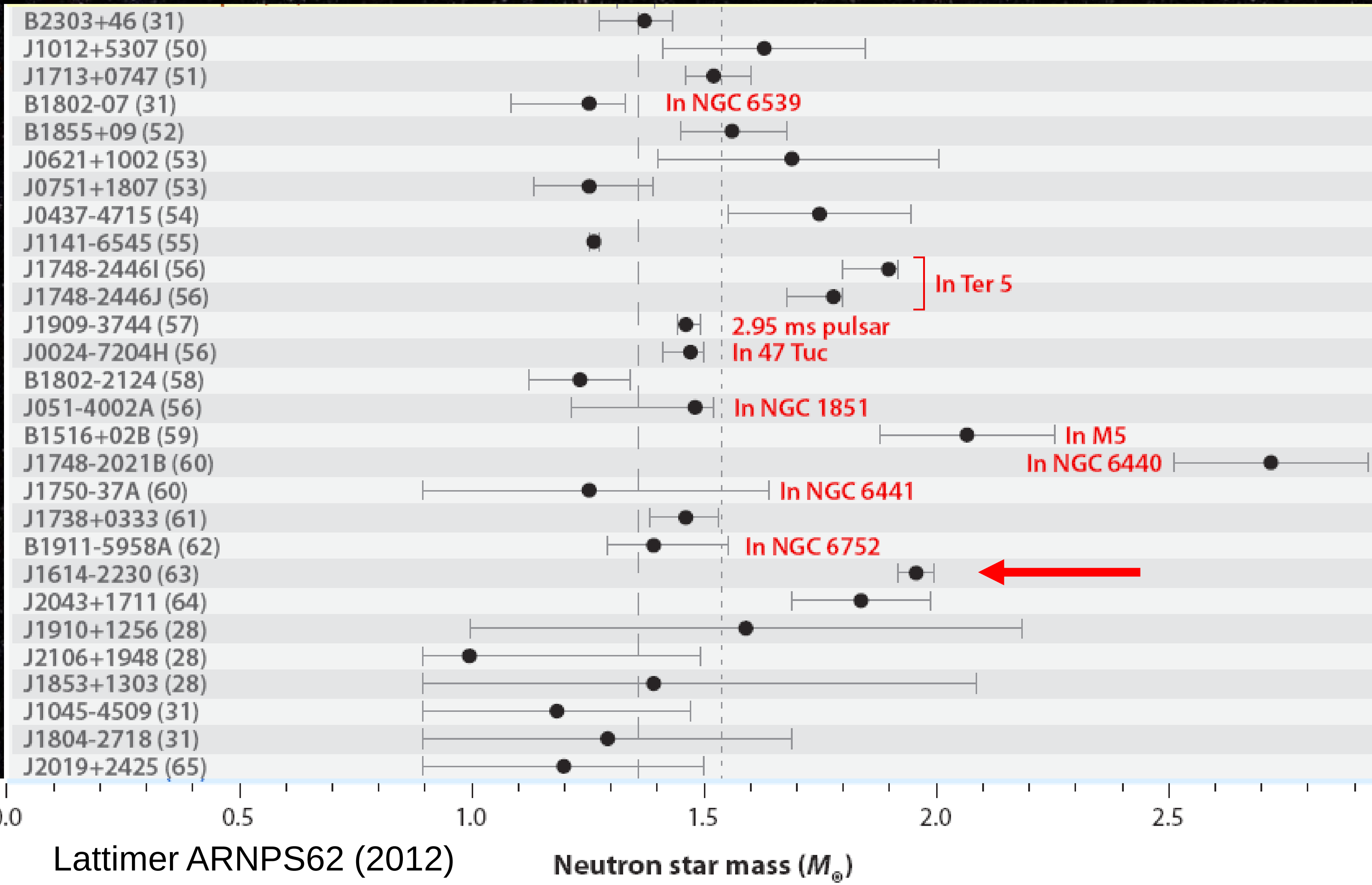
Newton gravity ⟶ 5 Keplerian orbital parameters:
orbital period, semi-major axis length,excentricity, …

Do not determine individual masses of stars and the orbital inclination.

Einstein gravity ⟶ 5 potentially measurable post-Keplerian parameters:
orbit precession, Shapiro delay, gravitational redshift, ….

Measurement of any 2 post-Keplerian parameters allows to determine the mass of each star.

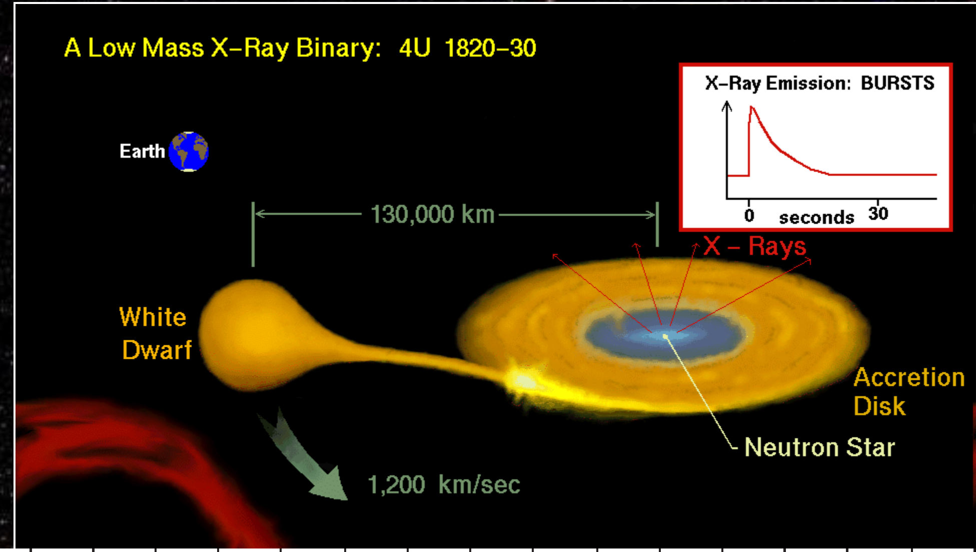
White dwarf -- neutron star binaries



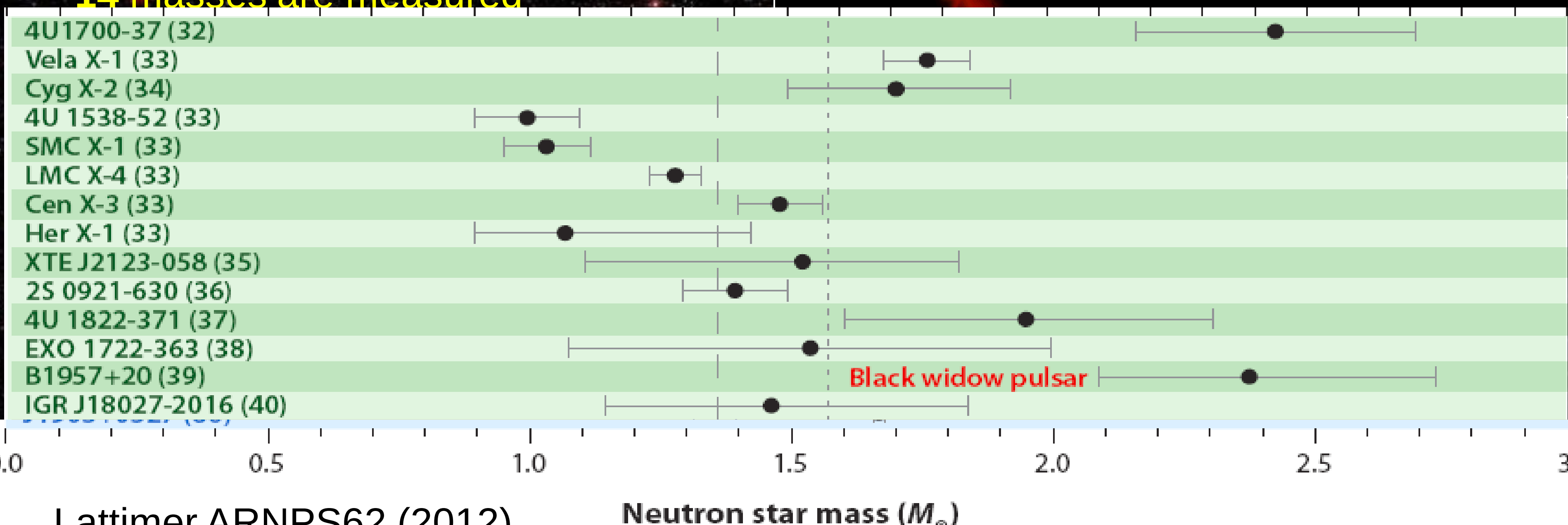
Lattimer ARNPS62 (2012)

Measuring pulsar mass

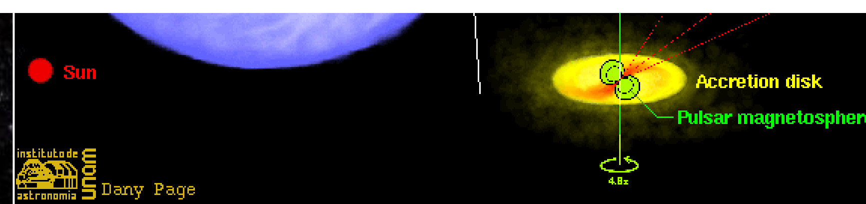
X-ray binaries



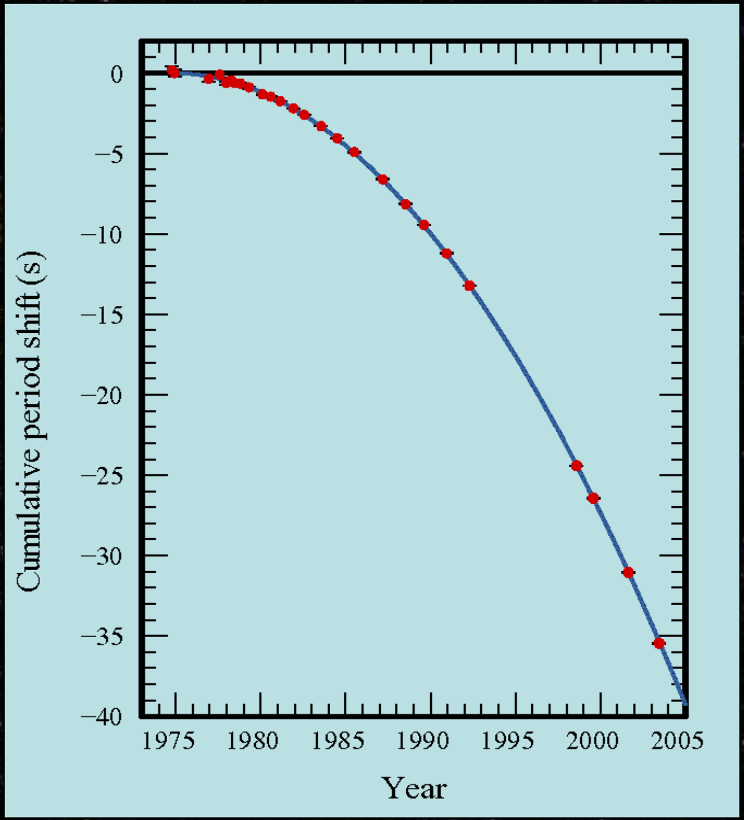
14 masses are measured



Lattimer ARNPS62 (2012)



Measuring pulsar mass

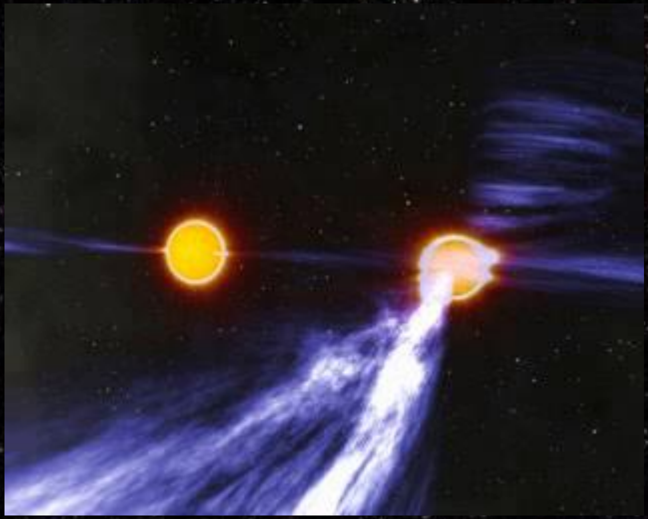


Double neutron star binaries

1974 PSR B1913+16 Hulse-Taylor pulsar

First precise test of Einstein gravitation theory

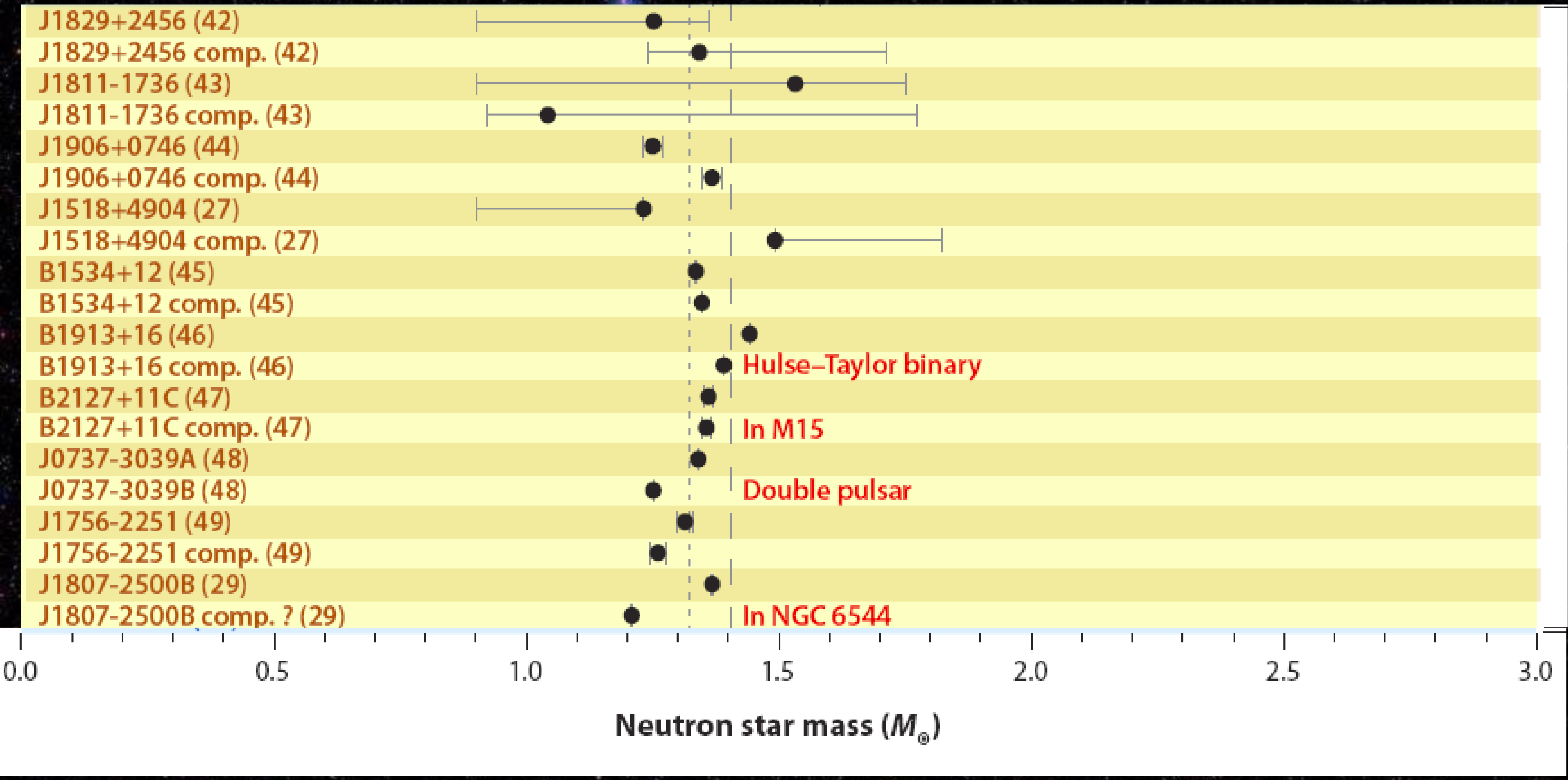
2003 J0737-3039 first double pulsar



Pulsar A: $P^{(A)}$=22.7 ms, $M^{(A)}$=1.338 M_{sol}
Pulsar B: $P^{(B)}$=2.77 ms, $M^{(A)}$=1.249±0.001 M_{sol}
Orbiting period 2.5 hours

[Nature 426, 531 (2003), Science 303, 1153 (2004)]

Double neutron star binaries



Pulsar J1614-2230

$$M = (1.97 \pm 0.04)\ M_{sol}$$

Highest well-known mass of NS

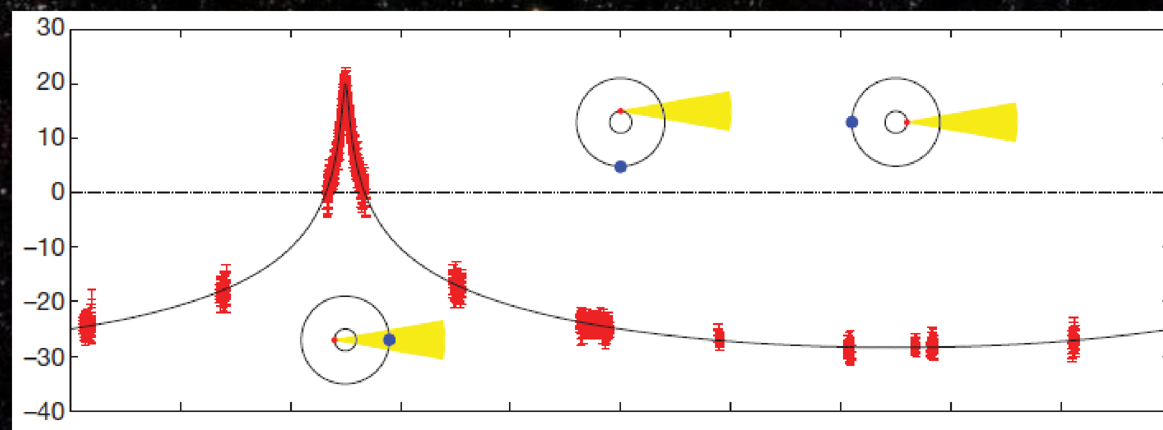
P.Demorest et al., Nature 467, 1081 (2010)

$$M = 2.14^{+0.20}_{-0.18}\ M_{sol} \quad (95\%)$$

H.T. Cromartie et al., Nat. Astr. (2019)

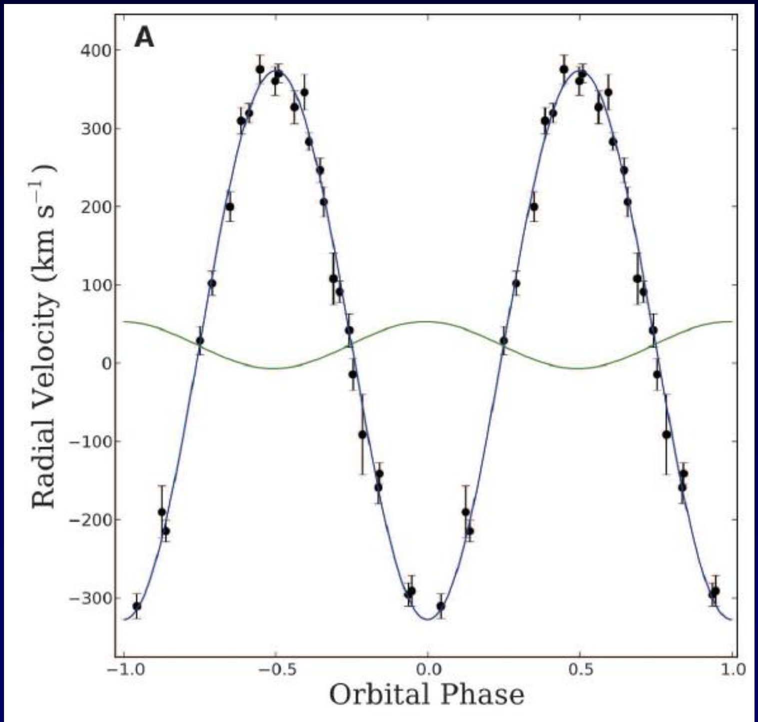
there are heavier, but far less precisely measured candidates)

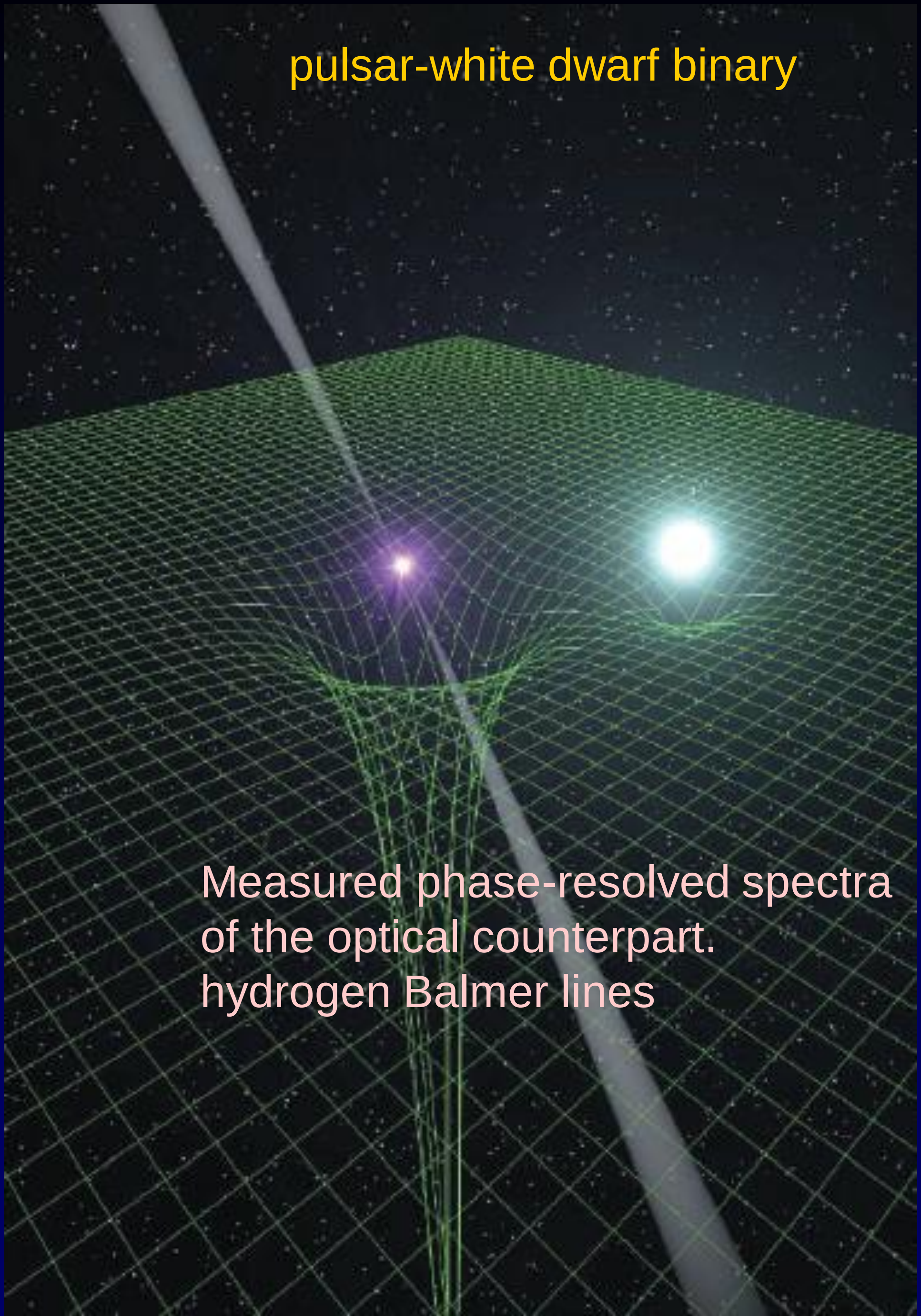
Measured Shapiro delay with high precision



Pulsar J1614-2230

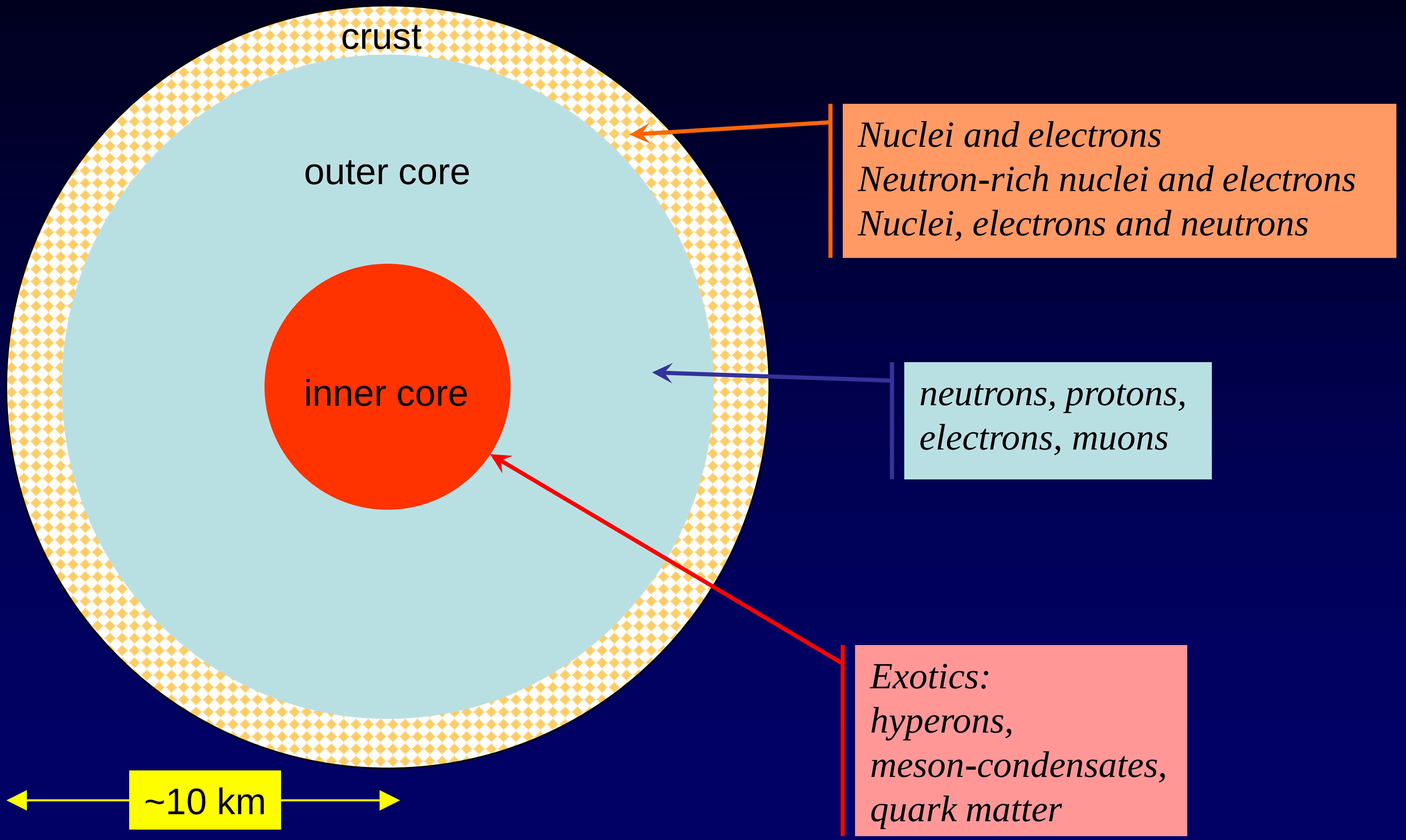
$$M = (2.01 \pm 0.04)\ M_{sol}$$





Antonadis et al, Science 340, 1233232

Cross section of a neutron star

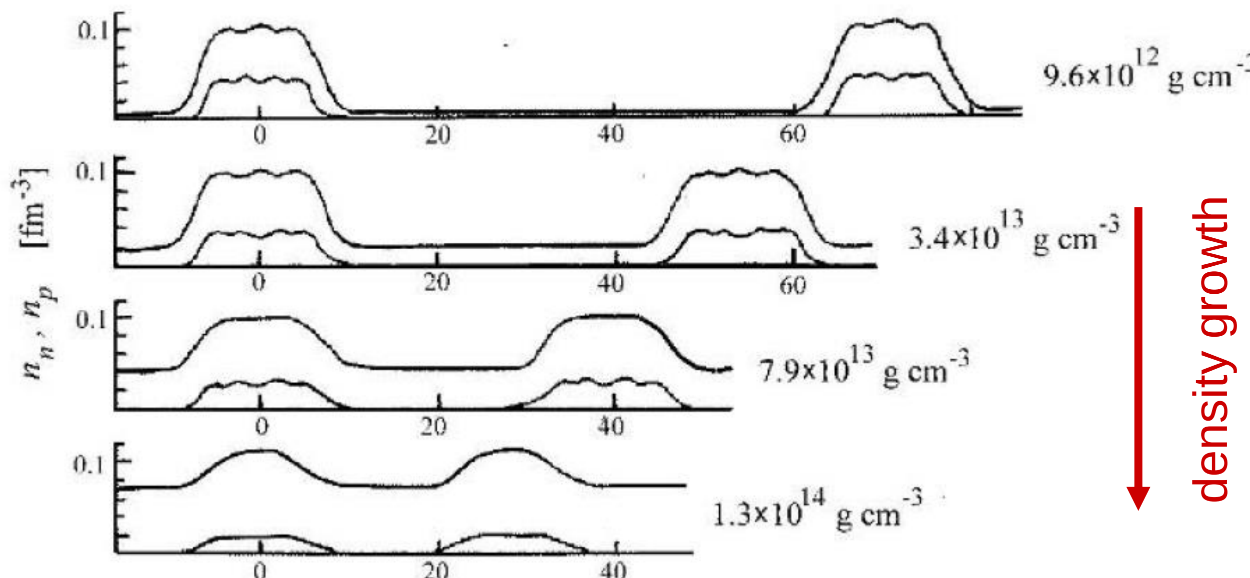


Crust

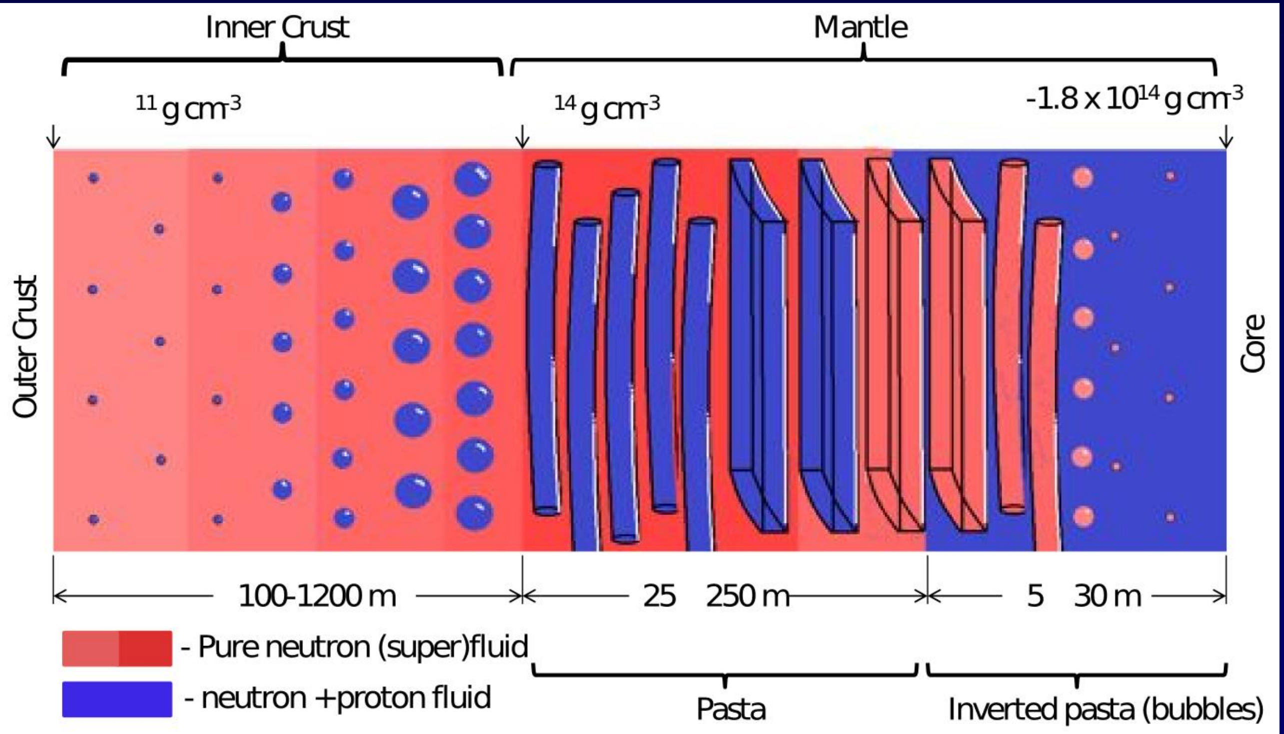
Nucleus melting

Pasta structure

interplay of Coulomb energy and surface tension



Negele & Vautherin (1973)



saturation density

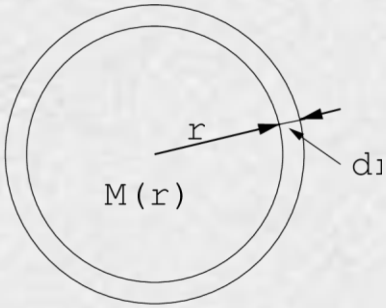
$$\rho_0 = 2.8 \times 10^{14} \frac{\mathrm{g}}{\mathrm{cm}^3}$$

M_{crust} ~$0.1 M_{sol}$

R_{crust}~10^2—10^3 m

Tolman-Oppenheimer-Volkov equation

Equilibrium condition for a shell in a non-rotating neutron star



$$S_\Omega(r)\, dp = dF_G$$ Newton's Law

$$4\,\pi\, r^2\, dp = G\,\frac{M(r)\, dM}{r^2} \qquad dM = 4\,\pi\, r^2\, \varepsilon(p)\, dr$$

INPUT: equation of state (EoS)

$$\varepsilon = \varepsilon(p) \quad \text{or} \quad \begin{cases} p = p(n) \\ \varepsilon = \varepsilon(n) \end{cases}$$

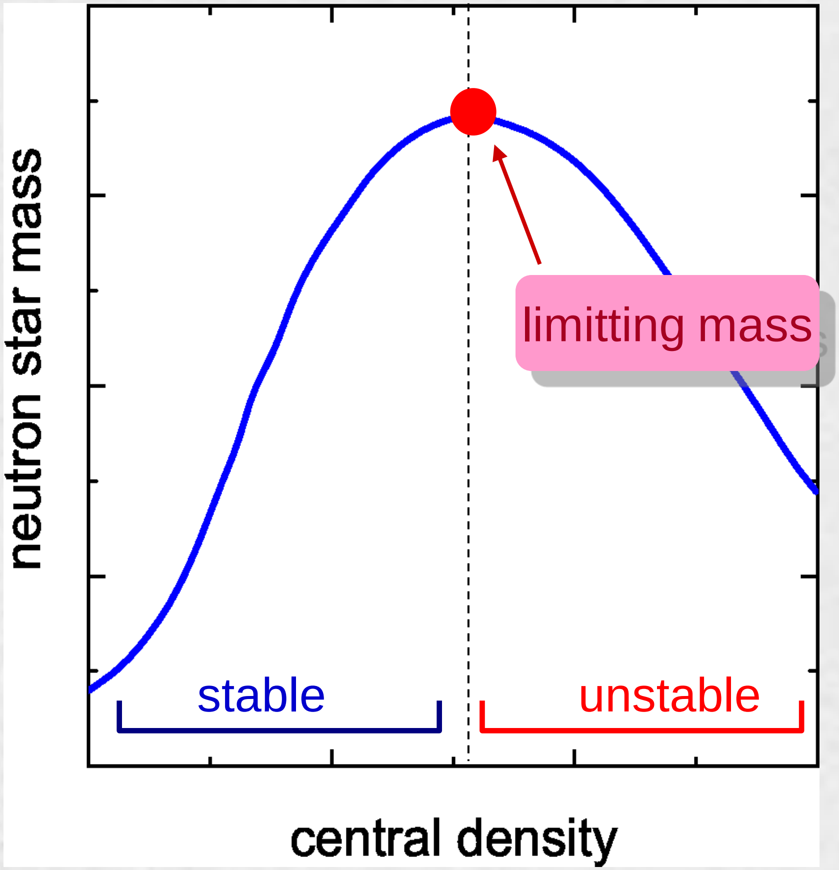
boundary conditions: $\varepsilon(r=0) = \varepsilon_c\,, \quad M(r=0) = 0\,, P(r=R) = 0$

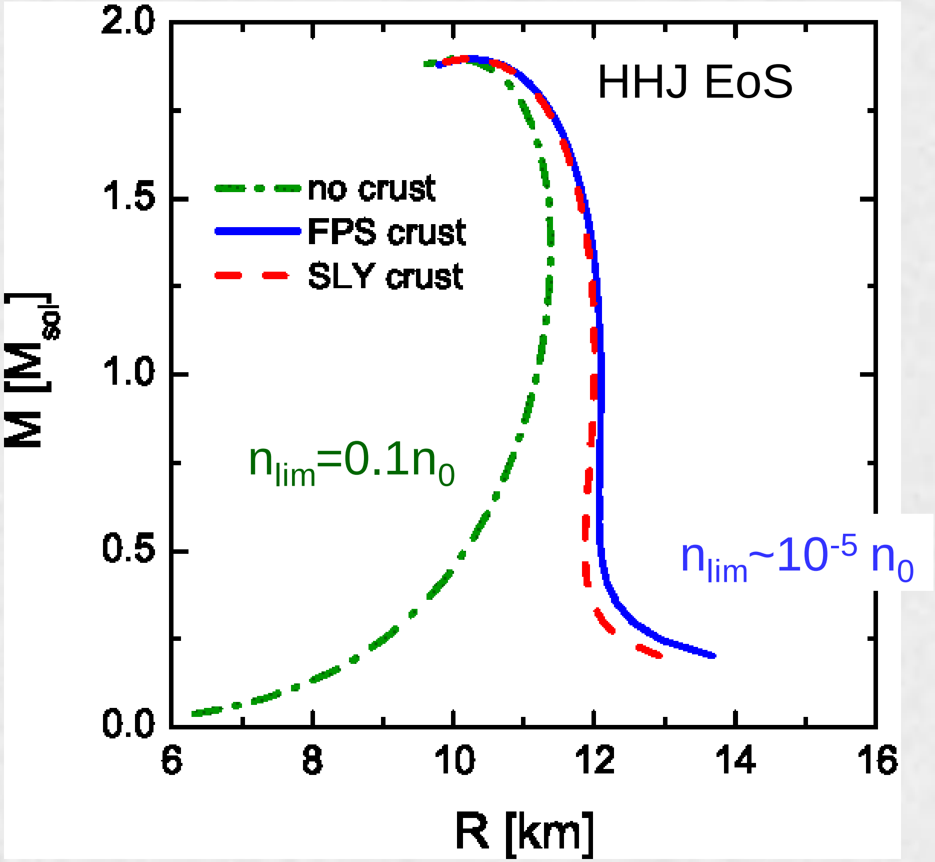
OUTPUT: neutron star density profile, radius R and mass M

relativistic corrections

$$\frac{dp}{dr} = -\frac{G\,\rho\, M}{r^2}\left(1+\frac{p}{\rho\, c^2}\right)\left(1+\frac{4\pi P r^3}{M c^2}\right)\left(1-\frac{2GM}{c^2 r}\right)^{-1}$$

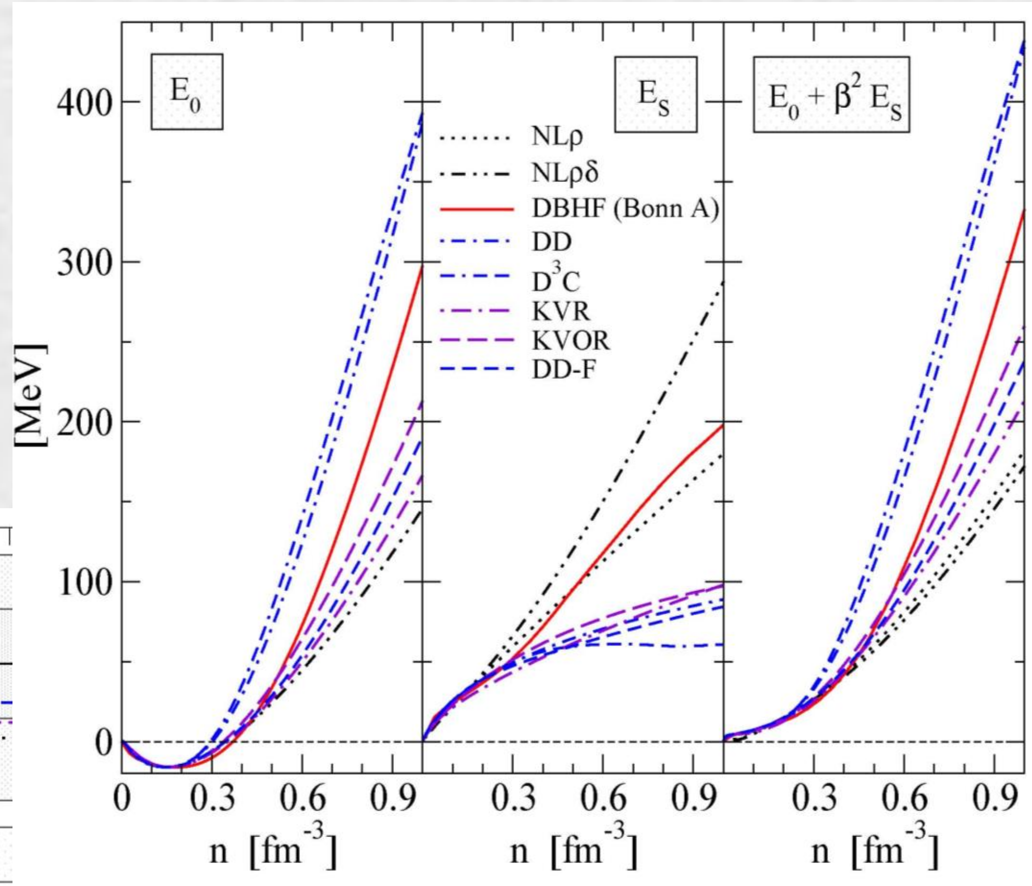
Neutron star configuration

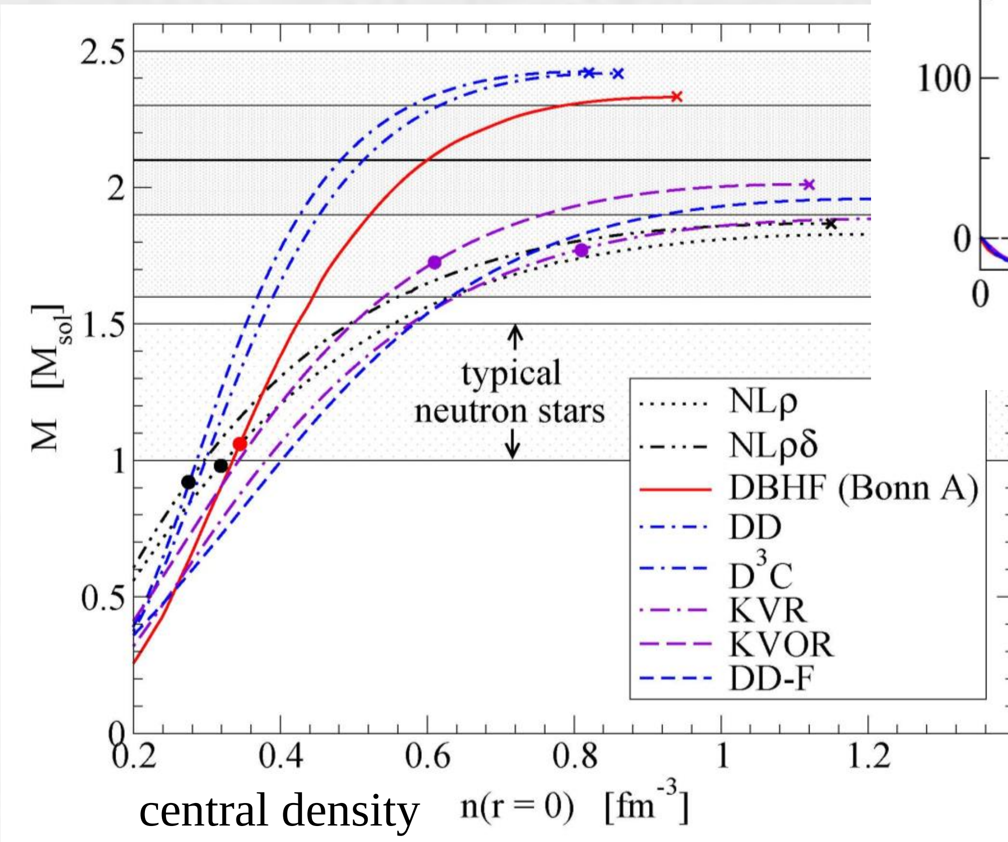




uncertainty in R~10^3 m

Selection of Nuclear Equations of State





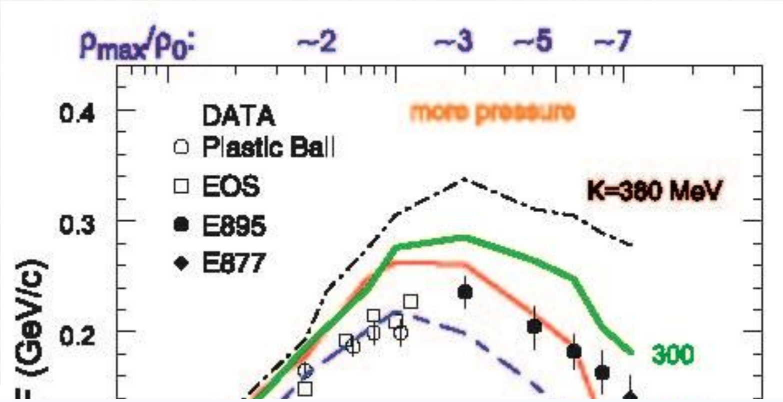
Nucleon part of EoS should be sufficiently stiff

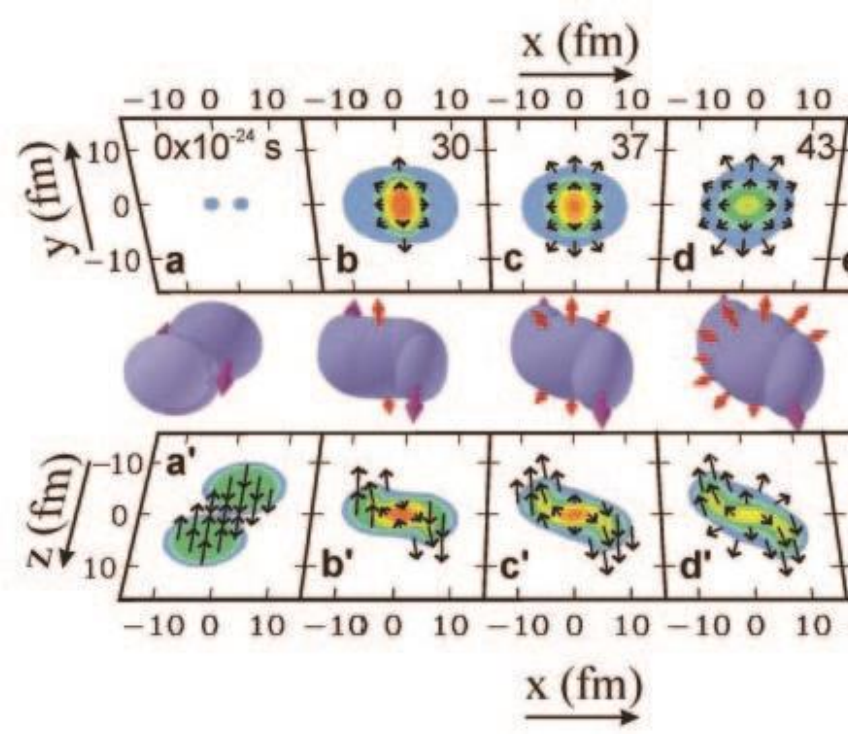
Constraints from heavy-ion collisions

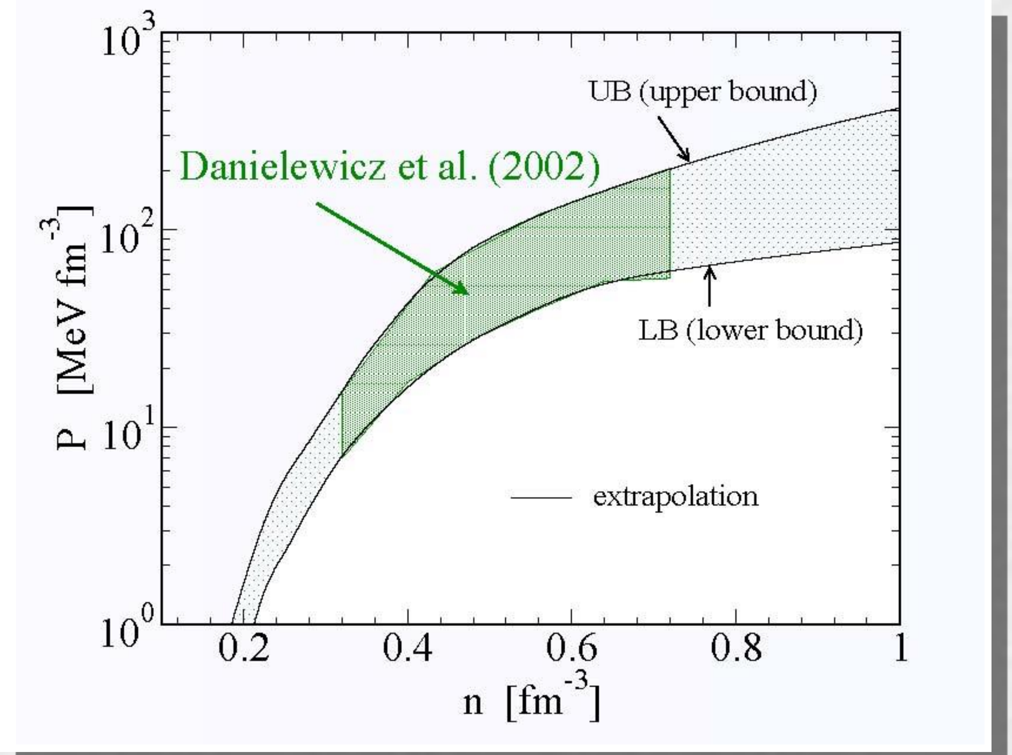
- Boltzmann kinetic equation
- Mean-field potential

$$U = (a\rho + b\rho^{\nu})/[1+(0.4\rho/\rho_0)^{\nu-1}] + \delta U_p$$

fitted to directed & elliptic flow

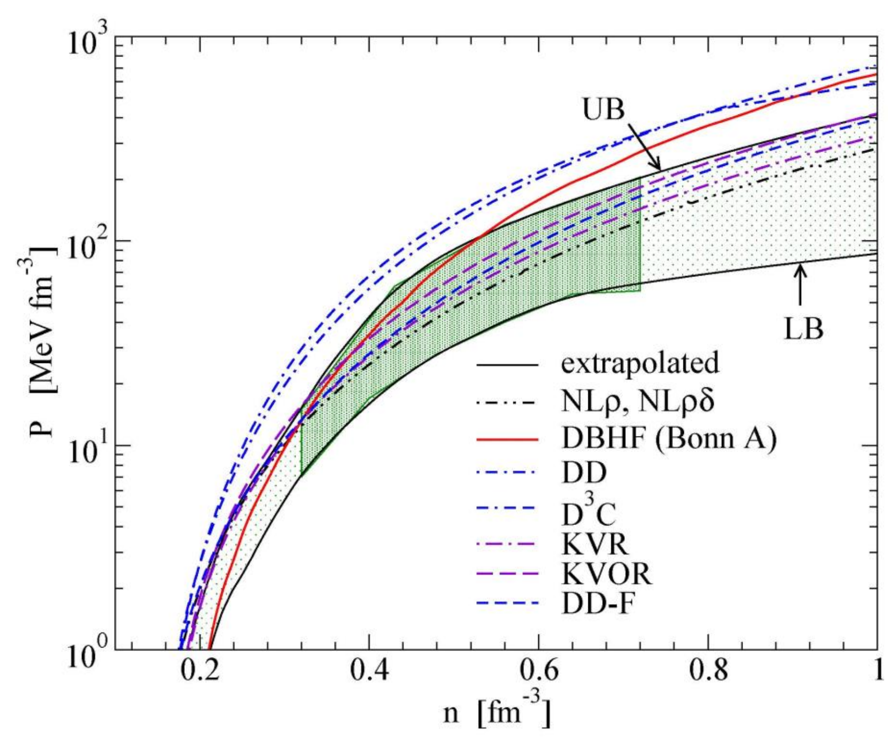


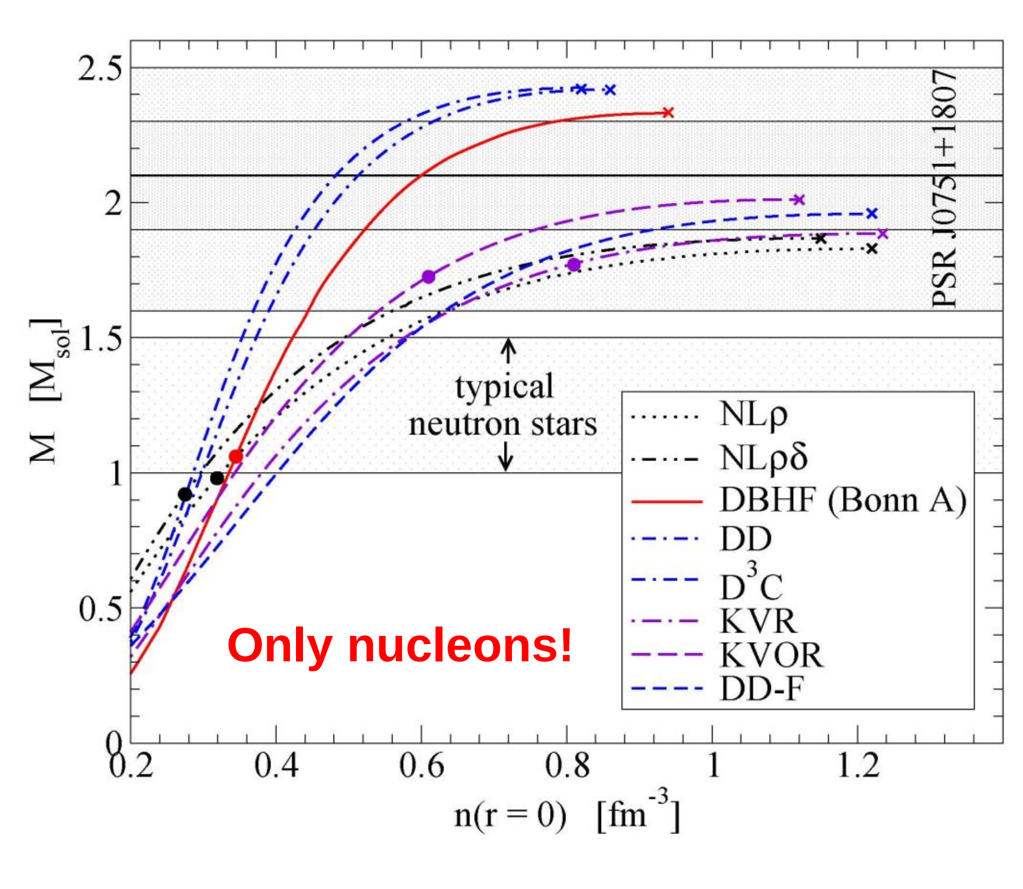




[Danielewicz, Lacey, Lynch, Science 298, 1592 (2002)]

✔ constraints from heavy-ion collisions ✔ maximum mass constraints



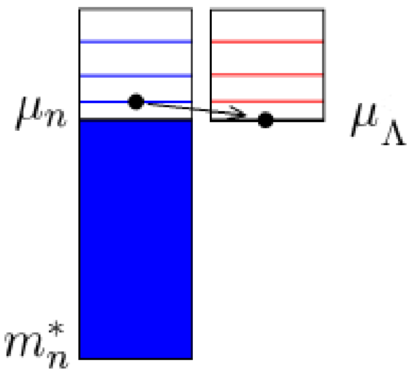


Puzzle

Nucleon part of EoS should be sufficiently stiff.
Pressure in isospin symmetric matter should be no to high. (particle flow in HIC)

[Klaehn et al., PRC 74 (2006) 035802.]

New degrees of freedom



Puzzles

strangeness

Hyperon puzzle. H-N interaction is attractive in nuclei.
Within RMF framework hyperons appear in neutron stars and reduce $M_{max}<2M_{sol}$

Delta puzzle. New fermions appear, maximum NS mass drops further [Drago et al.]
Light di-baryons, light nucleon resonances?

Mesonic condensates

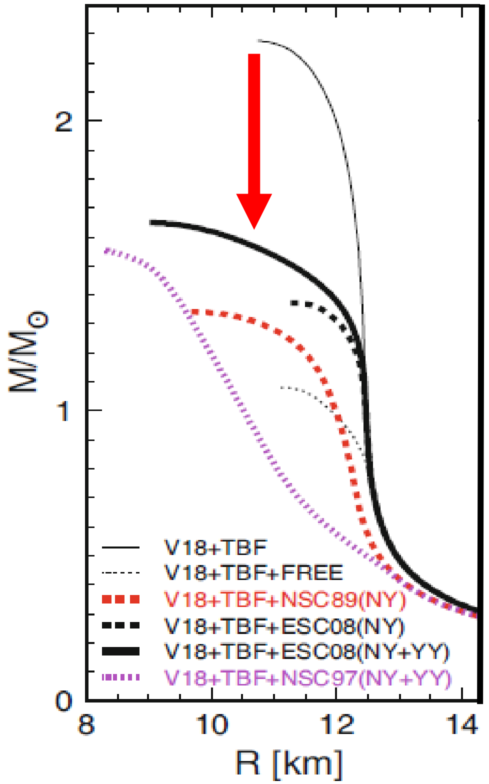
$$e^- \longrightarrow \pi_c^- + \nu_e$$
$$e^- \longrightarrow K_c^- + \nu_e$$

weak reactions start if

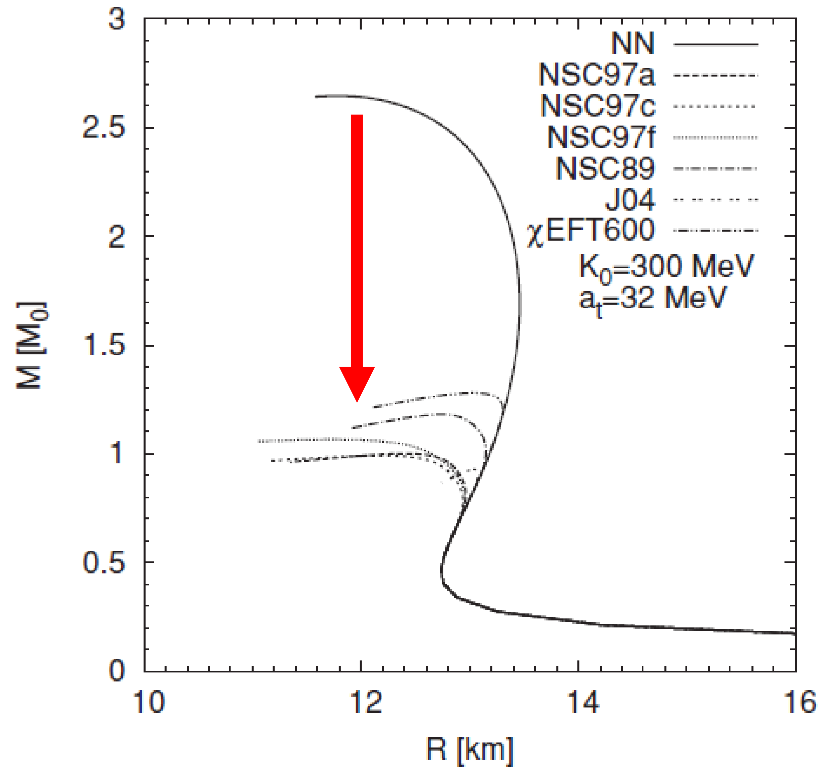
$$\mu_e \geq \min_p \omega_{\pi,K}(p)$$

“Hyperon puzzle”

If we allow for a population of new Fermi seas (hyperon, Δ baryons, …)
EoS will be softer and the NS will be smaller



[Rijken, Schulze, EPJA52 (2016) 21]



[Dapo, Schaefer, Wambach PRC 81 (2010) 035803]

Simple solutions: **-- make nuclear EoS as stiff as possible** [flow constraint]
-- suppress hyperon population (increase repulsion/reduce attraction)

against phenomenology of YN,NN,YY interaction in vacuum
+hypernuclear physics

Strangeness is HIC interesting because

✓ It is a tag on a hadron, saying
that it was not in colliding nuclei but is produced in the course of collision.

✓ Strange quarks like baryons: K,Λ,Σ,Ξ,Ω,..., anti-strange quarks like mesons K, .

→ strangeness/anti-strangeness separation in baryon-rich matter

✓ Strangeness is conserved in strong interaction

→ Strangeness production threshold is high,
→ sensitive to possible in-medium effect.
QGP signal? (Rafelski-Mueller conjecture)

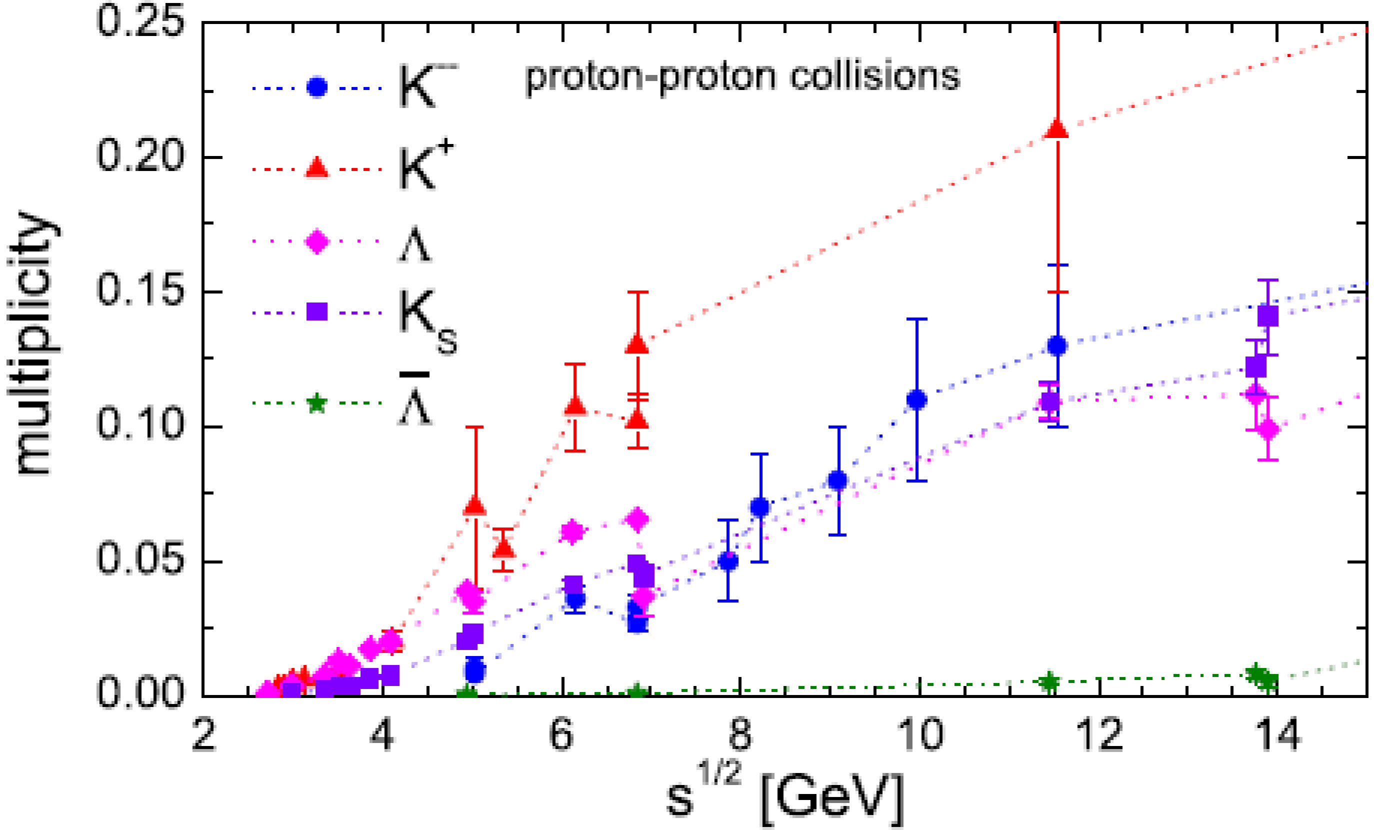
Strangeness is HIC difficult because

✓ Strangeness production cross sections poorly known
(new data from HADES on pp, COSY on pn, ANKA)

✓ Limited exp. information about elementary reactions among strange particles

✓ Strong couplings among various strange species. Complicated dynamics

Input. Elementary processes



Quality of data at high energies > 4GeV !

Change of the production mechanism at 4-5 GeV

Data: Gazdzicky, Roerich, Z. Phys. C 71, 55 (1996)

Strangeness production rate at AGS-SPS

- **strangeness production** K^+ and K^0 evolution calculated from

$$\frac{d\rho_K}{d\tau} = \rho_K \left(-\frac{1}{V}\frac{dV}{d\tau} \right) + \mathcal{R}^+ - \mathcal{R}^-$$

annihilation rate

production rate

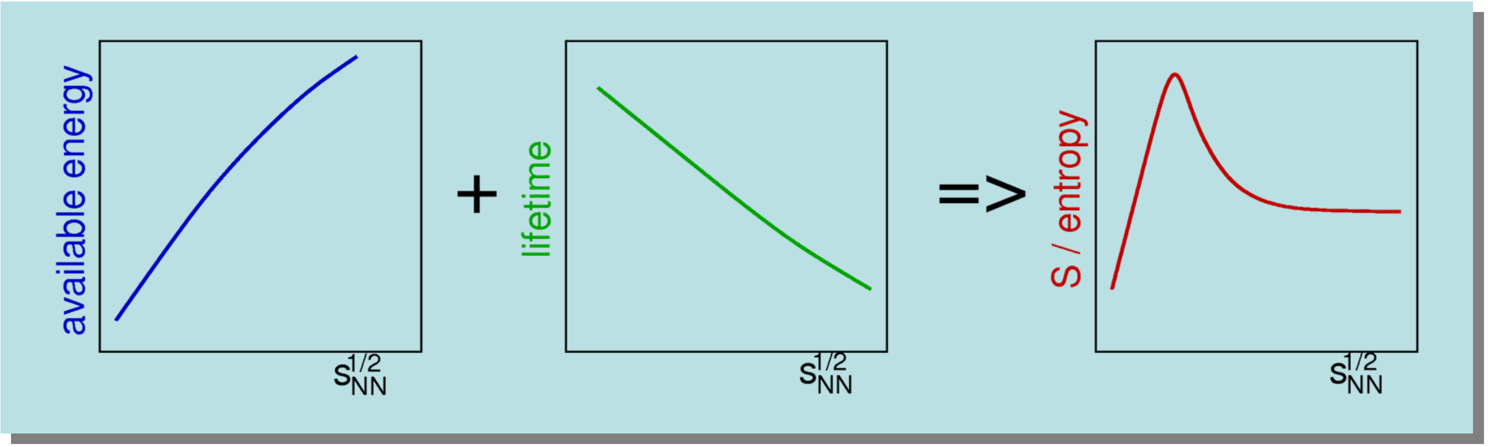
expansion rate

calculate from known cross-sections and evolved densities

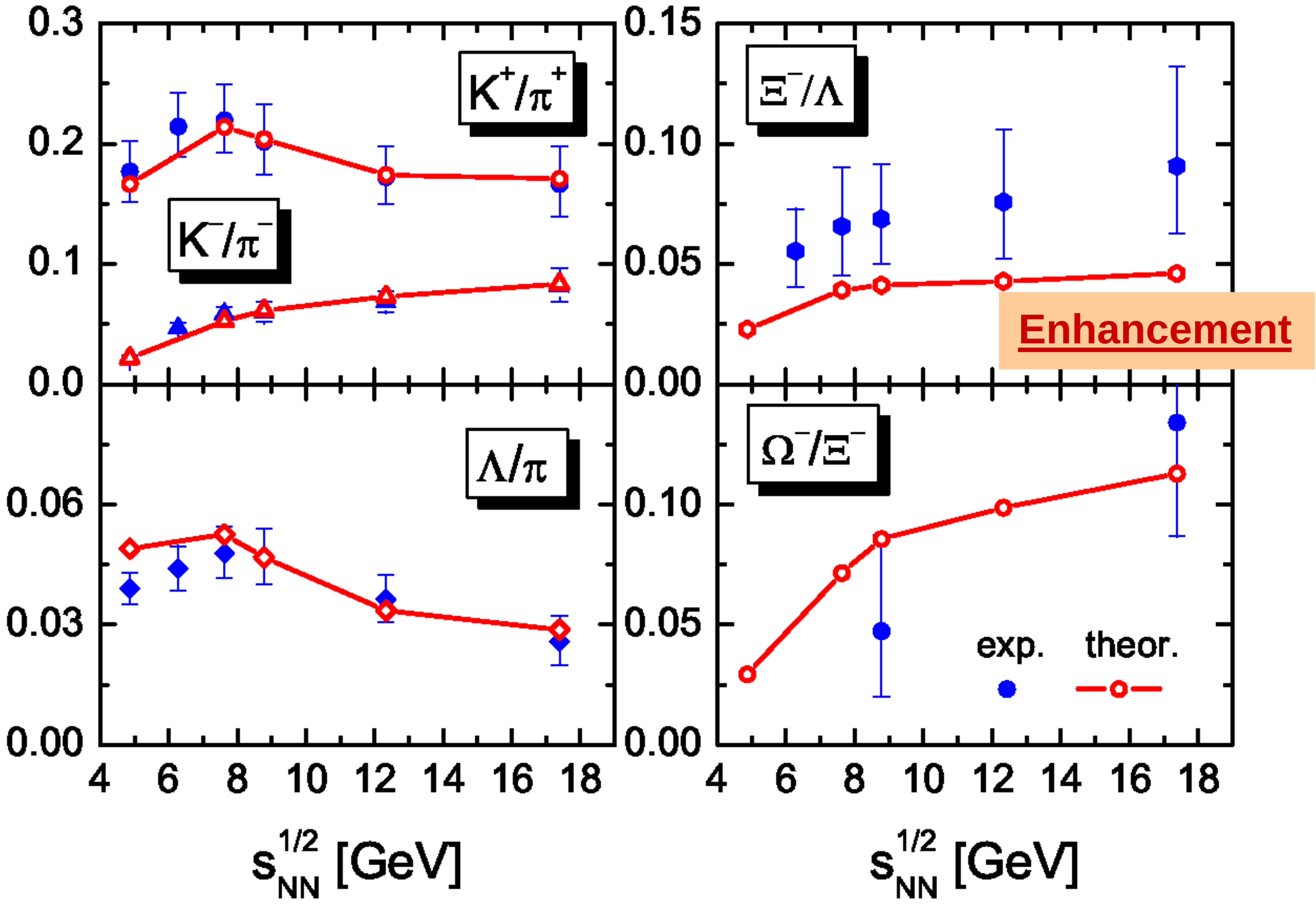
Initial strangeness: number of K^+ from pp collisions final state: chem. freeze-out parameters

- **fireball expansion time vs. energy** parameterized the space-time evolution

a data/experience (HBT, spectra) driven ansatz for expansion



- results



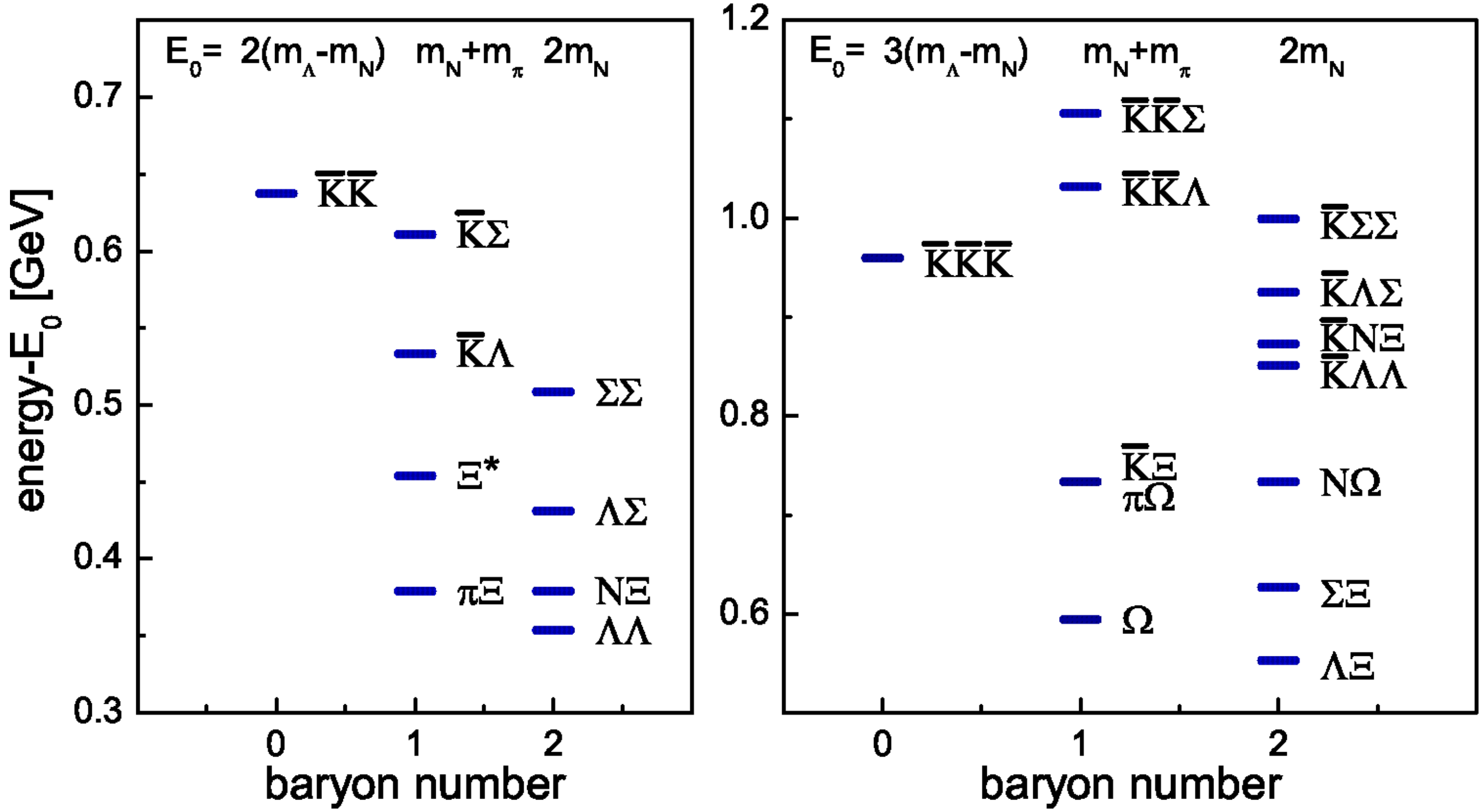
The time needed for a strangeness production is about **15-20 fm/c**.

In hydro the typical expansion time is **<10 fm/c!**.

[Tomasik, Kolomeitsev, EPJC49(2007) 115]

Multi-strangeness enhancement

Mass spectrum of strange hadronic states with different baryonic numbers

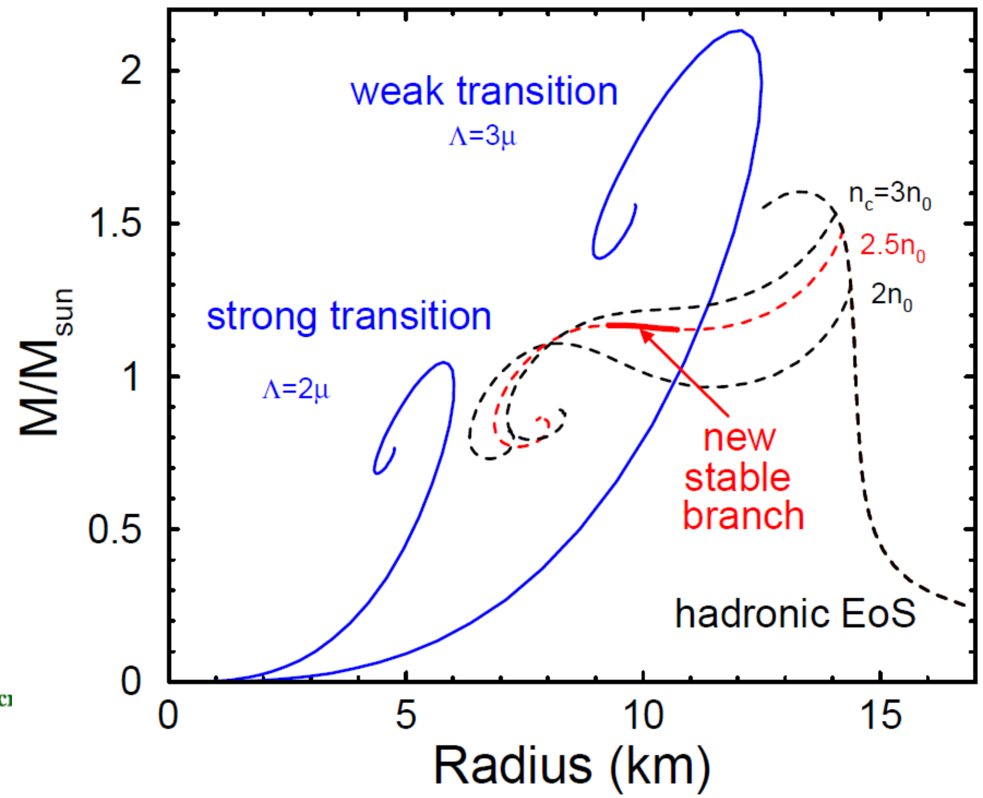


Once several s quarks appear in the hadronic system it is energetically favorable to “store” them together in a multistrange state Ξ or Ω. In both single and double baryon channels the states with the and baryon are at the bottom of the spectrum. This means that Ξs and Ωs would play a role of a strangeness reservoir, being filled with the decrease of temperature.

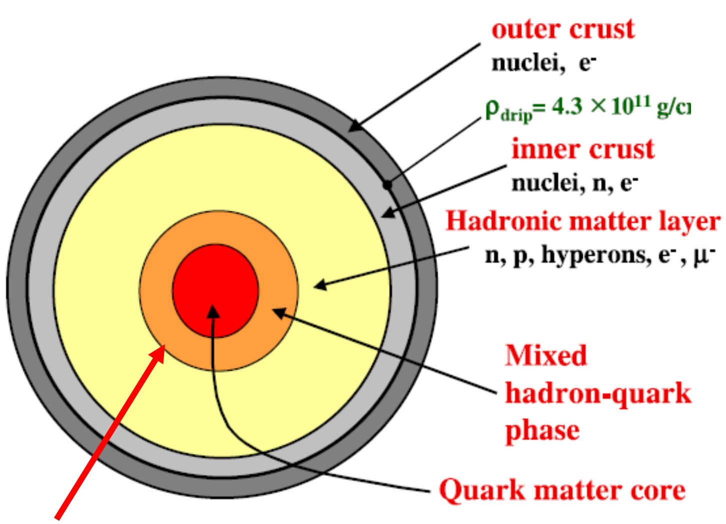
Quark Stars

Perturbative QCD EoS

[Fraga, Pisarski, Schaffner-Bielich, NPA 702,217]



Λ renormalization subtraction point



Interface?

[Bombaci 0809.4228]

no constraints from Lattice QCD!

Quasi-particle model

Peshier, Kampfer, Soff …

Propagator of transverse gluons

medium effects

$$D(\omega, k; T) = \frac{1}{\omega^2 - k^2 - \Pi(\omega, k; T)} \approx \frac{1}{\omega^2 - k^2 - m_g^2(T)}$$

HTL perturbative expression

$$m_g^2(T) = \frac{N_c}{6} g_{\text{eff}}^2(T)\, T^2$$

$$g_{\text{eff}}^2(T) = \frac{48\,\pi^2}{11\, N_c \ln\left(\frac{T+T_s}{T_c/\lambda}\right)}$$

$$P = \frac{d}{6\,\pi^2} \int \frac{\mathrm{d}k\, k^4}{\omega_g^*(k)} f_g^*(k) - B(m_g(T))$$

$$\varepsilon = \frac{d}{6\,\pi^2} \int \mathrm{d}k\, k^2\, \omega_g^*(k)\, f_g^*(k) + B(m_g(T))$$

$$\omega_g^*(k) = \sqrt{k^2 + m_g^2(T)}$$

$$f^*(k;T) = [\exp(\omega_g^*(k;T)/T) - 1]^{-1}$$

thermodynamical consistency

$$\frac{\delta P}{\delta m_g} = 0$$

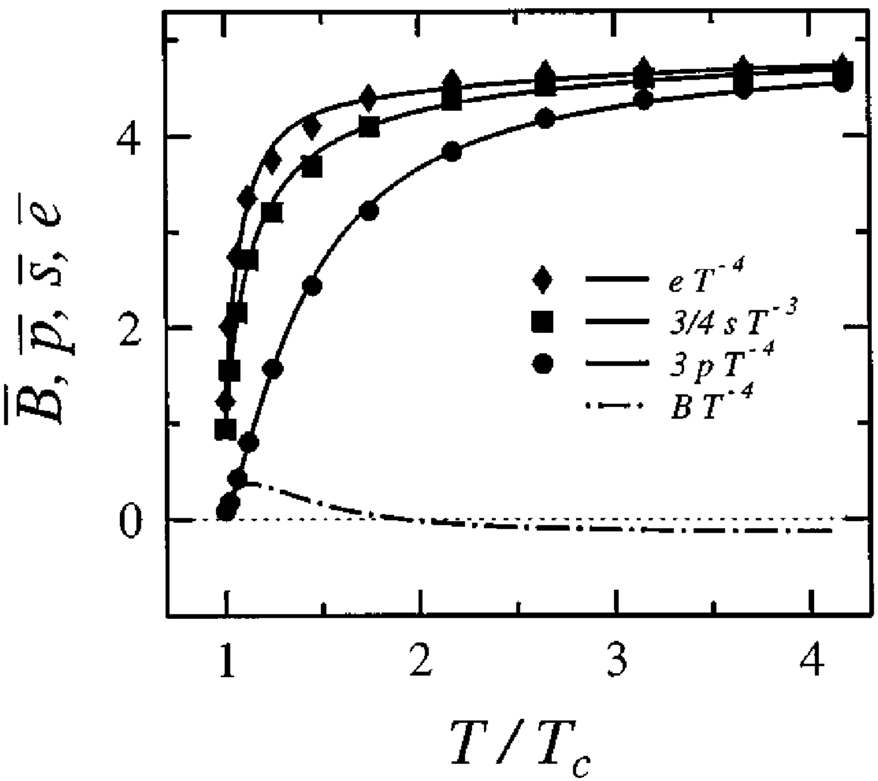
$$B = B_0 - \frac{d}{2\,\pi^2} \int_{T_0}^{T} \mathrm{d}T'\, m_g^*(T') \frac{dm_g^*}{dT'} \int \frac{\mathrm{d}k k^2}{\omega_g^*(k)} f^*(k)$$

tune T_s, λ, B_0, d

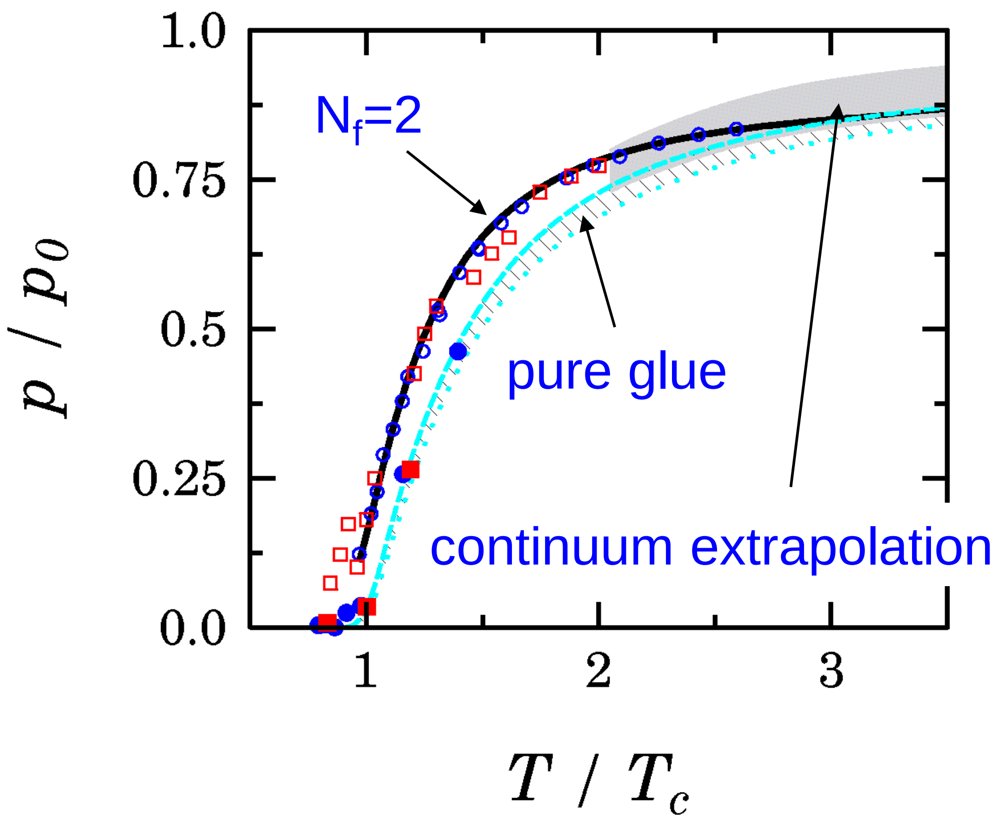
Peshier et al., PLB 337, 235 (1994)

Peshier et al., PRD 66, 094003 (2002)

gluons

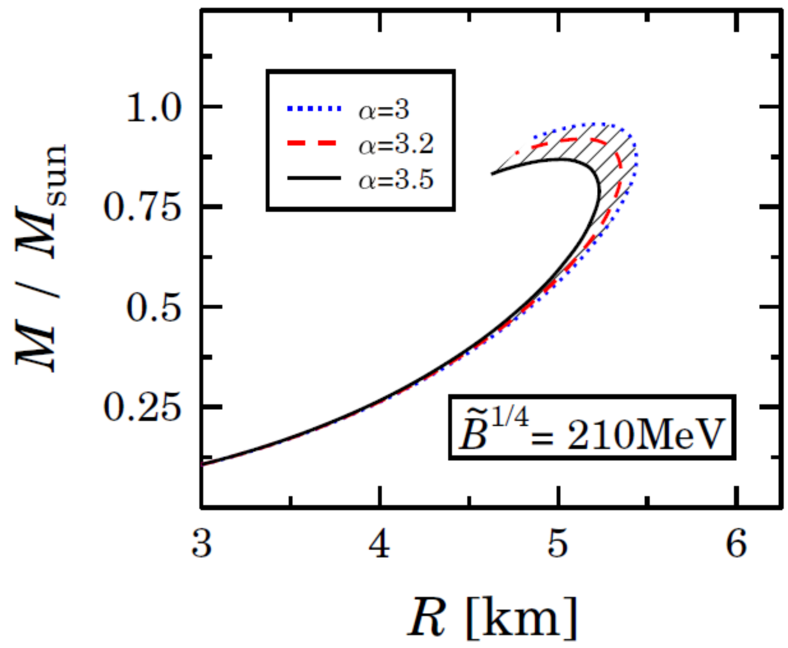


gluons + quarks



“rotation” to the μ axis

$$\frac{\partial s(T, \mu, m_i)}{\partial \mu} = \frac{\partial n(T, \mu, m_i)}{\partial T}$$



Quark stars are
very small (R<6 km)
and very light (M<1 Msol)

Matching between the realistic hadronic EoS and the quark EoS fitted to the lattice date is not always possible

[Ivanov et al. PRC72 (2005) 025804]

No hybrid stars are possible

Conclusion

Kaleidoscope of different facets of QCP which can be addressed in HIC and in space

On each facet, even if we do not use words “quarks” and “gluons
we deal with strong interaction, with QCD in dynamics.

NSs and HICs are the only sources of the information about properties of the strongly interacting matter under extreme condition.

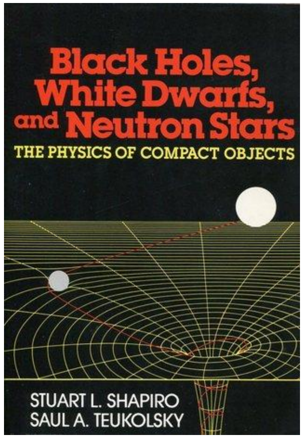
They provide test for our theories and models in dynamical systems.

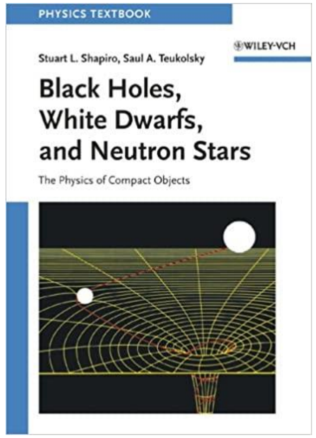
Problems in discussion:

Relativistic equation of state for high densities?
Inclusion of new particles (hyperons, Deltas)?
Hadrons in medium?
Quark-hadron phase transition?

We always have to expect unexpectable!

Book of the Physics of Compact Stars





Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects

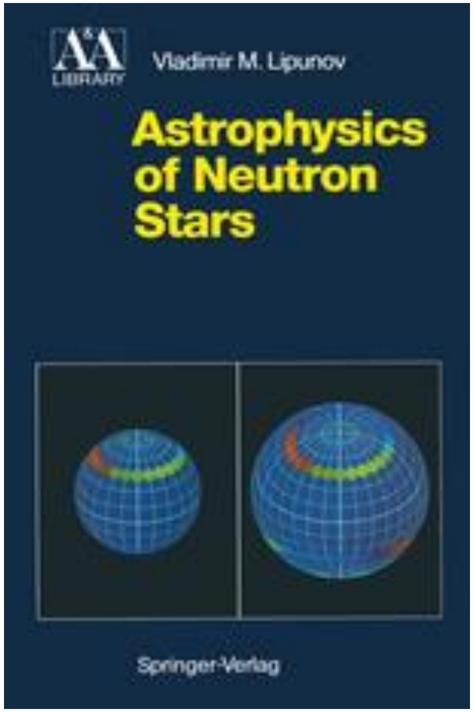
•Author(s): Stuart L. Shapiro

•Saul A. Teukolsky

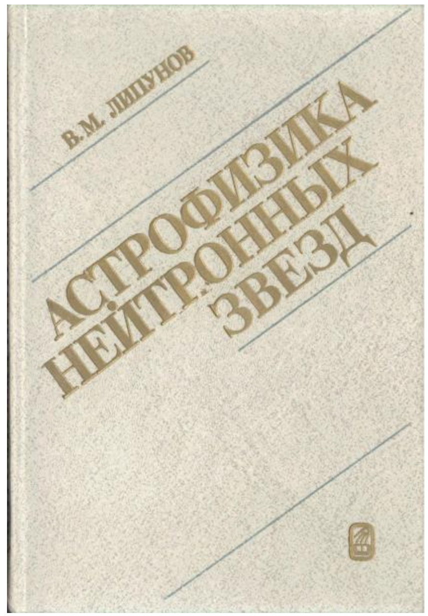
First published:27 July 1983

Print ISBN:9780471873167 |Online ISBN:9783527617661 |DOI:10.1002/9783527617661

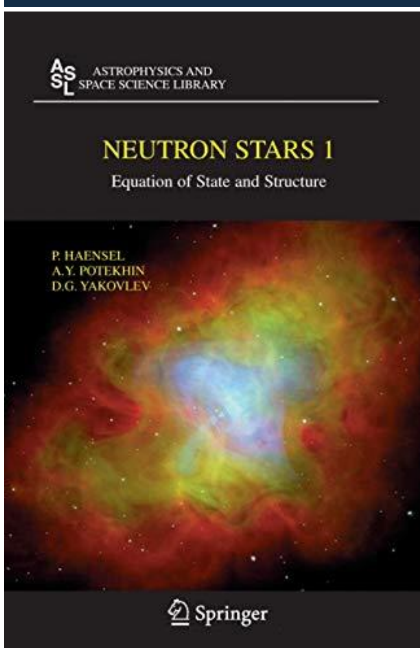
http://alexandr4784.narod.ru/shcapt2.html



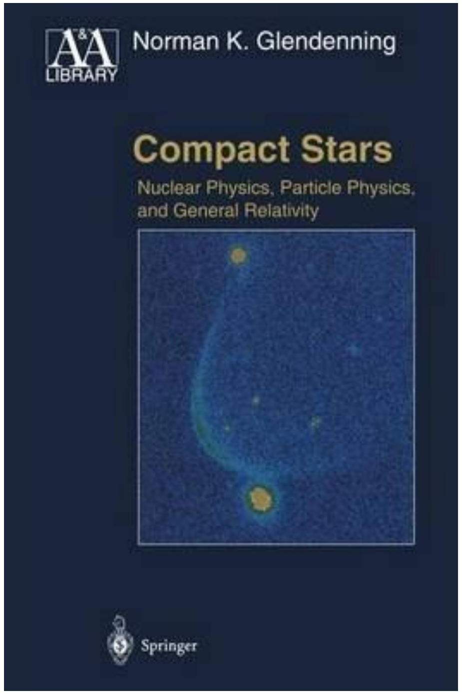
Astrophysics of Neutron Stars
Authors: **Lipunov**, Vladimir M.
https://www.springer.com/gp/book/9783642763526

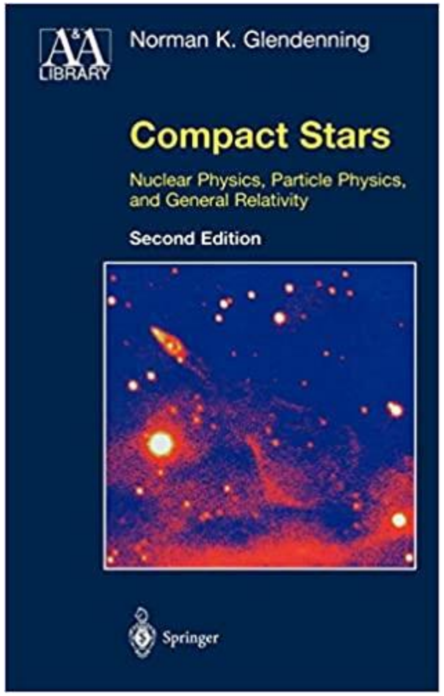


http://ind.pskgu.ru/ebooks/lipunov.html



Neutron Stars 1
Equation of State and Structure
Authors: **Haensel**, P., **Potekhin**, A.Y., **Yakovlev**, D.G.
https://www.springer.com/gp/book/9780387335438





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