Astrophysics @ FAIR - an introduction

DAAD

3rd German-Cuban School
Havana, January 2022

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ICIMAF

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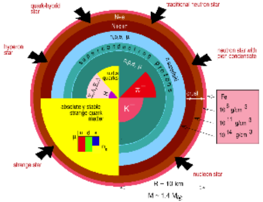
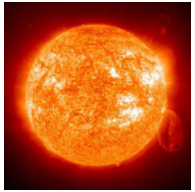
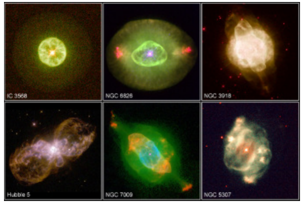
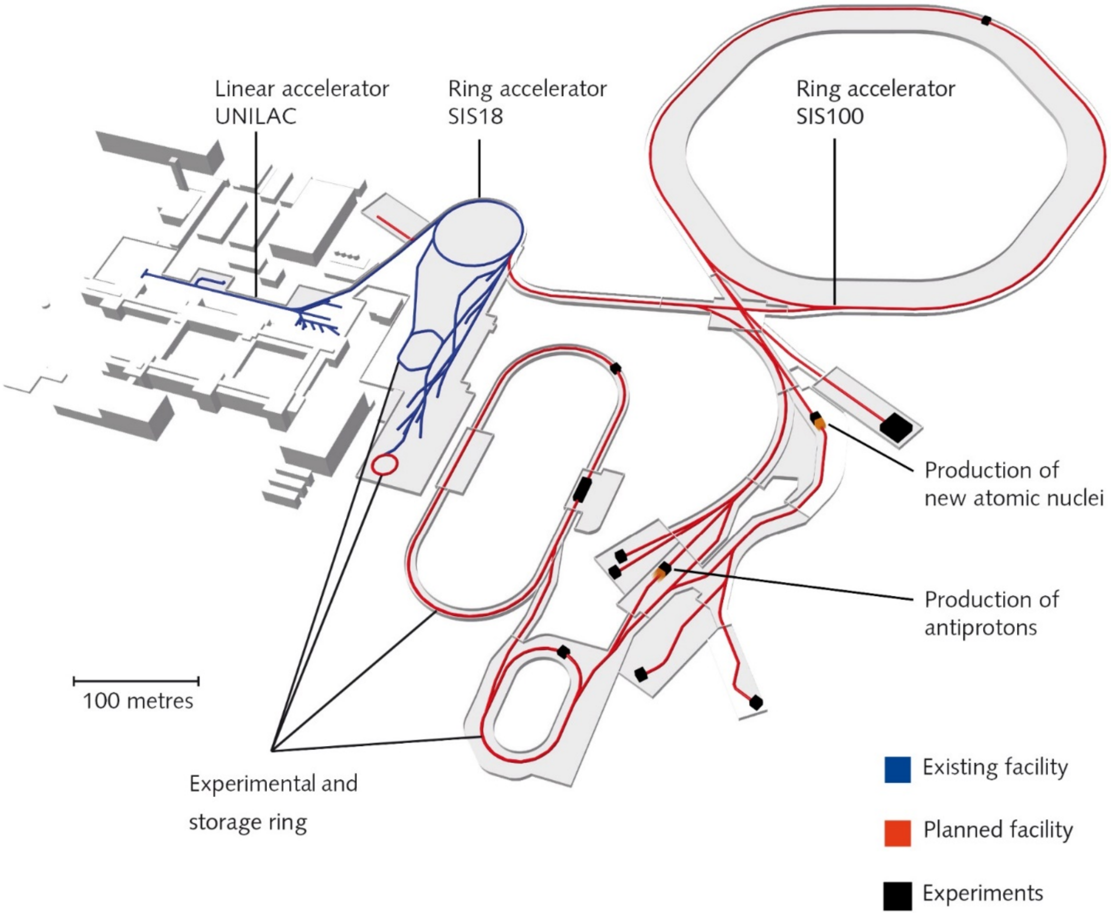
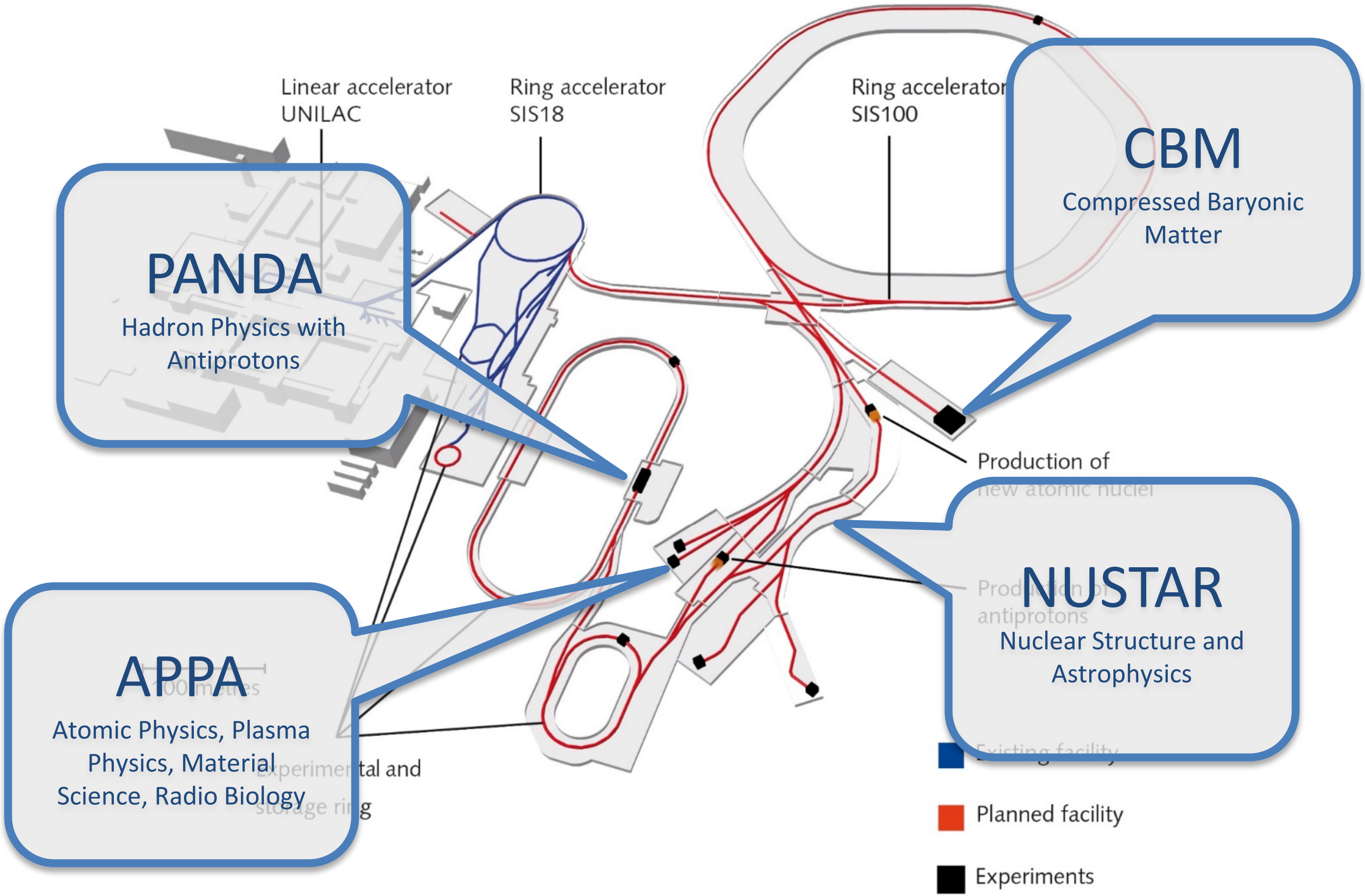


... or cosmic matter in the laboratory
(a personal collection)






Linear accelerator UNILAC
Ring accelerator SIS18
Ring accelerator SIS100
Production of new atomic nuclei
Production of antiprotons
100 metres
Experimental and storage ring
🟦 Existing facility
🟥 Planned facility
■ Experiments



CBM

Compressed Baryonic Matter

PANDA

Hadron Physics with Antiprotons

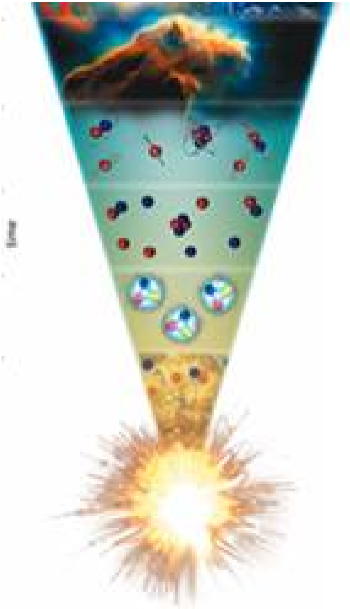
NUSTAR

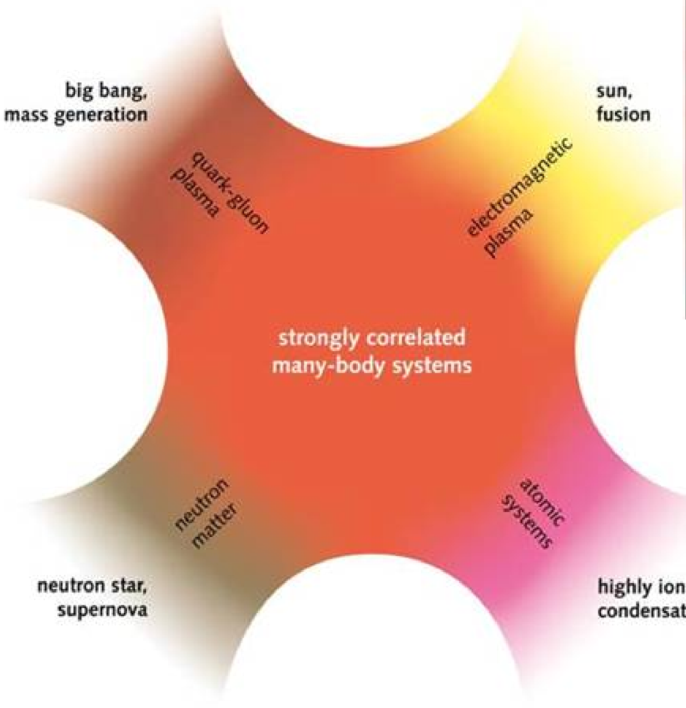
Nuclear Structure and Astrophysics

APPA

Atomic Physics, Plasma Physics, Material Science, Radio Biology

FAIR – Cosmic Matter in the Laboratory





big bang,
mass generation

quark-gluon plasma

sun,
fusion

electromagnetic plasma

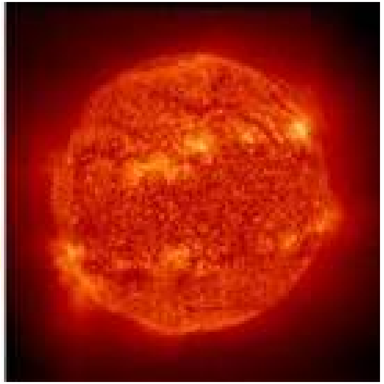
strongly correlated
many-body systems

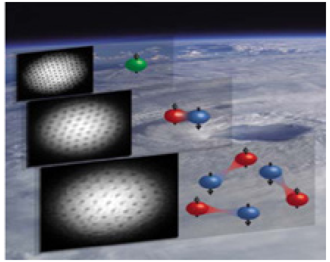
neutron matter

atomic systems

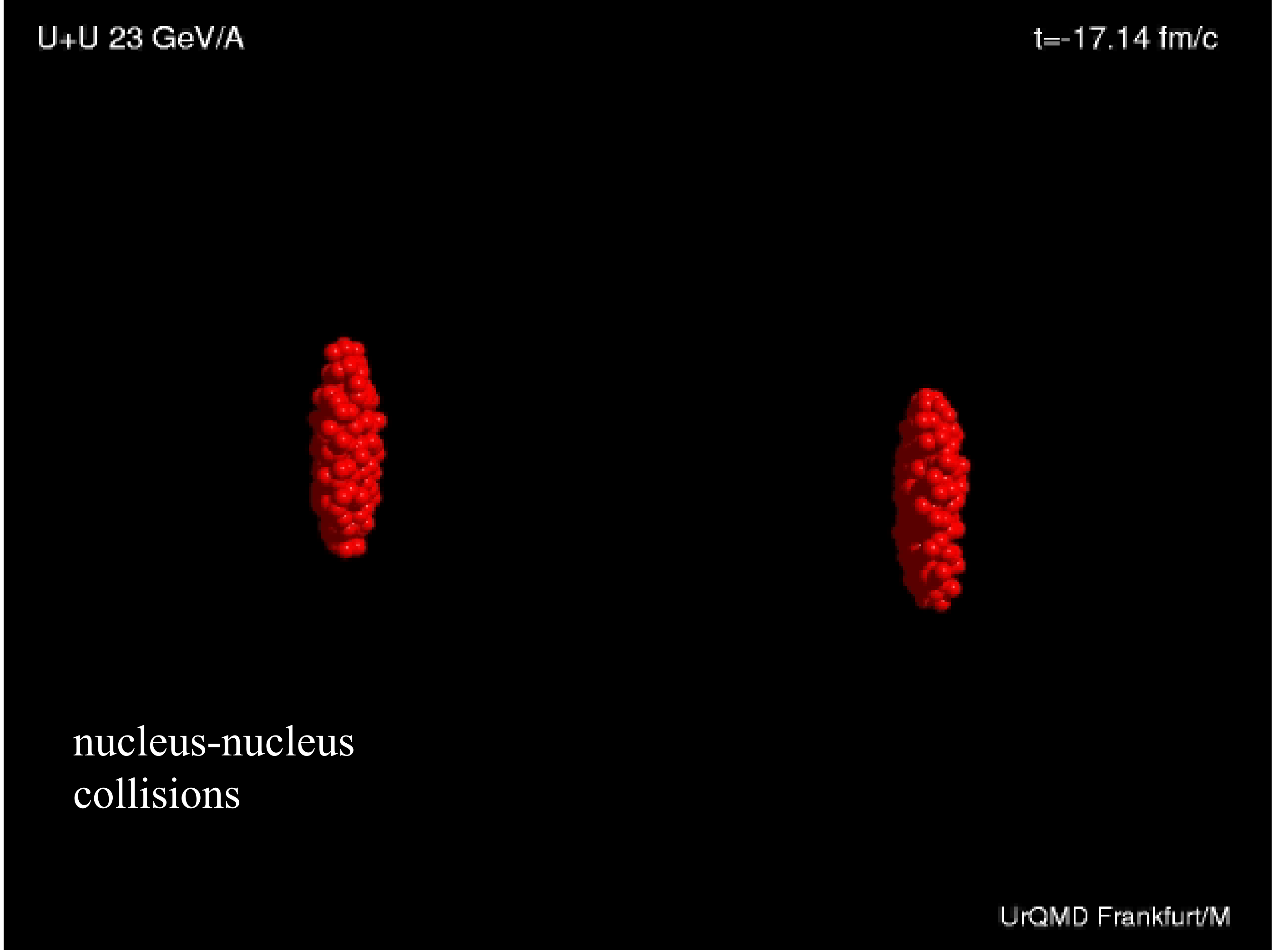
neutron star,
supernova

highly ionized matter,
condensates





How to explore it in the laboratory ?



nucleus-nucleus collisions

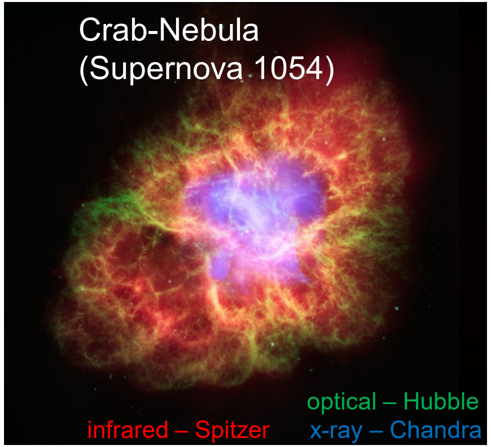
Investigating dense nuclear matter

Neutron stars

Temperature
$T < 20$ MeV

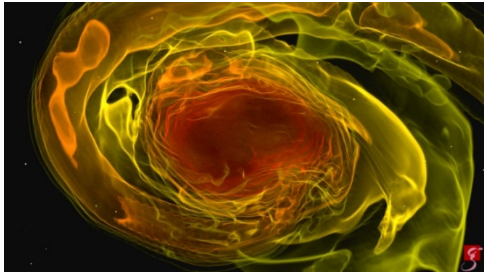
Core density
$\rho < 10\ \rho_0$

Lifetime
$\Delta t \sim$ infinity



Crab pulsar T = 33.4 ms, Mass ~ 1.5 $M_\odot$

Neutron star merger



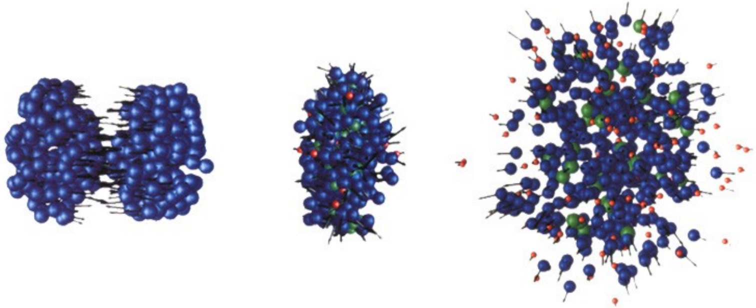
numerical simulation, GW170817
T. Dietrich (Max Planck Institute for Gravitational Physics)

Temperature
$T < 70$ MeV

Density
$\rho < 2 – 6\ \rho_0$

Reaction time
$\Delta t \sim 10$ ms

Relativistic nucleus-nucleus collisions

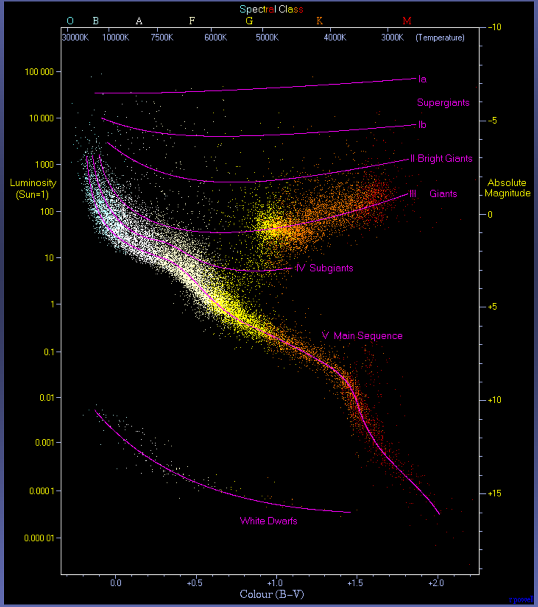


Temperature
$T < 120$ MeV

Density
$\rho < 8\ \rho_0$

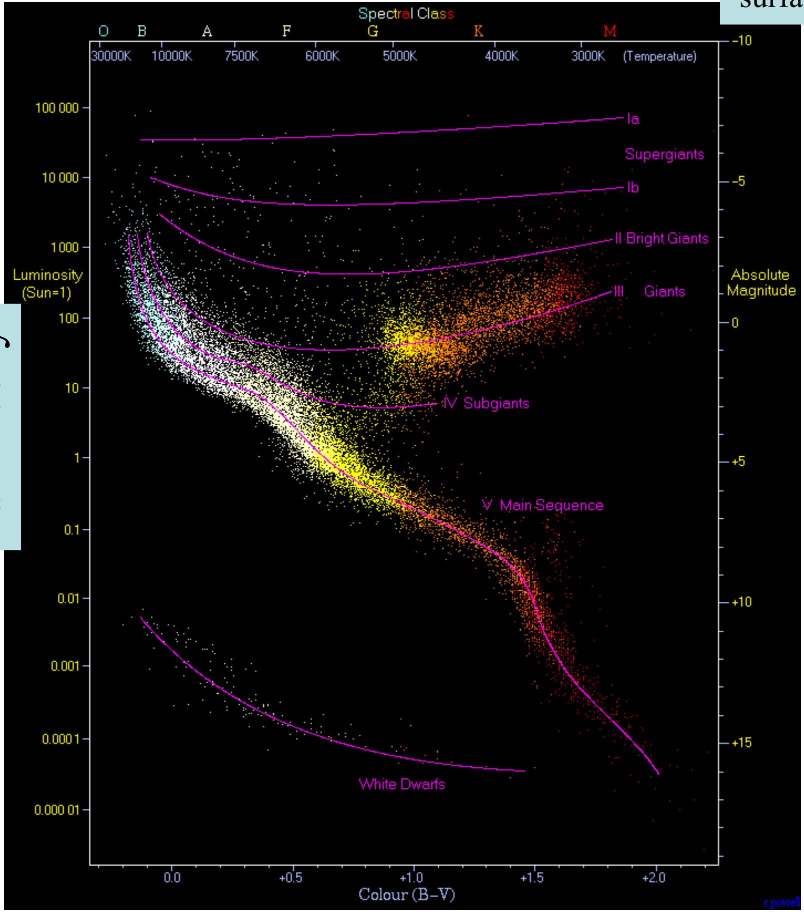
Reaction time
$\Delta t \sim 10^{-23}$ s

Introduction to Stellar Evolution



Experts may apologize !

Stellar evolution: Hertzsprung-Russel diagram

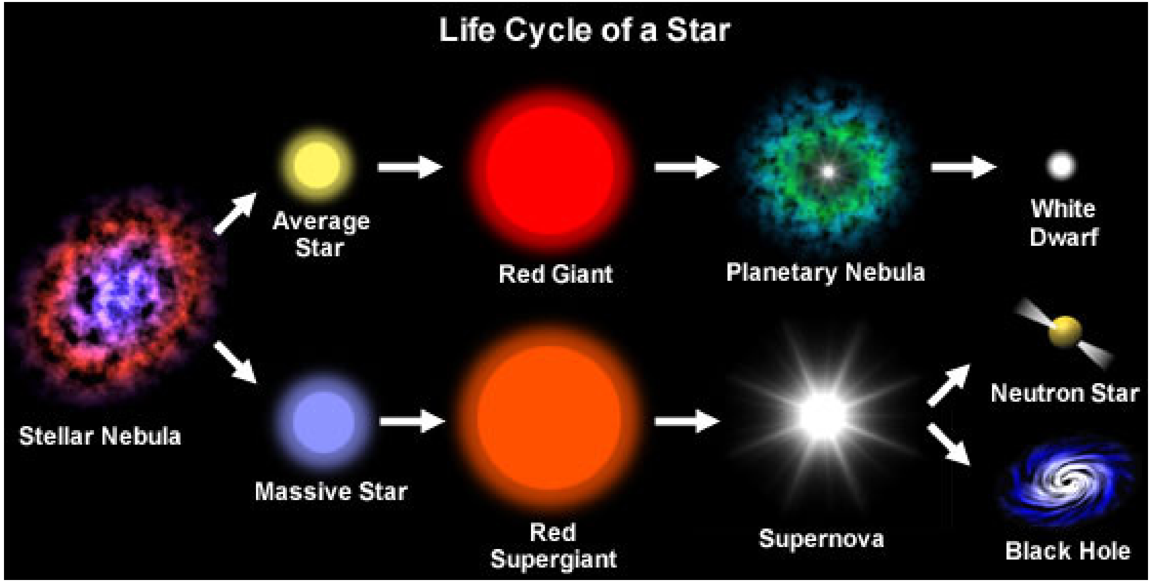


surface temperature

luminosity

mass	life time [years]
main sequence	
1.0 $M_\odot$	$9.0 \cdot 10^9$
2.2 $M_\odot$	$5.0 \cdot 10^9$
15. $M_\odot$	$1.0 \cdot 10^7$
giant branch	
1.0 $M_\odot$	$1.0 \cdot 10^9$
2.2 $M_\odot$	$3.8 \cdot 10^7$
15. $M_\odot$	$1.5 \cdot 10^6$

Stellar evolution

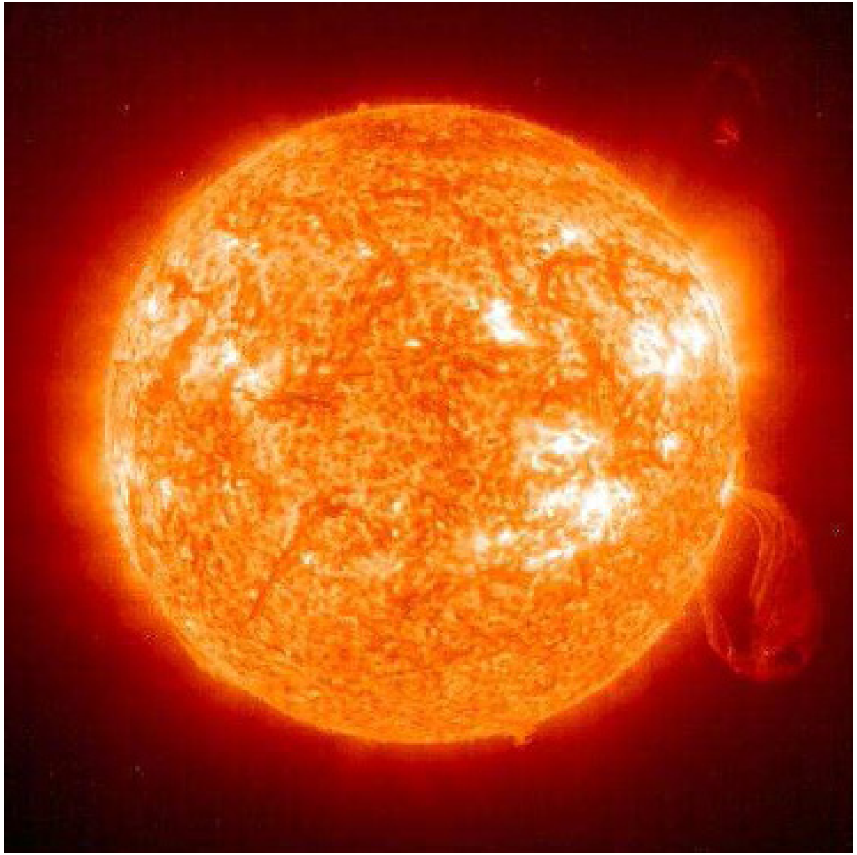


$M < 8\,M_\odot$

$M \geq 8\,M_\odot$

note: $M_\odot \equiv M_{sun}$

Stellar evolution: M < 8 $M_\odot$



our sun will reach

- the read giant stage in $\approx 4 - 5 \times 10^9$ years

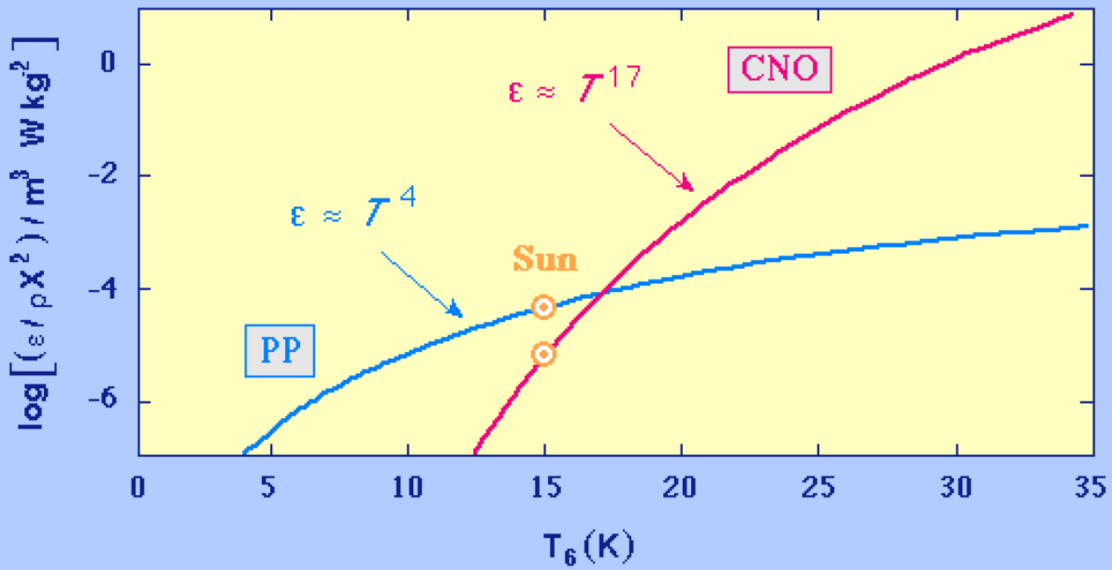
- and become a white dwarf $\approx 10^9$ years later !

Cosmic burn-outs

pp-chain $^{1}\mathrm{H}(p,e^{+}\nu_e)\ ^{2}\mathrm{D}(p,\gamma)\ ^{3}\mathrm{He}(^{3}\mathrm{He},2p)\ ^{4}\mathrm{He}+26.21\,\mathrm{MeV}$

CNO-cycle $^{12}\mathrm{C}(p,\gamma)\ ^{13}\mathrm{N}(,e^{+}\nu)\ ^{13}\mathrm{C}(p,\gamma)\ ^{14}\mathrm{N}(p,\gamma)\ ^{15}\mathrm{O}(,e^{+}\nu_e)\ ^{15}\mathrm{N}(p,\alpha)\ ^{12}\mathrm{C}+25.0\,\mathrm{MeV}$

(note: carbon, nitrogen and oxygen act only as catalysts !)



sun: 98 % – 99 % via pp-chain !

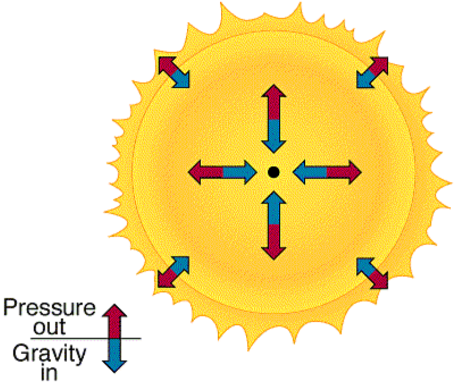
Cosmic burn-outs

stability of stars:

$$\frac{dP(r)}{dr} = -GM(r)\frac{\rho(r)}{r^2}$$

pressure by nuclear reactions

gravity



	T_{thr} [K]	mass limit
H-burning	$2 - 5 \cdot 10^7$	$M \geq 0.1\, M_\odot$
He-burning	$1 \cdot 10^8$	$M \geq 0.5\, M_\odot$
C-burning	$6 \cdot 10^8$	$M \geq 5\, M_\odot$
O-burning	$2 \cdot 10^9$	
$^{28}Si \rightarrow {}^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$	$4 \cdot 10^9$	

But, if their nuclear fuel is exhausted, gravity takes over! Since there is no counter pressure by nuclear reactions, the star would seem to collapse irresistibly....

The final destiny of a collapsing star is, determined by **quantum mechanics** !

Stellar evolution: $M < 8\ M_\odot$

What remains **after the star runs out of fuel** ?

A dense core of carbon and perhaps some oxygen

there is not enough gravitational pressure to ignite further nuclear reactions

contraction

contraction of the core up to a density $\rho \approx 10^6$ g/cm^3

fully ionized matter: ions + electrons

(Maxwell-Boltzmann statistics)

Fermi-Dirac statistics (Pauli exclusion principle)

→ $\boxed{p_F \gg \langle p \rangle_{MB}}$

the degenerated Fermi gas of electrons produces counter pressure which stops further collapse by gravitation!

a **white dwarf** is born

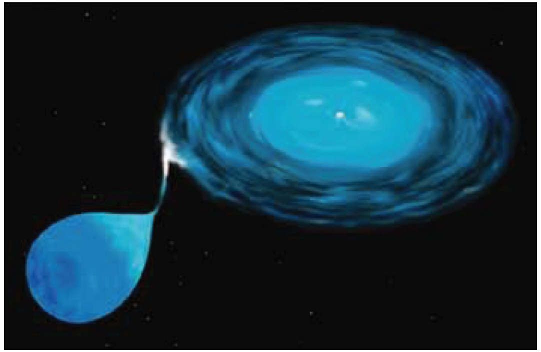
Stellar evolution: $M < 8\ M_\odot$

stability: the counter pressure by the degenerate electron gas stabilizes the white dwarf up to a mass of $\boxed{M_{crit} \approx 1.46\ M_\odot}$, the **Chandrasekhar** mass limit.

For $M > M_{crit}$ exists no stable solution → the white dwarf collapses !
This triggers a run-away fusion reactions (50 % of the mass is transformed to Fe!)
released energy let the white dwarf explode → Supernova Ia

The white dwarf mass falls generally well below the Chandrasekhar mass limit: a typical mass is about $0.6\ M_\odot$!

But how can it happen ?
by accretion of mass from a close companion star !



Stellar evolution: $M \geq 8\ M_{\odot}$

After the Si-burning to Fe the star has exhausted all its energy sources

the electrons are pushed into the nucleons via inverse β-decay $p + e^{-} \rightarrow n + \overline{\nu}_e$

→ reduces the degeneracy pressure of electrons strongly

→ the core collapses in free fall

the total collapse of the iron core lasts only milliseconds !

$\rho \approx 10^{12}$ g/cm^3 large fraction of the core already transformed into neutrons

$\rho \approx 10^{14}$ g/cm^3 almost saturation density ρ_0 of nuclear matter is reached

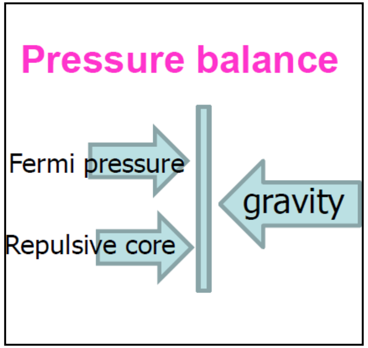
$\mathbf{M_{core} < 2\ M_{\odot}}$

the core is stabilized by

- degeneracy pressure of the neutrons
- repulsive component of the strong force

a neutron star is born

$\mathbf{M_{core} > 2\ M_{\odot}}$ → collapse to a **black hole** !



Supernova 1987a

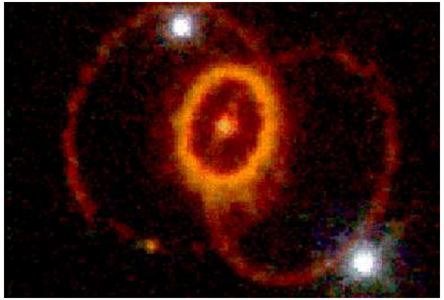
The outer stellar material falling onto the **neutron star** is strongly shocked and heated up causing the explosive expansion of the envelope.

Once the outgoing shock wave brakes through the outermost layers of the star a **supernova** had started ...

Christ

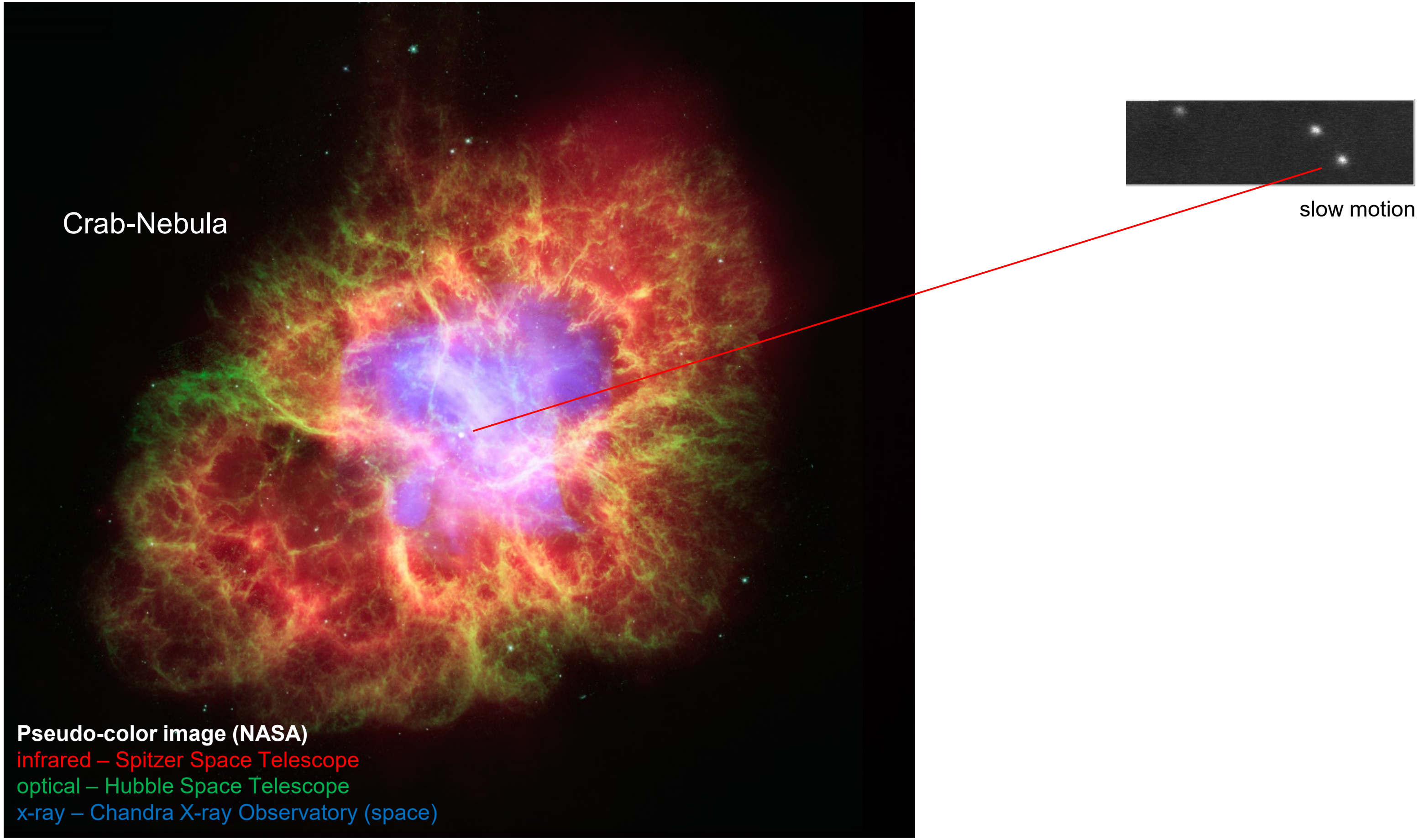
$L_{\mathrm{SN}} \approx 10^{10} L_{\odot}$

near the Tarantula nebula
in the Large Magellanic Cloud



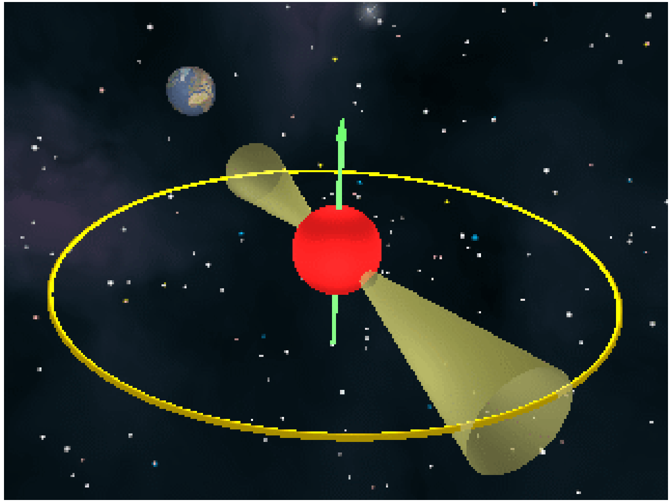
Remnant of SN 1987a

Crab-Nebula - remnant of a supernova in the year 1054



Pseudo-color image (NASA)
infrared – Spitzer Space Telescope
optical – Hubble Space Telescope
x-ray – Chandra X-ray Observatory (space)

Pulsars - rotating neutron stars



“The Sounds of Pulsars” http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html

PSR B0531+21 (Crab Pulsar)
rotation: 30 times a second

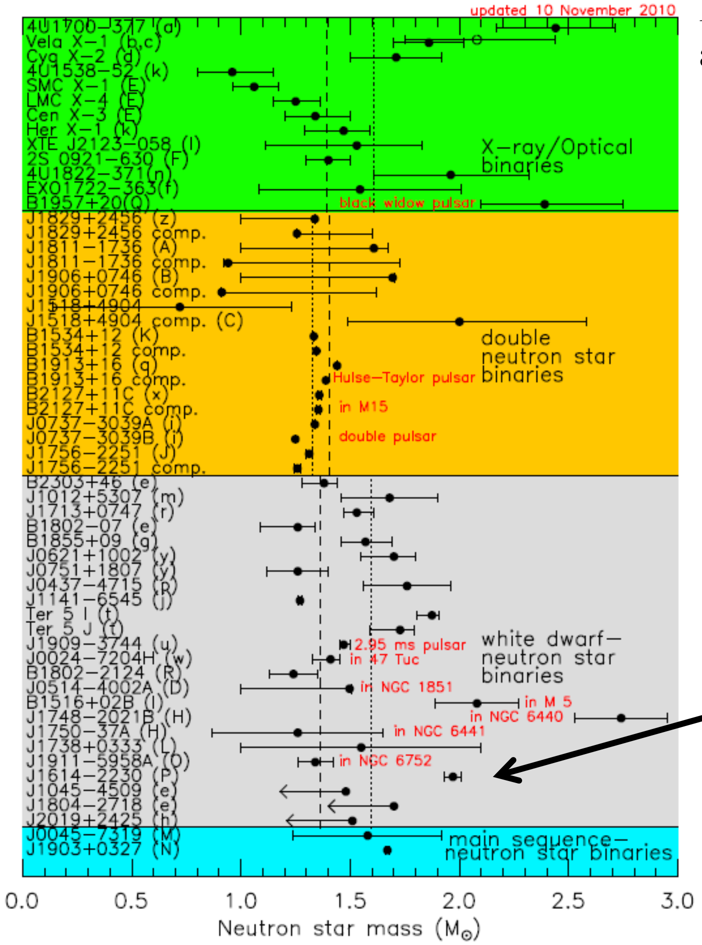
PSR B1937+21
rotation: 642 times a second

Fastest-rotating pulsar: PSR J1748-2446ad
rotation: 716 times a second

The surface of the fastest-rotating pulsars are moving at about 14% of the speed of light !

Enormous gravitational forces which prevent it flying apart due to the immense centrifugal forces ...

Observed neutron star masses



Lattimerand Prakash,
arXiv:1012.3208 [astro-ph.SR]

PSR J1614-2230

Green Bank Radio Observatory (2010)

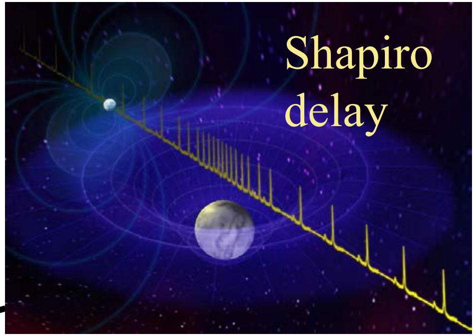
Mass: $(1.976 \pm 0.04)\ M_\odot$

Distance: ~1 kPc (~3200 Ly)

Pulsar spin period: 3.1508076534271(6) ms

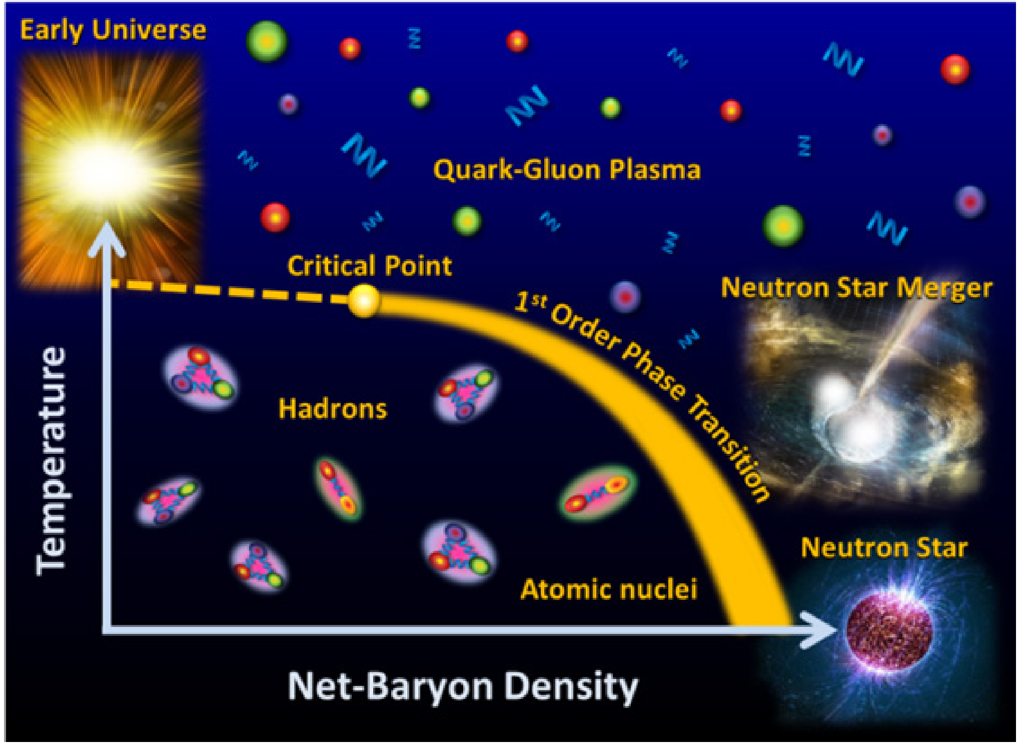
Companion mass: 0.5 $M_\odot$

Orbital period: 8.6866194196(2) d



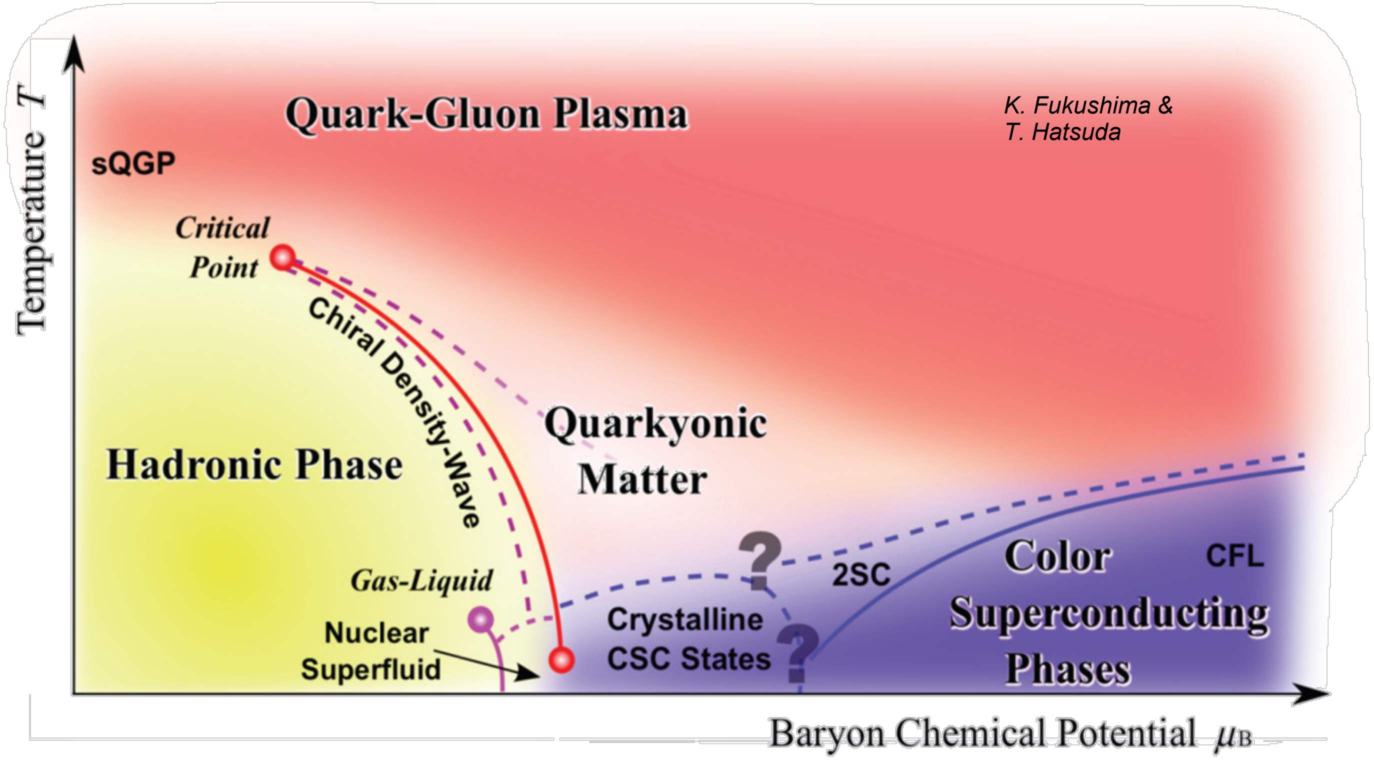
Shapiro delay – a general relativistic effect !
Time signal is getting delayed when passing near massive object - size of the effect depends on mass and inclination angle.

The phase diagram of strongly interacting matter



$$\text{net baryon density} = \frac{1}{V}\frac{1}{3}(n_q - n_{\bar{q}})$$

The phase diagram of strongly interacting matter



Recall & discussion

Discuss with your neighbor(s) ... recalling the stellar evolution ... 5 minutes:

Fusion reactions inside stars - why do they stop at Fe ?

What does white dwarfs stabilize ?

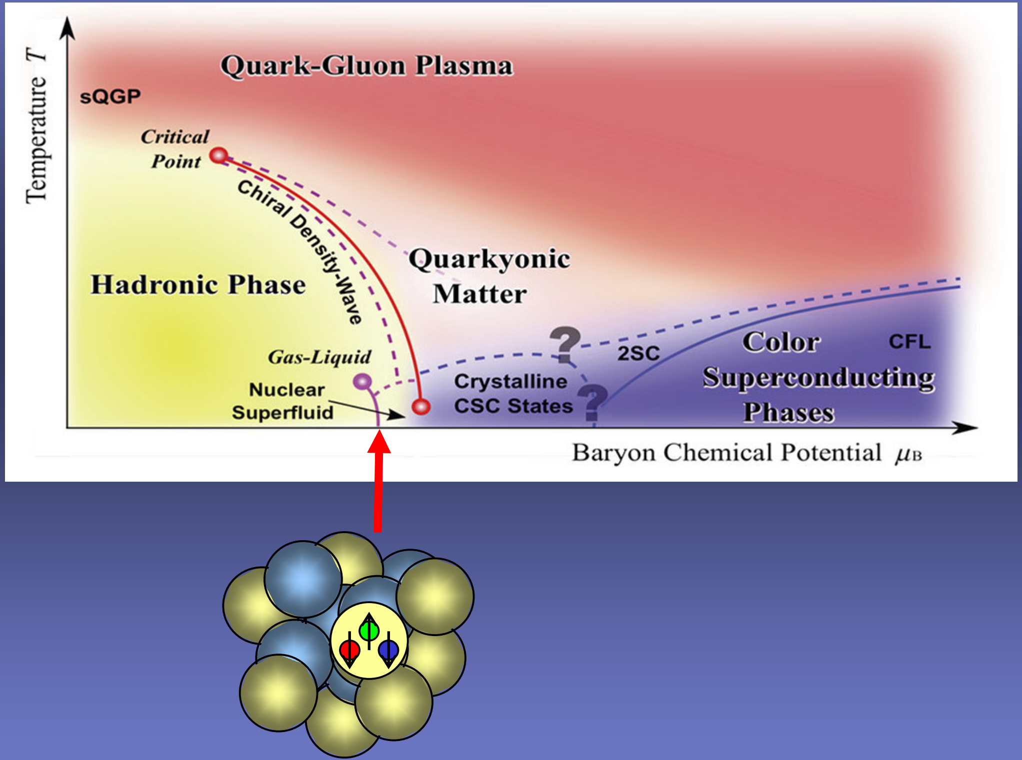
Neutron Stars ?

Black Holes ?

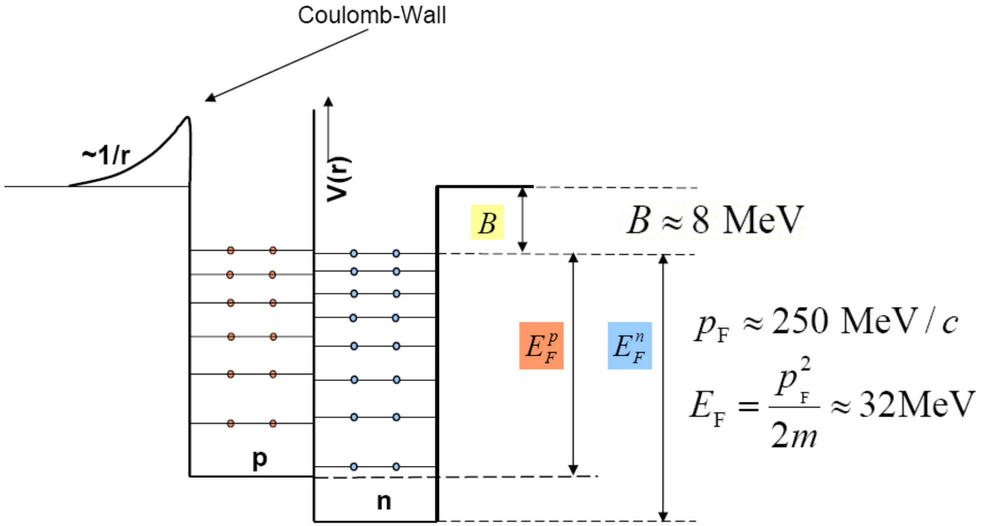
Any other final state ?

Stabilized by quantum mechanics - how to overcome ?

Nuclear Matter at (or close to) ground state



Nuclear matter at ground state: the Fermi Gas Model



$B \approx 8$ MeV

$p_\mathrm{F} \approx 250\ \mathrm{MeV}/c$

$$E_\mathrm{F} = \frac{p_\mathrm{F}^2}{2m} \approx 32\mathrm{MeV}$$

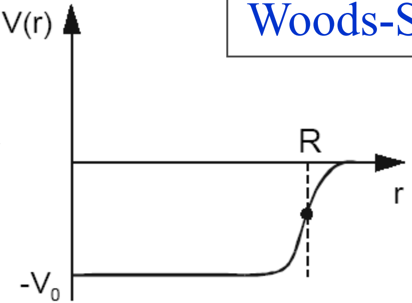
protons and neutrons
are Fermions (spin ½)
→ Pauli exclusion principle !

- the nucleons are bound in a mean potential V(r) caused by the interaction of all neighboring nucleons
- the Pauli exclusion principle avoids that more than one proton / neutron occupies a state

→ the nucleons are quasi-free inside the nucleus, because free states are energetically unavailable !

Nuclear matter at ground state: the Nuclear Shell Model

density distribution of nucleons inside (heavy) nuclei



Woods-Saxon Potential

$$V(r) = \frac{-V_o}{1+\exp\left(\frac{r-R}{a}\right)}$$

solving the Schrödinger equation

$$\left\{\frac{\hbar^2}{2m}\Delta + [E - V(r)]\right\}\Psi = 0$$

splitting of shells due to the spin-orbit coupling has to be taken into account !

observed magic numbers

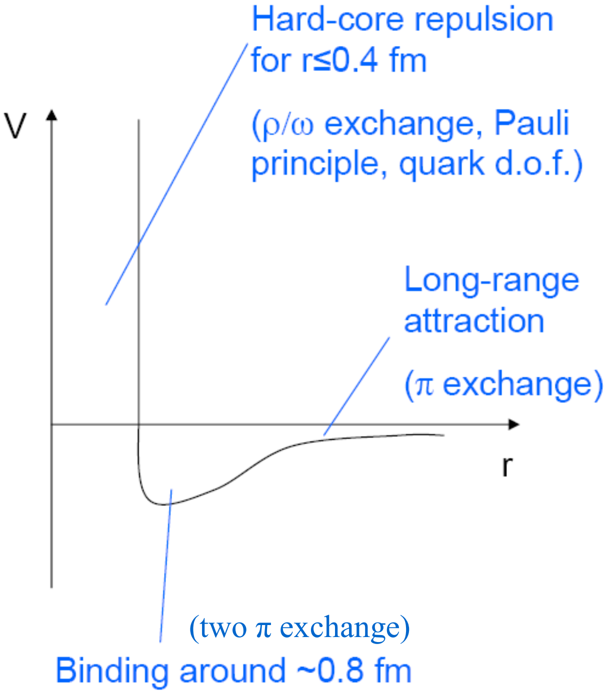
N	2	8	20	28	50	82	126	(184)	(196)
Z	2	8	20	28	50	82	(114)	(164)	

Effective nucleon-nucleon interaction

The meson exchange is a model to describe the effective nucleon-nucleon-interaction

range R of the interaction is determined by the uncertainty principle:

$$R = c\Delta t = \frac{\hbar c}{m_x c^2} = \frac{197\,MeV \bullet fm}{m_x c^2}$$



ρ- , ω-meson:

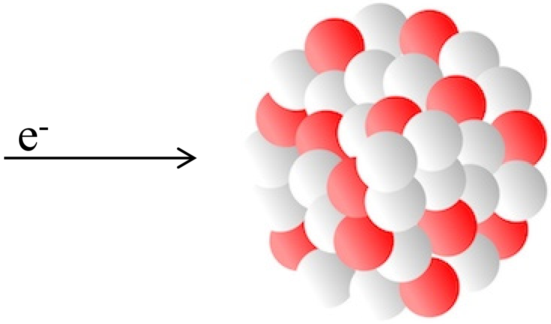
- vector particle $J^P = 1^-$
- $m_{\rho,\omega} \approx 780$ MeV

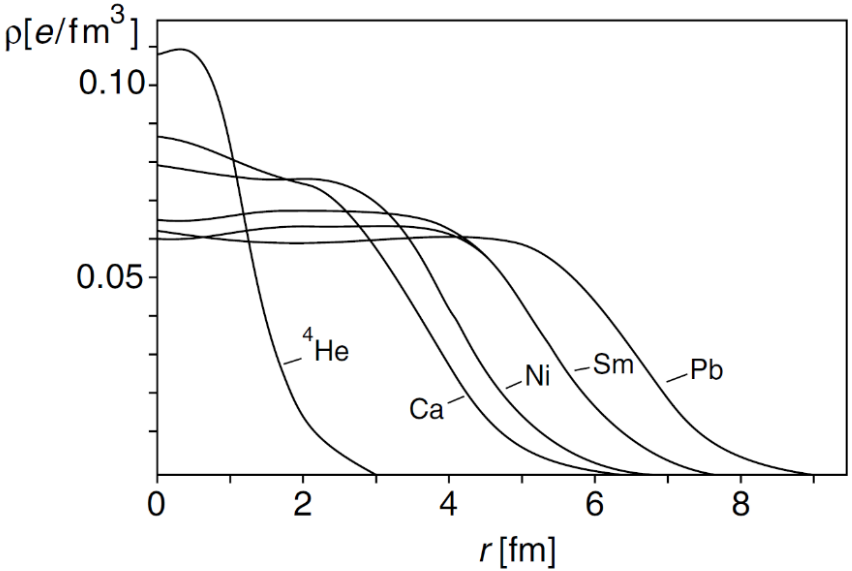
Pion (π-meson):

- pseudo-scalar particle $J^P = 0^-$
- $m_\pi = 140$ MeV

Nuclear matter at ground state

Charge distribution of nuclei obtained in electron-nucleus scattering





(taken from text book Povh/Rith)

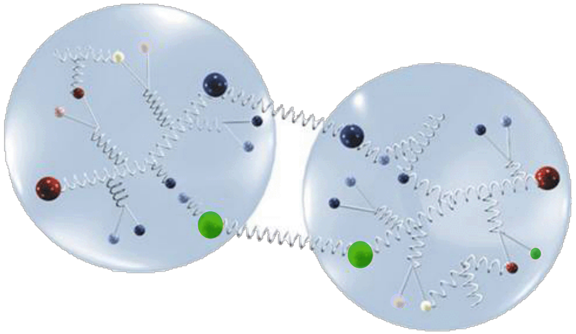
$$\rho_0 = \rho^e(0) \cdot \frac{A}{Z}$$

$$^{208}_{82}Pb: \ \frac{A}{Z} = 2.53$$

saturation density $\rho_0 \approx 0.15 - 0.17$ nucleons / fm^3

Nuclear matter in ground state – link to QCD ?

The **bonds** between nucleons inside the nucleus are **relatively "weak"**.
The average distance is much larger than the hard core radius of the nucleon.



Nucleons are not localized inside the nucleus - they can move almost free inside the nucleus → $p_f = 250$ MeV/c .

Link to **QCD** ?
Quarks and gluons are not the relevant degree of freedom (in this energy regime).
The largest fraction of the interaction strength is shielded because quarks and gluons are bound to color-neutral hadrons.

The equation-of-state of nuclear matter

$$\varepsilon(\rho,T) = \varepsilon_T(\rho,T) + \varepsilon_C(\rho,T=0) + \varepsilon_0$$

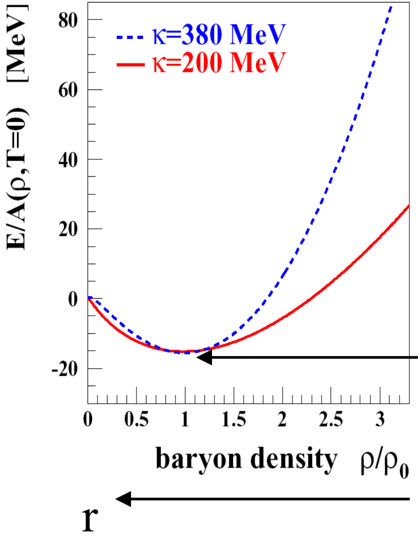
$(\varepsilon = E/A)$ thermal compressional ground state energy

thermodynamical concept

nuclear equation-of-state at T = 0 : the "compressional" energy

$$E/A\,(\rho, T=0) \;=\; \frac{1}{\rho}\int U\,(\rho)\,d\rho$$

$U(\rho)$: density dependent local potential



Curvature at saturation density:
compression modulus

$$\kappa \;=\; \left(9\rho^2\,\frac{\partial^2 E/A(\rho,T=0)}{\partial\rho^2}\right)_{\rho=\rho_0}$$

Example for a nuclear equation-of-state (EoS)

example for an
effective NN-Potential
(Skyrme type)

$$U(\rho) = \alpha\left(\frac{\rho}{\rho_0}\right) + \beta\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

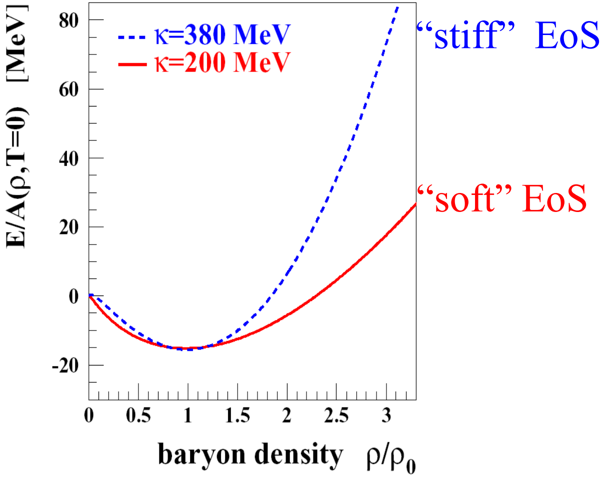
constraints for the parameters of the potential :

$$\varepsilon(\rho=\rho_0, T=0) = -16 MeV$$

$$\left(\frac{\partial\varepsilon(\rho, T=0)}{\partial\rho}\right)_{\rho=\rho_0} = 0$$

	α [MeV]	β [MeV]	γ
κ = 380 MeV	**-124**	**70.5**	**2**
κ = 200 MeV	**-356**	**303**	**7/6**

$$E/A(\rho, T=0) = \frac{1}{\rho}\int U(\rho)\, d\rho$$

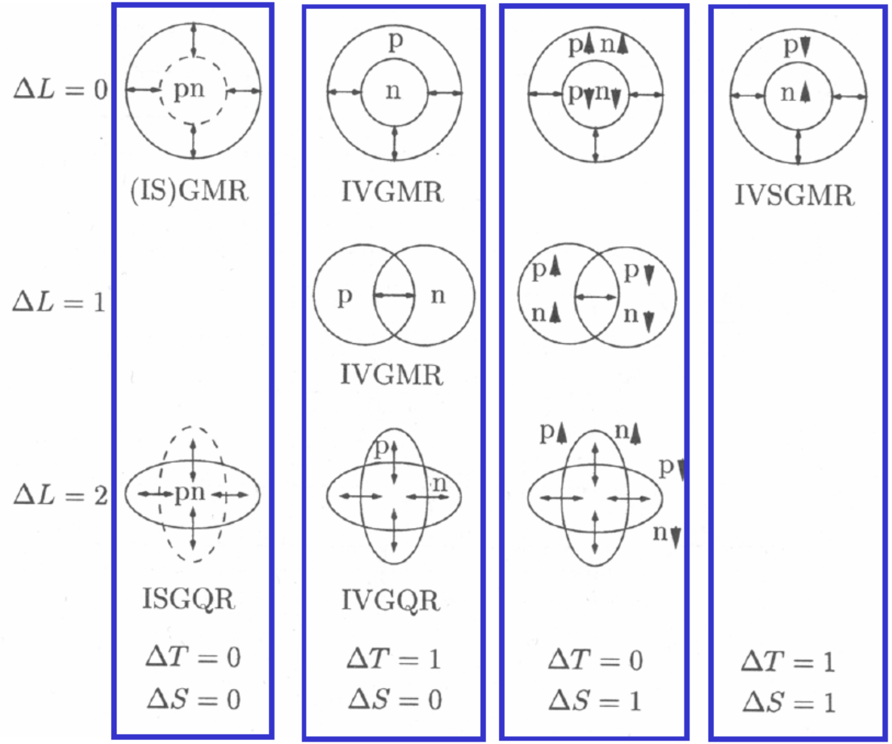


$$\kappa = \left(9\rho^2 \frac{\partial^2 E/A(\rho, T=0)}{\partial\rho^2}\right)_{\rho=\rho_0}$$

compression modulus

Nuclear EoS - how to measure ?

Excite collective excitation of nuclei: Giant Resonances



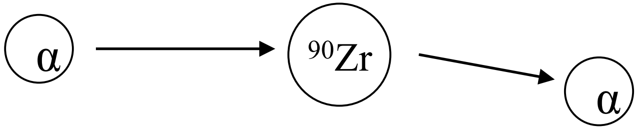
monopole vibration:
"breathing mode" of nuclei

dipole vibration:
"protons and neutrons
oscillate against each other"

quadruple vibrations

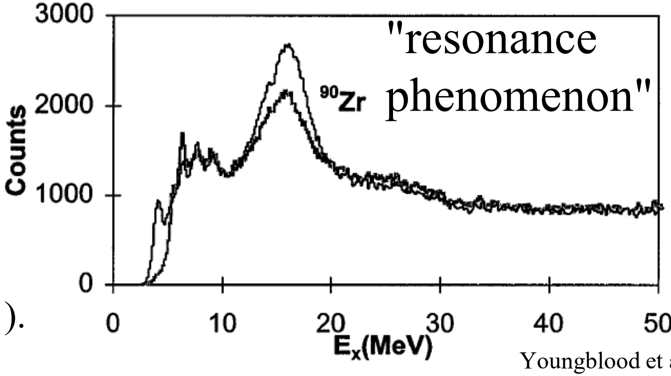
Nuclear EoS - how to measure ?

inelastic scattering of α particles on nuclei



$E_{kin} = 240$ MeV

measurement:
total energy of outgoing α particle
→ $E_x = E_{in} - E_{out}$



"resonance phenomenon"

Youngblood et al.
Phys. Rev. Lett. 82 (1999)691

energy loss of the α particle: 15 – 25 MeV

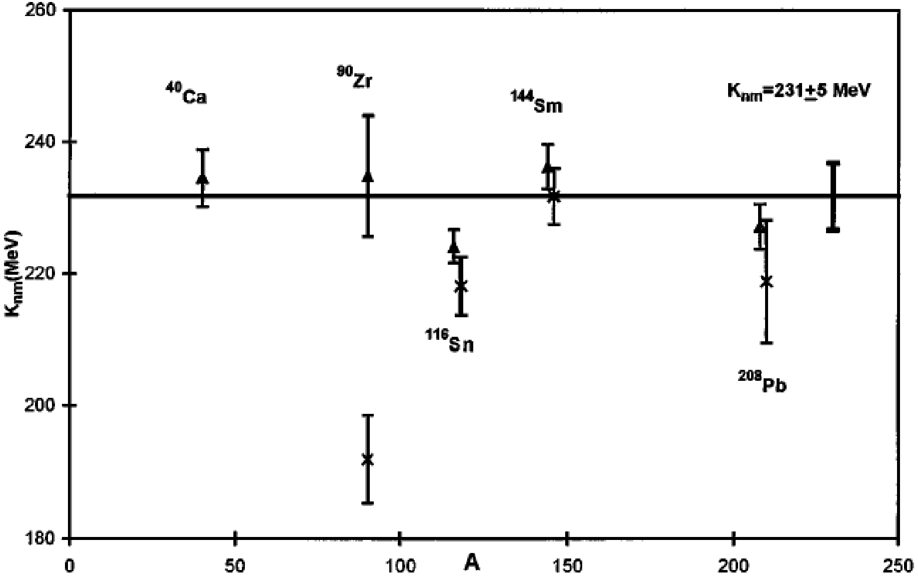
excites slight density oscillations with elongations of about 1/100 – 1/10 ρ_0 (around saturation density ρ_0).
→ **giant monopole resonance**

From the measured excitation energy distribution E_x :
→ frequency
→ restoring force (potential) of the oscillation
→ **"spring constant" κ = compression modulus**

The compression modulus κ at saturation density ρ_0

"Excitation of the Giant Monopole Resonance
by inelastic scattering of α particles on nuclei"

Youngblood et al. , Phys. Rev. Lett. 82 (1999)691



$\kappa = 231 \pm 5$ MeV

Recall & discussion

Discuss with your neighbor(s) ... 5 minutes:

How are nucleons bound to a nucleus ?
... obviously an attractive interaction, but what prevents the nucleus to collapse ?

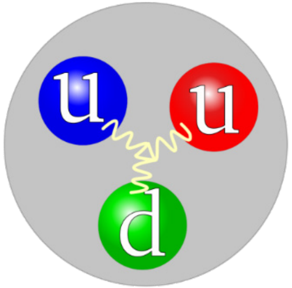
Properties of nuclear matter ? How can it be characterized ?

How to measure the properties of nuclear matter ?

... since we know that hadrons are composite objects ...

mass of hadrons ?

Proton

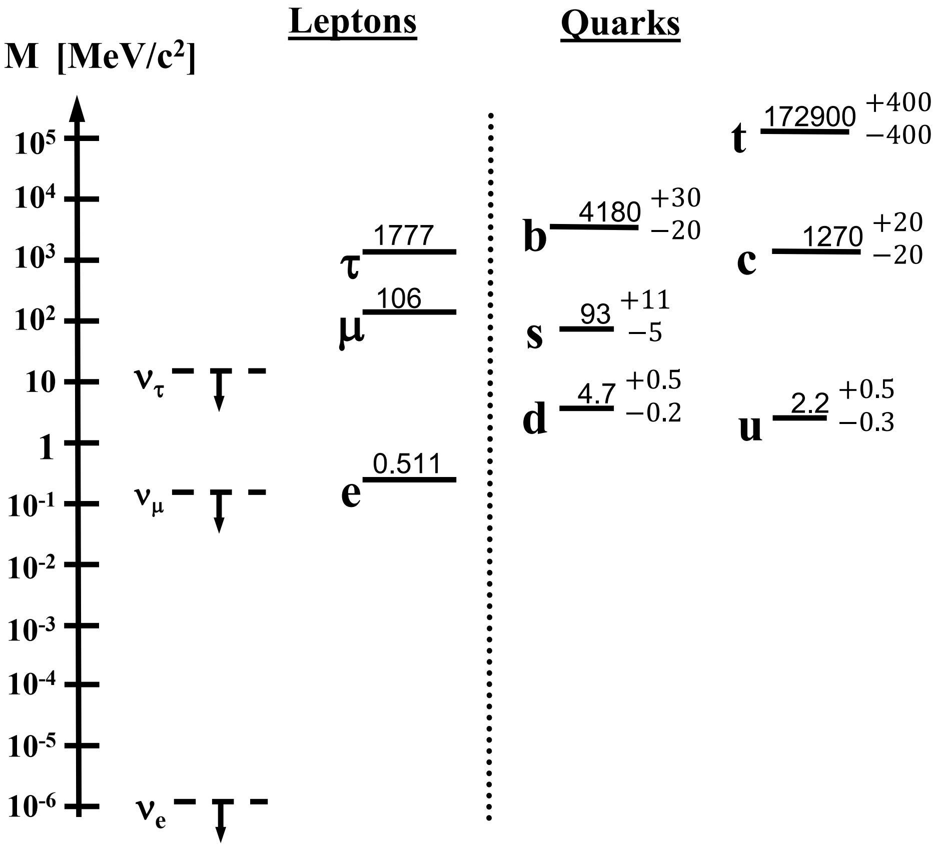


mass **not** determined
by the sum of current quark
masses !!!

Masses of elementary particles

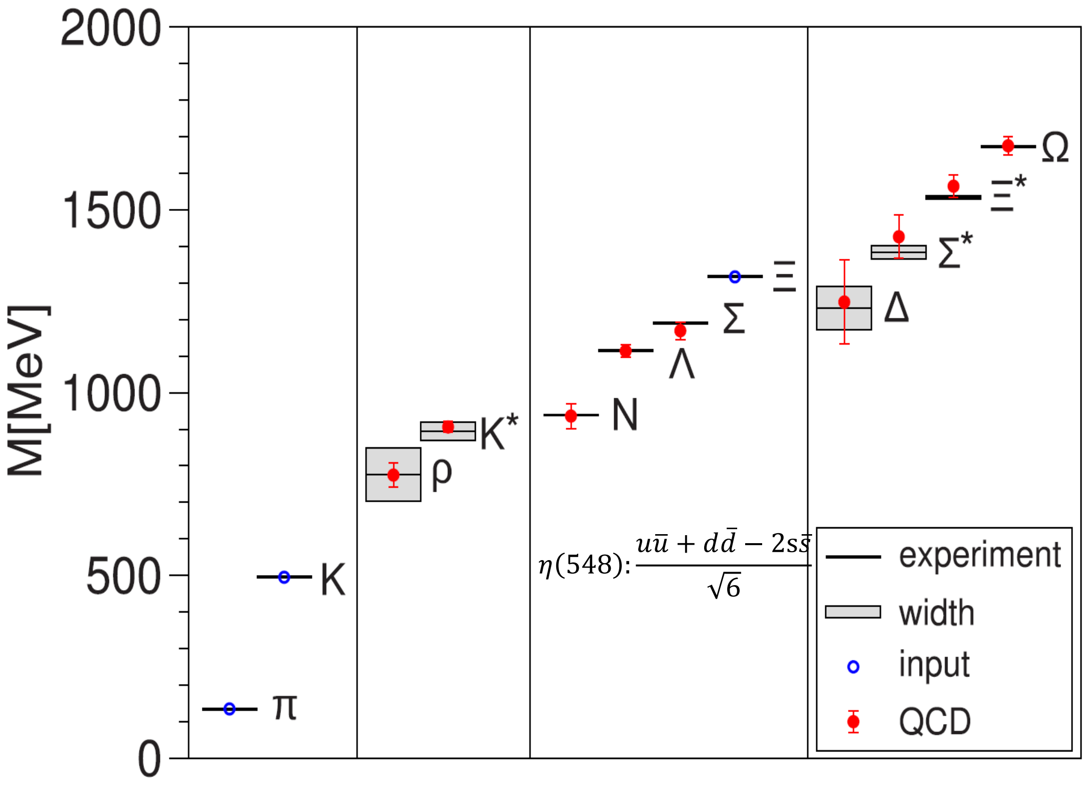
PDG PHYSICAL REVIEWD 98, 030001 (2018)

“mass” means:
current mass = weak mass



Observation: the hadronic mass spectrum

Lattice QCD
S. Dürr et al., Science 322, 1224 (2008)
Ab Initio Determination of Light Hadron Masses



$\eta(548)\text{:}\ \frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{6}}$

$\Delta^+\ (1232)\text{:}\ uud$

$\mathrm{p}\ (938)\text{:}\ uud$

$\rho^+(770)\text{:}\ u\bar{d}$

$K^+(494)\text{:}\ u\bar{s}$

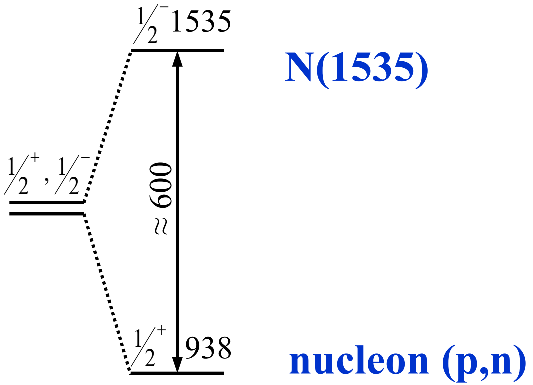
$\pi^+(140)\text{:}\ u\bar{d}$

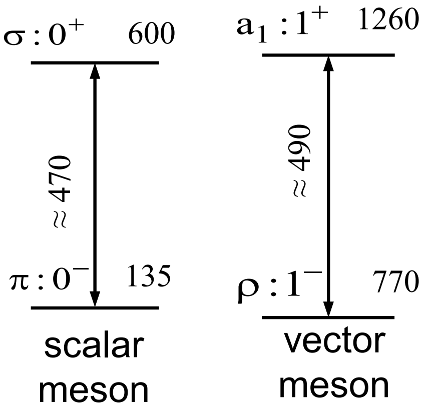
Observation: broken chiral symmetry

The QCD Lagrangian is **chirally symmetric**

“chiral” partners: same spin but opposite parity **should** degenerate in mass

p,n ↔ N(1535) (baryons) or π ↔ σ (mesons)





but in "nature" chiral symmetry **is obviously broken**!

Mass split is large, comparable to hadron masses

Chiral symmetry

explicitly broken

by small but finite quark masses

and

spontaneously broken

due to the existence of a massless mode (Goldstone-boson*)

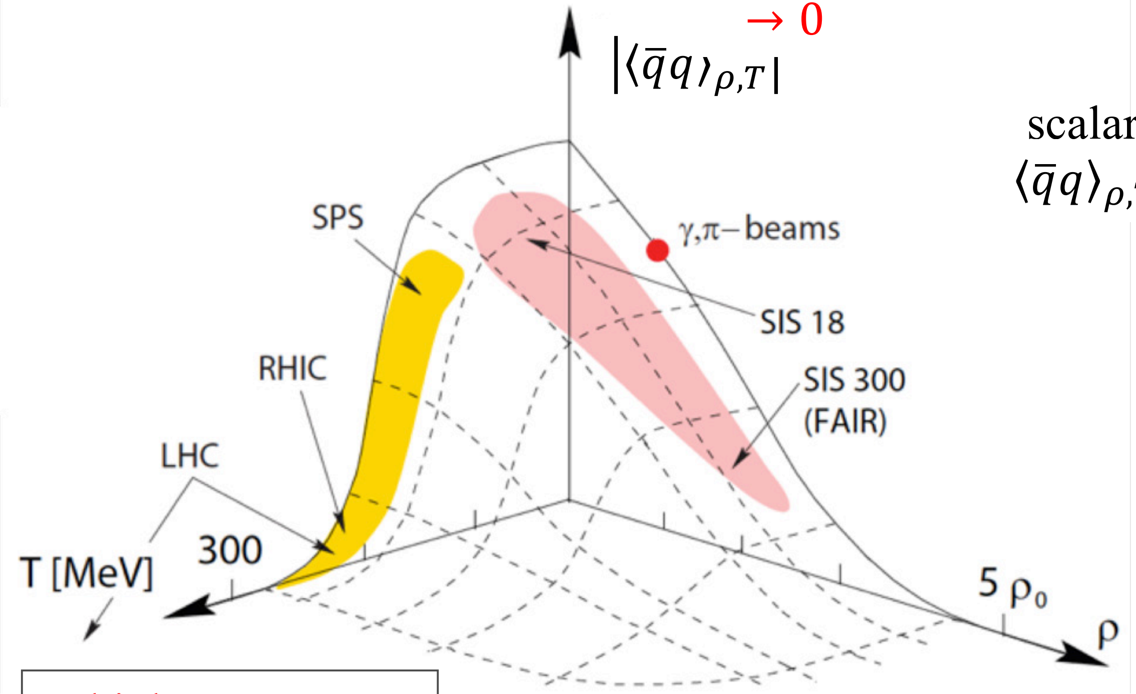
* Nambu-Goldstone boson

Consequence: chiral symmetry can be restored

According to theoretical predictions (i.e. by Lattice QCD)

chiral symmetry can be (partially) restored $\langle \bar{q}q \rangle_{\rho,T} \rightarrow 0$

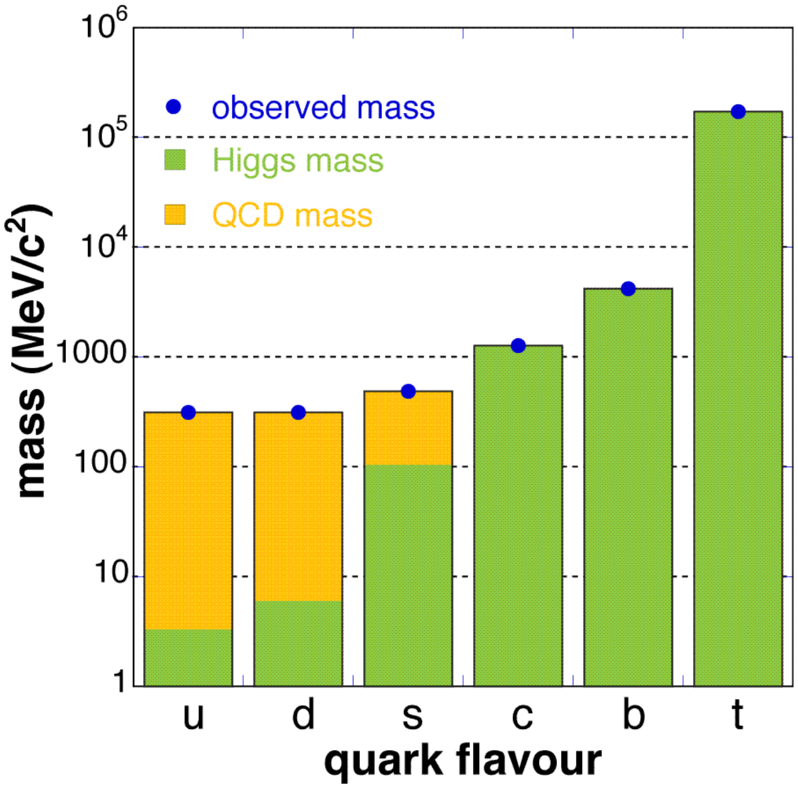
scalar quark condensate $\langle \bar{q}q \rangle_{\rho,T}$



at high temperature

at large baryon density

The strong interaction and the origin of hadron masses

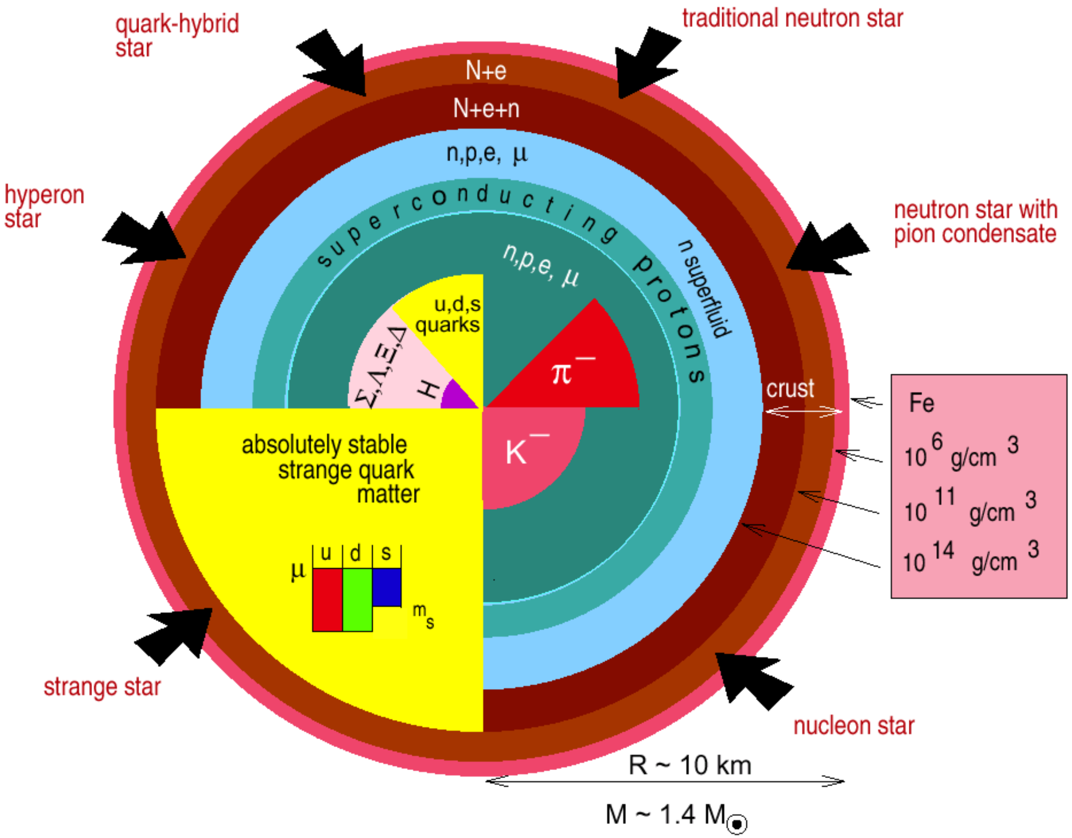


not valid
for the light
pseudo-scalar mesons
π , η and K

Composition of a neutron star

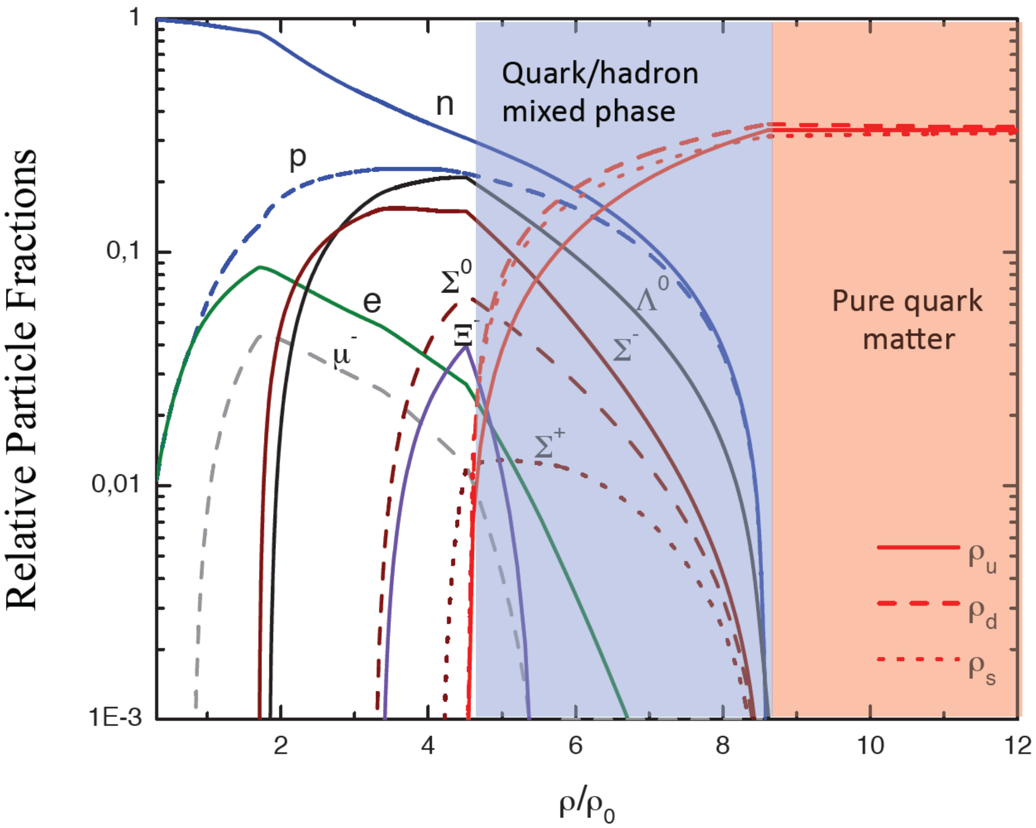
Each arrow indicates a different model for the neutron star.

Each model is based on assumptions on nuclear matter properties!



F. Weber,
J.Phys. G27 (2001) 465

Quark matter in massive neutron stars?



Equation-of-State:

Non-local SU(3) NJL with vector coupling

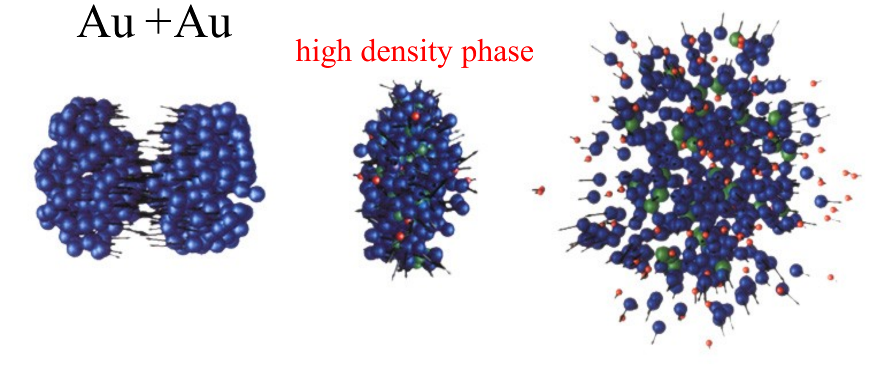
M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657

Recall & discussion

Discussion with your neighbor(s) ... 5 minutes:

Neutron stars - the enormous gravitational force compresses the matter inside the core to several times of normal nuclear matter ... 5 - 10 ρ_0 . How does the properties of nuclear matter influence this balance ?

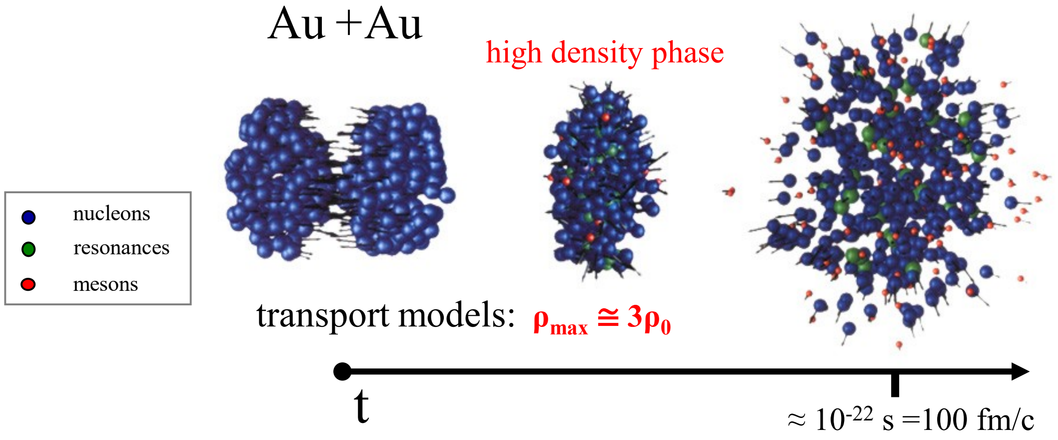
The nuclear equation-of-state at $\rho_B > \rho_0$?



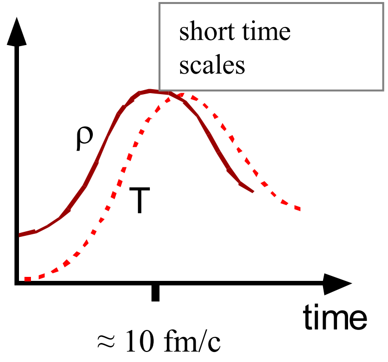
nucleus-nucleus collisions

Relativistic nucleus-nucleus collisions at SIS18

QMD , S. Bass , Uni. Frankfurt



transport models: $\rho_{max} \cong 3\rho_0$

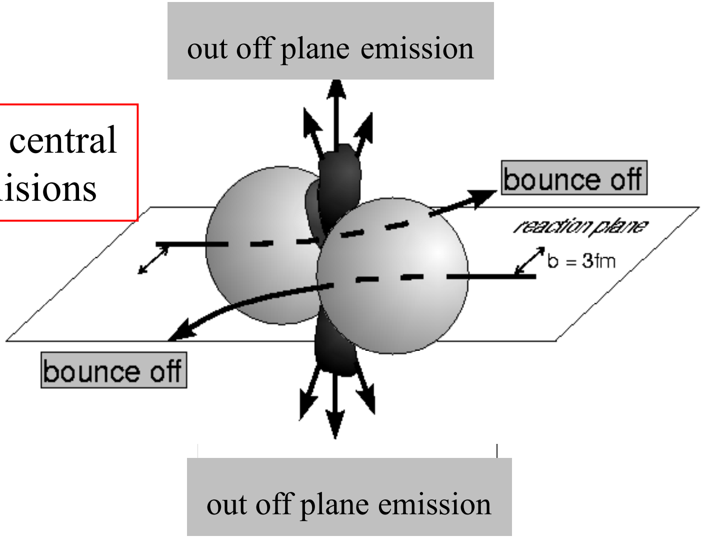


at SIS18 (max. 2 AGeV in A+A):
$\rho_B \approx 1 - 3\ \rho_0$, $T \approx 70 - 100$ MeV

note:
system not necessarily equilibrated

Azimuthal particle emission

semi central collisions

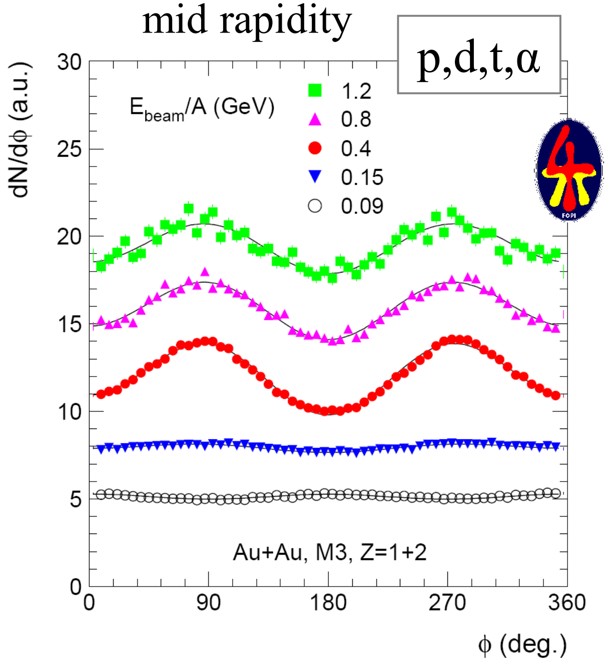


out off plane emission

out off plane emission

mid rapidity

p,d,t,α



<u>Fourier expansion of the dN/dφ distribution:</u>

$$\frac{dN}{d\phi} \sim [1 + 2v_1 \cdot \cos(\phi) + 2v_2 \cdot \cos(2\phi)]$$

the coefficients quantify :

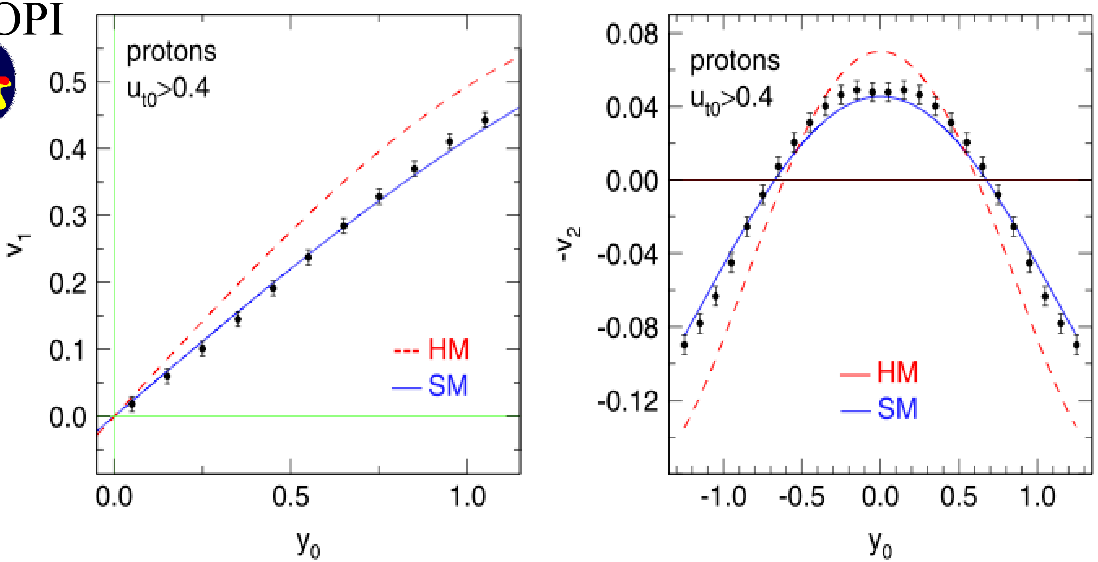
- v_1 the in-plane and
- v_2 the elliptic emission pattern

named as well as: v_1 directed flow , v_2 elliptic flow

Elliptic flow and the nuclear equation-of-state

W. Reisdorf et al. (FOPI), Nucl. Phys. A 876 (2012) 1

FOPI



Au+Au 1.5 AGeV

$y_0 = y - y_b$

IQMD transport calculation

SM: soft equation-of-state (by effective NN force), momentum dependent force

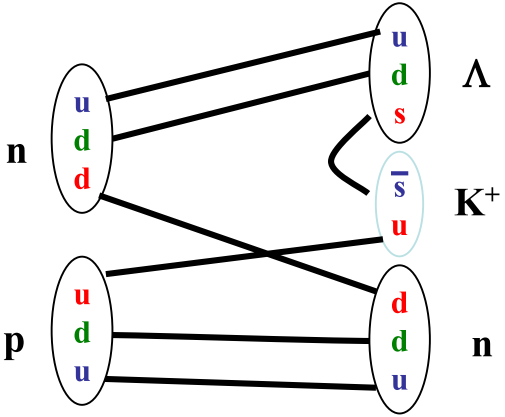
→ IQMD-SM describes $v_2(y_0)$ for $E_{lab} = 0.15$ AGeV to 1.5 AGeV !

The creation of strange mesons in elementary reactions

associate production !

K^+ mesons

$m = 493.7\ \mathrm{MeV}/c^2$

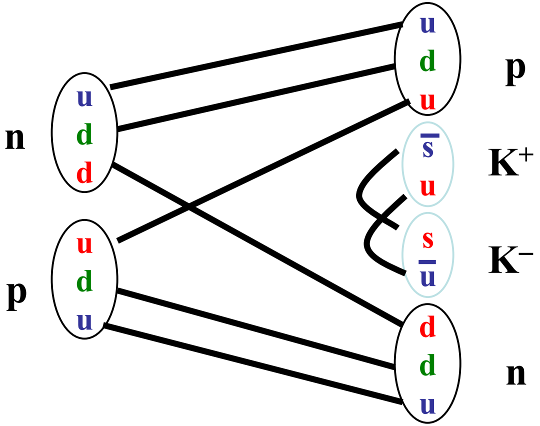


production threshold
(in lab. frame)

$$E_{lab} = 1.58\ GeV$$

K^- mesons

$m = 493.7\ \mathrm{MeV}/c^2$



production threshold
(in lab. frame)

$$E_{lab} = 2.5\ GeV$$

Additional channels in A+A collisions

e.g.

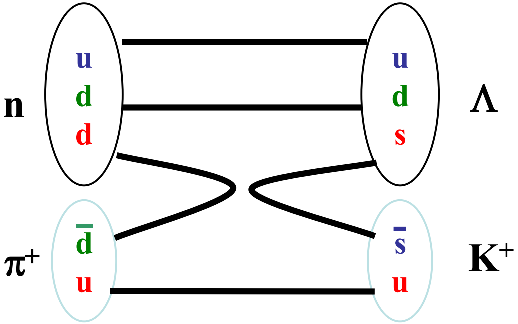
$$NN \rightarrow N\Delta$$

$$N\Delta \rightarrow NK^+Y$$

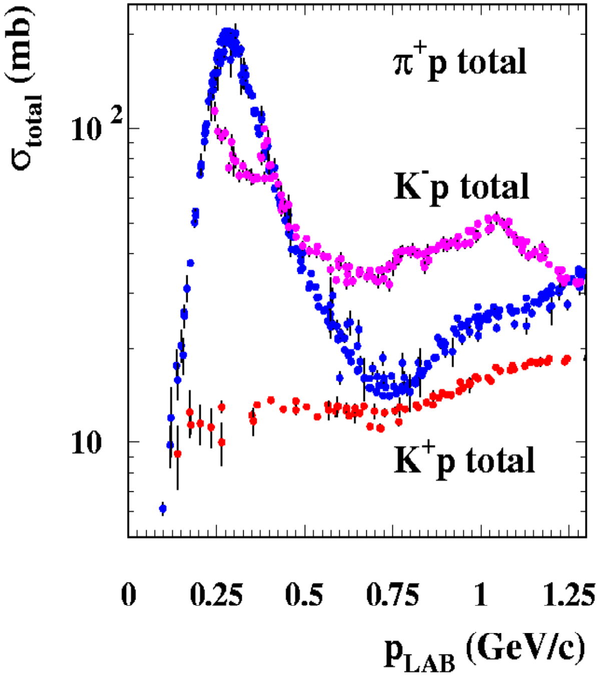
$$\pi N \rightarrow K^+Y$$

$(Y=\Lambda,\Sigma)$

multi step processes !



... and final state interaction !



The compression modulus of nuclear matter (ρ > ρ0)

Experiment: CS, Phys. Rev. Lett. 86 (2001) 39

Theory: QMD C. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649

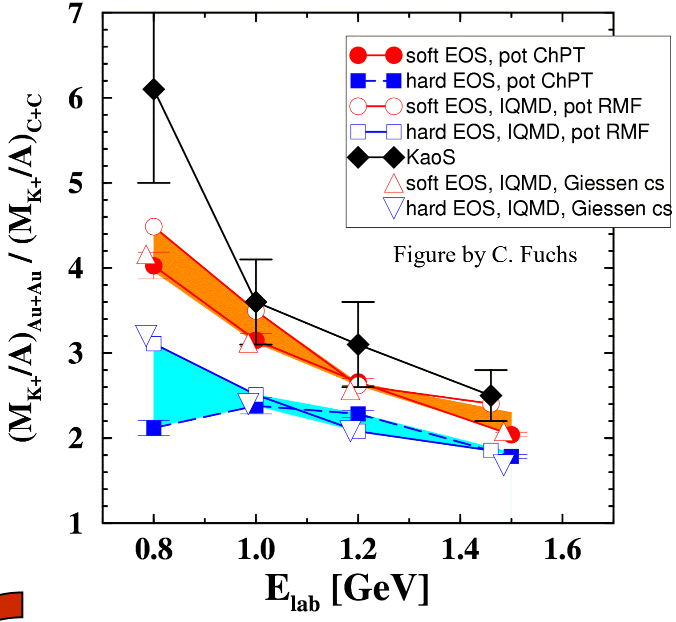
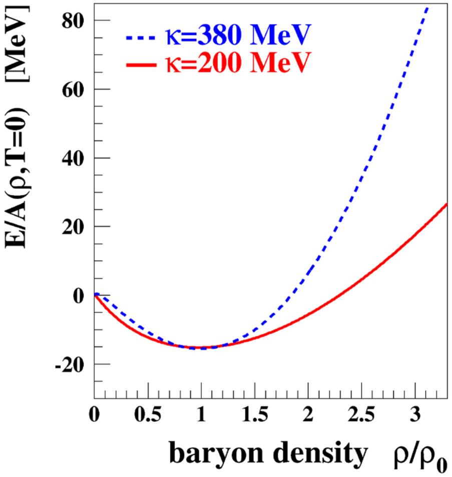


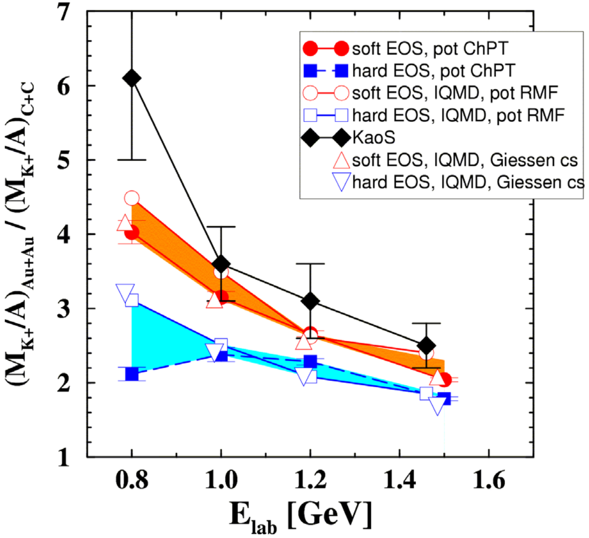
Figure by C. Fuchs



“soft” nuclear equation-of-state: $\kappa \approx 200$ MeV

Nuclear equation-of-state at high (net) baryon densities

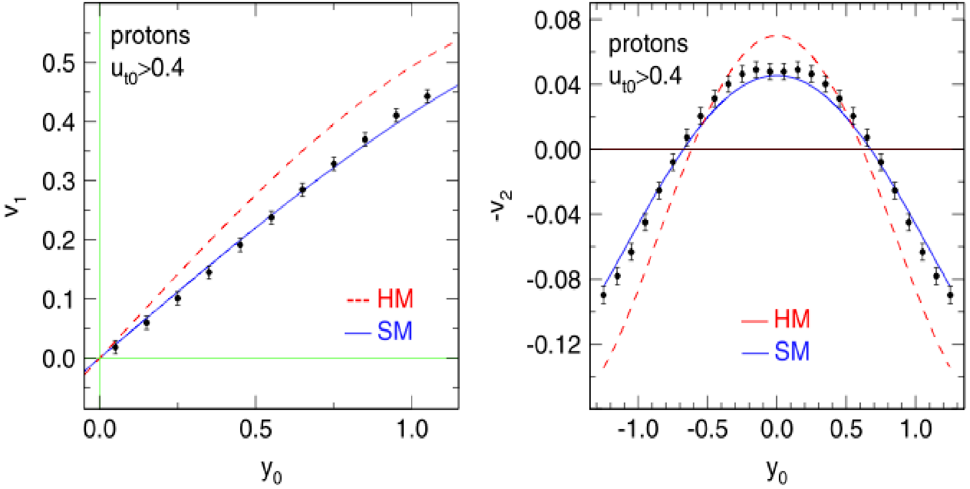
Experiment: CS et al., Phys. Rev. Lett. 86 (2001) 39
Theory: RQMD C. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649



FOPI

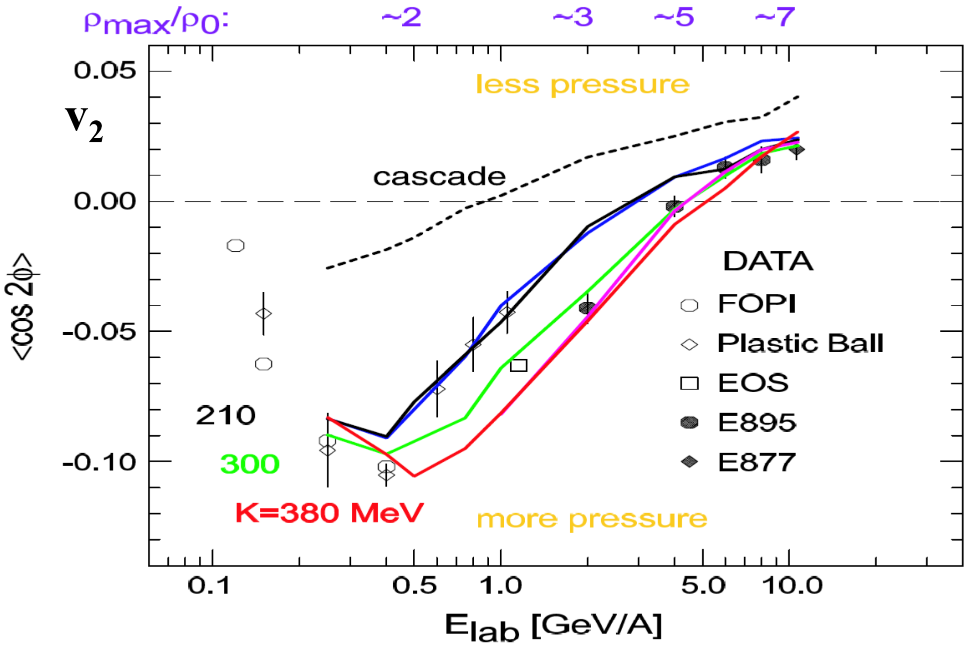
Au+Au 1.5 AGeV

W. Reisdorf et al. (FOPI), Nucl. Phys. A 876 (2012) 1



Nuclear equation-of-state at high (net) baryon densities

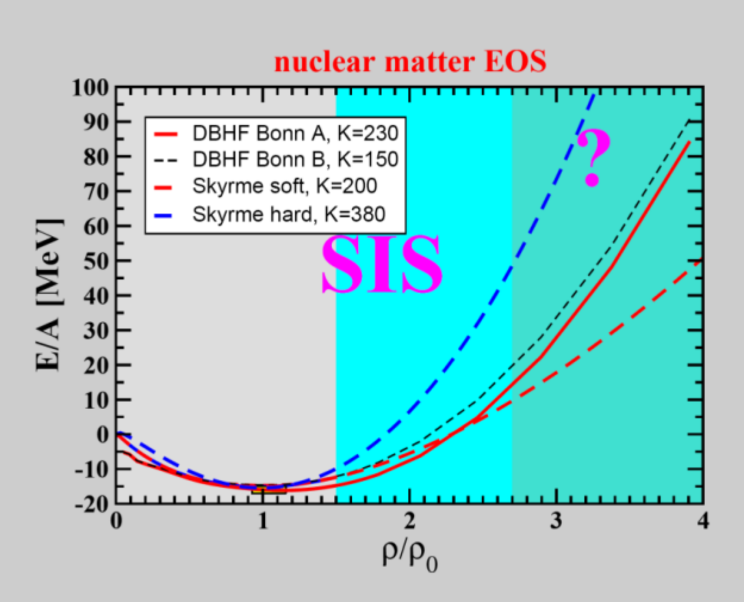
P. Danielewicz et al., Science 298 (2002) 1592



consistent picture at
SIS18 energies ($1.5 < \rho / \rho_0 < 3.0$)

inconclusive at AGS energies

Nuclear equation-of-state at the **highest** (net) baryon densities

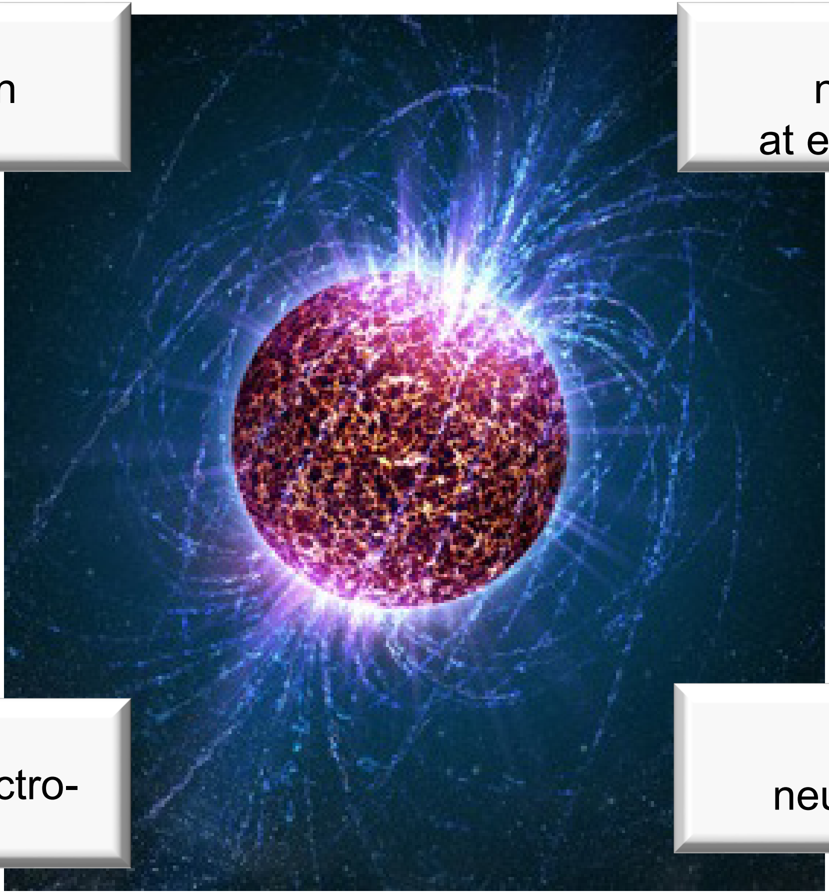


DBHF: E. N. E. van Dalen, C. Fuchs, A. Faessler
EPJ. A 31,29 (2007)

equation-of-state
at
neutron star core densities ?

→ (sub-threshold) production
of $\Omega^+(\bar{s}\bar{s}\bar{s})$ at FAIR energies ?
- refined to the high-density phase
- small final-state interaction

FAIR - Cosmic Matter in the Laboratory



PANDA
hyperon-hyperon interaction

CBM
nuclear matter
at extreme densities

APPA
ions in extreme electro-magnetic fields

NUSTAR
neutron-rich nuclei

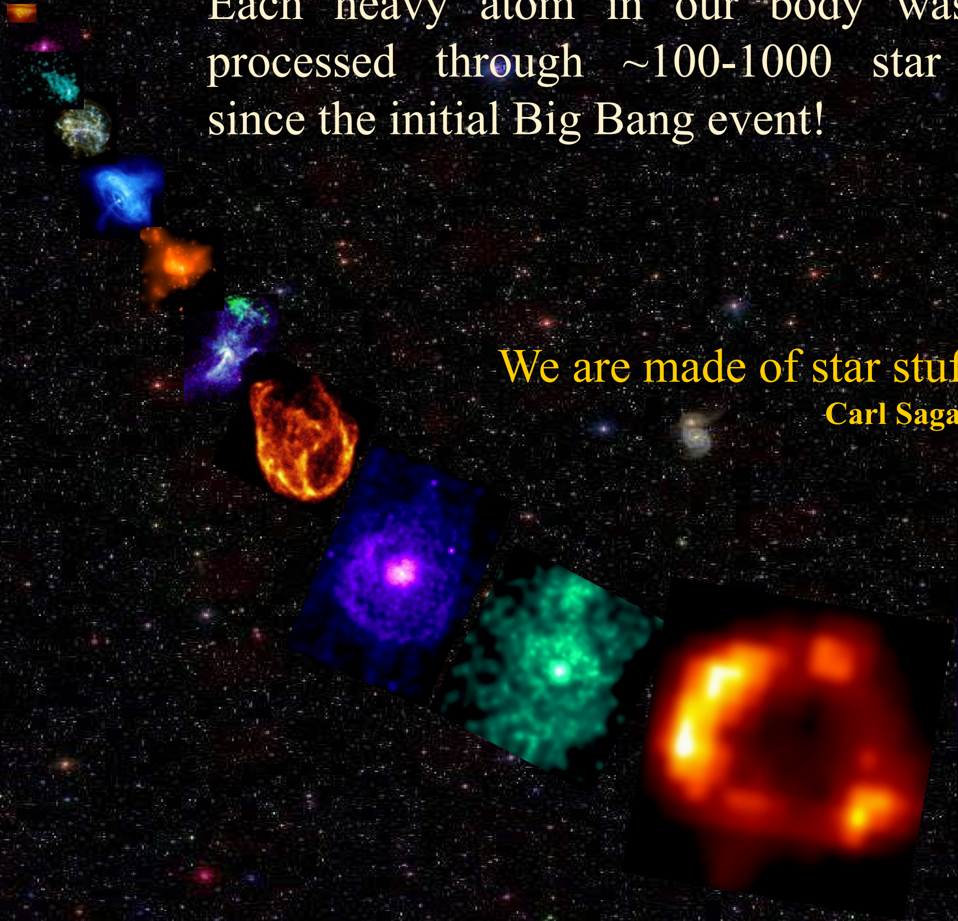
Recall & discussion

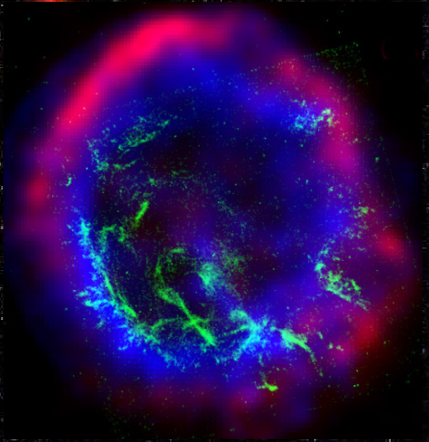
Discuss with your neighbor(s) ... 5 minutes:

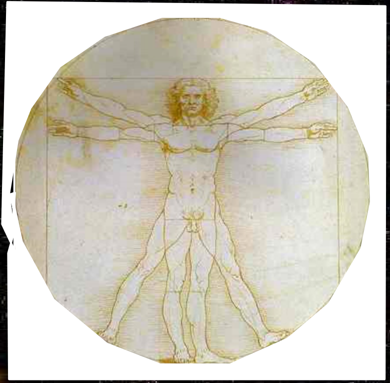
Astronomical observation and laboratory experiments - how do they complement regarding the description of neutron stars ?

backup slides ...

Each heavy atom in our body was build and processed through ~100-1000 star generations since the initial Big Bang event!





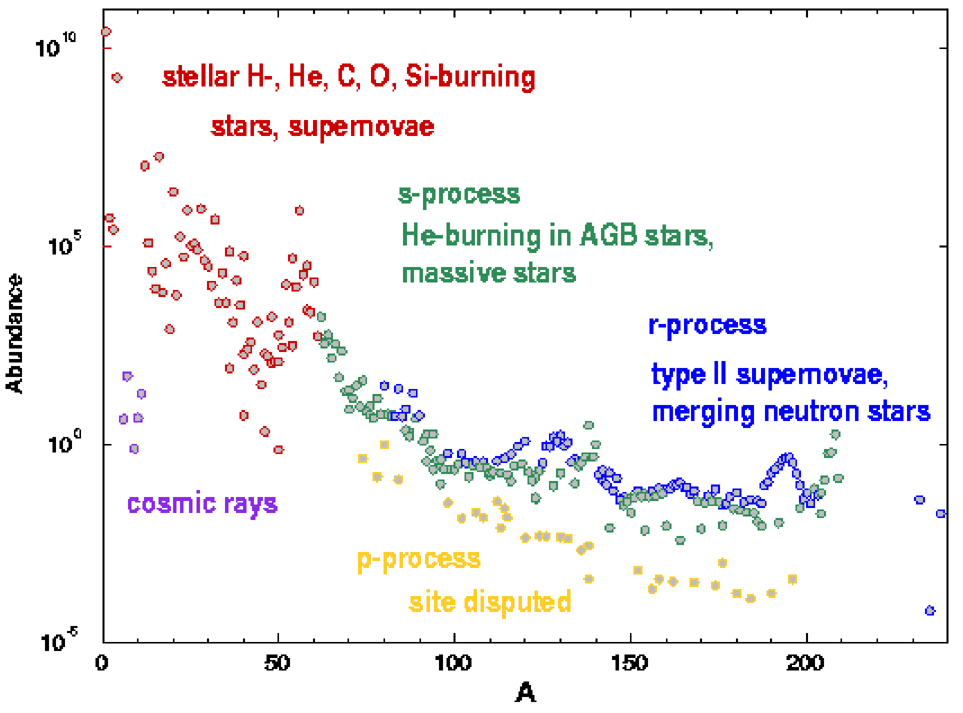


We are made of star stuff

Carl Sagan

Signatures of Nucleosynthesis

stellar abundance distribution

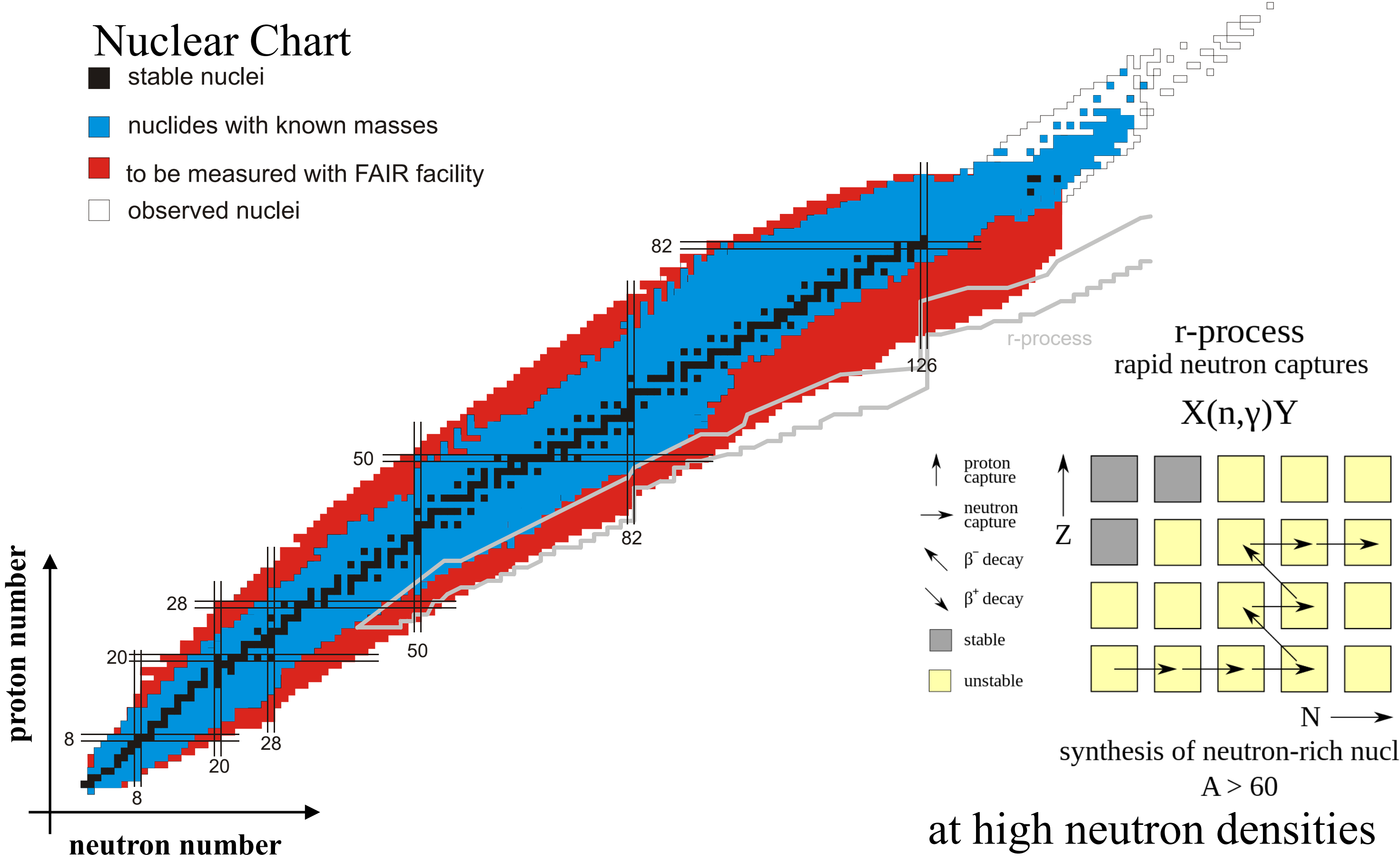


nucleosynthesis processes

nucleosynthesis history of our universe

stellar abundance distribution = reflection of nuclear structure and stability!

NUSTAR: Nuclear Structure, Astrophysics, Nuclear Reactions



Nuclear Chart

- ■ stable nuclei
- 🟦 nuclides with known masses
- 🟥 to be measured with FAIR facility
- ☐ observed nuclei

r-process

rapid neutron captures

$X(n,\gamma)Y$

synthesis of neutron-rich nuclei

$A > 60$

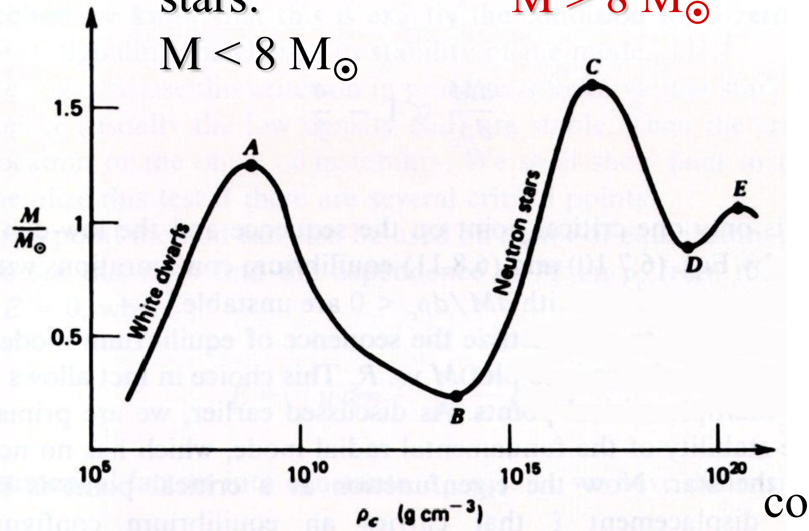
at high neutron densities and high temperatures

Summary: final states of stars

stars:
$M < 8\,M_\odot$

$M > 8\,M_\odot$

core mass



calculation !

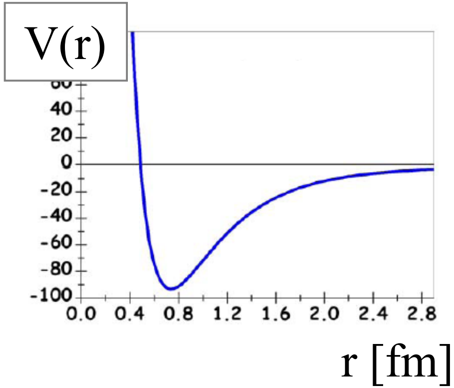
core density

stabilization mechanism :

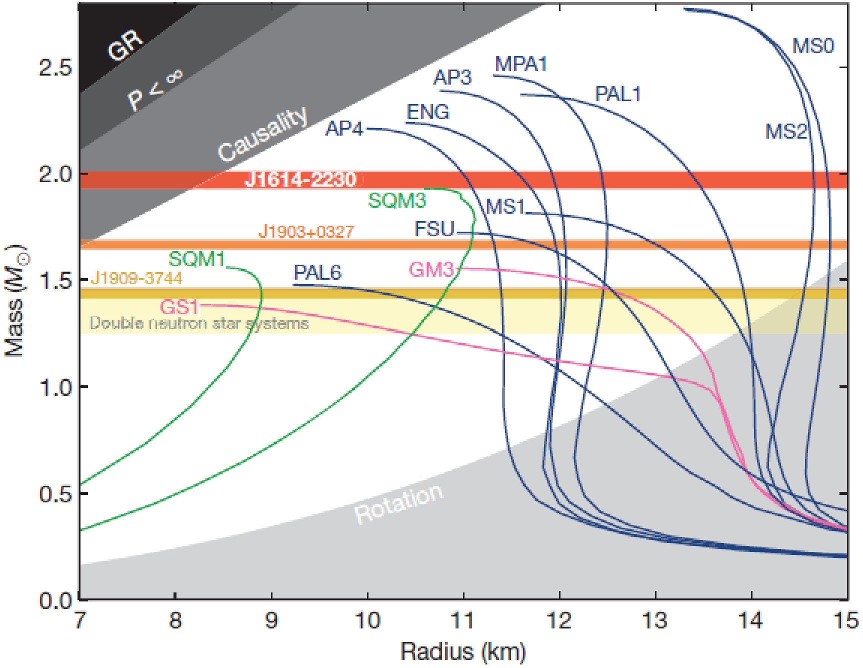
degeneracy pressure of electrons

degeneracy pressure of neutrons

+ repulsive component of the strong force



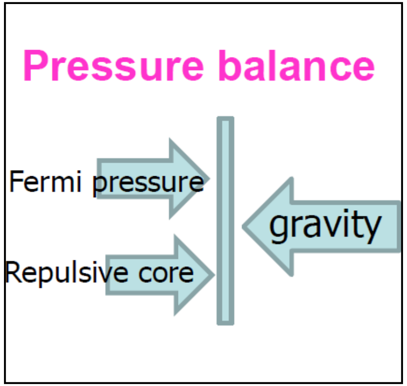
Neutron star mass-radius relation



doi:10.1038/nature09466

constraints to EoSs

- nucleons
- nucleons + exotic matter
- strange matter



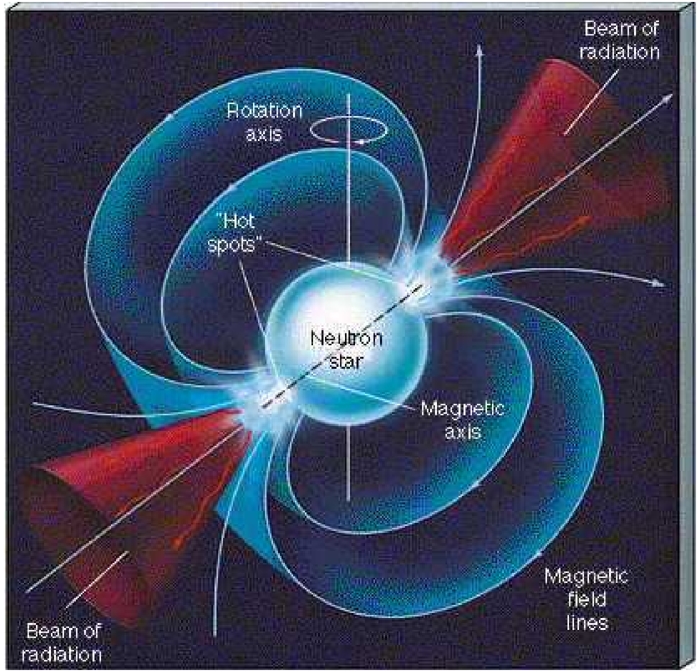
Pressure balance

Fermi pressure

Repulsive core

gravity

Light-House pulsar model



The rotating neutron star with a strong magnetic field emits synchrotron radiation from high energy electrons !

- **focused radiation** (x-ray to radio)
- frequency f = 0.25 - 1000 Hz
- magnetic field B = $5 \cdot 10^{12}$ Gauss
- “age” $\boldsymbol{\tau} = P/(2\ dP/dt)$

- radius ≈ 10 km
- mass ≈ 1.5 $M_{\odot}$

  $\Rightarrow$ 3-10 ρ_0