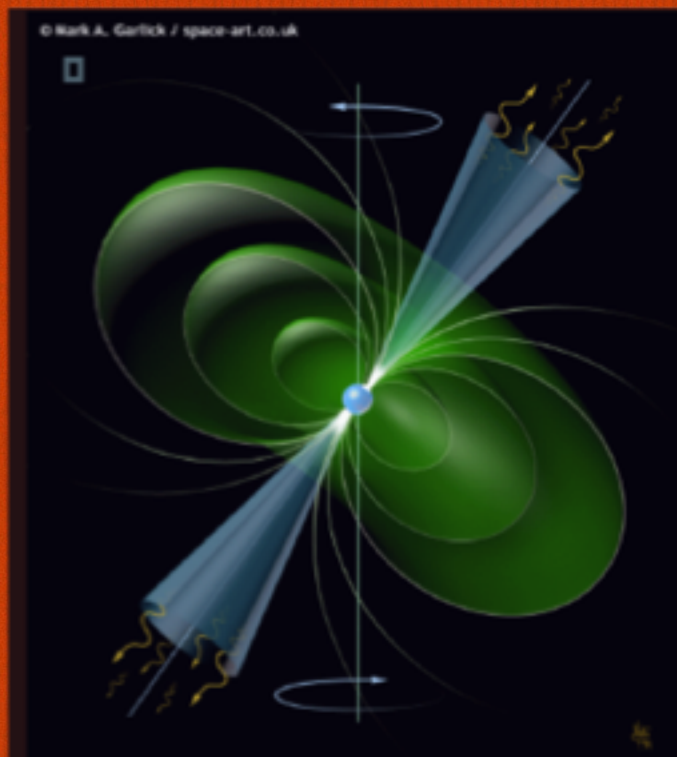
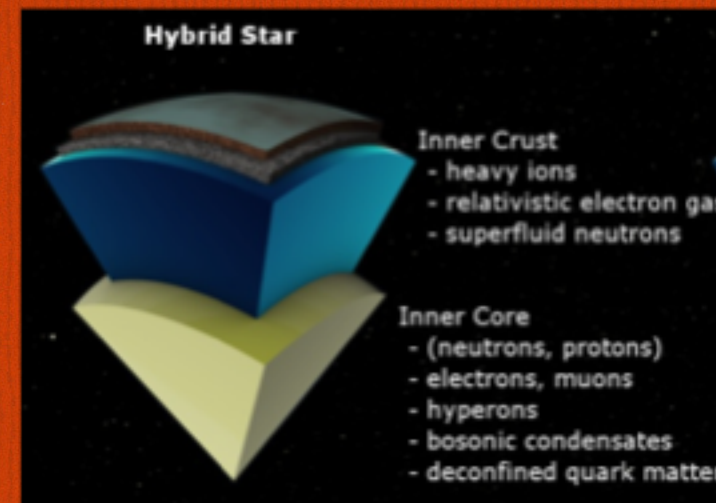
Facts about Neutron Stars



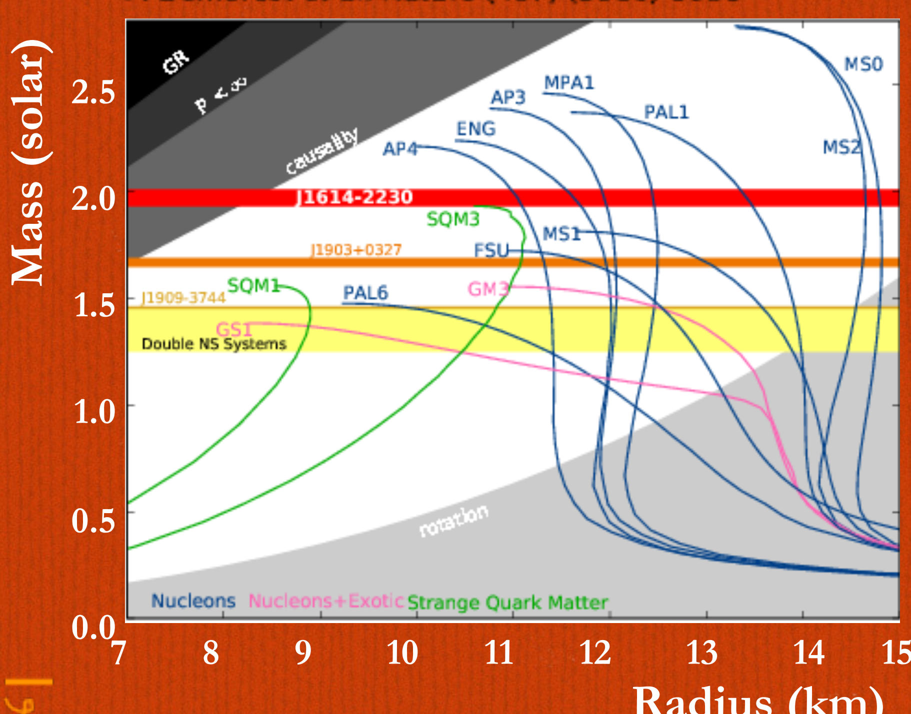
R ~ 10-15 km

M ~ 1.5 $M_\odot$

density



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

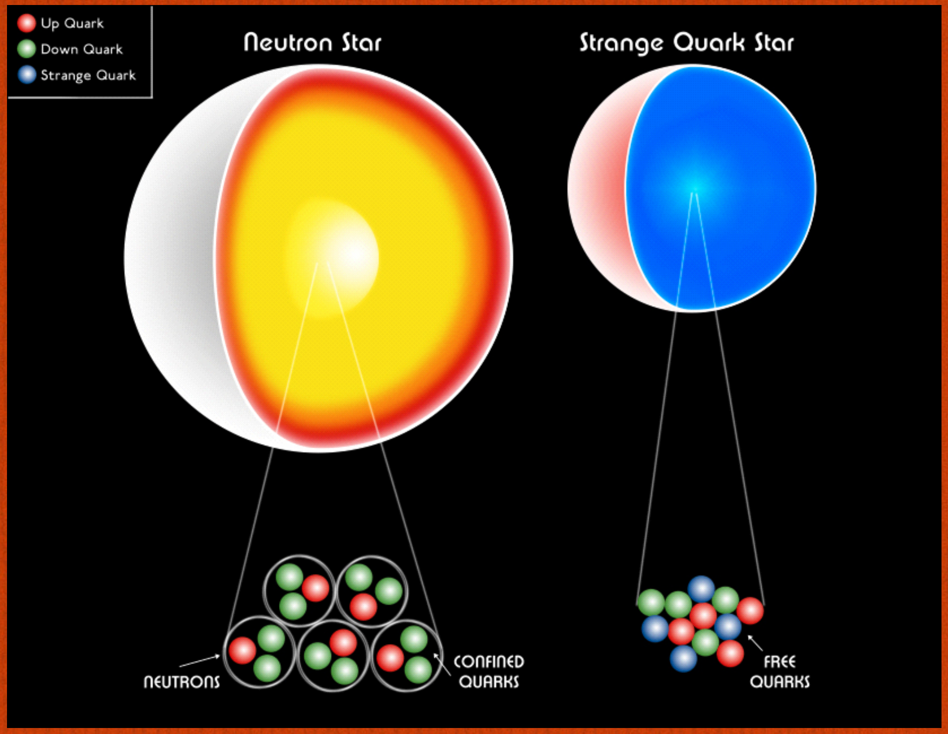


- Very high density in the interior
- Strong magnetic fields
- Rotating object emitting Synchrotron radiation in Radio-Frequency (Pulsar character)
- Mass measured in binary systems with White Dwarfs (Shapiro Delay, WD Spectroscopy)
- Radius Measurement very difficult
- Masses ranging from 1.4 $M_\odot$ to 2 $M_\odot$

What is inside Neutron Stars??

Speculations about Neutron Stars

NSF, universetoday.com



- Hadron composition
  - Only Nucleons
  - Antikaons-Nucleons condensate
  - Nucleons and Hyperons
- Nuclear Pasta
  - lasagne
  - spaghetti
- Quark star (Color super-conducting strange quark matter)

For each assumption about the content the specific Equation of State (EOS) should be determined to check whether this matches the NS Data

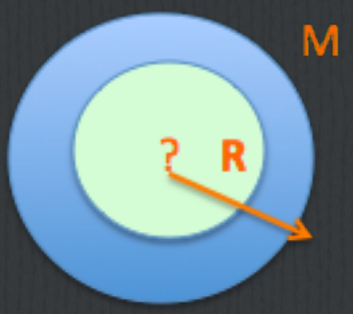
How to test different Hypotheses

1) Equation of State (EOS): How pressure depends on density
2) This equation is defined by a parameter we call <u>Compressibility</u>

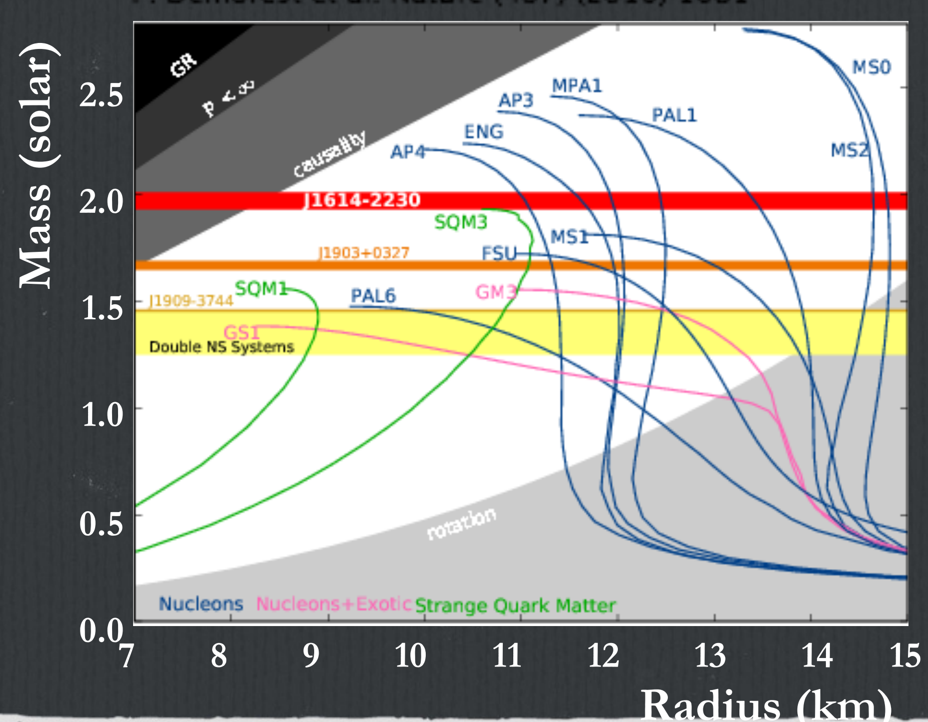
<u>Soft EOS:</u> matter can be compressed easily
Stiff <u>EOS:</u> compression becomes difficult

2) Given an object with a certain density the internal pressure must be compensated by gravity

3) From P(R)=0 -> the relation M(R) can be determined for each EOS as a function of the assumed density



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

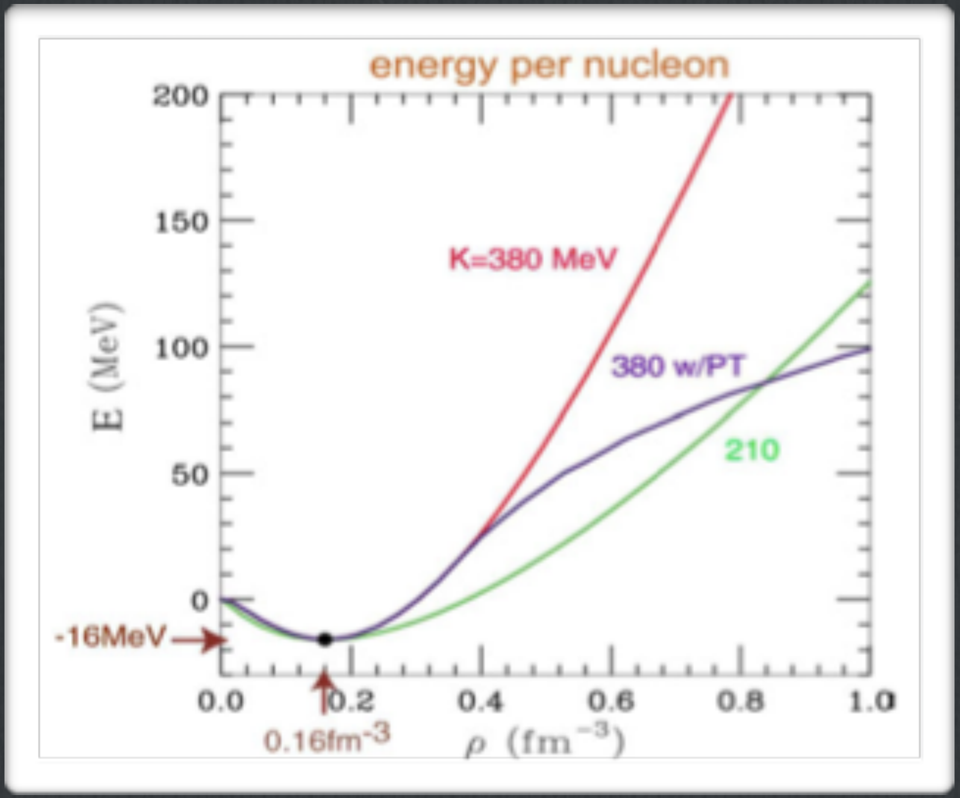


$\varrho = 2\text{-}8\ \varrho_0$

It is not so easy to fix the density but the EOS must cross the measured values of the masses!

Determination of the EOS of nuclear matter

P. Danielewicz nucl-th/0512009



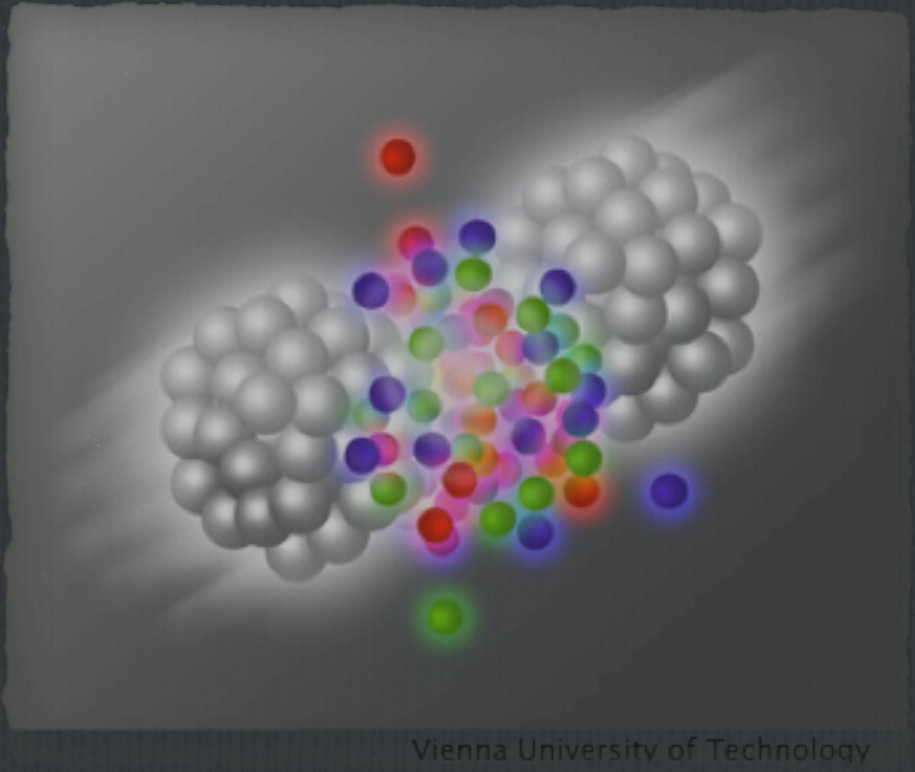
$$E = \alpha \cdot \rho + \beta \cdot \rho^{\gamma}$$

The compressibility parameter :

$$K = 9\rho_0^2 \frac{d^2}{d\rho^2}\left(\frac{E}{A}\right)$$

Soft EOS : K< 290 MeV
Stiff EOS: K> 290 MeV

Tool: Particle Production in heavy ion collisions



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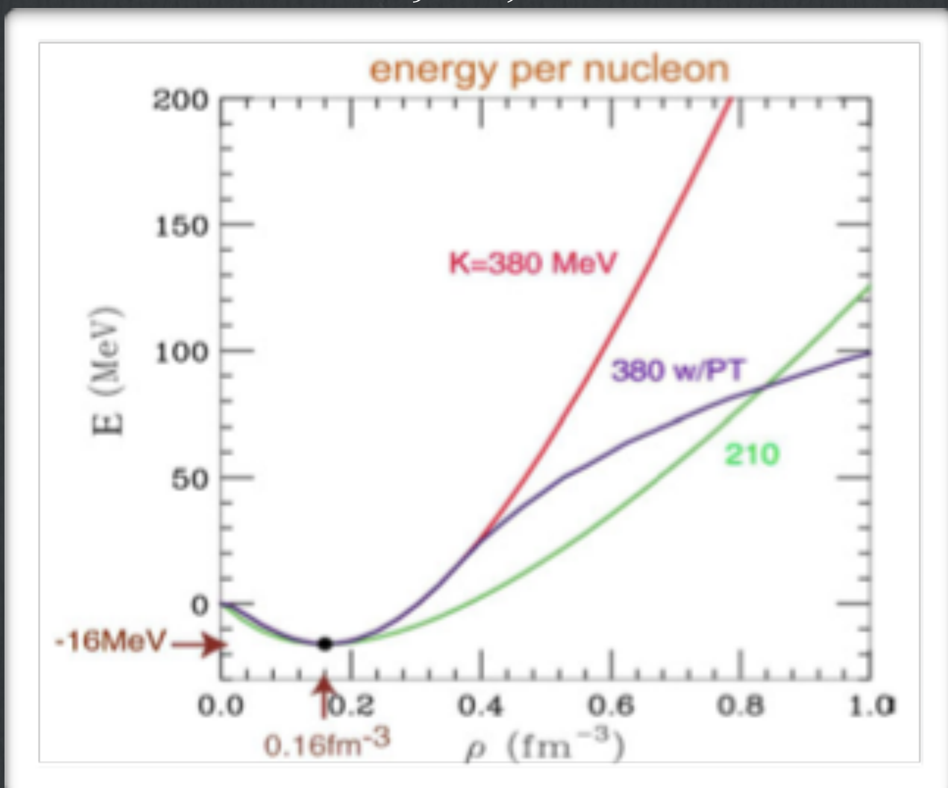


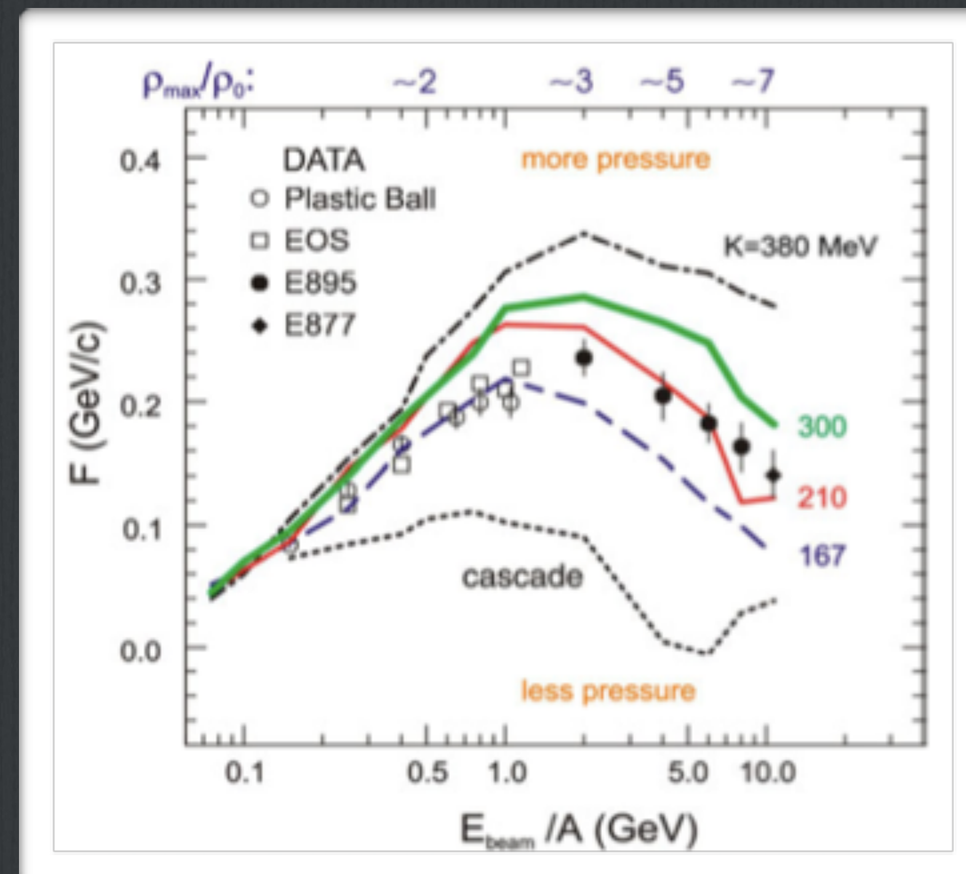
$$E = \alpha \cdot \rho + \beta \cdot \rho^{\gamma}$$

The compressibility parameter :

$$K = 9\rho_0^2 \frac{d^2}{d\rho^2}\left(\frac{E}{A}\right)$$

Soft EOS : K< 290 MeV
Stiff EOS: K> 290 MeV

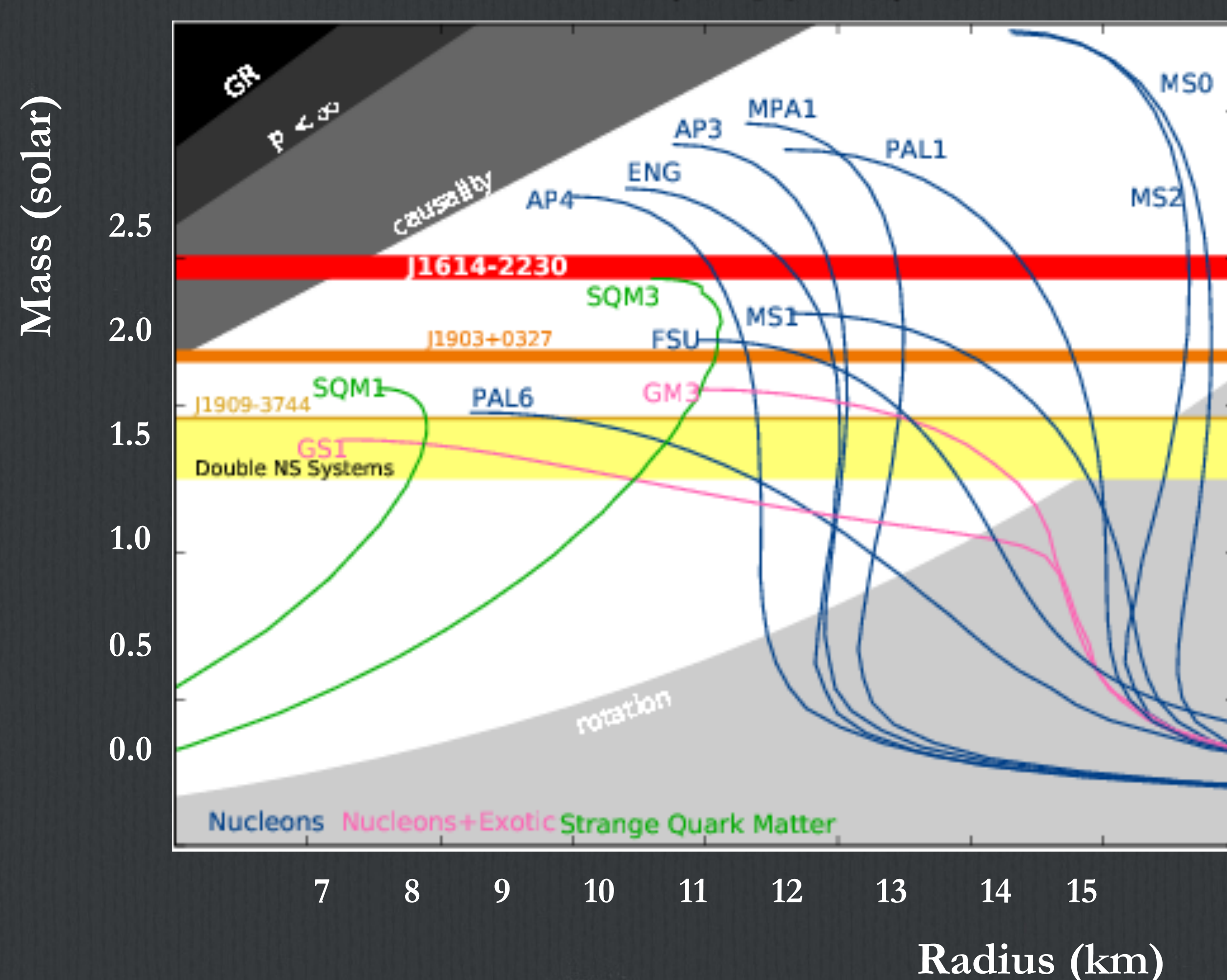
$$F = \left.\frac{dp_X}{dY_{CM}}\right|_{Y_{CM}=0}$$



<u>Soft EOS</u> from particle production in Heavy Ion Collisions

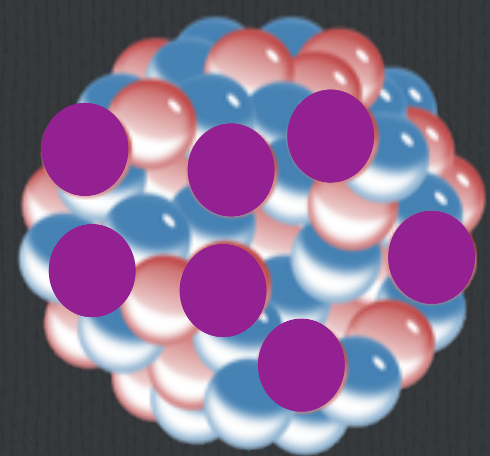
Large Masses Issue

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



- Production of strangeness is energetically favourable
- It relieves the Fermi pressure of neutrons and protons
- But… a decrease of the pressure softens the EOS
- Decrease of the maximum mass of neutron stars
- 2 $M_\odot$ neutron star measured
- EOS cannot be too soft
- Some EOS are disfavoured, for example Antikaon condensate

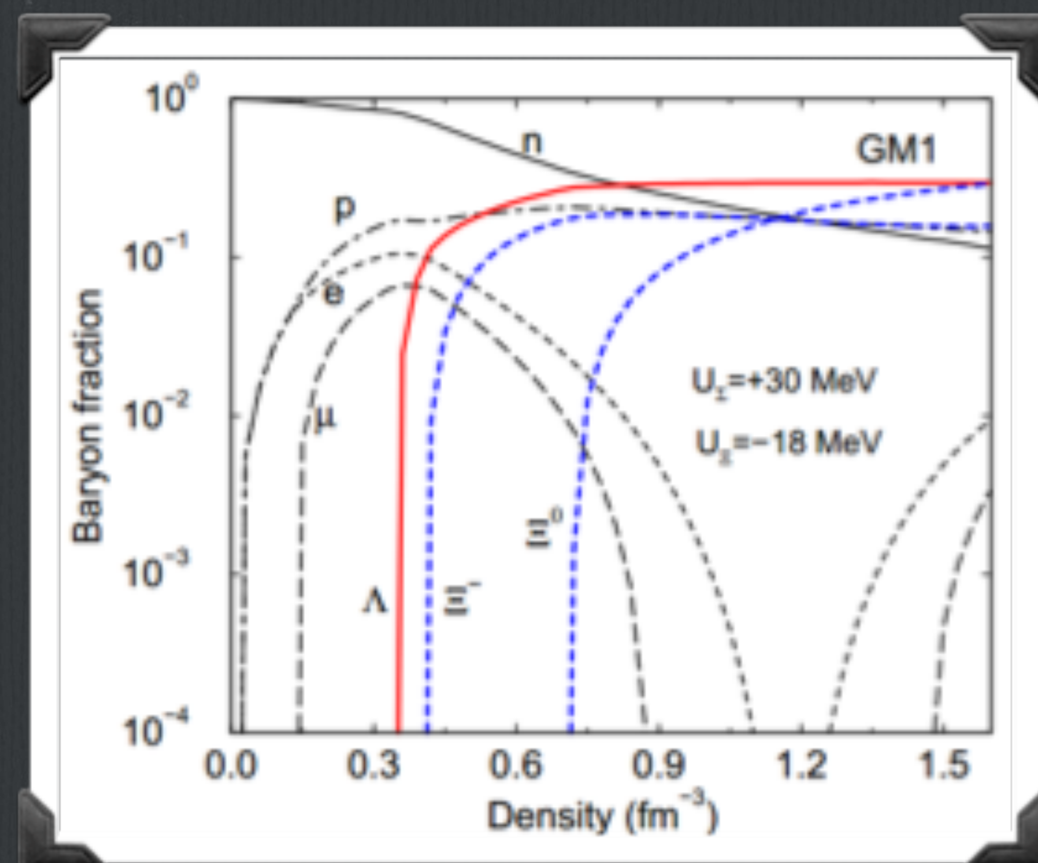
Hyperon Star



Neutron

Λ

J. Schaffner-Bielich, **NPA 804** (2008)



ϱ_0 $2\varrho_0$ $3\varrho_0$ $4\varrho_0$ …..

Possible Processes:

$$n + n \rightarrow n + \Lambda$$

$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

$$n + n \rightarrow p + \Sigma^-$$

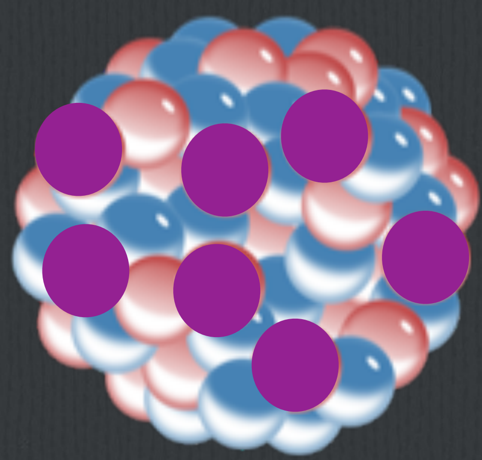
$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

Strangeness violation possible due to large time scale of NS

Appearance of Hyperon already starting at $2\varrho_0$

This scenario might also be problematic for large masses ($\sim 2M_\odot$) since the hyperon appearance implies new degree of freedom and hence a softening of the EOS

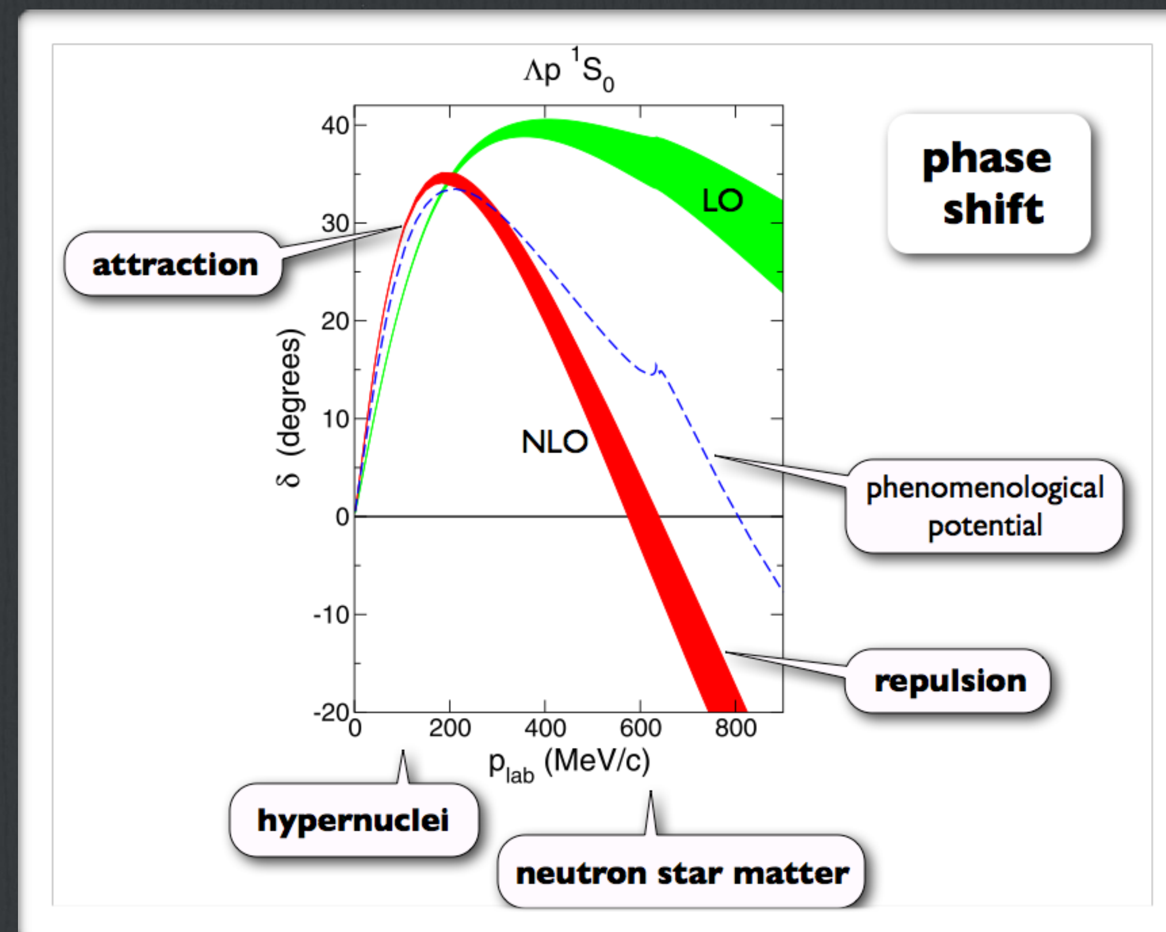
Hyperon Star



Neutron

Λ

J. Haidenbauer, S. Petschauer et al., Nucl. Phys. A 915 (2013) 24



$\longleftarrow$ **Λ-p distance**

Possible Processes:

$$n + n \rightarrow n + \Lambda$$

$$p + e^- \rightarrow \Lambda + \nu_{e^-}$$

$$n + n \rightarrow p + \Sigma^-$$

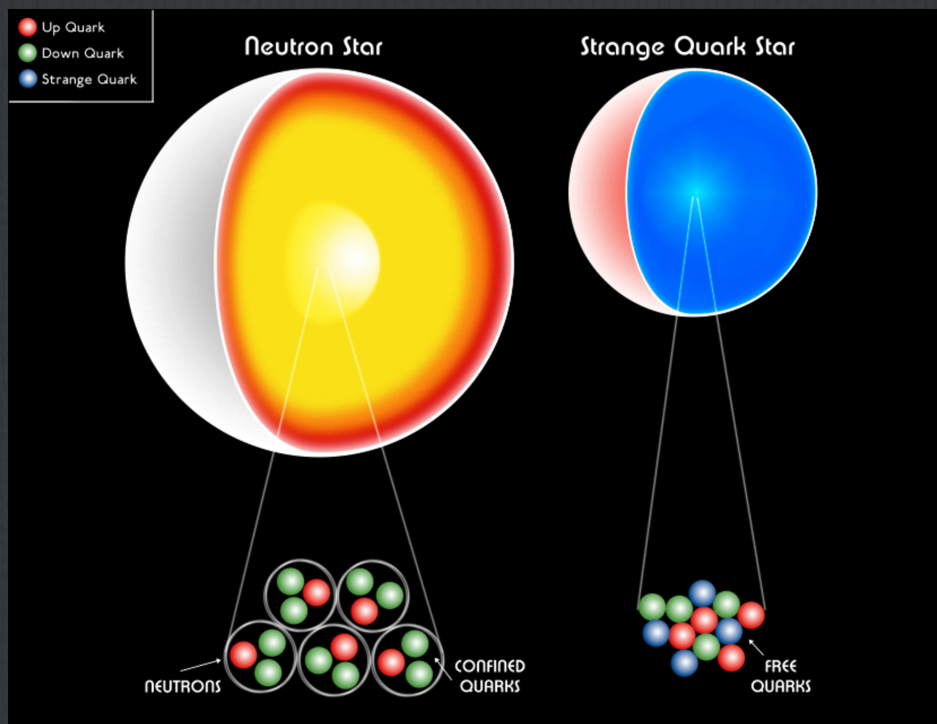
$$n + e^- \rightarrow \Sigma^- + \nu_{e^-}$$

It all depends upon the **Λ-N** and **Λ-NN** interaction and whether or not it has a repulsive core

This repulsive core could stiffen again the EOS allowing for heavy neutron stars

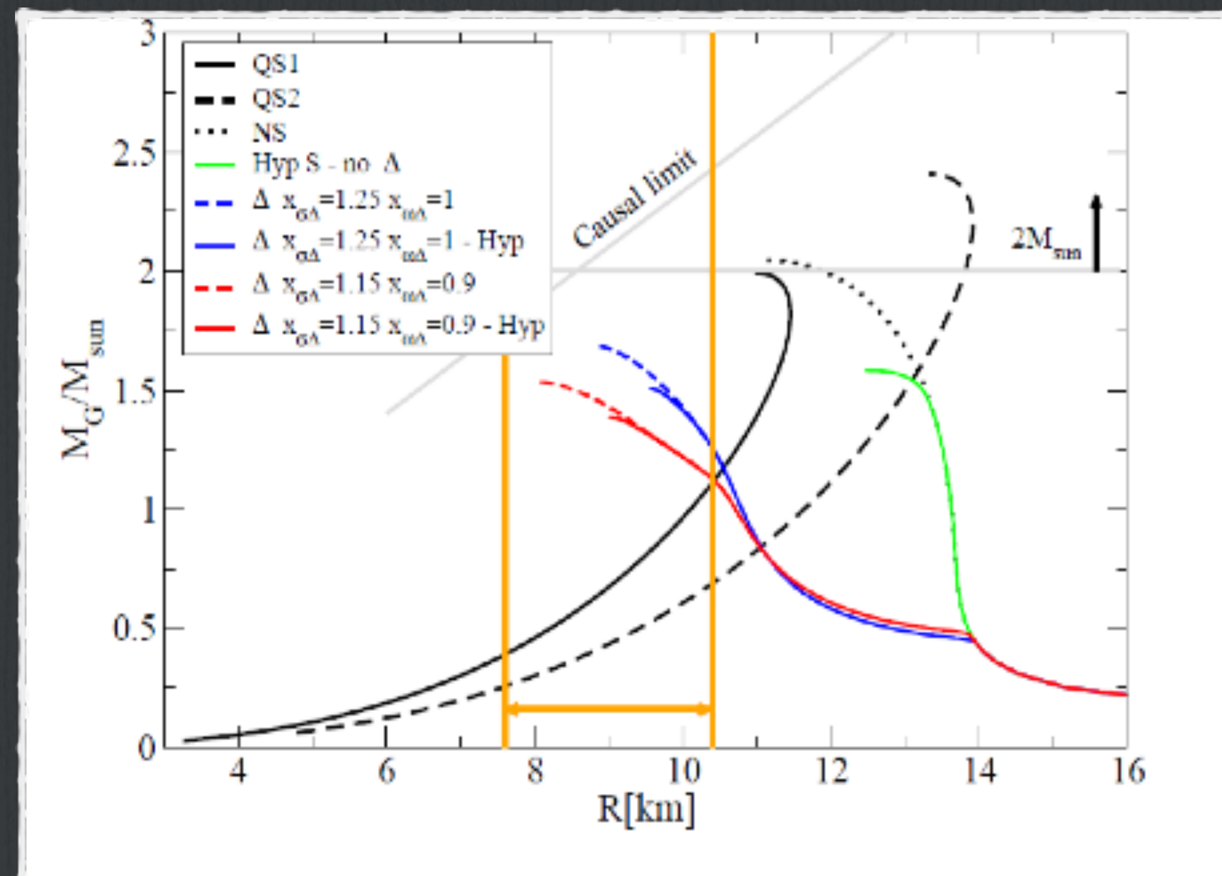
2 Families of Compact Stars

NSF, universetoday.com



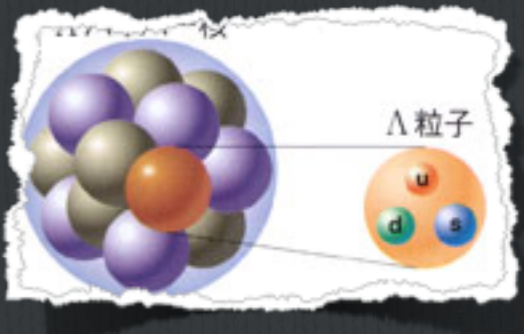
1) Hadronic Stars (with Nucleons, baryonic resonances and Hyperons inside) with low Mass (up to 1.5 $M_{\odot}$) and small Radii (9-10 Km)
2) Strange Quark Stars with high Mass and large Radii

A. Drago, A. Lavagno, G. Pagliara Phys. Rev. D89 (2014) 043014



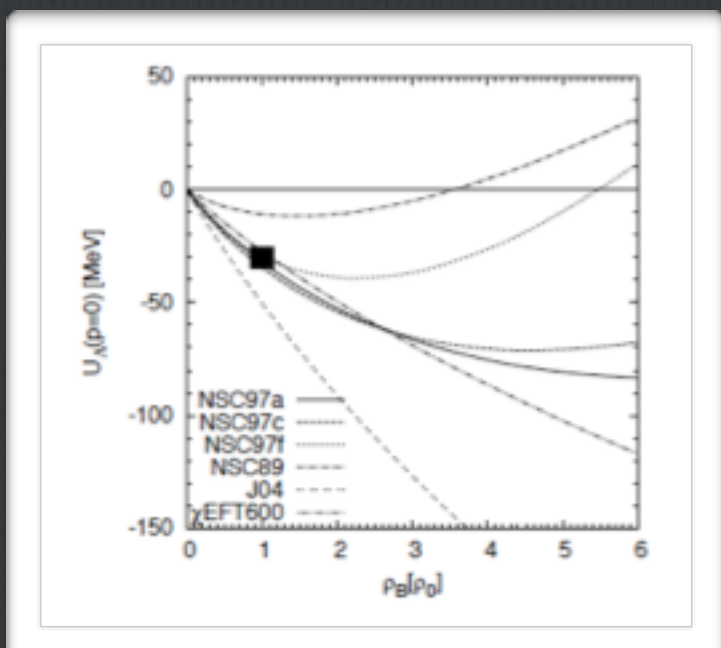
Transition from one kind of star to the other
Measurements of the Radii of low-mass NS are necessary!

Experimental Evidence I

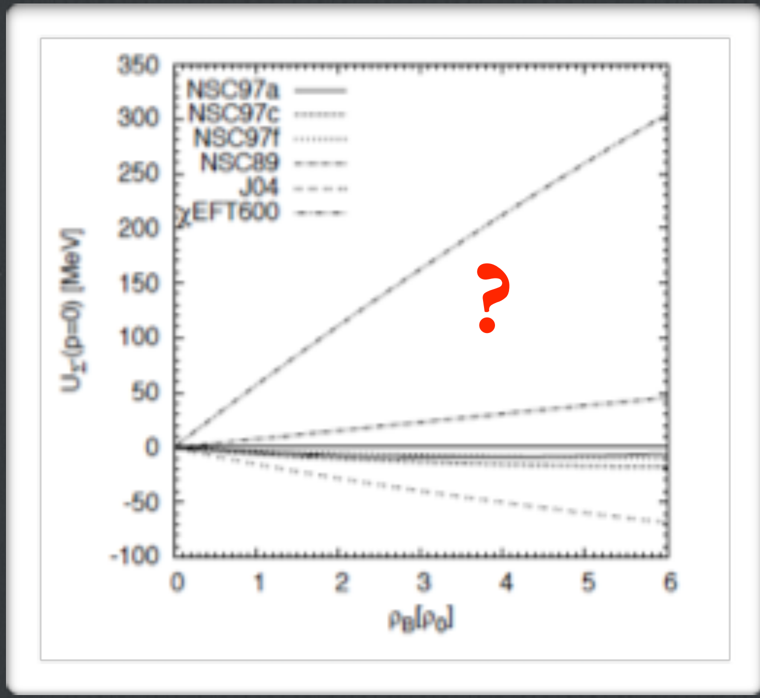


Λ- or Σ- Hypernuclei

Λ-Nucleon Potential



Σ-Nucleon Potential



U~ -30 MeV (attractive)
from Hypernuclei
No idea yet about the momentum and
density dependence

No Idea at all

Experimental Evidence II

Λ-p Σ-p scattering

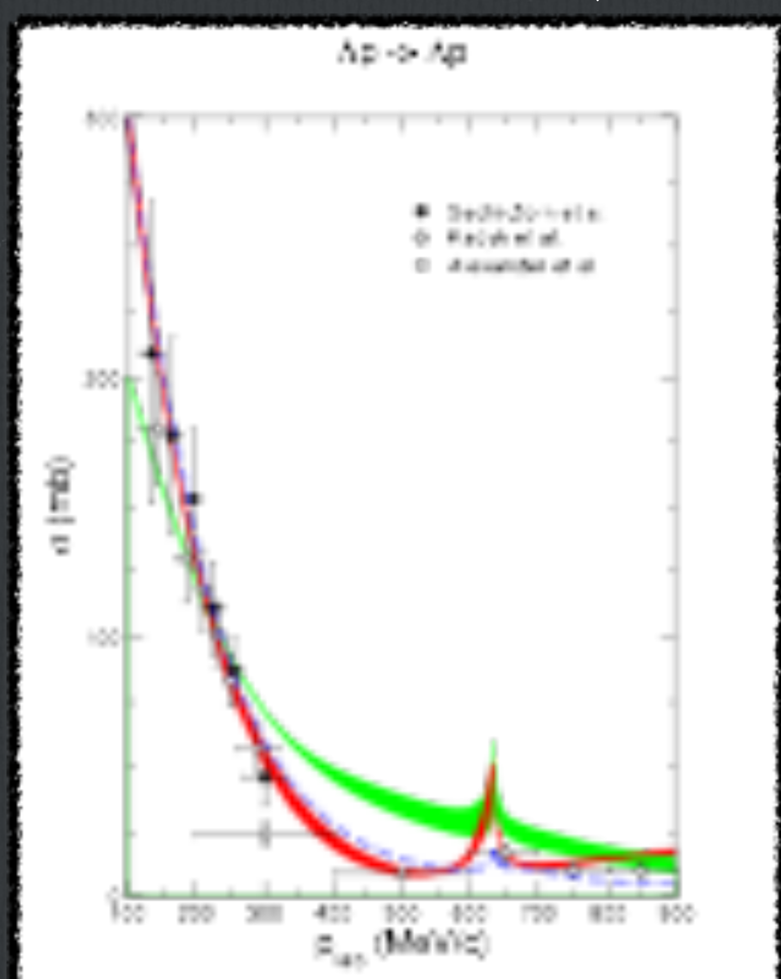
Λ and Σ beams from K-+p collisions "seen" by Bubble chambers

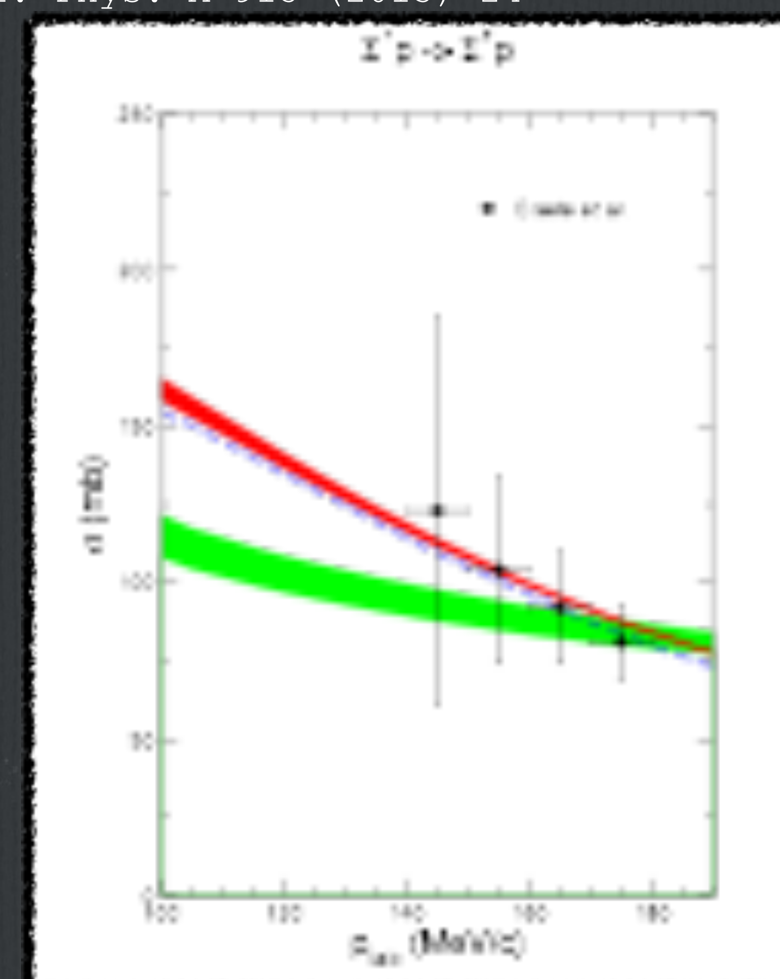
Λ

p

Cross-section -> scattering length -> Interacting Potential

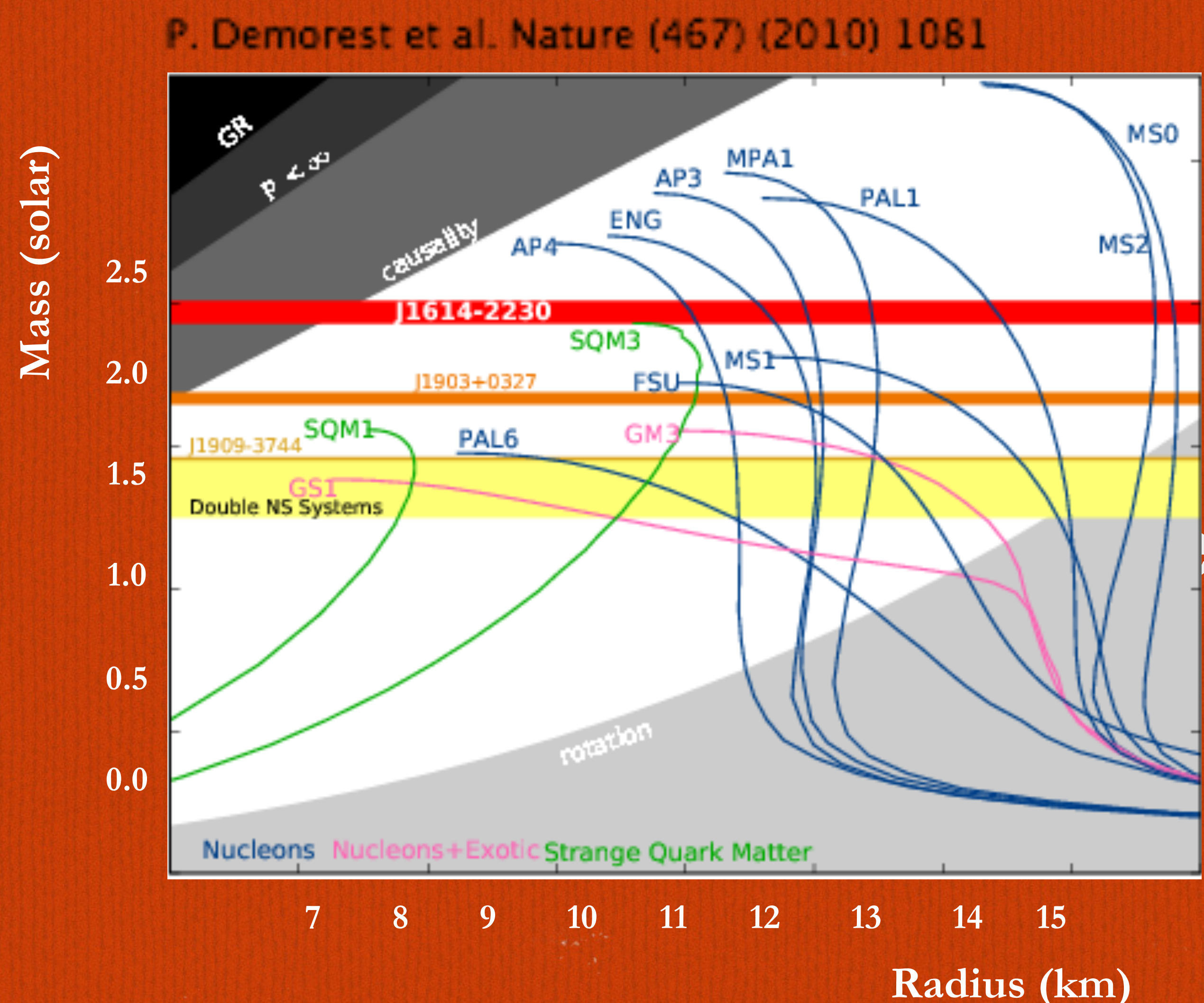
J. Haidenbauer, S. Petschauer et al., Nucl. Phys. A 915 (2013) 24





Scarce Data and all above 150 MeV/c

More simple scenarios???



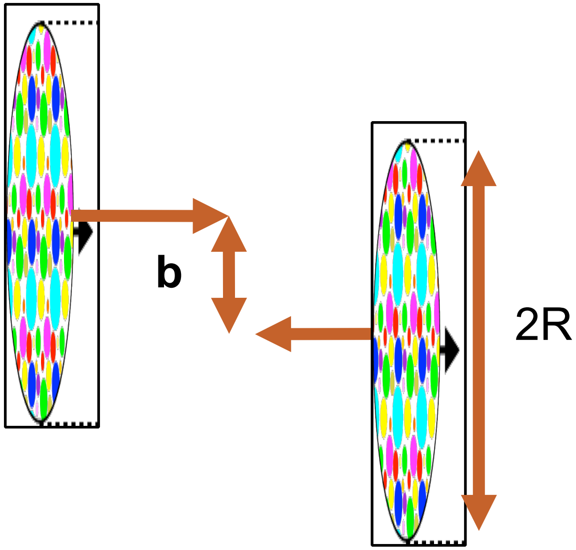
- Only nucleons in neutron stars?

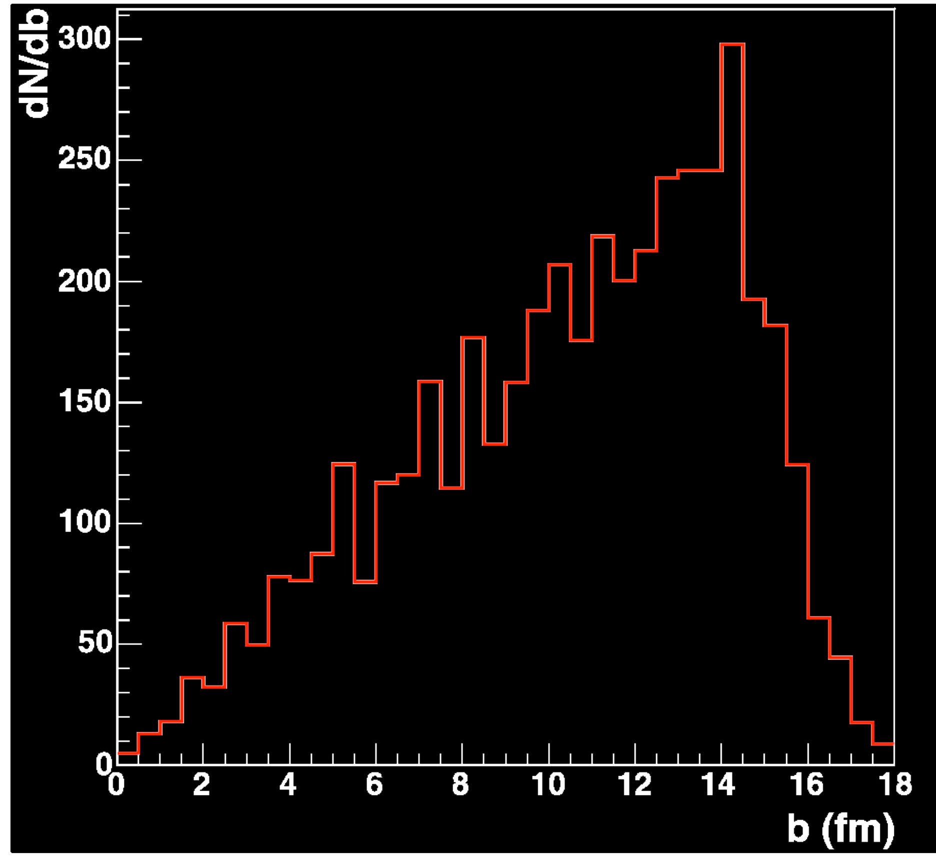
Some Concepts about Heavy Ion Reactions

- Neutron Stars and their consituents
- Centrality Determination
- QGP Transition and Statistical Hadron Models
- Quarkonia
- Open Charm

General Experimental Observables in heavy ion collisions

Impact Parameter

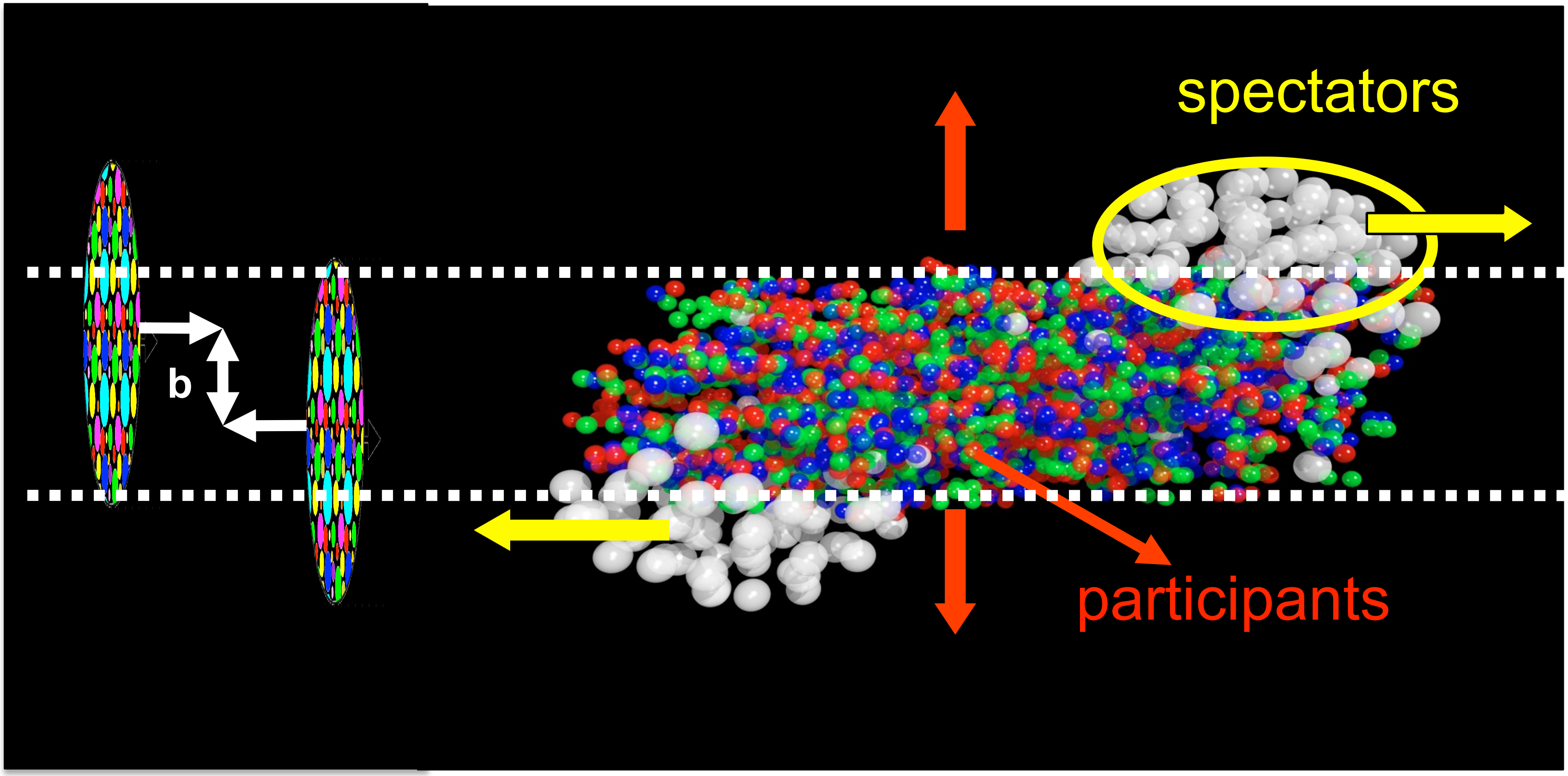




- impact parameter **b**
  - perpendicular to beam direction
  - connects centers of the colliding ions

$$d\sigma = 2\pi b\, db$$

Centrality Determination (I)



Centrality characterized by:

* N_{part}, $N_{wounded}$: number of nucleons which suffered at least one inelastic nucleon-nucleon collision
* N_{coll}, N_{bin}: number of inelastic nucleon-nucleon collisions

Glauber Model Calculations

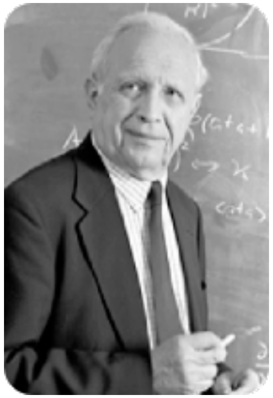
- ✓ nuclear density from Wood-Saxon distribution

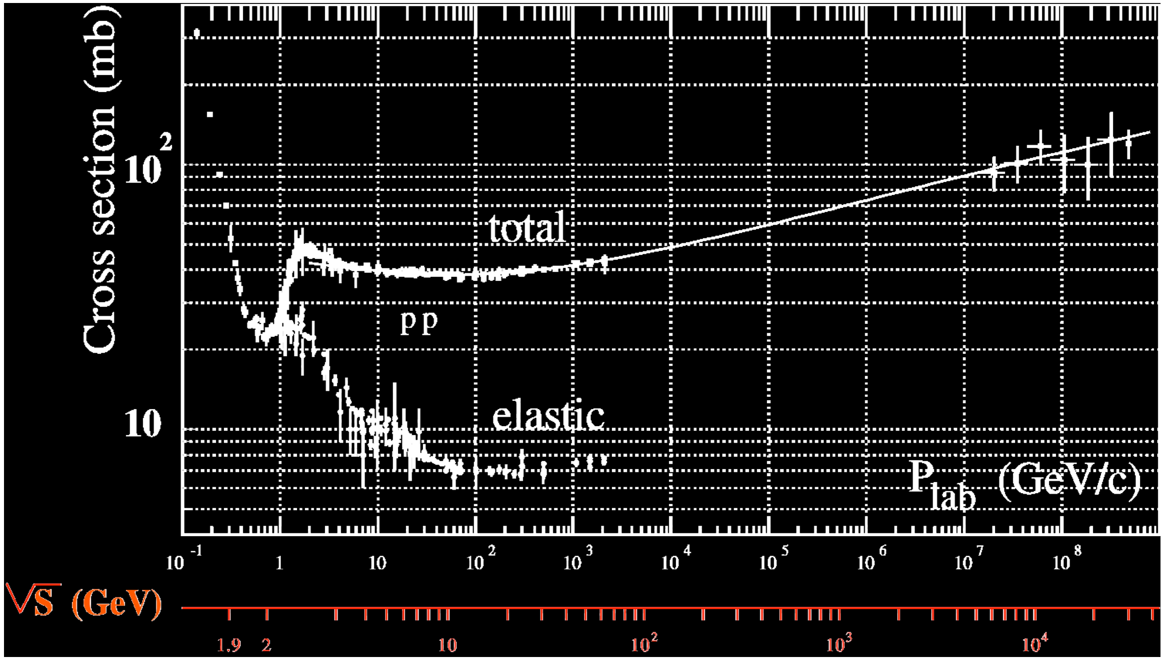
$$\rho(r) = \frac{\rho_0\left(1 + wr^2/R^2\right)}{1 + e^{(r-R)/a}}$$

Nucleus	A	R	a
Au	197	6.38	0.535
Pb	208	6.68	0.546

- ✓ nucleons travel on straight lines, no deflection after NN collision
- ✓ NN collision cross section from measured inelastic cross section in p+p
- ✓ NN cross section remains constant independent of how many collisions a nucleon suffered

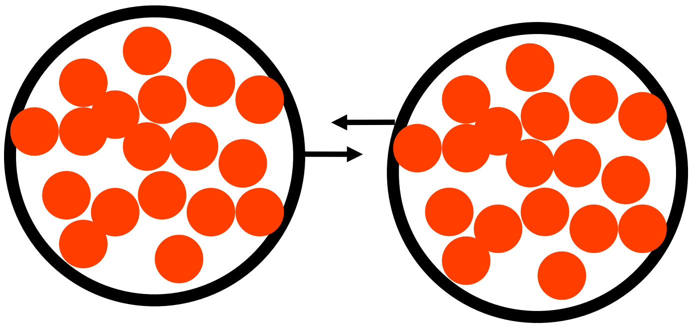
$\sqrt{s}$ (GeV)	$\sigma_{in,pp}$ (mb)
20	32
200	42
2700	~64





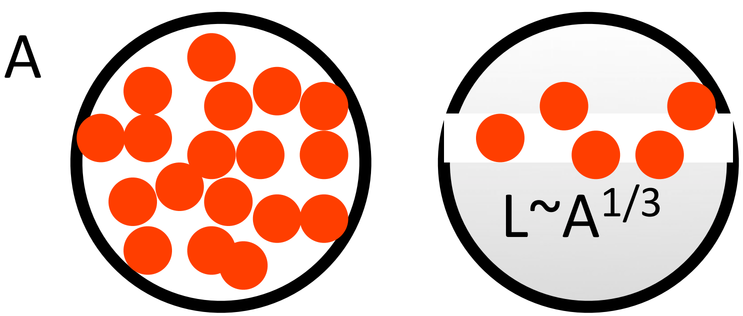
Wounded nucleons and binary collisions

wounded nucleon scaling

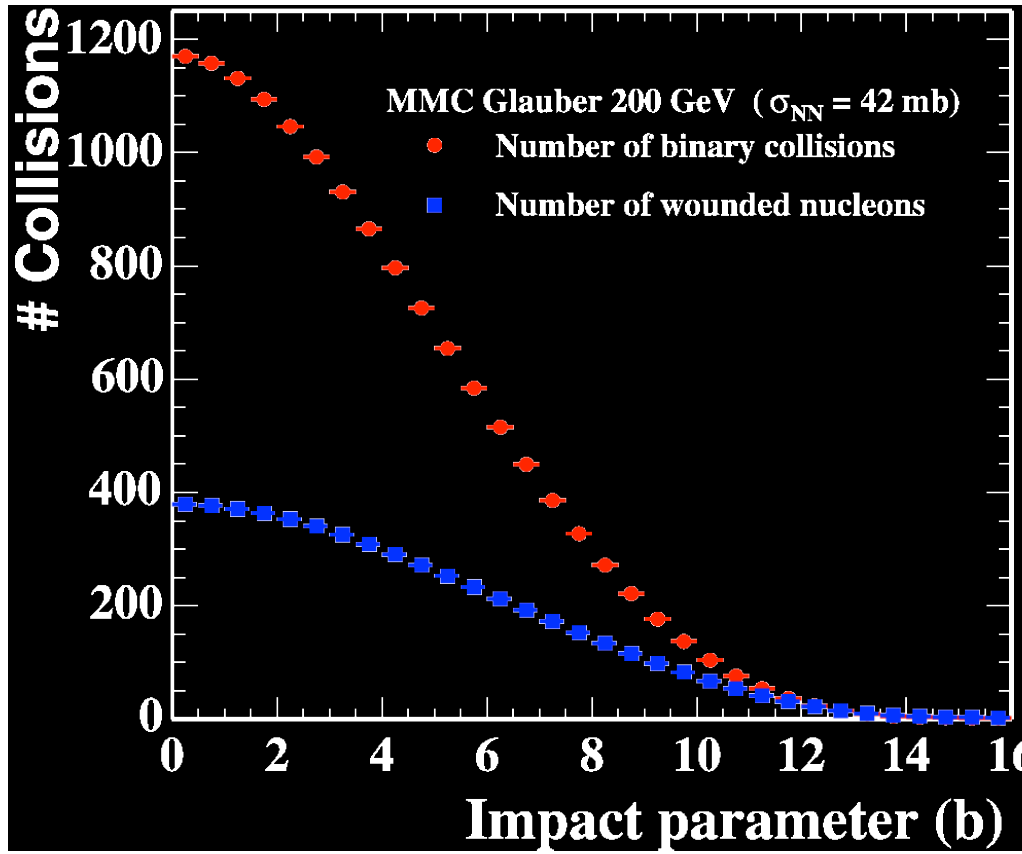


number of participating nucleons scales with volume ~ 2A

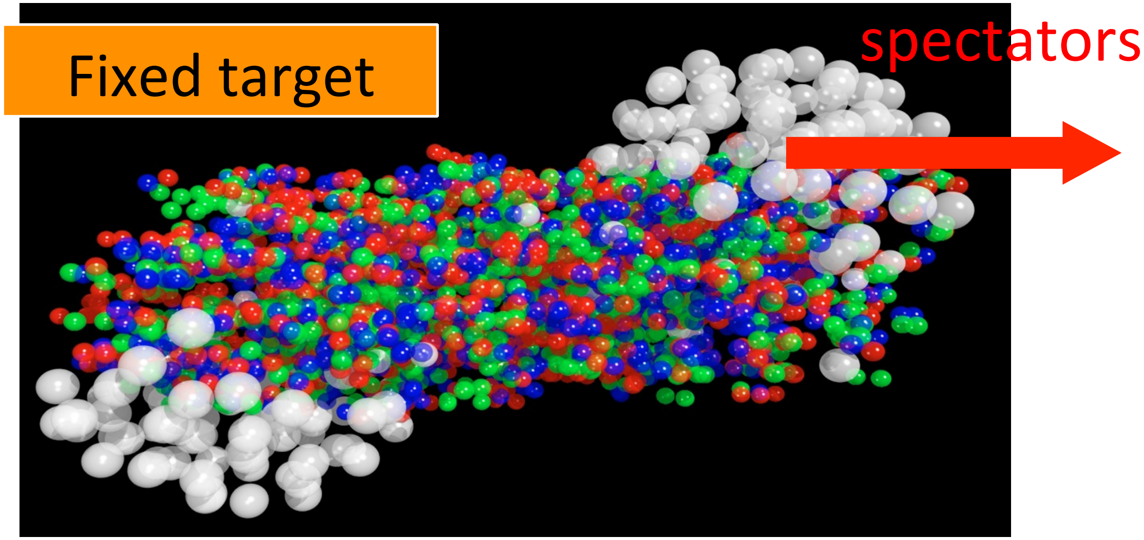
binary scaling



number of NN collisions, point like, scales with ~ $A^{4/3}$

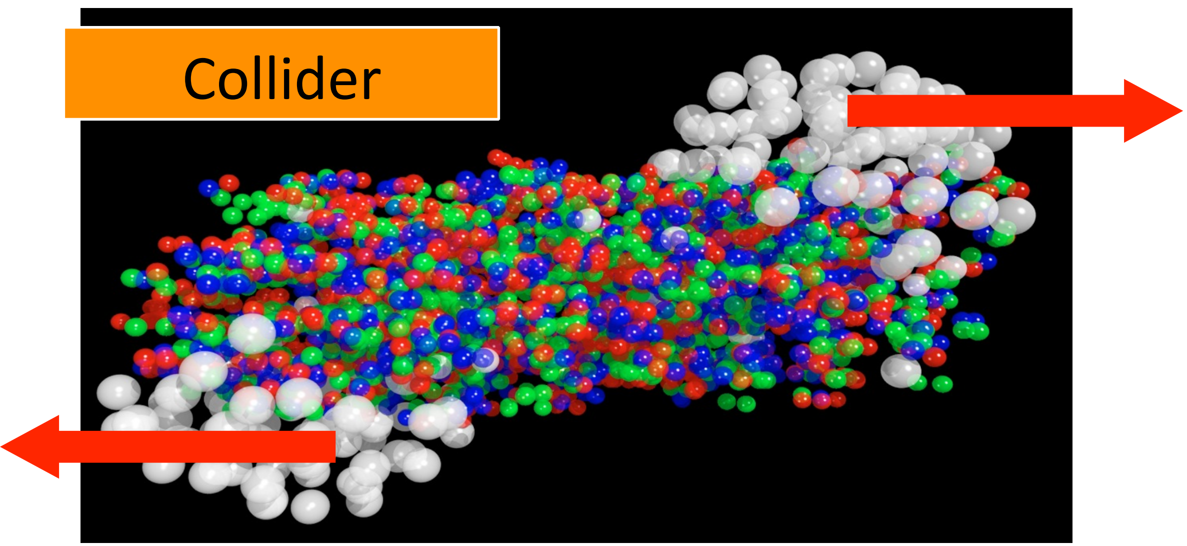


Centrality determination (II)



Zero-Degree-Calorimeter (ZDC) measures energy of all spectator nucleons

$$N_{\text{spec}} \approx E_{\text{ZDC}} / \left(E_{\text{beam}} / A\right),$$
$$N_{part} \approx 2 \cdot \left(A - N_{\text{spec}}\right)$$

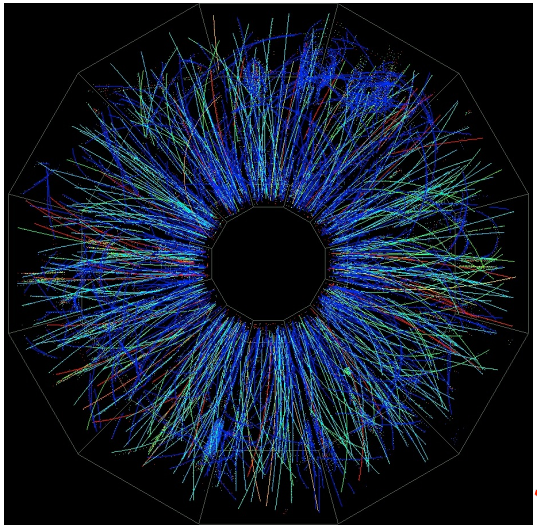


Zero-Degree-Calorimeter (ZDC) measures energy of all unbound spectator nucleons

➡charged fragments (p, d, and heavier) are deflected by accelerator magnets

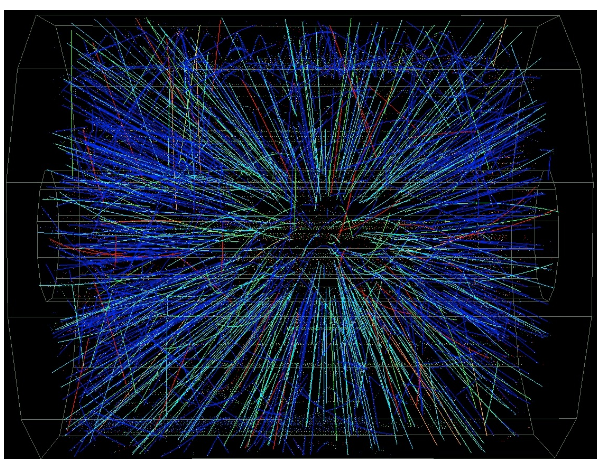
➡E_{ZDC} small for very central and very peripheral collisions, ambiguous

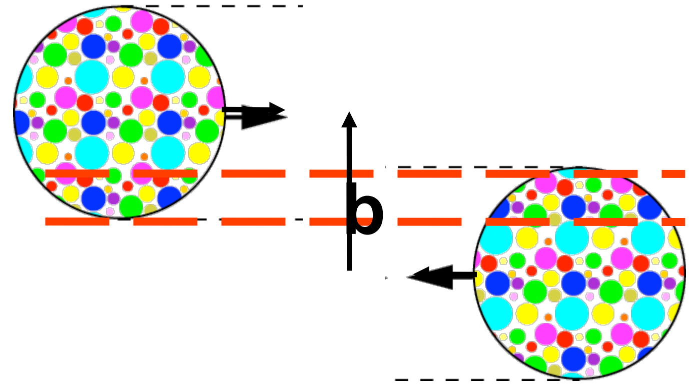
Centrality determination (III)



Peripheral Event

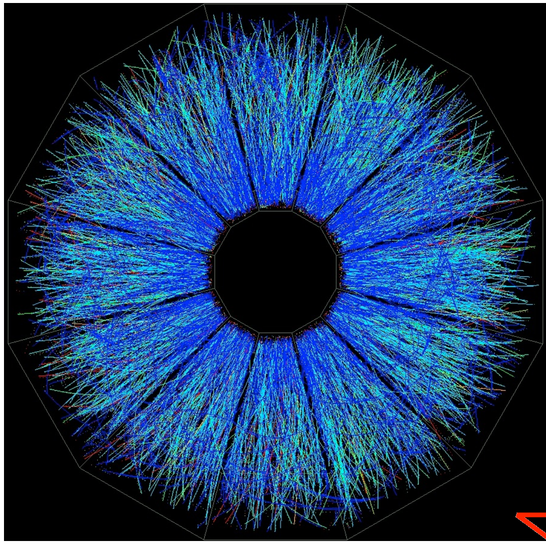
From real-time Level 3 display





- ✓ peripheral collisions, largest fraction cross section
- ✓ many spectators
- ✓ "few" particles produced

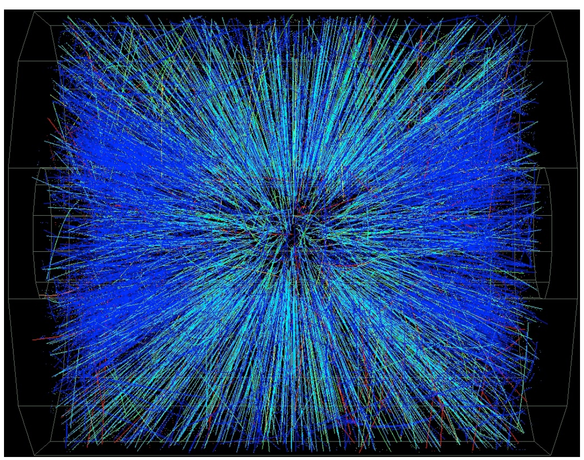
Centrality determination (IV)

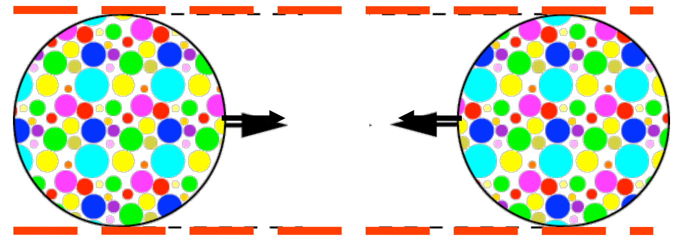


STAR

Central Event

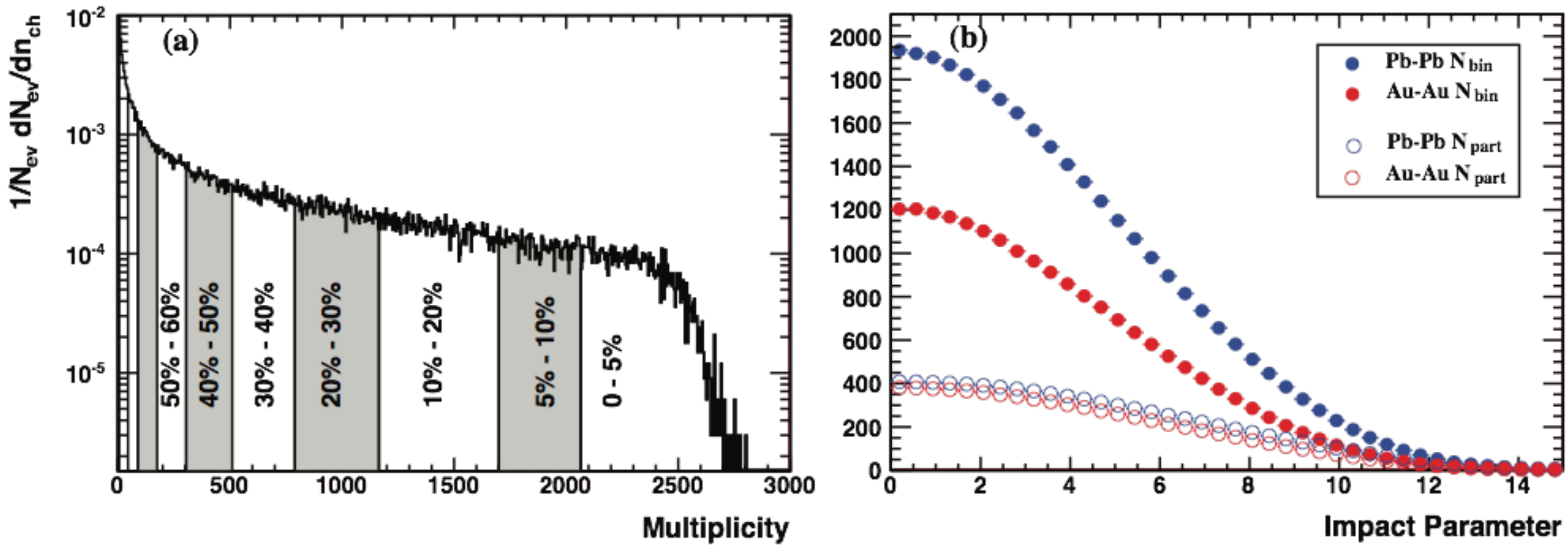
From real-time Level 3 display





- ✓ impact parameter **b** = 0
- ✓ central collisions, small cross section
- ✓ no spectators
- ✓ many particles produced

Centrality determination (ALICE)



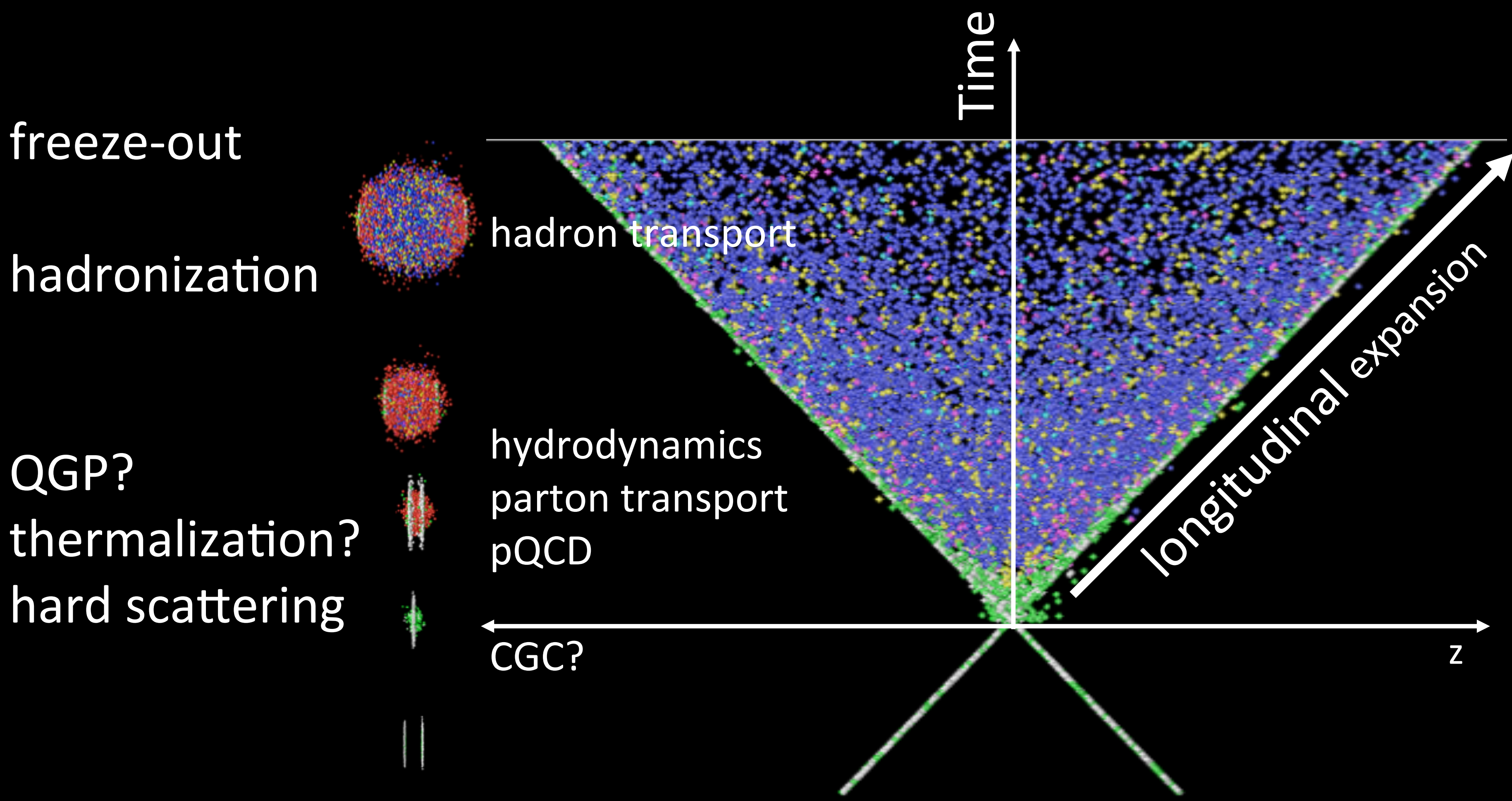
✓ Measure the nr of produced particles in the TPC
This scales like N_{PART}

✓ Determine the magnitude of the impact parameter

$\%\sigma_{tot}$	$<N_{part}>$	$<b>$
0-5	386	2.48
20-30	177	7.85
60-70	25	12.66

QGP Transition and Statistical Hadron Models

Time Evolution



Freeze-Outs

<u>Chemical Freeze-Out:</u>
"Sharp" end of inelastic collisions, from there on only elastic collisions
Particle Yields are then fixed
Entropy of the System stays constant

<u>Thermal Freeze-Out:</u>
Also elastic collisions stop

In-Between: Kinetic energy is reshuffled through elastic collisions among the particles. The slope of the p_T distributions get harder. One talks also about Temperatures:

<u>Chemical Temperature:</u> Under the assumption that the hadronization happens in a situation of local thermalization the chemical temperature tells the temperature of the system at the moment of the hadronization.

Freeze-Out slopes: express the parameter 'Temperature' extracted from the fit of the M_T distribution done with Boltzmann functions.

The Ensembles of Statistical Mechanics

Microcanonical Ensemble: it describes an **isolated** system

Canonical Ensemble: it describes a system in contact with a heat bath (**T is constant, Energy can be exchanged**)

Grand Canonical Ensemble: it describes a system in contact with a heat and particle bath (T is constant, **Number of particles can change, Energy can be exchanged**)

For these systems we can define

P_s: Probability of observing the System in the Energy state E_s

Z: partition function which describes how the probability is distributed among the states

S: Entropy of the system, S= k log(Z) Boltzmann law

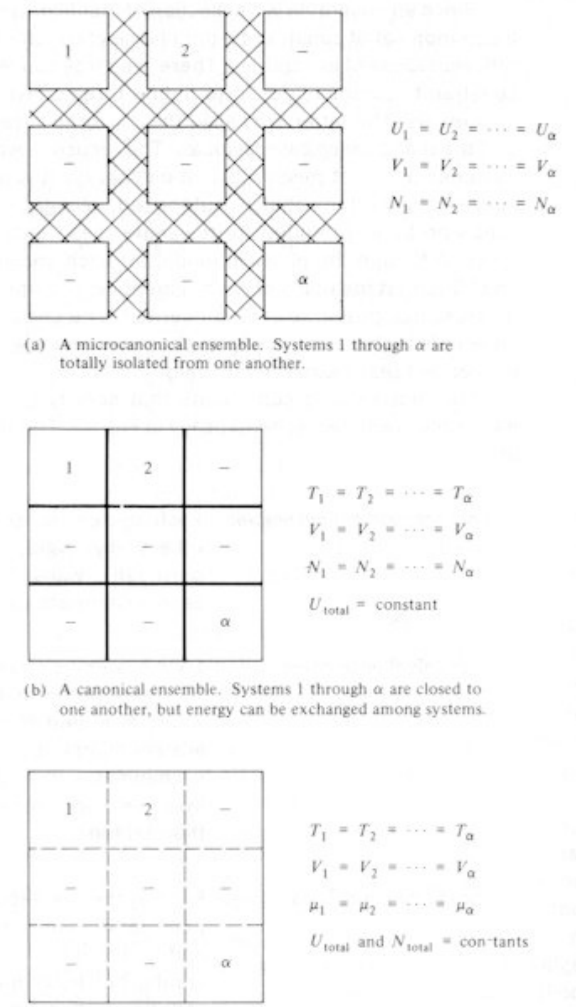


Fig. 8.1 Schematic representation of three kinds of ensembles.

(a) A microcanonical ensemble. Systems 1 through α are totally isolated from one another.

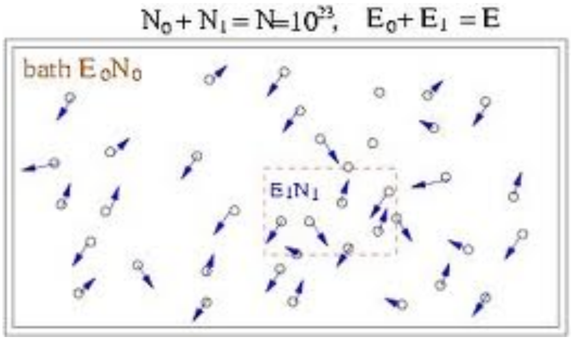
(b) A canonical ensemble. Systems 1 through α are closed to one another, but energy can be exchanged among systems.

(c) A grand canonical ensemble. Energy and mass can be exchanged among systems.

In our field we use the Grand Canonical Ensemble: How do we get there?

www.physics.udel.edu/~glyde/PHYS813/Lectures/chapter_6.pdf

The Canonical Ensemble



The canonical Ensemble is used because it defines a system with a constant T -> Equilibrium

$$P_S = \frac{1}{Z}\, e^{-\beta E_S}$$

$$Z = \sum_S e^{-\beta E_S}$$

Probability to see a state with energy Es
β = 1/(kT)

Z= Canonical partition function

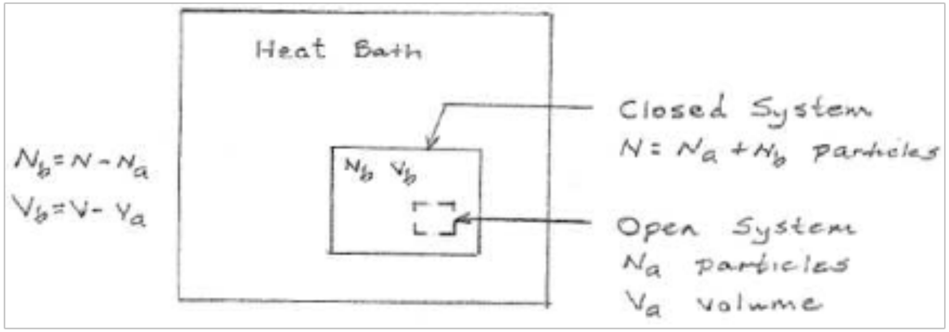
$$F\,(T,\, V,\, N) = -kT \;\log\; Z\,(T,\, V,\, N) \quad \rightarrow \quad Z = e^{\beta F}$$

⇨ F= U-TS Helmholtz free energy, maximal energy that can be converted into work

$$P_S = e^{\beta(F - E_S)} \quad \text{and} \quad \sum_S P_S = 1\,.$$

www.physics.udel.edu/~glyde/PHYS813/Lectures/chapter_6.pdf

Grand Canonical Ensemble



We build the GCE starting from the CE
We can have exchange of particles between Na and N-Na=Nb

$$P_S = Z^{-1}\, e^{-\beta E_S} = e^{\beta(F - E_S)}$$

$$E_S = E_{Sa}\,(N_a) + E_{Sb}\,(N_b)$$

$$F(T,\ V,\ N) = F_a(T,\ V_a,\ N_a) + F_b(T,\ V_b,\ N_b)$$

$$\rightarrow\ P_S = e^{-\beta E_{Sa}(N_a)} \times e^{-\beta E_{Sb}(N_b)} \times e^{\beta F(T,\ V,\ N)}$$

We consider now the probability of observing a subsystem Na with the energy $E_{S_a}(N_a)$

$$P_{Sa}(N_a) = \sum_{Sb} P_S(N) = e^{-\beta E_{Sa}(N_a)}\ e^{\beta(F - F_b)}$$ with (see previous slide): $$F_b = -kT\ \log \sum_{Sb} e^{-\beta E_{Sb}(N_b)}$$

Since $N_a \ll N - N_b$

$$F_a = F - F_b = \left(\frac{\partial F}{\partial N}\right) N_a + \left(\frac{\partial F}{\partial V}\right) V_a = \mu N_a - p_a V_a$$

$$\rightarrow\ \boxed{P_{Sa}(N_a) = e^{-\beta p_a V_a}\ \ e^{-\beta(E_{Sa}(N_a) - \mu N_a)}}$$

The probability to observe the open subsystem a depends on the number of particle Na and on the chemical potential μ

www.physics.udel.edu/~glyde/PHYS813/Lectures/chapter_6.pdf

Grand Canonical Ensemble

$$\boxed{P_{Sa}(N_a) = e^{-\beta p_a V_a} \; e^{-\beta(E_{Sa}(N_a) - \mu N_a)}}$$

$$F_a = \mu N_a - P_a V_a \quad \rightarrow \quad \boxed{N_a = \frac{dF_a}{d\mu} = \frac{dT \ln Z_a}{d\mu}}$$

$$P_S(N) \propto e^{-\beta(E_S(N) - \mu N)}$$

$$\mathcal{Z} = \sum_{S,N} e^{-\beta(E_S(N) - \mu N)}$$

In general given the total number of states N

$$N = \sum_i n_i \quad E = \sum_i n_i E_i$$

We can write the total partition function as:

$$Z(T, V, \mu) = \sum_{n_1, n_2, \ldots} e^{-\beta \Sigma (E_i - \mu) n_i} = \sum_{n_1, n_2, \ldots} \prod_i e^{-\beta(E_i - \mu) n_i}$$

$$= \prod_i \left[\sum_{n_i} e^{-\beta(E_i - \mu) n_i} \right]$$

Grand Canonical Ensemble

For Fermions and Bosons we get respectively:

$$Z_F = \prod_i \left(1 + e^{-\beta(E_i - \mu)}\right), \quad Z_B = \prod_i \frac{1}{1 - e^{-\beta(E_i - \mu)}}$$

lnZ transforms the product into a sum of ln. The sum runs over the number of states. If we include the phase space density $\frac{d^3p}{(2\pi\hbar)^3}$

Fermions

$$lnZ(T, V, \mu) = \pm gV \int \frac{d^3p}{(2\pi\hbar)^3} ln(1 \pm e^{-\beta(E_p - \mu)})$$

Bosons

and the usual thermodynamic variables are:

$$P = \frac{\partial TlnZ}{\partial V}, \quad N = \frac{\partial TlnZ}{\partial \mu}$$

$$E = V \int \frac{d^3p}{(2\pi\hbar)^3} \frac{E_p}{1 \pm e^{-\beta(E_p - \mu)}}$$

The massless Ideal Gas

given lnZ we can calculate the Helmholtz energy F and the energy density ε = F/V

$$F = \epsilon = -kTlnZ$$

$$\epsilon = -T \cdot \pm g \int \frac{d^3p}{(2\pi\hbar)^3} ln(1 \pm e^{-\beta(E_p - \mu)})$$

If we consider massless particles m=0, Ep=p and μ=0

for Bosons:

$$\epsilon = \frac{g}{2\pi^2} T^4 \int dx x^2 ln(1 - e^{-x}) \qquad x = \frac{p}{T}$$

$$\boxed{\epsilon = g_B \frac{T^4\pi^2}{30}}$$

analogously for Fermions:

$$\boxed{\epsilon = g_F \frac{7}{8} \frac{T^4\pi^2}{30}}$$

Hadron Gas

The Hadron Gas we think is produced after the heavy ion collisions at ultrarelativistic energies is mainly composed of pions which are considered as massless boson.
We only have to compute g_B

$$g_B = 3, \ \ \epsilon = 3\frac{\pi^2}{30}T^4, \quad P = \frac{1}{3}\epsilon$$

We consider a system with only 3 quark Flavours

Gluonen: $g_B = 8(\text{Color}) \cdot 2(\text{Polarisation}) = 16$
Quarks: $g_F = 2(\text{Anti/Materie}) \cdot 2(\text{Spin}) \cdot 3(\text{Flavor}) \cdot 3(\text{Color}) = 36$

For 3 flavours $\epsilon = \ (g_B + \frac{7}{8}g_F)\frac{\pi^2}{30}T^4 = \ 47.5\frac{\pi^2}{30}T^4, \quad P = \frac{1}{3}\epsilon$

For 2 Flavours: $\epsilon = 37\frac{\pi^2}{30}T^4, \quad P = \frac{1}{3}\epsilon$

Rough estimate: EoS and degrees of freedom

Ideal gas Equation of State:

$$p = \frac{1}{3}\varepsilon = g\frac{\pi^2}{90}T^4$$

➡ energy density of g massless degrees of freedom

$$\frac{\varepsilon}{T^4} = g\frac{\pi^2}{30}$$

➡ hadronic matter dominated by lightest mesons (π^+, π^-, and π^0)

$$\frac{\varepsilon}{T^4} = 3\frac{\pi^2}{30}$$

➡ deconfined matter, quarks and gluons

$$g = 2_{\text{spin}} \times 8_{\text{gluons}} + \frac{7}{8} \times 2_{\text{flavors}} \times 2_{\text{quark/anti-quark}} \times 2_{\text{spin}} \times 3_{\text{color}}$$

$$\frac{\varepsilon}{T^4} = 37\frac{\pi^2}{30}$$

➡ during phase transition large increase in degrees of freedom !

Rough estimate: QCD phase transition temperature

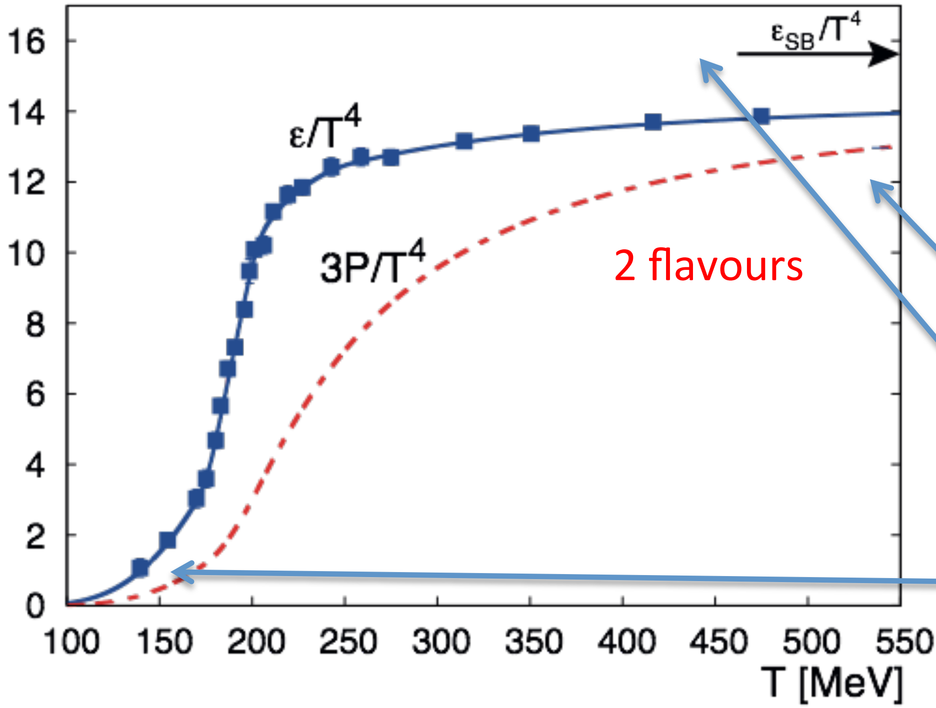
- confinement due to bag pressure B (from the QCD vacuum)
  - $B^{1/4} \sim 200$ MeV
- deconfinement when thermal pressure is larger than bag pressure

$$
\begin{aligned}
p &= \frac{1}{3}\epsilon = g\frac{\pi^2}{90}T^4 \\
T_c &= \left(\frac{90B}{37\pi^2}\right)^{1/4} = 140\ \mathrm{MeV}
\end{aligned}
$$

For 2 flavours

crude estimate!

QCD on the Lattice



T ~ 190 MeV, ε ~ 1 GeV/fm^3

at the critical temperature a strong **increase in the degrees of freedom**

✓ gluons, quarks & color!

2 or 3 flavours:

$$p = \frac{1}{3}\epsilon = g\frac{\pi^2}{90}T^4$$

$$g_H \approx 3$$

$$g_{QGP} \approx 37$$

$$g_{QGP-SB} \approx 48$$

$$g = 2_{Spin} \times 8_{Gluons} + \frac{7}{8} \times 2(3)_{Flavours} \times 2_{q\bar{q}} \times 2_{Spin} \times 3_{Color}$$

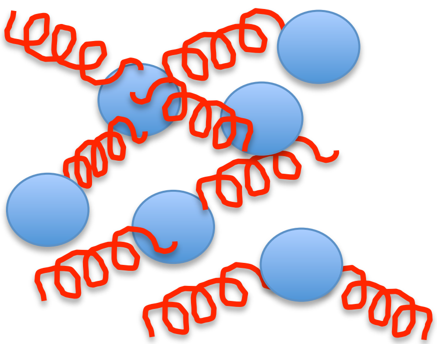
Lattice Calculation

not an ideal gas!?

✓ residual interactions -> Strong Interacting QGP, not FREE

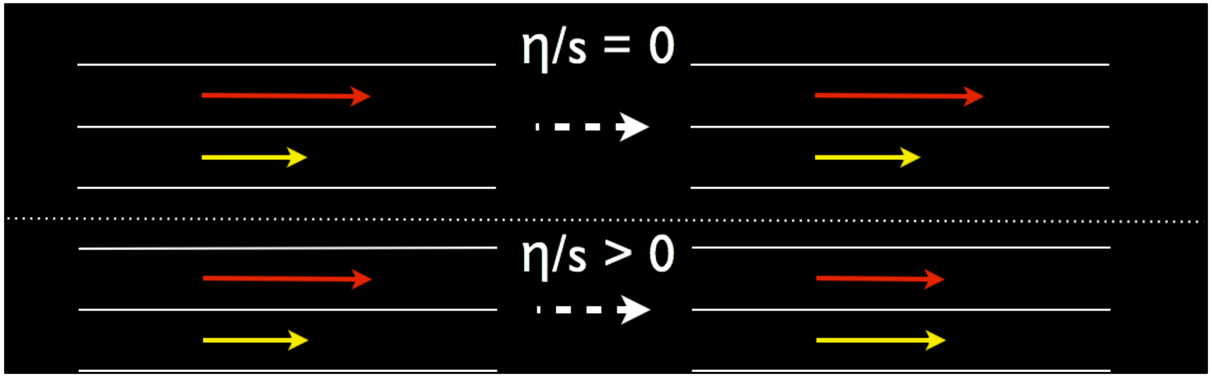
Viscosity

Non-interacting QGP: Infinity Viscosity, Large mean free path -> Flow is destroyed
Interaction QGP: Smaller Viscosity, smaller mean free path -> Like **Perfect Liquid**



Inreacting system: Wave can be propagated among the system constituents -> small viscosity

Infinite Viscosity= no wave can be propagates: Non-interacting system



Lower Viscosity -> Larger Flow

Back to the Statistical Model of Hadrons

Boundary Conditions:
Only Meson with Mass till 1.5 GeV and Baryons till 2 GeV can be considered in this model

The Chemical potential is ‘split’ into three components corresponding to a chemical potential for the charge, baryon number and strangeness states

$$\vec{\mu} = (\mu_B, \mu_S, \mu_Q)$$

Grand Canonical Ensemble for Hadron-Resonance Gas

$$lnZ(T,V,\vec{\mu}) = \sum_i lnZ_i(T,V,\vec{\mu})$$

where the index i runs over all the contributing particle species within the hadron gas.

$$lnZ_i(T,V,\vec{\mu}) = \frac{Vg_i}{2\pi^2}\int_0^\infty \pm p^2 dp ln[1 \pm \lambda_i exp(-\beta\epsilon_i)]$$

where (+) is for Fermions and (-) for Bosons

$$\epsilon_i = \sqrt{p^2 + m_i^2}$$

$$\lambda_i(T,\vec{\mu}) = exp\left(\frac{B_i\mu_B + S_i\mu_S + Q_i\mu_Q}{T}\right)$$

$$\rightarrow \quad T\, lnZ_i(T,V,\vec{\mu}) = \frac{VTg_i}{2\pi^2}\sum_{k=1}^{\infty}\frac{(\pm 1)^{k+1}}{k^2}\lambda_i^k m_i^2 K_2\left(\frac{km_i}{T}\right)$$

with K2 being the modified Bessel function

$$\rightarrow \quad T\, lnZ_i(T,V,\vec{\mu}) = \frac{VTg_i}{2\pi^2}\sum_{k=1}^{\infty}\frac{(\pm 1)^{k+1}}{k^2}\lambda_i^k m_i^2 K_2\left(\frac{km_i}{T}\right)$$

$$N = \frac{\partial TlnZ}{\partial \mu}$$

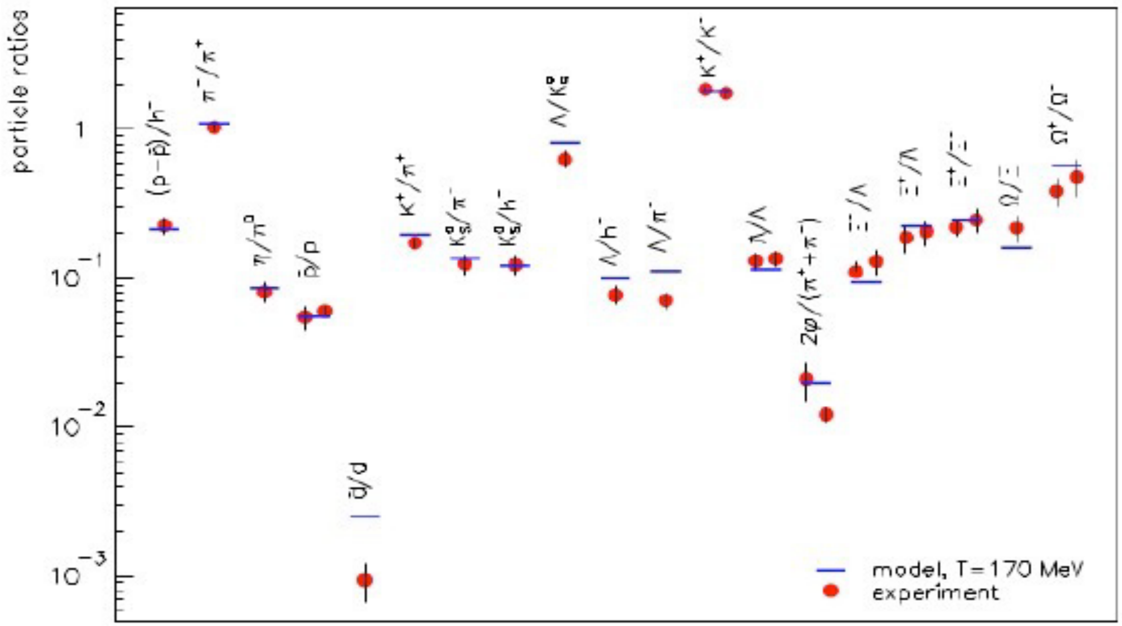
with K2 being the modified Bessel function

$$n_i(T,\vec{\mu}) = \frac{\langle N_i \rangle}{V} = \frac{Tg_i}{2\pi^2}\sum_{k=1}^{\infty}\frac{(\pm 1)^{k+1}}{k}\lambda_i^k m_i^2 K_2\left(\frac{km_i}{T}\right)$$

$$\lambda_i(T,\vec{\mu}) = exp\left(\frac{B_i\mu_B + S_i\mu_S + Q_i\mu_Q}{T}\right)$$

Fit to the Experimental data

Anpassen der yields für Teilchenverhältnisse liefert Werte für μ_B und T. zB für Pb-Pb-Kollisionen mit 158 GeV/Nukleon erhält man für einen Fit $T = 170$ MeV und $\mu_B = 255$ MeV.



arXiv:nucl-th/0304013v1