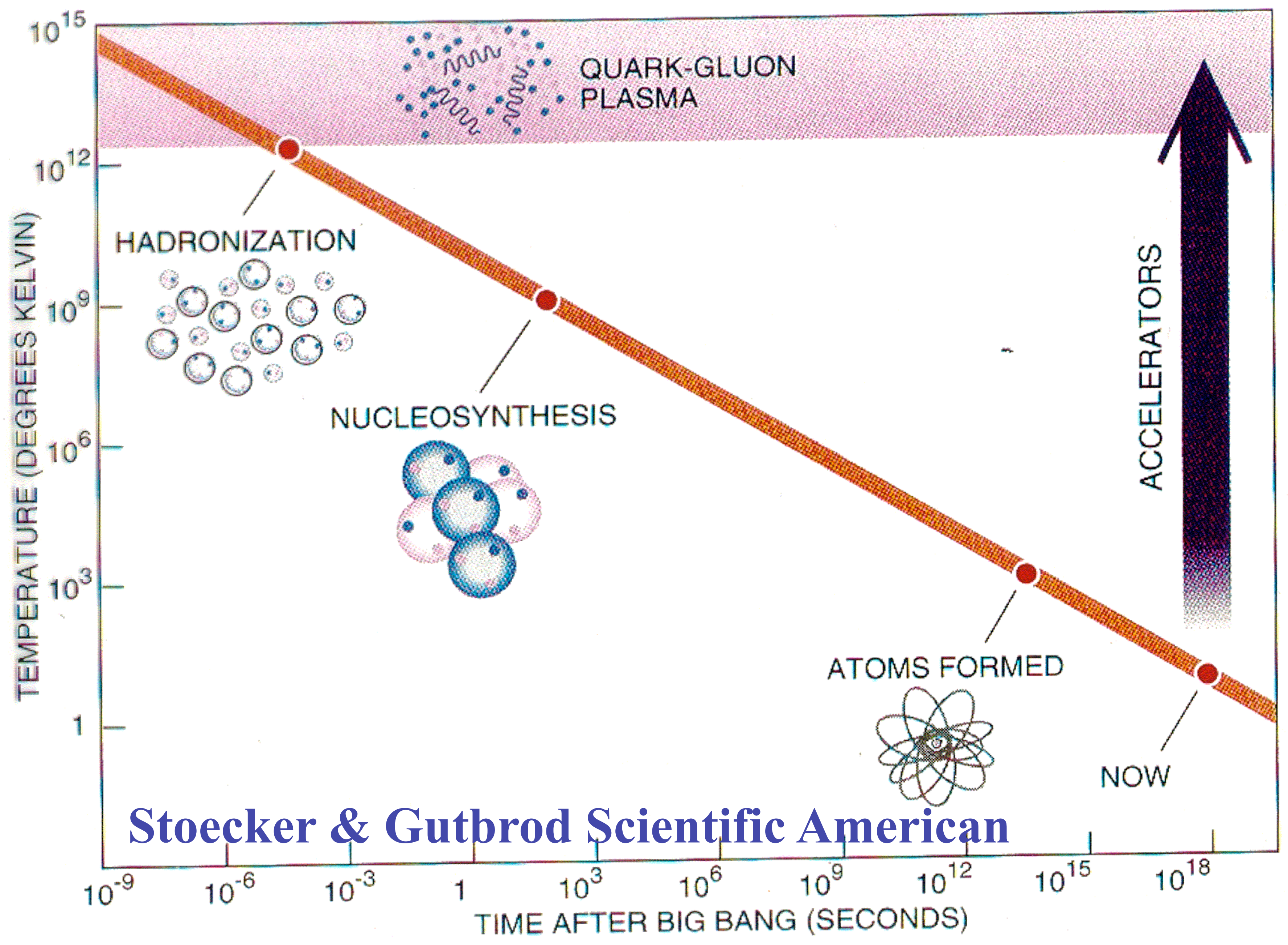
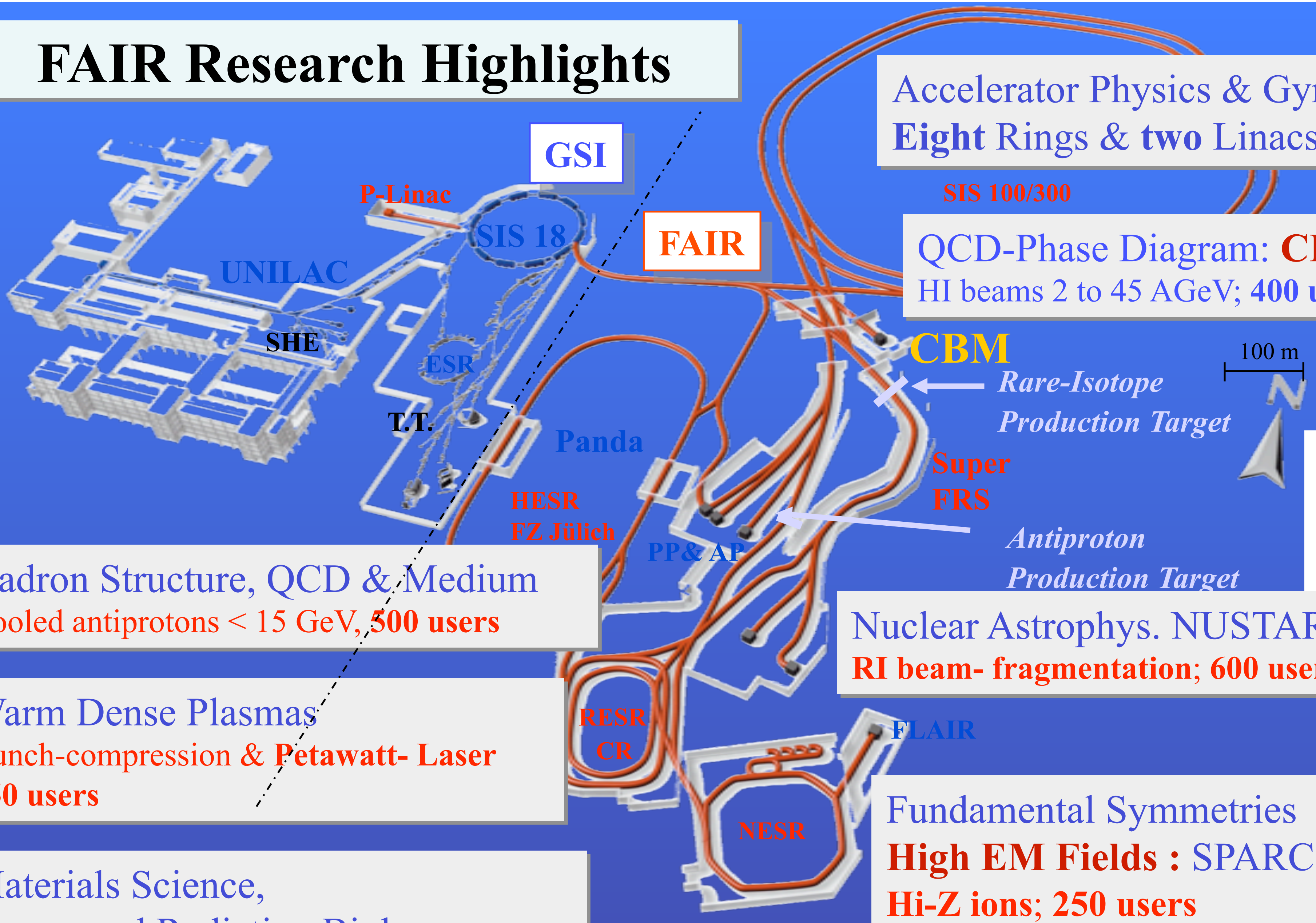
Strong Field QED & QCD @ FAIR



Stoecker & Gutbrod Scientific American

FAIR Research Highlights



Accelerator Physics & Gym:
Eight Rings & **two** Linacs

QCD-Phase Diagram: **CBM**
HI beams 2 to 45 AGeV; **400 users**

Hadron Structure, QCD & Medium
Cooled antiprotons < 15 GeV, **500 users**

Nuclear Astrophys. NUSTAR
RI beam- fragmentation; 600 users

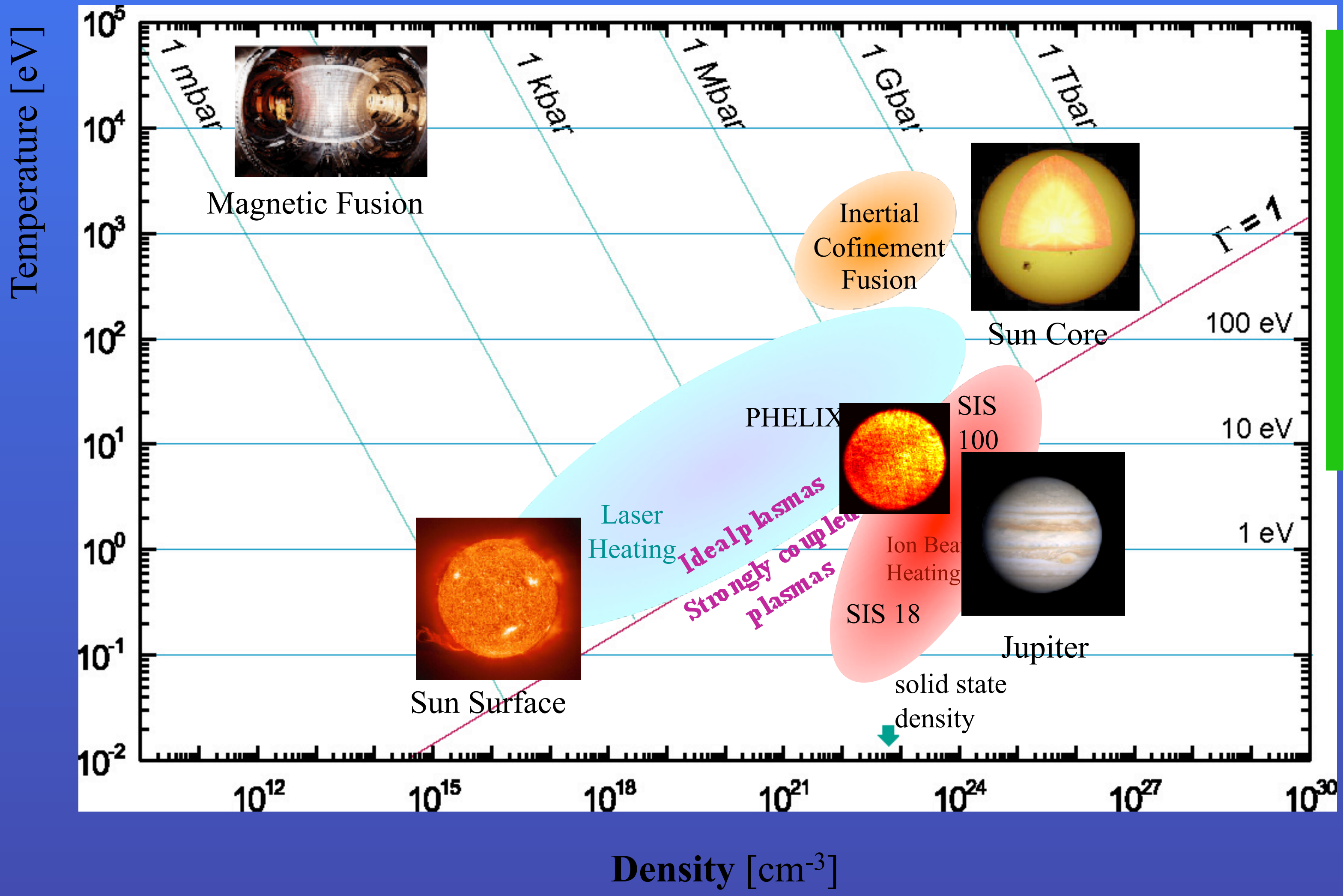
Warm Dense Plasmas
Bunch-compression & **Petawatt- Laser**
250 users

Fundamental Symmetries
High EM Fields : SPARC
Hi-Z ions; 250 users
Antiprotons@FLAIR

Materials Science,
Space- and Radiation Biology
(Ion- & antiproton- beams; **350 users**

APPA: Hot Plasmas: high intensity ion bunches hitting petawatt Laser pulses off PHELIX

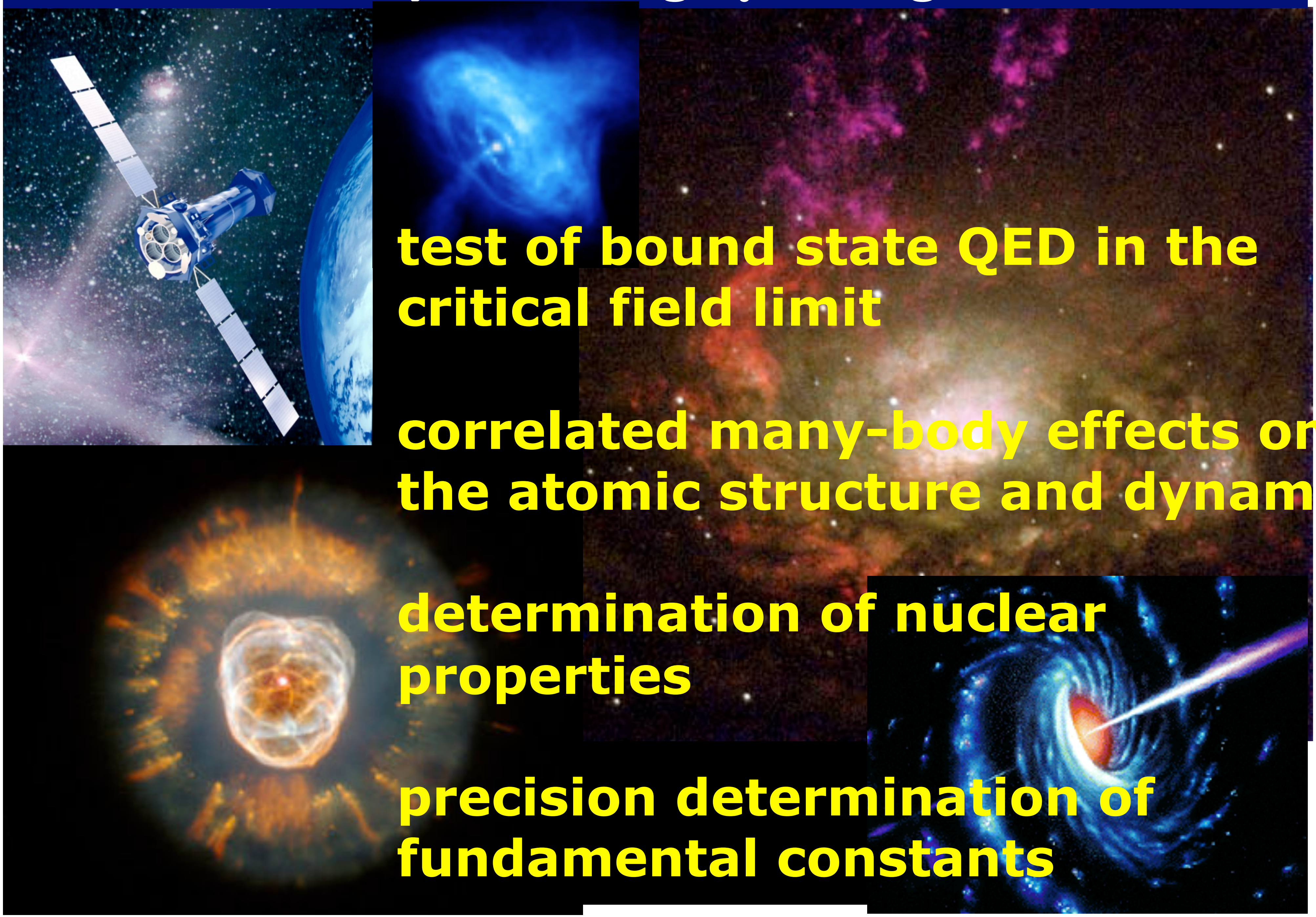
Hot Dense Strongly Coupled Matter at high energy densities



Physics of Fast Ignition (another way to clean energy production)

Equation of state of planetary and stellar matter

FAiR Physics of Highly Charged Ions



test of bound state QED in the critical field limit

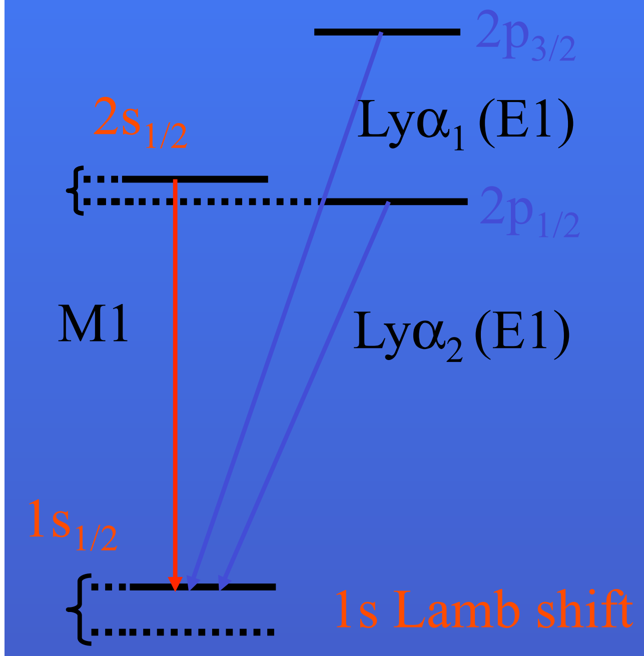
correlated many-body effects on the atomic structure and dynamics

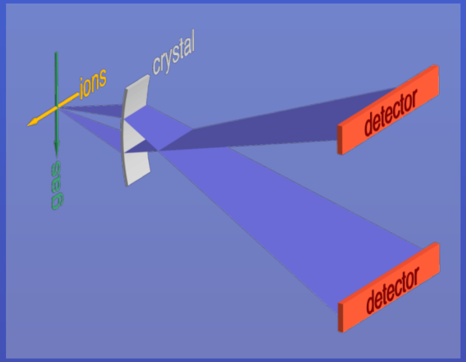
determination of nuclear properties

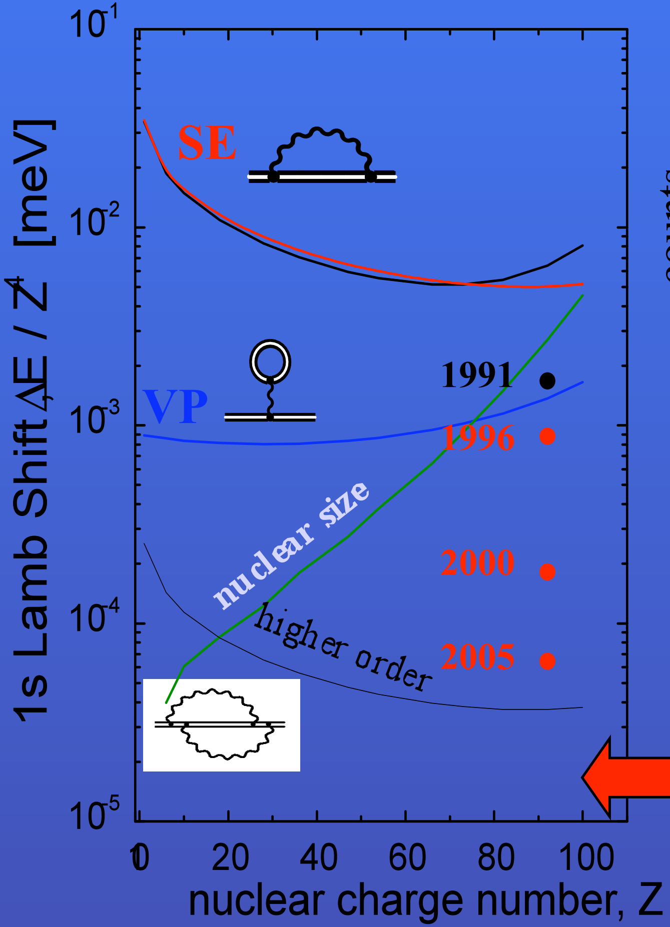
precision determination of fundamental constants

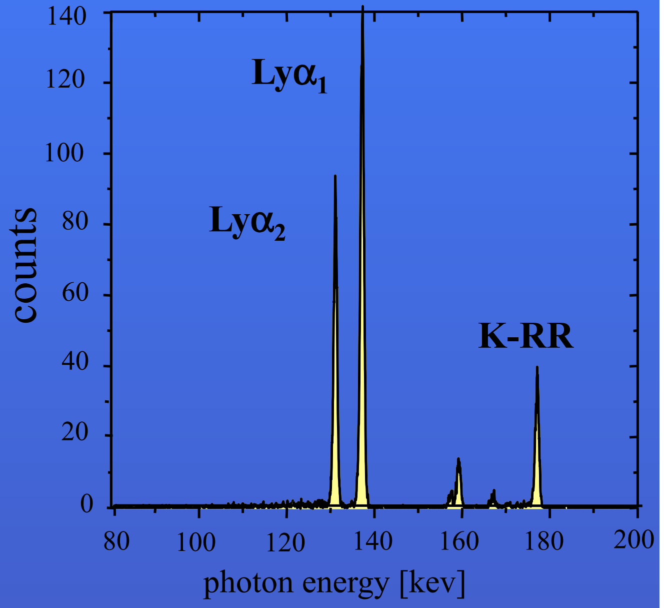
Quantum Electrodynamics @ FAIR

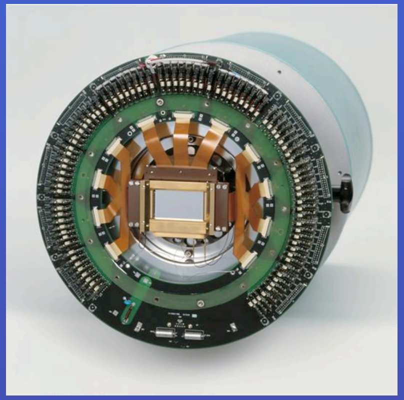
The 1s-LS in H-like Uranium (Exp. at GSI)





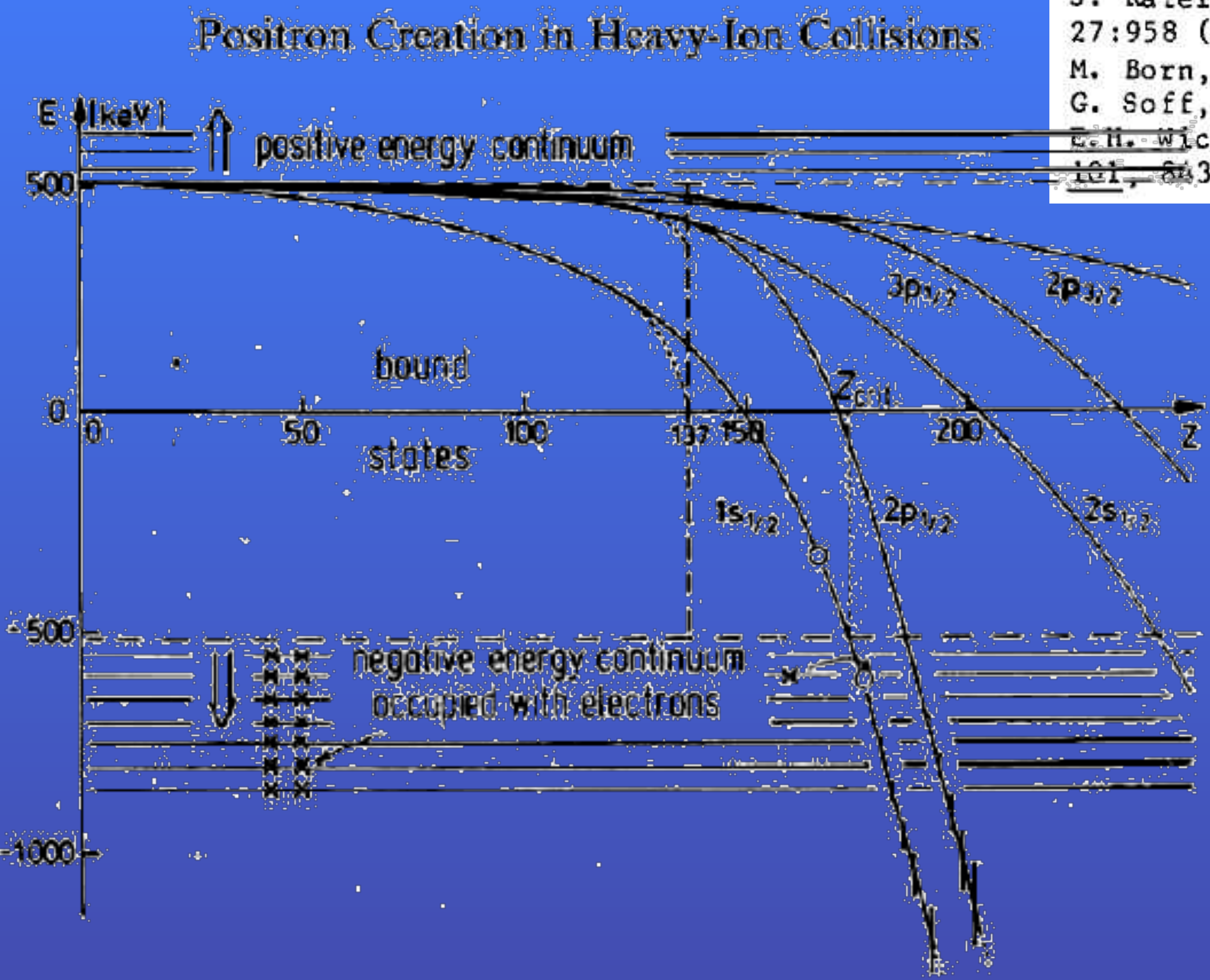






Diving into the negative energy sea

W. Pieper, W. Greiner, Z. Phys. 218:
B. Muller, J. Rafelski, W. Greiner,
Z. Phys. 257, 83 (1972); Nucl. Phys.
Ya.B. Zel'Dovich, V.S. Popov, Sov.
J. Rafelski, L.P. Fulcher, W. Greine
27:958 (1971).
M. Born, L. Infeld, Proc. Roy. Soc.
G. Soff, J. Rafelski, W. Greiner, Ph
E.H. Wichmann, N.M. Kroll, Phys. Rev
101, 843 (1956).


Positron Creation in Heavy-Ion Collisions

Binding energies of electronic states in atoms as function of nuclear charge Z. At $Z_c = 173$ the 1s-state dives into the negative energy continuum.

High precision measurements of continuum e+ shape distortions (vs Z_1,Z_2,b,…) needed to test detailed $Z\alpha>1$ QED diving physics

Positron Creation in Heavy-Ion Collisions

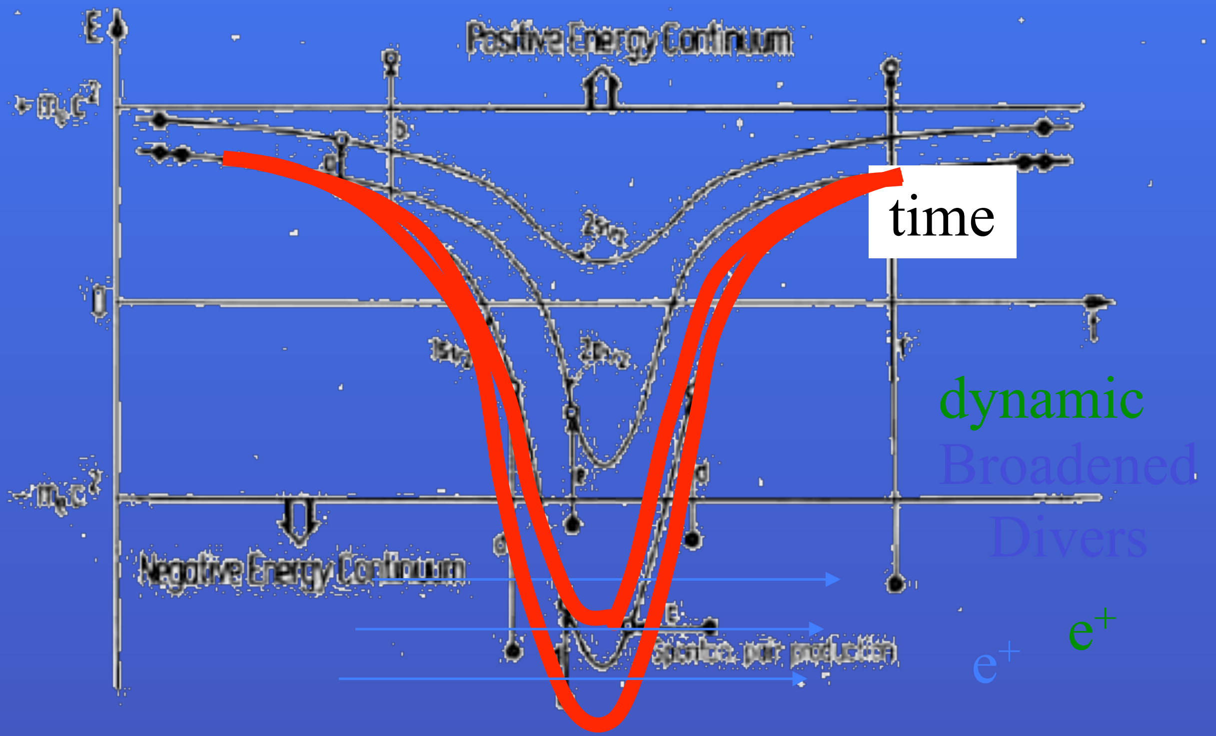


Fig. 6. Shows quasi-molecular states of electrons in a heavy-ion collision and indicates various excitation processes: (a and b) ejection of electrons out of the 1s-state, (c) spontaneous positron emission, (d and e) dynamical mechanisms of pair-production involving vacant bound states, (f) direct pair-production (shake-off of the vacuum polarization cloud).

Boris's famous and widely feared biweekly FAIR Management Meeting

熱気ムンムンのけいこ場、左から土佐ノ海、出島、旭鷲山、栃東

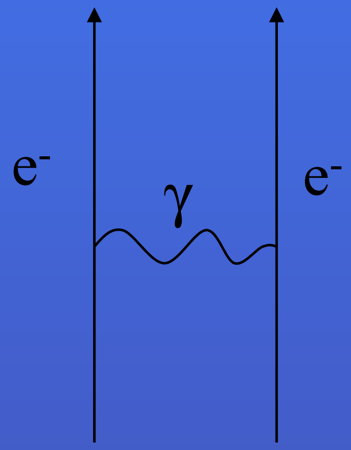
Strong fields, strong interactions: drastic consequences !

coupling strength:

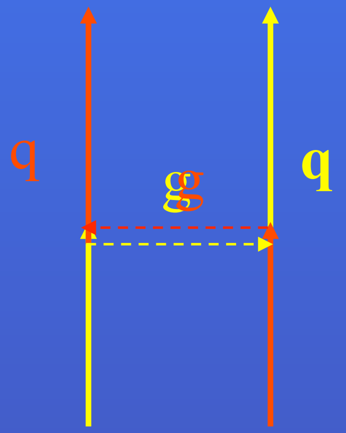
QED $\alpha \sim 1/137$, $\alpha^n << \alpha$

QCD $\boldsymbol{\alpha \sim 1}$, $\alpha^n \sim \alpha$

QED:



QCD:



(1-gluon exchange as important as 2-gluon exchange, …)

proton (uud), neutron (ddu) : m ~ 20 MeV

but total mass M_p , M_n ~ 1 GeV !

→ **dynamical mass creation**

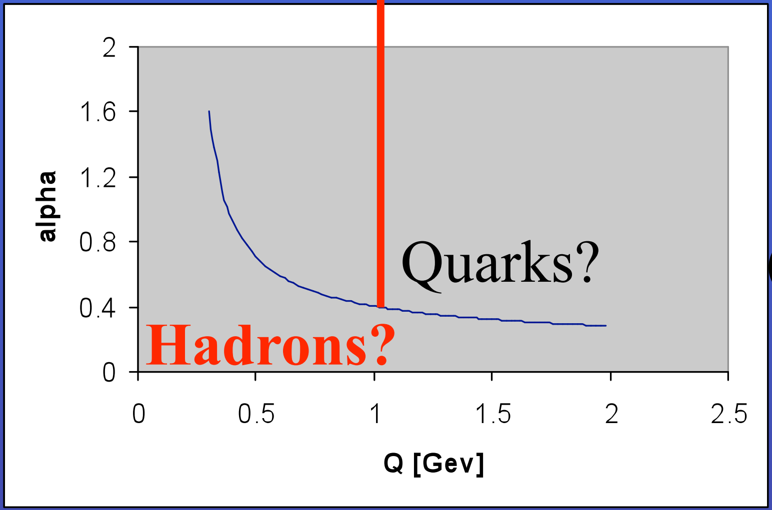
Strong coupling @ strong interactions

QCD as theory of strong interactions well established

radiative corrections generate running coupling constant α_{QCD}

$$\alpha_{QCD}(Q^2) = \frac{12\pi}{(33 - 2N_f)\ln(Q^2/\Lambda^2)}$$

Strong Coupling, Indeed !



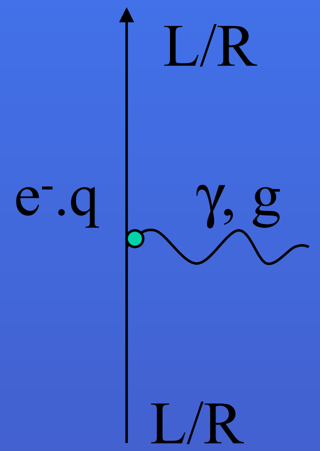
(asymptotic freedom)

Chiral Symmetry: left- and right-handed particles decouple

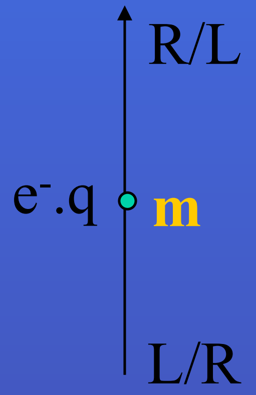
true for all vector interactions

$L/R = \frac{1}{2}\,(1 -/+ \gamma_5)\;\psi$

$\bar{\psi}\,\gamma_\mu A^\mu \psi = (\bar{L}+\bar{R})\,\gamma_\mu A^\mu\,(L+R) = \bar{L}\,\gamma_\mu A^\mu\,L + \bar{R}\,\gamma_\mu A^\mu\,R$



mass terms violate symmetry



$m\,\bar{\psi}\,\psi = m\,(\bar{L}+\bar{R})(L+R) = m\,(\bar{L}R + \bar{R}\,L)$

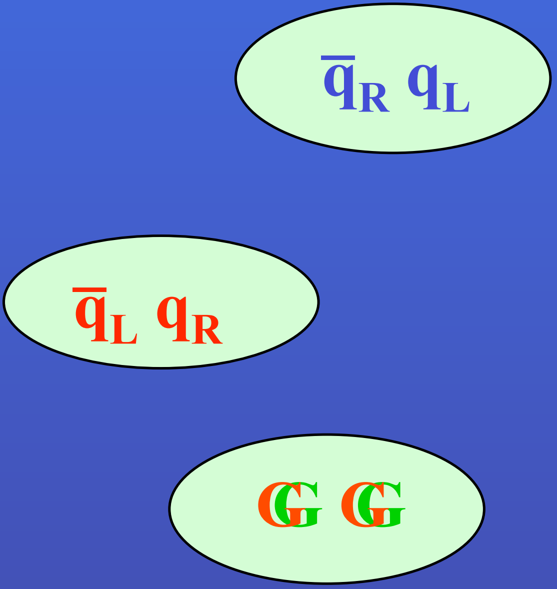
⟹ $m \ll E_{typical}$: chiral symmetry ok, $m_{u,d} \ll M_p$, $m_s < M_p$

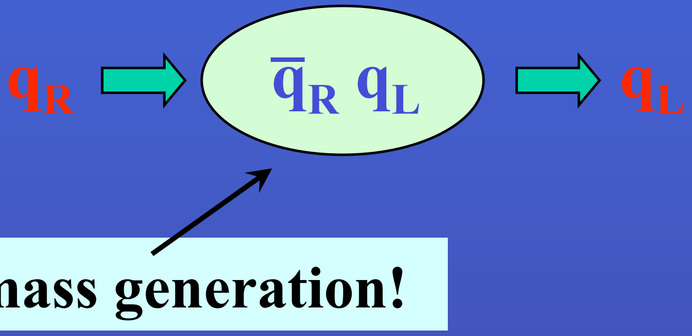
QCD vacuum has a complex structure!

$E_{q\bar{q}} \sim E_{kin} + E_{pot} < 0$! → Strong coupling: **condensates form !**

$$<0|\bar{q}\, q|0> \quad ; \quad <0|\, G_{\mu\nu}\, G^{\mu\nu}\, |0> \; = \; 0$$

left-handed $(\mathbf{k} \not\parallel \mathbf{s})$ right-handed $(\mathbf{k} \parallel \mathbf{s})$ particles
mass terms couple chirality





$$M\, \bar{\psi}\, \psi = M\, (\bar{L}+\bar{R})(L+R) = M\, (\bar{L}R + \bar{R}\,L)$$

$$\bar{\psi}\, \gamma_\mu A^\mu \psi = (\bar{L}+\bar{R})\, \gamma_\mu A^\mu\, (L+R) = \bar{L}\, \gamma_\mu A^\mu\, L + \bar{R}\, \gamma_\mu A^\mu\, R$$

Degrees of Freedom: SU(3) - flavor- multiplets:

n (ddu) p (uud)

Baryons Σ^- (sdd) Σ^0 Λ (sdu) Σ^+ (suu)

Ξ^- (ssd) Ξ^0 (ssu)

} **hyperons**

κ^0 ($s\bar{d}$) κ^+ ($s\bar{u}$)

Scalar Mesons δ^- ($u\bar{d}$) δ^0 , σ, ζ δ^+($d\bar{u}$)

κ^- ($u\bar{s}$) $\bar{\kappa}^0$ ($d\bar{s}$)

$\sigma \sim \langle \bar{u}\, u + \bar{d}\, d \rangle$ $\zeta \sim \langle \bar{s}\, s \rangle$ $\delta^0 \sim \langle u\, \bar{u} - d\, d \rangle$

K^{*0} ($\bar{s}d$) K^{*+} ($\bar{s}u$)

Vector Mesons ρ^- ($u\bar{d}$) ρ^0 , ω , ϕ ρ^+($d\bar{u}$)

K^{*-} ($u\bar{s}$) $\bar{K}^{*0}$ ($d\bar{s}$)

plus pseudoscalars, axial vectors and gluonic field χ

Mean-Field Lagrangean of Chiral SU(3)xSU(3) Model

$$\mathcal{L}^{\mathrm{chiral}} = \mathcal{L}_{\mathrm{BM}} + \mathcal{L}_{\mathrm{BV}} + \mathcal{L}_{\mathrm{vec}} + \mathcal{L}_0 + \mathcal{L}_{\mathrm{SB}}$$

- Baryon - Scalar-Meson Interaction ⇒ Dynamical Mass Generation

$$\mathcal{L}_{\mathrm{BM}} = -\sum_i \bar{\mathrm{B}}_i m_i^* \mathrm{B}_i \qquad m_i^* = g_{i\sigma}\sigma + g_{i\zeta}\zeta$$

$$i = N, \Lambda, \Sigma, \Xi, \Delta, \Sigma^*, \Xi^*, \Omega$$

- Baryon - Vector-Meson Interaction ⇒ Repulsion

$$\mathcal{L}_{\mathrm{BV}} = -\sum_i \bar{\mathrm{B}}_i \gamma_0 \left[g_{i\omega}\omega_0 + g_{i\phi}\phi_0 \right] \mathrm{B}_i$$

- Vector-Meson-Potential

$$\mathcal{L}_{vec} = \frac{1}{2} m_\omega^2 \frac{\chi^2}{\chi_0^2} \omega^2 + \frac{1}{2} m_\phi^2 \frac{\chi^2}{\chi_0^2} \phi^2 + g_4^4 (\omega^4 + 2\phi^4)$$

- Scalar-Meson-Potential ⇒ Spontaneous Chiral Symmetry Breaking, Scale Breaking

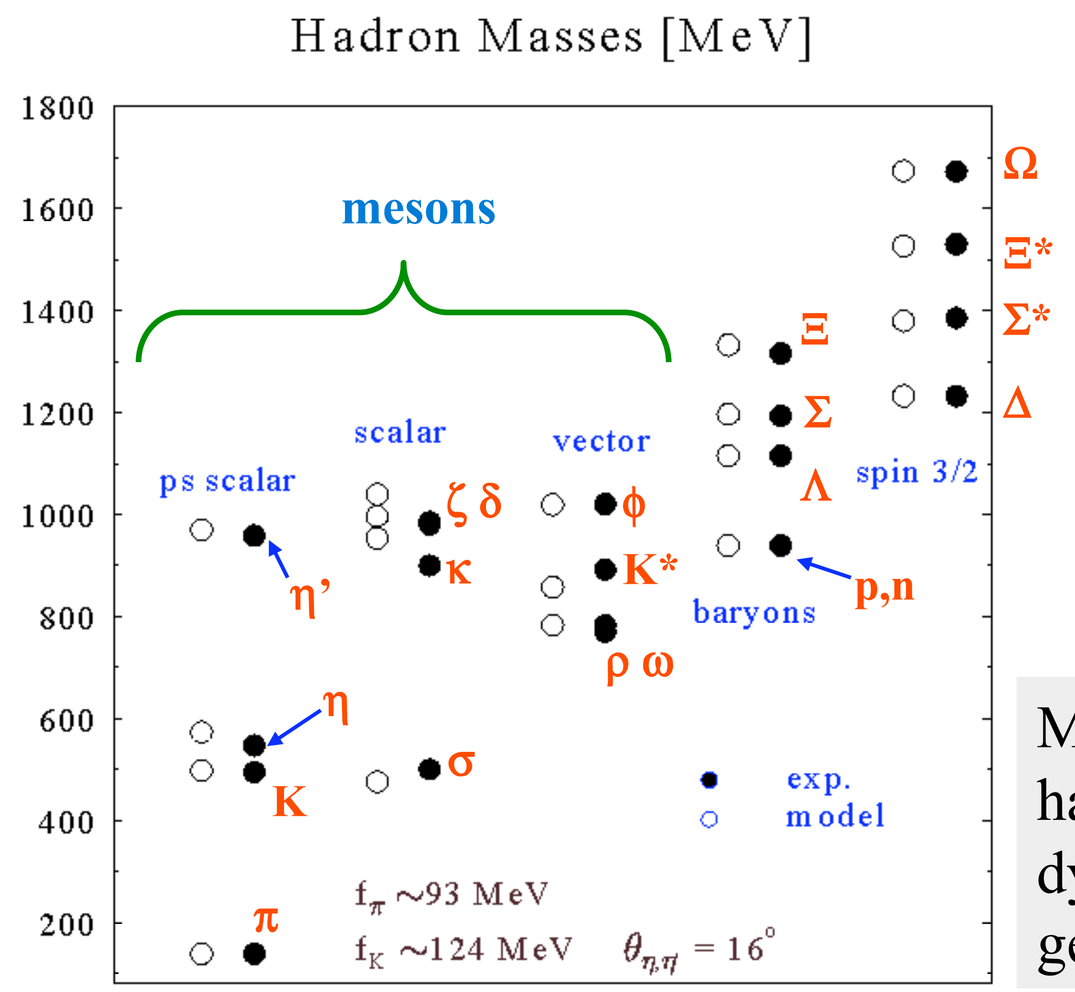
$$\mathcal{L}_0 = -\frac{1}{2} k_0 \chi^2 \left(\sigma^2 + \zeta^2\right) + k_1 \left(\sigma^2 + \zeta^2\right)^2 + k_2 \left(\frac{\sigma^4}{2}\right)$$

$$+ k_3 \chi \sigma^2 \zeta - k_4 \chi^4 - \frac{1}{4} \chi^4 \ln \frac{\chi^4}{\chi_0^4} + \frac{\delta}{3} \chi^4 \ln \frac{\sigma^2 \zeta}{\sigma_0^2 \zeta_0}$$

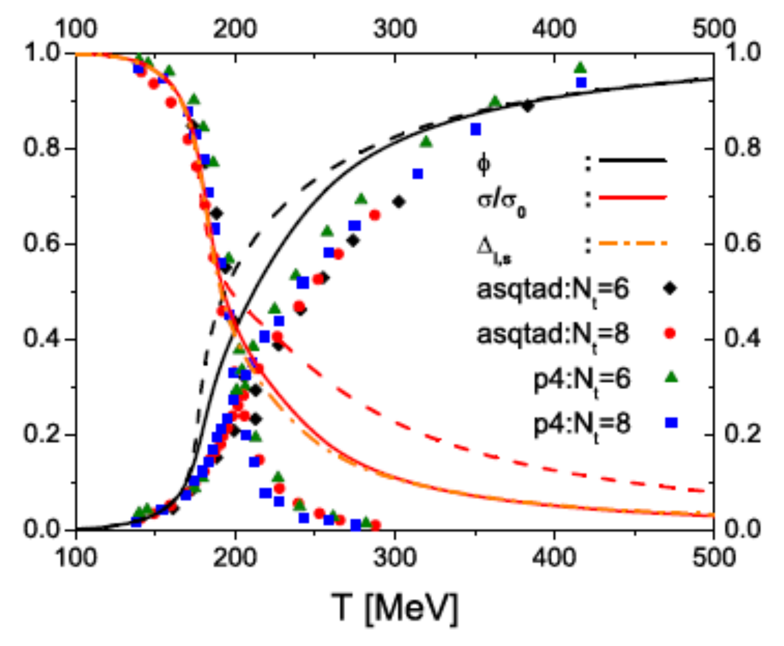
- Explicit Symmetry Breaking ⇒ Finite π Mass, PCAC

$$\mathcal{L}_{\mathrm{SB}} = -\left(\frac{\chi}{\chi_0}\right)^2 \left[m_\pi^2 f_\pi \sigma + (\sqrt{2} m_K^2 f_K - \frac{1}{\sqrt{2}} m_\pi^2 f_\pi) \zeta \right]$$

fit parameters to hadron masses

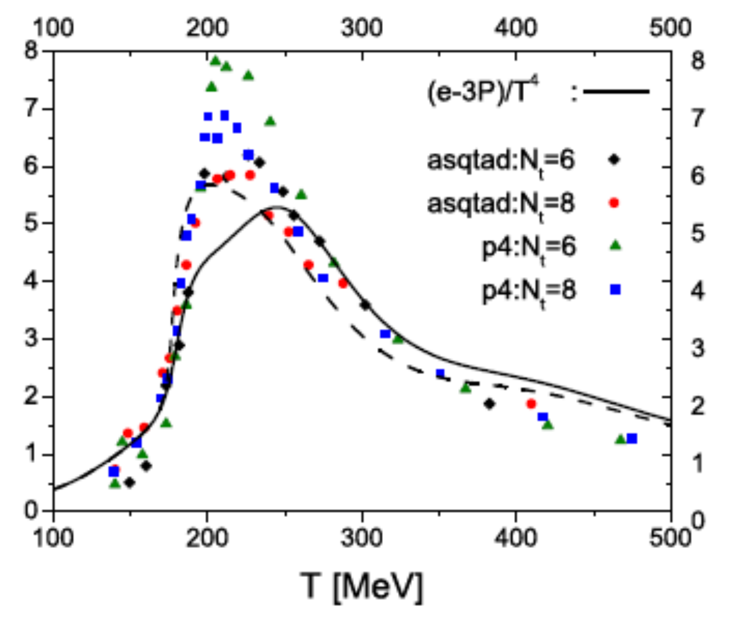


Model can reproduce hadron spectra via dynamical mass generation!

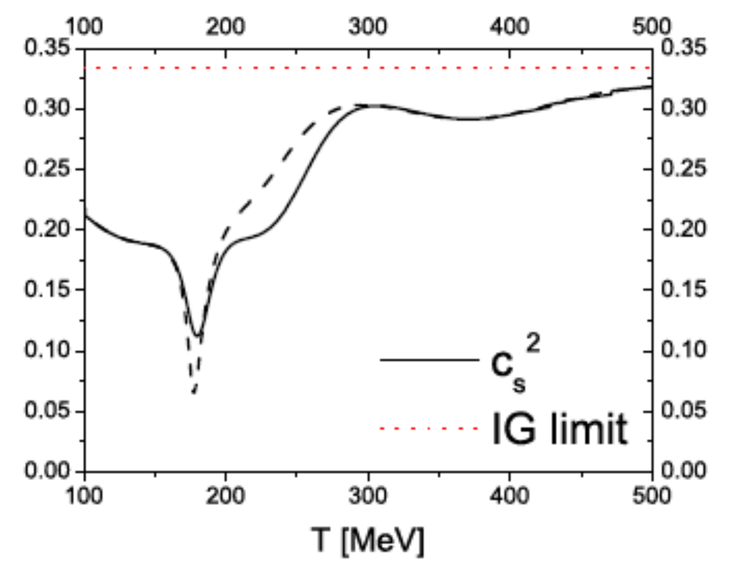


Temperature dependence of chiral condensate and Polaykov loop at $\mu = 0$

Interaction measure e – 3p



lattice data taken from Bazavov et al. PRD 80, 014504 (2009)



speed of sound shows a pronounced dip around T_c !

fields change in a dense and hot medium

$M_N \sim g^{\sigma} \sigma_0 \quad (+ \; g^{\zeta} \zeta_0 + g^{\delta} \delta_0) \qquad$ e.o.m: $\delta\sigma \sim - g^{\sigma} / m_{\sigma}^2 \rho_s$

In the medium the vacuum condensate is reduced $(\sigma < \sigma_0)$

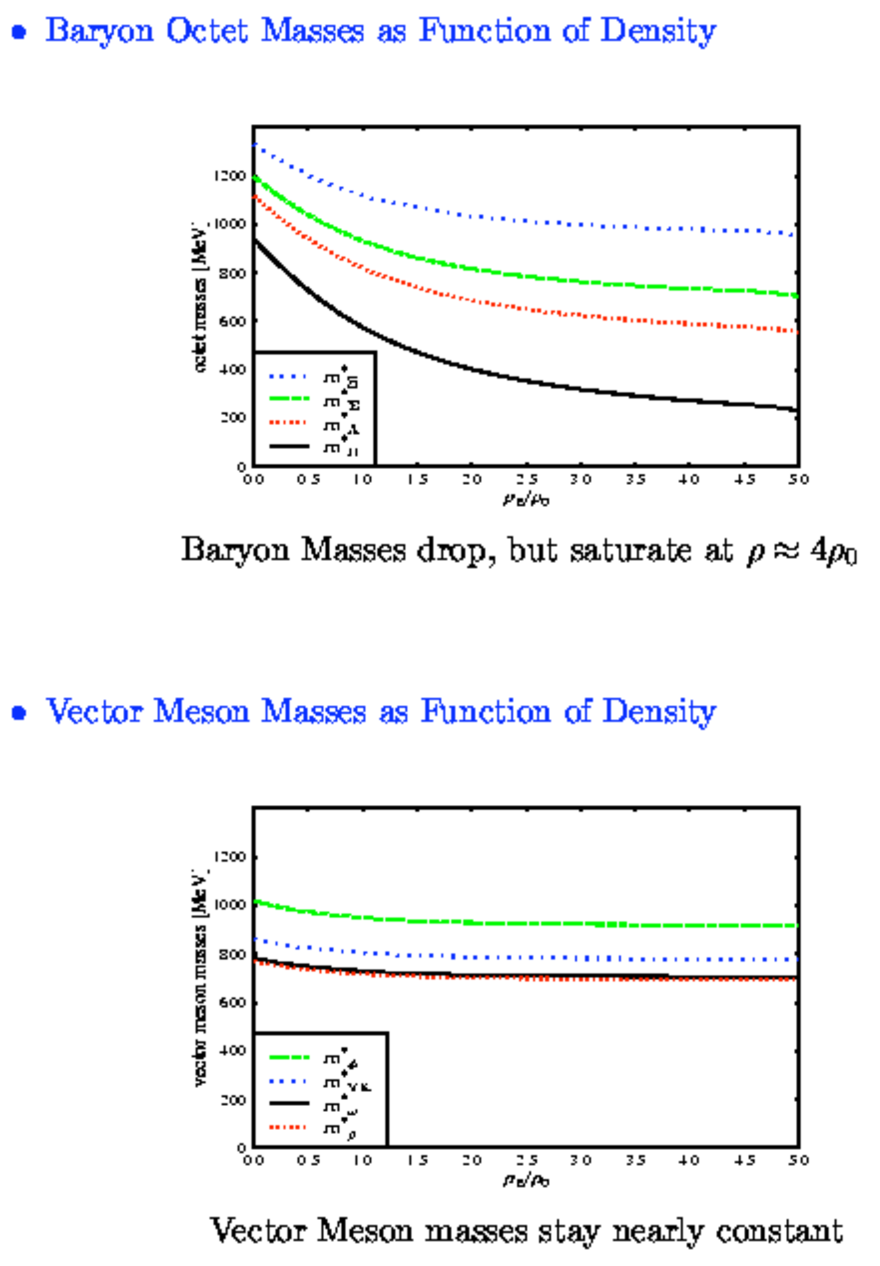
Inside of an atomic nucleus $\qquad M_N^* / M_N \sim 0.6$

strong scalar attraction! **~ - 300 MeV**

plus vector repulsion
from surrounding nucleons: $_V \sim g^{\omega} \omega \sim - g^{\omega} / m_{\omega}^{2} \rho_V \sim$ **240 MeV**

$[\; V_s - V_V \sim$ - 540 MeV $\quad V_{LS} \sim d/dR\,(V_S - V_V)$ **large LS splitting** $]$

Hadron Masses in Dense Matter



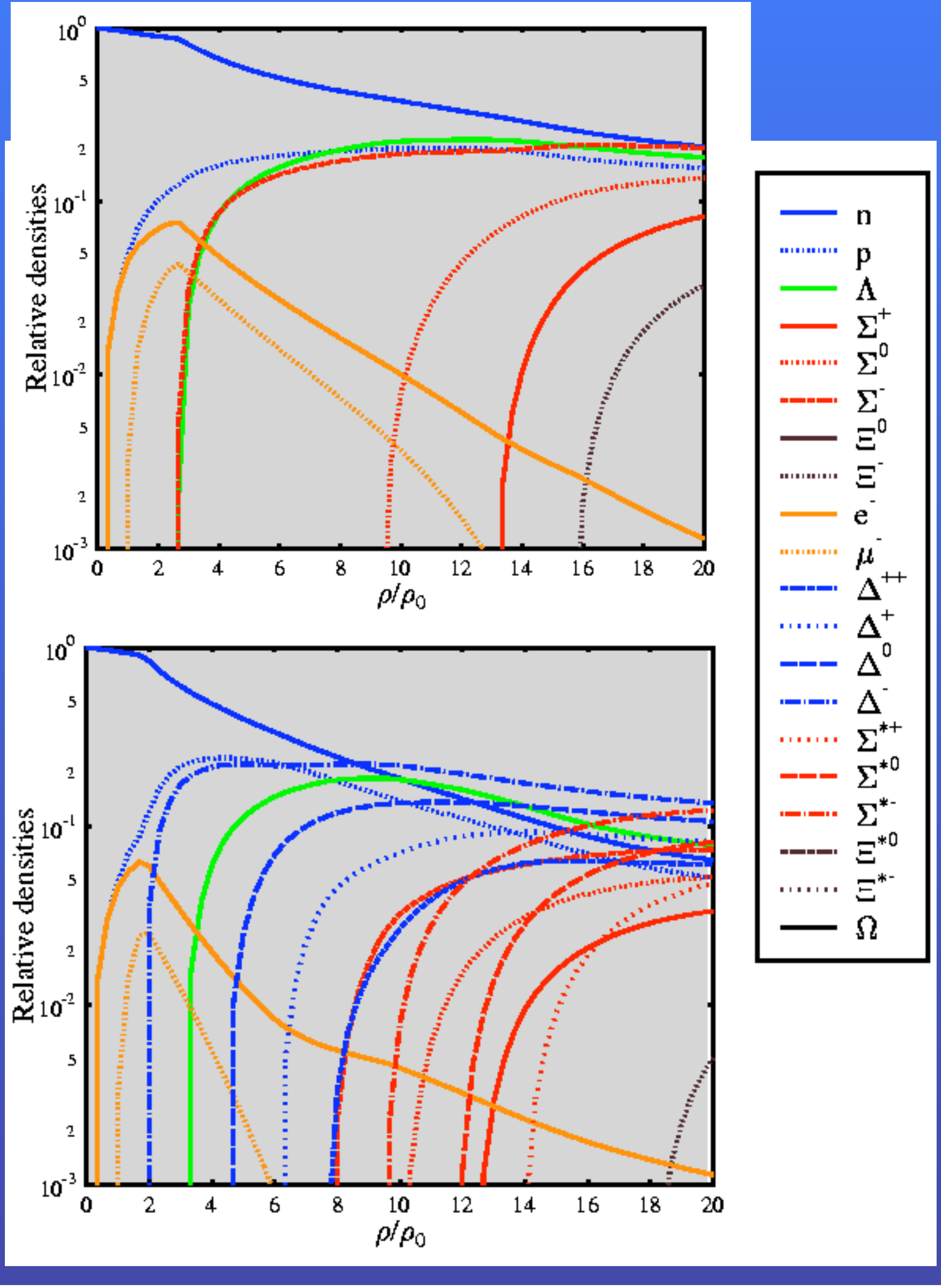
- Baryon Octet Masses as Function of Density

Baryon Masses drop, but saturate at $\rho \approx 4\rho_0$

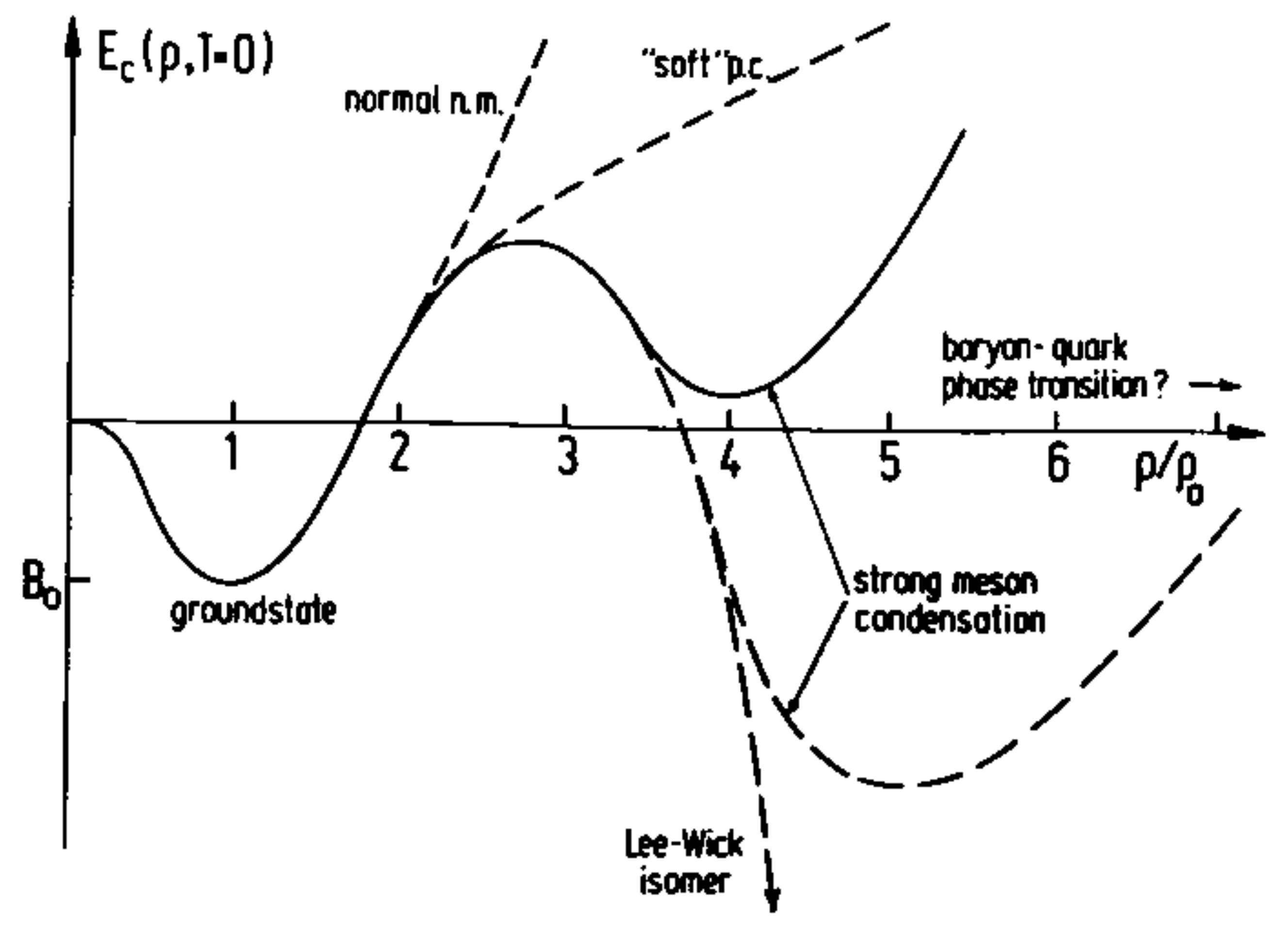
- Vector Meson Masses as Function of Density

Vector Meson masses stay nearly constant

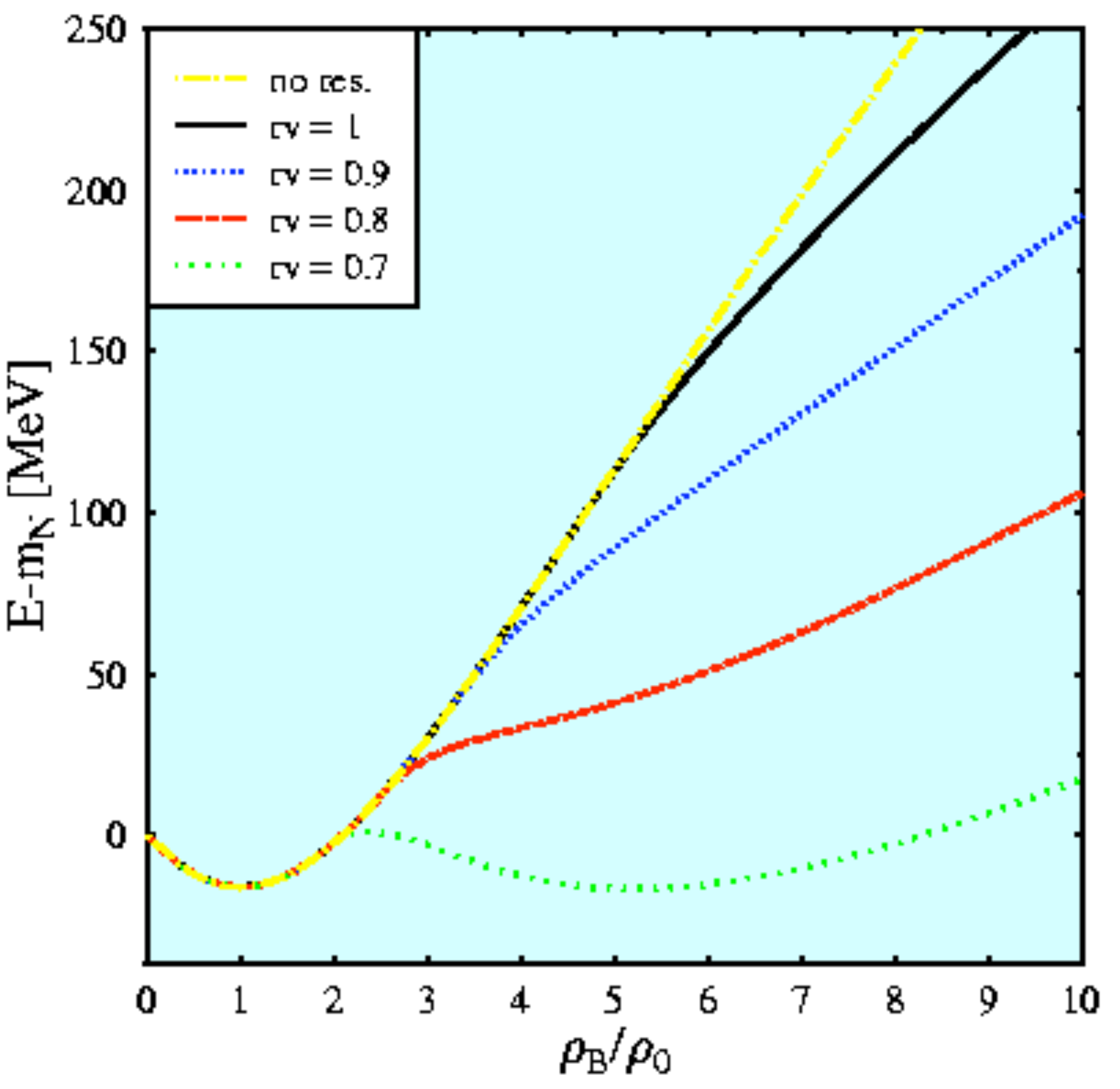
Particle Densities in Neutron Star I



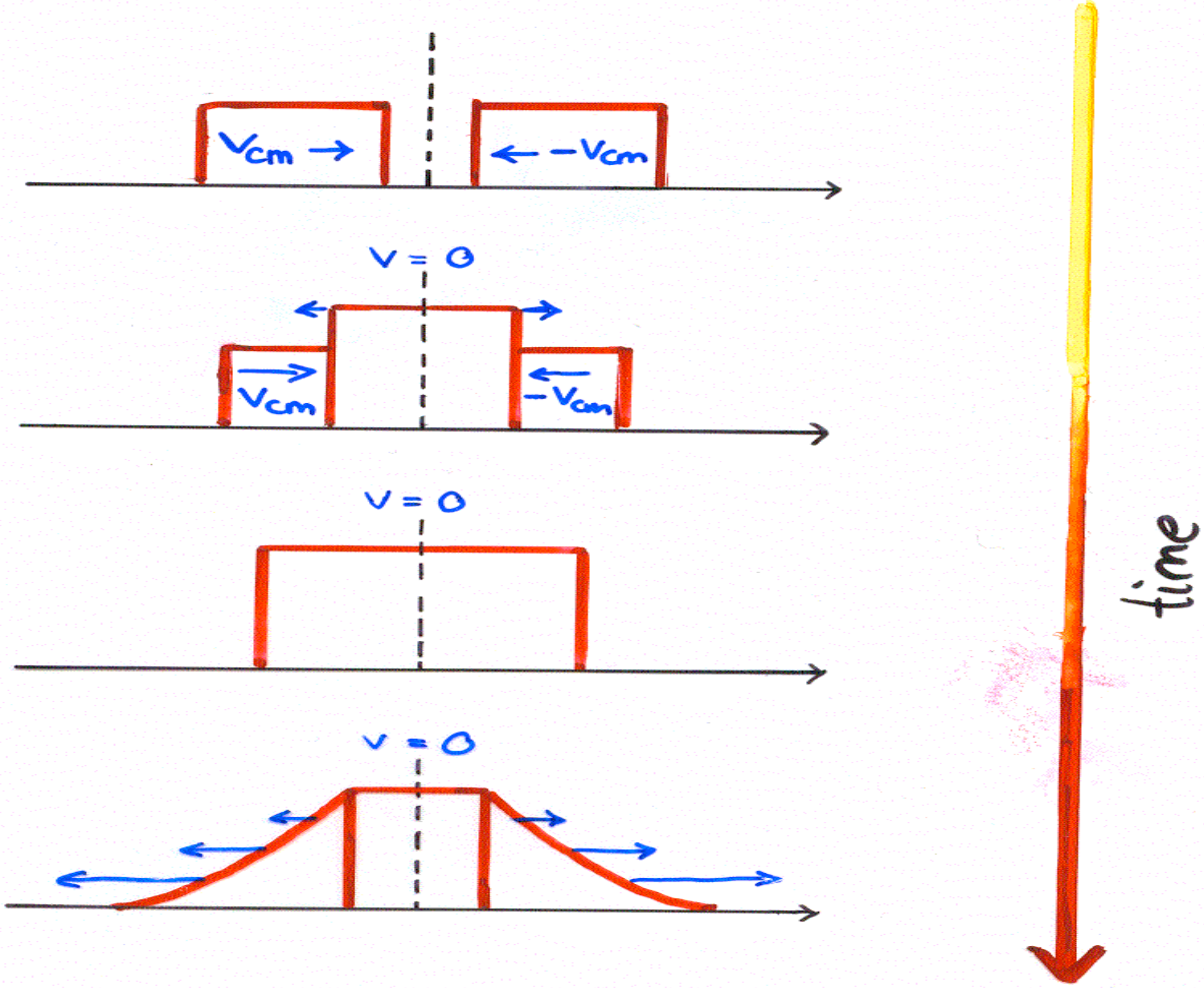
Speculative Possibilities for the EOS



Nuclear Matter in the Chiral Model



SHOCK WAVE MODEL



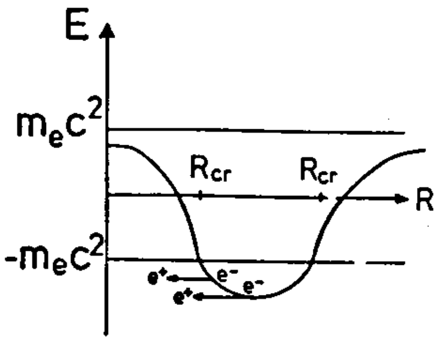


Abb. 8
Neutrales und geladenes Vakuum in starken elektrischen Feldern, wie sie im Stoß zweier Urankerne auftreten sollten. R bezeichnet den Abstand der Kerne.

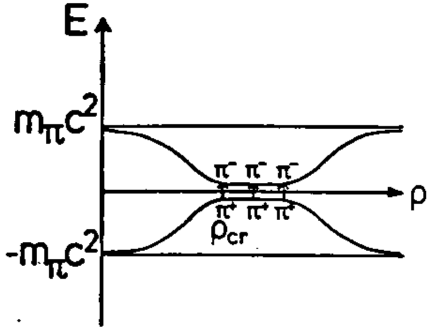


Abb. 9
Pionenkondensation als Funktion der Verdichtung $\rho(t)$ im Schwerionenstoß. ρc bedeutet die kritische Dichte für das Einsetzen energieloser Erzeugung von π^+-π^--Paaren.

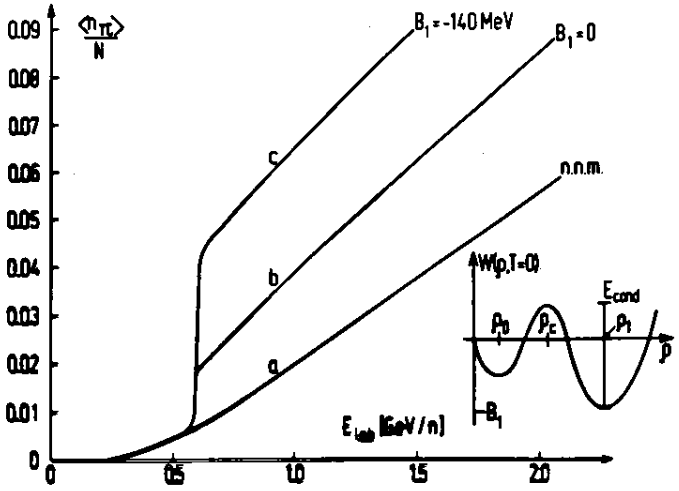
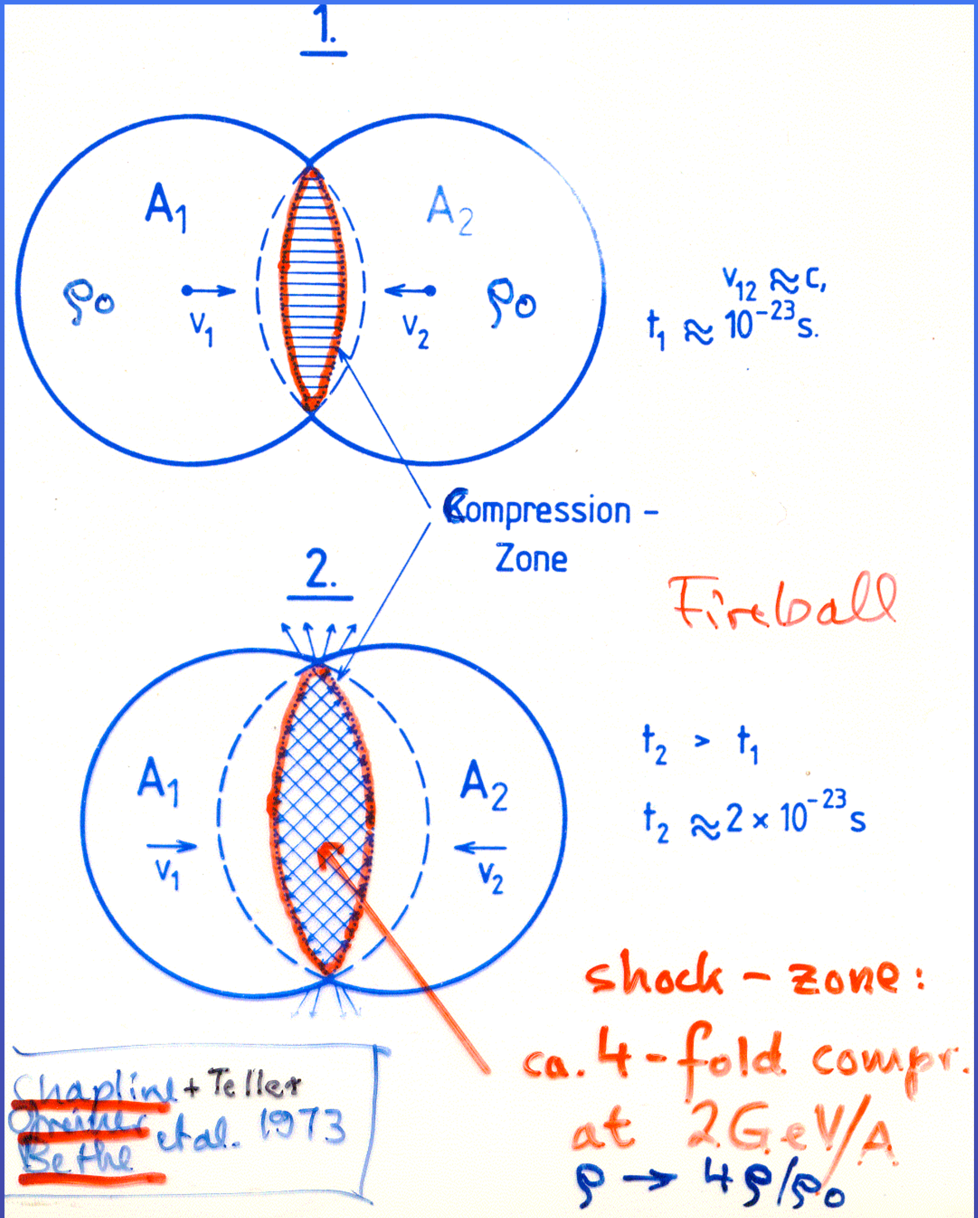


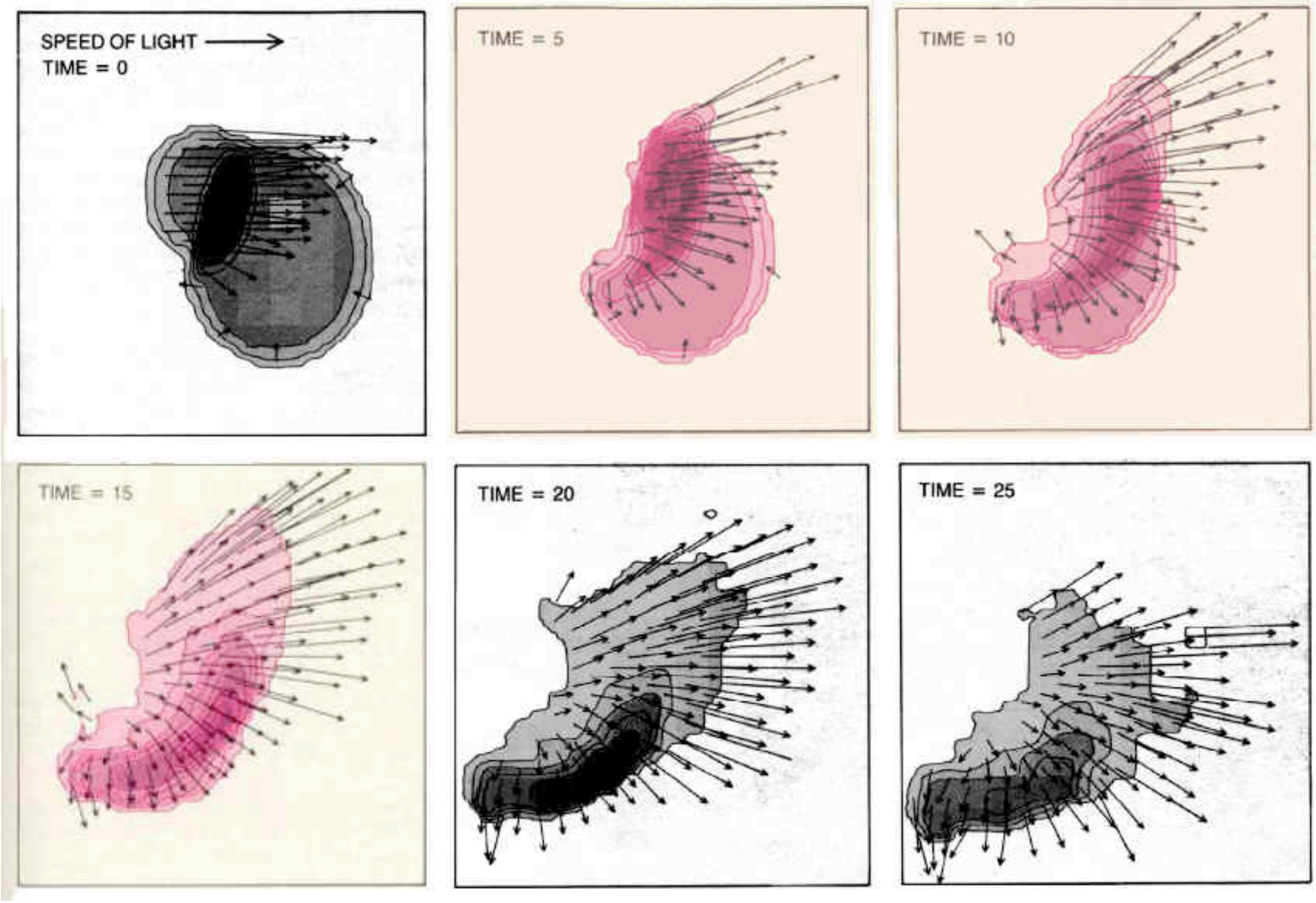
Abb. 10 Anregungsfunktion für die Pionen-Multiplizität in einem hydrodynamischen Modell für zentrale Stöße gleichschwerer Kerne, unter Annahme von drei verschiedenen Formen der Kernmaterie-Zustandsgleichung: a) normale hard core-Abstoßung, b) sekundäres Minimum bei ρ_1 mit $W(\rho_1)=0$, c) dasselbe für $W(\rho_1)=-140$ MeV. Für ρ_1 wurde hier etwa 3.0-fache Normaldichte ρ_0 von Kernmaterie angenommen.

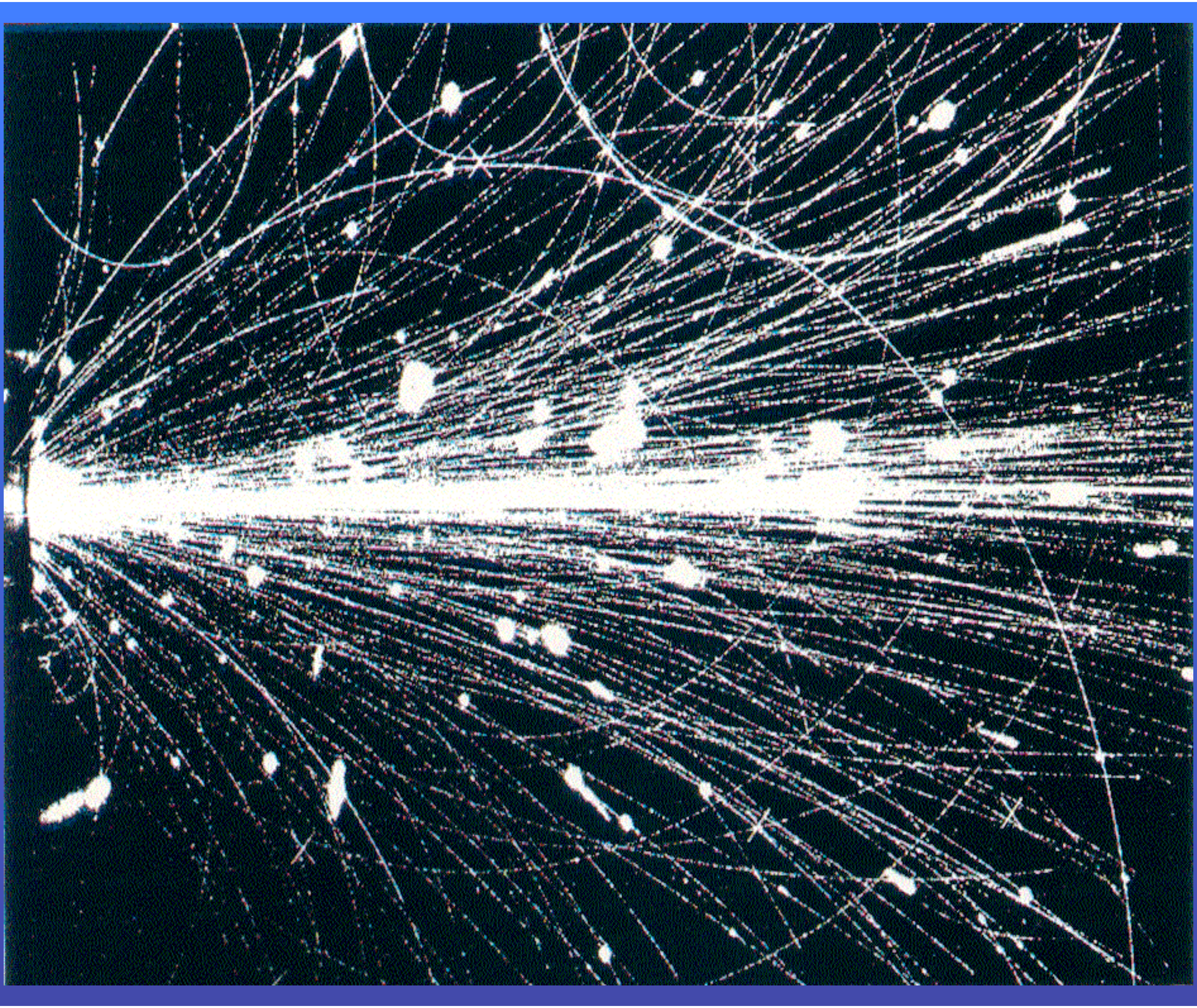
Compression of nuclear matter

by shock-formation, $E_{Lab} \sim$ 1-2 GeV/nucl

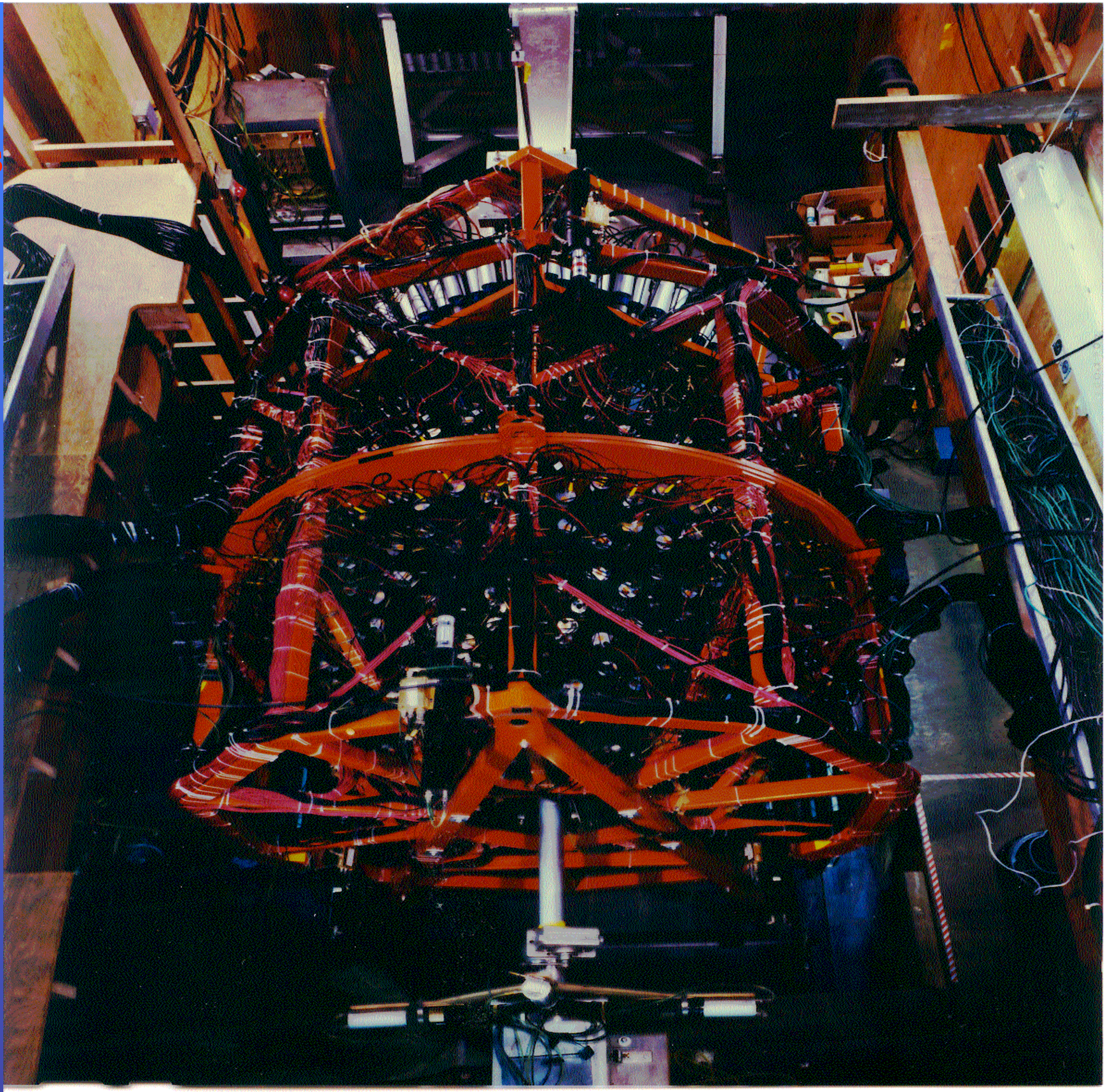


Searching for nuclear shocks



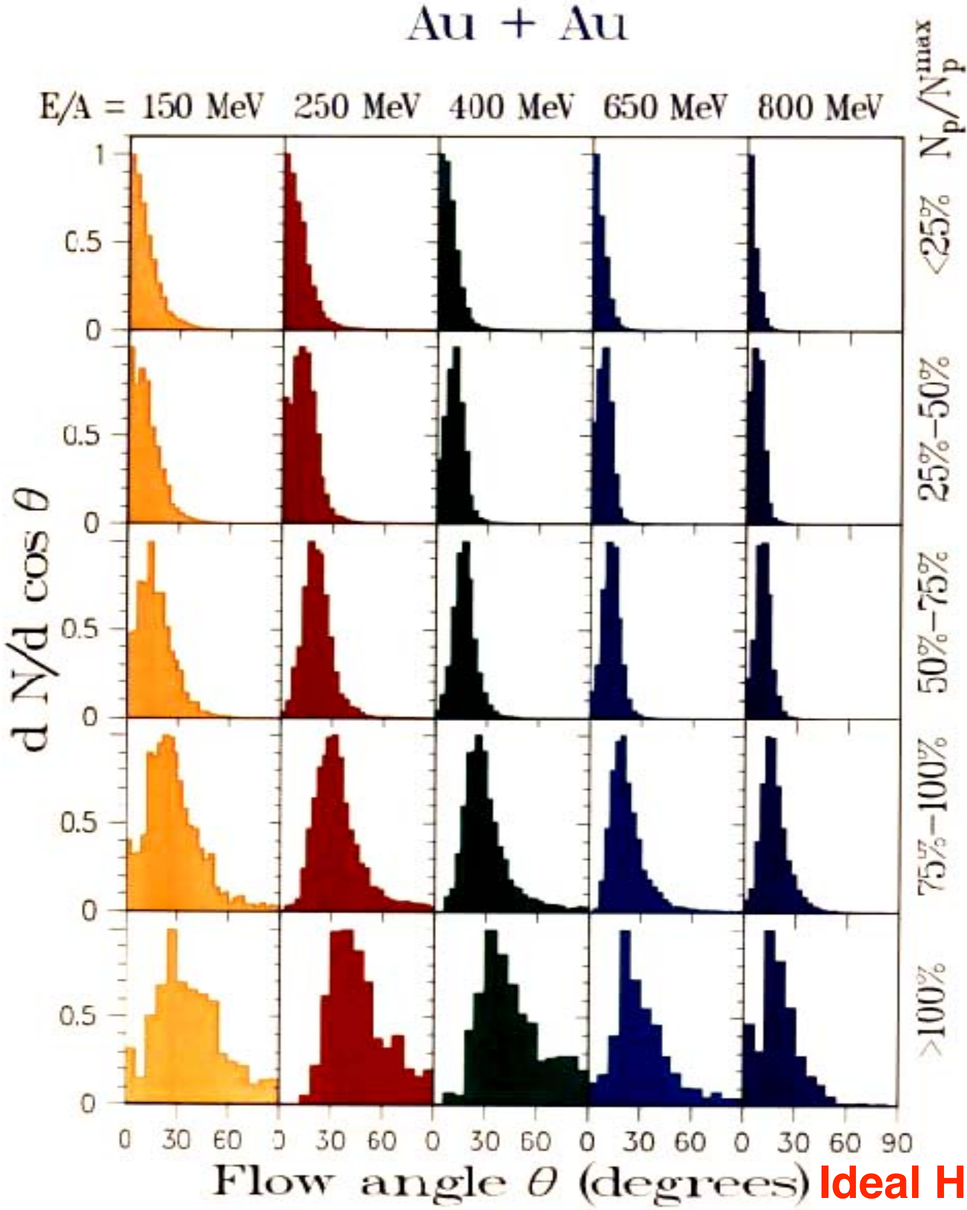


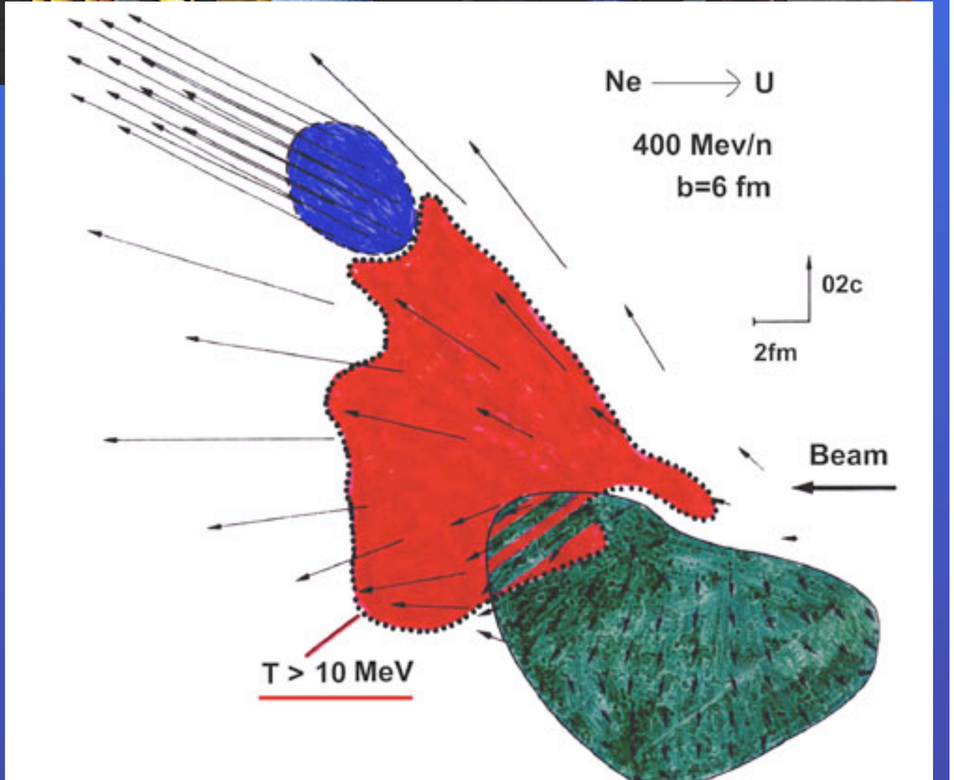
Gutbrod's
Plastic
Ball



1984: First Paper on Discovery of Collective Flow at the Bevalac:
PRL 52, 1590 (84)

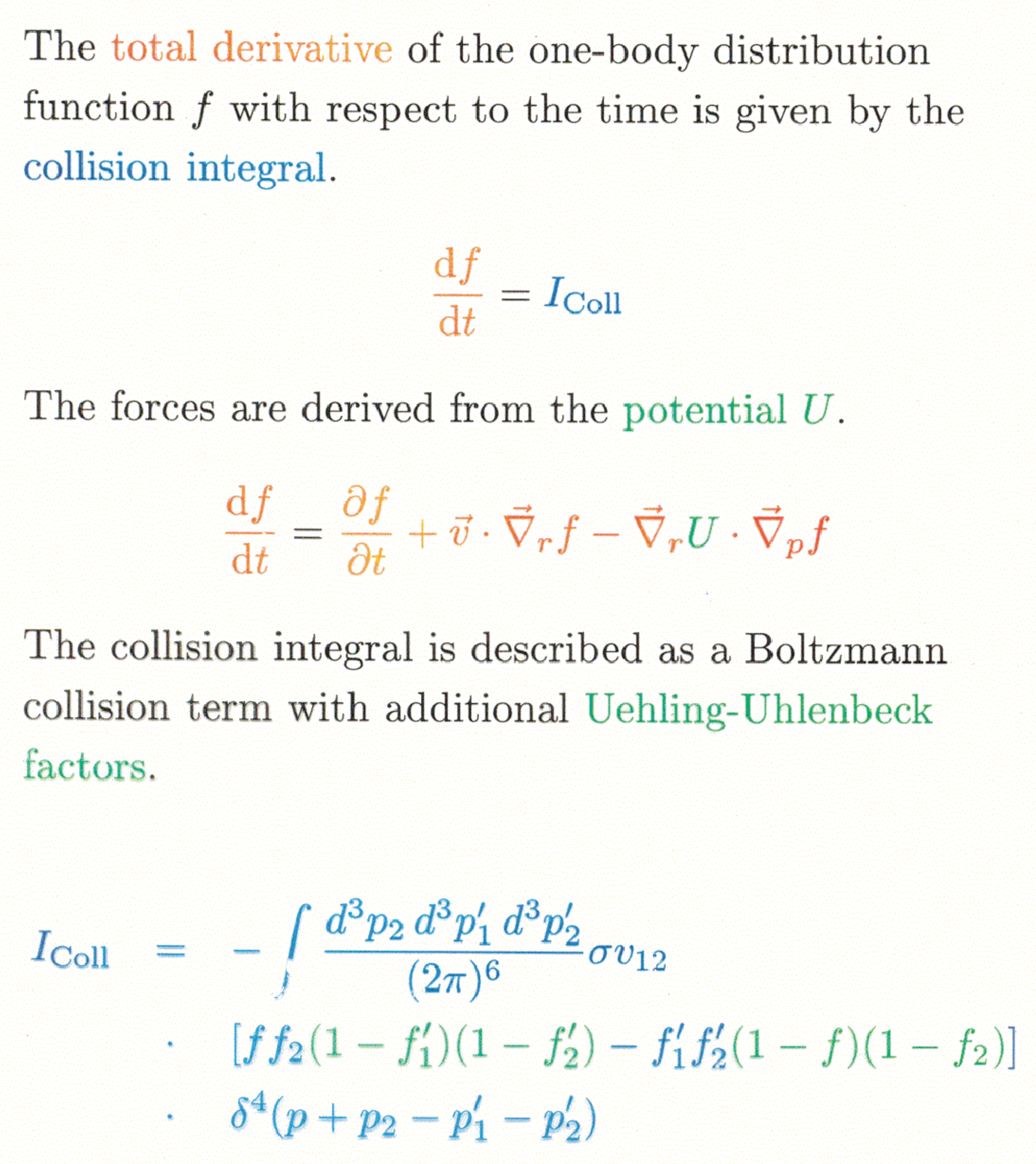
Plastic Ball and Streamer Chamber





Ideal Hydro Flow Stöcker Maruhn Greiner PRL1980 725

Vlasov-Uehling-Uhlenbeck one-component n.r.Transport Theory



The total derivative of the one-body distribution function f with respect to the time is given by the collision integral.

$$\frac{\mathrm{d}f}{\mathrm{d}t} = I_{\mathrm{Coll}}$$

The forces are derived from the potential U.

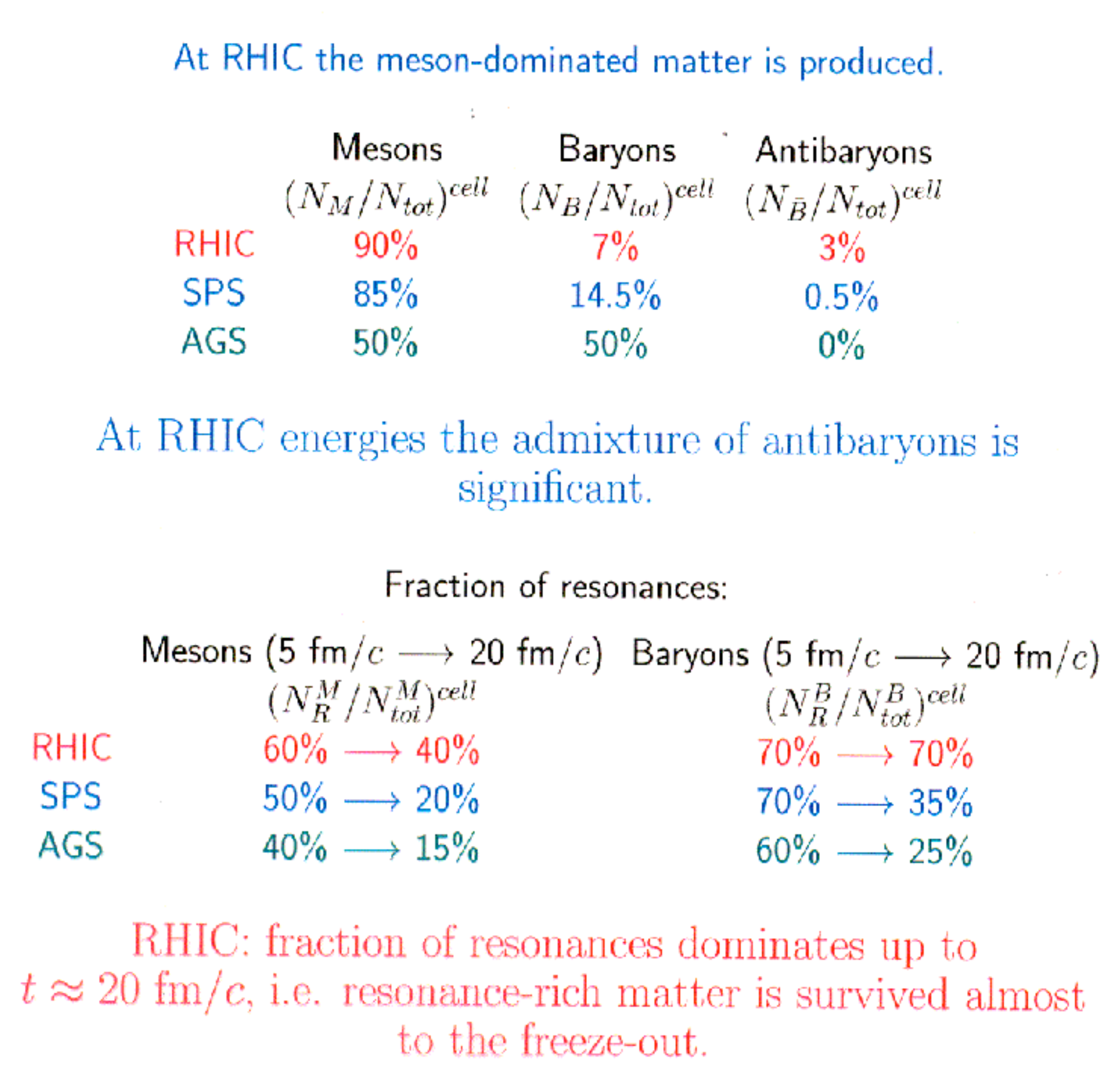
$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \vec{v} \cdot \vec{\nabla}_r f - \vec{\nabla}_r U \cdot \vec{\nabla}_p f$$

The collision integral is described as a Boltzmann collision term with additional Uehling-Uhlenbeck factors.

$$\begin{aligned} I_{\mathrm{Coll}} &= -\int \frac{d^3p_2\, d^3p'_1\, d^3p'_2}{(2\pi)^6} \sigma v_{12} \\ &\cdot \left[f f_2 (1-f'_1)(1-f'_2) - f'_1 f'_2 (1-f)(1-f_2)\right] \\ &\cdot \delta^4(p + p_2 - p'_1 - p'_2) \end{aligned}$$

Multi-Component, Relativistic TT: UrQMD

Baryon RICH - Resonance matter at FAIR



At RHIC the meson-dominated matter is produced.

	Mesons $(N_M/N_{tot})^{cell}$	Baryons $(N_B/N_{tot})^{cell}$	Antibaryons $(N_{\bar{B}}/N_{tot})^{cell}$
RHIC	90%	7%	3%
SPS	85%	14.5%	0.5%
AGS	50%	50%	0%

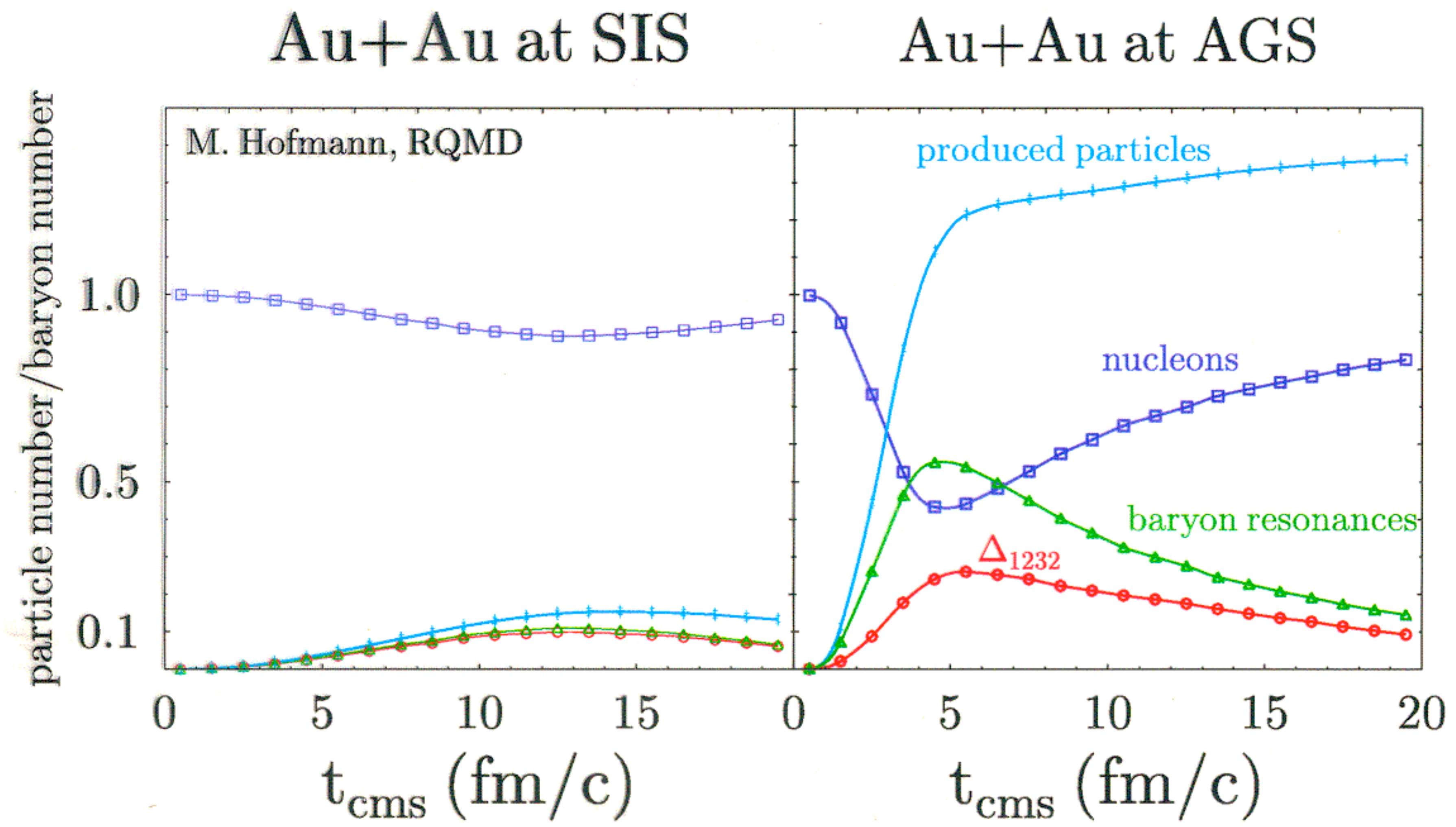
At RHIC energies the admixture of antibaryons is significant.

Fraction of resonances:

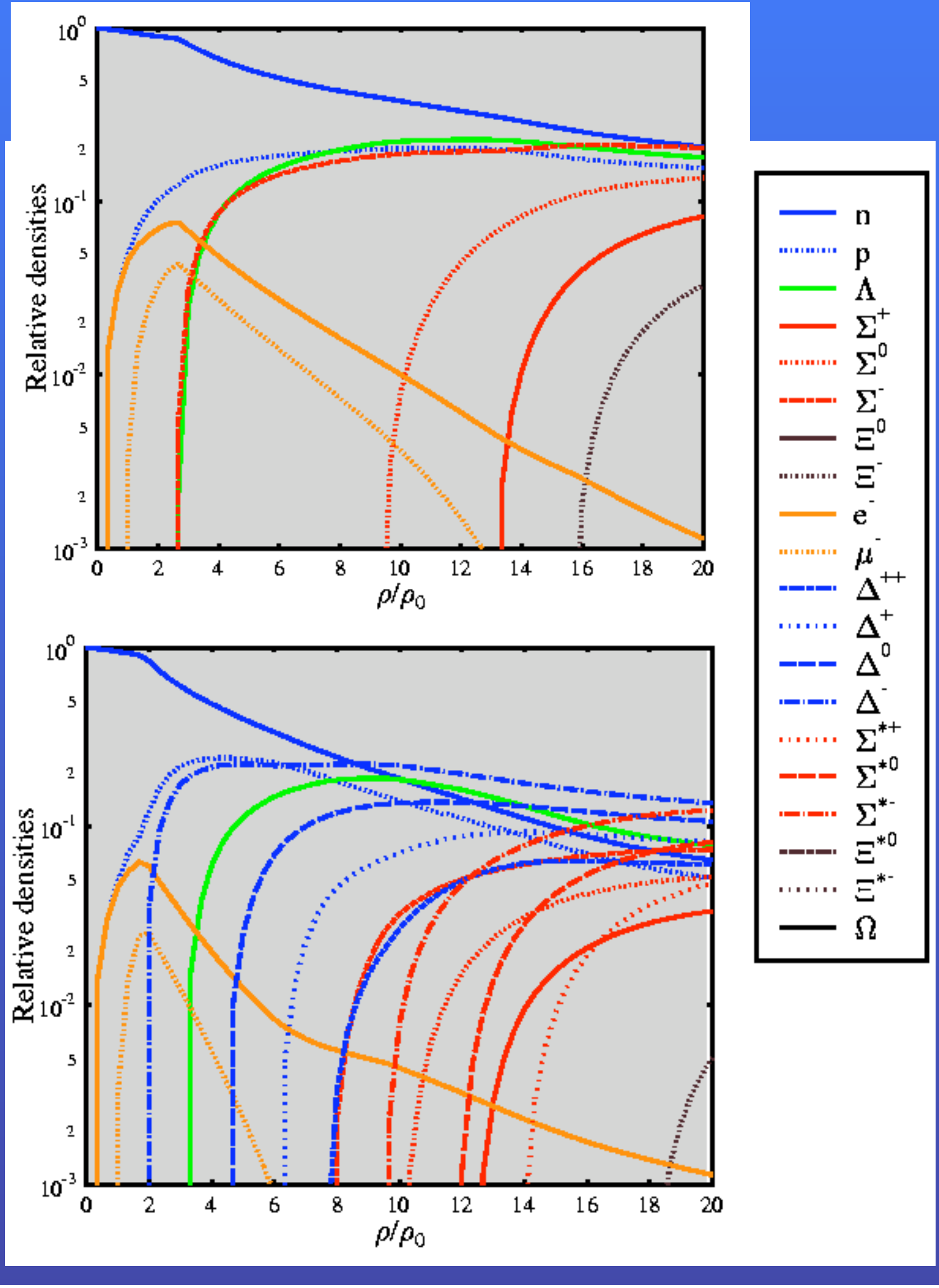
	Mesons (5 fm/c $\longrightarrow$ 20 fm/c) $(N_R^M/N_{tot}^M)^{cell}$	Baryons (5 fm/c $\longrightarrow$ 20 fm/c) $(N_R^B/N_{tot}^B)^{cell}$
RHIC	60% $\longrightarrow$ 40%	70% $\longrightarrow$ 70%
SPS	50% $\longrightarrow$ 20%	70% $\longrightarrow$ 35%
AGS	40% $\longrightarrow$ 15%	60% $\longrightarrow$ 25%

RHIC: fraction of resonances dominates up to $t \approx 20$ fm/c, i.e. resonance-rich matter is survived almost to the freeze-out.

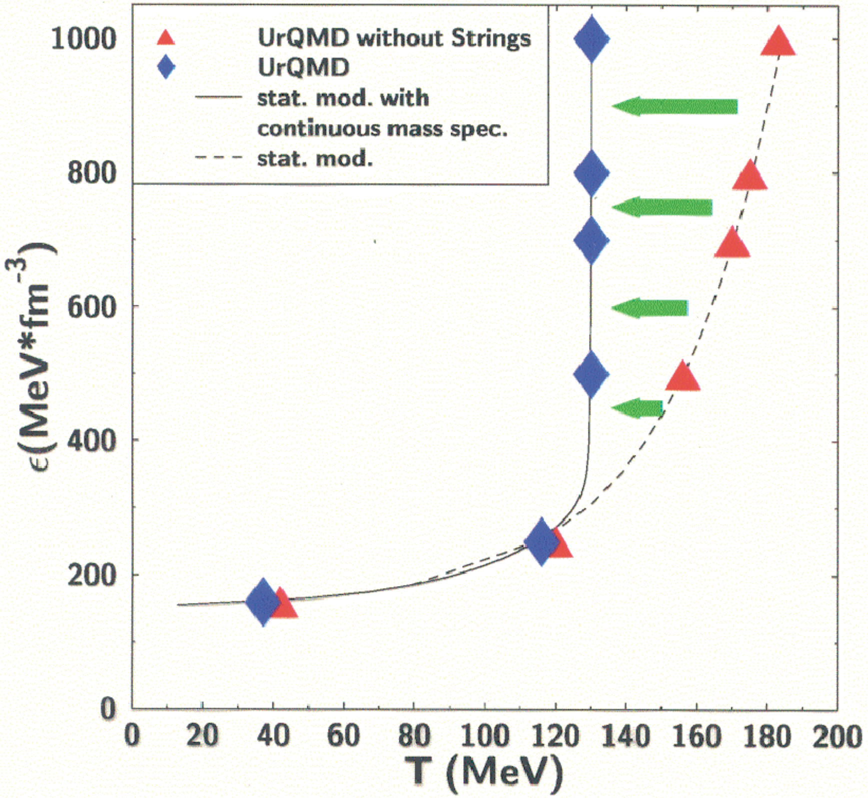
Creation of dense nuclear matter: Excitation of resonance matter



Particle Densities in Neutron Star I

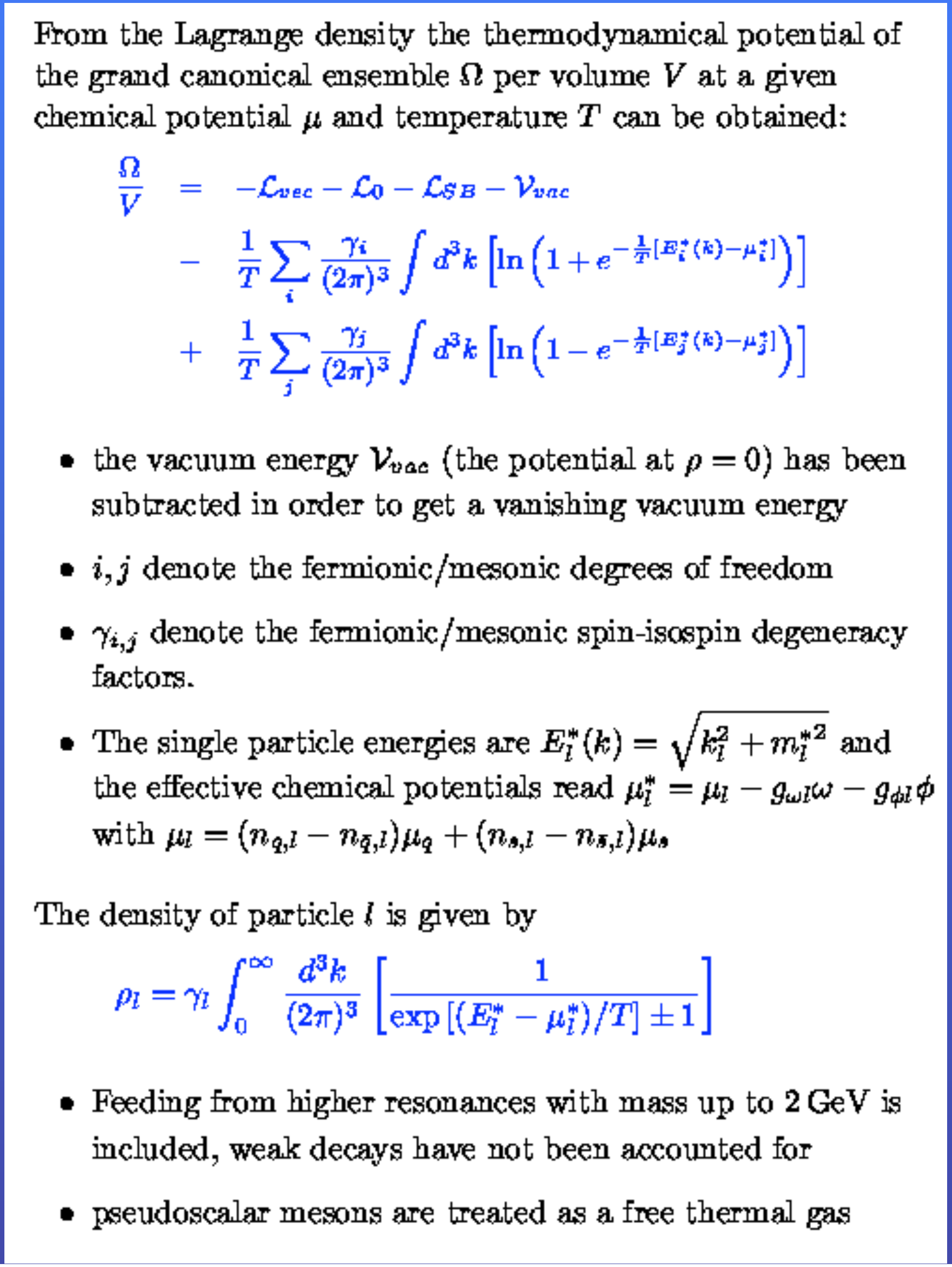


Equation of State of a microscopic model



- strings lead to a Hagedorn like EoS
- limiting temperature: 130 MeV
- without strings UrQMD shows continuous rise of T with ϵ

Calculation of Particle Ratios



From the Lagrange density the thermodynamical potential of the grand canonical ensemble Ω per volume V at a given chemical potential μ and temperature T can be obtained:

$$\begin{aligned}\frac{\Omega}{V} &= -\mathcal{L}_{vec} - \mathcal{L}_0 - \mathcal{L}_{SB} - \mathcal{V}_{vac} \\ &- \frac{1}{T}\sum_i \frac{\gamma_i}{(2\pi)^3}\int d^3k \left[\ln\left(1 + e^{-\frac{1}{T}[E_i^*(k)-\mu_i^*]}\right)\right] \\ &+ \frac{1}{T}\sum_j \frac{\gamma_j}{(2\pi)^3}\int d^3k \left[\ln\left(1 - e^{-\frac{1}{T}[E_j^*(k)-\mu_j^*]}\right)\right]\end{aligned}$$

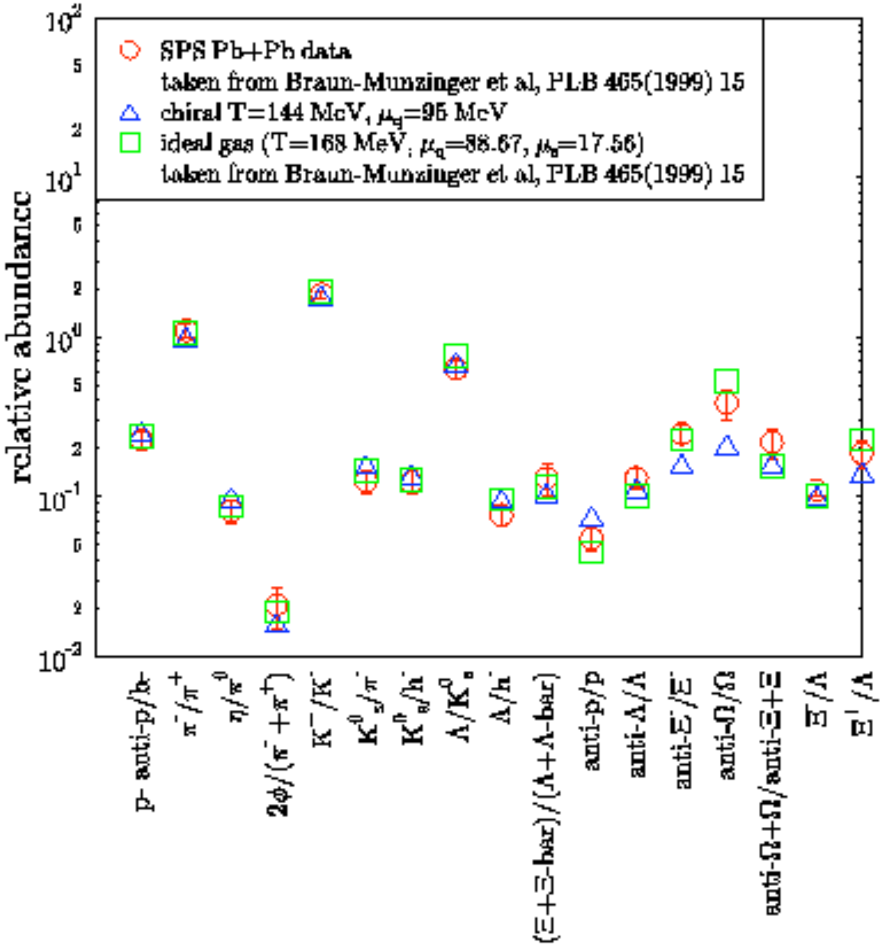
- the vacuum energy $\mathcal{V}_{vac}$ (the potential at $\rho = 0$) has been subtracted in order to get a vanishing vacuum energy
- i, j denote the fermionic/mesonic degrees of freedom
- $\gamma_{i,j}$ denote the fermionic/mesonic spin-isospin degeneracy factors.
- The single particle energies are $E_l^*(k) = \sqrt{k_l^2 + m_l^{*2}}$ and the effective chemical potentials read $\mu_l^* = \mu_l - g_{\omega l}\omega - g_{\phi l}\phi$ with $\mu_l = (n_{q,l} - n_{\bar{q},l})\mu_q + (n_{s,l} - n_{\bar{s},l})\mu_s$

The density of particle l is given by

$$\rho_l = \gamma_l \int_0^\infty \frac{d^3k}{(2\pi)^3}\left[\frac{1}{\exp\left[(E_l^* - \mu_l^*)/T\right] \pm 1}\right]$$

- Feeding from higher resonances with mass up to 2 GeV is included, weak decays have not been accounted for
- pseudoscalar mesons are treated as a free thermal gas

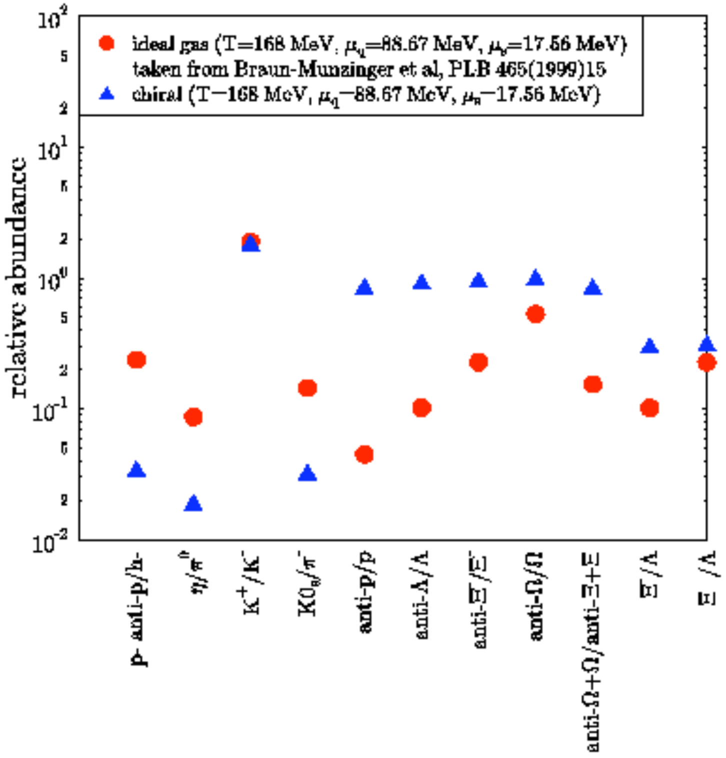
Ratios from Chiral Model for SPS Pb+Pb



Comparison of experimentally measured particle ratios for Pb+Pb collisions at CERN SPS and chiral model predictions for $T = 144\,\mathrm{MeV}$, $\mu_q = 95\,\mathrm{MeV}$ show reasonable agreement.

Comparison of Ideal Gas Calculation with Chiral Model

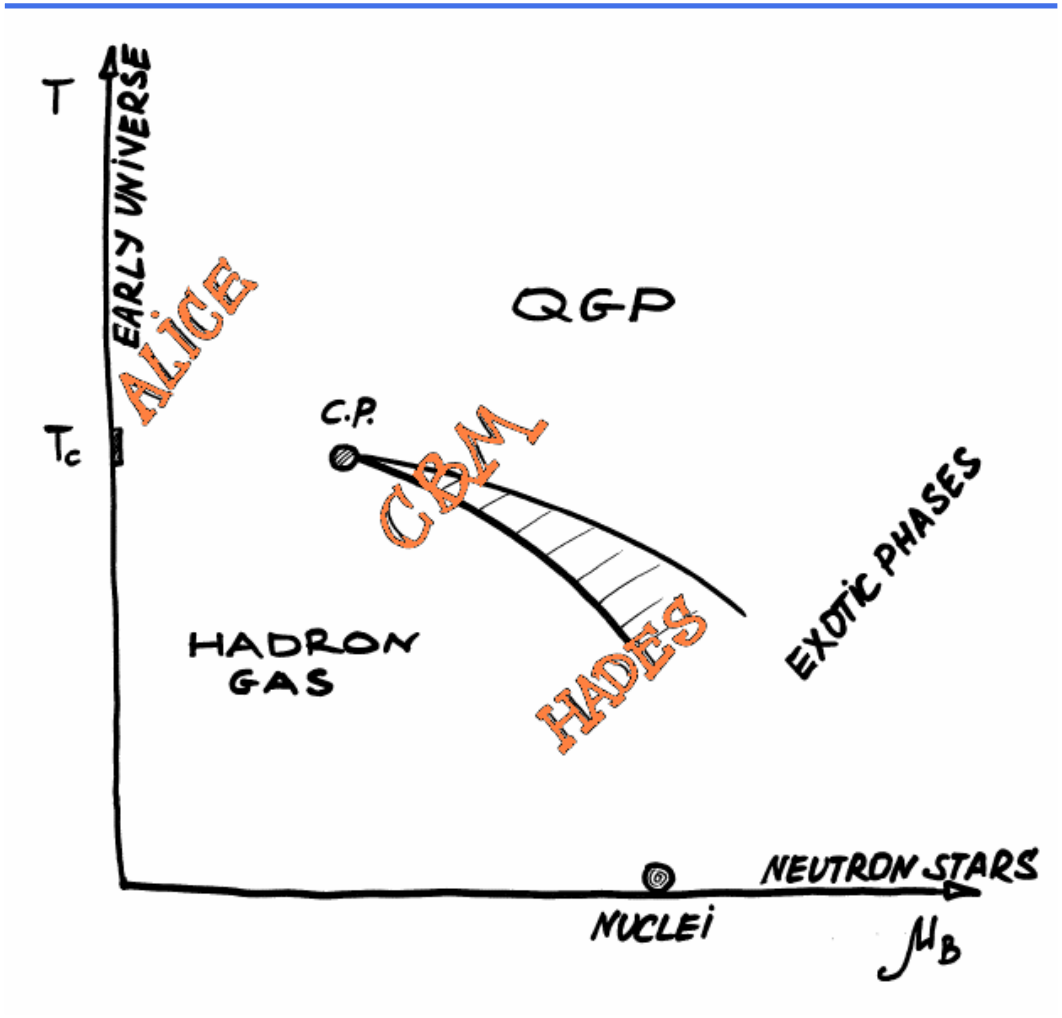
Predicted particle ratios from the ideal gas calculation (plus excluded volume correction) in [4] are compared with the predicted ratios in the chiral model for $T = 168\,\mathrm{MeV}$, $\mu_q = 88.67\,\mathrm{MeV}$



Particle ratios differ dramatically due to low effective baryon masses and small effective potentials in the chiral model.

CBM: Compressed Nuclear and Quark- Gluon Matter
Quarkyonic Matter @ FAIR

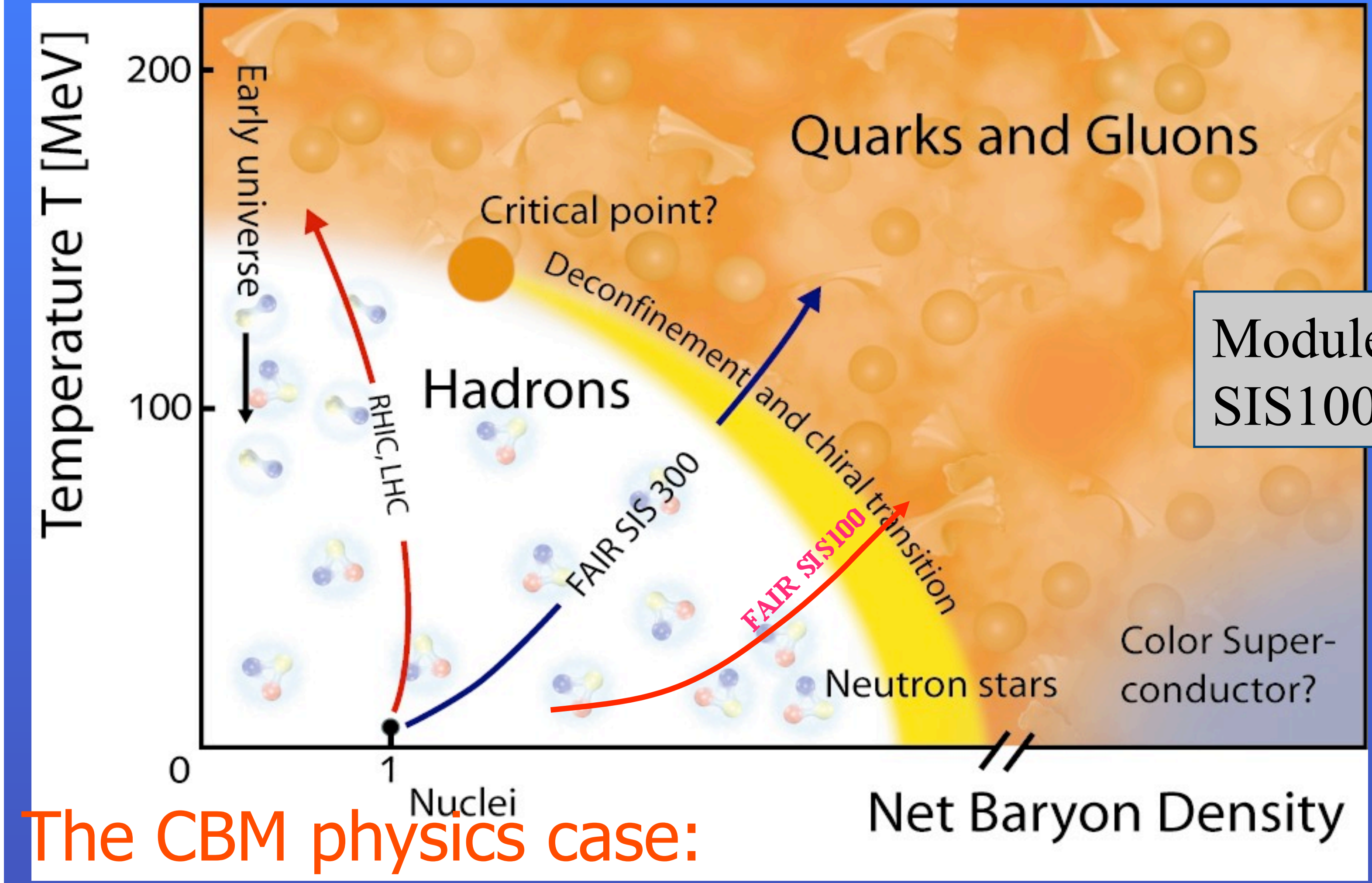
***Goal:** Create and investigate in the laboratory extreme states of (strange?) strongly coupled baryon matter ...*



Fundamental questions addresse

- → **What are the properties o dense deconfined matter?**
- → **Where are the phase boundaries located?**
- → **Is there a critical point?**
- → **Where are the limits of hadronic existence?**

The phase diagram of strongly interacting matter



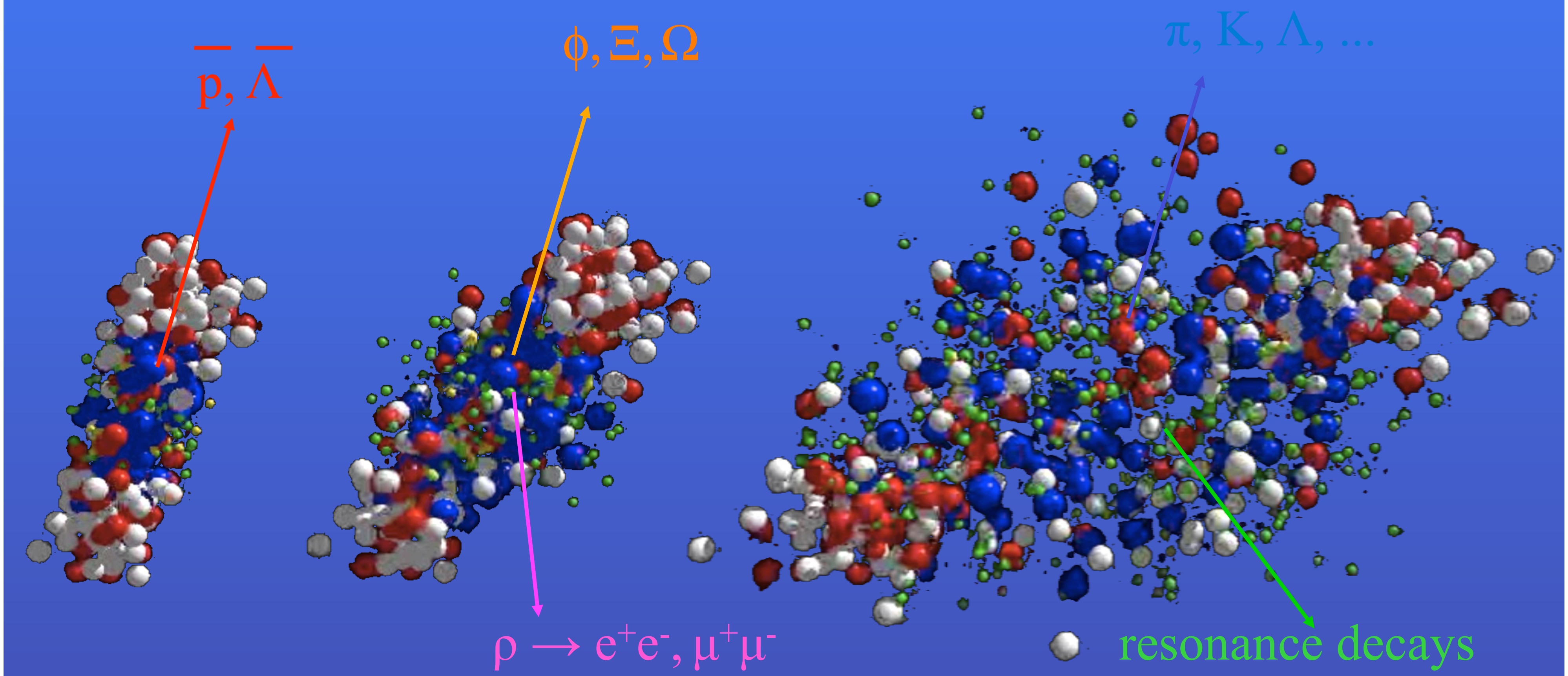
Modules 0,1:
SIS100

The CBM physics case:

- The deconfinement phase transition, the QCD critical endpoint
- The equation-of-state at neutron star densities
- The in-medium properties of hadrons, hadron mass generation

The evolution of the fireball

- Au+Au collision at 10.7 A GeV in UrQMD



$\bar{p}, \bar{\Lambda}$

ϕ, Ξ, Ω

$\pi, K, \Lambda, \ldots$

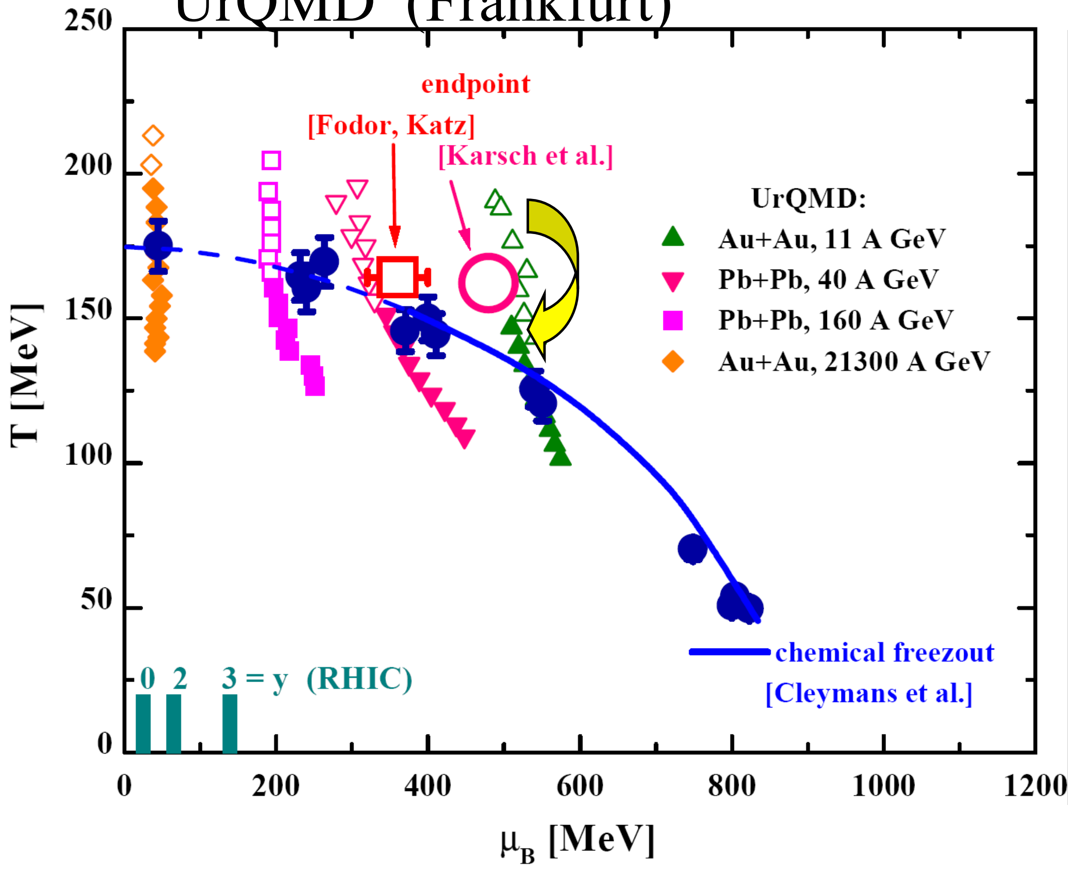
$\rho \rightarrow e^+e^-, \mu^+\mu^-$

resonance decays

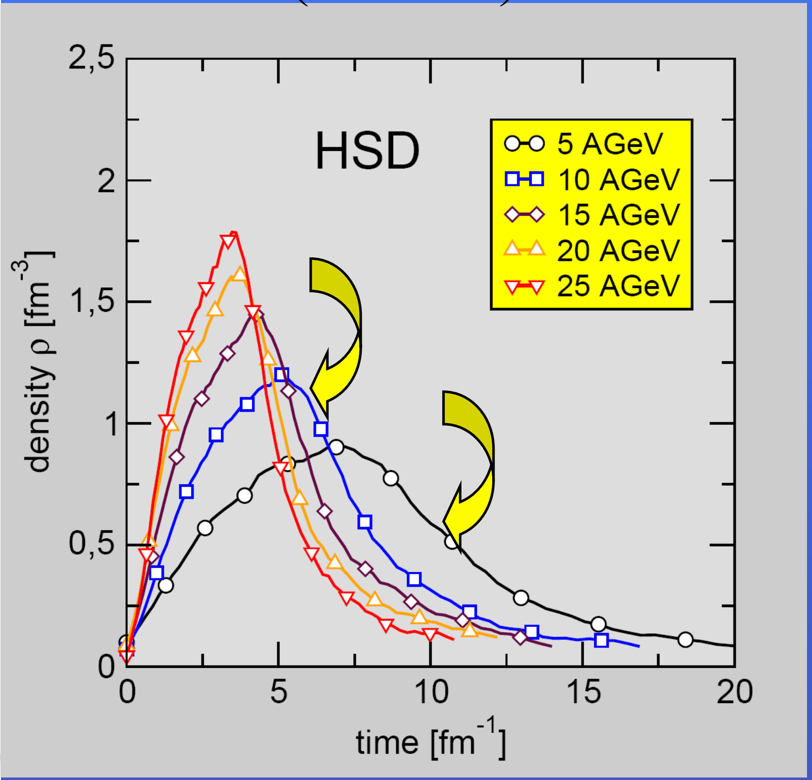
CBM/HADES : focus on rare probes with high luminosity and next generation detectors

Heavy-ion collisions in Transport Theory

UrQMD (Frankfurt)

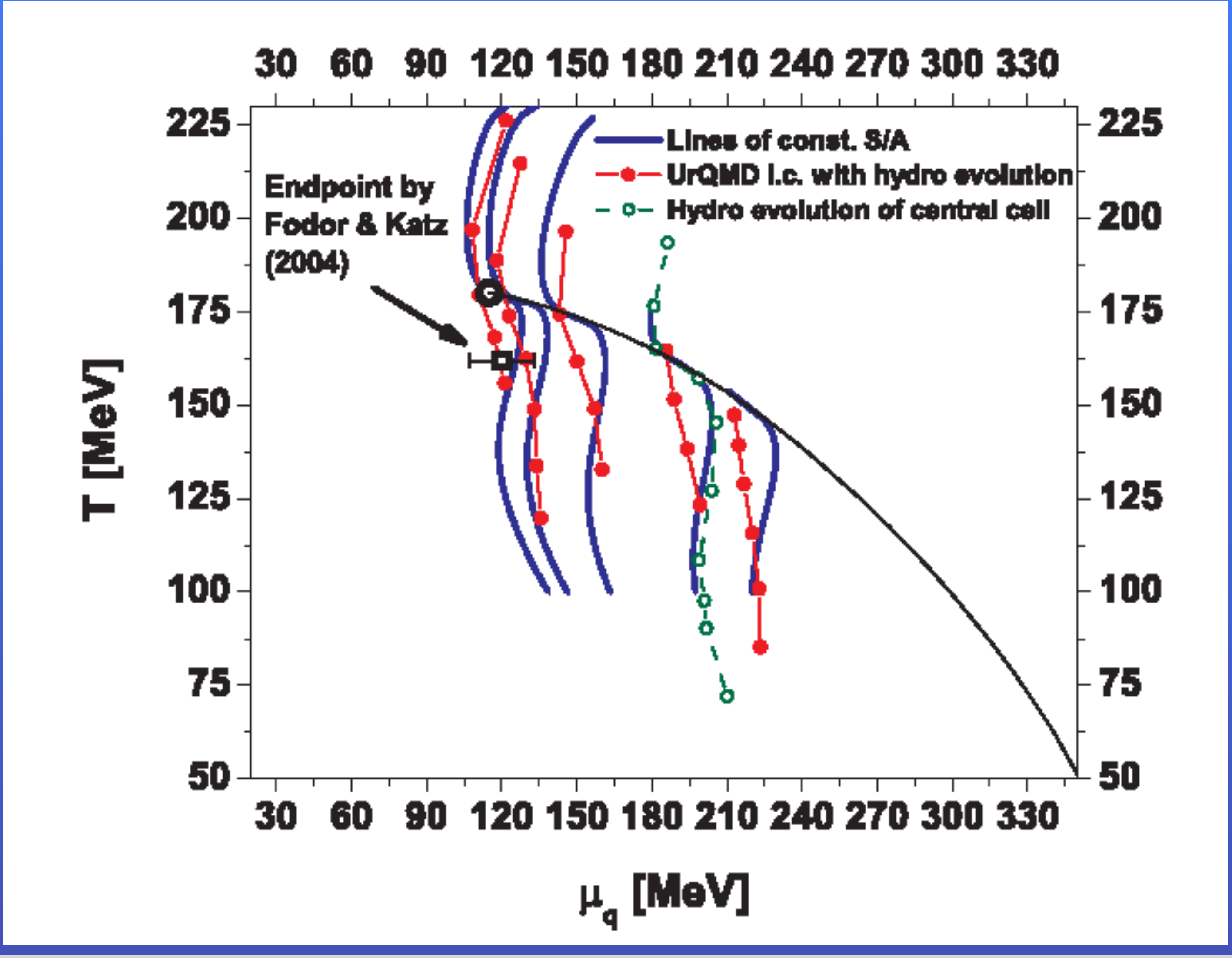


HSD (Giessen)



Au+Au collisions up to 11 A GeV (SIS100): exploring properties of dense hadronic (resonance) matter in the vicinity of the phase transition

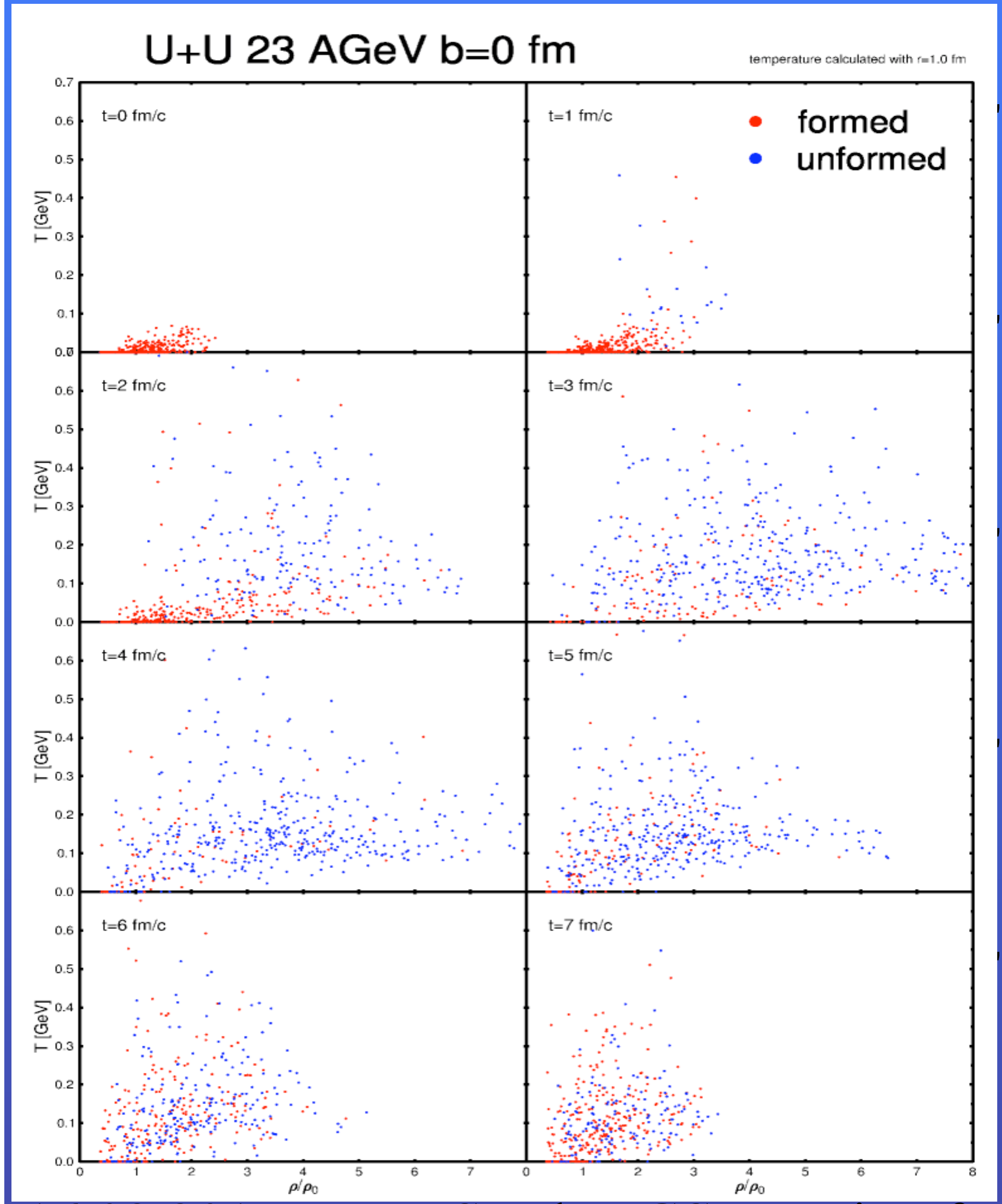
Isentropes, UrQMD and hydro evolution



lines of constant entropy per baryon, i.e. perfect fluid expansion
E/A = 5, 10, 40, 100, 160 GeV   E/A = 160 GeV goes through endpoint

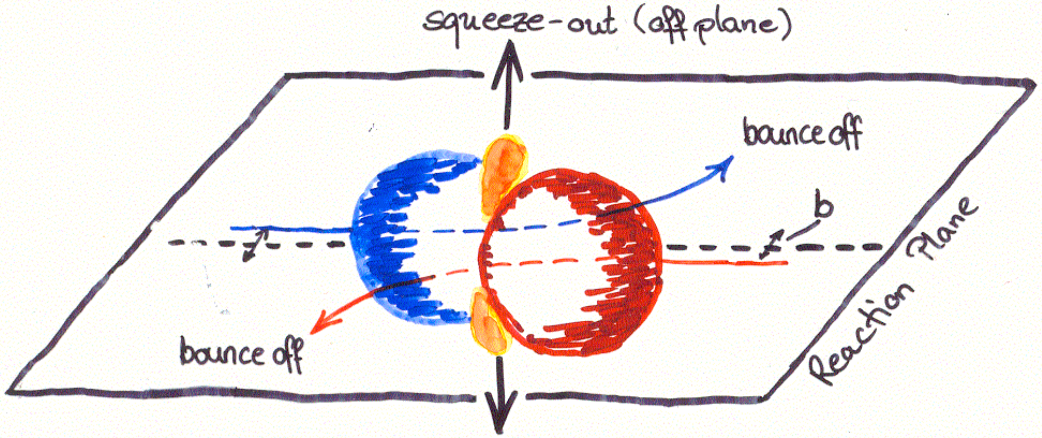
J. Steinheimer et al. PRC77, 034901 (2008)

Happy FAIRy Island at FAIR SIS 100/300?



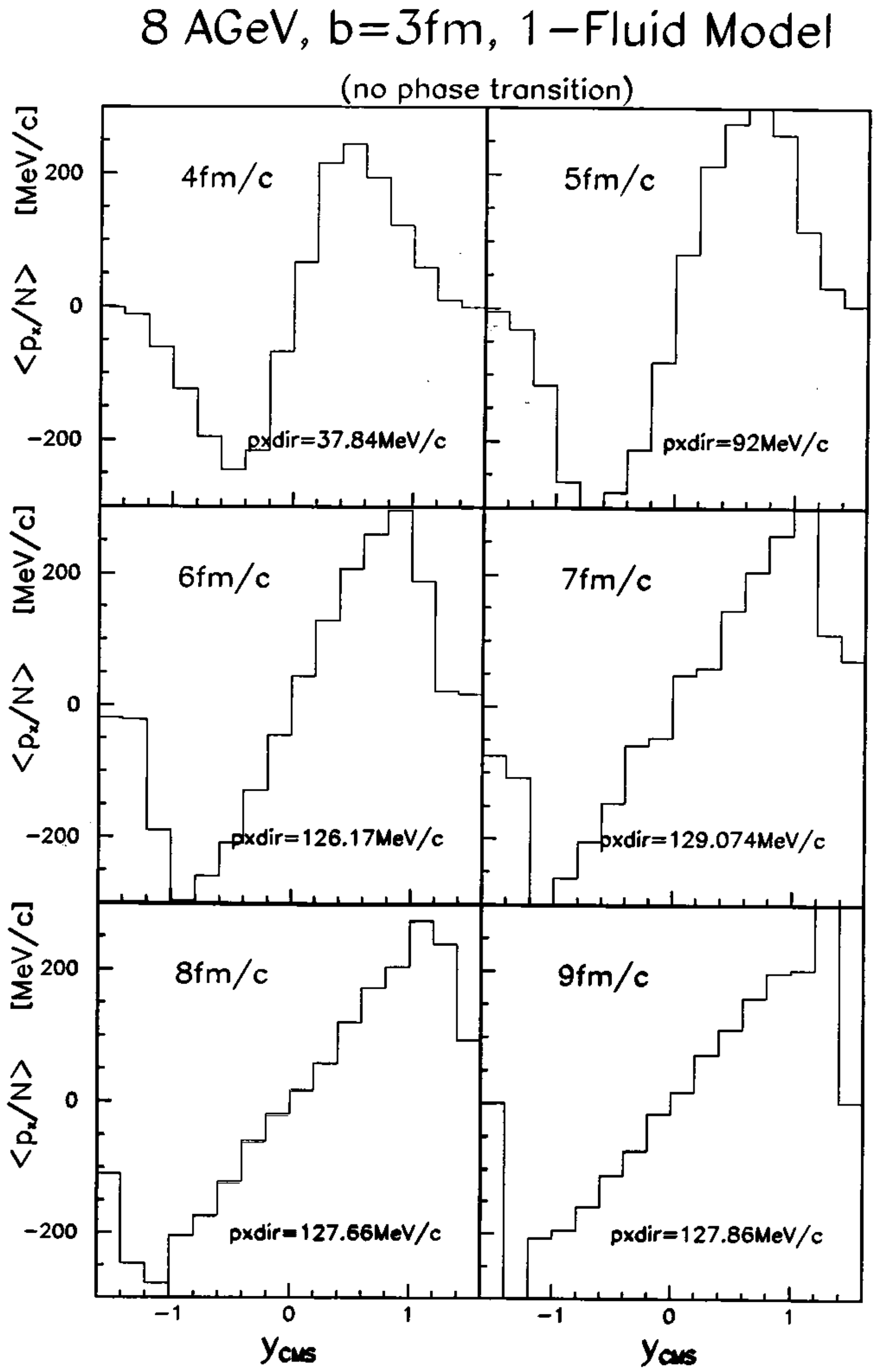
- Many constituent Quarks populate high rho/ low T regions!
- How many arrive in detectors?
- Which momenta, angles?
- That's where to look for !

Directed Flow



Pressure P can be measured by the momentum p_x:

$$\boxed{p_x \sim \int P(e,\varrho)\, dA\, dt}$$

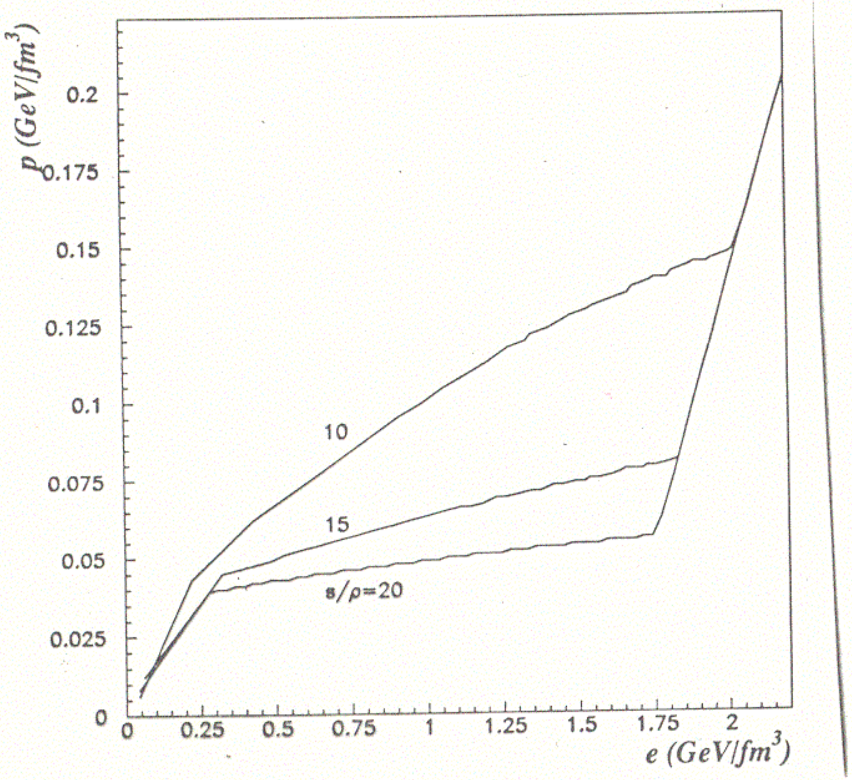


8 AGeV, b=3fm, 1−Fluid Model

(no phase transition)

„Softening" of the EoS

velocity of sound c_s : $$c_s^2 = \left.\frac{\partial p}{\partial e}\right|_s$$

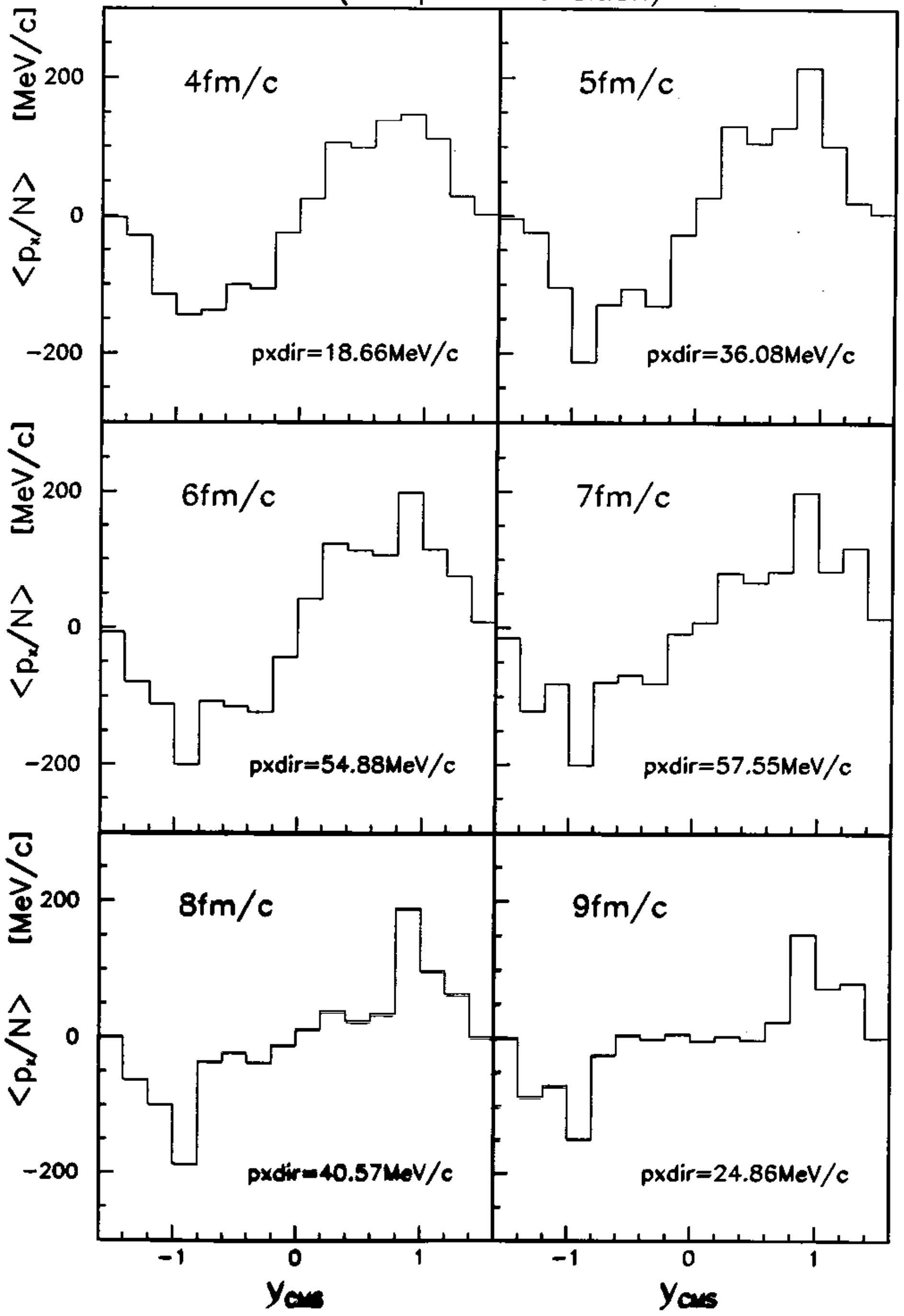


in case of phase transition :

c_s drops !

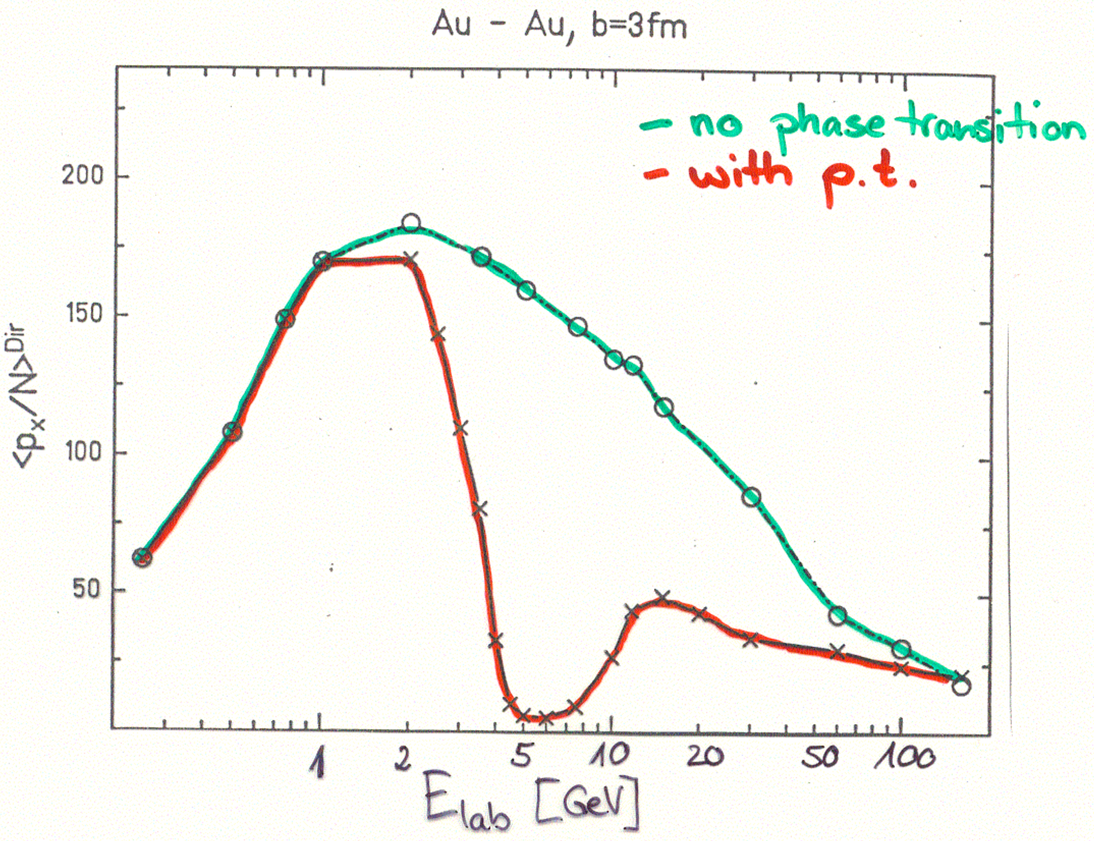
8 AGeV, b=3fm, 1−Fluid Model

(with phase transition)



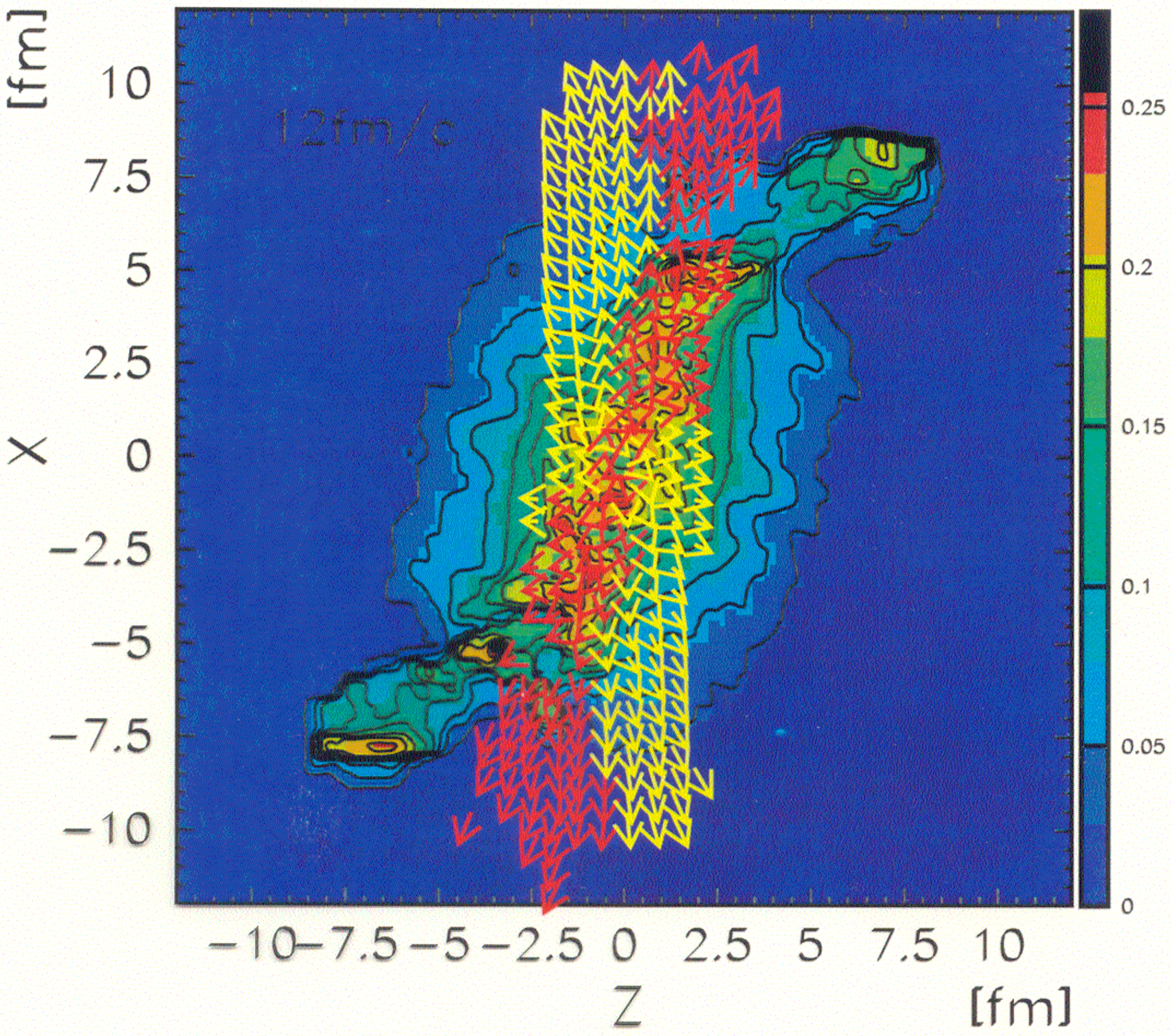
Directed Flow

1-fluid model

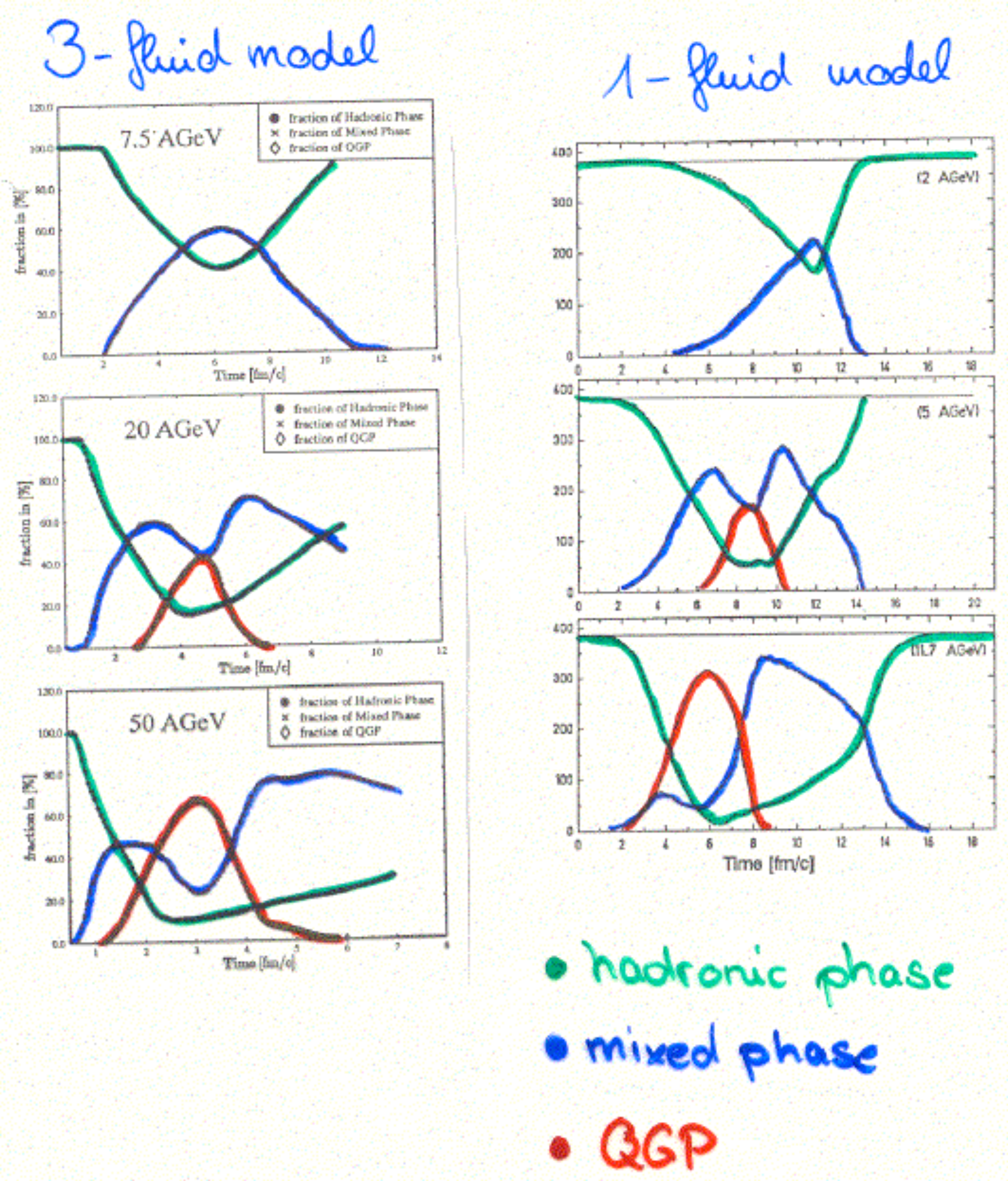


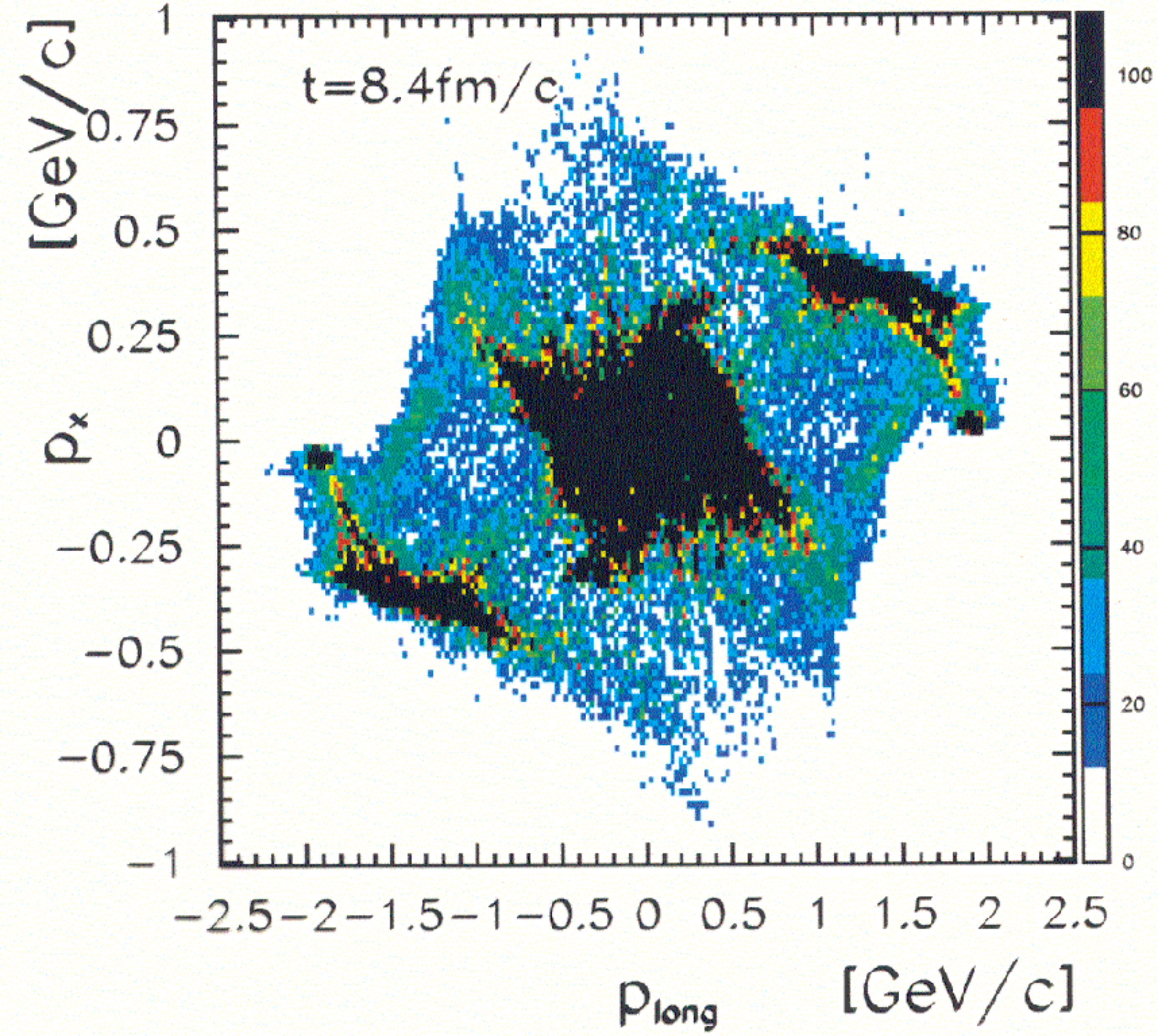
from D.H. Rischke, Y. Pürsün, J.A. Maruhn,
H. Stöcker, W. Greiner
HIP 1 (1995) 309

8 AGeV, b=3fm, 1−Fluid Limit with PT



Comparison of hydrodynamic modelsAu+Au, b=3fm



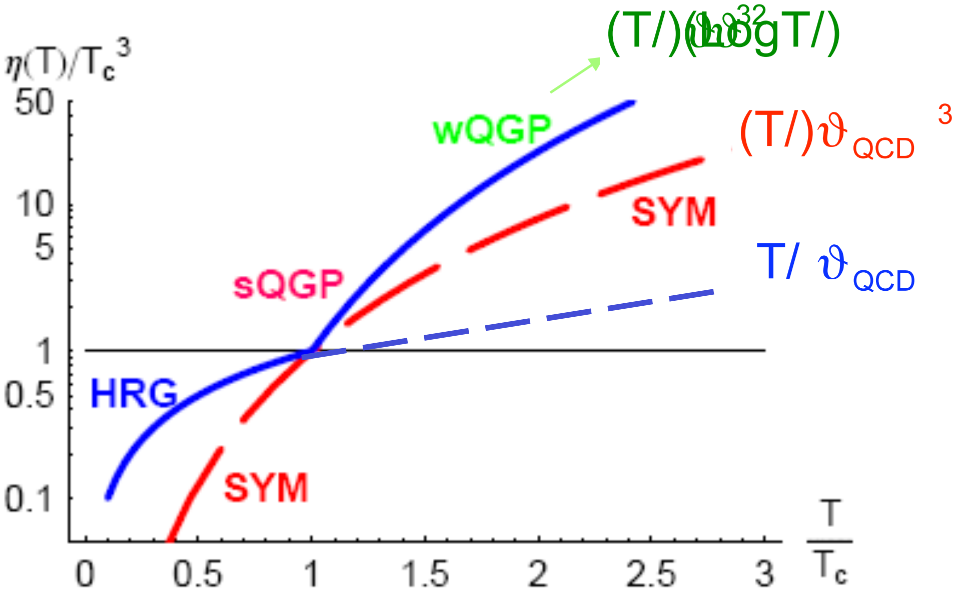


" **Au+Au, 8GeV, b=3fm**

The Perfect Fluidity of QGP Core is the Signature of Deconfinement

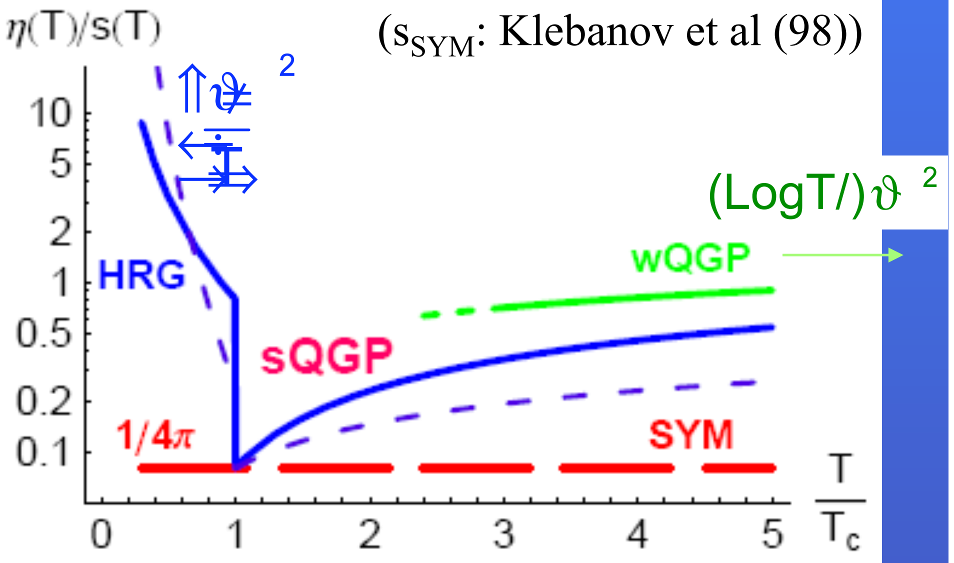
T. Hirano and MG (05)

$\eta(T)$: shear viscosity and s(T) : entropy density



(η_{SYM}: Son, et al (05))

(s_{SYM}: Klebanov et al (98))



- Absolute value of viscosity

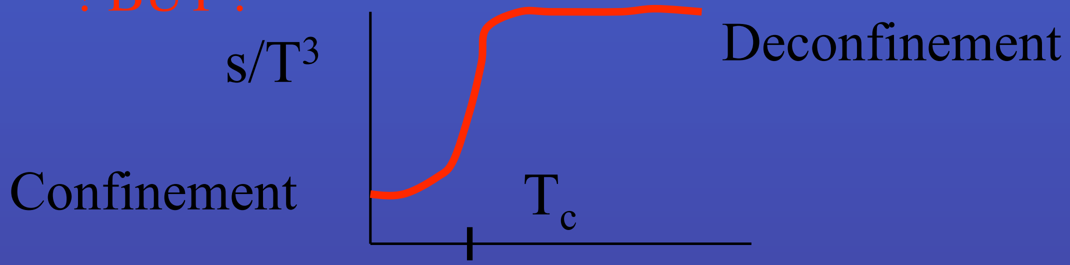
$\boxed{\eta(\mathrm{sQGP}) > \eta(\mathrm{hadron})}$

Viscosity is monotonic
Increasing with T

- Ratio to entropy density

$\boxed{\eta/s(\mathrm{sQGP}) \ll \eta/s(\mathrm{hadron})}$

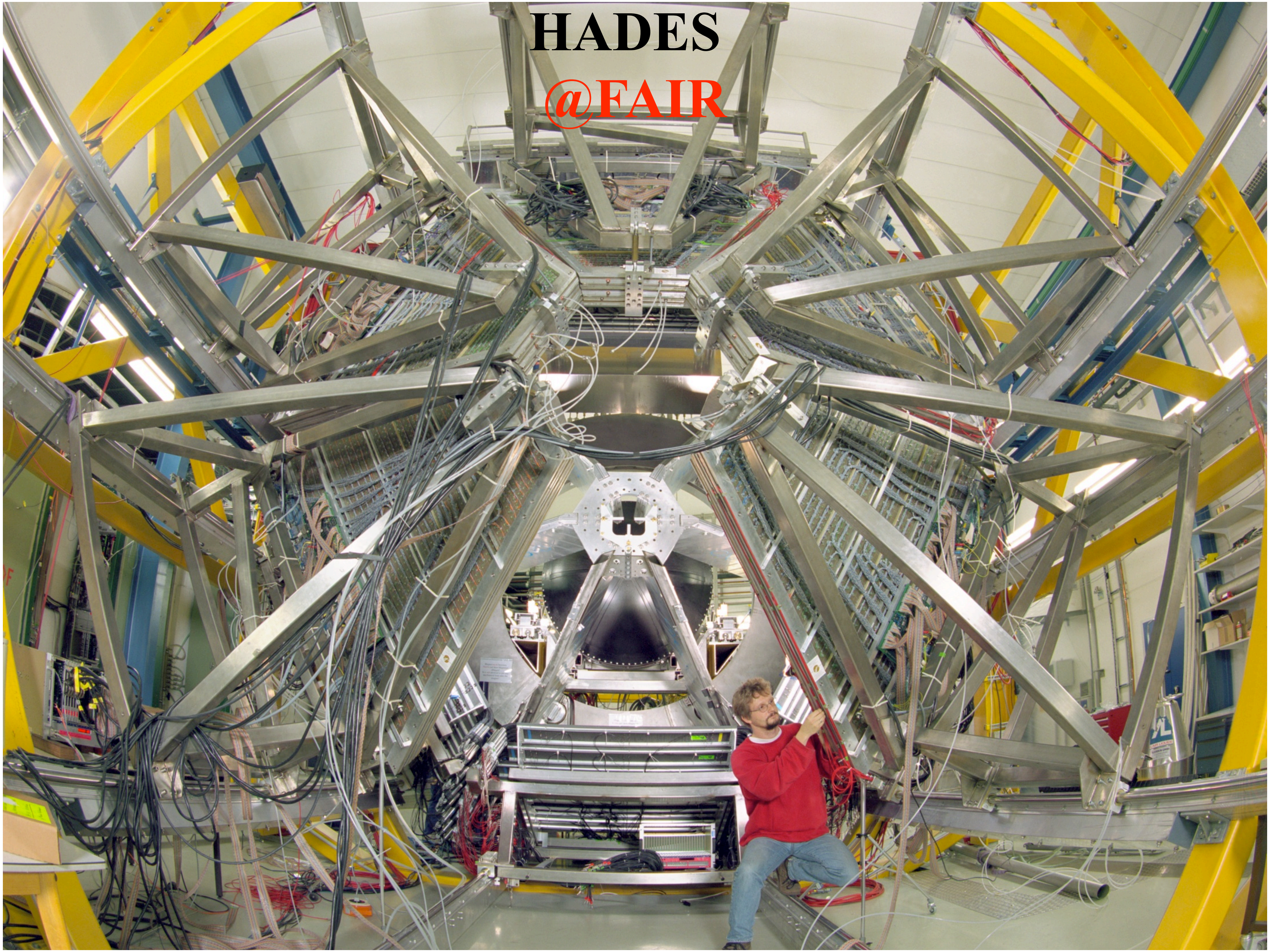
! BUT !



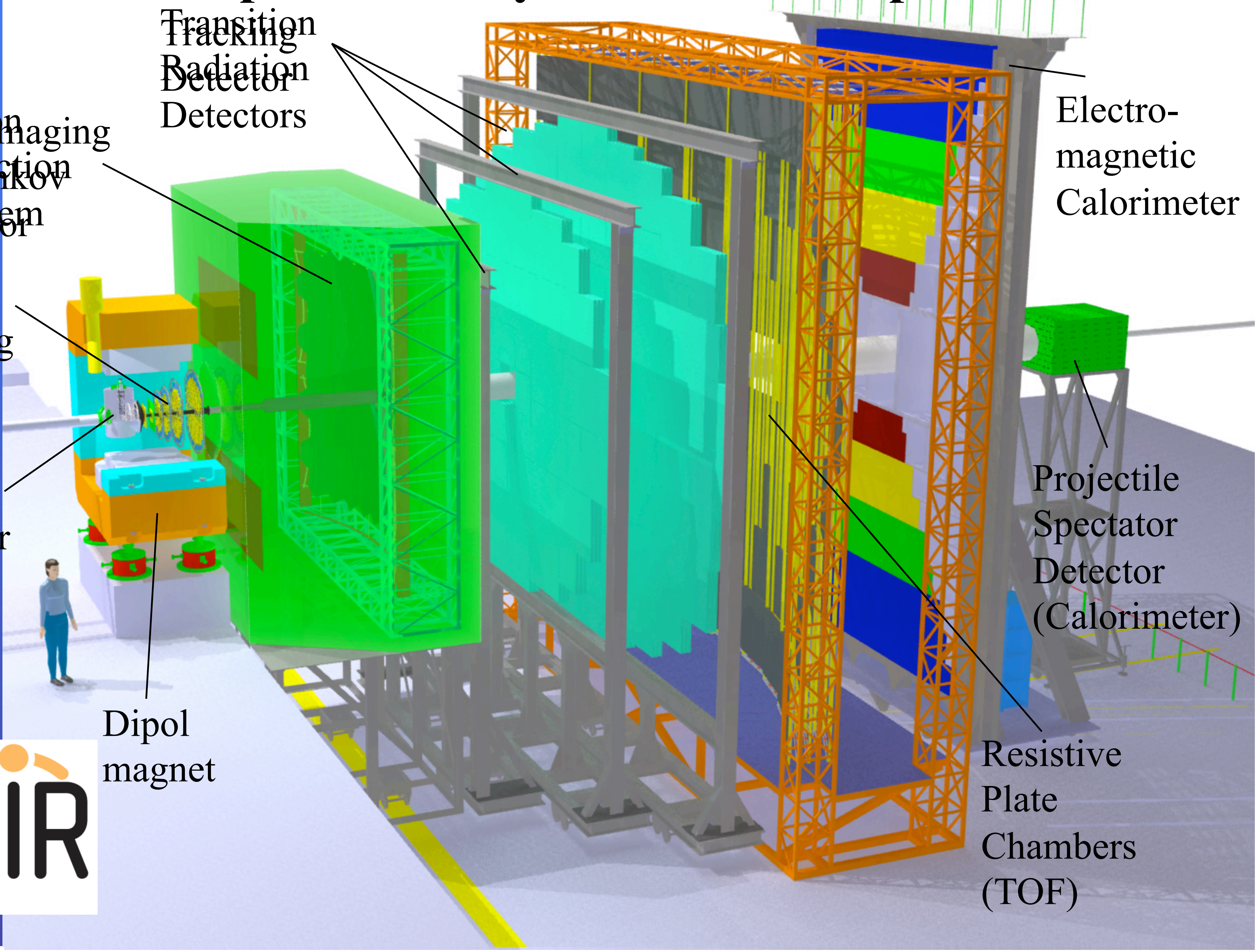
Iguassu Falls Analog of Ocean of Quarks Produced in Au+Au-> sQGP -> 10^4 hadrons

The FAIR council meetings

HADES
@FAIR



The Compressed Baryonic Matter Experiment



Transition Radiation Detectors

Tracking Detector

Ring Imaging Cherenkov Detector

Muon detection System

Silicon Tracking Stations

Vertex Detector

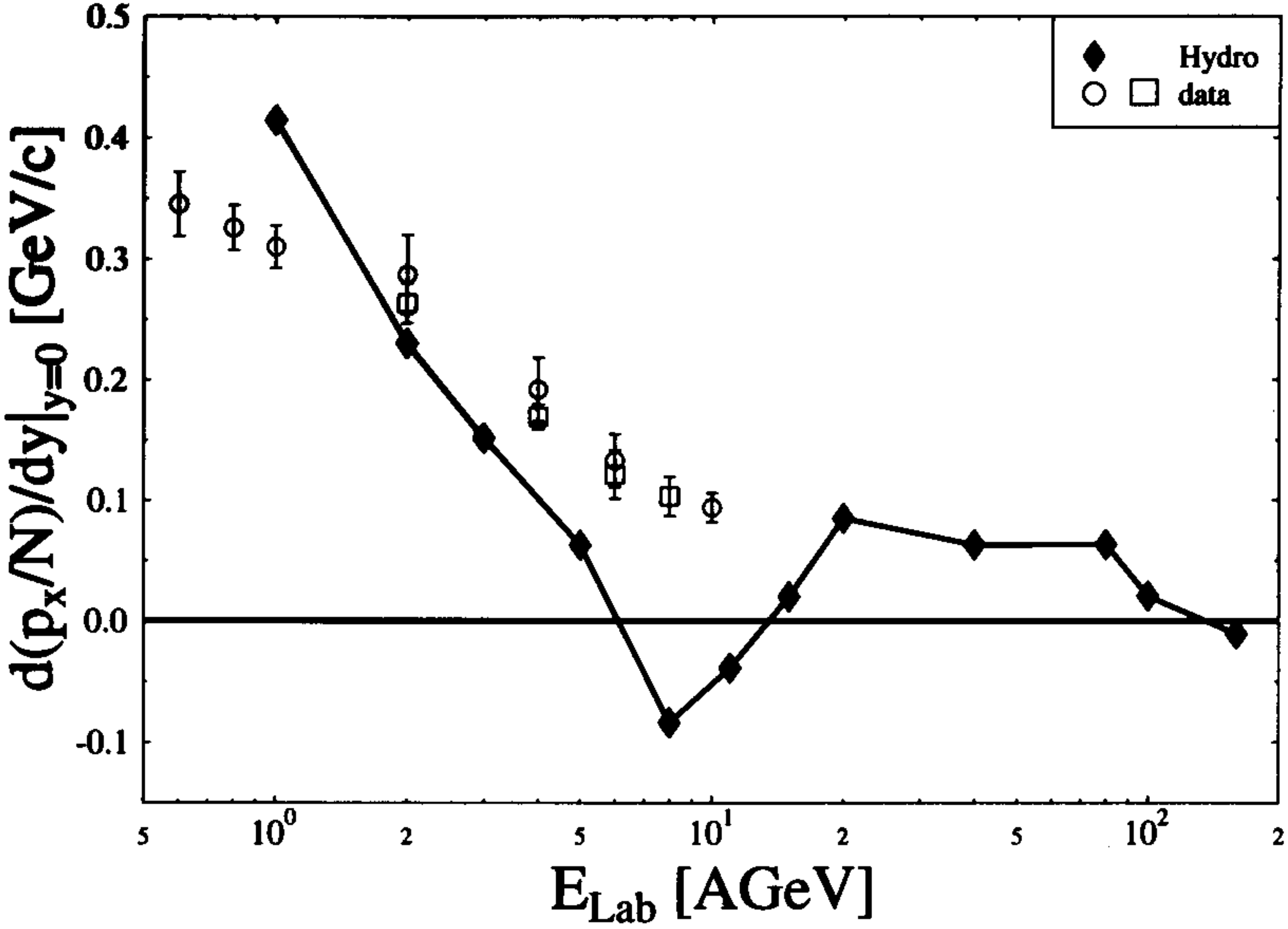
Dipol magnet

Electro-magnetic Calorimeter

Projectile Spectator Detector (Calorimeter)

Resistive Plate Chambers (TOF)

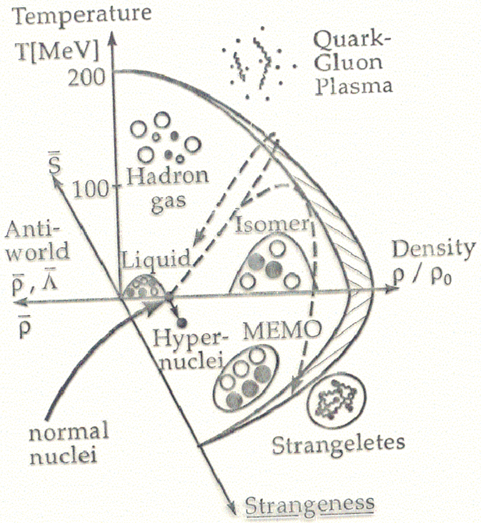
FAIR

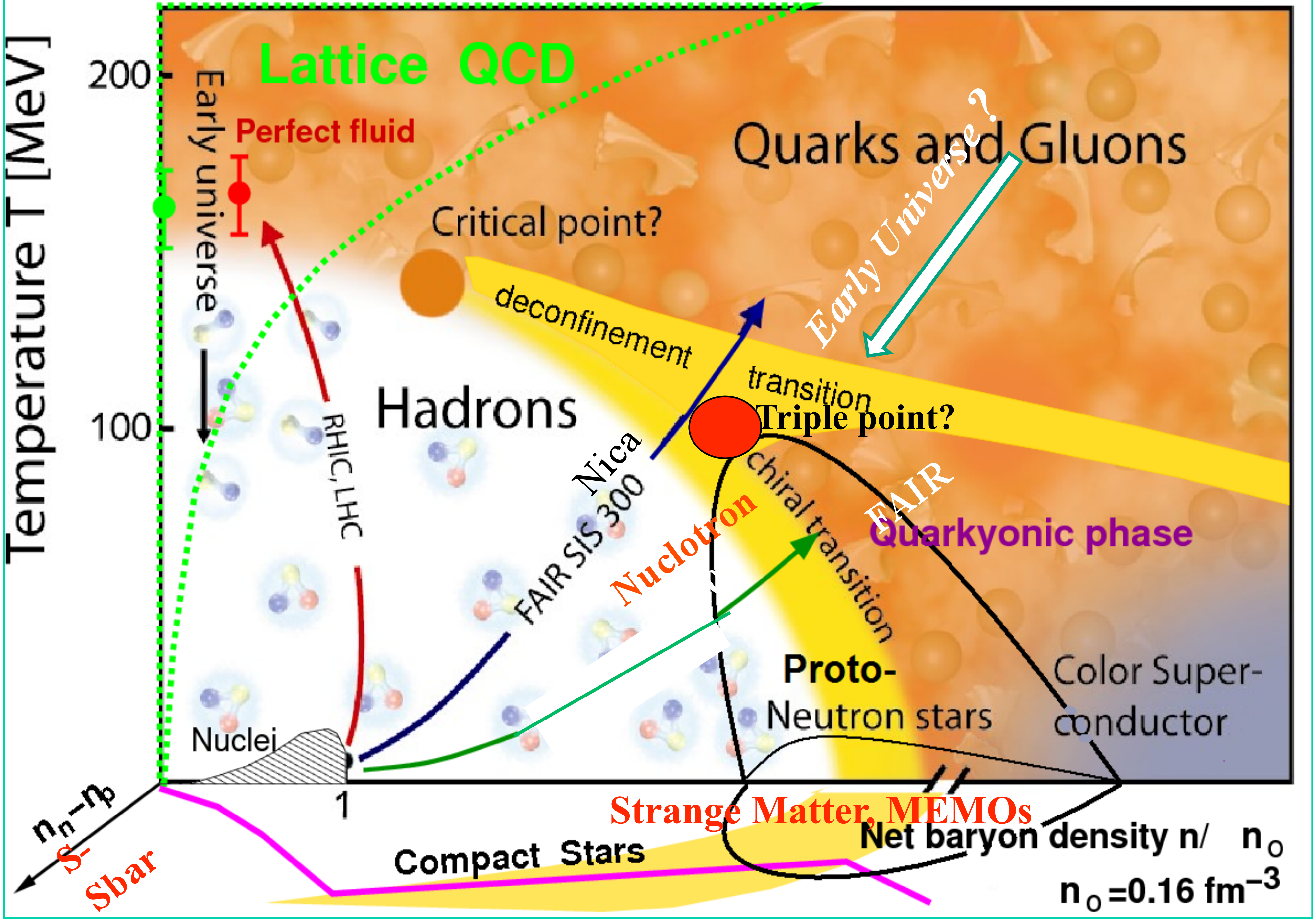


0.5
0.4
0.3
0.2
0.1
0.0
-0.1
$d(p_x/N)/dy|_{y=0}$ [GeV/c]
5
10^0
2
5
10^1
2
5
10^2
2
E_{Lab} [AGeV]
◆ Hydro
○ □ data

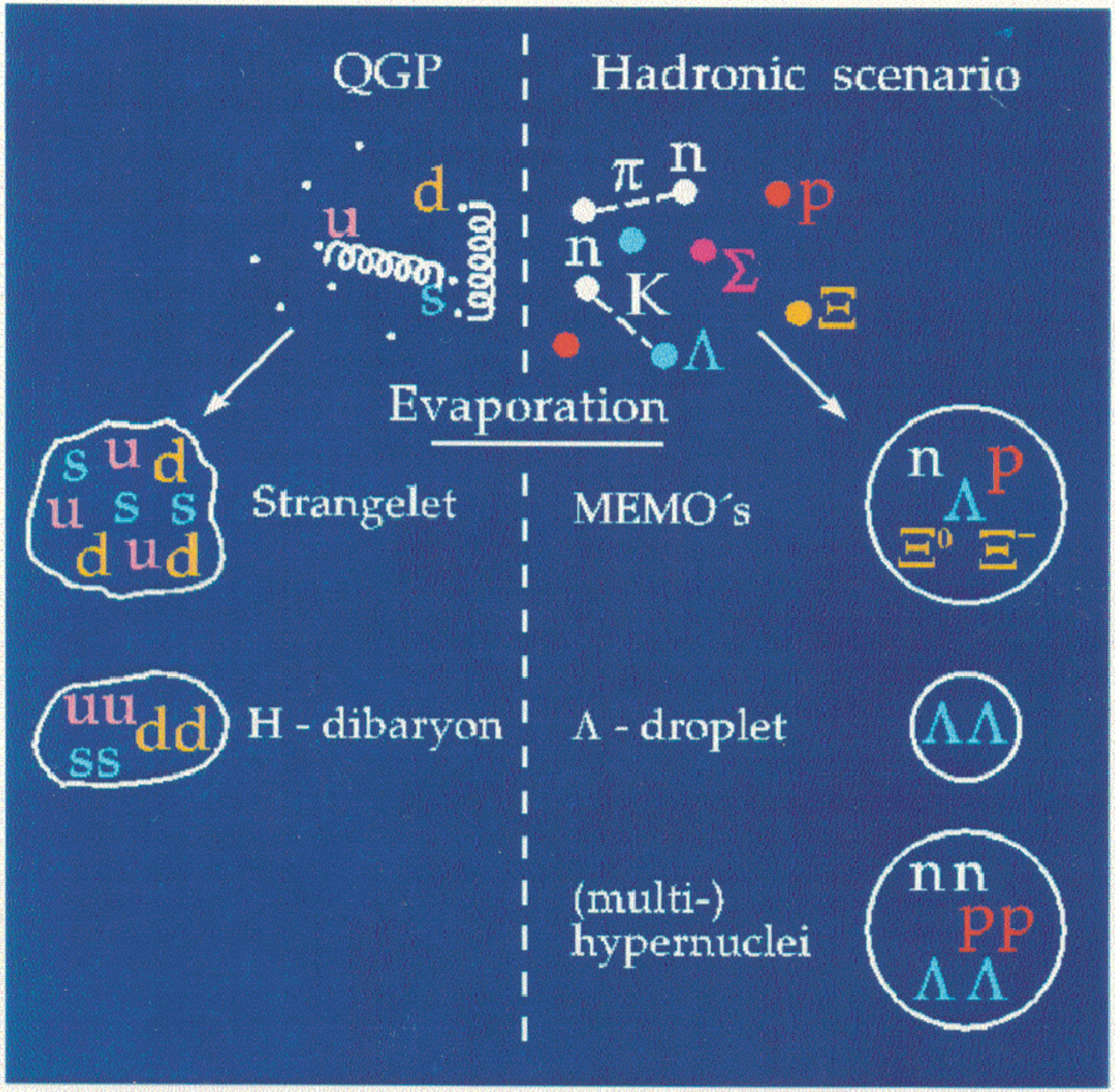
Extension to include Strangeness

- Higher symmetry → more constraints
- Self-consistent calculation at finite baryon density, temperature and strangeness including spin-0/spin-1/spin-$\frac{1}{2}$ multiplets
- Possibility to study in-medium masses, hypernuclei ; Extension of the periodic system into the novel $SU(3)_F$ dimension




Lattice QCD
Temperature T [MeV]
200
100
Early universe
Perfect fluid
Quarks and Gluons
Early Universe?
Critical point?
deconfinement
transition
Hadrons
RHIC, LHC
Triple point?
Nica
FAIR SIS 300
Nuclotron
chiral transition
FAIR
Quarkyonic phase
Proto-
Neutron stars
Color Super-
conductor
Nuclei
1
Strange Matter, MEMOs
Net baryon density n/ n_0
n_0=0.16 fm^{-3}
Compact Stars
n_n-n_p
S-
Sbar

The Formation of Strange Matter and Strange Nuclei

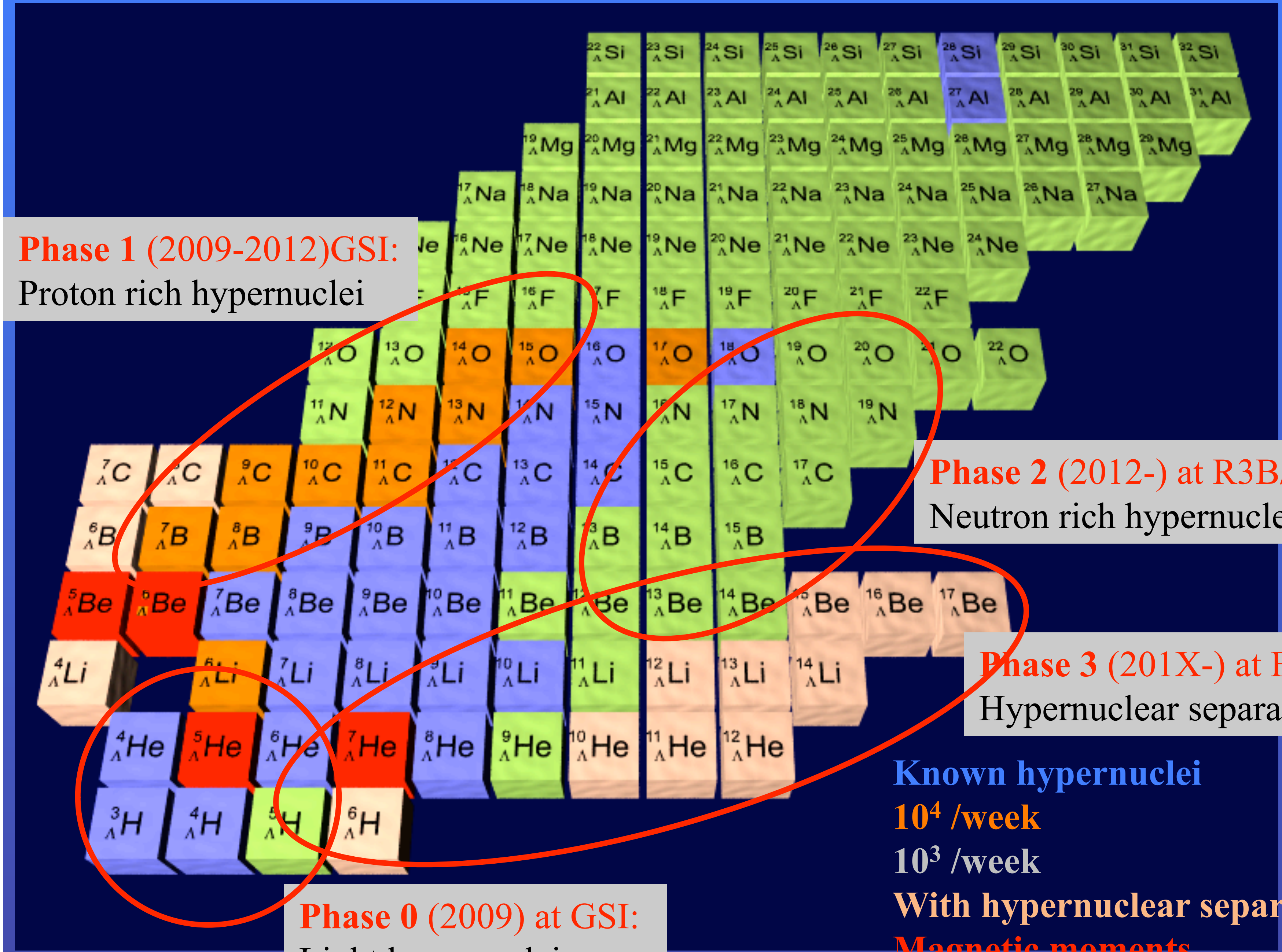


Links - Die
Destillation
von
Seltsamer
Quark-Mat
aus dem
Quark-Glu
(QGP)

Rechts -
Die
Clusterung
von
Seltsamen
Baryonen
zu
Seltsamen
Kernen

-lager -hst

The Hypernuclear landscape with HypHI at GSI and FAiR



Phase 1 (2009-2012)GSI:
Proton rich hypernuclei

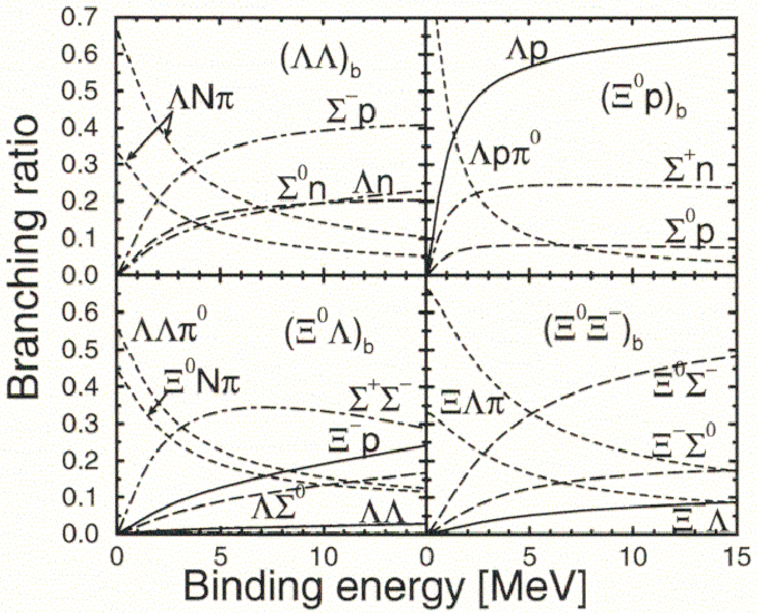
Phase 2 (2012-) at R3B/FAIR:
Neutron rich hypernuclei

Phase 3 (201X-) at FAIR:
Hypernuclear separator

Phase 0 (2009) at GSI:
Light hypernuclei

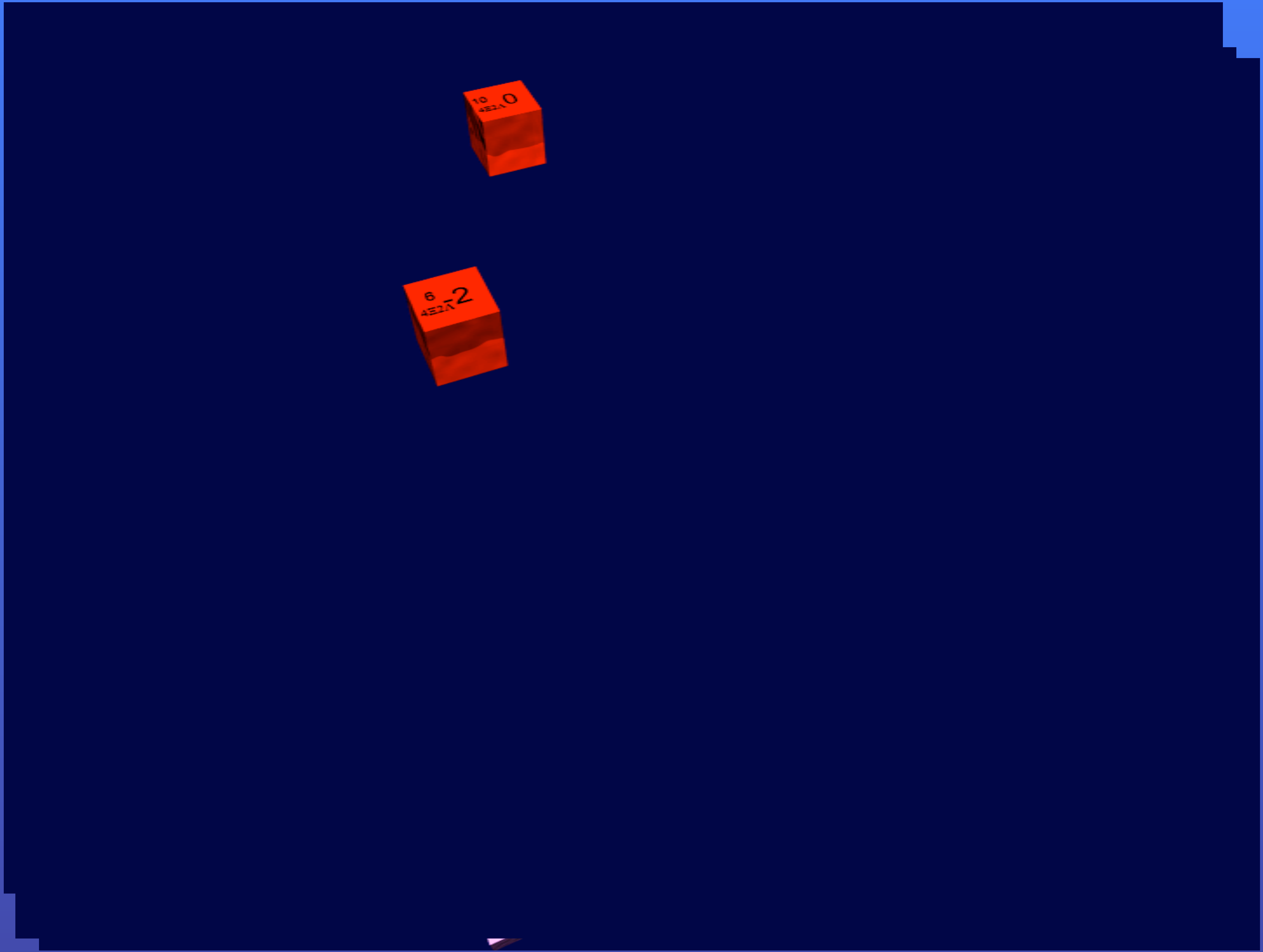
Known hypernuclei
10^4 /week
10^3 /week
With hypernuclear separator
Magnetic moments

Decay patterns of strange dibaryons



- can be detected by backtracking, invariant mass spectra, correlations ...
- exotic decays like $\Sigma^+\Sigma^+ \to \Sigma^+ + p$
- negatively charged (with positive baryon number)
- unique opportunity !!! (not likely to be produced in pp or in meson beams)

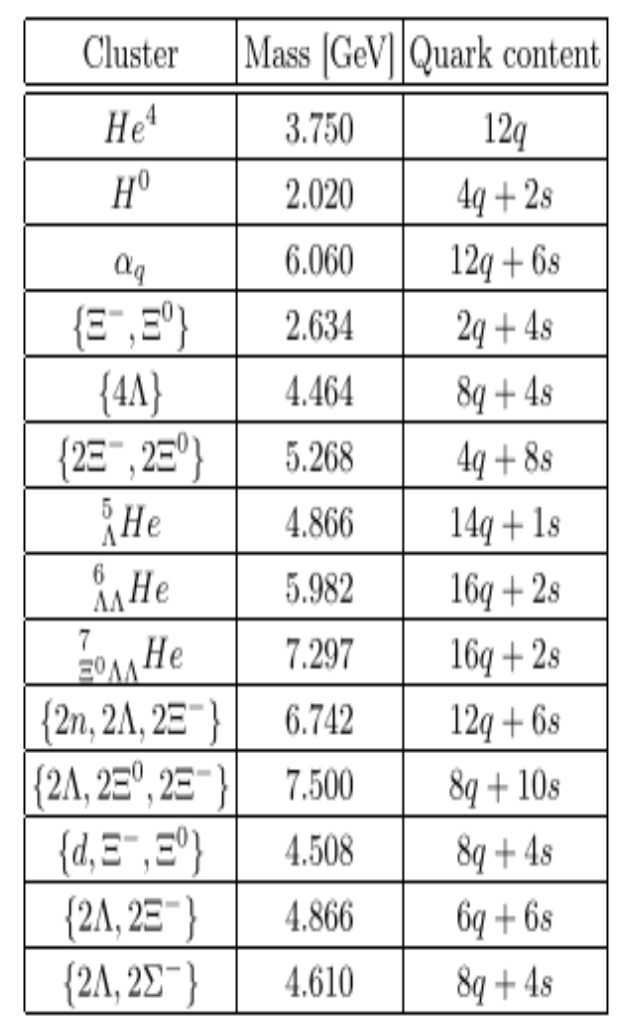
New dimension in the nuclear chart - Strangeness: **Hyperon Clusters at FAiR**



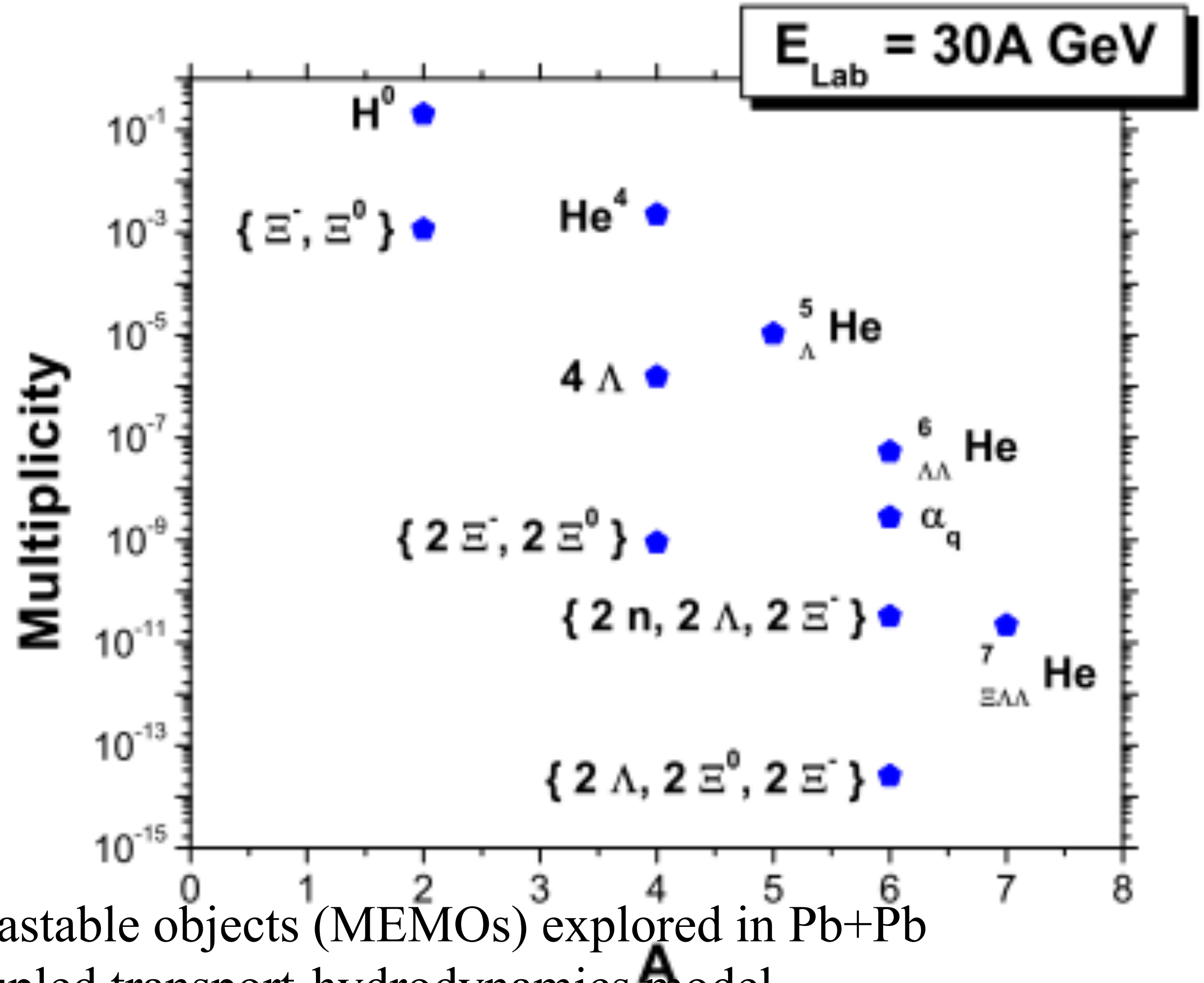
MEMO production at high baryon densities

.Bleicher ; Stefan Schramm & Jan Steinheimer

FIAS & Goethe University Frankfurt

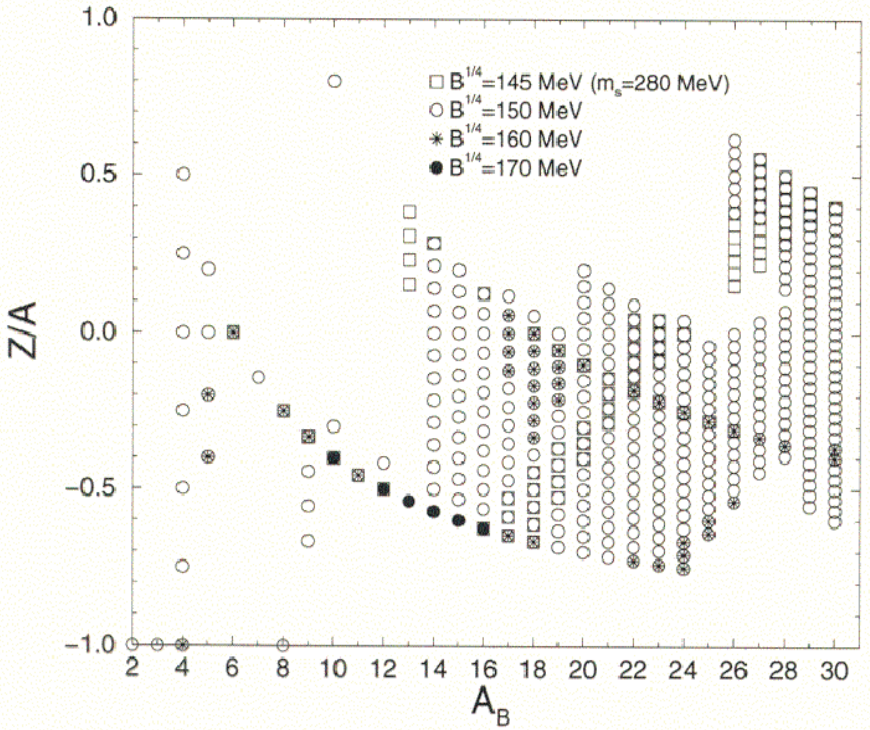


Cluster	Mass [GeV]	Quark content
He^4	3.750	$12q$
H^0	2.020	$4q+2s$
α_q	6.060	$12q+6s$
$\{\Xi^-,\Xi^0\}$	2.634	$2q+4s$
$\{4\Lambda\}$	4.464	$8q+4s$
$\{2\Xi^-,2\Xi^0\}$	5.268	$4q+8s$
${}^5_\Lambda He$	4.866	$14q+1s$
${}^6_{\Lambda\Lambda}He$	5.982	$16q+2s$
${}^7_{\Xi^0\Lambda\Lambda}He$	7.297	$16q+2s$
$\{2n,2\Lambda,2\Xi^-\}$	6.742	$12q+6s$
$\{2\Lambda,2\Xi^0,2\Xi^-\}$	7.500	$8q+10s$
$\{d,\Xi^-,\Xi^0\}$	4.508	$8q+4s$
$\{2\Lambda,2\Xi^-\}$	4.866	$6q+6s$
$\{2\Lambda,2\Sigma^-\}$	4.610	$8q+4s$



- Production of multi-strange metastable objects (MEMOs) explored in Pb+Pb reactions at 30 AGeV within coupled transport-hydrodynamics model
- Predictions for yields & particle-dependent rapidity and momentum distributions
- Excitation functions show clear maximum in the energy range of NICA and FAIR which are therefore the ideal place to study the production of these MEMOs

Stability of Strange Clusters



all strangelet candidates decay by single weak interaction (only one candidate which decays by $\Delta S = 2$ found) even for absolutely stable SQM

$\Rightarrow$ produced strangelets are short-lived!

TEILCHENPHYSIK

Angst vor dem großen Knall

Physiker wollen bei New York den Anfang des Universums erforschen und lösen Endzeitstimmung aus

VOR DEM ERSTEN STOSS Seit Juli flitzen Goldatome durch den unterirdischen Ringtunnel. Ab Herbst gehen sie auf Kollisionskurs

In der „Unendlichen Geschichte" von Michael Ende breitet sich das Nichts unaufhaltsam aus. Es reißt Tiere und Pflanzen fort, verschlingt Berge und Seen – und lässt von ganz Phantásien nicht mehr als ein Sandkorn übrig.

Solch ein Schicksal steht vielleicht der Erde bevor, fürchten jetzt viele Amerikaner, wenn ein neuer Teilchenbeschleuniger bei New York ab Herbst schwere Atome aufeinander hetzt. Der Relativistische Schwerionen-Collider (RHIC) in Brookhaven lässt die Teilchen so heftig zusammenkrachen, dass sie 10 000-mal heißer als die Sonne werden. Damit wollen die Physiker Bedingungen schaffen, wie sie direkt nach dem Urknall herrschten.

„Eine Kettenreaktion könnte den Planeten verschlingen", warnte im Juli Walter Wagner, ein weithin unbekannter Physiker auf Hawaii. Die angesehene „Sunday Times" meldete daraufhin: „Urknall-Maschine könnte Erde zerstören." Seitdem versuchen die RHIC-Forscher verzweifelt, besorgte Bürger zu beruhigen. Forschungsleiter John Marburger hat sogar ein Physikerkomitee einberufen, das diesen Monat zu den Katastrophenszenarien Stellung nimmt.

CRASH-TESTS MIT ATOMEN SIMULIEREN URKNALL

Goldatome umrunden den Beschleunigerring fast 80 000-mal pro Sekunde. Wenn sie zusammenstoßen, schmelzen ihre Kerne zu einem Quark-Gluon-Plasma. Dieser ***eigenartige Materiebrei*** *existierte nur einen Sekundenbruchteil nach dem Urknall.*

Elektrisch geladene Atome (Ionen) jagen in beiden Richtungen durch den Beschleunigerring. An sechs Kreuzungspunkten (blau) können sie zusammenprallen

Ein Physikerkomitee befasst sich mit mehreren Weltuntergangsszenarien

Es bilden sich aggressive Strangelets. Diese „seltsamen Teilchen" zerfallen nicht …

… sondern breiten sich unaufhaltsam aus, indem sie normale Partikel schlucken und in „seltsame" umwandeln

Beim Aufprall pressen sich die Goldkerne zu einem winzigen Schwarzen Loch zusammen

Das Schwarze Loch saugt alles in seiner Umgebung auf und verschlingt den ganzen Erdball in Minuten

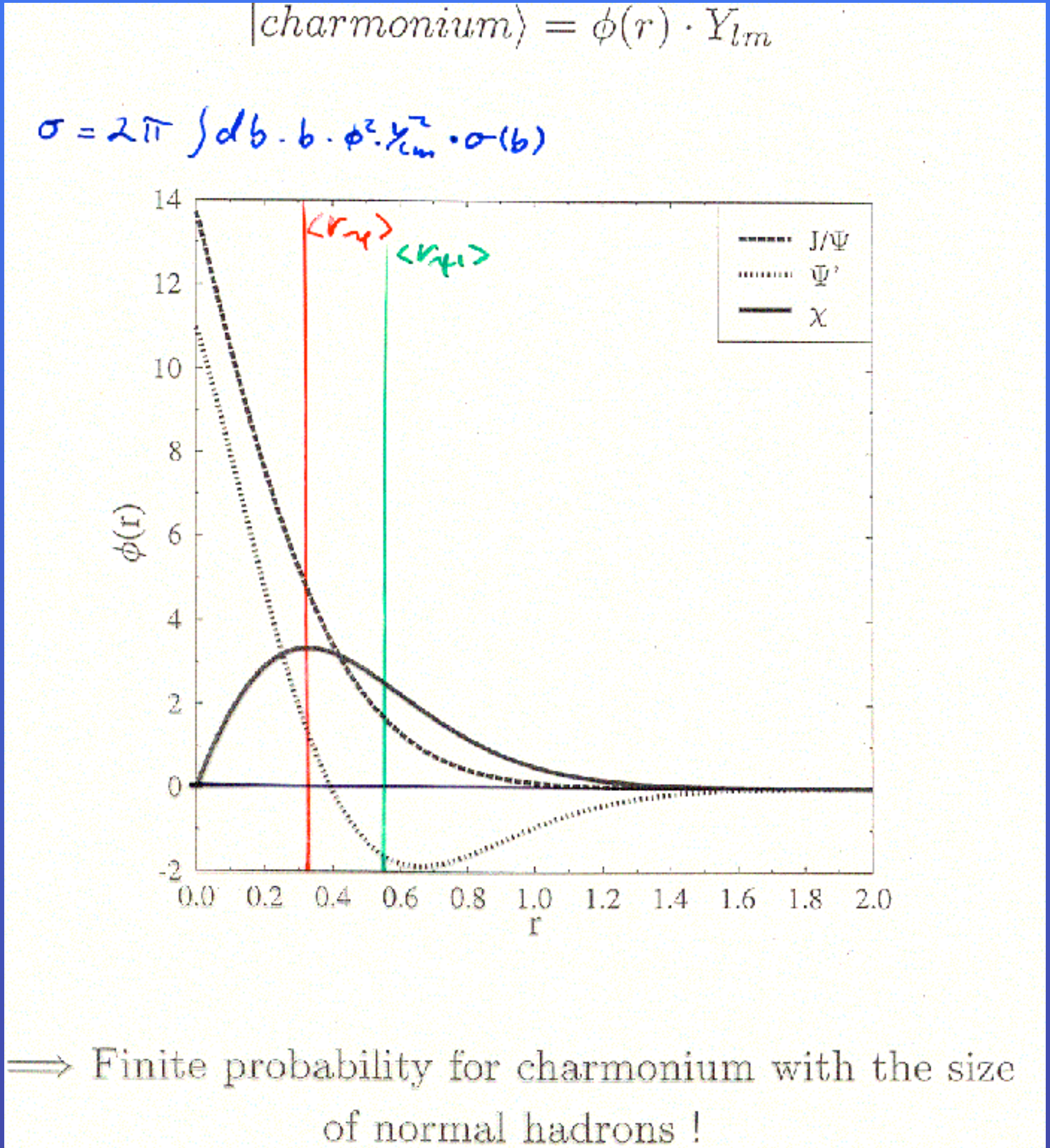
FOCUS 32/1999

GSI: 40 Years of Cooperation w. Internat. Partners Started 1965 by Bock, Greiner

- **Strategische Kooperationsverträge**
  with Univ. : DA, F, GI, HD, J, MZ, MR…
- **LOEWE Exzellenz- Zentrum "Helmholtz Int. Center for FAIR"**
  Univ. DA, F, GI, FIAS, GSI
- **Helmholtz Allianz EMMI (ExtreMe Matter Institute);**
  mit Univ. Da, F, HD, MS, GSI, FZJ, MPI HD + int. Partnern
- **Helmholtz Graduate School Hadron and Ion Research for FAIR "HIRe for FAIR"** mit Univ. in DA, F, GI, HD, MZ, J und FIAS
- **Helmholtz-Hochschul Nachwuchsgruppen & Virtuelle Institute**
- **Helmholtz Institute** HIMzHI Jena

Fair Russia Research Center

Non-relativistic charmonium wave functions



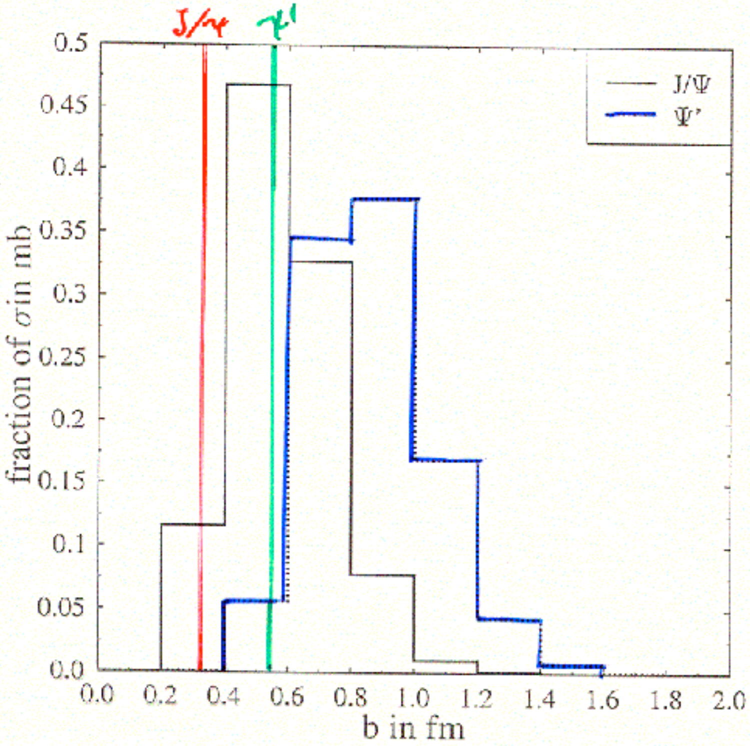
$$|charmonium\rangle = \phi(r) \cdot Y_{lm}$$

$$\sigma = 2\pi \int db \cdot b \cdot \phi^2 \cdot Y_{lm}^2 \cdot \sigma(b)$$

$\Longrightarrow$ Finite probability for charmonium with the size of normal hadrons !

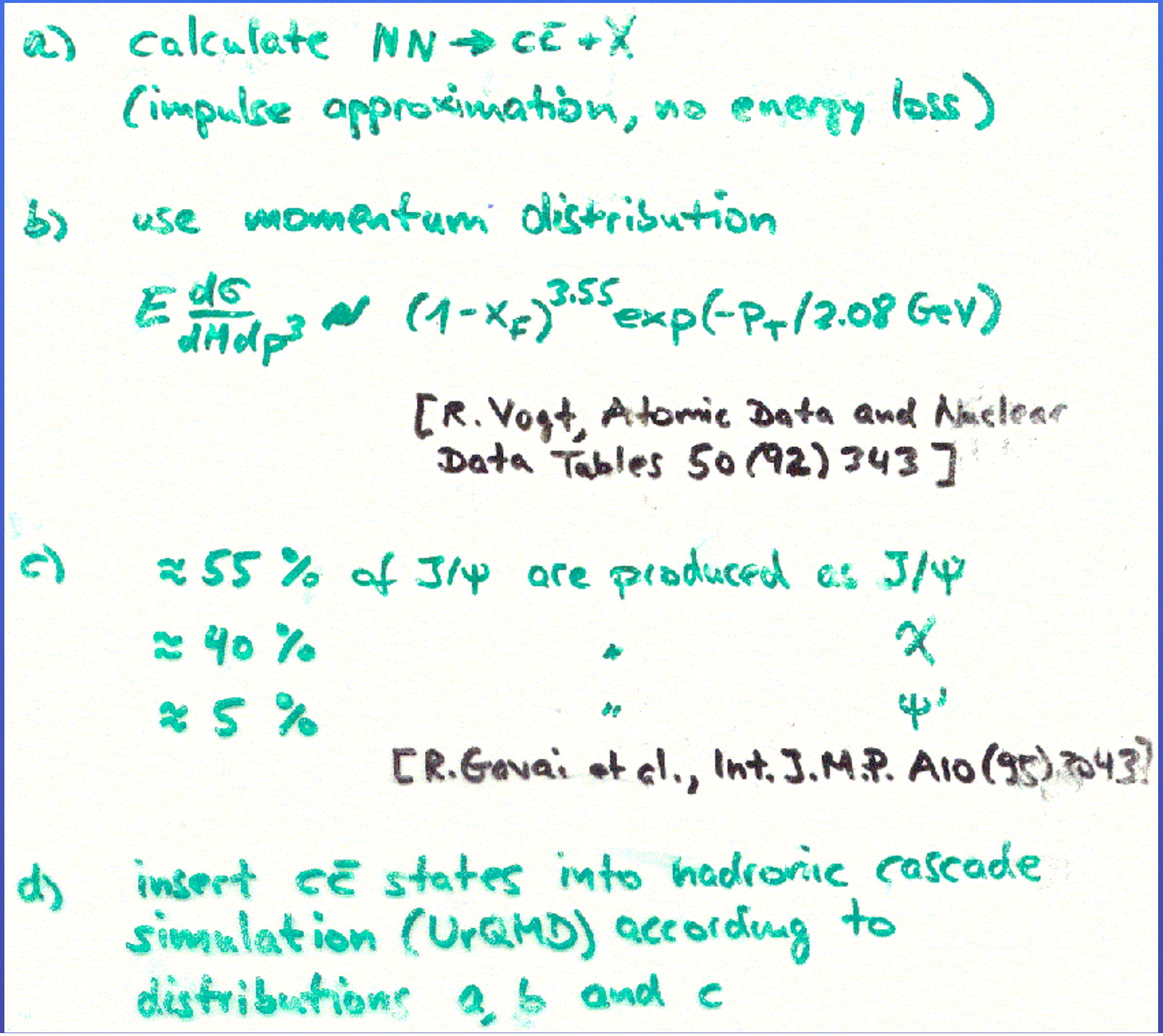
The contribution to the XN-cross section

$$\sigma = 2\pi \cdot \int \mathrm{d}b\,\mathrm{d}z\, b \cdot \sigma(b) \cdot |\Psi(b,z)|^2$$



$\Longrightarrow$ The main contributions to the charmonium-nucleon cross section comes from b-regions above the average transverse distance

Modelling charmonium interactions with comovers in AB collisions in the UrQMD-model



a) calculate $NN \rightarrow c\bar{c} + X$
(impulse approximation, no energy loss)

b) use momentum distribution

$$E\frac{d\sigma}{dM\,dp^3} \sim (1-x_F)^{3.55} \exp(-p_T/2.08\,\mathrm{GeV})$$

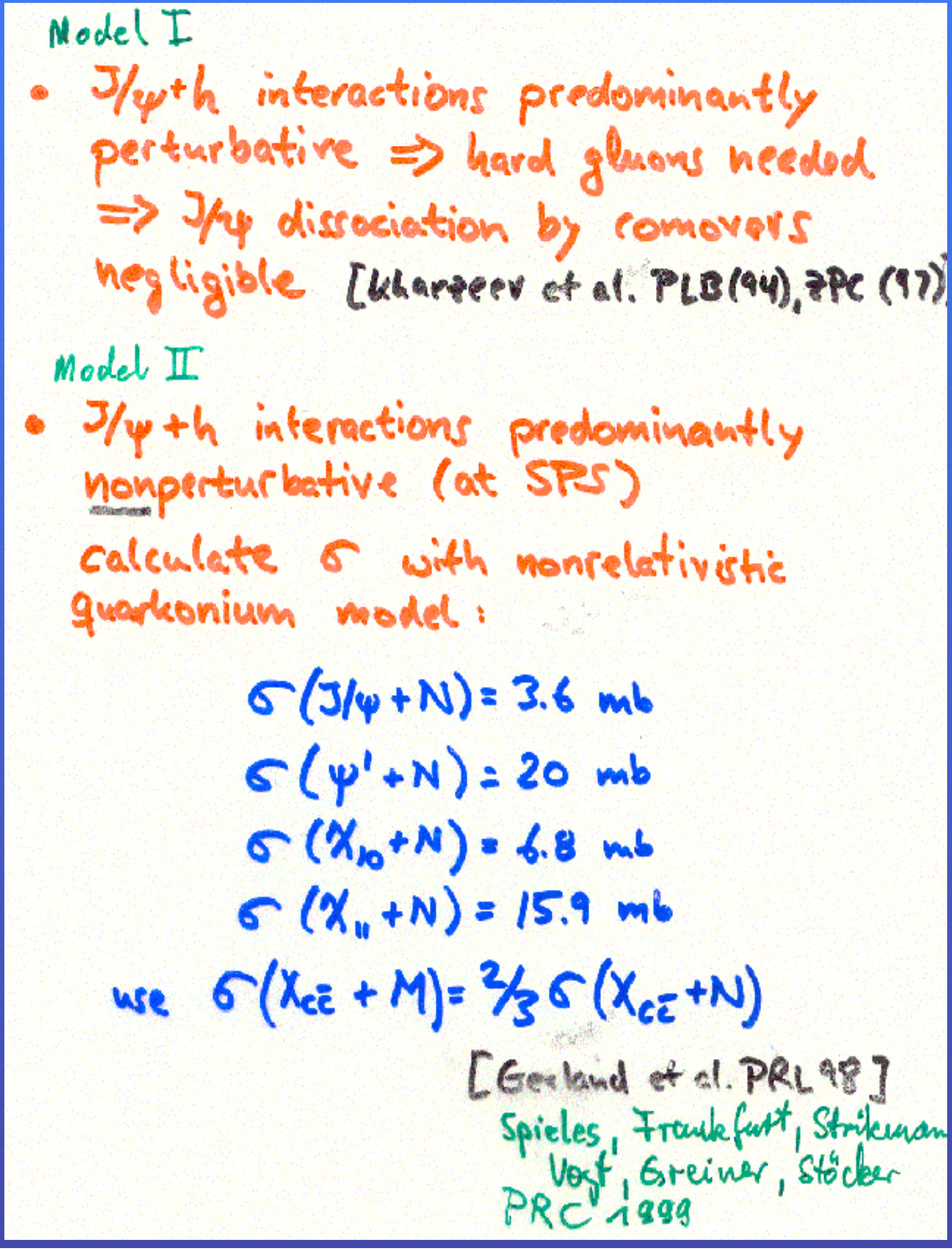
[R. Vogt, Atomic Data and Nuclear Data Tables 50 (92) 343]

c) ≈ 55 % of J/ψ are produced as J/ψ
≈ 40 % " χ
≈ 5 % " ψ'

[R. Gavai et al., Int. J. M. P. A10 (95) 3043]

d) insert $c\bar{c}$ states into hadronic cascade simulation (UrQMD) according to distributions a, b and c

Absorption by secondaries



Model I

- J/ψ+h interactions predominantly perturbative ⇒ hard gluons needed ⇒ J/ψ dissociation by comovers negligible [Kharzeev et al. PLB(94), ZPC (97)

Model II

- J/ψ+h interactions predominantly nonperturbative (at SPS)

calculate σ with nonrelativistic quarkonium model:

$$\sigma(J/\psi+N) = 3.6\ \text{mb}$$

$$\sigma(\psi'+N) = 20\ \text{mb}$$

$$\sigma(\chi_{10}+N) = 6.8\ \text{mb}$$

$$\sigma(\chi_{11}+N) = 15.9\ \text{mb}$$

use $\sigma(\chi_{c\bar{c}}+M) = \frac{2}{3}\,\sigma(\chi_{c\bar{c}}+N)$

[Gerland et al. PRL 98]

Spieles, Frankfurt, Strikman,
Vogt, Greiner, Stöcker
PRC 1999

The ratio J/ψ over open charm vs. the number of nucleon participants at RHIC energies