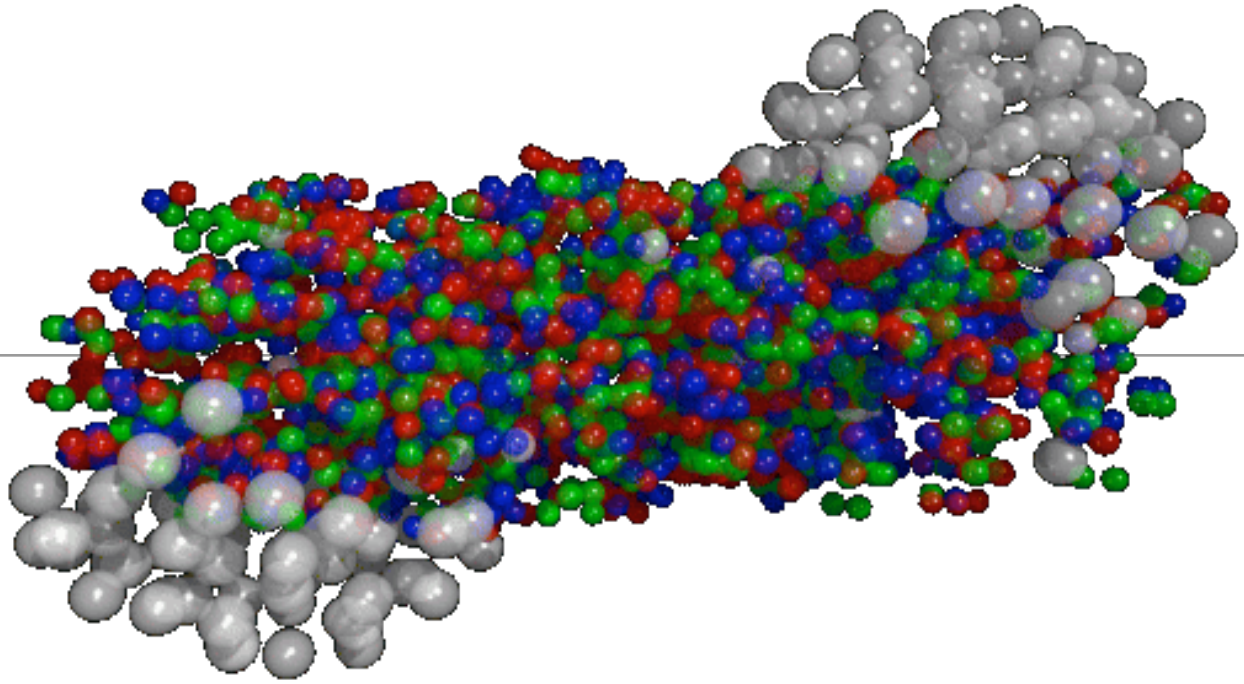
Heavy Ion Collisions for FAIR - modelling



Sascha Vogel

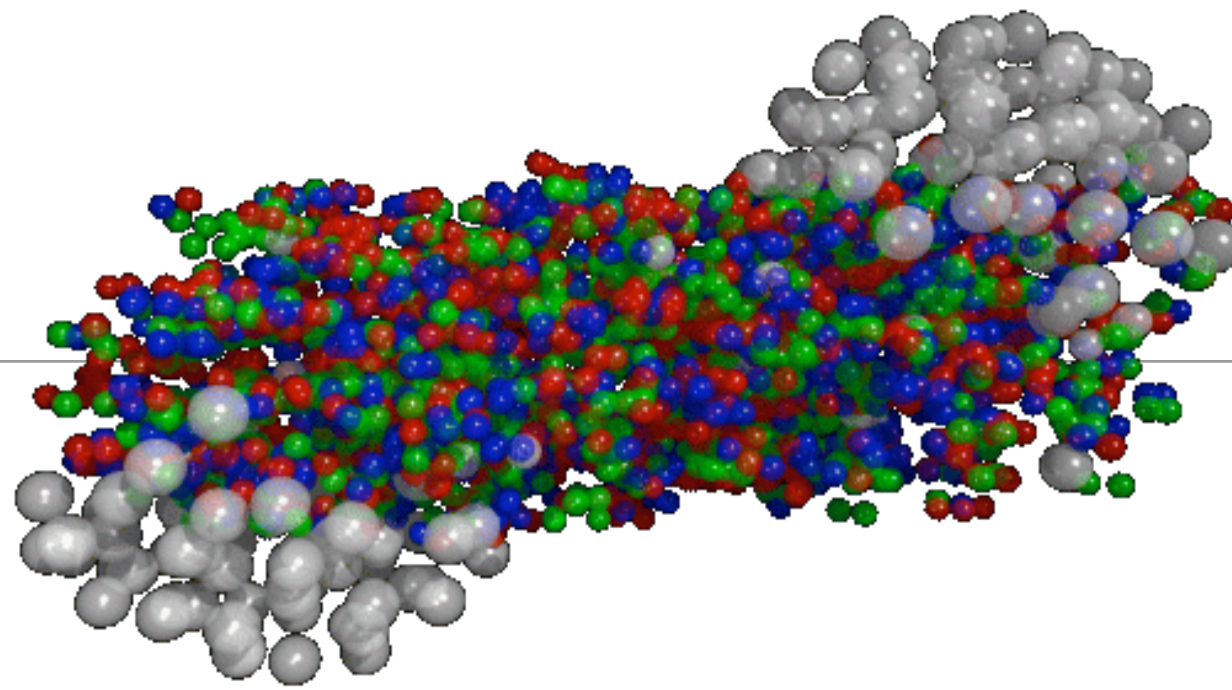
Helmholtz-Rosatom-Winterschool, 23.02.12, Bekasovo

FIAS Frankfurt Institute for Advanced Studies

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

Heavy Ion Collisions for FAIR - modelling

(spontaneous, basic, biased and sometimes wrong...)



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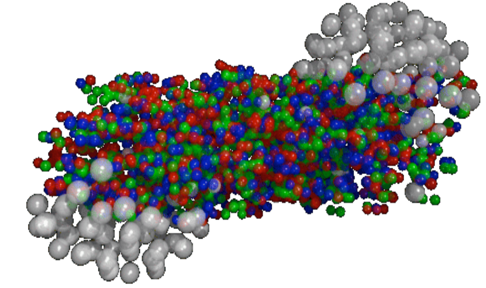


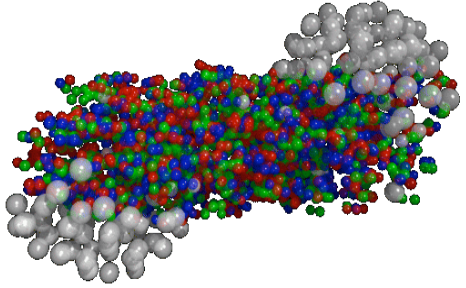
OPERA @ CERN

OPERA experiment reports anomaly in flight time of neutrinos from CERN to Gran Sasso

PR19.11
23.09.2011

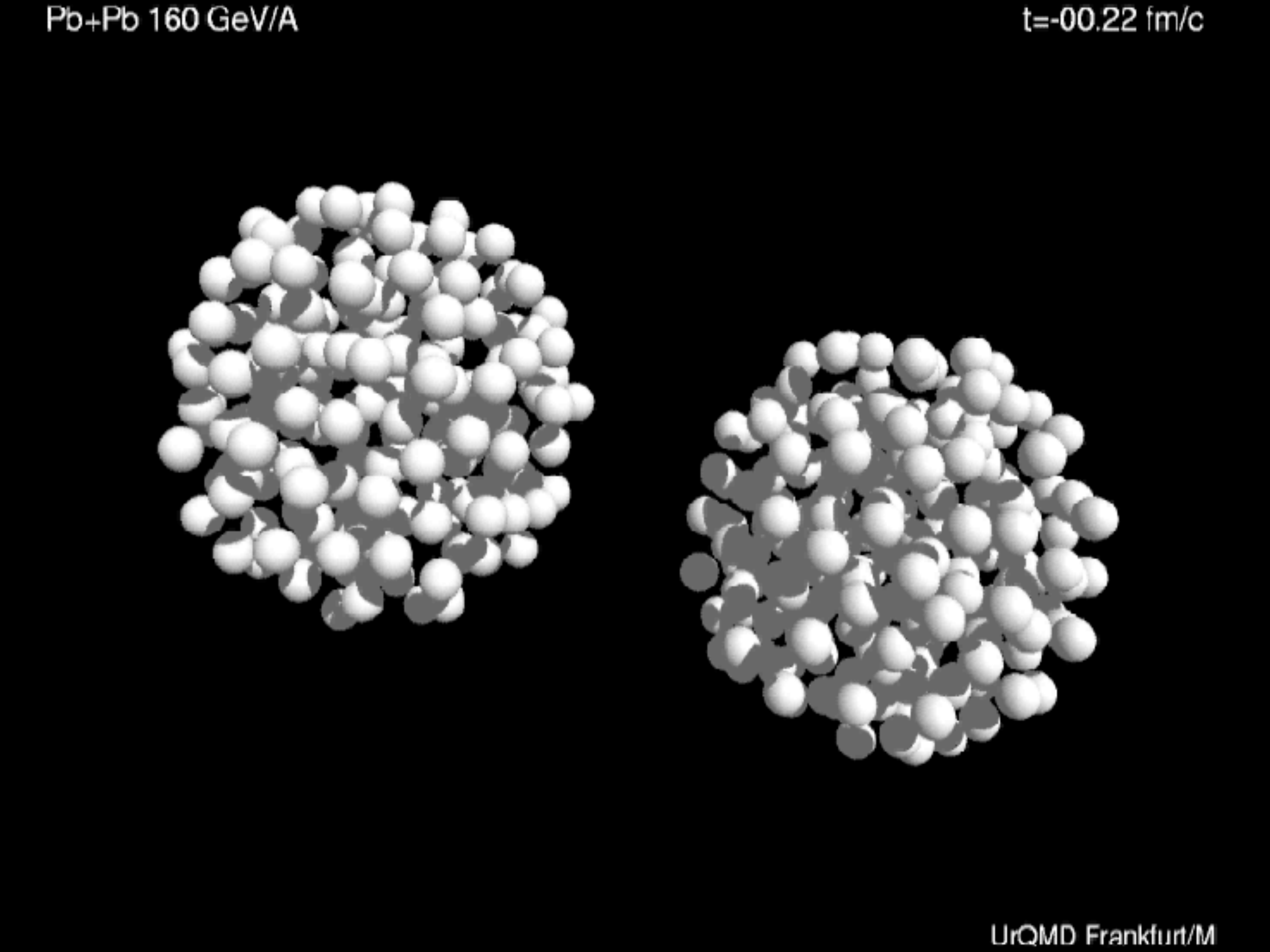
UPDATE 23 February 2012

The OPERA collaboration has informed its funding agencies and host laboratories that it has identified two possible effects that could have an influence on its neutrino timing measurement. These both require further tests with a short pulsed beam. If confirmed, one would increase the size of the measured effect, the other would diminish it. The first possible effect concerns an oscillator used to provide the time stamps for GPS synchronizations. It could have led to an overestimate of the neutrino's time of flight. The second concerns the optical fibre connector that brings the external GPS signal to the OPERA master clock, which may not have been functioning correctly when the measurements were taken. If this is the case, it could have led to an underestimate of the time of flight of the neutrinos. The potential extent of these two effects is being studied by the OPERA collaboration. New measurements with short pulsed beams are scheduled for May.

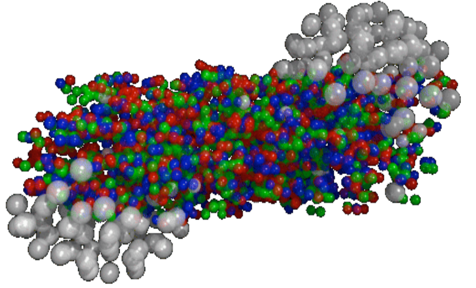


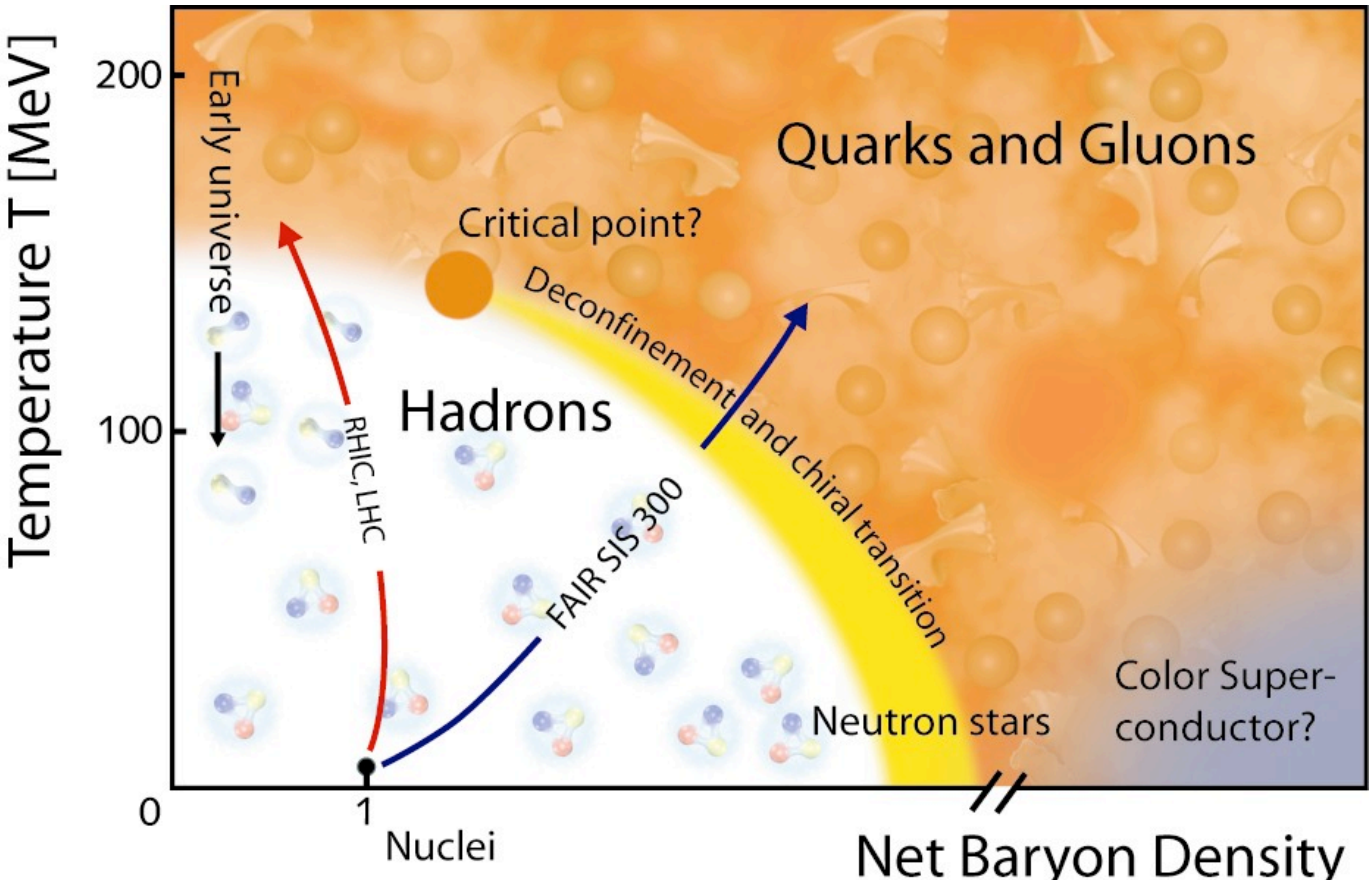
Outline

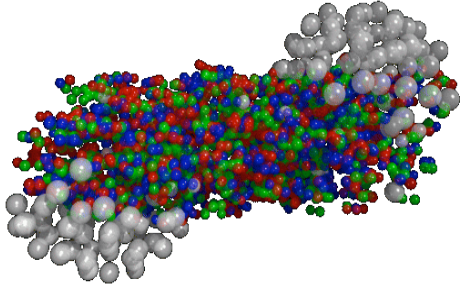
- Heavy Ion Collisions
- Models for Heavy Ion Collisions
  - Thermal Models
  - Hydrodynamic Models
  - Transport Models
- A specific transport model - UrQMD
- Observables
- Which ones should we measure at FAIR?


Pb+Pb 160 GeV/A
t=-00.22 fm/c
UrQMD Frankfurt/M

Phasediagram of QCD







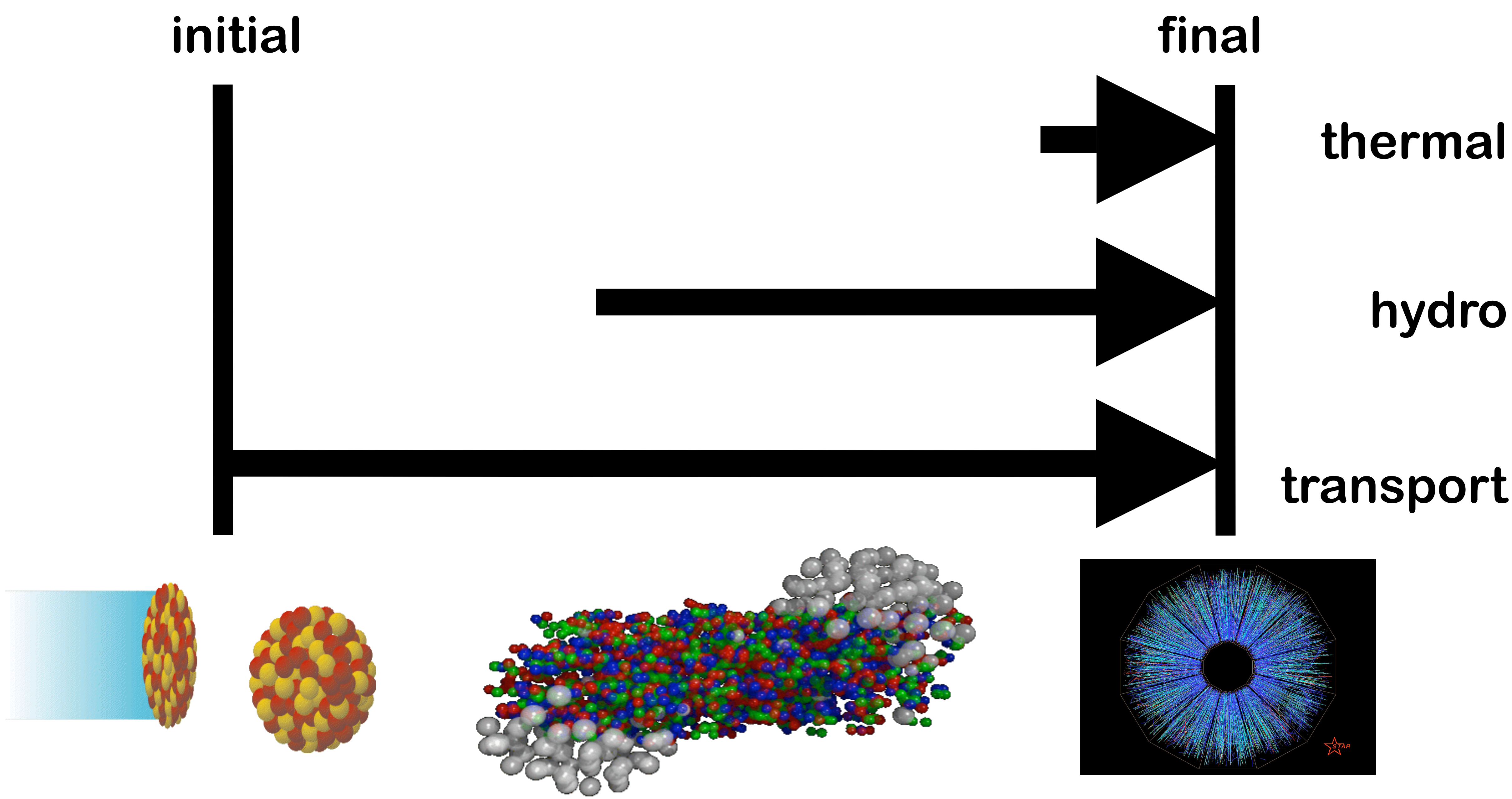
Models

Thermal Models

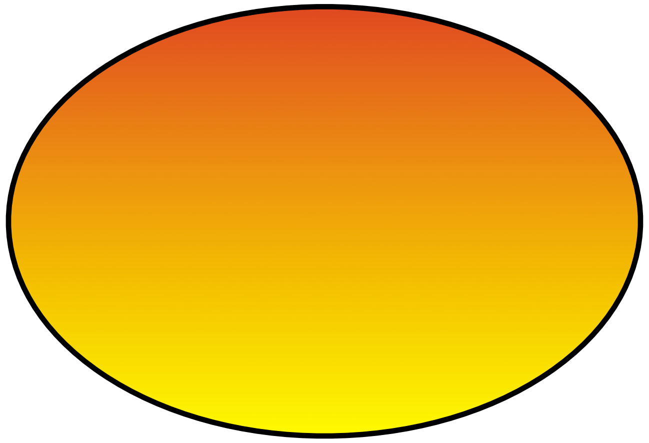
Hydrodynamic Models

Transport Models

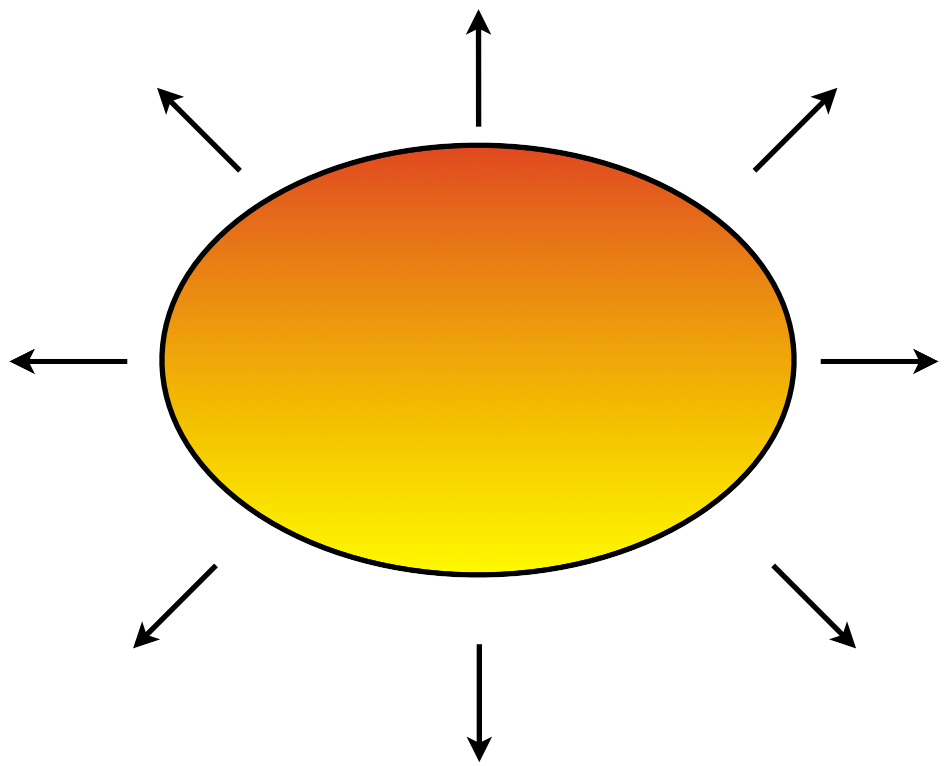
Model selection

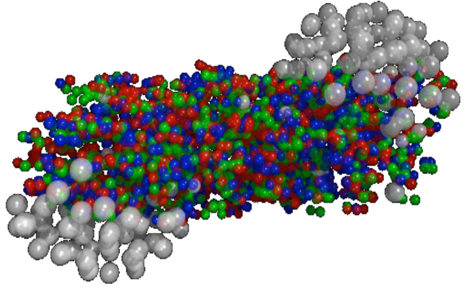


Thermal source

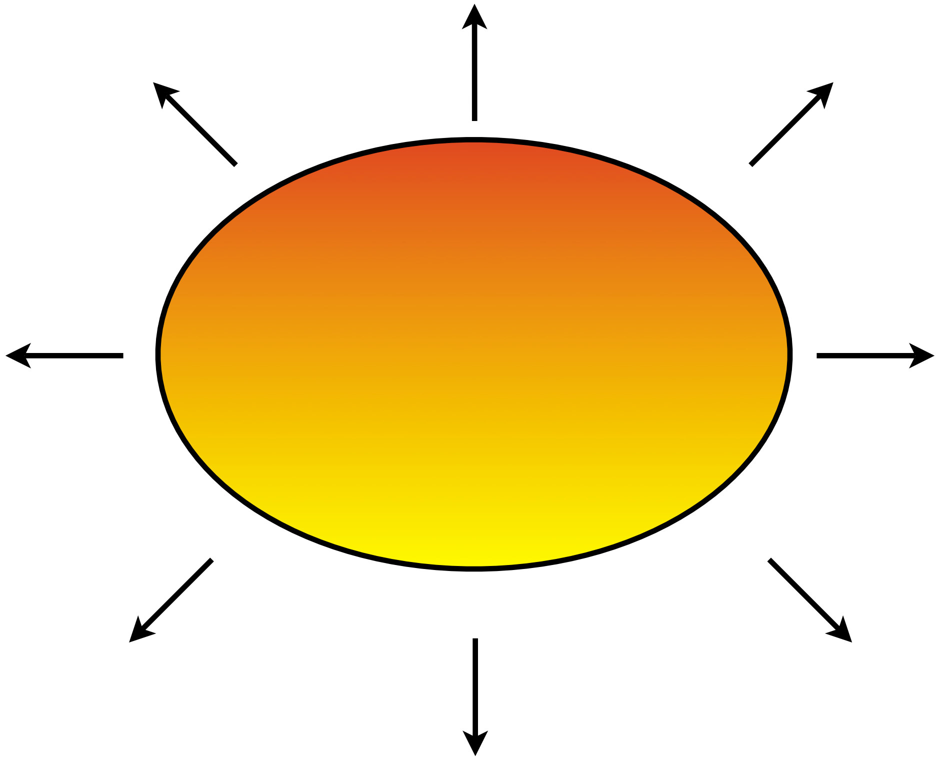


Thermal source



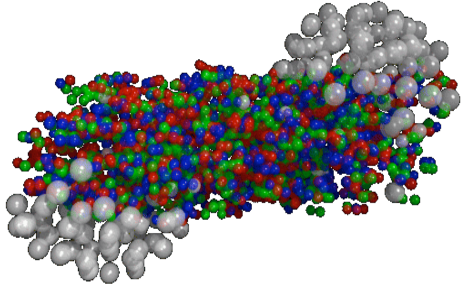


Thermal model

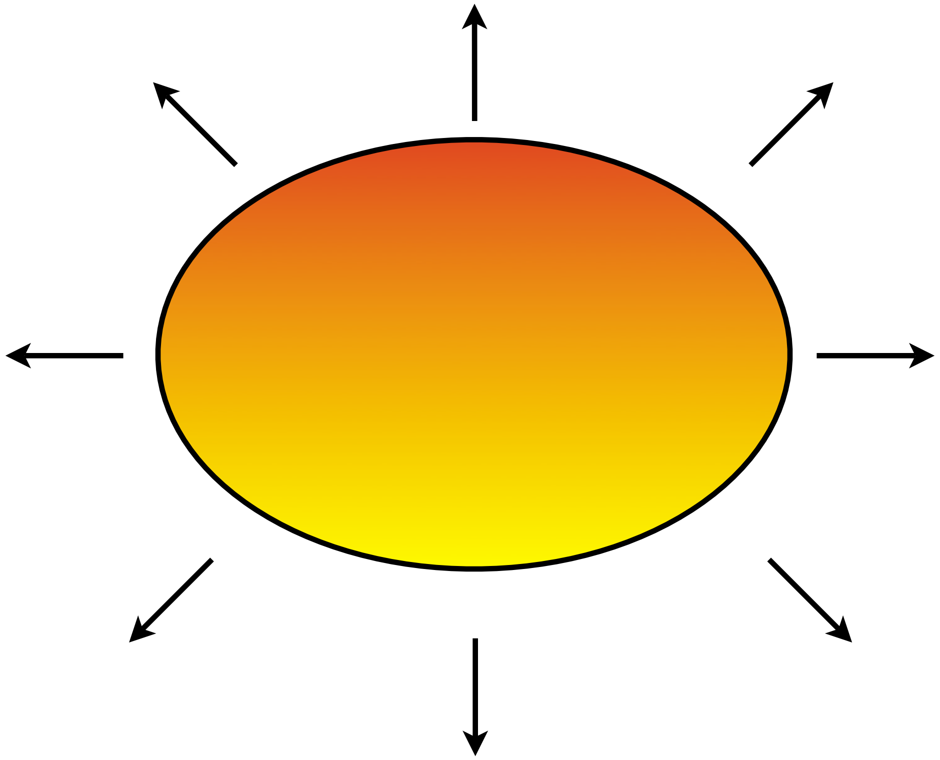


$$\rho_i^0 = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_b B_i - \mu_s S_i)/T] \pm 1}$$

$$E \frac{d^3 N}{d^3 p} \propto E \exp(-E/T) = m_t \cosh(y) \exp(-m_t \cosh(y)/T)$$



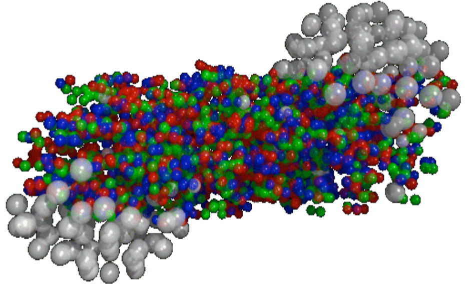
Thermal model



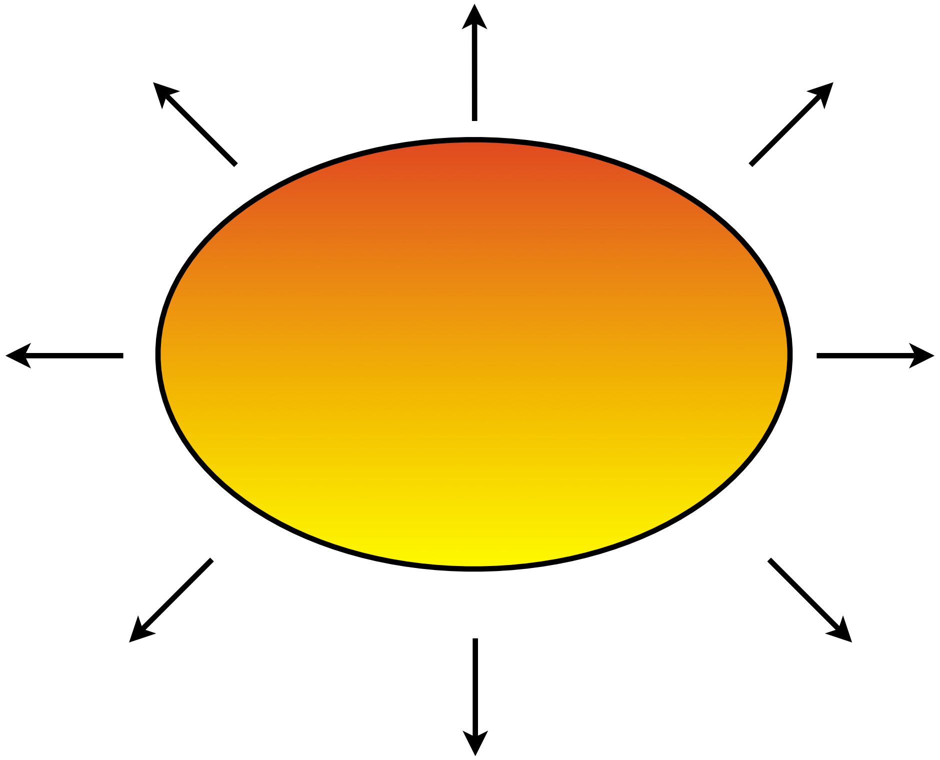
Simplifying assumptions:

isothermal source, isotropic source, instant freeze-out

no real dynamics!!



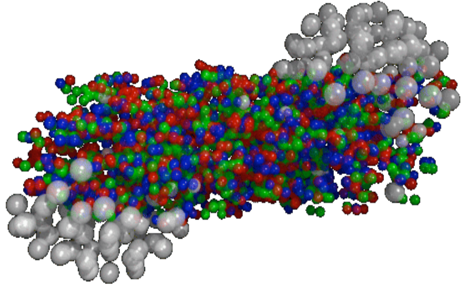
Hydrodynamics



dynamic fluid cells, moving according to the laws of hydrodynamics

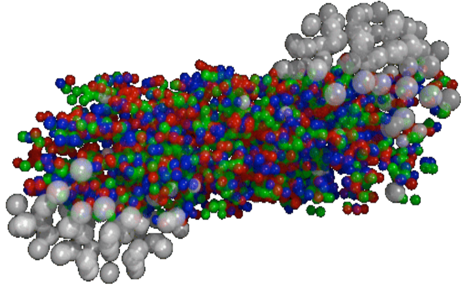
$$\partial_\mu T^{\mu\nu} = 0$$

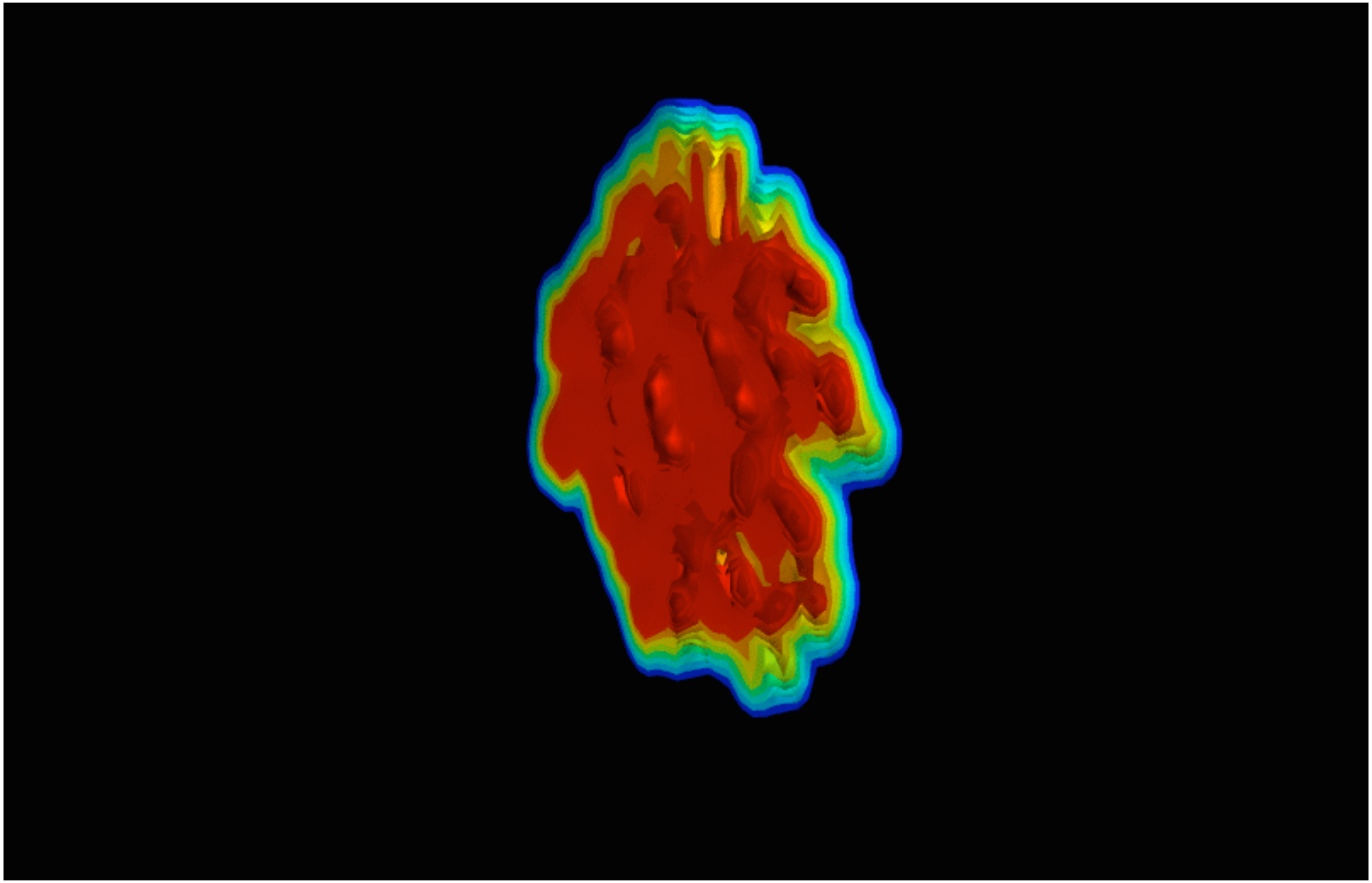
$$\partial_\mu j^\mu = 0$$



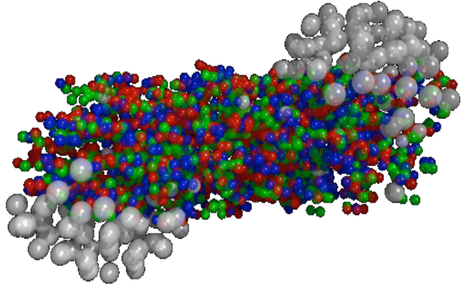
Hydrodynamics

Hydrodynamics





Björn Schenke



Hydrodynamics

Caveats on hydrodynamical models:

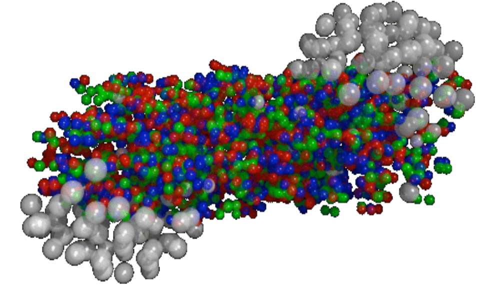
unknown initial conditions

unknown freeze-out conditions

thermalization has to be assumed

applicability at lower energies?

...



Transport Models

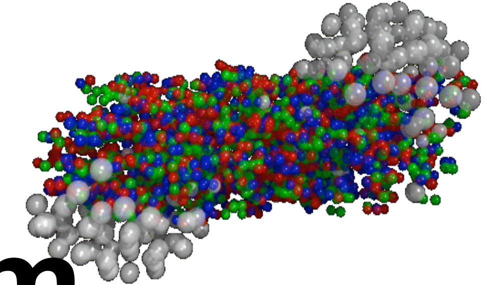
Vlasov equation

$$Df(\vec{r},\vec{v},t) = \frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{r}} + \frac{\vec{F}}{m}\frac{\partial f}{\partial \vec{v}} = 0$$

Boltzmann equation

$$Df(\vec{r},\vec{v},t) = I_{coll}$$

$$\frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{r}} + \frac{\vec{F}}{m}\frac{\partial f}{\partial \vec{v}} = \int\int (f' f_1' - f f_1)|\vec{v} - \vec{v_1}| \frac{d\sigma}{d\Omega'}(\vec{v},\vec{v'}) d\Omega' d^3 v_1$$



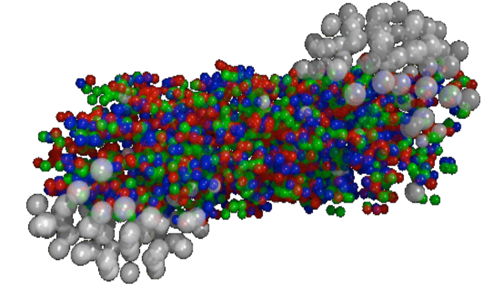
Collision term for N,π,Δ system

$$
\begin{aligned}
\frac{\partial f_N}{\partial t} &+ \vec{v}\cdot\frac{\partial f_N}{\partial r} - \nabla_r U_N \cdot \frac{\partial f_N}{\partial p} = I_{NN\to NN} + I_{N\Delta\to N\Delta} + I_{N\pi\to N\pi} + I_{NN\to N\Delta} + I_{NN\to\Delta\Delta} + I_{N\Delta\to\Delta\Delta} + I_{N\Delta\to NN} + I_{N\pi\to\Delta} \\
&= \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{NN}c^2\cdot\mu_{NN}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot \\
&\quad \left[\frac{p_1'-p_2'}{p_1-p_2}f_N(p_1')f_N(p_2')(1-f_N(p_1))(1-f_N(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}f_N(p_1)f_N(p_2)(1-f_N(p_1'))(1-f_N(p_2'))\right] \\
&+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{N\Delta}c^2\cdot\mu_{N\Delta}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot \\
&\quad \left[\frac{p_1'-p_2'}{p_1-p_2}f_N(p_1')f_\Delta(p_2')(1-f_N(p_1))(1-f_\Delta(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}N(p_1)f_\Delta(p_2)(1-f_N(p_1'))(1-f_\Delta(p_2'))\right] \\
&+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{N\pi}c^2\cdot\mu_{N\pi}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot \\
&\quad \left[\frac{p_1'-p_2'}{p_1-p_2}f_N(p_1')f_\pi(p_2')(1-f_N(p_1))(1+f_\pi(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}N(p_1)f_\pi(p_2)(1-f_N(p_1'))(1+f_\pi(p_2'))\right] \\
&+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{NN}c^2\cdot\mu_{N\Delta}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot \\
&\quad \left[\frac{p_1'-p_2'}{p_1-p_2}f_N(p_1')f_\Delta(p_2')(1-f_N(p_1))(1-f_N(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}N(p_1)f_N(p_2)(1-f_N(p_1'))(1-f_\Delta(p_2'))\right] \\
&+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{NN}c^2\cdot\mu_{\Delta\Delta}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot \\
&\quad \left[\frac{p_1'-p_2'}{p_1-p_2}f_\Delta(p_1')f_\Delta(p_2')(1-f_N(p_1))(1-f_N(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}N(p_1)f_N(p_2)(1-f_\Delta(p_1'))(1-f_\Delta(p_2'))\right] \\
&+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{N\Delta}c^2\cdot\mu_{\Delta\Delta}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot \\
&\quad \left[\frac{p_1'-p_2'}{p_1-p_2}f_\Delta(p_1')f_\Delta(p_2')(1-f_N(p_1))(1-f_\Delta(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}N(p_1)f_\Delta(p_2)(1-f_\Delta(p_1'))(1-f_\Delta(p_2'))\right] \\
&+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{N\Delta}c^2\cdot\mu_{NN}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot \\
&\quad \left[\frac{p_1'-p_2'}{p_1-p_2}f_N(p_1')f_N(p_2')(1-f_N(p_1))(1-f_\Delta(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}N(p_1)f_\Delta(p_2)(1-f_N(p_1'))(1-f_N(p_2'))\right] \\
&+ \int\frac{d^3p_\pi}{(2\pi\hbar)^3}\int\frac{d^3p_\Delta}{(2\pi\hbar)^3}|\langle p_\Delta|T|p_N p_\pi\rangle|^2\cdot(2\pi\hbar)^3\delta^3(p_N+p_\pi-p_\Delta)\delta(\varepsilon_N+\varepsilon_\pi-\varepsilon_\Delta)\cdot \\
&\quad [f_\Delta(p_\Delta)(1+f_\pi(p_\pi))(1-f_N(p_N)) - f_N(p_N)f_\pi(p_\pi)(1-f_\Delta(p_\Delta))]
\end{aligned}
$$

$+ I_{NN\to\Delta\Delta} + I_{N\Delta\to\Delta\Delta} + I_{N\Delta\to NN} + I_{N\pi\to\Delta}$

$$+ \int\frac{d^3p_\pi}{(2\pi\hbar)^3}\int\frac{d^3p_\Delta}{(2\pi\hbar)^3}|\langle p_\Delta|T|p_N p_\pi\rangle|^2\cdot(2\pi\hbar)^3\delta^3(p_N+p_\pi-p_\Delta)\delta(\varepsilon_N+\varepsilon_\pi-\varepsilon_\Delta)\cdot$$

$[f_\Delta(p_\Delta)(1+f_\pi(p_\pi))(1-f_N(p_N)) - f_N(p_N)f_\pi(p_\pi)(1-f_\Delta(p_\Delta))]$



Boltzmann equation

Mathematicians Solve 140-Year-Old Boltzmann Equation

May 12, 2010

PRINT EMAIL SHARE

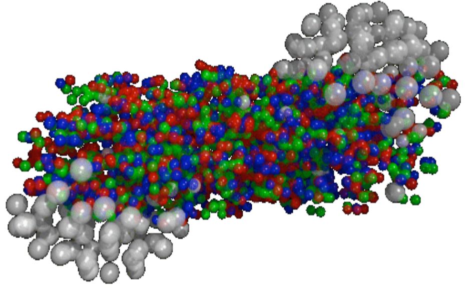
Philip T. Gressman (top) and Robert M. Strain (bottom)

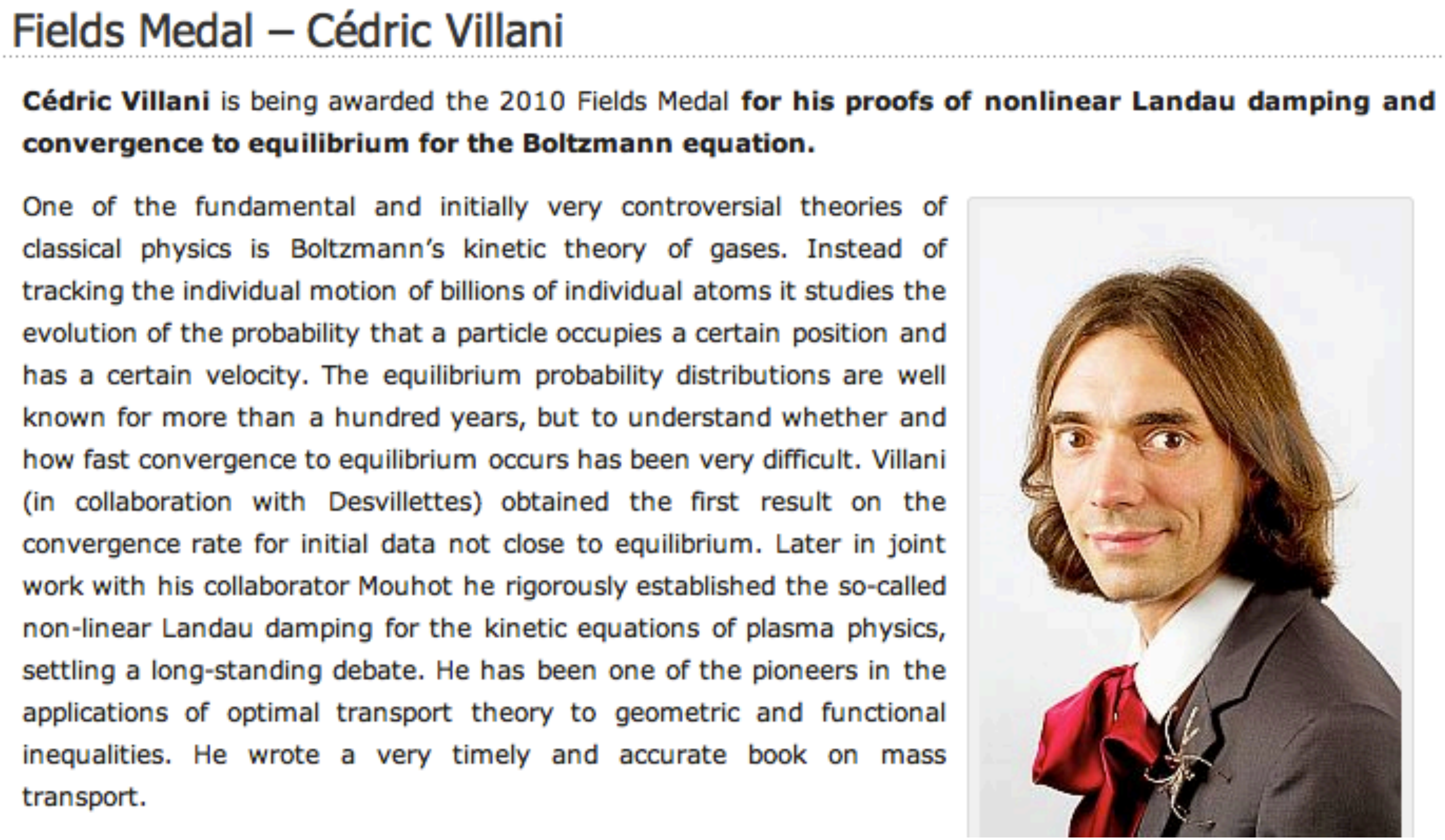
PHILADELPHIA — Two University of Pennsylvania mathematicians have found solutions to a 140-year-old, 7-dimensional equation that were not known to exist for more than a century despite its widespread use in modeling the behavior of gases.

The study, part historical journey but mostly mathematical proof, was conducted by Philip T. Gressman and Robert M. Strain of Penn's Department of Mathematics. The solution of the Boltzmann equation problem was published in the Proceedings of the National Academy of Sciences. Solutions of this equation, beyond current computational capabilities, describe the location of gas molecules probabilistically and predict the likelihood that a molecule will reside at any particular location and have a particular momentum at any given time in the future.

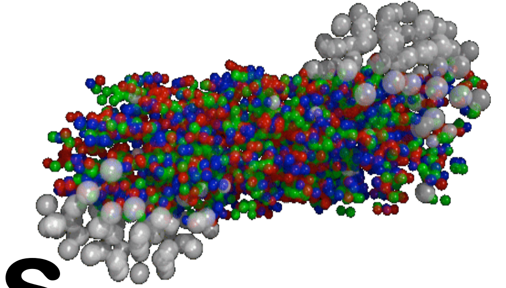
During the late 1860s and 1870s, physicists James Clerk Maxwell and Ludwig Boltzmann developed this equation to predict how

Boltzmann equation





Quantum Molecular Dynamics

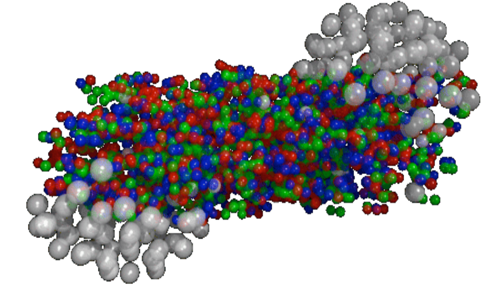


Nucleon = Gaussian Wave-Packet

$$\phi_i(\vec{x};\vec{q}_i,\vec{p}_i,t) = \left(\frac{2}{L\pi}\right)^{3/4} \exp\left\{-\frac{2}{L}(\vec{x}-\vec{q}_i(t))^2 + \frac{1}{\hbar}\mathrm{i}\vec{p}_i(t)\vec{x}\right\}$$

N-Body-State = product of coherent states

$$\Phi = \prod_i \phi_i(\vec{x},\vec{q_i},\vec{p_i},t)$$



QMD

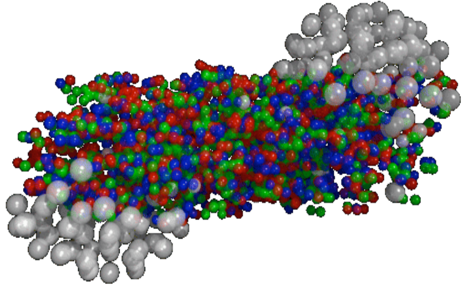
Lagrangian Density

$$\mathcal{L} = \sum_i \left[-\dot{\vec{q}}_i \vec{p}_i - T_i - \frac{1}{2} \sum_{j \neq i} \langle V_{ik} \rangle - \frac{3}{2Lm} \right]$$

Equations of motion

$$\dot{\vec{q}}_i = \frac{\vec{p}_i}{m} + \nabla_{\vec{p}_i} \sum_j \langle V_{ij} \rangle = \nabla_{\vec{p}_i} \langle H \rangle$$

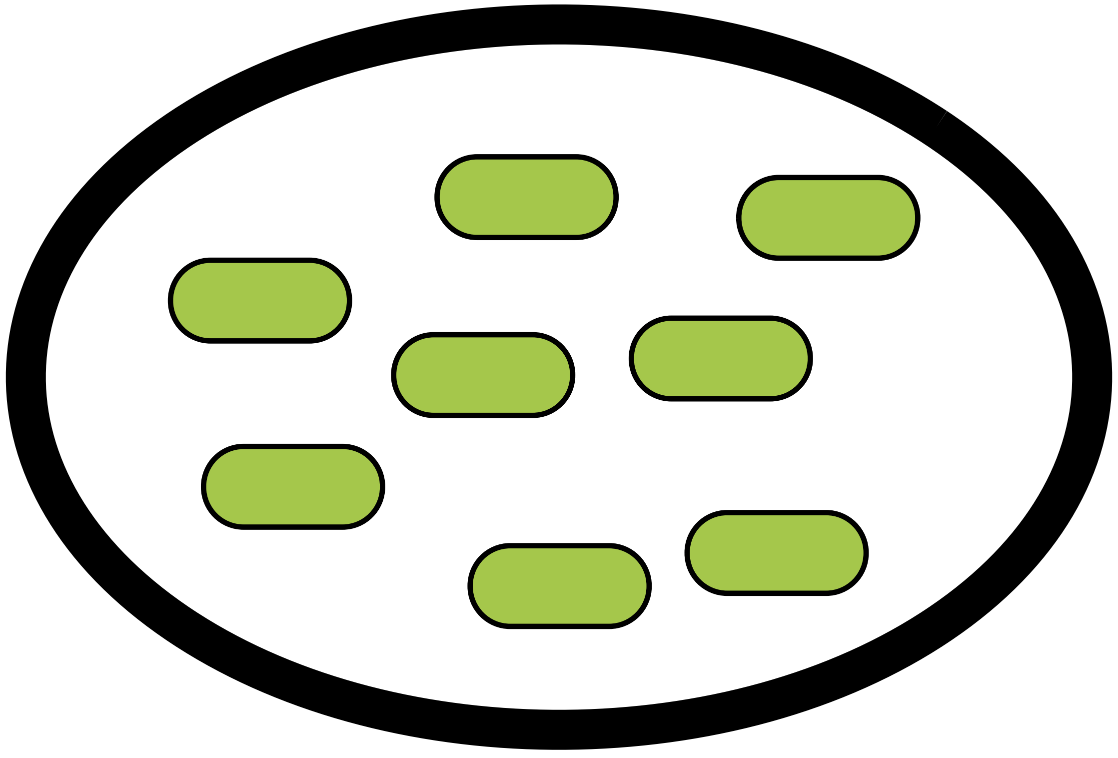
$$\dot{\vec{p}}_i = -\nabla_{\vec{q}_i} \sum_{j \neq i} \langle V_{ij} \rangle = -\nabla_{\vec{q}_i} \langle H \rangle .$$

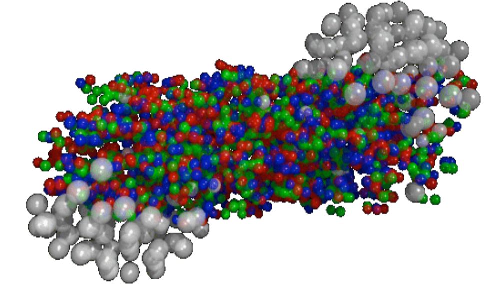


QMD

Complicated N-Body Schrödinger Problem

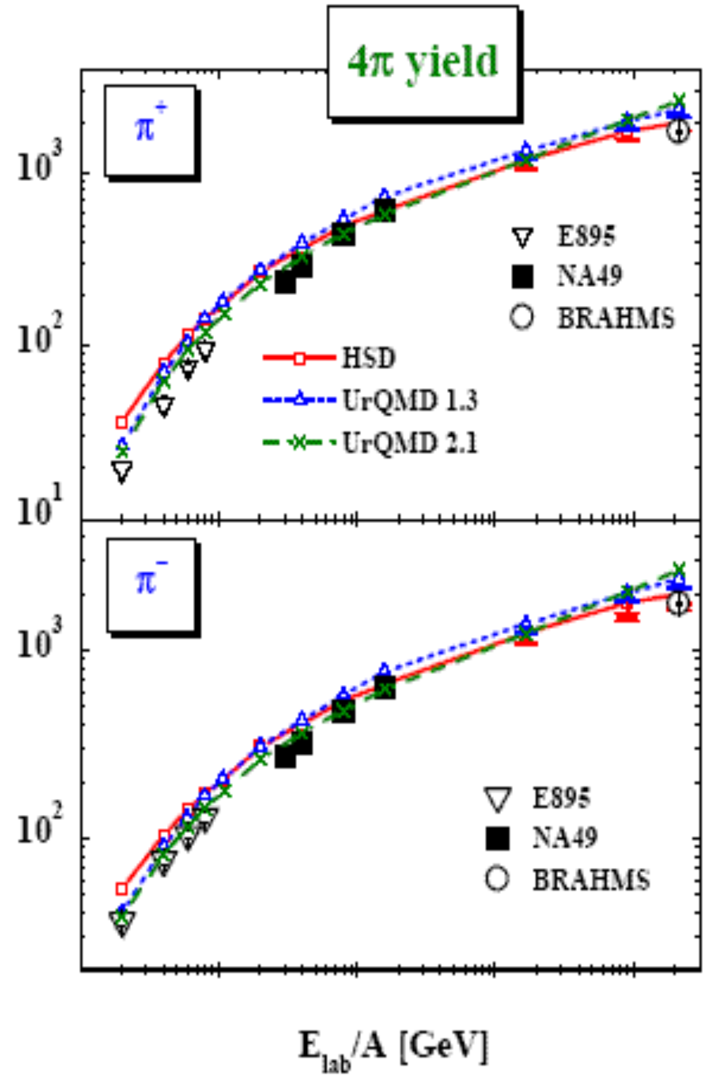
6 (N_P+N_T) equations

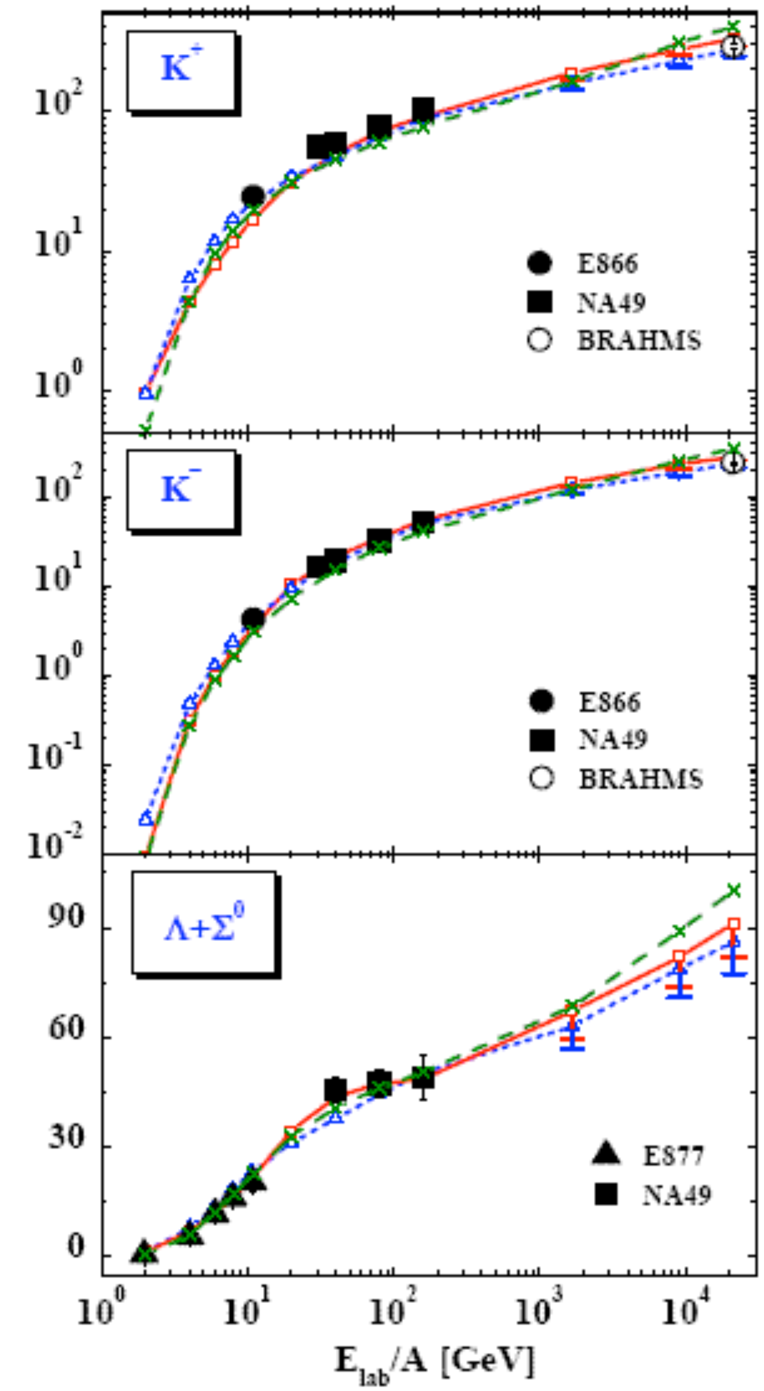




One model - UrQMD

- Ultra Relativistic Quantum Molecular Dynamics
- Non equilibrium transport model
- All hadrons and resonances up to 2.2 GeV included
- Particle production via string excitation and -fragmentation
- Cross sections
  - experimental data
  - detailed balance
  - additive quark model
- Dynamical canonical suppression

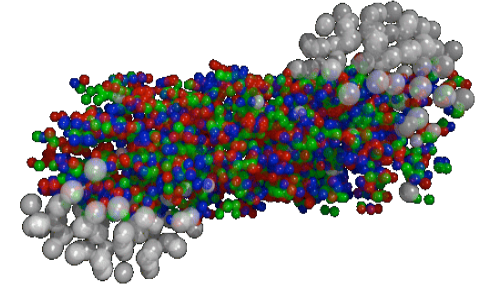




No explicit implementation of in-medium modifications!

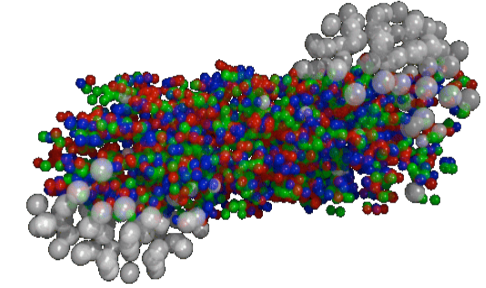
Phys.Rev.C69:054907,2004

Phys.Rev.C74:034902,2006



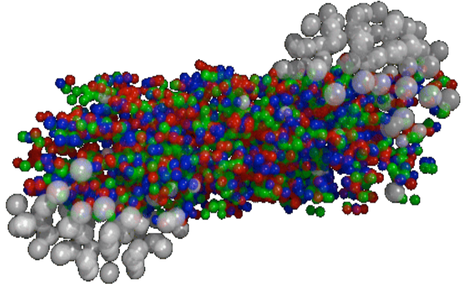
Particles in UrQMD

nucleon	Δ	Λ	Σ	Ξ	Ω
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1192}	Ξ_{1317}	Ω_{1672}
N_{1440}	Δ_{1600}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	
N_{1520}	Δ_{1620}	Λ_{1520}	Σ_{1660}	Ξ_{1690}	
N_{1535}	Δ_{1700}	Λ_{1600}	Σ_{1670}	Ξ_{1820}	
N_{1650}	Δ_{1900}	Λ_{1670}	Σ_{1775}	Ξ_{1950}	
N_{1675}	Δ_{1905}	Λ_{1690}	Σ_{1790}	Ξ_{2025}	
N_{1680}	Δ_{1910}	Λ_{1800}	Σ_{1915}		
N_{1700}	Δ_{1920}	Λ_{1810}	Σ_{1940}		
N_{1710}	Δ_{1930}	Λ_{1820}	Σ_{2030}		
N_{1720}	Δ_{1950}	Λ_{1830}			
N_{1900}		Λ_{1890}			
N_{1990}		Λ_{2100}			
N_{2080}		Λ_{2110}			
N_{2190}					
N_{2200}					
N_{2250}					



Particles in UrQMD

0^{-+}	1^{--}	0^{++}	1^{++}
π	ρ	a_0	a_1
K	K^*	K_0^*	K_1^*
η	ω	f_0	f_1
η'	ϕ	f_0^*	f_1'
1^{+-}	2^{++}	$(1^{--})^*$	$(1^{--})^{**}$
b_1	a_2	ρ_{1450}	ρ_{1700}
K_1	K_2^*	K_{1410}^*	K_{1680}^*
h_1	f_2	ω_{1420}	ω_{1662}
h_1'	f_2'	ϕ_{1680}	ϕ_{1900}



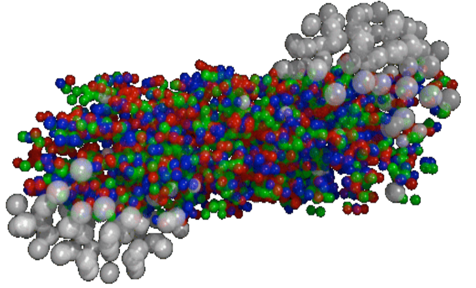
Steps in UrQMD

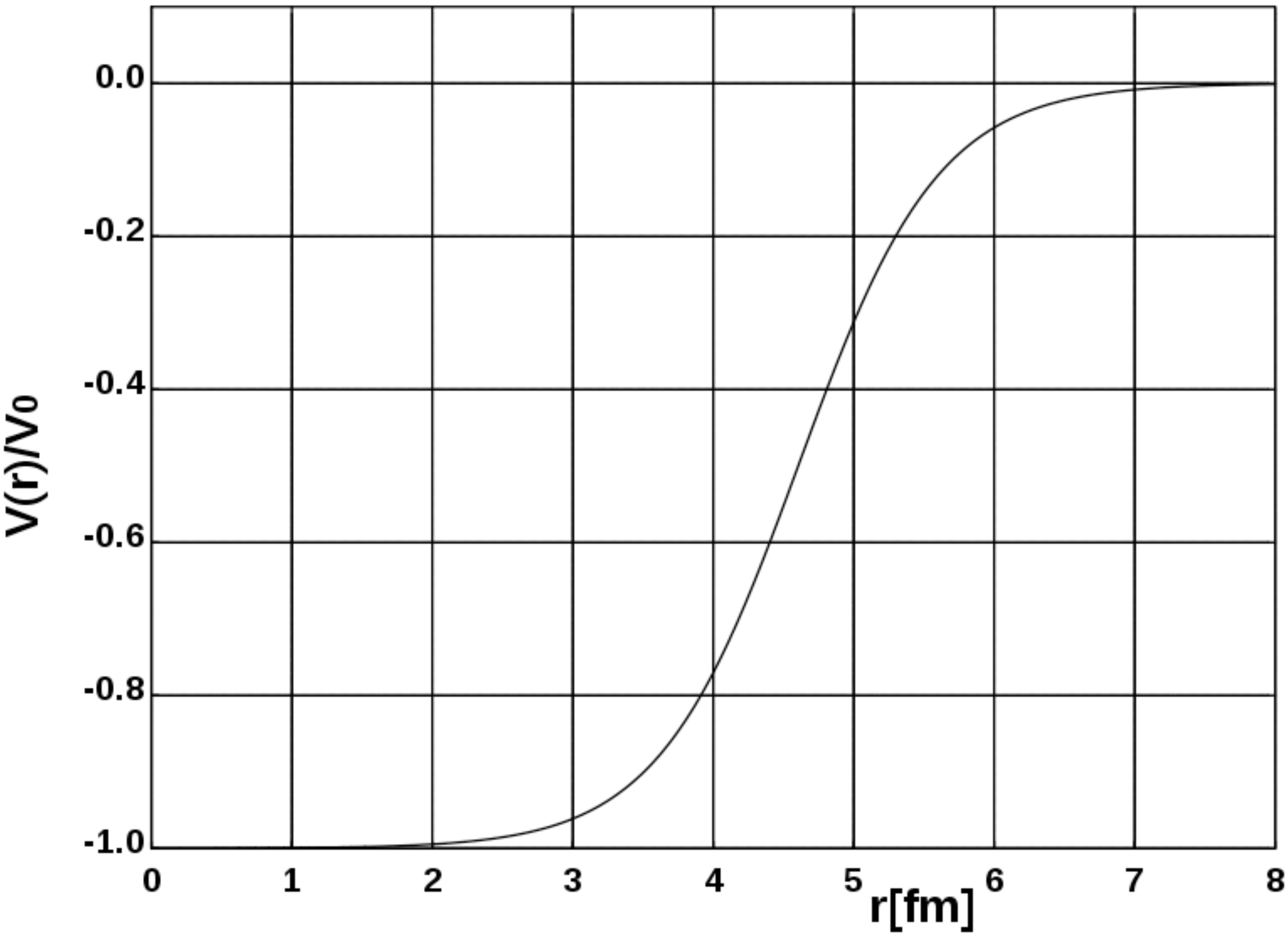
Initialization

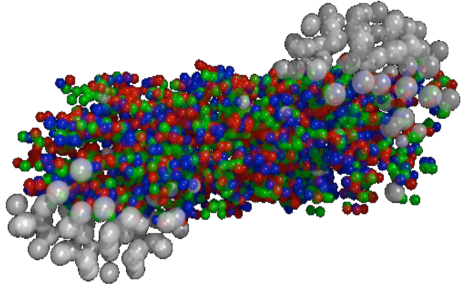
Propagation of nuclei and produced particles

Binary scatterings

Initialization





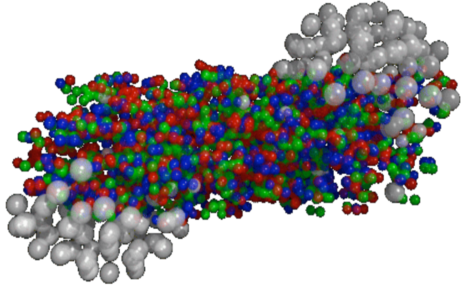


Collision criterium

When do particles collide?

1) Know cross section

2) Check collision criterium



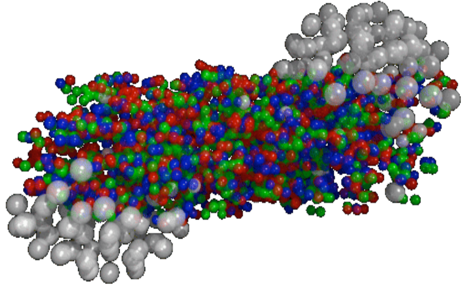
Collision criterium

When do particles collide?

1) Know cross section

2) Check collision criterium

$$\pi d^2 \leq \sigma_{tot}$$

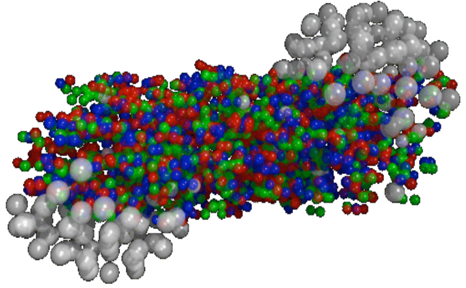


UrQMD hands-on

Demo

svogel — svogel@enton-2.local :: /Users/svogel/UrQMD/urqmd-3.3p1_LHC — bash — 217×60

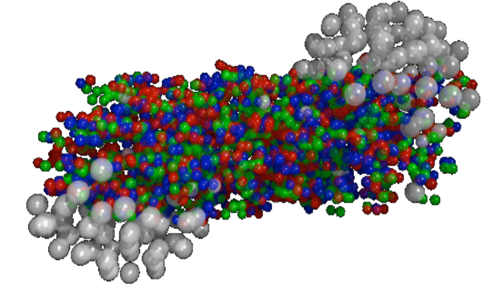
```
svogel@enton-2:~/UrQMD/urqmd-3.3p1_LHC>
```



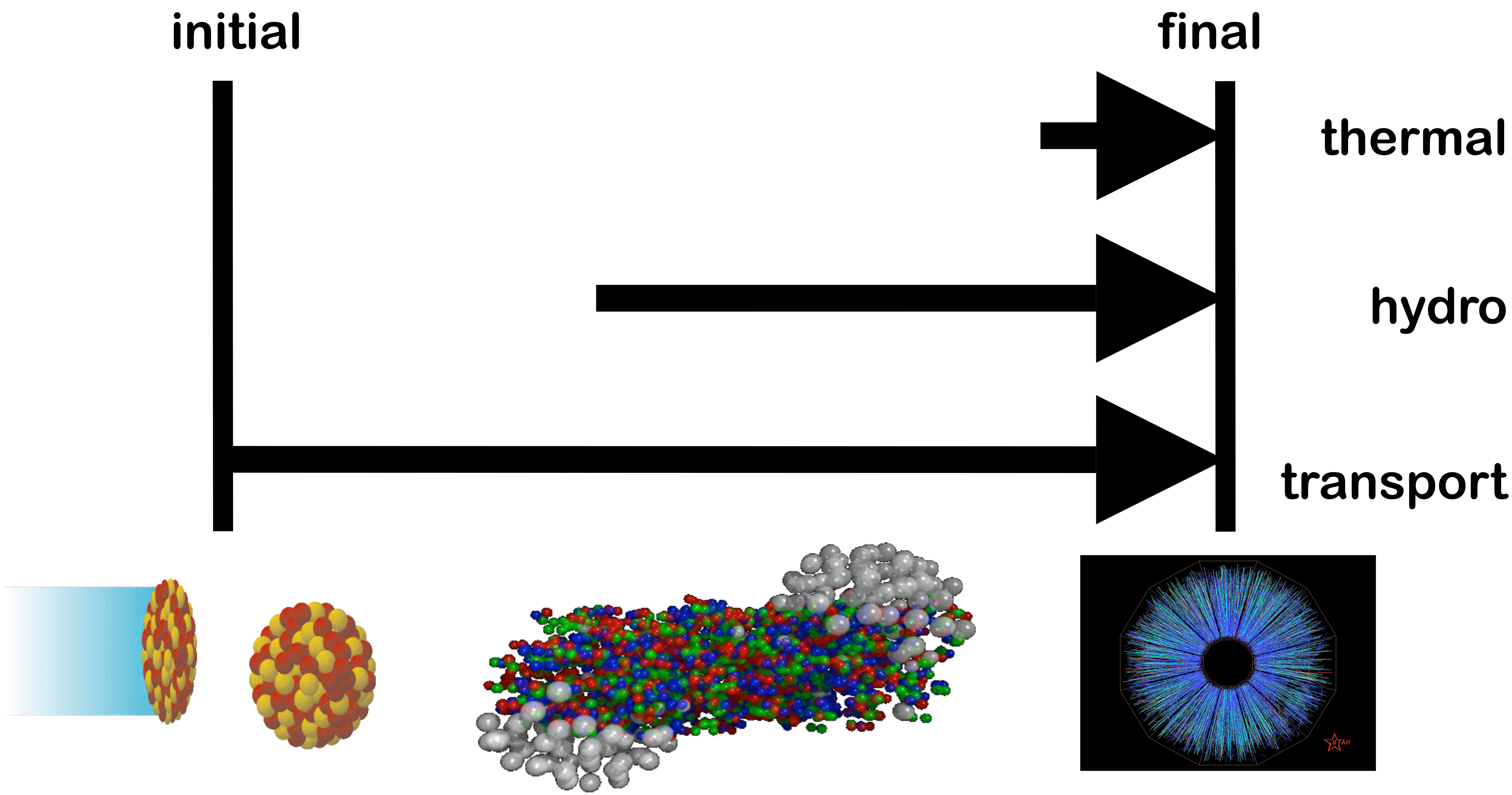
Let’s assume…

we want to study CBM!

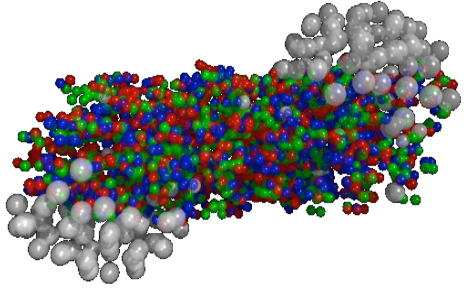
This is a FAIR Winterschool so everyone should!



Which model?

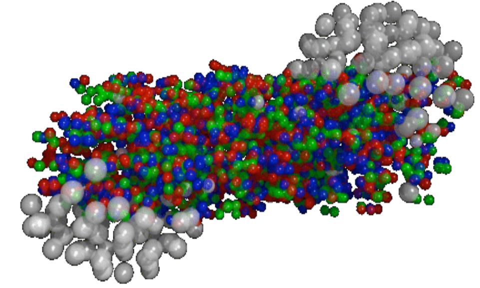


How to get the info we want?



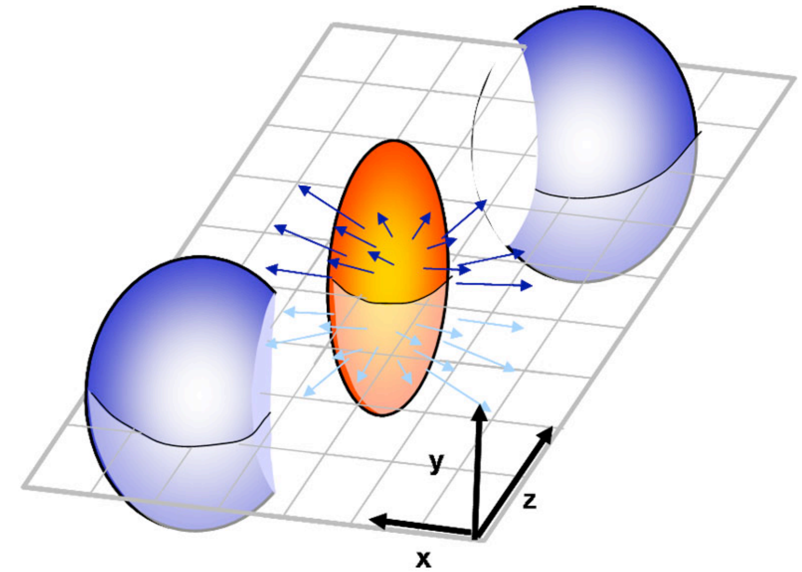
However...

How do we get information from this stage of the collision?

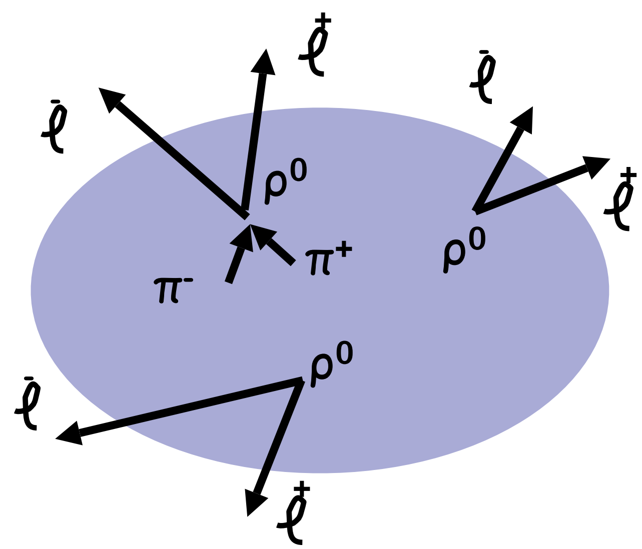


Observables

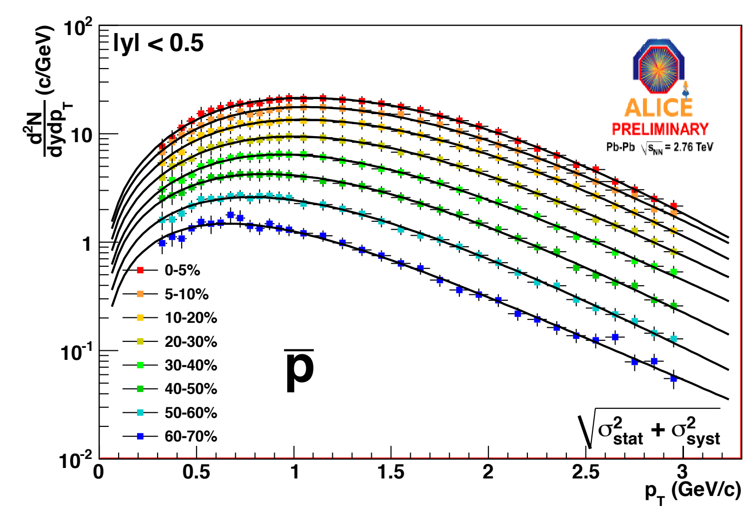
- **Collective Phenomena**
  - Elliptic Flow Patterns
  - Viscosity
  - ...



- **Rare probes**
  - Dileptons, resonances
  - Charm
  - ...



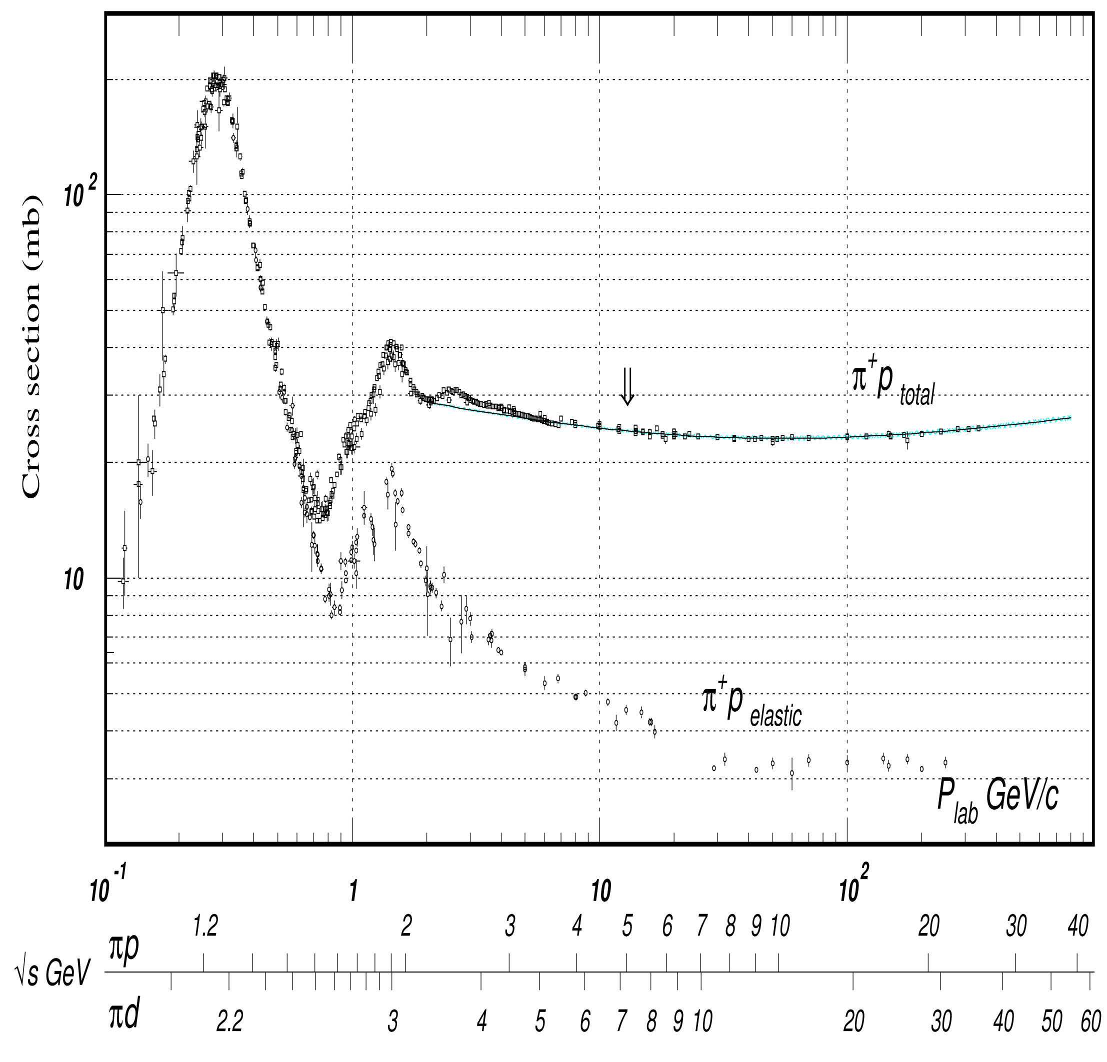
- **Spectra**
  - transverse momentum distributions
  - rapidity distributions
  - ...



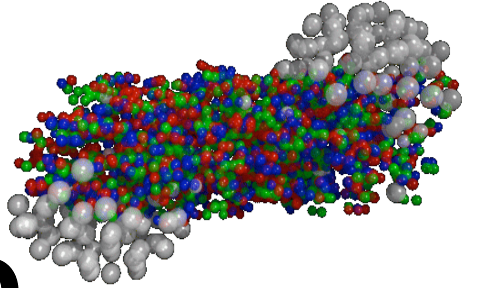
Measuring resonances

- **Since resonances decay on timescales of several fm they cannot be measured directly**

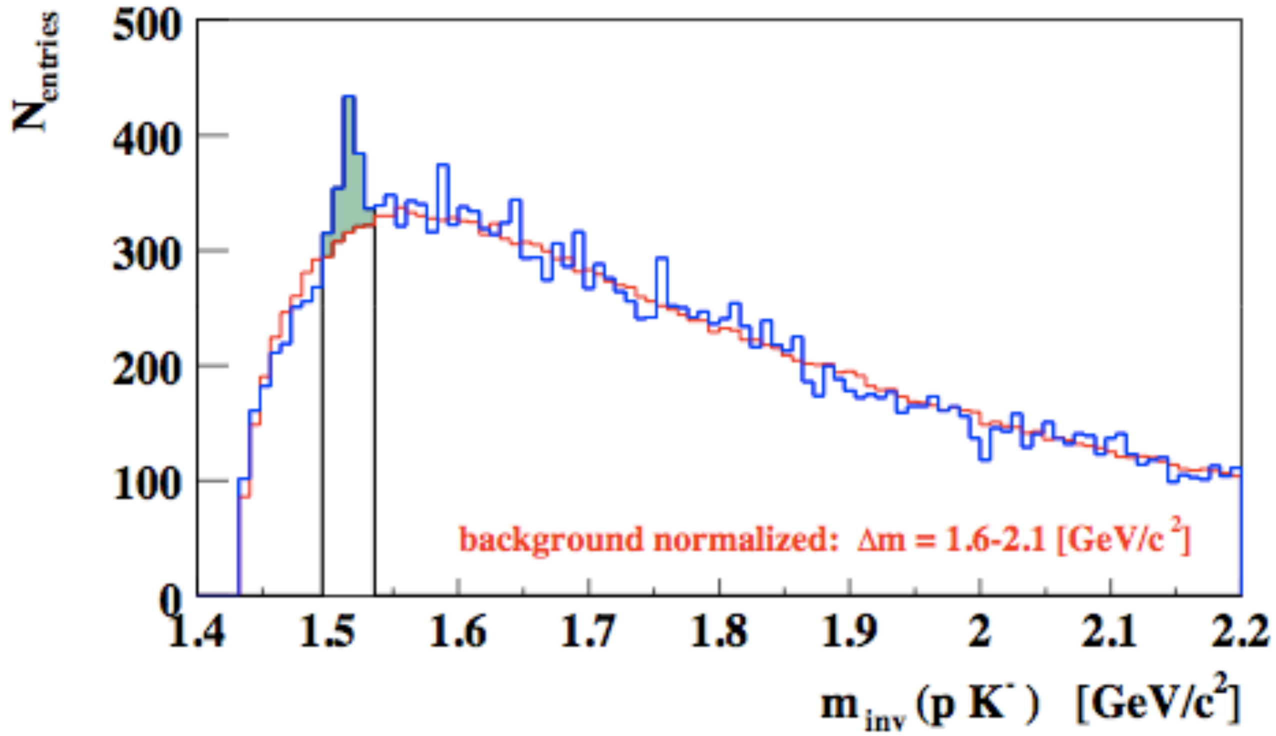
- **Resonances are measured via their decay products, cross section follows a Breit-Wigner law**



Measuring resonances in p+p

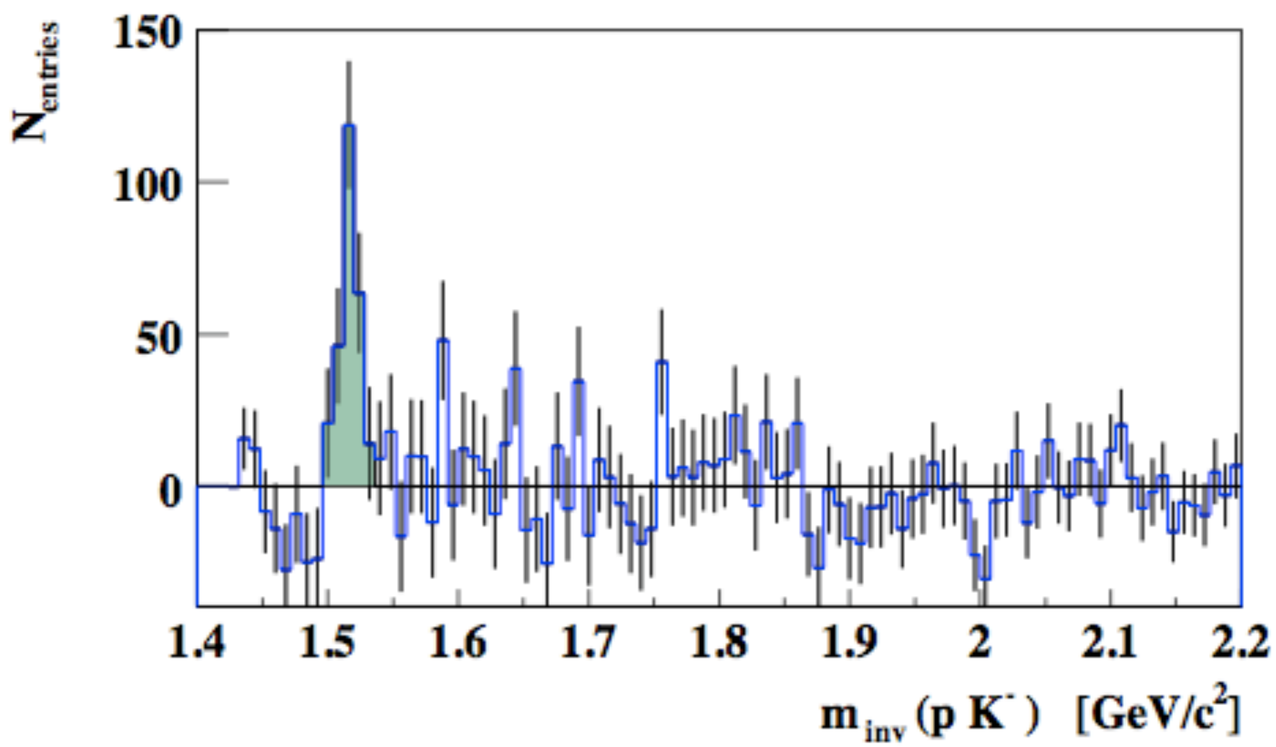


Correlate all protons and
kaons in the event,
plot invariant mass.



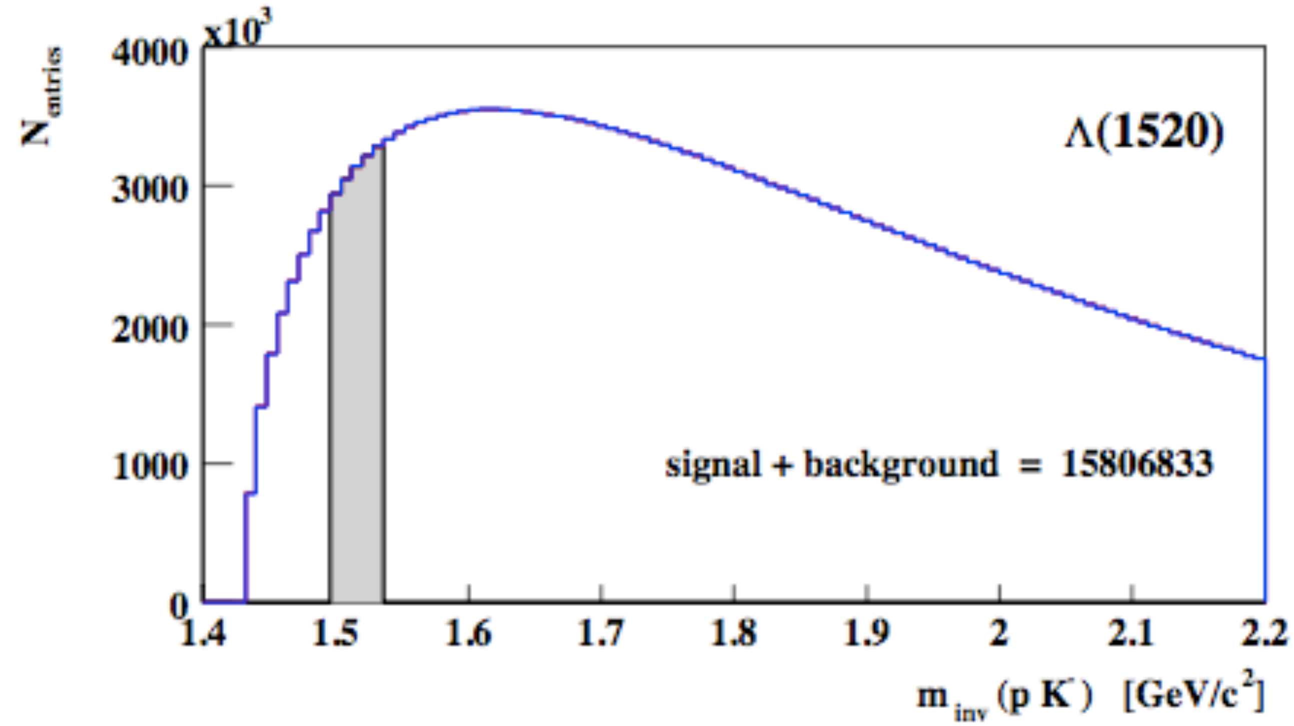
Lots of uncorrelated pairs
→ background subtraction
needed

Still a visible peak,
but not as clear as before.

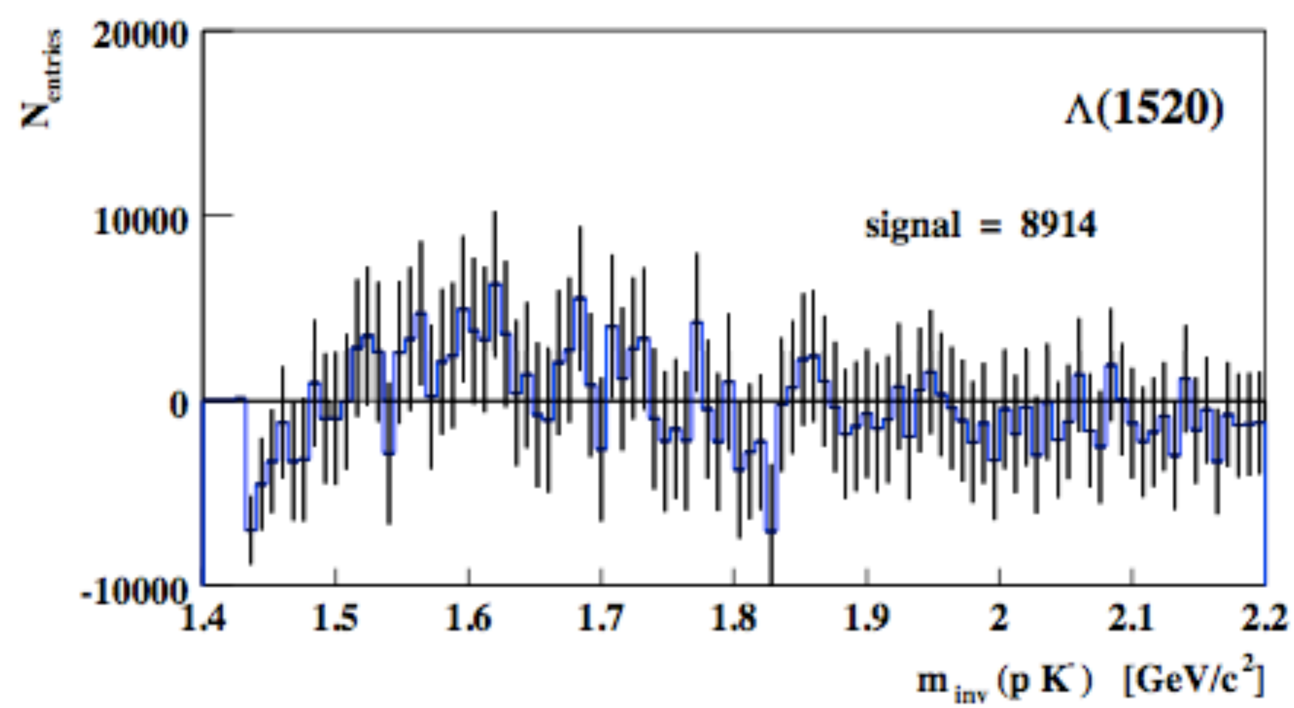


Measuring resonances in A+A

Correlate all protons and
kaons in the event,
plot invariant mass.

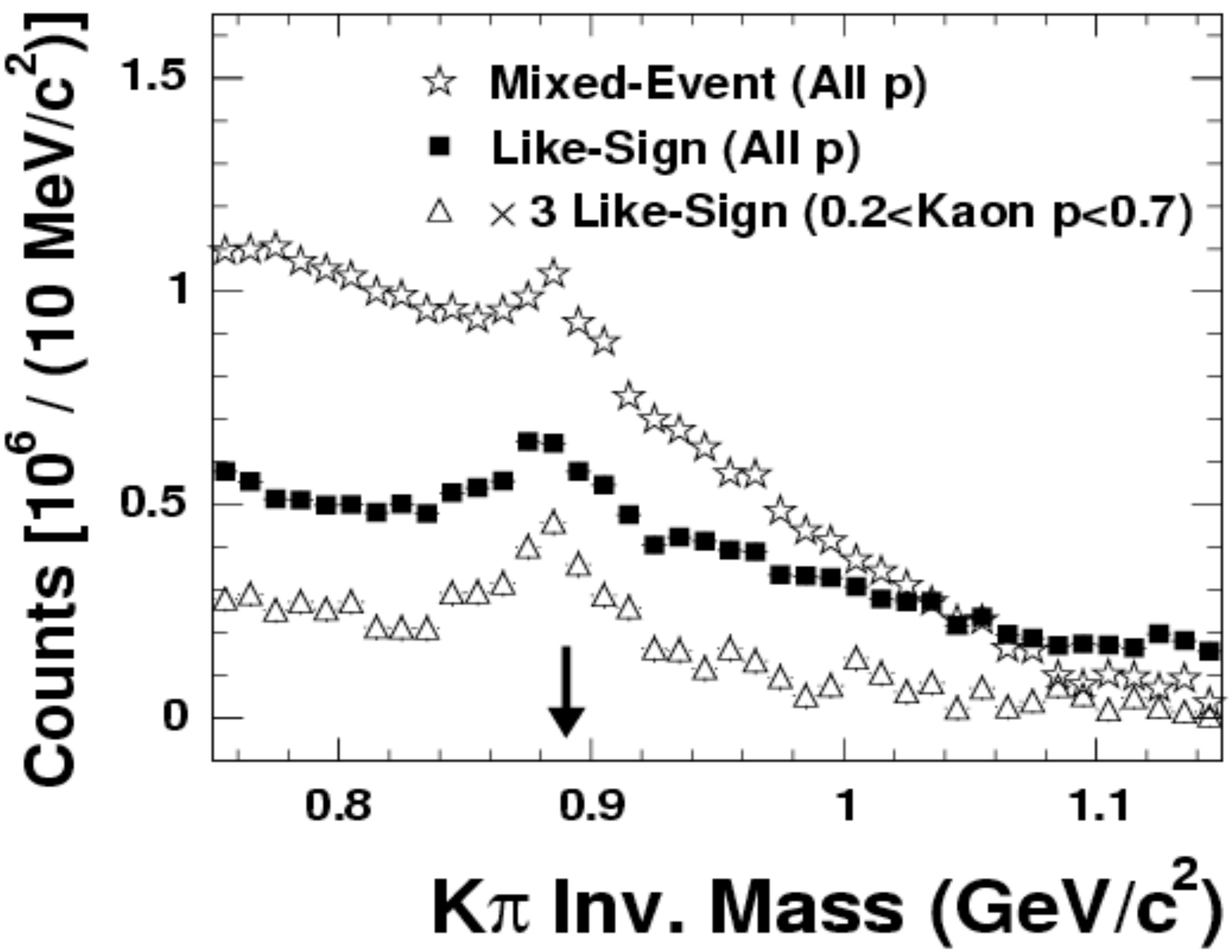


Peak?



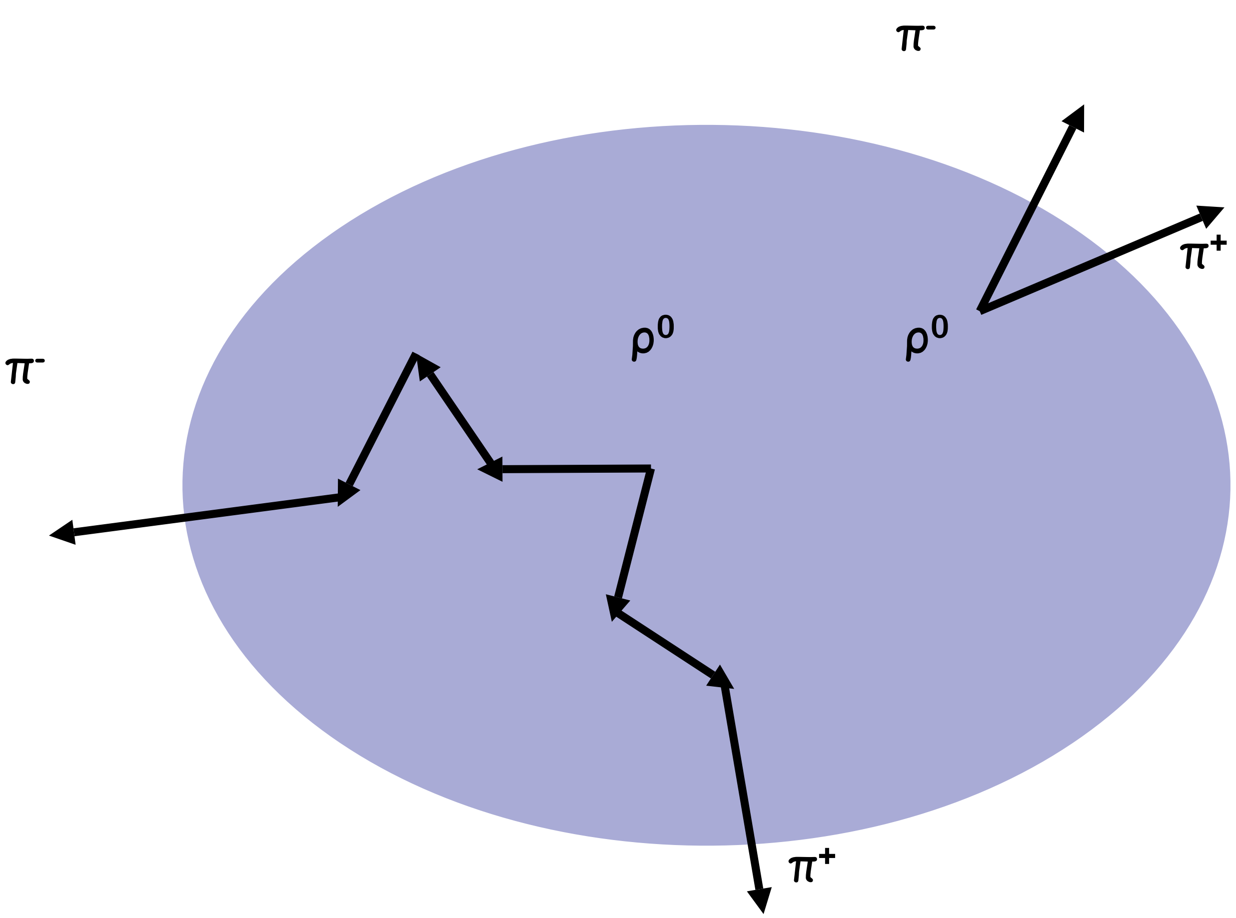
Measuring resonances in A+A

Different methods to subtract the background lead to slightly different results.

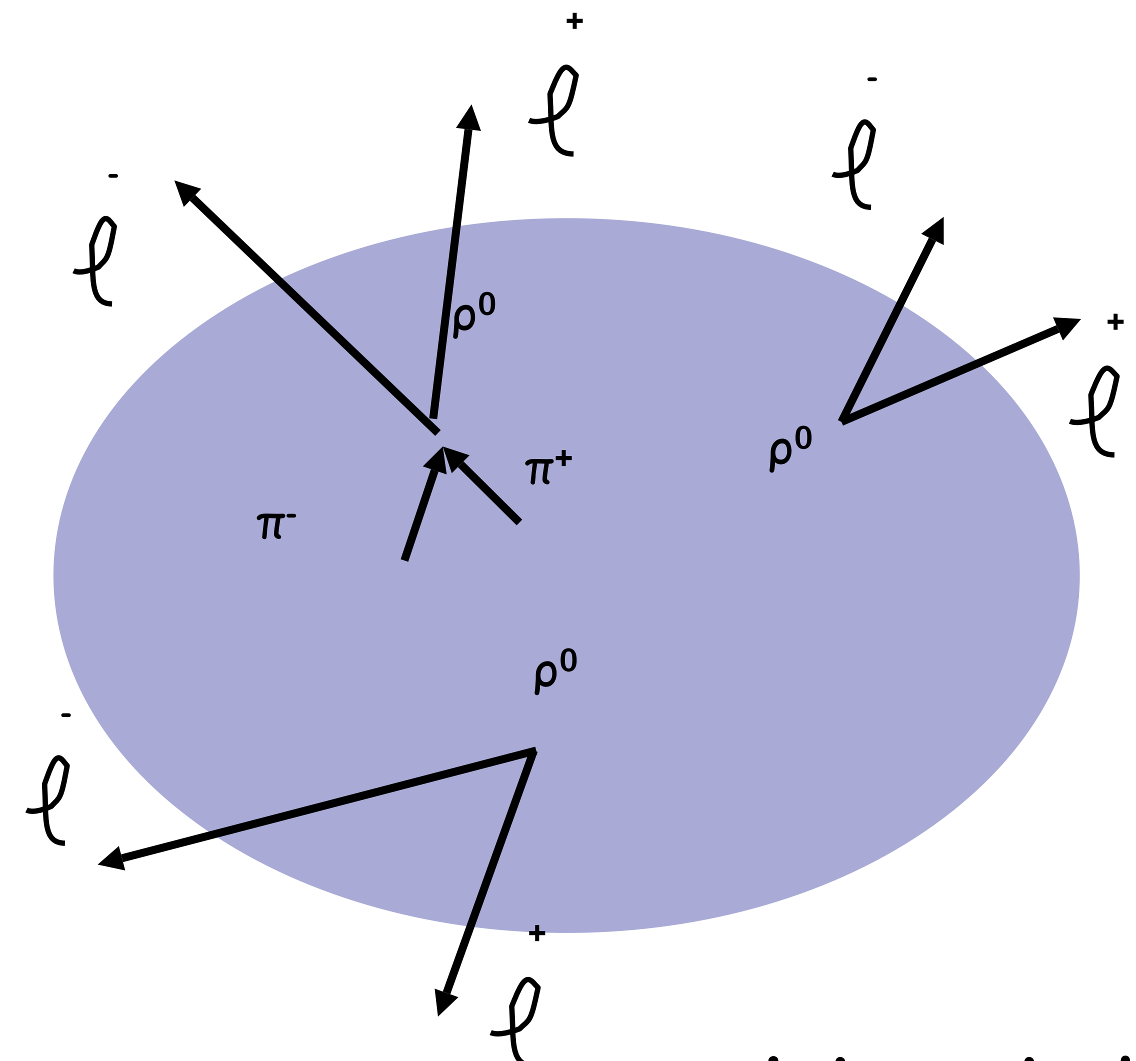


Dileptonic and hadronic decays

hadronic decay | **leptonic decay**

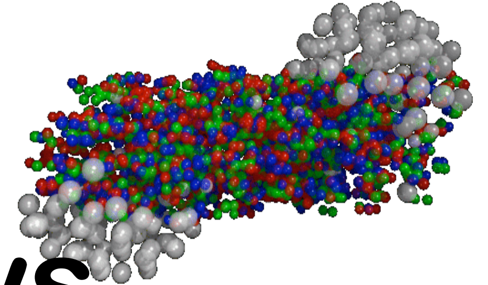


late stage

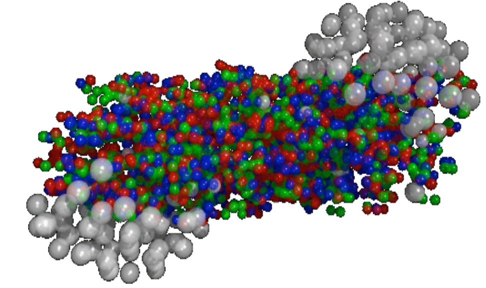


integrated collision

Dileptonic and hadronic decays



Dileptons	Hadrons
do not interact strongly with the surrounding medium	suffer from final state interactions
originate from various sources in various mass regions (note: Dalitz decays)	originate from various sources in various mass regions
Typical branching ratios on the order of 10^{-4} - 10^{-5}	Typical branching ratios on the order of 0.1 - 1
when measured reflect the integrated collision history	when measured reflect the late stage (after freezeout) of the collision



Density calculation

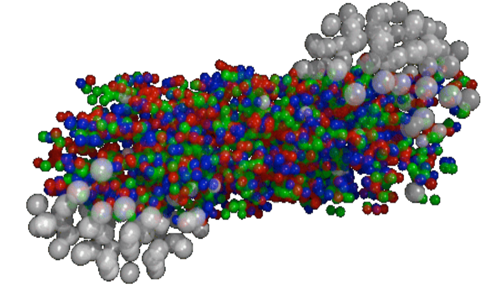
- **Local baryon density is the zeroth component of the baryon four-current** $j^\mu = (\rho_B, \vec{j})$ **when the baryon is at rest**

- **UrQMD calculates in the Computational Frame (CF), which is usually the CMS (due to symmetry)**

- $j^\mu_{CF} = (\rho_{B_{CF}}, \vec{j}_{CF})$ **can be calculated as a sum over Gaussians**

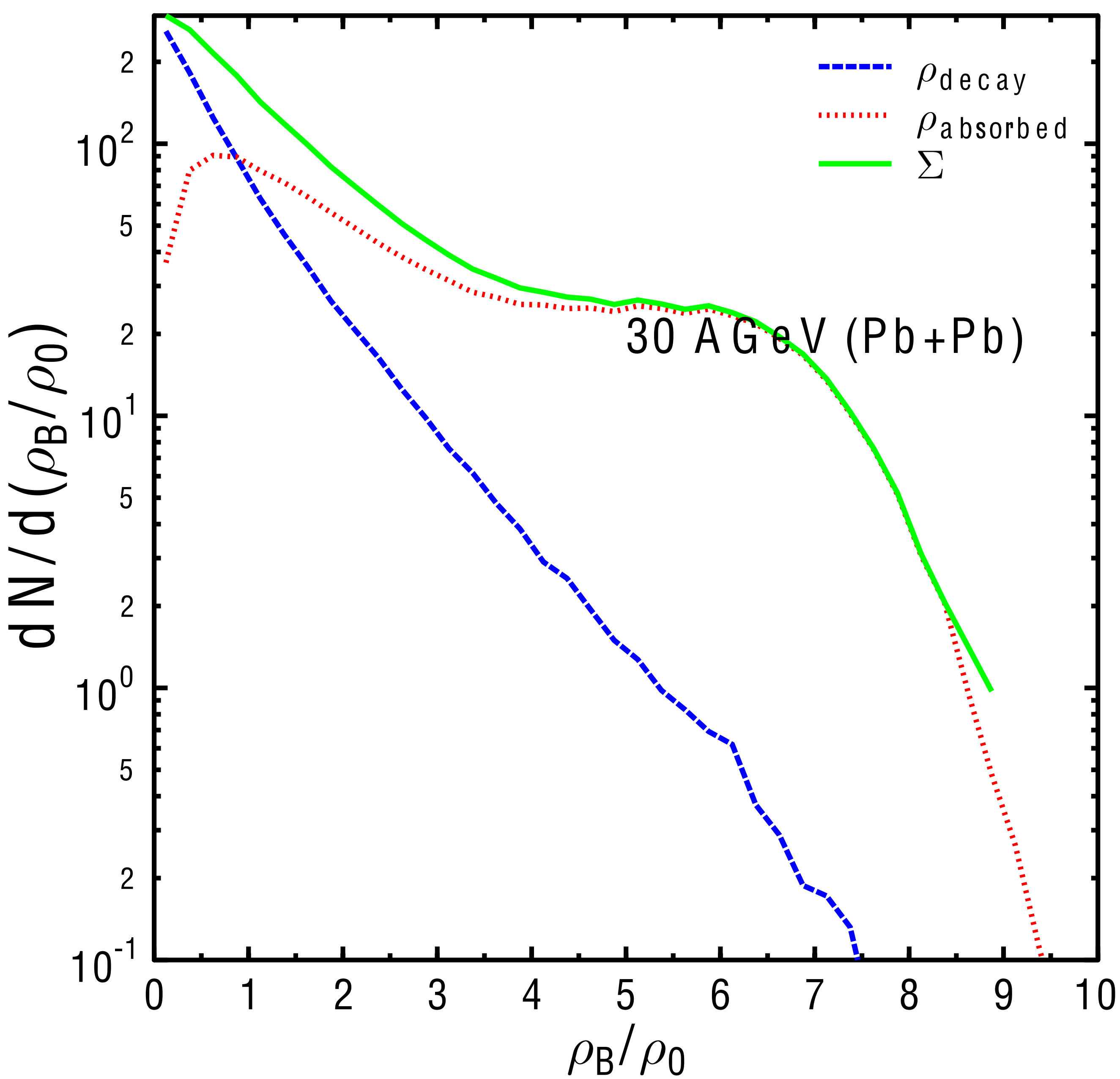
$$\rho_{CF}(\vec{r_i}) = \sum_{j=1}^{N} \left(\frac{1}{\sqrt{2\pi}\sigma}\right)^3 \gamma_z \, \mathrm{e}^{\left(-\frac{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2\gamma_z^2}{2\sigma^2}\right)}$$

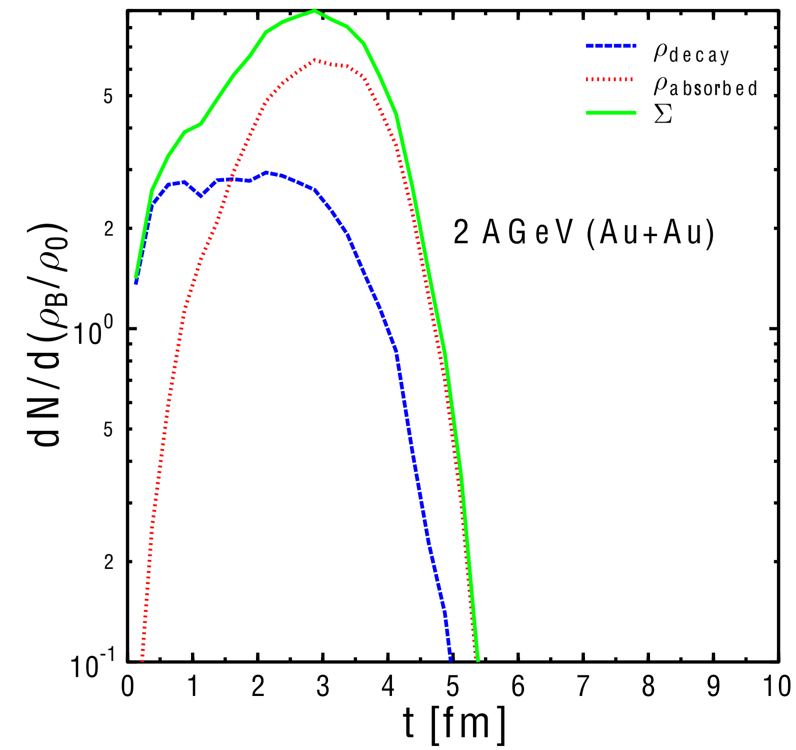
$$= \sum_{j=1}^{N} P_j$$

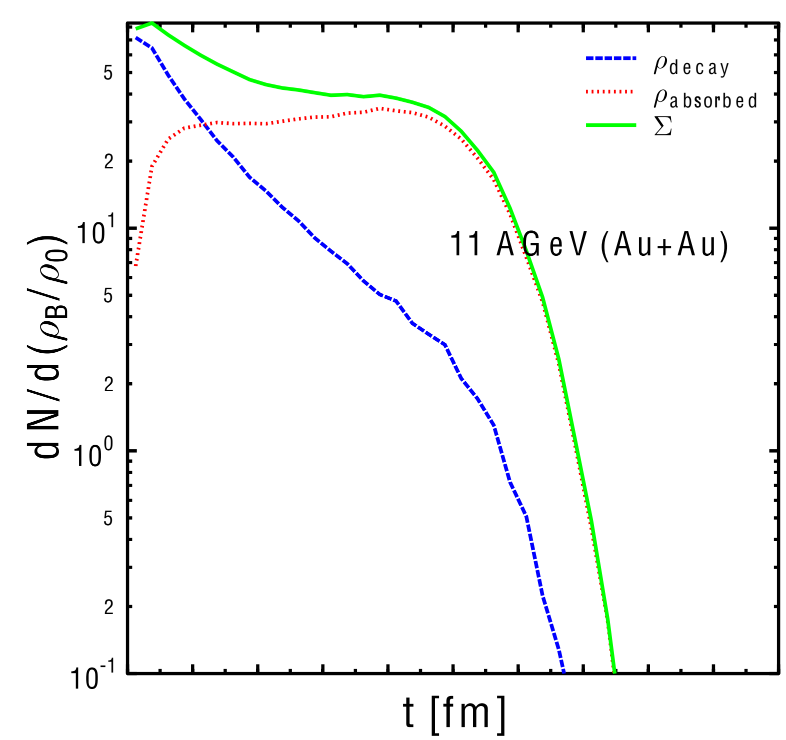


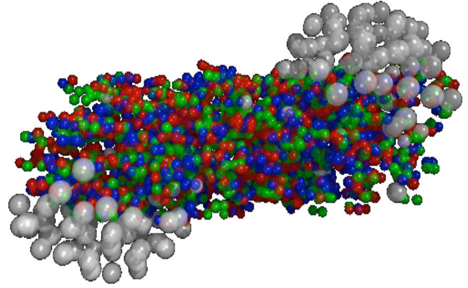
Density distribution

Resonance decays do not reach out very high in density, most resonances are being absorbed at high density



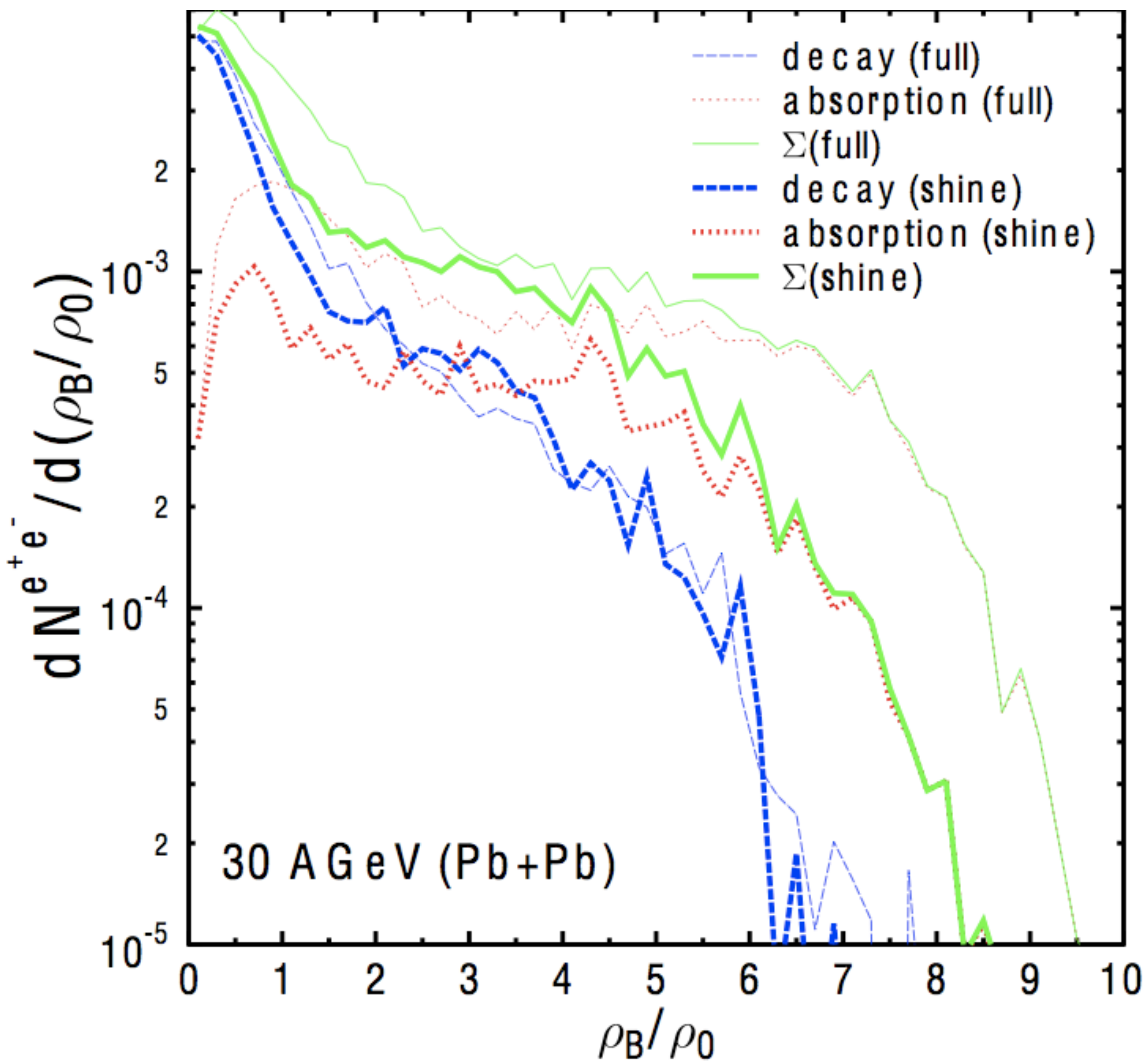


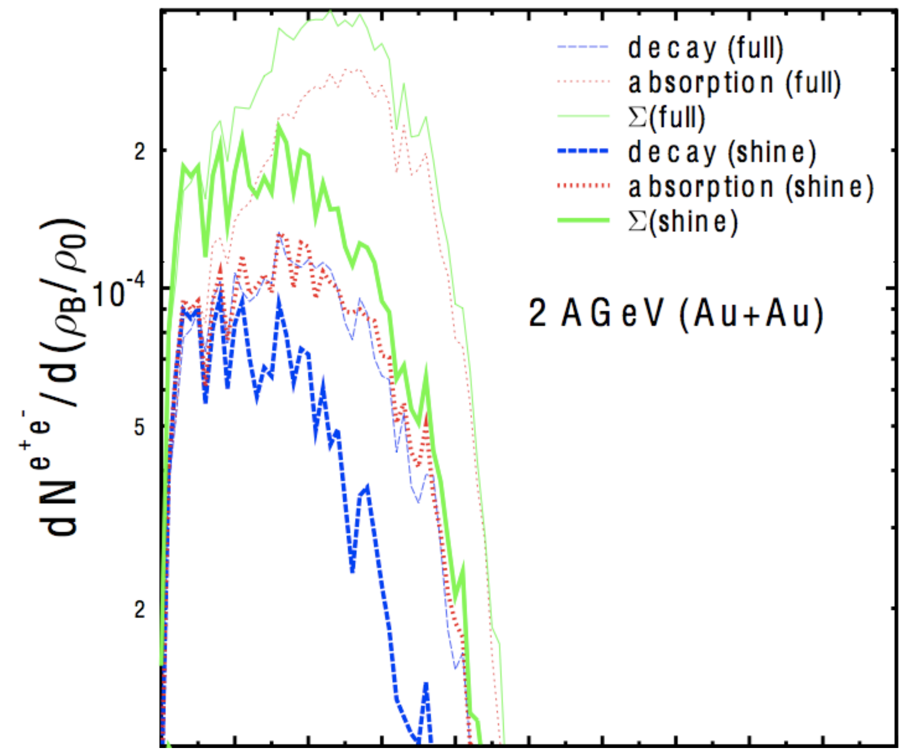


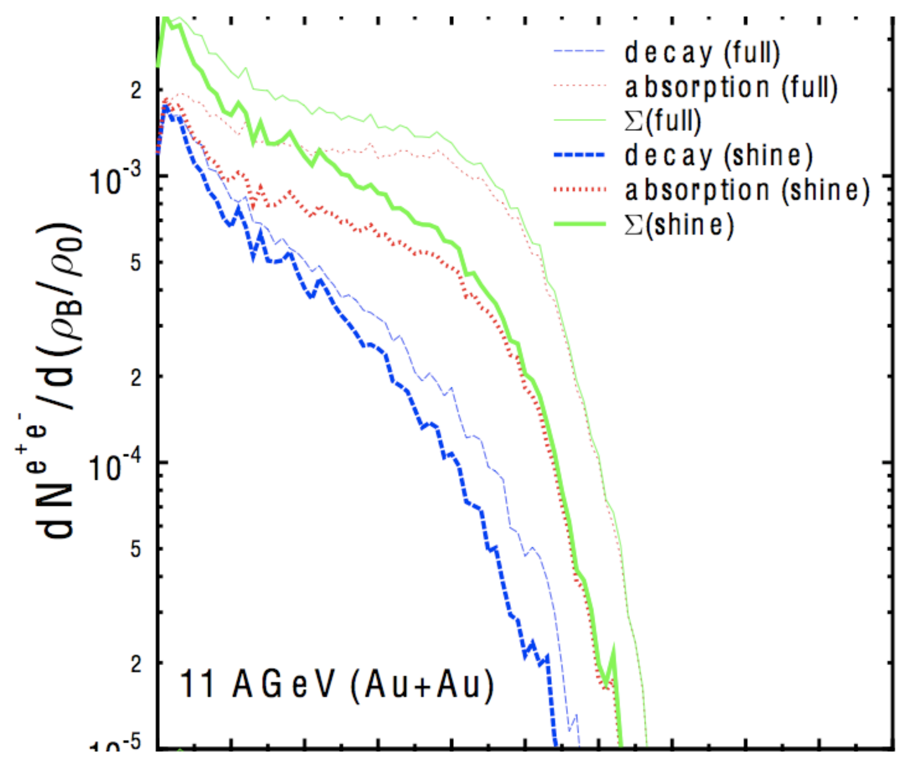


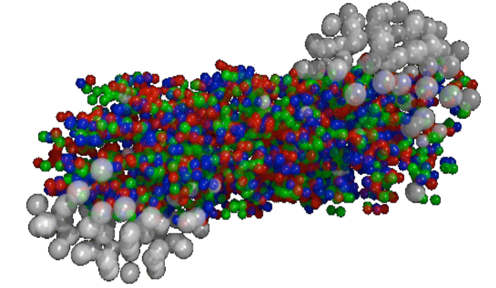
Dileptons

Even in the most optimistic approach dileptons only reach out to 2-3 ρ_0
Shining approach only reaches out to 1-2 ρ_0



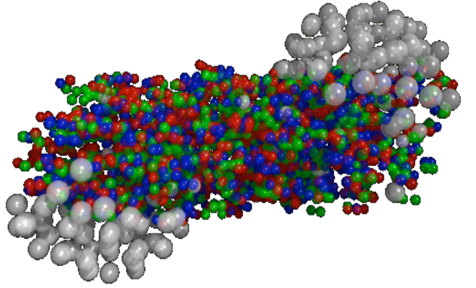






Summary

- Transport models are THE tool for heavy ion collisions at FAIR!
- A variety of observables is needed to pin down the matter created.
- High density physics needs an energy scan!
- Challenge to CBM: Will we see something from the high μ_B phase at all?



Summary

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Thanks!