GOETHE UNIVERSITÄT FRANKFURT AM MAIN

# Lecture
# Introduction:
# ‚Dynamical models for relativistic heavy-ion collisions‘

**Lectures:**

**Thursday, 11:15-12:45**

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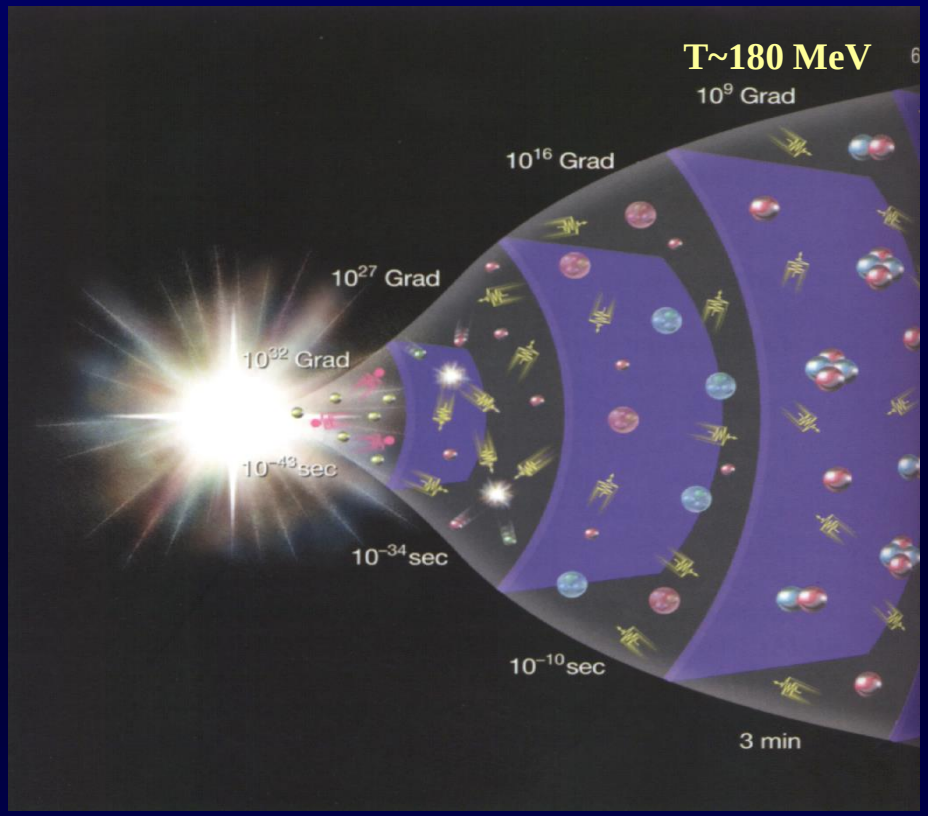
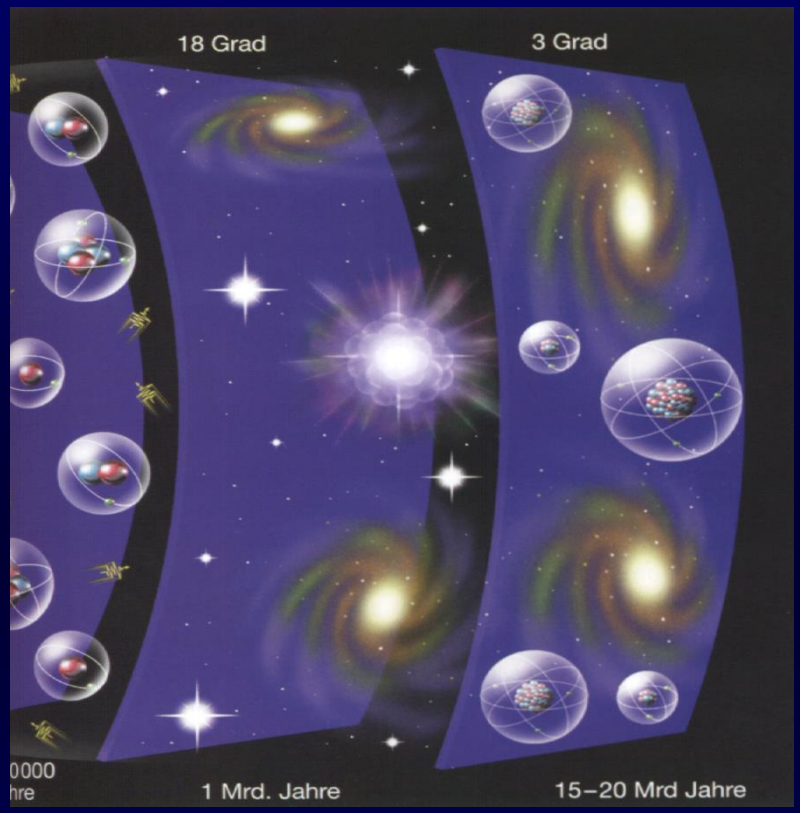
**http://theory.gsi.de/~ebratkov/LecturesSS2024/Lec_SS2024.html**

# From Big Bang to Formation of the Universe



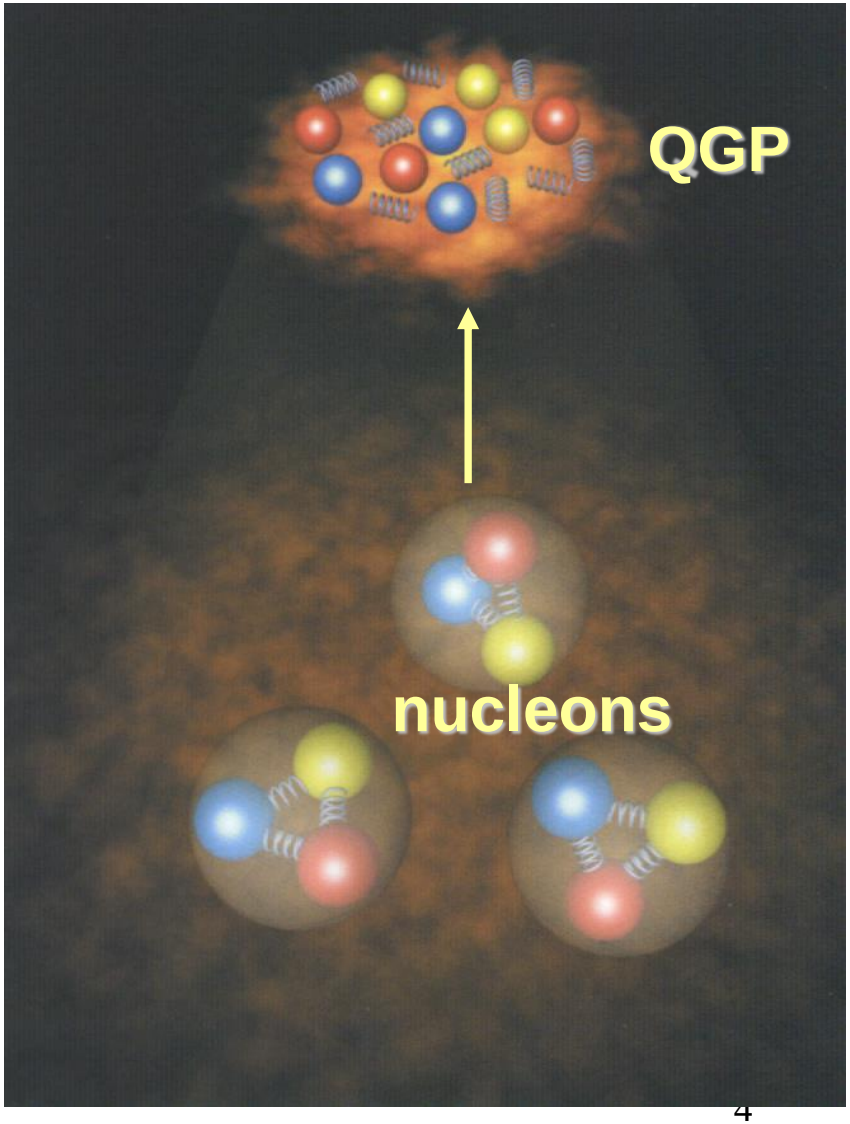

| *time* | $10^{-3}$sec | 3 min | 300000 years | 15 Mrd years |
|---|---|---|---|---|
| | quarks<br>gluons<br>photons | nucleons<br>deuterons<br>α–particles | atoms | our Universe |

Can we go back in time ?

# ... back in time

**‚Re-create' the Big Bang conditions:**
**matter at high temperature and pressure**
**such that**
**nucleons/mesons decouple to quarks and gluons -- Quark-Gluon-Plasma**

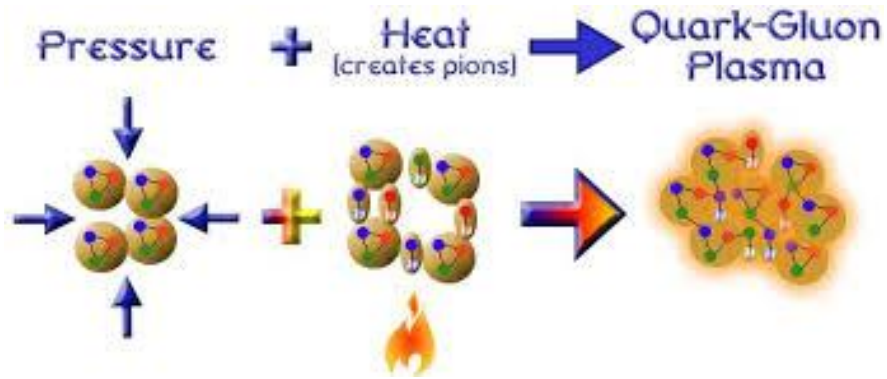
**‚Little Bangs' in the Laboratory :**
**Heavy-ion collisions at ultrarelativistic energies**

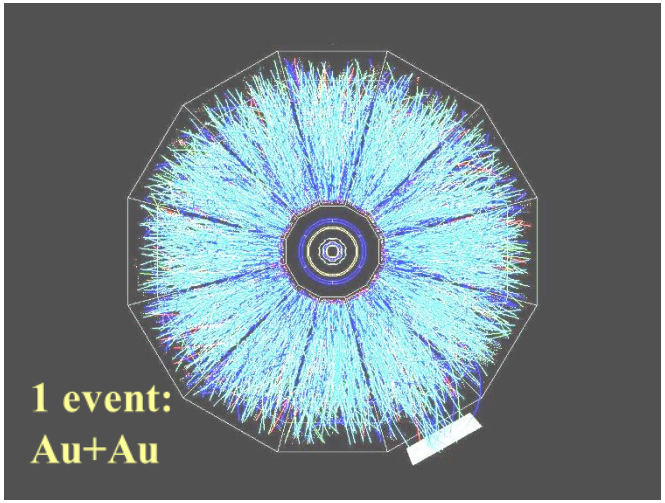


# Heavy-ion collisions

## ❑ Heavy-ion collision experiment

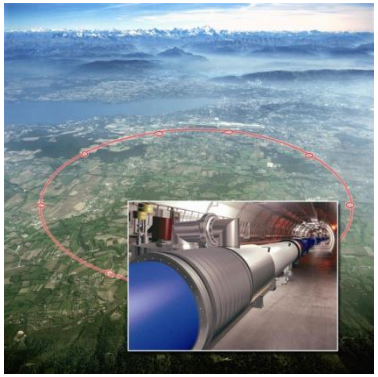
➔ ‚re-creation' of the Big Bang conditions in laboratory:
matter at high pressure and temperature



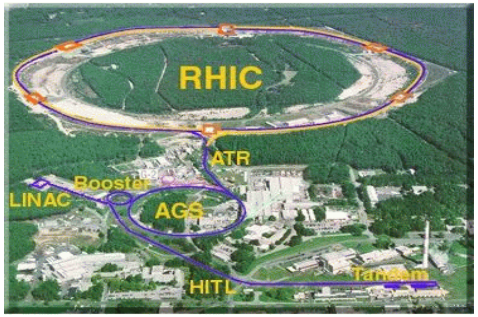




## ❑ Heavy-ion accelerators:

**Large Hadron Collider - LHC (CERN): Pb+Pb up to 574 A TeV**

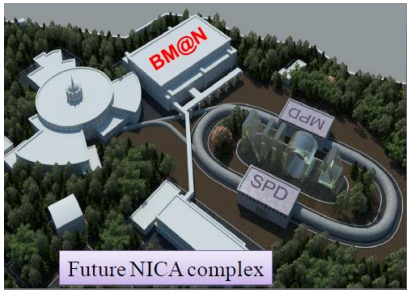


**Relativistic-Heavy-Ion-Collider - RHIC (Brookhaven): Au+Au up to 21.3 A TeV**




**Facility for Antiproton and Ion Research – FAIR (Darmstadt) (Under construction) Au+Au up to 10 (30) A GeV**

**Nuclotron-based Ion Collider fAcility – NICA (Dubna) (Under construction) Au+Au up to 70 A GeV**

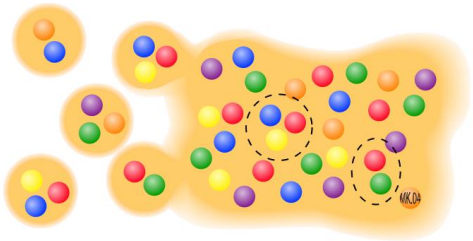


# The QGP in Lattice QCD

**Quantum Chromo Dynamics :**

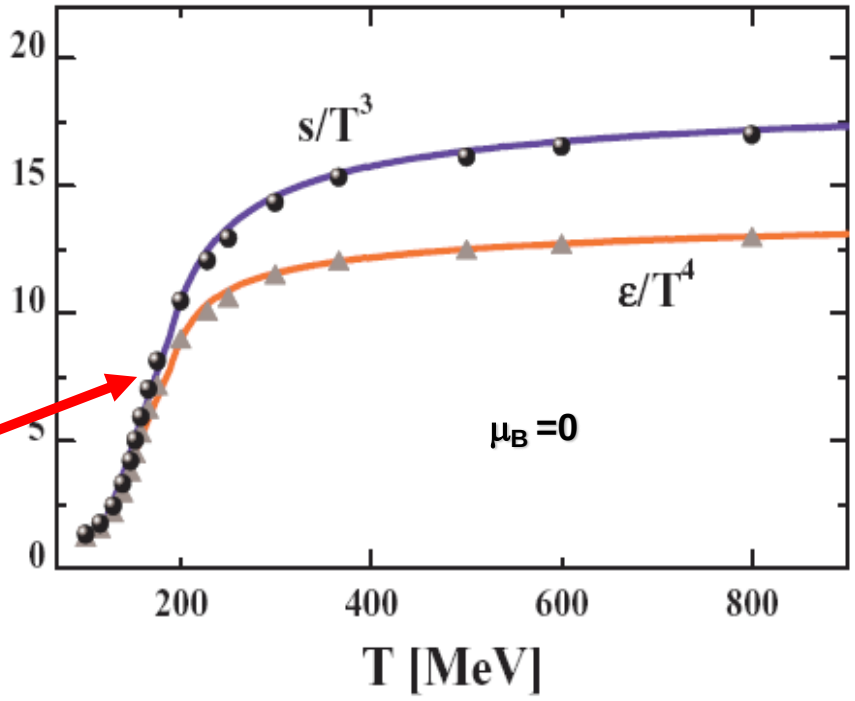
**predicts strong increase of the energy density e at critical temperature $T_C$ ~160 MeV**

**⇒ Possible phase transition from hadronic to partonic matter (quarks, gluons) at critical energy density $\varepsilon_C$ ~0.5 GeV/fm$^3$**



**Lattice QCD:**

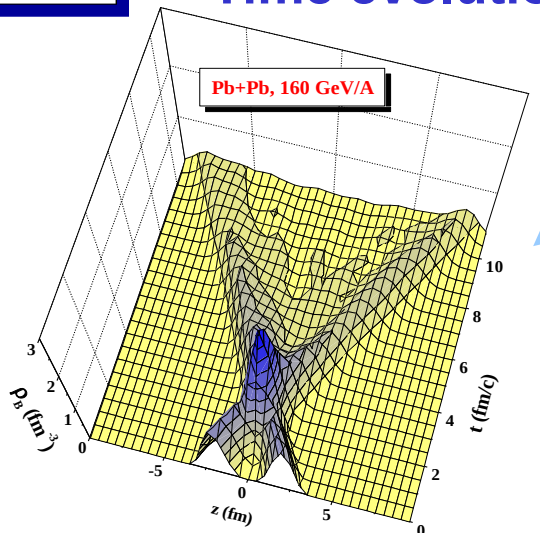
**energy density versus temperature**

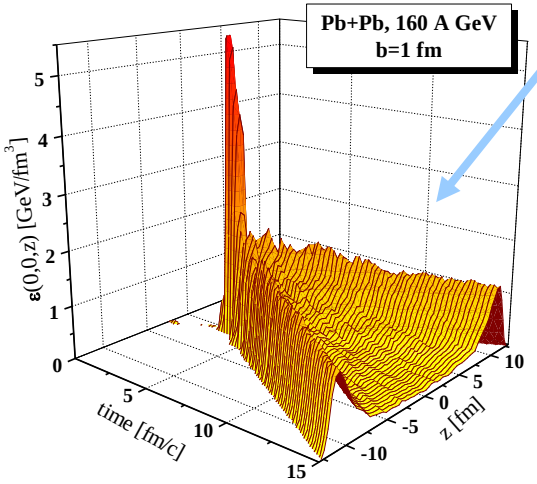


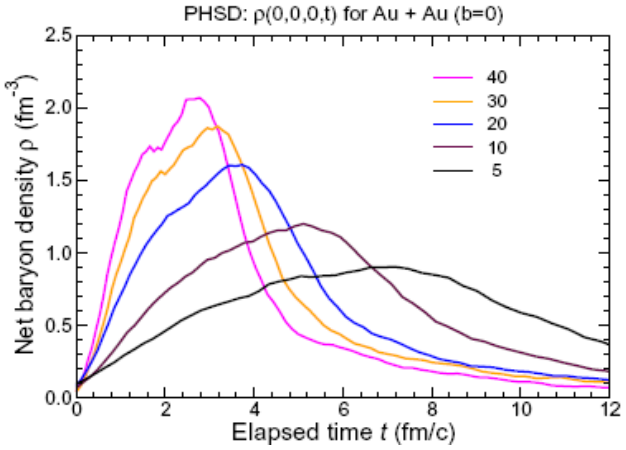

**Critical conditions - $\varepsilon_C$ ~0.5 GeV/fm$^3$ , $T_C$ ~160 MeV - can be reached in heavy-ion experiments at bombarding energies > 5 GeV/A**

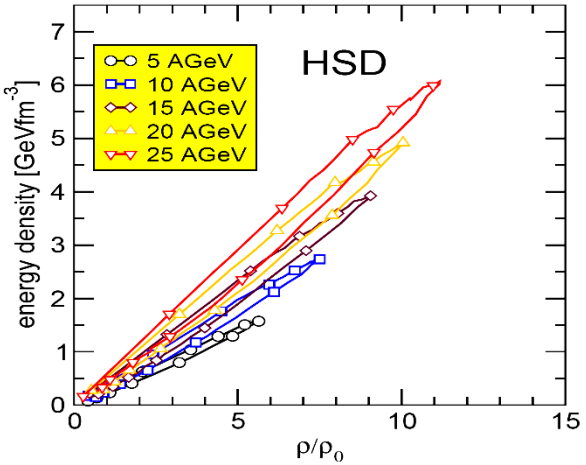
# Dense and hot matter – average quantities

## Time evolution of the baryon density and energy density



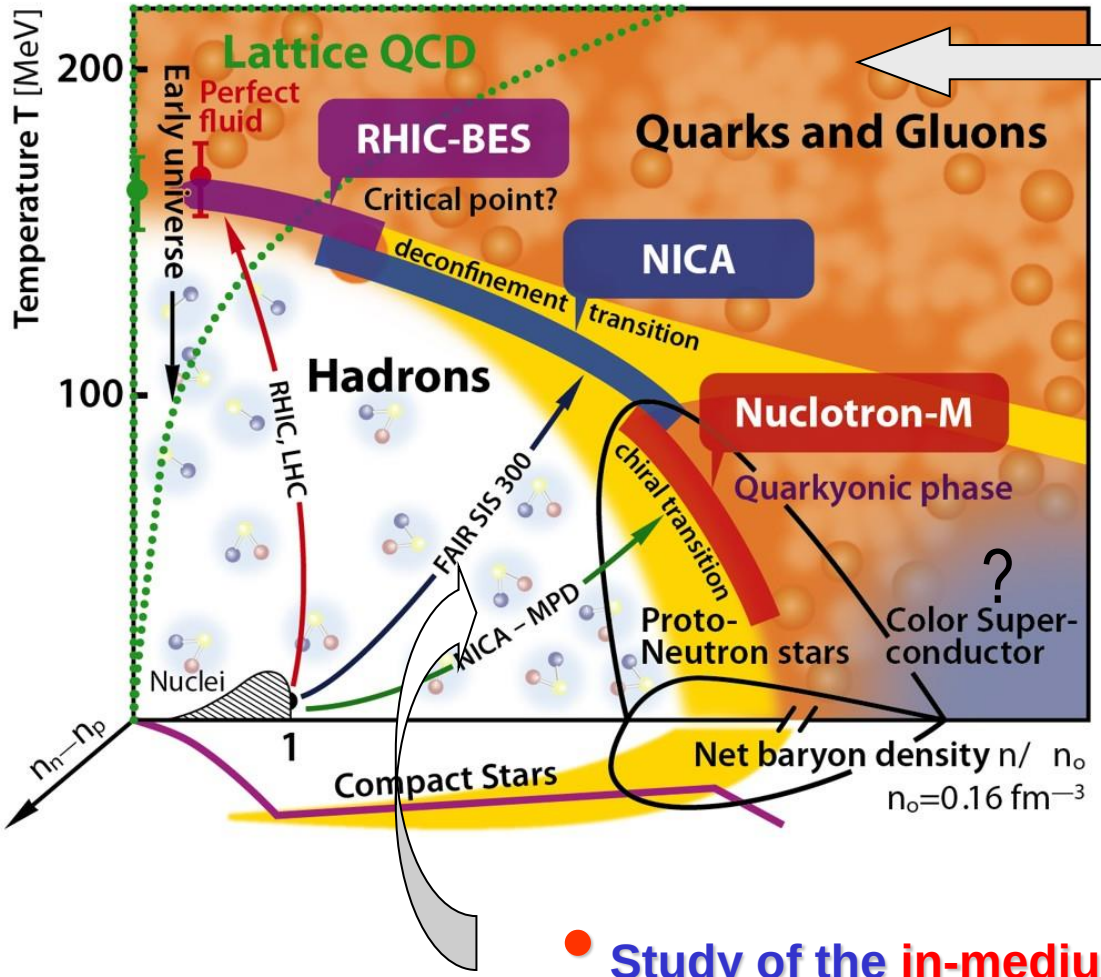




**huge energy and baryon densities are reached ($\varepsilon > \varepsilon_{crit}$=0.5 GeV/fm$^3$) at FAIR/NICA energies (> 5 A GeV)**

# The ‚holy grail' of heavy-ion physics:

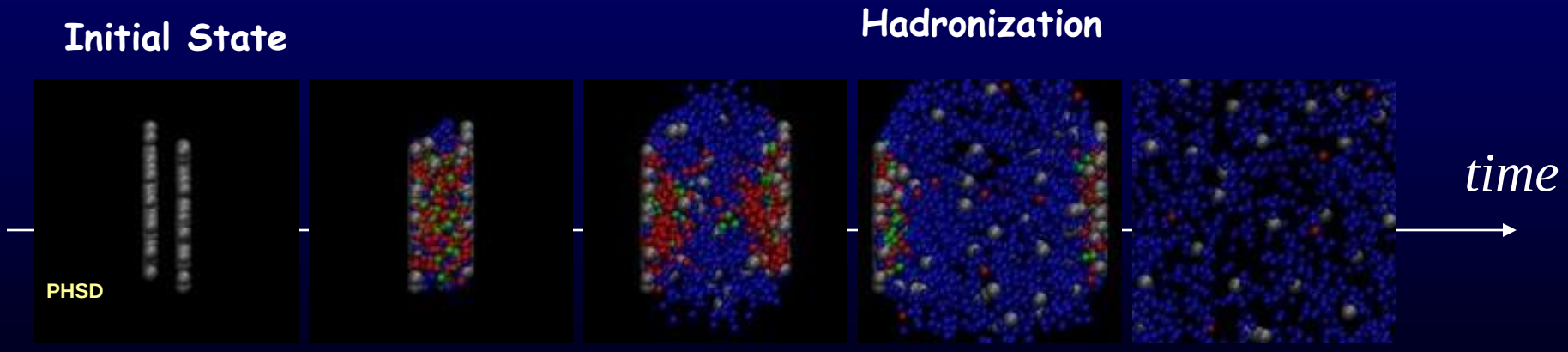
## The phase diagram of QCD




- Search for the critical point

- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma
- Search for signatures of chiral symmetry restoration
- Search for the critical point
- Study of the in-medium properties of hadrons at high baryon density and temperature

# ‚Little Bangs' in the Laboratory




hadron degrees of freedom → quarks and gluons → hadron degrees of freedom

**How can we proove that an equilibrium QGP has been created in central heavy-ion collisions ?!**

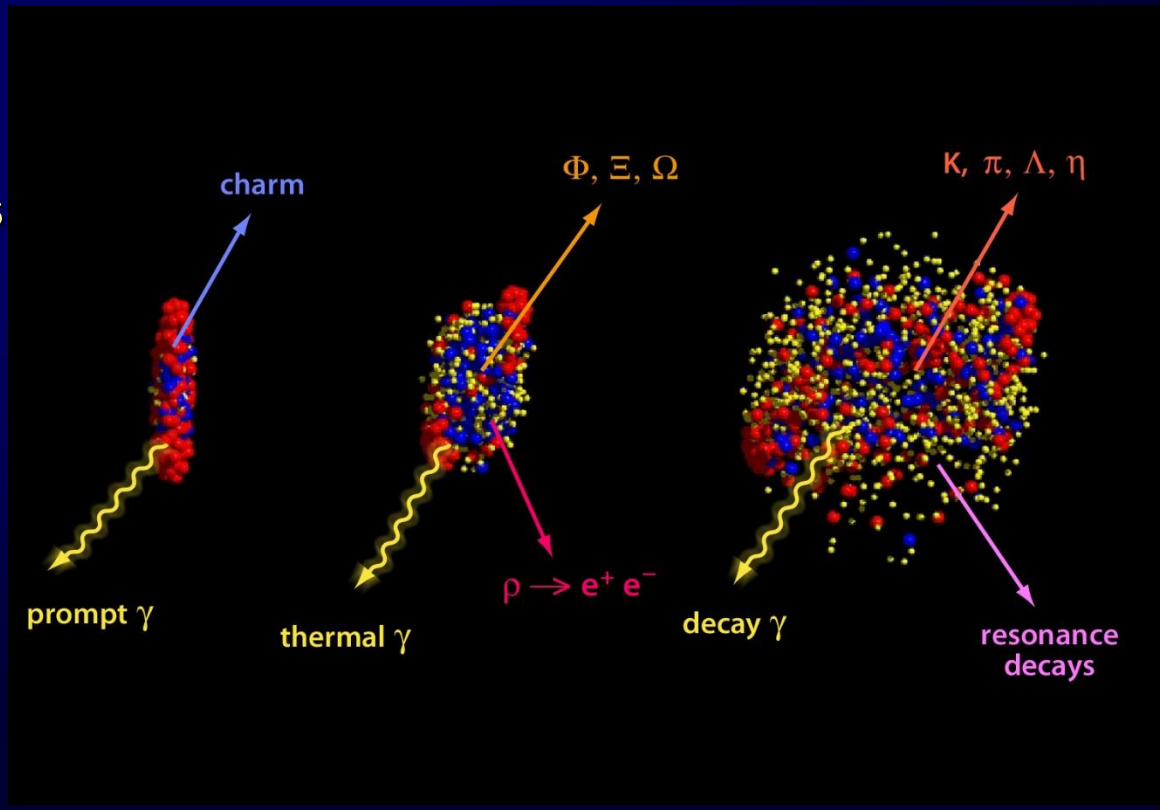
## Signals of the phase transition:

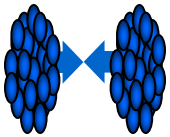
- Multi-strange particle enhancement in A+A
- Charm suppression
- Collective flow ($v_1$, $v_2$)
- Thermal dileptons
- Jet quenching and angular correlations
- High $p_T$ suppression of hadrons
- Nonstatistical event by event fluctuations and correlations
- ...

**Experiment:** measures final hadrons and leptons

How to learn about physics from data?

**Compare with theory!**





# Basic models for heavy-ion collisions

- **Statistical models:**

**basic assumption: system is described by a (grand) canonical ensemble of non-interacting fermions and bosons in thermal and chemical equilibrium**
**= thermal hadron gas at freeze-out with common T and $\mu_B$**

**[ - : no dynamical information]**

- **Hydrodynamical models:**

**basic assumption: conservation laws + equation of state (EoS);**
**assumption of local thermal and chemical equilibrium**
**- Interactions are ‚hidden' in properties of the fluid described by transport coefficients (shear and bulk viscosity $\eta$, $\zeta$, ..), which is 'input' for the hydro models**

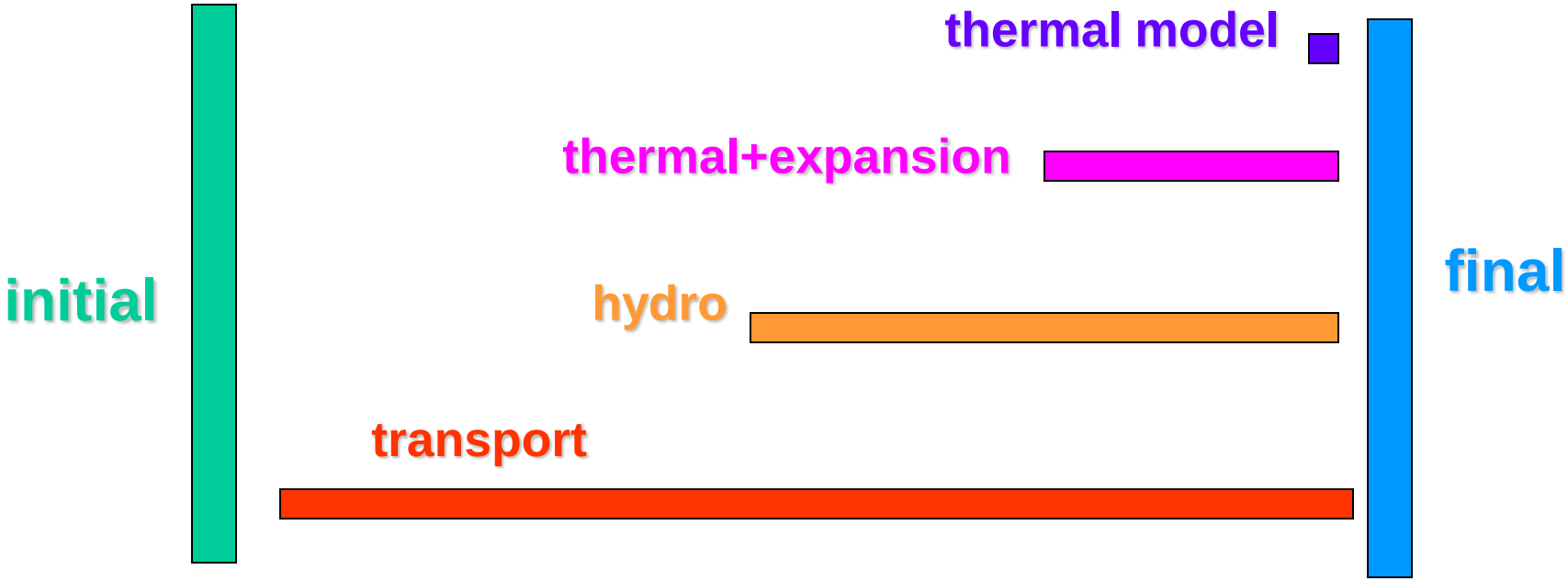
**[ - : simplified dynamics]**

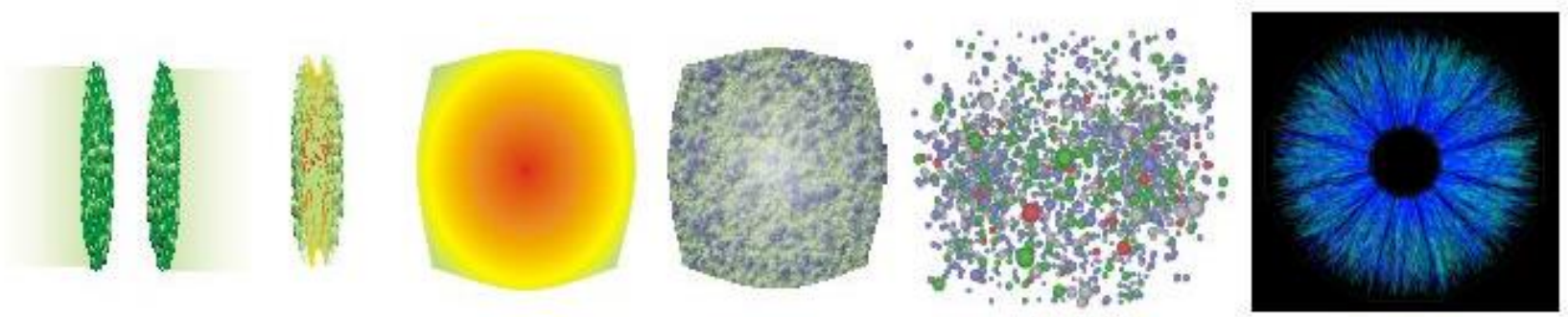
- **Microscopic transport models:**

**based on transport theory of relativistic quantum many-body systems**
**- Explicitly account for the interactions of all degrees of freedom (hadrons and partons) in terms of cross sections and potentials**
**- Provide a unique dynamical description of strongly interaction matter in- and out-off equilibrium:**
**- In-equilibrium: transport coefficients are calculated in a box – controled by lQCD**
**- Nonequilibrium dynamics – controled by HIC**
**Actual solutions: Monte Carlo simulations**

**[+ : full dynamics | - : very complicated]**

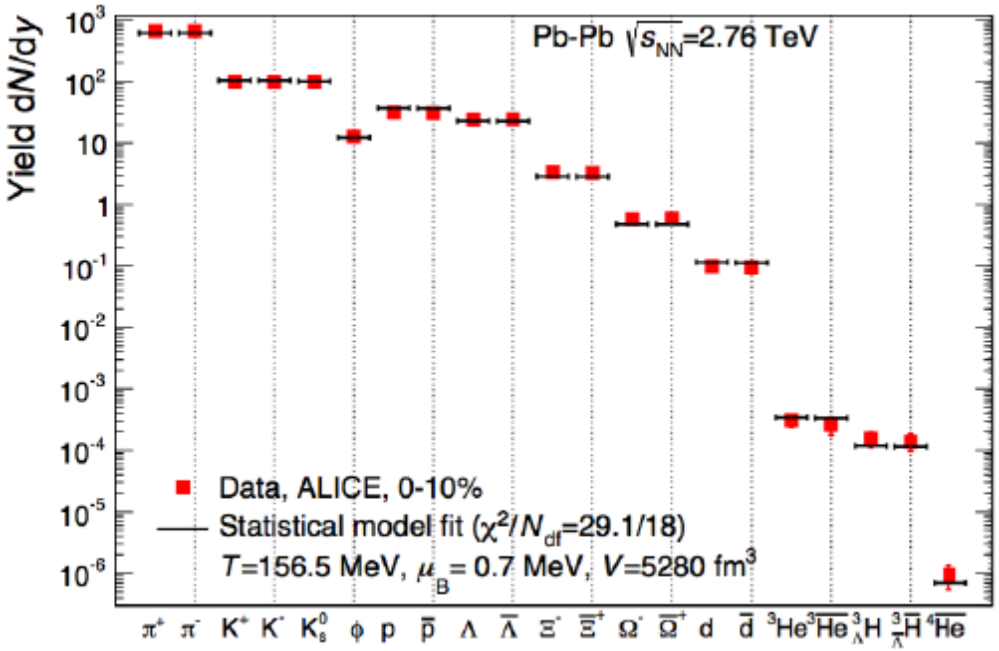
# Models of heavy-ion collisions

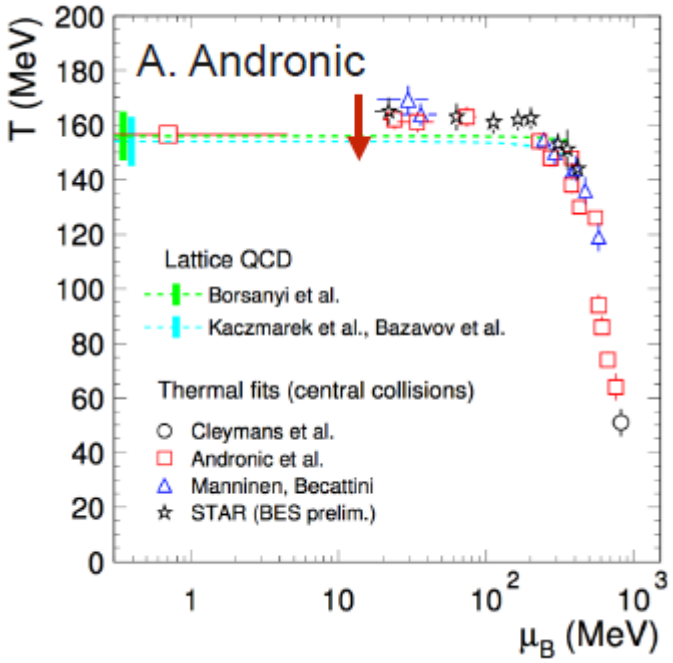


# Results from statistical models for HIC

J. Stachel at al., J.Phys. Conf. Ser. 509 (2014) 012019



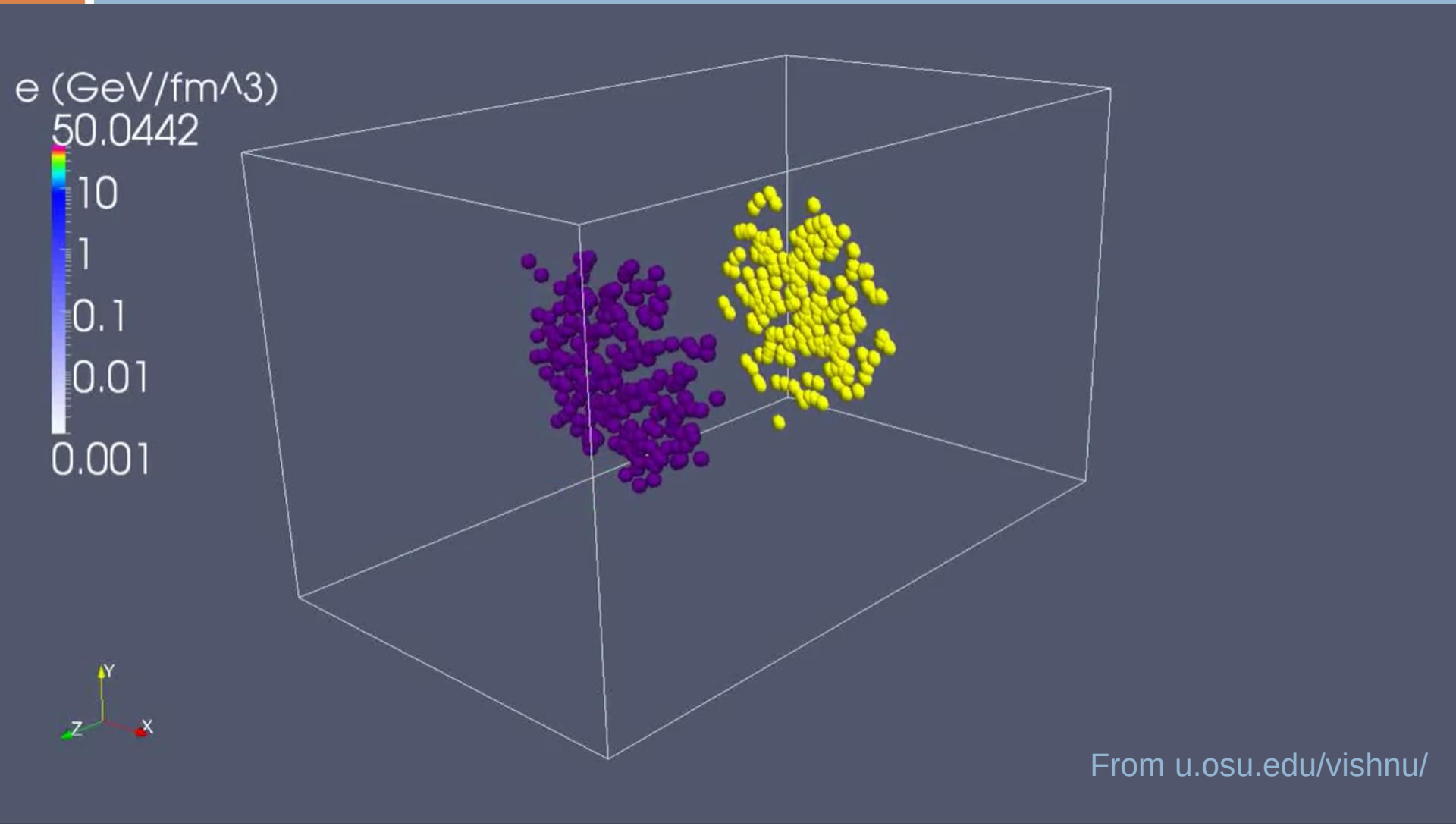

**Good description of the hadron abundances by the thermal hadron gas model ➔**
**The hadron abundances are in rough agreement with a thermally equilibrated system !**

**➔ Partial thermal and chemical equilibration is approximately reached in central heavy-ion collisions at relativistic energies!**

**! Statistical models do not provide an answer to the origin of thermalization.**
**HIC dynamics and the approach to thermal equilibrium is driven by the interactions !**

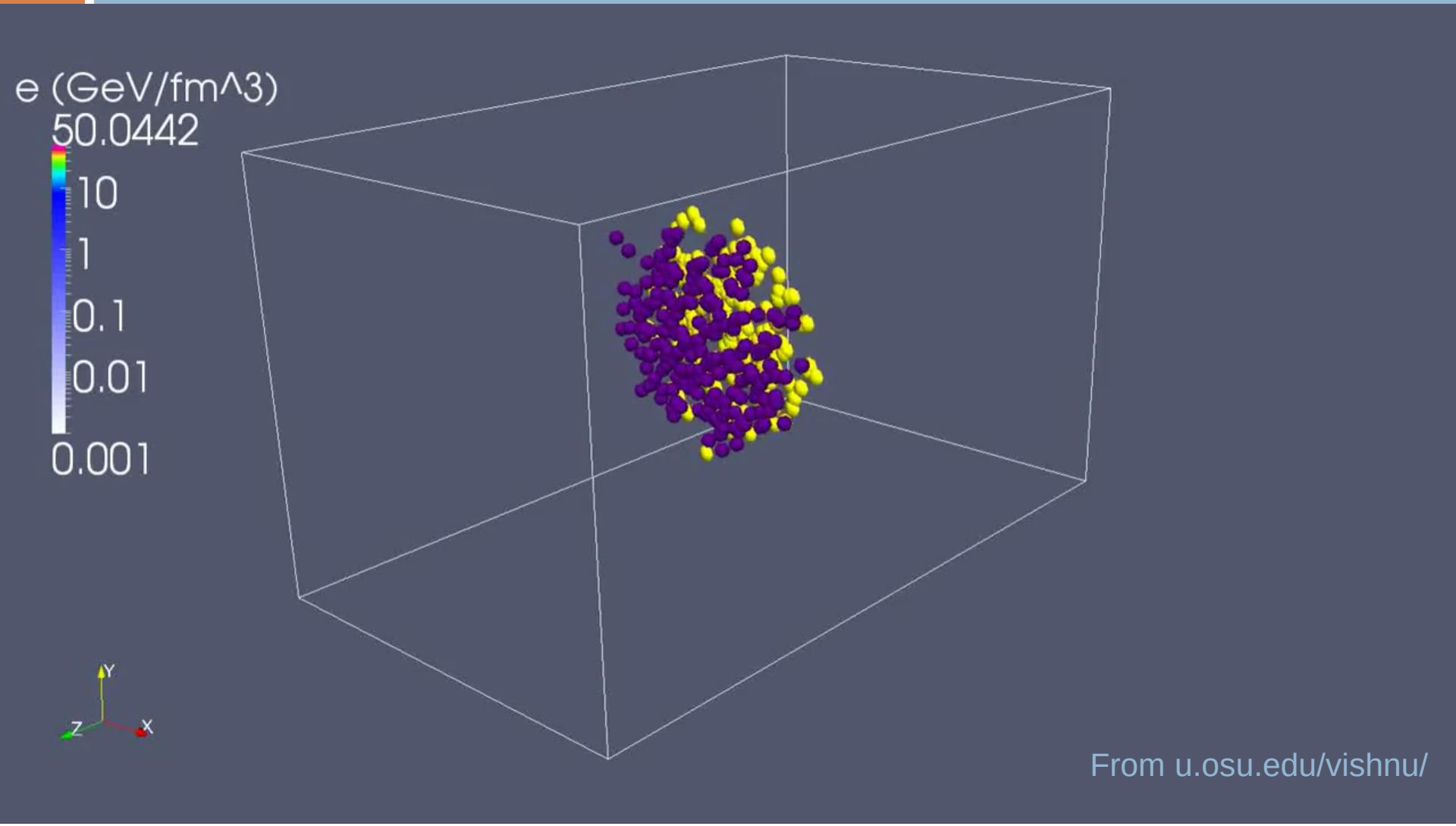
**➔ dynamical models of HIC**

# Stages of a collision in VISHNU




From u.osu.edu/vishnu/

# Stages of a collision in VISHNU




From u.osu.edu/vishnu/

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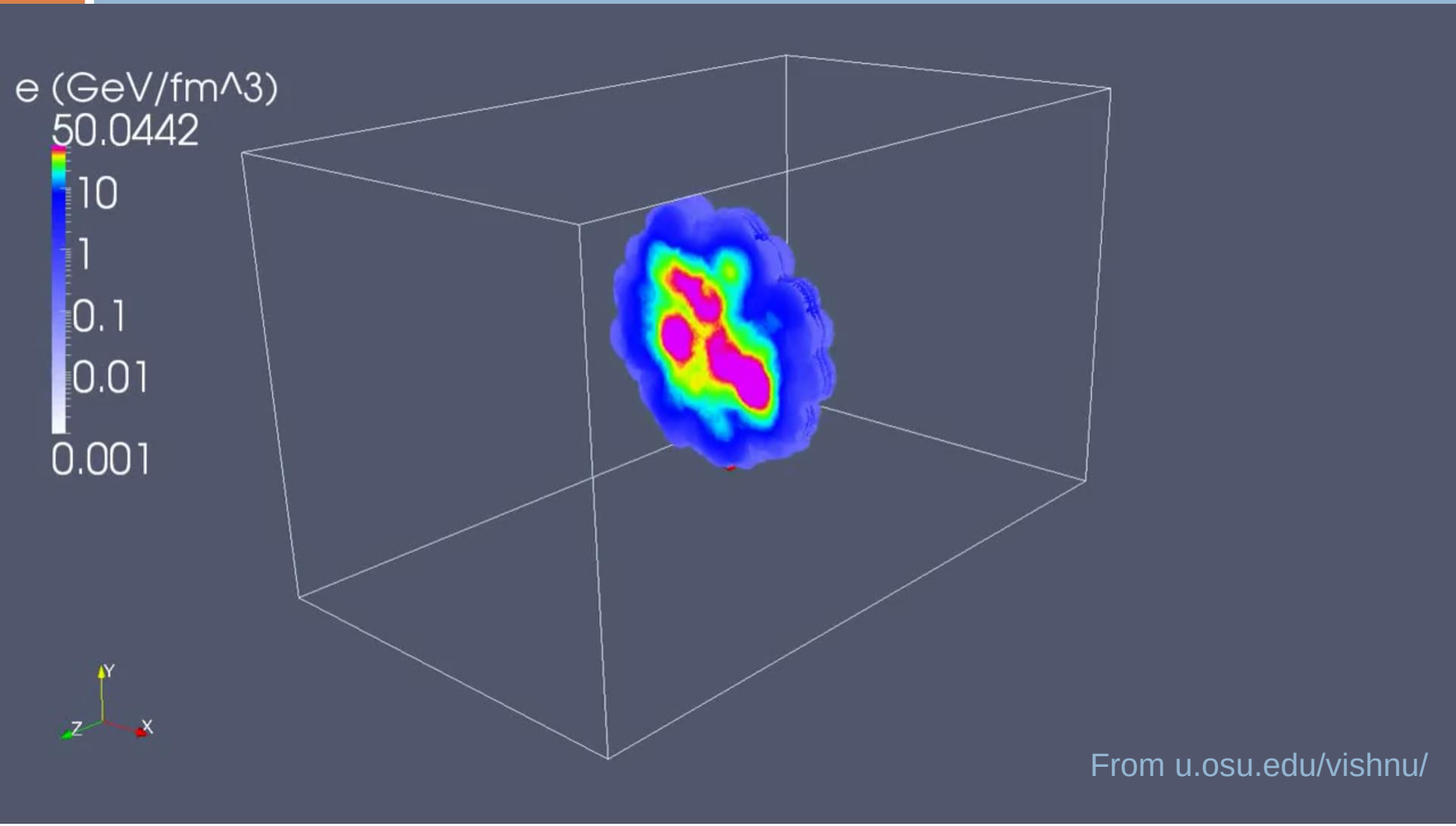
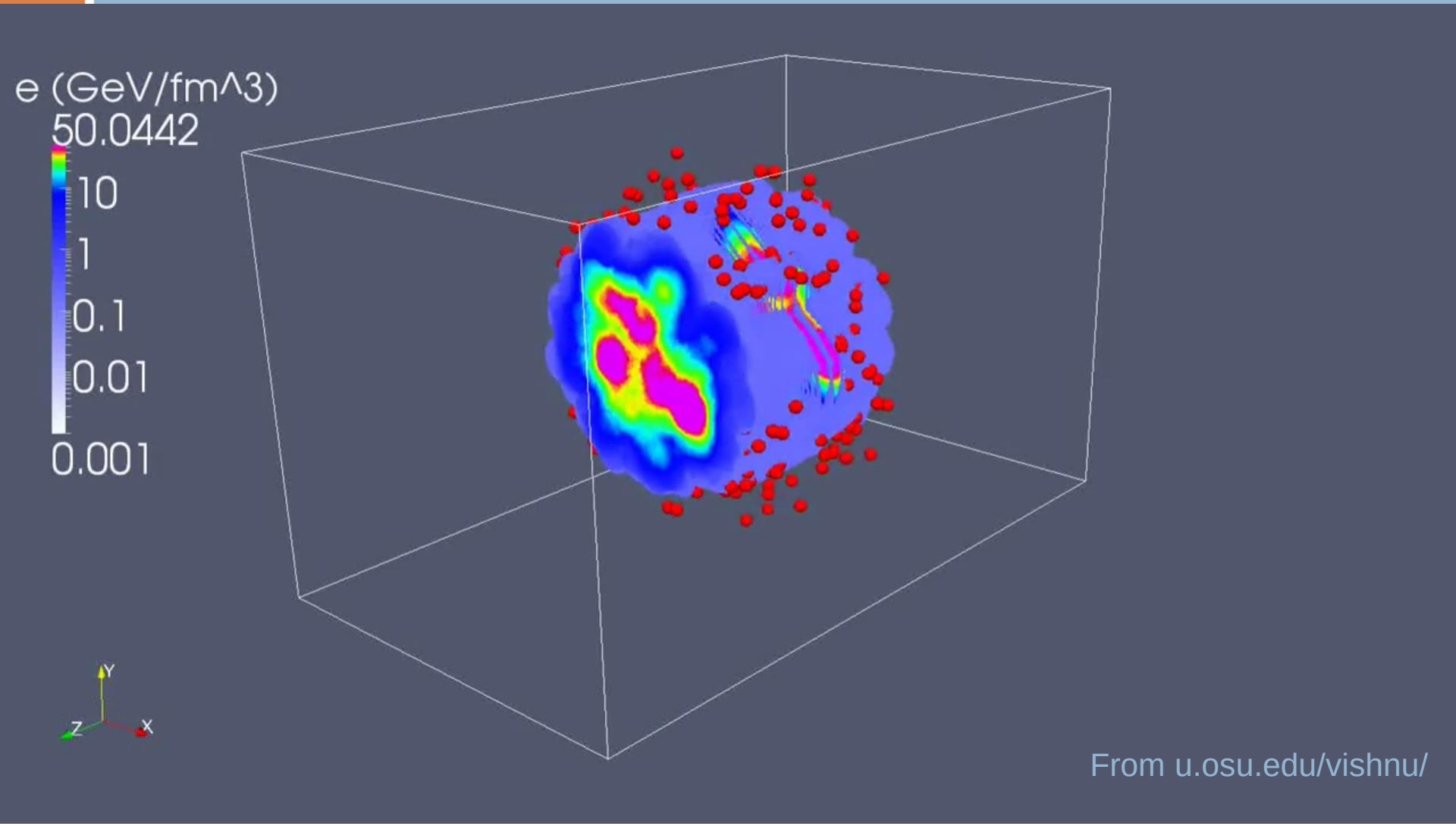



From u.osu.edu/vishnu/

# Stages of a collision in VISHNU




From u.osu.edu/vishnu/

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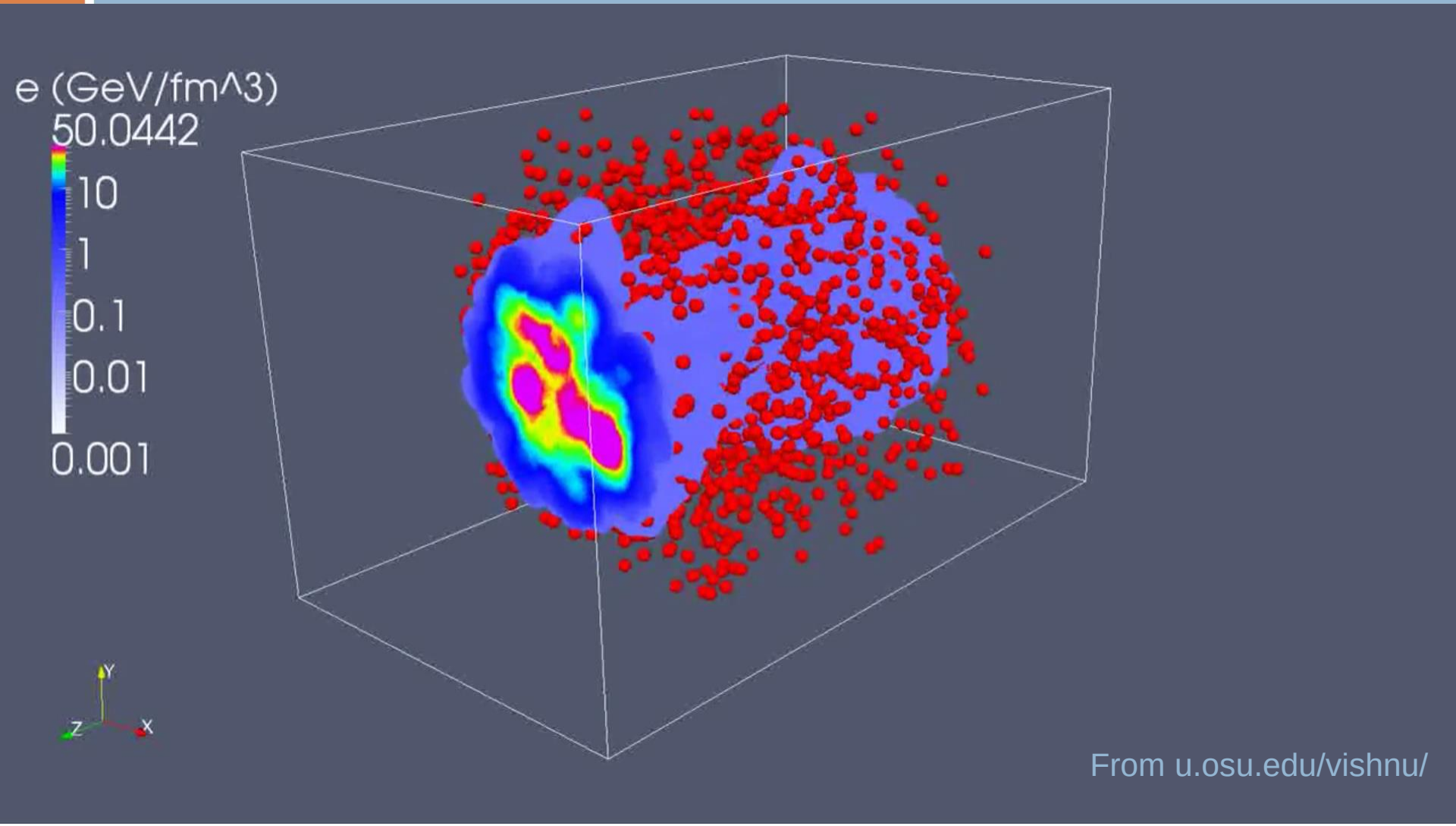
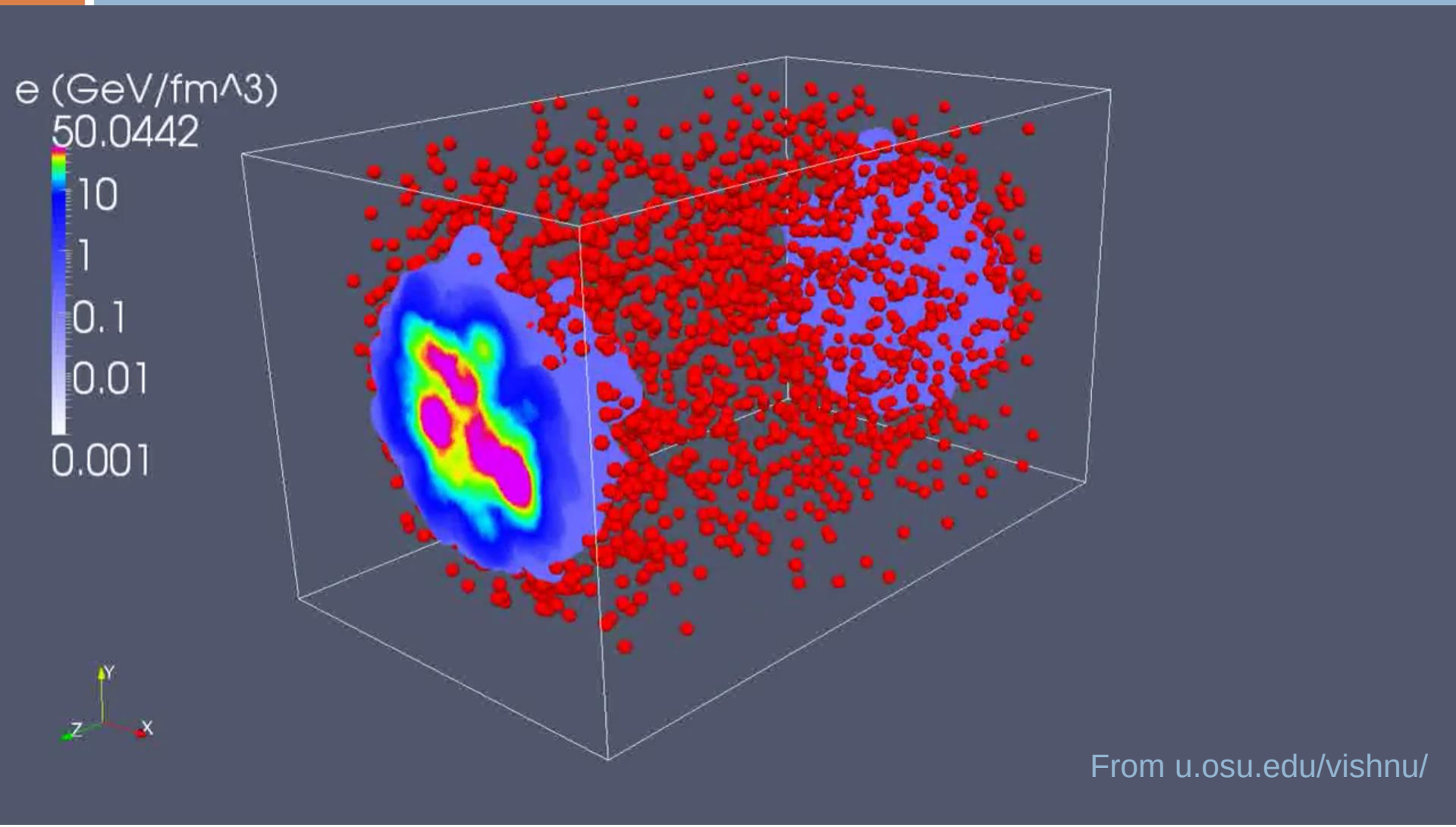


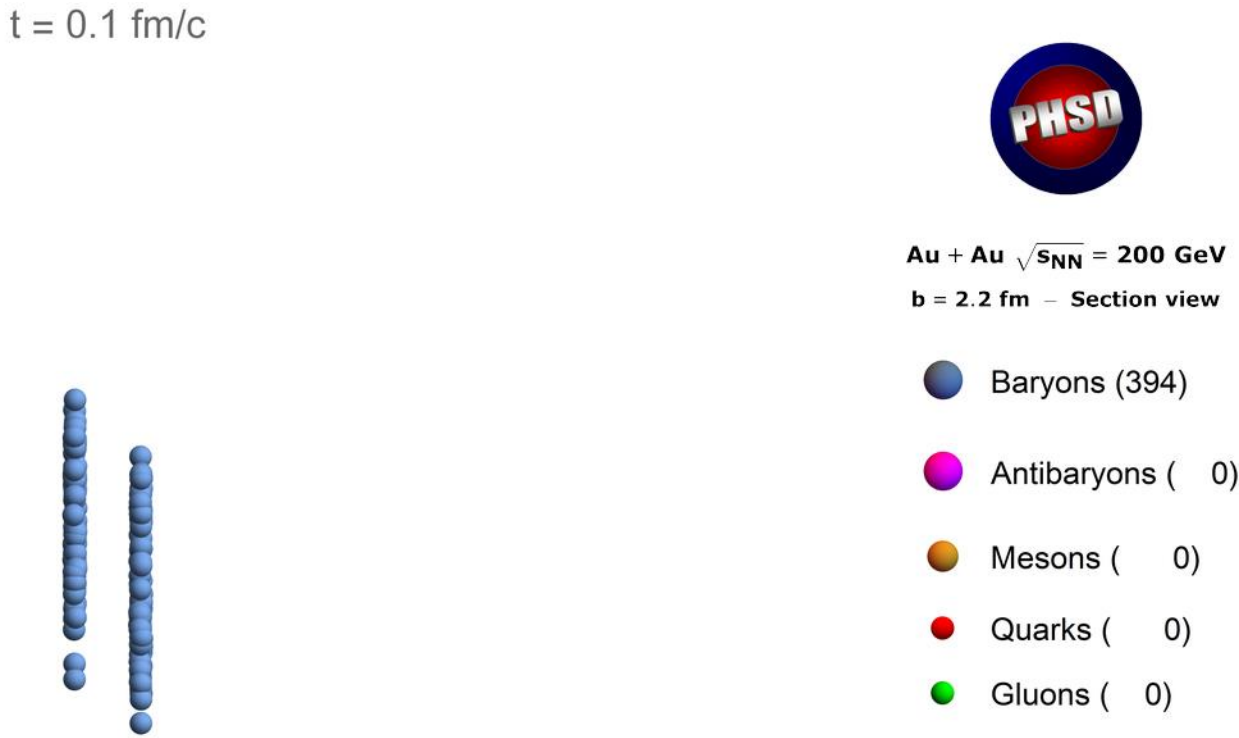

From u.osu.edu/vishnu/

# Stages of a collision in VISHNU



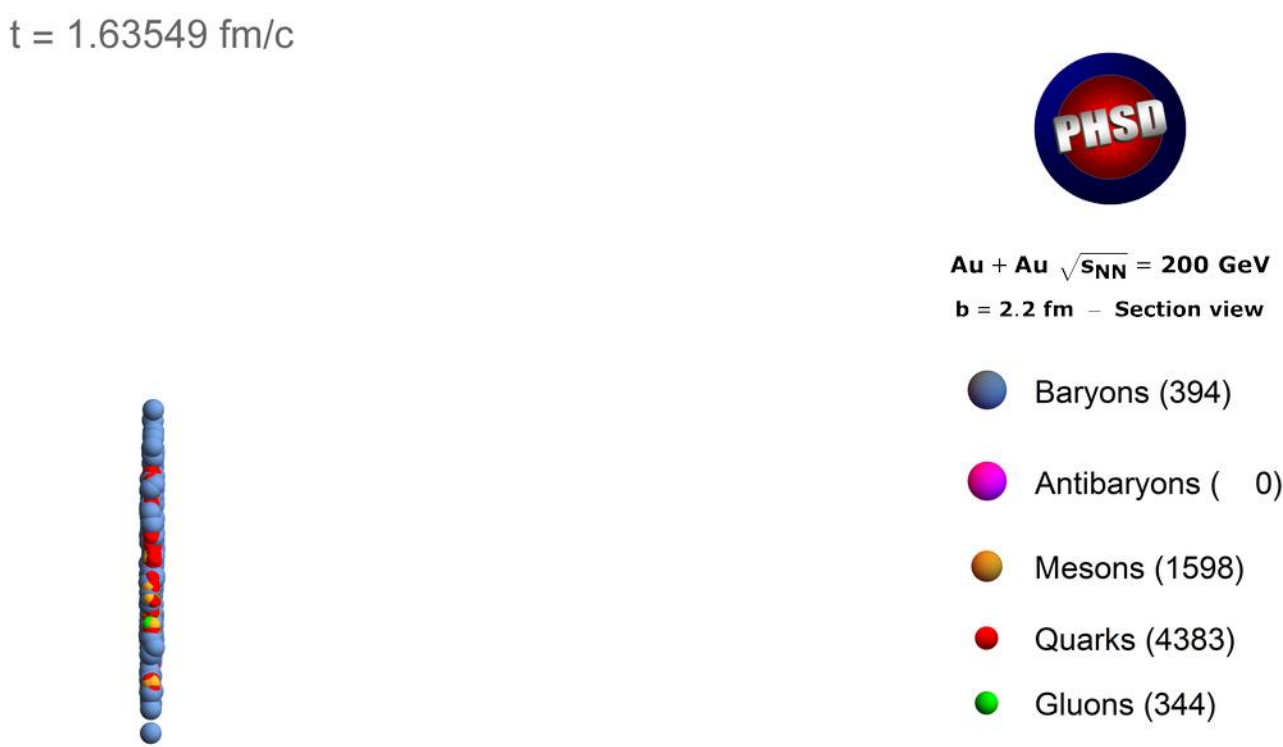

From u.osu.edu/vishnu/

# Au+Au at 200 A GeV, b=2.2 fm



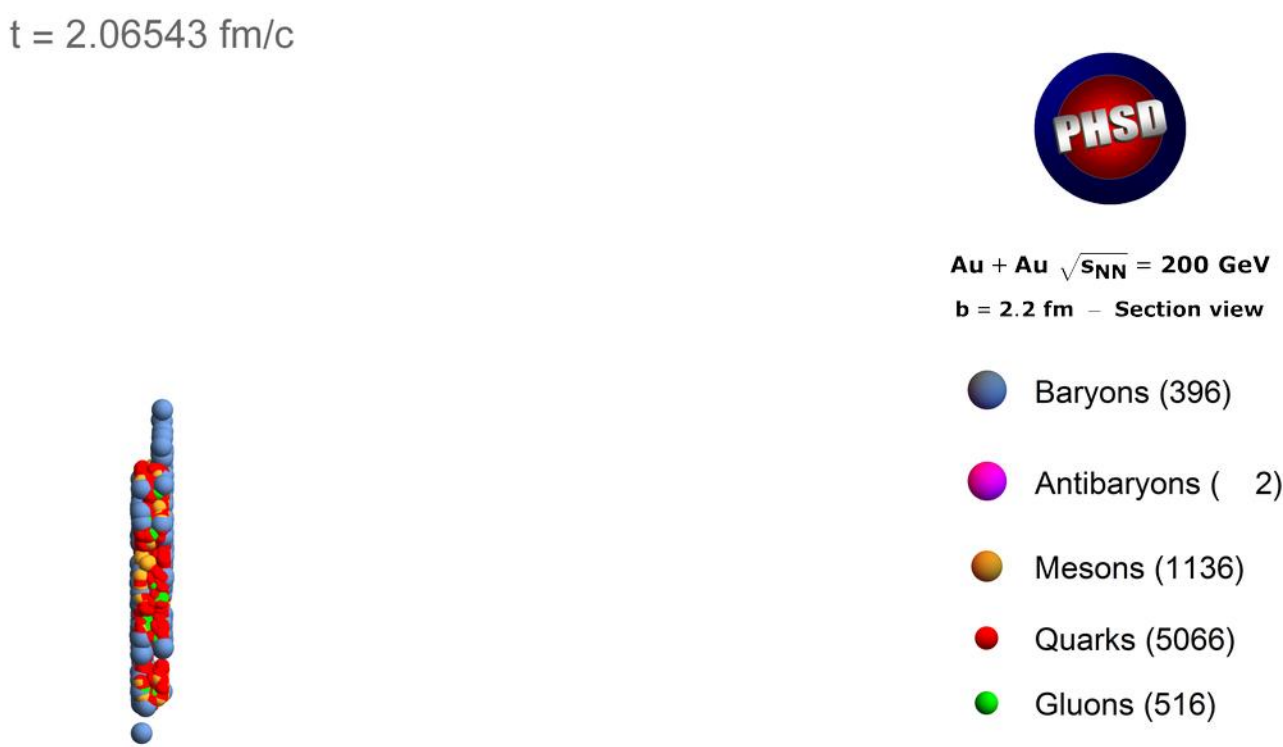

P.Moreau

# Au+Au at 200 A GeV, b=2.2 fm




P.Moreau

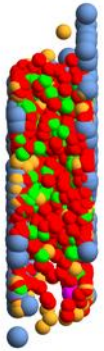
# Au+Au at 200 A GeV, b=2.2 fm




P.Moreau

# Au+Au at 200 A GeV, b=2.2 fm

t = 3.20258 fm/c



PHSD

Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

Baryons (413)

Antibaryons ( 13)

Mesons (1080)

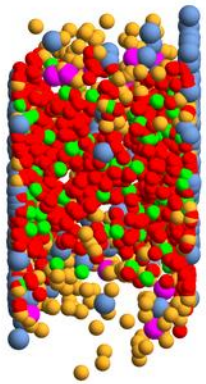
Quarks (4708)

Gluons (761)

P.Moreau

# Au+Au at 200 A GeV, b=2.2 fm

t = 5.56921 fm/c



PHSD

Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

Baryons (472)

Antibaryons ( 70)

Mesons (1724)

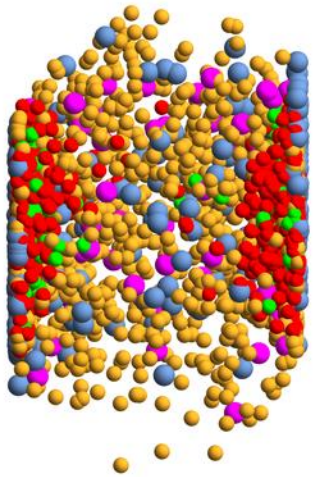
Quarks (3843)

Gluons (652)

P.Moreau

# Au+Au at 200 A GeV, b=2.2 fm

t = 8.06922 fm/c



PHSD

Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

Baryons (559)

Antibaryons (139)

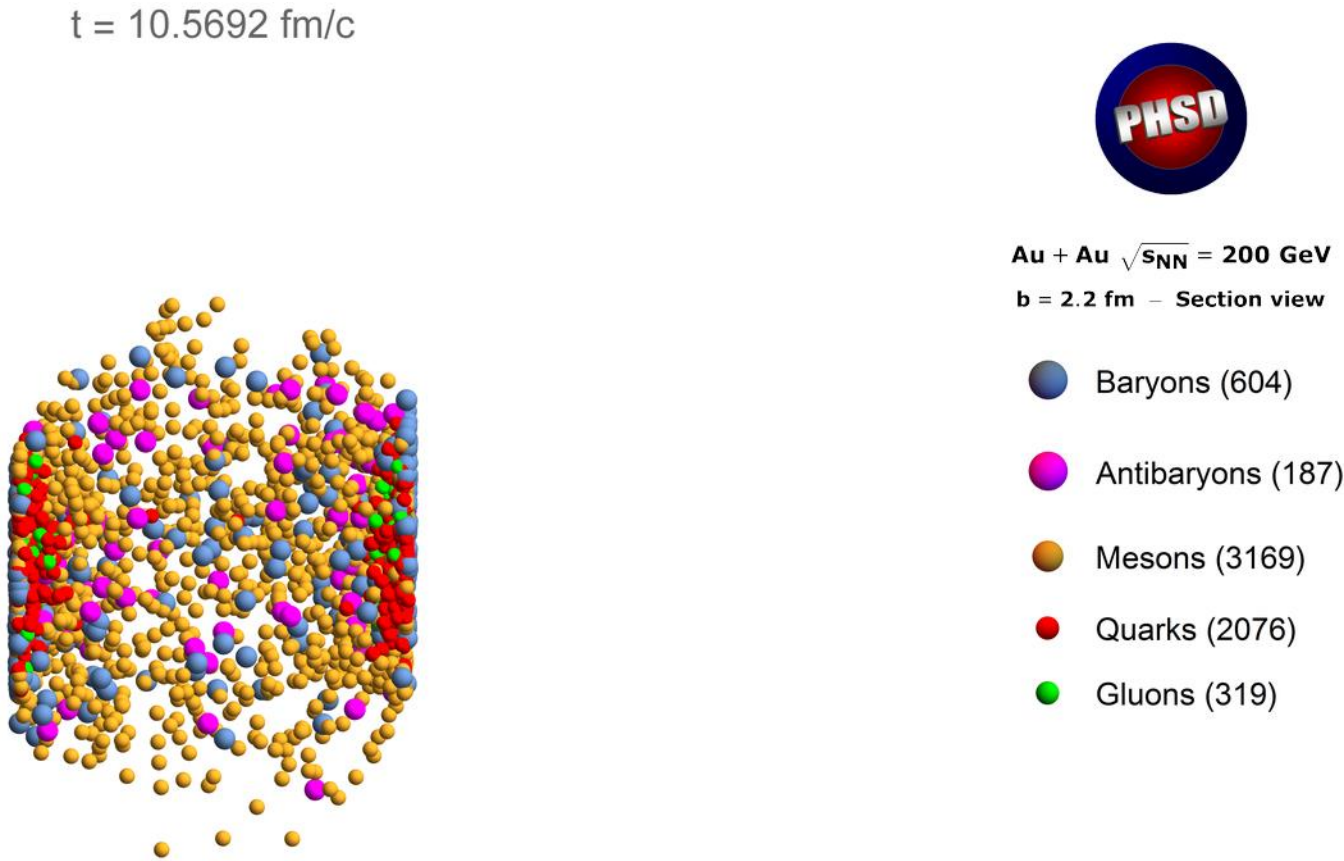
Mesons (2686)

Quarks (2628)

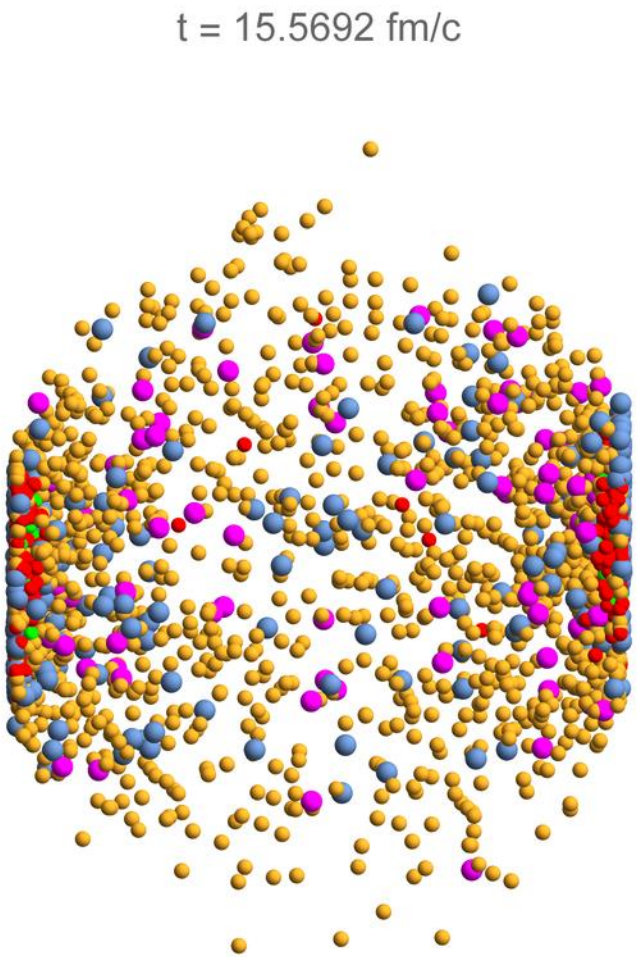
Gluons (442)

P.Moreau

# Au+Au at 200 A GeV, b=2.2 fm



# Au+Au at 200 A GeV, b=2.2 fm




PHSD

Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

Baryons (662)

Antibaryons (229)

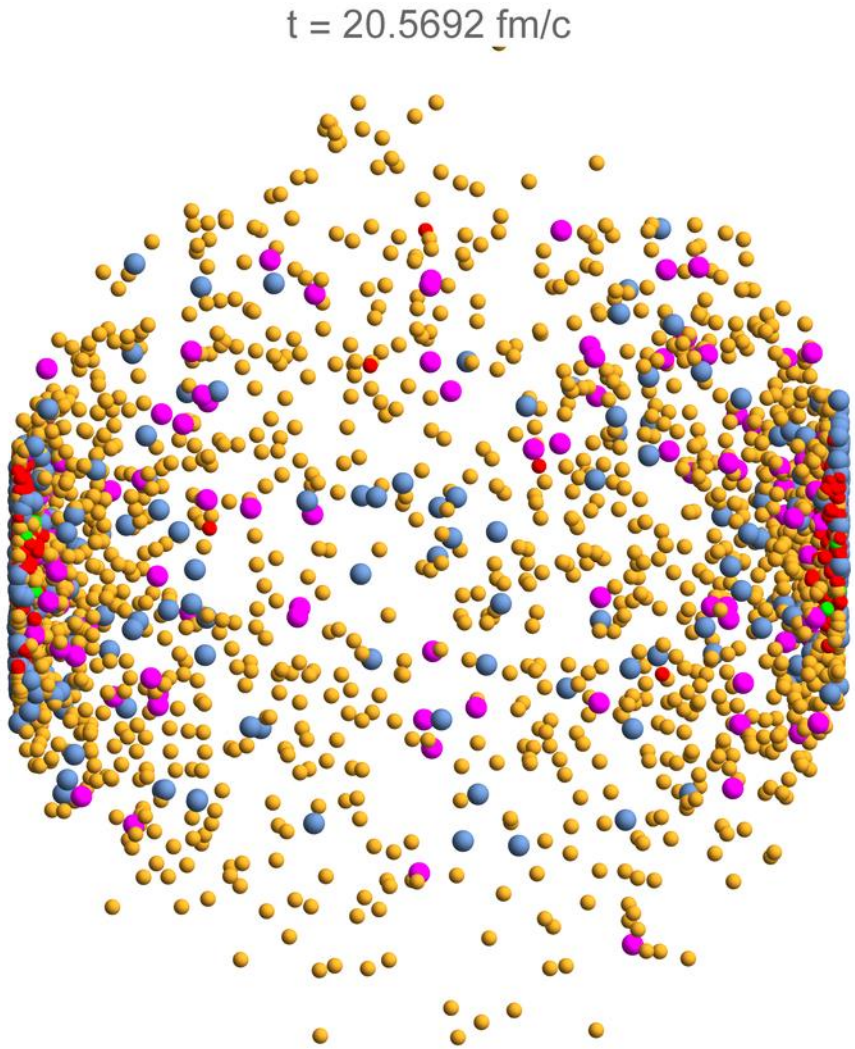
Mesons (3661)

Quarks (1499)

Gluons (175)

P.Moreau

# Au+Au at 200 A GeV, b=2.2 fm




PHSD

Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

Baryons (692)

Antibaryons (266)

Mesons (4022)

Quarks (1184)

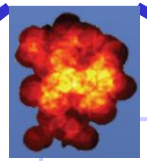
Gluons ( 90)

# Dynamical models for HIC

## Macroscopic

### hydro-models:

- description of QGP and hadronic phase by hydrodanamical equations for fluid
- assumption of local equilibrium
- EoS with phase transition from QGP to HG
- initial conditions (e-b-e, fluctuating)



**ideal**
(Jyväskylä,SHASTA, TAMU, …)

**viscous**
(Romachkke,(2+1)D VISH2+1, (3+1)D MUSIC,…)

### fireball models:

- no explicit dynamics: parametrized time evolution (TAMU)

## Microscopic

**Non-equilibrium microscopic transport models – based on many-body theory**

**Hadron-string models**
(UrQMD, IQMD, HSD, QGSM, SMASH …)

**Partonic cascades**
**pQCD based**
(Duke, BAMPS, …)

### Parton-hadron models:

- QGP: pQCD based cascade
- massless q, g
- hadronization: coalescence

(AMPT, HIJING)

- QGP: lQCD EoS
- massive quasi-particles (q and g with spectral functions) in self-generated mean-field
- dynamical hadronization
- HG: off-shell dynamics

(applicable for strongly interacting systems)

PHSD

### ‚Hybrid‘

QGP phase: hydro with QGP EoS

- hadronic freeze-out: after burner - hadron-string transport model

(‚hybrid‘-UrQMD, EPOS, …)

# References

**Eds: B. L. Friman, C. Höhne, J. E. Knoll, S. K. K. Leupold, J. Randrup, R. Rapp,and P. Senger;**

**Springer, Series: 'Lecture Notes in Physics', Vol. 815 (2010), 960 p.;**
**ISBN: 978-3-642-13292-6**