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

Lectures:
Thursday, 11:15-12:45

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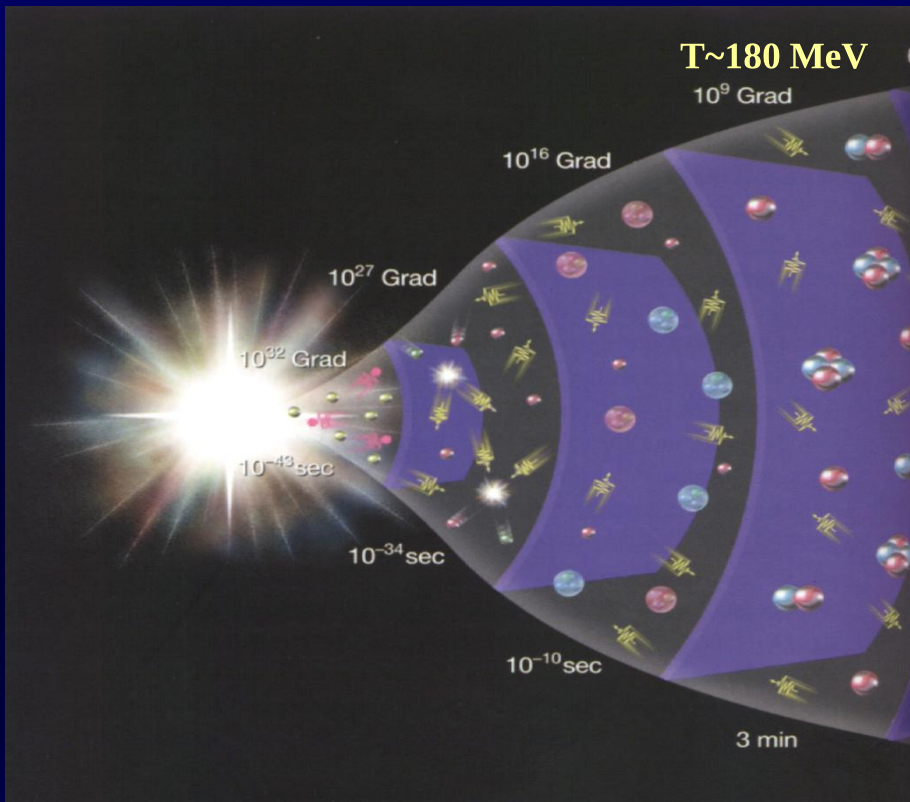
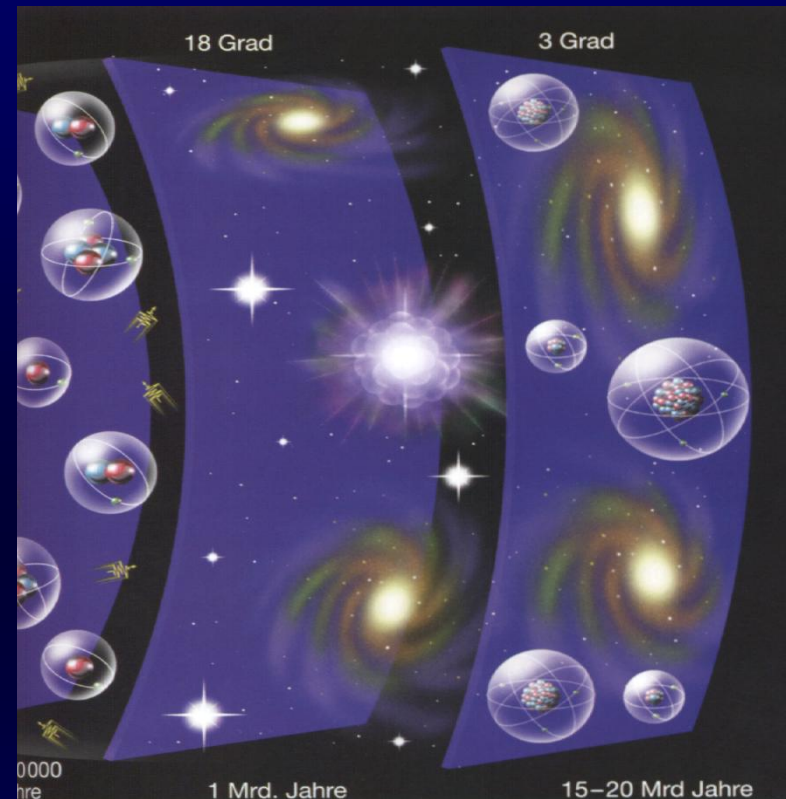
http://theory.gsi.de/~ebratkov/LecturesSS2025/Lec_SS2025.html

From Big Bang to Formation of the Universe



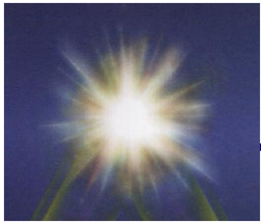
➔



time →

10^{-3}sec	3 min	300000 years	15 Mrd years
quarks gluons photons	nucleons deuterons α–particles	atoms	our Universe

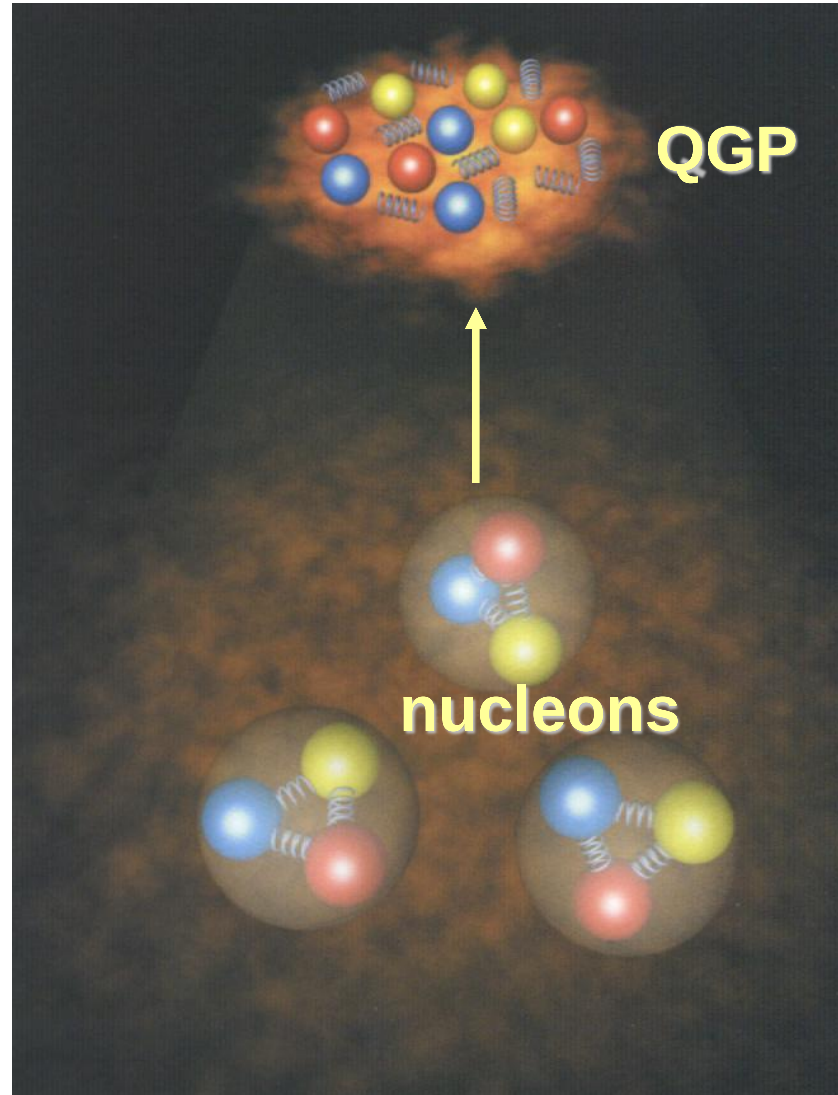
⟵ **Can we go back in time ?**



... 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**

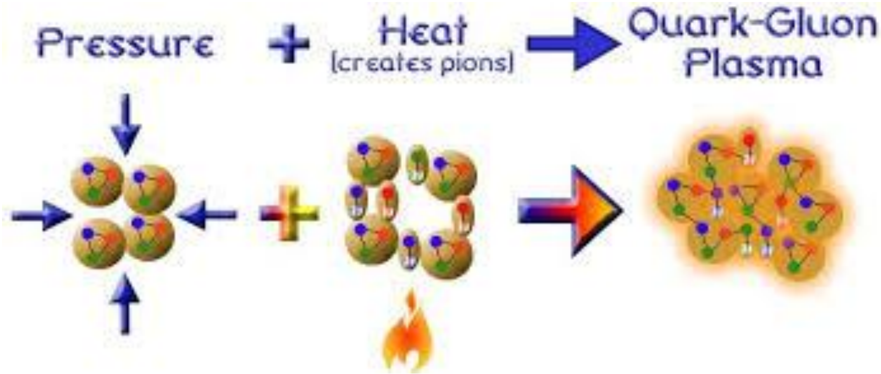
‚Little Bangs‘ in the Laboratory :
Heavy-ion collisions at ultrarelativistic energies

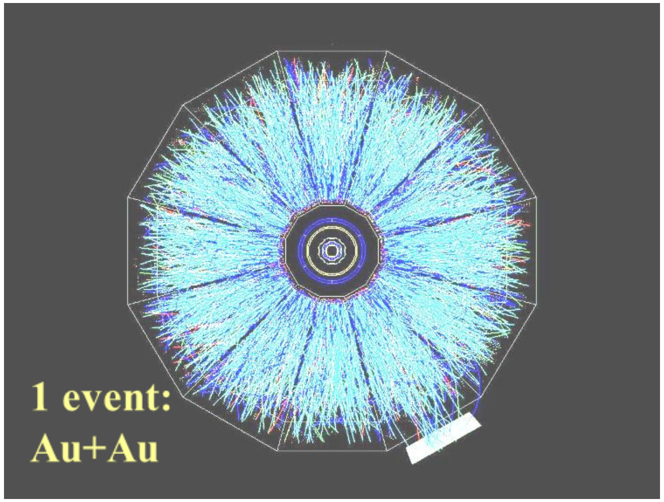


Heavy-ion collisions

❑ Heavy-ion collision experiment

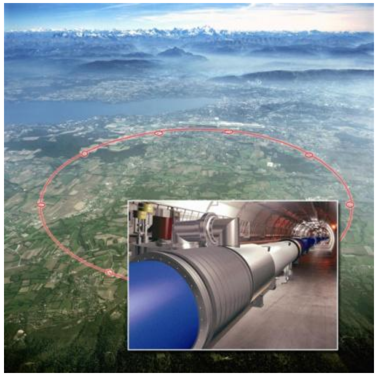
➔ ‚re-creation' of the Big Bang conditions in laboratory: matter at high pressure and temperature



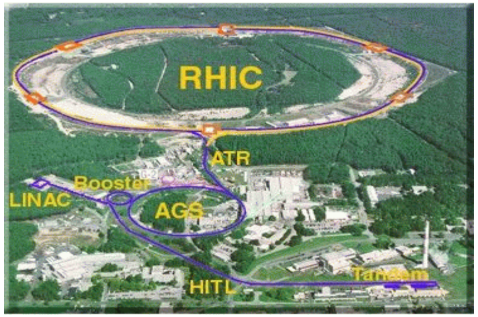


❑ Heavy-ion accelerators:

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

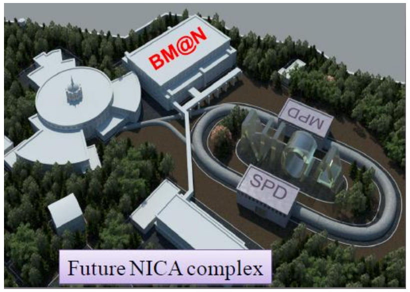


Relativistic-Heavy-Ion-Collider - RHIC (Brookhaven): Au+Au up to 21.3 A TeV



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

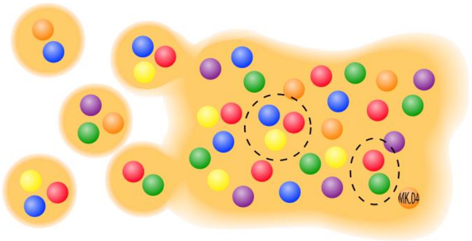


The QGP in Lattice QCD

Quantum Chromo Dynamics :

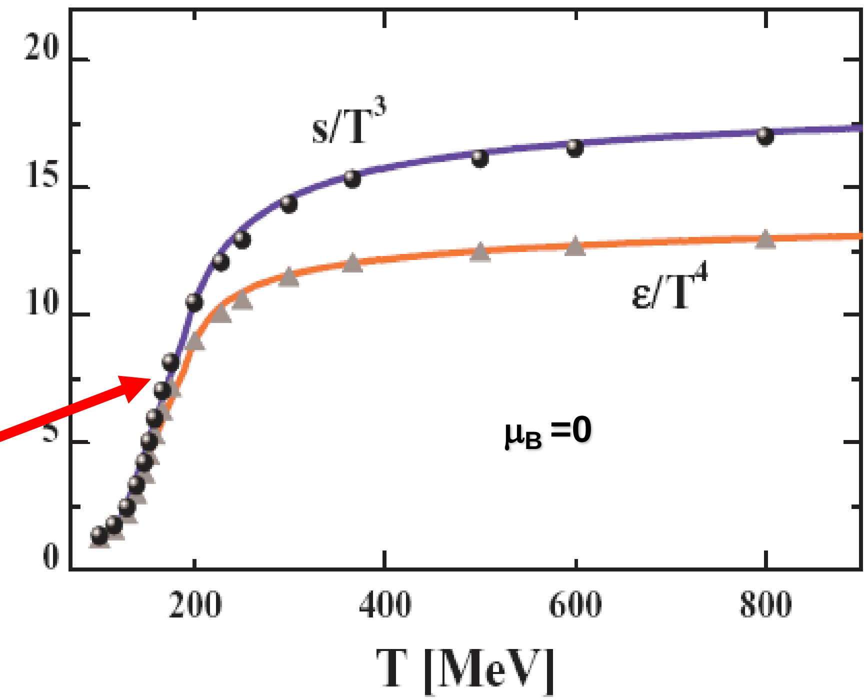
predicts strong increase of the energy density e at critical temperature T_C ~160 MeV

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



Lattice QCD:

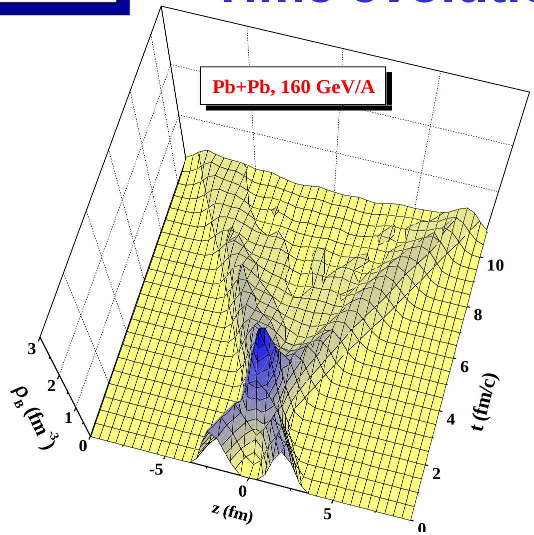
energy density versus temperature

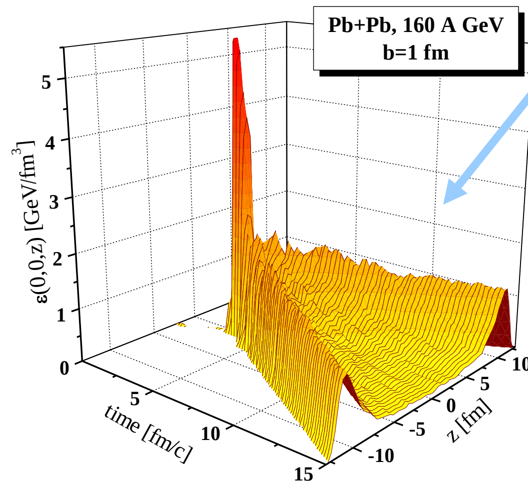


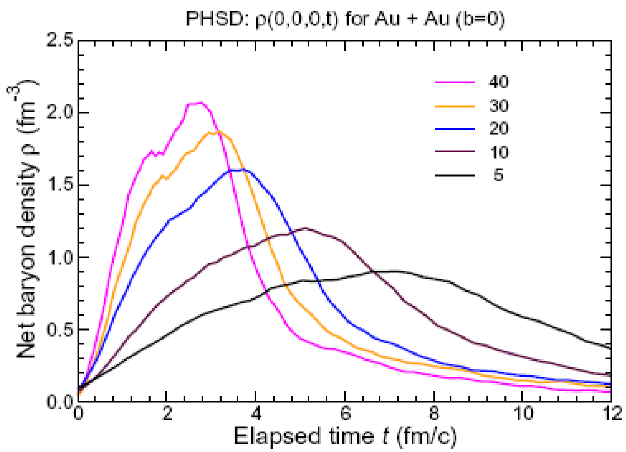
Critical conditions - ε_C ~0.5 GeV/fm^3 , T_C ~160 MeV - can be reached in heavy-ion experiments at bombarding energies > 5 GeV/A

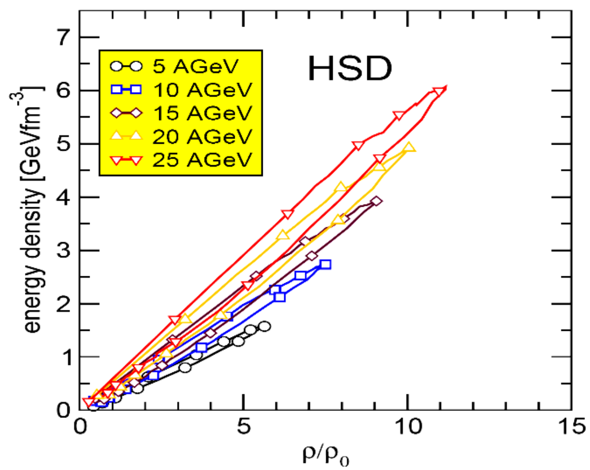
Dense and hot matter – average quantities

Time evolution of the baryon density and energy density





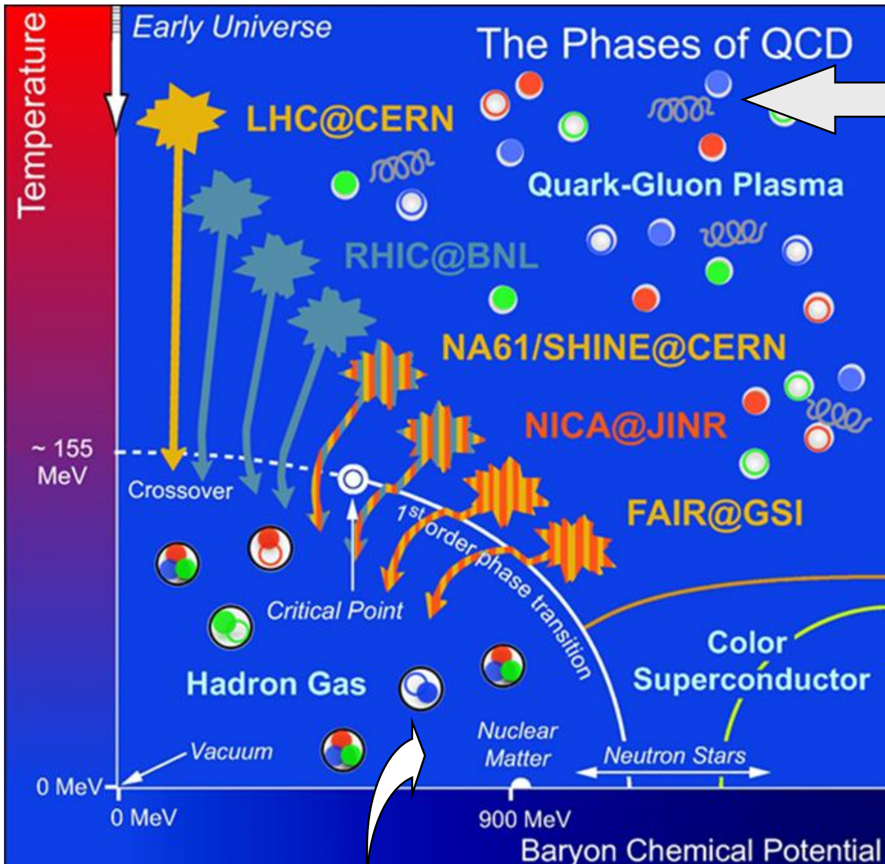




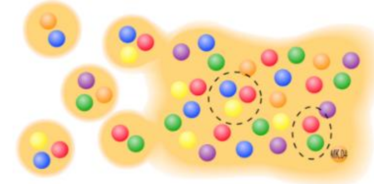
huge energy and baryon densities are reached ($\varepsilon > \varepsilon_{crit}$=0.5 GeV/fm^3) at FAIR/NICA energies (> 5 A GeV)

The ‚holy grail‘ of heavy-ion physics:

The phase diagram of QCD

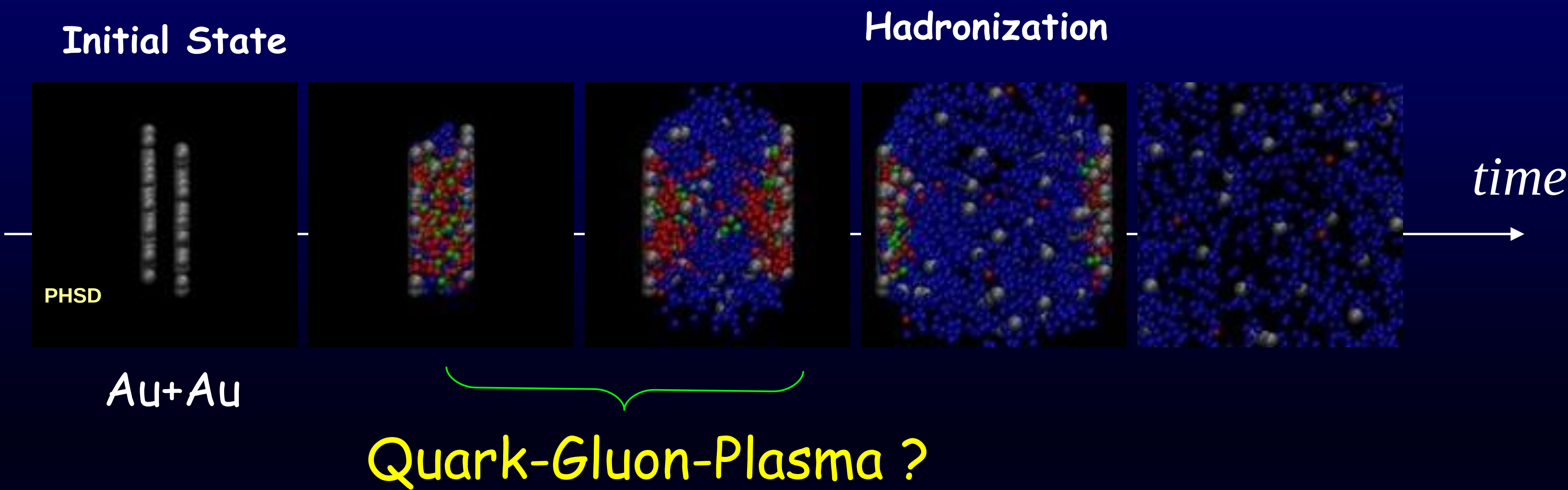


- Search for the **critical point**



- 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 ?!

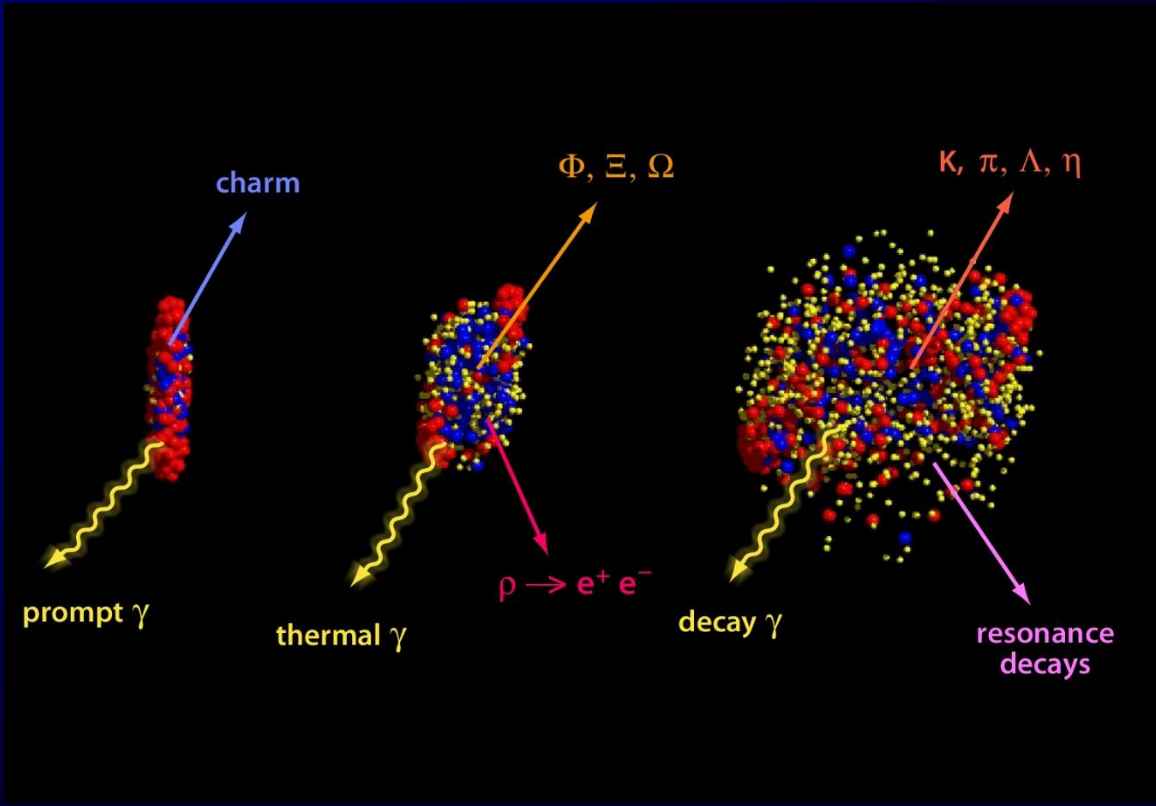
Signals of the phase transition:

- 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 μ_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 η, ζ, ..), which is 'input' for the hydro models

[- : simplified dynamics]

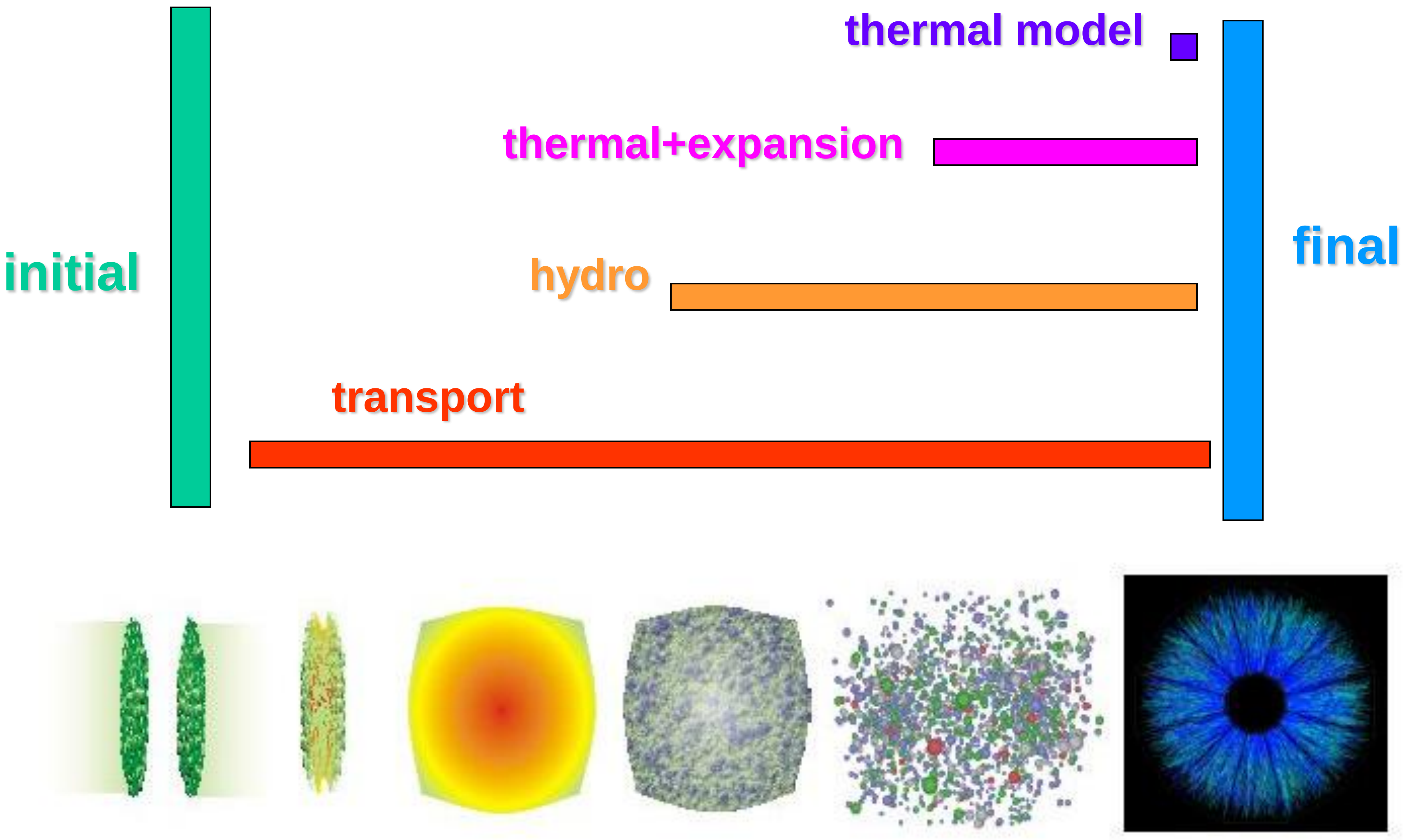
- **Microscopic transport models:**

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

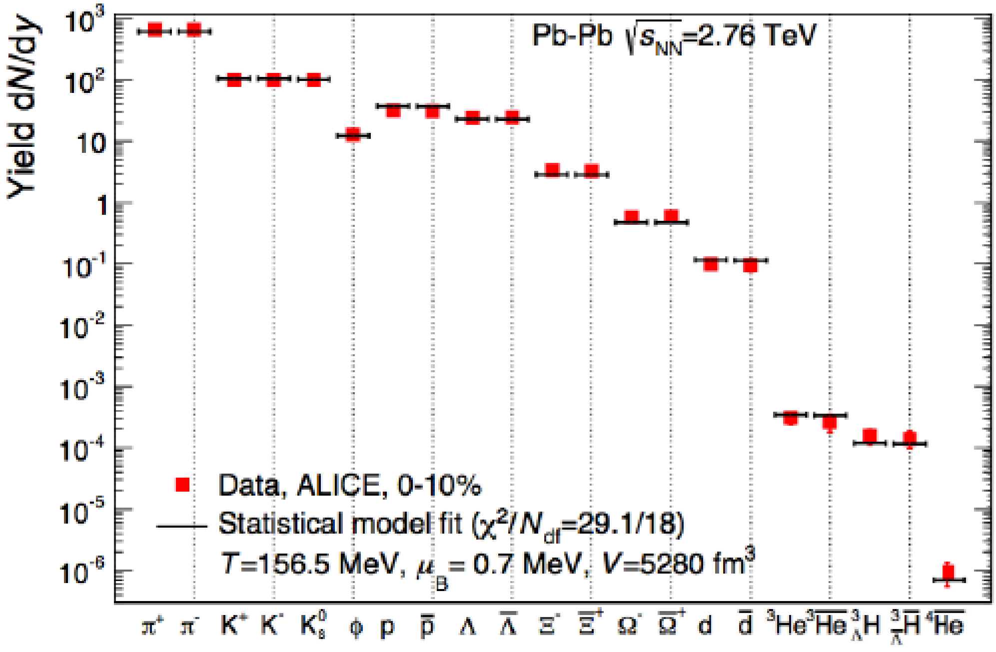
[+ : full dynamics | - : very complicated]

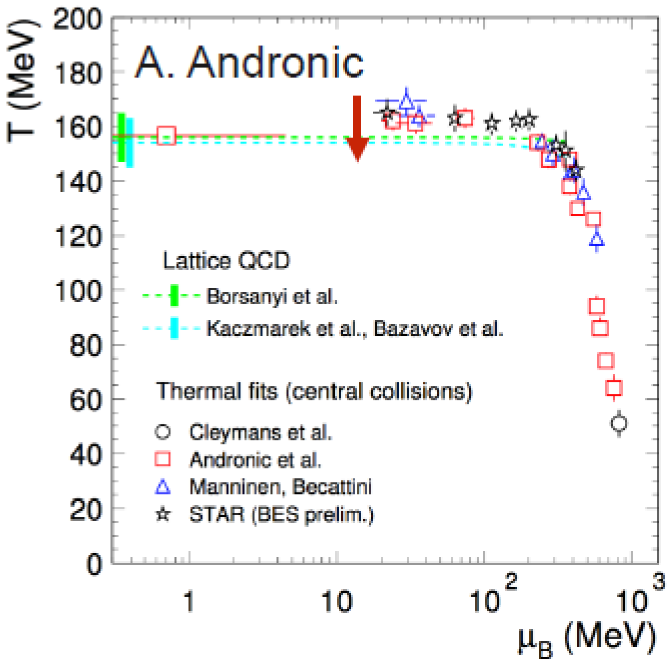
Models of heavy-ion collisions



Results from statistical models for HIC

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





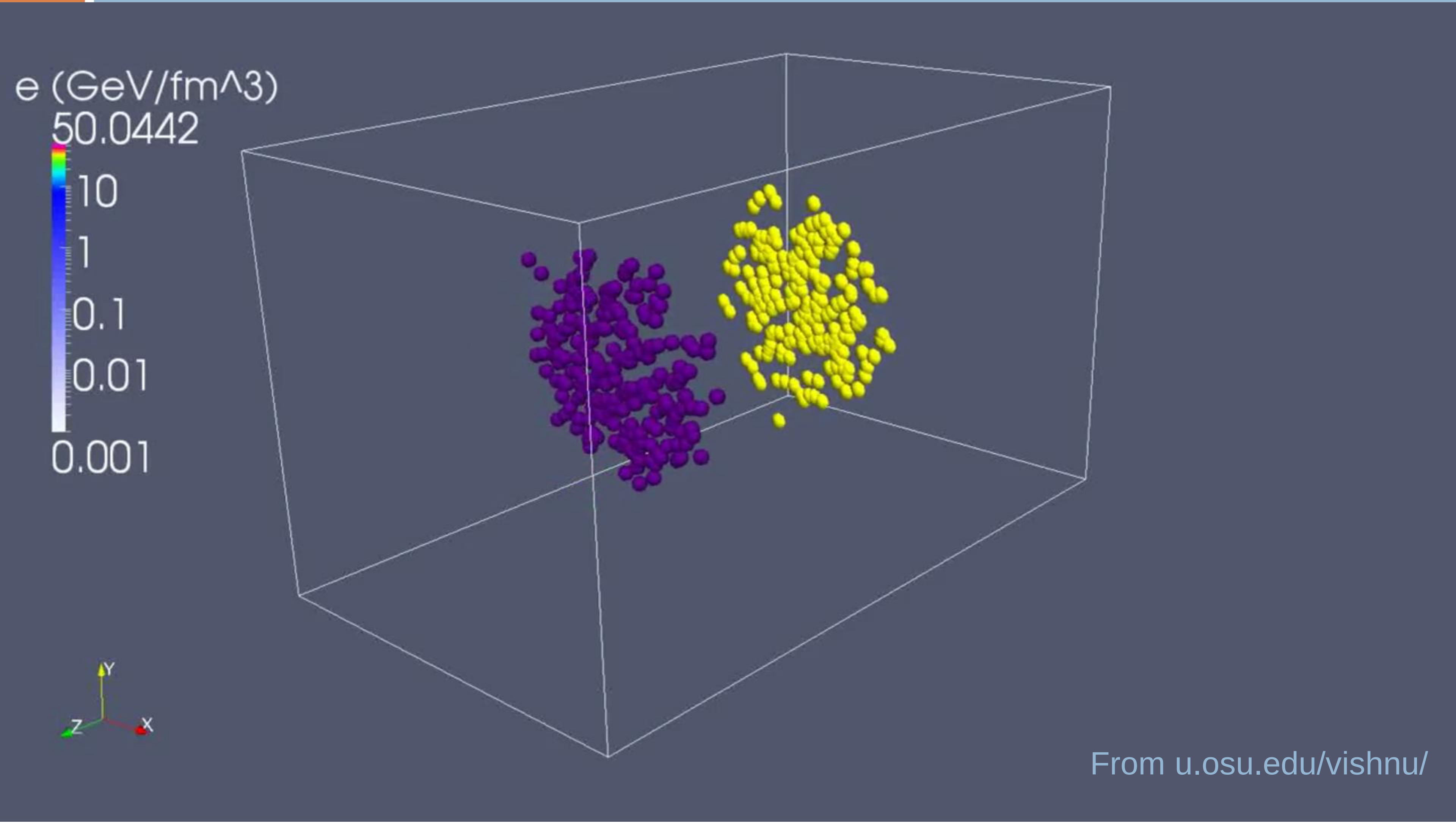
Good description of the hadron abundances by the thermal hadron gas model ➔
The hadron abundances are in rough agreement with a thermally equilibrated system !

➔ 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 !

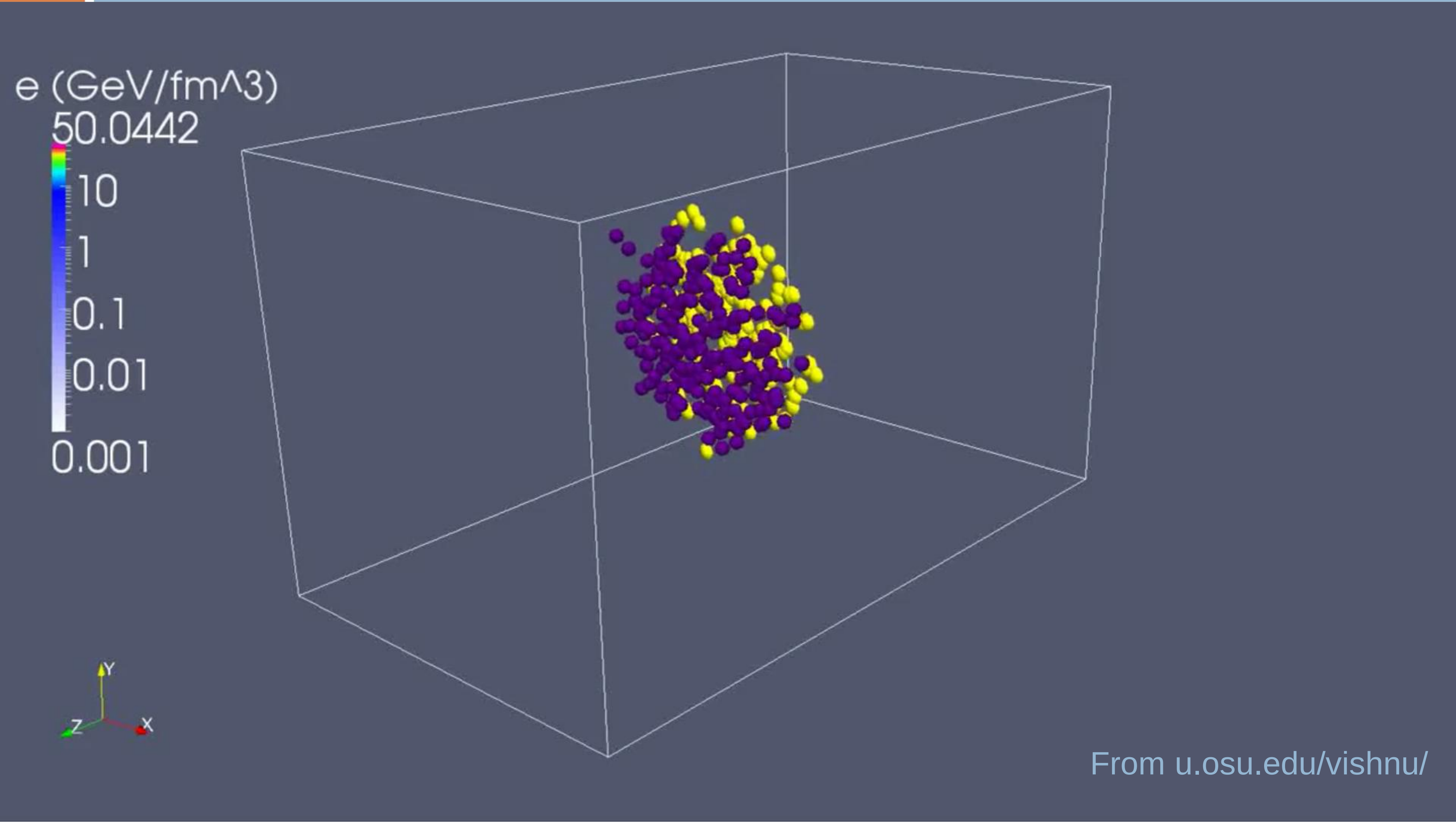
➔ dynamical models of HIC

Stages of a collision in VISHNU



From u.osu.edu/vishnu/

Stages of a collision in VISHNU



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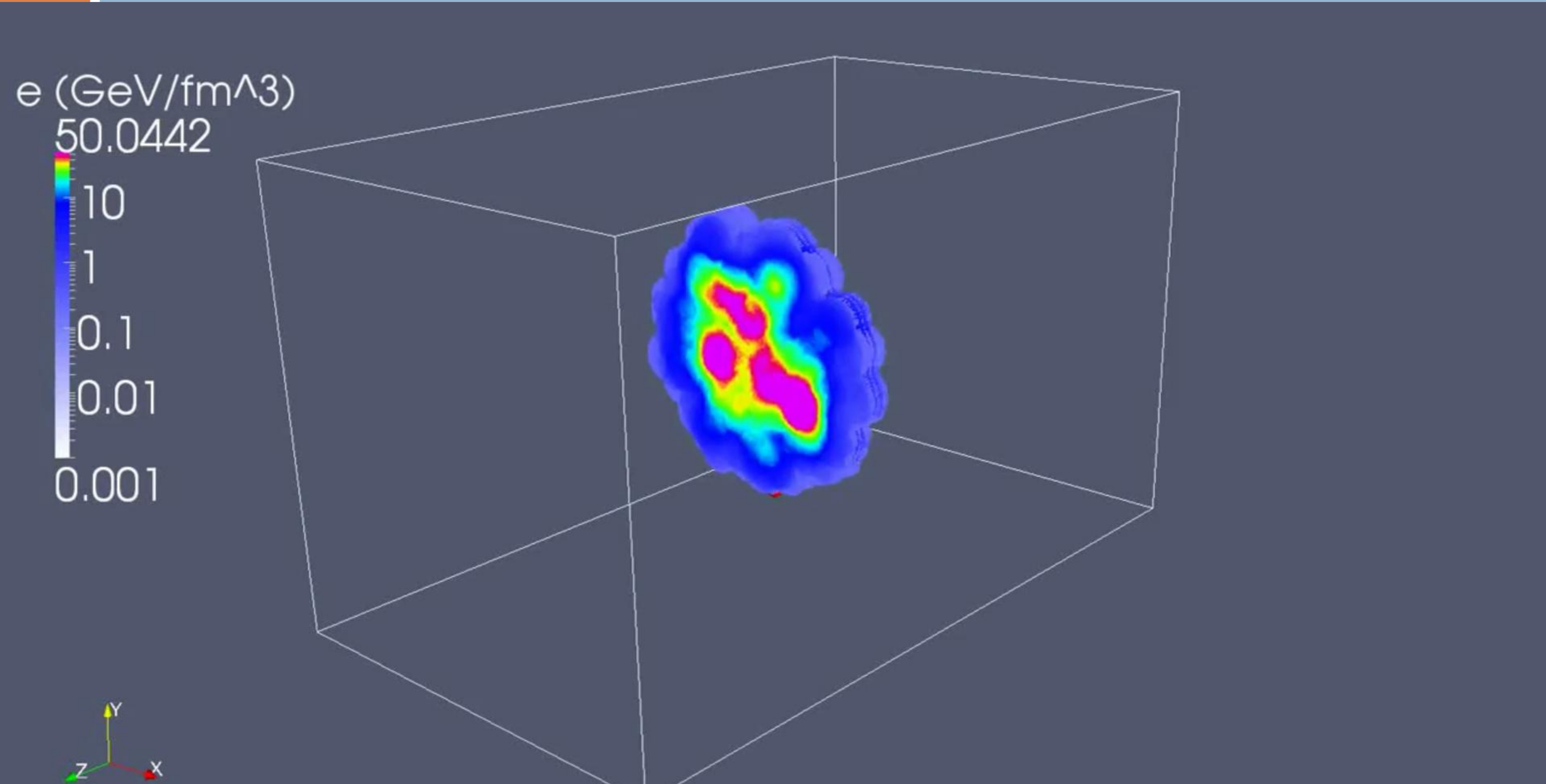

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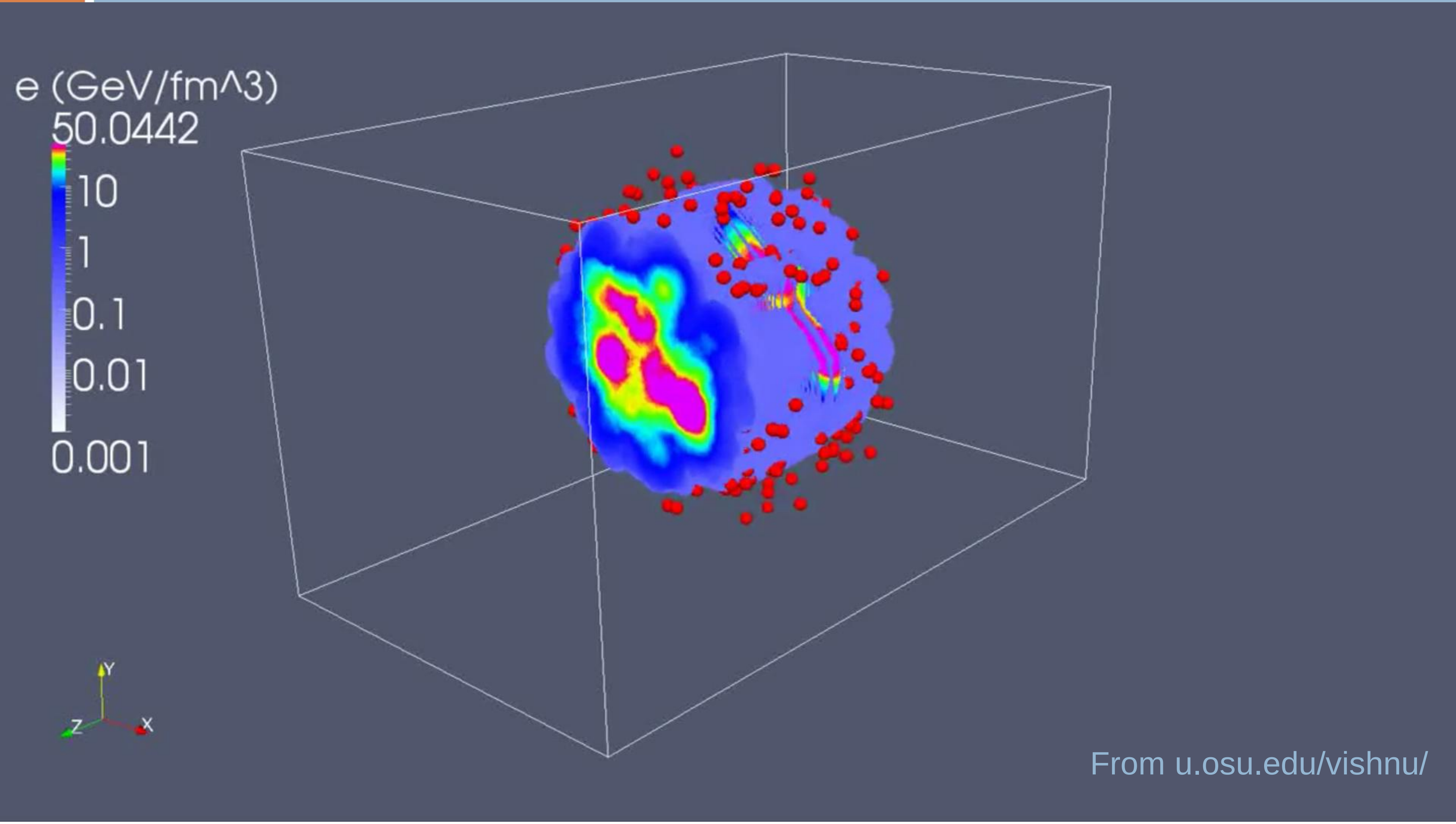

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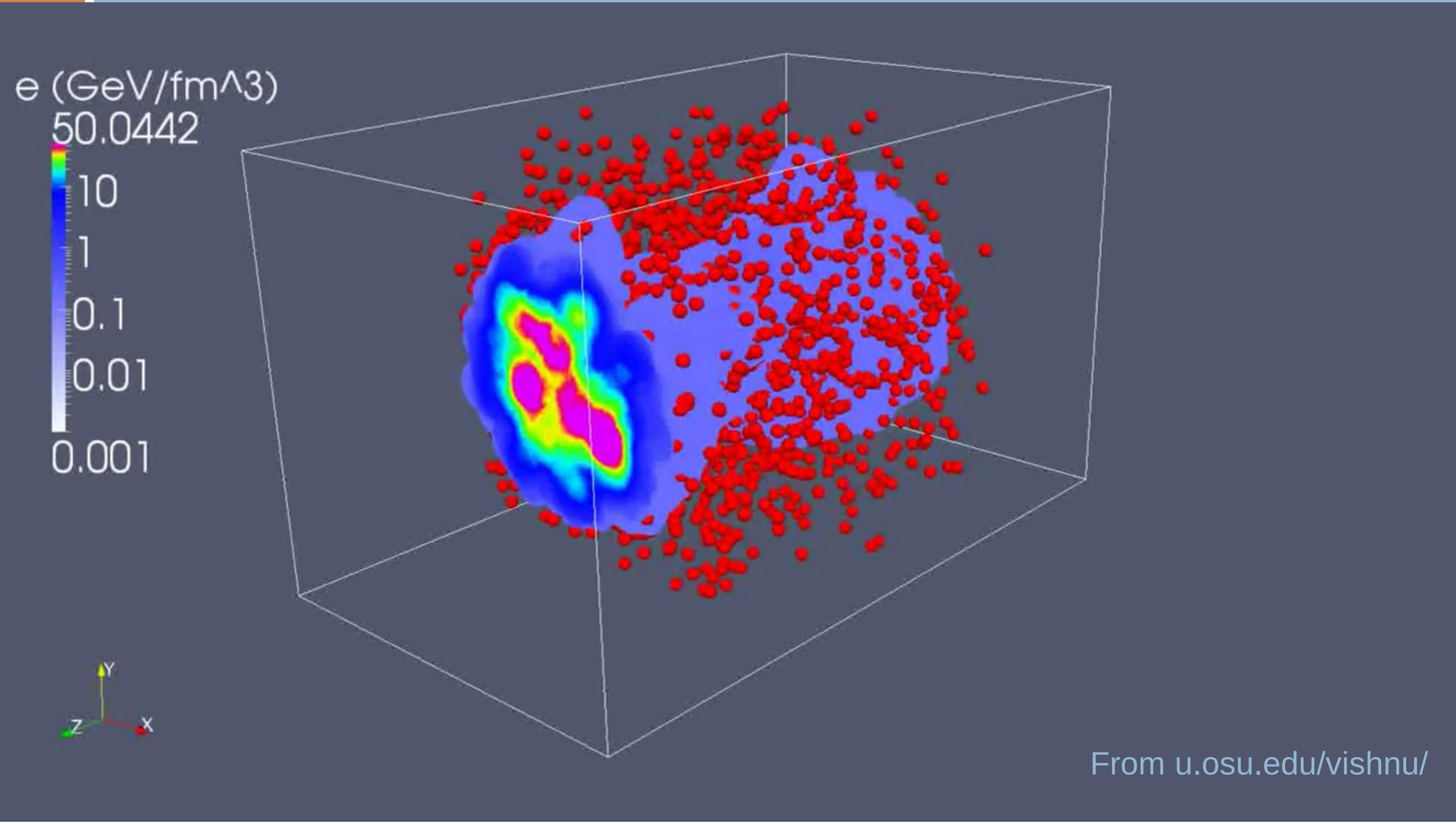

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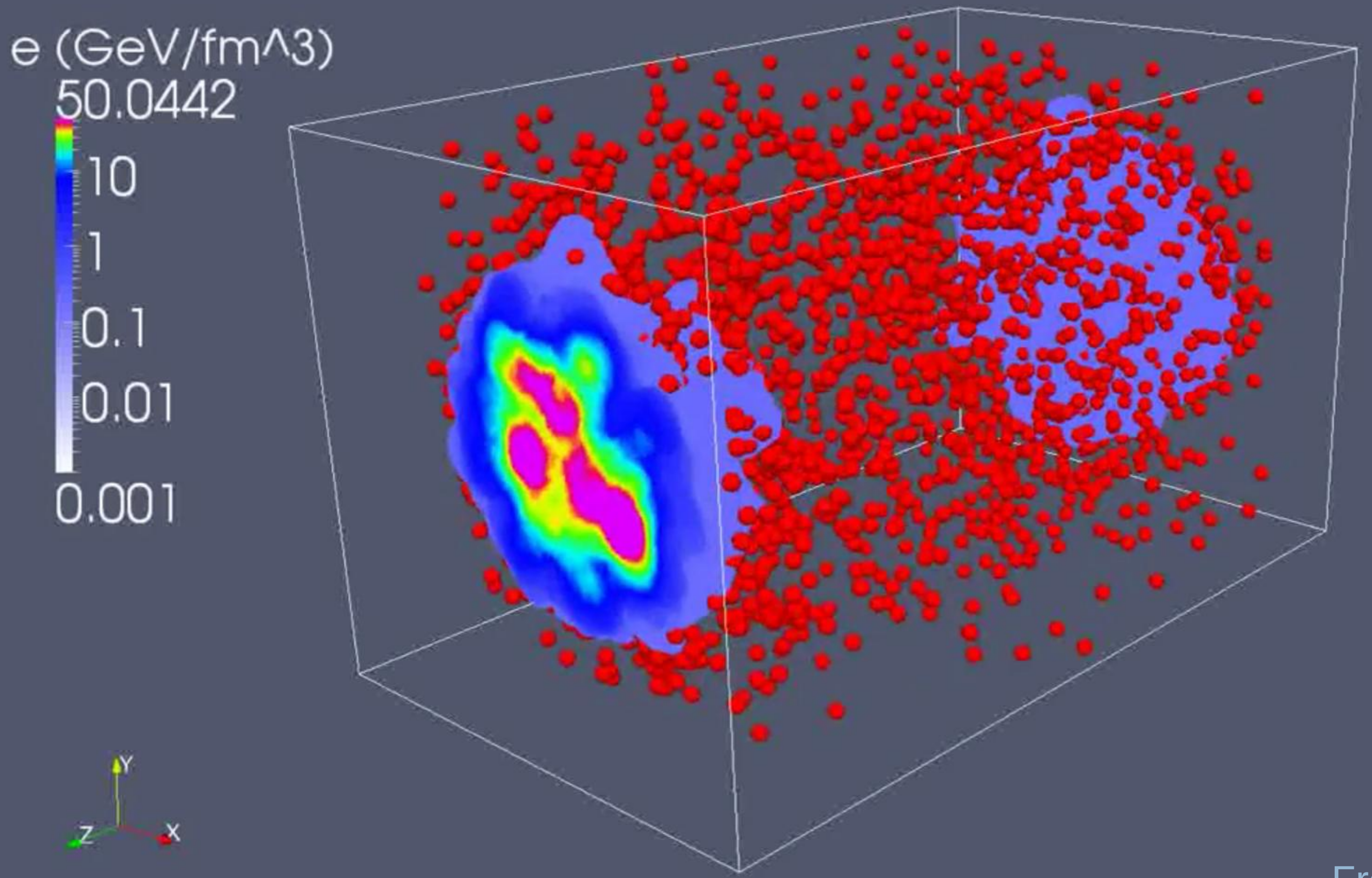
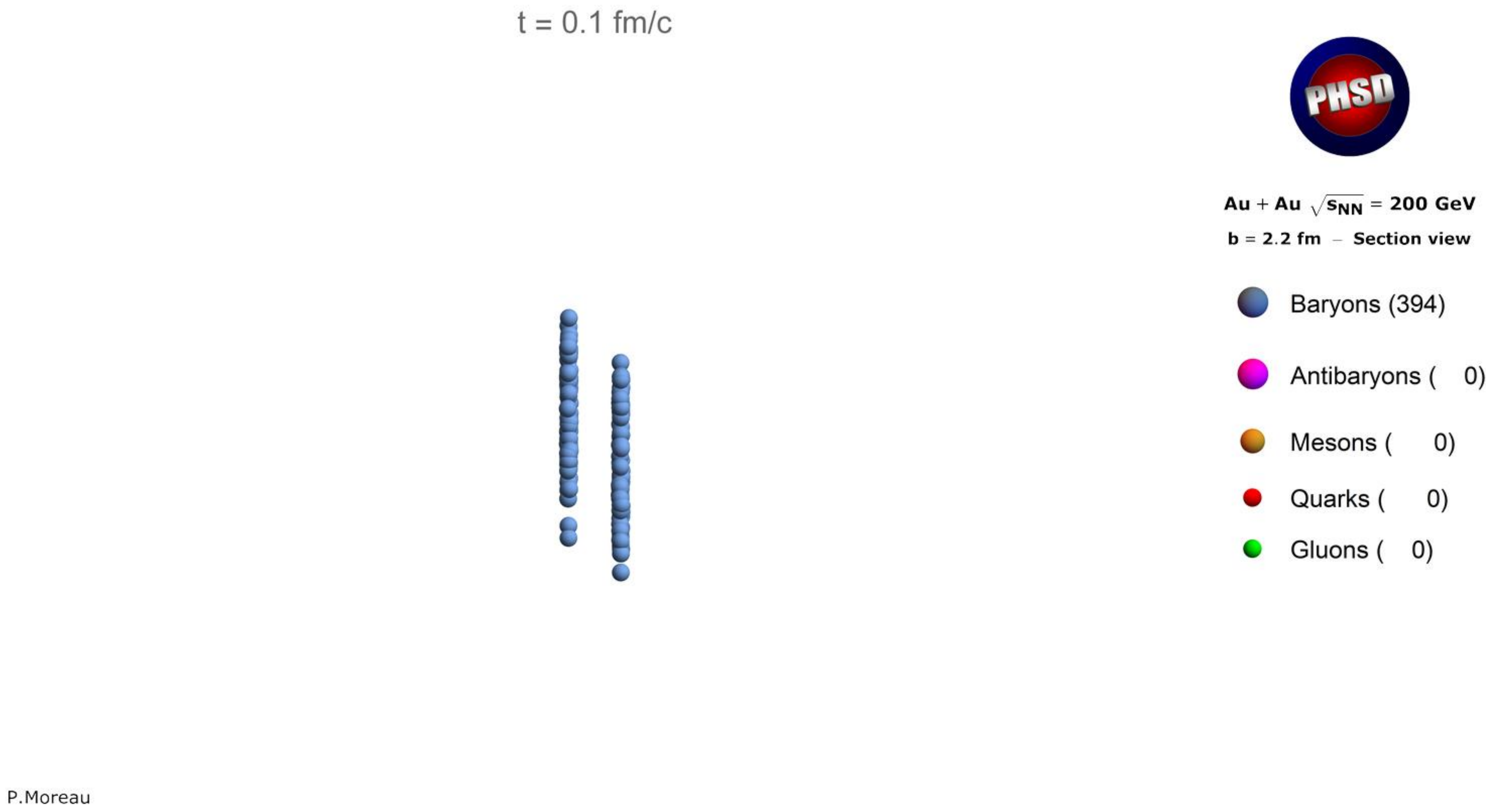


From u.osu.edu/vishnu/

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



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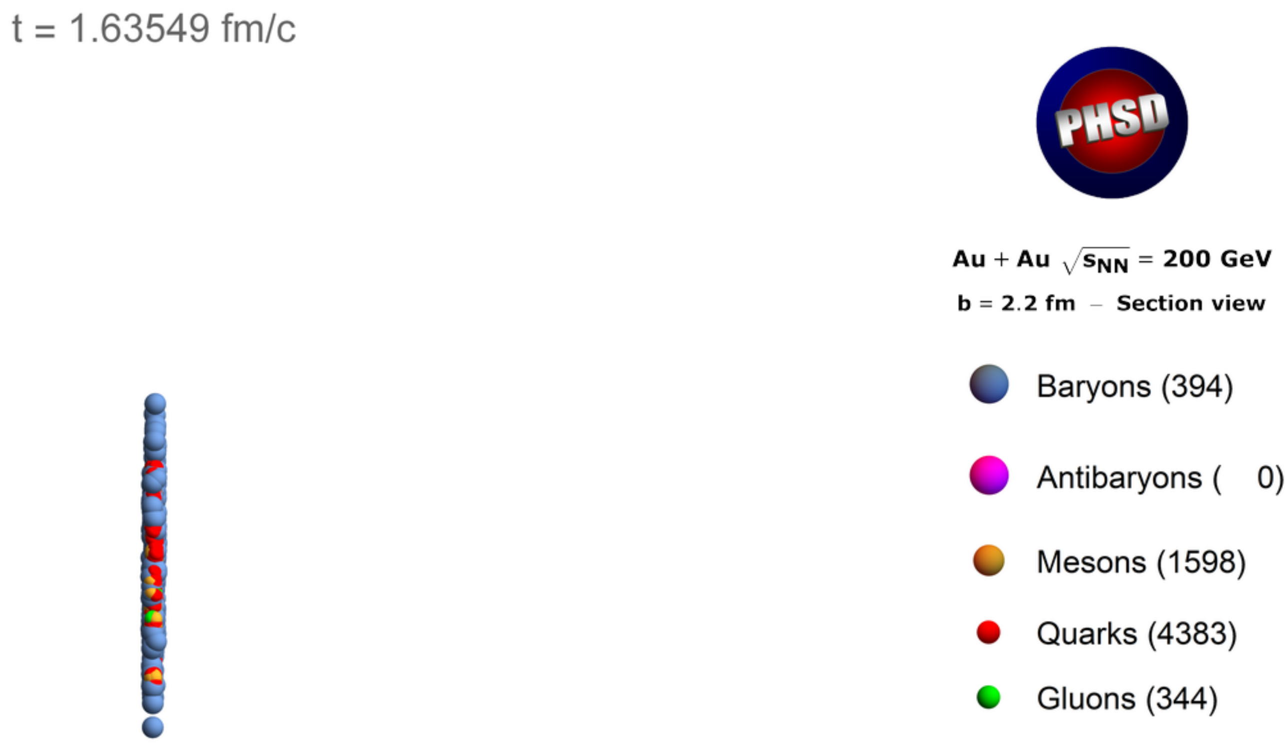
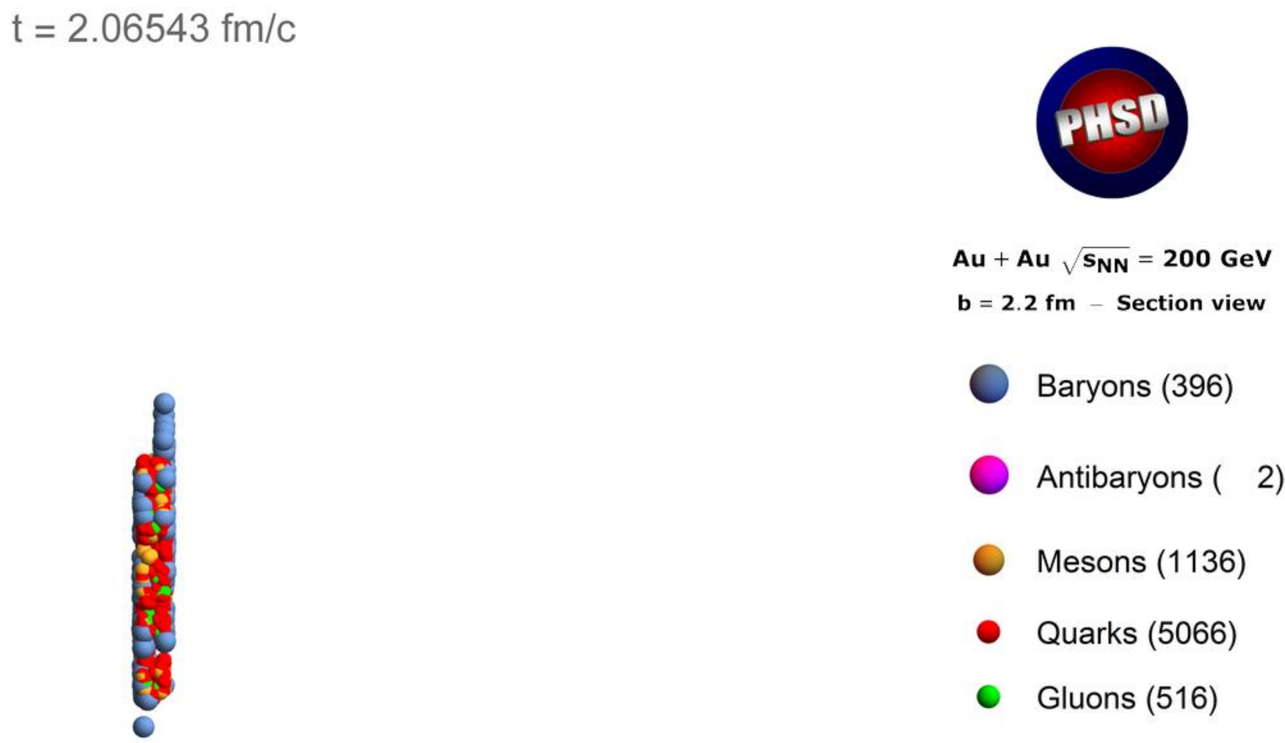


P.Moreau

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



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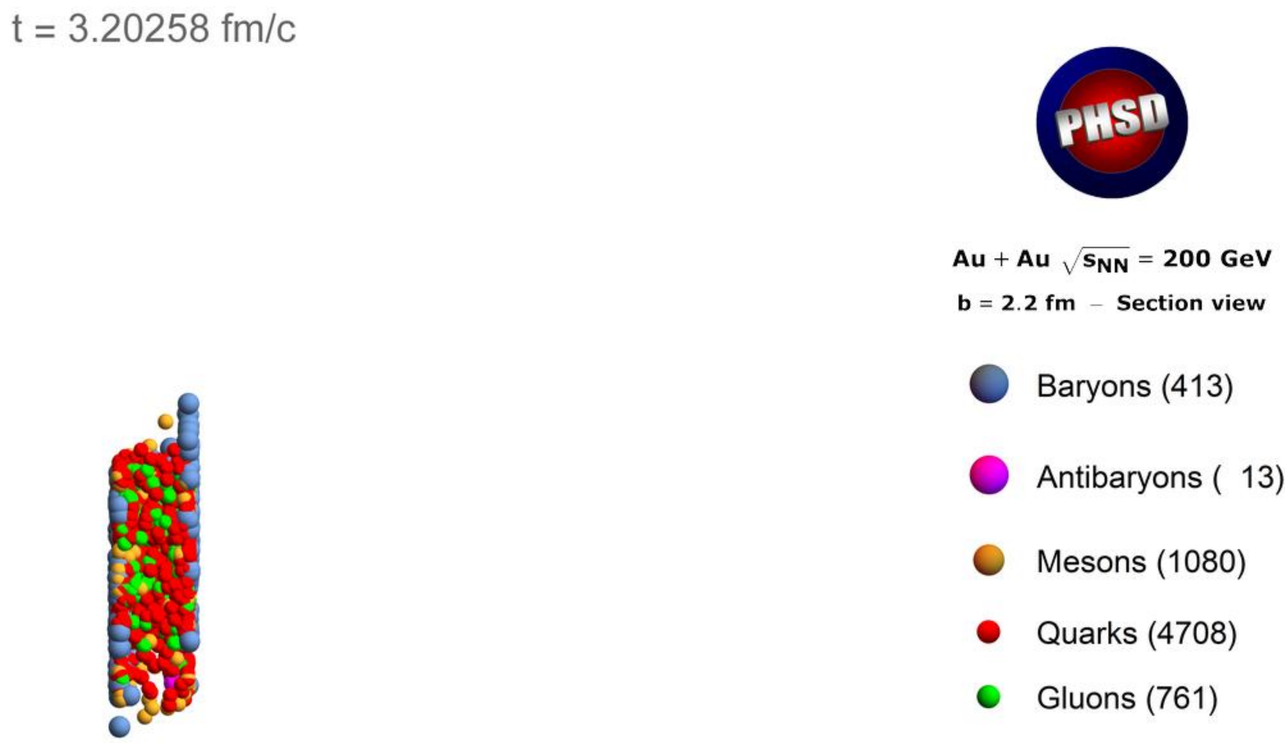

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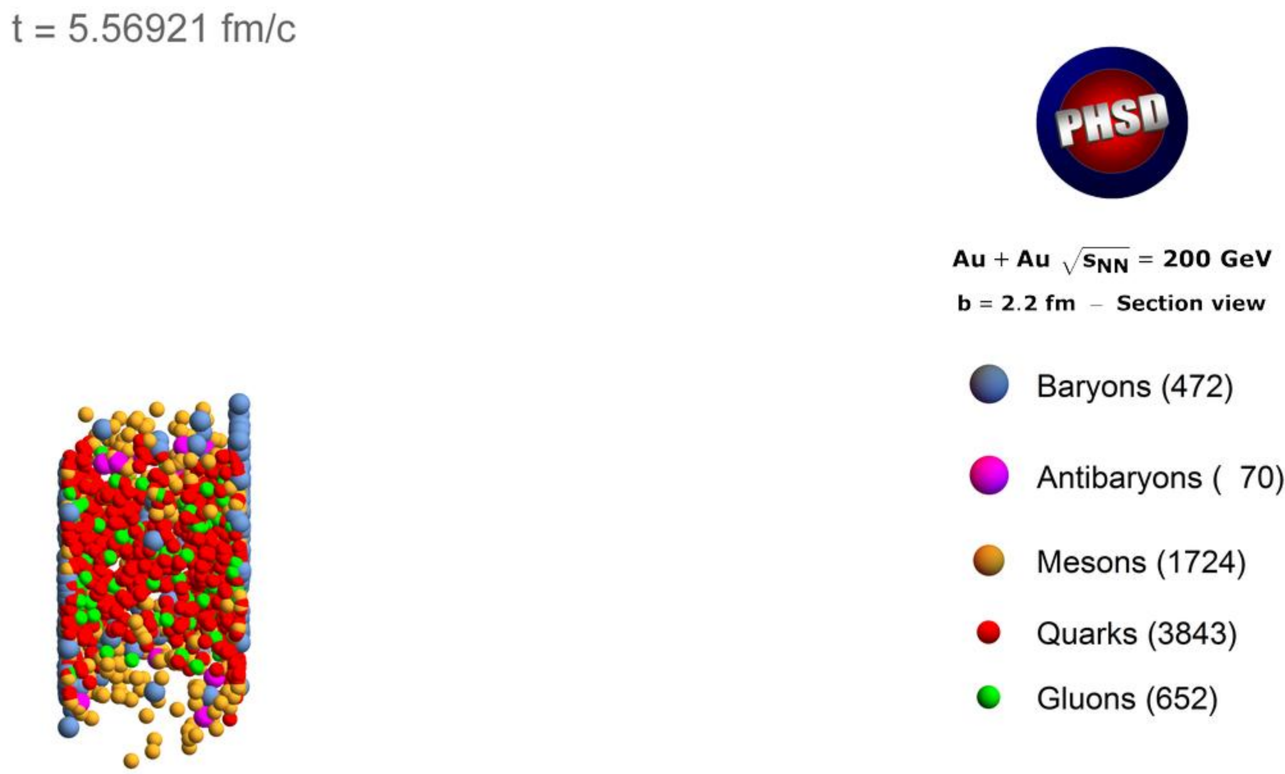


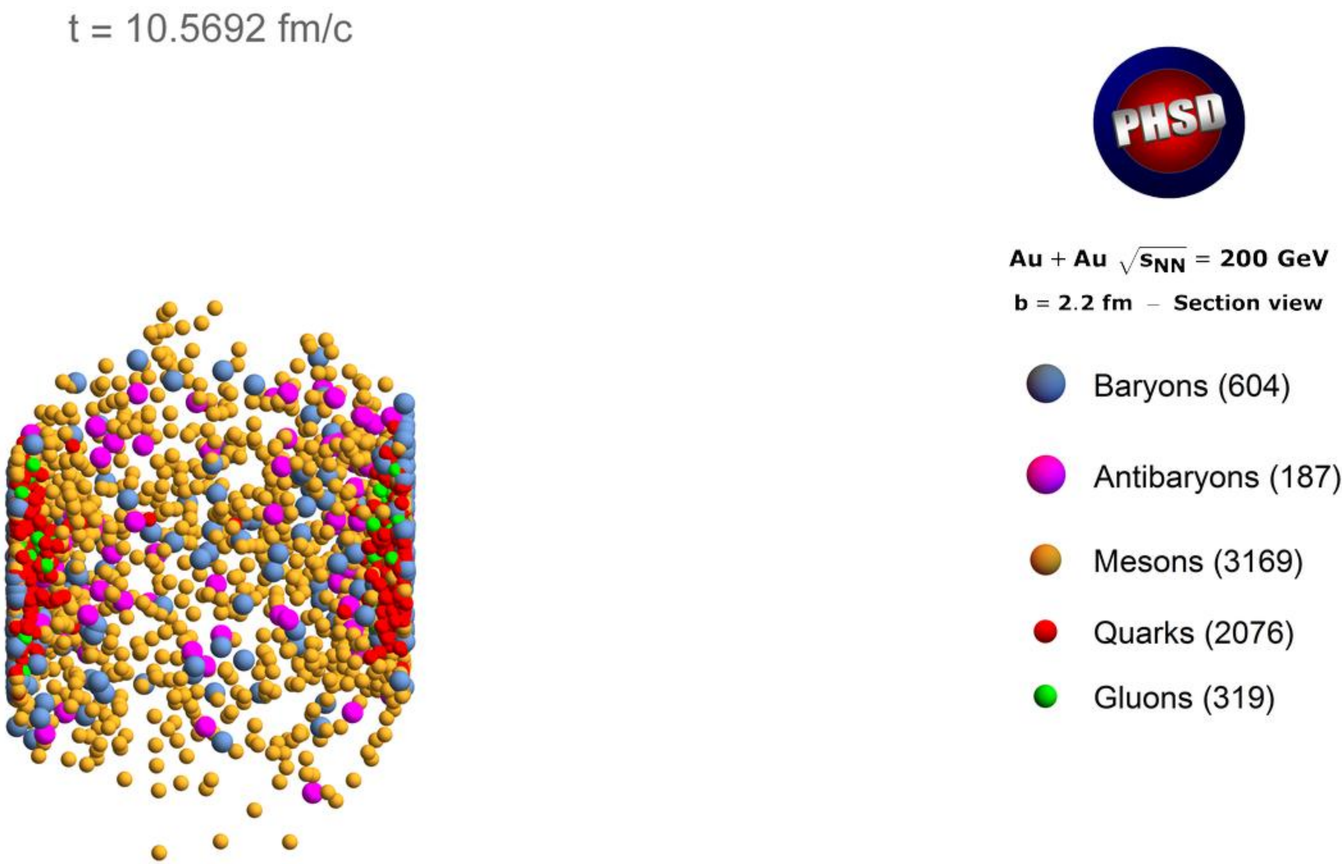
P.Moreau

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

t = 8.06922 fm/c

P.Moreau

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



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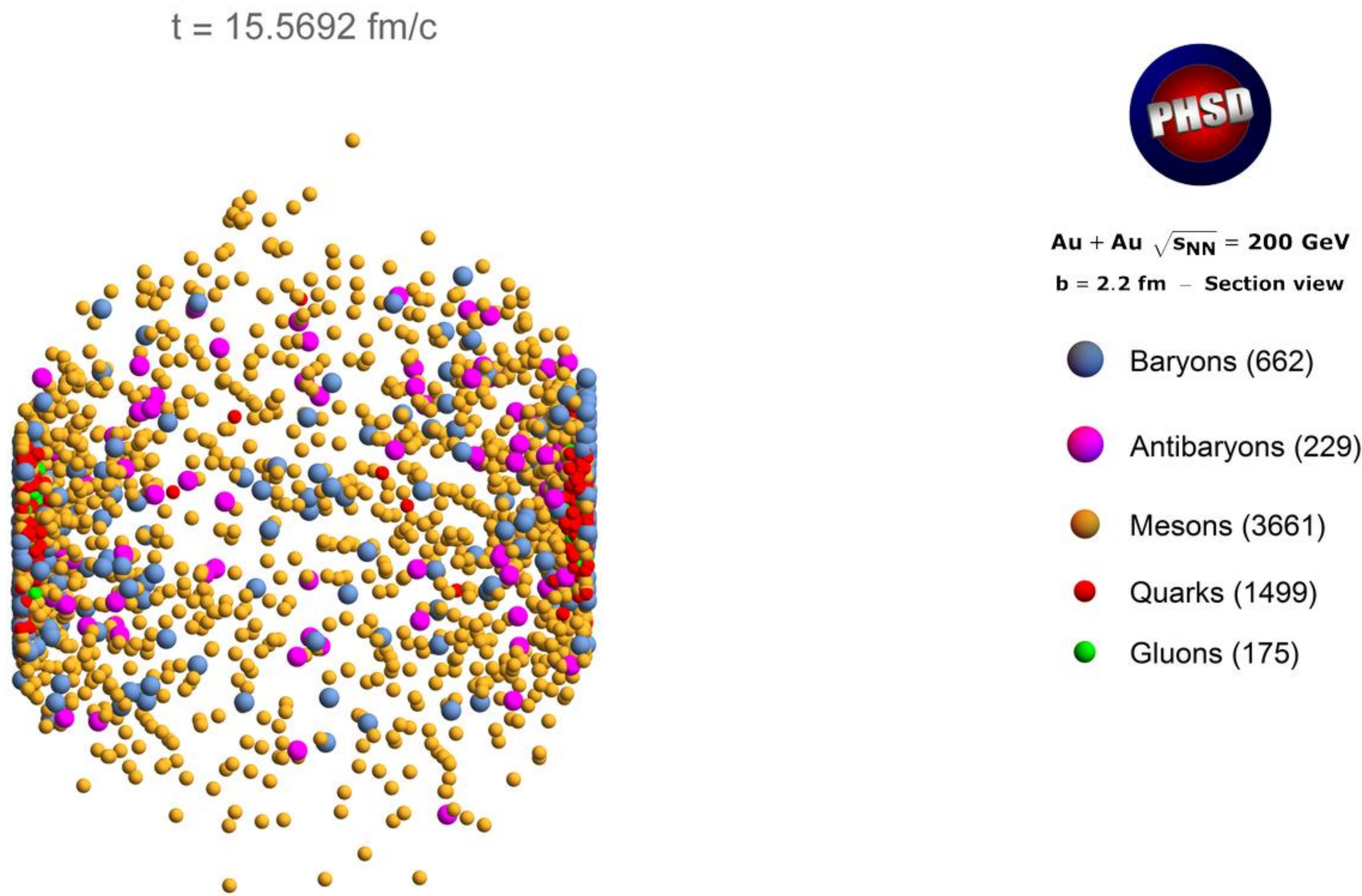

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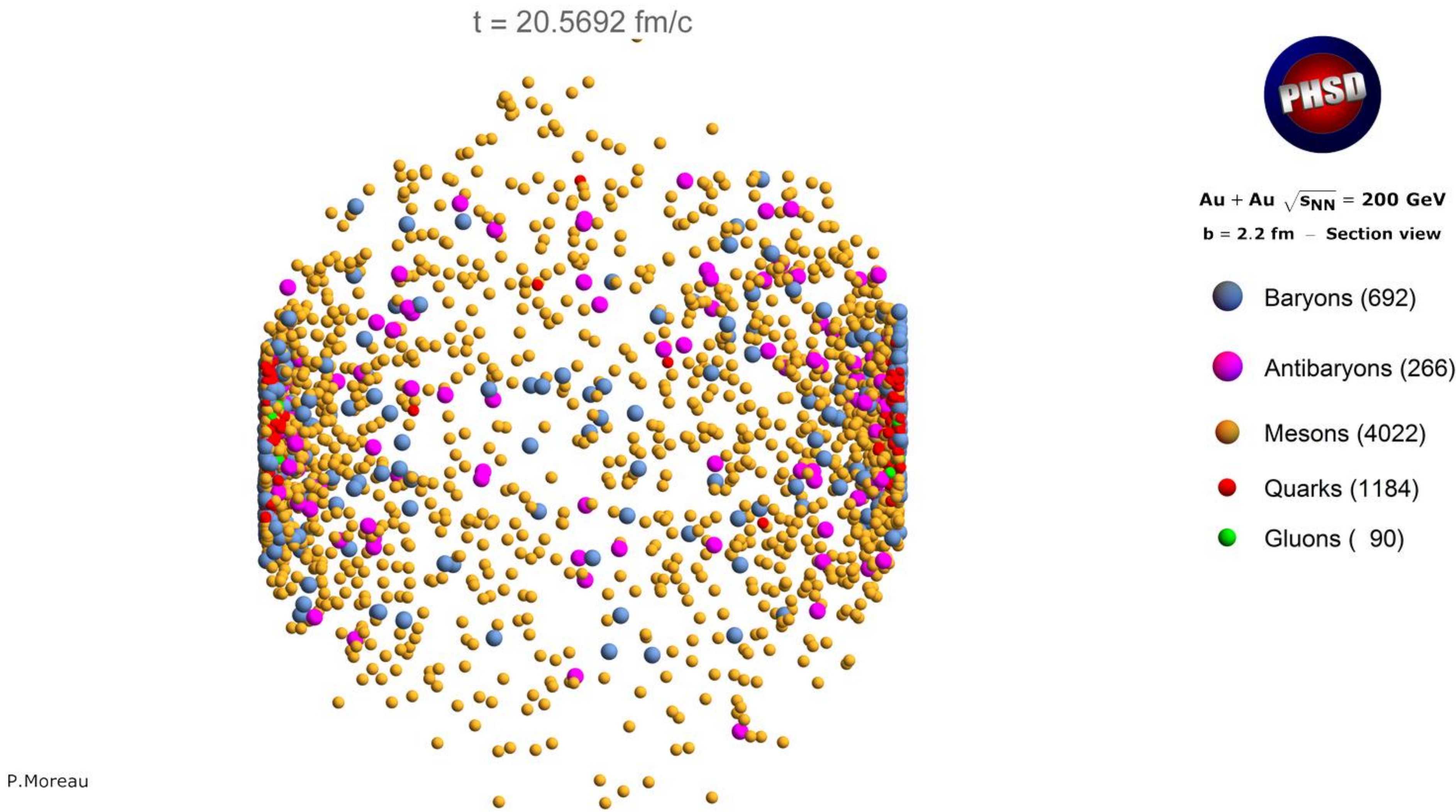
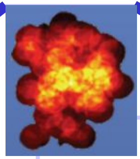


Dynamical models for HIC

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)

PHSD
- 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)

‚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