ACAT 2017

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Modeling of modifications induced by jets in the relativistic bulk nuclear matter

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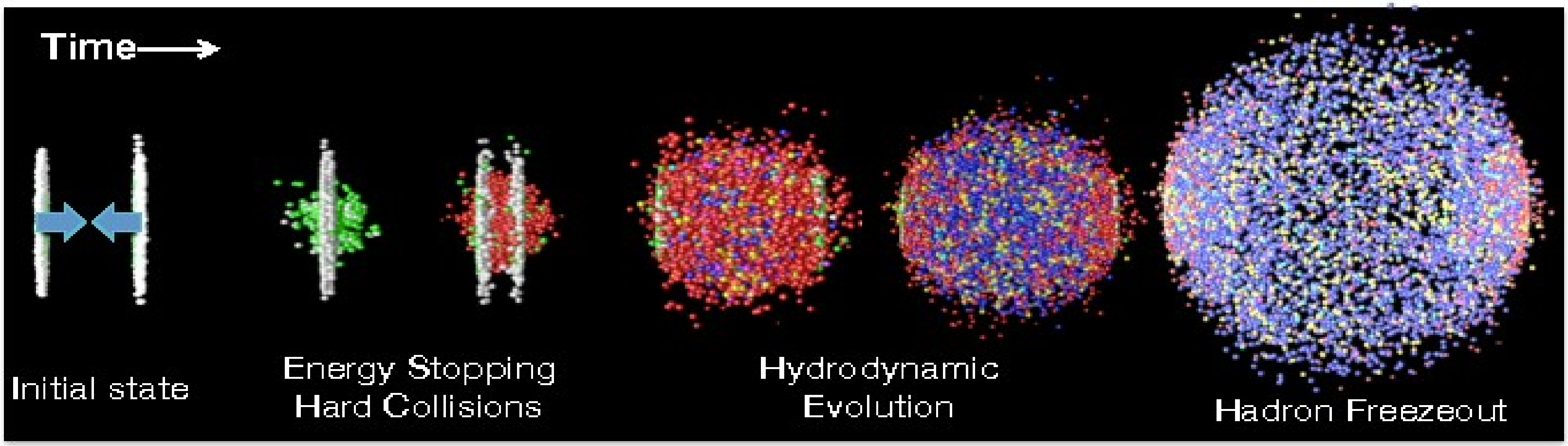
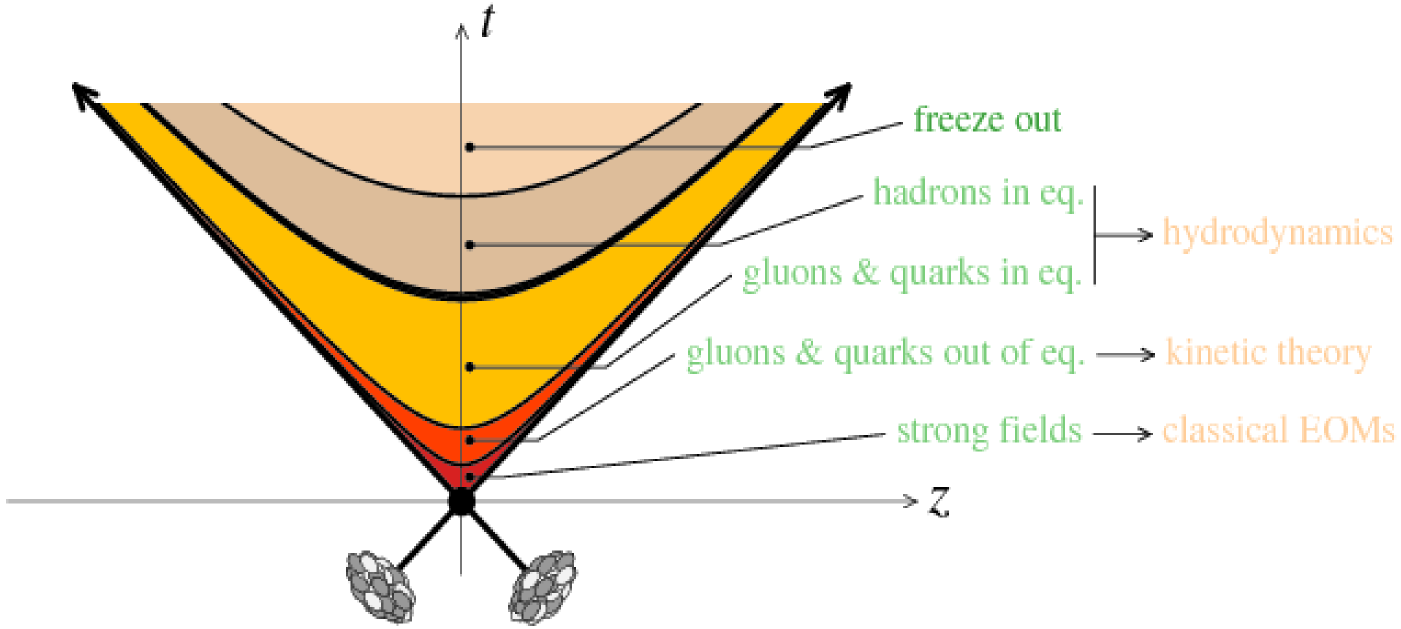
Agenda

- **Introduction**
- **Questions to address/study**
  - Jet-medium interactions and jet-induced flow
  - Event-by-event flow and flow fluctuations
- **Our (3+1) hydrodynamic code approach**
- **Graphics Cards (GPU) implementation**
- **Simulation results**

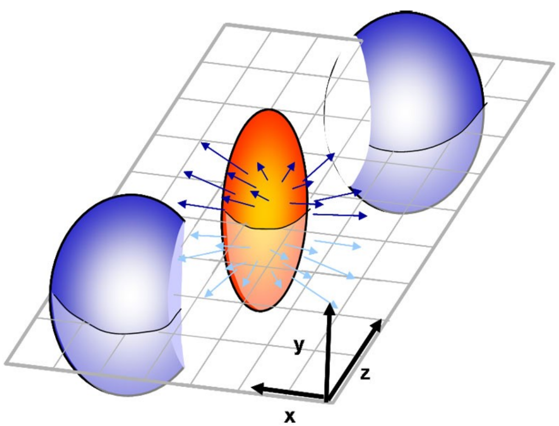
Introduction – heavy ion collision





Anisotropic Flow and Nonflow

- **Questions to address/study:**
  - Jet-medium interactions and jet-induced flow
  - Event-by-event flow and flow fluctuations



Measured momentum anisotropy

Flow → **Bulk properties**

Nonflow → **Jet-medium interactions, Energy loss**

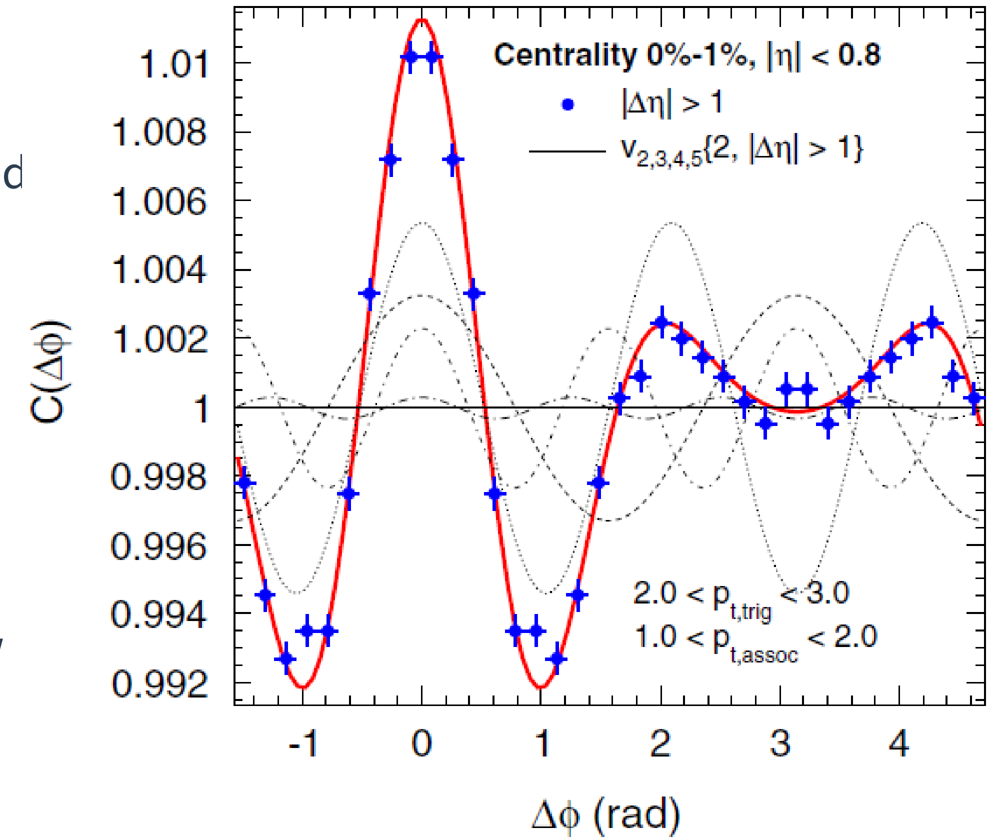
Flow fluctuations → **Initial state fluct.**

Questions to address/study

- Collective behaviours
- Study of high resolution of jets dynamics
- Event-by-event flow and flow fluctuations fast enough for good statistic
- Sophisticated implementation
- A lot of computer power (large amount of data grid)
- Single thread simulation on CPU takes ~ a few days
- Our multi thread simulation on GPU takes ~ a few minutes

Jet-medium interactions and jet-induced flow

- **ALICE and ATLAS claim:**
  - "double peak structure on away side in triggered two-particle correlations can be naturally explained by sum of measured anisotropic flow Fourier coefficients" → **everything is flow**
  - Is this really hydro-like flow (pressure driven expansion) ?
  - Or this structure is due to jet-medium interactions which show up in two-particle flow measurement?
- **We could use 3+1 hydro code + jet energy loss algorithm to address this question**

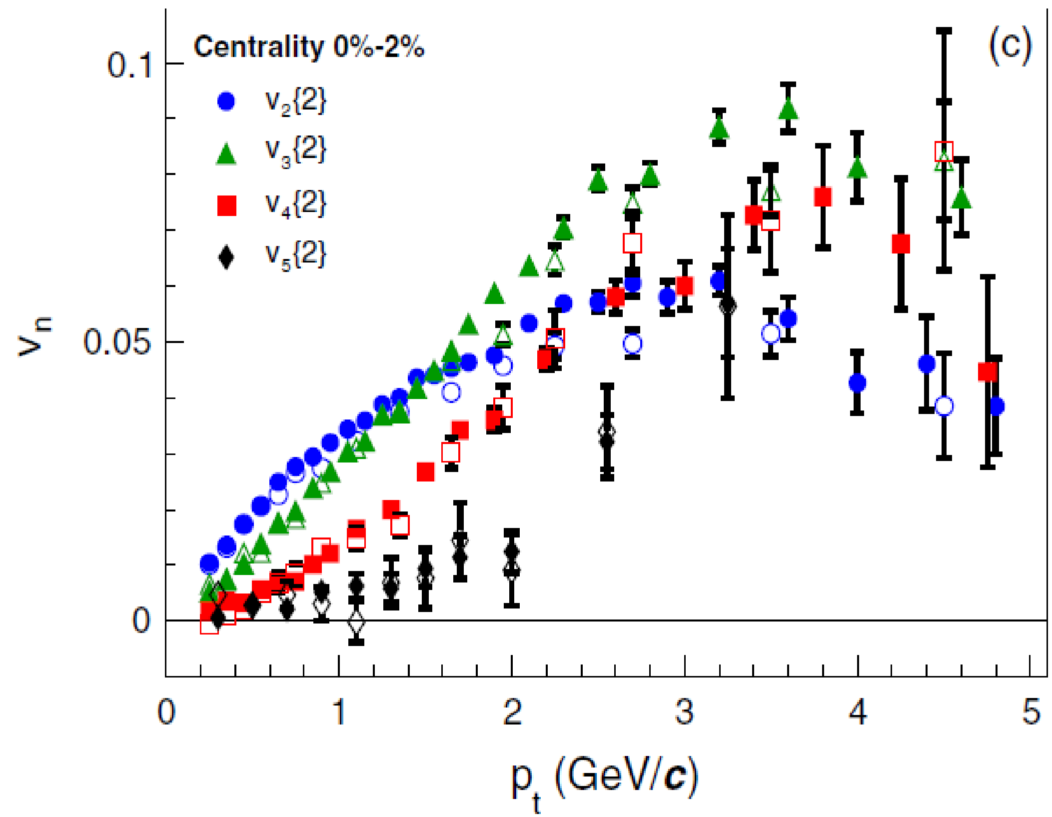


Alice, Phys. Rev. Lett. 107, 032301 (2011)

Event-by-event flow and flow fluctuations

- Hot topic: higher harmonic anisotropic flow
- Odd flow harmonics (v3 , v5 …) generated only due to fluctuations
- Fast and efficient hydro code is needed to study event-by-event fluctuations and flow*

→ GPU may help



Alice, Phys. Rev. Lett. 107, 032301 (2011)

(*) This can be (approximately) studied using averaged fluctuations, but full event-by-event simulations give more flexibility

Our hydrodynamic program sequence

- **Simulation stages:**
  - generating initial conditions
  - solving differential equations
  - check for freeze-out condition
  - computing freeze-out surface and particle emission functions

Hiperbolic conservation laws

$$\begin{aligned}\partial_t E + \nabla \cdot [(E+p)\,\vec{v}] &= 0 \\ \partial_t \vec{M} + \nabla \cdot \left[\vec{M}\vec{v} + p\hat{I}\right] &= 0 \\ \partial_t R + \nabla \cdot [R\,\vec{v}] &= 0\end{aligned}$$

Lab frame variables: **E,M,R, v**
Fluid element frame variables: **e,p,n**.

$$\begin{aligned}E &= (e+p)\gamma^2 - p \\ \vec{M} &= (e+p)\gamma^2\,\vec{v} \\ R &= n\gamma\end{aligned}$$

R -net charge density in calculational frame (laboratory frame),
E - energy density in calculational frame,
M - momentum density in calculational frame,
- energy density in the local rest frame of fluid
p - pressure in the local rest frame of fluid
n - charge density in the local rest frame of fluid

transformation from the calculational frame to the local rest frame of the fluid

$$\begin{aligned}e &= E - Mv\,, \\ n &= R\sqrt{1-v^2}\,.\end{aligned}$$

$$v = \frac{M}{E + p(E - Mv, R\sqrt{1-v^2})}$$

Equation system for the Riemann problem

$$\frac{\partial U}{\partial t}+\frac{\partial F(U)}{\partial x}+\frac{\partial G(U)}{\partial y}+\frac{\partial H(U)}{\partial z}=0$$

where U = (E, Mx, My, Mz, R) is a vector of conserved quantities in the laboratory rest frame

$$F(U)=\begin{bmatrix}(E+p)v_x\\ M_x v_x+p\\ M_y v_x\\ M_z v_x\\ Rv_x\end{bmatrix}\quad G(U)=\begin{bmatrix}(E+p)v_y\\ M_x v_y\\ M_y v_y+p\\ M_z v_y\\ Rv_y\end{bmatrix}\quad H(U)=\begin{bmatrix}(E+p)v_z\\ M_x v_z\\ M_y v_z\\ M_z v_z+p\\ Rv_z\end{bmatrix}$$

F, G, H are vectors of fluxes of those quantities in the x, y, z directions

$$U_{i,j,k}^{n+1}=U_{i,j,k}^{n}+\frac{\Delta t}{\Delta x}\left(F_{i-\frac{1}{2},j,k}-F_{i+\frac{1}{2},j,k}\right)+$$

$$+\frac{\Delta t}{\Delta y}\left(G_{i,j-\frac{1}{2},k}-G_{i,j+\frac{1}{2},k}\right)+\frac{\Delta t}{\Delta z}\left(H_{i,j,k-\frac{1}{2}}-H_{i,j,k+\frac{1}{2}}\right)$$

Numerical Scheme for a three-dimensional problem

WENO algorithm

- **Weighted Essentially Non-Oscillatory scheme**
  - high order in space
  - weighing reconstruction candidates (vertices):
  - in high gradient regions the oscillations are cut down
  - in monotonic field region algorithm is of highest order possible
  - in some cases may be more dissipative than classical reconstruction methods
  - two types: 5th and 7th order

→ generally very **good performance**

Hydrodynamics with sources

- Our goal: study of jet-QGP interactions (parton propagating through plasma)
- Source term form is of vital importance

$$\boxed{\partial_\mu T^{\mu\nu}(x) = J^\nu(x)\,.}$$

$$T^{\mu\nu} = (e+P)u^\mu u^\nu - P g^{\mu\nu},$$

$$\mathbf{w}_t + \mathbf{f}(\mathbf{w})_x = \mathbf{s}(\mathbf{w}, x),$$

$$\mathbf{w}_i^{n+1} = \mathbf{w}_i^n - \lambda\left(\widehat{\mathbf{f}}_{i+\frac{1}{2}} - \widehat{\mathbf{f}}_{i-\frac{1}{2}}\right) + \Delta t\mathbf{s}(\mathbf{w}_i^n, x_i)$$

$$-\frac{dp_a^0}{dt} = A \times \frac{8}{3}\pi\alpha_s{}^2 T^2\left(1 + \frac{1}{6}n_f\right)\log\frac{\sqrt{4Tp_a^0}}{m_D}.$$

arXiv:1402.6469v2 [nucl-th]

QGP – jet interaction

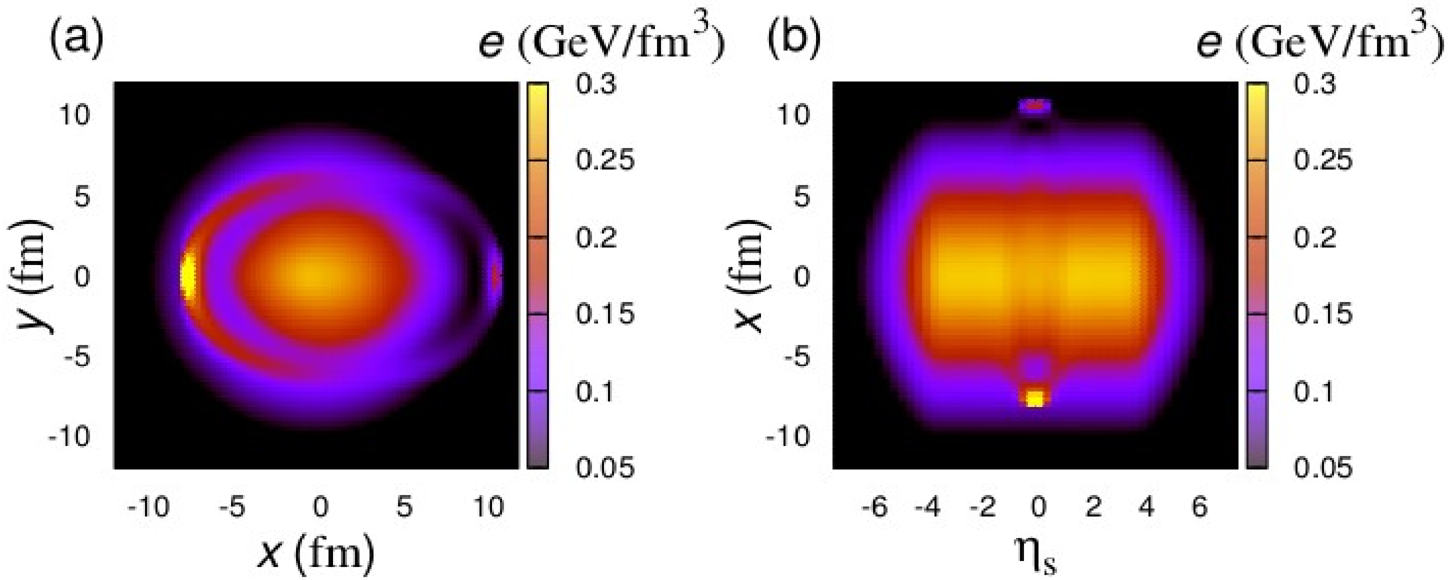


FIG. 1: (Color online) Energy density distribution of the expanding QGP fluid at $\tau = 9.6$ fm/c (a) in transverse plane at $\eta_s = 0$ and (b) in reaction plane at $y = 0$. A pair of energetic partons is created at $(\tau = 0, x = 1.5\,\text{fm}, y = 0, \eta_s = 0)$ and travels in the opposite direction along the x-axis at the speed of light.

arXiv:1402.6469v2 [nucl-th]

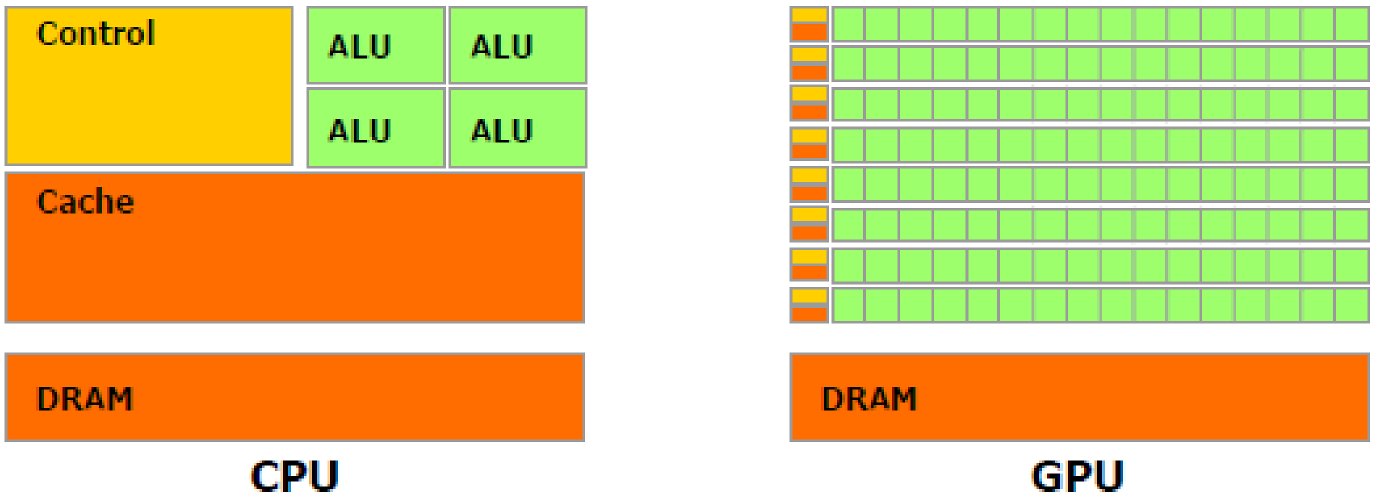
Energy deposition

- Term responsible for modeling interactions between the jet and the plasma
- We used:

$$\left(-\frac{\mathrm{d}E}{\mathrm{d}x}\right) = \kappa_{rad}\frac{C_R}{C_F}T^3x + \kappa_{coll}\frac{C_R}{C_F}T^2,$$

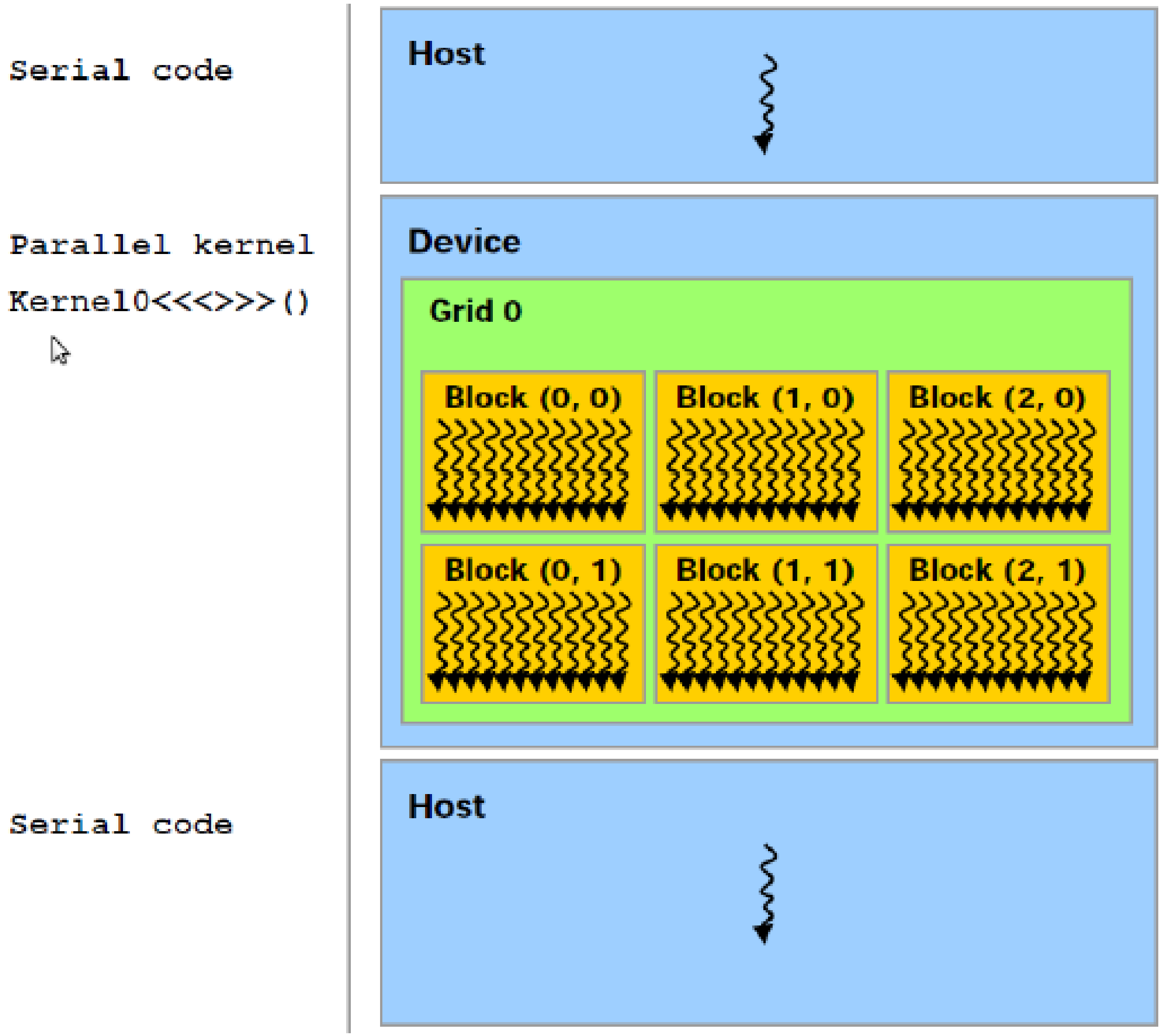
- Two mechanisms of jet energy loss:
  - gluon radiation
  - collisions of partons in dense medium

CPU vs. GPU architectures



- CPU multiple cores
- GPU thousands of cores
- A lot of resources dedicated to computations
- Parallel streaming multiprocessors
- Limited memory hierarchy

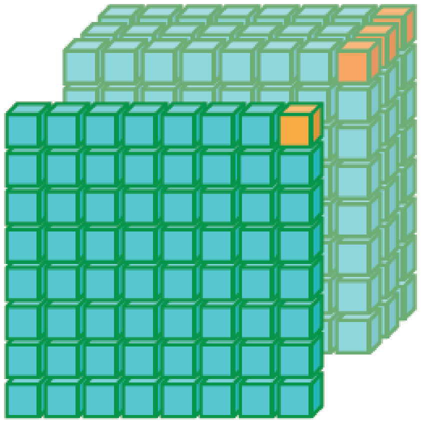
GPU execution

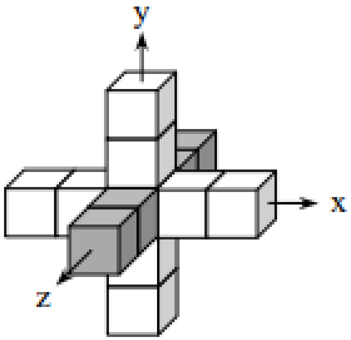


Hydrodynamics on GPU

- Each thread corresponds to a point in XY plane. The kernel then loops over Z axis, so that each thread calculates points on a line parallel to OZ.

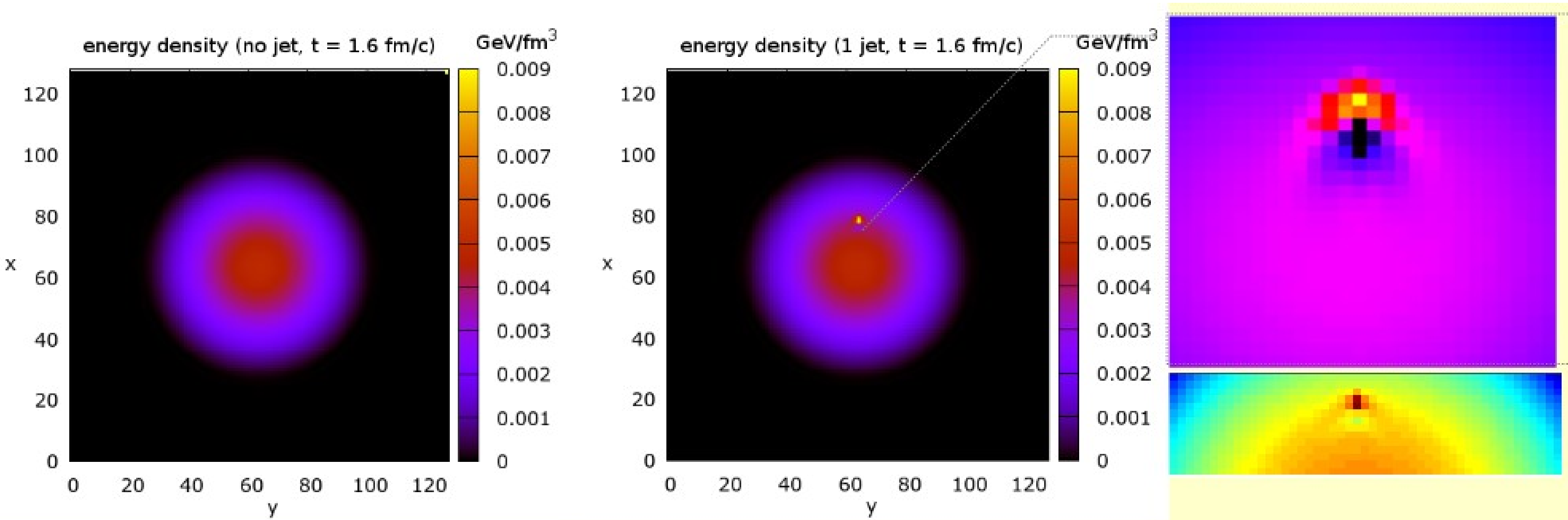
```
For n in 1..N do
   For k in 3..Z-Dimension - 2 do
      Load neighbor cells from surface
      memory.
      Compute cell U(i,j,k).
      Write result to surface memory.
      Synchronize threads.
   End for
End for
```





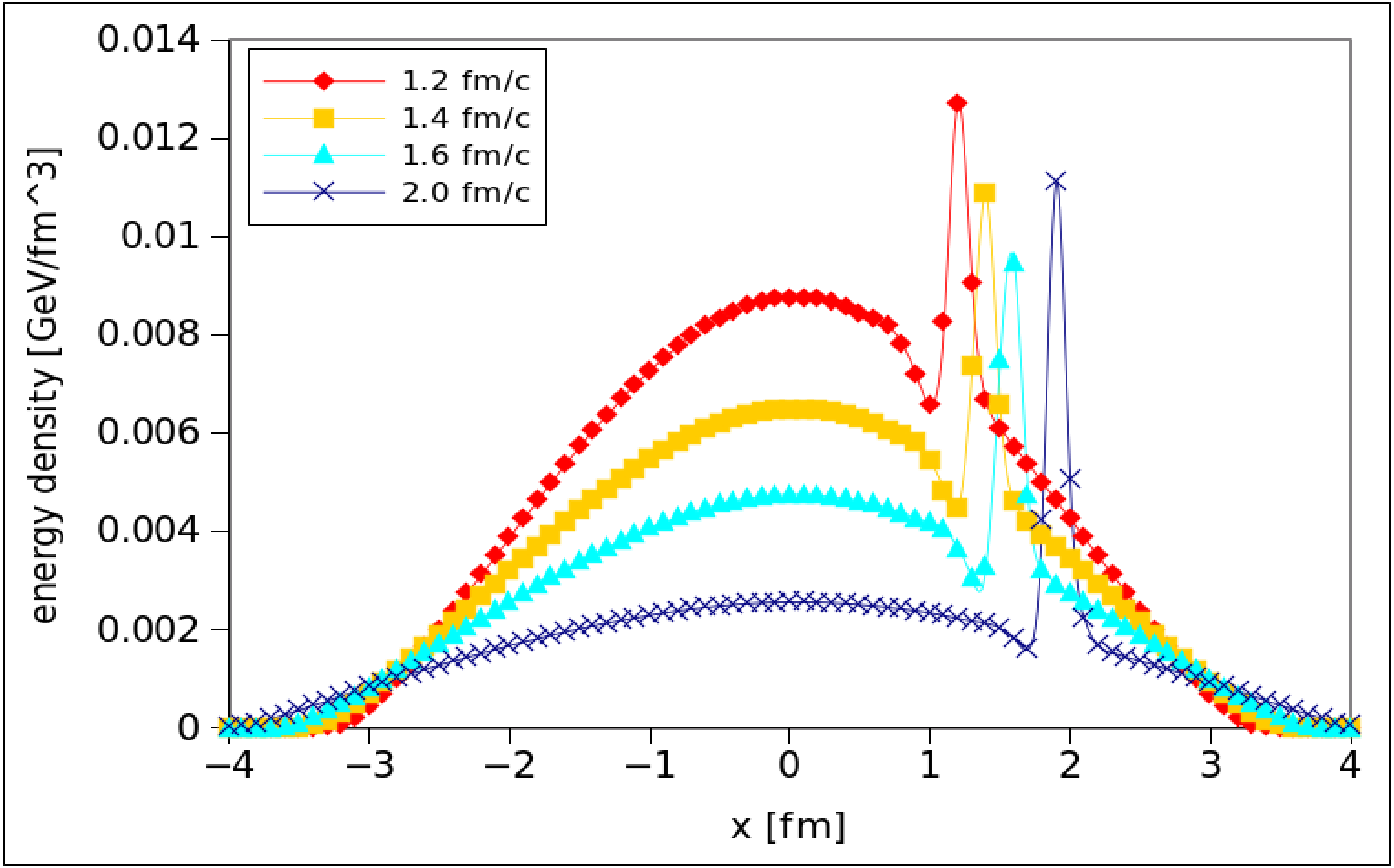
Algorithm is implemented using **surface memory**

Simulation results



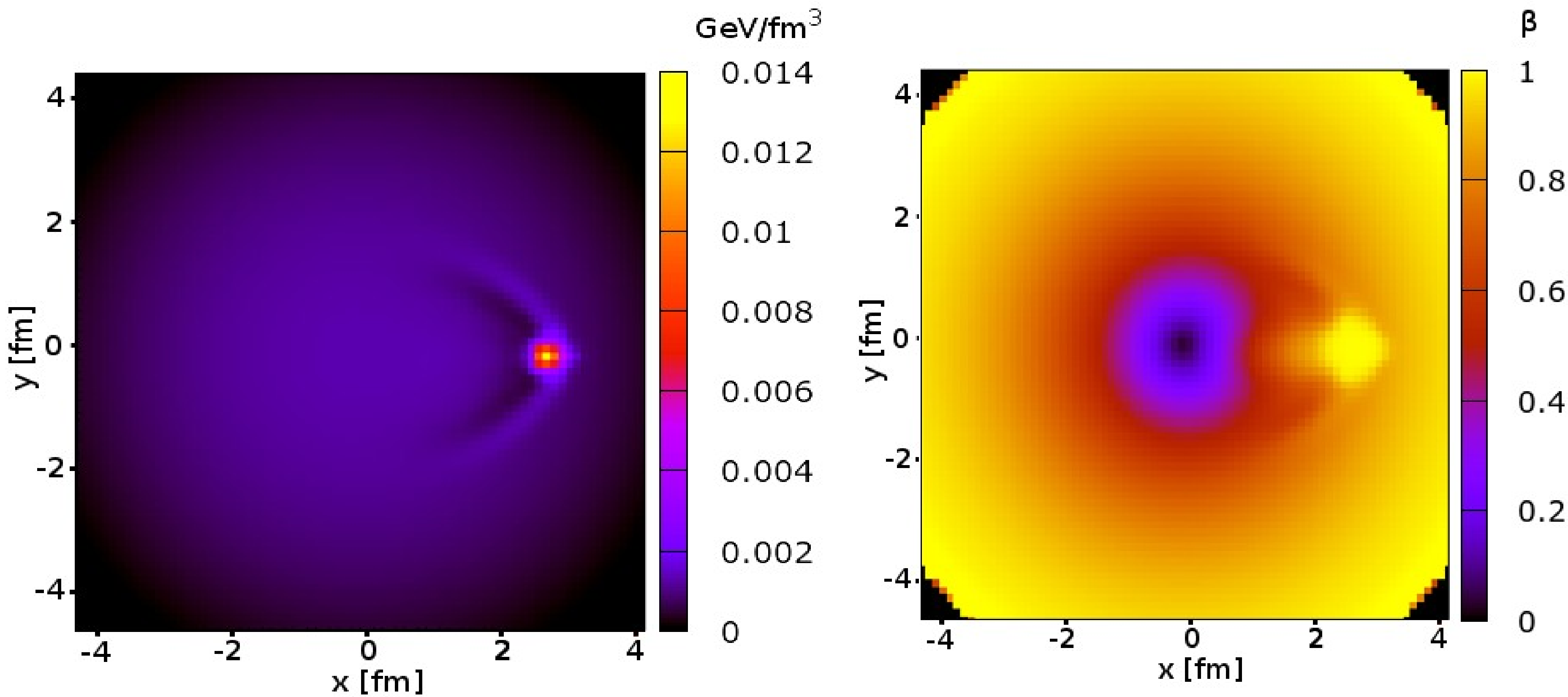
Energy density cross-section at $z = 0$. Left: no jet, middle: propagation of jet, right: zoom on the forming Mach cone (x, y are cell indices)

Simulation results

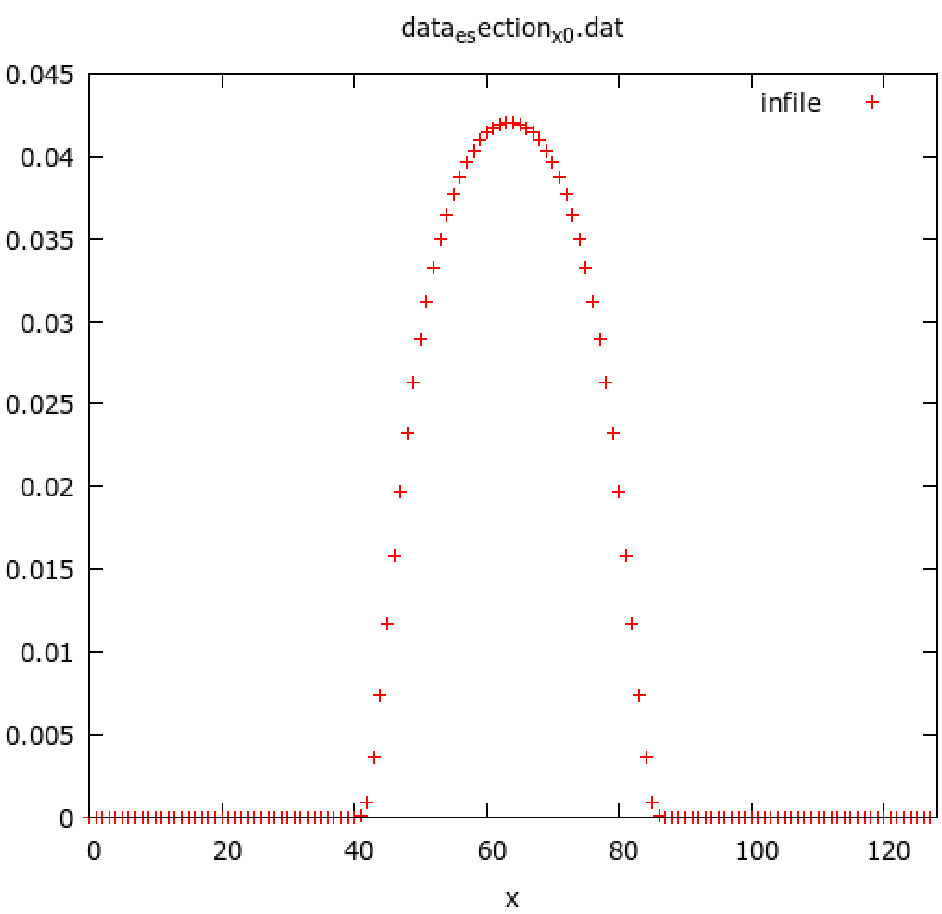


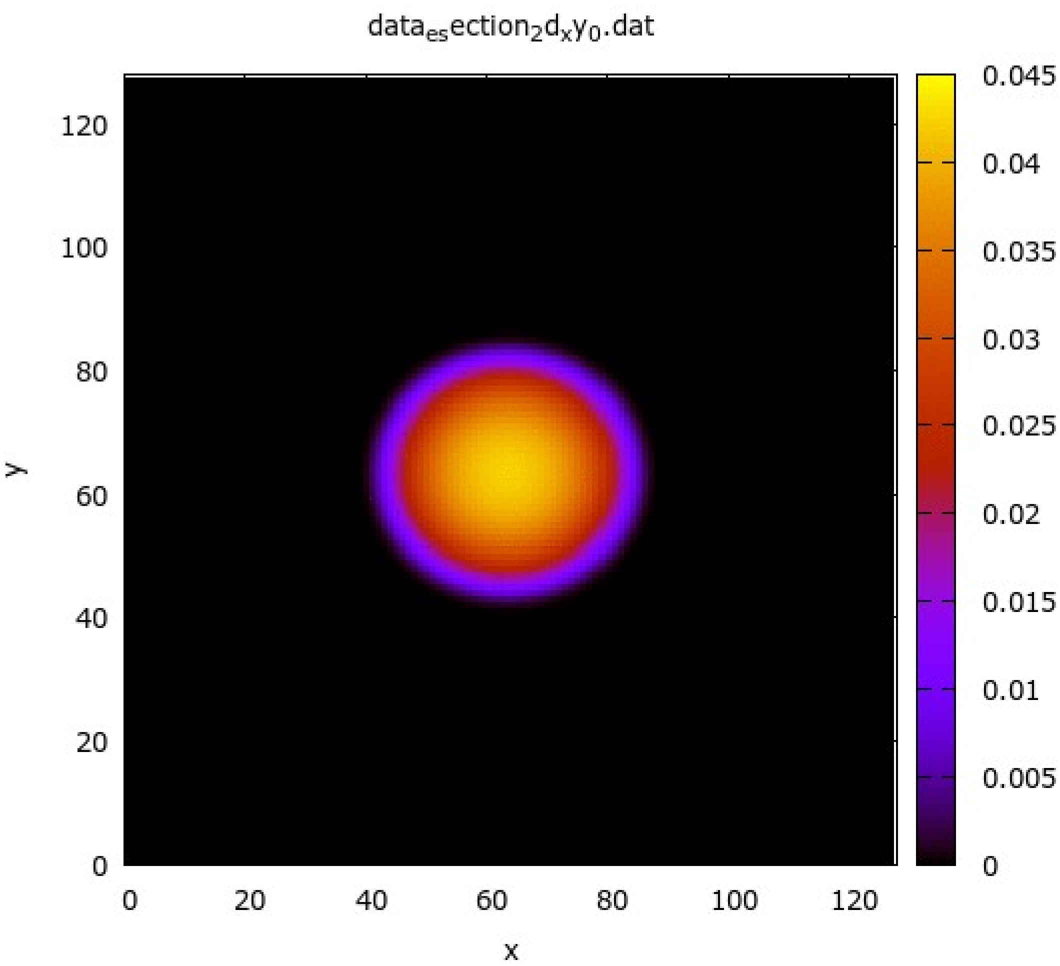
Simulation results – single parton

- Energy density and velocity profile (xy plane, z=0)
  - dx = 0.1 fm, dt = 0.02 fm/c, grid: 256^3, EOS p = e/3, t = 2.4 fm/c

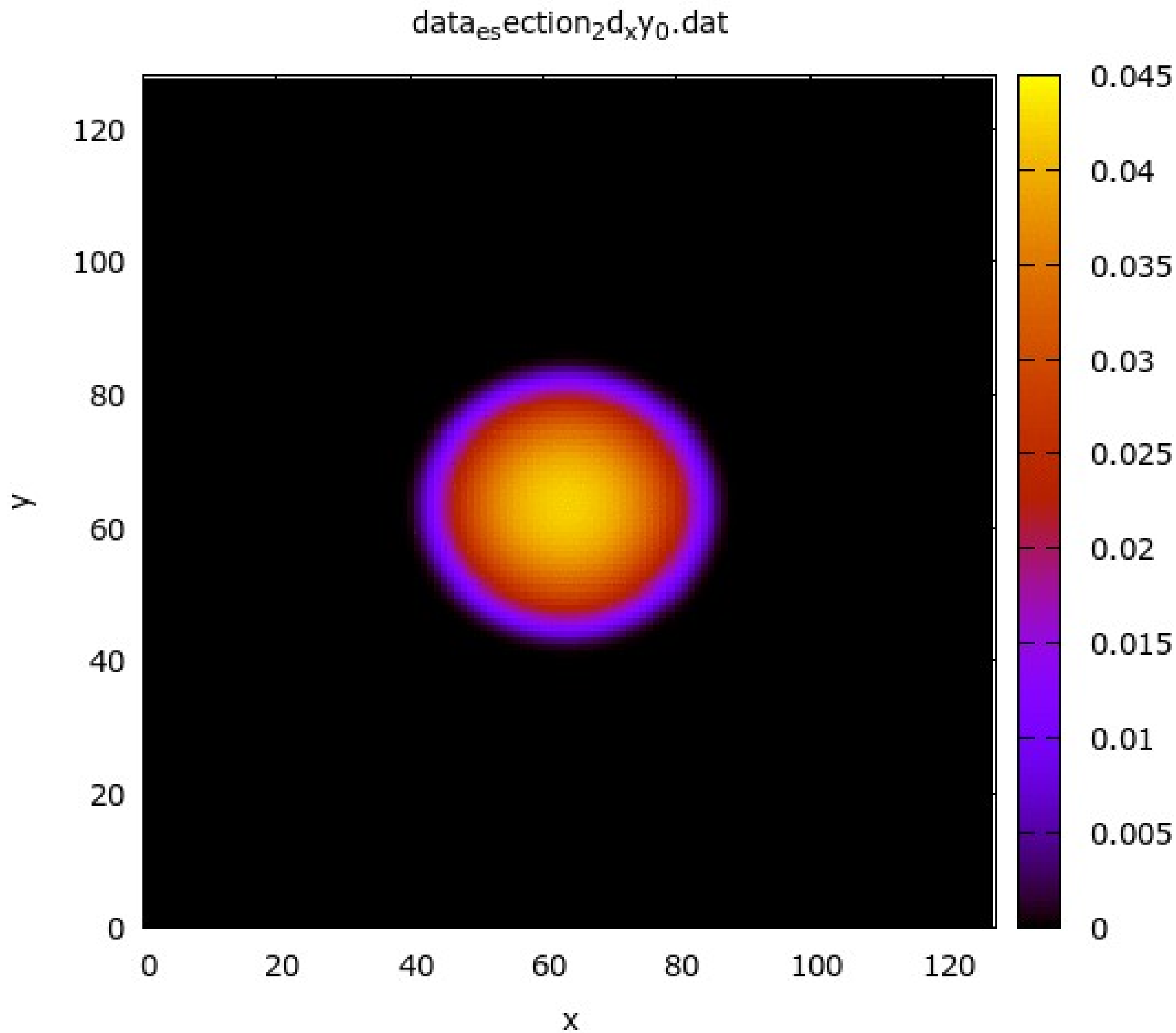


Simulation results





Simulation results – two partons



Freeze-out

- **freeze-out implementation – in progress**
  - Cooper-Frye formula:

$$E\frac{\mathrm{d}N}{\mathrm{d}p^3} = \int_\sigma \mathrm{d}\sigma_\mu p^\mu f(x,p) \approx \sum_\sigma \Delta\sigma_\mu p^\mu f(x,p)$$

  - freezeout conditions: isochronic, isothermal
  - momentum distribution on hypersurface
  - use existing hadron freeze-out generator
    - THERMINATOR 2

Summary

- **initial conditions from UrQMD**
  - short simulation (~1fm/c)
  - Monte Carlo → energy & momentum density
- **hydrodynamics with sources**
- **algorithms, performance & stability tests**
  - implemented & tested: WENO
- **matching the parametrization (custom class / THERMINATOR2::Lhyquid3d) is ongoing**

Thank you for your attention

additional / backup slides

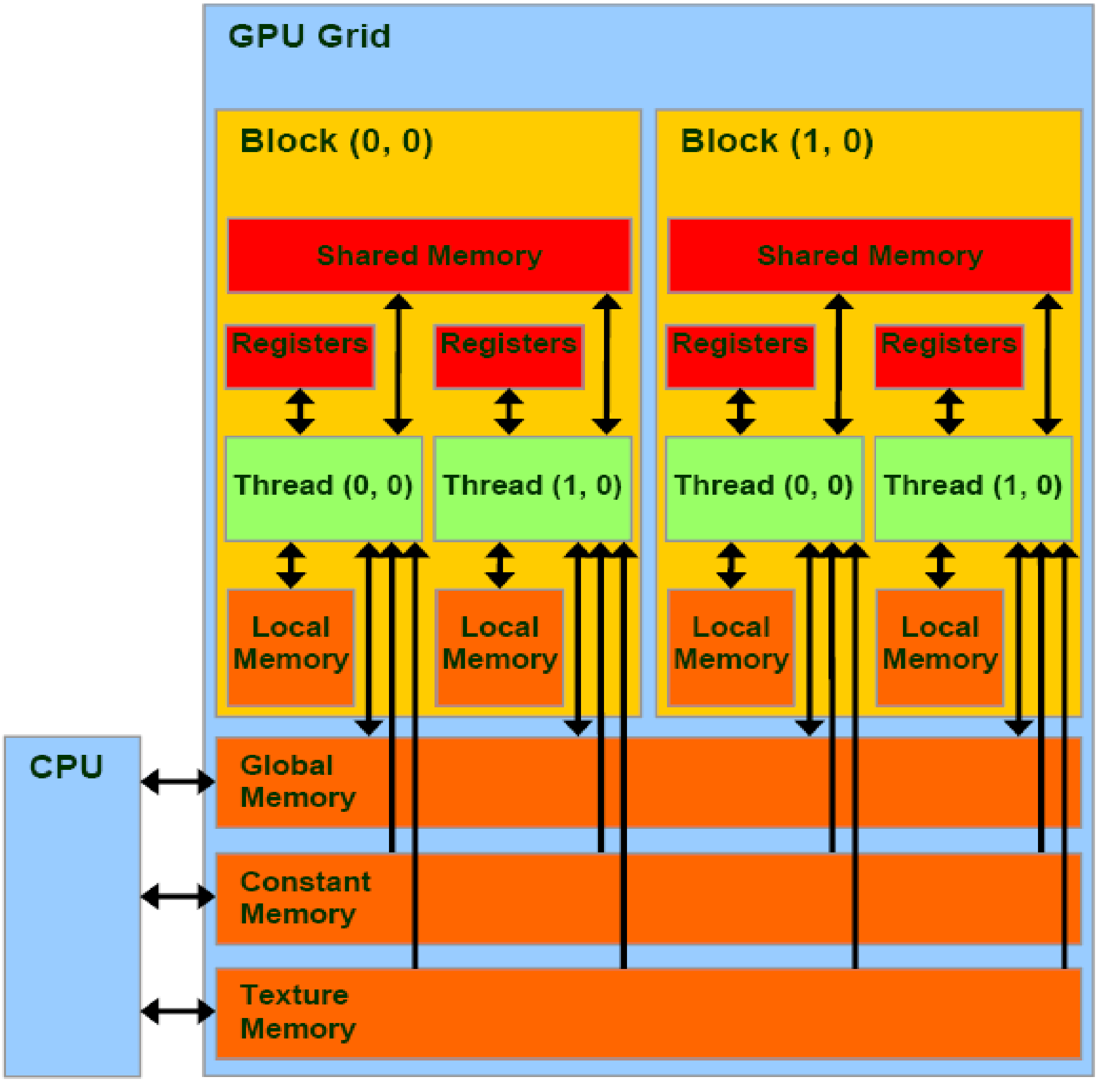
Why GPU?

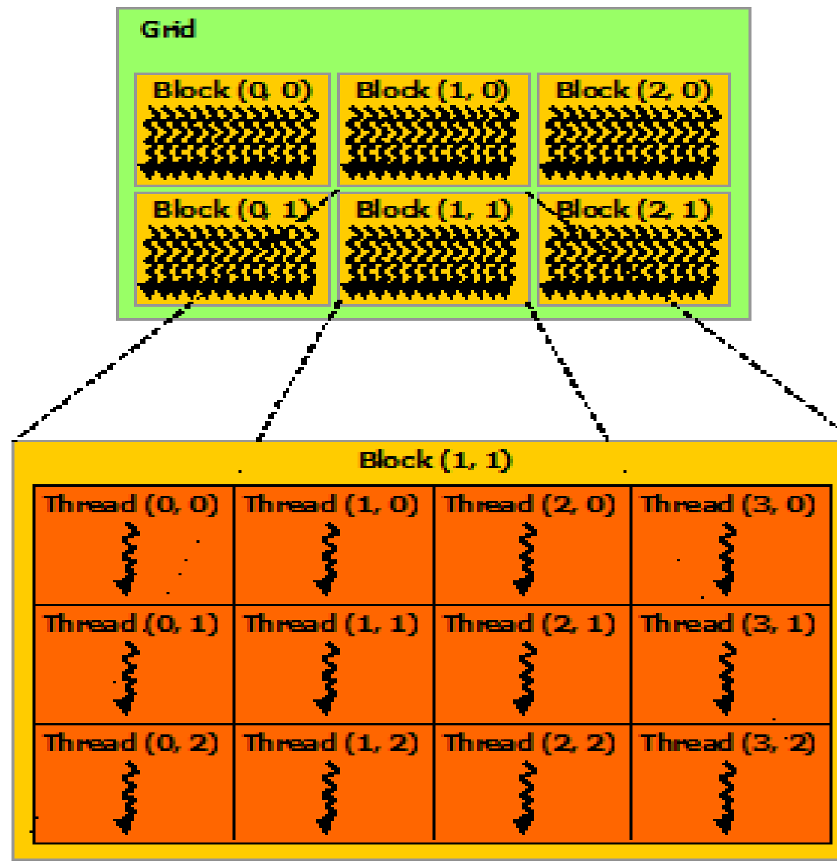
- **Full simulation on standard CPU:**
  - from few hours to few days (depending on grid size)
- **Computing on clusters (CPU)?**
  - effective but costly
- **Another solution – GPU computing**
  - great speed-up for parallel problems
  - cost effective (lowest price per FLOPS)
  - flexible (scalable)
  - C-based language (easy to learn)

GPU architecture

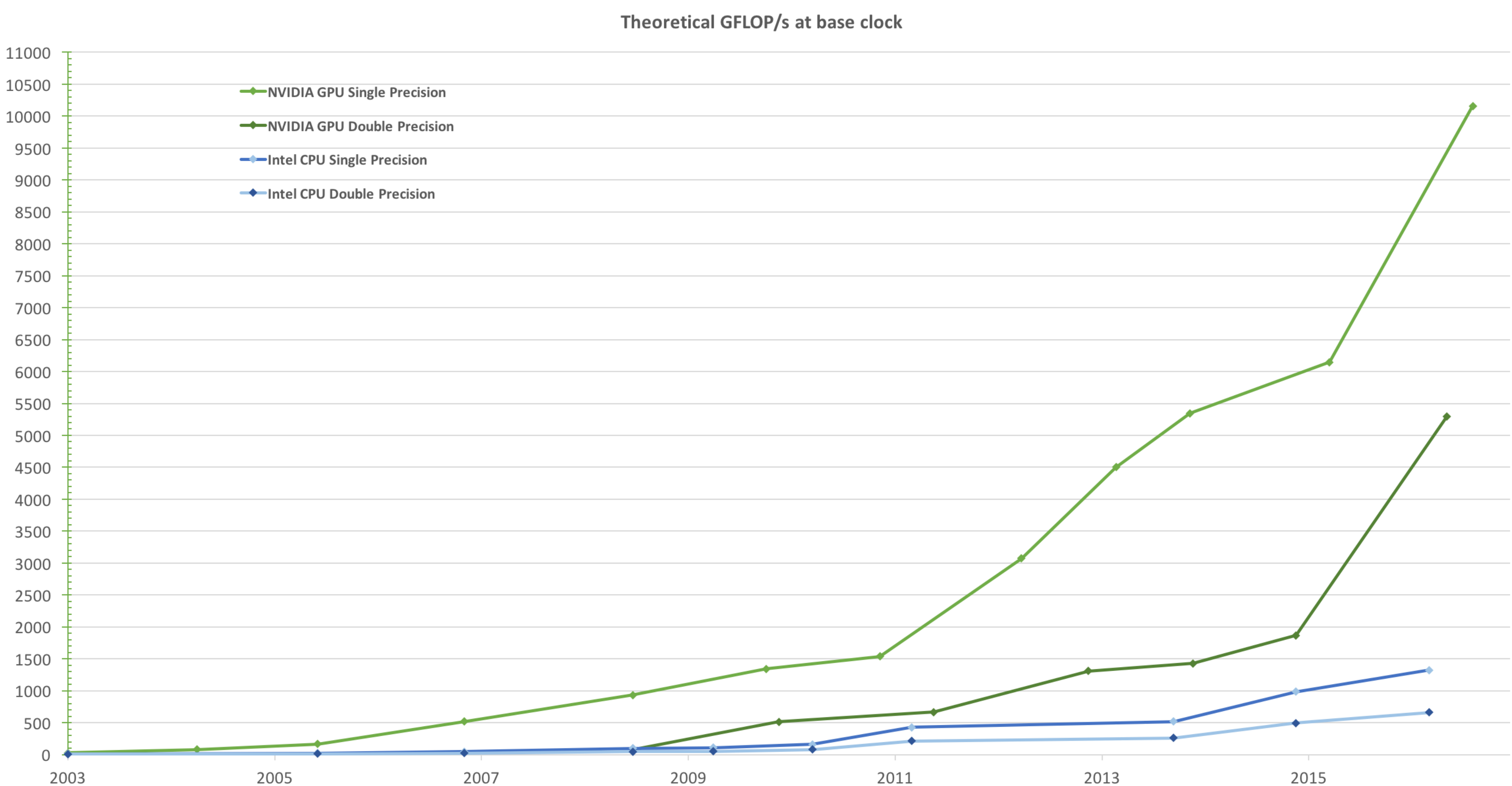
- GPU is specialized for compute-intensive, highly parallel computation - exactly what graphics rendering is about - and therefore designed such that more units are devoted to data processing rather than data caching and flow control
- well-suited to address problems that can be expressed as data-parallel computations - the same program is executed on many data elements in parallel - with high arithmetic intensity - the ratio of arithmetic operations to memory operations
- relative speed-up (GPU vs. CPU): up to $\sim 10^2$

Memory hierarchy and threads organization





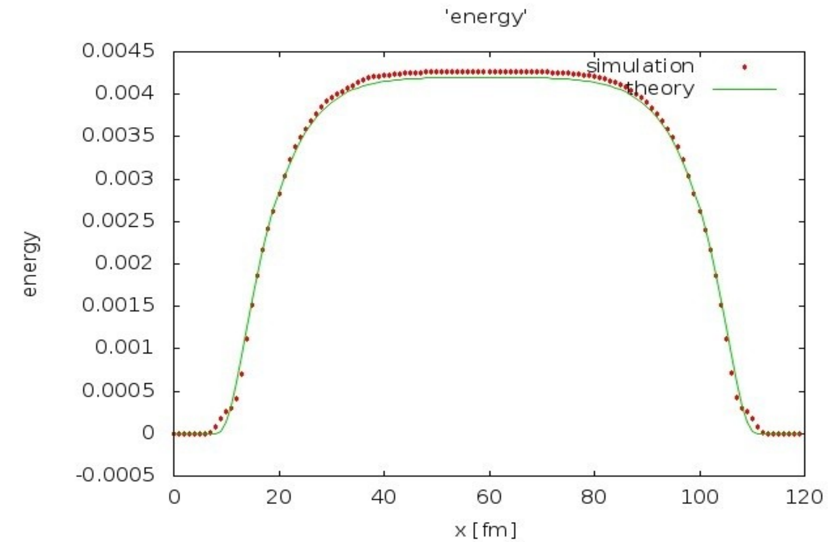
Comparison of performance tests

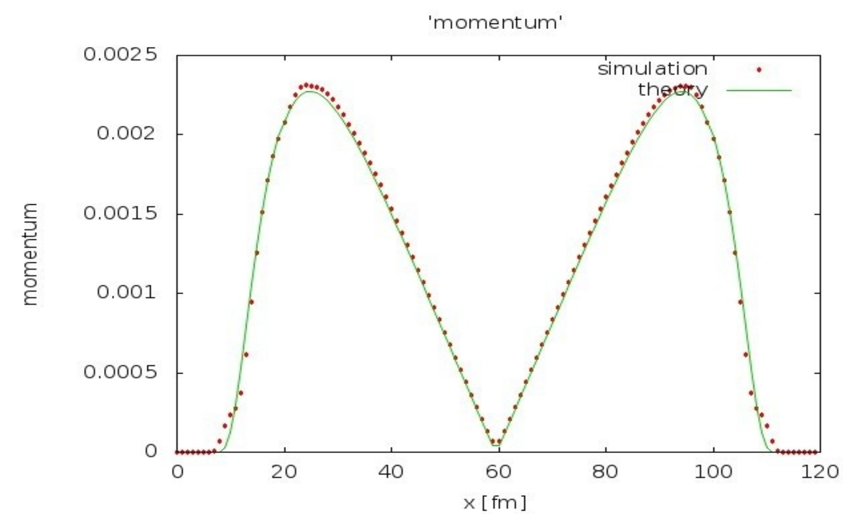


Ellipsoidal flow (initial conditions)

- Collective effect (QGP characteristic)
  - finite system, EOS: p=0
- dimensions: 120×120×120 cells
- $\Delta x = 0.1$fm, $\Delta t = 0.02$fm/c
- 150 steps

$C_e = 2.0$ GeV/fm3
$C_n = 0.75$ GeV/fm3
$T_0 = 2.0$
$T_1 = 0.4$
$T_2 = 0.6$
$T_3 = 0.8$
$b_e = 1.0$
$b_n = 1.0$
$p_0 = 0.0$





UrQMD model

- Ultra-relativistic Quantum Molecular Dynamics
- Monte Carlo simulation package for nuclear collisions (including early stage interactions and post-freezeout kinematics)

UrQMD - output

outputfile_Pb.txt (~/MGR_HYDRO/initial_urqmd) - gedit

File Edit View Search Tools Documents Help

outputfile_Pb.txt

```
UQMD   version:       20030   1000  20030  output_file  14
projectile:  (mass, char)  208  82   target:  (mass, char)  208  82
transformation betas (NN,lab,pro)     0.0000000  0.9953427 -0.9953427
impact_parameter_real/min/max(fm):    2.00  0.00  2.00  total_cross_section(mbarn):     125.66
equation_of_state:    0  E_lab(GeV/u): 0.2000E+03  sqrt(s)(GeV): 0.1946E+02  p_lab(GeV/u): 0.2009E+03
event#         1 random seed:       12345 (fixed)  total_time(fm/c):        1 Delta(t)_O(fm/c):        1.000
op  0    0    0    1 *  0    0    0    0    0    0    0    0    0    0    0
op  0    0    0    0    0    0    1    0    1    0    0    0    0    2    1
op  0    0    0    1    1    0    0    0    0    0    0    0    0    1    0
pa 0.1000E+01 * 0.5200E+00   0.2000E+01   0.3000E+00   0.0000E+00   0.3700E+00   0.0000E+00   0.9300E-01   0.3500E+00   0.2500E+00   0.0000E+00   0.5000E+00
pa 0.2700E+00   0.4900E+00   0.2700E+00   0.1000E+01   0.1600E+01   0.8500E+00   0.1550E+01   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00
pa 0.9000E+00   0.5000E+02   0.1000E+01   0.1000E+01   0.1000E+01   0.1500E+01   0.1600E+01   0.0000E+00   0.2500E+01   0.1000E+00   0.3000E+01   0.2750E+00
pa 0.4200E+00   0.1080E+01   0.8000E+00   0.5000E+00   0.0000E+00   0.5500E+00   0.5000E+01   0.8000E+00   0.5000E+00   0.8000E+06   0.1000E+01   0.2000E+01
pvec: r0              rx              ry              rz              p0              px              py              pz              m          ityp 2i3 chg lcl#  ncl or
         416           0
       0        0        0        0        0        0        0        0
  0.00000000E+00  0.61099591E+01 -0.28393721E+01 -0.99626092E+00  0.11001949E+02  0.16037956E+00 -0.11840749E+00  0.10962950E+02  0.90380091E+00        1   1   1       0    0   0
  0.00000000E+00 -0.18987429E+01 -0.13829171E+01 -0.92541293E+00  0.91657277E+01 -0.17692738E+00  0.40985448E-01  0.91187084E+01  0.90925109E+00        1   1   1       0    0   0
  0.00000000E+00 -0.35632387E+01 -0.70830572E+00 -0.70868658E+00  0.11117605E+02  0.16259113E-01  0.90984848E-01  0.11079269E+02  0.91781738E+00        1   1   1       0    0   0
  0.00000000E+00  0.22001082E+01 -0.13372307E+01 -0.43907619E+00  0.85340738E+01  0.83976038E-01 -0.36548416E-01  0.84841743E+01  0.91695976E+00        1   1   1       0    0   0
  0.00000000E+00  0.10153121E+01 -0.49639108E+01 -0.10555902E+01  0.10943882E+02 -0.19740149E+00  0.18157218E+00  0.10904503E+02  0.88792929E+00        1   1   1       0    0   0
  0.00000000E+00 -0.16195766E+01 -0.22302280E+01 -0.45642678E+00  0.97478235E+01  0.12660479E+00  0.19021252E+00  0.97033829E+01  0.90122902E+00        1   1   1       0    0   0
  0.00000000E+00  0.36048057E+01  0.14602044E+01 -0.66712296E+00  0.98734190E+01 -0.95380914E-01 -0.11568479E+00  0.98295091E+01  0.91797284E+00        1   1   1       0    0   0
  0.00000000E+00  0.13130267E+01 -0.41542281E+01 -0.11685357E+01  0.10670021E+02  0.14764340E+00 -0.86859783E-01  0.10629632E+02  0.91154462E+00        1   1   1       0    0   0
  0.00000000E+00  0.17755413E+00  0.16886709E+01 -0.91141529E+00  0.10563075E+02 -0.13306053E+00  0.43823594E-03  0.10522257E+02  0.91812603E+00        1   1   1       0    0   0
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  0.00000000E+00  0.23452131E+01 -0.60361293E+01 -0.10067200E+01  0.91368083E+01 -0.13780045E+00 -0.16949629E+00  0.90897376E+01  0.90012095E+00        1   1   1       0    0   0
  0.00000000E+00 -0.32612488E+01 -0.27037071E+01 -0.96017069E+00  0.88883892E+01 -0.10211154E-01  0.15995070E+00  0.88401332E+01  0.91094423E+00        1   1   1       0    0   0
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  0.00000000E+00 -0.91715486E+00  0.46796862E+01 -0.48441300E+00  0.95083602E+01  0.31083883E-01  0.12158875E+00  0.94628038E+01  0.92114450E+00        1   1   1       0    0   0
  0.00000000E+00 -0.23249251E+01 -0.67729907E+00 -0.10845515E+01  0.10459035E+02  0.17616040E+00 -0.58439968E-01  0.10417707E+02  0.91013410E+00        1   1   1       0    0   0
  0.00000000E+00  0.23551537E+01  0.30623579E+01 -0.51094082E+00  0.87148899E+01  0.12451564E+00  0.54372328E-01  0.86658411E+01  0.91325977E+00        1   1   1       0    0   0
  0.00000000E+00  0.42546944E+01  0.20689252E+01 -0.73401790E+00  0.10656352E+02  0.23306757E+00 -0.67608183E-01  0.10615810E+02  0.89640483E+00        1   1   1       0    0   0
  0.00000000E+00  0.23238839E+01 -0.31861250E+01 -0.32055131E+00  0.10210140E+02 -0.23121119E-01  0.14493777E+00  0.10167739E+02  0.91788010E+00        1   1   1       0    0   0
```
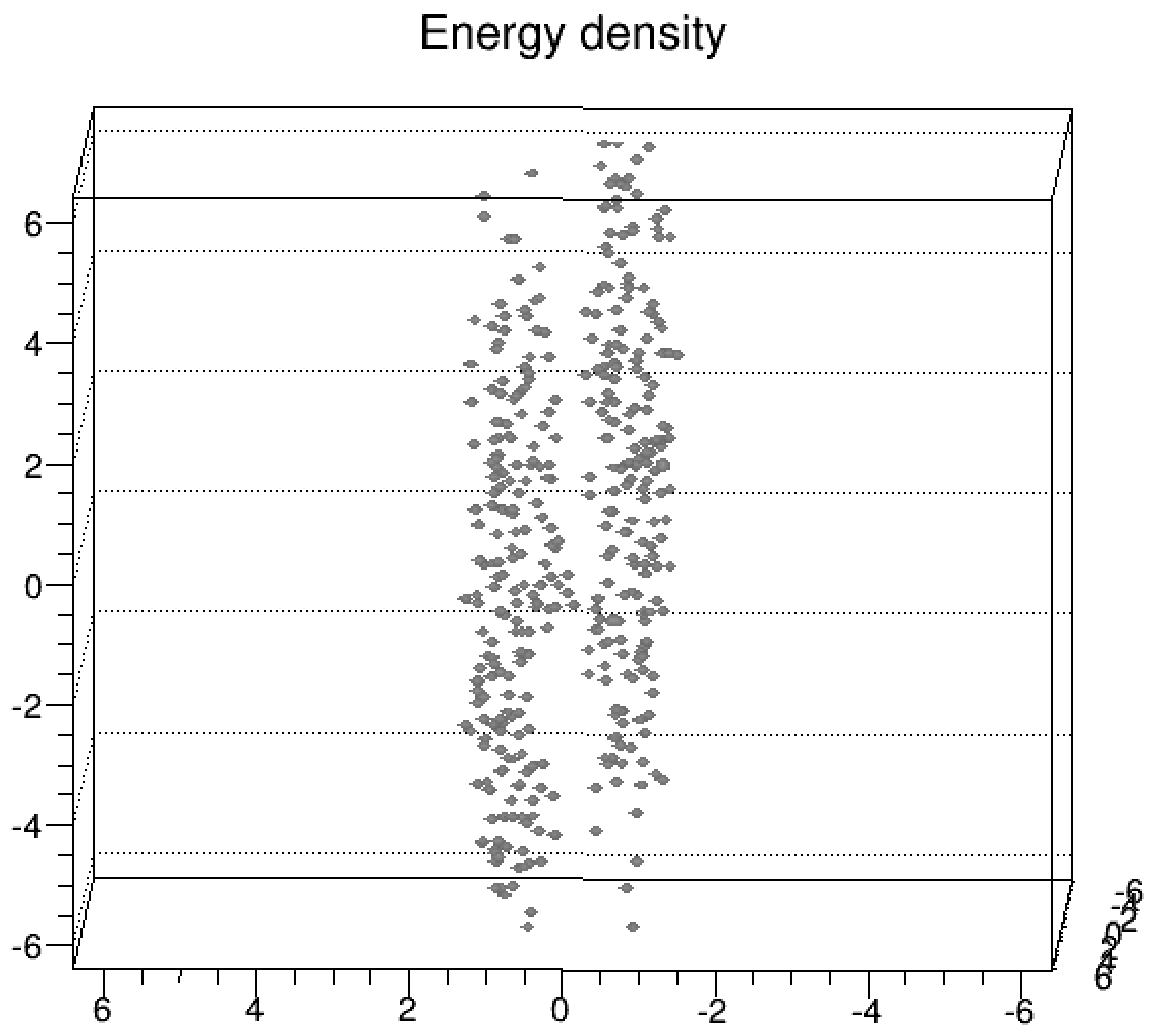

UrQMD – initial conditions

- Au-Au 200AGeV
- b = 2fm
- t = 1fm/c

Simulation:

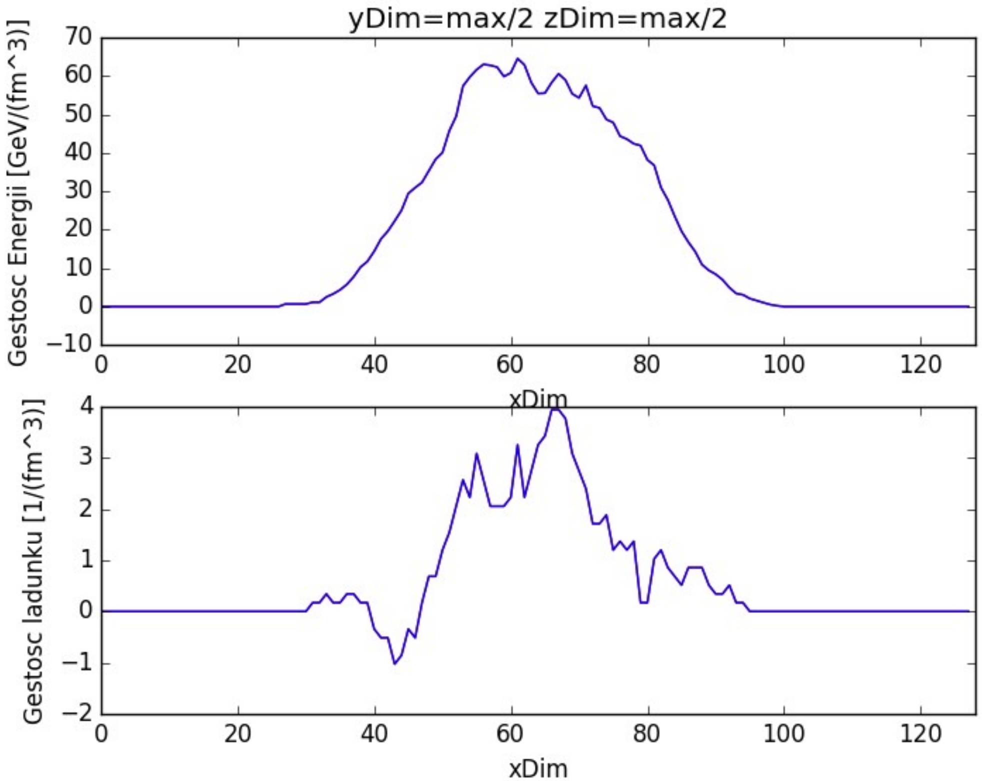
- EOS: p = e^2/3
- 128 x 128 x 128
- dx = 0.1 fm
- dt = 0.02fm/c

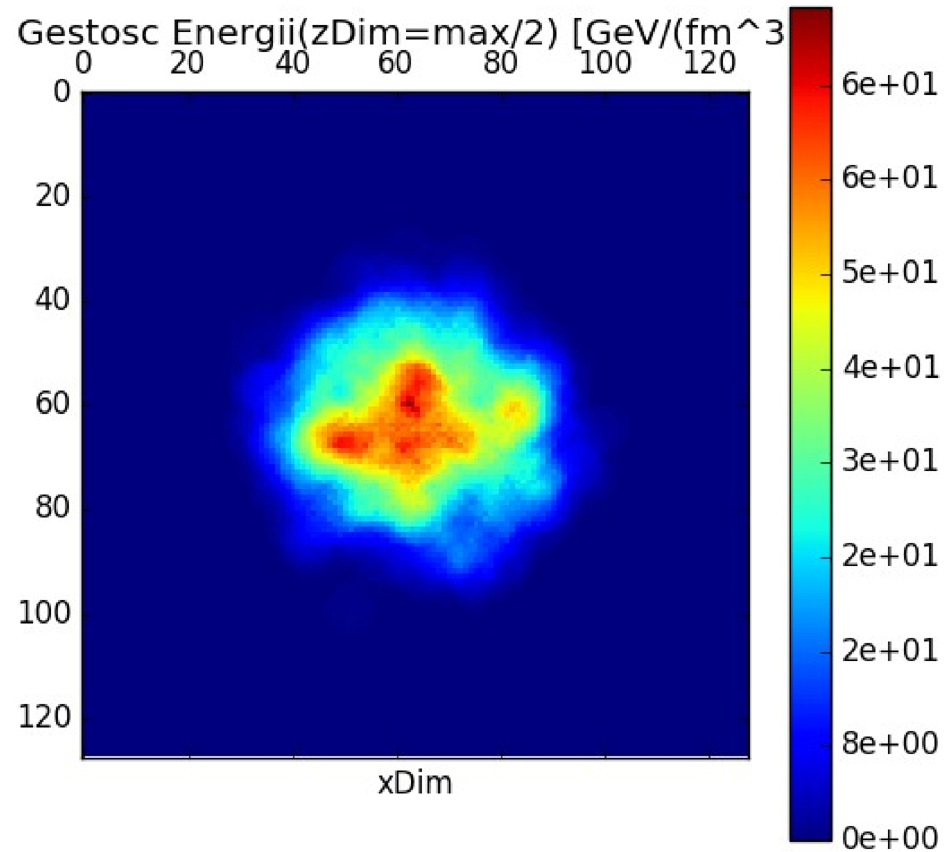


Simulation: energy density (I)

Initial conditions for averaging 10 UrQMD events

Au+Au @ 200 GeV/c
0-10% most central

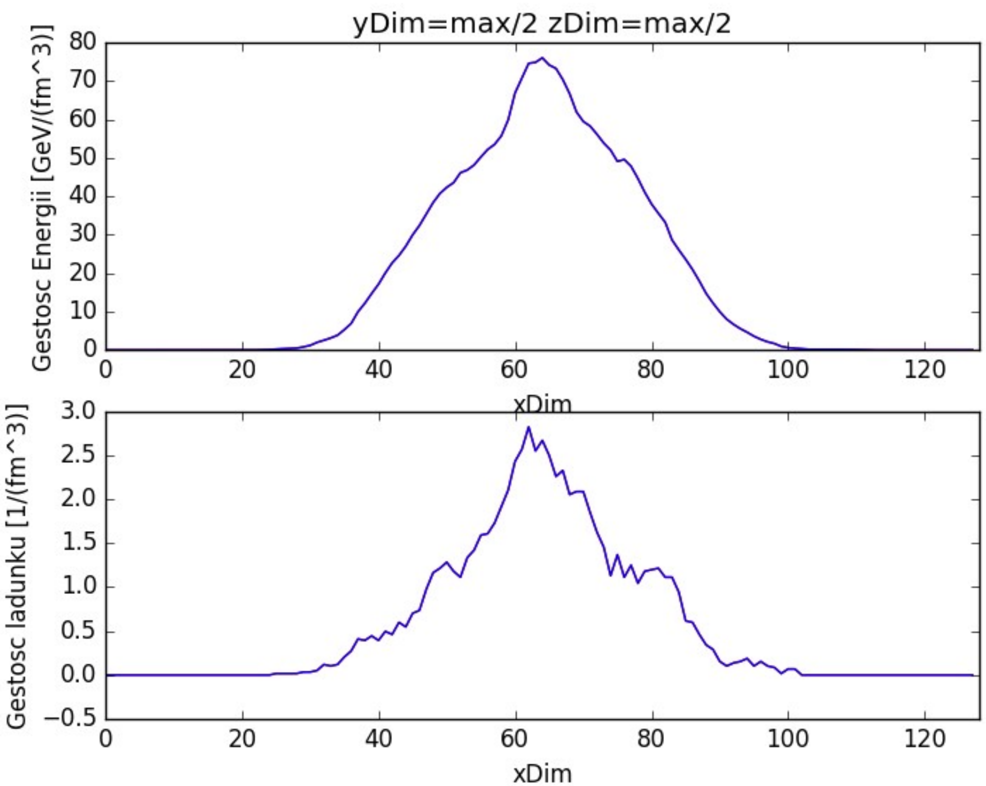


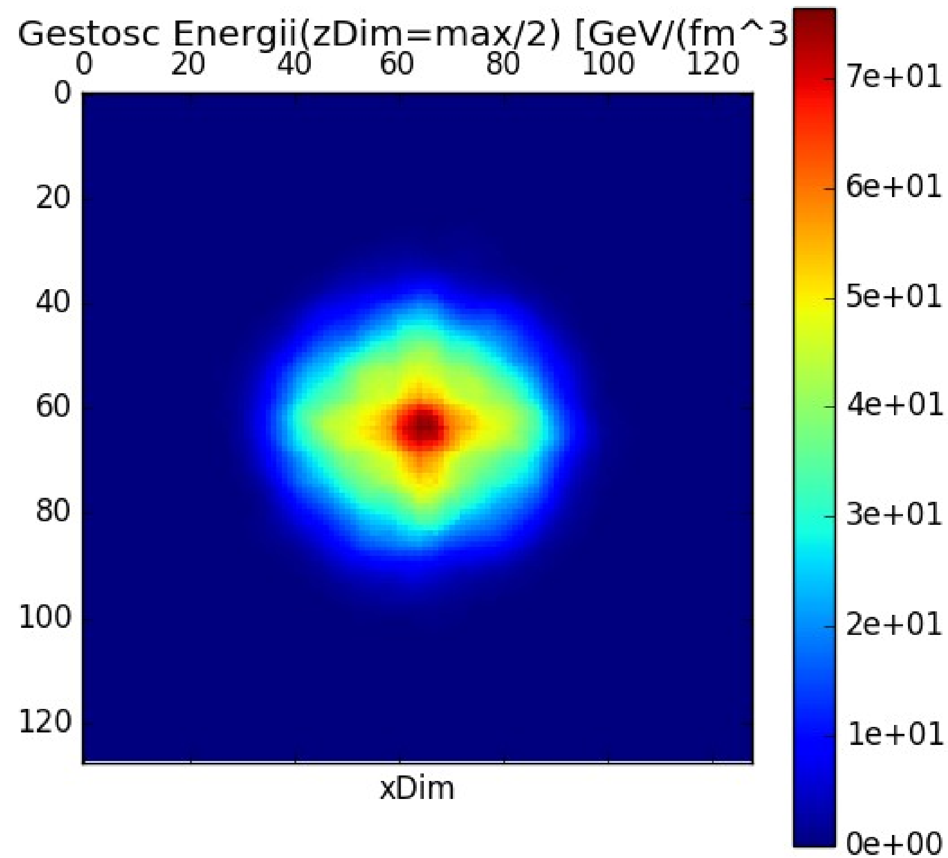


Simulation: energy density (II)

Initial conditions for averaging 100 UrQMD events

Au+Au @ 200 GeV/c
0-10% most central





Simulation: energy density (III)

Initial conditions for averaging 150 UrQMD events

Au+Au @ 200 GeV/c
0-10% most central