Hybrid Modeling of Heavy Ion Collisions

Marcus Bleicher

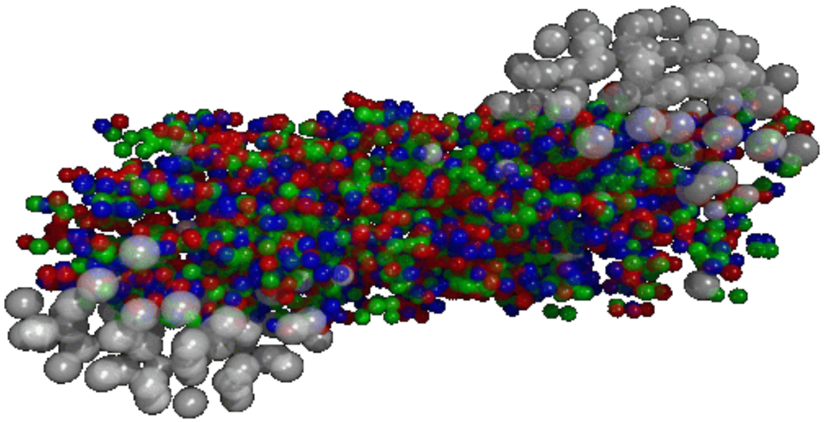
Institut für Theoretische Physik

Goethe Universität Frankfurt &

Helmholtz International Center for FAIR &

GSI Darmstadt

Germany



Thanks to

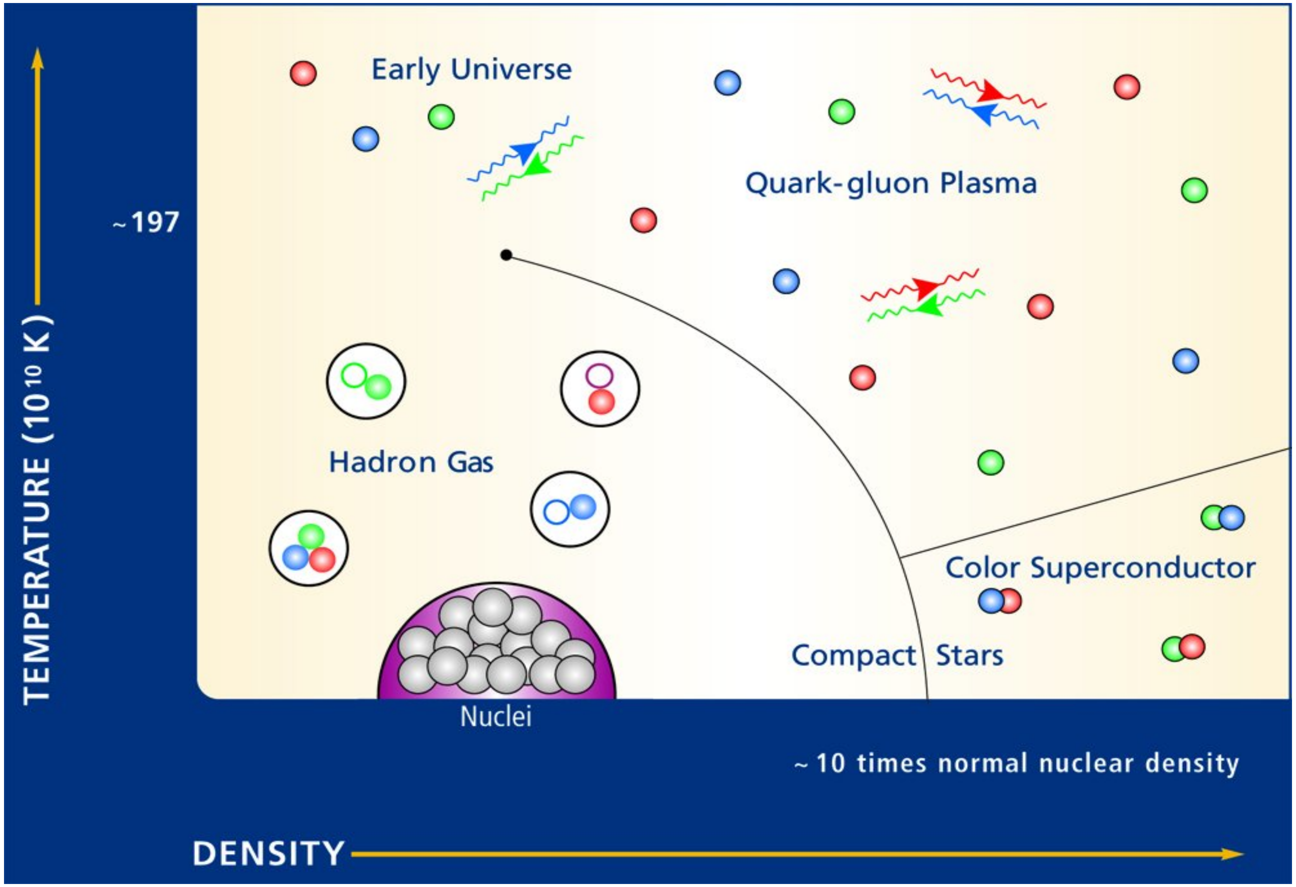
HIC for FAIR
Helmholtz International Center

- Hannah Petersen
- Jan Steinheimer
- Yurii Karpenko
- Pasi Huovinen
- Hendrik van Hees

QCD Phase Diagram: Sketch

HIC for FAIR
Helmholtz International Center

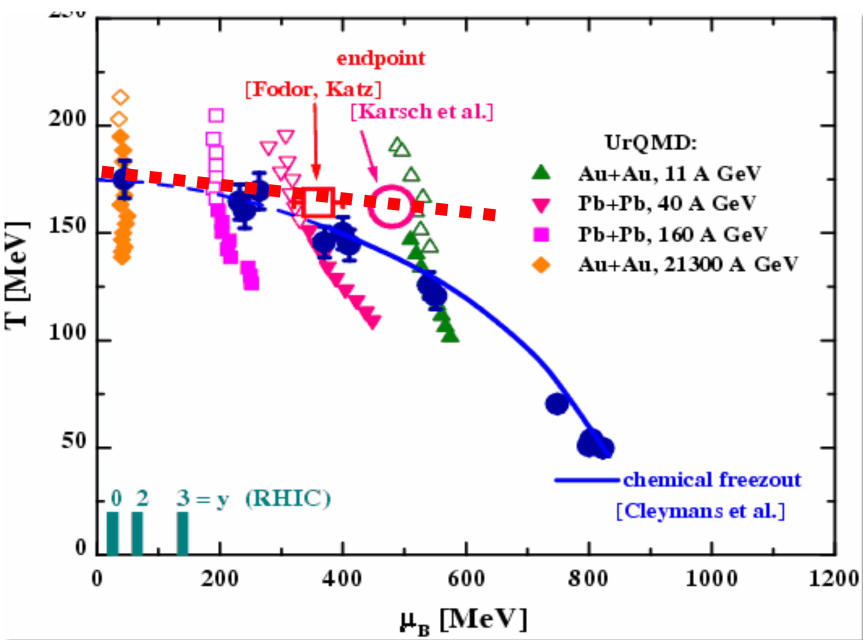
http://www.ice.csic.es/en/graphics/phase.jpg

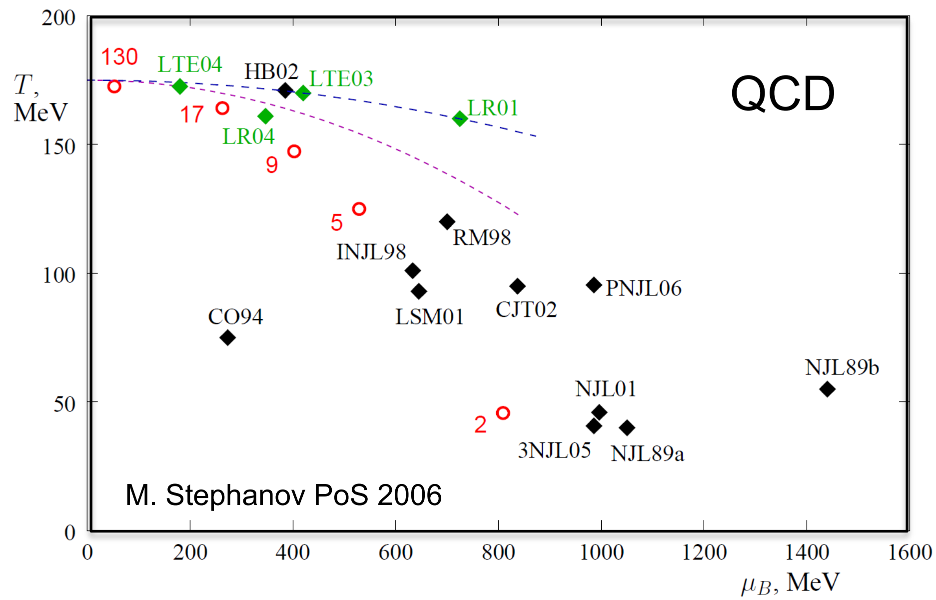


In heavy ion collisions heated and compressed nuclear matter is produced under controlled conditions

QCD Phase Diagram

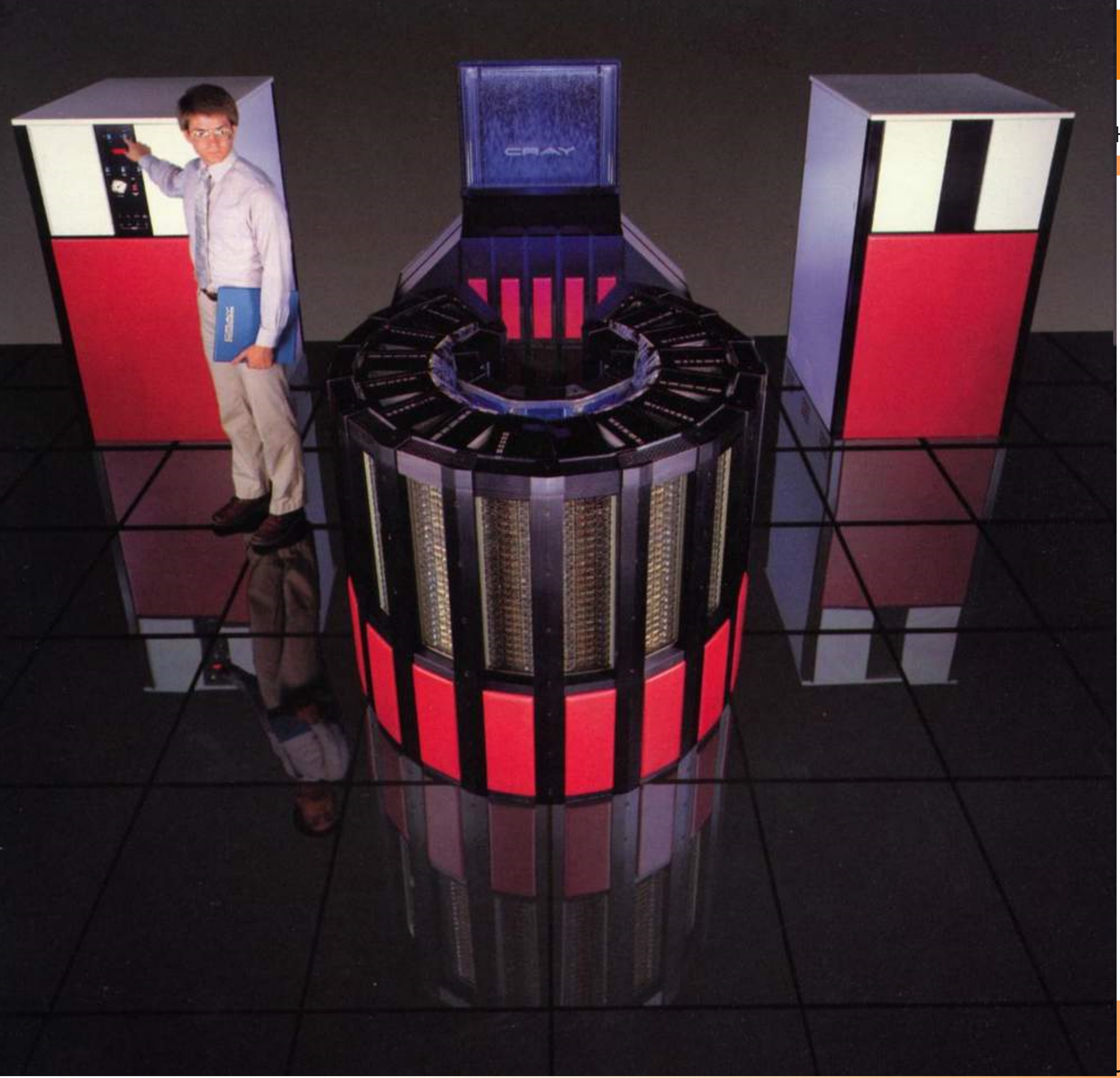
HIC for FAIR
Helmholtz International Center





L. Bravina, M.B., et al., JPG 1999
I. Arsene et al., PRC 2007

- Except for $\mu_B \rightarrow 0$, many features are unknown
- Order of PT, critical points, dof (Quarkyonic matter?)


CRAY

Time Evolution of Heavy Ion Collisions

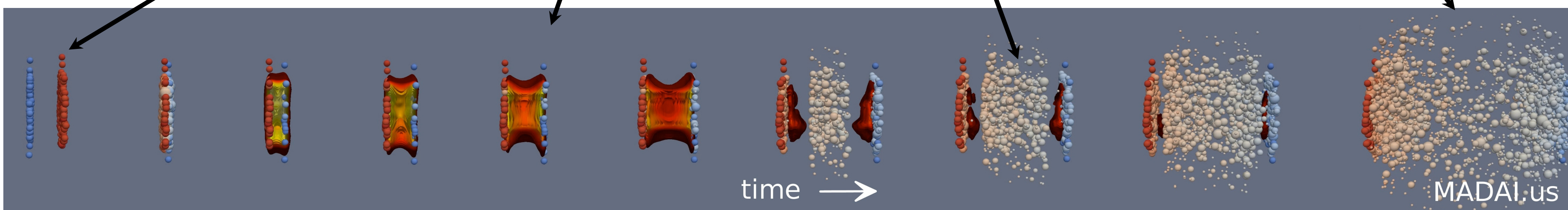
Helmholtz International Center

Nuclei at 99 % speed of light

Quark Gluon Plasma

Hadronic Rescattering

Measurable Fragments in the detector



1x 10^{-23} s

10 x 10^{-23} s

30 x 10^{-23} s

Nonequilibrium initial state dynamics → Relativistic Hydrodynamics → Hadron Transport

Hybrid approaches are very successful for the description of the dynamics

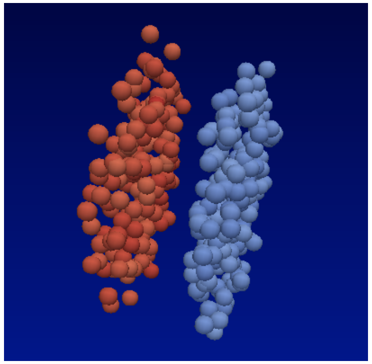
Hannah Petersen, special issue JPG, arXiv:1404.1763

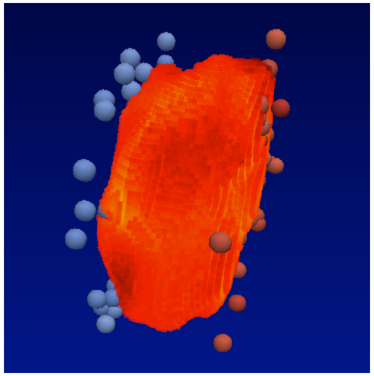
History of Hybrid Approaches

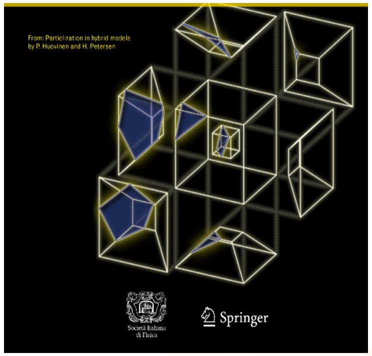
HIC for FAIR
Helmholtz International Center

- Integrated (open source) UrQMD 3.4
  H. Petersen, J. Steinheimer, M. Bleicher, Phys. Rev. C 78:044901, 2008
- Hadronic dissipative effects on elliptic flow in ultrarelativistic heavy-ion collisions.
  T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, Phys.Lett.B636:299-304,2006
- 3-D hydro + cascade model at RHIC.
  C. Nonaka, S.A. Bass, Nucl.Phys.A774:873-876,2006
- Results On Transverse Mass Spectra Obtained With Nexspherio
  F. Grassi, T. Kodama, Y. Hama, J.Phys.G31:S1041-S1044,2005
- EPOS+Hydro+UrQMD at LHC
  K. Werner, M. Bleicher, T. Pierog, Phys. Rev. C (2010)
- MUSIC@RHIC and LHC
  B. Schenke, S. Jeon, C. Gale, ... (2008)
- Started with S. Bass, A. Dumitru, M. Bleicher, Phys.Rev.C60:021902,1999

UrQMD hybrid







H.Petersen, et al, PRC78 (2008) 044901
P. Huovinen, H. P. EPJ A48 (2012) 171

- Initial State:
  - Initialization of two nuclei
  - Non-equilibrium hadron-string dynamics
  - Initial state fluctuations are included naturally

- 3+1d Hydro +EoS:
  - **SHASTA** ideal relativistic fluid dynamics
  - Net baryon density is explicitly propagated
  - Equation of state at finit μ_B

- Final State:
  - Hypersurface at constant energy density
  - Hadronic rescattering and resonance decays within UrQMD

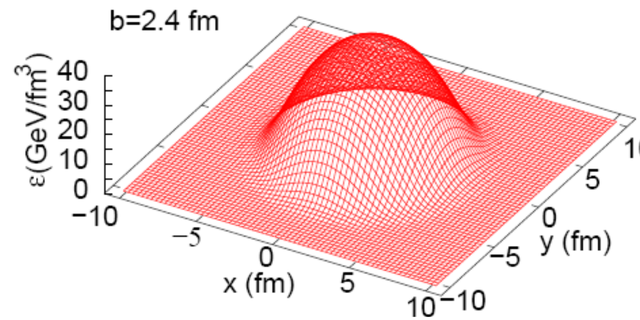
Initial State

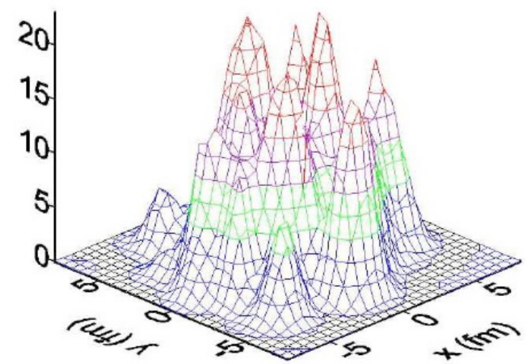
- Contracted nuclei have passed through each other

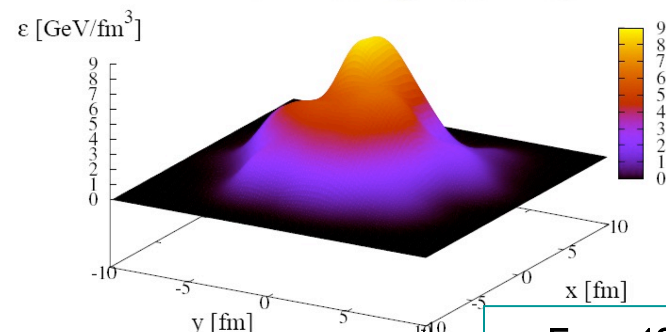
$$\boxed{t_{start} = \frac{2R}{\gamma v}}$$

  - Energy is deposited
  - Baryon currents have separated
- Energy-, momentum- and baryon number densities are mapped onto the hydro grid
- **Event-by-event fluctuations** are taken into account
- Spectators are propagated separately in the cascade

(J.Steinheimer et al., PRC 77,034901,2008)







(nucl-th/0607018, nucl-th/0511021)

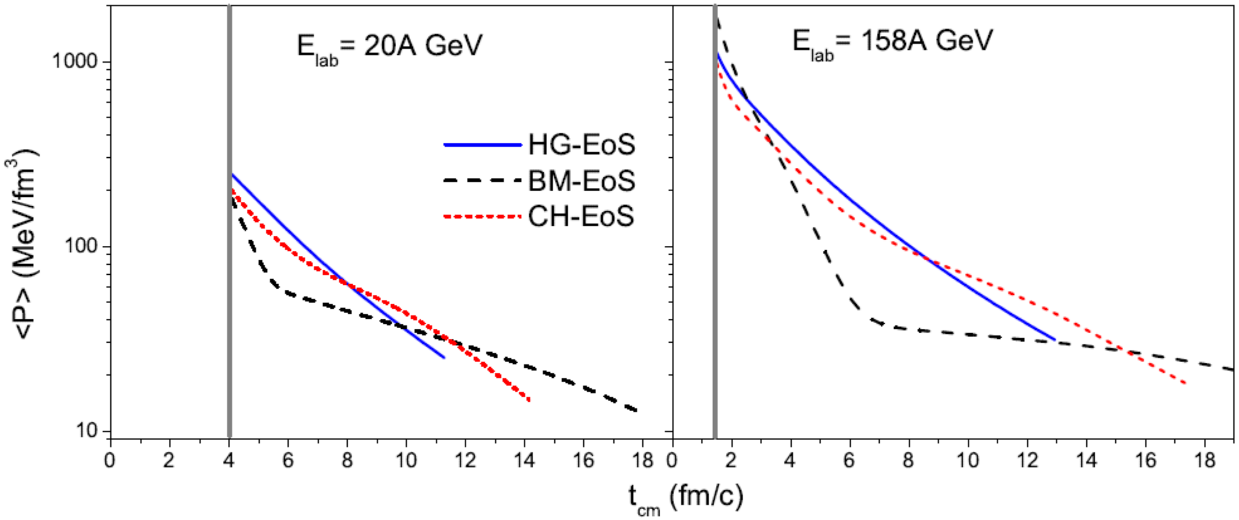
E_{lab}=40 AGeV
b=0 fm

Equations of State

Ideal relativistic one fluid dynamics:

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{and} \quad \partial_\mu \left(n u^\mu\right) = 0$$

- HG: **Hadron gas** including the same degrees of freedom as in UrQMD (all hadrons with masses up to 2.2 GeV)
- CH: **Chiral EoS** from quark-meson model with first order transition and critical endpoint
- BM: **Bag Model EoS** with a strong first order phase transition between QGP and hadronic phase



D. Rischke et al., NPA 595, 346, 1995,

D. Zschiesche et al., PLB 547, 7, 2002

Papazoglou et al., PRC 59, 411, 1999

J. Steinheimer, et al., J. Phys. G38 (2011) 035001

Hadronization, Particlization, Decoupling

HIC for FAIR
Helmholtz International Center

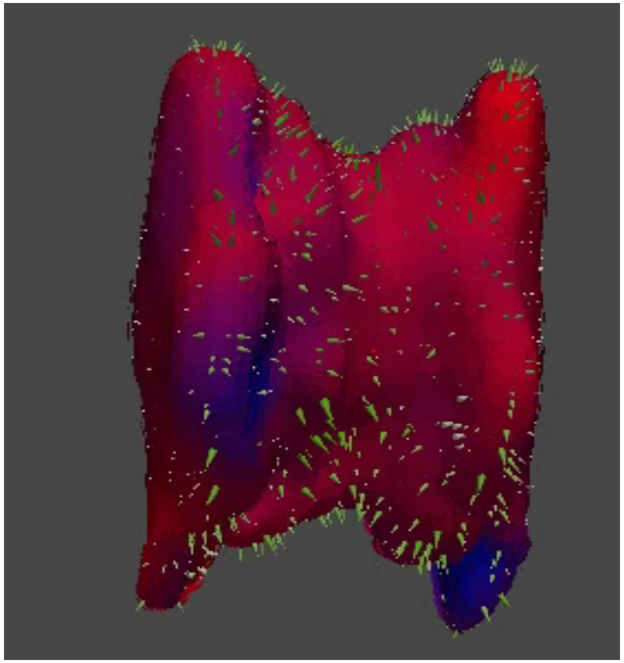
Experiments observe **finite number** of hadrons in detectors

Hadronization controlled by the equation of state

Sampling of particles according to **Cooper-Frye** equation:

-Respect **conservation laws**, maybe even locally?
-Introduces fluctuations on its own

$$E\frac{dN}{d^3p} = \int_\sigma f(x,p)p^\mu d\sigma_\mu$$



→ Yields 4-momenta, 4-positions of hadrons on the hypersurface

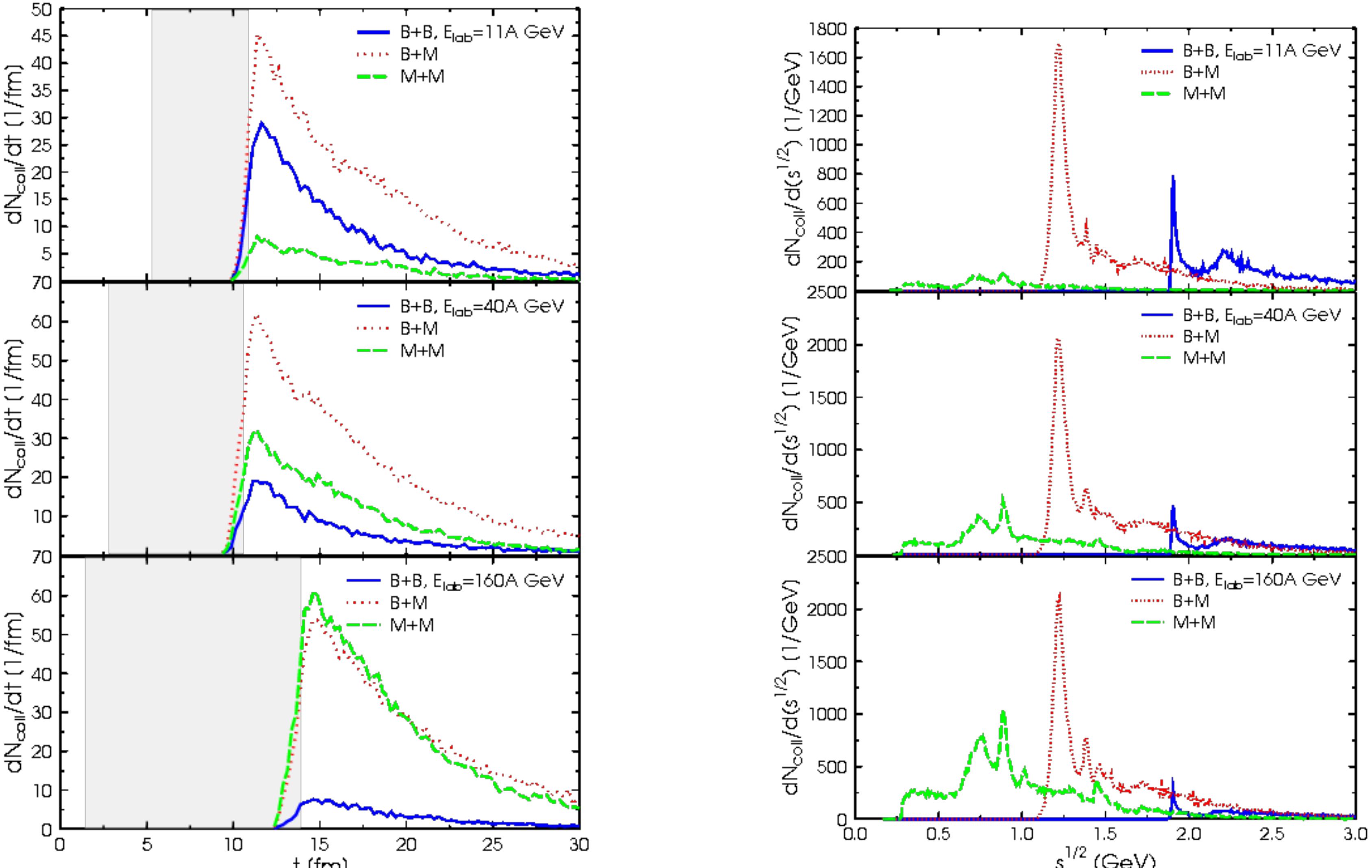
→ Final propagation
Relativistic Boltzmann equation

$$\left(p^\mu \partial_\mu\right) f = I_{coll}$$

Sophisticated 3D hypersurface finder to resolve interesting structures in event-by-event simulations

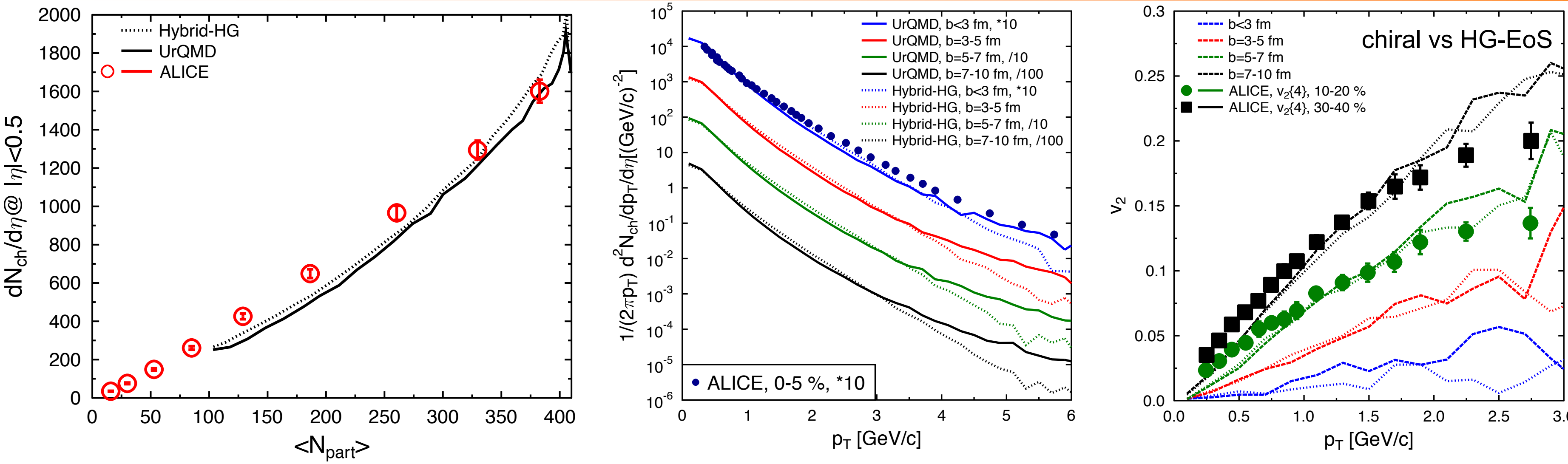
Petersen, Huovinen, arXiv:1206.3371

Final State Interactions (after Hydro)



Hybrid model at LHC

HIC for FAIR
Helmholtz International Center



- PbPb, 2.76 TeV
- Excellent description of centrality dependence,
- Transverse momenta,
- Elliptic flow.

H. Petersen, Phys.Rev. C84 (2011) 034912

How can we obtain information from the different stages of the reaction?

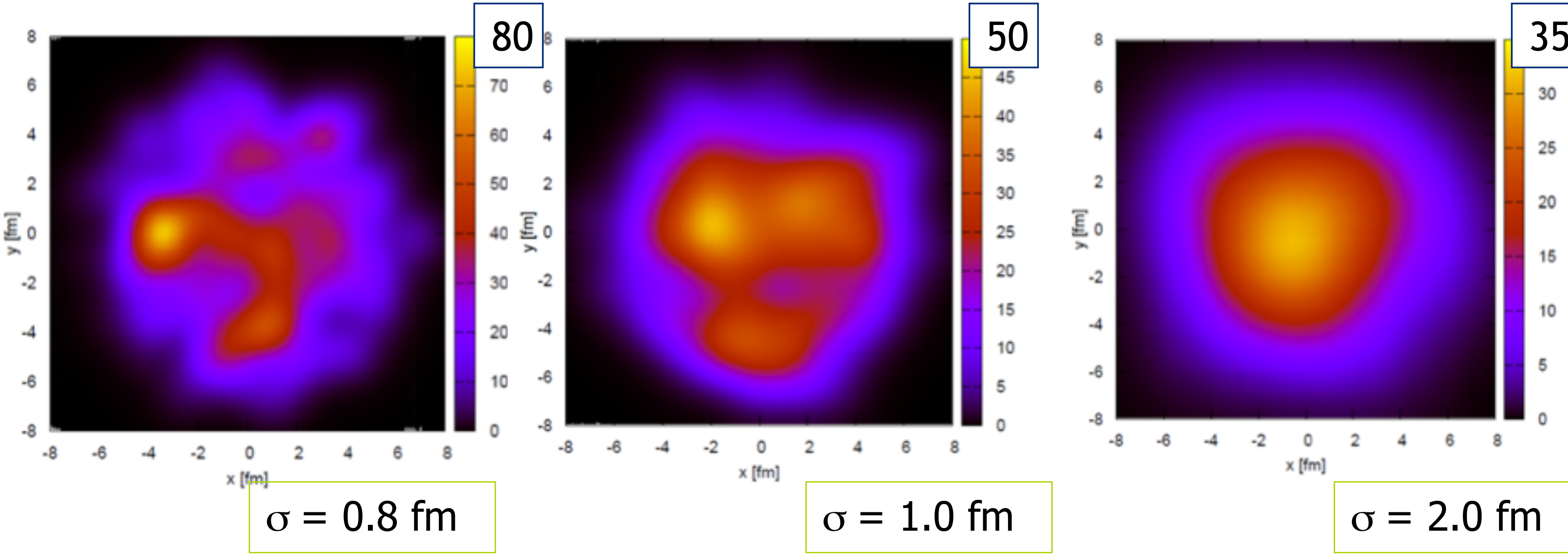
From H. Petersen

Initial State at RHIC

- Energy-, momentum- and baryon number densities are mapped onto the hydro grid using for each particle

$$\epsilon(x,y,z) = \left(\frac{1}{2\pi}\right)^{\frac{3}{2}} \frac{\gamma_z}{\sigma^3} E_p \exp - \frac{(x-x_p)^2 + (y-y_p)^2 + (\gamma_z(z-z_p))^2}{2\sigma^2}$$

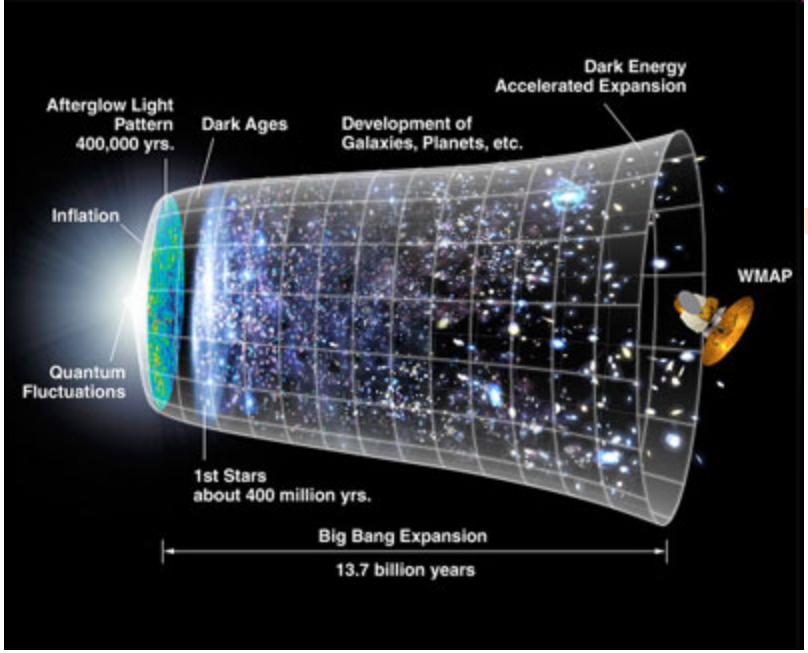
- Changing σ leads to different granularities, but also changes in the overall profile

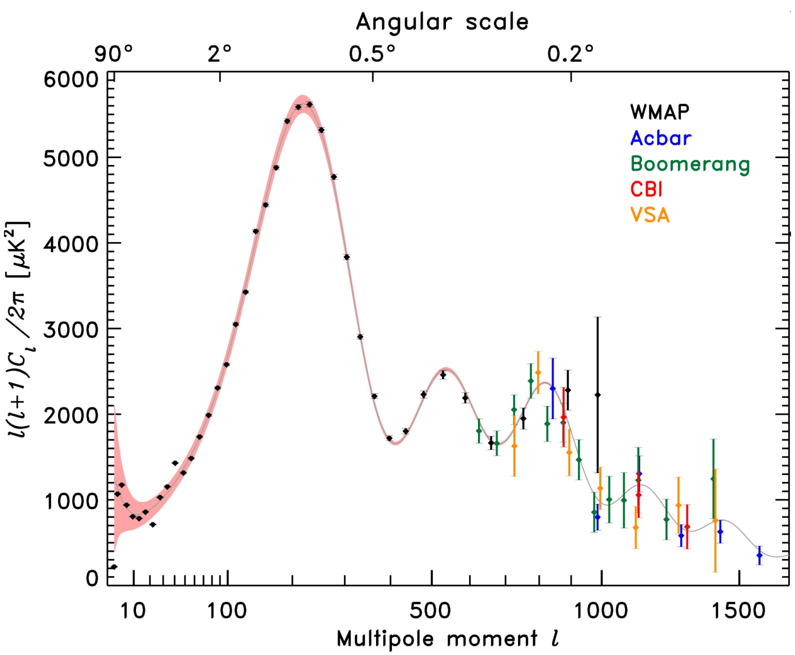


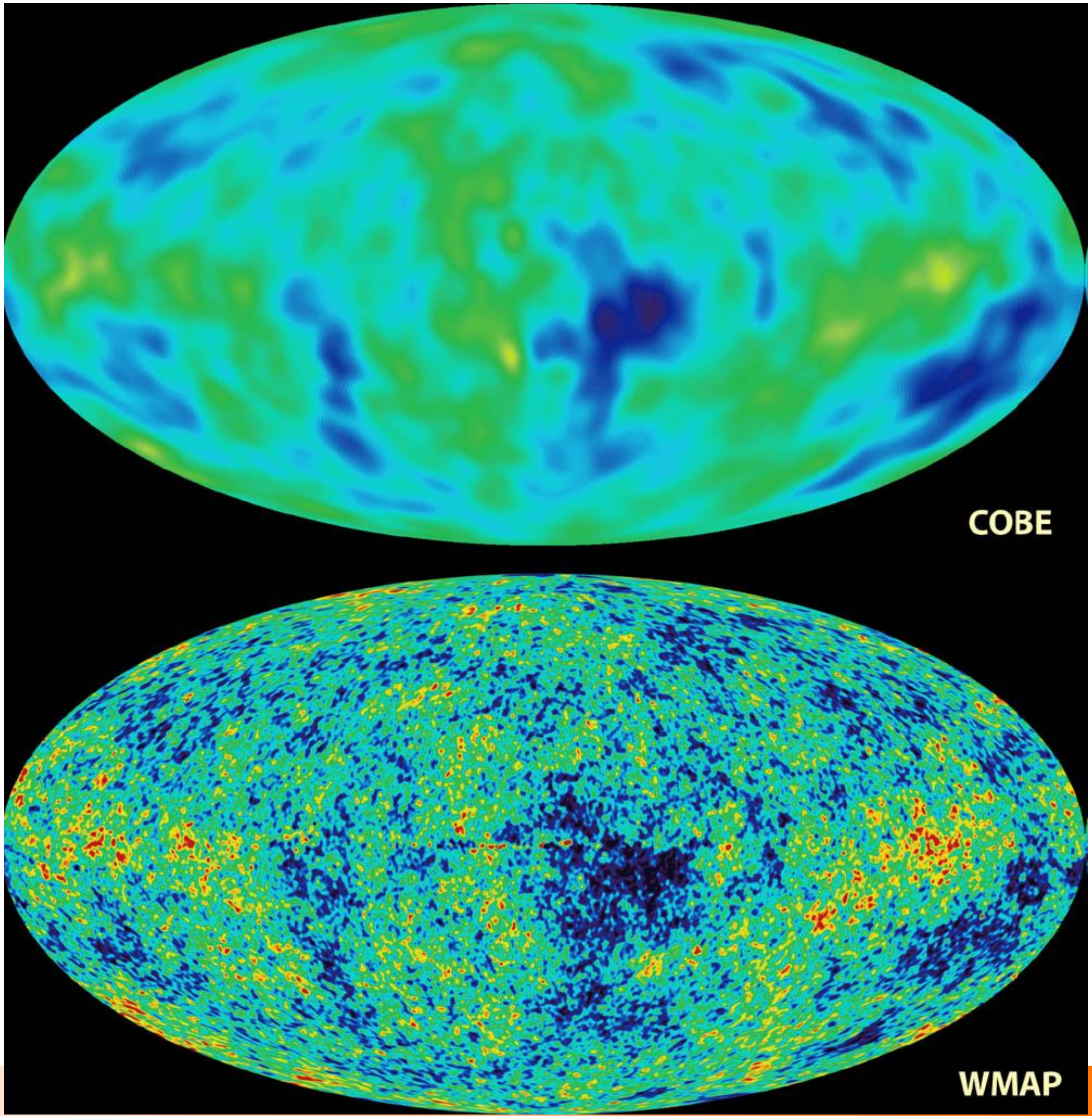
H.P. et al, PRC 83, 014916, 2011 and JPG 38, 045102, 2011

- How does changing the starting time affect the picture?

Angular correlation

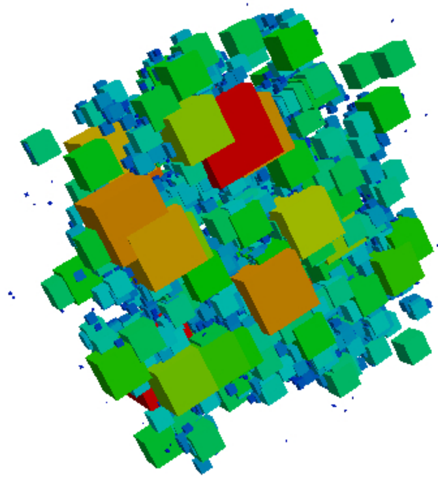






Sources of Fluctuations

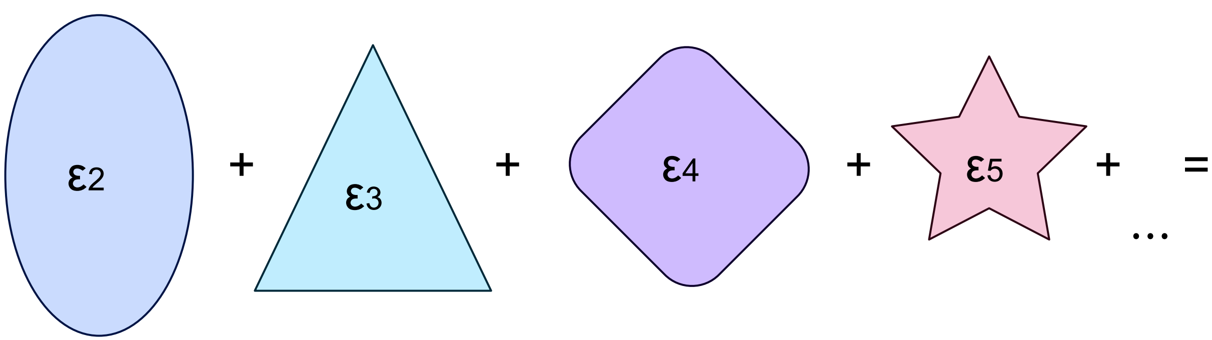
- **Granularity is driven by**
  - position of nucleons
  - distribution of collisions
  - type of interaction
  - degree of thermalization

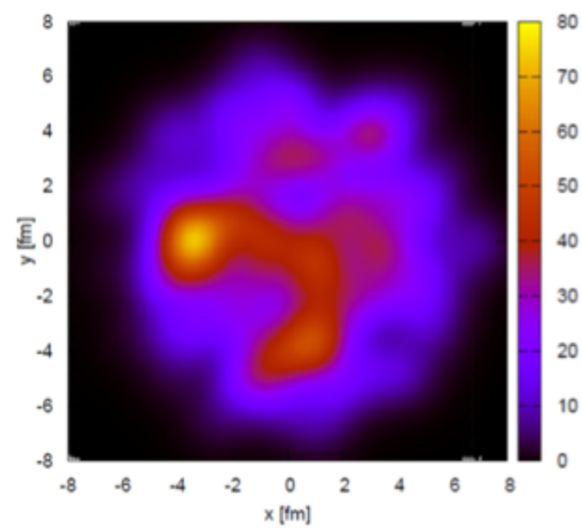


UrQMD @ 200 AGeV

- How to quantify the fluctuating shape of the initial state?

  → Fourier-expansion in position space

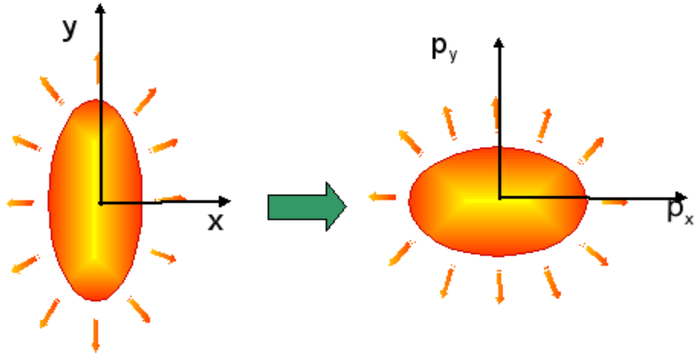




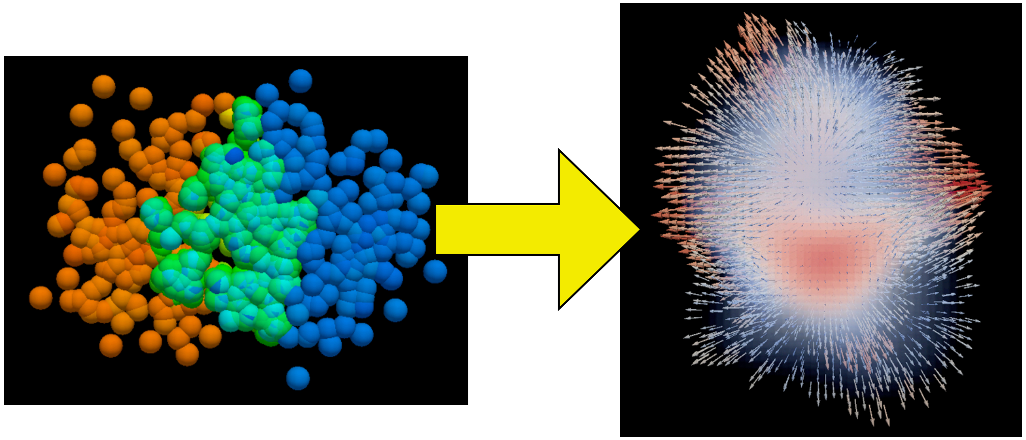
Anisotropic Flow – Higher Order Fourier Coefficients

Simplified picture:

Position-space anisotropy
→ Momentum-space anisotropy



Real picture:
Complicated state,
mean free paths,…



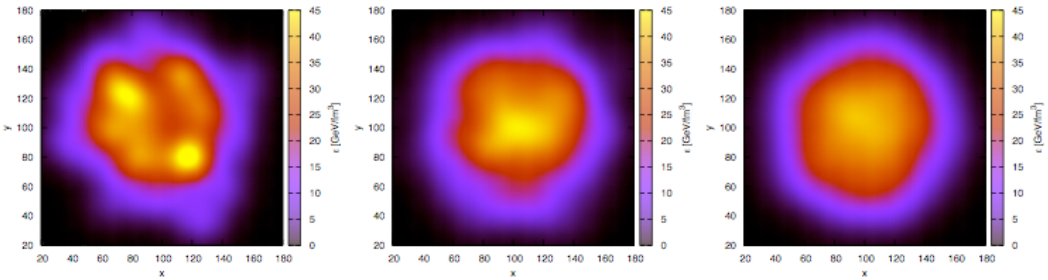
by MADAI.us

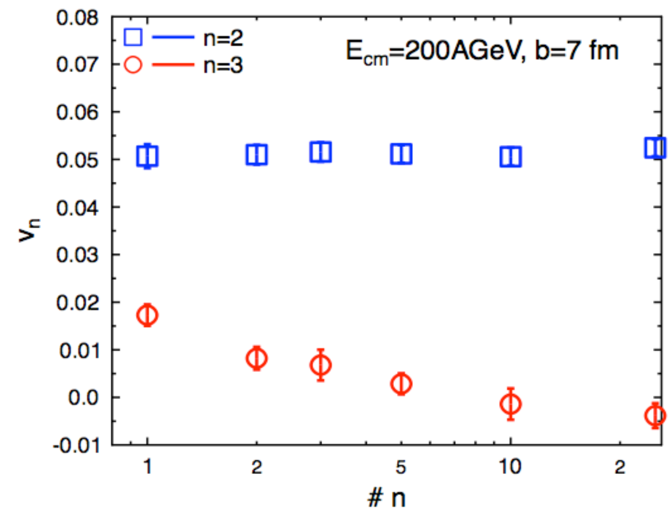
Use these coefficients to learn about the initial state

Constraining Granularity

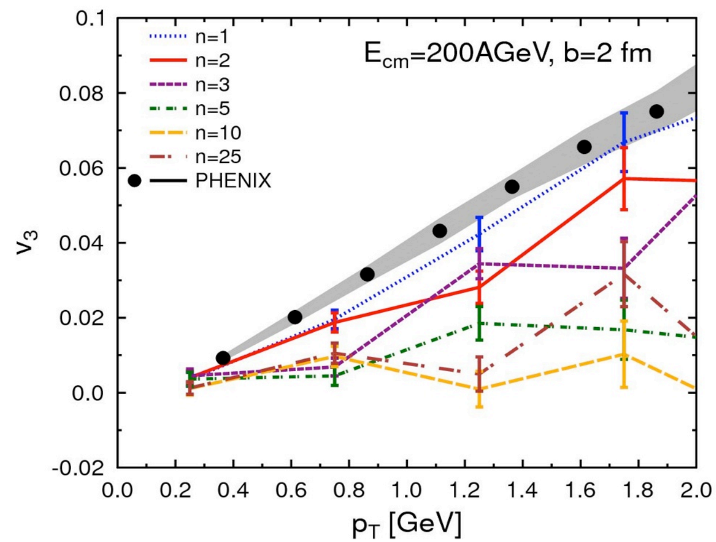
HIC for FAIR
Helmholtz International Center

H.P. et al, J.Phys.G G39 (2012) 055102



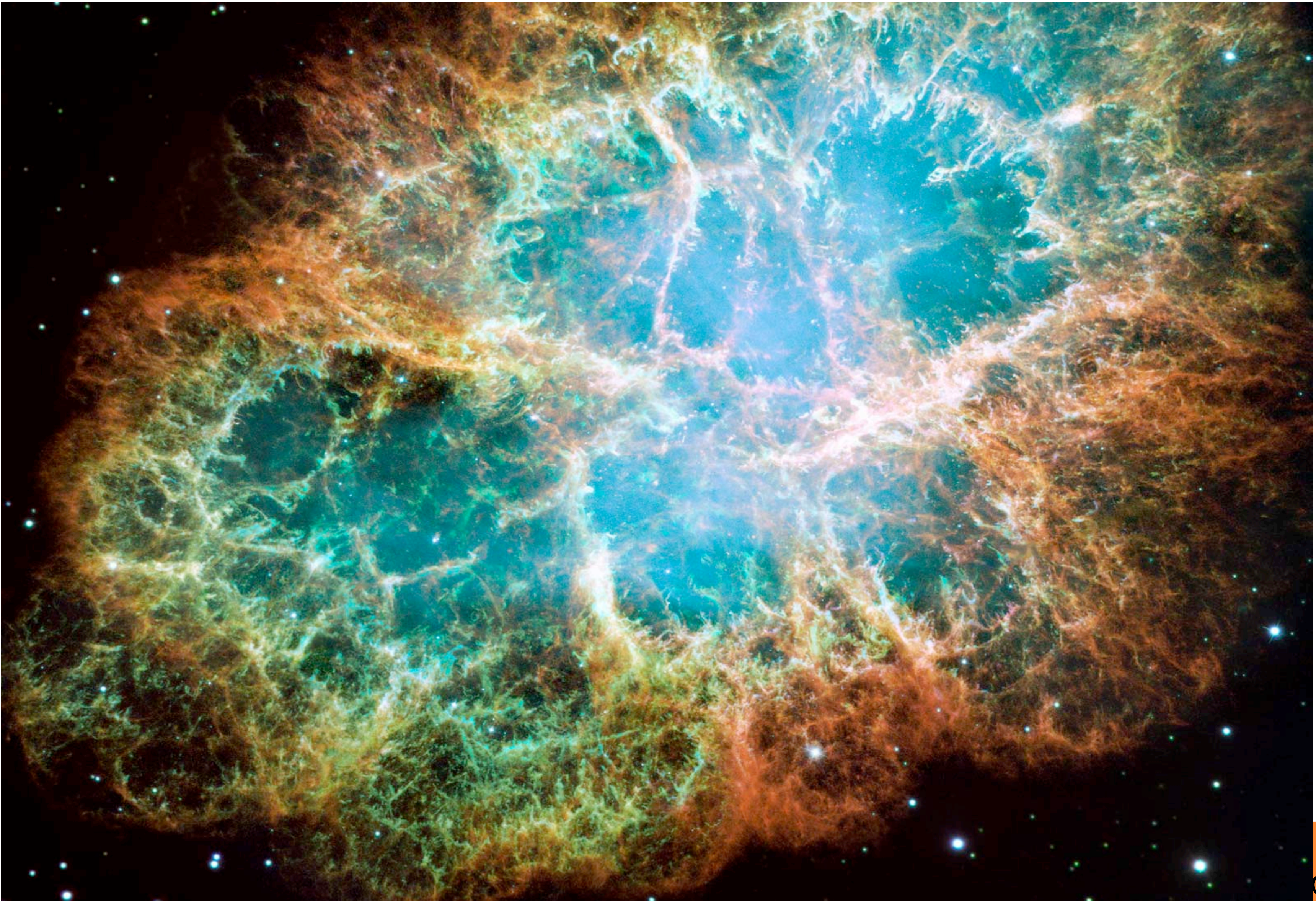


- Triangular flow is **very sensitive** to amount of initial state fluctuations
- It is important to have final state particle distributions to apply **same analysis** as in experiment
- Single-event initial condition provides best agreement with PHENIX data
- Does that imply that the initial state is well-described by binary nucleon interactions +PYTHIA?
- Lower bound for fluctuations!

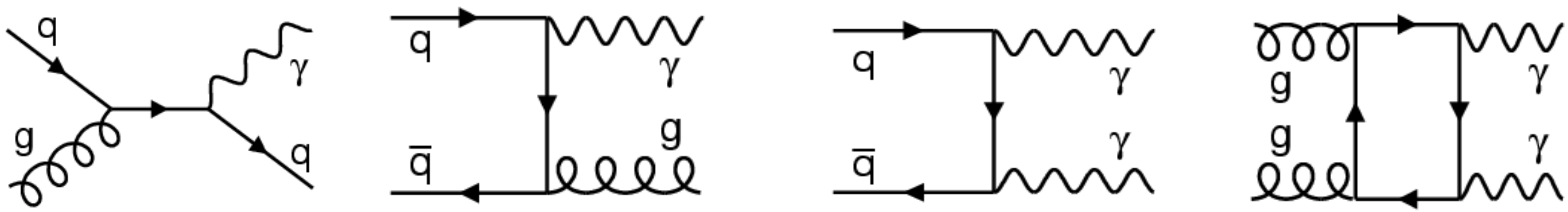


From H. Petersen

Use Photons to Learn More



Photons:
Partonic channels vs hadronic channels



→ from QGP: sensitivity to parton density and temperature
→ from initial state: sensitivity to PDFs (gluon!)
→ Compare to hadronic channels, i.e. $\pi+\rho \rightarrow \gamma+\pi$, …

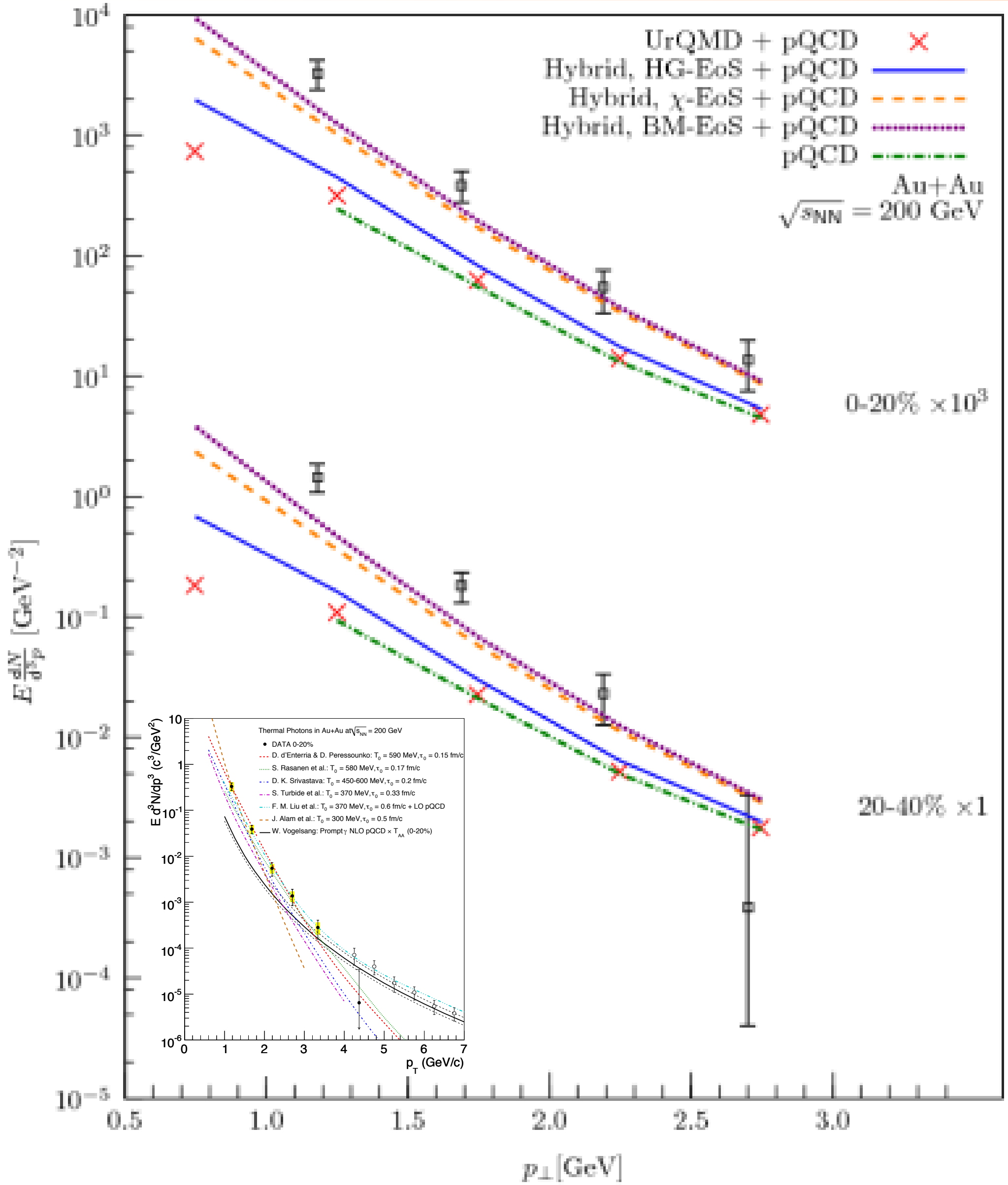
Cross section Refs

[1] E.g. Aurenche, Fontannaz *et. al*, PRD **73**, 094007 (2006)

[2] Turbide, Rapp and Gale, PRC **69**, 014903 (2004); Turbide, Gale *et al.*, PRC **72**, 014906 (2005); Liu and Werner, arXiv:0712.3612 [hep-ph]; Vitev and Zhang, arXiv:0804.3805 [hep-ph]; Haglin, PRC **50**, 1688 (1994); Haglin, JPG **30**, L27 (2004), Chatterjee *et al.*, Nucl. Phys. A **830** (2009) 503C

[3] Dumitru, Bleicher, Bass, Spieles, Neise, Stöcker and Greiner, PRC **57**, 3271 (1998); Huovinen, Belkacem, Ellis and Kapusta, PRC **66**, 014903 (2002); Li, Brown, Gale and Ko, arXiv:nucl-th/9712048; Bratkovskaya and Cassing, NPA **619**, 413 (1997); Bratkovskaya, Kiselev and Sharkov, arXiv:0806.3465 [nucl.th]

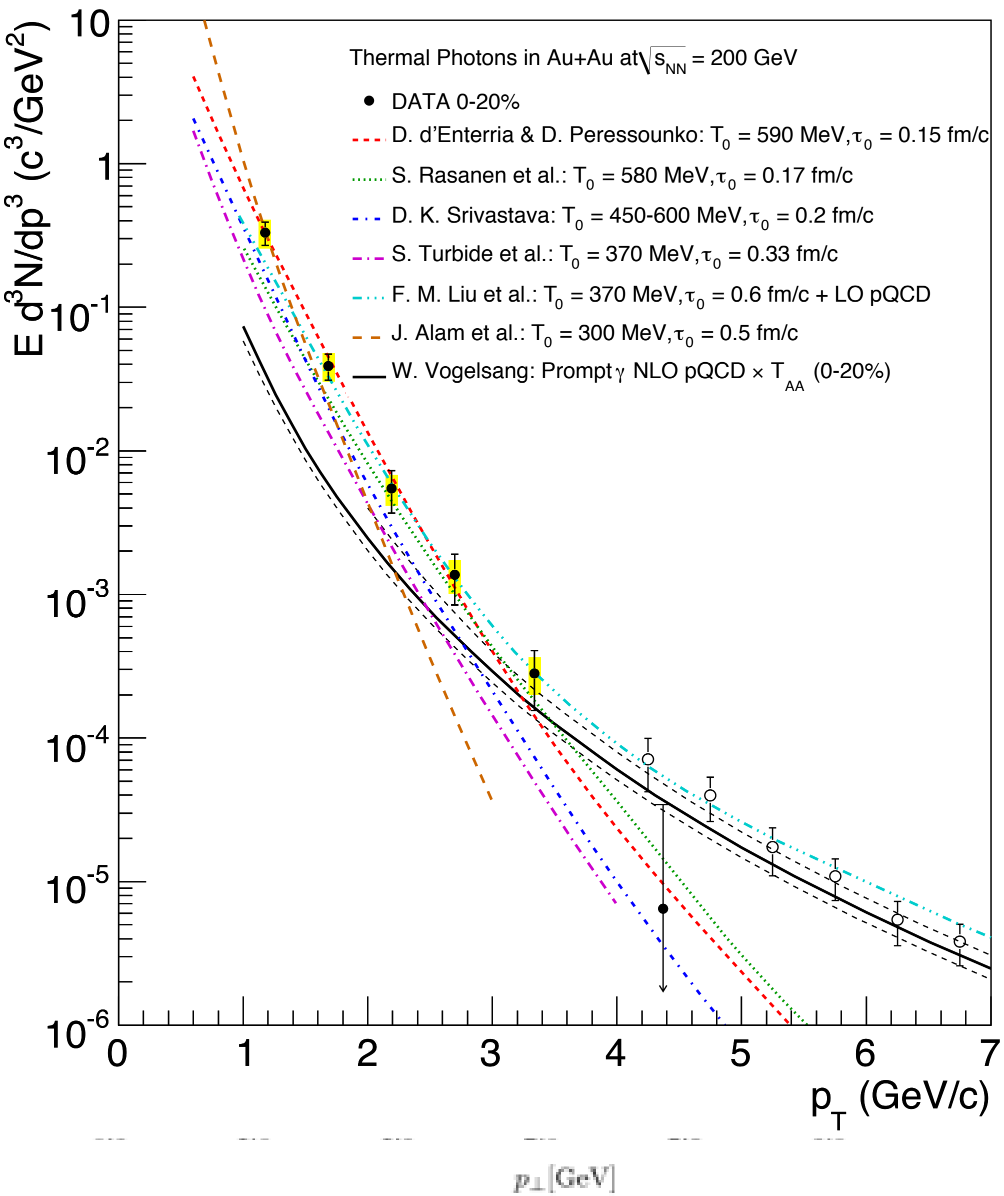
Temperature and dof: Photons



- Clear separation hadronic vs. partonic
- partonic calc. fit data
- Reasons for missing contributions in UrQMD/Hadron gas:
  - late equilibration,
  - hadronic rates,
  - shorter life time

Data points from:
PHENIX, PRC 81 (2010) 034911
fig: Bäuchle, MB, PRC 82 (2010) 064901

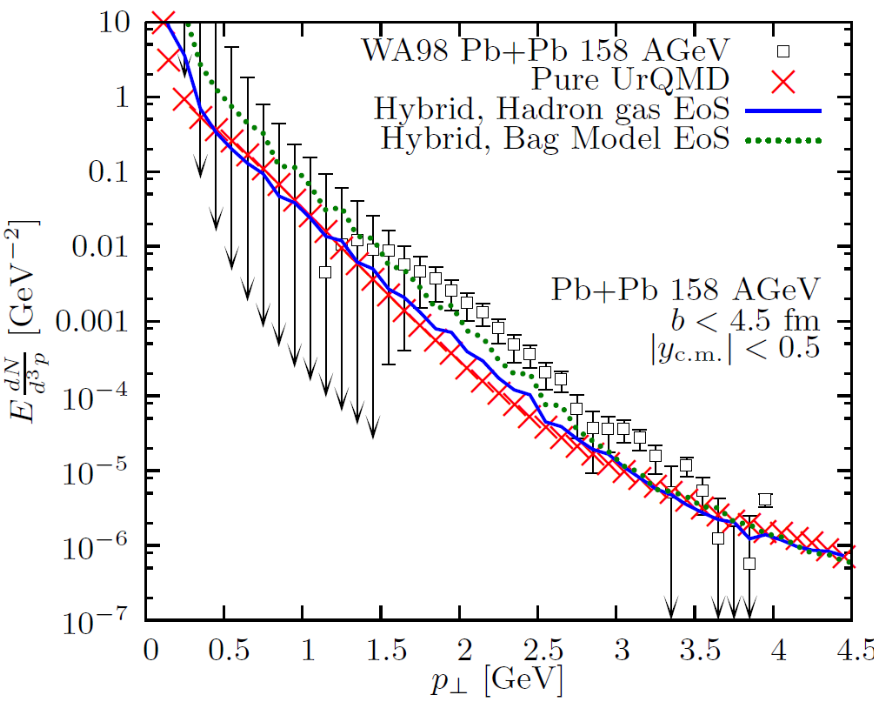
Temperature and dof: Photons



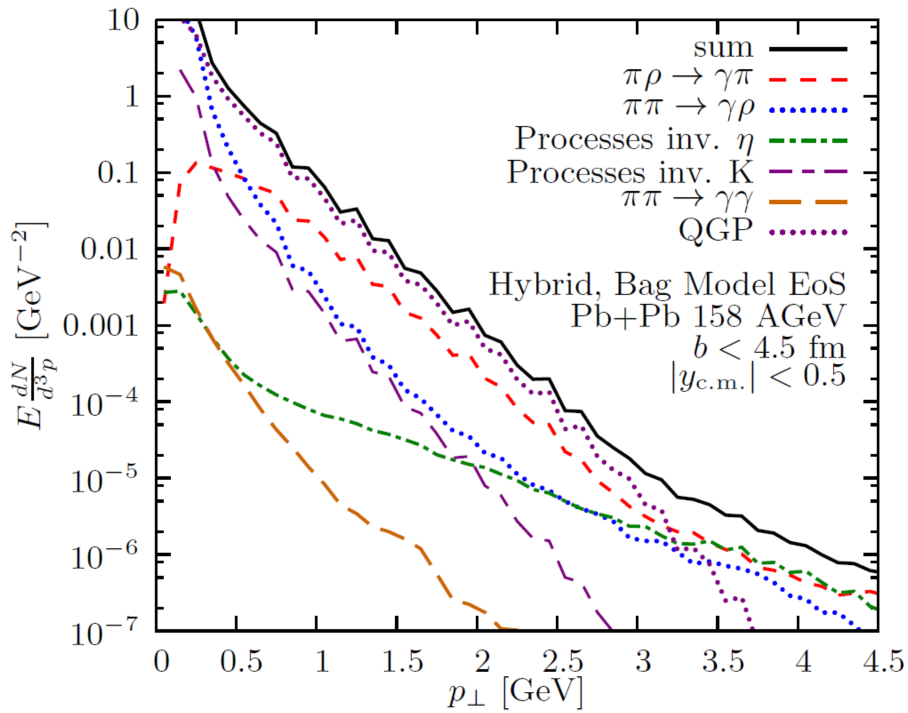
- Clear separation hadronic vs. partonic
- partonic calc. fit data
- Reasons for missing contributions in UrQMD/Hadron gas:
  - late equilibration,
  - hadronic rates,
  - shorter life time

Data points from:
PHENIX, PRC 81 (2010) 034911
fig: Bäuchle, MB, PRC 82 (2010) 064901

Is there QGP?



Comparisons



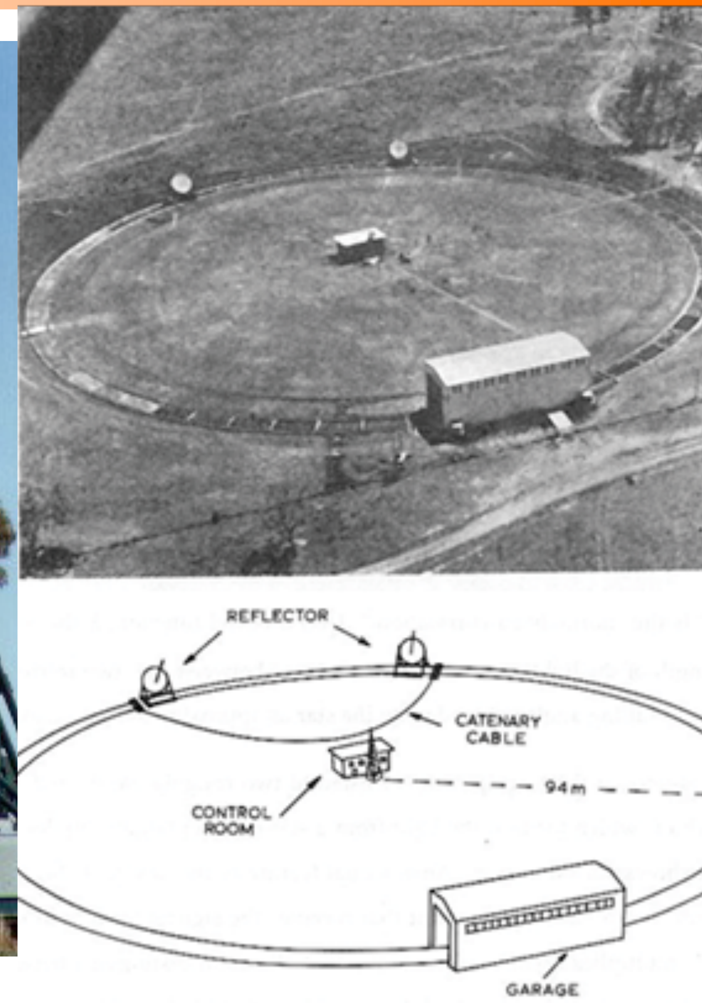
Hybrid, QGP: Channels

Bjoern Bauechle, MB, PRC (2010)

Use HBT Correlations

HIC for FAIR
Helmholtz International Center

Hanbury-Brown-Twiss Correlations



1. Aerial photo and illustration of the original HBT
ey have been extracted from Ref.[1].

HBT correlations: Idea

HIC for FAIR
Helmholtz International Center

(R. Hanbury-Brown, R.Q. Twiss, 1956)

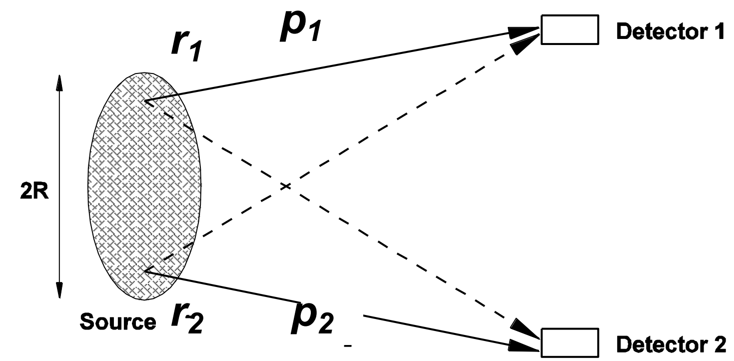
Bose-Einstein-statistics leads to short range correlations of bosons in momentum

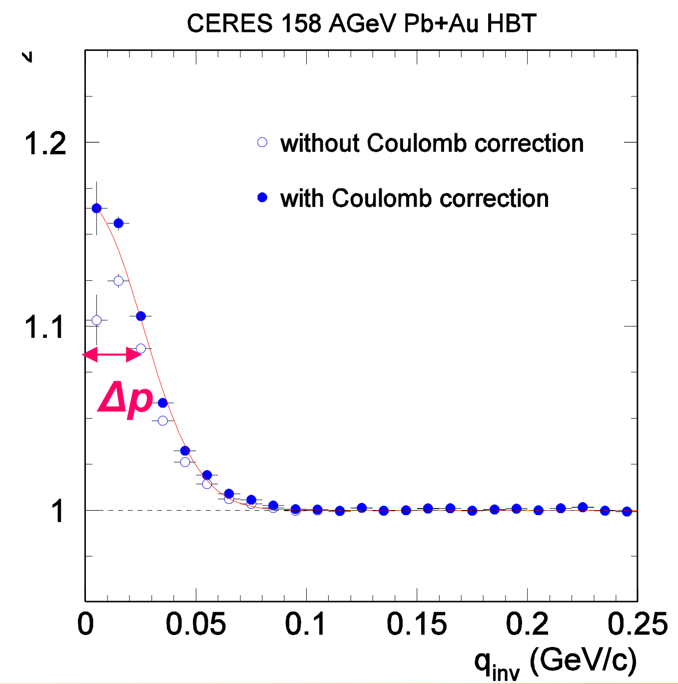
$$C_2(\vec{p}_1,\vec{p}_2) = \frac{P_2(\vec{p}_1,\vec{p}_2)}{P_1(\vec{p}_1)\cdot P_1(\vec{p}_2)} = 1+\chi(\vec{p}_2-\vec{p}_1)$$

χ allows to obtain information on the emission source (Imaging, Gauss-Source)

In heavy ion collisions: Pions, Kaons, …

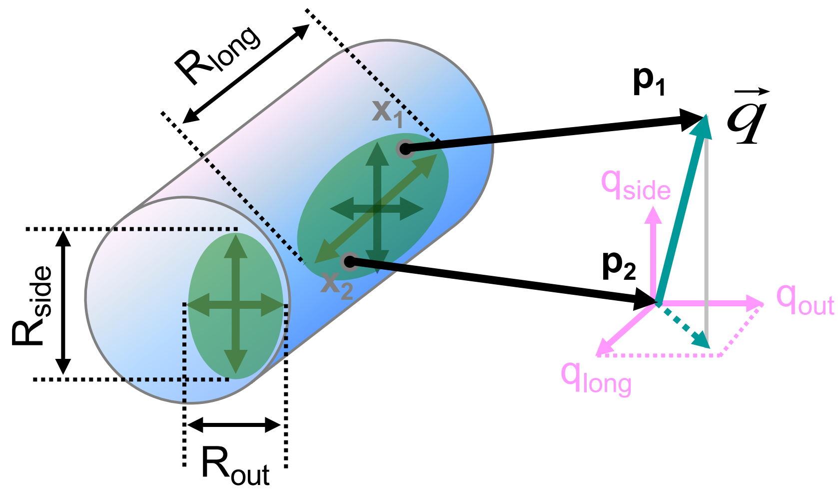
$$\Delta r = \frac{\hbar c}{\Delta p} = \frac{197\,\mathrm{MeV/c}}{\Delta p}\,\mathrm{fm}$$



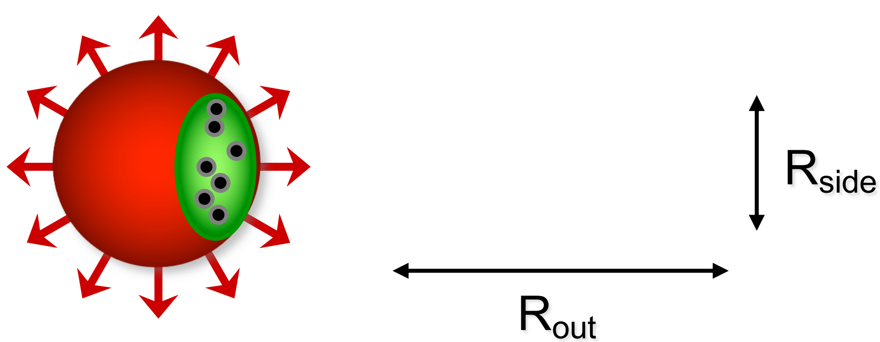


Meaning of Components

- Two particle interferometry: Image and emission duration



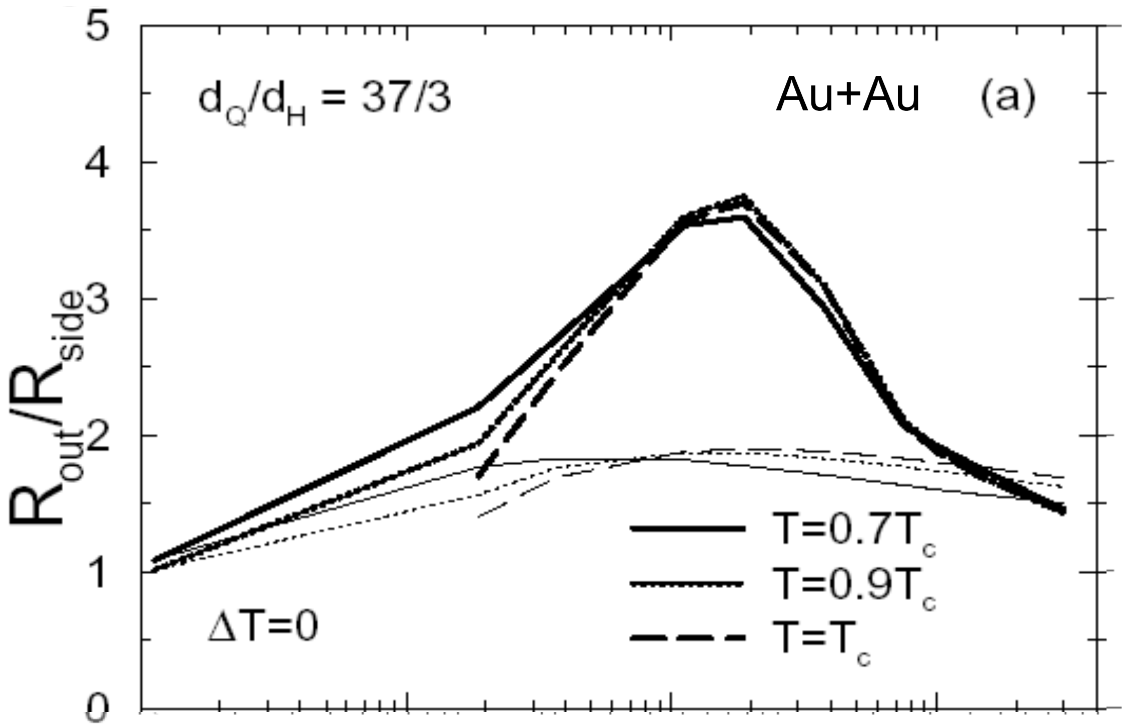
R_{out}/R_{side}-ratio measures emission time of the system



Pratt-Bertsch ("out-side-long") coordinanates allow to obtain space and time information

Prediction

- Mixed phase should lead to drastic increase in life time, visible in R_o/R_s ratio



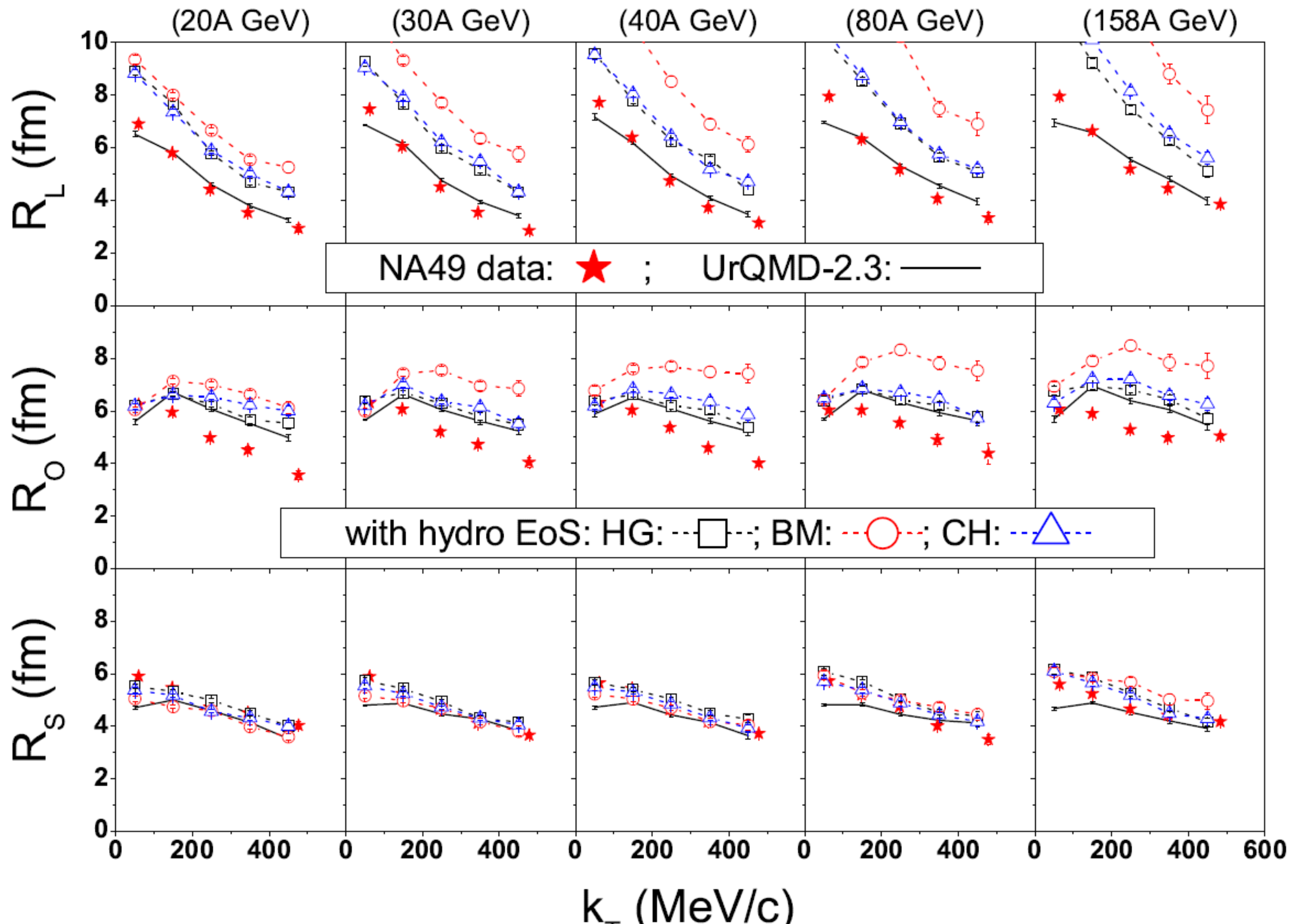
~ beam energy

- 10 times increased life time
- Factor 2-4 increased R_{out}/R_{side} ratio

From: Rischke, Gyulassy, Nucl.Phys.A608:479-512,1996

HBT radii → Lifetime

HIC for FAIR
Helmholtz International Center

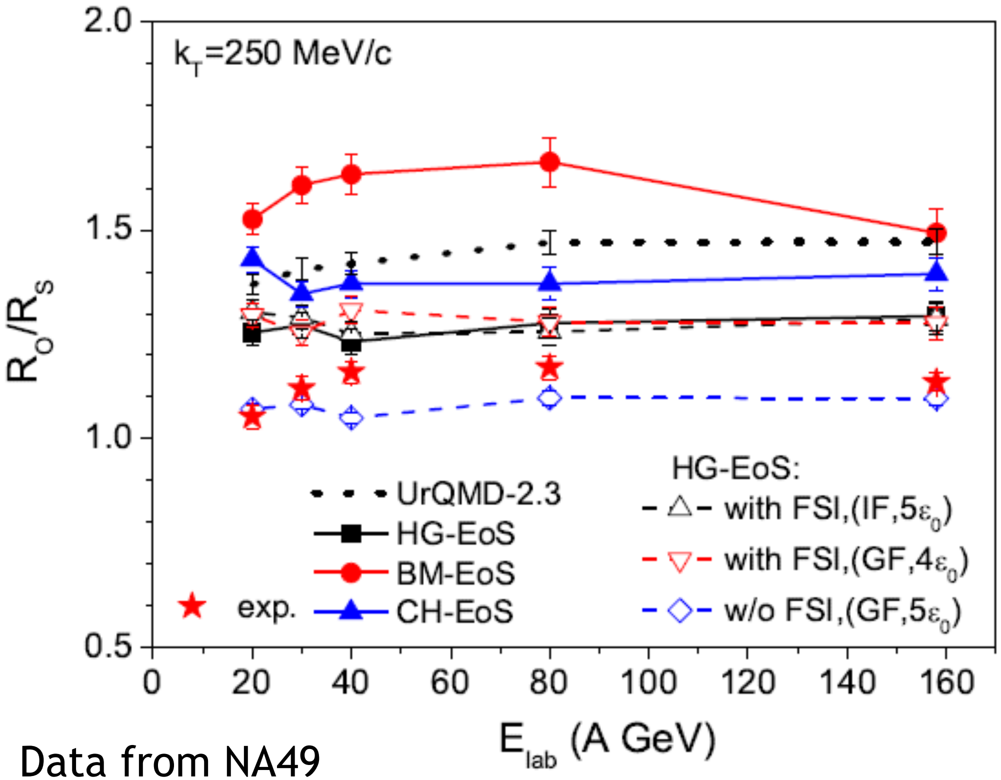


(Q. Li et al., arXiv: 0812.0375, PLB 2009)

Hydro evolution leads to larger radii, esp. with phase transition

R_O/R_S Ratio

HIC for FAIR
Helmholtz International Center



Data from NA49

(Q. Li et al., PLB 674, 111, 2009)

- Hydro phase leads to smaller ratios
- Hydro to transport transition does not matter, if final **rescattering** is taken into account
- **EoS dependence** is visible, but not as strong as previously predicted (factor of 5)

Summary

- Hybrid approaches have become the „Standard Model“ for Heavy Ion collisions at relativistic energies
- Angular correlations constrain initial state
- Photon yields support the existence of QGP
- HBT correlations may indicate increased life times