# Baryon Stopping in Heavy-Ion Collisions from AGS to SPS Energies

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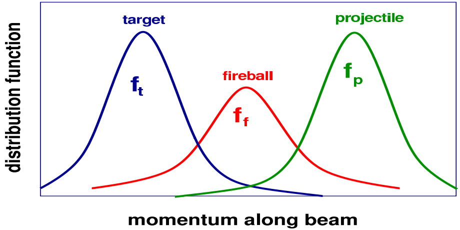
# 3-Fluid Dynamics

Produced particles populate mid-rapidity $\Rightarrow$ fireball fluid




**Target-like fluid:** $\partial_\mu J_t^\mu = 0$ $\quad \partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$

Leading particles carry bar. charge $\quad$ exchange/emission

**Projectile-like fluid:** $\partial_\mu J_p^\mu = 0$, $\quad \partial_\mu T_p^{\mu\nu} = -F_{pt}^\nu + F_{fp}^\nu$

**Fireball fluid:** $J_f^\mu = 0$, $\quad \partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$

Baryon-free fluid $\quad$ Source term $\quad$ Exchange

The source term is delayed due to a formation time $\tau \sim 1$ fm/c

**Total energy-momentum conservation:**

$$\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$$

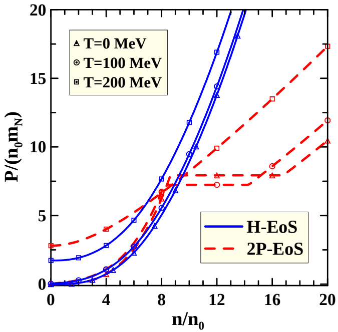
- Equation of State (EoS)

**Hadronic EoS (H-EoS)**

[Galitsky and Mishustin, Sov. J. Nucl. Phys. **29**, 181 (1979)]

**1st-order transition to QGP (2P-EoS)**

[Khvorostukhin, Skokov, Redlich, Toneev, EPJ **C48**, 531 (2006)]




**Phase transition $\Longrightarrow$ EoS softening** (in dense baryon matter)

- Freeze-out energy-density: $\varepsilon_{frz} = 0.4$ GeV/fm$^3$
- Friction: estimated and tuned
- Formation Time: $\tau = 2$ fm/c for H-EoS and $\tau = 0.33$ fm/c for 2P-EoS
- Coalescence coefficients for fragments

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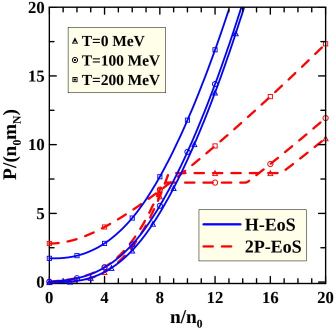


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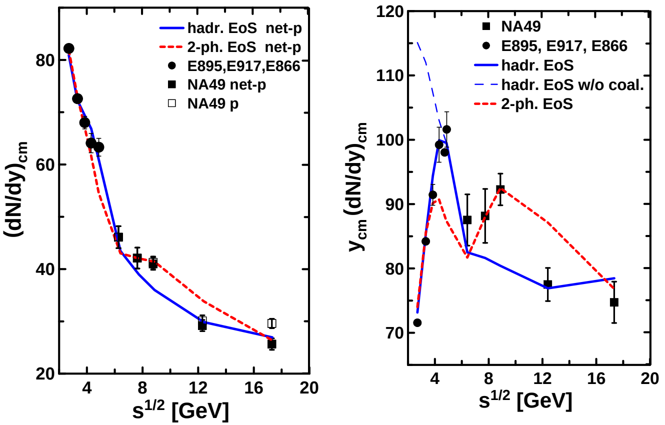
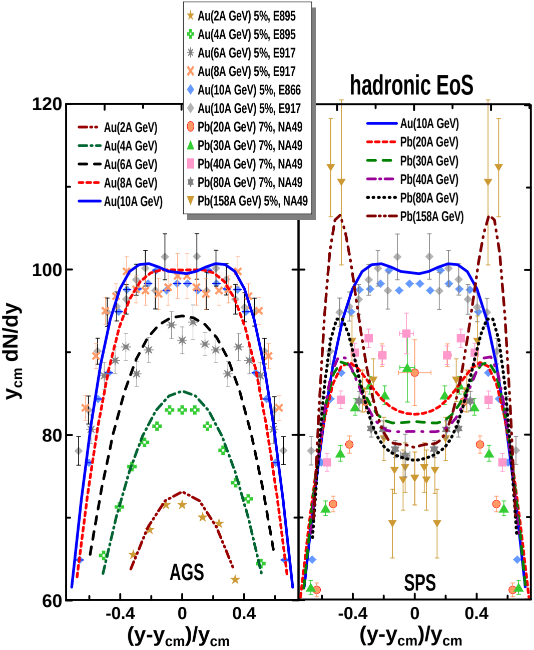



**Scaled $y_{cm} dN/dy$ acts as a zoom.**

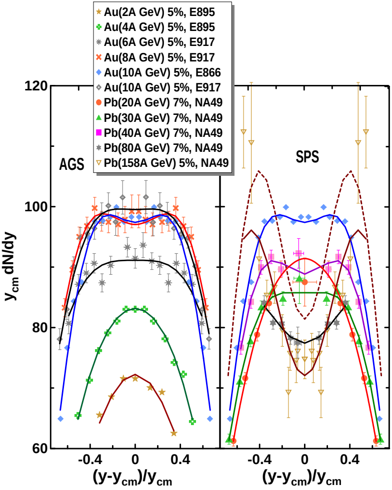
# 3FD calculations versus exp. data




**How to quantify agreement or disagreement with $y_{cm}dN/dy$?**

# Two-Thermal-Sources Fit

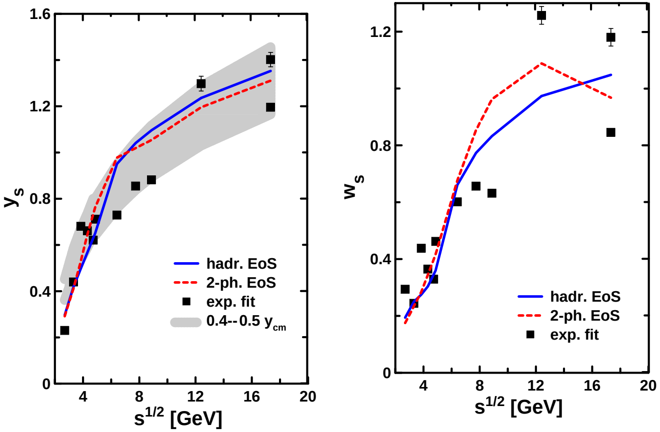
$$\frac{dN}{dy} = a\,(\exp\{-(1/w_s)\cosh(y - y_{cm} - y_s)\} + \exp\{-(1/w_s)\cosh(y - y_{cm} + y_s)\})$$




Two thermal sources shifted by $\pm y_s$ from the midrapidity.

$w_s$ = width of the sources

# Parameters of the fit




**Not very spectacular. Is there something better?**

# Reduced curvature in the midrapidity



$$C_y \equiv \left(y_{cm}^3 \frac{d^3N}{dy^3}\right)_{y=y_{cm}} \Big/ \left(y_{cm}\frac{dN}{dy}\right)_{y=y_{cm}}$$
$$= (y_{cm}/w_s)^2 \left(\sinh^2 y_s - w_s \cosh y_s\right)$$

with respect to the "dimensionless" rapidity $(y - y_{cm})/y_{cm}$.

$C_y$ is independent of the overall normalization

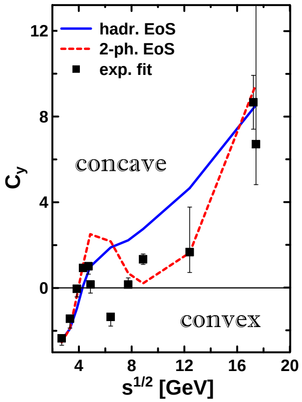
$C_y =$ **shape (concave or convex) at midrapidity**

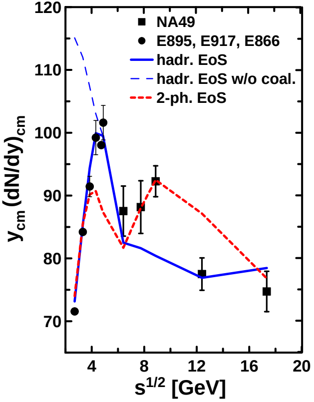
and

$(y_{cm}dN/dy)_{y=y_{cm}} =$ **magnitude at midrapidity**

**two independent characteristics of a spectrum**

# “zig-zag” irregularity

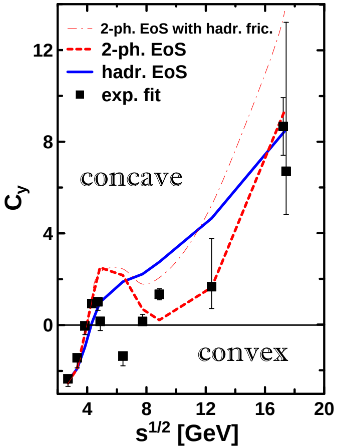



**$C_y$ in 2P-EoS scenario ⇒ zig-zag irregularity**
**[qualitatively similar to that in the data]**

Hadronic scenario ⇒ monotonous behaviour

# Why “zig-zag”?




**Phase transition results in:**

change of content of constituents

$\Downarrow$

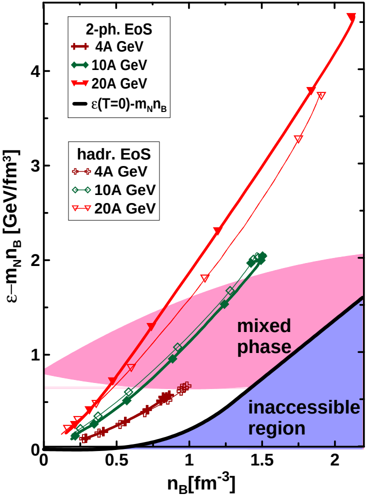
**change of stopping power**

the softer EoS

$\Downarrow$

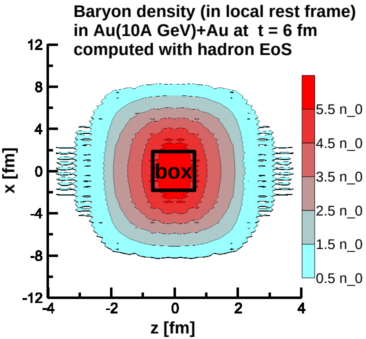
**the higher stopping power**

# Trajectories of matter evolution in the center box




Densities in the center box

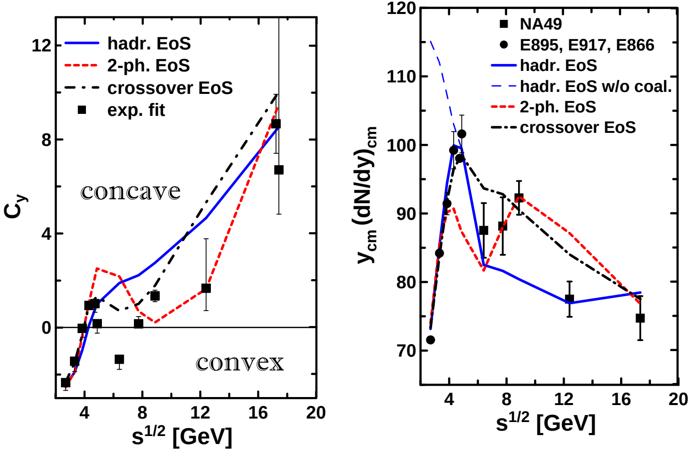
$4 \times 4 \times 4\gamma_{cm}$




**System gets into phase-transition region ⇒ Zig-zag starts**

## Crossover transition to QGP

[Khvorostukhin, Skokov, Redlich, Toneev, Eur. Phys. J. **C48**, 531 (2006)]




**Phase transition is smoother ⇒ wiggle instead of zig-zag**

- **Baryon stopping is sensitive to phase transition into QGP**

- **Data qualitatively favor onset of a phase transition between 10 and 20 GeV/nucl.**

- **Why there is no quantitative agreement?**
  **neither with the 1st-order transition scenario nor with the crossover one**

- **Probable answers:**

  **(i) Real EoS at high baryon densities ($n_B$) is very different from those fitted to lattice data near $n_B = 0$ and then extrapolated to high $n_B$.**

  **(ii) We have to consider a Van-der-Waals EoS [i.e. supercooled QGP, superheated hadronic matter, etc.] instead of the Gibbs construction.**