Partonic EoS in High-Energy Nuclear Collisions

Nu Xu

Lawrence Berkeley National Laboratory

Many thanks to the conference organizers

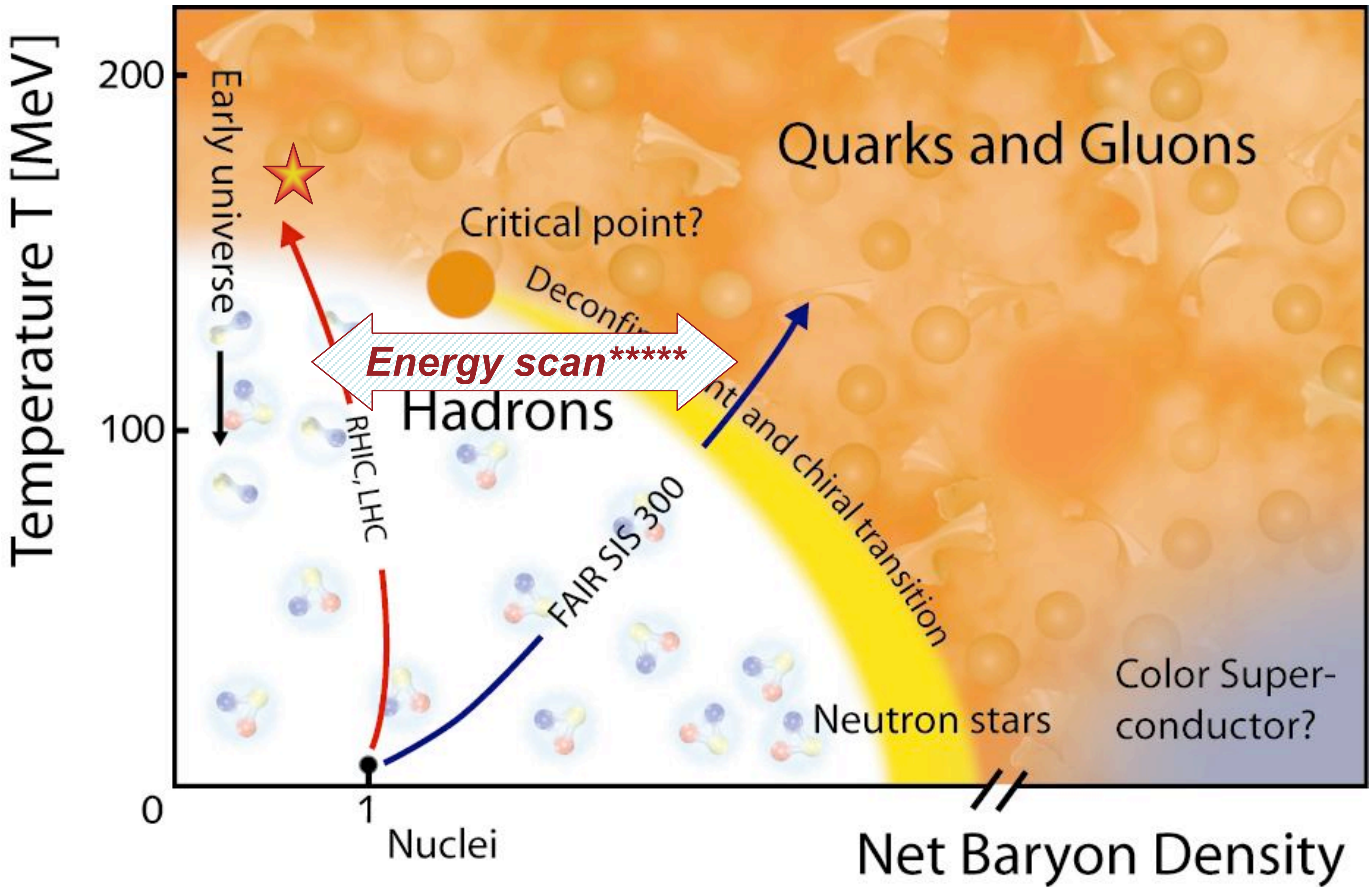
and

S. Blyth, *X. Dong, H. Huang,* **Y. Lu**, *H. Ritter, K. Schweda, Z. Xu,* **Y.F. Zhang**

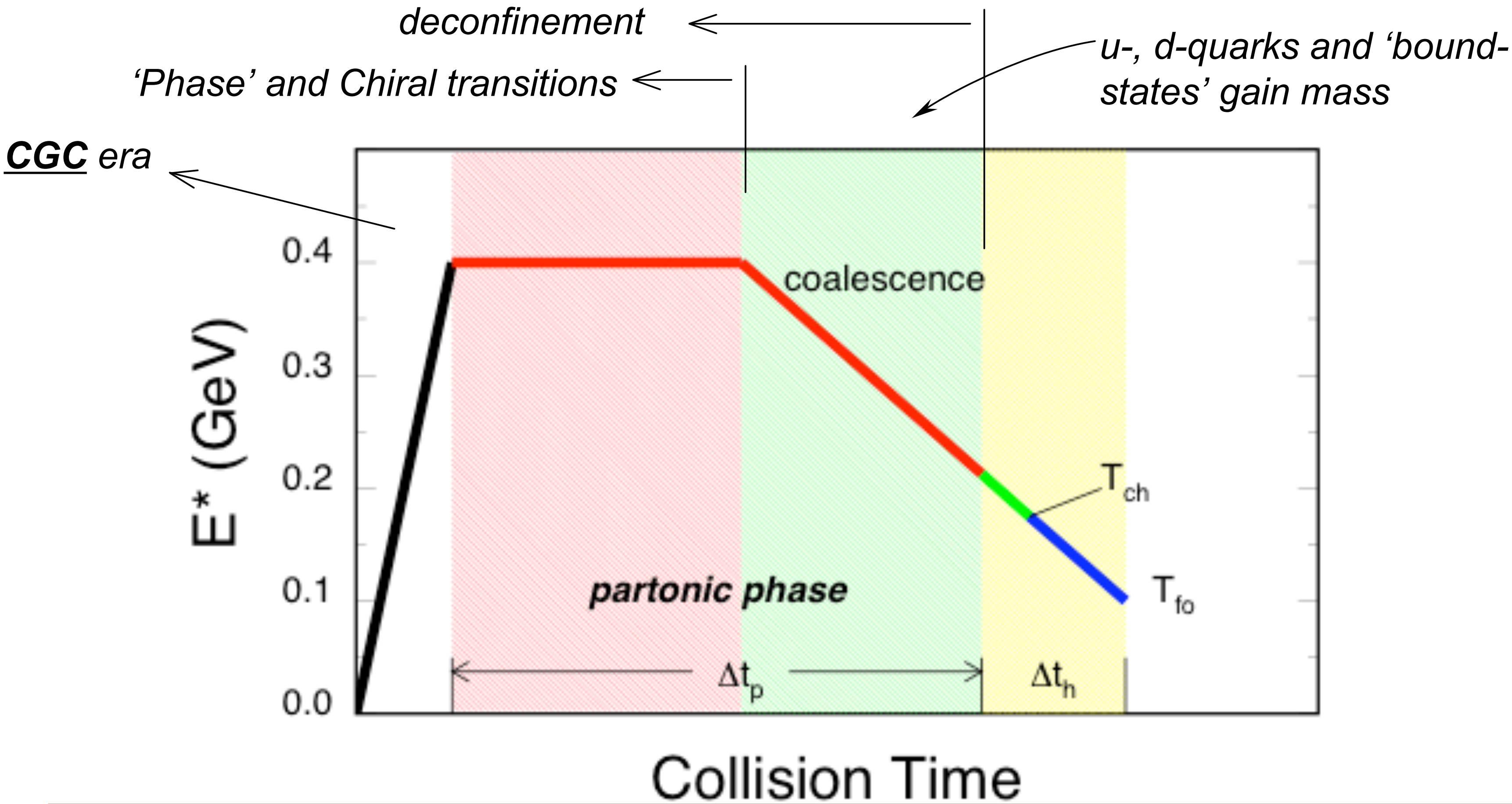
M. Bleicher, V. Koch, K. Redlich, **X.L. Zhu**….

*S. Jobs (iMac, iPod, iTunes, iBook, iChat, **iSHIP, … iQGP**)*

Nuclear phase diagram



Glasma, Plasma, Quarkma at RHIC

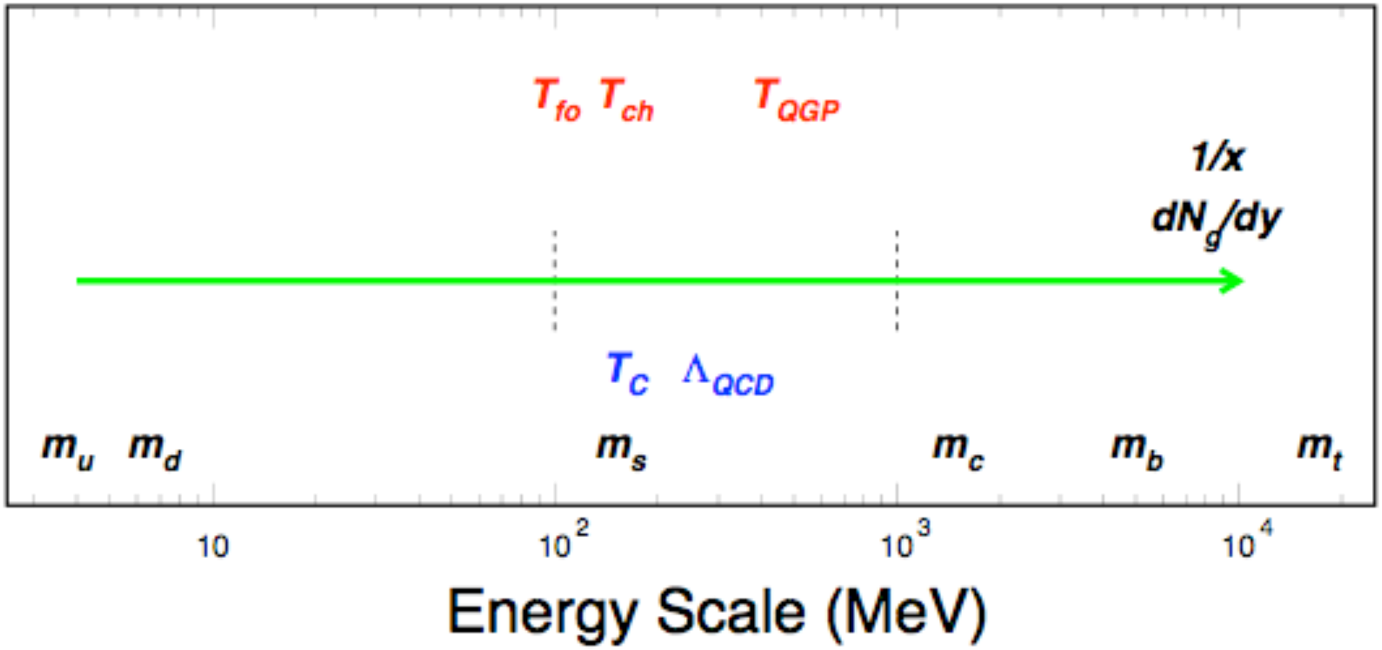


1) *Coalescence processes occur during phase transition and hadronization;*
2) *The u-,d-quarks and 'bound-states' gain mass accompanied by expansion;*
3) ***Early partonic thermalization and its duration need to be checked.***
4) ***Chiral symmetry restoration need to be checked.***

Outline

- **Motivation**
  - s-quark and c-quark are special
  - equation of state
  - collectivity, local thermalization
- **Particle spectra and v_2**
  - partonic collectivity from multi-strange hadrons
  - hint of charm collectivity
- **Summary and outlook**

Energy scales



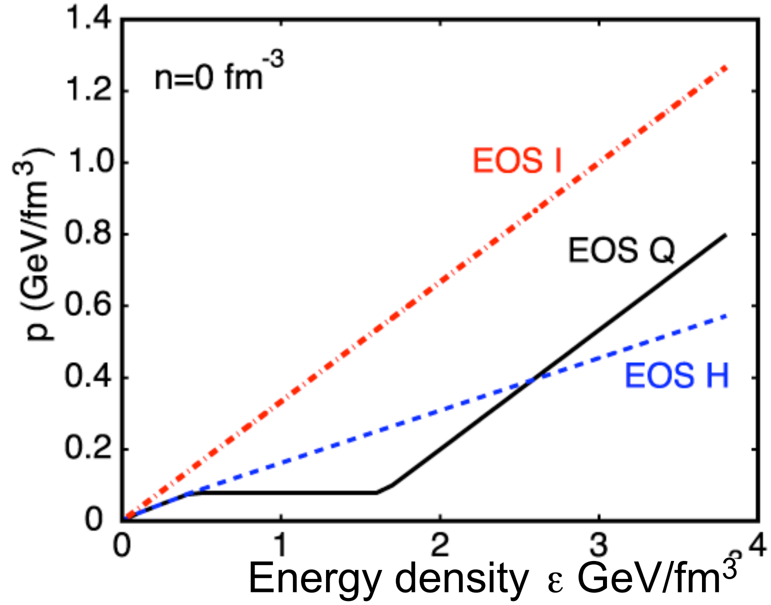
m_s ~ 0.2 GeV, similar to values **T_C critical temperature** **Λ_{QCD} QCD scale parameter** **T_{CH} chemical freeze-out temperature** **$\Lambda_\chi = 4\pi f_\pi$ scale for χ symmetry breaking**	**m_c ~ 1.2 - 1.5 GeV >> Λ_{QCD}** **- pQCD production - parton density at small-x** **- QCD interaction - medium properties** **R_{cc} ~ $1/m_C$ => color screening** **J/ψ => deconfinement and thermalization**
u-, d-, s-quarks: ***light-flavors*** Strange-quark⇒ hadronization	c-, b-quarks: ***heavy-flavors*** Charm-quark⇒ thermalization

Equation of State

$$\partial_\mu T^{\mu\nu} = 0$$

$$\partial_\mu j^\mu = 0 \qquad j^\mu(x) = n(x)u^\mu(x)$$

$$T^{\mu\nu} = [\varepsilon(x) + p(x)]u^\mu u^\nu - g^{\mu\nu} * p(x)$$



EOS - the system response to the changes of the thermal conditions - is fixed by its ***p*** and ***T*** (ε).

<u>Equation of state</u>:

- **EOS I** : relativistic ideal gas: $p = \varepsilon/3$
- **EOS H**: resonance gas: $p \sim \varepsilon/6$
- **EOS Q**: Maxwell construction:
  T_{crit}= 165 MeV, $B^{1/4}$ = 0.23 GeV
  ε_{lat}=1.15 GeV/fm^3

P. Kolb et al., Phys. Rev. ***<u>C62</u>****, 054909 (2000).*

Physics goals at RHIC

Identify and study the properties of matter with partonic degrees of freedom.

Penetrating probes

- direct photons, leptons
- "jets" and heavy flavor

Bulk probes

- spectra, v_1, v_2 …
- partonic collectivity
- fluctuations

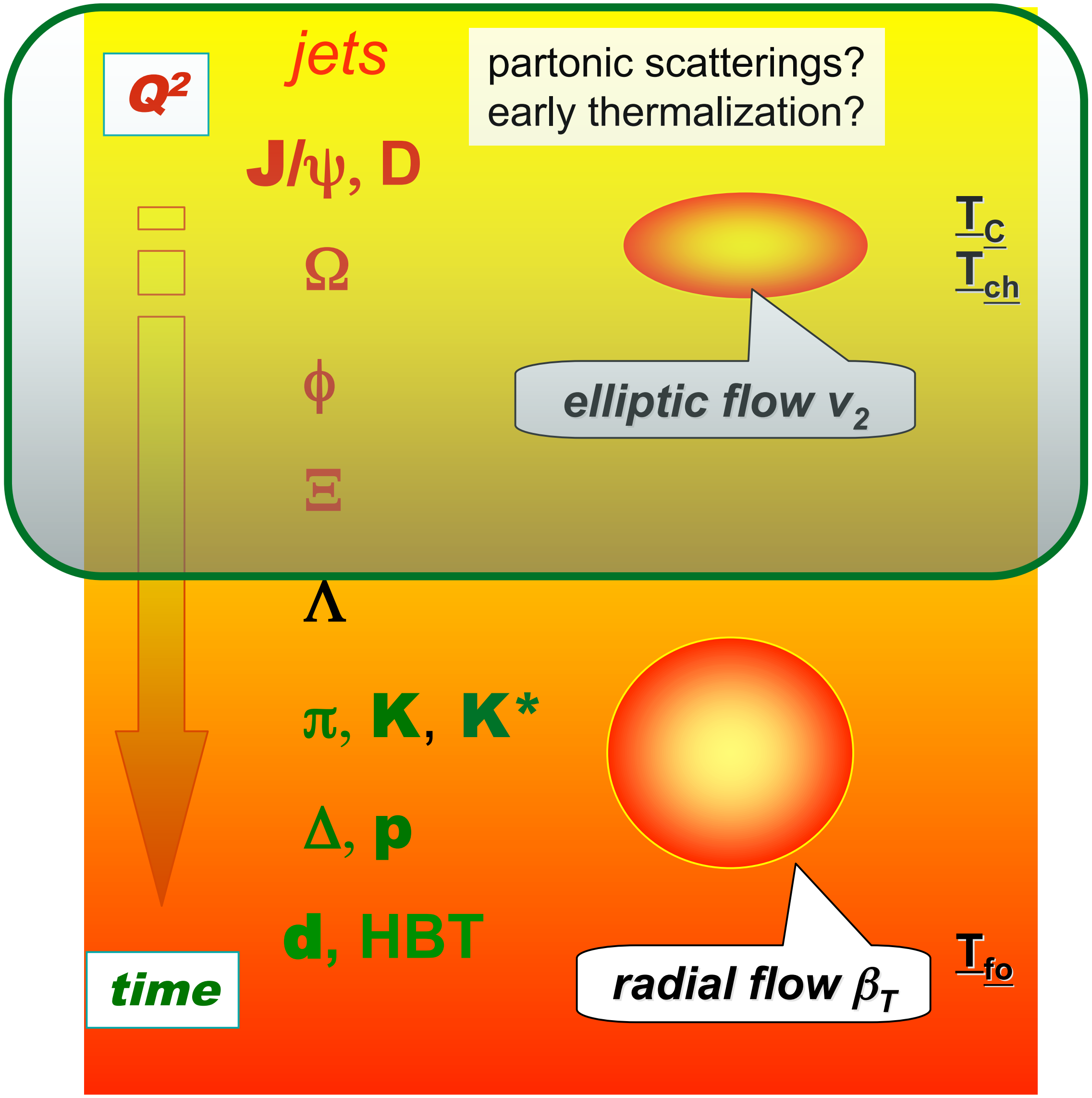
Hydrodynamic Flow = ***Collectivity*** ⊗ Local Thermalization

High-Energy Nuclear Collisions

Initial Condition
- initial scatterings
- baryon transfer
- E_T production
- parton dof

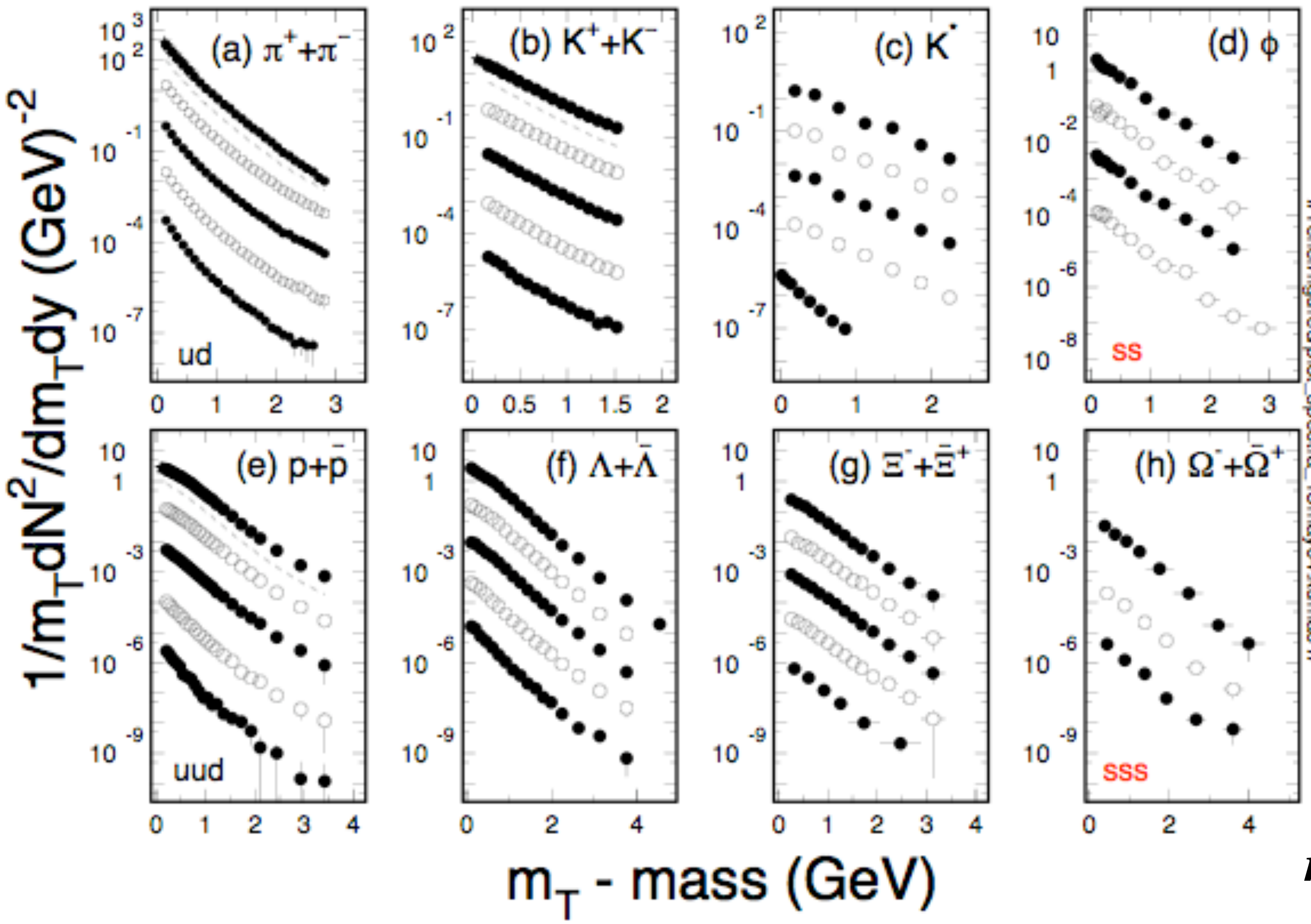
System Evolves
- parton interaction
- parton/hadron expansion

Bulk Freeze-out
- hadron dof
- interactions stop



Hadron spectra from RHIC

p+p and Au+Au collisions at 200 GeV

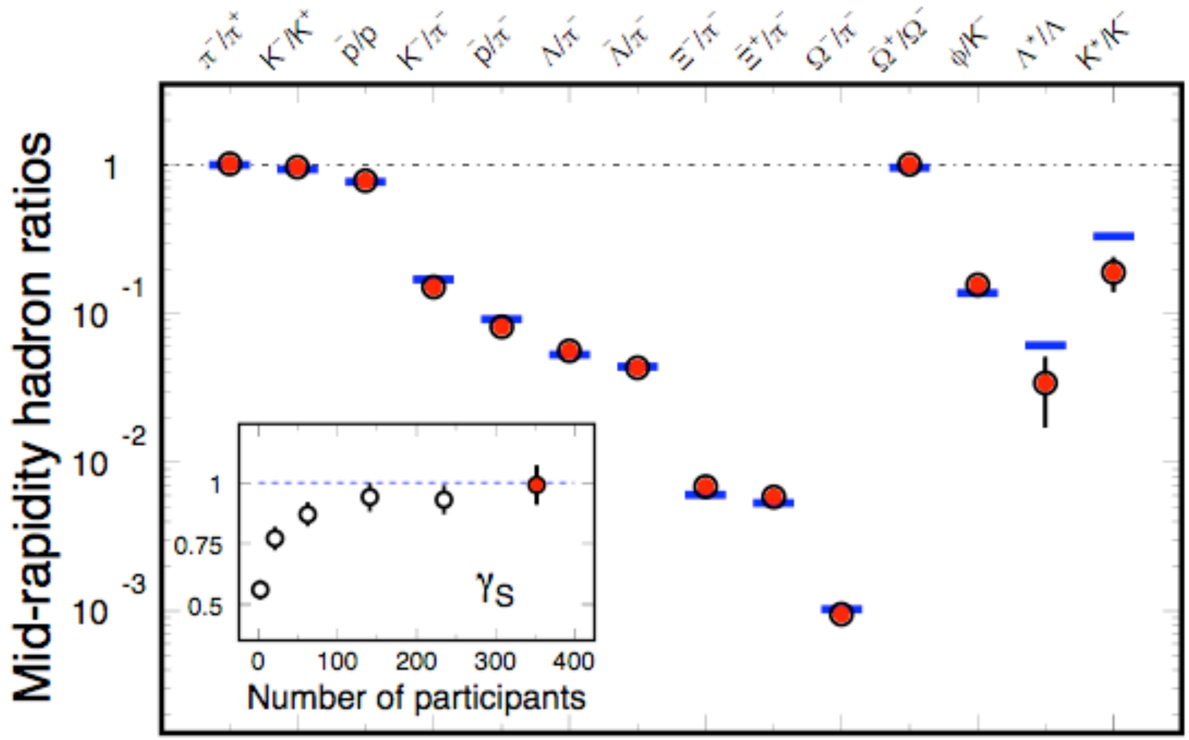


$$m_T = \sqrt{p_T^2 + m^2}$$

Multi-strange hadron spectra are exponential in their shapes.

STAR white papers - Nucl. Phys. A757, 102(2005).

Yields ratio results



200 GeV ^{197}Au + ^{197}Au central collision

data

Thermal model fits

T_{ch} = 163 ± 4 MeV

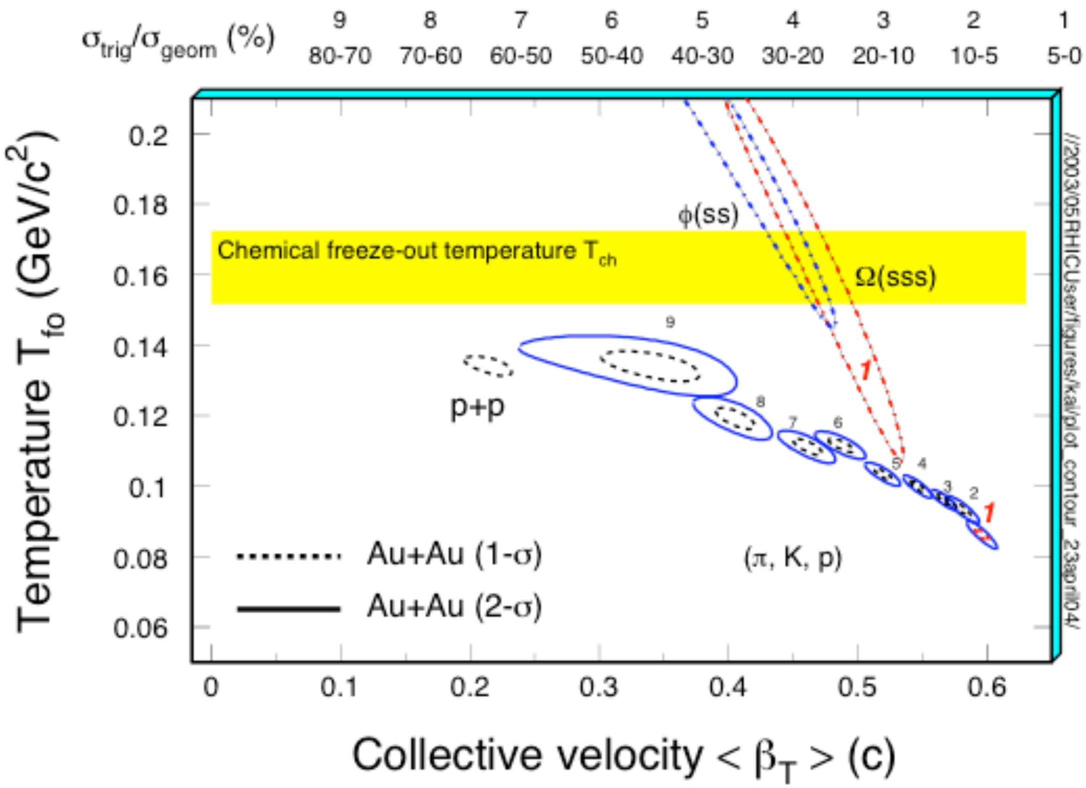
μ_B = 24 ± 4 MeV

- In central collisions, thermal model fit well with γ_S = 1. **The system is thermalized at RHIC.**
- Short-lived resonances show deviations. **There is life after chemical freeze-out.**

RHIC white papers - 2005, Nucl. Phys. A757, STAR: p102; PHENIX: p184.

Blast wave fits: T_{fo} vs. $< \beta_T >$

200GeV Au + Au collisions



Multi-strange hadrons freeze-out with higher T_{fo} ($\sim T_{ch}$) and smaller $\langle \beta_T \rangle$

1) π, K, and p change smoothly from peripheral to central collisions.

2) At the most central collisions, $\langle \beta_T \rangle$ reaches 0.6c.

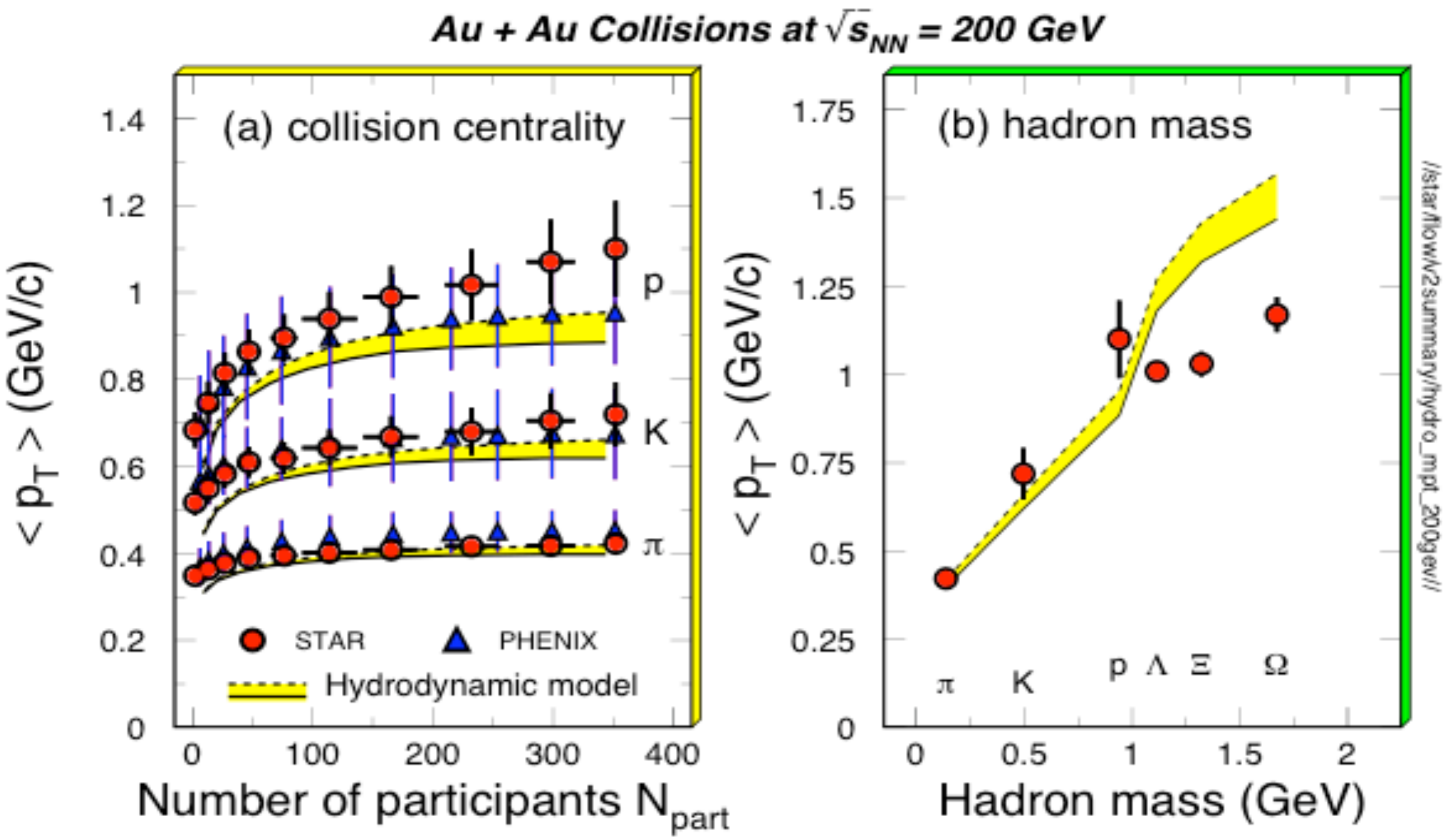
3) Multi-strange particles ϕ, Ω are found at higher T and lower $\langle \beta_T \rangle$

➪ **Sensitive to early partonic stage!**

➪ **How about v_2?**

STAR: NP**A715**, 458c(03); *PRL* ***92****, 112301(04);* ***92****, 182301(04).*

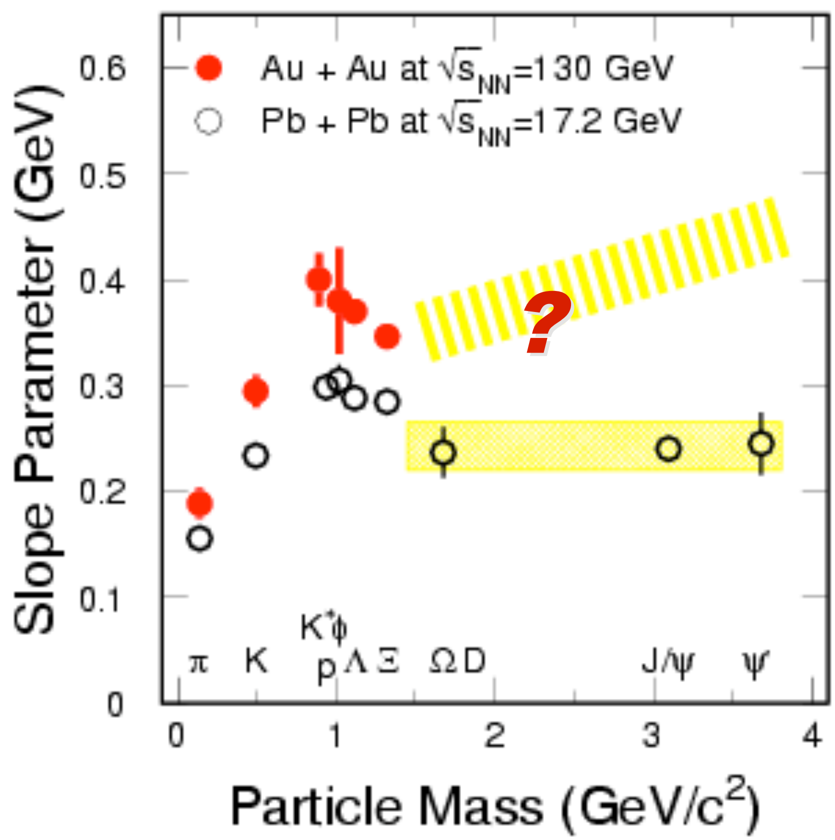
Compare with hydro-model results

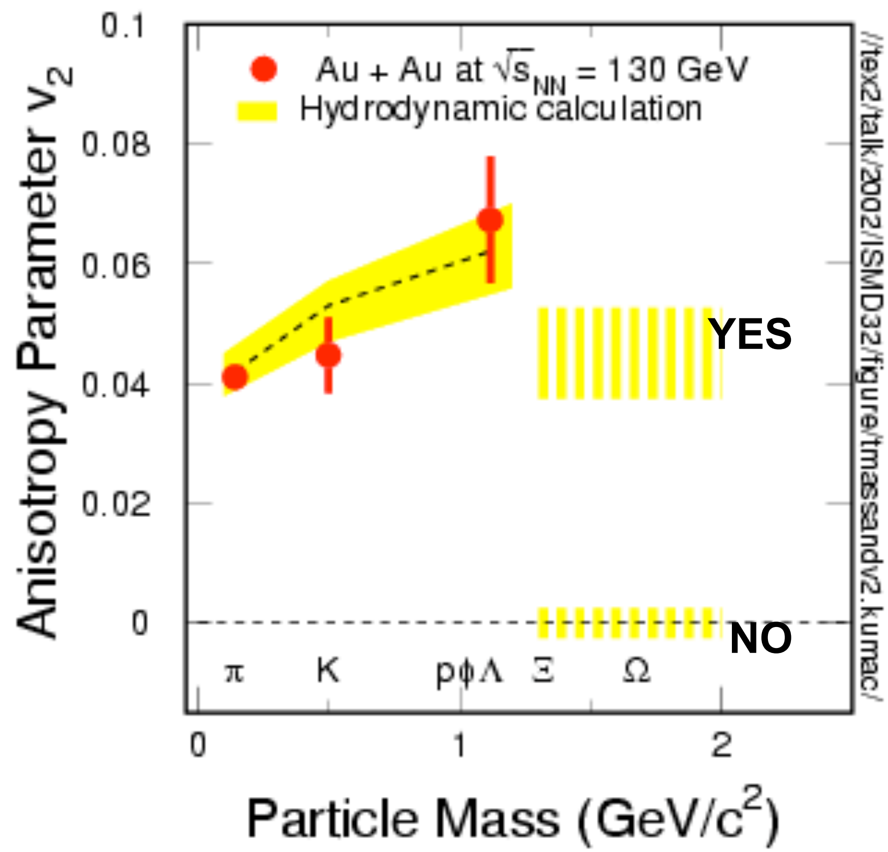


The model results fit to pion, Kaon, and proton spectra well, but over predicted the values of $<p_T>$ for multi-strange hadrons. Multi-strange hadrons freeze-out earlier!

*P. Kolb and R. Rapp, Phys. Rev. **C62**, 054909 (2000).*

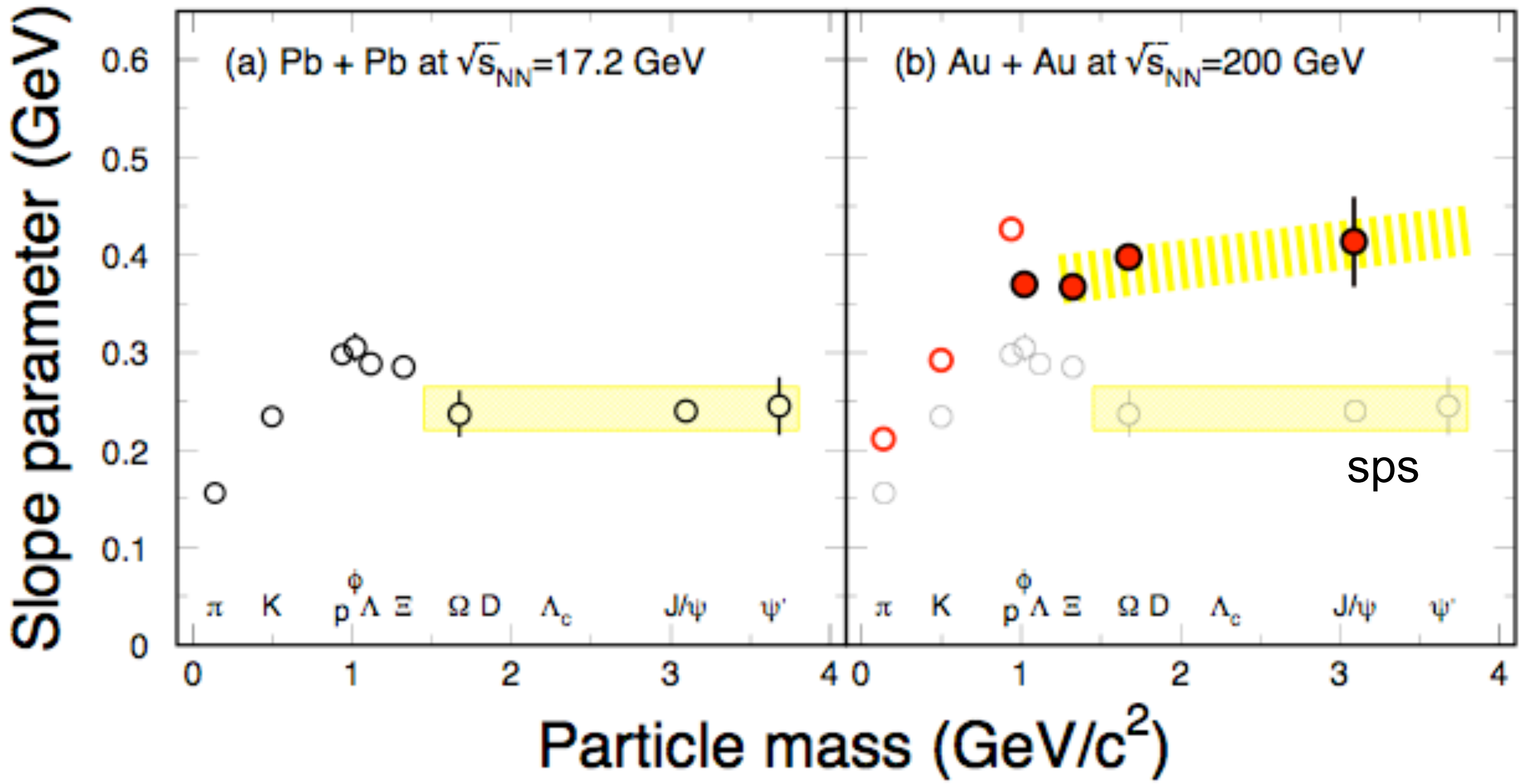
Outlook: Partonic Flow (2002)





We need: 1) Non-zero values of v_2 for Ω
2) Increase of T for Ω, D, J/ψ …

Slope parameter systematics

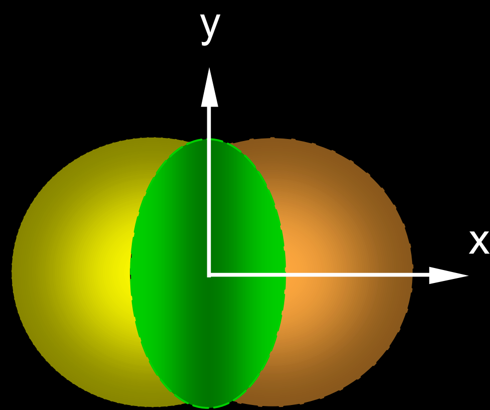


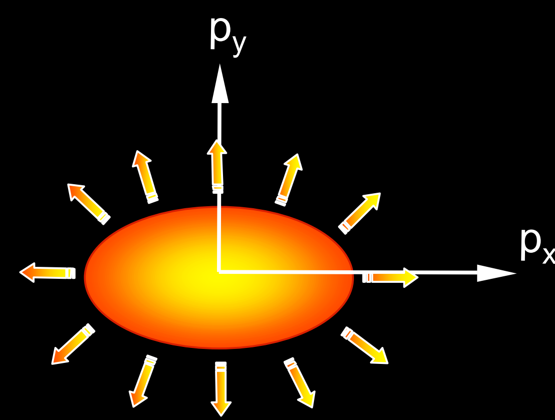
At RHIC, φ, Ξ, Ω, and J/ψ show collective motion in 200 GeV Au + Au central collisions!

PHENIX (π, K, p, J/ψ): PRC69, 034909(04), QM05; STAR (φ, Ξ, Ω): QM05.

Anisotropy parameter v_2

coordinate-space-anisotropy ➪ momentum-space-anisotropy



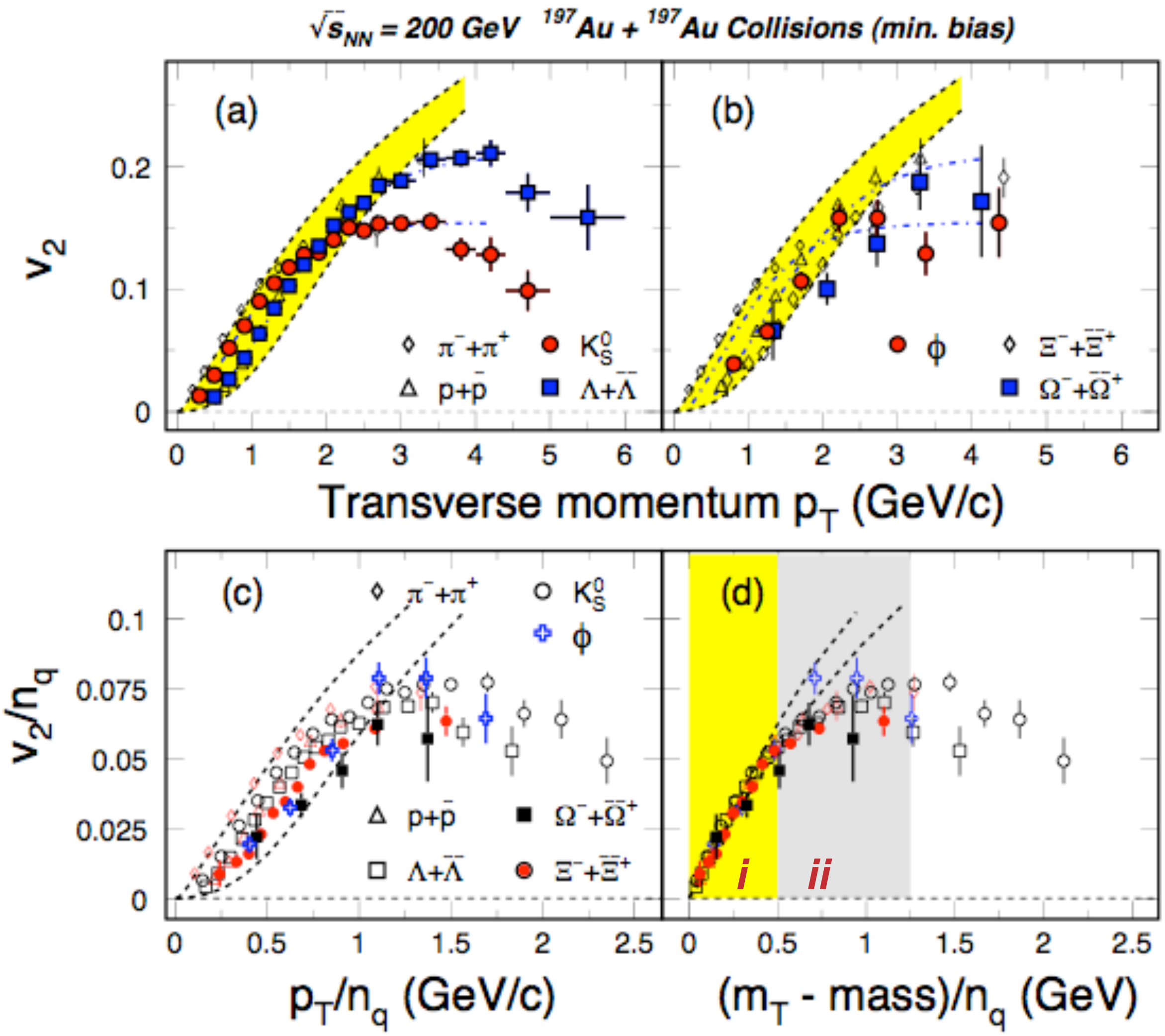


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

Collectivity, Deconfinement at RHIC



- v_2, spectra of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

➪ **m_T - NQ scaling**

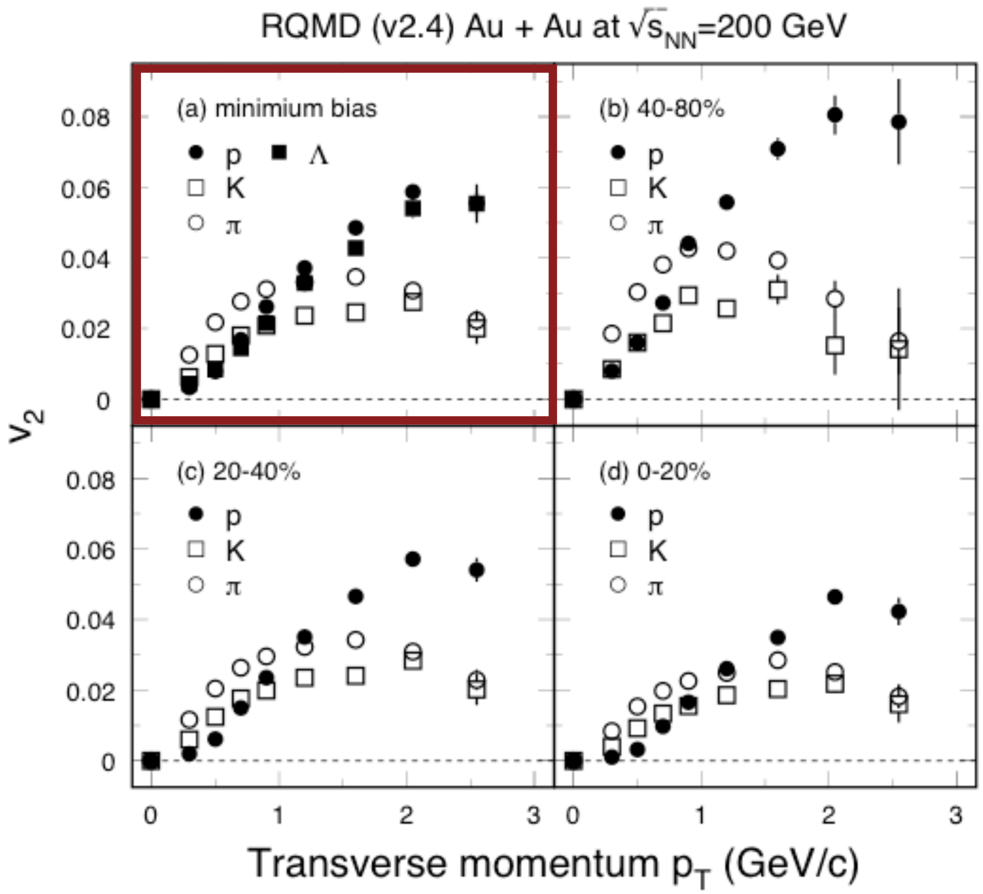
➪ **Partonic Collectivity**

➪ **Deconfinement**

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05)*
nucl-ex/0405022, QM05

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

However, hadronic transport …



uRQMD results show the particle type dependence although the absolute amplitudes of v_2 are a factor of 2 or so too small!

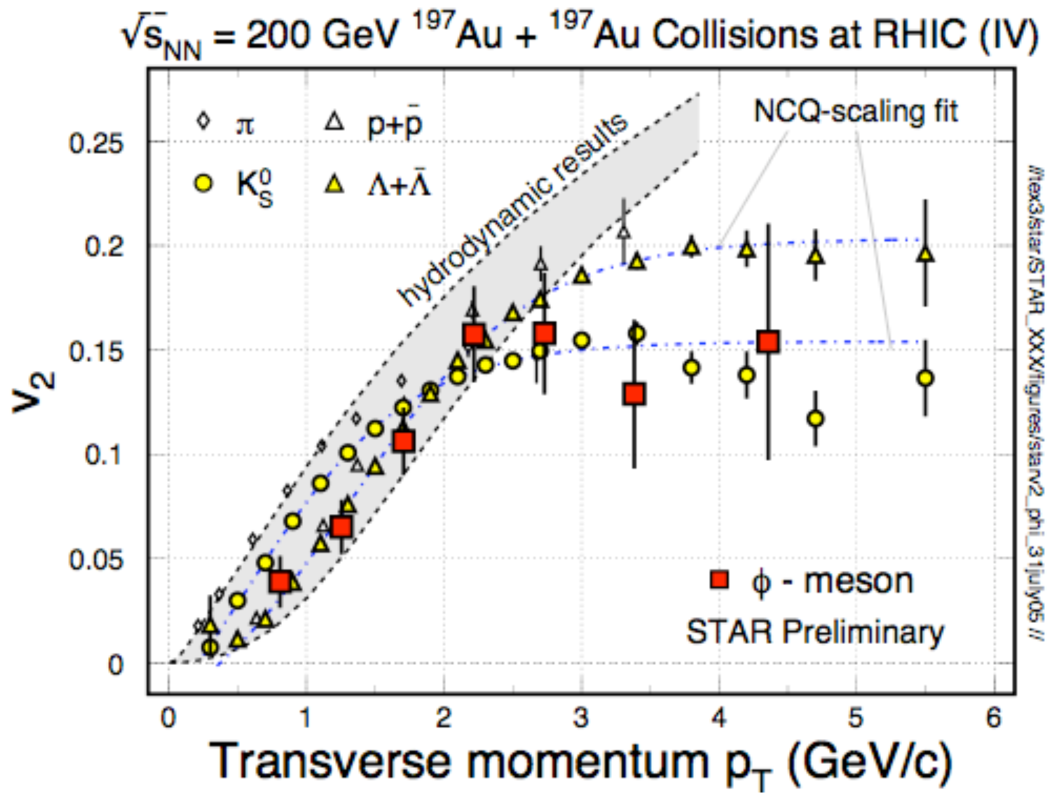
1) At low p_T region: mass ordering - feature of hydrodynamic motion

2) Hadron type dependence at the intermediate p_T region - vacuum hadronic cross sections used in the model.

Y. Lu *et al.*, nucl-th/0602009

The observation of the NQ-scaling is unique, but the explanation may not be!

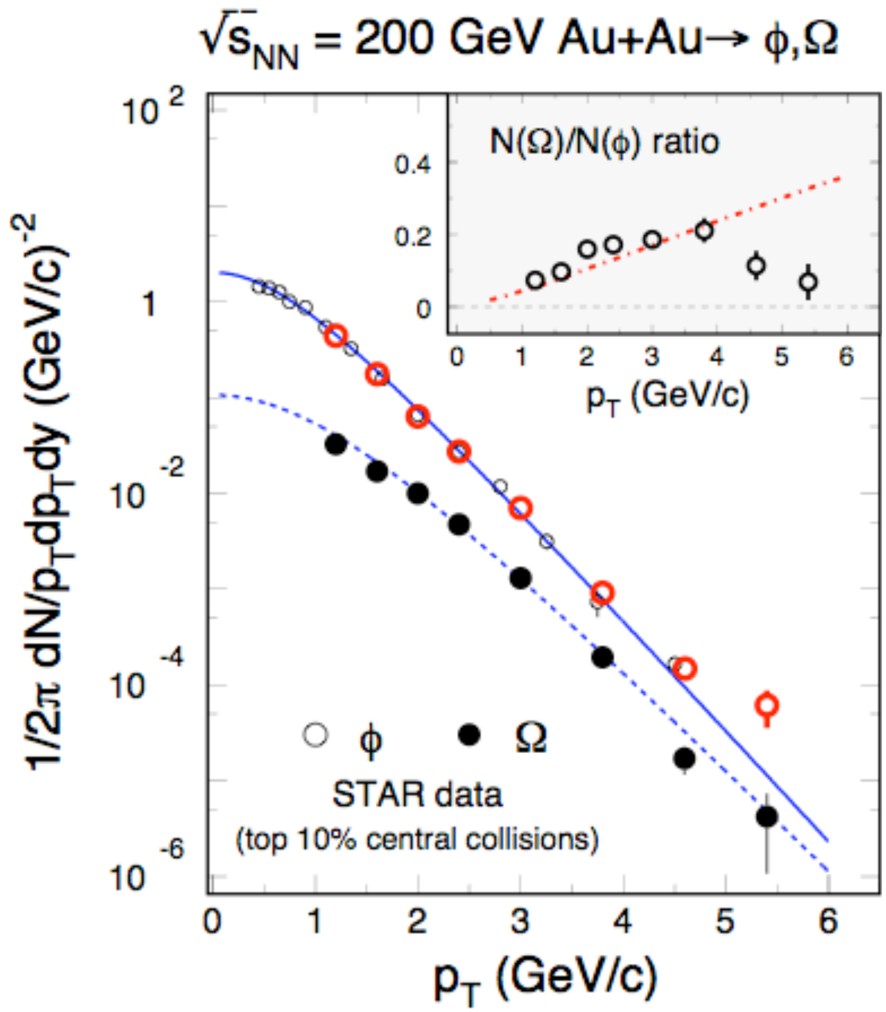
ϕ -mesons flow = partonic flow



ϕ-mesons are very special:
- they do not re-interact in hadronic environment
- they are formed via coalescence with thermal s-quarks
- they show strong collective flow

STAR Preliminary: QM05, M. Lemont, S. Blyth talks

Multi-strange hadron ratios



1) Up to p_T~ 4 GeV/c, both ϕ, Ω spectra are exponential

2) In heavy ion collisions at RHIC, up to p_T ~ 4 GeV/c, (*model predicts 8 GeV/c) the strangeness production is dominated by the thermal like processes.

**Hwa and Yang, nucl-th/0602024*

STAR data: QM05/SQM06, J. Chen, S. Blyth et al.

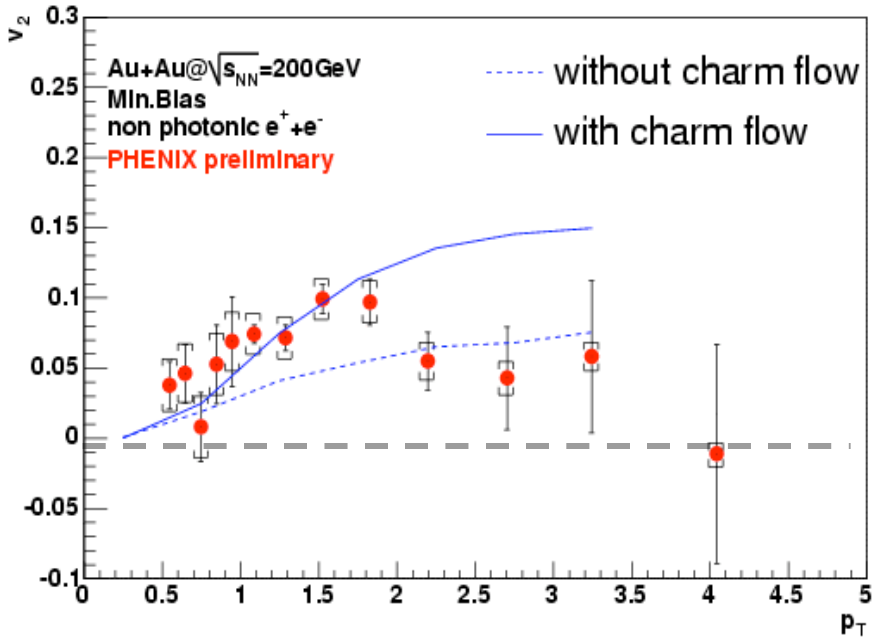
Recent new results from RHIC

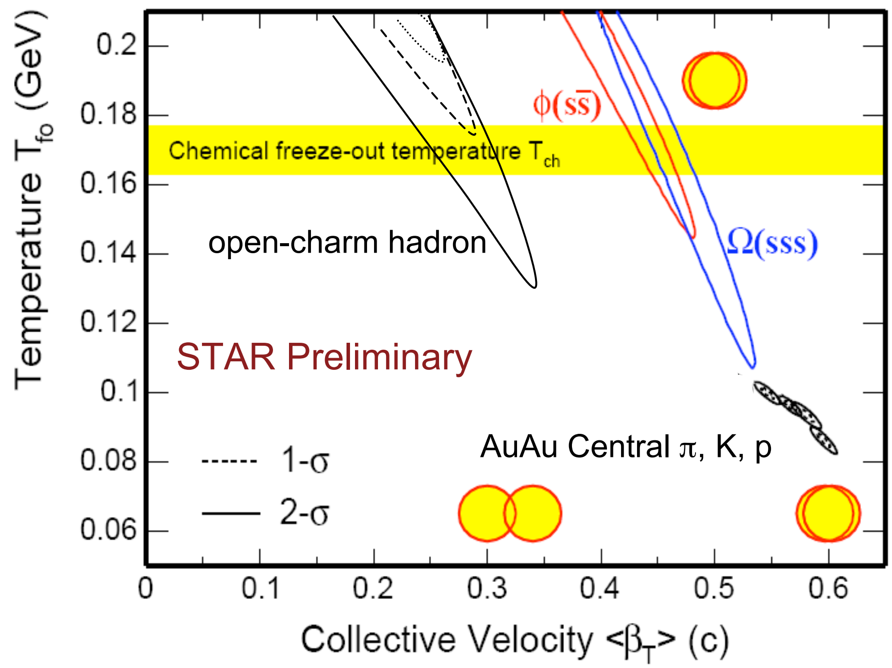
Non-photonic electrons:

taken from ShinIchi Esumi (SQM06)

Open-charm hadron spectra:

taken from Yifei ZHang (SQM06)





1) data prefers charm (heavy-flavor) hadrons flow
2) for charm to flow interactions must be very strong

*Greco, Ko, Rapp PL**B595** ,202(04)*

Summary and outlook

Experimental results from RHIC:

⇒ *Jet-quenching - hot and dense matter*

⇒ *Strong collective flow -Interacting matter*

⇒ *Chemical freeze-out near the phase boundary*

⇒ ϕ (ss), Ω (sss), J/ψ (cc) show partonic collectivity at RHIC (at SPS: ϕ, Ω, J/ψ v_2 should be close to zero)

Next Step:

⇒ Measure the partonic velocity to infer pressure parameter - important for **mapping the EoS** at RHIC.

⇒ In order to further demonstrate the early partonic thermalization, one needs to measure the **heavy-flavor collectivity = light-flavor thermalization** - RHIC heavy-flavor program, LHC.

⇒ In order to demonstrate the phase transition in high-energy nuclear collisions, one needs to **identify the critical point** - RHIC low energy scan and GSI CBM experiment.

Thanks to **the family** members:

H. Stöcker

H. Sorge (RQMD)

J. Rafelski

L. McLerran

…..

S. Bass, M. Bleicher, S. Soff (uRQMD)

Xianglei Zhu

…

A high tide lifts many boats!

Prof. Dr. Walter Greiner

祝贺您 健康， 长寿!