Seeking the QCD mixed phase in the RHIC Beam Energy Scan with STAR

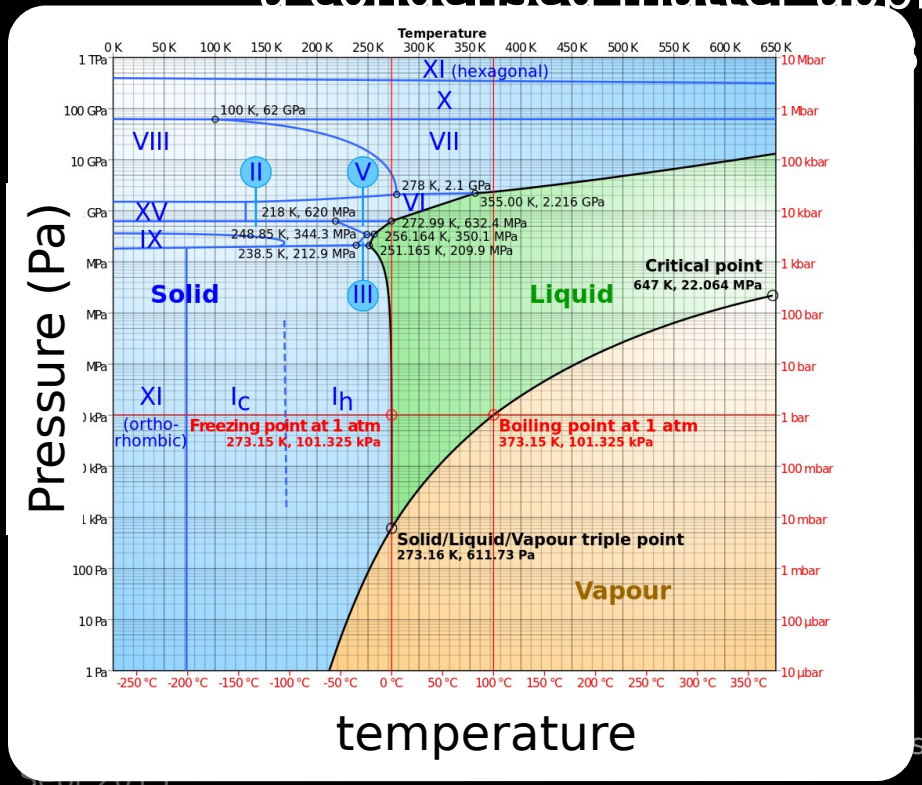
Mike Lisa, Ohio State University
for the STAR Collaboration

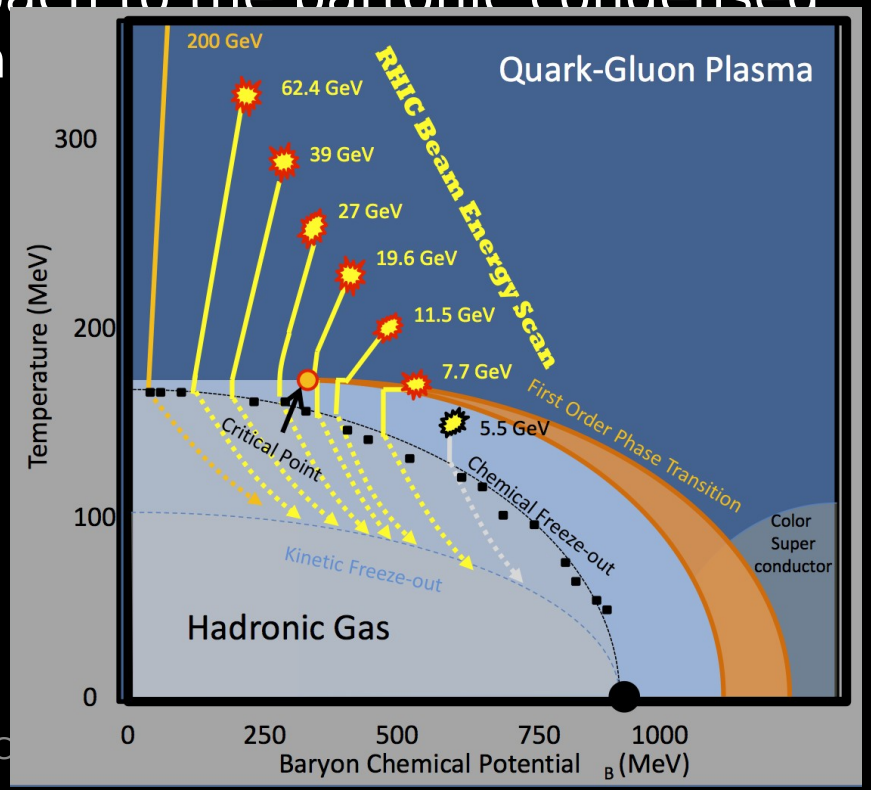
Outline

- Context and Motivation
- Beam Energy Scan with STAR/RHIC
- Selected results on bulk dynamics
  - momentum space
  - coordinate space
- Summary and outlook

The RHIC Beam Energy Scan

- Experimental exploration of the QCD phase diagram
  - understanding the fundamental theory through its phase structure
- Focus on the transitions
  - a condensed matter approach to the partonic condensed





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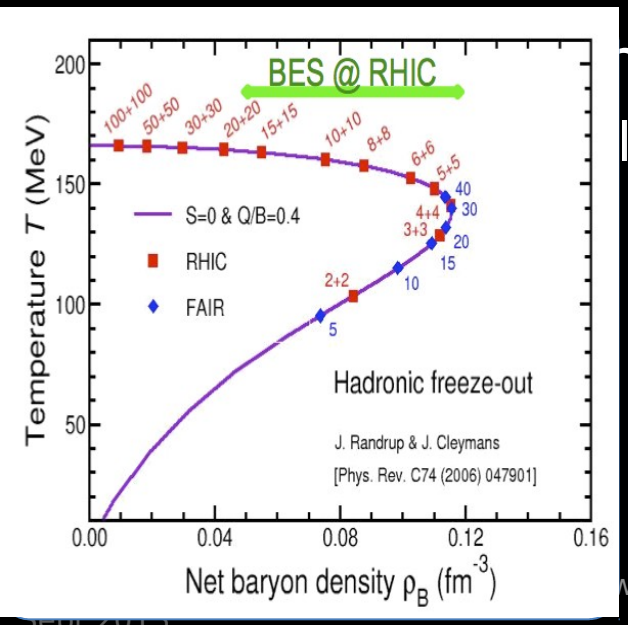

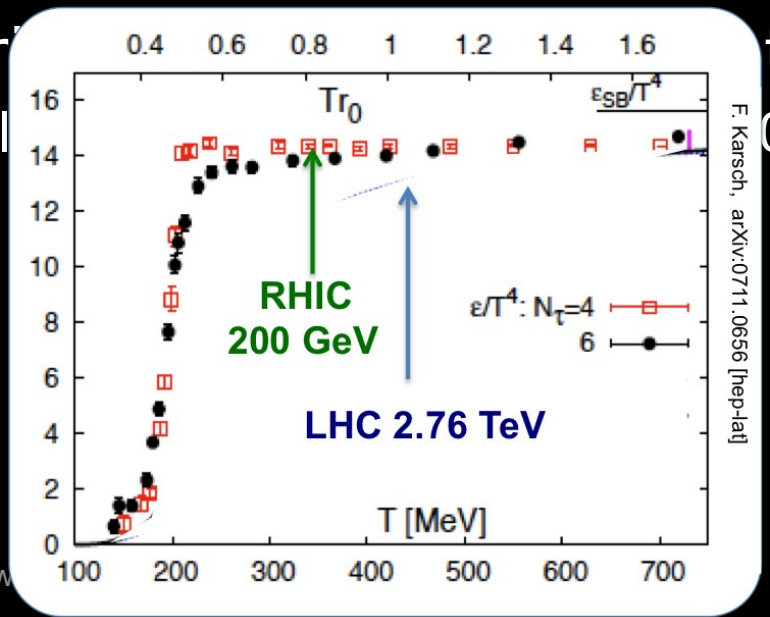

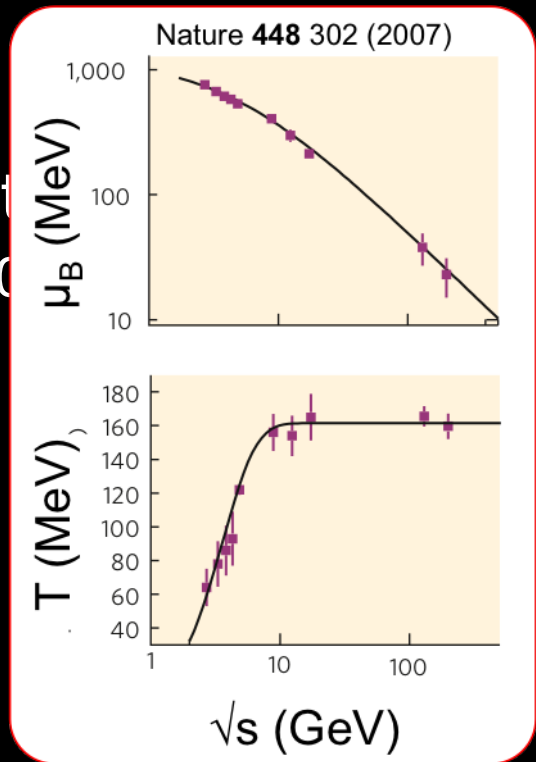

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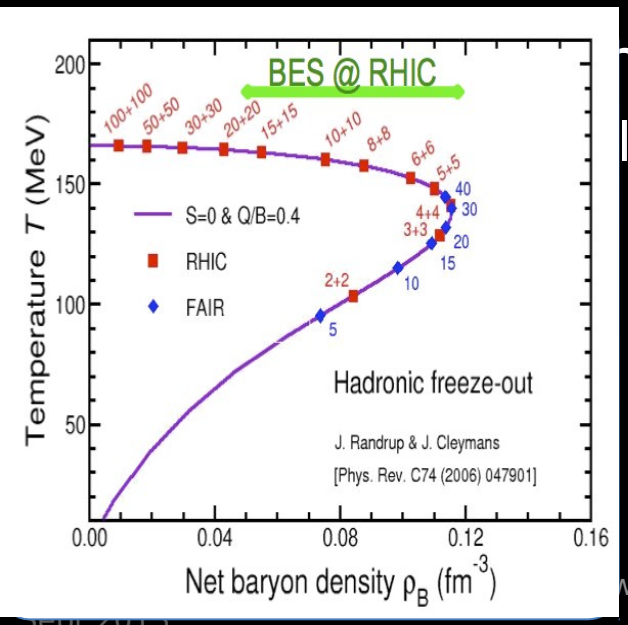

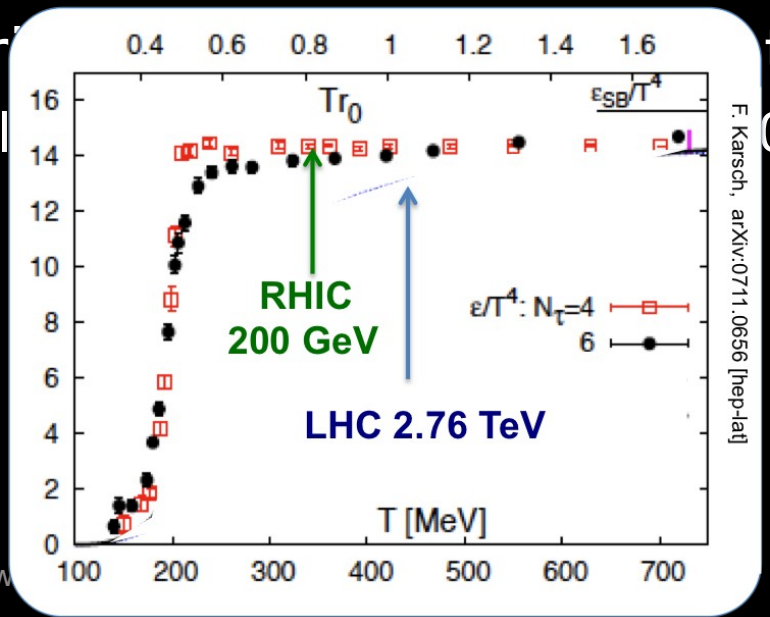

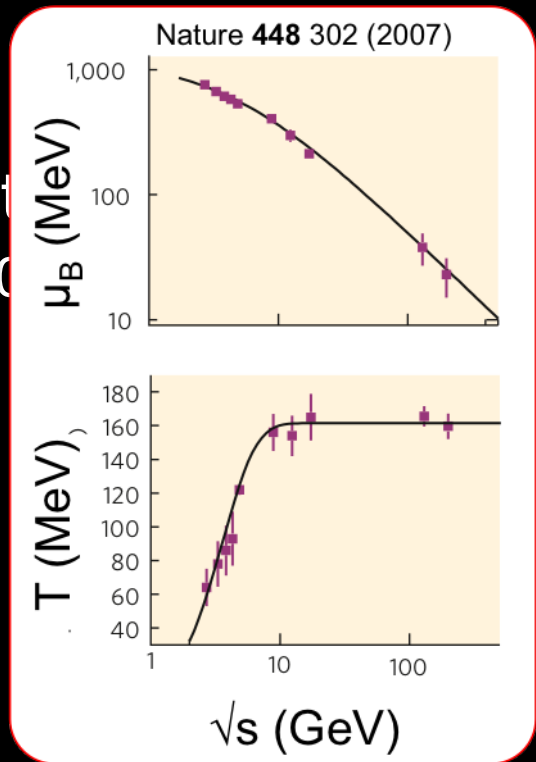

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- Experimental exploration of the QCD phase diagram
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  - theory, models, data systematics: √s=5-50 GeV

Condensed QCD Matter physics is not Energy Frontier Science
- Steve Vigdor, 2012

The RHIC Beam Energy Scan

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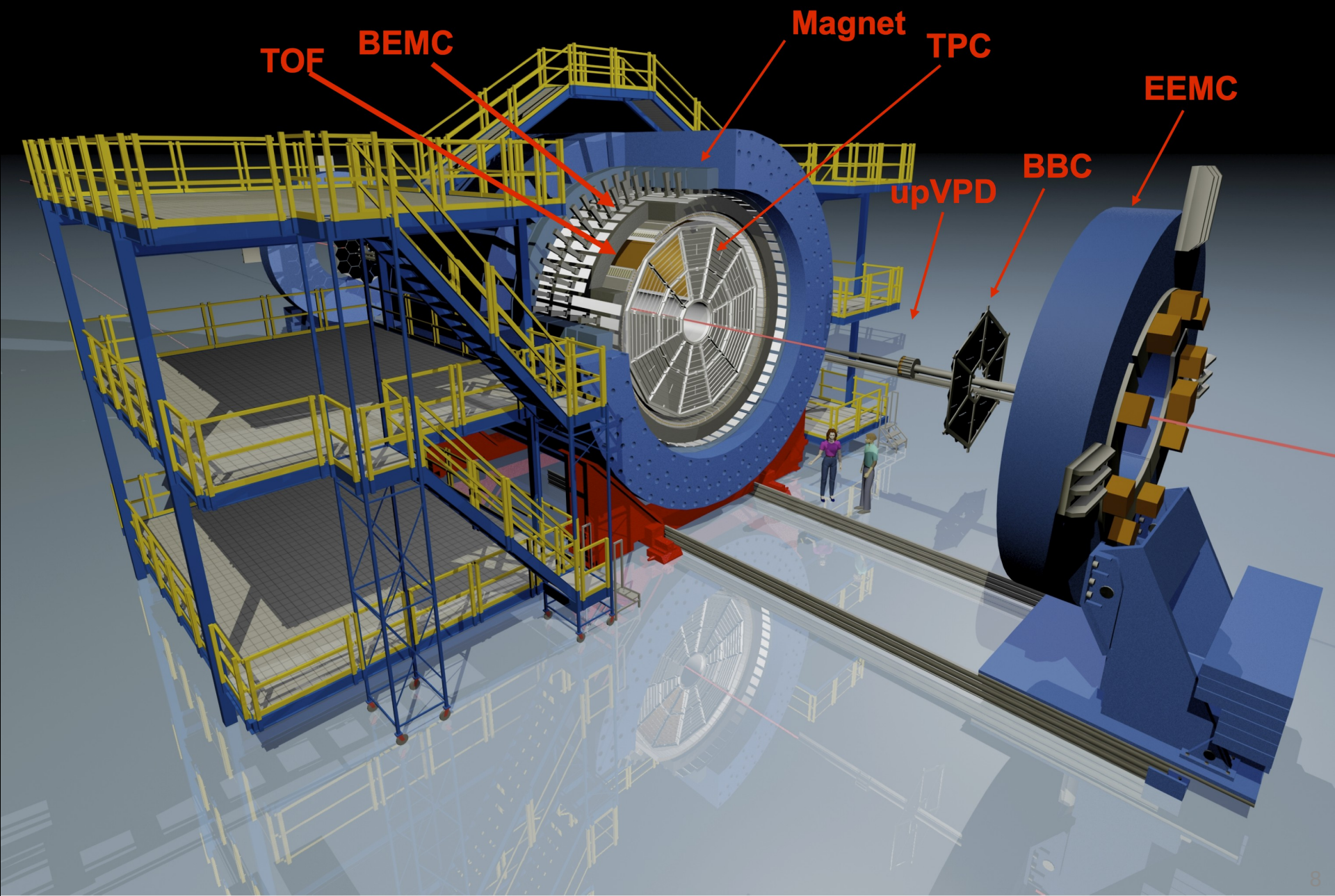
- Focus on the transitions
  - a condensed matter approach to the partonic condensed matter system vary μB and T by varying collision energy
- Focus on the right energy – QCD sets the scale
  - theory, models, data systematics: √s=5-50 GeV
- Limited theory guidance: watch for possibly subtle system
  - unifor ial collid
  - highly variable control of energy & colliding species

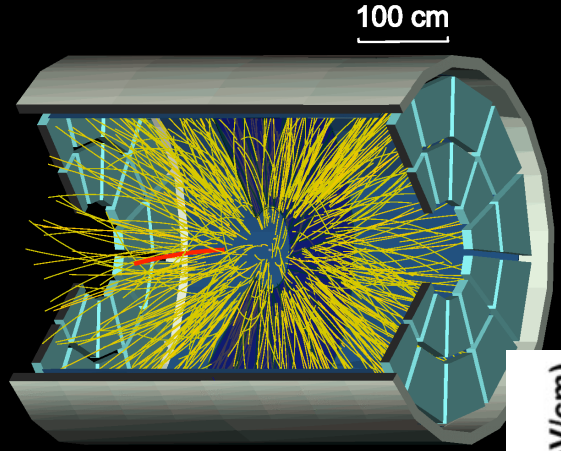
> If RHIC did not exist, we would have to build it
>
> - Berndt Mueller, 2012

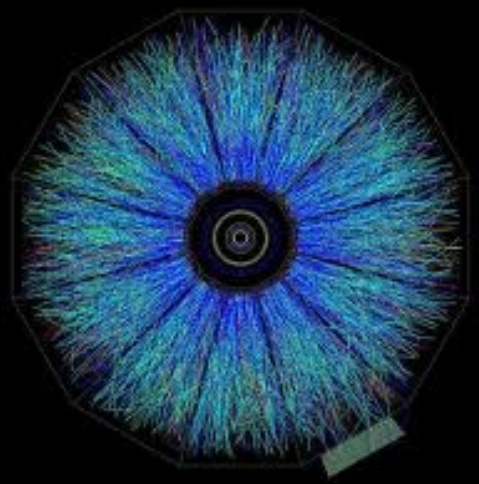
The STAR Experiment at RHIC

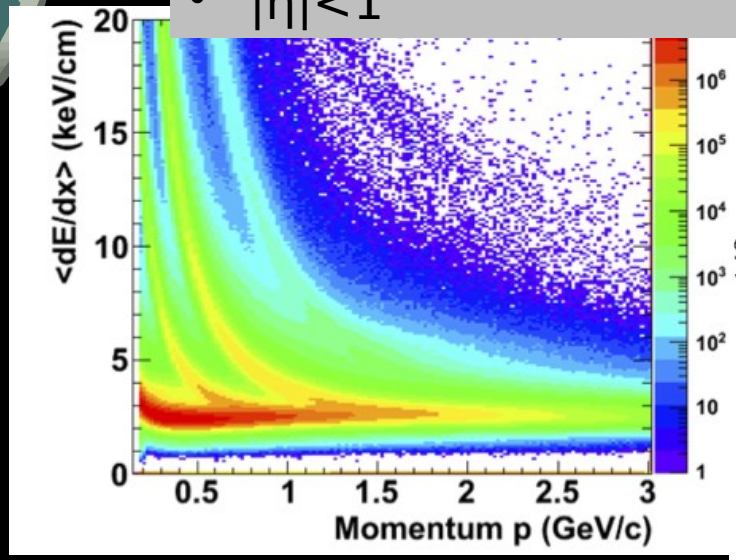


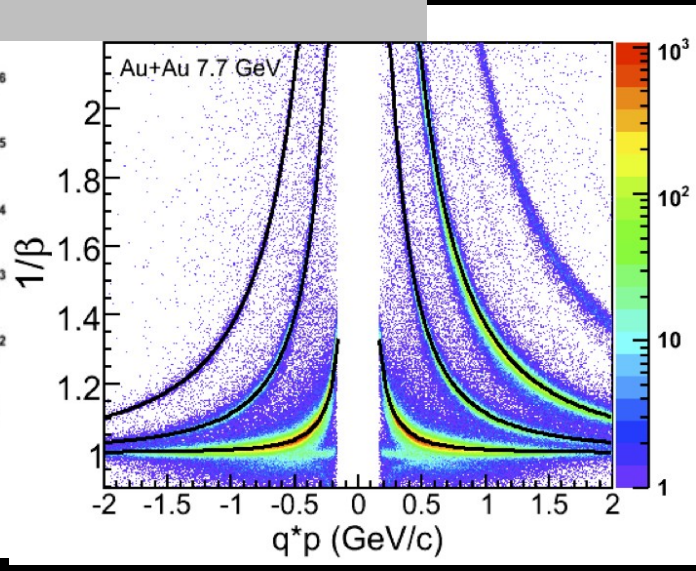
TOF and TPC

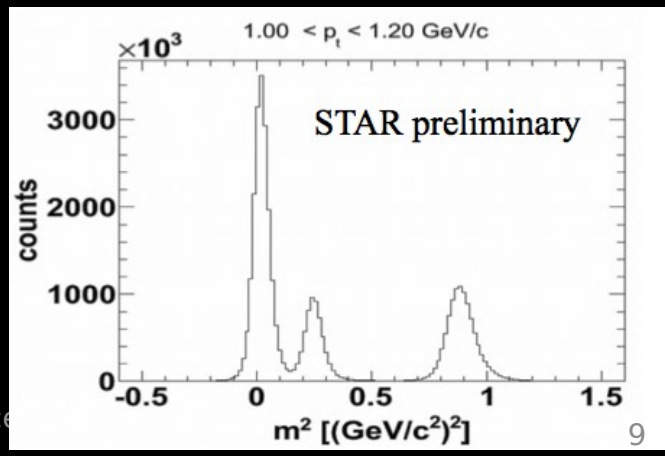
- clean separation of pi/K to pT~1.6 GeV
- full azimuthal coverage
- |η|<1











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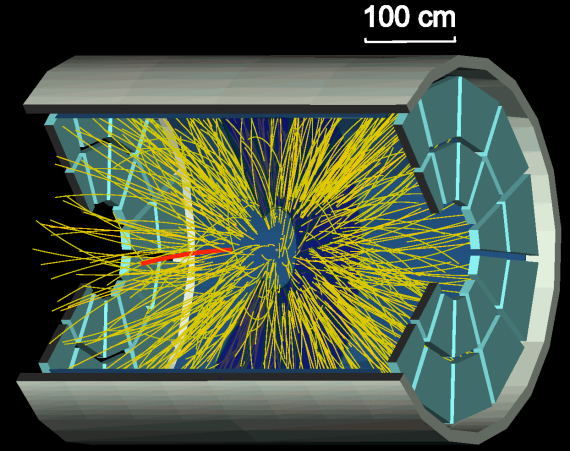
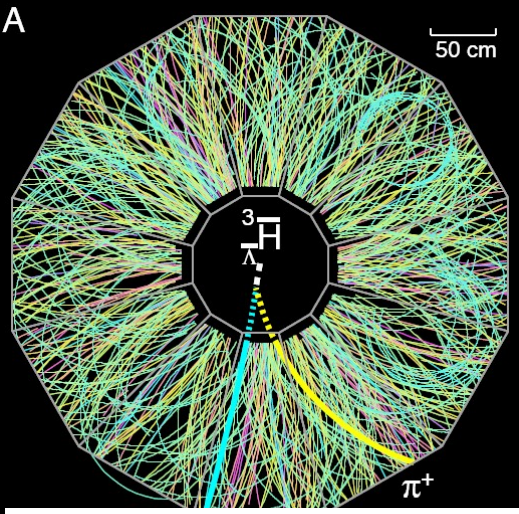
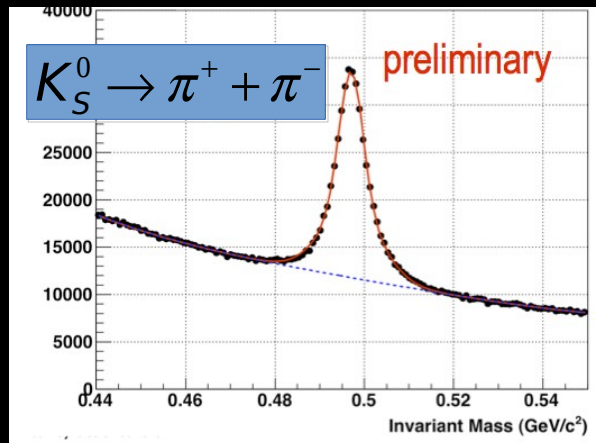
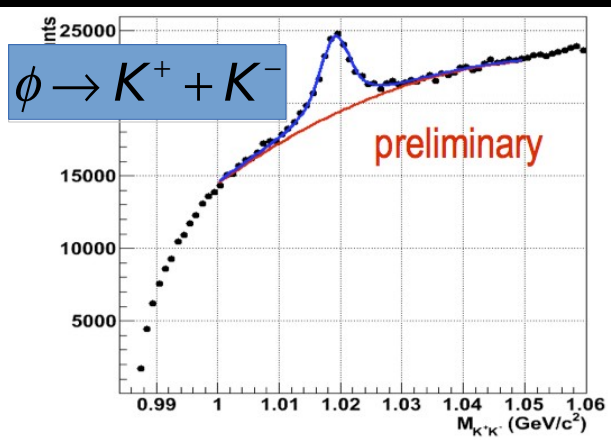
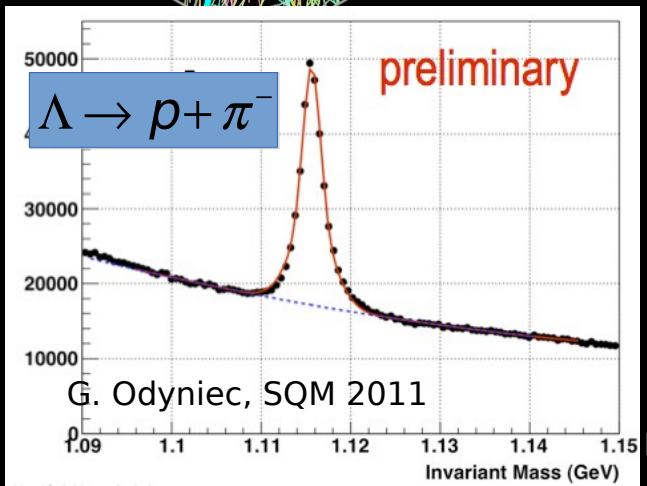
- topological/combinatoric reconstruction of weak decays



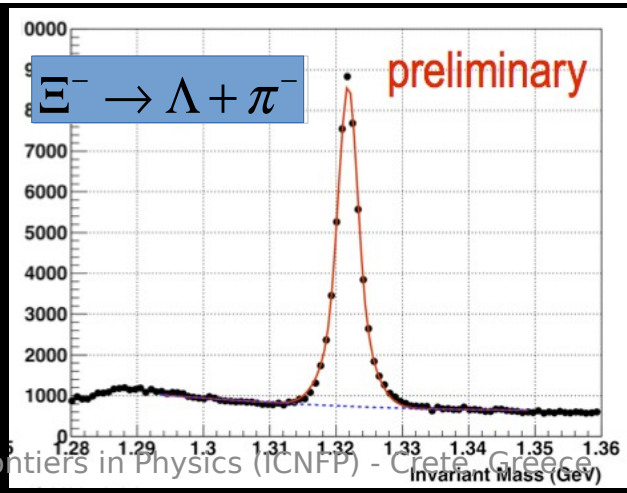


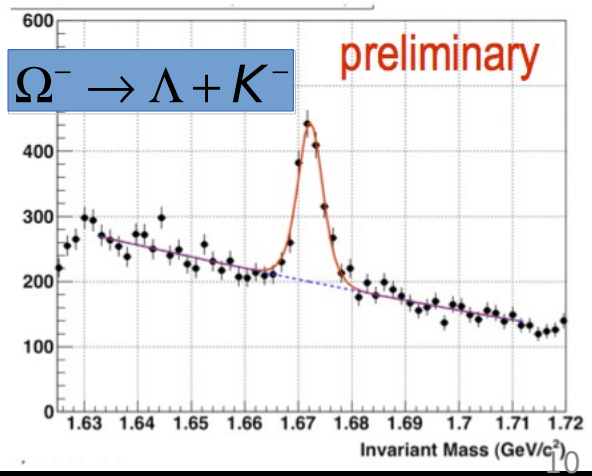


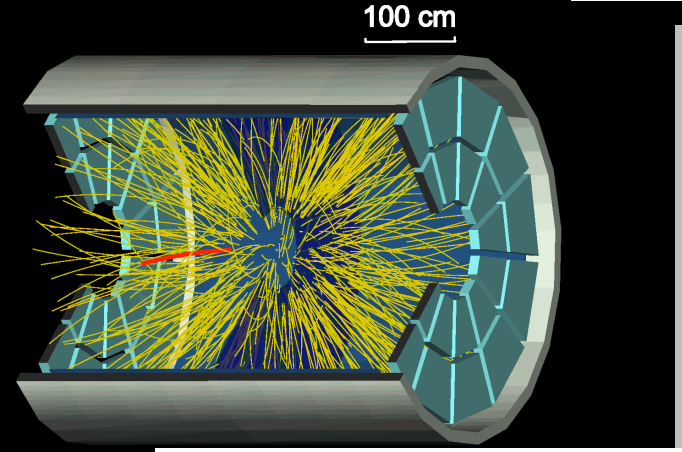




G. Odyniec, SQM 2011







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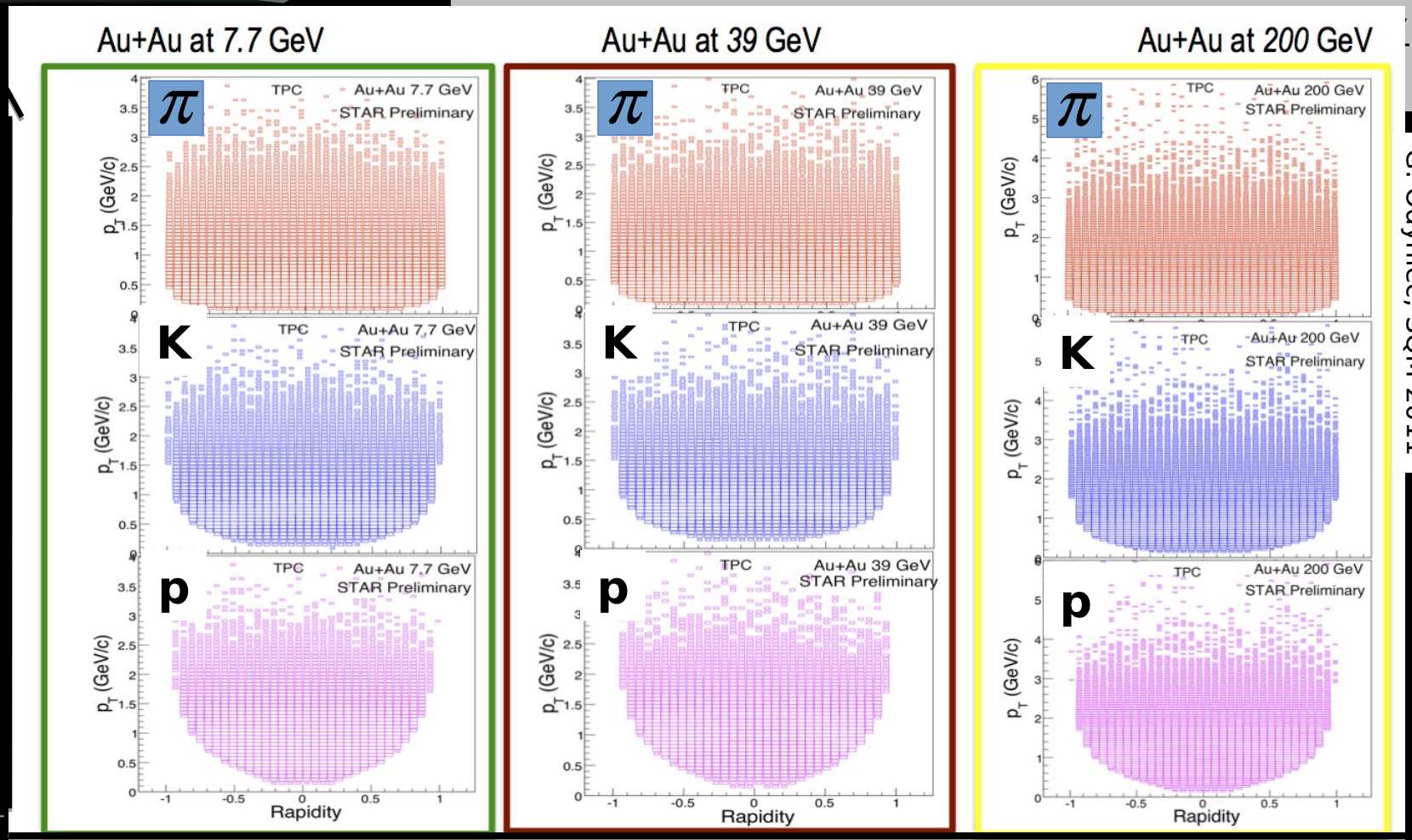

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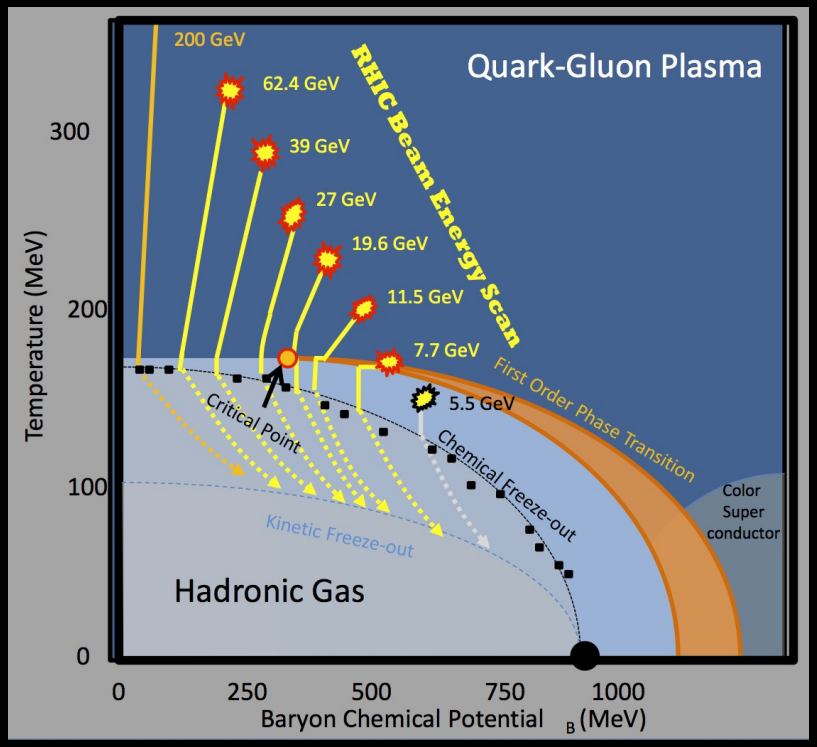
RHIC BES Phase I

- 2009: Detailed plan proposed and accepted by RHIC PAC
  - arXiv:1007.2613
  - specific energies & stats for specific questions



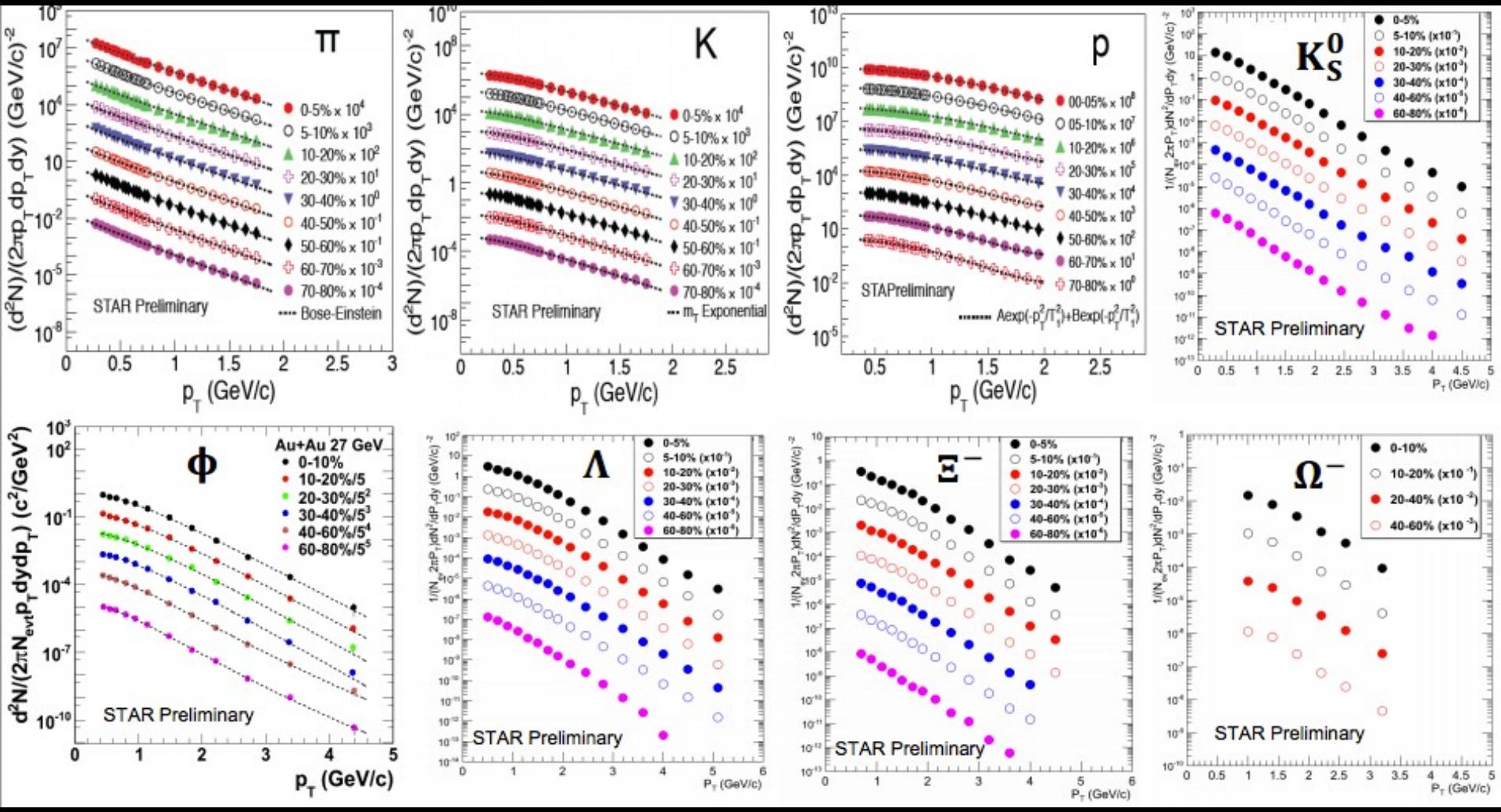
0) location on the phase diagram?
1) sQGP signatures turn off/on?
2) evidence of mixed phase?
3) critical fluctuations?

theory feedback & questions for further exploration

		(x106)
2010	7.7	5
2011	11.5	12
2011	19.6	36
2010	27	70
2010	39	130

Step 0) Particle Yields

Xin Dong, Future Trends Workshop, Beijing 20



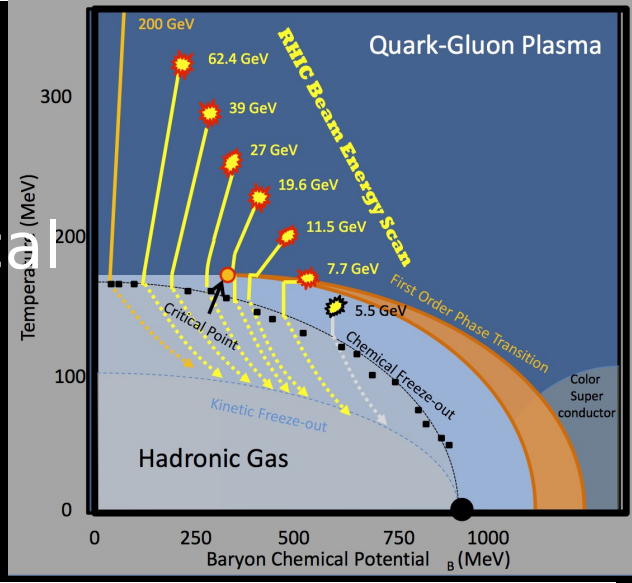
Step 0: location on the PD

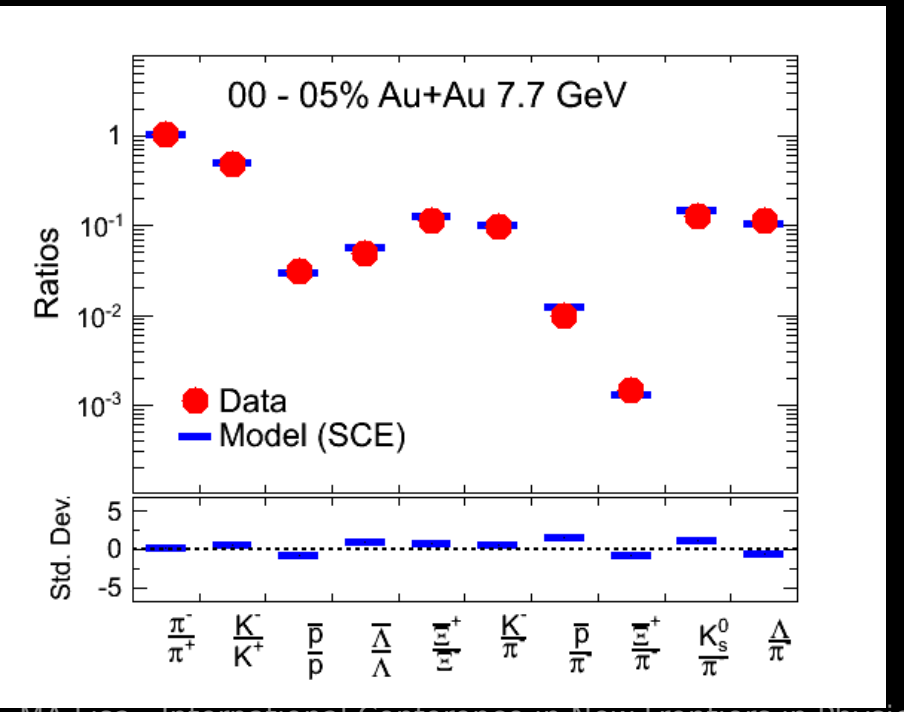
- Fits to particle yields reveals chemical *freeze-out* location

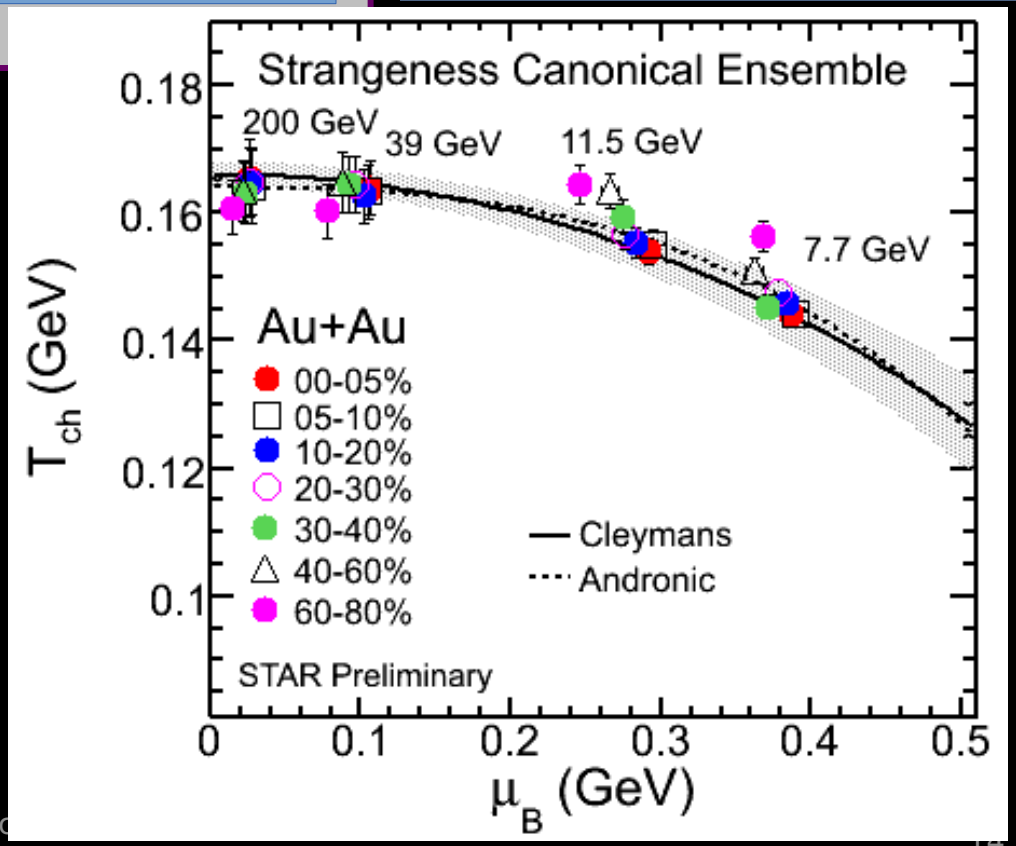
$$N_i(T,\mu_i) \sim \exp\left(\frac{\mu_i - m_i}{T}\right)$$

$$\mu_i = B_i\mu_B + S_i\mu_S + \ldots$$

$$\frac{N_i}{N_j} \sim \exp\left(\frac{\mu_i - \mu_j}{T} - \frac{m_i - m_j}{T}\right)$$







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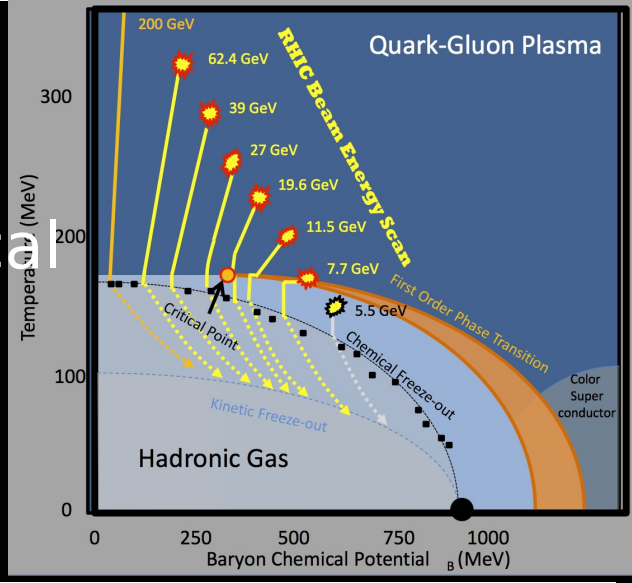
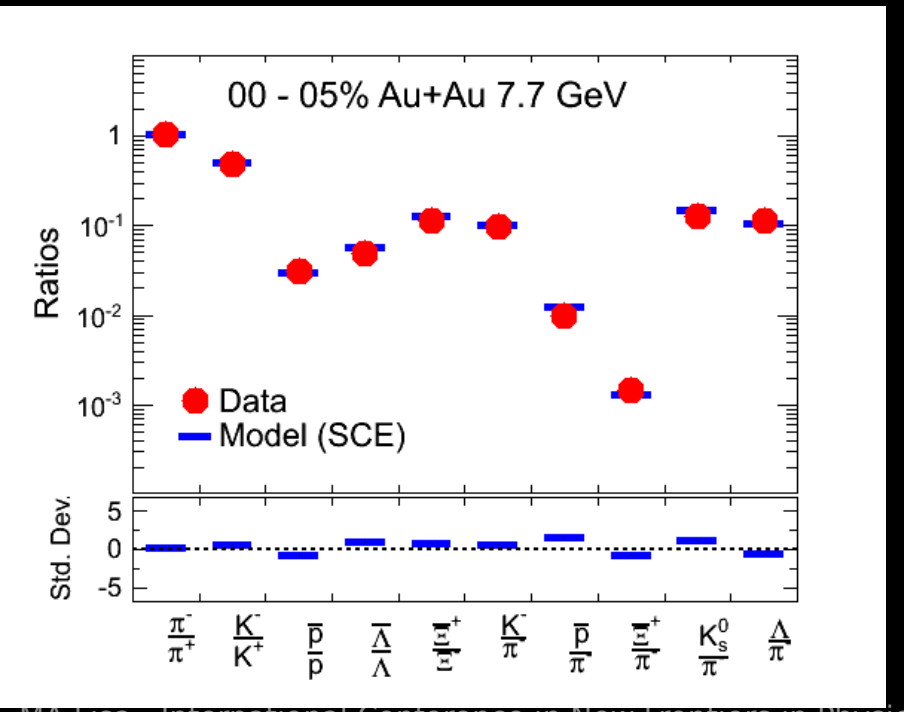
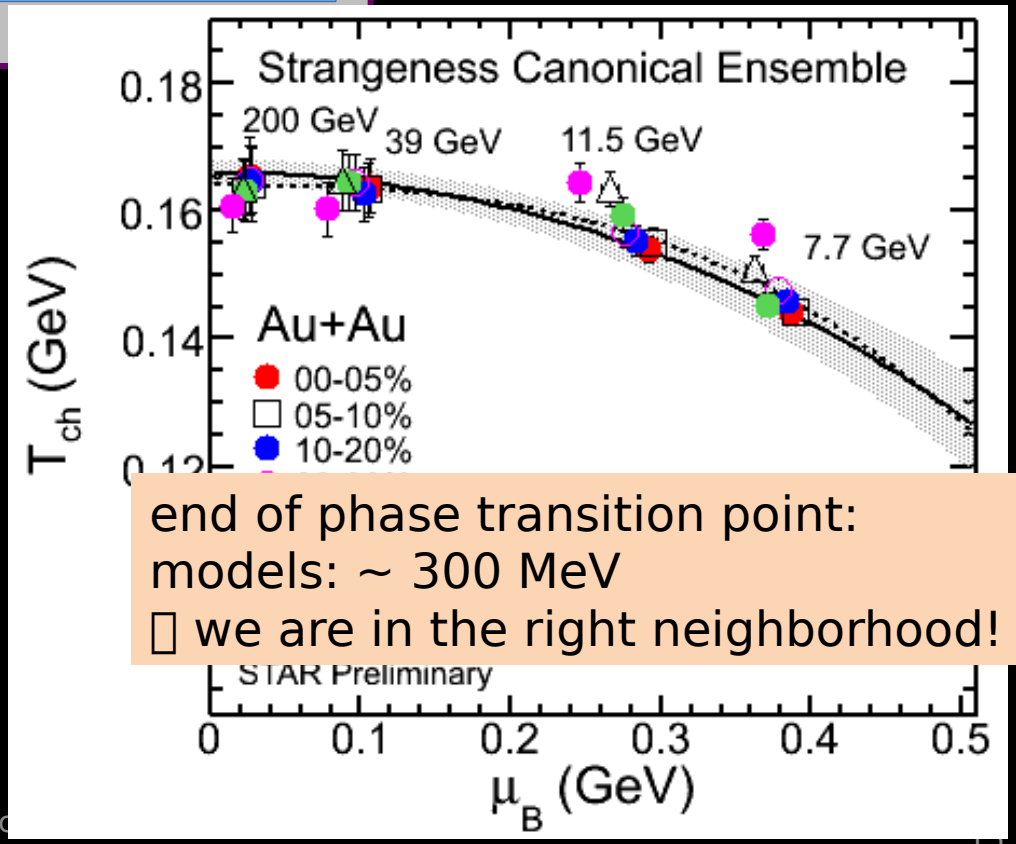


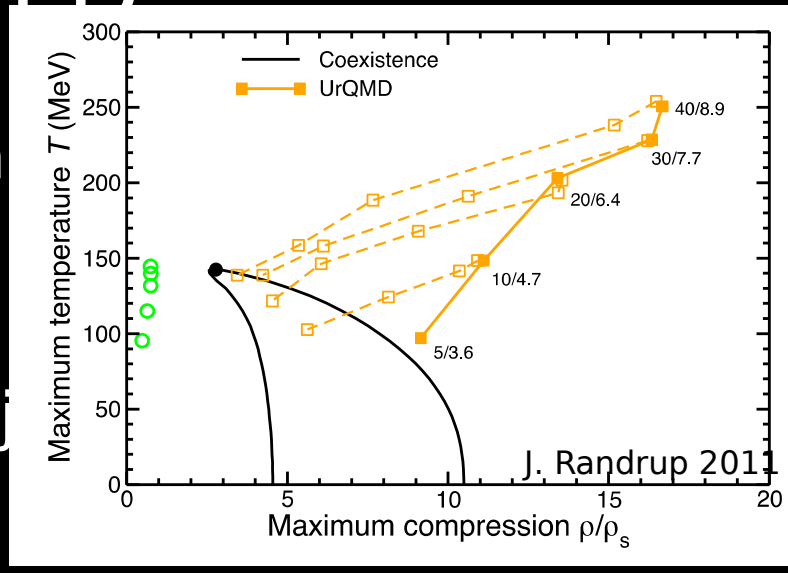


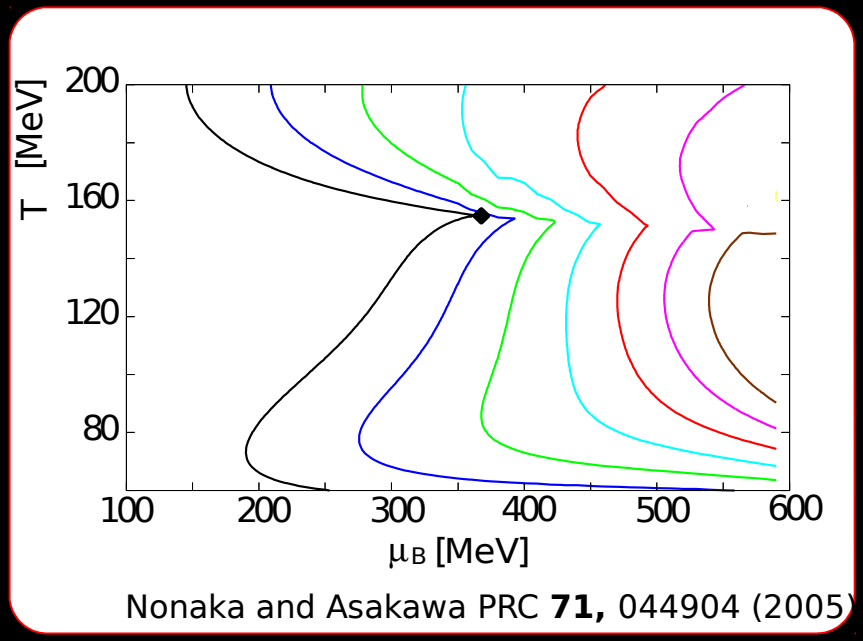


end of phase transition point:
models: ~ 300 MeV
 we are in the right neighborhood!

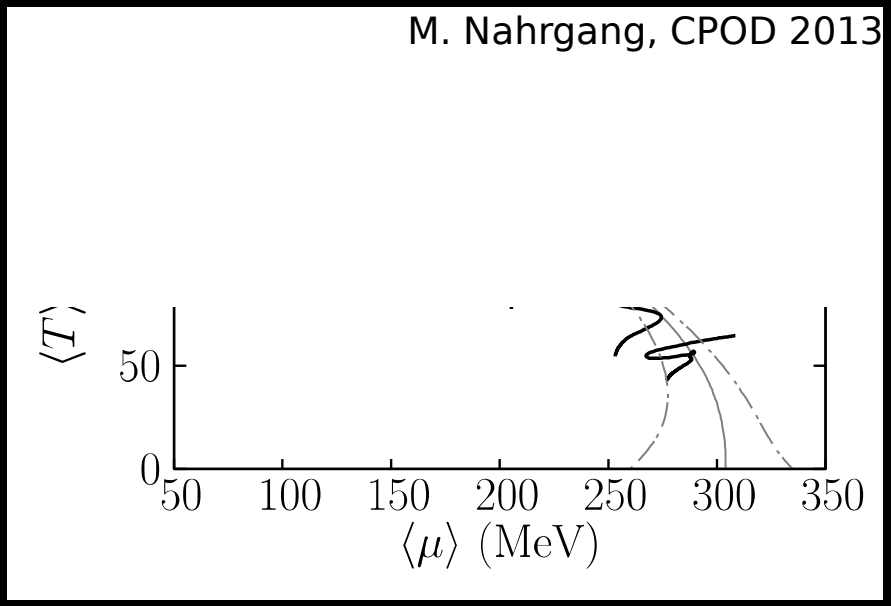
Step 0: location on the PD

- Fits to particle yields reveals ch
  freeze-out location
  - experimental anchor
- Rely on dynamic models for traj





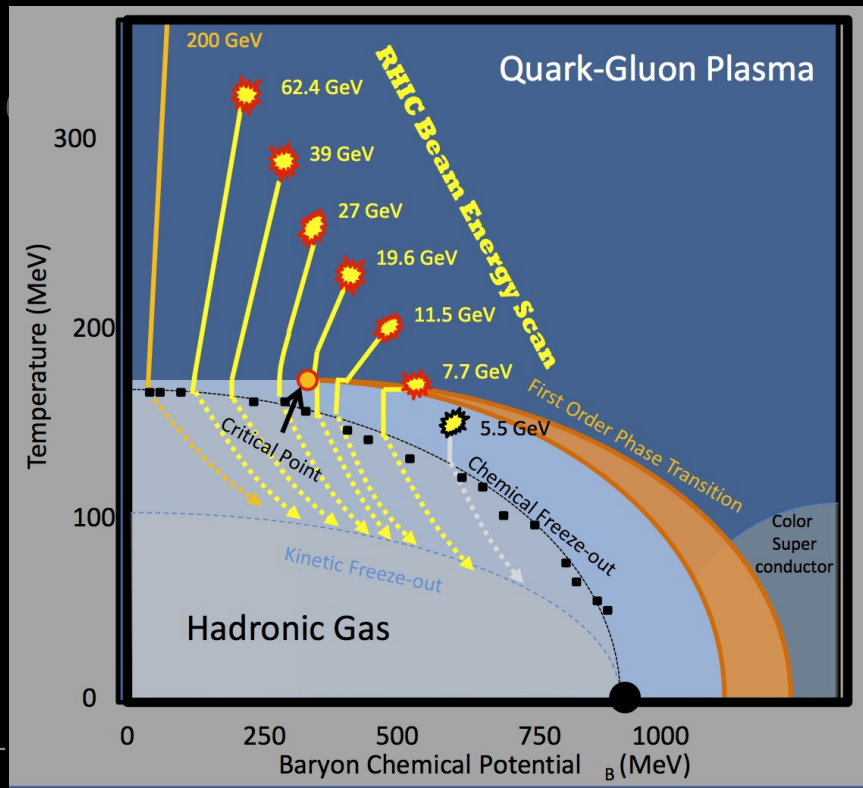
Nonaka and Asakawa PRC **71,** 044904 (2005)



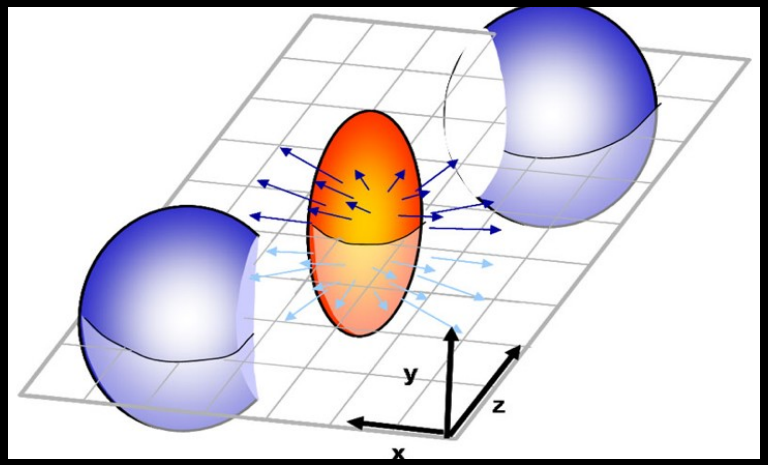
Next step: Is the QGP "turning off?"

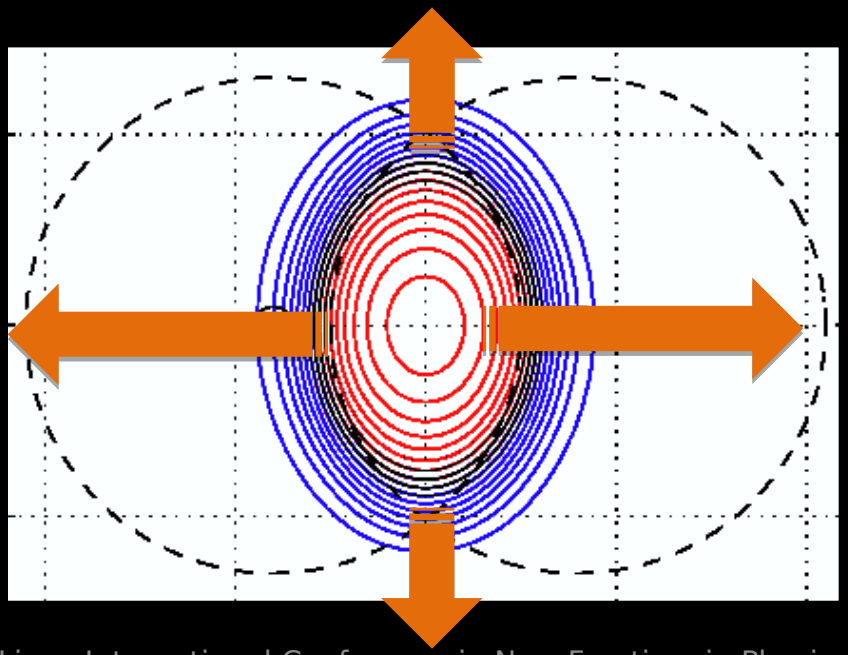
Evidence for a QGP at top RHIC energy (and above):

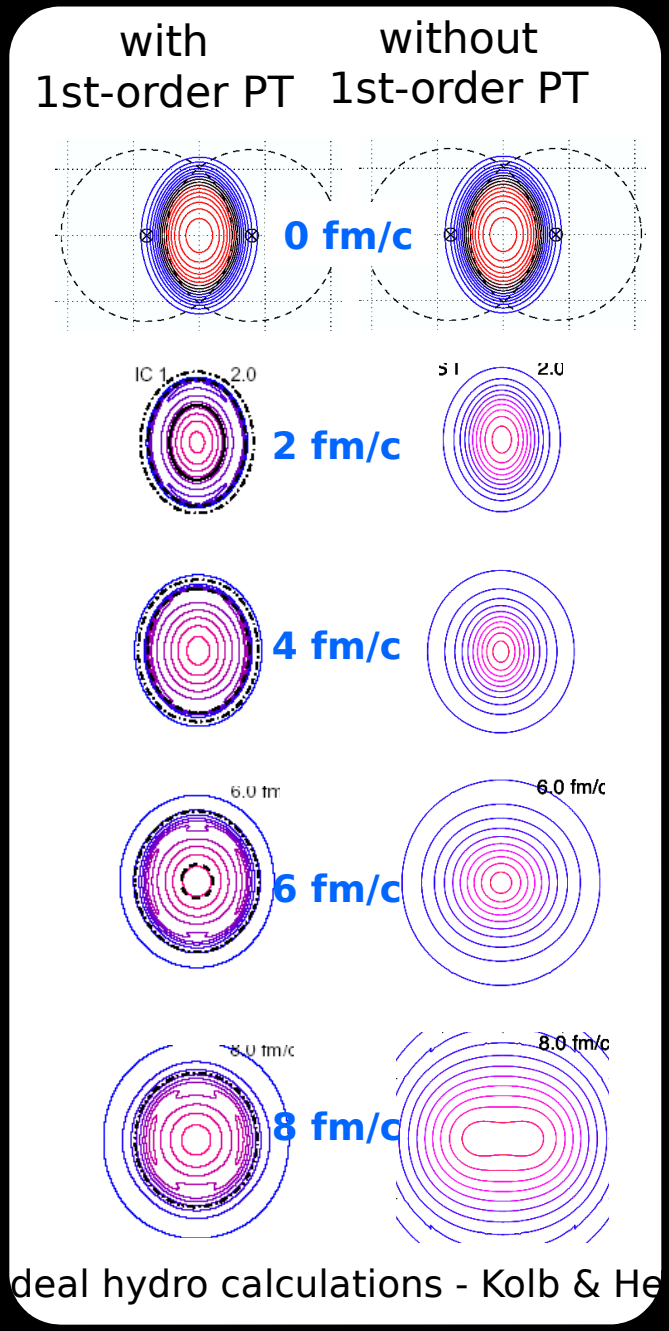
- species dependence of elliptic flow (and spectra)
  - scaling with number of constituent quarks (?!)
- high-pT suppression
  - QGP opacity to fast partons
- B-field-induced charge-depen
  correlations
  - event-wise local parity violation



Elliptic flow 101







deal hydro calculations - Kolb & He

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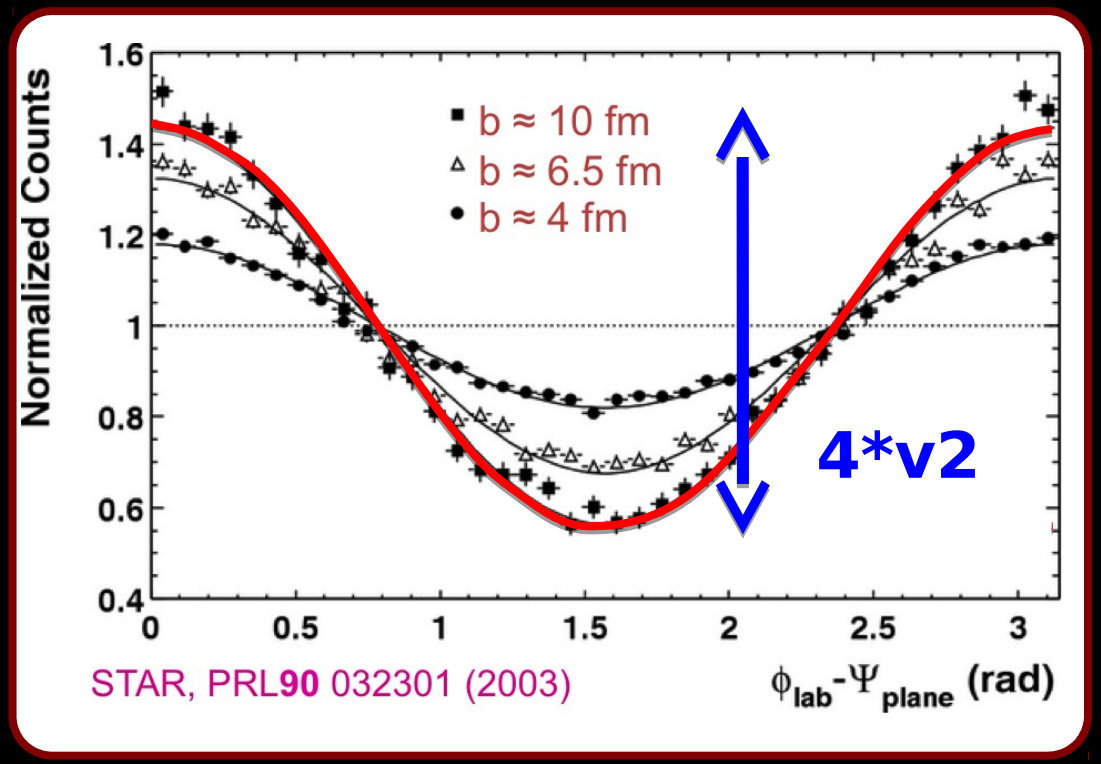
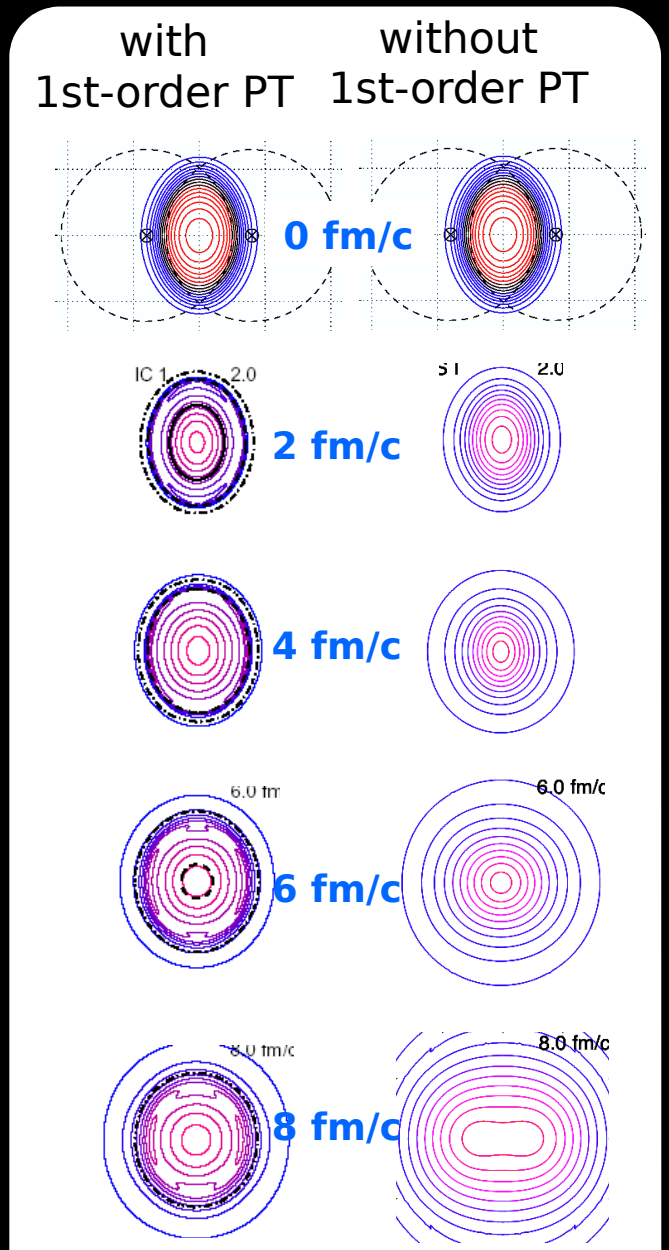




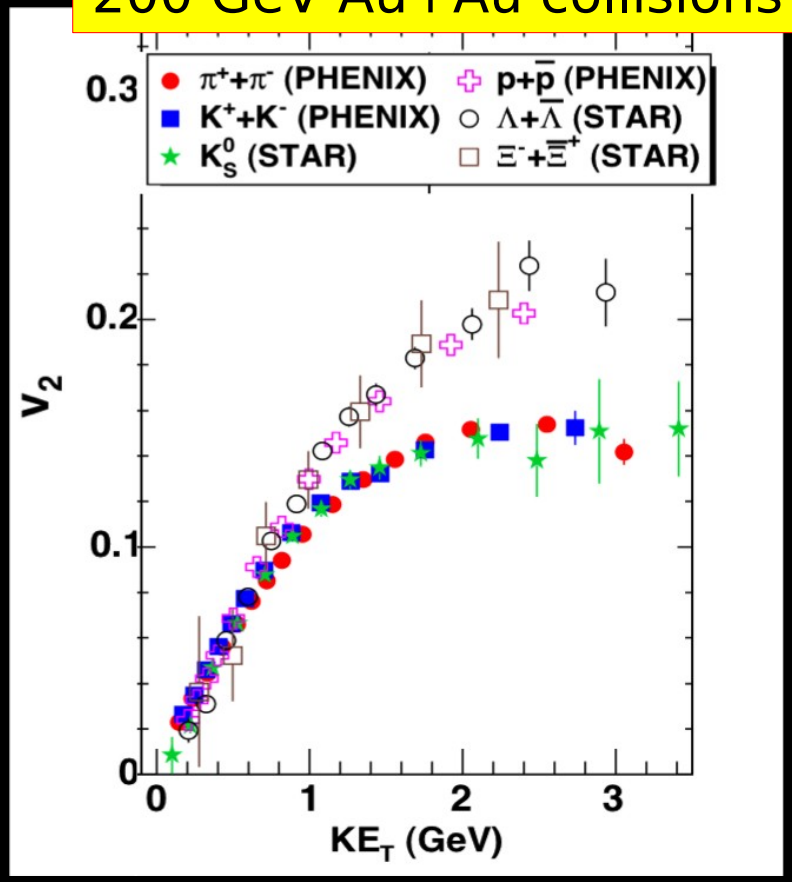
deal hydro calculations - Kolb & He

v2 sensitive to
- EoS
- viscosity
- initial geometry

v2 measured versus
- particle species
- pT (& η...)
- √s

Elliptic flow 102 – NCQ scaling

200 GeV Au+Au collisions



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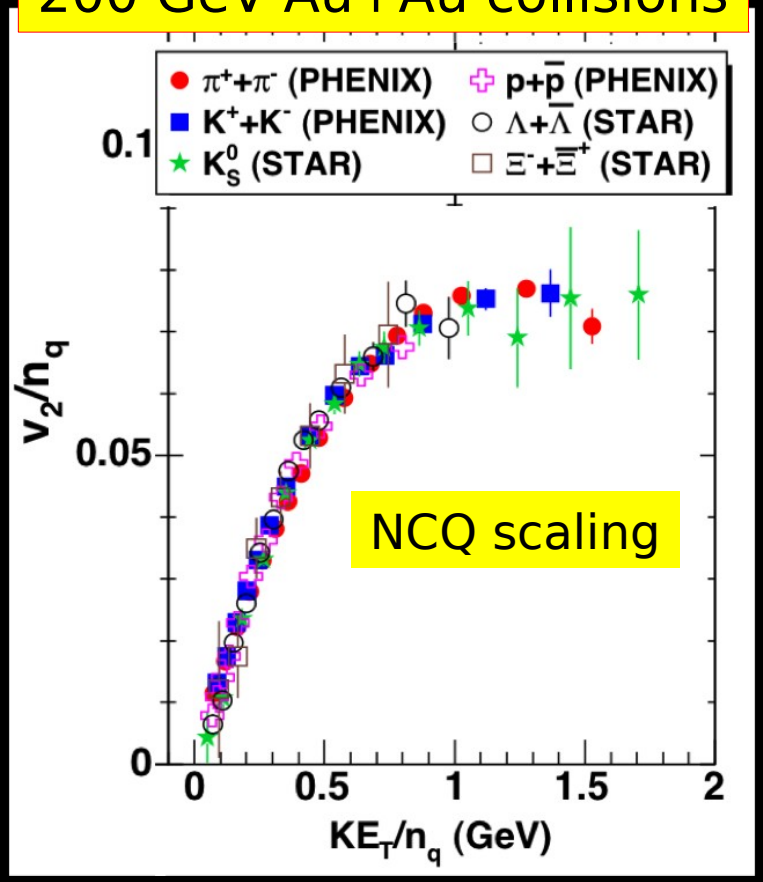

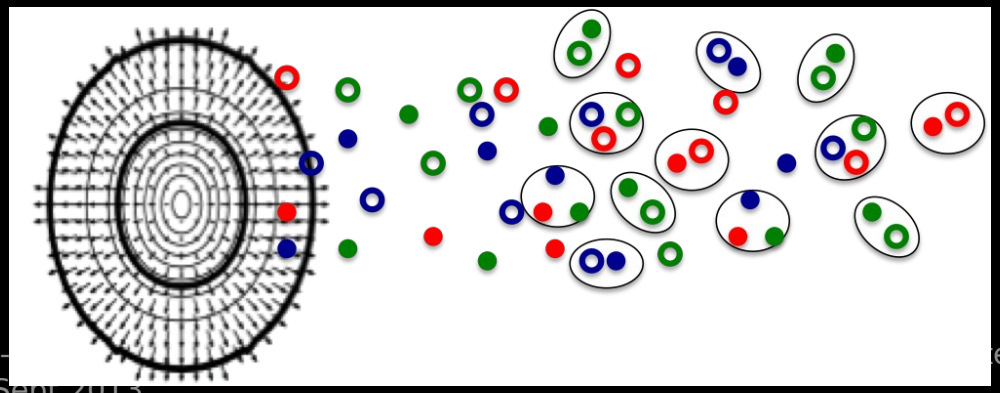

Flowing *constituent* quarks! (?)

Elliptic flow 102 – NCQ scaling

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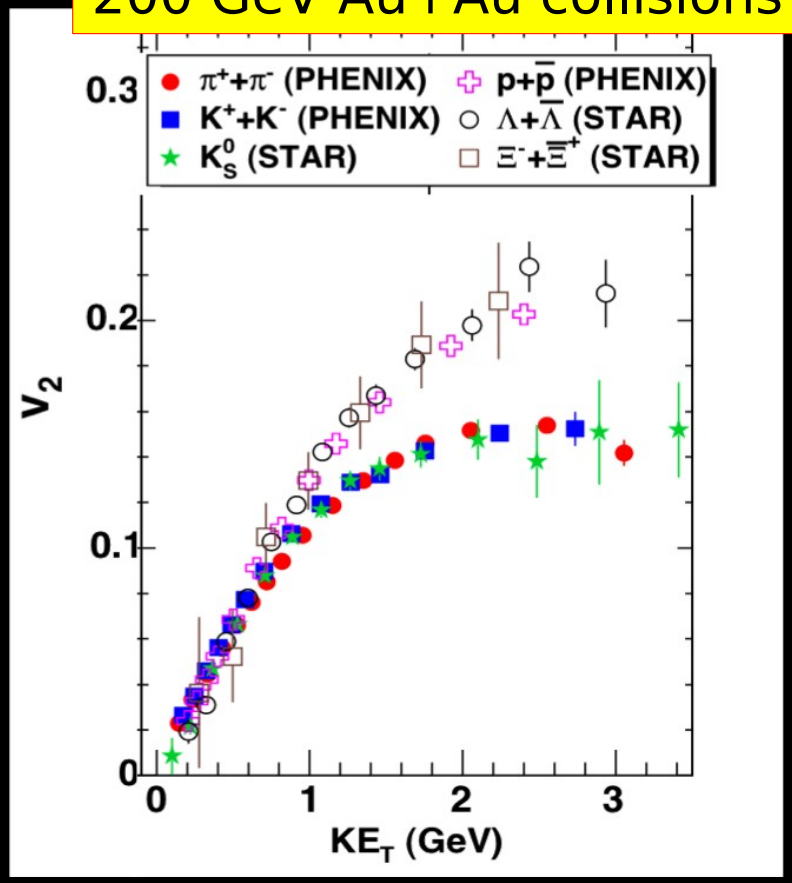
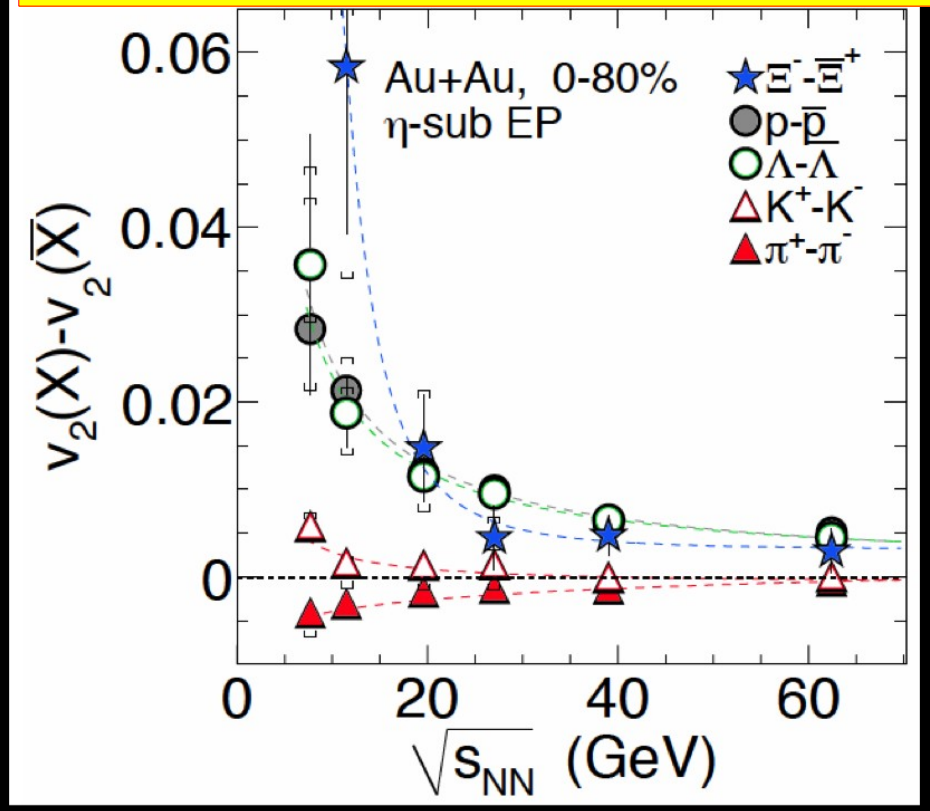
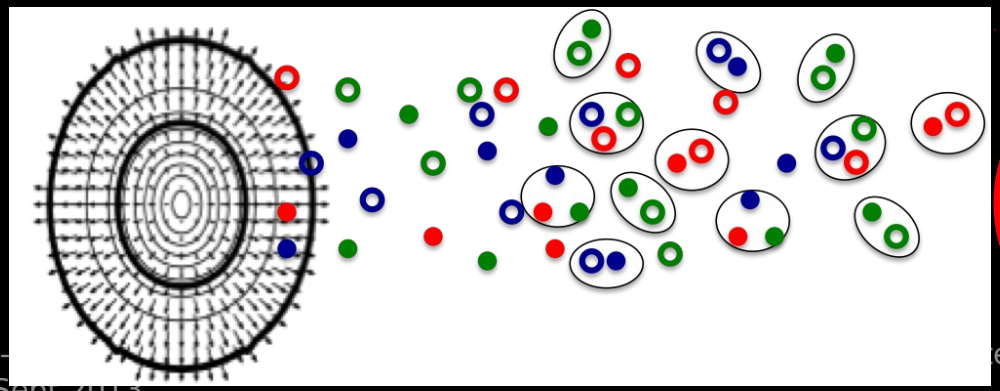


particle minus antiparticle v2



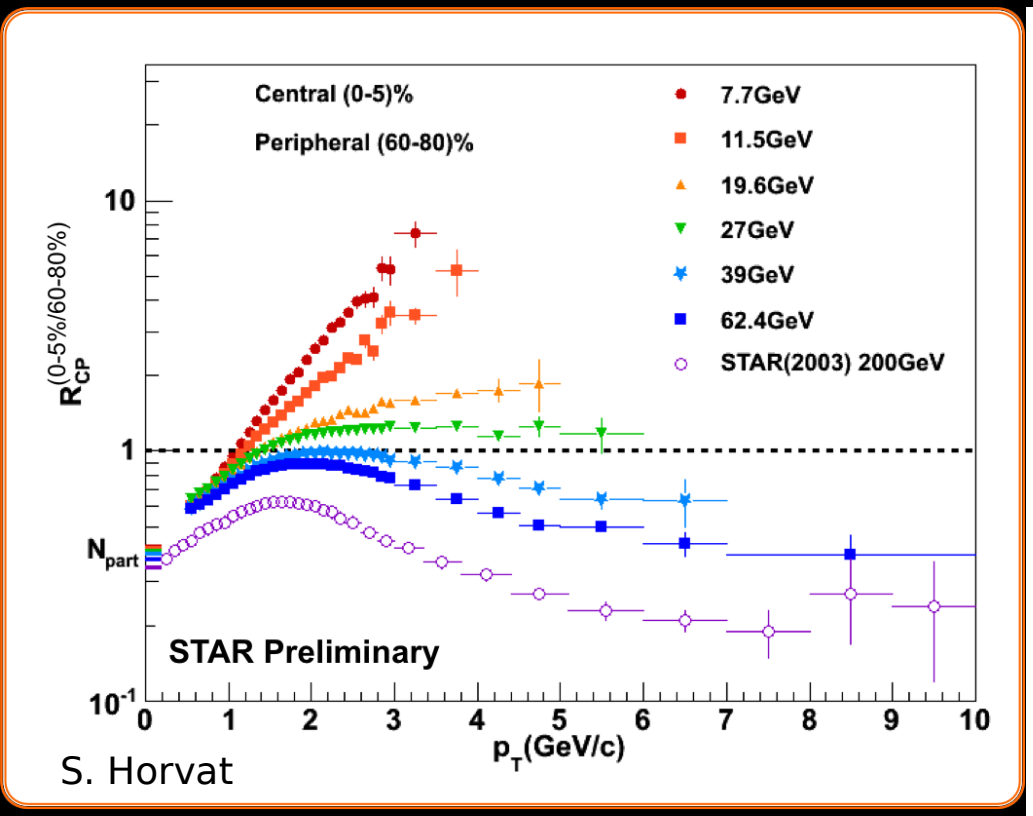


Flowing *constituent* quarks! (?)

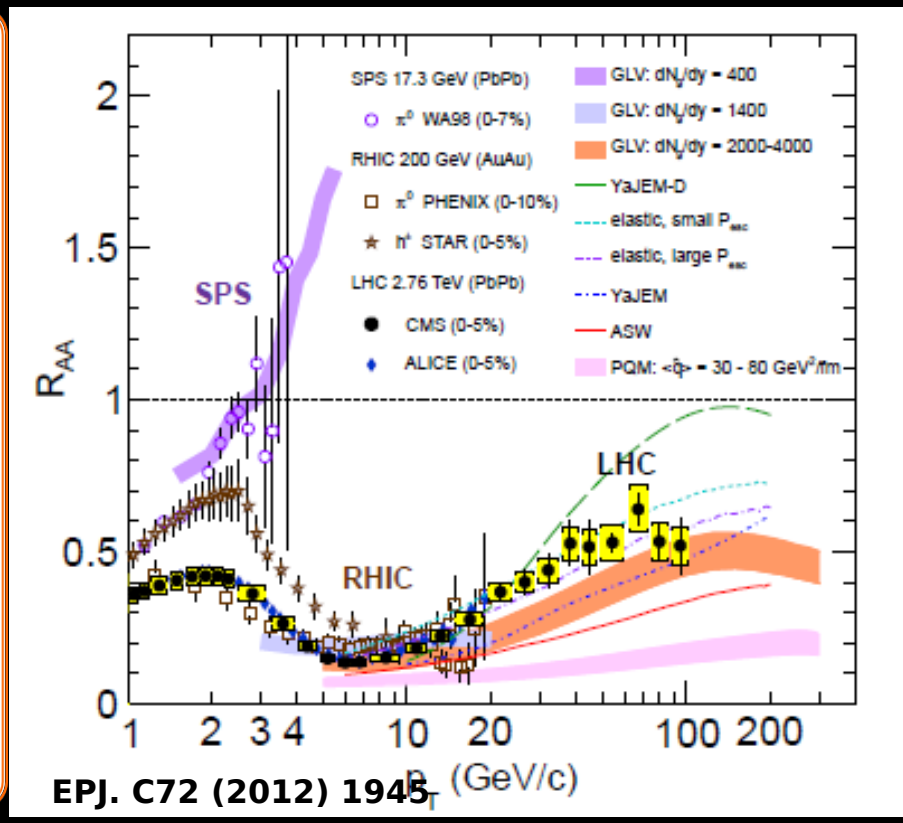
Not below ~50 Ge

Suppression of high-pT hadrons

a measure of the opaqueness of the QGP



S. Horvat



EPJ. C72 (2012) 1945

suppression @ LHC ~ RHIC

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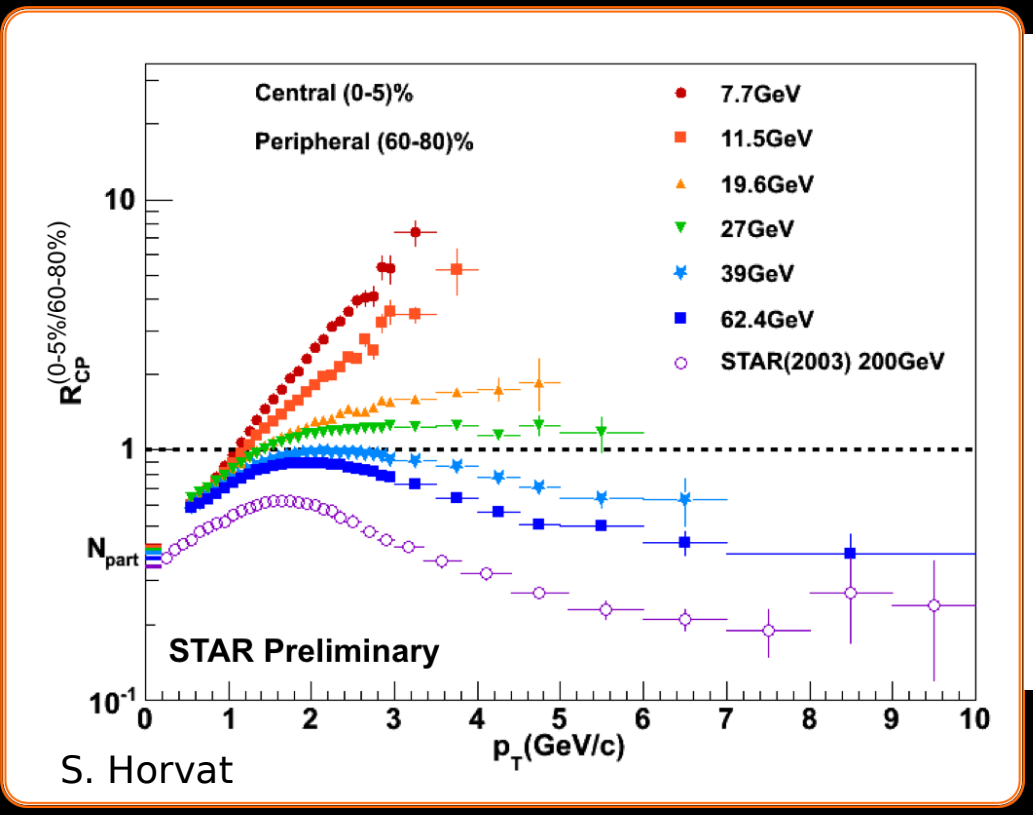

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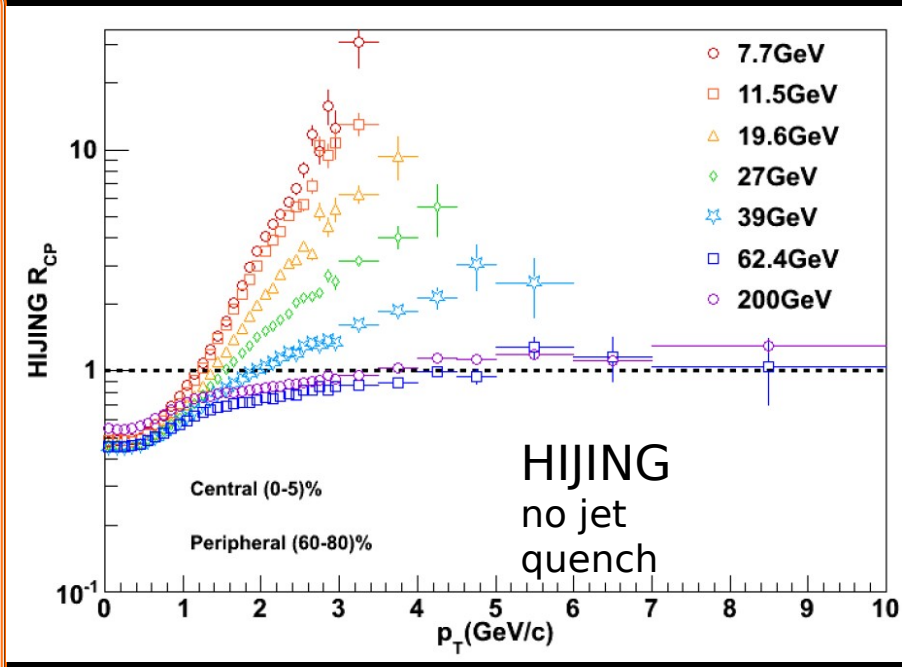


suppression comes on strong around 20 GeV

So... the action is at √sNN~ 10-30 GeV

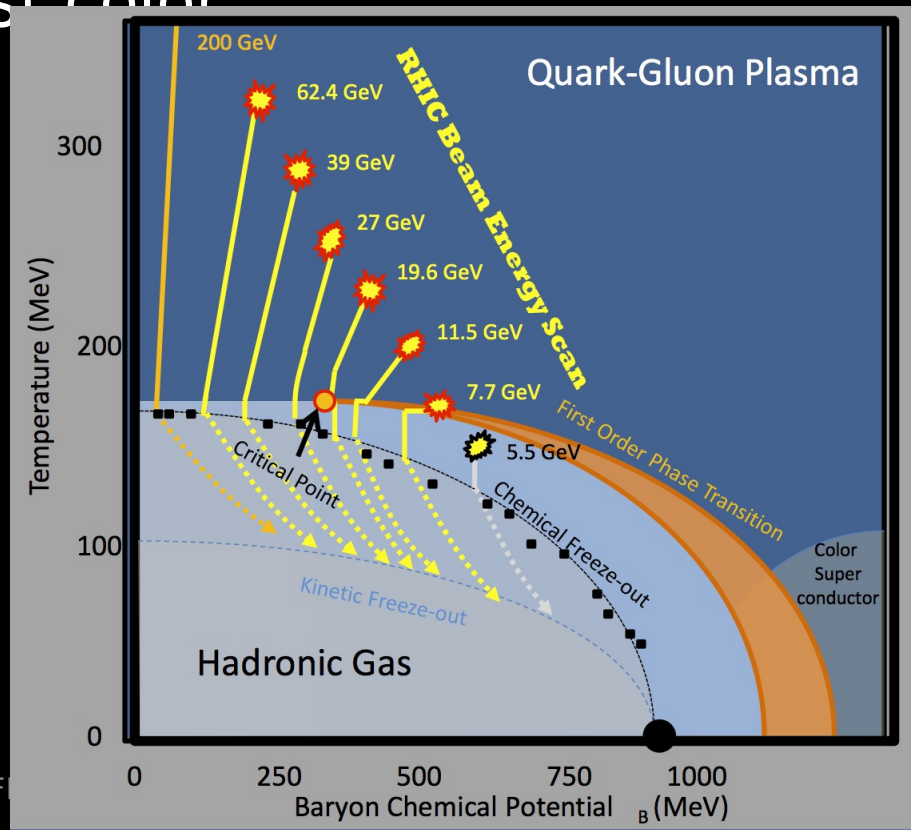
matter at lower energy...

- doesn't flow as well; (inflection?)
- isn't (easily) characterized by flowing quarks
- is much less opaque to fast color
- does not support an EDM

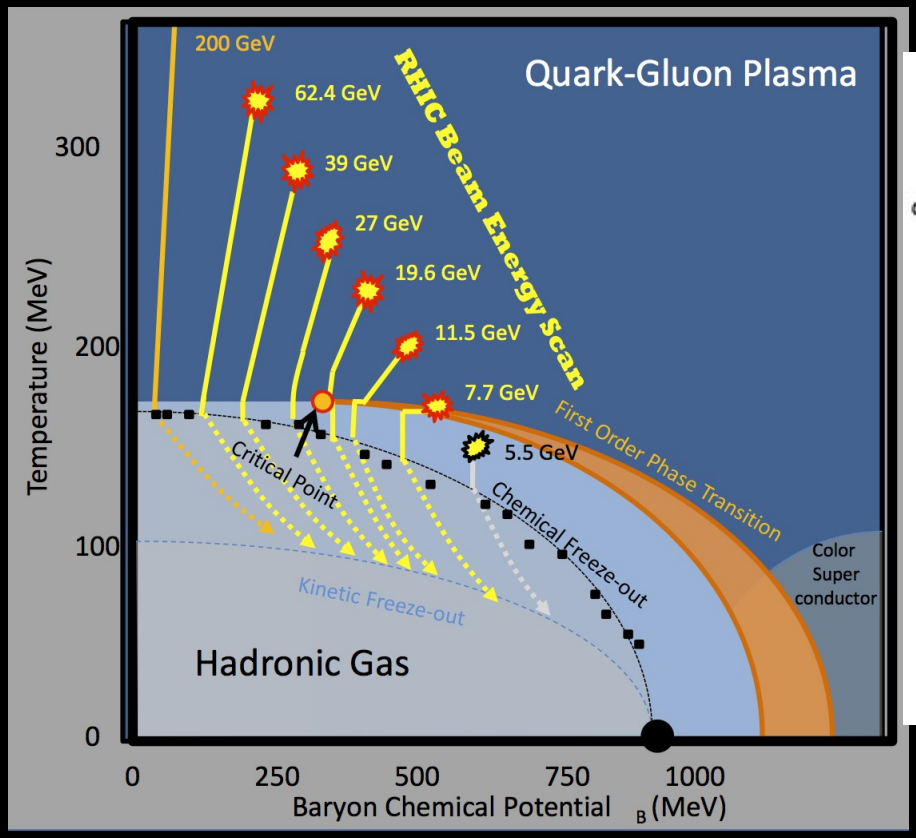
In this changing region:

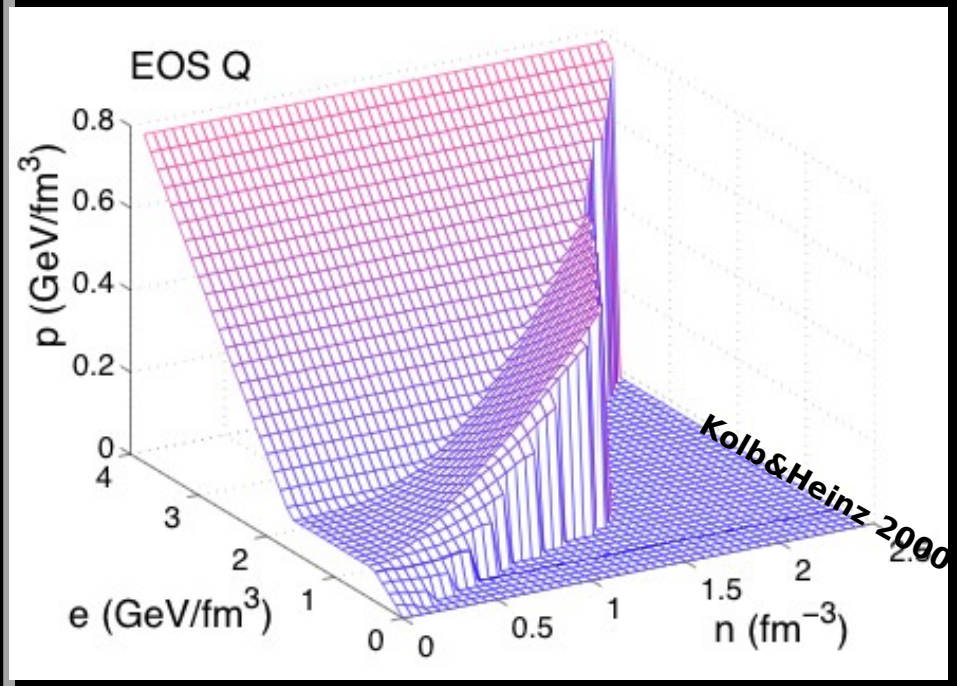
- evidence of 1st-order PT?

I'll just discuss three of ~20 probes currently being applied



Is there a “soft region” in the QCD phase diagram?





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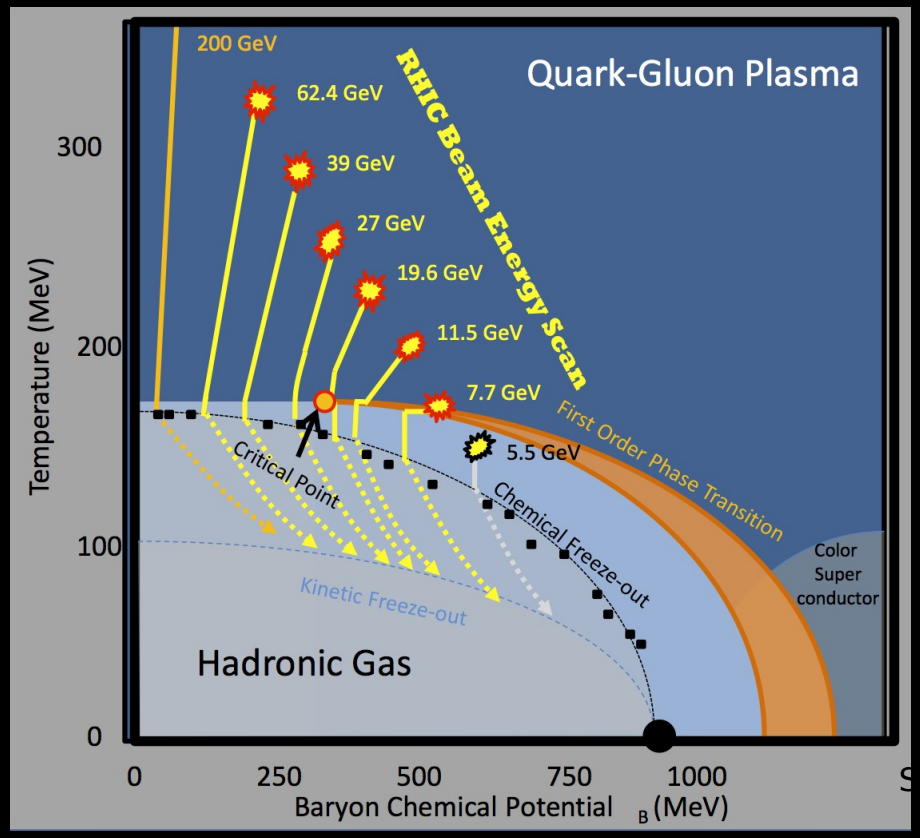
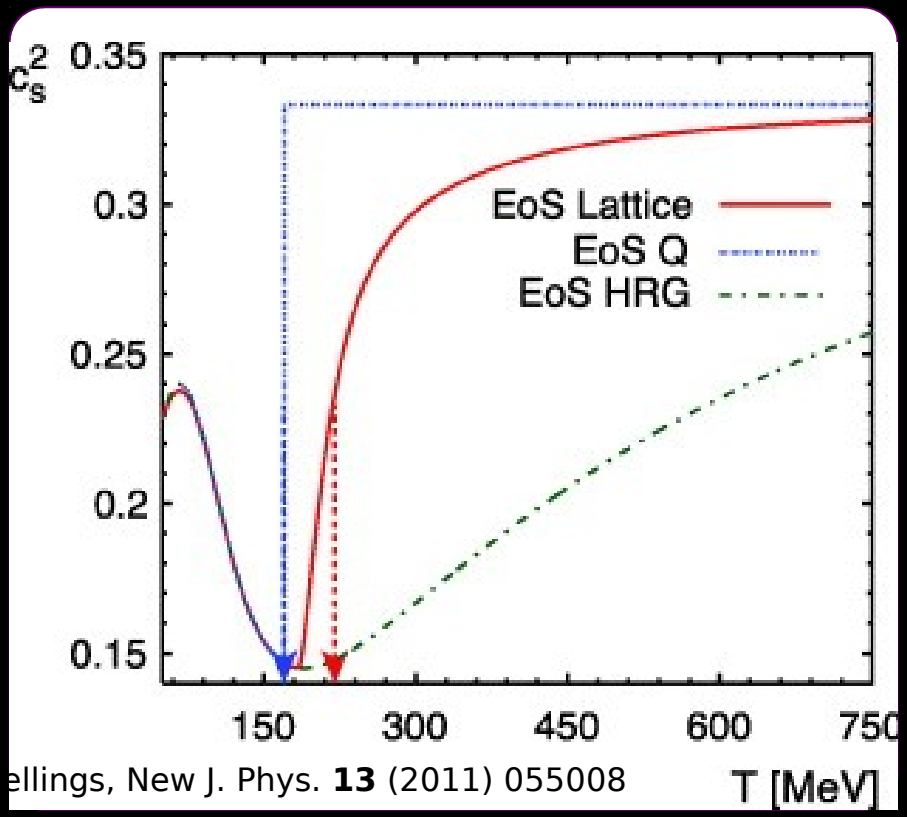


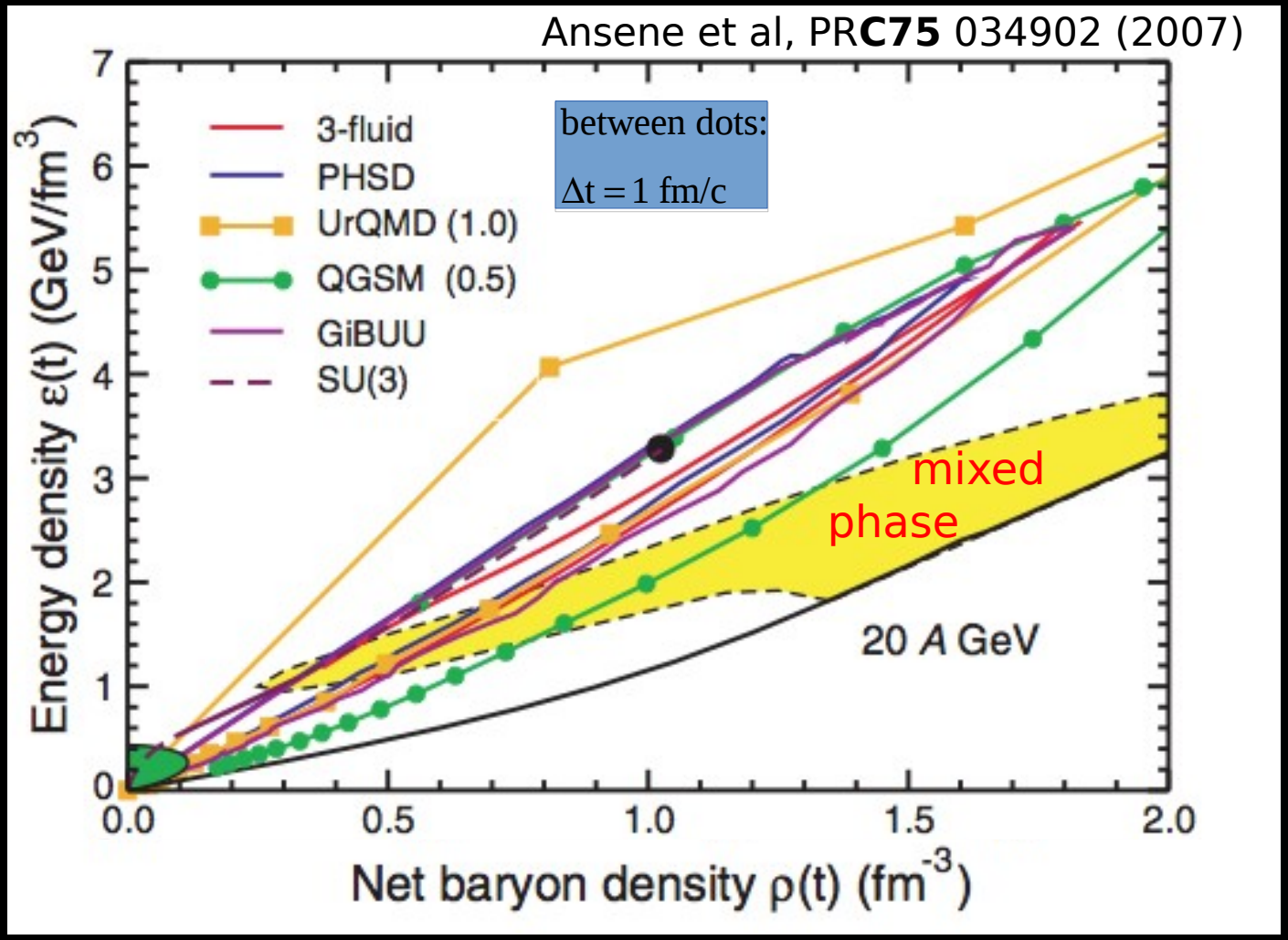


ellings, New J. Phys. **13** (2011) 055008

... and if so, how could we find it?

low (“zero?”) pressure – look at flow systematics

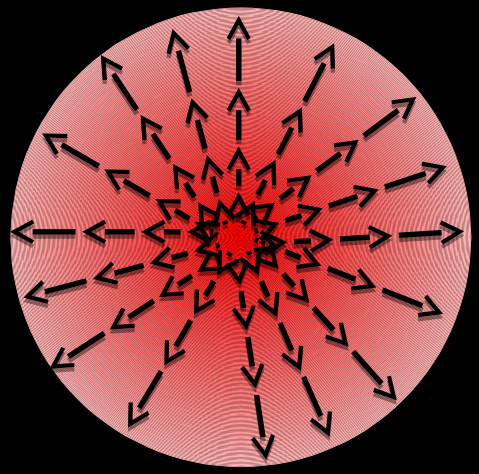
Is there a “soft region” in the QCD phase diagram?

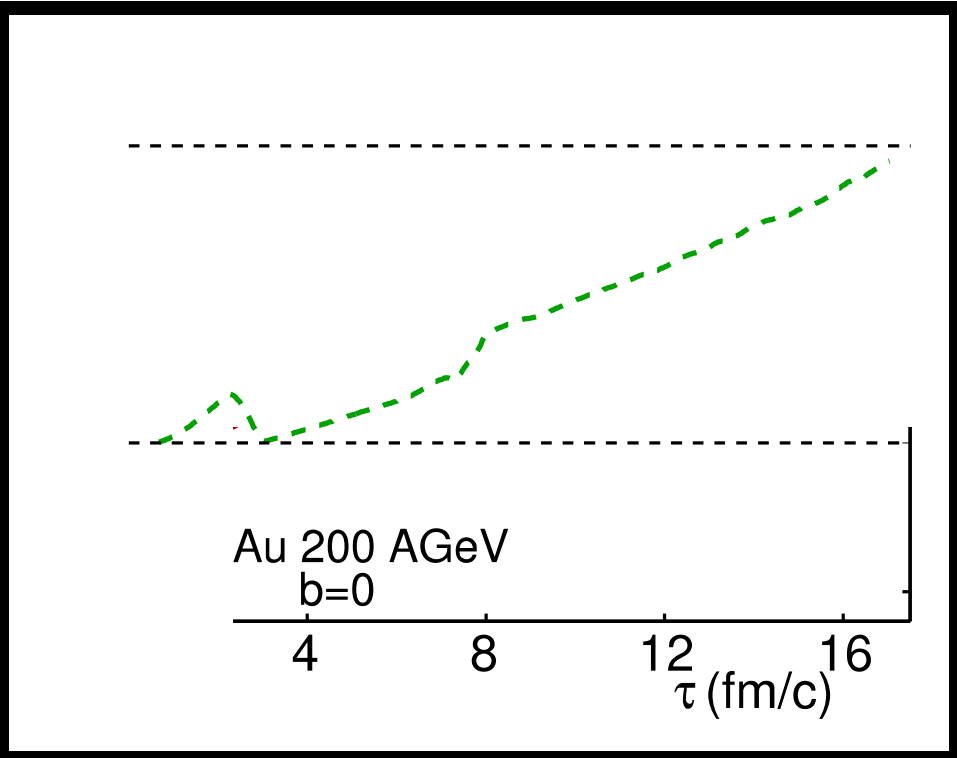


UT... system evolves quickly concentrate on signals dominated by short time p

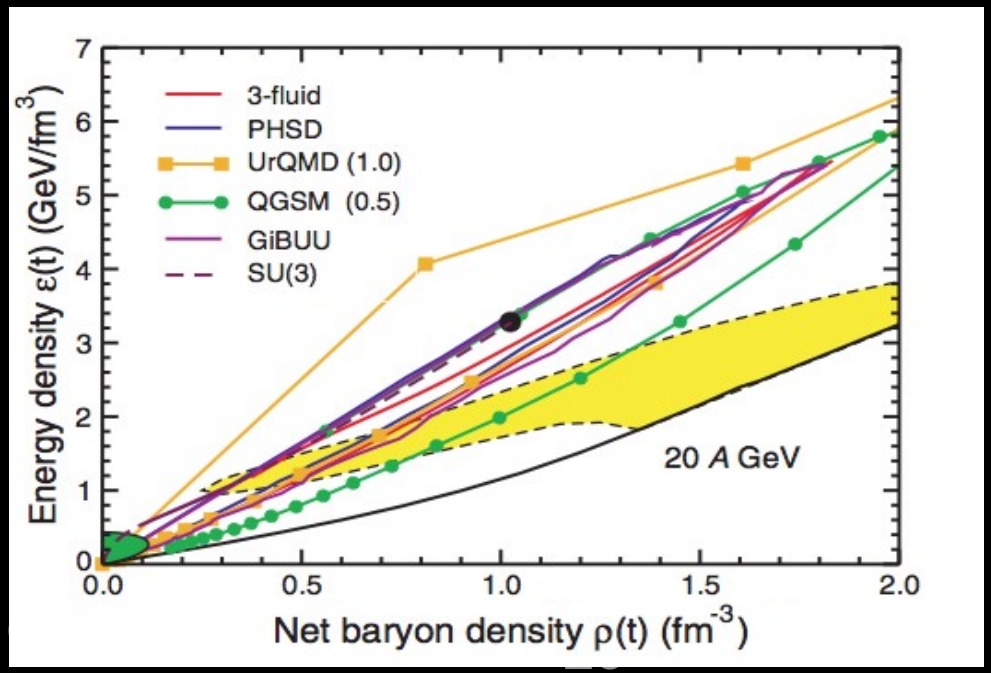
Signals
Azimuthally Integrated

Radial flow

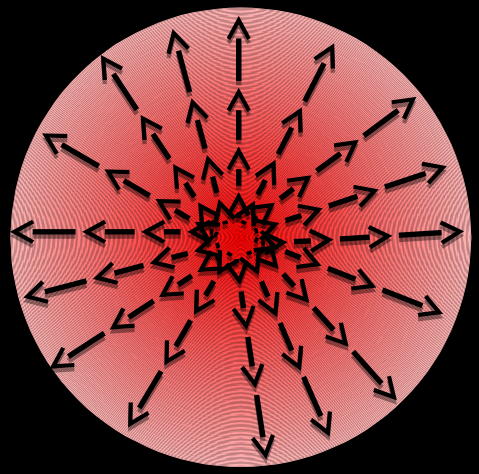


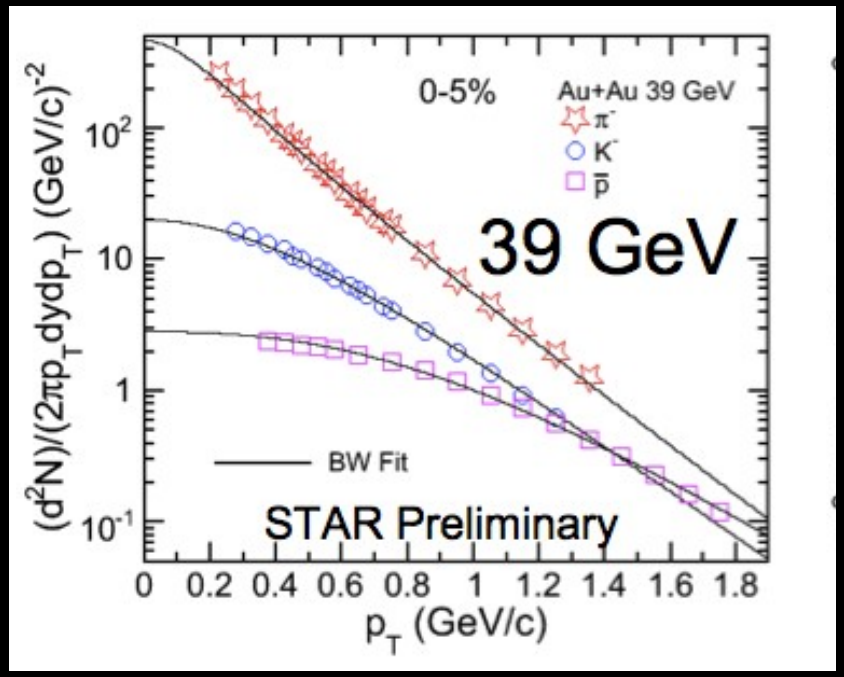


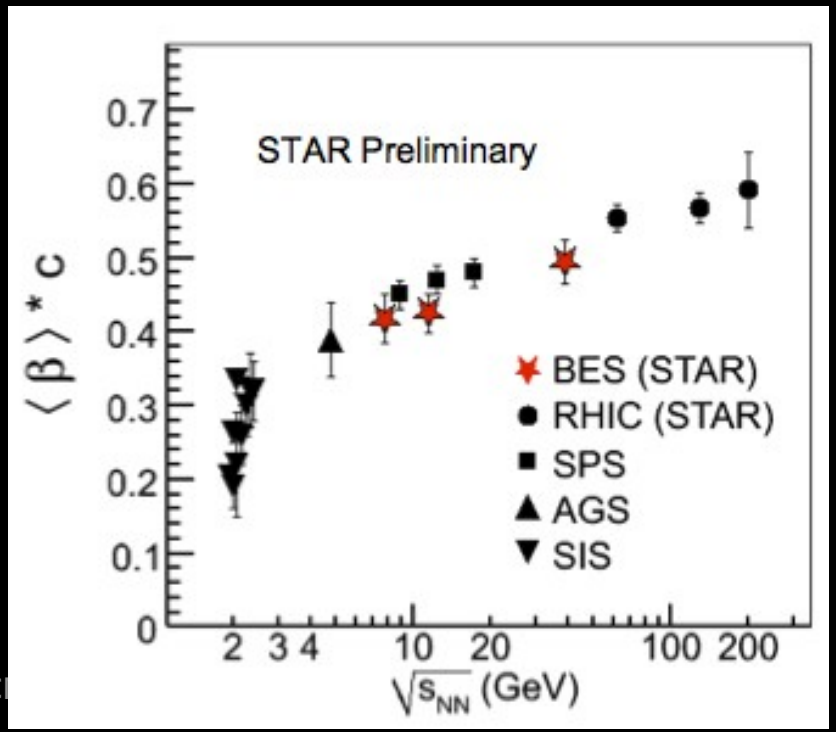
azimuthally-integrated flow strength develops over entire collision history



Radial flow





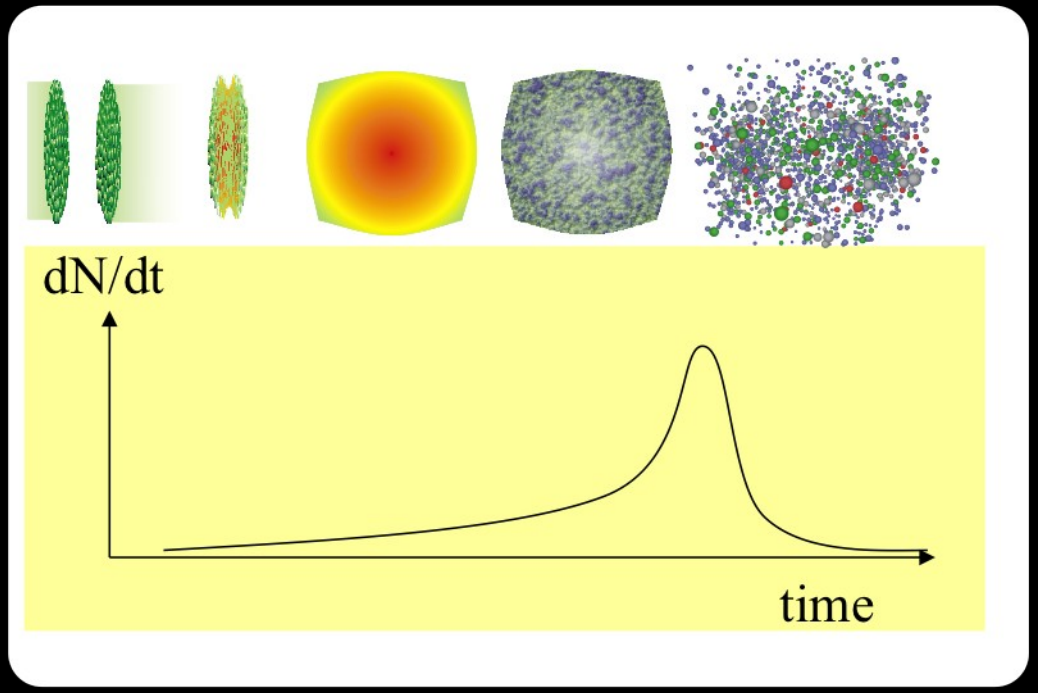


azimuthally-integrated flow strength develops over entire collision history

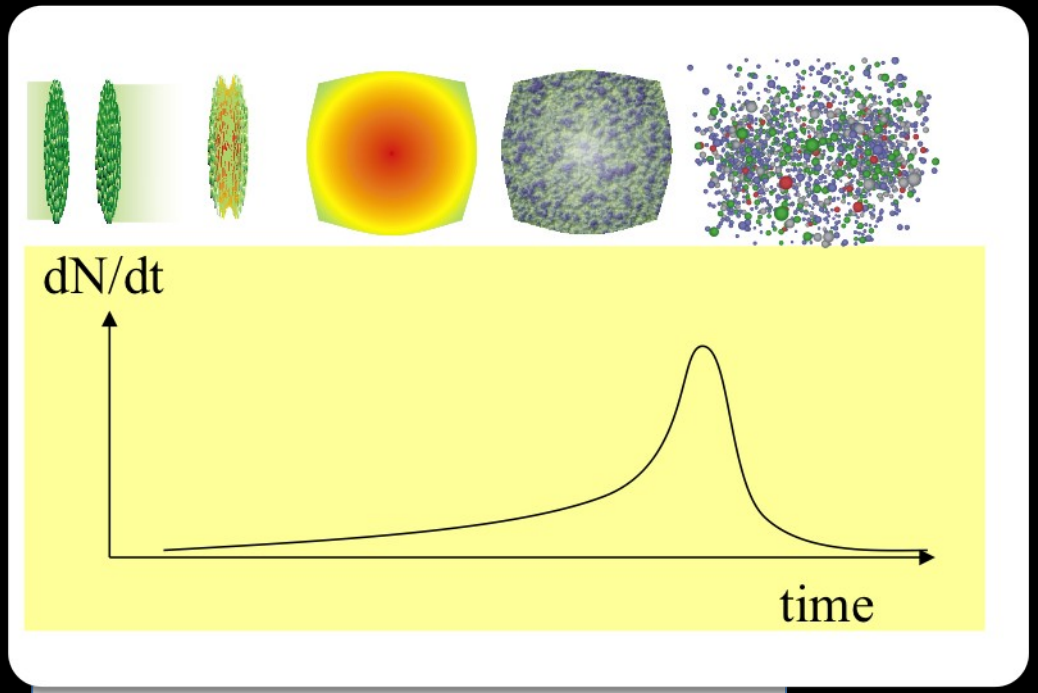
velocities extracted from fits to spectra show no effect of "special" history.

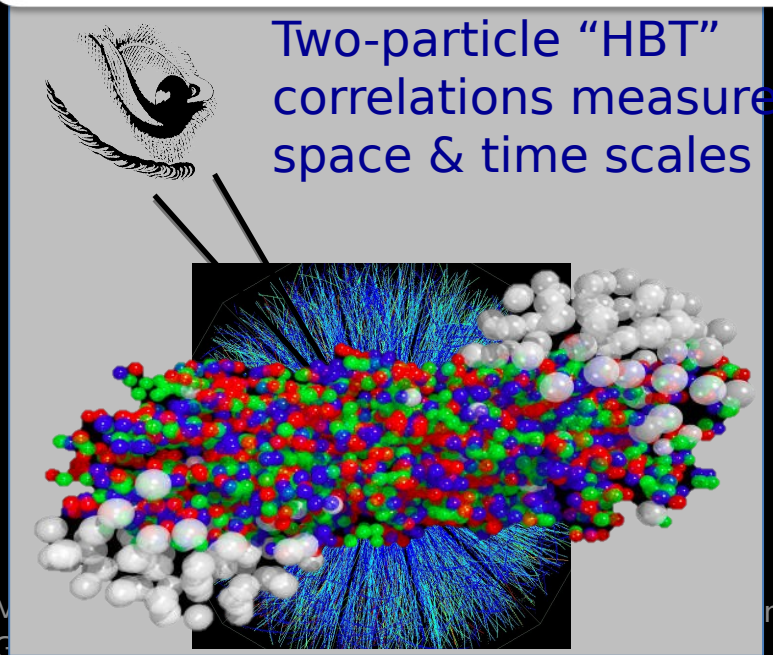
- (unsurprising)

“radial HBT” - Long emission duration



“radial HBT” - Long emission duration





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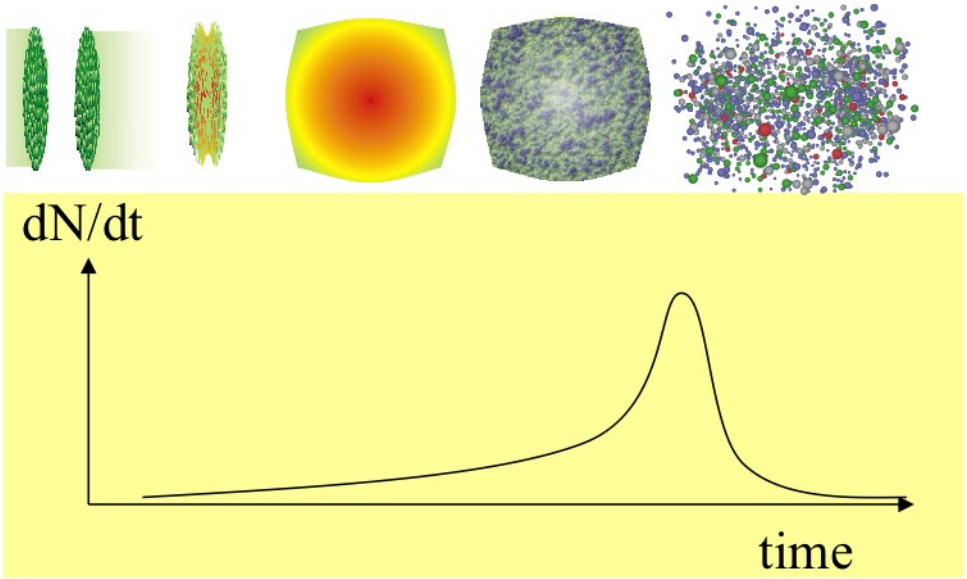
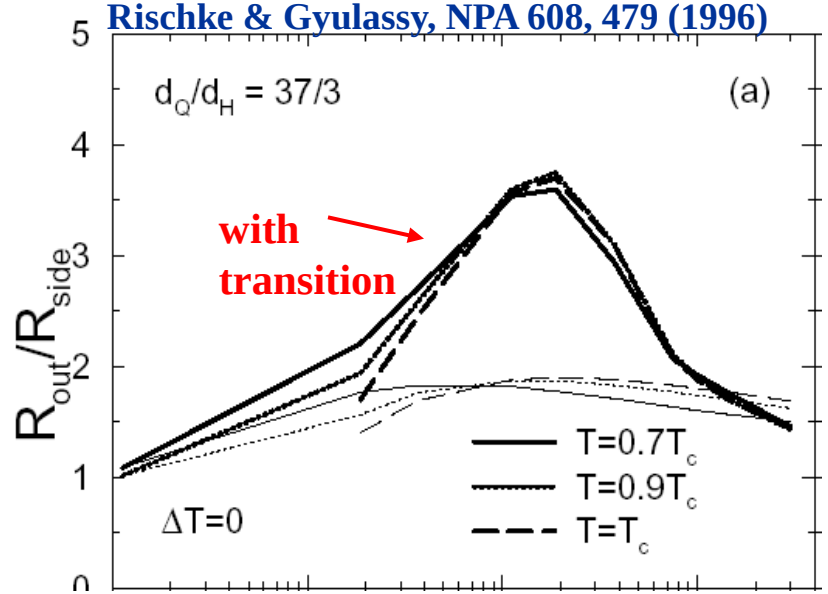
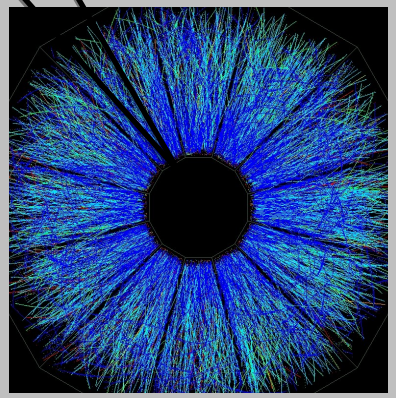


3D 1-fluid Hydrodynamics

Rischke & Gyulassy, NPA 608, 479 (1996)



Two-particle “HBT” correlations measure space & time scales



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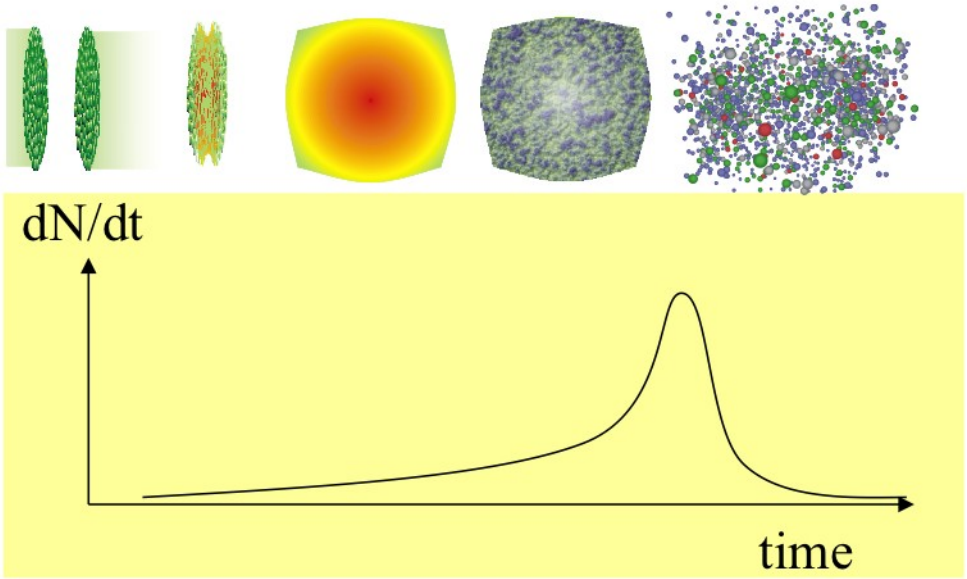

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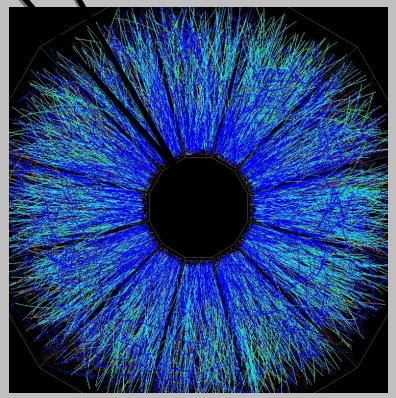

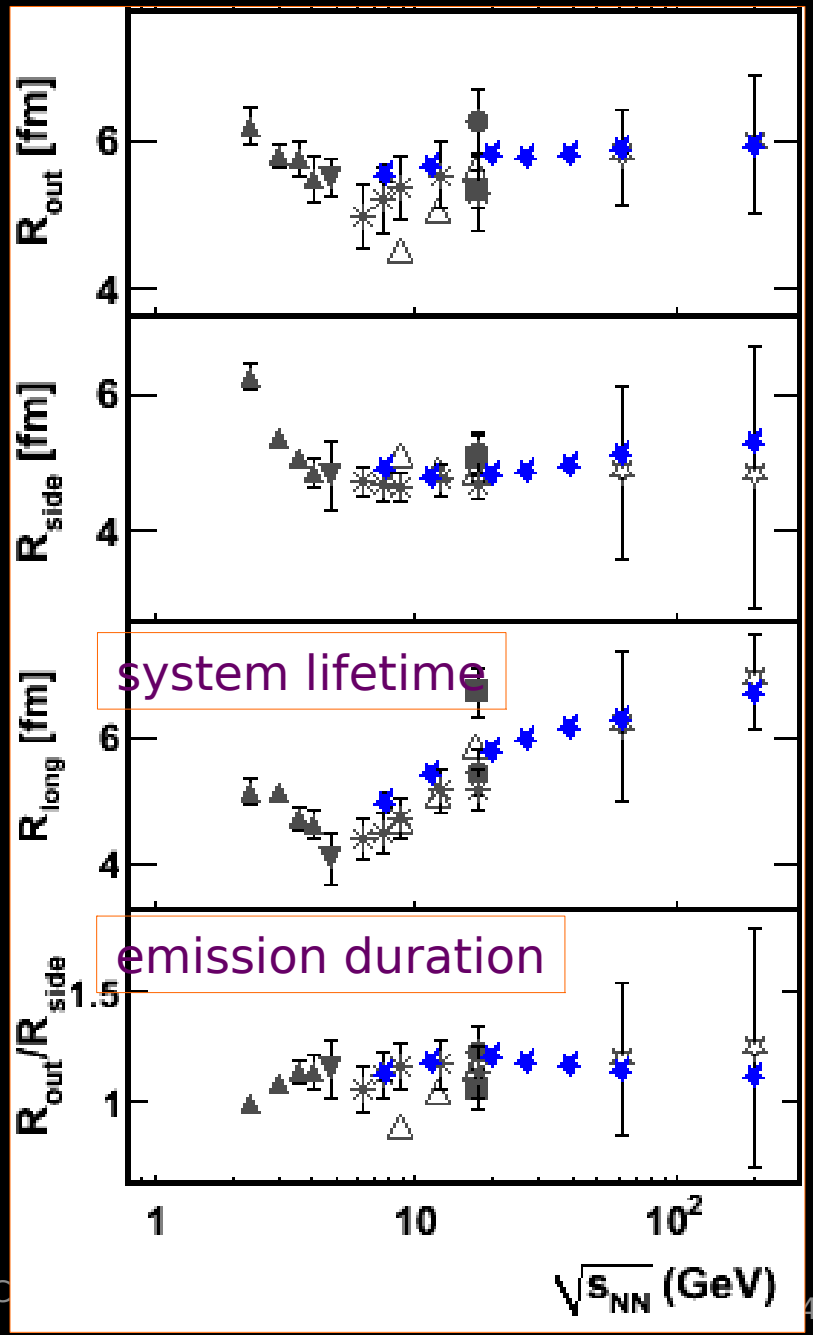

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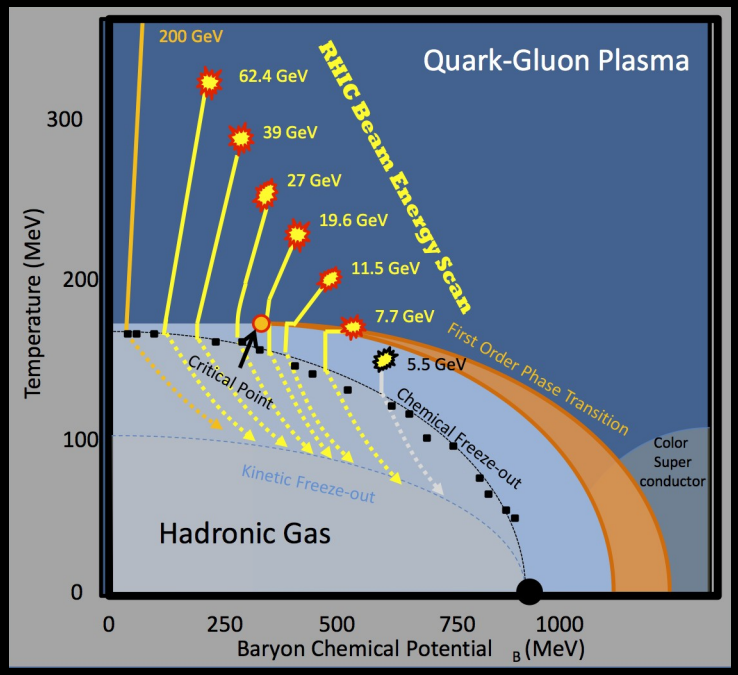
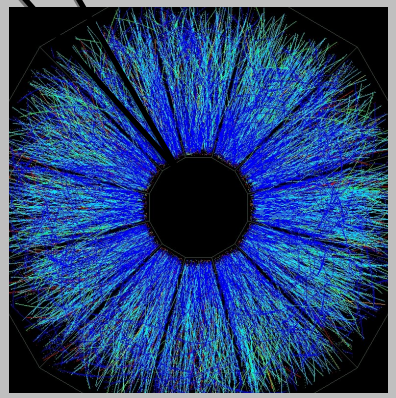


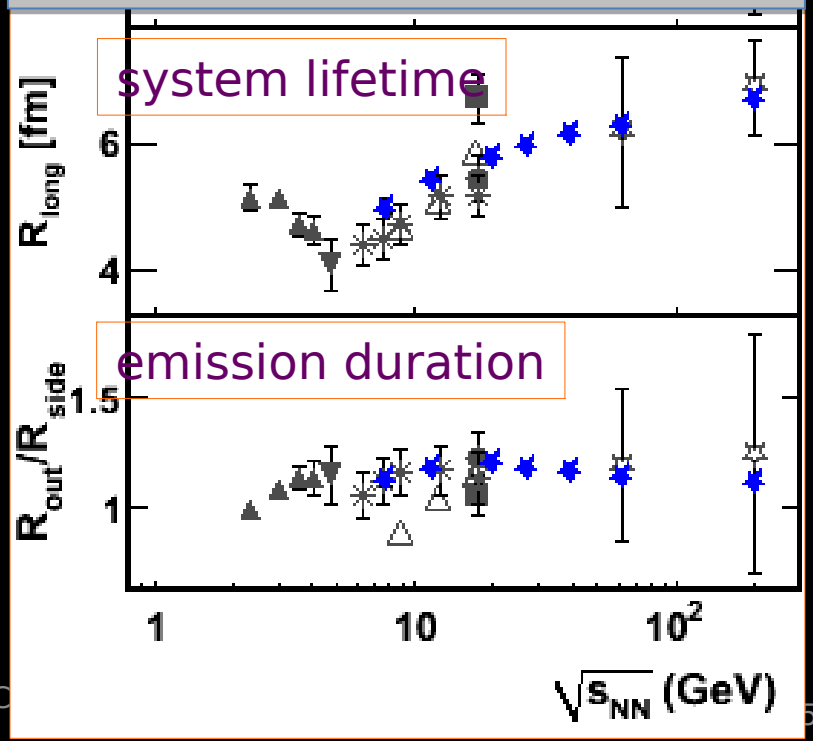
Multidimensional femtoscopy:

- No evidence for jump in system timescales

late-stage rescattering clouds signal

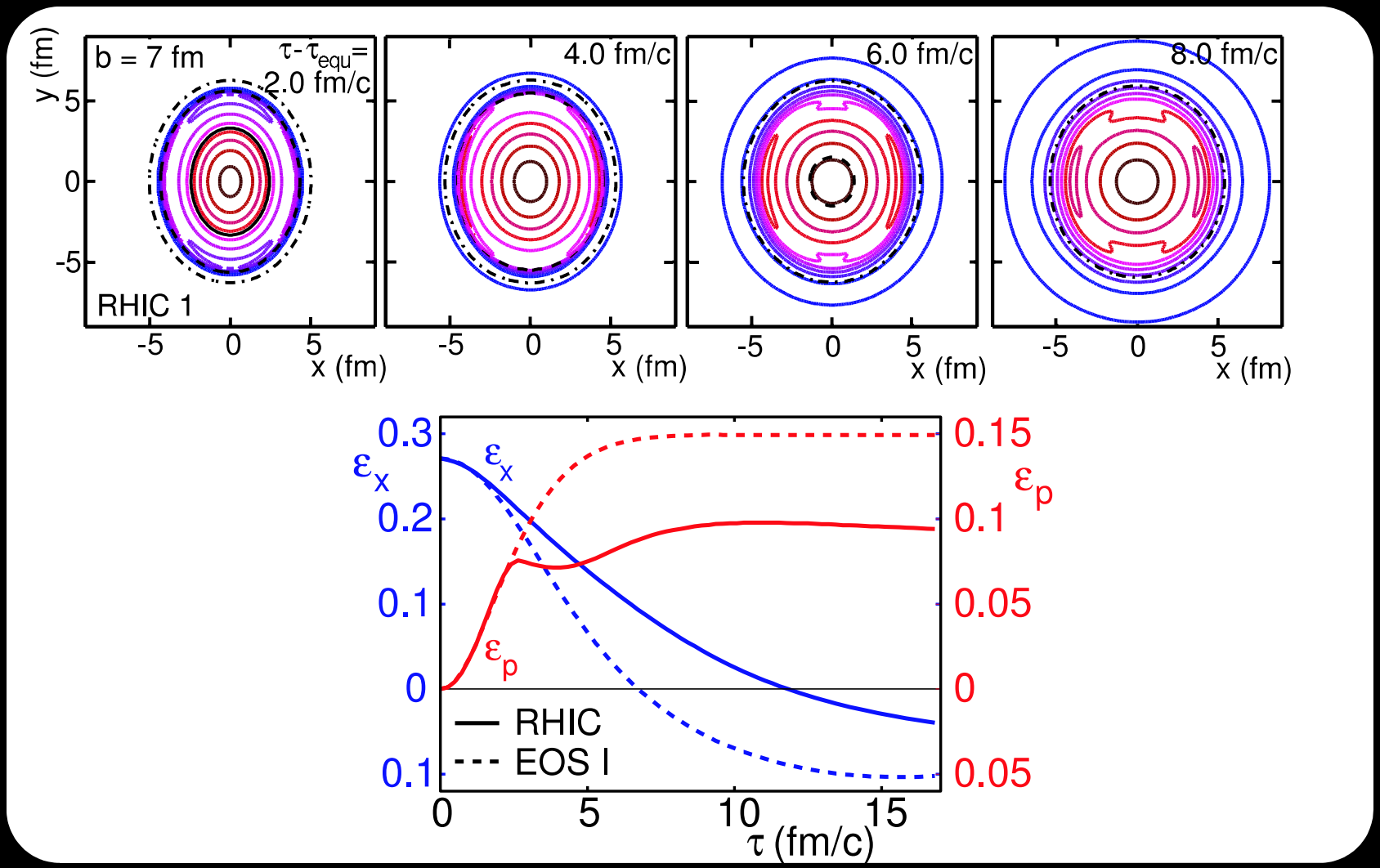
Two-particle “HBT” correlations measure space & time scales



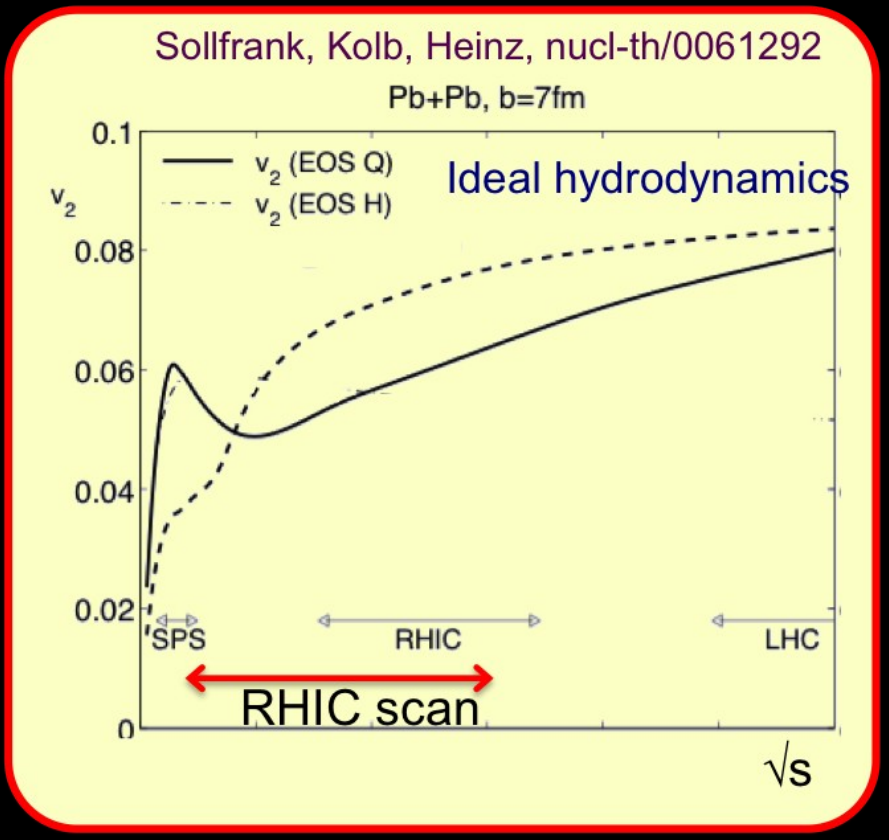


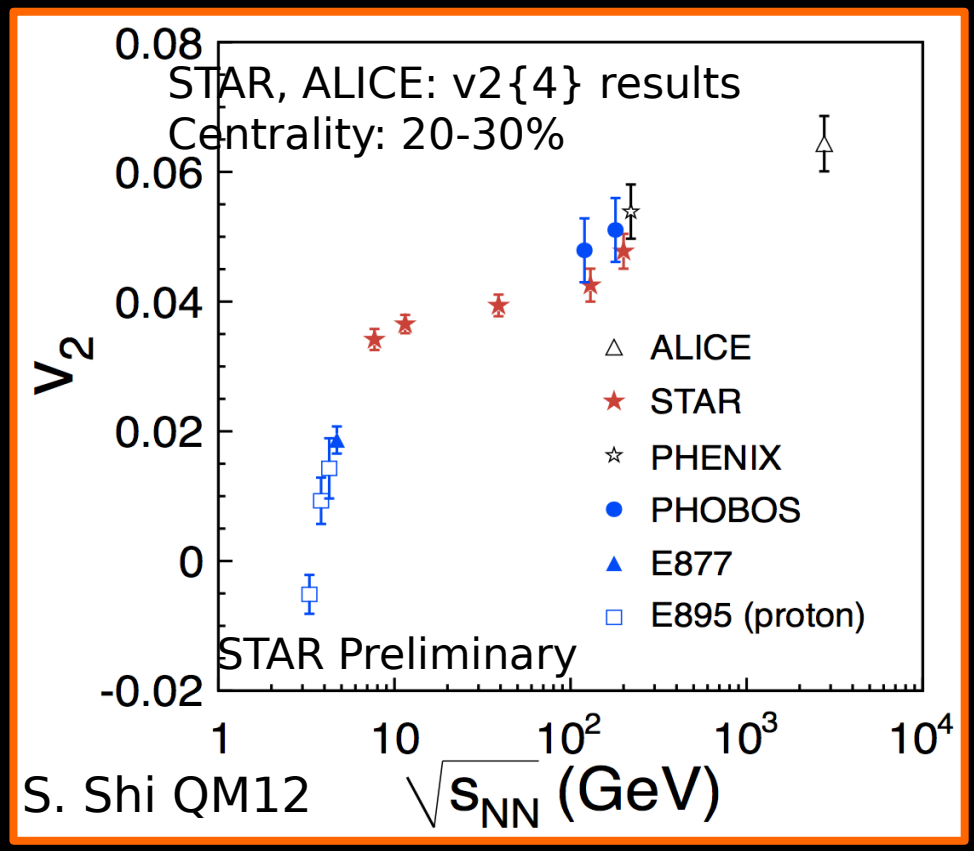
2nd-order Azimuthal dependence - shorter timescales

“Self-quenching” elliptic flow –pressure @0~4 fm/c



Elliptic flow scan – predictions and reality





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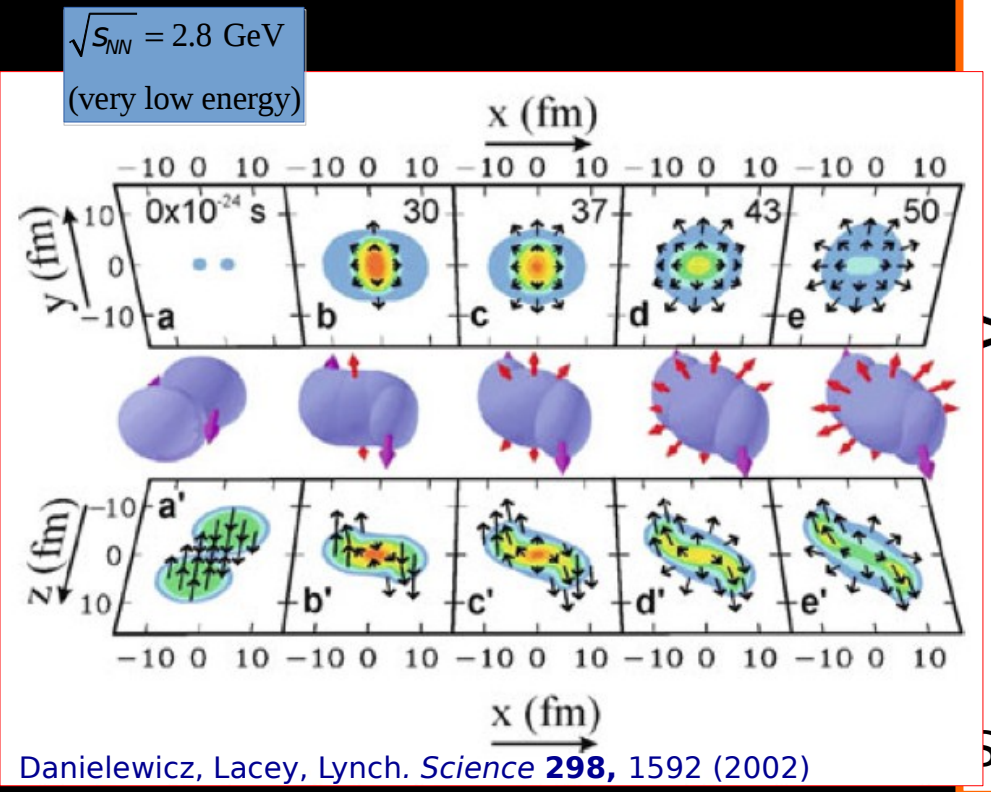
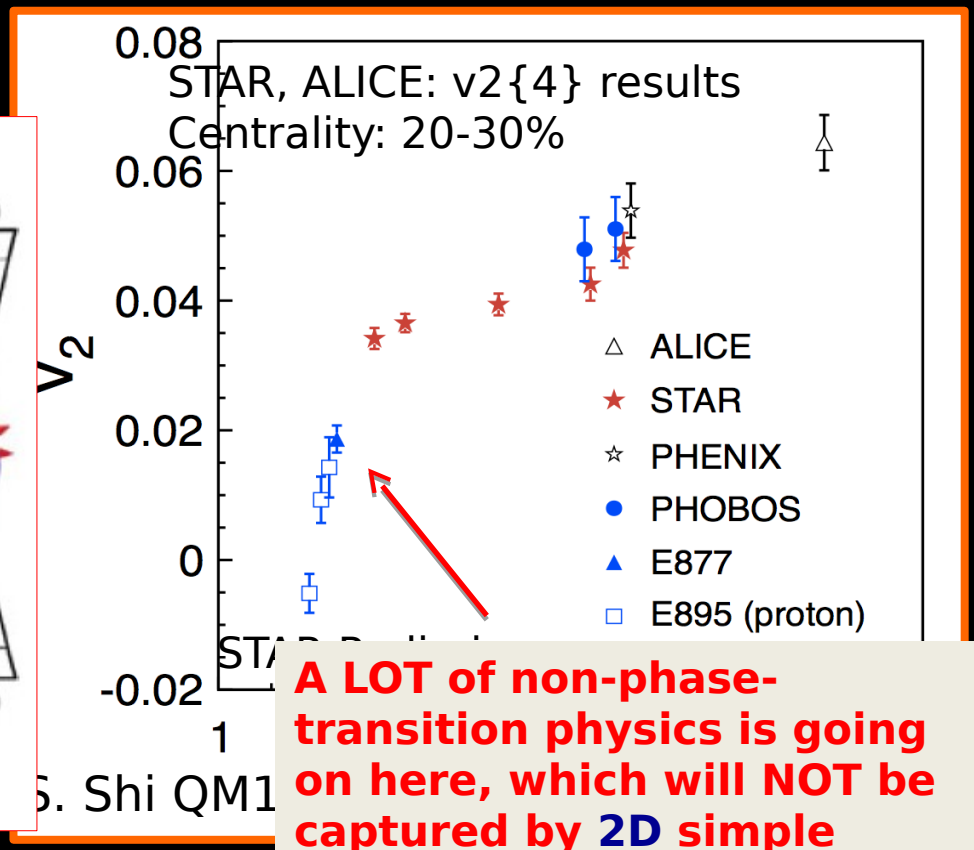


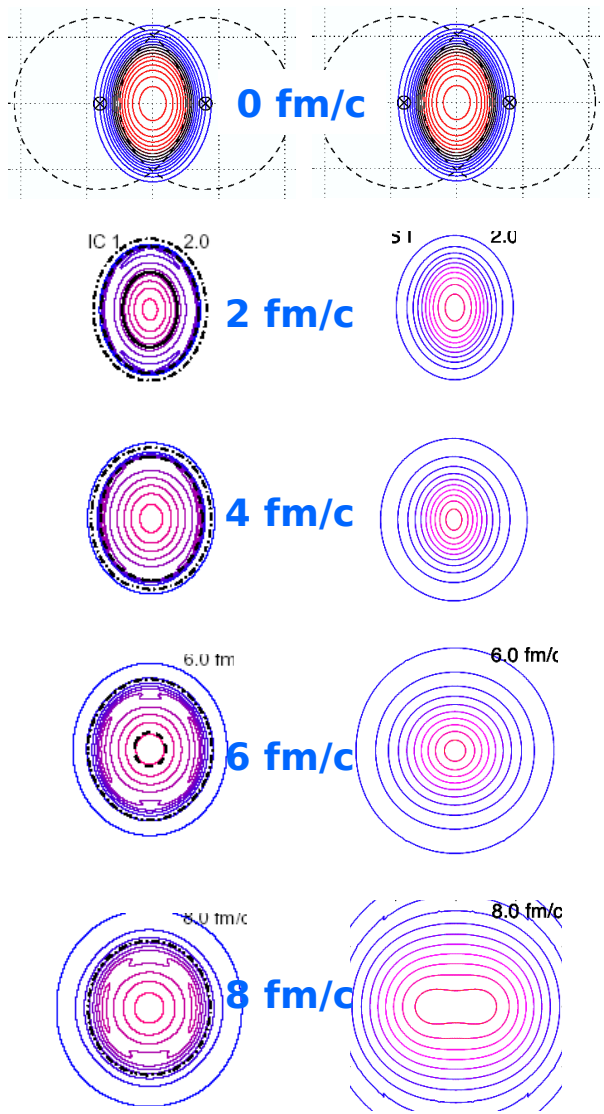
Danielewicz, Lacey, Lynch. *Science* **298,** 1592 (2002)

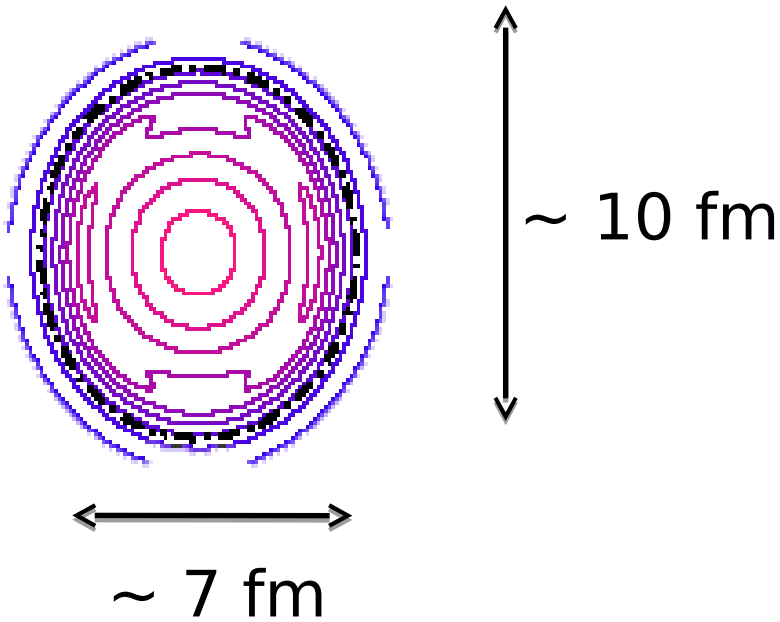


A LOT of non-phase-transition physics is going on here, which will NOT be captured by 2D simple hydro

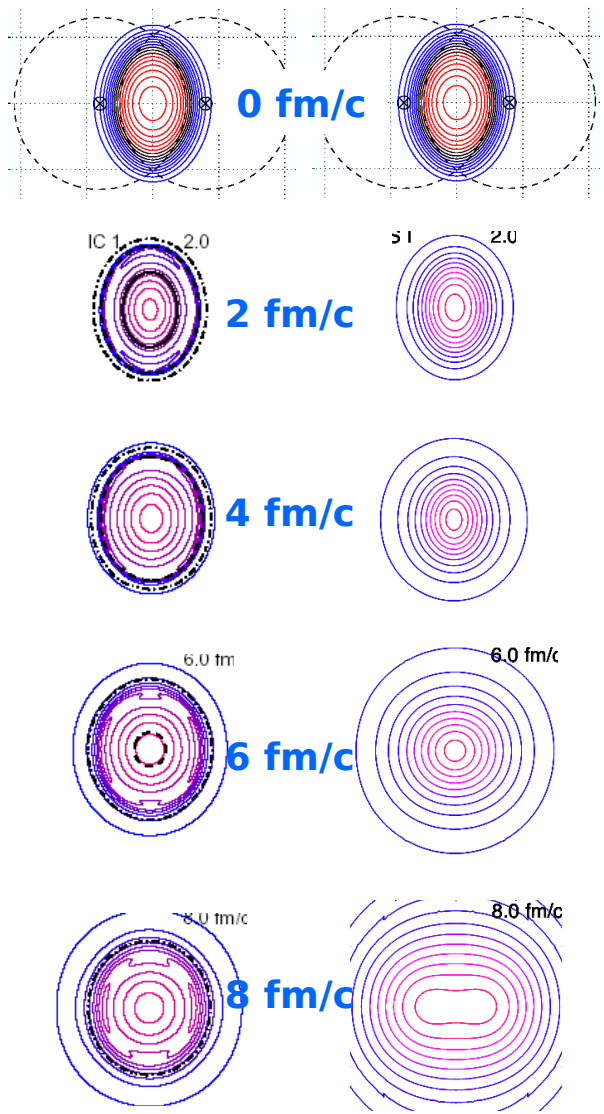
- v2 evolution timescale competes with passing dynamics at lower energy
- Even at high energies, by ~4 fm/c, system may well have evolved out of mixed phase.
- elliptic flow as P.T. signature **highly non-trivial**, especially in the ~10

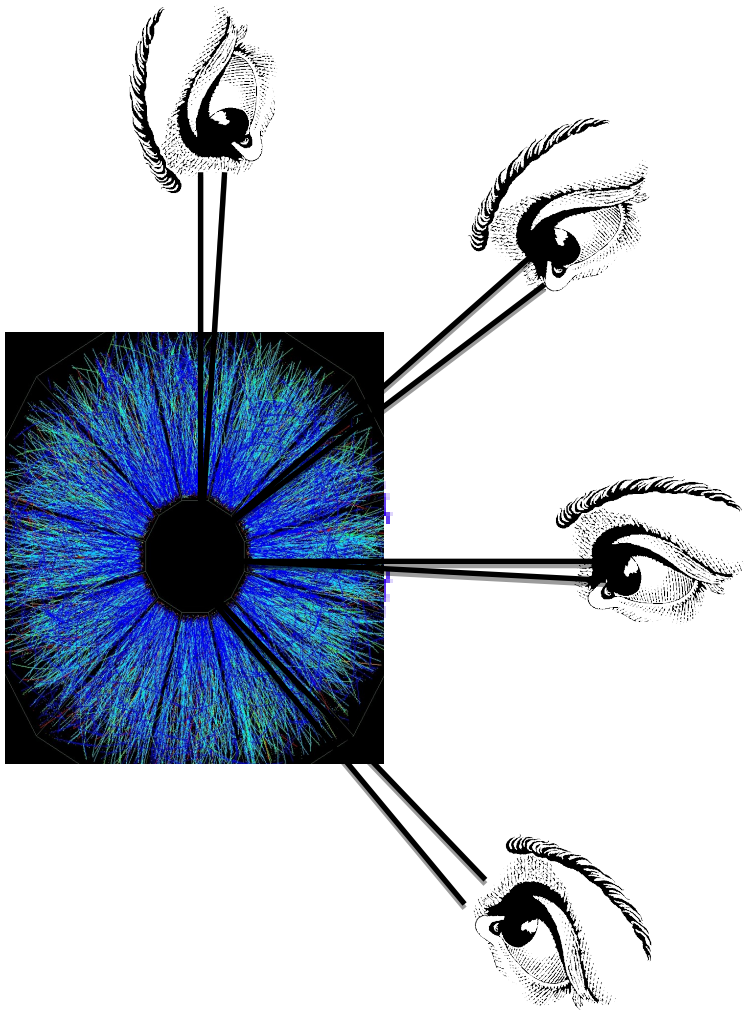
spatial shape evolution

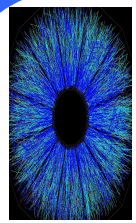


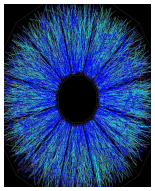


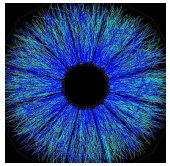
spatial shape evolution

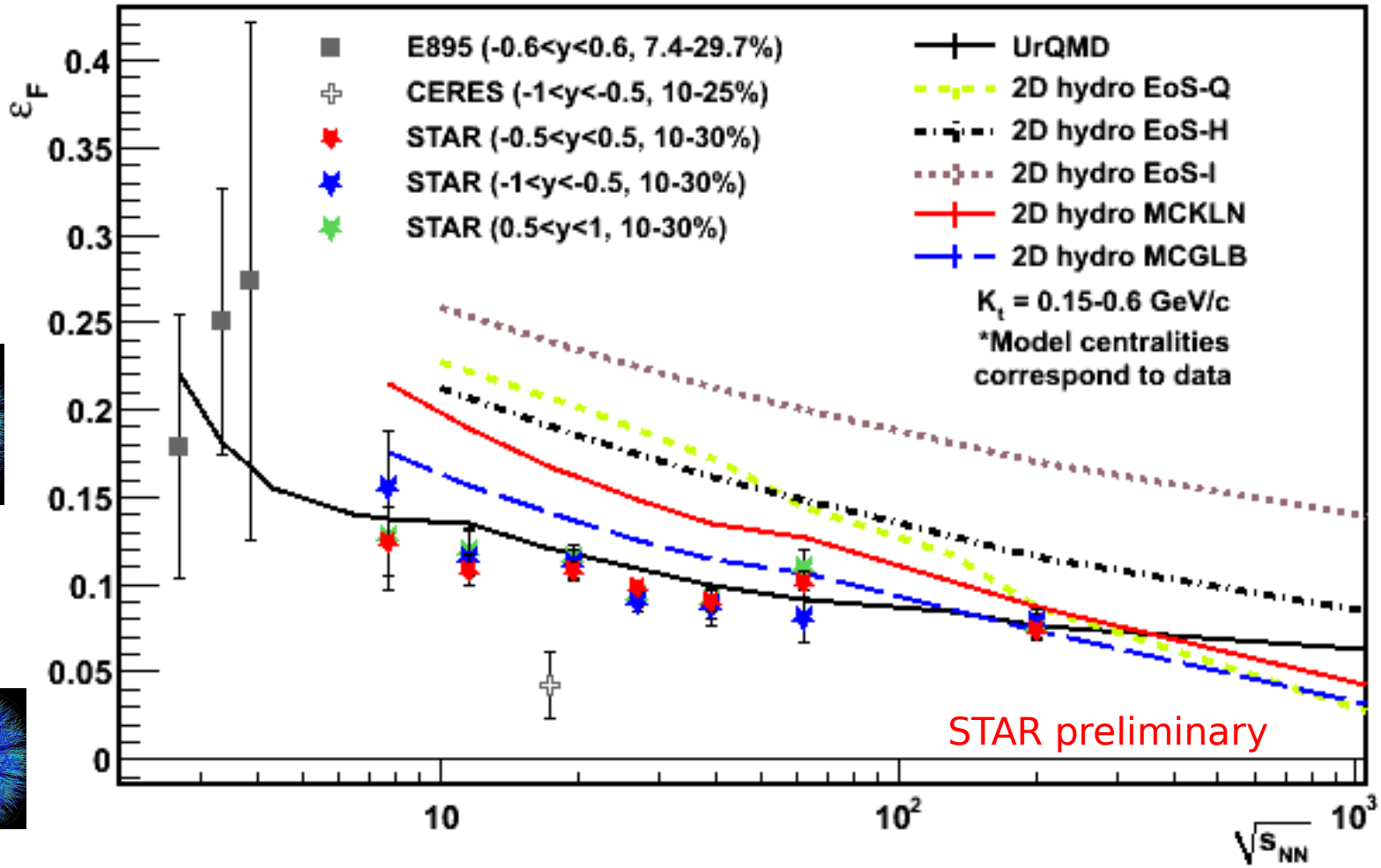








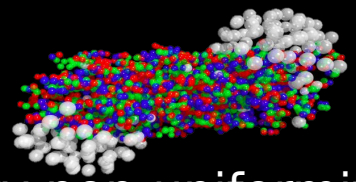




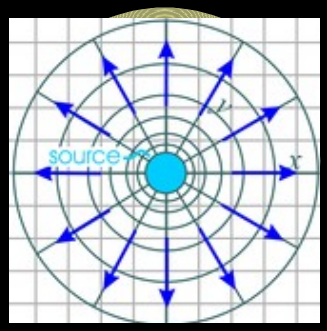
evidence of sudden shape change (despite lone SPS datapoint)
ificant sensitivity to EoS, viscosity, initial-state geometry fluctuati
king agreement with purely hadronic+string-based transport calcu

1st-order Azimuthal dependence
- even shorter timescales?

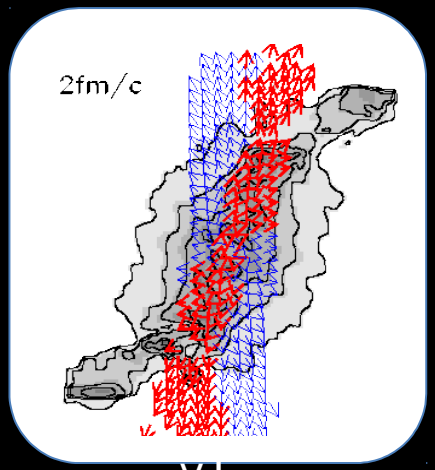
Directed flow



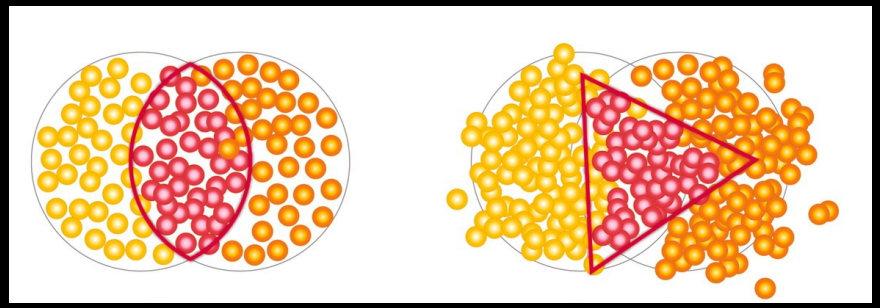
In general, any type of flow is a system response to initial density non-uniformit



"v0"
Transverse (x-y)
plane



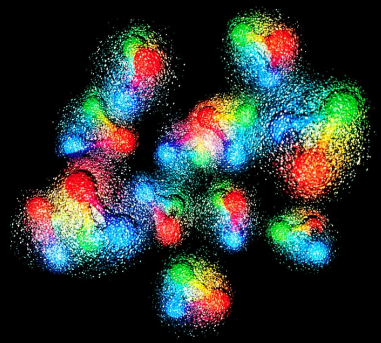
v1
Reaction (x-z)
plane



v2
Transverse (x-y)
plane

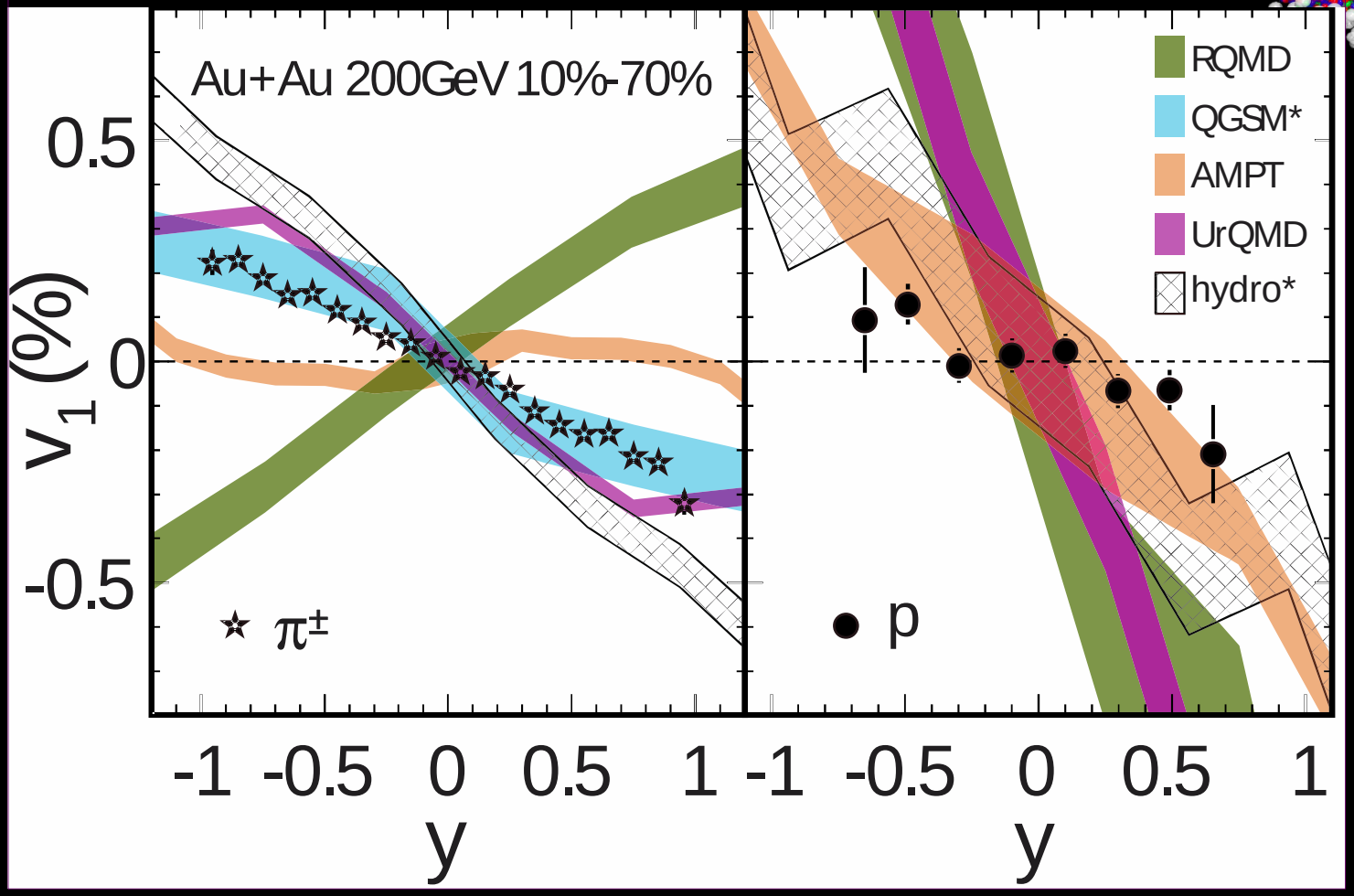
v3
Transverse (x-y)
plane

Except v1, all can be studied with 2D models
(which have dominated at RHIC)



vn
Transverse (x-y)
plane

Directed flow – early pressure probe



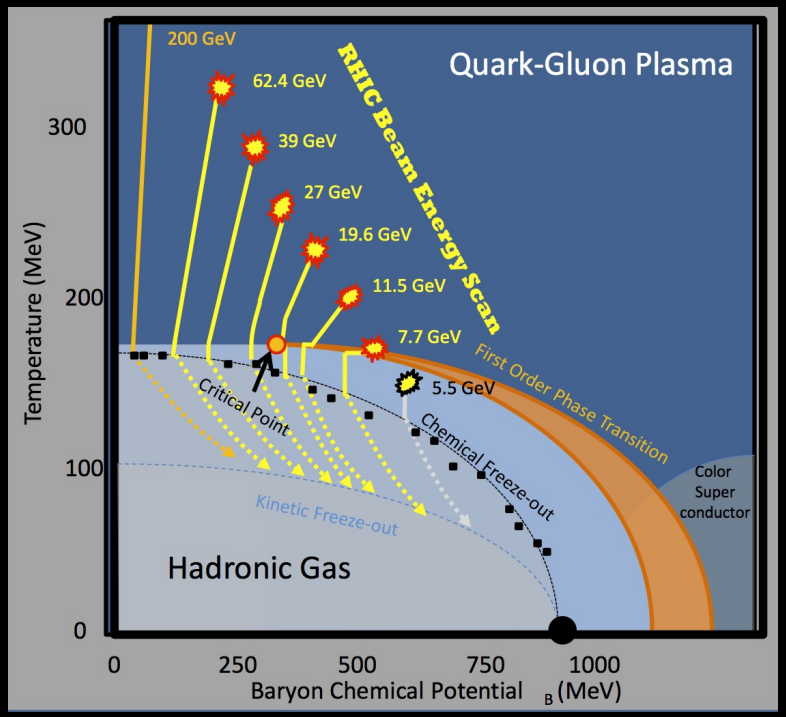
e SPS, “always” antiflow (v1<0)

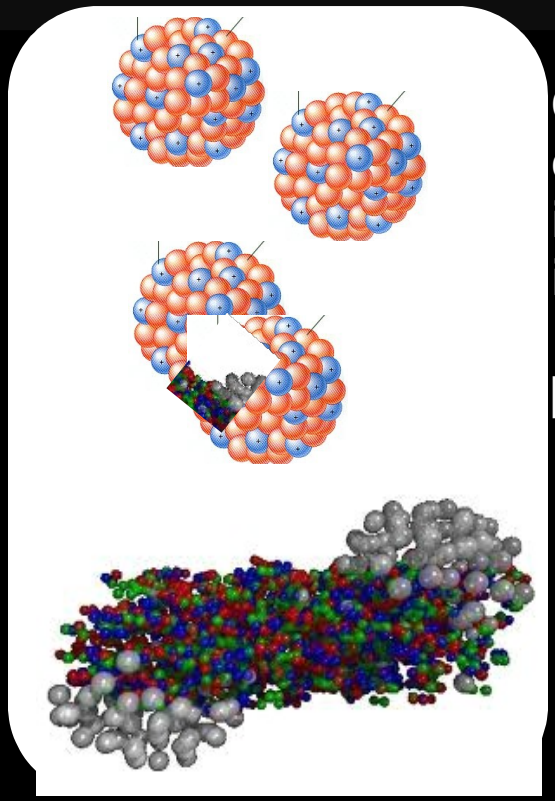
enging for all transport models at RHIC

ps ***the best*** **probe** for a soft spot, due to rapid dynamics

Directed flow

st form of flow predicted (one-fluid hydro) and observed (Plastic Ball) in 1980's
ditionally less focus on v1 at higher energies, where
signal is small
v2 stole the limelight
2D models cannot address this explicitly 3-D phenomenon

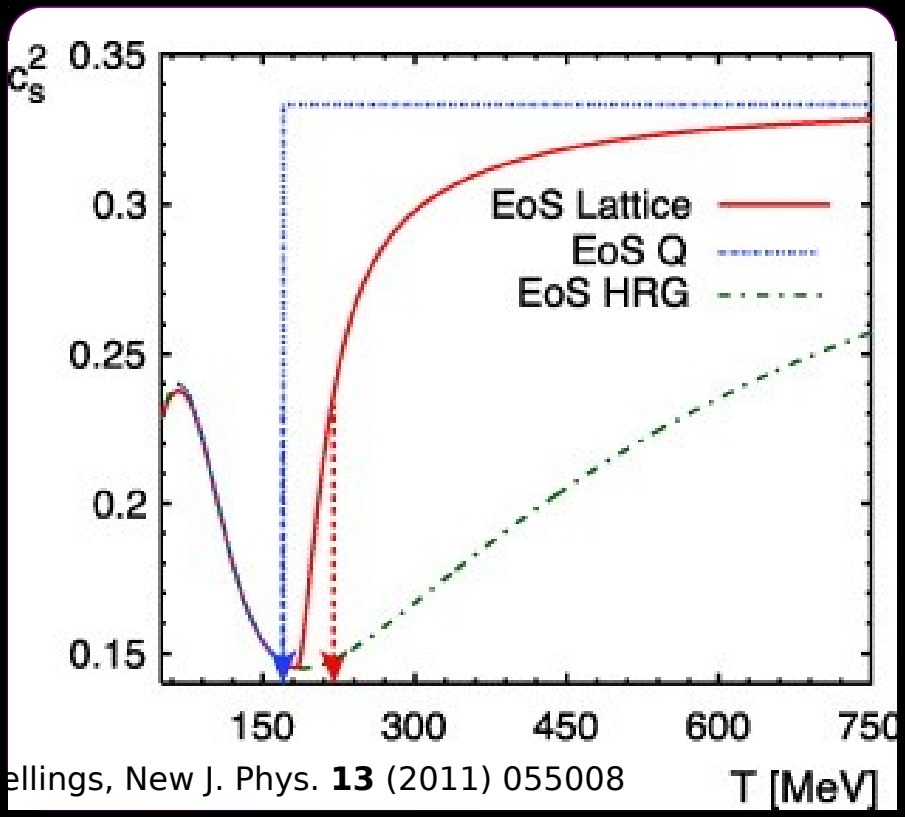




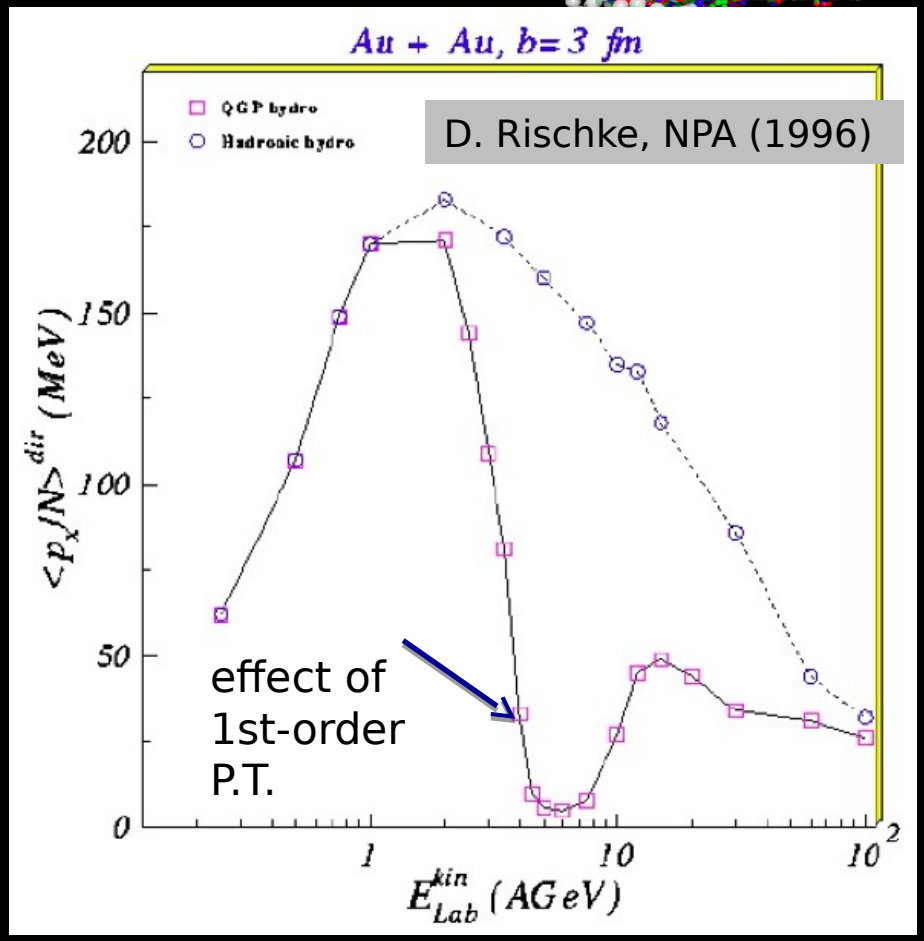
Geometrical seed of directed flow imprinted during interpenetration

 early signal?

Directed flow – early pressure probe

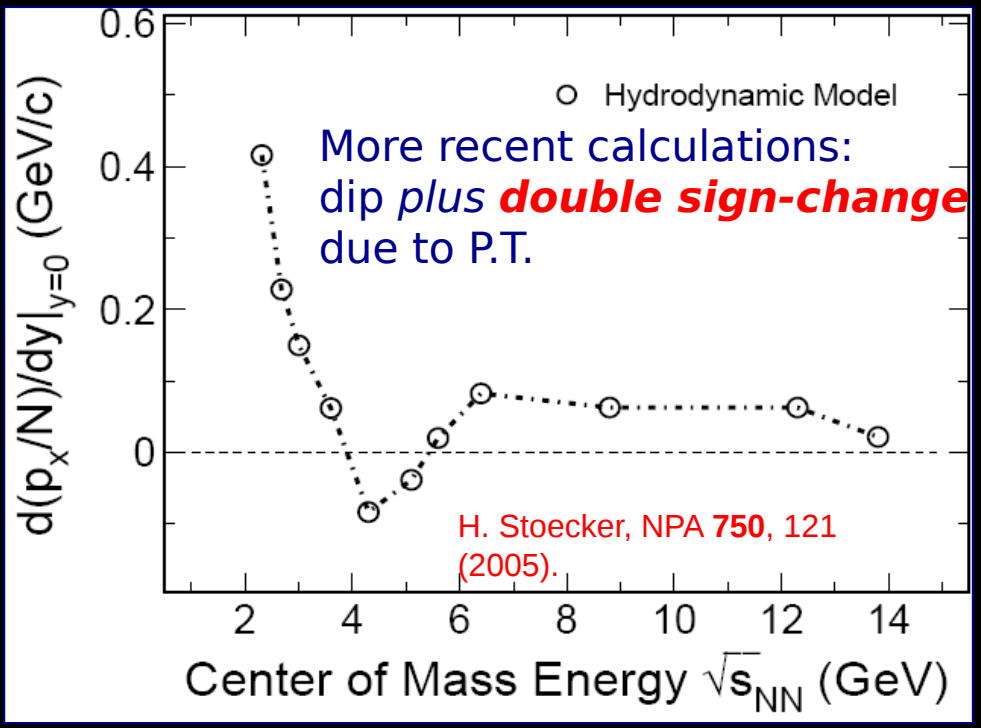


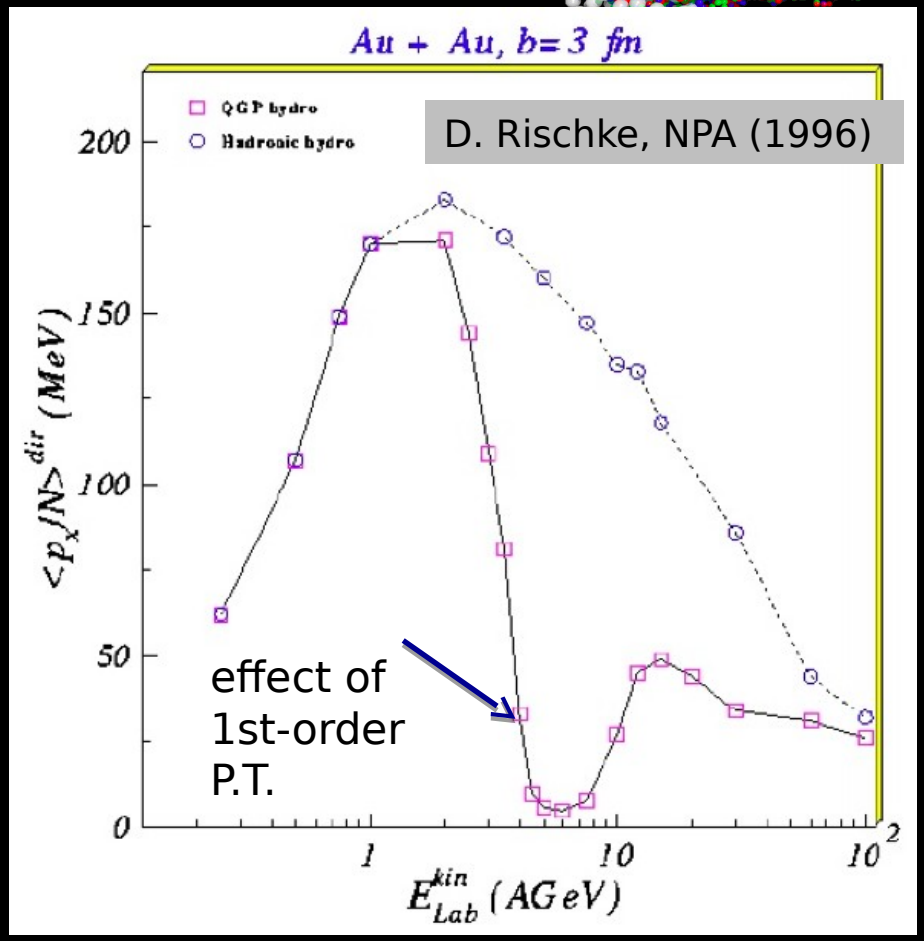
ellings, New J. Phys. **13** (2011) 055008



der anisotropy imprints itself on momentum space in first instants of collision
y feature for soft-spot probe, due to rapid dynamics
nding probe for 1st-order transition (neglected in v2 frenzy of ea

Directed flow – early pressure probe





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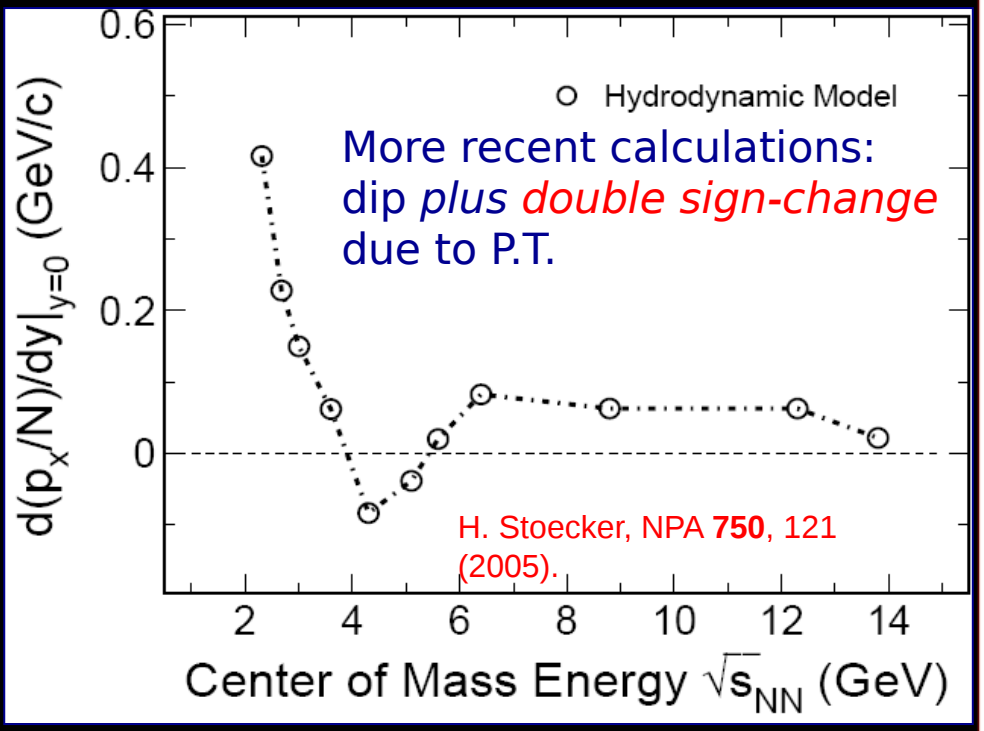
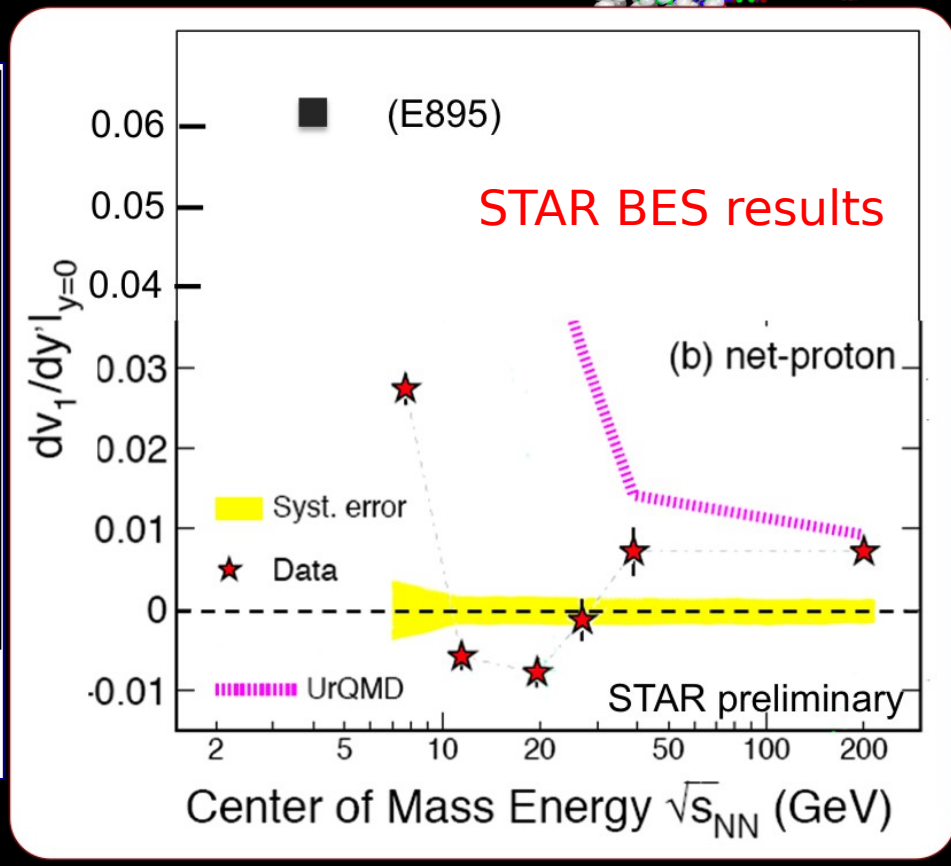
Directed flow – early pressure probe

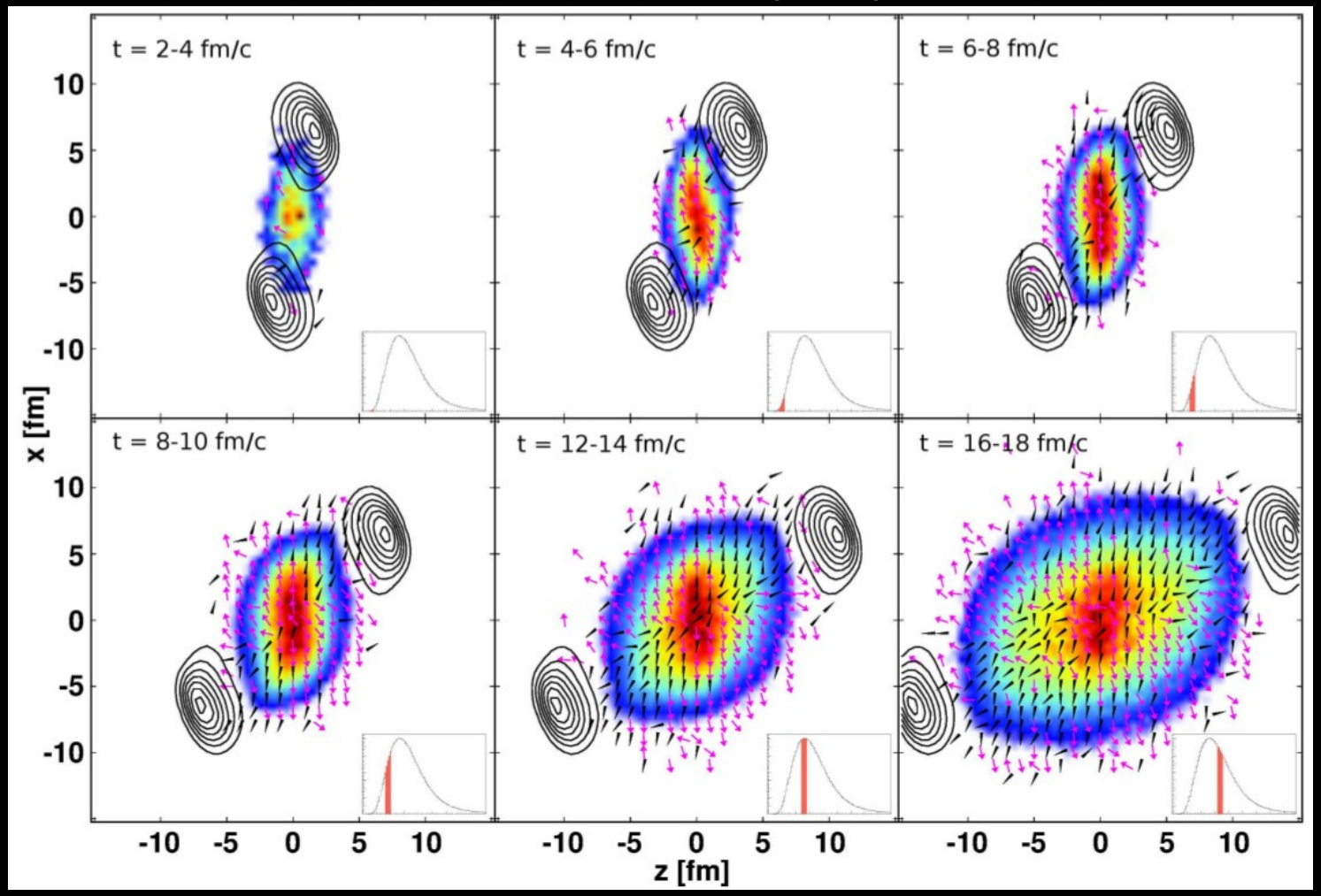




der anisotropy imprints itself on momentum space in first instants of collision
y feature for soft-spot probe, due to rapid dynamics
nding probe for 1st-order transition (neglected in v2 frenzy of ea
ative feature confirmed at RHIC BES!

What drives directed flow?

Graef, Lisa, Bleicher sub PRC arXiv:1302.3408

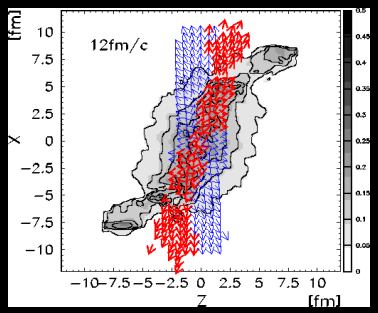


Most models at high energy suggest emission from a “tilted disc”...
... that must certainly evolve non-trivially with time

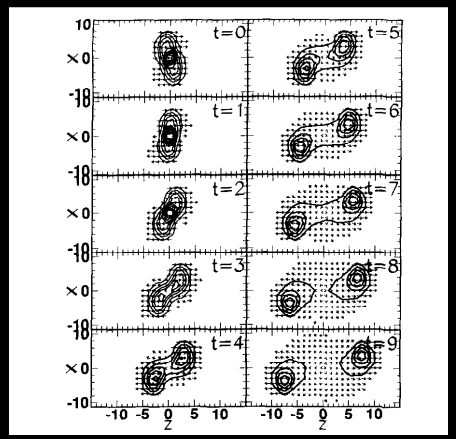
Tilted disc papers

FLOW | HBT

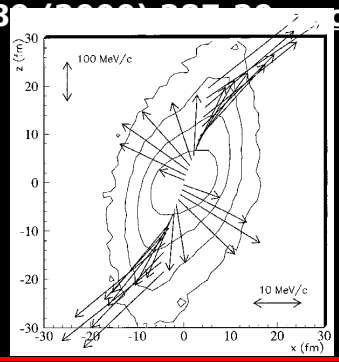
Antiflow of Nucleons at the Softest Point of the EoS
Brachmann et al, Phys.Rev. C61 (2000) 024909
nucl-th/9908010



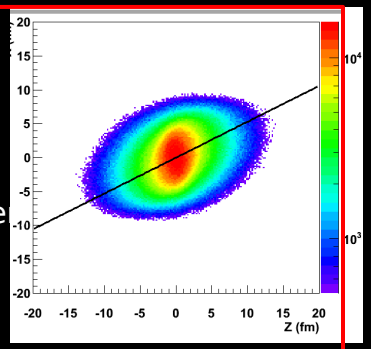
Scaling violation of transverse flow in HIC at AGS
Bravina, PLB 344 (1995) 49

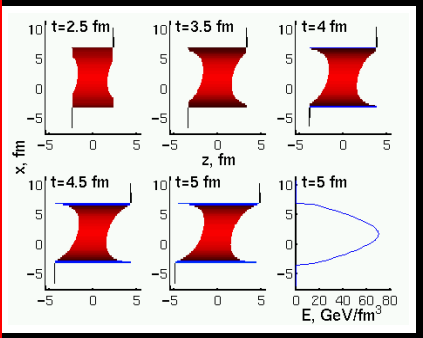


Tilted pion sources from azimuthally sensitive HBT
Lisa, Heinz, Weidemann
Phys.Lett. B48 cl
-th/00030222



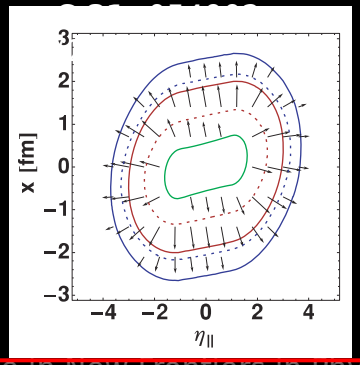
Correspondence between HBT radii and the emission zone in non-central HIC.
Mount, Graef, Mitrovski, Bleiche
Lisa **Phys.Rev. C84 (2011) 014908** **arXiv:1012.5941**



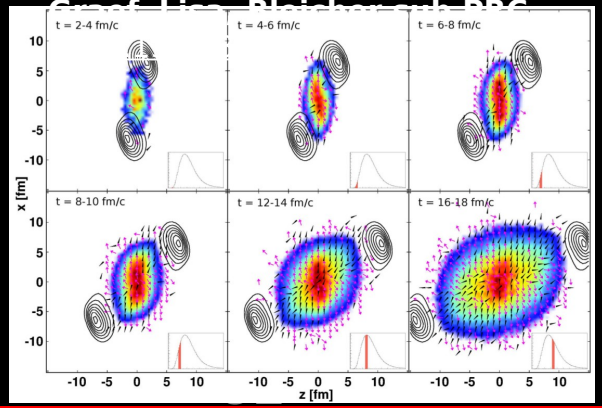


Effective string-rope model...
Magas, Csernai, Strottmann
Nucl.Phys. A712 (2002) 167-204
arXiv:hep-ph/0202085

Directed flow in ultrarelativistic heavy-ion collisions
Bozek and Wyskiel
PHYSICAL REVIEW



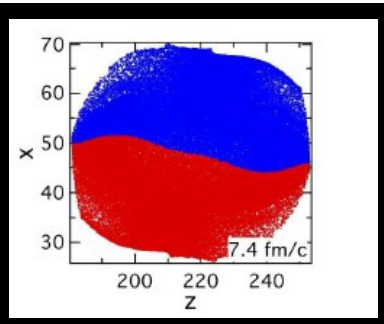
A twisted emission geometry in non-central Pb+Pb collisions measurable via azimuthally sensitive HBT



Csernai's talk

FLOW | HBT

L.P. Csernai[1,2,3], D.D. Strottman[2,3], and Cs. Anderlik[4]
PHYSICAL REVIEW C **85**, 054901 (2012)

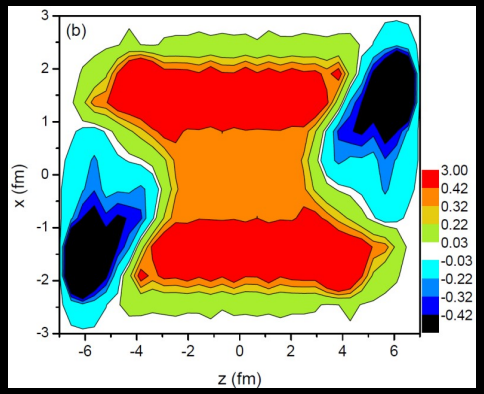


Focus on RHIC!

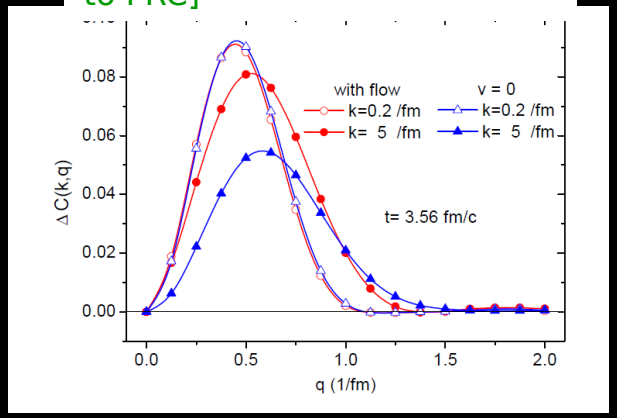
PHYSICAL REVIEW C **87**, 034906 (2013)

Flow vorticity in peripheral high-energy heavy-ion collisions

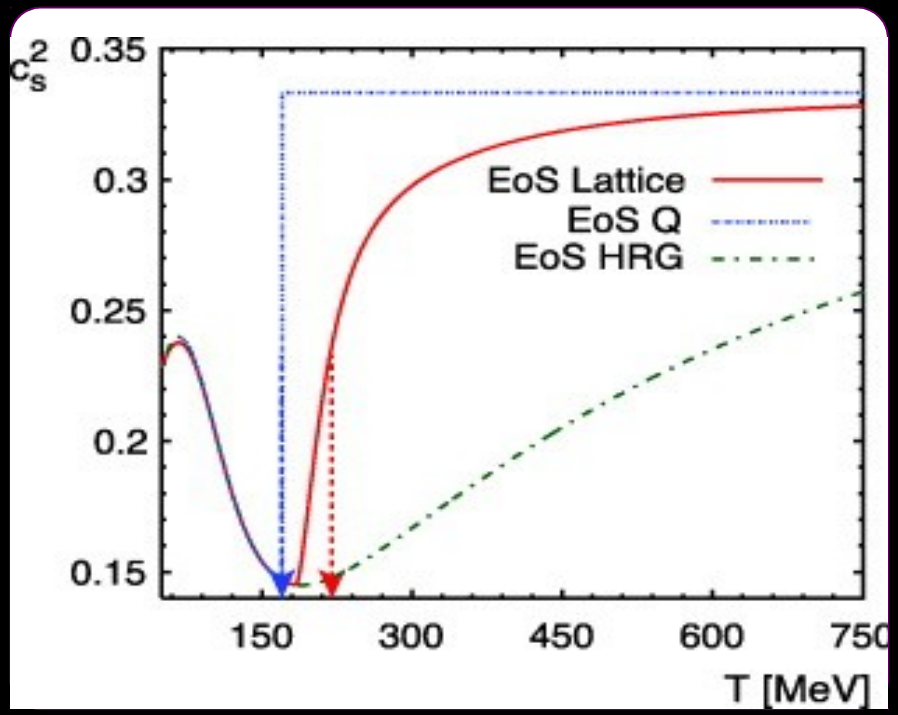
L. P. Csernai,[1] V. K. Magas,[2] and D. J. Wang[1]

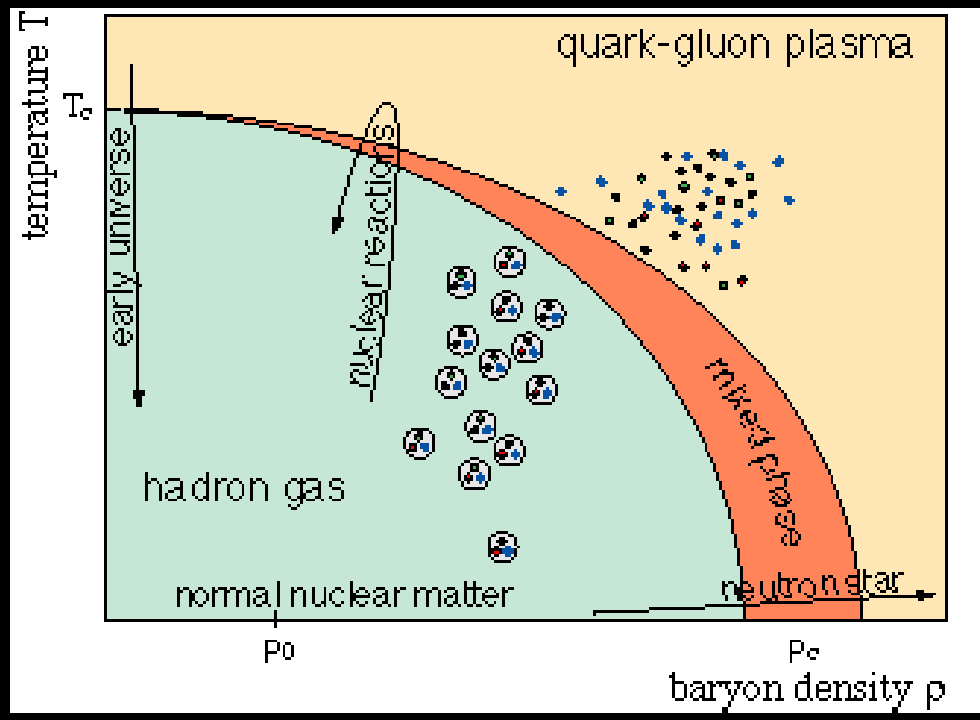


[L.P. Csernai, S. Velle, subm. to PRC]



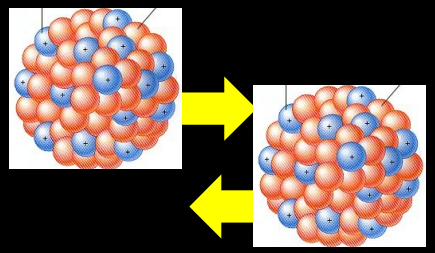
A possible (& *way* oversimplified) scenario...

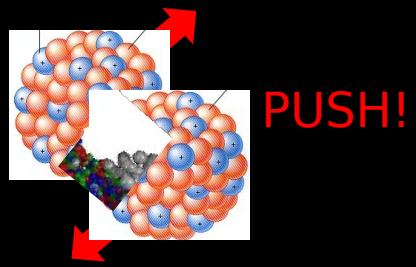


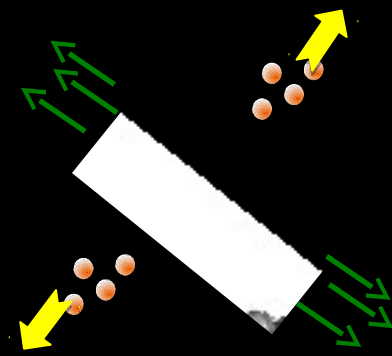


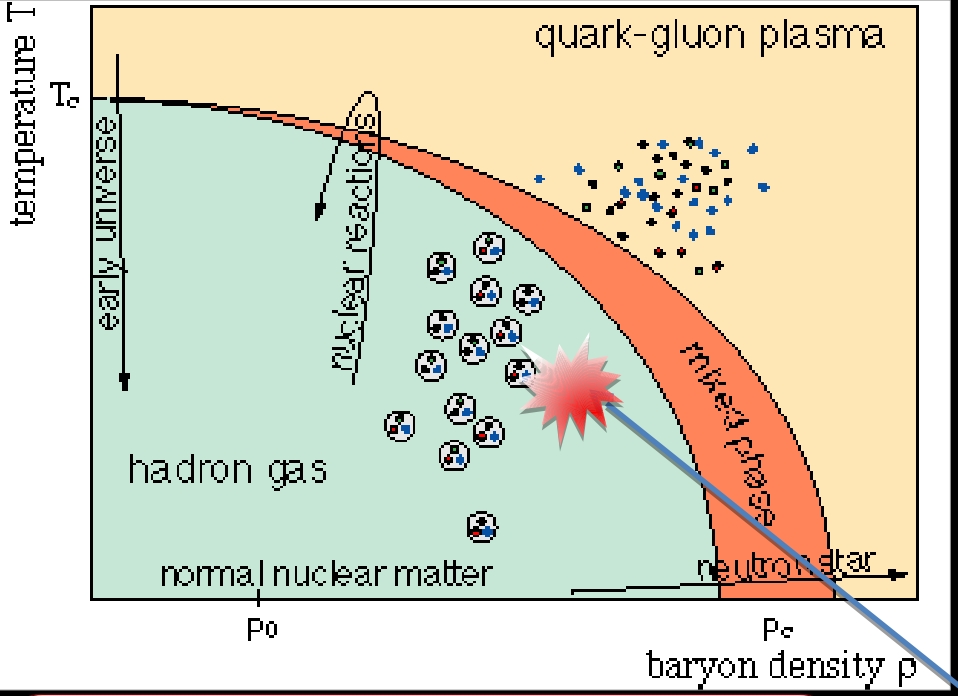
large sound velocity ⇒ repulsion

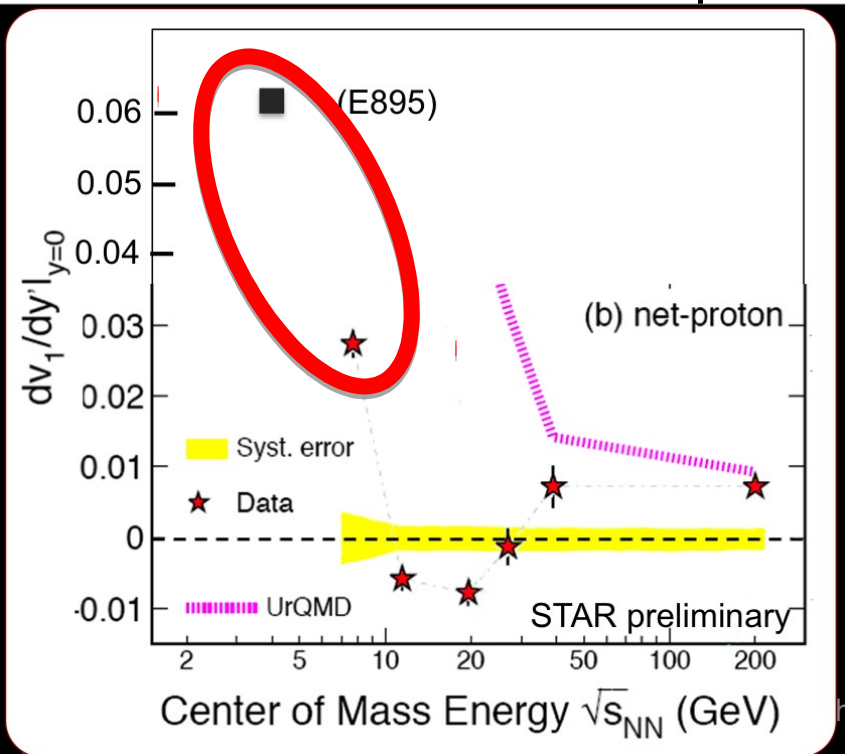
... what is the sound velocity in the first moment of a collision?



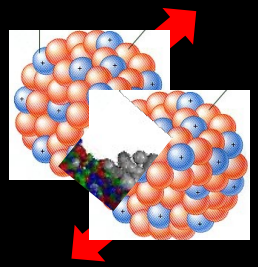

PUSH!



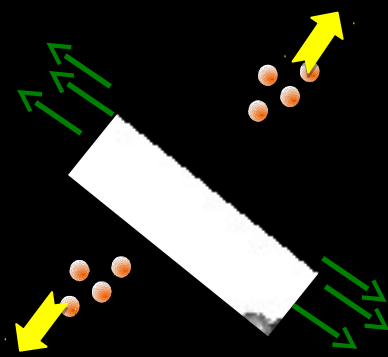


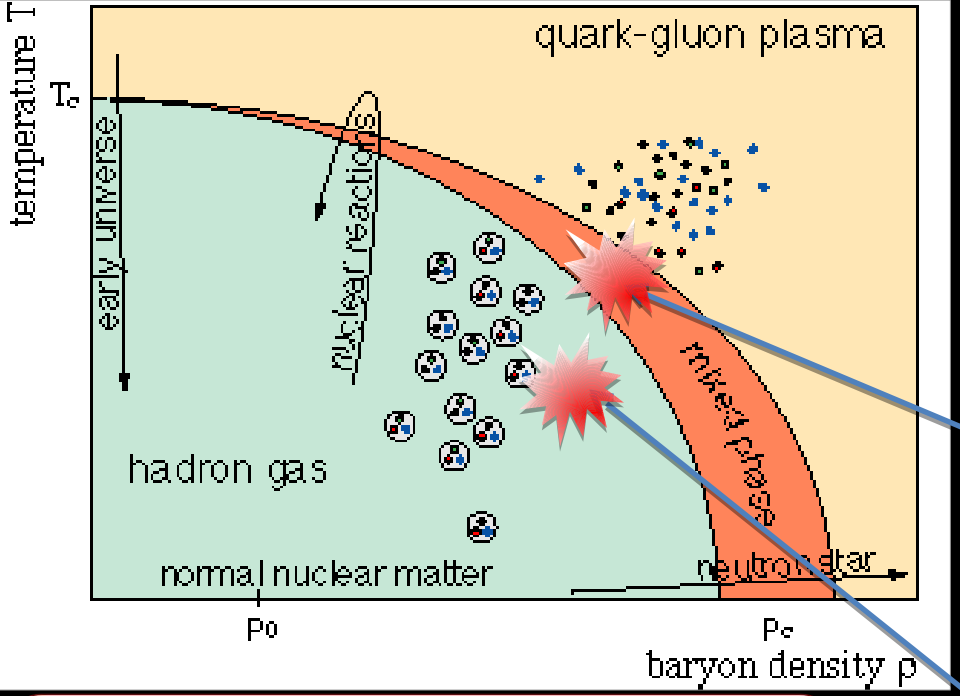


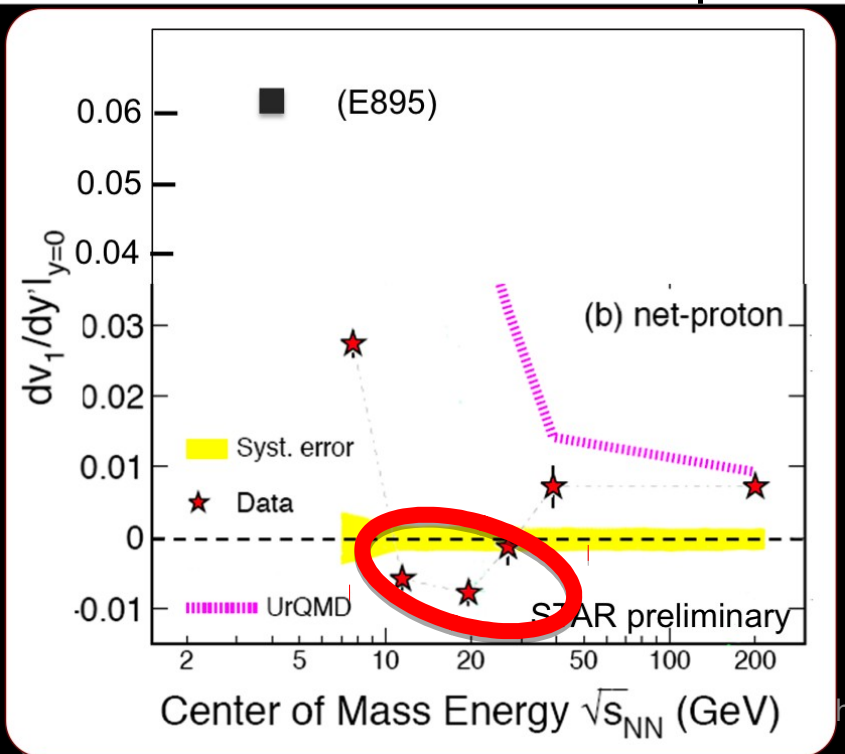
net ("valence") proto

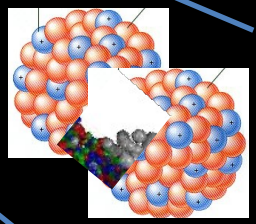


PUSH!

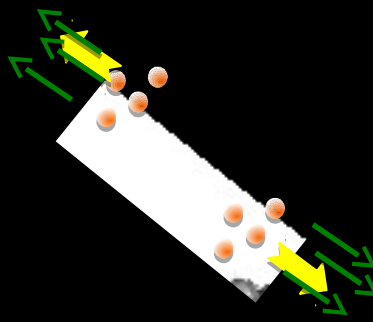


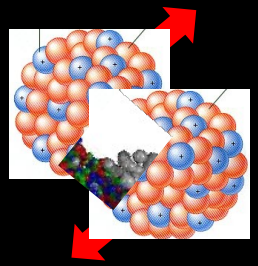

quark-gluon plasma
temperature T
T_c
early universe
nuclear reactions
mixed phase
hadron gas
normal nuclear matter
neutron star
ρ_0
ρ_c
baryon density ρ


(E895)
(b) net-proton
Syst. error
Data
UrQMD
STAR preliminary
$dv_1/dy'|_{y=0}$
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
2
5
10
20
50
100
200
Center of Mass Energy $\sqrt{s_{NN}}$ (GeV)

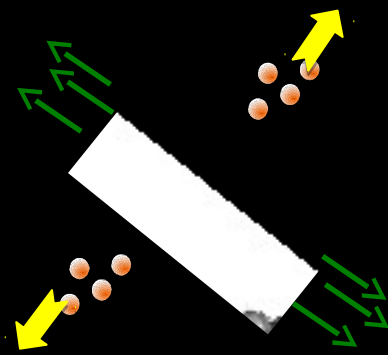


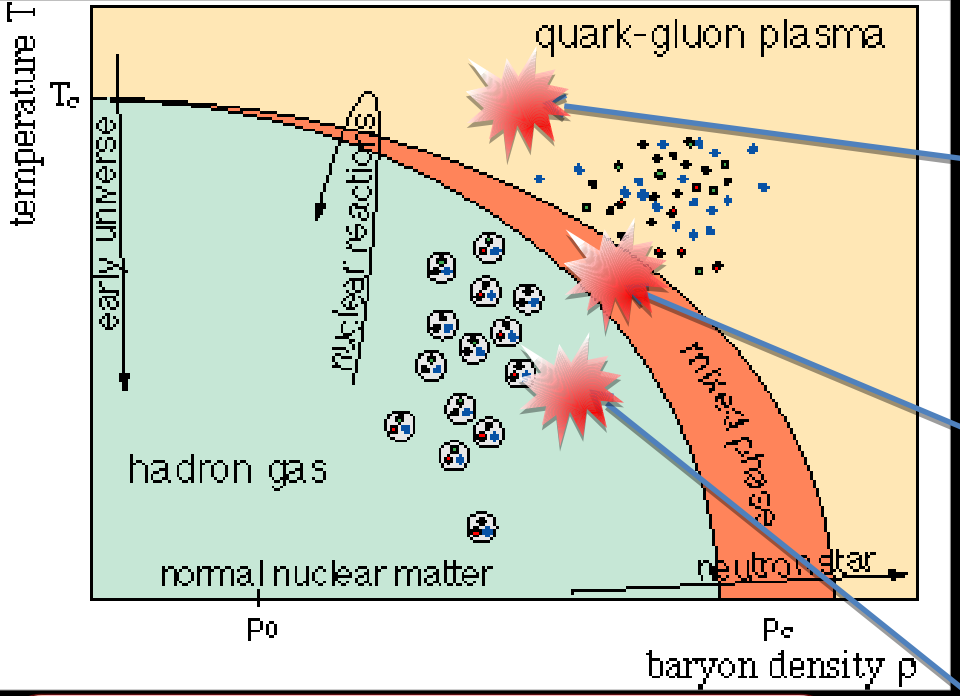
SOFT...





PUSH!




quark-gluon plasma
temperature T
T_c
early universe
nuclear reactions
mixed phase
hadron gas
normal nuclear matter
neutron star
ρ_0
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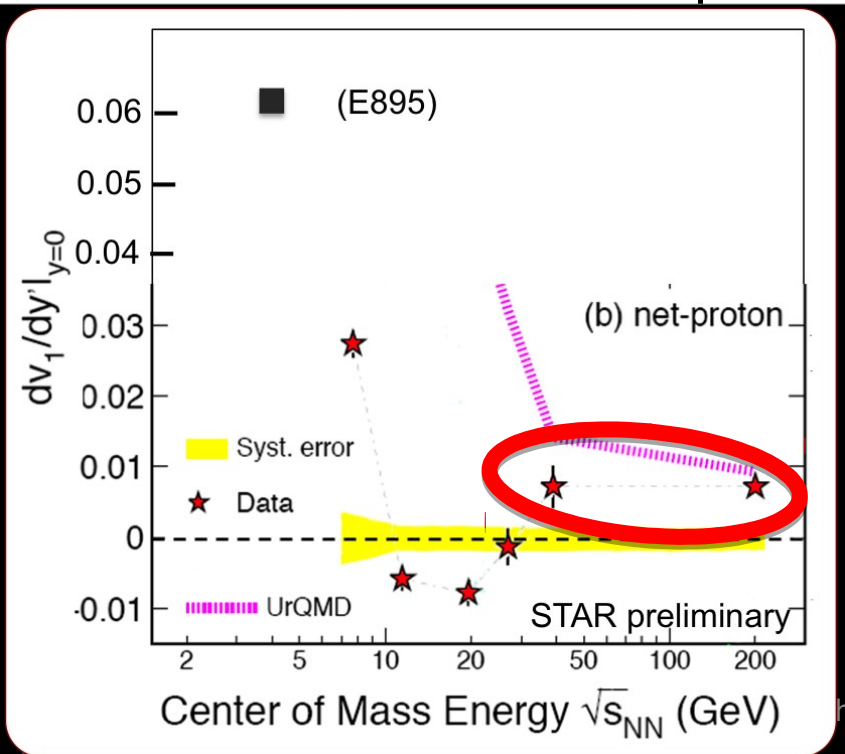
baryon density ρ


(E895)
(b) net-proton
Syst. error
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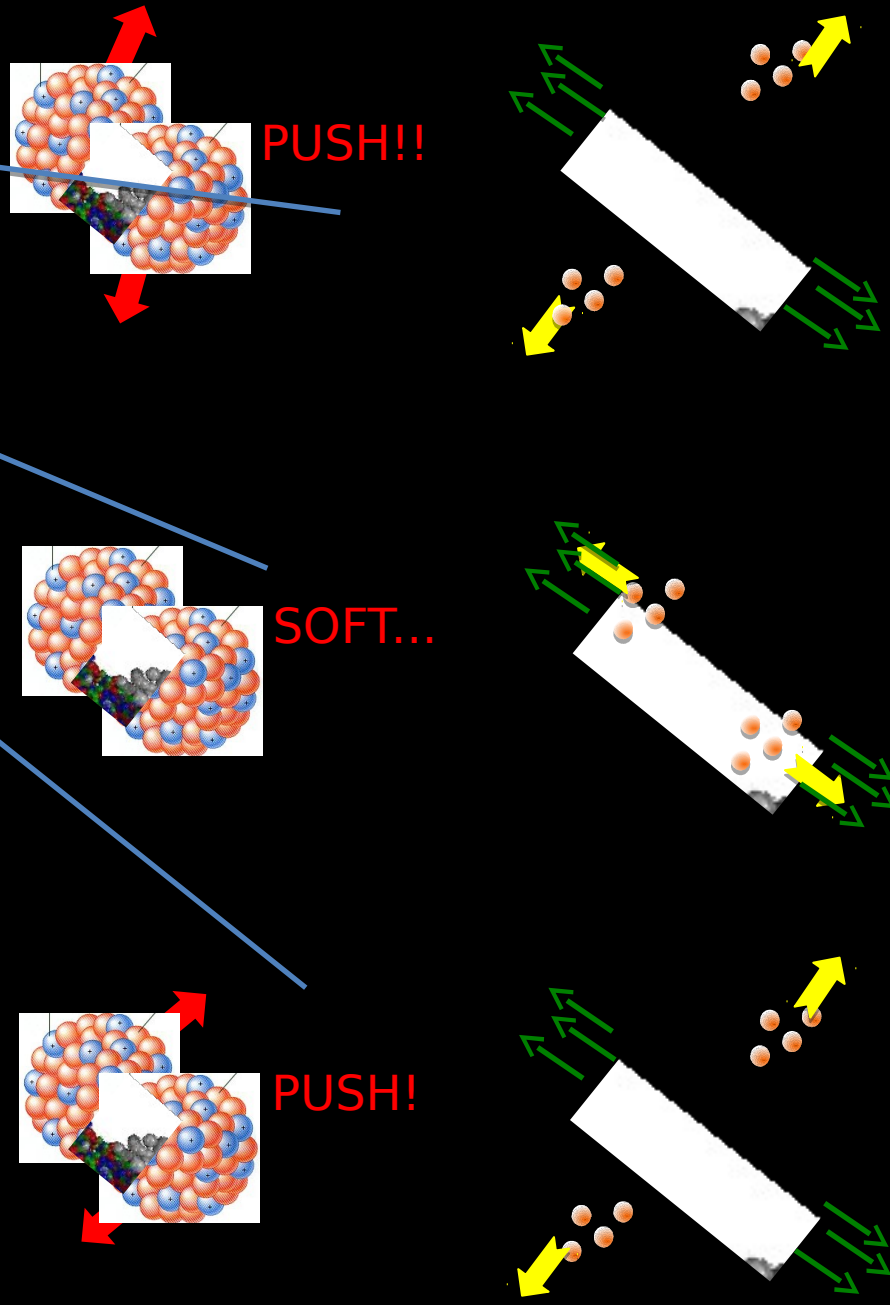
UrQMD
STAR preliminary
$dv_1/dy'|_{y=0}$
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
2
5
10
20
50
100
200
Center of Mass Energy $\sqrt{s_{NN}}$ (GeV)


PUSH!!
SOFT...
PUSH!

Summary

- Very successful beam energy scan program <u>begun</u> at RHIC
  - Only a sampling of data shown

Also: no time to mention

- balance functions
- proton femtoscopy
- first-order pion azimuthal femtoscopy
- pion-kaon correlations
- hyper- and anti-hypernuclei yields
- light fragment yields
- spectral fits
- higher-order azimuthal moments (vN)
- yield-fraction fluctuations
- fluctuations of net-X (proton, charge, pion, kaon...)
- ...

Summary

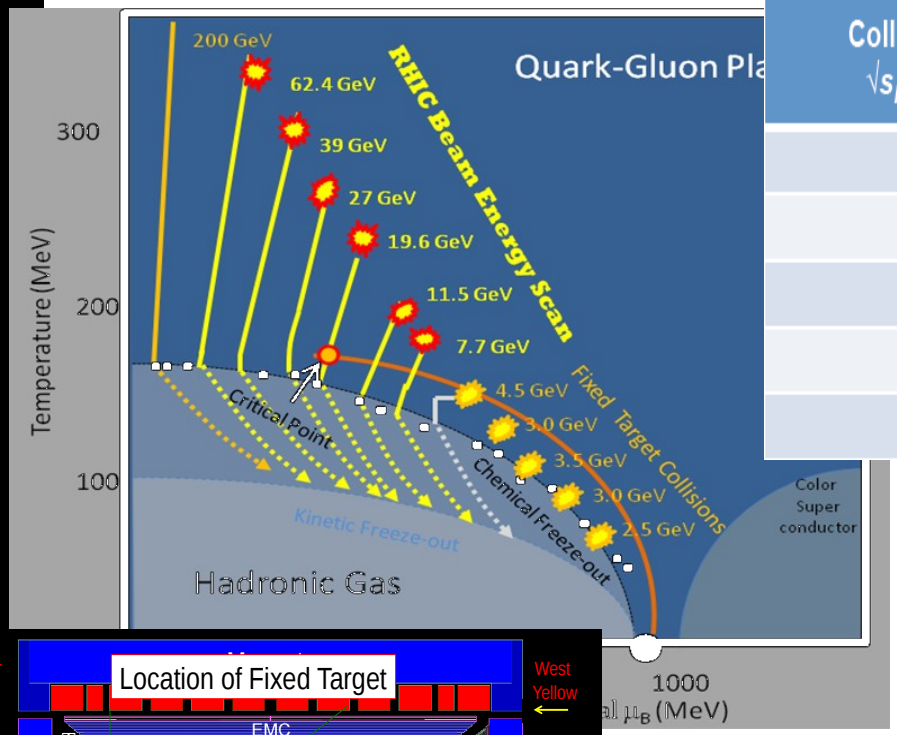
- Very successful beam energy scan program <u>begun</u> at RHIC
  - Only a sampling of data shown
- QGP signals “turn off” in scanned region
- Collective flow as a probe of reduced pressure
  - rapid system evolution: optimal if signal is determined in an “instant”
  - azimuthally anisotropic flow probes early times
  - first-order flow sensitive to initial interpenetration.
    - qualitative signal proposed and **observed** by STAR

Outlook

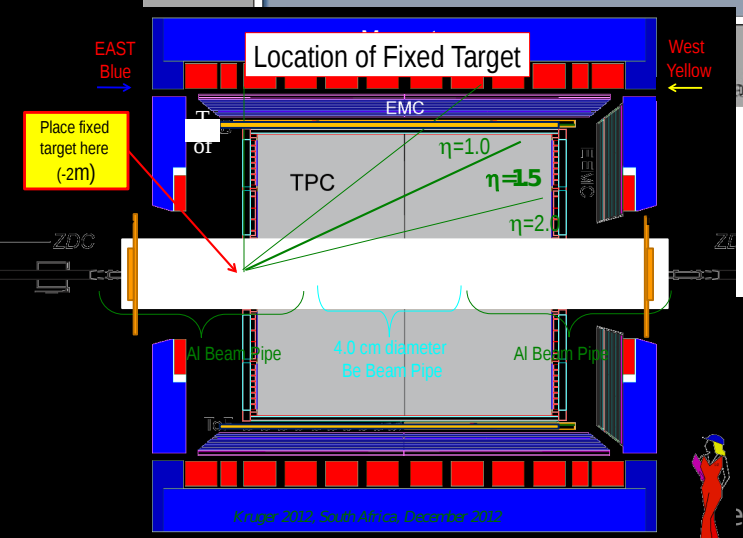
- Continue to explore observables sensitive to a short snapshot of the evolution
  - including Lambda v1
  - first-order azimuthal HBT
- work with theorists with <u>realistic</u>, <u>3D</u> transport with phase features
- finer energy scan in follow-up BES II
- fixed-target program being explored...

Under consideration...

μ_B extended range in STAR due to fixed target program



Collider mode $\sqrt{s_{NN}}$ (GeV)	Fixed-target mode $\sqrt{s_{NN}}$ (GeV)	Fixed-target mode μ_B (MeV)
19.6	4.5	585
15	4.0	625
11.5	3.5	670
7.7	3.0	720
5	2.5	775



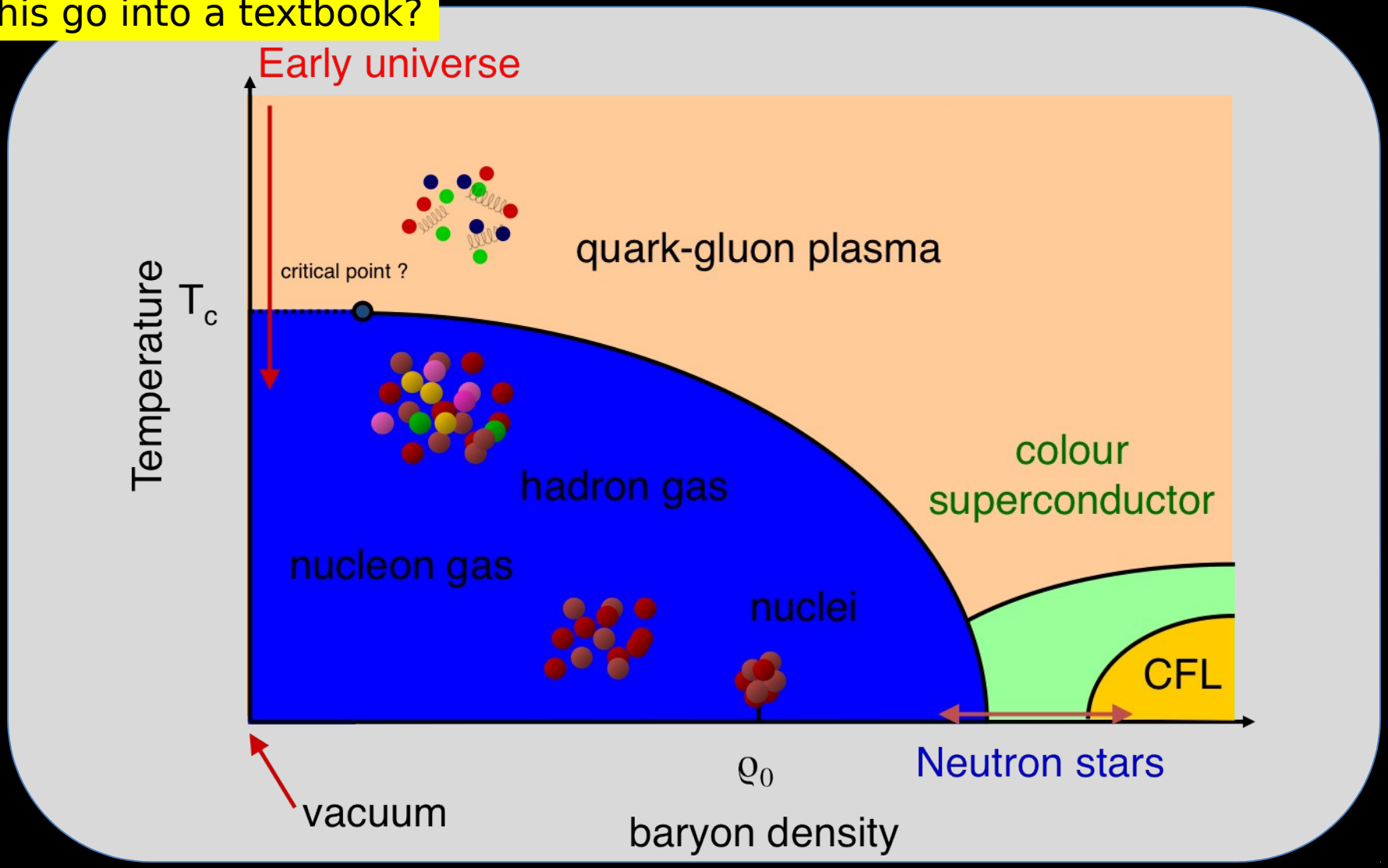
Fixed-target running allows much higher rates without e-cooling at lower energies

Minimal impact on concurrent operation

Motivation for Beam Energy Scan (BES) program

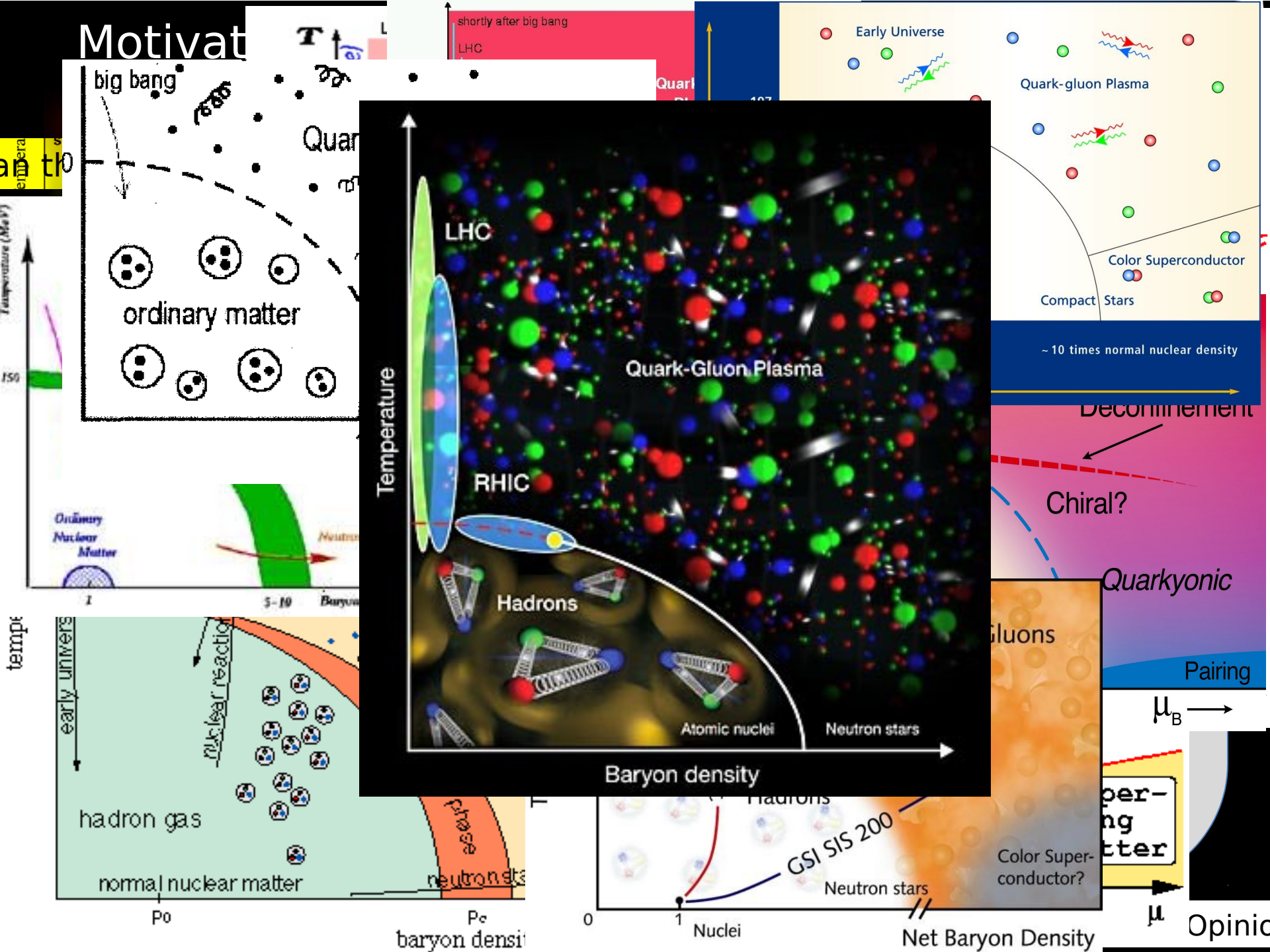
the field of relativistic heavy ion physics (IMHO*)

an this go into a textbook?

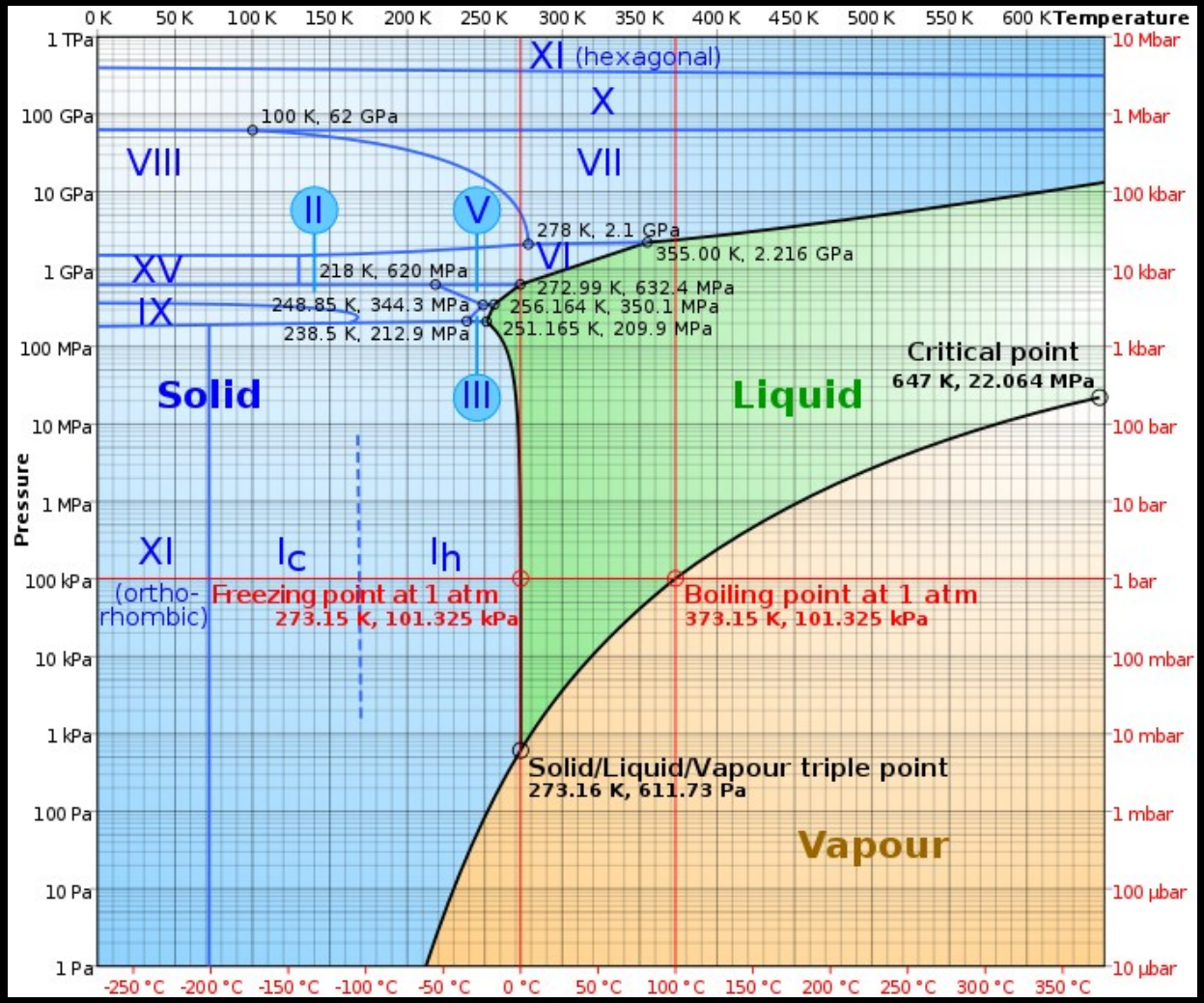


* IMHO = In Mike's Humble Opinio

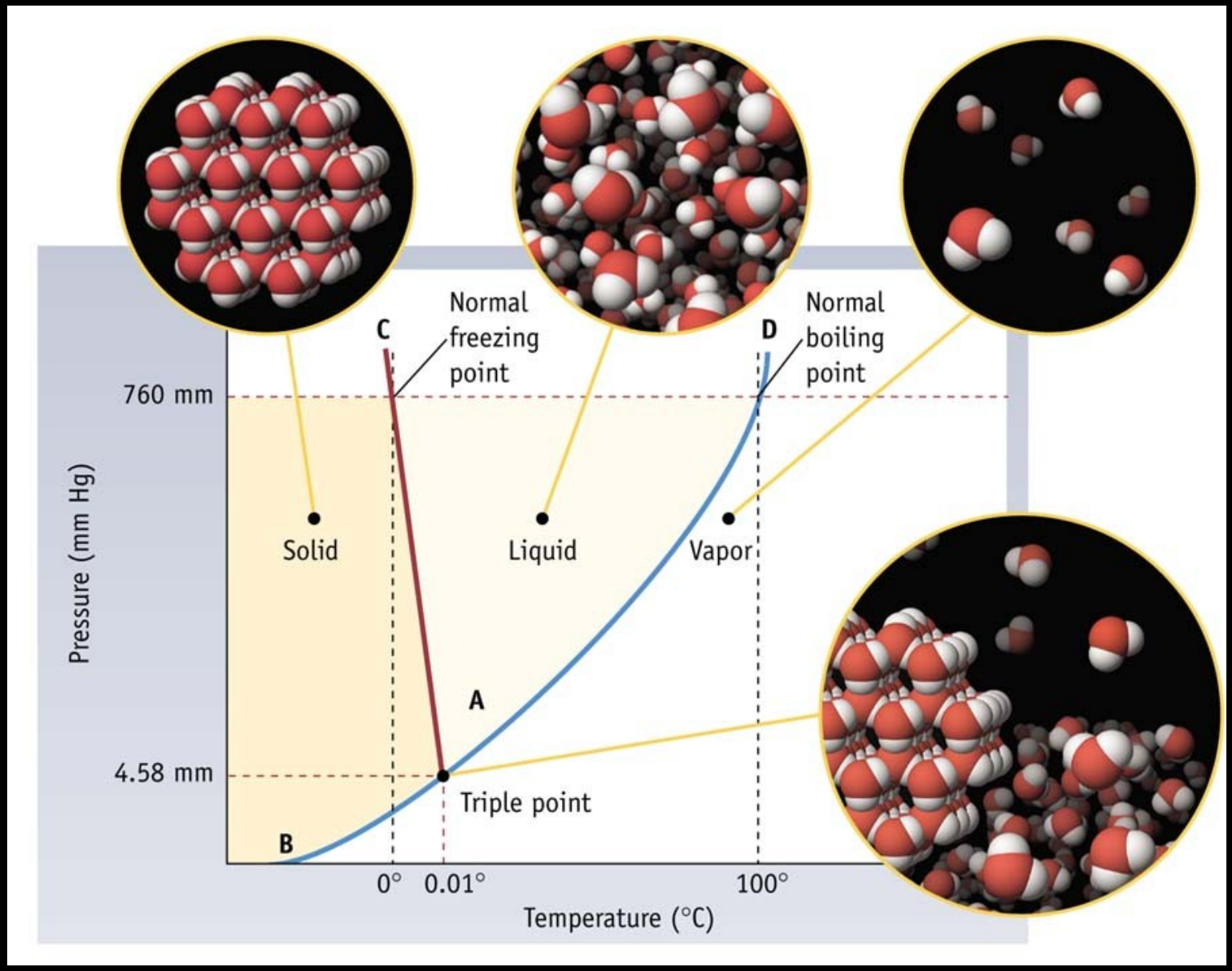
Motivat


big bang
ordinary matter
shortly after big bang
LHC
Early Universe
Quark-gluon Plasma
Color Superconductor
Compact Stars
~ 10 times normal nuclear density
Temperature
LHC
RHIC
Quark-Gluon Plasma
Hadrons
Atomic nuclei
Neutron stars
Baryon density
Chiral?
Quarkyonic
Pairing
early universe
hadron gas
normal nuclear matter
GSI SIS 200
Neutron stars
Color Super-
conductor?
Nuclei
Net Baryon Density

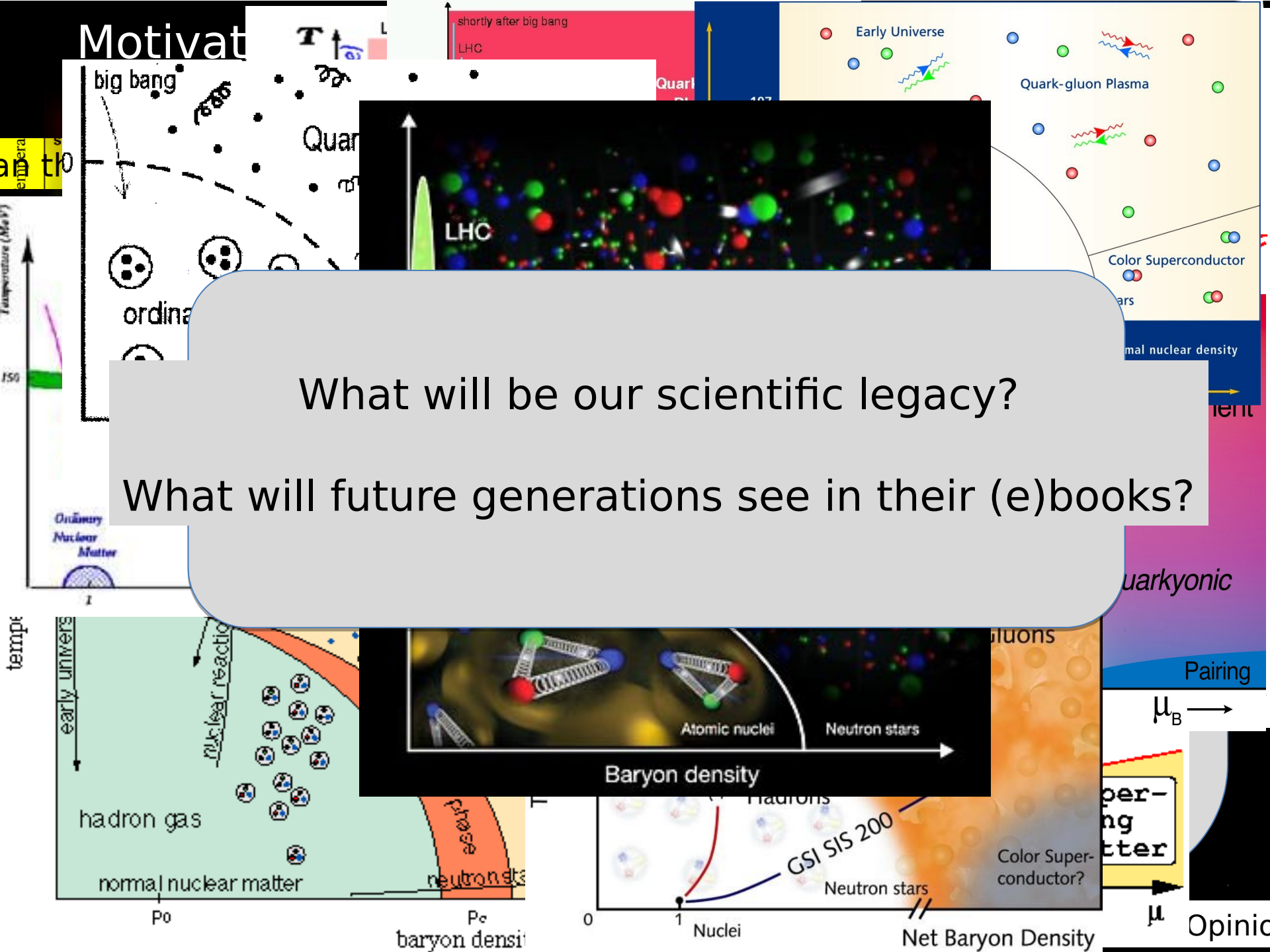
or can we reach something like this?



Okay, then how about something like this?



Motivat



What will be our scientific legacy?

What will future generations see in their (e)books?

THANK YOU FOR ATTENTION