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
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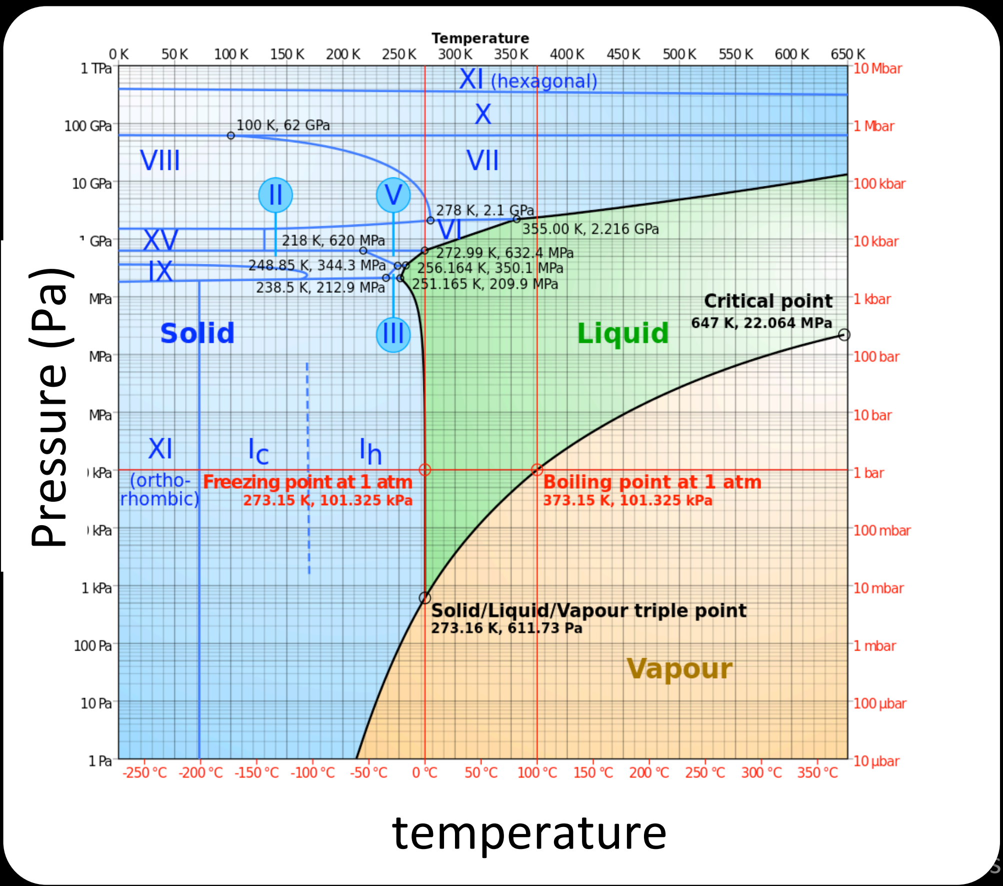
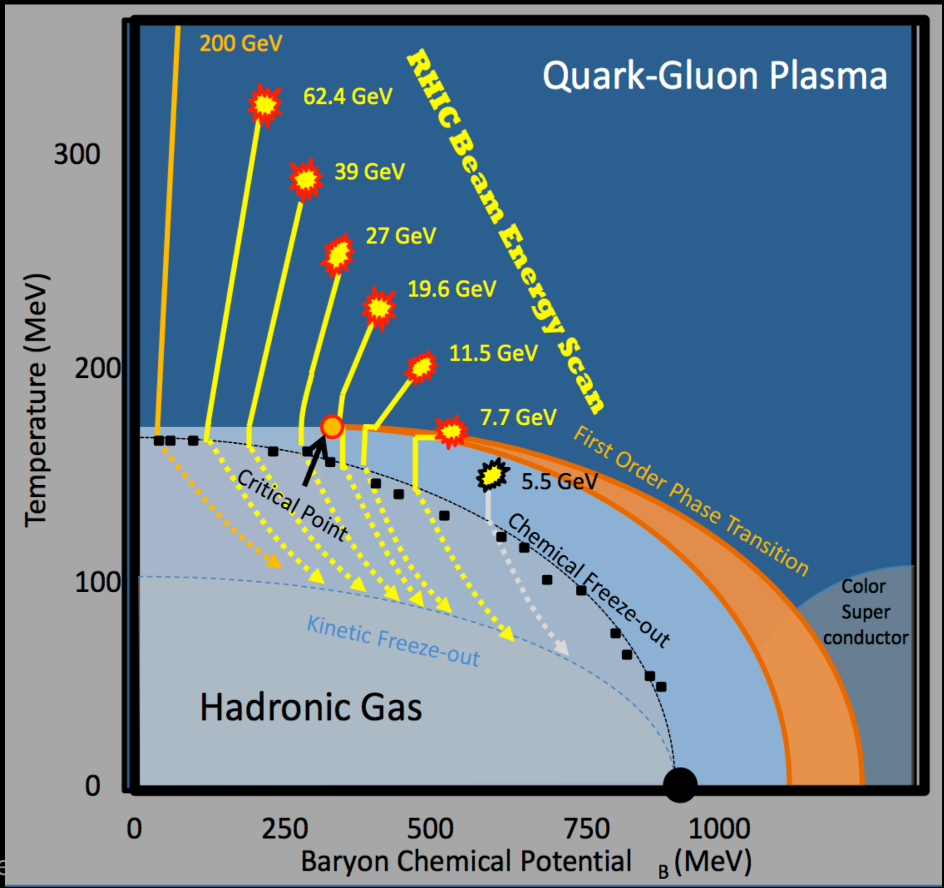
  - a condensed matter approach to the partonic condensed matter system → vary μ_B and T by varying collision energy





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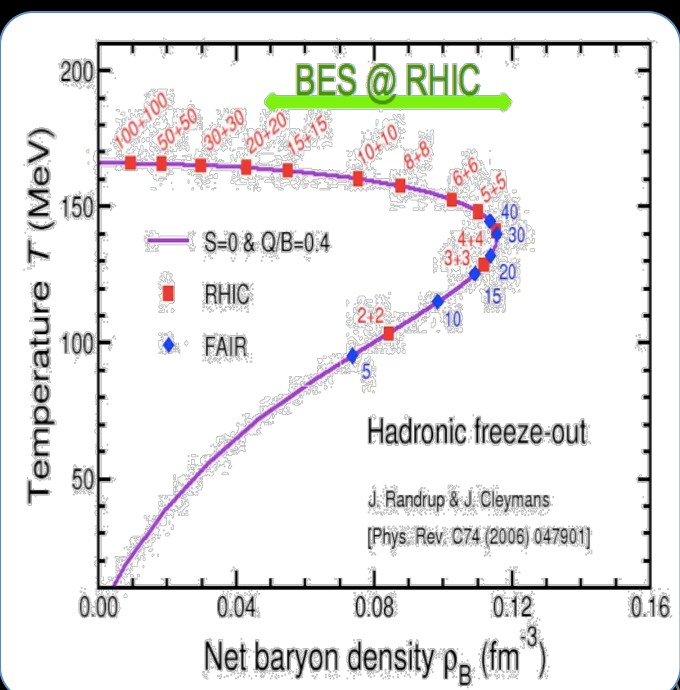
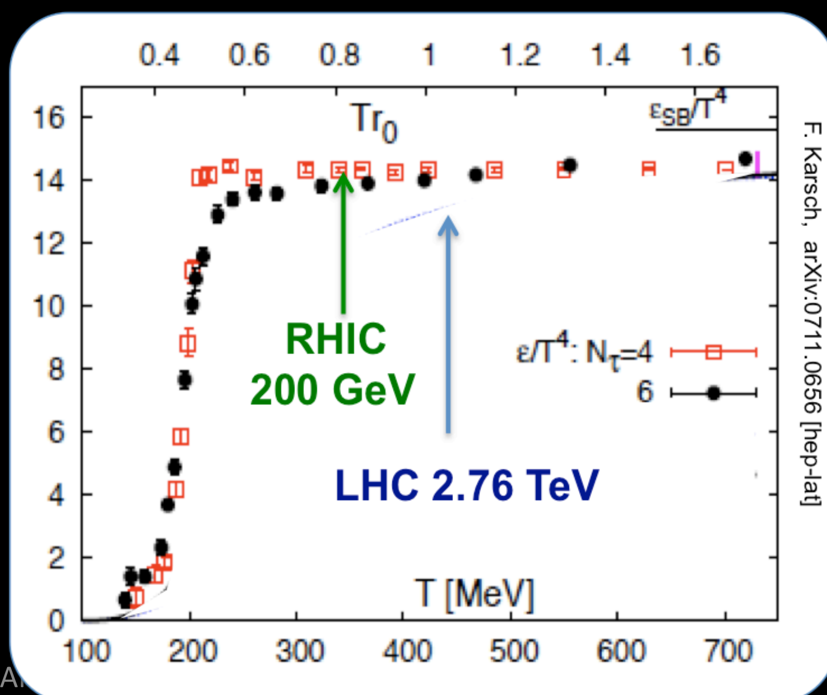
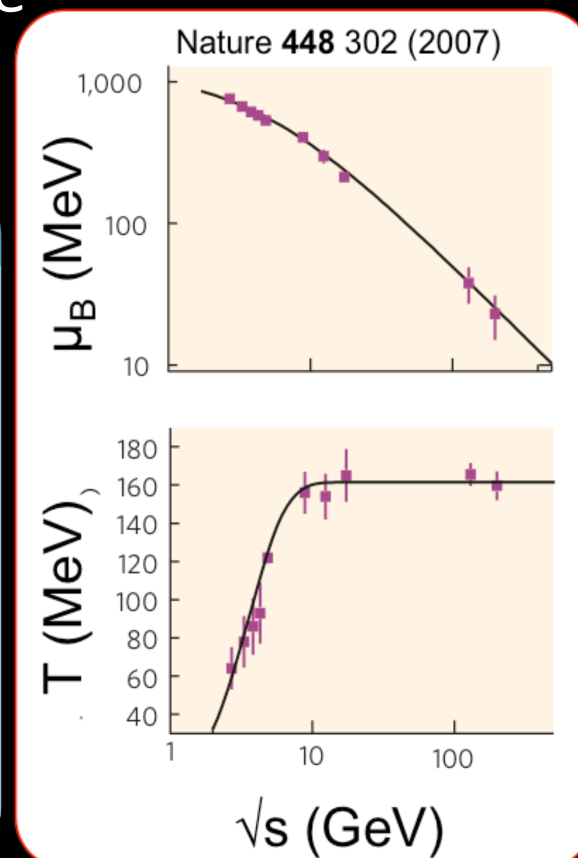
  - theory, models, data systematics: √s=5-50 GeV







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> <u>Condensed QCD Matter physics is not Energy Frontier Science</u>
>
> - Steve Vigdor, 2012

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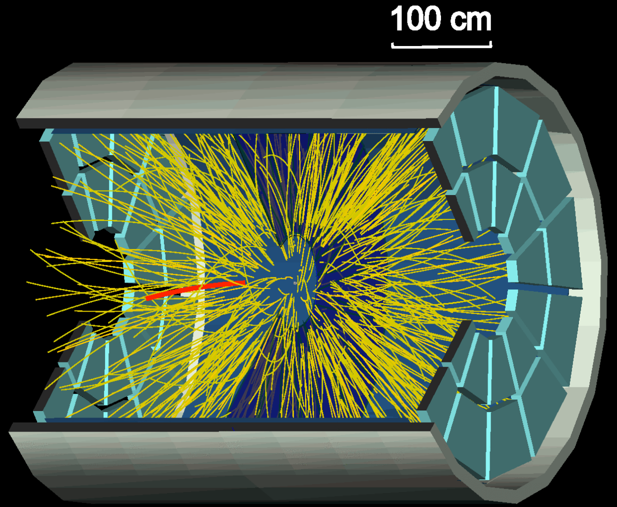
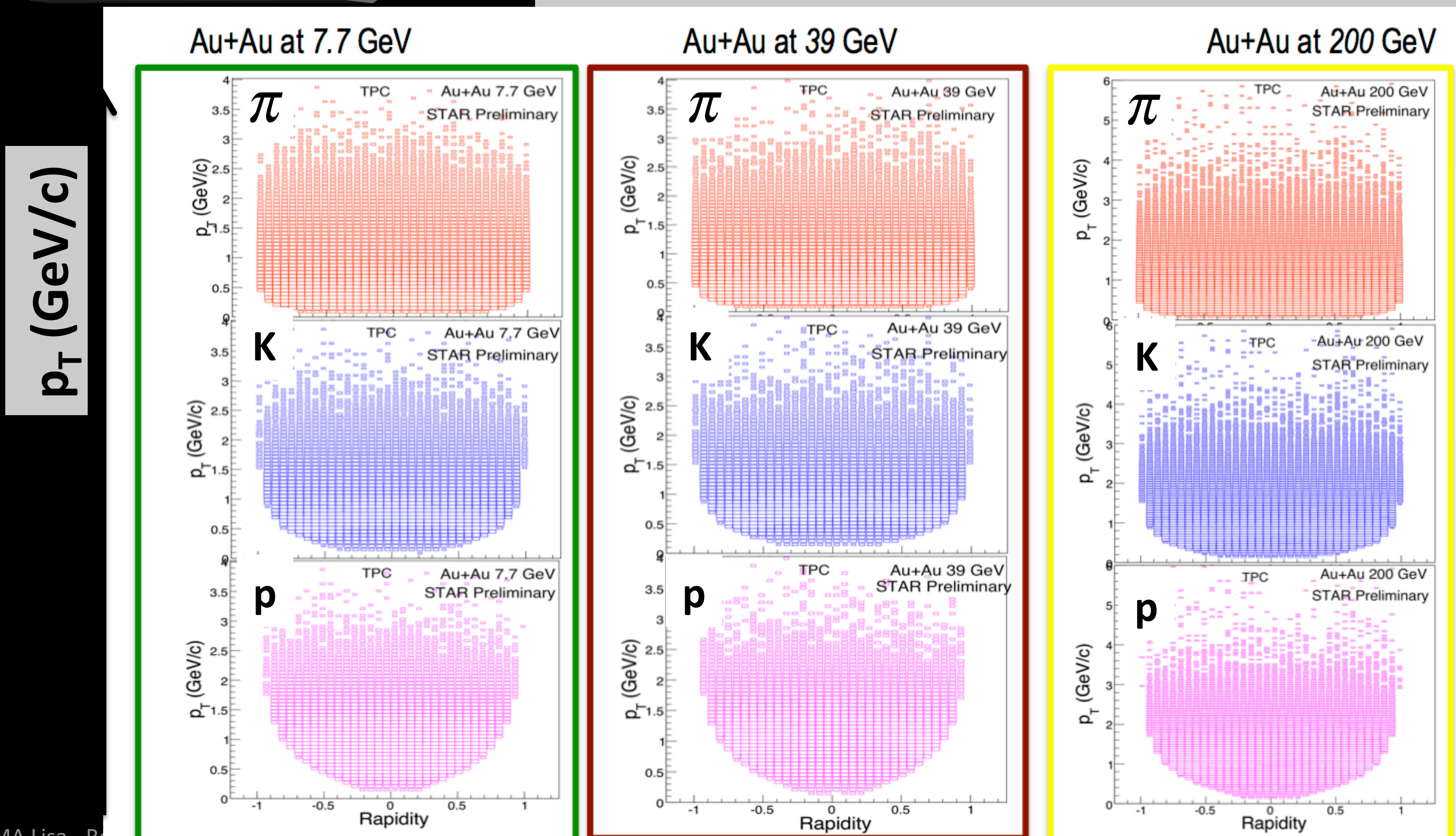
> If RHIC did not exist, we would have to build it
> - Berndt Mueller, 2012



TOF and TPC

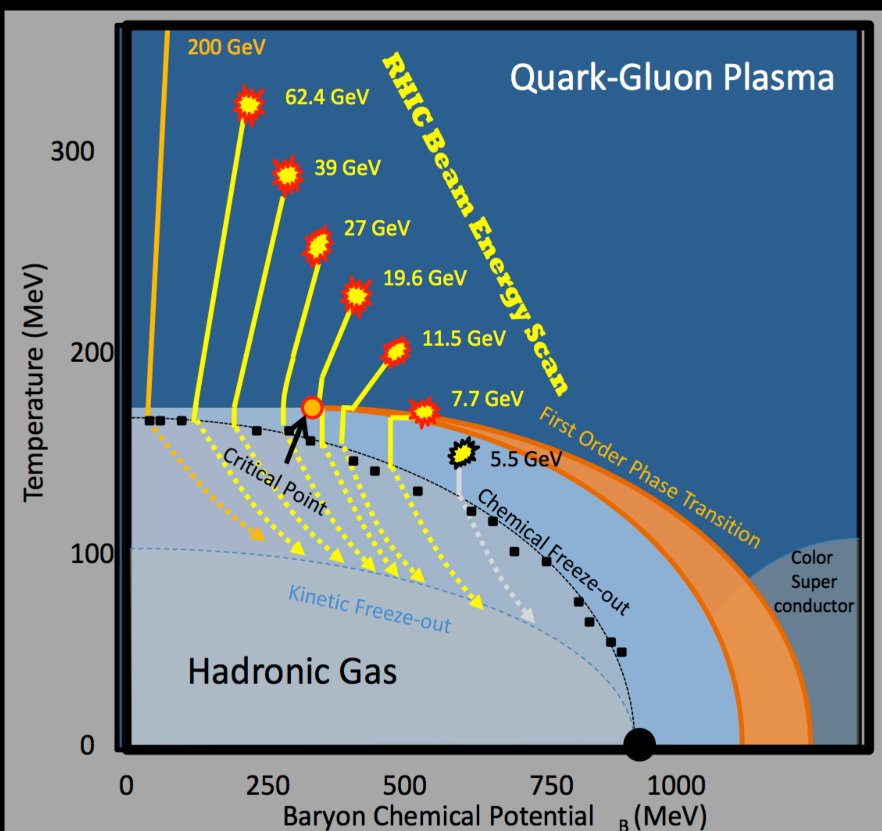
- clean separation of pi/K to pT~1.6 GeV
- full azimuthal coverage
- |η|<1
- topological/combinatoric reconstruction of weak decays
- acceptance independent of collision energy (important!)



G. Odyniec, SQM 2011

RHIC BES Phase I

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



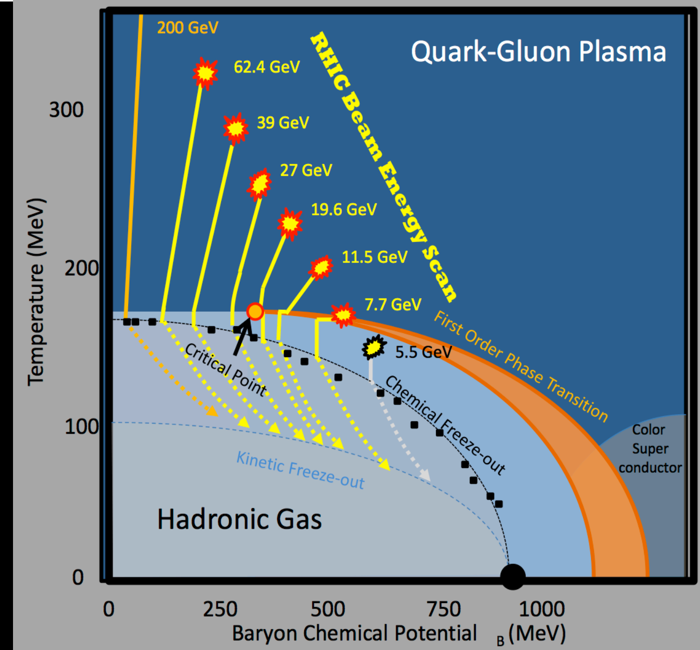
0) location on the phase diagram?
1) sQGP signatures turn off/on?
2) evidence of mixed phase?
3) critical fluctuations?

theory feedback & questions for further exploration

year	$\sqrt{s_{NN}}$ (GeV)	mb events ($x10^6$)
2010	7.7	5
2011	11.5	12
2011	19.6	36
2010	27	70
2010	39	130

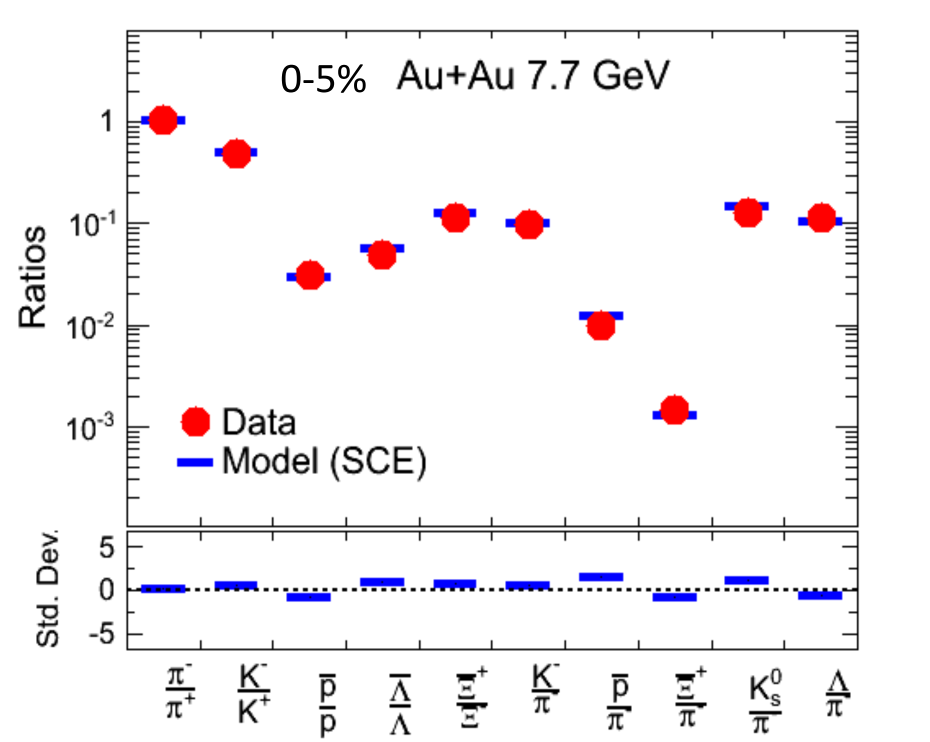
Step 0: location on the phase diagram

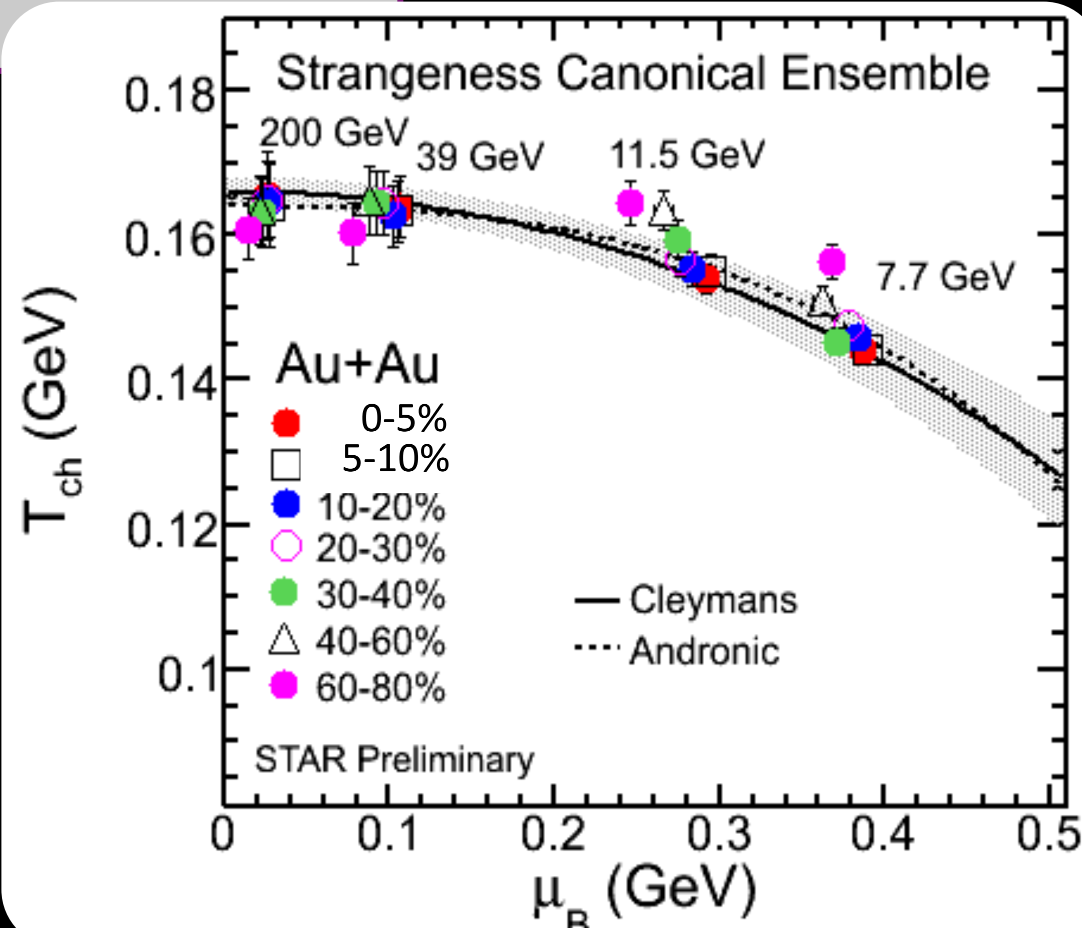
- Fits to particle yields reveals chemical *freeze-out* location



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

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





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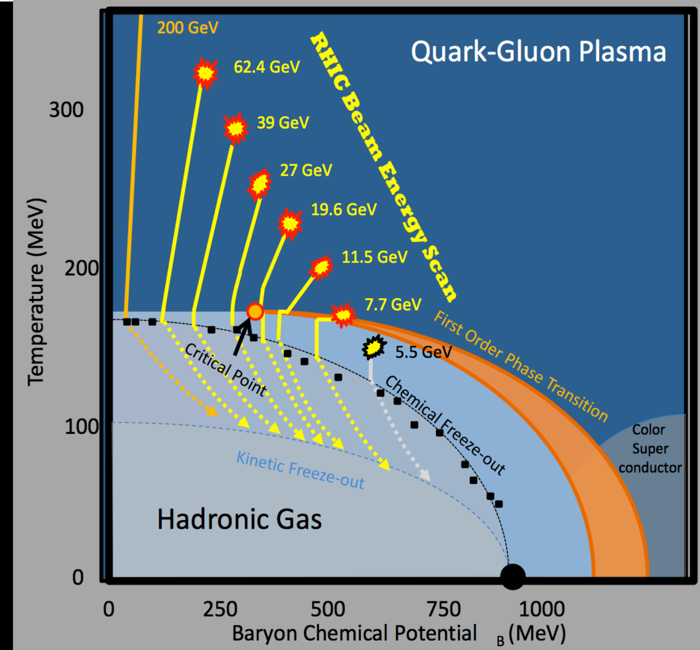
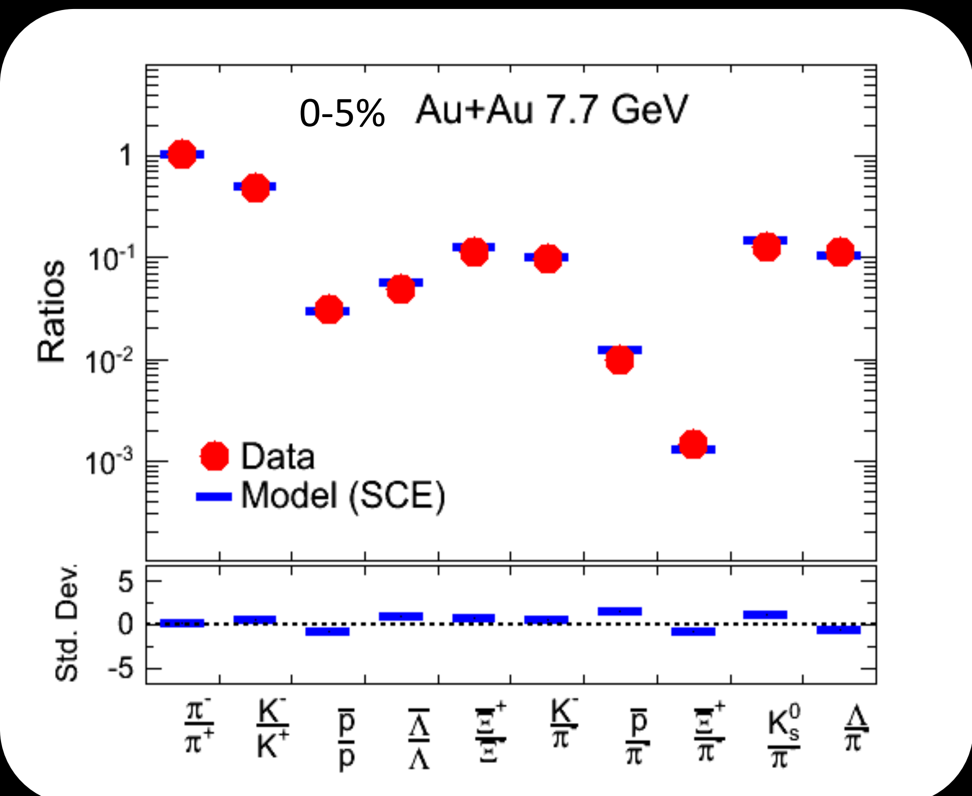
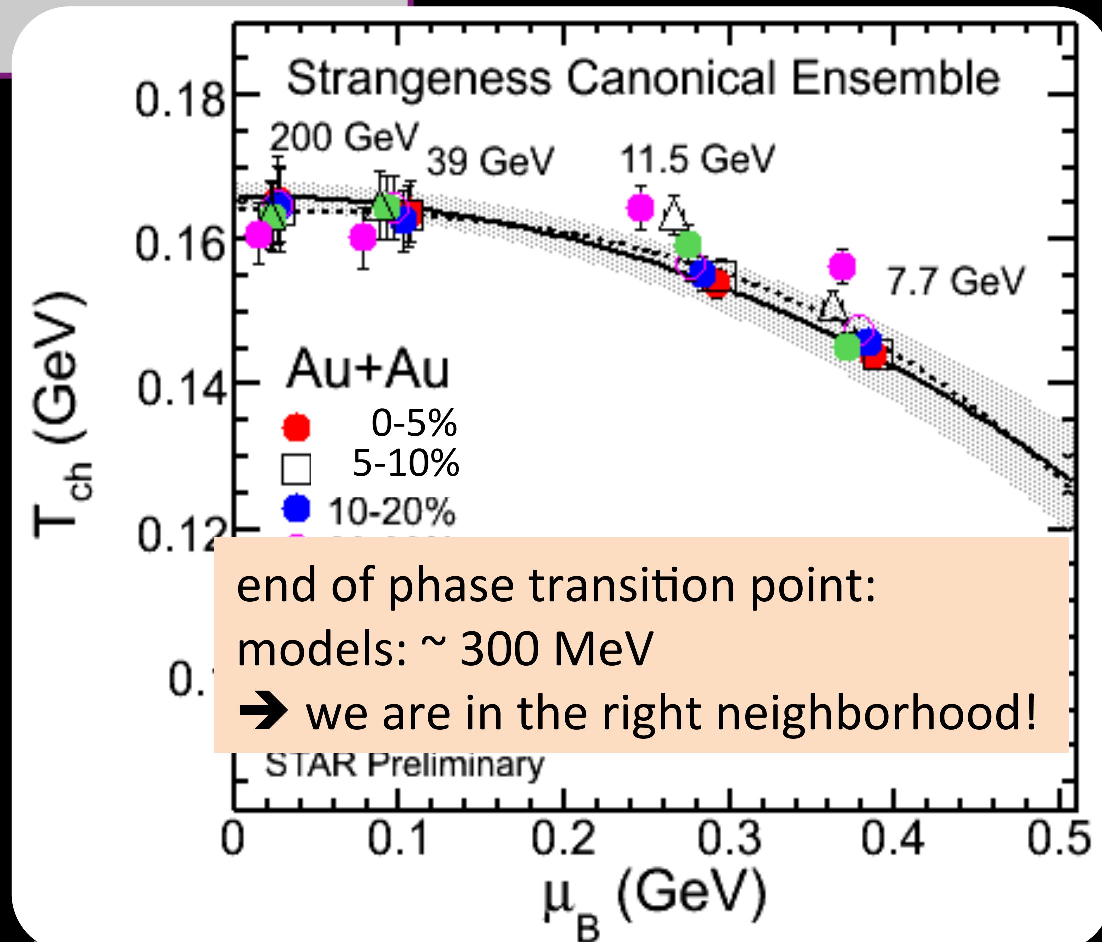


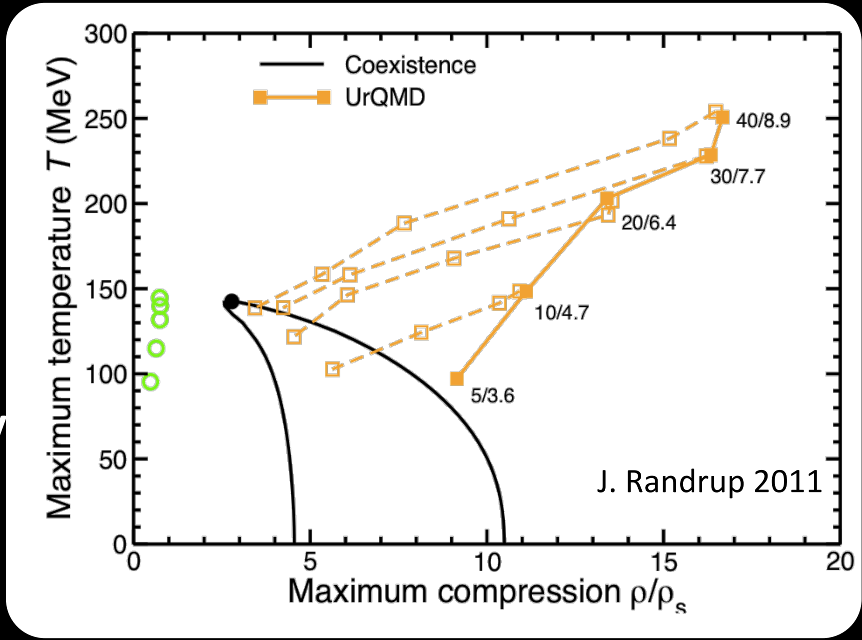


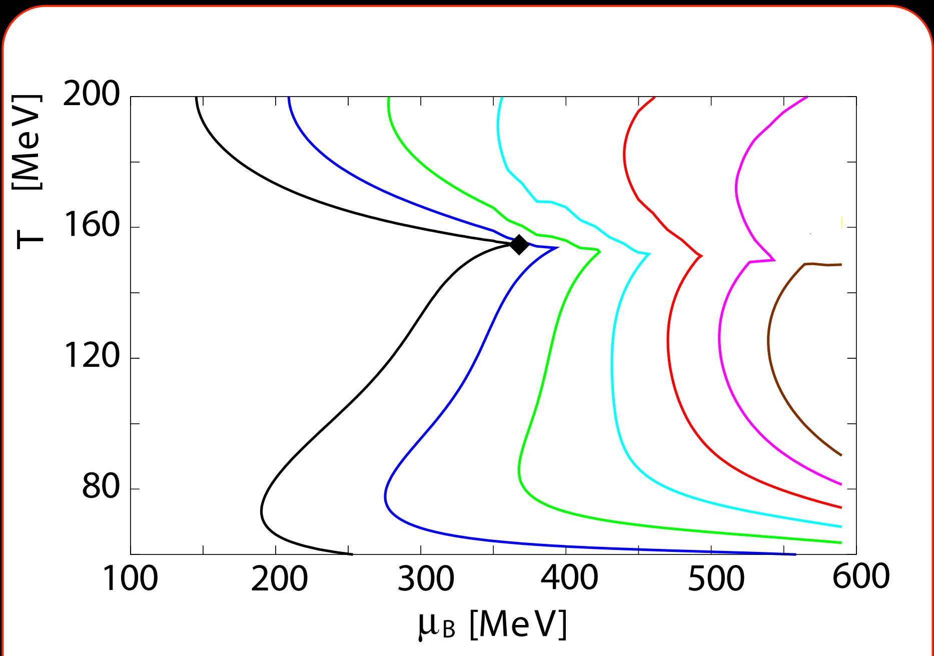


end of phase transition point:
models: ~ 300 MeV
➔ we are in the right neighborhood!

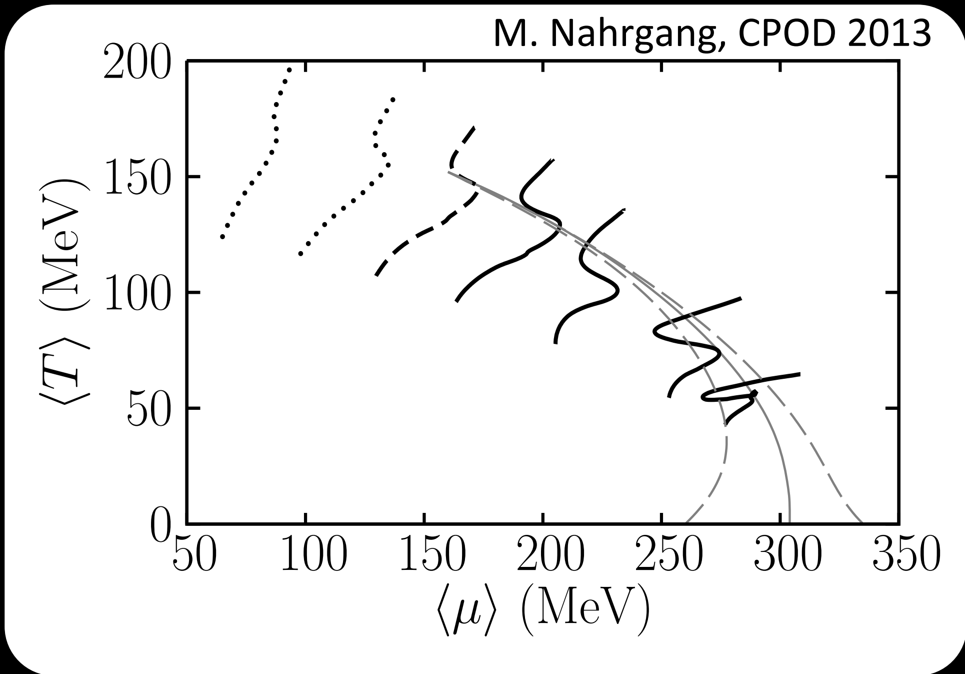
Step 0: location on the phase diagram

- Fits to particle yields reveals chemical *freeze-out* location
  - experimental anchor
- Rely on dynamic models for trajectory





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



Next step: Is the QGP "turning off?"

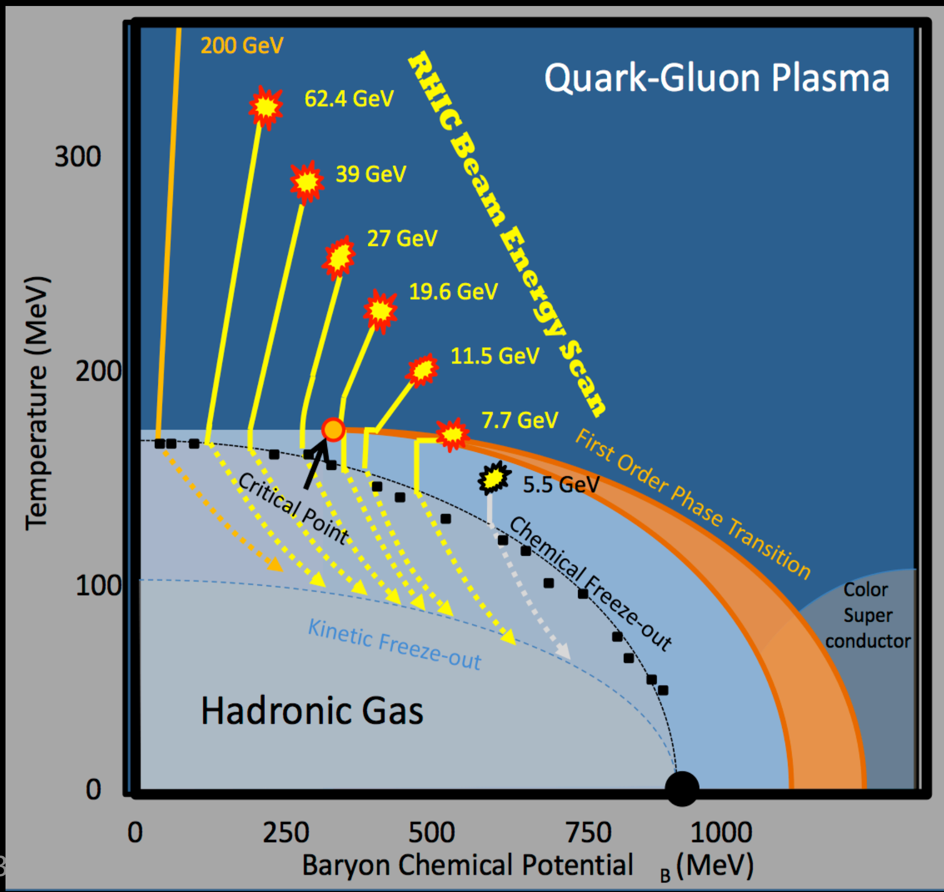
Evidence for a QGP at top RHIC energy (and above):

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

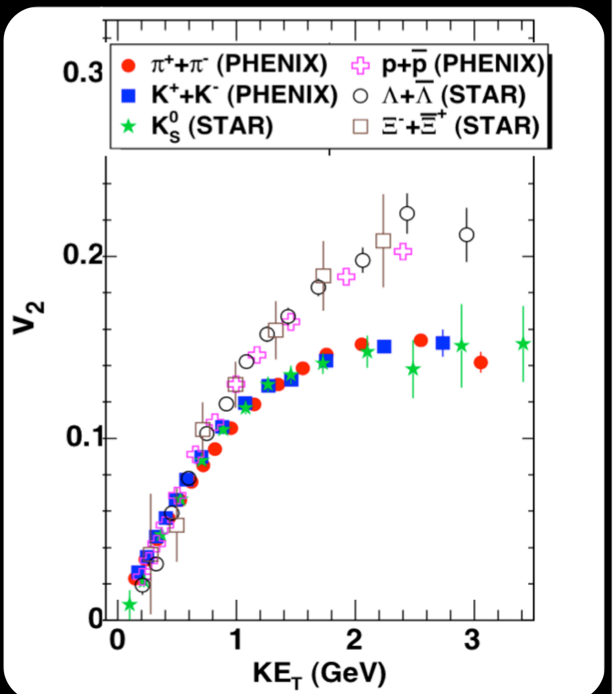
Nu: Looks like...

Paul: But...

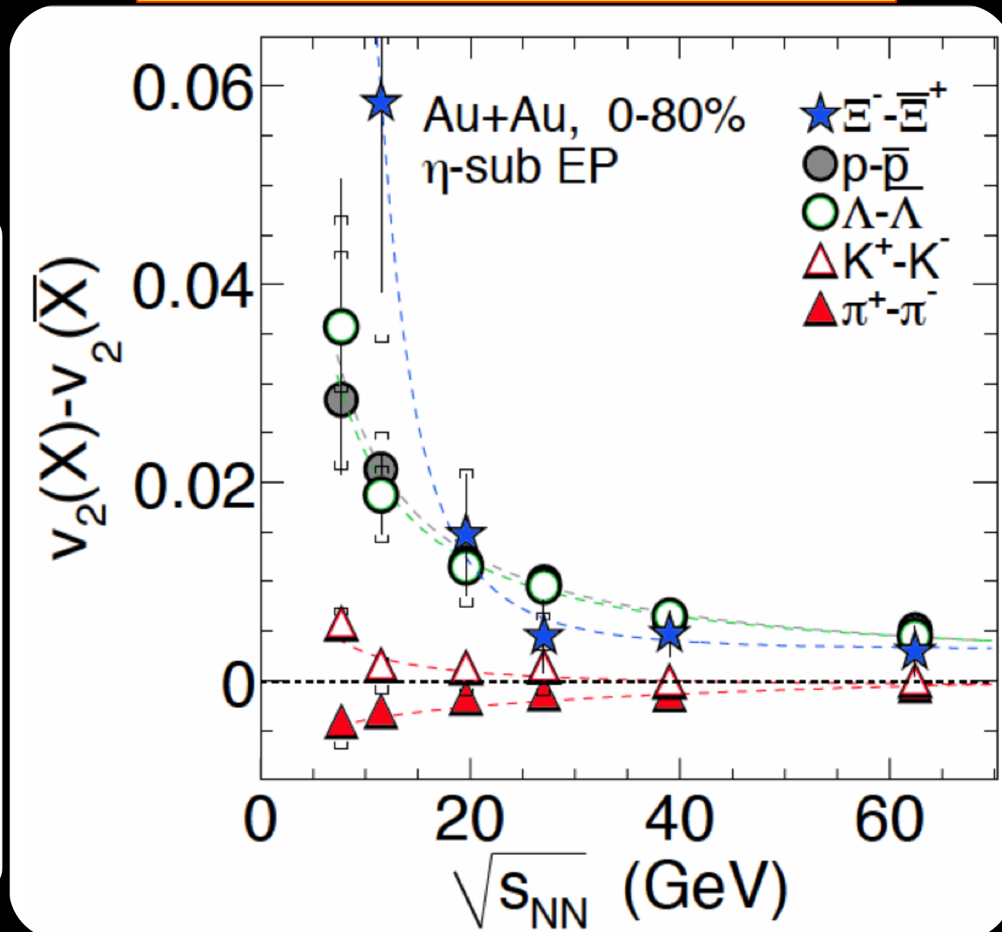
Me: a few words

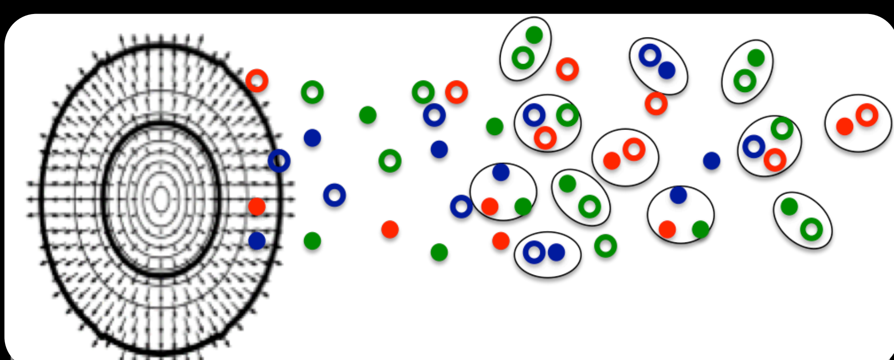


NCQ scaling



particle minus antiparticle v2





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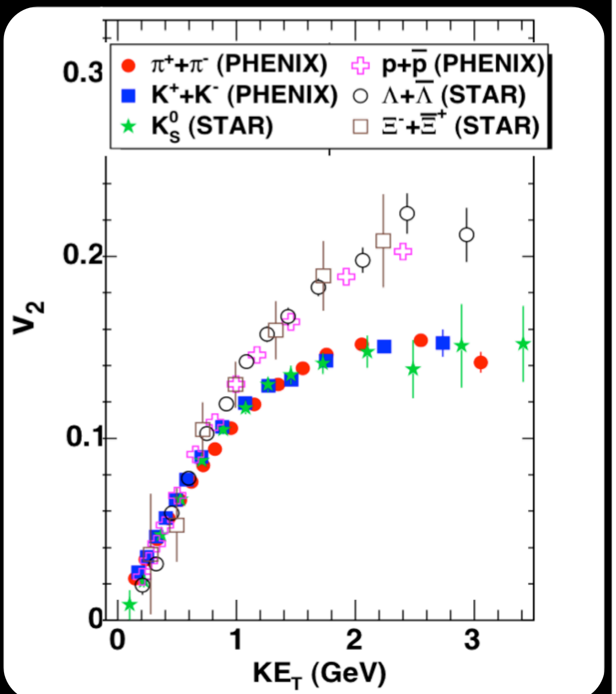

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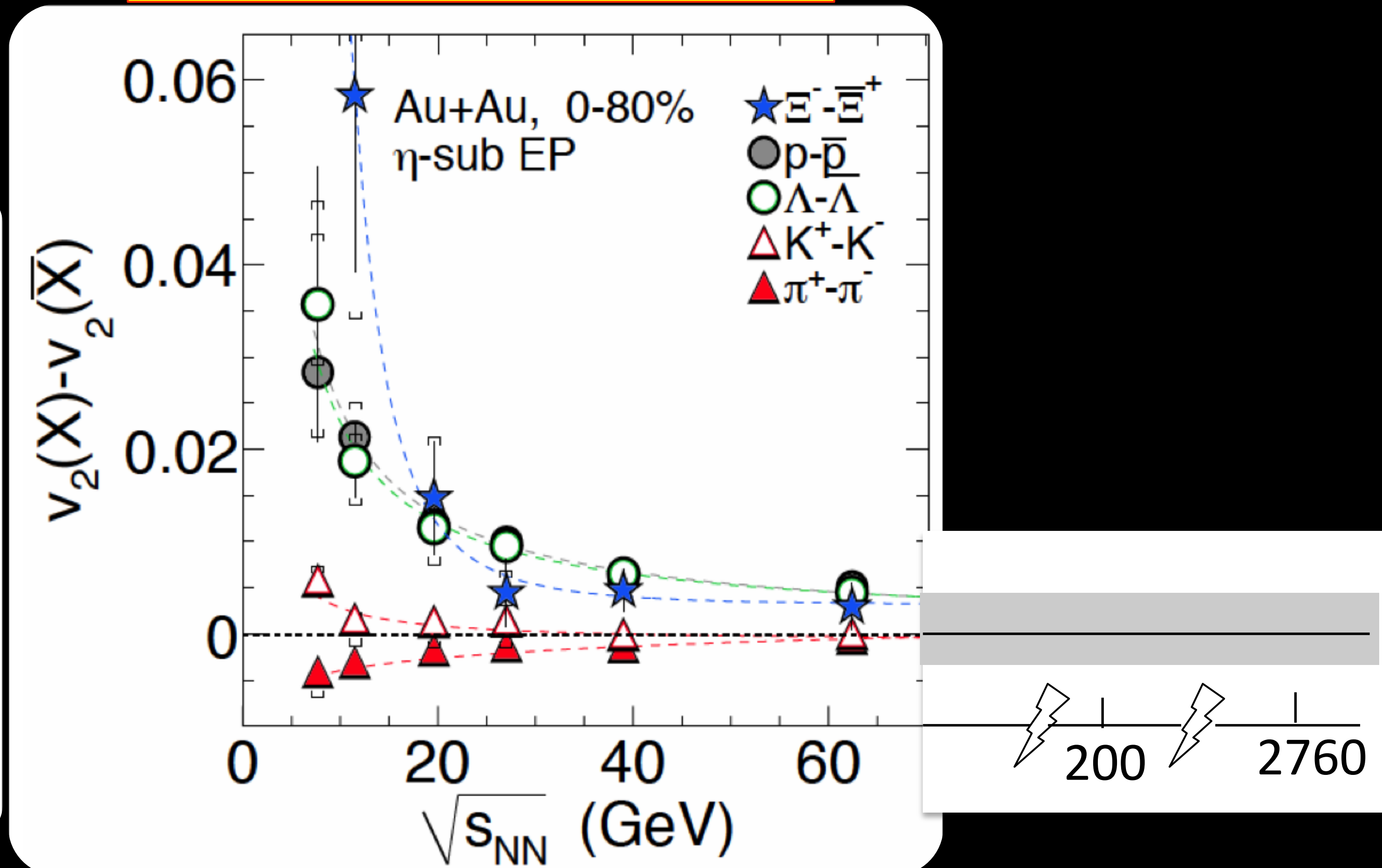
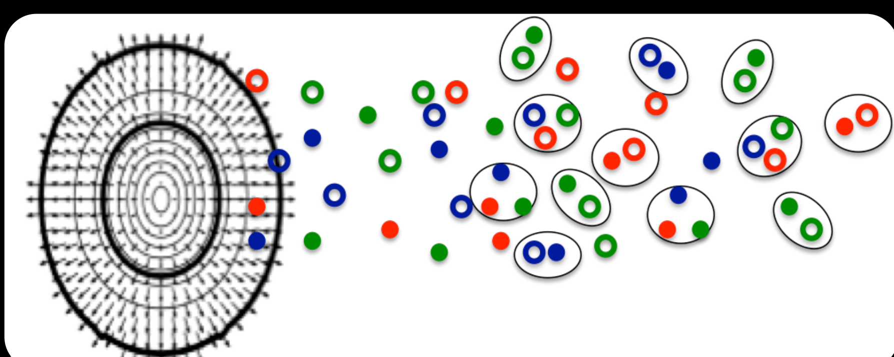
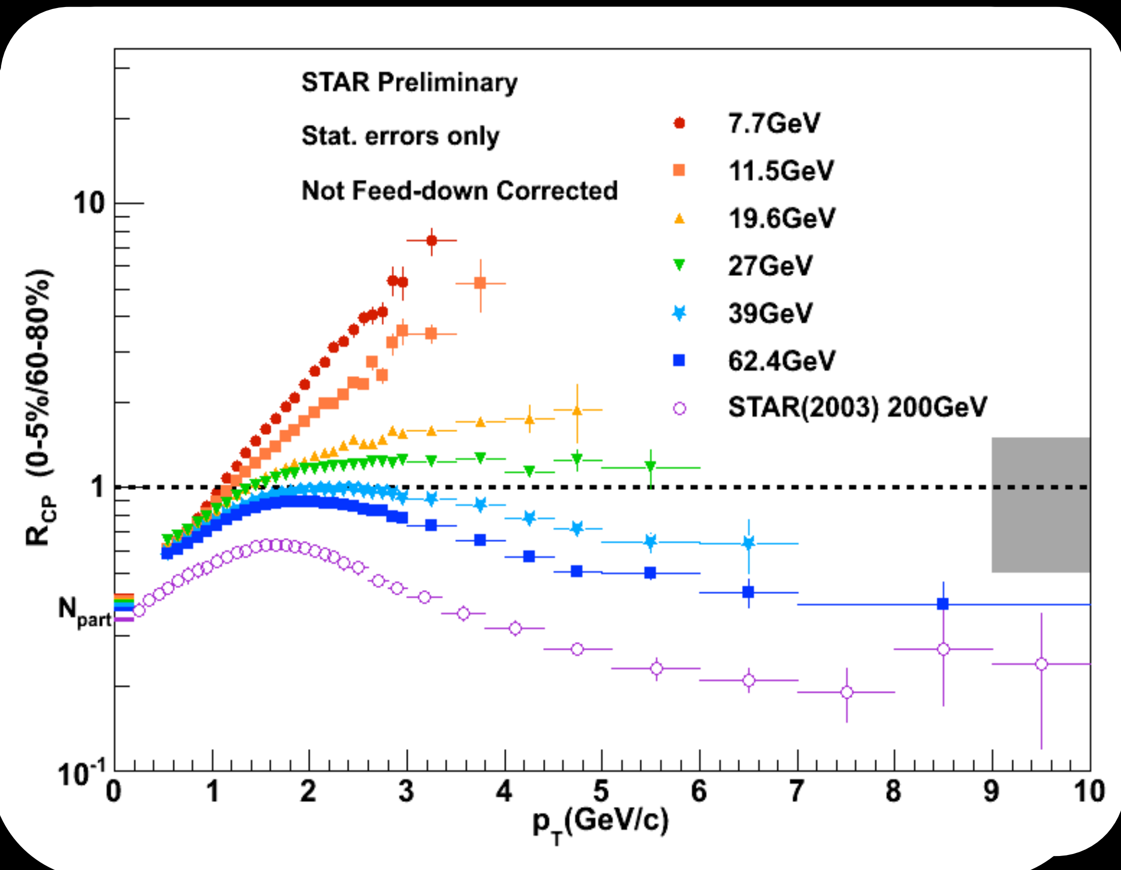




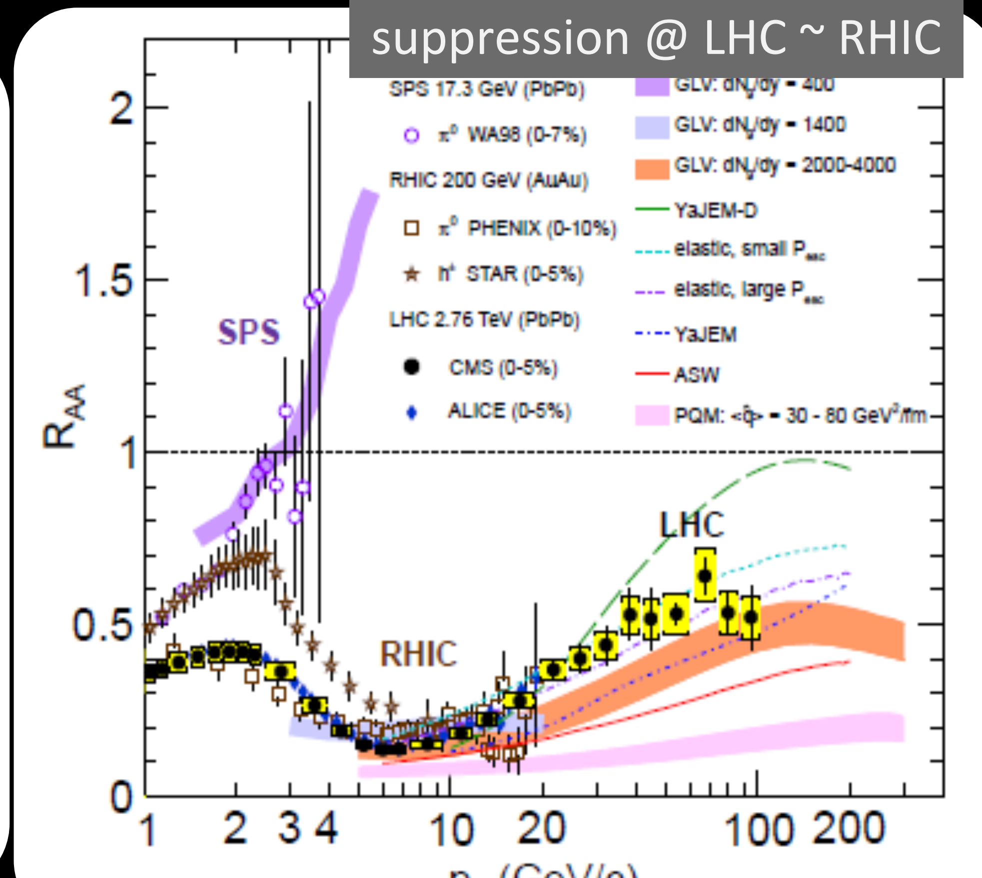
The action is below 39 GeV

Suppression of high-pT hadrons

a measure of the opaqueness of the QGP



suppression @ LHC ~ RHIC



EPJ. C72 (2012) 1945

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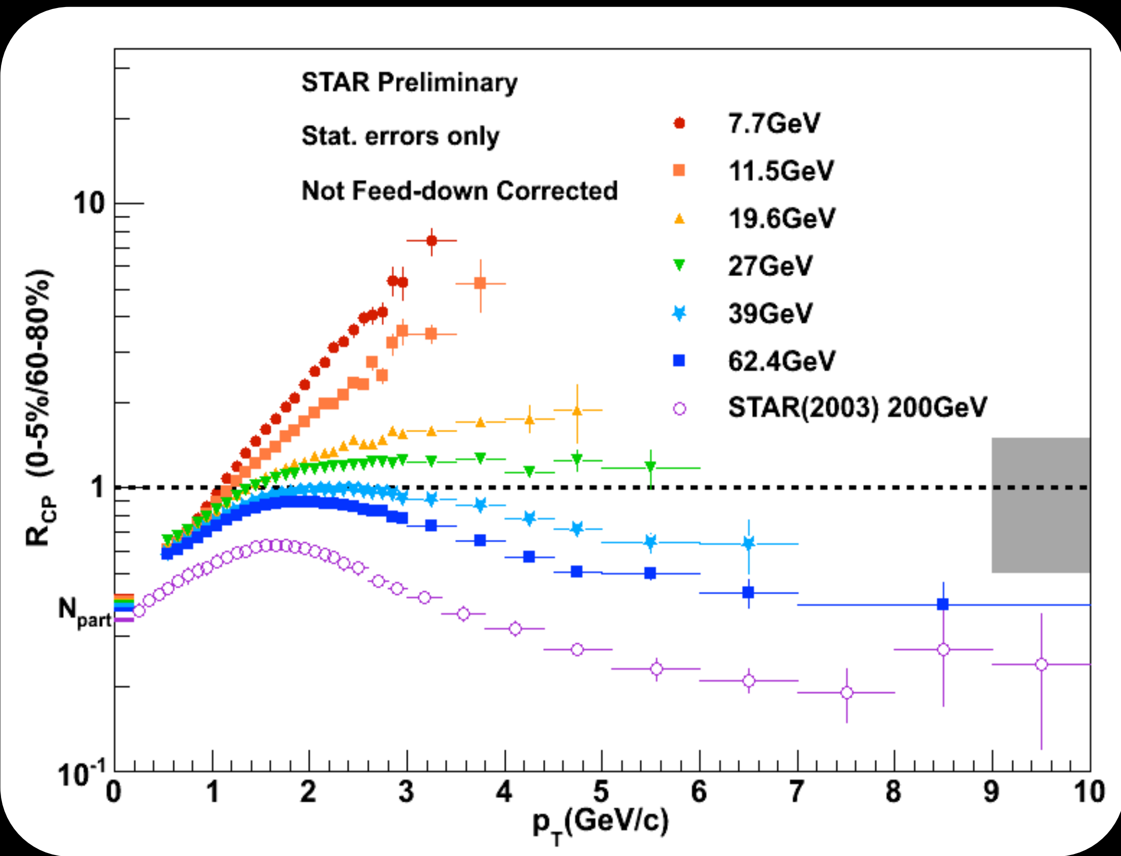
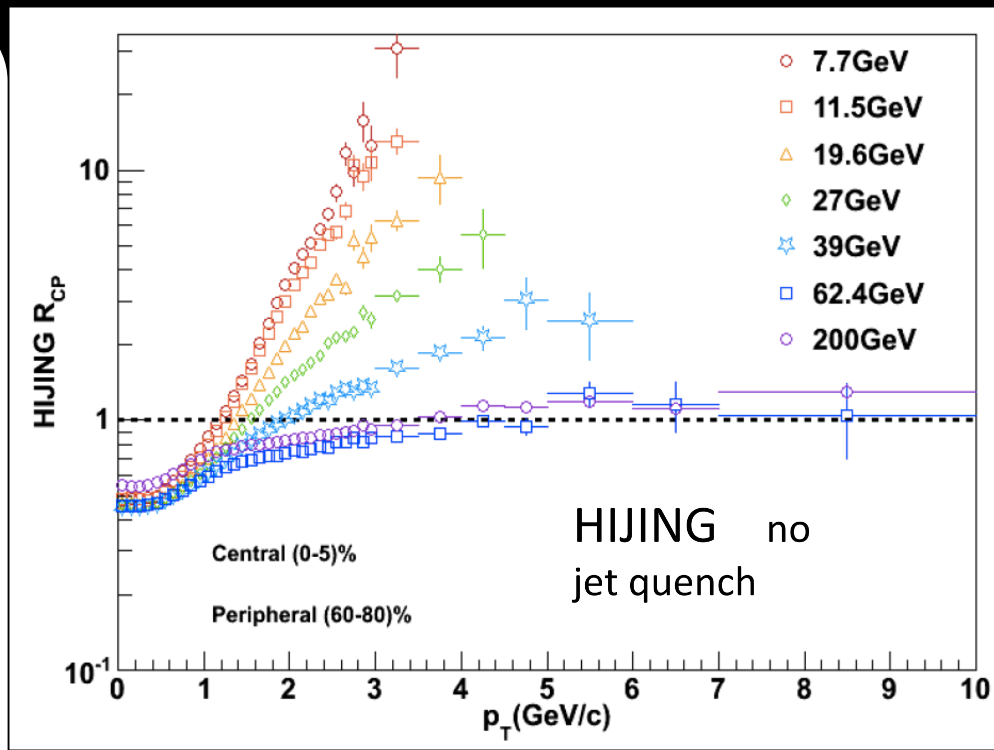
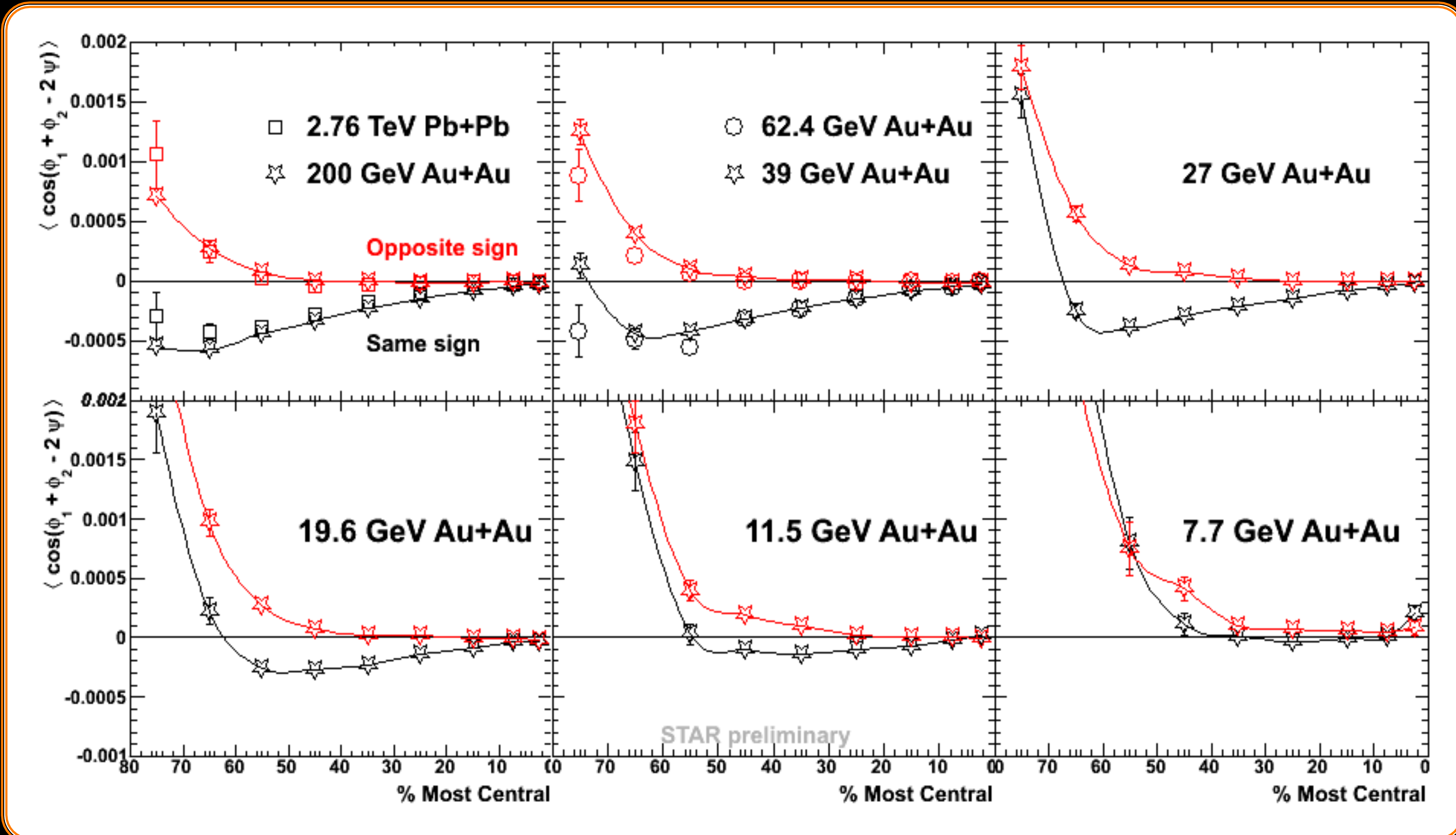
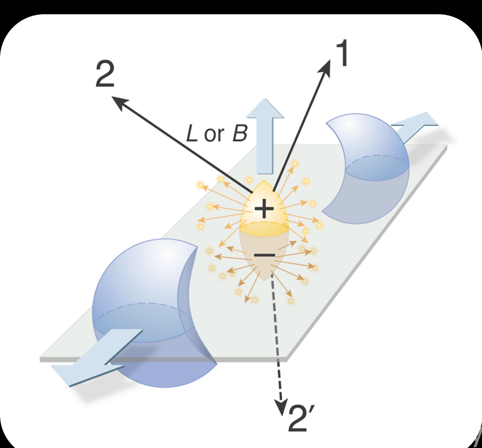




suppression comes on strong around 20 GeV

Charge-separation correlations





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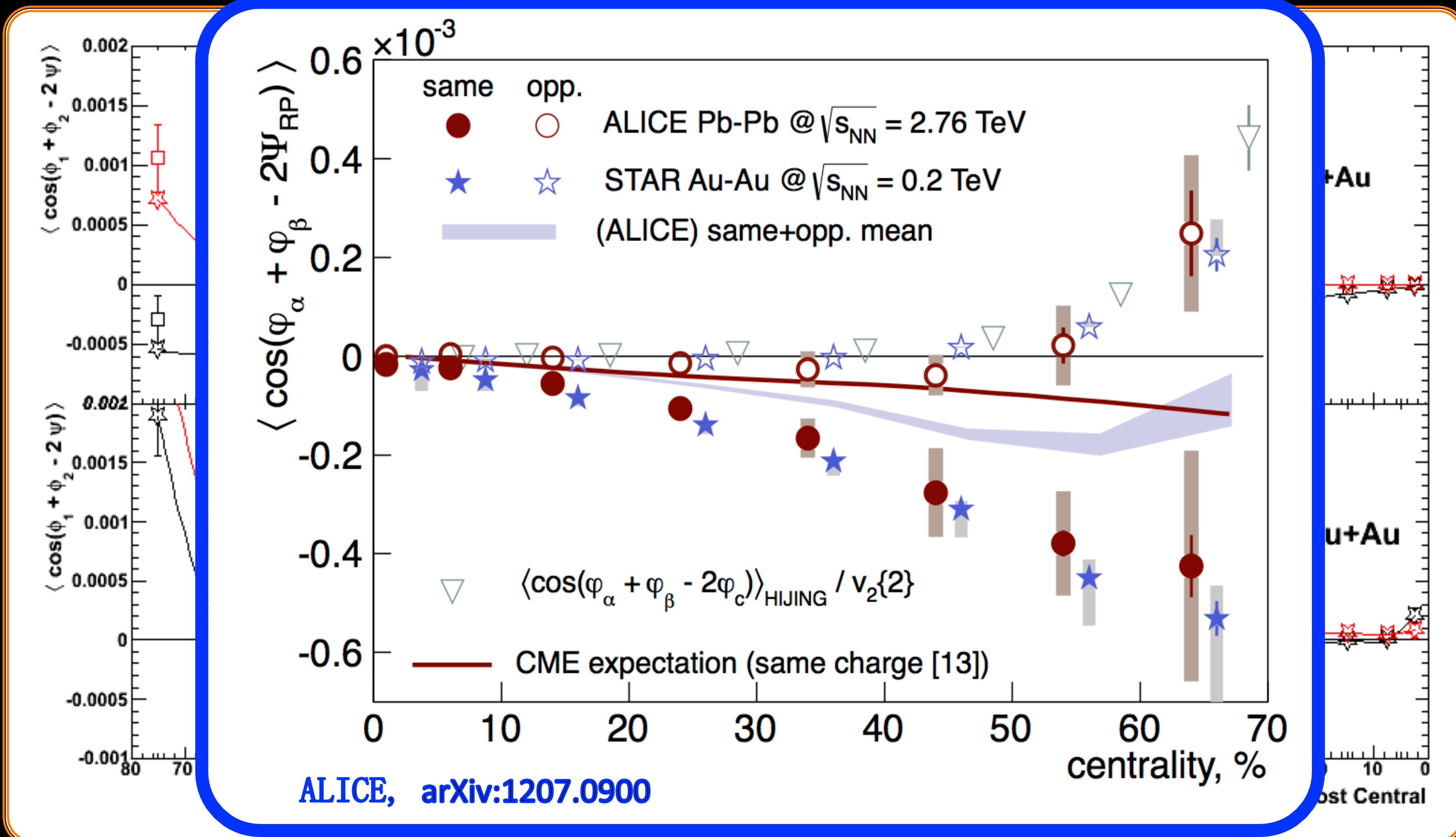
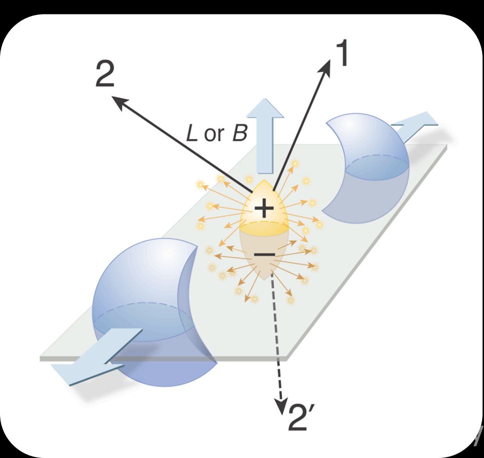




LHC astonishingly similar to RHIC

The action is below 39 GeV

So... the action is at $\sqrt{s_{NN}}$~ 10-30 GeV

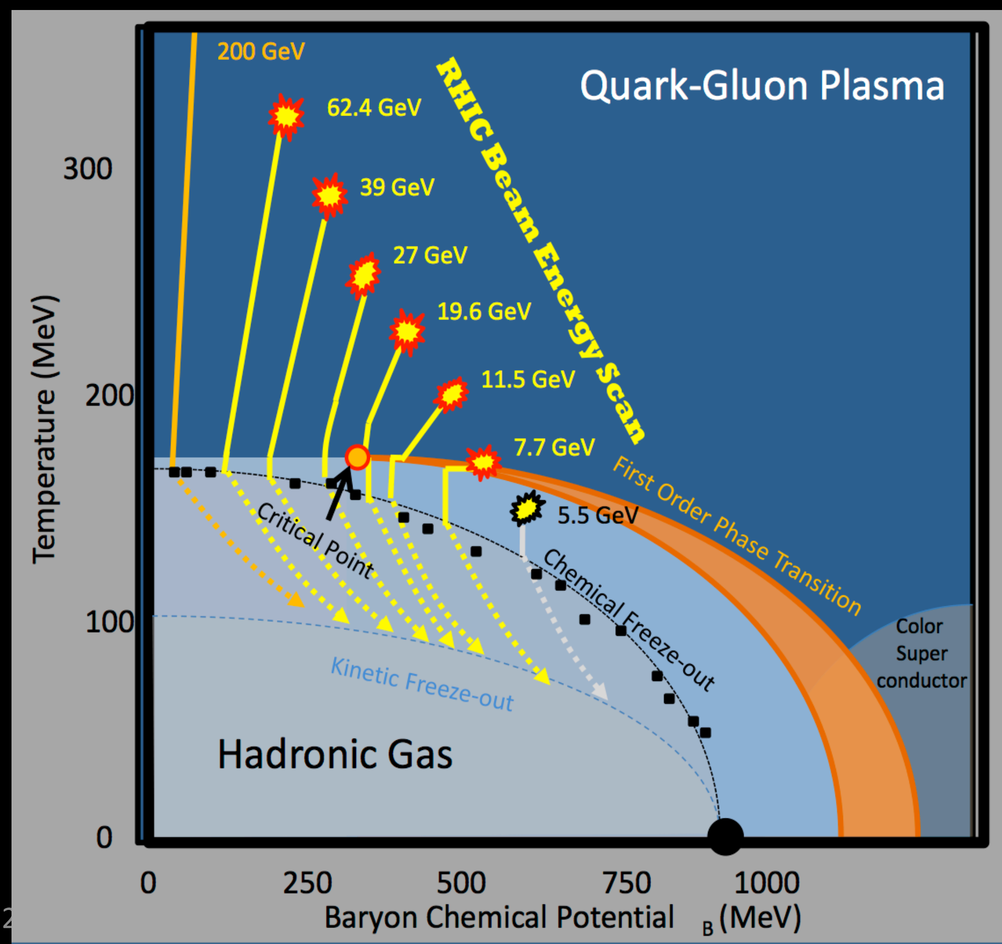
matter at lower energy...

- isn't (easily) characterized by flowing quarks
- is much less opaque to fast color
- does not support an EDM

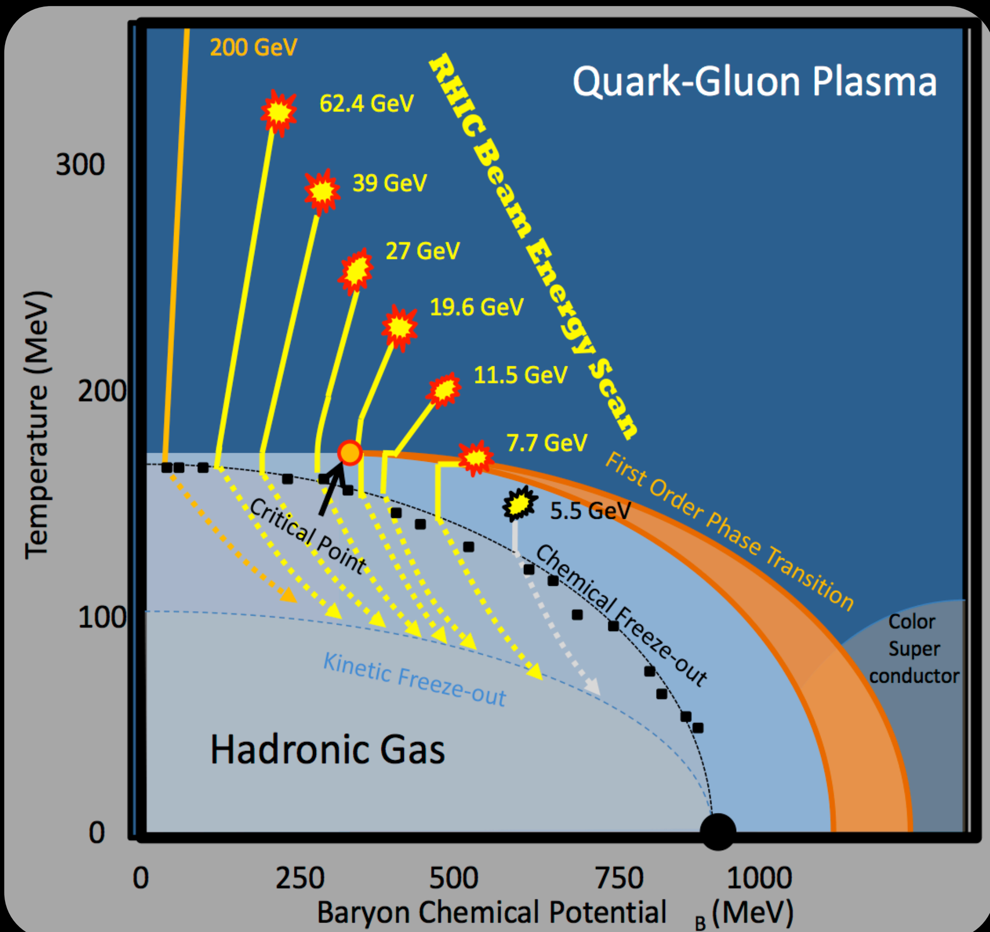
In this changing region:

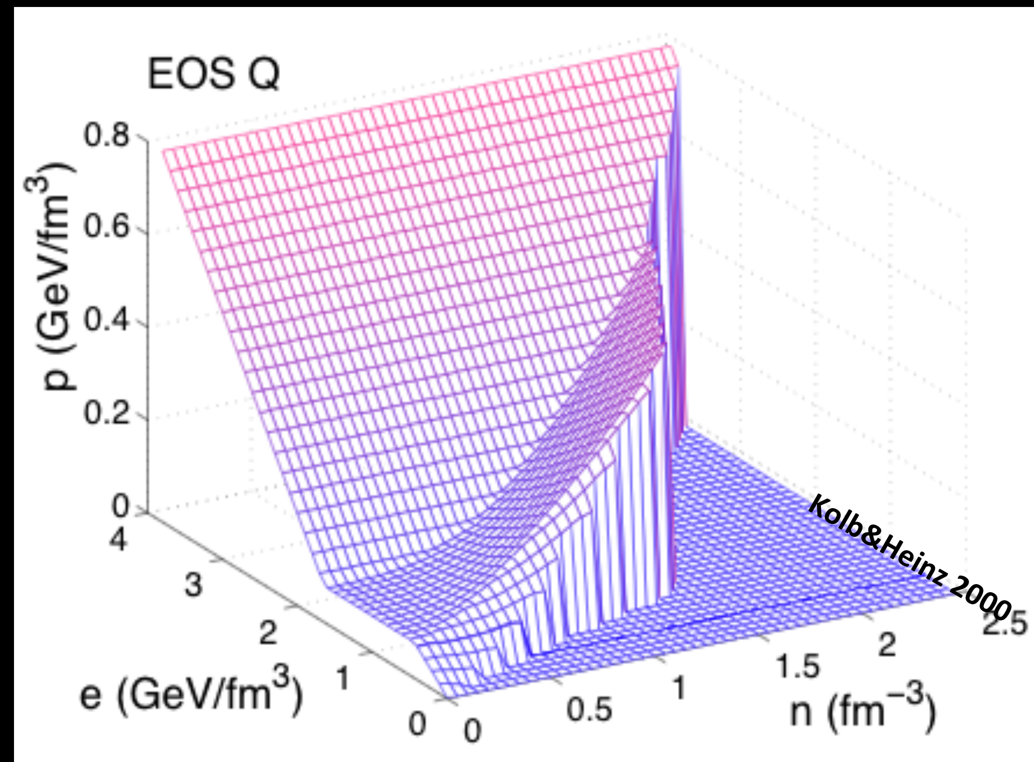
- evidence of 1st-order PT?

I'll just discuss a few of ~20 probes currently being studied



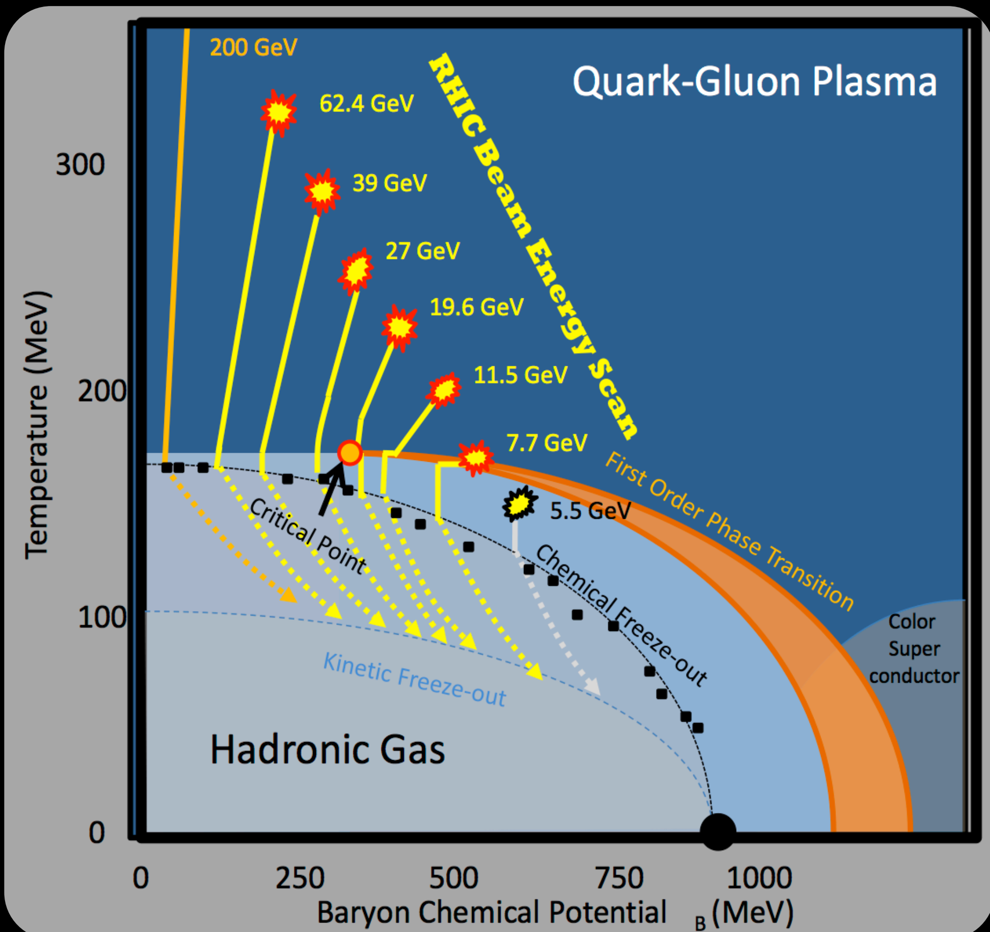
Is there a “soft region” in the QCD phase diagram?

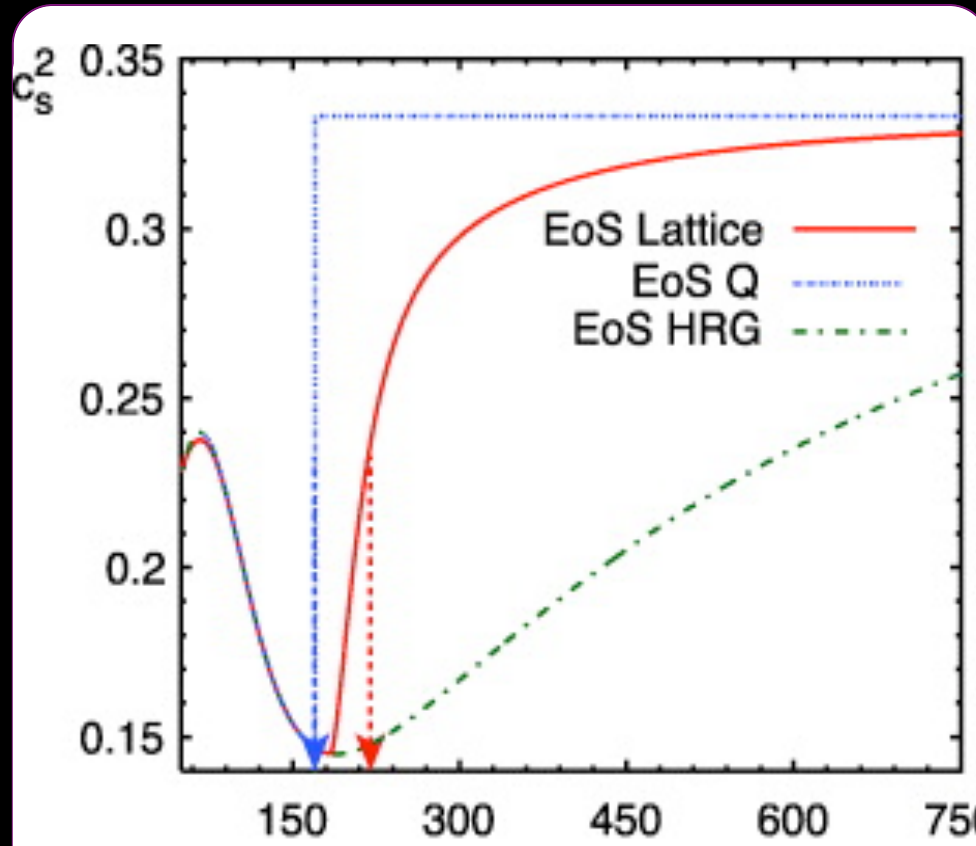




Is there a "soft region" in the QCD phase diagram?

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





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

low ("zero?") pressure – look at flow systematics

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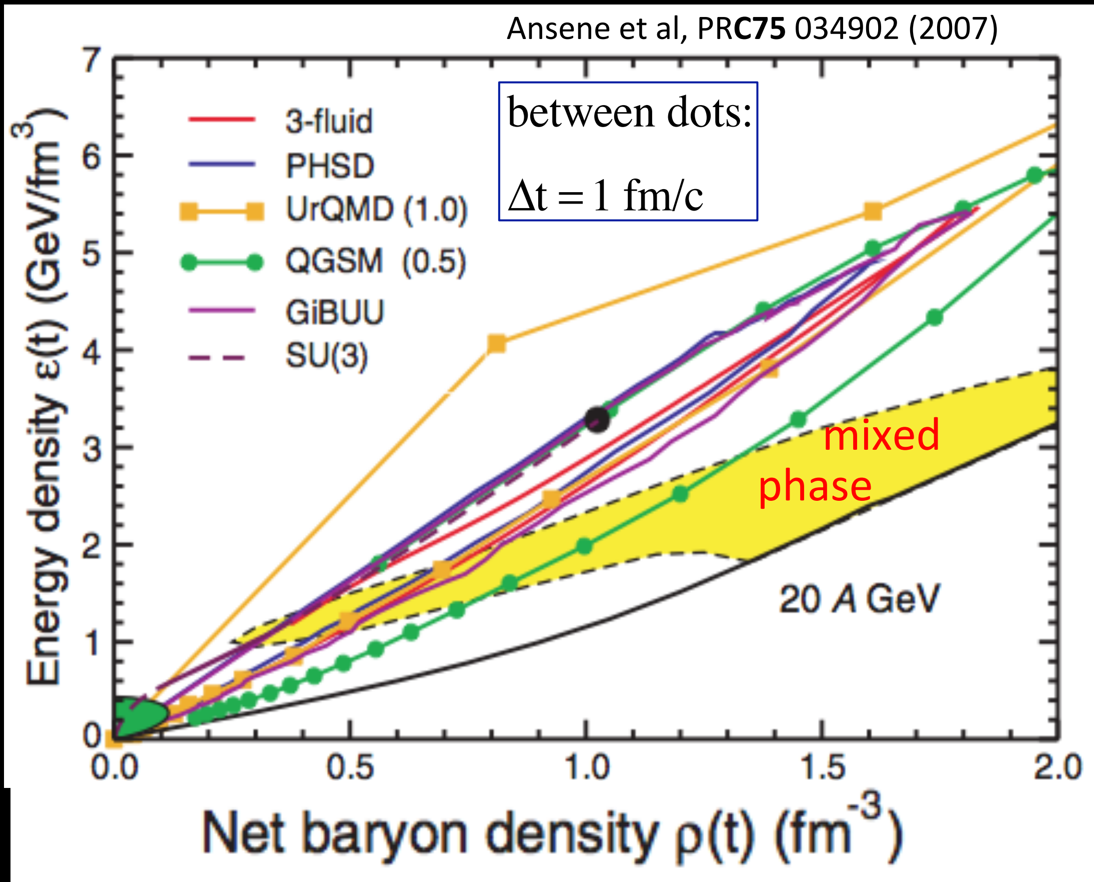
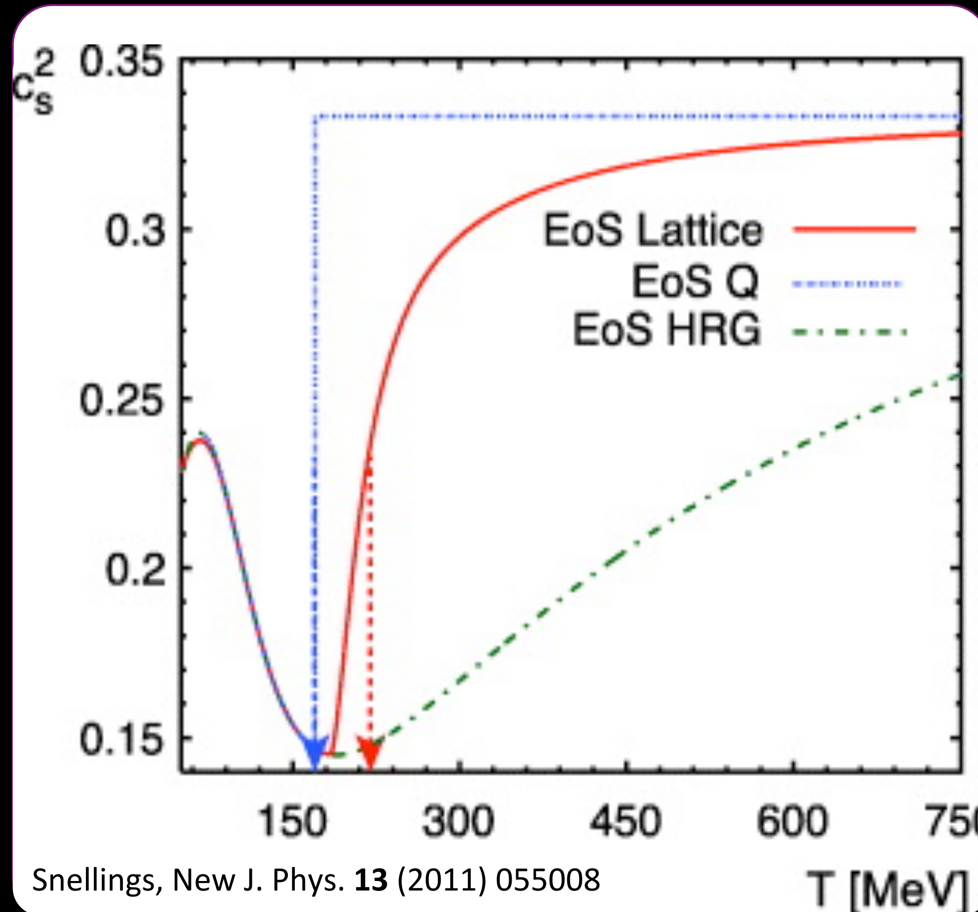




low ("zero?") pressure – look at flow systematics

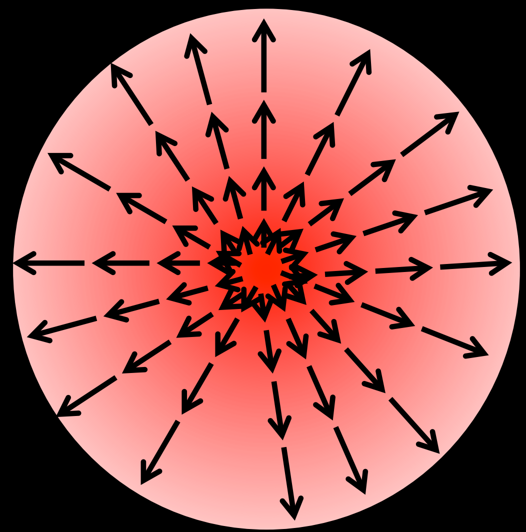
Beware: in mixed phase for short time.

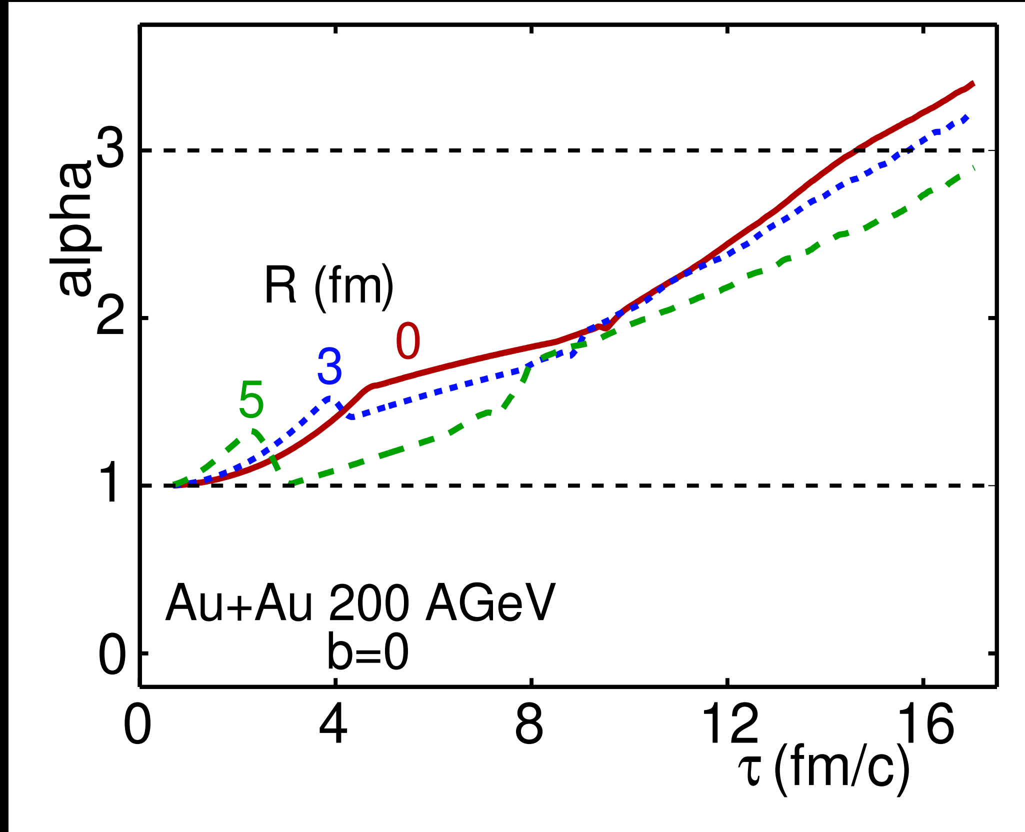
Will it "blast through" soft region?

SIGNALS

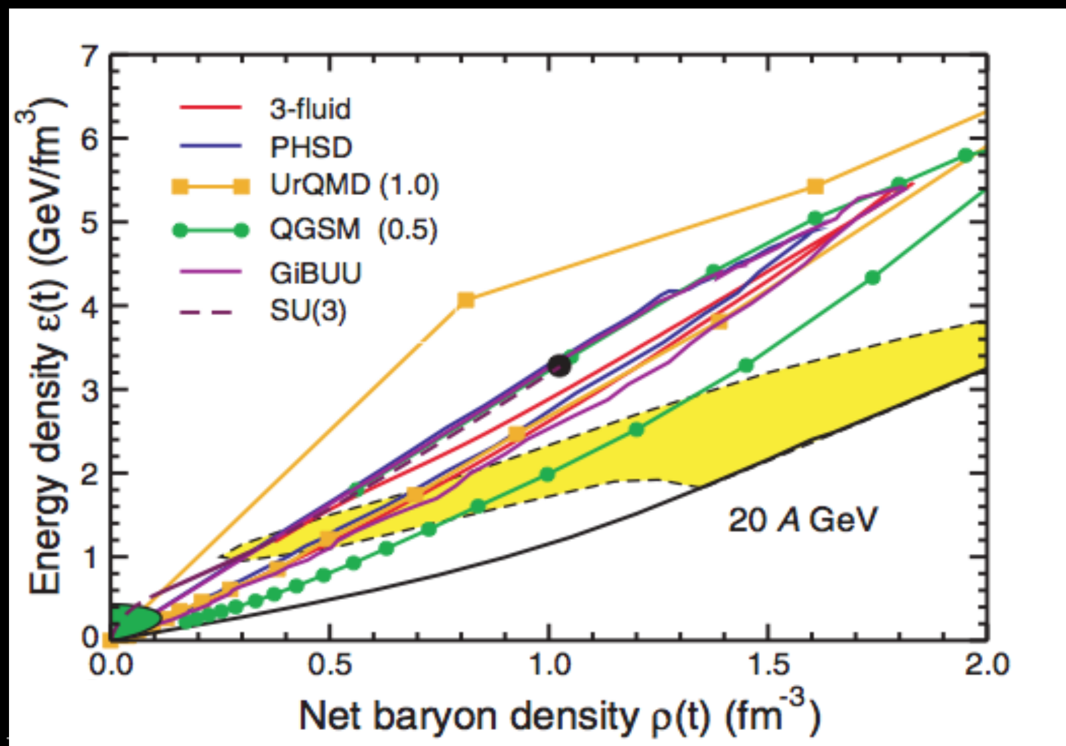
AZIMUTHALLY INTEGRATED

Radial flow





azimuthally-integrated flow strength
develops over entire collision history



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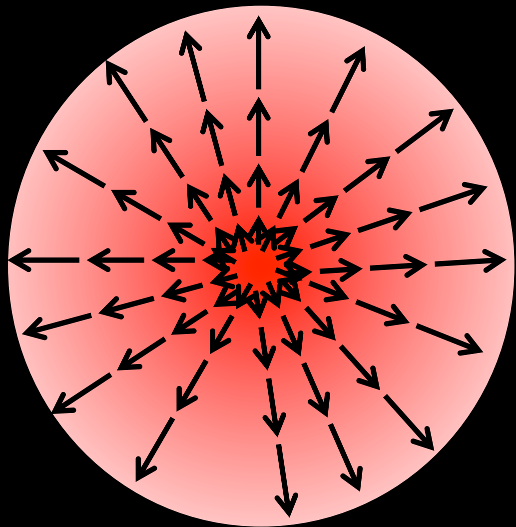

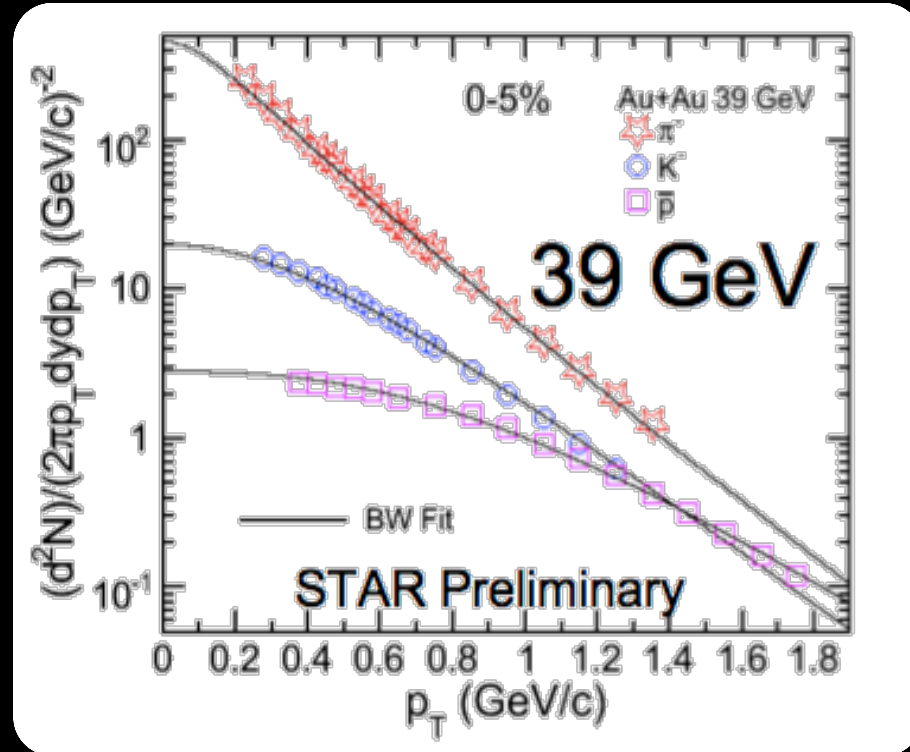

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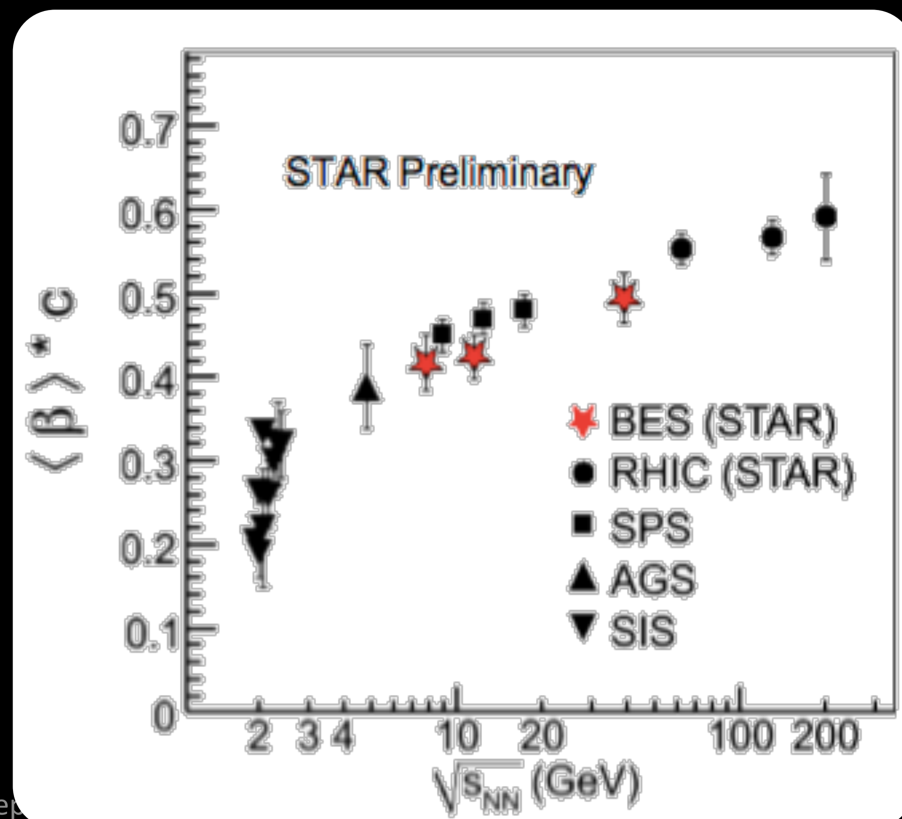
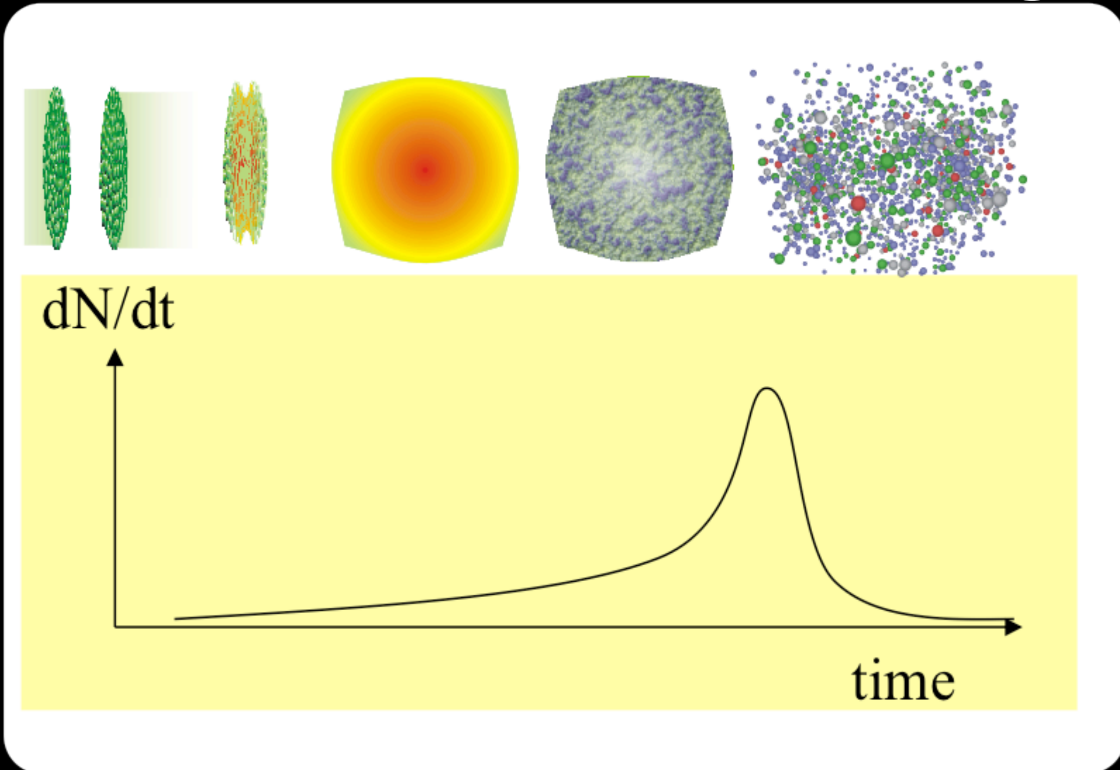
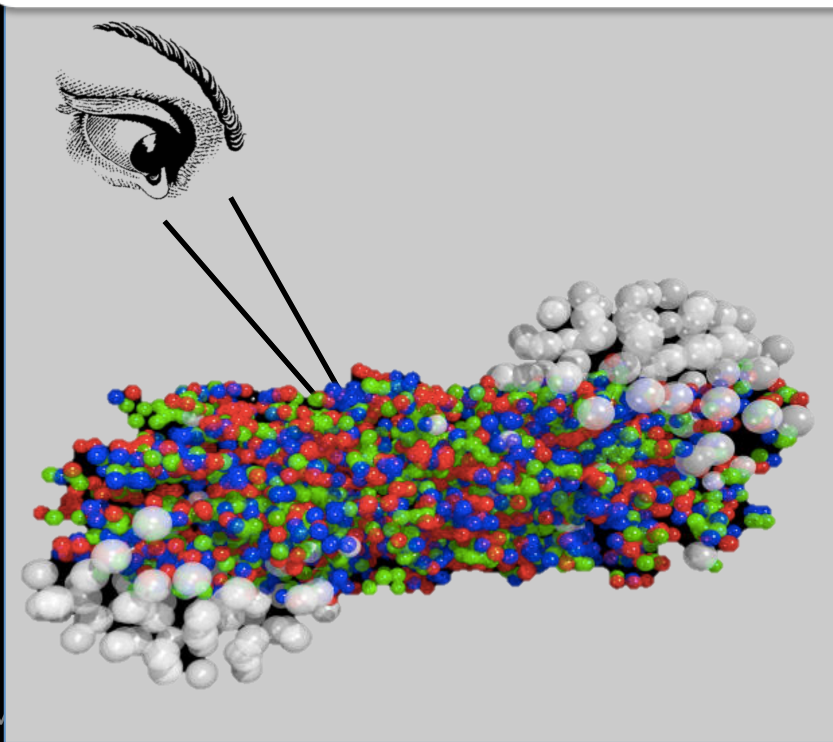


velocities extracted from fits to spectra show no effect of “special” history.

- (unsurprising)

“radial HBT” - Long emission duration





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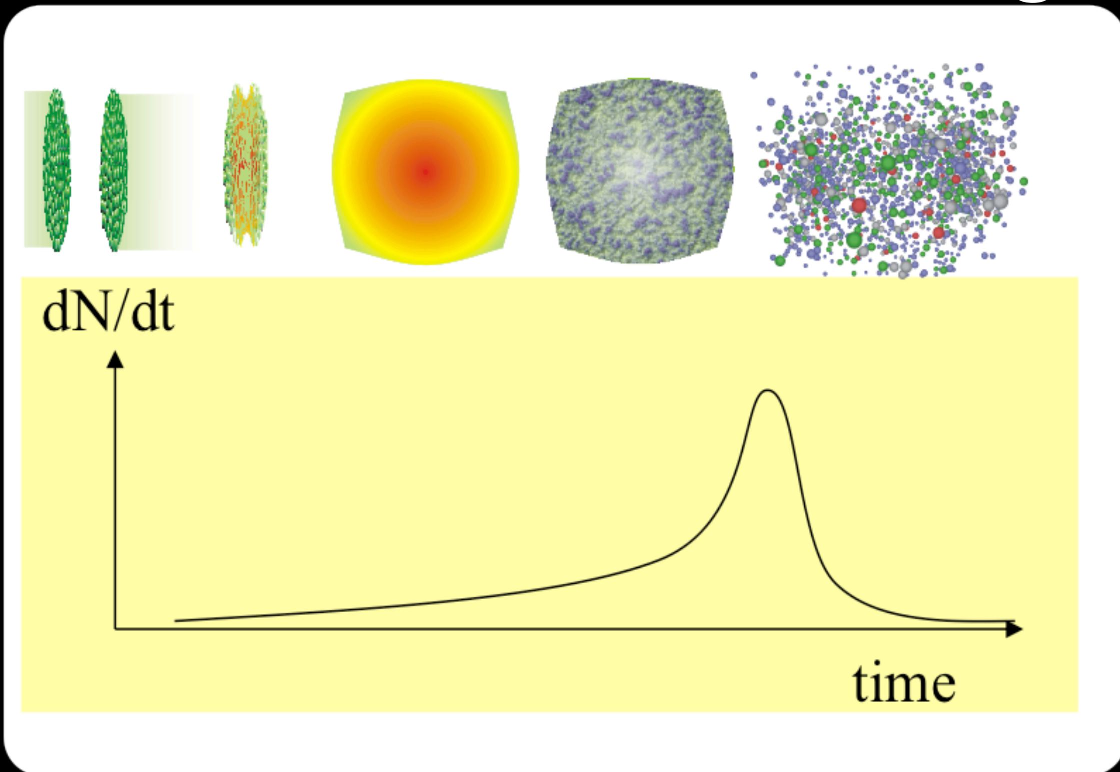

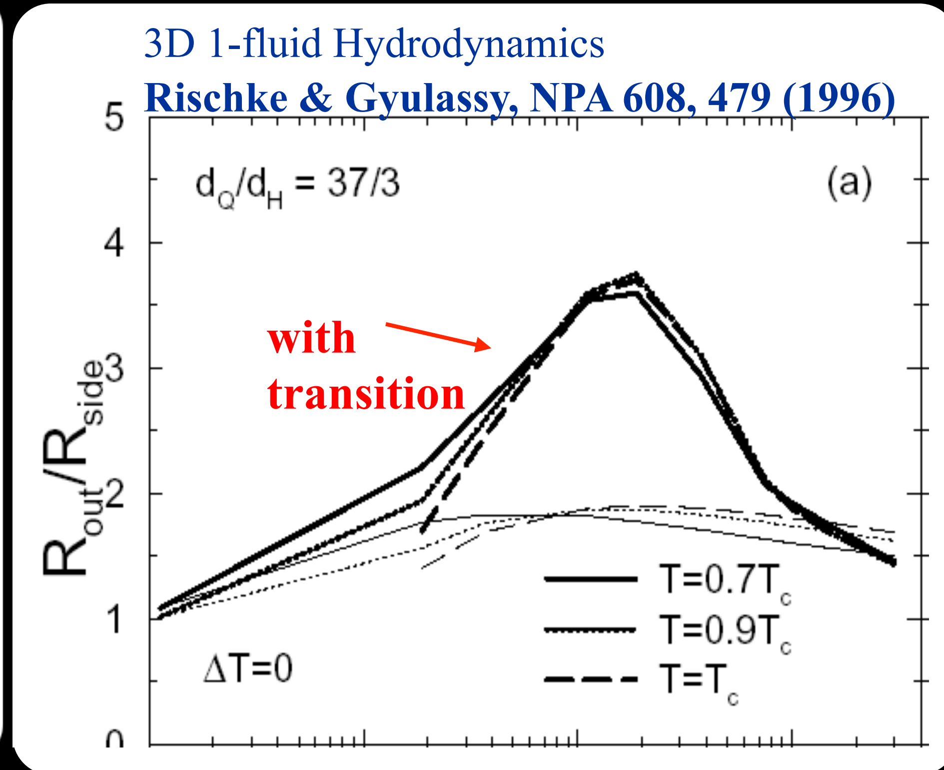

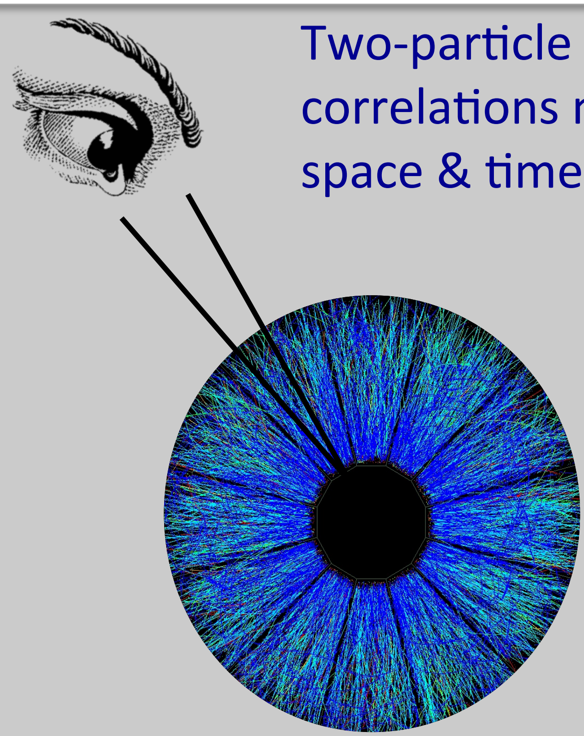

Two-particle “HBT” correlations measure space & time scales

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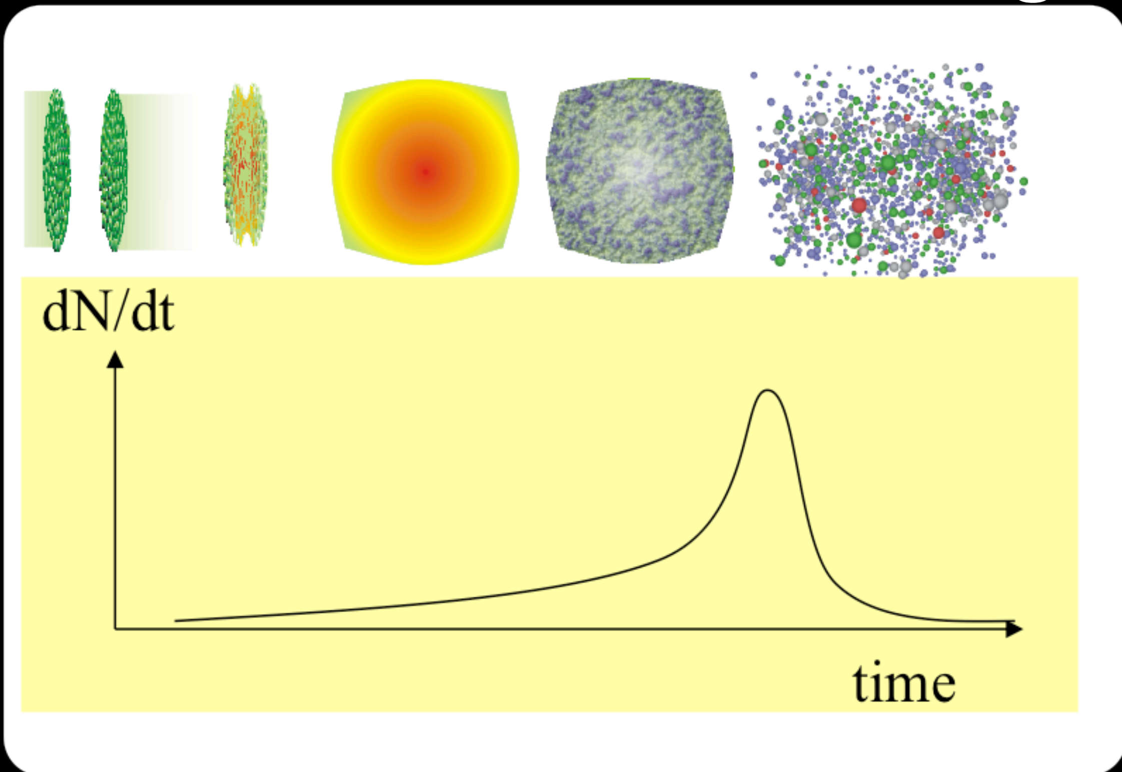

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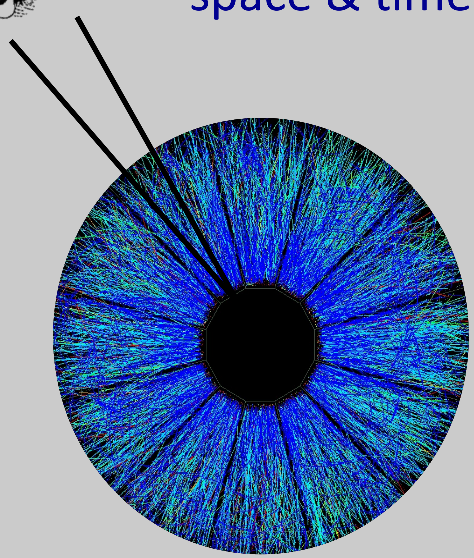

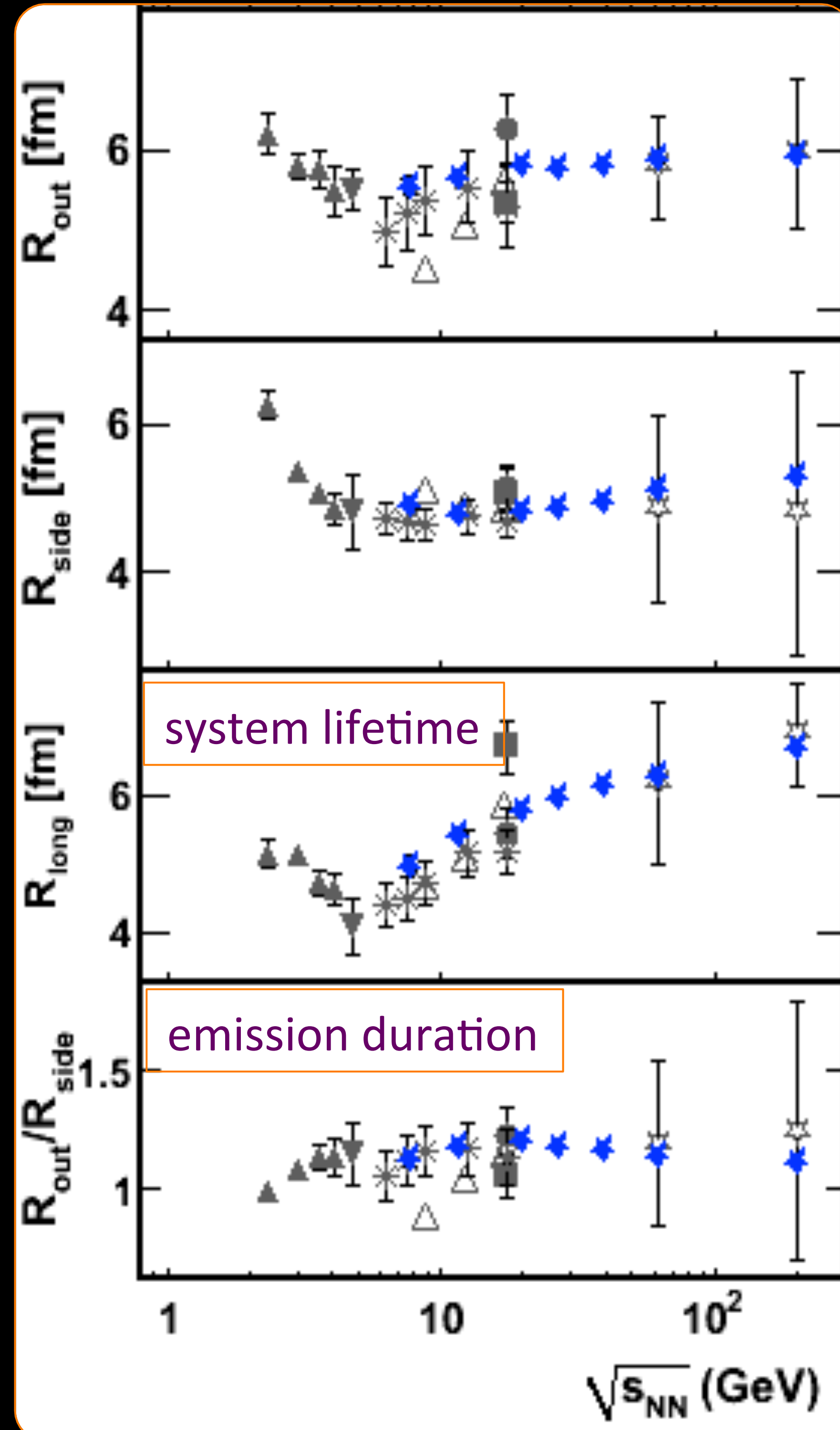

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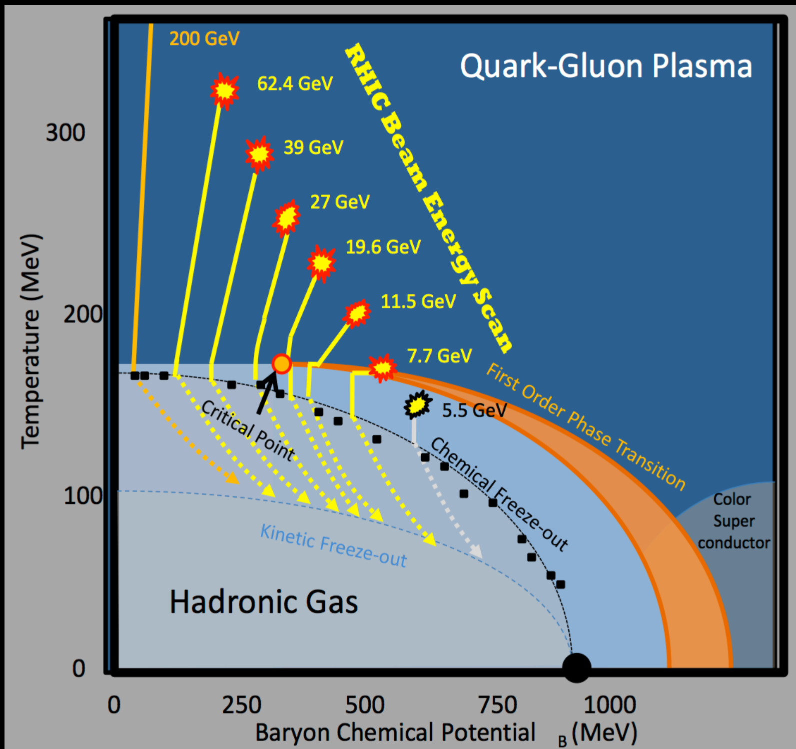

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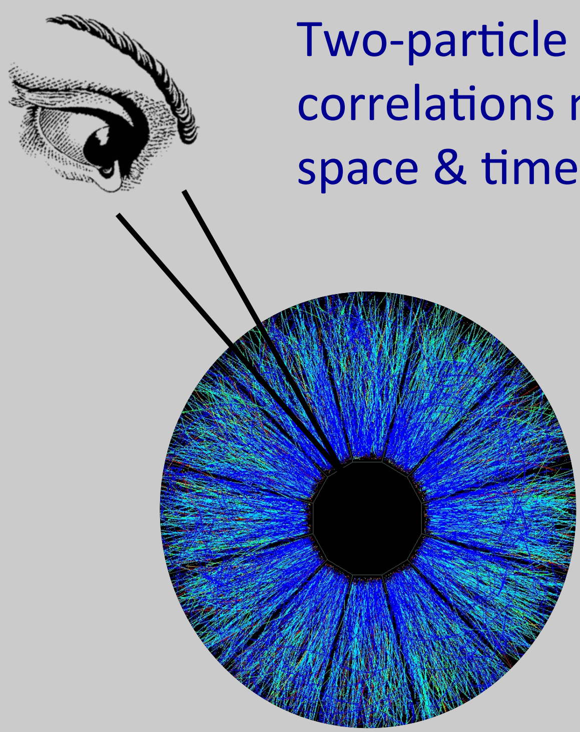
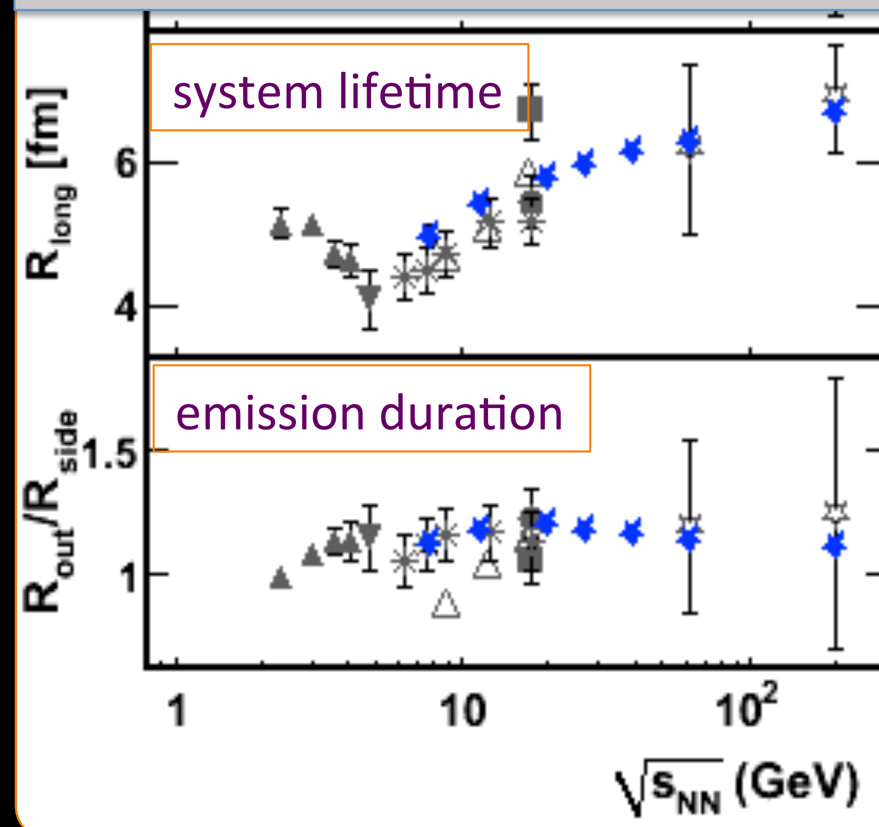


<u>Multidimensional femtoscopy:</u>

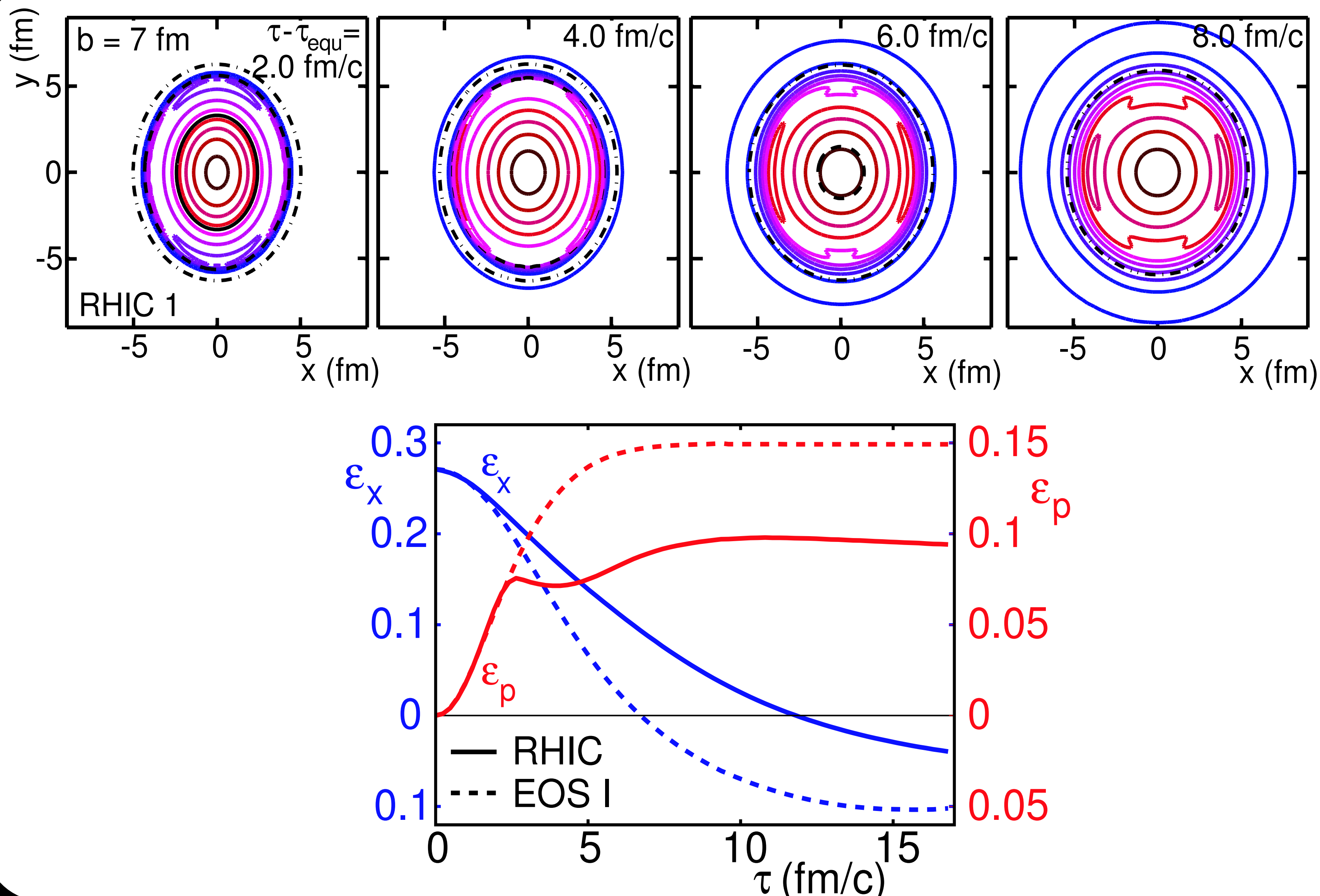
- No evidence for jump in system timescales

late-stage rescattering clouds signal

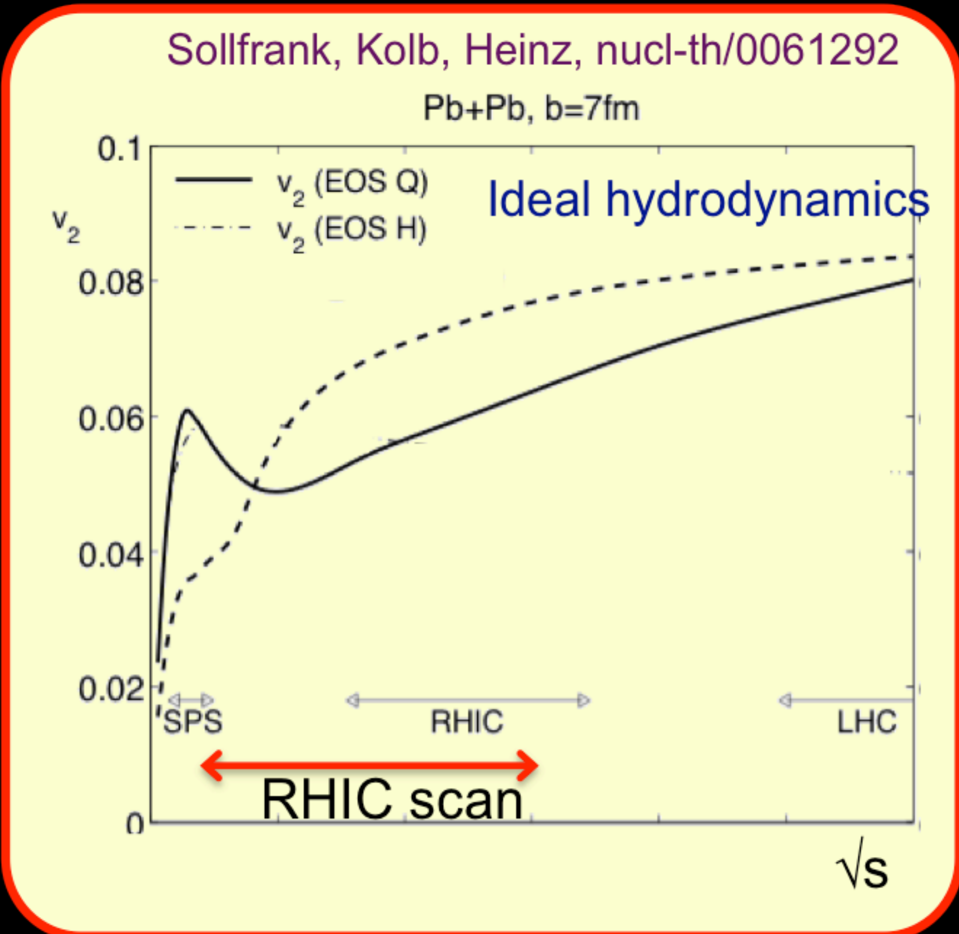


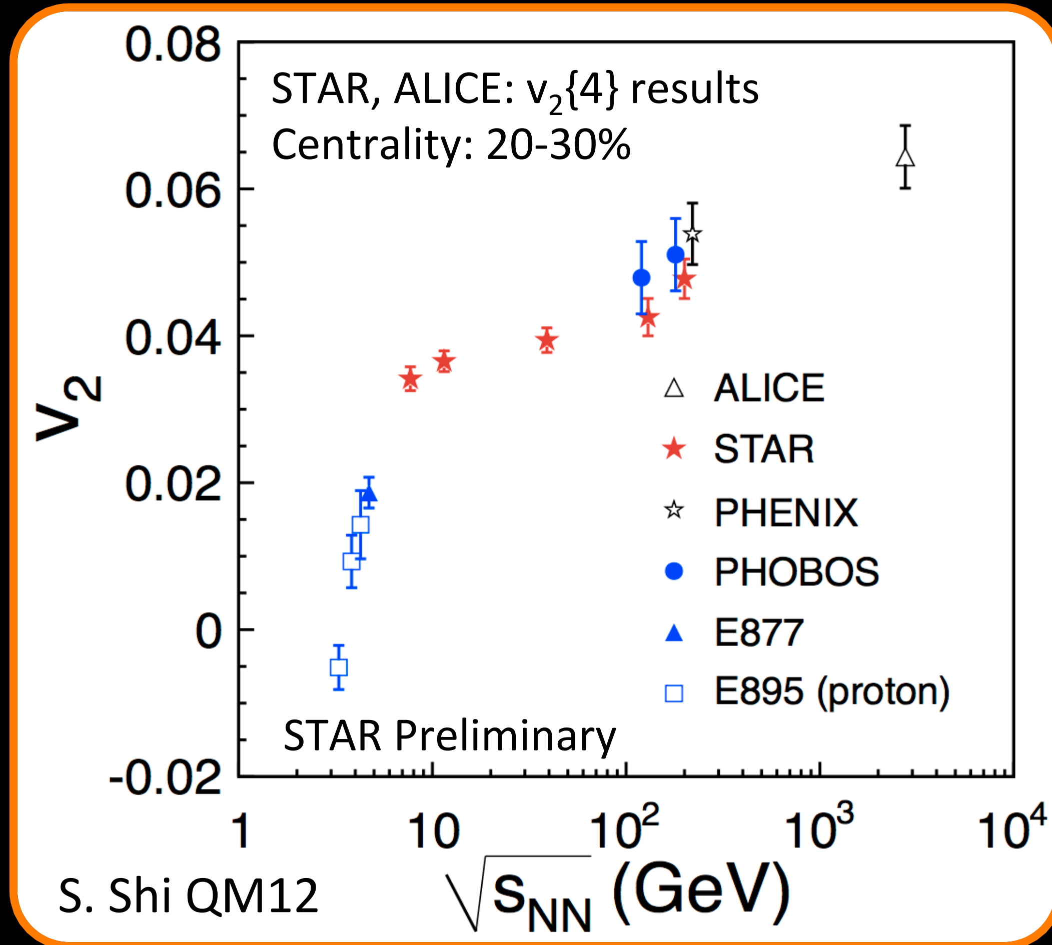
2^{ND}-ORDER AZIMUTHAL DEPENDENCE - SHORTER TIMESCALES

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

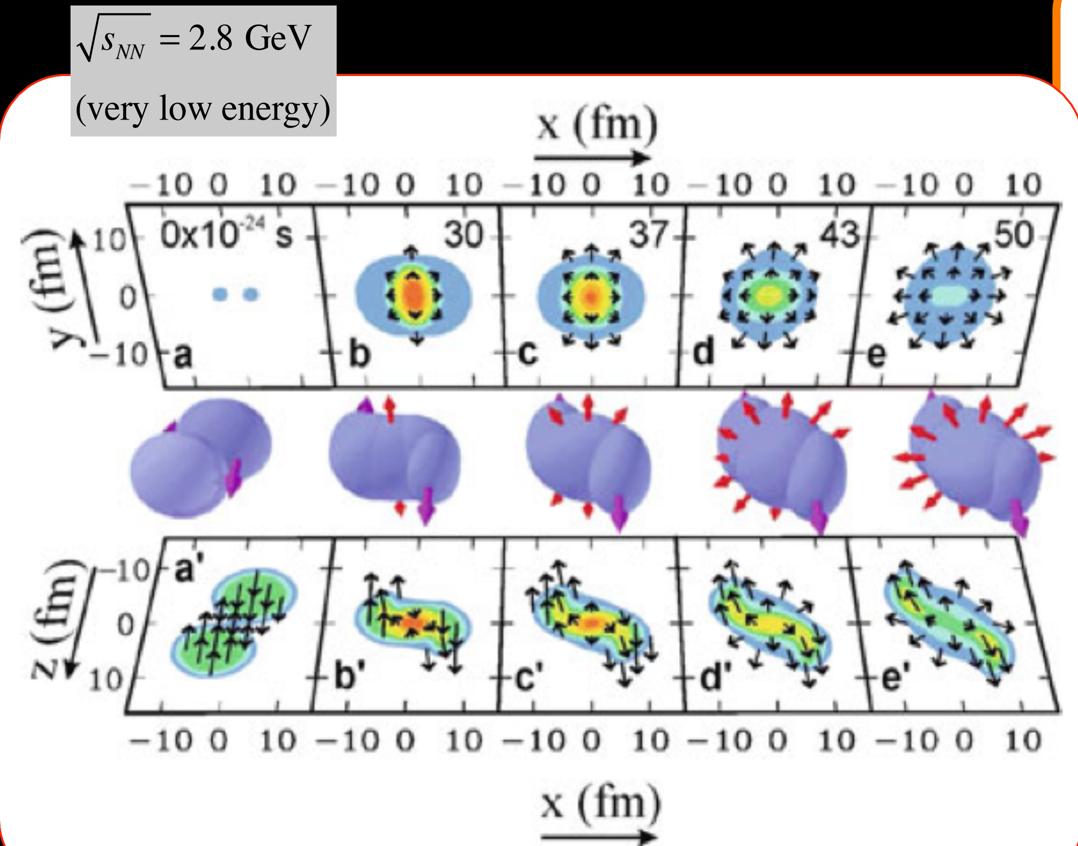


Elliptic flow scan – predictions and reality

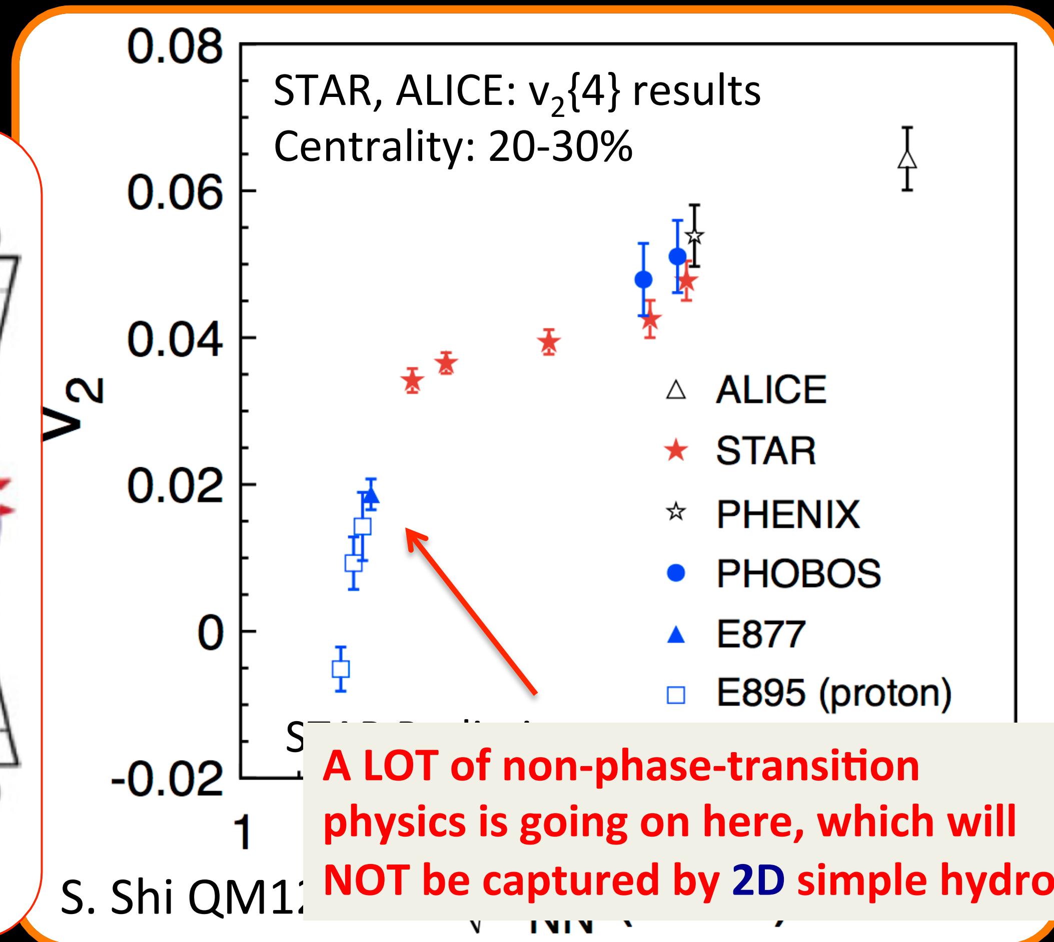




“Self-quenching” elliptic flow –pressure @0~4 fm/c

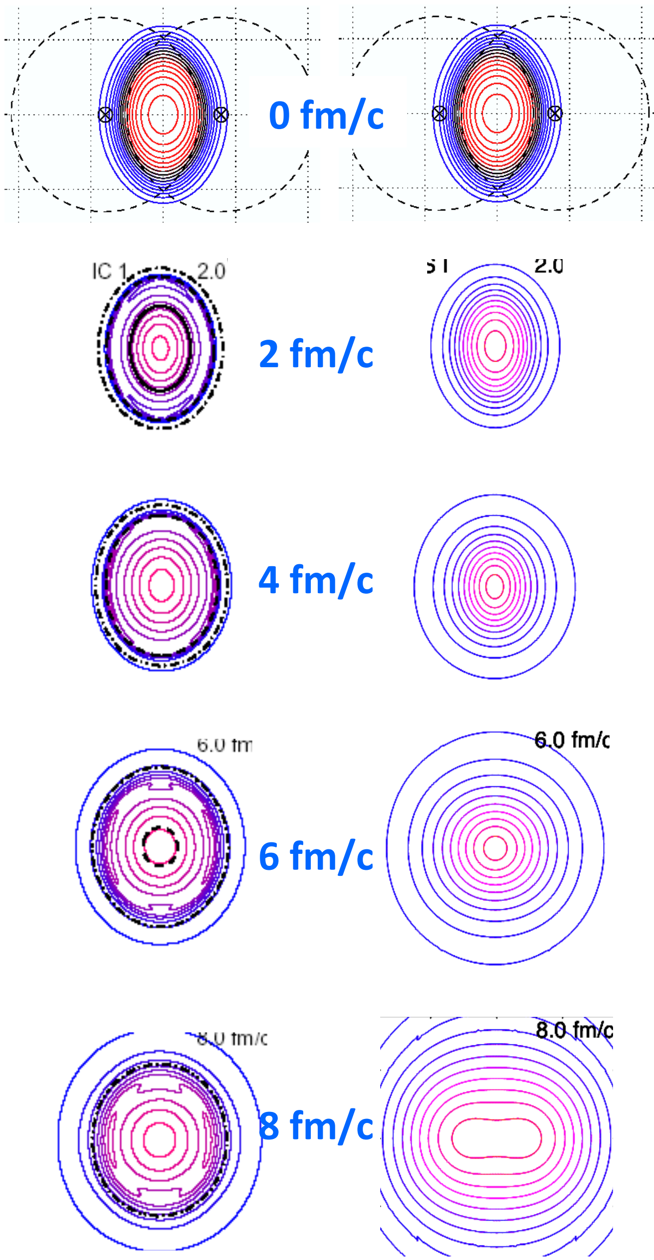


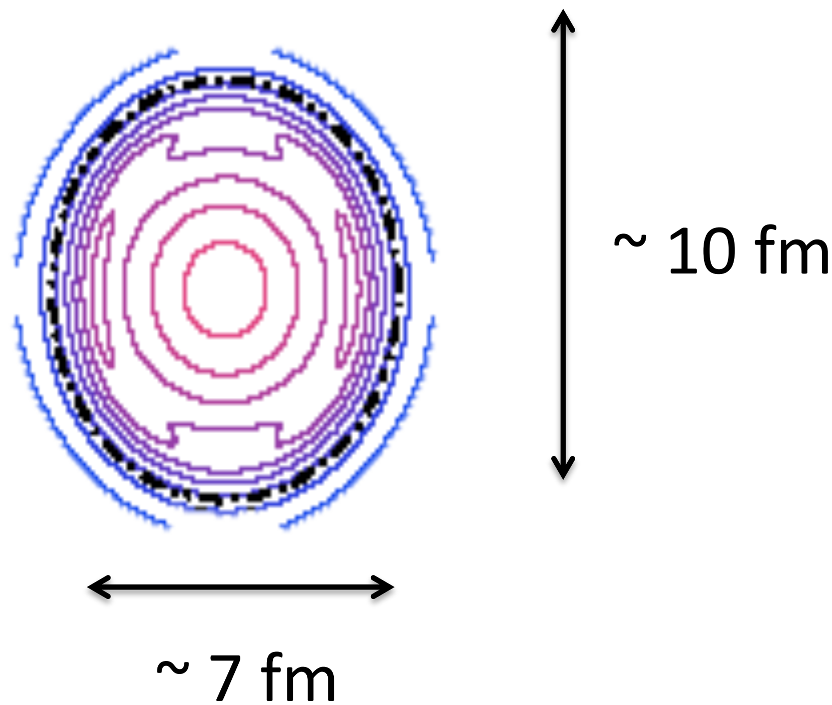
Danielewicz, Lacey, Lynch. *Science* **298,** 1592 (2002)



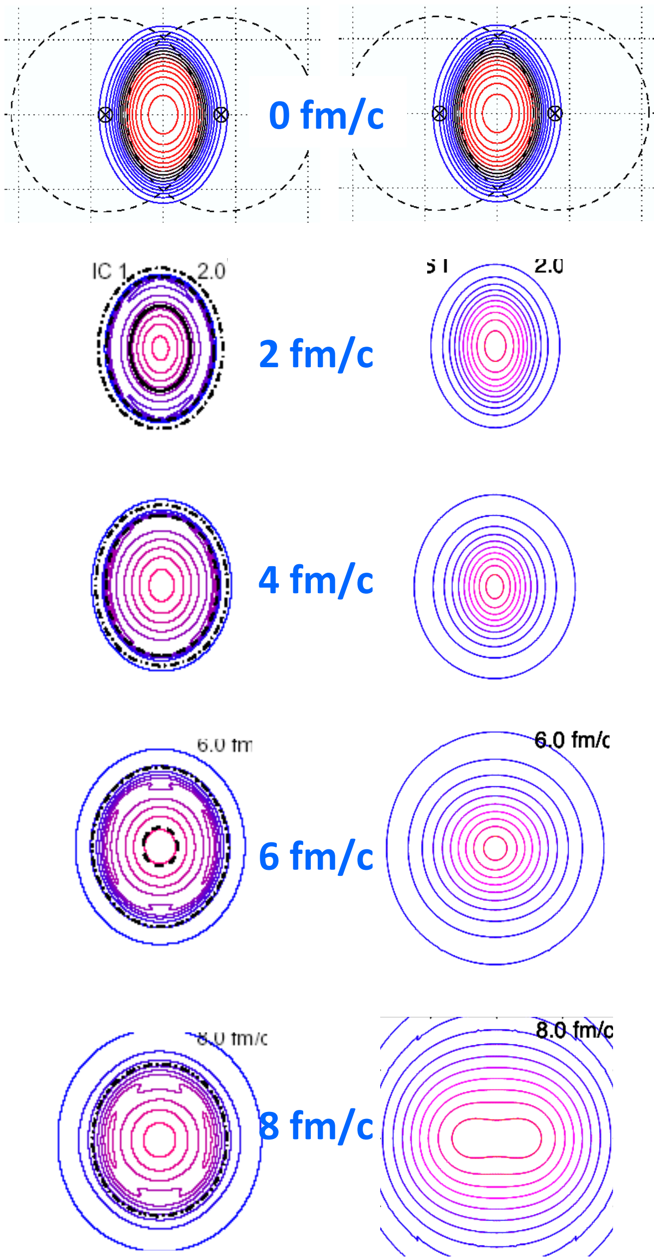
- v2 evolution timescale competes with passing dynamics at lower energy
- Even at high energies, by ~4 fm/c, system may well have evolved out of mixed phase.
- elliptic flow as P.T. signature **highly non-trivial**, especially in the ~10 GeV region

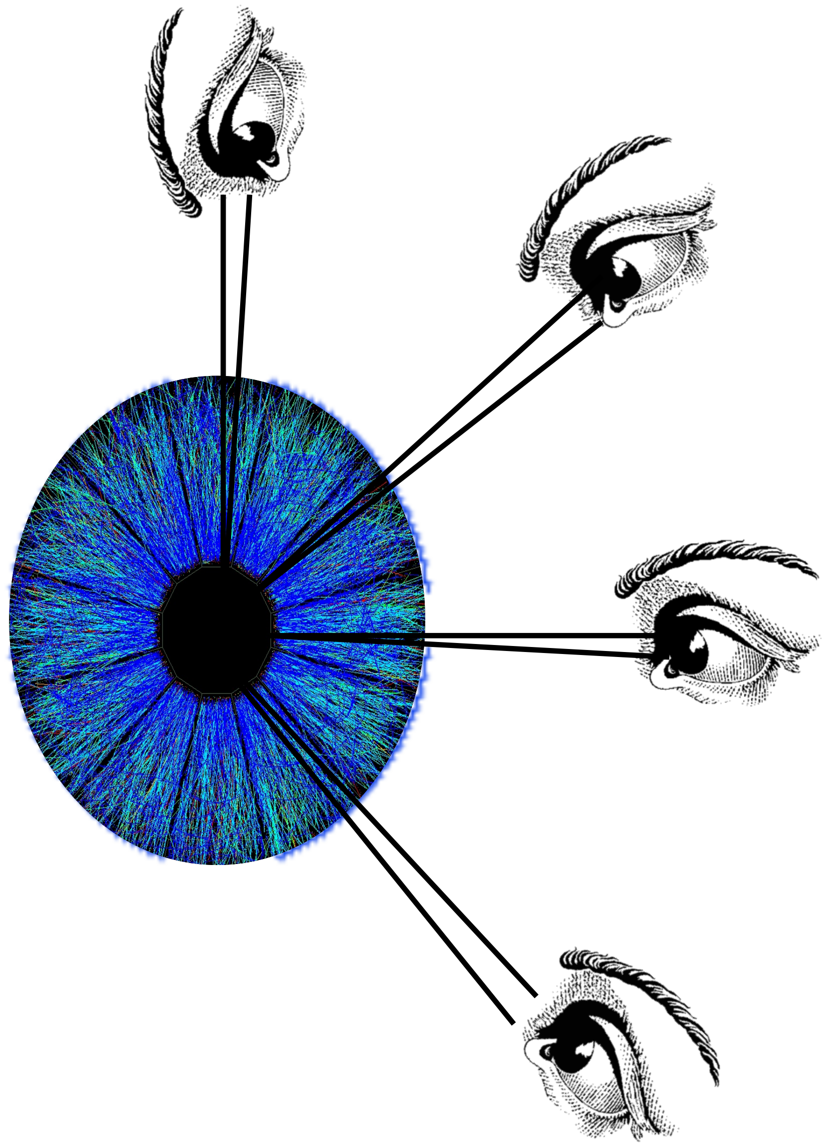
spatial shape evolution

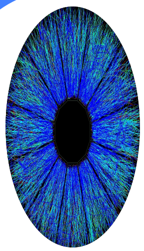


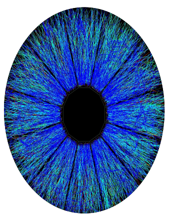


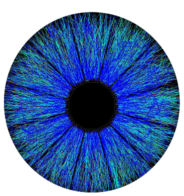
spatial shape evolution

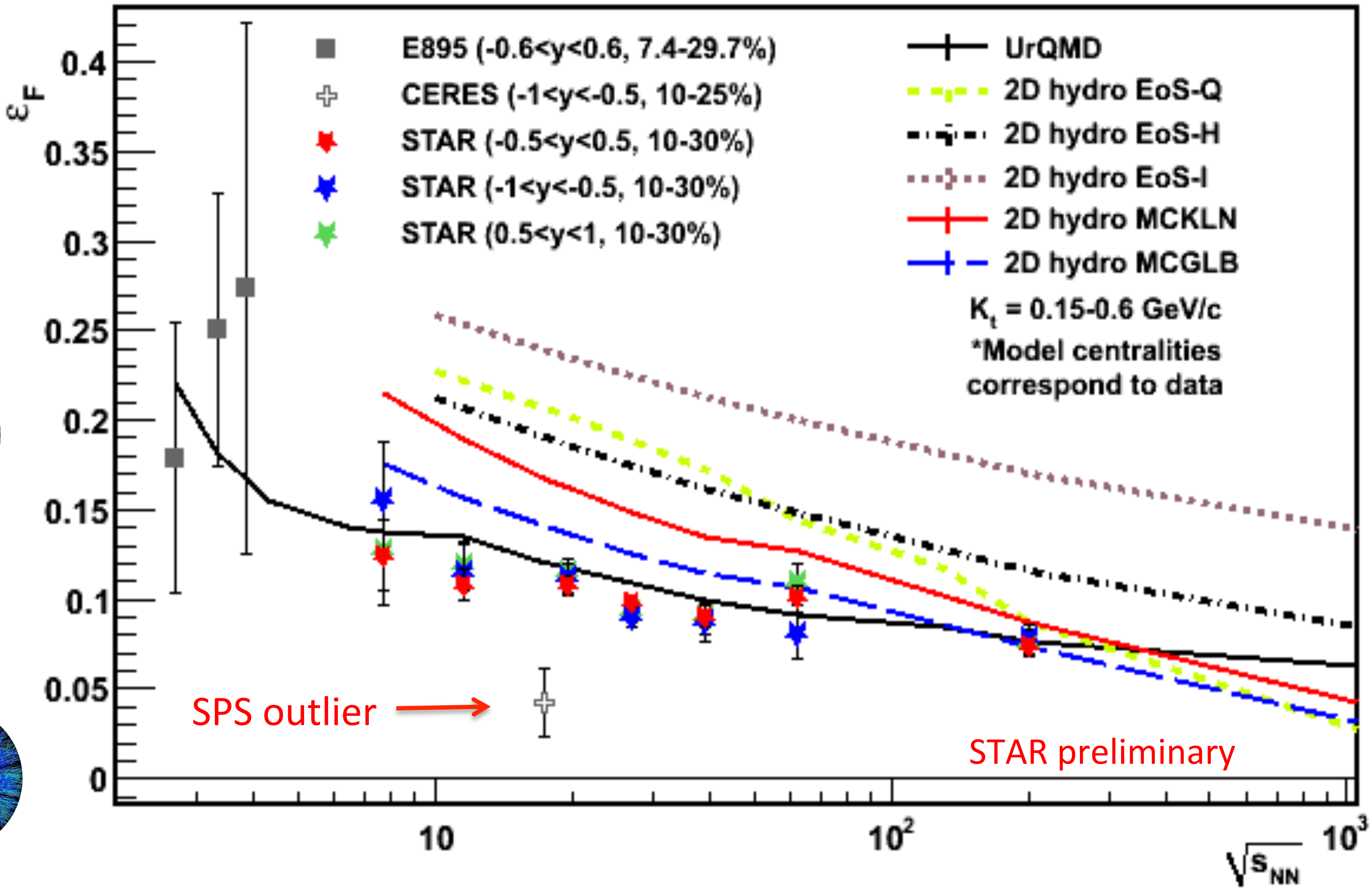




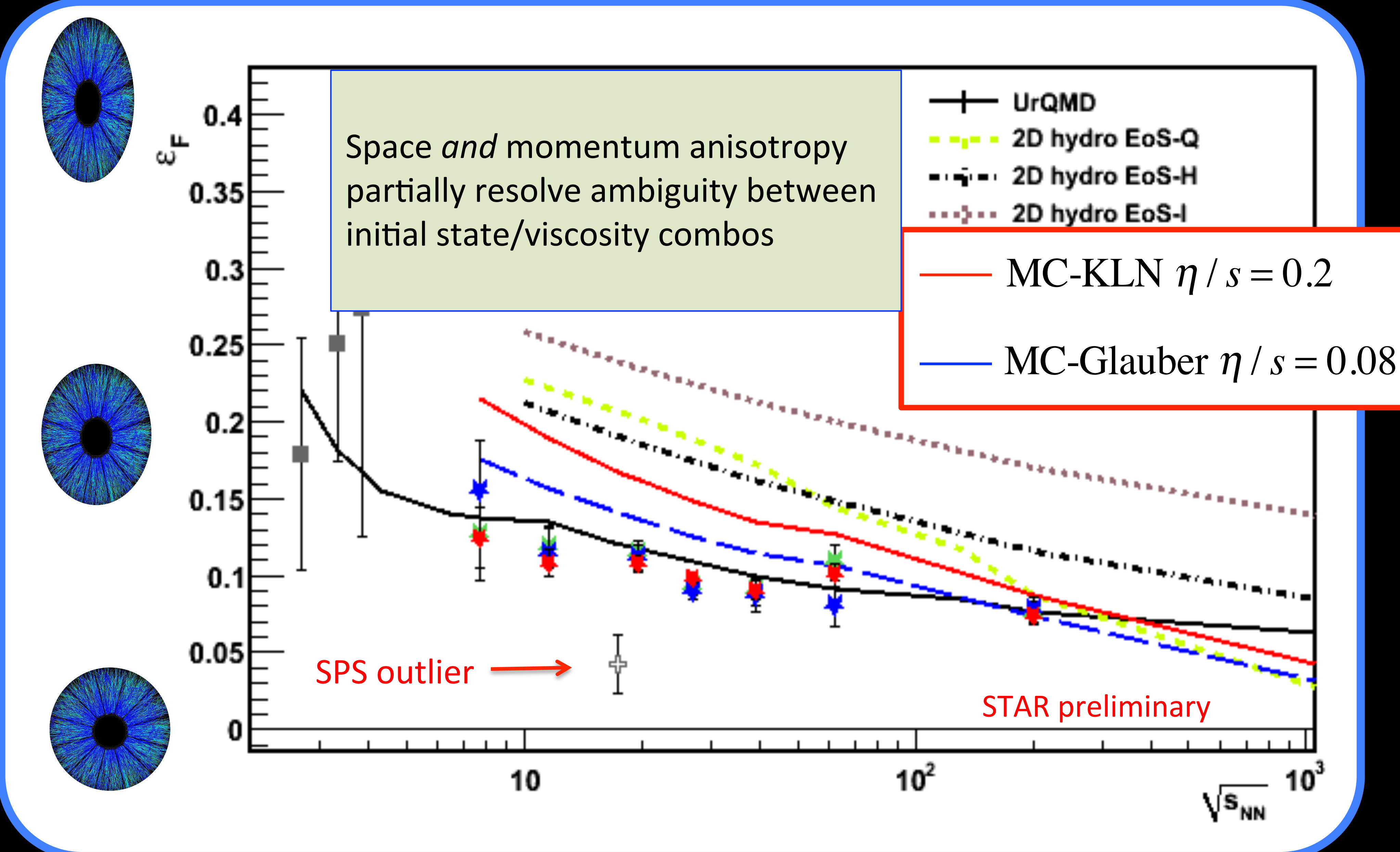








- No evidence of sudden shape change (despite lone SPS datapoint)
- significant sensitivity to EoS, viscosity, initial-state geometry fluctuations
- striking agreement with purely hadronic+string-based transport calculation



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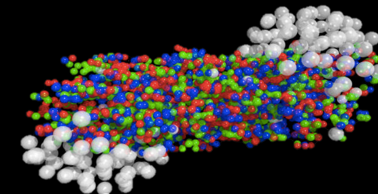
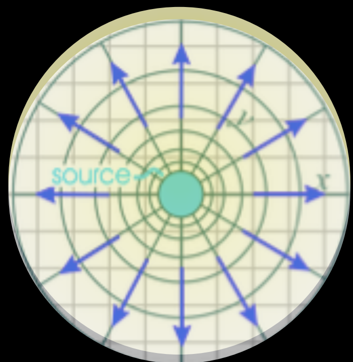
1^{ST}-ORDER AZIMUTHAL DEPENDENCE - EVEN SHORTER TIMESCALES?

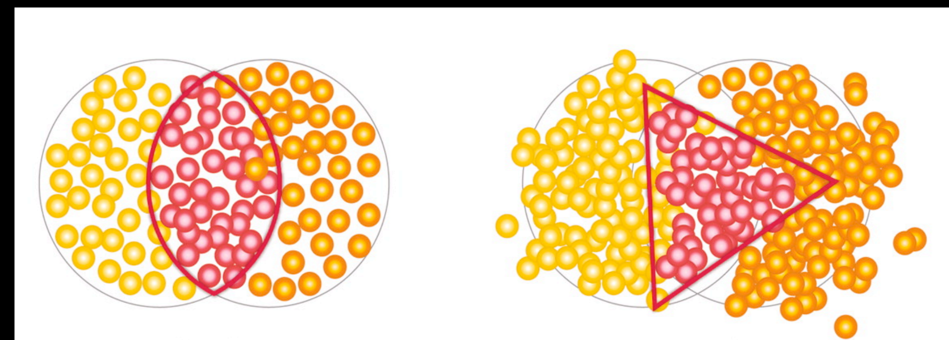
Directed flow



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

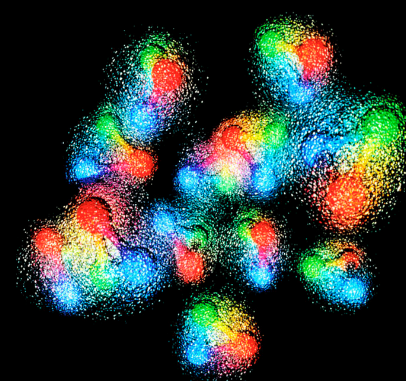


"v0"
Transverse (x-y) plane



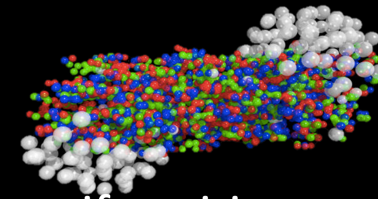
v2
Transverse (x-y) plane

v3
Transverse (x-y) plane

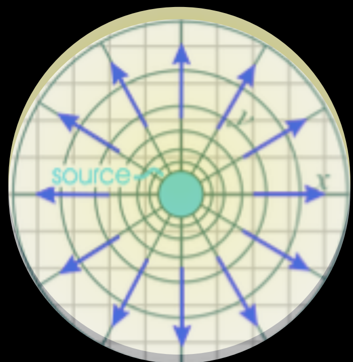


vn
Transverse (x-y) plane

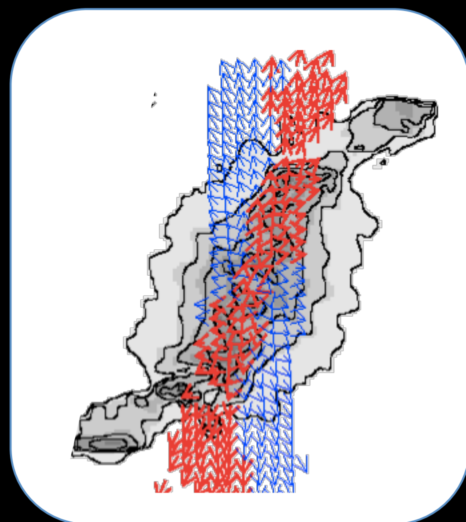
Directed flow



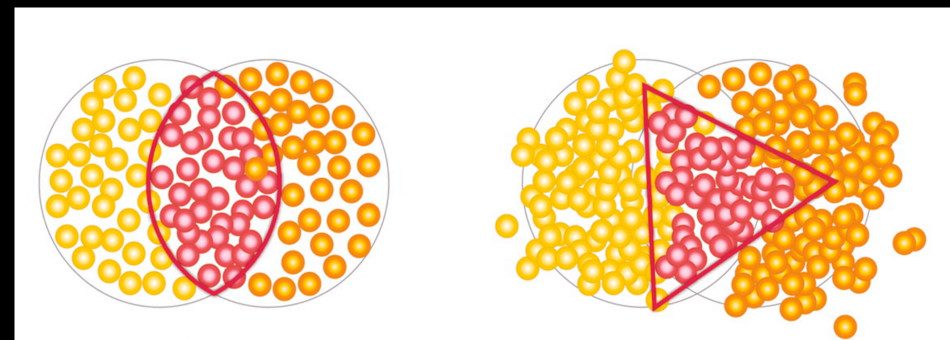
In general, any type of flow is a system response to initial density non-uniformities



“v0”
Transverse (x-y) plane



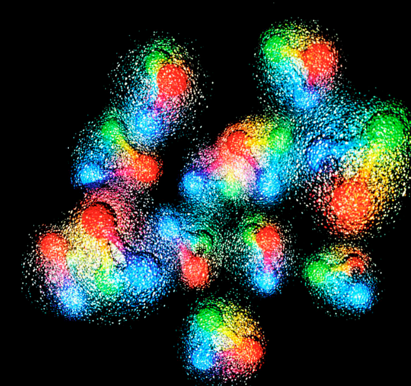
v1
Reaction (x-z) plane



v2
Transverse (x-y) plane

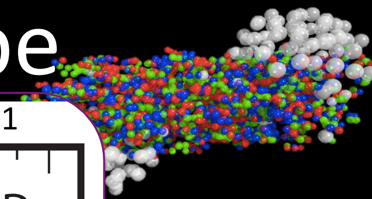
v3
Transverse (x-y) plane

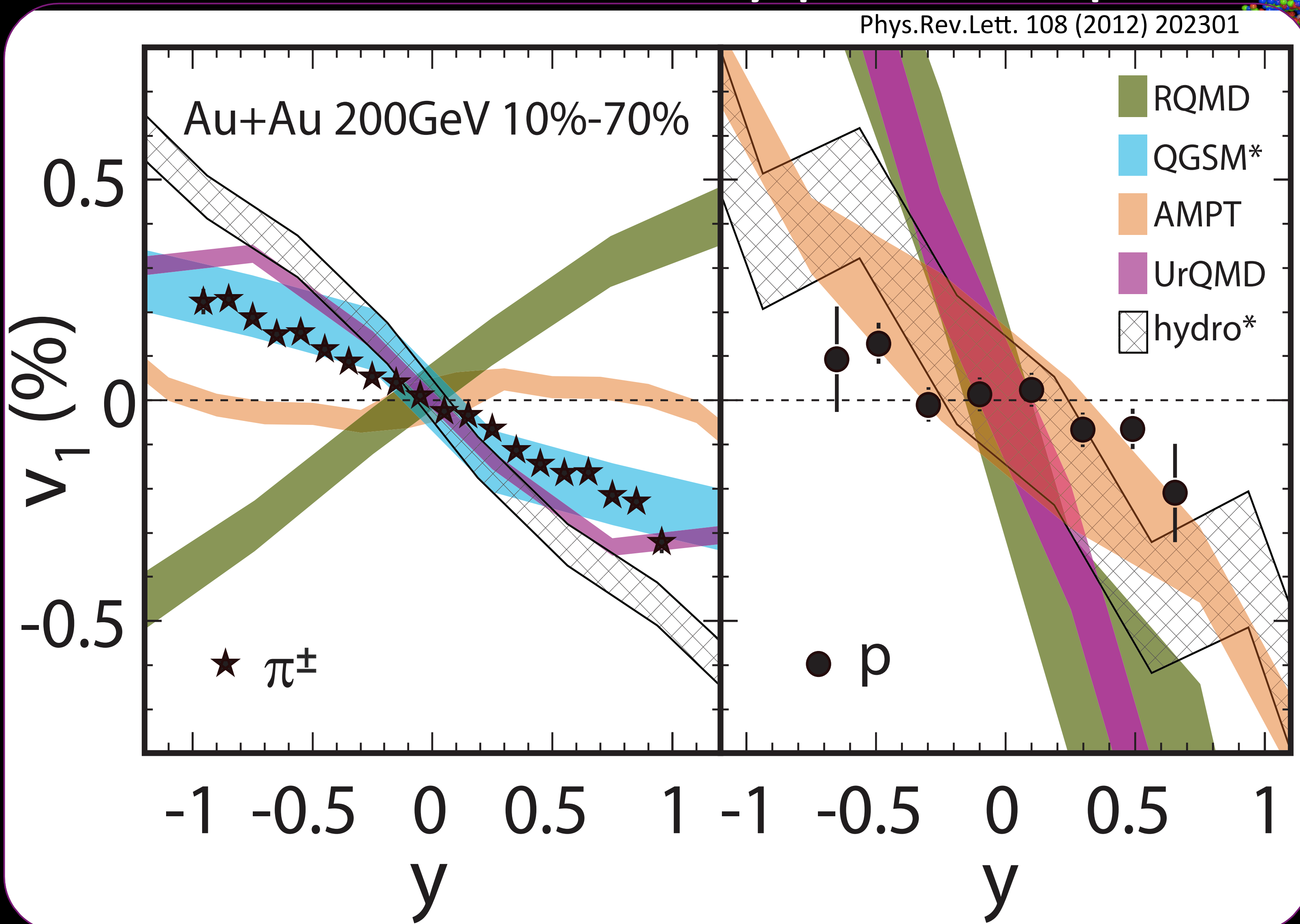
Except v1, all can be studied with 2D models
(which have dominated at RHIC)



vn
Transverse (x-y) plane

Directed flow – early pressure probe





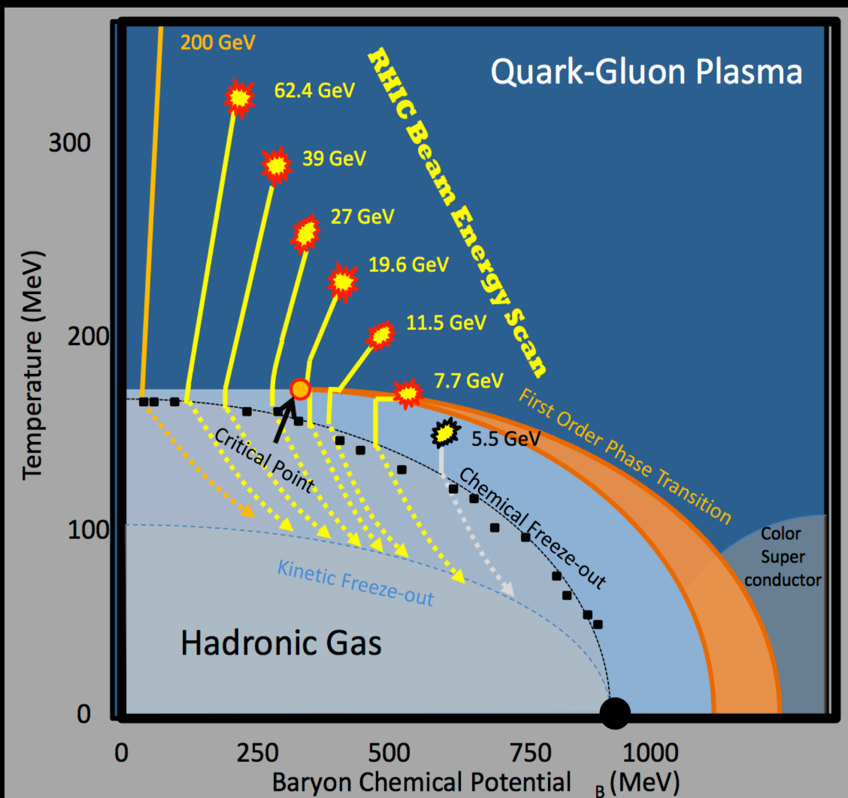
Above SPS, "always" antiflow (v_1<0)

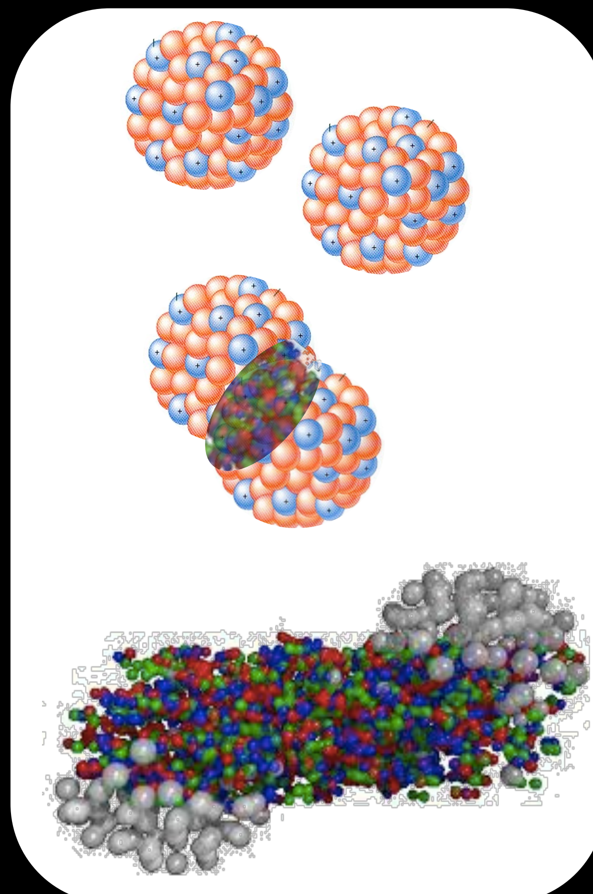
Challenging for all transport models at RHIC

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

Directed flow

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

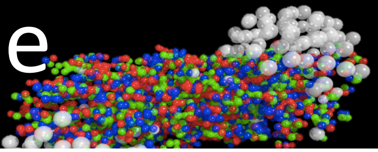


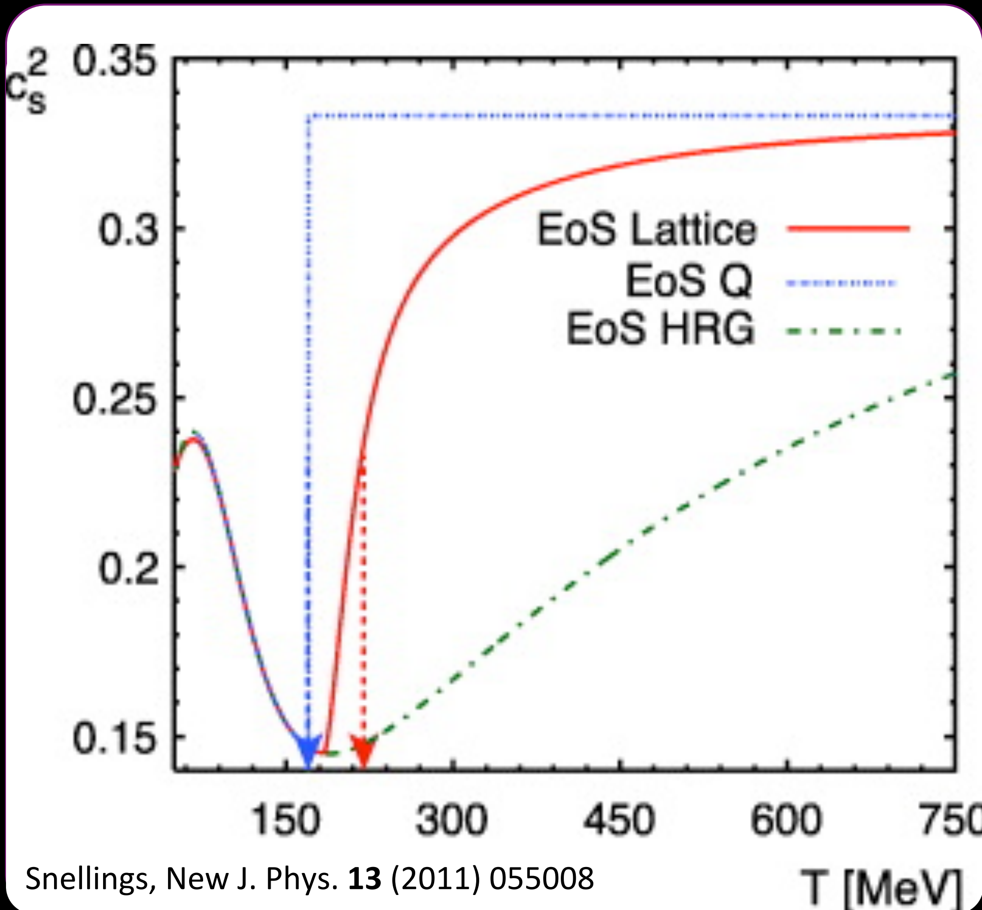


Geometrical seeds of directed flow imprinted during interpenetration

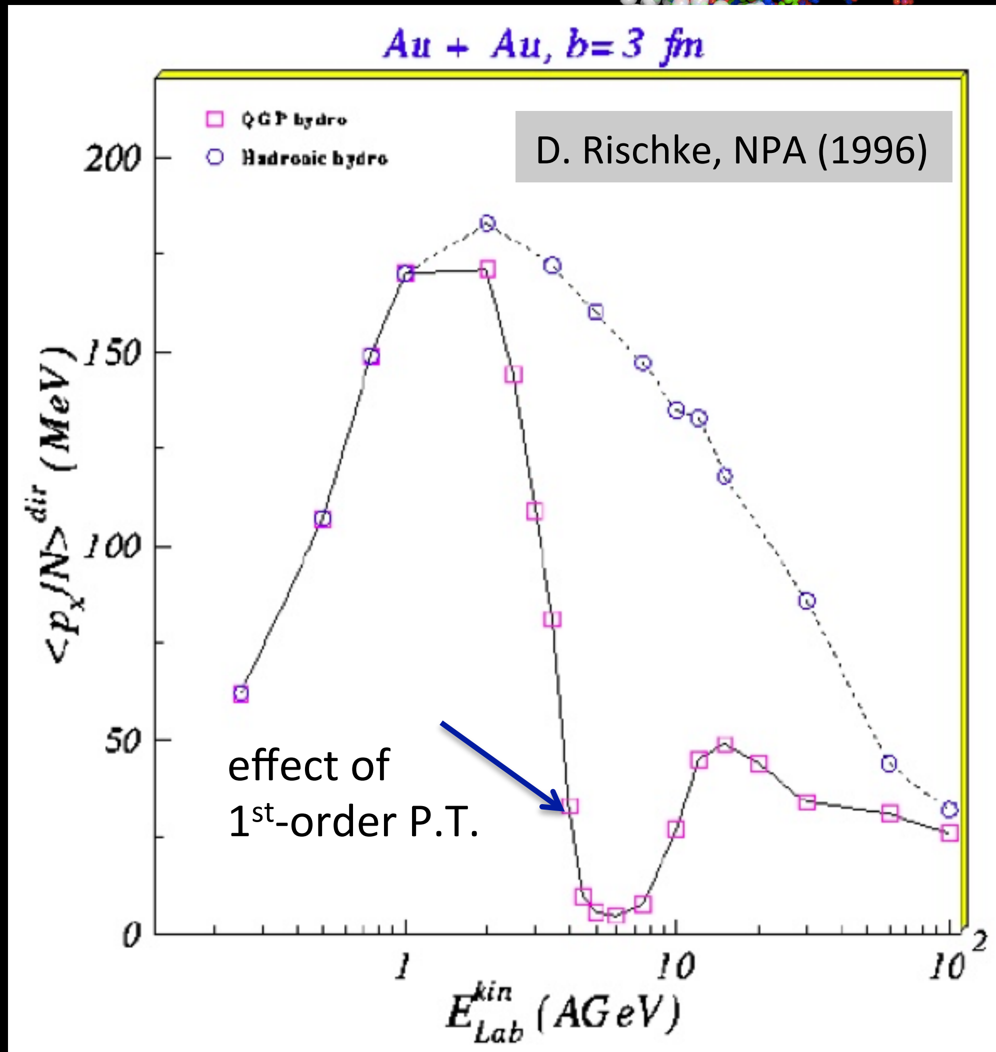
→ early signal?

Directed flow – early pressure probe





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



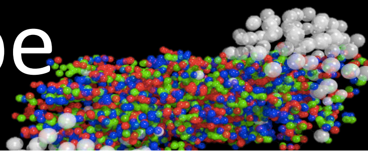
D. Rischke, NPA (1996)

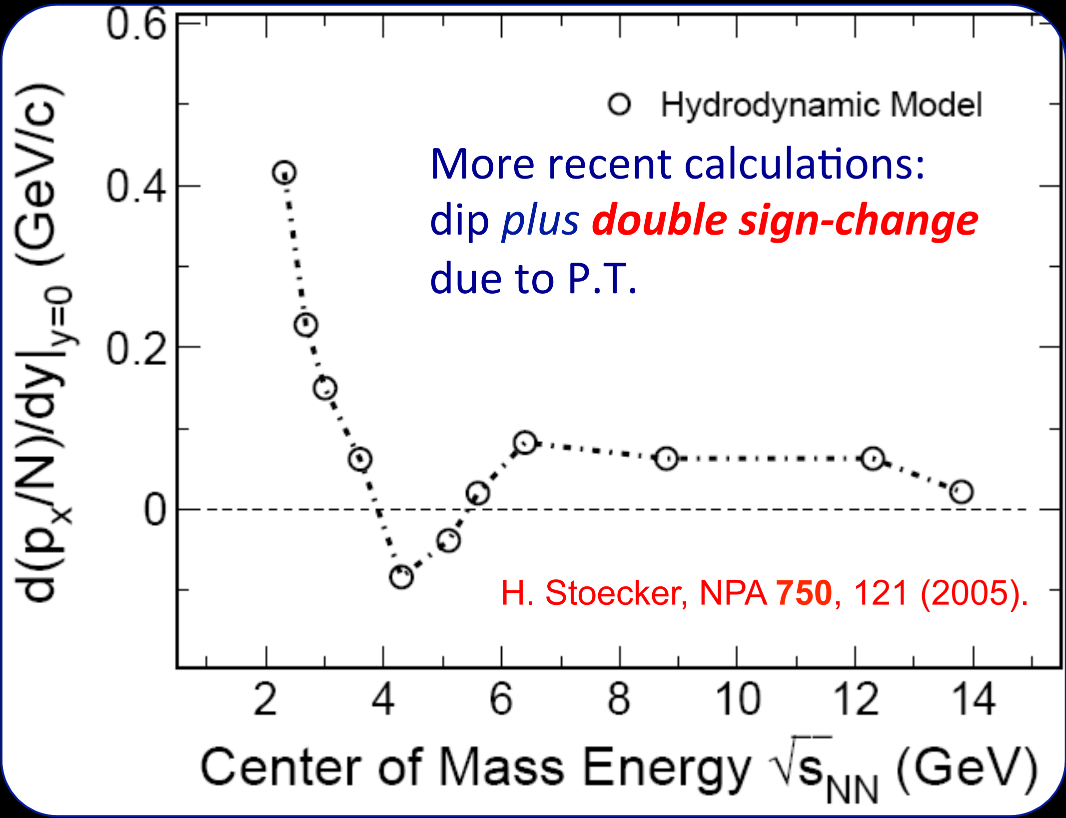
First-order anisotropy imprints itself on momentum space in first instants of collision

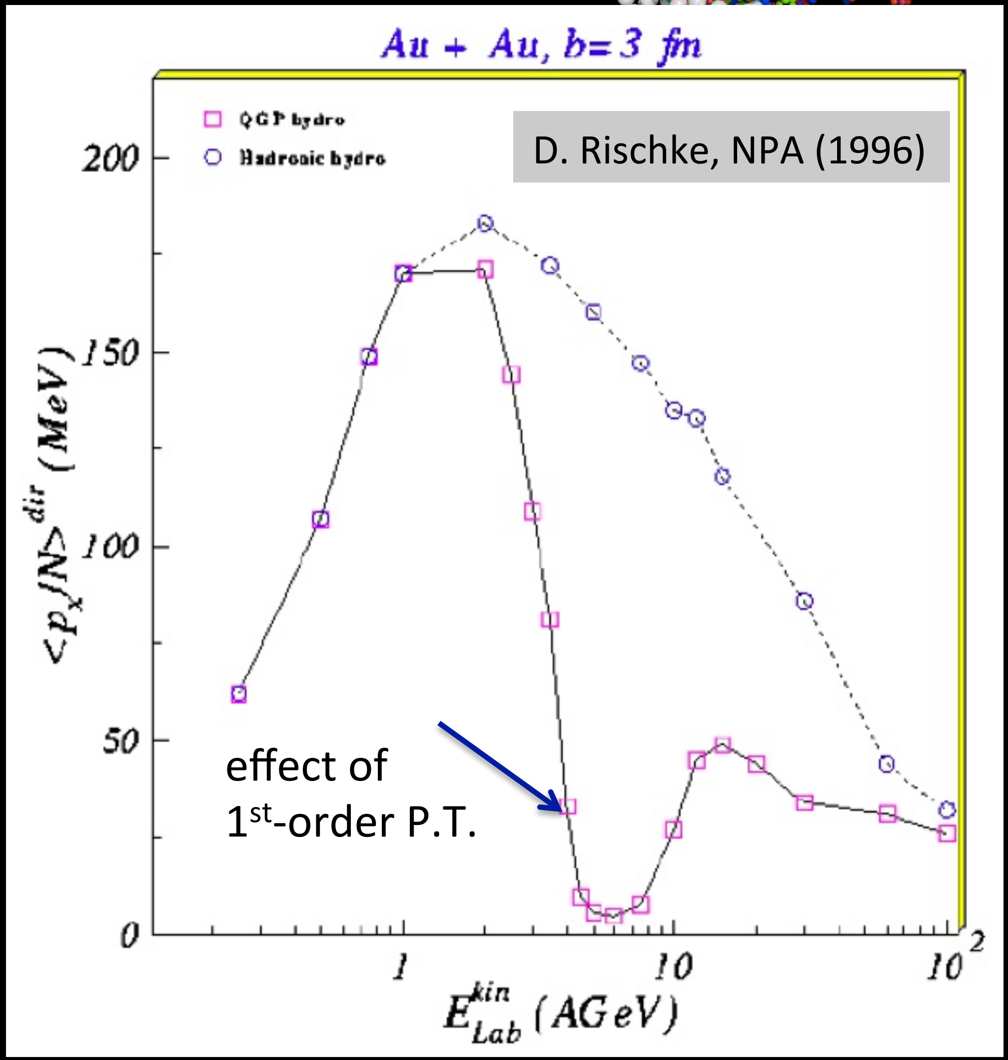
- Promising soft-spot probe, due to rapid dynamics

Long-standing probe for 1st-order transition (neglected/forgotten in v2 frenzy of early RHIC)

Directed flow – early pressure probe







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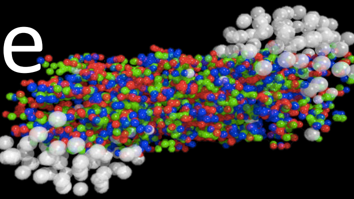

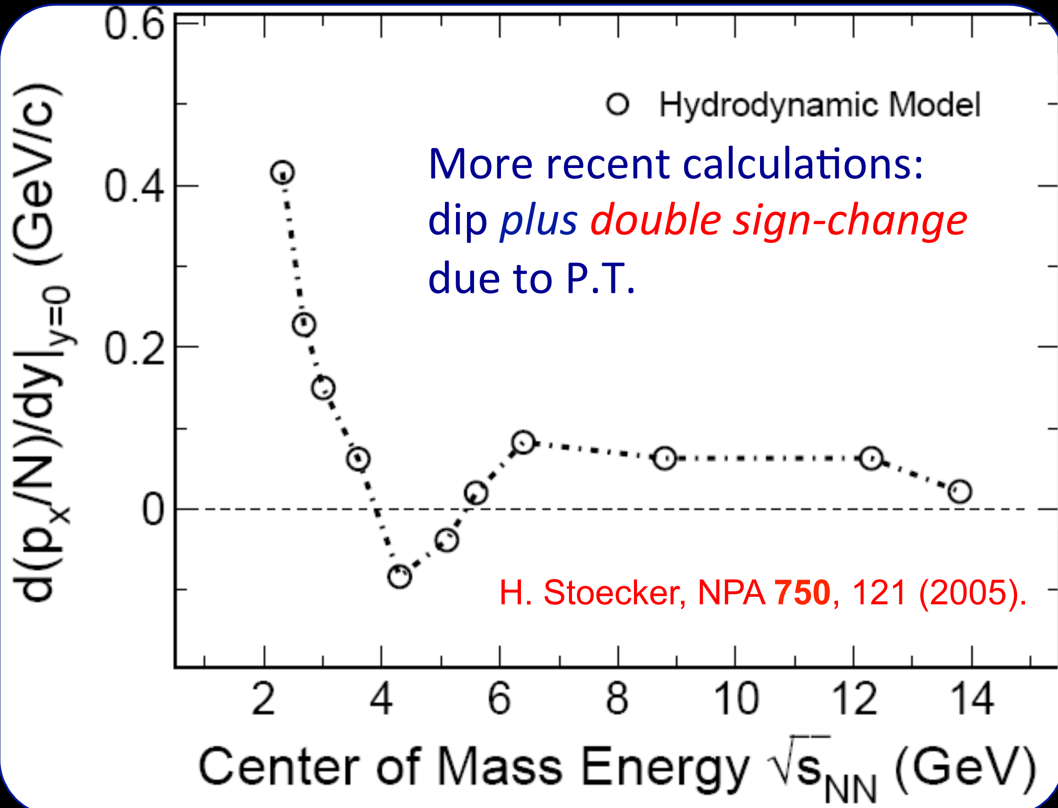

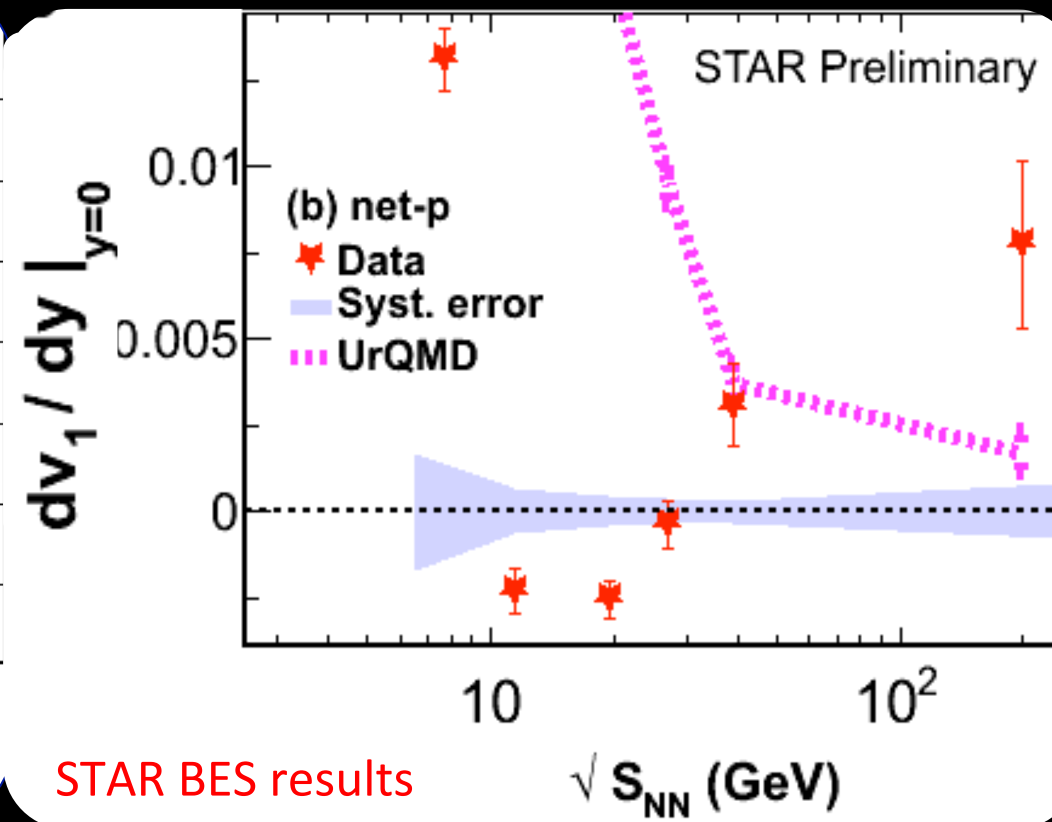

Nontrivial qualitative soft-spot prediction confirmed at RHIC

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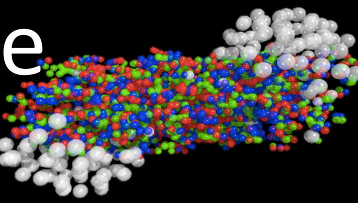

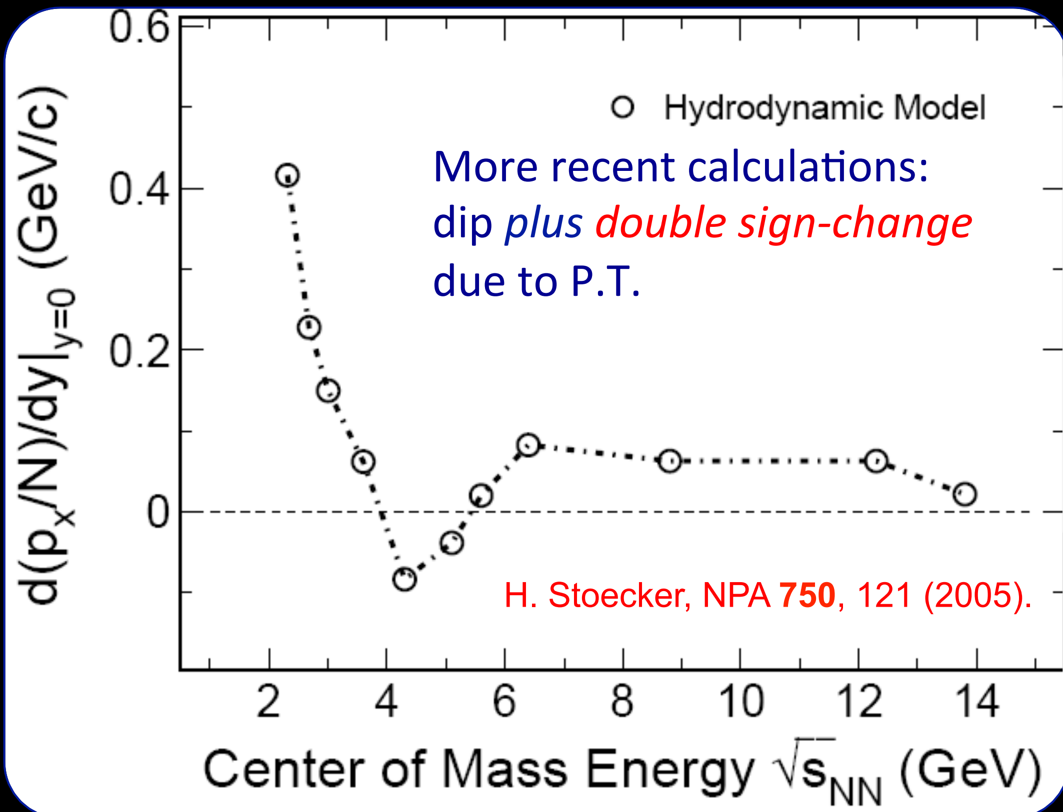

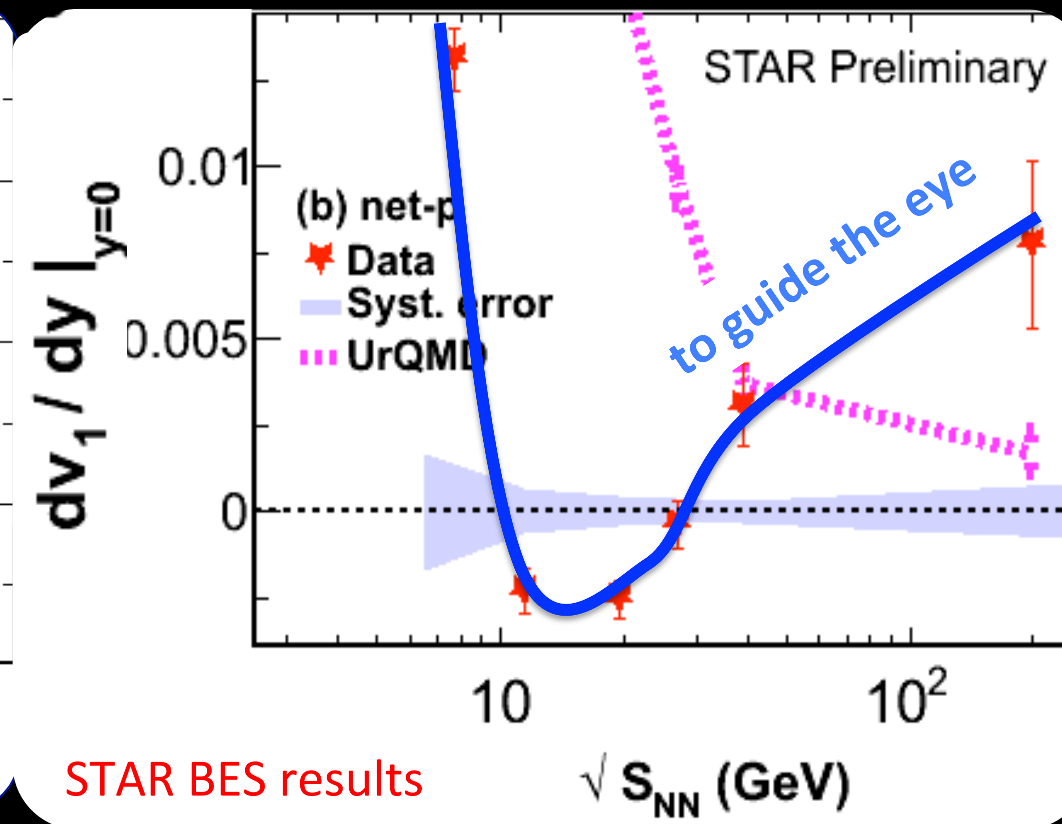

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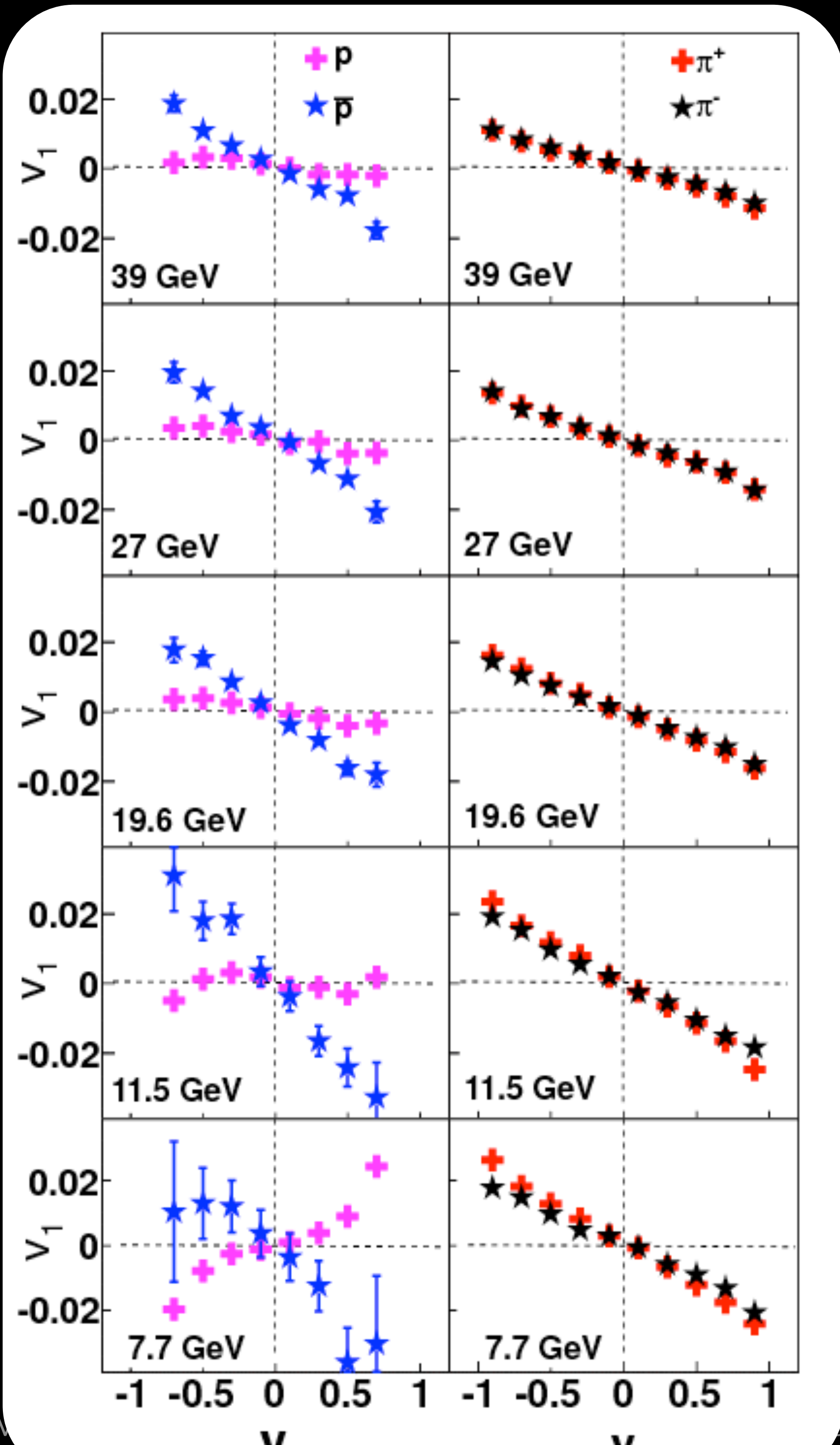
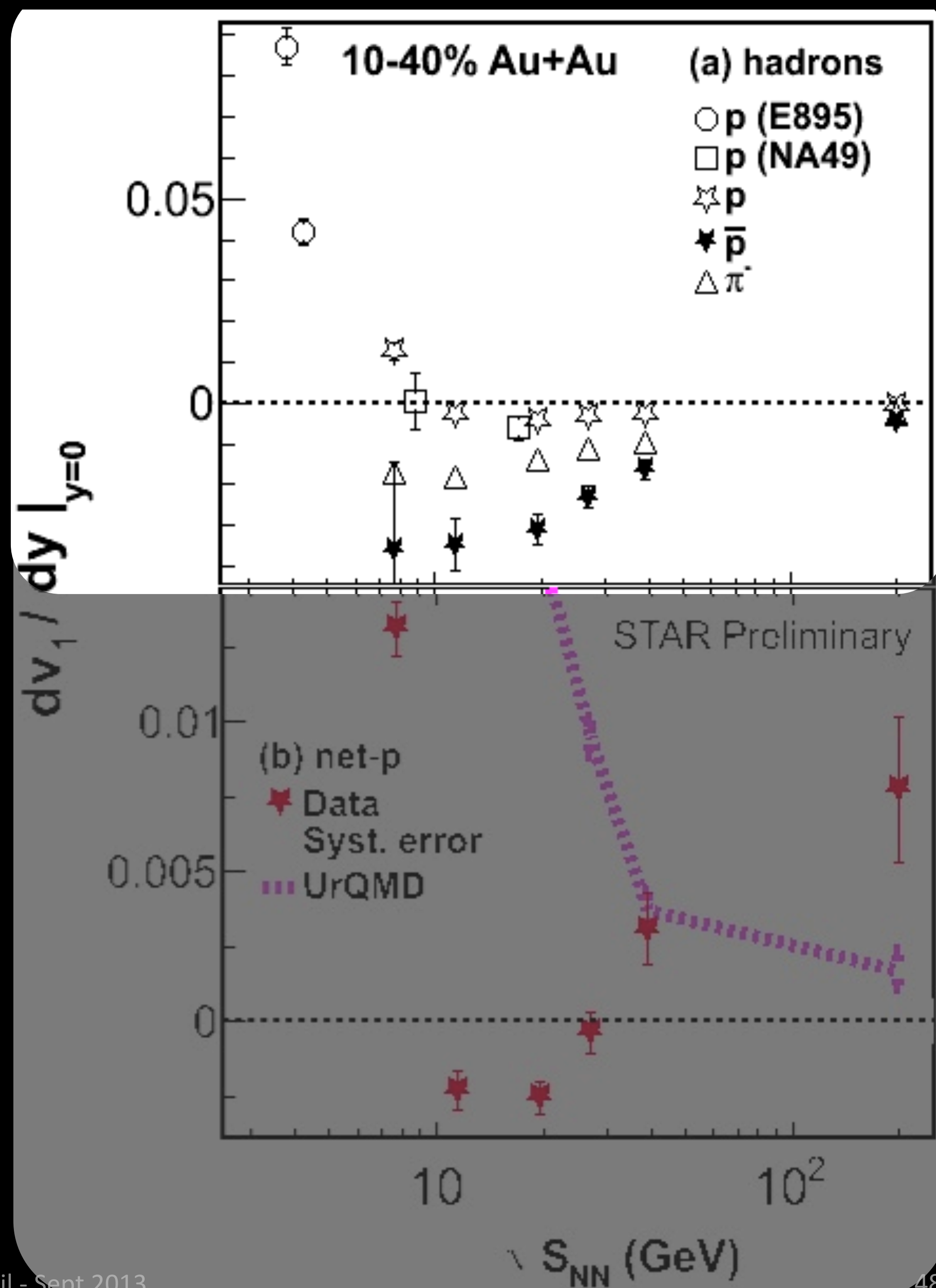
Details


p
p̄
π+
π-
v1
0.02
0
-0.02
39 GeV
27 GeV
19.6 GeV
11.5 GeV
7.7 GeV
-1 -0.5 0 0.5 1
y


10-40% Au+Au
(a) hadrons
p (E895)
p (NA49)
p
p̄
π-
0.05
0
dv1 / dy |y=0
STAR Preliminary
(b) net-p
Data
Syst. error
UrQMD
0.01
0.005
0
10
10^2
√sNN (GeV)

Details

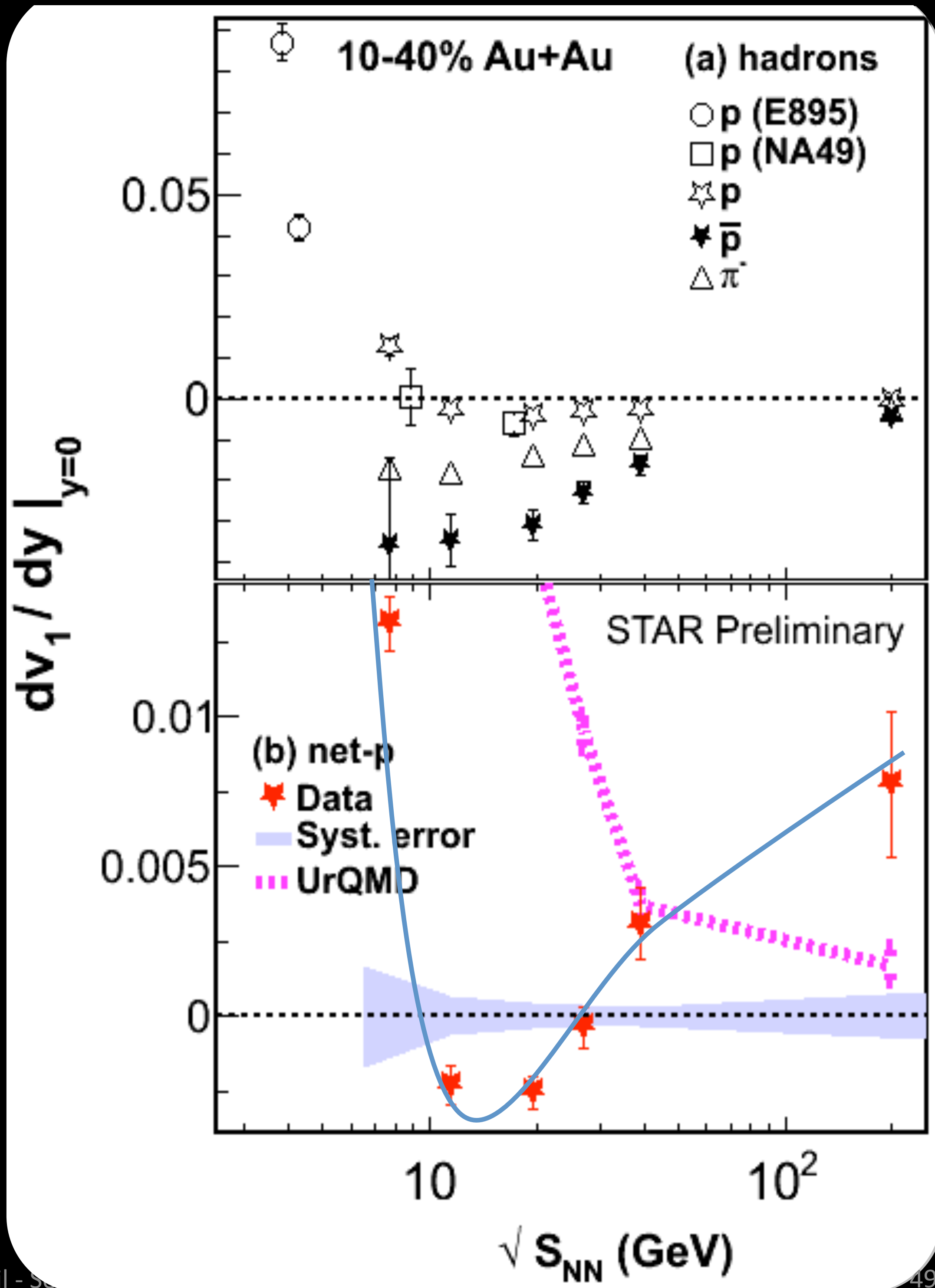
$$\left.\frac{dN}{dy}\right|_{\text{proton}} = \left.\frac{dN}{dy}\right|_{\substack{\text{transported}\\\text{protons}}} + \left.\frac{dN}{dy}\right|_{\substack{\text{created}\\\text{protons}}}$$

$$\Updownarrow$$

$$\left.\frac{dN}{dy}\right|_{\substack{\text{transported}\\\text{protons}\\\text{(net protons)}}} = \left.\frac{dN}{dy}\right|_{\text{proton}} - \left.\frac{dN}{dy}\right|_{\text{antiprotons}}$$

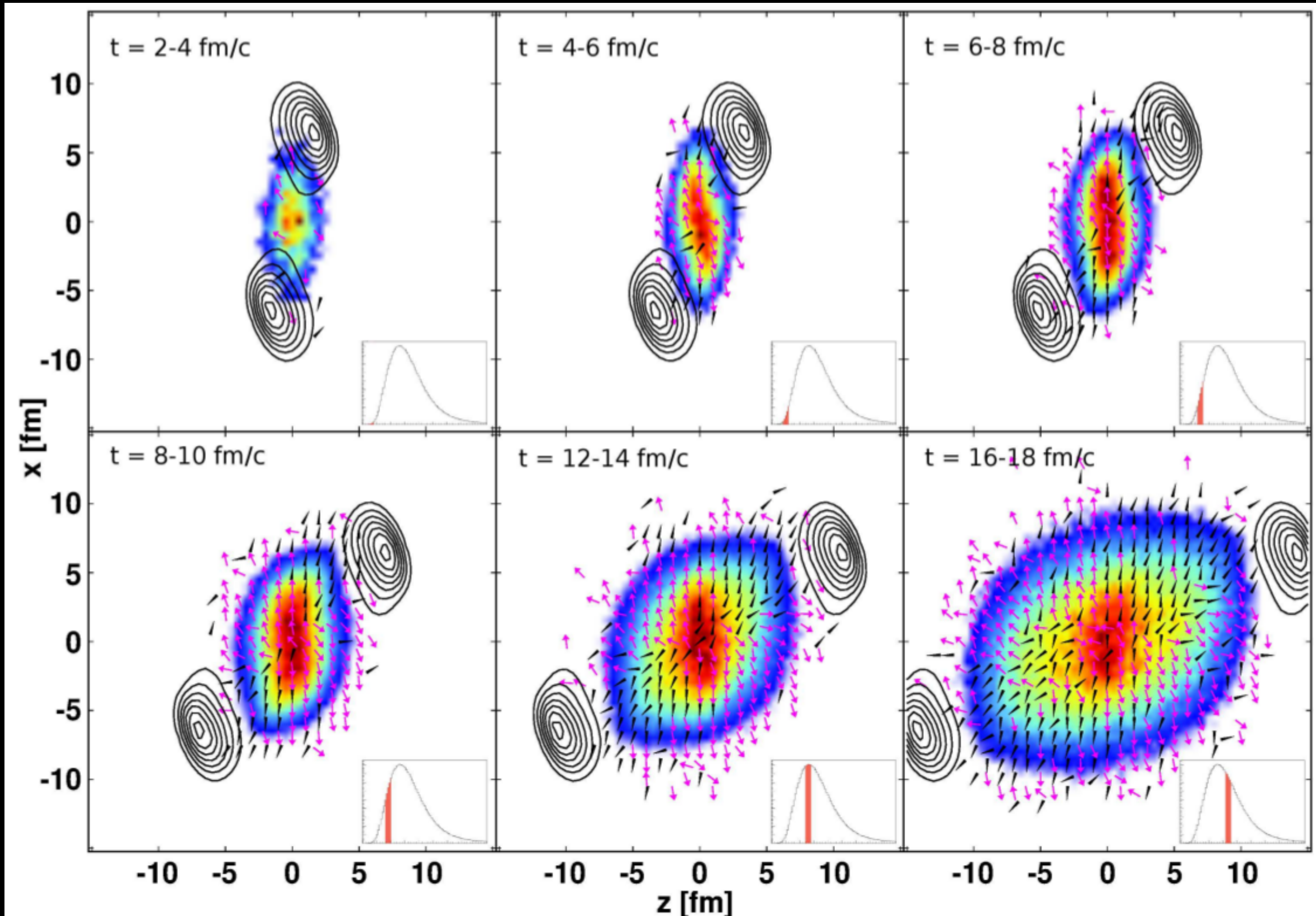
$$v_1\big|_{\text{proton}} = (1-r)\cdot v_1\big|_{\substack{\text{transported}\\\text{(net) protons}}} + r\cdot v_1\big|_{\text{antiprotons}}$$

$$r = \frac{\bar{p}}{p}$$



What drives directed flow?

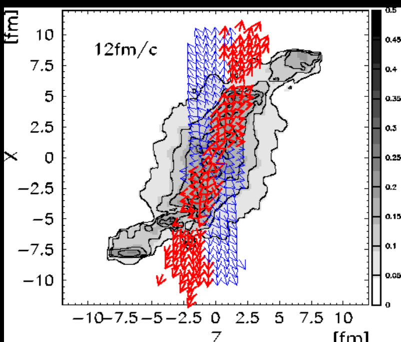
Graef, Lisa, Bleicher sub PRC [arXiv:1302.3408]()



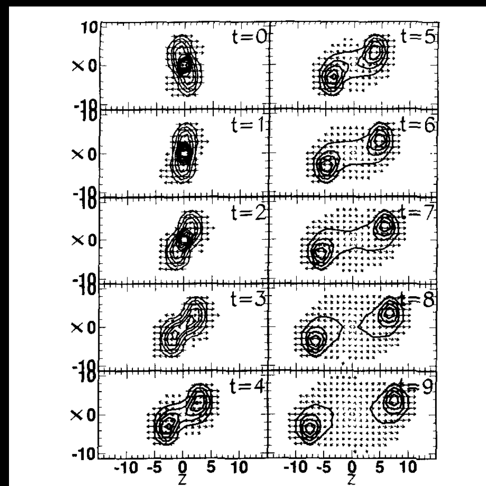
Most models at high energy suggest emission from a "tilted disc"...
... that must certainly evolve non-trivially with time

Tilted disc papers FLOW HBT

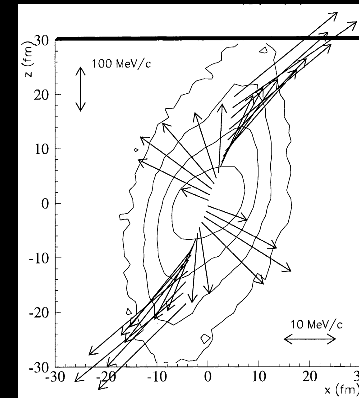
Antiflow of Nucleons at the Softest Point of the EoS
Brachmann et al, Phys.Rev. C61 (2000) 024909
nucl-th/9908010



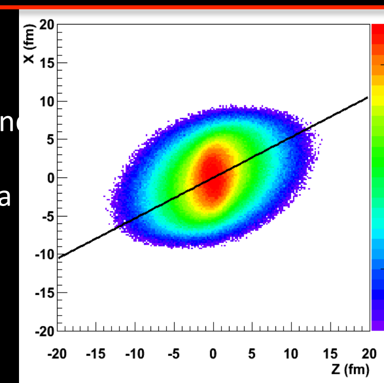
Scaling violation of transverse flow in HIC at AGS
Bravina, PLB 344 (1995) 49

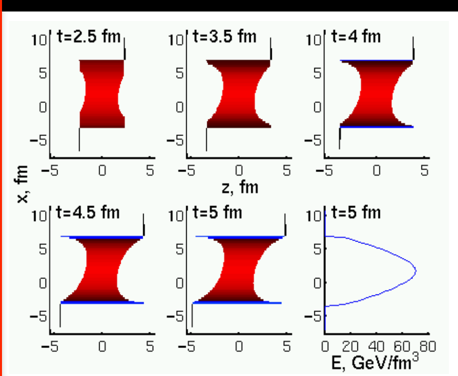


Tilted pion sources from azimuthally sensitive HBT
Lisa, Heinz, Weidemann
Phys.Lett. B489 (2000) 287-29 nucl-th/00030222



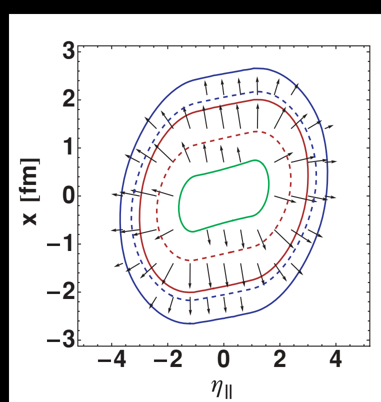
Correspondence between HBT radii and the emission zone in non-central HIC.
Mount, Graef, Mitrovski, Bleicher, Lisa
Phys.Rev. C84 (2011) 014908
arXiv:1012.5941



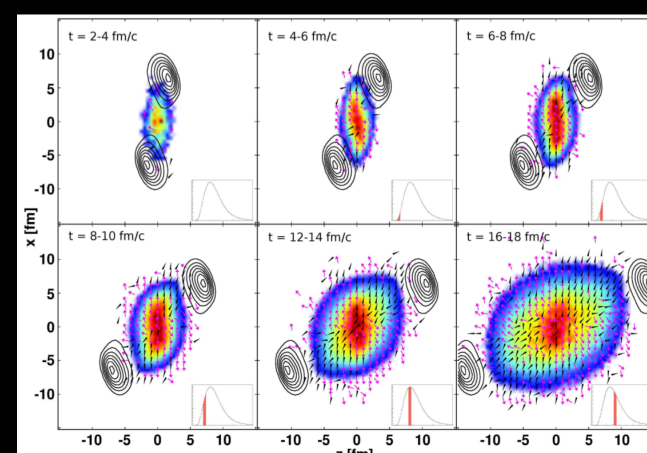


Effective string-rope model...
Magas, Csernai, Strottmann
Nucl.Phys. A712 (2002) 167-204
arXiv:hep-ph/0202085

Directed flow in ultrarelativistic heavy-ion collisions
Bozek and Wyskiel
PHYSICAL REVIEW C
81, 054902 (2010)



A twisted emission geometry in non-central Pb+Pb collisions measurable via azimuthally sensitive HBT
Graef, Lisa, Bleicher sub PRC arXiv:1302.3408

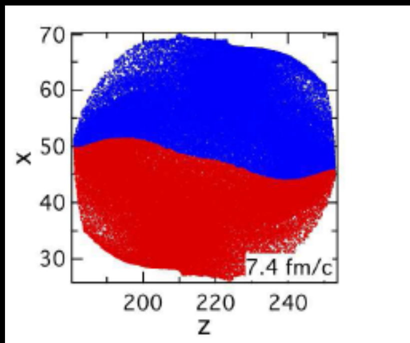


Recent Work by Csernai

FLOW | **HBT**

Laszlo -- Focus on RHIC!

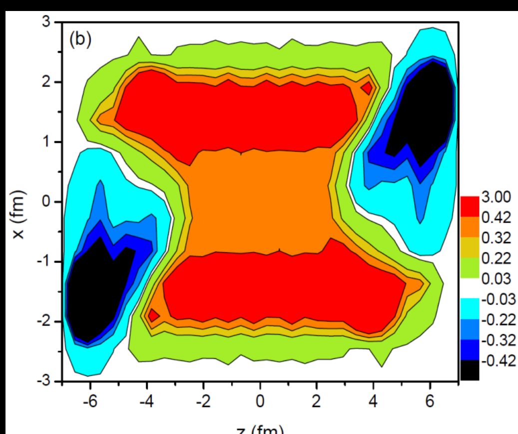
L.P. Csernai[1,2,3], D.D. Strottman[2,3], and Cs. Anderlik[4]
PHYSICAL REVIEW C **85**, 054901 (2012)



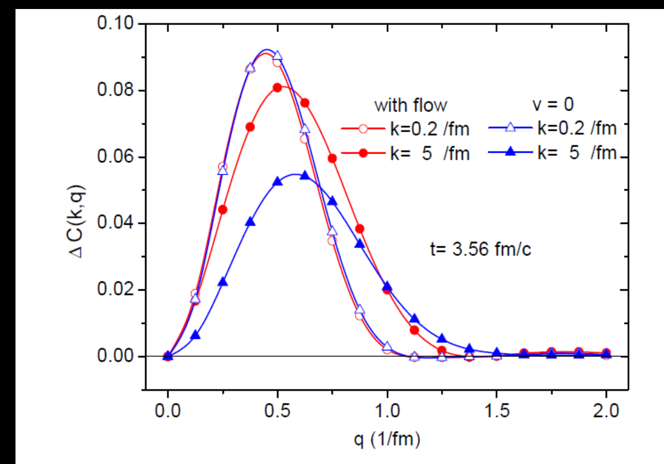
PHYSICAL REVIEW C **87**, 034906 (2013)

Flow vorticity in peripheral high-energy heavy-ion collisions

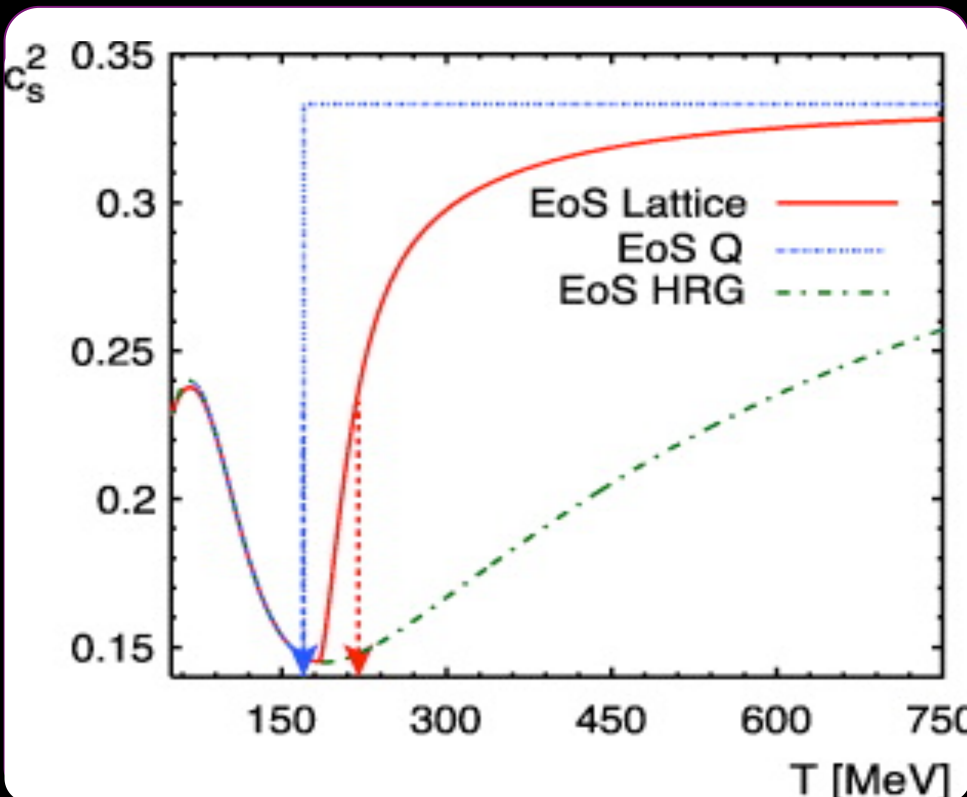
L. P. Csernai,[1] V. K. Magas,[2] and D. J. Wang[1]

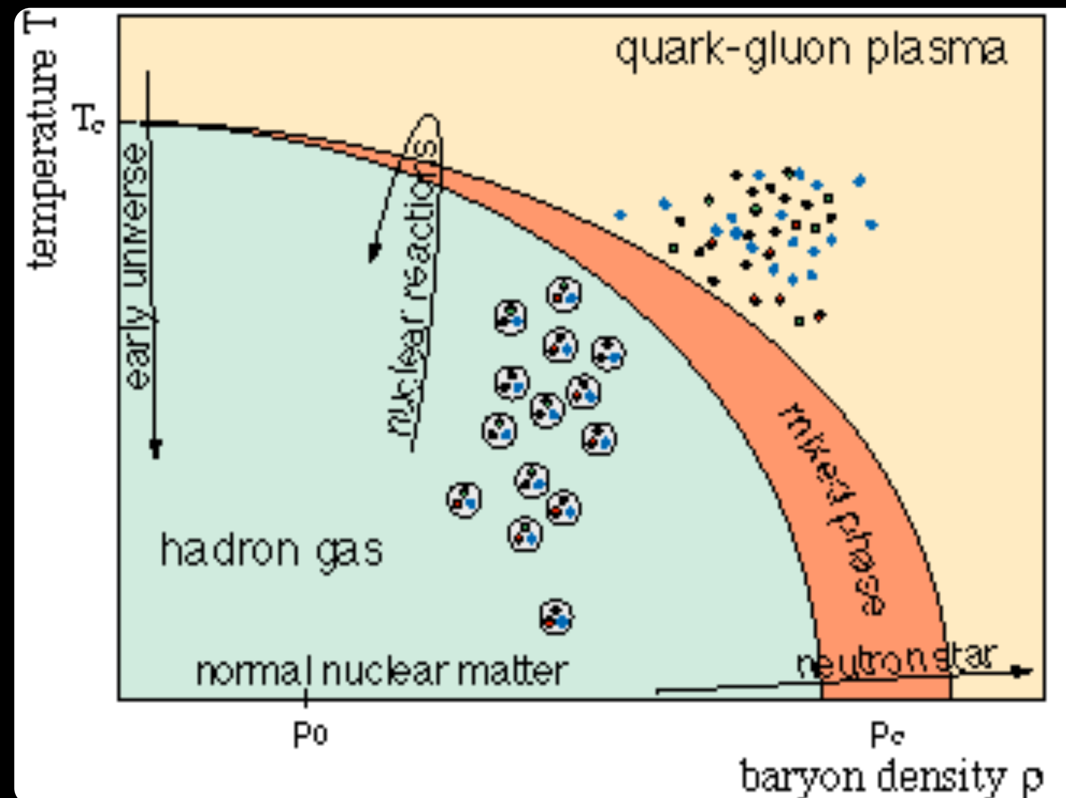


[L.P. Csernai, S. Velle, subm. to PRC]



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

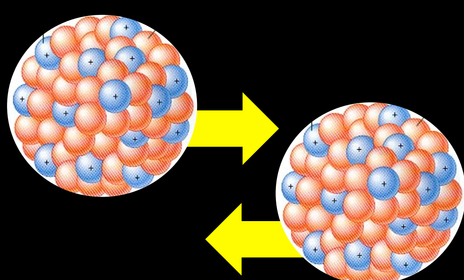


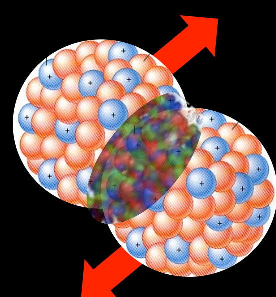


large sound velocity → repulsion

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

● net ("valence") proton





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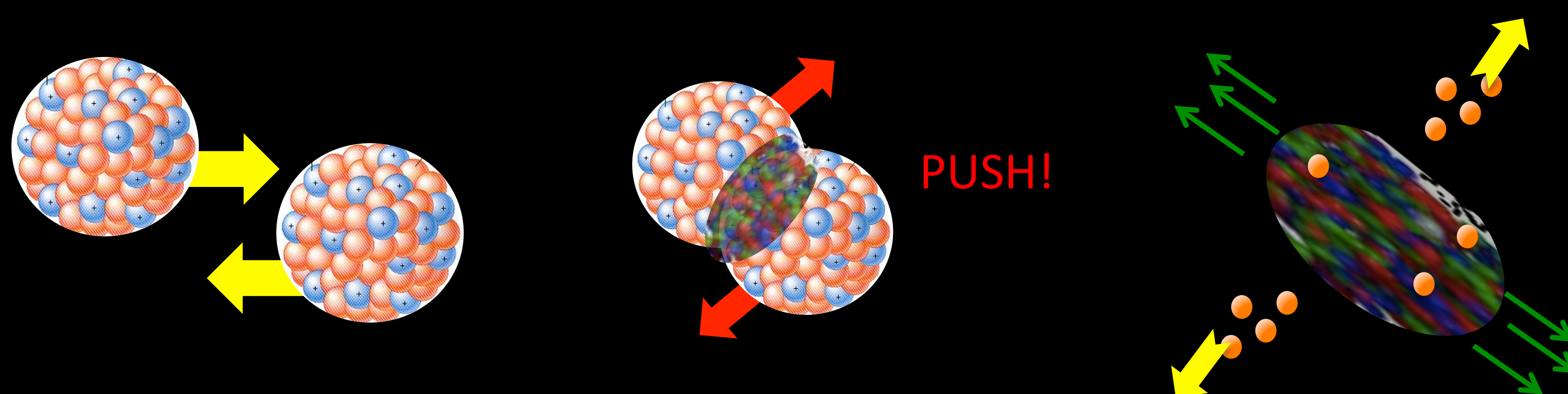
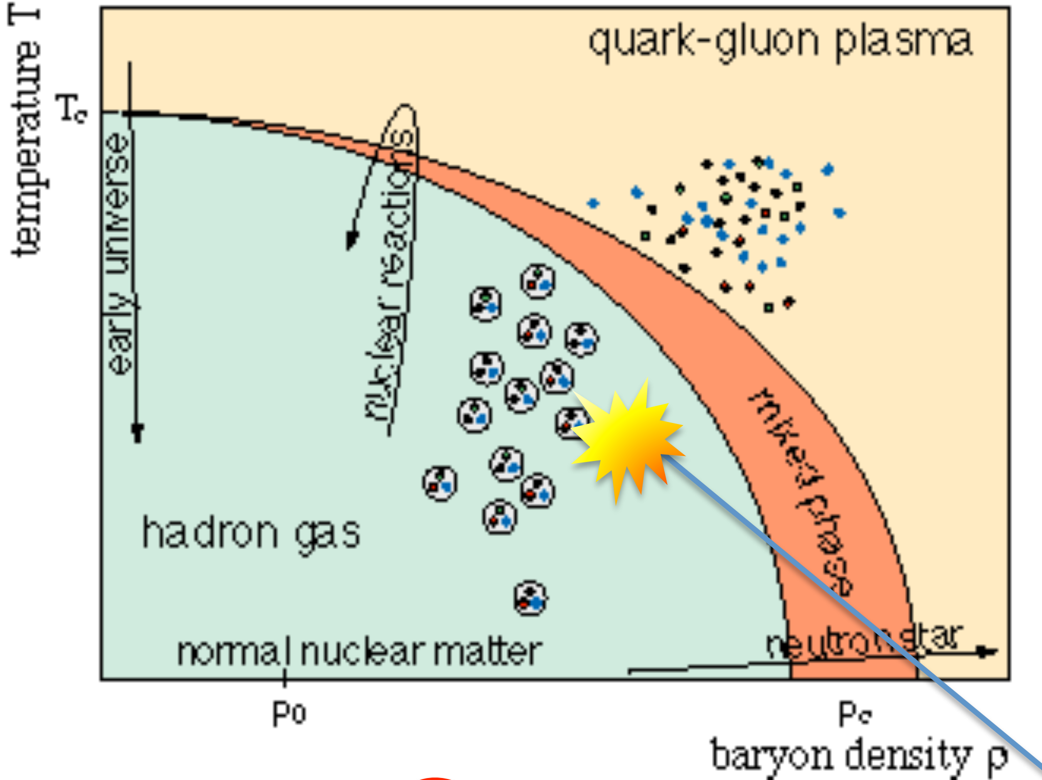
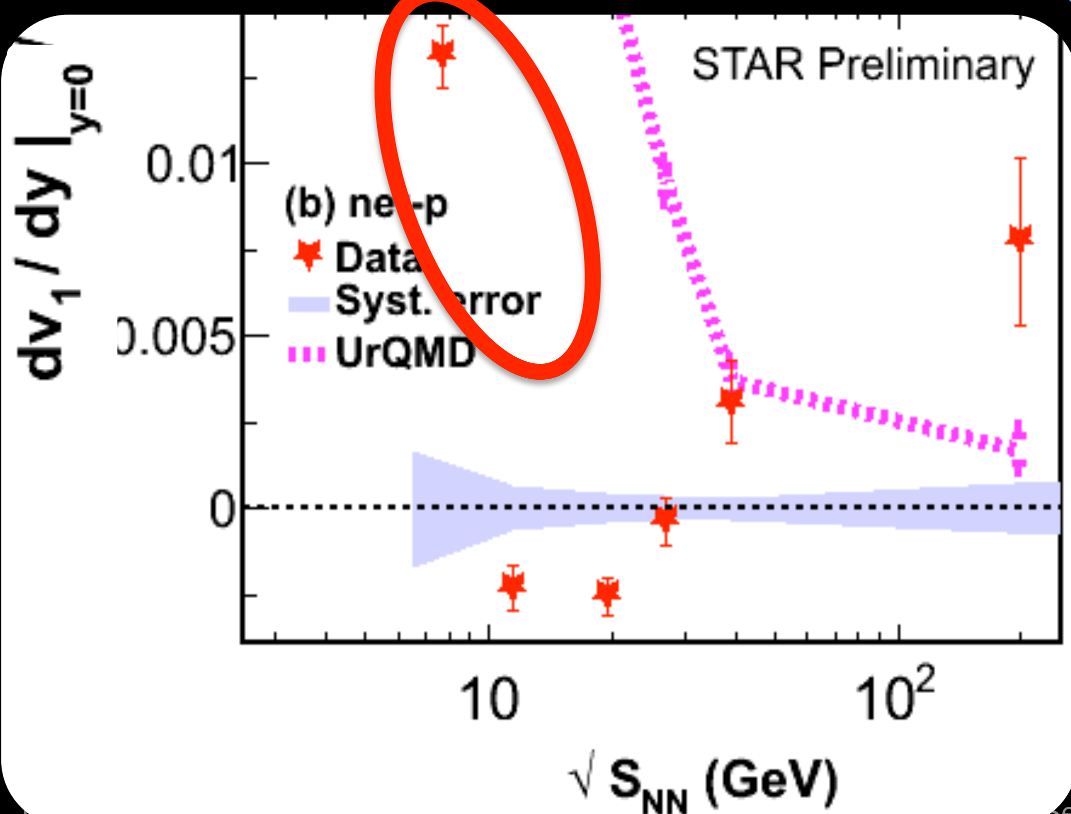
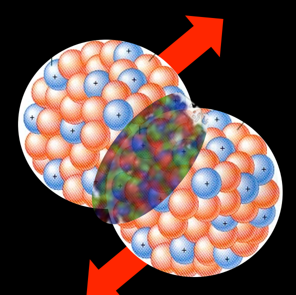
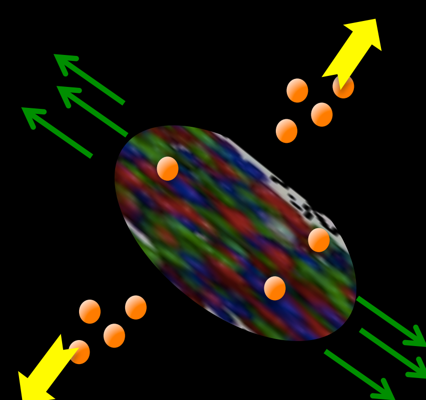


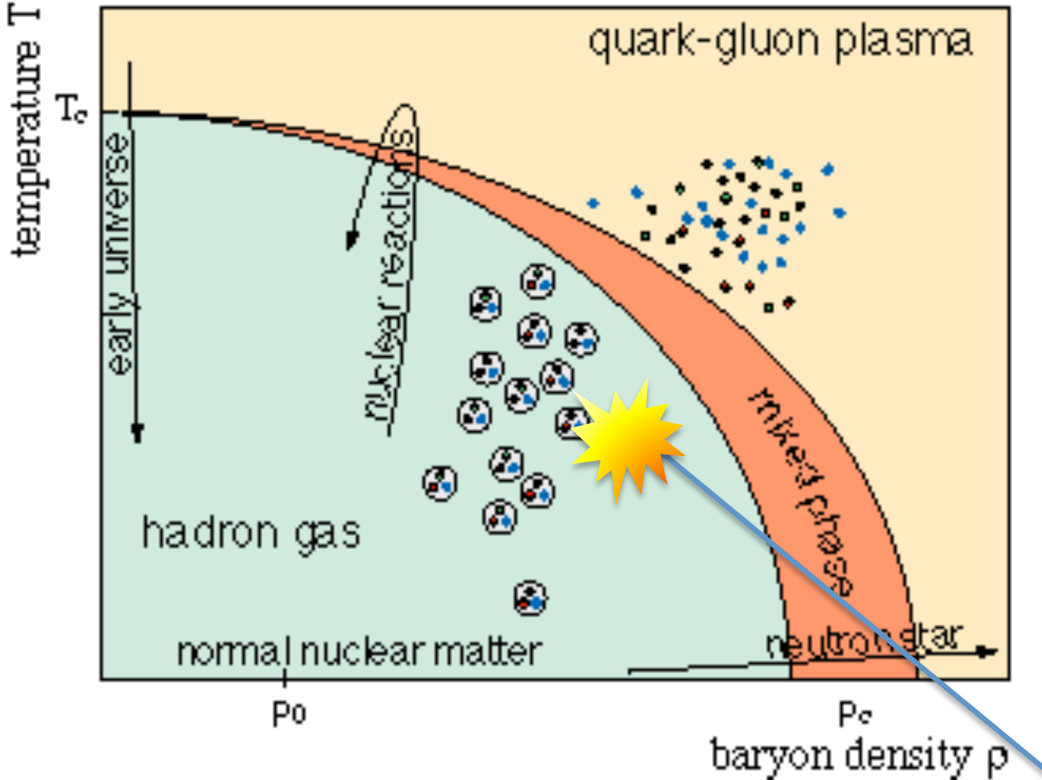


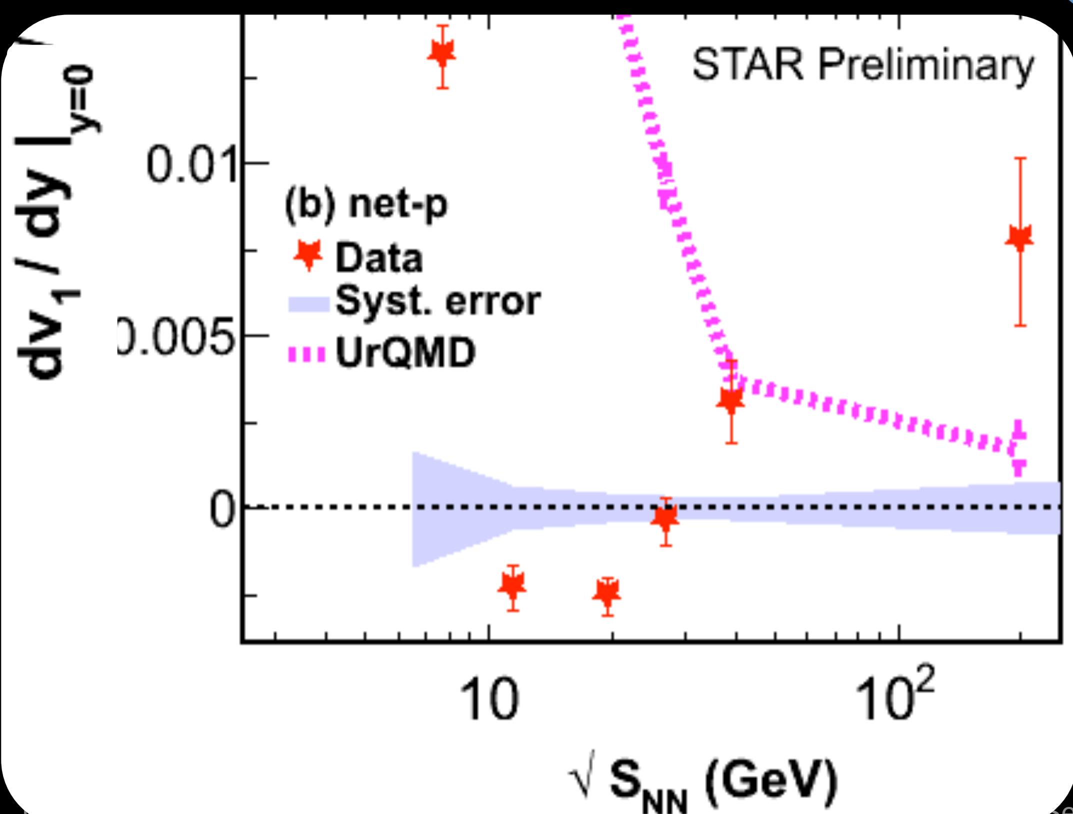


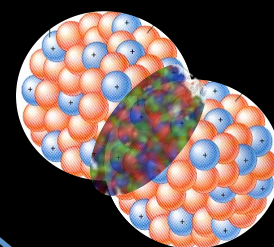




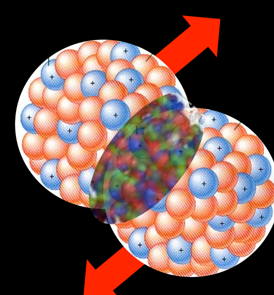
net ("valence") proton


quark-gluon plasma
temperature T
Tc
early universe
nuclear reactions
mixed phase
hadron gas
normal nuclear matter
neutron star
ρ0
ρc
baryon density ρ

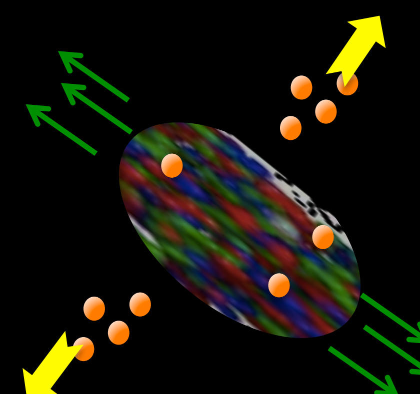

STAR Preliminary
dv1 / dy |y=0
(b) net-p
Data
Syst. error
UrQMD
0.01
0.005
0
10
10^2
√ SNN (GeV)

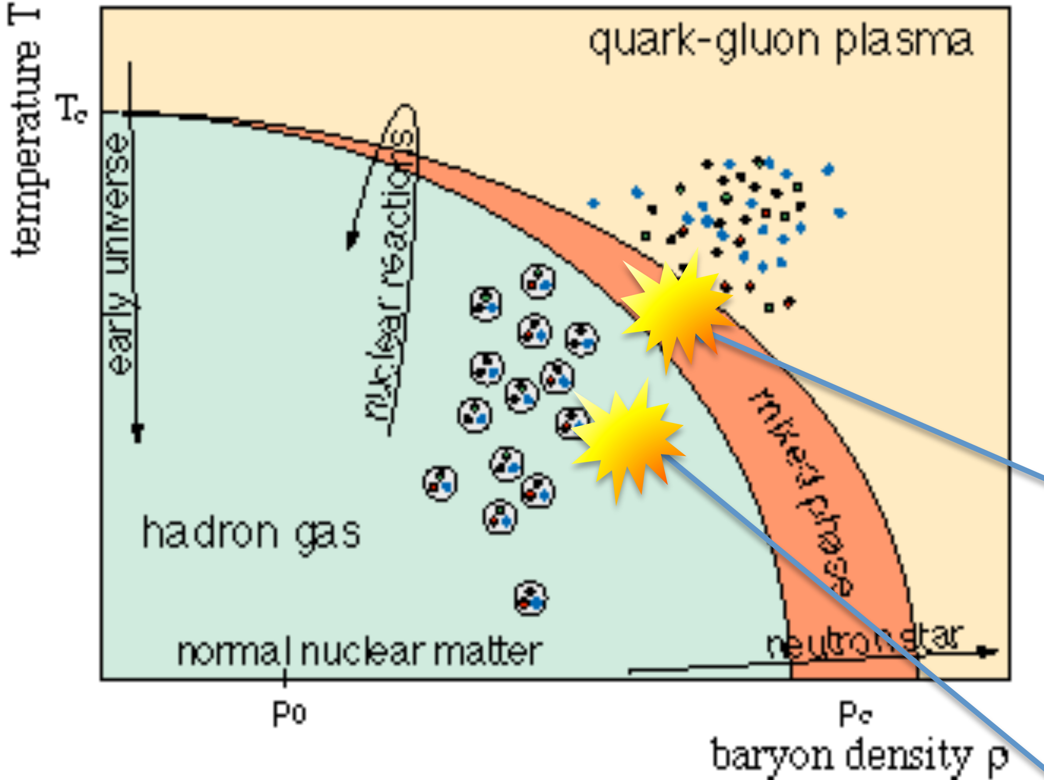


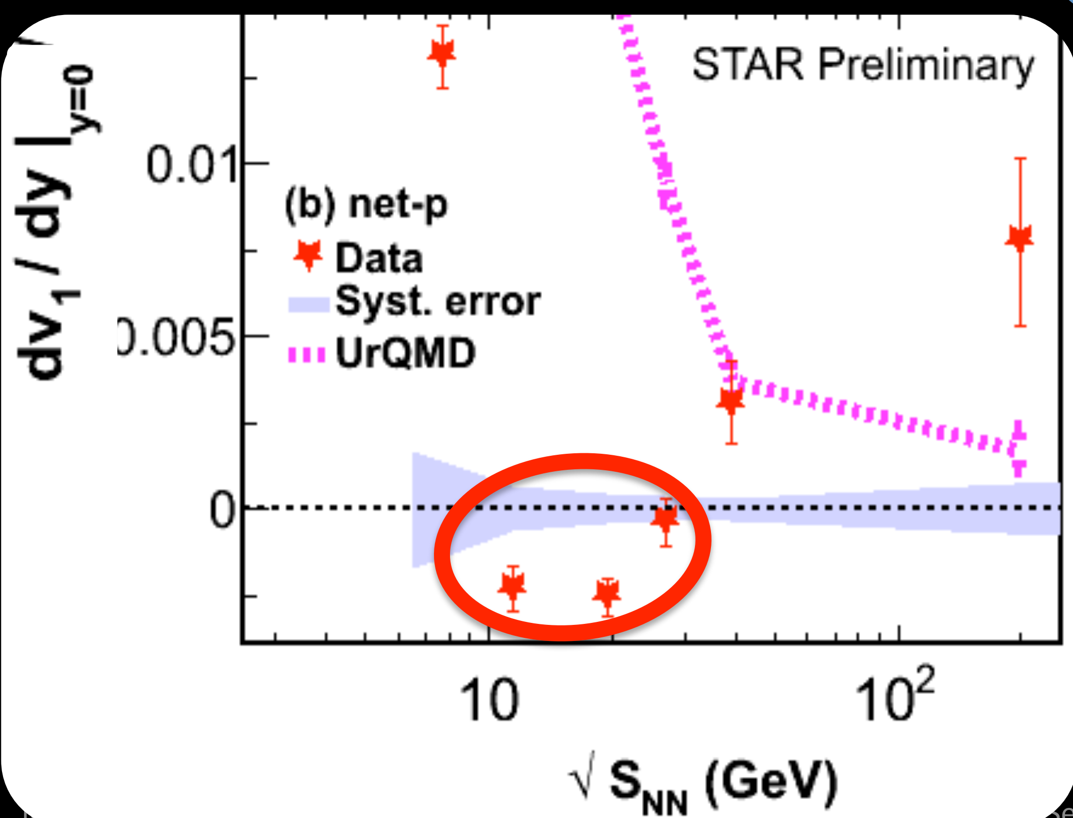
SOFT…

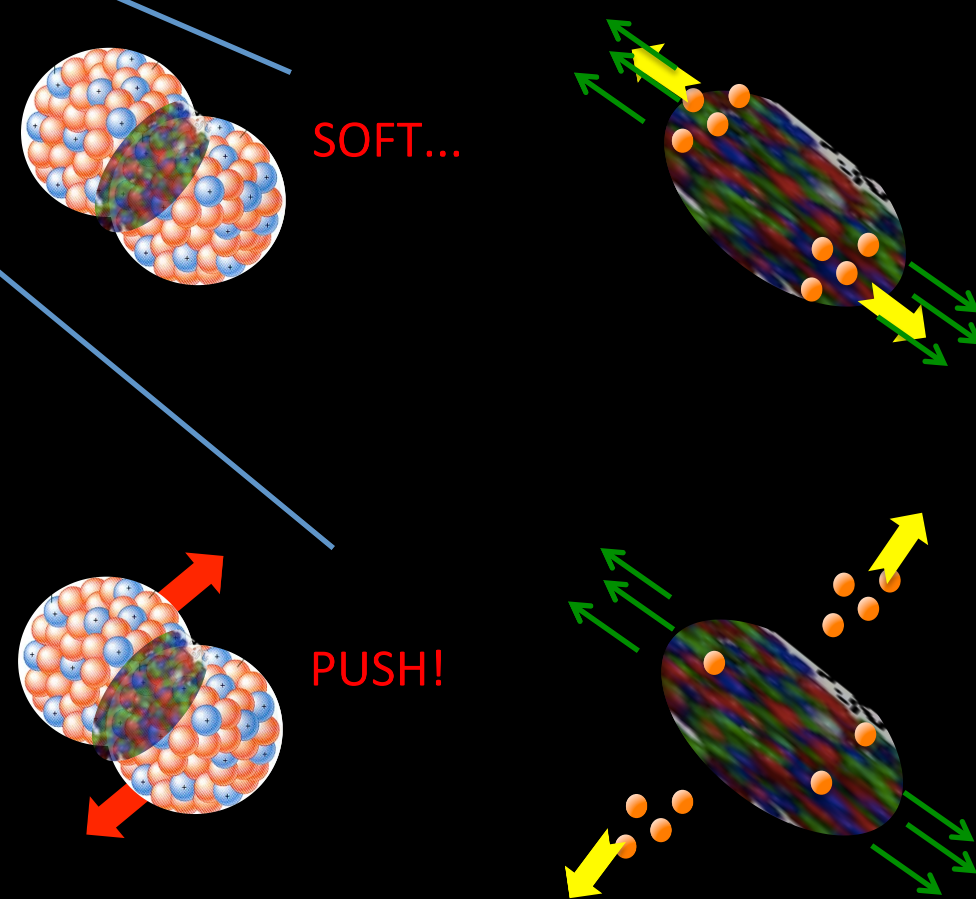


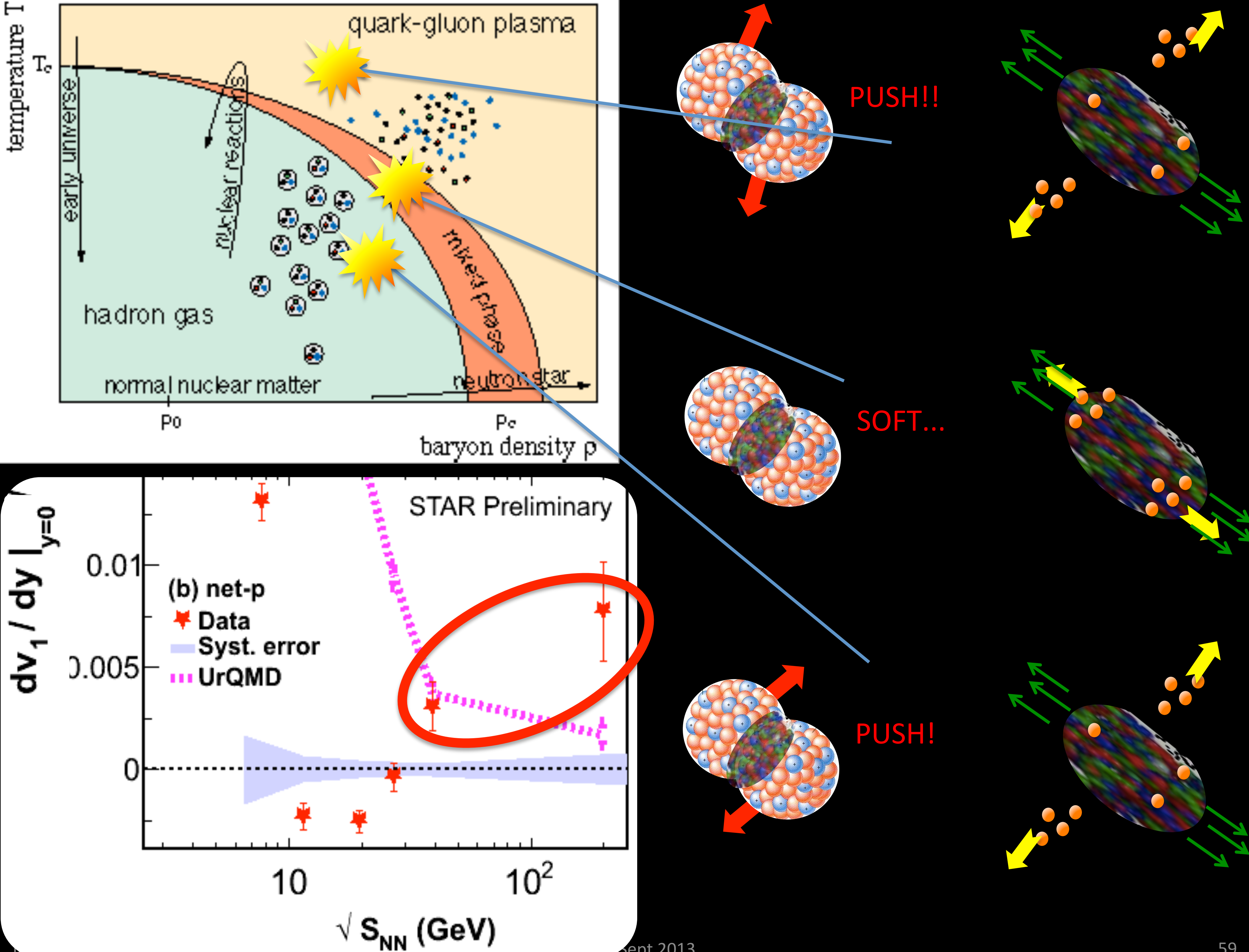
PUSH!




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


STAR Preliminary
$dv_1 / dy |_{y=0}$
0.01
0.005
0
(b) net-p
Data
Syst. error
UrQMD
10
10^2
$\sqrt{S_{NN}}$ (GeV)


SOFT…
PUSH!


quark-gluon plasma
temperature T
T_c
early universe
nuclear reactions
hadron gas
mixed phase
normal nuclear matter
neutron star
ρ_0
ρ_c
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PUSH!!
SOFT...
PUSH!
STAR Preliminary
(b) net-p
Data
Syst. error
UrQMD
$dv_1 / dy |_{y=0}$
0.01
0.005
0
10
10^2
$\sqrt{S_{NN}}$ (GeV)

Summary

- Very successful beam energy scan program begun 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 begun at RHIC
  - Only a sampling of data shown
- QGP signals “turn off” in scanned region
  - maybe... (see Paul’s talk)
- 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

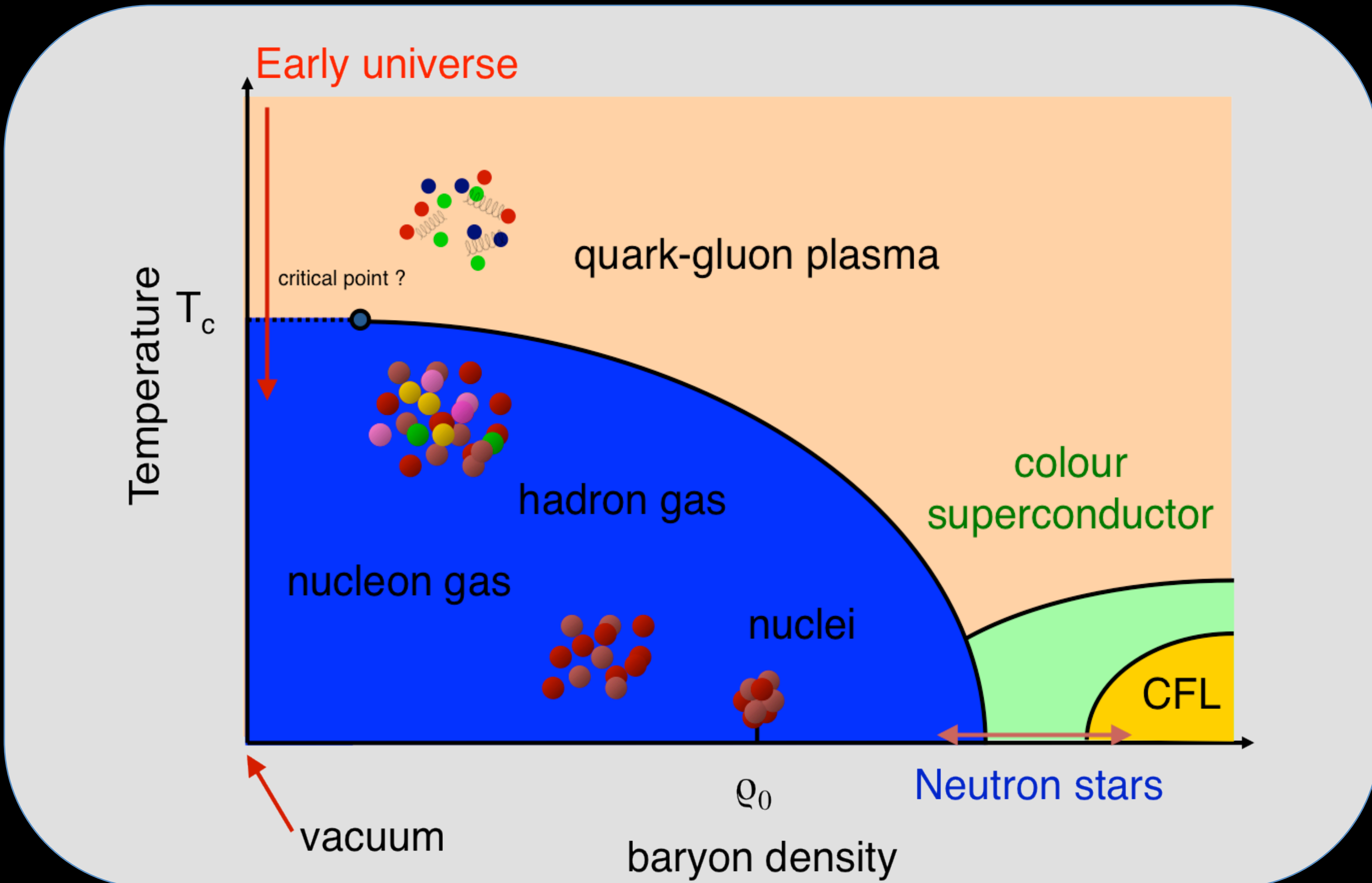
Outlook

- Multi-faceted approach: Special focus on 1st-order observables
  - Lambda v1
  - first-order azimuthal HBT
  - Lambda polarization

Outlook

- Multi-faceted approach: Special focus on 1st-order observables
  - Lambda v1
  - first-order azimuthal HBT
  - Lambda polarization
- urge theorists to apply realistic, 3D transport with phase features
- finer energy scan in follow-up BES II
- fixed-target program being explored...

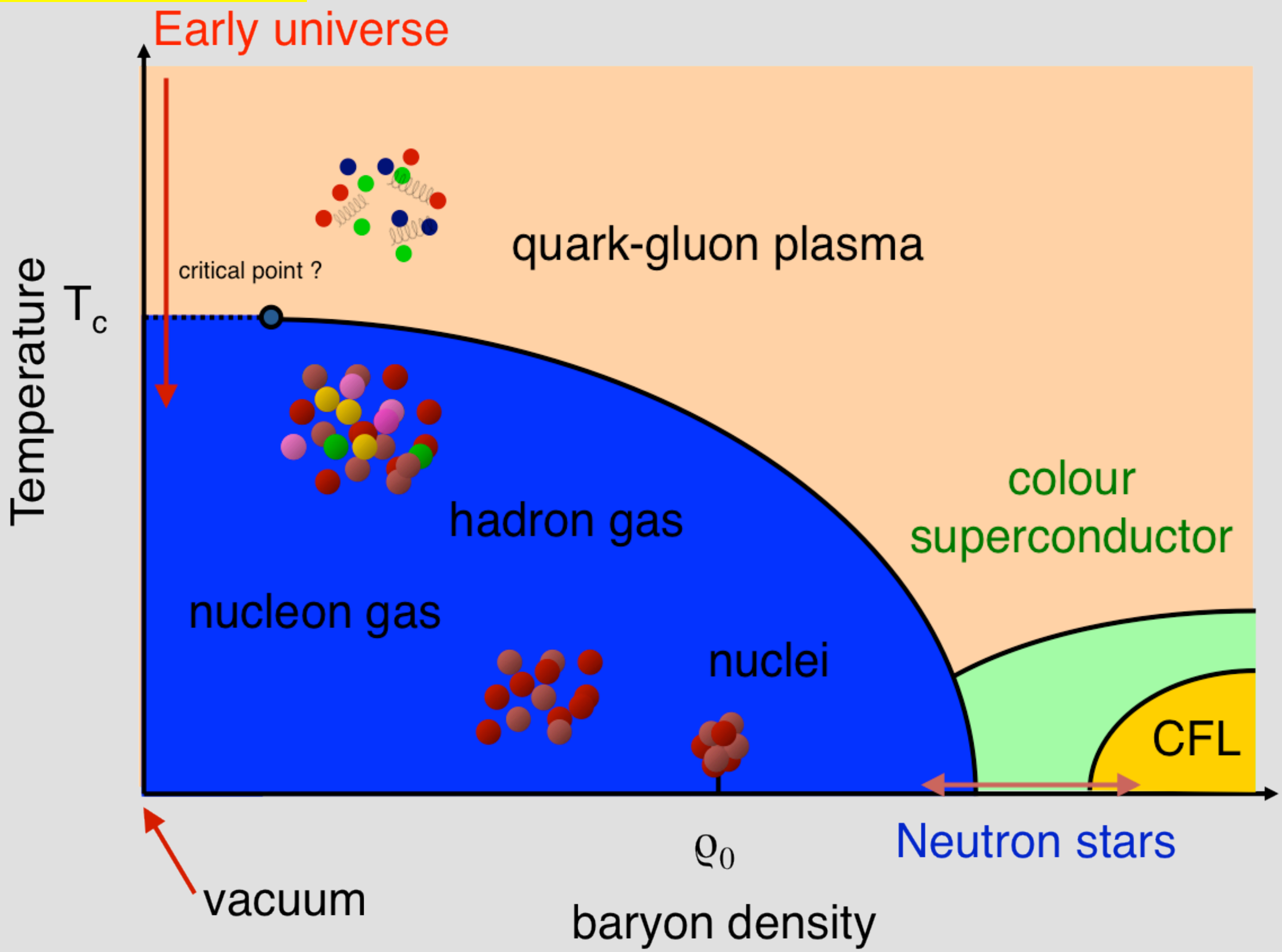
Motivation for Beam Energy Scan (BES) program



Motivation for Beam Energy Scan (BES) program

the field of relativistic heavy ion physics (IMHO*)

Can this go into a textbook?



* IMHO = In Mike's Humble Opinion

Motivation for Beam Energy Scan (BES) program

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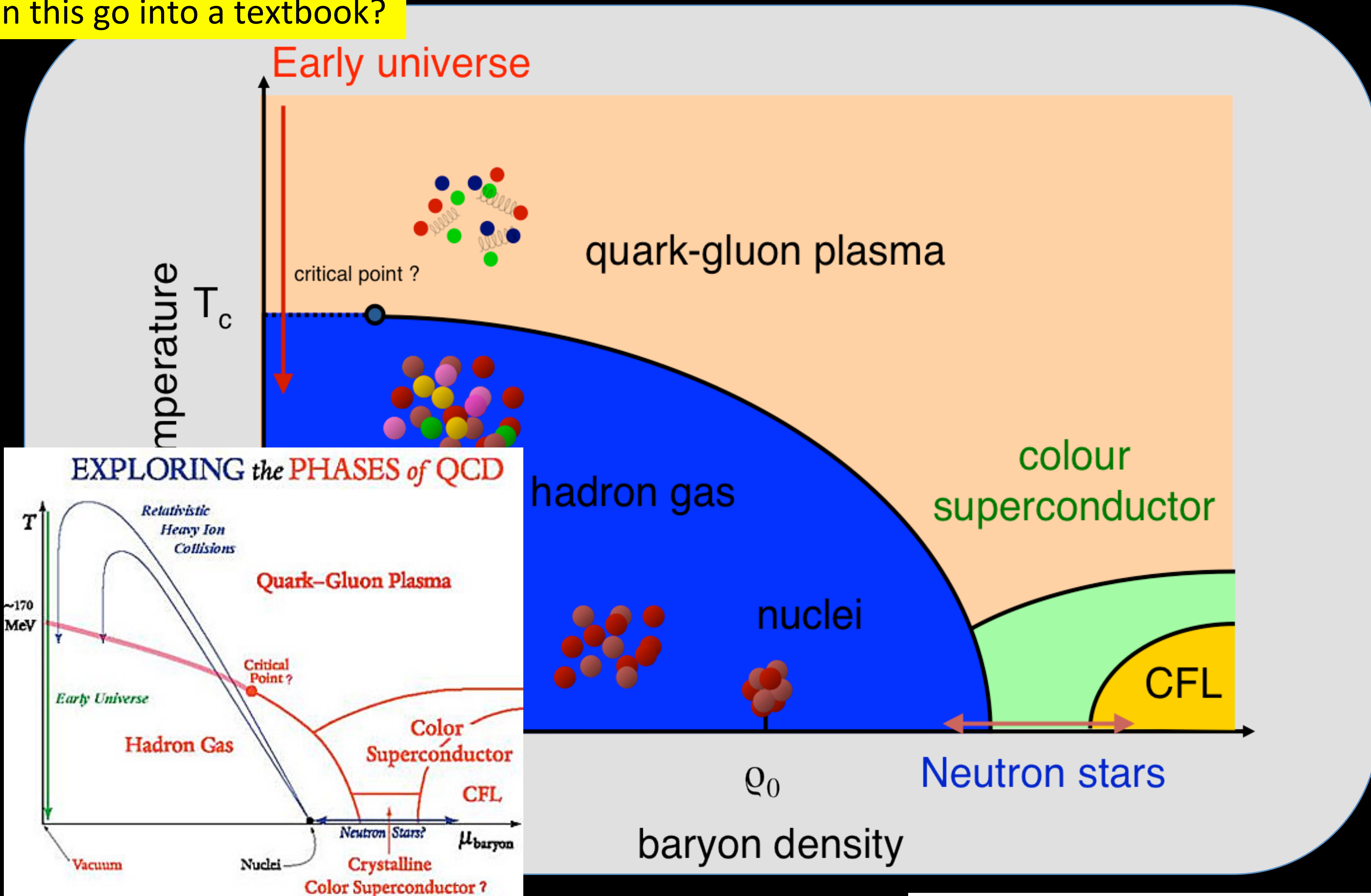

* IMHO = In Mike's Humble Opinion

Motivatio ... ysics (IMHO*)

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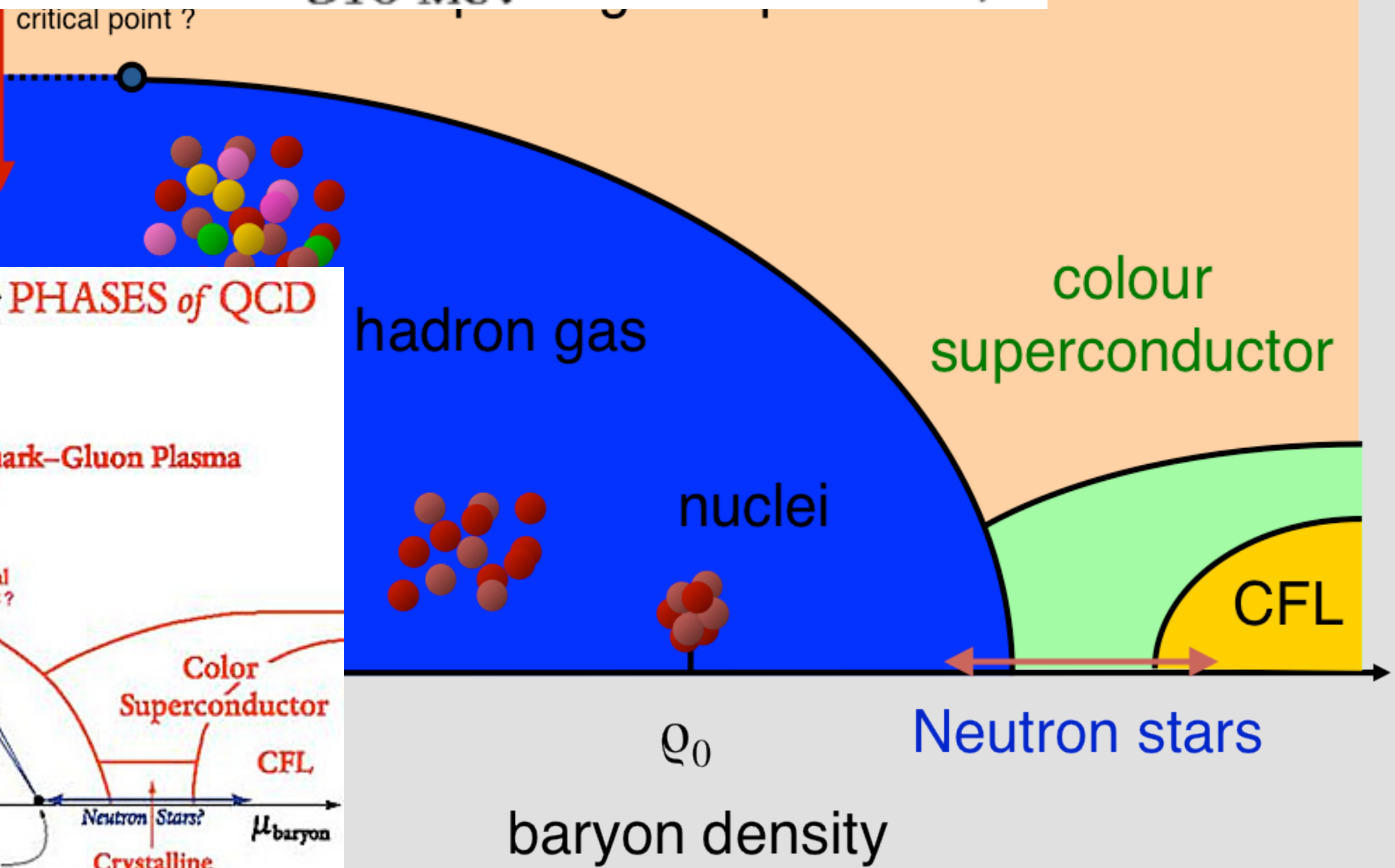

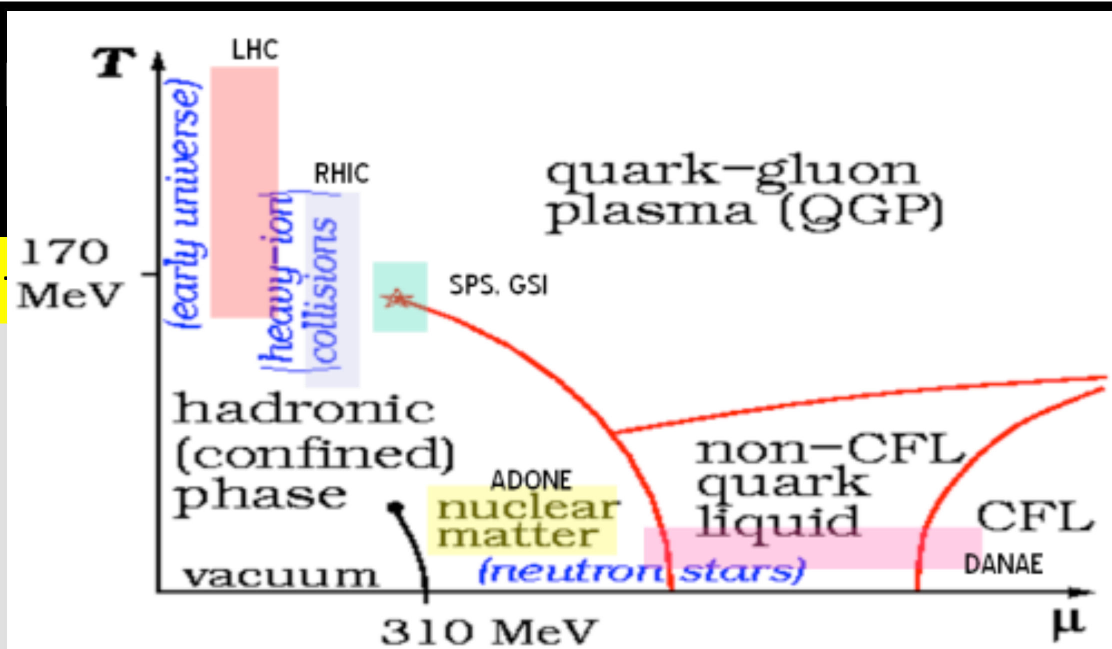

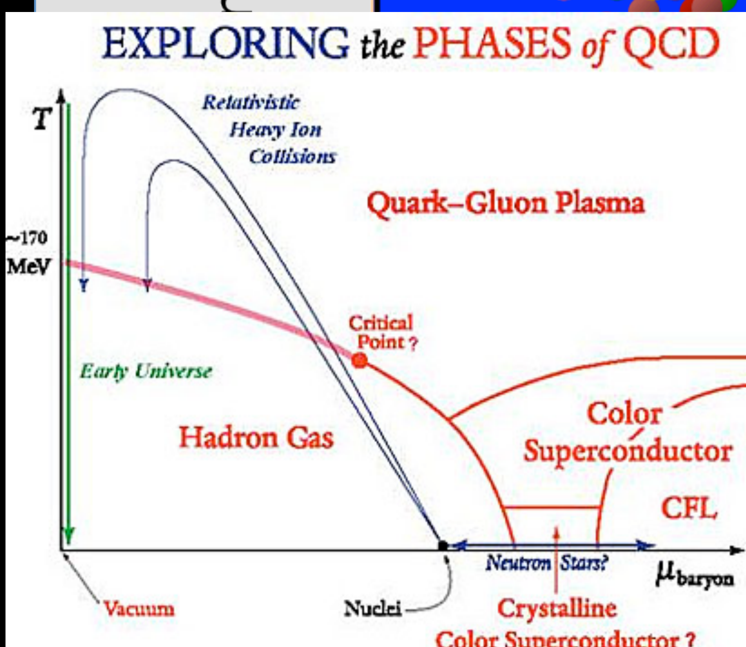

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Motivatio… …ysics (IMHO*)

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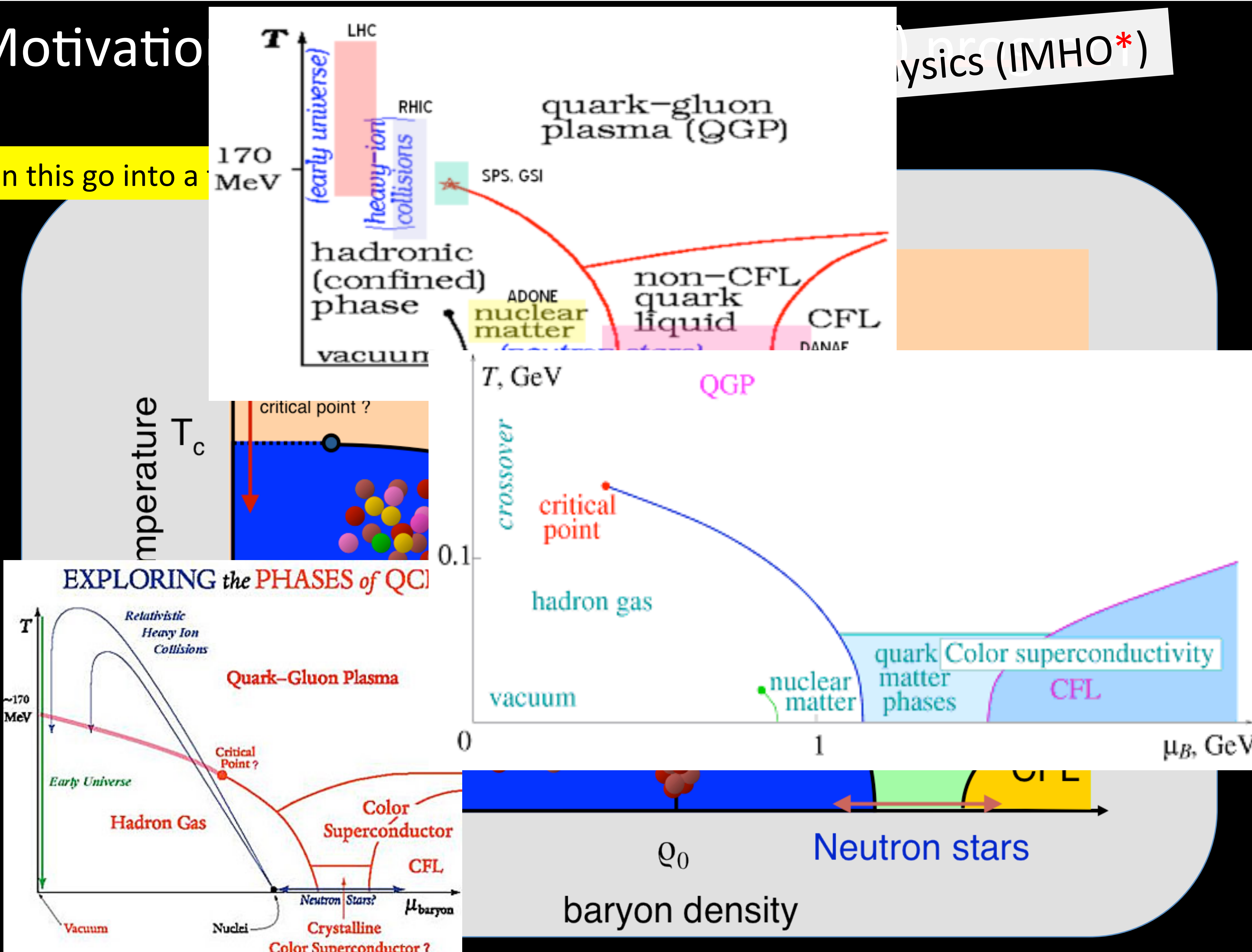

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Motivatio... ...ysics (IMHO*)

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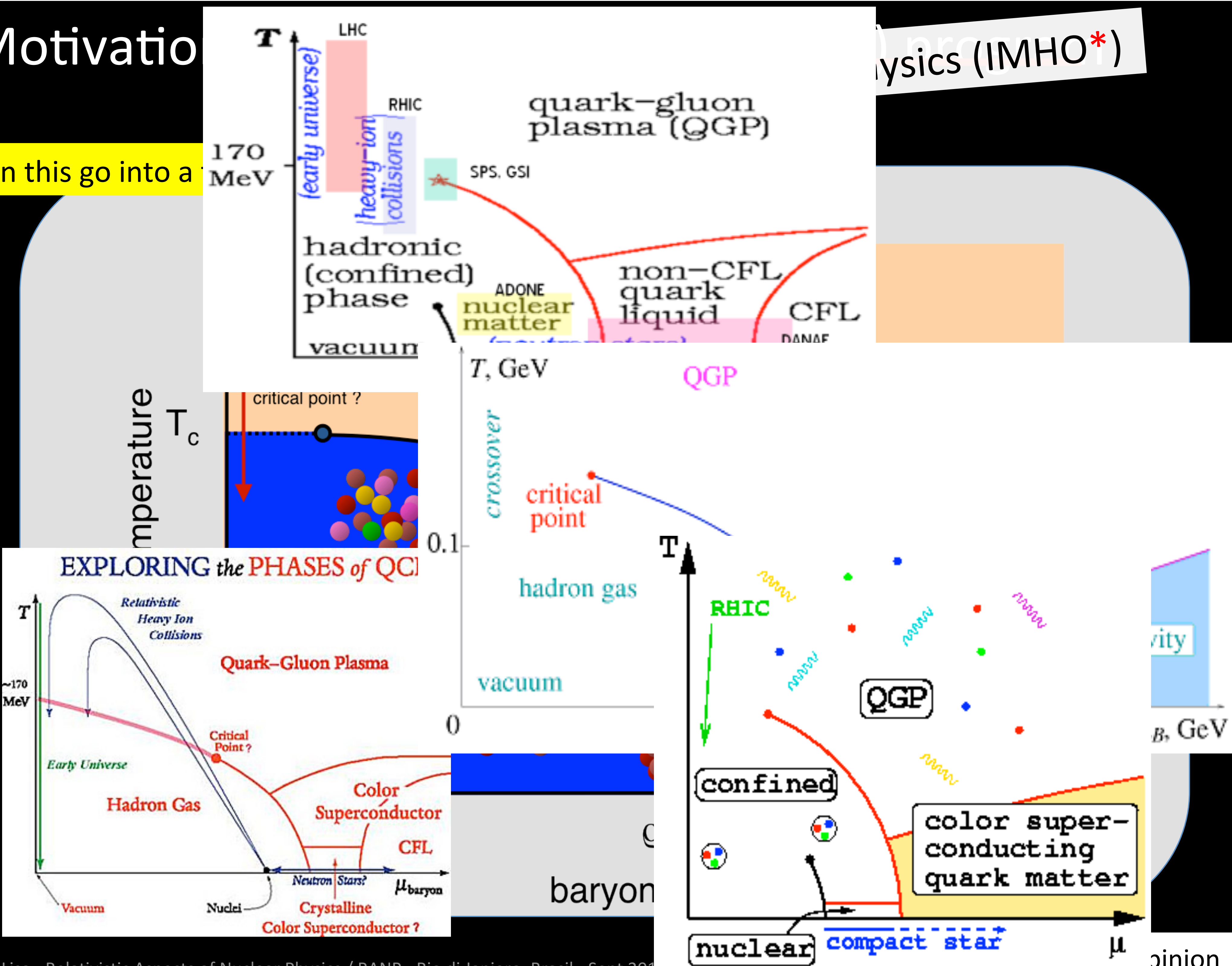
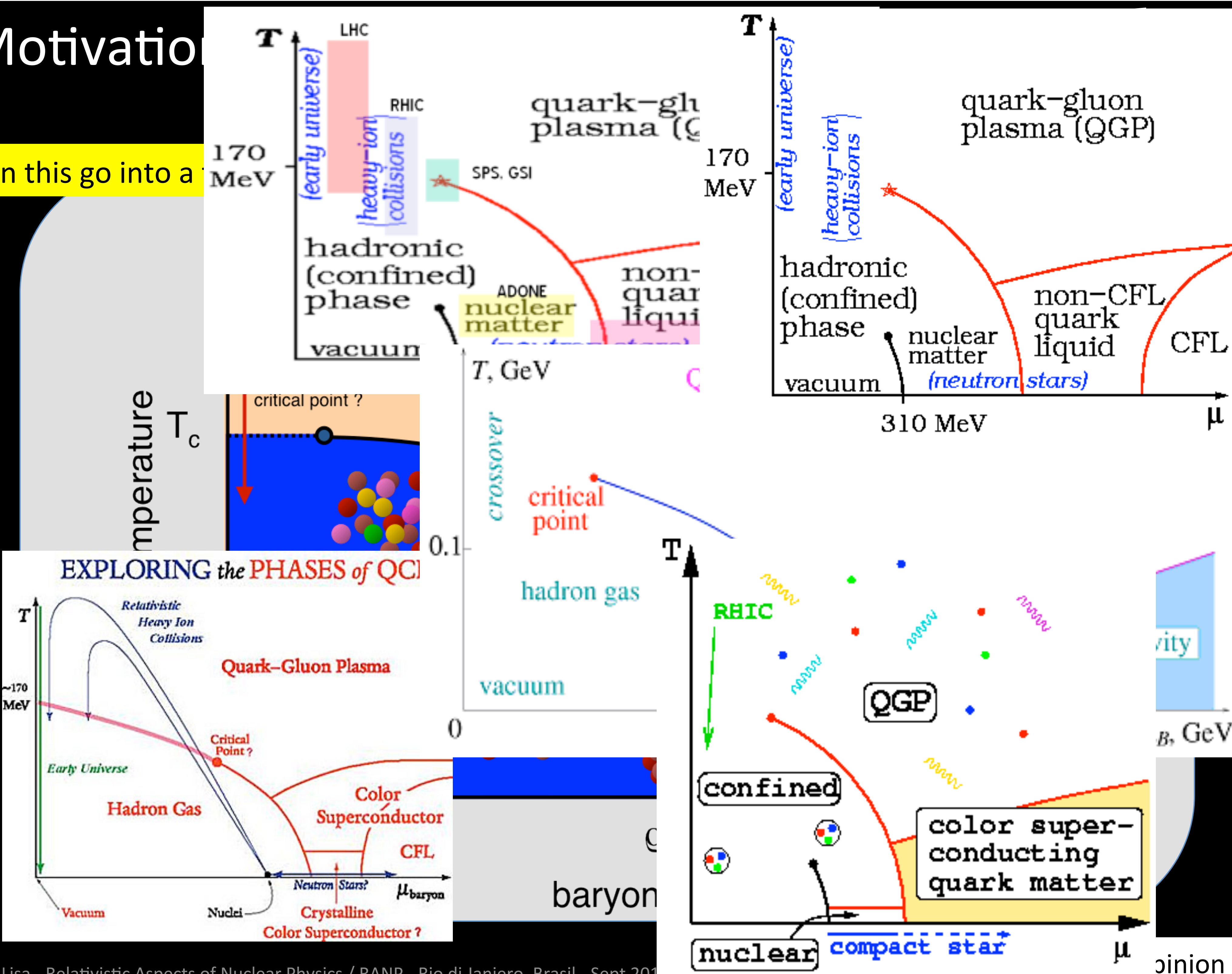


...pinion

Motivatio

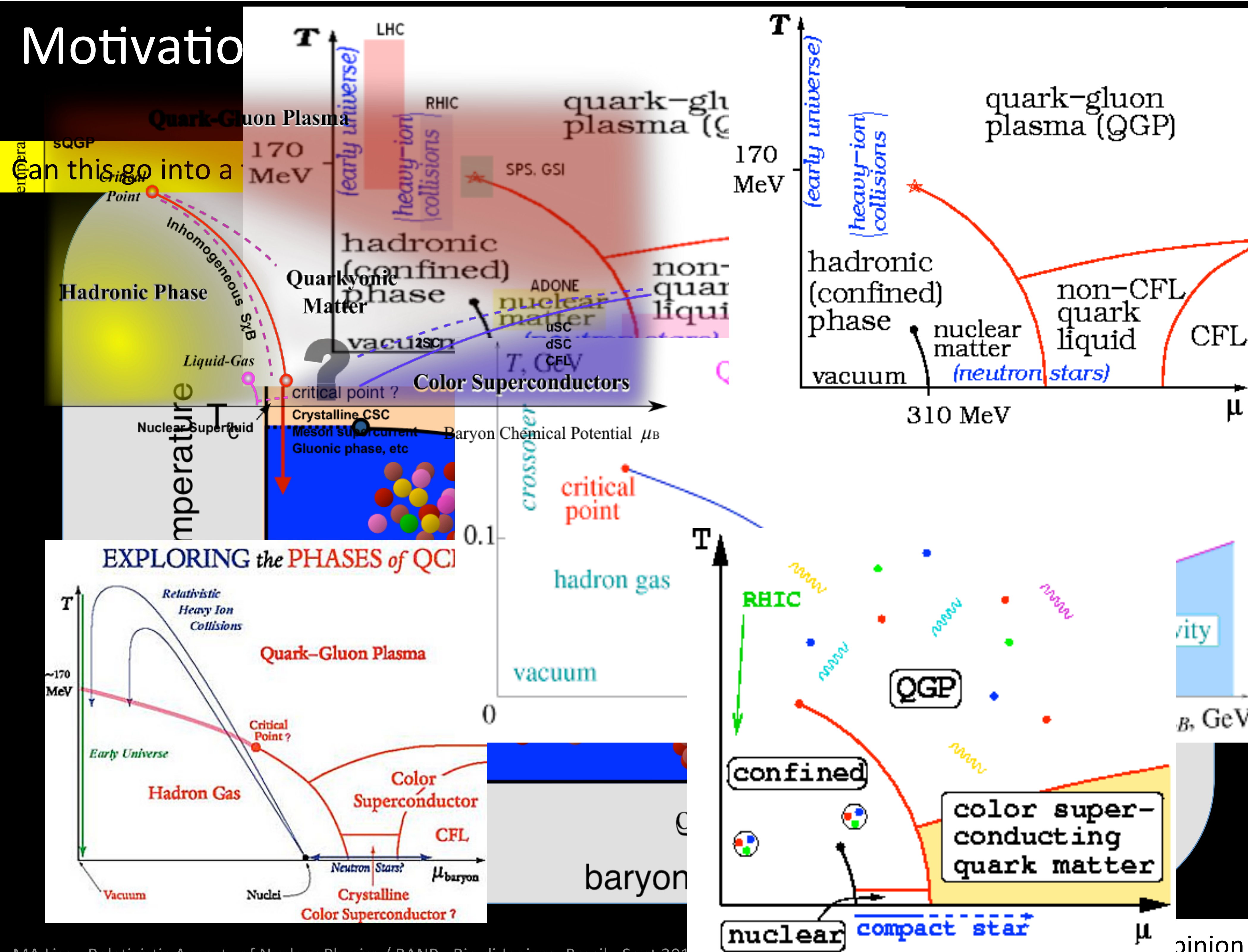
Can this go into a



opinion

Motivatio

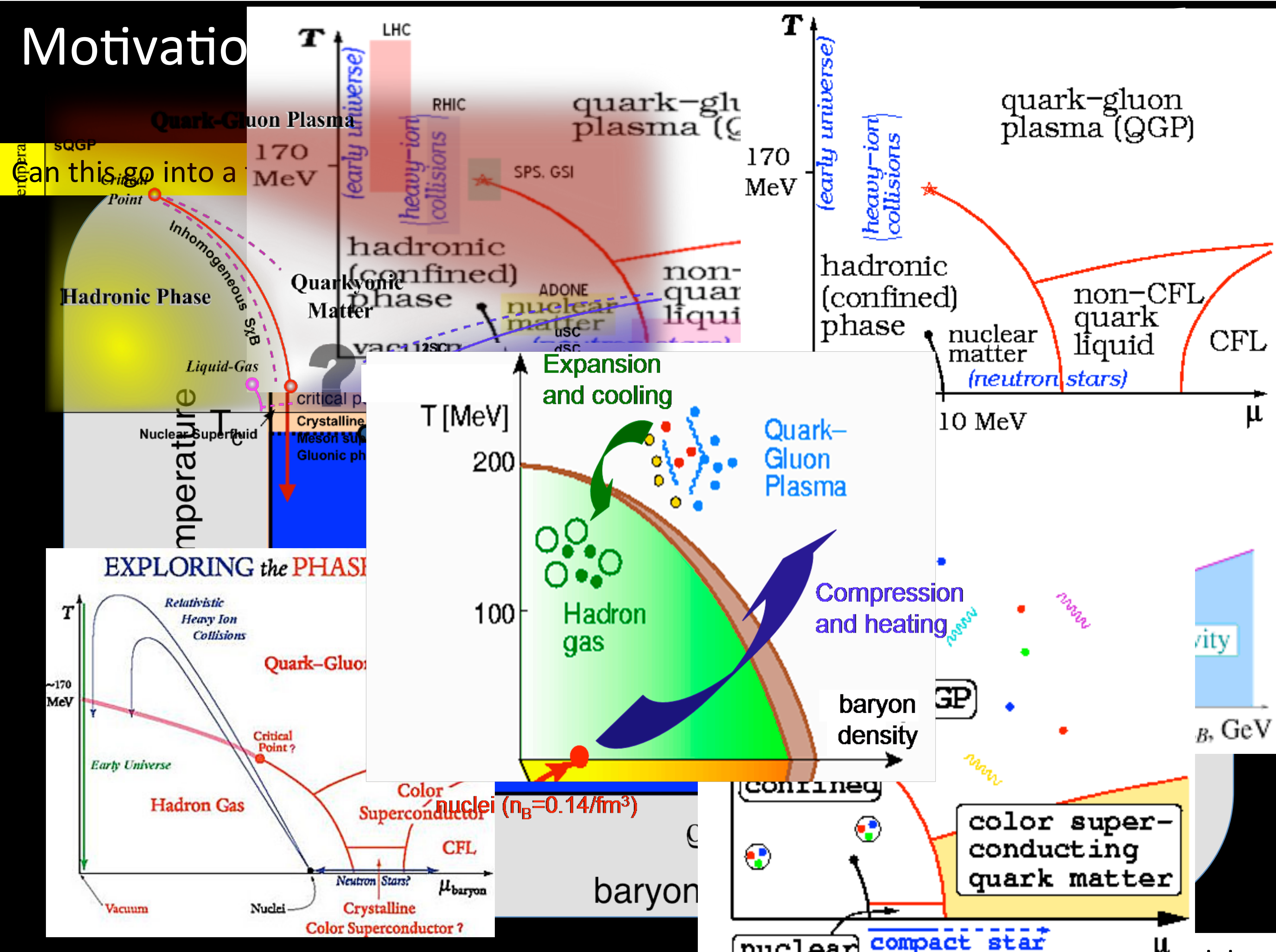
Can this go into a



pinion

Motivatio

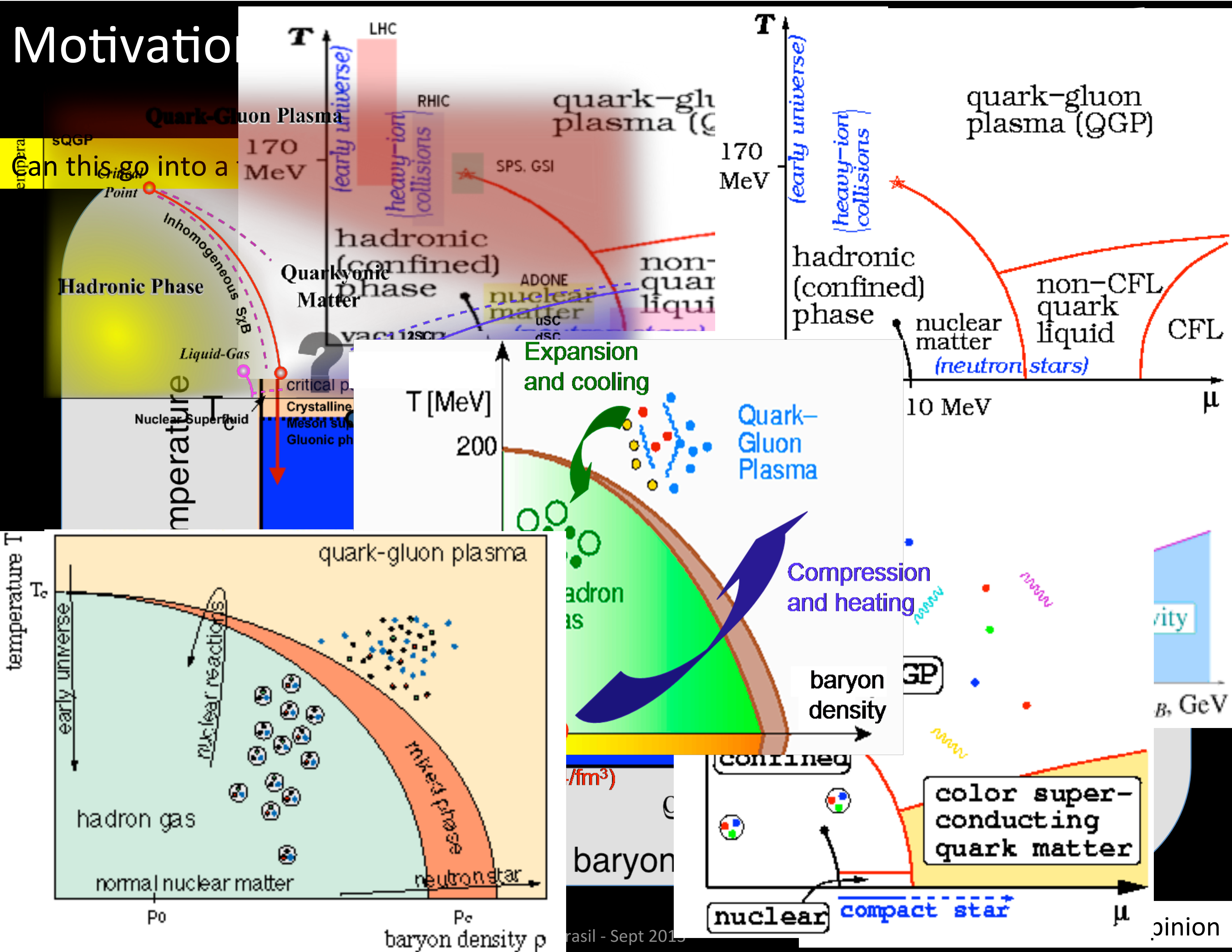
Can this go into a



pinion

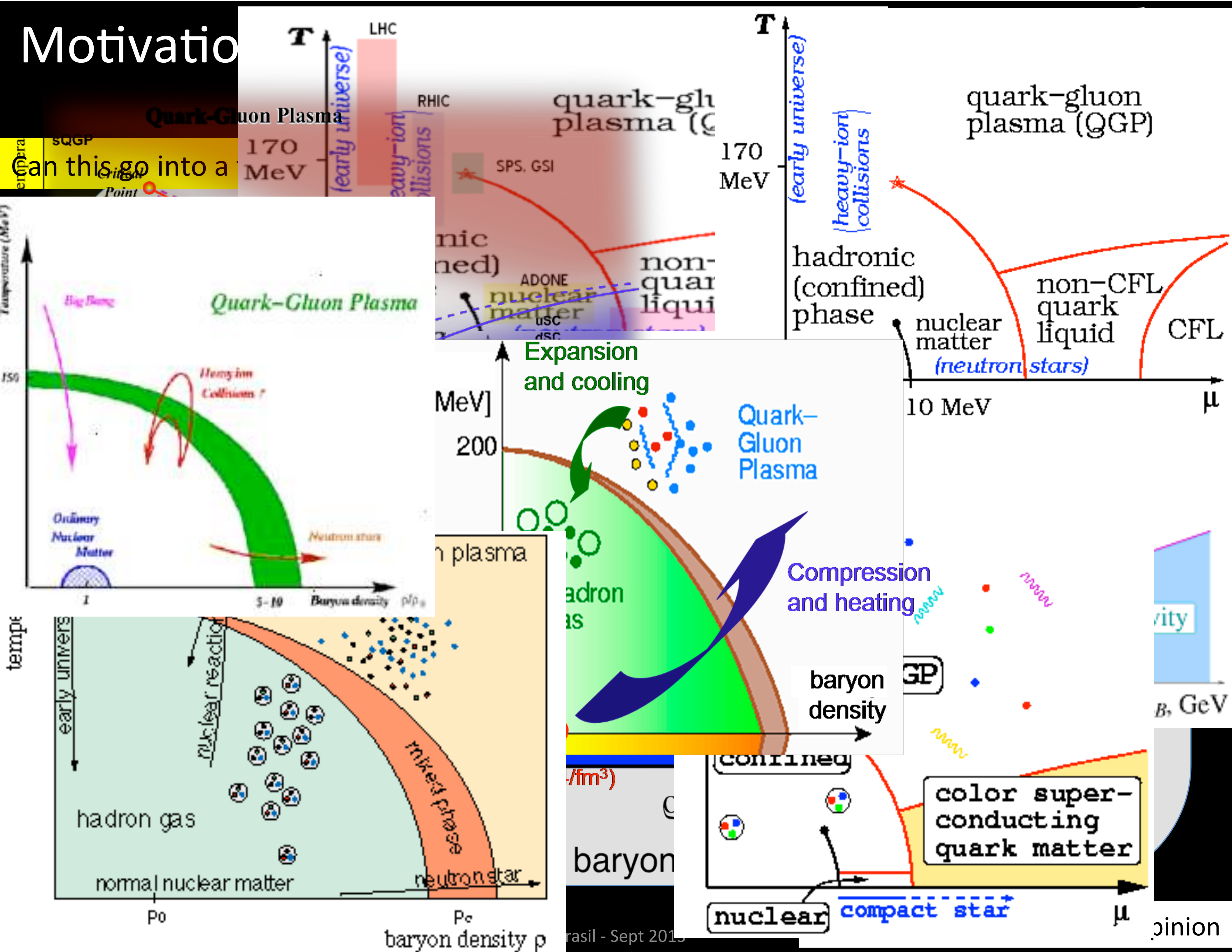
Motivatio

Can this go into a



rasil - Sept 201

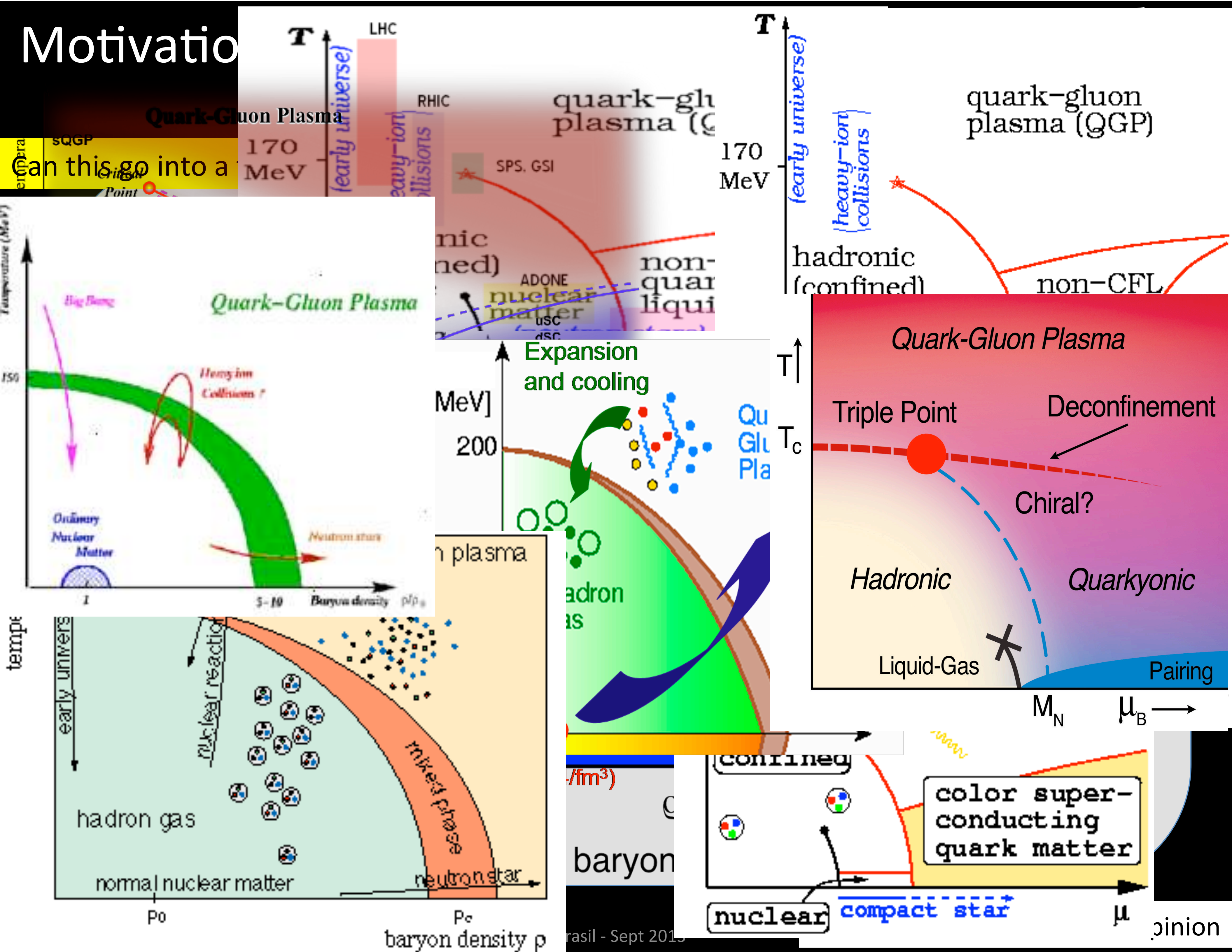
pinion



Motivatio
Can this go into a
Quark-Gluon Plasma
sQGP
Critical Point
T
LHC
RHIC
SPS, GSI
ADONE
170 MeV
(early universe)
(heavy-ion collisions)
quark-gluon plasma (QGP)
hadronic (confined) phase
nuclear matter
(neutron stars)
non-CFL quark liquid
CFL
10 MeV
μ
Quark-Gluon Plasma
Big Bang
Heavy ion Collisions ?
Ordinary Nuclear Matter
Neutron stars
150
1
5-10
Baryon density
Temperature (MeV)
[MeV]
200
Expansion and cooling
Quark-Gluon Plasma
Compression and heating
hadron gas
baryon density
hadron gas
normal nuclear matter
mixed phase
nuclear reaction
early universe
neutron star
ρ₀
ρc
baryon density ρ
quark-gluon plasma
temperature
baryon
confined
color super-conducting quark matter
nuclear
compact star
μ
QGP
gravity
μB, GeV
opinion
Brasil - Sept 2013

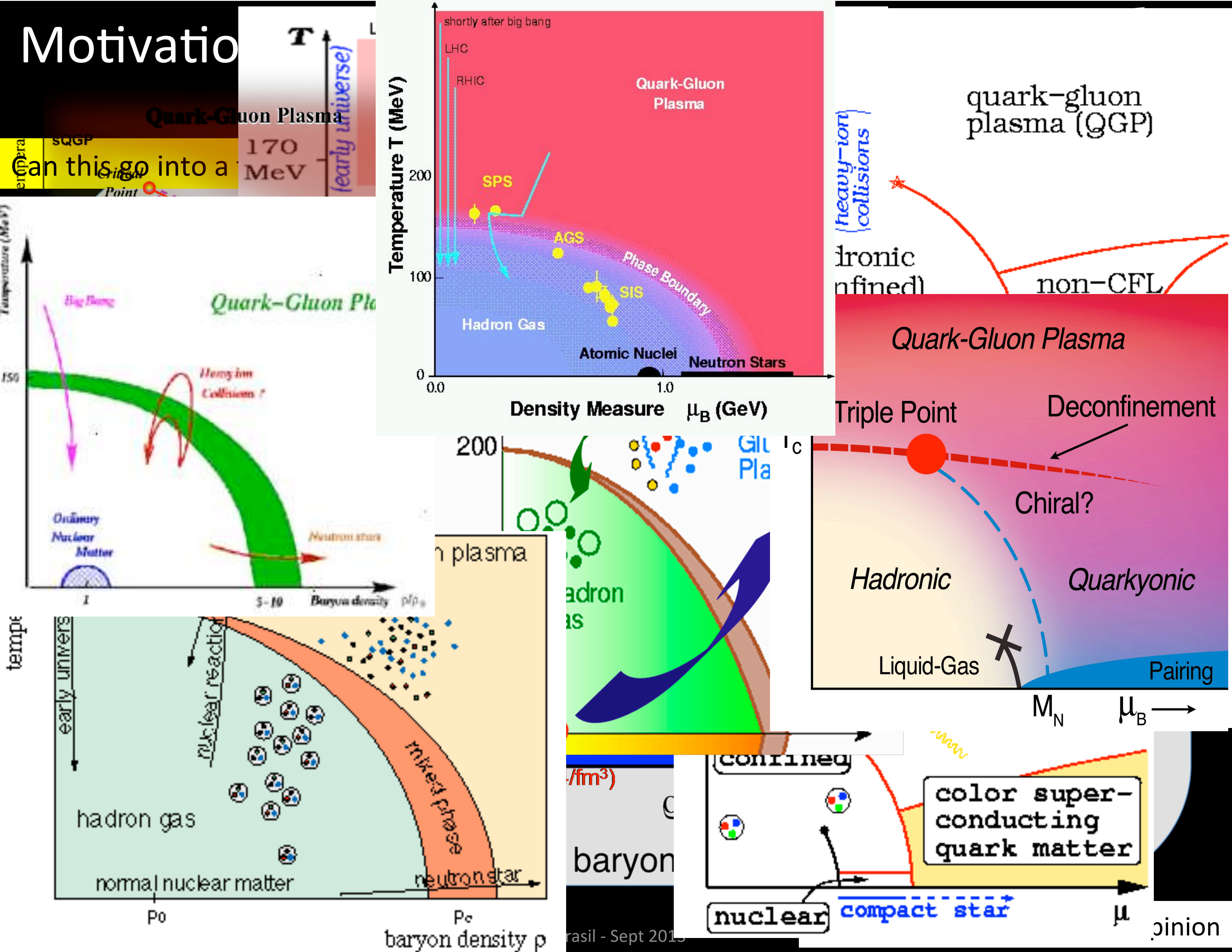
Motivatio

Can this go into a



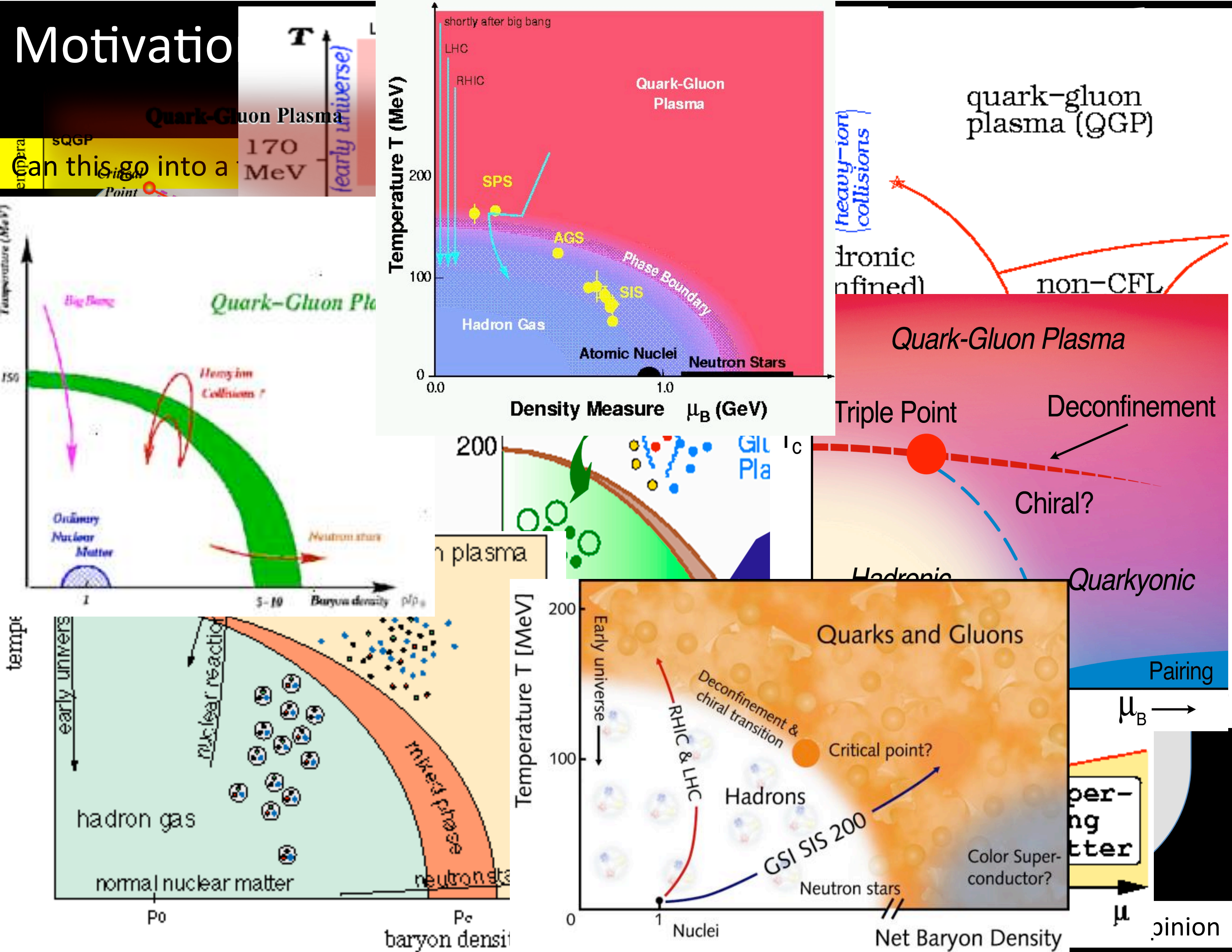
Brasil - Sept 2015

opinion

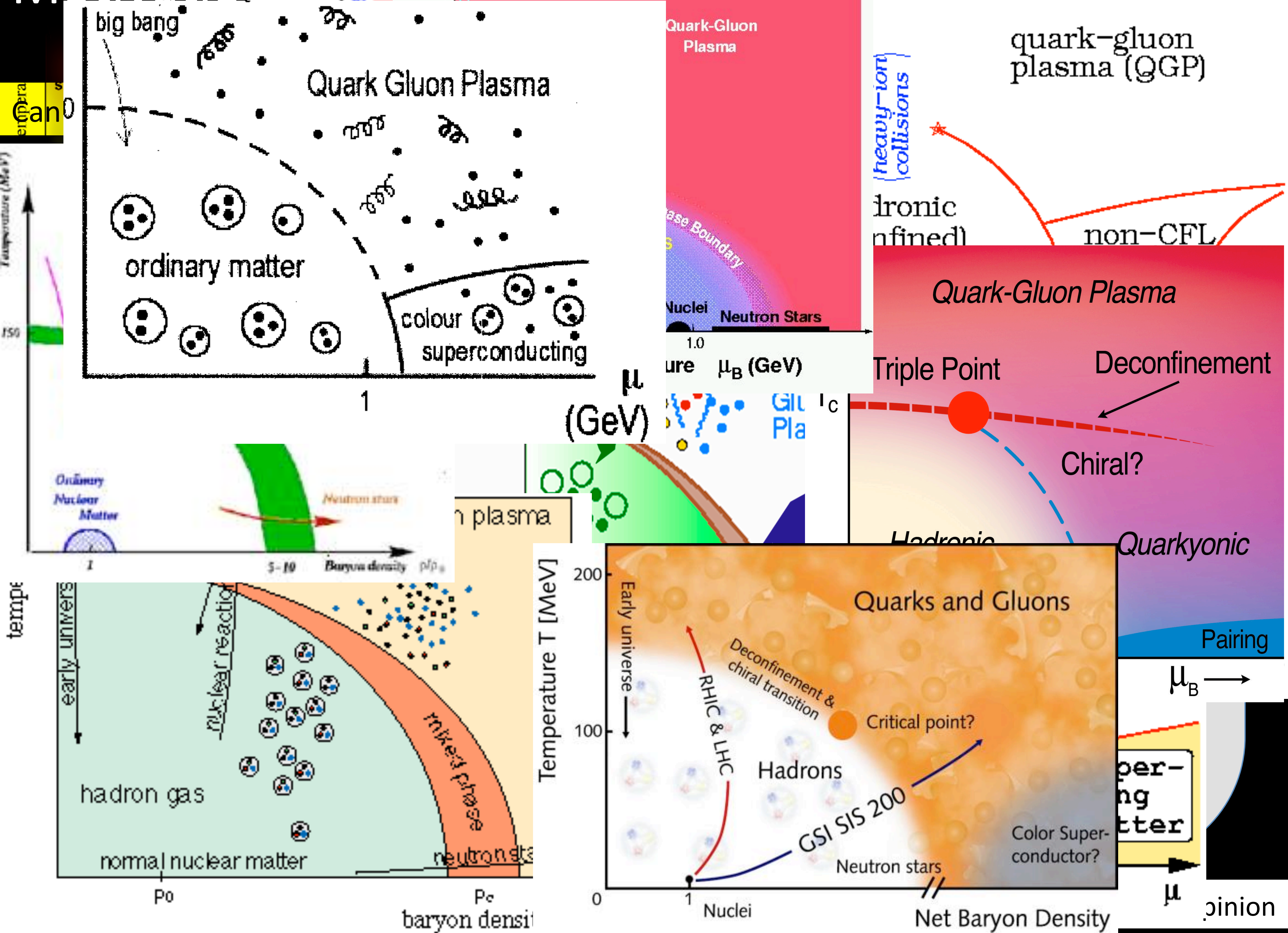

Motivatio
Can this go into a
Quark-Gluon Plasma
sQGP
Critical Point
170 MeV
(early universe)
shortly after big bang
LHC
RHIC
Quark-Gluon Plasma
SPS
AGS
SIS
Phase Boundary
Hadron Gas
Atomic Nuclei
Neutron Stars
Temperature T (MeV)
200
100
0
0.0
1.0
Density Measure μ_B (GeV)
quark-gluon plasma (QGP)
(heavy-ion collisions)
dronic
nfined)
non-CFL
Quark-Gluon Plasma
Triple Point
Deconfinement
T_c
Chiral?
Hadronic
Quarkyonic
Liquid-Gas
Pairing
M_N
μ_B
Big Bang
Heavy ion Collisions ?
Ordinary Nuclear Matter
Neutron stars
Baryon density ρ/ρ_0
150
5-10
n plasma
early univers
nuclear reactio
hadron gas
mixed phase
normal nuclear matter
neutron star
ρ_0
ρ_c
baryon density ρ
adron
as
baryon
confined
color super-conducting quark matter
nuclear
compact star
μ
pinion
rasil - Sept 201

Motivatio

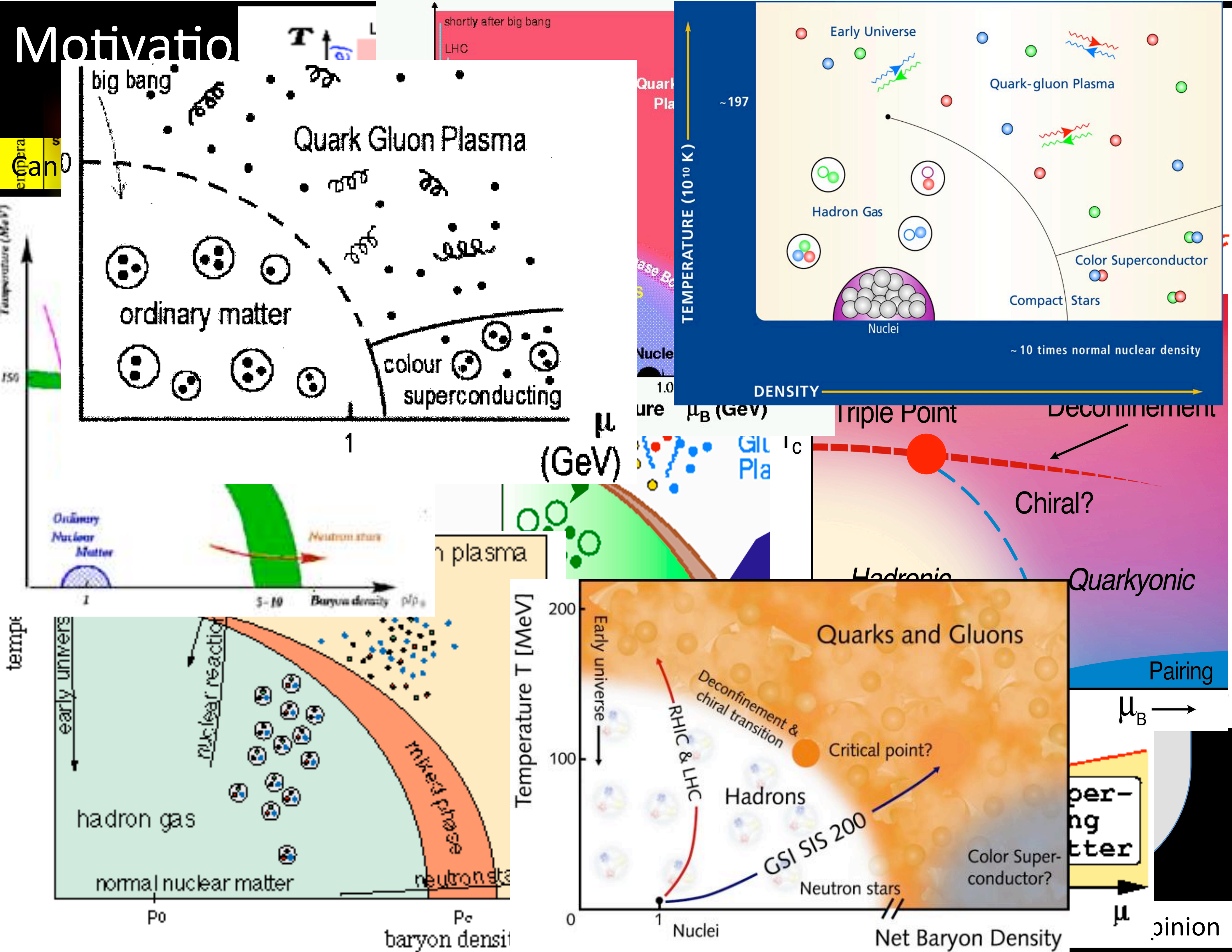
Can this go into a



Motivatio



big bang
Quark Gluon Plasma
ordinary matter
colour superconducting
1
μ (GeV)
shortly after big bang
LHC
Quark-Gluon Plasma
Nuclei
Neutron Stars
1.0
μB (GeV)
quark−gluon plasma (QGP)
heavy−ion collisions
non−CFL
Quark-Gluon Plasma
Triple Point
Deconfinement
Chiral?
Quarkyonic
Pairing
μB
Ordinary Nuclear Matter
Neutron stars
Baryon density
early universe
nuclear reactions
mixed phase
hadron gas
normal nuclear matter
neutron sta
ρ0
ρc
baryon densit
Temperature T [MeV]
200
100
0
Early universe
Quarks and Gluons
Deconfinement & chiral transition
RHIC & LHC
Critical point?
Hadrons
GSI SIS 200
Color Super-conductor?
Neutron stars
Nuclei
1
Net Baryon Density
μ


Motivatio
big bang
Quark Gluon Plasma
ordinary matter
colour
superconducting
1
μ
(GeV)
shortly after big bang
LHC
Early Universe
Quark-gluon Plasma
~197
TEMPERATURE (10^10 K)
Hadron Gas
Color Superconductor
Compact Stars
Nuclei
~10 times normal nuclear density
DENSITY
μB (GeV)
Triple Point
Chiral?
Quarkyonic
Pairing
μB
Ordinary
Nuclear
Matter
Neutron stars
Baryon density
plasma
early univers
nuclear reactio
mixed phase
hadron gas
normal nuclear matter
neutron sta
P0
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baryon densi
Temperature T [MeV]
200
100
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Early universe
Quarks and Gluons
Deconfinement &
chiral transition
RHIC & LHC
Critical point?
Hadrons
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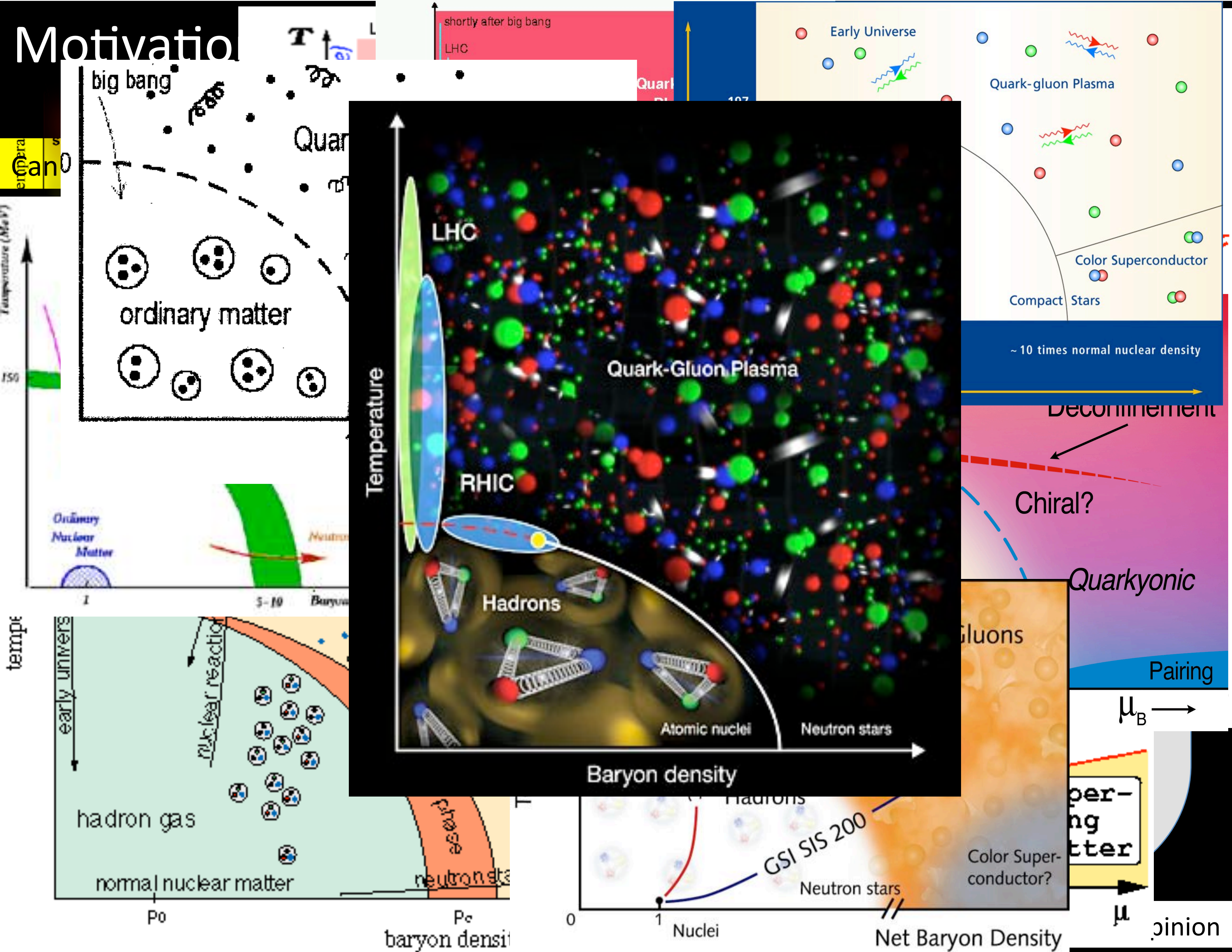
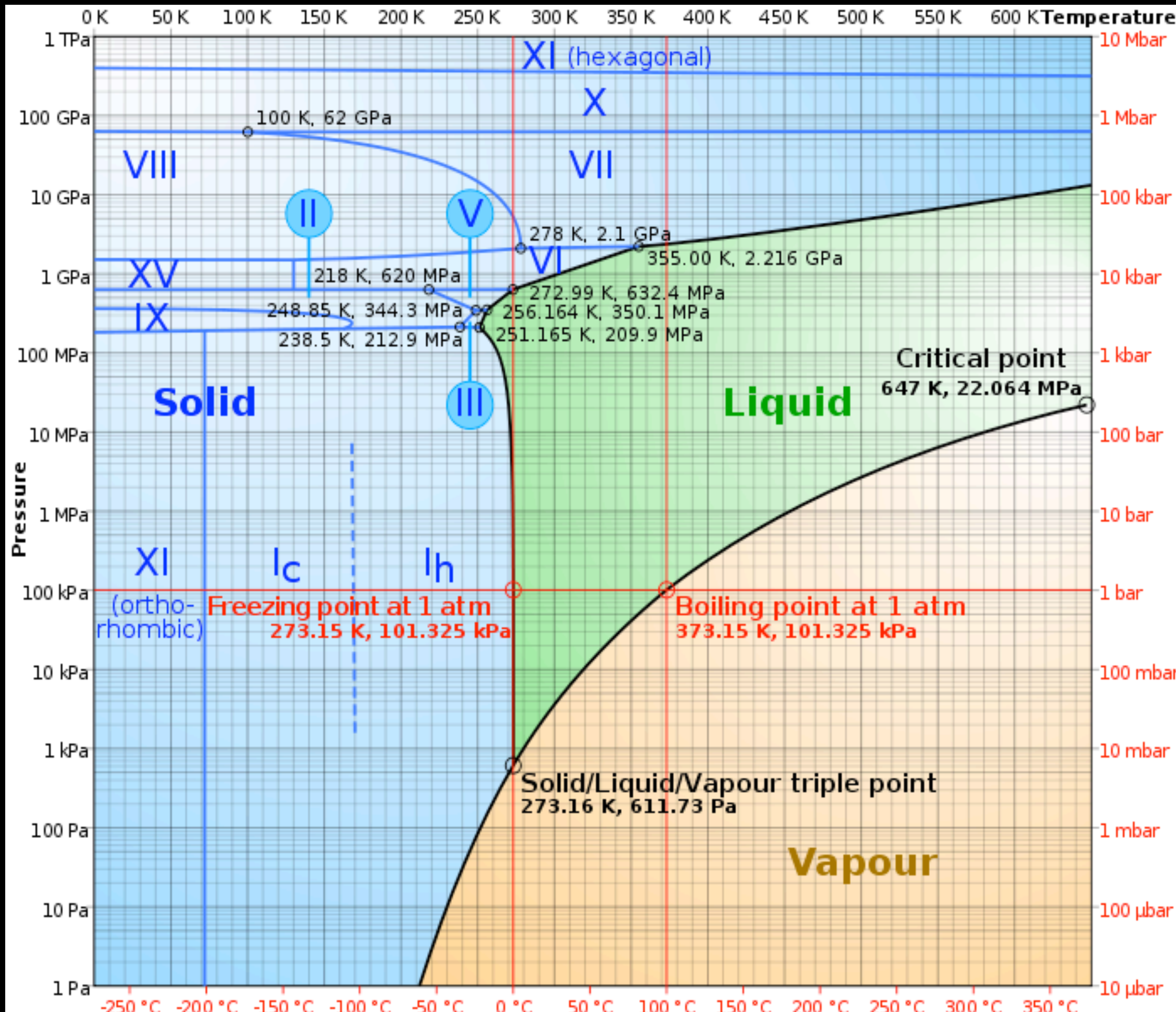
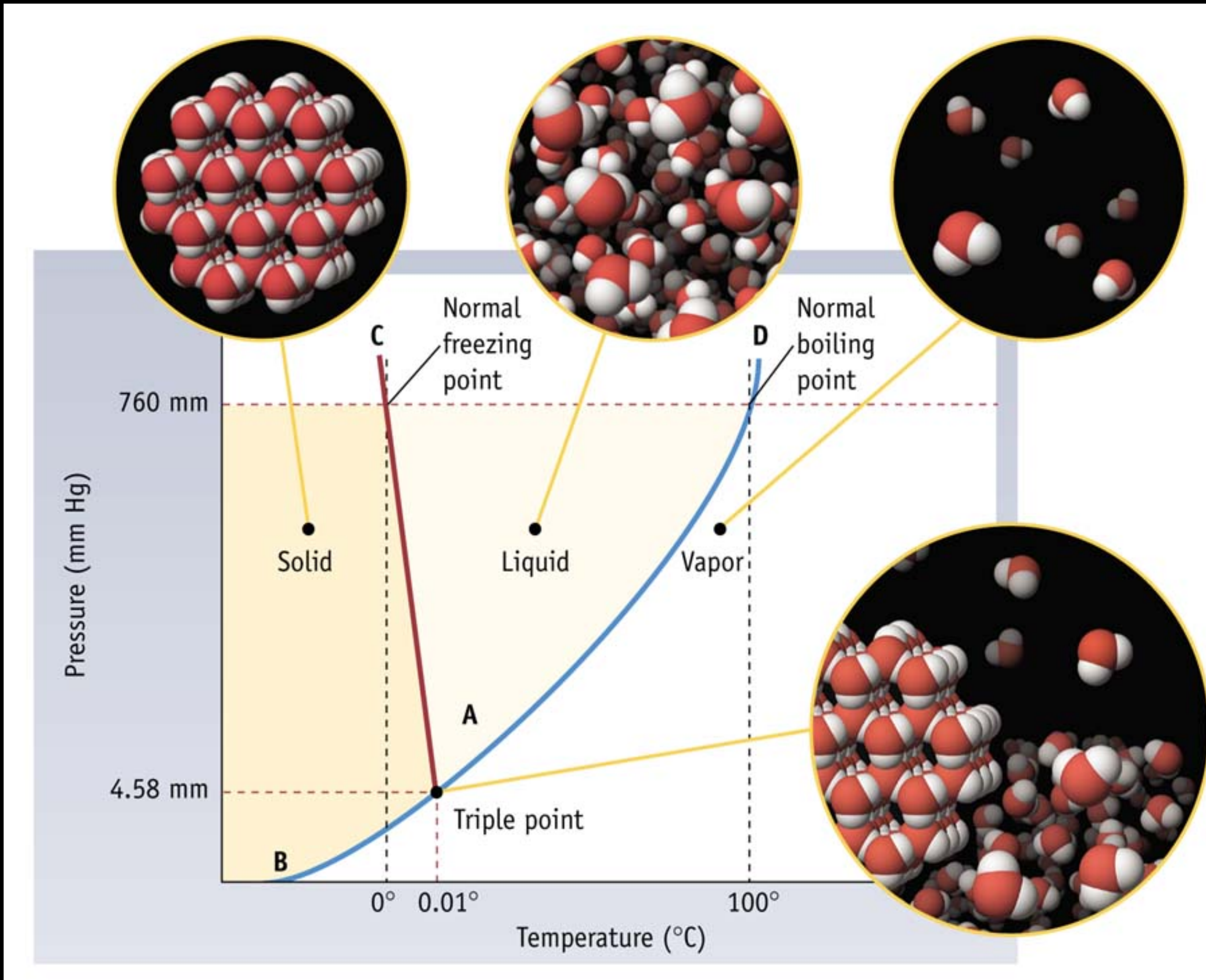
Color Super-
conductor?
Neutron stars
1
Nuclei
Net Baryon Density
μ


Motivatio
big bang
ordinary matter
Temperature
LHC
RHIC
Quark-Gluon Plasma
Hadrons
Atomic nuclei
Neutron stars
Baryon density
shortly after big bang
Early Universe
Quark-gluon Plasma
Color Superconductor
Compact Stars
~ 10 times normal nuclear density
Chiral?
Quarkyonic
Pairing
Gluons
Color Super-
conductor?
GSI SIS 200
Neutron stars
Nuclei
Net Baryon Density
early univers
nuclear reactio
hadron gas
normal nuclear matter
neutron sta
baryon densi
Ordinary
Nuclear
Matter

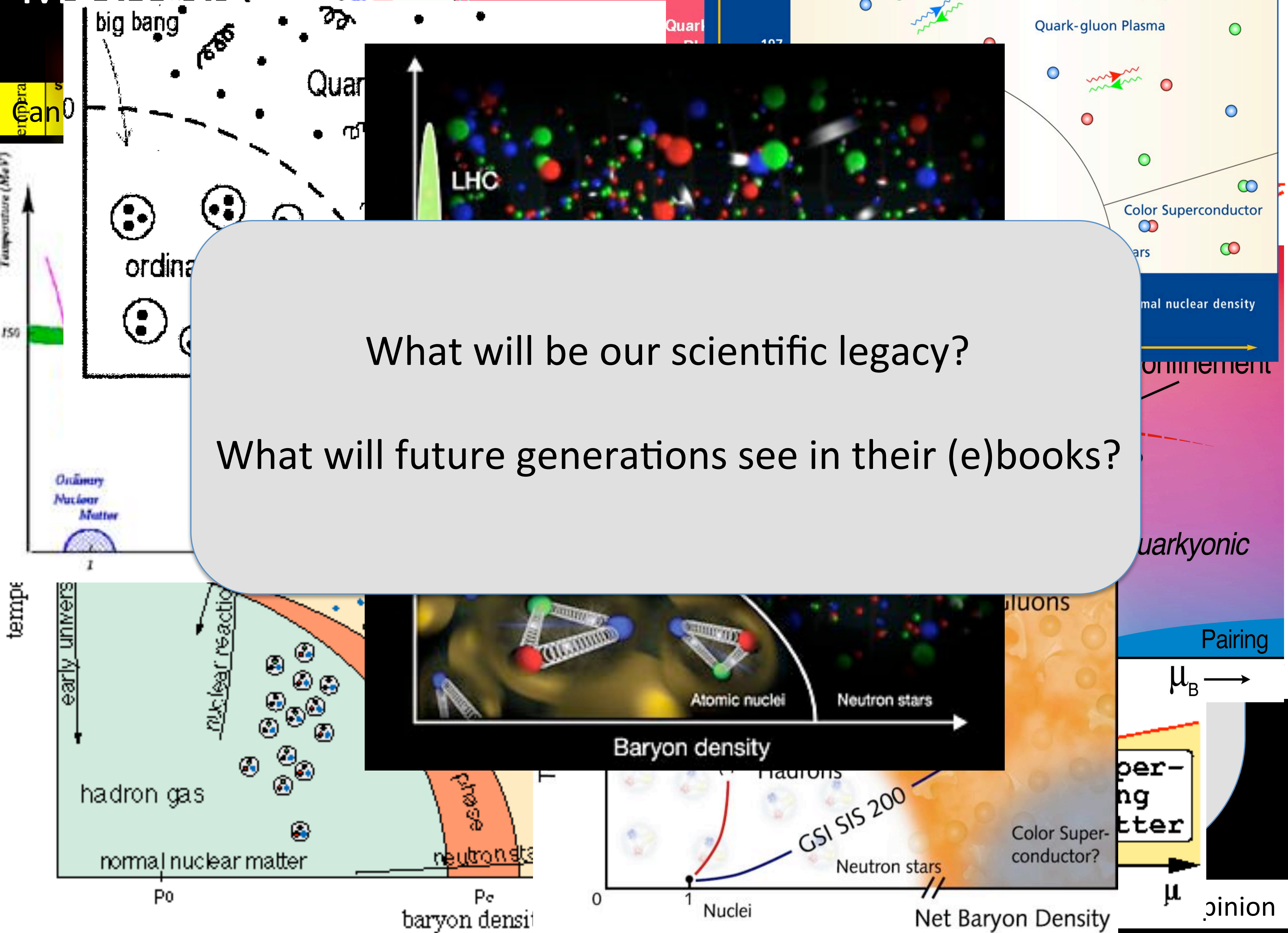
or can we reach something like this?



Okay, then how about something like this?



Motivatio



What will be our scientific legacy?

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

Because this doesn't cut it...

Onset of deconfinement – Wikipedia, the free encyclopedia

Onset of deconfinement – Wiki...

en.wikipedia.org/wiki/Onset_of_deconfinement

onset of deconfinement wiki

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Contact Wikipedia

Toolbox

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Create a book
Download as PDF
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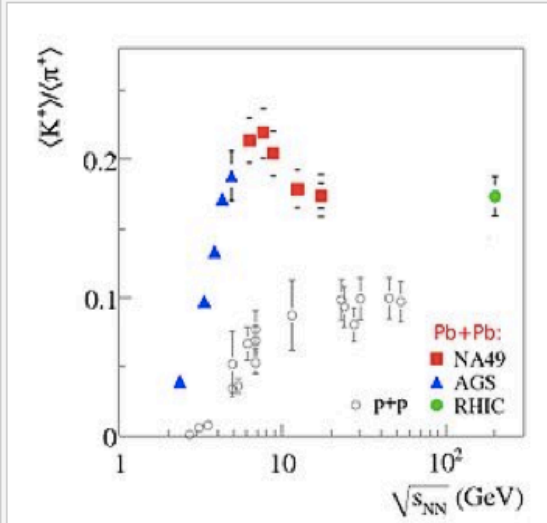
Onset of deconfinement

From Wikipedia, the free encyclopedia

The **onset of deconfinement** refers to the beginning of the creation of deconfined states of strongly interacting matter produced in nucleus-nucleus collisions with increasing collision energy (a quark–gluon plasma).

The onset of deconfinement was predicted by Marek Gazdzicki and Mark I. Gorenstein to be located in the low energy range of the Super Proton Synchrotron (SPS) at the European Organization for Nuclear Research (CERN).[1] These predictions have been confirmed by the NA49 experiment at the CERN SPS within the energy scan programme.[2] The most famous of these is the "horn" (dubbed the "strange matter-horn") in the ratio of mean multiplicities of positively charged kaons and pions observed in collisions of two lead nuclei at the low energies of the SPS. The horn is not seen in proton–proton interactions.



The "strange matter-horn". The ratio of mean multiplicities of positively charged kaons and pions as a function of collision energy in collisions of two lead nuclei and proton–proton interactions.

References [edit]

1. ^ M. Gazdzicki, M.I. Gorenstein; Gorenstein (1999). "On the early stage of nucleus–nucleus collisions". *Acta Physica Polonica B* **30**: 2705. arXiv:hep-ph/9803462. Bibcode:1999AcPPB..30.2705G.
2. ^ C. Alt *et al.* (NA49 collaboration) (2008). "Pion and kaon production in central Pb+Pb collisions at 20*A* and 30*A* GeV: Evidence for the onset of deconfinement". *Physical Review C* **77** (2): 024903. arXiv:0710.0118. Bibcode:2008PhRvC..77b4903A. doi:10.1103/PhysRevC.77.024903.

External links [edit]

- Description of the NA49 experiment


Feliz aniversário, Prof. Kodama