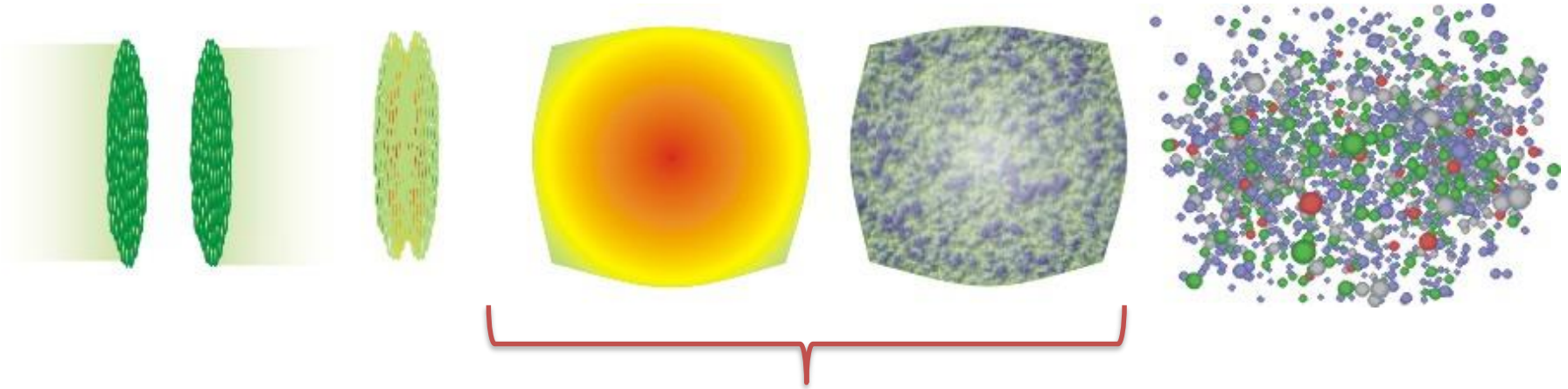
Physics of Dense Matter in Heavy-ion Collisions at J-PARC

Masakiyo Kitazawa

J-PARC研究会、2015/8/5、J-PARC

Heavy Ion Collisions before 2005

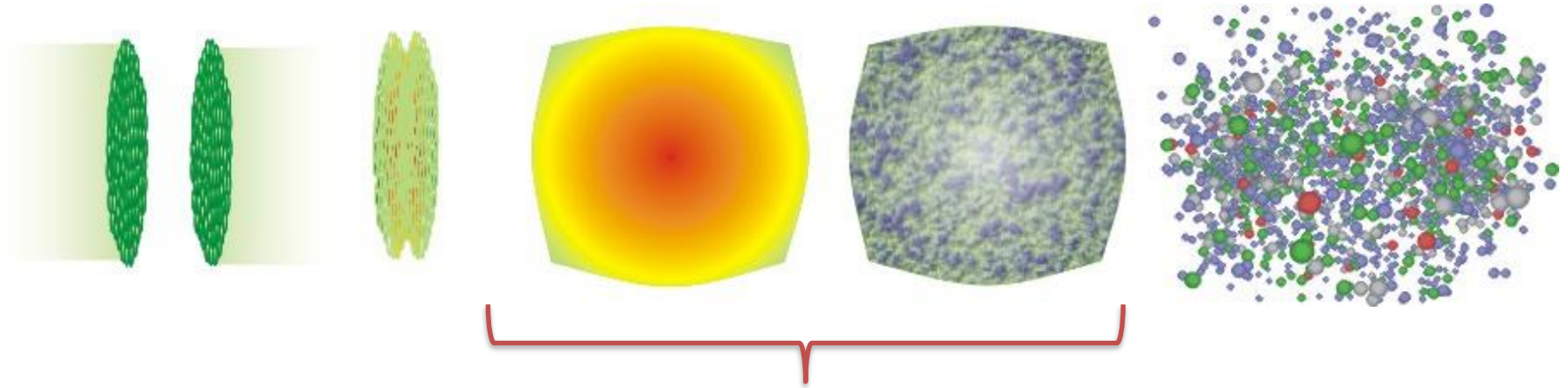
relativistic heavy ion collisions



hot and dense medium

Heavy Ion Collisions before 2005

relativistic heavy ion collisions



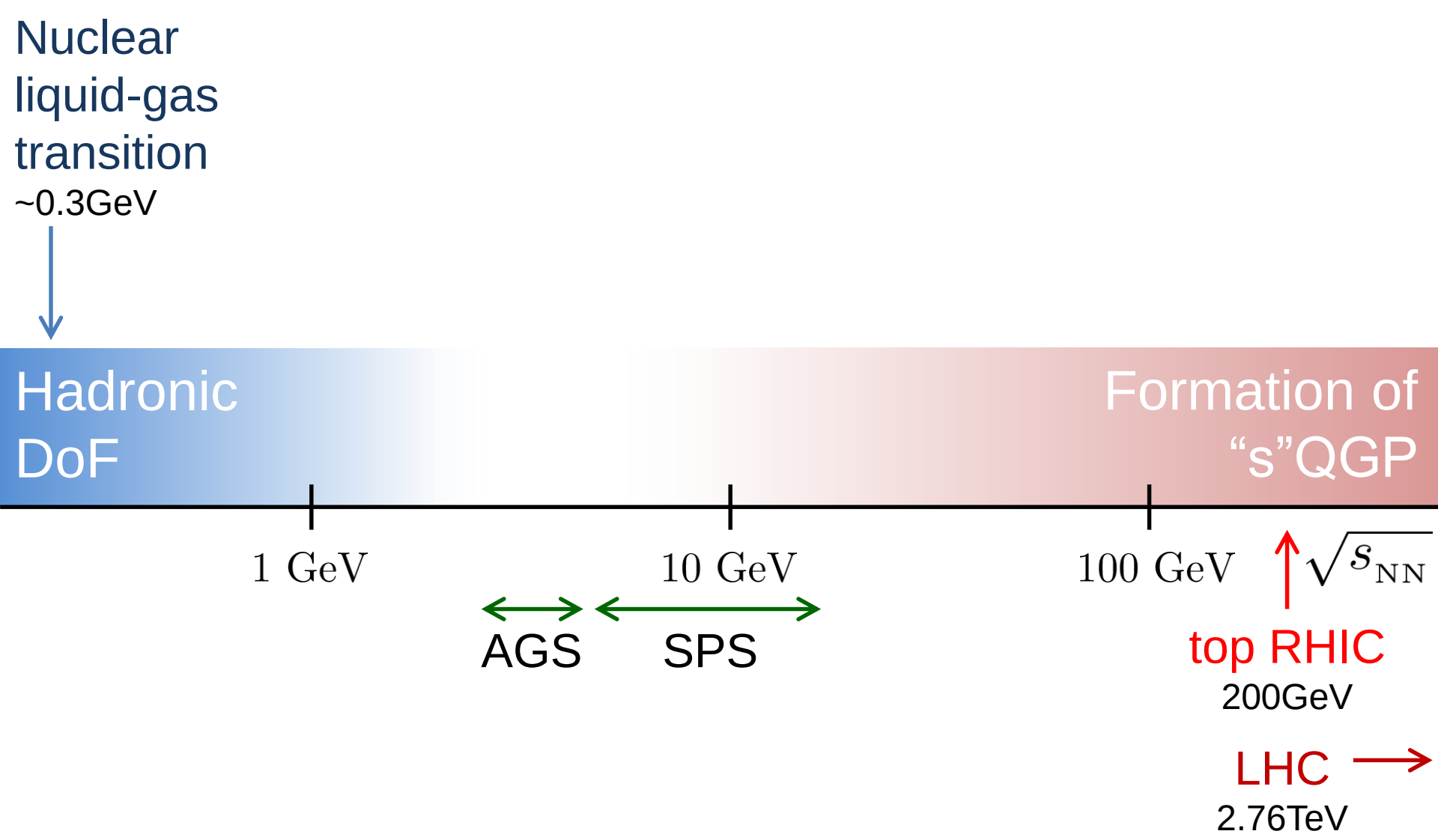
hot and dense medium

The most important objective **before** 2005

Creation of the quark-gluon plasma (QGP)

established at RHIC

√s Dep. of Heavy Ion Collisions



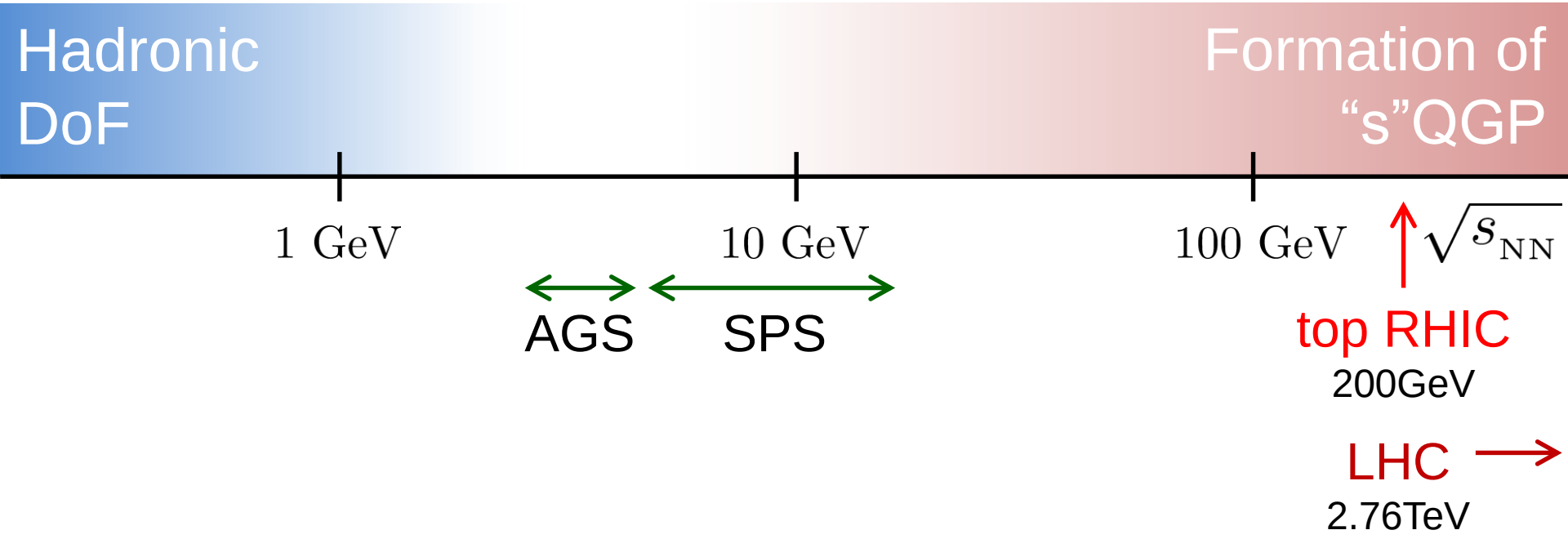
√s Dep. of Heavy Ion Collisions

Nuclear liquid-gas transition ~0.3GeV

Directions after RHIC

② Explore the "crossover" region

① Understand QGP more quantitatively



√s Dep. of Heavy Ion Collisions

Hadronic DoF

Formation of "s"QGP

1 GeV | 10 GeV | 100 GeV | $\sqrt{s_{NN}}$

AGS

SPS

top RHIC
200GeV

LHC →
2.76TeV

J-PARC
1.9 ~ 6.2 GeV

RHIC-BES I 7.7 ~ 62 GeV

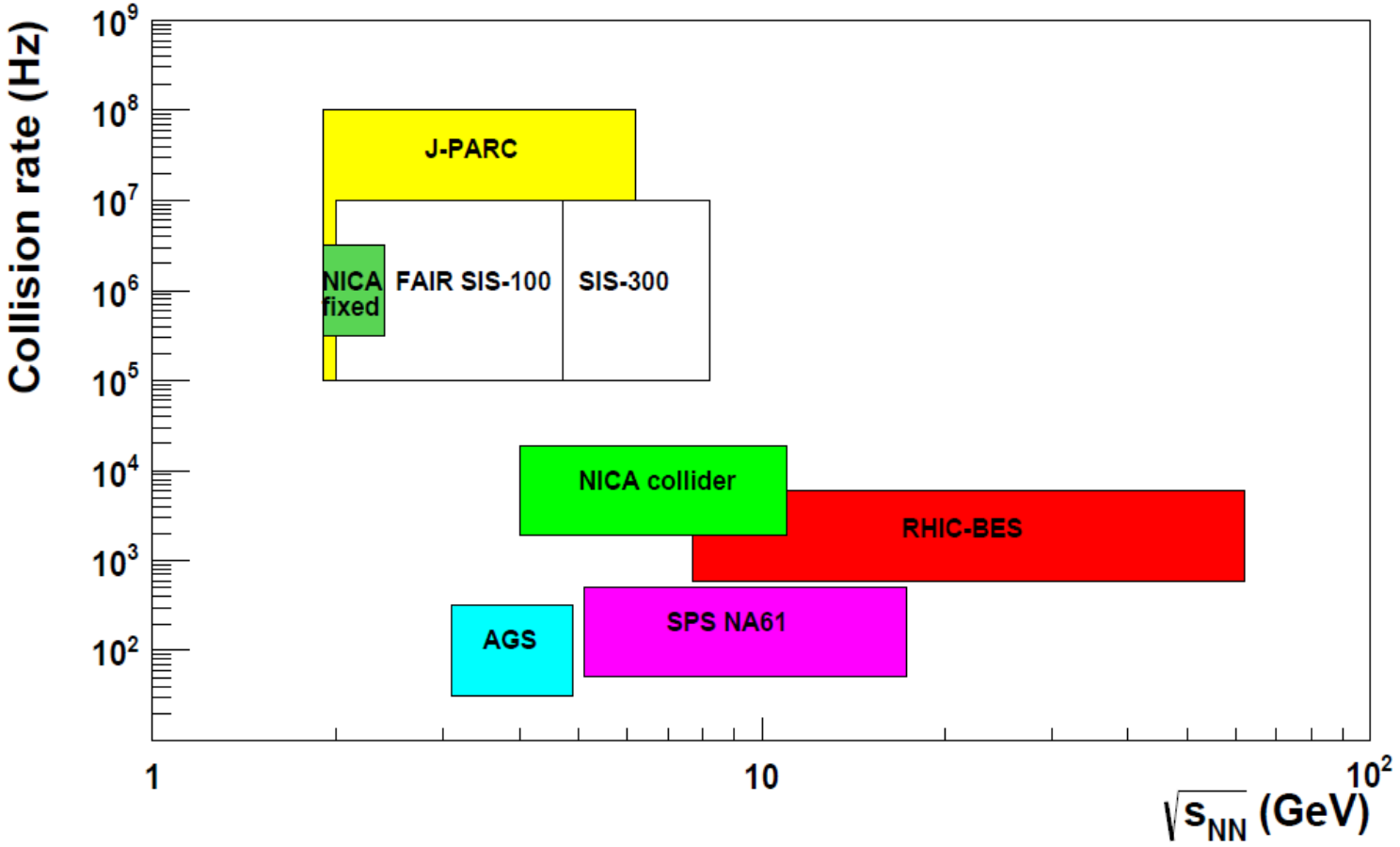
RHIC-BES II 7.7 ~ 20 GeV
2018~

NICA
2019~??

FAIR
2021~??

BES:
Beam
Energy
Scan

figure by 佐甲さん
佐甲、北沢、原子核研究



High collision rate at J-PARC

Findings at Top-RHIC Energy

$$\sqrt{s_{\mathrm{NN}}} = 200\mathrm{GeV}$$

- Formation of QGP
  - Quark number scaling / Jet quenching

- "Strongly-coupled" QGP
  - strong collective flow / success of ideal hydro models

Establishment of dynamical modelling for time evolution of the hot medium

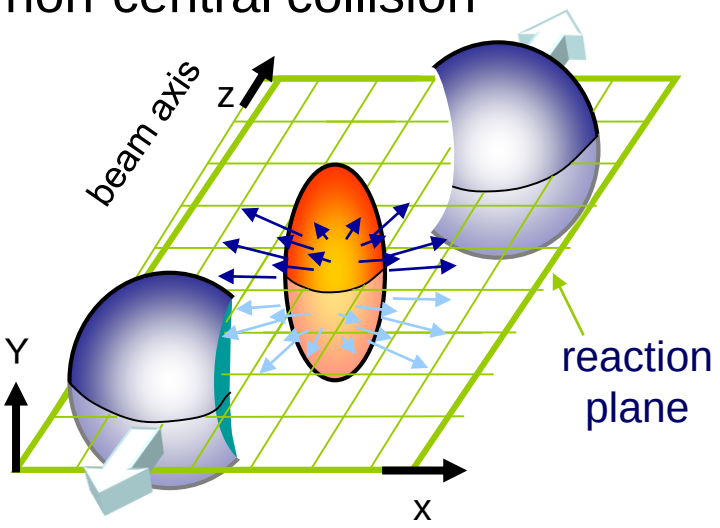
⟺ Lack of such a picture for low E

Note: Top-RHIC energy environment

- justification of Bjorken picture
- high statistical data due to high multiplicity

Elliptic Flow and Quark Number Scaling

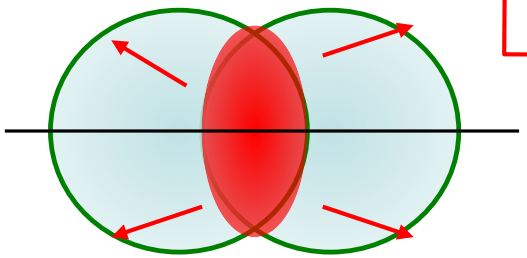
non-central collision



Flow

$$\frac{dN}{d\phi} \sim 1 + v_1 \cos\phi + v_2 \cos 2\phi + \cdots$$

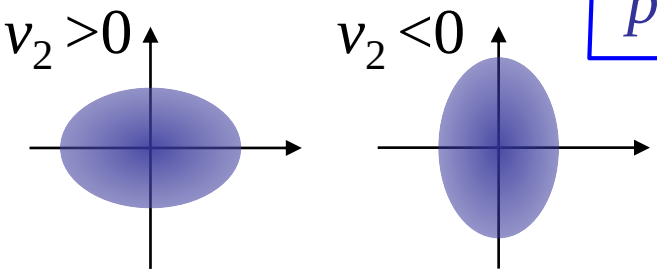
coordinate space

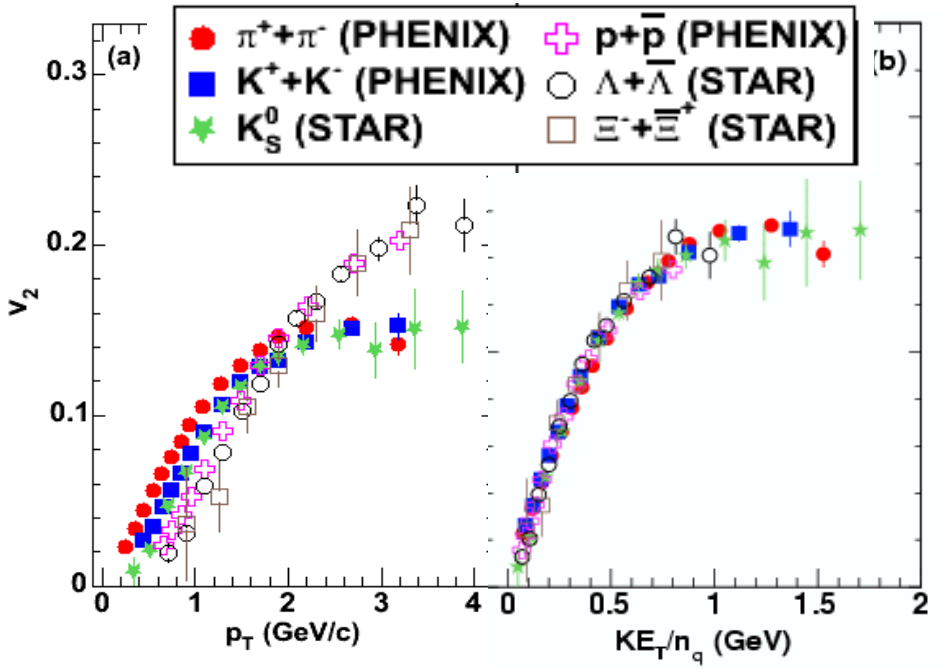


reaction plane

p_T space

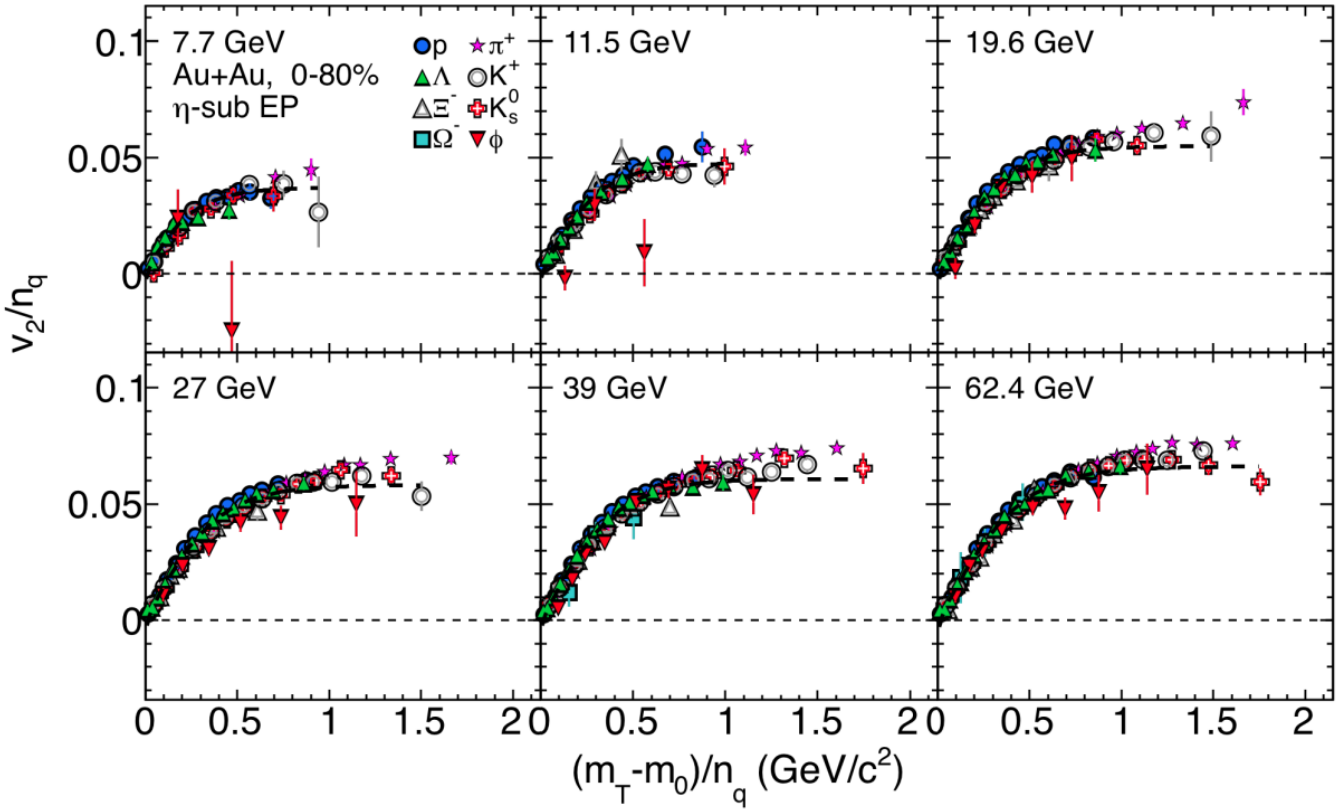
$v_2 > 0$ $v_2 < 0$





√s Dependence of QNS

STAR BES-I

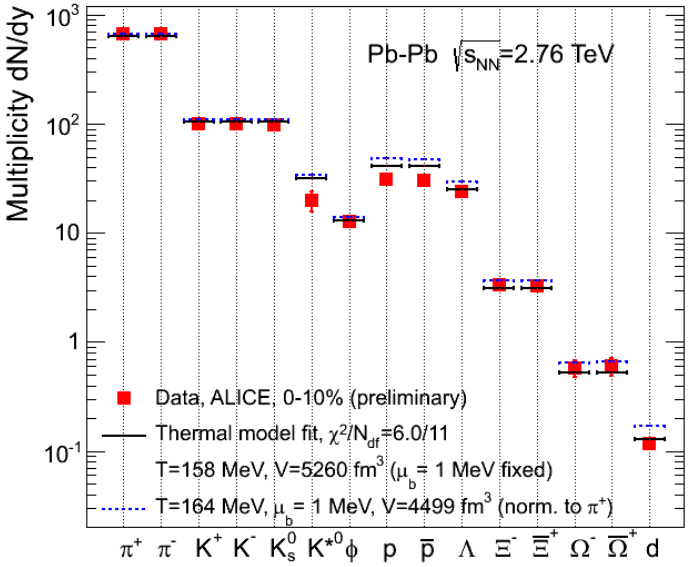


- QNS is well applicable even for 19.6GeV
  - ➡ Evidence of QGP formation for this energy??
- Deviation of strangeness <11.5GeV
  - Why and how??

Chemical / Kinetic Freezeouts

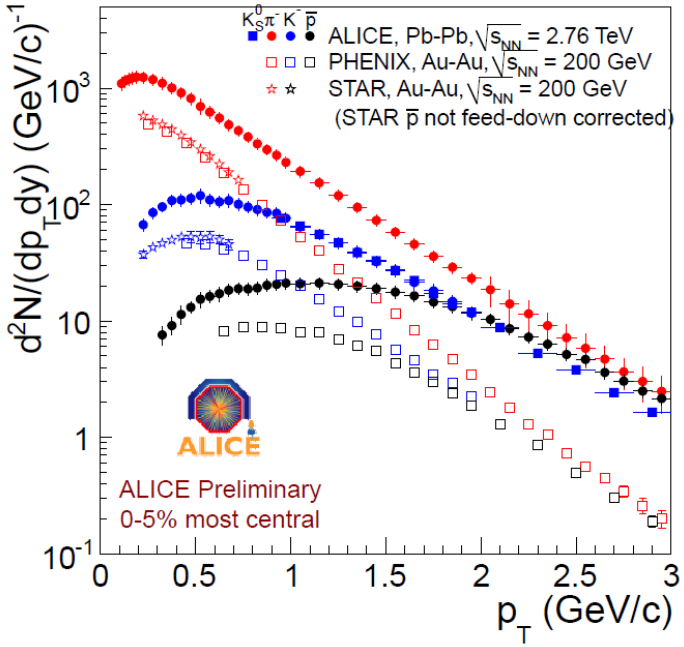
Chemical Freezeout

- Particle abundances are well described by a thermal fit.
  - chemical equilibration
  - estimate *T* and μ

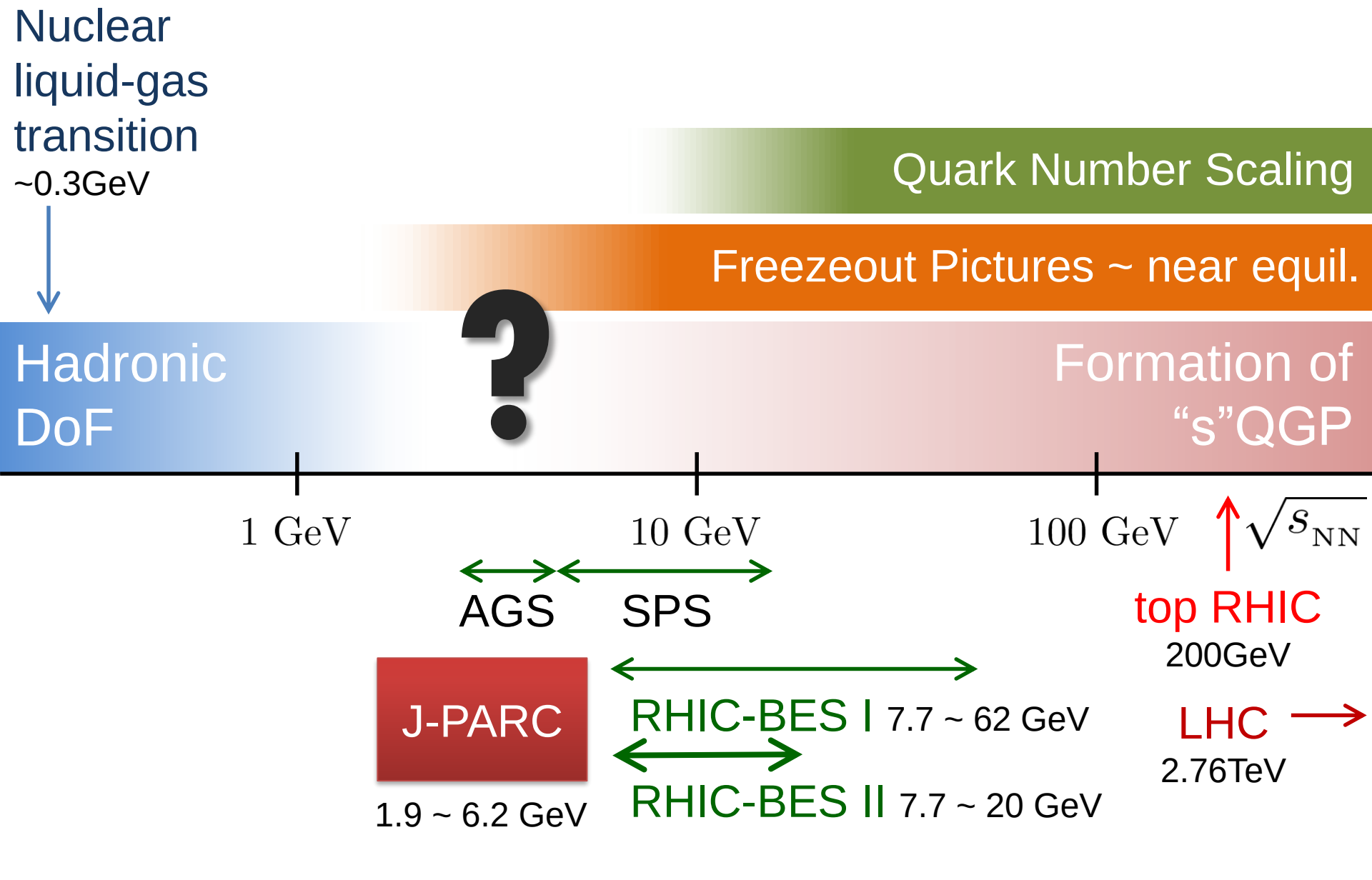


Kinetic (Thermal) Freezeout

- pT spectra is well described by thermal + blastwave model.
  - (radial) collective flow
  - estimate *T*



√s Dep. of Heavy Ion Collisions

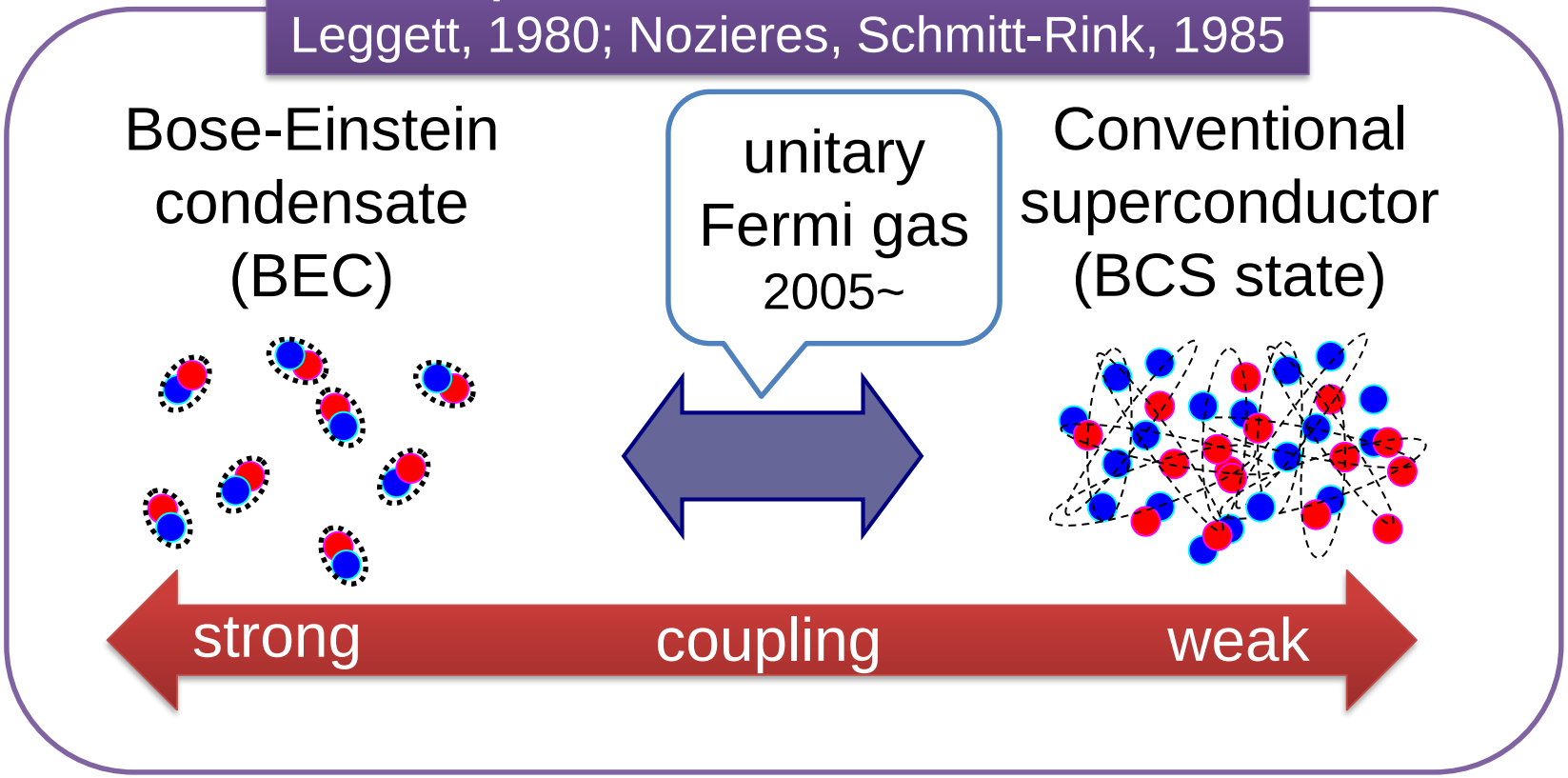


Crossover Phenomena

- low T ←→ high T
- weak-strong couplings

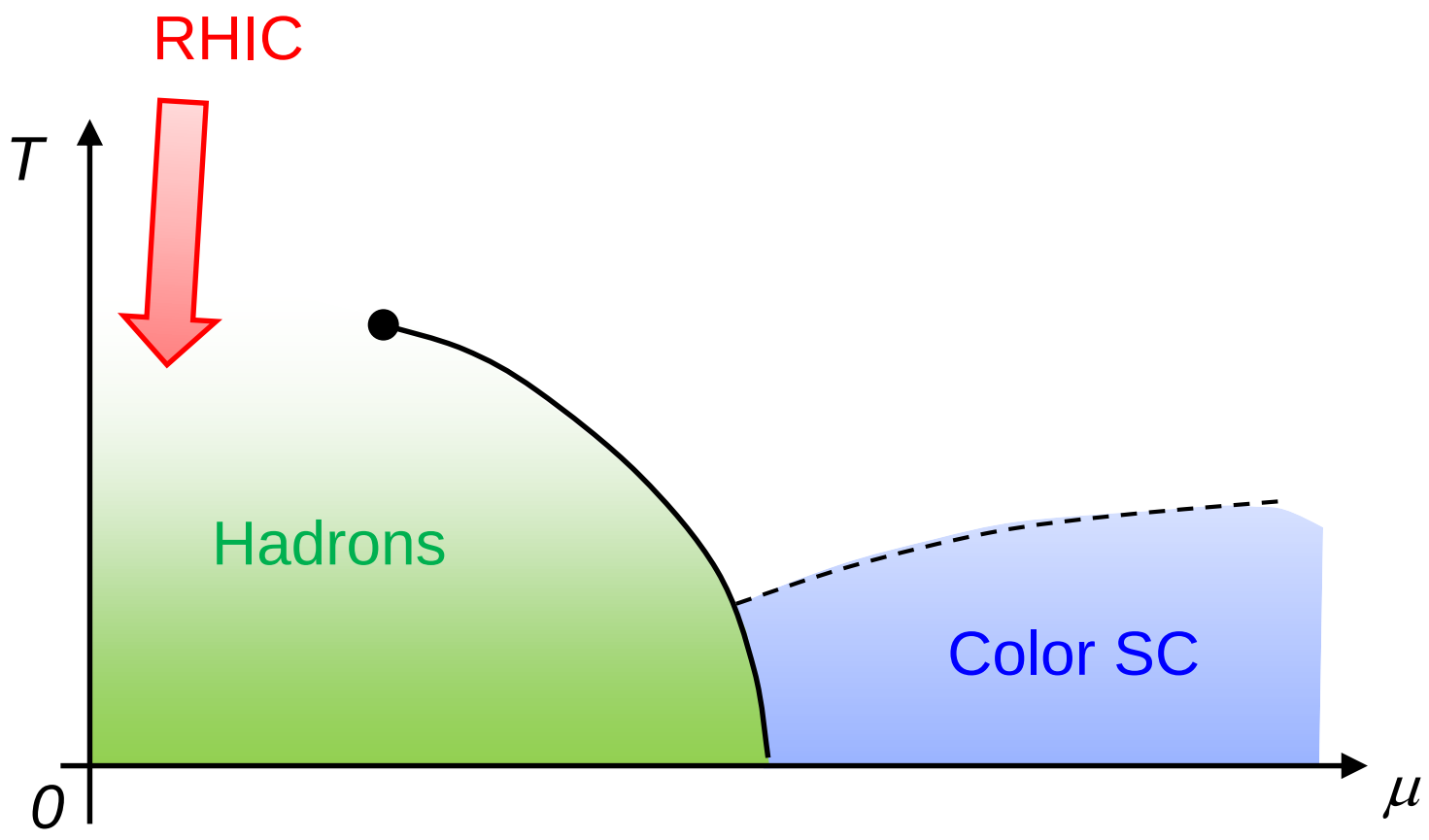
Example: BCS-BEC crossover

Leggett, 1980; Nozieres, Schmitt-Rink, 1985



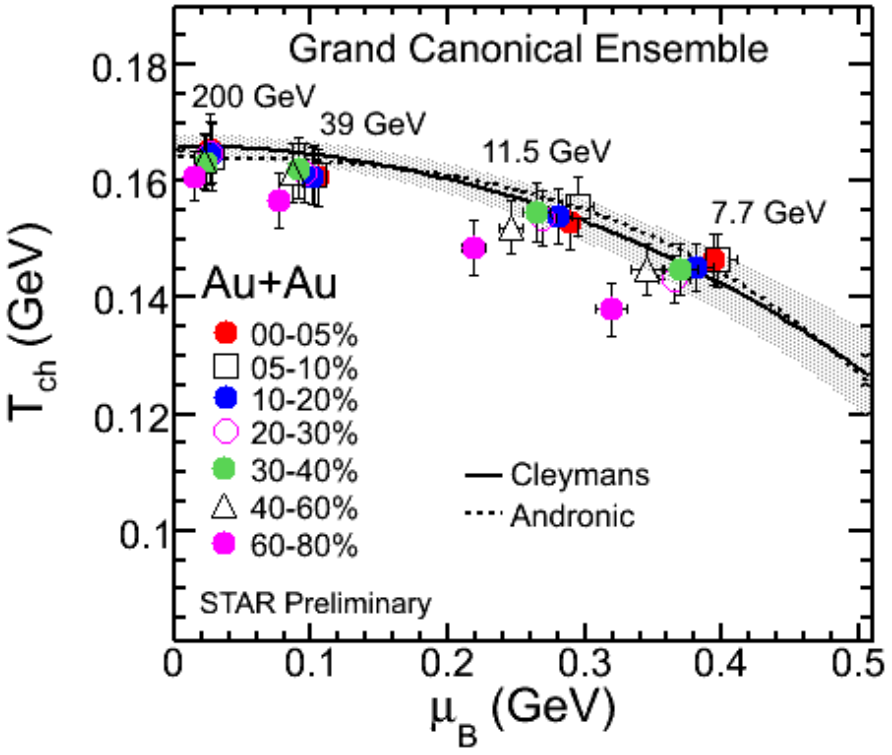
History of physics: simple limiting cases → intermediate region

QCD Phase Diagram



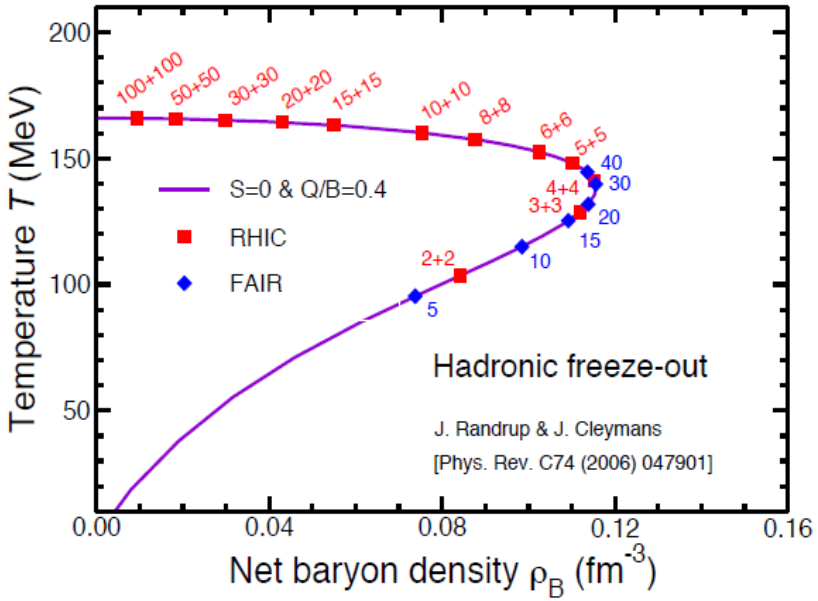
Beam-Energy Scan

STAR 2012

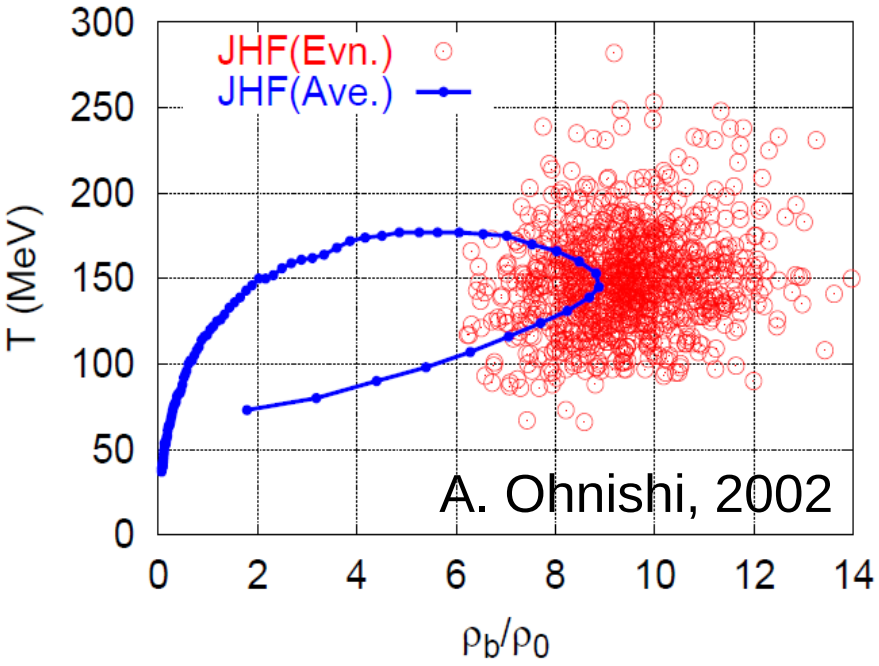


√s vs Maximum Density

Density at freezeout

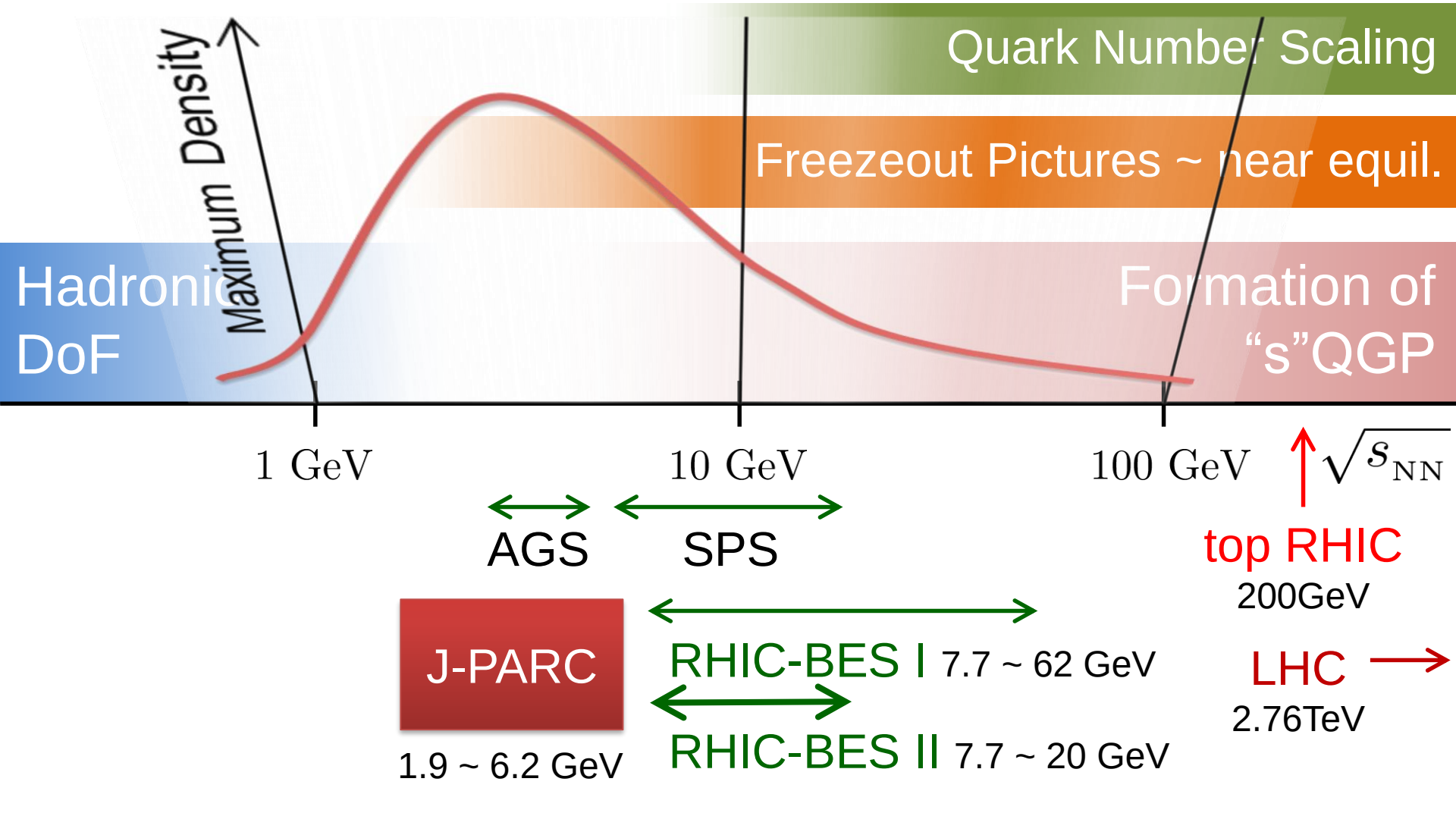


Trajectory on T-ρ plane



- Maximally compressed medium would be created at J-PARC energy.
- Density would exceed 5~10ρ_0
- Large event-by-event fluctuations of stopping?

√s Dep. of Heavy Ion Collisions



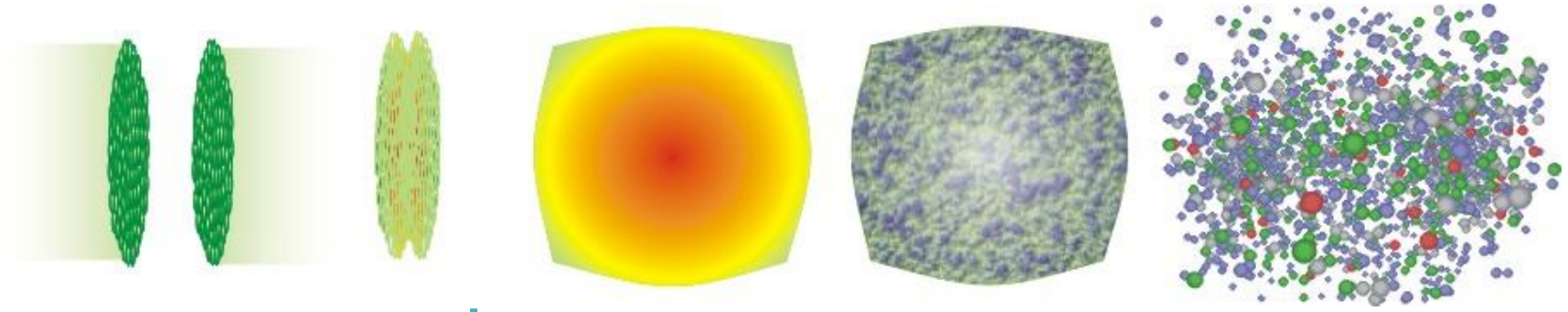
HIC@J-PARC : Motivations

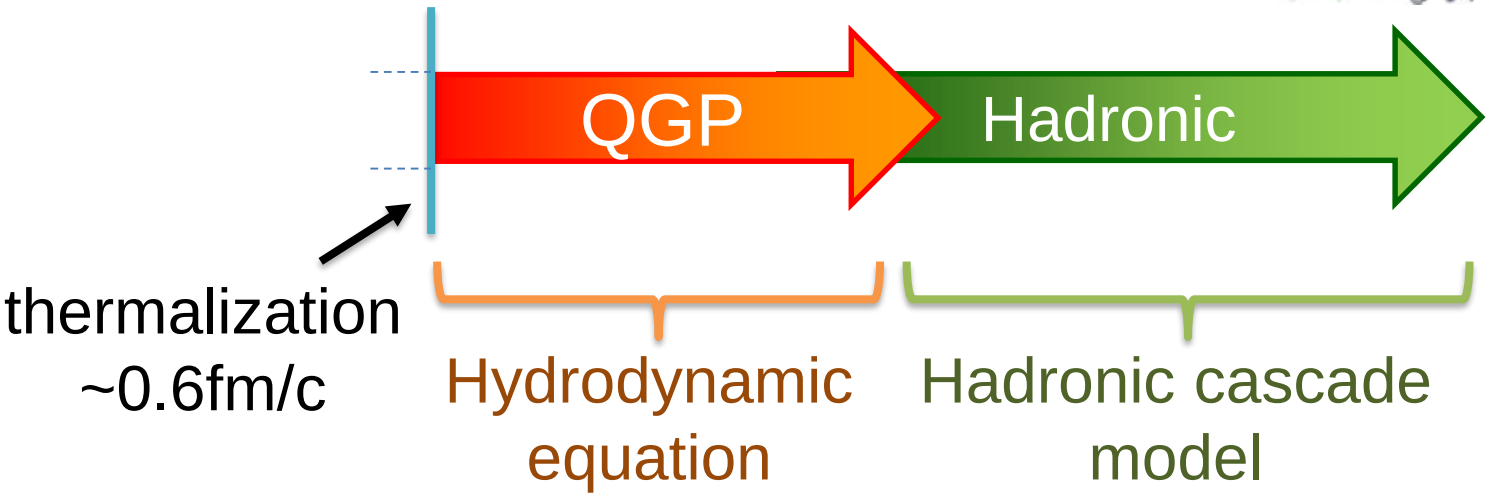
- Intermediate energy collisions
  - Fill the gap between two different pictures for low- and high-energy collisions
  - Onset of deconfinement phase transition
  - Construction of dynamical models

- Medium at high baryon density
  - QCD phase structure
  - EoS of dense medium → Neutron stars

Toward Dynamical Picture for Time Evolution / Collective Flow

Dynamical Model for RHIC Energy

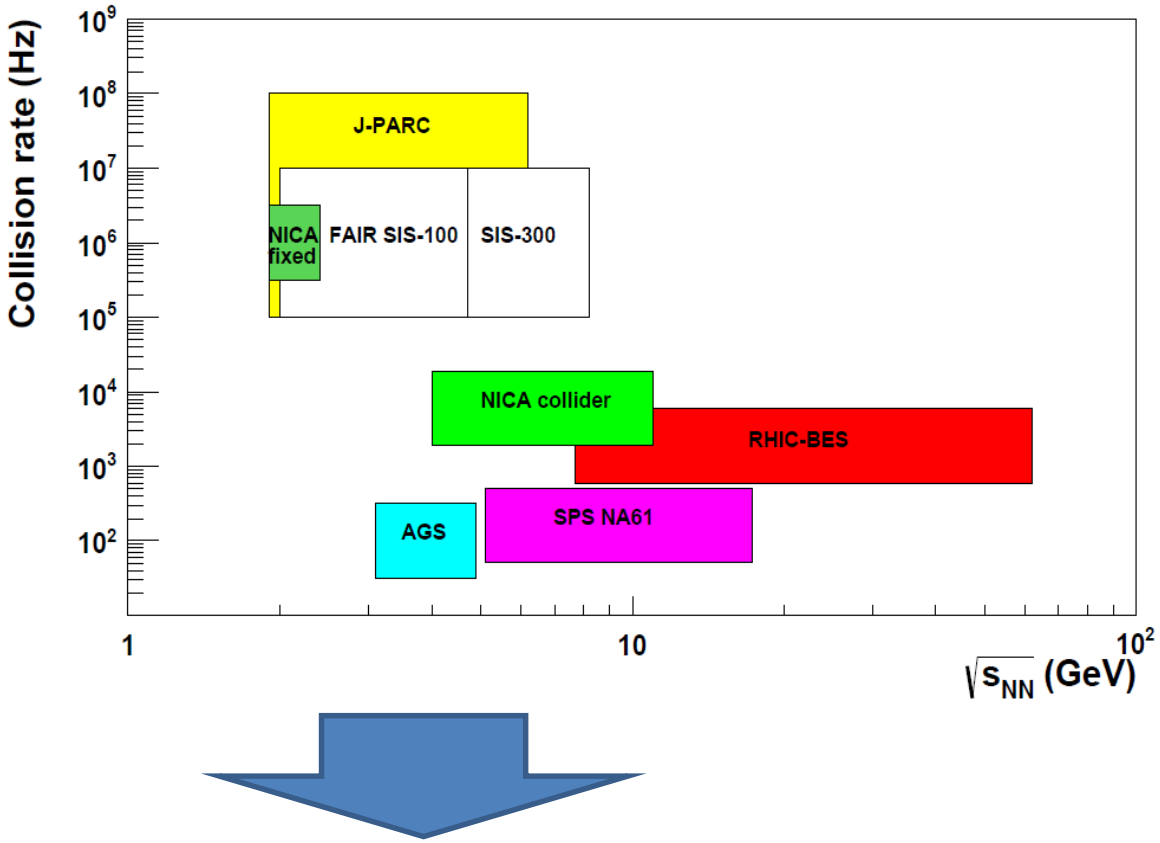




Heavy ion collisions at J-PARC energy does not have this kind of dynamical picture.

Is hydro applicable? Then, how long??

High Intensity Beam at J-PARC



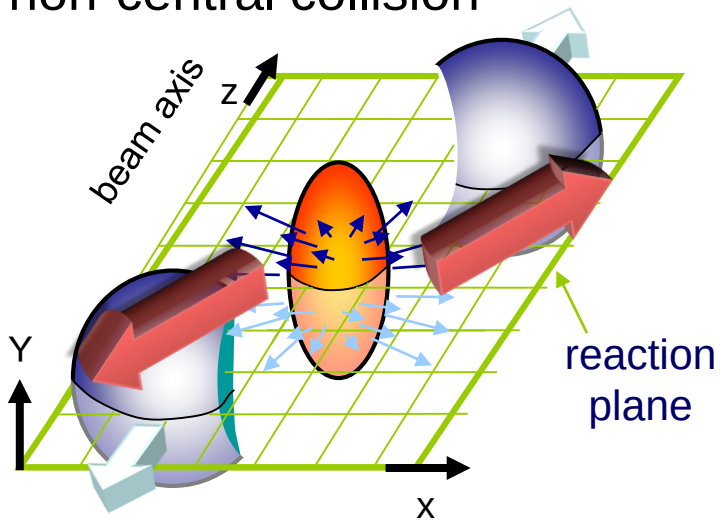
Statistics at J-PARC

more than **4 order** better than previous exps. with similar energy

- J-PARC will provide us with
  - high-precision data
  - detailed bin dependences (centrality, p_T, etc.)
  - various event selections

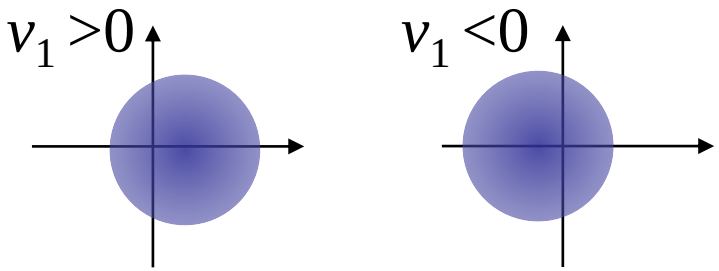
Directed Flow v_1

non-central collision



Flow

$$\frac{dN}{d\phi} \sim 1 + v_1 \cos\phi + v_2 \cos 2\phi + \cdots$$

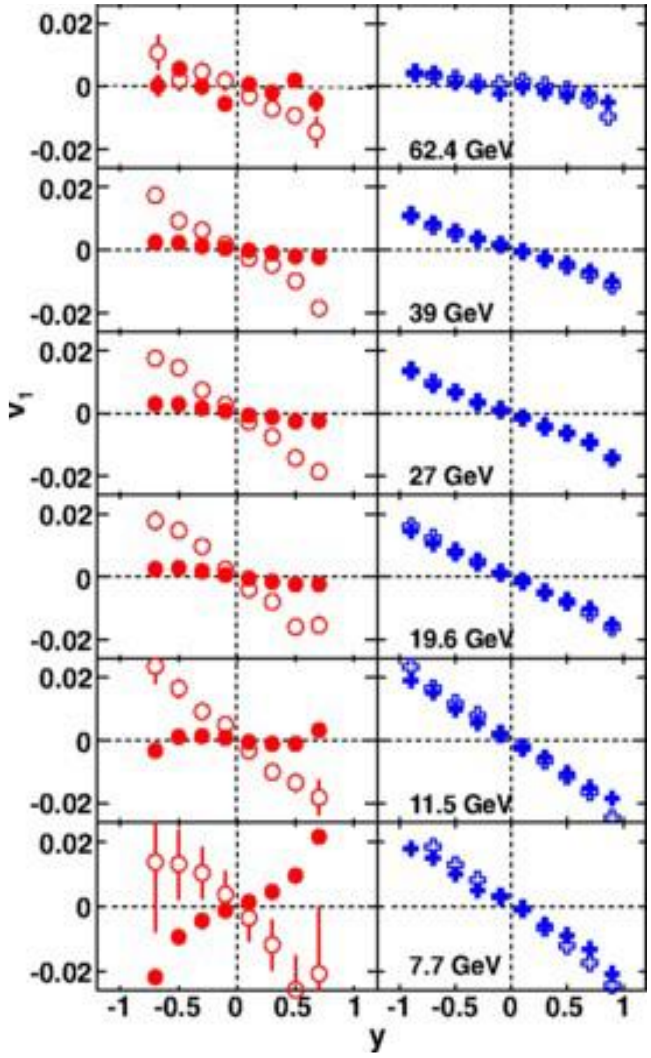


- v_1=0 at mid-rapidity
- v_1 can take nonzero value at nonzero η

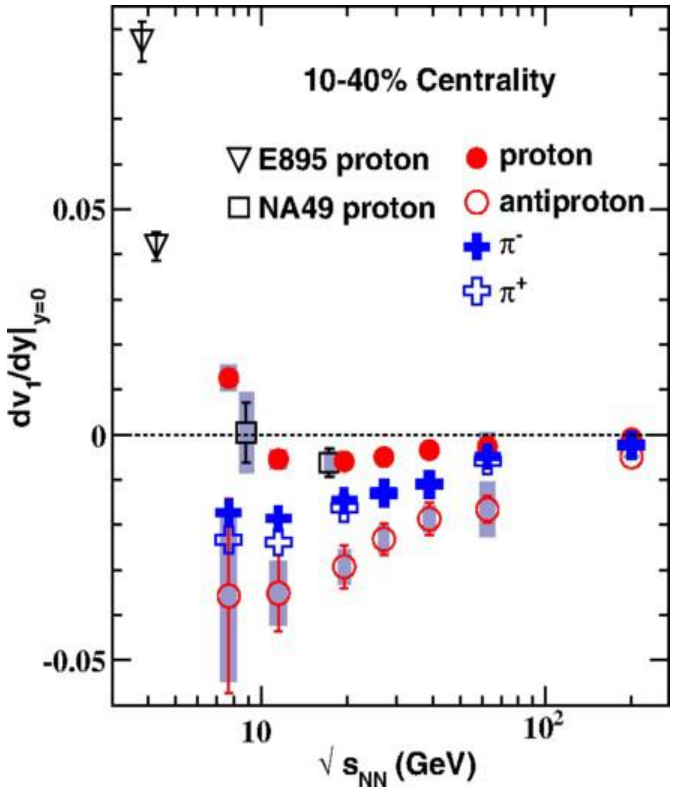
Directed Flow v_1 @ BES-I

y dependence

STAR BES I



$$\left.\frac{dv_1}{dy}\right|_{y=0}$$



- sign change at √s ~ 9 GeV
- not fully understood
- recent progress: Nara-san, heavy-ion pub

High statistics will also provide us with

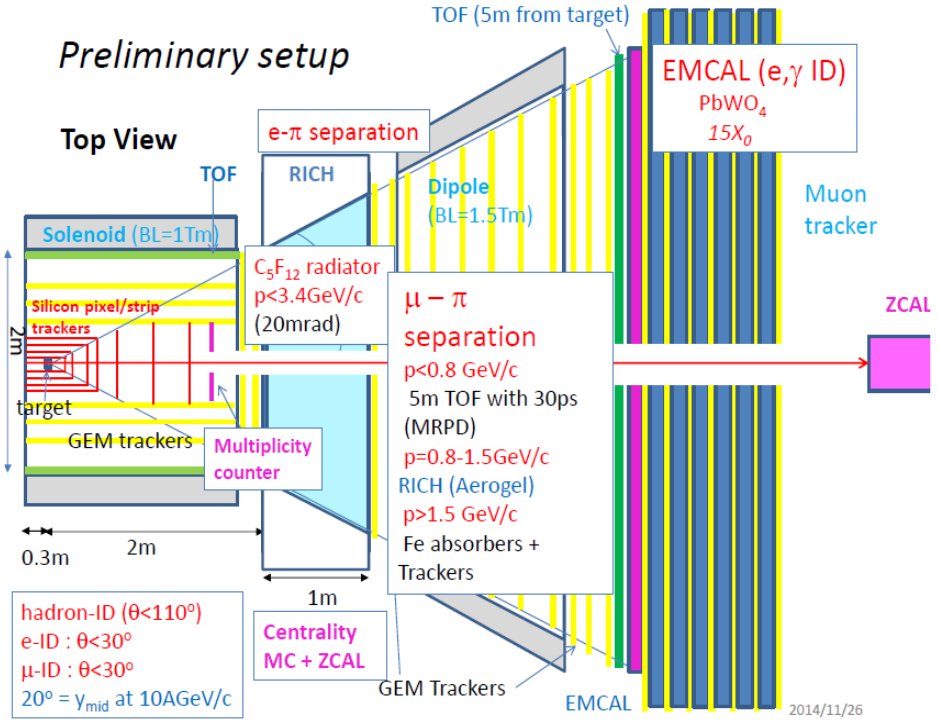
- rare probes (anti-proton, strangeness, …)
- higher harmonics v_3, v_4, …
- event-by-event harmonics / baryon stopping
- event selection

New Observables
(at J-PARC energy)

Advantages of J-PARC Detector

(that I heard from Sako-san)

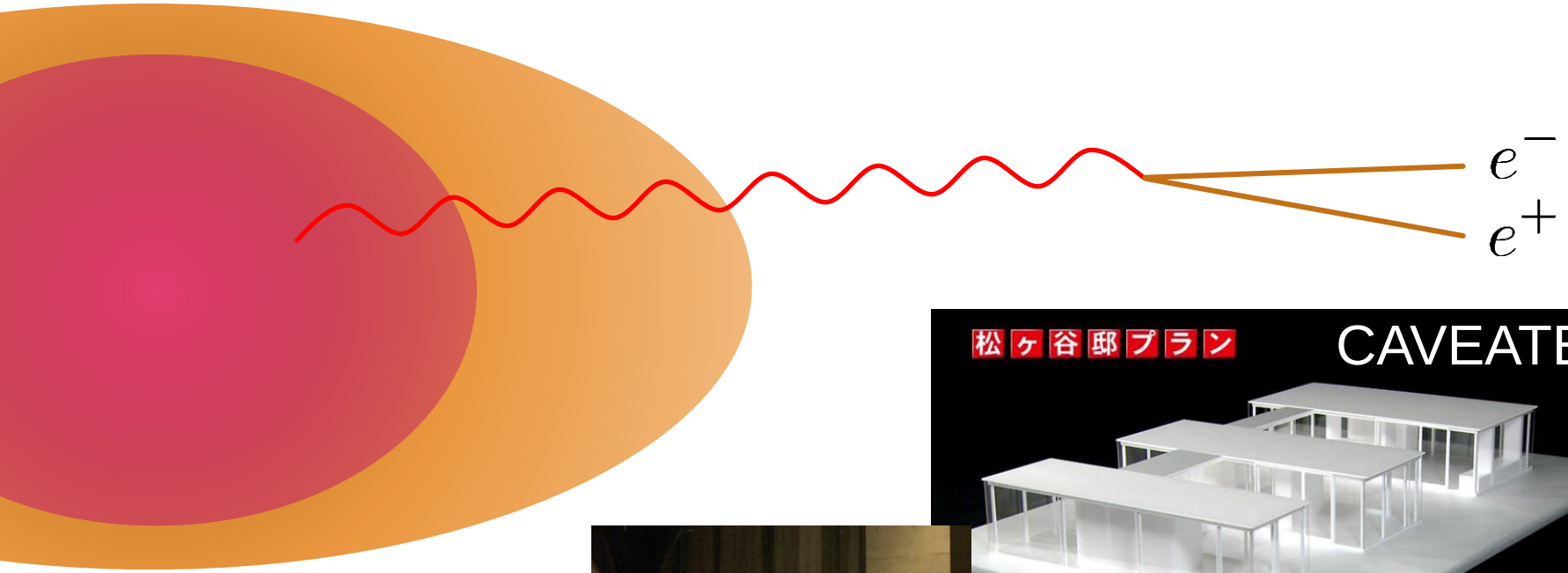
- Detector design
  - lepton and photon
  - 4π coverage



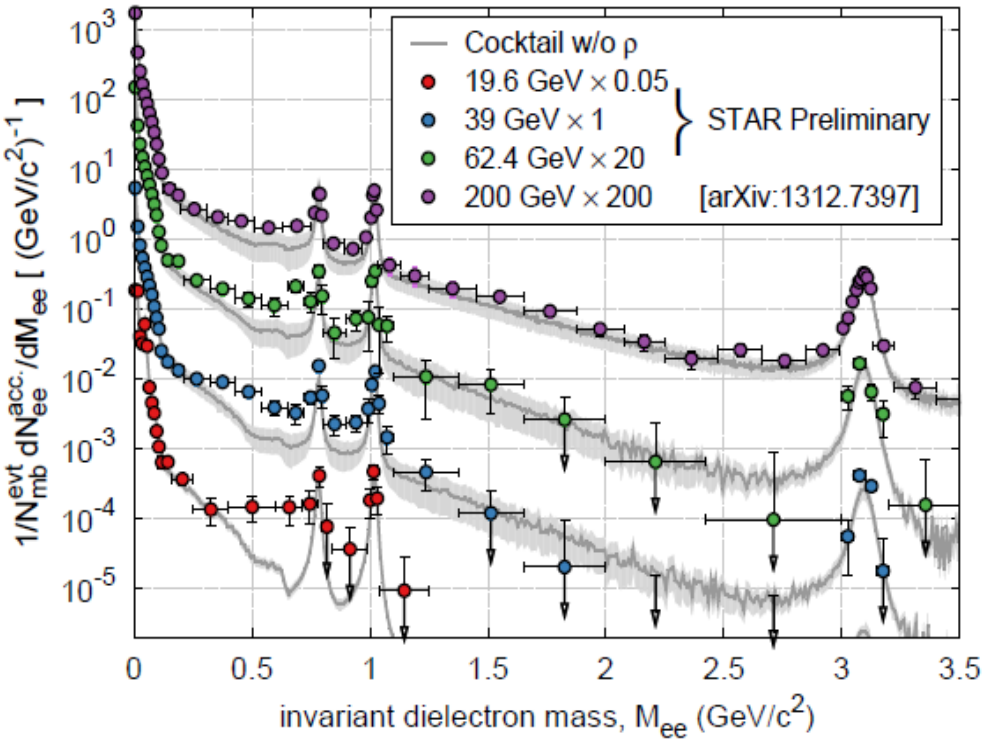
- Observables
  - dilepton production rate
  - conserved-charge fluctuations
  - correlation functions

Dilepton Production Rate

- Photon / lepton : no color charge
  - pass through hot medium without interaction
  - direct observables of hot medium



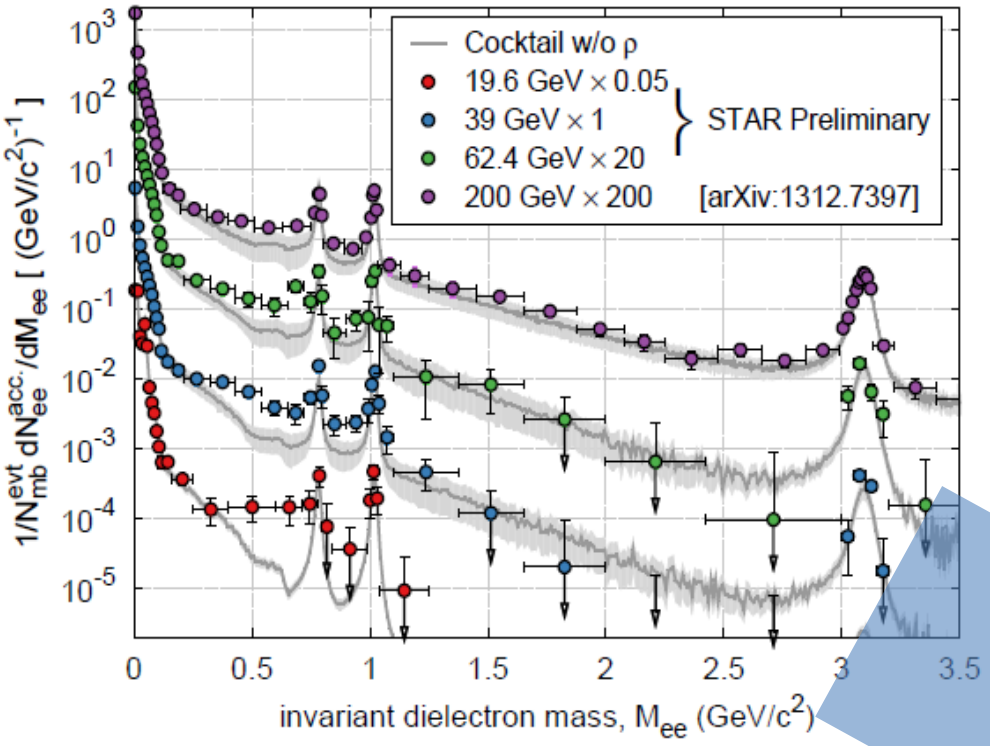
Dilepton Production Rate



Result at STAR BES-I

- minimum bias
- large errorbar for low E

Dilepton Production Rate

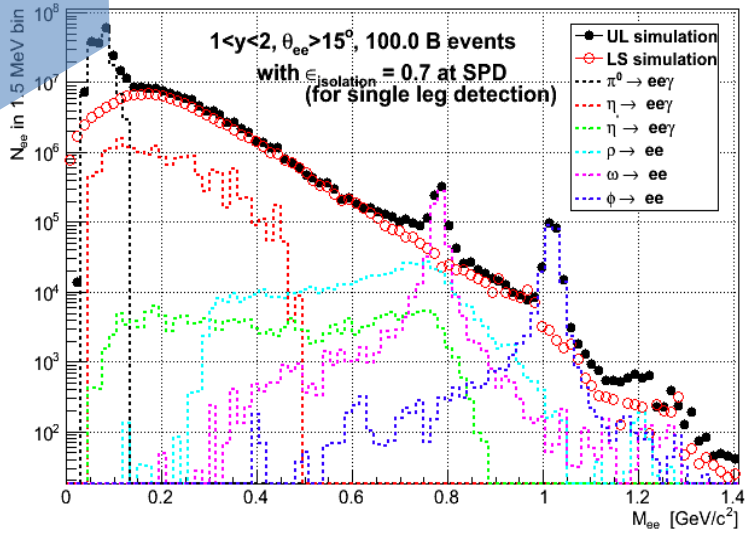


Result at STAR BES-I

- minimum bias
- large errorbar for low E

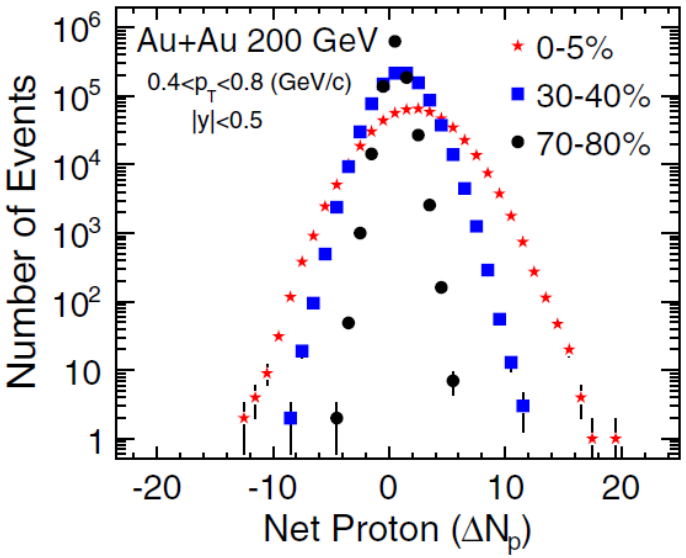
at J-PARC …

- high precision data
- centrality / pT dependence
- moment analysis



Event-by-event Fluctuations

STAR, PRL**105** (2010)



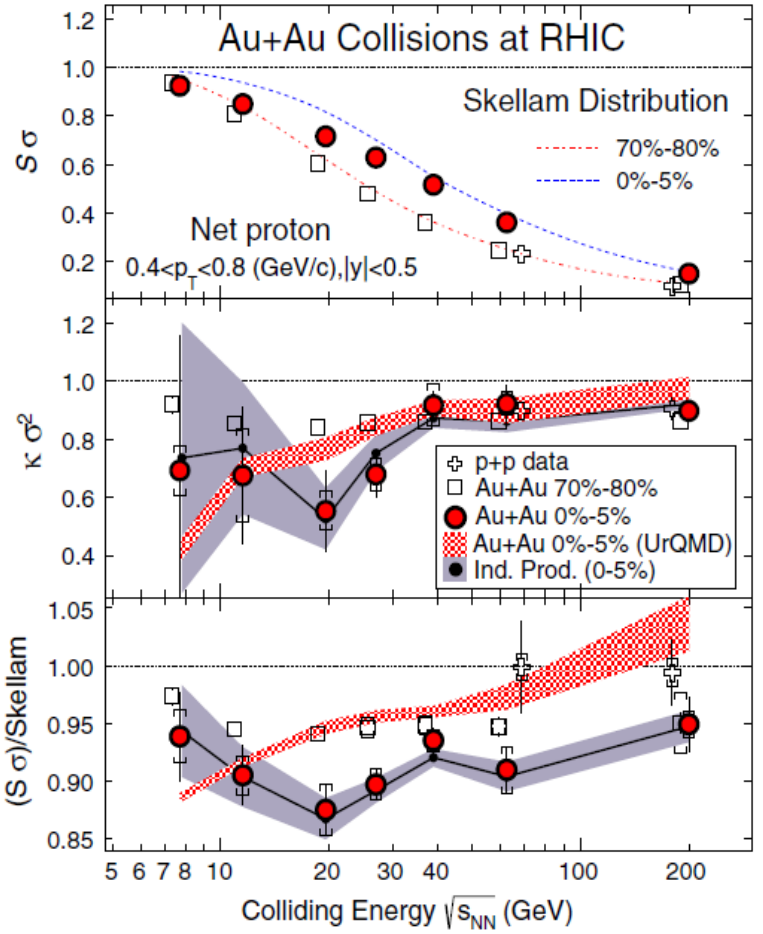
particle numbers in each event

thermal fluctuation

thermal property of hot medium

Event-by-event
non-Gauusian fluctuation

STAR BES-I

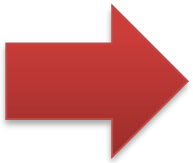


Summary

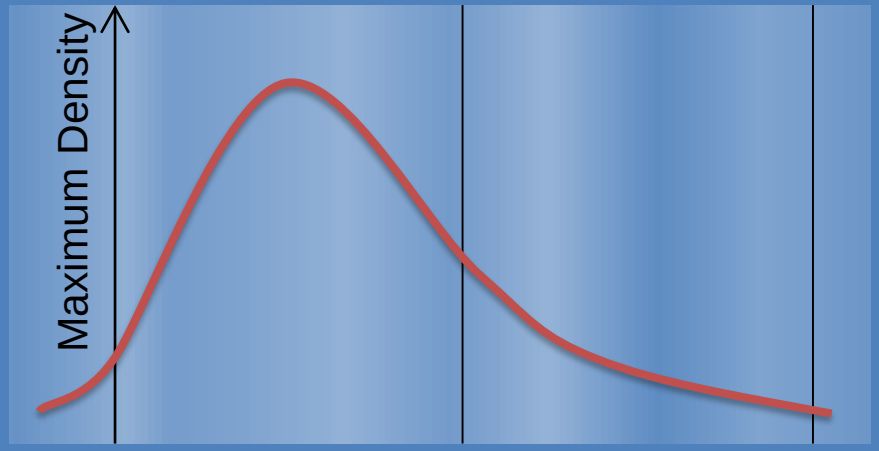
- Many interesting Physics in heavy ion collisions at J-PARC
  - onset of deconfinement
  - medium with highest baryon density
  - limits of hadronic and partonic models

- Experimental data with high statistics
  - needed for a contruction of dynamical model
  - precise understanding of the dense medium

- New experimental techniques
  - dilepton production rate
  - fluctuations / correlaions



Understanding of the dense QCD medium will be deepened with heavy ion collisions at J-PARC!!


Maximum Density