



# INVESTIGATING QCD MATTER WITH PHENIX AT RHIC

## WITH SPECIAL FOCUS ON SMALL SYSTEMS

---

MÁTÉ CSANÁD, EÖTVÖS UNIVERSITY, BUDAPEST, HUNGARY

HIX 2019, AUGUST 16-21, CRETE, GREECE





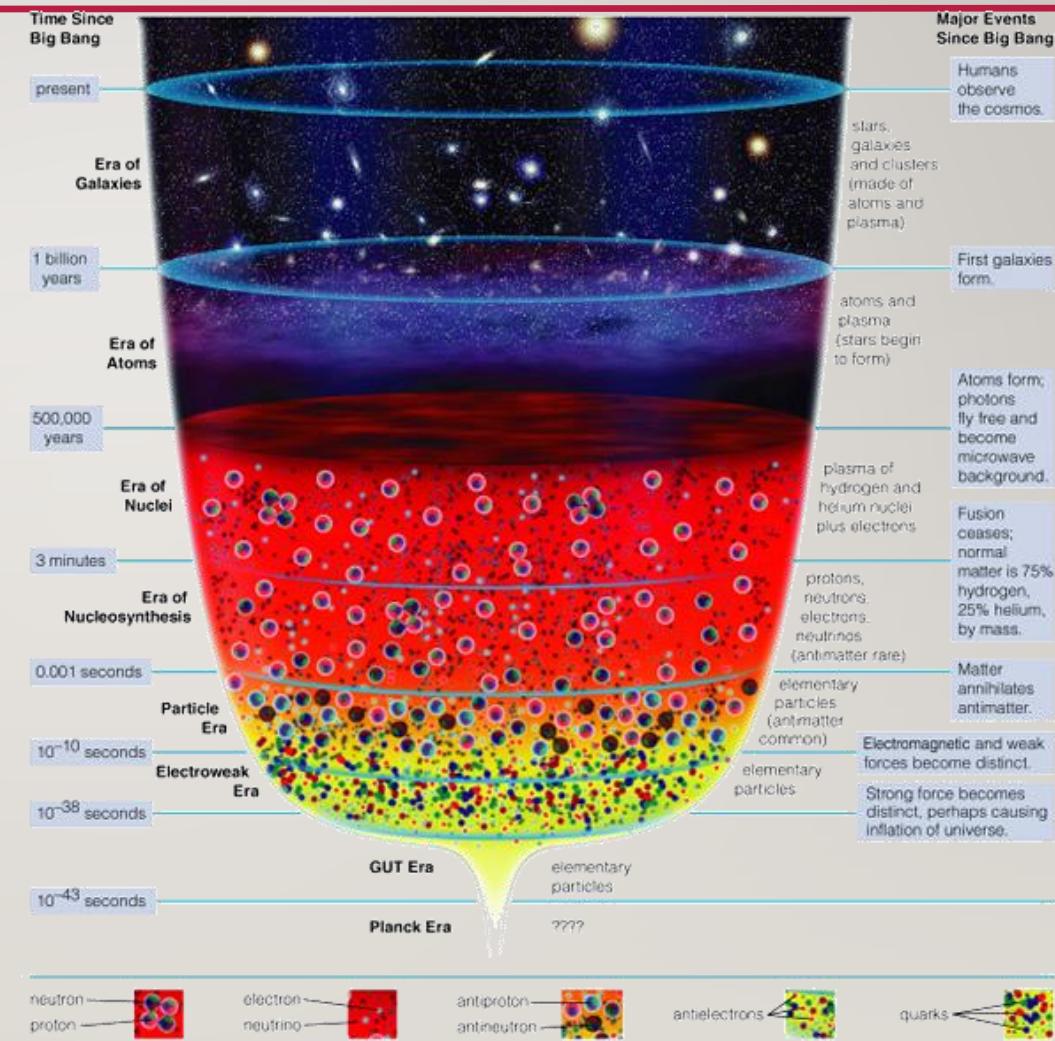
# CONTENT OF THIS TALK

---

- INTRODUCTION
  - The Big Bang and the Little Bangs in the lab
  - Experimental control parameters
  - RHIC and PHENIX
- BASIC OBSERVATIONS
  - Nuclear modification, flow, thermal photons, heavy flavor, HBT, fluctuations
- RECENT SMALL SYSTEMS RESULTS FROM PHENIX
  - Nuclear modification
  - Thermal photons
  - Flow

# 3/29 BIG BANG IN THE LAB

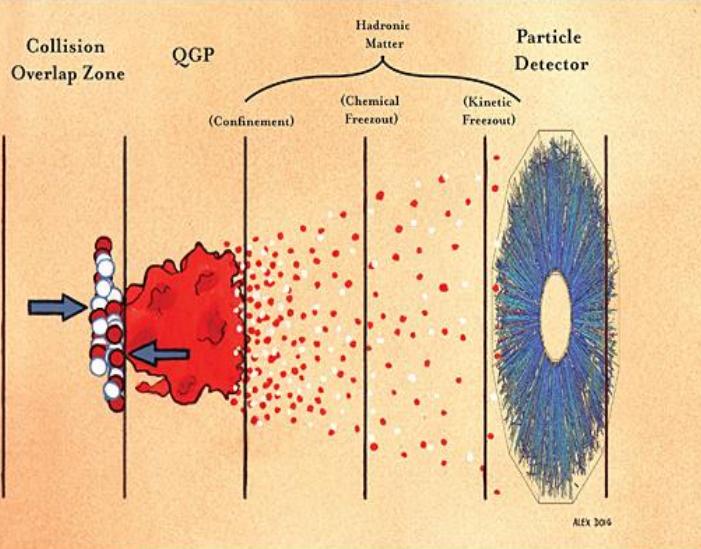
- Ages of the Universe:
  - Stars & Galaxies
  - Atoms
  - Nuclei
  - Nucleosynthesis
  - Elementary particles
  - ... ?
- How to investigate?
- Create little bangs
- Collisions of heavy ions
- Record outcoming particles



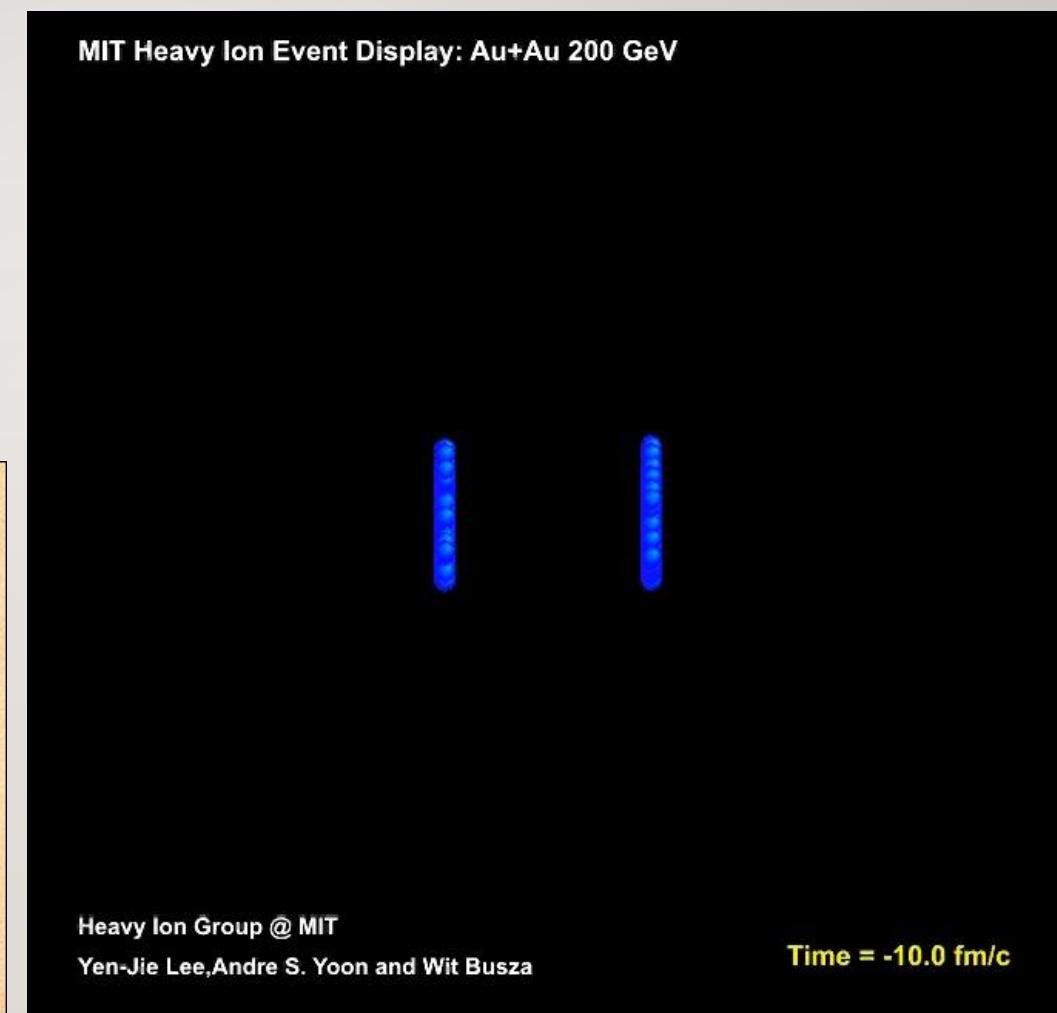
4<sub>/29</sub>

# TIMELINE OF A HEAVY ION COLLISION

- Pre-thermalization stage:  
 $\sim 1 \text{ fm}/c$
- Quark-hadron transition:  
 $\sim 7\text{-}10 \text{ fm}/c$
- Chemical + kinetic freeze-out

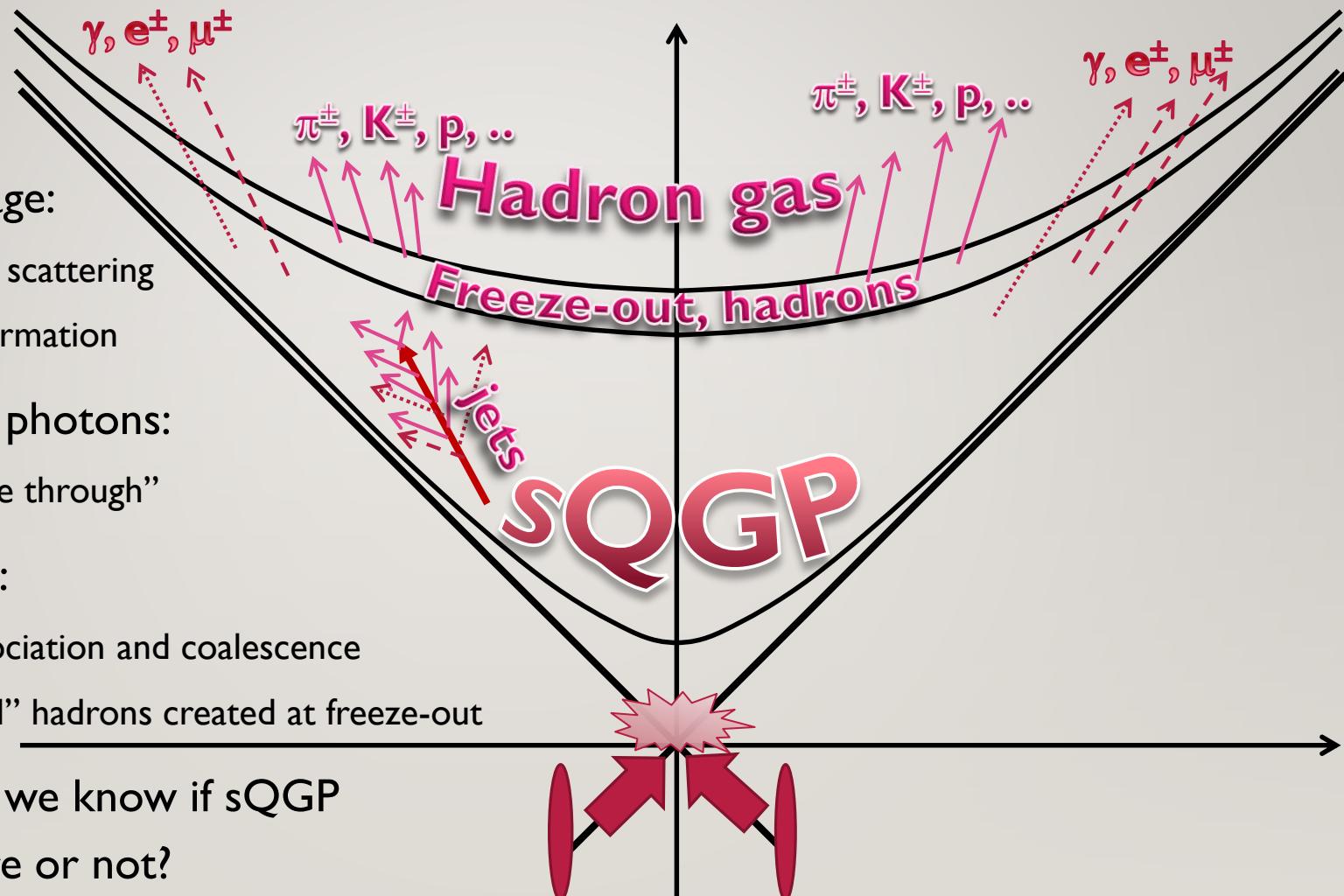


MIT Heavy Ion Event Display: Au+Au 200 GeV



# TIME EVOLUTION OF A HEAVY ION COLLISION

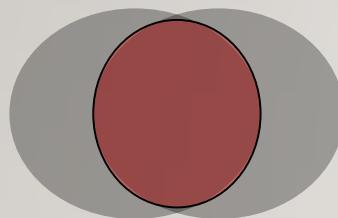
- Initial stage:
  - Hard scattering
  - Jet formation
- Leptons, photons:
  - "shine through"
- Hadrons:
  - Dissociation and coalescence
  - "Final" hadrons created at freeze-out
- How do we know if sQGP was there or not?



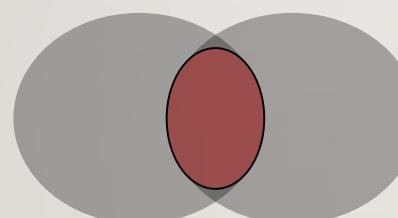
6/29

# EXPERIMENTAL CONTROL PARAMETERS

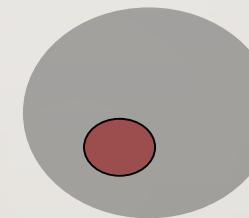
- Collision energy: controls initial temperature, initial  $\mu_B$
- Collision system & centrality: controls available volume
- Event geometry: reaction plane, event plane, fluctuations
- Important parameters:  $N_{\text{part}}$  (system size),  $N_{\text{coll}}$  (x-sect)



Central Au+Au  
 $N_{\text{part}} \sim 300$



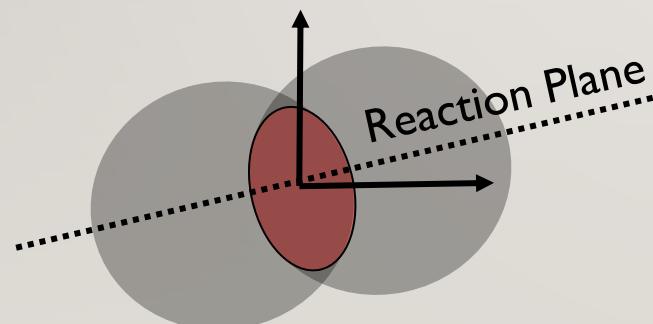
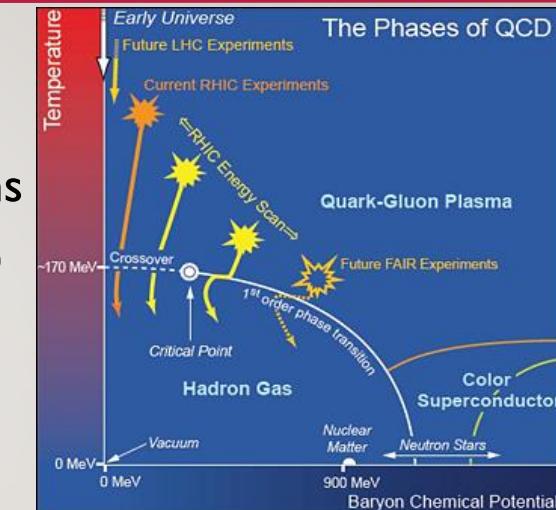
Peripheral Au+Au  
 $N_{\text{part}} \sim 50$



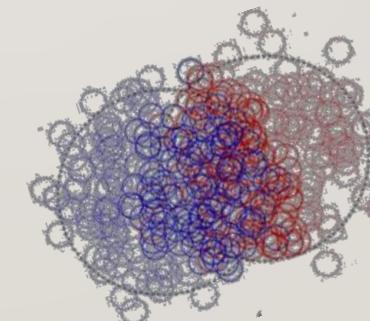
d+Au



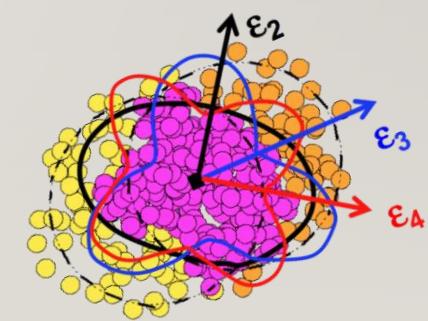
p+p



Reality



Multipole event planes



# INTRODUCTION

# BASIC QGP OBSERVATIONS

# SMALL SYSTEMS

# THE RELATIVISTIC HEAVY ION COLLIDER

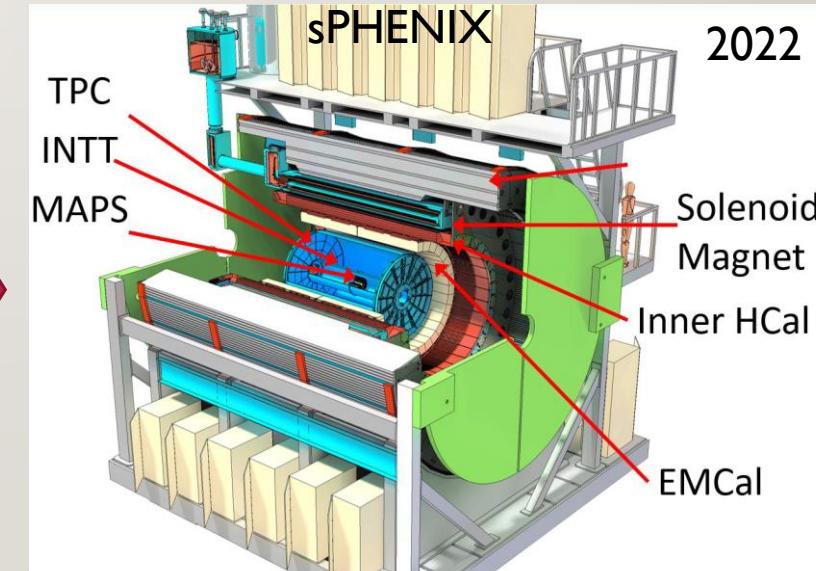
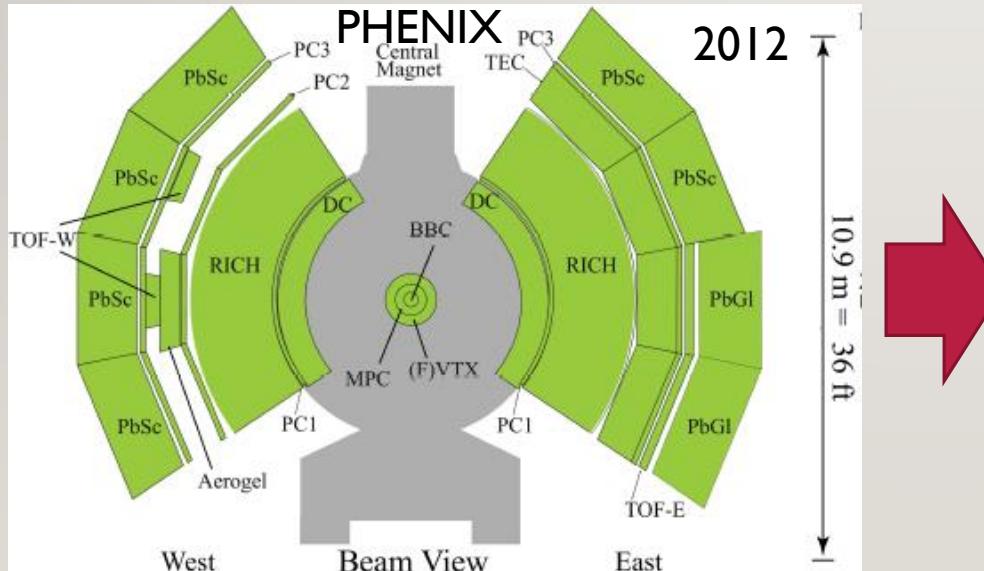
- At the Brookhaven National Laboratory, Long Island, New York, USA
- Collisions of:  $\vec{p}$ , d,  $^3\text{He}$ , Al, Cu, Au, U
- Accelerator energies: 7.7-200 GeV/nucleon, even 0.51 TeV for  $\vec{p}$
- Experiments: STAR; future: sPHENIX; past: BRAHMS & PHOBOS & PHENIX



INTRODUCTION BASIC QGP OBSERVATIONS SMALL SYSTEMS

# PHENIX AND sPHENIX

- PHENIX: versatile detector identifying many different particles, recording large amount of collisions. Dismantled in 2016, to give way to sPHENIX
- sPHENIX: to take data in ~2023
  - Jets, jet correlations, Upsilon states
  - EM+Hadronic calorimetry, high resolution tracking, fast (~100 kHz) data acquisition



## 9<sub>/29</sub> THE RHIC BEAM ENERGY/SPECIES SCAN

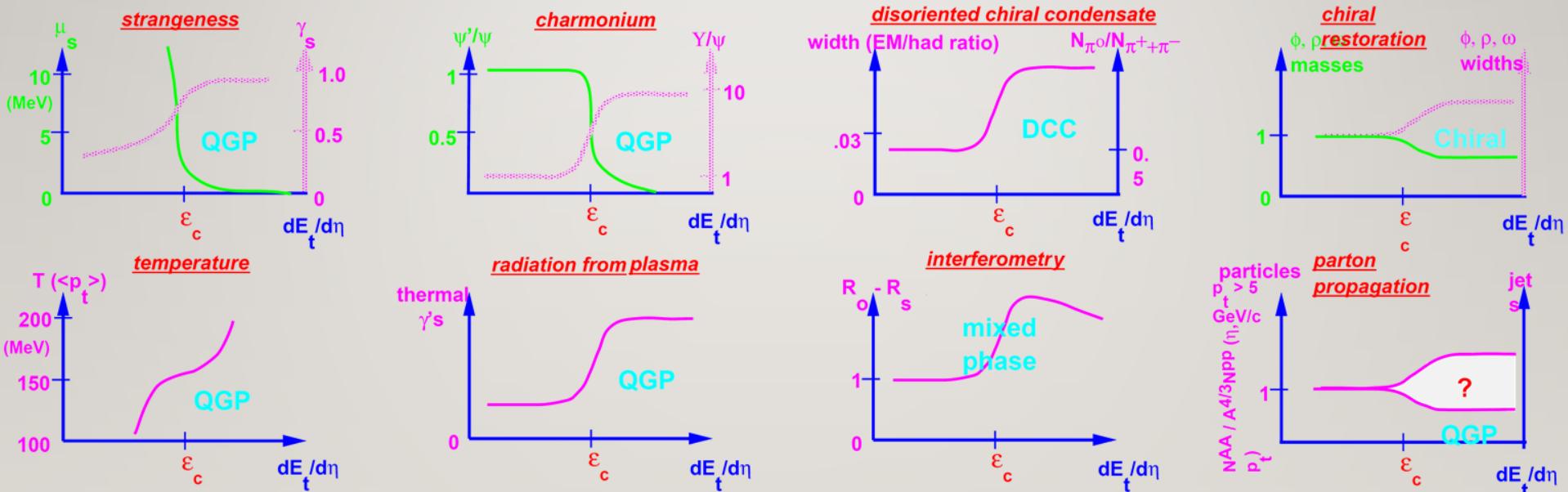
- Collision experiments: acceptance independent of energy
- BES-I: 7.7-200 GeV; BES-II: 7.7-19.9 GeV, increased luminosity
- Small system scan: x+Au, 19.6-200 GeV
- STAR fixed target mode: down to 3 GeV

$\sqrt{s_{NN}}$ [GeV]	STAR Au+Au events [ $10^6$ ]	PHENIX Au+Au events [ $10^6$ ]	Year
200.0	2000	7000	2010
62.4	67	830	2010
54.4	1300	-	2017
39.0	130	385	2010
27.0	70	220	2011
19.6	36	88	2011
14.5	20	247	2014
11.5	12	-	2010
7.7	4	1.4	2010

$\sqrt{s_{NN}}$ [GeV]	PHENIX events [ $10^6$ ]	Species
200.0	2.2	p+Au
200.0	1600	$^3\text{He}+\text{Au}$
200.0	2057	d+Au
62.4	1655	d+Au
39.0	2000	d+Au
19.6	1040	d+Au

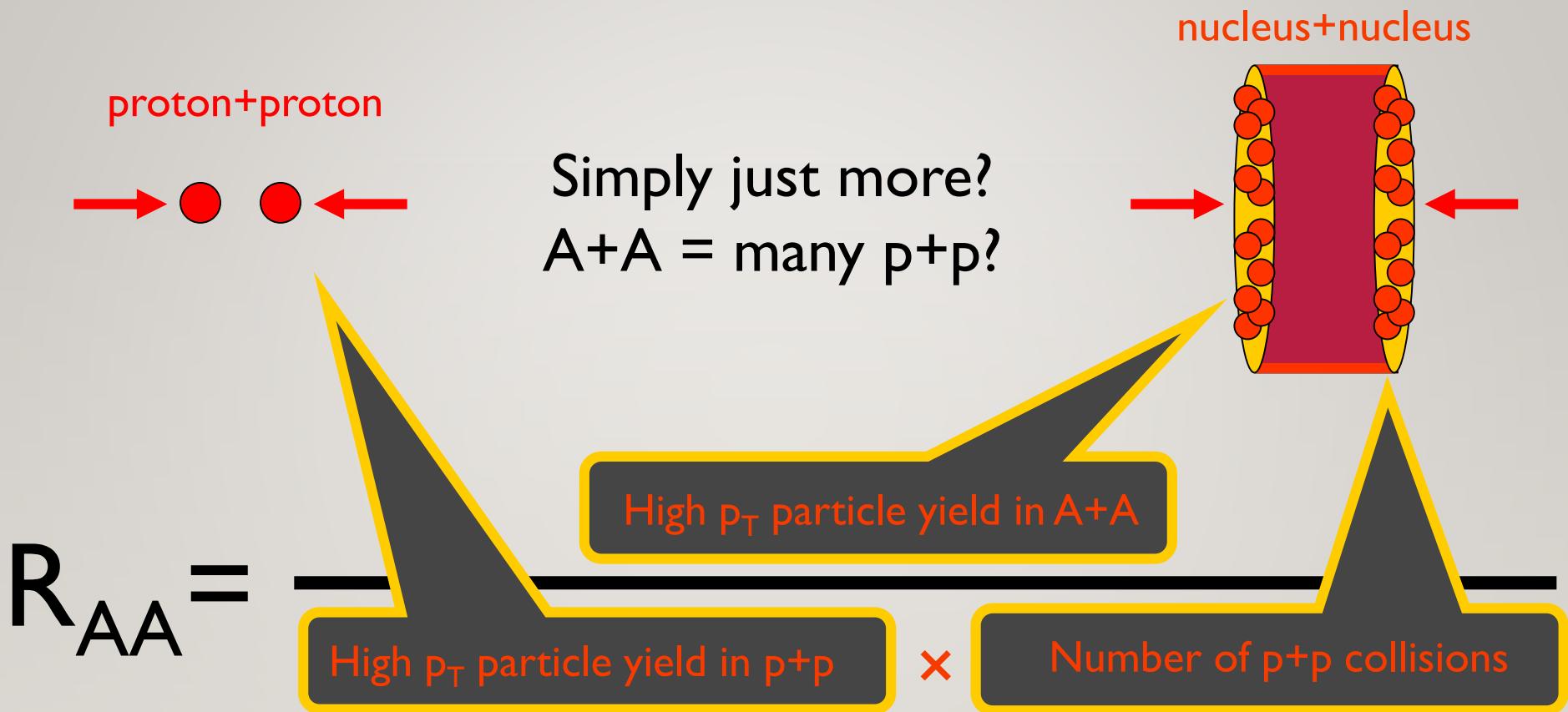
# 10<sub>/29</sub> QGP SIGNATURES EXPECTATIONS, 1996

- Critical energy density:  $\epsilon_c \approx 1 \text{ GeV/fm}^3$ , temperature  $T_c \approx 170 \text{ MeV}$
- Some observed, some not...



J. Harris & B. Mueller, „The Search for the QGP”, Ann.Rev.Nucl.Part.Sci. 46 (1996) 71 [hep-ph/9602235]

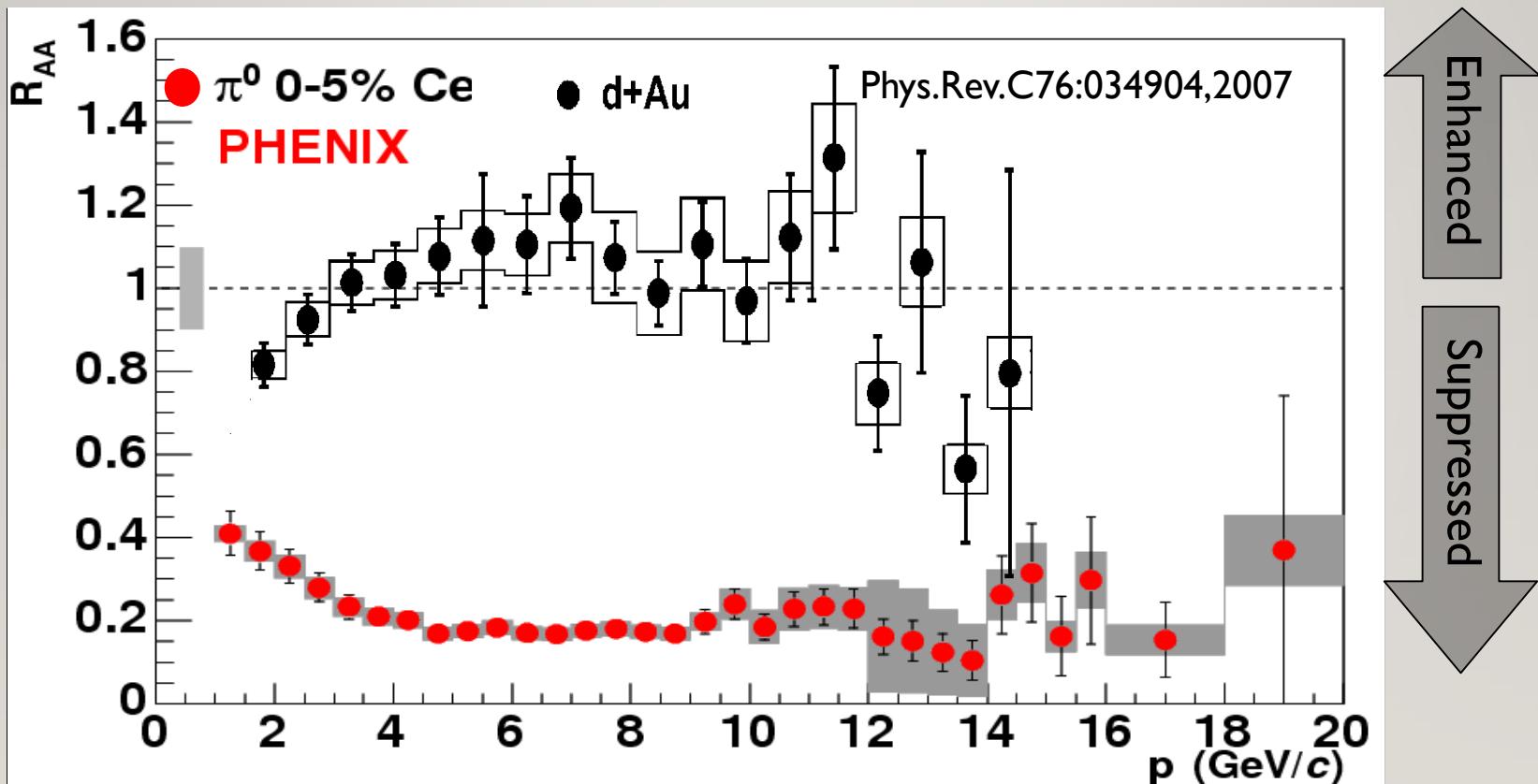
# NUCLEAR MODIFICATION: TOMOGRAPHY!



12<sub>/29</sub>

# SUPPRESSION AS A FUNCTION OF CENTRALITY

- No suppression in d+Au or peripheral Au+Au; strong suppression in central!



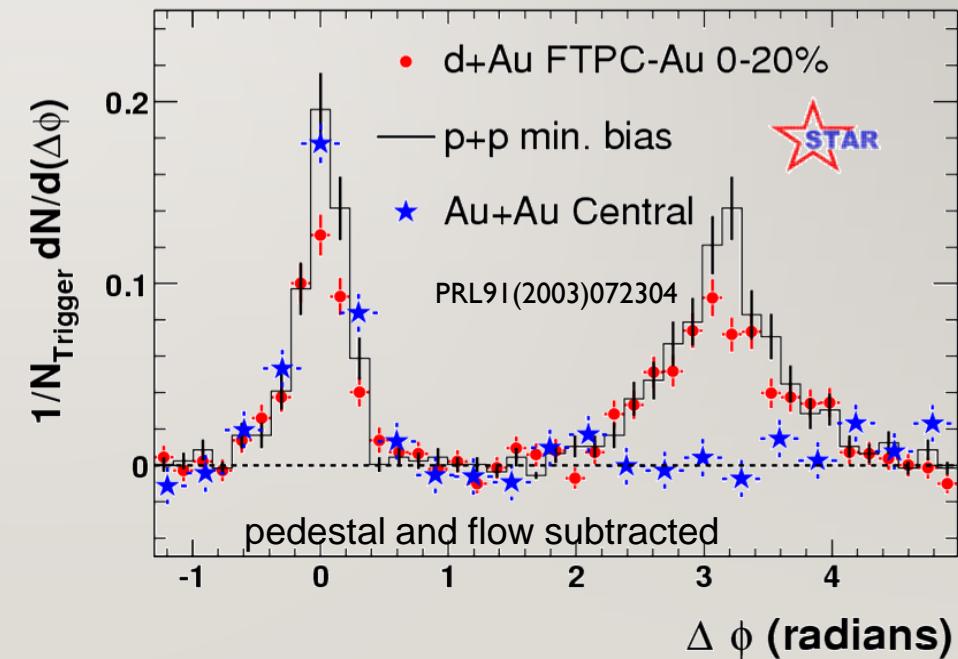
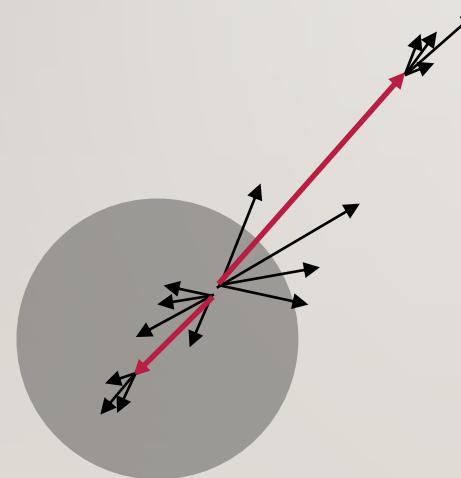
## INTRODUCTION

## BASIC QGP OBSERVATIONS

## SMALL SYSTEMS

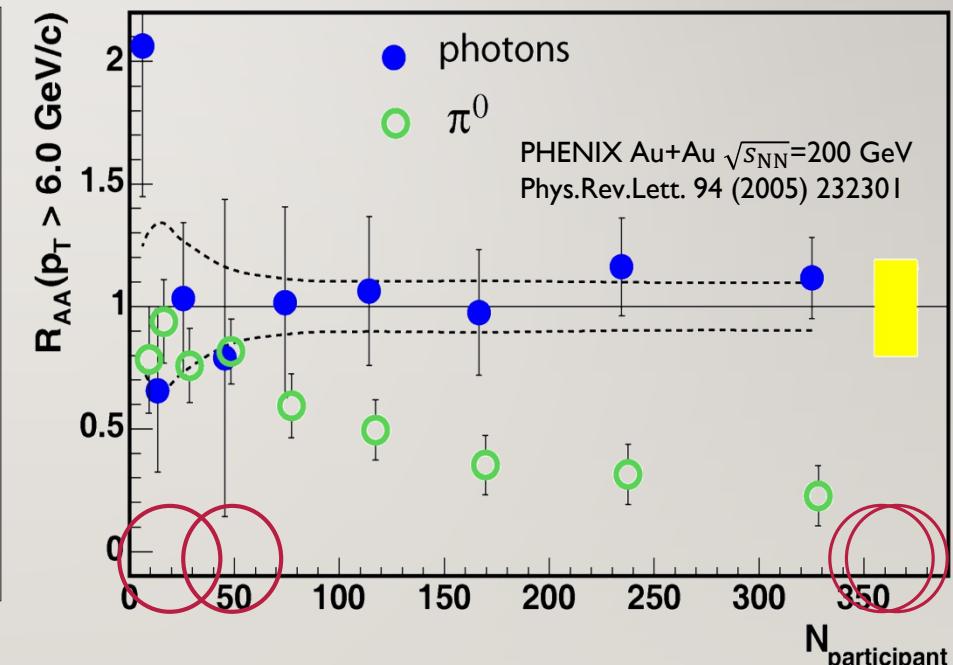
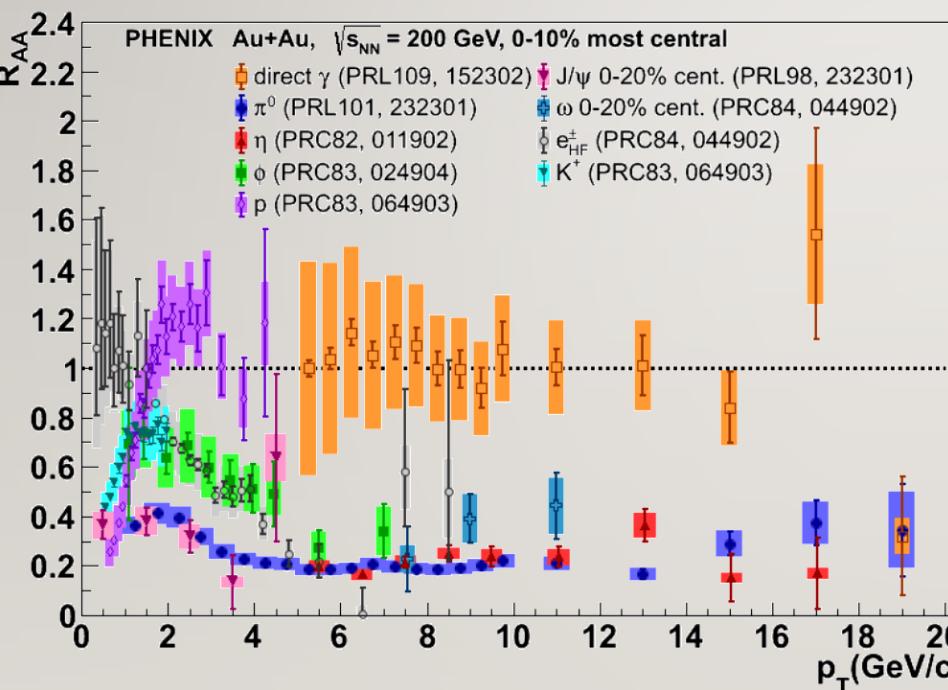
13<sub>/29</sub> SUPPRESSION OF THE AWAY SIDE JET

- Angular correlation of high energy hadrons
- Outgoing jet: similar in p+p, d+Au, Au+Au
- Inward going (away side) jet: missing in central Au+Au



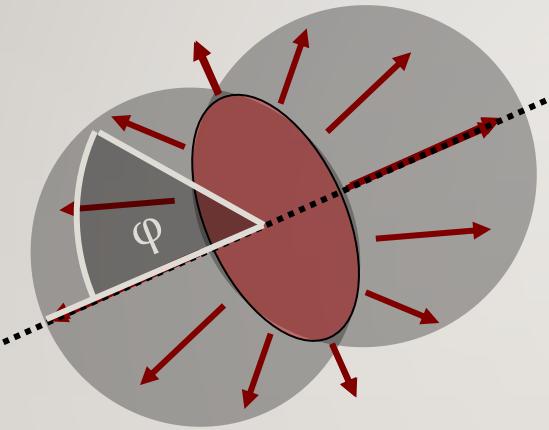
# 14<sub>/29</sub> HOW DO OTHER PARTICLES BEHAVE?

- All hadrons suppressed, direct photons „shine through”
- Suppression dependent of system size (controlled by centrality or  $N_{\text{part}}$ )

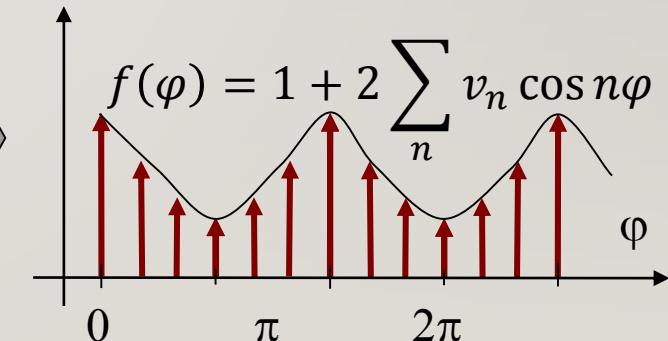
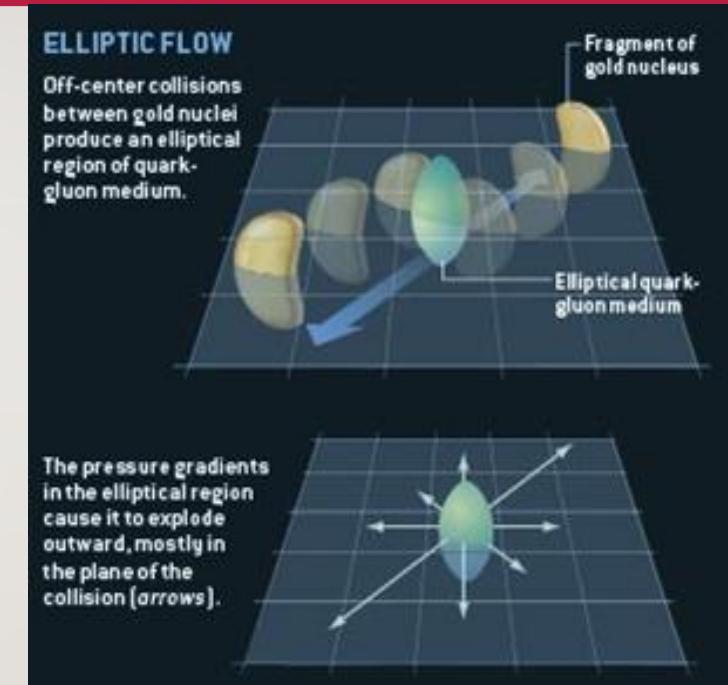
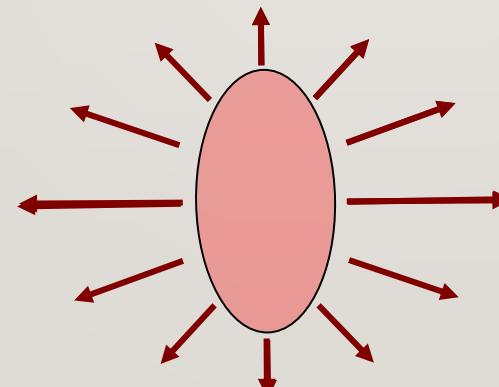


15<sub>/29</sub> OBSERVATION OF THE ELLIPTIC FLOW

- Spatial anisotropy creates momentum-space anisotropy!



- Quantified via anisotropy parameters



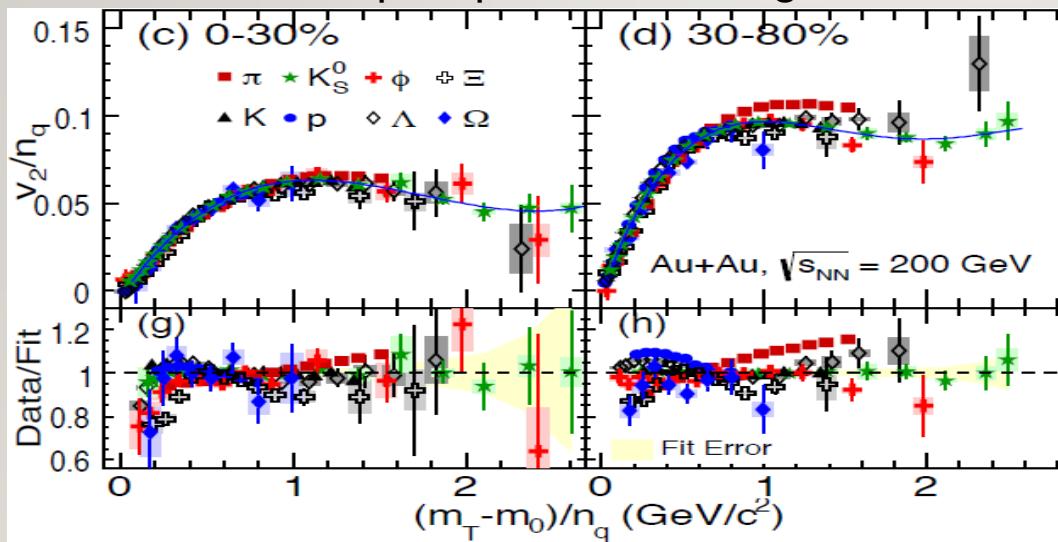
# ELLIPTIC FLOW SCALING

- Hydro predicts scaling ( $v_2$  versus  $w \sim E_K/T_{\text{eff}}$ )
- Coalescence predicts quark number scaling

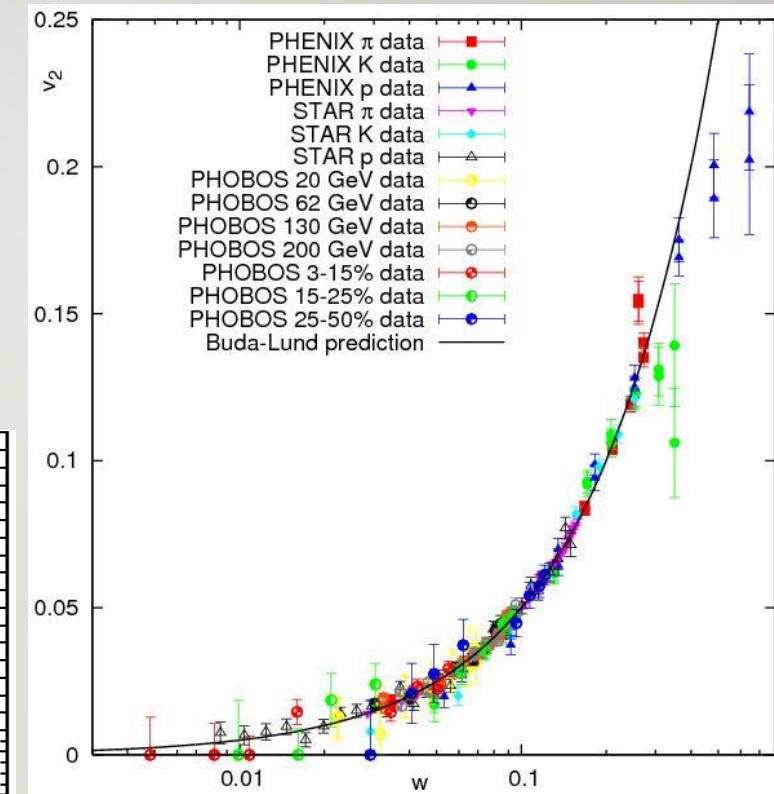
$$E_K^{\text{hadron}} = n_q E_K^{\text{quark}}$$

$$v_n^{\text{hadron}}(E_K^{\text{hadron}}) \cong n_q v_n^{\text{quark}}(E_K^{\text{quark}})$$

- Flow develops in pre-hadronic stage!



PHENIX, PRL98(2007)162301; STAR, PRL116(2016)62301

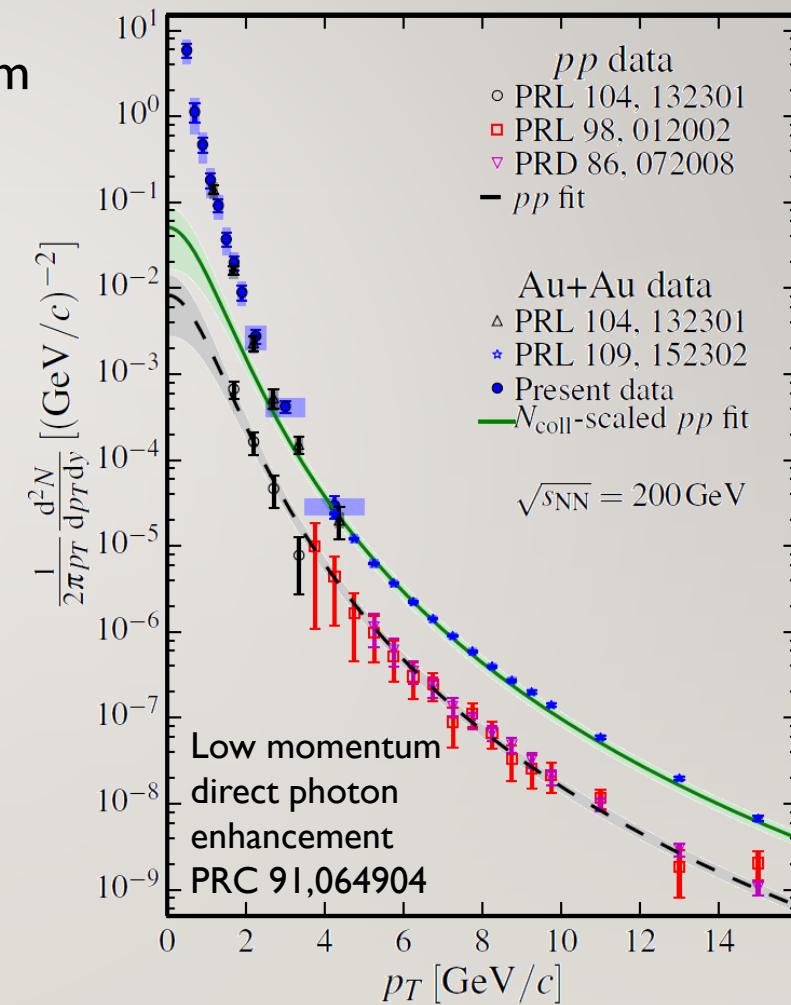


Csand, Csorg, Lrstad, Ster (NPA742:80-94,2004)

Csand, Csorg, Lrstad, Ster et al. (EPJA38:363-368,2008)

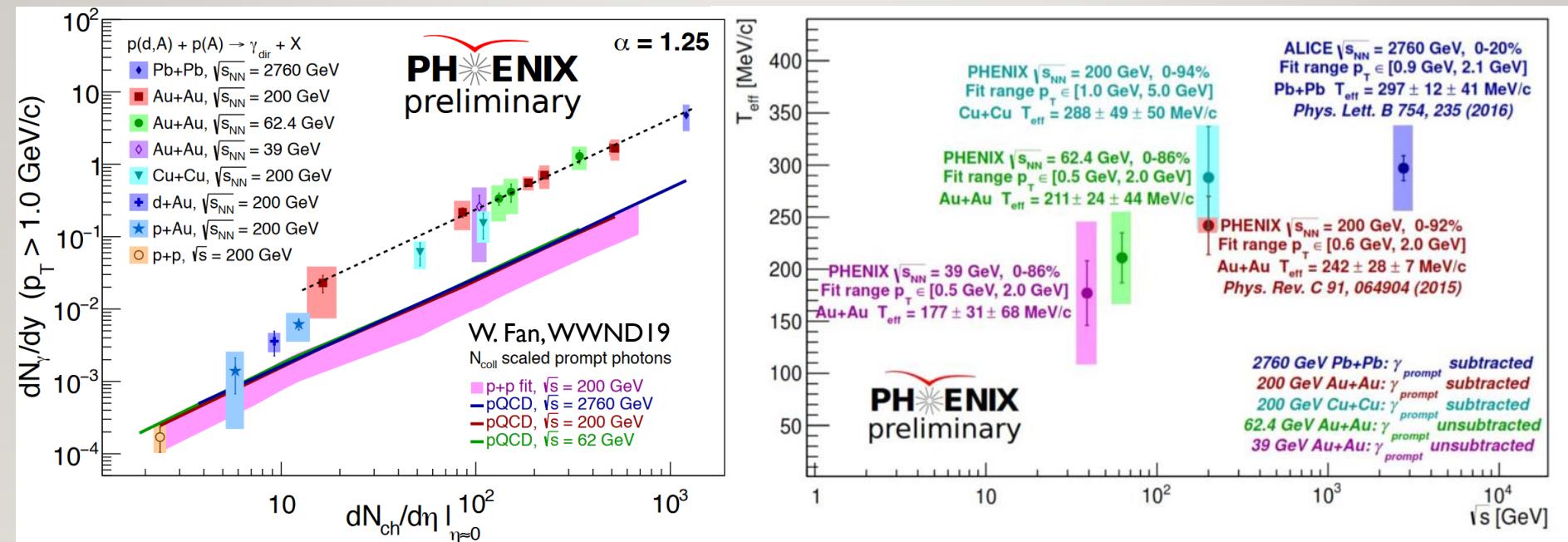
# THERMAL PHOTONS

- Soft component in direct photon spectrum compared to p+p extrapolation
- These are thermal photons!
- Large initial temperature, 3-600 MeV!



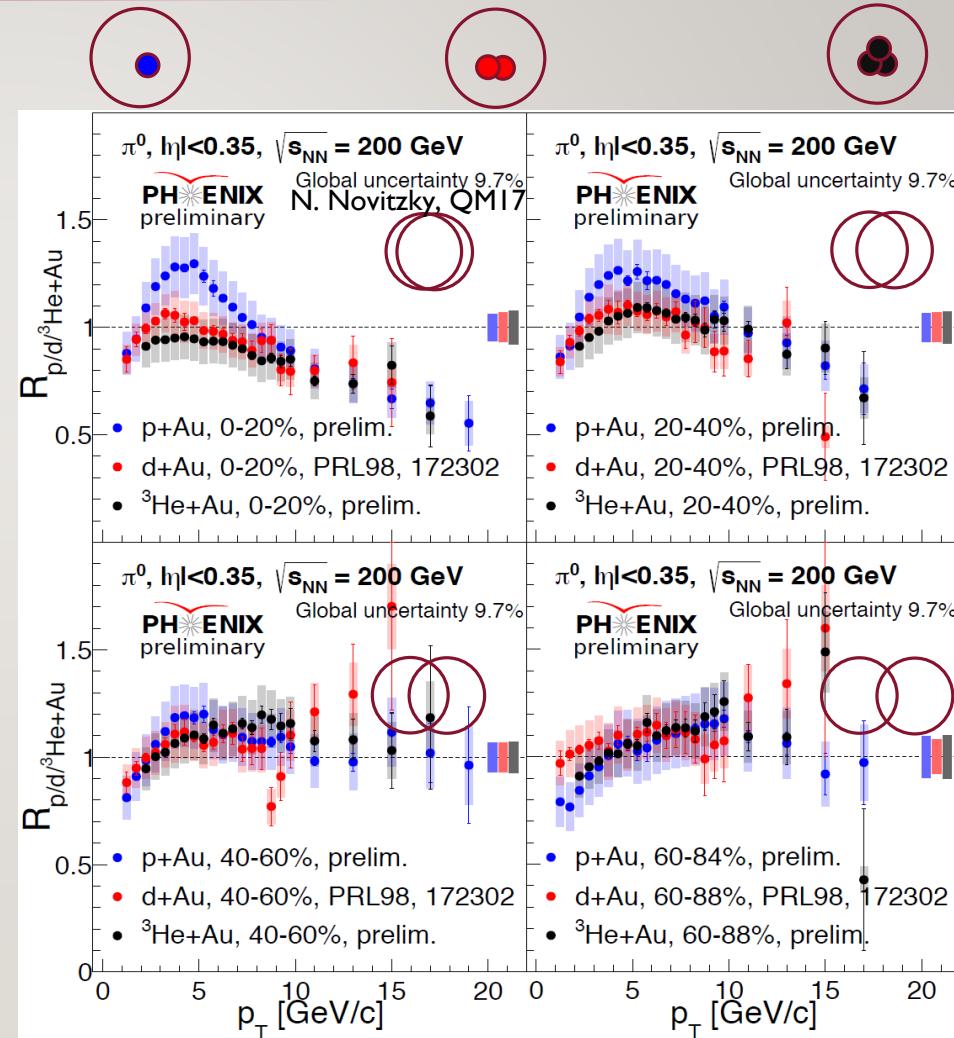
# DIRECT PHOTONS

- Clear direct  $\gamma$  signal at lower energies
- Yield scaling from RHIC to LHC, transition from p+p, to A+A: p+Au, d+Au
- Effective photon temperature similar from 39 to 2760 GeV
- Note overlapping mechanisms: hadron gas, sQGP, jets, bremsstrahlung, hard scatt.



# SUPPRESSION IN HIGHLY ASYMMETRIC SYSTEMS

- p+Au, d+Au,  $^3\text{He}+\text{Au}$  compared
- Centralities determined as for large systems
- New p+Au results show large centrality dependence
- All systems agree at high pT
- At moderate pT, ordering seen
- Model comparision:
  - Vitev, HIJING++ investigated
  - No full match of ordering, peak location, high pT region



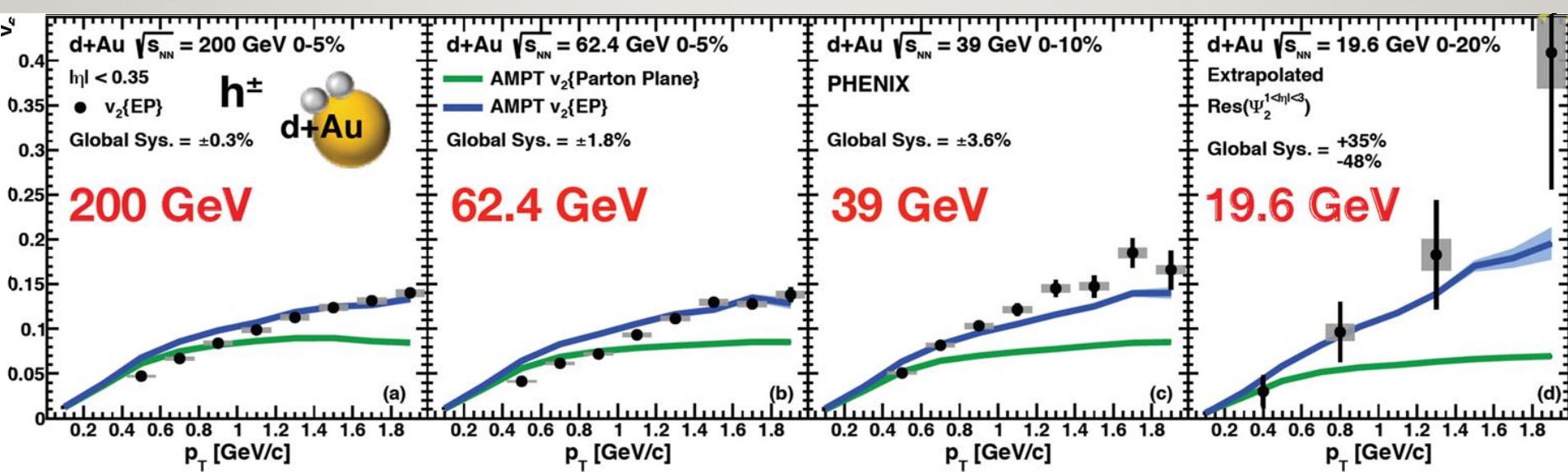
## INTRODUCTION

## BASIC QGP OBSERVATIONS

## SMALL SYSTEMS

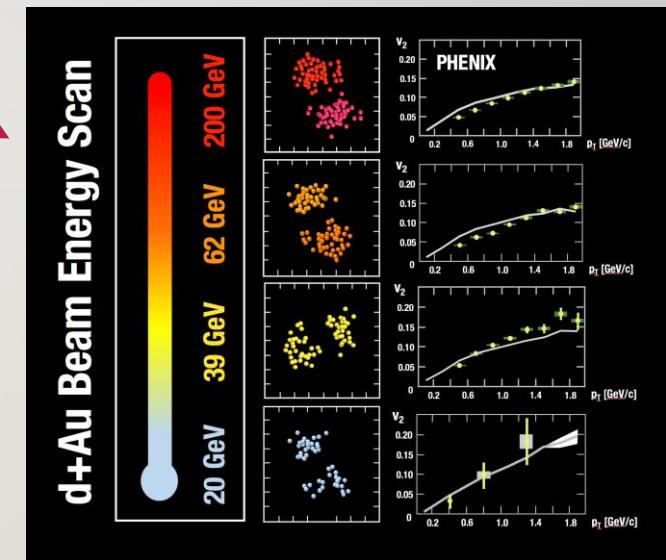
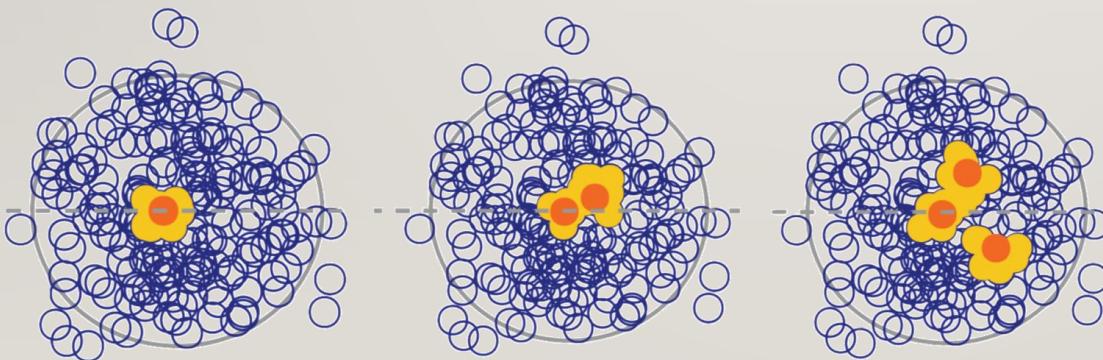
## 20<sub>/29</sub> ELLIPTIC FLOW IN SMALL SYSTEMS

- Deuteron-gold energy scan (19.6-200 GeV), PHENIX, PRC96, 064905 (2017)
- superSONIC in good agreement at 62.4 GeV and 200 GeV
- Underpredicts data at 19.6 GeV and 39 GeV
- Data still contains nonflow effects: AMPT(EventPlane) w/ nonflow matches



# ORIGIN OF FINAL STATE COLLECTIVITY?

- Is it due to the appearance of the sQGP (i.e. a strongly coupled fluid)?
  - If yes, how much time is needed to spend in QGP phase?
  - Test: d+Au collisions from 20 to 200 GeV
- Is it due to initial geometry and hydro?
  - Hydrodynamics: initial spatial correlations
  - Alternative: initial momentum correlations
  - Test: p+Au, d+Au,  $^3\text{He}+\text{Au}$
  - How do  $v_2$  and  $v_3$  evolve with initial state geom.?

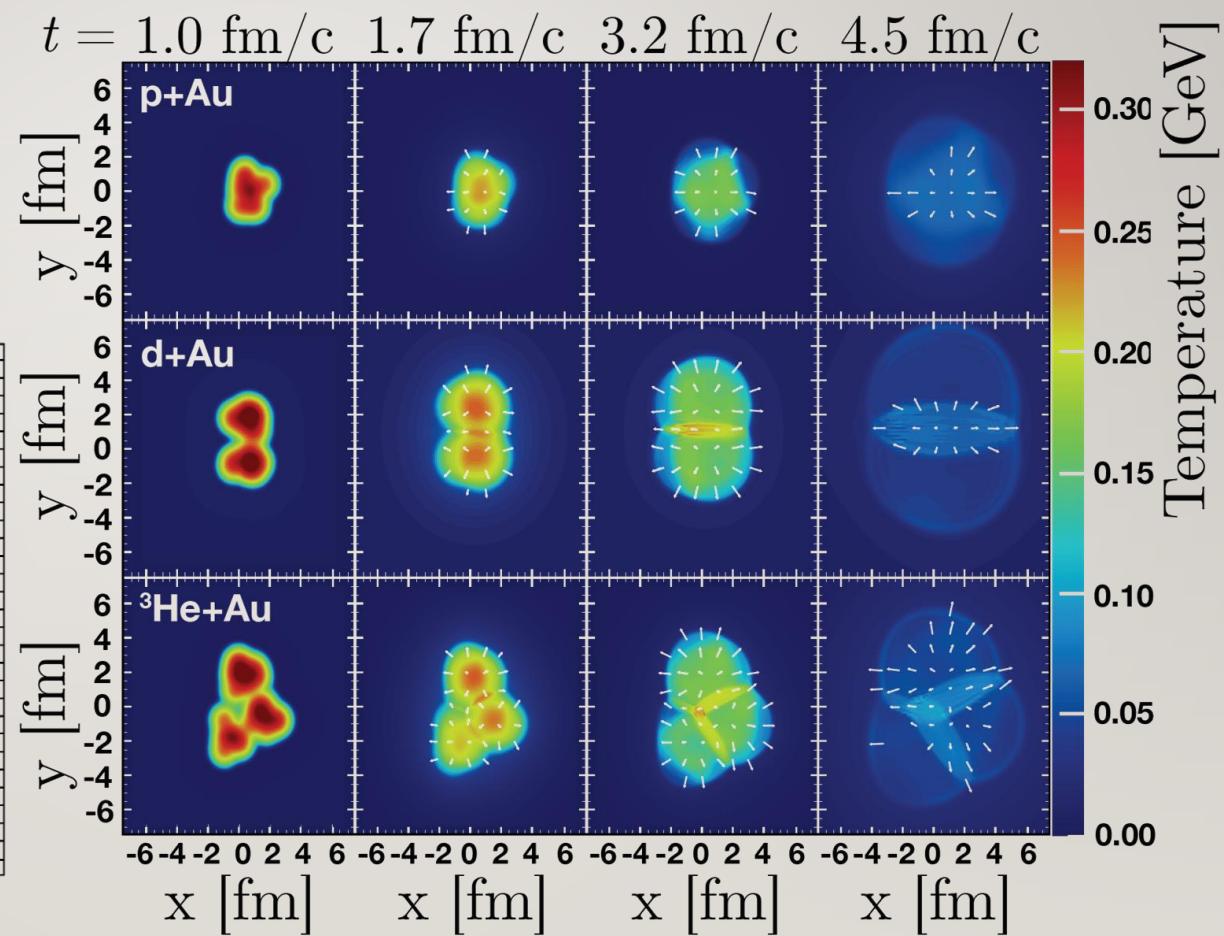
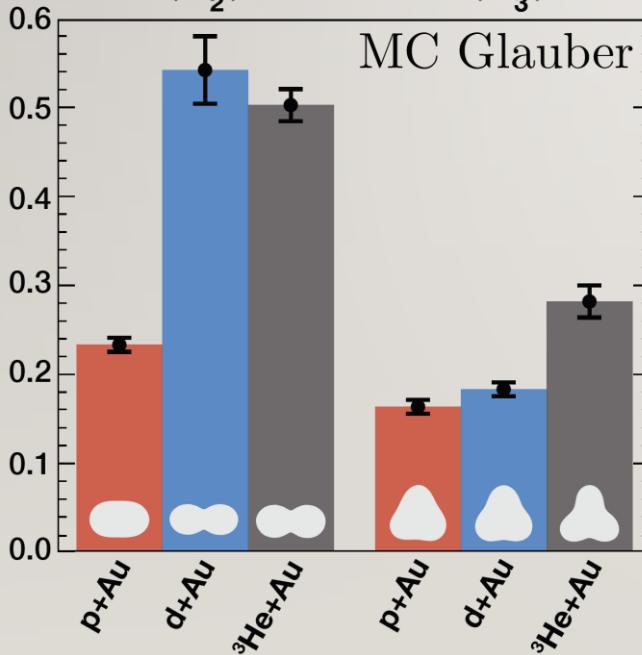


# INITIAL STATE AND HYDRO EVOLUTION

- Evolution from SONIC
- Initial stage:

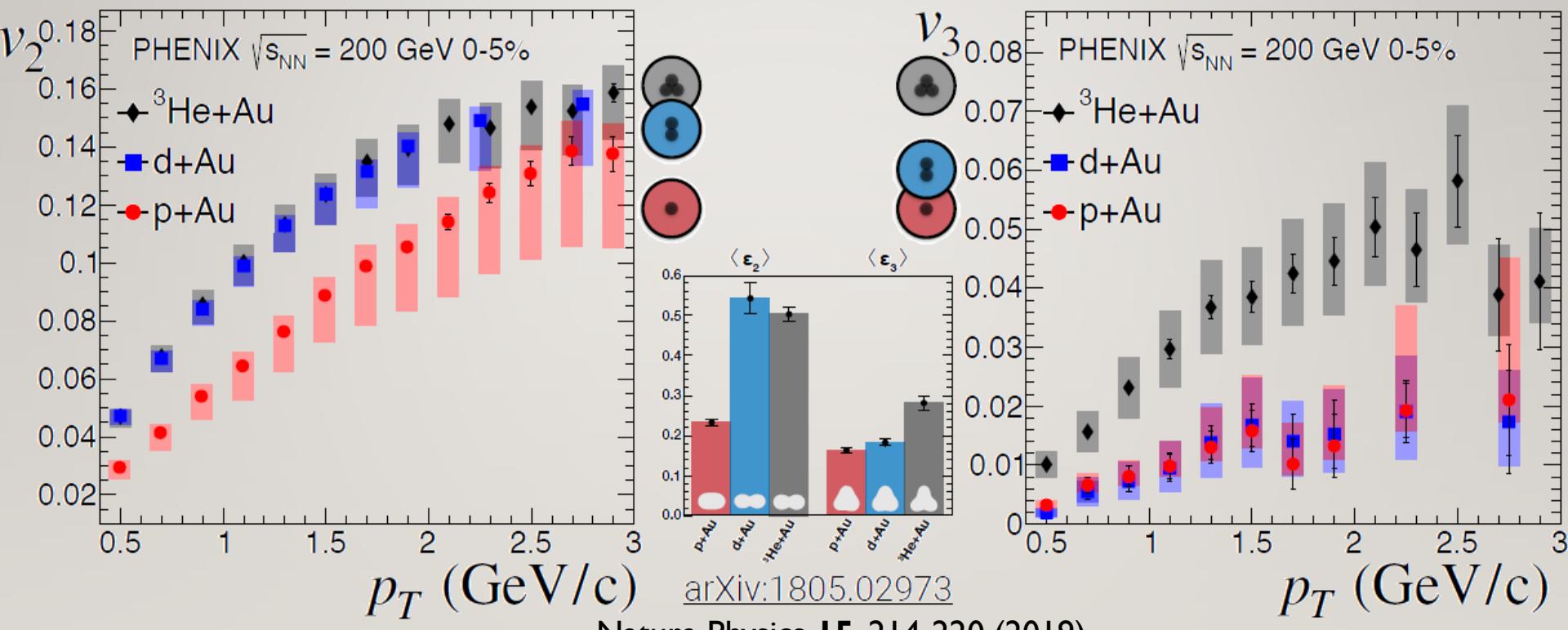
$$\epsilon_2^{p+\text{Au}} < \epsilon_2^{d+\text{Au}} \approx \epsilon_2^{\text{He}+\text{Au}}$$

$$\epsilon_3^{p+\text{Au}} \approx \epsilon_3^{d+\text{Au}} < \epsilon_3^{\text{He}+\text{Au}}$$

 $\langle \epsilon_2 \rangle$ 
 $\langle \epsilon_3 \rangle$ 


# FLOW IN SMALL SYSTEMS: GEOMETRIC ORDERING

- Flow ordered similarly as initial state:



$$v_2^{p+\text{Au}} < v_2^{d+\text{Au}} \approx v_2^{^3\text{He}+\text{Au}}$$

$$v_3^{p+\text{Au}} \approx v_3^{d+\text{Au}} < v_3^{^3\text{He}+\text{Au}}$$

INTRODUCTION

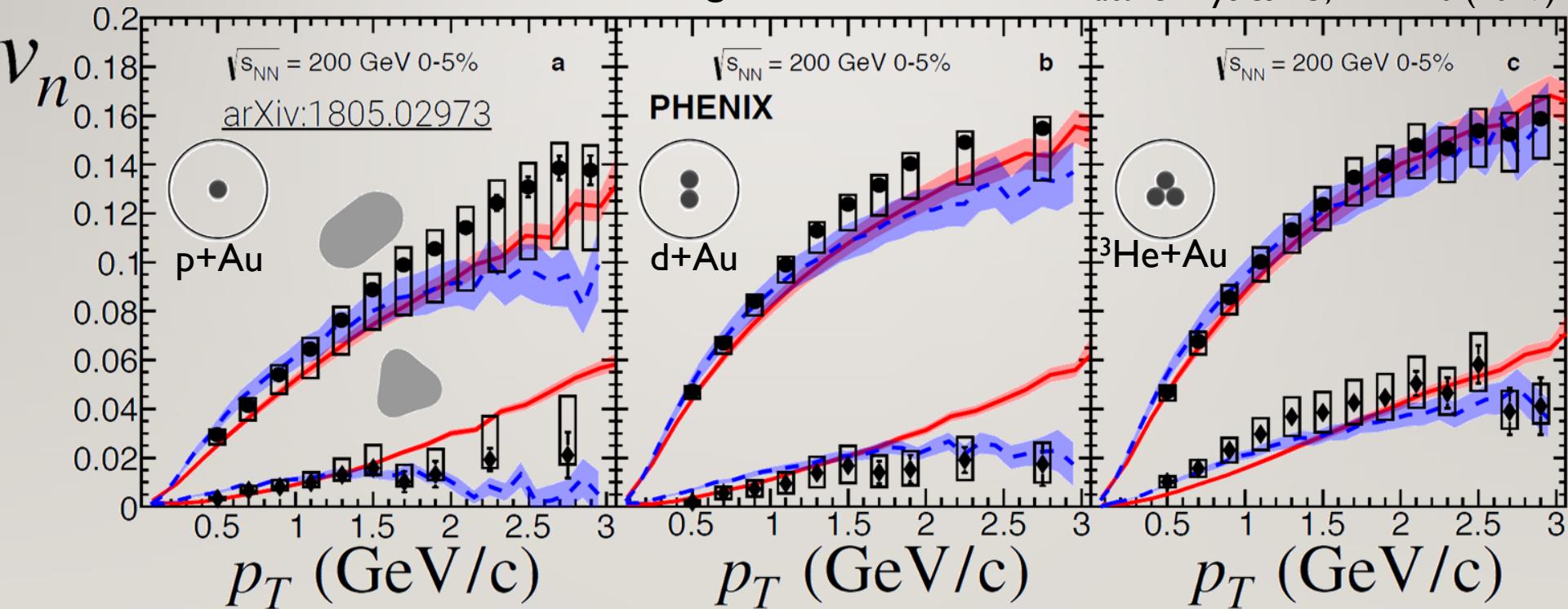
BASIC QGP OBSERVATIONS

SMALL SYSTEMS

24<sub>/29</sub> COMPARISON TO HYDRO CALCULATIONS

- Hydro calculations
- Both 2+1D,  $\eta/s = 0.08$ , MC Glauber initial cond.
- Different hadronic rescattering

●  $v_2$  Data  
●  $v_3$  Data  
—  $v_n$  SONIC [Eur. Phys. J. C 75, 15 \(2015\)](#)  
—  $v_n$  iEBE-VISHNU [PRC 95, 014906 \(2017\)](#)  
**Nature Physics 15, 214-220 (2019)**



INTRODUCTION

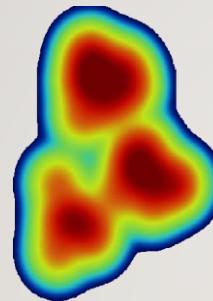
BASIC QGP OBSERVATIONS

SMALL SYSTEMS

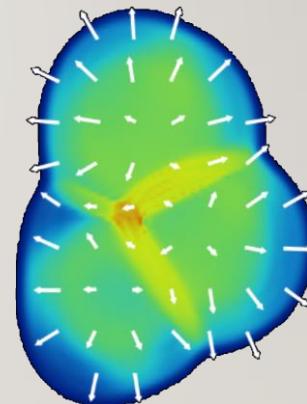
25<sub>/29</sub>

# IS THERE AN ALTERNATIVE EXPLANATION?

- Hydro: initial state spatial correlations a.k.a. geometry

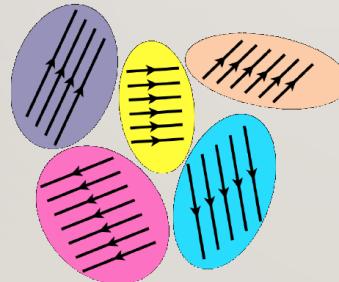


Final state momentum correlations



- Alternative: initial state momentum correlations

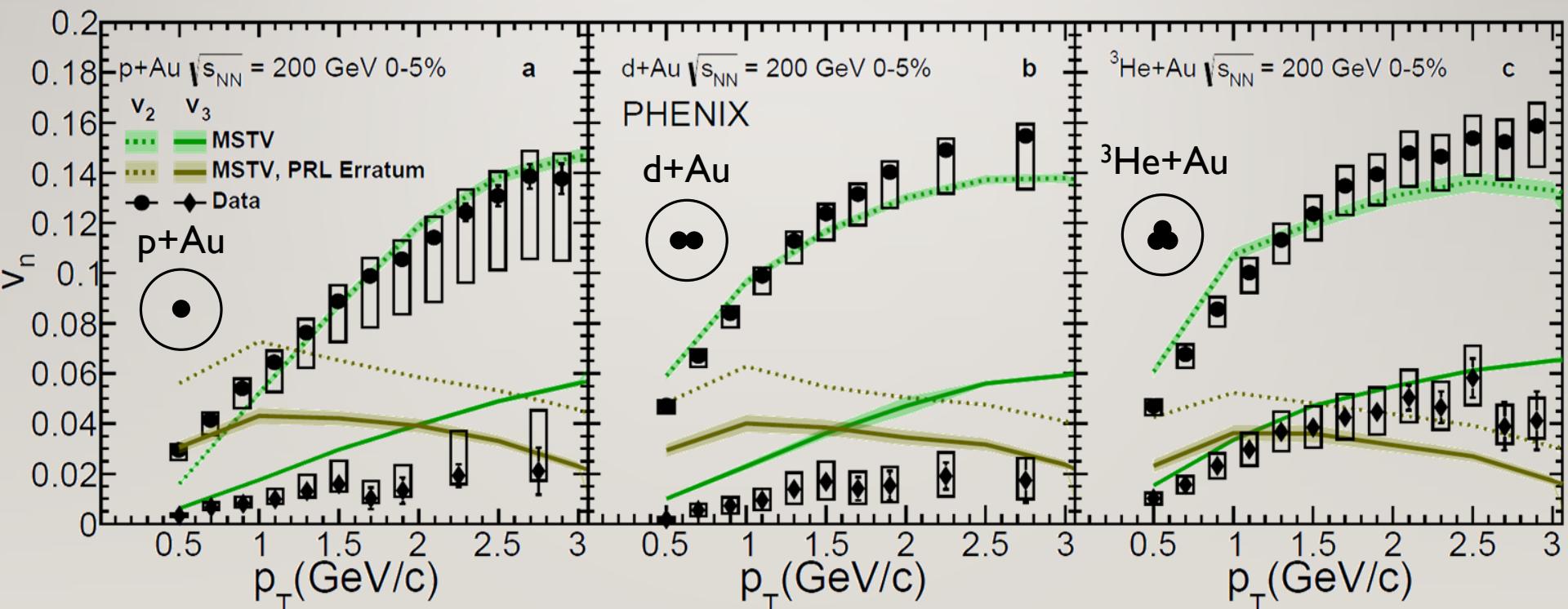
Mace et al. Phys. Rev. Lett. 121, 052301 (2018)



26<sub>/29</sub>

# ALTERNATIVE MODEL VS DATA

- MSTV postdiction (Mace, Skokov, Tribedy, Venugopalan, PRL 121, 052301)
  - Official PRL Erratum: Phys. Rev. Lett. 123, 039901(E) (2019)
- Before erratum: reasonable  $v_2$  description, misses  $v_3$  ordering



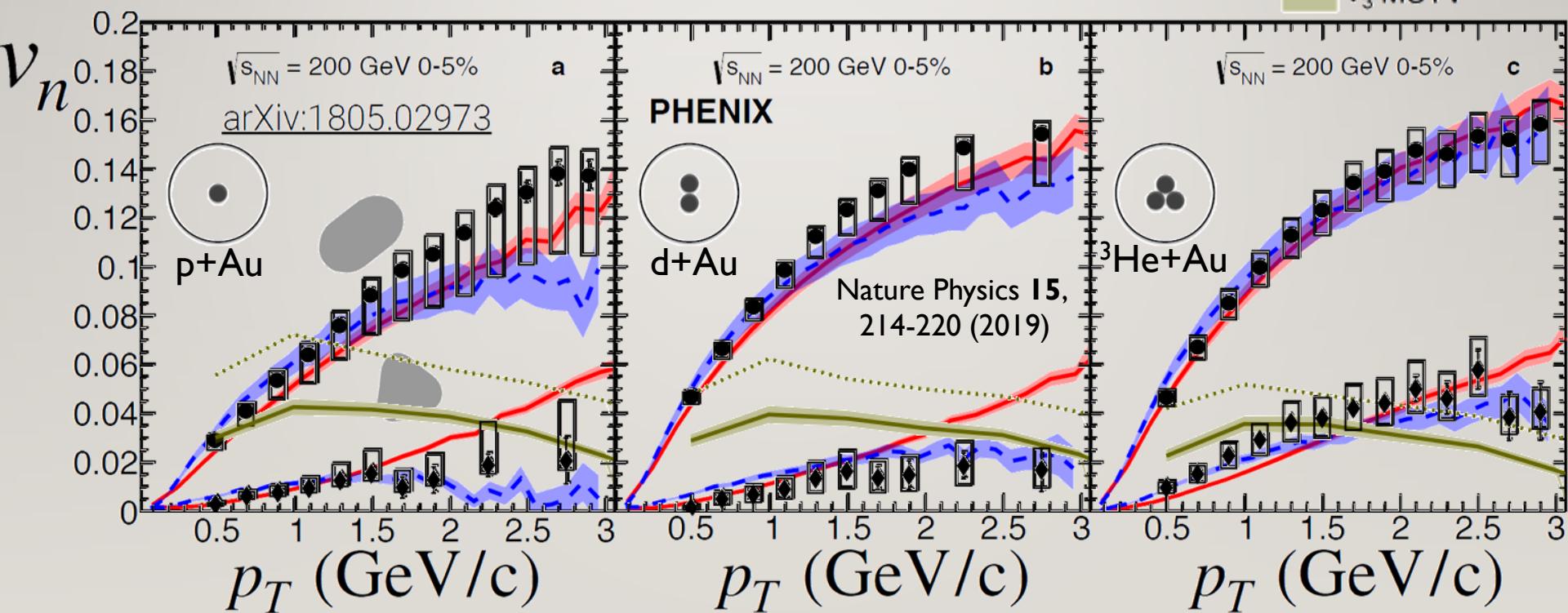
## INTRODUCTION

## BASIC QGP OBSERVATIONS

## SMALL SYSTEMS

# 27<sub>/29</sub> ALL MODELS VS DATA

- Hydro description much better already „by eye”
- Tools for discrimination: confidence level
- MSTV: multiplicity dependence; test  $v_2$  at same  $dN/d\eta$



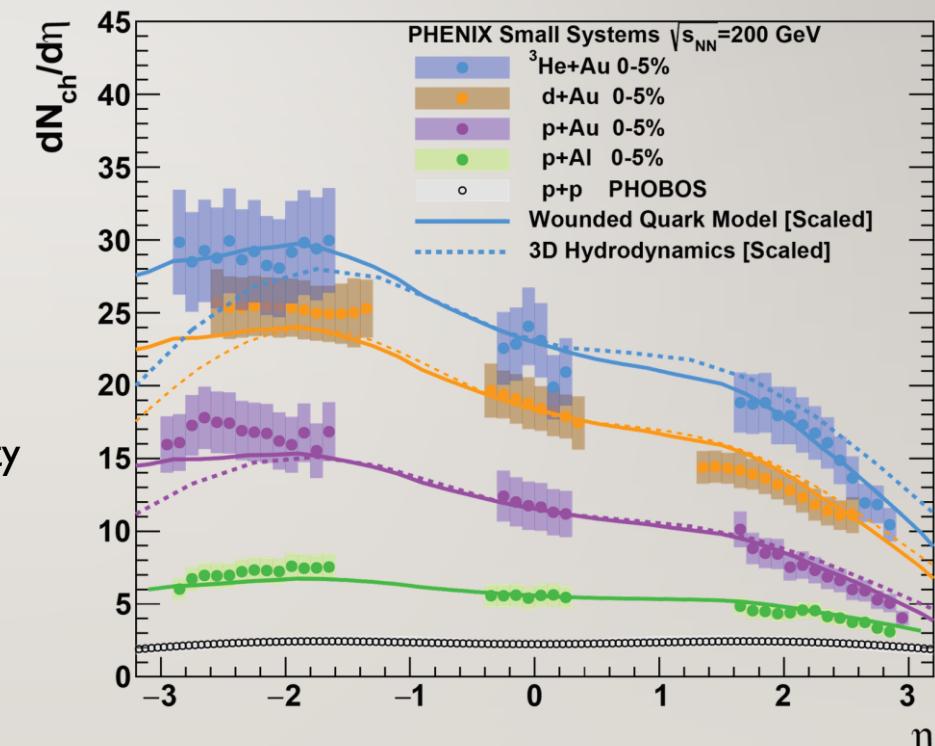
INTRODUCTION

BASIC QGP OBSERVATIONS

SMALL SYSTEMS

# FORWARD PARTICLE PRODUCTION?

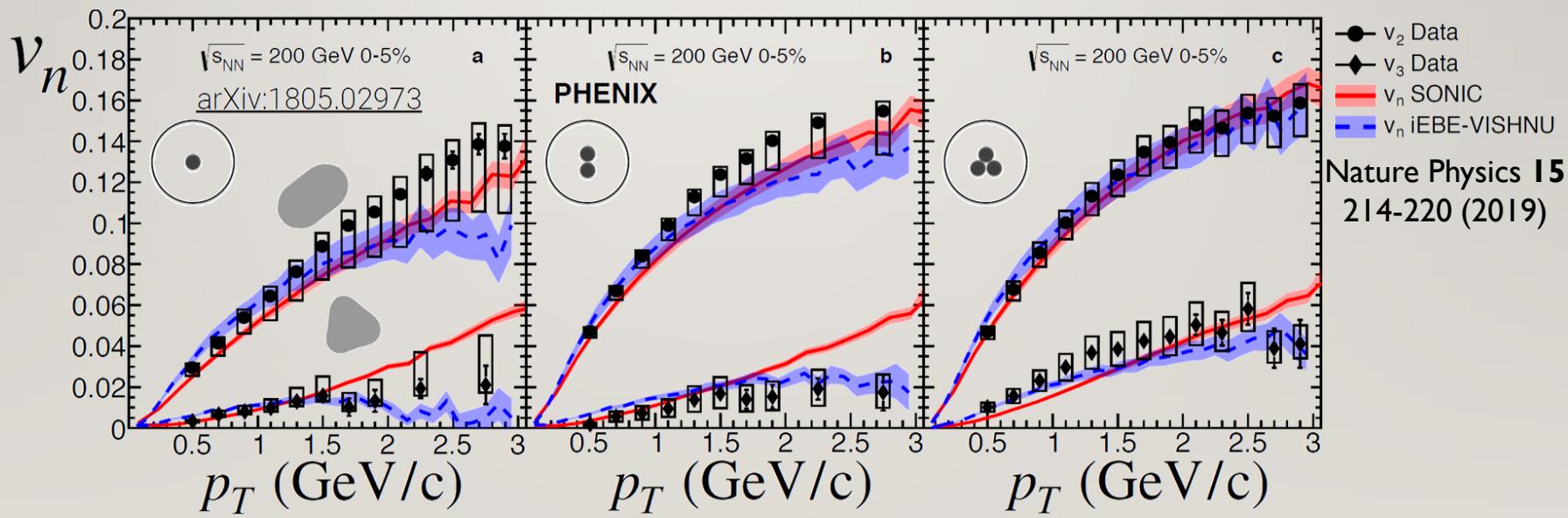
- Wounded quark model:
  - Each quark participant produces hadrons, common emission function  $F(\eta)$
  - Constrained by  $dN/d\eta$  in d+Au
- Barej, Bzdak, Gutowski, PRC97, 034901 (2018)
- Hydrodynamic simulation
  - MC Glauber initial condition
  - Longitudinal entropy distribution
  - 3+1D viscous evolution
  - $\eta/s = 1/4\pi$ , T-dependent bulk viscosity
  - Statistical hadronization
- Bozek, Broniowski, PLB739, 308 (2014)
- Wounded quark model works at all centralities, p+Al to  $^3\text{He}+\text{Au}$



Phys.Rev.Lett. 121 (2018) 222301

29<sub>/29</sub> SUMMARY

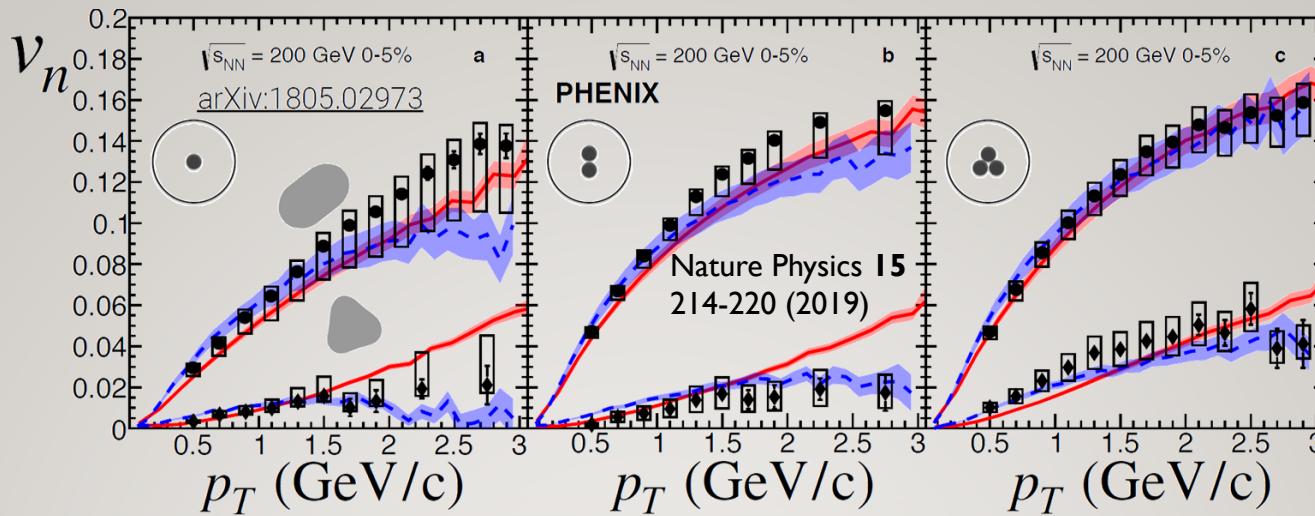
- Clear consensus on a list of QGP signs found in Au+Au
  - Suppression, flow, thermal photons
- Strong evidence for QGP droplets in small systems
  - Acceptable confidence levels for hydro in p/d/<sup>3</sup>He+Au
- Longitudinal dynamics of small systems also explored in detail



INTRODUCTION

BASIC QGP OBSERVATIONS

SMALL SYSTEMS



30

## THANK YOU FOR YOUR ATTENTION

If you are interested in these subjects, come to our  
**Zimányi School 2019**  
 December 2-6., Budapest, Hungary



<http://zimanyischool.kfki.hu/19>

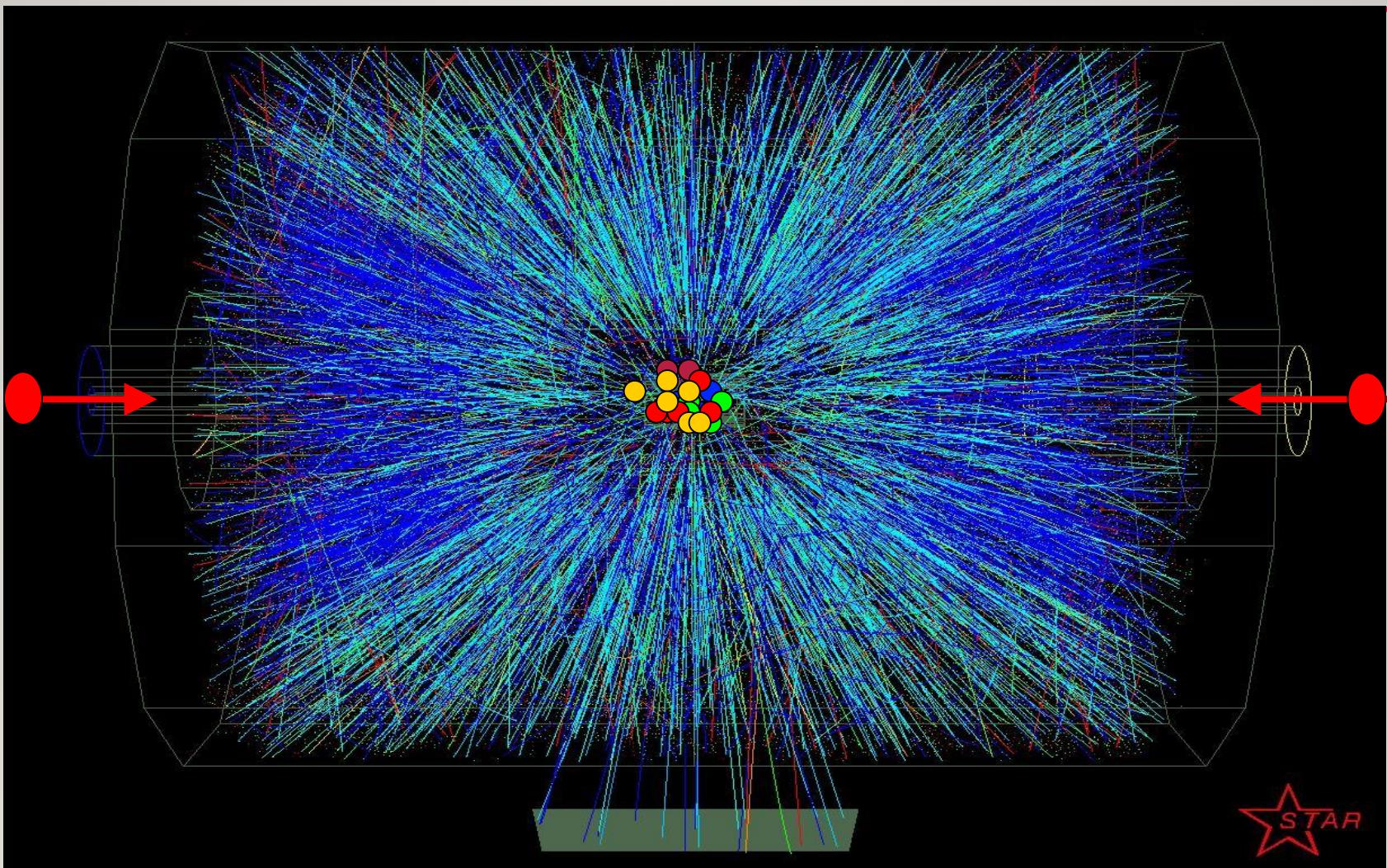
3 |

## BACKUP SLIDES

---

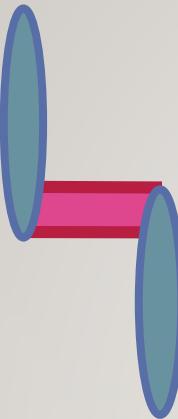
32<sub>/29</sub>

# HOW TO INVESTIGATE THESE LITTLE BANGS?

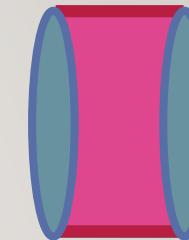
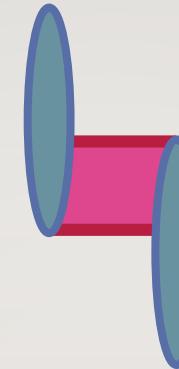


33<sub>/29</sub>

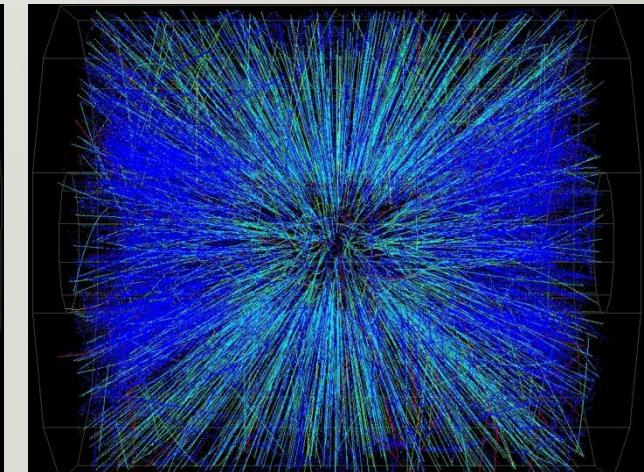
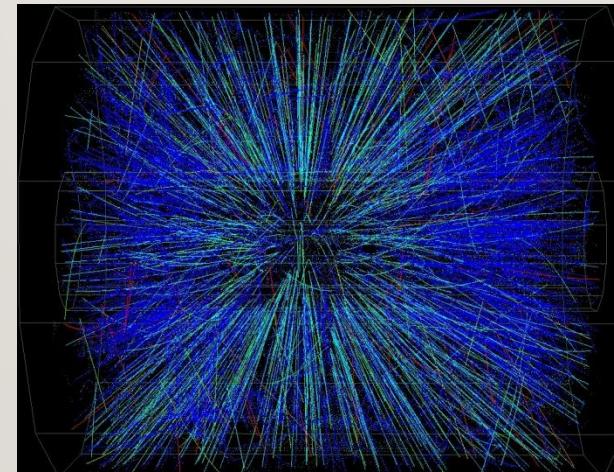
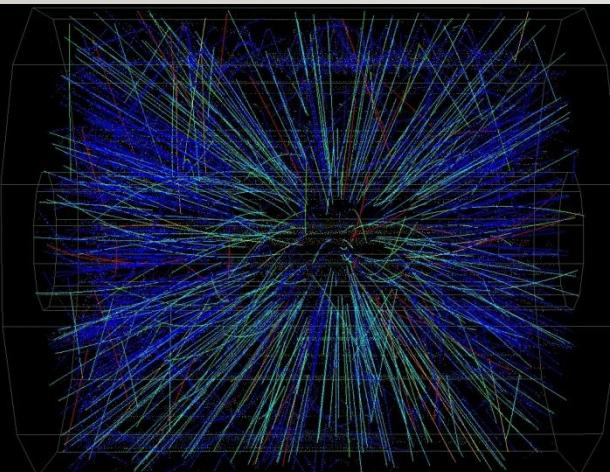
# COLLISIONS OF DIFFERENT CENTRALITY



Peripheral



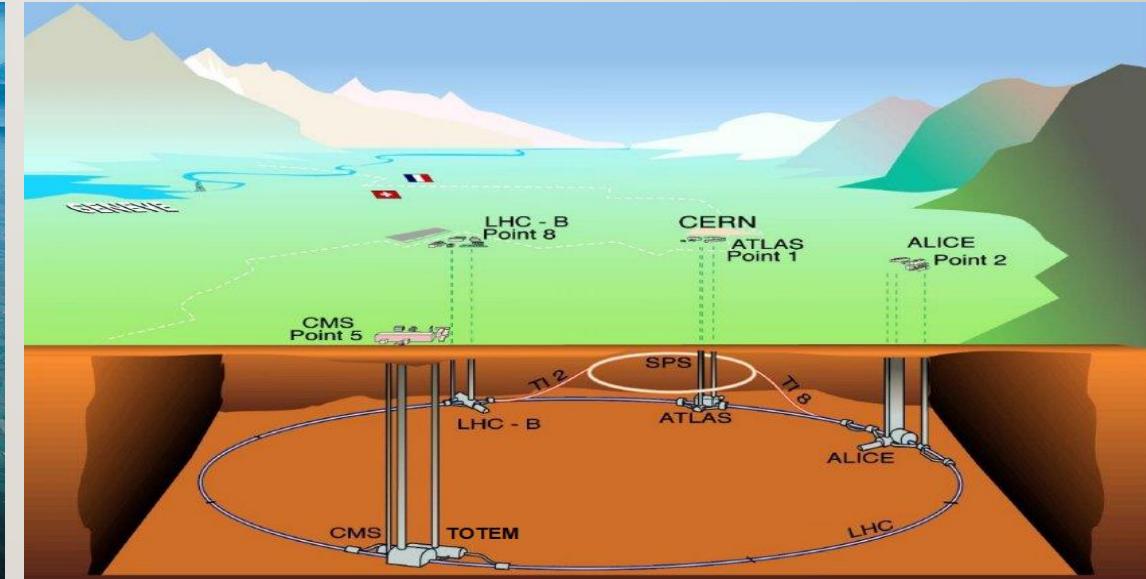
Central



34<sub>/29</sub>

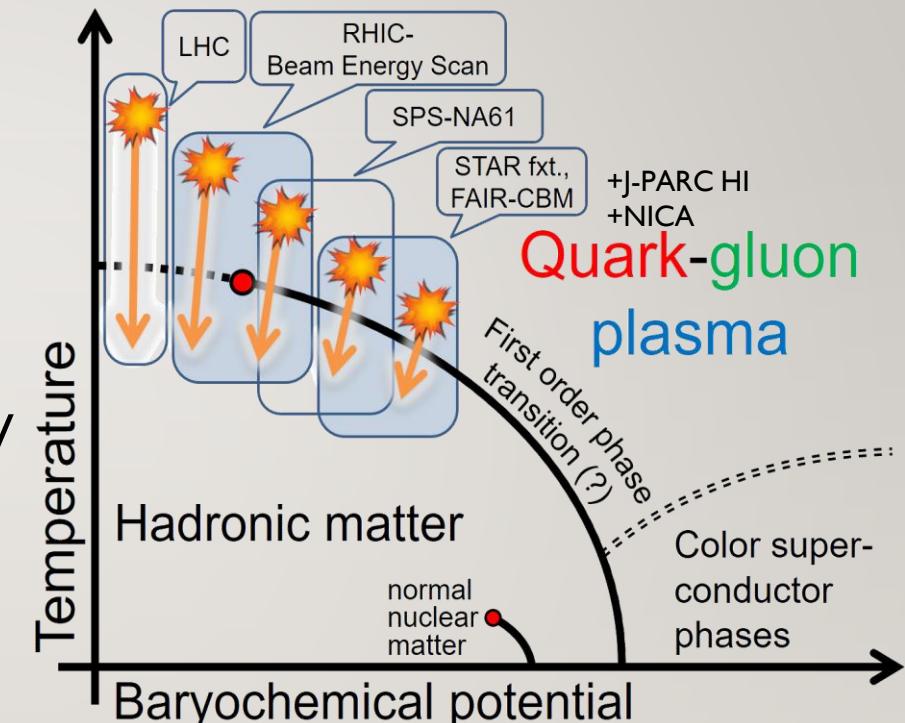
# FACILITIES: LARGE HADRON COLLIDER (+SPS)

- LHC collisions: p+p, p+Pb and Pb+Pb
- Energies: from 2.76 TeV/nucleon to 13 TeV (p+p only)
- Experiments: ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL, TOTEM
- Phase diagram related studies: SPS (NA61/SHINE, previously NA49)



# 35<sub>/29</sub> EXPLORING THE PHASE MAP OF QCD

- Phase map: temperature versus matter excess (baryochem. pot.  $\mu_B$ )
- Control parameters:
  - Collision energy, system
  - Collision geometry
- Crossover at low  $\mu_B$  and  $T \cong 170$  MeV
- Probably 1<sup>st</sup> order quark-hadron p.t. at high  $\mu_B$  (NJL, bag model, etc)
- Critical End Point (CEP) in between?
- High  $\mu_B$ : nuclear matter, neutron stars, color superconductors...
- Phase transition importance: even in core-collapse supernovae!

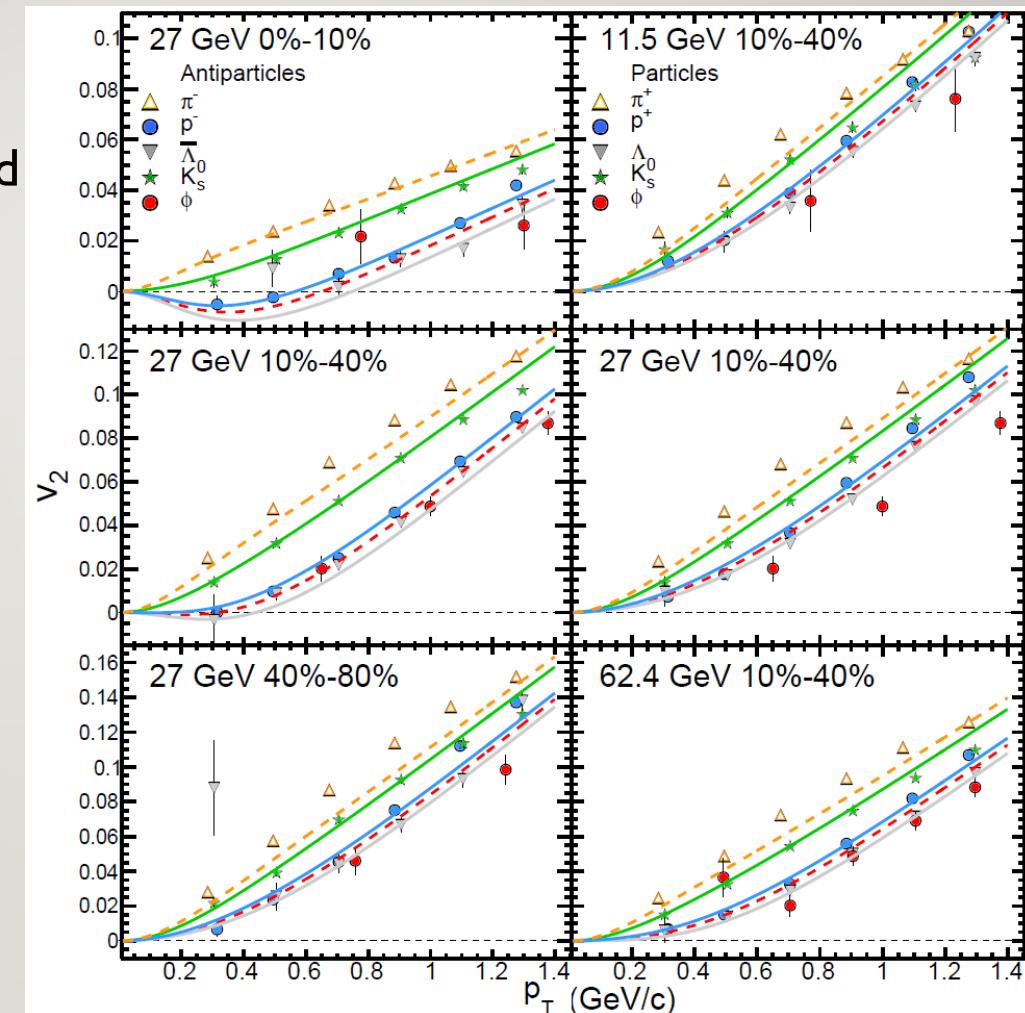


36<sub>/29</sub>

# ELLIPTIC FLOW IN THE BEAM ENERGY SCAN

- With Blast-Wave fits
- Predictions for not fitted particles agree well
- Flow in all systems!

STAR Collaboration,  
PRC93, 014907 (2016)



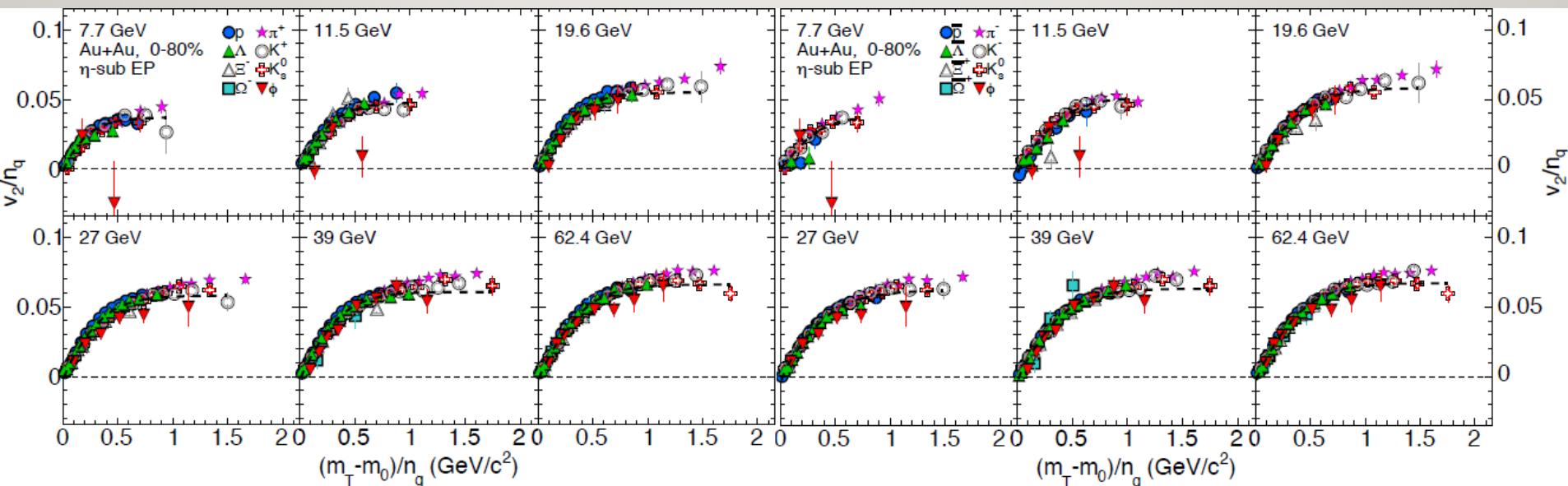
37<sub>/29</sub> ELLIPTIC FLOW SCALING IN THE BES

- STAR data on mesons from  $\pi$  to  $\phi$ , baryons from  $p$  to  $\Omega$
- Scaling everywhere, except  $\phi$  below 11.5 GeV, but little statistics

Phys. Rev. C 88 (2013) 14902

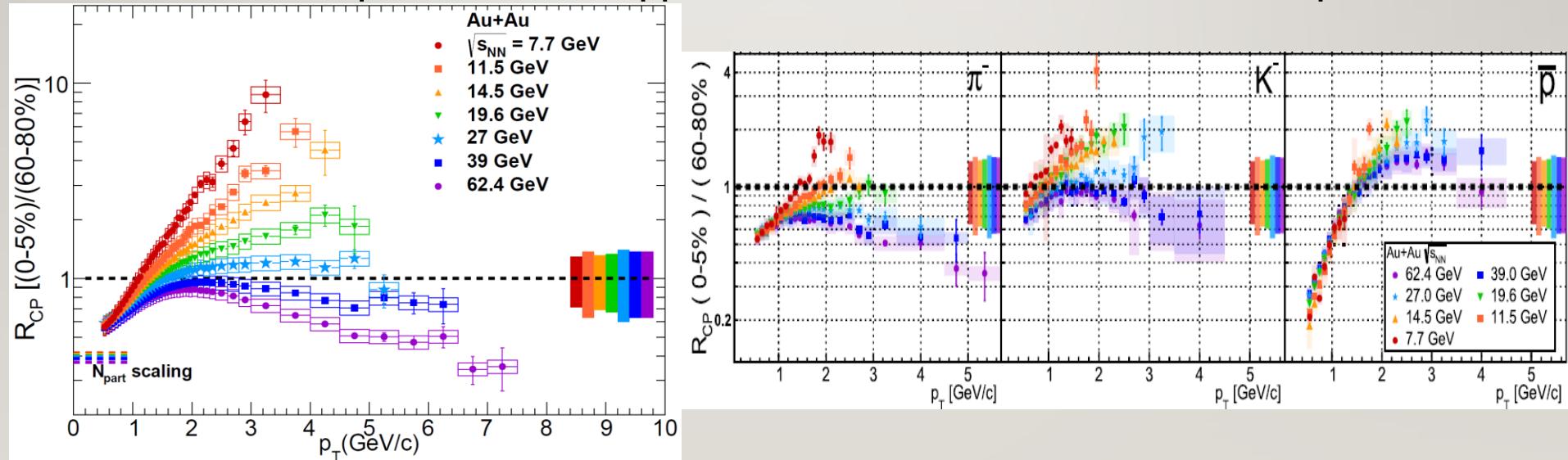
Phys. Rev. C 93 (2016) 014907

Phys. Rev. Lett. 116 (2016) 062301



# SUPPRESSION IN THE BEAM ENERGY SCAN

- $R_{CP}$  analyzed here instead of  $R_{AA}$ , transition to above one with coll. energy
- Hadron enhancement: Cronin-effect, radial flow, coalescence domination
- Competing effects, HIJING reproduces enhancement w/o jet quenching
- Identified particles: less suppression for kaons, enhancement for protons

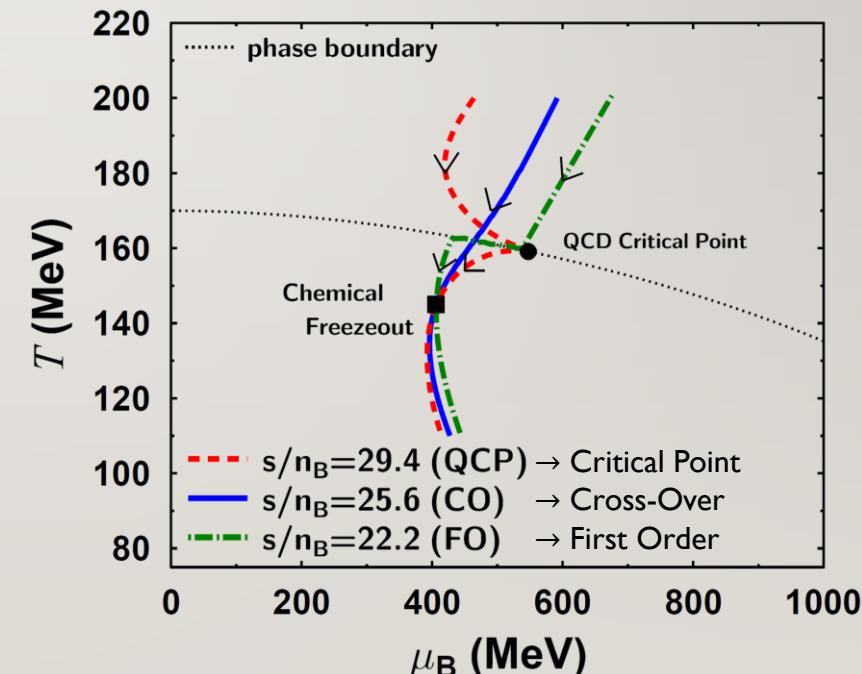
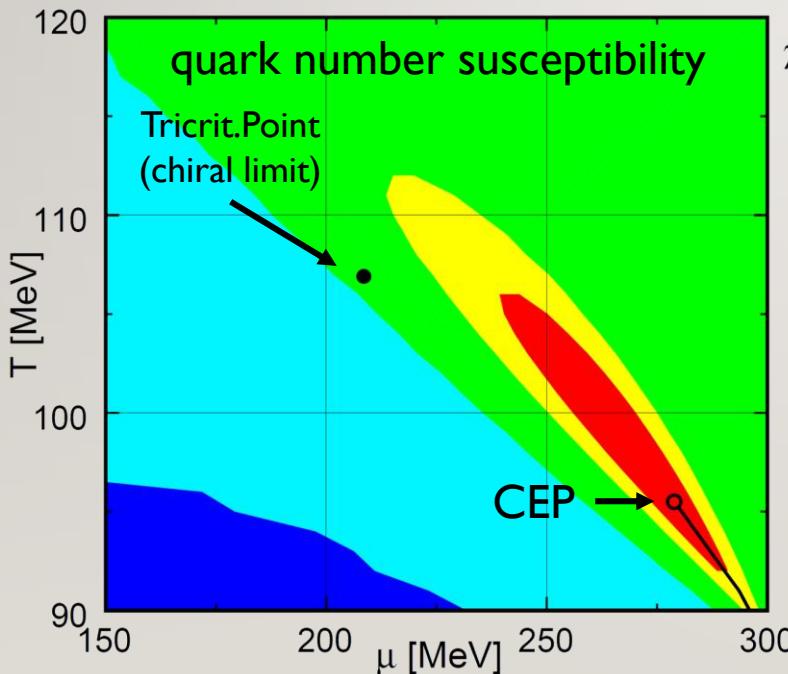


STAR collaboration, Phys. Rev. Lett. 121, 032301 (2018) [arXiv:1707.01988]

39<sub>/29</sub>

# SEARCH FOR THE CRITICAL POINT POSSIBLE?

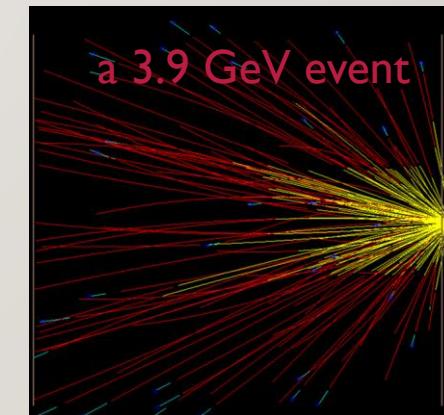
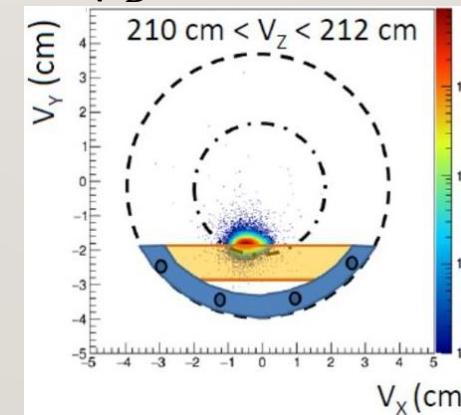
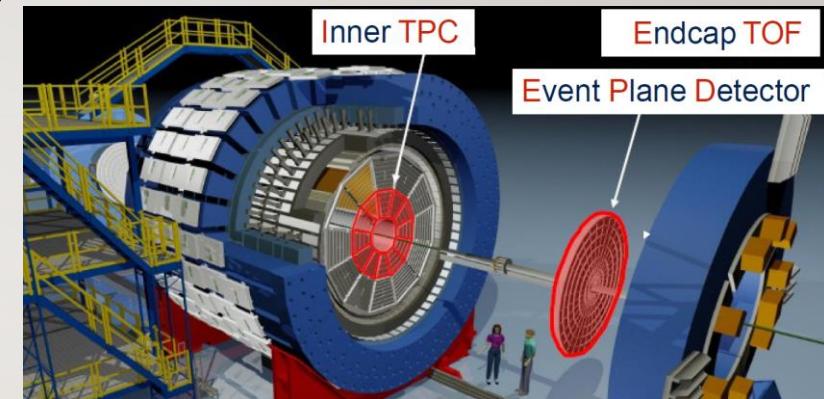
- Effects of the CEP in a broad region (via an effective potential  $\sim N_f=2$  QCD)
  - Y. Hatta and T. Ikeda, PRD67,014028(2003) [hep-ph/0210284]
- Hydro evolution attracted to the critical point
  - M. Asakawa et al., PRL101,122302(2008) [arXiv:0803.2449]



40<sub>/29</sub>

# STAR: UPGRADES AND FIXED TARGET PROGRAM

- Large acceptance, great PID capabilities: great for identified hadrons
- Upgrades for BES-II
  - innerTPC: better  $dE/dx$  (PID) and momentum resolution, by 2019
  - Event Plane Detector: replace BBC, better triggering & EP resolution, by 2018
  - Endcap TOF: extended fwd PID, by 2019
- Fixed target program: 1 cm wide, 1mm thick target at 2.1 m
- At the lowest energies: out to  $\mu_B > 700$  MeV



# FIXED TARGET BARYOCHEMICAL POTENTIALS

- Reach down to 3 GeV in center of mass energy!

Collider Energy	Fixed Target Coll. Energy	Single Beam C.M. Energy	Rapidity	$\mu_B$ (MeV)
62.4	7.7	30.3	2.10	420
39.0	6.2	18.6	1.87	487
27.0	5.2	12.6	1.68	541
19.6	4.5	8.9	1.52	589
14.5	3.9	6.3	1.37	633
11.5	3.5	4.8	1.25	666
9.1	3.2	3.6	1.13	699
7.7	3.0	2.9	1.05	721



Energies unreachable in collider mode

# FUTURE FACILITIES: NICA, FAIR, J-PARC HI

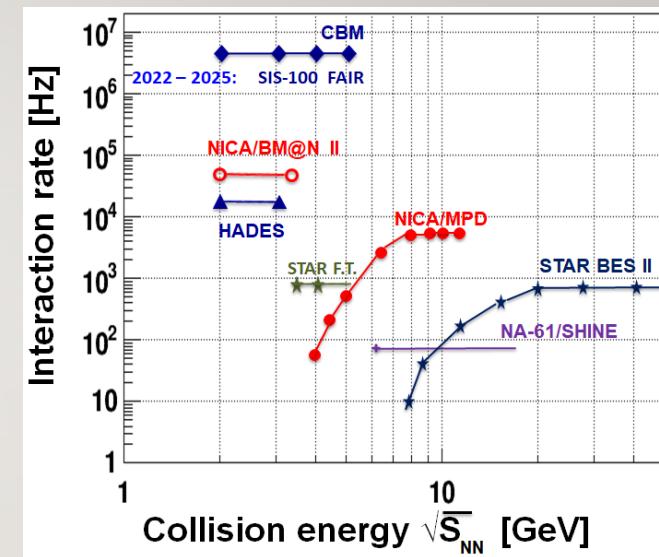
- New facilities planned/built
- NICA: 2020, MPD&BM@N
- FAIR: 2022, CBM
- J-PARC HI: 2025, JHITS



# (FUTURE) FACILITIES COMPARISON

- Many future facilities and experiments, SPS and RHIC already running
- RHIC, NICA: Collider and fixed target
- SPS, FAIR, J-PARC: fixed target
- Energy ranges from 2 to 20 GeV in  $\sqrt{s_{NN}}$

Compilation from Daniel Cebra and Olga Evkodomov:

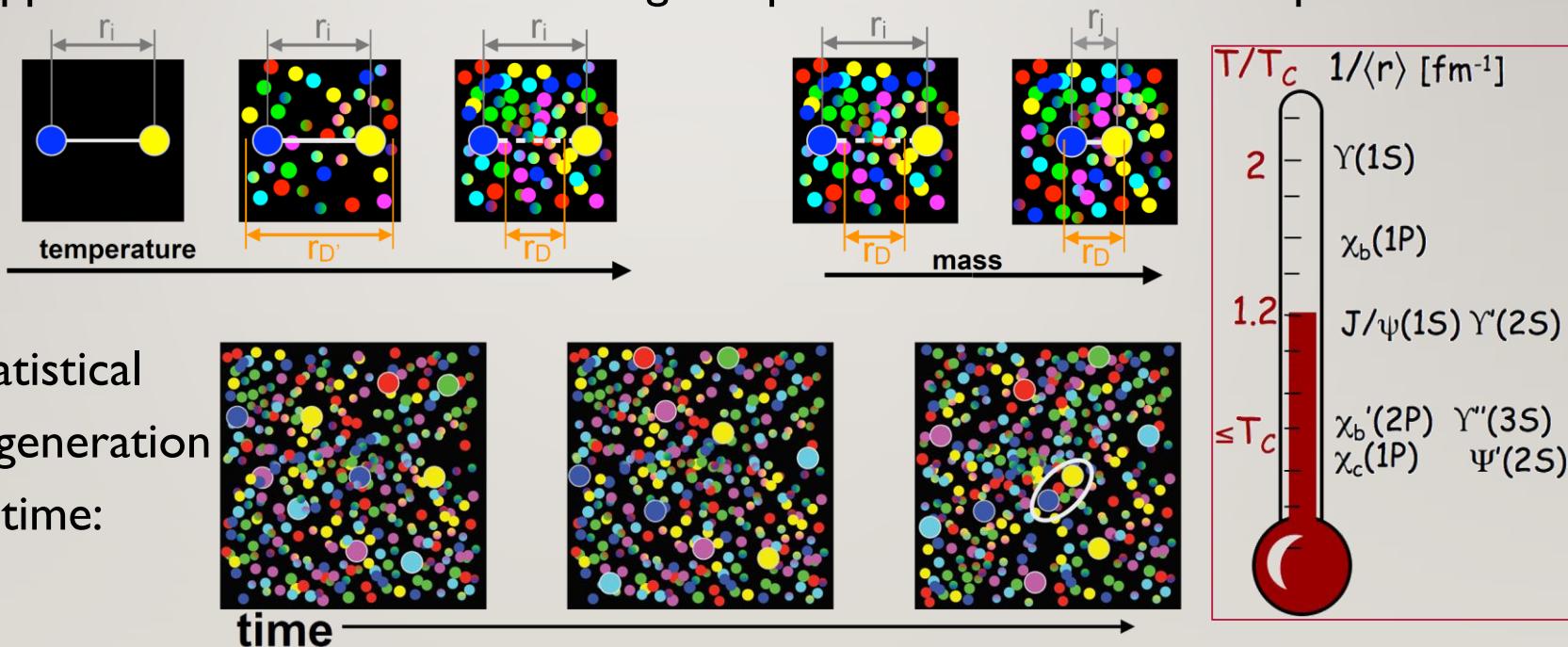


Facility	RHIC BES-II & Fixed Target	SPS	NICA	FAIR	J-PARC HI
Experiment	STAR	NA61	MPD & BM@N	CBM	JHITS
Start	2019	2009	2020-23	2025	2025
Energy ( $\sqrt{s_{NN}}$ , GeV)	2.9-19.6 GeV	4.9-17.3	2.0-11	2.7-8.2	2.0-6.2
Rate	100-1000 Hz	100 Hz	10 kHz	10 MHz	10-100 MHz
Physics	Critical Point Onset of Deconf.	Critical Point Onset of Deconf.	Onset of Deconfinement Compr. Hadronic Matter	Onset of Deconfinement Compr. Hadronic Matter	Onset of Deconfinement Compr. Hadronic Matter

44<sub>/29</sub>

# HEAVY FLAVOR SUPPRESSION & REGENERATION

- Timeline: quarkonium ( $q\bar{q}$ ) formation  $\rightarrow$  QGP evolution  $\rightarrow$   $q\bar{q}$  decay
- Quarkonia experience the whole QGP evolution, competing processes
- Suppression due to color-screening: temperature and size/mass dependence



- Statistical regeneration in time:

Images from J Castillo, SQM17 and A Mocsy, HardProbes2009

INTRODUCTION

BASIC OBSERVATIONS

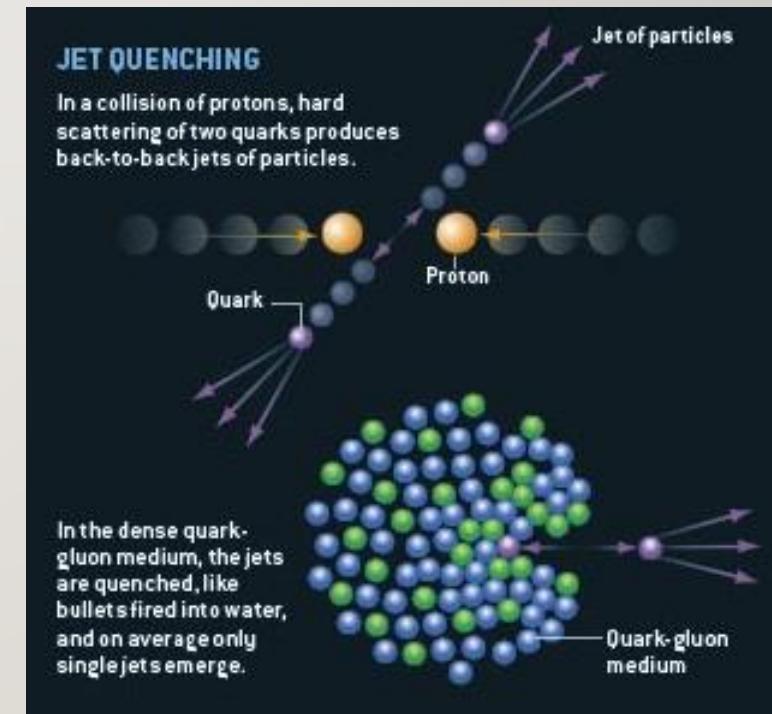
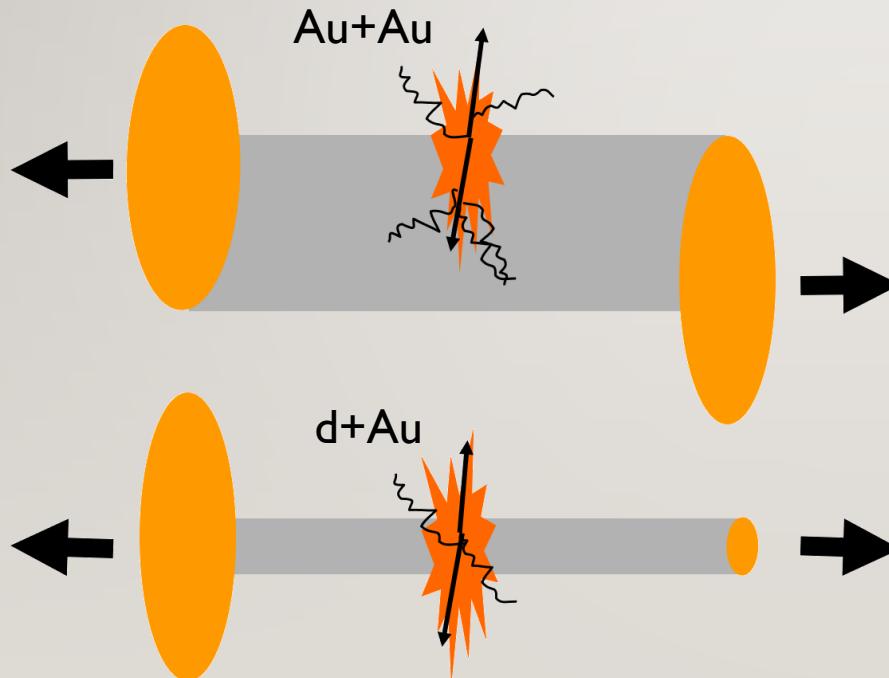
RECENT BES RESULTS

LENNY HBT

45<sub>/29</sub>

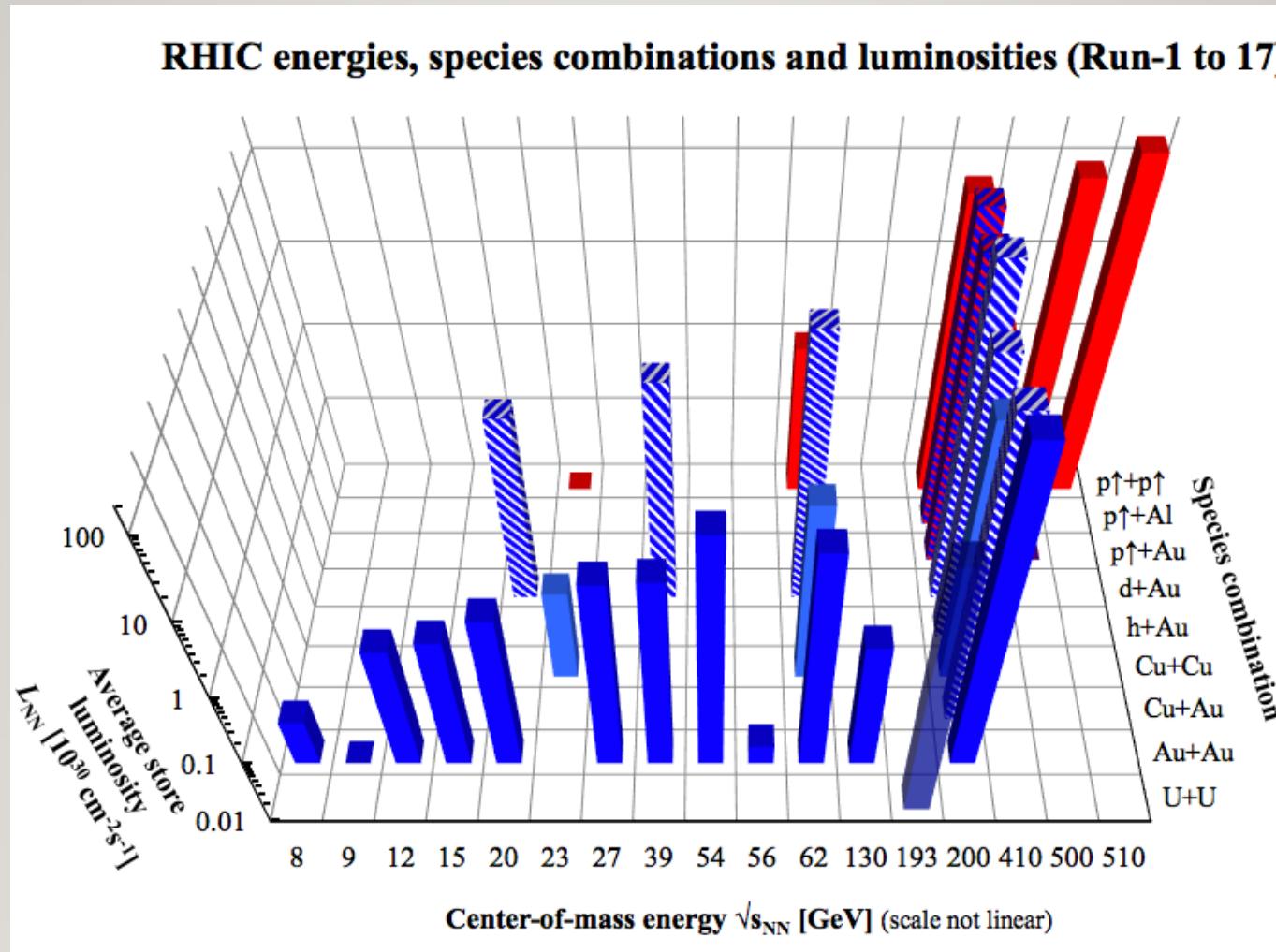
# CONTROL EXPERIMENT: D+AU COLLISIONS

- Suppression in Au+Au collisions: 1<sup>st</sup> milestone
- Lack of suppression in d+Au: 2<sup>nd</sup> milestone
- Two PRL covers



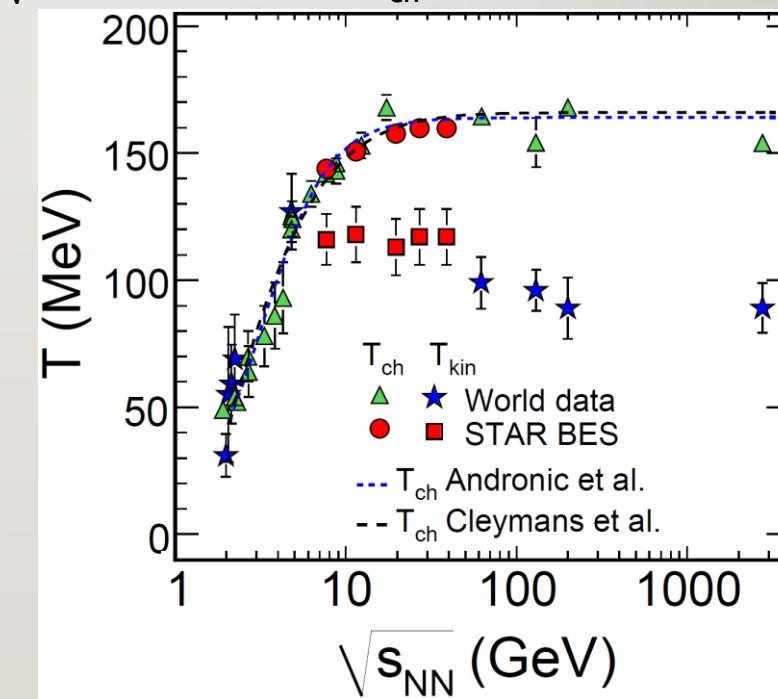
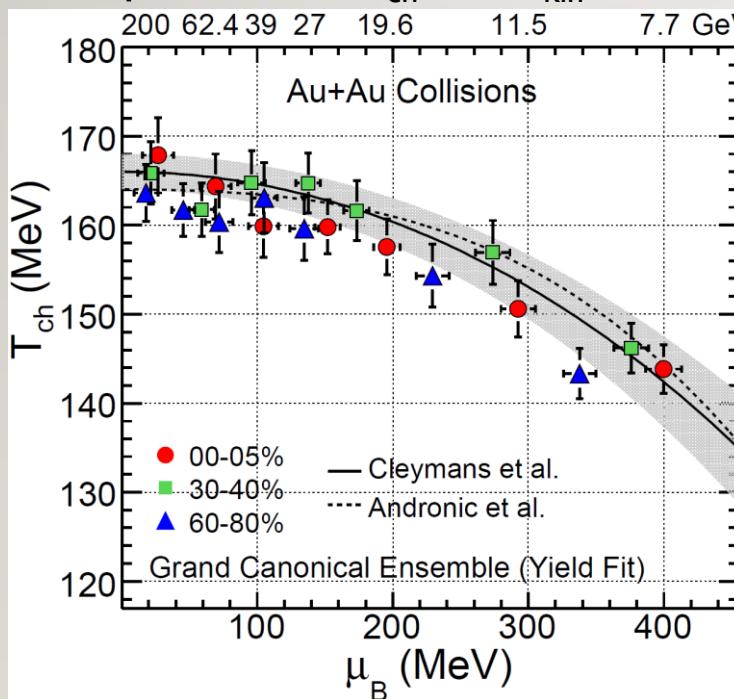
Zajc, Riordan, Scientific American

# RHIC RECORDED RUNS AND LUMINOSITY



# 47<sub>/29</sub> FREEZE-OUT FROM PARTICLE YIELDS

- Chemical and kinetic freeze-out parameters via THERMUS and BlastWave
- Thermal multiplicity assumption valid
- Systematics investigated (parameter constraints, included species)
- Separation of  $T_{ch}$  and  $T_{kin}$  around  $\sqrt{s_{NN}} = 4-5 \text{ GeV}$ ,  $T_{ch}$  flattens at  $\sim 10 \text{ GeV}$

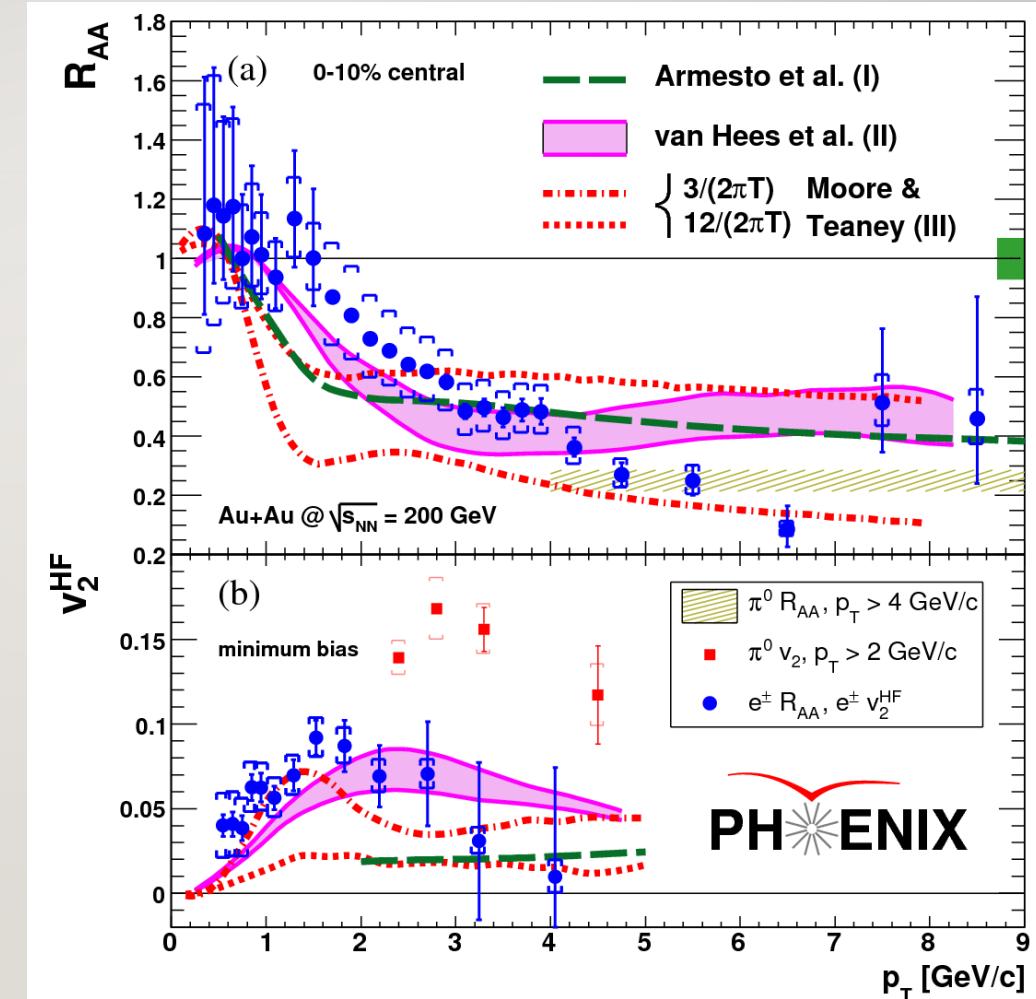


STAR Collaboration, Phys. Rev. C 96, 044904 (2017) [arXiv:1701.07065]

48<sub>/29</sub>

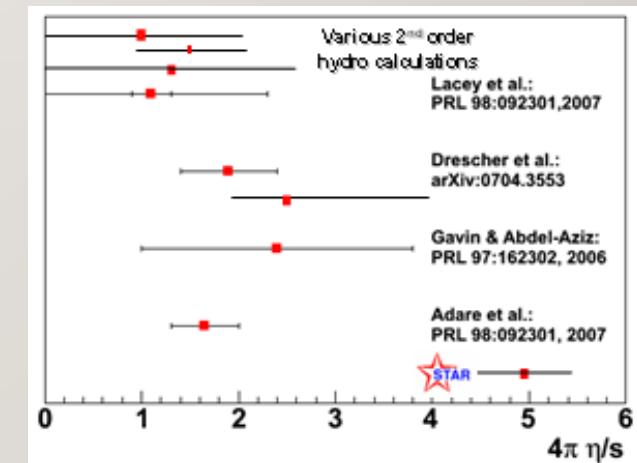
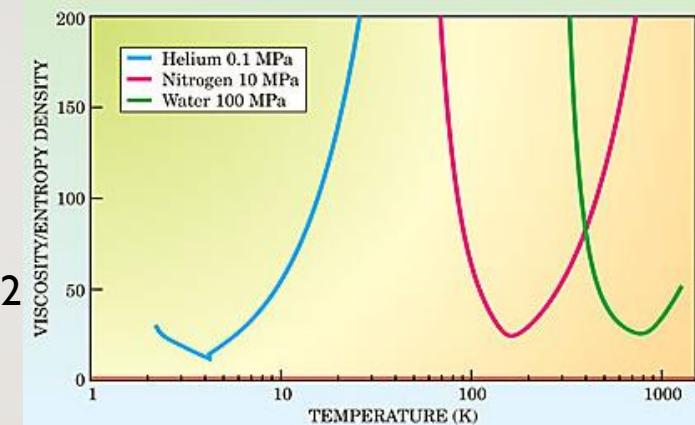
# EVEN HEAVY FLAVOR FLOWS!

- Electrons from heavy flavor measured
- Even heavy flavor is suppressed
- Even heavy flavor flows
- Strong coupling of charm&bottom to the medium
- Small charm&bottom relaxation time in medium and *small viscosity*



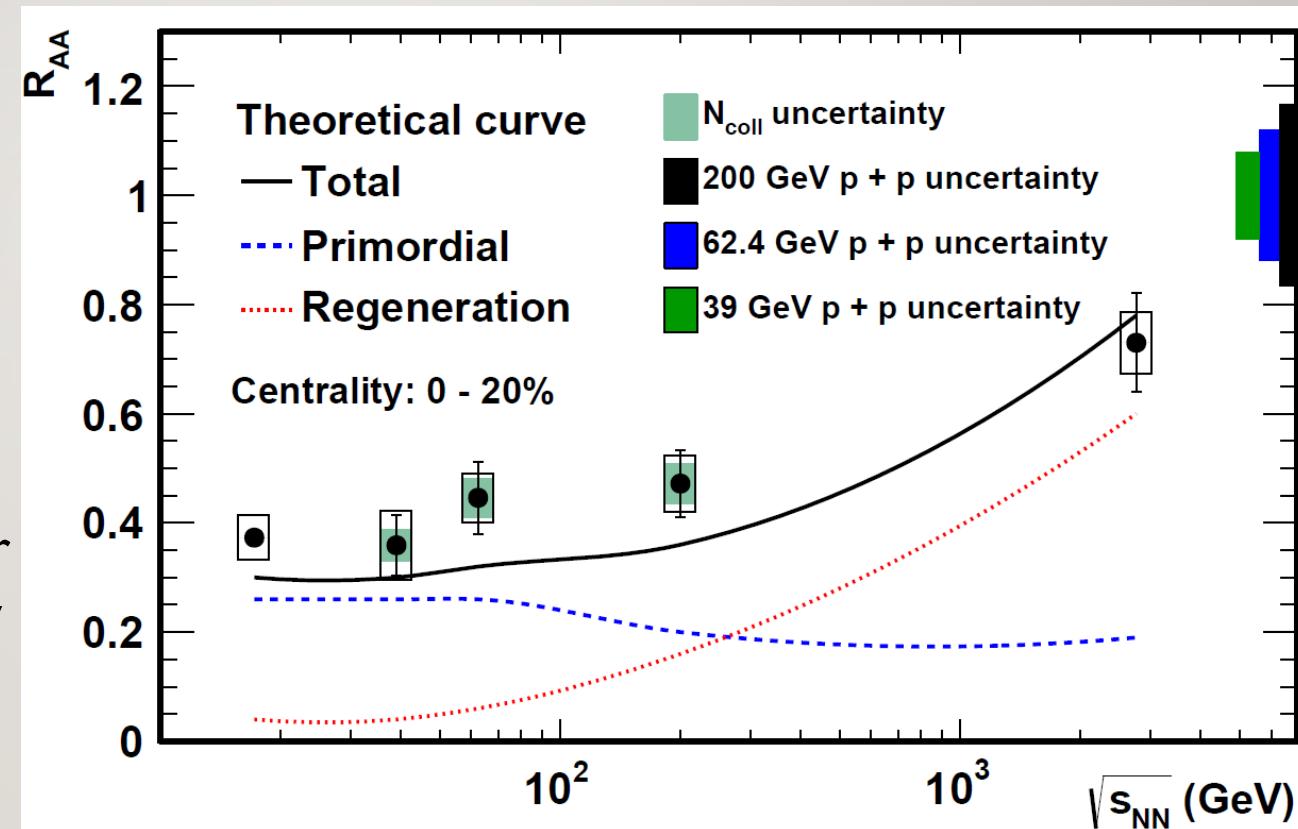
# VISCOSITY

- Viscosity/entropy density: proportional to mean free path
- Strong coupling: small  $\eta/s$
- AdS<sub>D+1</sub>/CFT<sub>D</sub> lower bound:  $\frac{\eta}{s} \geq \frac{\hbar}{4\pi}$ 
  - Maldacena et al.: Adv.Theor.Math.Phys.2:231-252
  - Kovtun et al.: Phys.Rev.Lett. 94 (2005) 111601
- Measurement and calculation results:
  - R. Lacey et al., Phys.Rev.Lett.98:092301,2007
  - H.-J. Drescher et al., Phys.Rev.C76:024905,2007
  - S. Gavin, M. Abdel-Aziz, Phys.Rev.Lett.97(2006)162302
  - A. Adare et al. (PHENIX), PRL98:172301,2007



# 50<sub>/29</sub> J/ IN THE BEAM ENERGY SCAN

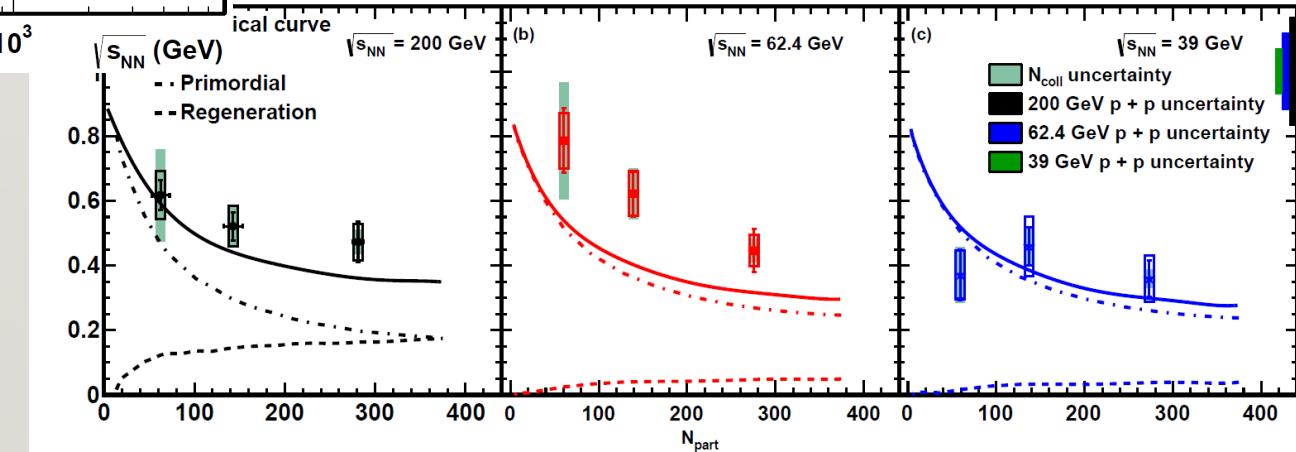
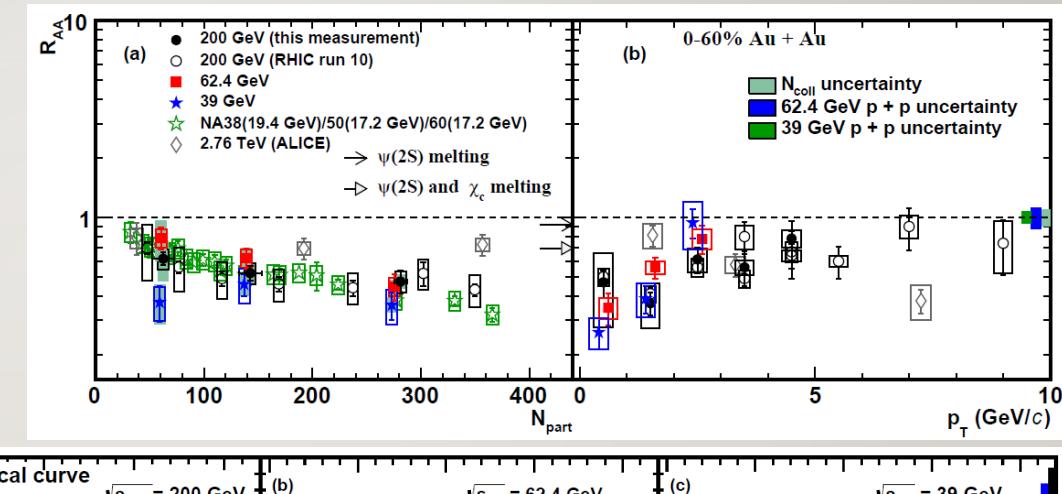
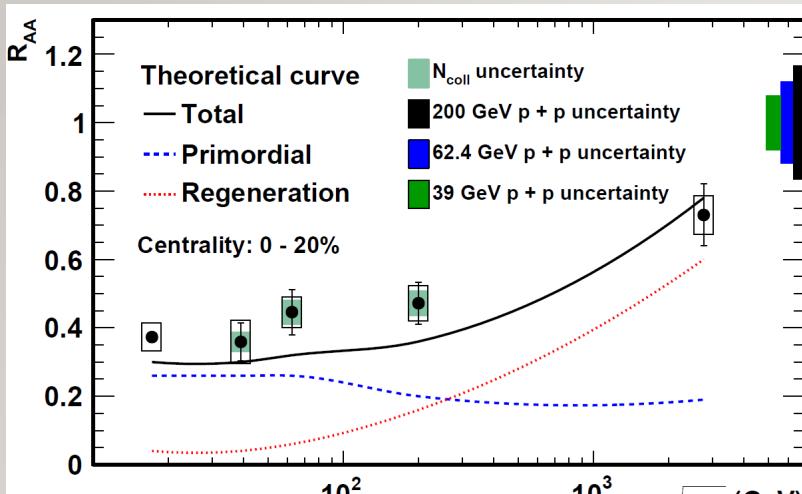
- Regeneration from  $c\bar{c}$  and feed-down from  $\chi_c$  and  $\psi'$ , increases with  $\sqrt{s_{NN}}$
- Screening and cold nucl. matt.: less primordial charmonium with increasing  $\sqrt{s_{NN}}$
- Two effects seem to compensate for  $\sqrt{s_{NN}} < 200$  GeV



STAR Collaboration, Phys.Lett. B771 (2017) 13-20

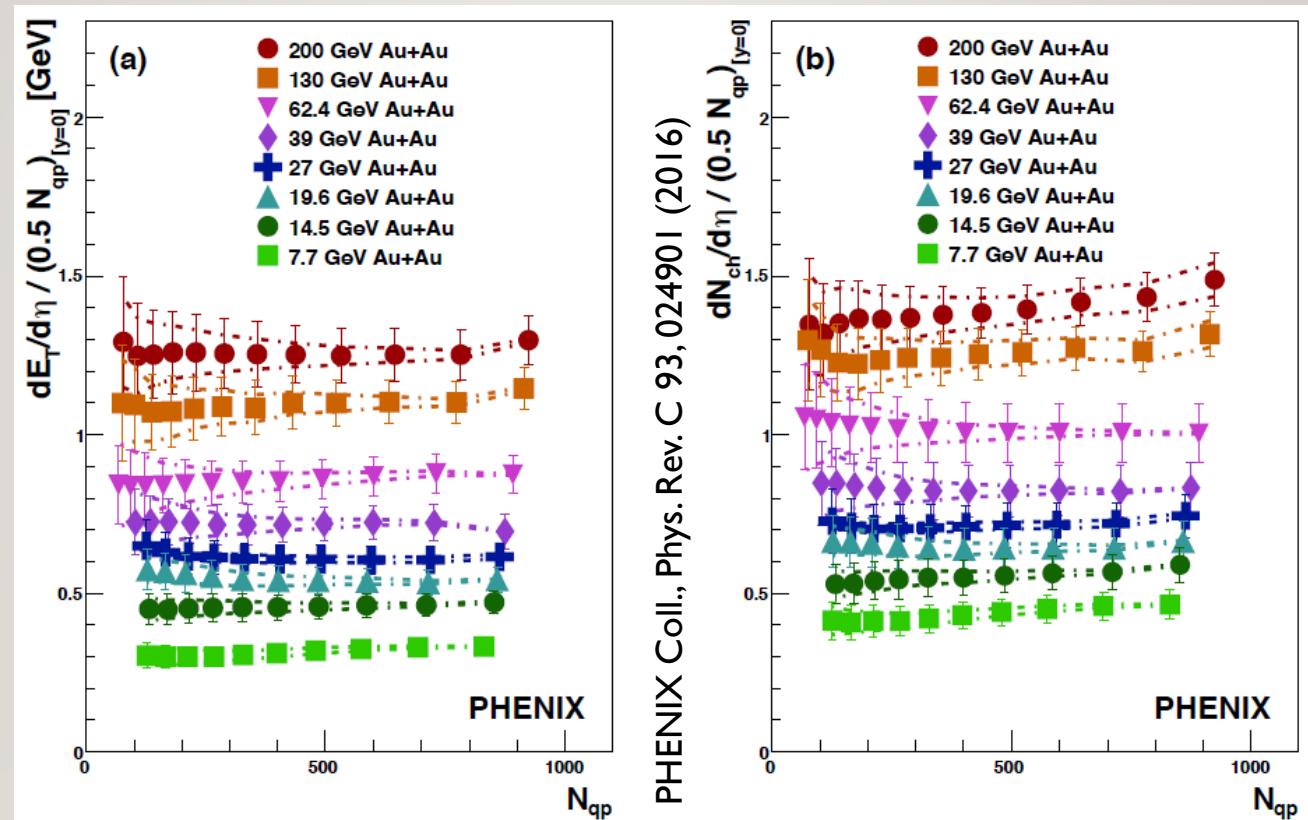
# 51/29 J/PSI IN THE BEAM ENERGY SCAN

- STAR Collaboration, Phys.Lett.B771 (2017) 13-20



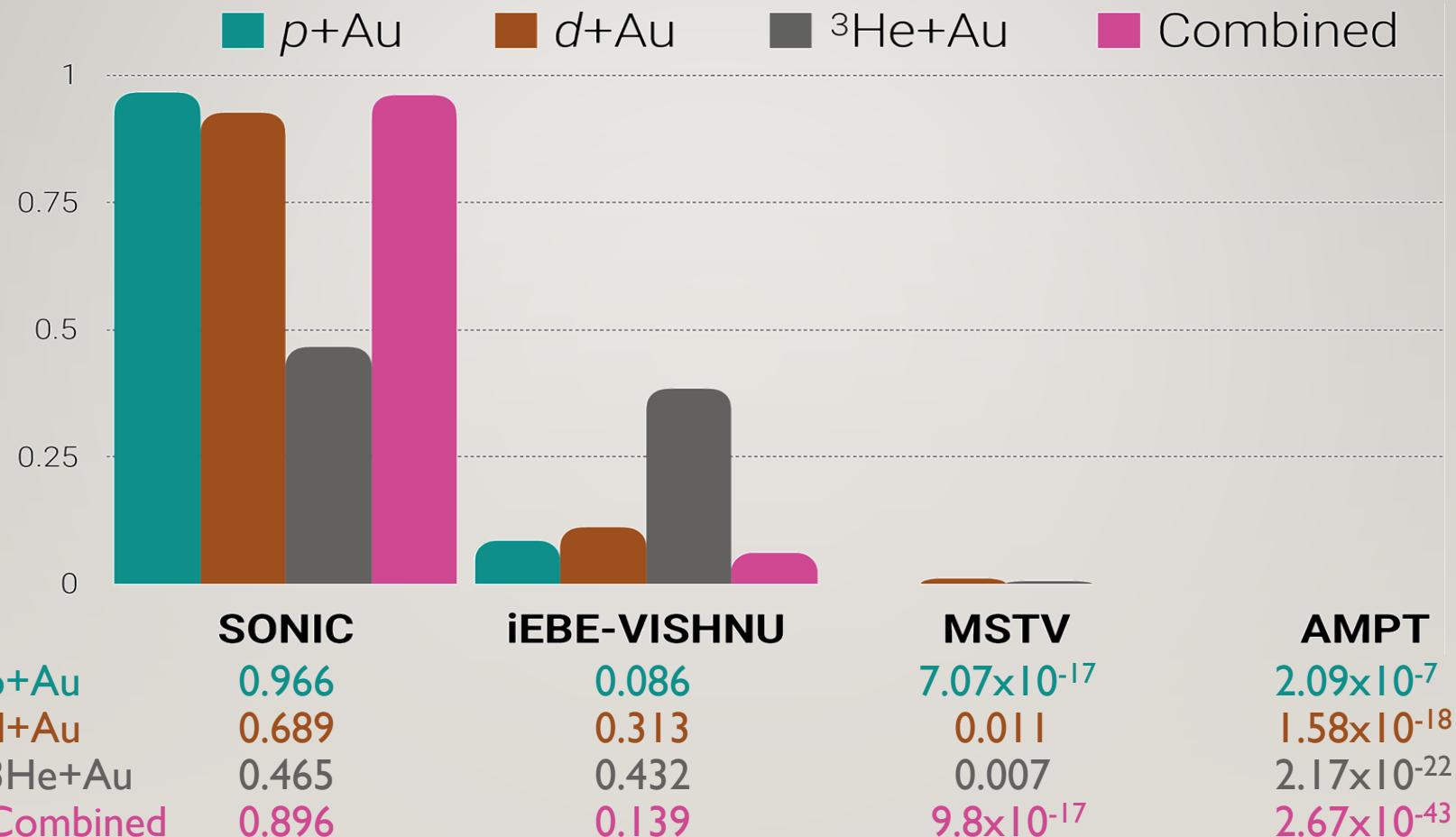
# QUARK PARTICIPANT SCALING

- Transverse energy and particle number: not constant vs Npart!
- Number of quark participants: a better estimator, quark degrees of freedom?



# STATISTICAL TEST OF ALL MODELS

- QGP droplet and hydro describes data the best; MSVT close to marginal



# MVST PREDICTION FOR FIXED MULTIPLICITY

- Compare similar collision systems
  - d+Au 20-40% ( $dN/d\eta = 12.2 \pm 0.9$ )  
PRC 96, 064905 (2017)
  - p+Au 0-5% ( $dN/d\eta = 12.3 \pm 1.7$ )  
PRC 95, 034910 (2017)
- Fixed multiplicity:  
same MVST prediction for  $v_2$
- Hydro description:  
better qualitative agreement  
(same multiplicity scales with eccentricity)
- Note: no nonflow systematics estimate in d+Au ( $\leq$  than in p+Au)

