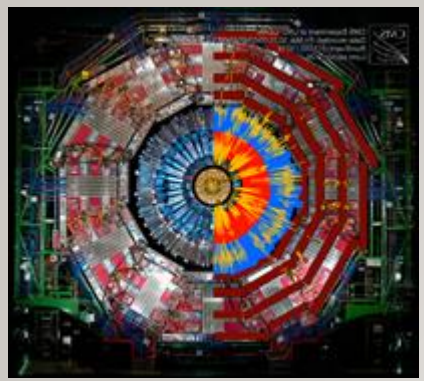

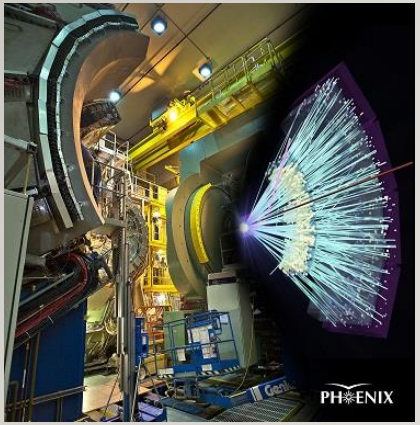

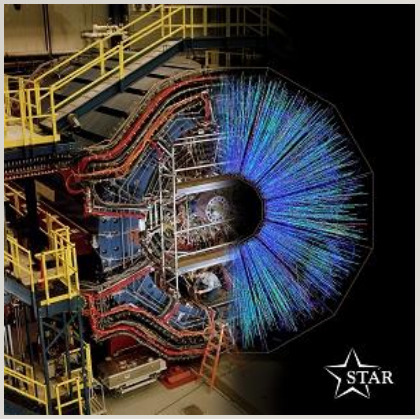

INTRODUCTION TO HIGH ENERGY HEAVY ION PHYSICS

EXPERIMENTS & PHENOMENOLOGY

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CONTENT OF THIS TALK

- INTRODUCTION
  - Particle accelerators and detectors
  - The strong interaction a.k.a. QCD
- HIGH ENERGY HEAVY ION EXPERIMENTS
  - The Big Bang and the Little Bangs in the lab
  - Timeline of a heavy ion collision
  - Phase map of QCD and the experimental control parameters
  - High energy physics facilities, experiments
- IMPORTANT OBSERVATIONS & THEIR PHENOMENOLOGY
  - Nuclear modification
  - Flow, hydrodynamics, viscosity
  - Thermal photons, HBT, fluctuations, search for the critical point

3 INTRODUCTION

Particle physics, accelerators and detectors

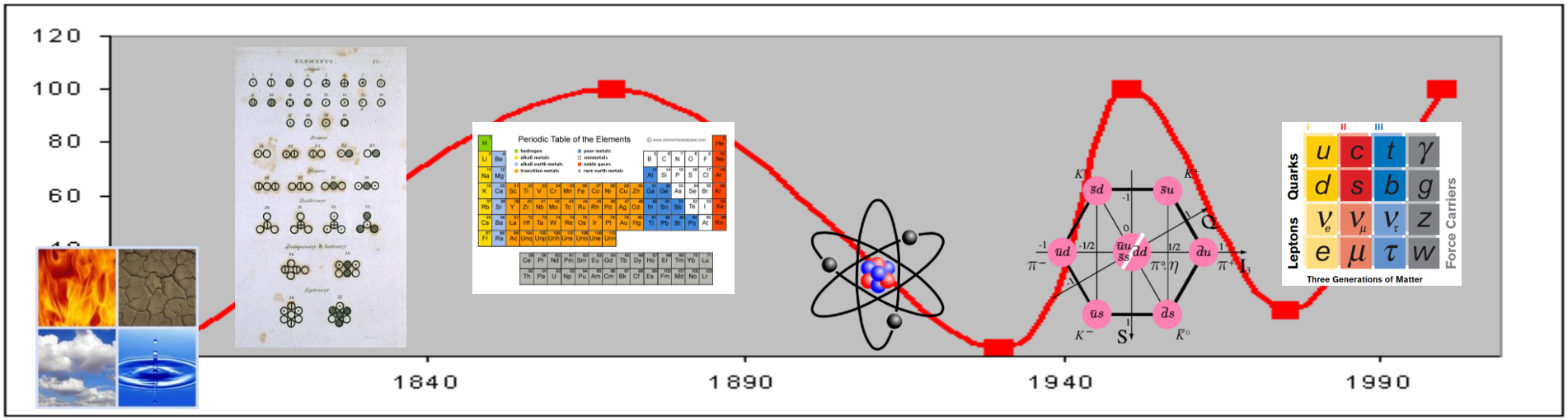
The Standard Model and QCD

Hadrons, quark confinement

Phases of QCD

4/70 WHAT ARE THE BUILDING BLOCKS OF MATTER?

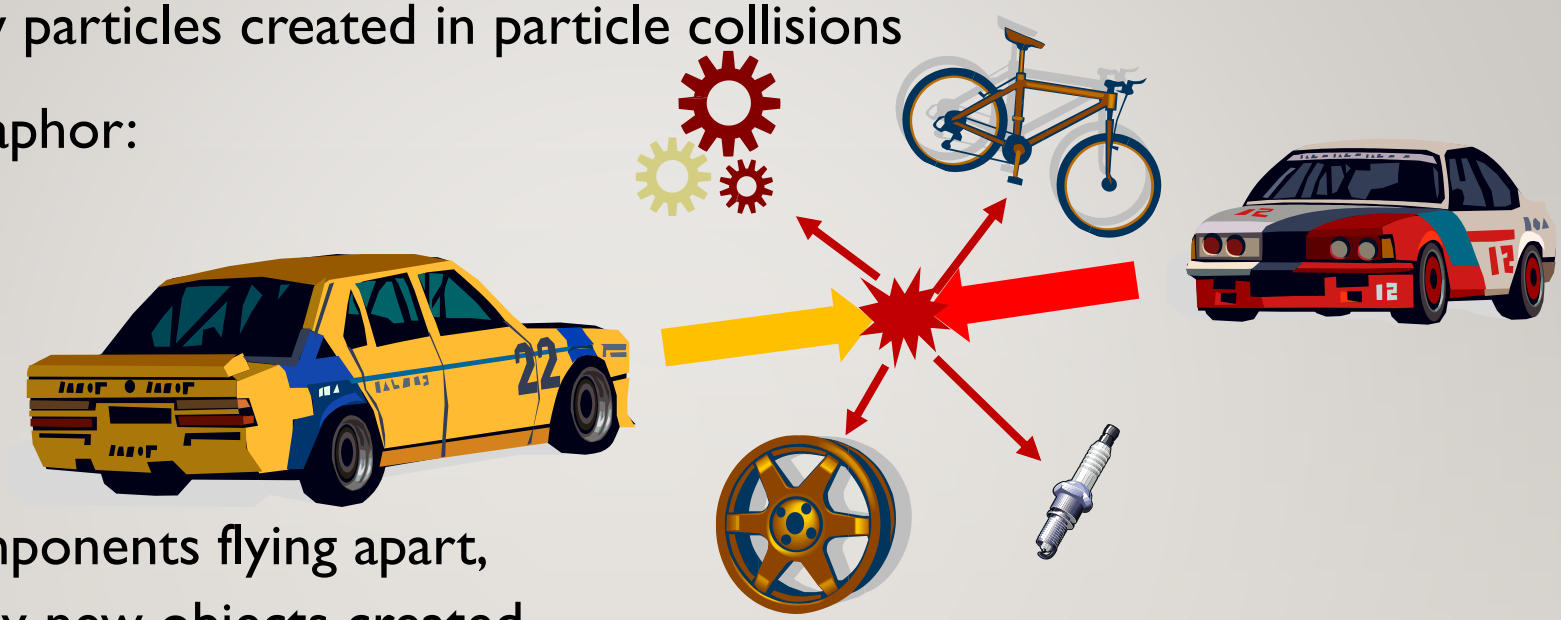
- Ancient history: four/five elements
- 1789: Dalton's elements 33
- 1869: atoms, periodic system ~100
- 1930: proton, neutron, electron 3
- 1930-1960: „hadrons" ~100
- 1975: the Standard Modell 4



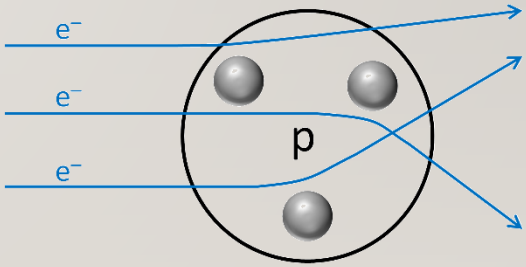
INTRODUCTION EXPERIMENTS OBSERVATIONS

5/70 METHOD OF PARTICLE PHYSICS

- New particles created in particle collisions
- Metaphor:

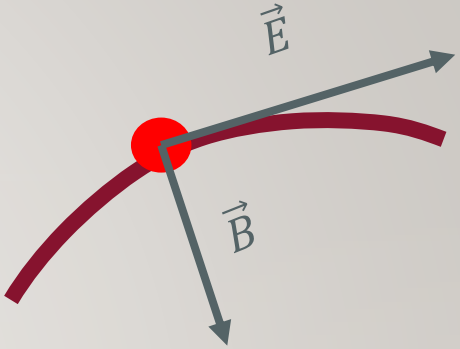


- Components flying apart, rarely new objects created
- This is how proton structure was discovered
- Resolution $\approx hc/E$, proton size: 1 GeV
- Particle accelerators!

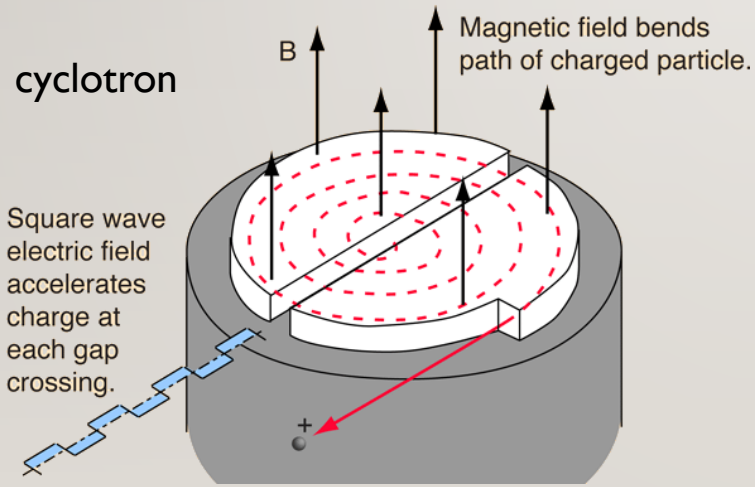


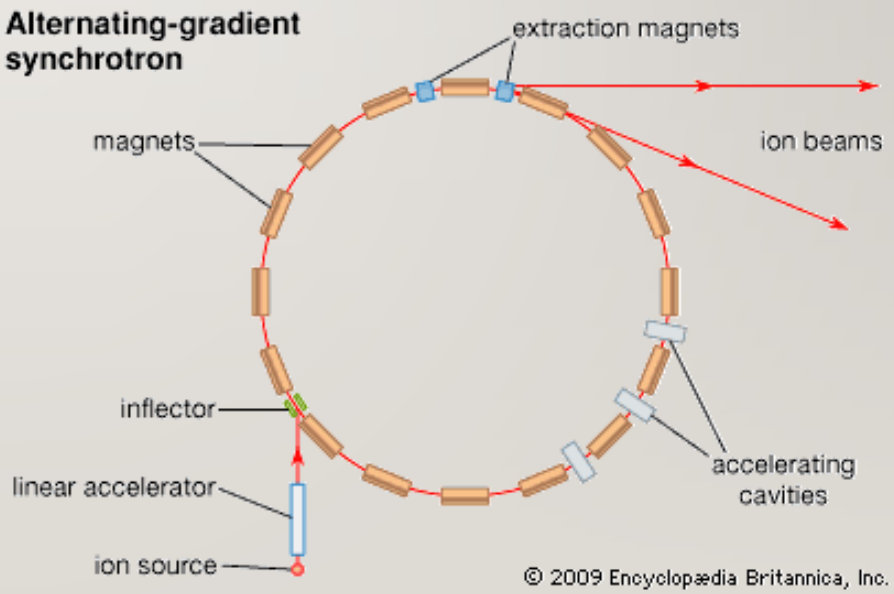
6/70 PARTICLE ACCELERATORS

- Fwd acceleration: electric field (voltage)
- Circular orbit: magnetic field (focusing as well)
- Cyclotron: acceleration between semicircles
- Synchrotron: fixed orbit



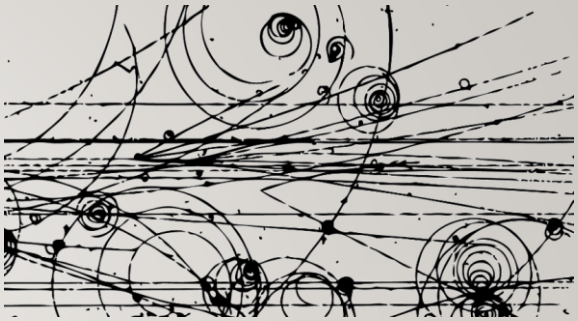
cyclotron

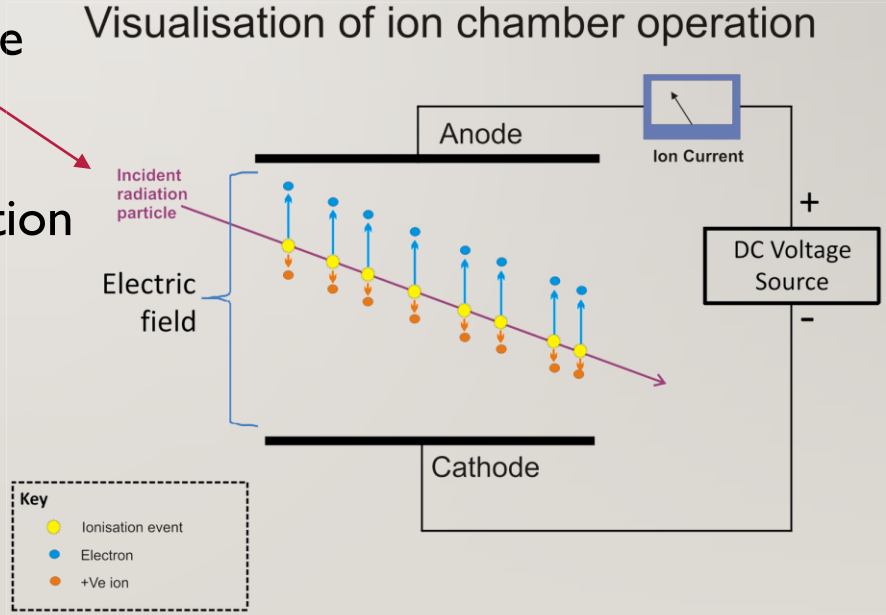




7/70 PARTICLE DETECTORS

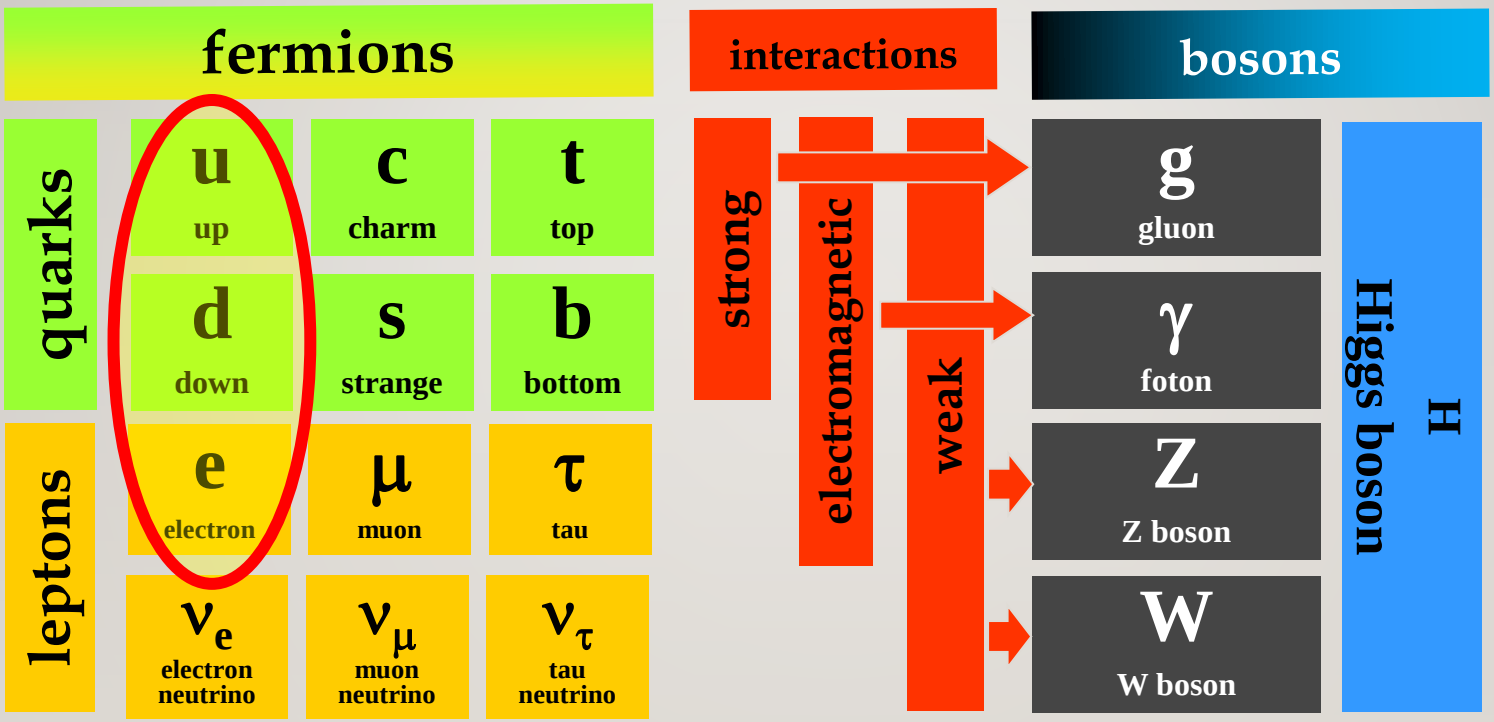
- Bubble chamber: overheated fluid, bubble creation image reveals particle tracks
- Cloud chamber: supersaturated gas, condensation, tracks visible
- Ionization detector: traversing particle ionizes gas, electronical tracking
- Scintillator: luminescence, light detection
- Semiconductor detectors: similar to CCD chip
- Many Nobel prizes: Wilson, Glaser, Charpak





8/70 STANDARD MODEL OF PARTICLE PHYSICS

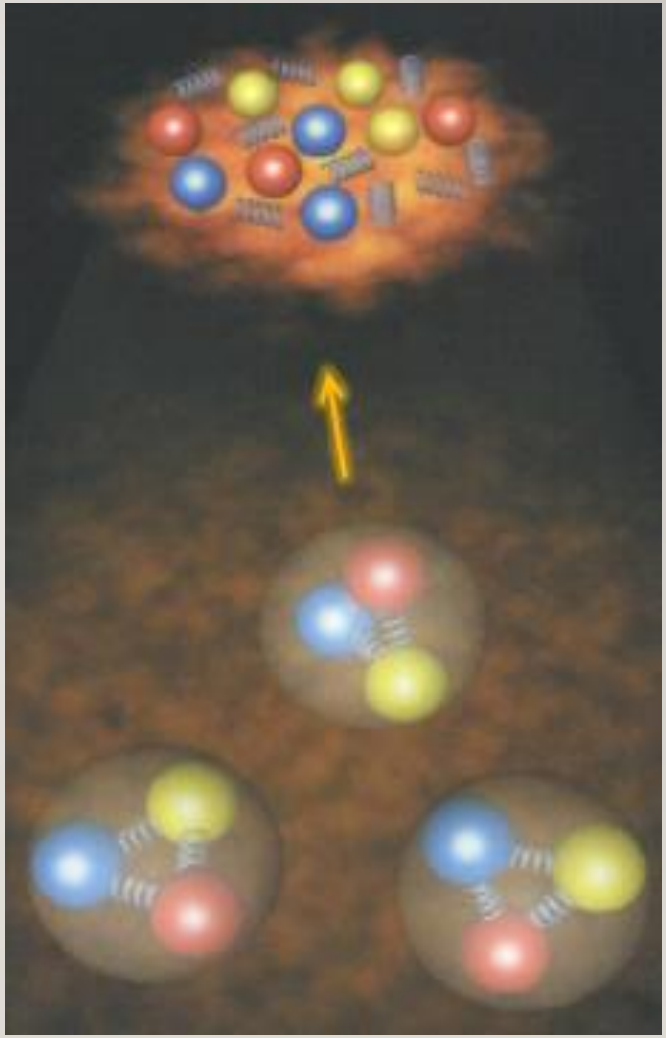
- Three interactions: weak, electromagnetic, strong
- Mediated by gauge bosons



- Ordinary matter: u, d quarks, electrons
- First microseconds after the Big Bang: strong interaction important

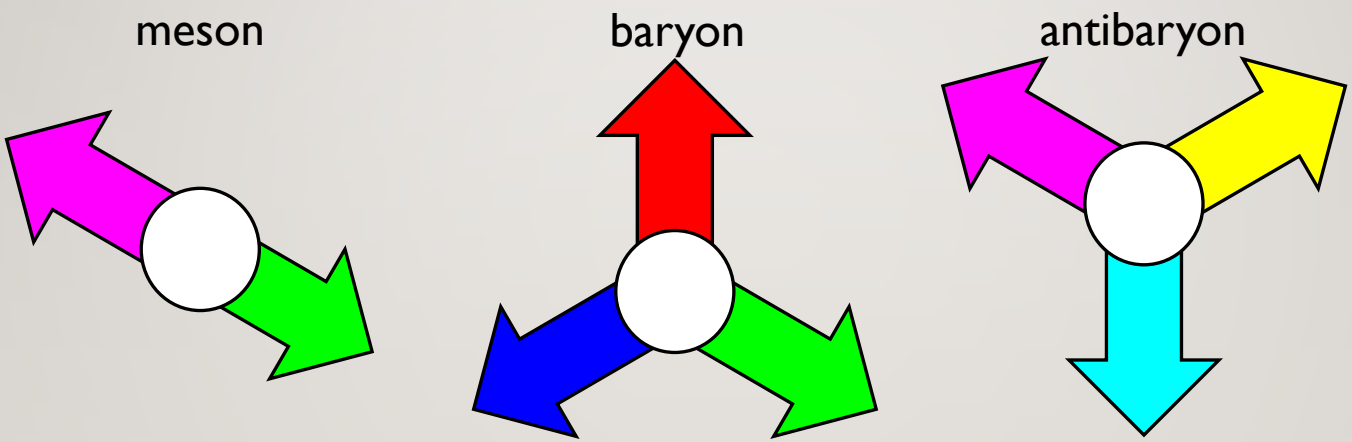
9/70 WHY THE STRONG INTERACTION?

- Understanding the strong interaction
  - ~1930: discovery
  - ~1970: explanation
  - ~1990: huge particle accelerators
- Similar to electromagnetism
  - 1750-90: discovery
  - 1830-70: explanation
  - 1876: telephone
  - Early 20th century: TV, computers
  - Late 20th century: Internet, touchscreen
- Maybe strong interaction technology in 20-50-100 years?



10/70 THE STRONG INTERACTION

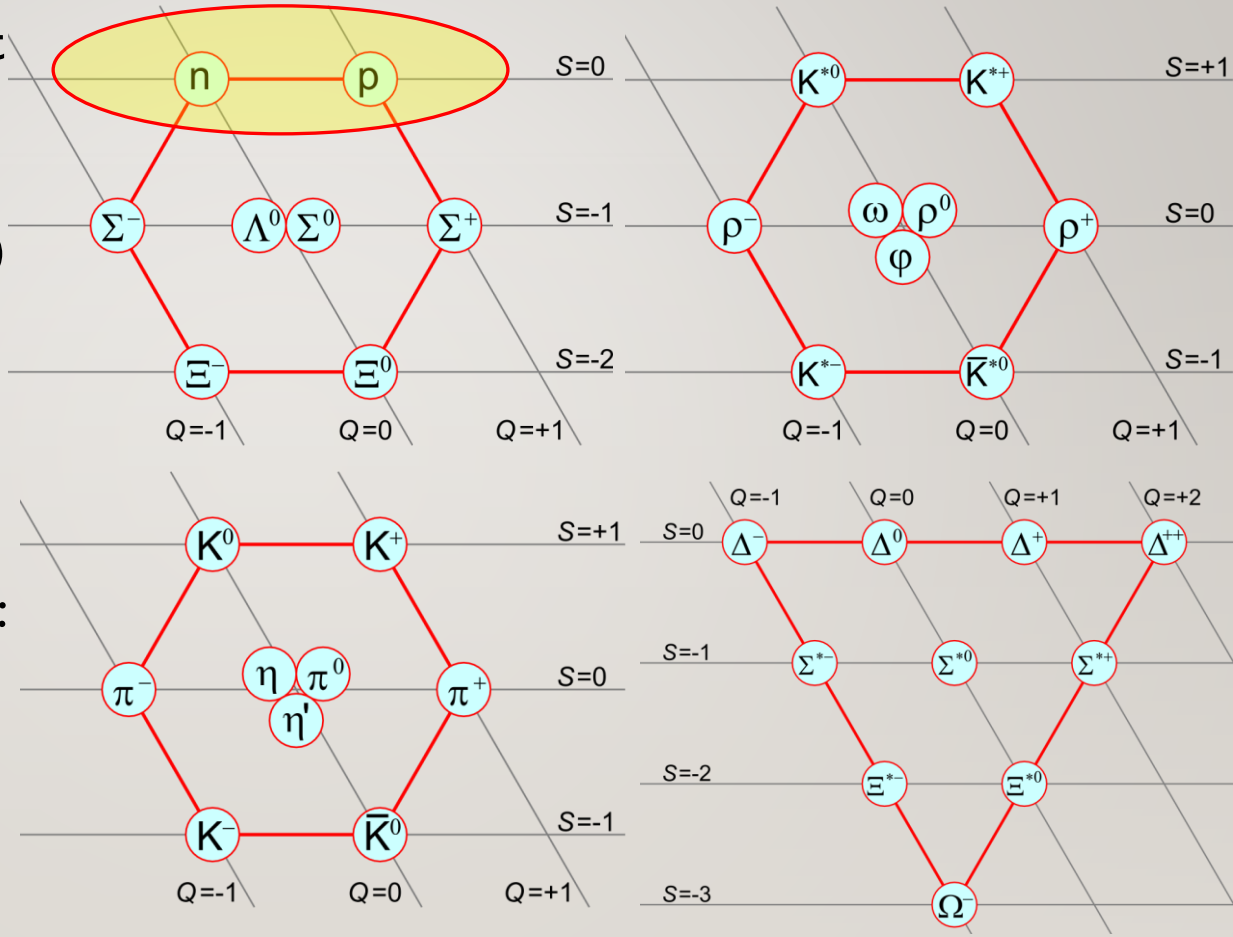
- Interaction of quarks, mediated by gluons (like E-M by photons)
- Electromagnetic interaction: electric charge; Strong interaction: color charge
  - Colors: red, green & blue; Anticolors: magenta, cyan & yellow



- Observable mesons and baryons: color neutral ("white")
- Quarks observable outside mesons and baryons?
- Theory: SU(3) representations
  - Mesons: $3 \otimes \overline{3} = 8 \oplus 1$, Baryons: $3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

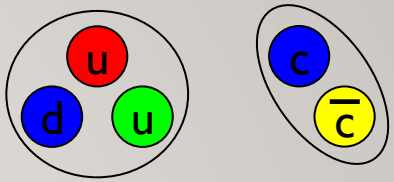
KNOWN MESONS AND BARYONS

- Octet/nonet/decuplet
- Triangular symmetry
- Revealing flavor SU(3) for u,d,s quarks
- Each hadron is a representation
- Other possible states:
  - Tetraquark
  - Pentaquark
  - Glueball
  - Meson molecules

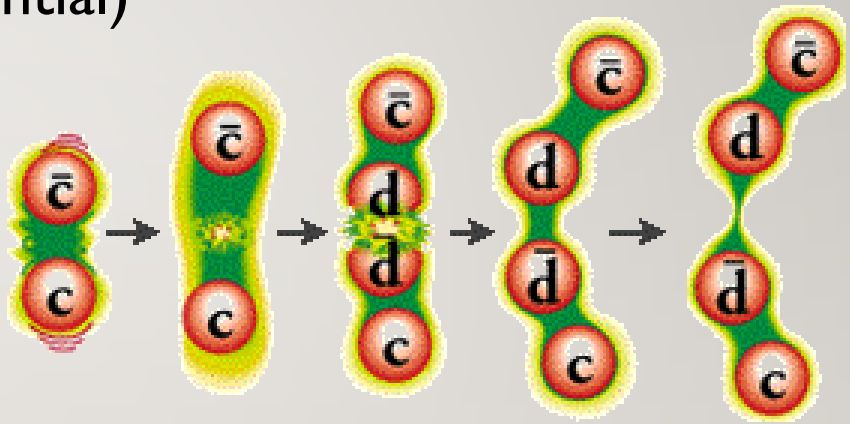


12/70 QUARK CONFINEMENT

- Free quarks not observable, only in hadrons, e.g:

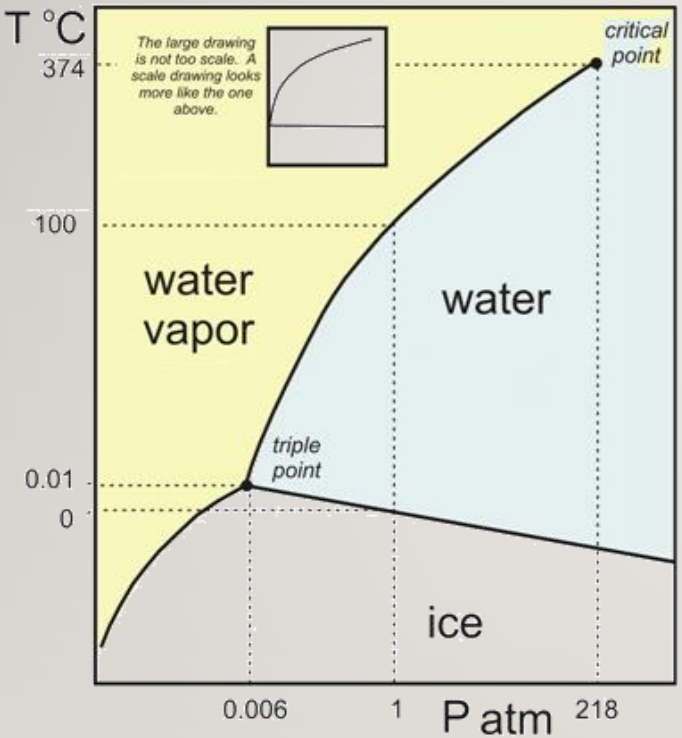


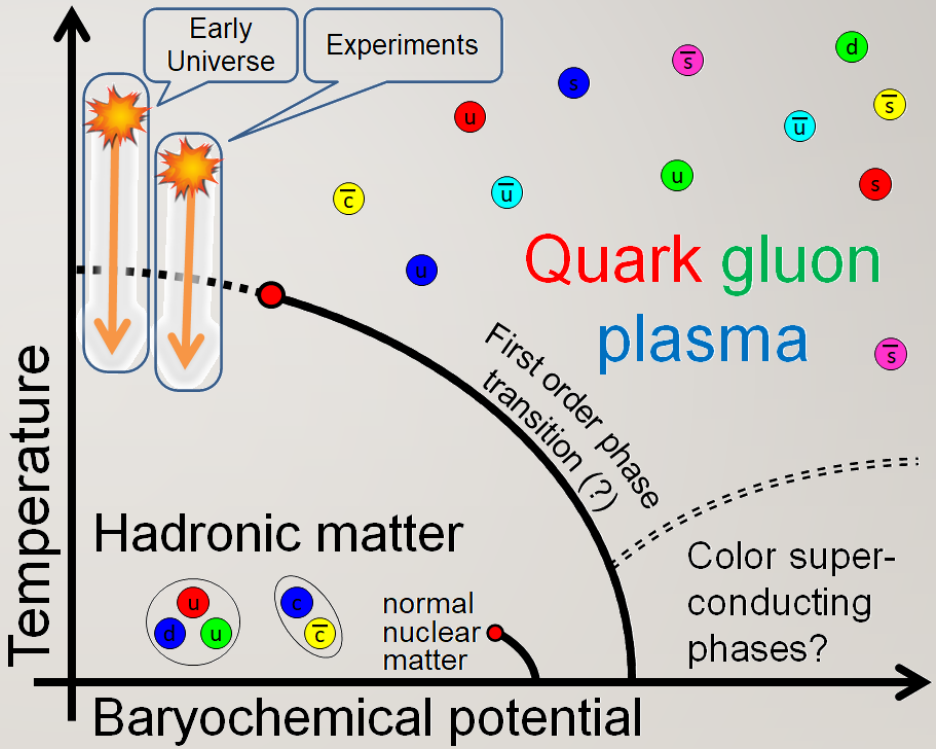
- Increased distance: energy (potential)
- Additional quarks created
- Again confined
- "Opposite": asymptotic freedom
- Extreme temperatures: free quarks?



13/70 PHASES OF NUCLEAR/QCD MATTER

- Phase diagram: state functions, phases (pressure↔density↔chemical potential)





- Water and nuclear matter: similar phase diagrams
- Theoretical calculations: above $T_c \approx 2 \cdot 10^{12}$ K quark matter!

14 HEAVY ION EXPERIMENTS

Big Bang and Little Bangs

Time evolution of heavy ion collisions

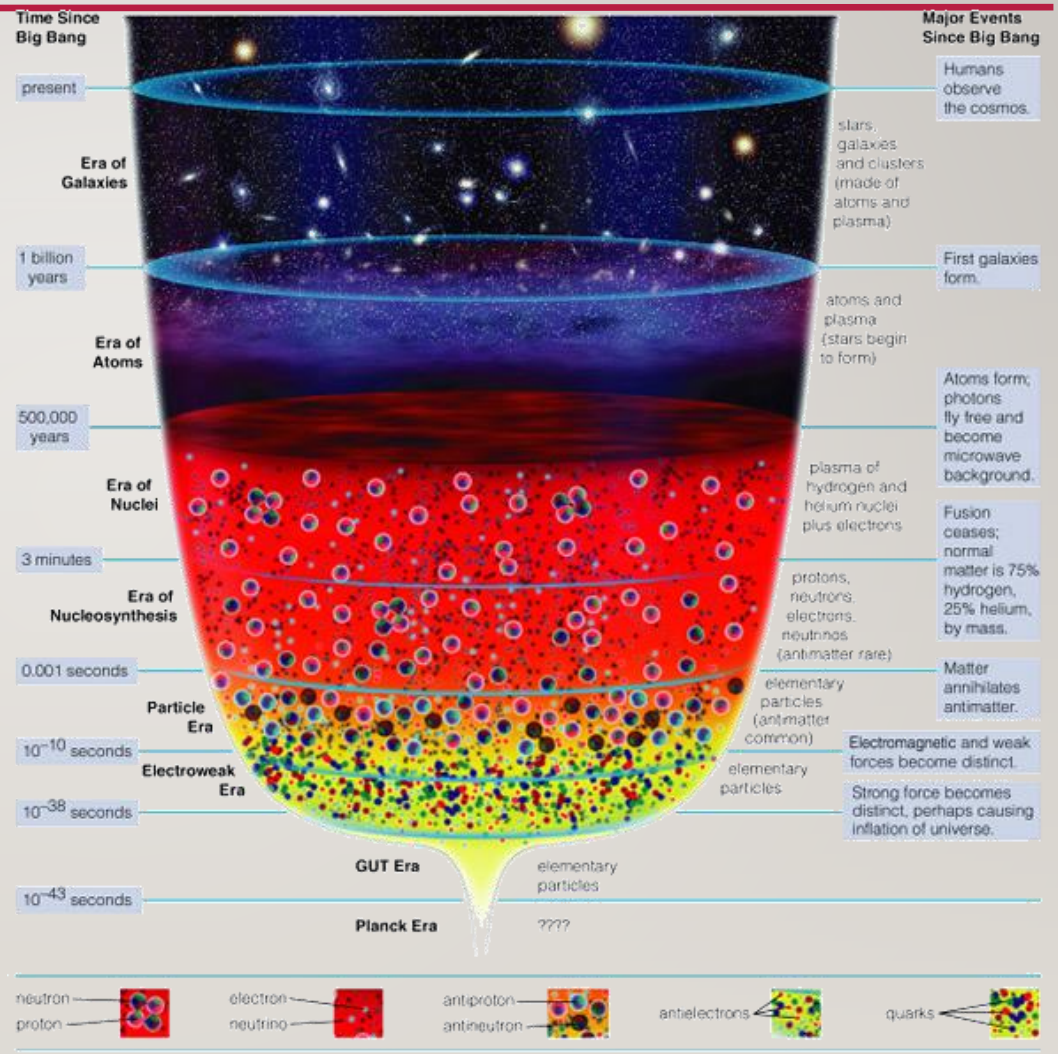
LHC and some of its experiments

RHIC and some of its experiments

Future facilities

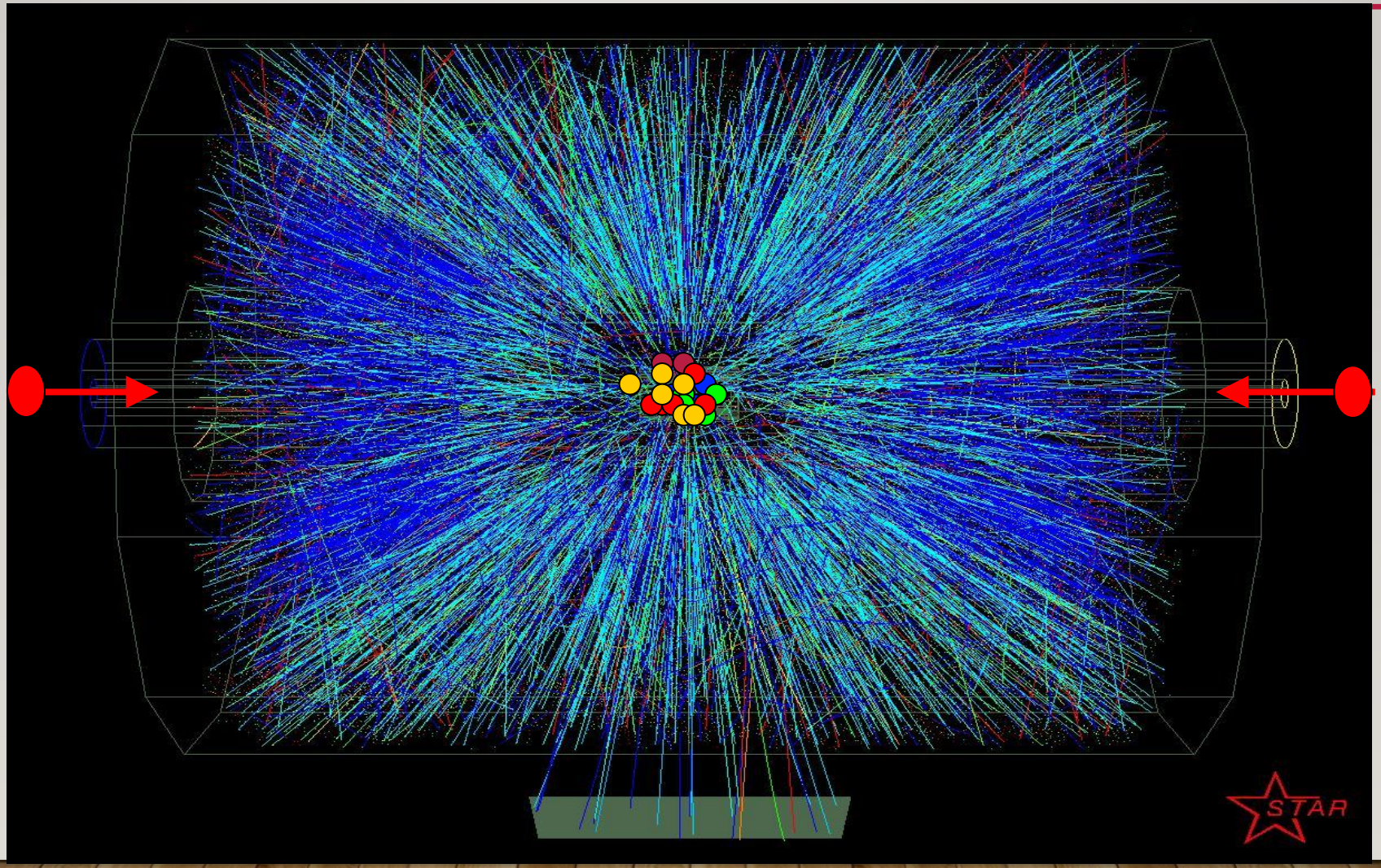
15/70 BIG BANG IN THE LAB

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



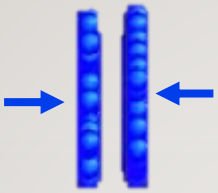
INTRODUCTION EXPERIMENTS OBSERVATIONS

16/70 HOW TO INVESTIGATE THE LITTLE BANGS?

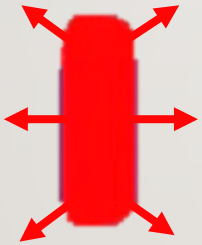


HOW TO IMAGINE A COLLISION?

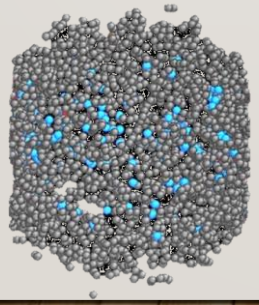
Before collision:
Lorentz-contr.
nuclei

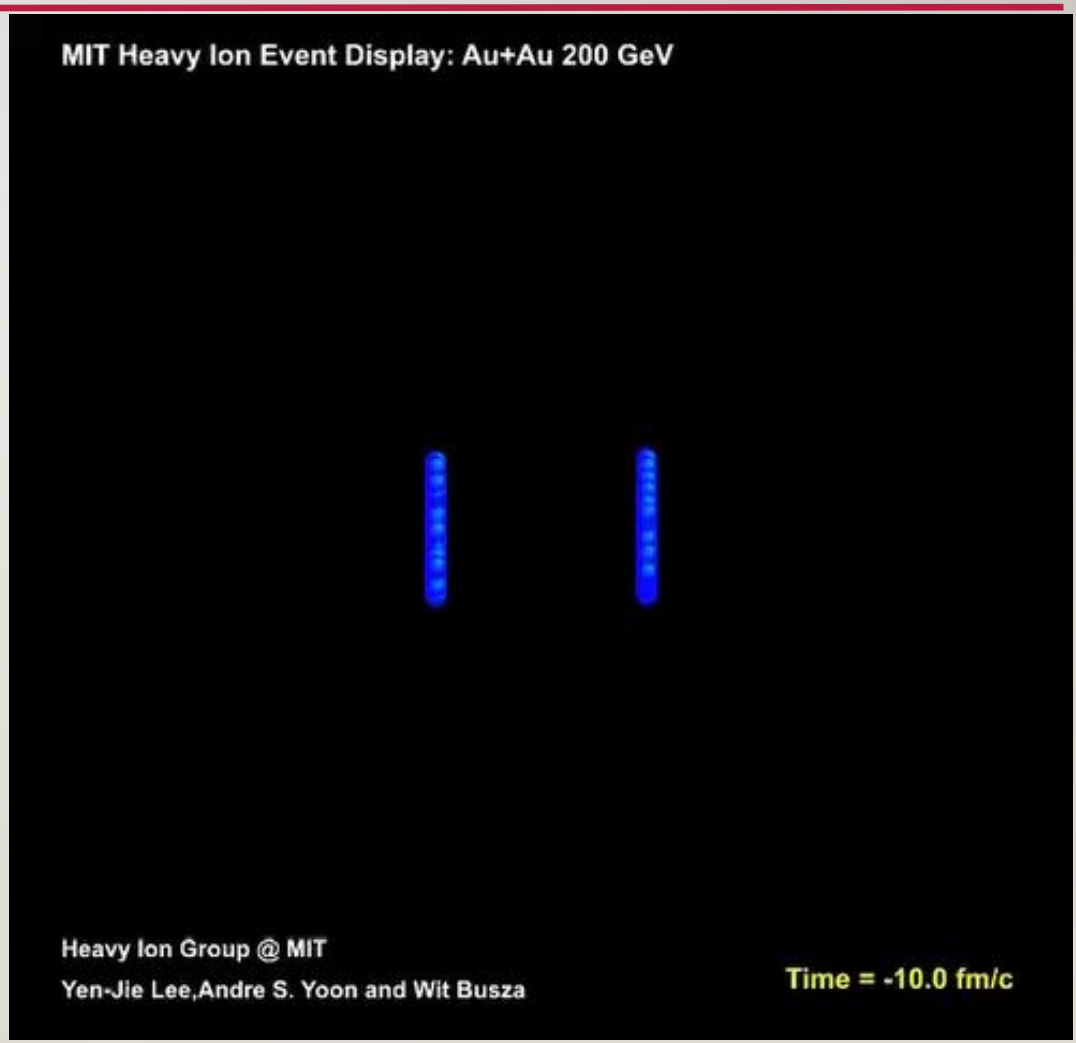


After collision:
quark matter
(for 10^{-22} sec)



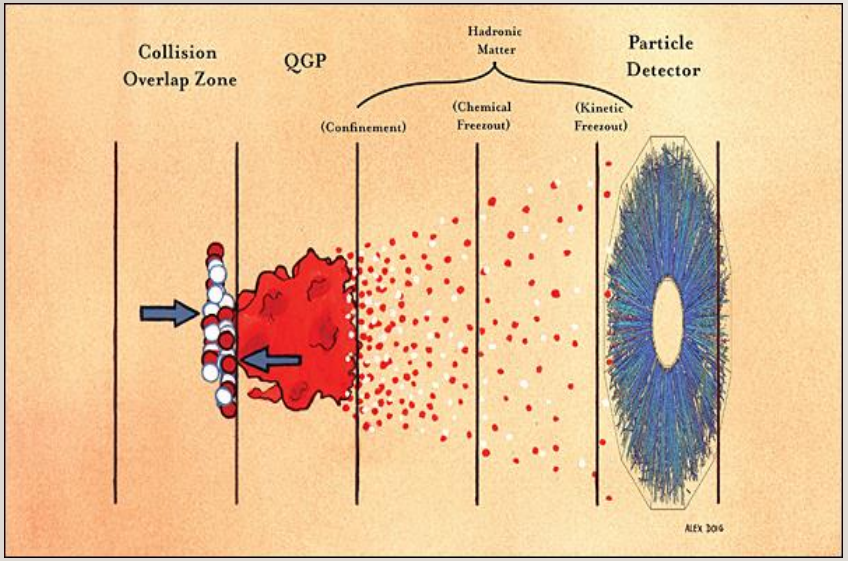
then hadron gas,
free streaming

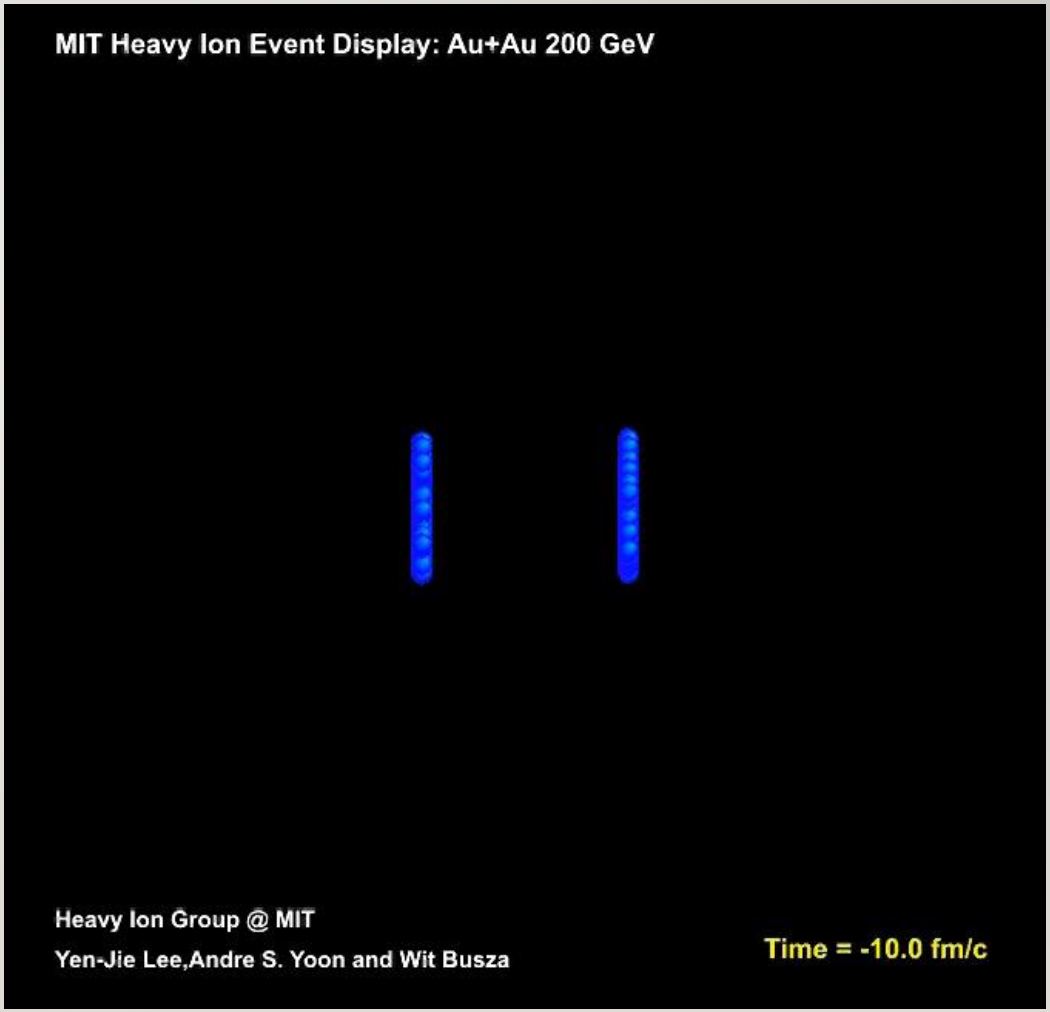




18/70 TIMELINE OF A HEAVY ION COLLISION

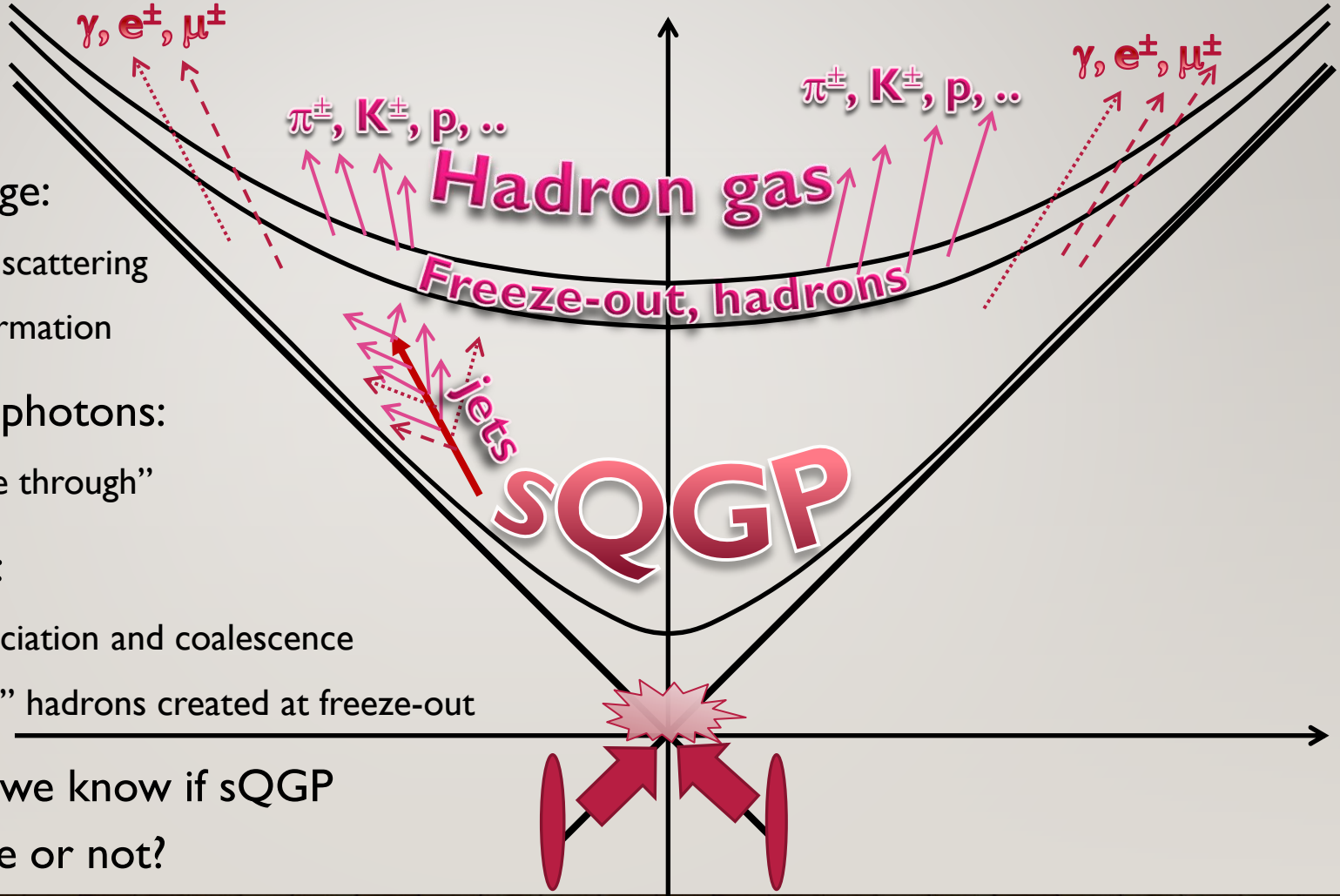
- Pre-thermalization stage: ~1 fm/c
- Quark-hadron transition: ~7-10 fm/c
- Chemical + kinetic freeze-out





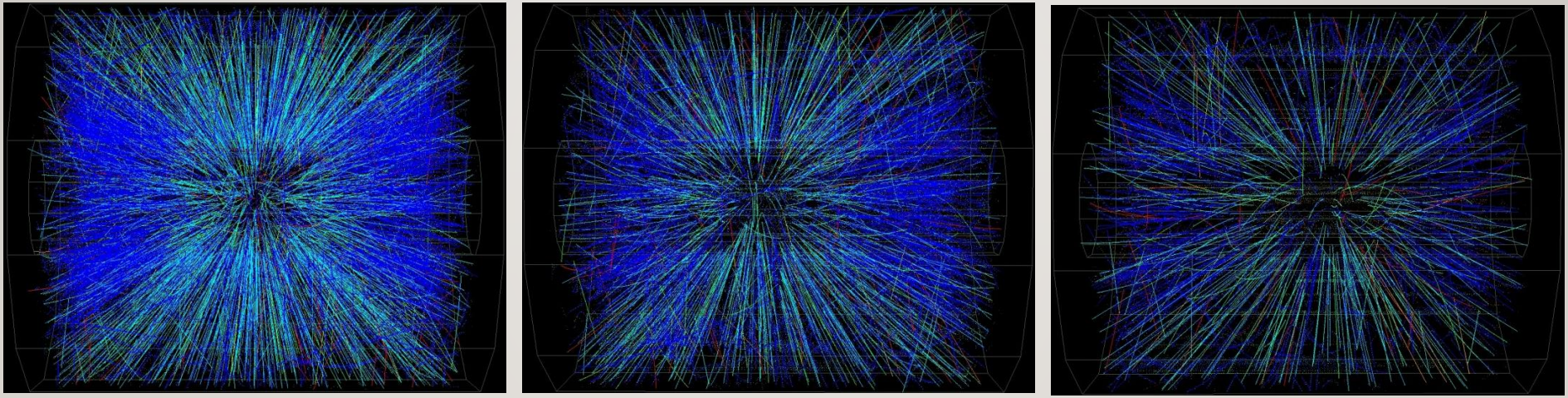
19/70 TIME EVOLUTION OF A HEAVY ION COLLISION

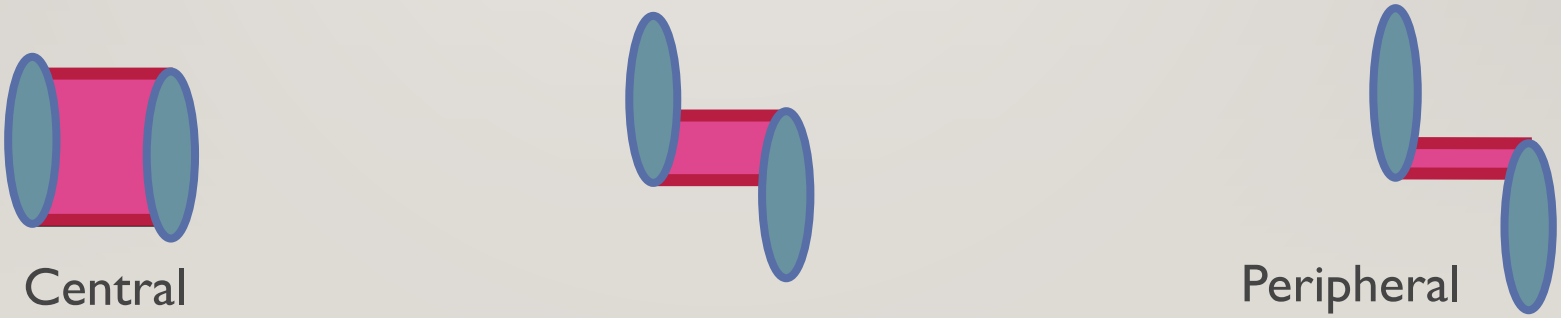
- Initial stage:
  - Hard scattering
  - Jet formation
- Leptons, photons:
  - "shine through"
- Hadrons:
  - Dissociation and coalescence
  - "Final" hadrons created at freeze-out
- How do we know if sQGP was there or not?



COLLISIONS OF DIFFERENT CENTRALITY

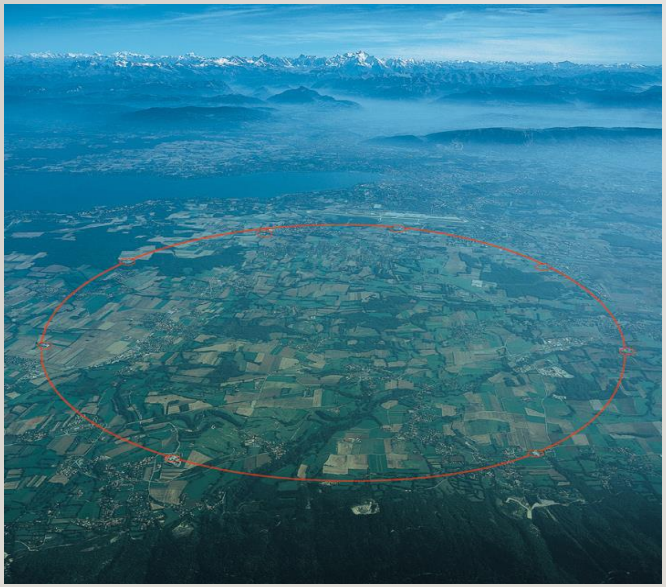
- Centrality: how head-on the collision was
- Measure: how many events are more central?
  - 0%: most central collision; 0-5%: most central 1/20th of all; 90-100%: least central 1/10th of all

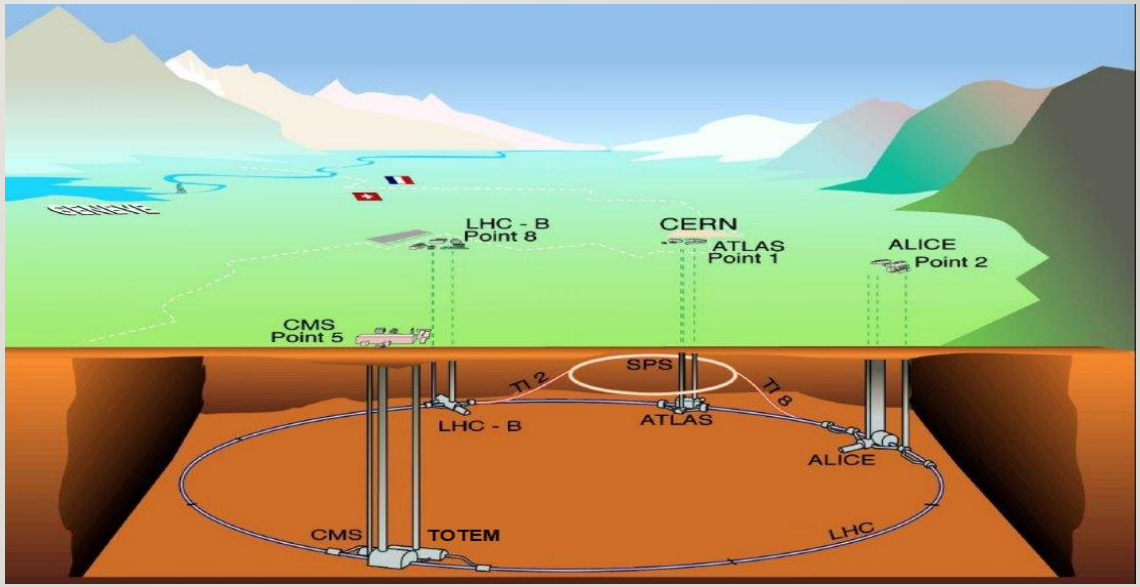




FACILITIES: LARGE HADRON COLLIDER (+SPS)

- LHC collisions: p+p, p+Pb and Pb+Pb; also Xe+Xe, soon probably O+O
- 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)
- Energy: $s = (p_1 + p_2)^2 = E^2_{\text{center-of-mass}}$; usually quoted: $\sqrt{s_{NN}} = \frac{\sqrt{s}}{A}$ (E per nucl. pairs)





22/70 CERN, LHC AND SURROUNDINGS

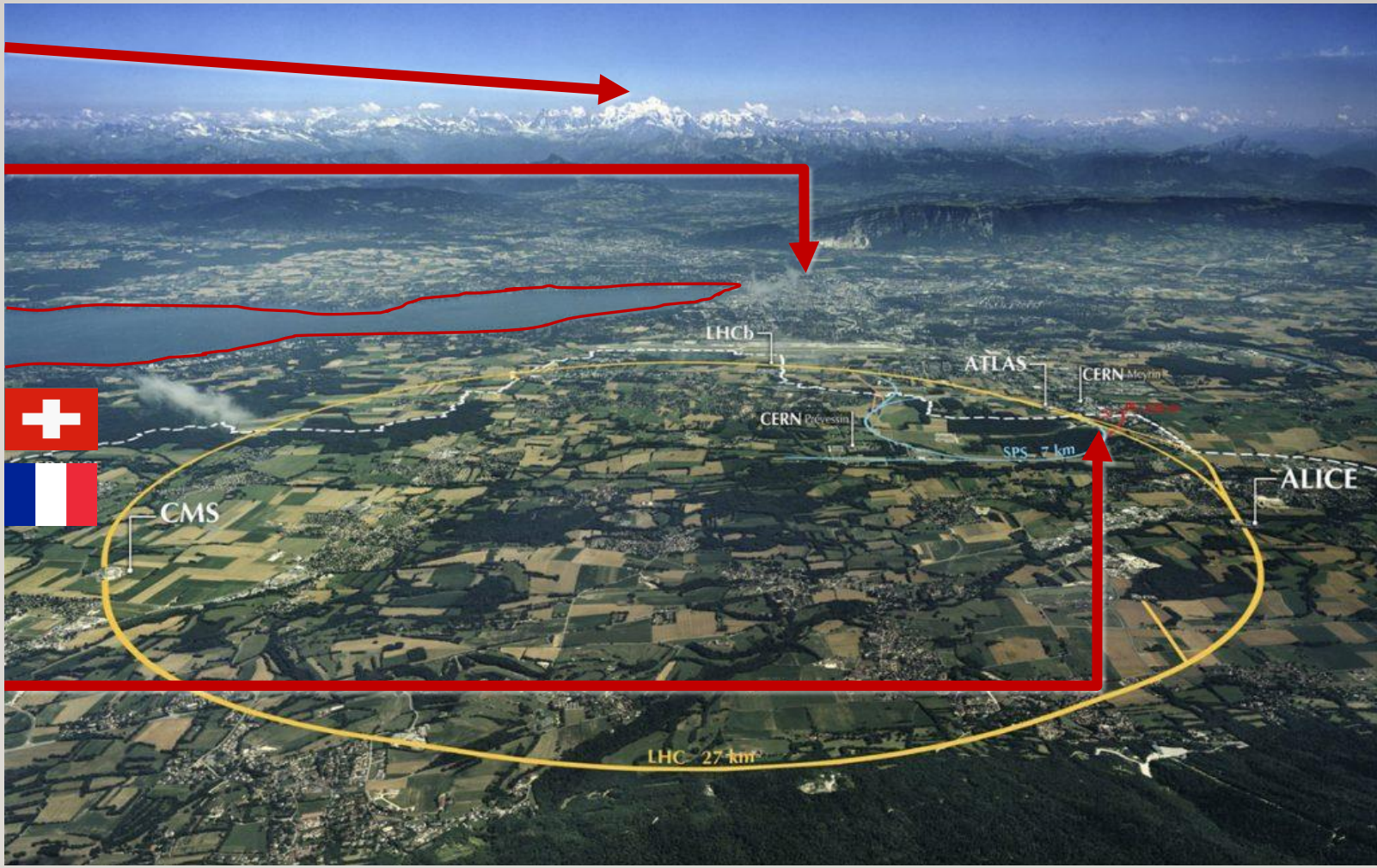
Mont Blanc

Geneve

Lake Geneva

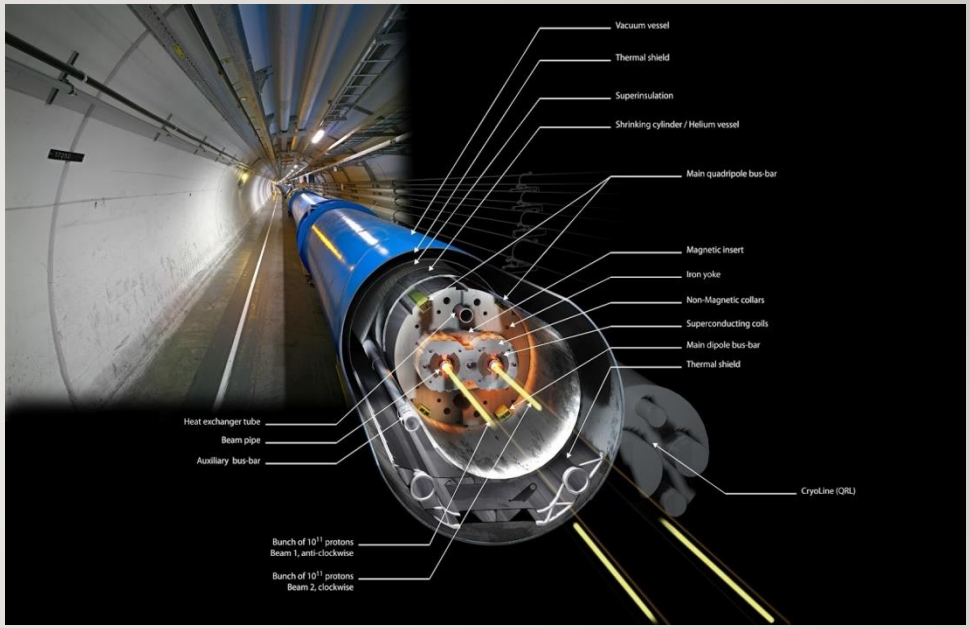
Swiss-French border

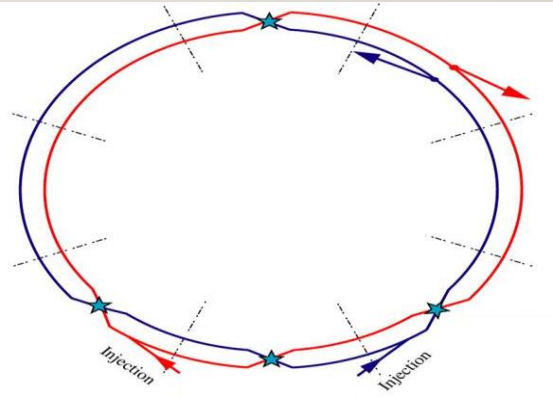
CERN



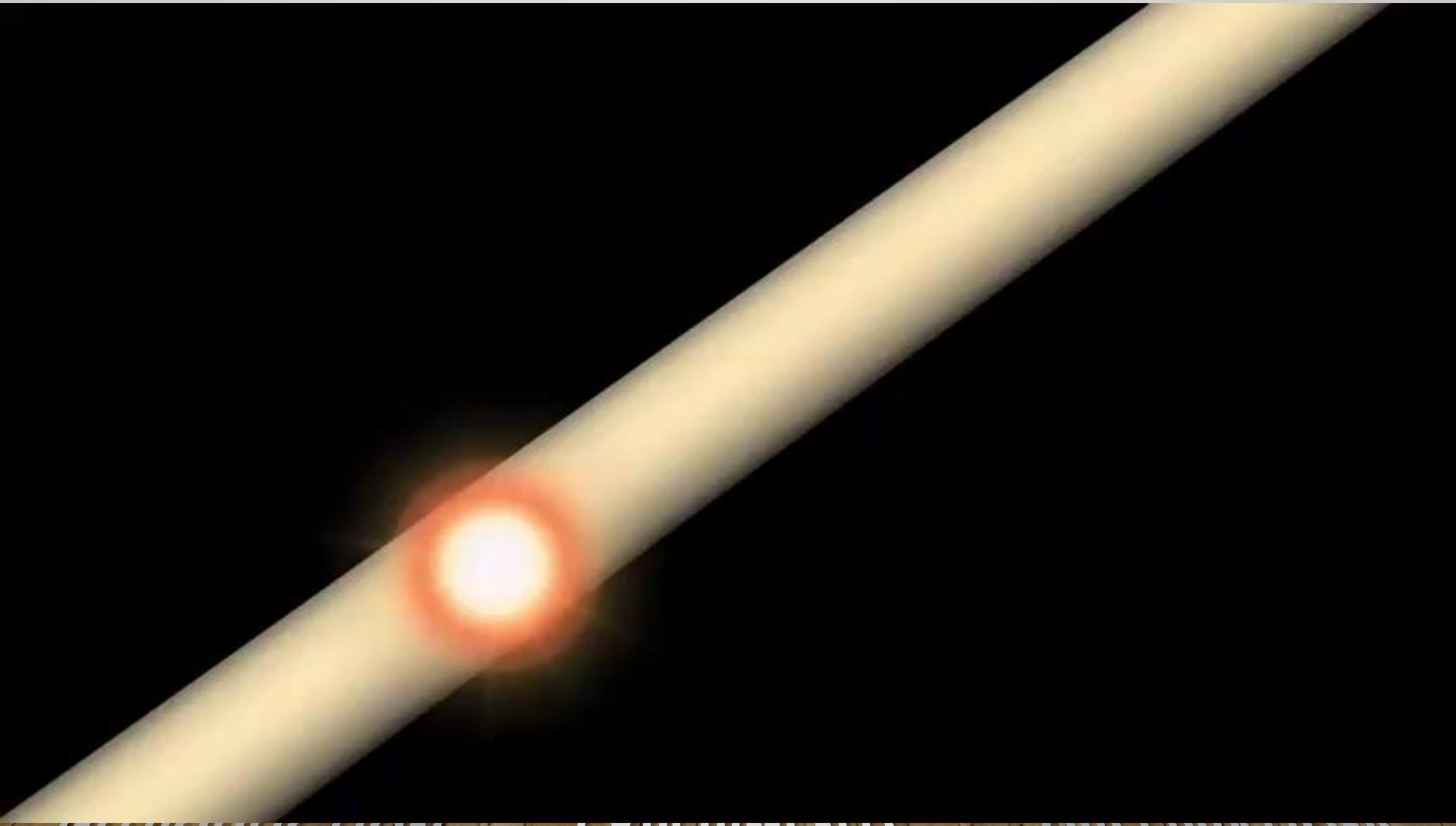
23/70 LHC IN NUMBERS

- 2x27 km, 150-200 m deep
- Collisions: 4 intersections
- ~3000 bunches
- 99.9999991% speed of light
- 10 000 rounds/sec
- 600 million collisions/sec
- 10 000 superconducting magnets
- 10 000 tons of liquid N_2: 80 K
- 120 tons of liquid He: 2 K
- 120 MW electricity consumption (c.f. a large city)
- 6 μg H^+ in 10 years
- 25 000 terabyte data yearly



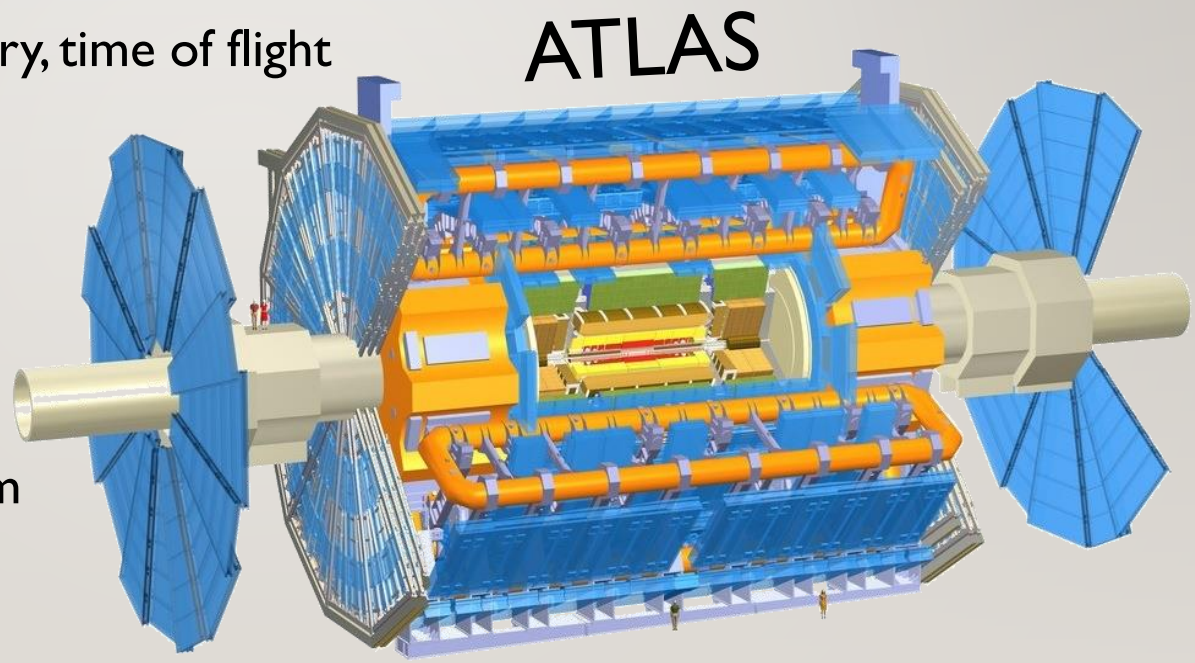


24/70 ACCELERATION AND COLLISIONS

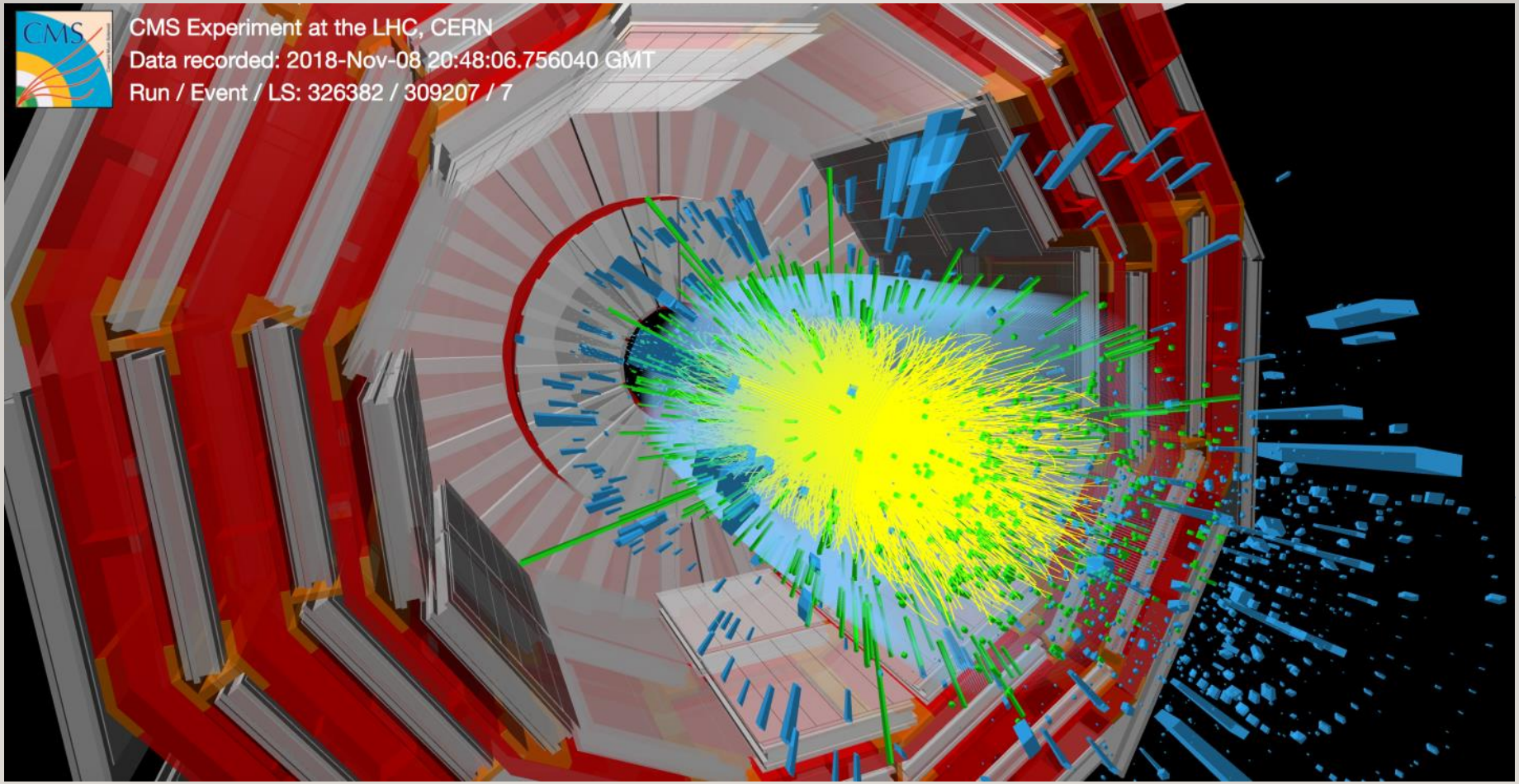


SETUP OF LARGE DETECTOR SYSTEMS

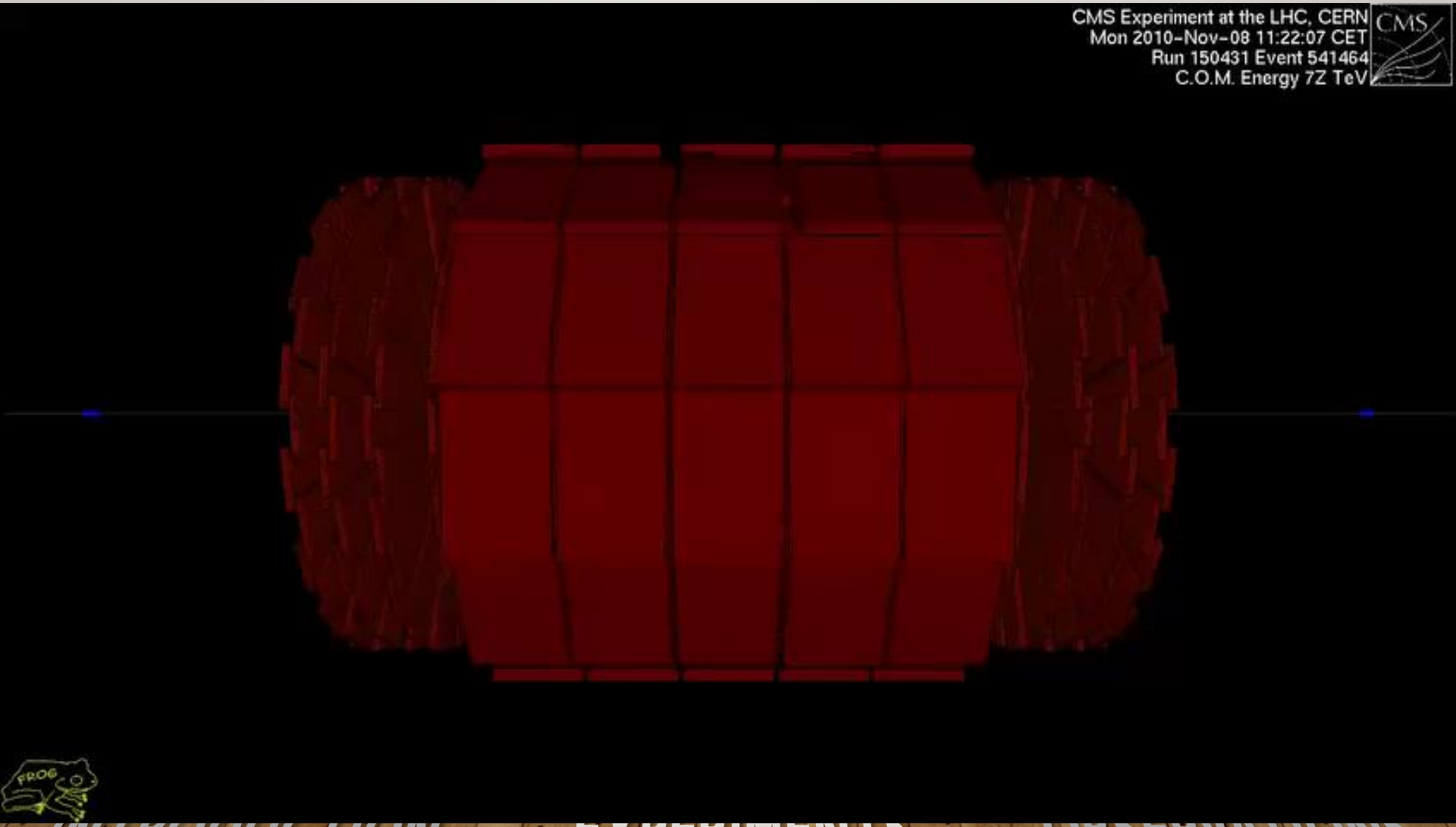
- Close to the collision (plus very far outside): event characterization; determining event vertex (location) and collision ”time zero”
- Internal layers: tracking, measurement of energy deposit (dE/dx)
- Outer layers: calorimetry, time of flight → particle type
- Forward/backward: muon detection
- Connected by: Data Acquisition System (million events/sec)



26/70 THE CMS DETECTOR

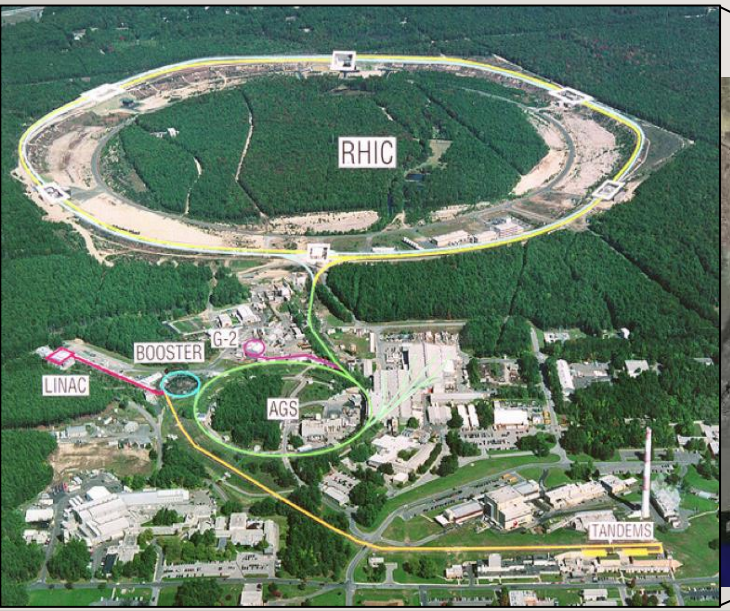


27/70 A COLLISION IN CMS

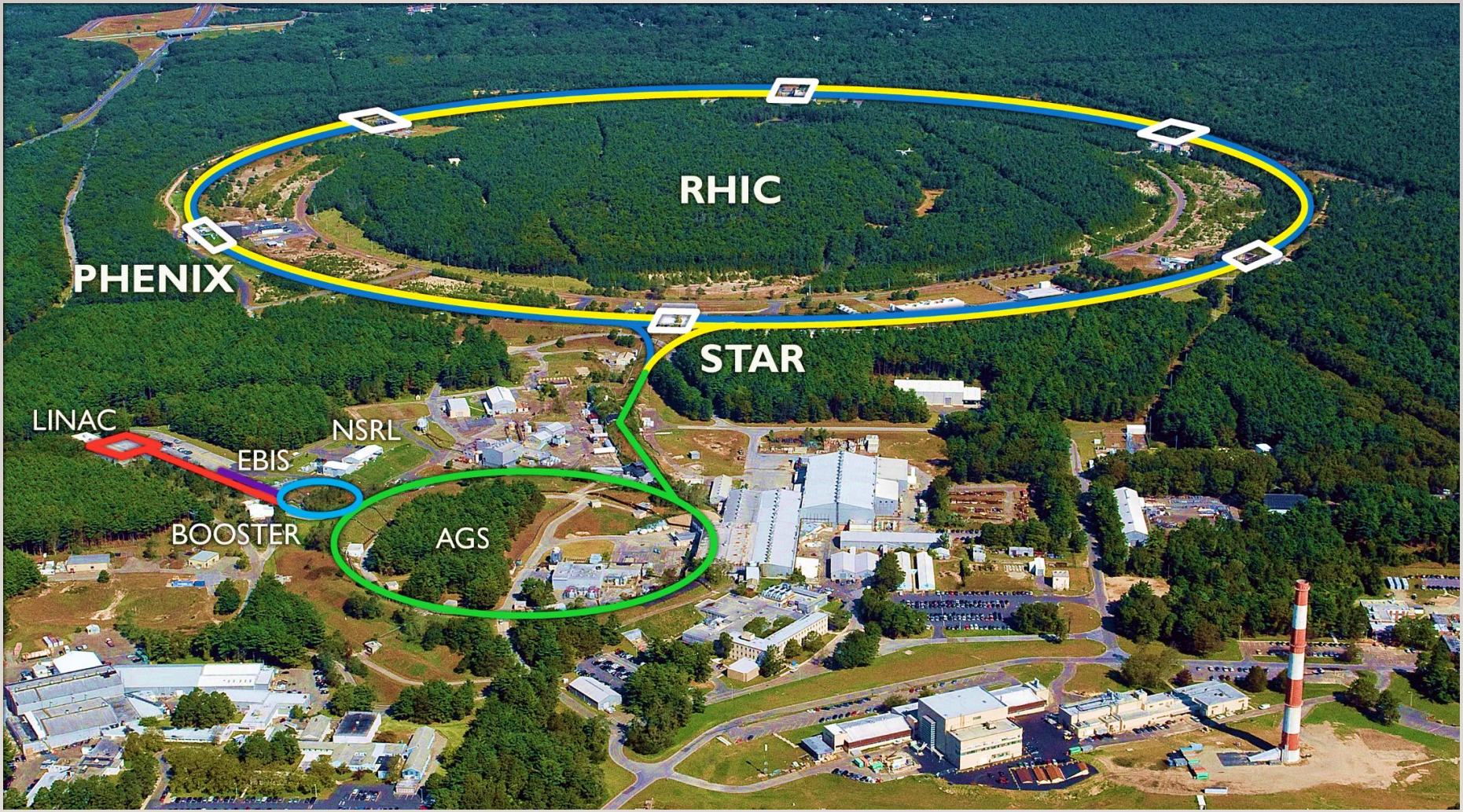


THE RELATIVISTIC HEAVY ION COLLIDER

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

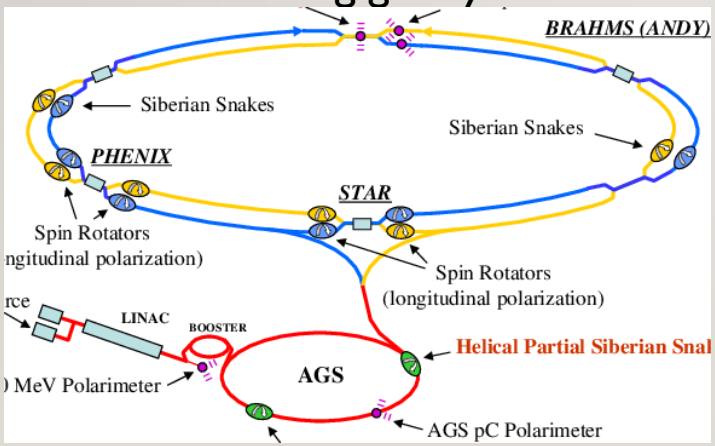


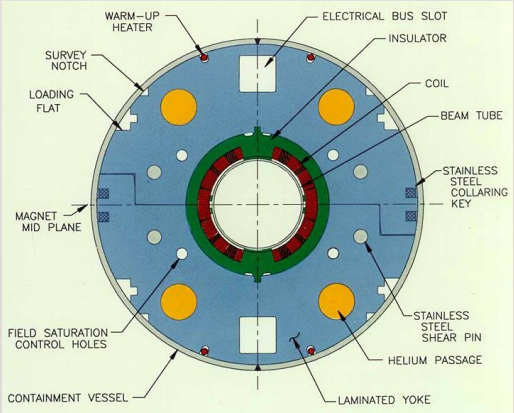
29/70 AREAL PHOTO OF RHIC



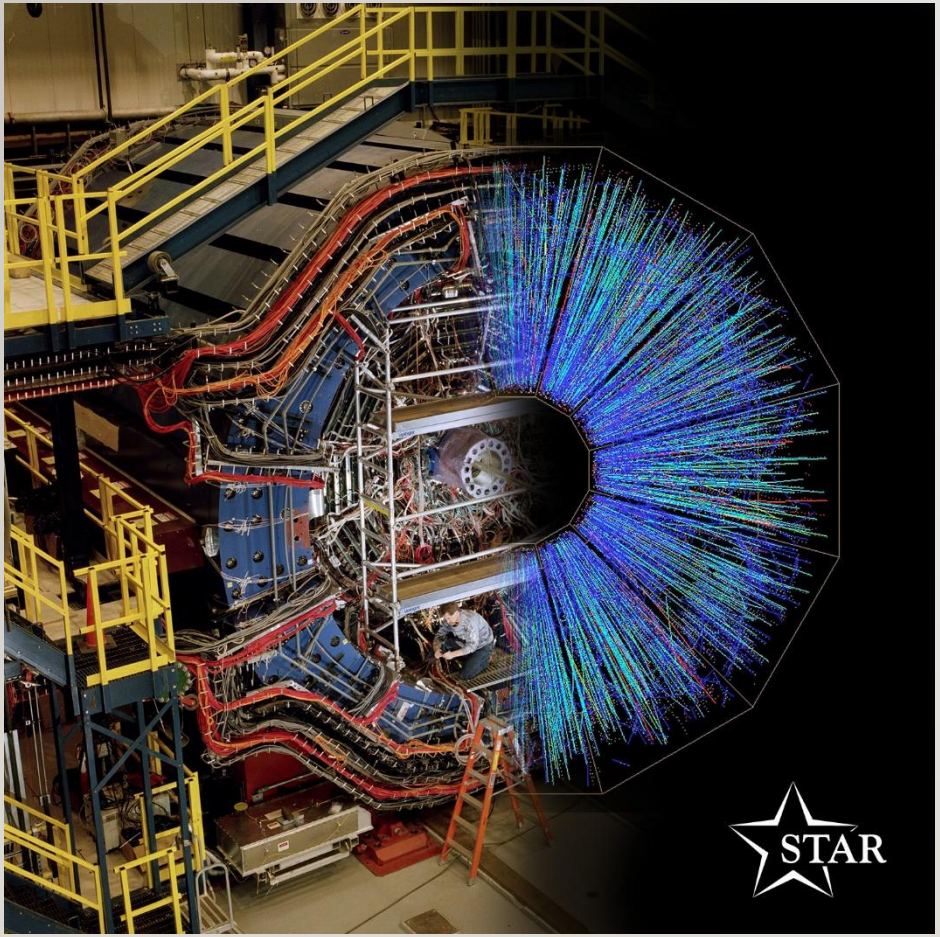
30/70 RHIC IN NUMBERS

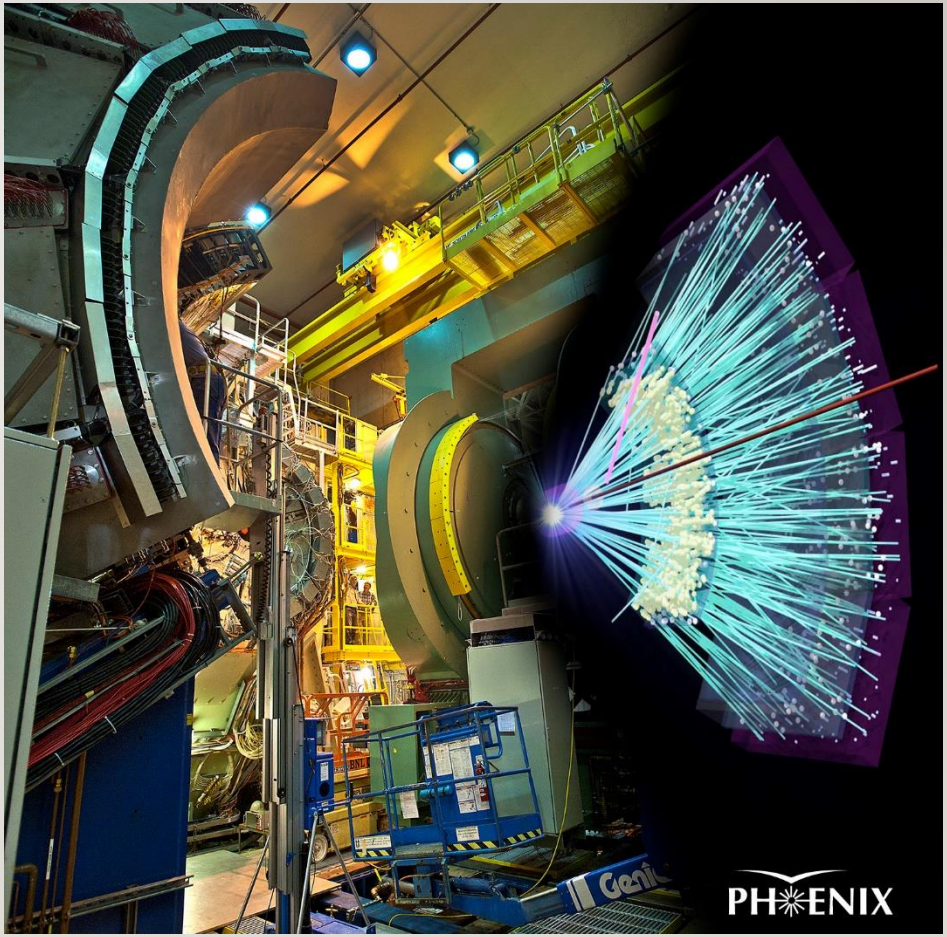
- Two rings, 4 km each
- 99.995% speed of light
- 111 bunches
- 80 000 rounds/sec
- Thousands of collisions/sec
- 1740 superconducting magnets
- 21 000 km superconducting wires
- 25 tons of liquid He
- 0.00005 mg gold/year





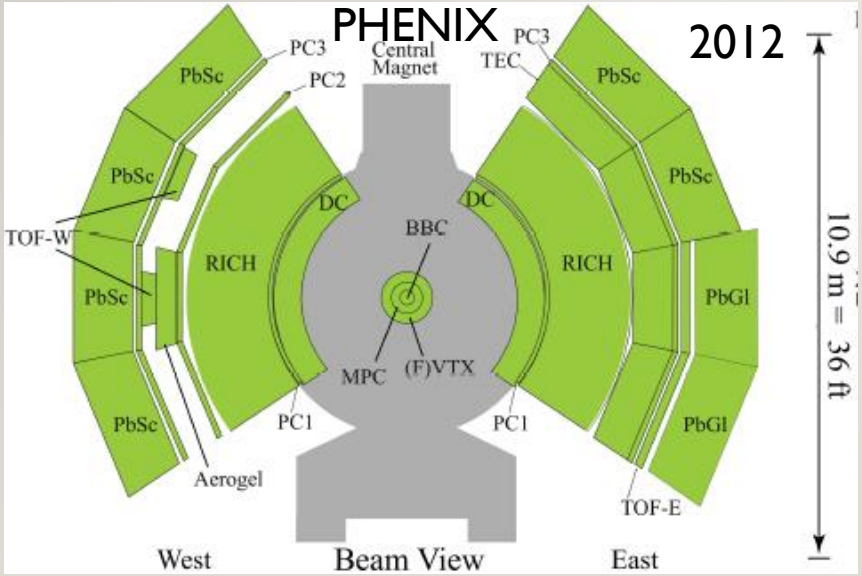
COLLISION IN STAR & PHENIX AT RHIC

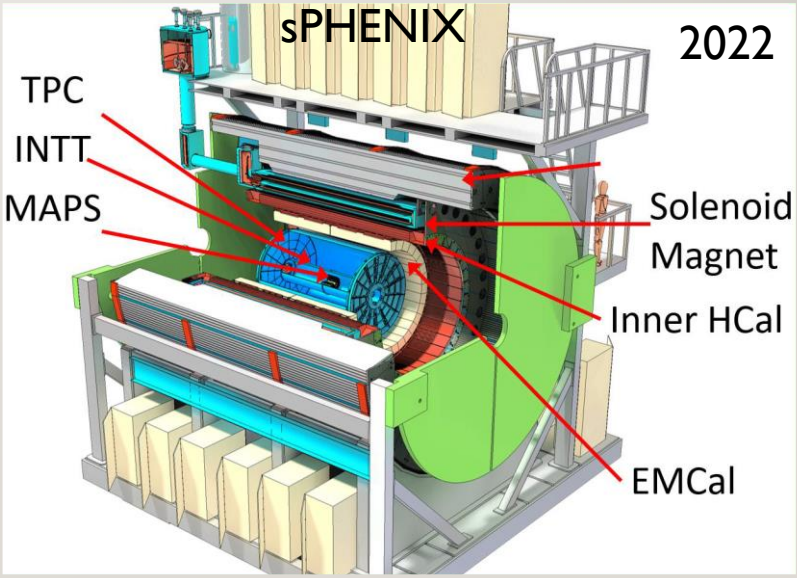




32/70 PHENIX AND sPHENIX

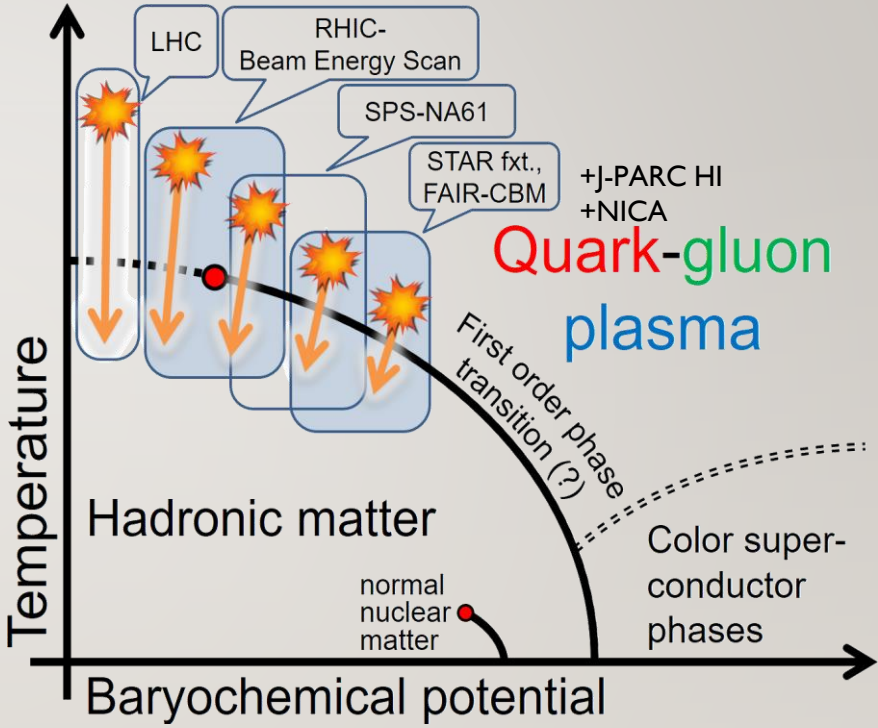
- PHENIX: versatile detector identifying many different particles, recording large amount of collisions. Dismantled in 2016, to give way to sPHENIX
- sPHENIX: to take data in ~2023
  - Jets, jet correlations, Upsilon states
  - EM+Hadronic calorimetry, high resolution tracking, fast (~100 kHz) data aquisition





EXPLORING THE PHASE MAP OF QCD

- Why so many facilities? Explore phase map!
- Phase map: temperature versus matter excess (baryochemical pot. μ_B)
- Control parameters:
  - Collision energy, system, geometry
- Crossover at low μ_B and $T \cong 170$ MeV
- Probably 1st order quark-hadron p.t. at high μ_B (NJL, bag model, etc)
- Critical End Point (CEP) in between?



- High μ_B: nuclear matter, neutron stars, color superconductors…
- Phase transition importance: even in core-collapse supernovae!

THE RHIC BEAM ENERGY/SPECIES SCAN

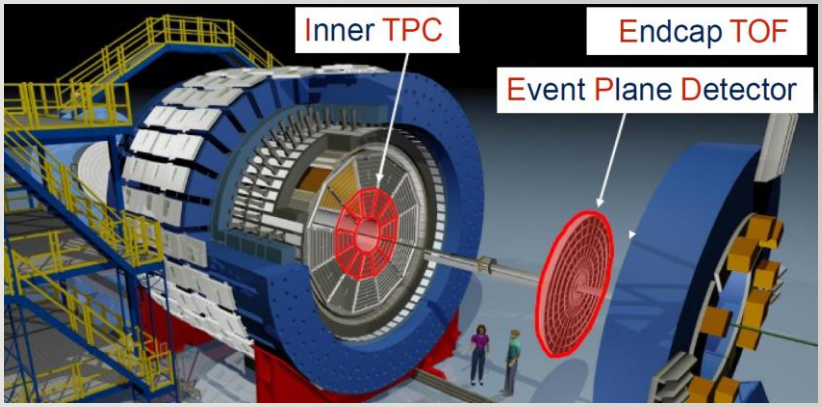
- Collision experiments: acceptance independent of energy
- BES-I: 7.7-200 GeV; BES-II: 7.7-19.9 GeV, increased luminosity
- Small system scan: x+Au, 19.6-200 GeV
- STAR fixed target mode: down to 3 GeV

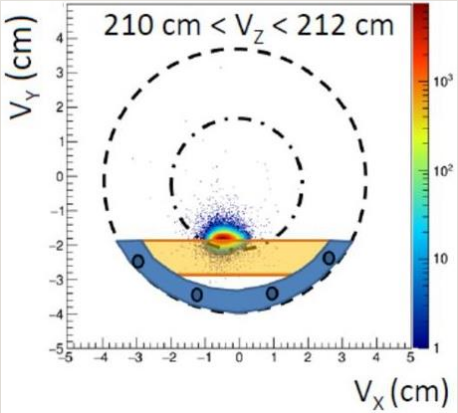
$\sqrt{s_{NN}}$ [GeV]	STAR Au+Au events [10^6]	PHENIX Au+Au events [10^6]	Year
200.0	2000	7000	2010
62.4	67	830	2010
54.4	1300	-	2017
39.0	130	385	2010
27.0	70	220	2011
19.6	36	88	2011
14.5	20	247	2014
11.5	12	-	2010
7.7	4	1.4	2010

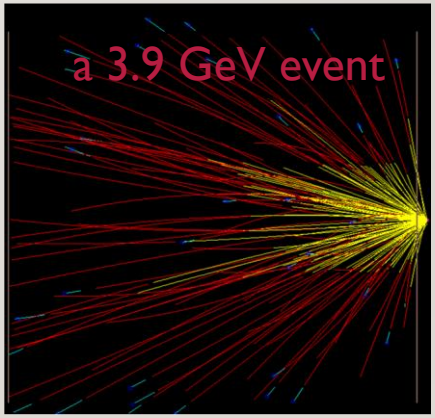
$\sqrt{s_{NN}}$ [GeV]	PHENIX events [10^6]	Species
200.0	2.2	p+Au
200.0	1600	^{3}He+Au
200.0	2057	d+Au
62.4	1655	d+Au
39.0	2000	d+Au
19.6	1040	d+Au

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 mom. res.
  - Event Plane Detector: replace BBC, better triggering & EP resolution
  - Endcap TOF: extended fwd PID
- Fixed target program: to reach lower energies
  - 1 cm wide, 1mm thick target at 2.1 m
  - Collider: $\sqrt{s_{NN}} = E_{beam} + E_{beam}$ Fixed target: $\sqrt{s_{NN}} = \sqrt{2 \cdot M_p \cdot E_{beam}}$ (here E_{beam}: per nucleon)
  - At the lowest energies: out to $\mu_B > 700$ MeV







FIXED TARGET BARYOCHEMICAL POTENTIALS

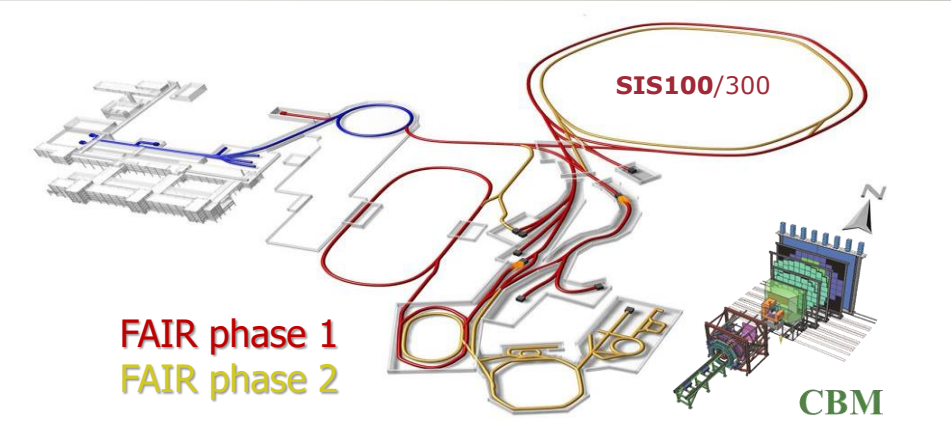
- Collider: $\sqrt{s_{NN}} = E_{\text{beam}} + E_{\text{beam}}$ Fixed target: $\sqrt{s_{NN}} = \sqrt{2 \cdot M_p \cdot E_{\text{beam}}}$

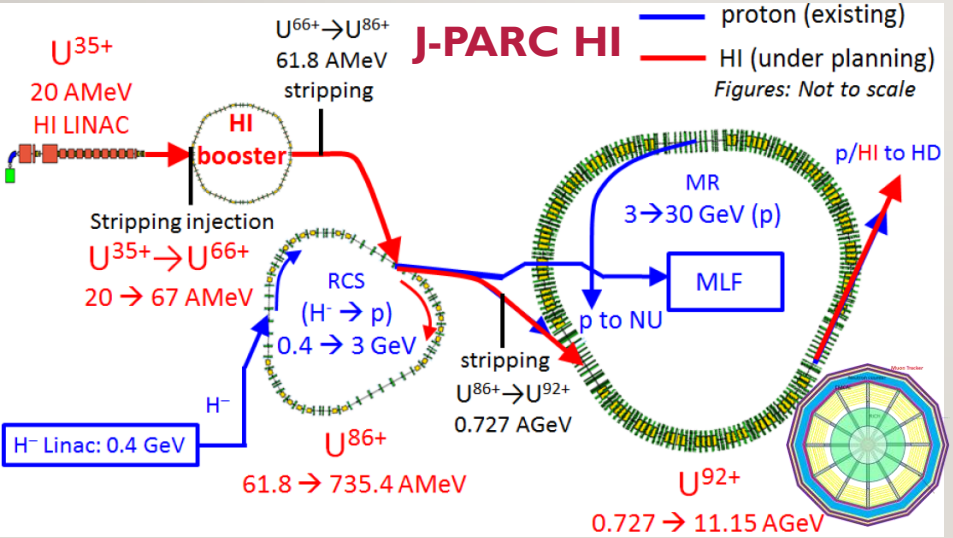
Collider Energy [GeV]	Single beam energy [GeV]	Fixed target c.m. energy[GeV]	Beam rapidity	μ_B (MeV)
200.0	100.00	13.71	2.10	260
62.4	31.20	7.74	2.10	420
39.0	19.50	6.17	1.87	487
27.0	13.50	5.19	1.68	541
19.6	9.80	4.47	1.52	589
11.5	5.75	3.53	1.25	666
9.1	4.59	3.20	1.13	699
7.7	3.85	2.98	1.05	721

- Energies unreachable in collider mode
- Chemical potentials reachable by RHIC in collider mode: 20-420 MeV
- Chemical potentials in fixed target mode: 420-721 MeV
- LHC: ~0.5-1 MeV

37/70 FUTURE FACILITIES: NICA, FAIR, J-PARC HI

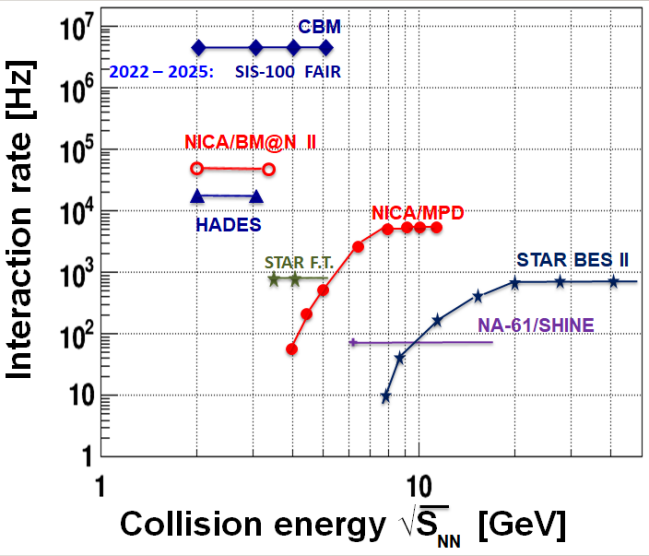
- New facilities planned/built
- NICA: 2020, MPD&BM@N
- FAIR: 2022, CBM
- J-PARC HI: 2025, JHITS





(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 Evkidomiv:

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

SUMMARY OF ACCELERATORS & EXPERIMENTS

- Big Bang ”recreated” in high energy heavy ion collisions
- Timeline: hard processes, thermalization, liquid phase, freeze-outs
- Most energetic collider: LHC
- Experiments observe millions of collisions per second
- Most versatile collider: RHIC
- Beam energy scan program performed
- Current and future facilities to explore phase diagram

40 OBSERVATIONS & PHENOMENOLOGY

Nuclear modification & jets

Elliptic flow and hydro behavior

Heavy flavors and viscosity

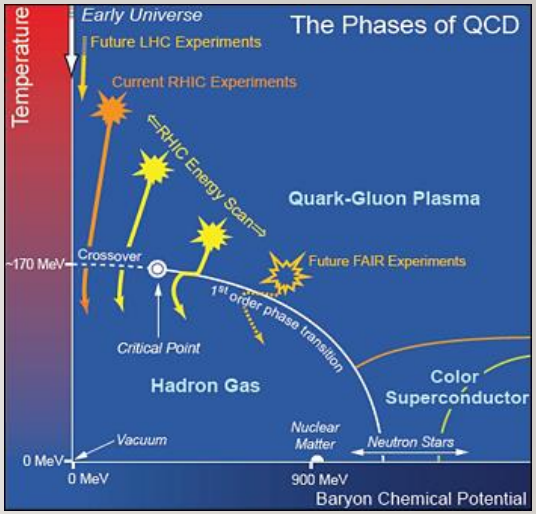
Thermal photons and quark number scaling

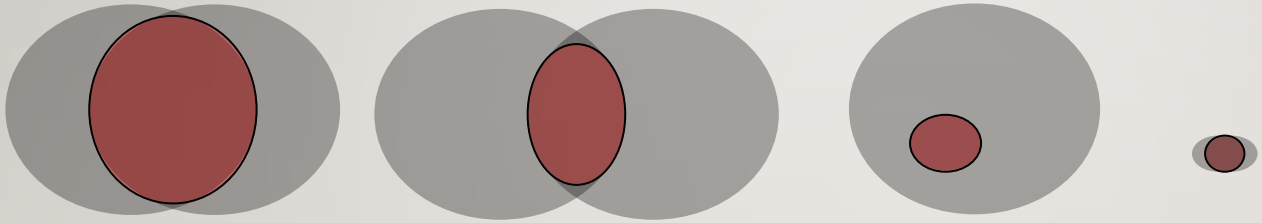
Bose-Einstein correlations

Critical point observables

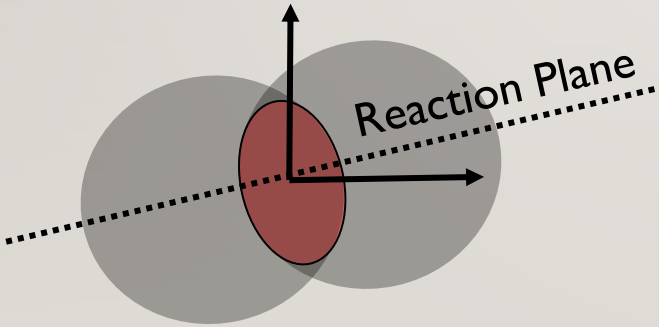
EXPERIMENTAL CONTROL PARAMETERS

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

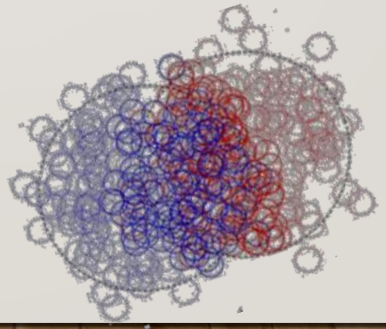




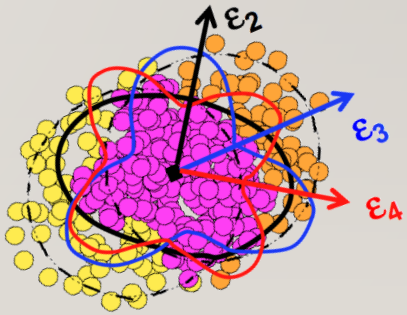
Central Au+Au N_{part}~300 | Peripheral Au+Au N_{part}~50 | d+Au | p+p



Reality



Multipole event planes



IMPORTANT KINEMATIC QUANTITIES

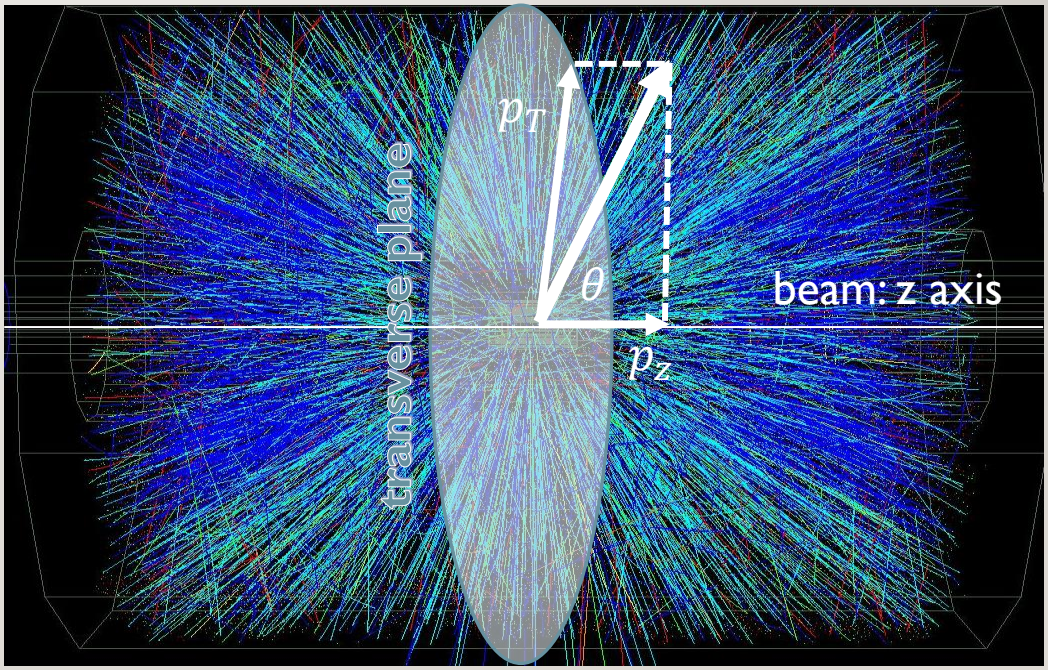
- Particle four-momentum: $p = (E, p_x, p_y, p_z)$
- Beam direction: z; transverse plane: perpendicular to z: (x,y) coordinates
- Transverse momentum: $p_T = \sqrt{p_x^2 + p_y^2}$; transverse mass: $m_T = \sqrt{m^2 + p_T^2}$
- Spherical coordinates:

  $p_x = p_T \cos\phi, p_y = p_T \sin\phi$

  $p_T = |p| \sin\theta, p_z = |p| \cos\theta$
- Rapidity:

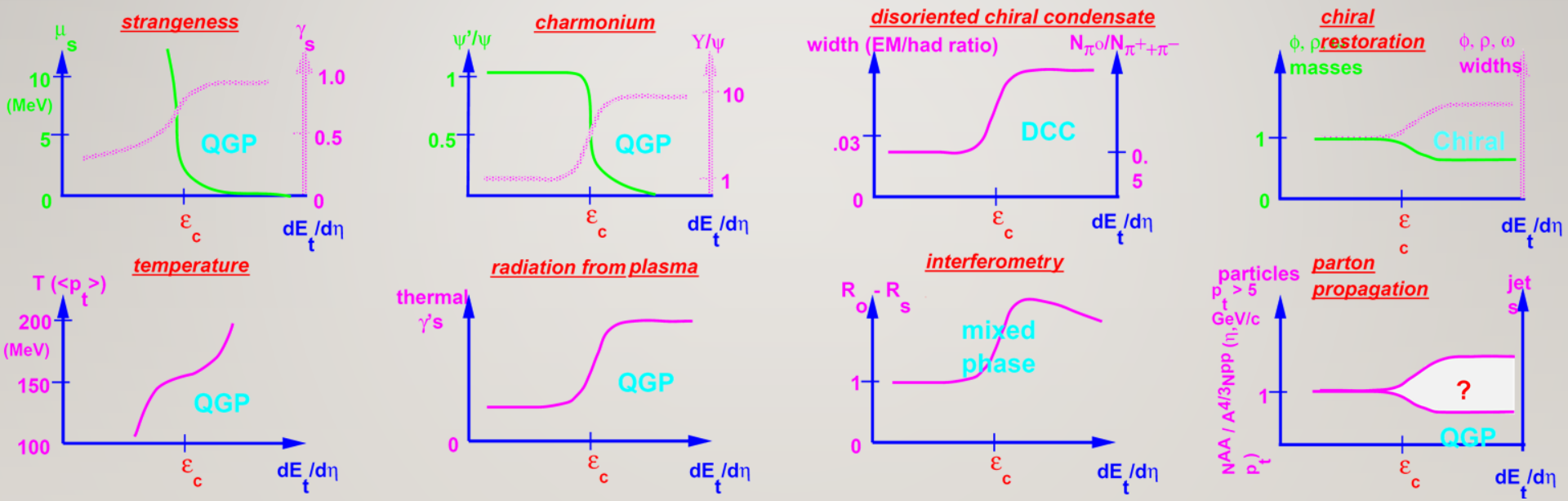
  $$y = 0.5 \ln \frac{E+p_z}{E-p_z} = \operatorname{atanh} \frac{p_z}{E}$$
- Pseudorapidity:

  $$\eta = 0.5 \ln \frac{|p|+p_z}{|p|-p_z} = -\ln \operatorname{tg} \frac{\theta}{2}$$



43/70 QGP SIGNATURES EXPECTATIONS, 1996

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

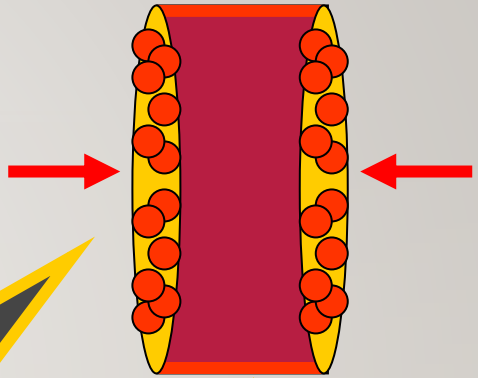


J. Harris & B. Mueller, „The Search for the QGP", Ann.Rev.Nucl.Part.Sci. 46 (1996) 71 [hep-ph/9602235]

44/70 NUCLEAR MODIFICATION: TOMOGRAPHY!

proton+proton

nucleus+nucleus



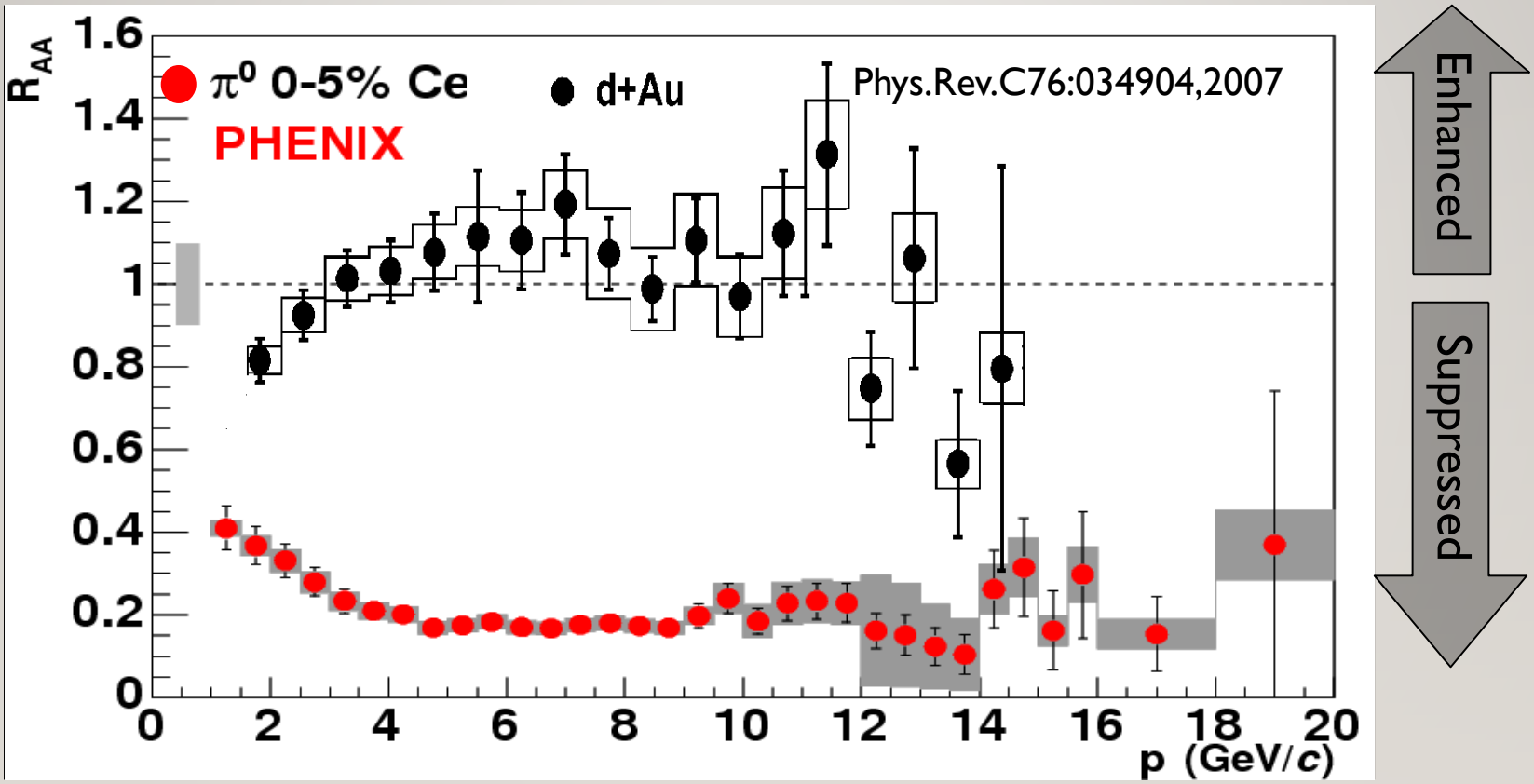
Simply just more?
A+A = many p+p?

$$R_{AA} = \frac{\text{High } p_T \text{ particle yield in A+A}}{\text{High } p_T \text{ particle yield in p+p} \times \text{Number of p+p collisions}}$$

If $R_{AA} \neq 1$: sign of nuclear modification

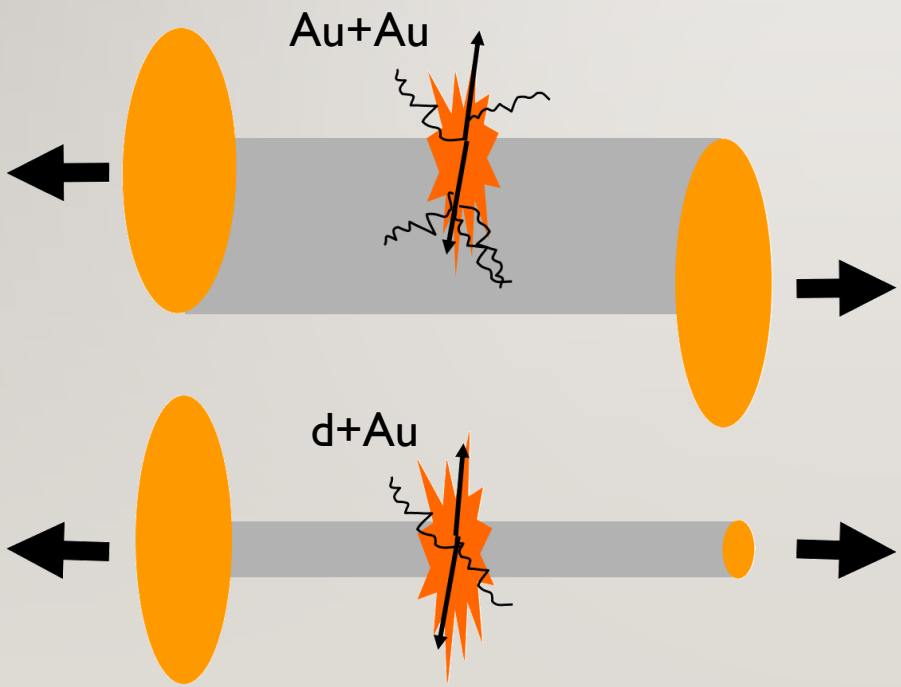
45/70 SUPPRESSION AS A FUNCTION OF CENTRALITY

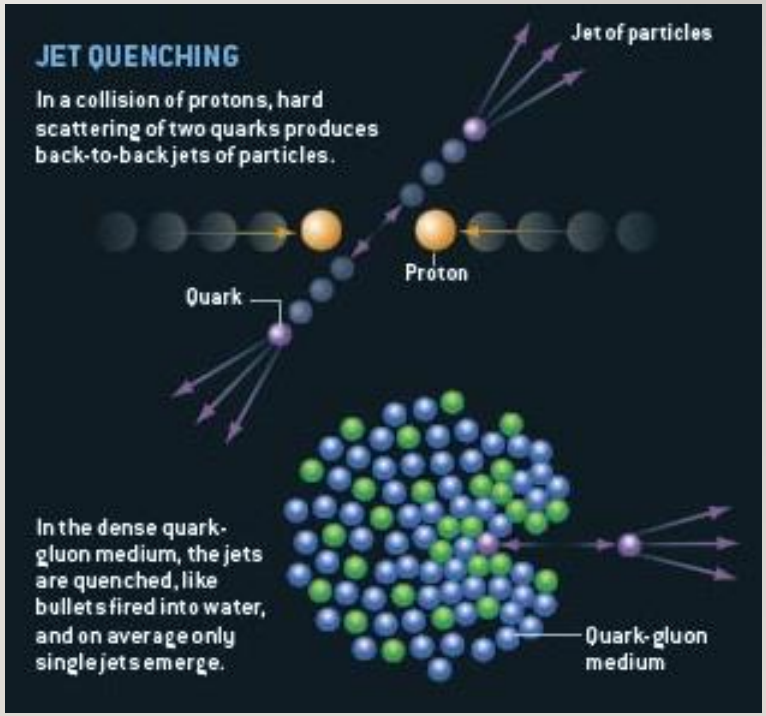
- No suppression in d+Au or peripheral Au+Au; strong suppression in central!



CONTROL EXPERIMENT: D+AU COLLISIONS

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

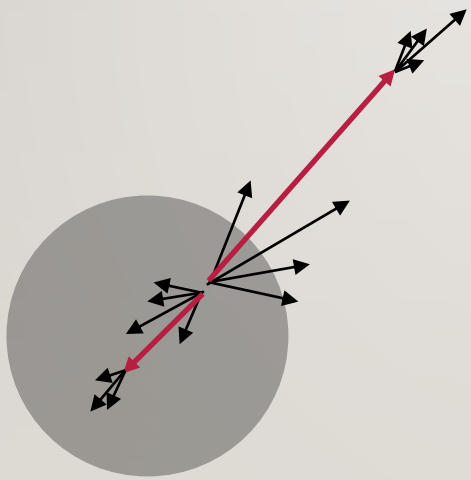


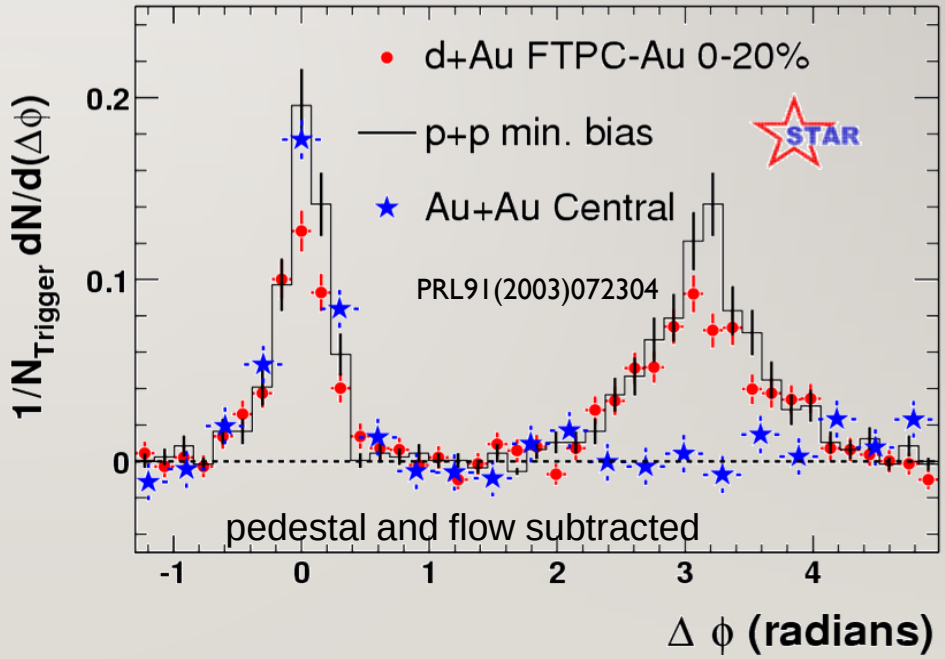


Zajc, Riordan, Scientific American

SUPPRESSION OF THE AWAY SIDE JET

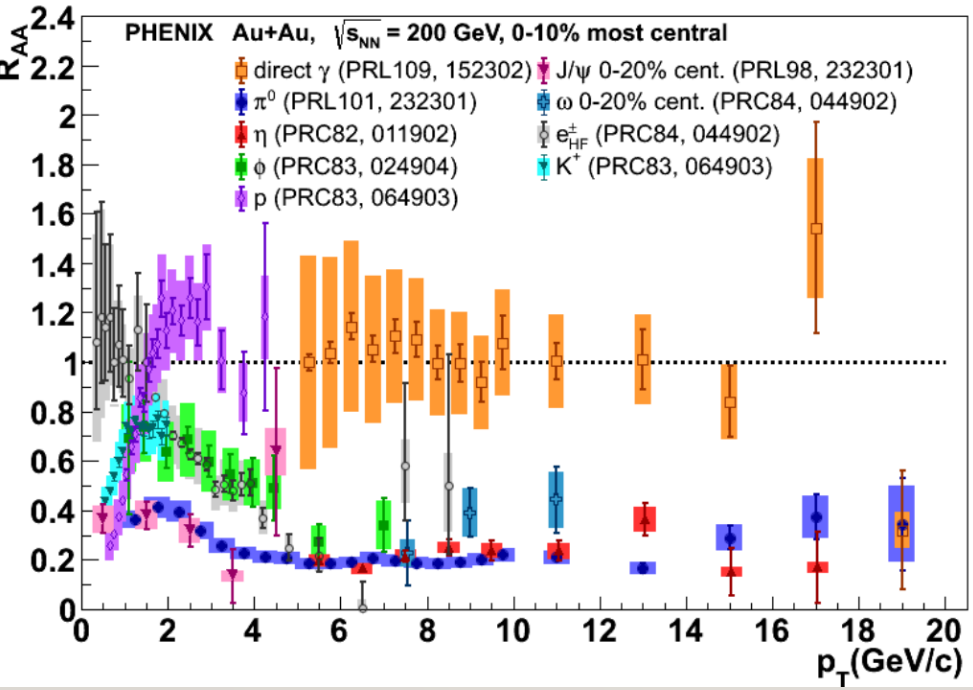
- Angular correlation of high energy hadrons
- Outgoing jet: similar in p+p, d+Au, Au+Au
- Inward going (away side) jet: missing in central Au+Au

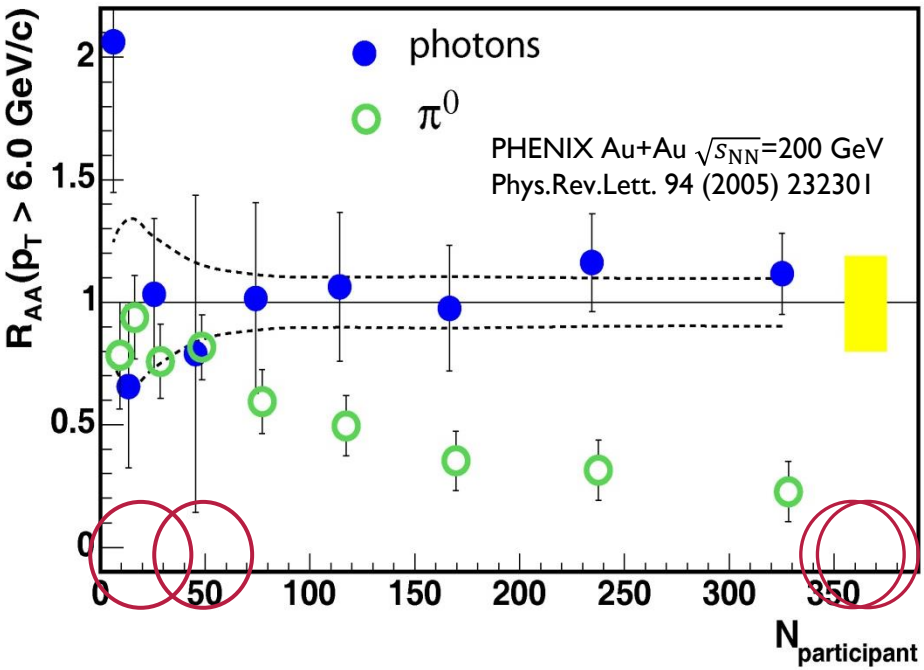




HOW DO OTHER PARTICLES BEHAVE?

- All hadrons suppressed, after 4-6 GeV/c transverse momentum
- Direct photons „shine through”

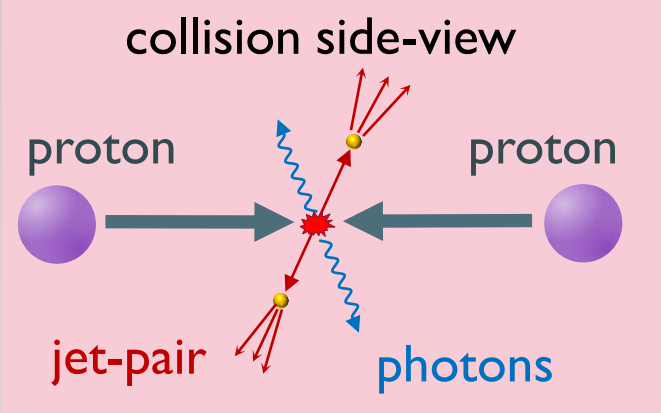


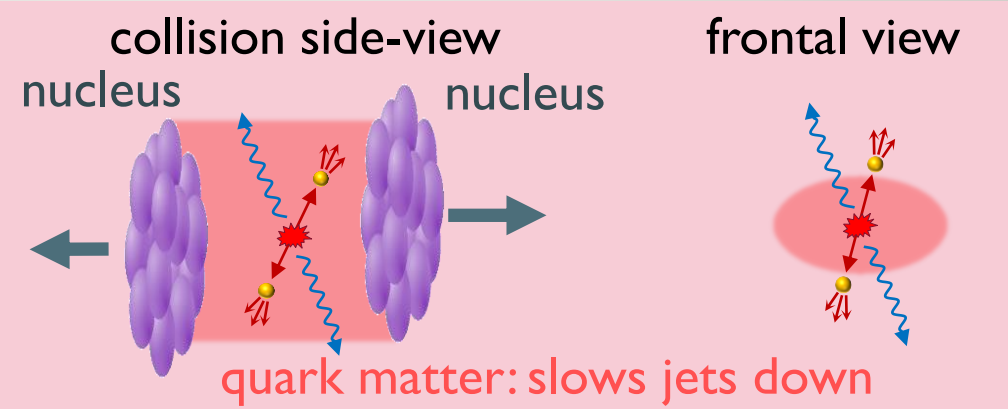


- Suppression dependent of system size (controlled by centrality or N_{part})

STRONGLY INTERACTING MEDIUM

- Collsion → extremely energetic colored particles, jets
- Nucleus-sized medium: slows down jets
- Does not affect photons: strongly interacting matter!

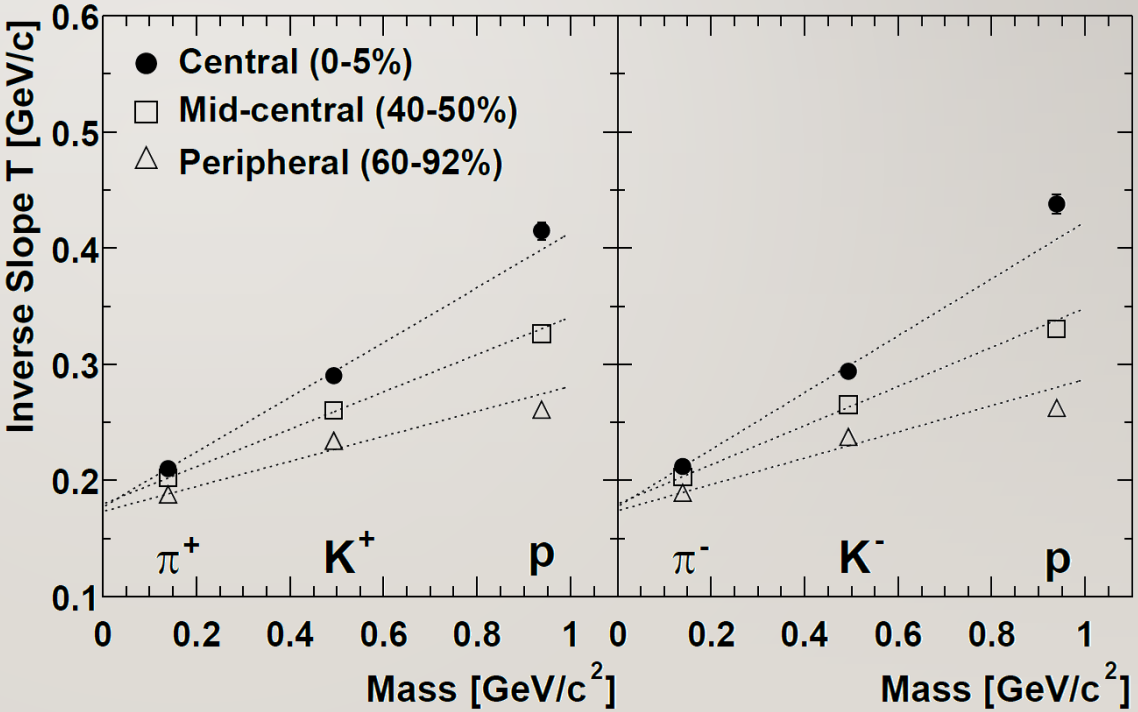




- Comparision of suppression strength:
  - Gamma radiation in lead: few cm distance
  - Alpha radiation in water: 0.001 cm distance
  - Jets in quark matter: 0.0000000000001 cm

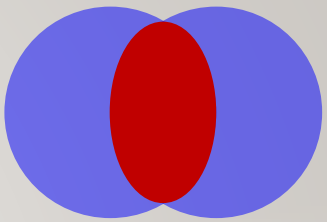
HYDRODYNAMICAL SCALING

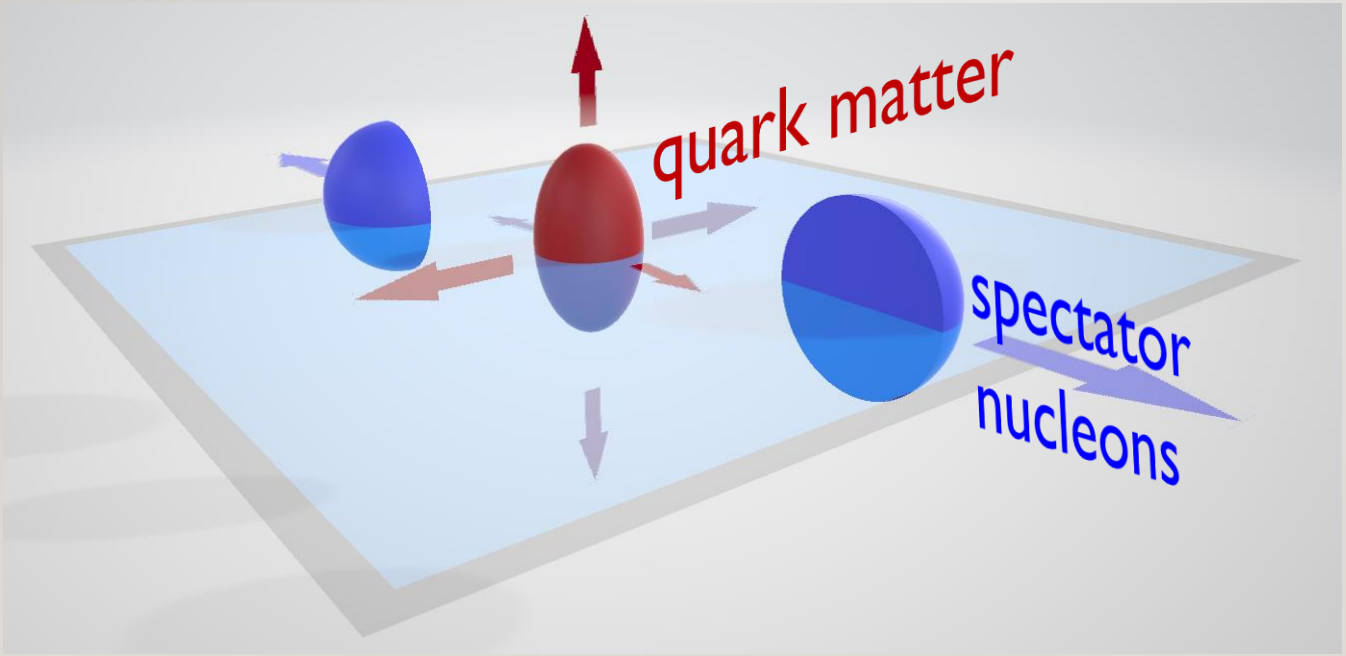
- Large cross-sections, many collisions, early thermalization
- Thermalization timescale: ~1 fm/c
- Measured hadron spectra Boltzmannian: $\exp(-E/T_{eff})$
- Effective temperature: T_{eff}: due to expansion ≠ temperature
- Simple hydro model: $T_{eff} = T + m \cdot u^2$
- Experimental confirmation
- General observation: thermalization & hydro creates scaling

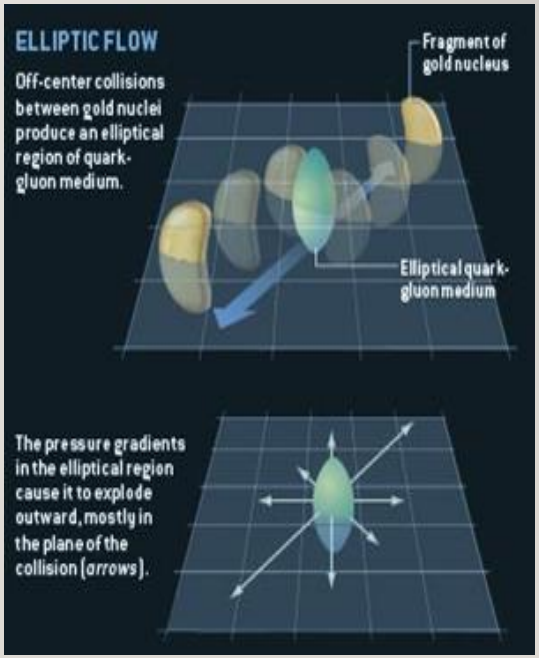


HYDRO BEHAVIOR

- Collision (participant) zone: almond shape (ellipsoid)
- Residual (spectator) nucleons: continue flight
- Created medium: collision-like expansion
- If fluid: pressure anisotropy → expansion asymmetry

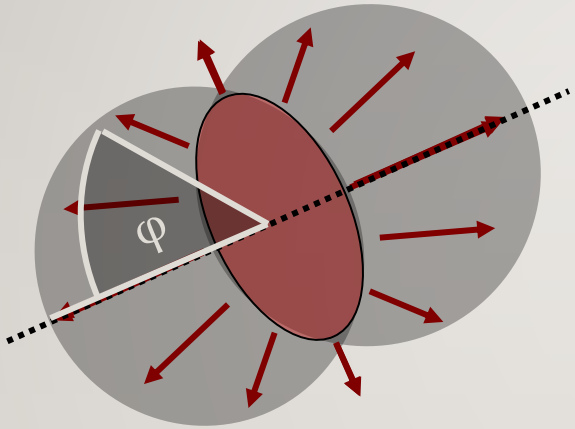


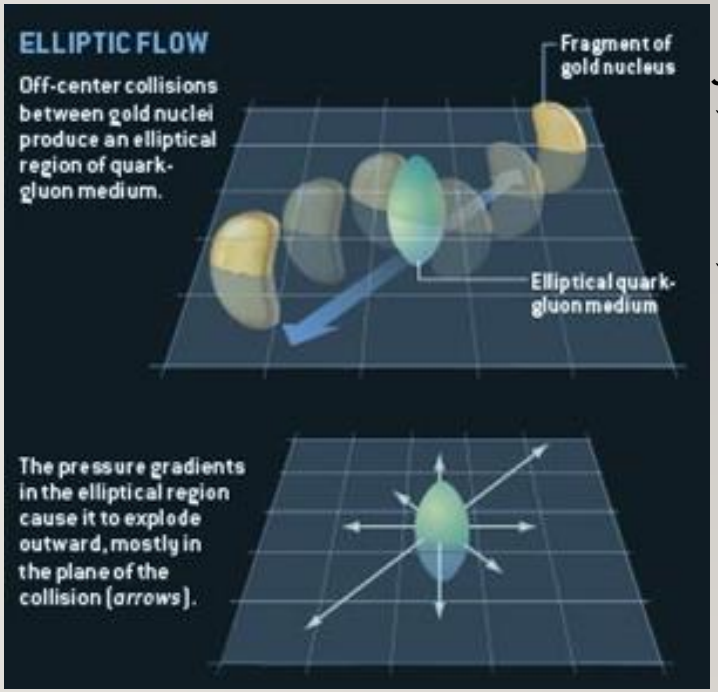




OBSERVATION OF THE ELLIPTIC FLOW

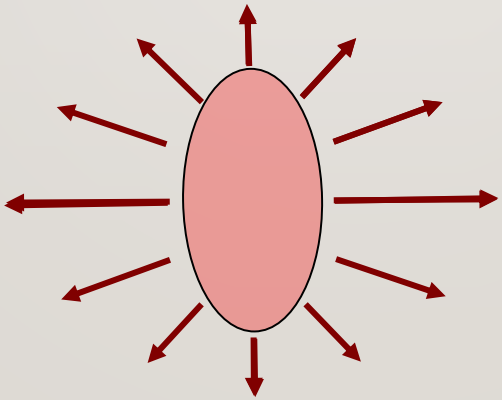
- Initial spatial anisotropy creates momentum-space anisotropy!

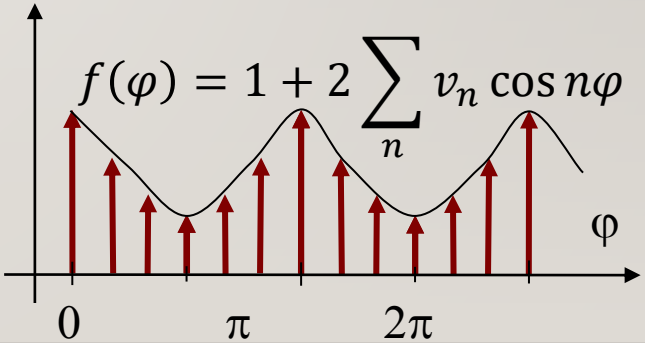




Zajc, Riordan, Scientific American

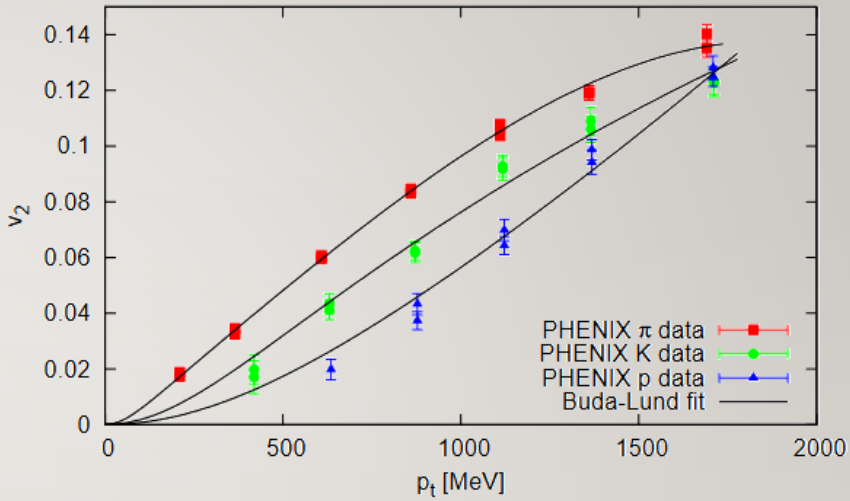
- Quantified via anisotropy parameters

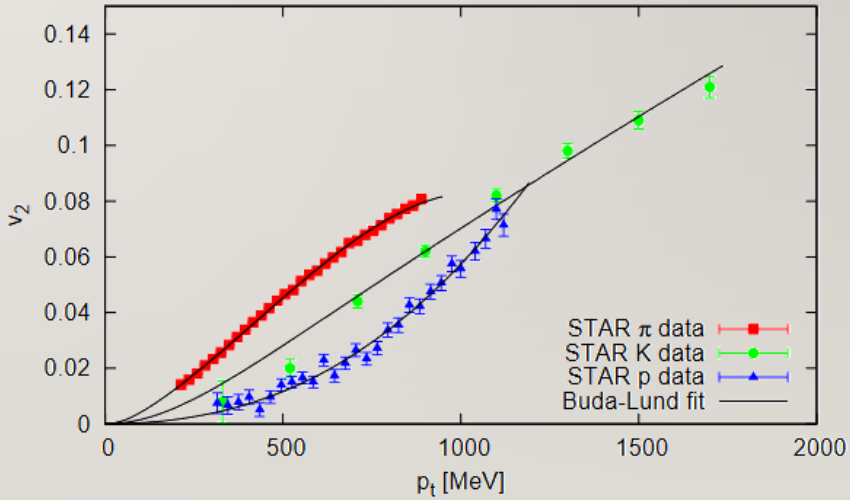




ELLIPTIC FLOW MEASUREMENTS VS THEORY

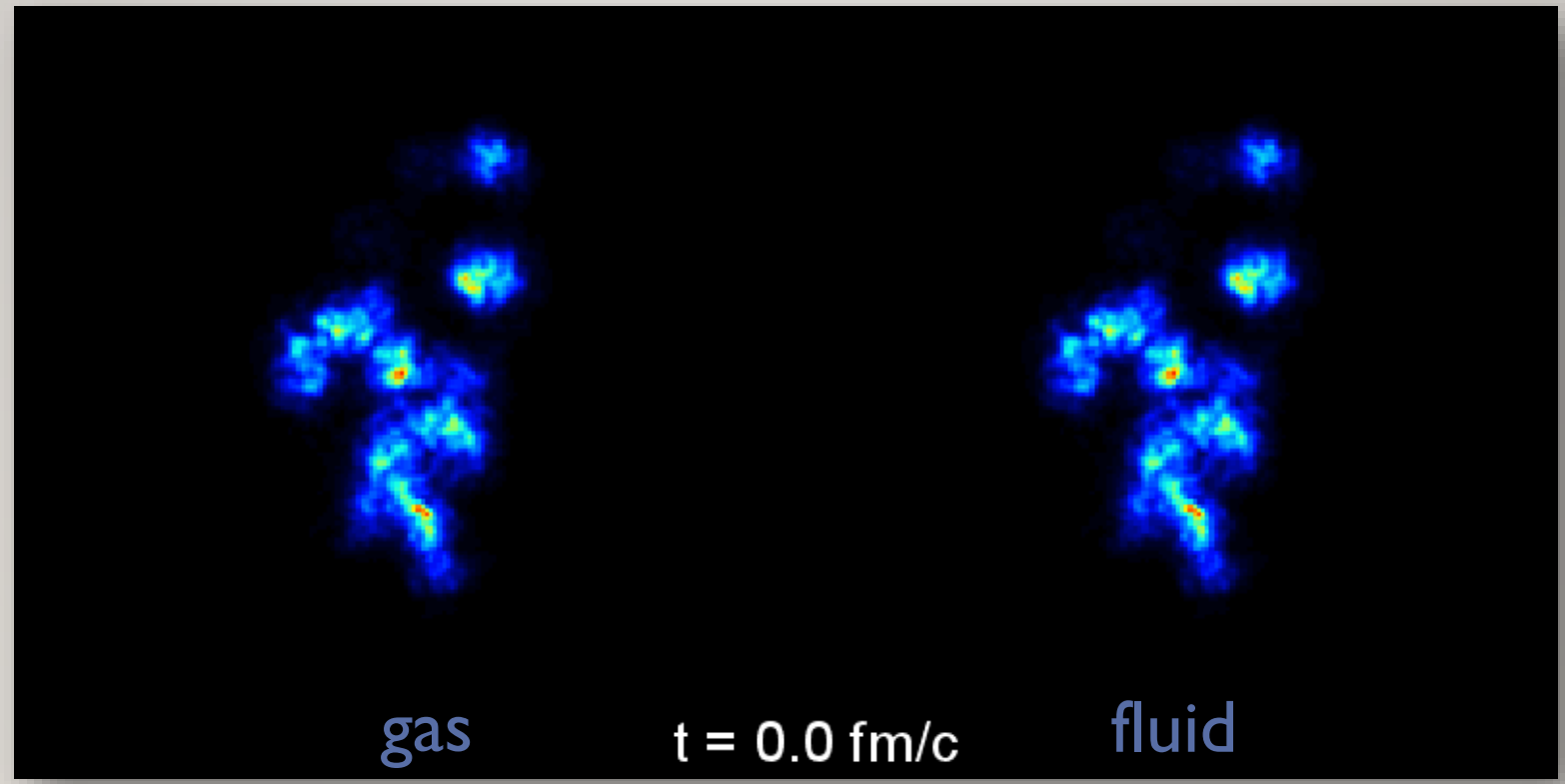
- Elliptic flow (v_2) nonzero ⇒ collective effect
  - Initial spatial anisotropy turning into final state momentum anisotropy
- Concrete measured values: can be described by hydro models
  - In this case, the Buda-Lund model
    Csanád, Csörgő, Lörstad, Nucl.Phys.A 742 (2004) 80
- Data and hydro match up to ~2 GeV
- Above that, hard processes, jets dominate results
  - To be described by perturbative QCD





HYDRO BEHAVIOR

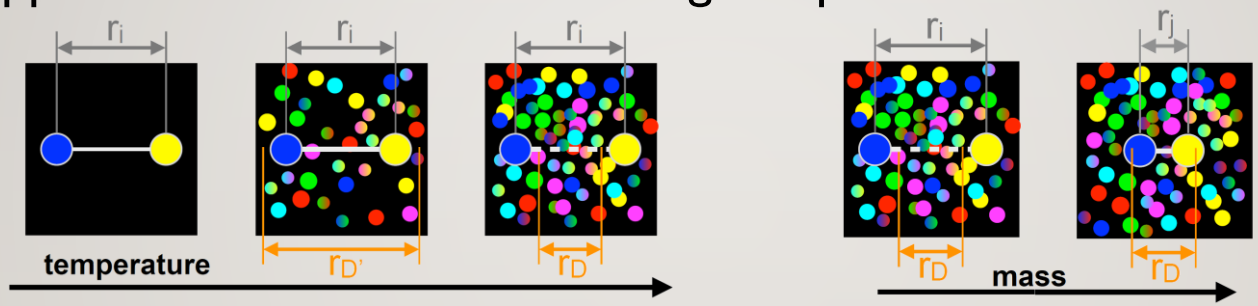
- Distributions of observed hadrons: proves hydro behavior

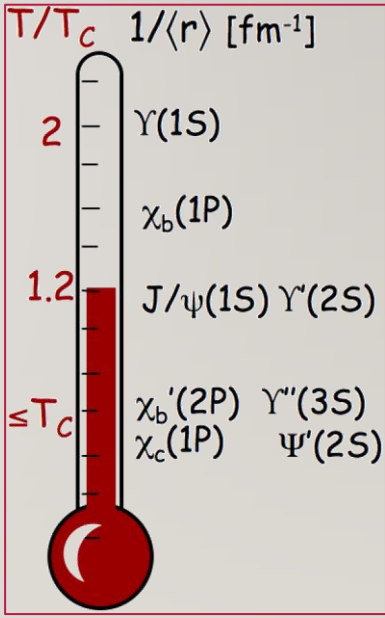


- Timescale of the above plot: fm/c, time of light to traverse a proton
- Gas: free streaming; Fluid: strong interactions

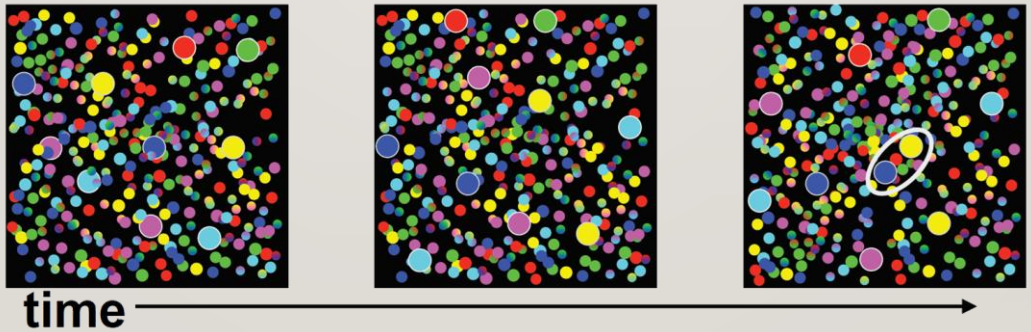
55/70 HEAVY FLAVOR SUPPRESSION & REGENERATION

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





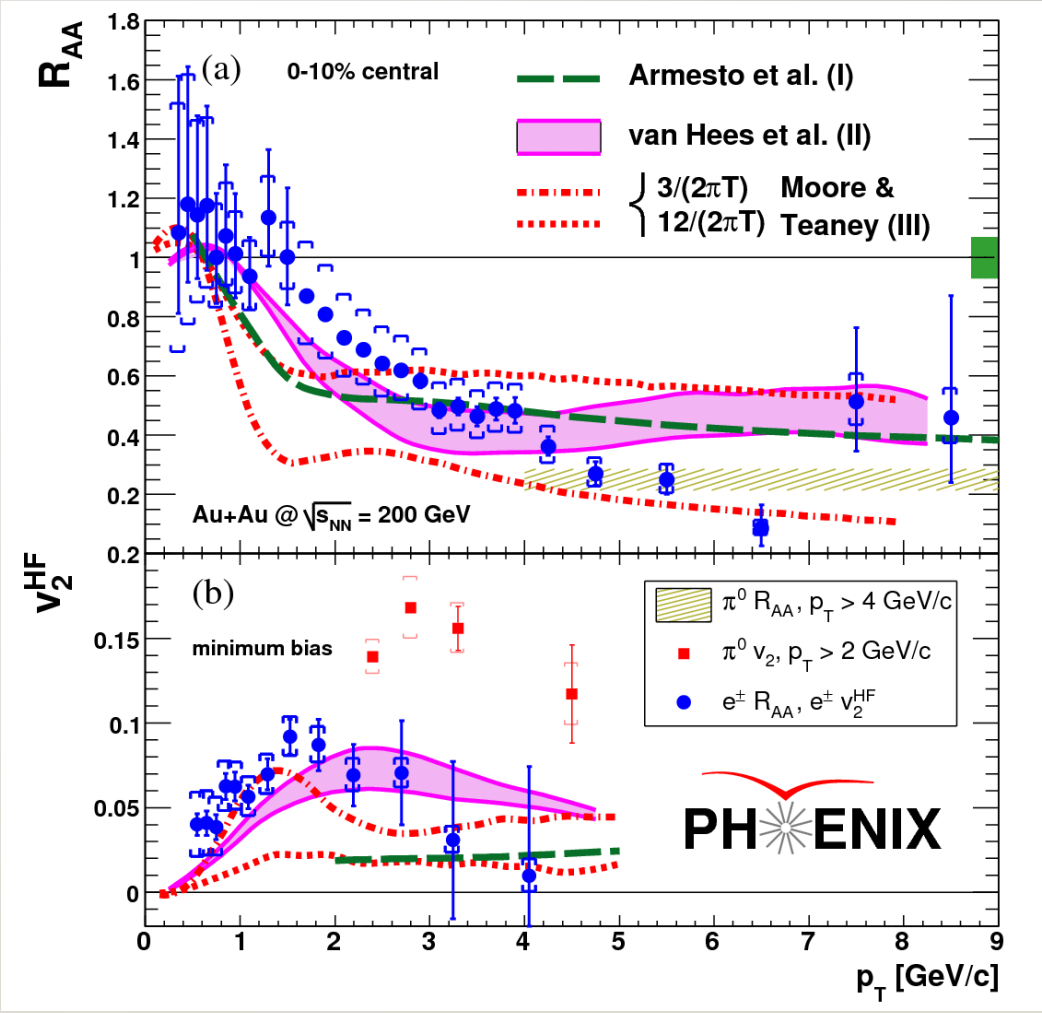
- Statistical regeneration in time:



Images from J Castillo, SQM17 and A Mócsy, HardProbes2009

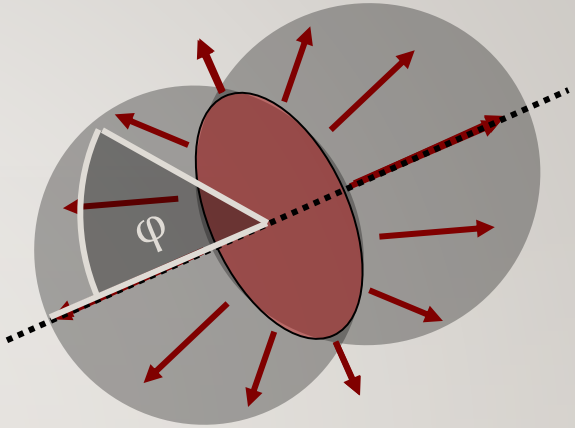
EVEN HEAVY FLAVOR FLOWS!

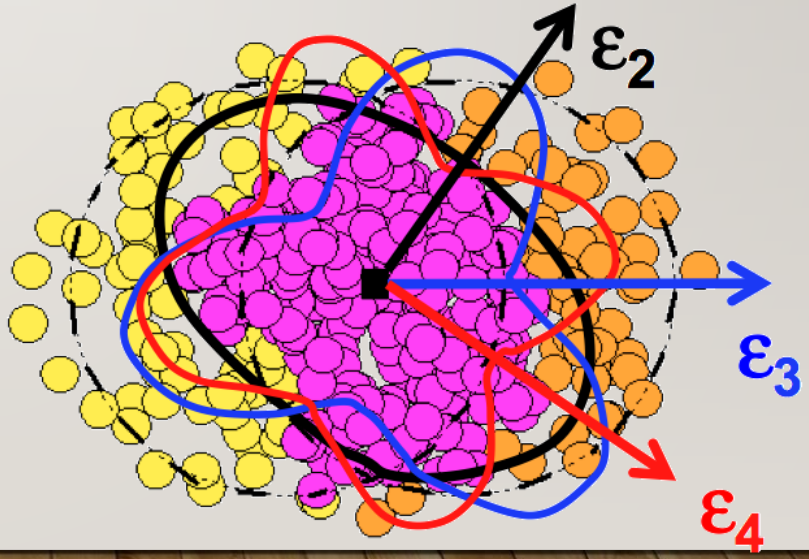
- Electrons from heavy flavor measured
- Even heavy flavor is suppressed
- Even heavy flavor flows
- Strong coupling of charm&bottom to the medium
- Small charm&bottom relaxation time in medium and *small viscosity*



HIGHER ORDER ANISOTROPIES

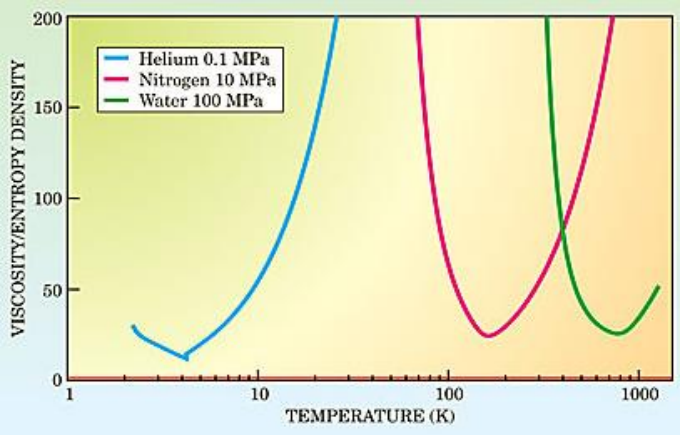
- Created medium is ~ellipsoidal on average
  - With respect to event plane
- In reality: finite number of nucleons
- Single event: fluctuating location of nucleons
- Fluctuating shape of initial fireball
- Various orders of planes defined
  - $\tan \Psi_n = \frac{\Sigma \sin n\phi_i}{\Sigma \cos n\phi_i}$
- Eccentricity of various orders
- Higher order: washed out by viscosity
- If still present: low viscosity

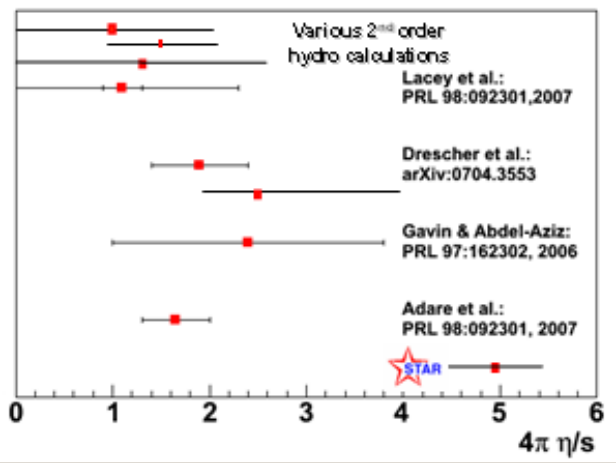




VISCOSITY OF THE SQGP

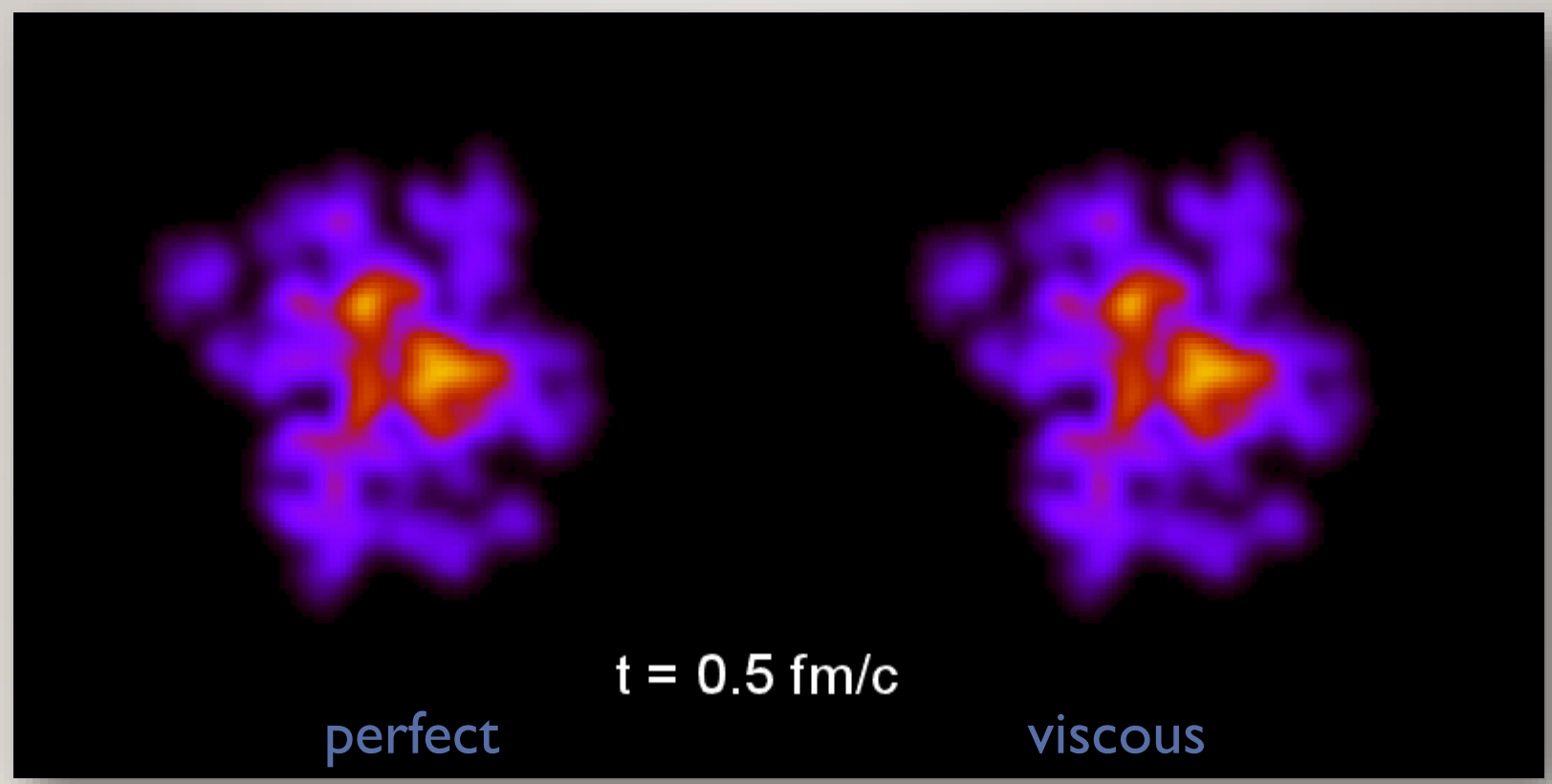
- Viscosity/entropy density: proportional to mean free path
- Strong coupling: small η/s
- AdS_{D+1}/CFT_D lower bound: $\frac{\eta}{s} \geq \frac{\hbar}{4\pi}$
  - Malcadena et al.: Adv.Theor.Math.Phys.2:231-252
  - Kovtun et al.: Phys.Rev.Lett. 94 (2005) 111601
- Measurement and calculation results:
  - 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





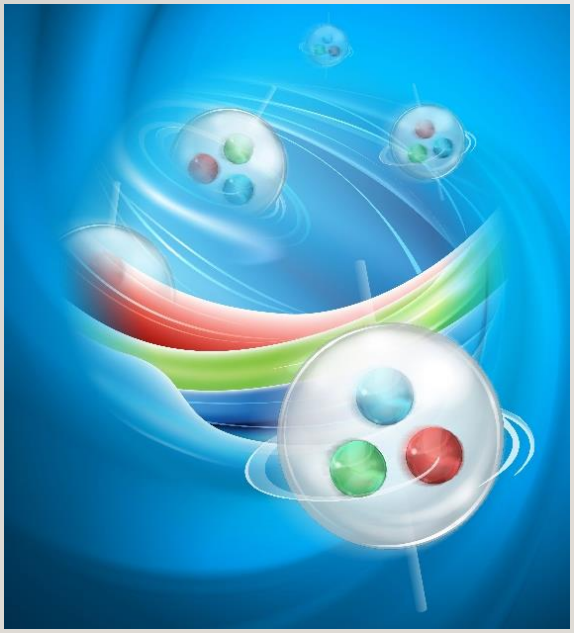
THE PERFECT LIQUID

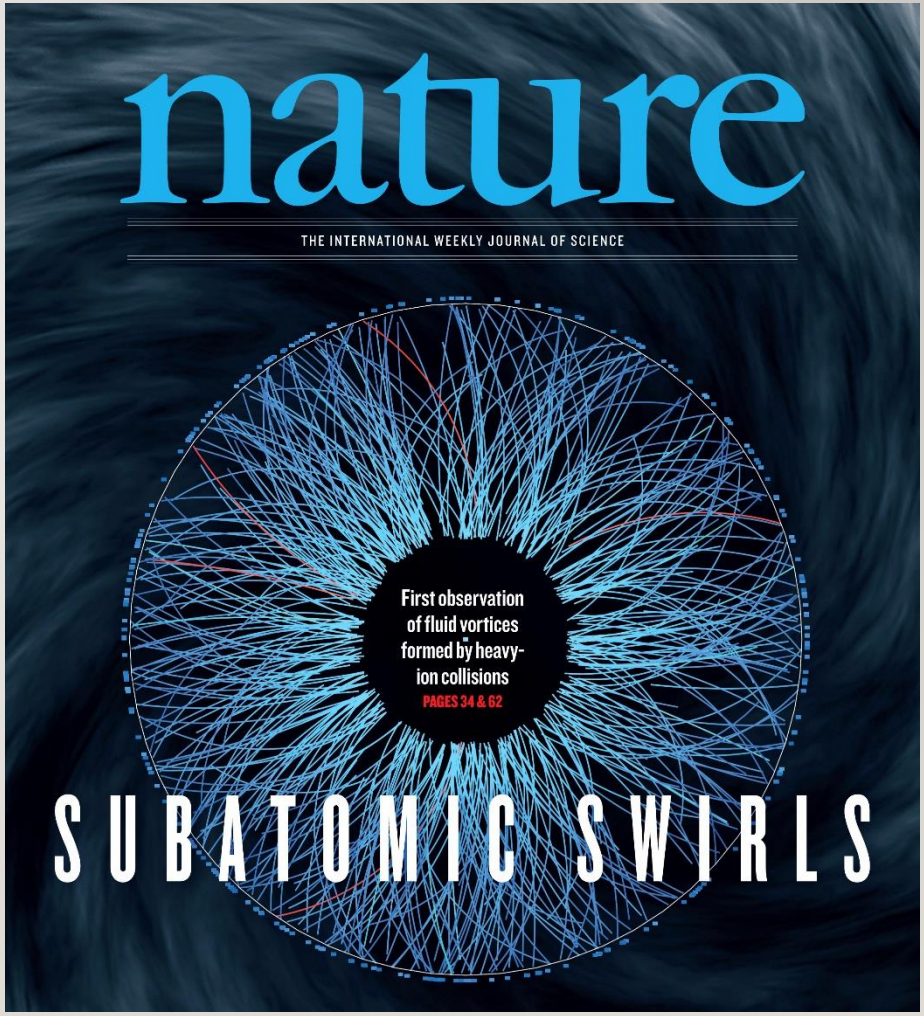
- Viscosity: appearance of shear stress/force
- Viscosity of the sQGP: nearly zero



THE MOST VORTICAL FLUID

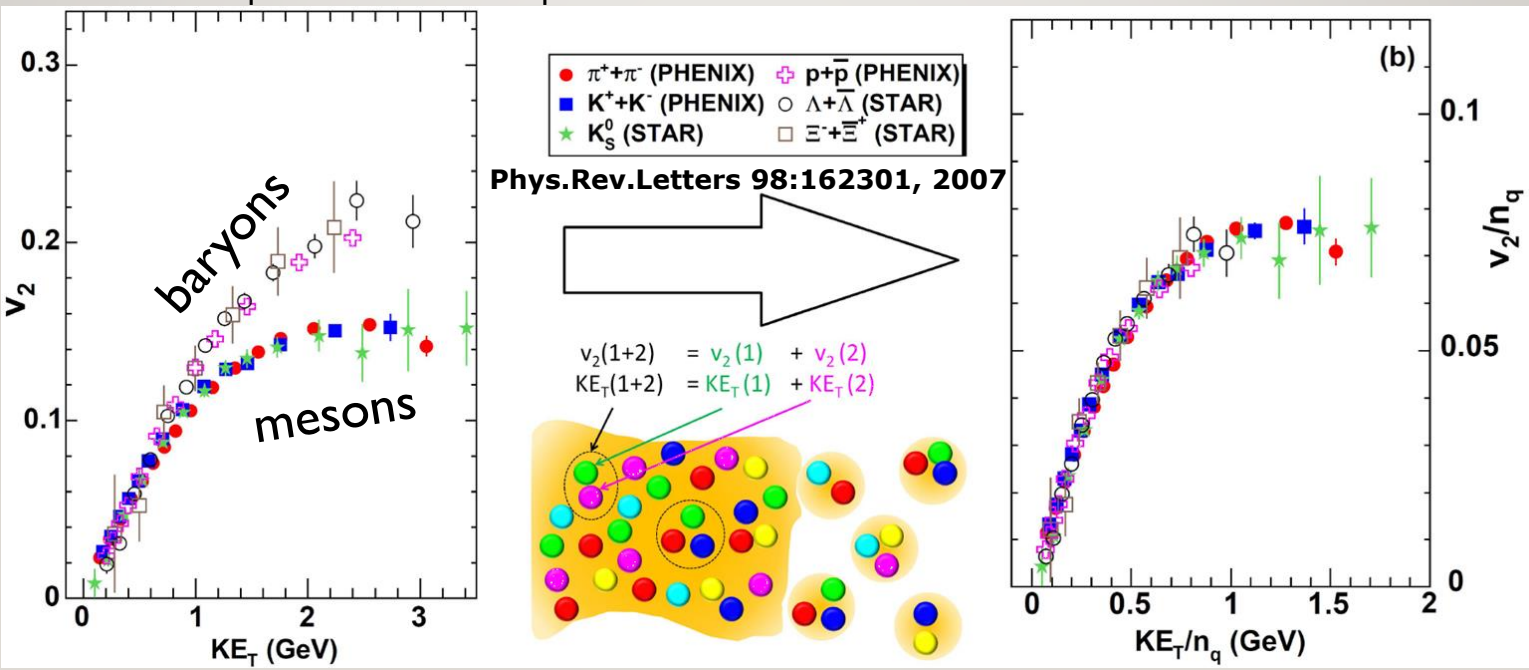
- Measurement: polarization of baryons observable
- Reason: vorticity
- Most vortical fluid ever seen





QUARK DEGREES OF FREEDOM

- Scaling of elliptic flow, when measured versus transverse kinetic energy (KE_T)
- Different particle types: scaling curve depends on valence quark content (n_q)
- Reason: coalescence
- Scaling: v_2/n_q versus KE_T/n_q, baryons = mesons



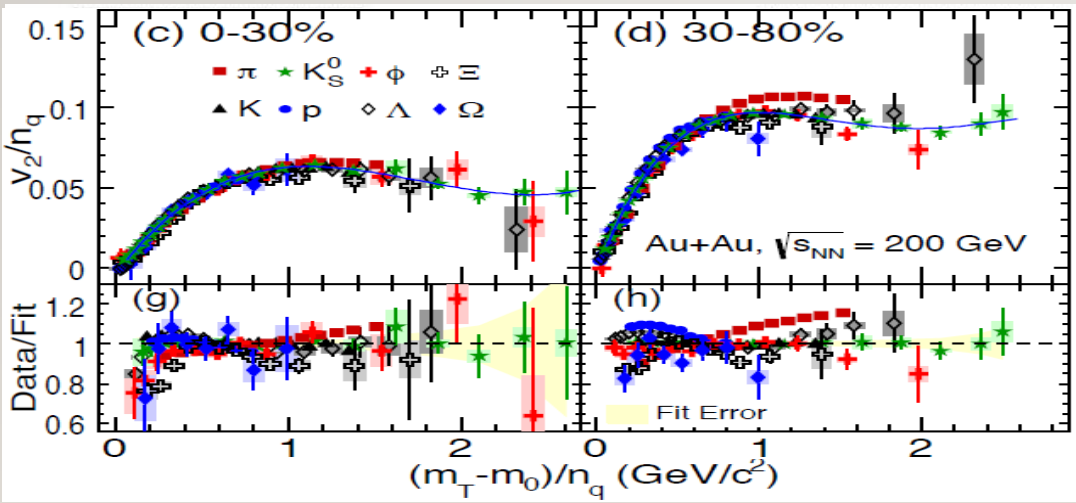
ELLIPTIC FLOW SCALING

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

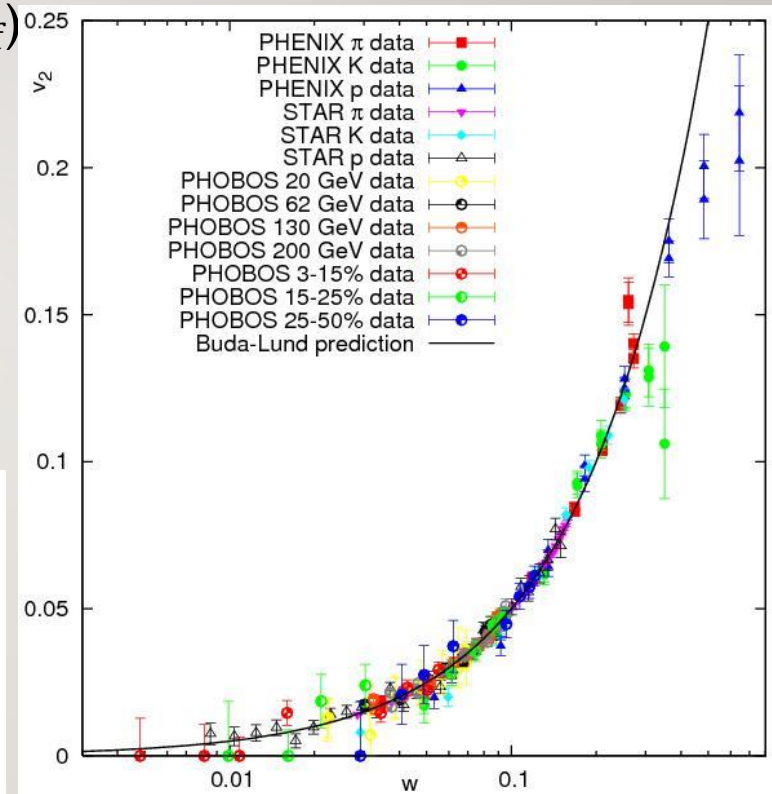
$$E_K^{\mathrm{hadron}} = n_q E_K^{\mathrm{quark}}$$

$$v_n^{\mathrm{hadron}}\left(E_K^{\mathrm{hadron}}\right) \cong \mathrm{n_q} v_n^{\mathrm{quark}}\left(E_K^{\mathrm{quark}}\right)$$

- Flow develops in pre-hadronic stage!



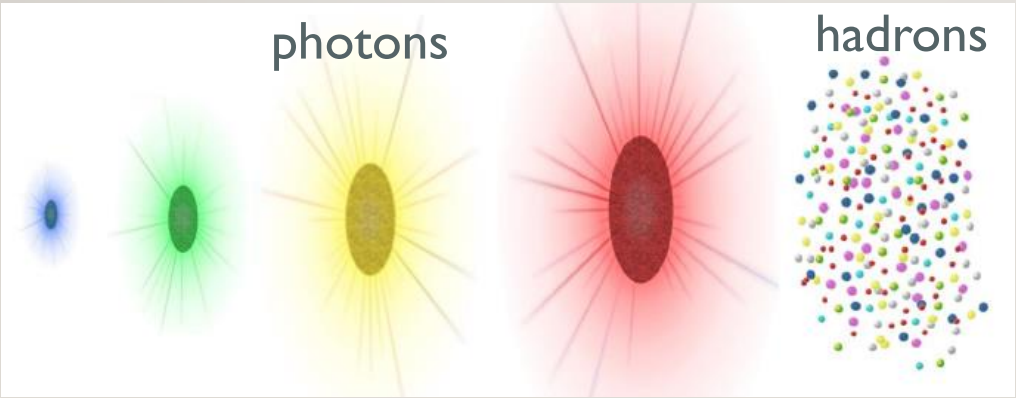
PHENIX, PRL98(2007)162301; STAR, PRL116(2016)62301

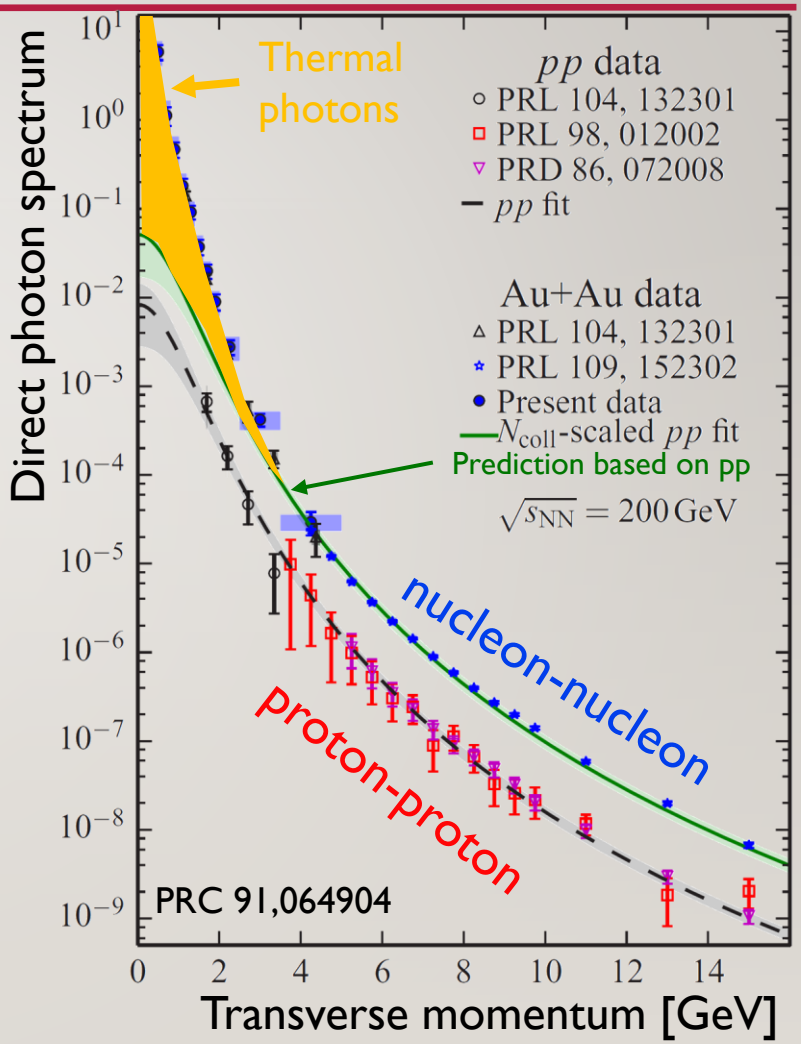


Csanád, Csörgő, Lörstad, Ster (NPA742:80-94,2004)
Csanád, Csörgő, Lörstad, Ster et al. (EPJA38:363-368,2008)

THERMAL PHOTONS

- Hadron creation: after freeze-out
- Direct vs decay photons measured
- Soft component in direct photon spectra: compared to p+p extrapolation
- These are thermal photons!
- Large initial temperature, 3-600 MeV!



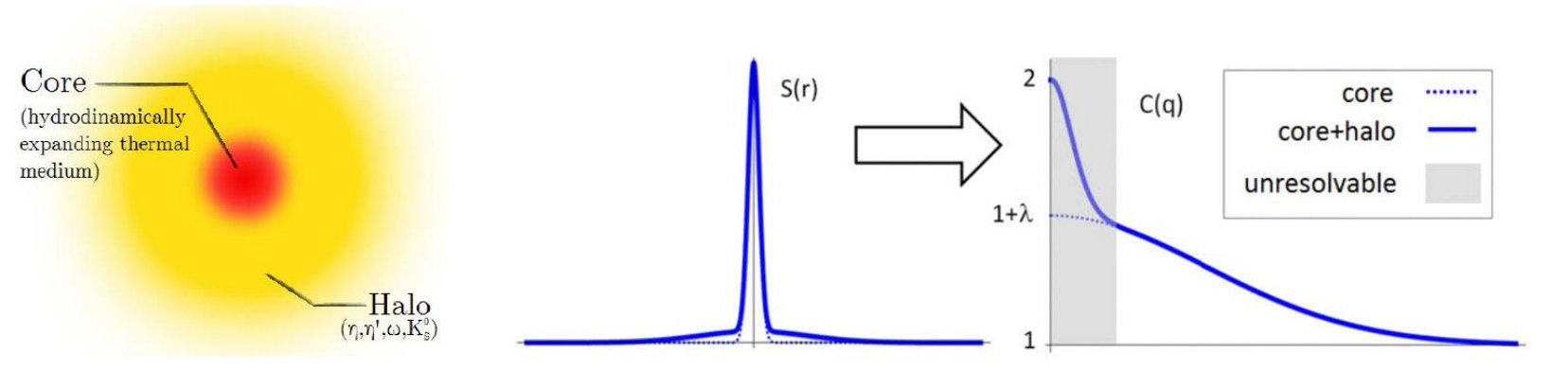


BOSE-EINSTEIN CORRELATIONS

- Quantum statistics connects spatial and momentum space distributions
- Spatial source $S(x)$ versus momentum correlation function $C_2(q)$:

$C_2(q) \cong 1 + \left|\tilde{S}(q)/\tilde{S}(0)\right|^2$, where $\tilde{S}(q) = \int S(x) e^{iqx} d^4x, \quad q = p_1 - p_2$

- Final state interactions distort the simple Bose-Einstein picture
- Coulomb interaction important, handled via two-particle wave function
- Resonance pions: Halo around primordial Core



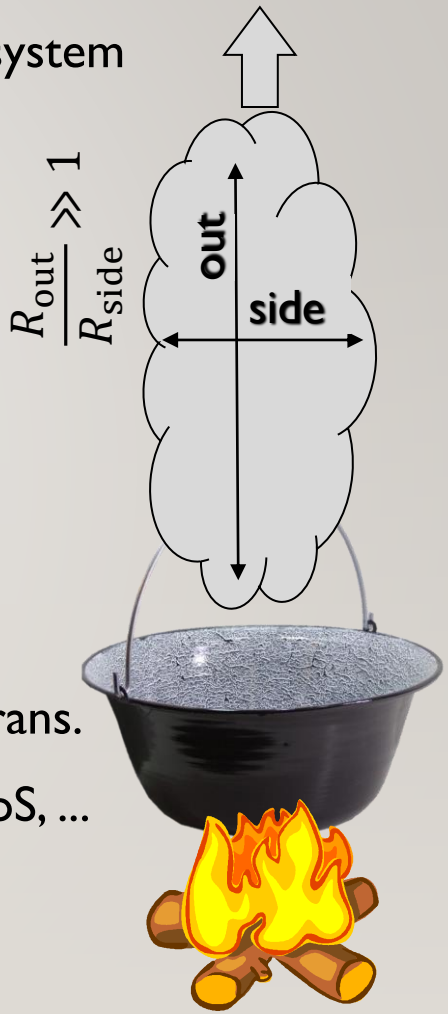
Bolz et al, Phys.Rev. D47 (1993) 3860-3870
Csörgő, Lörstad, Zimányi, Z.Phys. C71 (1996) 491-497

HBT AND THE PHASE TRANSITION

- C(q) usually measured in the Bertsch-Pratt pair coordinate-system
  - out: direction of the average transverse momentum
  - long: beam direction
  - side: orthogonal to the latter two
- R_{out}, R_{side}, R_{long} : HBT radii
- Out-side difference → Δτ emission duration
- From a simple hydro calculation:

$$R_{\mathrm{out}}^2 = \frac{R^2}{1+u_T^2 m_T/T_0} + \beta_T^2 \Delta\tau^2, \qquad R_{\mathrm{side}}^2 = \frac{R^2}{1+u_T^2 m_T/T_0}$$

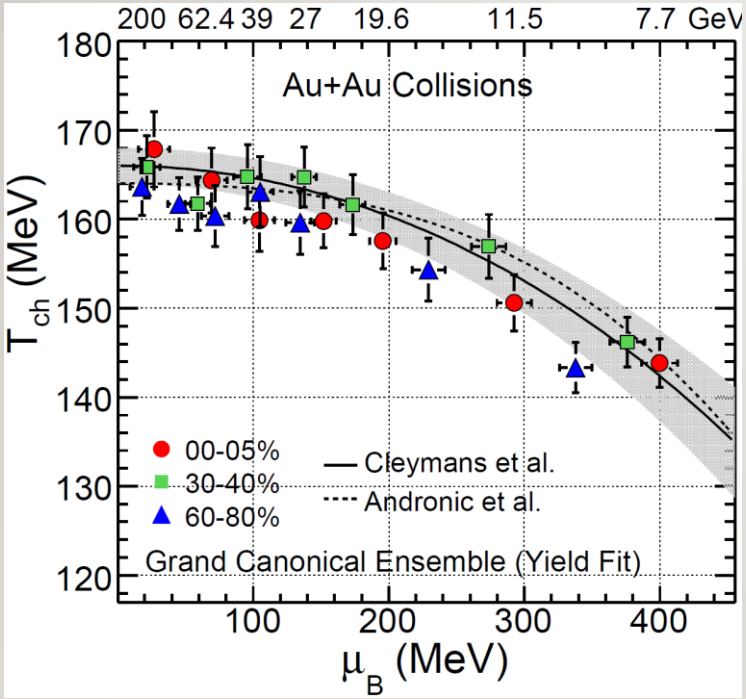
- RHIC, 200 GeV: $R_{\mathrm{out}} \approx R_{\mathrm{side}}$ → no strong 1st order phase trans.
- Plus, lots of other details: pre-equilibrium flow, initial state, EoS, ...

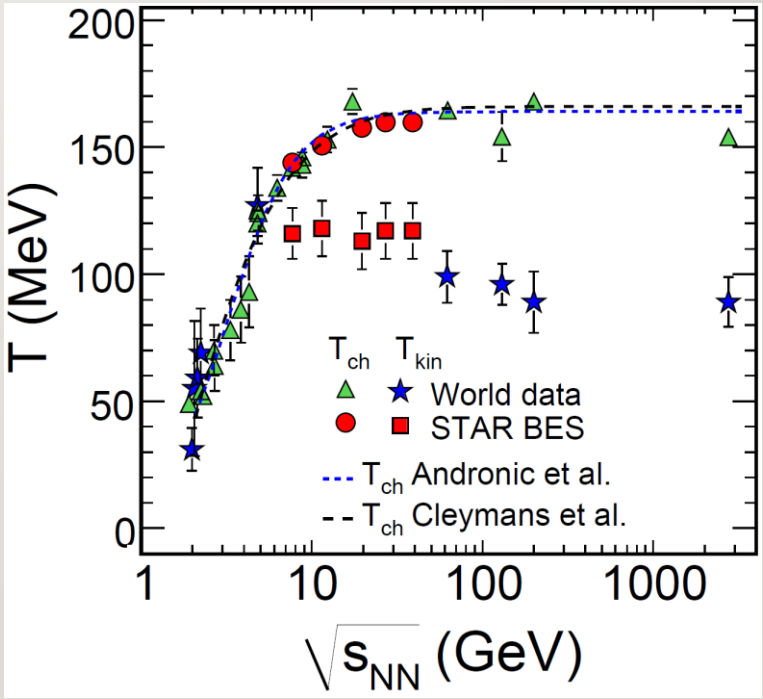


S. Chapman, P. Scotto, U. Heinz, Phys.Rev.Lett. 74 (1995) 4400
T. Csörgő and B. Lörstad, Phys.Rev. C54 (1996) 1390
S. Pratt, Nucl.Phys. A830 (2009) 51C

FREEZE-OUT CURVE 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 GeV, T_{ch} flattens at ~10 GeV

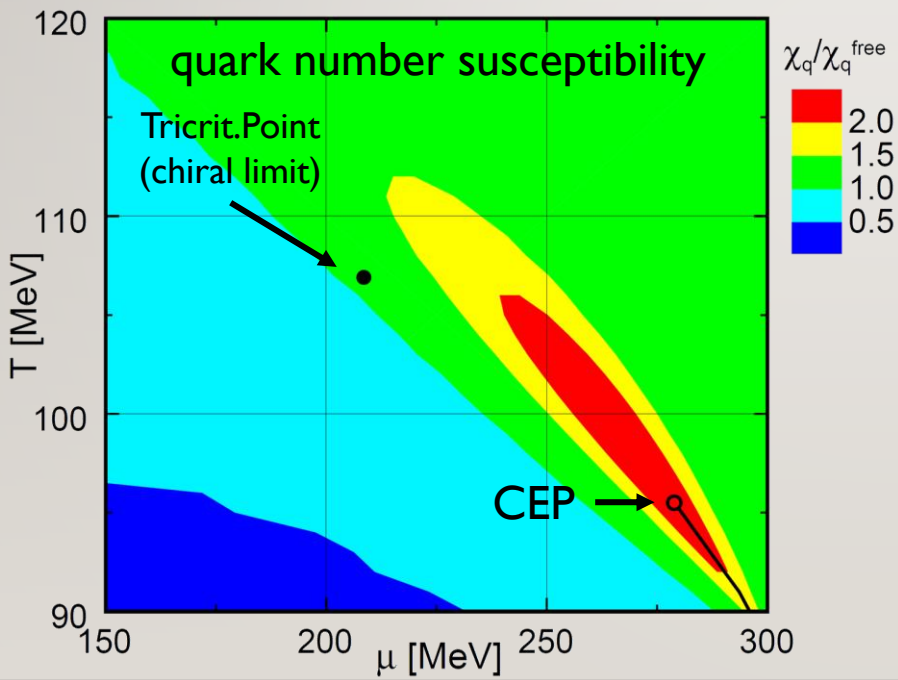


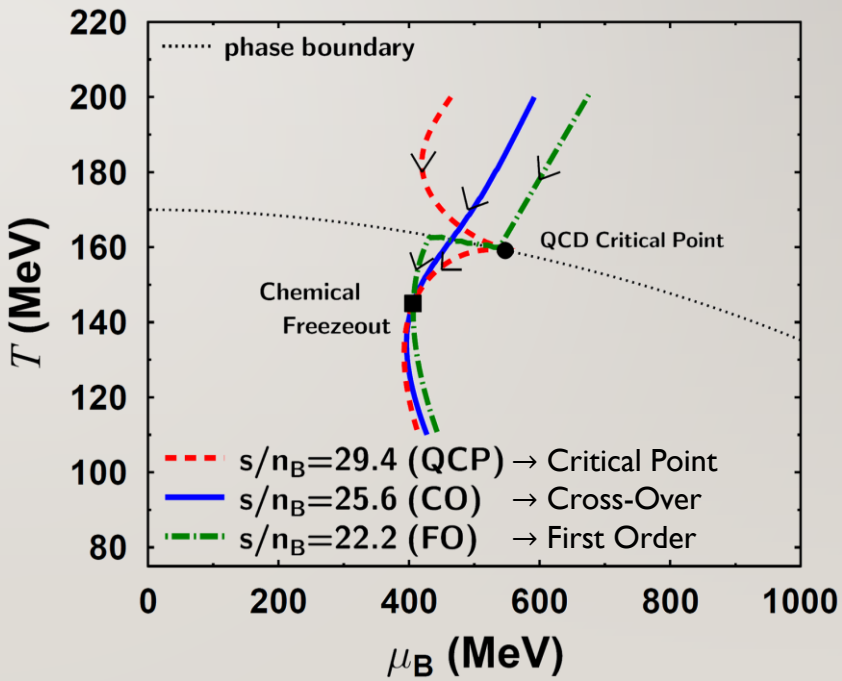


STAR Collaboration, Phys. Rev. C 96, 044904 (2017) [arXiv:1701.07065]

SEARCH FOR THE CRITICAL POINT POSSIBLE?

- Effects of the CEP in a broad region (via an effective potential ~ 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]



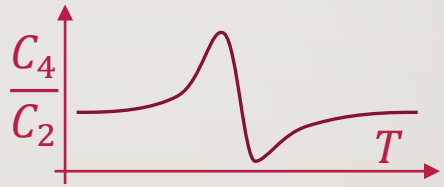


SEARCH FOR THE CEP: FLUCTUATIONS

- Static universality class: 3D Ising (or random field 3D Ising?)
- Dynamic universality class? 1 or 3 slow modes? Finite size/time effects?
- Look at cumulants: $C_n = \langle (n - \langle n \rangle)^n \rangle$, function of corr. length $\xi \sim |T - T_c|^{-\nu}$

$C_n \sim \xi^{2.5n-3}$ $(C_2 \sim \xi^2, C_3 \sim \xi^{4.5}, C_4 \sim \xi^7)$

- Non-monotonicity at CEP:

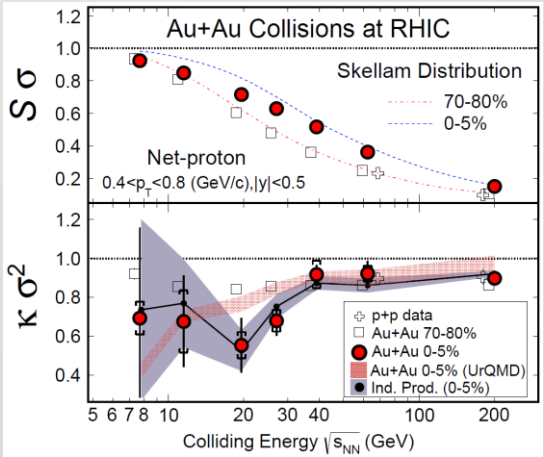


- Usual observables:

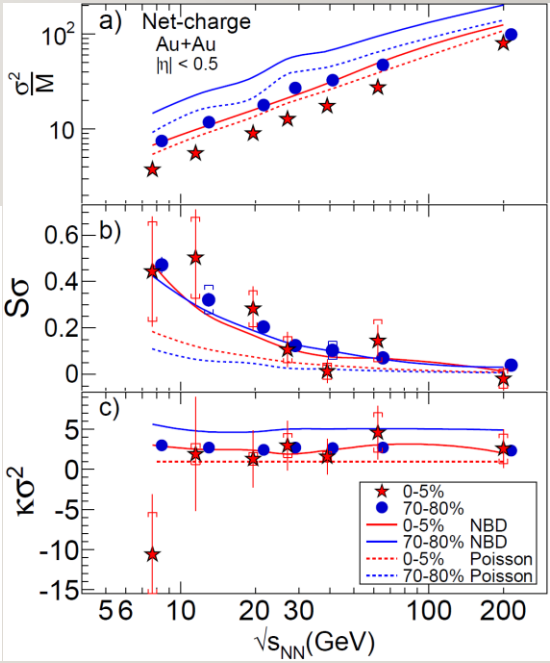
$$\frac{M}{\sigma^2} = \frac{C_1}{C_2}, S\sigma = \frac{C_3}{C_2}, \kappa\sigma^2 = \frac{C_4}{C_2}$$

- Finite size effects dampen divergencies in ξ!

Stephanov, IJMPA20,4387(2005)
Stephanov, PRL102, 032301(2009)
Stephanov, PRL107, 052301(2011)
Asakawa et al., PRL103, 262301(2009)
Hatta et al., PRL91,102003(2003)



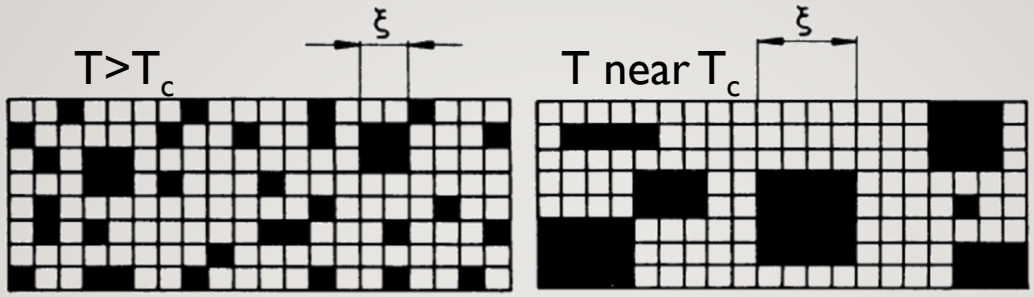
STAR, PRL113(2014)092301



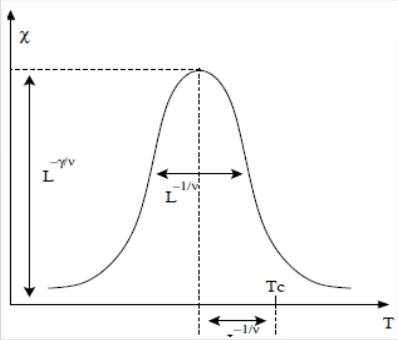
STAR, PRL112(2014)032302

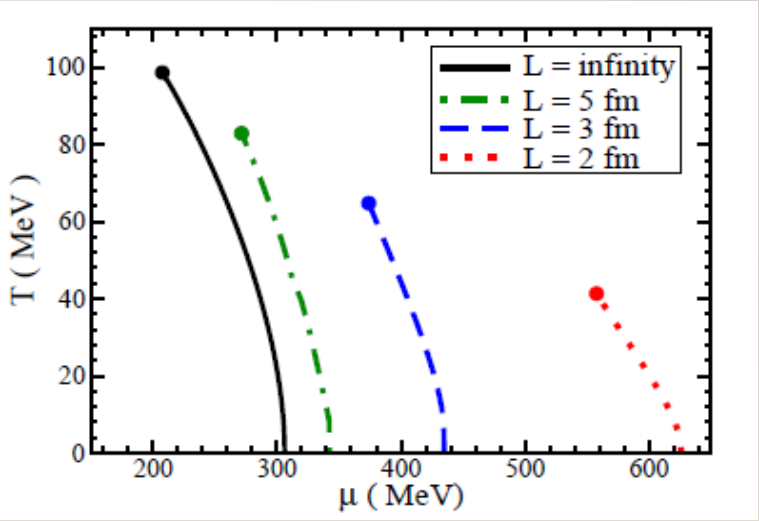
SEARCH FOR THE CEP, FINITE SIZE/TIME EFFECTS

- Finite size limits correlation length: $\xi \sim |T - T_c|^{-\nu}$ but $\xi < L$!



- Only a pseudocritical point can be observed
- Clear influence on the phase diagram
- Convenient situation: finite size scaling discloses CEP location *and* universality class
  - Shift: $\sim L^{-1/\nu}$
  - Broadening: $\sim L^{-1/\nu}$
  - Dampening: $\sim L^{-\gamma/\nu}$



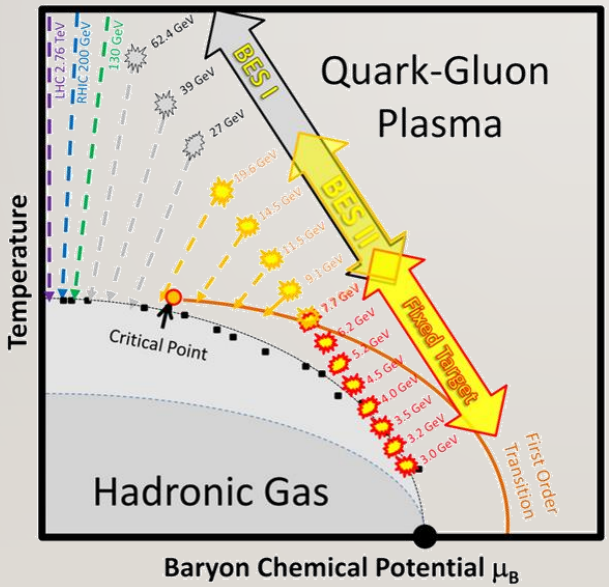


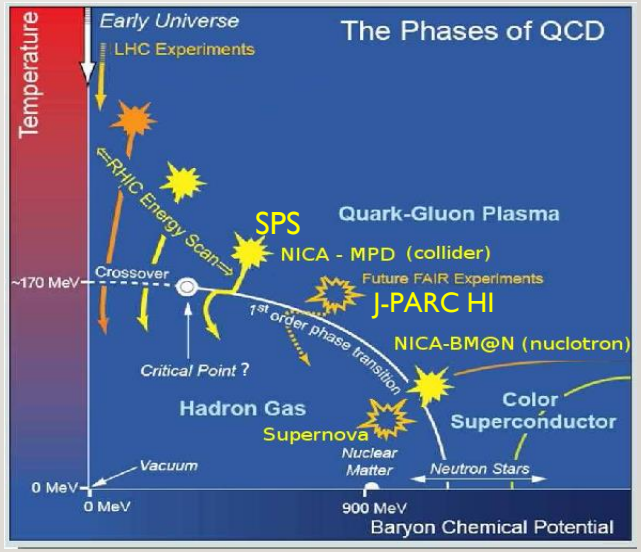
SUMMARY OF OUR KNOWLEDGE ABOUT QGP

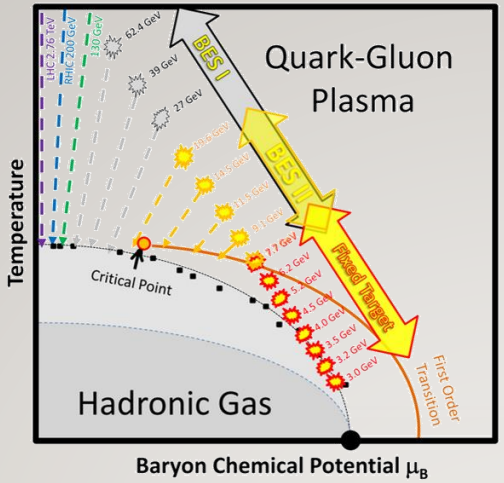
- Jet suppression in A+A
- Lack of suppression in d+A
- Photons shine through, thermal photons prevail at low momenta
- Scaling of the elliptic flow: hydrodynamic medium, quark degrees of freedom
- Heavy flavour suppression appears
- Bose-Einstein correlations: no 1st order phase transition; 2nd order?
- Correlations and fluctuations to search for the CEP
- Finite size and time effects important!

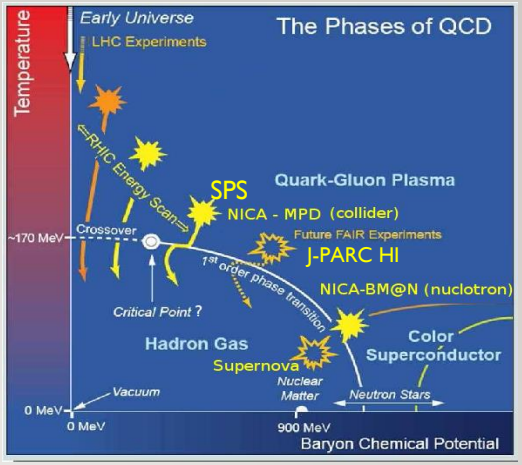
SUMMARY

- Clear consensus on a list of QGP signs
- Some appear also at low energies, for small systems, no consensus yet
- Beam Energy Scan Phase II starts now at RHIC
- Strong efforts and plans also at SPS, NICA, FAIR, J-PARC





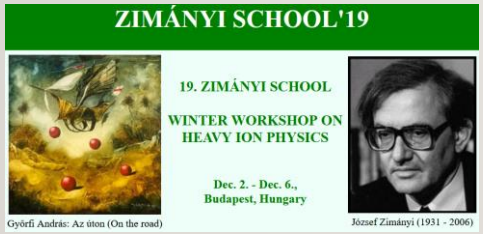


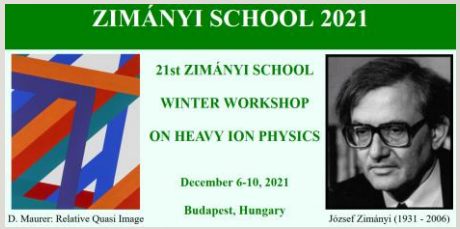


THANK YOU FOR YOUR ATTENTION

If you are interested in these subjects, participate in our annual Zimányi School

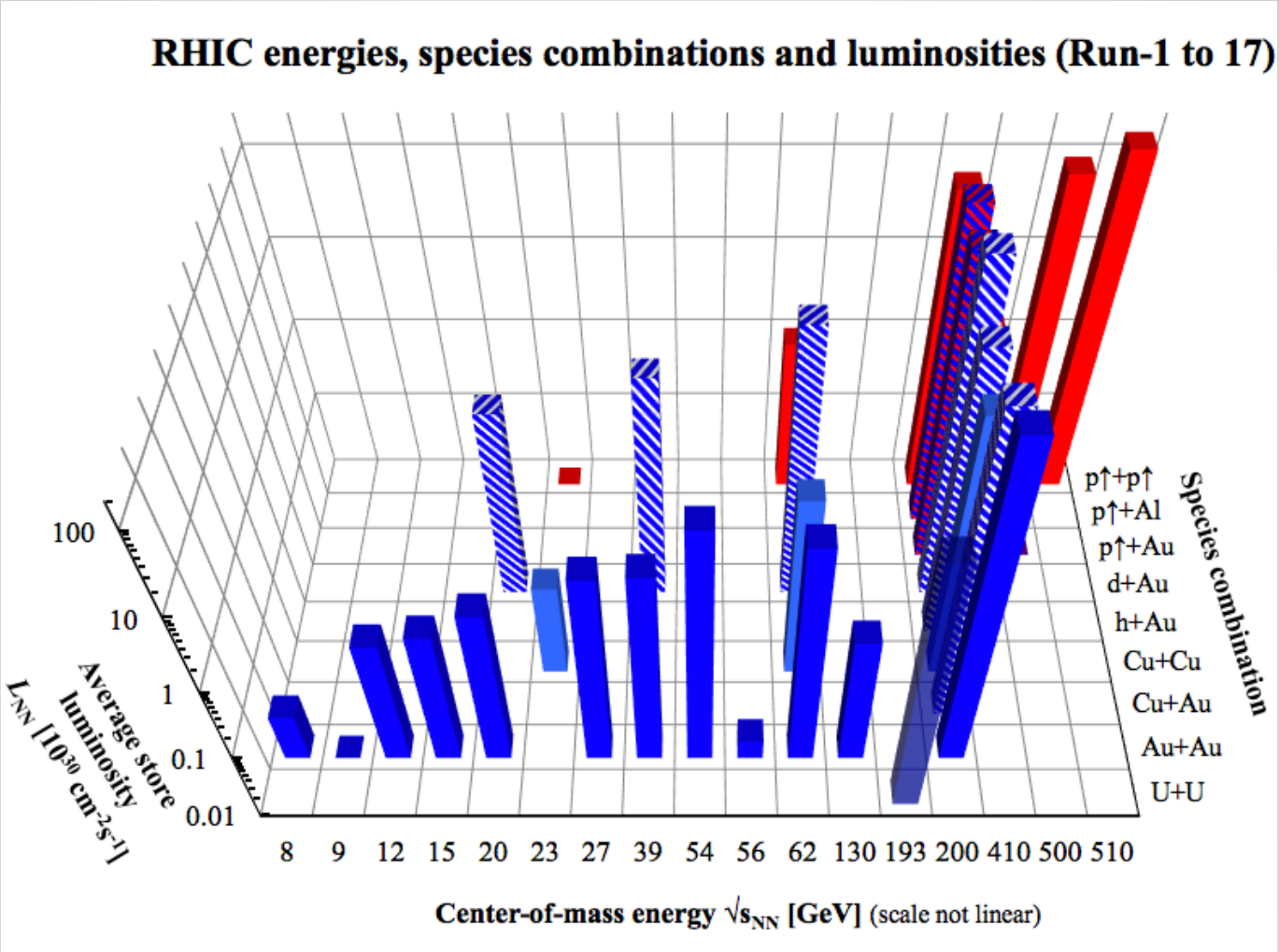
https://zimanyischool.kfki.hu/





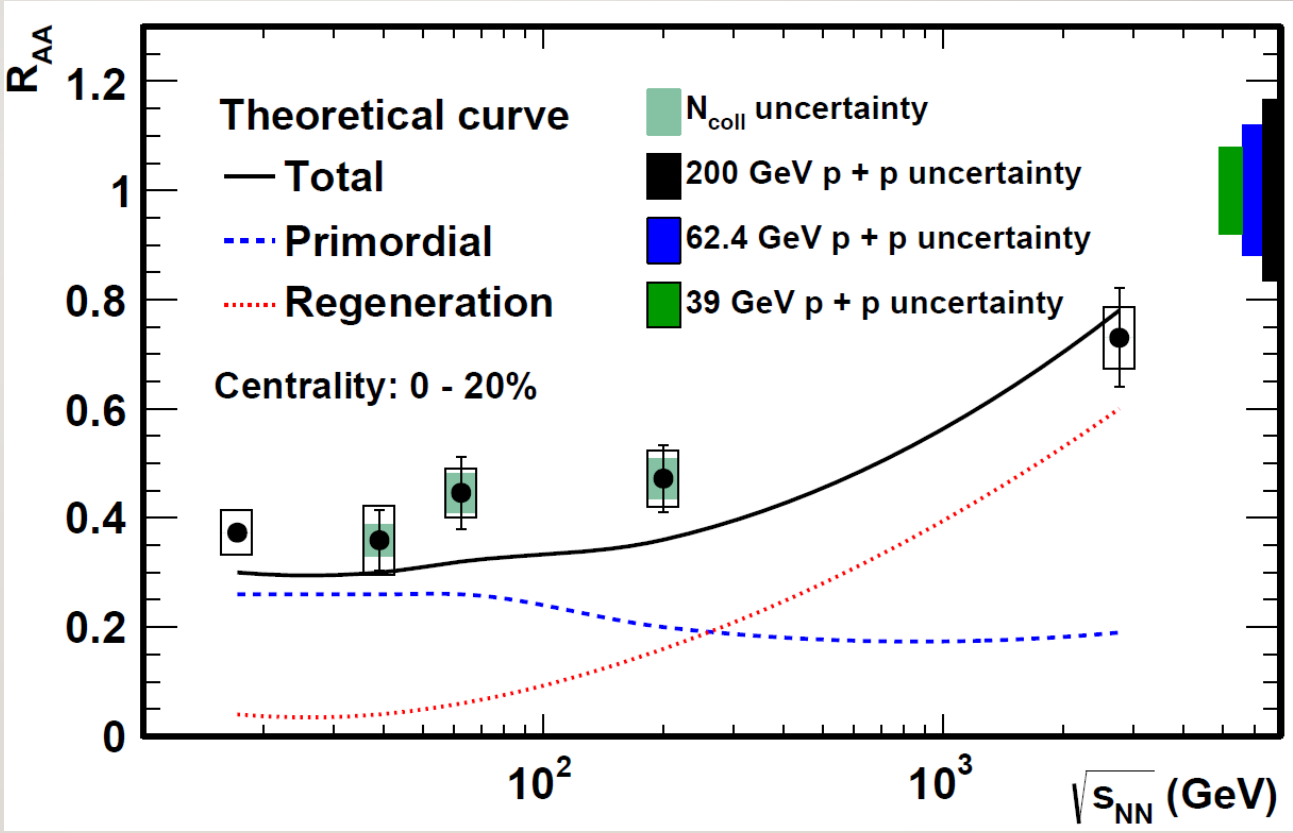
BACKUP SLIDES

74/70 RHIC RECORDED RUNS AND LUMINOSITY



J/Ψ IN THE BEAM ENERGY SCAN

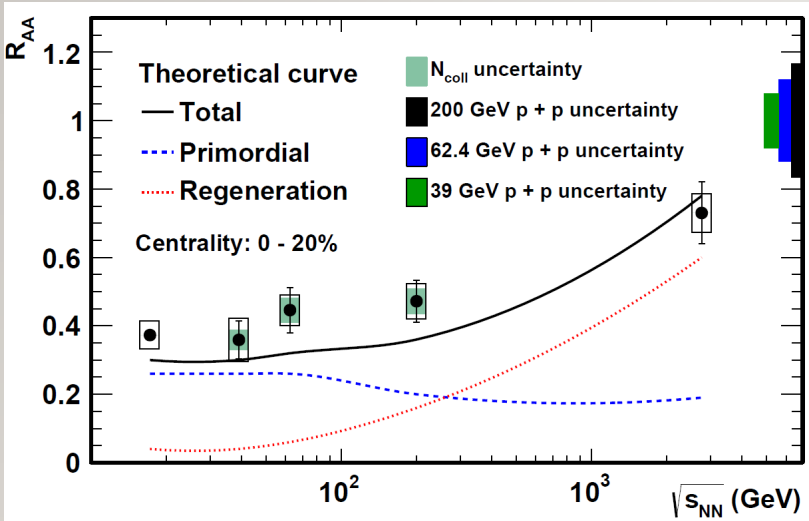
- Regeneration from $c\bar{c}$ and feed-down from χ_c and ψ', increases with $\sqrt{s_{NN}}$
- Screening and cold nucl. matt.: less primordial charmonium with increasing $\sqrt{s_{NN}}$
- Two effects seem to compensate for $\sqrt{s_{NN}} < 200$ GeV

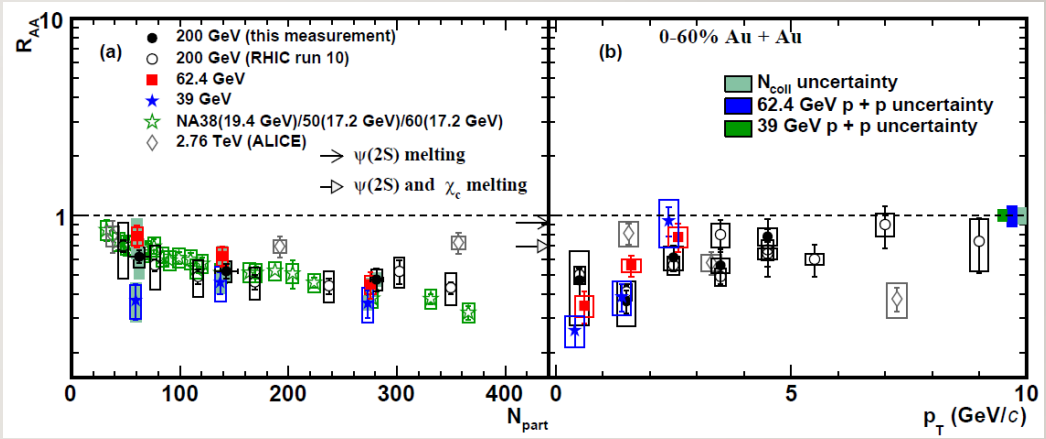


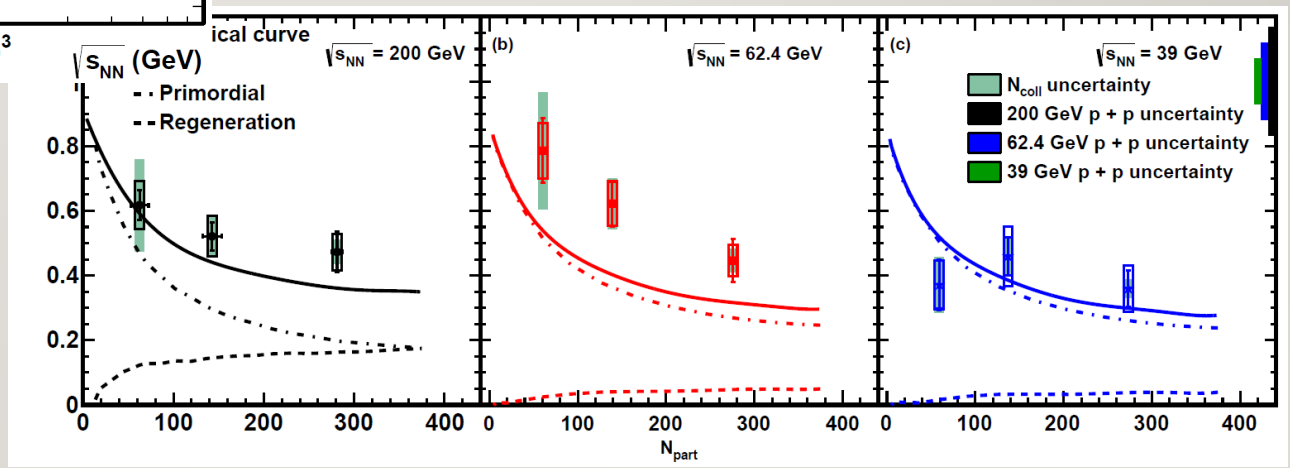
STAR Collaboration, Phys.Lett. B771 (2017) 13-20

76/70 J/PSI IN THE BEAM ENERGY SCAN

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

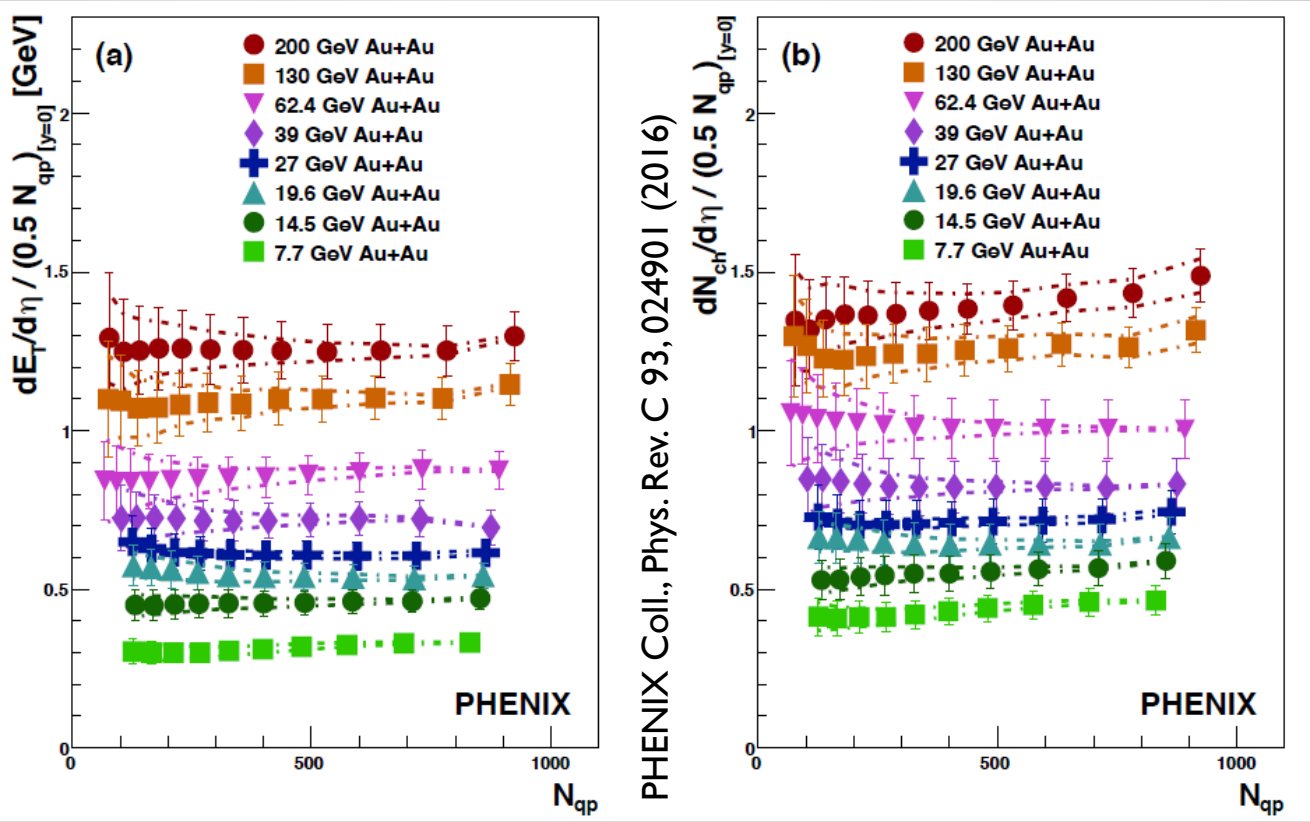






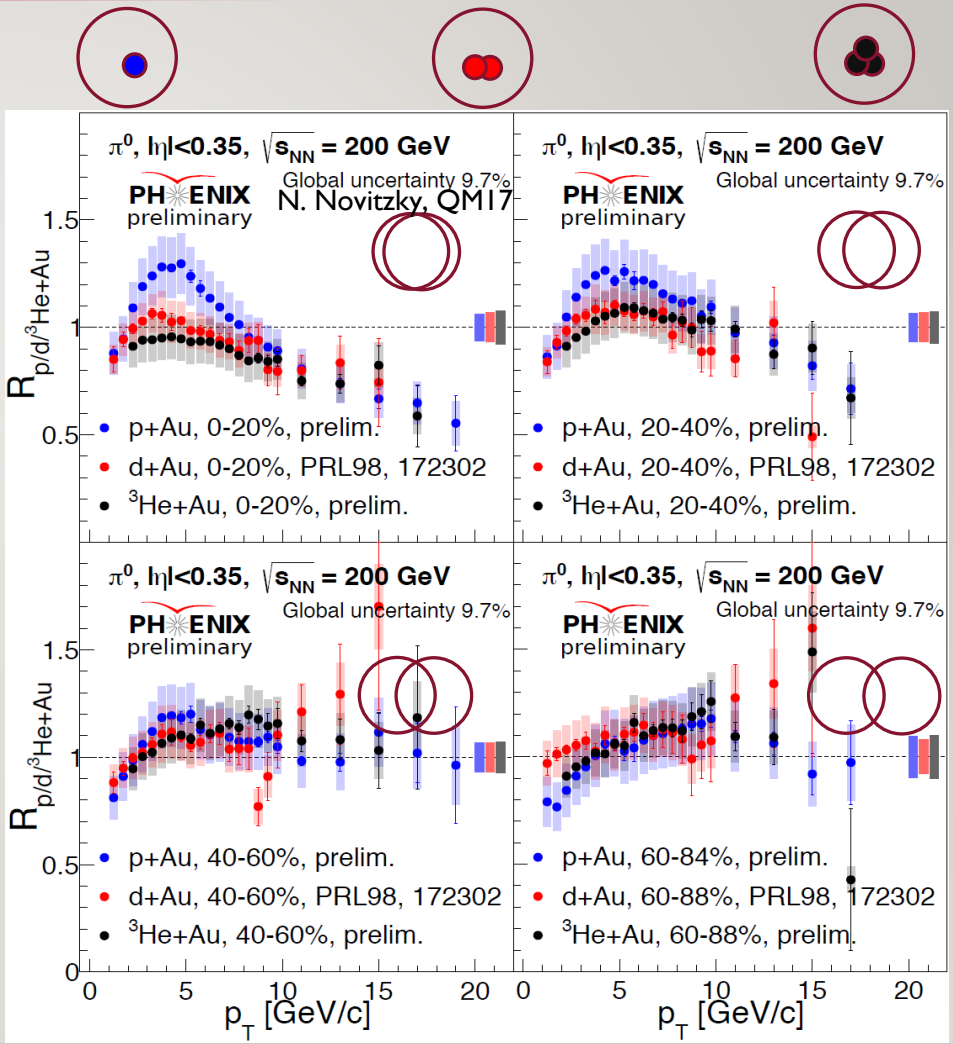
77/70 QUARK PARTICIPANT SCALING

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



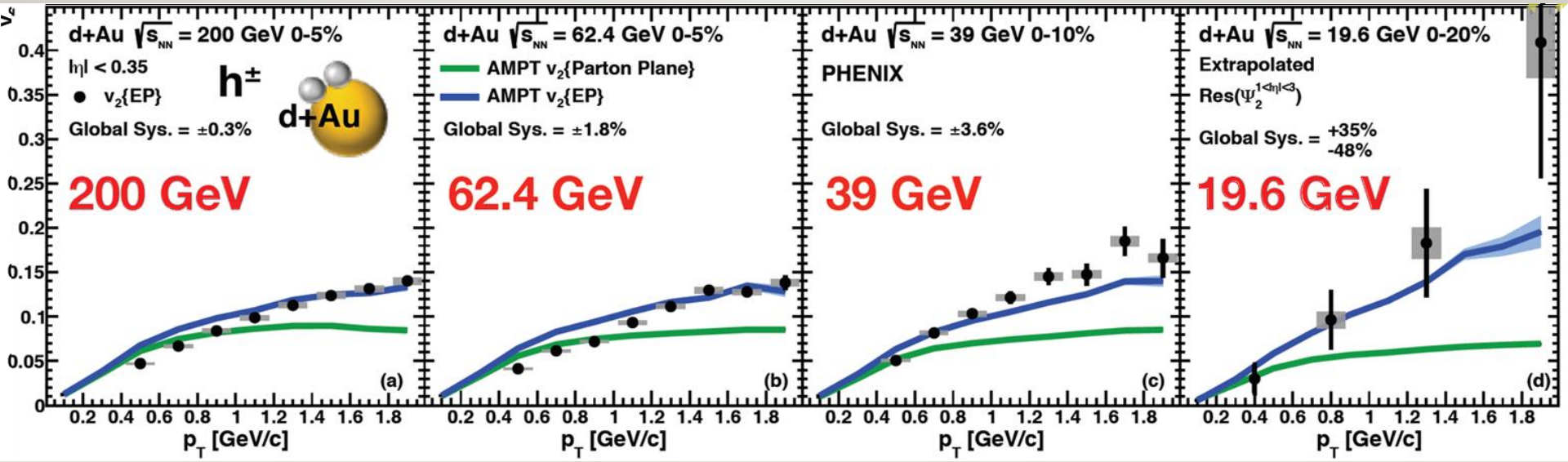
SUPPRESSION IN HIGHLY ASYMMETRIC SYSYTEMS

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



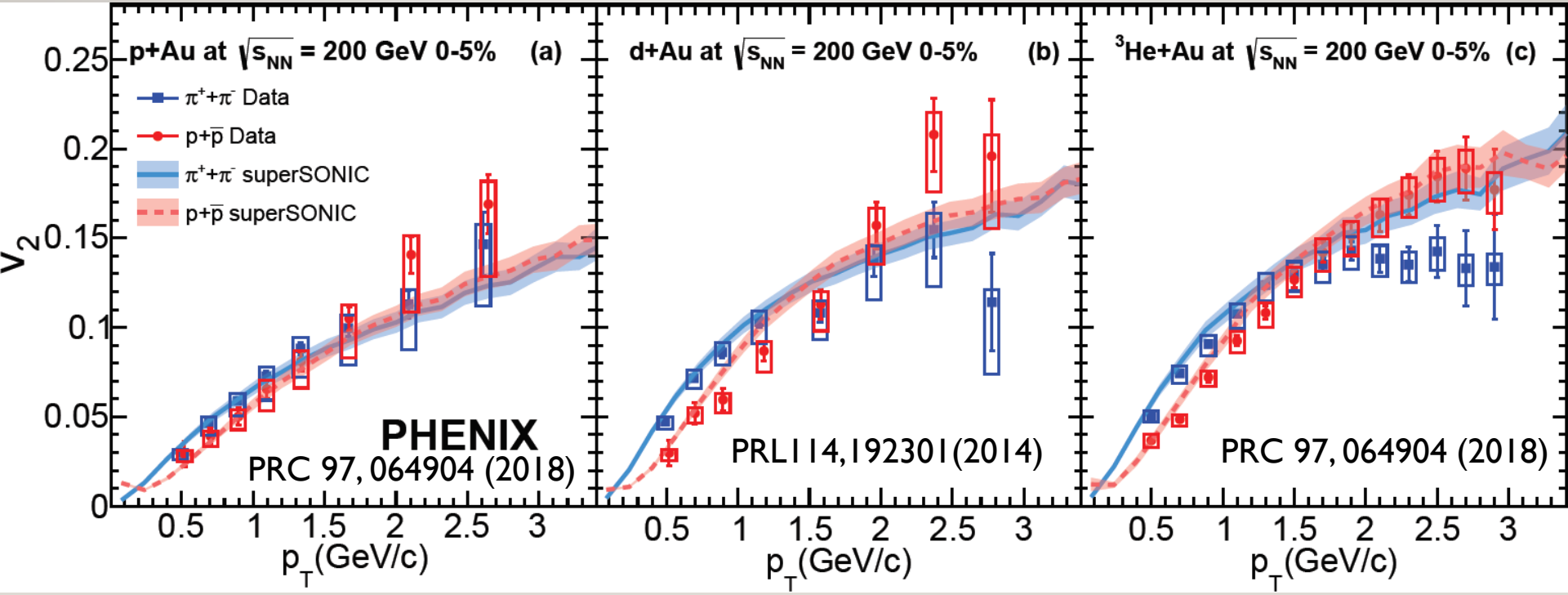
79/70 ELLIPTIC FLOW IN SMALL SYSTEMS

- 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



ELLIPTIC FLOW IN SMALL SYSTEMS

- Mass ordering in all cases, smallest effect in p+Au
- Hydro+… codes describe results well (superSONIC, iEBE-VISHNU)
  - Shen et al, Phys.Rev. C95, 014906(2017); Habich et al, Eur.Phys.J. C 75, 15 (2015).



RESEARCH GROUPS @ ELTE

- LHC, RHIC: ELTE participates in cutting-edge experiments
- Theory: field theories, hydrodynamics, femtoscopy, …
- All possible from Budapest
- Some visints are necessary though…

82/70 KNOWN MESONS AND BARYONS

- Mesons ($q\bar{q}$)

π^0	0	0	0.135 GeV	$(\bar{u}u - \bar{d}d)/\sqrt{2}$
π^+,π^-	$+1,-1$	0	0.139 GeV	$\bar{d}u,\bar{u}d$
K^+,K^-	$+1,-1$	0	0.494 GeV	$\bar{s}u,\bar{u}s$
$K^0,\bar{K}^0$	0	0	0.498 GeV	$\bar{s}d,\bar{d}s$
η	0	0	0.548 GeV	$(\bar{u}u + \bar{d}d)/\sqrt{2}$
η'	0	0	0.958 GeV	$\bar{s}s$
ρ^0	0	1	0.776 GeV	$(\bar{u}u - \bar{d}d)/\sqrt{2}$
ρ^+,ρ^-	$+1,-1$	1	0.776 GeV	$u\bar{d},\bar{u}d$
ω	0	1	0.783 GeV	$(\bar{u}u + \bar{d}d)/\sqrt{2}$
ϕ	0	1	1.019 GeV	$\bar{s}s$
K^{*+},K^{*-}	$+1,-1$	1	0.892 GeV	$\bar{s}u,\bar{u}s$
$K^{*0},\bar{K}^{*0}$	0	1	0.896 GeV	$\bar{s}d,\bar{d}s$
$D^0,\bar{D}^0$	0	0	1.865 GeV	$c\bar{u},\bar{c}u$
D^+,D^-	+1,-1	0	1.870 GeV	$c\bar{d},\bar{c}d$
J/ψ	0	0	3.096 GeV	$\bar{c}c$
$\psi(2S)$	0	0	3.686 GeV	$\bar{c}c$
$B^0,\bar{B}^0$	0	0	5.280 GeV	$d\bar{b},\bar{d}b$
B^+,B^-	+1,-1	0	5.279 GeV	$d\bar{b},\bar{d}b$
$B_s^0,\bar{B}_s^0$	0	0	5.367 GeV	$s\bar{b},\bar{s}b$
$\Upsilon(1S)$	0	1	9.460 GeV	$\bar{b}b$
$\Upsilon(2S)$	0	1	10.023 GeV	$\bar{b}b$
$\Upsilon(3S)$	0	1	10.355 GeV	$\bar{b}b$

Baryons (qqq)

p	1	1/2	0.938 GeV	uud
n	1	1/2	0.940 GeV	uud
Λ	0	1/2	1.116 GeV	uds
Σ^+	+1	1/2	1.189 GeV	uus
Σ^0	0	1/2	1.193 GeV	dds
Σ^-	-1	1/2	1.197 GeV	uds
Ξ^0	0	1/2	1.315 GeV	uss
Ξ^-	-1	1/2	1.321 GeV	dss
Δ^{++},Δ^+	$+2,+1$	3/2	1.232 GeV	uuu,uud
Δ^0,Δ^-	$0,-1$	3/2	1.232 GeV	udd,ddd
Σ^*	$+1,0,-1$	3/2	1.385 GeV(平均)	uus,uds,dds
Ξ^*	$0,-1$	3/2	1.533 GeV(平均)	uus,uds,dds
Ω^-	-1	3/2	1.672 GeV	sss
Λ_c	+1	1/2	2.286 GeV	udc
Λ_b	0	1/2	5.619 GeV	udb

- And many more…