Physics at High Baryon Density

- Study the QCD Phase Structure in High-Energy Nuclear Collisions

Nu Xu

LBNL / GSI

Outline

1) Introduction

2) Results from RHIC BES Program

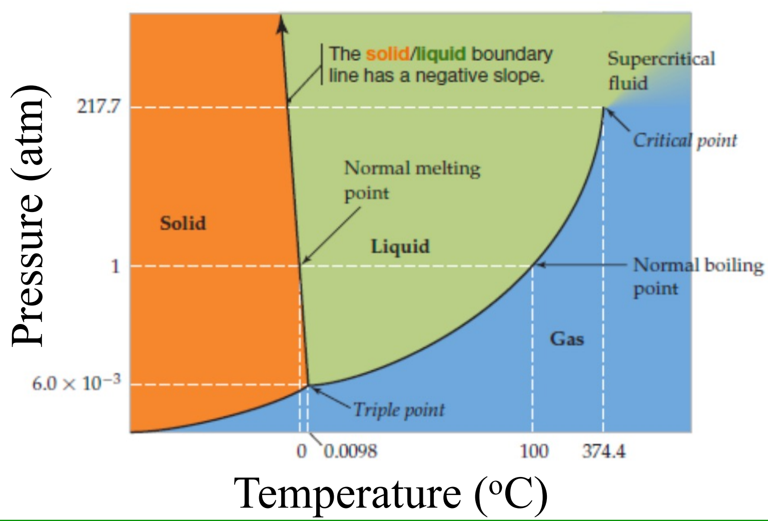
i. Collectivity (EOS)
ii. Criticality (EOS, CP)
iii. Baryon Correlations (EOS, NN, YN)

3) Outlook

Phase Structure of Strong Interactions

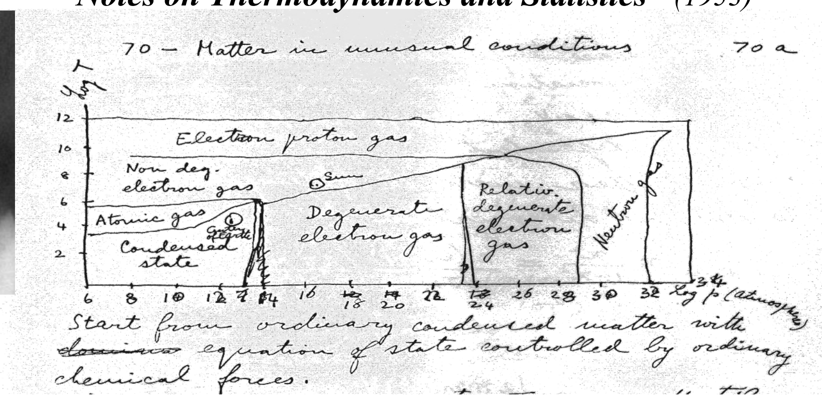
Phase Diagram: For given degrees of freedom, how matter (re)organizes itself under external conditions

Phase Diagram of Water: QED at Work



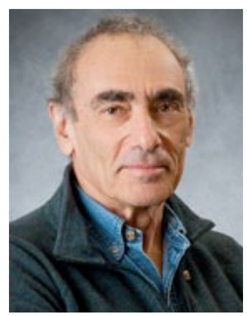
"Notes on Thermodynamics and Statistics" (1953)

E. Fermi

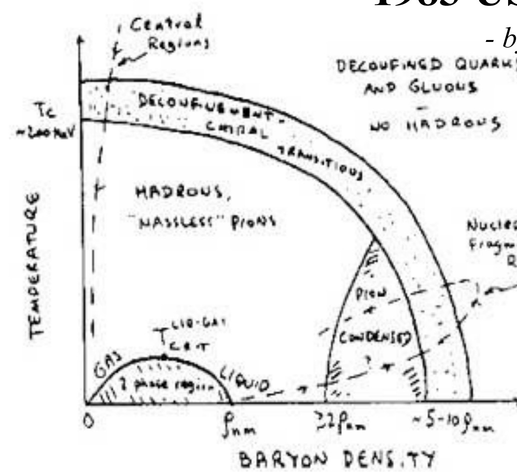


1983 US NP LRP

- by Gordon Baym



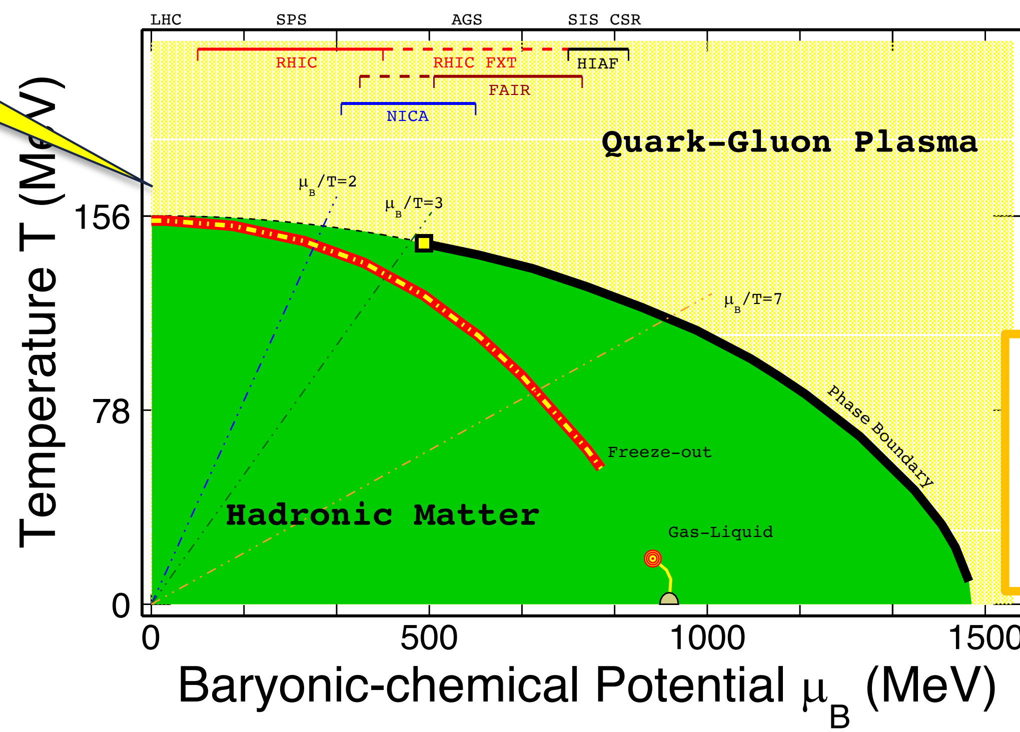
Gordon Baym



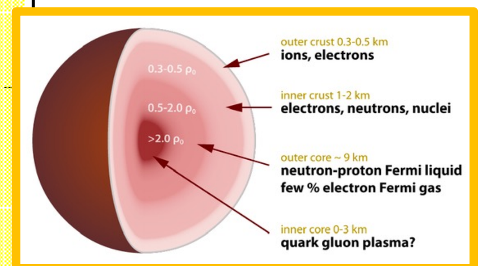
QCD Phase Diagram

Nuclear Collisions and QCD Phase Diagram

Early Universe

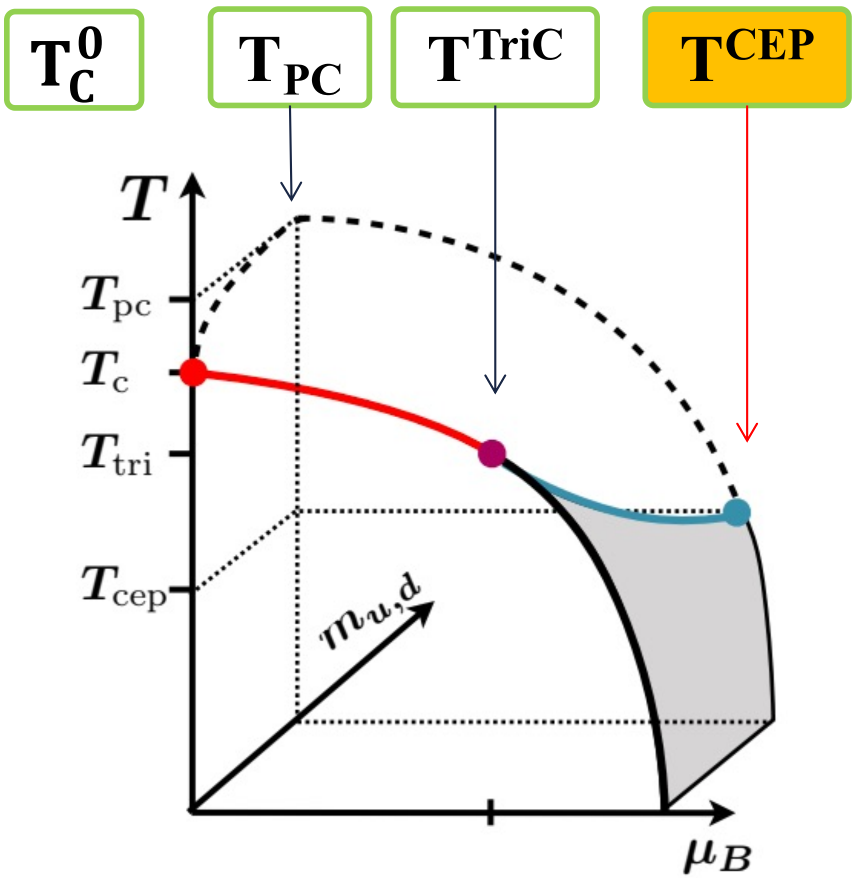


High baryon density: Inner structure of compact stars



1) RHIC BES: → search for 1st-order phase transition and **QCD critical point**;
2) Baryon interactions (*e.g.* $N-N$, $Y-N$) → inner structure of compact stars

LGT Calculation: QCD Phase Structure



F. Karsch *et al.*, 2020

1) QCD transition temperature:
   $\mathbf{T_{PC} = 156.5 \pm 1.5\ MeV}$

2) Chiral crossover line

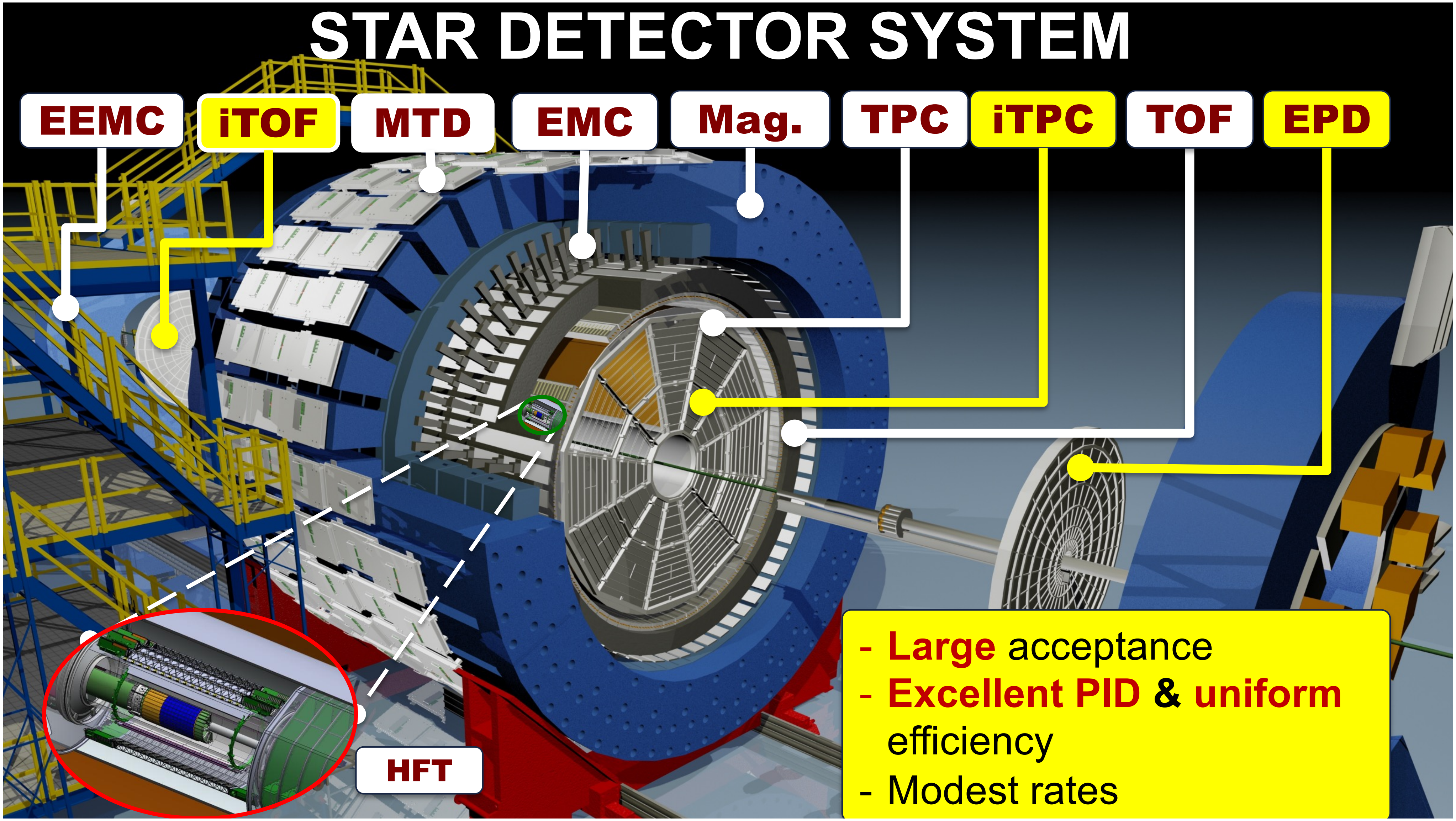
$$\mathbf{T_{PC}(\mu_B) = T_{PC}^0 \left[1 - \kappa_2 \left(\frac{\mu_B}{T_{PC}^0}\right)^2 - \kappa_4 \left(\frac{\mu_B}{T_{PC}^0}\right)^4\right]}$$

$\kappa_2 = 0.012(4),\ \kappa_4 = 0.00(4)$

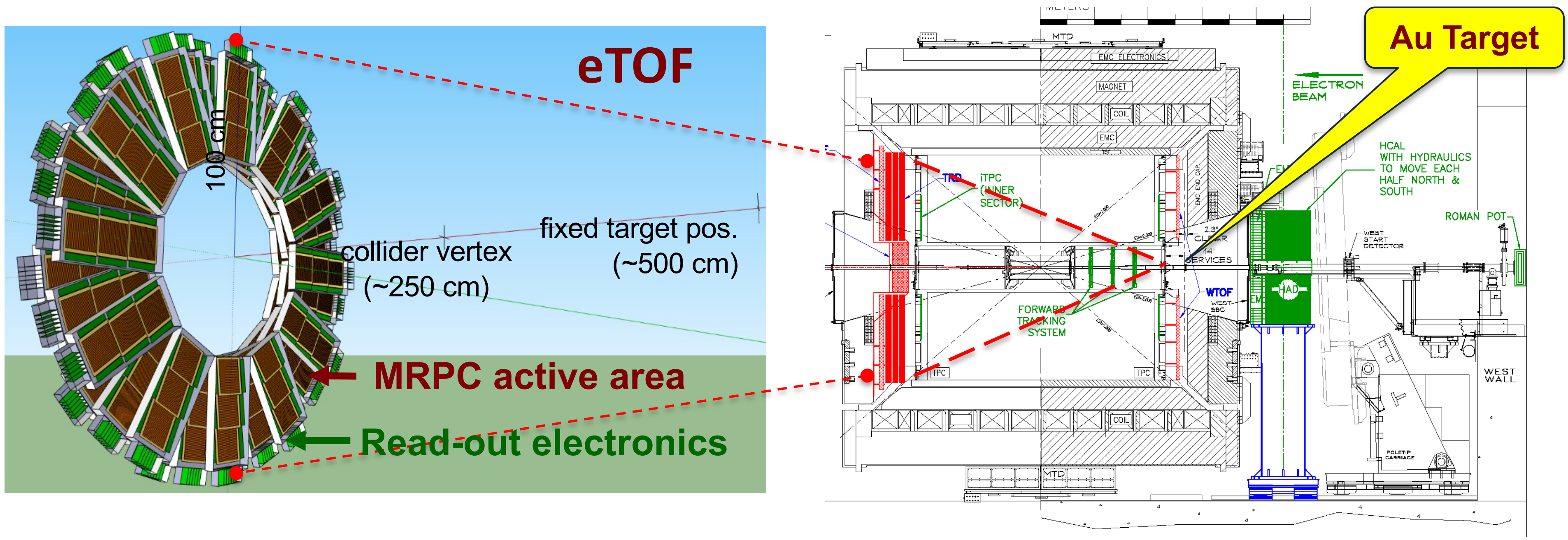
3) Chiral transition temperature:
   $\mathbf{T_C = 132^{+3}_{-6}\ MeV}$

4) QCD critical end point, if exits:
   $\mathbf{T^{CEP} < T_C,\quad \mu_B^{CEP} \gtrsim 3T_C}$

HotQCD: Phys.Lett.**B795**, 15(2019);
Phys. Rev. Lett. **123**, 062002(2019)


STAR DETECTOR SYSTEM
EEMC
iTOF
MTD
EMC
Mag.
TPC
iTPC
TOF
EPD
HFT
- Large acceptance
- Excellent PID & uniform efficiency
- Modest rates

STAR Fixed Target Setup



CBM participates in RHIC BES-II in 2019 – 2021:

- Complementary to CBM program: $\sqrt{s_{NN}}$ = 3 - 7.2 GeV (**760 ≥ μ_B ≥ 420 MeV**)
- Strange-hadron, hyper-nuclei and fluctuation at the high baryon density region

STAR BES-I and BES-II Data Sets

Au+Au Collisions at RHIC

Collider Runs

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19
2	62.4	46 M	75 MeV		Run-10
3	54.4	1200 M	85 MeV		Run-17
4	39	86 M	112 MeV		Run-10
5	27	585 M	156 MeV	3.36	Run-11, 18
6	19.6	595 M	206 MeV	3.1	Run-11, 19
7	17.3	256 M	230 MeV		Run-21
8	14.6	340 M	262 MeV		Run-14, 19
9	11.5	57 M	316 MeV		Run-10, 20
10	9.2	160 M	372 MeV		Run-10, 20
11	7.7	104 M	420 MeV		Run-21

Fixed-Target Runs

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
12	**3.0** (3.85)	**260** + 2000 M	**760** MeV	-1.05	Run-18, 21

Most precise data to map the QCD phase diagram

$$3 < \sqrt{s_{NN}} < 200 \text{ GeV}; \quad 760 > \mu_B > 25 \text{ MeV}$$

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Collectivity

$$\partial_\mu[(\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu}] = 0$$
$$\partial_\mu[s\, u^\mu] = 0$$

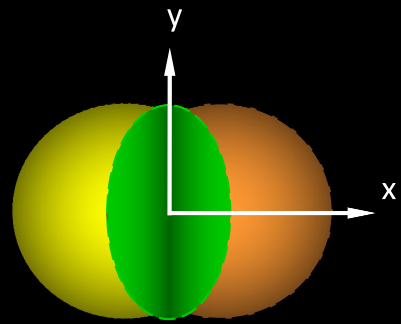
$$\frac{d^2N}{p_T dp_T d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T}\left\{1 + \sum_{n=1}^{\infty} 2v_n(p_T)cos[n(\varphi - \Psi_R)]\right\}$$

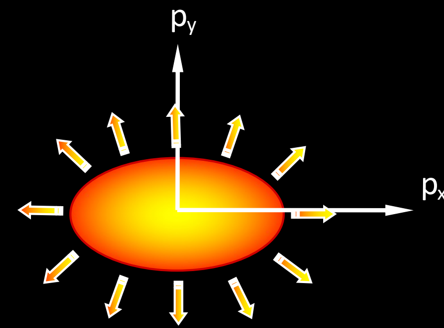
− v_1 Directed flow;

− v_2 Elliptic flow; − v_3 Triangle flow

Anisotropy Parameter v_2

coordinate-space-anisotropy ➡ momentum-space-anisotropy

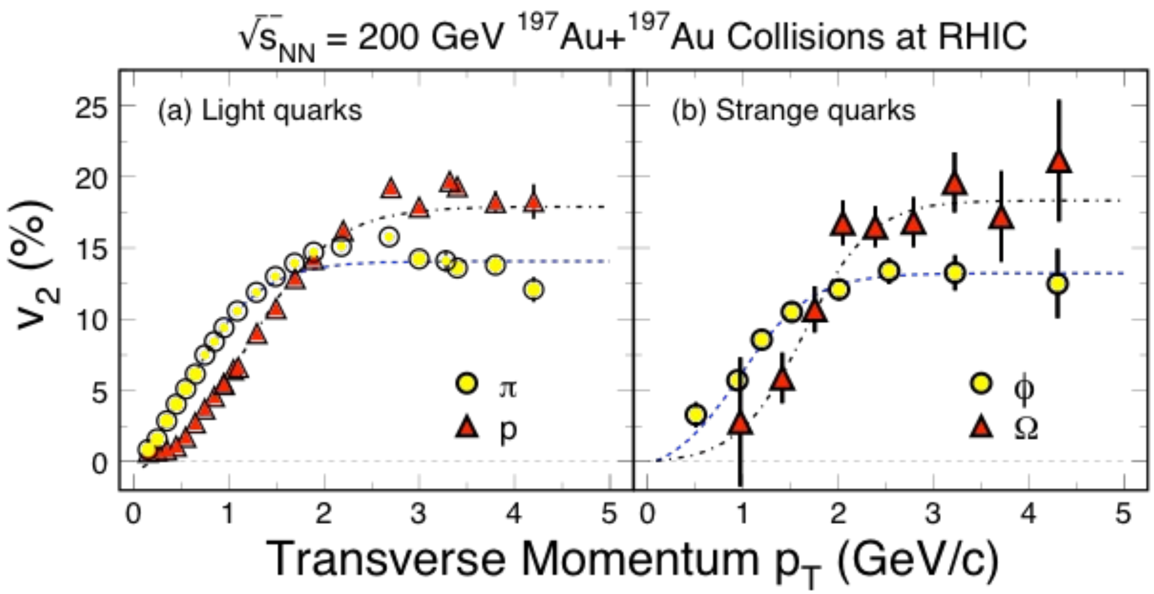




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle cos2\varphi \rangle, \qquad \varphi = tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Sensitive to initial/final conditions, EoS and degrees of freedom

Partonic Collectivity at RHIC



STAR: PRL**116**, 62301(2016)

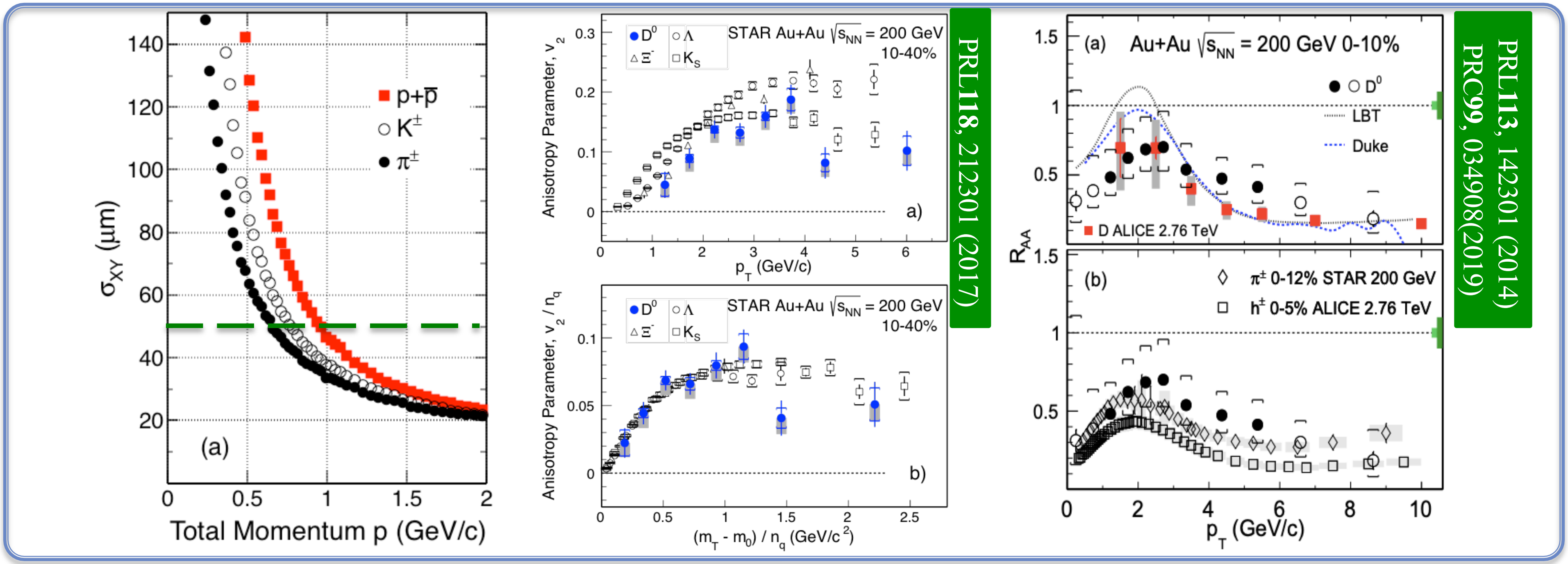
- ✓ Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
- ✓ High p_T (> 2 GeV/c): ***number of quarks scaling (NCQ)***

u-, d-, and s-quarks flow!

- ➢ **Partonic Collectivity!**
- ➢ **De-confinement Au+Au collisions at RHIC!**

STAR: PRL**116**, 62301(2016)

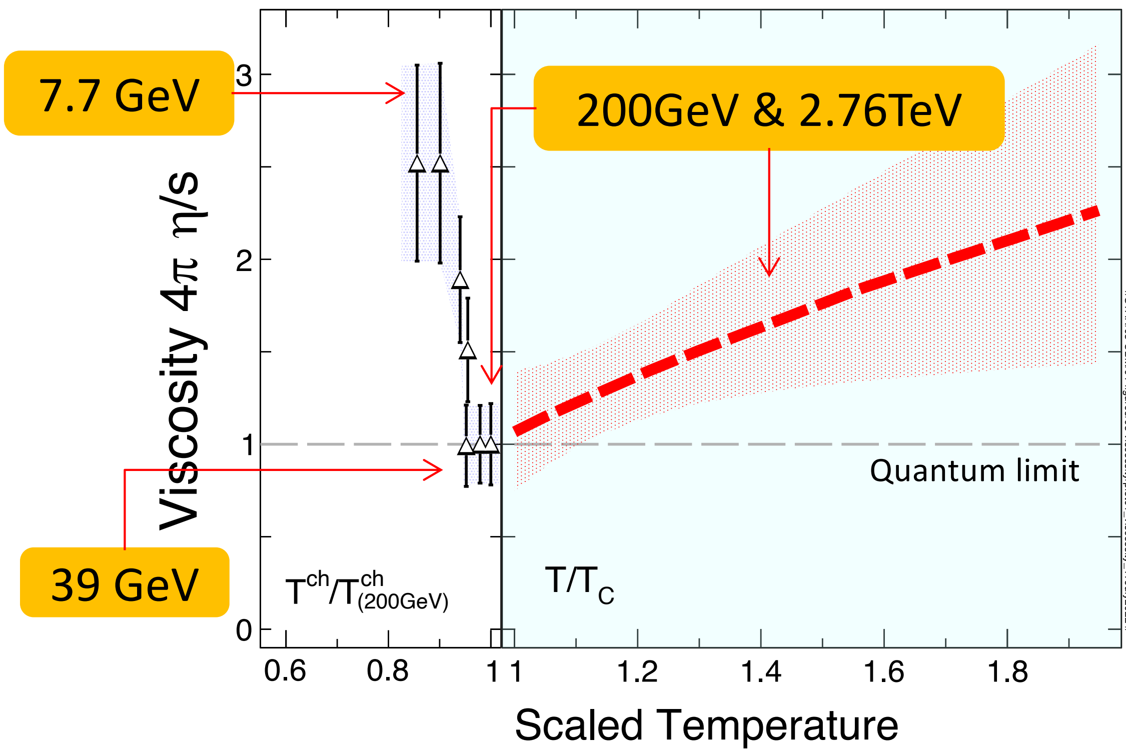
Heavy Flavor D^0 Collectivity at HRIC



1) First application of MAPS technology in high energy collisions, excellent position resolution;
   - "These results suggest that charm quarks have achieved **local thermal equilibrium** with the medium created in such (200GeV Au+Au) collisions"
   - Hadronization via **quark coalescence** process

STAR: PRL**113**, 142301(14); PRC**99**, 034908(19); PRL**118**, 212301(17); PRL**123**, 162301(19); PRL**124**, 172301(20)

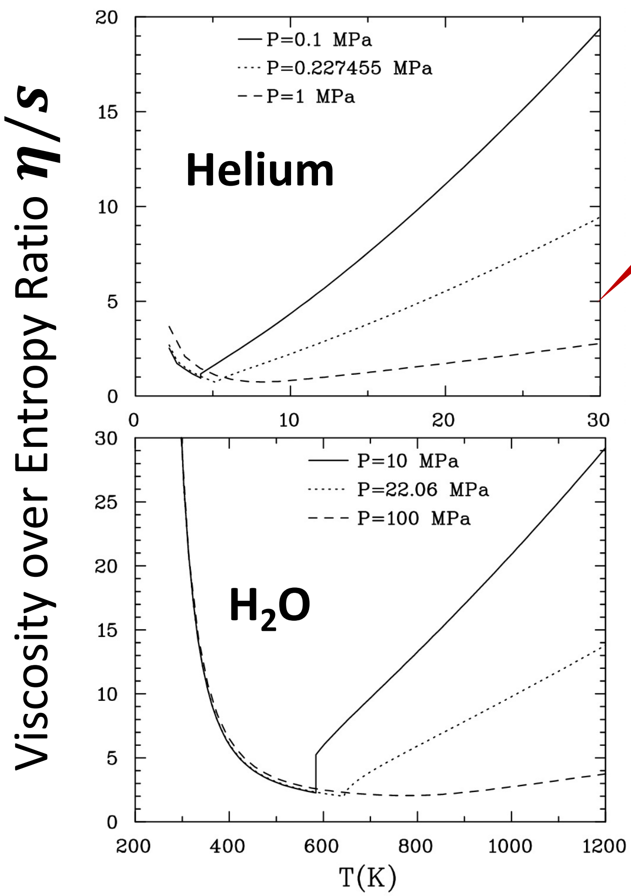
Equation of State for Strong Interaction



1) Left-plot: Energy dependence of η/s extracted from light-flavor hadron v_2 and v_3. Right-plot: extracted from Bayesian fits to R_{AA} and v_2 at 200GeV collisions;
2) Both sides meet at the unity of the scaled temperature;
3) The values of η/s increase quickly below $\sqrt{s_{NN}}$ = 39 GeV → QGP dominants in higher energies;
4) **Evidence of the QCD transition!**

1) L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL**97** (2006) 152303
2) X.Dong, Y.J. Lee & R.Rapp, ARNPS, **69** (2019) 417
3) J.E.Bernhard, J.S.Moreland & S. Bass, Nat. Phys. **15** (2015) 1113
4) I. Karpenko, P. Huovinen, H. Petersen, and M. Bleicher, Phys.Rev.**C91**, 064901 (2015).
5) G.Nijs, W.van der Schee, U. Gürsoy and R. Snellings, PRL**126**, (2021) 202301

Strongly-Interacting Low-Viscosity Matter

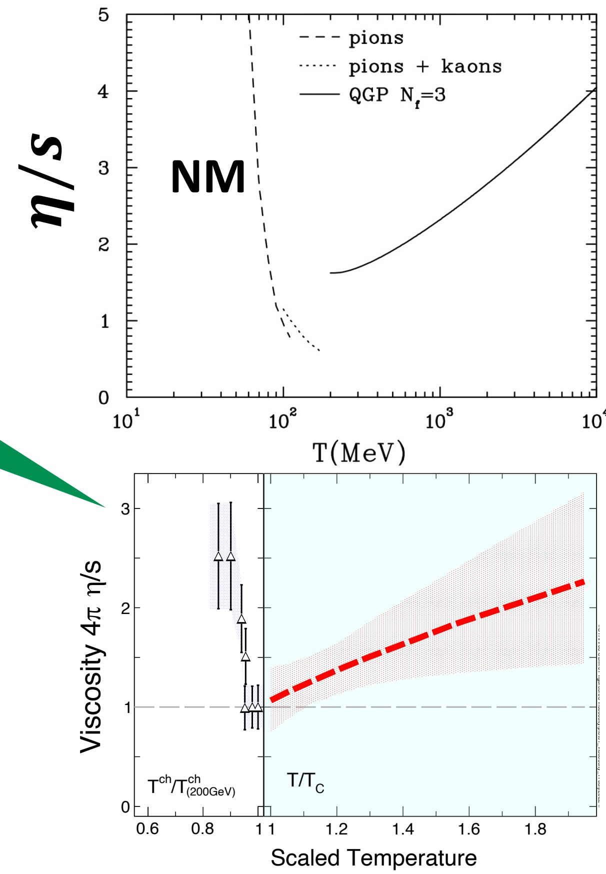


EM interaction
η/s ~ 1

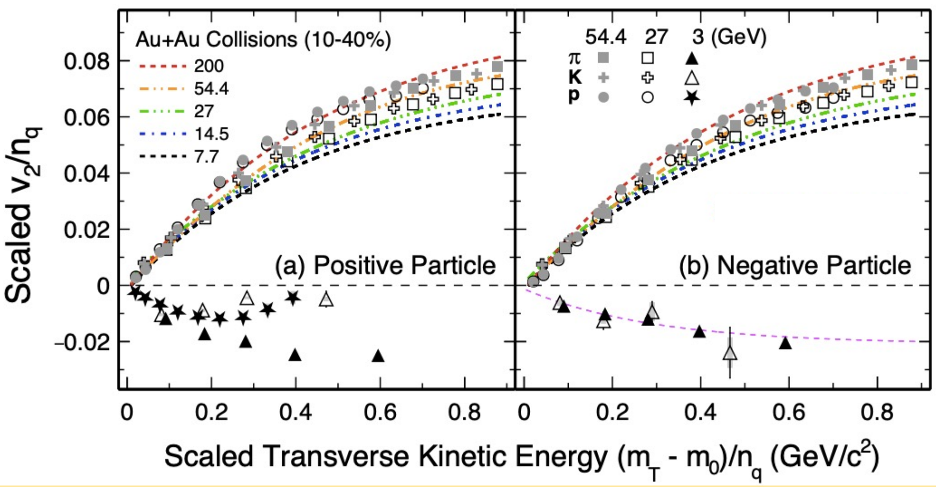
L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL**97** (2006) 152303

Strong Interaction
η/s ~ 0.1

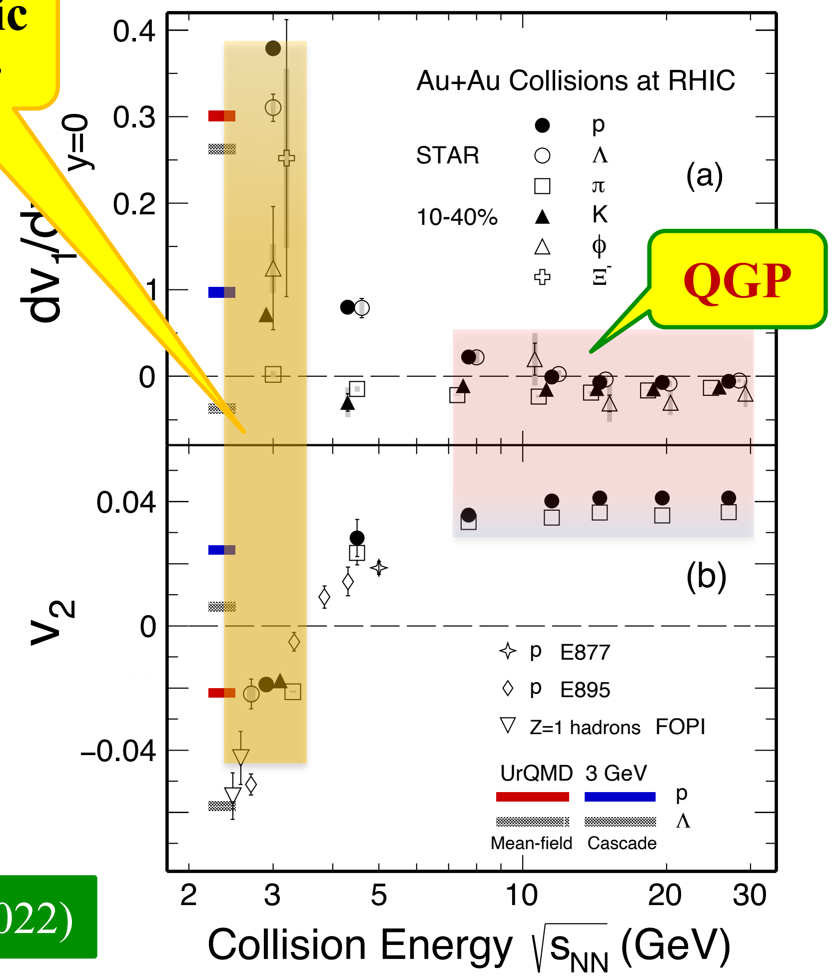
- QGP matter in $\sqrt{s_{NN}} \geq$ 39 GeV collisions!
- Universal behavior for phase transition!



Disappearance of Partonic Collectivity



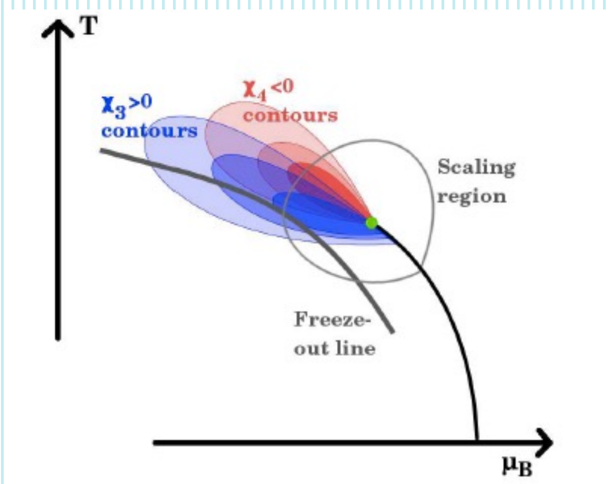
Hadronic Matter



- At **3 GeV**, NCQ scaling is absent;
- Transport model calculations, with baryonic mean field, reproduce both v_1 and v_2 results;
- **hadronic interactions dominant!**

STAR: PLB**827**, 137003(2022)

Criticality



Conserved Quantities (B, Q, S)

1) In strong interactions, baryons (B), charges (Q) and strangeness (S) are conserved;
2) Higher order moments/cumulants describe the shape of distributions and quantify fluctuations. They are sensitive to the correlation length ξ, phase structure;
3) Direct connection to theoretical calculations of susceptibilities.

Measured multiplicity N, $\langle \delta N \rangle = \mathbf{N} - \langle N \rangle$

mean: $M = \langle N \rangle = C_1$

variance: $\sigma^2 = \langle (\delta N)^2 \rangle = C_2$

skewness: $S = \langle (\delta N)^3 \rangle / \sigma^3 = C_3 / C_2^{3/2}$

kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^3 - 3 = C_4 / C_2^2$

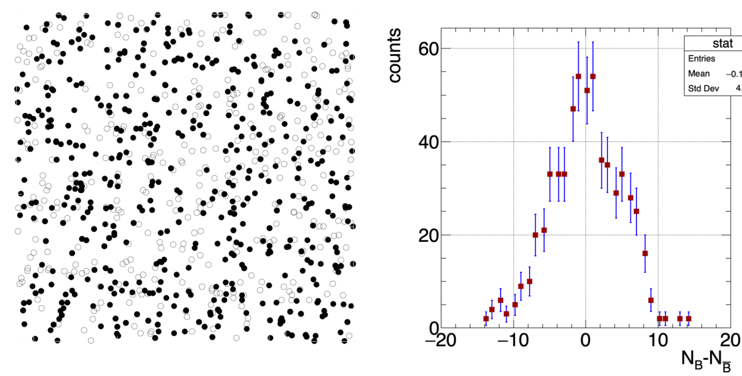
Moments, cumulants and susceptibilities:

2^{nd} order: $\sigma^2 / M \equiv C_2 / C_1 = \chi_2 / \chi_1$

3^{rd} order: $S\sigma \equiv C_3 / C_2 = \chi_3 / \chi_2$

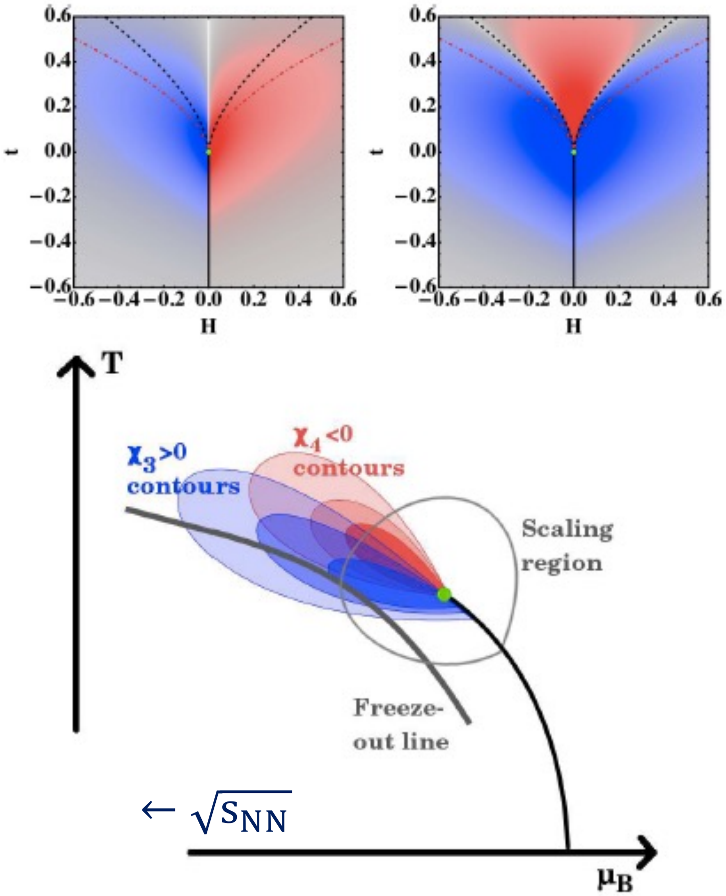
4^{th} order: $\kappa\sigma^2 \equiv C_4 / C_2 = \chi_4 / \chi_2$

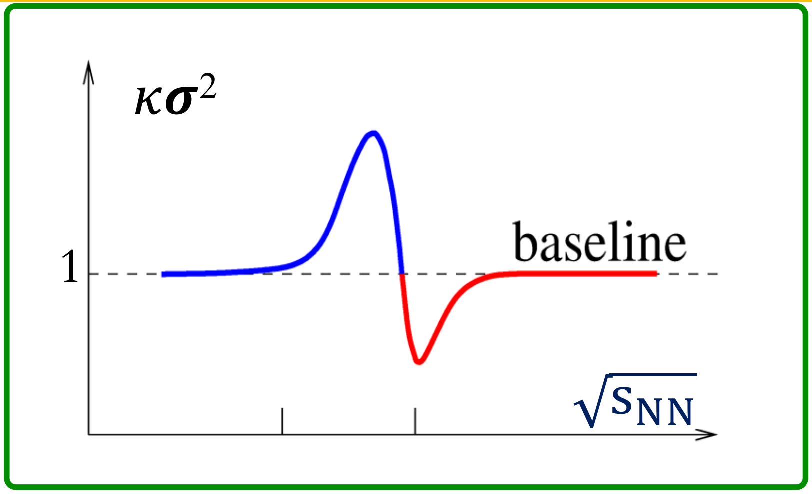
Animation: A.Rustamov



INT 2008-2b : The QCD Critical Point

Expectations for Models

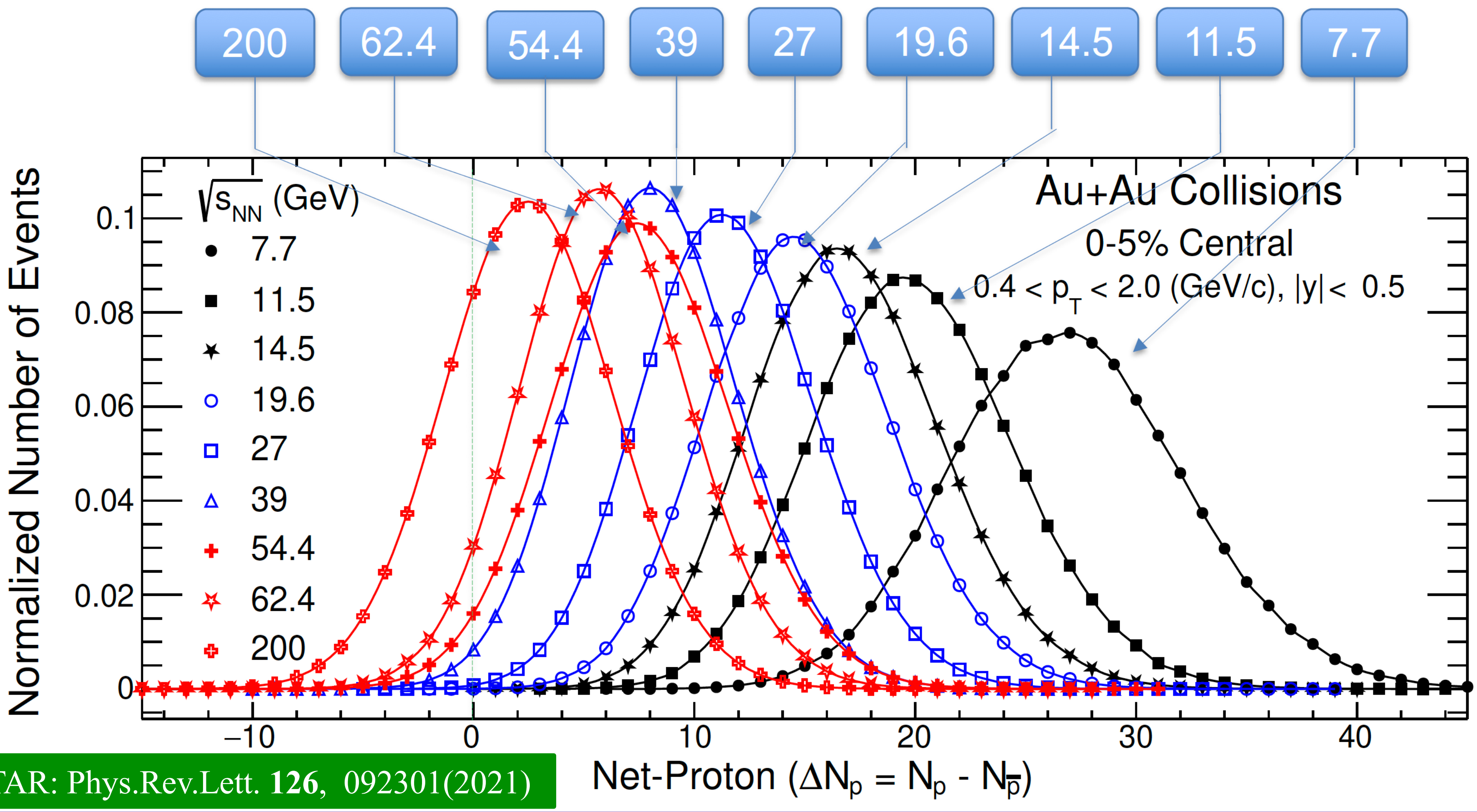




- Characteristic "Oscillating pattern" is expected for the QCD critical point but the exact shape depends on the location of freeze-out with respect to the location of CP
- Critical Region (CR)

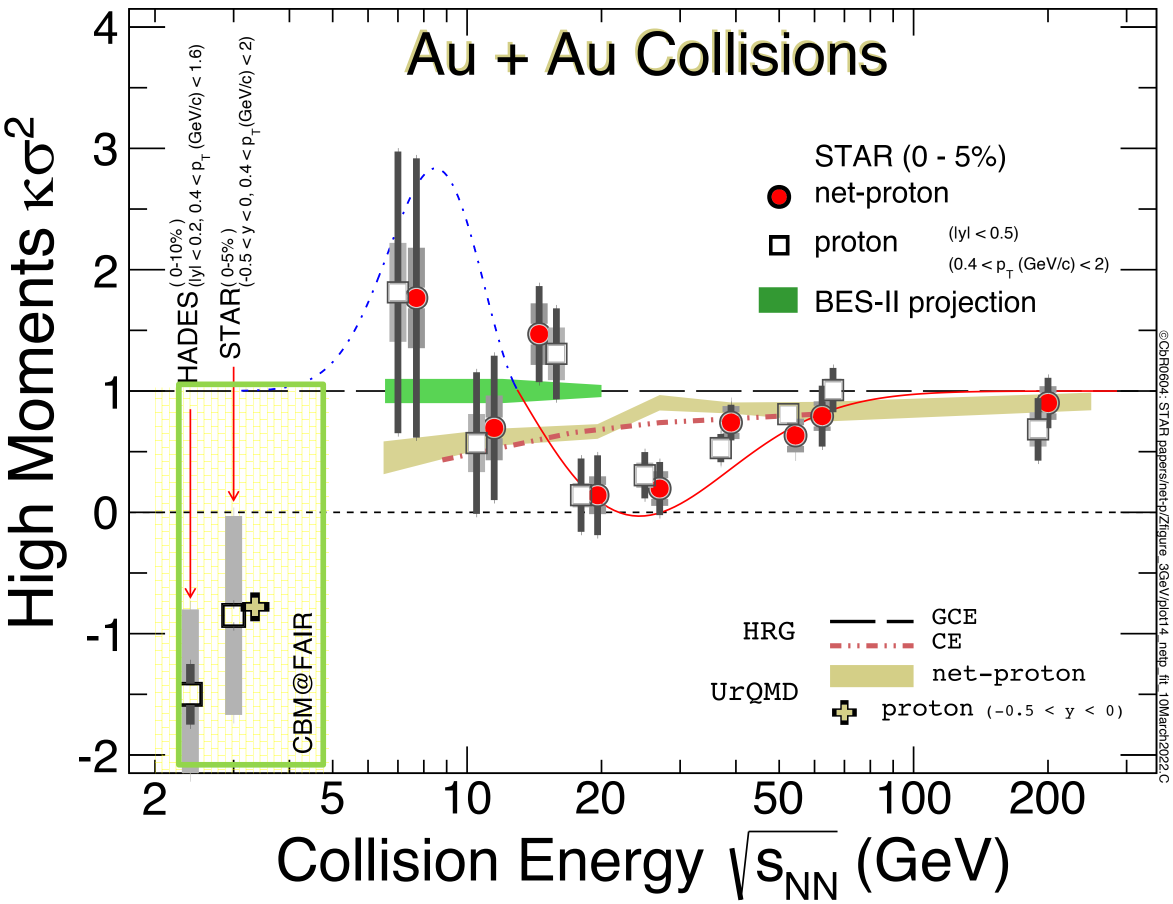
- M. Stephanov, PRL**107**, 052301(2011) - V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, Phys. Rev. **D93** (2016) 034037

Event-by-Event Net-Proton Distributions (raw)



STAR: Phys.Rev.Lett. **126**, 092301(2021)

Energy Dependence of the Net-p $\kappa\sigma^2$

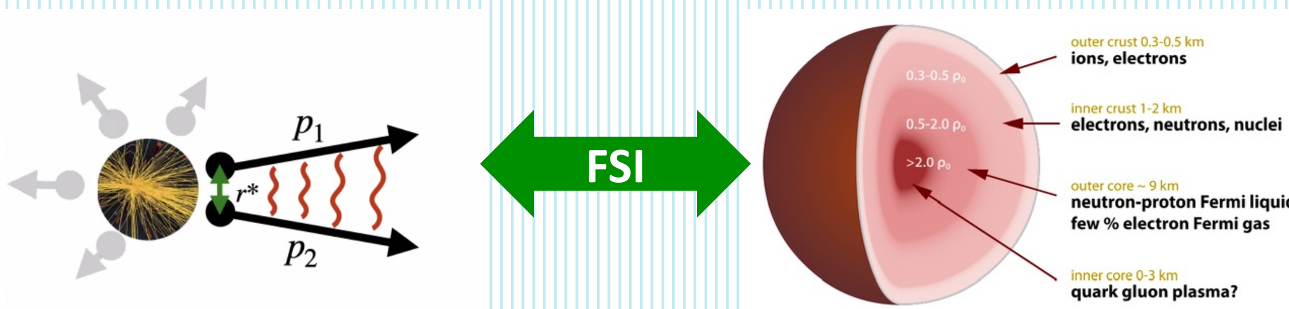


1) Non-monotonic energy dependence;
2) 3 GeV proton high moments data → **Hadronic interaction dominant!**
3) Energy gap between 3 and 7.7 GeV, important for **Critical Point search**

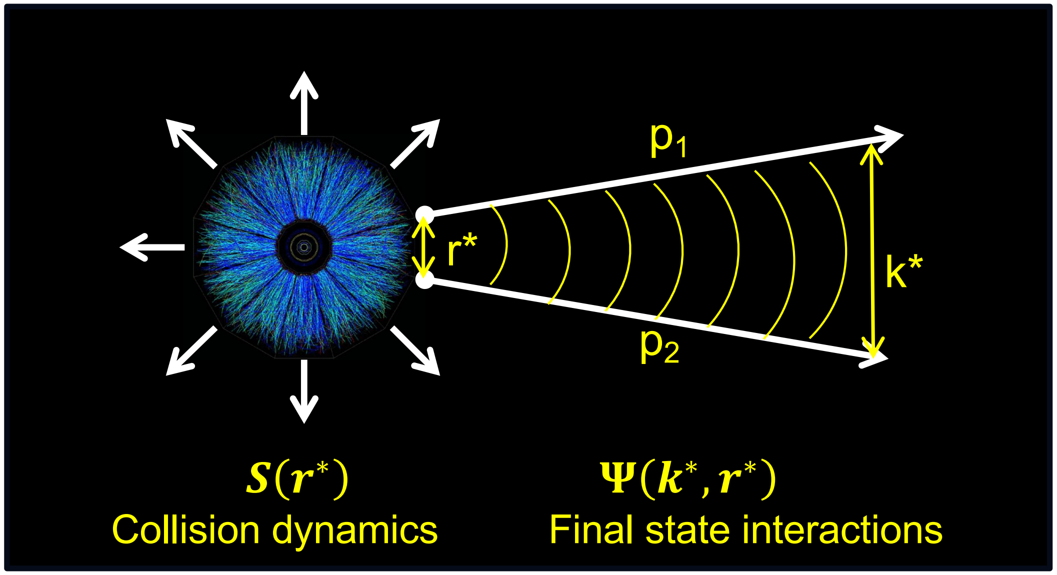
STAR: PRL**126**, 92301(2021)
PRL**128**, 202303(2022)
HADES: PRC**102**, 024914(2020)

The emergent properties of QCD matter

Baryon Correlations



Baryon Correlation Functions



STAR:

(1) Meson HBT: $\pi - \pi$, $K - K$;

(2) **Baryon correlations:**

$p - p$		reference
$p - \Lambda$,	$p - \Xi^-$	*YN*
$p - d$,	$d - d$	*NNN*
$d - \Lambda$		*YNN*

Source

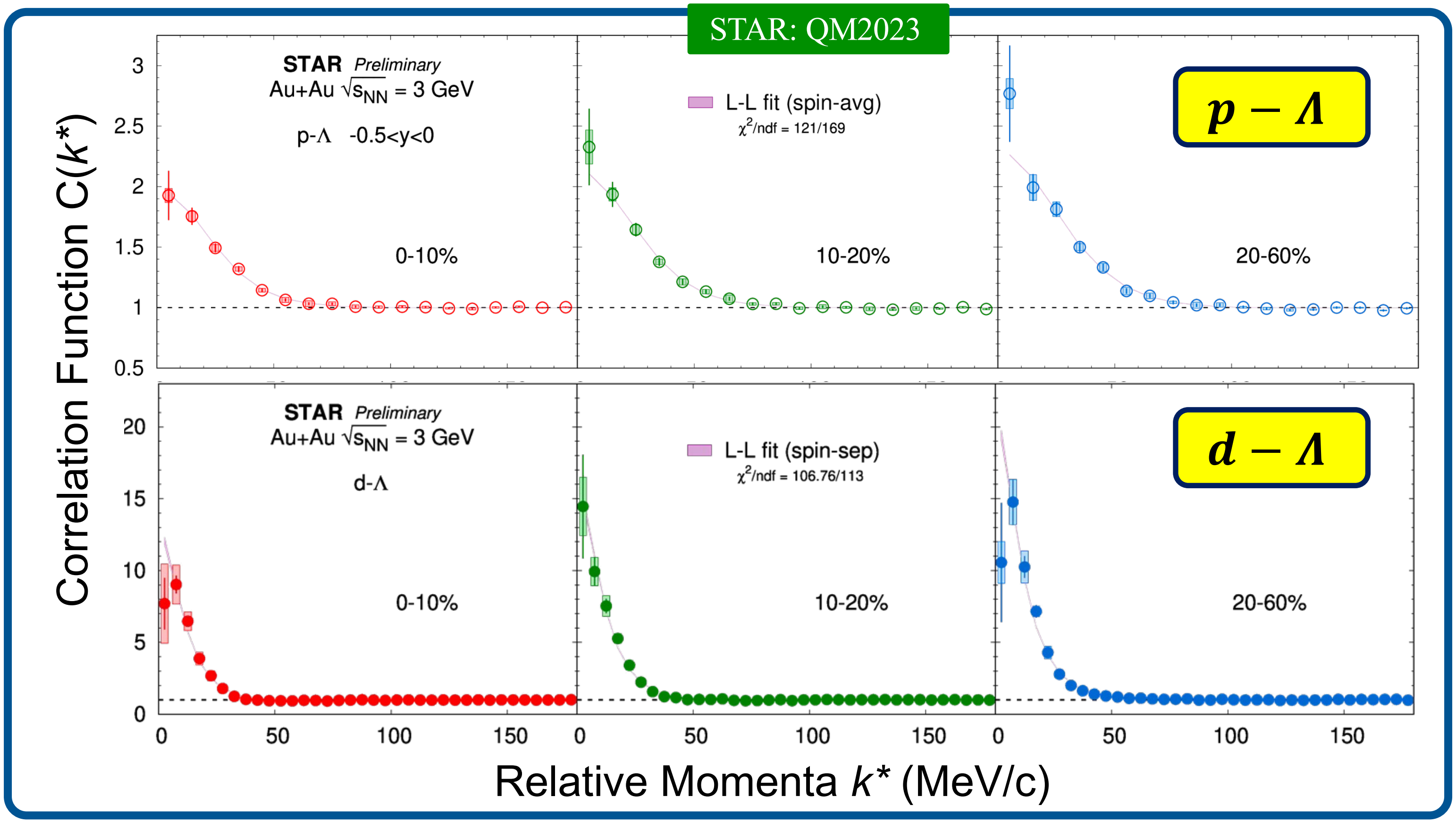
$$C_{the}(k^*) = \int d^3 r^* S(r^*) |\Psi(r^*, k^*)|^2$$

Interaction potential

$$C_{exp}(k^*) = \lambda \frac{N_{same}(p_1, p_2)}{N(p_1) N(p_2)}$$ → **Source and FSI**

$$k^* = \frac{1}{2} |p_1^* - p_2^*|$$

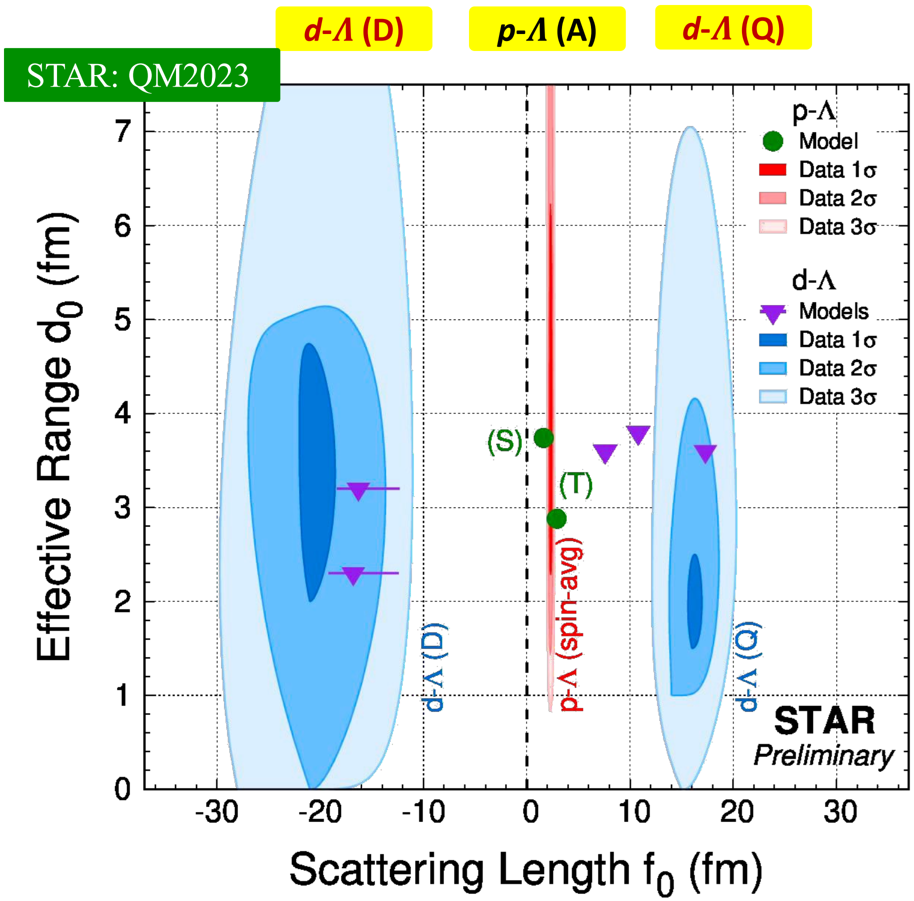
$p - \Lambda,\ d - \Lambda$ Correlation Functions



Corrections:
1) Track merging;
2) Track splitting;
3) Resonance decays;
4) Purity;
5) Momentum smearing;
6) Contribution of $^{3}_{\Lambda}H$

Acceptance:
- All: 0.5< y<0;
- **p**: 0.25< p_T < 2 (GeV/c);
- **d**: 0.25< p_T < 3 (GeV/c);
- Λ: 0.25< p_T < 2 (GeV/c)

$d-\Lambda$ Correlation Function: Final State Interactions



Forward scattering amplitude: $f(k^*) = \left\{\frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - ik^*\right\}^{-1}$

$p-\Lambda$: $\frac{1}{4}\ {}^1S_0 + \frac{3}{4}\ {}^2S_1$

$d-\Lambda$: $\frac{1}{3}\ {}^2S_{1/2} + \frac{2}{3}\ {}^4S_{3/2}$

1) Scattering amplitude shrinks once s-quark hadrons are involved. For ***d–Λ***, the spin-averaged f_0 is very close to zero, evidence for interference between different spin states;
2) When $f_0 < 0$, bound state becomes available: ${}^3He,\ {}^4He,\ {}^3_\Lambda H$;

First experimental data on identified scattering length for spin-states!

References: Hildenbrand, HWH, PRC**100** (2019) 034002

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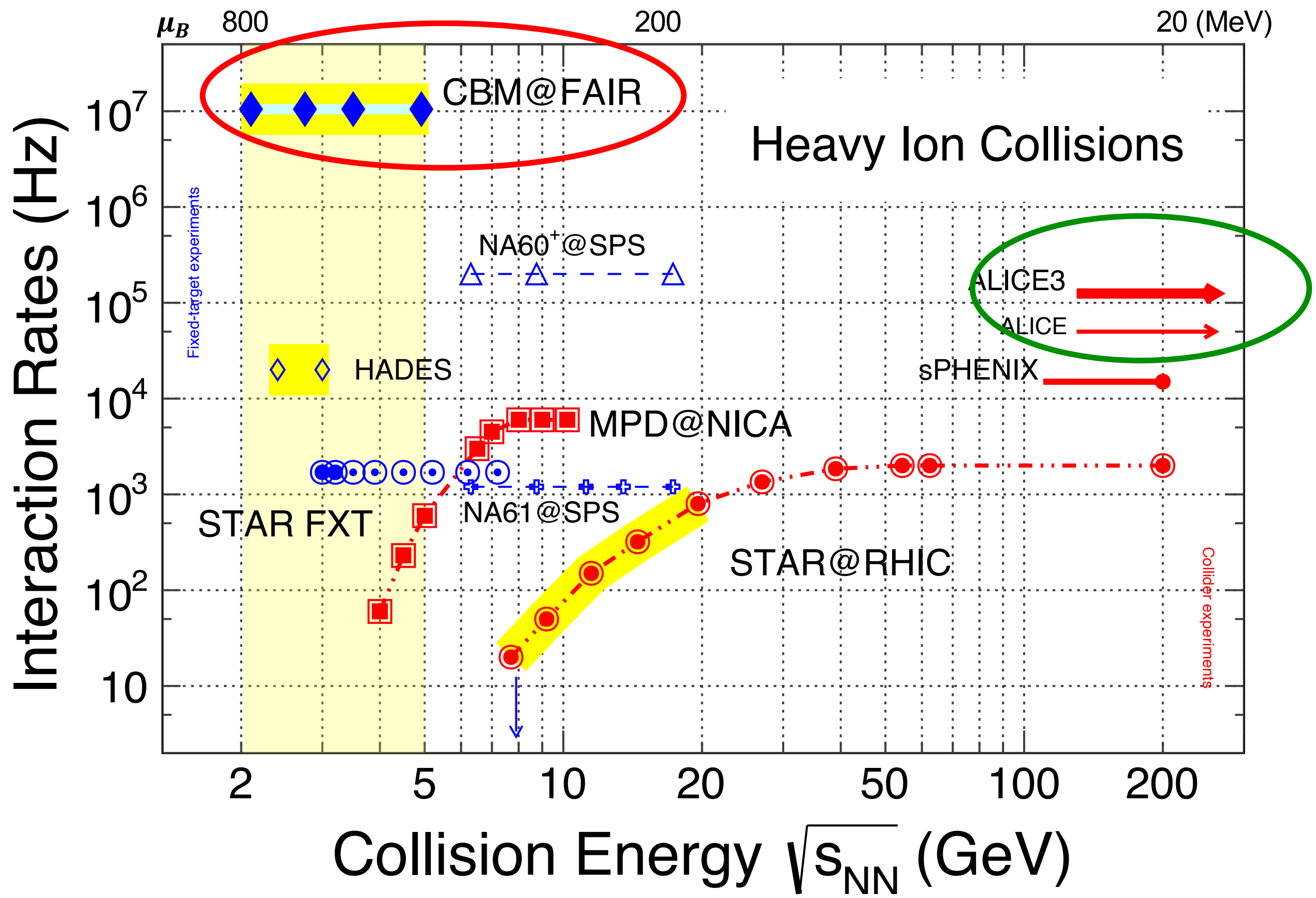
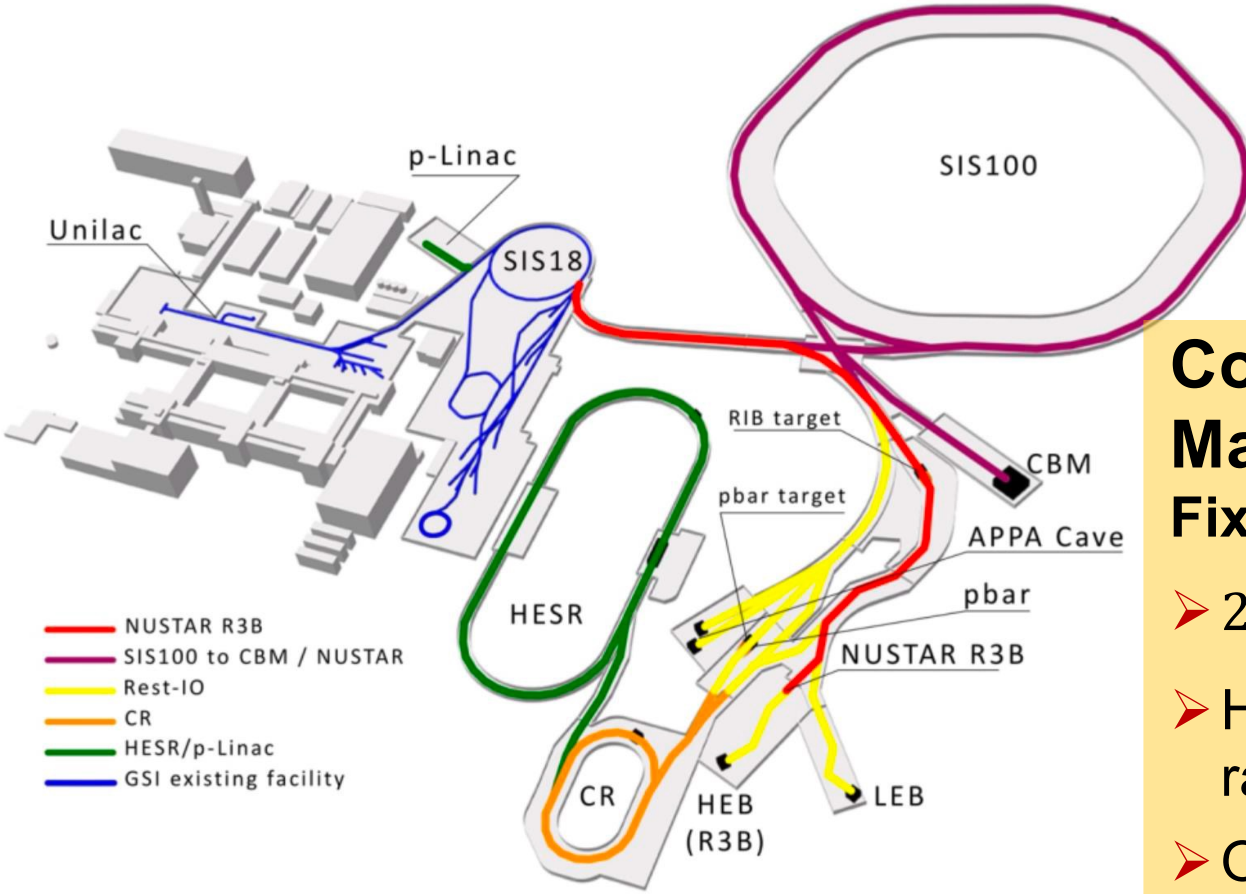
3) **Outlook**

Future High Rates Experiments

- **ALICE3:** μ_B ~ 0 Properties of QGP!
- **CBM:** Unprecedented rate capability and μ_B ~ 800 MeV
  1) High order baryon fluctuation and correlation;
  2) 3D di-lepton spectra (collision centrality, pair mass and p_T) ;
  3) Hyper-nuclei production and Y-N interactions



CBM Experiment at FAIR

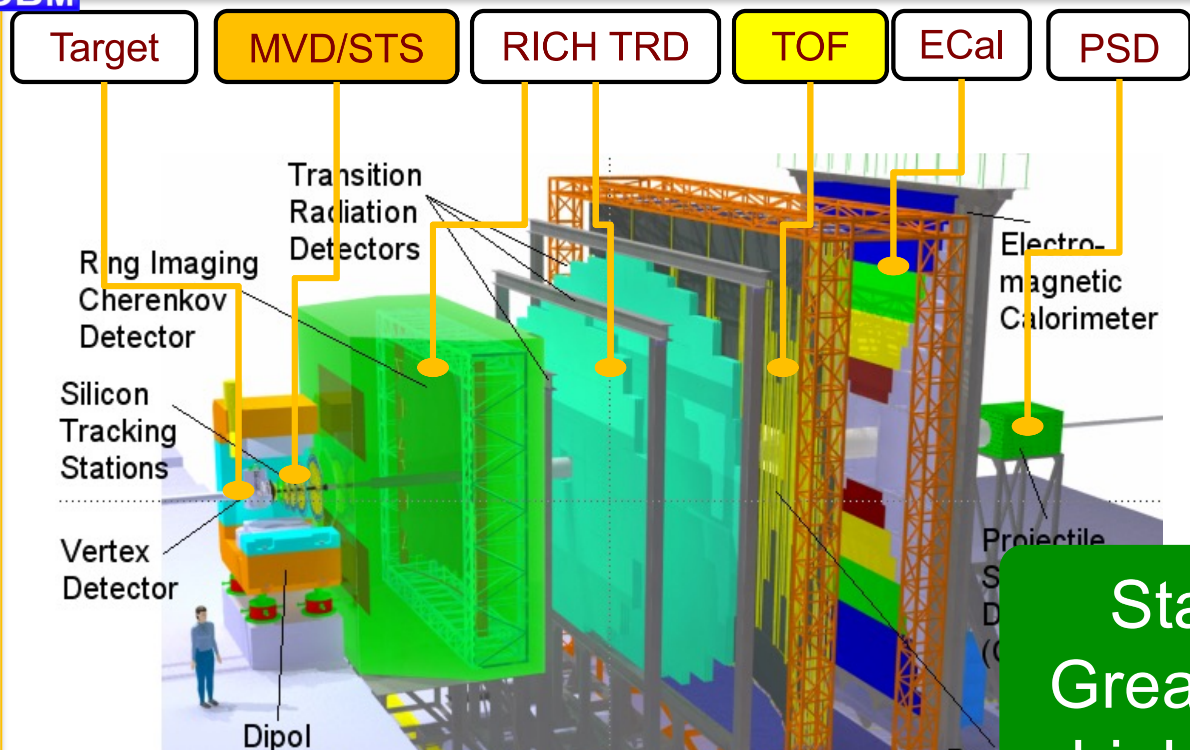


Compressed Baryonic Matter (CBM)

Fixed-target experiment:

- $2.4 < \sqrt{s_{\mathrm{NN}}} < 4.9$ GeV
- High intensity & collision rates up to 10MHz
- Operation starts in 2028

CBM Experiment at FAIR



- FAIR: One of the brightest accelerator complexes
- Precision measurements at high baryon density region:
  (i) Dileptons (*e*, *μ*);
  (ii) High order correlations;
  (iii) Flavor productions (s, c)

State-of-the-art detector!
Great discovery potentials at high baryon density region!

A dream experiment!

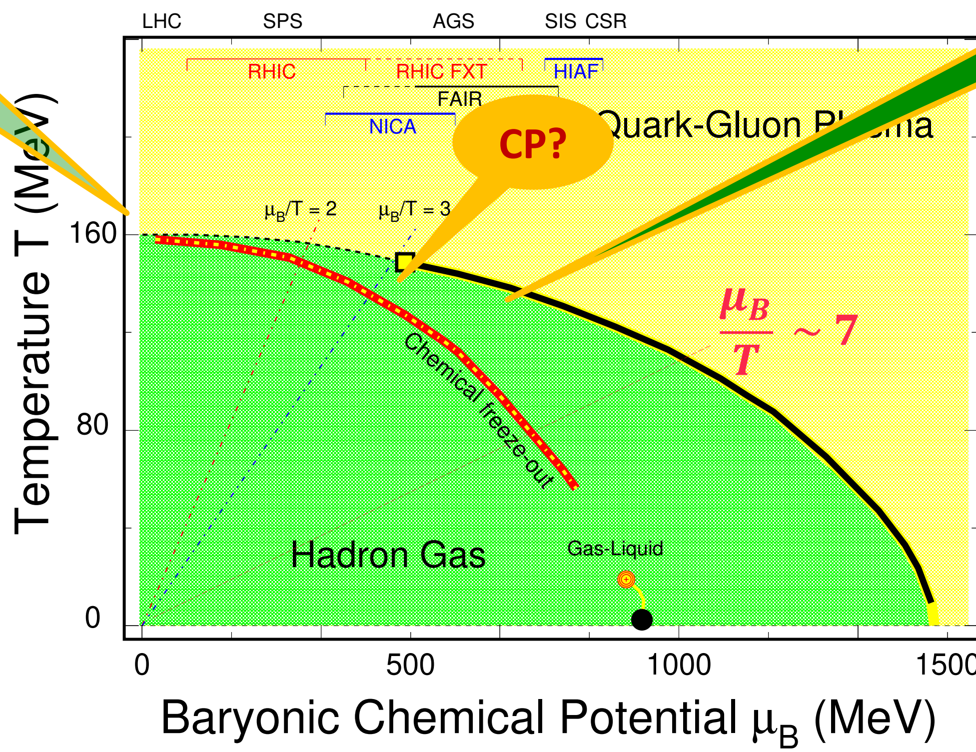
1) "The CBM Physics Book", B. Friman *et al.*, Lect.Notes Phys. **814**, 1 (2011)
2) "Challenges in QCD Matter Physics – The Scientific Program of the Compressed Baryonic Matter Experiment at FAIR", T. Ablyazimov *et al.* Eur.Phys. J. **A53**, 3 (2017).

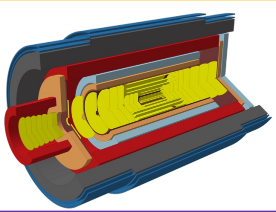
Future Physics Programs

BES-II
CBM (BES-III)

ALICE

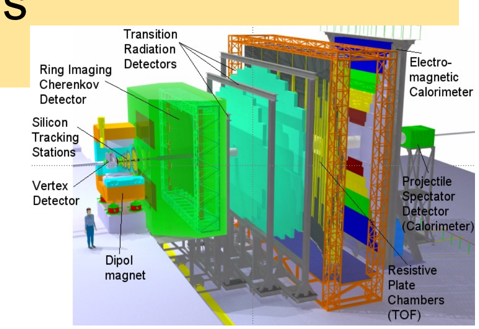
- Properties of the smooth cross-over;
- p+p collisions;
- Full lepton distributions with **ALICE3**





- Critical point and phase boundary;
- Nuclear matter EOS at high baryon density;
- Y-N interactions, inner structure of compact stars

CBM



Acknowledgements:

P. Braun-Munzinger, X. Dong, S. Esumi, V. Koch, XF. Luo, B. Mohanty, A. Pandav, K. Redlich, A. Rustamov, P. Senger, M. Stephanov, J. Stroth, I. Vassiliev, YJ. Zhou // BLUE: Theory // **RED**: Experiment //

Alexander von Humboldt Foundation

Alexander von Humboldt Stiftung/Foundation

Thank you very much for your attention!

Dear Declan:

With physics insights and *real* leadership, you have made tremendous contributions to the physics programs at the STAR experiment: in the study of Collectivity, Criticality, Femtoscopy and BES and more.

STAR is shining brightly *because of you*.

Congratulations all of the achievements!

Best wishes for your new endeavors!

Thank you!