Swagato Mukherjee

October, 2019, Virginia
Beam Energy Scan (BES) @ Relativistic Heavy Ion Collider

concerns on the existence of a critical point in the QCD phase diagram
properties of baryon-rich QGP
probe chiral symmetry restoration through chiral anomaly induced phenomena
intriguing hints in many observables from BES-I

phase I of BES ended in 2014; scanned collision energies $\sqrt{s_{\text{NN}}} = 200 - 7.7$ GeV
BES-II: 2019-2021

significant accelerator and detector upgrades to insure high statistics

from hints to definitive answers …
from hints to definitive answers …

Beam Energy Scan Theory

Topical Collaboration in Nuclear Theory
funded by DOE Office of Nuclear Physics for 2016-2021

construct a comprehensive theoretical framework for interpreting BES results

★ constraints on the existence of a critical point in the QCD phase diagram
★ properties of baryon-rich QGP
★ probe chiral symmetry restoration through chiral anomaly induced phenomena
initial conditions

chiral anomaly & EM fields: dynamics

critical fluctuations: dynamics

new phenomenology

hot-dense LQCD

EoS with critical point

global analysis of expt. data

hydrodynamic evolution

particlization

hadronic dynamics

60+ published in journals
★★ total 1200+ citations
★★ 15 Letters
★★ 3 Editors’ Suggestions
★★ 50+ conference proceedings

350+ talks
★★ 40+ plenary talks Quark Matter, CPOD, Strange Quark Matter, Lattice …
★★ 35+ colloquiums

open access code repository https://bitbucket.org/bestcollaboration/
the BEST people ...

**core:**
- 2 national labs & 12 universities
- 20 principal investigators
- 12 students, 6 postdocs

**corona:**
- ~15 active external collaborators
  - ⭐ 4 students, 2 postdoc: 100%
    funded by non-BEST sources
- ~10 close experimental contacts
the BEST research practice …

- **steering committee**: coordinate, disseminate
  - Mukherjee (project director & co-spokesperson), Koch (co-spokesperson), Gale, Kharzeev, Rajagopal

- **inter working groups**: incorporate, amalgamate
  - inter-WG video conferencing coordinated by the WG conveners
  - inter-institution visits and exchanges of students & postdocs

- **intra working groups (WG)**: communicate, assimilate, implement
  - 5 WG: EoS & critical fluctuations, initial conditions, hydrodynamics, chirality anomaly, hadronic transport & data analyses
  - regular intra-WG video conferencing lead by each WG convener
  - inter-institution, inter-/intra-WG 1-4 week long visits of students & postdocs: ~15

- **core institutions/groups**: germinate, formulate, demonstrate
  - many times same topics for 2 groups: independent formulations & reproduction

- **annual all-hands-meeting**: delineate, agreement, accept
  - open, democratic, voluntary
  - having pre-defined goals naturally helps the process
the BEST training practice …

- **train**: 12 graduate students so far
  - ★ ~50% funded by BEST, ~50% funded by non-BEST resources
  - ★ enormously helped by inter-institutional exchanges & visits
  - ★ interaction & direct collaboration with multi-institutional group

- **retain**: 6 postdocs so far
  - ★ if possible, from already trained BEST student pool: new collaborations, productive
  - ★ ~50% funded by BEST, ~50% funded by non-BEST resources
  - ★ senior postdocs becomes WG conveners (3+)
  - ★ students + postdocs: ~75% of total BEST budget

- **broaden**: 7 BEST postdocs have became faculties so far
  - ★ South Korea (1), France (1), China (2), US (3, including bridge positions)
the BEST bridge positions …

Chun Shen
Assistant Professor
Wayne State University

Vladimir Skokov
Assistant Professor
North Carolina State University

★ ~25% BEST for first 3 years (~20% of total BEST budget)
★ ~ 25% RIKEN-BNL Research Center for first 3 years; ~50% for next 2 years
★ ~ 50% universities for 5 years
★ both were active & important postdoc members of BEST
the BEST liaising with experimenters …

- ~10 close experimental contacts
- overview talks in annual STAR collaboration meetings
- lectures in STAR Junior’s day for young experimenters
- co-authored research publications and review article with experimenters
- conferences and workshops organized with experimenters (~ 7)
  ★ with partial BEST support
initial conditions

chiral anomaly & EM fields: dynamics

critical fluctuations: dynamics

new phenomenology

hydrodynamic evolution

particlization

hadronic dynamics

global analysis of expt. data

EoS with critical point

hot-dense LQCD

BESr COLLABORATION
QCD phase boundary

2 groups (BNL, UH),
2 approaches,
2 independent calculations,
excellent agreements!


scaled kurtosis of net baryon number fluctuation


QCD EoS @ $\mu_B > 0$

Borsanyi et. al.: JHEP 1810, 205 (2018)
initial conditions

hot-dense LQCD

critical fluctuations: dynamics

critical fluctuations: dynamics

chiral anomaly & EM fields: dynamics

EoS with critical point

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hydrodynamic evolution
led by a UH grad student,
9 authors across 7 BEST institutions,
open access code

extended to transport coefficients (NCSU)

hot-dense LQCD

EoS with critical point

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initial conditions

chiral anomaly & EM fields: dynamics

critical fluctuations: dynamics

new phenomenology
rapidity distribution of net proton

thermal conditions of the fireball at different points

Shen, Schenke: in preparation


led by C. Shen: postdoc (BNL) → faculty (WSU)
convener of the hydrodynamics WG

2 groups (BNL-McGill, OSU),
2 algorithms, reproducibility checked,
open access codes
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dynamics

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full implementations of Hydro+ in BEST hydro codes are in progress

OSU+MIT: lead OSU grad student; possible by his MIT visit

McGill+WSU+BNL: completely different fluctuating hydro approach; lead McGill grad student; possible by his WSU, BNL visits

numerical demonstration of Hydro+ at work in simple case (MIT)

Rajagopal, Ridgway, Weller, Yin, arXiv:1908.08539

Hydro+: include backreaction of critical fluctuations on hydrodynamics (MIT+UIC)


dynamics of critical fluctuations on hydrodynamic background (BNL)

Monnai, Mukherjee, Yin Phys. Rev. C 95, 034902
Mukherjee, Venugopalan, Yin: Phys. Rev. Lett.117, no.22, 222301 (2016) (Editors’ Suggestion); DOE Science Highlights

led by Y. Yin: Ph.D (UIC) → postdoc (BNL) → postdoc (MIT) → faculty (IMP, China)

convener of the EoS & critical fluctuation WG
initial conditions

Chiral anomaly & EM fields: dynamics

critical fluctuations: dynamics

New phenomenology

hydrodynamic evolution

Particlization

Hadronic dynamics

global analysis of expt. data

Hot-dense LQCD

EoS with critical point

Hydrodynamic evolution
background characterization

dynamics of magnetic field

chiral anomaly + viscous hydro

collaboration with experimenter; open access code
SBU + BNL + MIT + WSU; open access code
lead former IU grad student; now postdoc in McGill; possible by visits to OSU (hydro)
hot-dense LQCD

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global analysis of expt. data

EoS with critical point
critical point search using rapidity dependence of proton cumulants


constraints on $\mu_B$-range of validity of LQCD calculations

Mukherjee, Skokov: arXiv:1909.04639

out of unexpected collaborations!
(MIT-BNL; NCSU-BNL)
difficulties encountered …

- small pot of money for a single institution
  - unable to support a full student/postdoc
  - success of TC critically dependent on other fundings
  - difficulties in retaining trained talent pool; hard to maintain codes

- had to choose student/postdoc visits & exchange over summer school due to lack of money

- prioritizing research deliverables severely limited money for bridge positions
  - w/o RIKEN/BNL help even one bridge position would have been difficult

- bridge positions might not materialize within the planned budget-year due extraneous factors
  - flexibility to continuing the bridge position support beyond the TC's lifespan might help
BEST: delivering excellent world-leading science; on track to achieve goals
★ tackling big problems — bigger than the sum of its parts
★ generating new ideas & innovative solutions
★ producing unique results
★ making those open access

BEST: effective in training & retaining talent pool

BEST: successful in facilitating, promoting junior faculty positions

BEST: excelling in connecting, liaising outside nuclear theory

the Topical Collaboration framework is essential for this success
★ invigorates, coalesces, focuses large communities
★ encourages communities to address big, difficult open issues
★ generates new collaborations, leading to new ideas, solutions
★ attracts additional supports, fundings
★ insures long-term success of communities well beyond its lifespan

summary …