

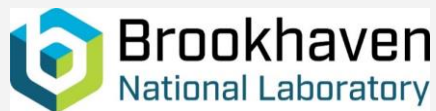
# Heavy-Flavor Theory for QCD Matter:

## Structure, Objectives + HF Transport in Media



**Ralf Rapp (for the Collaboration)**

**DOE TCNT PI Exchange Meeting,  
Washington (DC), May 02, 2024**

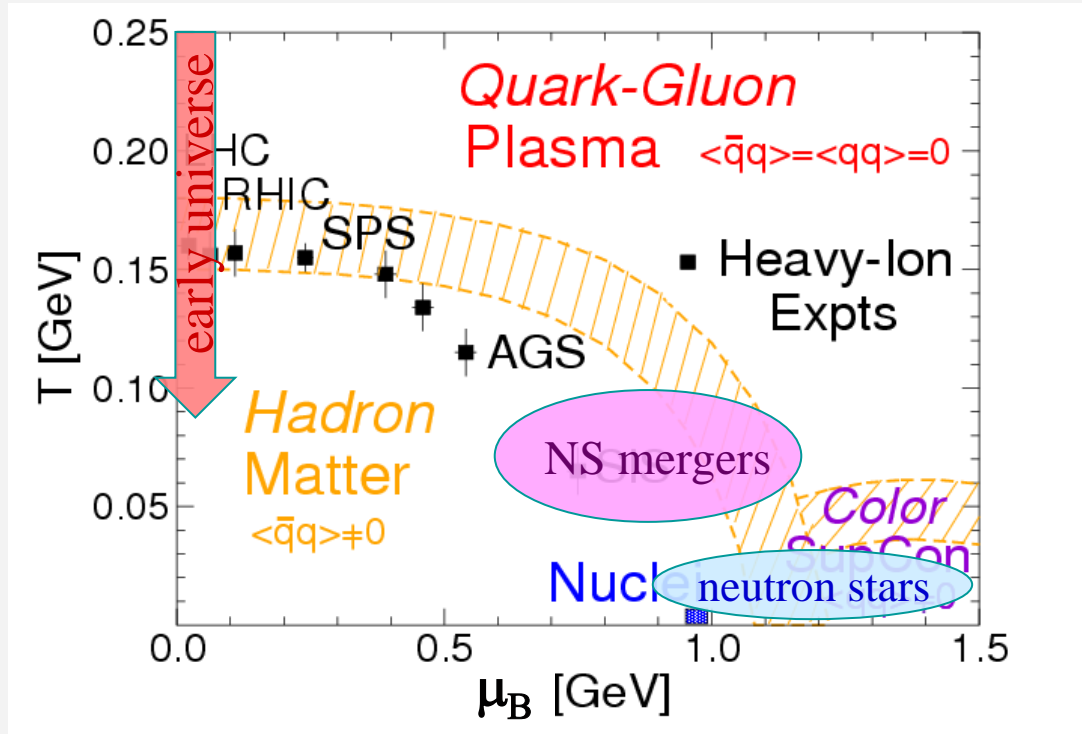


# Outline

- **Overview + Organization**
- **Webpage**
- **Publications + Highlights**
- **Working Groups + Personnel**
- **Progress toward Milestones (WGs 3+4)**

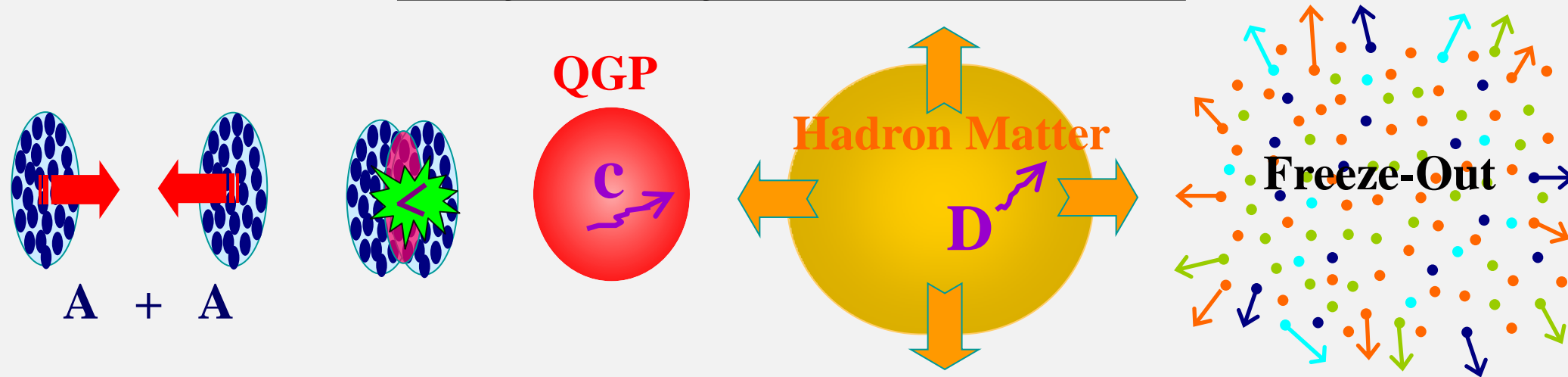
Following talks: Ethics + WG-2 → R. Vogt  
Collab. Efforts + WG-1 → P. Petreczky

# QCD Matter: Open Questions



- **Transport properties** + their emergence from the underlying interaction
- **Spectral functions** + degrees of freedom
- Mechanisms for **converting** quarks + gluons into hadrons
- Role of **quantum effects** in the strongly-coupled QGP

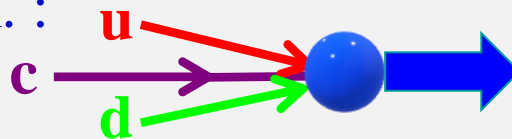
# Why Heavy-Flavor Probes?



- Large mass:  $m_Q \gg \Lambda_{\text{QCD}}, T, T_c$
- Produced early, **diffuse** through QCD medium
- Delayed thermalization: gauge of **interaction strength**
- Ample connections to thermal **lattice QCD**

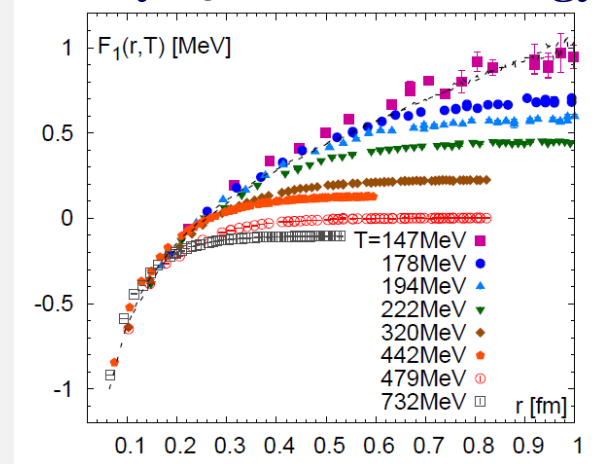
- **Hadronization:** reco. vs fragm. :

$$c \rightarrow \mathbf{D}, \mathbf{D}_s, \Lambda_c, \mathbf{J}/\psi, \dots$$



- Discernible **transition** from diffusion to radiation
- Mass effects in **radiation**
- **Hot vs. cold** matter effects

Heavy-Quark Free Energy

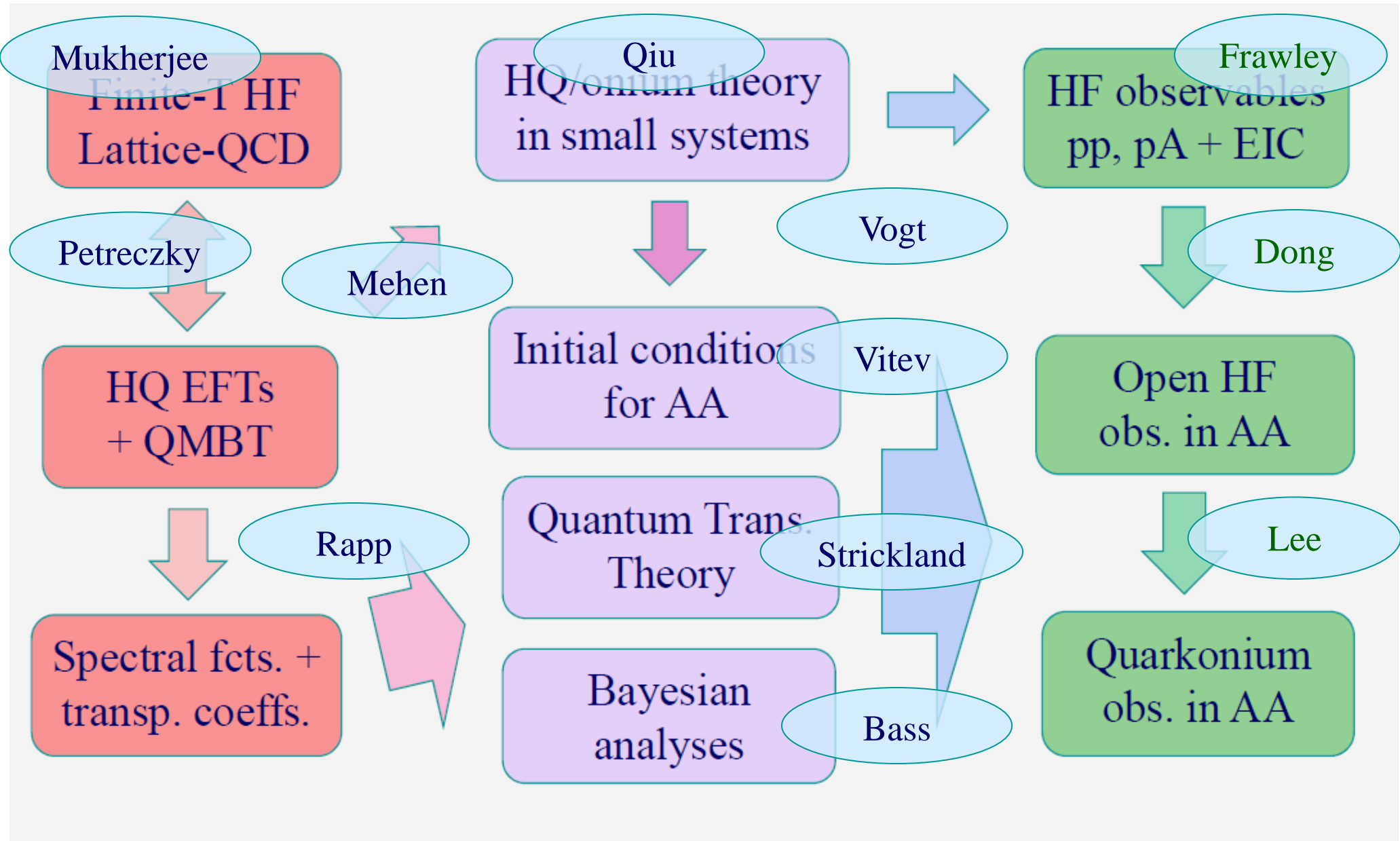


*Integrated approach needed!*

# HEFTY Overview + Organization

- 12 PIs from 10 institutions, 10 active junior personnel
- Management: PI (Rapp) + 2 co-spokespersons (Petreczky + Vogt)  
+ ombuds person (Vogt)
- 4 Working Groups [4 conveners], meet biweekly, detailed minutes:
  - WG-1: **Heavy flavor in equilibrium QCD matter** [Petreczky]
  - WG-2: **Heavy flavor in small systems** [Vitev/Vogt]
  - WG-3: **Open HF transport** [RR]
  - WG-4: **Quarkonium transport** [RR]
  - a few inter-WG projects to date
- Quarterly PI Meetings (6 since Dec. '22)
- 1<sup>st</sup> Collaboration meeting (in-person, June 7-9, '23, LBNL)
- HEFTY Summer School + 2<sup>nd</sup> Coll Mtg (June 24-28, '24, Santa Fe)
- Collaboration webpage ([tamu.hefty.edu](http://tamu.hefty.edu))

# HEFTY Flow Chart + PI Expertise



# HEFTY Webpage

- [hefty.tamu.edu](http://hefty.tamu.edu)
  - announcements (press releases, etc.)
  - working group schedules + minutes
  - publications, talks + data repository
  - calendar + events (non-/HEFTY mtgs.)
  - bylaws, code of conduct
  - several pwd protected areas

**Topical Collaboration on Heavy-Flavor Theory (HEFTY) for QCD Matter**

U.S. DEPARTMENT OF ENERGY | Office of Science  
A Department of Energy funded collaboration in Nuclear Theory

**Mission Statement:**

High-energy collisions of heavy atomic nuclei provide the fascinating opportunity to study strongly interacting matter under extreme collision, including the quark-gluon plasma (QGP), that last existed just a few microseconds after the Big Bang. The heavy charm and bottom quarks ("heavy flavors") are premier probes of the fascinating properties of the QGP and its transition back into hadrons, which involves the fundamental phenomena of quark confinement and mass generation.

The HEFTY collaboration aims at developing a comprehensive theory framework to study the spectral and transport properties of heavy quarks and quarkonia in strongly interacting matter, and implement these into quantum transport approaches that will be deployed to the analysis of heavy-flavor observables at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), providing unprecedented and quantitative insights into the microscopic properties of the QGP and its hadronization.

**Announcements**

DOE: Department of Energy Announces \$11.24 Million for Research on Nuclear Theory Topical Collaborations | Department of Energy

TAMU: Heavy duty: \$2.5 million of effort will expand knowledge of nuclear matter's basic ingredients, properties and processes – Research@Texas A&M | Inform, Inspire, Amaze (tamu.edu)

BNL: [https://www.bnl.gov/newsroom/news.p hp?w=120966\\_spacexdality](https://www.bnl.gov/newsroom/news.p hp?w=120966_spacexdality)

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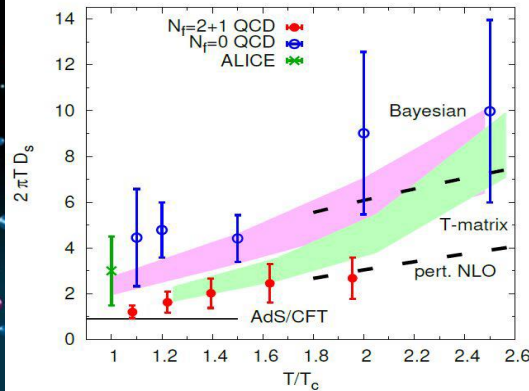
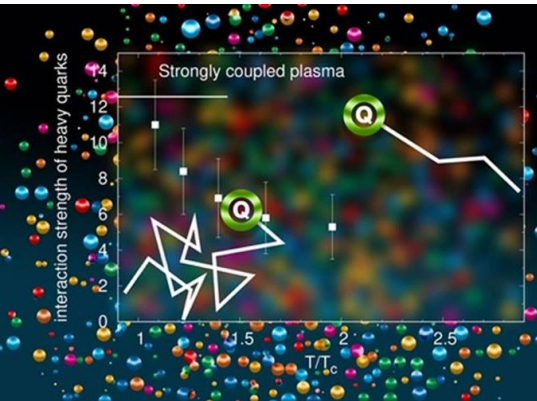
[About Us](#) | [Code of Conduct](#) | [Collaboration Members](#) | [News](#) | [Contact](#) | [Publications and talks](#) | [Activities](#) | [Data Repository](#)  
[Calendar and Events](#) | [Zoominfo](#) | [Working Group 1: Open LF Transport](#) | [HEFTY PI Meeting](#) | [Working Group 4: Quarkonium Transport](#)  
[Requests](#)



# Publications

- Preprints posted on internal webpage ~7 days prior to arXiv submission
- HEFTY acknowledgment
- 15 papers thus far (+procs.), including 2 DOE web highlights

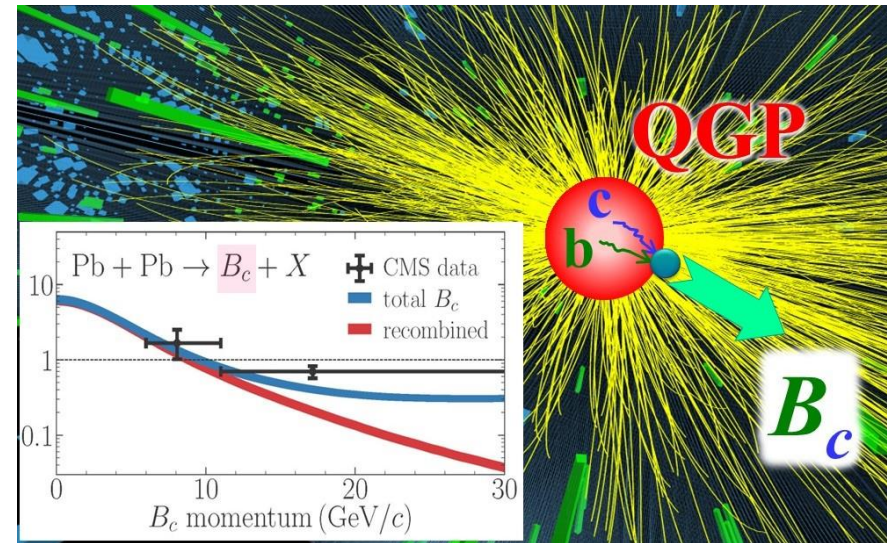
## Heavy-Quark Diffusion from Lattice QCD



Altenkort, Mukherjee, Petreczky et al [PRL '23]

- Spatial diffusion coefficient close to quantum bound, weak  $T$ -dependence

## Recombination of $B_c$ Mesons at the LHC



Wu, Tang, He+Rapp [PRC'24]

- Diffusing  $b + c$  quarks recombine  $\Rightarrow$  large enhancement at low momenta



# Working Group Personnel + Hiring

- **WG-1:** Petreczky (conv), Mukherjee, Rapp;  
Zhanduo Tang, Hai-Tao Shu, Jorge DaSilva;  
HF spectral + transport properties in equilibrium matter (lQCD +EFT)
- **WG-2:** Vitev (conv), Dong, Frawley, Mehen, Qiu, Vogt;  
Vincent Cheung, Reed Hodges, Jia-Yue Zhang;  
HF production mechanisms in small systems: pp, pA, eA (pQCD + EFT)
- **WG-3:** Rapp (conv), Bass, Dong, Lee, Vitev, Vogt;  
Yu Fu, Weiyao Ke, Tharun Krishna;  
HF transport + hadronization in AA (diffusion, radiation, Bayesian analyses)
- **WG-4:** Rapp (conv), Frawley, Lee, Mehen, Strickland, Vitev, Vogt;  
Jacob Boyd, Biaogang Wu; **KSU-faculty bridge hire ongoing**  
Quarkonium transport in AA (quantum diss/reco coupled to open HF)

*Dedicated (junior) personnel critical to develop collaborative synergy!*

# Summary of Milestones

[WG]

## • Years 1-2

**MS-1:** Complete set of bottomonium spectral functions in sQGP with uncertainties [1]

**MS-2:** Comprehensive theory of open HF production + hadronization in  $pp$  and  $ep$  [2]

## • Years 2-3

**MS-3:** Lattice based microscopic description of open and hidden HF in sQGP [1]

**MS-4:** Over-constrained extraction of T- and p-dependent HF trans. coeffs. in AA [3]

**MS-5:** Quantified extraction of HF jet-transport coefficients in AA [3]

**MS-6:** Comprehensive quantum transport approach for quarkonia in sQGP [4]

## • Years 4-5

**MS-7:** Complete set of nonperturbative quarkonium transport coefficients [4]

**MS-8:** Microscopic theory of quarkonia and open HF production in  $pA$  and  $eA$  [2]

**MS-9:** Assessment of HF transport + hadronization mechanisms: diffusive  $\rightarrow$  radiation [3]

**MS-10:** Microscopic IQCD-based quantum transport analysis of quarkonia in AA [4]

# Working Group-3 Progress: Open HF Transport

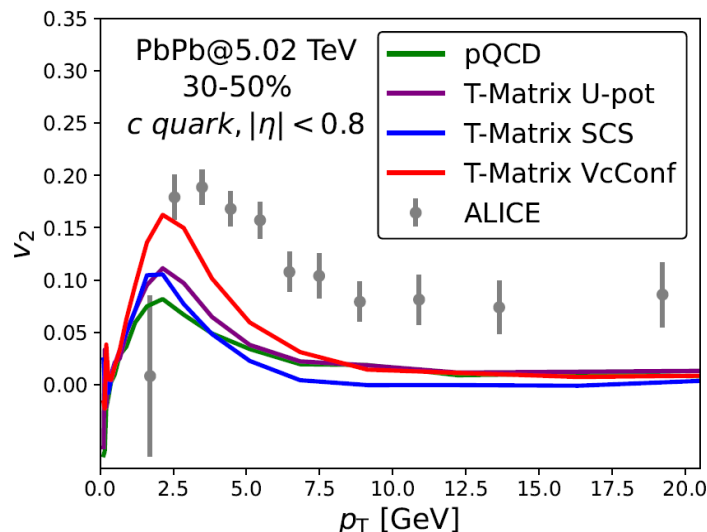
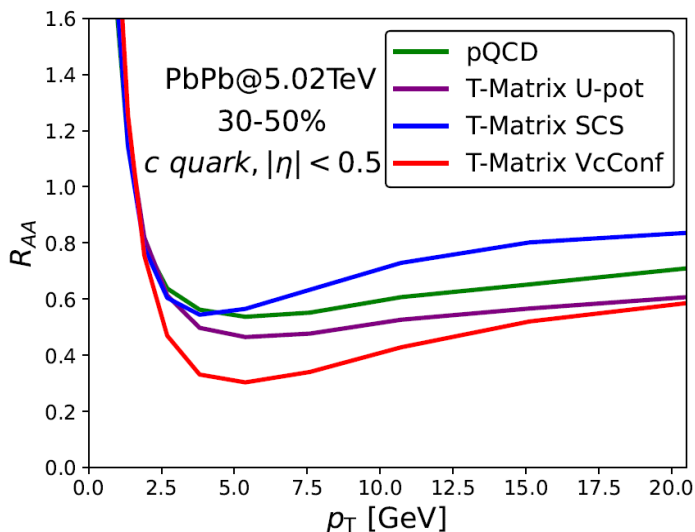
## **Deliverable:**

A theoretical framework for transport + hadronization of heavy quarks in heavy-ion collisions based on first-principles transport coefficients utilizing rigorous data analysis methods

- **MS-4:** Over-constrained extraction of T- and p-dependent HF transport coefficients from Bayesian data analysis based on MS-3 (trans. coeffs. WG1) MS-8 (initial conds. WG2)
  - T-matrix charm-quark trans. coeffs. implemented into realistic QGP-hydro [Y.Fu, Z.Tang]
- **MS-5:** Quantified extraction of HF jet-transport coefficients
  - Systematic comparisons of radiative energy loss calculations (opacity expansion) with effective transport implementation of coherent radiation [W.Ke, Z.Tang]
- **MS-9:** Novel assessment of HF transport + hadronization mechanisms in transition from diffusive to energy loss regime
  - Implementing resonance recombination model utilizing 6-dim heavy-quark phase distributions from hydro transport output [T.Krishna, Y.Fu]

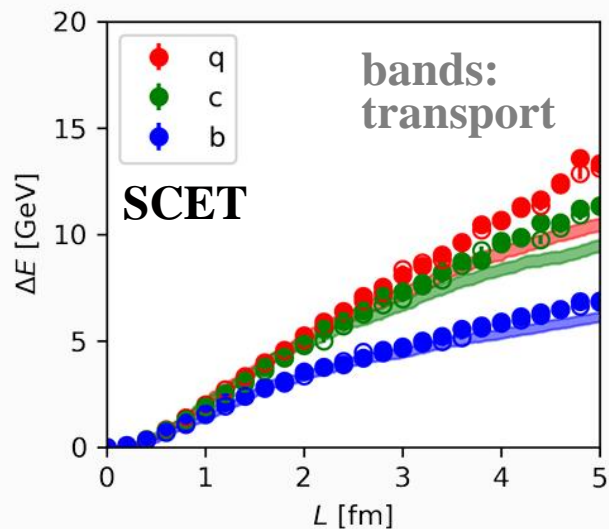
# WG-3 Highlights: Open HF Transport

- **MS-4:** TAMU T-matrix  $c$ -quark trans. coeffs in Duke QGP-hydro [Y.Fu, T.Krishna, Z.Tang]



- Sensitive to interaction
- reco in progress
- promising  $v_2$  values

- **MS-5:** Radiative energy loss: opacity expansion vs. effective transport [W.Ke, I.Vitev]



- Effective interference + dead cone effect agrees with high- $p_T$  theory
- Paves the way to connect to low- $p_T$  transport

# Working Group-4 Progress: Quarkonium Transport

## **Deliverable:**

A theoretical framework for quantum transport of quarkonia in heavy-ion collisions utilizing density matrices based on lattice-QCD derived potentials + reaction rates, coupled to open HF

- **MS-6:** Microscopic quantum transport approach for quarkonia in sQGP based on matching of Brownian motion and semi-classical regimes
  - Constructing semiclassical transport with nonpert. reaction rates and regeneration via explicit HF diffusion [J.Boyd]
- **MS-7:** Complete set of nonperturbative quarkonium transport coefficients
  - Calculated charmonium and bottomonium reaction rates utilizing T-matrix (WG1) [B.Wu]
- **MS-10:** Comprehensive analysis of quarkonium data at RHIC + LHC to extract transport parameters + in-medium heavy-quark potential based on MS-7 + MS-8 (WG-2)
  - Published analysis of bottomonium suppression in pA collisions using cold-nuclear-matter effects (WG2) + QGP suppression in hydro evolution [S.Thapa]

# WG-4 Highlights: Quarkonium Transport

- MS-6:** Transport with recombination via explicit HQ diffusion [J.Boyd]

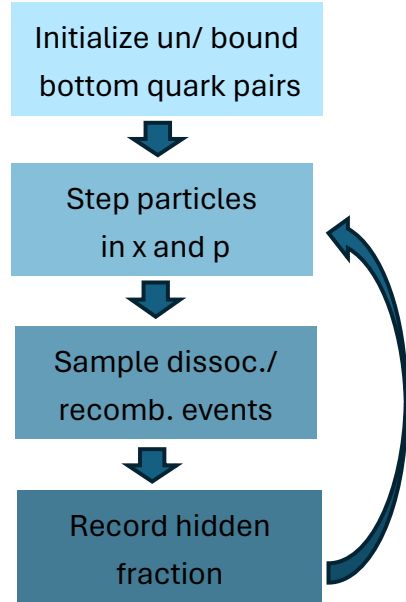
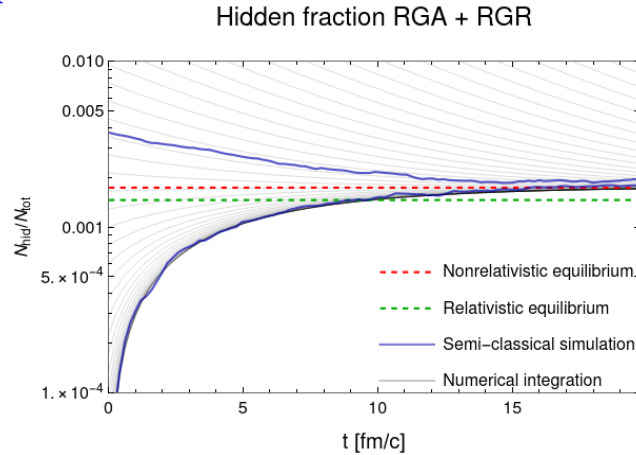
- Numerically simulate coupled Boltzmann transport for bottom/onium

- MC sampling reco. + dissoc. + diffusion

$$\Gamma_{\text{diss},i}^{\text{tot}}(\mathbf{p}_i) = \Gamma_{\text{diss},i}^{\text{RGA}} + \Gamma_{\text{diss},i}^{\text{IDG}} + \Gamma_{\text{diss},i}^{\text{IDQ}}$$

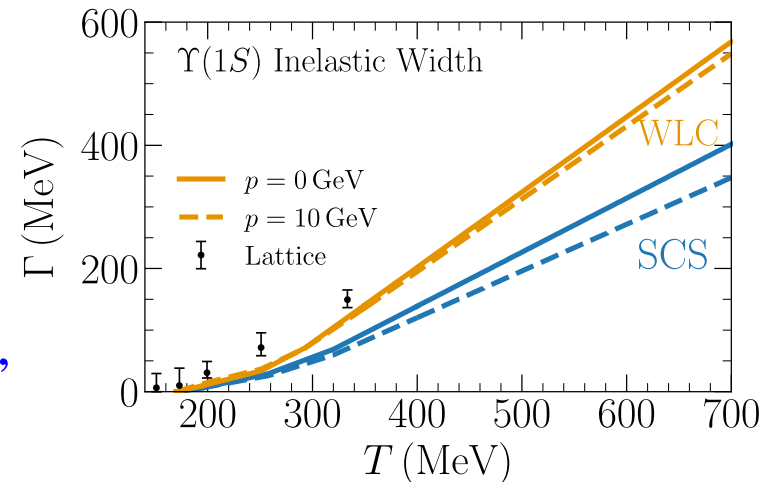
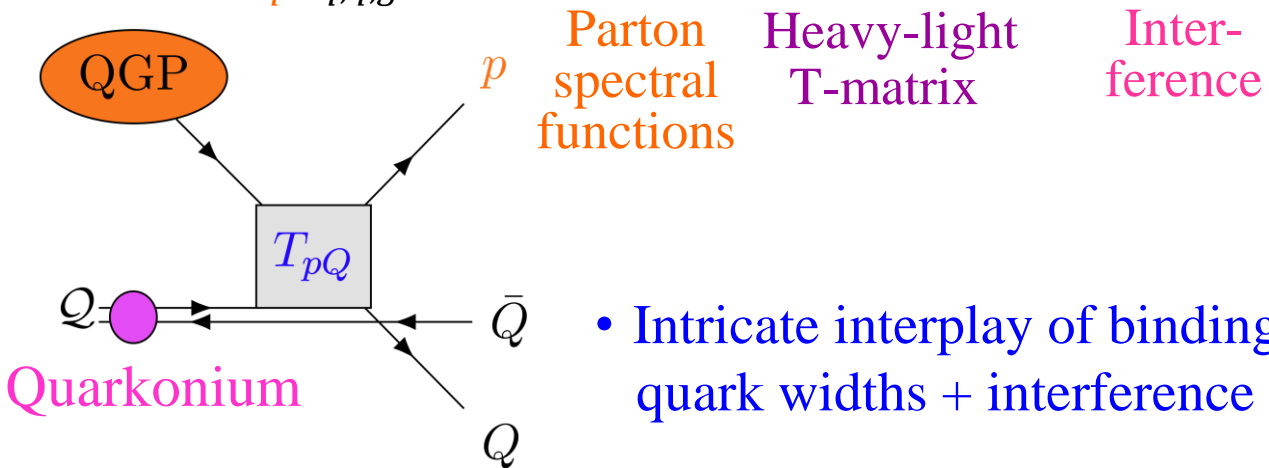
$$\Gamma_{\text{rec},i}^{\text{tot}}(\mathbf{x}_i, \mathbf{p}_i) = \sum_j \Gamma_{\text{rec},ij}^{\text{RGR}} + \Gamma_{\text{rec},ij}^{\text{IRG}} + \Gamma_{\text{rec},ij}^{\text{IRQ}}$$

✓
✗
✗



- MS-7:** Charmonium + bottomonium reaction rates in sQGP from T-matrix [B.Wu, WG1]

$$\Gamma_Q(p_Q; T) = \sum_{p=q, \bar{q}, g} \int \rho_i \rho_f \rho_Q |T_{pQ \rightarrow pQ}|^2 \delta^{(4)}(P - P') f_p(E_i) [1 - e^{iq \cdot r}]$$



# Summary + Future Perspectives

- Development and synergy of HF transport components beyond state-of-the-art, covering RHIC/LHC + EIC
- Systematic + sustained WG structure + activities
- Genuine HEFTY **collaborative** efforts in year-1, progressing towards MSs
- Increasing **inter-WG** activities
- **Exchange visits** of junior personnel throughout HEFTY institutions
- **Bridge** position at Kent State Univ
- Year-2 **summer school**