Jets and Quarkonium as Open Quantum Systems

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Jets:
Varun Vaidya, XY, arXiv:2004.11403

Quarkonium:
XY, Thomas Mehen, 1811.07027
Thomas Mehen, XY, 2009.02408
XY, 2102.01736

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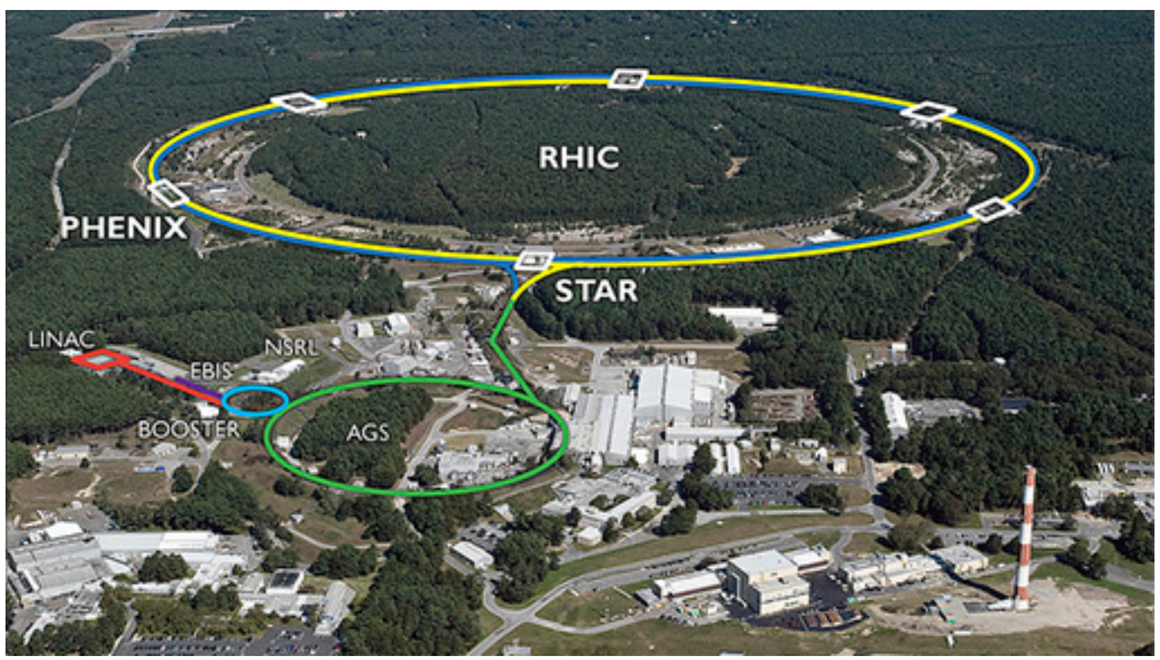
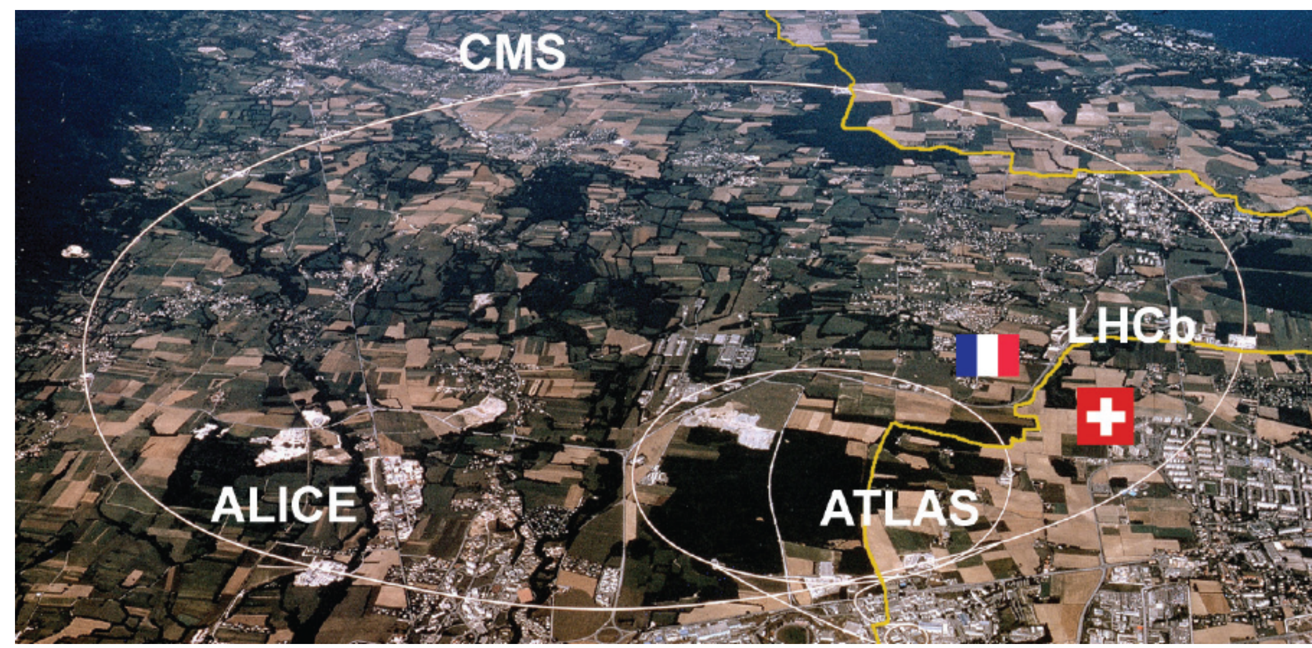
Heavy Ion Collisions and Quark-Gluon Plasma

- Asymptotic freedom —> deconfined phase of QCD expected at high temperature / density —> quark-gluon plasma (QGP)

- Study QGP: heavy ion collision experiments at RHIC and LHC





- Quark gluon plasma created in Au-Au / Pb-Pb collisions: nearly “perfect” fluid (small viscosity), strongly coupled, temperature ~150-500 MeV, lifetime ~ 10 fm/c

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Hard Probes of Quark-Gluon Plasma

- Probe QGP properties: DIS-like scattering using jets or heavy quarks
  - Hard scale involved (jet energy, heavy quark mass) >> temperature, so not part of thermal medium
  - Produced early in collisions due to hard scales
  - Compare AA / pp difference in observables, learn QGP
  - Rigorous factorization not established yet
- Separation of scales: hard modes evolve in environment of soft modes —> **treat hard modes as open quantum system**

Contents

- Introduction: **open quantum system**
- General procedure: derive semiclassical transport from open quantum system, with **effective field theory (EFT)**
- Two examples:
  - Jet transverse momentum broadening: **SCET with Glauber**
  - Quarkonium dissociation / recombination: **pNRQCD**

Open Quantum System

- Total system = subsystem + environment: $H = H_S + H_E + H_I$

$$U(t,0) = \mathcal{T} e^{-i\int_0^t \mathrm{d}t' H_I(t')}$$

$\rho(t=0) = \rho_S \otimes \rho_E$

Subsystem & environment

(Jets/heavy quarks & QGP)

Unitary evolution →

Time reversible

$U(t,0)(\rho_S \otimes \rho_E)U^\dagger(t,0)$

Subsystem & environment

↓ **Trace out (integrate out) environment** ↓

$\rho_S(t=0)$

Subsystem

Non-unitary →

Time irreversible

$\mathrm{Tr}_E\left[U(t,0)(\rho_S \otimes \rho_E)U^\dagger(t,0)\right]$

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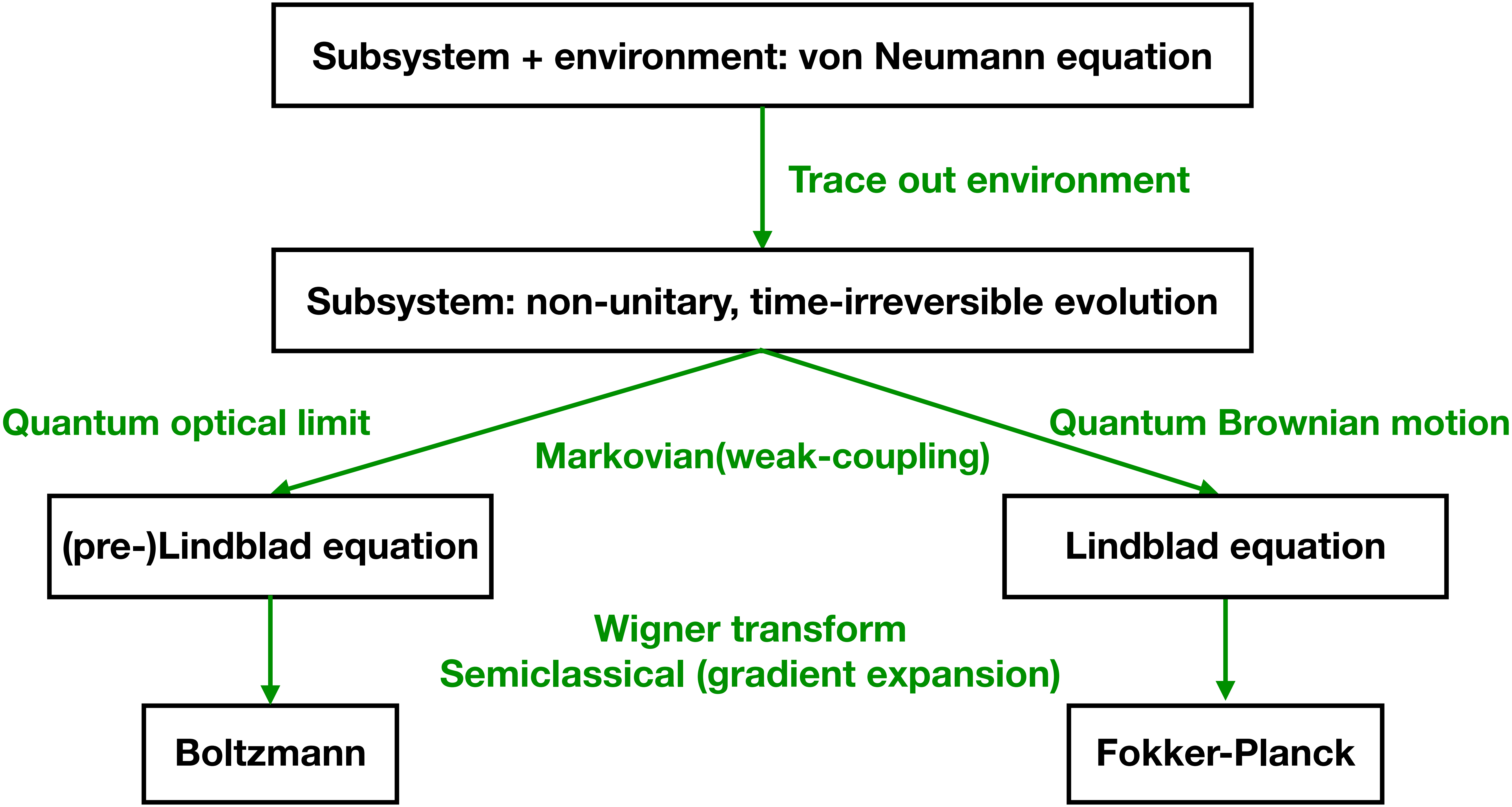
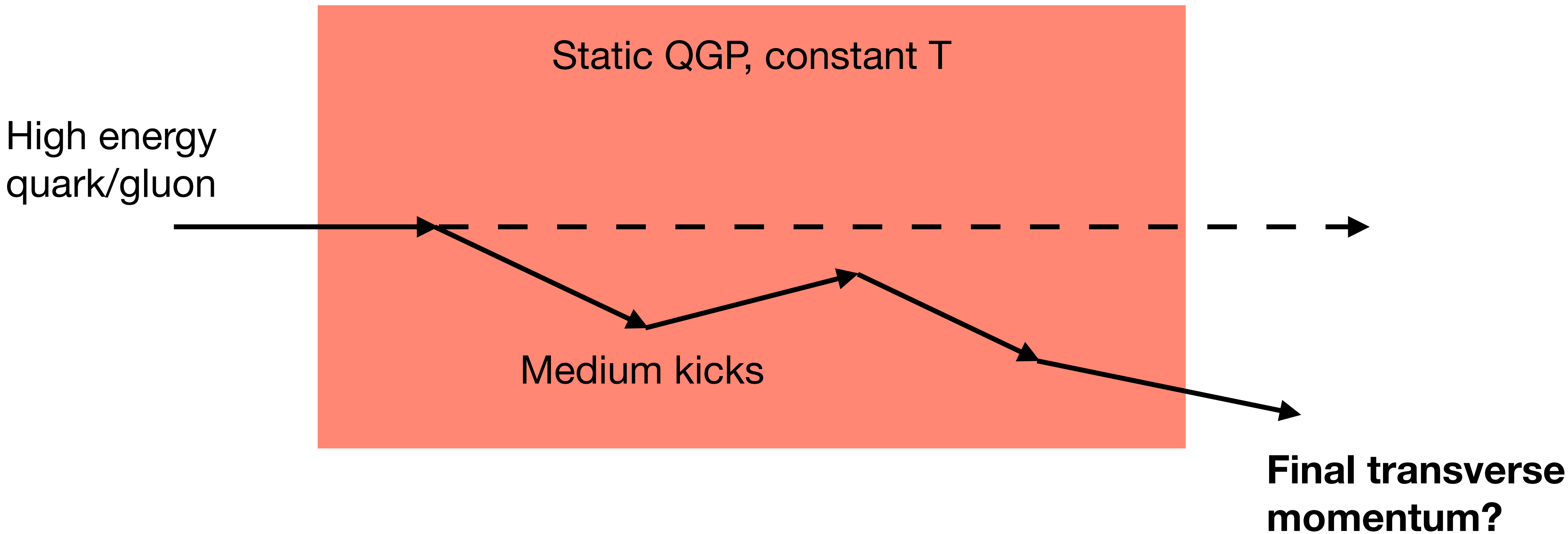
From Open Quantum System to Semiclassical Transport



Wigner transform $f(\boldsymbol{x}, \boldsymbol{k}, t) \equiv \int \frac{d^3k'}{(2\pi)^3} e^{i\boldsymbol{k}'\cdot\boldsymbol{x}} \left\langle \boldsymbol{k} + \frac{\boldsymbol{k}'}{2} \middle| \rho_S(t) \middle| \boldsymbol{k} - \frac{\boldsymbol{k}'}{2} \right\rangle$

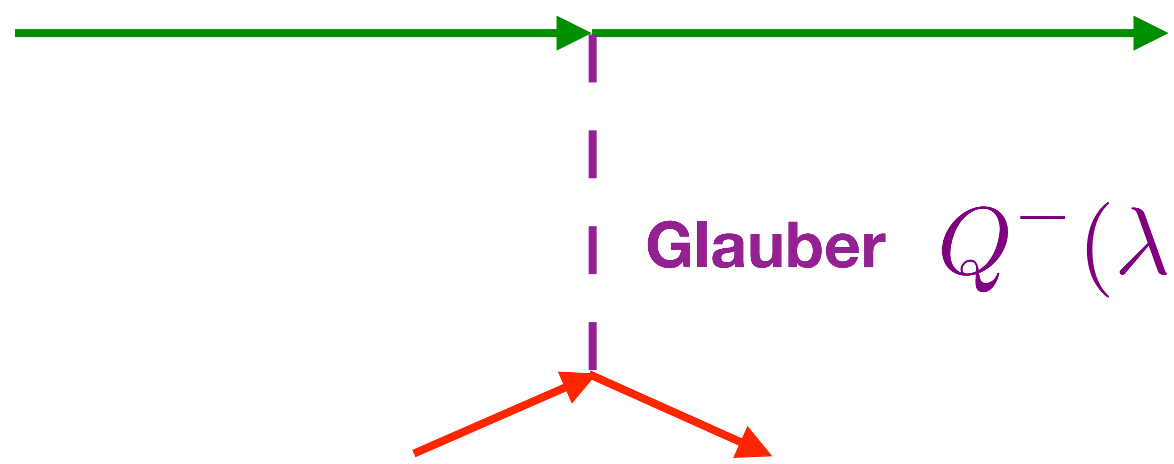
Example 1: Jet Transverse Momentum Broadening



- High energy limit $Q^- \gg Q_\perp \sim T \gg \Lambda_{QCD}$
- Power counting parameter in each kick $\lambda \lesssim \dfrac{Q_\perp}{Q^-}$
- High energy particle = **collinear mode** $Q^-(1, \lambda^2, \lambda)$
- Medium kick sources = **soft mode** $(T, T, T) \sim Q^-(\lambda, \lambda, \lambda)$

Interact via Glauber $Q^-(\lambda, \lambda^2, \lambda)$

Soft-Collinear Effective Theory with Glauber



collinear mode $Q^-(1, \lambda^2, \lambda)$

Glauber $Q^-(\lambda, \lambda^2, \lambda)$

soft mode from medium $(T, T, T) \sim Q^-(\lambda, \lambda, \lambda)$

- Effective operators worked out by Ira Rothstein, Iain W. Stewart, arXiv:1601.04695
- For quark-quark scattering $\mathcal{O}^{qq}_{ns} = \mathcal{O}^{qB}_{n} \frac{1}{\mathcal{P}_\perp^2} \mathcal{O}^{q_n B}_{s}$

$$\mathcal{O}^{qB}_{n} = \bar{\chi}_n T^B \frac{\not{\bar{n}}}{2} \chi_n \qquad \chi_n = W_n^\dagger \xi_n = W_n^\dagger \frac{\not{n}\not{\bar{n}}}{4} \psi$$

$$\mathcal{O}^{q_n B}_{s} = 8\pi\alpha_s \left(\bar{\psi}^n_s T^B \frac{\not{n}}{2} \psi^n_s \right) \qquad \psi^n_s = S_n^\dagger \psi_s$$

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Markovian Master Equation

- Markovian master equation for $P(Q,t) = \langle Q|\rho_S(t)|Q\rangle$

$$\partial_t P(Q,t) = -R(Q)P(Q,t) + \int \widetilde{\mathrm{d}q} K(Q,q)P(q,t)$$

- Solution w/ initial condition $P\left(\left[Q^-, \frac{|Q_\perp|^2}{Q^-}, Q_\perp\right], t=0\right) = f(Q^-)\delta^2(\boldsymbol{Q}_\perp)$

$$P(Q^-,Q_\perp,t) = \frac{f(Q^-)}{(2\pi)^2}\int \mathrm{d}^2 r_\perp e^{-i\boldsymbol{r}_\perp\cdot\boldsymbol{Q}_\perp} e^{\left[-R(Q)+\widetilde{K}(Q,-r_\perp)\right]t}$$

$$= f(Q^-)e^{-R(Q)t}\delta^2(\boldsymbol{Q}_\perp) + \frac{f(Q^-)}{(2\pi)^2}\int \mathrm{d}^2 r_\perp e^{-i\boldsymbol{r}_\perp\cdot\boldsymbol{Q}_\perp}\left(e^{\left[-R(Q)+\widetilde{K}(Q,-r_\perp)\right]t} - e^{-R(Q)t}\right)$$

- **Sudakov-like factor**

$$-R+\widetilde{K} = \frac{4\alpha_s^2 N_f C_F T_F}{\pi^2}\int \frac{|k_\perp|\mathrm{d}|k_\perp|}{|k_\perp|^4}\left[J_0(|r_\perp||k_\perp|)-1\right]\int \mathrm{d}|p_\perp|\mathrm{d}p^-\mathrm{d}\phi\,\frac{|p_\perp|^3}{(p^-)^2}$$
$$\times\, n_F\left(\frac{(p^-)^2+|p_\perp|^2}{2p^-}\right)\left[1-n_F\left(\frac{(p^-)^2(|p_\perp|^2+|k_\perp|^2+2|p_\perp||k_\perp|\cos\phi)+|p_\perp|^4}{2|p_\perp|^2p^-}\right)\right]$$

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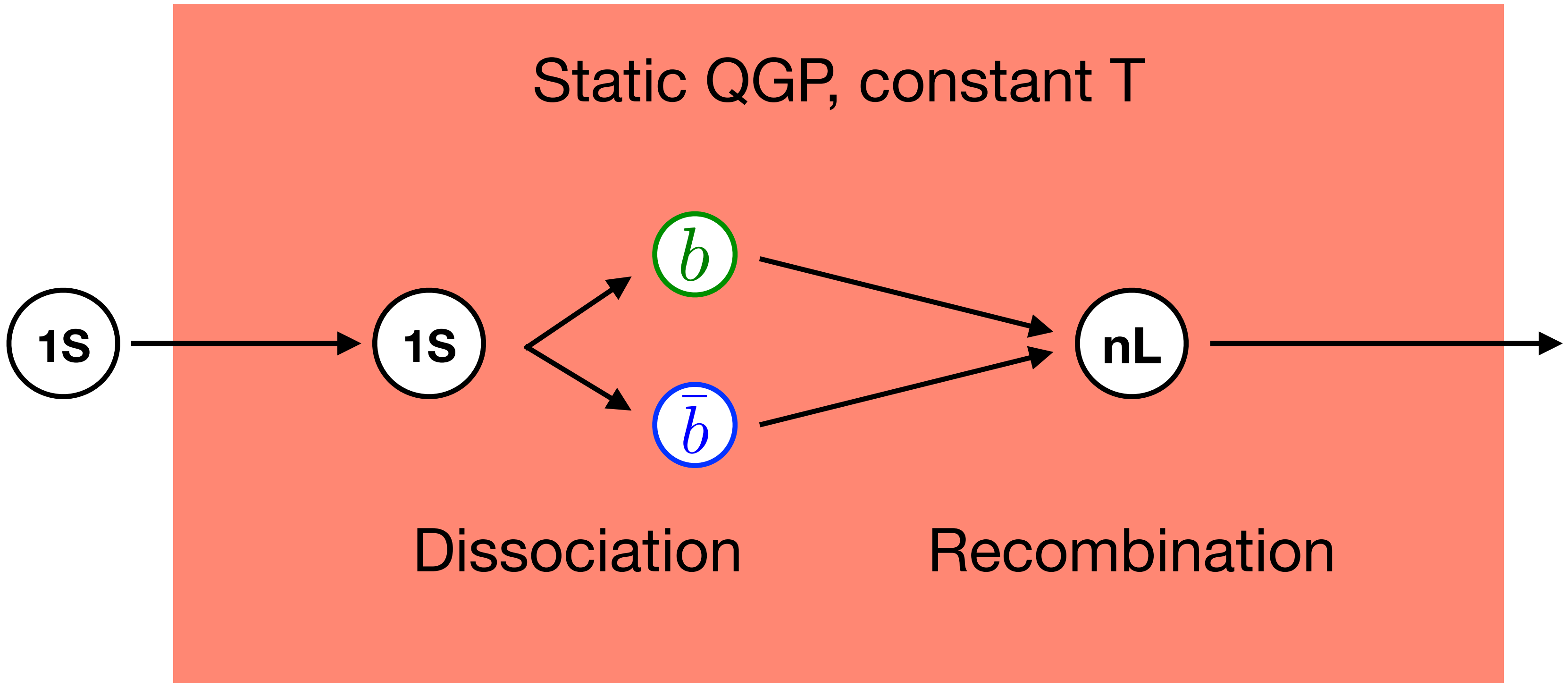
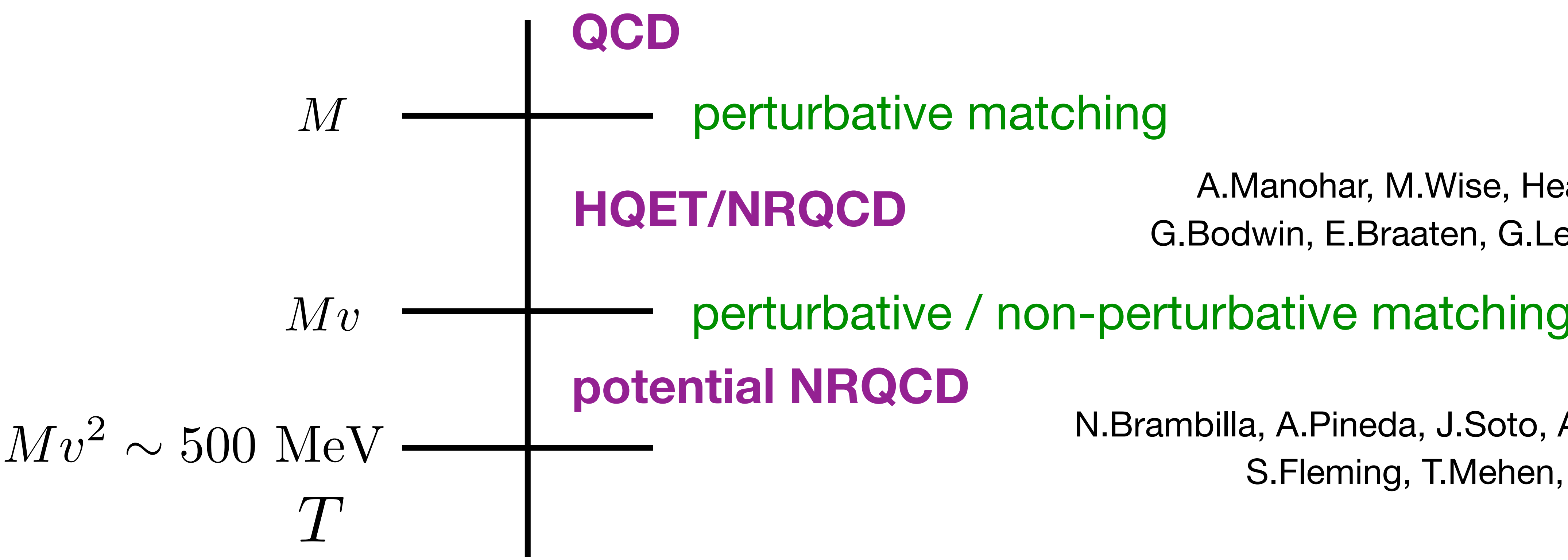
Example 2: Quarkonium Dissociation and Recombination



Probability of each state?

Hierarchy of scales: $M \gg Mv \gg Mv^2 \gtrsim T$



A.Manohar, M.Wise, Heavy quark physics
G.Bodwin, E.Braaten, G.Lepage, hep-ph/9407339

N.Brambilla, A.Pineda, J.Soto, A.Vairo, hep-ph/9907240
S.Fleming, T.Mehen, hep-ph/0509313

Boltzmann Equation and Chromoelectric Correlator

Boltzmann equation

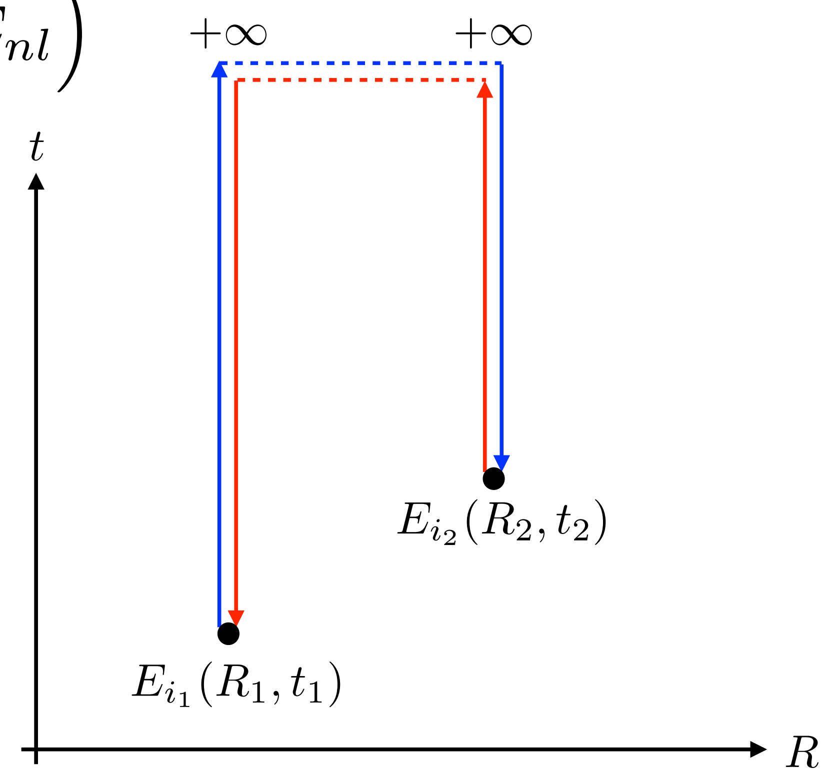
$$\frac{\partial}{\partial t} f_{nl}(\boldsymbol{x},\boldsymbol{k},t) + \frac{\boldsymbol{k}}{2M}\cdot\nabla_{\boldsymbol{x}} f_{nl}(\boldsymbol{x},\boldsymbol{k},t) = \mathcal{C}^{+}_{nl}(\boldsymbol{x},\boldsymbol{k},t) - \mathcal{C}^{-}_{nl}(\boldsymbol{x},\boldsymbol{k},t)$$

Dissociation rate $$R^{-}_{nl}(\boldsymbol{x},\boldsymbol{k},t) = \frac{\mathcal{C}^{-}_{nl}(\boldsymbol{x},\boldsymbol{k},t)}{f_{nl}(\boldsymbol{x},\boldsymbol{k},t)}$$

Differential $$(2\pi)^3\frac{\mathrm{d}R^{-}_{nl}}{\mathrm{d}^3p_{\mathrm{cm}}} = \int \frac{\mathrm{d}^3p_{\mathrm{rel}}}{(2\pi)^3}\bar{d}_{nl}(\boldsymbol{p}_{\mathrm{rel}})\, g^{E++}\Big(\frac{(\boldsymbol{p}_{\mathrm{rel}})^2}{M} - E_{nl}, \boldsymbol{p}_{\mathrm{cm}} - \boldsymbol{k}\Big)$$

Inclusive $$R^{-}_{nl} = \int \frac{\mathrm{d}^3p_{\mathrm{rel}}}{(2\pi)^3}\bar{d}_{nl}(\boldsymbol{p}_{\mathrm{rel}})\, G^{E++}\Big(\frac{(\boldsymbol{p}_{\mathrm{rel}})^2}{M} - E_{nl}\Big)$$

$$g^{E++} = \langle WE(\boldsymbol{R}_1,t_1)WE(\boldsymbol{R}_2,t_2)\rangle_T$$
$$G^{E++} = \langle E(t_1)W_{[t_1,t_2]}E(t_2)\rangle_T$$



Similar to Weizsacker-Williams Sivers v.s. PDF

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Conclusions

- From open quantum system to semiclassical transport equations
- Weak coupling limit, Lindblad equation, Markovian, EFT
  - Jet transverse momentum broadening: **SCET with Glauber**, Markovian master equation
  - Quarkonium dissociation / recombination: **pNRQCD**, Boltzmann equation, QGP chromoelectric correlator

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