Pre-Equilibrium Photon Production in QCD Kinetic Theory

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CRC-TR 211
Strong-interaction matter under extreme conditions

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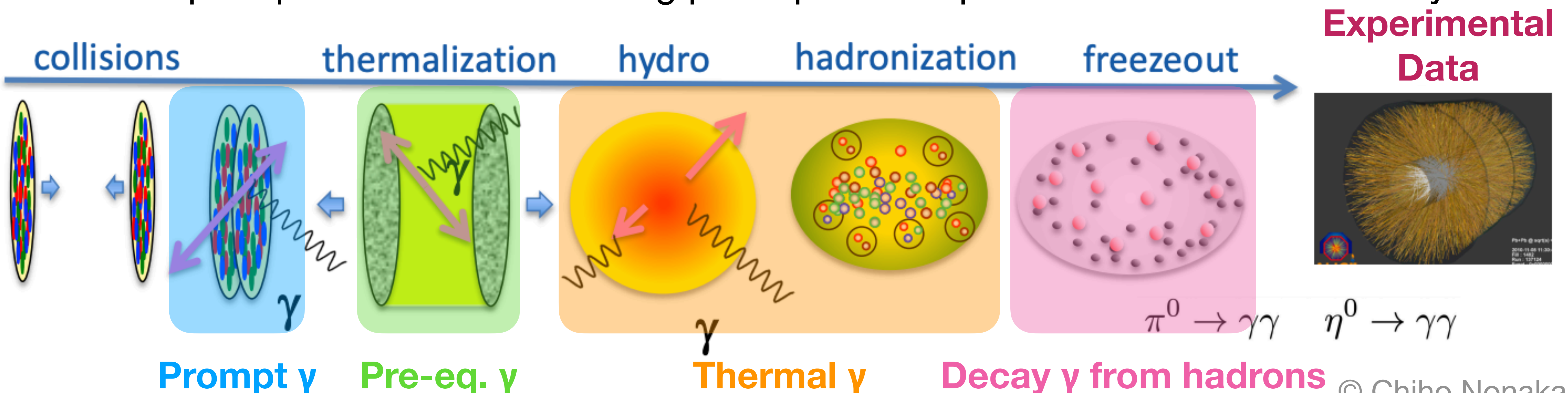
Photon Production in Heavy-Ion Collisions

- Electromagnetic probes are produced throughout the entire space-time evolution of heavy-ion collisions
  - Escape plasma without re-interaction ⇒ provide important information on the various stages
- State-of-the-art calculations typically take into account emissions from hydrodynamic QGP and hadronic phase
  - Study of pre-equilibrium production often done in terms of corrections to thermal productions
- Compute production rates during pre-equilibrium phase in QCD kinetic theory



Recall talk by Jean-François Paquet on Monday for later stages

QCD Kinetic Theory

- Dynamics described by relativistic Boltzmann equation [Arnold et al., JHEP 0301, (2003)]

Elastic 2↔2 scattering screened by Debye mass

$$p^\mu \partial_\mu f(x,p) = C_{2\leftrightarrow 2}[f] + C_{1\leftrightarrow 2}[f]$$

Collinear 1↔2 including Landau-Pomeranchuk-Migdal (LPM) effect via effective vertex resummation

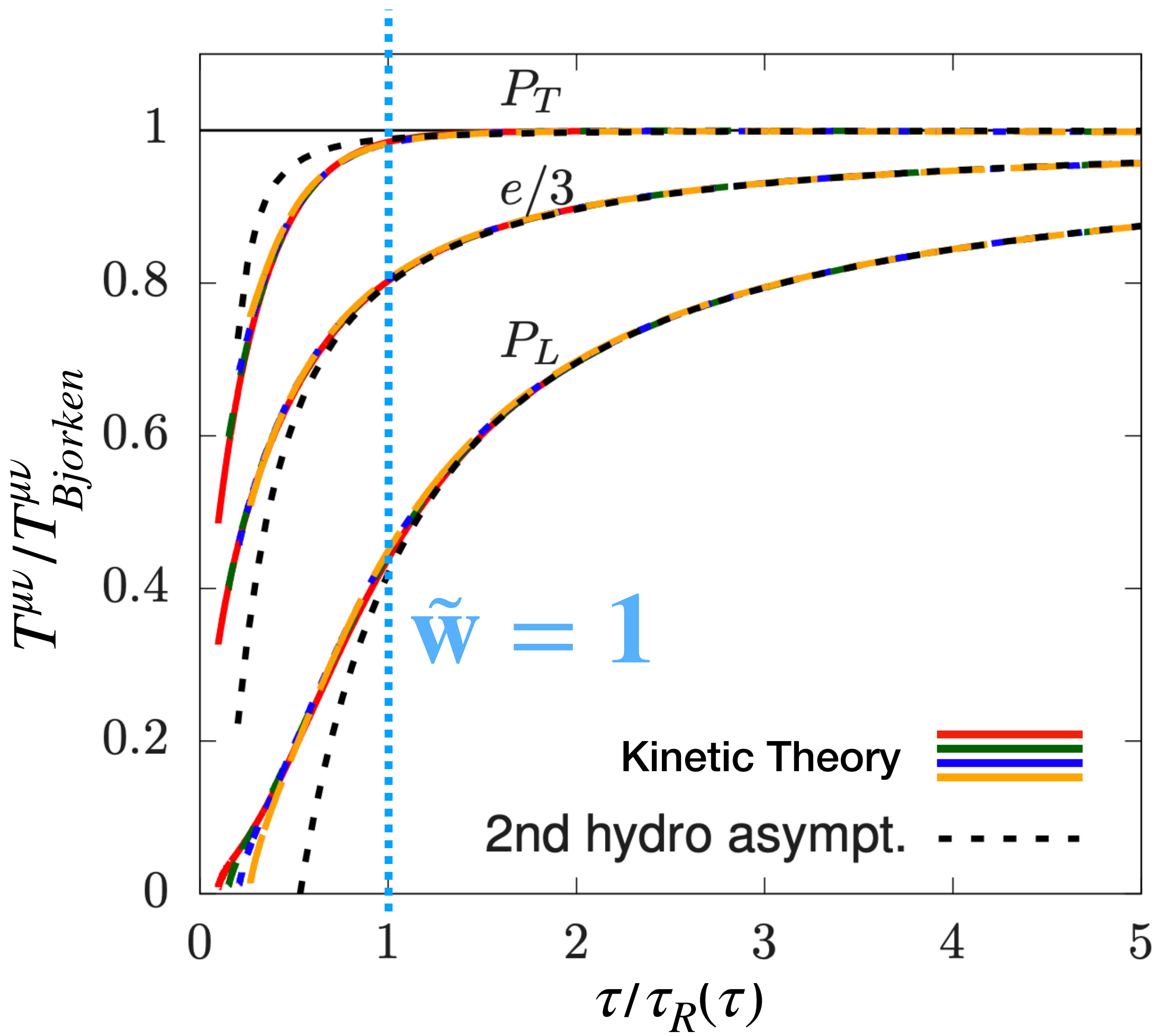
- Equilibration controlled by single relaxation rate $\tau_R(\tau) = 4\pi(\eta/s)/T_{eff}(\tau)$

- Evolution time:

$$\tilde{w} = \frac{\tau}{\tau_R(\tau)} = \frac{\tau T_{eff}(\tau)}{4\pi\eta/s}$$

⇒ Hydrodynamics applicable on timescales of the order of unity in rescaled time

Recall talk by
Kirill Boguslavski on Monday



[Kurkela et al., Phys.Rev.C 99 (2019)]

QCD Kinetic Theory

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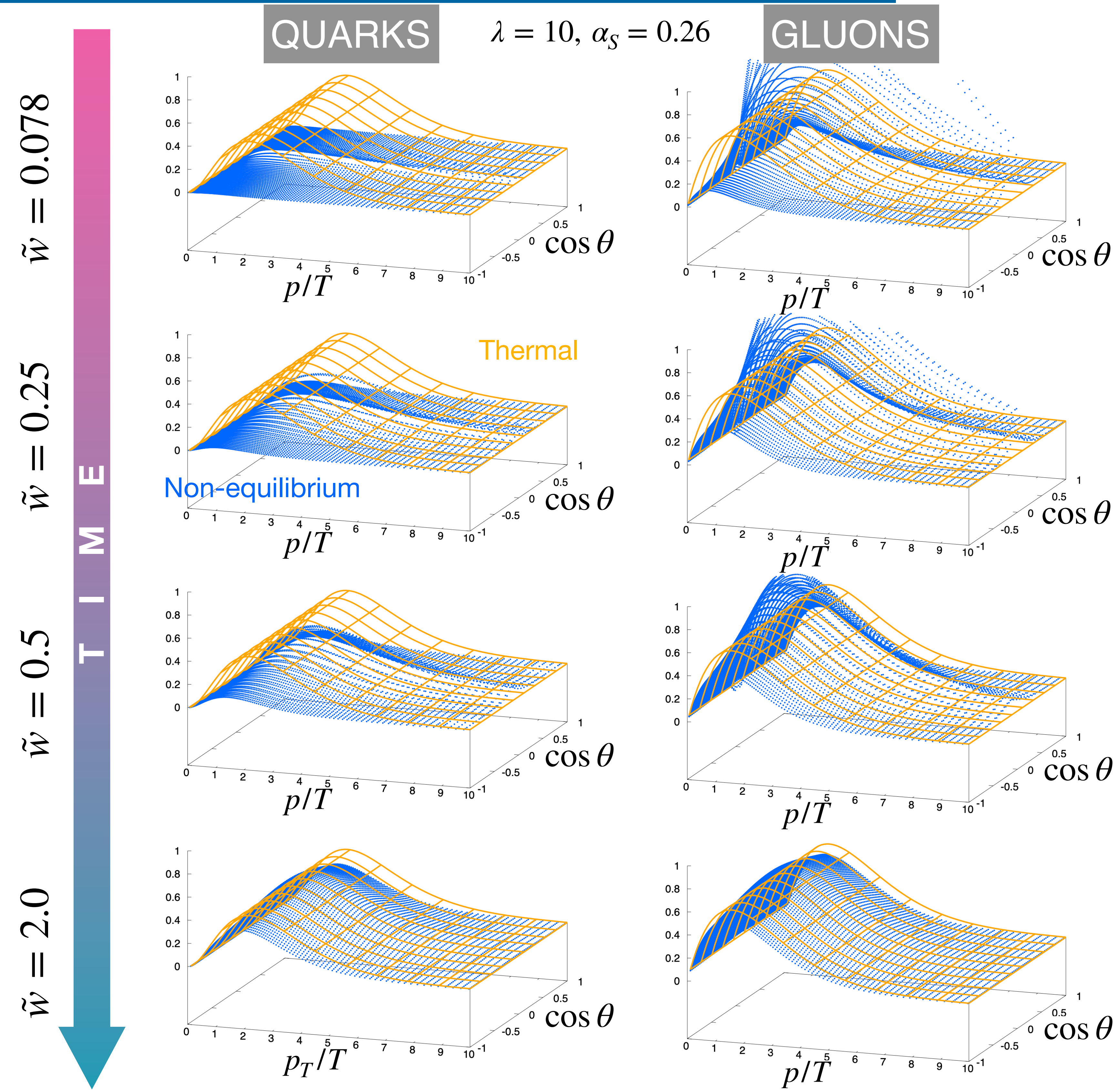
- Gluon dominated initial state
- Quarks produced dynamically
- System initially highly anisotropic
  → peak at $\cos\theta \approx 0$ represents $p_L \ll p_T$

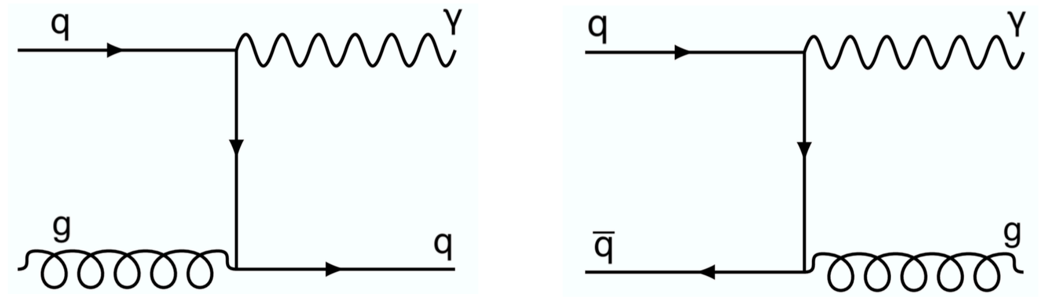


Relevant Processes at Leading Order

- Leading order production rates can be derived from effective kinetic theory [Arnold et al., JHEP, (2001)]

- 2↔2 processes include Compton scattering and elastic pair annihilation

$2 \leftrightarrow 2$ processes

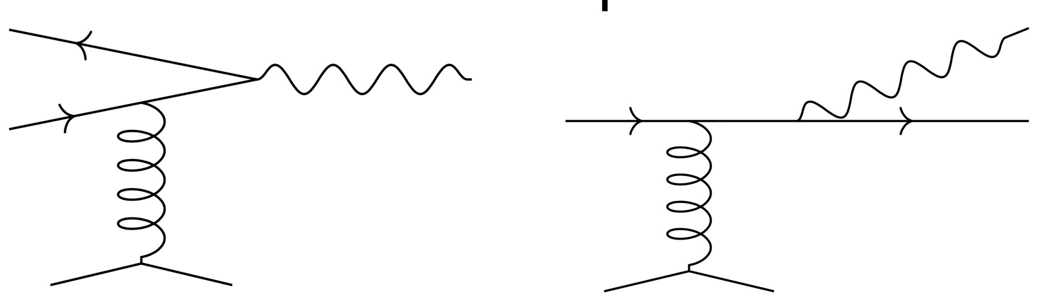


Compton Scattering   Elastic pair annihilation

+ appropriate other channels

- Collinear effective 1↔2 processes in order to capture Landau-Pomeranchuk-Migdal (LPM) effect via effective vertex resummation

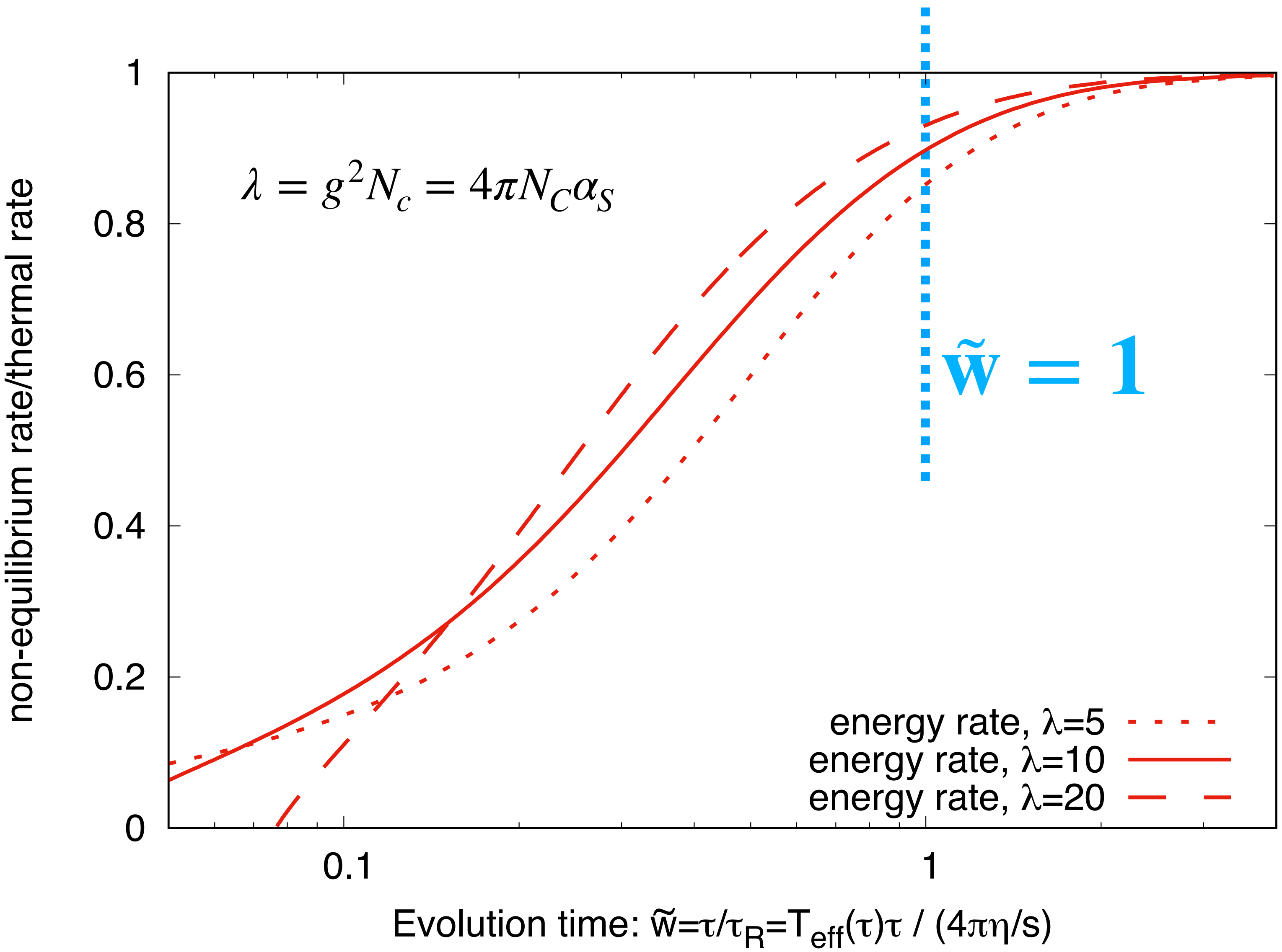
Effective $1 \leftrightarrow 2$ processes



Inelastic pair annihilation   Bremsstrahlung off q & q̄

Electromagnetic energy loss rate

- Non-equilibrium energy loss rate due to photons compared to thermal energy rate



Energy rate:

$$\partial_\tau e_\gamma(\tau) = \int \frac{d^3p}{(2\pi)^3}\; p C_\gamma(\tau, \vec{p})$$

where:

$$C_\gamma = \frac{dN}{\tau d\tau d^3p d^2x_T}$$

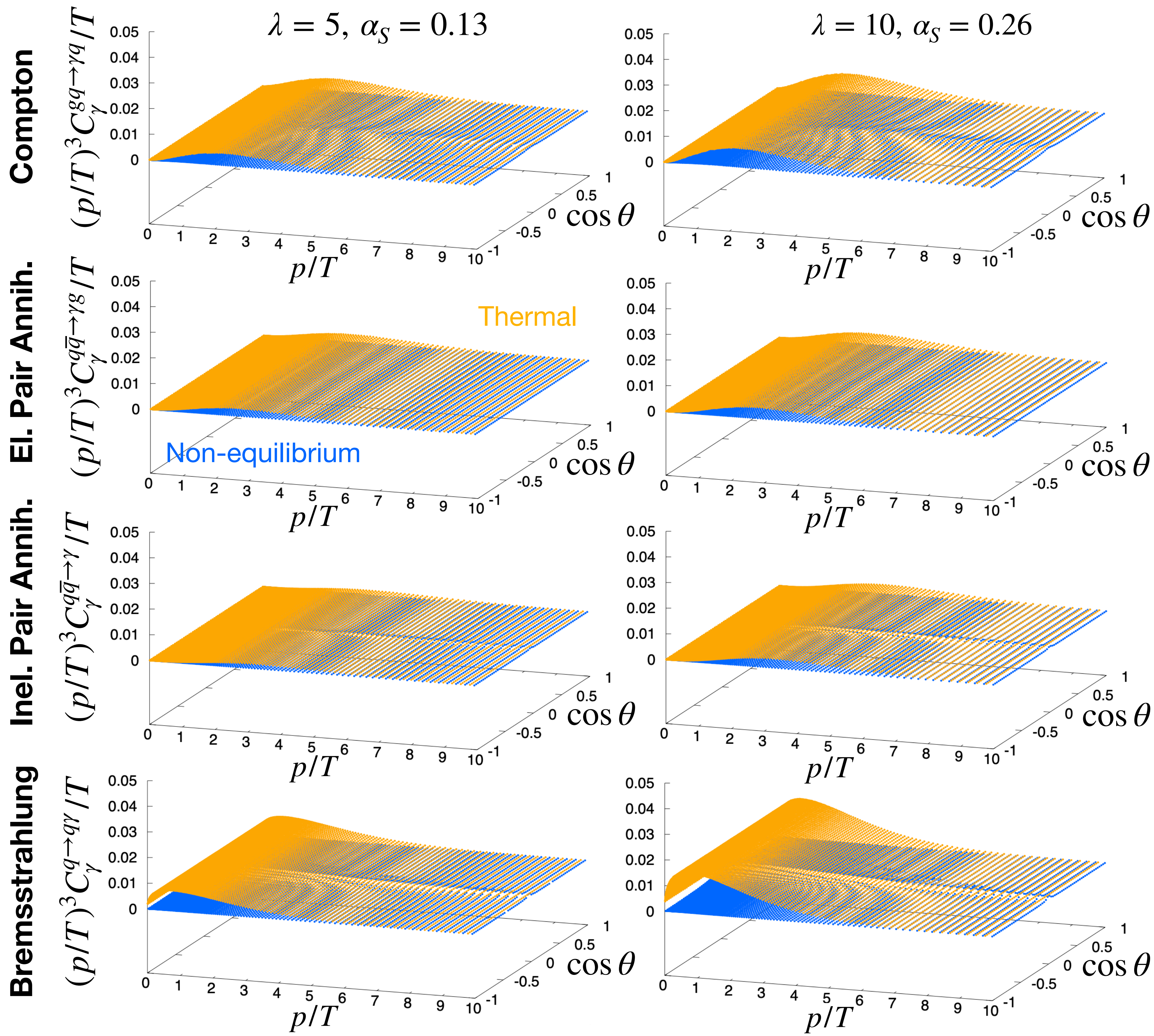
Recover thermal energy rate on timescales when hydrodynamics becomes applicable

Results - 2D-Spectrum

$$\tilde{w} = \frac{\tau T_{eff}(\tau)}{4\pi\eta/s} = 0.076$$

$$C_\gamma = \frac{dN}{\tau d\tau d^3p d^2x_T}$$

- At early times: no quarks → non-eq. rate small

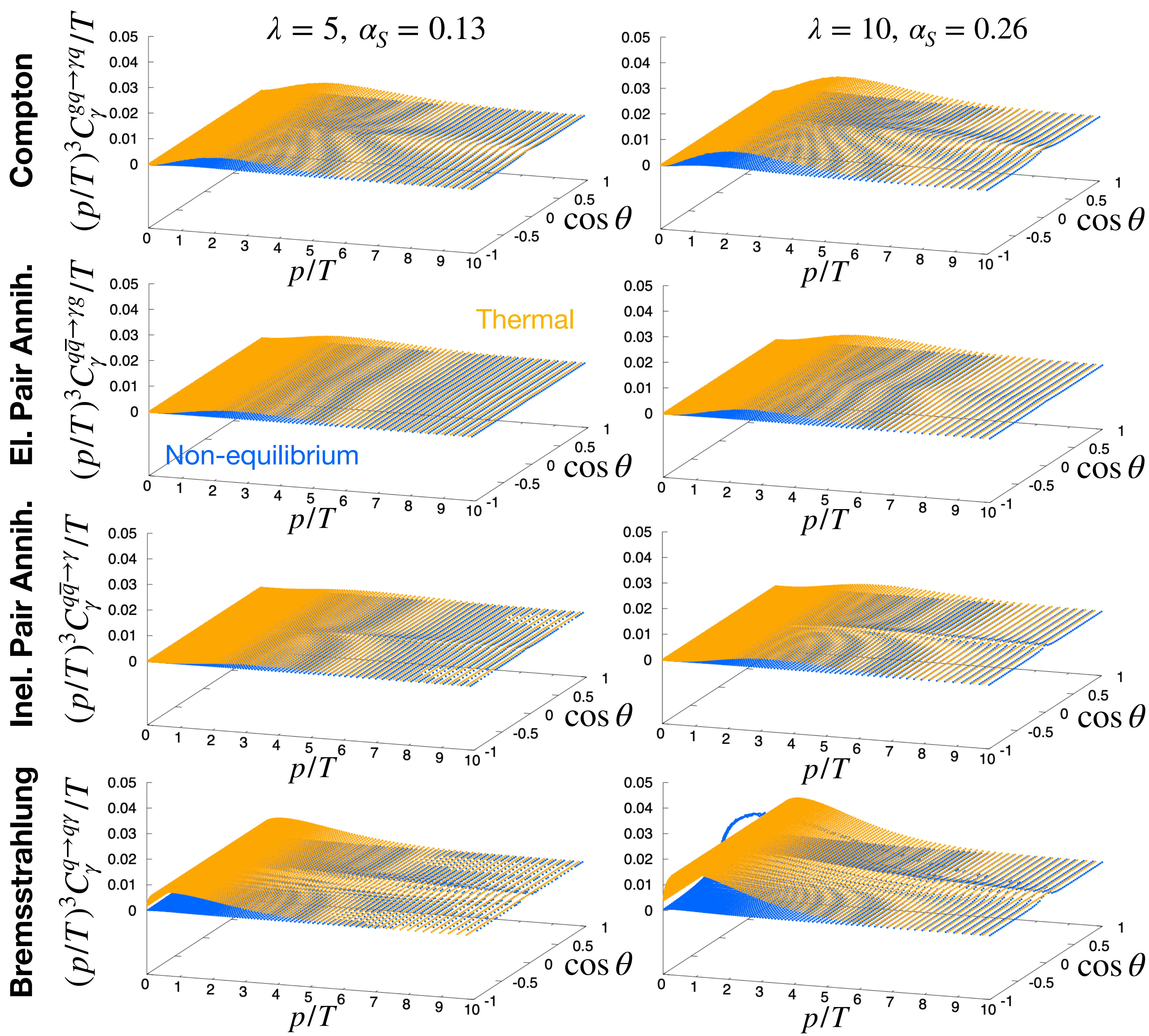


Results - 2D-Spectrum

$$\tilde{w} = \frac{\tau T_{eff}(\tau)}{4\pi\eta/s} = 0.2$$

$$C_\gamma = \frac{dN}{\tau d\tau d^3p d^2x_T}$$

- At early times: no quarks → non-eq. rate small

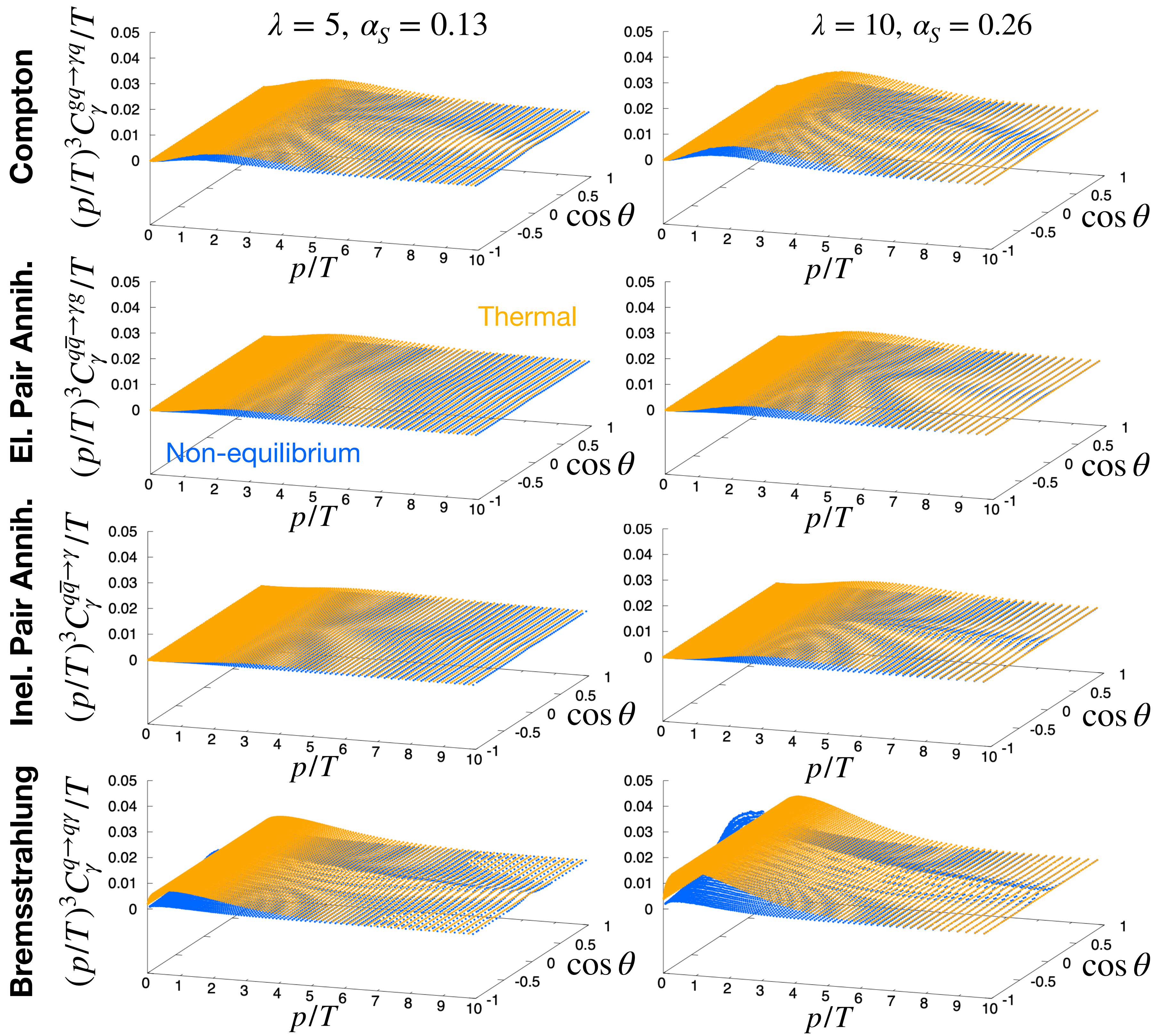


Results - 2D-Spectrum

$$\tilde{w} = \frac{\tau T_{eff}(\tau)}{4\pi\eta/s} = 0.5$$

$$C_\gamma = \frac{dN}{\tau d\tau d^3p d^2x_T}$$

- At early times: no quarks → non-eq. rate small
- Peak at $\cos\theta \approx 0$: Gluon distribution highly anisotropic at early times

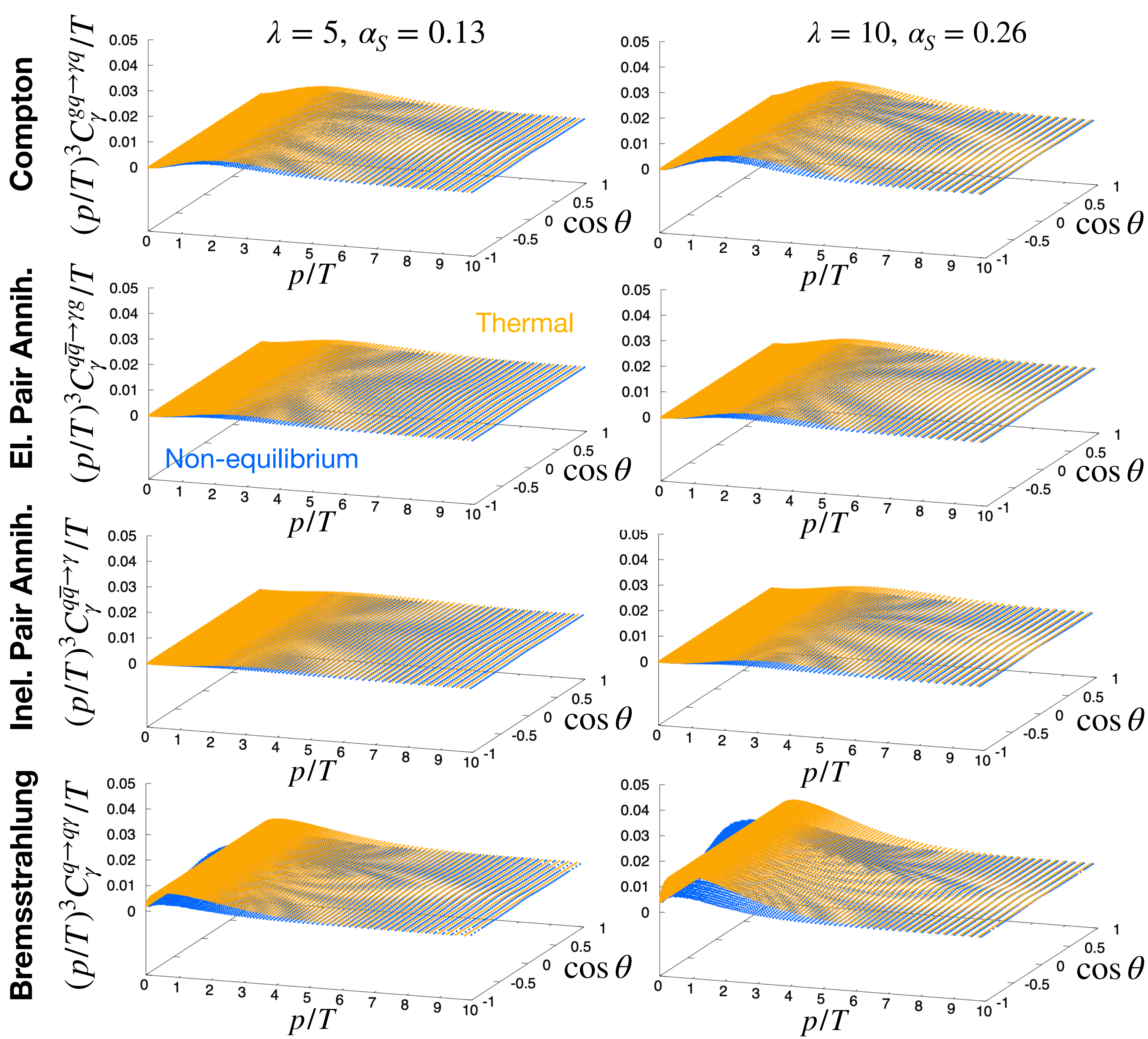


Results - 2D-Spectrum

$$\tilde{w} = \frac{\tau T_{eff}(\tau)}{4\pi\eta/s} = 1.0$$

$$C_\gamma = \frac{dN}{\tau d\tau d^3p d^2x_T}$$

- At early times: no quarks → non-eq. rate small
- Peak at $\cos\theta \approx 0$: Gluon distribution highly anisotropic at early times
- As quarks get created → non-eq. rate approaches thermal production rate



Results - 2D-Spectrum

$$\tilde{w} = \frac{\tau T_{eff}(\tau)}{4\pi\eta/s} = 3.86$$

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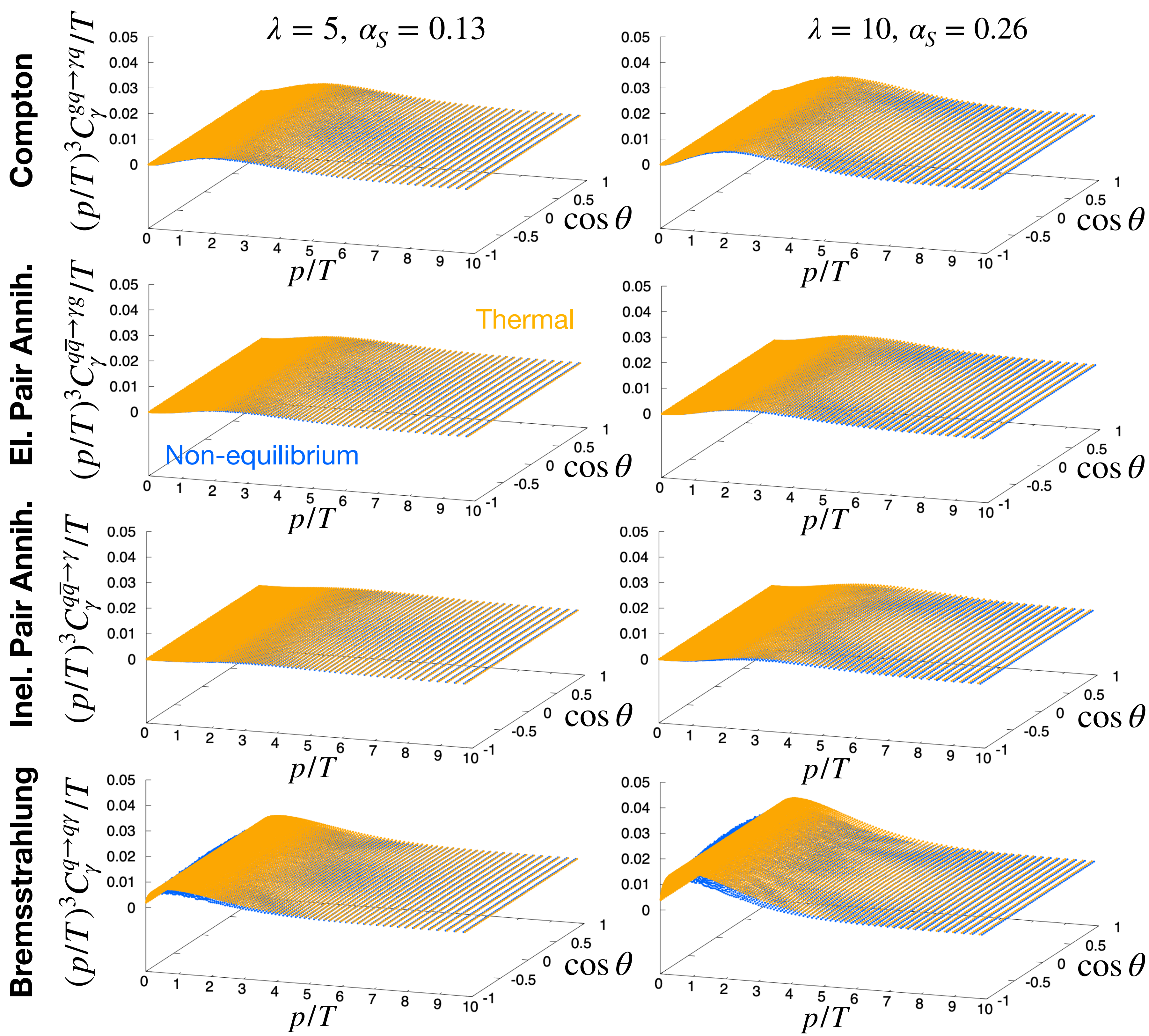
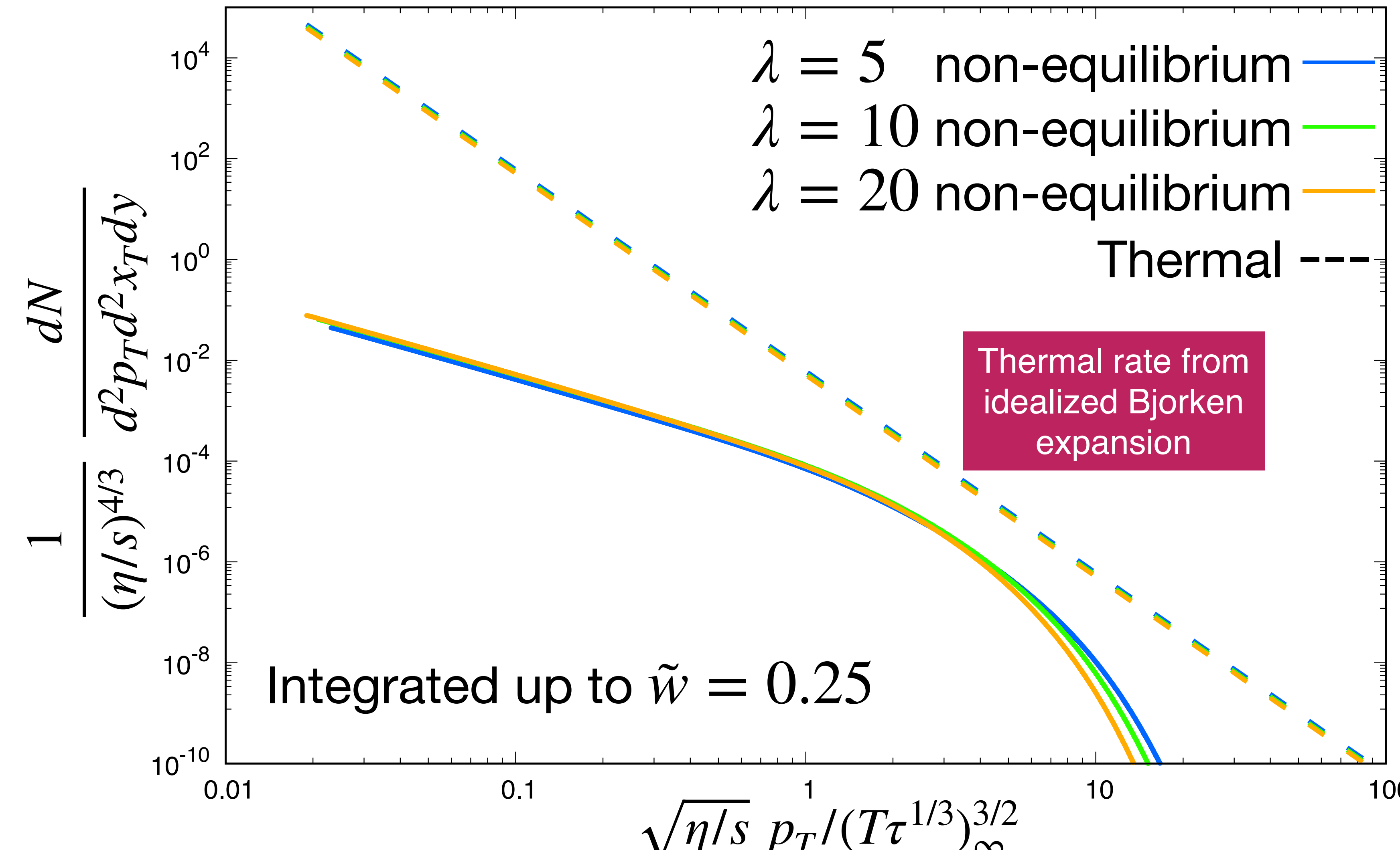


Results - p_T-Spectrum

- At late times: entropy per unit rapidity constant $\Rightarrow T\tau^{1/3}$ becomes constant at late times
- High $p_T/(T\tau^{1/3})^{3/2}_\infty$-regime produced at early times $\rightarrow$ spectrum falls off since no quarks present at early times



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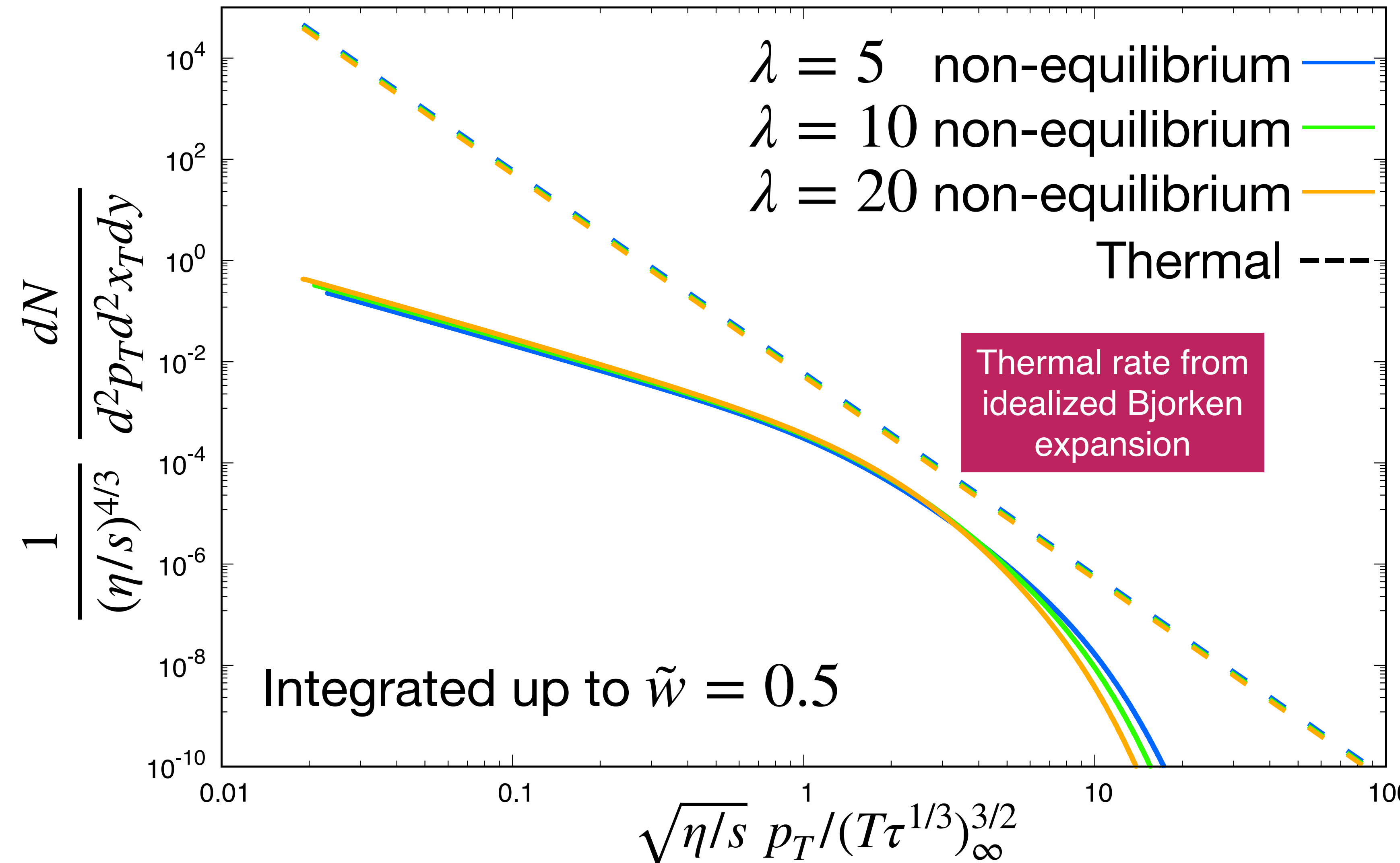
- Intermediate $p_T/(T\tau^{1/3})^{3/2}_\infty$-regime starts to be produced from $\tilde{w} \approx 0.5$ onwards



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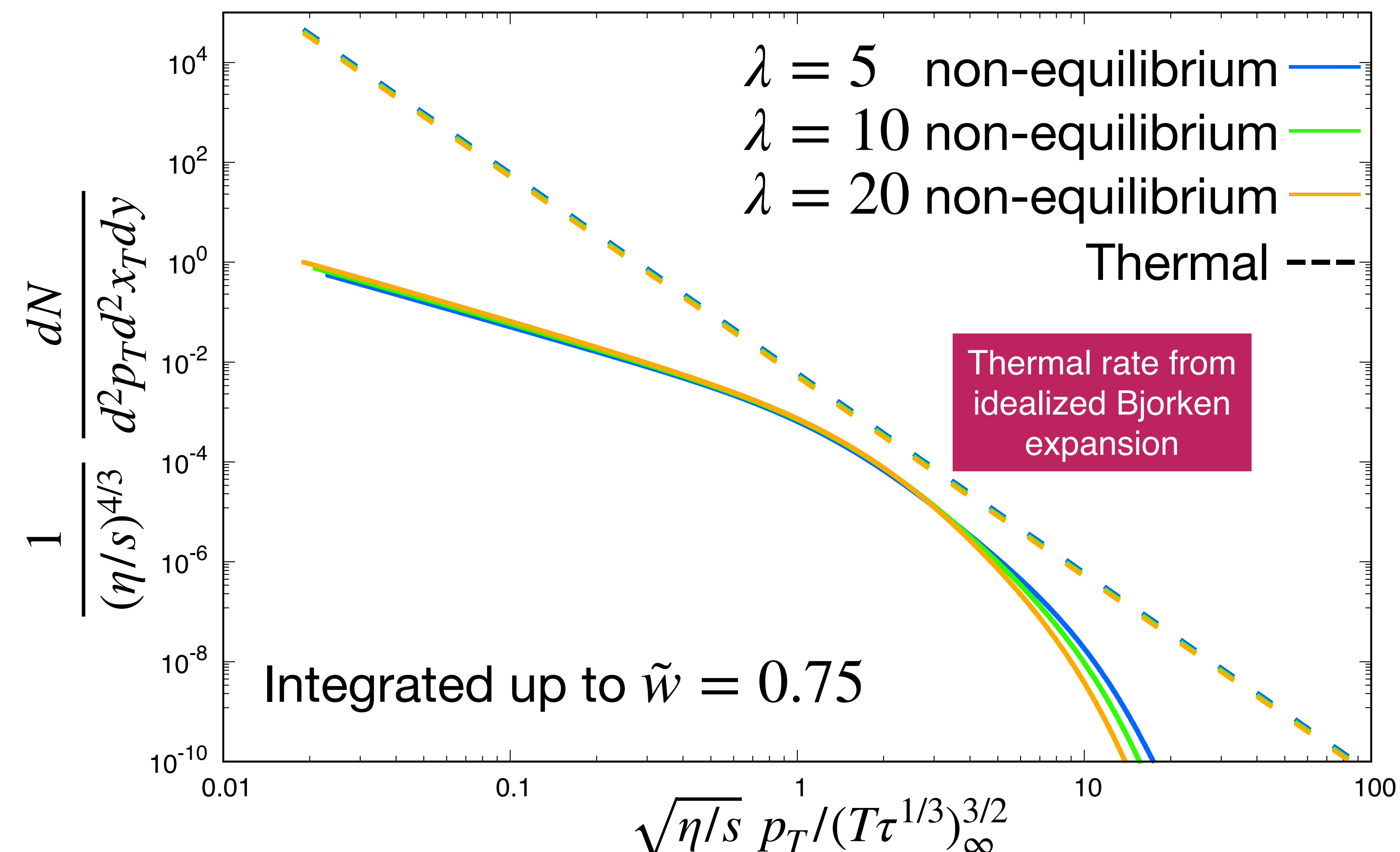

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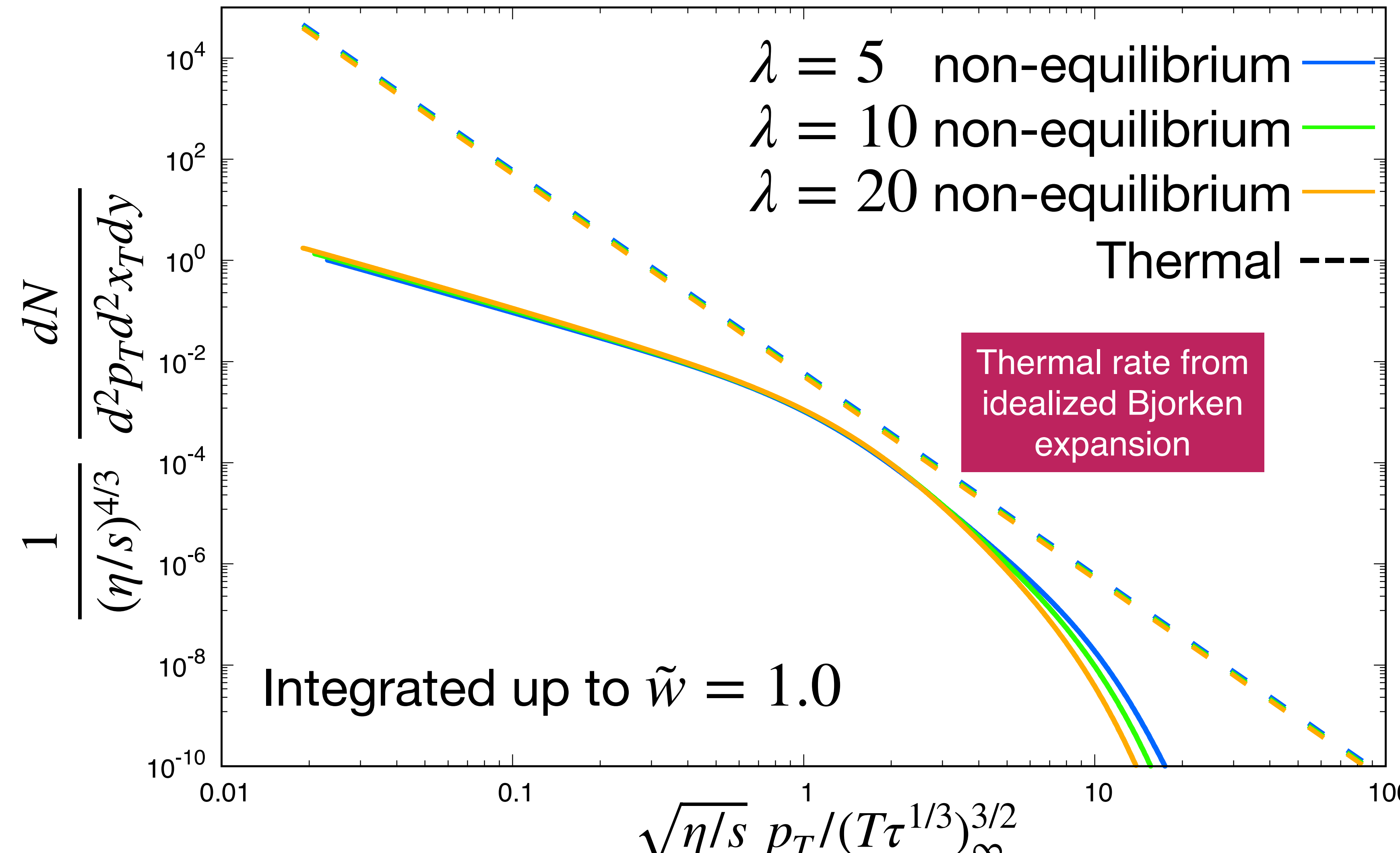

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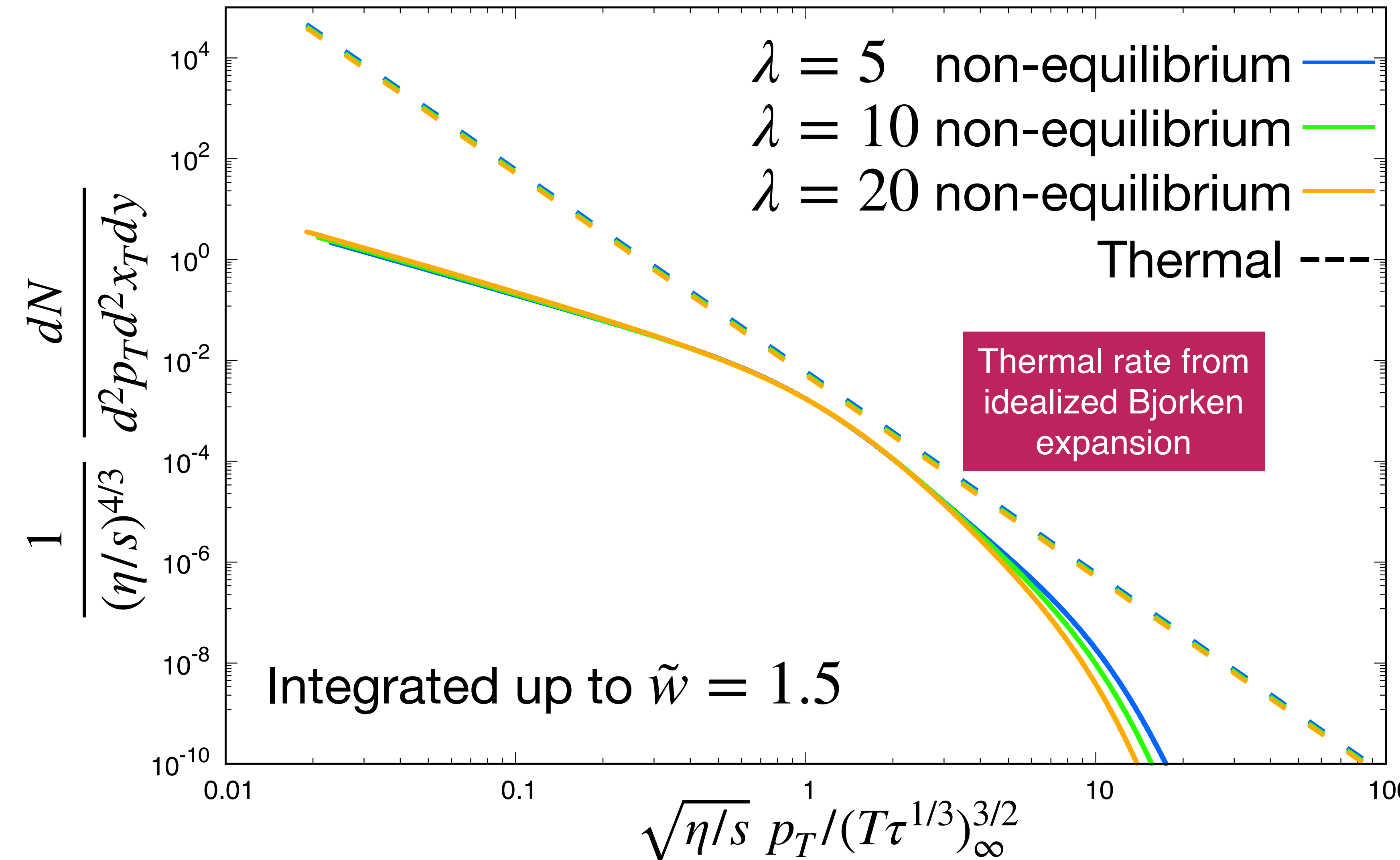

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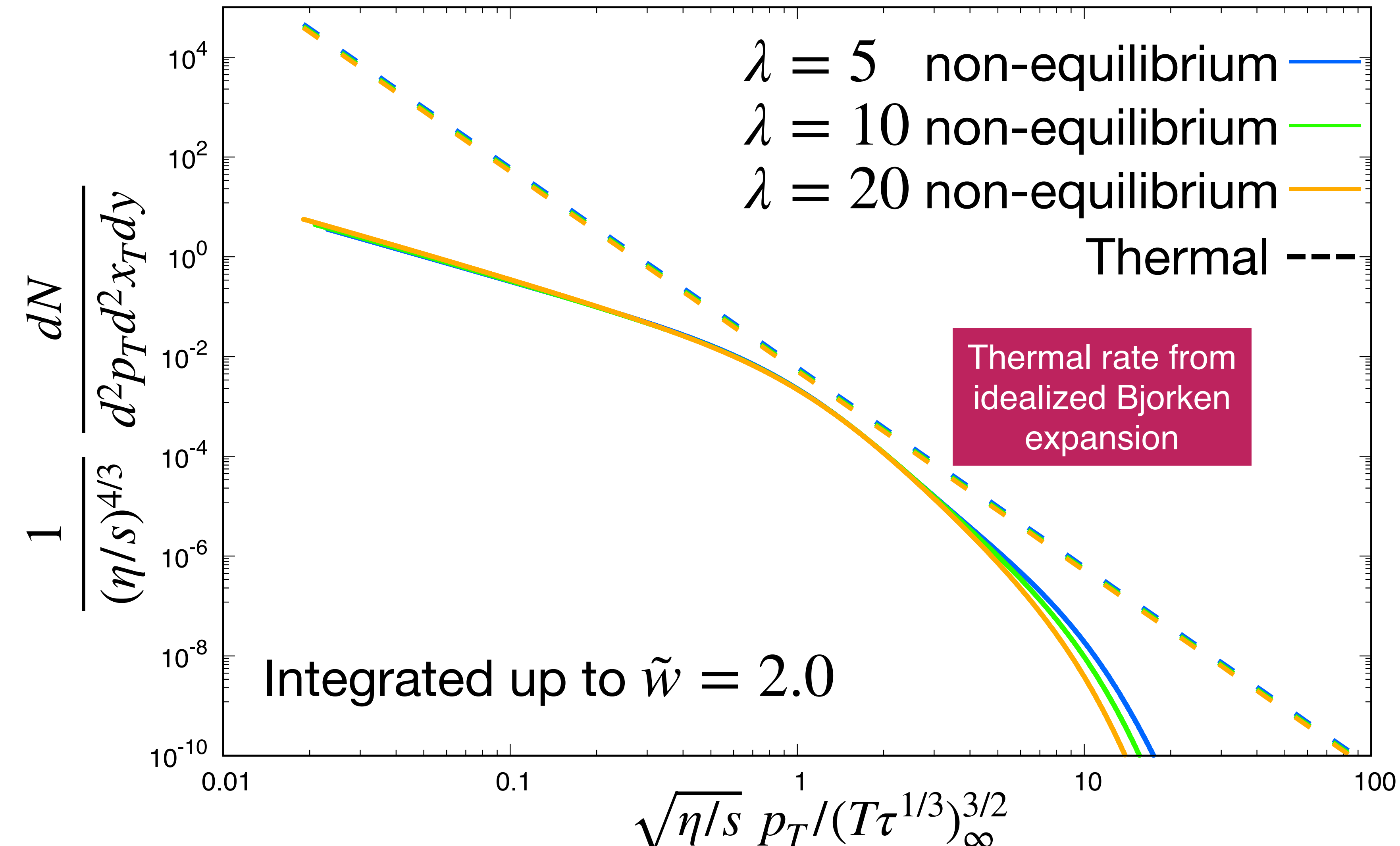
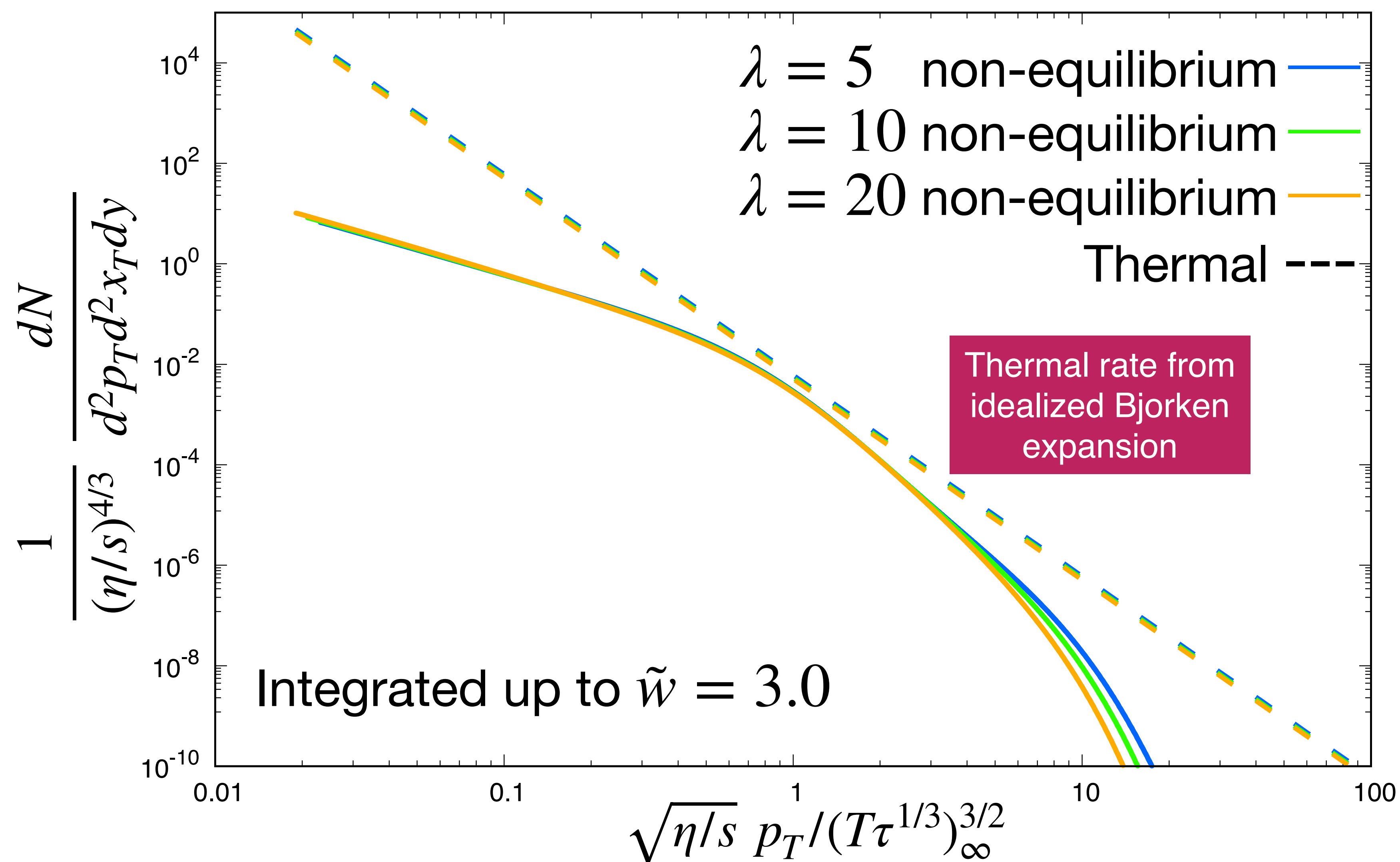


Results - p_T-Spectrum

- At late times: entropy per unit rapidity constant ⇒ $T\tau^{1/3}$ becomes constant at late times
- High $p_T/(T\tau^{1/3})^{3/2}_\infty$-regime produced at early times → spectrum falls off since no quarks present at early times
- Intermediate $p_T/(T\tau^{1/3})^{3/2}_\infty$-regime starts to be produced from $\tilde{w} \approx 0.5$ onwards
- In low and intermediate regime: empirical scaling behavior in η/s



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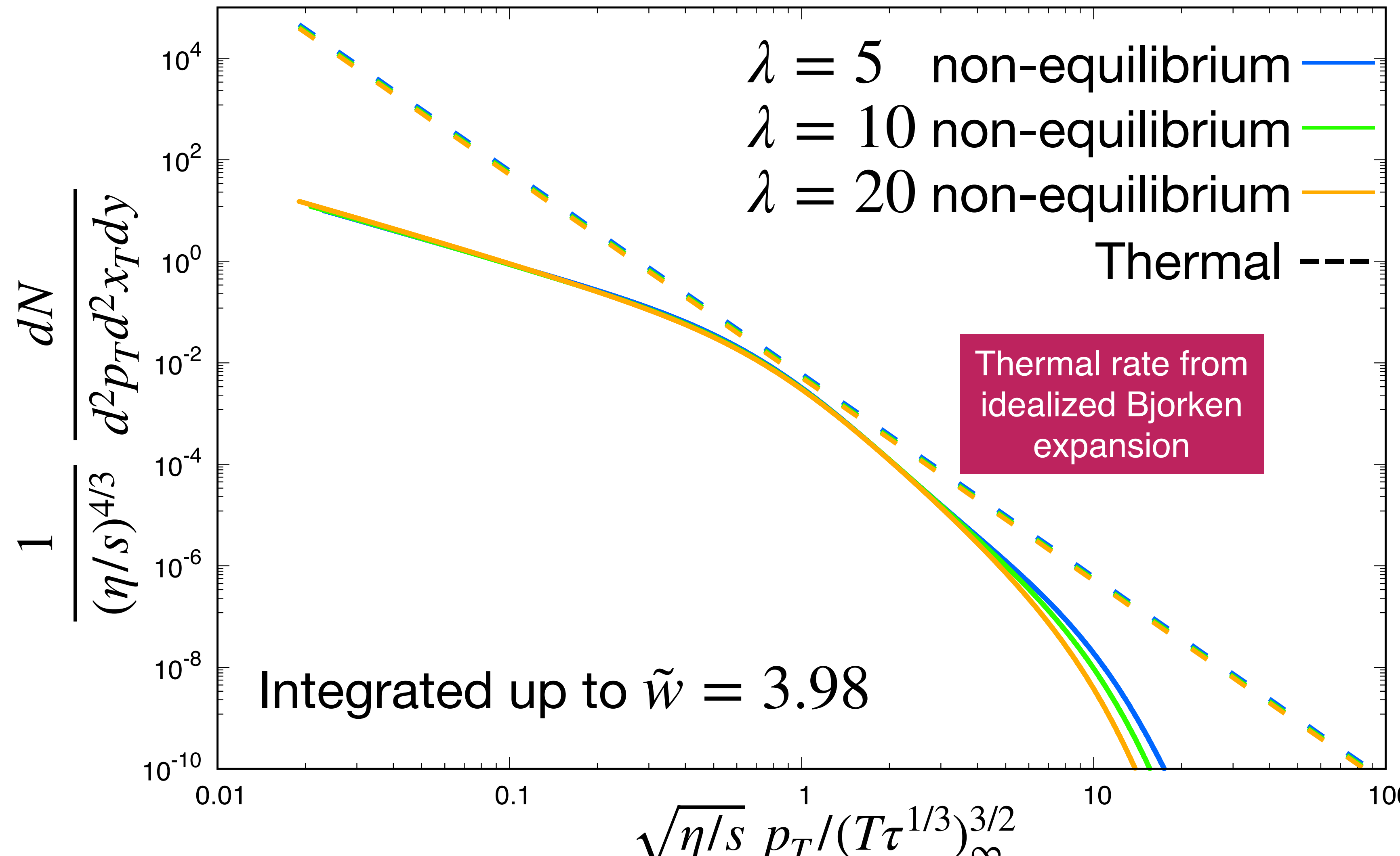

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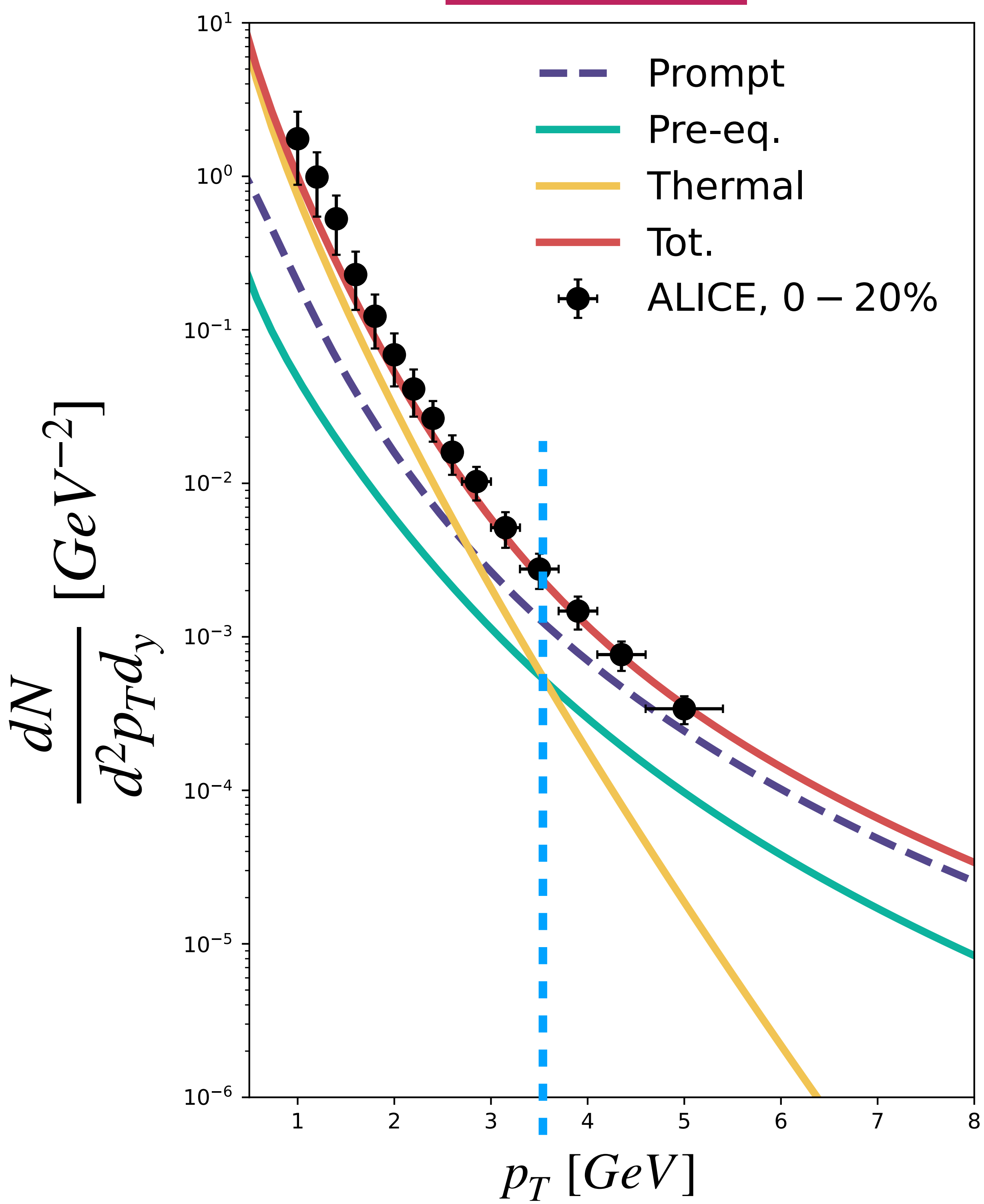
- Background obtained from VISHNU hydro with η/s=0.08 tuned to 0-20% PbPb collisions at 2.76TeV

  [Garcia-Montero et al., *Phys.Rev.C,* (2020)]

- Pre-eq. photon spectrum can be obtained from rescaled solution by matching event-by-event fluctuations in the temperature profile

- Above $p_T \approx 3.5$GeV pre-equilibrium production dominates thermal production but stays below prompt contribution

preliminary



$\tau_{hydro} = 1fm$

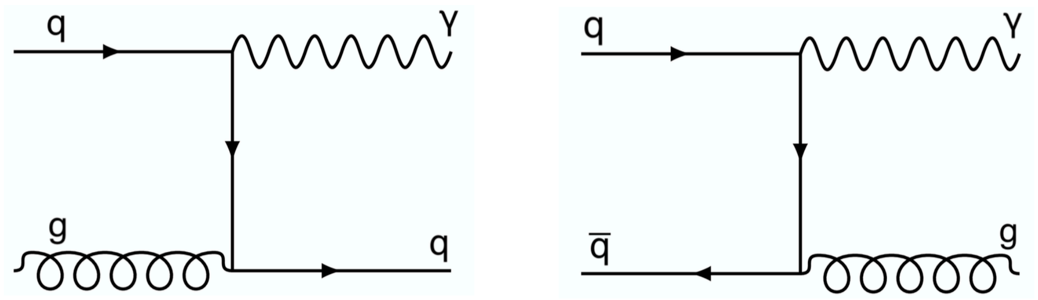
Conclusion and Ongoing Work

- Produced first computations for pre-equilibrium photon production rate computed from QCD kinetic theory
- Bremsstrahlung dominates production rate once quarks were produced
- Empirical scaling behavior for different couplings in time integrated photon p_T-spectrum
- Future: Include photon production into KøMPøST

Backup

Relevant Processes at Leading Order - 2↔2

2 ↔ 2 processes



Compton Scattering   Elastic pair annihilation

+ appropriate other channels

- Compton scattering:

$$\left.\frac{dN}{d^3p d^4x}\right|_{\mathrm{CS}} = -\frac{1}{2\nu_\gamma}\frac{1}{2E_p}\int \mathrm{d}\Pi_{2\leftrightarrow 2}\left|\mathcal{M}^{gq}_{\gamma q}(\mathbf{p}_1,\mathbf{p}_2|\mathbf{p},\mathbf{p}_3)\right|^2(2\pi)^4\delta^{(4)}(P_1+P_2-P-P_3)f_g(\mathbf{p}_1)f_q(\mathbf{p}_2)[1-f_q(\mathbf{p}_3)]$$

$$\left|\mathcal{M}^{gq}_{\gamma q}\right|^2 = -8e^2\sum_s q_s^2 g^2 d_F C_F\left[\frac{s}{t}+\frac{t}{s}\right]$$

- Elastic pair annihilation:

$$\left.\frac{dN}{d^3p d^4x}\right|_{\mathrm{EPA}} = -\frac{1}{2\nu_\gamma}\frac{1}{2E_p}\int \mathrm{d}\Pi_{2\leftrightarrow 2}\left|\mathcal{M}^{q\bar{q}}_{\gamma g}(\mathbf{p}_1,\mathbf{p}_2|\mathbf{p},\mathbf{p}_3)\right|^2(2\pi)^4\delta^{(4)}(P_1+P_2-P-P_3)f_q(\mathbf{p}_1)f_{\bar{q}}(\mathbf{p}_2)[1+f_g(\mathbf{p}_3)]$$

$$\left|\mathcal{M}^{q\bar{q}}_{\gamma g}\right|^2 = +8e^2\sum_s q_s^2 g^2 d_F C_F\left[\frac{u}{t}+\frac{t}{u}\right]$$

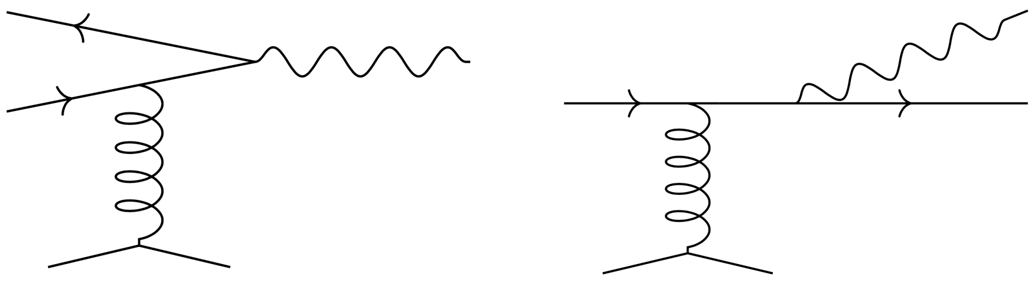
Effective isotropic screening regulated by screening masses

s, t, u: Mandelstam variables

Relevant Processes at Leading Order - Effective 1↔2

- Collinear effective 1 <-> 2 processes in order to capture Landau-Pomeranchuk-Migdal (LPM) effect via effective vertex resummation

Effective 1 ↔ 2 processes



Inelastic pair annihilation Bremsstrahlung off q & q̄

[Hauksson et al., Phys. Rev. C (2018)]

- Bremsstrahlung:

$$\frac{dN}{d^3p d^4x}\bigg|_{\mathrm{B}} = -\frac{2\sum_s q_s^2}{2\nu_\gamma}\int_0^1 \mathrm{d}z\,\nu_q \left[\frac{1}{z^3}\frac{\mathrm{d}\Gamma^q_{\gamma q}}{\mathrm{d}z}\left(\tfrac{p}{z},z\right) f_q\left(\tfrac{p}{z}\right)\left[1-f_q\left(\tfrac{\bar{z}}{z}p\right)\right] + \frac{1}{\bar{z}^3}\frac{\mathrm{d}\Gamma^q_{\gamma q}}{\mathrm{d}z}\left(\tfrac{p}{\bar{z}},\bar{z}\right) f_q\left(\tfrac{p}{\bar{z}}\right)\left[1-f_q\left(\tfrac{z}{\bar{z}}p\right)\right]\right]$$

- Inelastic pair annihilation:

$$\frac{dN}{d^3p d^4x}\bigg|_{\mathrm{IPA}} = -\frac{2\sum_s q_s^2}{2\nu_\gamma}\int_0^1 \mathrm{d}z\,\nu_\gamma \frac{\mathrm{d}\Gamma^\gamma_{q\bar{q}}}{\mathrm{d}z}(p,z) f_q(zp) f_q(\bar{z}p)$$

Effective inelastic rate; captures relevant aspects of current-current correlation function inside the medium