

For HP, 長崎  
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# AN ELECTRO-MAGNETIC PHENOMENOLOGY OF THE EARLY STAGES

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+ based on *JHEP* 03 (2024) 053  
and 2309.00555



Bundesministerium  
für Bildung  
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**FSP ALICE**  
Erforschung von  
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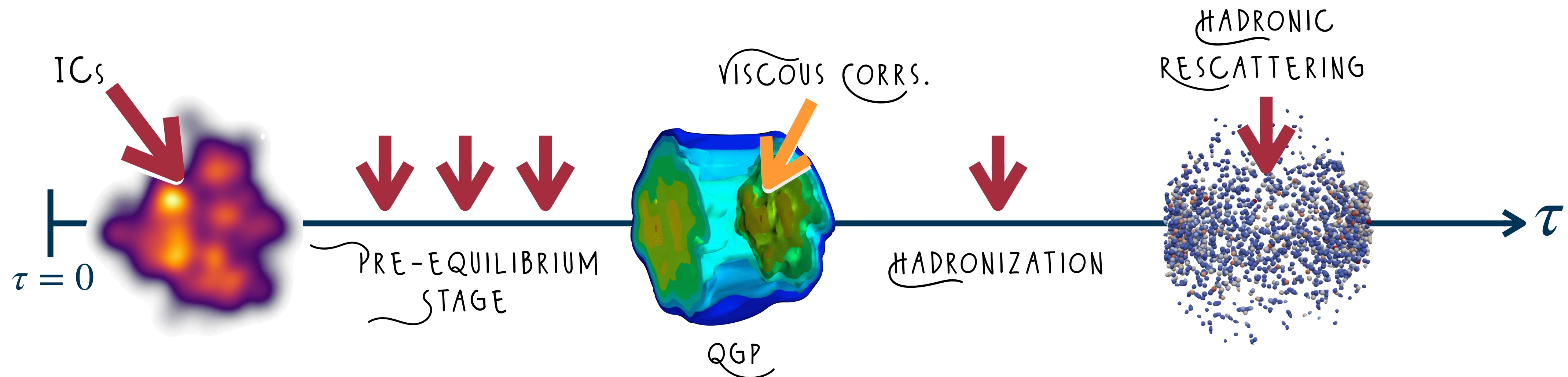


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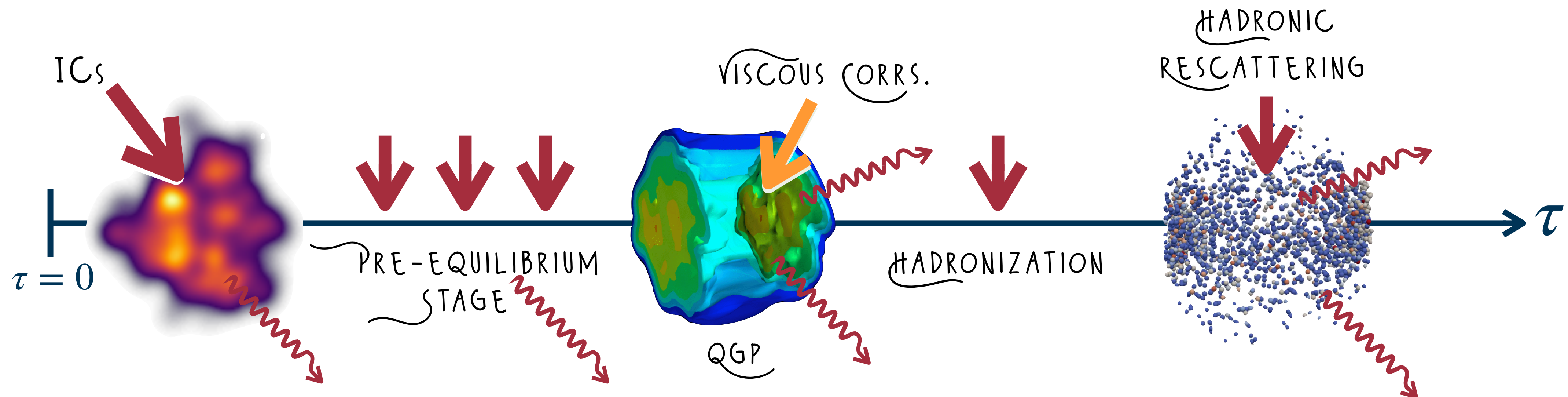
# THE TENUOUSLY THERMAL QGP

- Heavy-Ion Collisions create an Isolated Quantum System which is
  - Initially far away from any equilibrium
  - Self-interacting
  - Expanding against the vacuum
- A system battling to thermalize against all odds.



# ELECTROMAGNETIC PROBES

- Photons/Dileptons are a unique way of probing the system
  - No strong interactions
  - Mean free path in medium  $>$  medium size
  - Photons escape, virtually unscathed
- Photons are particularly sensitive to the evolution of the system



# KEY MESSAGE TODAY

The dynamics and evolution of the pre-equilibrium phase of HICs can be accessed based on a phenomenology of the electromagnetic probes.



# QCD KINETIC THEORY

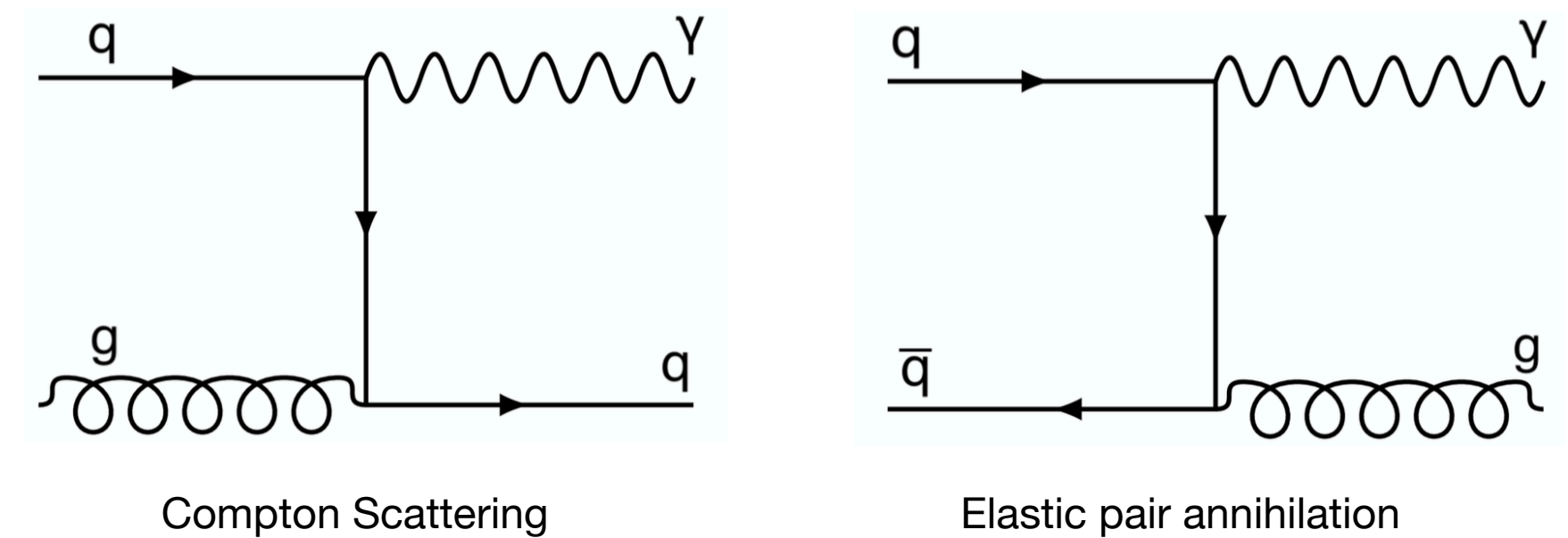
- ▶ Leading order production rates can be derived from effective kinetic theory

[Arnold et al., JHEP, (2001)]

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

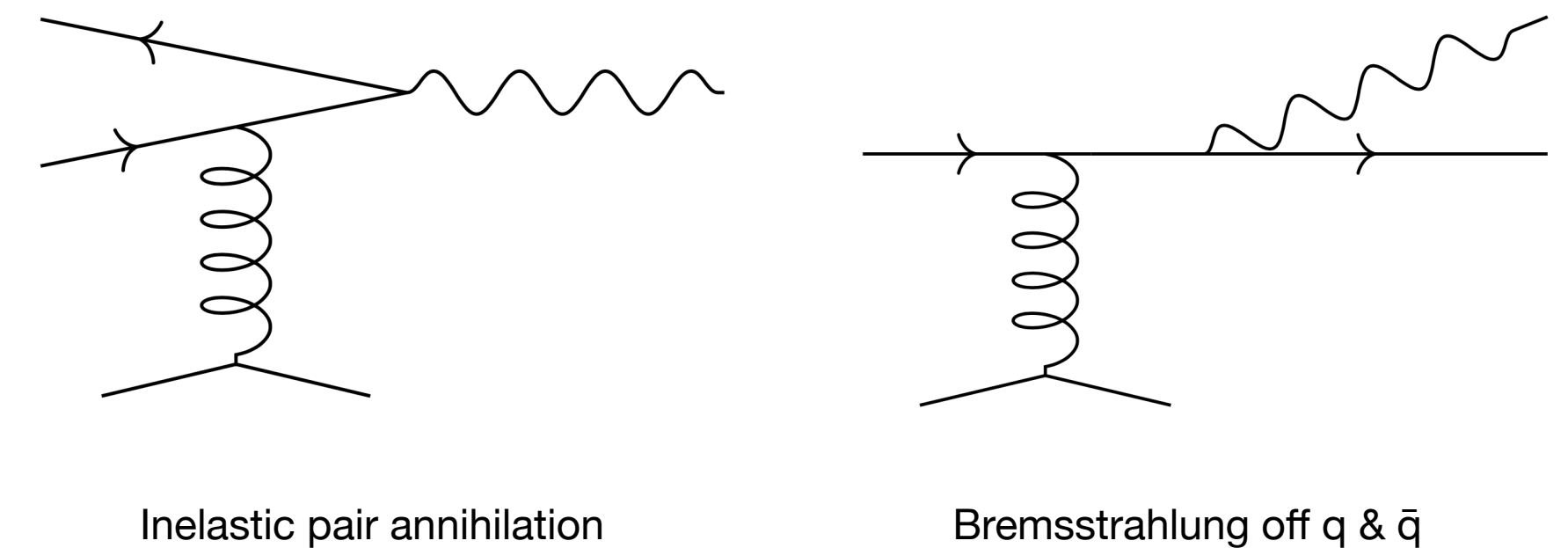
- ▶  $2 \leftrightarrow 2$  processes include Compton scattering and elastic pair annihilation
- ▶ Collinear effective  $1 \leftrightarrow 2$  processes in order to capture Landau-Pomeranchuk-Migdal (LPM) effect via effective vertex resummation

$2 \leftrightarrow 2$  processes



+ appropriate other channels

Effective  $1 \leftrightarrow 2$  processes



# QCD KINETIC THEORY

- ▶ Dynamics described by relativistic Boltzmann equation

Elastic  $2 \leftrightarrow 2$  scattering screened by Debye mass

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

[Arnold et al., JHEP 0301, (2003)]

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

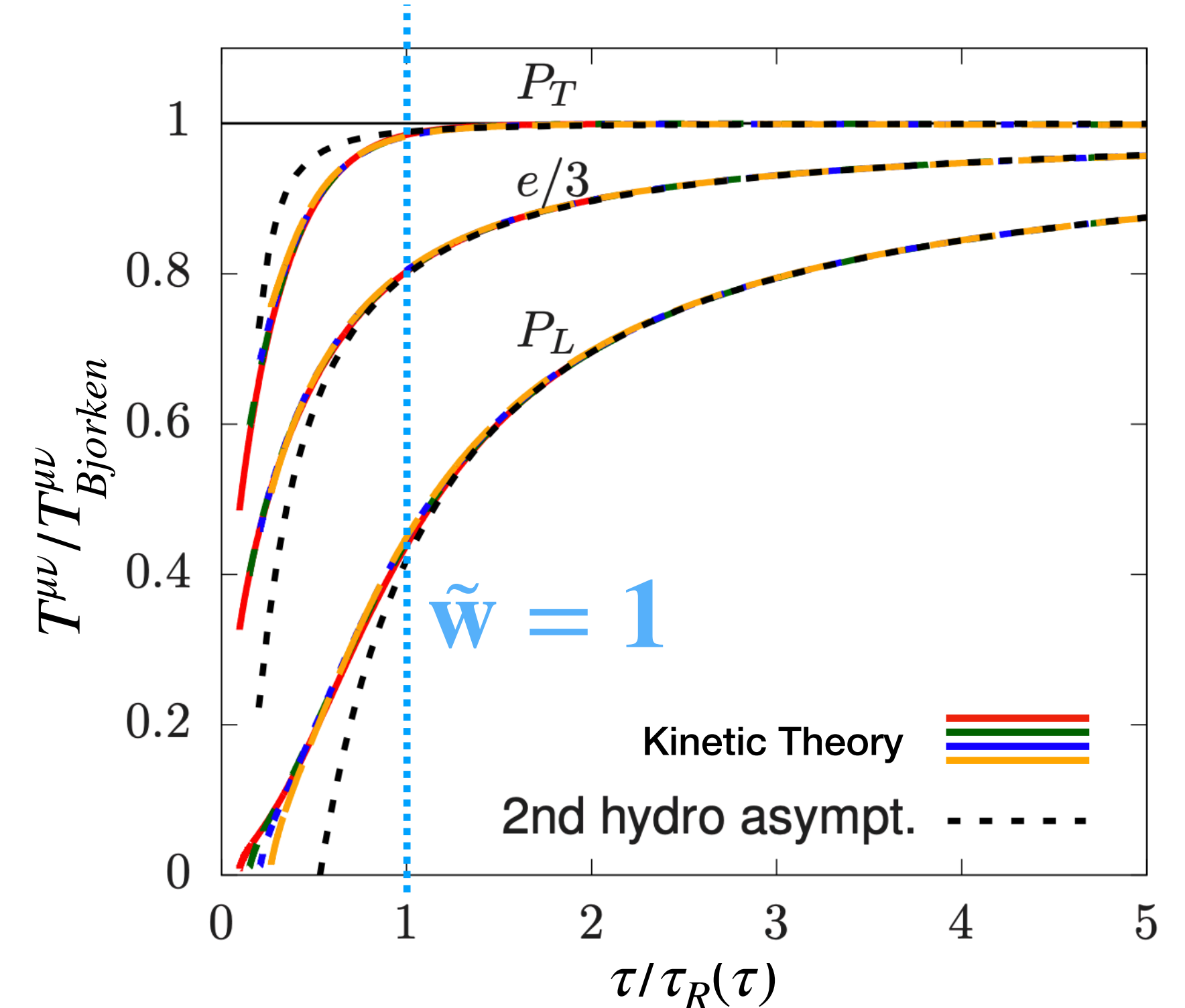
- ▶ Equilibration controlled by single relaxation rate

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

- ▶ 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



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



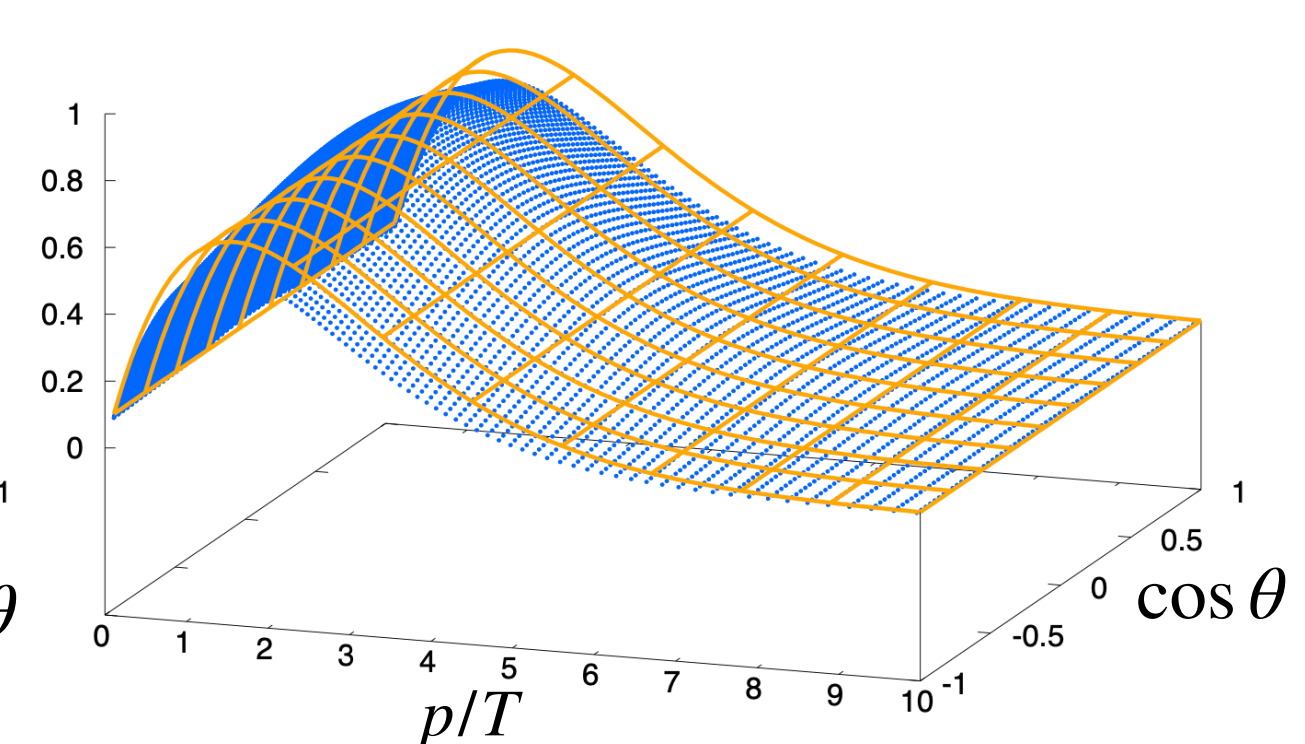
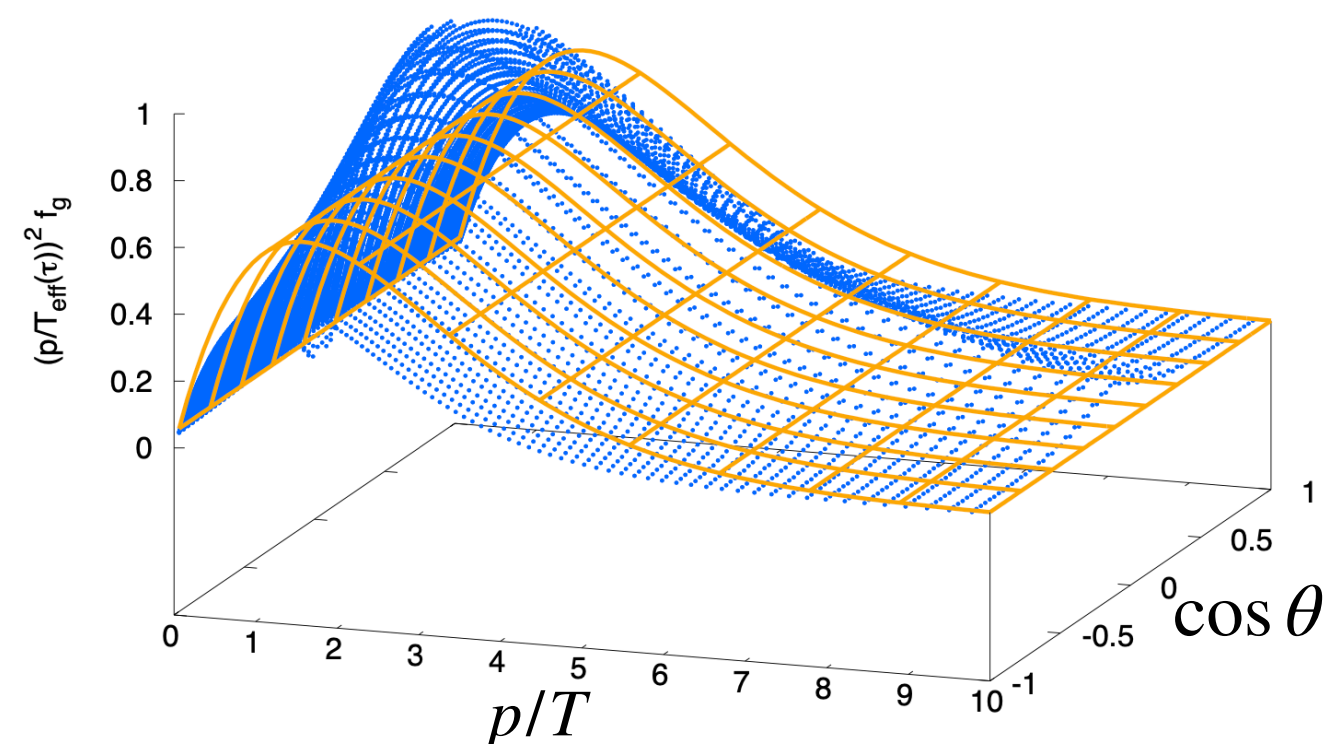
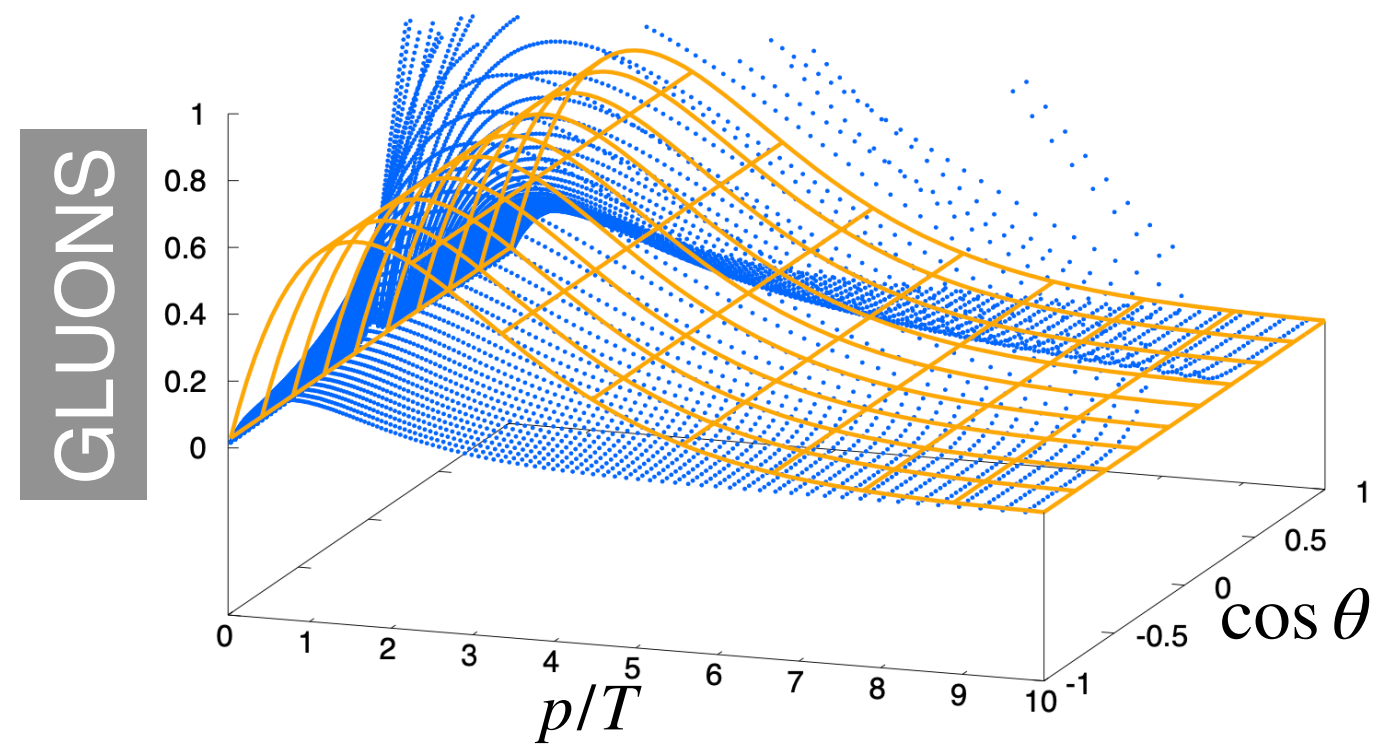
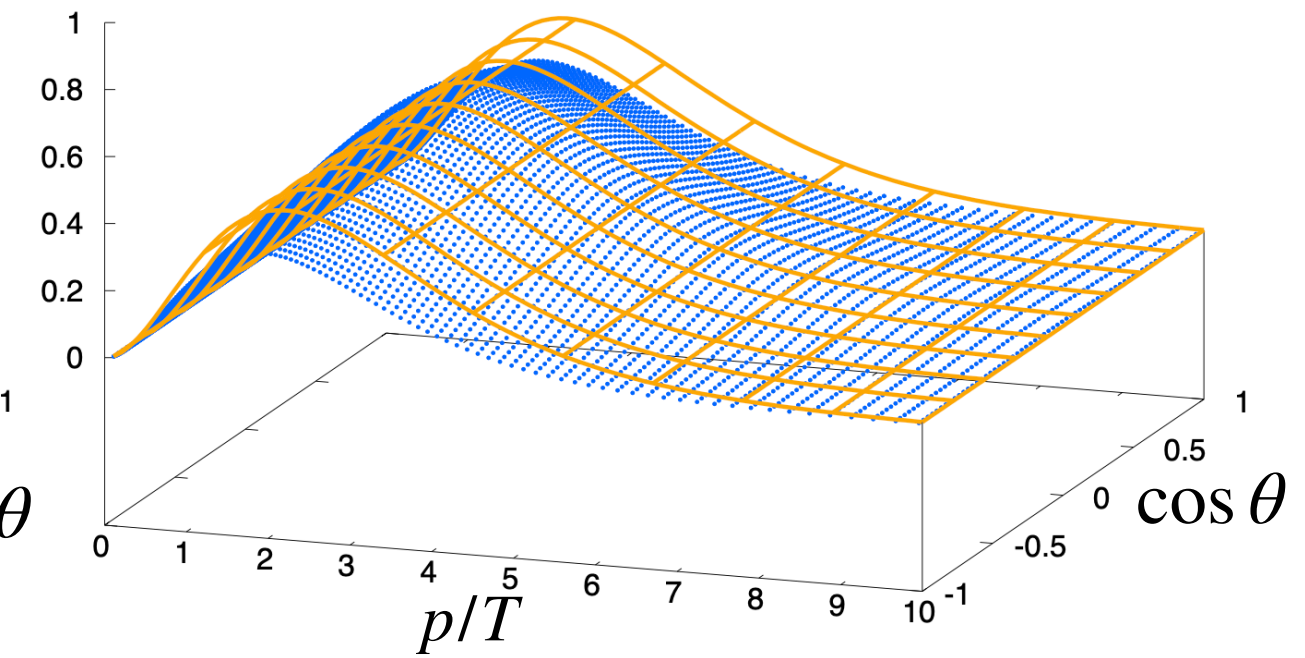
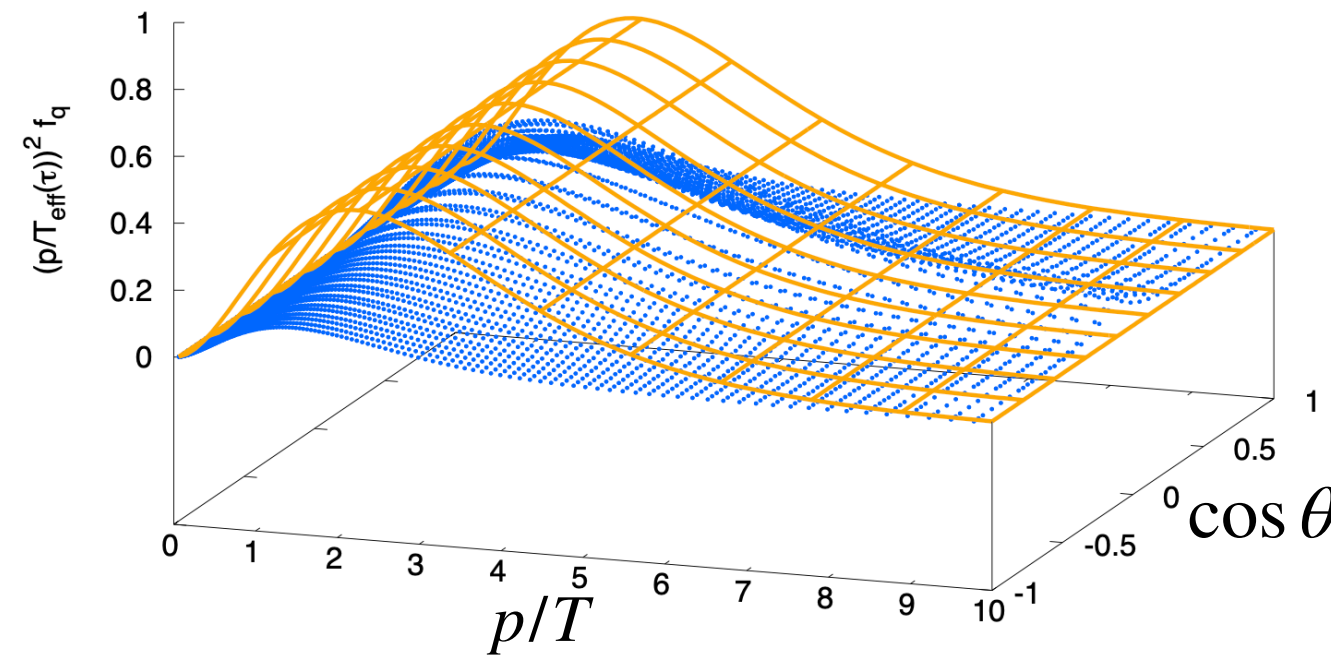
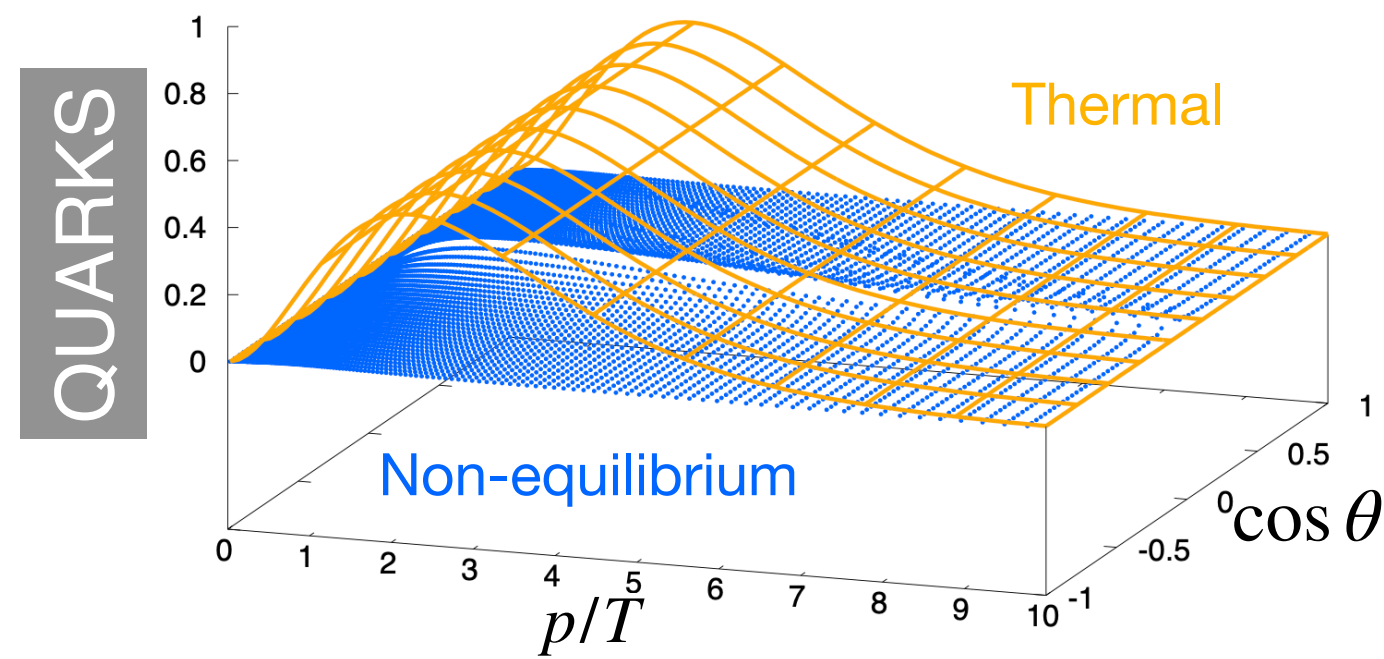
# QCD KINETIC THEORY

- ▶ Gluon dominated initial state

- ▶ Quarks produced dynamically

- ▶ System initially highly anisotropic  
→ peak at  $\cos \theta \approx 0$   
represents  $p_L \ll p_T$

$\lambda = 10, \alpha_s = 0.26$



$\tilde{w} = 0.078$

$\tilde{w} = 0.5$

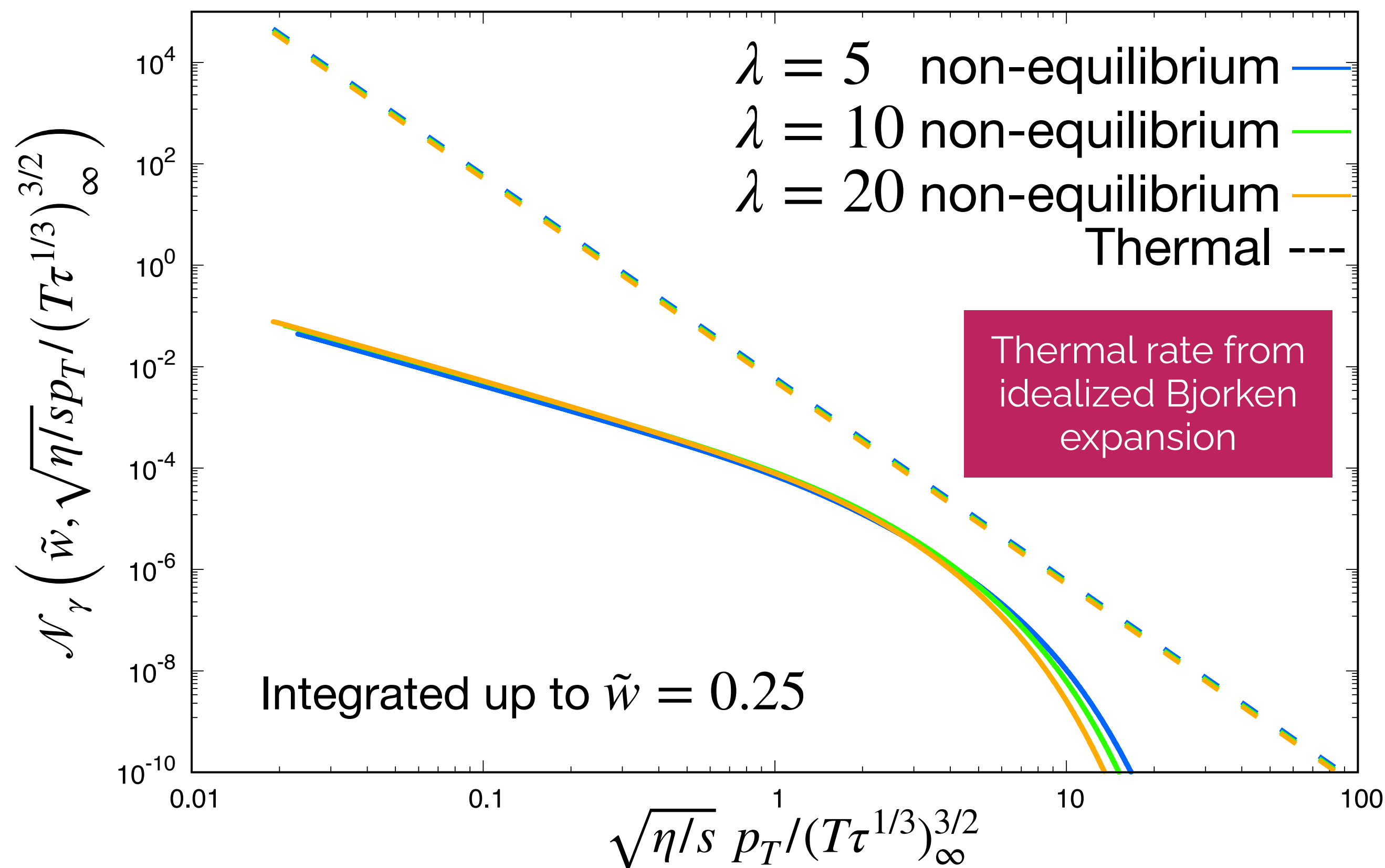
$\tilde{w} = 2.0$





# PHOTONS - SCALING

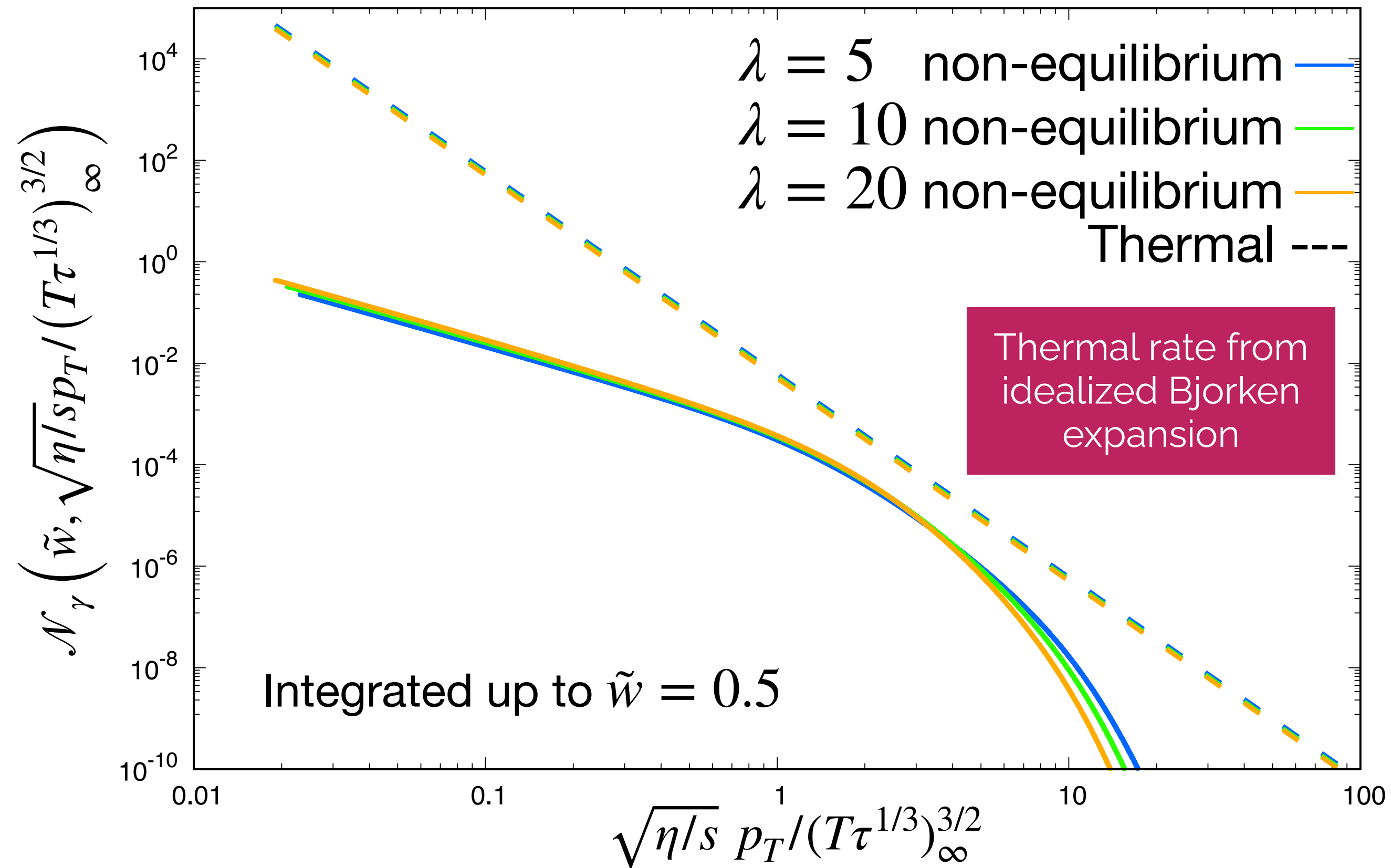
- ▶ Competing effects: cooling dynamics and quark production  
 $\Rightarrow$  reflected in time integrated pre-eq. photon spectrum
- ▶ Suppression wrt to „ideal“ photon spectrum (thermal equilibrium throughout evolution)
- ▶ Universal scaling of pre-eq photon spectrum in terms of shear viscosity  $\eta/s$  and entropy density  $T\tau^{1/3} \sim (\tau s)_{eq}^{1/3}$   
 $\Rightarrow$  valid for each theory with energy attractor



$$\frac{dN}{d^2x_T d^2p_T dy} = (\eta/s)^2 \tilde{C}_\gamma^{ideal} \mathcal{N}_\gamma \left( \tilde{w}, \sqrt{\eta/s} p_T / (T\tau^{1/3})_\infty^{3/2} \right)$$

# RESULTS - $p_T$ -SPECTRUM

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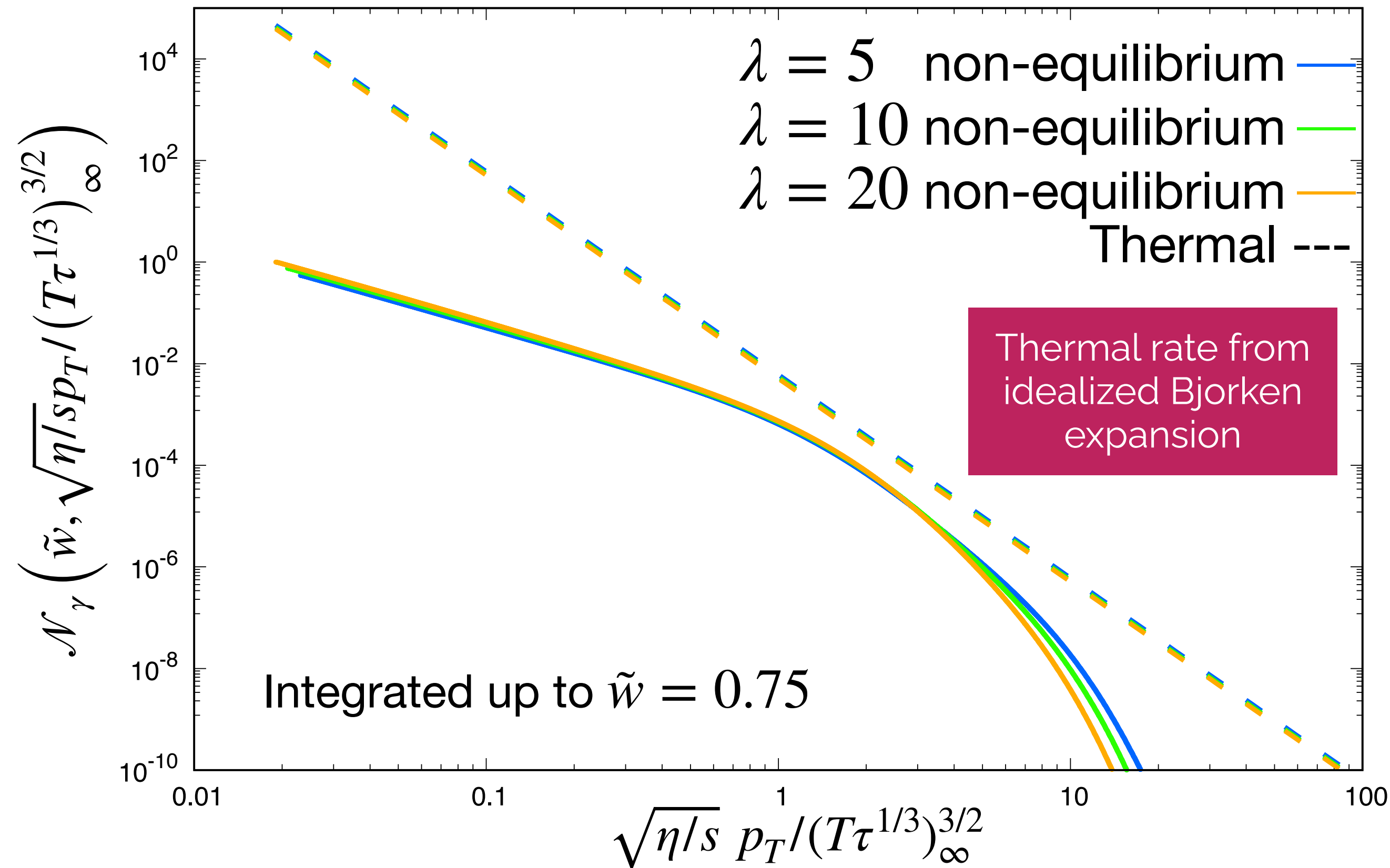


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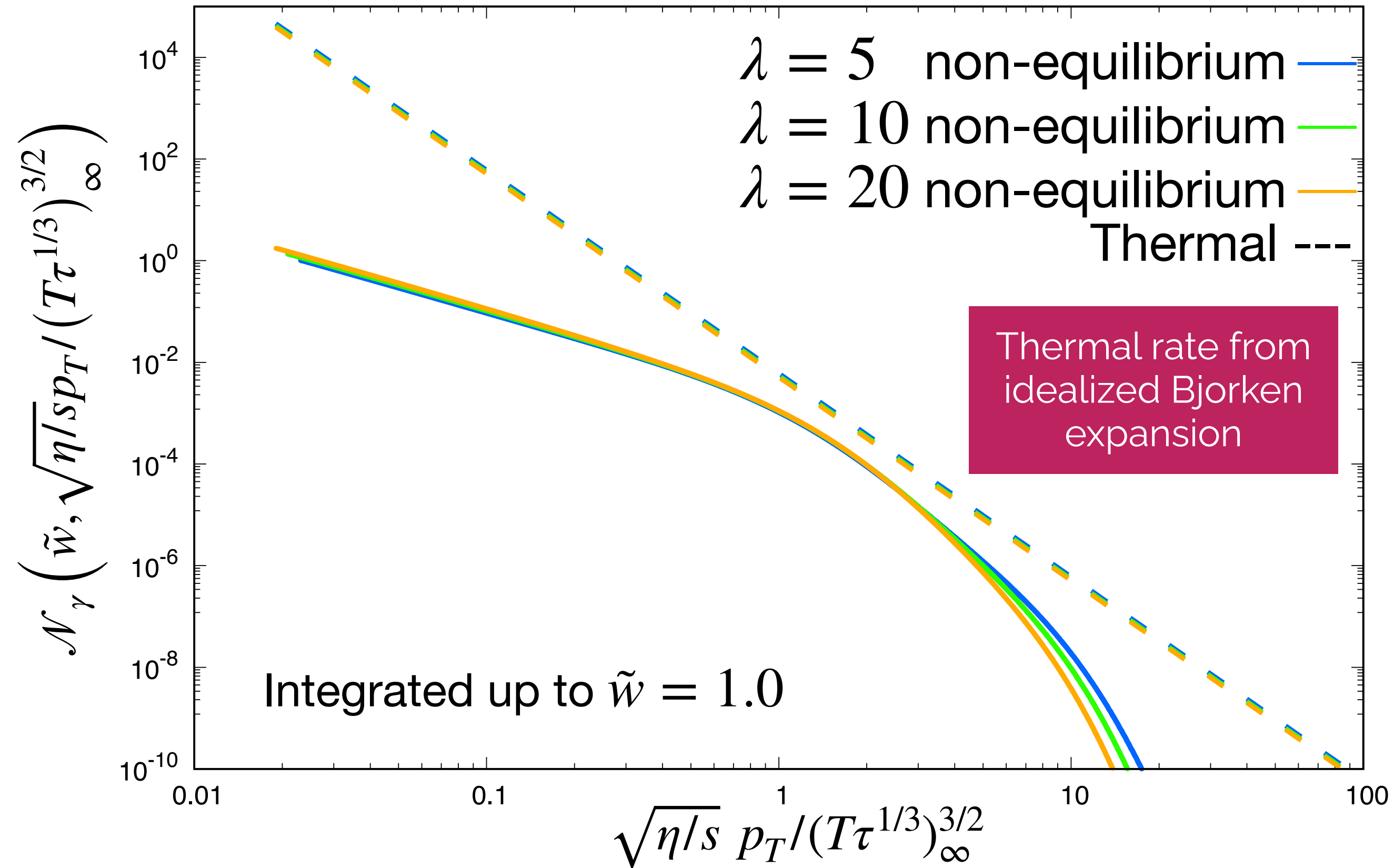
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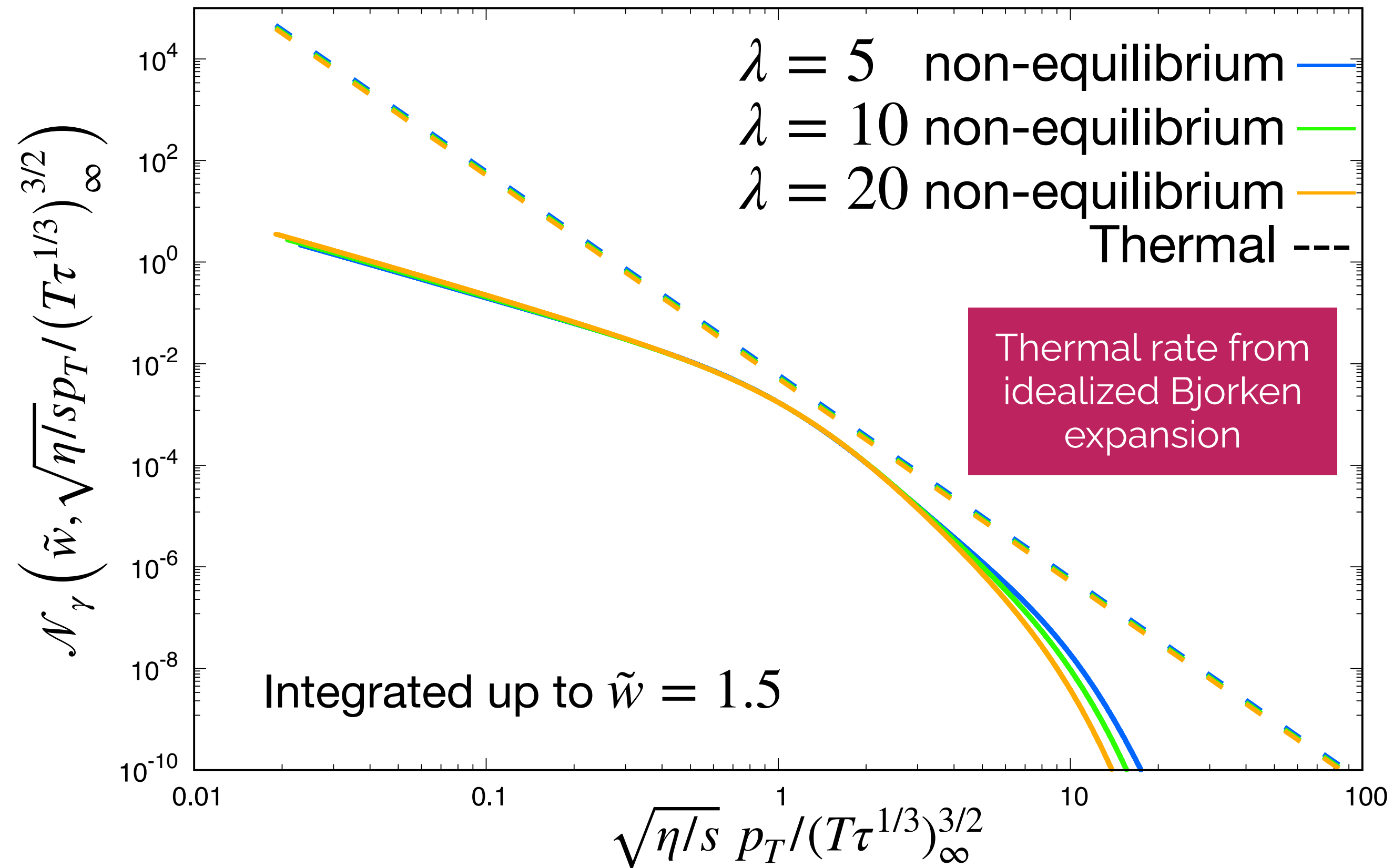


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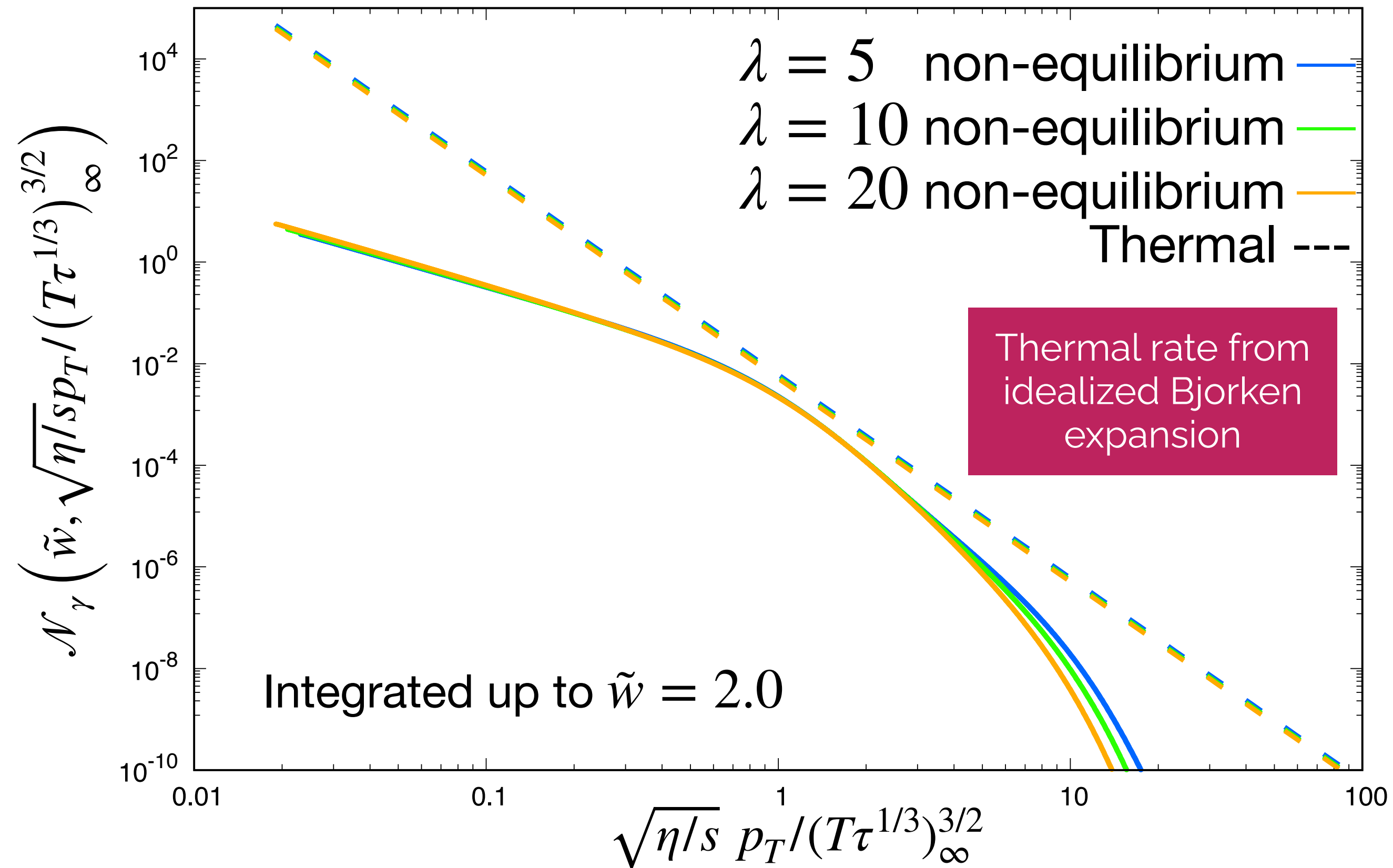
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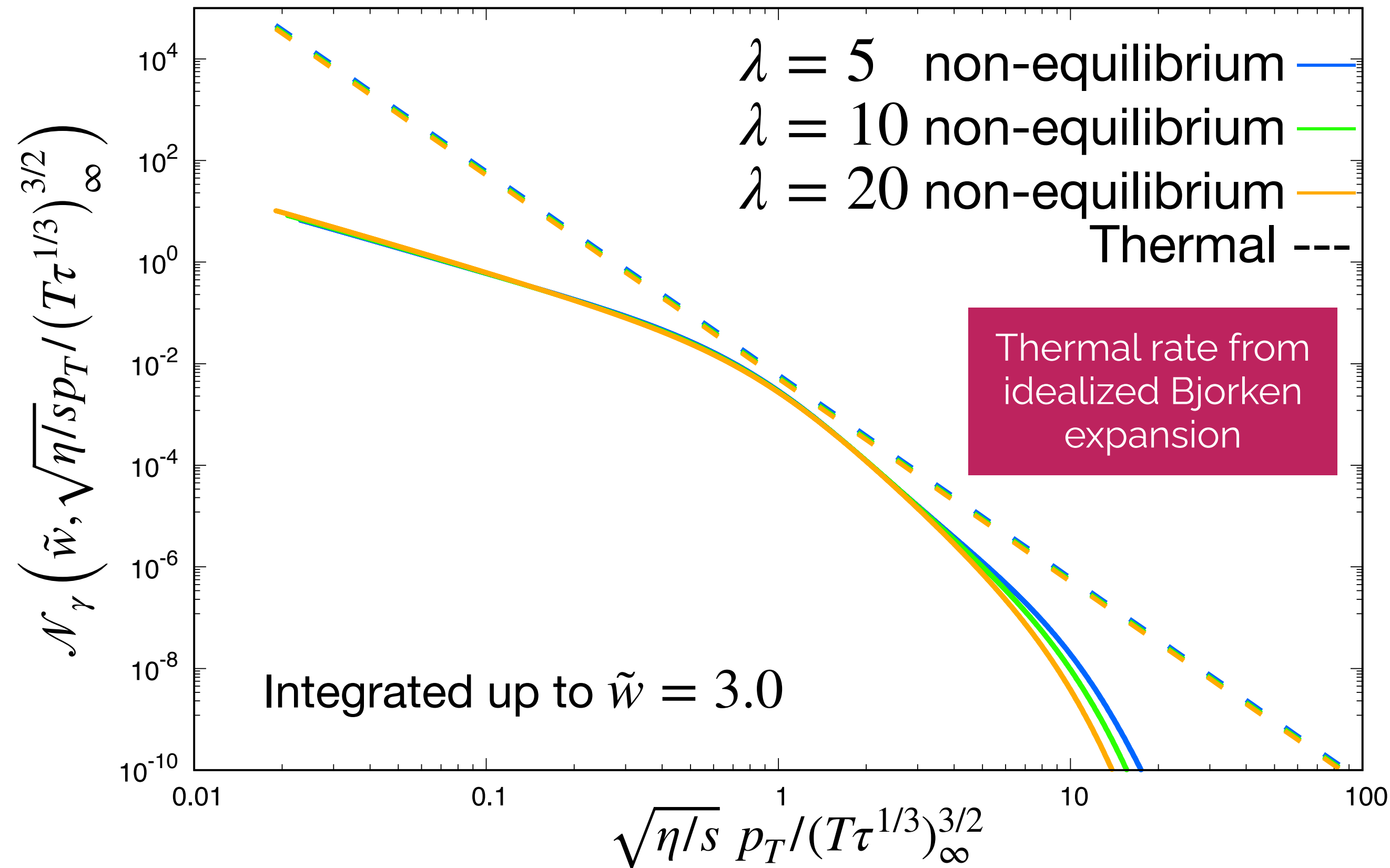


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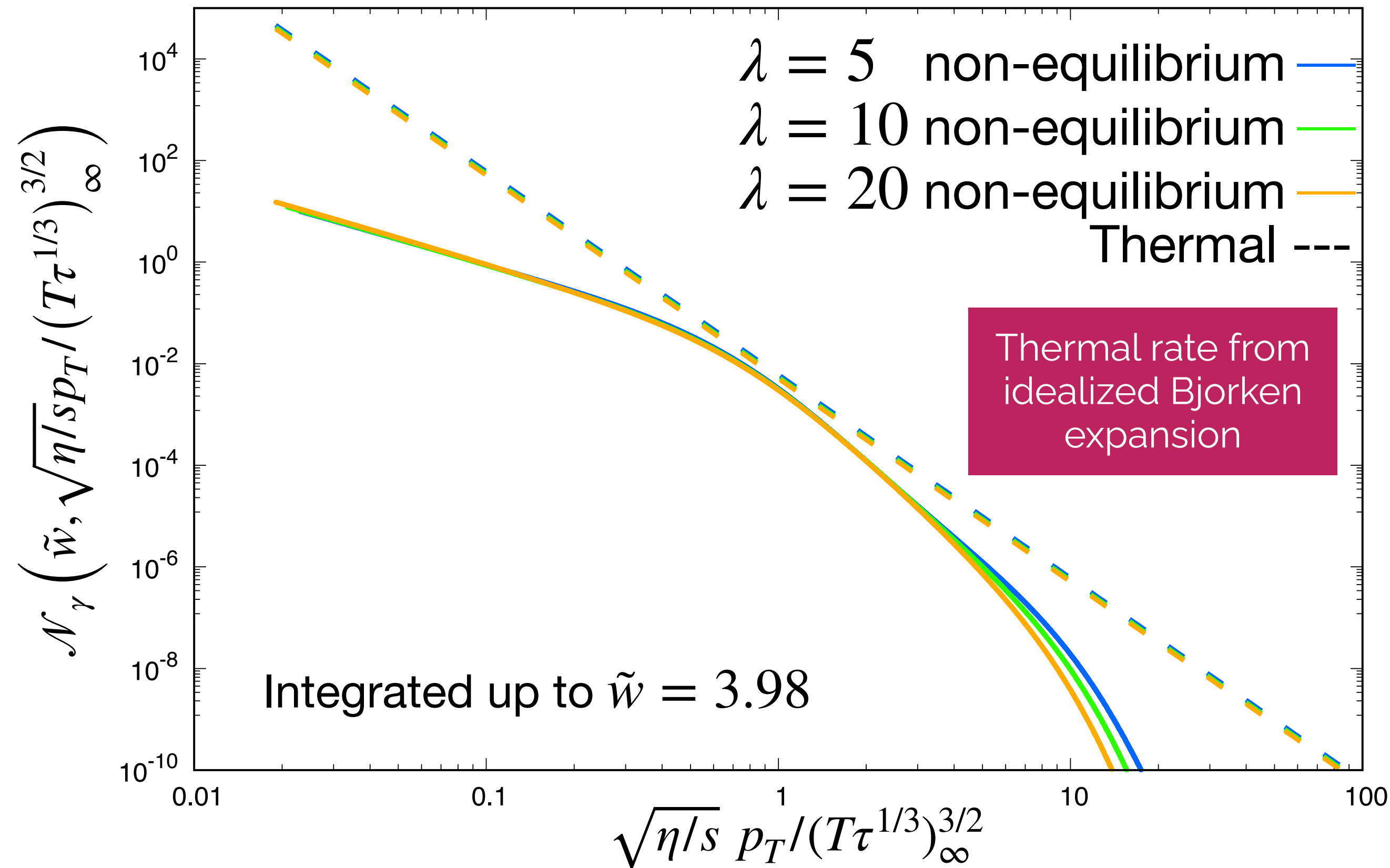
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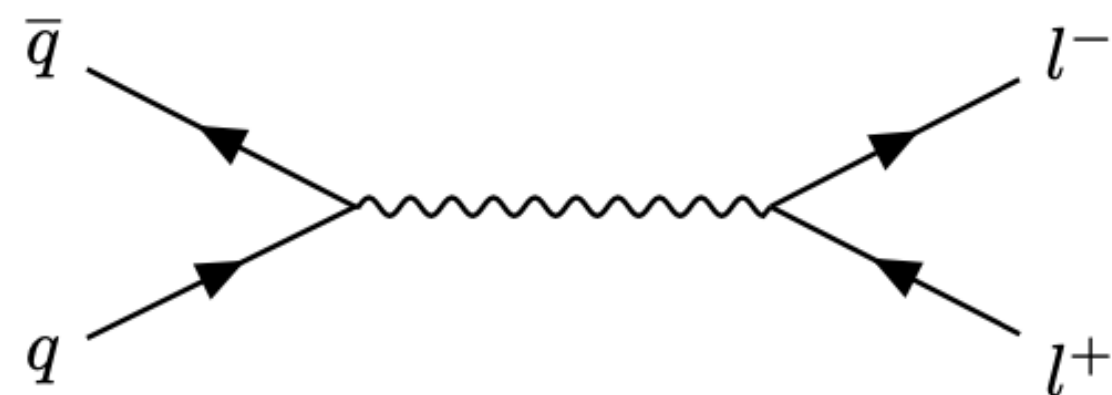


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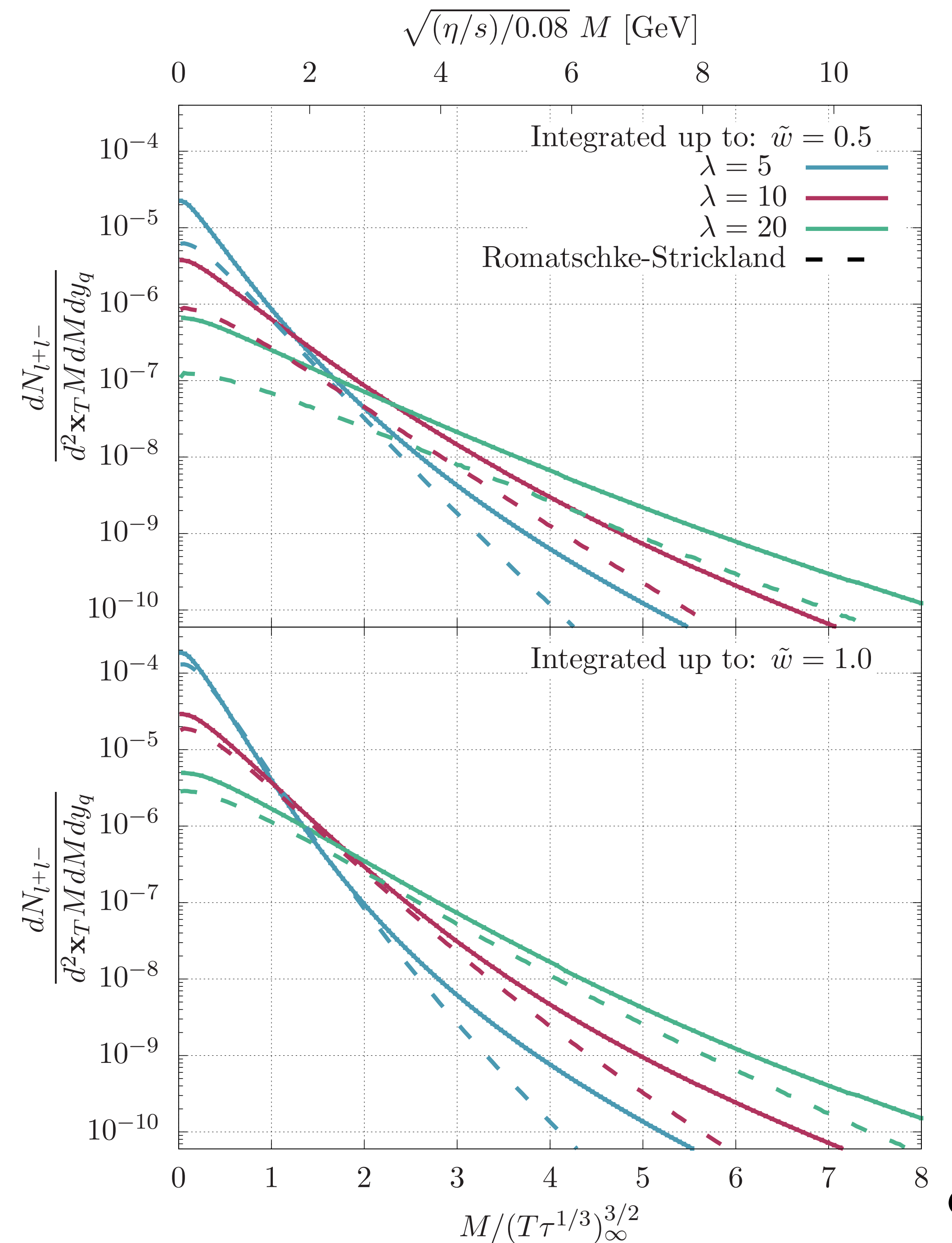
# DILEPTON PRODUCTION

- LO dilepton production is effective 2-2 via quark annihilation



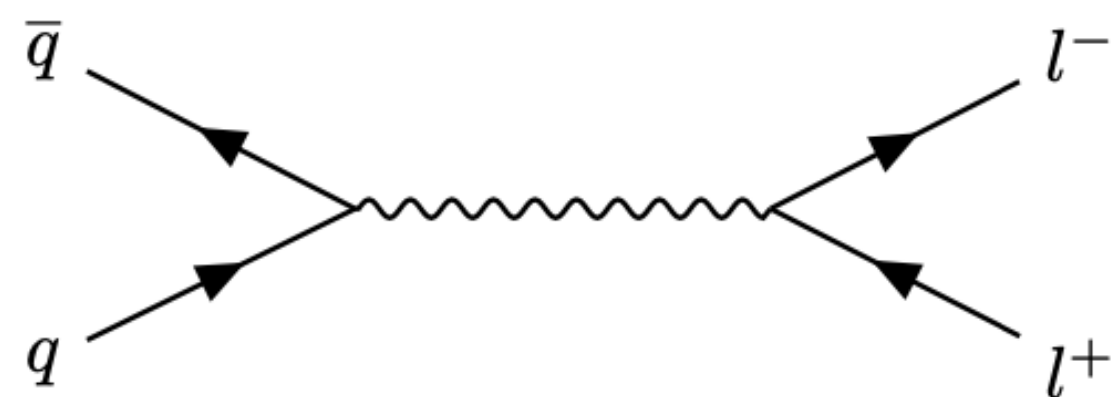
- Analytically and numerically (EKT) found scaling for dileptons

$$\frac{dN_{l+l^-}}{d^2\mathbf{x}_T M dM dy_Q} = (4\pi\eta/s)^2 \mathcal{N}_{l+l^-} \left( \frac{\sqrt{4\pi\eta/s} M}{(T\tau^{1/3})_\infty^{3/2}} \right)$$



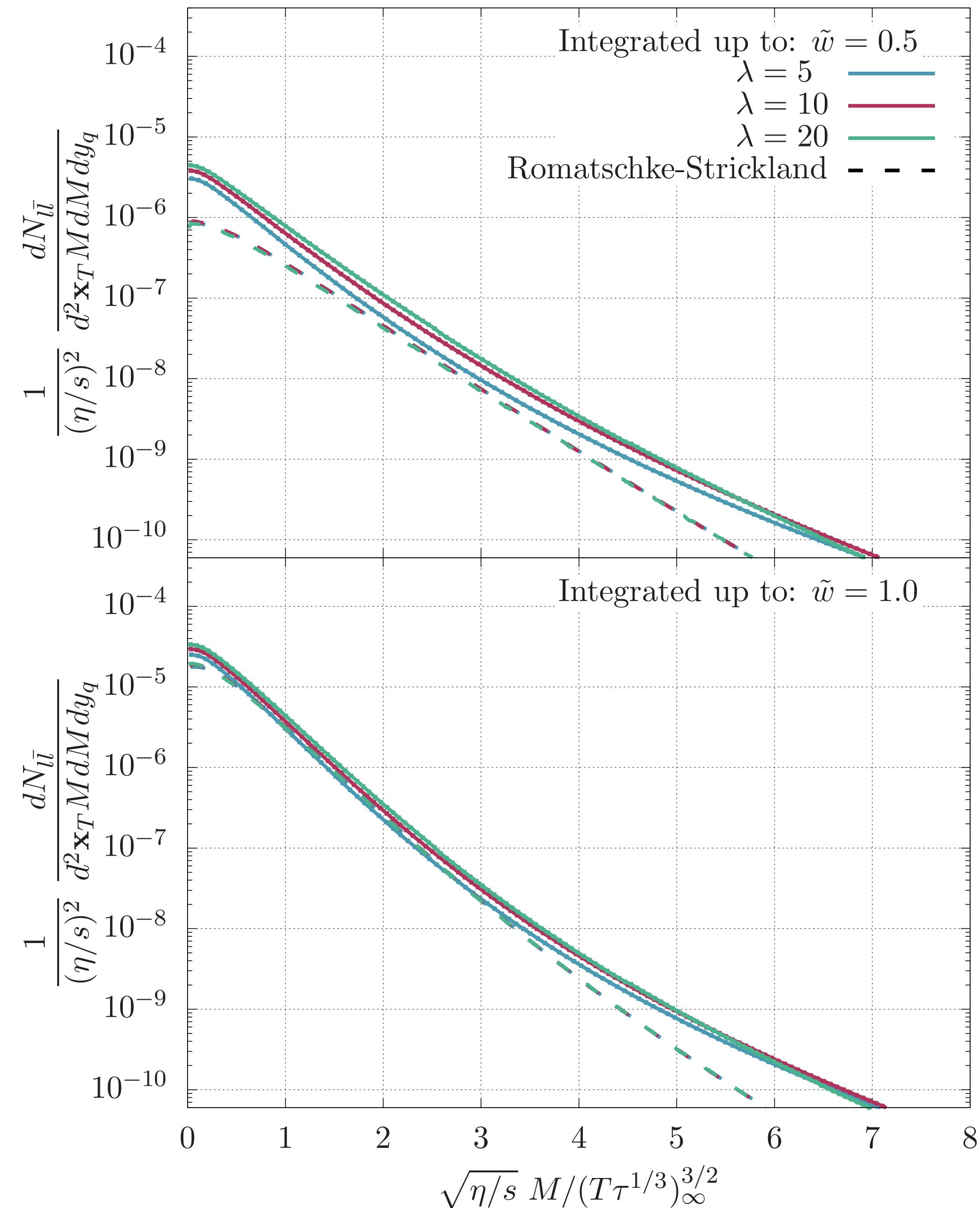
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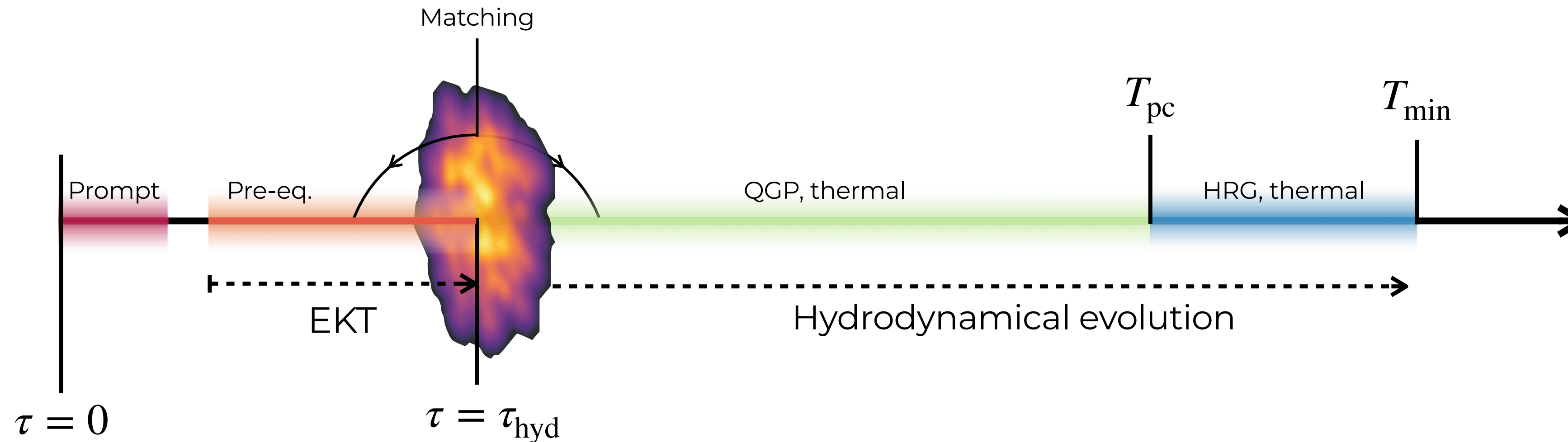




# RESULTS - PHENOMENOLOGY

- ▶ Compute pre-eq. photon production by matching scaling form of pre-eq. photon spectrum to event-by-event fluctuations of the energy density profile

- ▶ Matching is performed by using “external” hydro parameters  $(\tau^{1/3}T)_\infty(x_T) = \tau_{\text{hyd}}^{1/3} \left( T_{\text{hyd}}(x_T) + \frac{2}{3} \frac{\eta/s}{\tau_{\text{hyd}}} \right)$  and scaling time,  $\tilde{w}_{\text{match}} = T_{\text{hyd}}\tau_{\text{hyd}}/(4\pi\eta/s)$ .



- ▶ Vary matching times. Robust under assumptions:

$$\langle \tilde{w}(\tau_{\text{hydro}} = 0.6 \text{ fm}) \rangle = 1.002$$

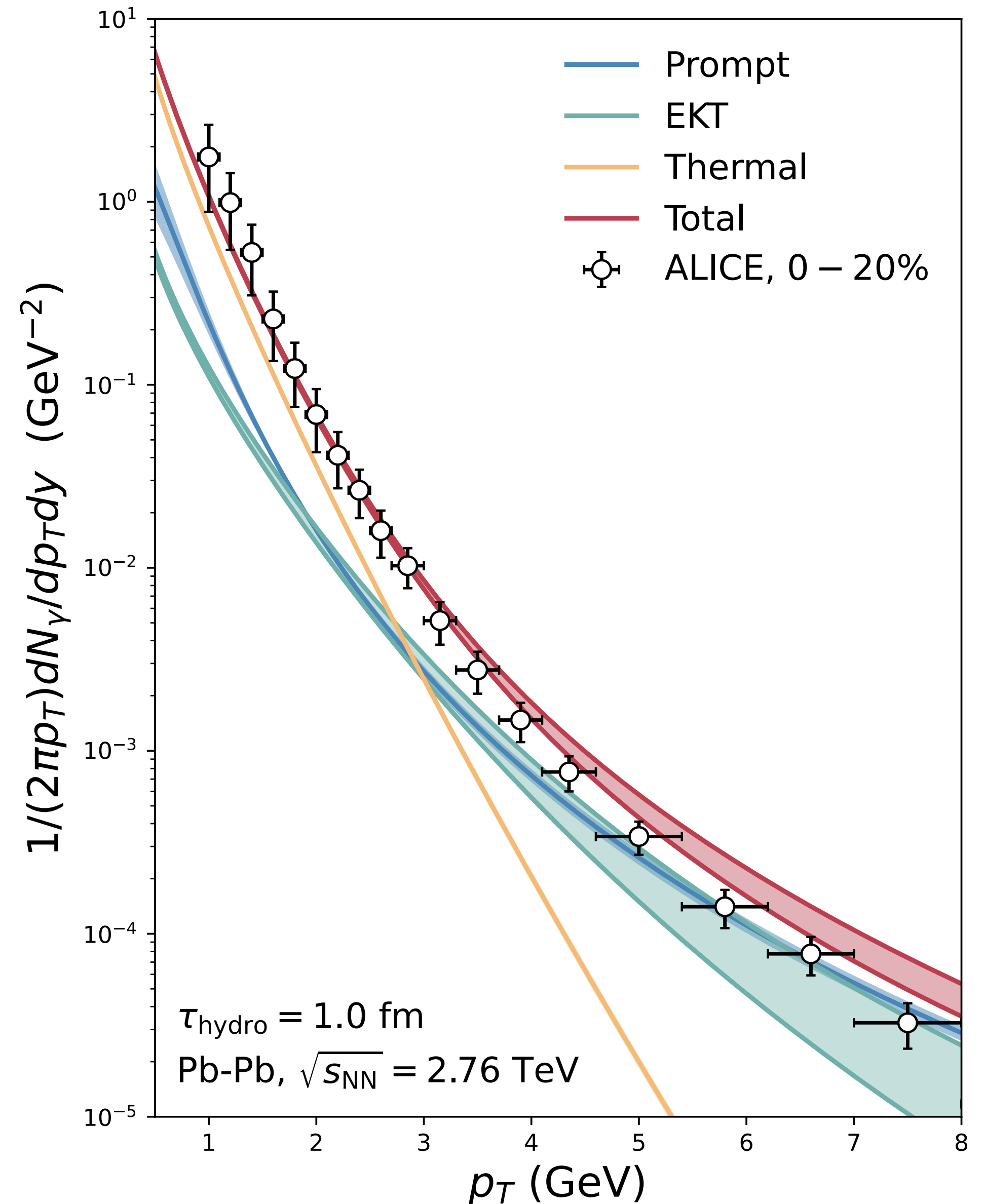
$$\langle \tilde{w}(\tau_{\text{hydro}} = 1 \text{ fm}) \rangle = 1.45$$

# PHOTONS - PHENOMENOLOGY

- ▶ Background evolution obtained from VISH2+1 hydro with  $\eta/s=0.08$  tuned to 0-20% PbPb collisions at 2.76TeV

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

- ▶ Above  $p_T \approx 3\text{GeV}$  pre-equilibrium production dominates in- medium photon production
- ▶ Sensitivity to initialisation time and initial conditions.



# RESULTS - PHENOMENOLOGY

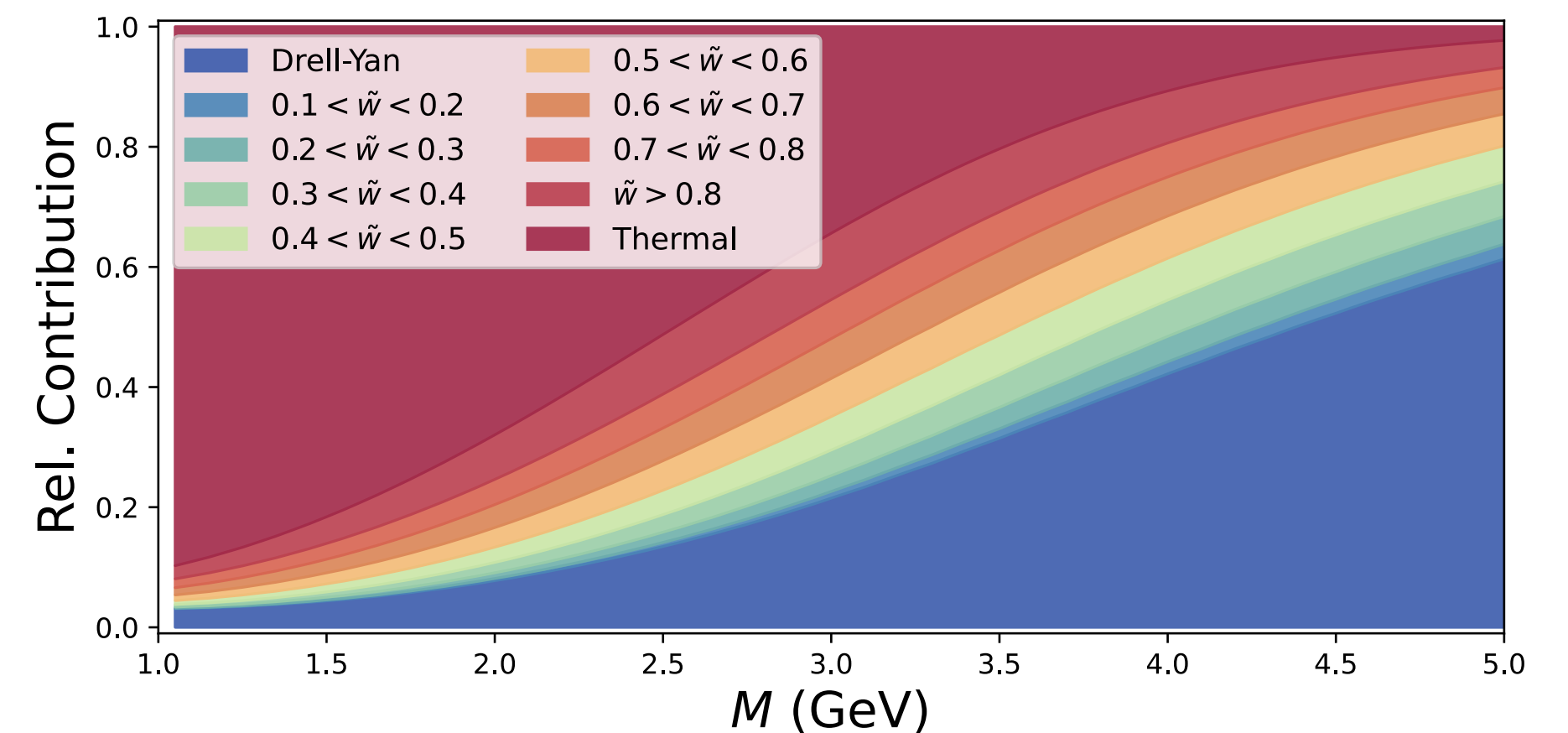
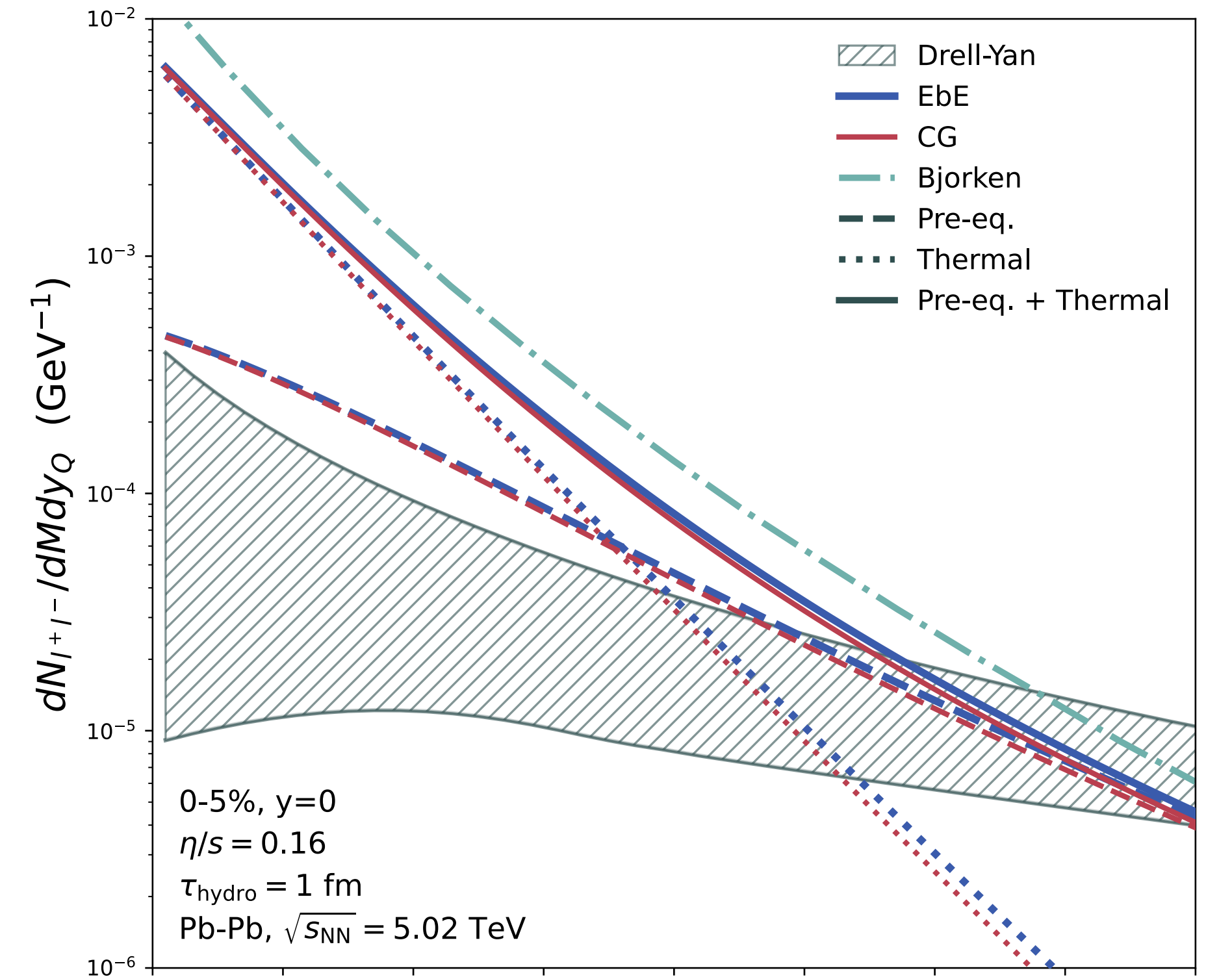
- ▶ Pre-eq. dilepton production event-by-event using a background evolution obtained from *Trajectum* tuned to 0-20% PbPb collisions at 5.02 TeV

[Giacalone *et al.* Phys. Rev. Lett. 131, 202302 (2023)]

- ▶ Comparison of EbE dilepton to a homogeneous and Coarse grained (CG) background

[Coquet *et al.* Phys. Lett. B 821, 136626 (2021)]

- ▶ Pre-equilibrium production relevant between  $p_T \sim 2 - 5$  GeV





# SUMMARY AND CONCLUSIONS



Pre-equilibrium **photon** and **dilepton** production rates computed from QCD KT



Universal scaling for different couplings in time integrated photon  $p_T$ -spectrum  
Analogous scaling for dileptons in  $M_{ee}$



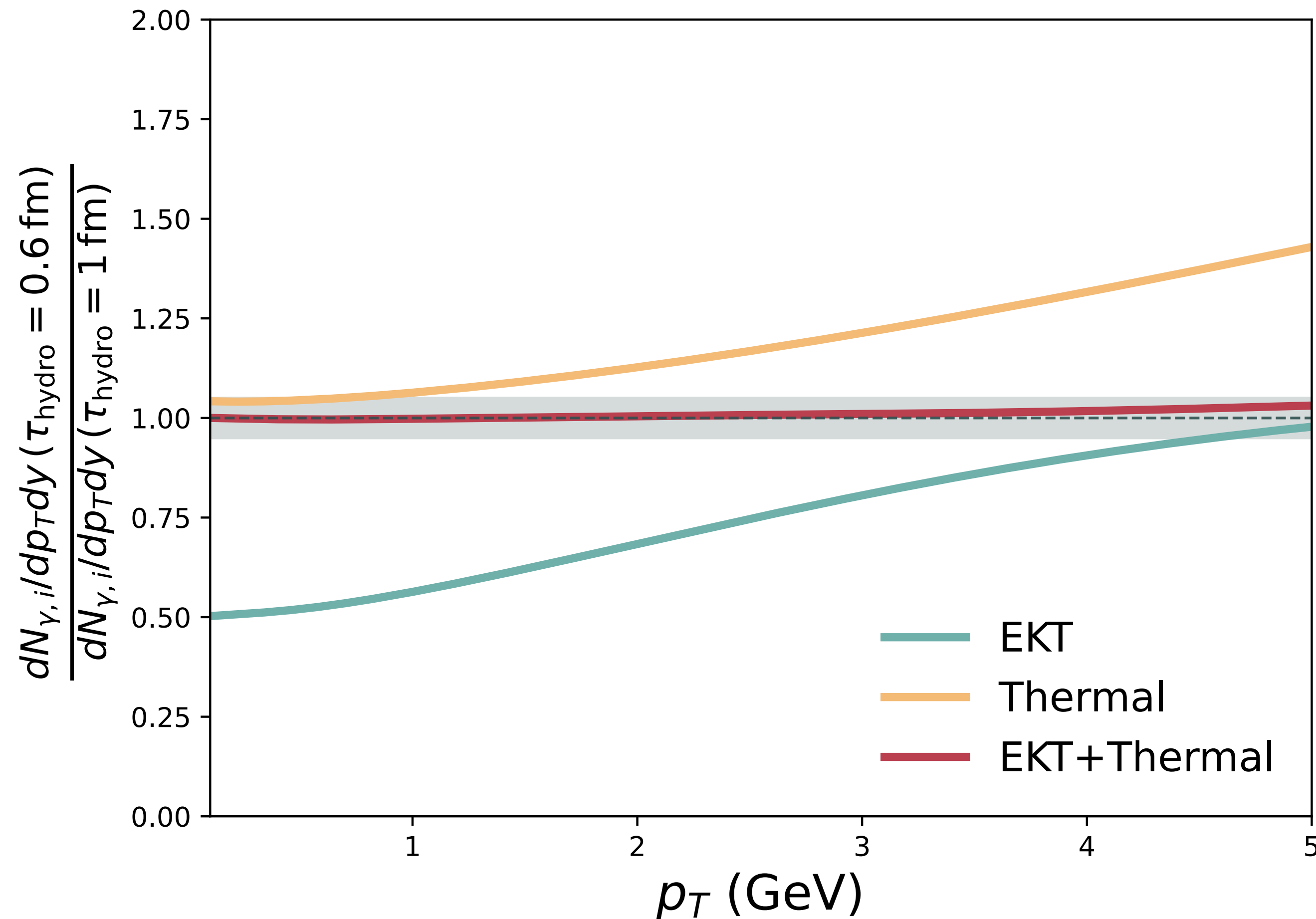
**Implemented:** dilepton/photon production into KØMPØST  
(git-branch: ShinyKØMPØST)



**Next:** Comprehensive exploration of EM probe observables, (e.g. dilepton polarisation,etc) for a new phenomenology of the early stage.

**BACK-UP**

# RESULTS - PHENOMENOLOGY

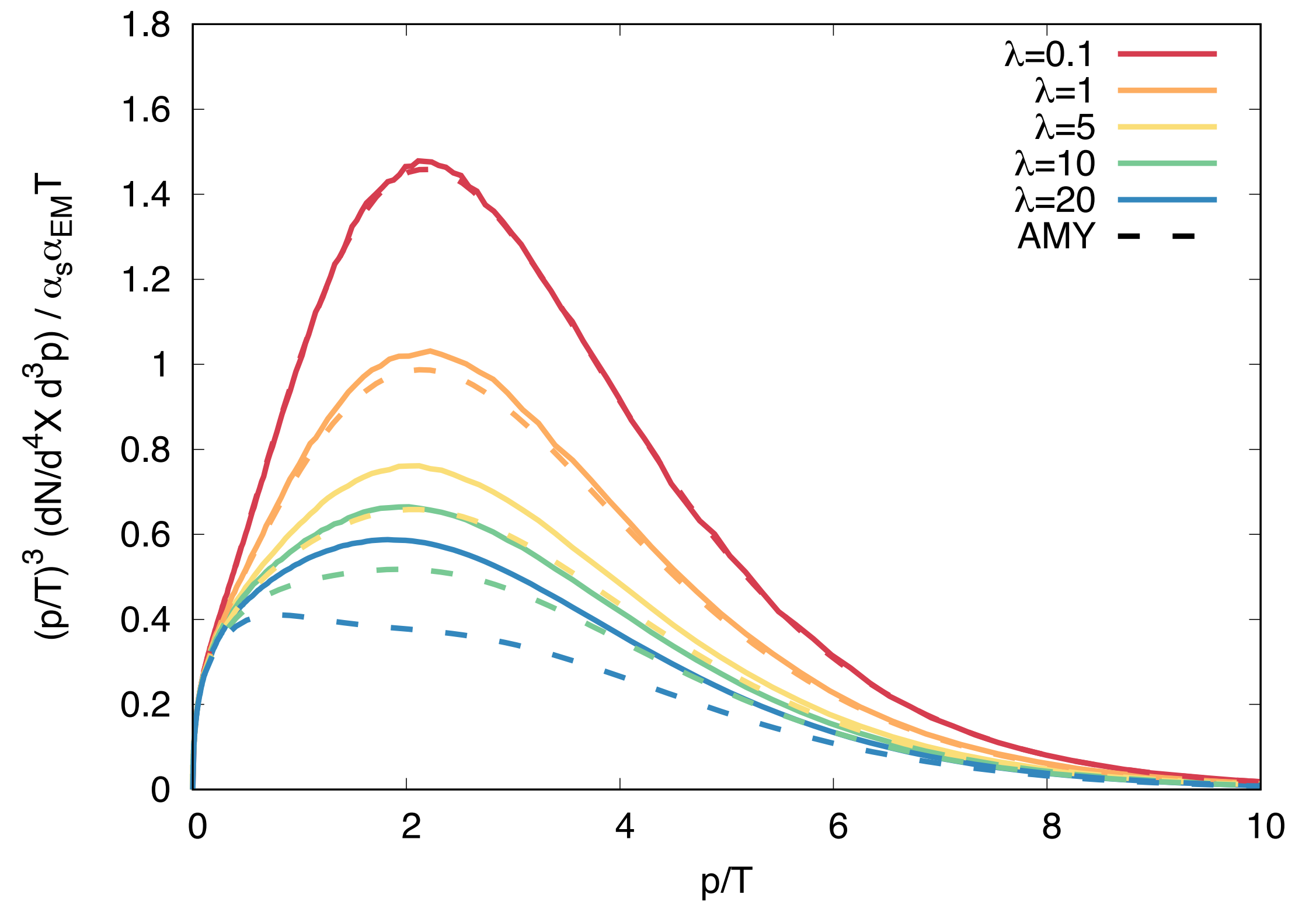
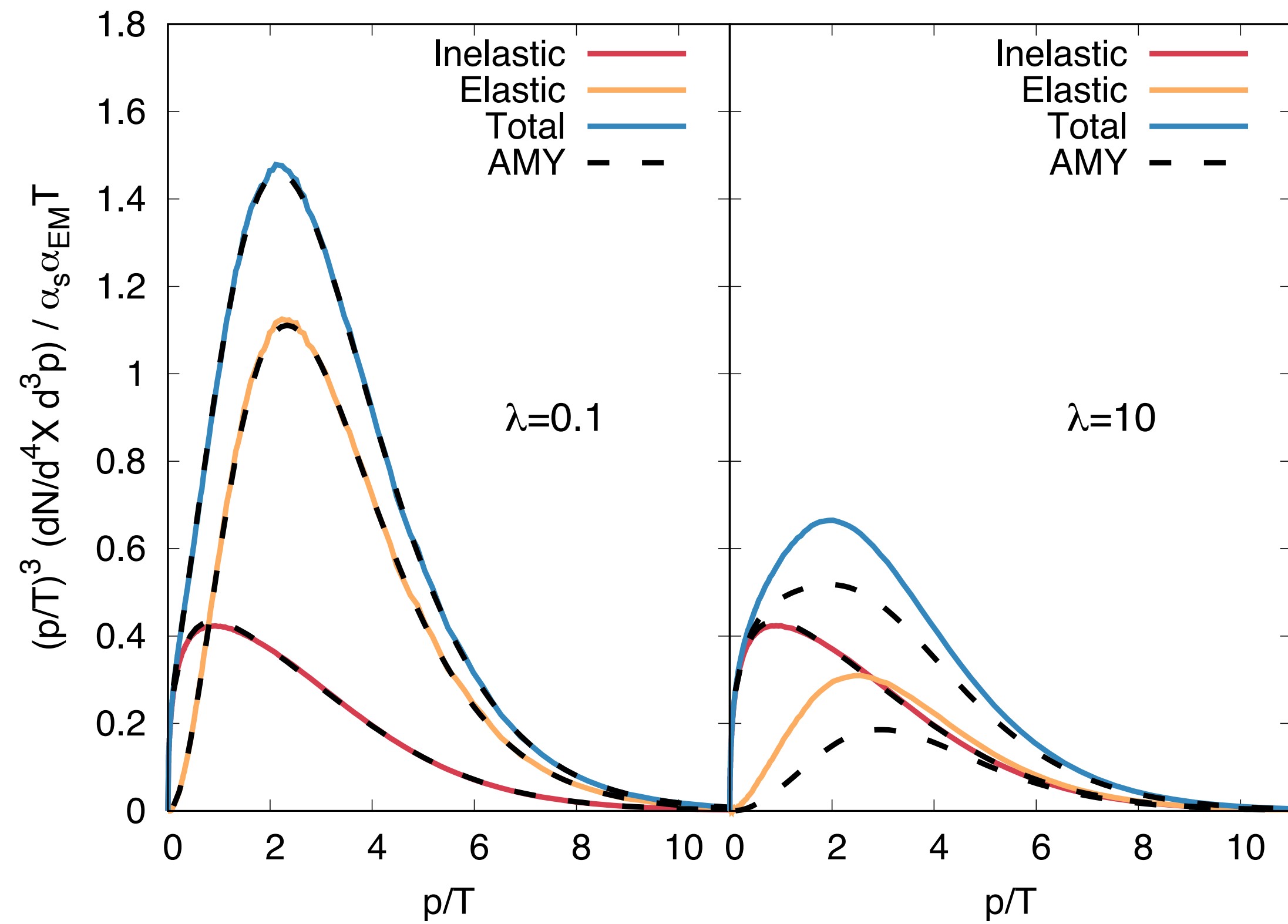


- ▶ Variations on  $\tau_{\text{hyd}}$  trigger differences on the specific contributions of the yield
- ▶ Total in medium contribution (EKT+Thermal) is relatively unchanged

In medium yield robust w.r.t. switching time!

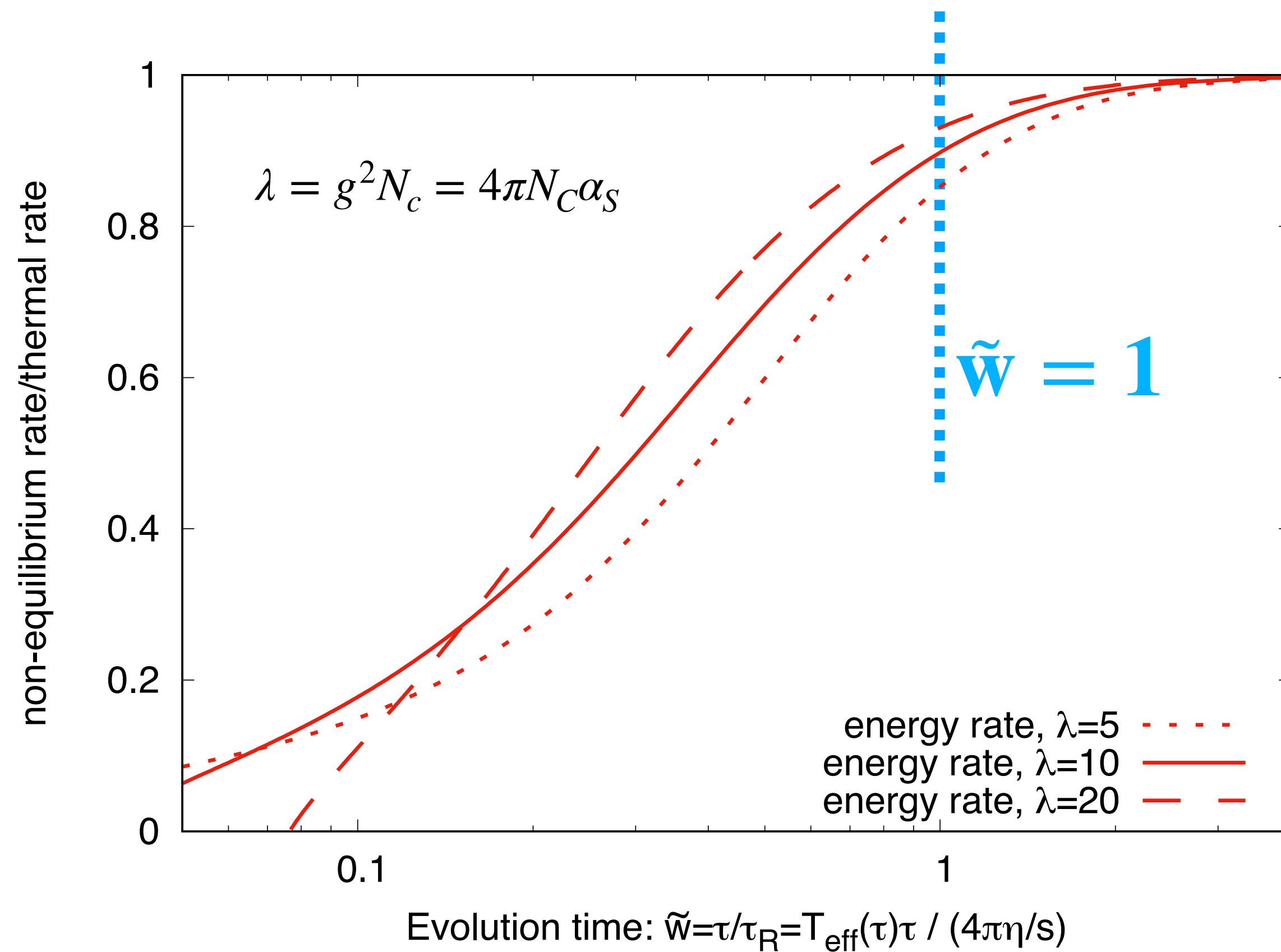


# COMPARISON TO SEMI-ANALYTICAL AMY RATES



# ELECTROMAGNETIC ENERGY LOSS RATE

- ▶ Non-equilibrium photon rate compared to thermal energy rate



Energy rate:

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

where:

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

Recover thermal energy rate on timescales when hydrodynamics becomes applicable



# RESULTS - 2D SPECTRUM

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

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

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

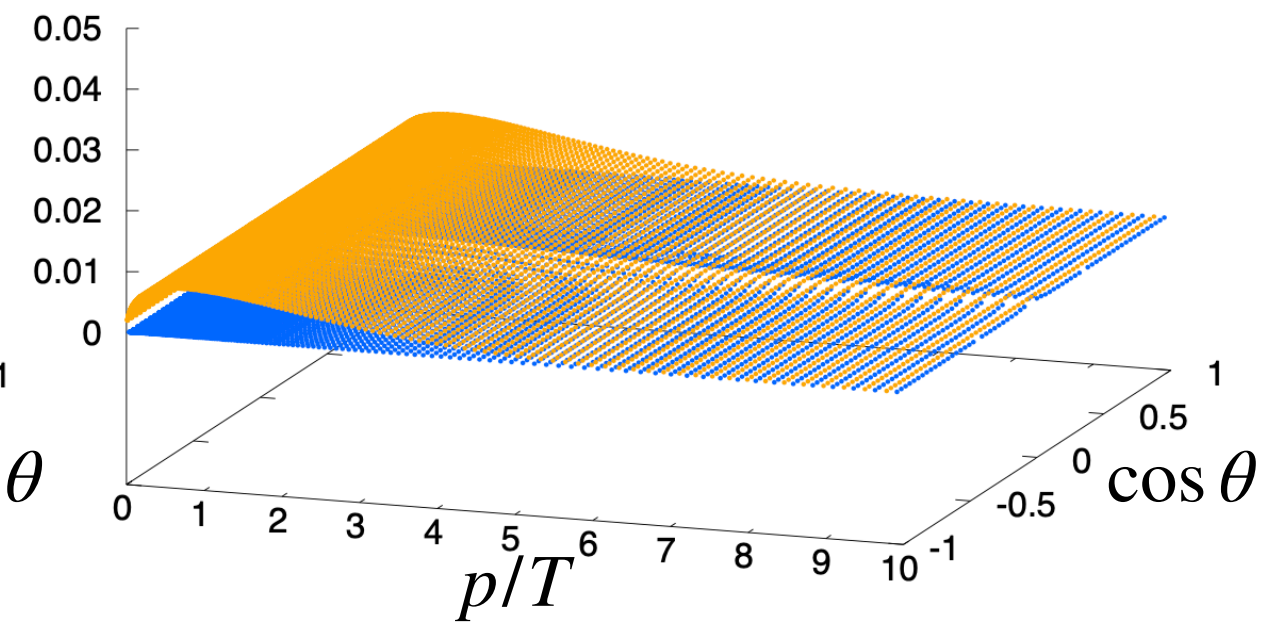
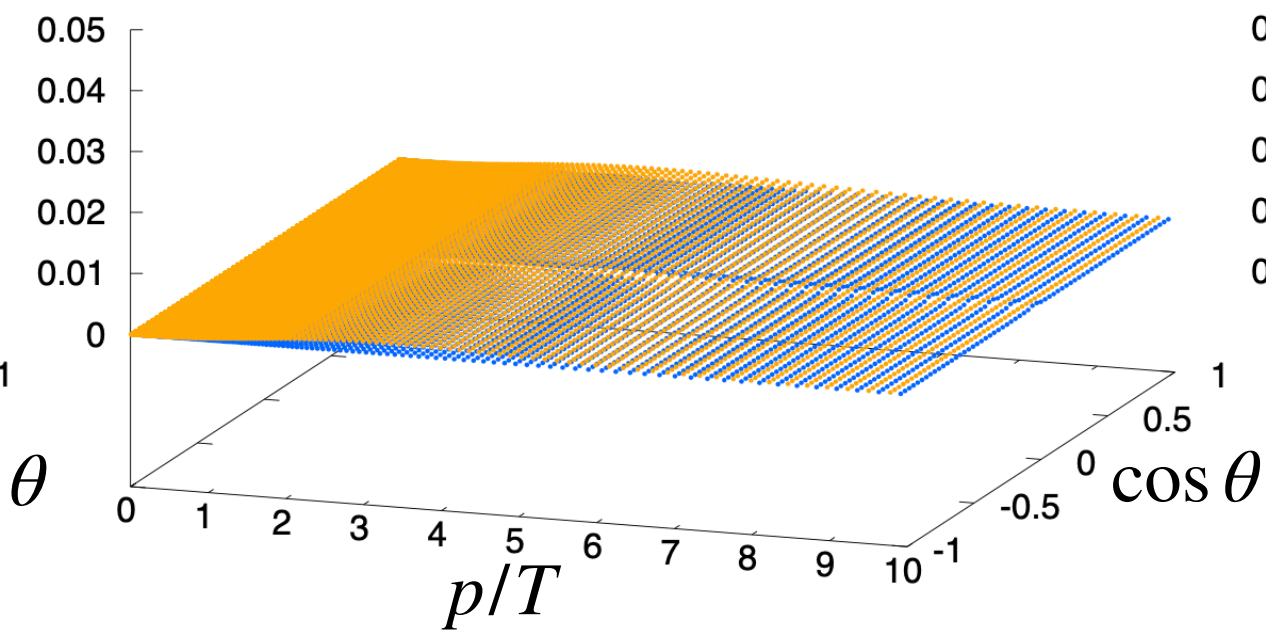
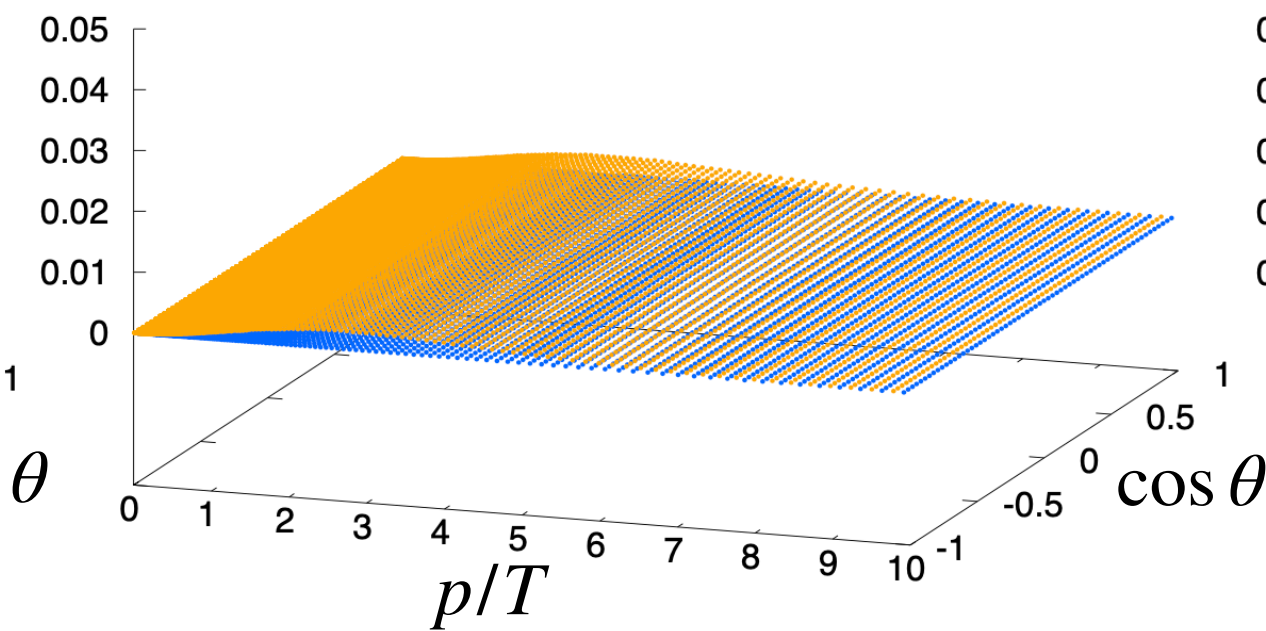
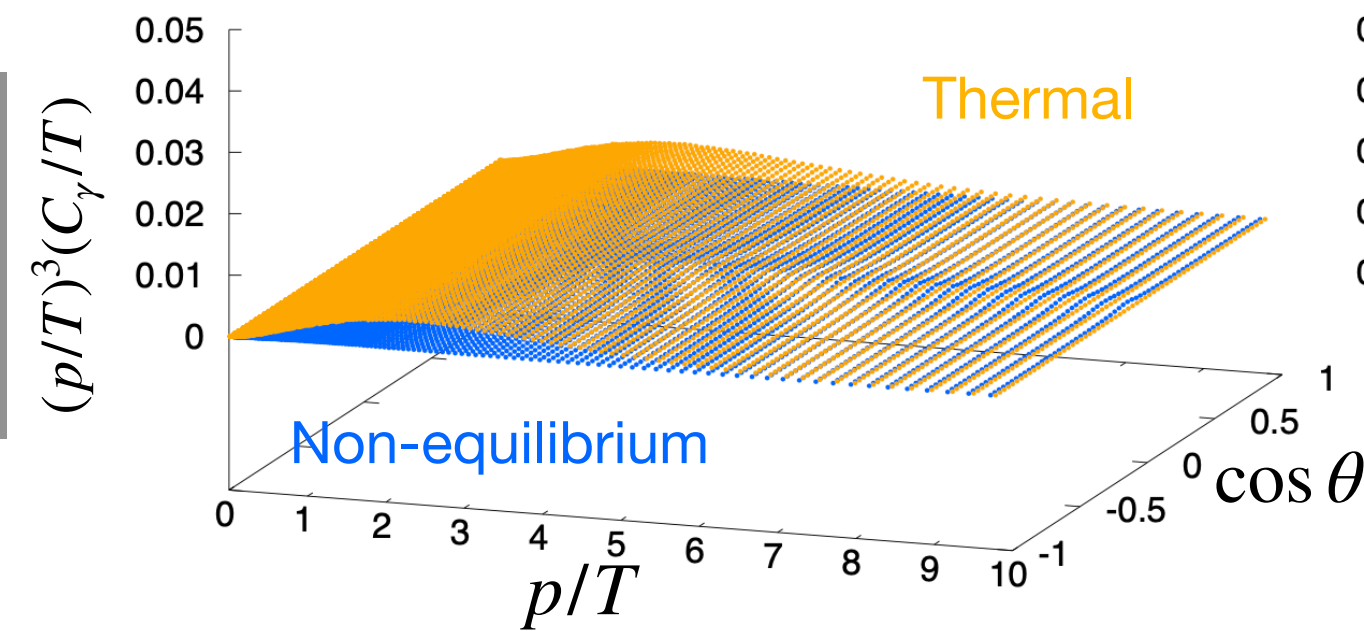
**Compton**

**El. Pair Annih.**

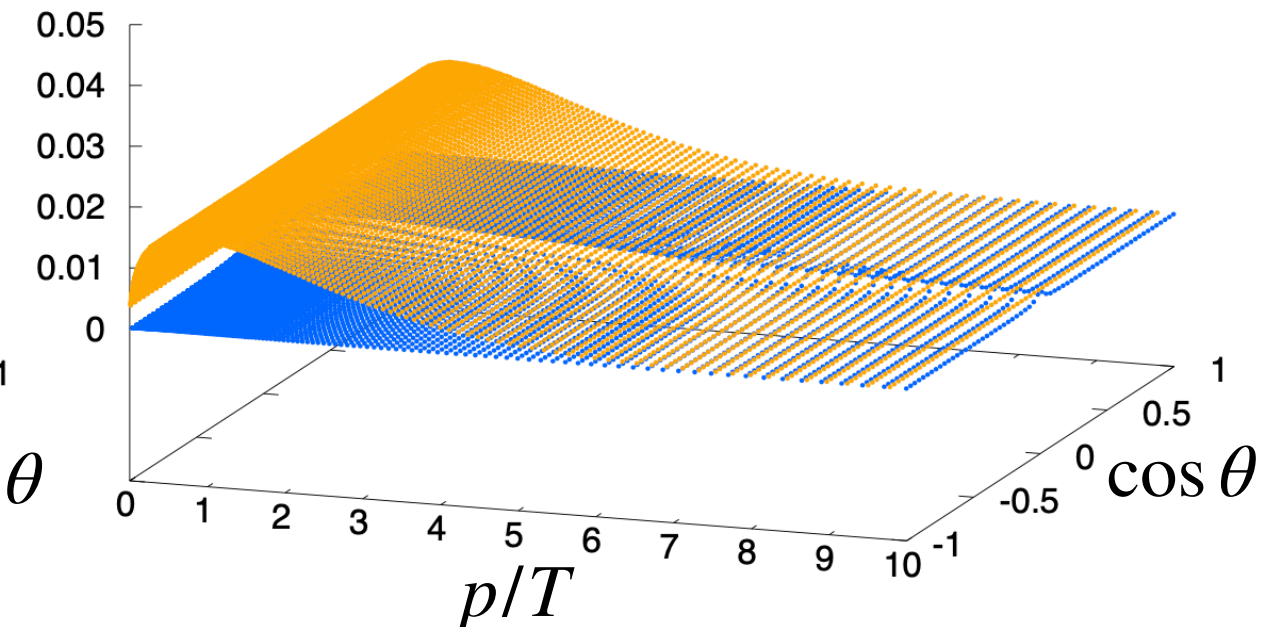
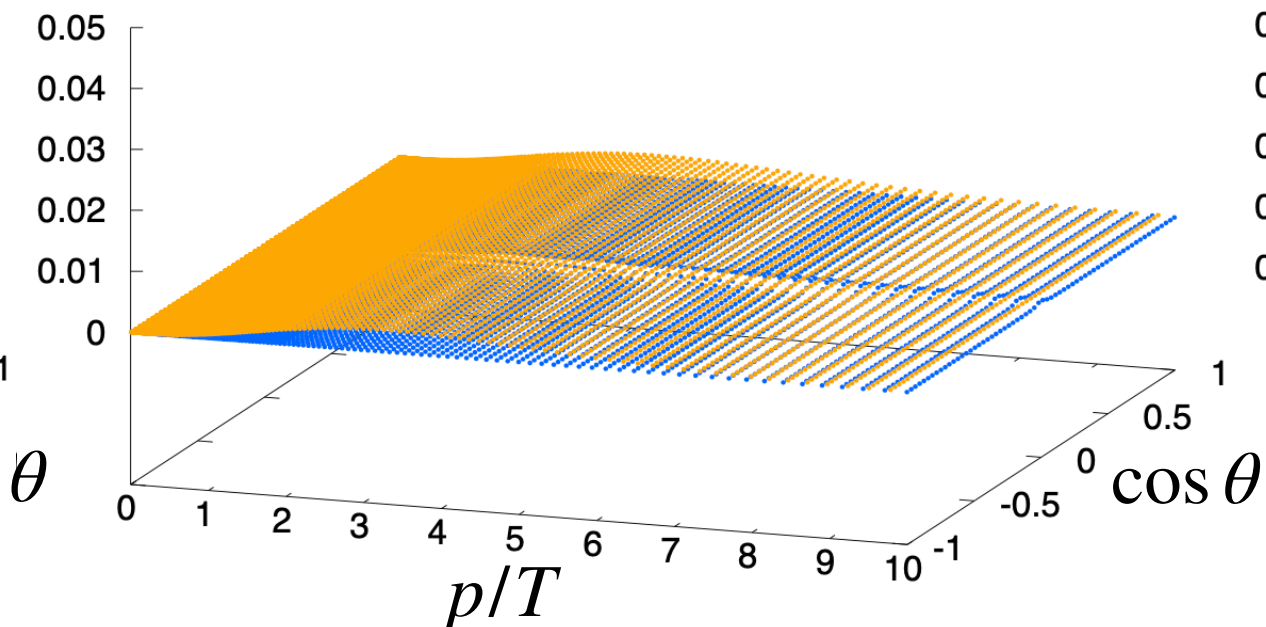
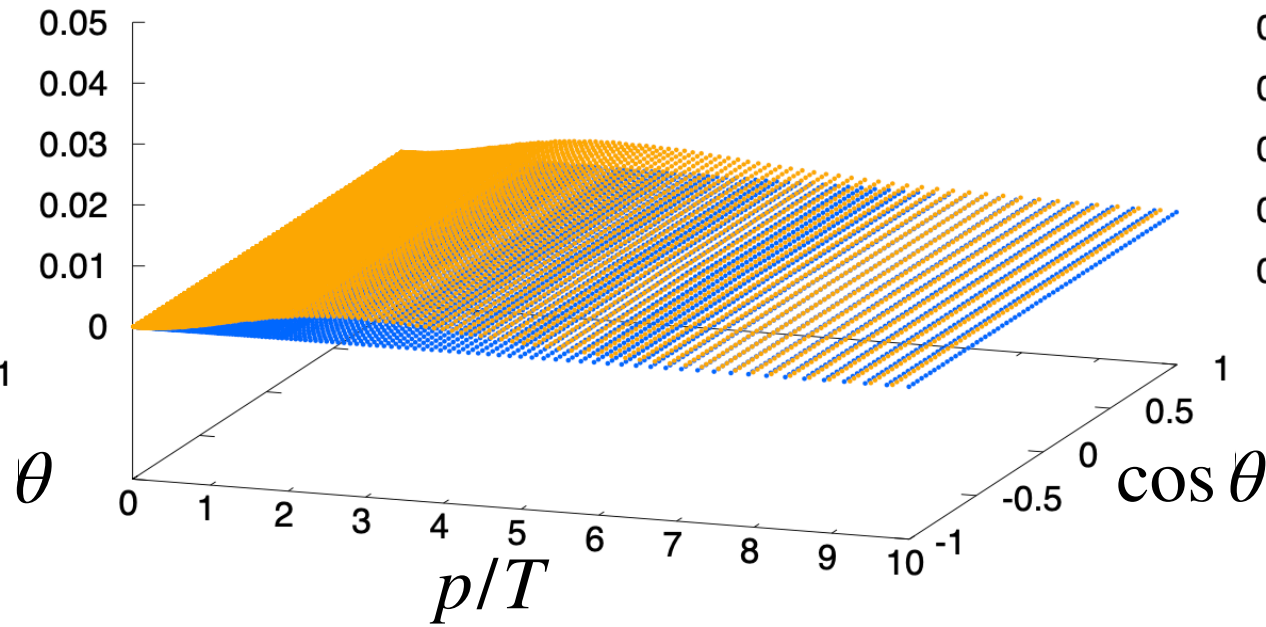
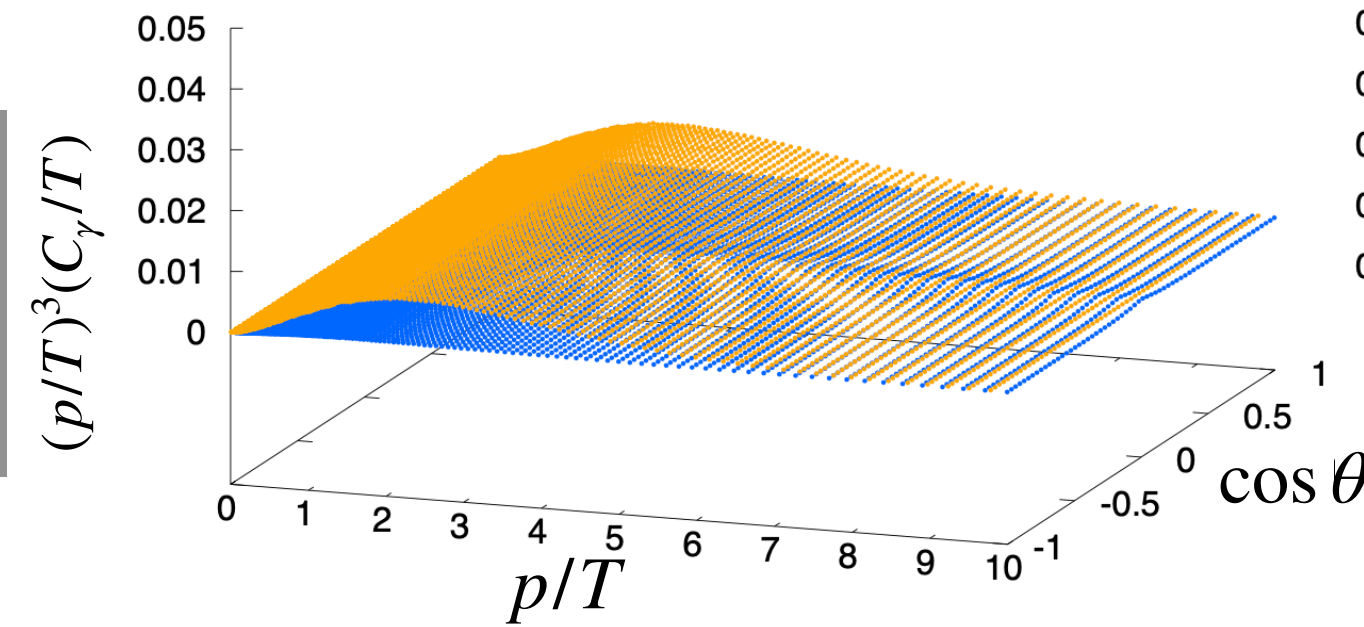
**Inel. Pair Annih.**

**Bremsstrahlung**

$\lambda = 5, \alpha_s = 0.13$



$\lambda = 10, \alpha_s = 0.26$





# RESULTS - 2D SPECTRUM

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

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

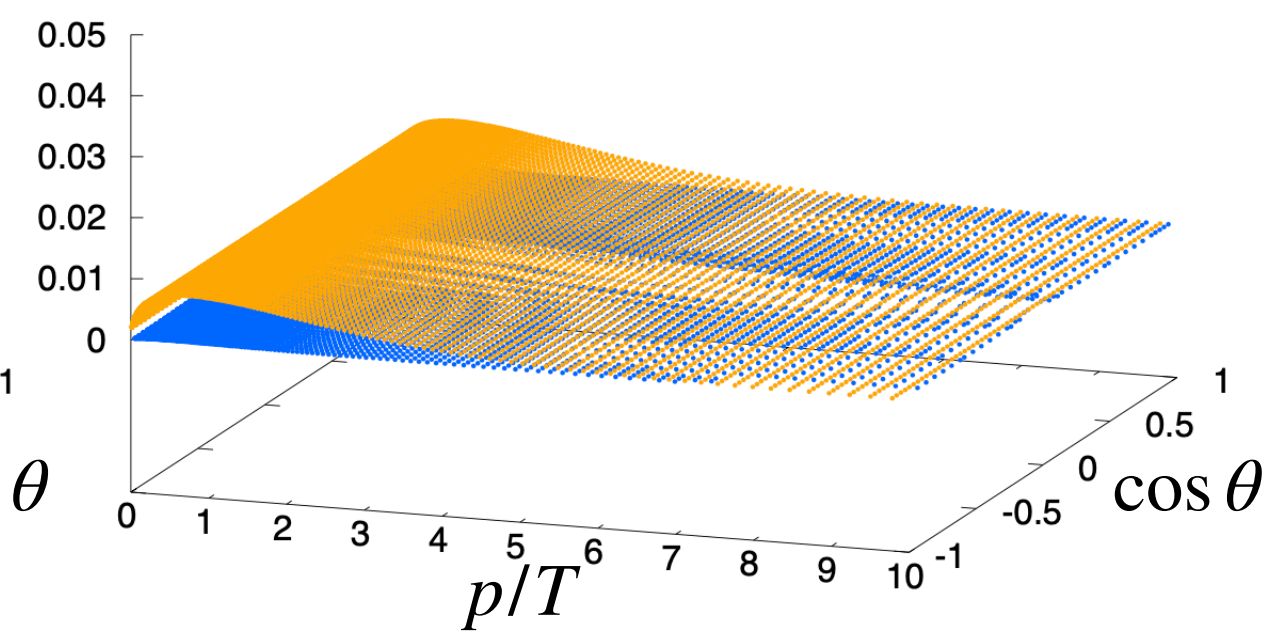
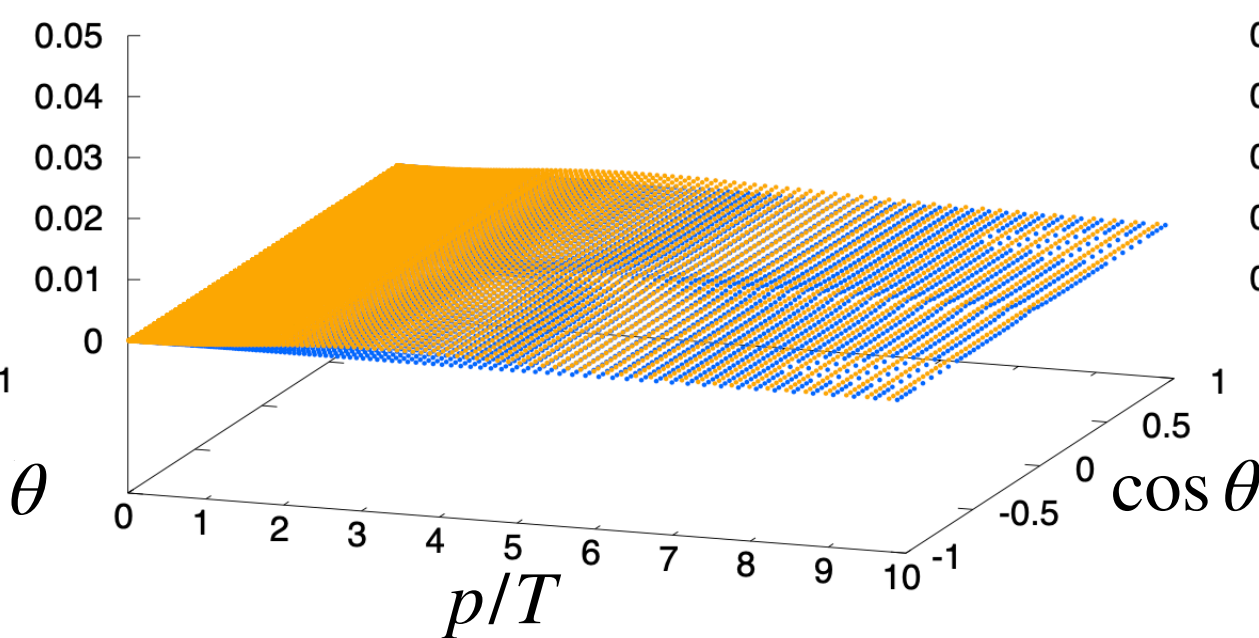
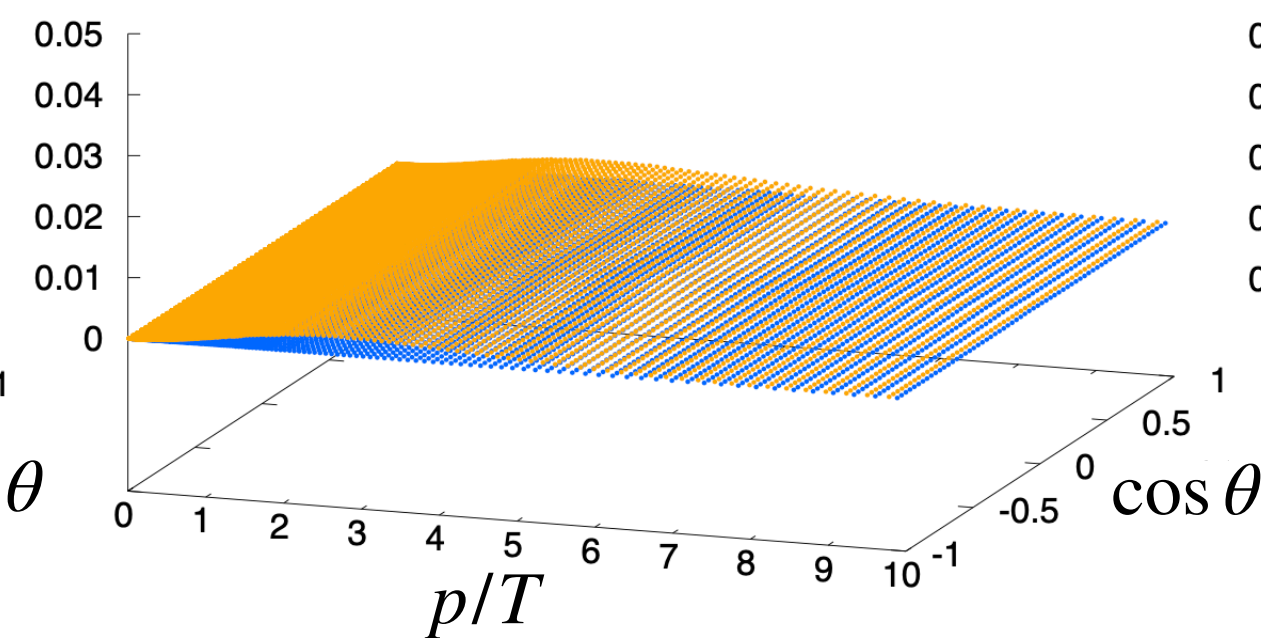
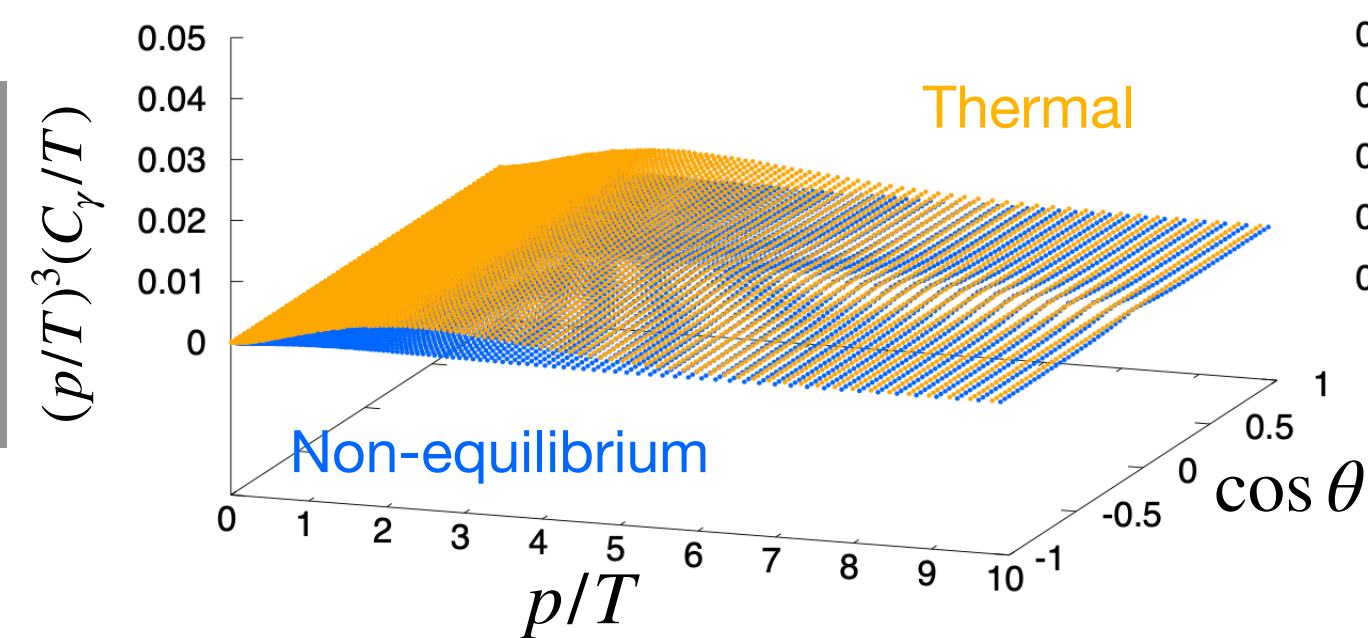
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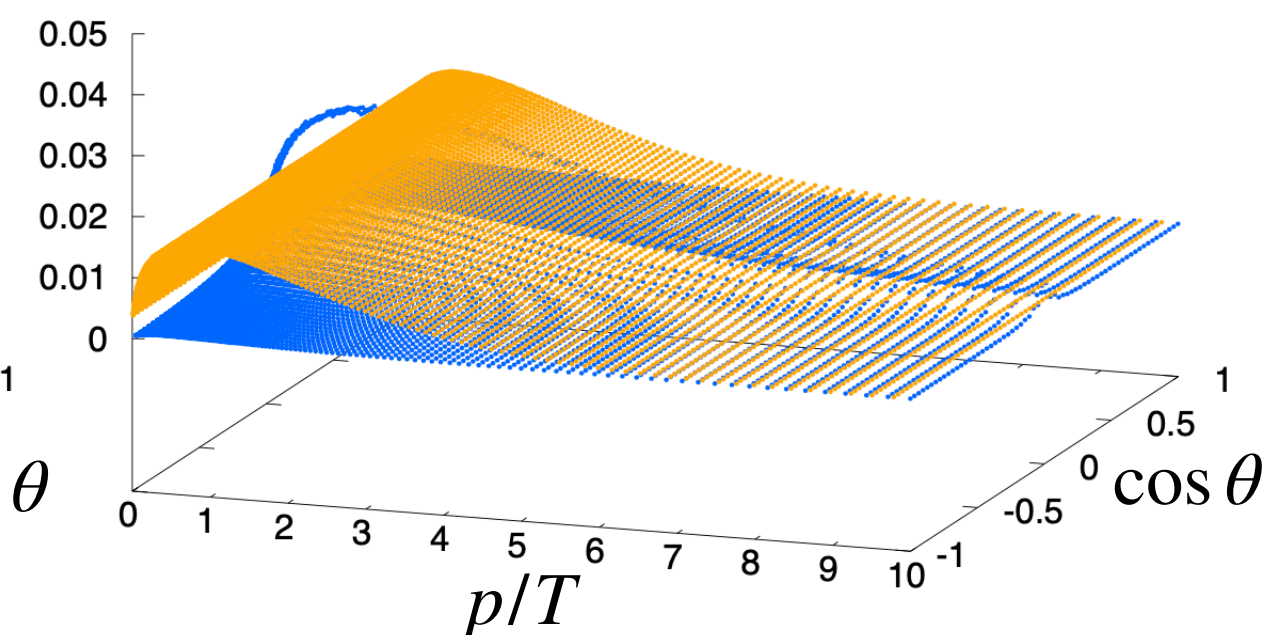
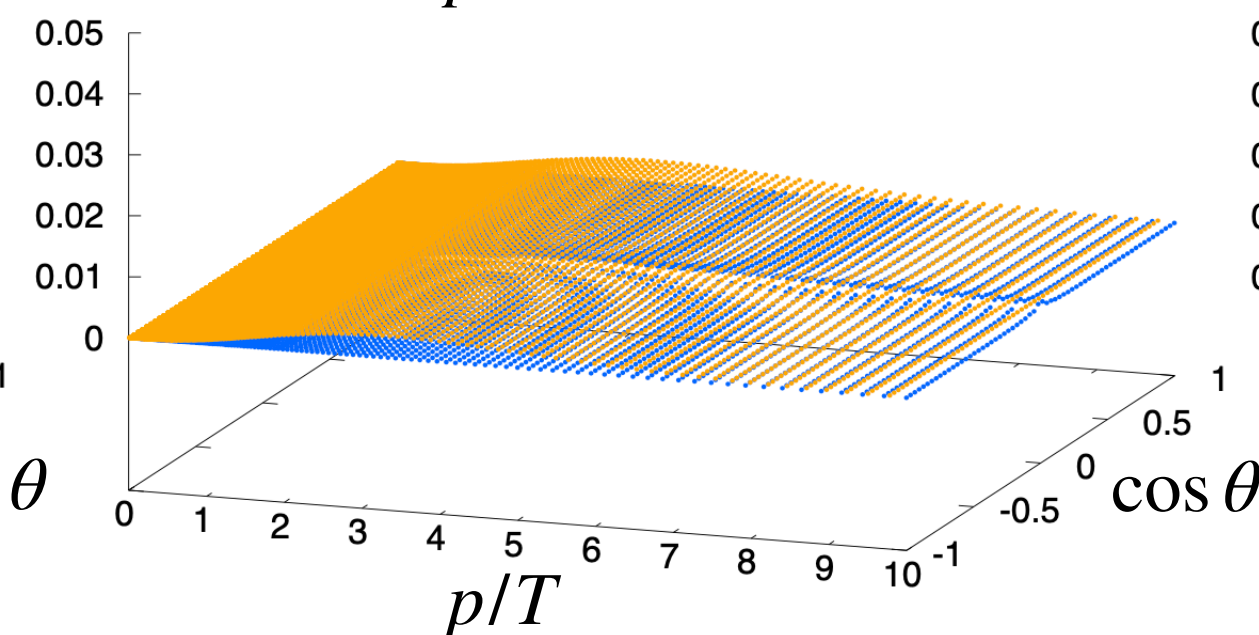
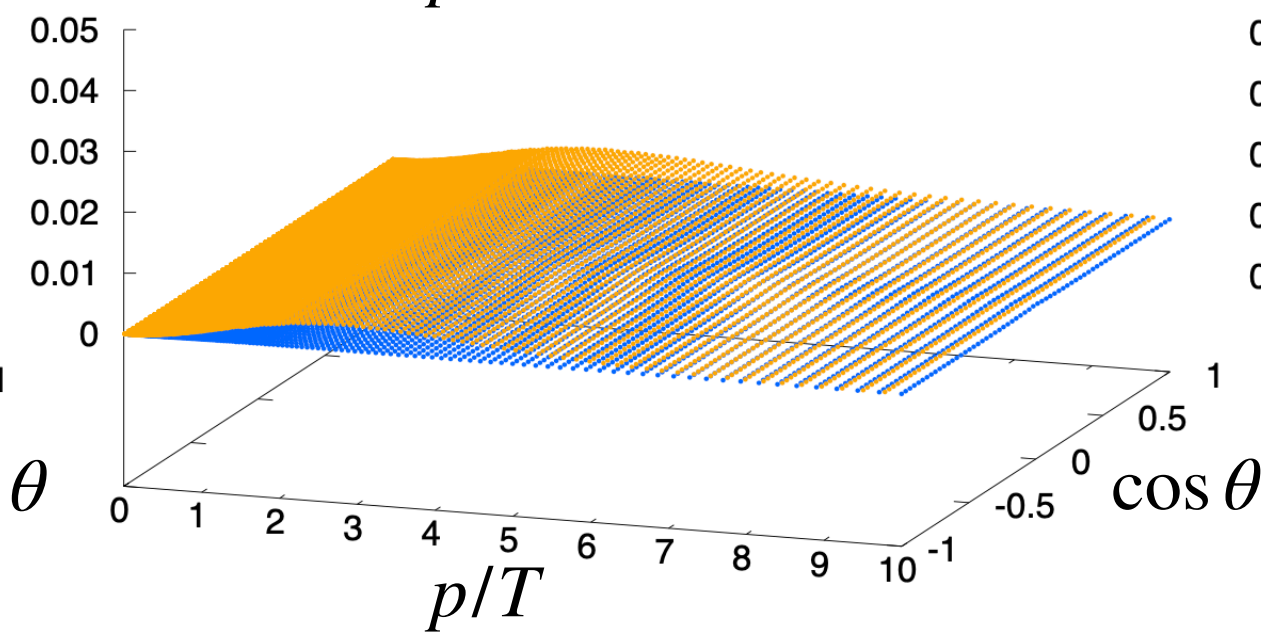
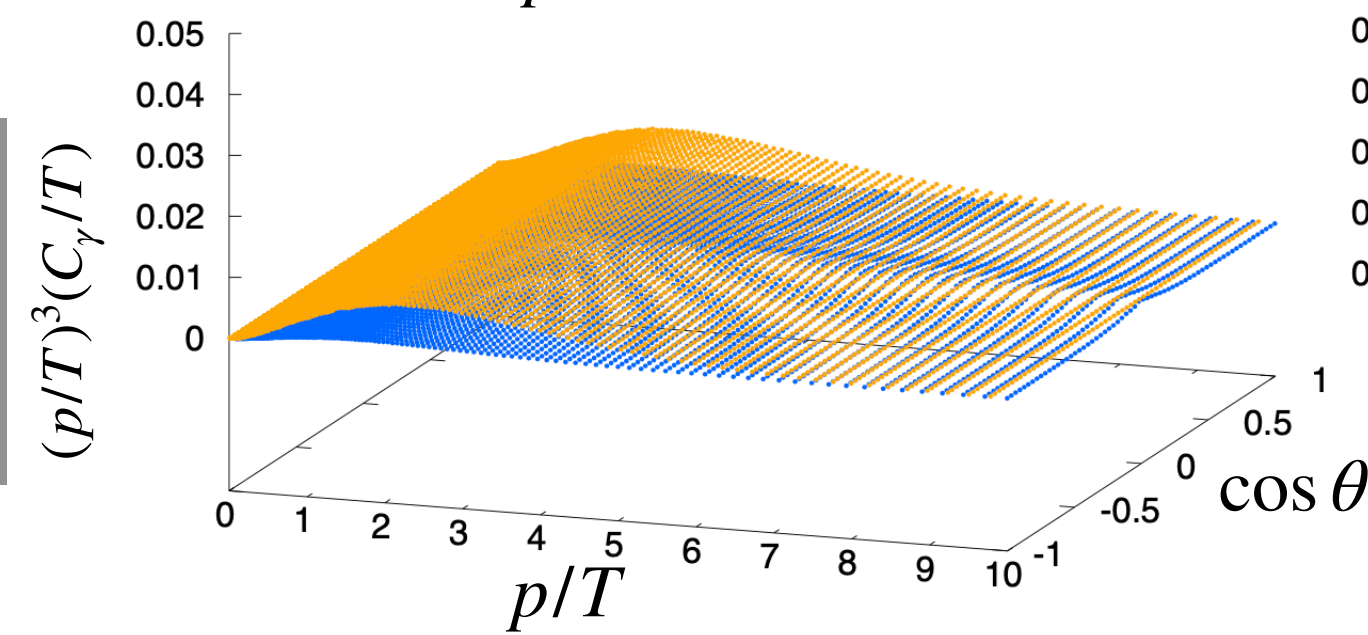
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$$C_\gamma = \frac{dN}{\tau d\tau d^3p d^2x_T}$$

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

► Peak at  $\cos \theta \approx 0$ : Gluon distribution highly anisotropic at early times

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

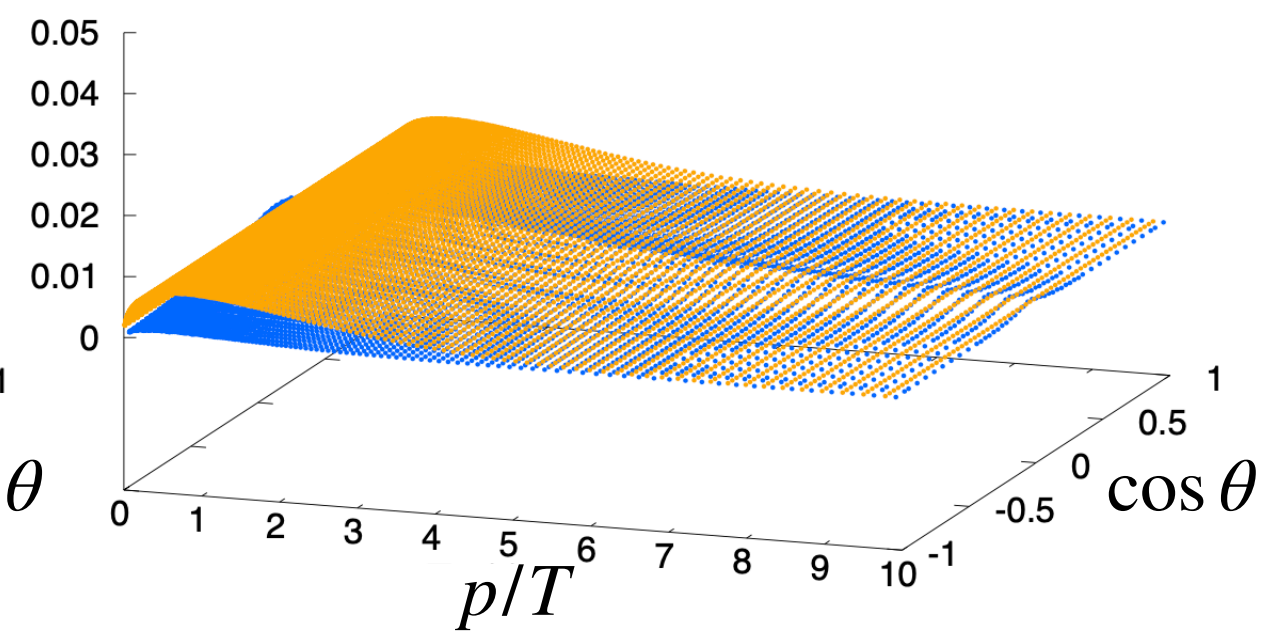
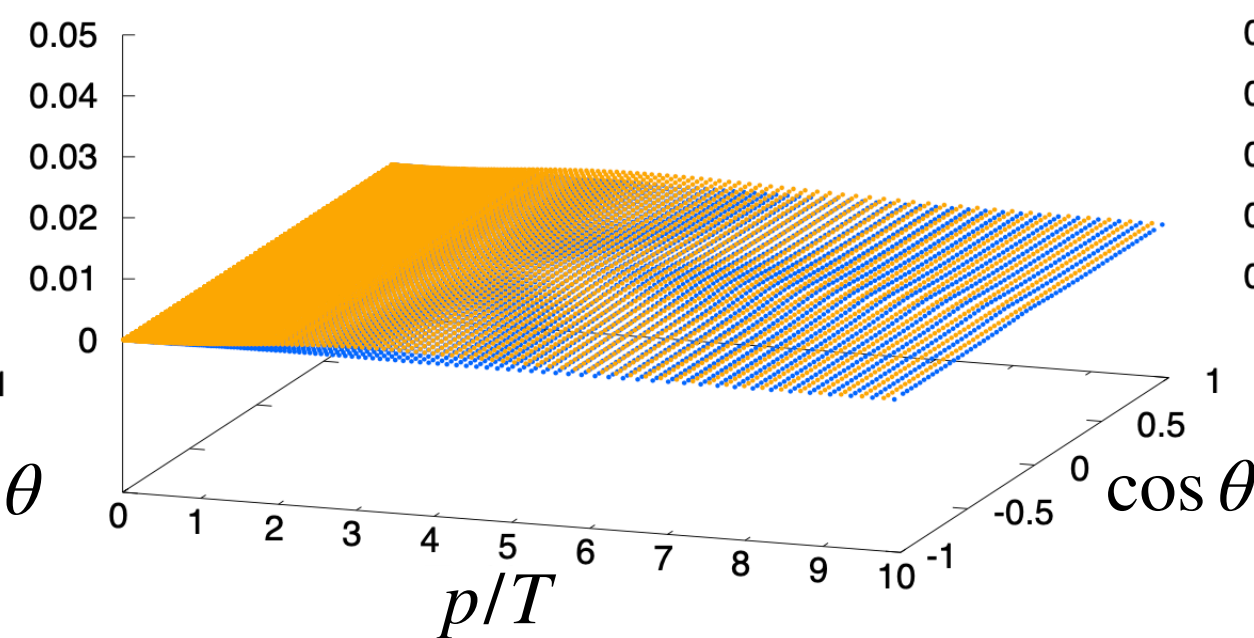
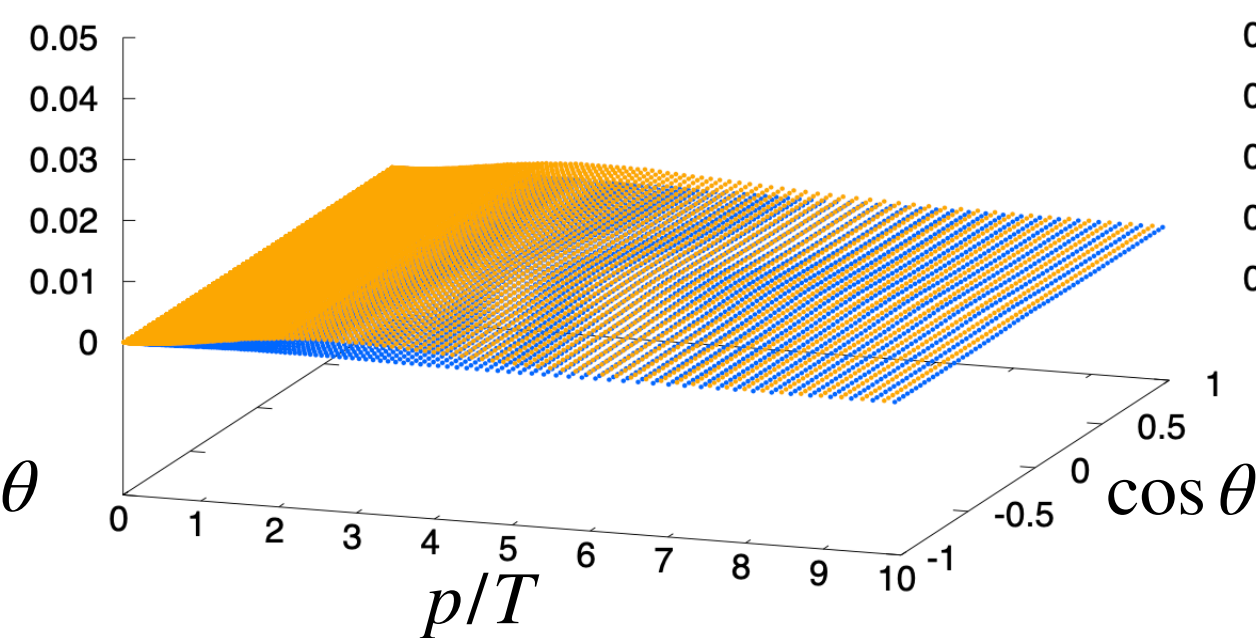
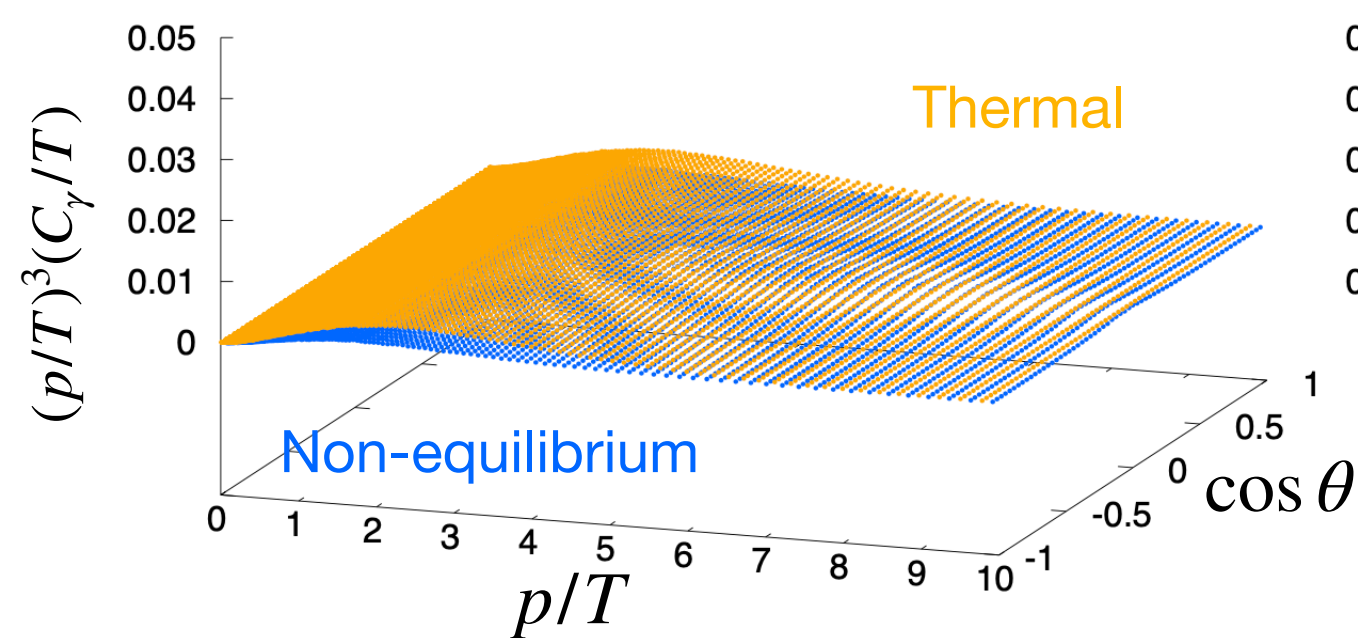
**Compton**

**El. Pair Annih.**

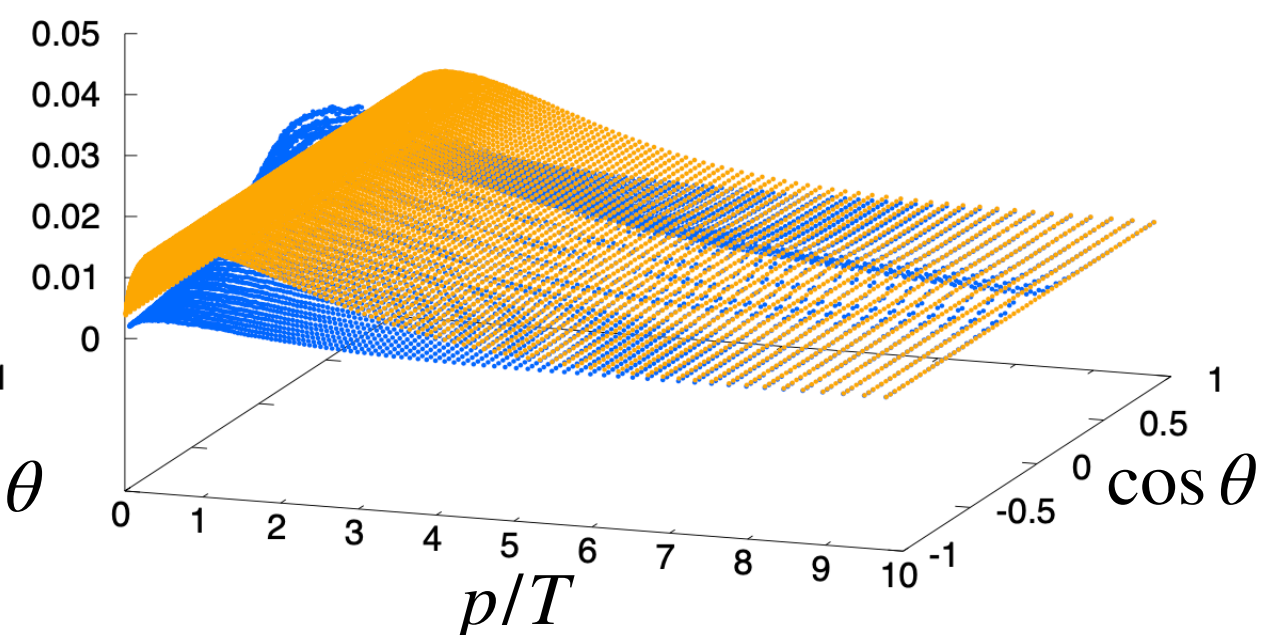
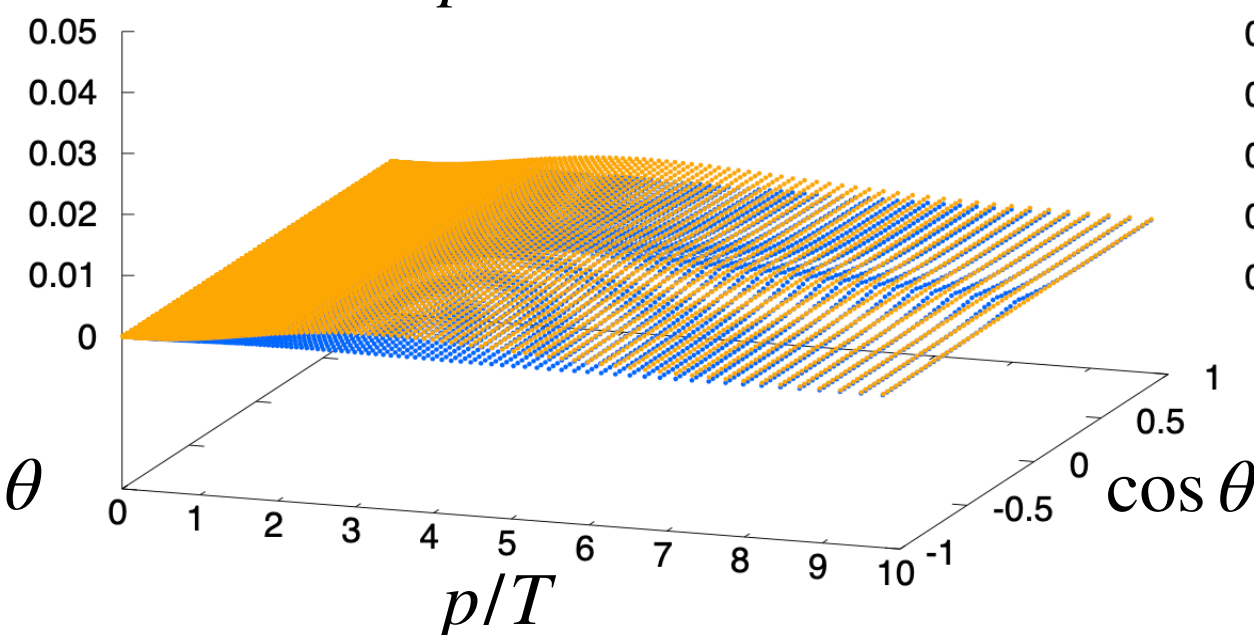
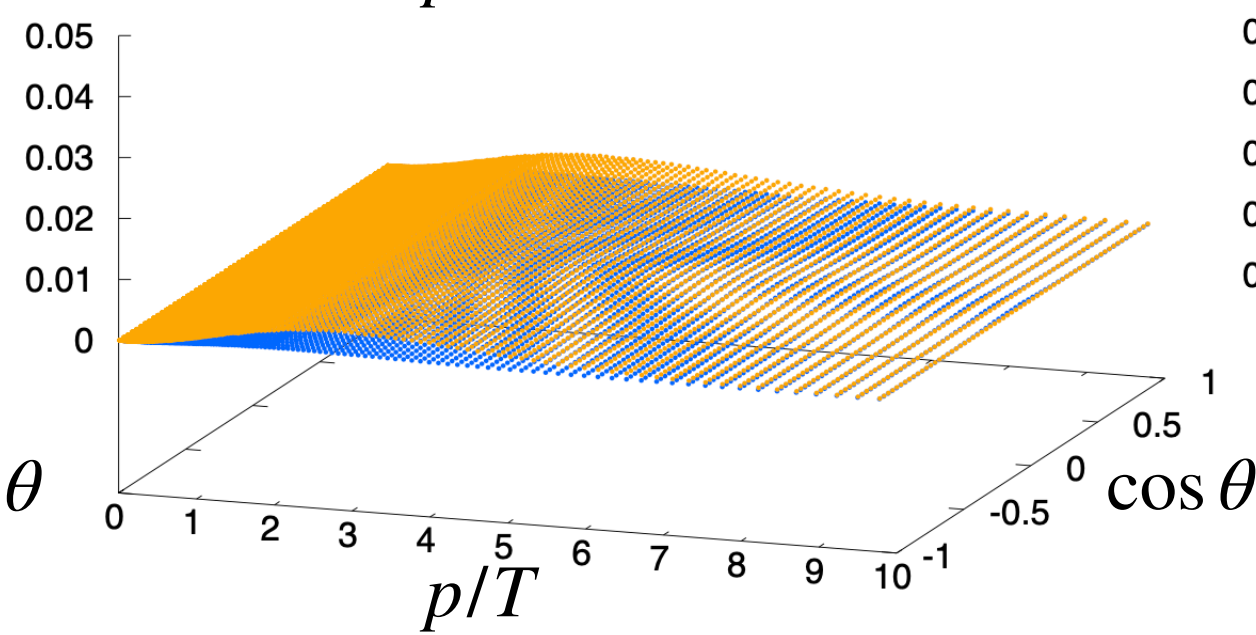
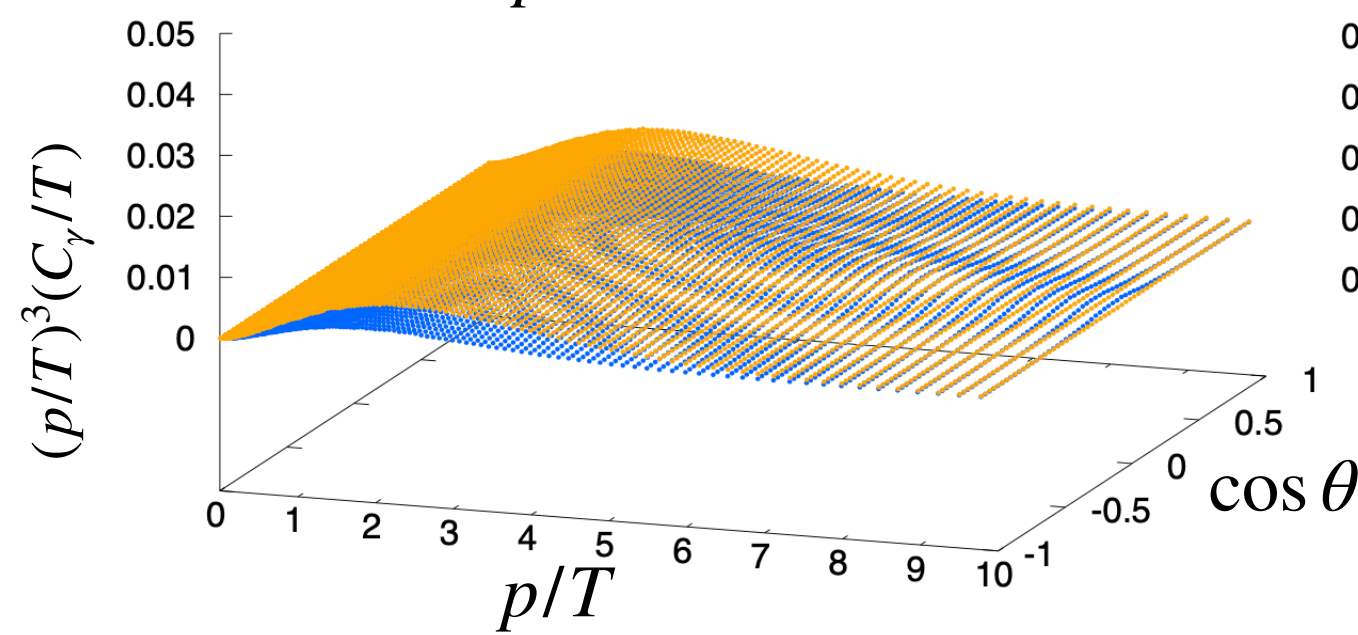
**Inel. Pair Annih.**

**Bremsstrahlung**

$\lambda = 5, \alpha_s = 0.13$



$\lambda = 10, \alpha_s = 0.26$





# RESULTS - 2D SPECTRUM

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

► 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

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

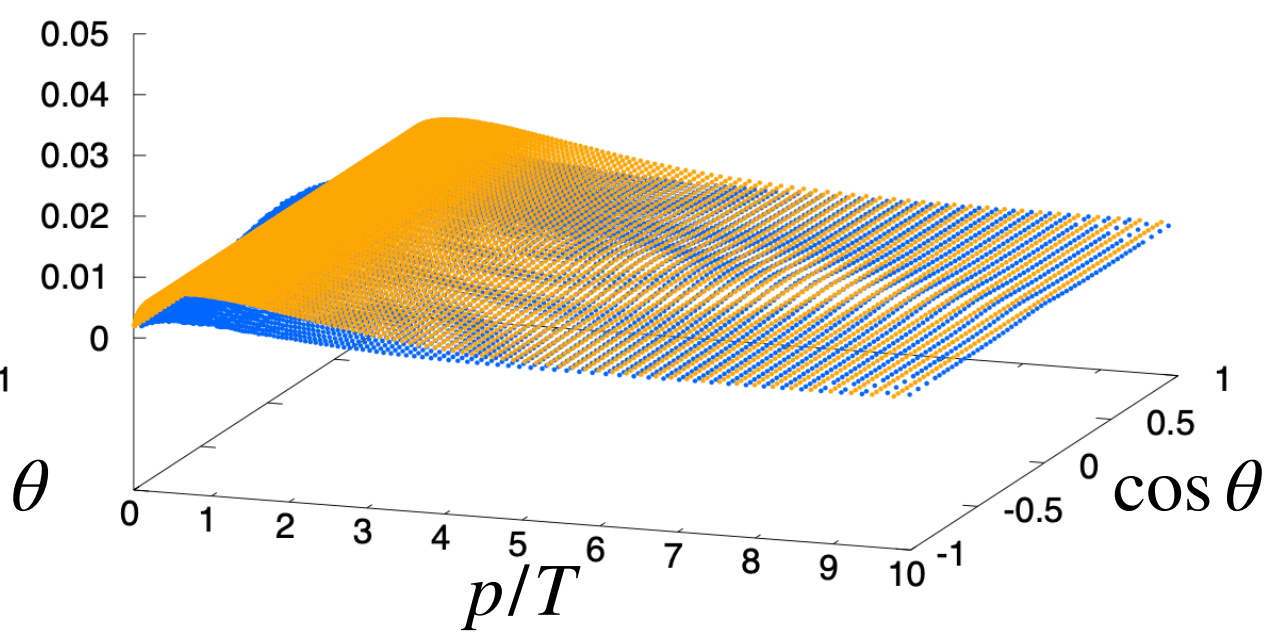
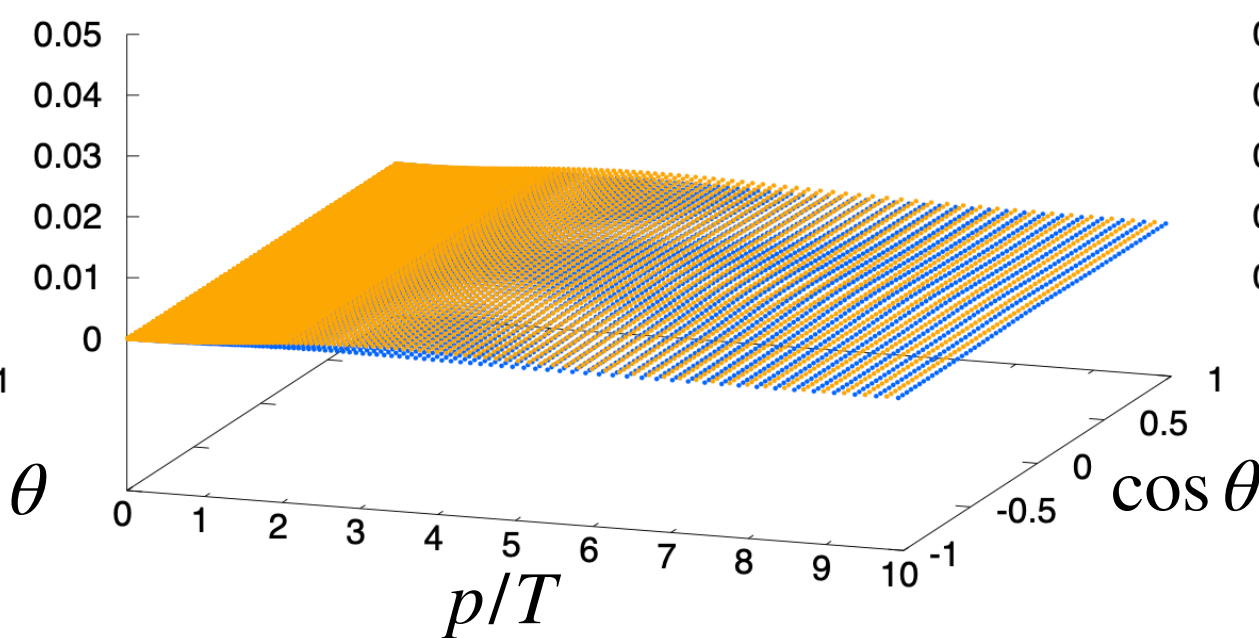
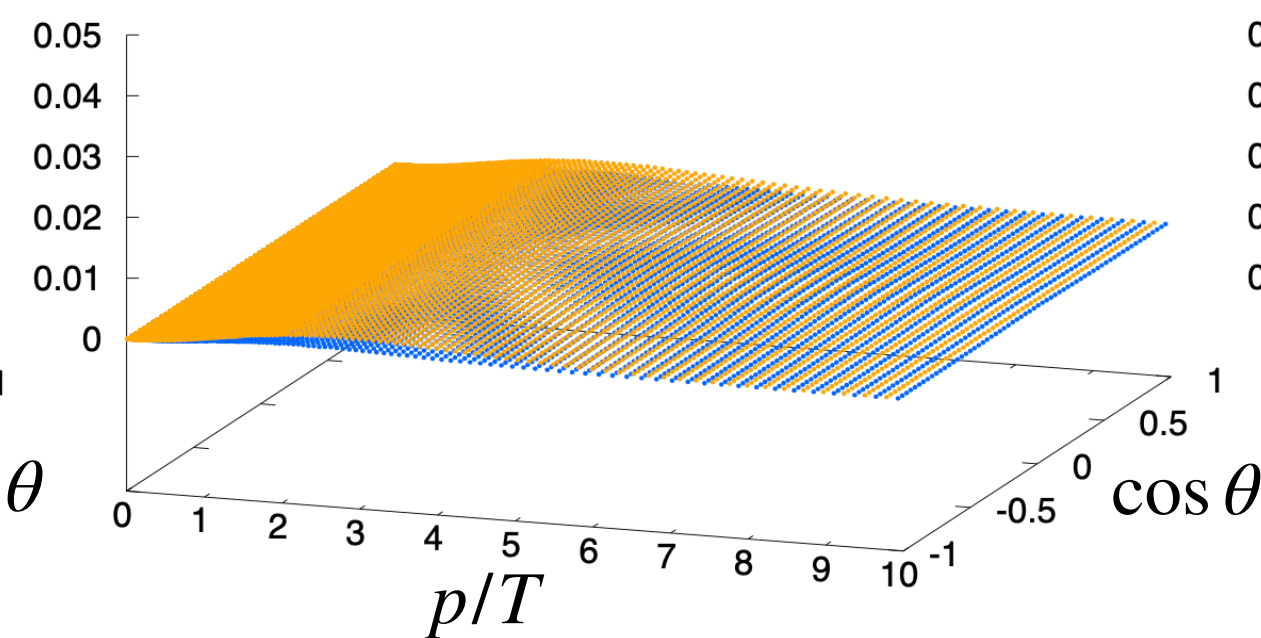
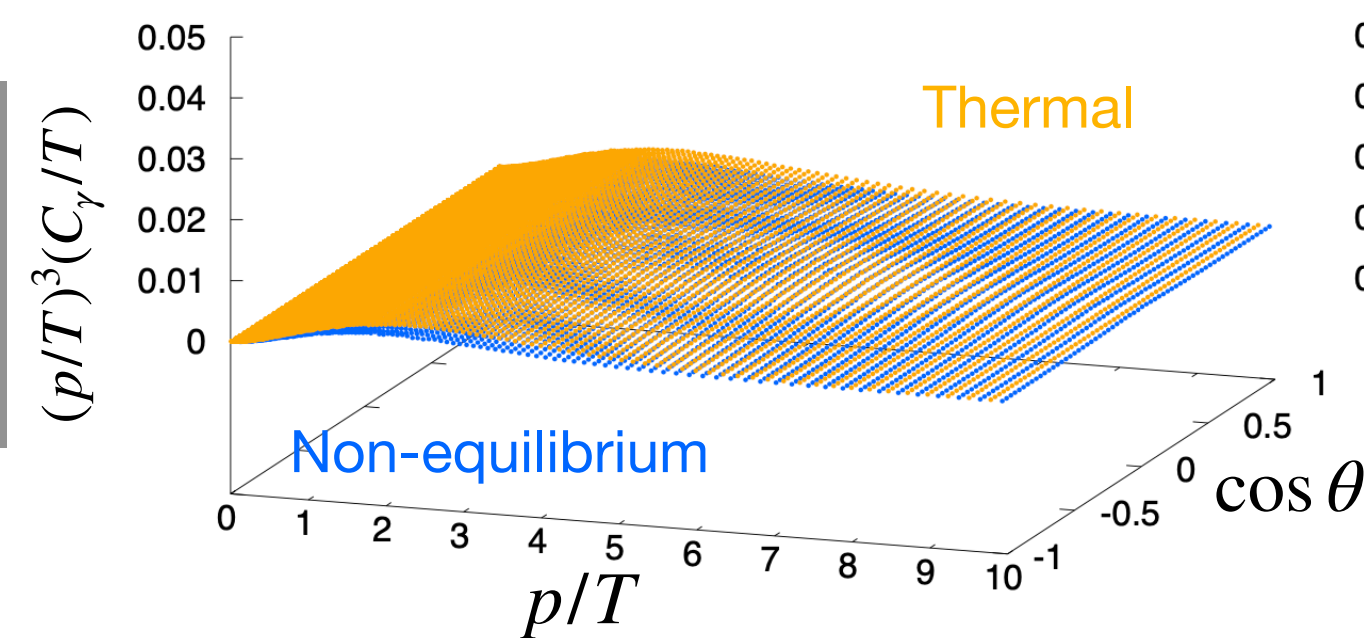
**Compton**

**El. Pair Annih.**

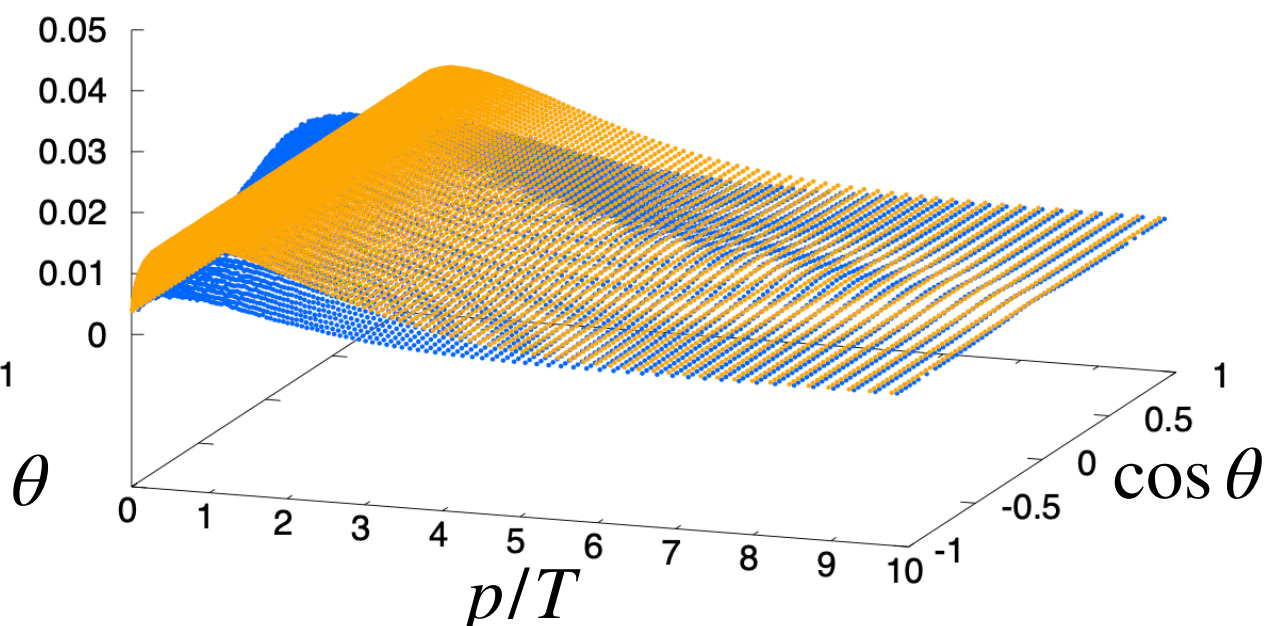
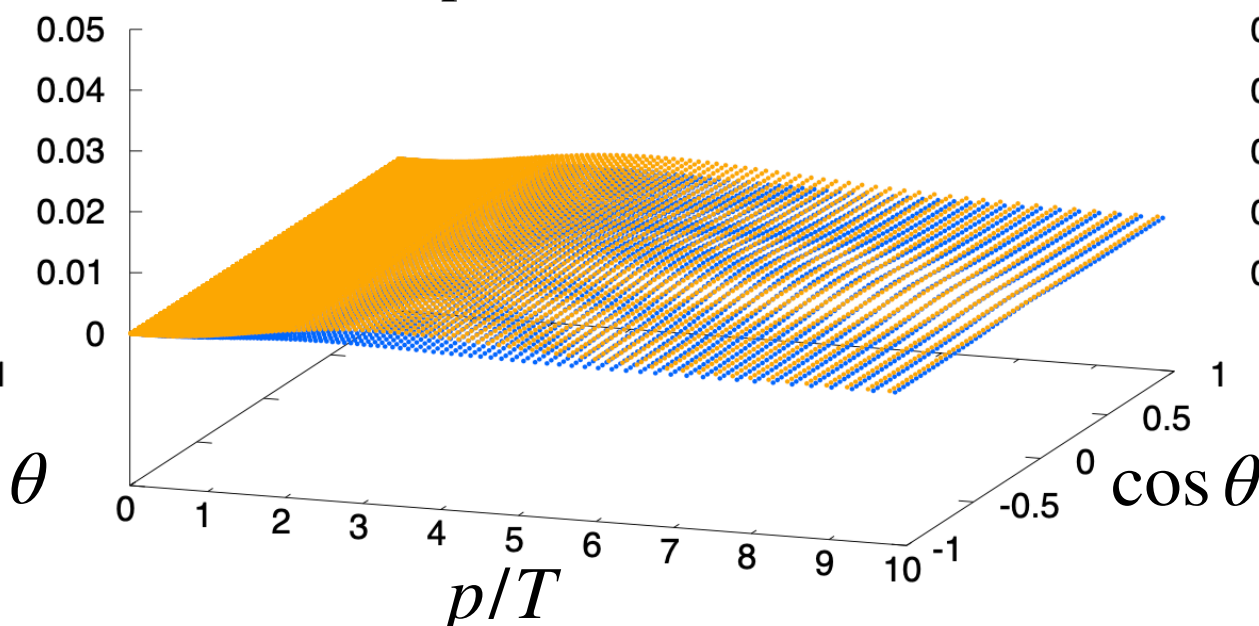
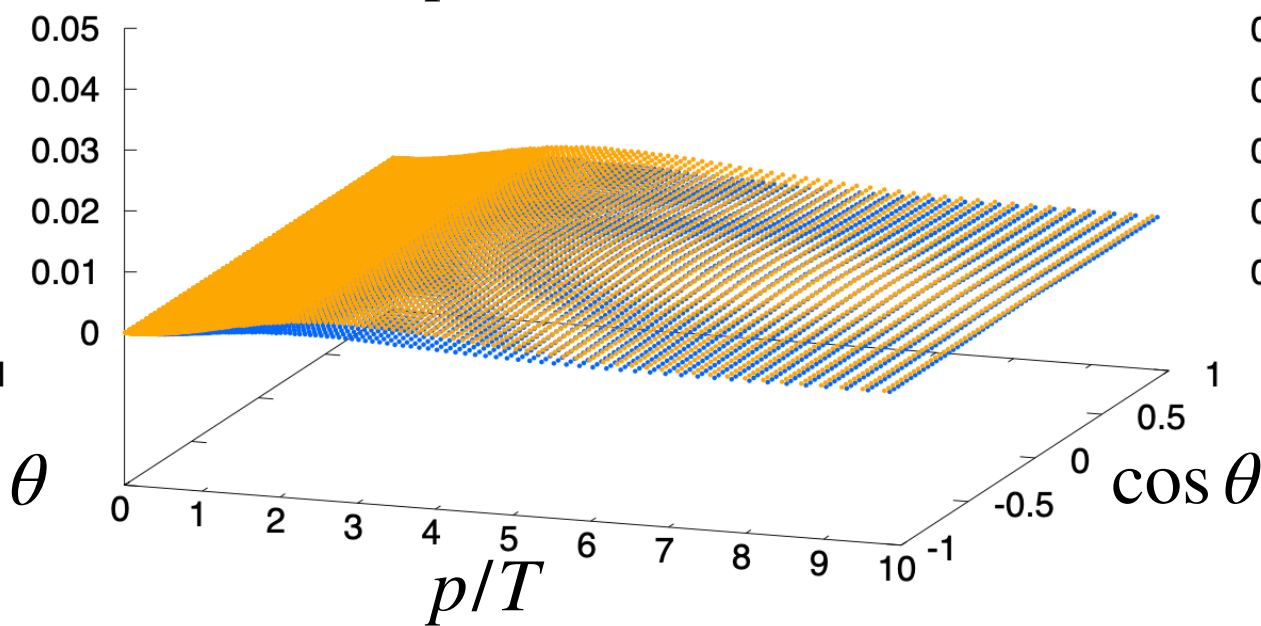
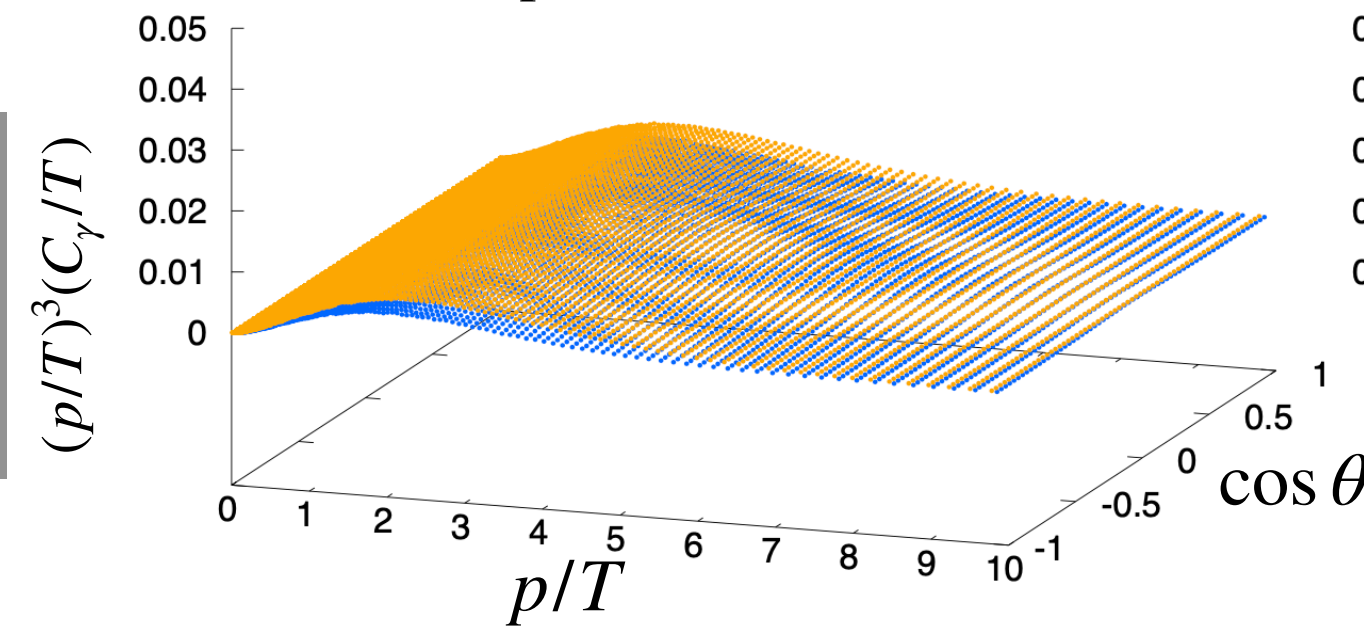
**Inel. Pair Annih.**

**Bremsstrahlung**

$\lambda = 5, \alpha_s = 0.13$



$\lambda = 10, \alpha_s = 0.26$





# RESULTS - 2D SPECTRUM

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

► 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

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

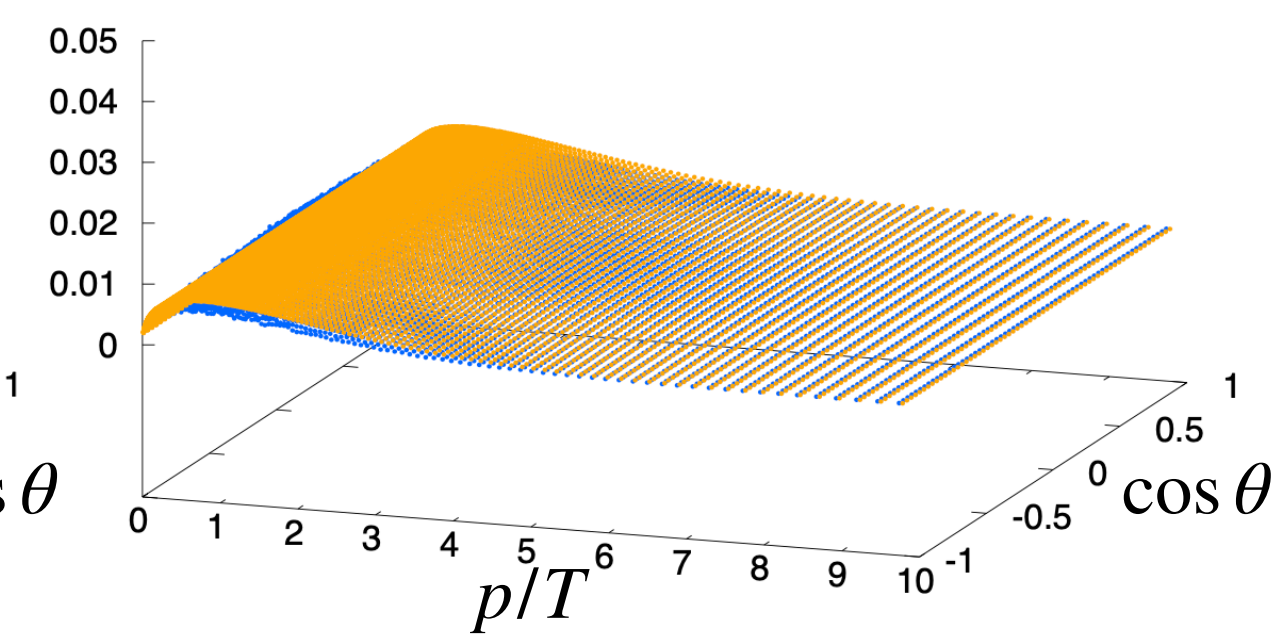
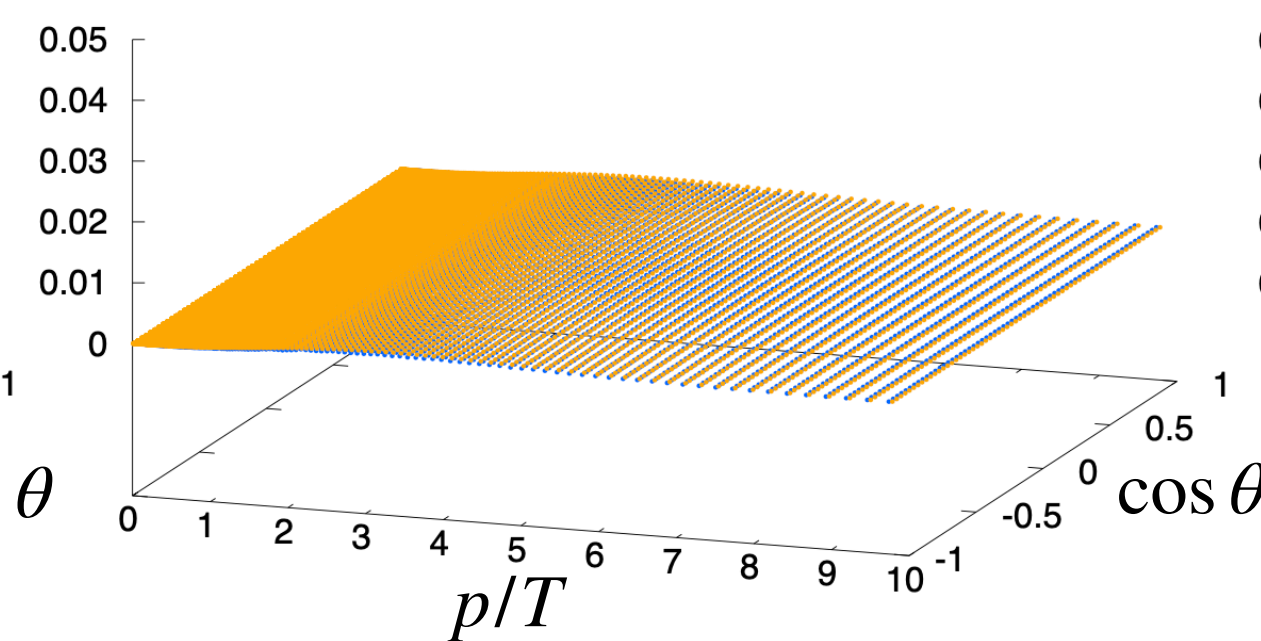
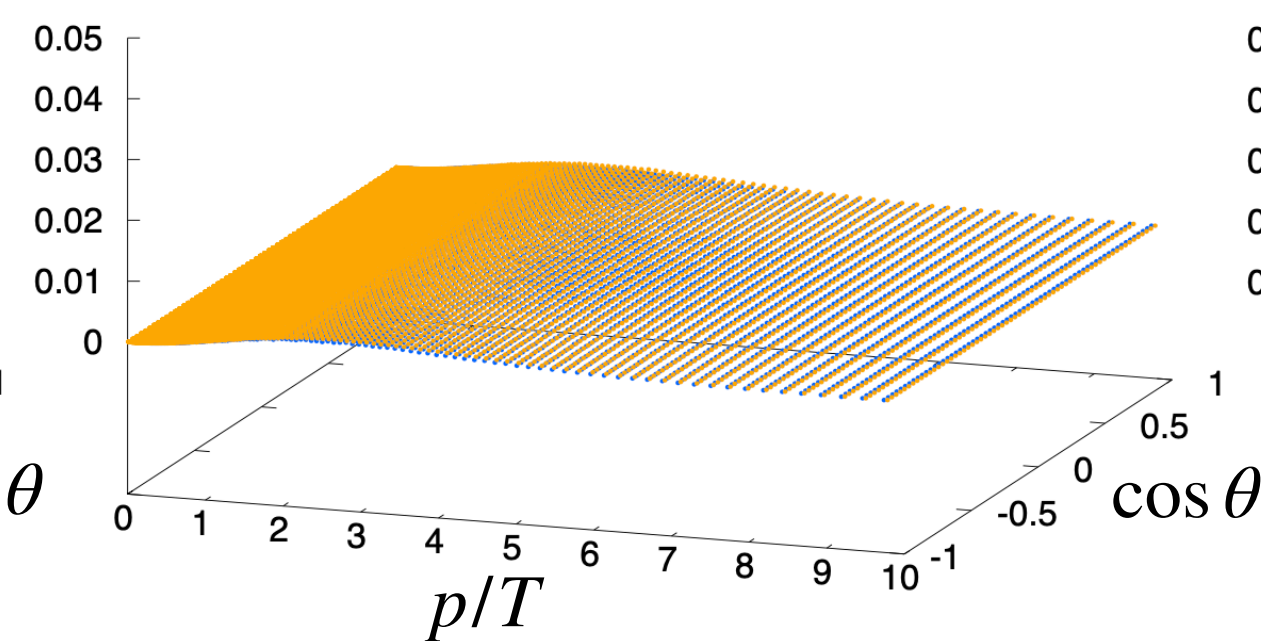
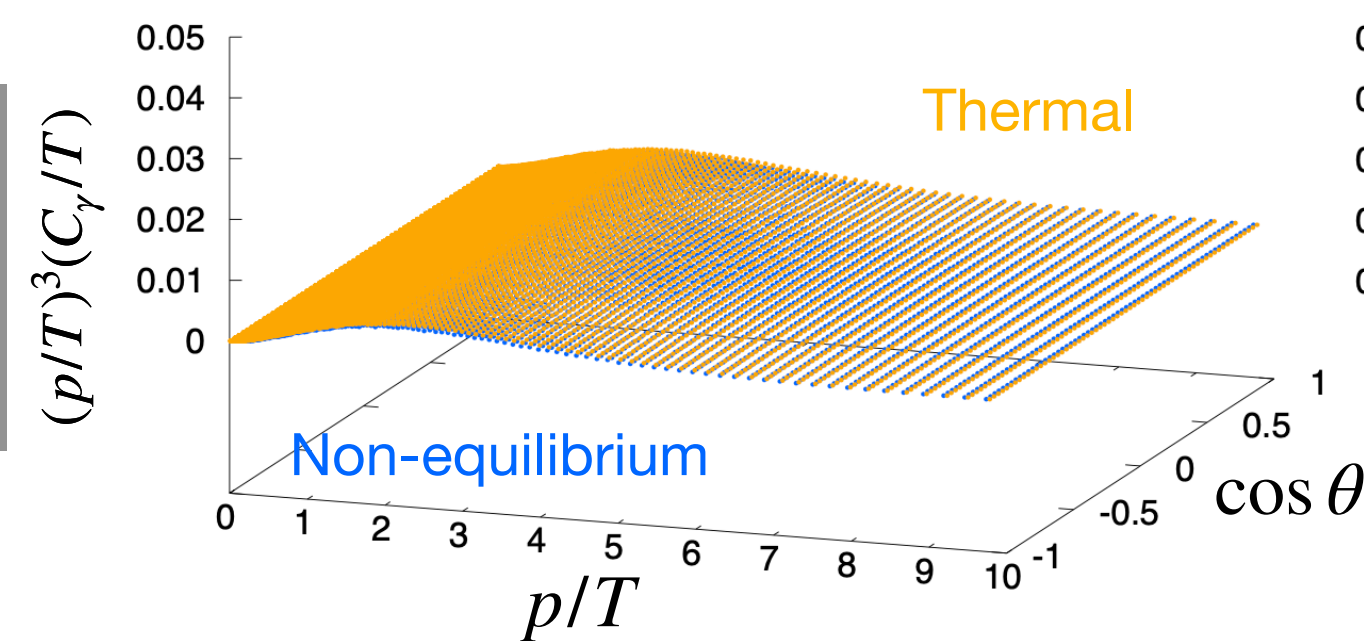
**Compton**

**El. Pair Annih.**

**Inel. Pair Annih.**

**Bremsstrahlung**

$\lambda = 5, \alpha_s = 0.13$



$\lambda = 10, \alpha_s = 0.26$

