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AN ELECTRO-MAGNETIC PHENOMENOLOGY OF THE EARLY STAGES

Oscar Garcia-Montero

Fakultät für Physik

Universität Bielefeld

GARCIA@PHYSIK.UNI-BIELEFELD.DE

In collaboration with Philip Plaschke, Aleksas Mazeliauskas and Soeren Schlichting

+ based on JHEP 03 (2024) 053 and 2403.04846

CRC-TR 211
Strong-interaction matter under extreme conditions

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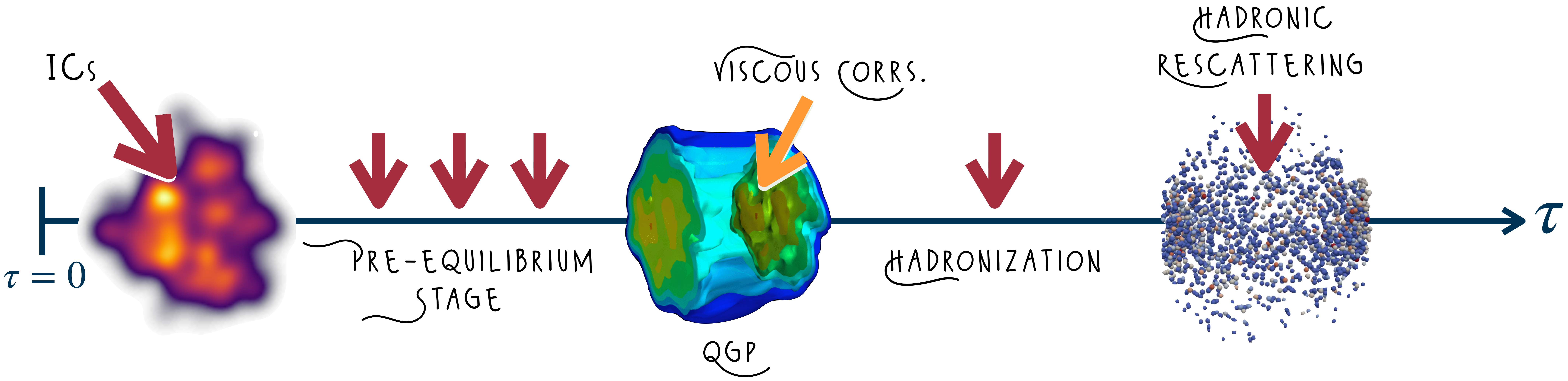
THE TENOUSLY THERMAL QGP

- Heavy-Ion Collisions create an Isolated Quantum System

  which is
  - Initially far away from any equilibrium
  - Self-interacting
  - Expanding against the vacuum

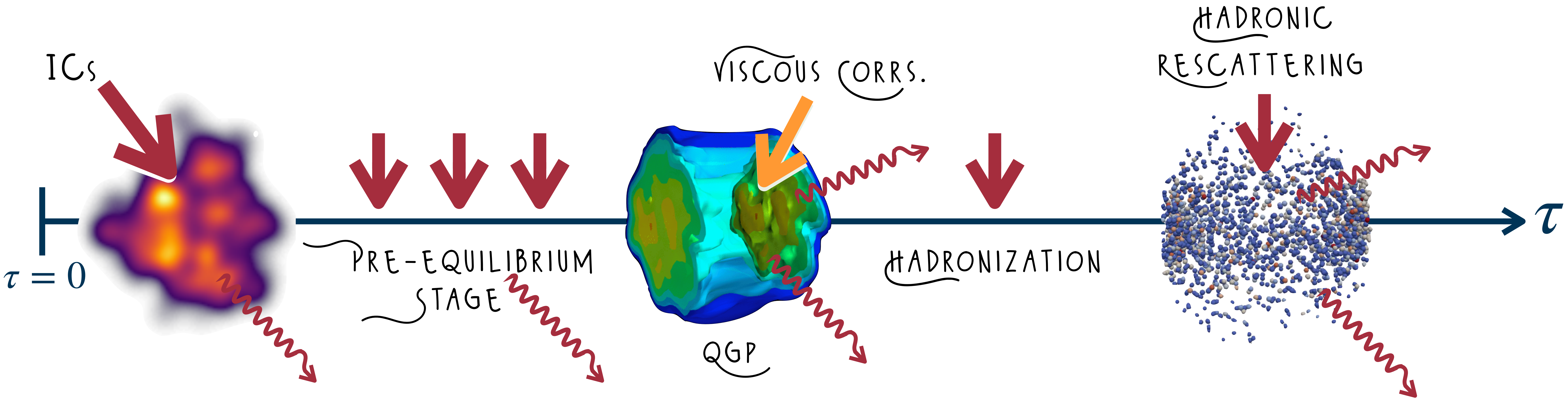
- A system battling to thermalize against all odds.



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

- Dynamics described by relativistic Boltzmann equation

Elastic 2↔2 scattering screened by Debye mass

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

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

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

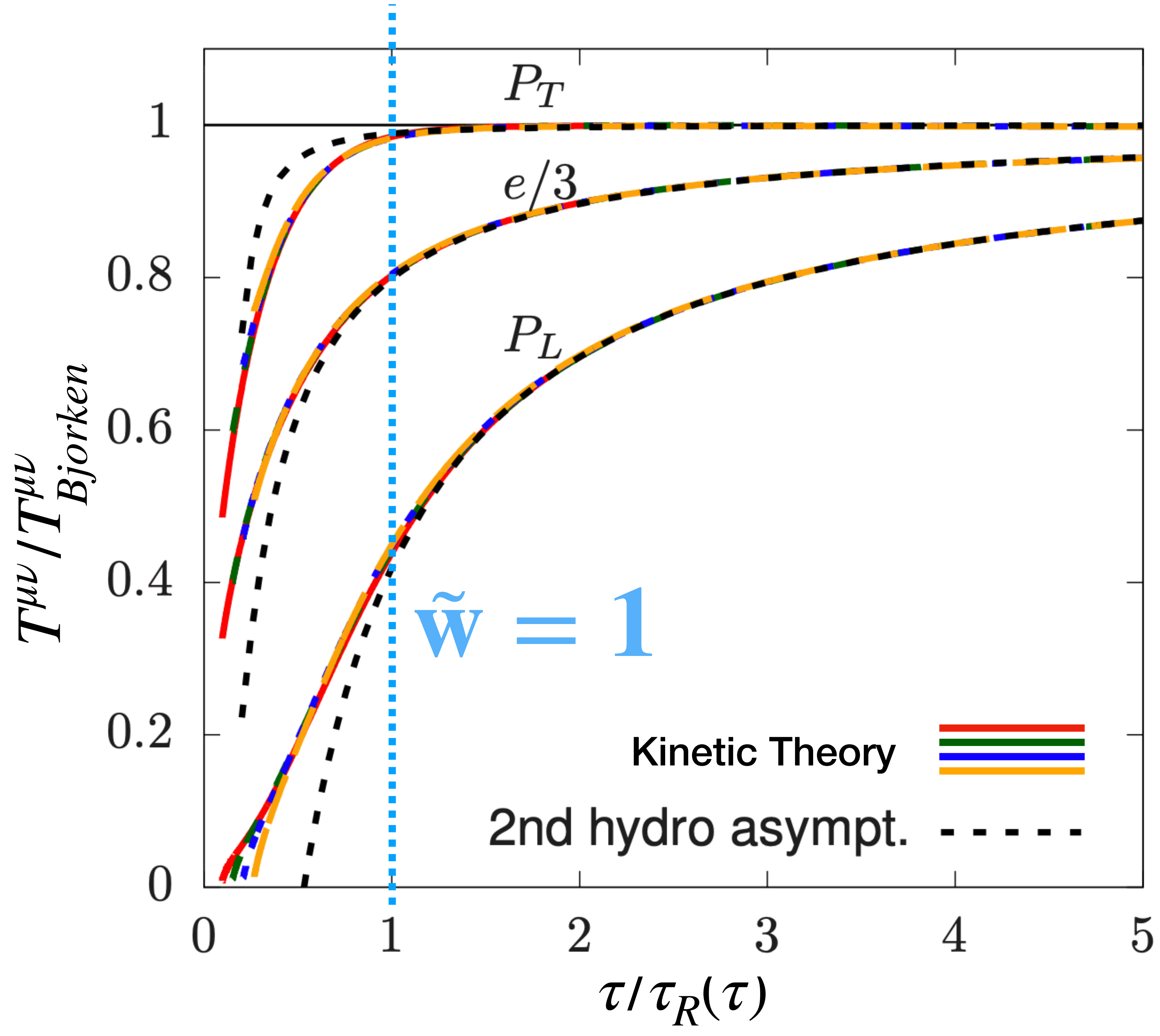
- Equilibration controlled by single relaxation rate

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

- 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



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

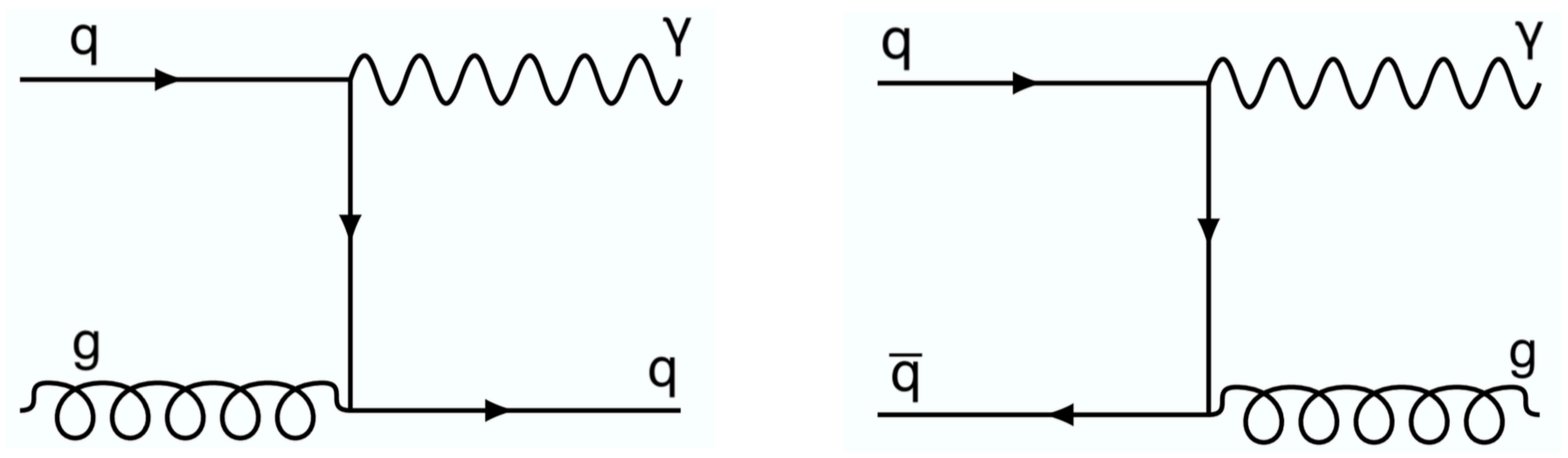
RELEVANT PROCESSES AT LEADING ORDER

- 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 ↔ 2 processes



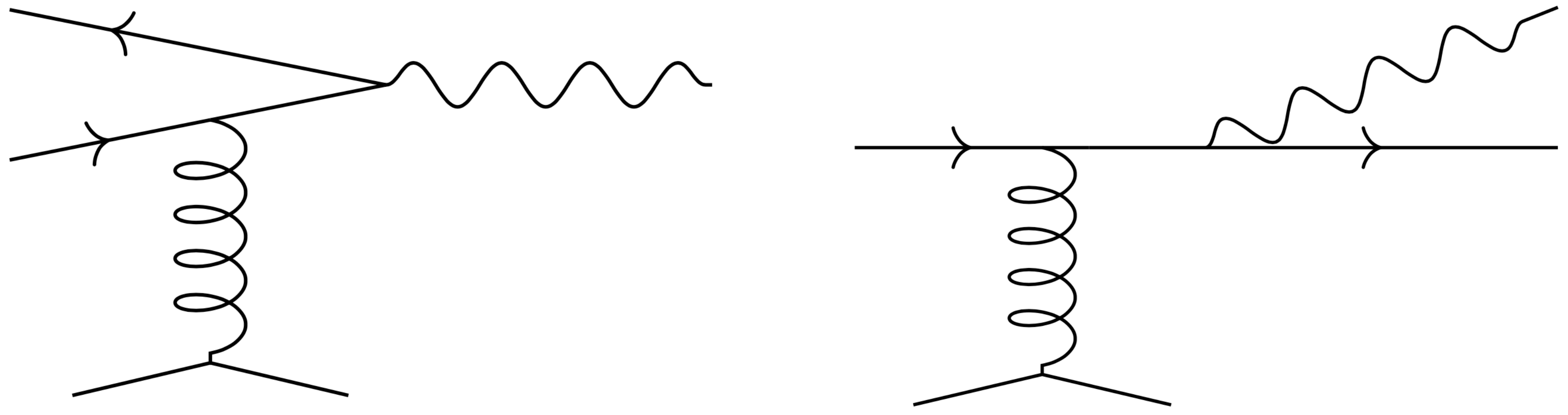
Compton Scattering

Elastic pair annihilation

+ appropriate other channels

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

Effective 1 ↔ 2 processes



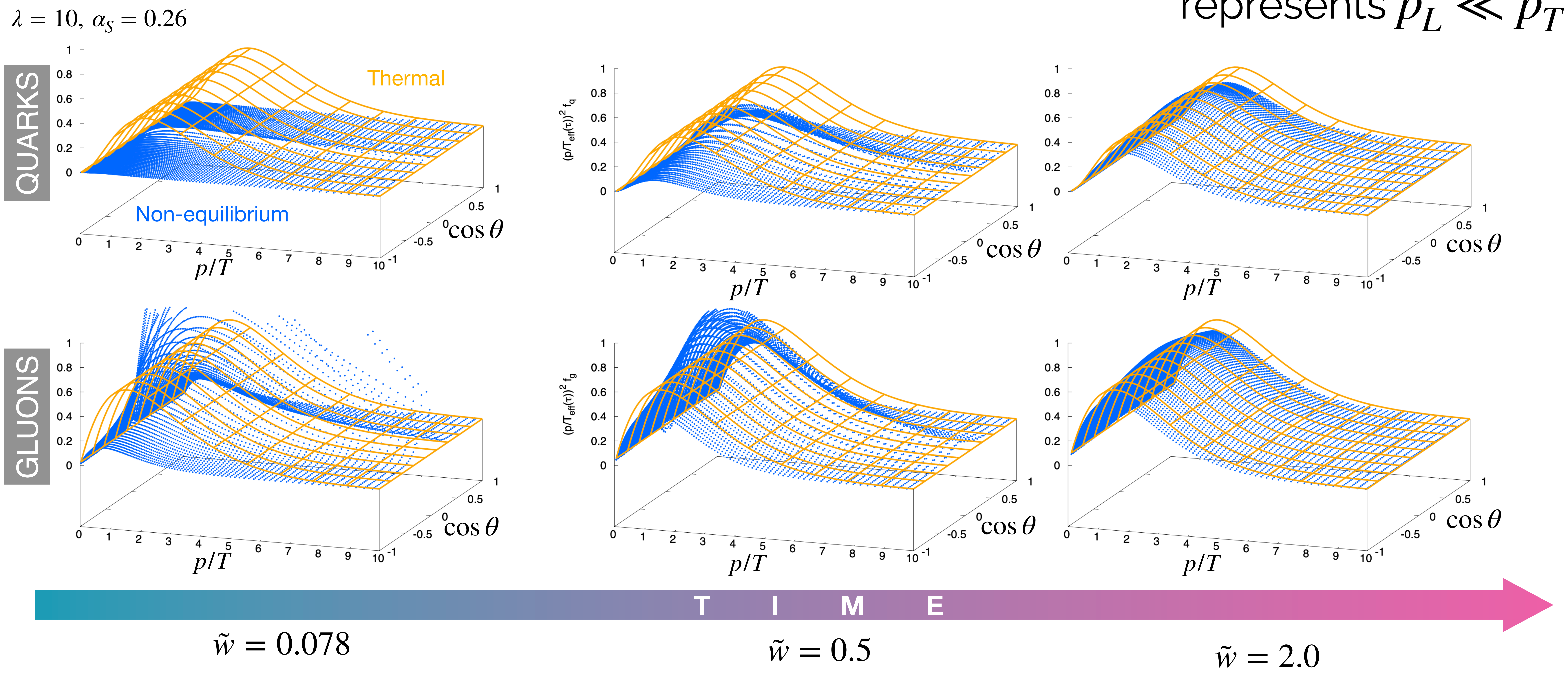
Inelastic pair annihilation

Bremsstrahlung off q & q̄

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

QCD KINETIC THEORY

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

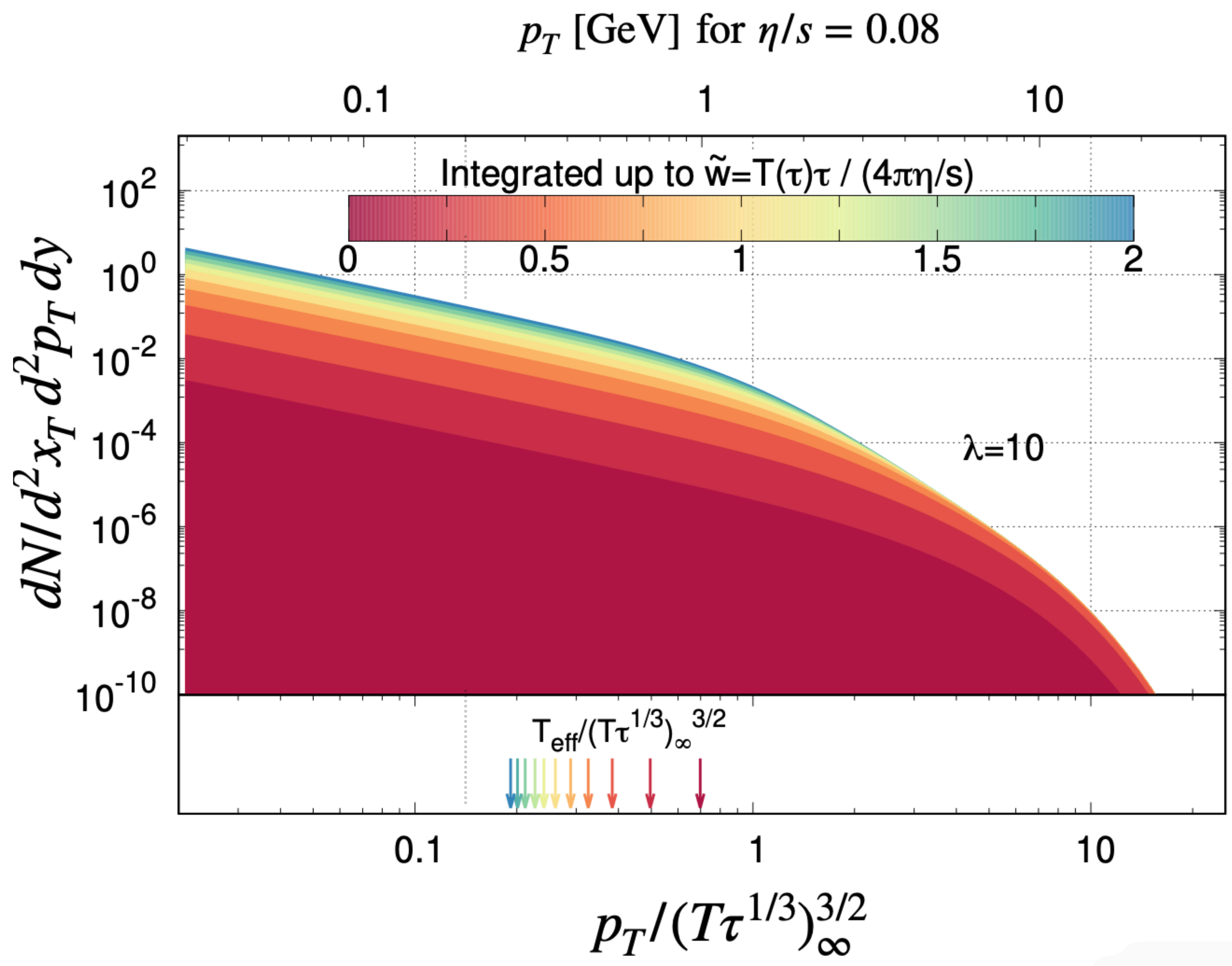


PHOTON - p_T -SPECTRUM

- Hard p_T-regime produced at early times

- Early time production ($\tilde{w} \lesssim 0.5$) suppressed due to absence of quarks

- Competition between increase of non-eq. photon production rate relative to thermal rate and rapid cooling of pre-eq. QGP
  $\Rightarrow$ smooth convergence to thermal
  photon rate

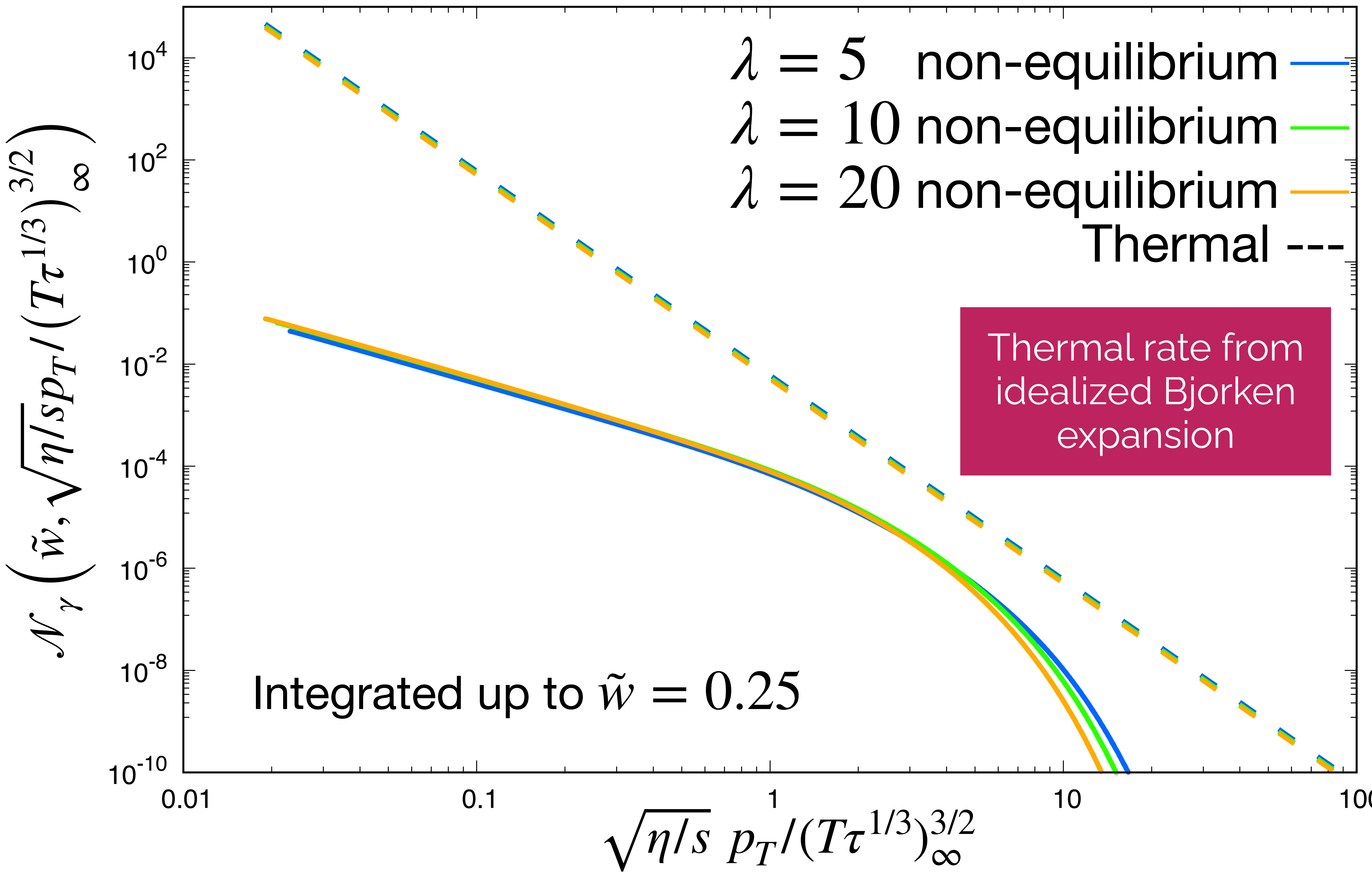


PHOTONS - SCALING

- Competing effects: cooling dynamics and quark production
  ⇒ 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 η/s and entropy density $T\tau^{1/3} \sim (\tau s)_{eq}^{1/3}$
  ⇒ valid for each theory with energy attractor



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

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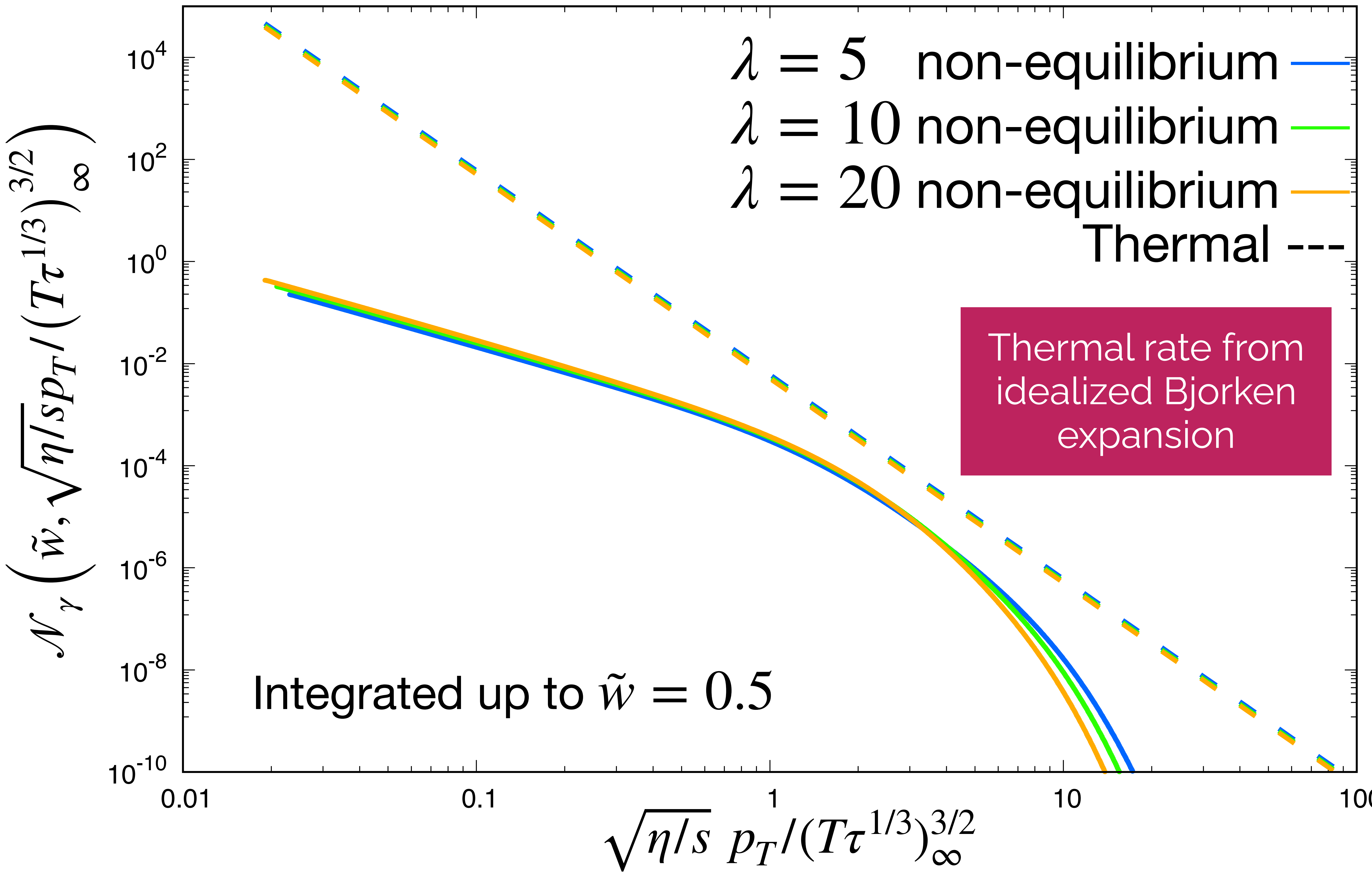

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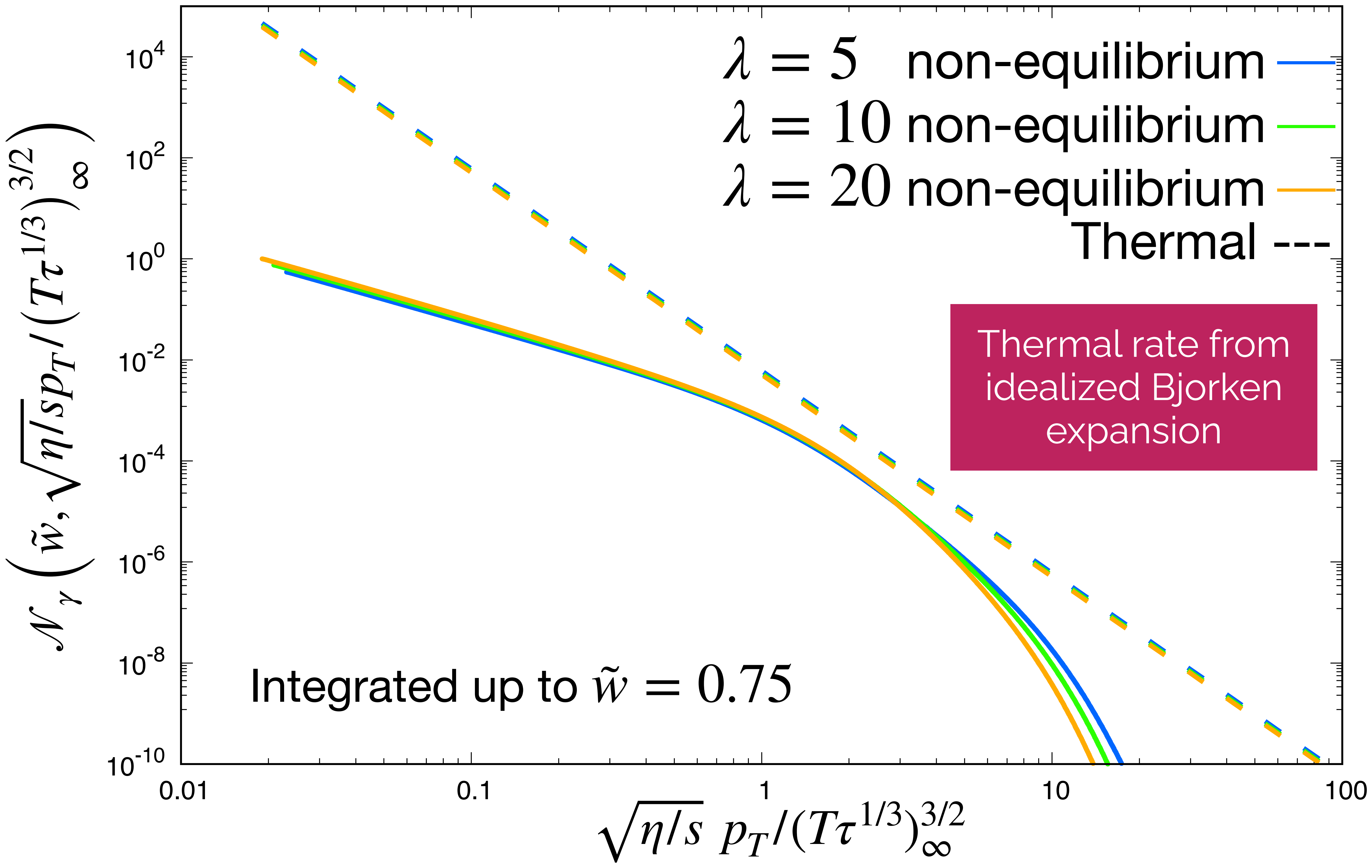

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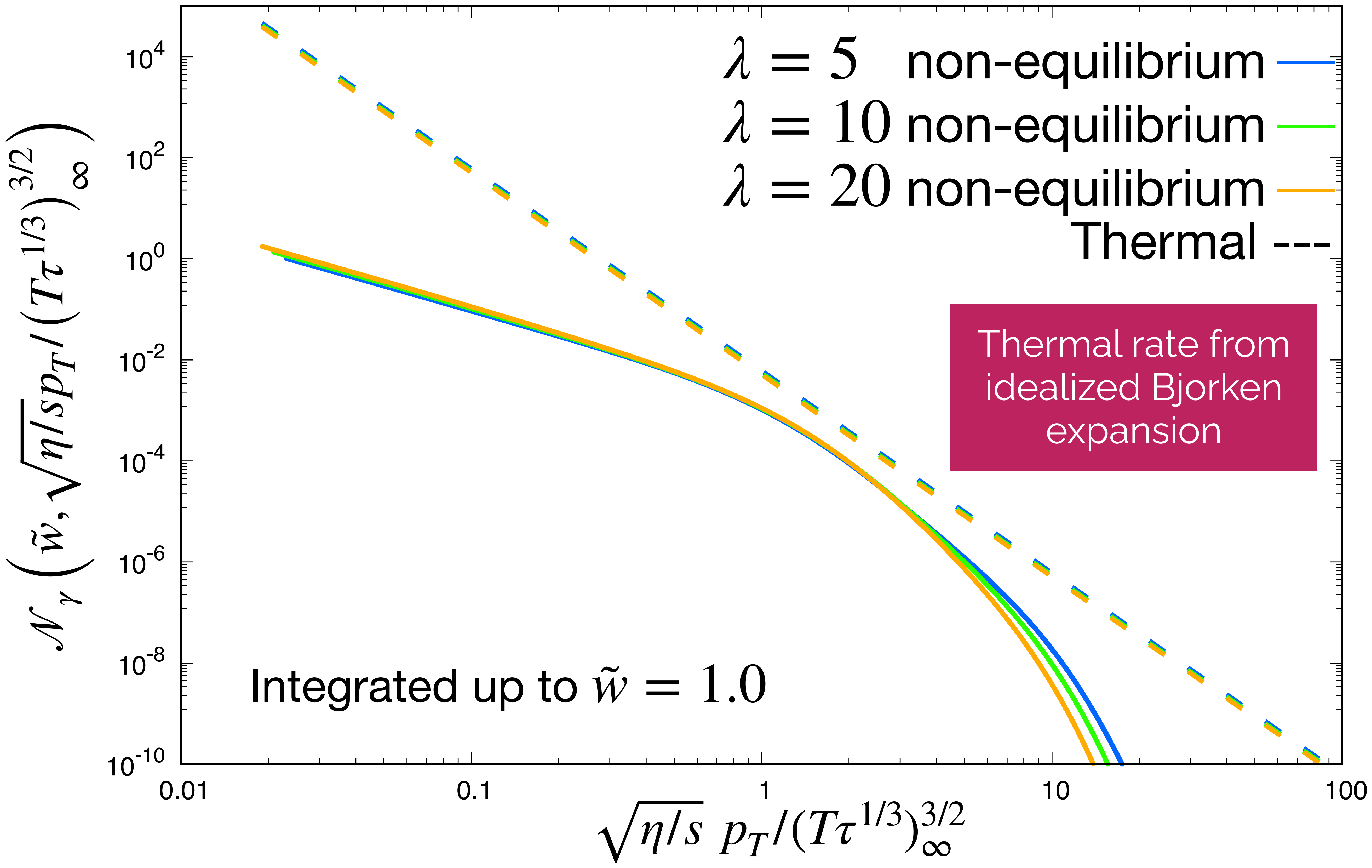

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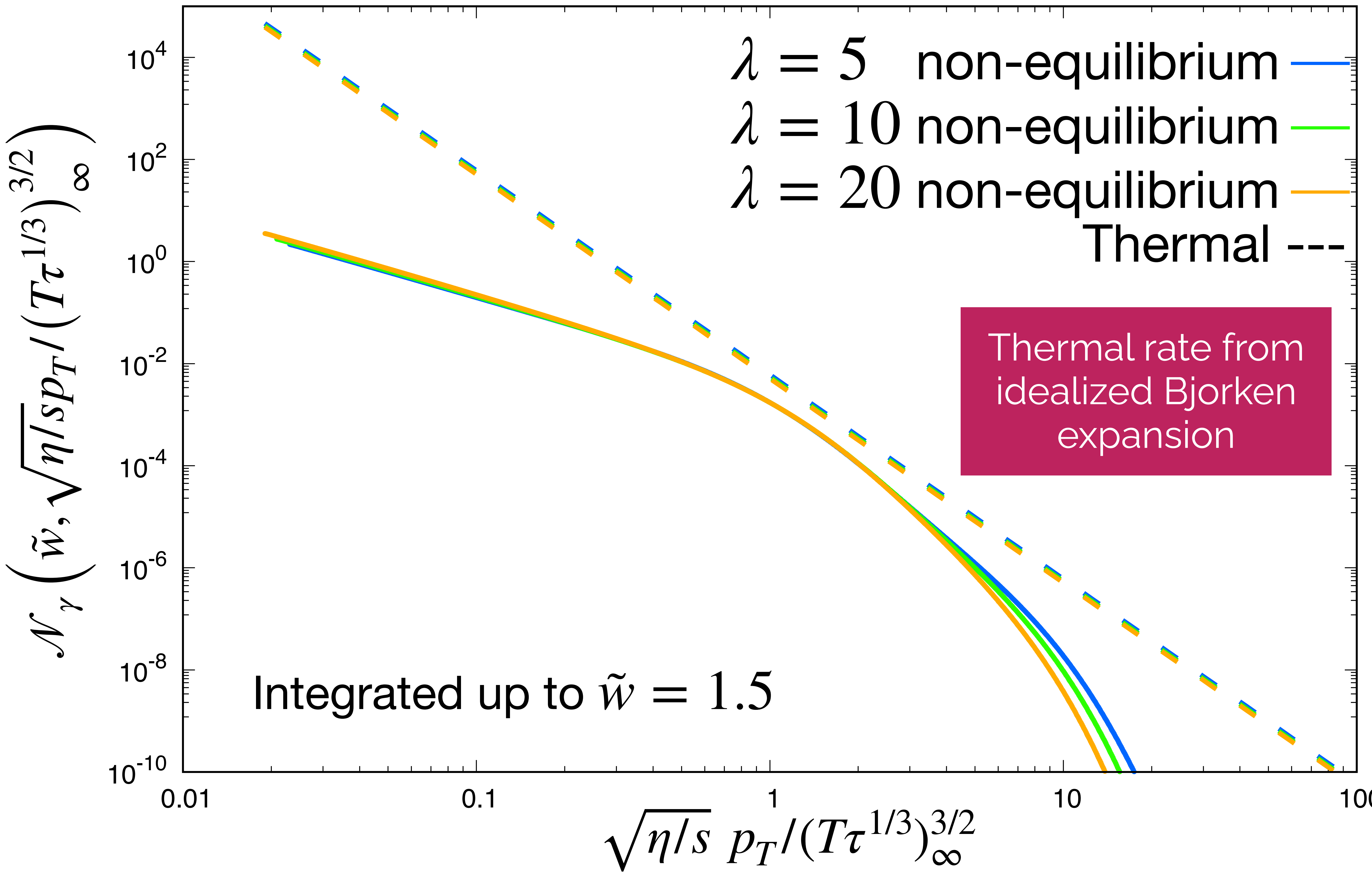

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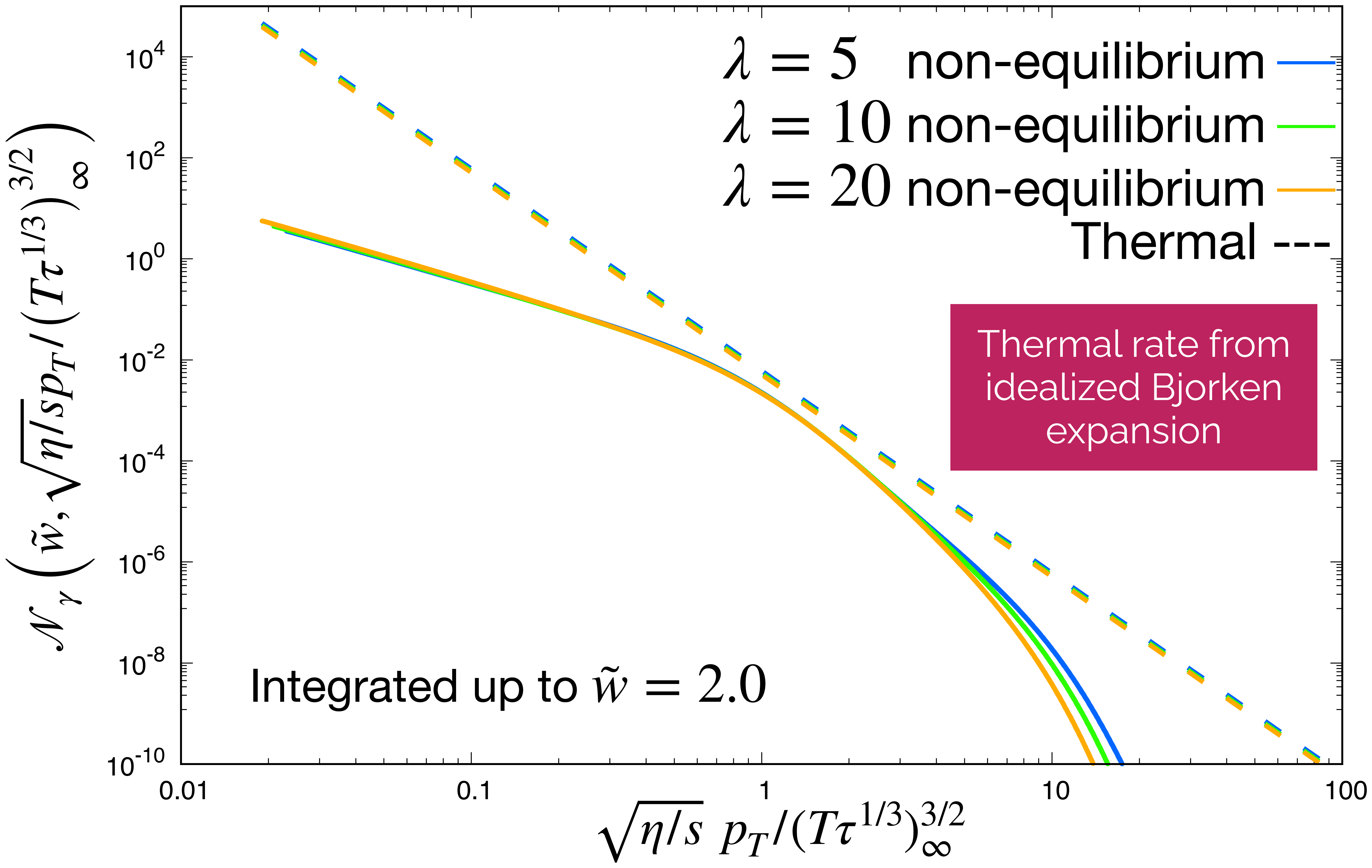

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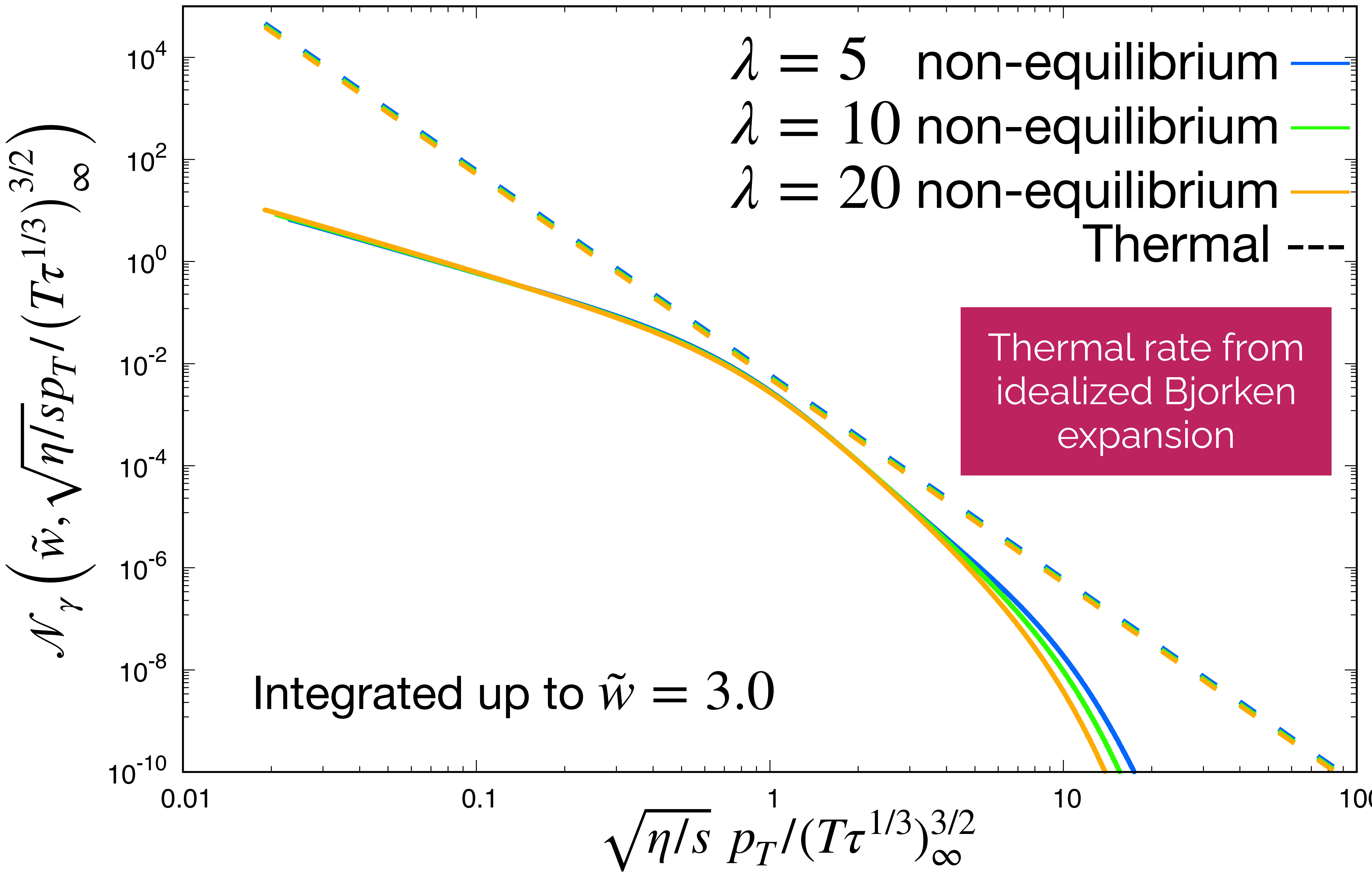

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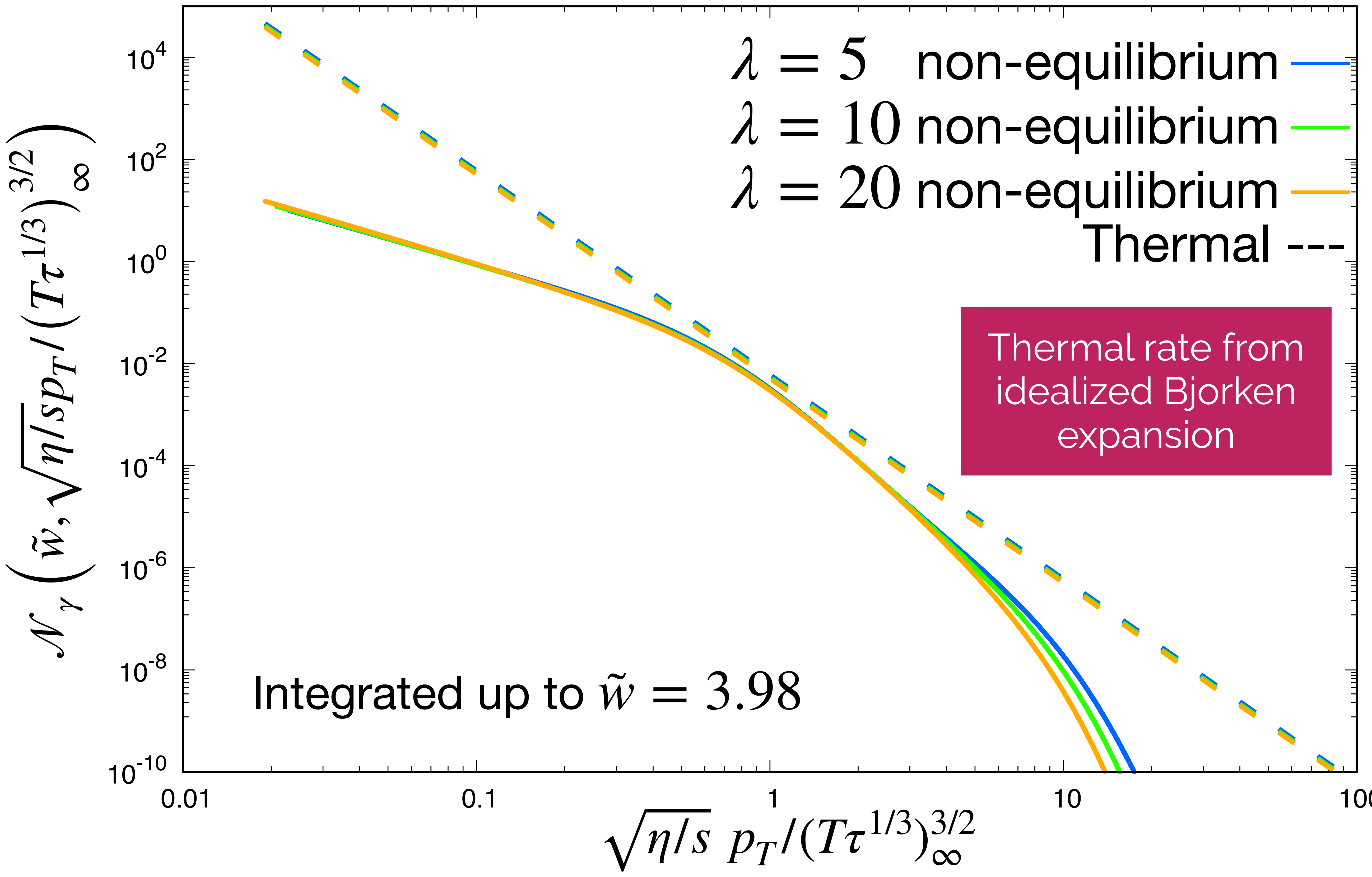

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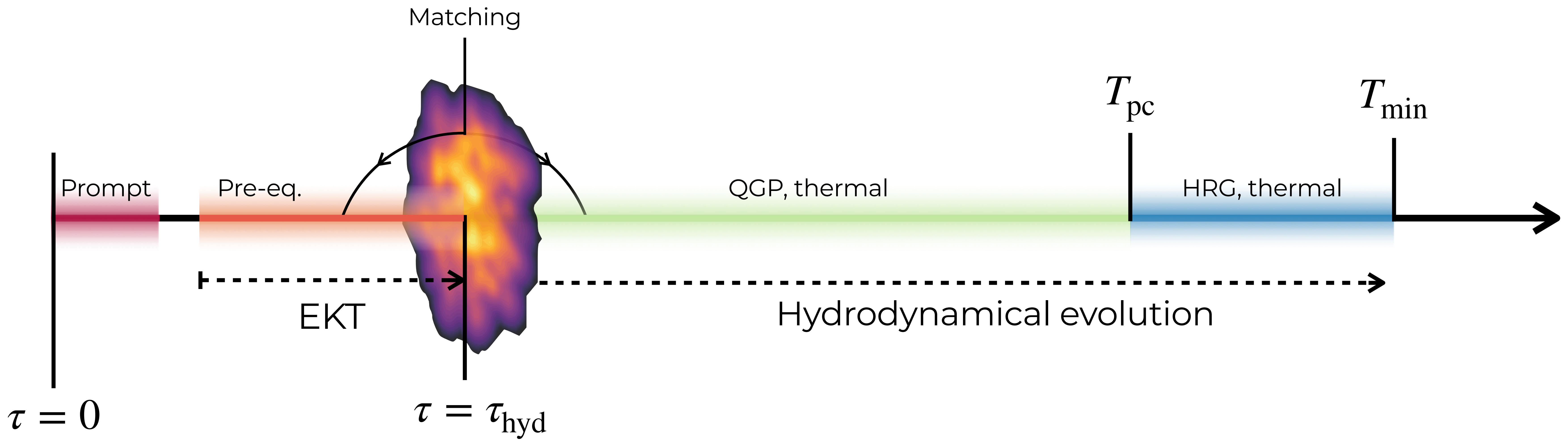
RESULTS - PHENOMENOLOGY

- 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 and scaling time, $\tilde{w}_{match} = T_{\rm hyd}\tau_{\rm hyd}/(4\pi\eta/s)$.

$$(\tau^{1/3}T)_\infty(x_T) = \tau_{\rm hyd}^{1/3}\left(T_{\rm hyd}(x_T) + \frac{2}{3}\frac{\eta/s}{\tau_{\rm hyd}}\right)$$



- Vary matching times. Robust under assumptions:

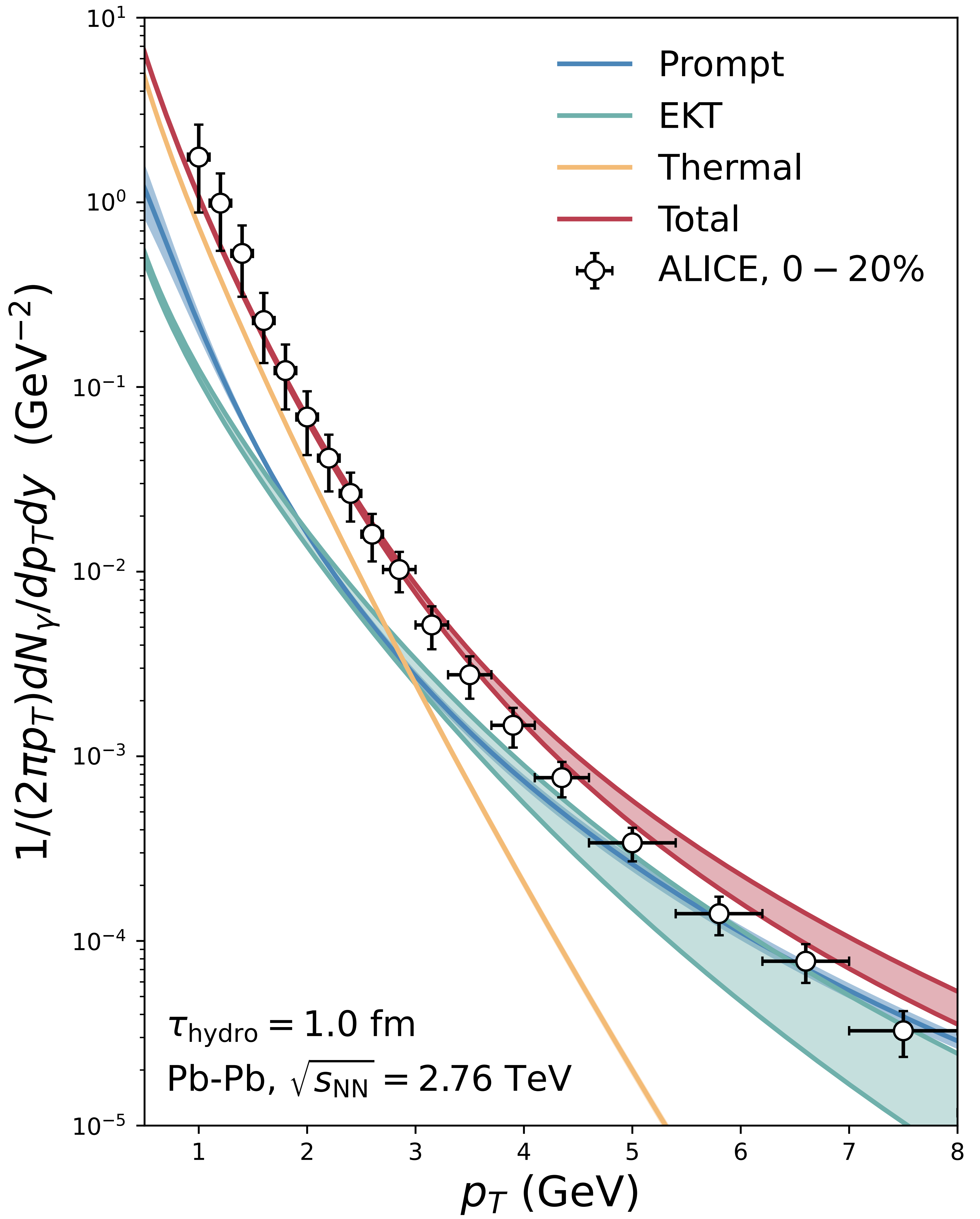
$$\langle\tilde{w}(\tau_{\rm hydro} = 0.6\,{\rm fm})\rangle = 1.002$$
$$\langle\tilde{w}(\tau_{\rm hydro} = 1\,{\rm fm})\rangle = 1.45$$

PHOTONS - PHENOMENOLOGY

- Background evolution obtained from VISH2+1 hydro with η/s=0.08 tuned to 0-20% PbPb collisions at 2.76TeV [Garcia-Montero et al., *Phys.Rev.C,* (2020)]

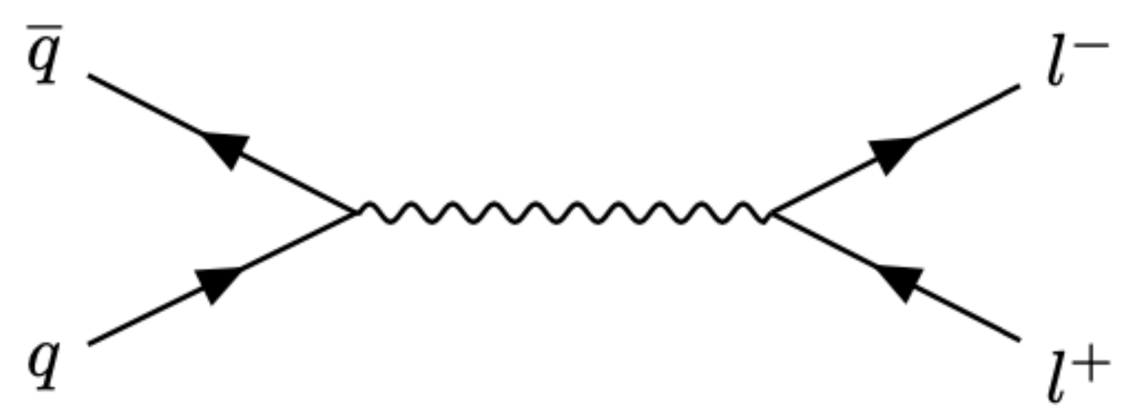
- Above $p_T \approx 3$GeV pre-equilibrium production dominates in- medium photon production

- Sensitivity to initialisation time and initial conditions.



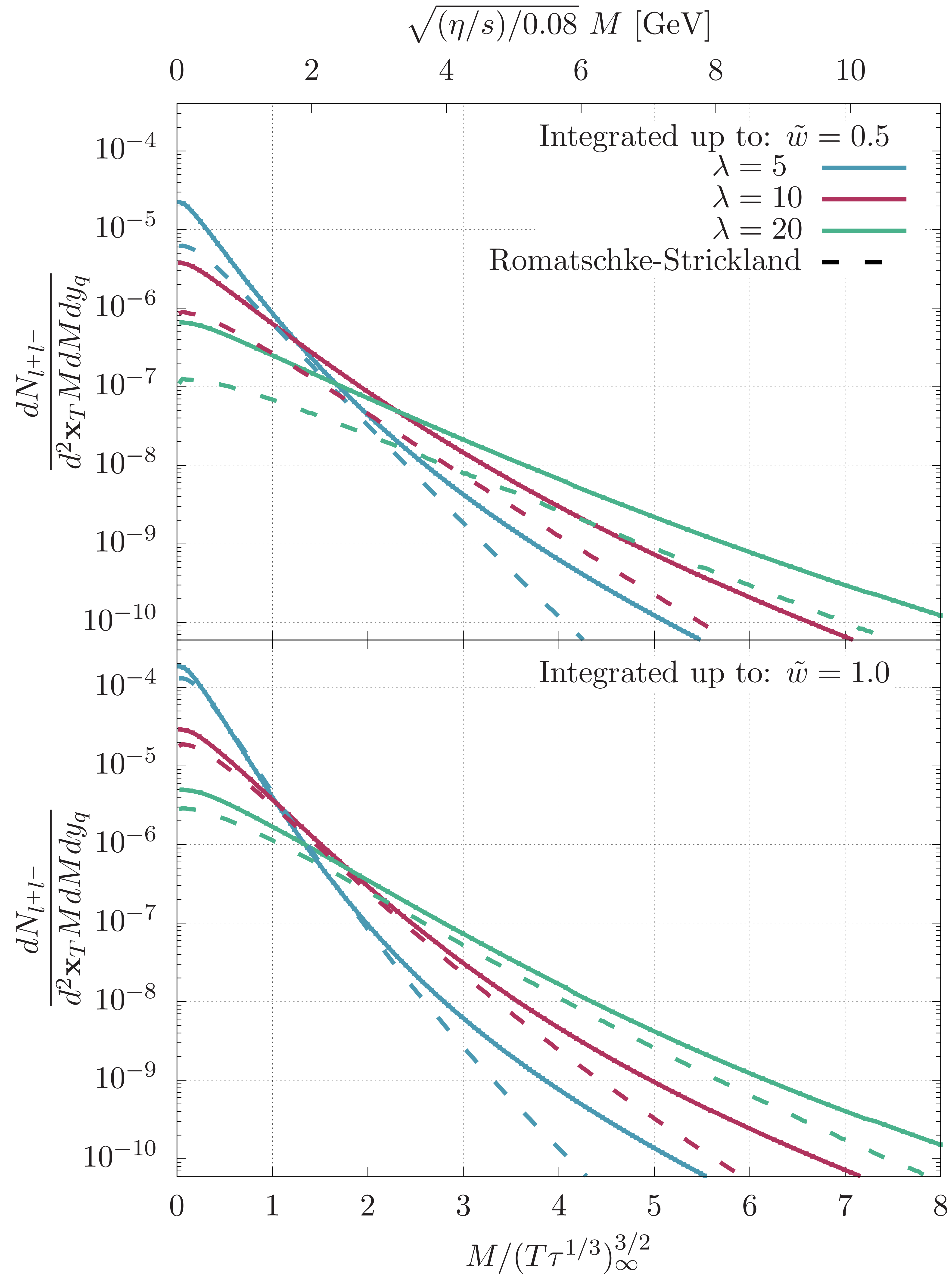
DILEPTON PRODUCTION

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



- Analytically and numerically (EKT) found scaling for dileptons

$$\frac{dN_{\|}}{dMdy} = (\eta/s)^2\, \tilde{C}_{\gamma}^{ideal}\; \mathcal{N}_{\|}\left(\tilde{w}, \sqrt{\eta/s}\; M/(\tau^{1/3}T)^3/2_{\infty}\right)$$



[Garcia-Montero *et al.* 2403.04846]

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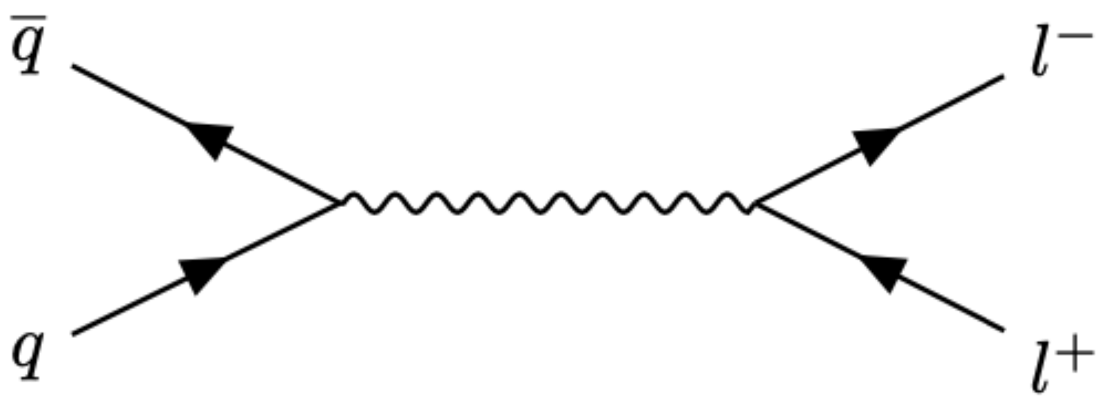

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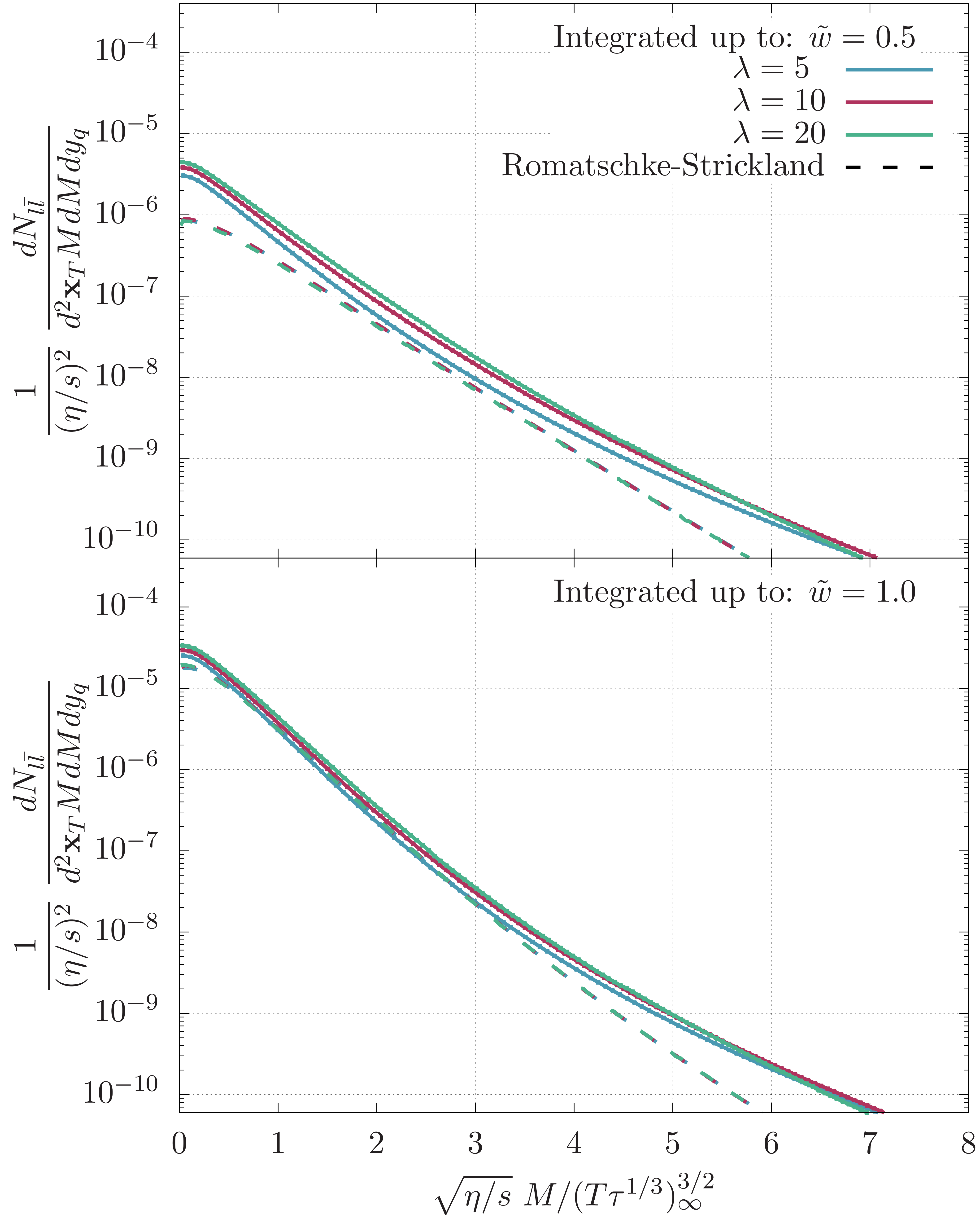


[Garcia-Montero *et al.* 2403.04846]

RESULTS - PHENOMENOLOGY

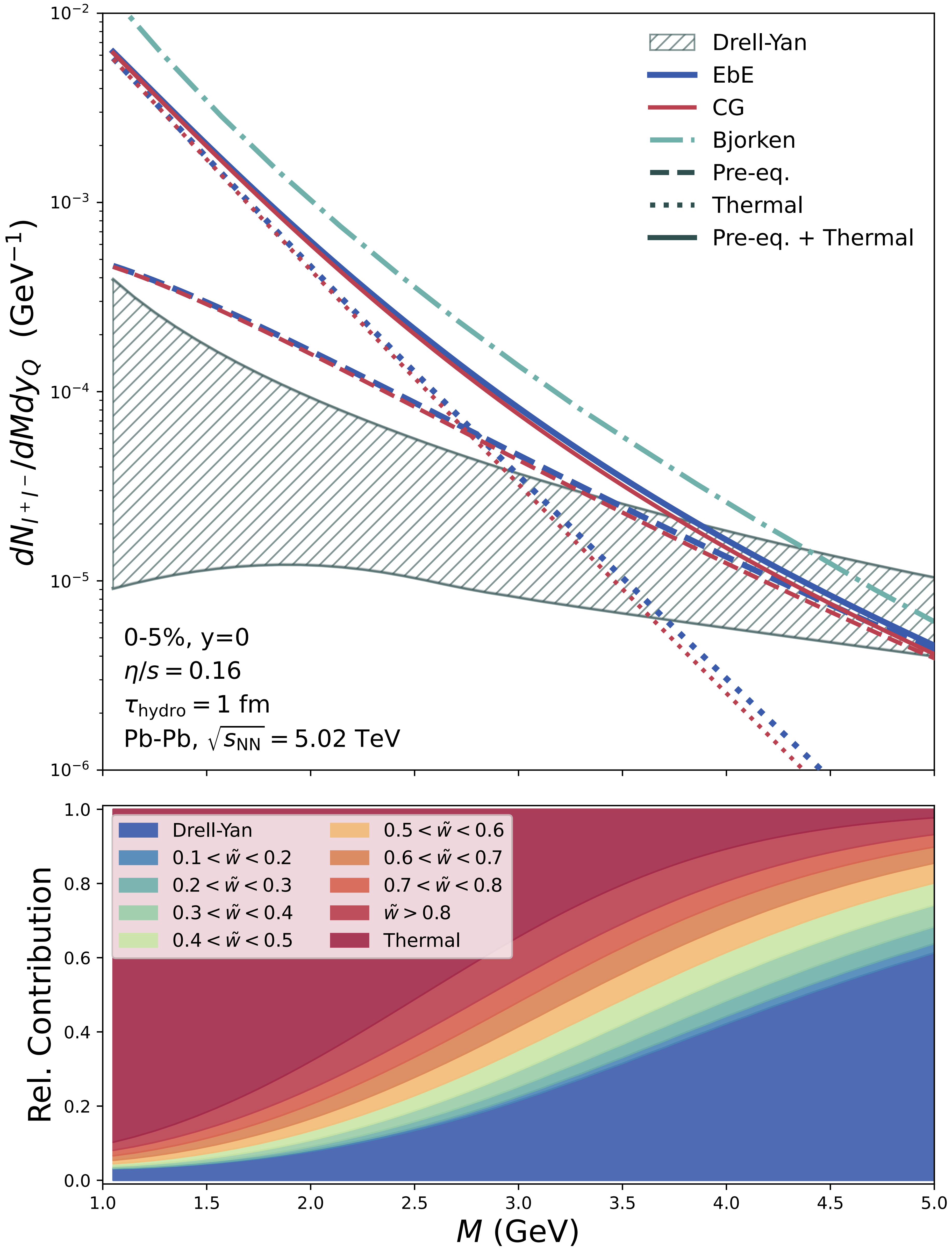
- Pre-eq. dilepton production event-by-event using a background evolution obtained from *Trajectum* tuned to 0-20% PbPb collisions at 5.02 TeV

  [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

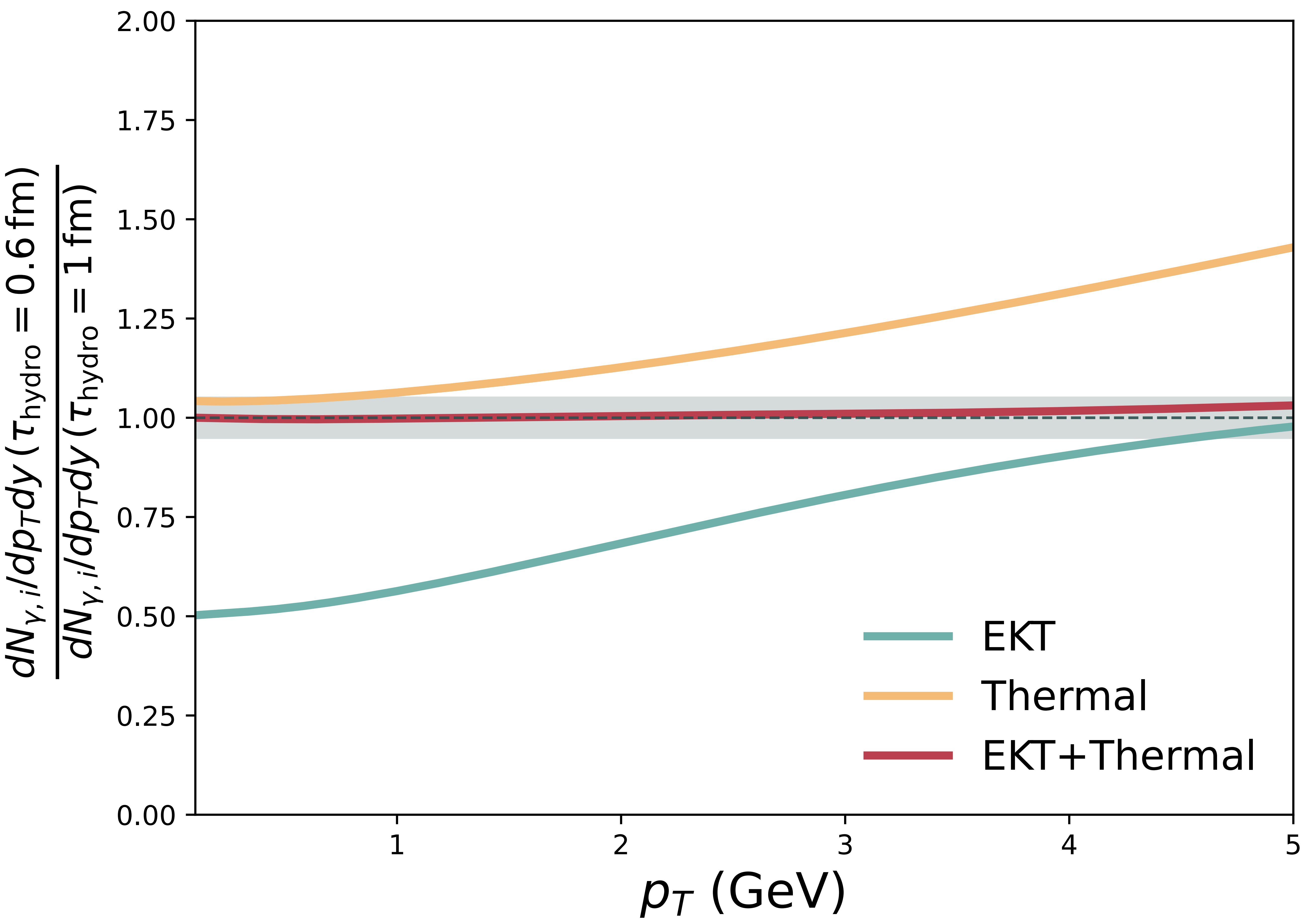
Universal scaling for different couplings in time integrated photon p_T-spectrum
Analogous scaling for dileptons in M_{ee}

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

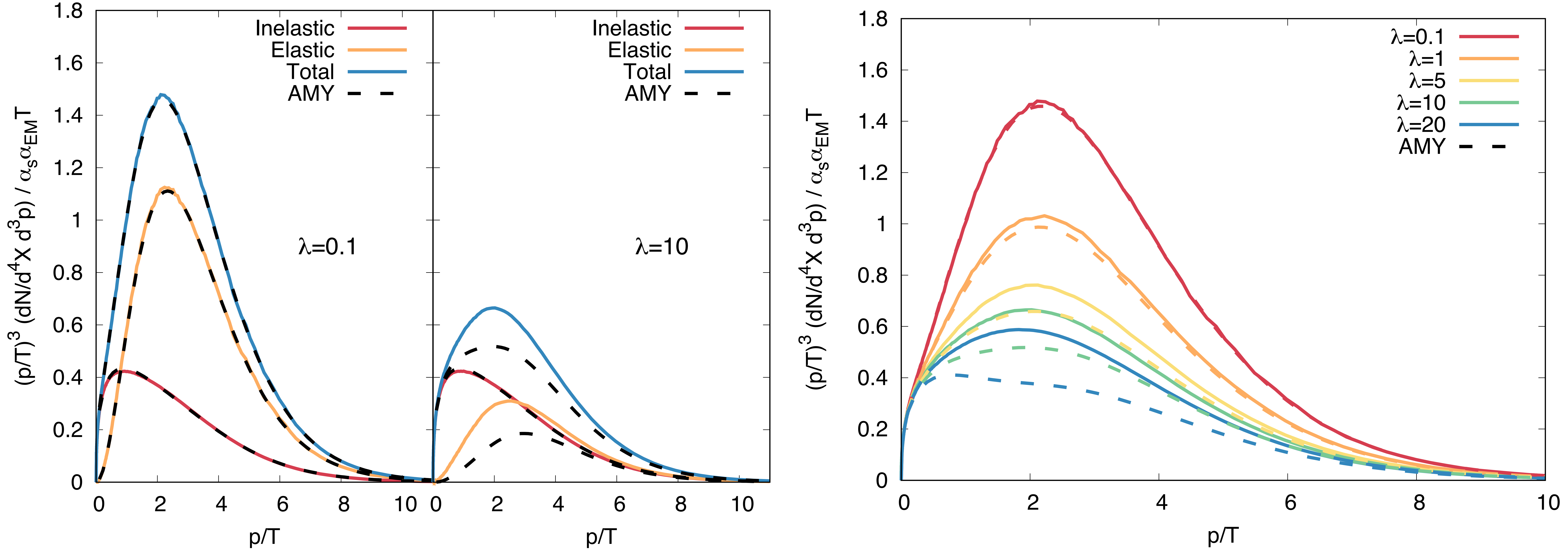
RESULTS - PHENOMENOLOGY



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

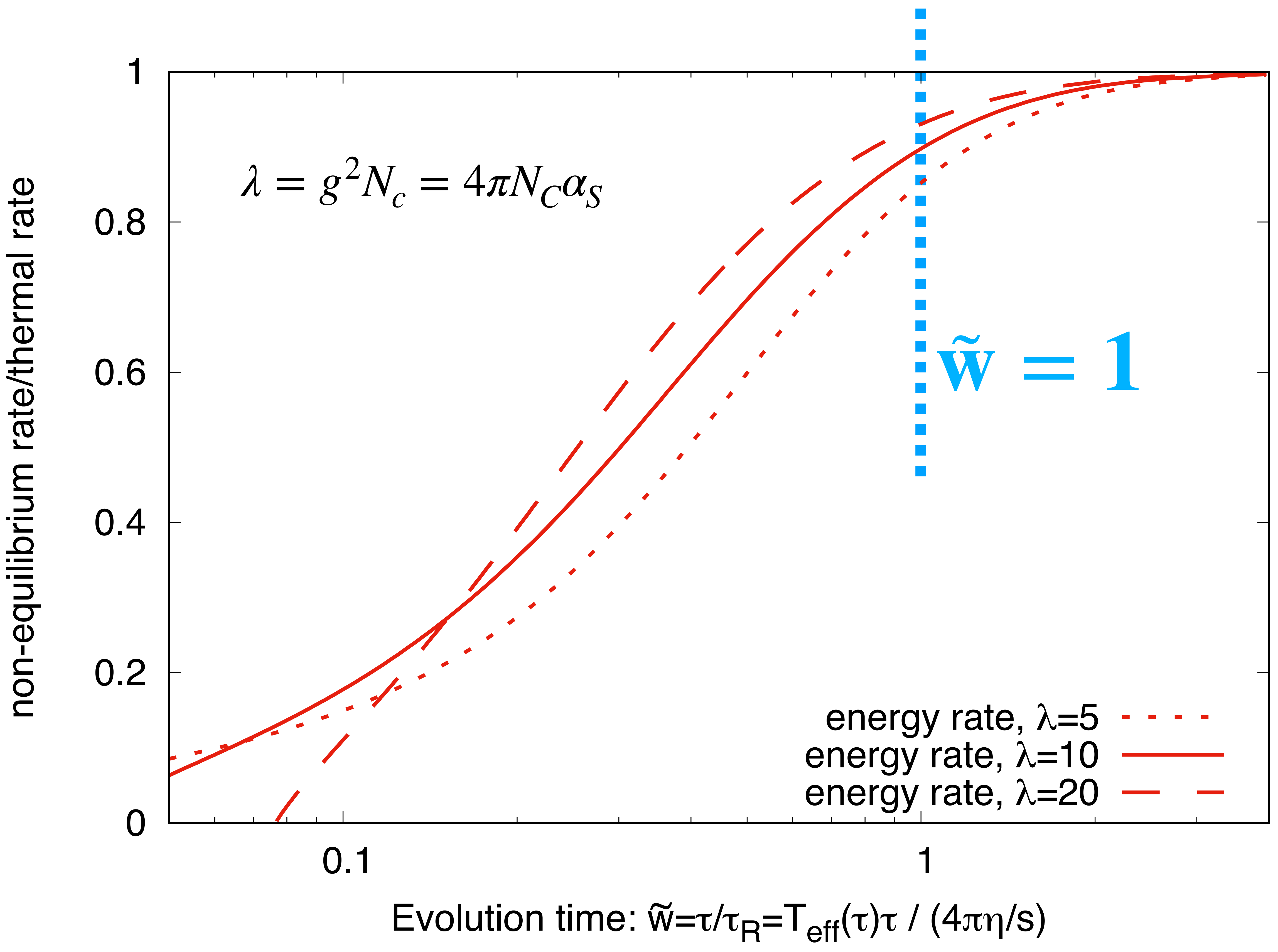
In medium yield robust w.r.t. switching time!

COMPARISON TO SEMI-ANALYTICAL AMY RATES



ELECTROMAGNETIC ENERGY LOSS RATE

- Non-equilibrium photon rate compared to thermal energy rate



Energy rate:

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

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

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

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

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

RESULTS - 2D SPECTRUM

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

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

RESULTS - 2D SPECTRUM

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

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

- 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

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

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

- 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

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

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

- 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