NIKHEF
Amsterdam
May 2024

HEAVY ION COLLISIONS 101

+ AN ELECTROMAGNETIC PHENOMENOLOGY OF THE EARLY STAGES

Oscar Garcia-Montero

Fakultät für Physik

Universität Bielefeld

GARCIA@PHYSIK.UNI-BIELEFELD.DE

+ based on JHEP 03 (2024) 053 and 2309.00555

CRC-TR 211
Strong-interaction matter under extreme conditions

UNIVERSITÄT BIELEFELD

QCD...

QCD…

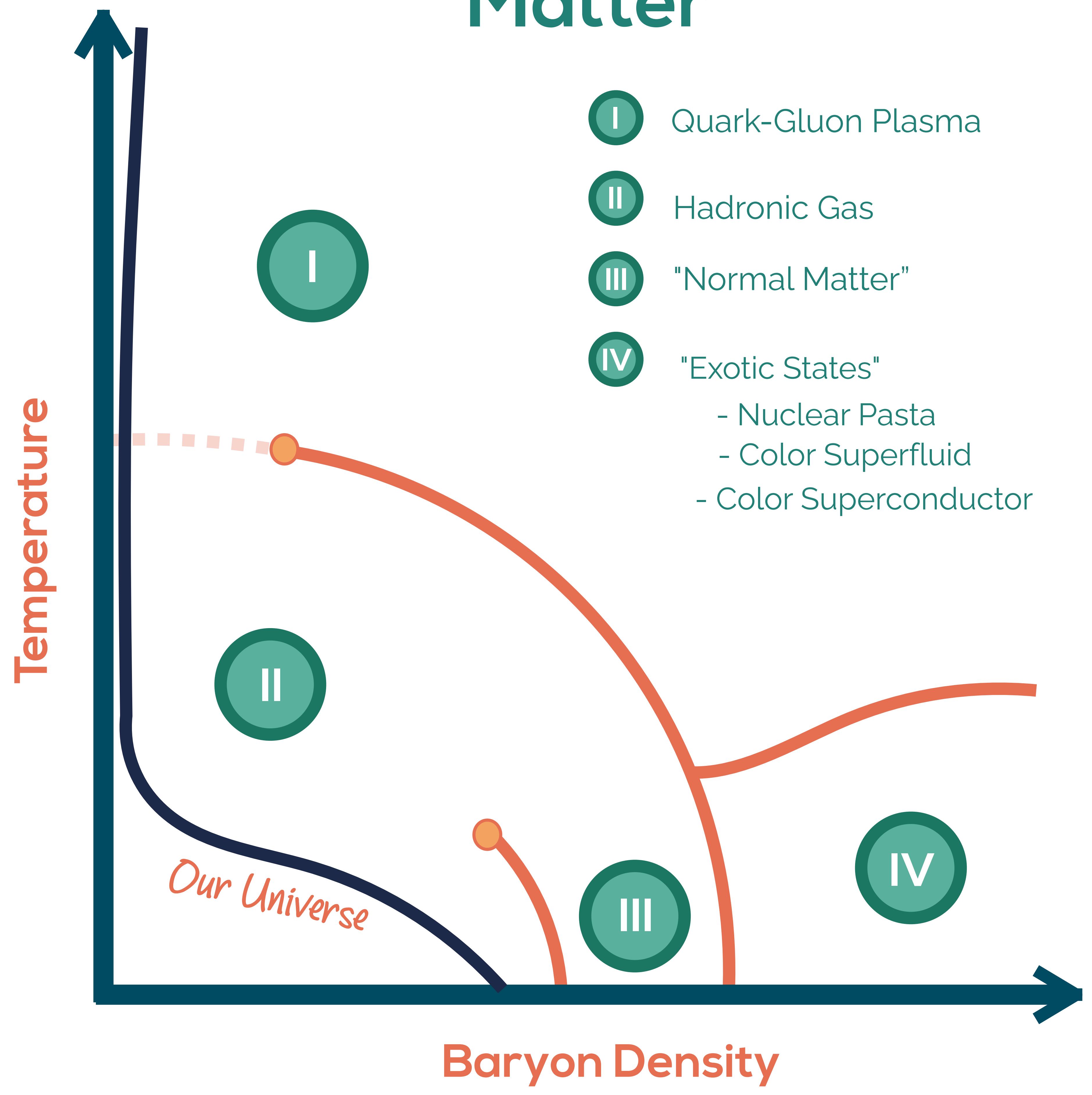
IS

DIFFICULT.

QCD...

IS VERY INTERESTING.

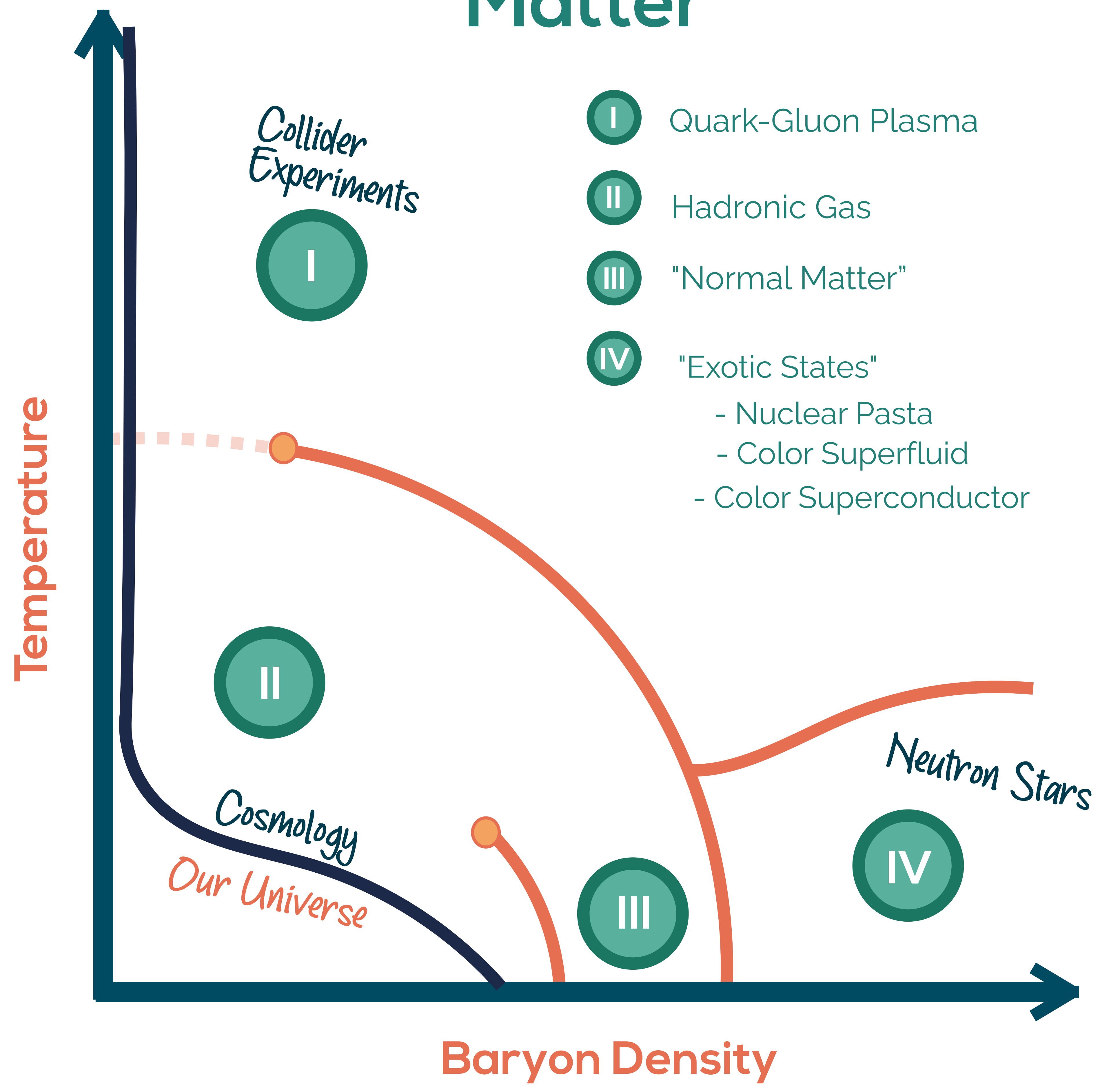
Phase Diagram of Nuclear Matter



QCD...

IS VERY INTERESTING.

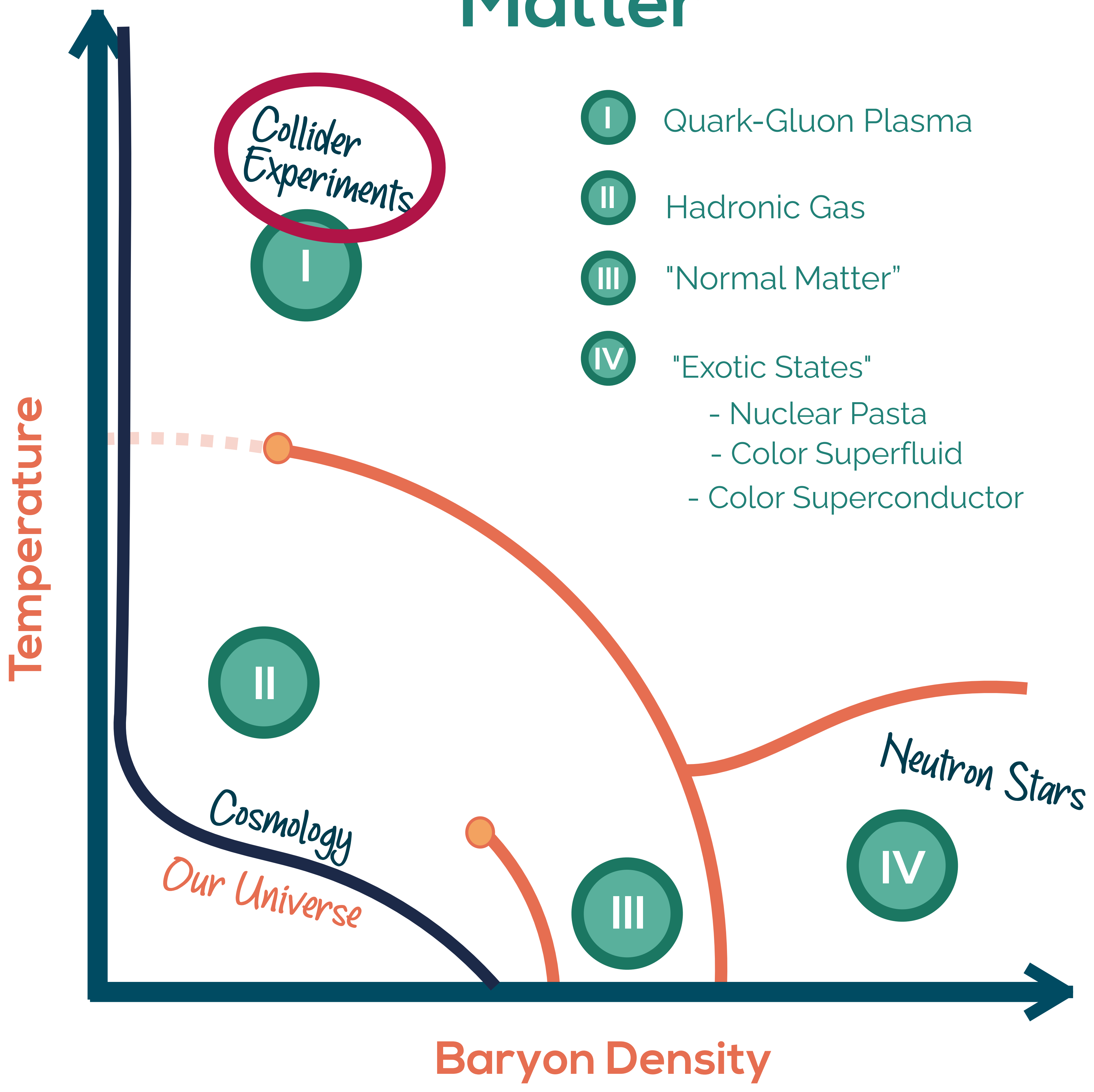
Phase Diagram of Nuclear Matter



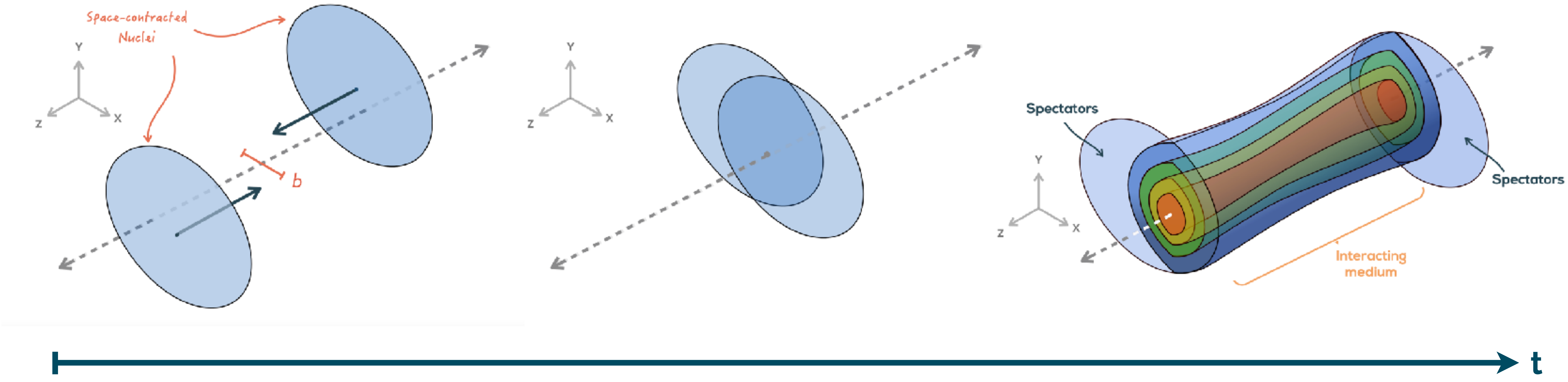
QCD...

IS VERY INTERESTING.

Phase Diagram of Nuclear Matter



Heavy Ion Collisions: The basic idea



FAQ

Q: Why heavy-ions?

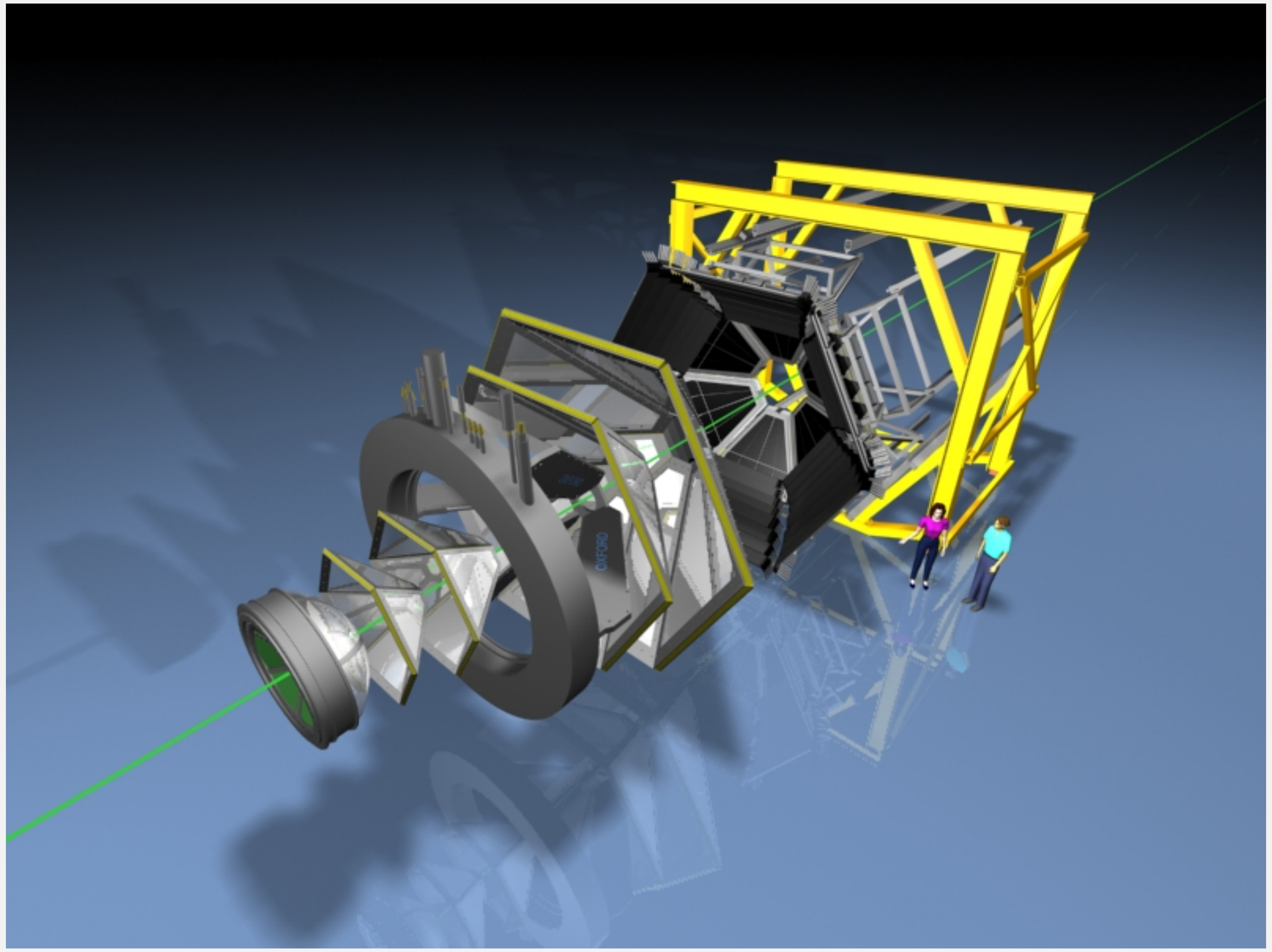
A: Many initial nucleons, higher energy and number density

Q: Why an interacting medium?

A: **Spoiler**:
We have observed collective dynamics in the experiments

SIS18 at GSI

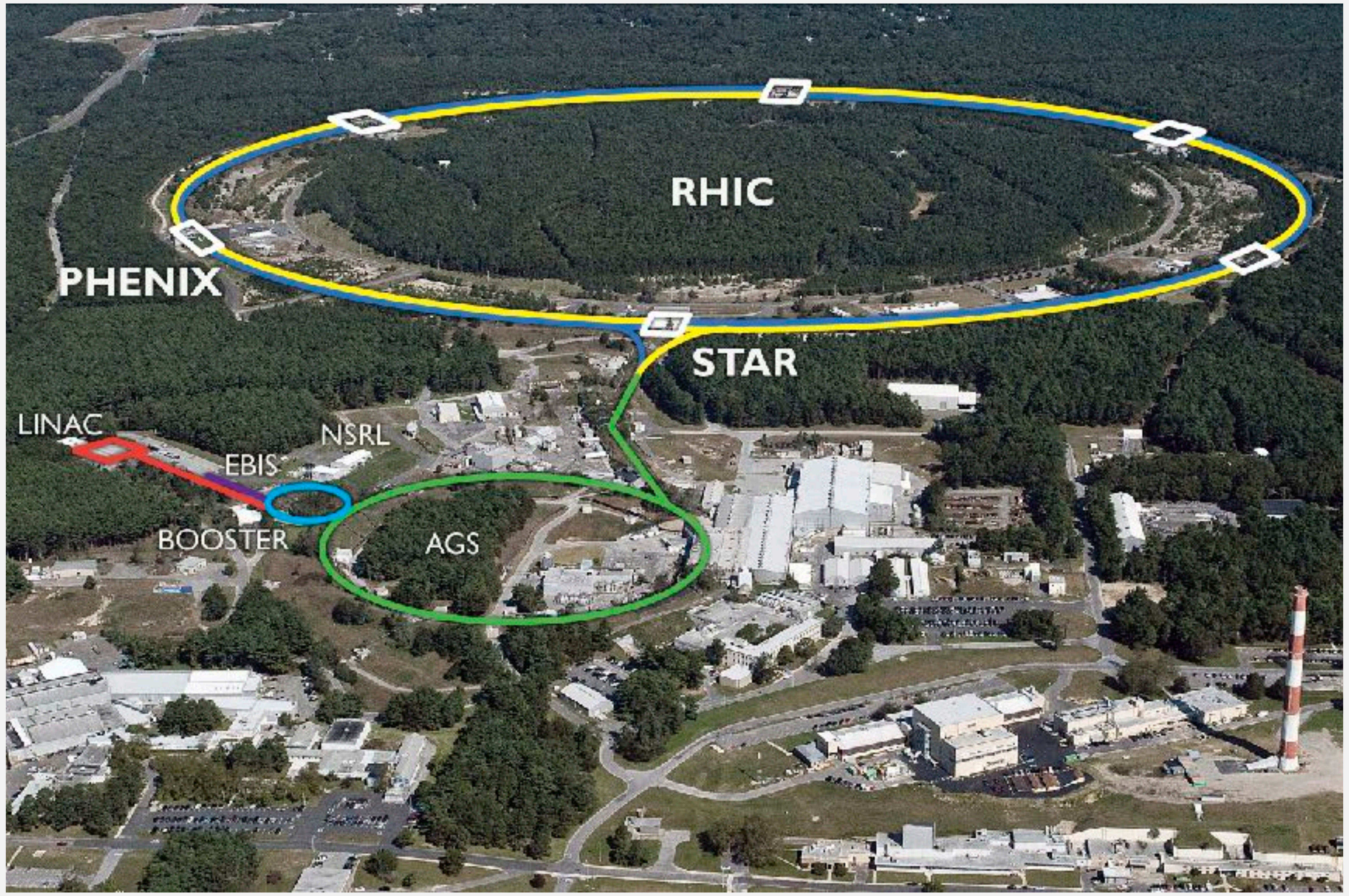
(And the HADES experiment)



Collision Energy = 1-5 GeV

Relativistic Heavy Ion Collider

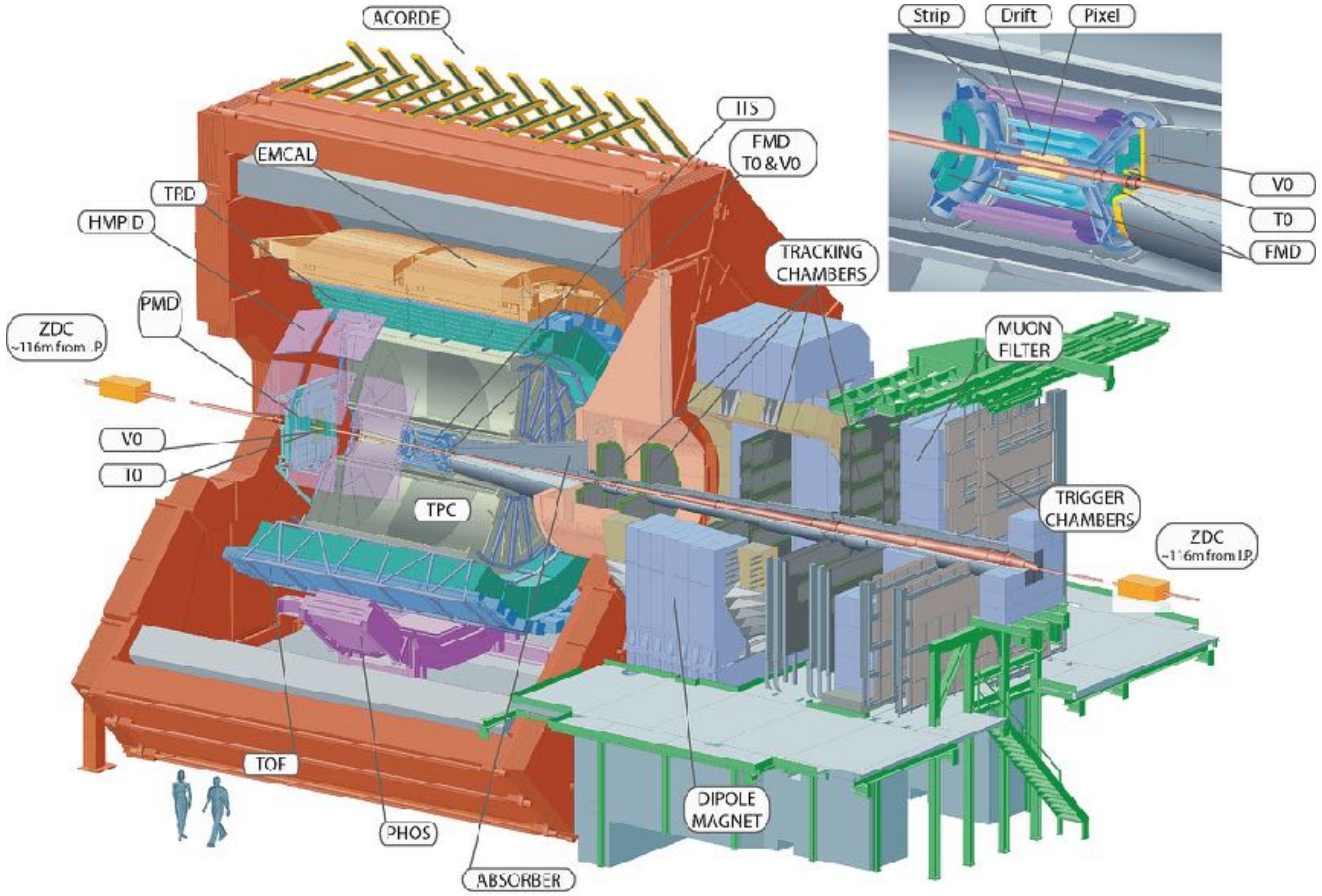
(And the STAR experiment)



Collision Energy = 200 GeV

Large Hadron Collider

(And the ALICE experiment)



Collision Energies = 2760, 5020 GeV

Heavy Ion Collisions: A cheat sheet.

The Systems

p+p → Baseline ("Control Group")

p+A → Cold Nuclear Matter lab

A+A → Hot Nuclear Matter lab

A=C, O, Au, Pb, ..., U

What we can observe

Invariant Yields

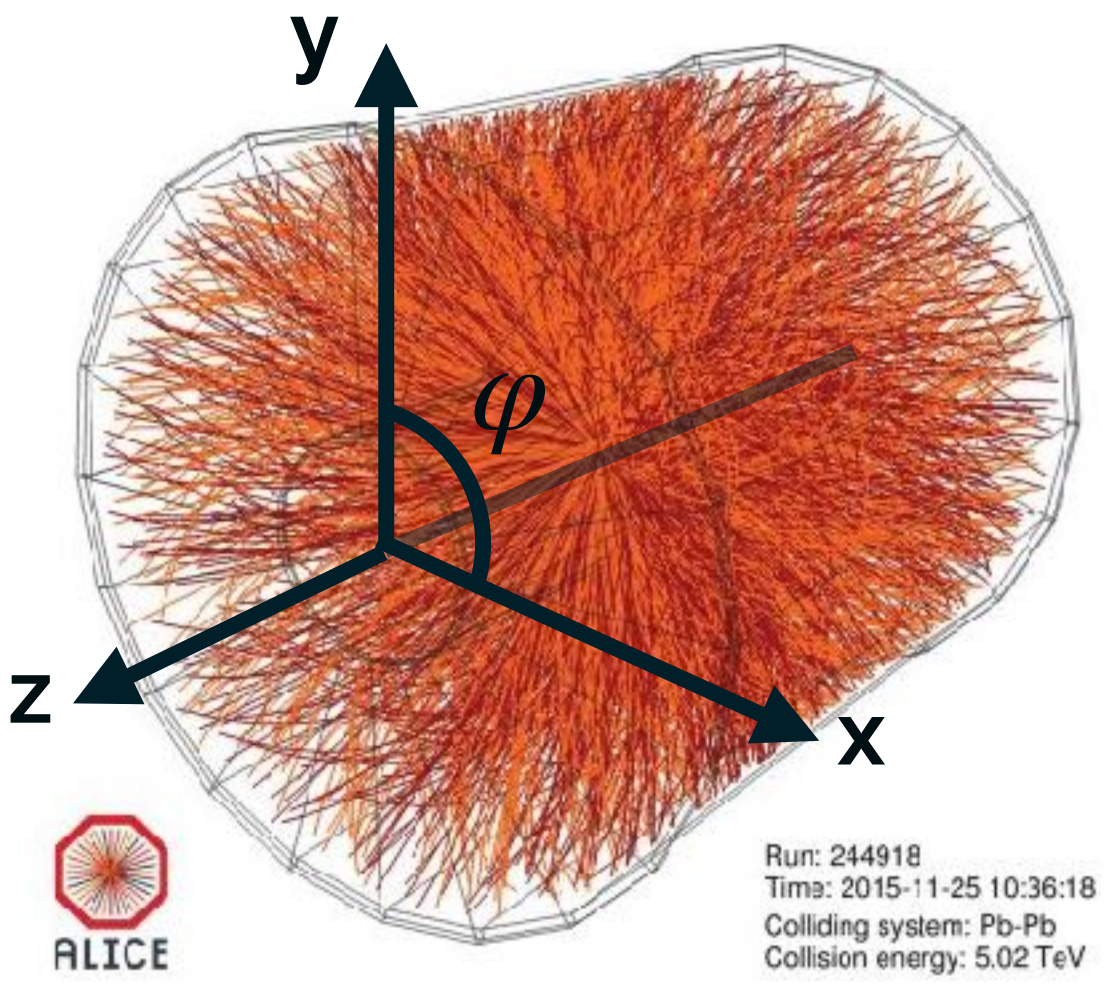
$$\frac{\mathrm{d}N}{\mathrm{d}y\mathrm{d}^2p_\perp}$$

- Yields: $\mathrm{d}N/\mathrm{d}y$
- $p_\perp$ spectrum: $\mathrm{d}N/\mathrm{d}p_\perp$
- Angular spectrum: $\mathrm{d}N/\mathrm{d}\phi$

Particle Correlations

$$\frac{\mathrm{d}N}{\mathrm{d}y_1\mathrm{d}^2p_\perp\mathrm{d}y_2\mathrm{d}^2q_\perp}$$

- Interferometry functions
- Cumulants



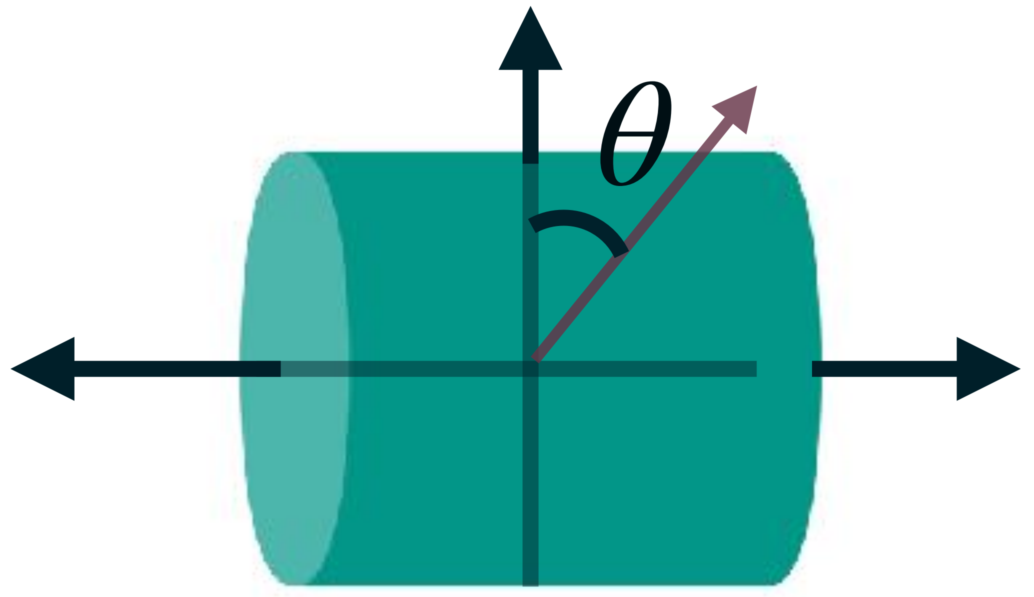
The variables we use

Momentum rapidity $y = \frac{1}{2}\log\left[(E+p_z)/(E-p_z)\right]$

$\sim \theta$ if massless...

Transverse momentum $\mathbf{p}_\perp = (p_x, p_y)$

Center of mass energy. $s = (p_1 + p_2)^2$



Heavy Ion Collisions: A cheat sheet.

The Systems

p+p → Baseline ("Control Group")

p+A → Cold Nuclear Matter lab

A+A → Hot Nuclear Matter lab

A=C, O, Au, Pb, ..., U

AS ALWAYS:
MORE COMPLICATED THAN FIRST THOUGHT

What we can observe

Invariant Yields

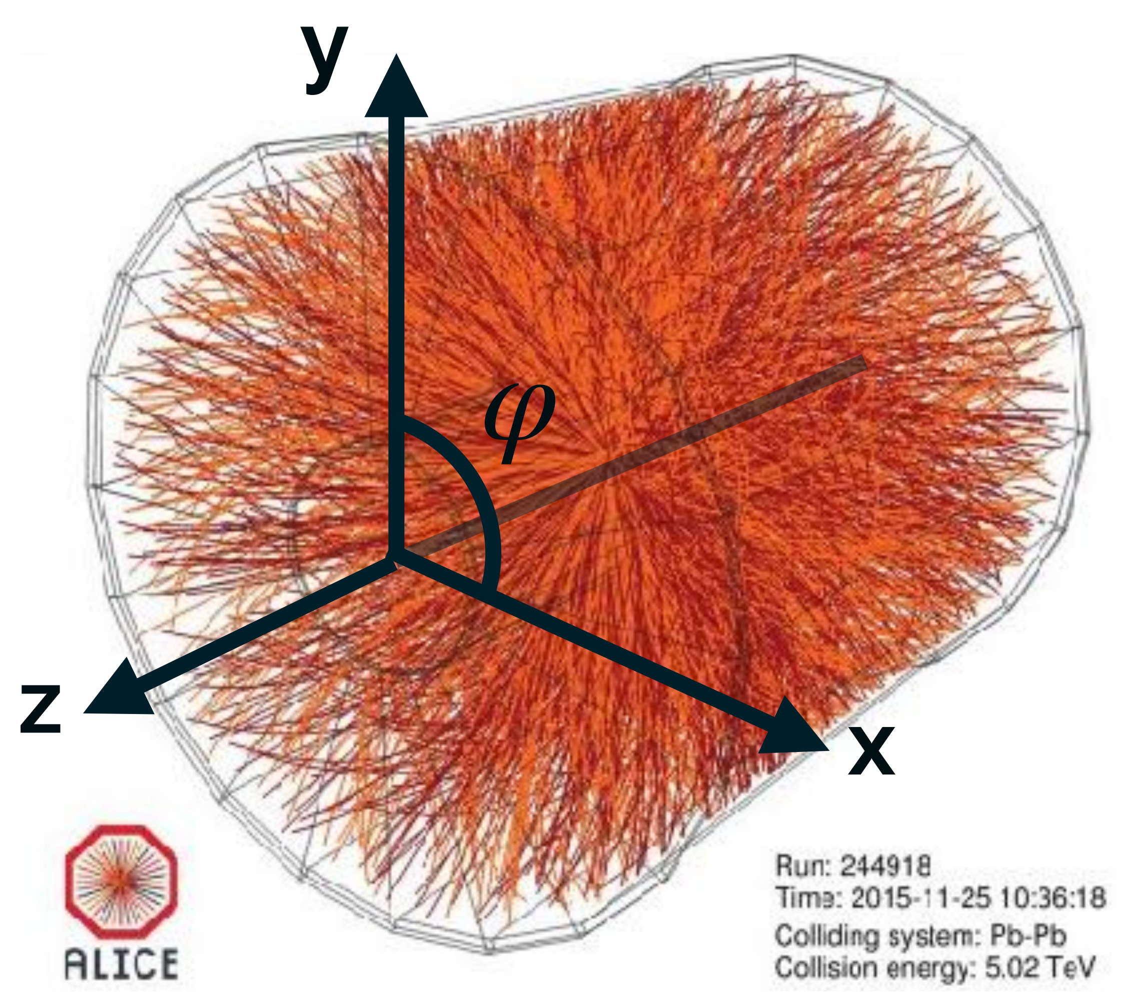
$$\frac{\mathrm{d}N}{\mathrm{d}y\mathrm{d}^2p_\perp}$$

- Yields: $\mathrm{d}N/\mathrm{d}y$
- $p_\perp$ spectrum: $\mathrm{d}N/\mathrm{d}p_\perp$
- Angular spectrum: $\mathrm{d}N/\mathrm{d}\phi$

Particle Correlations

$$\frac{\mathrm{d}N}{\mathrm{d}y_1\mathrm{d}^2p_\perp\mathrm{d}y_2\mathrm{d}^2q_\perp}$$

- Interferometry functions
- Cumulants



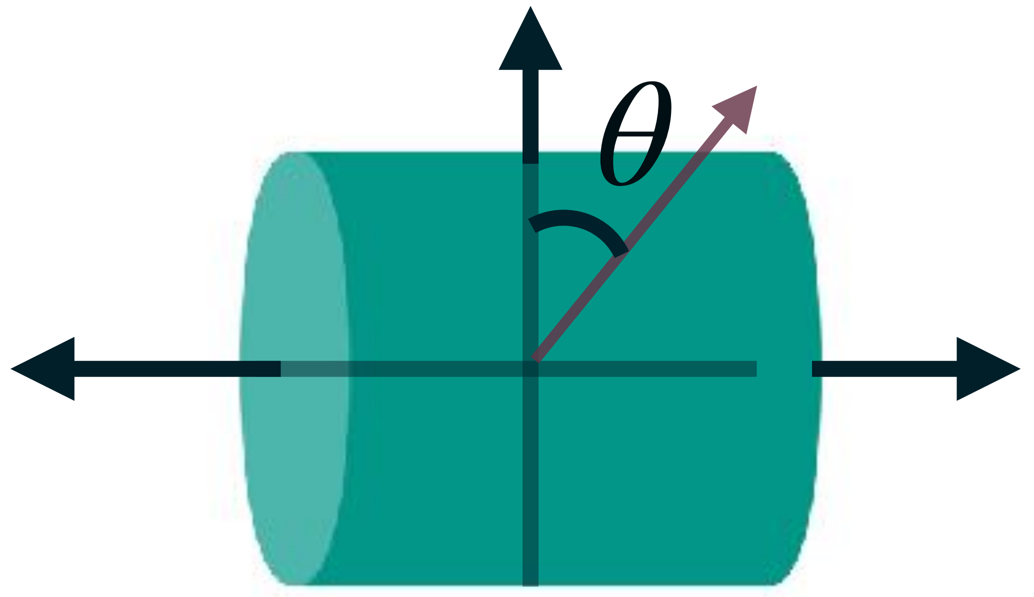
The variables we use

Momentum rapidity $\quad y = \frac{1}{2}\log\left[(E+p_z)/(E-p_z)\right]$

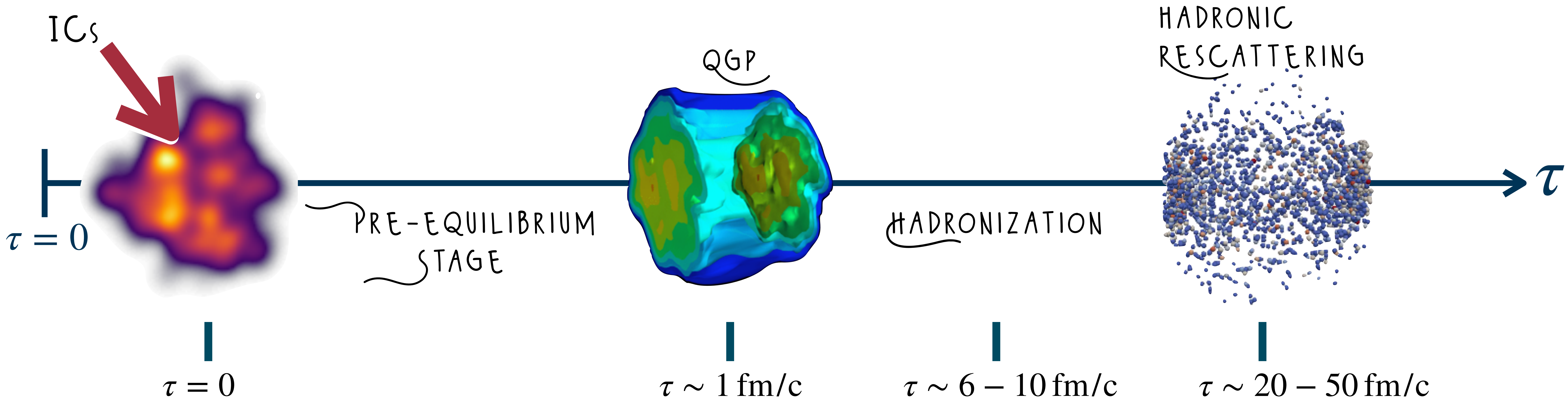
$\sim \theta \quad$ if massless...

Transverse momentum $\quad \mathbf{p}_\perp = (p_x, p_y)$

Center of mass energy. $\quad s = (p_1 + p_2)^2$

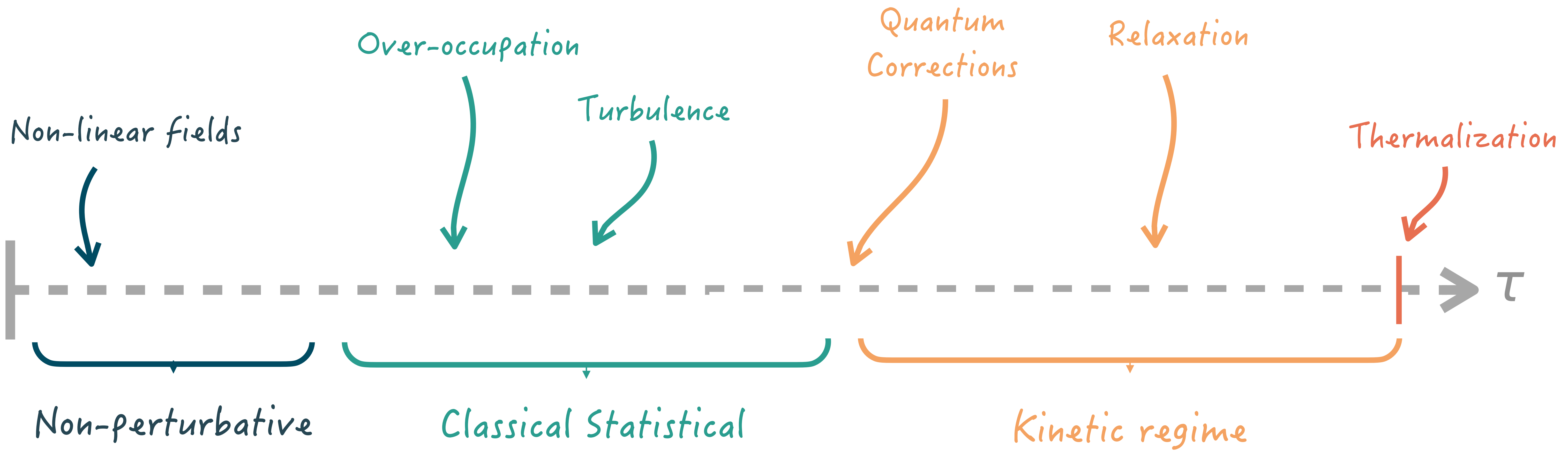


The Standard Model of Heavy Ion Collisions



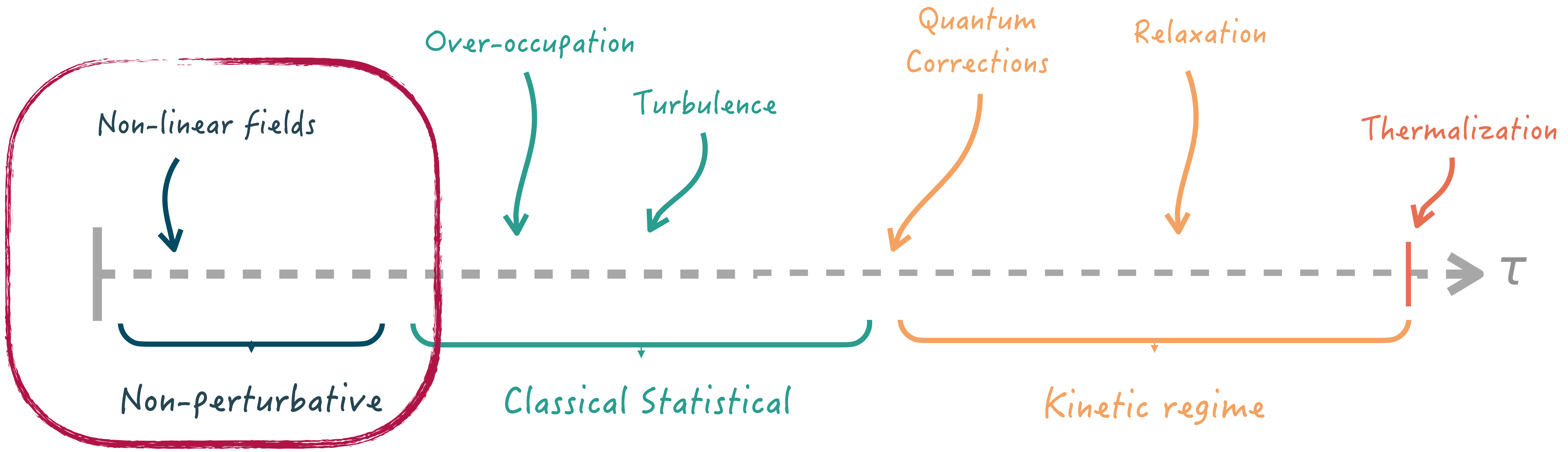
PRE-EQUILIBRIUM DYNAMICS: TURBULENT THERMALIZATION

How does one go from an **extremely violent** event turn into a nicely thermalized fluid?



PRE-EQUILIBRIUM DYNAMICS: TURBULENT THERMALIZATION

How does one go from an **extremely violent** event turn into a nicely thermalized fluid?

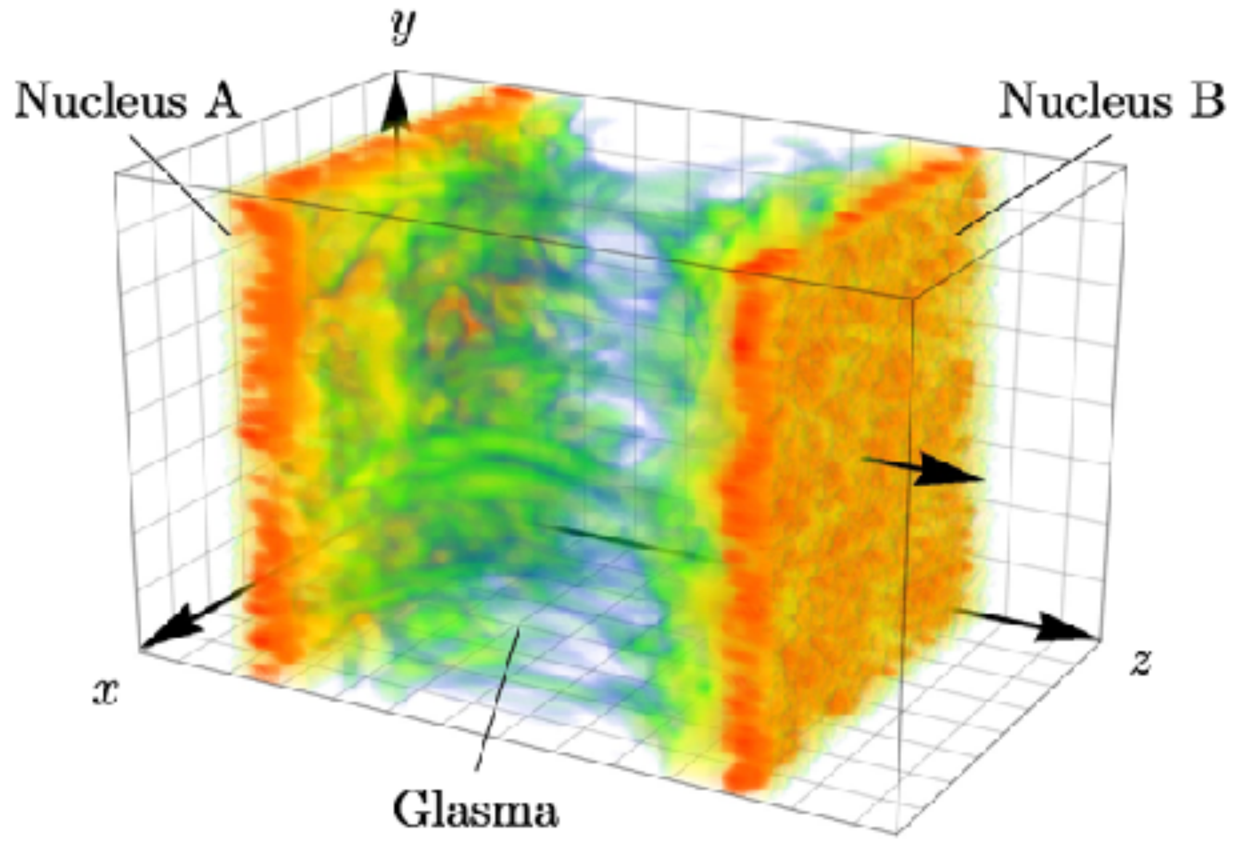


GLASMA

Large longitudinal "classical" fields

Gluon Dominated

Evolution given by classical CYM

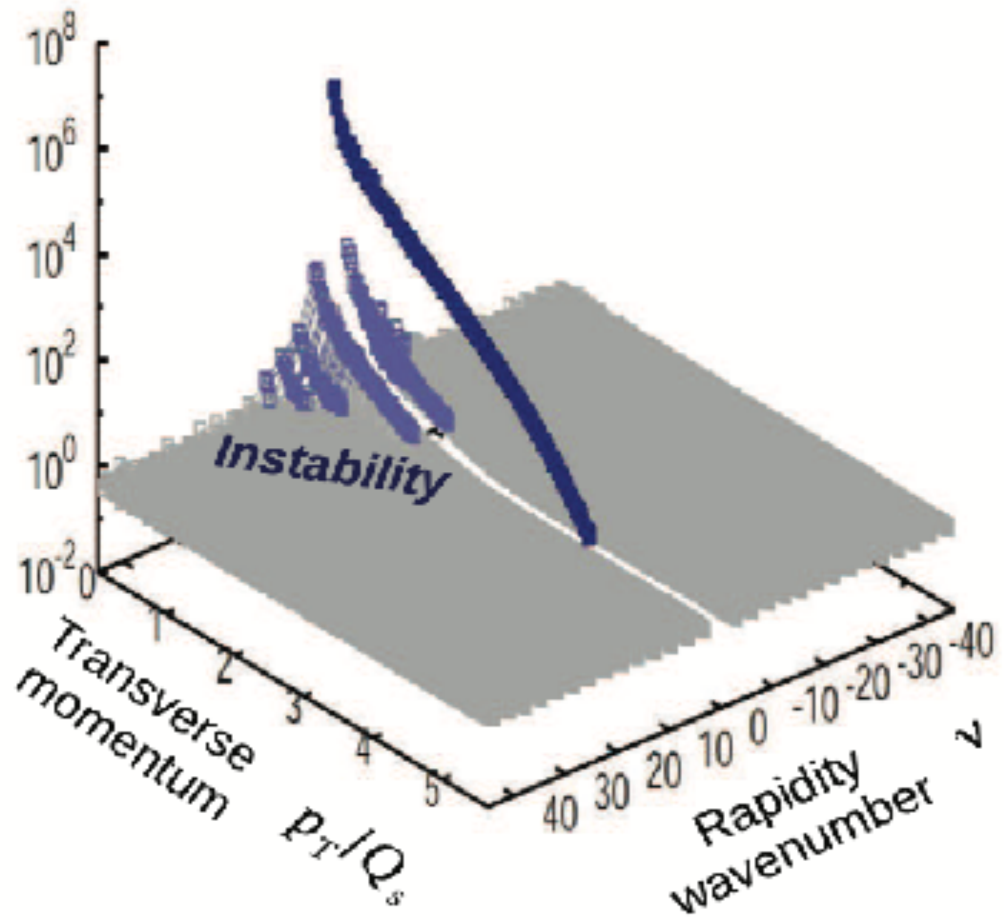


PLB 771 (2017) 74-79

Long. Plasma Instabilities

From boost-invariant Glasma $(p_z \approx 0)$ to highly occupied plasma $(|p_z| > 0)$

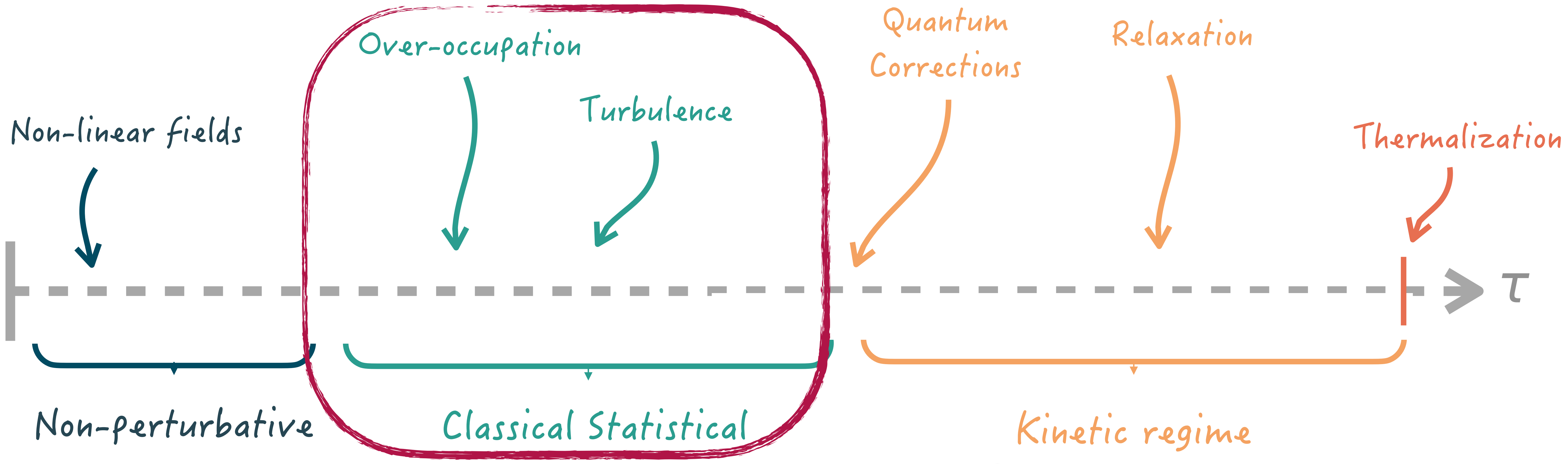
$1 < Q_s \tau < \log^2(\alpha_s^{-1})$

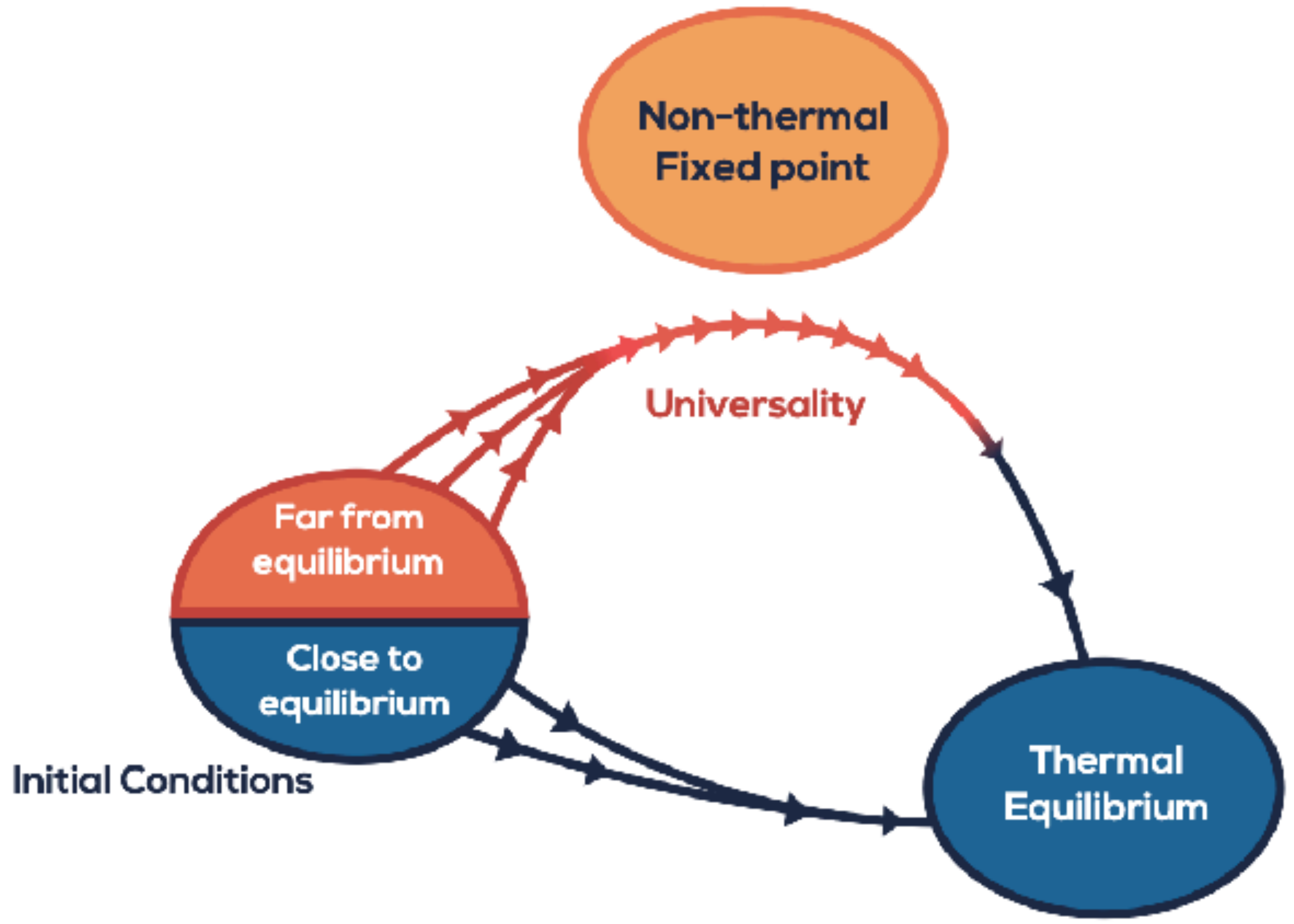


NPA 931 (2014) 348-353
JHEP 05 (2014) 054

PRE-EQUILIBRIUM DYNAMICS: TURBULENT THERMALIZATION

How does one go from an **extremely violent** event turn into a nicely thermalized fluid?





Non-thermal fixed point

def. Parametrically long self-similar regime quantum fields under go in their way to Thermal Equilibrium

Self - Similarity

def. distribution function depends on a Universal, time-independent function

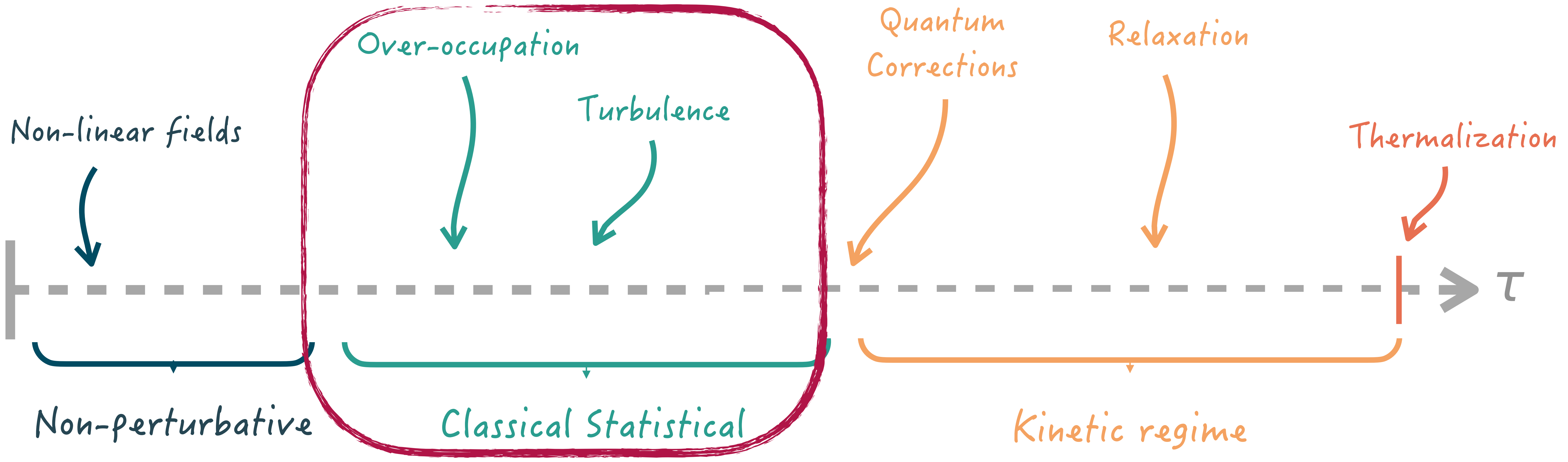
$$f(t,p) = t^{\alpha} f_S(p_{\perp} t^{\beta}, p_z t^{\gamma})$$

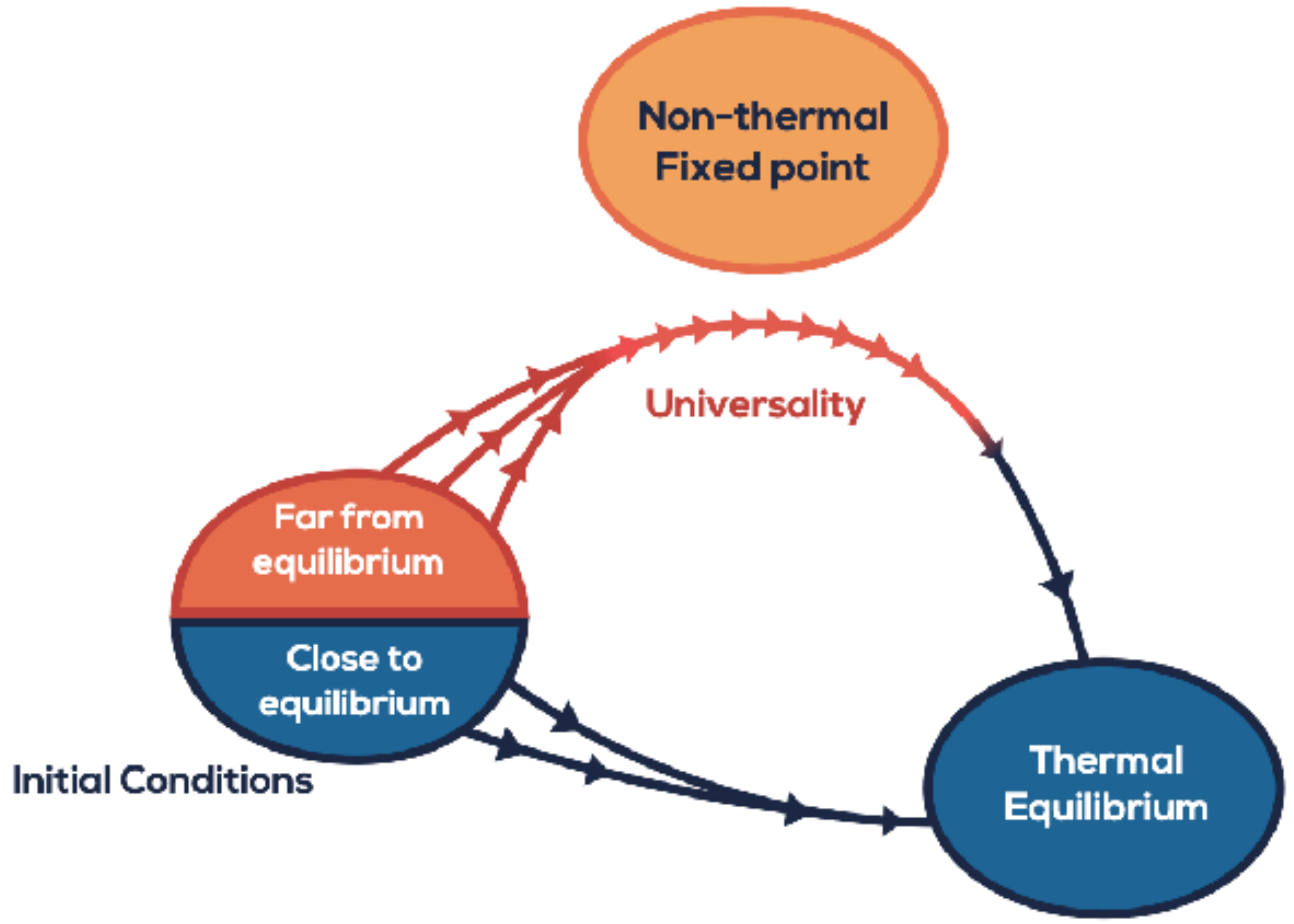
Transport and Turbulence

def. Local flow of conserved charges to accommodate better the total corresponding charge. The flow is turbulent when is self-similar

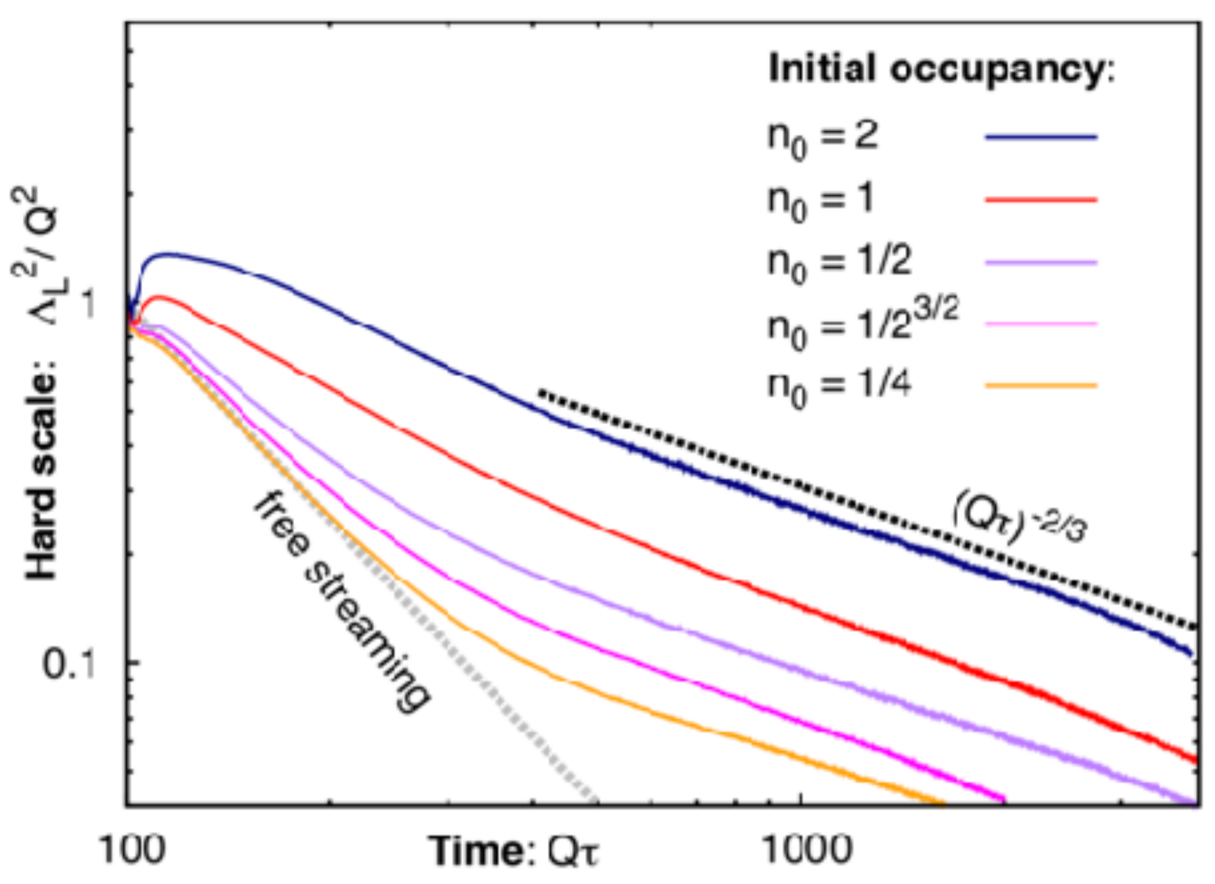
PRE-EQUILIBRIUM DYNAMICS: TURBULENT THERMALIZATION

How does one go from an **extremely violent** event turn into a nicely thermalized fluid?

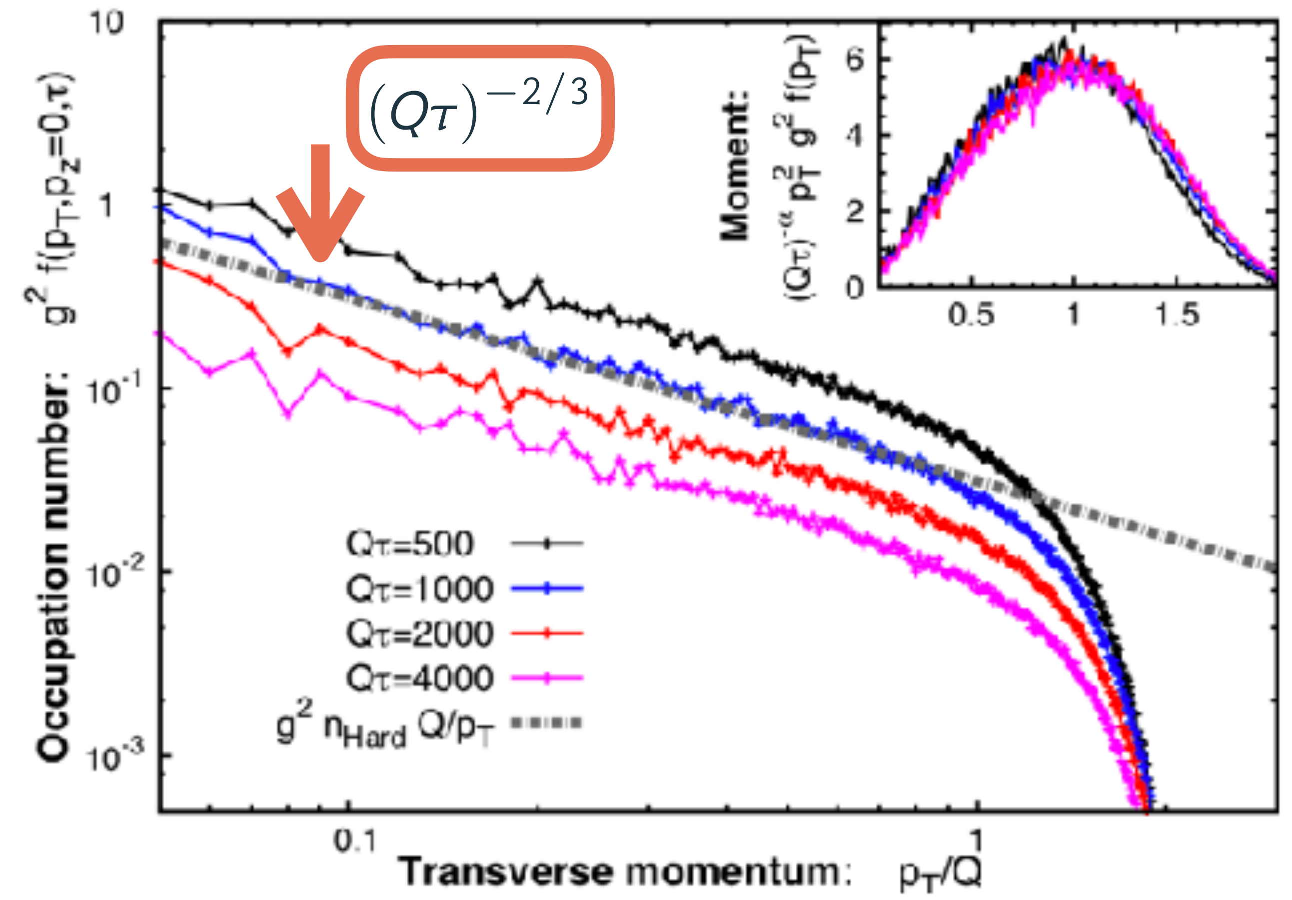




Hard Scale: $\Lambda_L^2 \sim \langle p_z \rangle^2$



Transverse $p_\perp$



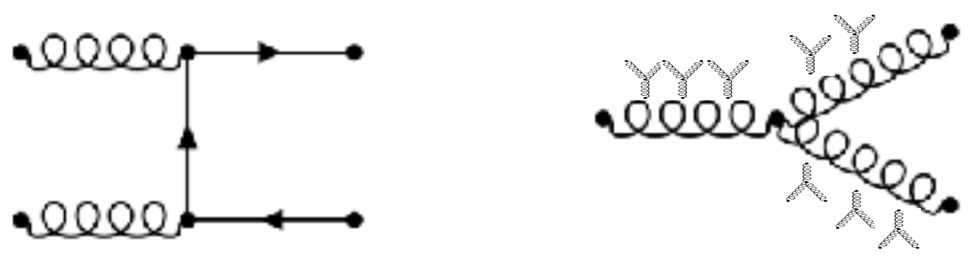
$$f(t,p) = t^{\alpha} f_S(p_\perp t^{\beta}, p_z t^{\gamma})$$

$\alpha = -2/3 \quad \beta = 0 \quad \gamma = 1/3$

THE KINETIC STAGE: BOTTOM-UP THERMALIZATION

Thermalisation can be tracked using AMY Kinetic Theory

$$-\frac{d}{d\tau} f_p = C_{2\leftrightarrow 2}[f_p] + C_{1\leftrightarrow 2}[f_p] + C_{exp}[f_p]$$



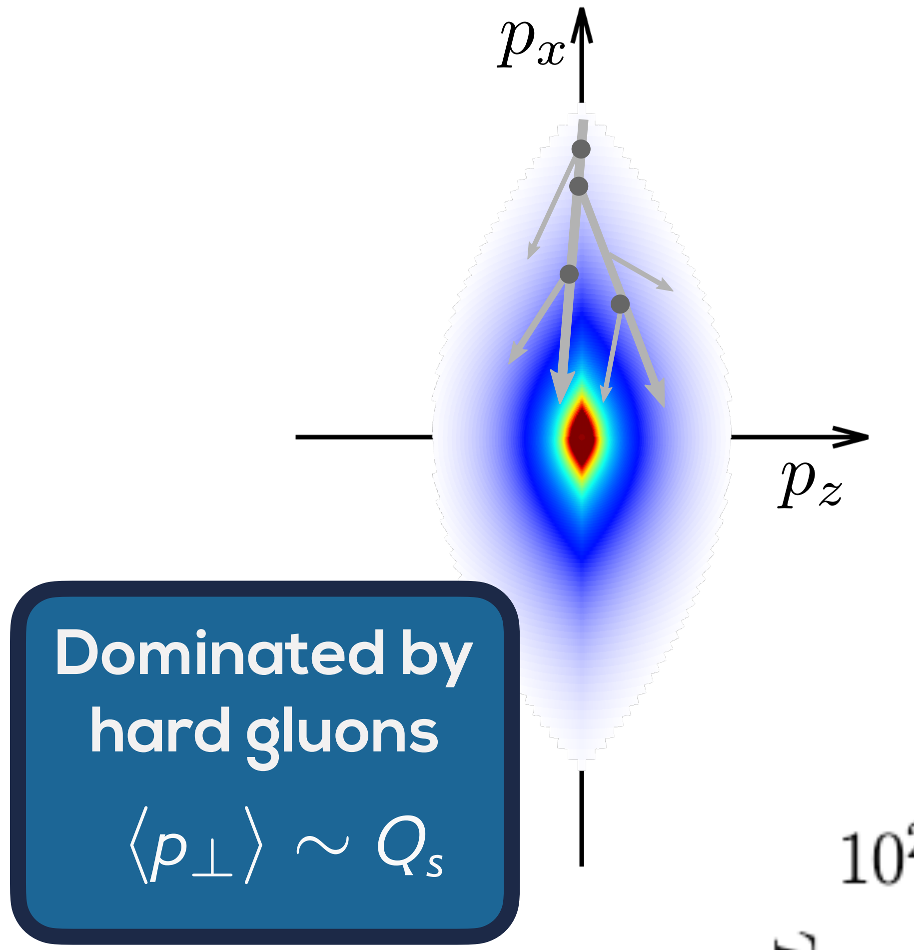
Effective effect of expansion

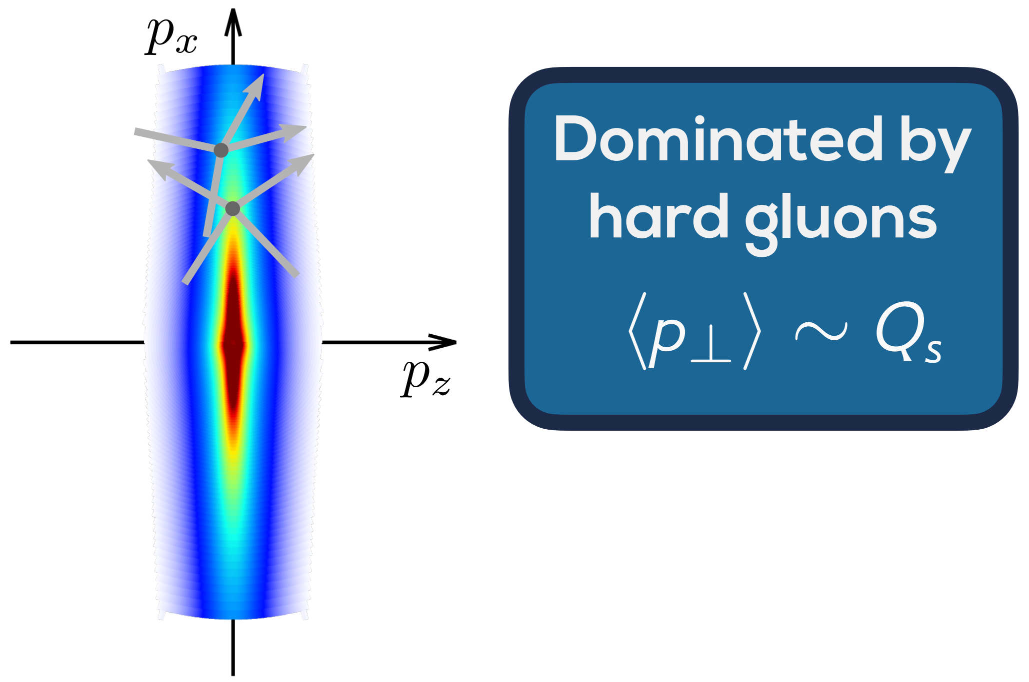
3 stages of **bottom-up thermalization**

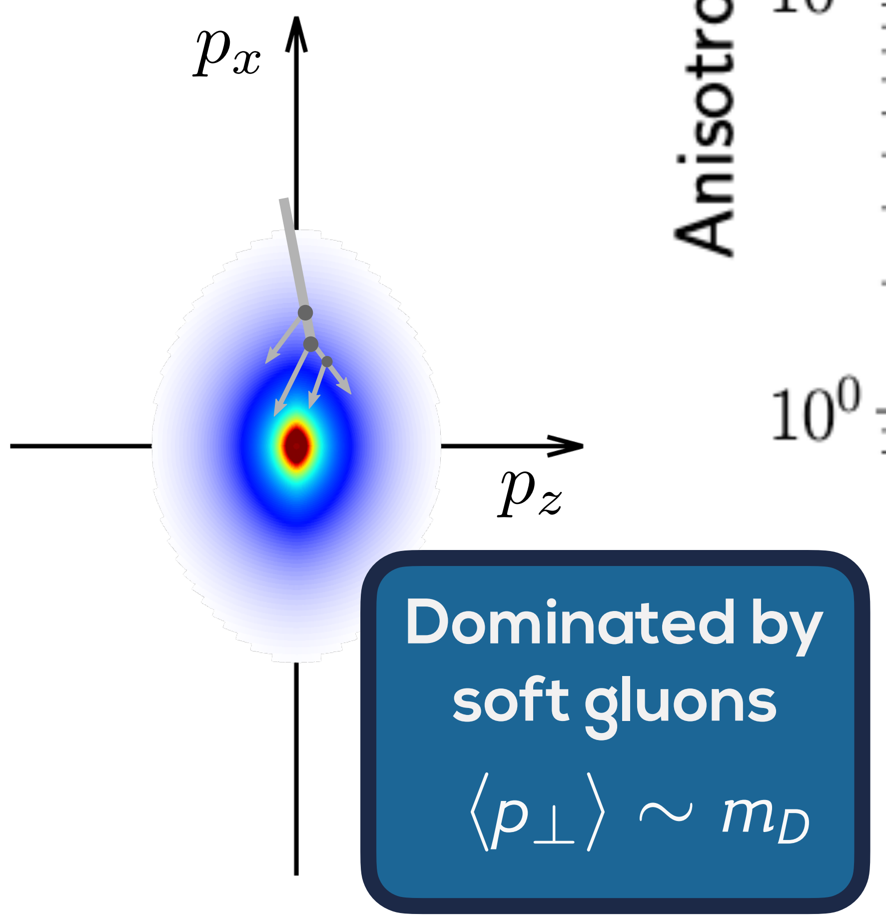
1. Classical field stage: (o → ★)
   growing anisotropy of hard $\sim Q_s$ modes
2. Bath of soft particles develops (★→ ●)
3. Radiative breakup of hard particles (● → ▼)

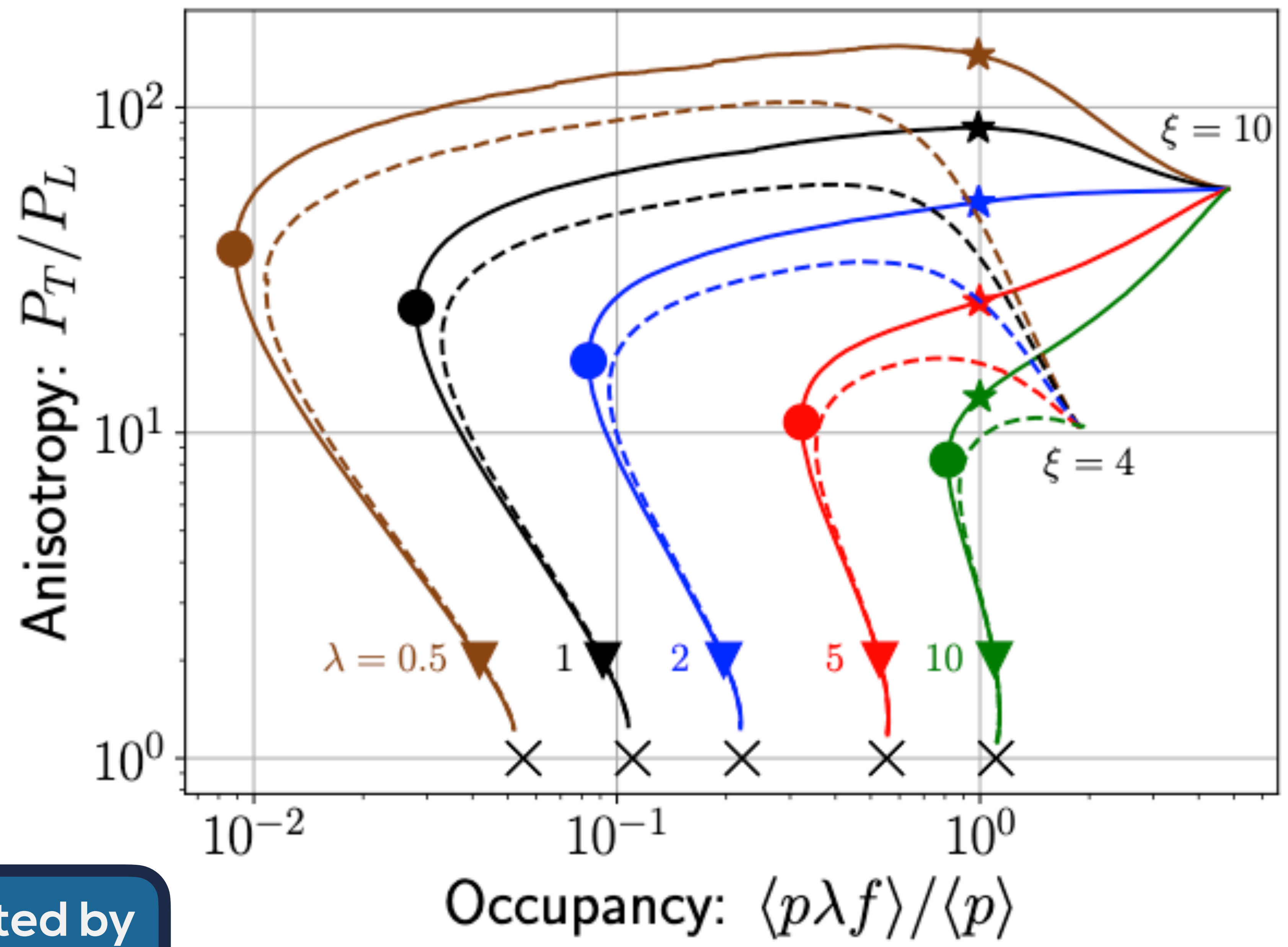
Thermalisation time $\Rightarrow \tau_{BMSS} = \alpha_s^{-13/5} Q_s^{-1}$

Baier, Mueller, Schiff, Son (BMSS)









(ξ: initial anisotropy, $\lambda = 4\pi N_c \alpha_s$)

From Kurkela et al.
Phys.Rev. C99 (2019) no.3, 034910

THE KINETIC STAGE: BOTTOM-UP THERMALIZATION

3 stages of bottom-up thermalization

1. Classical field stage: (o → ★)
   growing anisotropy of hard $\sim Q_s$ modes

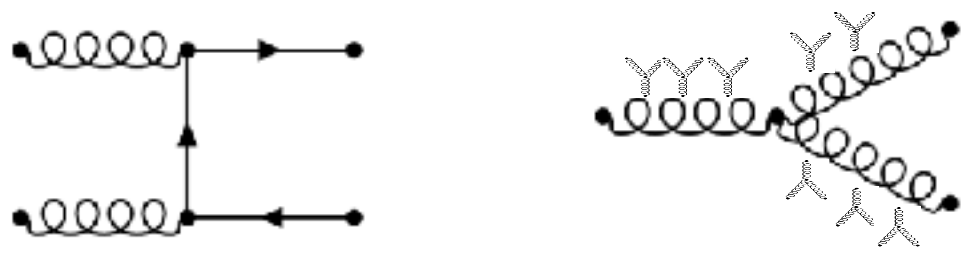
2. Bath of soft particles develops (★→ ●)

3. Radiative breakup of hard particles (● → ▼)

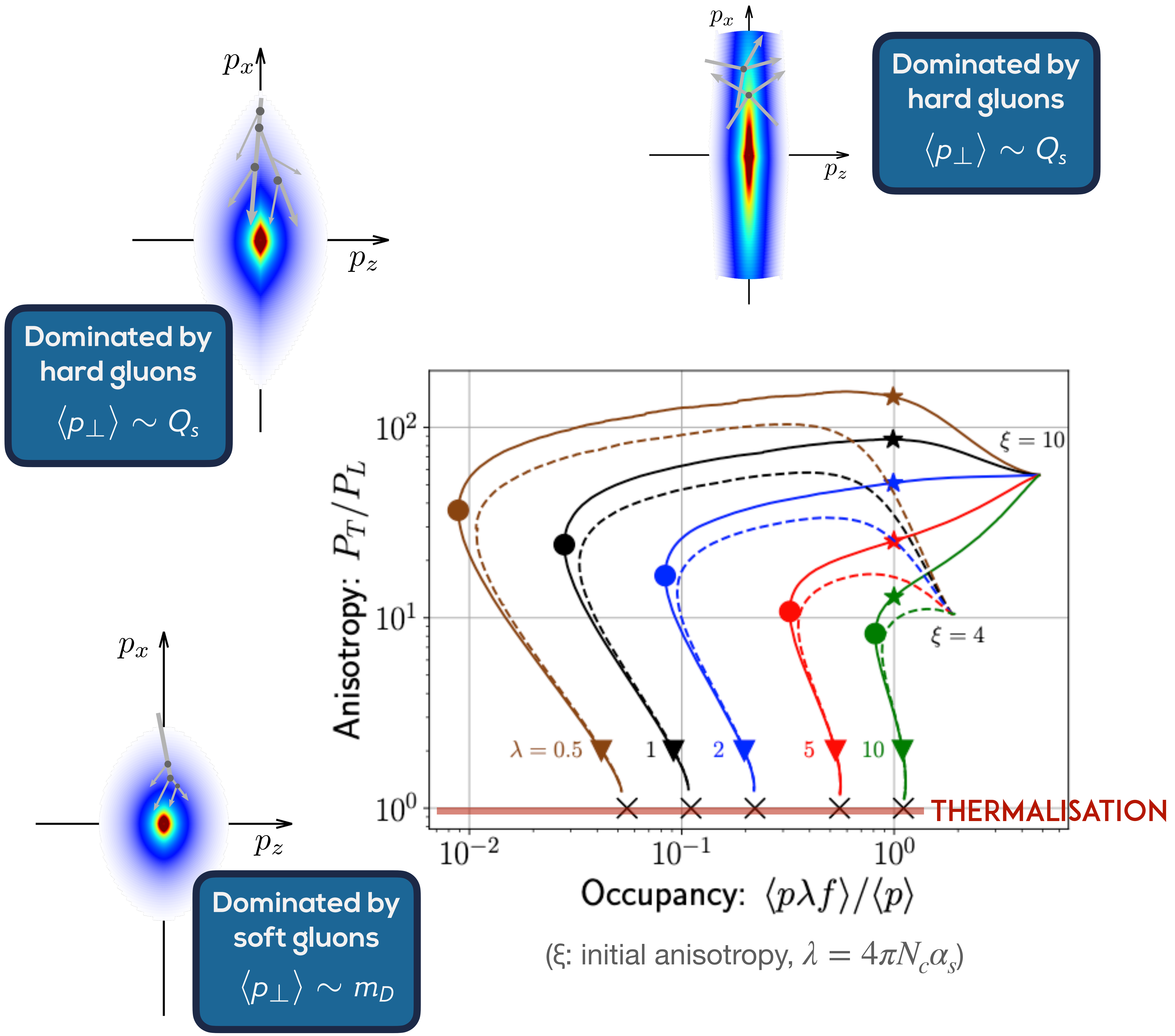
Thermalisation time $\Rightarrow \tau_{BMSS} = \alpha_s^{-13/5}\, Q_s^{-1}$

Thermalisation can be tracked using AMY Kinetic Theory

$$-\frac{d}{d\tau} f_p = C_{2\leftrightarrow 2}[f_p] + C_{1\leftrightarrow 2}[f_p] + C_{exp}[f_p]$$



Effective effect of expansion



(ξ: initial anisotropy, $\lambda = 4\pi N_c \alpha_s$)

Baier, Mueller, Schiff, Son (BMSS)

From Kurkela et al.
Phys.Rev. C99 (2019) no.3, 034910

THE KINETIC STAGE: BOTTOM-UP THERMALIZATION

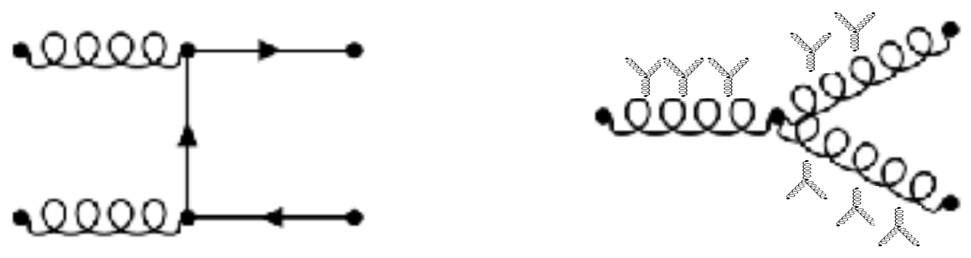
3 stages of bottom-up thermalization

1. Classical field stage: (o → ★)
   growing anisotropy of hard $\sim Q_s$ modes
2. Bath of soft particles develops (★→ ●)
3. Radiative breakup of hard particles (● → ▼)

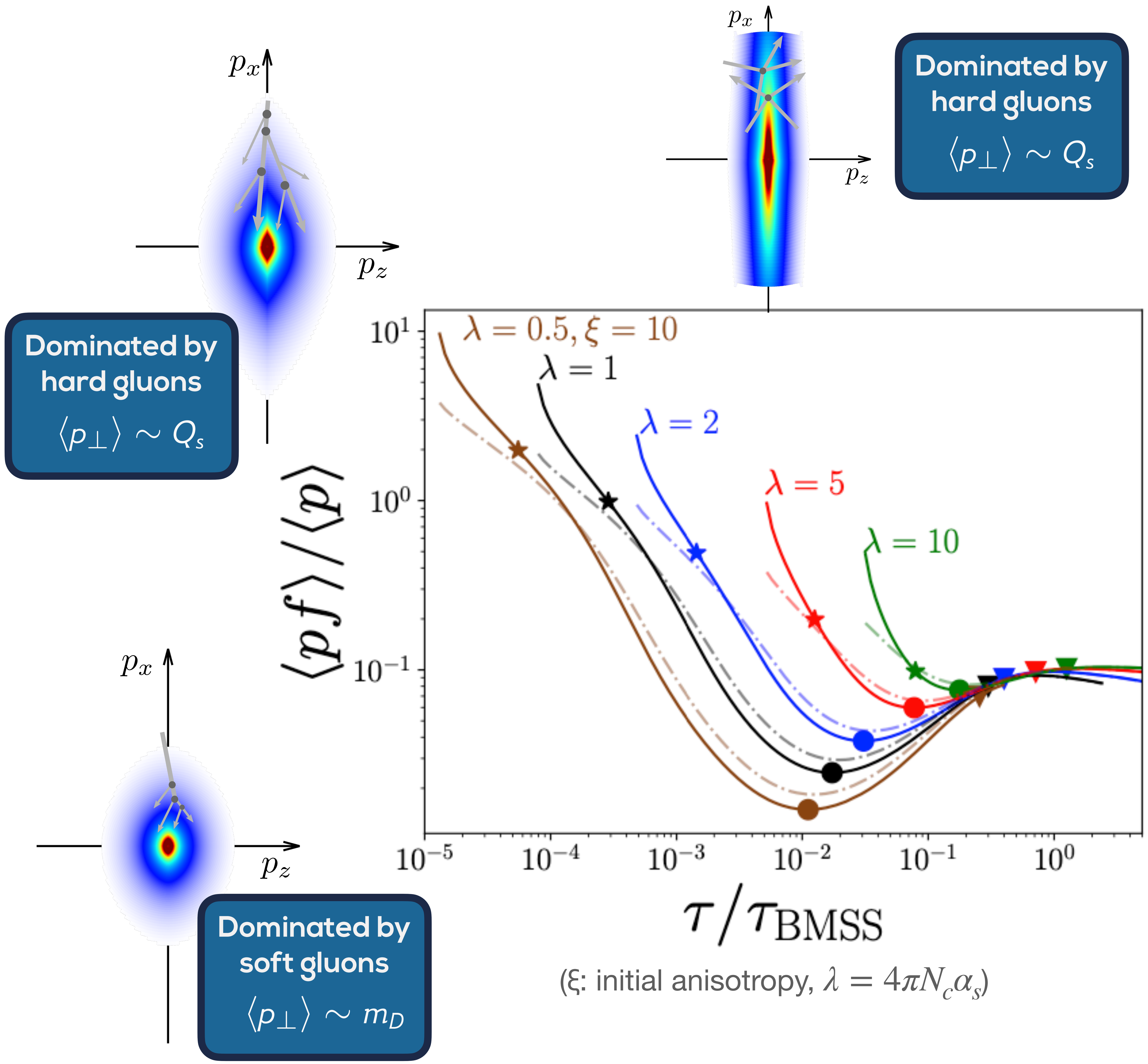
Thermalisation time $\Rightarrow \tau_{BMSS} = \alpha_s^{-13/5}\, Q_s^{-1}$

Thermalisation can be tracked using AMY Kinetic Theory

$$-\frac{d}{d\tau} f_p = C_{2\leftrightarrow 2}[f_p] + C_{1\leftrightarrow 2}[f_p] + C_{exp}[f_p]$$



Effective effect of expansion



(ξ: initial anisotropy, $\lambda = 4\pi N_c \alpha_s$)

Baier, Mueller, Schiff, Son (BMSS)

From Kurkela et al. Phys.Rev. C99 (2019) no.3, 034910

THE KINETIC STAGE: BOTTOM-UP THERMALIZATION

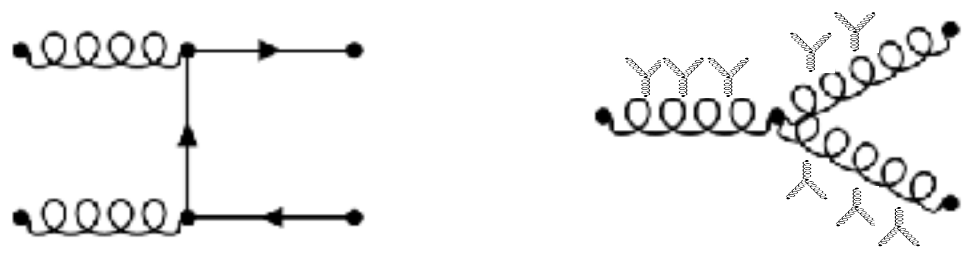
3 stages of bottom-up thermalization

1. Classical field stage: (o → ★)
   growing anisotropy of hard $\sim Q_s$ modes
2. Bath of soft particles develops (★→ ●)
3. Radiative breakup of hard particles (●→ ▼)

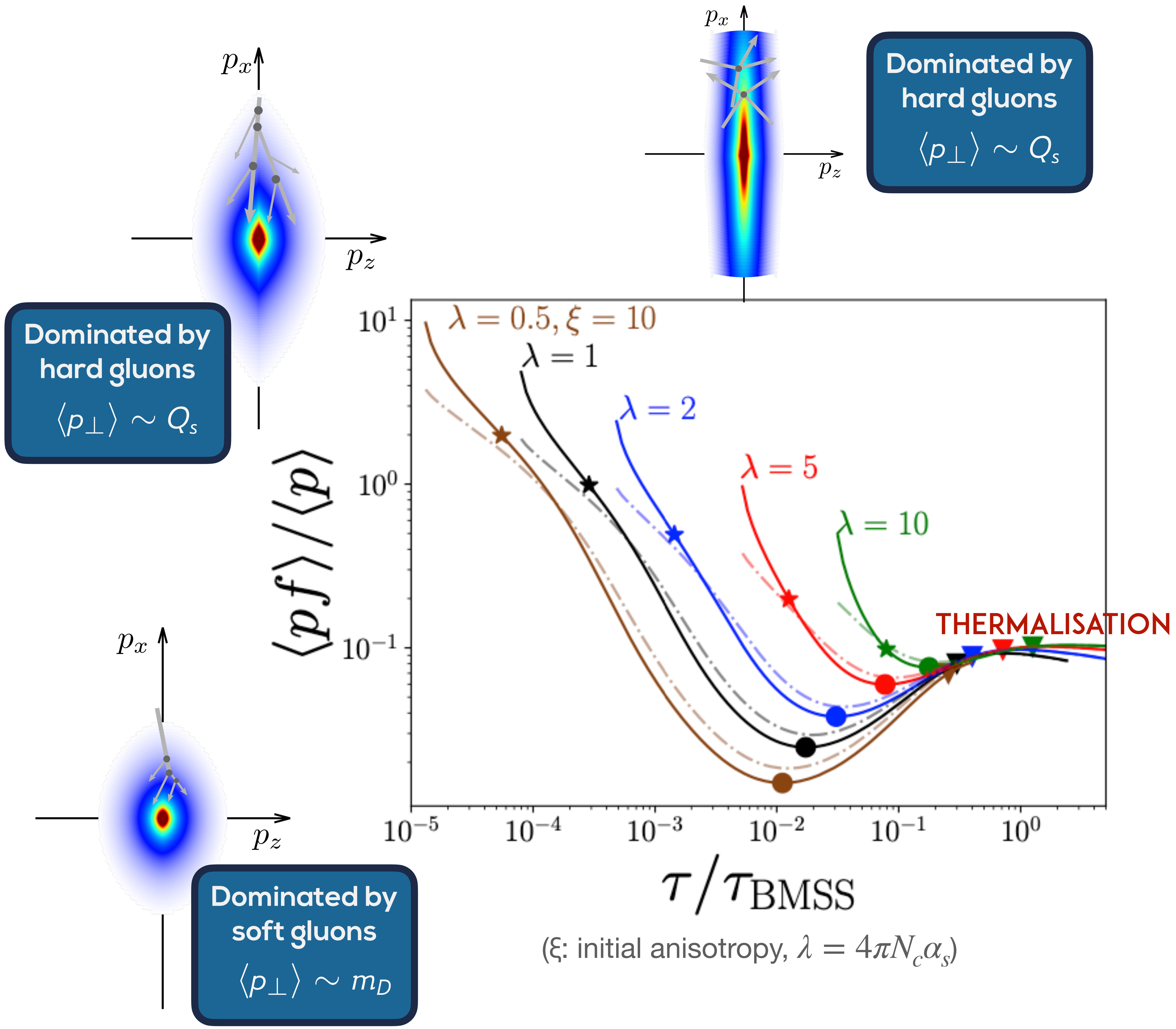
Thermalisation time $\Rightarrow \tau_{BMSS} = \alpha_s^{-13/5}\, Q_s^{-1}$

Thermalisation can be tracked using AMY Kinetic Theory

$$-\frac{d}{d\tau} f_p = C_{2\leftrightarrow 2}[f_p] + C_{1\leftrightarrow 2}[f_p] + C_{exp}[f_p]$$



Effective effect of expansion



Baier, Mueller, Schiff, Son (BMSS)

From Kurkela et al.
Phys.Rev. C99 (2019) no.3, 034910

QGP stage: the hottest fluid in existence

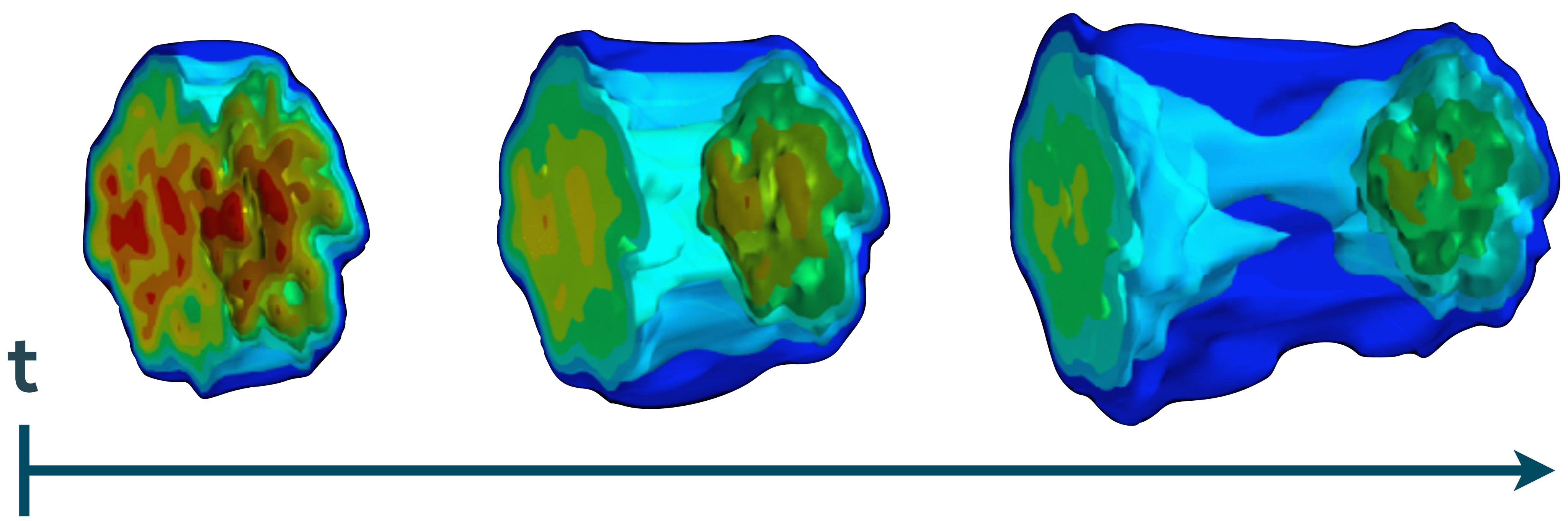
Another FAQ:

Q: Why is a system with some O(100) particles hydrodynamical?

A: Uff, tough question, but! The nucleon assessment is not the full story → Parton density!

Q: What characterizes a hydrodynamical system

A: Hydro is conservation of charges + constituent eqs. (Thermodynamics)



$$\partial_\mu T^{\mu\nu} = 0 \quad \text{and} \quad \partial_\mu N_i^\mu = 0 \quad \text{with} \quad i = Q, B, S$$

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (p + \Pi)\,\Delta^{\mu\nu} + 2\,q^{(\mu} q^{\nu)} + \pi^{\mu\nu}$$

- Energy density
- Fluid 4-velocity $u^\mu u_\mu = 1$
- Rest frame pressure
- Bulk viscous pressure $3(p + \Pi) = -\Delta^{\mu\nu} T_{\mu\nu}$
- Heat flux current $u_\mu q^\mu = 0$
- Projector $u_\mu \Delta^{\mu\nu} = 0$
- Shear stress tensor $\pi^\mu{}_\mu = 0$, $u_\mu \pi^{\mu\nu} = 0$

Too many degrees of freedom!
Hydro needs extra knowledge
(assumptions to close the system)

Equation of state $P = P(E, S, N_i)$

Bulk Pressure $\dot{\Pi} = F_{(\zeta,T)}[\Pi, u]$

Shear Stress $\dot{\pi} = F_{(\eta,T)}[\pi, u]$

QGP stage: the hottest fluid in existence

Another FAQ:

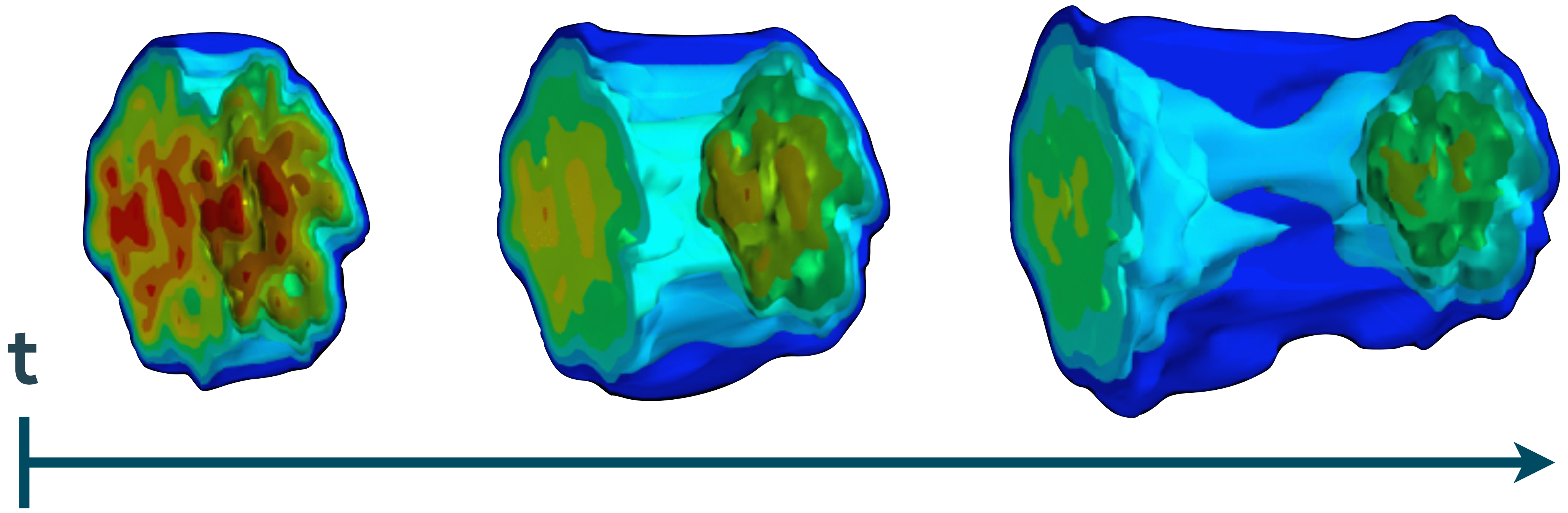
Q: Why is a system with some O(100) particles hydrodynamical?

A: Uff, tough question, but! The nucleon assessment is not the full story → Parton density!

Q: What characterizes a hydrodynamical system

A: Hydro is conservation of charges + constituent eqs.

(Thermodynamics)

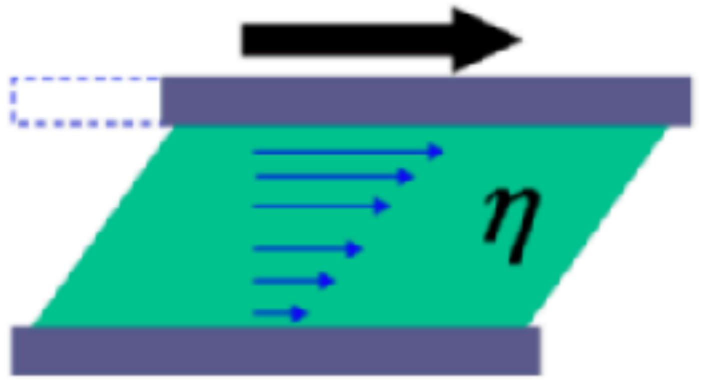


$$\partial_\mu T^{\mu\nu} = 0 \quad \text{and} \quad \partial_\mu N^\mu_i = 0 \quad \text{with} \quad i = Q, B, S$$

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (p + \Pi)\, \Delta^{\mu\nu} + 2\, q^{(\mu} q^{\nu)} + \pi^{\mu\nu}$$

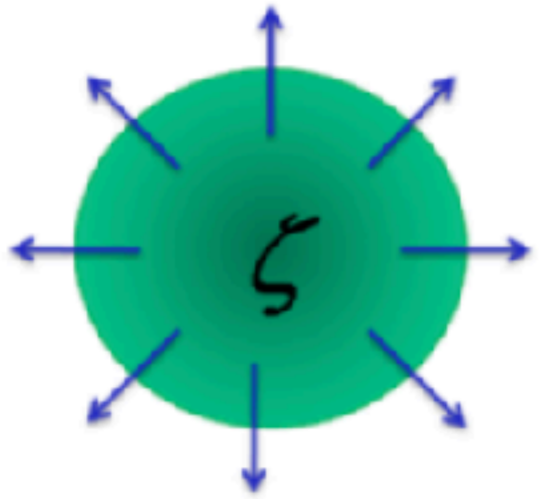
- Energy density
- Fluid 4-velocity: $u^\mu u_\mu = 1$
- Rest frame pressure
- Bulk viscous pressure: $3(p + \Pi) = -\Delta^{\mu\nu} T_{\mu\nu}$
- Projector: $u_\mu \Delta^{\mu\nu} = 0$
- Heat flux current: $u_\mu q^\mu = 0$
- Shear stress tensor: $\pi^\mu{}_\mu = 0$, $u_\mu \pi^{\mu\nu} = 0$

Transport coefficients



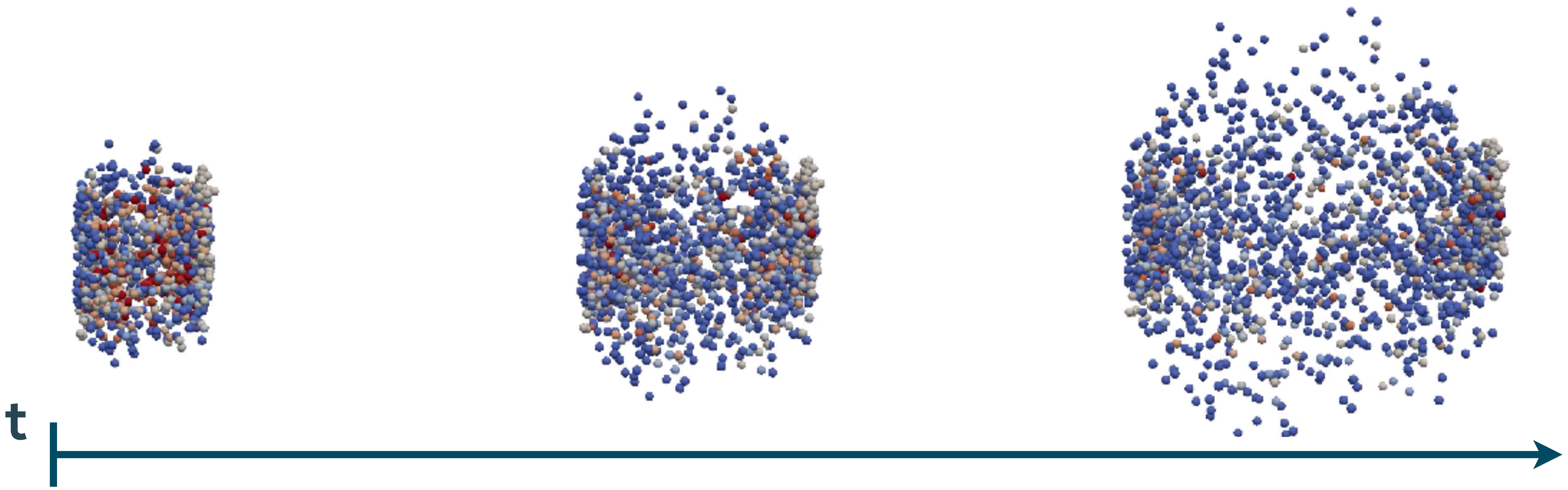
Shear Viscosity
Resistence to flow and ability of momentum transfer

Bulk Viscosity
Resistence to isotropic expansion and dynamics of compressibility of the fluid



The hadronic stage

- After hadronization, one can continue modelling the evolution as a hydrodynamical fluid, or use hadrons as microscopic DoFs.
- Evidence suggests out-equilibrium effects (hadronic rescattering) are important to match data.
- Hadronic non-hydro effects are included using Afterburner Codes
- Particles propagate and collide on the basis of physical cross sections
- Effective solution to Boltzmann equation: $p_\mu \partial^\mu f + m\, \partial_{p_\mu} (F^\mu f)^\mu = C[f]$
- Hadronic transport codes in our collaboration: (SMASH, UrQMD ...)



Now some of the promised

OBSERVABLES

of collective, emergent dynamics

Πάντα ῥεῖ - Everything Flows

- Angular anisotropies found in particle spectra produced in Nucleus-Nucleus collisions

$$\frac{dN}{d^2p_\perp dy} = \frac{1}{2\pi\, p_\perp}\frac{dN}{dp_\perp dy}\left\{1 + 2\sum_i v_i(p_\perp)\cos\left[n(\phi - \Phi_{ev})\right]\right\}$$

(Just a run-of-the-mill Fourier expansion...)

- Flow dynamics signals collectivity, medium creation

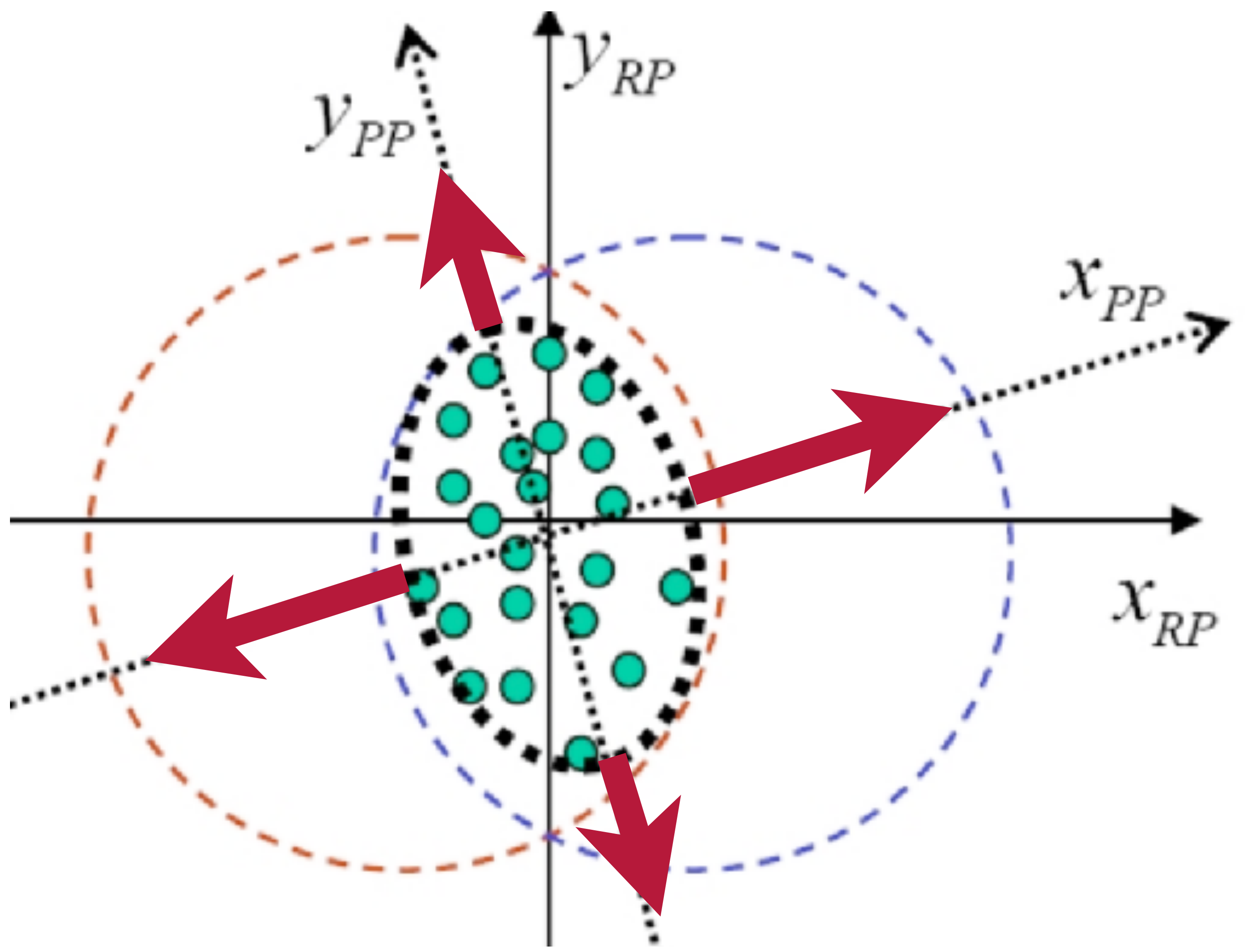
- Why is does this mean collective dynamics?

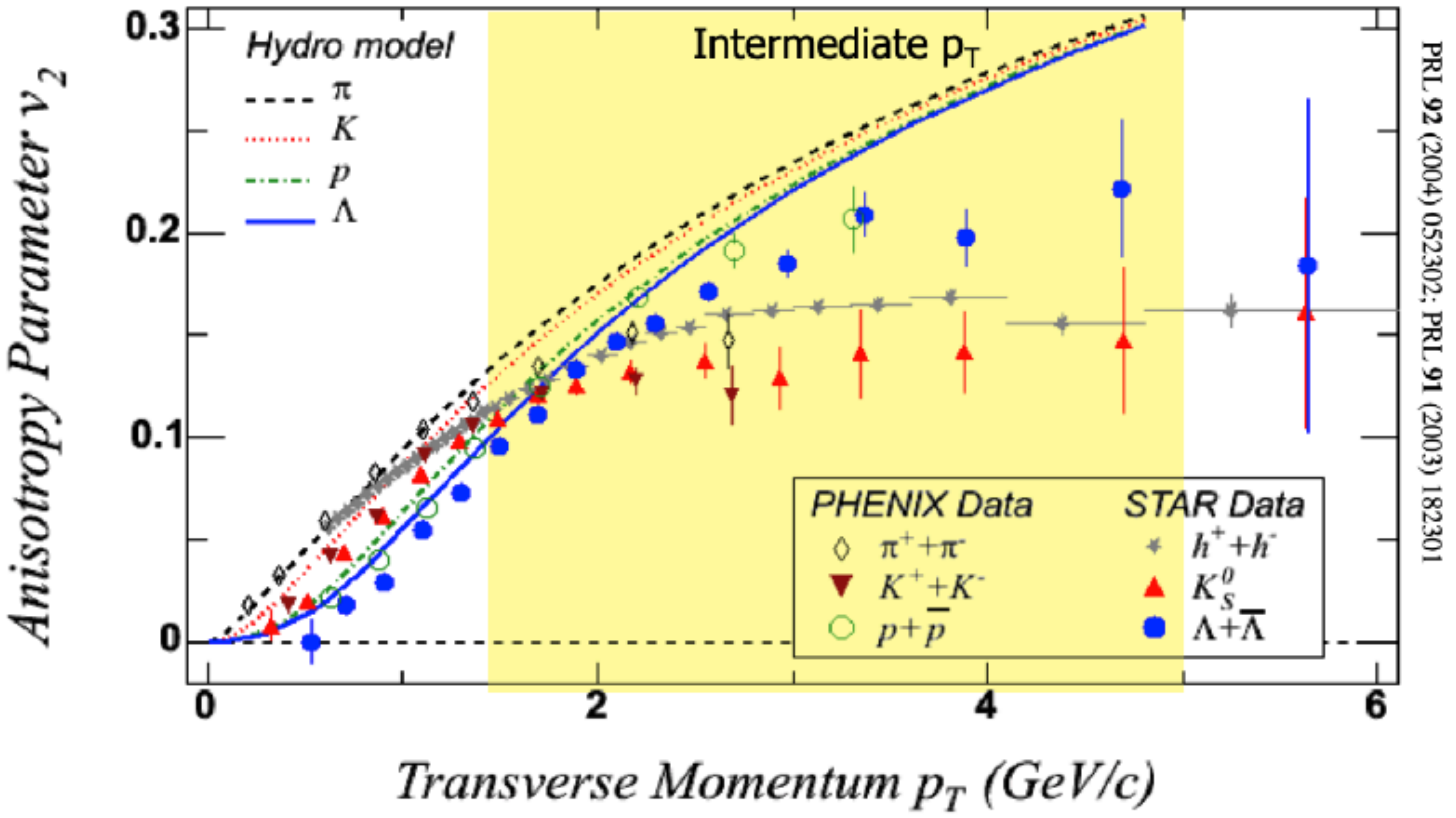
Interactions

$$\varepsilon = \frac{\langle y^2 - x^2\rangle}{\langle y^2 - x^2\rangle} \qquad v_2 = \frac{\langle p_y^2 - p_x^2\rangle}{\langle p_y^2 - p_x^2\rangle}$$

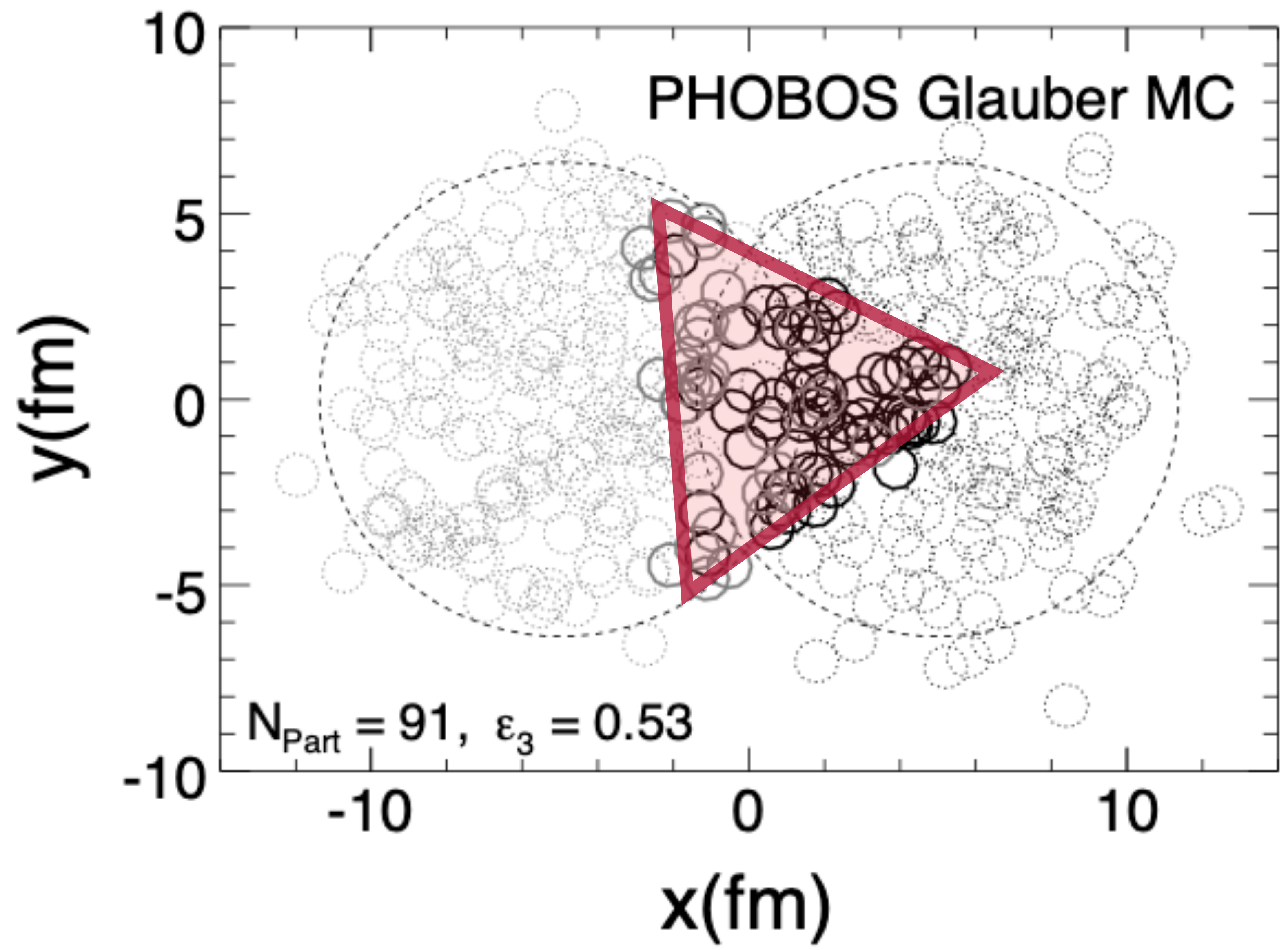
Spatial anisotropy (eccentricity)

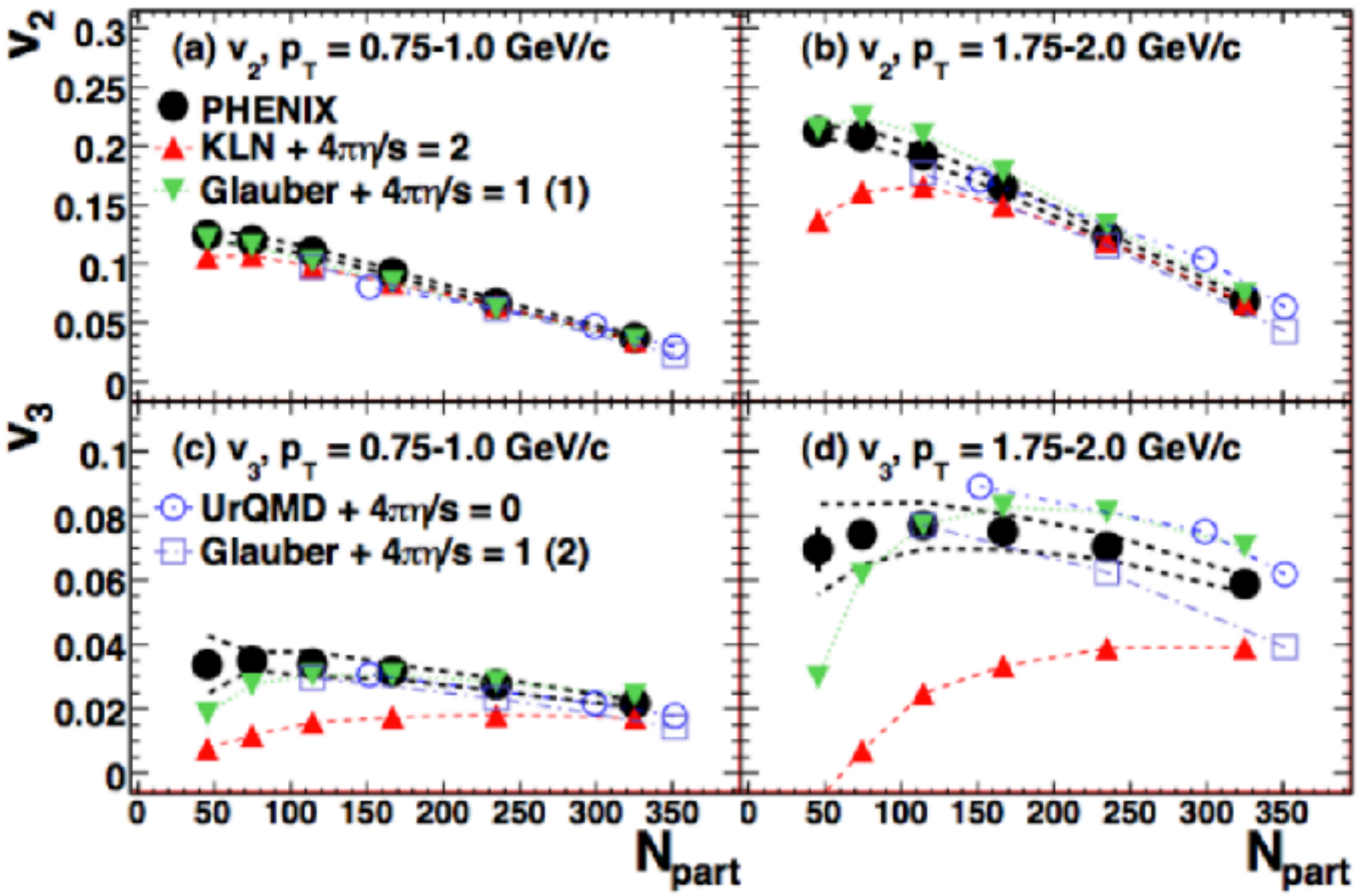
Momentum anisotropy





The initial State: Geometry and Correlations?





Higher flow coefficients have been found to be non-vanishing at RHIC and LHC energies.

What can we learn from these observables?

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 - x^2 \rangle} \quad \longrightarrow \quad v_2 = \frac{\langle p_y^2 - p_x^2 \rangle}{\langle p_y^2 - p_x^2 \rangle}$$

Interactions!!!

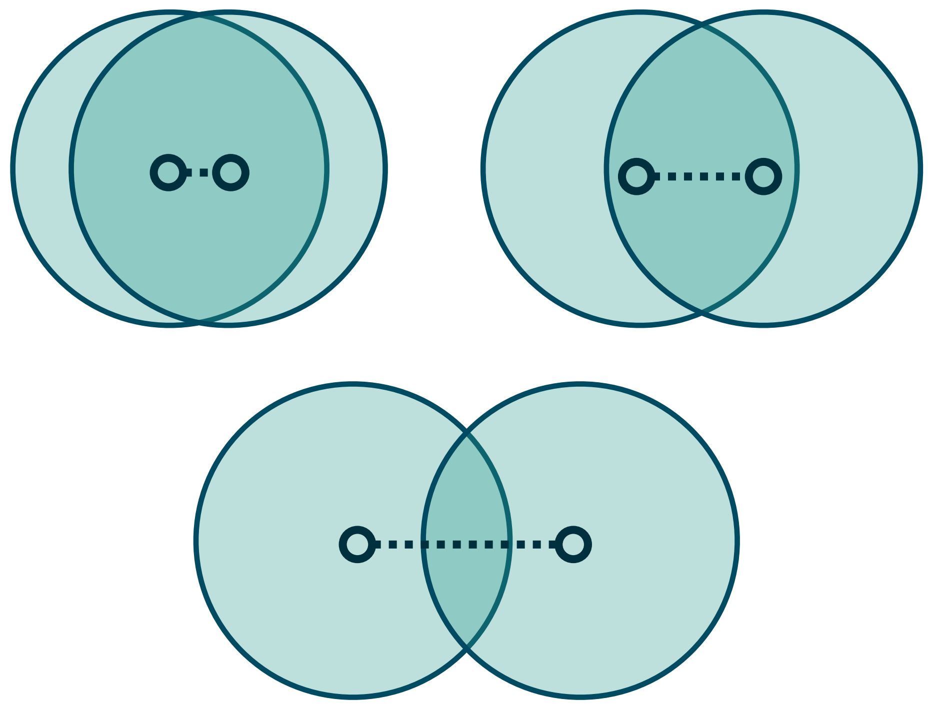
Spatial anisotropy (eccentricity) — Momentum anisotropy

A little intermezzo:
Two useful tools.

Centrality

Organizational variable to organize events by number of particles created $\mathrm{d}N_{ch}/\mathrm{d}y$

Traditional Physical interpretation: overlap area of collision. Basically volume dependence



How to read it?
"A 10-20% observable is the collection of events between the 10 and 20% of the largest particle output"

Nuclear Modification Factor

Way to isolate and compare nuclear effects using the p+p *baseline*.

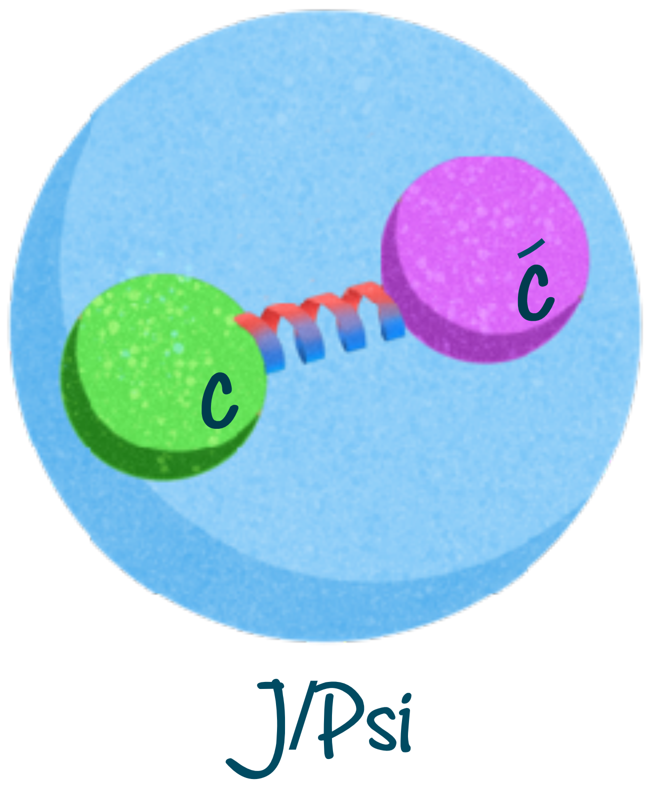
$$R_i = \frac{\mathrm{d}N_i/\mathrm{d}^2p_\perp \mathrm{d}y}{N_{coll}\, \mathrm{d}N_{pp}/\mathrm{d}^2p_\perp \mathrm{d}y} \quad \text{with} \quad i = \{pA, AA\}$$

One needs to rescale with respect N_{coll}, the average number of nucleonic collisions expected from the area overlap.

If $R_i = 1$, then the nuclear collision is a collection of incoherent (uncorrelated) collisions

Quarkonia Suppression

- In-medium screening reduces strength of quark-antiquark bonding
- Suppression is used as a "thermometer"



$$R_i = \frac{dN_i/d^2p_\perp dy}{N_{coll}\, dN_{pp}/d^2p_\perp dy}$$

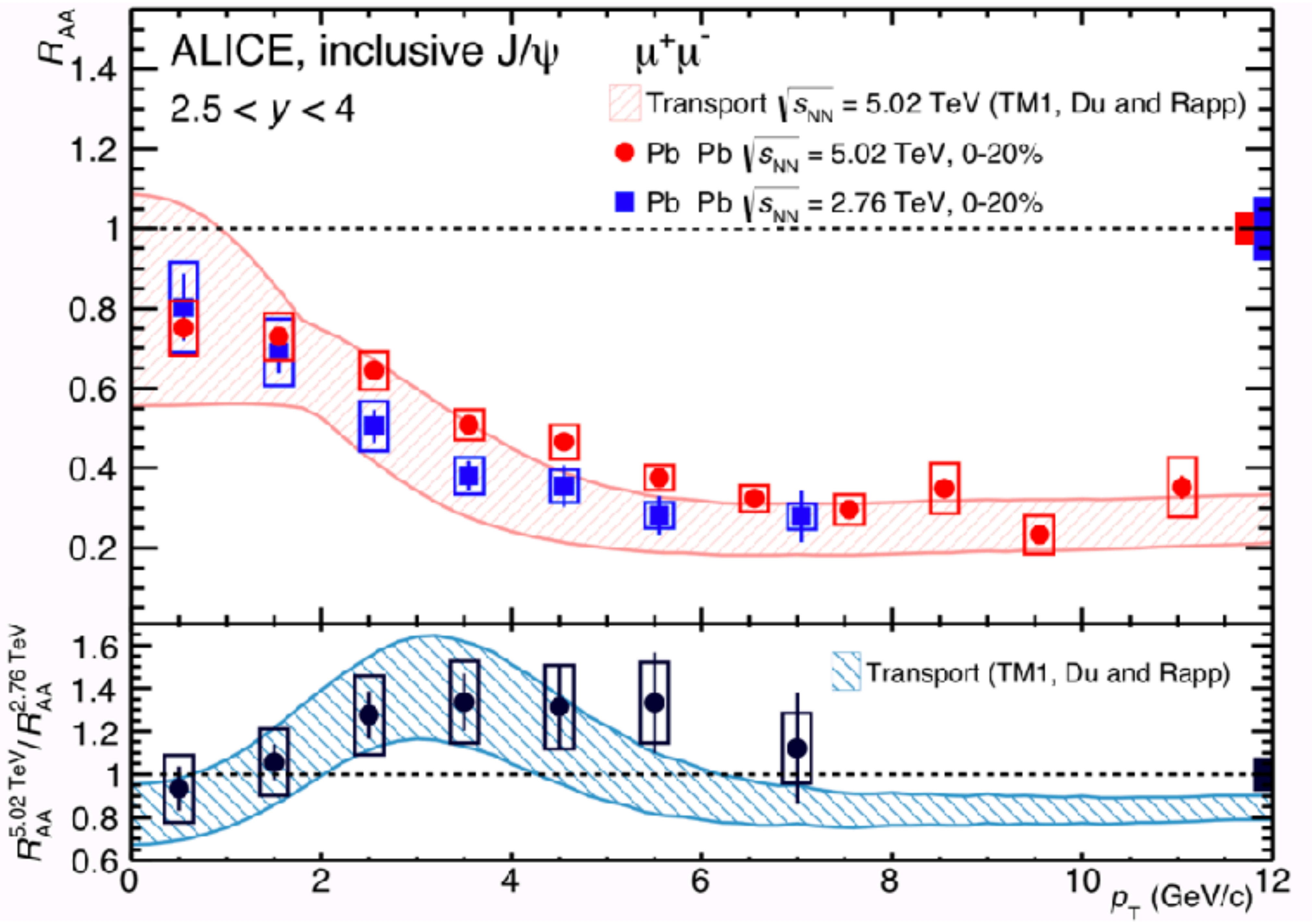


Figure from ALICE collaboration, Phys.Lett. B766 (2017) 212-224

Quarkonia Suppression

- In-medium screening reduces strength of quark-antiquark bonding
- Here in this example, we observe sequential suppression on Υ states.
- Resonances are larger and more weakly bound
- Checking relative suppression of higher mass states can give hints at the temperature of the QGP

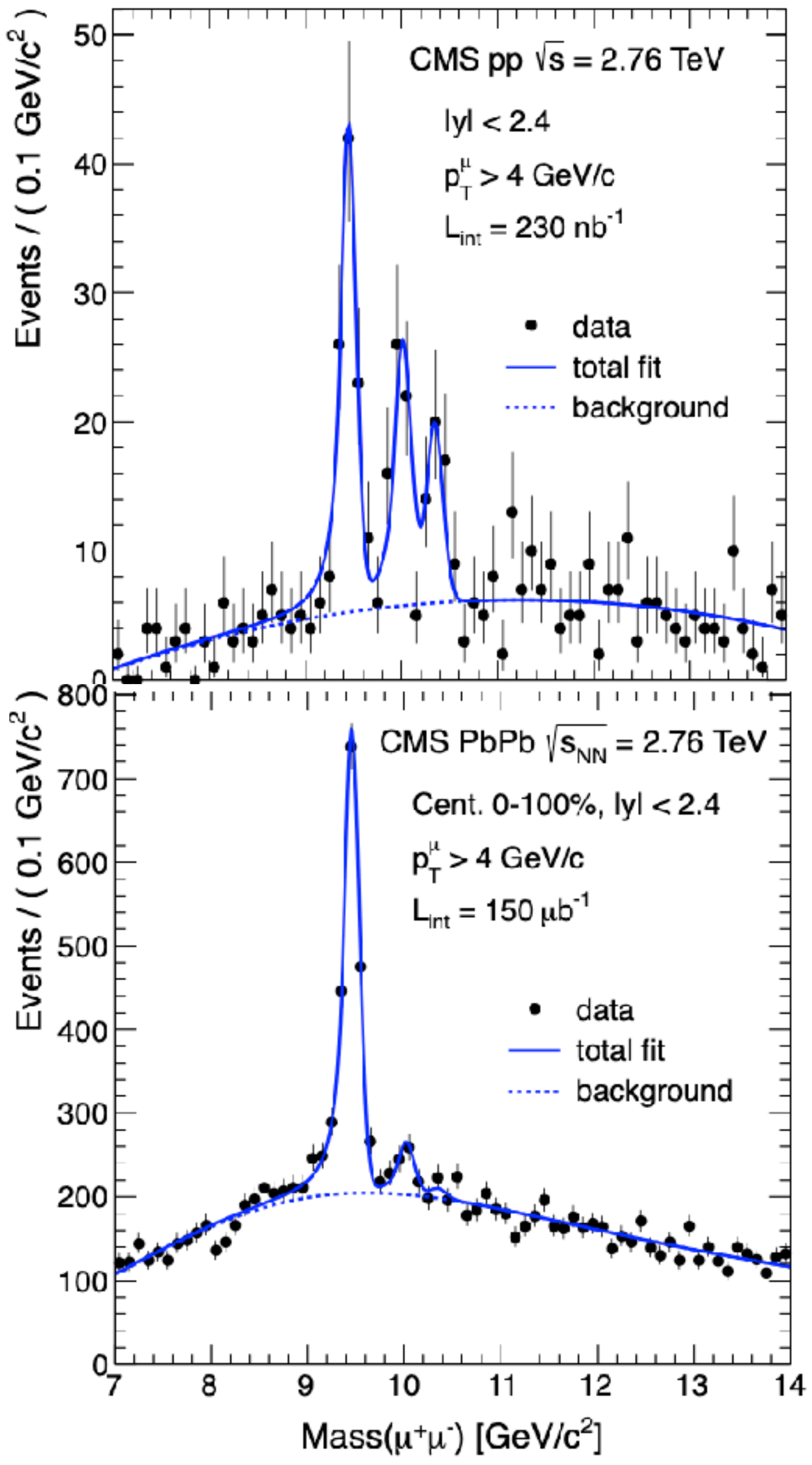
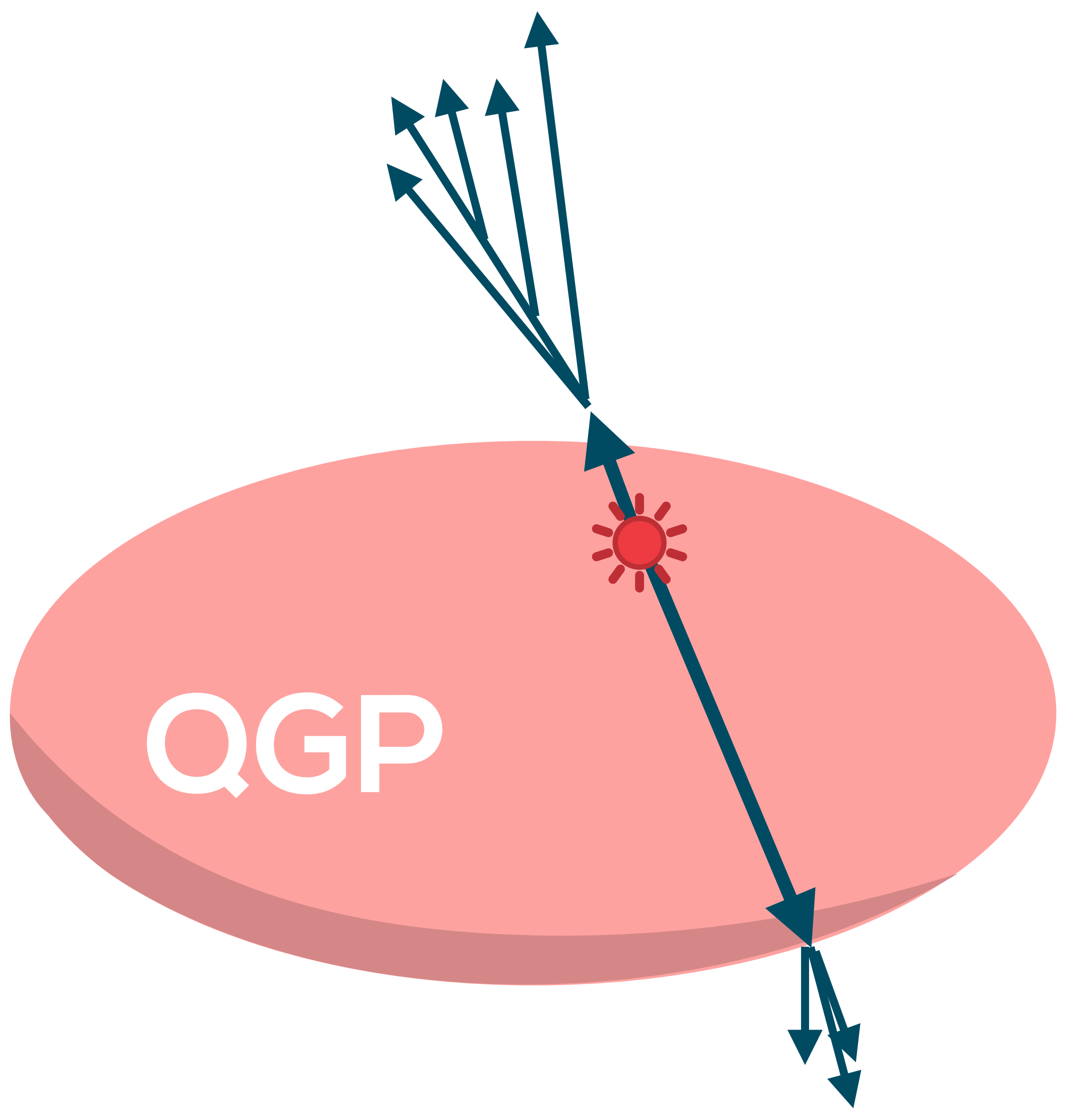


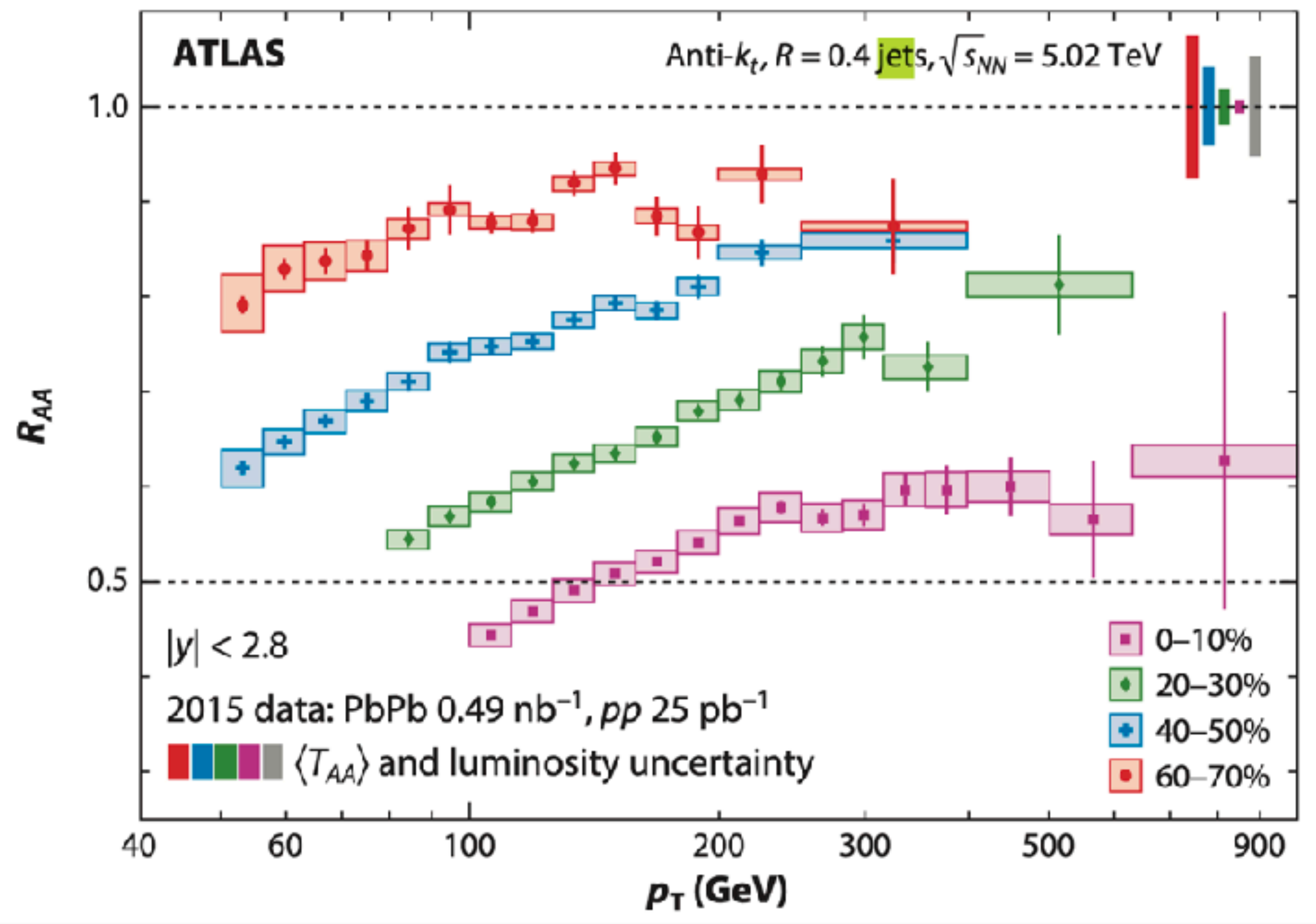
Figure from CMS collaboration, Phys.Rev.Lett. 109 (2012) 222301

Jet Quenching

- Jets are collimated influx of particles produced by highly energetic energetic initial collisions.
- With the production of a medium, jet looses energy to the plasma.
- Nuclear Modification Factor is centrality dependent, which is pretty telling

$$R_i = \frac{dN_i/d^2p_\perp dy}{N_{coll}\, dN_{pp}/d^2p_\perp dy}$$





What can we learn from hot deconfined QCD?

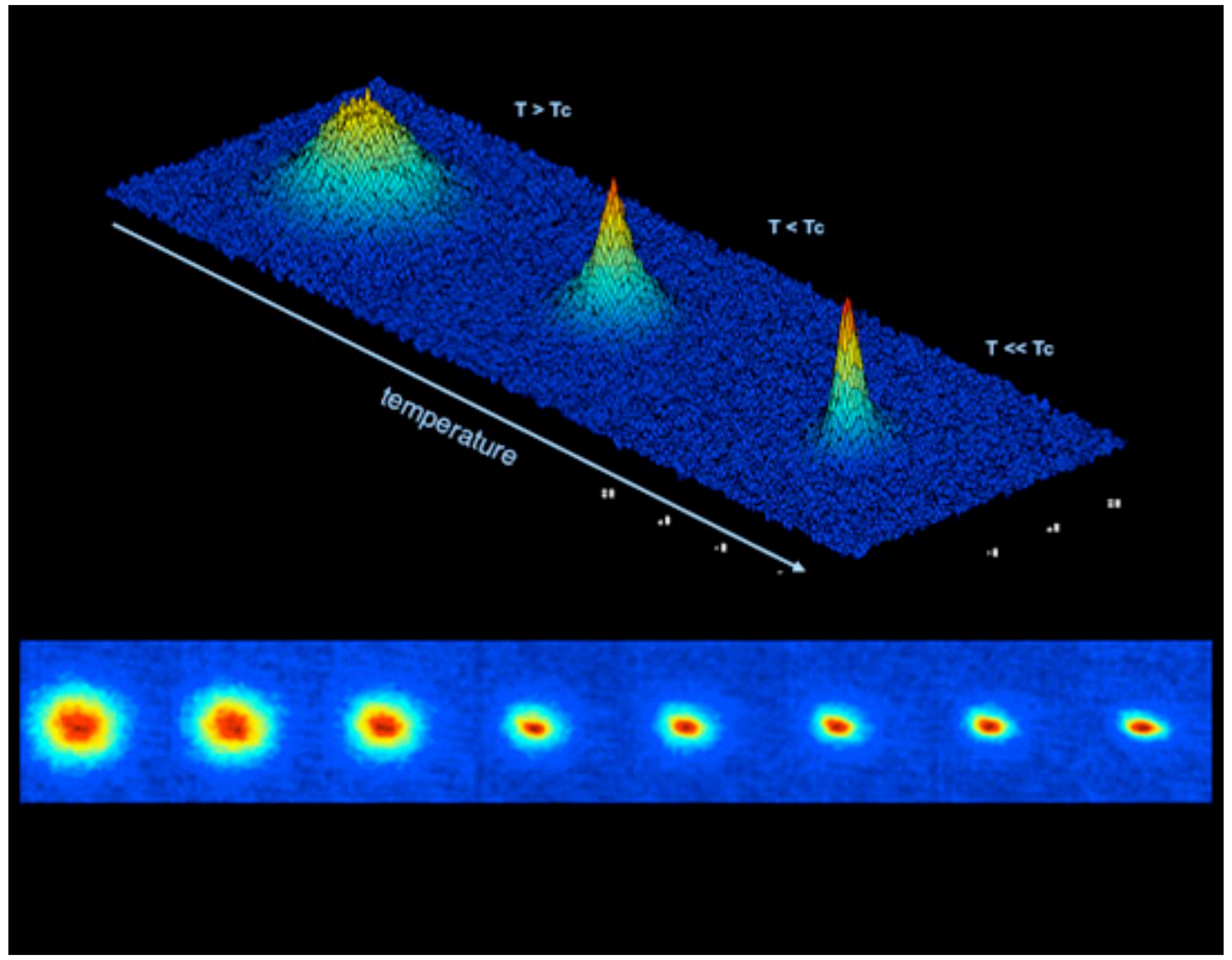
QCD Thermodynamics		Actual measureable quantities
Equation of state ϵ, p, s		Spectra, collective flow, *particle* fluctuations
Speed of sound $c_s^2 = \partial p / \partial \epsilon$		Particle correlations
Shear Viscosity η	Affects →	Anisotropic flow
Bulk Viscosity ζ	← We can learn/extract	Hadronic average momentum
Momentum, energy and charge diffusion coefficients $\hat{q}, \hat{e}, \hat{e}_2$		Parton energy loss/jet fragmentation
Color screening mass m_D^2		Abundance of $q\bar{q}$ (quarkonic) mesonic states

Caveat: Complex Quantum Matter

Heavy ion collisions are creating isolated quantum systems.

Testing the construction of complex quantum matter in the high energy frontier.

Many interesting questions: Entanglement, Non-equilibrium dynamics and thermalization, dynamical phase transitions, and so much more.

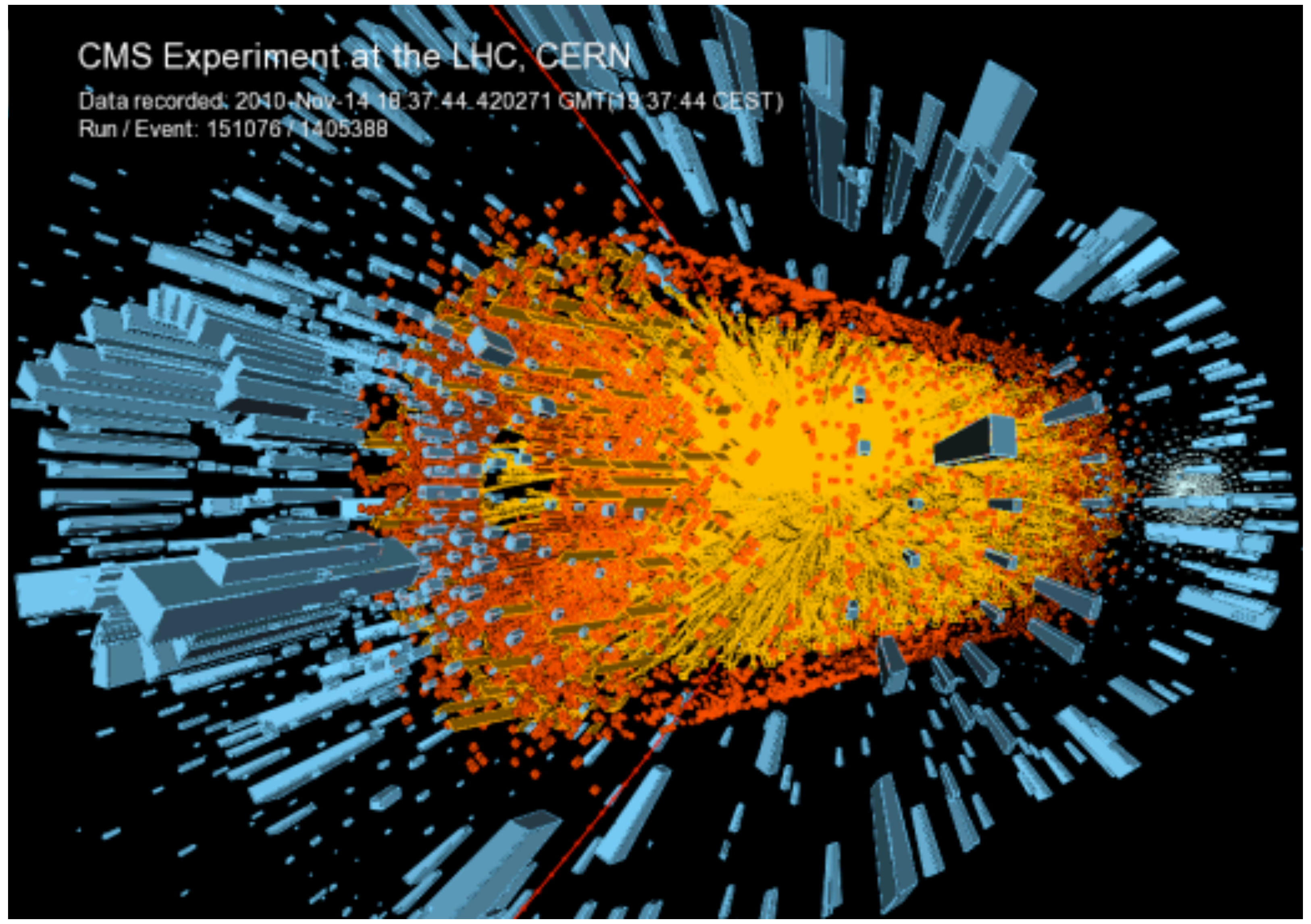


Ultracold Quantum Gases, production of BEC

Understanding quantum dynamics

↔

Throughout scales and many, many orders of magnitude



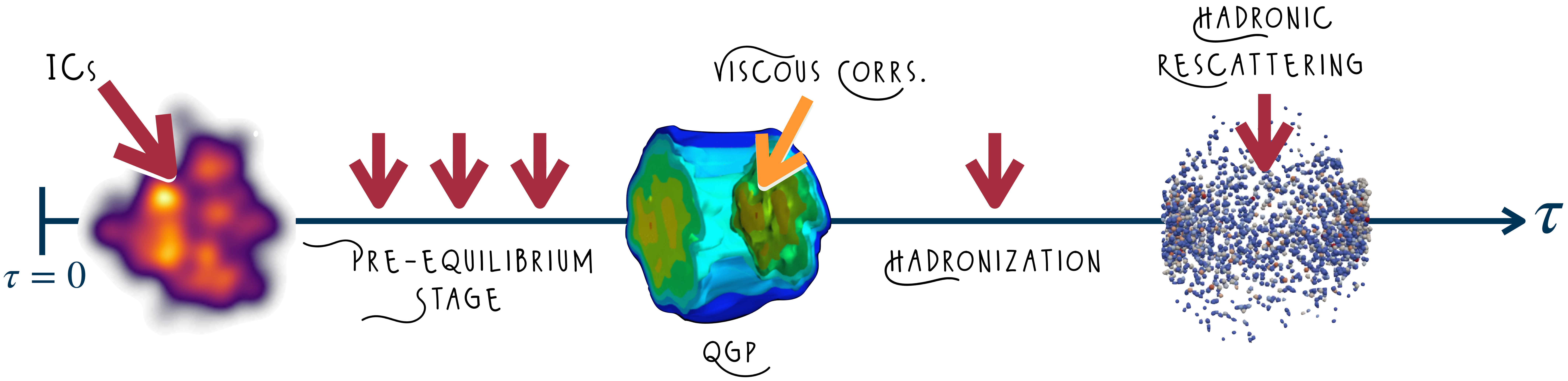
HICS PRODUCE:

A TENOUSLY THERMAL QGP

- Heavy-Ion Collisions create an Isolated Quantum System

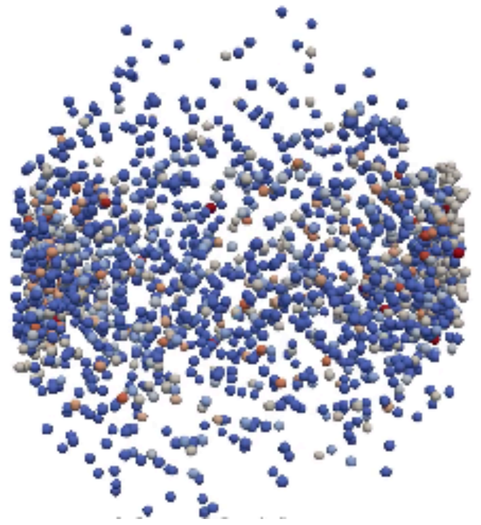
  which is
  - Initially far away from any equilibrium
  - Self-interacting
  - Expanding against the vacuum

- A system battling to thermalize against all odds.



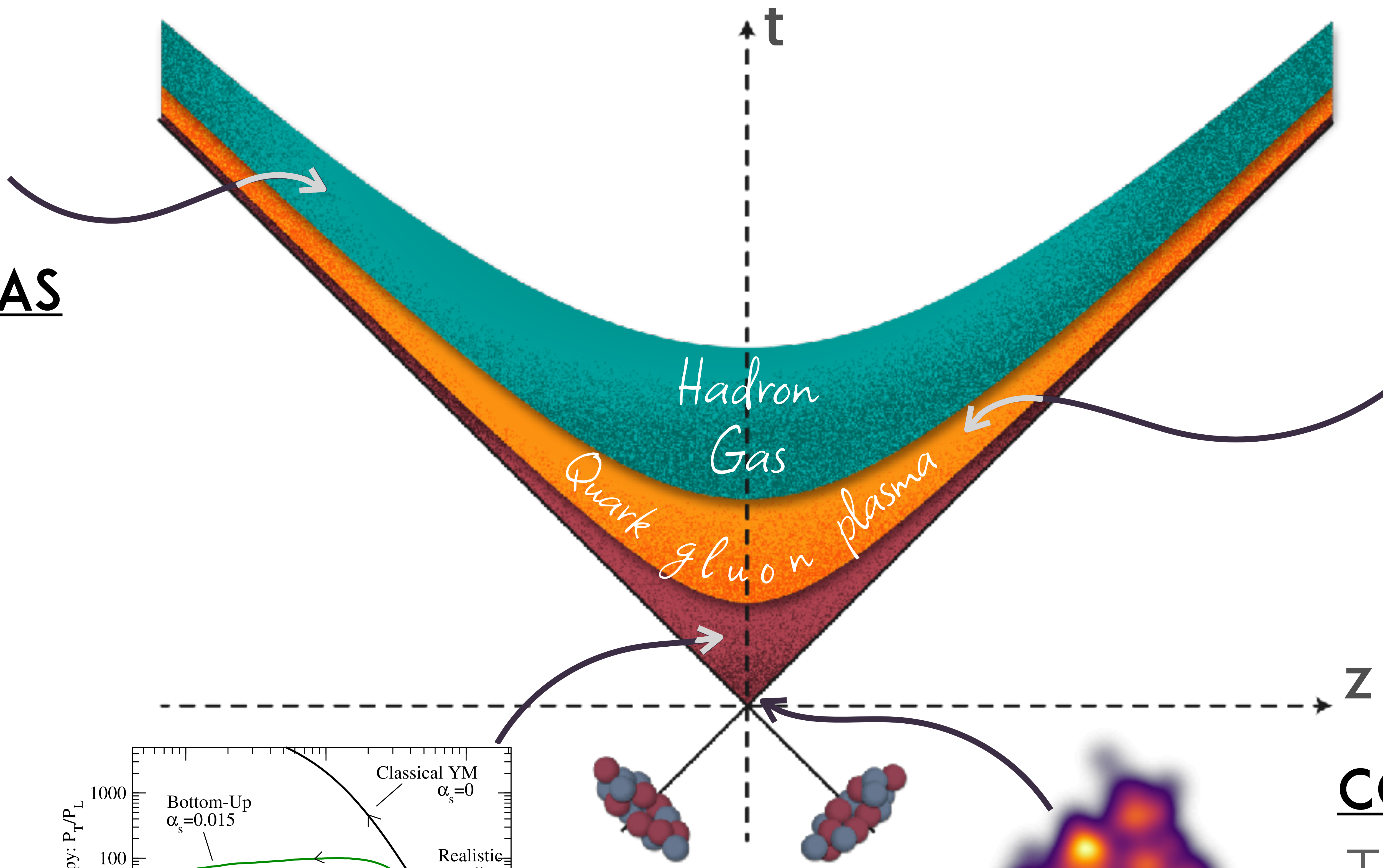
CAN WE LEARN ABOUT THE INITIAL STAGE AND THE EVOLUTION DIRECTLY?

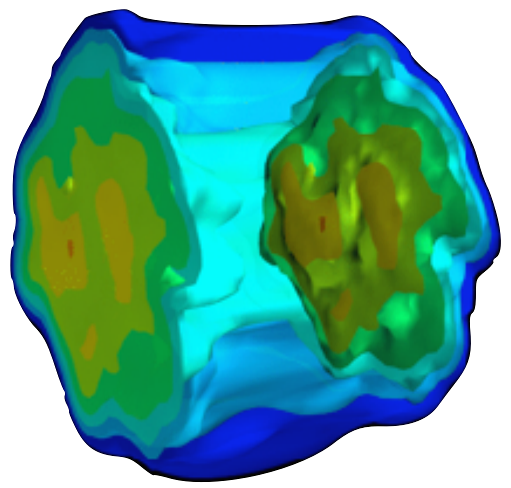
THE STANDARD MODEL OF HEAVY ION COLLISIONS: A HYBRID MODEL



HADRON GAS

SMASH
UrQMD



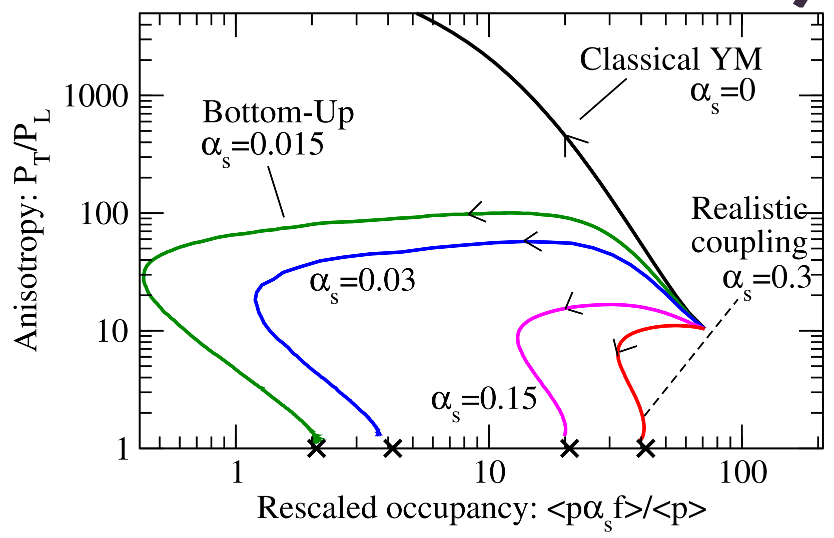


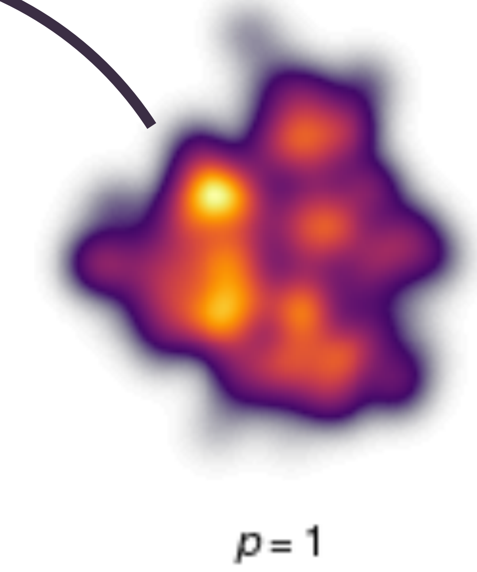
QGP

VISH
MUSIC
vHLLE

PRE-EQUILIBRIUM

AMY EKT
KøMPøST



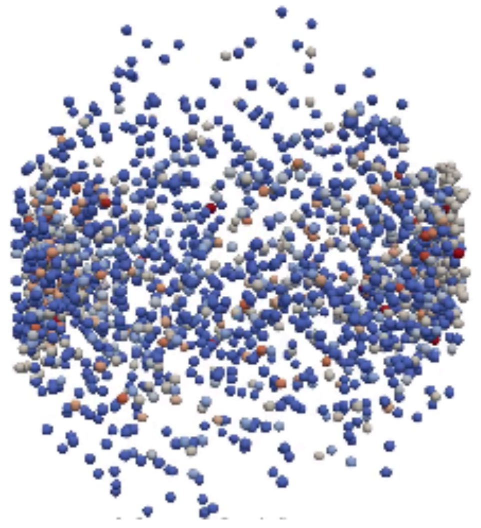


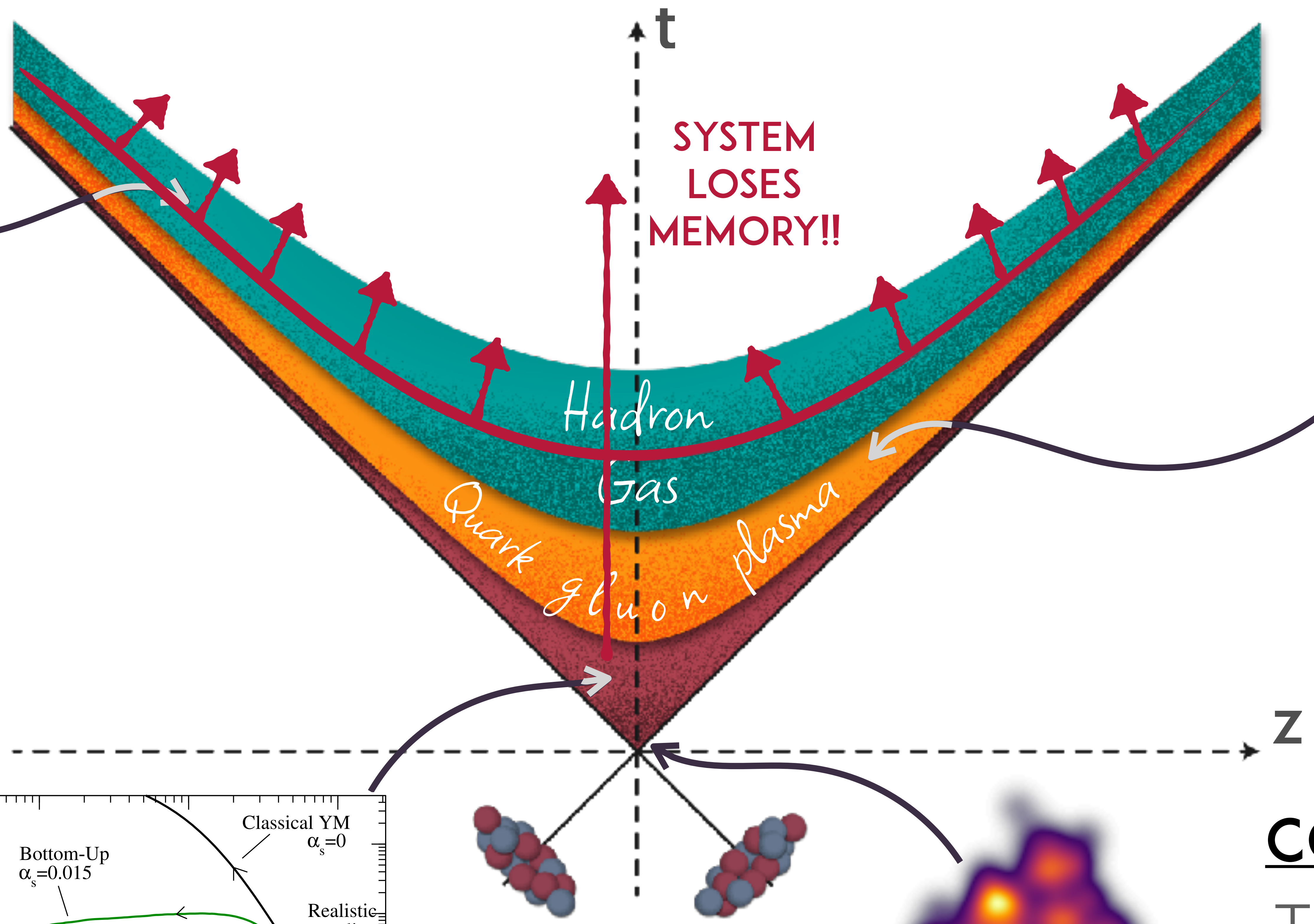
INITIAL CONDITIONS

TRENTO
IP-Glasma

[1] From Kurkela and Zhu Phys.Rev.Lett. 115 (2015) no.18, 182301

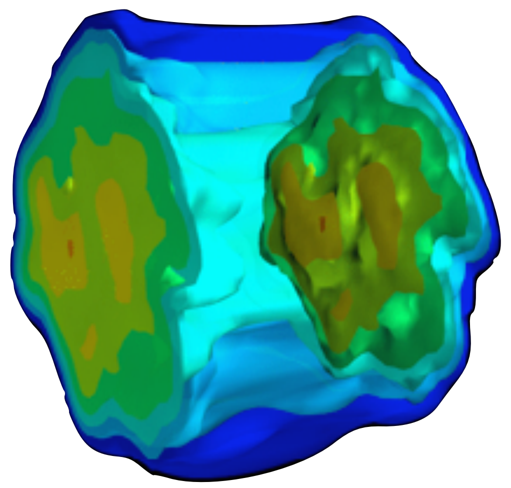
THE STANDARD MODEL OF HEAVY ION COLLISIONS: A HYBRID MODEL





HADRON GAS

SMASH
UrQMD

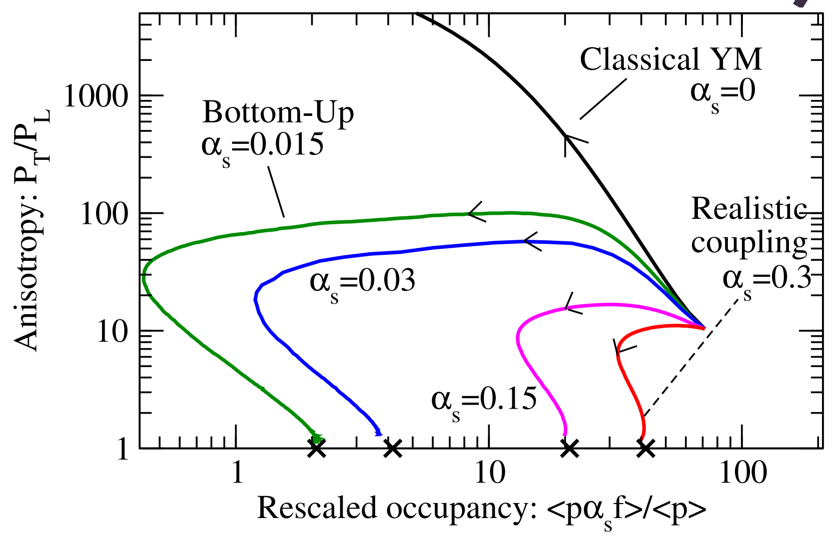


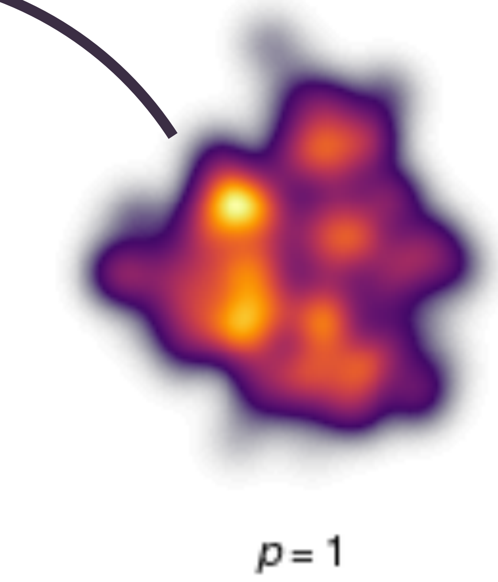
QGP

VISH
MUSIC
vHLLE

PRE-EQUILIBRIUM

AMY EKT
KøMPøST



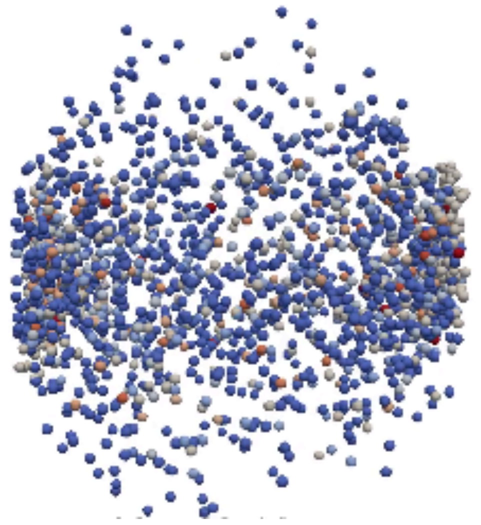


INITIAL CONDITIONS

TRENTO
IP-Glasma

[1] From Kurkela and Zhu Phys.Rev.Lett. 115 (2015) no.18, 182301

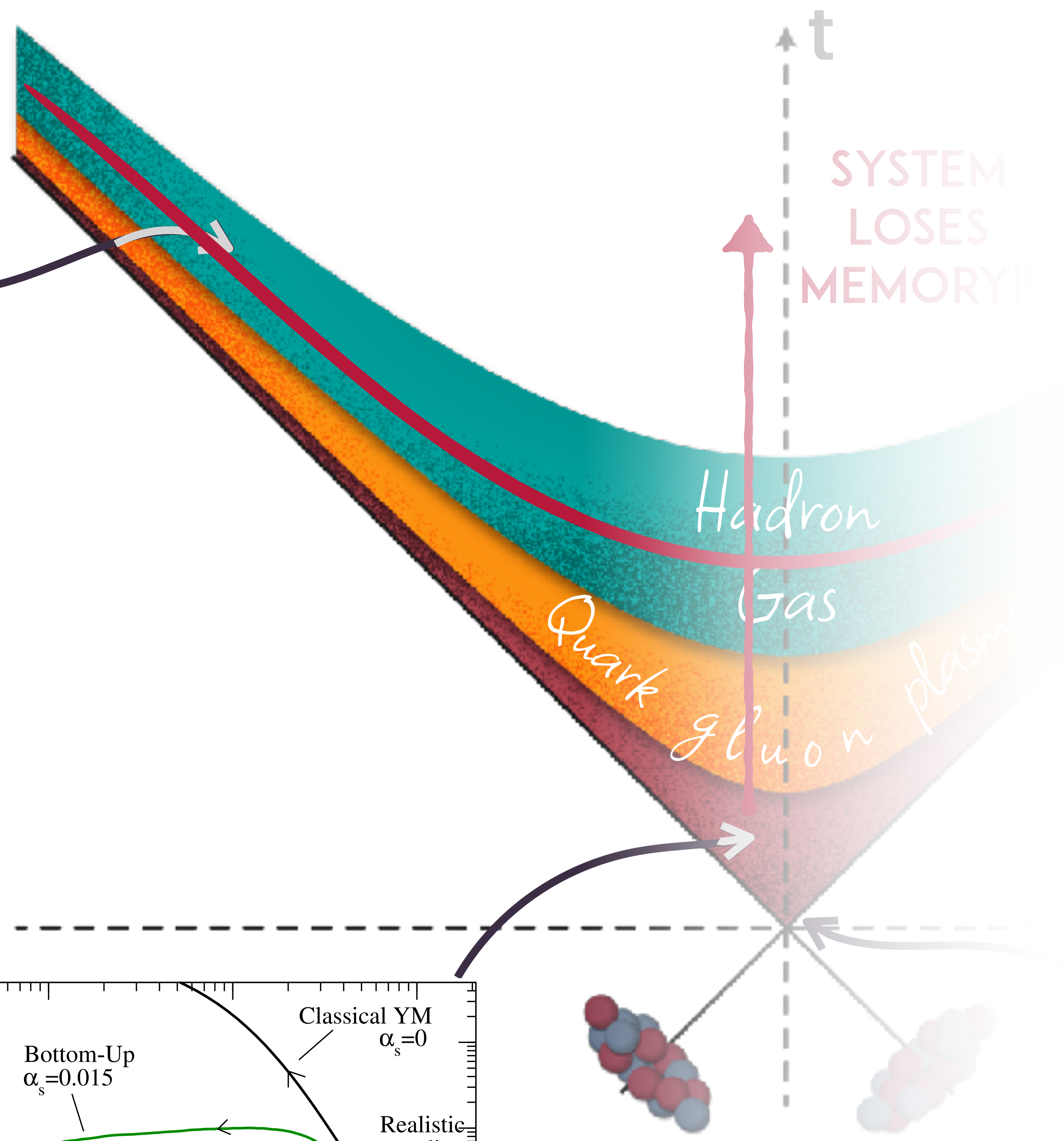
THE STANDARD MODEL OF
COLLISIONS: A HYBRID



HADRON GAS

SMASH

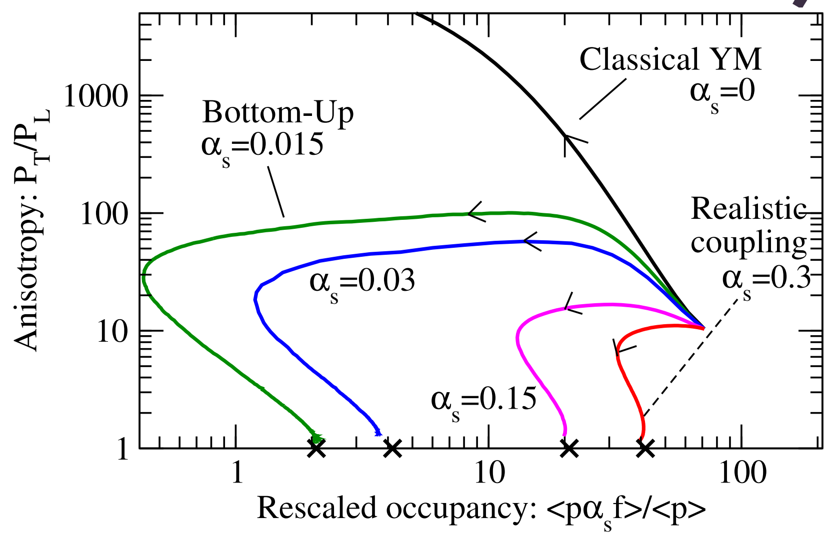
UrQMD

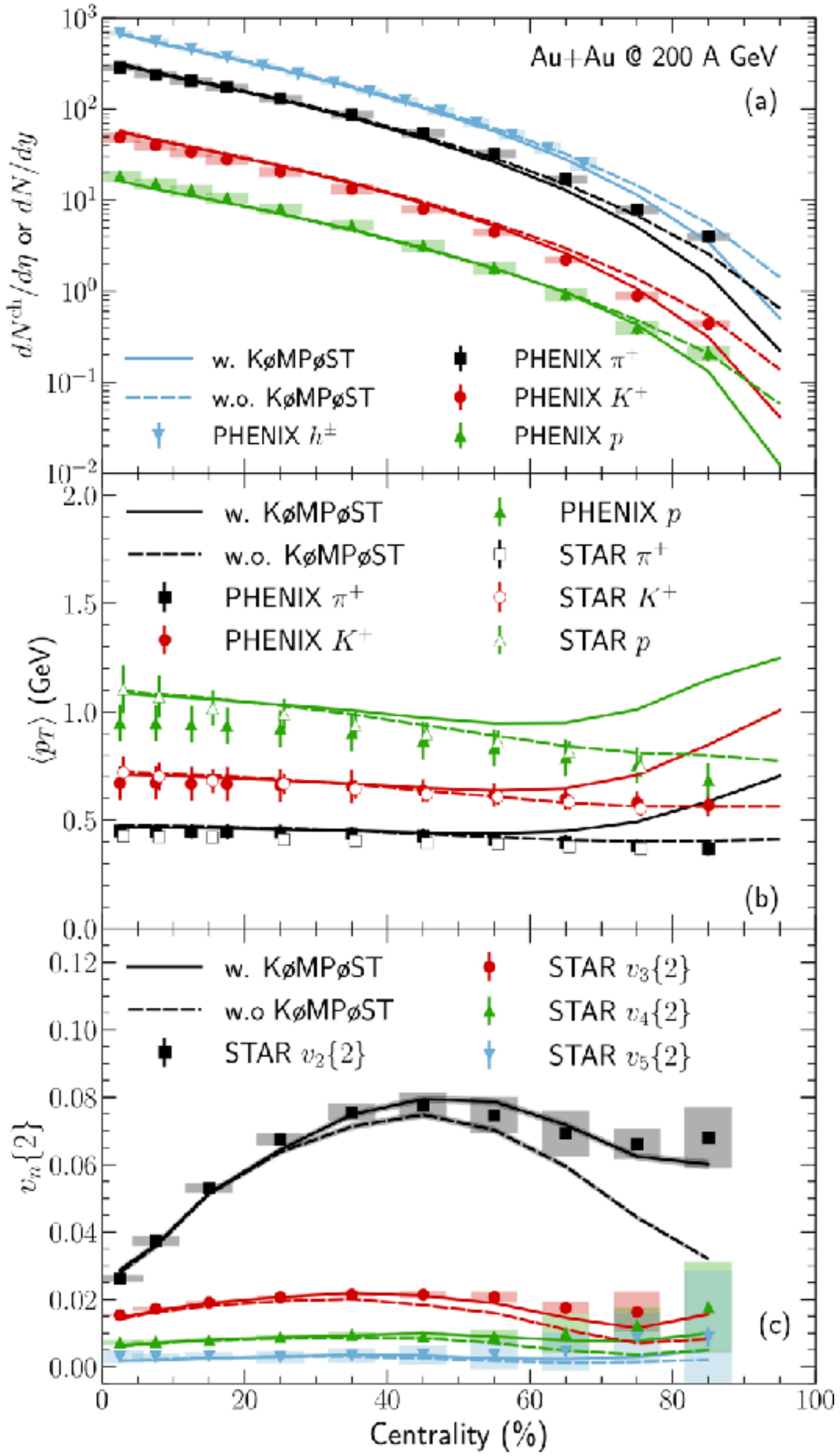


PRE-EQUILIBRIUM

AMY EKT

KøMPøST



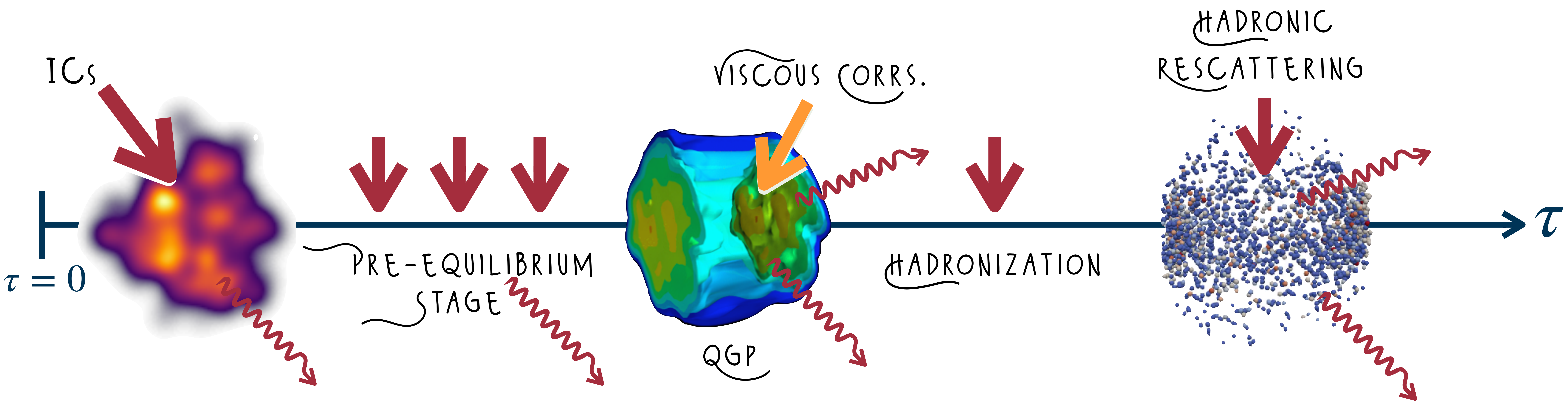


[1] From Kurkela and Zhu Phys.Rev.Lett. 115 (2015) no.18, 182301

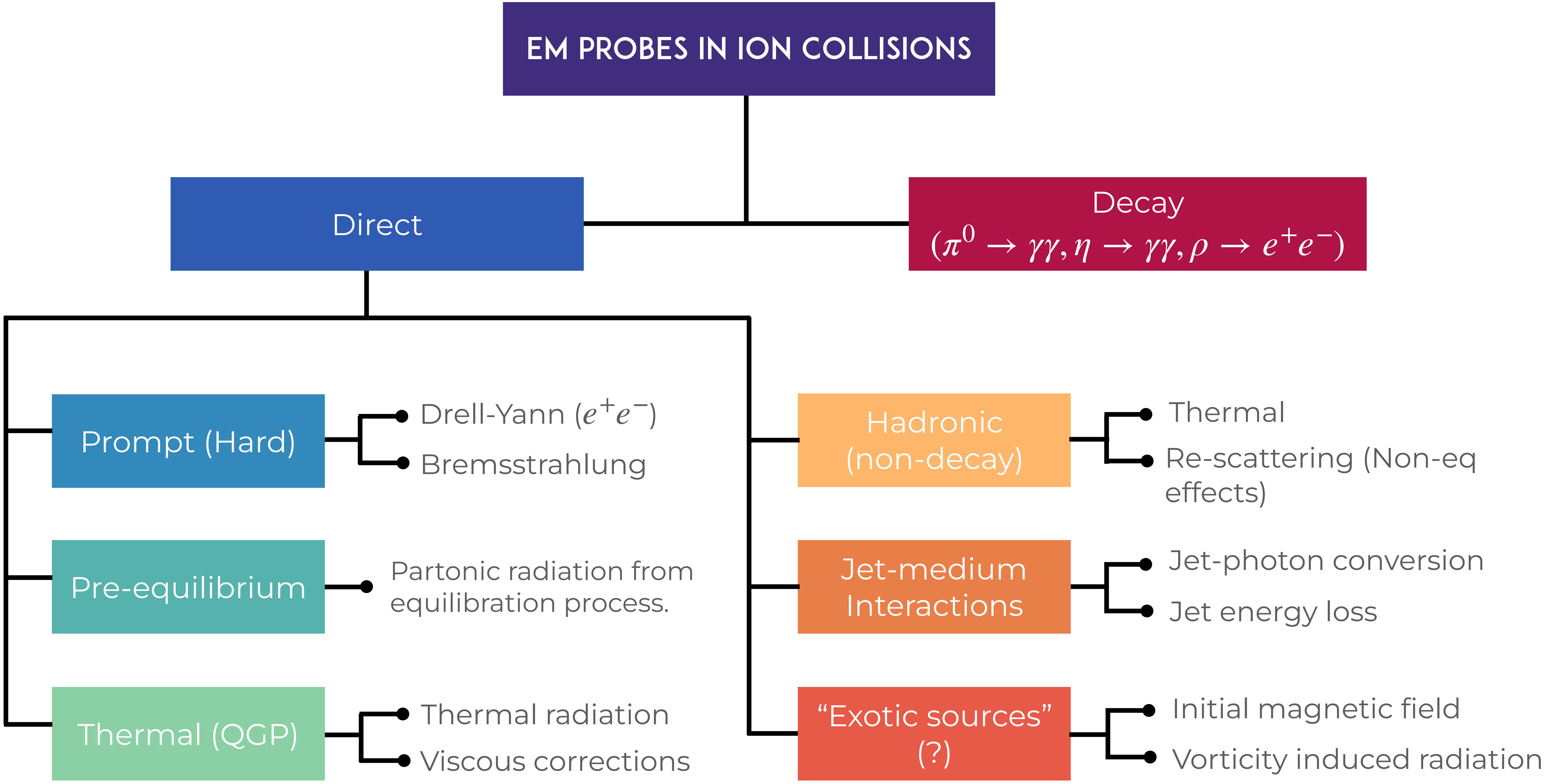
ELECTROMAGNETIC PROBES

- 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



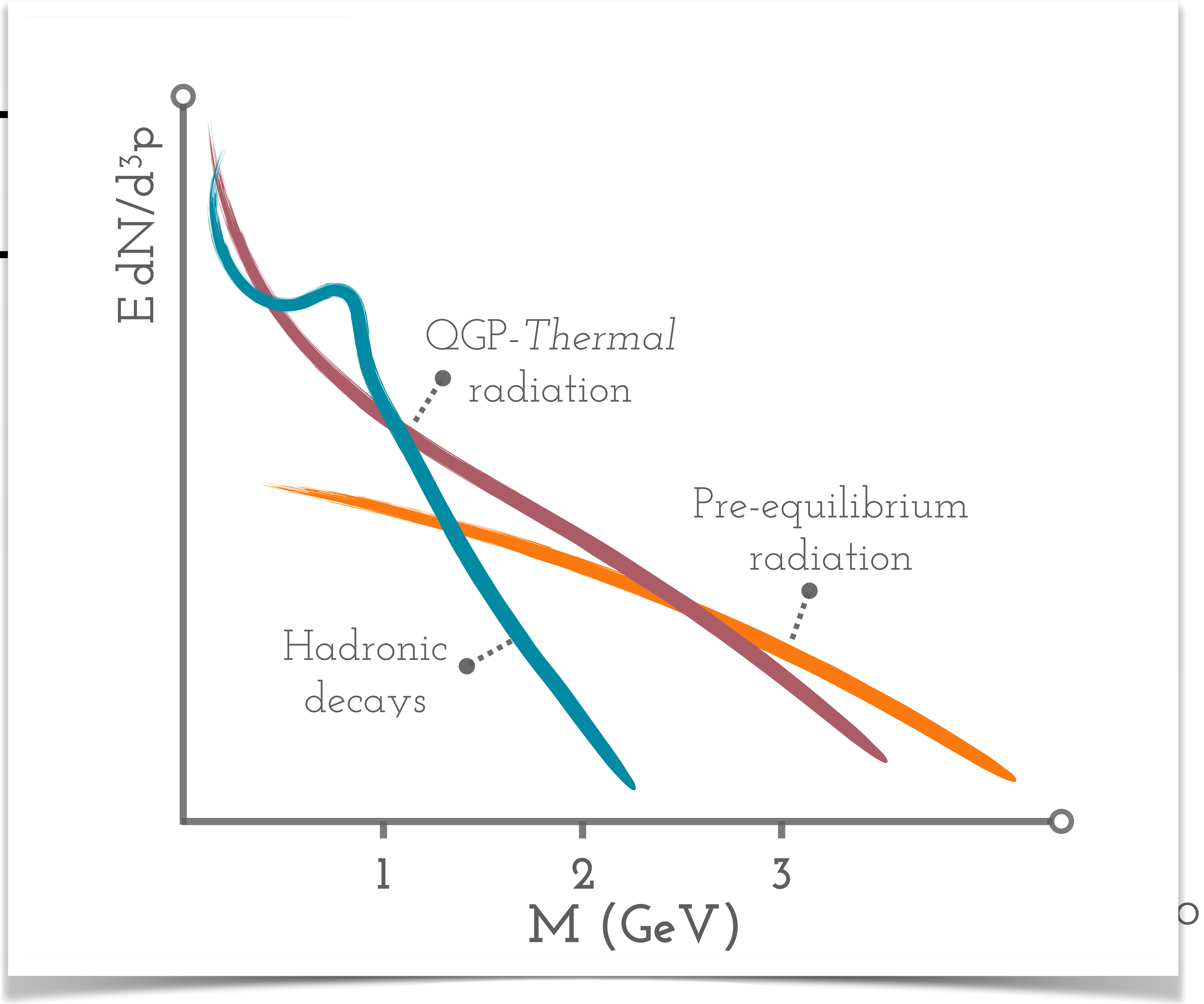
CAN WE USE EM PROBES TO LEARN ABOUT THE INITIAL STAGES AND THE EVOLUTION DIRECTLY?


EM PROBES IN ION COLLISIONS
Direct
Decay
$(\pi^0 \to \gamma\gamma, \eta \to \gamma\gamma, \rho \to e^+e^-)$
Prompt (Hard)
Drell-Yann (e^+e^-)
Bremsstrahlung
Pre-equilibrium
Partonic radiation from equilibration process.
Thermal (QGP)
Thermal radiation
Viscous corrections
Hadronic (non-decay)
Thermal
Re-scattering (Non-eq effects)
Jet-medium Interactions
Jet-photon conversion
Jet energy loss
"Exotic sources" (?)
Initial magnetic field
Vorticity induced radiation

EM PROBES IN ION COLLISIONS

Direct

- **Prompt (Hard)**
  - Drell-Yann (e^+e^-)
  - Bremsstrahlung
- **Pre-equilibrium**
  - Partonic radiation from equilibration process.
- **Thermal (QGP)**
  - Thermal radiation
  - Viscous corrections

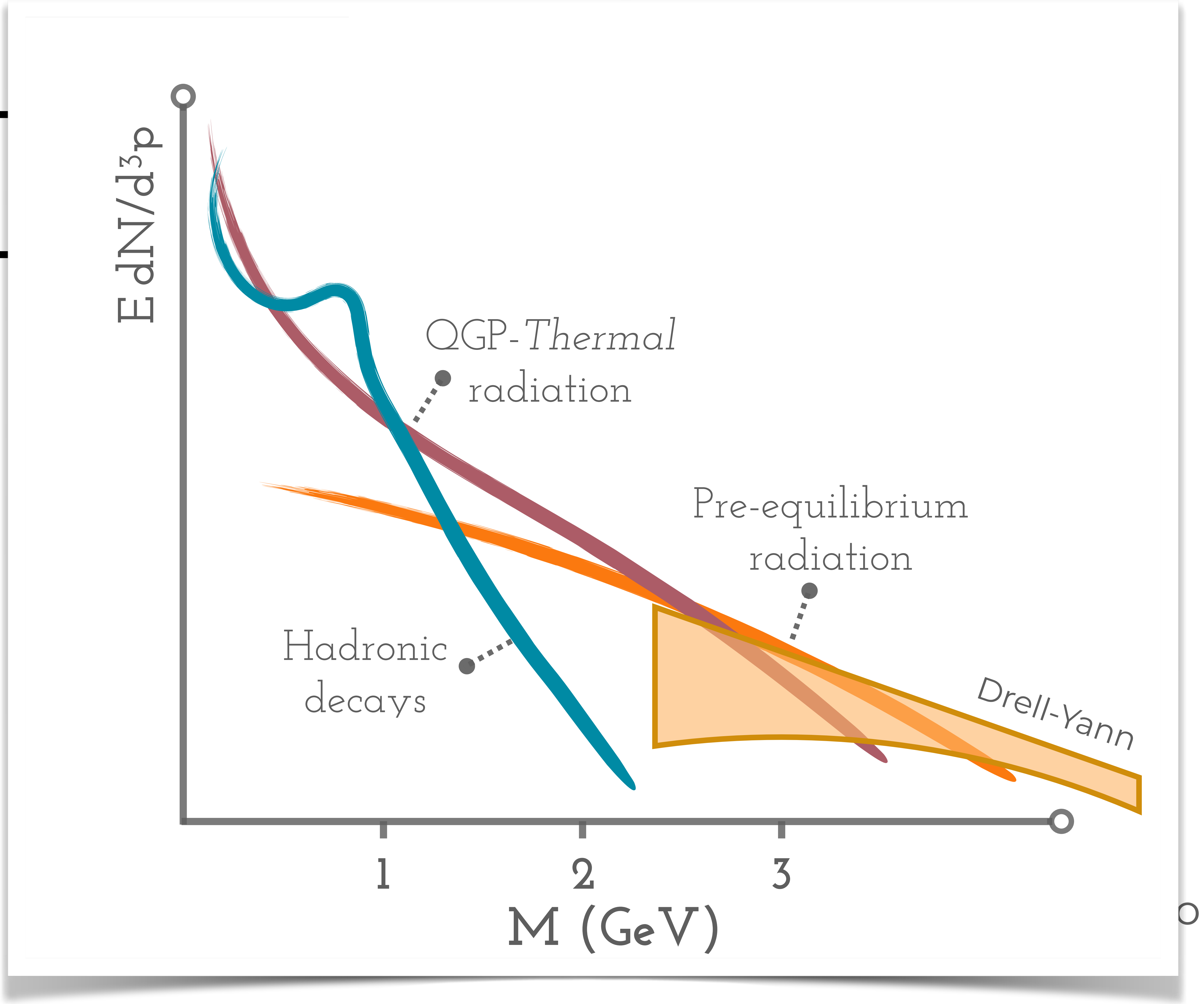


on

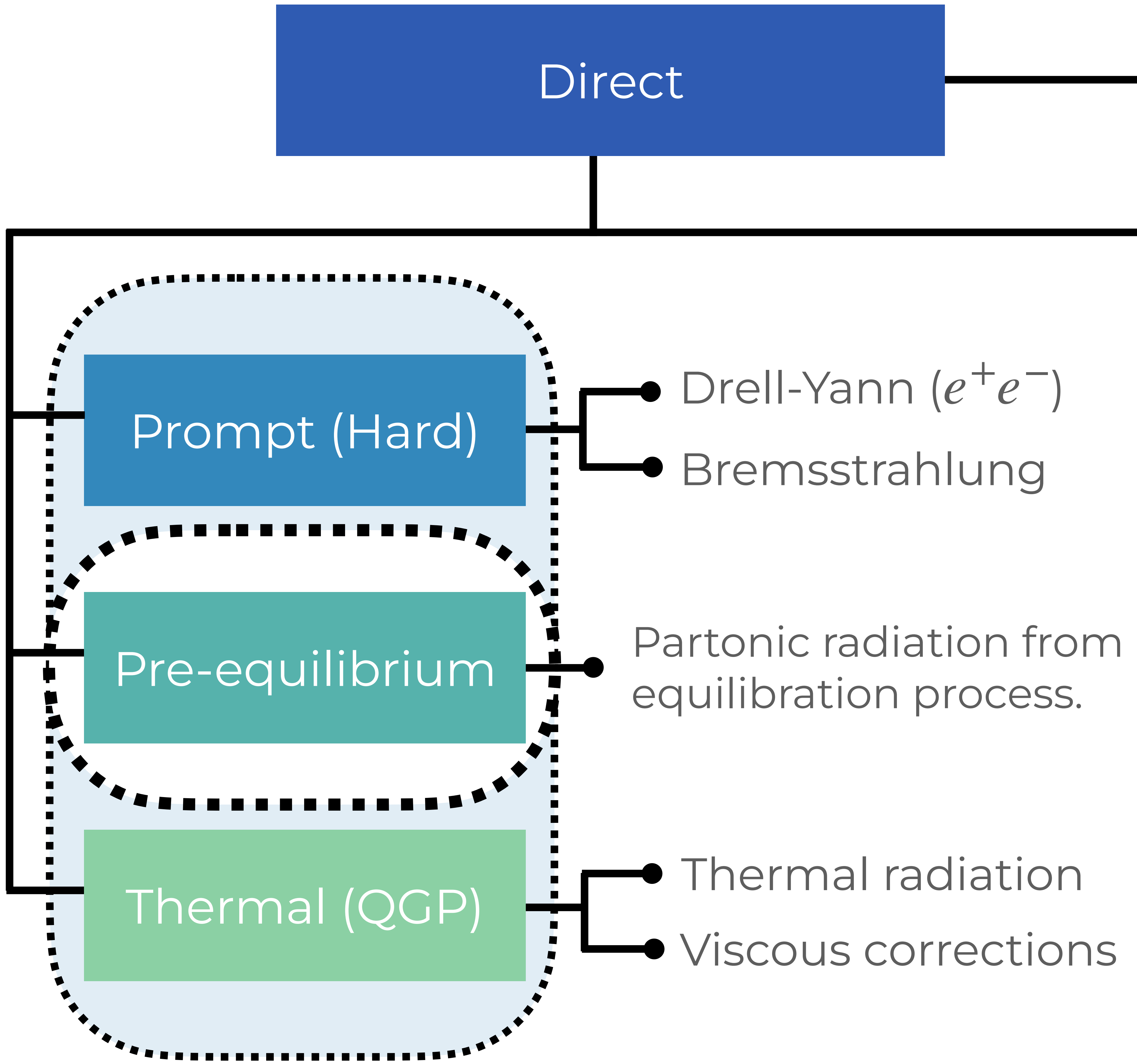
EM PROBES IN ION COLLISIONS

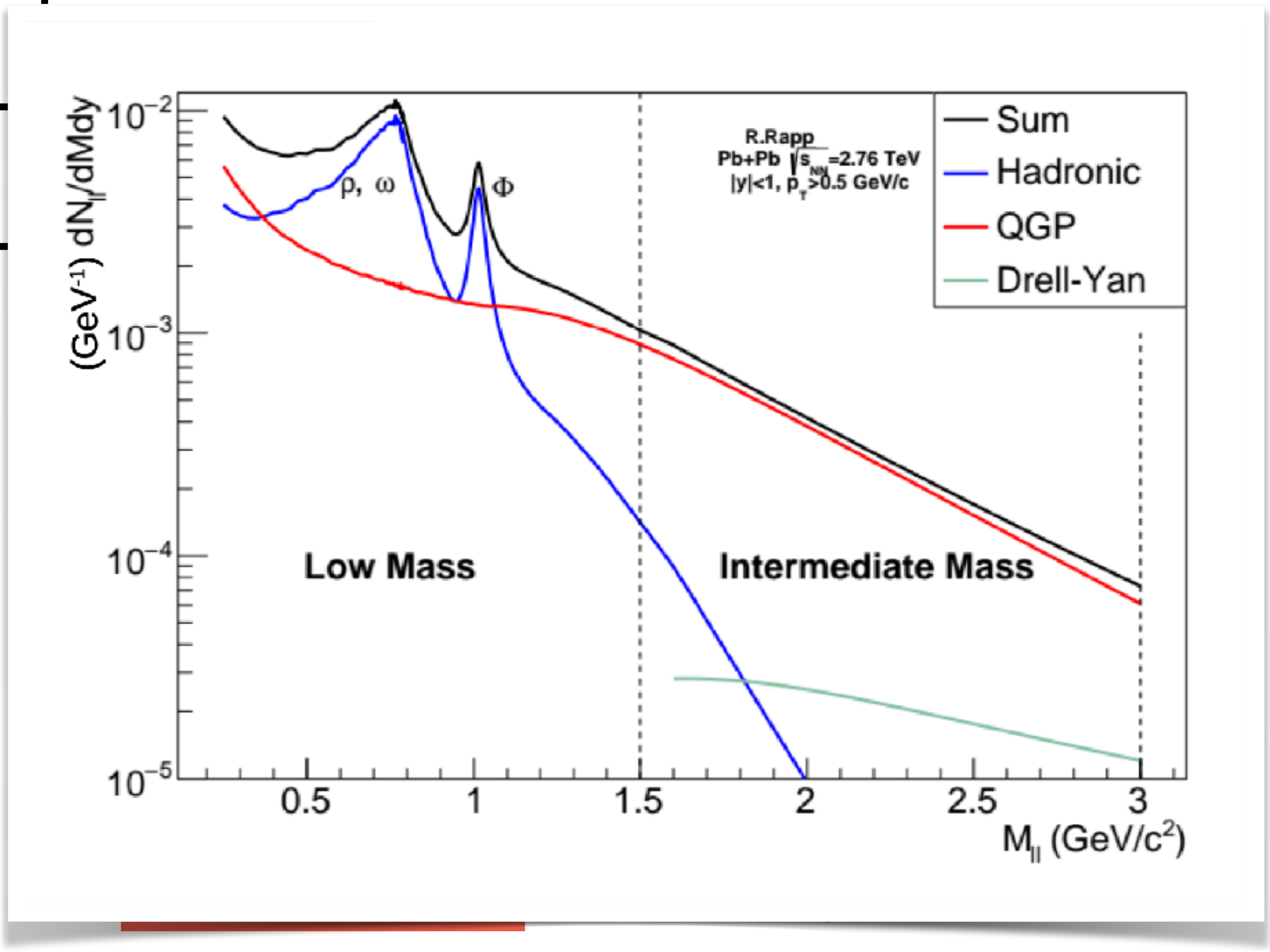
Direct

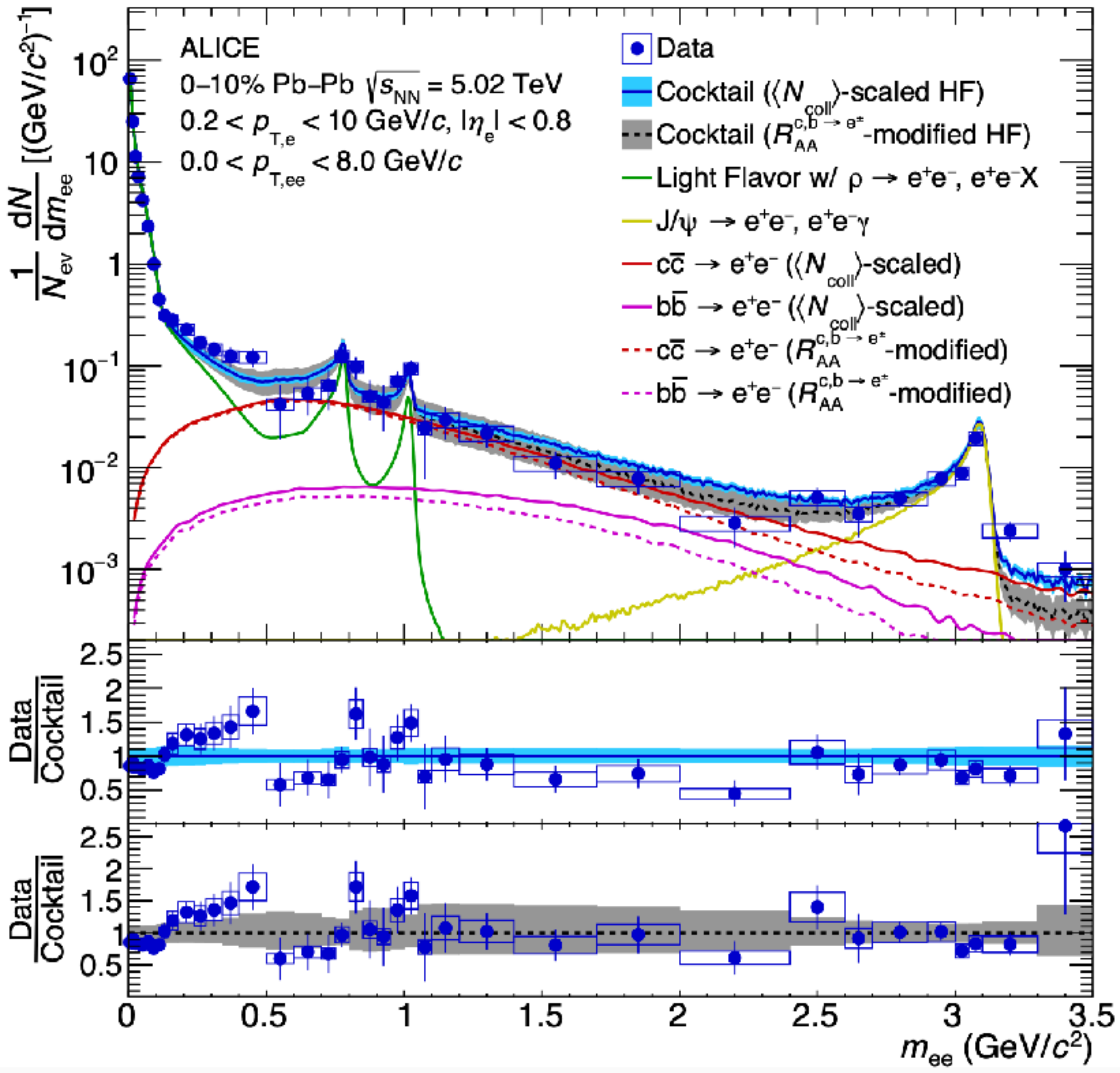
- **Prompt (Hard)**
  - Drell-Yann (e^+e^-)
  - Bremsstrahlung
- **Pre-equilibrium**
  - Partonic radiation from equilibration process.
- **Thermal (QGP)**
  - Thermal radiation
  - Viscous corrections



EM PROBES IN ION COLLISIONS

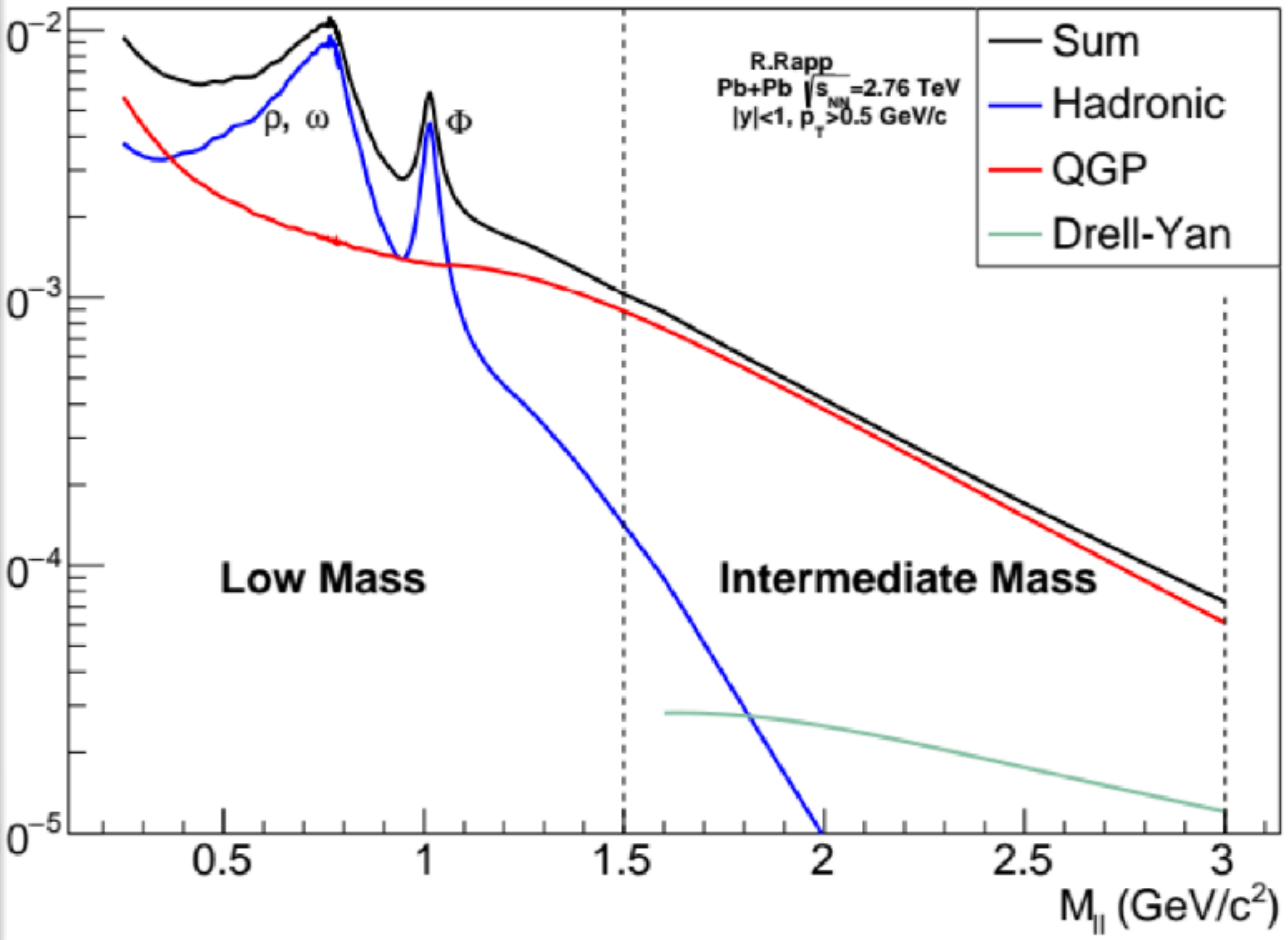






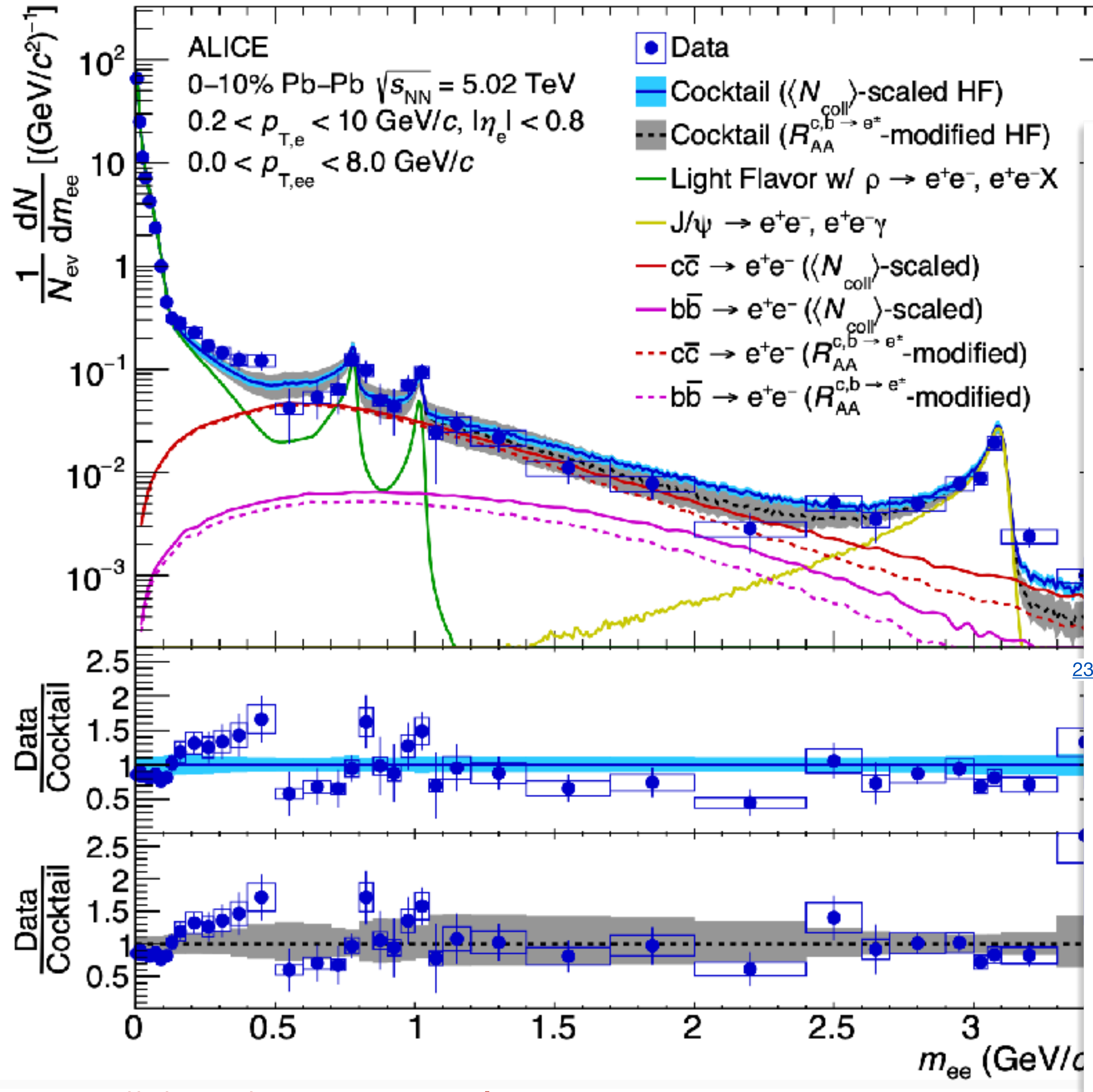
[ALICE Collaboration 2308.16704]

COLLISIONS



Viscous corrections

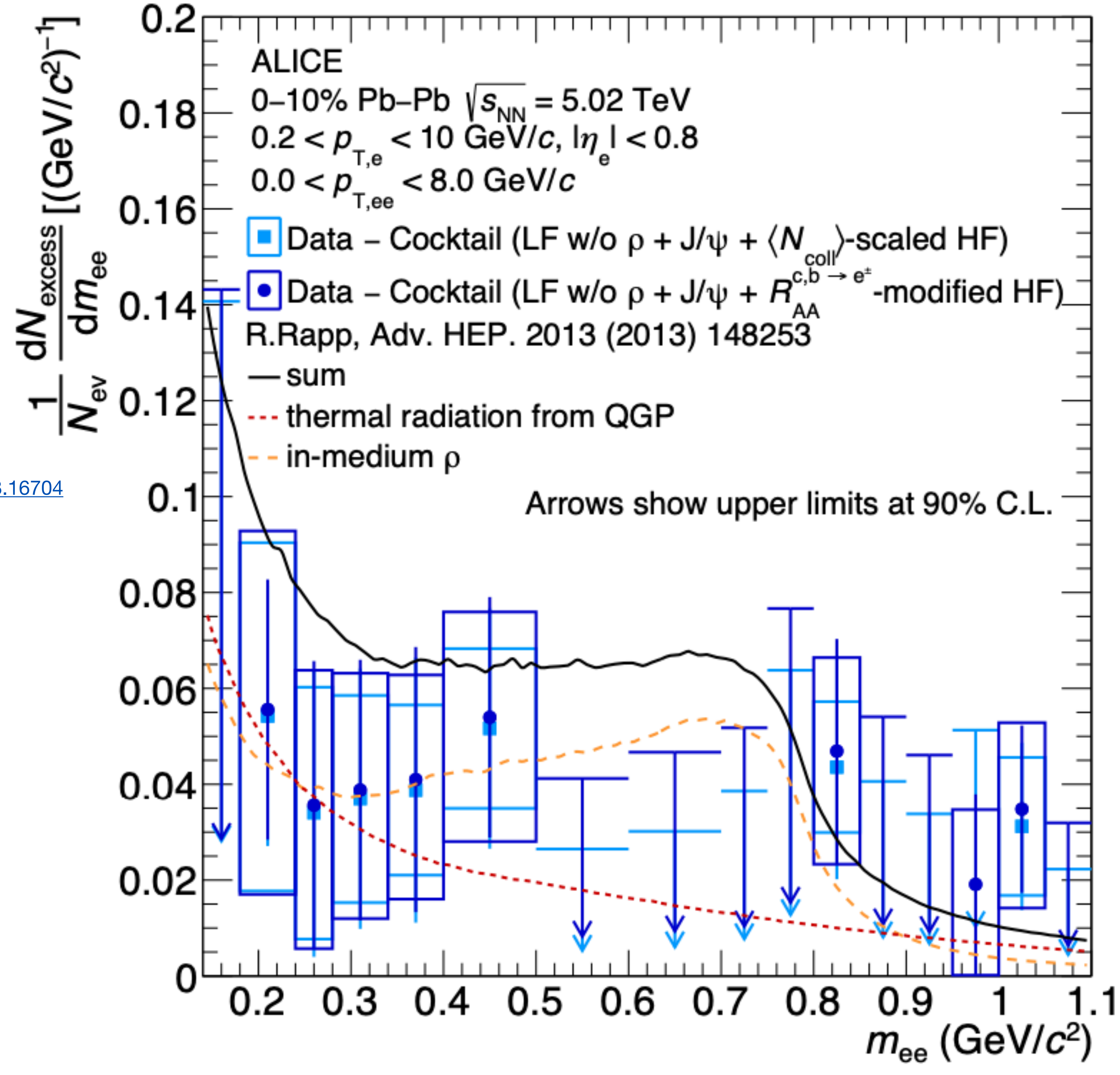
COLLISIONS



[ALICE Collaboration 2308.16704]

2308.16704

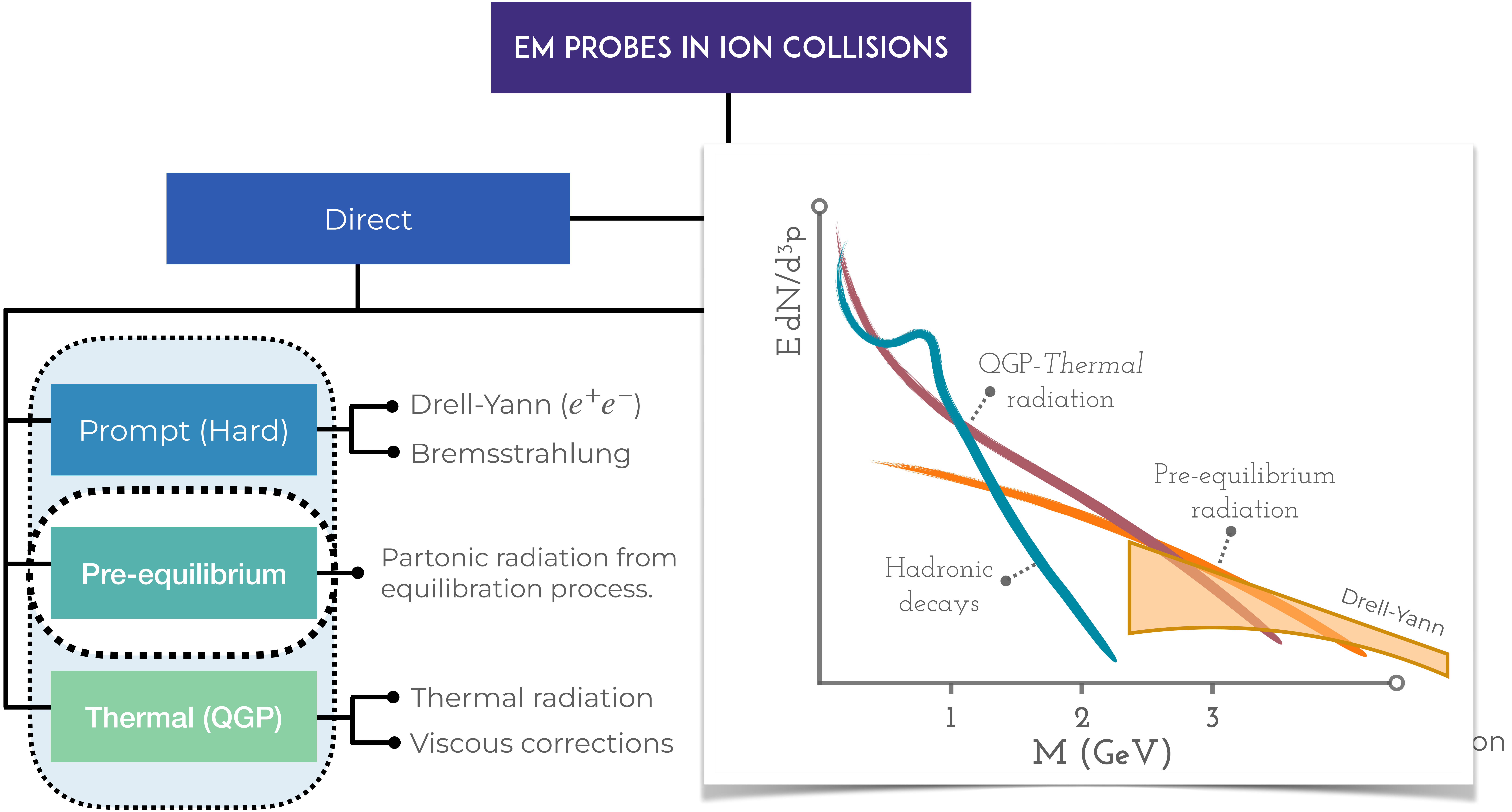
[ALICE Collaboration 2308.16704]



Viscous corrections

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.


EM PROBES IN ION COLLISIONS
Direct
Prompt (Hard)
Drell-Yann (e^+e^-)
Bremsstrahlung
Pre-equilibrium
Partonic radiation from equilibration process.
Thermal (QGP)
Thermal radiation
Viscous corrections
EdN/d³p
QGP-Thermal radiation
Pre-equilibrium radiation
Hadronic decays
Drell-Yann
1
2
3
M (GeV)

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

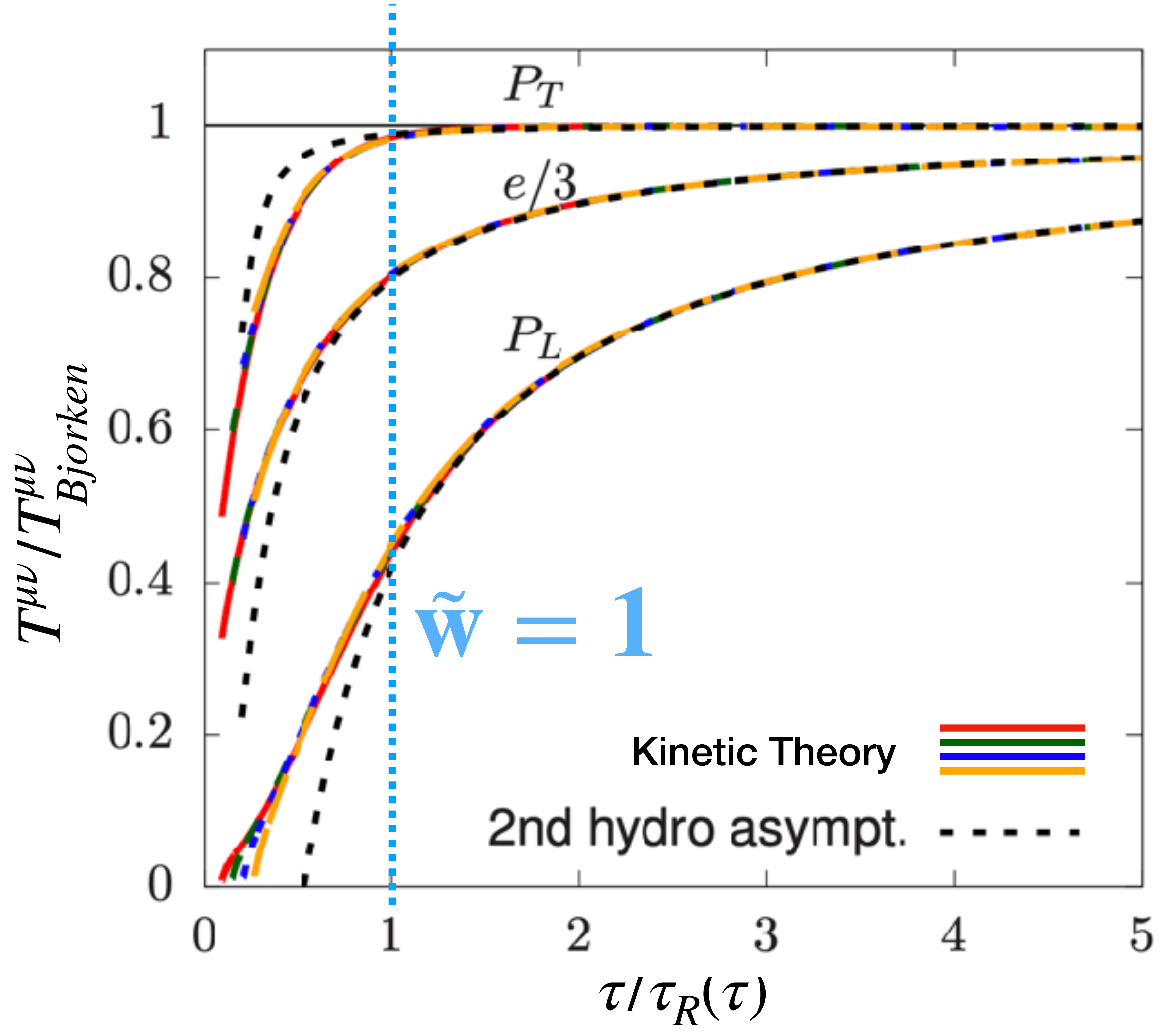
- Equilibration controlled by single relaxation rate

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

- 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

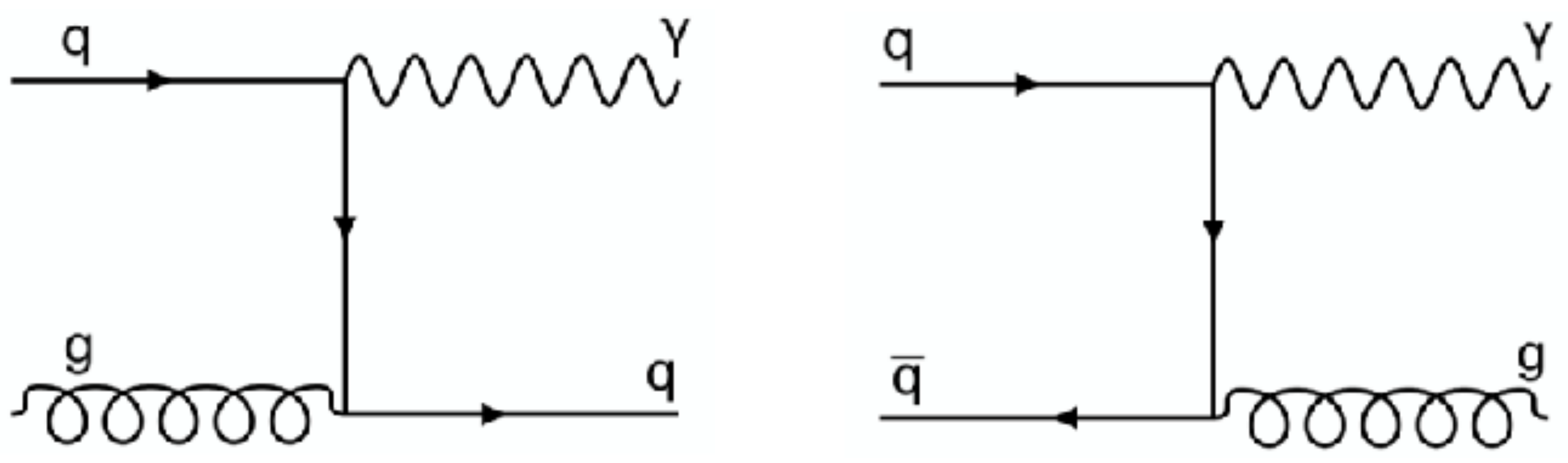
[Arnold et al., JHEP, (2001)]

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

- $2\leftrightarrow 2$ 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

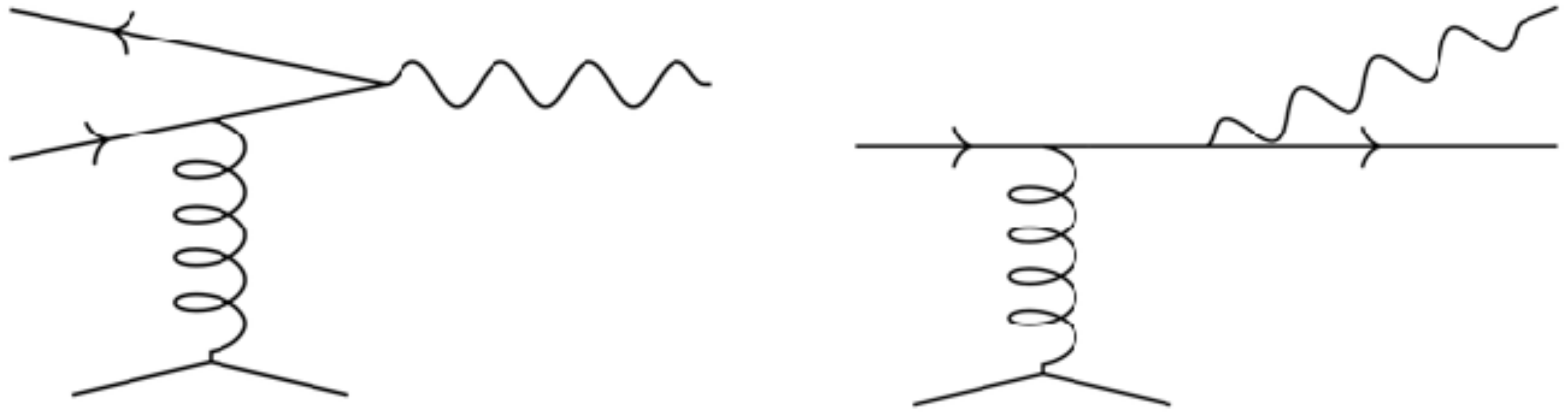


Compton Scattering

Elastic pair annihilation

+ appropriate other channels

Effective $1 \leftrightarrow 2$ processes

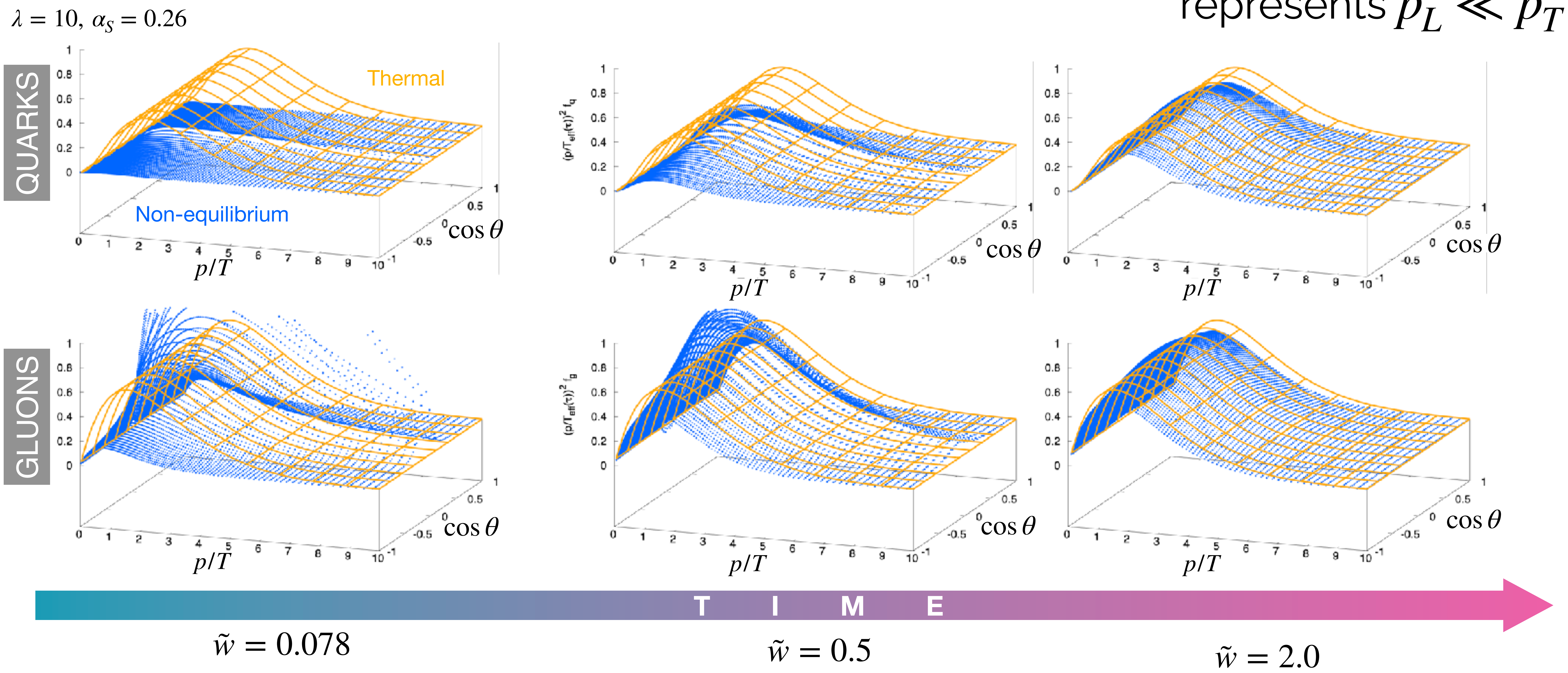


Inelastic pair annihilation

Bremsstrahlung off q & q̄

QCD KINETIC THEORY

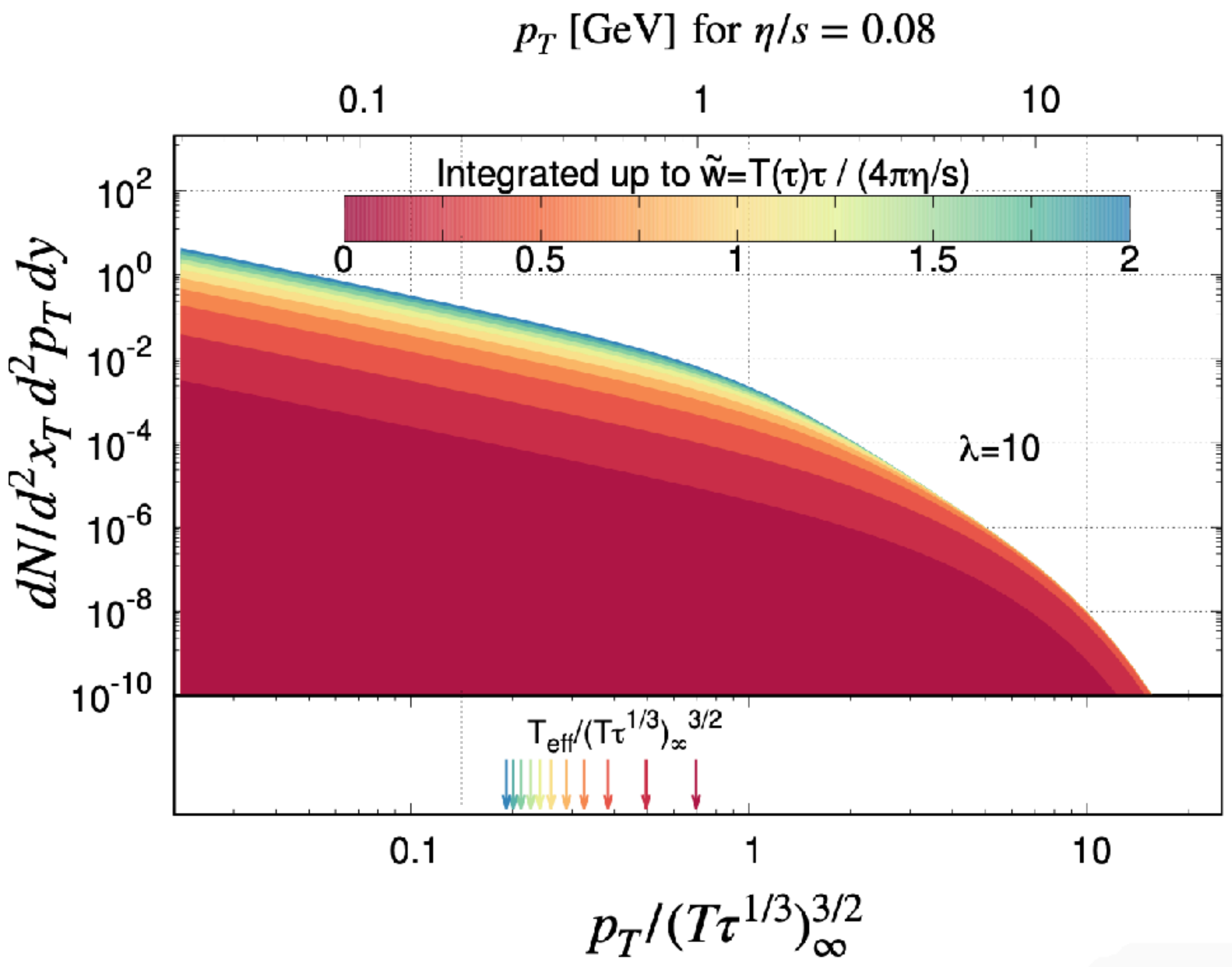
- Gluon dominated initial state
- Quarks produced dynamically
- System initially highly anisotropic
  → peak at $\cos\theta \approx 0$
  represents $p_L \ll p_T$



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
  ⇒ smooth convergence to thermal

  photon rate

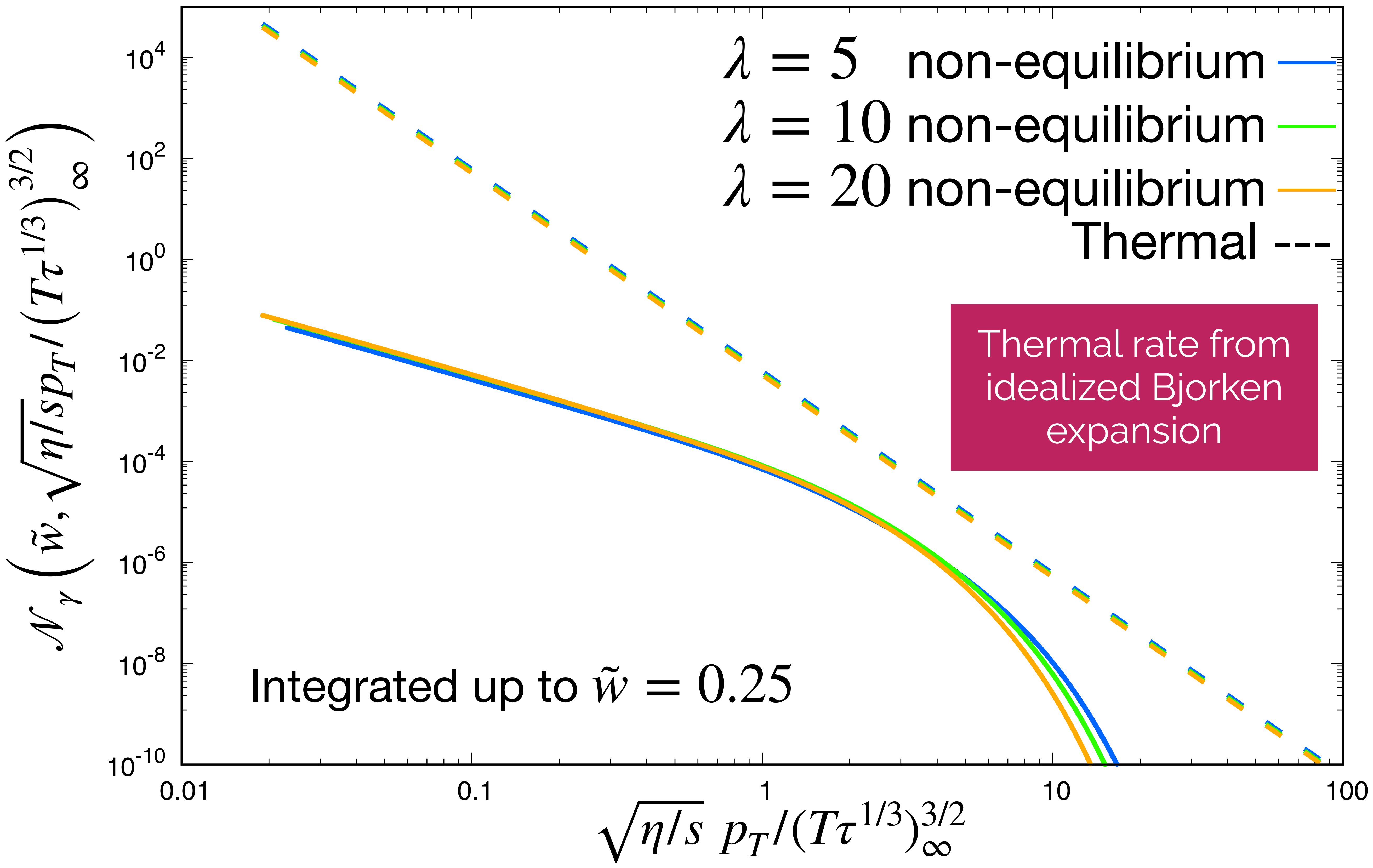


PHOTONS - SCALING

- 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 η/s and entropy density $T\tau^{1/3} \sim (\tau s)^{1/3}_{eq}$
  $\Rightarrow$ valid for each theory with energy attractor



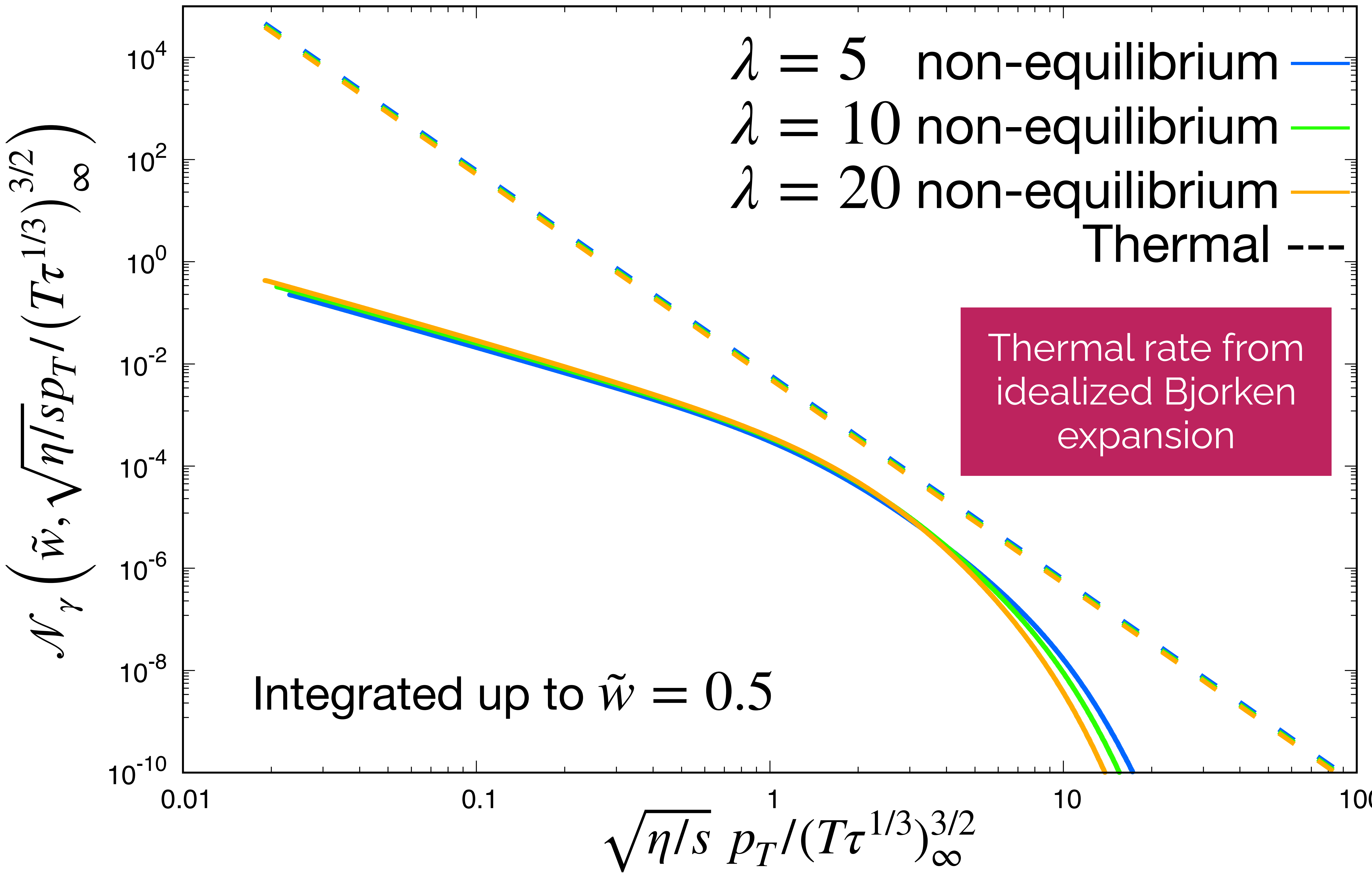
$$\frac{dN}{d^2x_T d^2p_T dy} = (\eta/s)^2\ \tilde{C}_\gamma^{ideal}\ \mathcal{N}_\gamma\left(\tilde{w}, \sqrt{\eta/s}p_T/\left(T\tau^{1/3}\right)^{3/2}_\infty\right)$$

RESULTS - p_T-SPECTRUM

- 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 η/s and entropy density $T\tau^{1/3} \sim (\tau s)^{1/3}_{eq}$
  $\Rightarrow$ valid for each theory with energy attractor



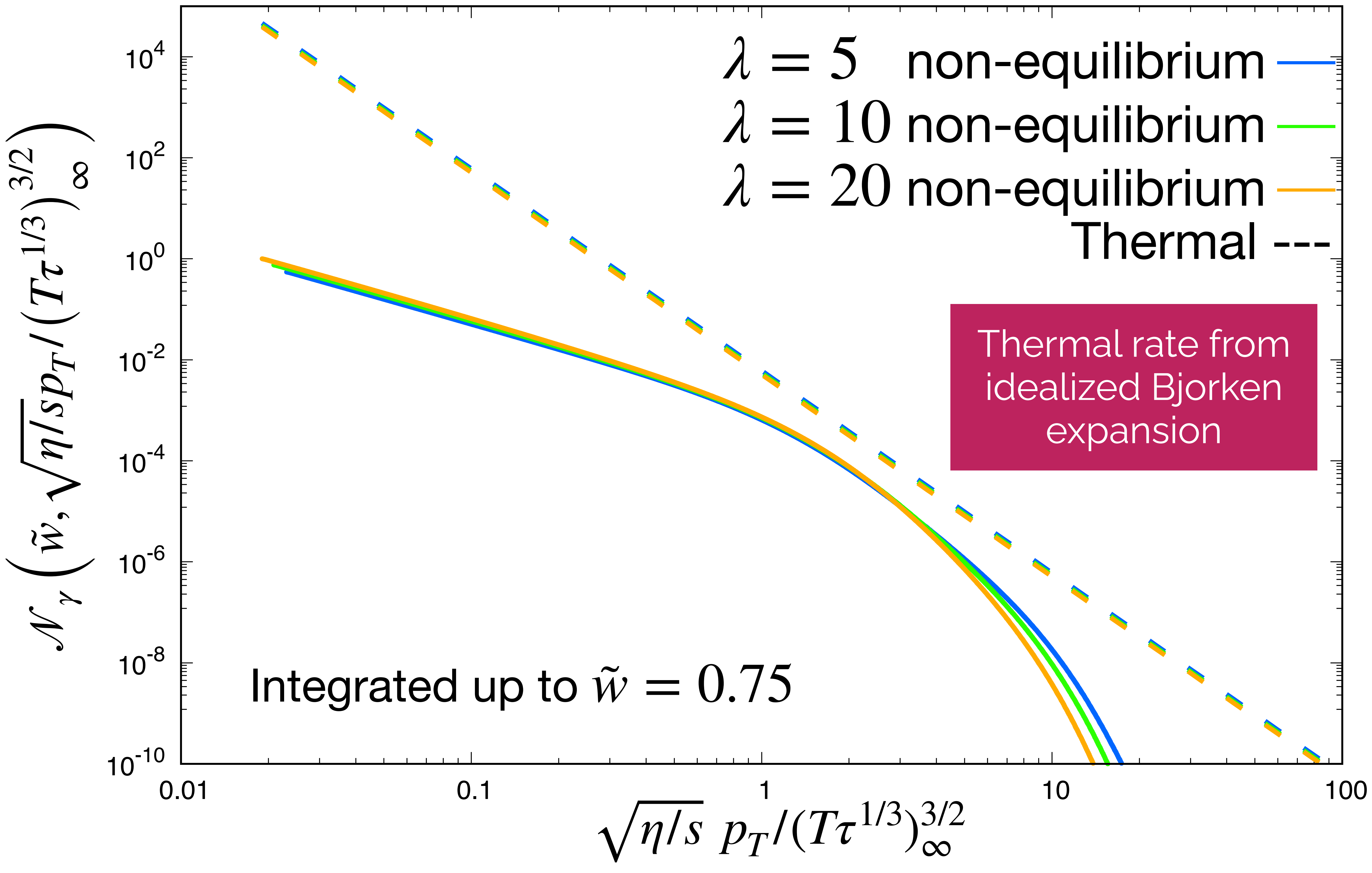
$$\frac{dN}{d^2x_T d^2p_T dy} = (\eta/s)^2\ \tilde{C}^{ideal}_\gamma\ \mathcal{N}_\gamma\left(\tilde{w}, \sqrt{\eta/s}\, p_T/\left(T\tau^{1/3}\right)^{3/2}_\infty\right)$$

RESULTS - p_T-SPECTRUM

- 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 η/s and entropy density $T\tau^{1/3} \sim (\tau s)_{eq}^{1/3}$
  $\Rightarrow$ valid for each theory with energy attractor



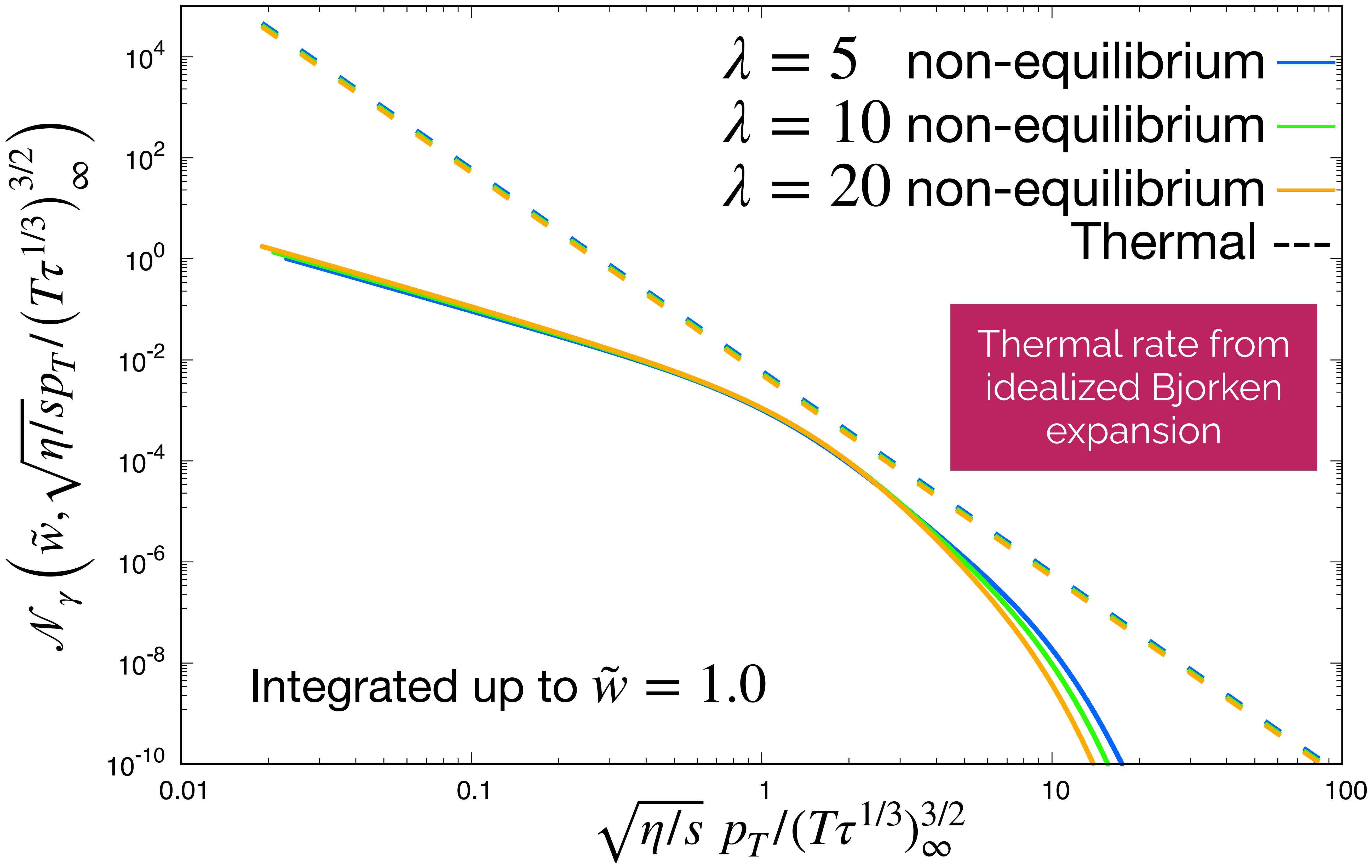
$$\frac{dN}{d^2x_T d^2p_T dy} = (\eta/s)^2\ \tilde{C}_\gamma^{ideal}\ \mathcal{N}_\gamma\left(\tilde{w}, \sqrt{\eta/s}\,p_T/\left(T\tau^{1/3}\right)_\infty^{3/2}\right)$$

RESULTS - p_T -SPECTRUM

- 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)

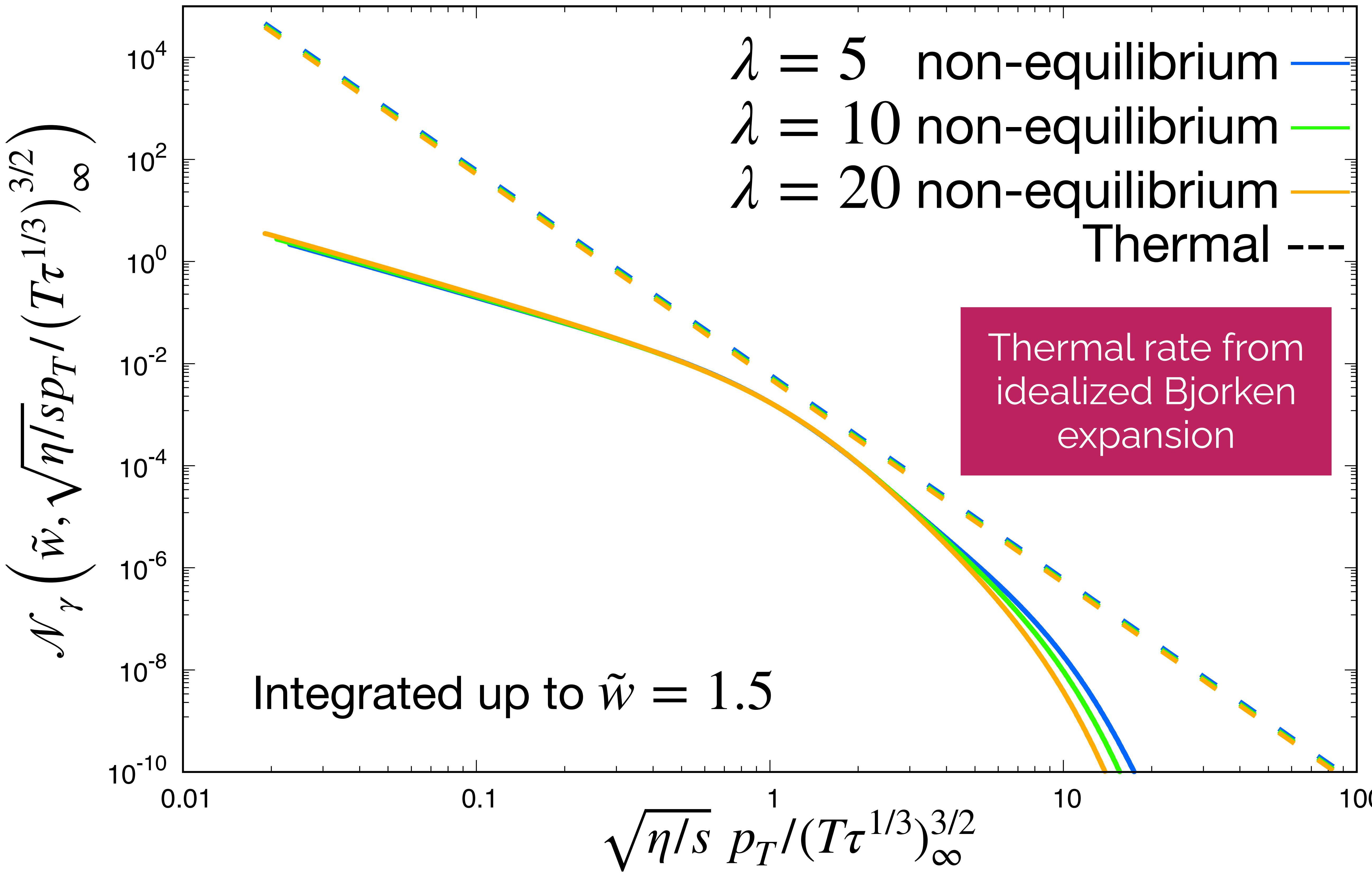
- Universal scaling of pre-eq photon spectrum in terms of shear viscosity η/s and entropy density $T\tau^{1/3} \sim (\tau s)_{eq}^{1/3}$
  $\Rightarrow$ valid for each theory with energy attractor



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

RESULTS - p_T-SPECTRUM

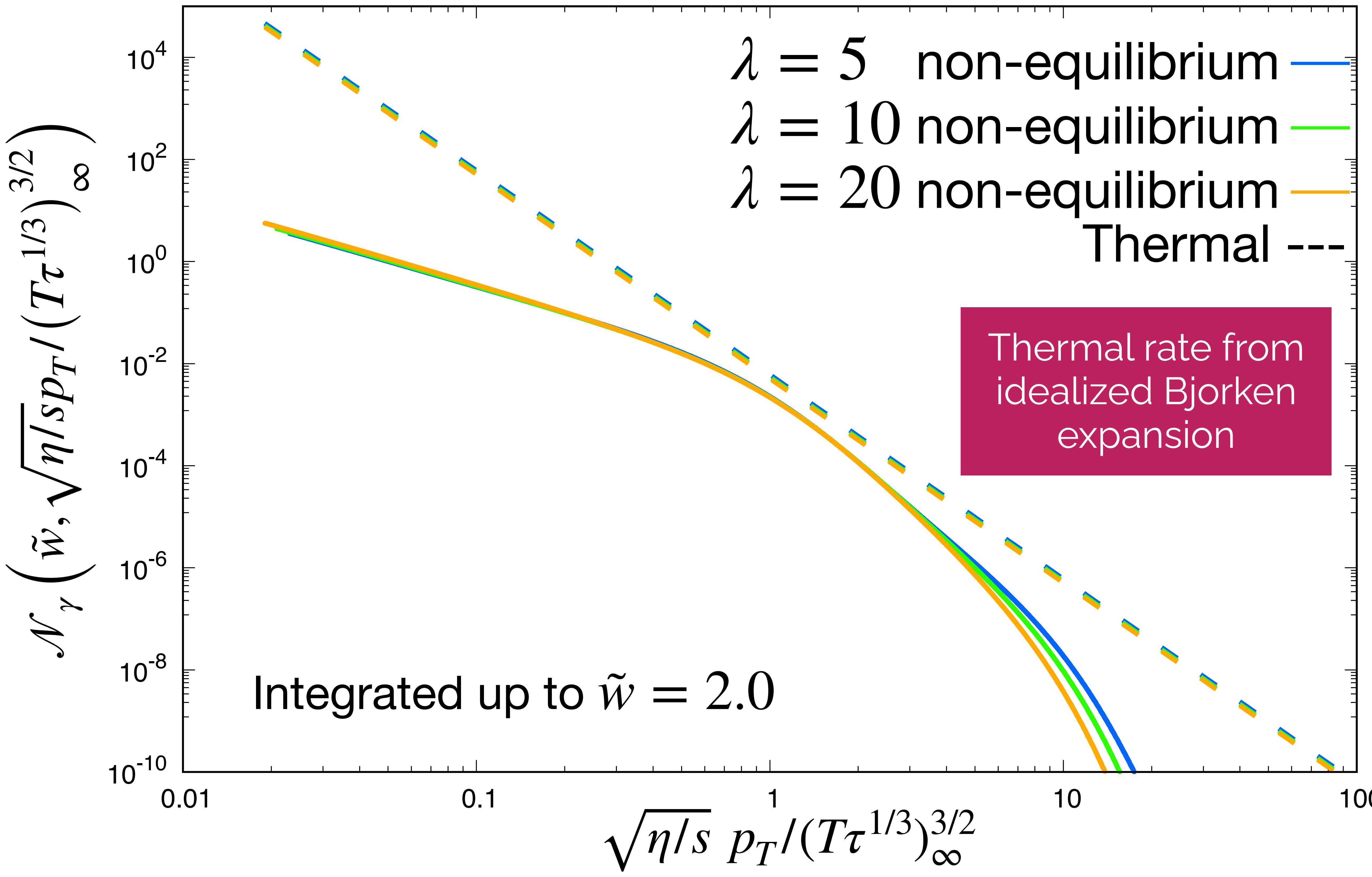
- Competing effects: cooling dynamics and quark production
  $\Rightarrow$ reflected in time integrated pre-eq. photon spectrum
- Suppression wrt to „ideal“ photon spectrum (thermal equilibrium throughout evolution)
- Universal scaling of pre-eq photon spectrum in terms of shear viscosity η/s and entropy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



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

RESULTS - p_T-SPECTRUM

- 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 η/s and entropy density $T\tau^{1/3} \sim (\tau s)_{eq}^{1/3}$
  $\Rightarrow$ valid for each theory with energy attractor



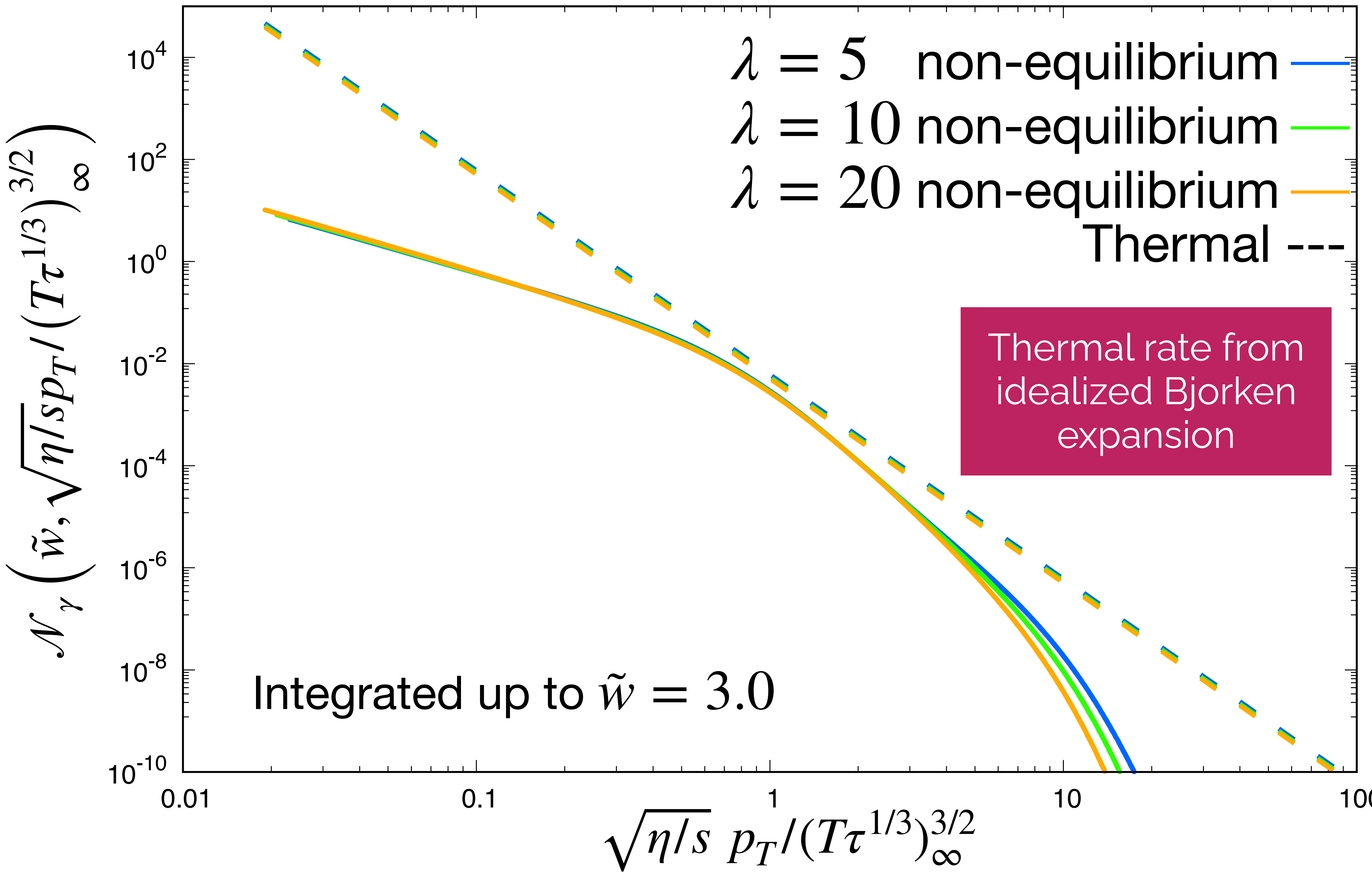
$$\frac{dN}{d^2x_T d^2p_T dy} = (\eta/s)^2\ \tilde{C}_\gamma^{ideal}\ \mathcal{N}_\gamma\left(\tilde{w}, \sqrt{\eta/s}\, p_T/\left(T\tau^{1/3}\right)_\infty^{3/2}\right)$$

RESULTS - p_T-SPECTRUM

- 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 η/s and entropy density $T\tau^{1/3} \sim (\tau s)_{eq}^{1/3}$
  $\Rightarrow$ valid for each theory with energy attractor



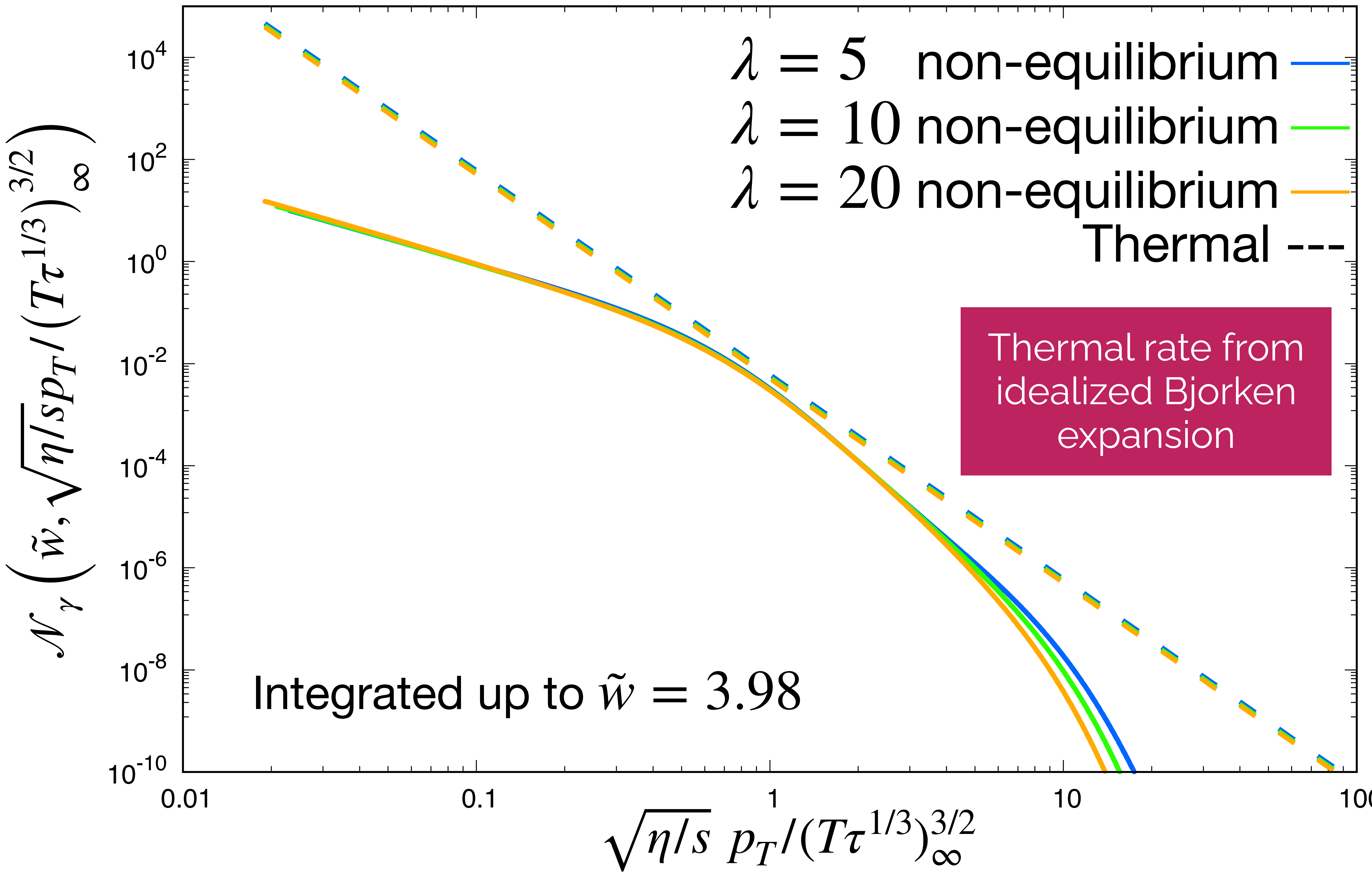
$$\frac{dN}{d^2x_T d^2p_T dy} = (\eta/s)^2\ \tilde{C}_\gamma^{ideal}\ \mathcal{N}_\gamma\left(\tilde{w}, \sqrt{\eta/s}p_T/\left(T\tau^{1/3}\right)^{3/2}_\infty\right)$$

RESULTS - p_T-SPECTRUM

- 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 η/s and entropy density $T\tau^{1/3} \sim (\tau s)_{eq}^{1/3}$
  $\Rightarrow$ valid for each theory with energy attractor



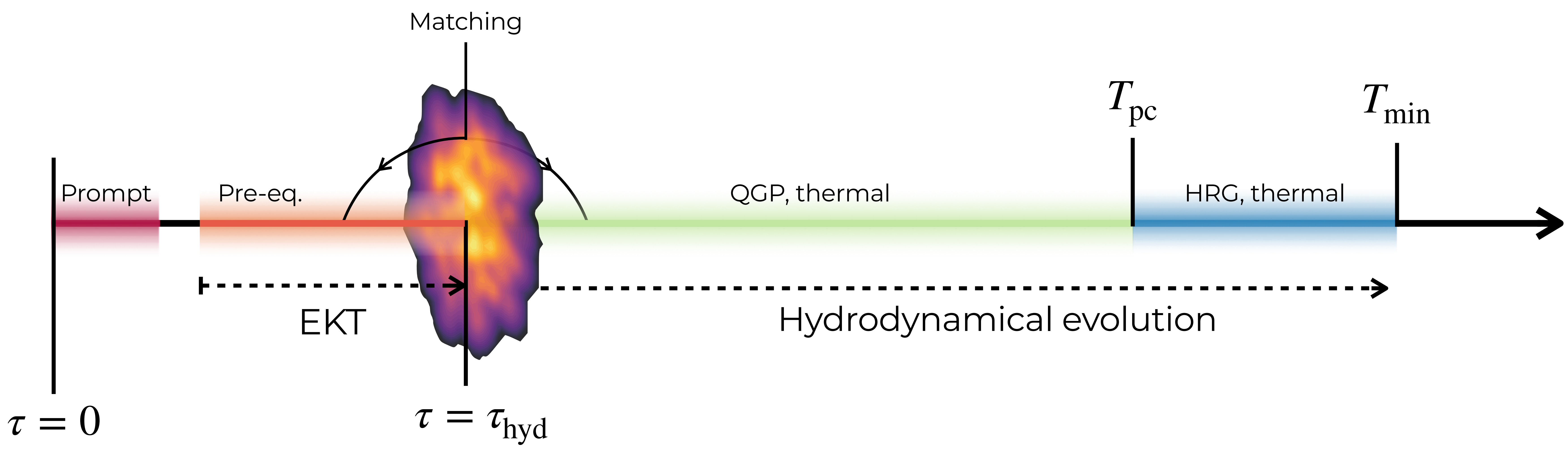
$$\frac{dN}{d^2x_T d^2p_T dy} = (\eta/s)^2\ \tilde{C}_\gamma^{ideal}\ \mathcal{N}_\gamma\left(\tilde{w}, \sqrt{\eta/s}p_T/\left(T\tau^{1/3}\right)_\infty^{3/2}\right)$$

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:

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

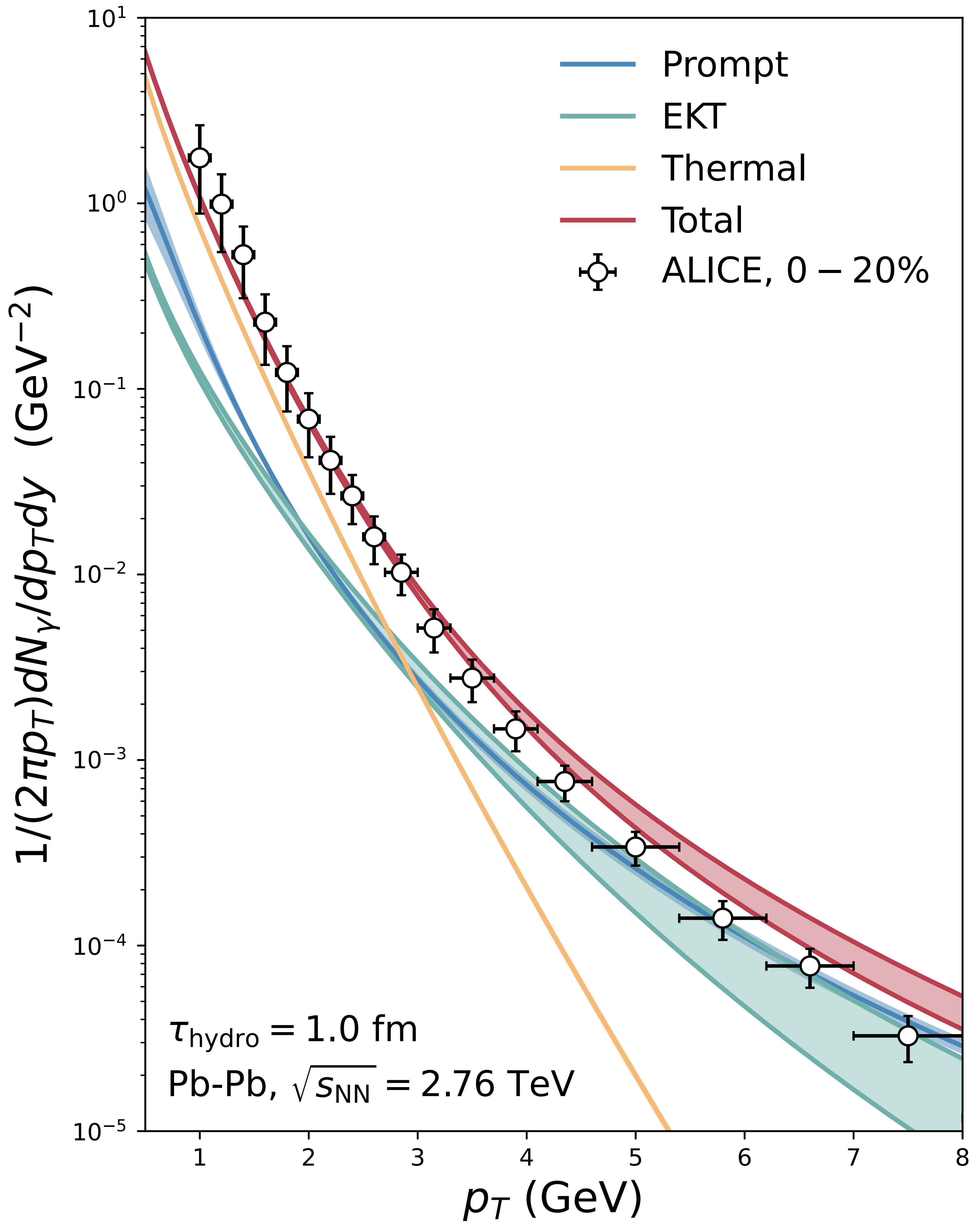
PHOTONS - PHENOMENOLOGY

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

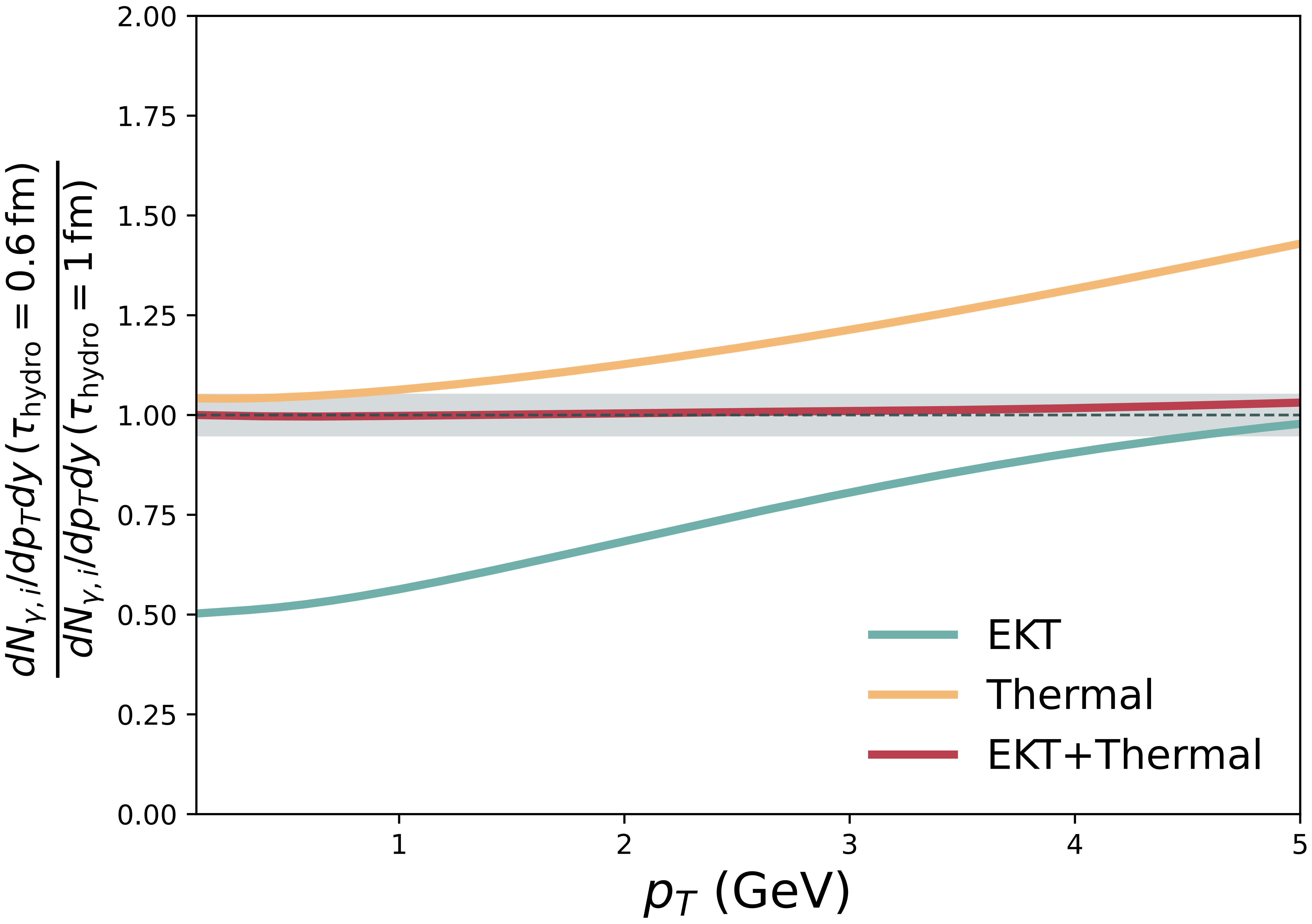
  [Garcia-Montero et al., *Phys.Rev.C*, (2020)]

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

- Sensitivity to initialisation time and initial conditions.



RESULTS - PHENOMENOLOGY

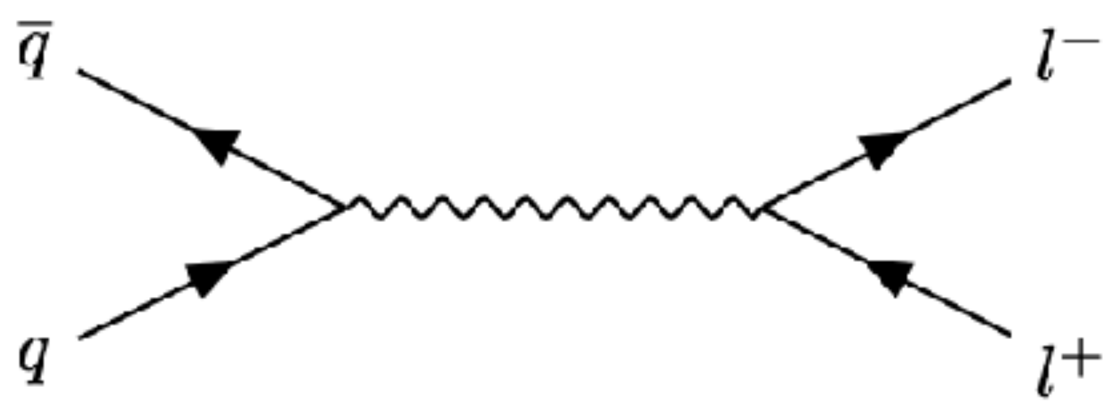


- Variations on $\tau_{\rm hyd}$ trigger differences on the specific contributions of the yield
- Total in medium contribution (EKT+Thermal) is relatively unchanged

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

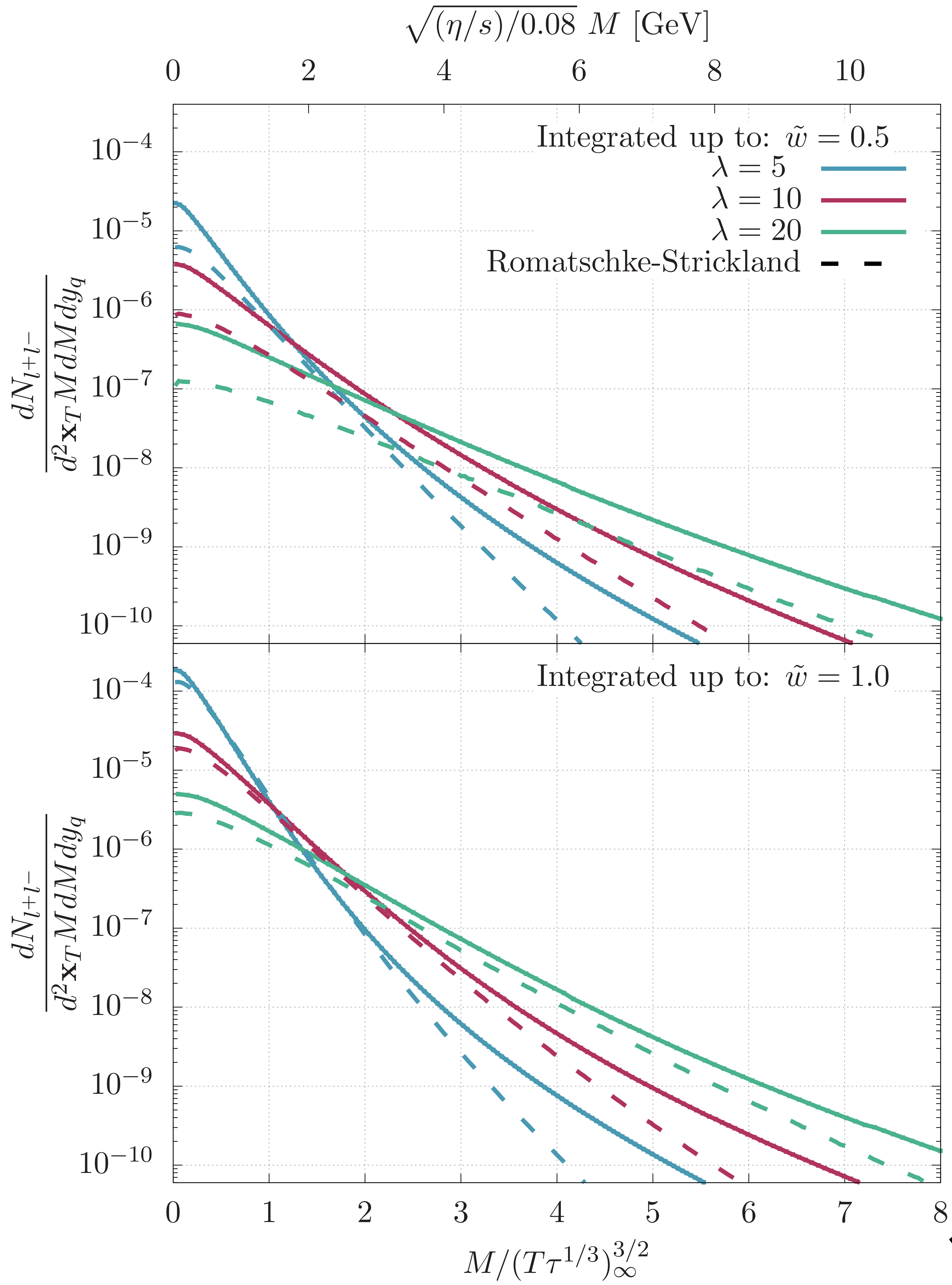
DILEPTON PRODUCTION

- LO dilepton production via 2-2 quark annihilation



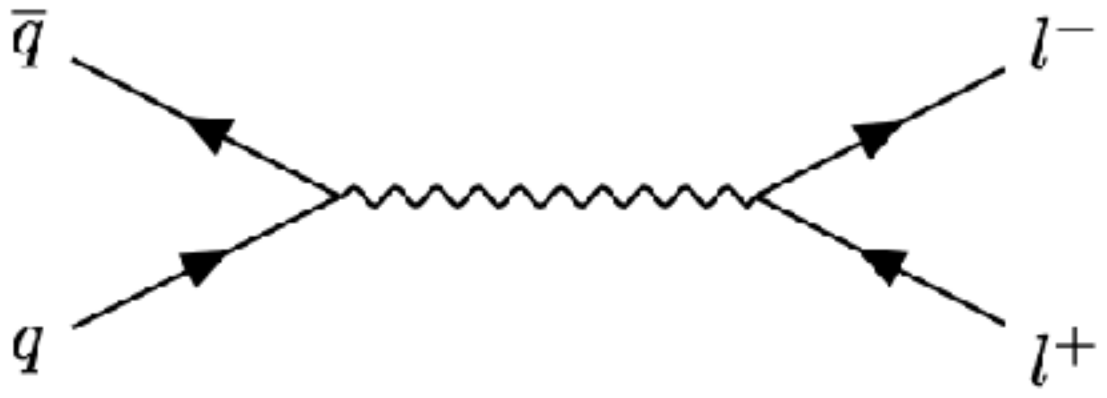
- Analytically and numerically (EKT) found scaling for dileptons

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



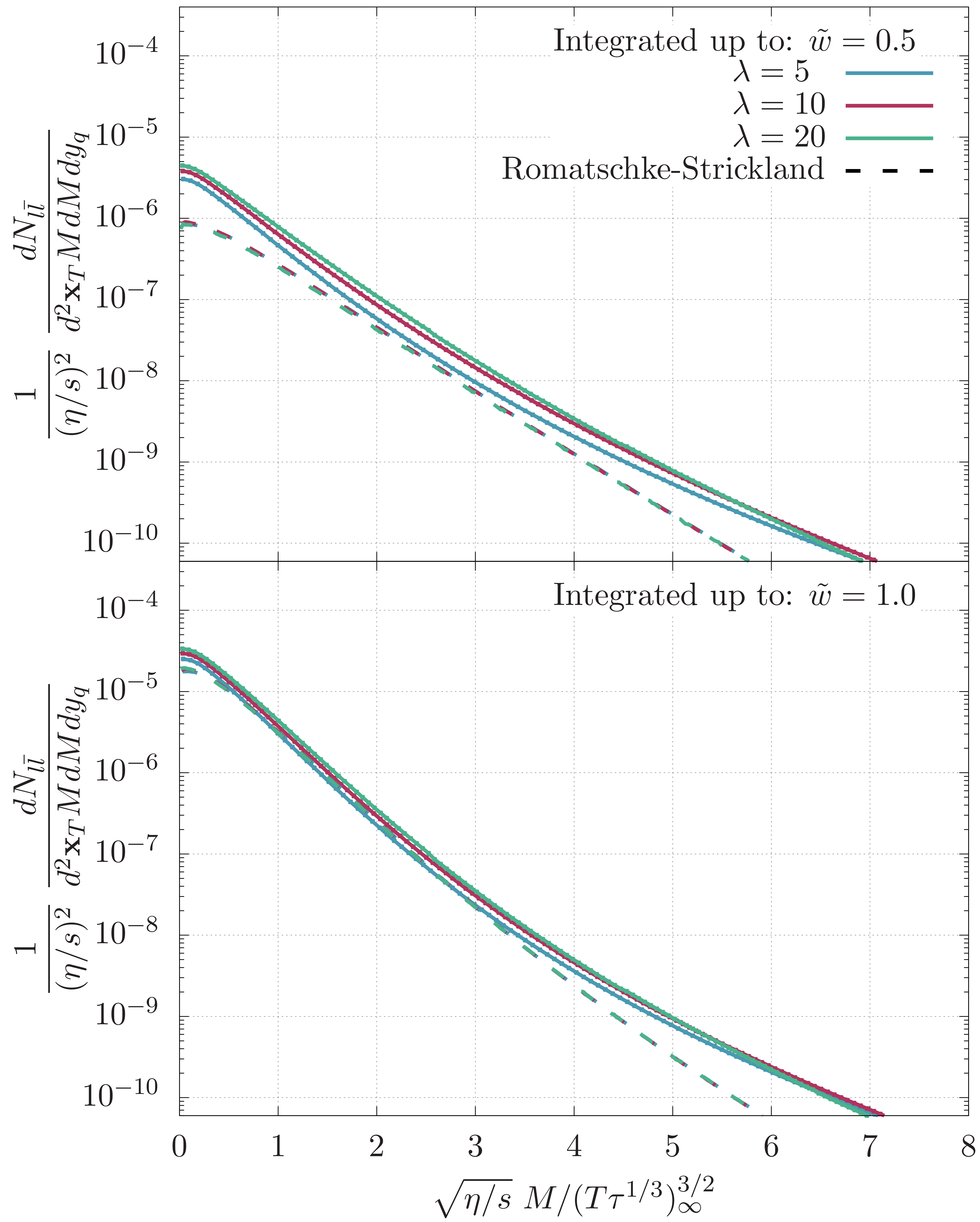
DILEPTON PRODUCTION

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



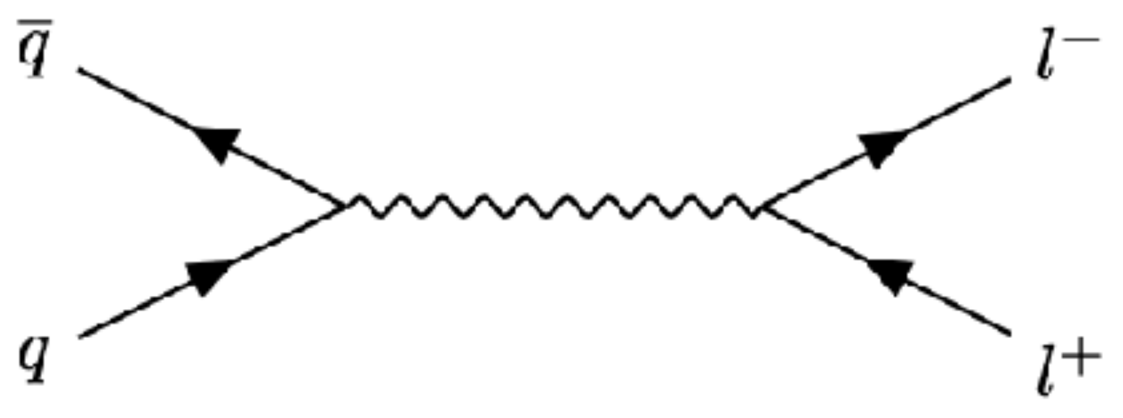
- Analytically and numerically (EKT) found scaling for dileptons

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



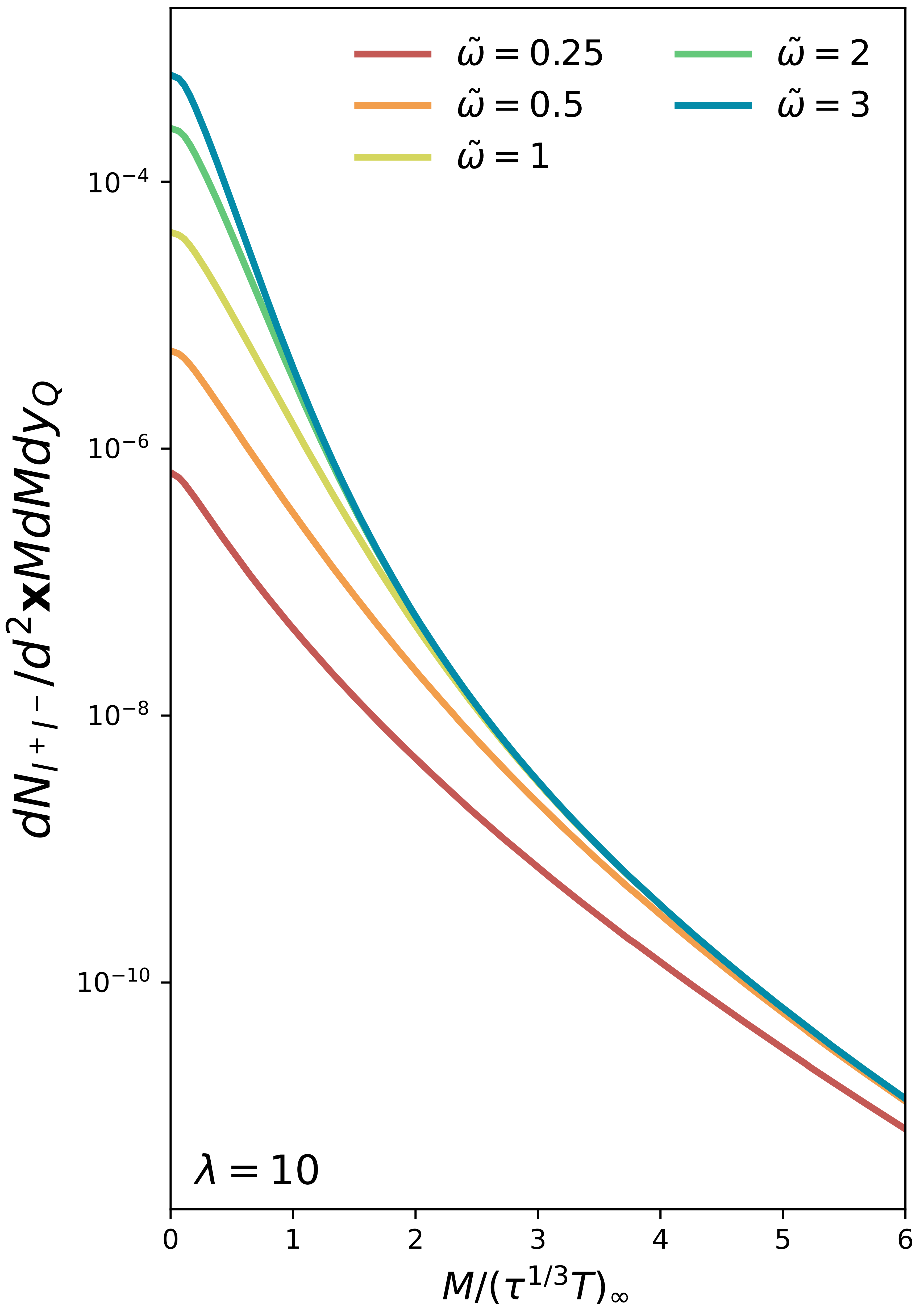
DILEPTON PRODUCTION

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



- Analytically and numerically (EKT) found scaling for dileptons

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



RESULTS - PHENOMENOLOGY

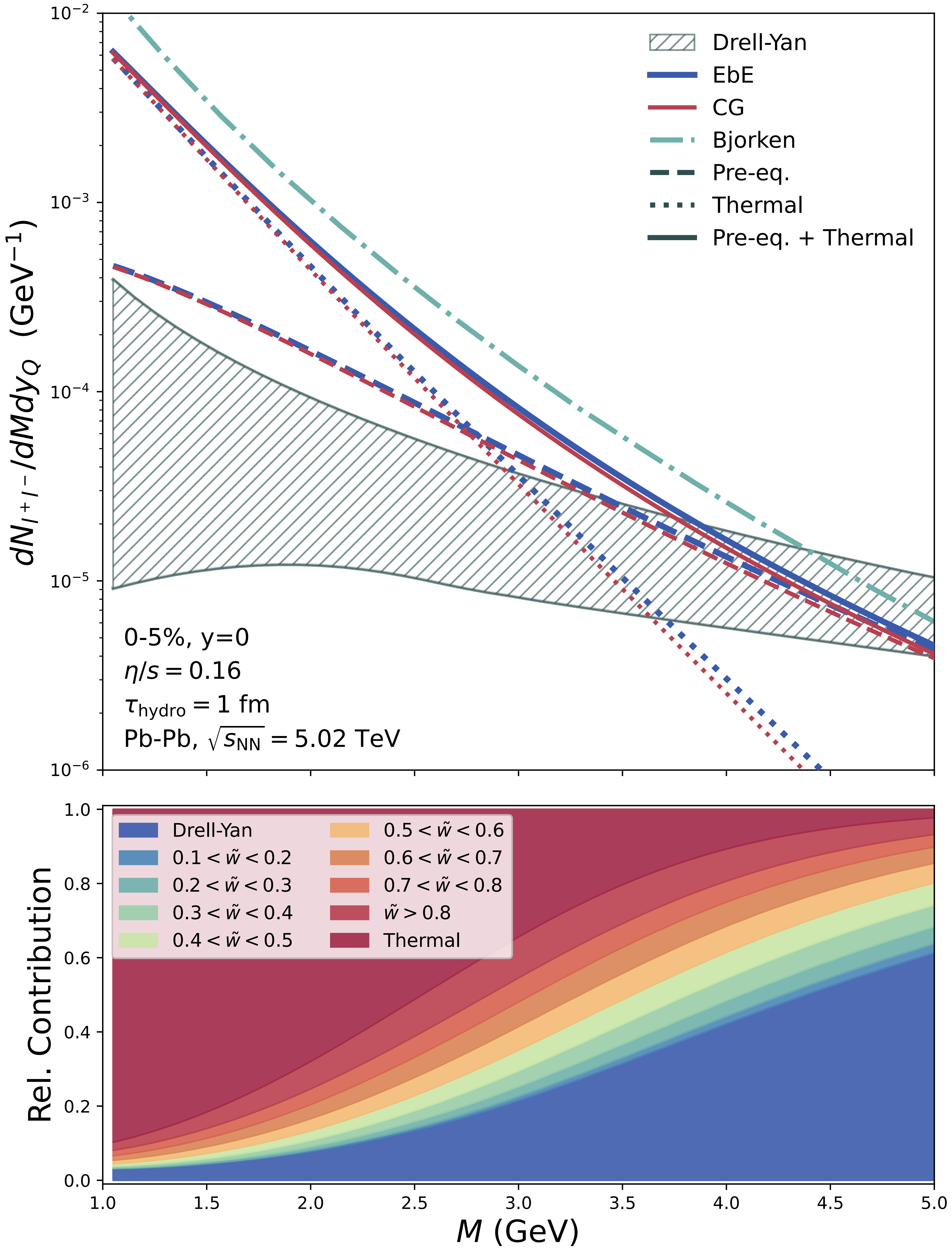
- Pre-eq. dilepton production event-by-event using a background evolution obtained from *Trajectum* tuned to 0-20% PbPb collisions at 5.02 TeV

  [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)]

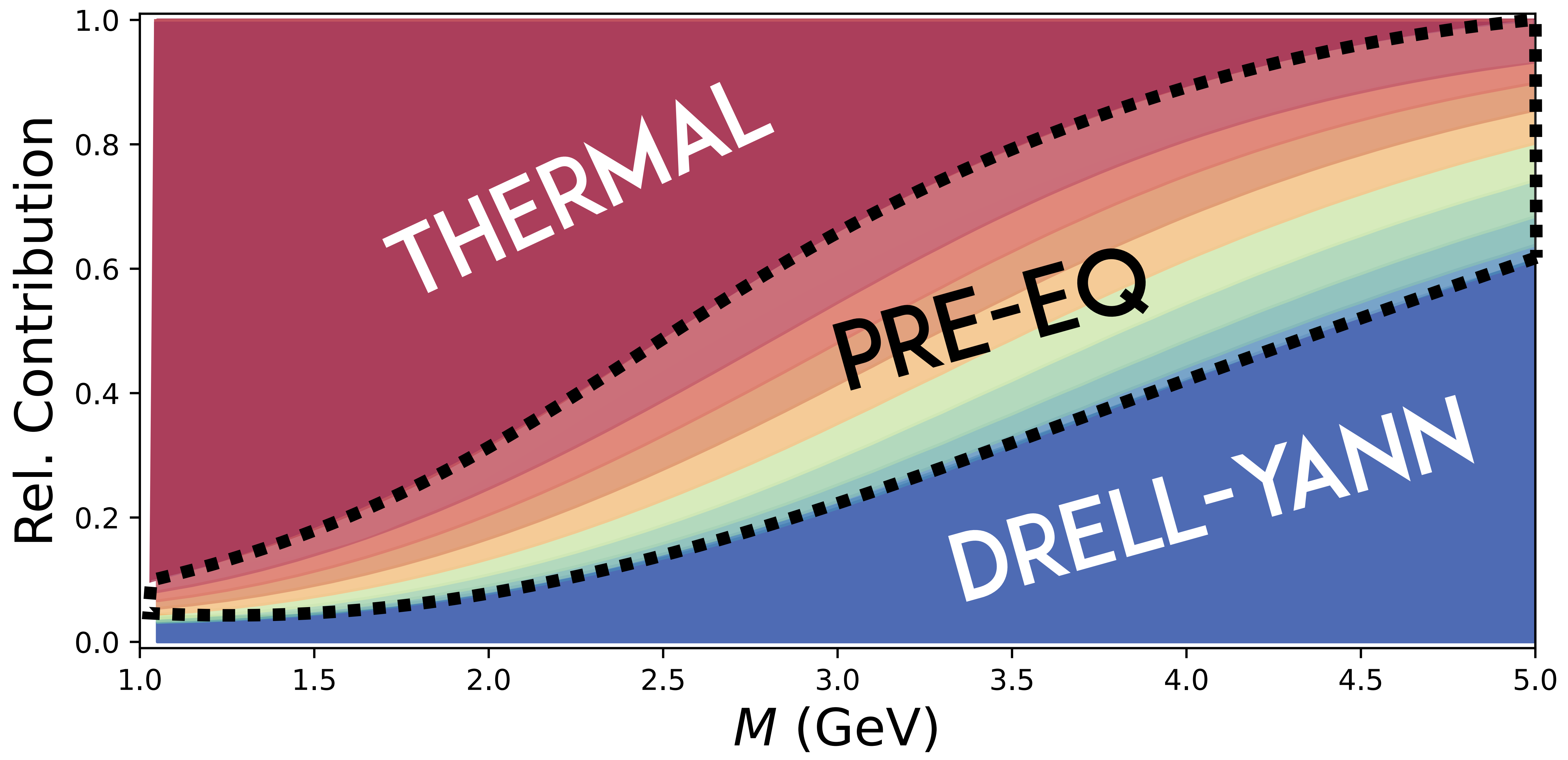
- Pre-equilibrium production relevant between $p_T \sim 2 - 5$ GeV

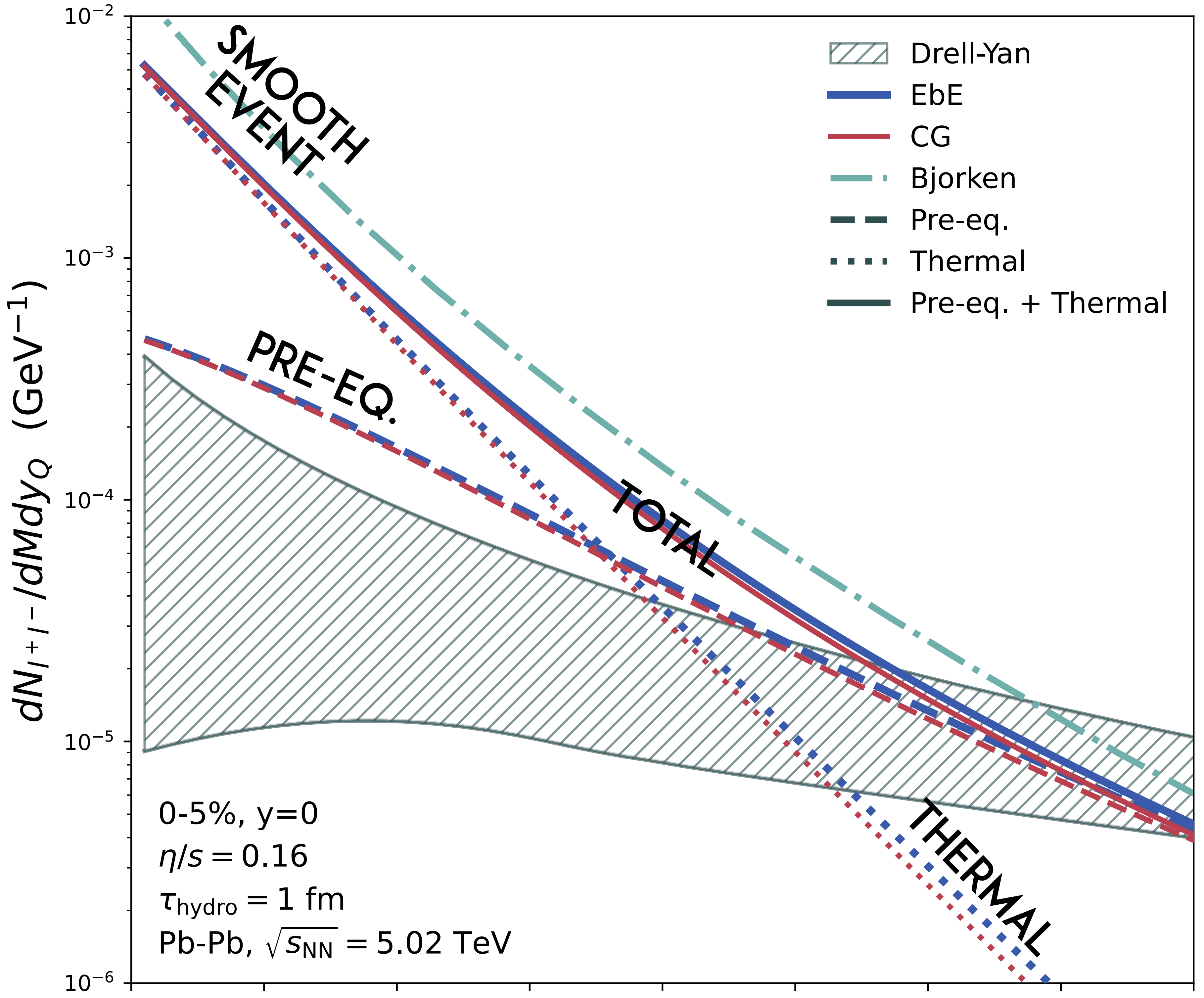


RESULTS - PHENOMENOLOGY

- 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)]



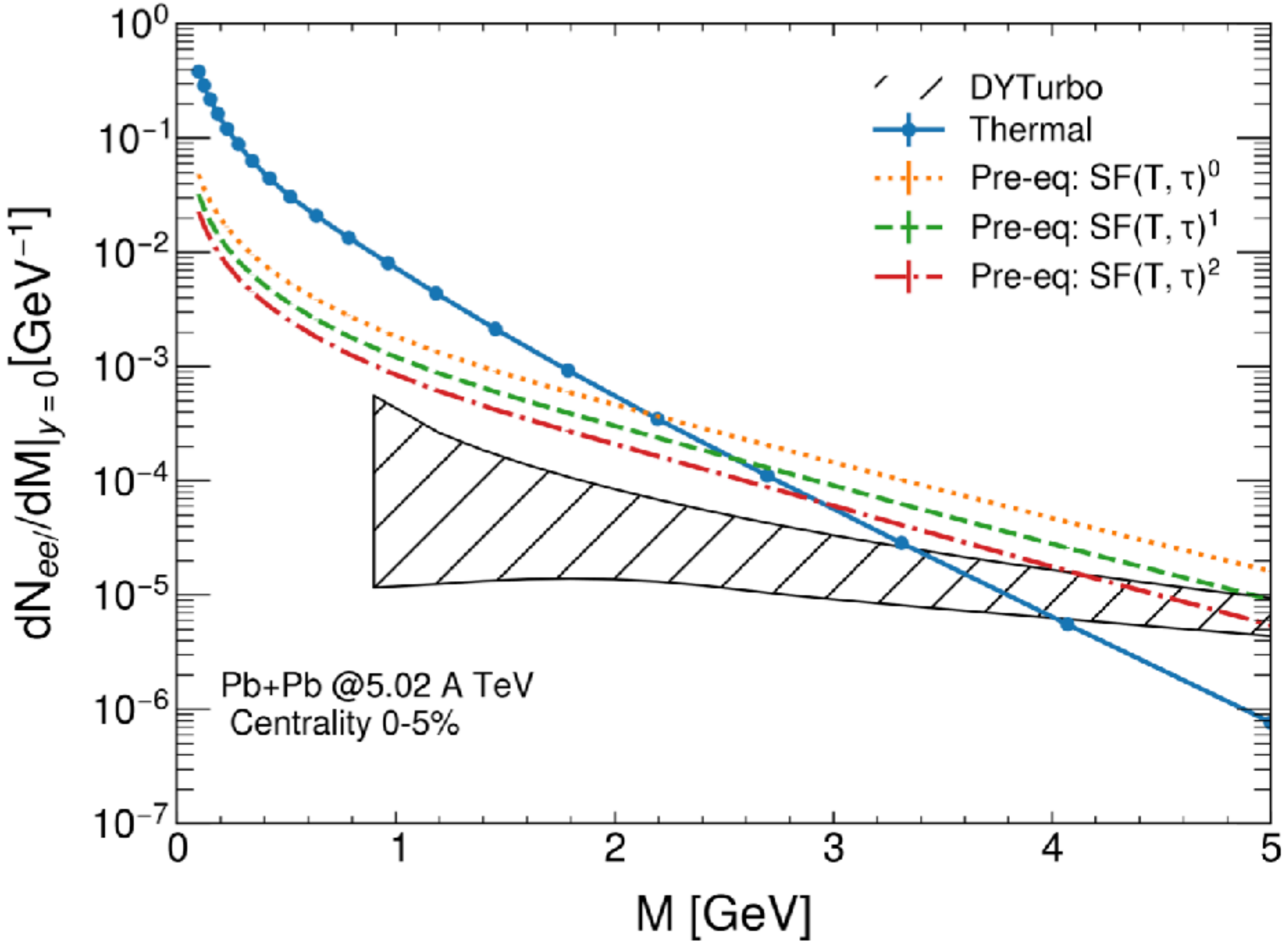


A COMMENT ON DILEPTON PHENO

- Interesting Point:
  [*Phys.Rev.C* 110 (2024) 5, 054904]

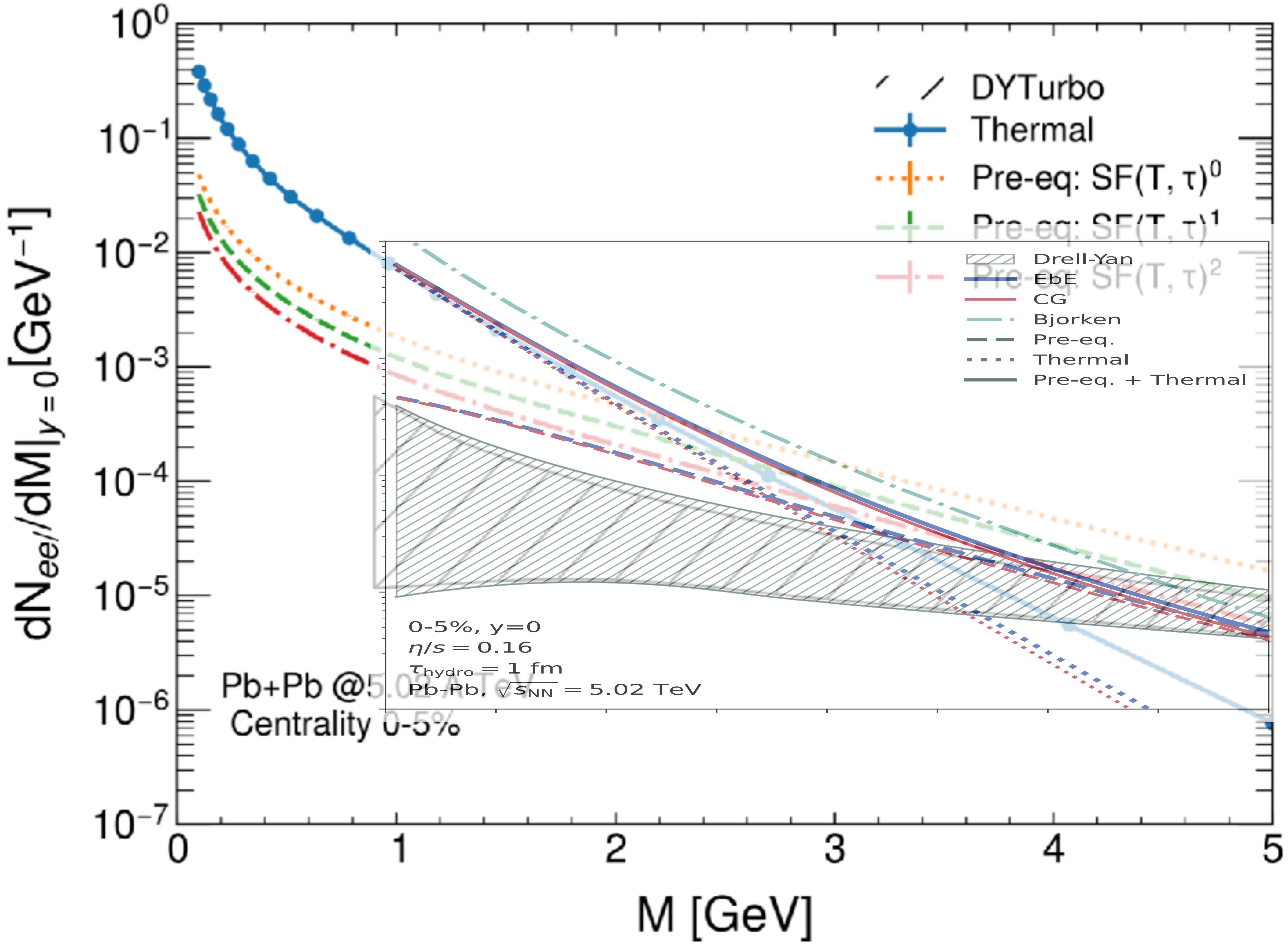
- Dilepton Production in another realistic hybrid setting (IP-Glasma + KøMPøST + MUSIC + UrQMD)

- Dilepton production through **thermal rates,** evaluated at some effective Temperature, extracted from KøMPøST.



A COMMENT ON DILEPTON PHENO

- Interesting Point:
  [*Phys.Rev.C* 110 (2024) 5, 054904]
- Dilepton Production in another realistic hybrid setting (IP-Glasma + KøMPøST + MUSIC + UrQMD)
- Dilepton production through **thermal rates,** evaluated at some effective Temperature, extracted from KøMPøST.



YIELDS MAY NOT BE ENOUGH

We need to be smarter to separate these contributions

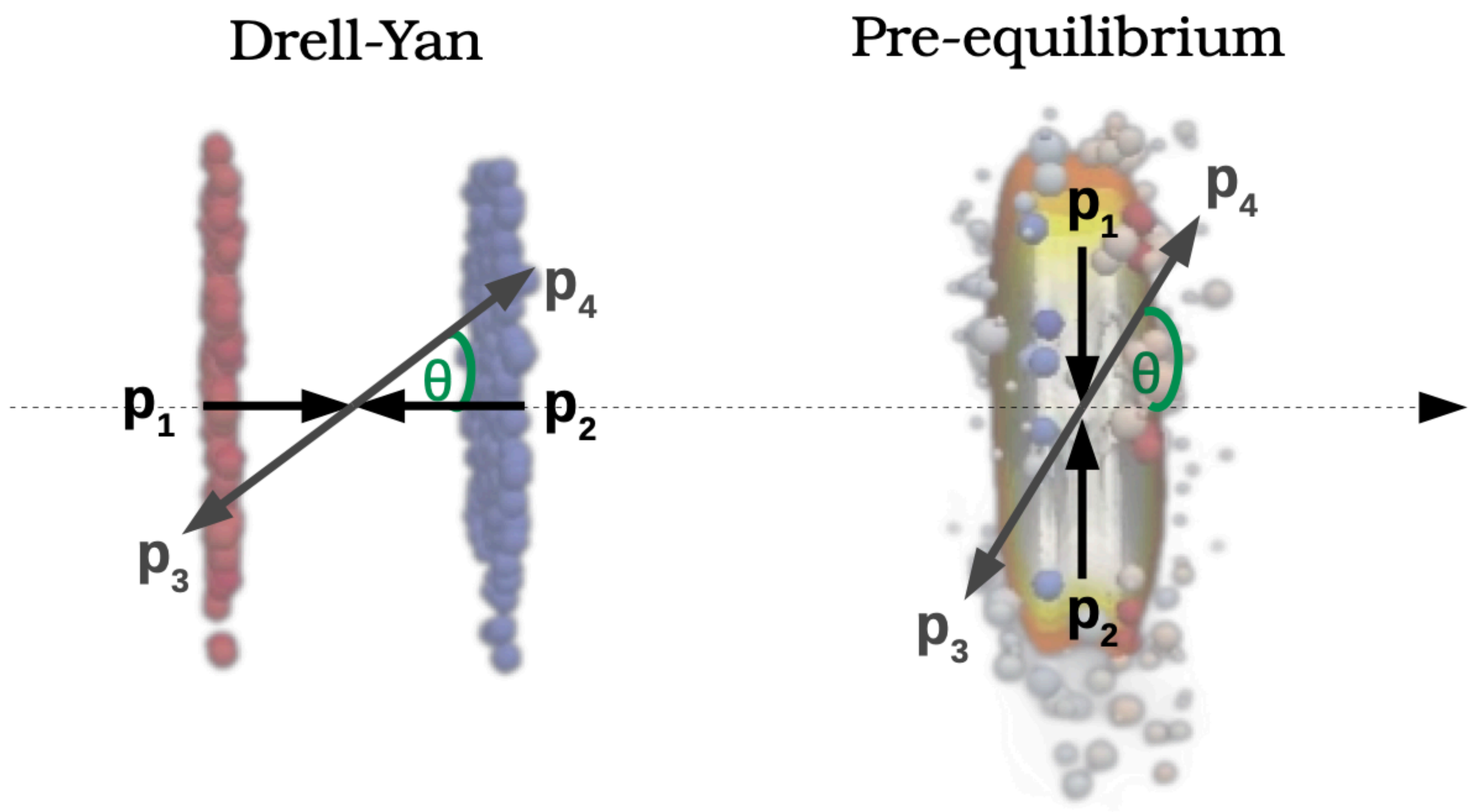
PROMISING: DILEPTON POLARIZATION

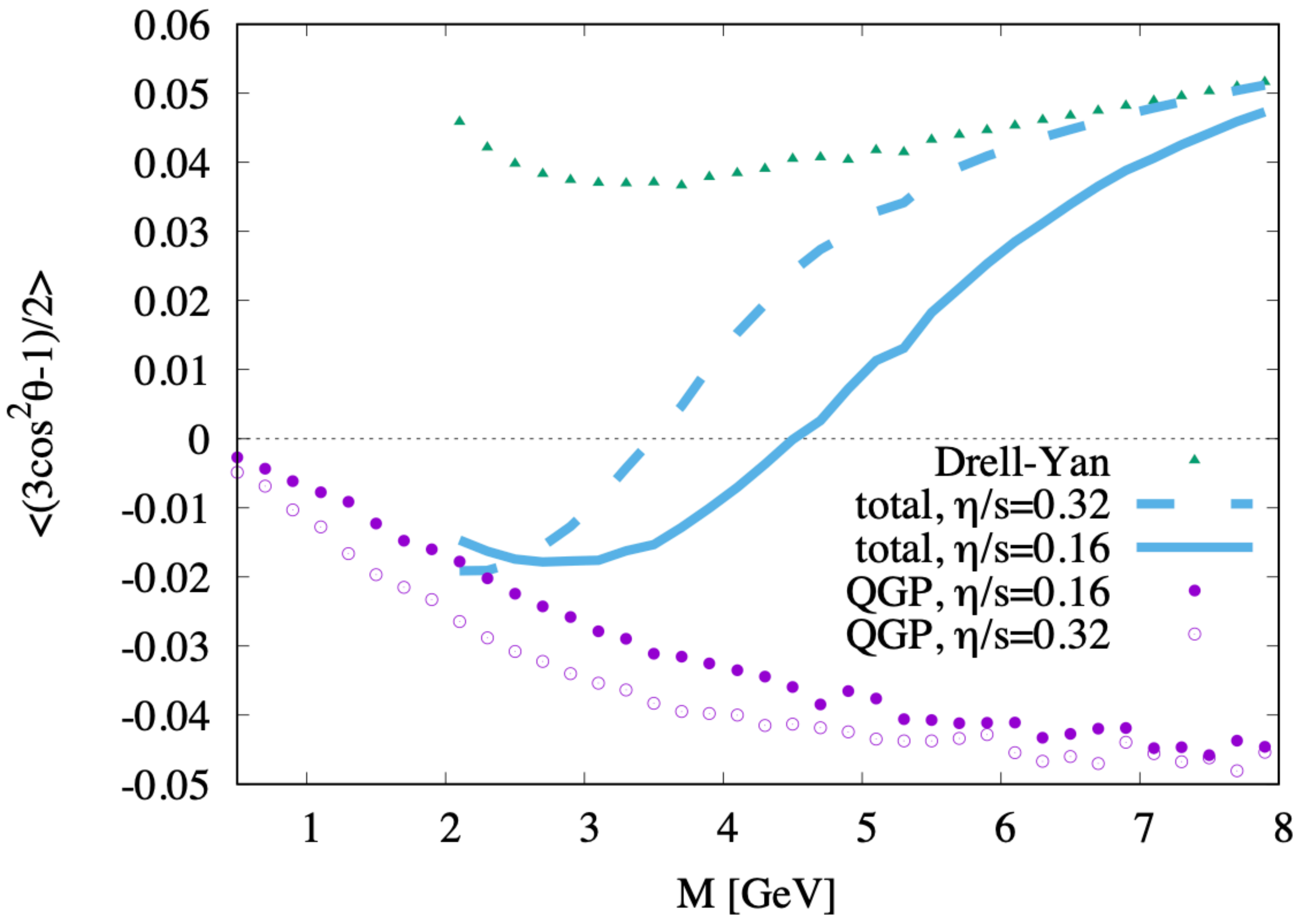
- At intermediate masses $M \sim 1.2 - 4\,\mathrm{GeV}$ dilepton radiation from the QGP is expected to exceed Drell-Yann

- We need a handle to separate them:
  New observable: the quadrupole moment of the lepton distribution →Negative for QGP, positive for Drell-Yan

$$\left\langle \frac{3\cos^2\theta - 1}{2} \right\rangle \equiv \frac{\int_{-1}^{1} d\cos\theta \; \frac{1}{2}(3\cos^2\theta - 1) \frac{dN}{d\cos\theta}}{\int_{-1}^{1} d\cos\theta \; \frac{dN}{d\cos\theta}}.$$

- Measurement of this observable in future LHC experiments will provide a first direct experimental constraint on the isotropization time of the quark-gluon plasma.





[*PRL* 132 (2024) 23, 232301]

WE ARE NOT DONE YET

TO DO LIST

Dileptons: We need to go more differential

Can we do **dilepton correlations**? Is it feasible?

How sensitive are EM-Probes to the initial state:
- Fluctuations
- Initial Charges

EM-Probe Flow *in the pre-equilibrium stage? Can we do it?*

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

ARE EM-PROBES SENSITIVE TO THE INITIAL FLUCTUATIONS?

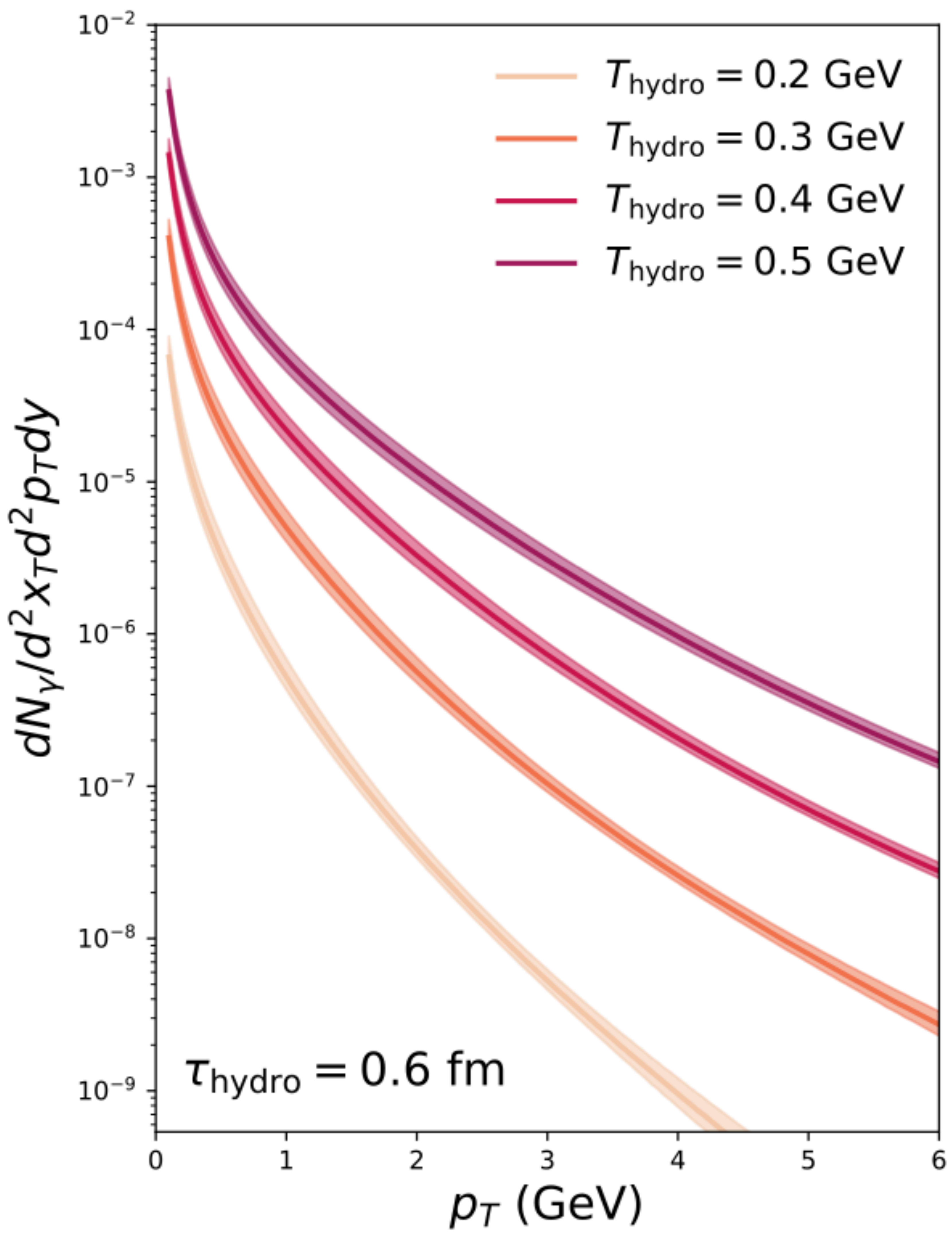
- Photon rate $\Gamma \sim T^2 e^{-E/T}$, dilepton rate $\Gamma \sim T e^{-E/T}$

It is reasonable to think that such rates can be affected by the deposited energy density and the "peakiness" of the event

- McDIPPER v1.2 + ShinyKøMPøST for Pb-Pb collisions @ 5.02 TeV

Two Setups

- Smooth Nucleons
- Hotspots



ARE EM-PROBES SENSITIVE TO THE INITIAL FLUCTUATIONS?

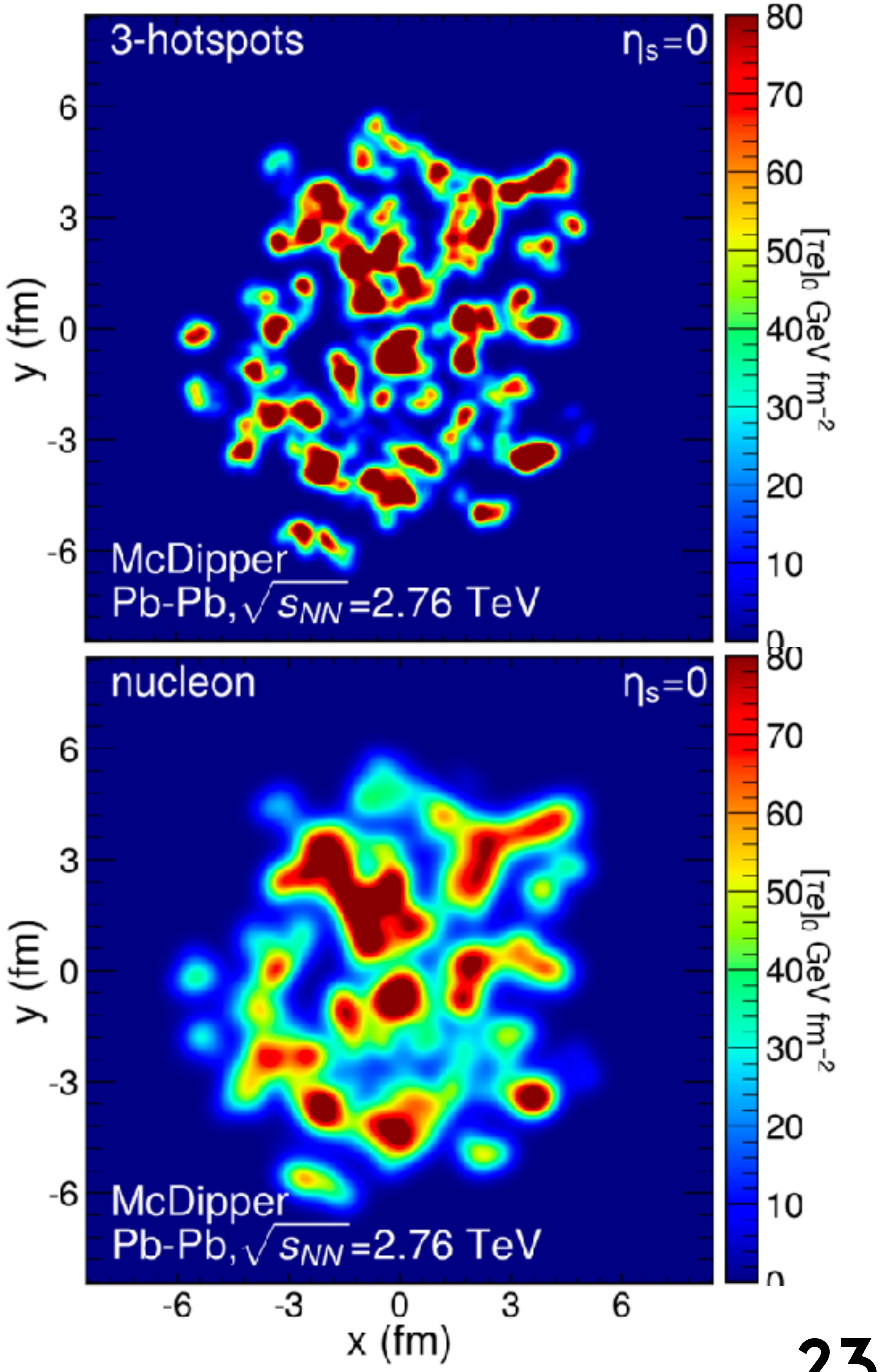
- Photon rate $\Gamma \sim T^2 e^{-E/T}$, dilepton rate $\Gamma \sim T e^{-E/T}$

It is reasonable to think that such rates can be affected by the deposited energy density and the "peakiness" of the event

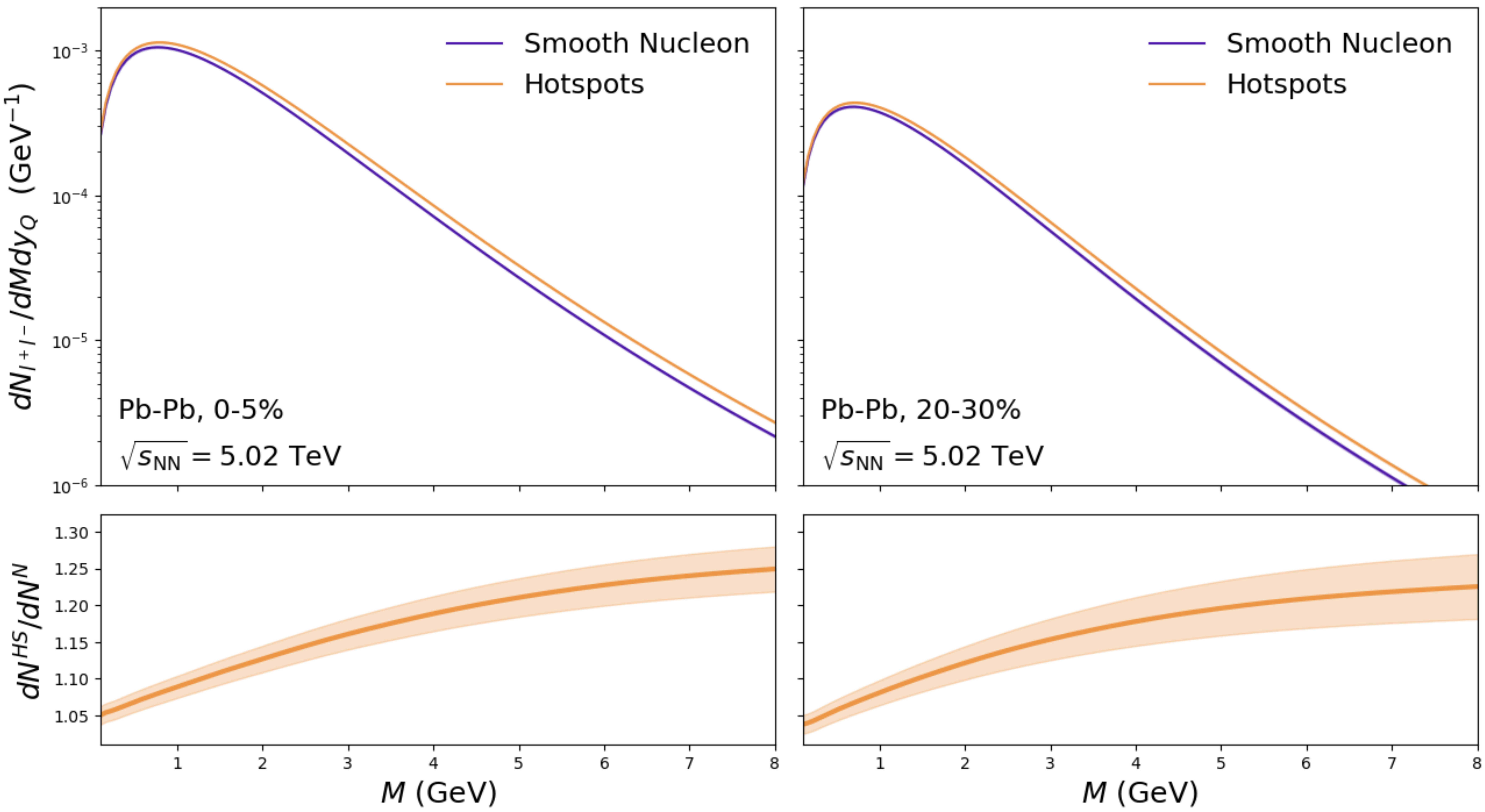
- McDIPPER v1.2 + ShinyKøMPøST for Pb-Pb collisions @ 5.02 TeV

Two Setups

- Smooth Nucleons
- Hotspots



ARE EM-PROBES SENSITIVE TO THE INITIAL FLUCTUATIONS?



WE ARE NOT DONE YET

TO DO LIST

Dileptons: We need to go more differential

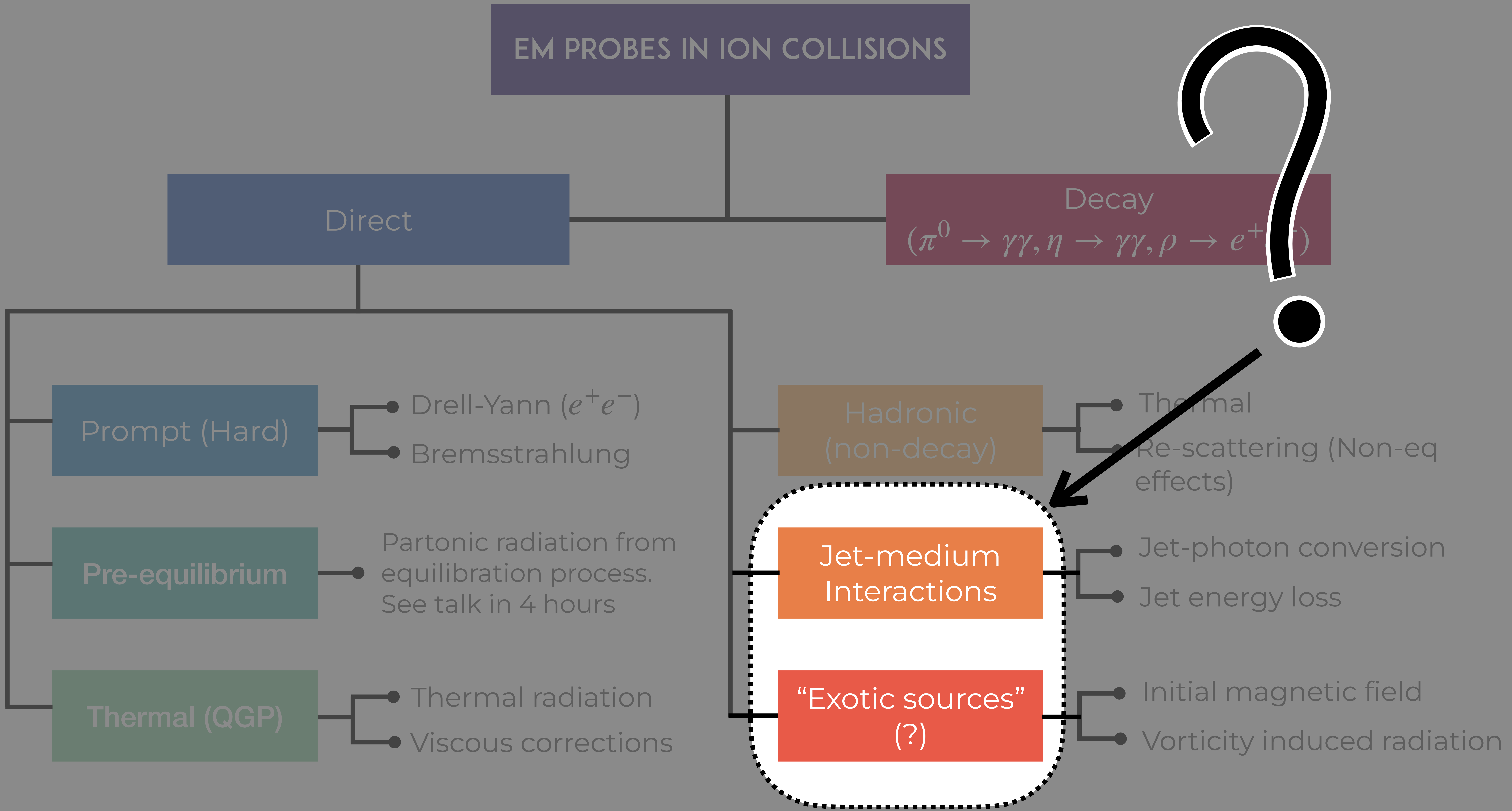
Can we do **dilepton correlations**? Is it feasible?

How sensitive are EM-Probes to the initial state:
- Fluctuations
- Initial Charges

EM-Probe Flow *in the pre-equilibrium stage? Can we do it?*

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

POST CREDITS SCENE



EM PROBES IN ION COLLISIONS
Direct
Decay
$(\pi^0 \to \gamma\gamma, \eta \to \gamma\gamma, \rho \to e^+$
Prompt (Hard)
Drell-Yann (e^+e^-)
Bremsstrahlung
Pre-equilibrium
Partonic radiation from equilibration process. See talk in 4 hours
Thermal (QGP)
Thermal radiation
Viscous corrections
Hadronic (non-decay)
Thermal
Re-scattering (Non-eq effects)
Jet-medium Interactions
Jet-photon conversion
Jet energy loss
"Exotic sources" (?)
Initial magnetic field
Vorticity induced radiation
?

WE ARE NOT DONE YET

TO DO LIST

Dileptons: We need to go more differential

Can we do **dilepton correlations**? Is it feasible?

How sensitive are EM-Probes to the initial state:
- Fluctuations
- Initial Charges

EM-Probe Flow *in the pre-equilibrium stage? Can we do it?*

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