Non-equilibrium photons from the thermalizing Glasma

Oscar Garcia-Montero

Institute for Theoretical Physics
Goethe Universität Frankfurt

GARCIA@FIAS.UNI-FRANKFURT.DE

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

isoQuant SFB1225

In collaboration with J. Berges, Nicole Löher, A. Mazeliauskas and K. Reygers

Based on: Garcia-Montero, **arXiv:1909.12294**
Garcia-Montero *et al* , **arXiv:1909.12246**

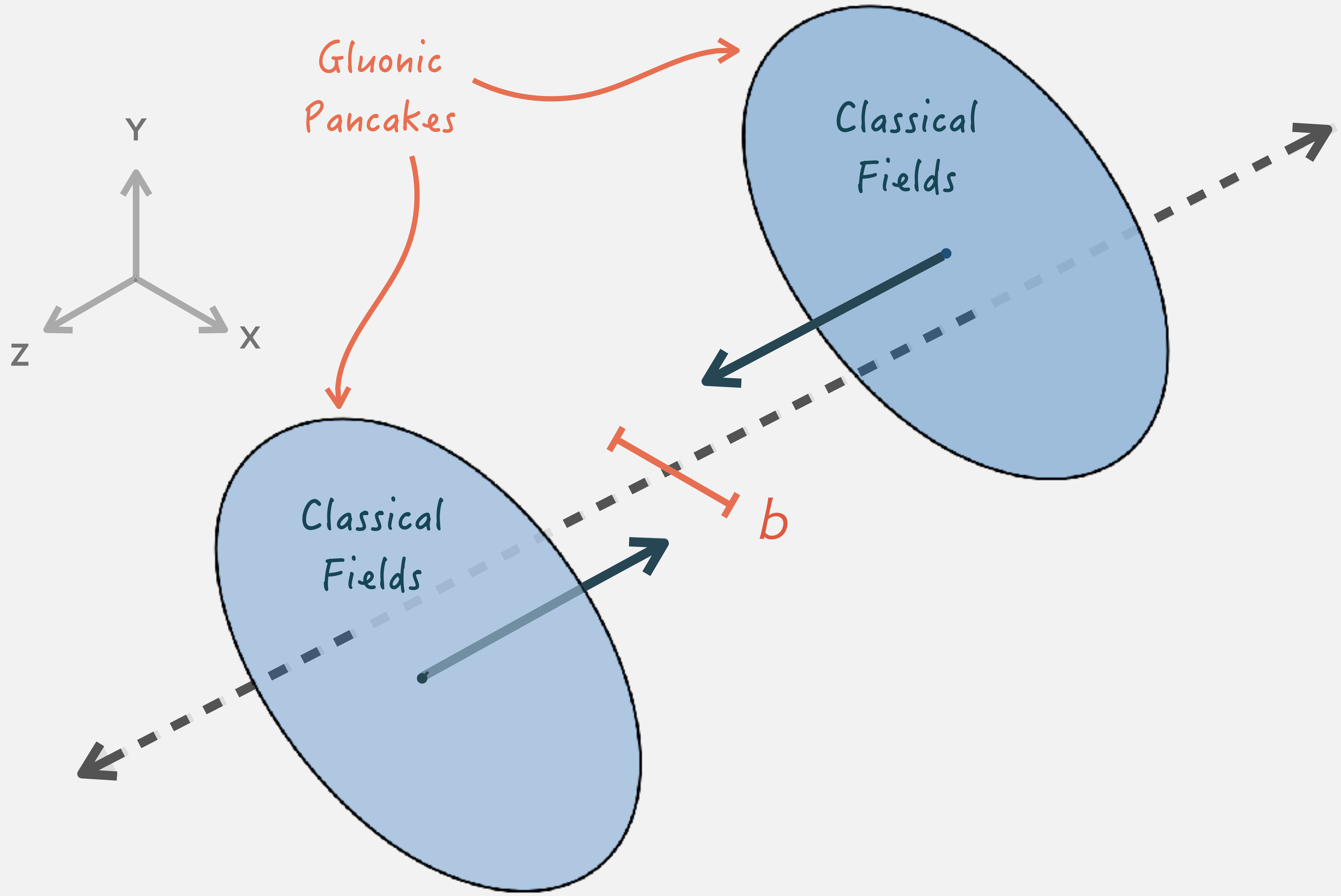
CRC-TR 211
Strong-interaction matter under extreme conditions

Contents

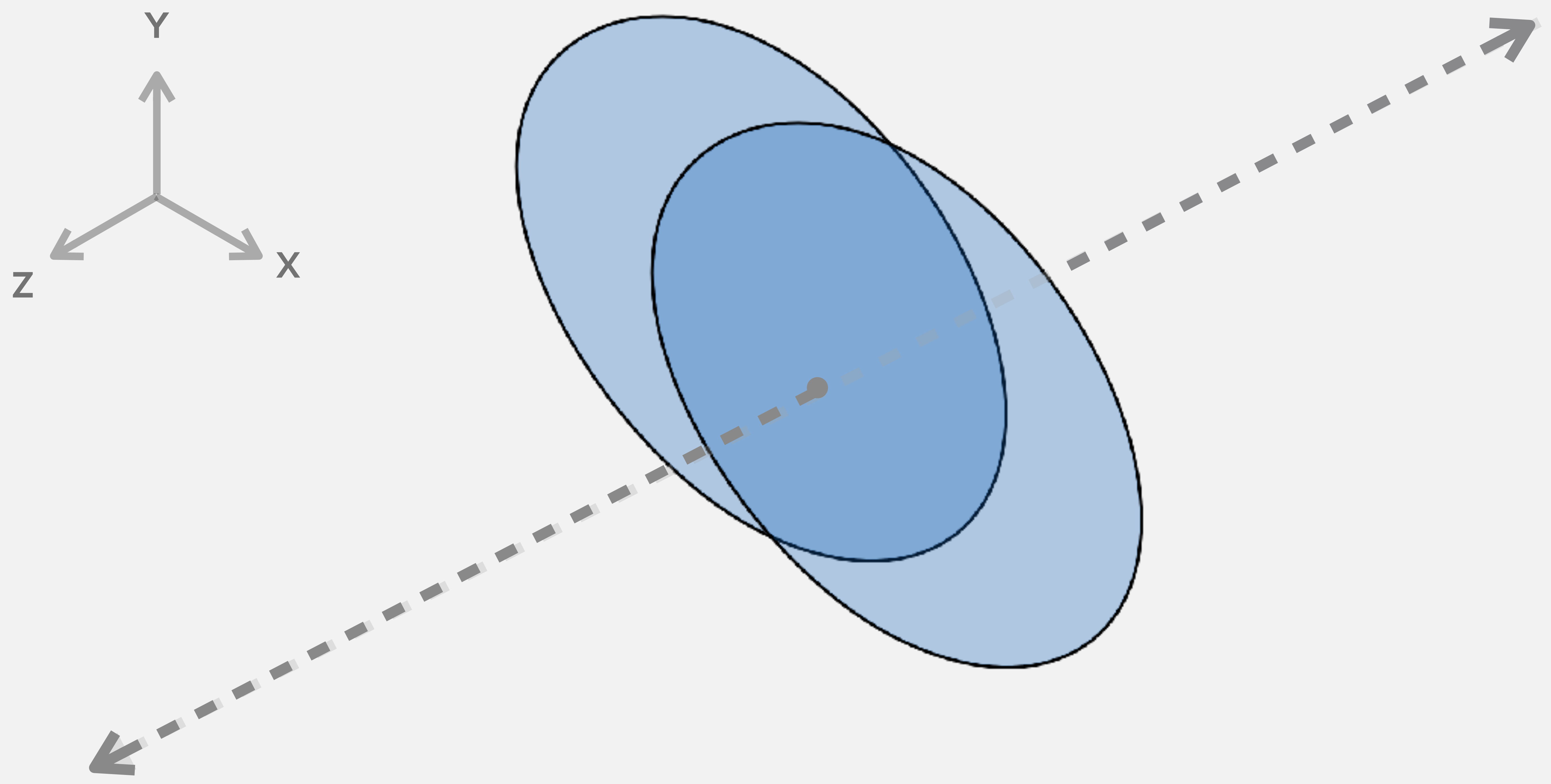
Early Stages and Turbulence

(Retitled: **highly occupied non-abelian** plasmas very far from equilibrium)

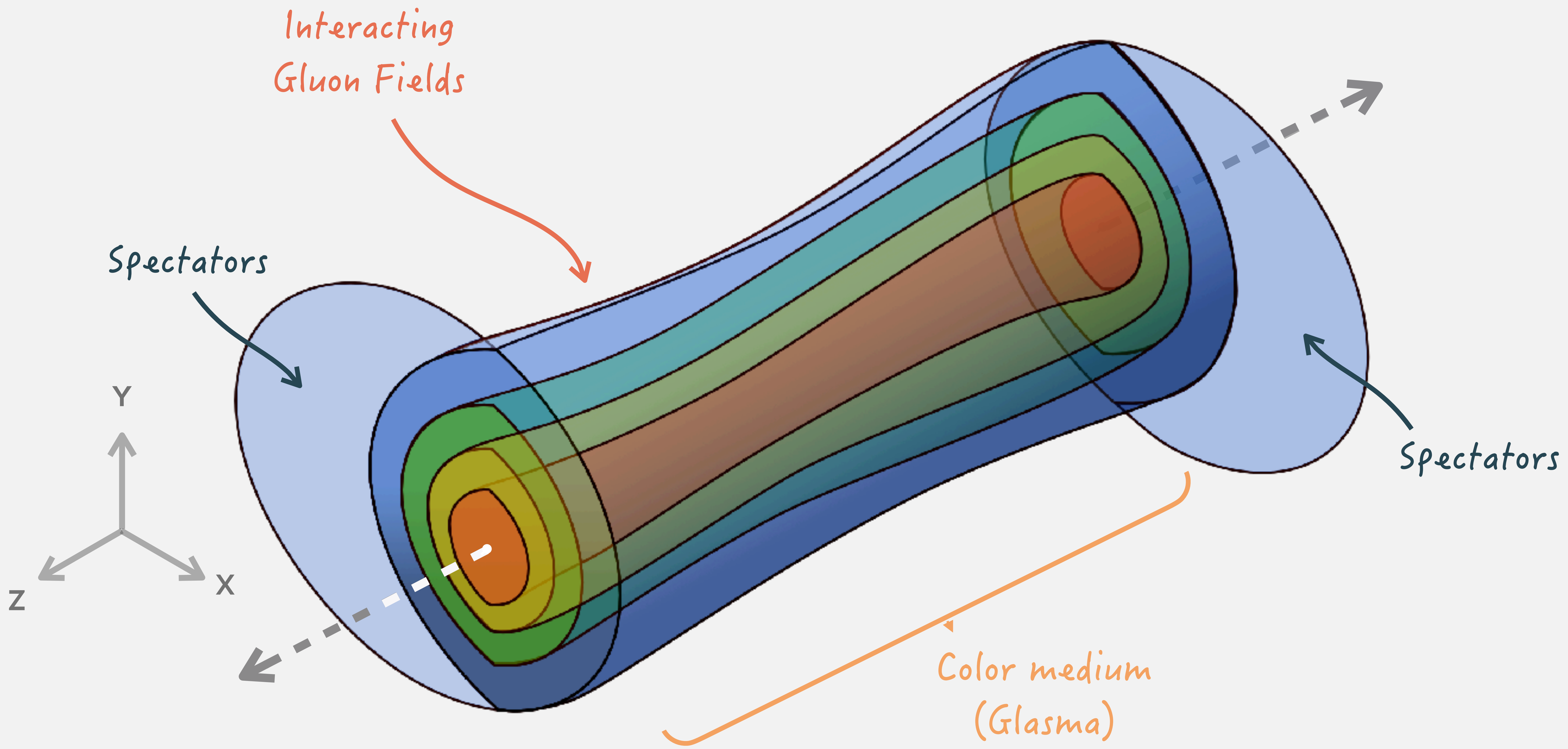
Ultra-relativistic Nucleus-Nucleus (A+A) Collisions



Ultrarelativistic Nucleus-Nucleus (A+A) Collisions



Ultrarelativistic Nucleus-Nucleus (A+A) Collisions



Turbulent thermalization

Classical Fields → **High Occupancy** → **Turbulence**

Color Glass Condensate is the energy source of the system.

Fast production of particles via quantum fluctuations and secondary plasma instabilities.

Relaxation period. Energy flows from IR source to UV sink. Memory loss.

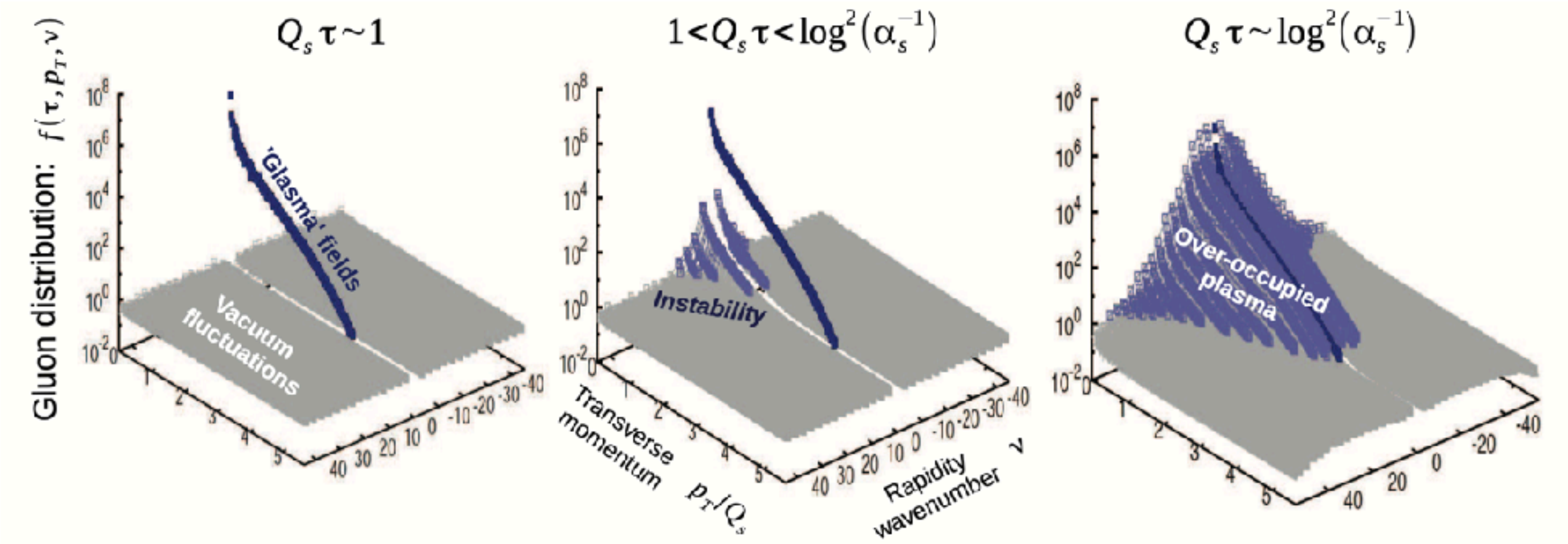


Fig. from Berges *et al.* Nucl. Phys. A931, 348 (2014)

Micha and Tkachev, Phys.Rev. D70 (2004) 043538

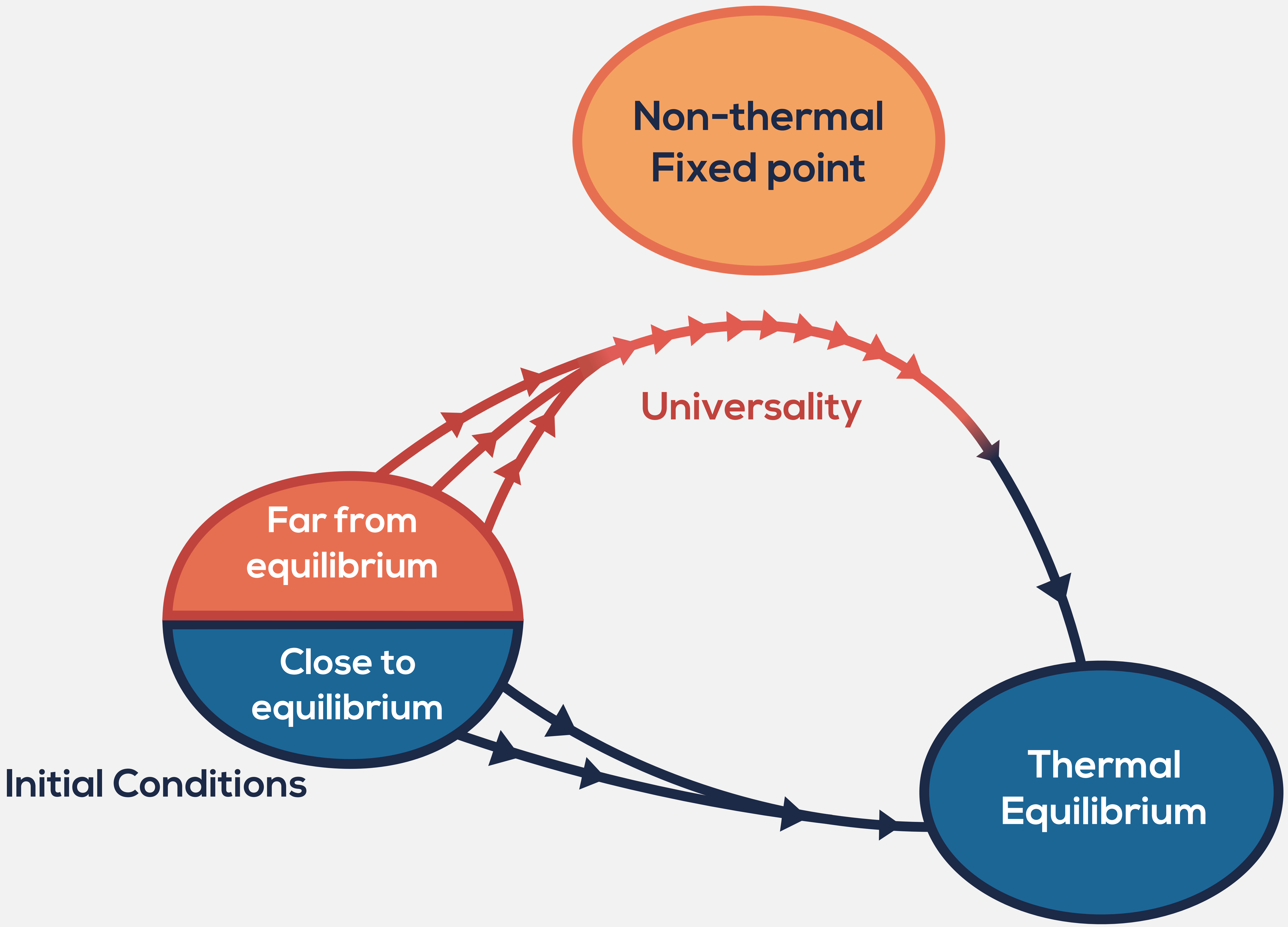
Berges *et al.* Phys.Rev. D89 (2014) no.11, 114007

Berges *et al.* arXiV: *2005.12299*

Epelbaum and Gelis. Phys.Rev. D89 (2014) no.11, 114007

Berges, Boguslavski, Schlichting. Phys. Rev. D 85, 076005

Berges *et al.* JHEP 05, 054 (2014)


Non-thermal
Fixed point
Universality
Far from
equilibrium
Close to
equilibrium
Initial Conditions
Thermal
Equilibrium

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

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

Self - Similarity

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

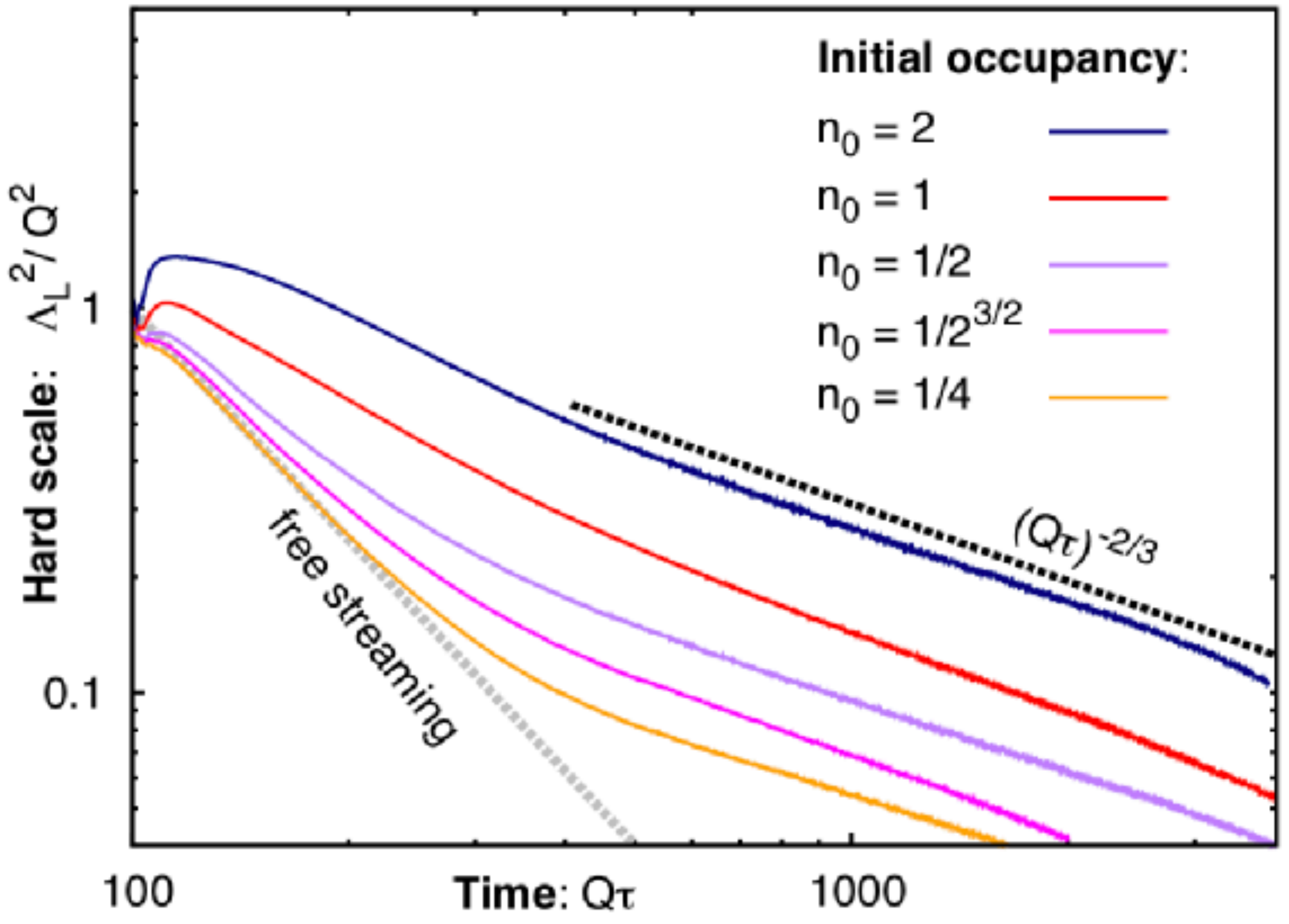
$$f(t,p) = t^{\alpha} f_S(p_\perp t^{\beta}, p_z t^{\gamma})$$

Transport and Turbulence

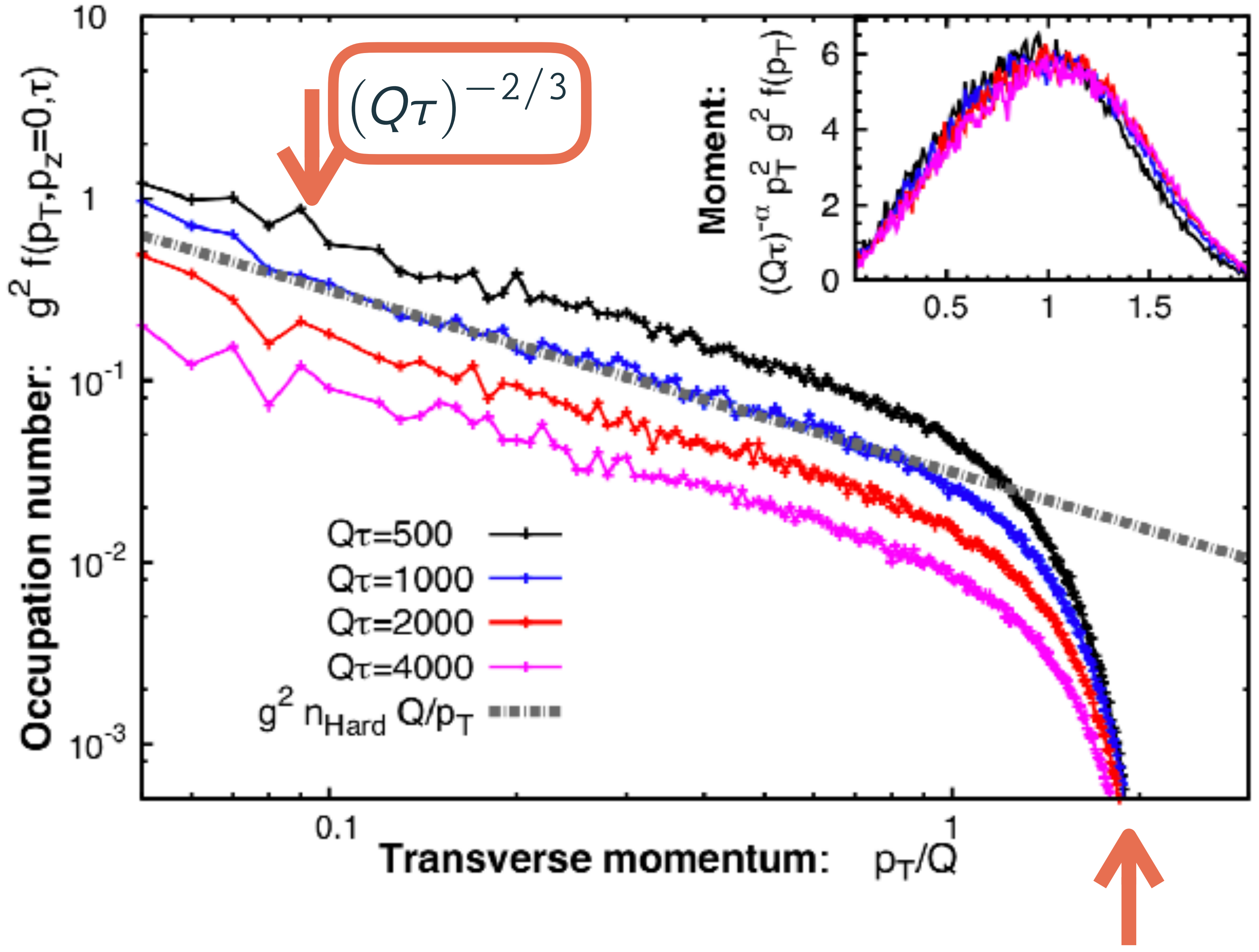
def. Local flow of conserved charges to accommodate better the total corresponding charge. The flow is turbulent when is self-similar

Gluon occupation: High

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



Transverse $p_\perp$

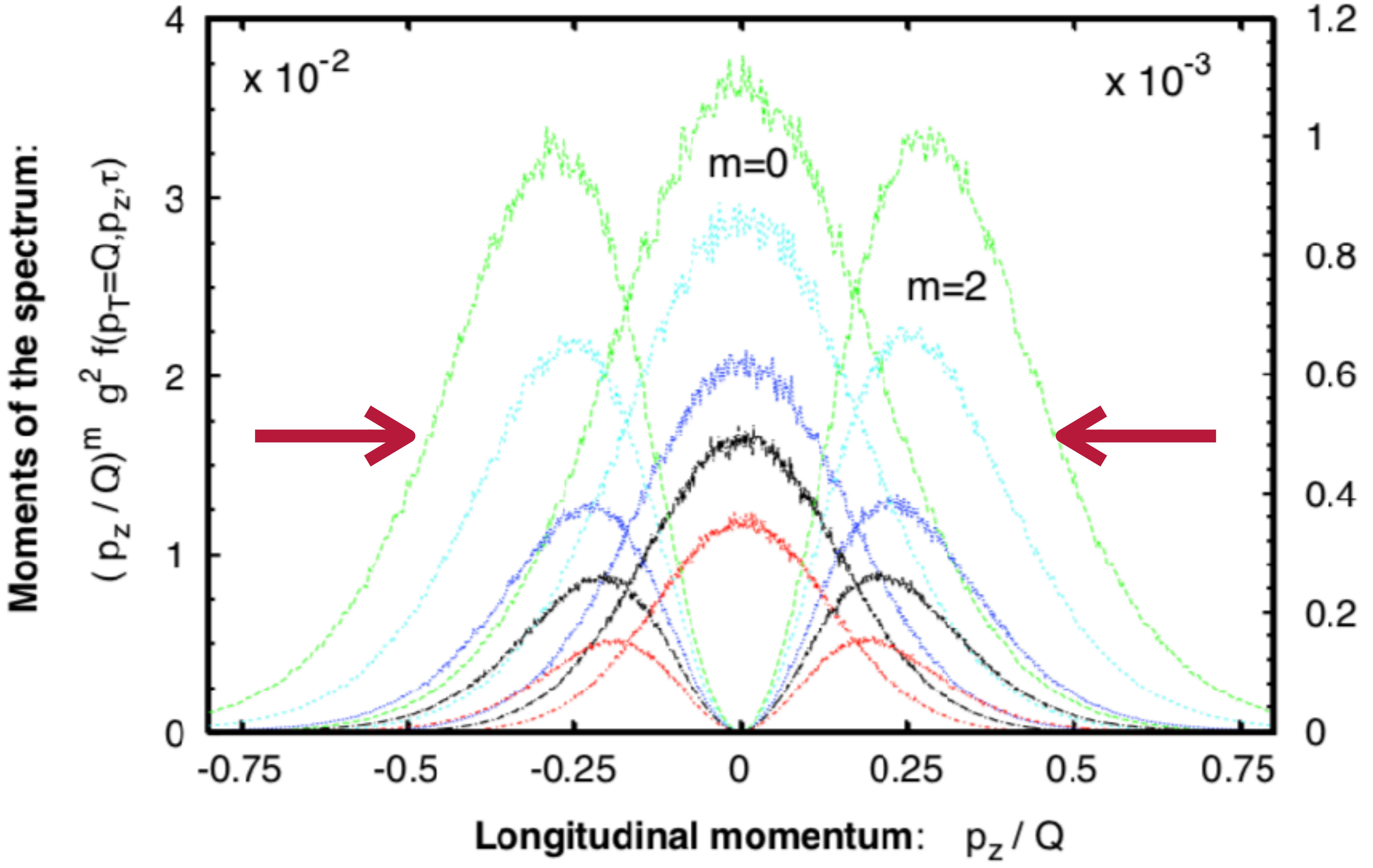


$$f_g\left(\tau, p_\perp, p_z\right) = \frac{1}{\alpha_s}\left(Q_s\,\tau\right)^{\alpha} f_S\left(p_\perp,\, \left(Q_s\,\tau\right)^{\gamma} p_z\right)$$

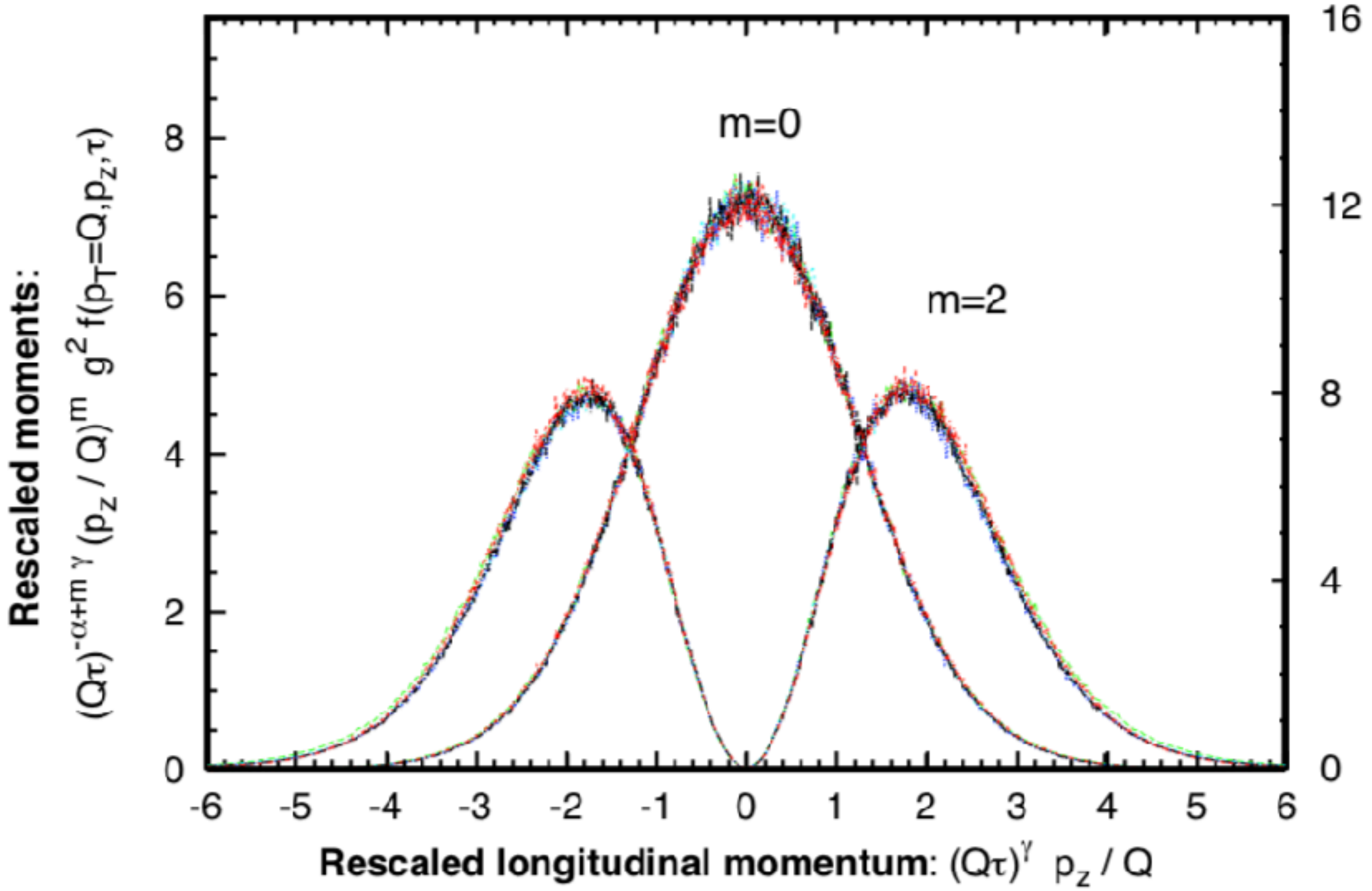
$\alpha = -2/3 \quad \beta = 0 \quad \gamma = 1/3$

$N(\tau)$ $\quad \langle p_\perp \rangle$ $\quad \langle p_z \rangle$

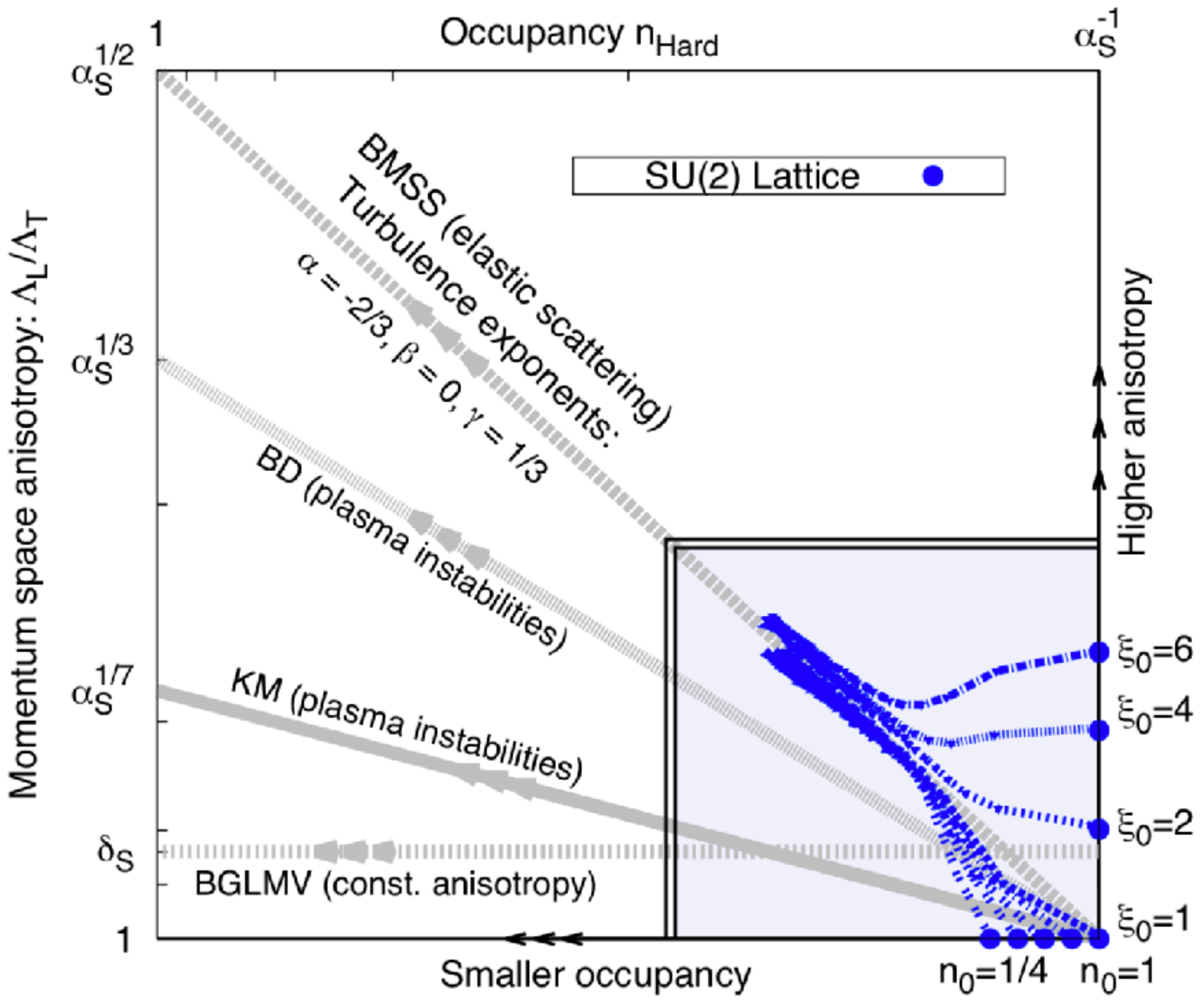
Occupancy: p_z



Phys.Rev. D89 (2014) no.11, 114007



Finding the right scenario



Phys.Rev. D89 (2014) no.11, 114007

Given that…

- System later becomes Hydrodynamical
- Hadrons are produced at later stages from lower energy densities
- Hadrons observables are robust to change of Initial Conditions

…the question is then

Should we care (phenomenologically) about the early stages?

Find probe that “feels” the turbulent stage

↓

Photons and dileptons

Direct Photons

The Good

- No strong interactions
- Mean free path in medium > medium size

⇨ Photons escape, virtually unscathed

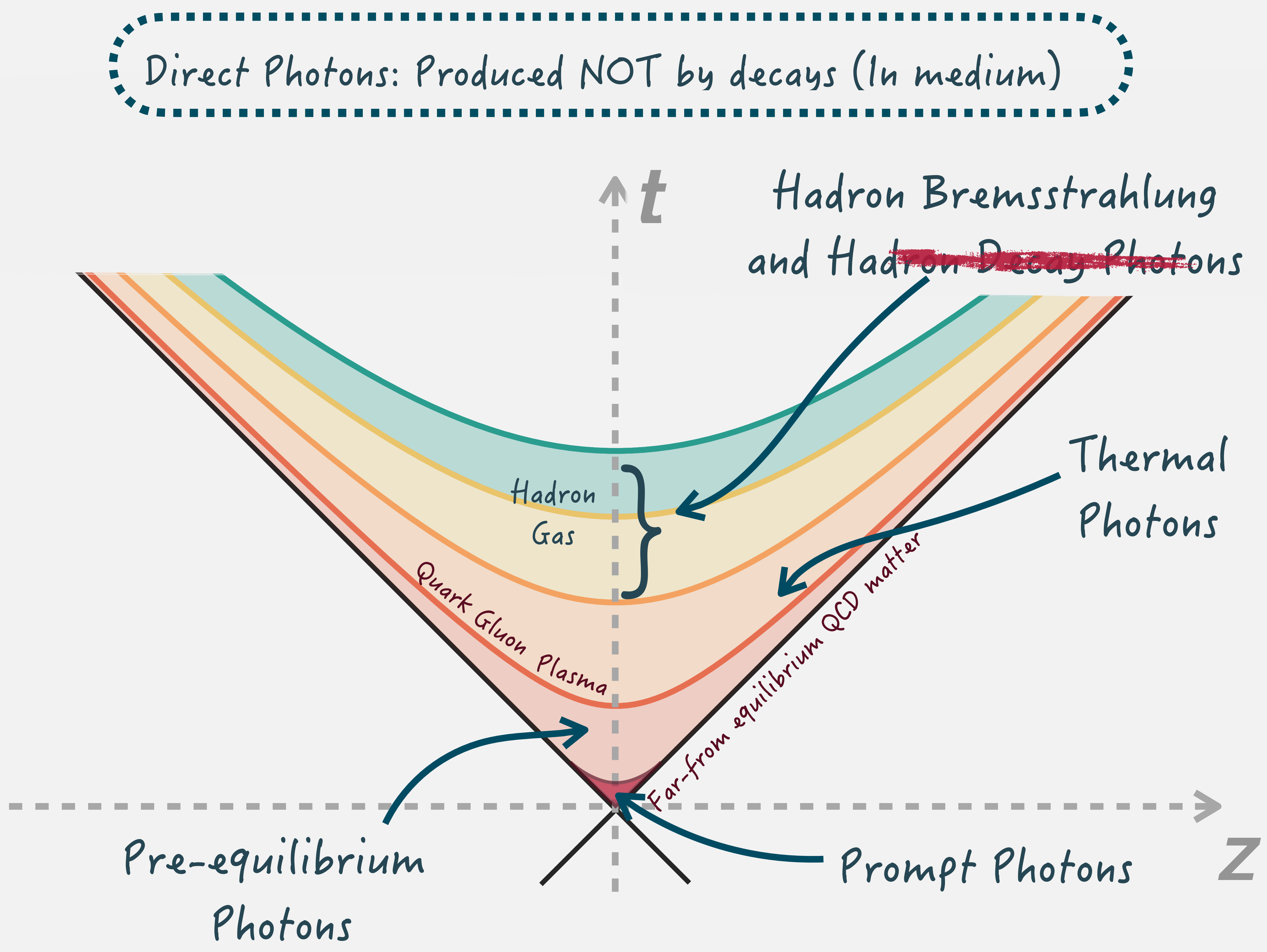
The Bad

- Produced at every stage
- Their signal has to be extracted from total by subtracting hadronic decays.

The Ugly

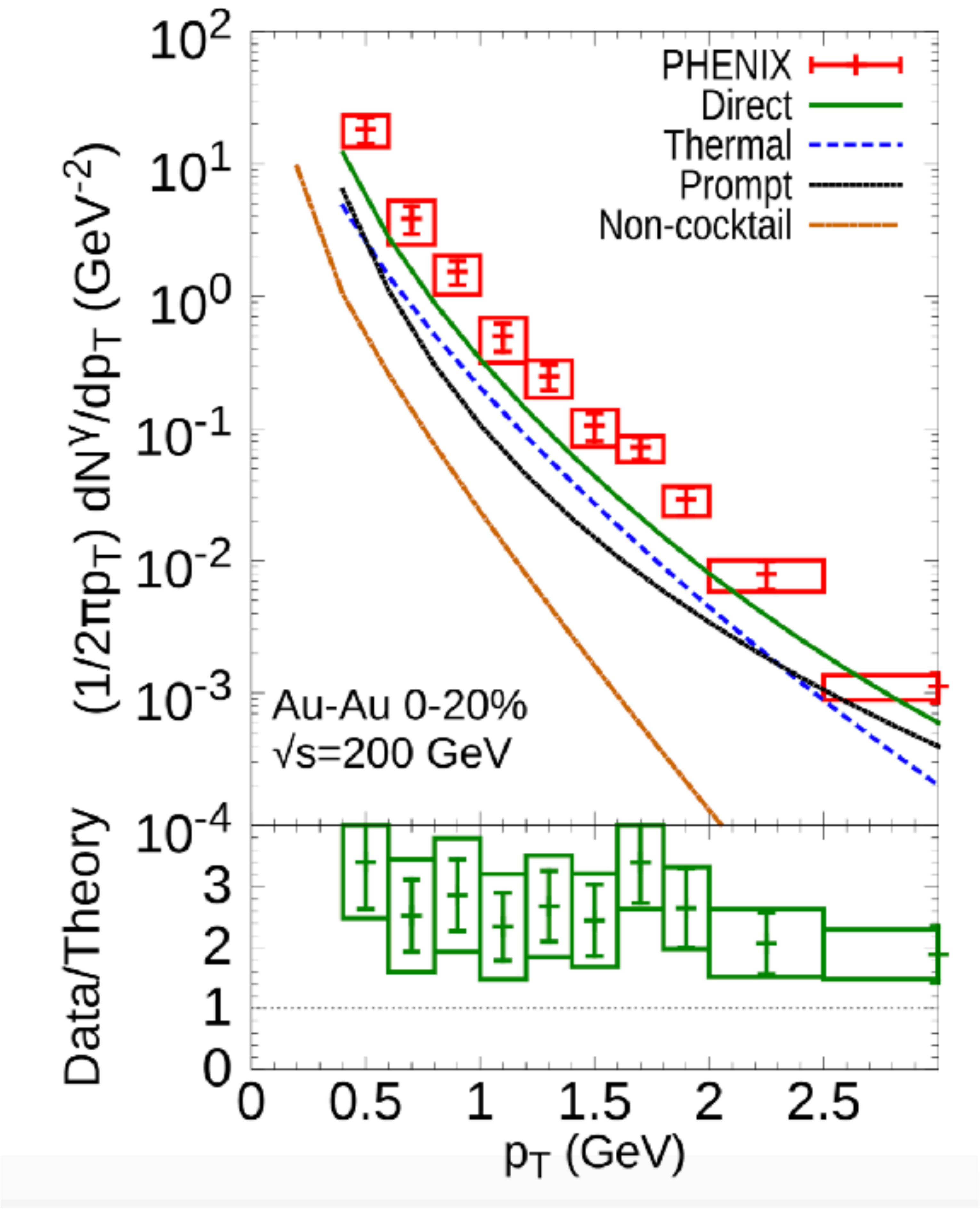
- Compared with a lot of observables, signal is hard to get.

The Standard Model of Heavy Ion Collisions



Direct Photon Puzzle

Direct Photon Puzzle



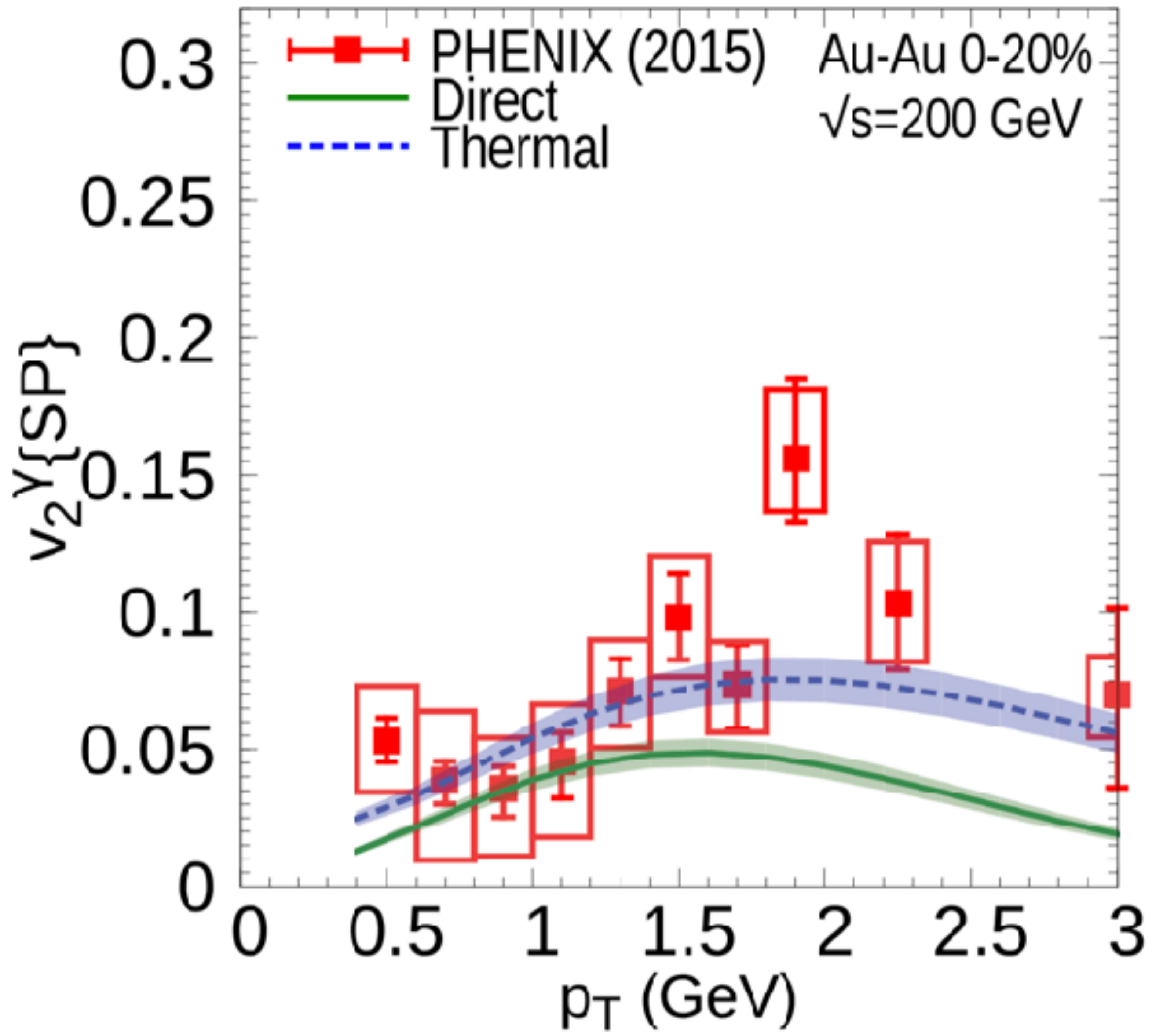
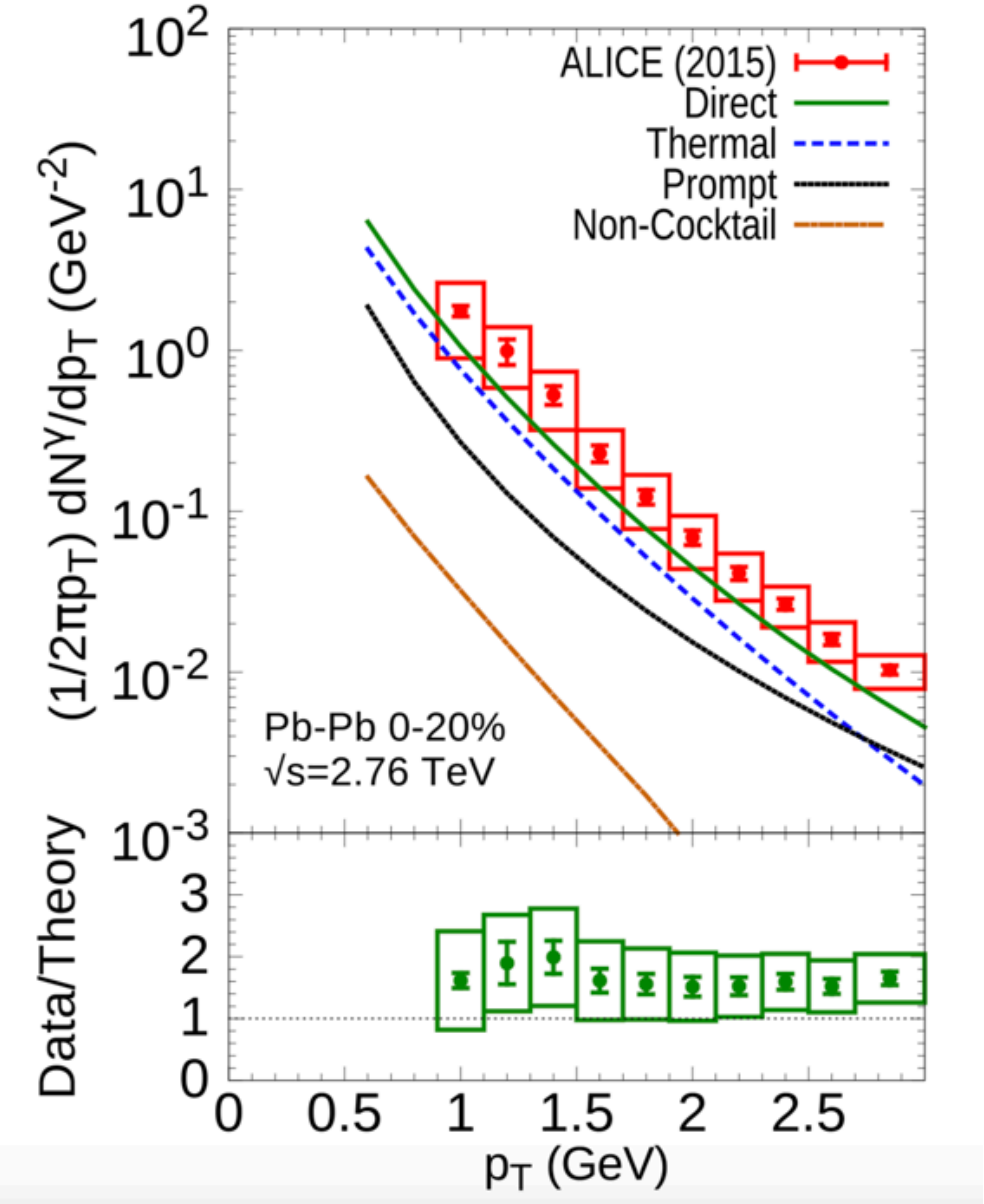


Figure from Paquet *et al*,
Phys.Rev. C93 (2016) no.4, 044906

Photons @ LHC



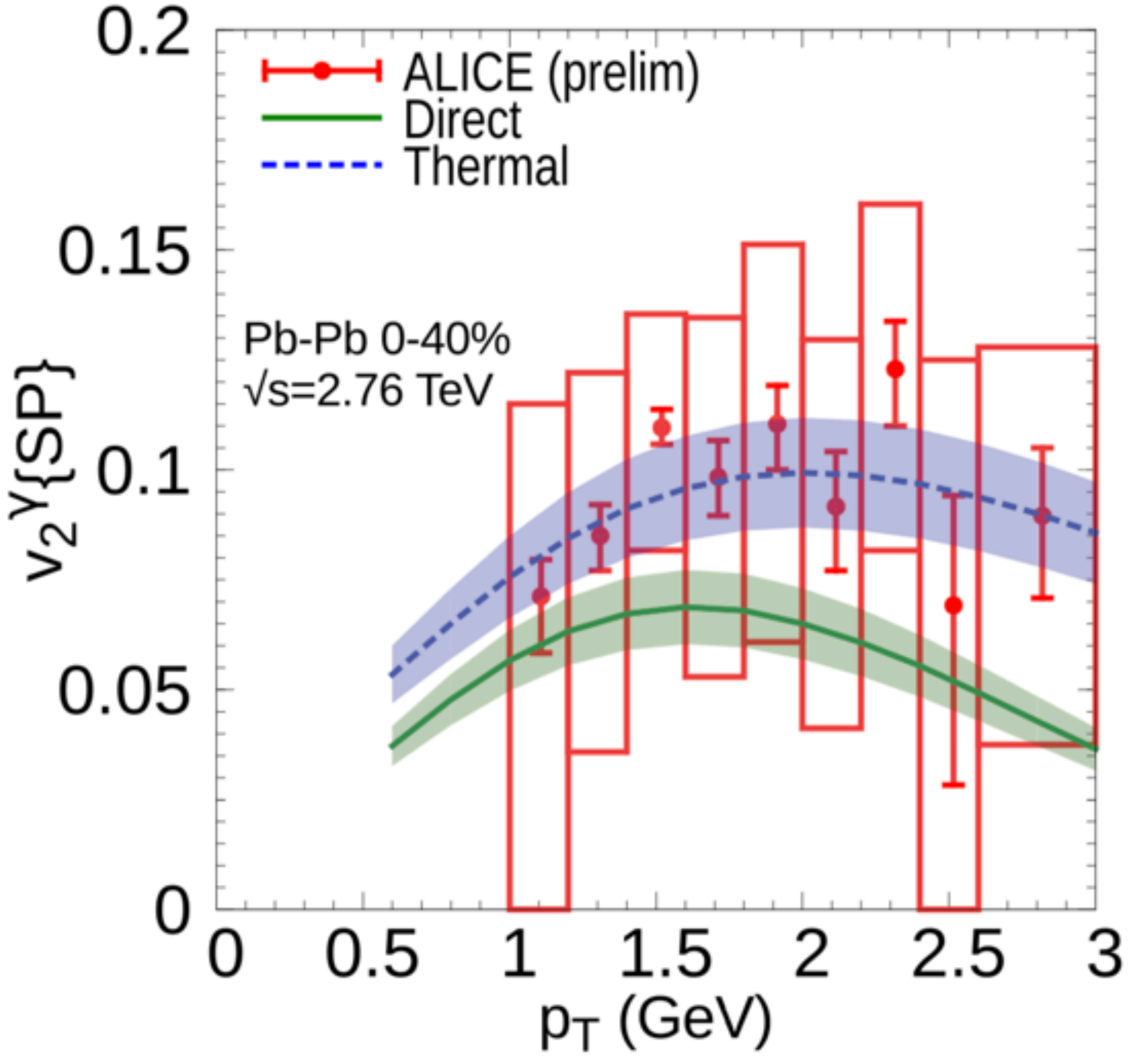


Figure from Paquet *et al*, Phys.Rev. C93 (2016) no.4, 044906

See also Shen, Nucl.Phys. A956 (2016) 184-191

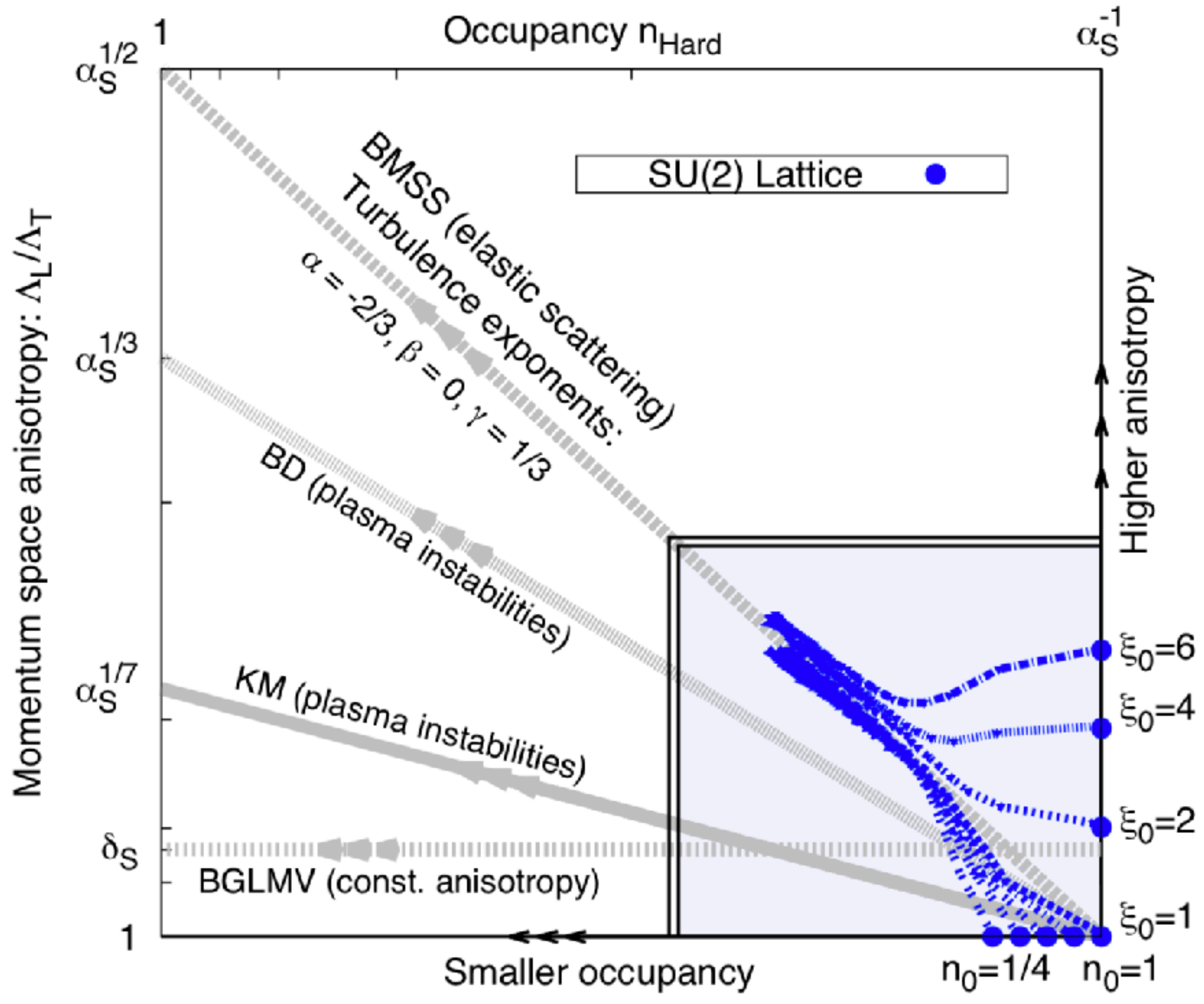
Direct Photon Puzzle™

"The inability to simultaneously describe both the photon yield and anisotropy."

Part 1

Non-Thermal photons from a thermalizing QCD medium

Or.: Calculate photon radiation from out-of-equilibrium plasma, using the "bottom-up" scenario



Bottom-up thermalization

Three Stages

I. Early Times. 2-2 broadening

$$1 \ll Q\tau \ll \alpha_s^{-3/2}$$

II. Onset of thermalization

$$\alpha_s^{-3/2} \ll Q\tau \ll \alpha_s^{-5/2}$$

III. Mini-jet quenching

$$\alpha_s^{-5/2} \ll Q\tau \ll \alpha_s^{-13/5}$$

BMSS. Phys.Lett. B502, 51 (2001)

I. Early Times: 2↔2 broadening $1 \ll Q\tau \ll \alpha_s^{-3/2}$

$$\frac{dN_g}{d^2p_\perp dy} = \frac{1}{\alpha_s} f\left(\frac{p_\perp}{Q_s}\right)$$

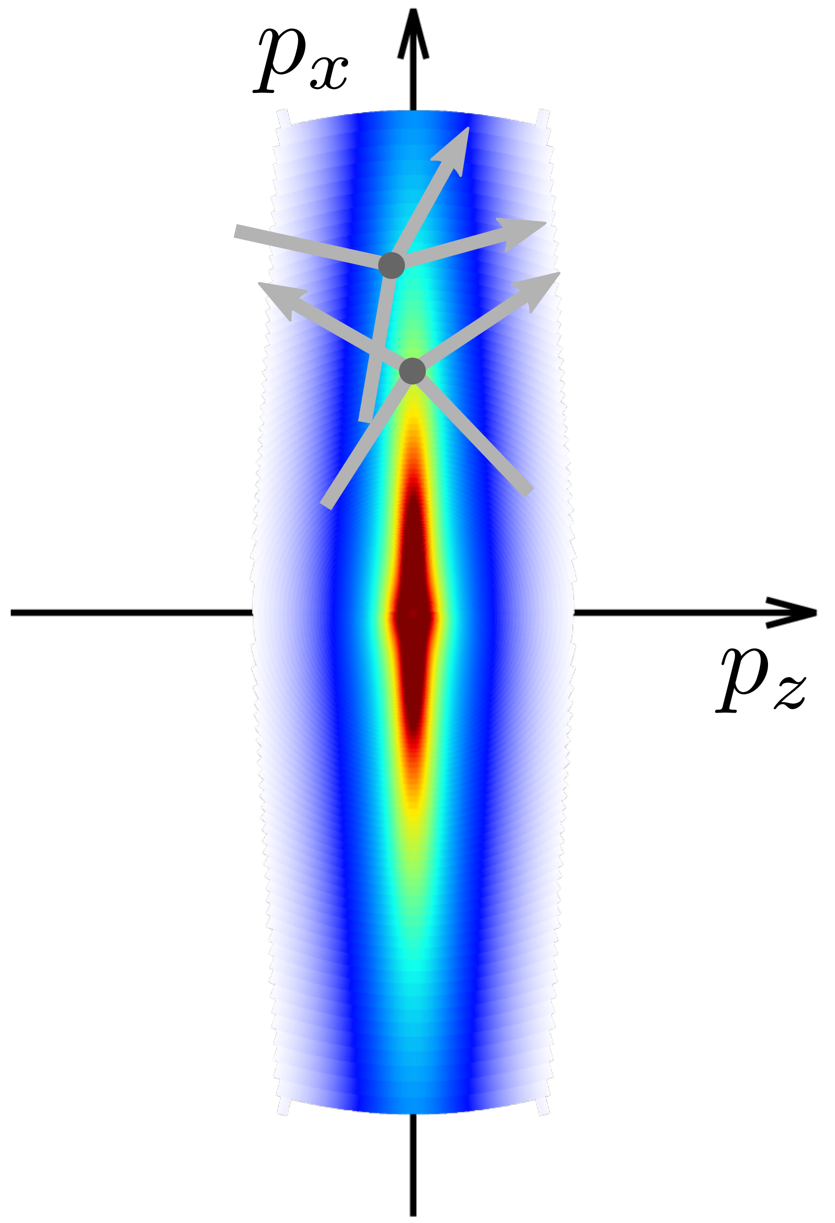
Dominated by hard gluons

$\langle p_\perp \rangle \sim Q_s$

Instabilities freed hard Gluons $n_h \sim \frac{1}{\alpha_s}\frac{Q^3}{Q_s\tau}$

Hard-hard interactions dominated by soft exchange $m_D^2 \sim \alpha_s \int \frac{d^3p}{p} f_g \sim \frac{Q_s^2}{Q_S\tau}$

Longitudinal broadening $\langle p_z \rangle \sim Q_s\,(Q_s\tau)^{-1/3}$



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

I. Early Times: 2↔2 broadening $1 \ll Q\tau \ll \alpha_s^{-3/2}$

$$\frac{dN_g}{d^2p_\perp dy} = \frac{1}{\alpha_s} f\left(\frac{p_\perp}{Q_s}\right) \sim \frac{1}{\alpha_s}(Q_s\tau)^{-2/3}$$

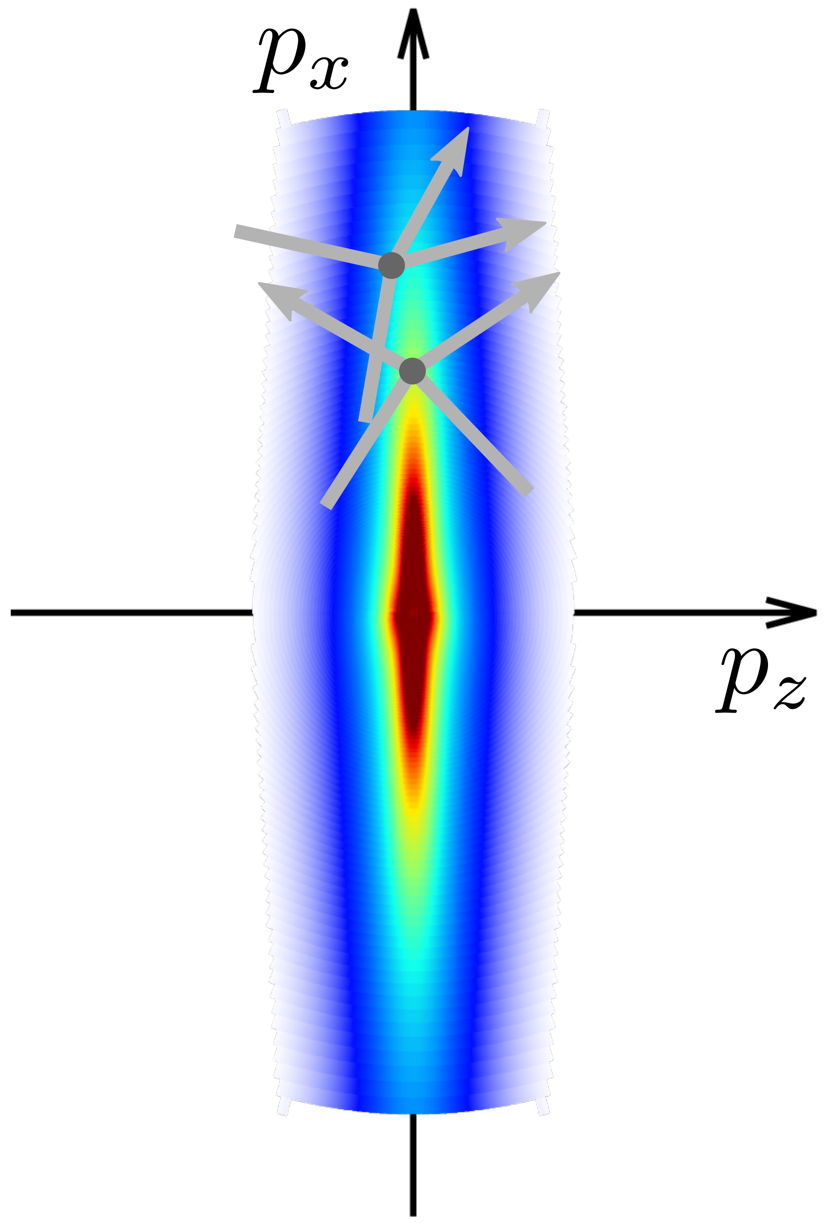
Dominated by hard gluons

$\langle p_\perp \rangle \sim Q_s$

Instabilities freed hard Gluons $\quad n_h \sim \frac{1}{\alpha_s}\frac{Q^3}{Q_s\tau}$

Hard-hard interactions dominated by soft exchange $\quad m_D^2 \sim \alpha_s \int \frac{d^3p}{p} f_g \sim \frac{Q_s^2}{Q_S\tau}$

Longitudinal broadening $\quad \langle p_z \rangle \sim Q_s (Q_s\tau)^{-1/3}$



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

II. Onset of thermalization

$$\alpha_s^{-3/2} \ll Q\tau \ll \alpha_s^{-5/2}$$

Dominated by hard gluons

$$\langle p_\perp \rangle \sim Q_s$$

Occupation of Hard Gluon drops below unity

$$\frac{dN_g}{d^2p_\perp dy} \sim (Q_s\tau)^{-2/3}$$

Soft gluons dominate the screening mass

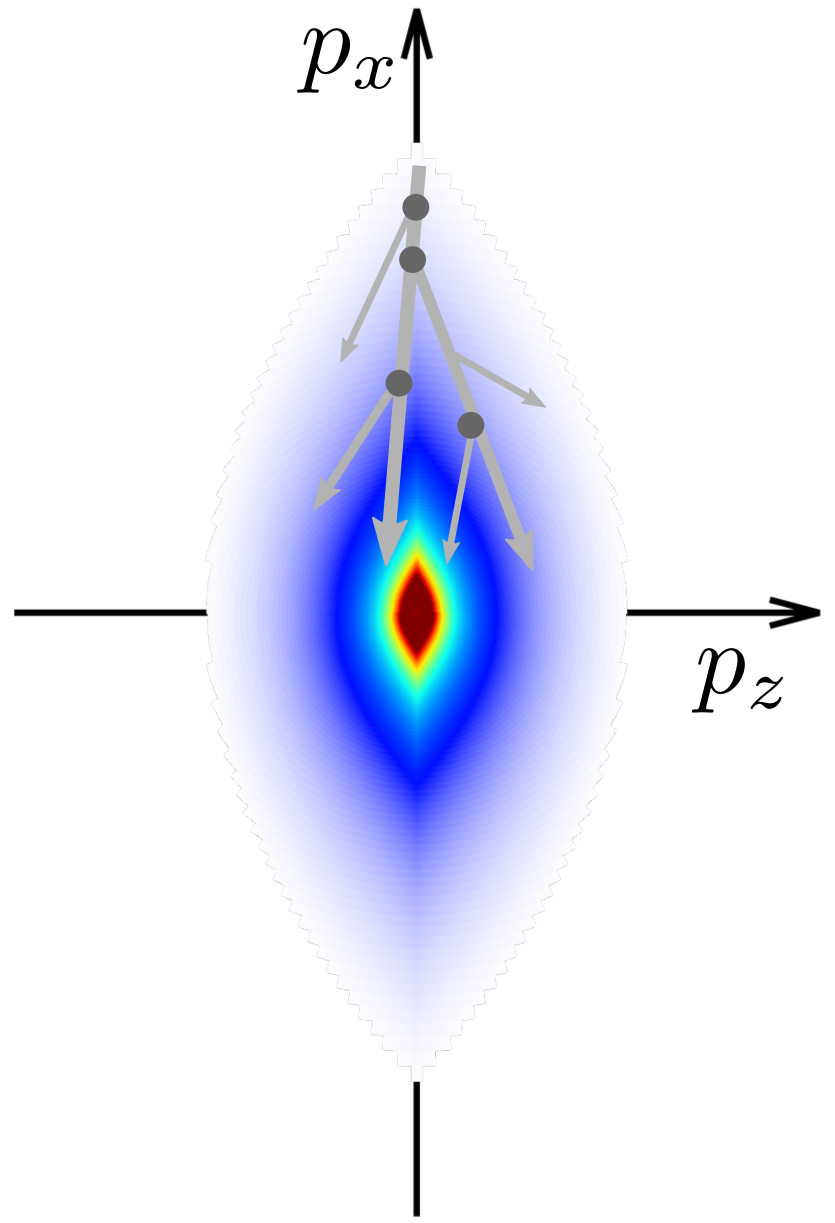
$$n_s \sim \frac{\alpha_s^{1/4} Q_S^3}{(Q_S\,\tau)^{1/2}}$$

Longitudinal momentum

$$\langle p_z \rangle \sim \sqrt{\alpha_s} Q_s$$

Screening mass is dominated by soft sector

$$m_D^2 \sim \frac{\alpha_s^{3/4} Q_s}{(Q_s\tau)^{1/2}}$$



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

III. Mini-jet Quenching

$$\alpha_s^{-5/2} \ll Q\tau \ll \alpha_s^{-13/5}$$

Soft sector thermalizes

→ Acts like a bath

Hard sector looses energy to soft bath

→ Temperature rises as

$$T = c_T \alpha_s^3 Q_s (Q_s \tau)$$

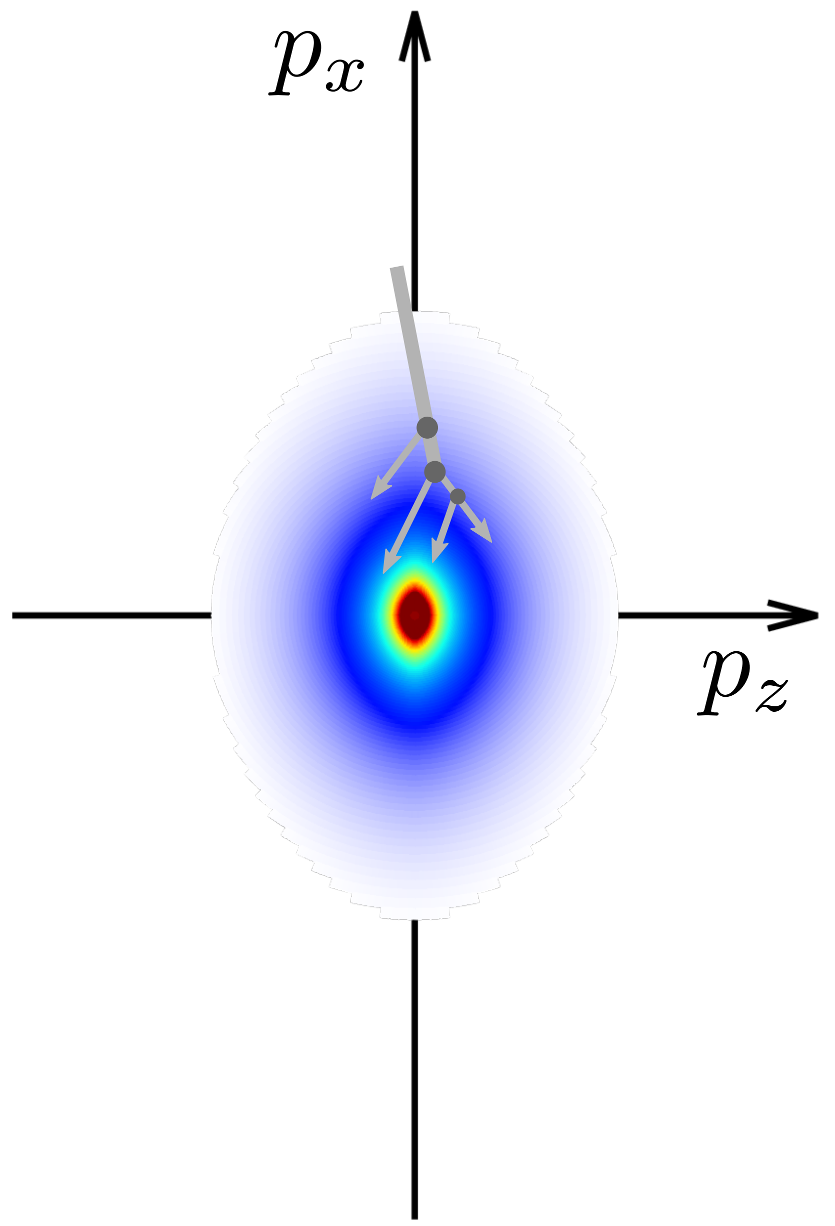
Thermalization happens at →

$$\tau_{th} \sim c_{eq}\, \alpha_s^{-13/5} Q_S^{-1}$$

$$T_{th} \sim c_T\, c_{eq}\, \alpha_s^{2/5} Q_S$$

Dominated by soft gluons

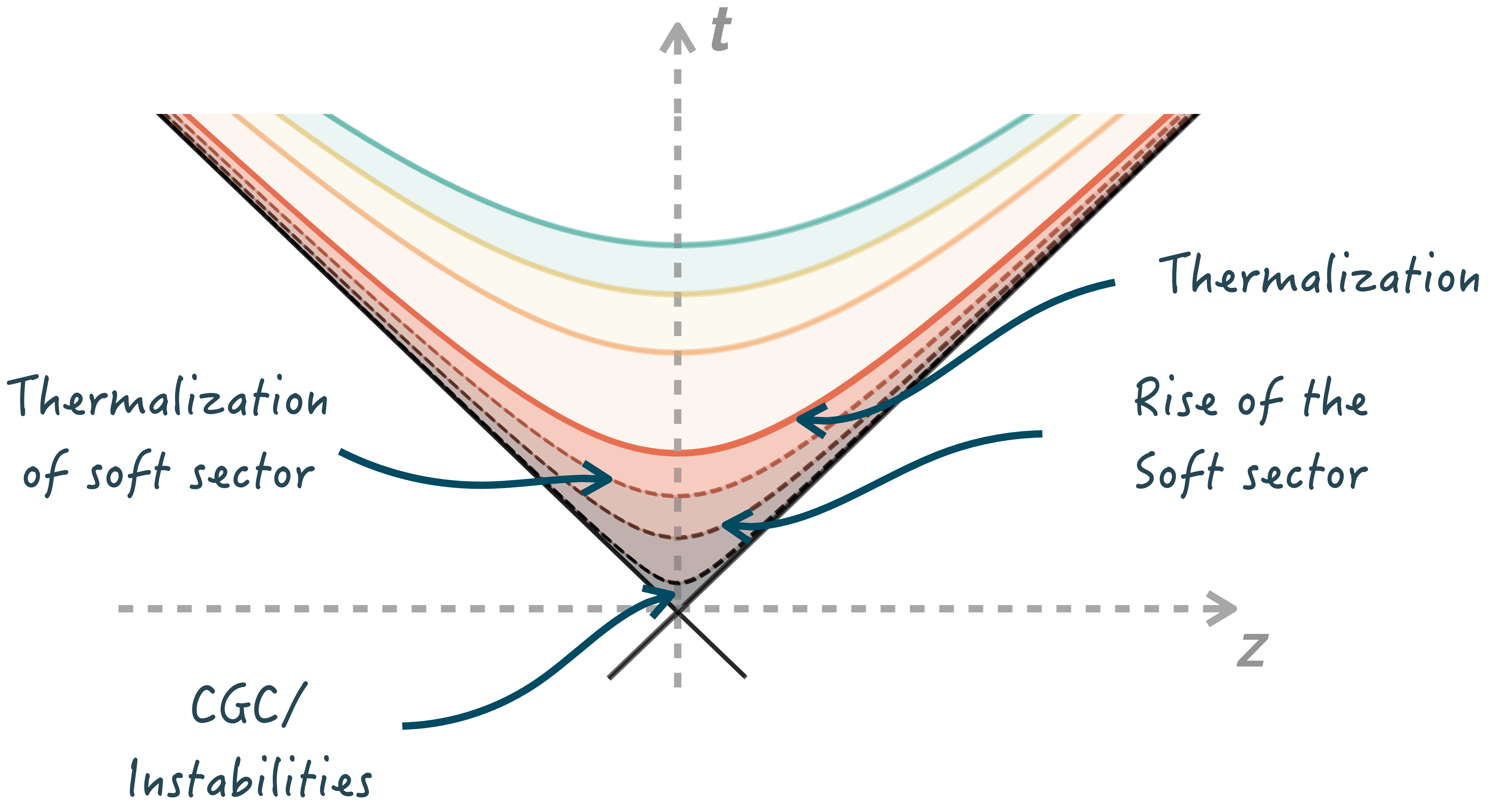
$\langle p_\perp \rangle \sim m_D$



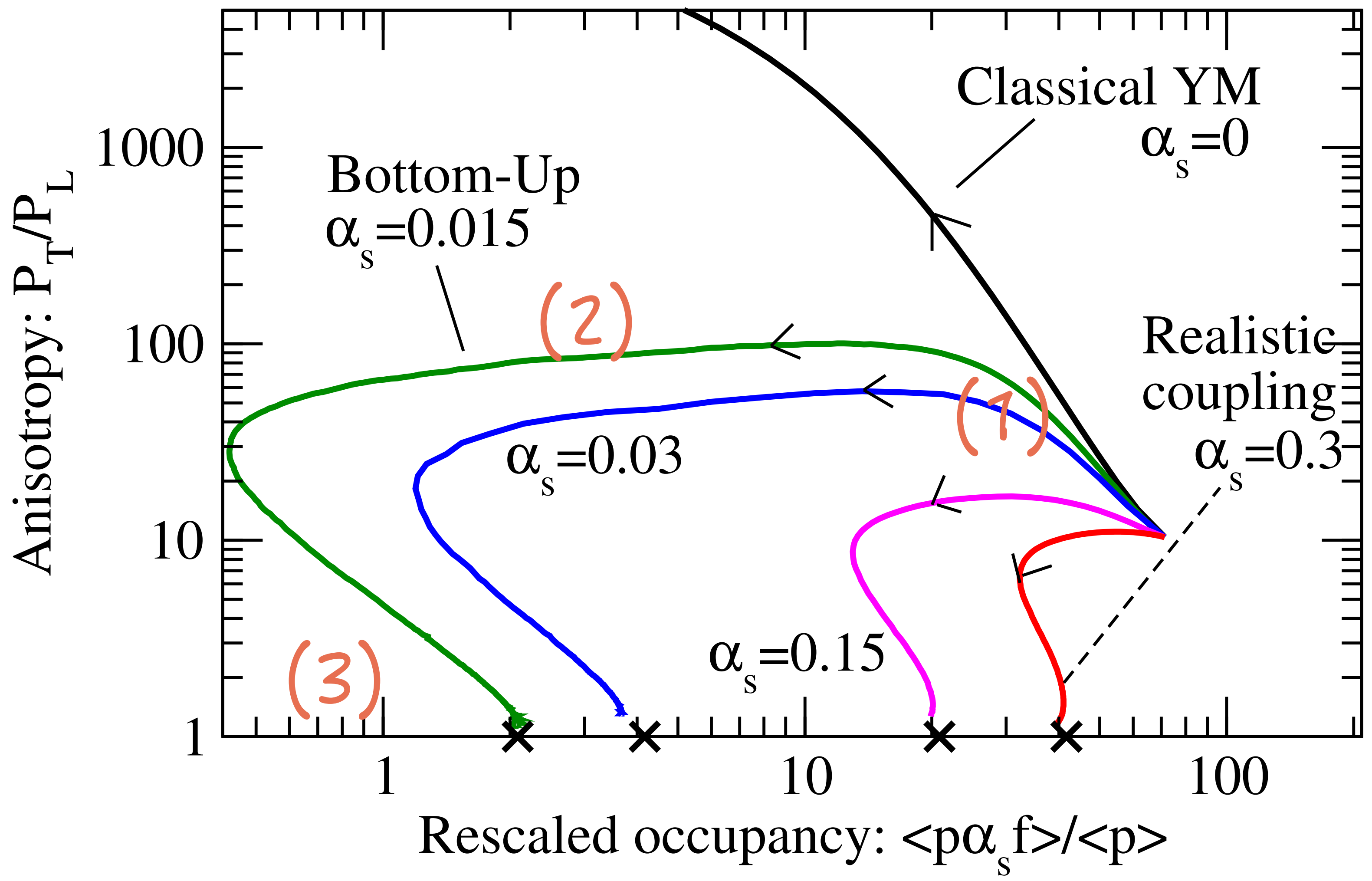
From Kurkela et al.
Phys.Rev. C99 (2019) no.3, 034910

The Standard Model of Heavy Ion Collisions

(revisited)



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



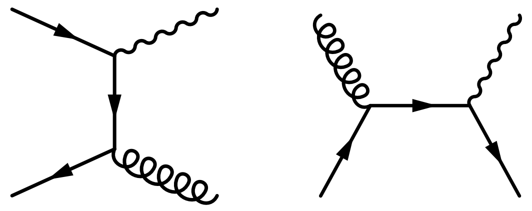
Photon Production: Kinetic Rates

$$E\frac{\mathrm{d}N_\gamma}{\mathrm{d}^4X\mathrm{d}^3p} = |\mathcal{M}|^2 \otimes F[f_i] \otimes \delta(p_{in} - p_{out})$$

Focus for now → **Leading Log**

Dominate at hard scale

- $2 \leftrightarrow 2$ scatterings

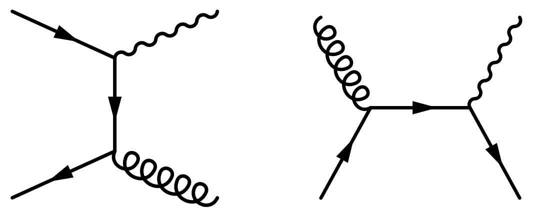


- Momentum transfer: $gT \leftrightarrow T$, $g\,Q_s \leftrightarrow Q_s$

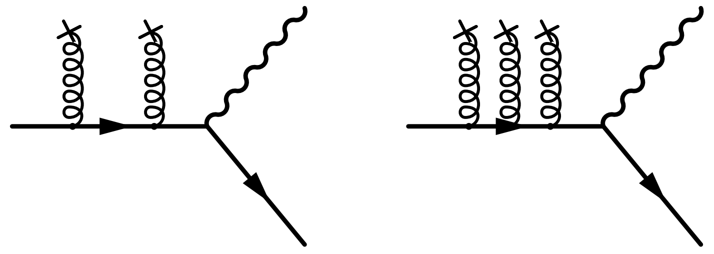
Complete LO

Dominate at softer scales

- $2 \leftrightarrow 2$ scatterings



- $1 \leftrightarrow 2$ scatterings



Colinearly enhanced, inelastic processes

LPM

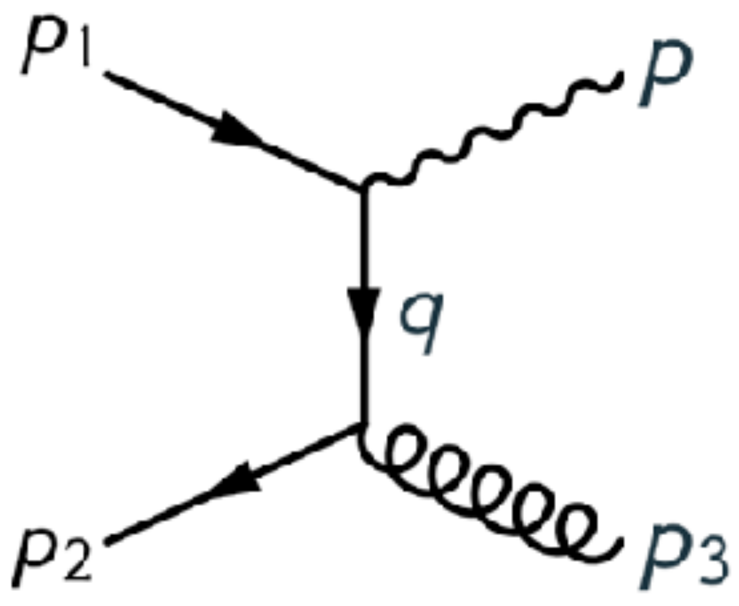
OGM. arXiv: 1909.12294
Phys. Rev. D44 (1991) 2774-2788
JHEP 0112 (2001) 009

Kinetic Rates

$$E\frac{dN_\gamma}{d^4X d^3p} = \frac{1}{2(2\pi)^{12}}\int \frac{d^3p_3}{2E_3}\frac{d^3p_2}{2E_2}\frac{d^3p_1}{2E_1}|\mathcal{M}|^2 (2\pi)^4 \delta^4(P_1+P_2-P_3-P)\, f_1(p_1) f_2(p_2)\,[1 \pm f_3(p_3)]$$

Small angle approximation

Expansion on momentum exchange



$$|\mathbf{p}| = \sqrt{(\mathbf{p}_1+\mathbf{q})^2} \sim |\mathbf{p}_1| + \mathbf{q}\cdot\mathbf{p}_1/|\mathbf{p}_1|$$

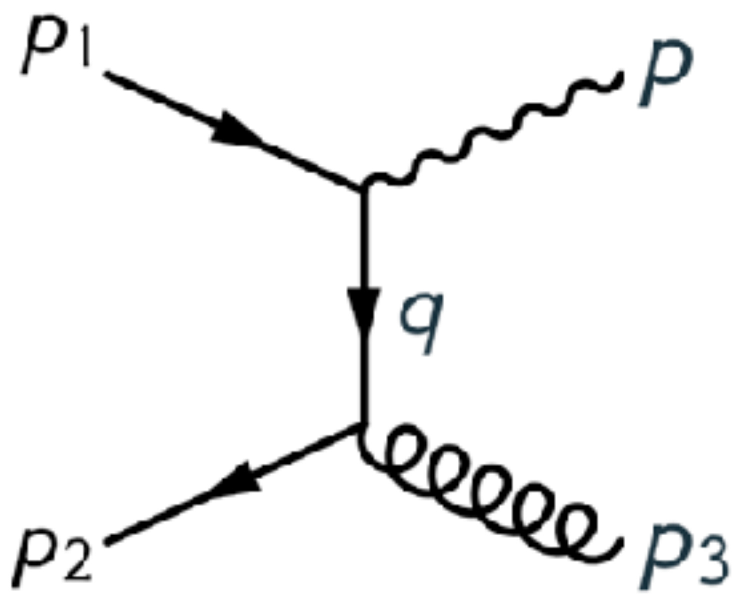
$$|\mathbf{p}_3| = \sqrt{(\mathbf{p}_2-\mathbf{q})^2} \sim |\mathbf{p}_2| - \mathbf{q}\cdot\mathbf{p}_2/|\mathbf{p}_2|$$

Kinetic Rates

$$E\frac{\mathrm{d}N_\gamma}{\mathrm{d}^4X\mathrm{d}^3p} = \frac{1}{2\,(2\,\pi)^{12}}\int\frac{\mathrm{d}^3p_3}{2E_3}\frac{\mathrm{d}^3p_2}{2E_2}\frac{\mathrm{d}^3p_1}{2E_1}\,|\mathcal{M}|^2\,(2\,\pi)^4\,\delta^4(P_1+P_2-P_3-P)\,f_1(p_1)\,f_2(p_2)\,[1\pm f_3(p_3)]$$

Small angle approximation

Expansion on momentum exchange



$$|\mathbf{p}| = \sqrt{(\mathbf{p}_1+\mathbf{q})^2} \sim |\mathbf{p}_1| + \mathbf{q}\cdot\mathbf{p}_1/|\mathbf{p}_1|$$

$$|\mathbf{p}_3| = \sqrt{(\mathbf{p}_2-\mathbf{q})^2} \sim |\mathbf{p}_2| - \mathbf{q}\cdot\mathbf{p}_2/|\mathbf{p}_2|$$

Rate: $$E\frac{dN}{d^4X\,d^3p} = \frac{40}{9\pi^2}\,\alpha\,\alpha_S\,\mathcal{L}\,f_q(\mathbf{p})\,(I_g+I_q)$$

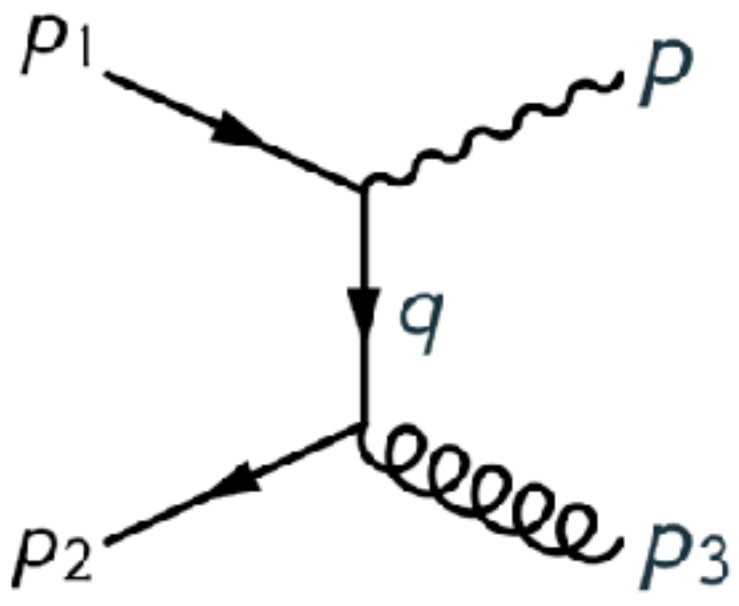
Phys.Rev.C95 (2017) no.5 054904

Kinetic Rates

$$E\frac{dN_\gamma}{d^4X d^3p} = \frac{1}{2\,(2\,\pi)^{12}} \int \frac{d^3p_3}{2E_3}\frac{d^3p_2}{2E_2}\frac{d^3p_1}{2E_1} |\mathcal{M}|^2 (2\,\pi)^4\,\delta^4(P_1 + P_2 - P_3 - P)\, f_1(p_1) f_2(p_2)\, [1 \pm f_3(p_3)]$$

Small angle approximation

Expansion on momentum exchange



$$|\mathbf{p}| = \sqrt{(\mathbf{p}_1 + \mathbf{q})^2} \sim |\mathbf{p}_1| + \mathbf{q}\cdot\mathbf{p}_1/|\mathbf{p}_1|$$

$$|\mathbf{p}_3| = \sqrt{(\mathbf{p}_2 - \mathbf{q})^2} \sim |\mathbf{p}_2| - \mathbf{q}\cdot\mathbf{p}_2/|\mathbf{p}_2|$$

Rate:

$$E\frac{dN}{d^4X\,d^3p} = \frac{40}{9\pi^2}\,\alpha\,\alpha_S\,\mathcal{L}\, f_q(\mathbf{p})\,(I_g + I_q)$$

Amplitude

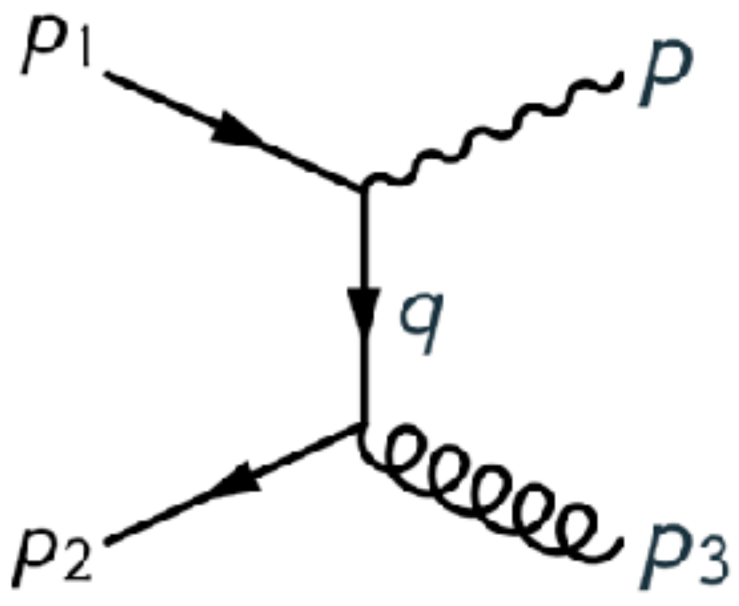
Phys.Rev.C95 (2017) no.5 054904

Kinetic Rates

$$E\frac{\mathrm{d}N_\gamma}{\mathrm{d}^4X\mathrm{d}^3p} = \frac{1}{2\,(2\,\pi)^{12}}\int \frac{\mathrm{d}^3p_3}{2E_3}\frac{\mathrm{d}^3p_2}{2E_2}\frac{\mathrm{d}^3p_1}{2E_1}\,|\mathcal{M}|^2\,(2\,\pi)^4\,\delta^4(P_1+P_2-P_3-P)\,f_1(p_1)\,f_2(p_2)\,[1\pm f_3(p_3)]$$

Small angle approximation

Expansion on momentum exchange



$$|\mathbf{p}| = \sqrt{(\mathbf{p}_1+\mathbf{q})^2} \sim |\mathbf{p}_1| + \mathbf{q}\cdot\mathbf{p}_1/|\mathbf{p}_1|$$

$$|\mathbf{p}_3| = \sqrt{(\mathbf{p}_2-\mathbf{q})^2} \sim |\mathbf{p}_2| - \mathbf{q}\cdot\mathbf{p}_2/|\mathbf{p}_2|$$

Rate: $$E\frac{dN}{d^4X\,d^3p} = \frac{40}{9\pi^2}\,\alpha\,\alpha_s\,\mathcal{L}\,f_q(\mathbf{p})\,(I_g+I_q)$$

Regulator

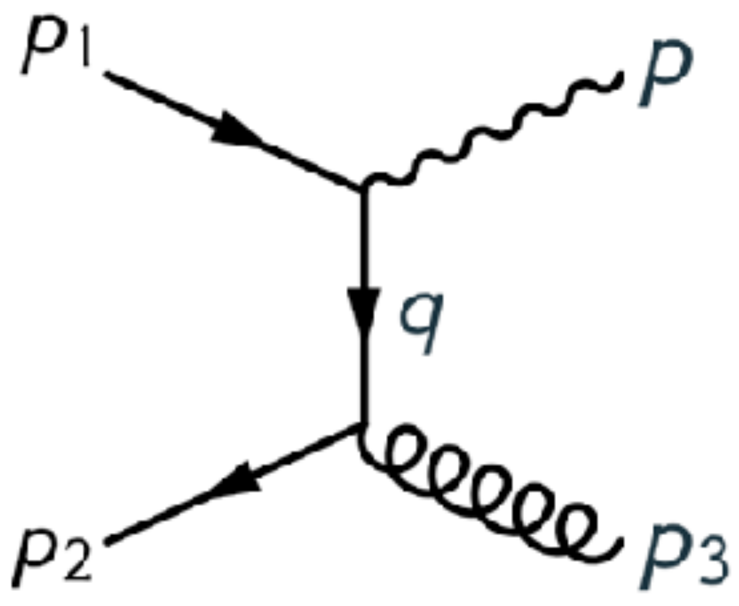
with $$\mathcal{L} = 2\,log\left(\frac{2.912}{g_s^2}\frac{E}{T}\right) \to 2\,log\left(1+\frac{2.912}{g_s^2}\right)$$

Kinetic Rates

$$E\frac{\mathrm{d}N_\gamma}{\mathrm{d}^4X\mathrm{d}^3p} = \frac{1}{2\,(2\,\pi)^{12}}\int \frac{\mathrm{d}^3p_3}{2E_3}\frac{\mathrm{d}^3p_2}{2E_2}\frac{\mathrm{d}^3p_1}{2E_1}\,|\mathcal{M}|^2\,(2\,\pi)^4\,\delta^4(P_1+P_2-P_3-P)\,\underbrace{f_1(p_1)\,f_2(p_2)\,[1\pm f_3(p_3)]}$$

Small angle approximation

Expansion on momentum exchange →



$$|\mathbf{p}| = \sqrt{(\mathbf{p}_1+\mathbf{q})^2} \sim |\mathbf{p}_1| + \mathbf{q}\cdot\mathbf{p}_1/|\mathbf{p}_1|$$

$$|\mathbf{p}_3| = \sqrt{(\mathbf{p}_2-\mathbf{q})^2} \sim |\mathbf{p}_2| - \mathbf{q}\cdot\mathbf{p}_2/|\mathbf{p}_2|$$

Rate:

$$E\frac{dN}{d^4X\,d^3p} = \frac{40}{9\pi^2}\,\alpha\,\alpha_S\,\mathcal{L}\,f_q(\mathbf{p})\,(I_g+I_q)$$

Screening Masses

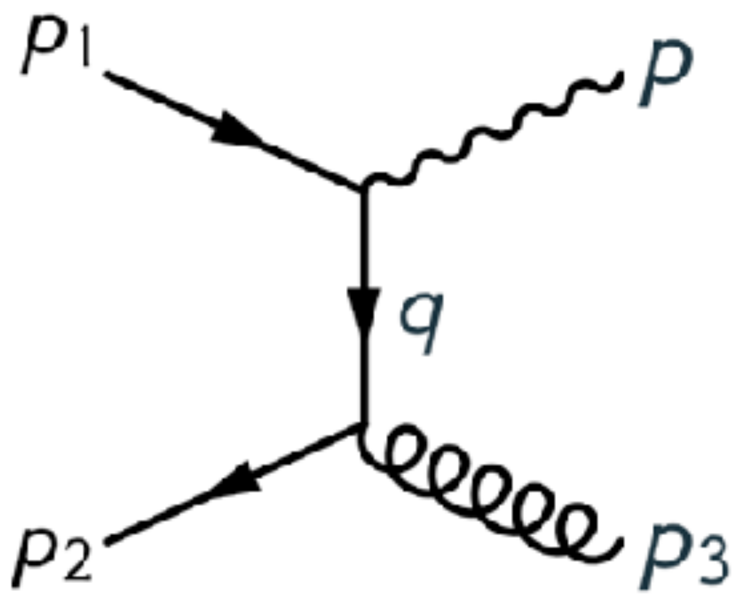
$$I_{q,g}(\tau) = \int \frac{\mathrm{d}^3p}{(2\pi)^3}\frac{1}{p}f_{q,g}(\tau,p)$$

Kinetic Rates

$$E\frac{\mathrm{d}N_\gamma}{\mathrm{d}^4X\mathrm{d}^3p} = \frac{1}{2\,(2\,\pi)^{12}}\int\frac{\mathrm{d}^3p_3}{2E_3}\frac{\mathrm{d}^3p_2}{2E_2}\frac{\mathrm{d}^3p_1}{2E_1}\,|\mathcal{M}|^2\,(2\,\pi)^4\,\delta^4(P_1+P_2-P_3-P)\,f_1(p_1)\,f_2(p_2)\,[1\pm f_3(p_3)]$$

Small angle approximation

Expansion on momentum exchange



$$|\mathbf{p}| = \sqrt{(\mathbf{p}_1+\mathbf{q})^2} \sim |\mathbf{p}_1| + \mathbf{q}\cdot\mathbf{p}_1/|\mathbf{p}_1|$$

$$|\mathbf{p}_3| = \sqrt{(\mathbf{p}_2-\mathbf{q})^2} \sim |\mathbf{p}_2| - \mathbf{q}\cdot\mathbf{p}_2/|\mathbf{p}_2|$$

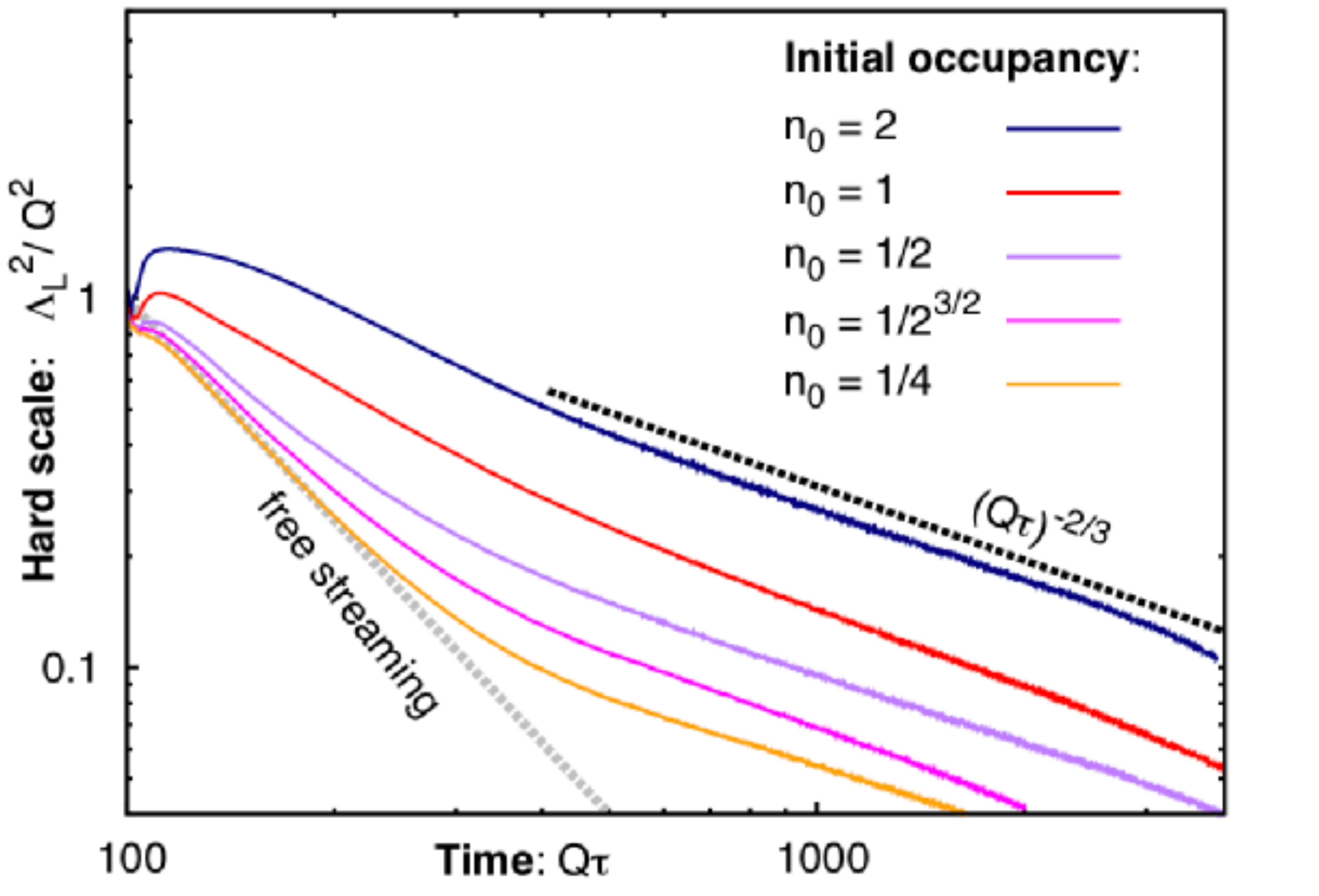
Rate: $$E\frac{dN}{d^4X\,d^3p} = \frac{40}{9\pi^2}\,\alpha\,\alpha_S\,\mathcal{L}\,f_q(\mathbf{p})\,(I_g+I_q)$$

Quark Distribution → BMSS Scenario

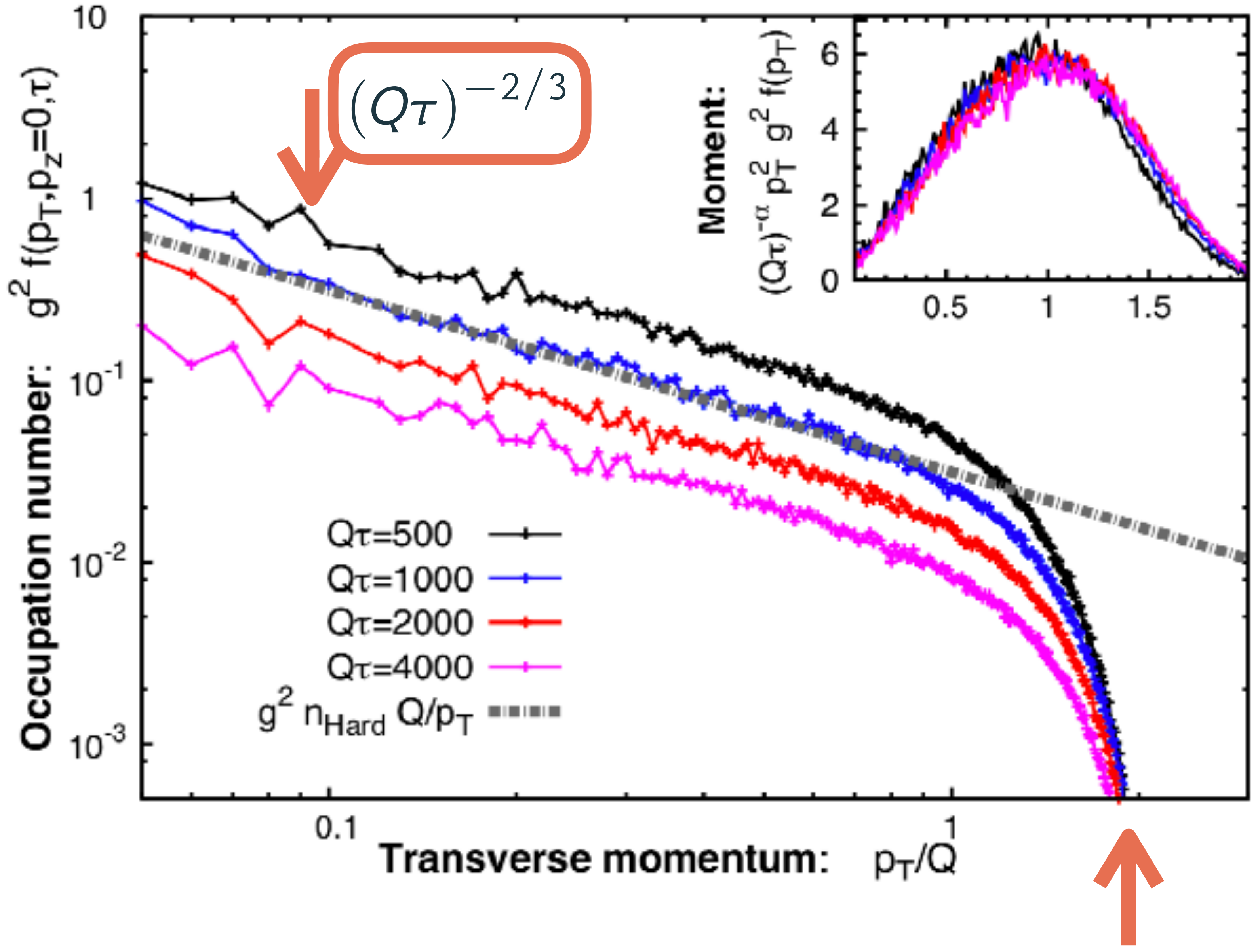
→ Dynamical Lattice Simulations

Gluon occupation: Fit lattice results

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



Transverse $p_\perp$



$$f_g(\tau, p_\perp, p_z) = \frac{1}{\alpha_s}(Q_s\tau)^{\alpha} f_S\left(p_\perp, (Q_s\tau)^{\gamma} p_z\right)$$

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

$N(\tau) \quad \langle p_\perp \rangle \quad \langle p_z \rangle$

Other approximations

Extension

Quark Distribution*

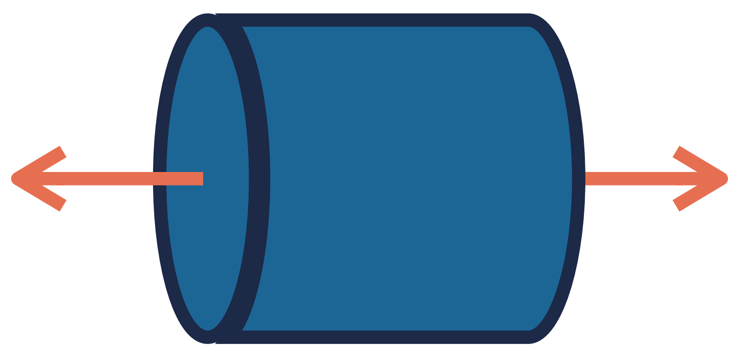
Hard dipole approximation

$$f_q(\tau, p_\perp, p_z) = \alpha_s f_g(\tau, p_\perp, p_z)$$

Weak coupling limit

$\alpha_s \to 0$

Bjorken Expansion



$$u = (\cosh\eta, u_x, u_y, \sinh\eta)$$

Transverse Translation Invariance

* Q.Stat. kick in outside the region of interest.

Phenomenological Matching

$$\langle Q_s^2 \rangle = \frac{\int d^2x_\perp Q_s^2(x_\perp)}{\langle S_\perp \rangle}$$

Glauber

IP-Glasma

$\langle Q_s^2 \rangle = 2\,\mathrm{GeV}^2$ → RHIC, 200GeV, 0-5% (Reference)

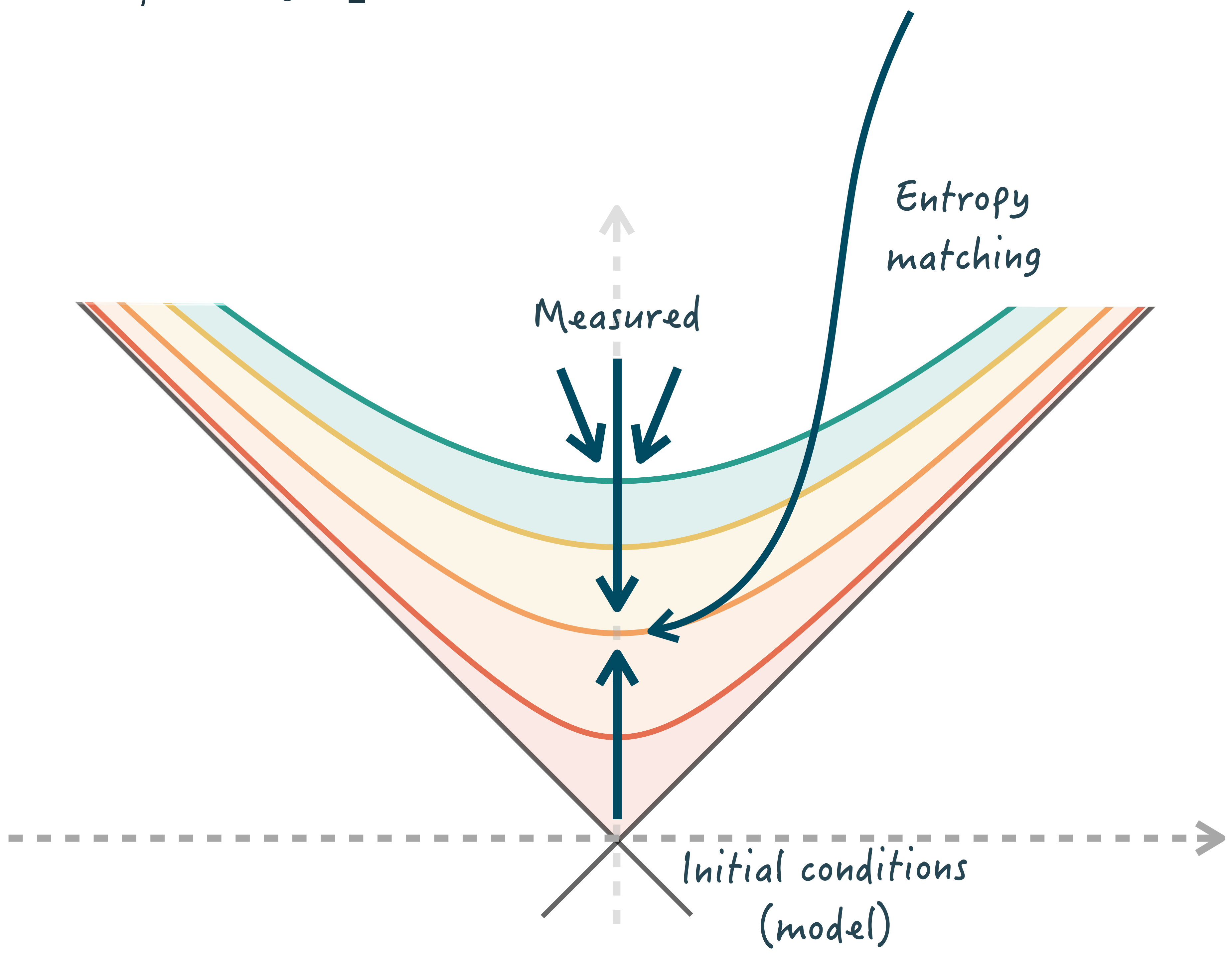
$\langle Q_s^2 \rangle = 1.67\,\mathrm{GeV}^2$ → RHIC, 200GeV, 0-20%

$\langle Q_s^2 \rangle = 2.97\,\mathrm{GeV}^2$ → ALICE, 2.76TeV, 0-20%

Phenomenological Matching

$$c_{eq}\, c_T^{3/4} = \left[\frac{45}{148\pi^2} k_{S/N} \alpha^{7/5} \frac{N_{part}}{Q_S^2\, S_\perp} \frac{2}{N_{part}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}y} \right]^{1/4}$$

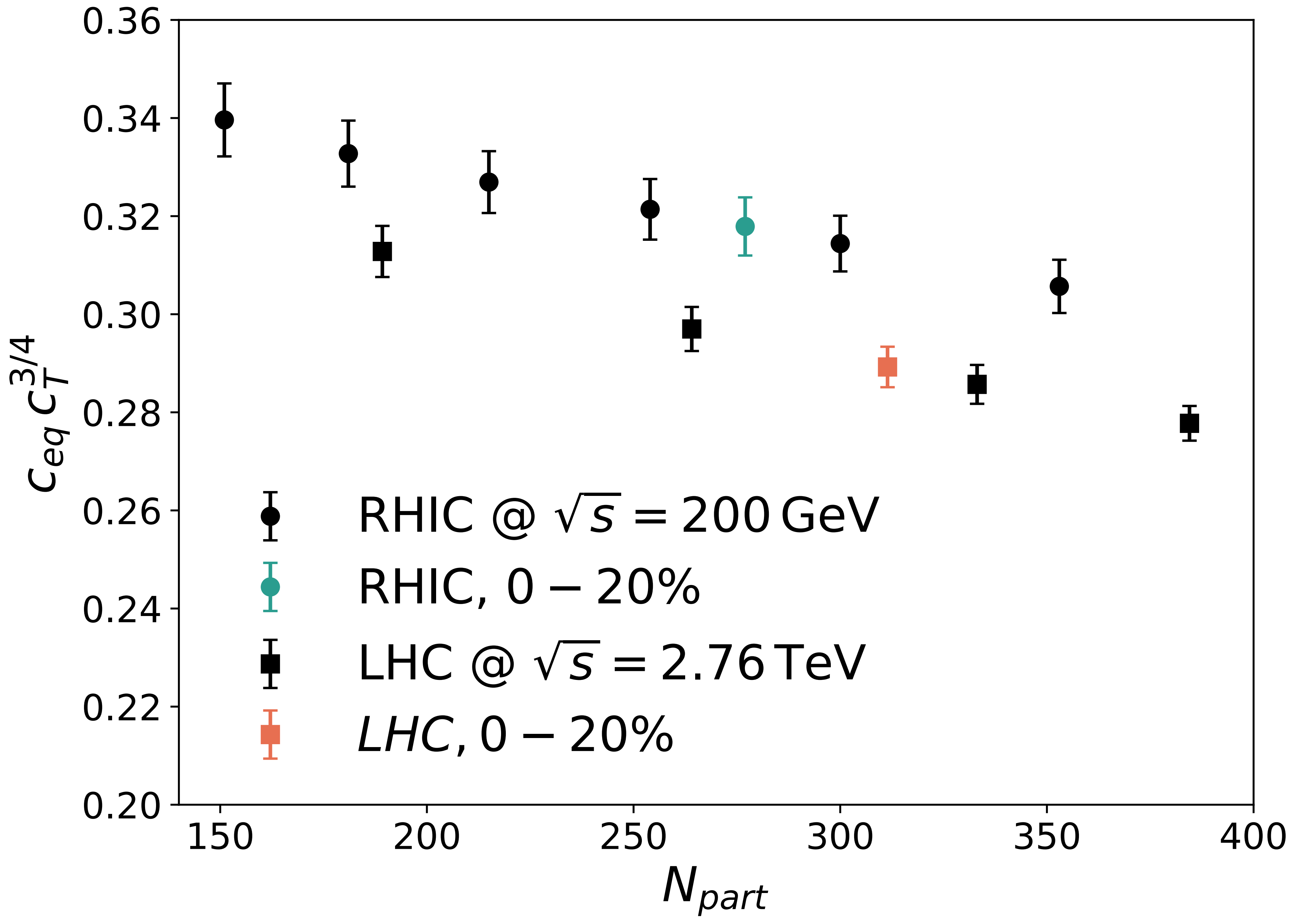
Entropy transport via $\frac{dS_{QGP}}{d\eta} = k_{S/N} \frac{dN_{ch}}{d\eta}$



Phenomenological Matching

$$c_{eq}\, c_T^{3/4} = \left[\frac{45}{148\pi^2} k_{S/N} \alpha^{7/5} \frac{N_{part}}{Q_S^2 S_\perp} \frac{2}{N_{part}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}y} \right]^{1/4}$$

Entropy transport via $\frac{dS_{QGP}}{d\eta} = k_{S/N} \frac{dN_{ch}}{d\eta}$



C_T known to logarithmic precision $C_T = 0.18$

τ_c is independent of match

$\tau_{th} \sim 2\,\mathrm{fm}$

$T_{th} \sim 0.25\,\mathrm{GeV}$

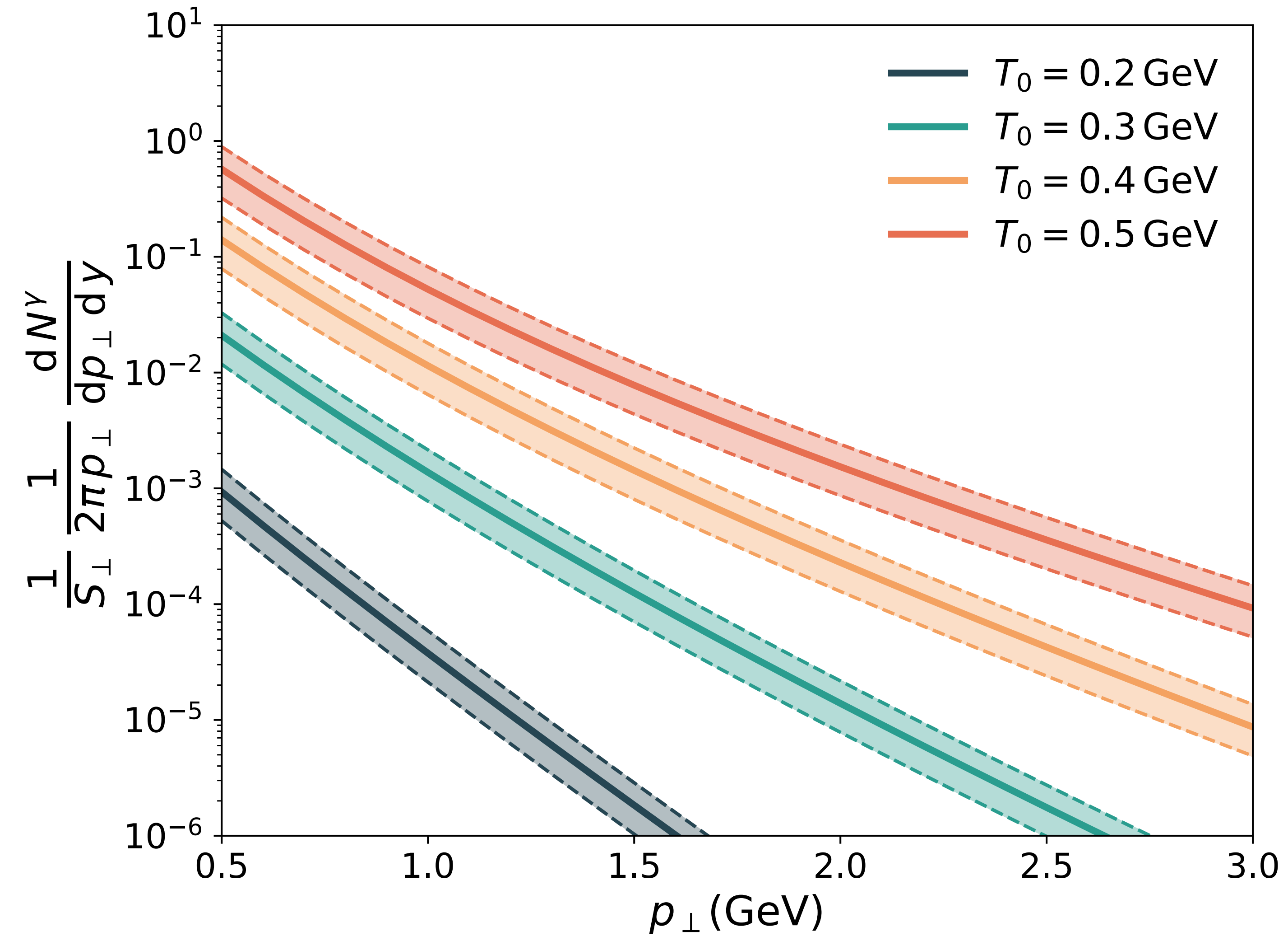
Results

- Computed analytical solution for the full “bottom-up" scenario **OGM. arXiv: 1909.12294**

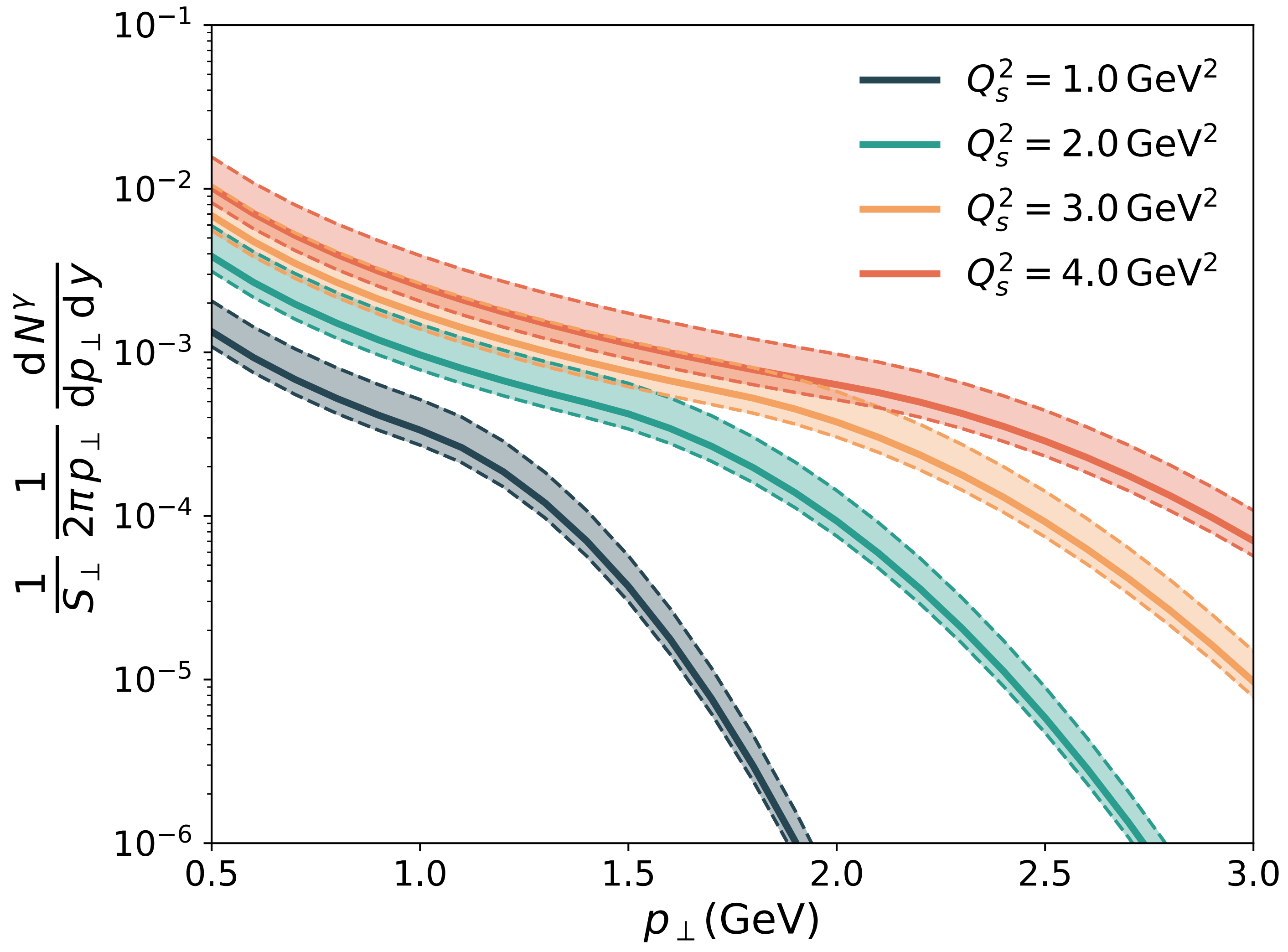
- Solution only includes hard scatterings via 2-2 processes.

- Thermal means QGP + Hadronic

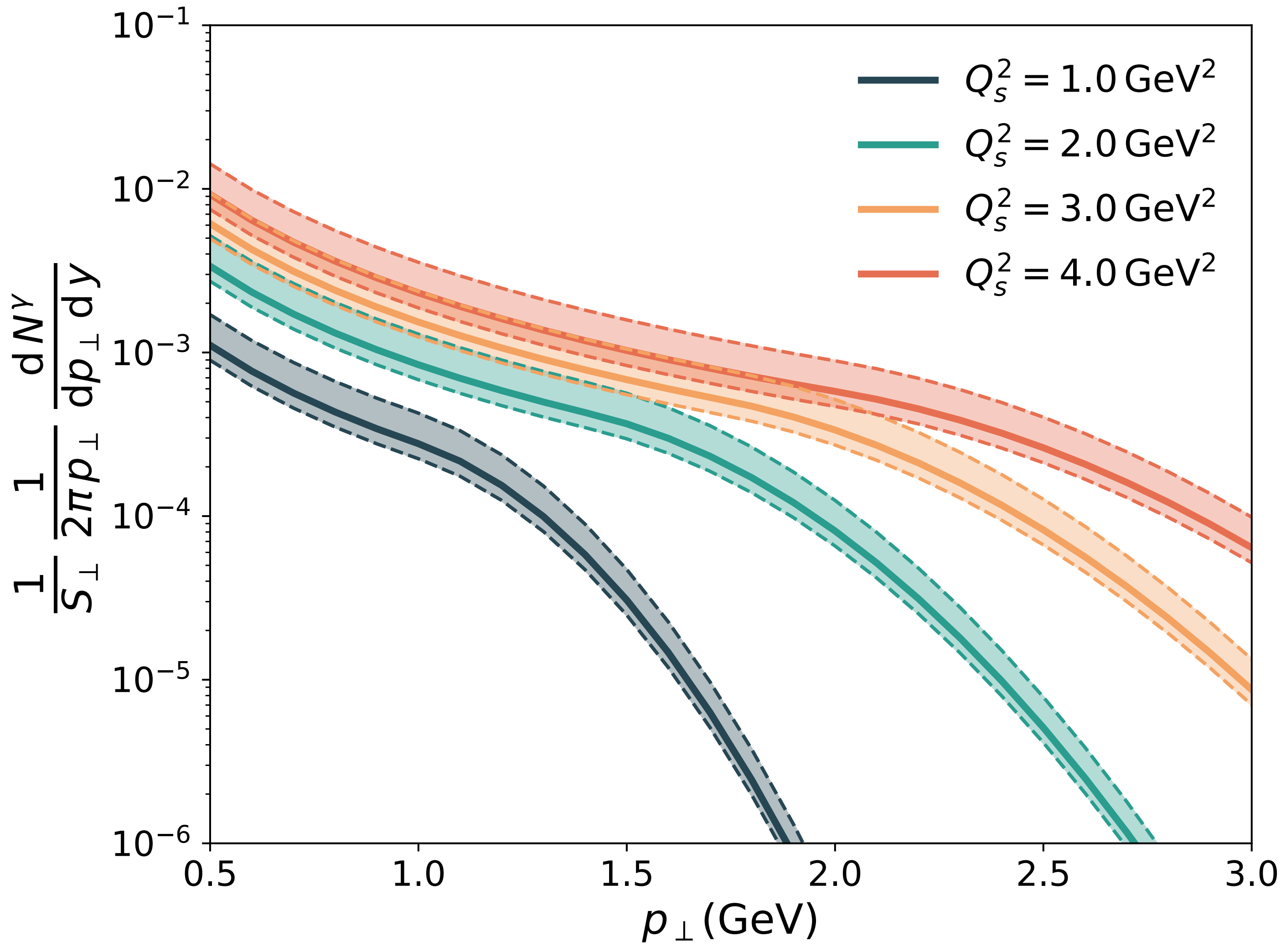
Thermal Stage



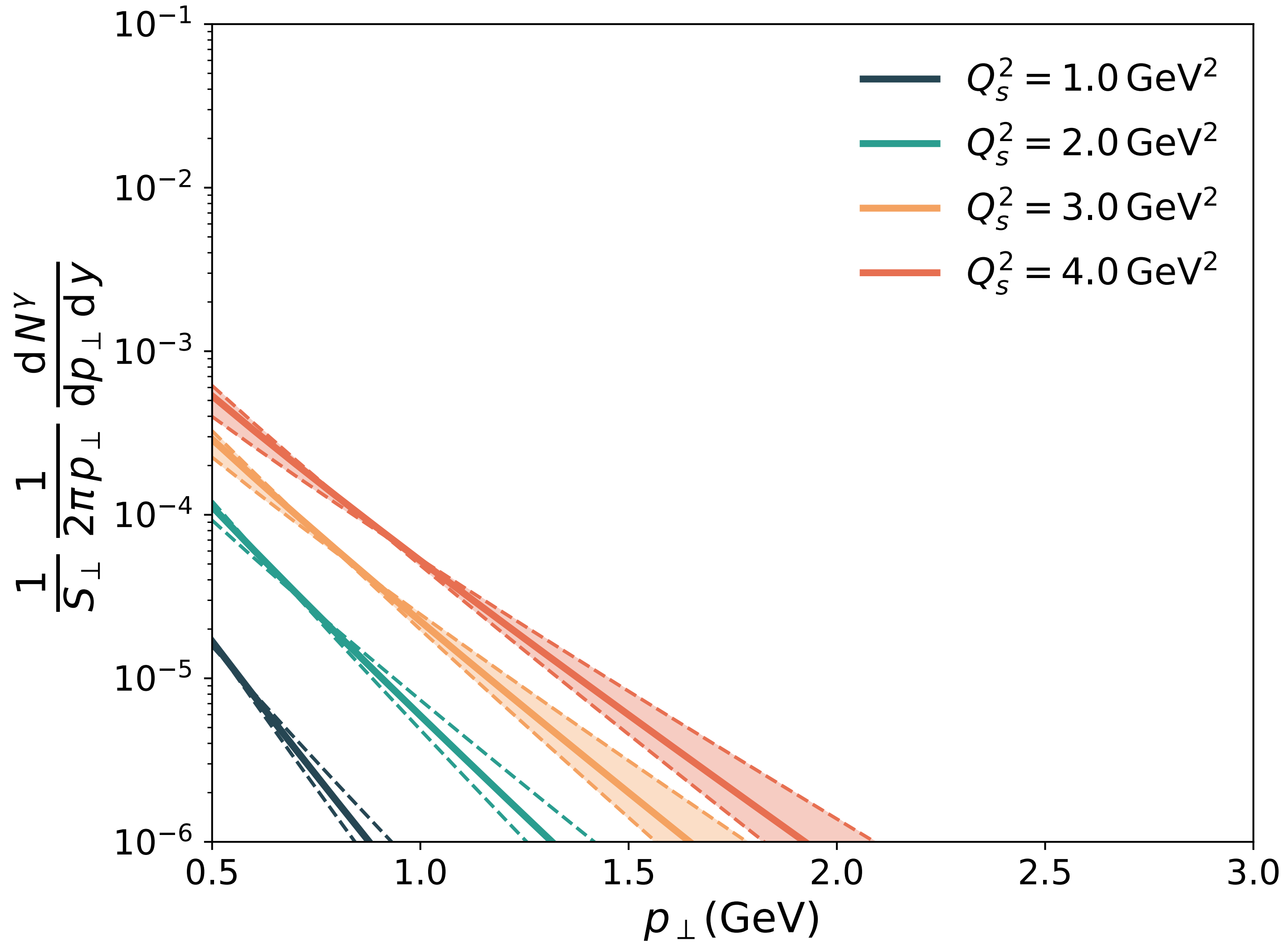
“Bottom-up”, stage I



“Bottom-up”, stage II



“Bottom-up”, stage III



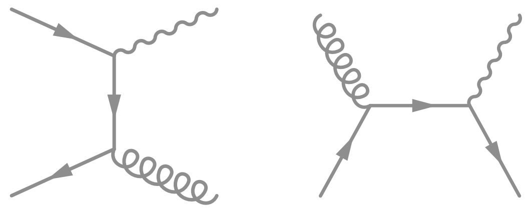
Photon Production: Kinetic Rates

$$E\frac{\mathrm{d}N_\gamma}{\mathrm{d}^4X\mathrm{d}^3p} = |\mathcal{M}|^2 \otimes F\left[f_i\right] \otimes \delta(p_{in} - p_{out})$$

Leading Log

Dominate at hard scale

- $2 \leftrightarrow 2$ scatterings



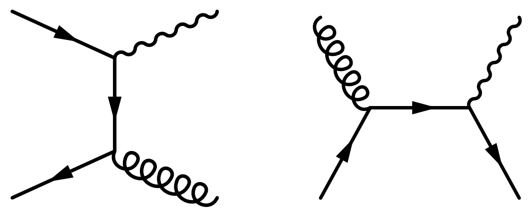
- Momentum transfer: $gT \leftrightarrow T$, $g\,Q_s \leftrightarrow Q_s$

Very complex

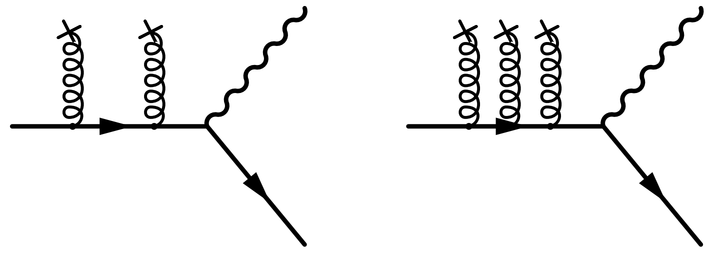
Complete LO

Dominate at softer scales

- $2 \leftrightarrow 2$ scatterings



- $1 \leftrightarrow 2$ scatterings



Colinearly enhanced, inelastic processes

LPM

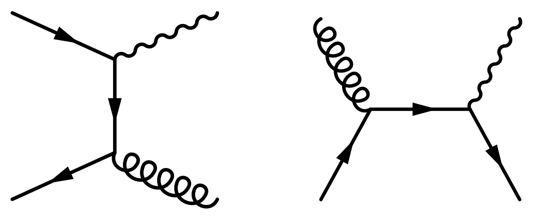
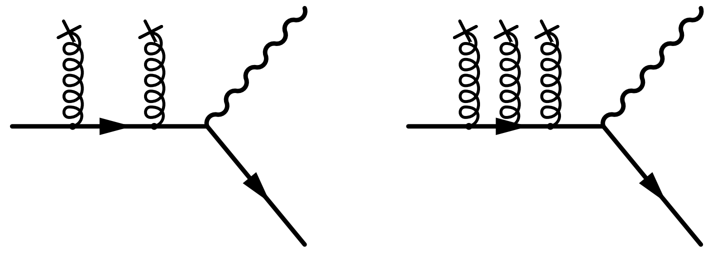
OGM. arXiv: 1909.12294

Phys. Rev. D44 (1991) 2774-2788

JHEP 0112 (2001) 009

Photon Production: Kinetic Rates

Complete LO

- $2 \leftrightarrow 2$ scatterings 
- $1 \leftrightarrow 2$ scatterings 

Thermal (AMY)

$$E\frac{dN}{d^4X\,d^3p} = 2\alpha d_F \sum_c q_c^2 \frac{C_F g_s^2 T^2}{4} f_{q,eq}\left(\frac{E}{T}\right)\,\nu\left(\frac{E}{T}\right)$$

$$LL : \nu\left(\frac{E}{T}\right) \rightarrow \mathcal{L}$$

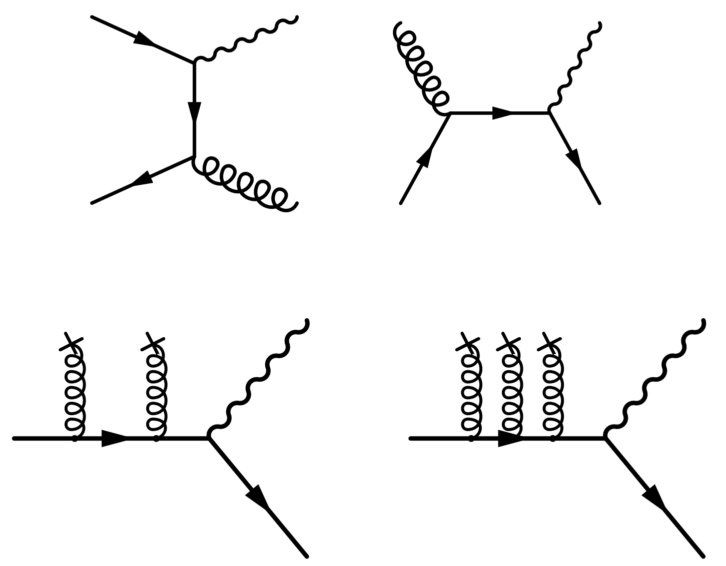
$$LO : \nu\left(\frac{E}{T}\right) \rightarrow LL\left(\frac{E}{T}\right) + C_{bremss}\left(\frac{E}{T}\right) + C_{anni}\left(\frac{E}{T}\right)$$

AMY: JHEP 0112 (2001) 009

Photon Production: Kinetic Rates

Complete LO

- $2 \leftrightarrow 2$ scatterings
- $1 \leftrightarrow 2$ scatterings



"Non-Thermal"

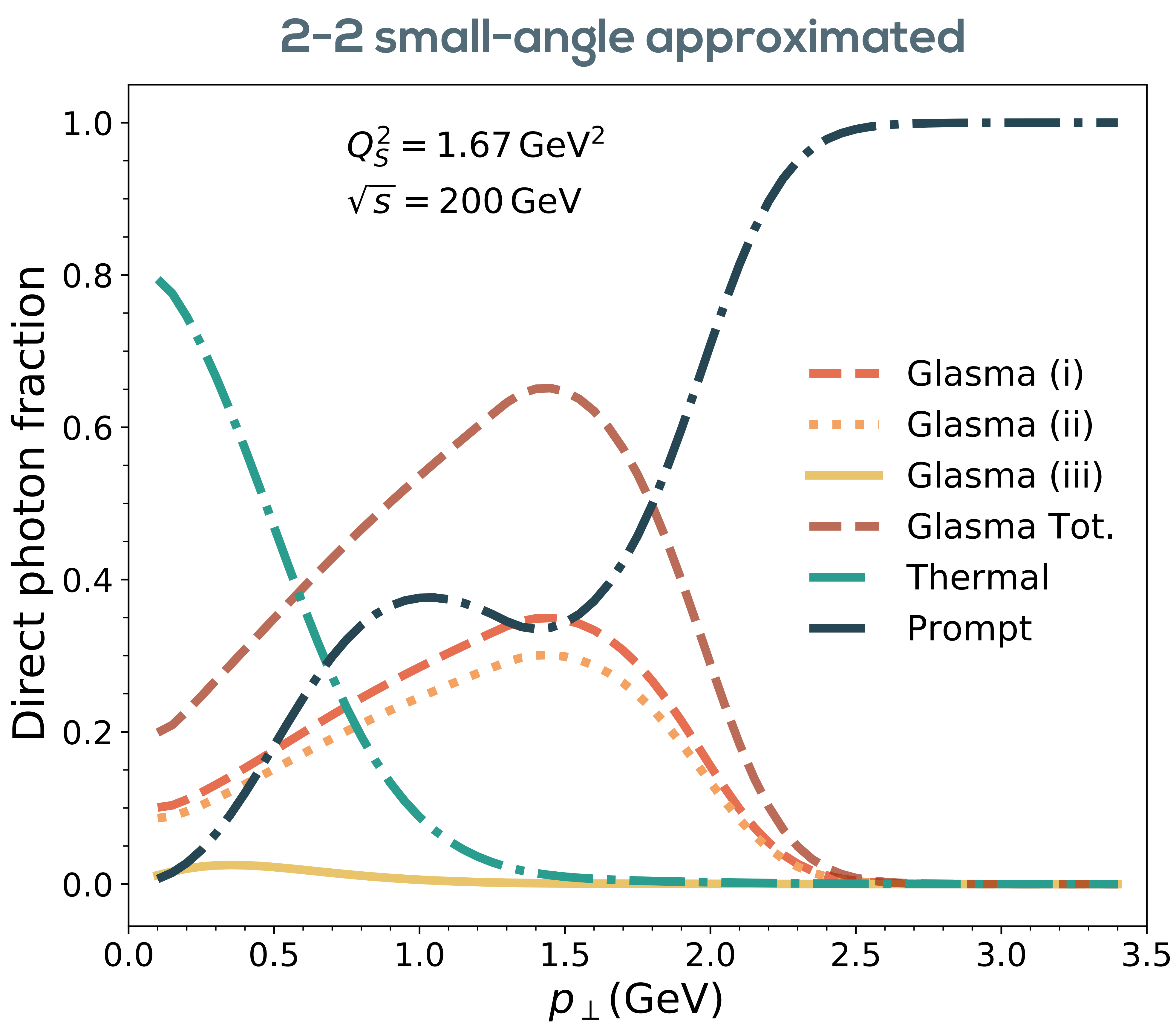
$$E\frac{dN}{d^4X\,d^3p} = \frac{40}{9\pi^2}\,\alpha\,\alpha_S\,f_{q,eq}(\tau,\mathbf{p})\,I_g(\tau)\,\nu\left(\frac{E}{Q}\right)$$

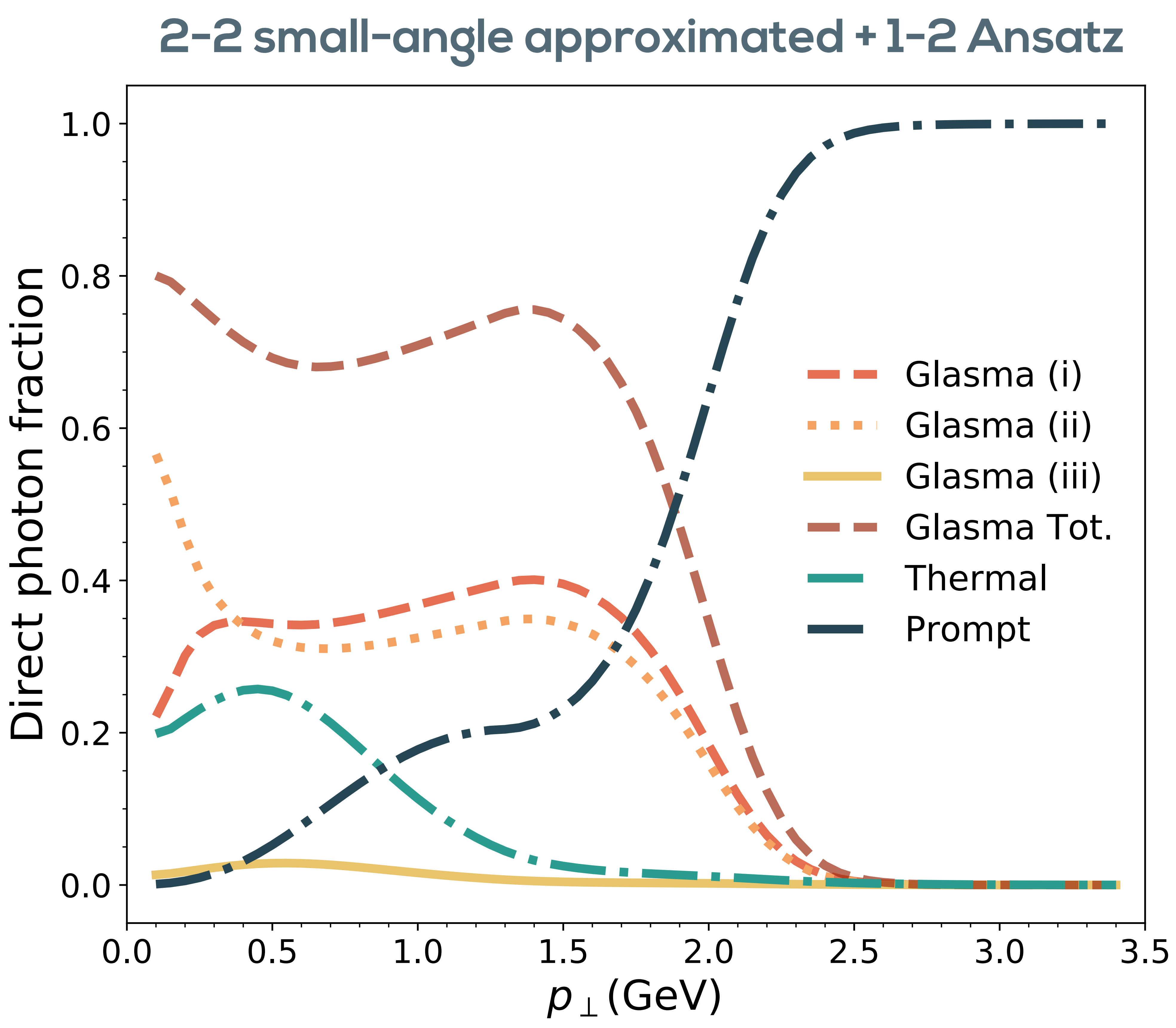
$$LL:\nu\left(\frac{E}{Q}\right)\to\mathcal{L}$$

$$LO:\nu\left(\frac{E}{Q}\right)\to LL\left(\frac{E}{Q}\right)+C_{bremss}\left(\frac{E}{Q}\right)+C_{anni}\left(\frac{E}{Q}\right)$$

OGM. arXiv: 1909.12294

OGM, Löher, Mazeliauskas, Berges, Reygers. Phys.Rev.C 102 (2020) 2, 024915

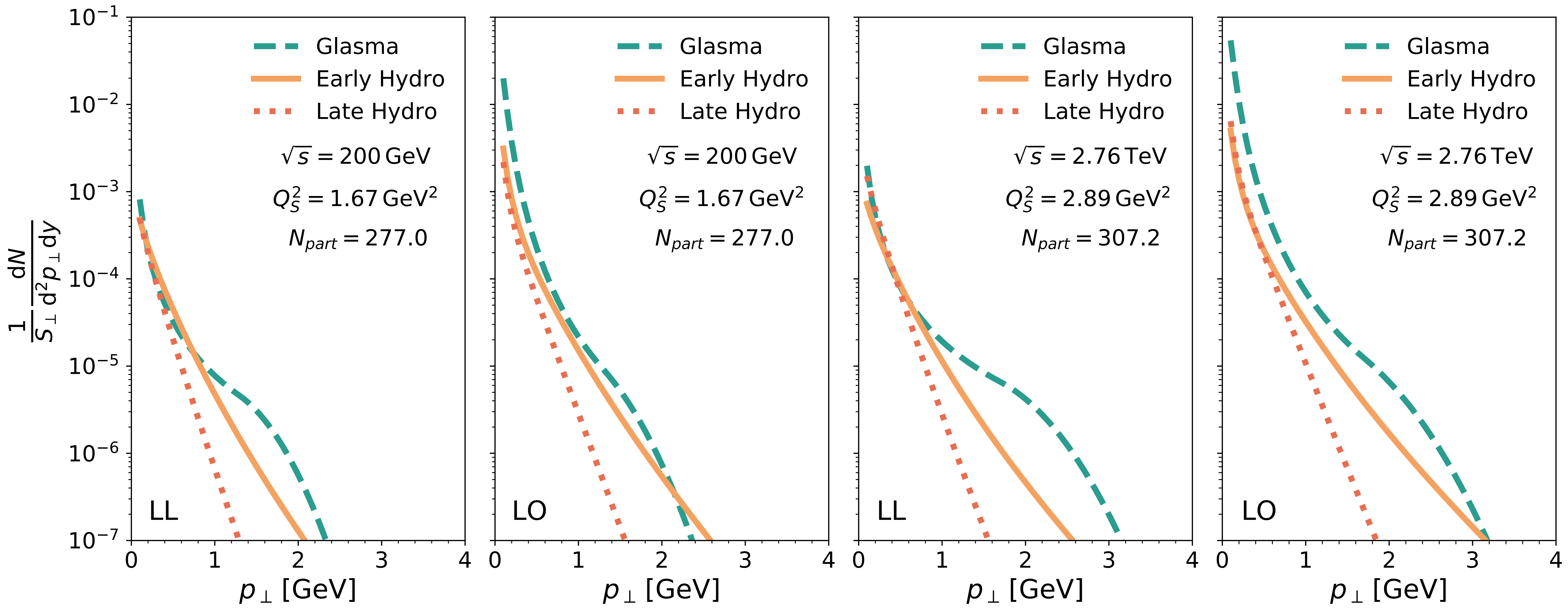




Non-equilibrium photons become more relevant in the IR

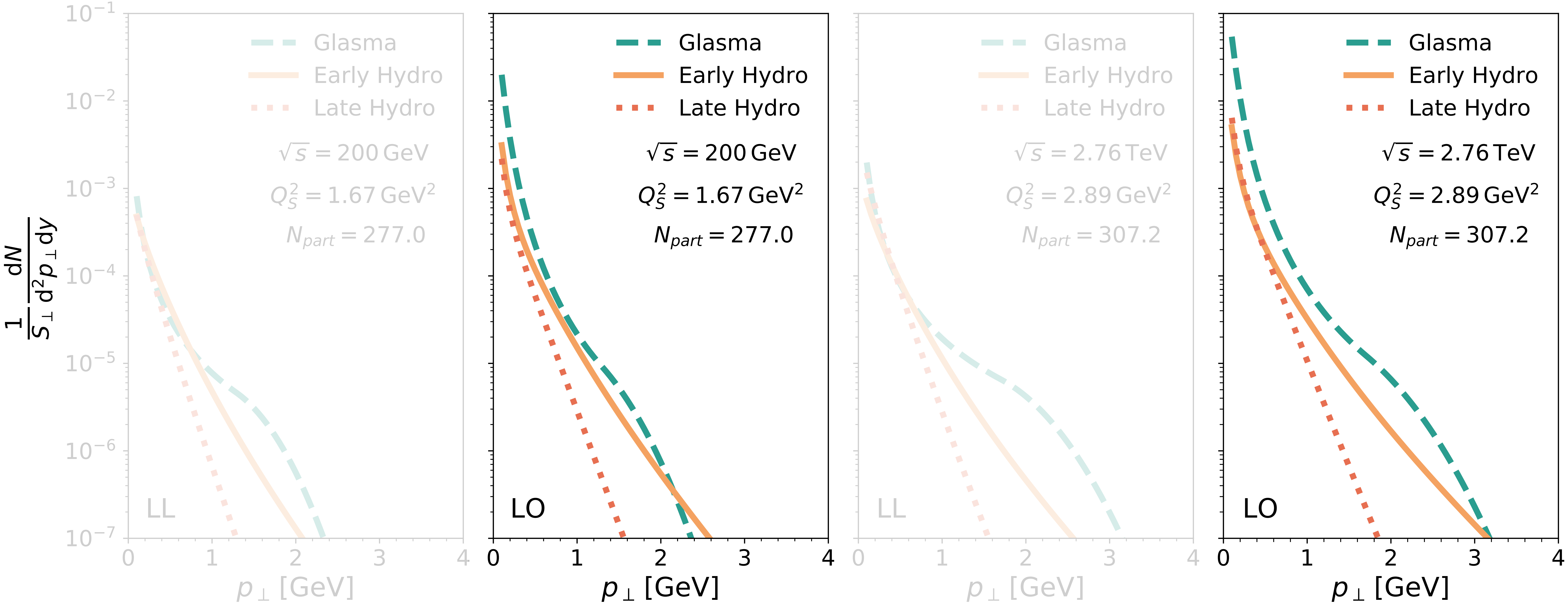
Early Thermalization vs “bottom-up”

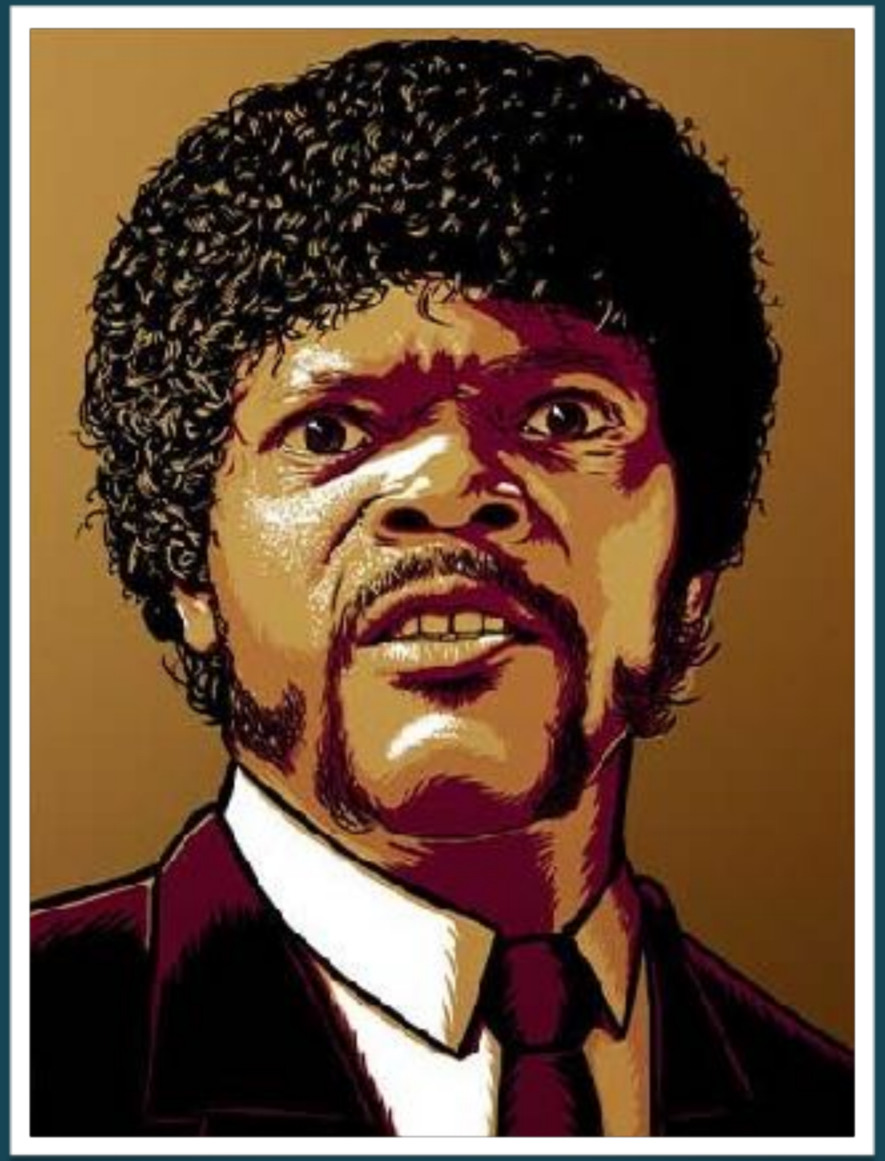
- Early Thermalization: Thermal stage is initialized at
- Non-equilibrium photons increase the yields.



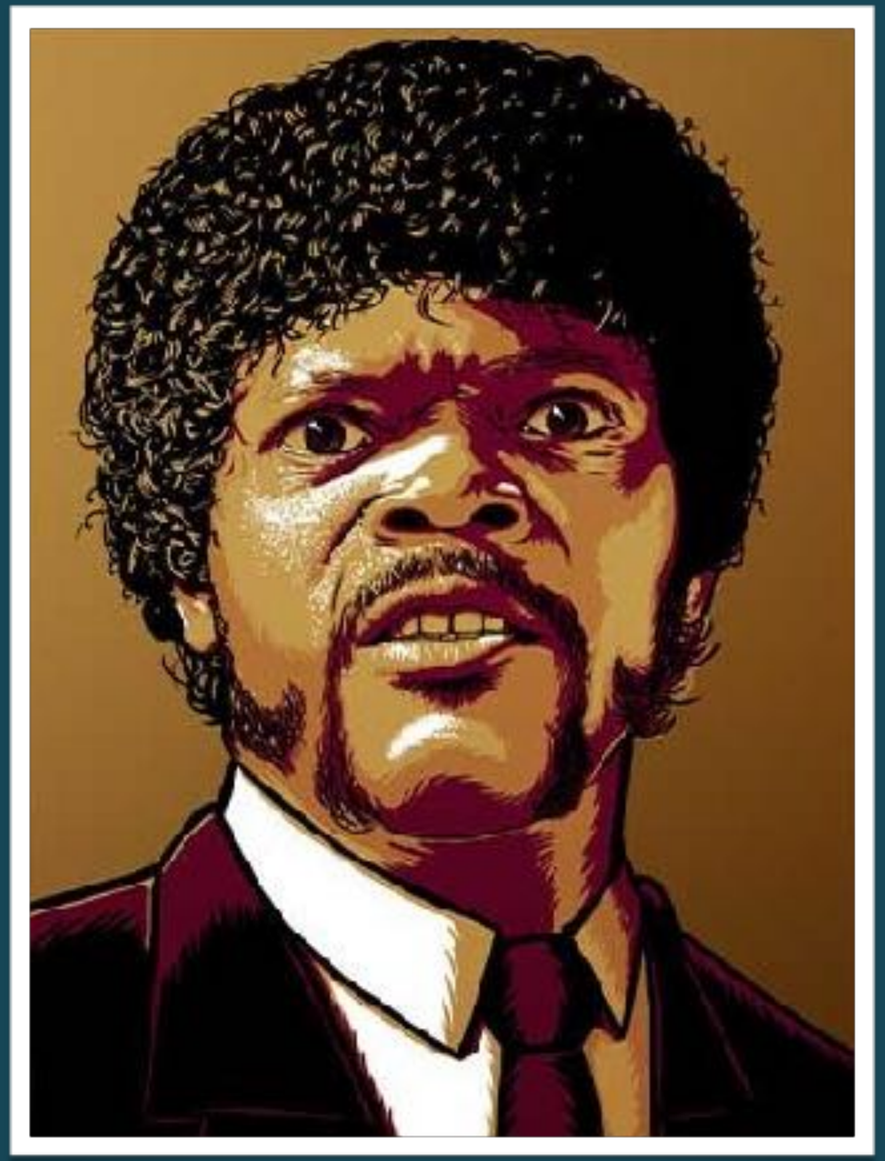
Early Thermalization vs “bottom-up”

- Early Thermalization: Thermal stage is initialized at
- Non-equilibrium photons increase the yields.

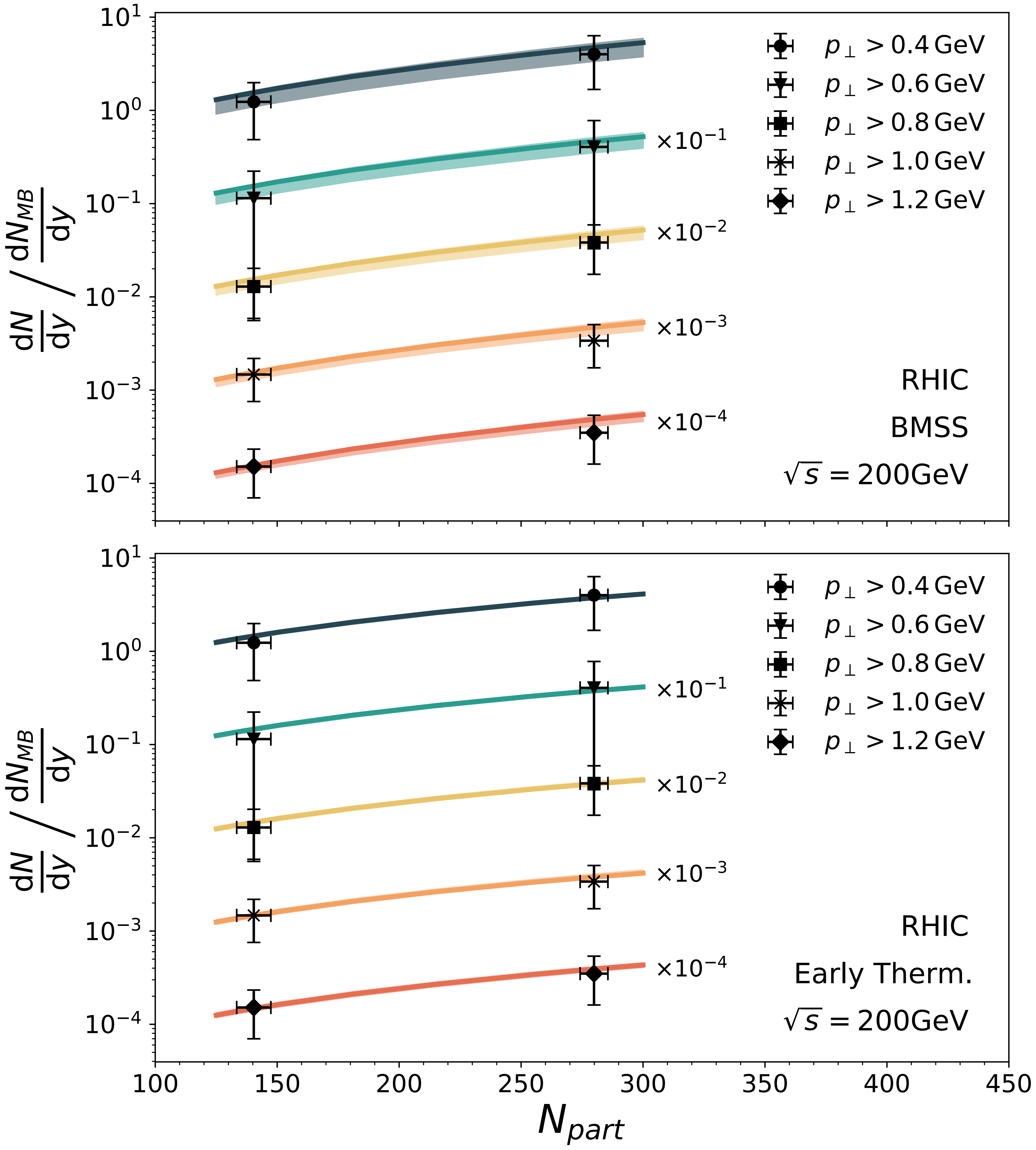


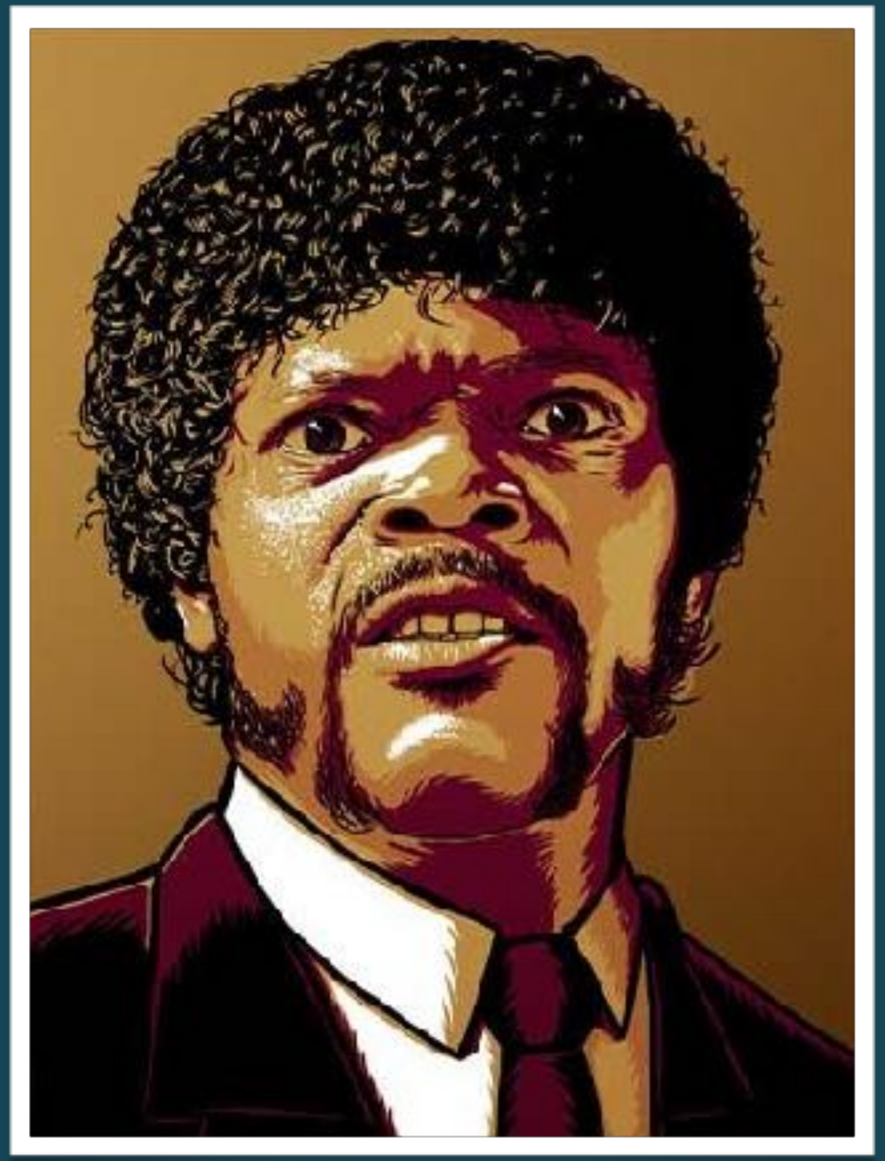


DATA, DO YOU SPEAK IT?



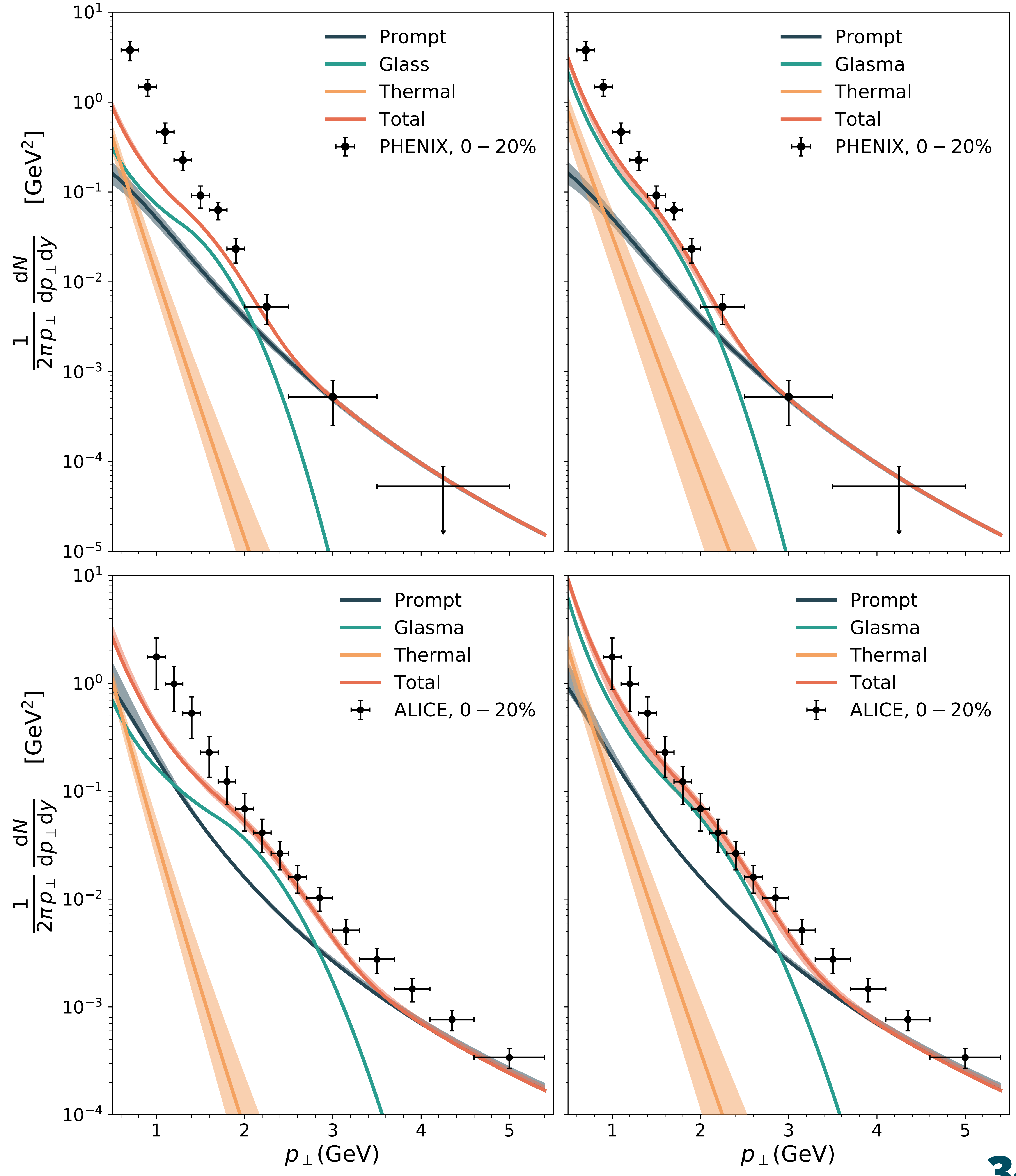
DATA, DO YOU SPEAK IT?





DATA, DO YOU SPEAK IT?

(with a caveat, perhaps)



Summary: First Part

- Early time photons are at relevant for the completion of direct photon observables.
  - Surprisingly fair agreement to data for such a simplistic model
    - This is a very best case scenario. In reality, pre-eq expected to be shorter.

So much to do still...

- Proper non-eq simulation of photons on a QCD background should be performed

  Work in progress with Berges, Ye and Spitz

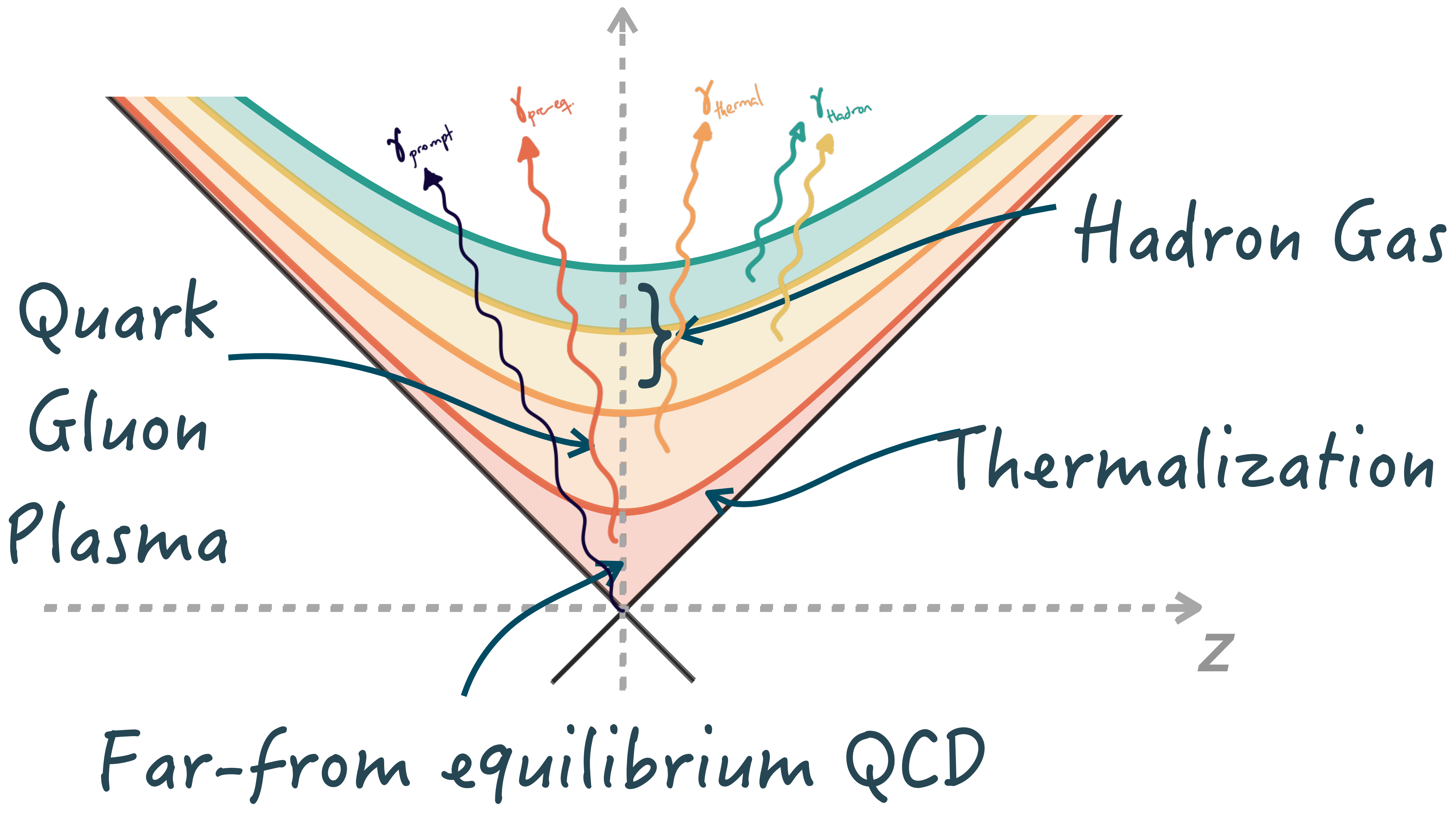
  - IR, and deep IR behaviour of non-equilibrium photons still not understood. Many exciting possibiliities lie there.

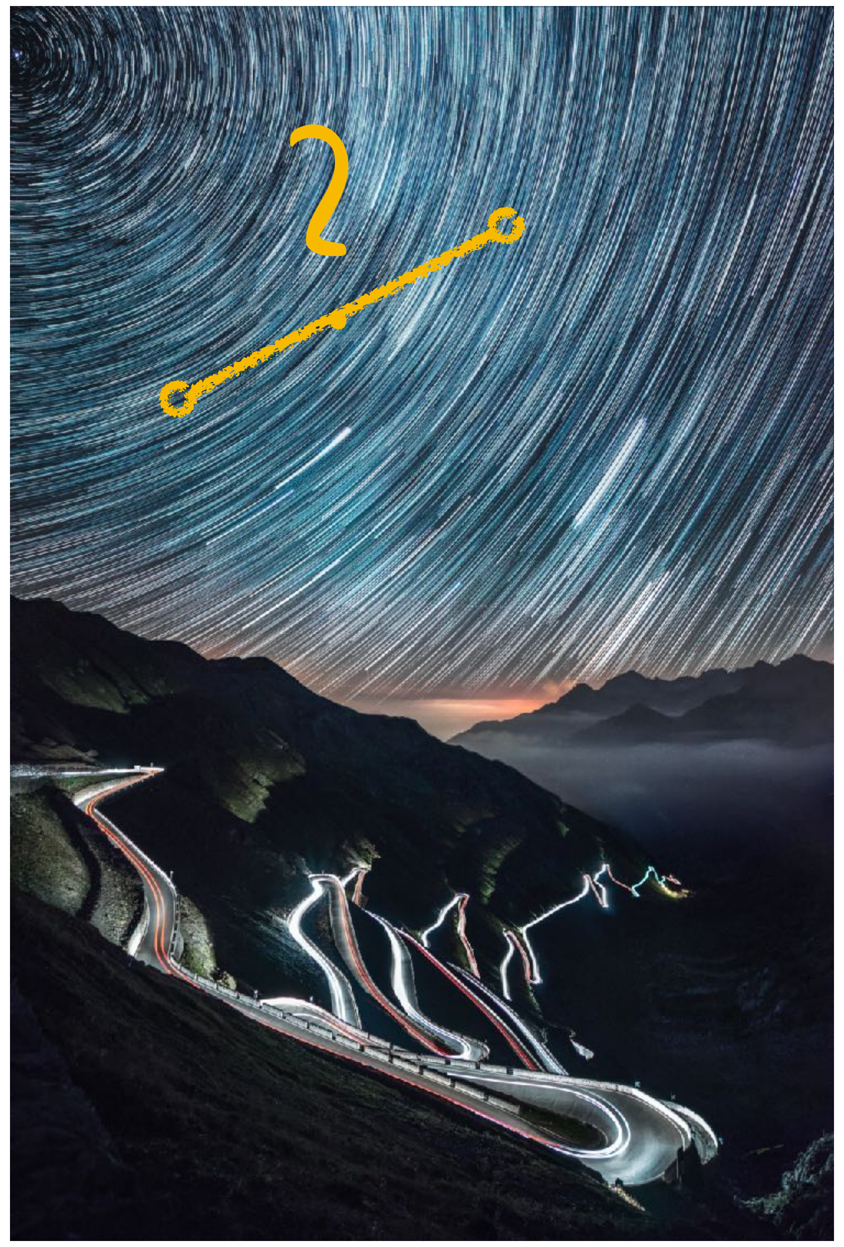
Part 2

Using photon correlations to probe the spacetime evolution of the fireball

Or: how to disentangle a long-exposure picture

Direct Photons





How to disentangle a long exposure picture?

Use photon Hanbury-Brown-Twiss (HBT) correlations to extract space-time information

Phys. Rev. C80, 0449 (2009)

The Plan

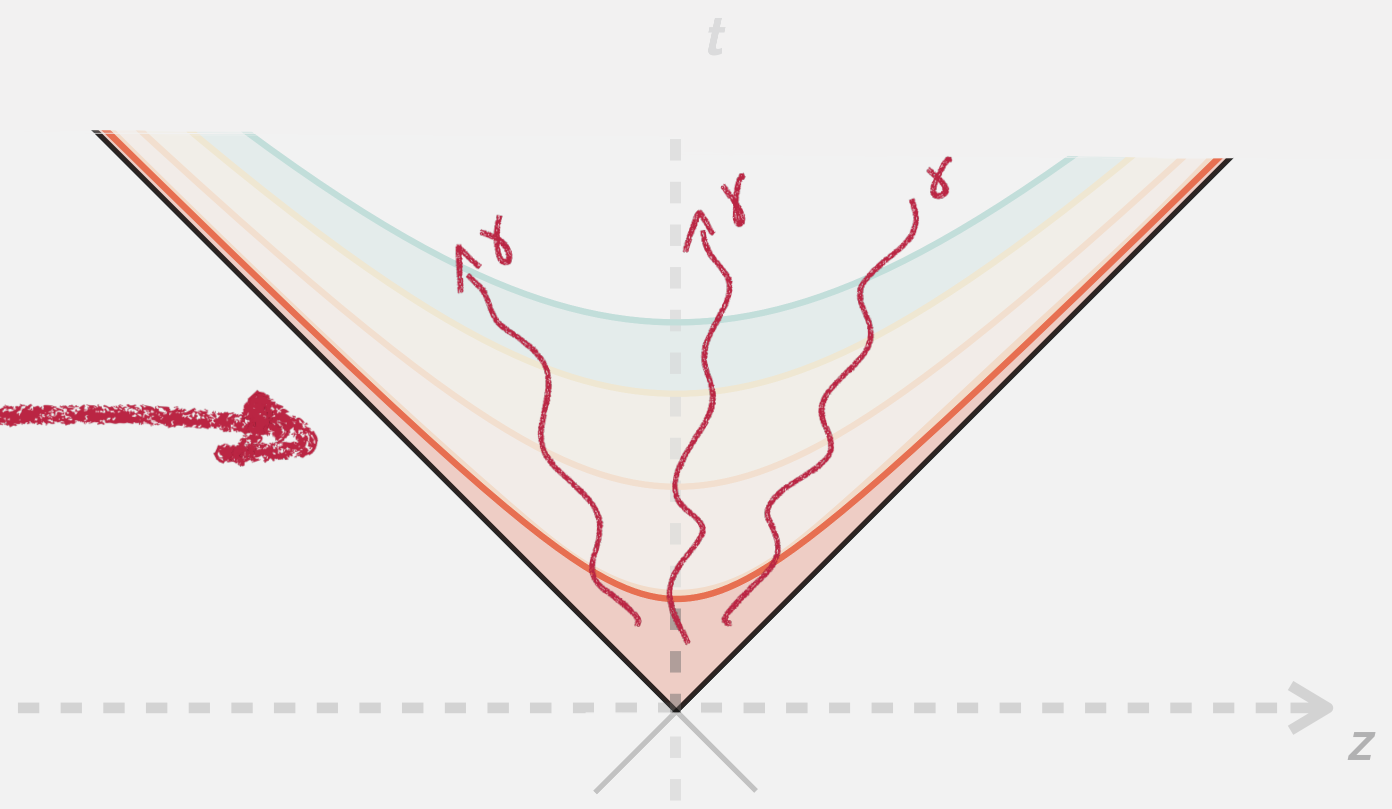
Use photon interferometry (HBT) to extract information on the evolution of the medium

How?

Use two contrasting scenarios to showcase HBT as a tool to further discriminate results.

René Magritte
Empire of Light

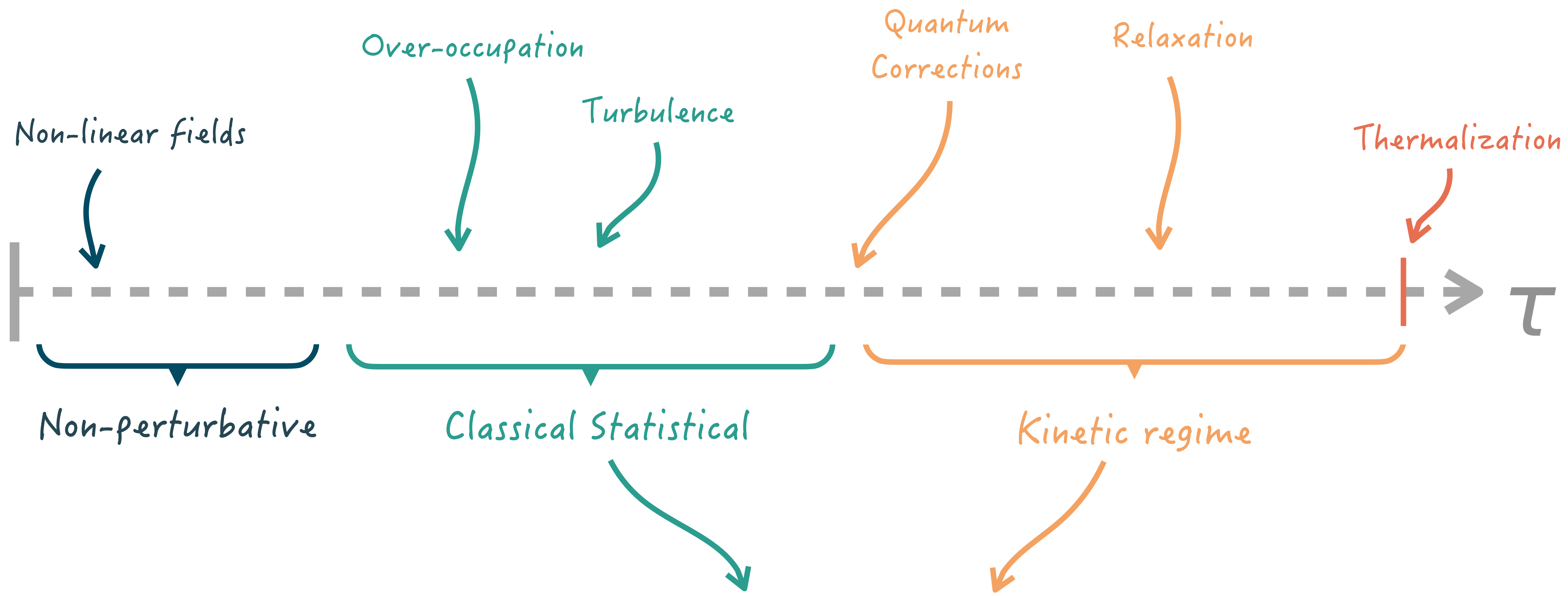
Early time
Production



Photons from the "bottom-up" scenario

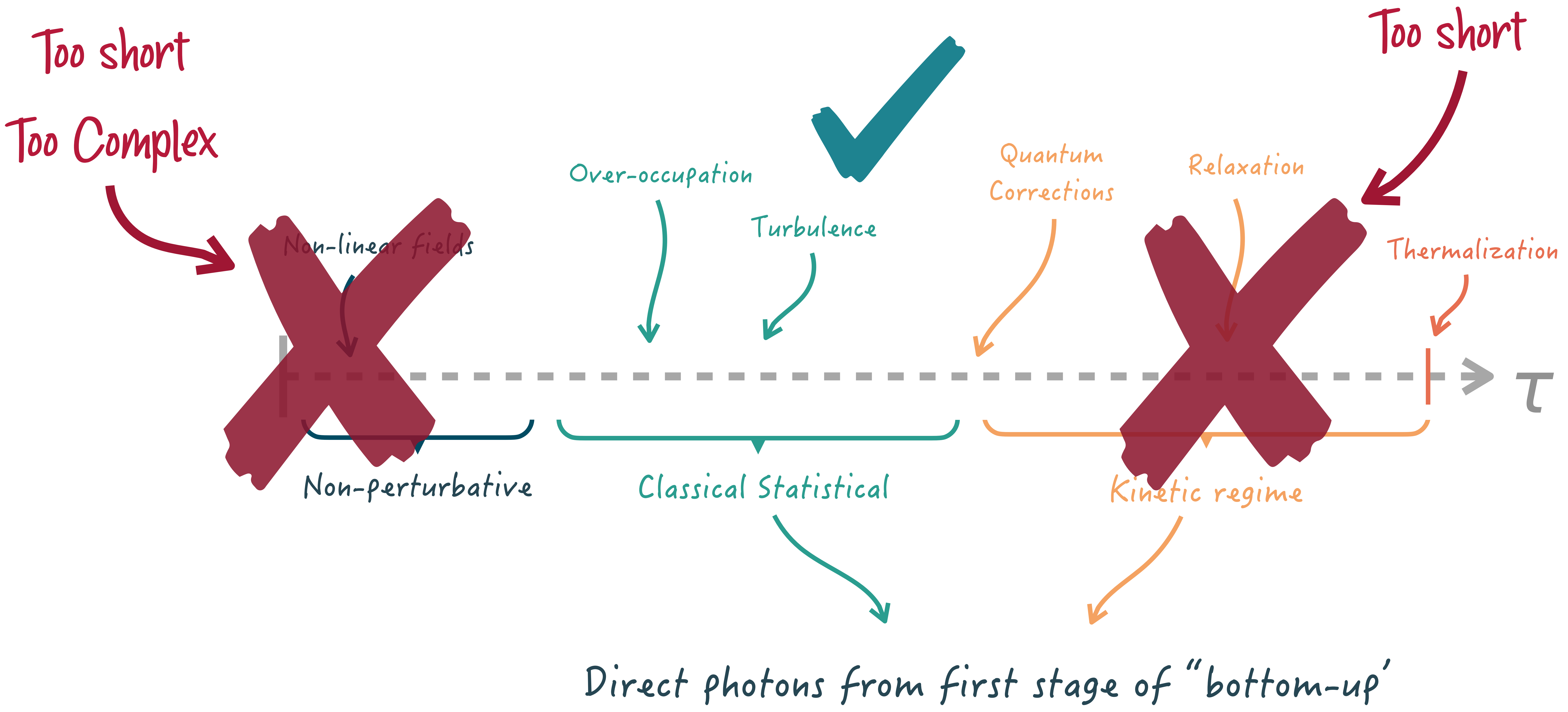
(QCD Kinetic Thermalization)

Far-from equilibrium QCD matter



Direct photons from pre-equilibrium epochs! *

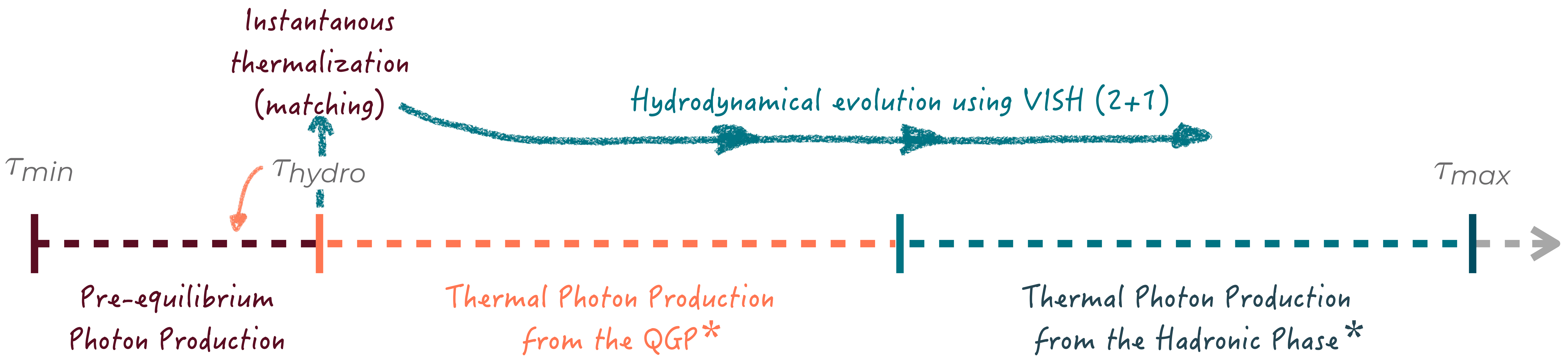
Far-from equilibrium QCD matter



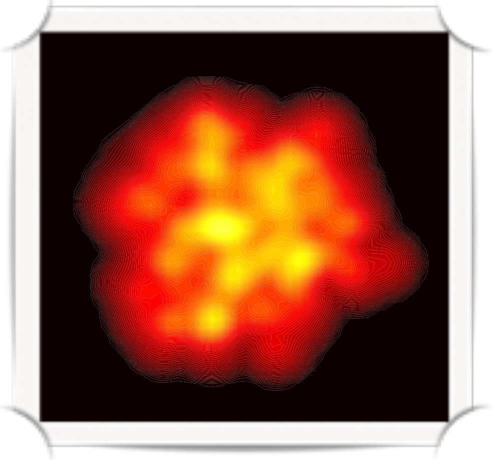
OGM. arXiv: 1909.12294

OGM, Löher, Mazeliauskas, Berges, Reygers. Phys.Rev.C 102 (2020) 2, 024915

The model



MC-Glauber



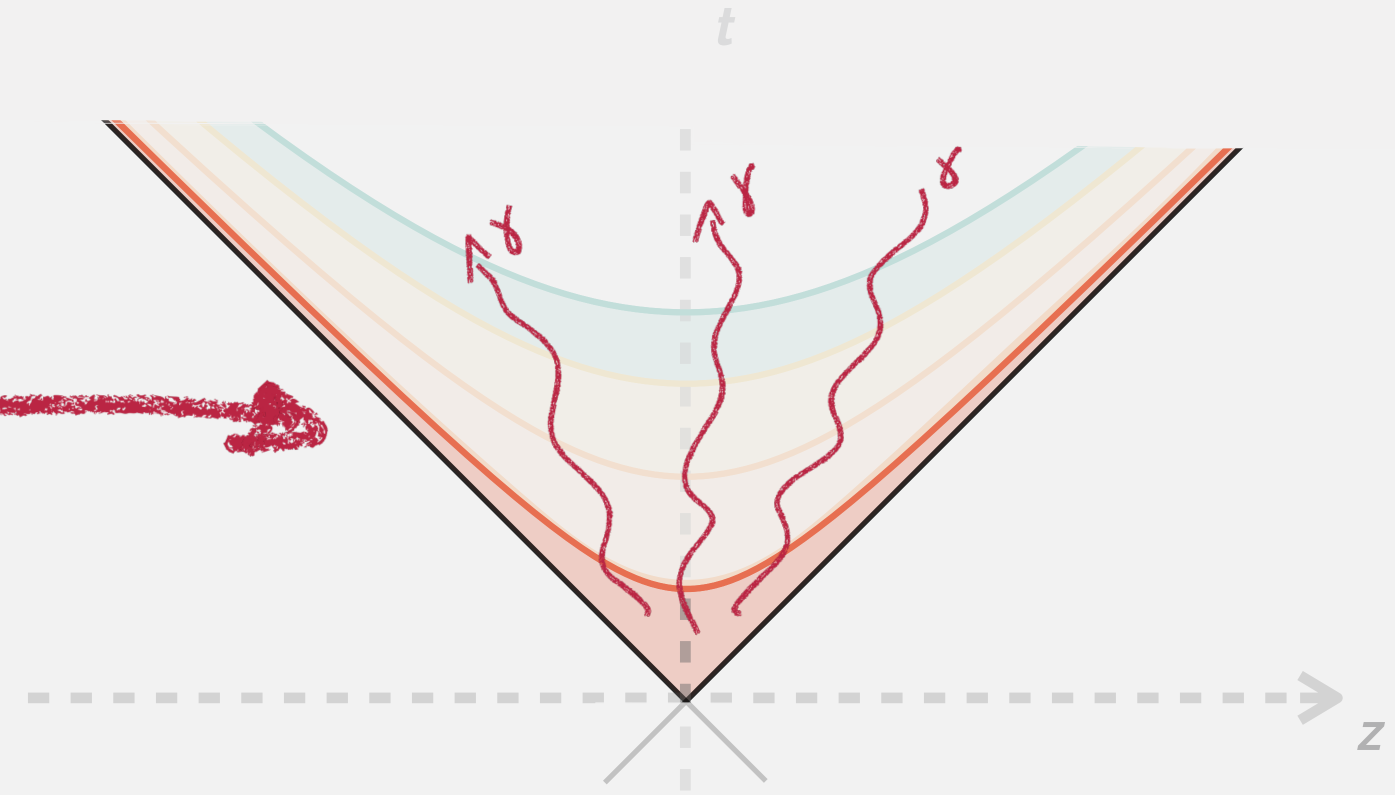
$$\tau_{min} = 0.1\text{fm}$$
$$\tau_{hydro} = 0.6\text{fm}$$
$$\tau_{max} = 15\text{fm}$$

* Using the thermal rates in

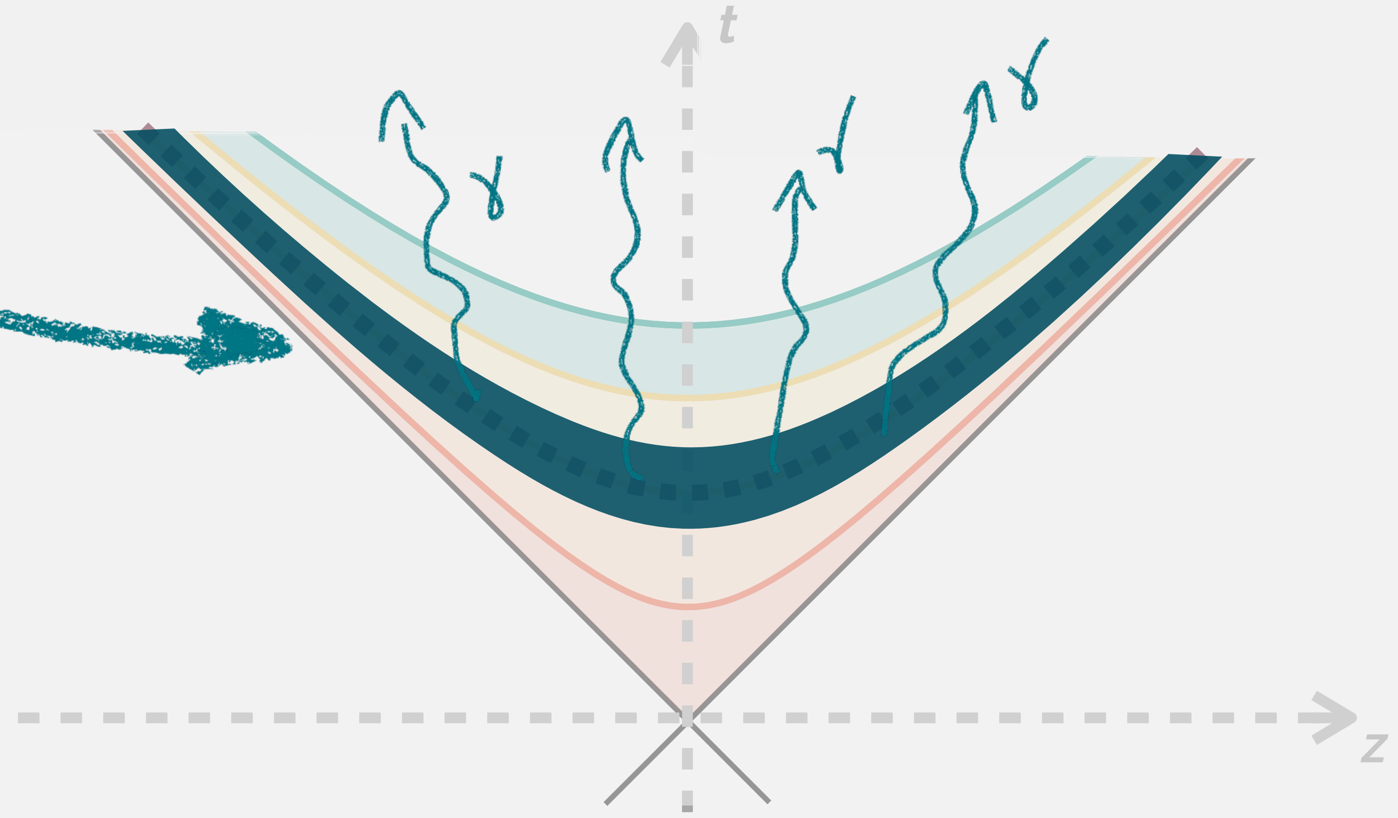
P. B. Arnold, *et al*, JHEP 12, 009 (2001)
S. Turbide, *et al*, Phys. Rev. C69, 014903 (2004)
M. Heffernan, *et al*, Phys. Rev. C91, 027902 (2015)

René Magritte
Empire of Light

Early time
Production



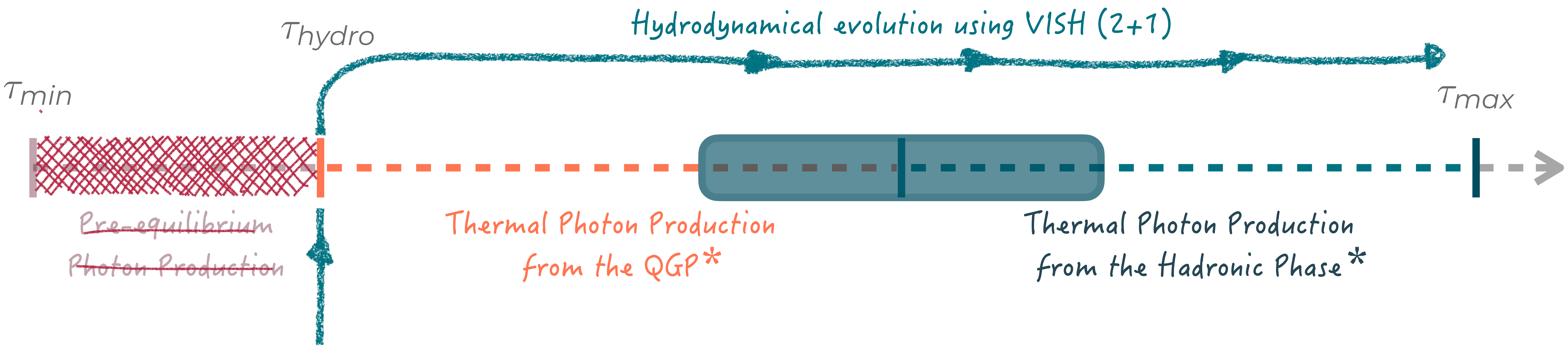
Late time
enhancement



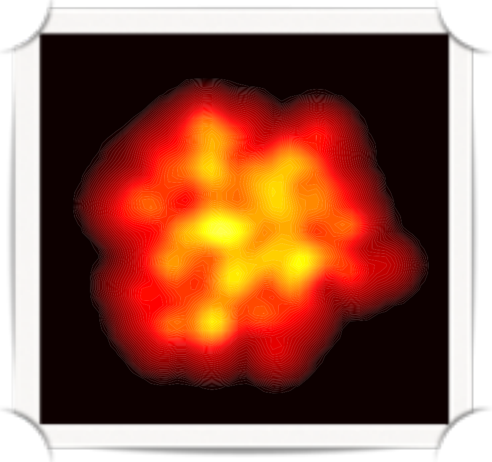
Photons from pseudocritical enhancement

(Non-perturbative partonic enhancement)

The model



MC-Glauber



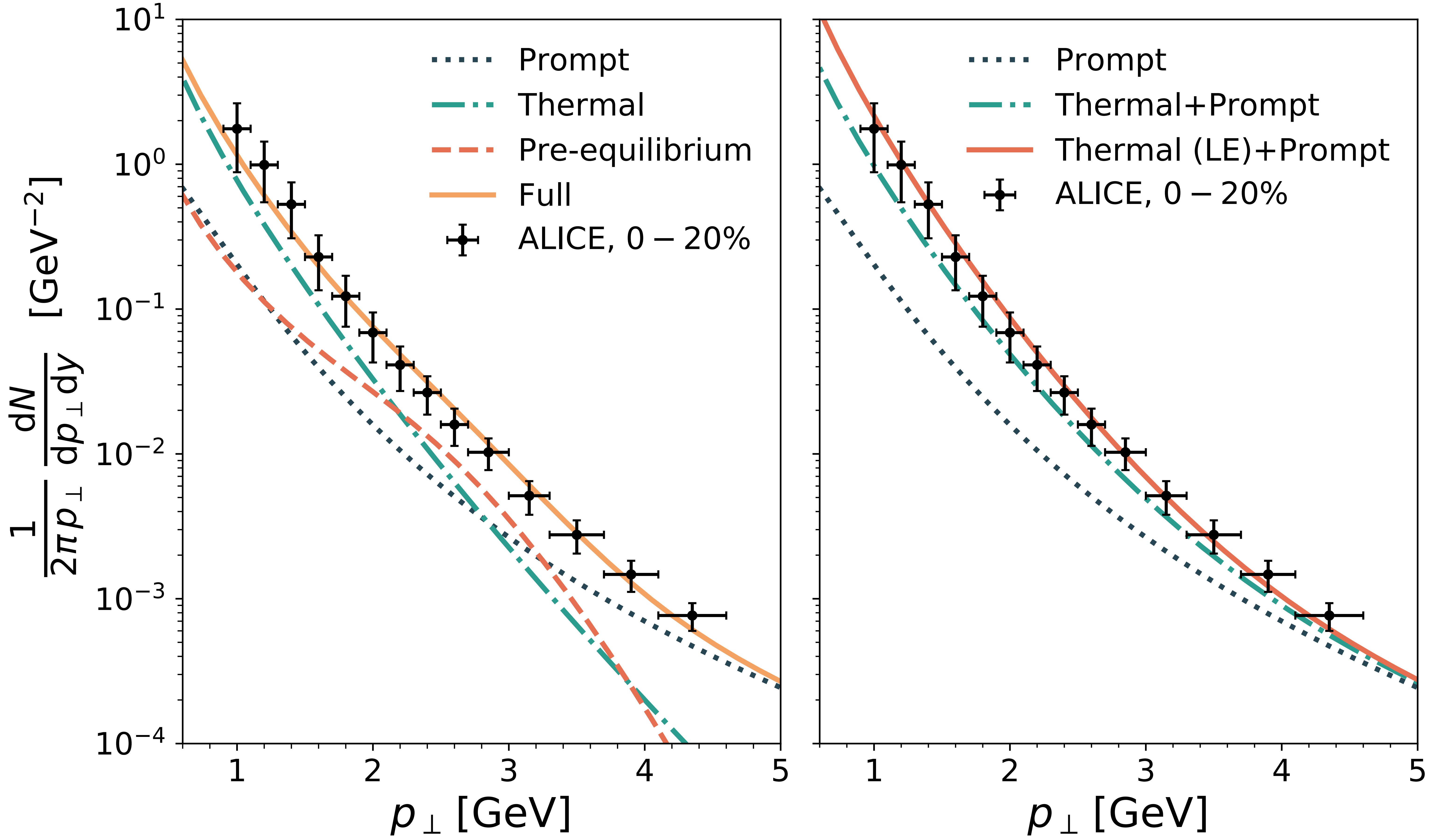
Enhancement around T_{pc}

$$E\frac{\mathrm{d}N_{\mathrm{enh}}}{\mathrm{d}^4x\,\mathrm{d}^3p} \equiv h(T)\,E\frac{\mathrm{d}N_{\mathrm{thermal}}}{\mathrm{d}^4x\,\mathrm{d}^3p}$$

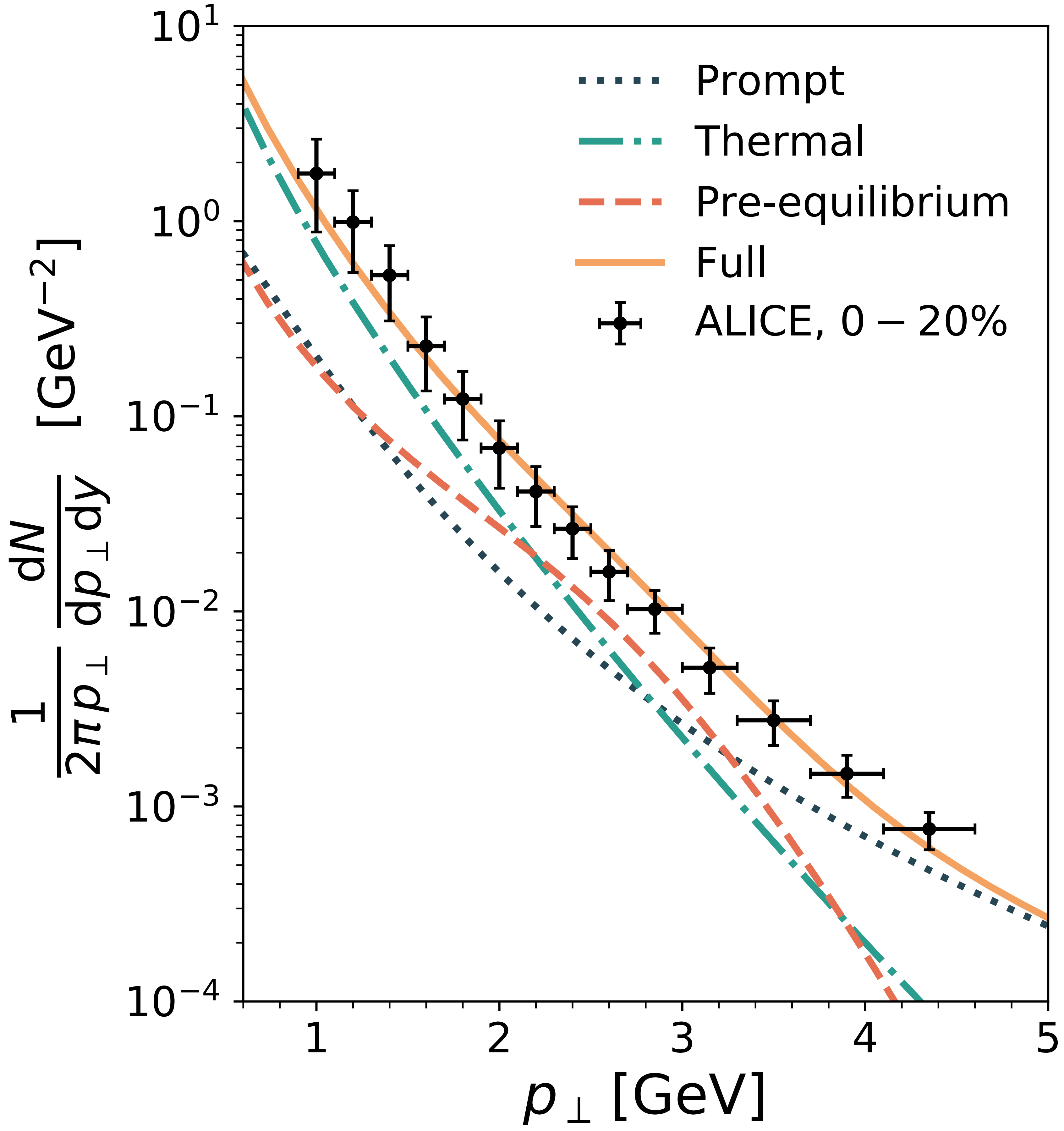
$$h(T) = 1 + h_0 \exp\left\{-\frac{(T-T_{pc})^2}{d^2}\right\}$$

* Inspired by: H. van Hees, *et al*, Nucl. Phys. A933, 256 (2015)

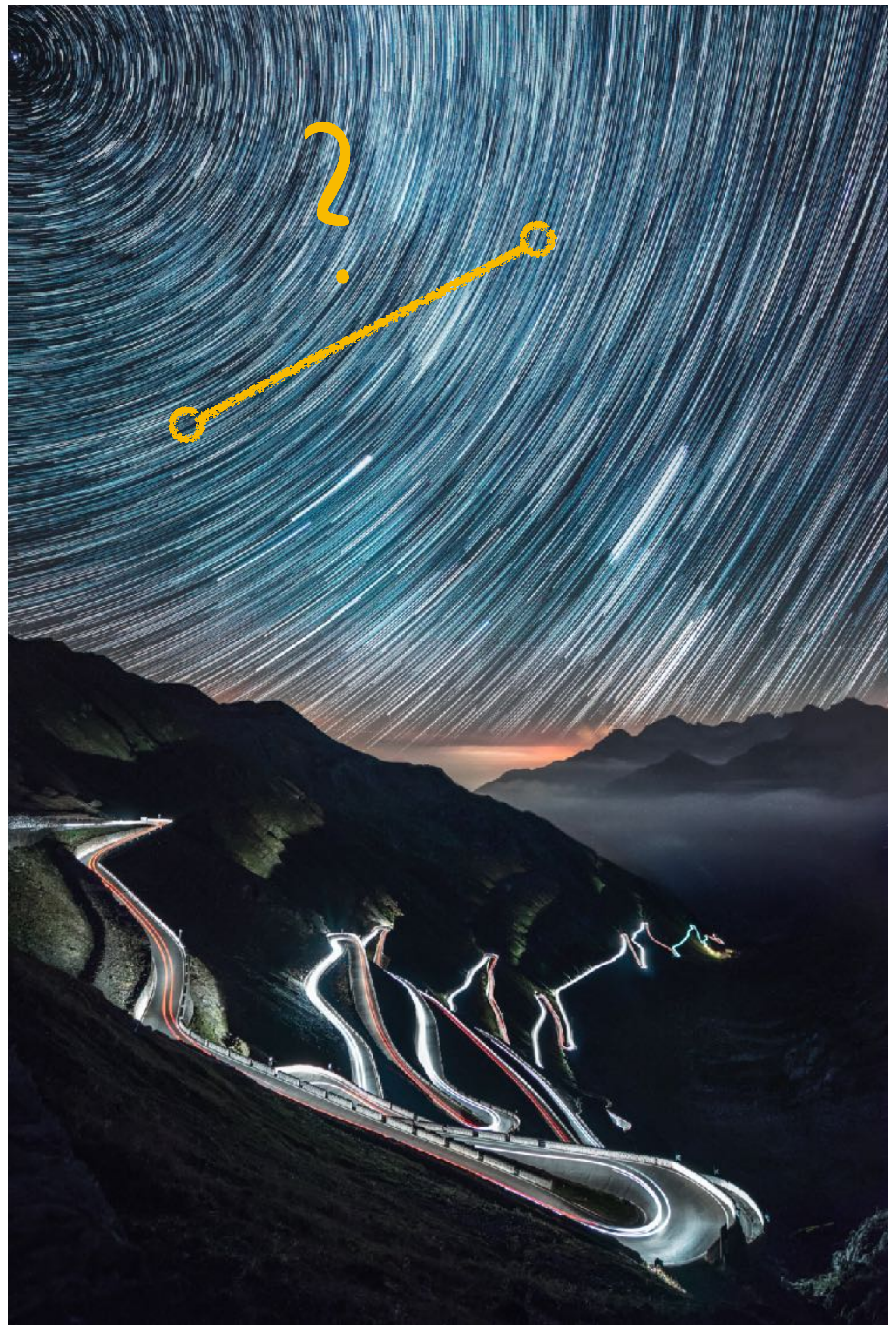
Direct photon yield



How to disentangle a long exposure picture?



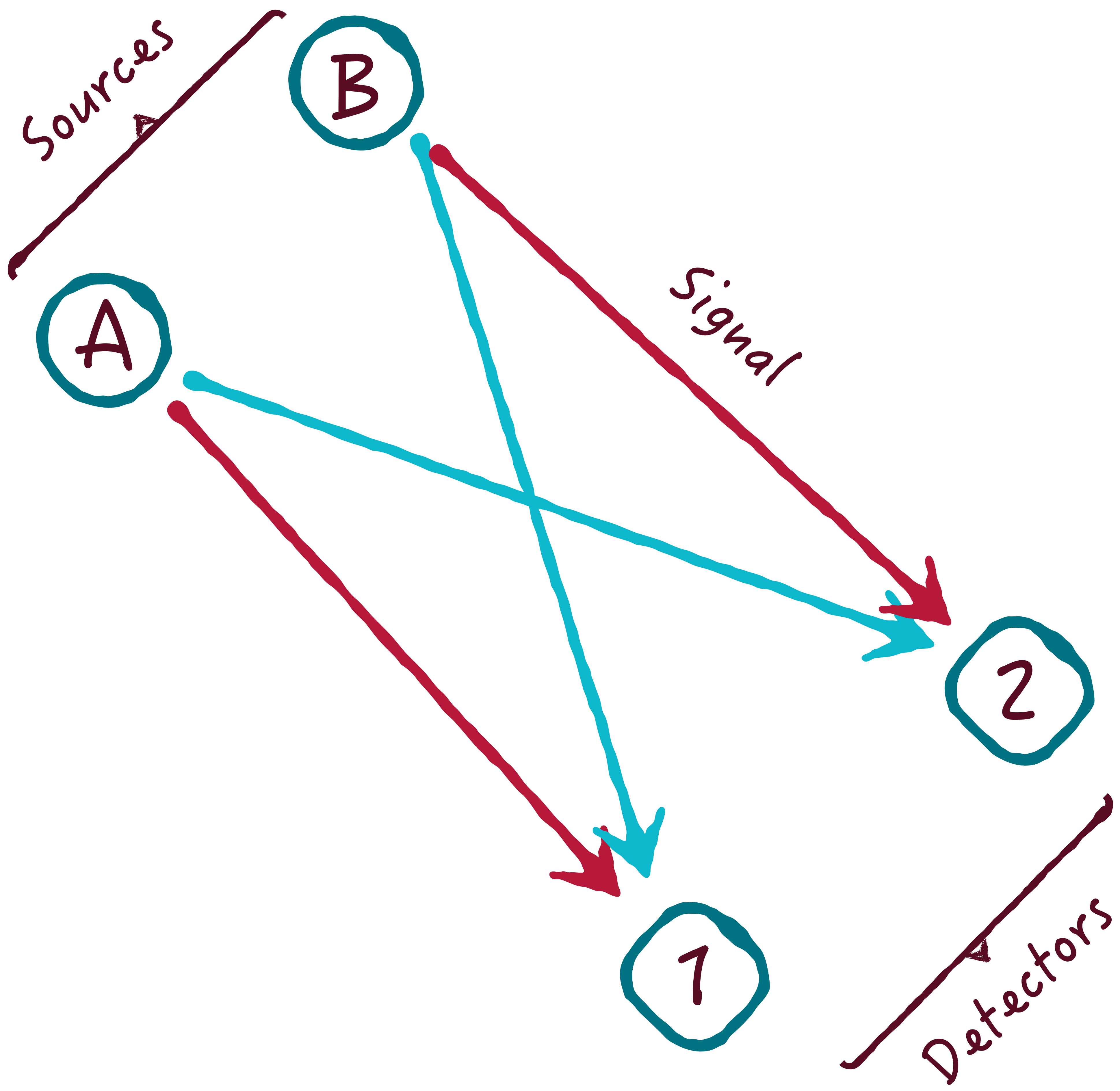
↔



HBT

(Hanbury Brown-Twiss correlations)

HBT - What are they?



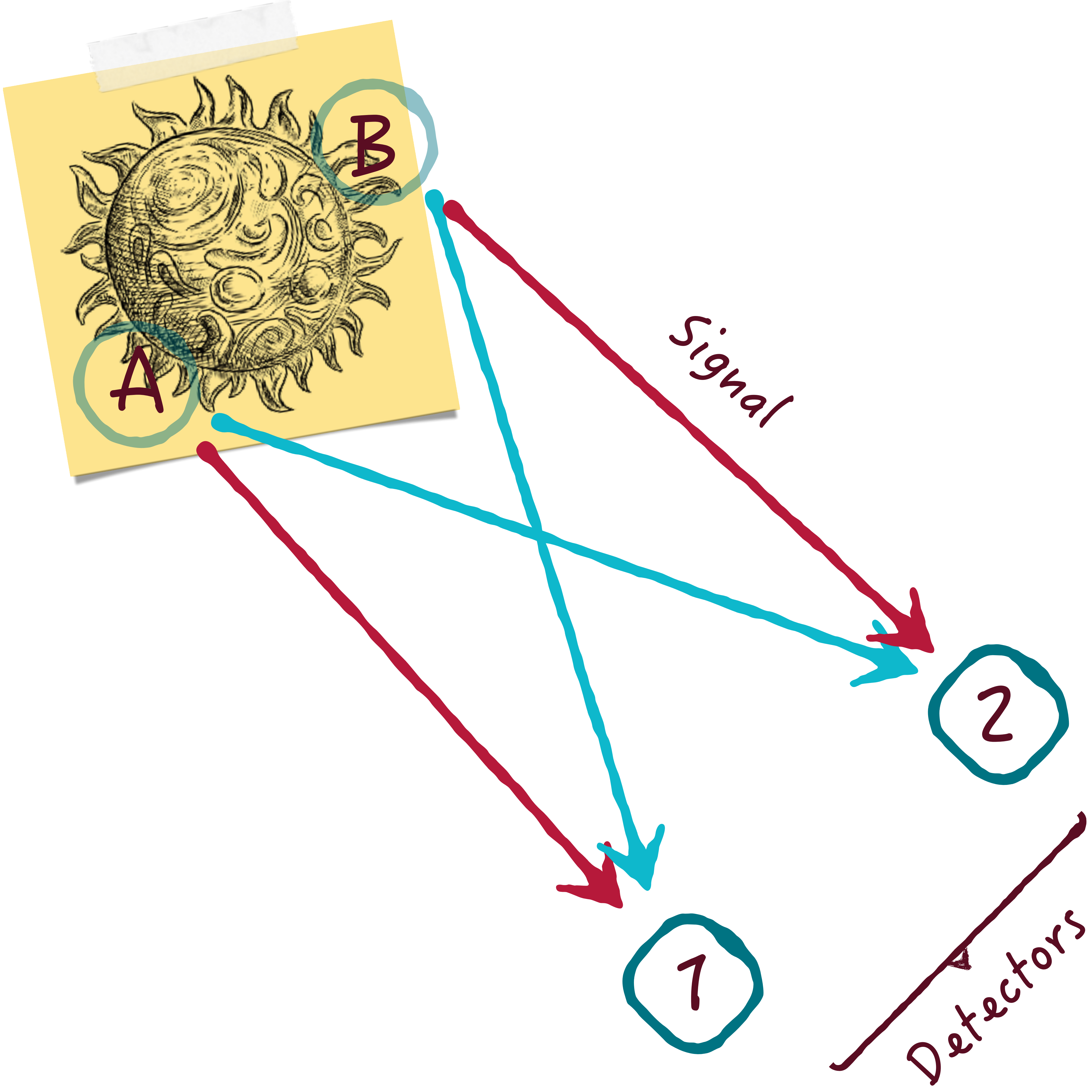
"IF THE RADIATION RECEIVED AT TWO PLACES IS MUTUALLY COHERENT, THEN THE FLUCTUATION IN THE INTENSITY OF THE SIGNALS RECEIVED AT THOSE TWO PLACES IS ALSO CORRELATED"

Robert Hanbury Brown

Main Object : HBT Correlator

$$C \sim \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle} \quad \rightarrow \quad \frac{\langle N_1 N_2 \rangle}{\langle N_1 \rangle \langle N_2 \rangle}$$

HBT - What are they?



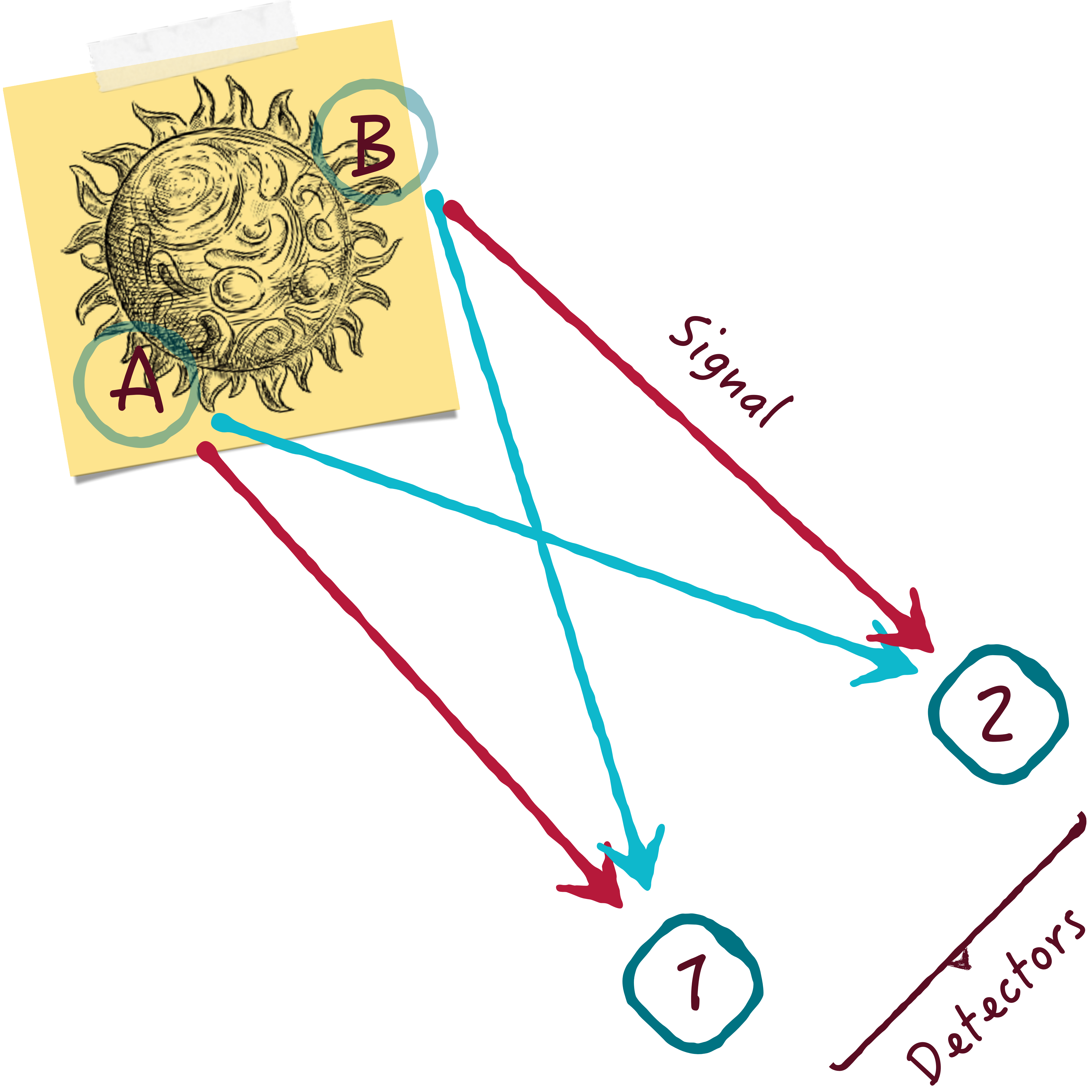
A little bit of History

Used to measure the size of astronomical light sources.

→ Cassiopeia A and Cygnus A

How?

HBT - What are they?



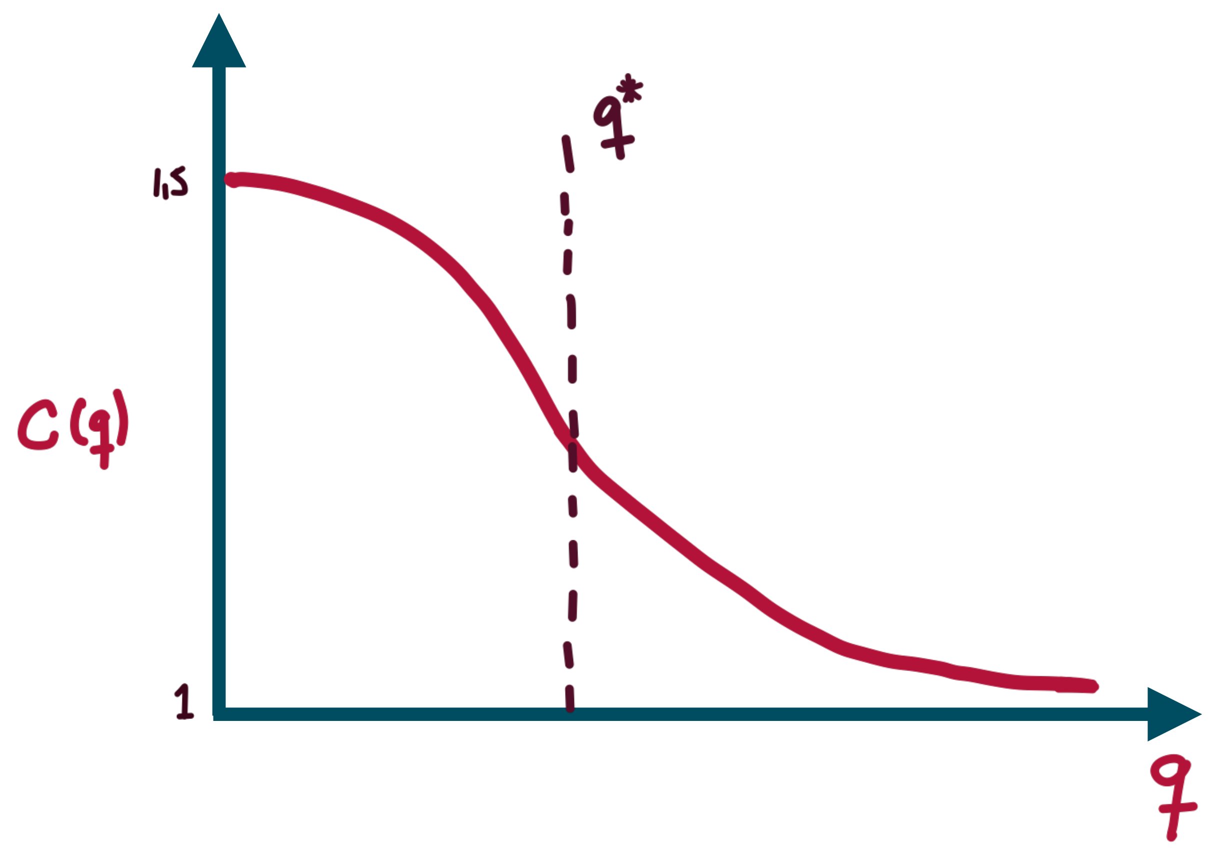
A little bit of History

Used to measure the size of astronomical light sources.

→ Cassiopeia A and Cygnus A

How? $\delta x\, \delta p \gg 2\pi\hbar$ Photons behave classical

$\delta x\, \delta p \lesssim 2\pi\hbar$ Photons behave quantum



$$\delta x_{max} \sim 2R$$

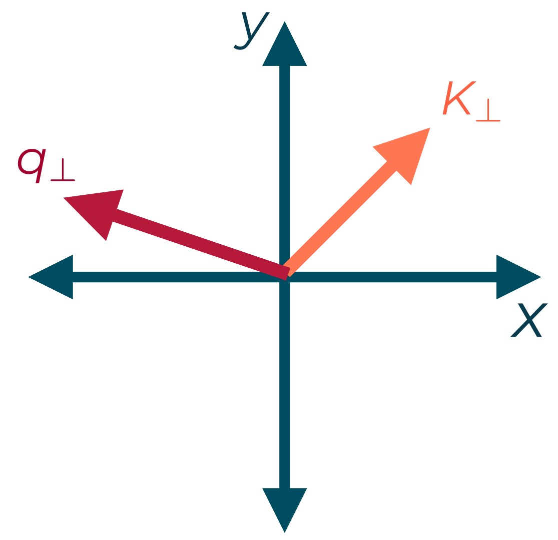
Quantum effects start at

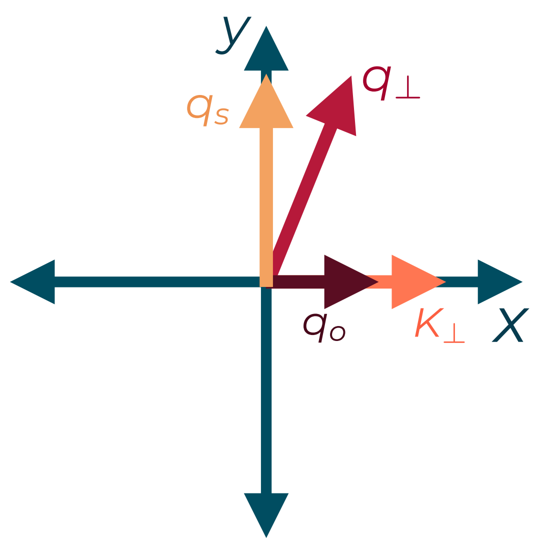
$$q^* = \frac{\pi\hbar}{R}$$

HBT Correlators

Main Object: HBT Correlator

$$C(p_1, p_2) = \frac{E_{p_1} E_{p_2} \frac{\mathrm{d}N}{\mathrm{d}^3 p_1 \mathrm{d}^3 p_2}}{E_{p_1} \frac{\mathrm{d}N}{\mathrm{d}^3 p_1} E_{p_2} \frac{\mathrm{d}N}{\mathrm{d}^3 p_2}}$$





Pair variables

$$K^\mu = (K^0, K_\perp, 0, K^z)$$
$$q^\mu = (q^0, q_\mathrm{o}, q_\mathrm{s}, q_\mathrm{l}) \,,$$

Extract some information: The HBT Radii

$$\langle\langle q_i q_j \rangle\rangle = \int \mathrm{d}^3 q \, q_i \, q_j \, g(q; K) \equiv \frac{1}{2} (R^{-1})_{ij}$$

$$g(q; K) \equiv \frac{C(q, K) - 1}{\int \mathrm{d}^3 q \, [C(q, K) - 1]}$$

The HBT-Radii are the characteristic scales of the correlator

In this talk, we will only be interested in the diagonal!

A little but important caveat

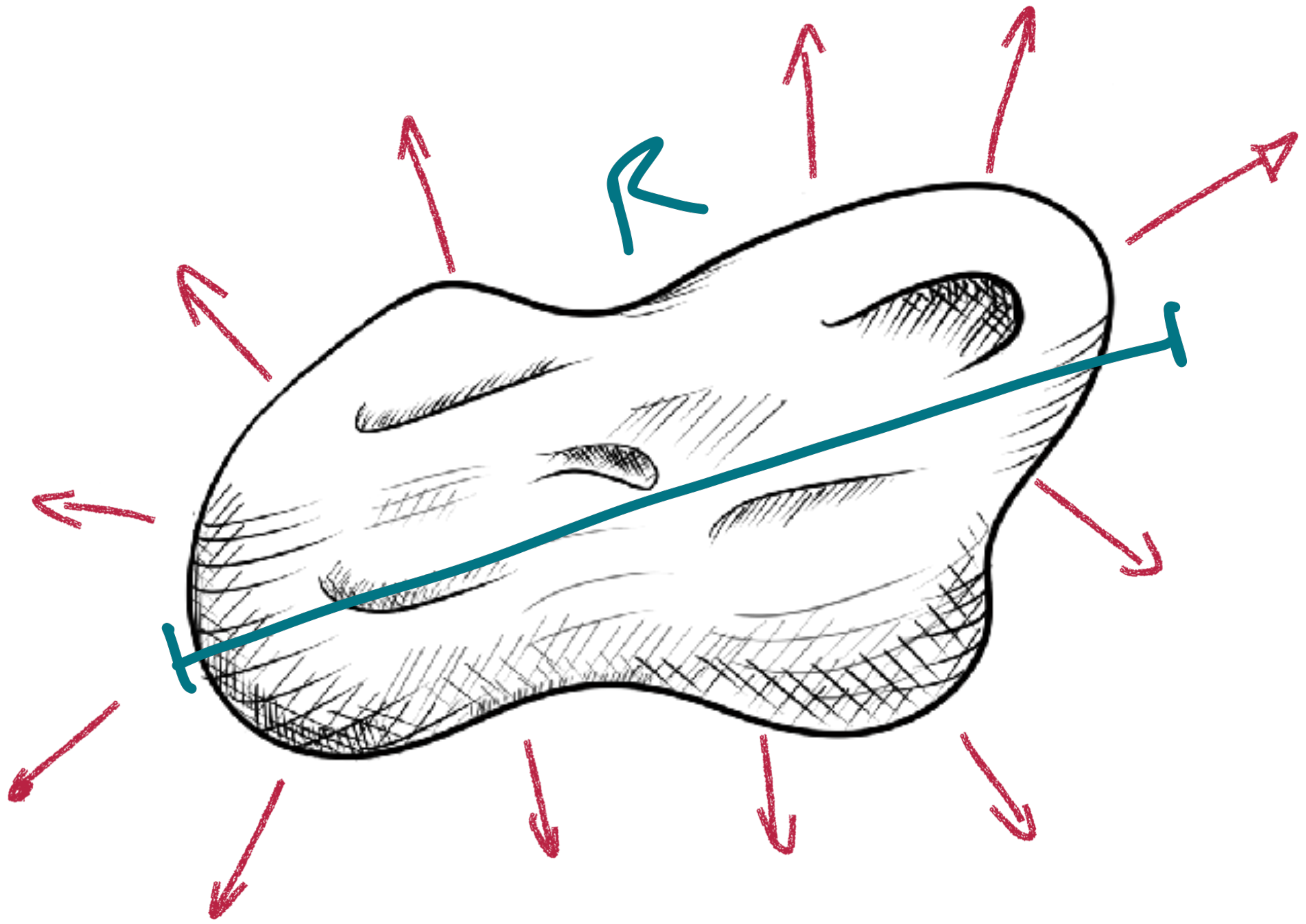
Stars are relatively close to being "Static Sources"

BUT In the context of Particle Physics

Pion Interferometry

Photon Interferometry

↔ Dynamical sources



Radii are more like weighted averages, in fact.

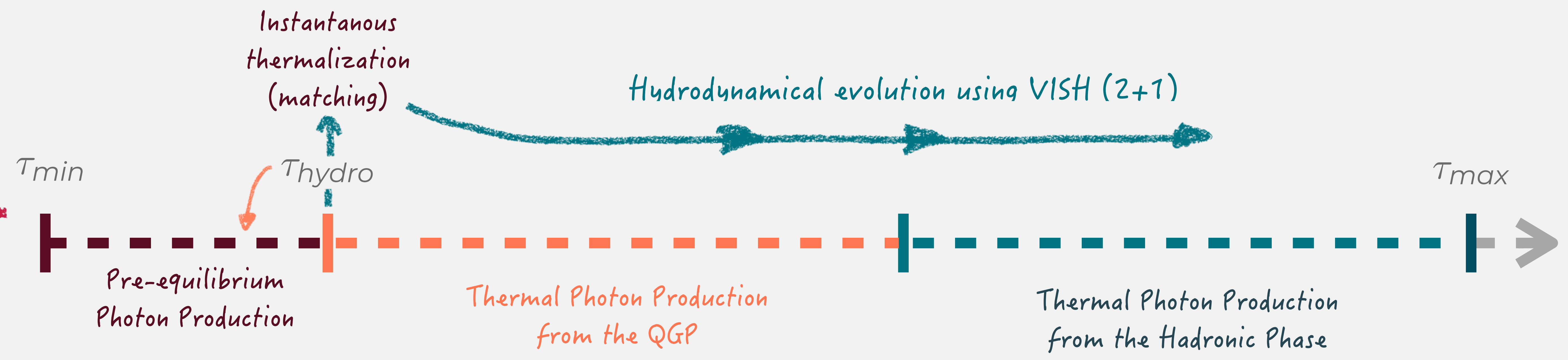
Use photon HBT not to extract source sizes, but to cross-compare models

Some Results

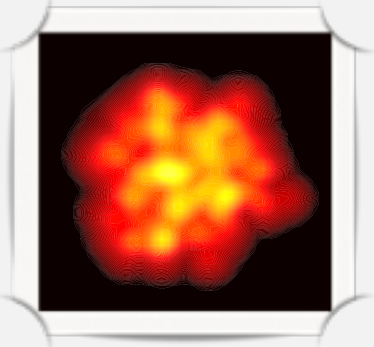
(Hanbury Brown-Twiss correlations)

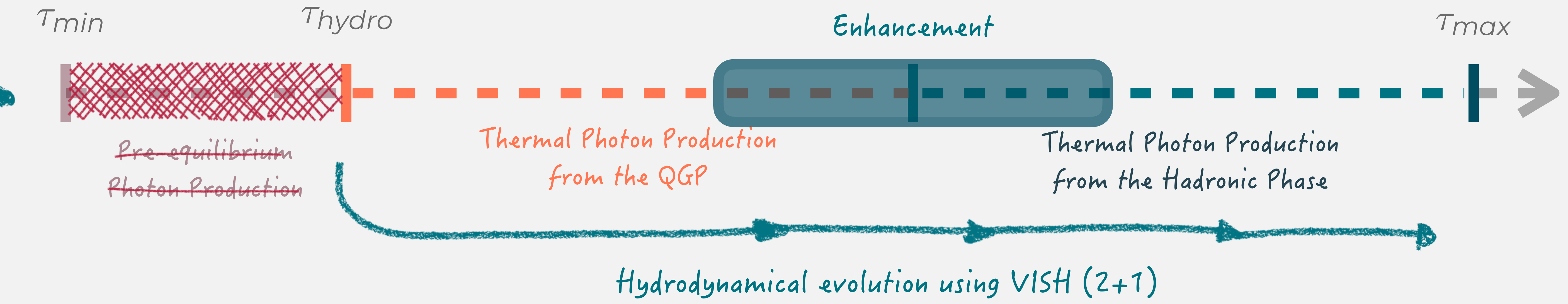
The Models

René Magritte
Empire of Light

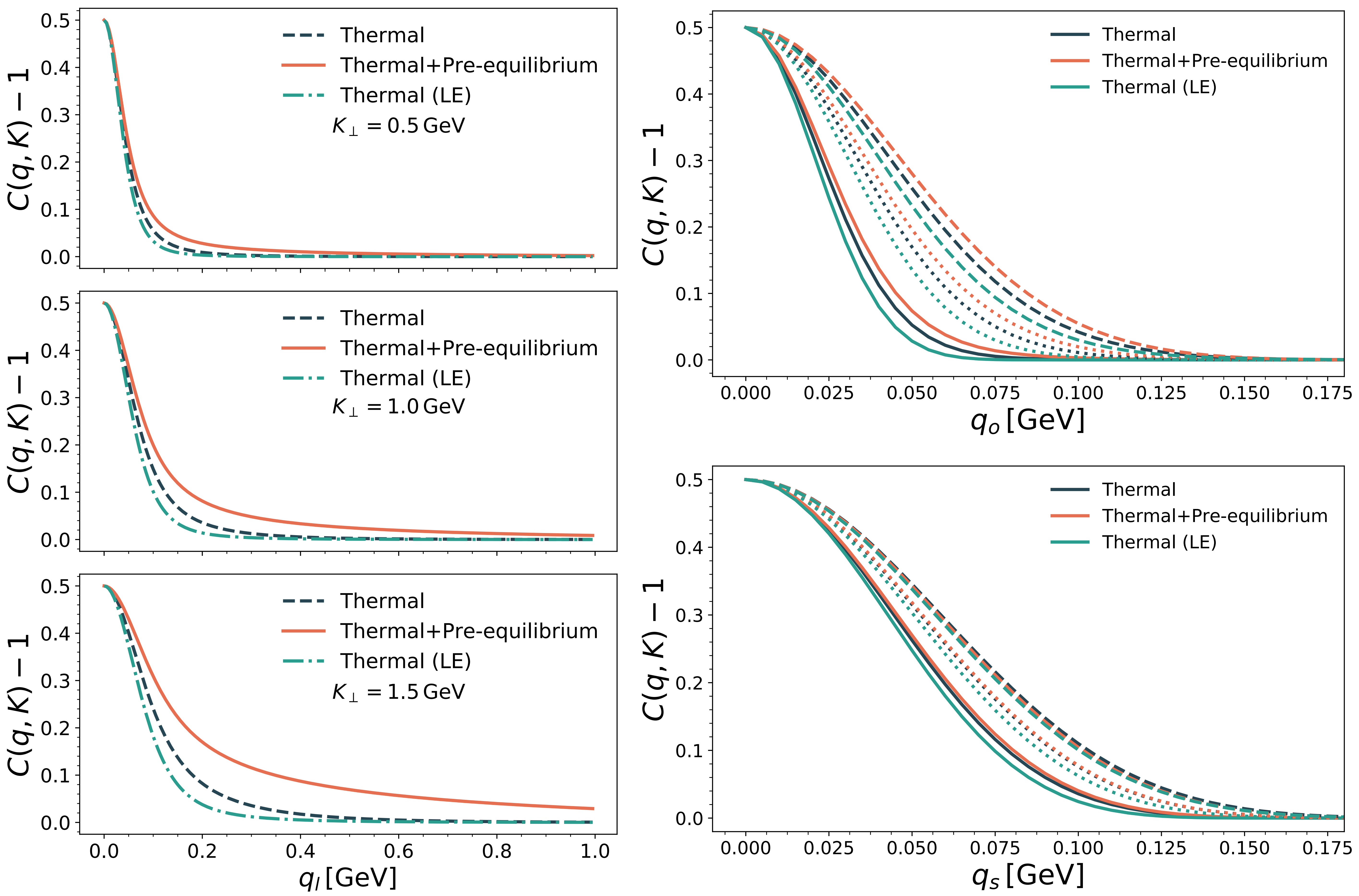


MC-Glauber





The HBT-Correlator



$$C(p_1,p_2) = 1 + \frac{1}{d}\frac{|S(q,K)|^2}{S(0,p_1)S(0,p_2)}$$

Longitudinal direction affected the most by the inclusion of the sources.

Non-gaussianities strong at early times, thanks to Bjorken expansion

Early-times production reduces effective radii, while late times increase them.

The HBT-Radii

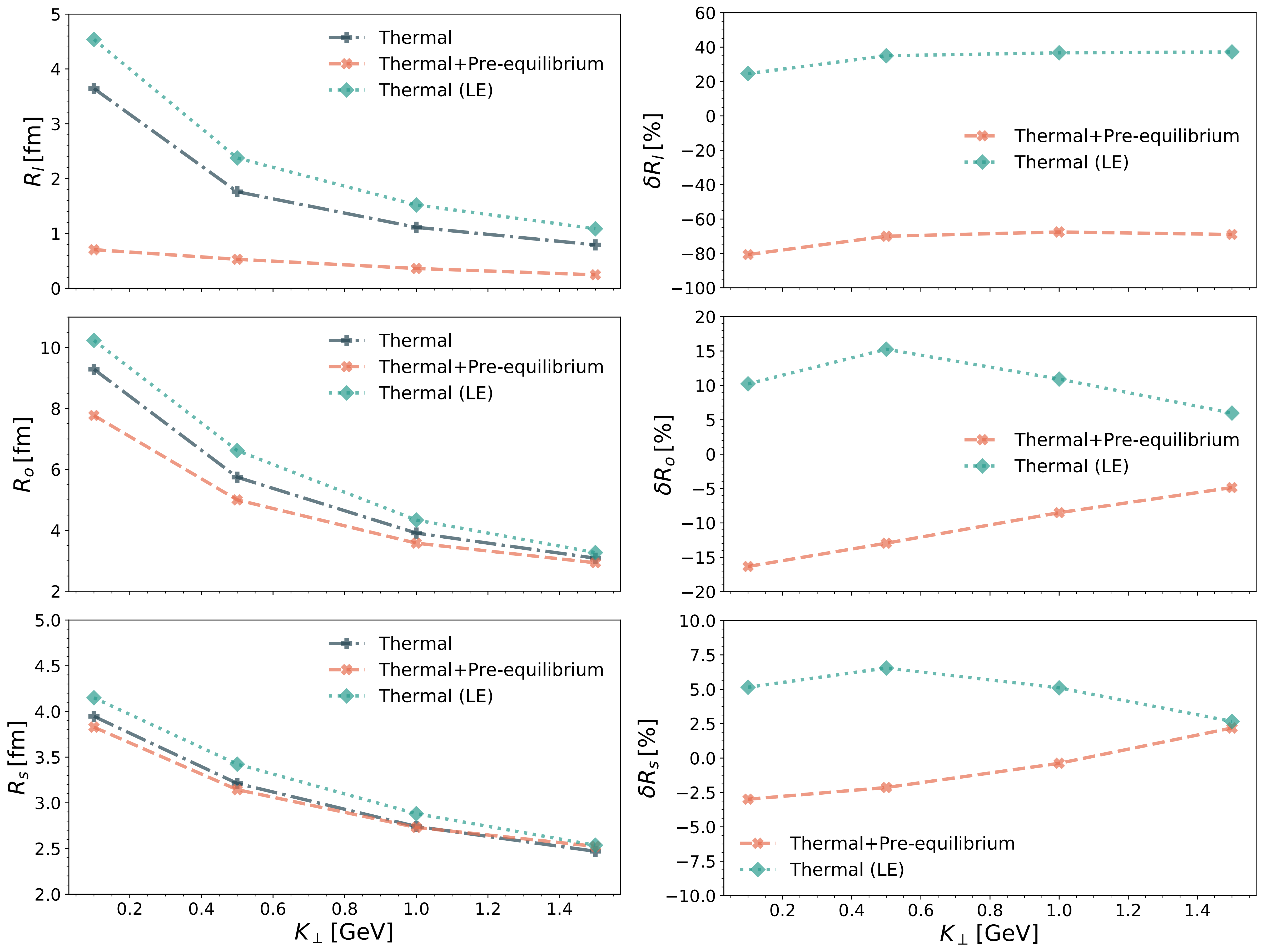
$$\langle\langle q_i q_j \rangle\rangle = \int \mathrm{d}^3 q \, q_i \, q_j \, g(q;K) \equiv \frac{1}{2}(R^{-1})_{ij}$$

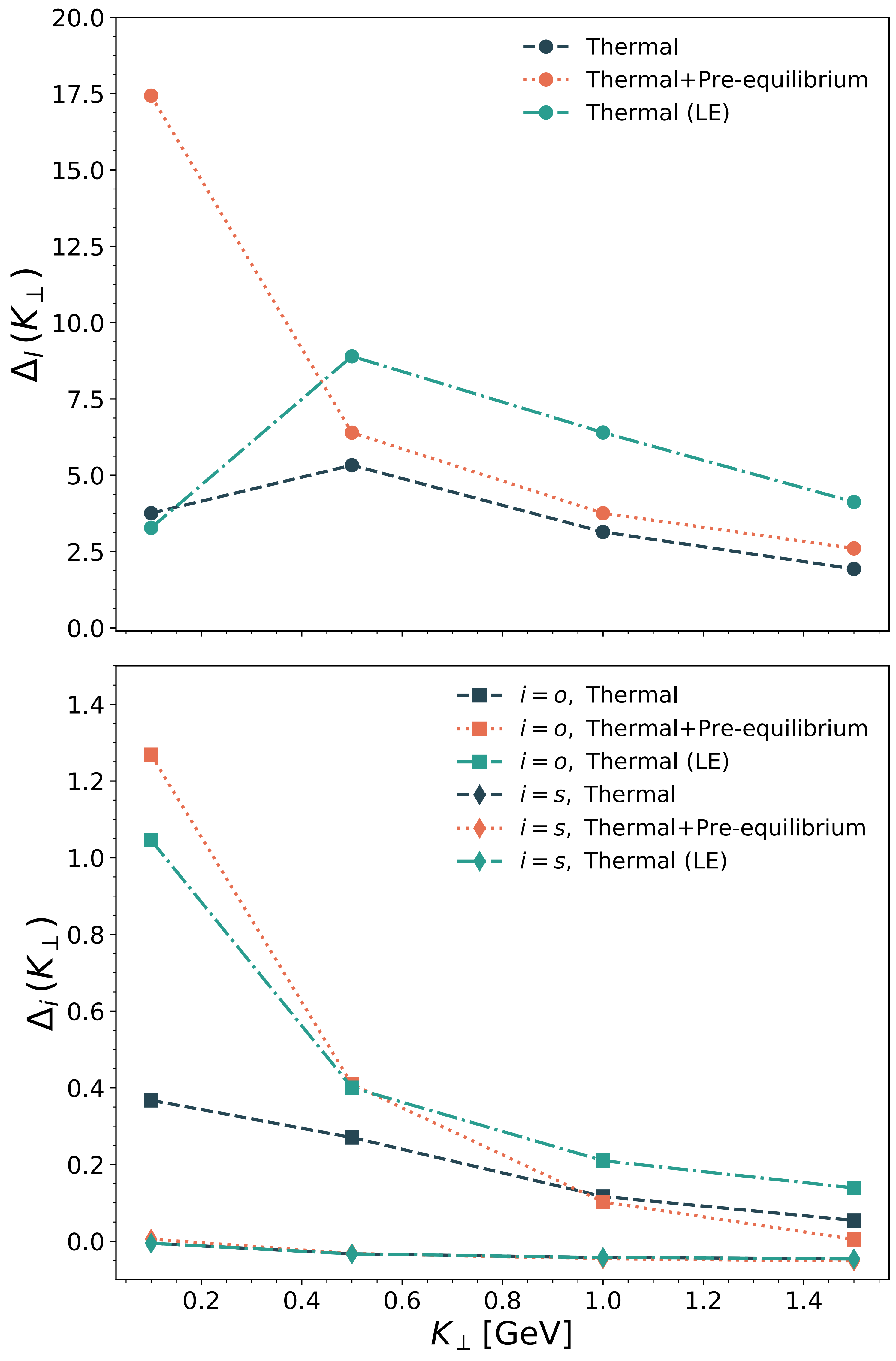
$$g(q;K) \equiv \frac{C(q,K)-1}{\int \mathrm{d}^3 q \, [C(q,K)-1]}$$

Longitudinal direction affected the most by the inclusion of the sources.

Early-times production reduces effective radii, while late times increase it.

Are these differences enough to measure it?





But wait, there is more!

The Normalized Excess Kurtosis

$$\Delta_i = \frac{\langle\langle q_i^4 \rangle\rangle}{3\langle\langle q_i^2 \rangle\rangle^2} - 1$$

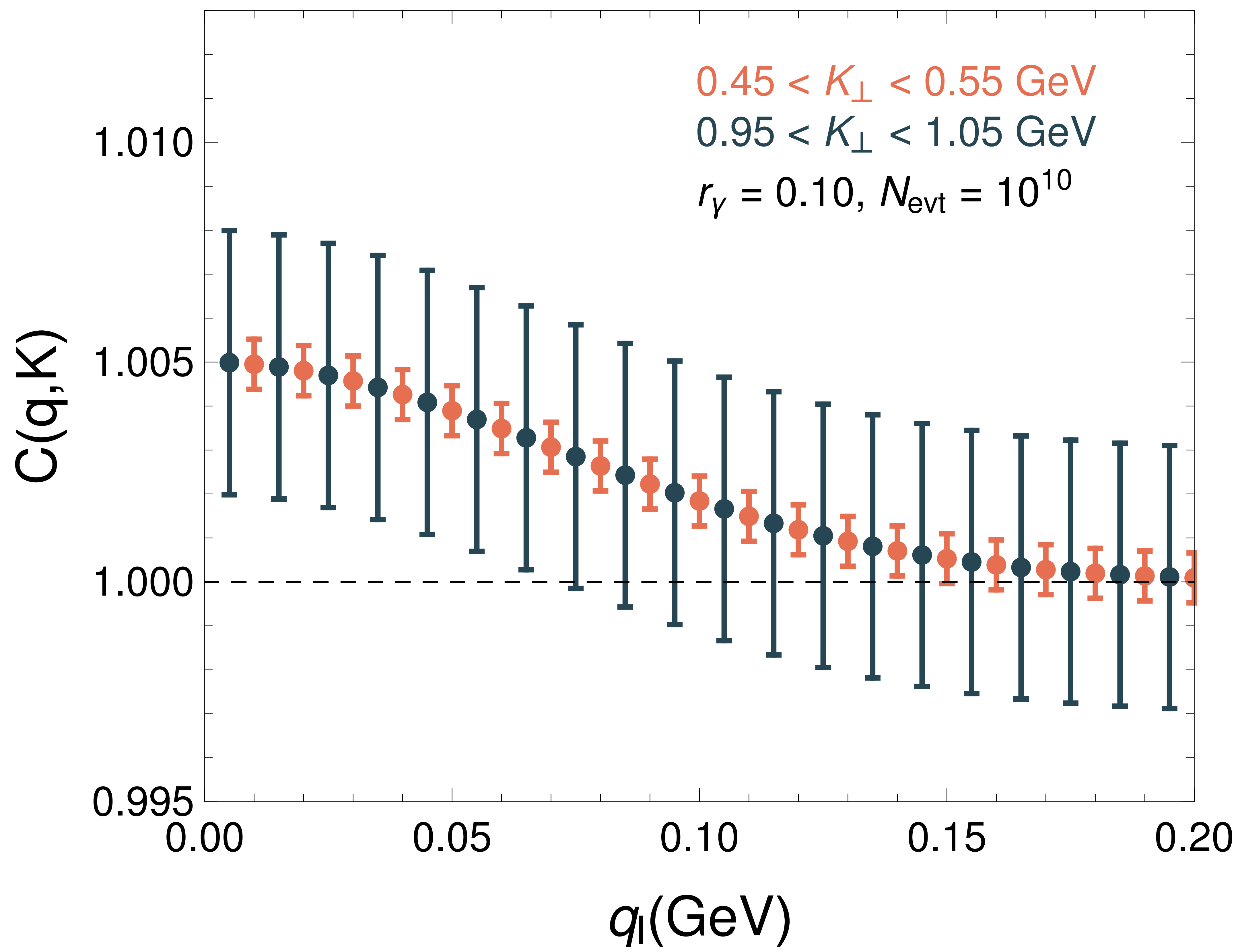
Measures “how much non-Gaussian is a distribution

Early-times non-Gaussianities strong, particularly at small pair momenta.

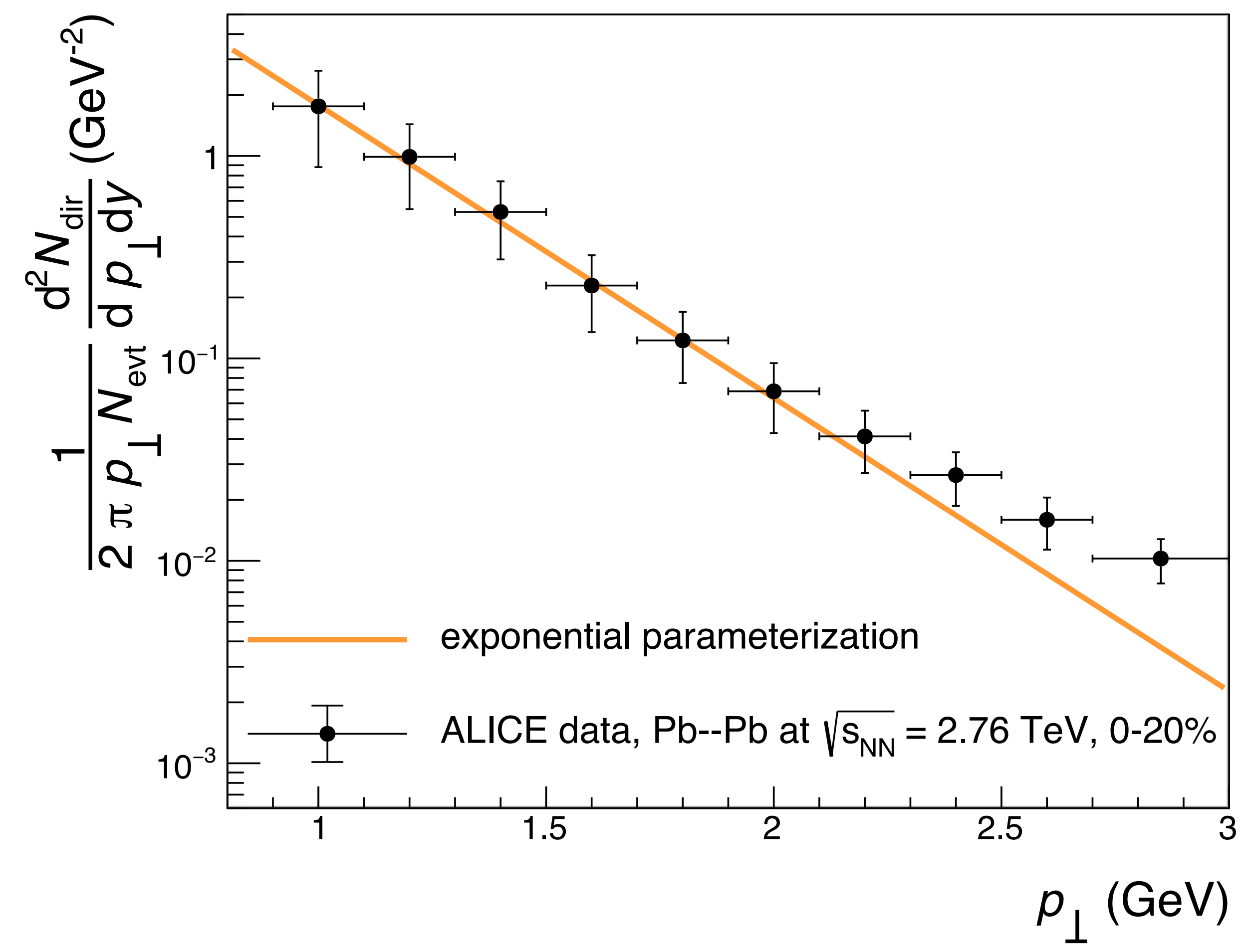
Very interesting observable, hard to measure.

Statistical Model

Effective dilution of the signal!



Exponential distribution



Exponential-like source used as test model.

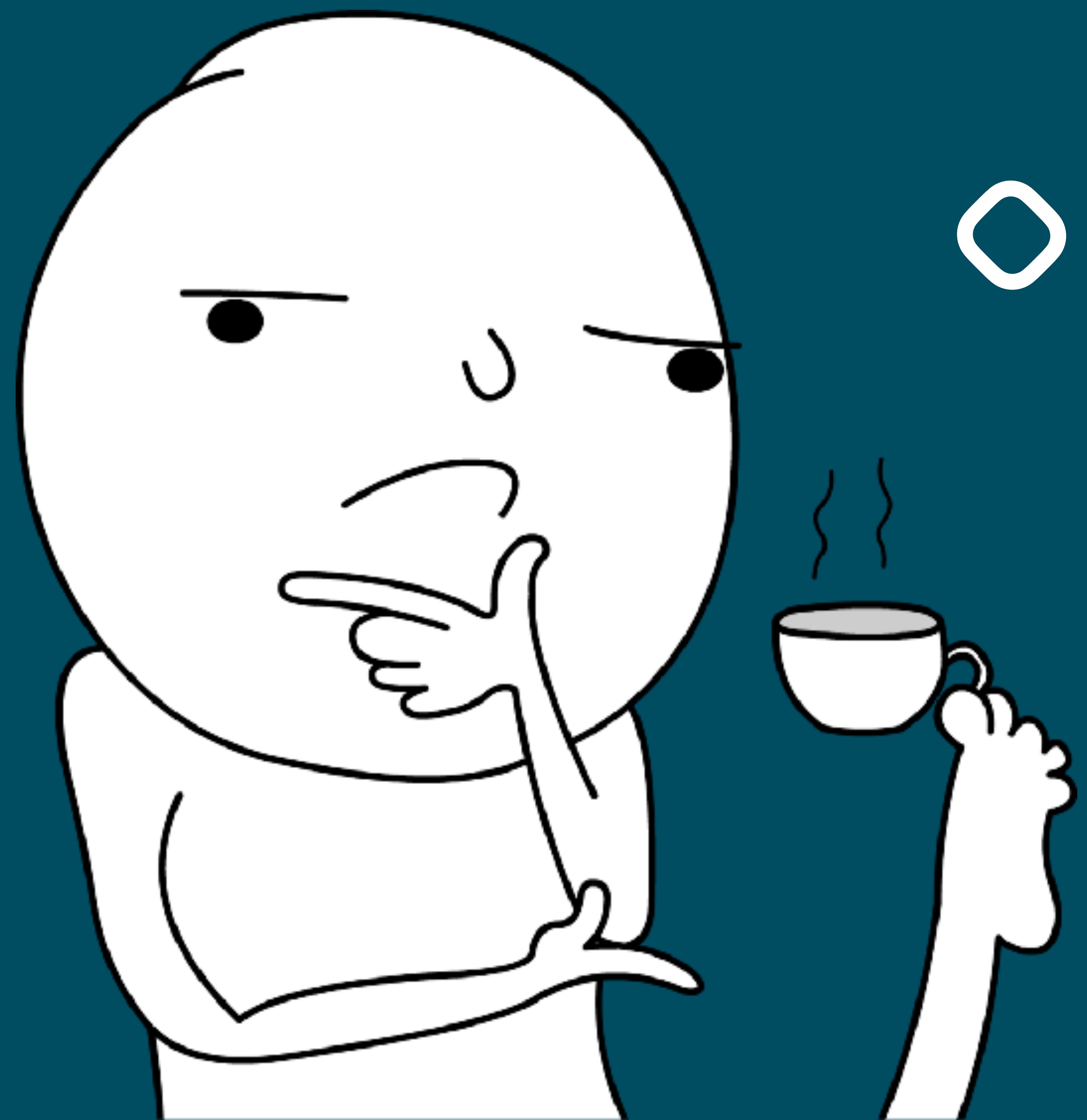
Correlator simulated sampling from source.

Error depends strongly on the average momentum of the pair.

Low momentum pairs statistically significant.

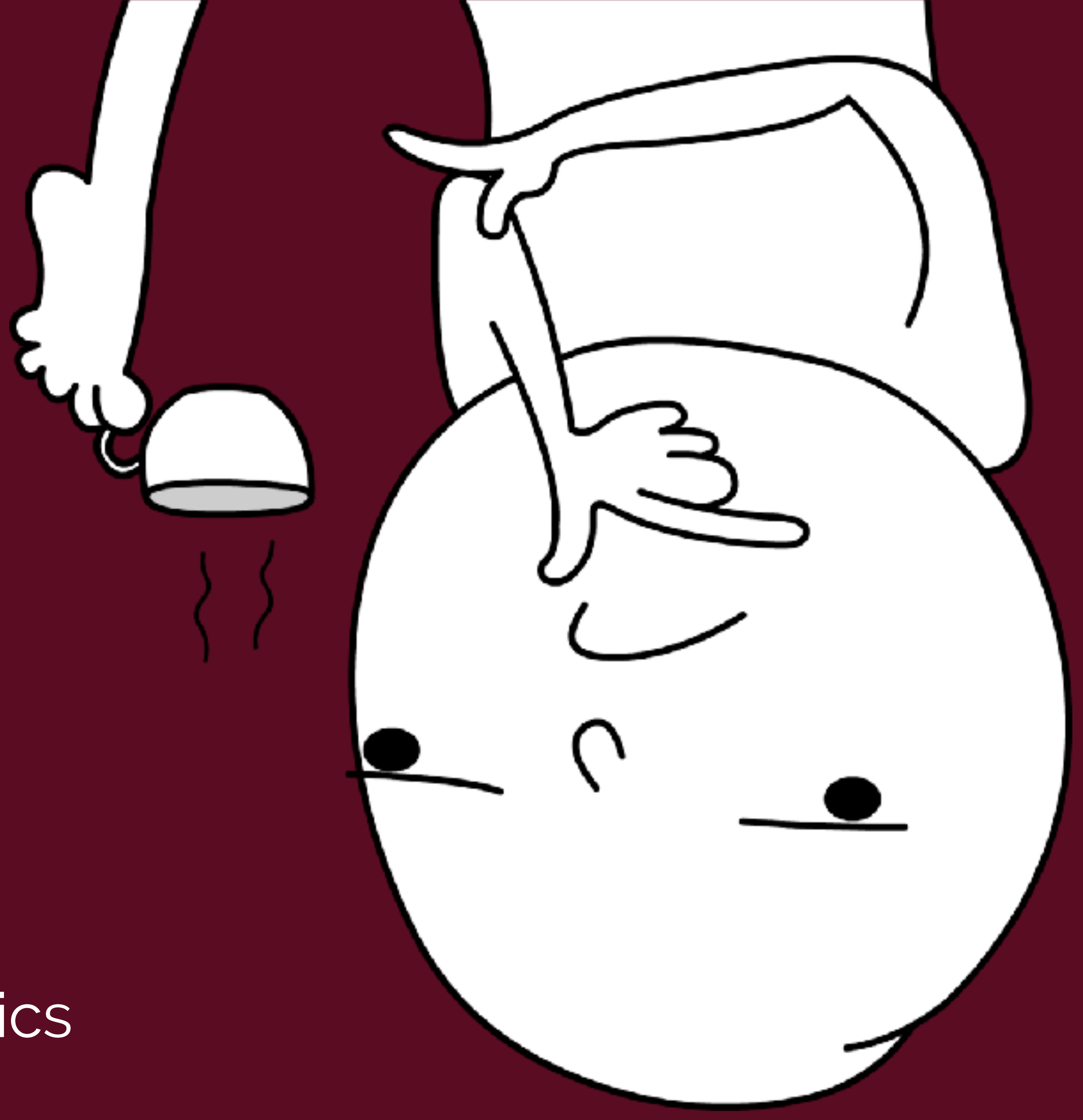
Summary

- Even when the discrepancies of the *Direct Photon Puzzle* are solved, we need to differentiate between the different models in the market.
- Photon correlations are the tool that we need to do so.
- Yes, they are very hard measurements, but not impossible anymore. We should start walking before we run.
- Remember that the endgame here is to untangle the space-time evolution of the medium created in a Heavy Ion Collision.



Outlook

- Refine existing models to be able to compare against experimental results.
  - Get better grasp of the enhancement at
  - Model/Simulate the pre-eq time expansion dynamics
- Compare new ideas in the HBT framework
- "New" non-equilibrium phenomena at lower photon energies



GARCIA@FIAS.UNI-FRANKFURT.DE