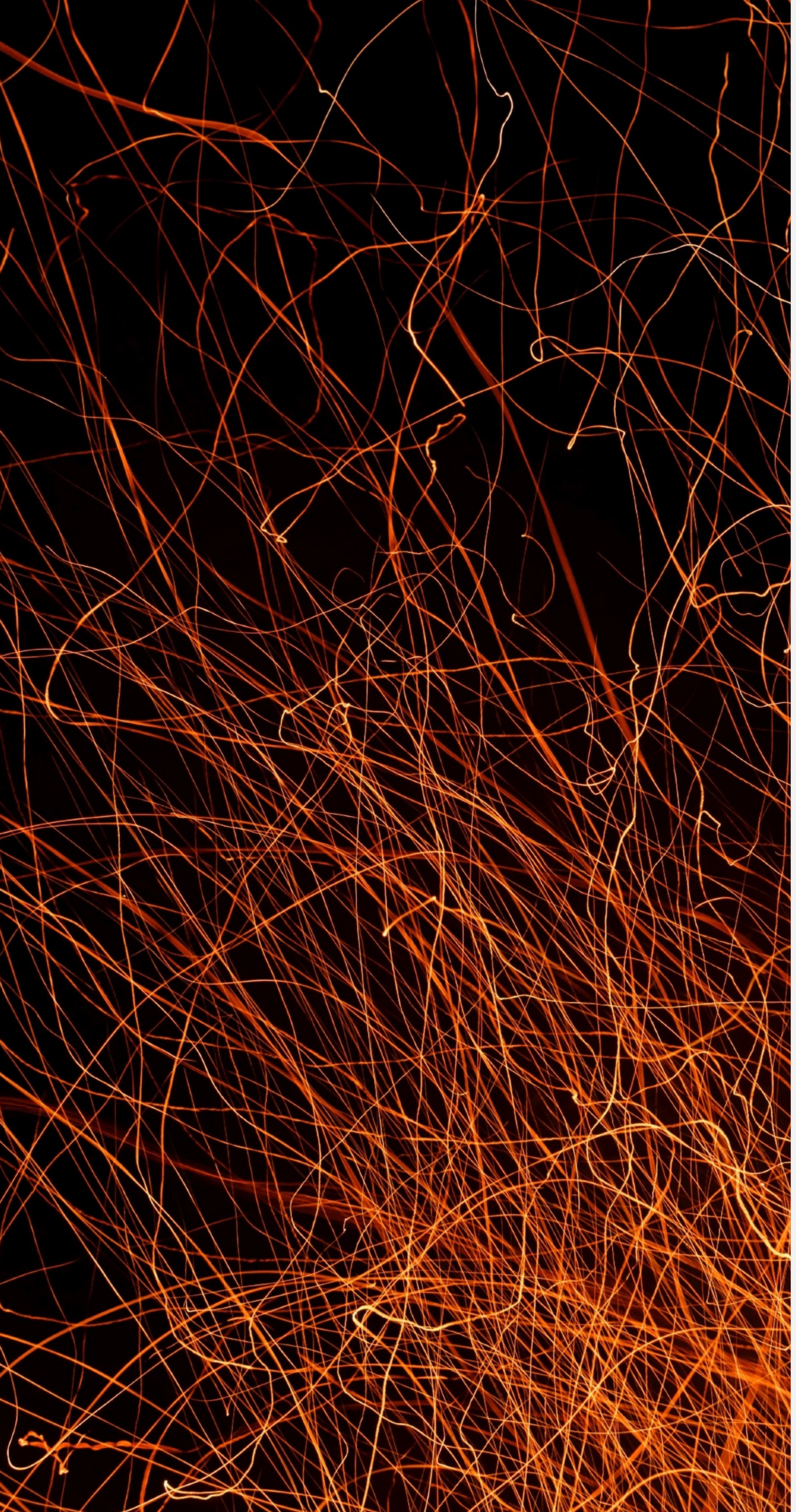

Untangling the evolution of heavy ion collisions using direct photon interferometry

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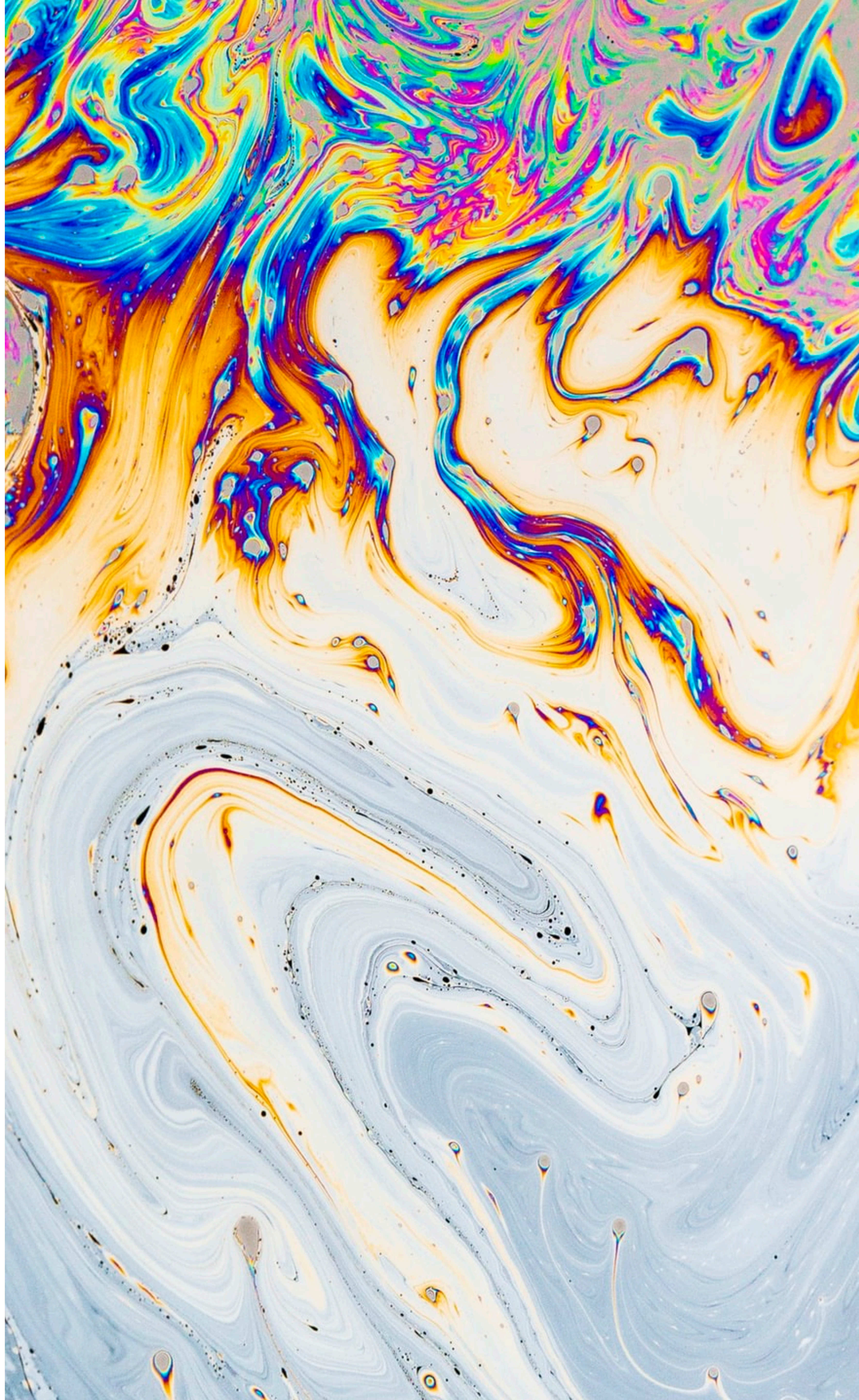
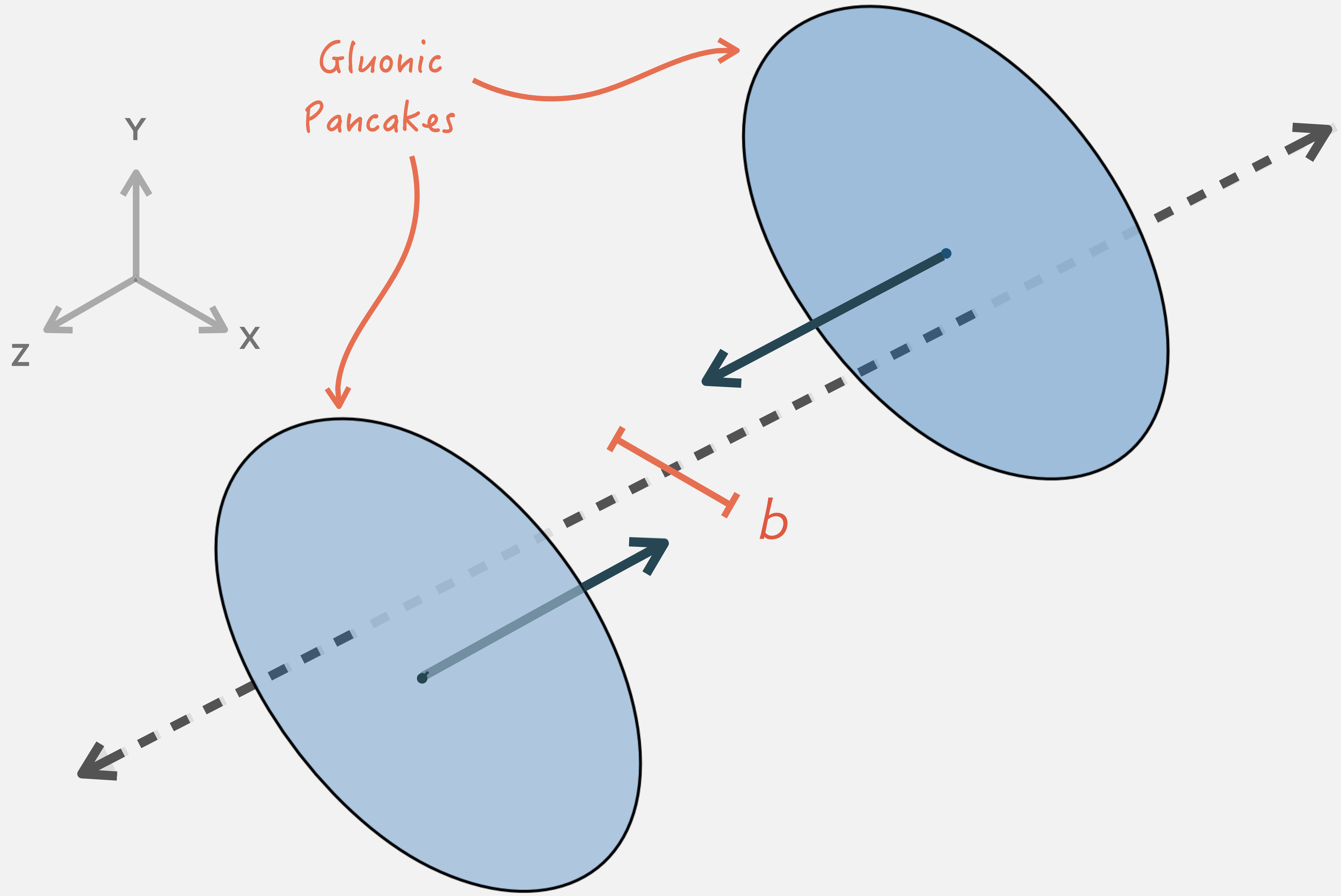
In collaboration with J. Berges, Nicole Löher, A. Mazeliauskas and K. Reygers

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

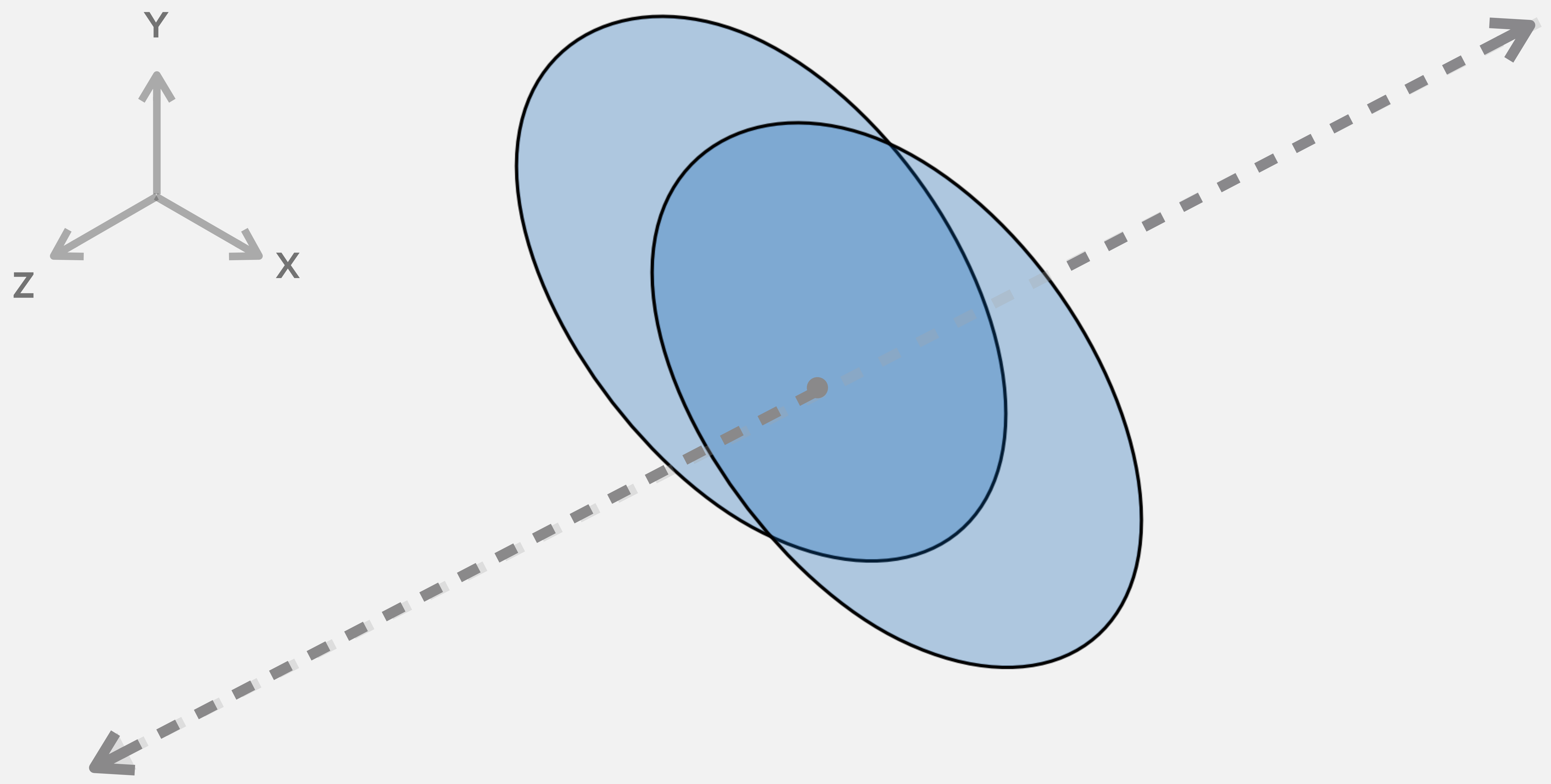
Contents



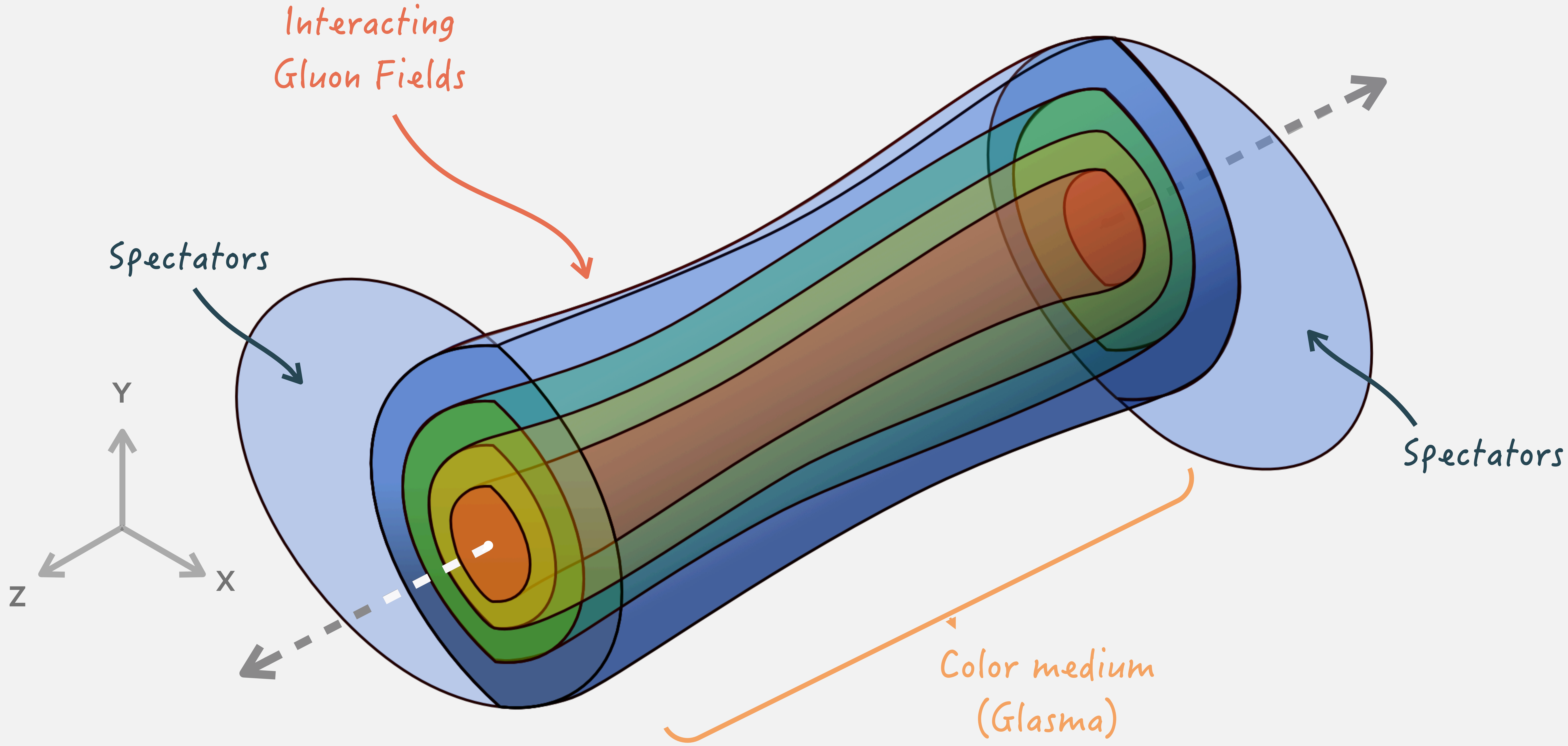
Ultra-relativistic Nucleus-Nucleus (A+A) Collisions



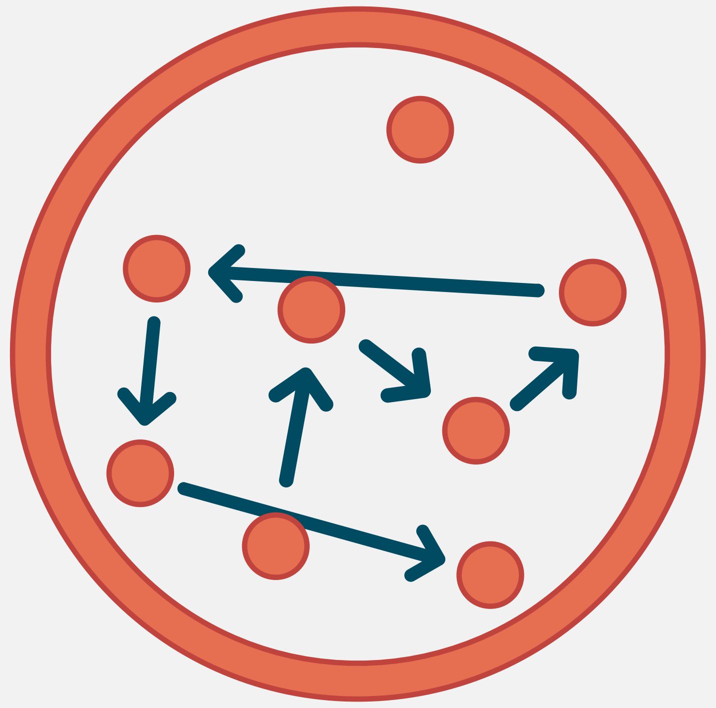
Ultrarelativistic Nucleus-Nucleus (A+A) Collisions



Ultrarelativistic Nucleus-Nucleus (A+A) Collisions



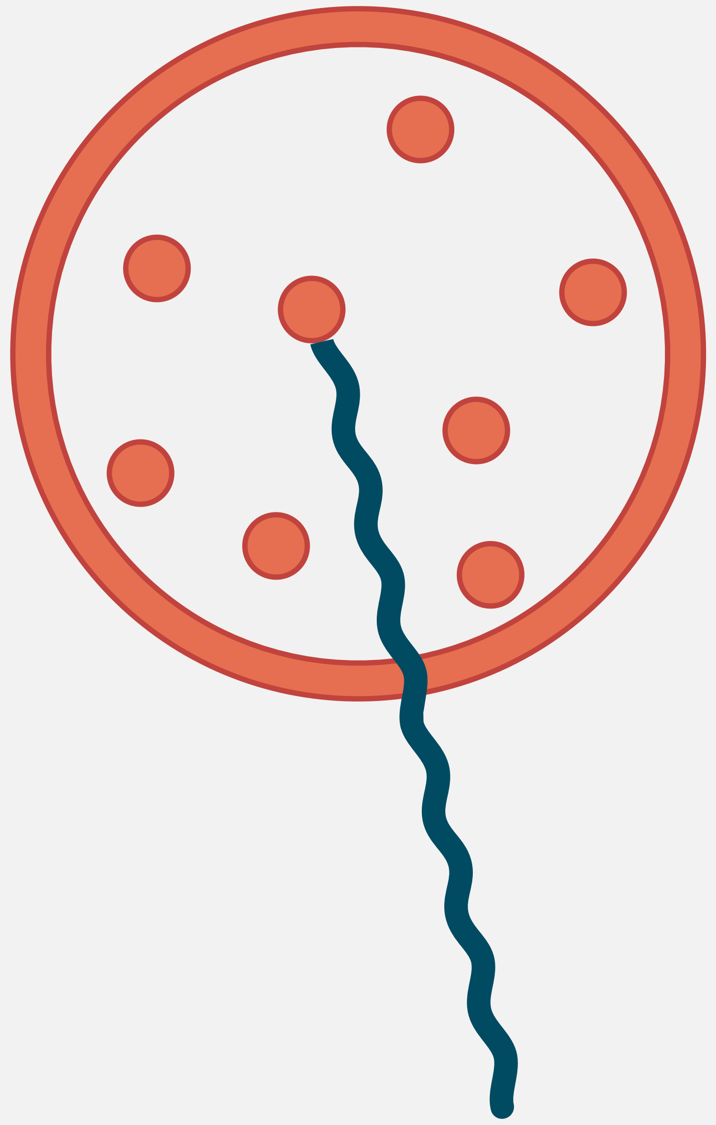
Why photons?



-Produced at every stage

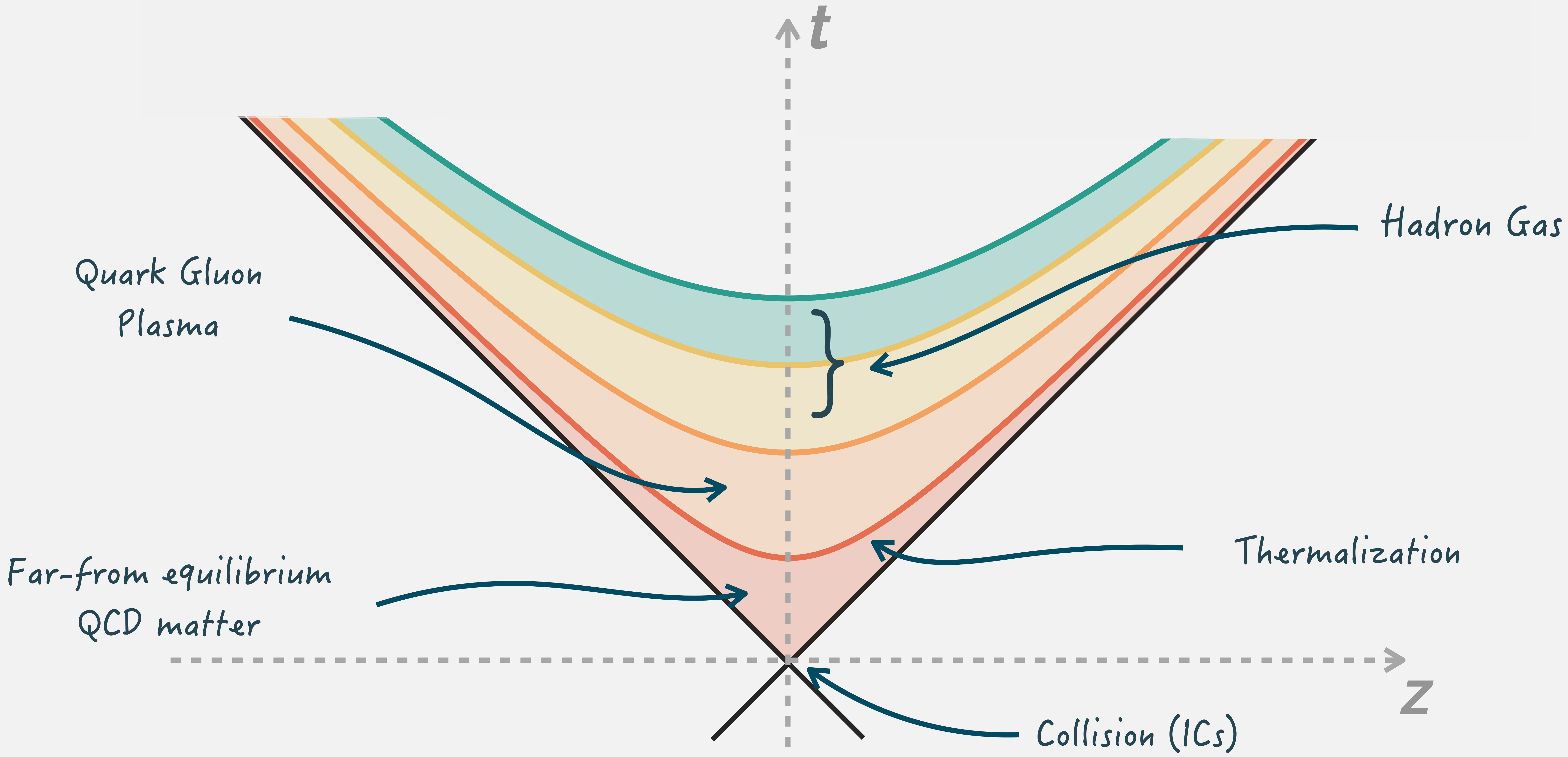
-No strong interactions

-Mean free path in medium > medium size



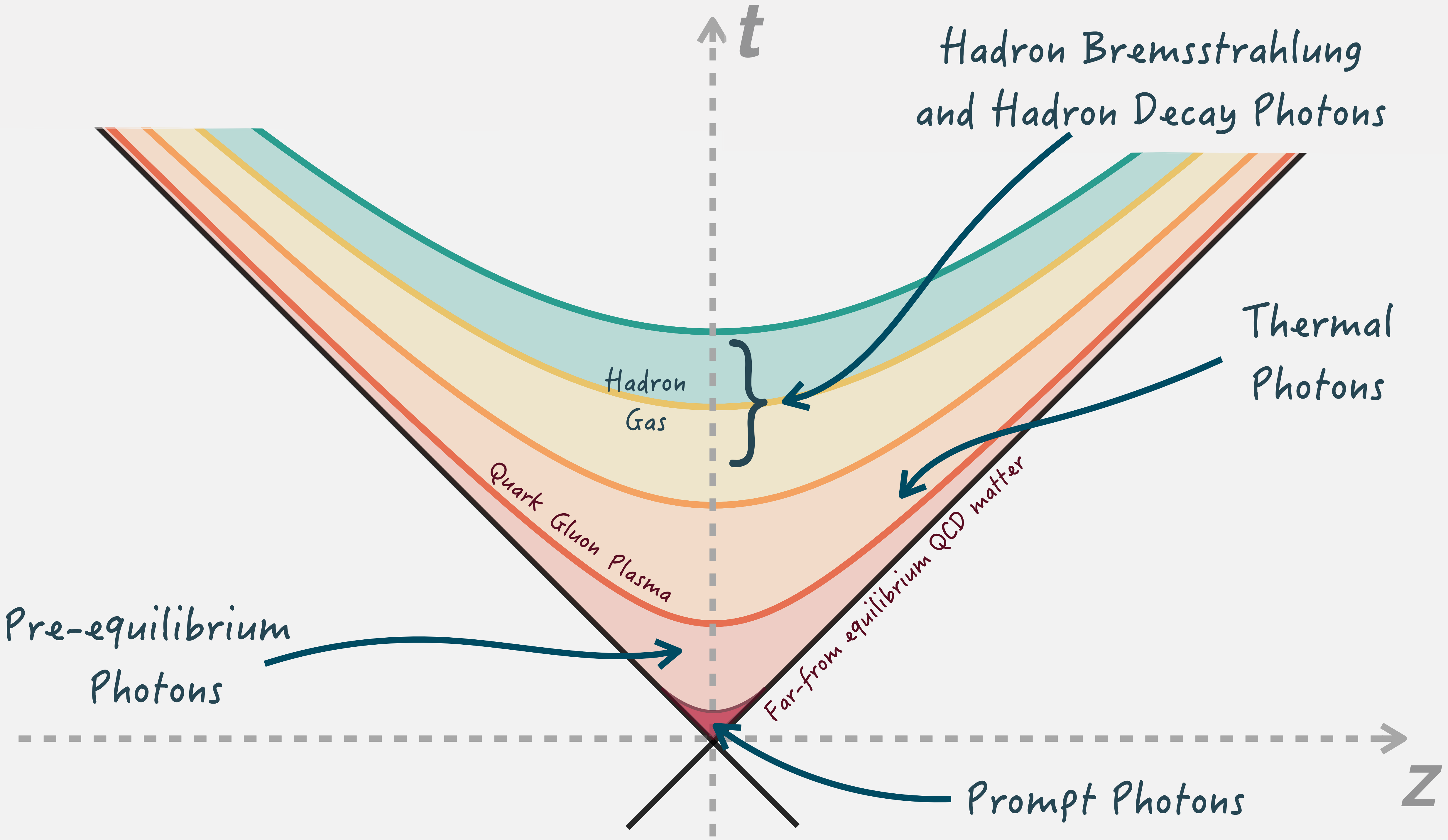
Photons escape, virtually unscathed

The Standard model of Heavy Ion Collisons



Photon Production

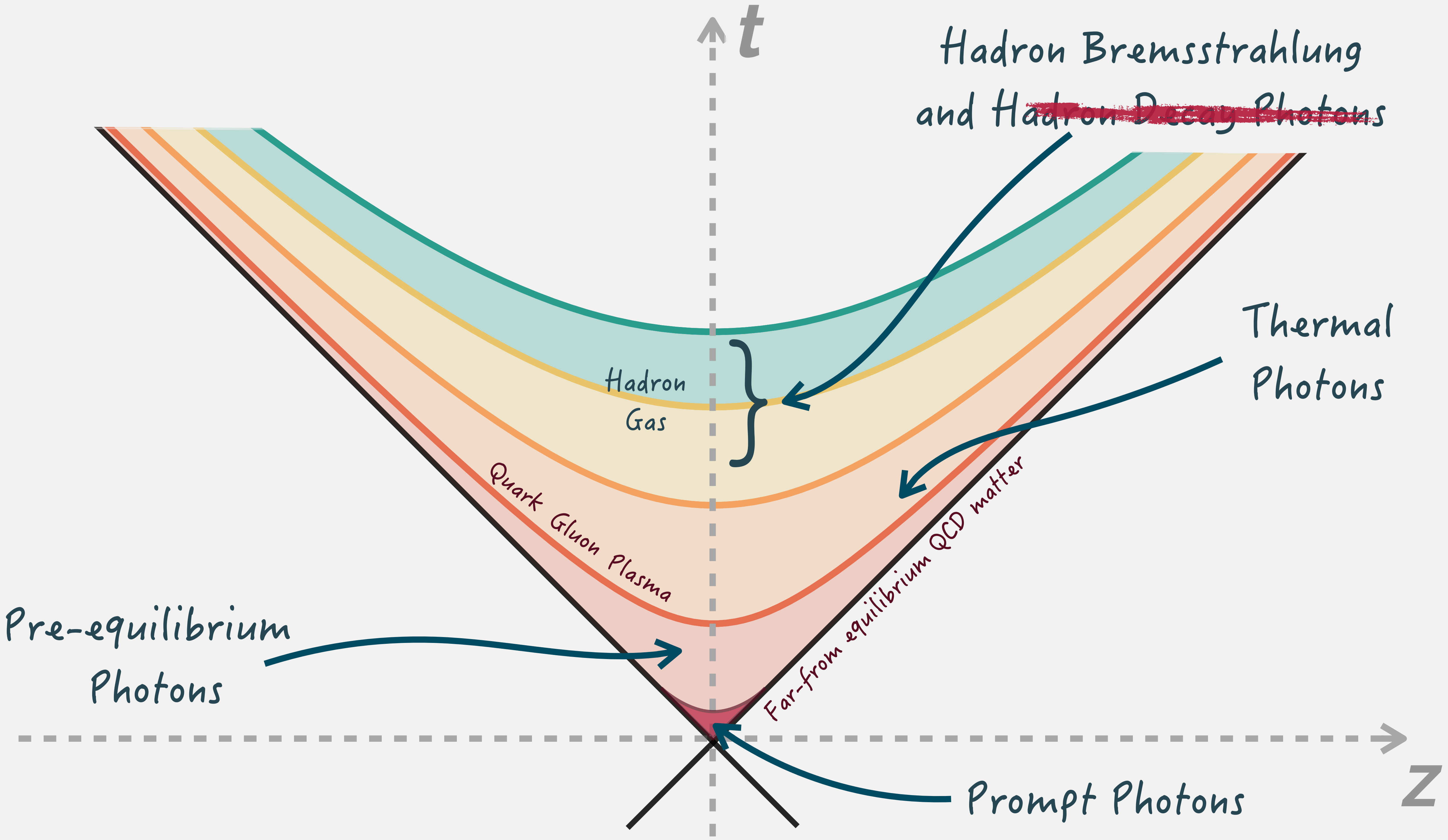
Photons are produced throughout the evolution by different processes, and fly away to the detectors



Photon Production

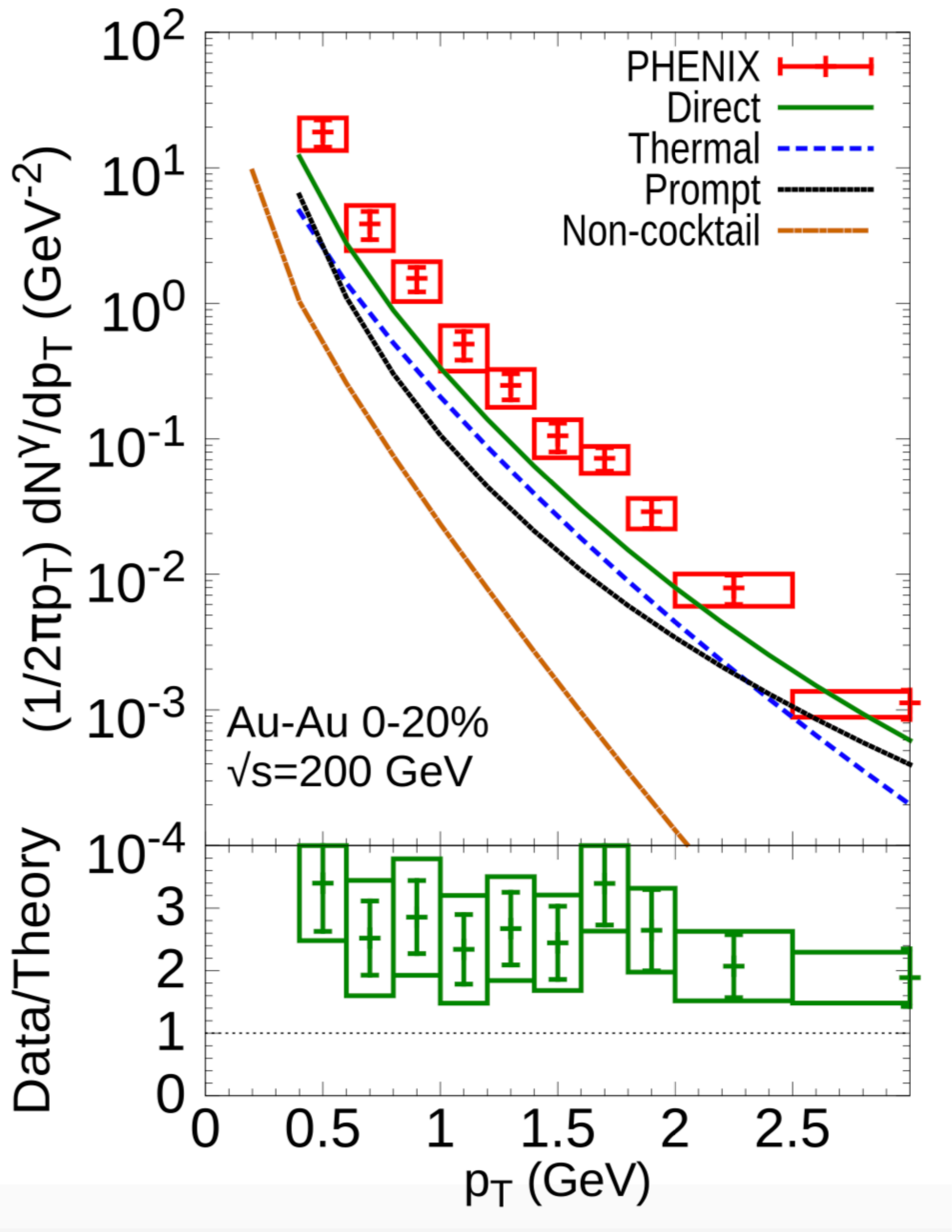
Photons are produced throughout the evolution by different processes, and fly away to the detectors

Direct Photons: Produced NOT by decays (In medium)



Direct Photon Puzzle

Photons @ RHIC



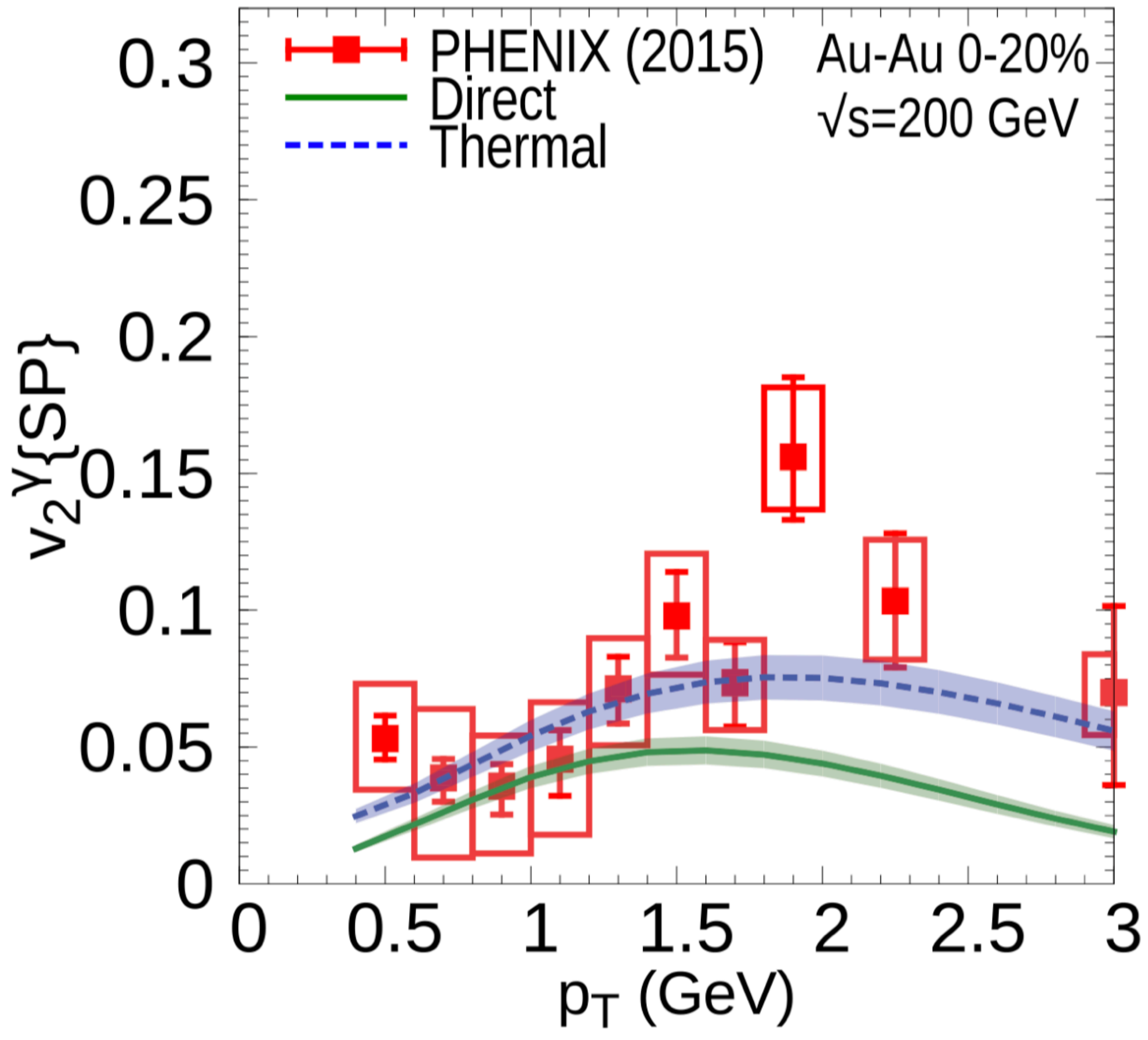
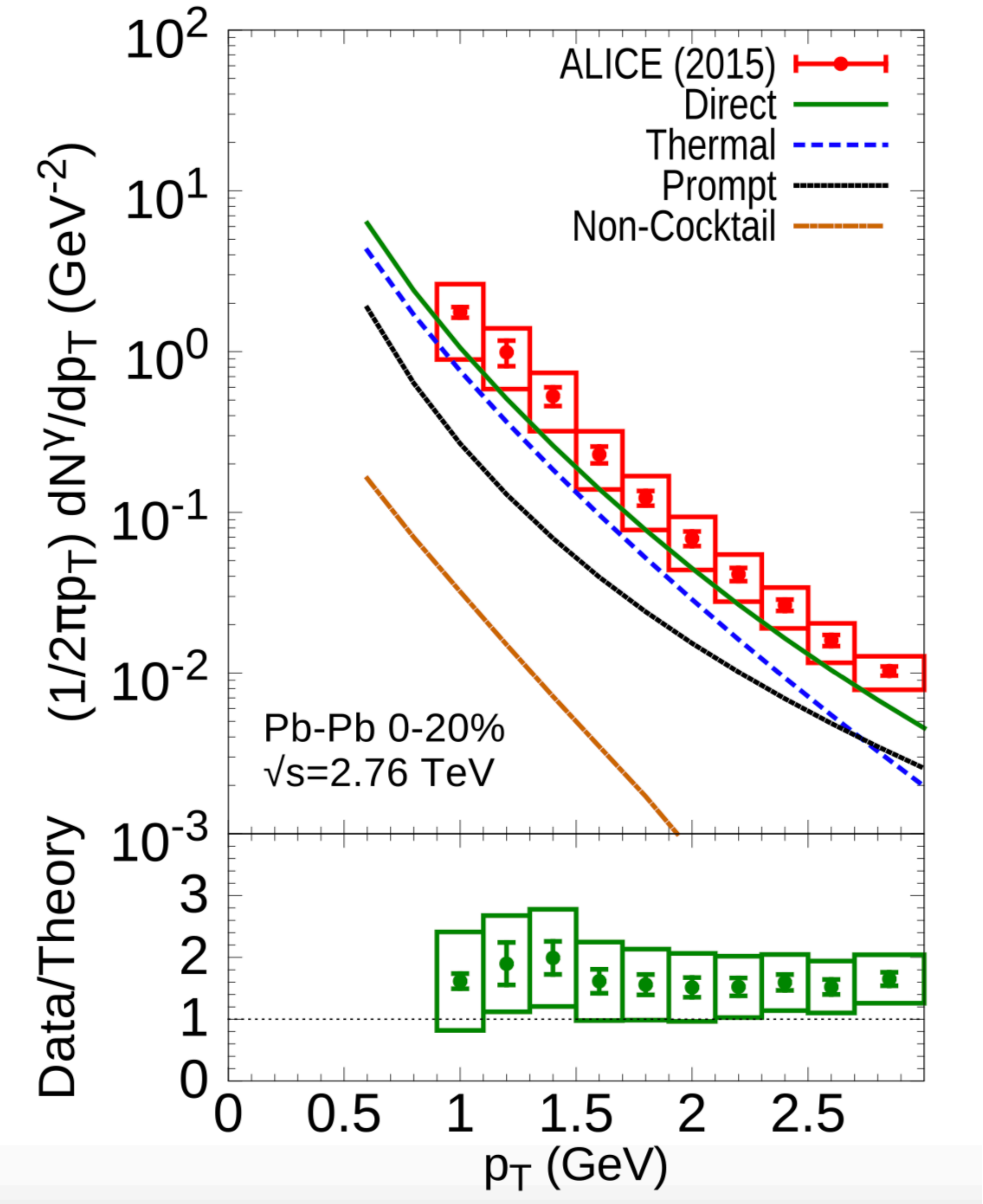


Figure from Paquet *et al*,
Phys.Rev. C93 (2016) no.4, 044906

Photons @ LHC



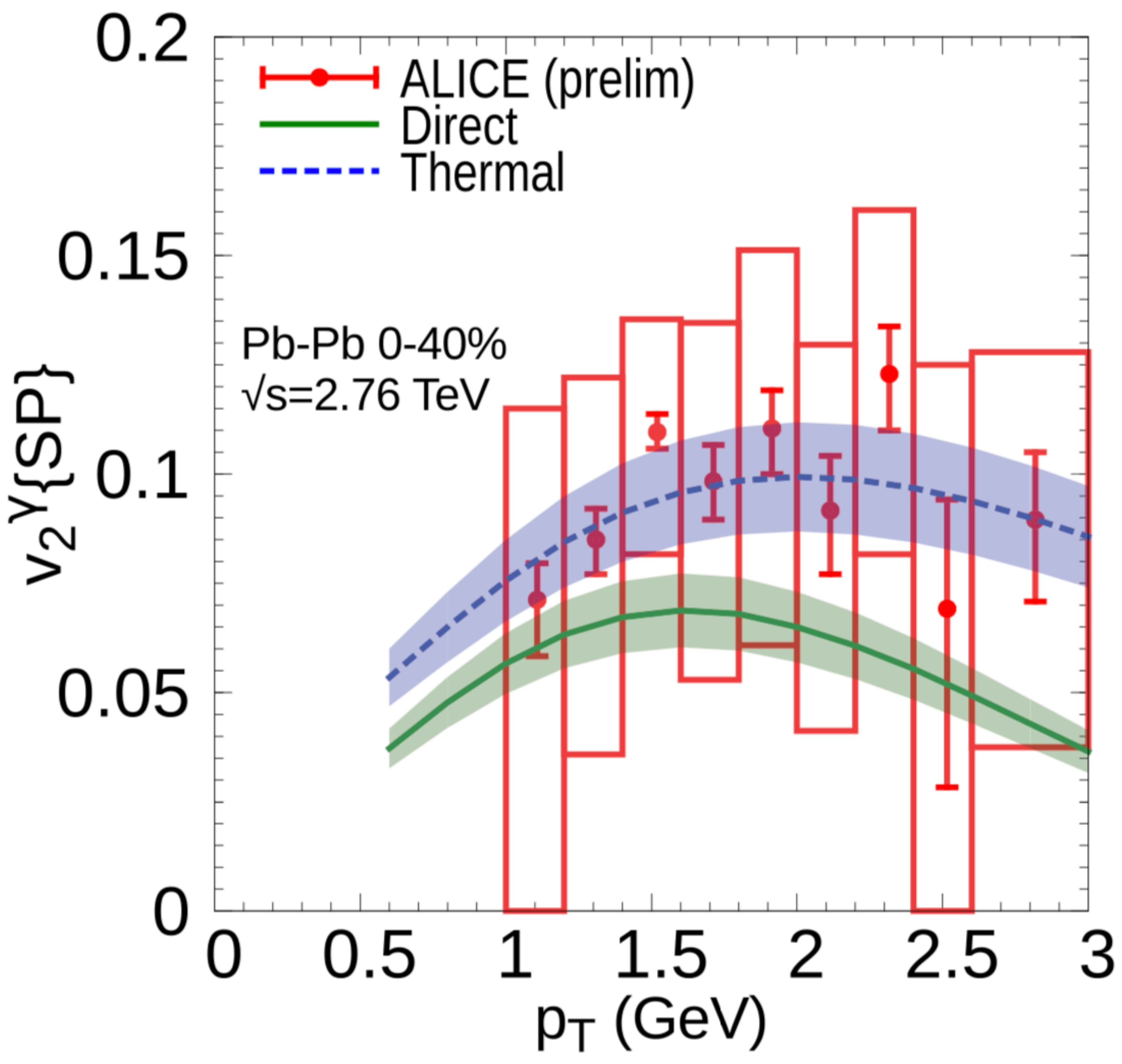


Figure from Paquet *et al*, Phys.Rev. C93 (2016) no.4, 044906

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

Direct Photon Puzzle

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

Solution

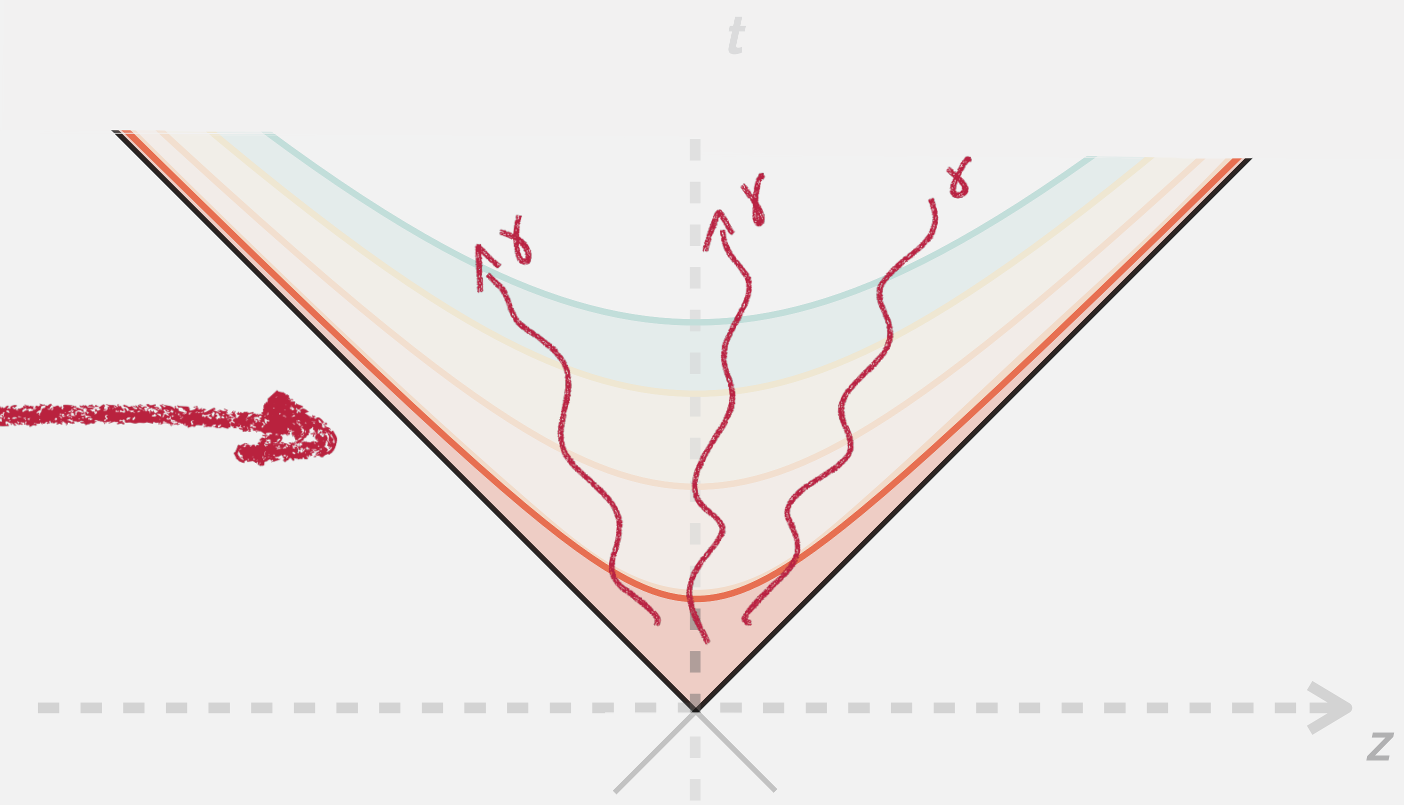
- We are lacking a source of photons.

- Source can act as an extra knob for tuning.

René Magritte
Empire of Light

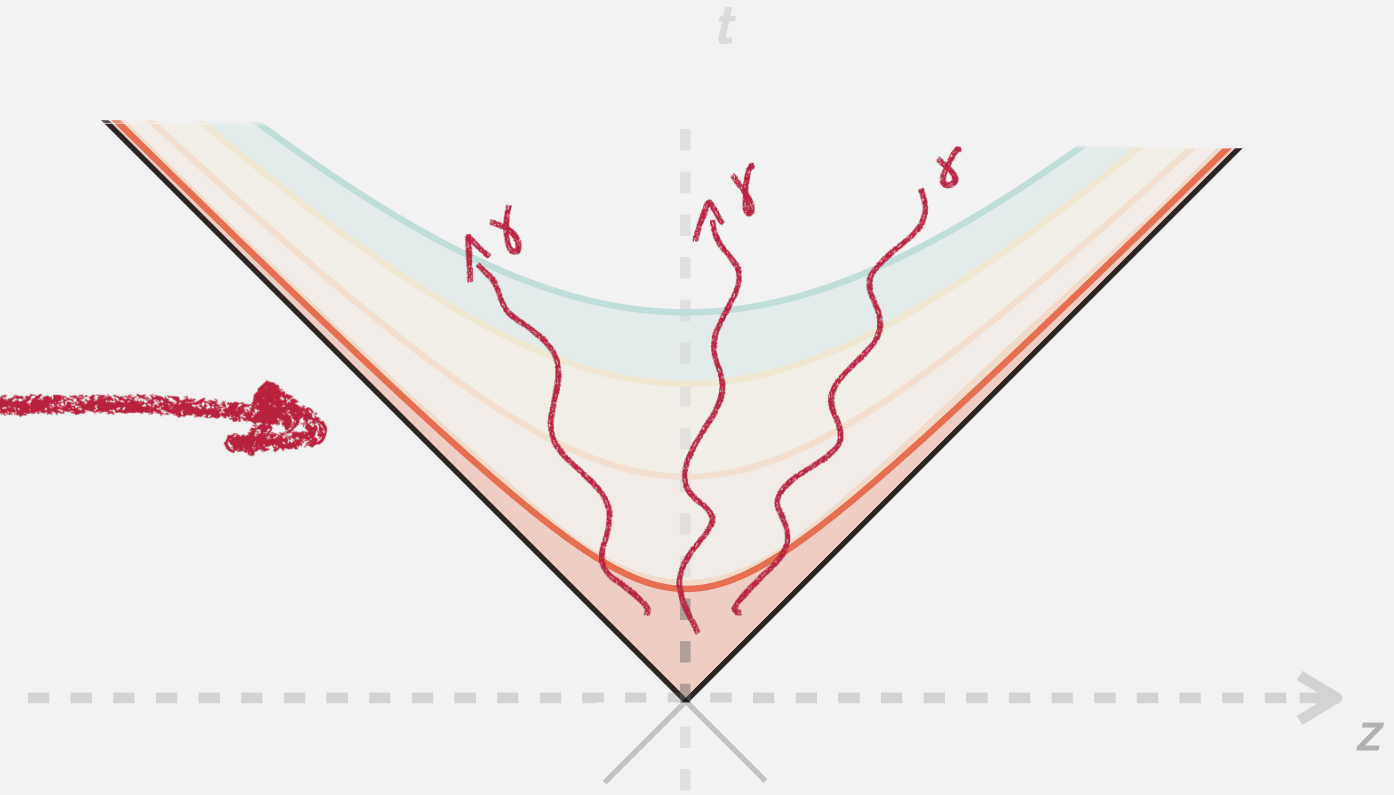
René Magritte
Empire of Light

Early time
enhancement

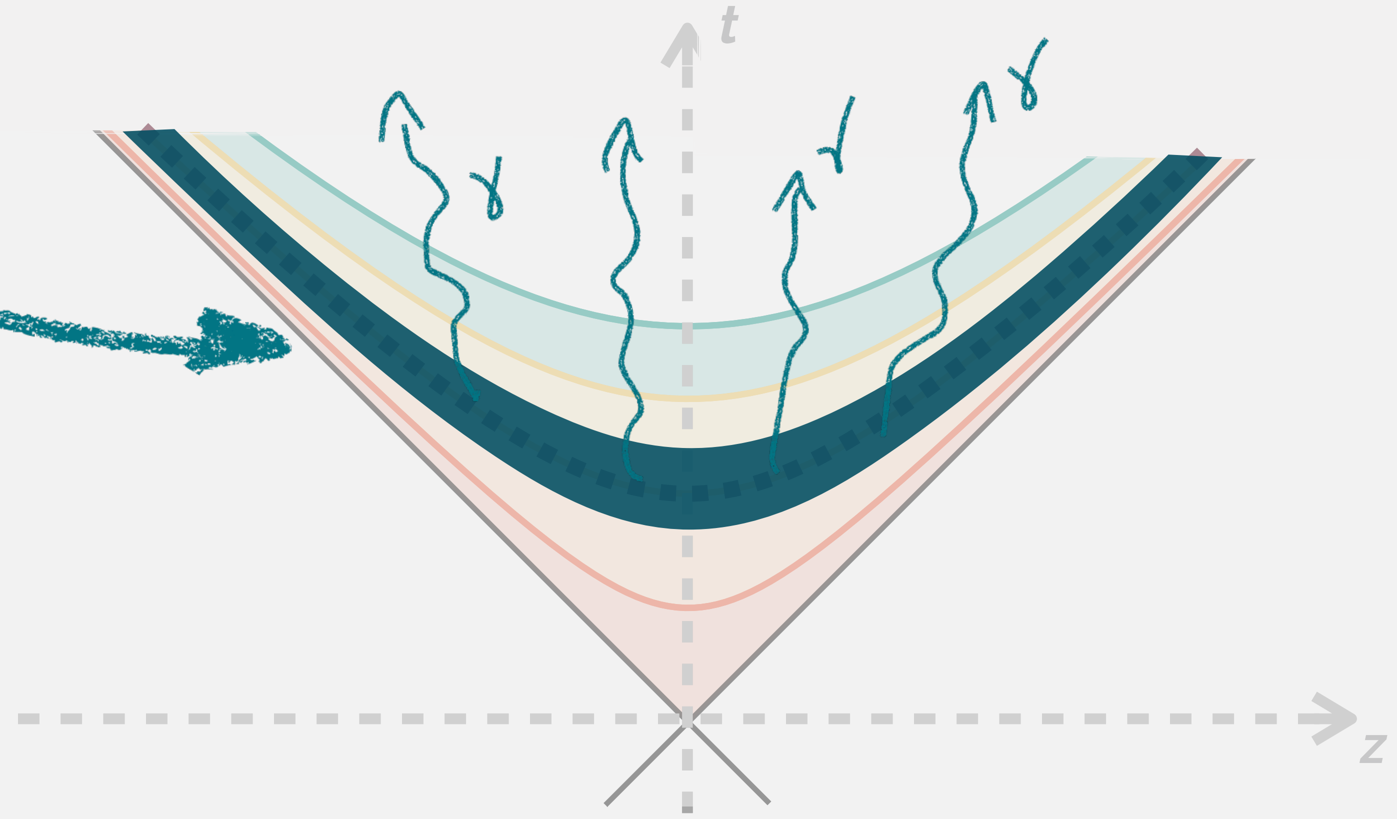


René Magritte
Empire of Light

Early time enhancement



Late time enhancement



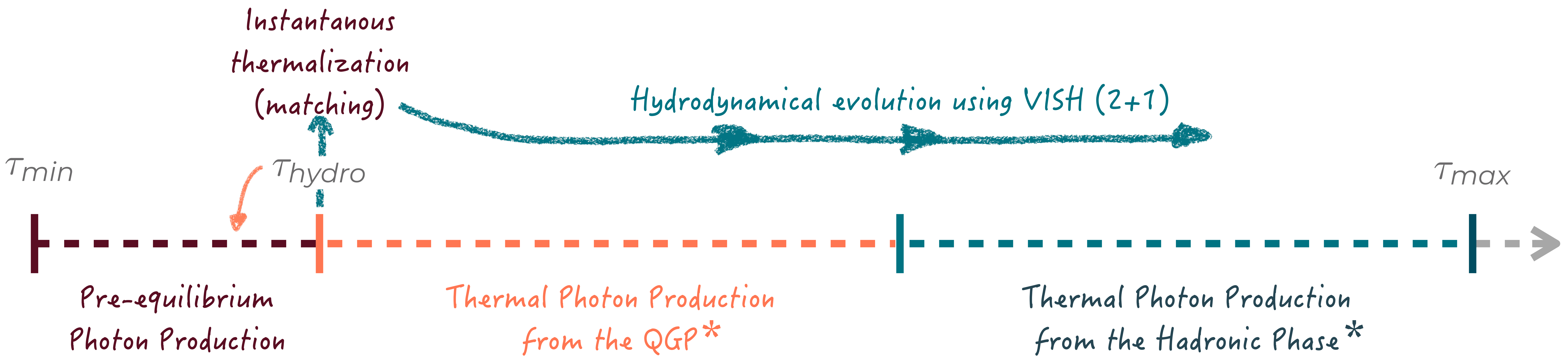
Two Models

(Early vs Late time production)

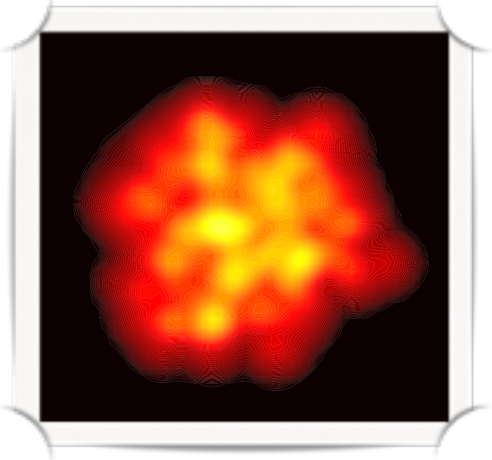
Photons from the "bottom-up" scenario

(QCD Kinetic Thermalization)

The model



MC-Glauber

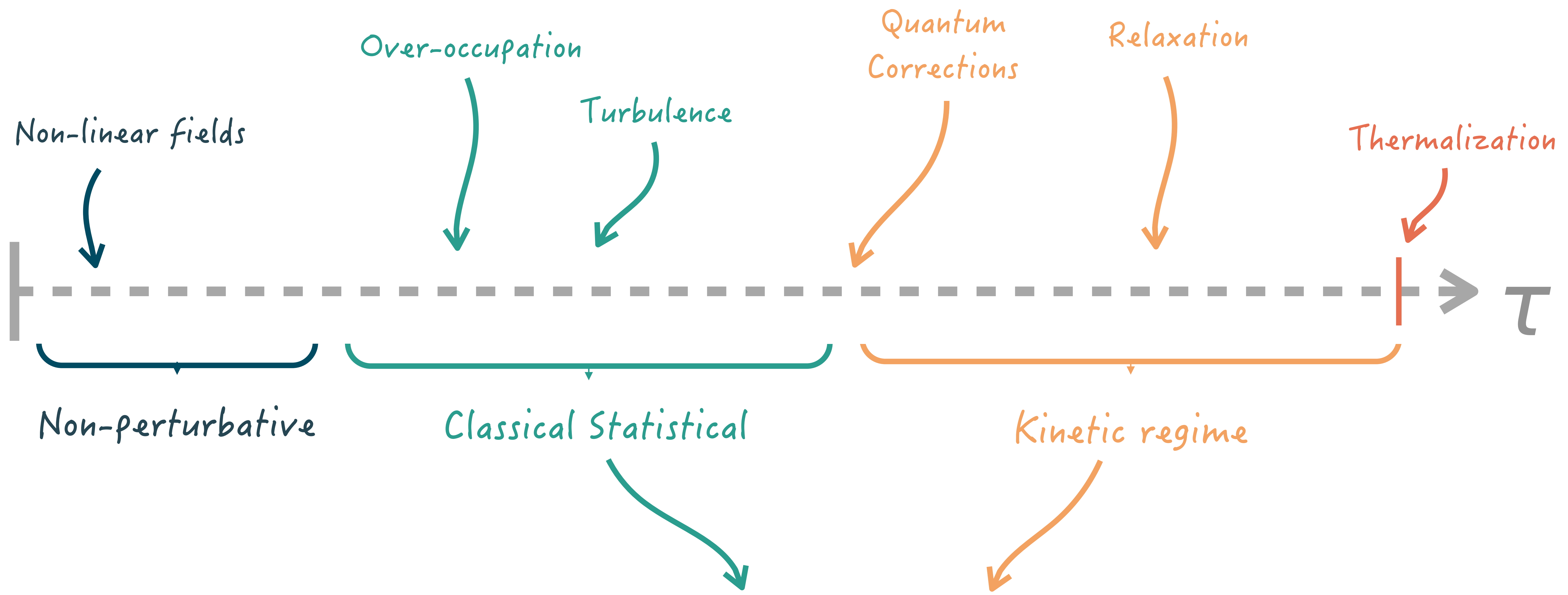


$$\tau_{min} = 0.1\text{fm}$$
$$\tau_{hydro} = 0.6\text{fm}$$
$$\tau_{max} = 15\text{fm}$$

* Using the thermal rates in

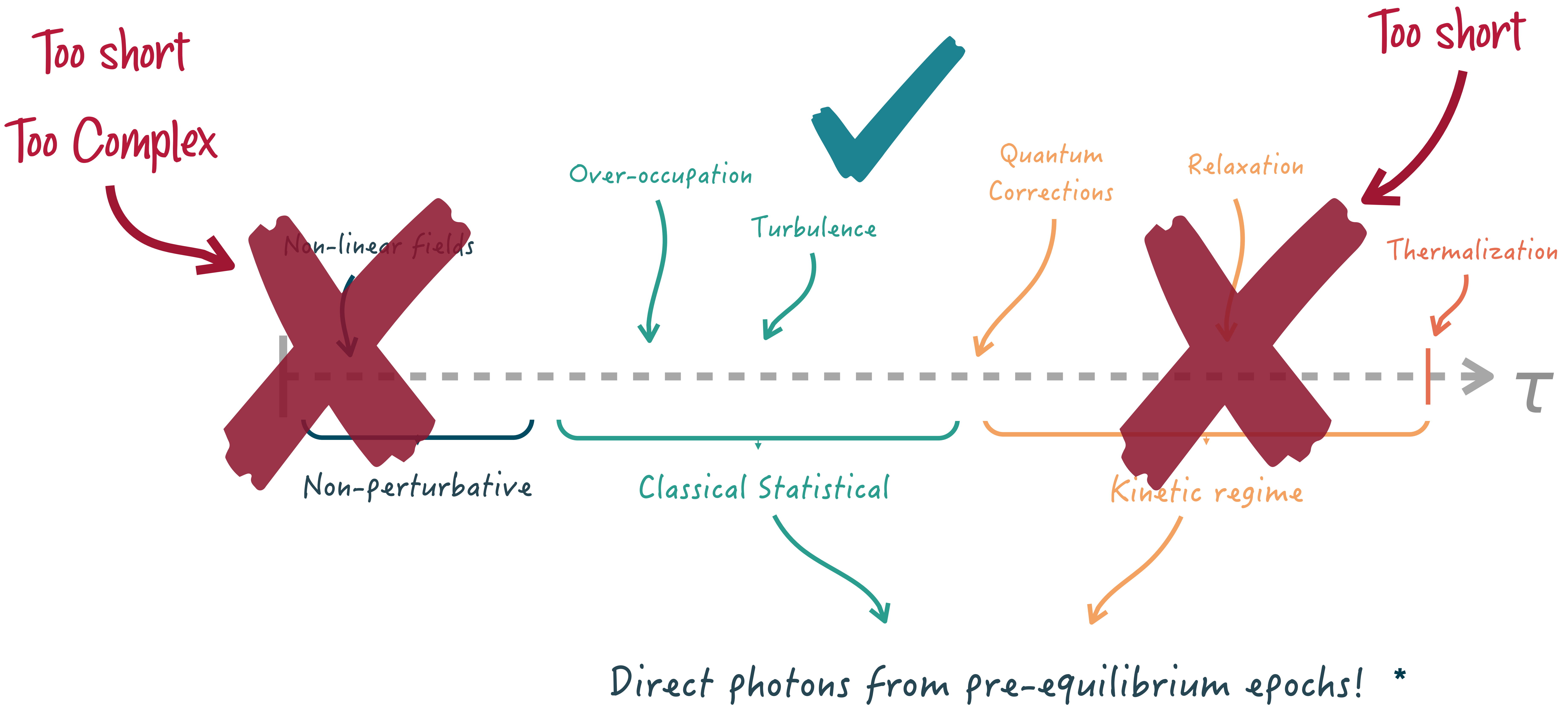
P. B. Arnold, *et al*, JHEP 12, 009 (2001)
S. Turbide, *et al*, Phys. Rev. C69, 014903 (2004)
M. Heffernan, *et al*, Phys. Rev. C91, 027902 (2015)

Far-from equilibrium QCD matter



Direct photons from pre-equilibrium epochs! *

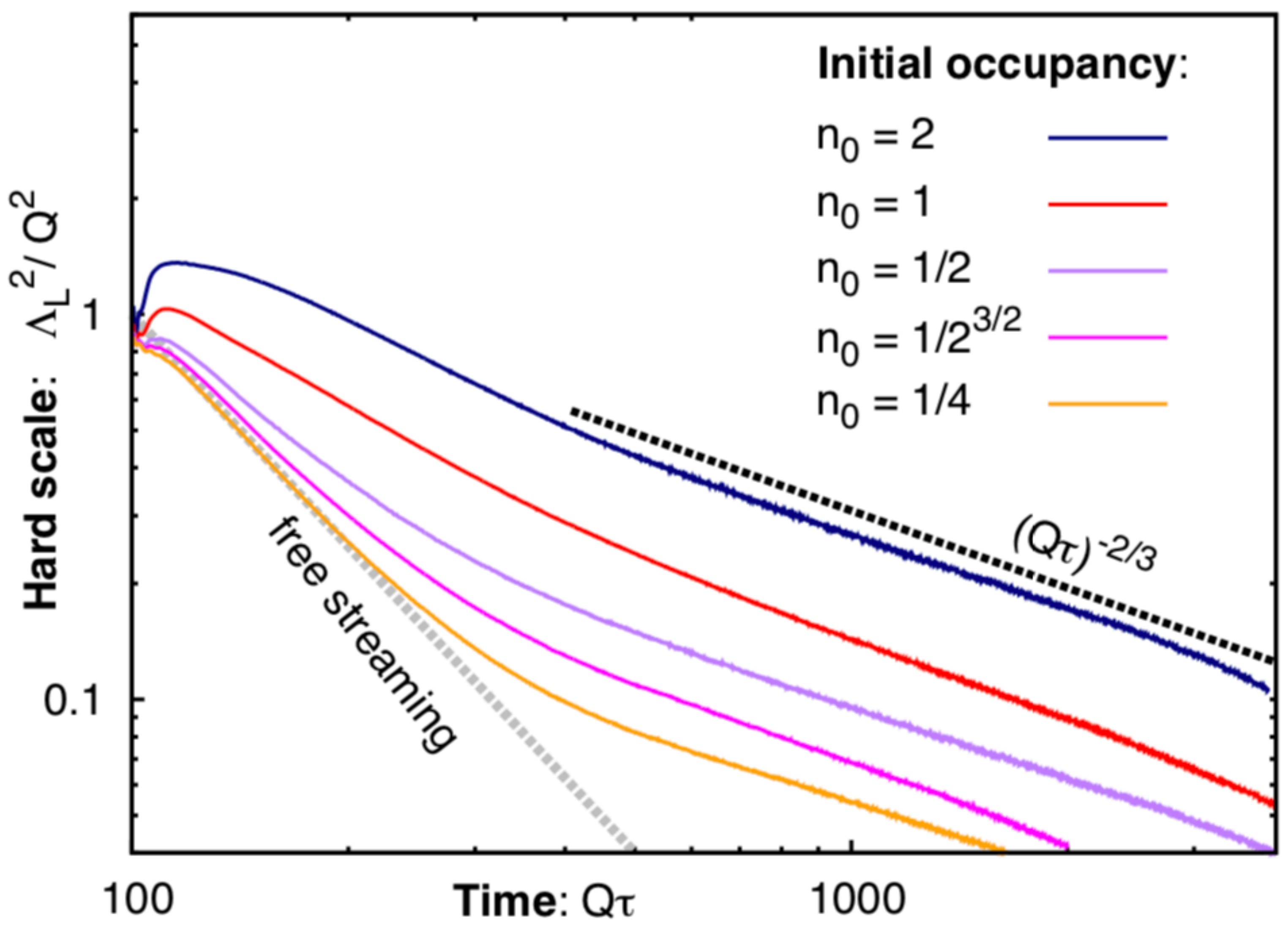
Far-from equilibrium QCD matter



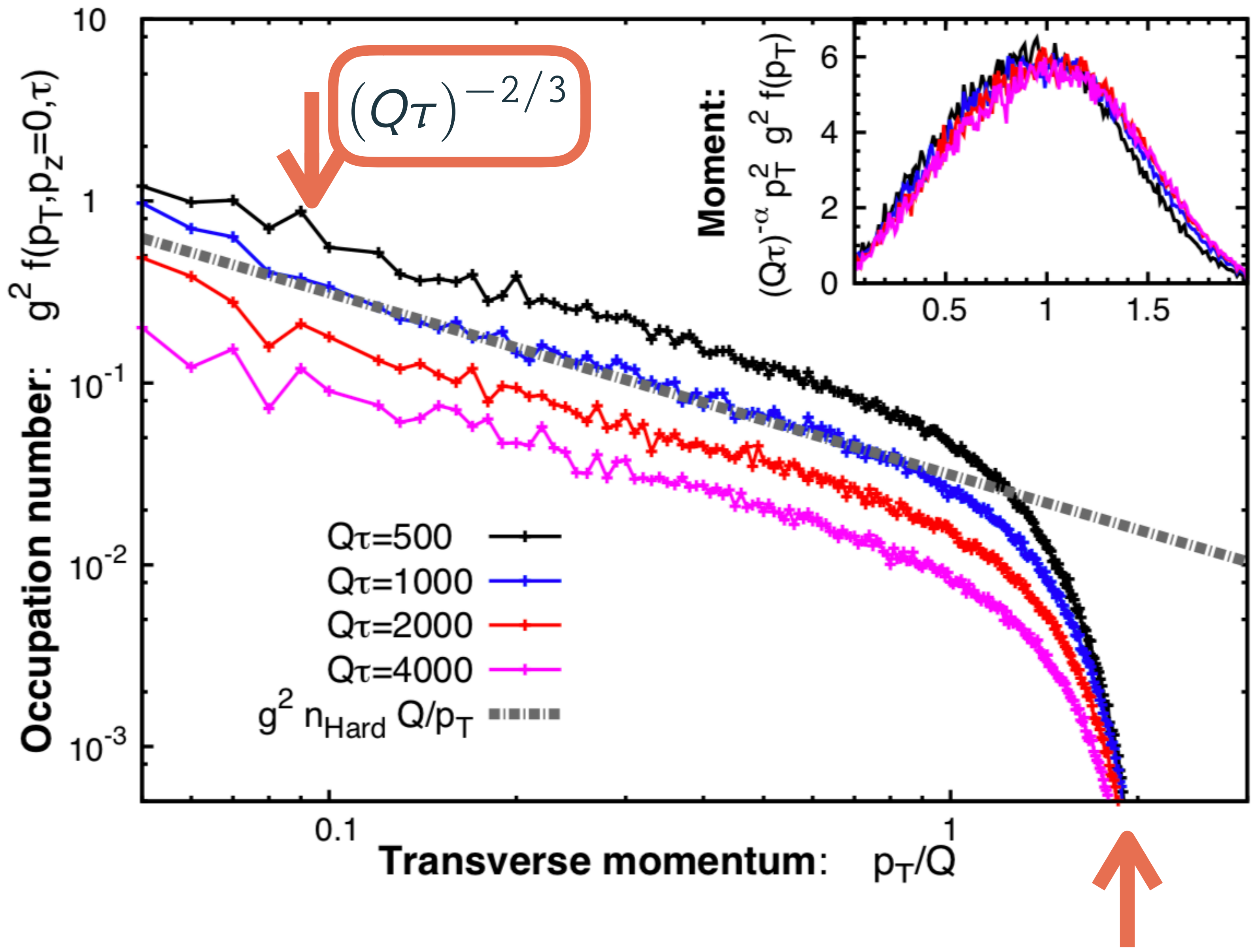
*OGM. In Preparation

Gluon occupation

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



Transverse $p_\perp$



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

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

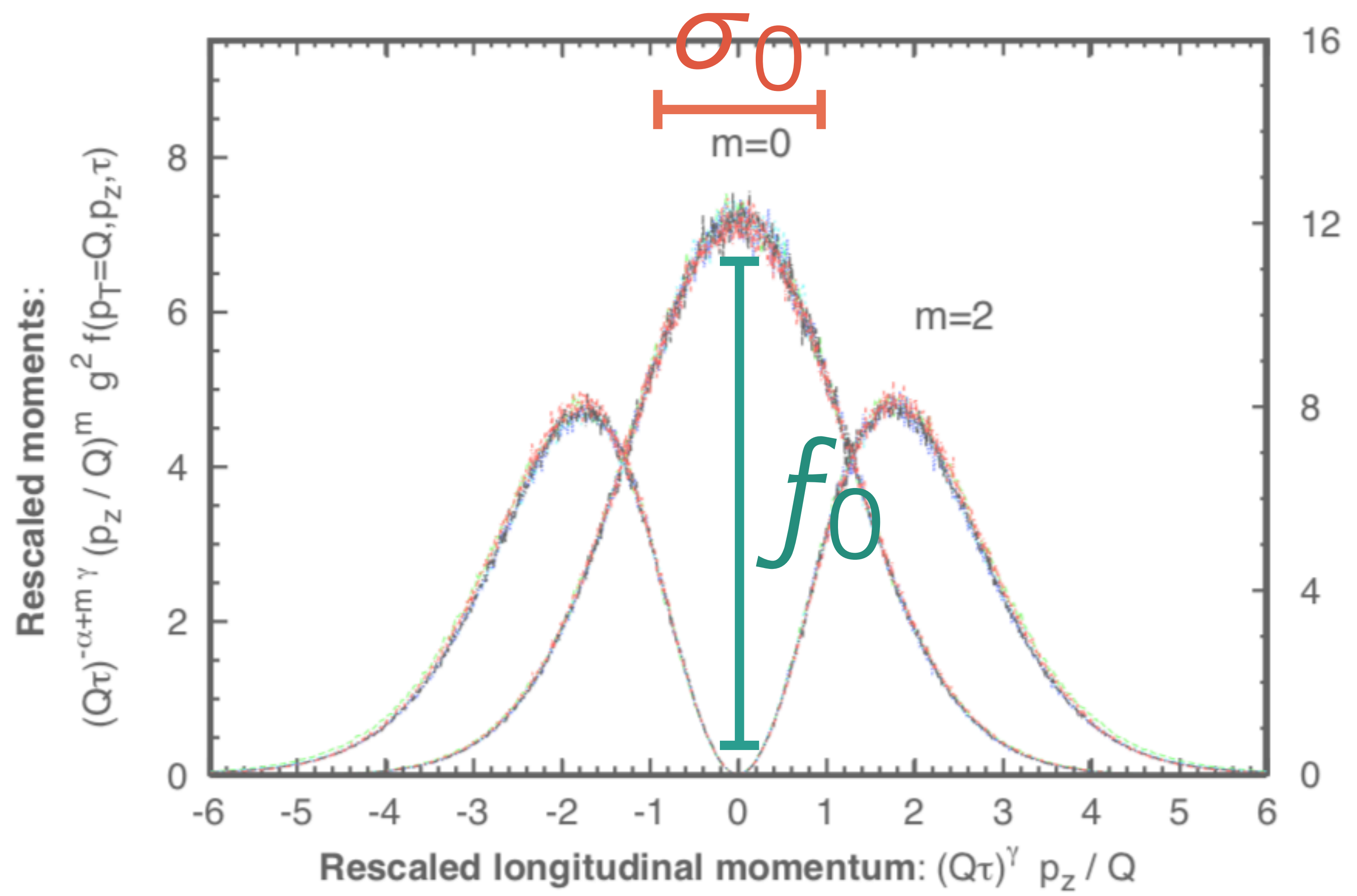
Phys.Rev. D89 (2014) no.11, 114007

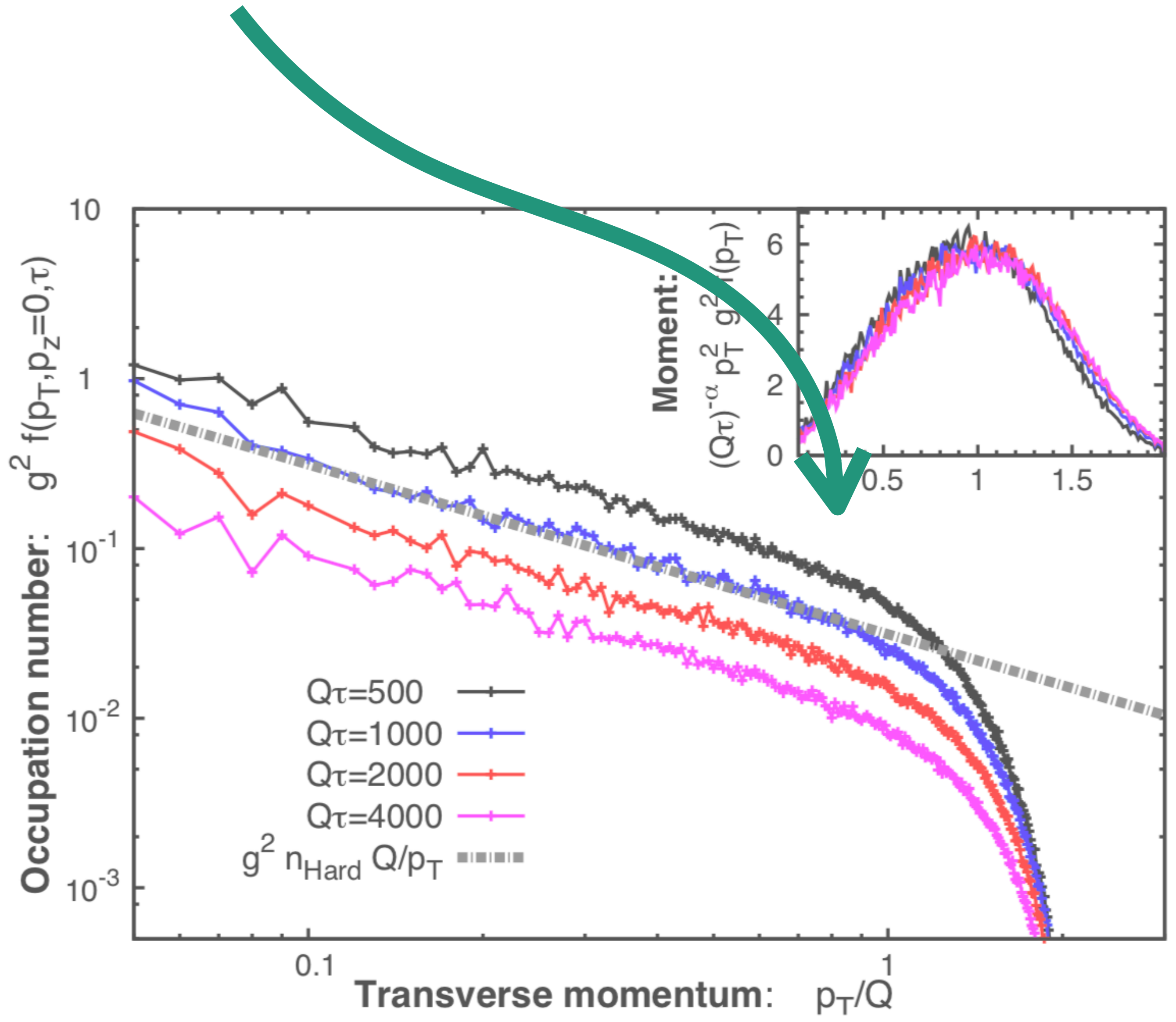
Fit the lattice results

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

with $f_S(p_\perp, p_z) = f_0 \frac{Q_s}{p_\perp} e^{-\frac{1}{2}\left(\frac{p_z}{\sigma_0}\right)^2} W_r(p_\perp - Q_s, r)$

and $W_r(p_\perp - Q_s, r) = \theta(Q_s - p_\perp) + \theta(p_\perp - Q_s) e^{-\frac{1}{2}\left(\frac{p_\perp - Q_s}{r\,Q_s}\right)^2}$



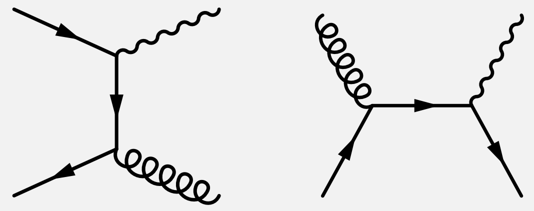


Kinetic Rates

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

Leading Log

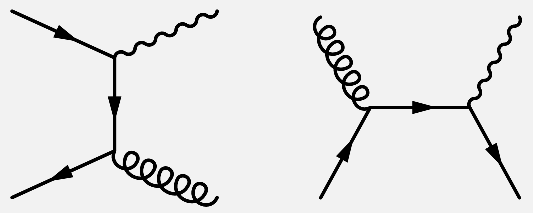
- $2 \leftrightarrow 2$ scatterings



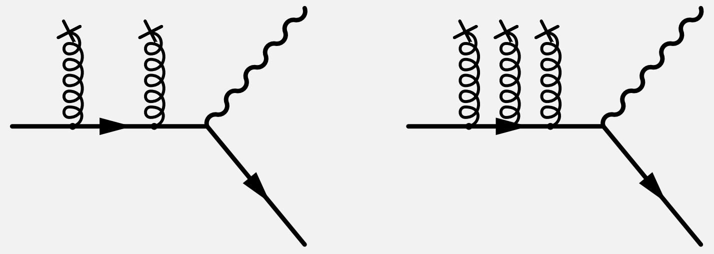
- Momentum transfer: $gT \leftrightarrow T$, $g\,Q_s \leftrightarrow Q_s$

Complete LO

- $2 \leftrightarrow 2$ scatterings



- $1 \leftrightarrow 2$ scatterings



Colinearly enhanced,
inelastic processes

LPM

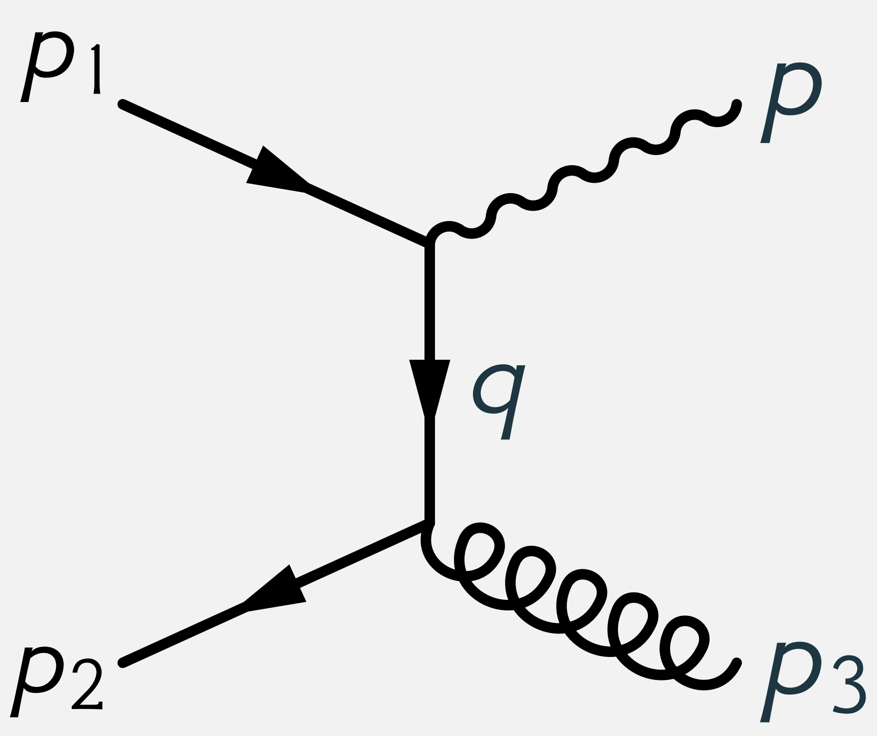
Phys. Rev. D44 (1991) 2774-2788

JHEP 0112 (2001) 009

Kinetic Rates

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

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

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

Small angle approximation

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

Amplitude

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

Kinetic Rates

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

Small angle approximation

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

Regulator

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

Kinetic Rates

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

Small angle approximation

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

Screening Masses

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

Kinetic Rates

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

Small angle approximation

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

Quark Distribution

Kinetic Rates

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

Small angle approximation

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

Quark Distribution → BMSS Scenario

Quark Distribution → Dynamical Lattice Simulations

Occupation in the lattice

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

with $$f_S\left(p_\perp,\ p_z\right) = f_0\,\frac{Q_s}{p_\perp}\,e^{-\frac{1}{2}\left(\frac{p_z}{\sigma_0}\right)^2} W_r(p_\perp - Q_s, r)$$

and $$W_r(p_\perp - Q_s, r) = \theta(Q_s - p_\perp) + \theta(p_\perp - Q_s)e^{-\frac{1}{2}\left(\frac{p_\perp - Q_s}{r\,Q_s}\right)^2}$$

Extension

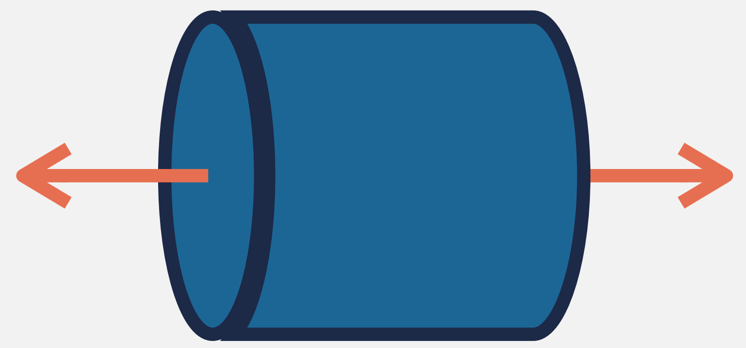
Quark Distribution

Hard dipole approximation → $$f_q\left(\tau, p_\perp, p_z\right) = \alpha_s f_g\left(\tau, p_\perp, p_z\right)$$

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

ASSUMPTIONS

Bjorken Expansion



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

Transverse Translation Invariance

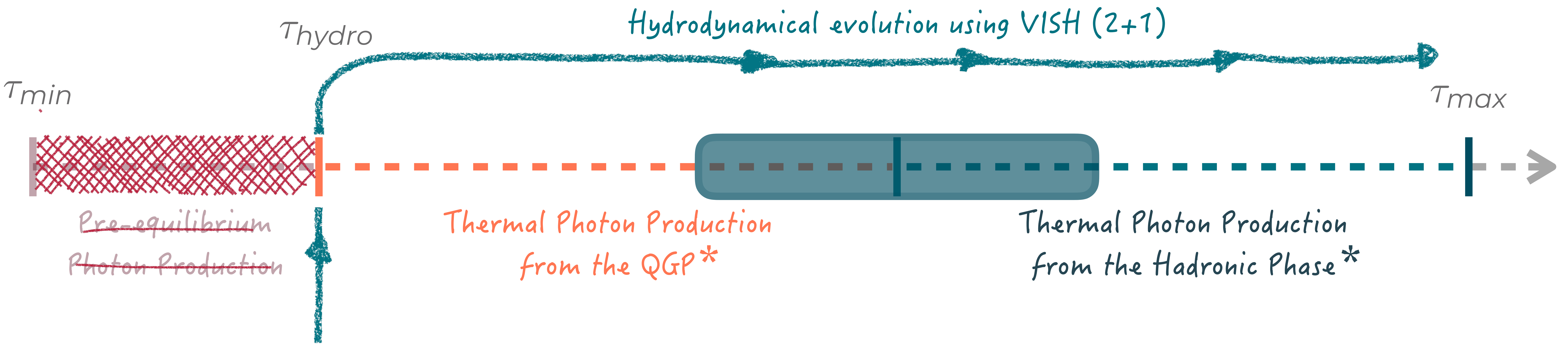
Weak coupling limit

$$\alpha_s \to 0$$

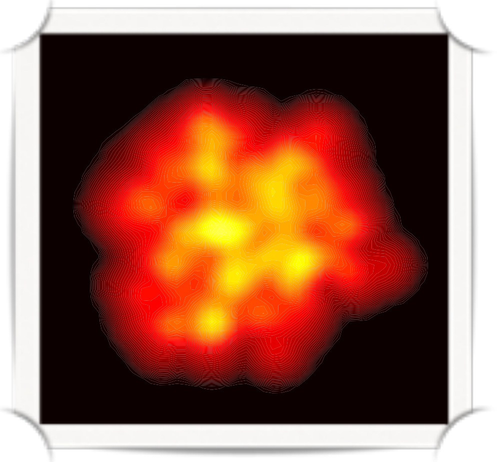
Photons from pseudocritical enhancement

(Non-perturbative partonic enhancement)

The model



MC-Glauber



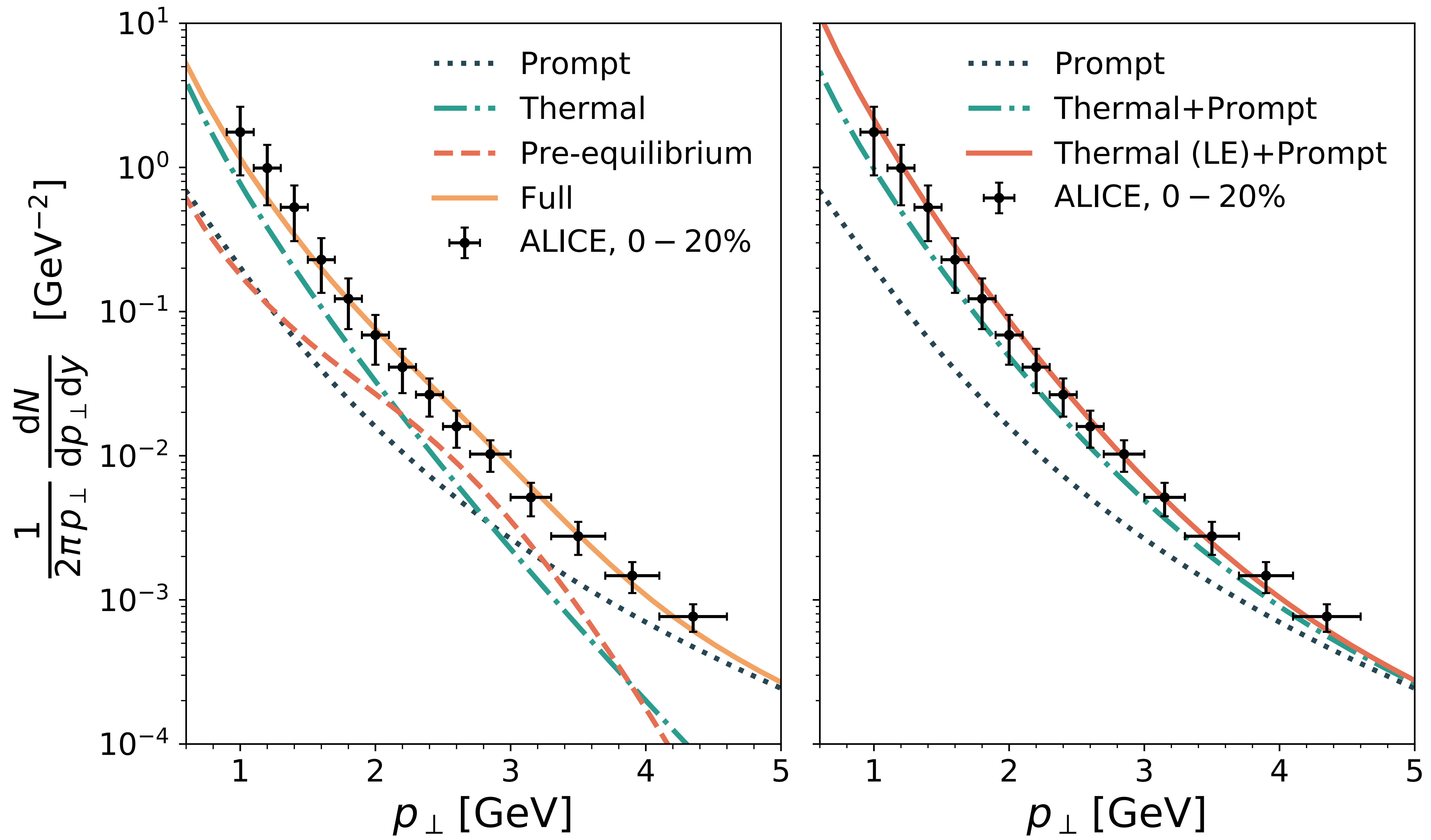
Enhancement around T_{pc}

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

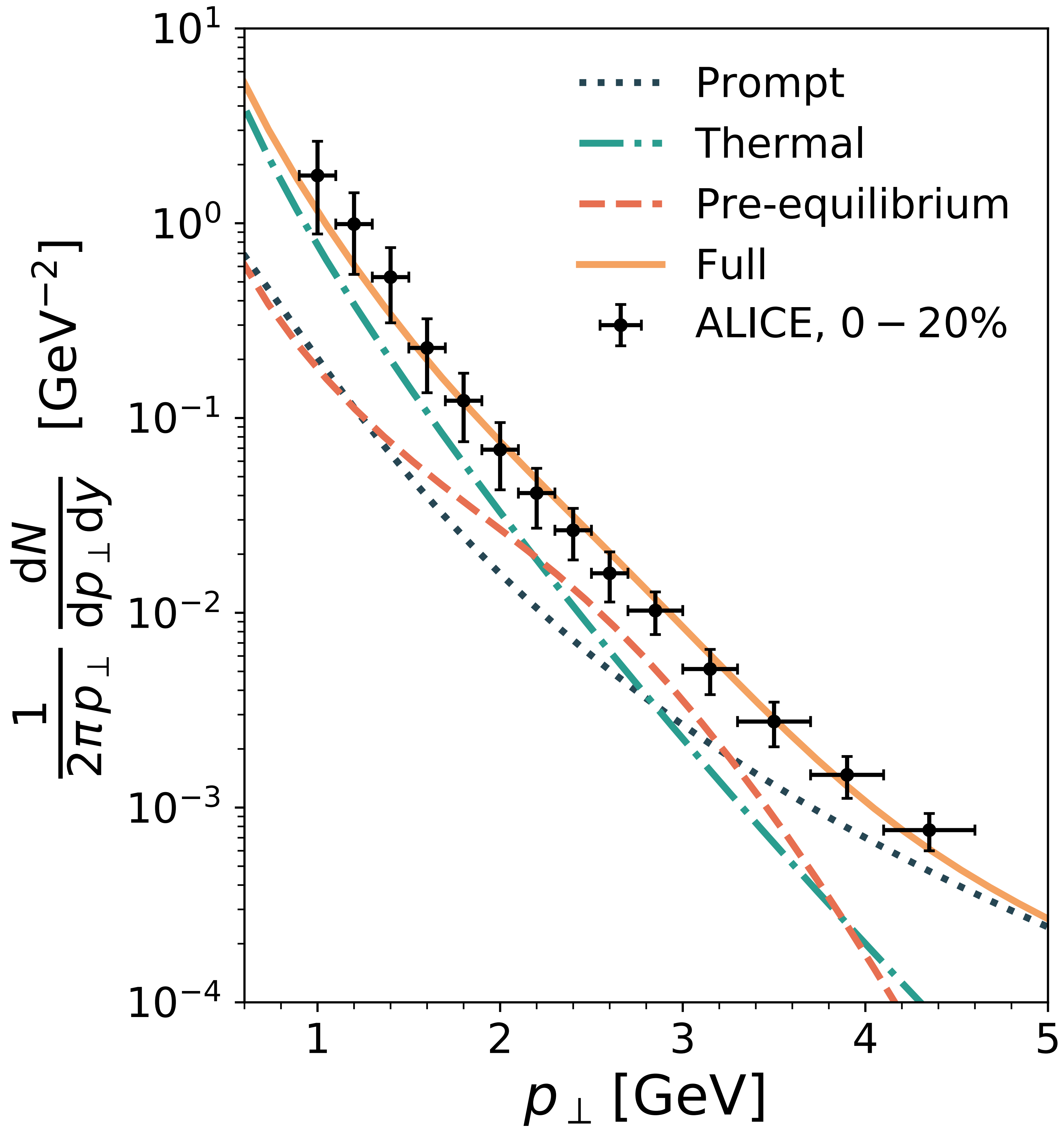
$$h(T) = 1 + h_0 \exp\left\{-\frac{(T-T_{pc})^2}{d^2}\right\}$$

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

Direct photon yield



How to disentangle a long exposure picture?



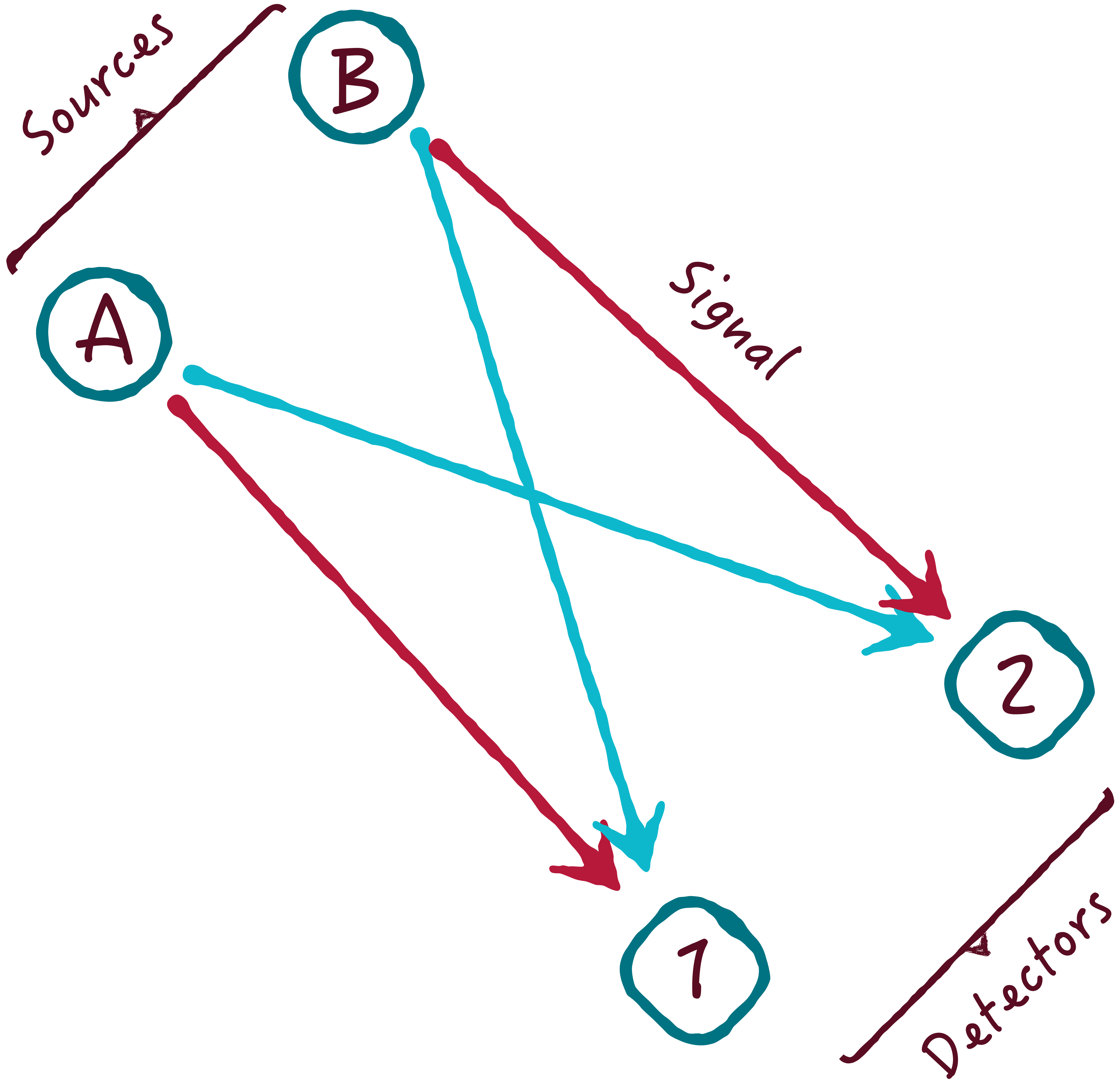
HBT

(Hanbury Brown-Twiss correlations)

"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*

HBT - What are they?



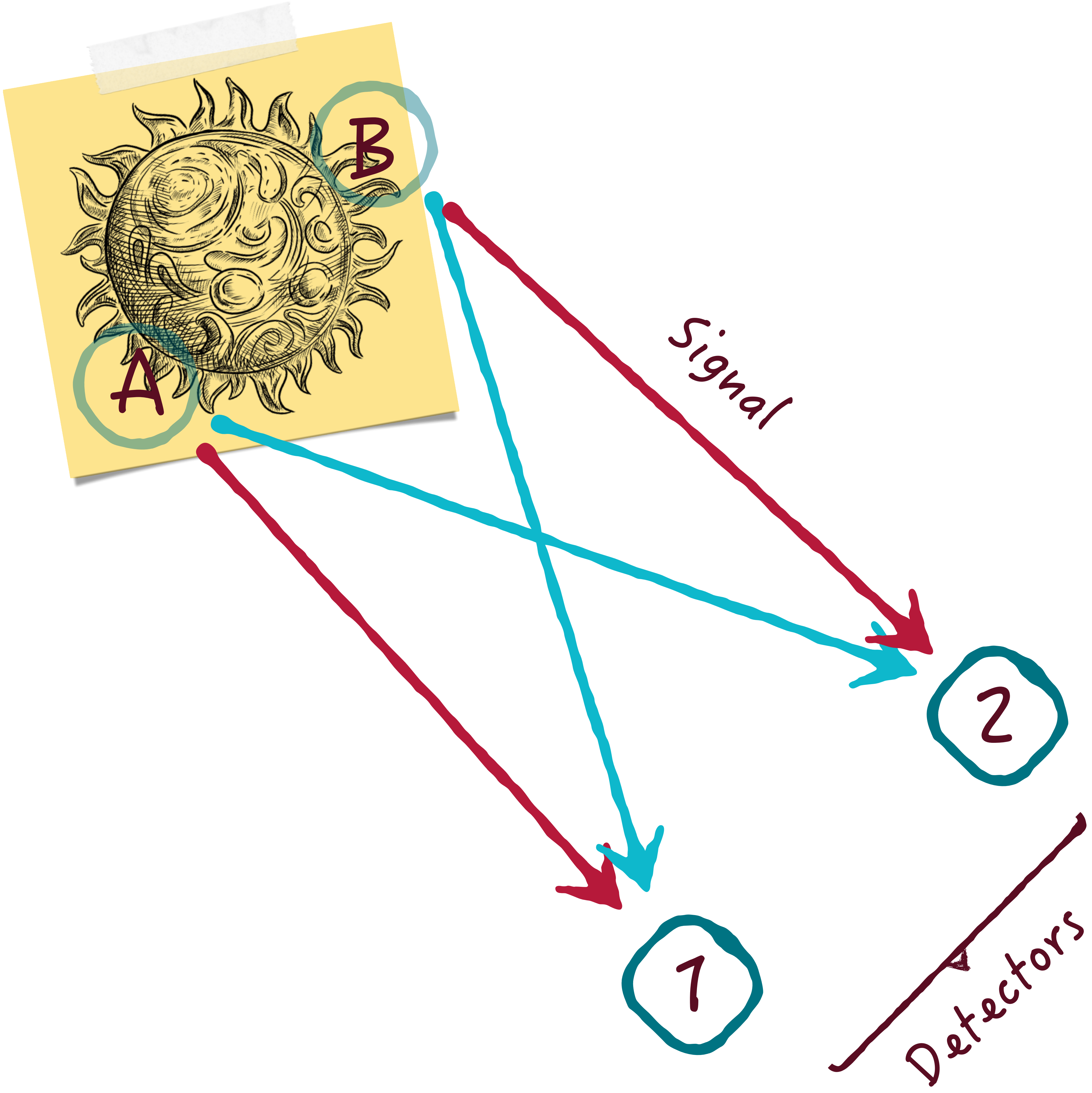
Intensity Interferometry

The distance between two sources using interference at the level of intensity

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?



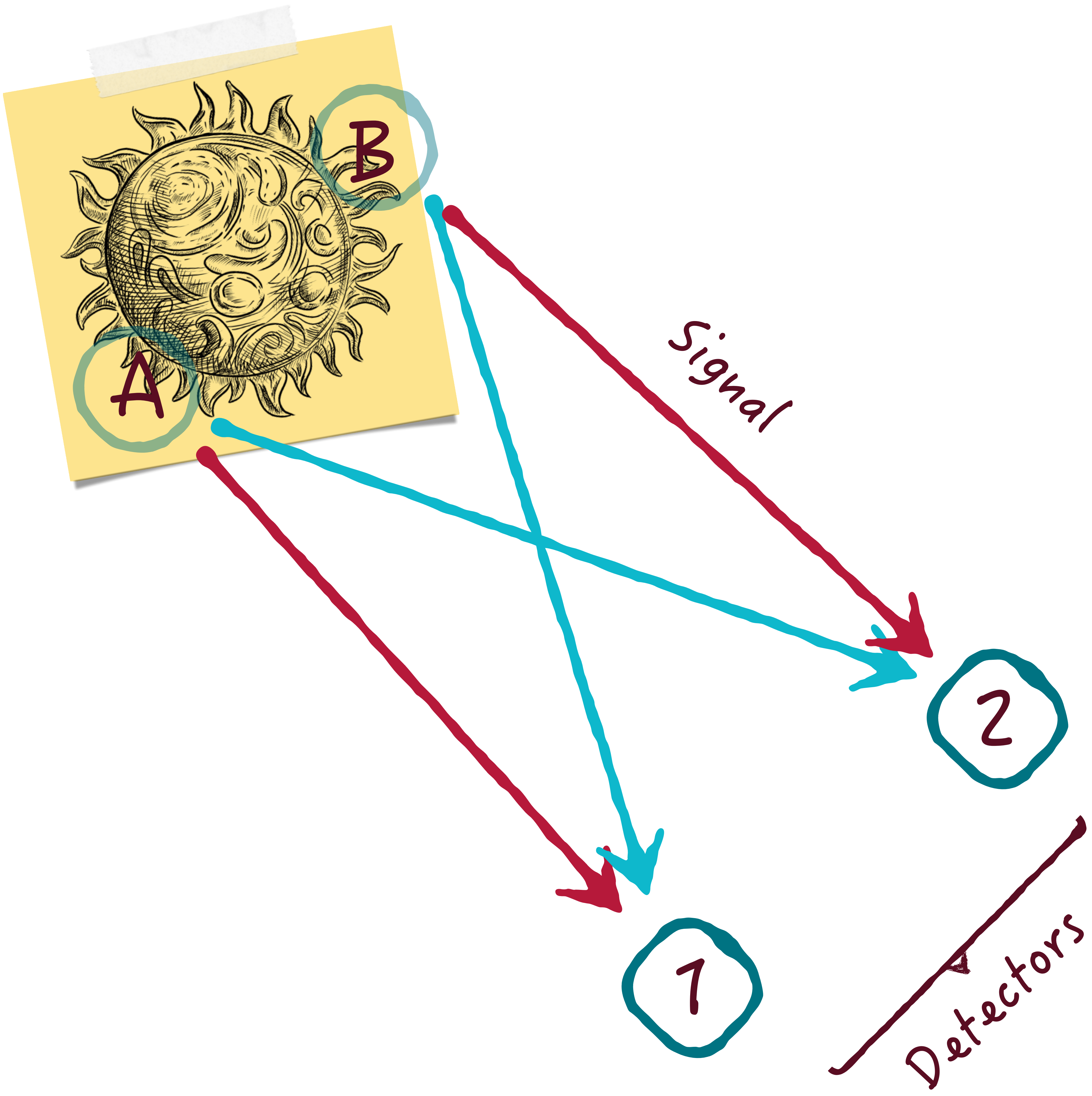
A little bit of History

Used to measure the size of astronomical light sources.

→ Cassiopeia A and Cygnus A

How?

HBT - What are they?



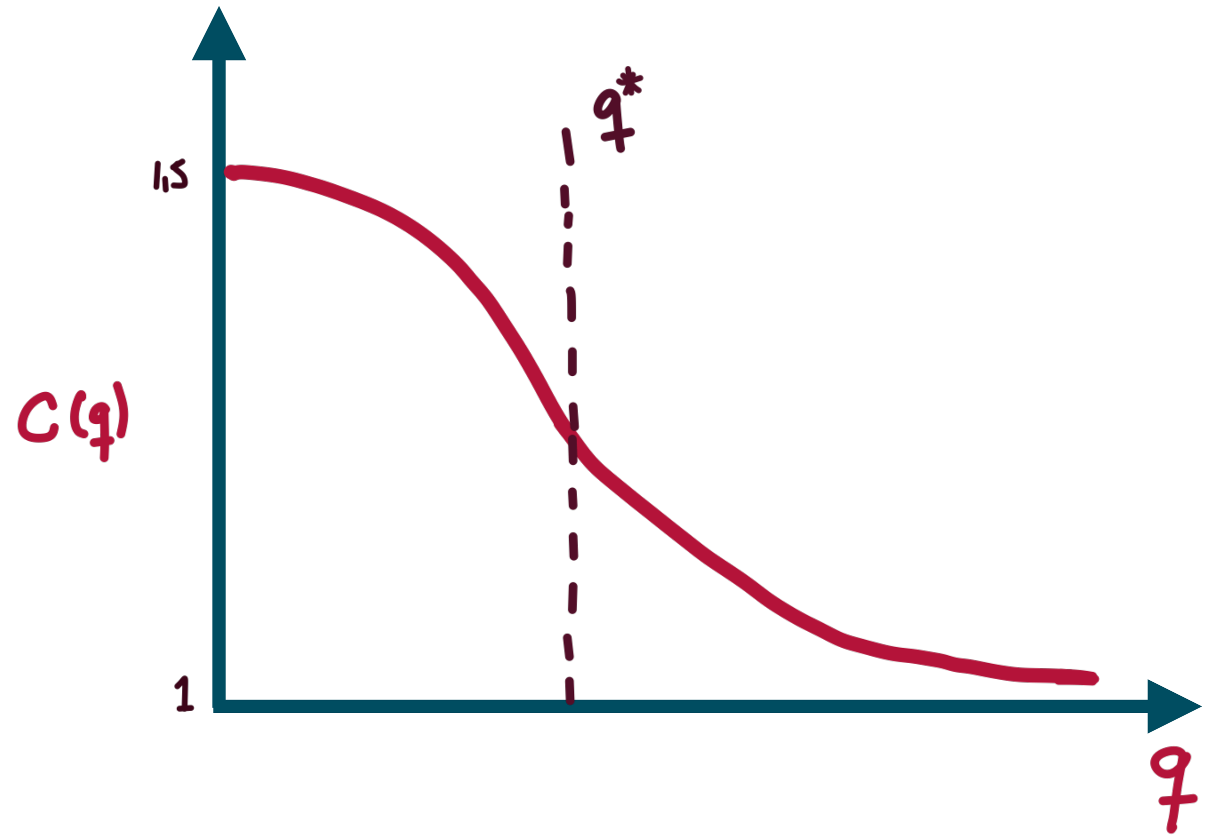
A little bit of History

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 - What are they (for us)?

Main Object : HBT Correlator

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

In the context of Particle Physics

Two-particle correlations

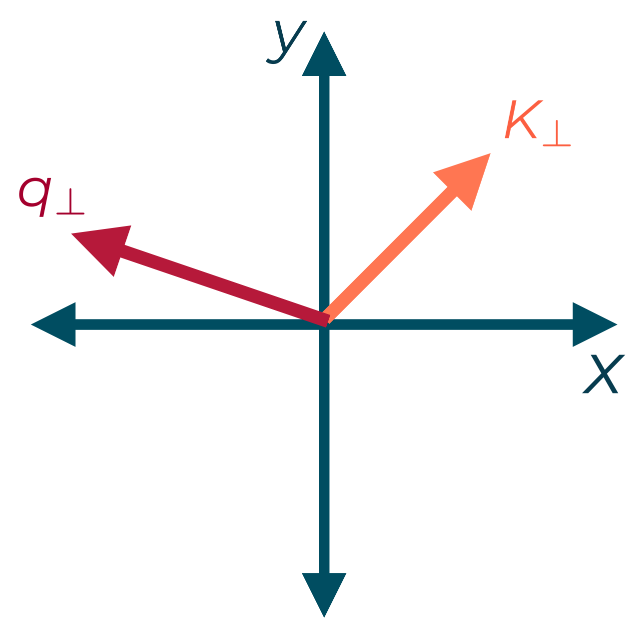
Fermions	Anticorrelate
Bosons	Correlate

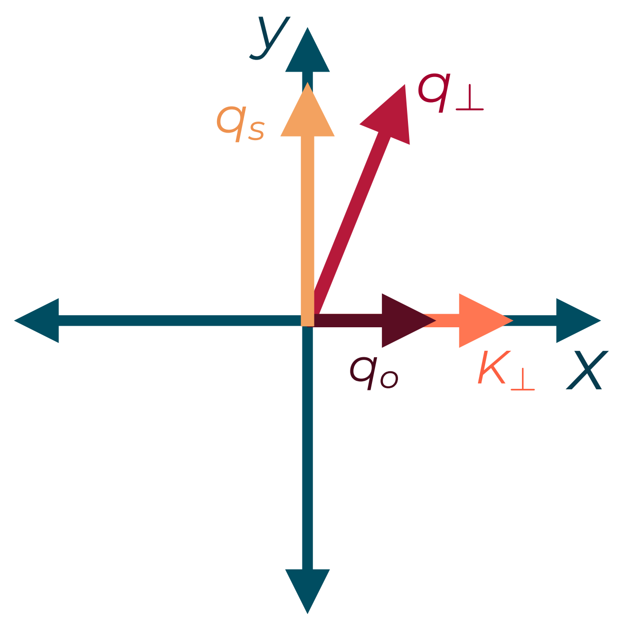
$$C(p_1, p_2) = \frac{E_{p_1} E_{p_2} \dfrac{\mathrm{d}N}{\mathrm{d}^3 p_1 \mathrm{d}^3 p_2}}{E_{p_1} \dfrac{\mathrm{d}N}{\mathrm{d}^3 p_1} E_{p_2} \dfrac{\mathrm{d}N}{\mathrm{d}^3 p_2}} = 1 + \frac{1}{d} \frac{|S(q,K)|^2}{S(0,p_1) S(0,p_2)}$$

$S(q,K)$ Fourier Transform of $S(x,K)$ → Emission Function (rate)

d (Spin) Degeneracy

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





HBT - What are they (for us)?

Main Object : HBT Correlator

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

In the context of Particle Physics

Two-particle correlations

Fermions Anticorrelate

Bosons Correlate

$$C(p_1, p_2) = 1 + \frac{1}{d} \frac{|S(q,K)|^2}{S(0,p_1)S(0,p_2)} \sim 1 + \frac{1}{2} \exp\left[-q_i R^{ij} q_j\right] ,$$

where $$R_{ij}(K) = \begin{bmatrix} R_o^2 & R_{os}^2 & R_{ol}^2 \\ R_{os}^2 & R_s^2 & R_{sl}^2 \\ R_{ol}^2 & R_{sl}^2 & R_l^2 \end{bmatrix}$$ are the HBT Radii

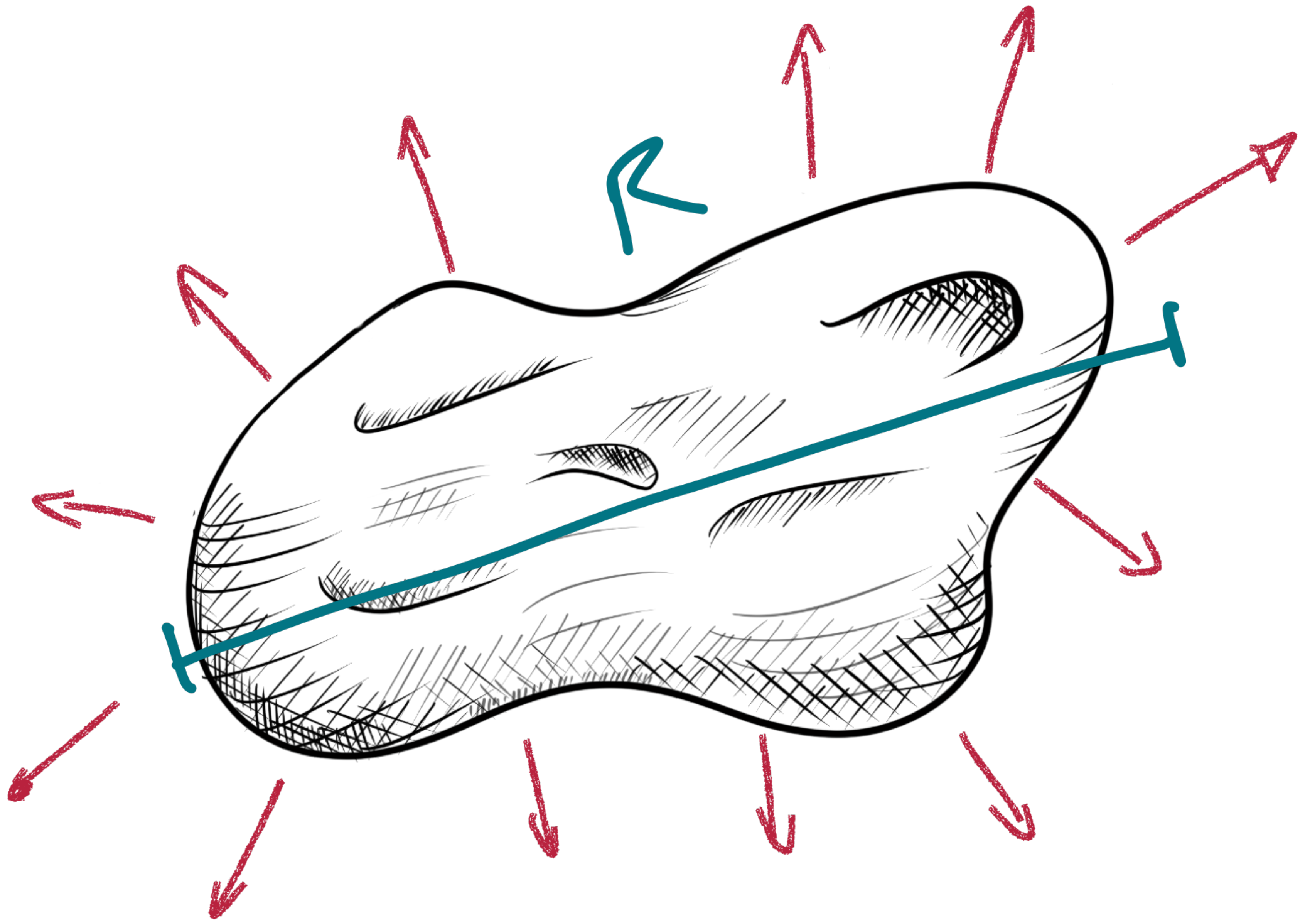
$$\langle\langle q_i q_j \rangle\rangle = \int \mathrm{d}^3 q \, q_i \, q_j \, g(q;K) \equiv \frac{1}{2}(R^{-1})_{ij}$$

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

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.

!

MAIN POINT OF MY TALK

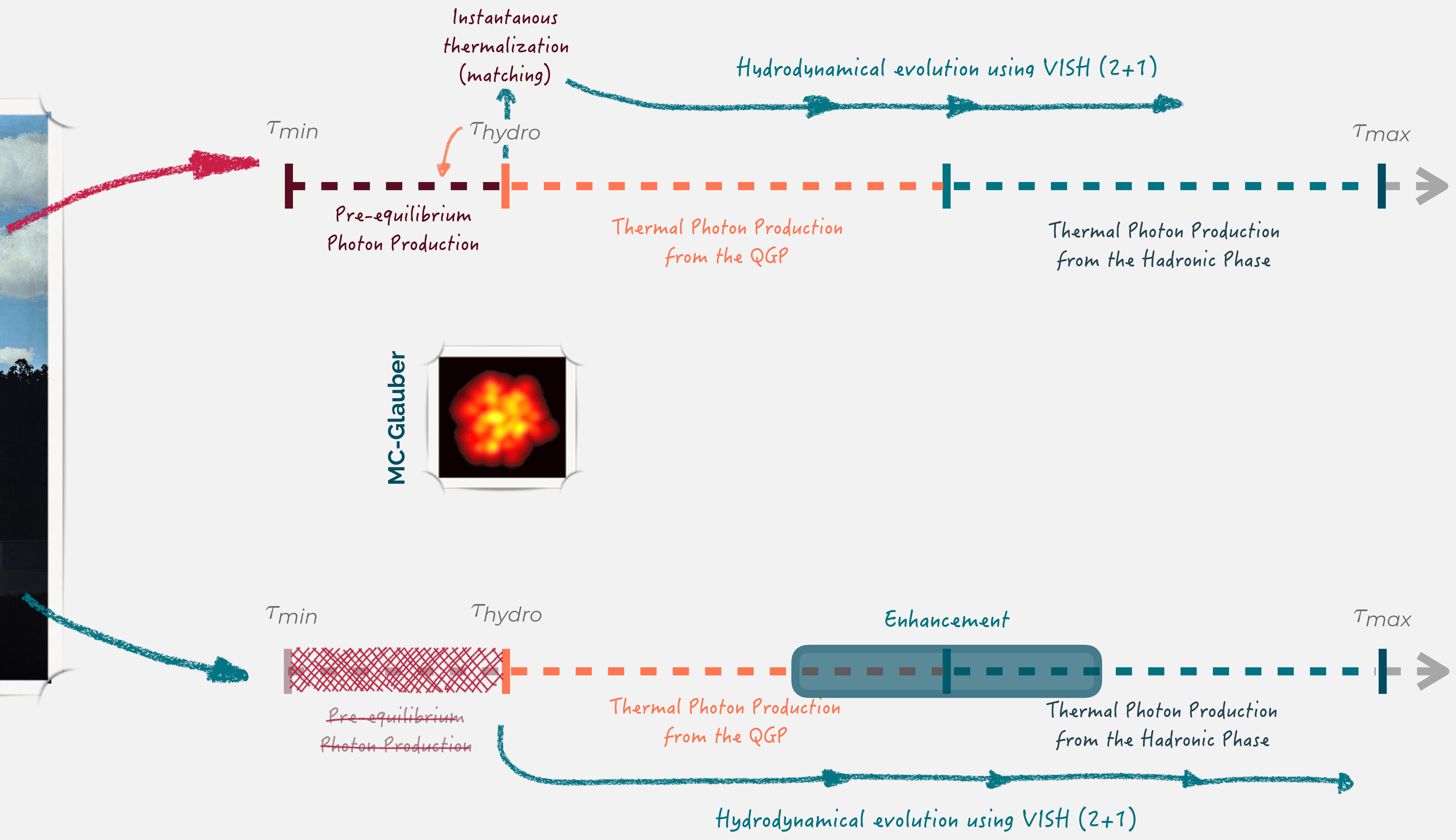
Use photon HBT not to extract source sizes, but to cross-compare models

Some Results

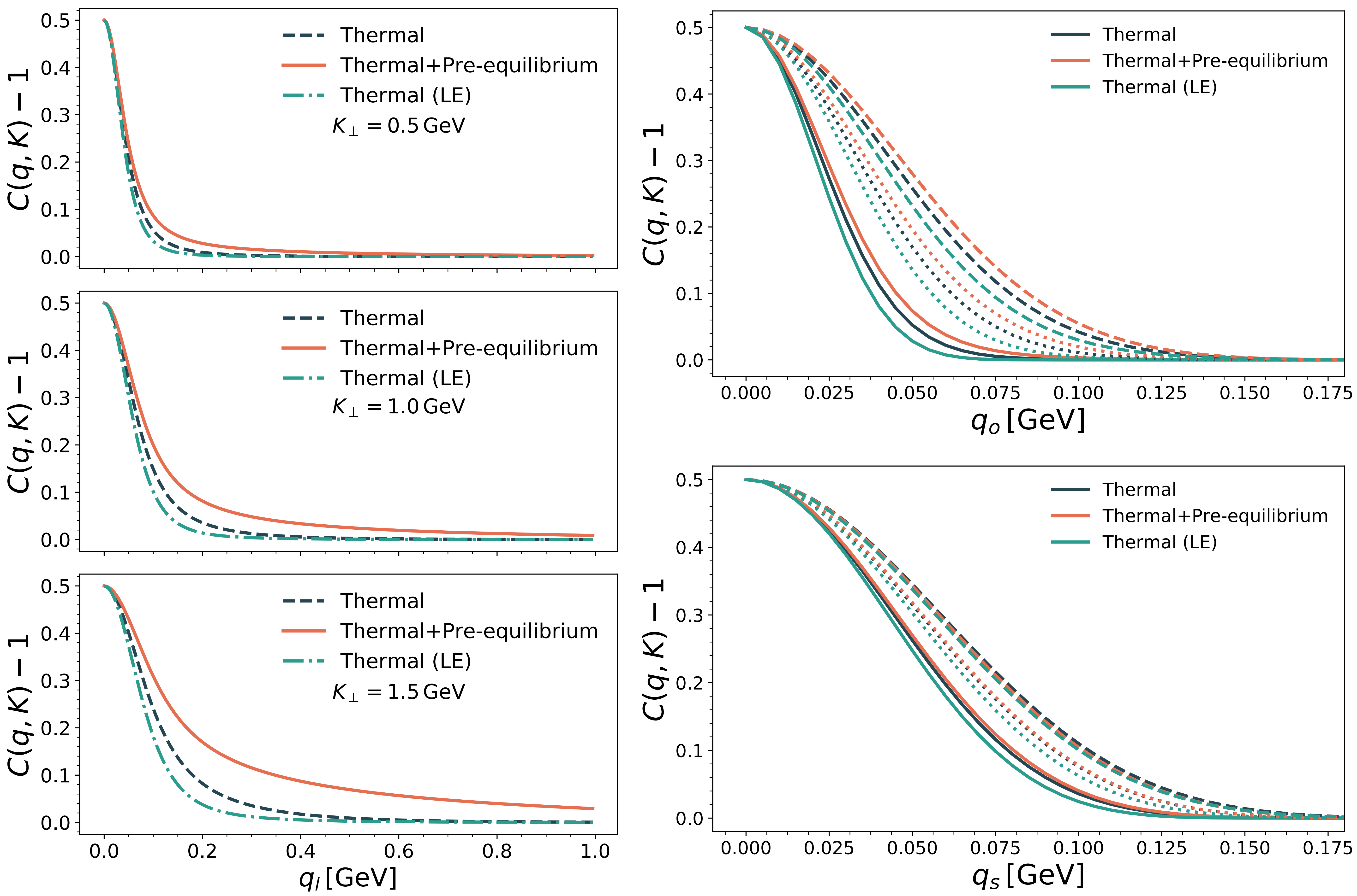
(Hanbury Brown-Twiss correlations)

The Models

René Magritte
Empire of Light



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

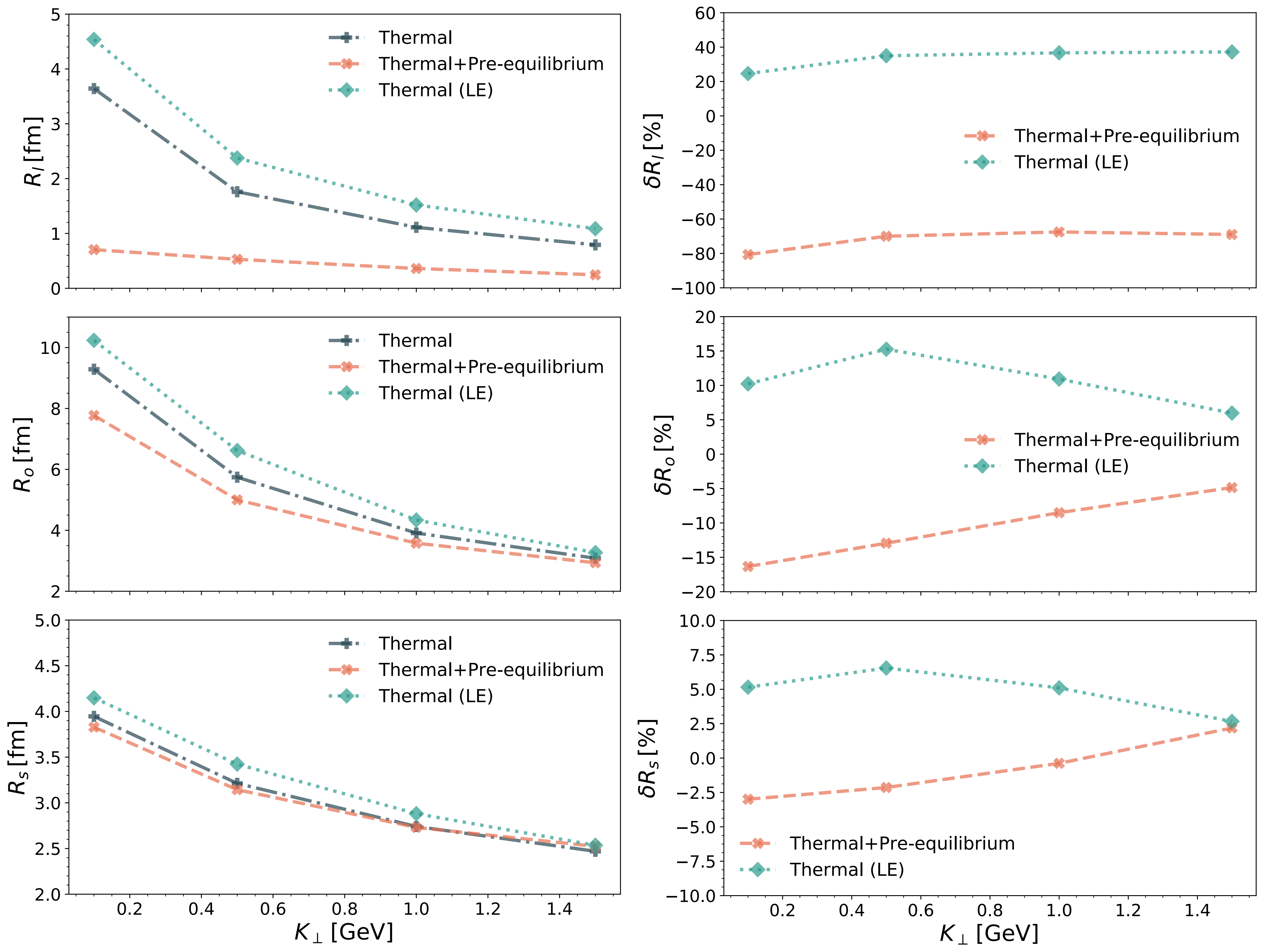
$$\langle\langle q_i q_j \rangle\rangle = \int \mathrm{d}^3 q \, q_i \, q_j \, g(q;K) \equiv \frac{1}{2}(R^{-1})_{ij}$$

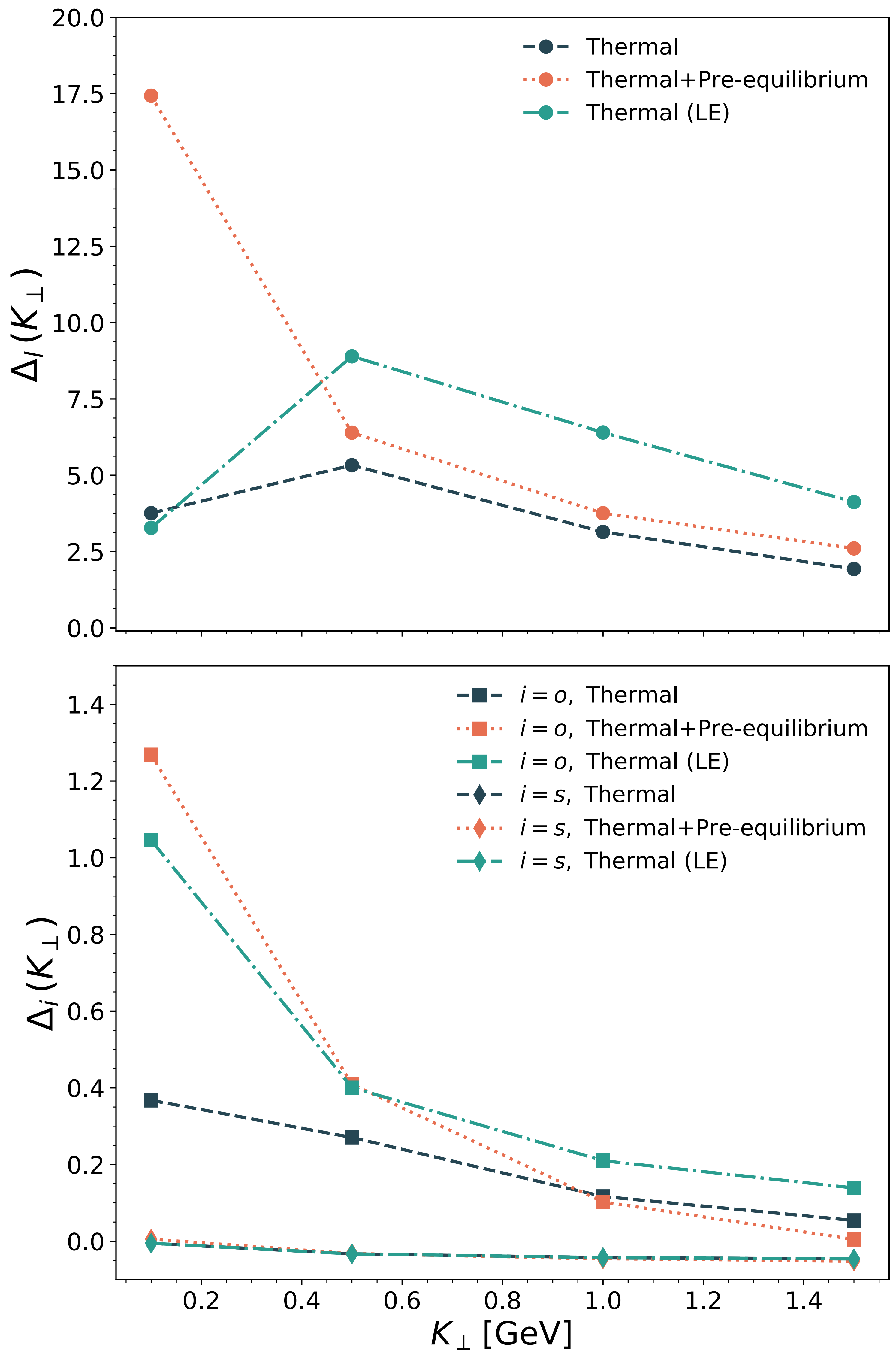
$$g(q;K) \equiv \frac{C(q,K)-1}{\int \mathrm{d}^3 q \, [C(q,K)-1]}$$

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

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

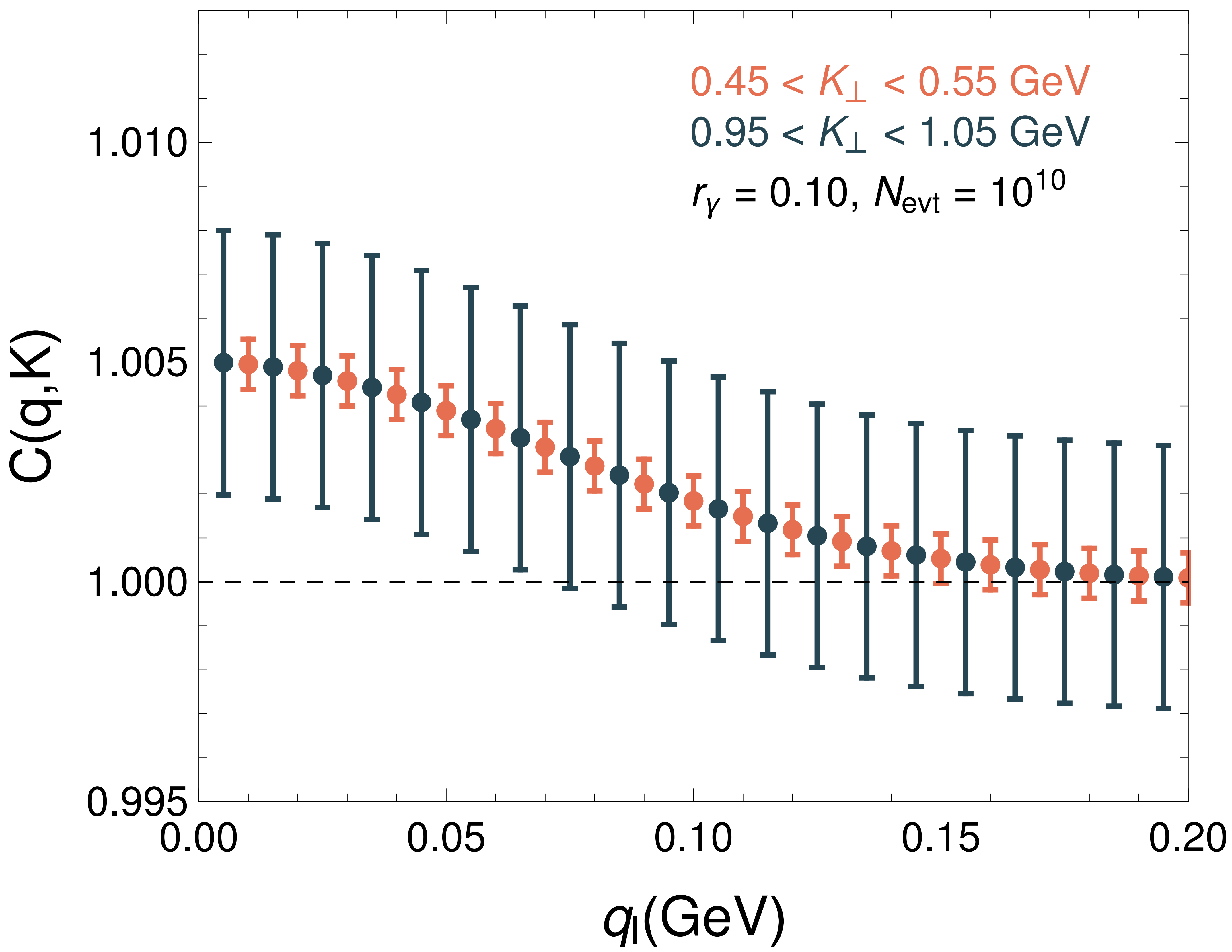
Measures "how much non-Gaussian is a distribution

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

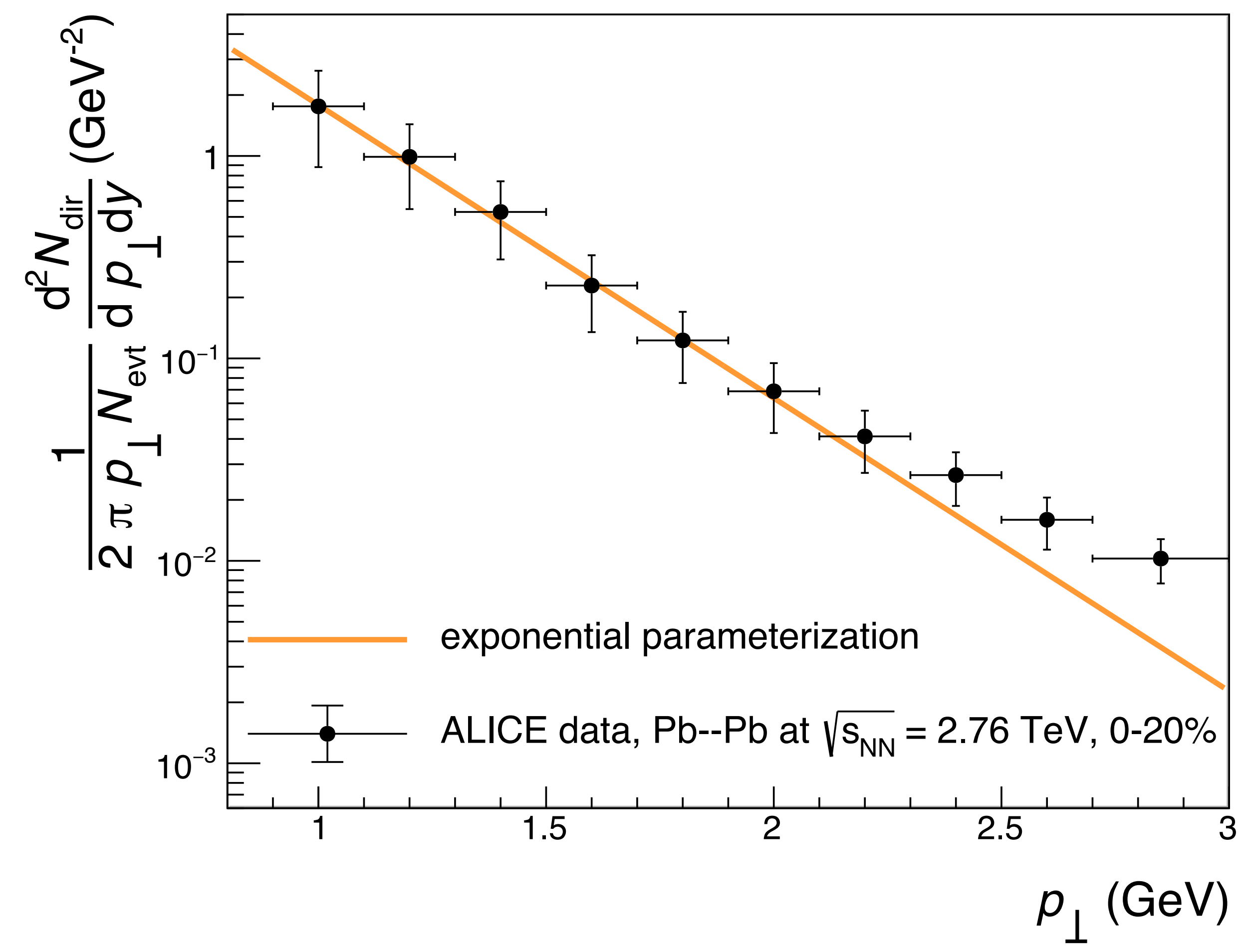
Very interesting observable, hard to measure.

Statistical Model

Effective dilution of the signal!



Exponential distribution



Exponential-like source used as test model.

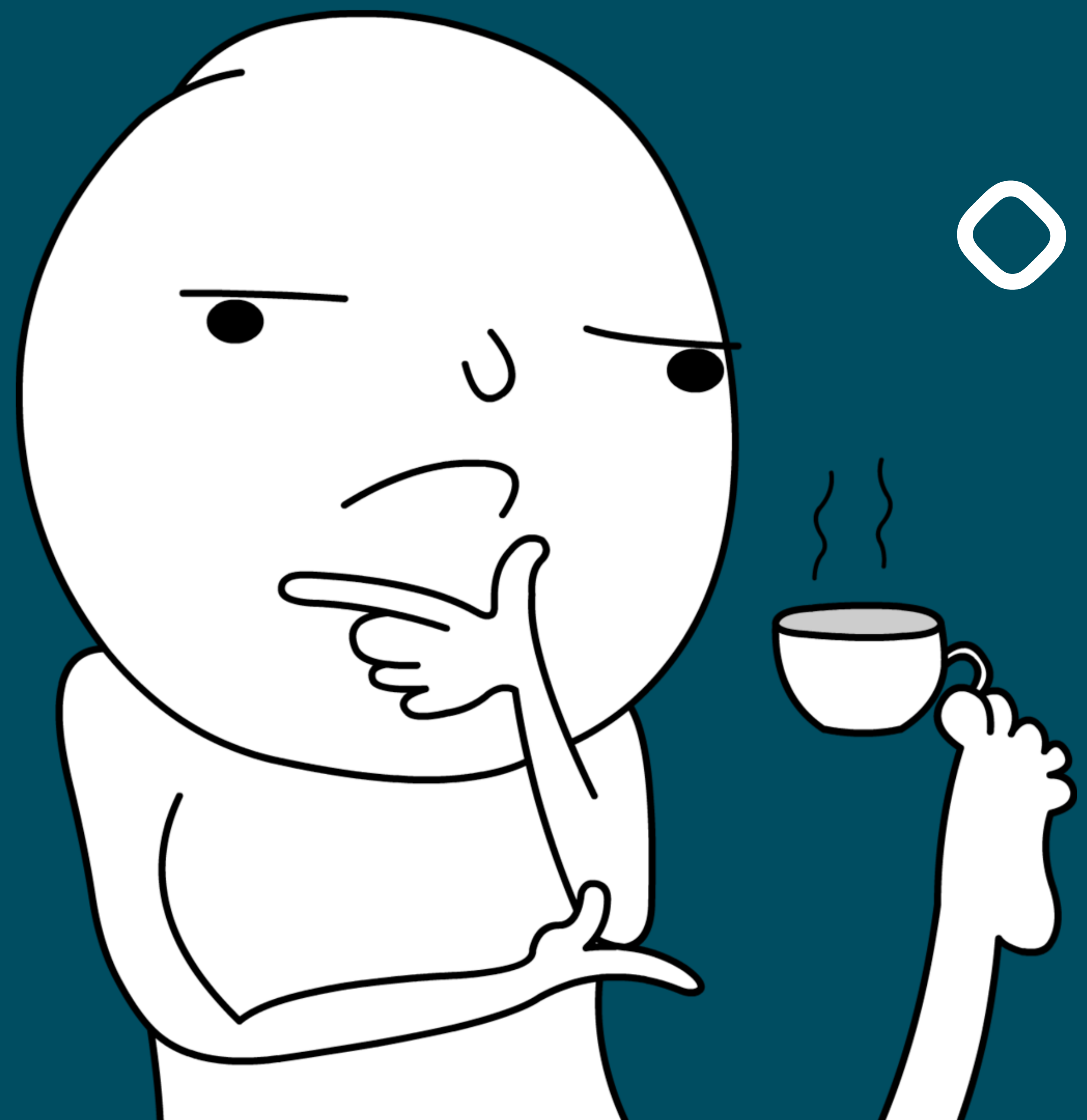
Correlator simulated sampling from source.

Error depends strongly on the average momentum of the pair.

Low momentum pairs statistically significant.

Summary

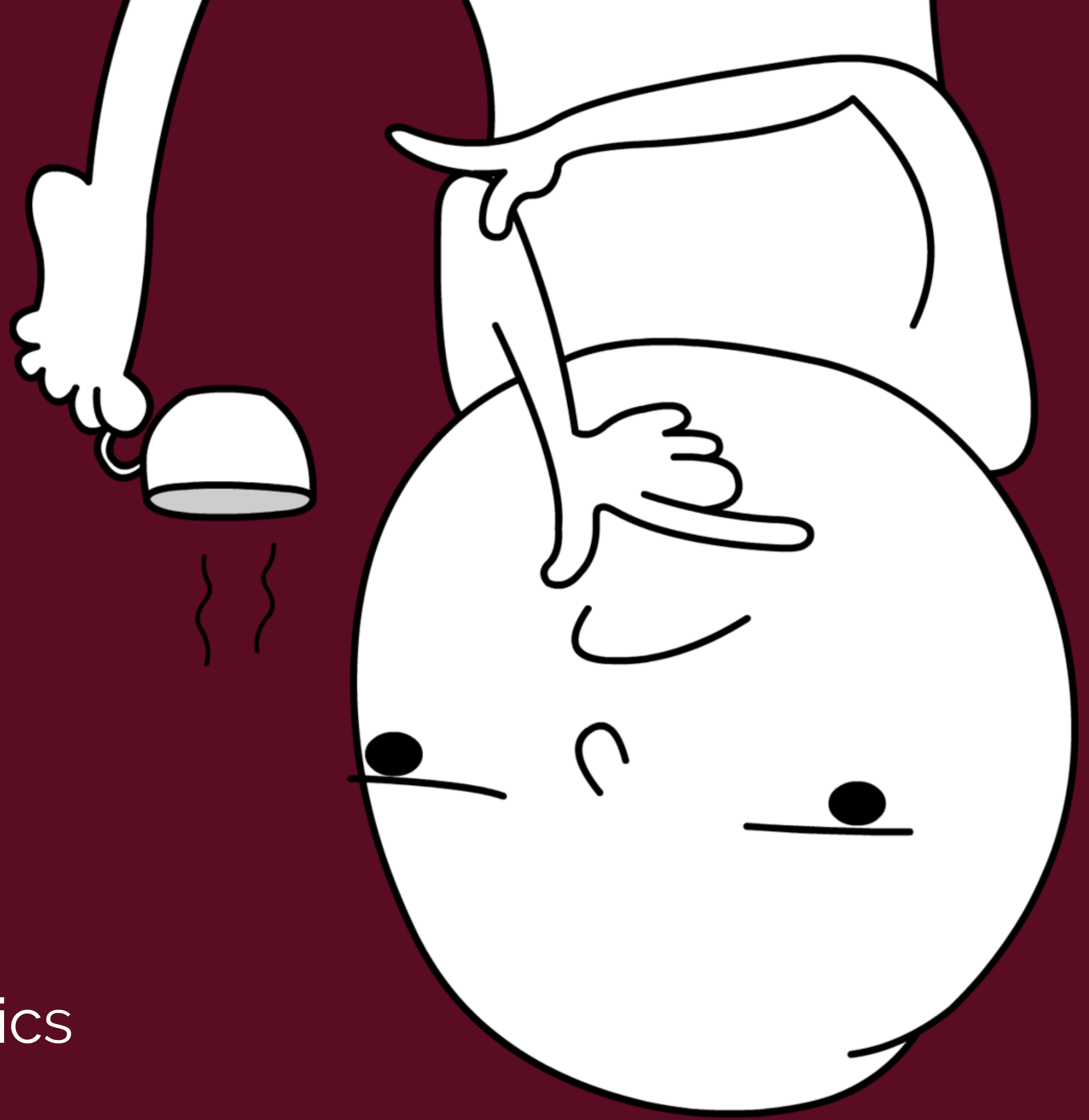
- Even when the discrepancies of the *Direct Photon Puzzle* are solved, we need to differentiate between the different models in the market.
- Photon correlations are the tool that we need to do so.
- Yes, they are very hard measurements, but not impossible anymore. We should start walking before we 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



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Back-up Slides

Bottom-up thermalization

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

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

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

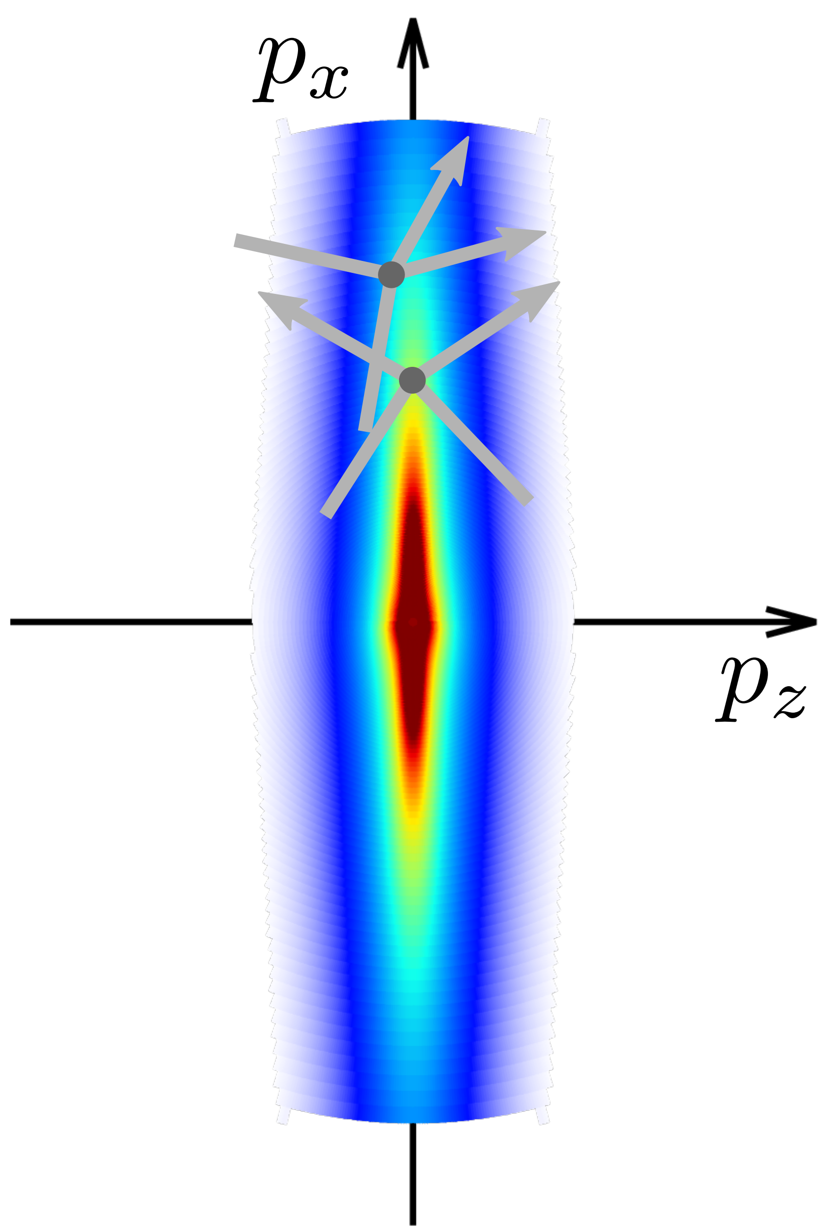
Dominated by hard gluons

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

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

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

I. Early Times: 2 ↔2 broadening

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

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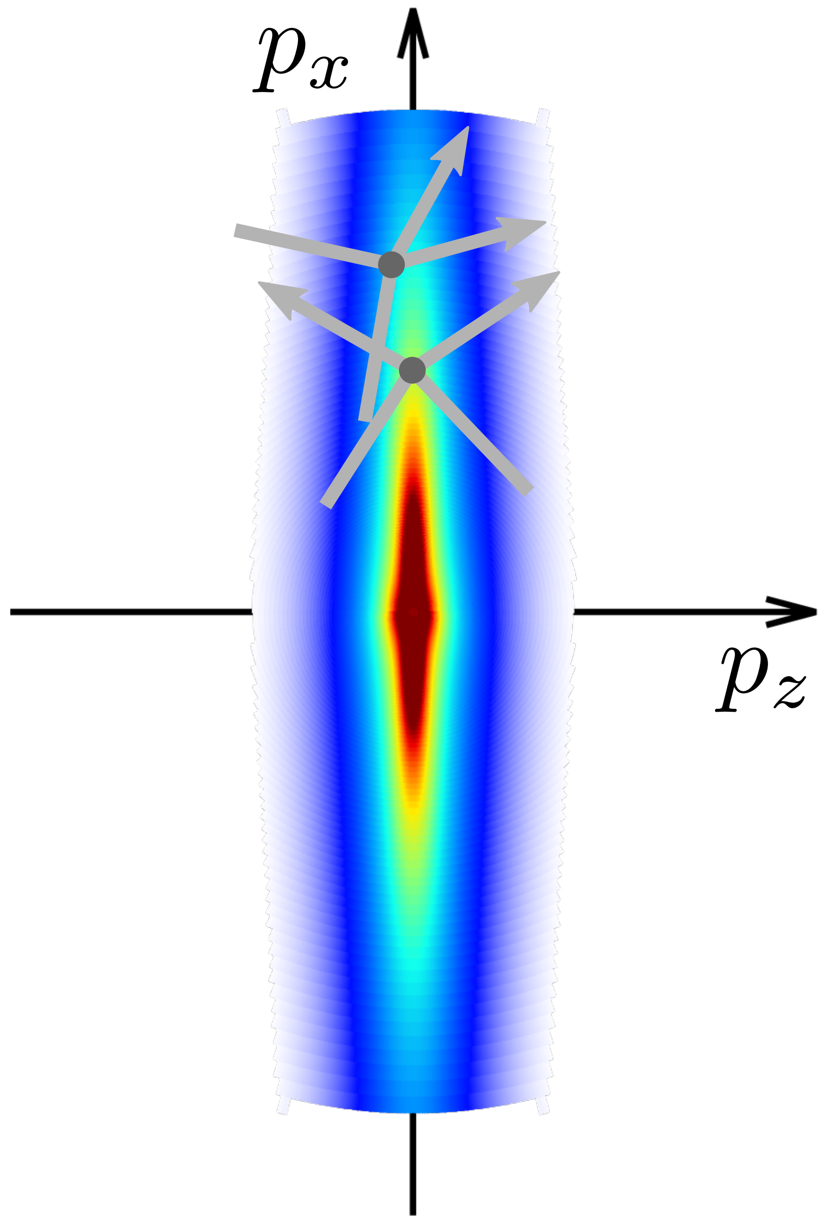


From Kurkela et al.
Phys.Rev. C99 (2019) no.3, 034910

II. Onset of thermalization

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

Occupation of Hard Gluon drops below unity

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

Dominated by hard gluons

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

Soft gluons dominate the screening mass

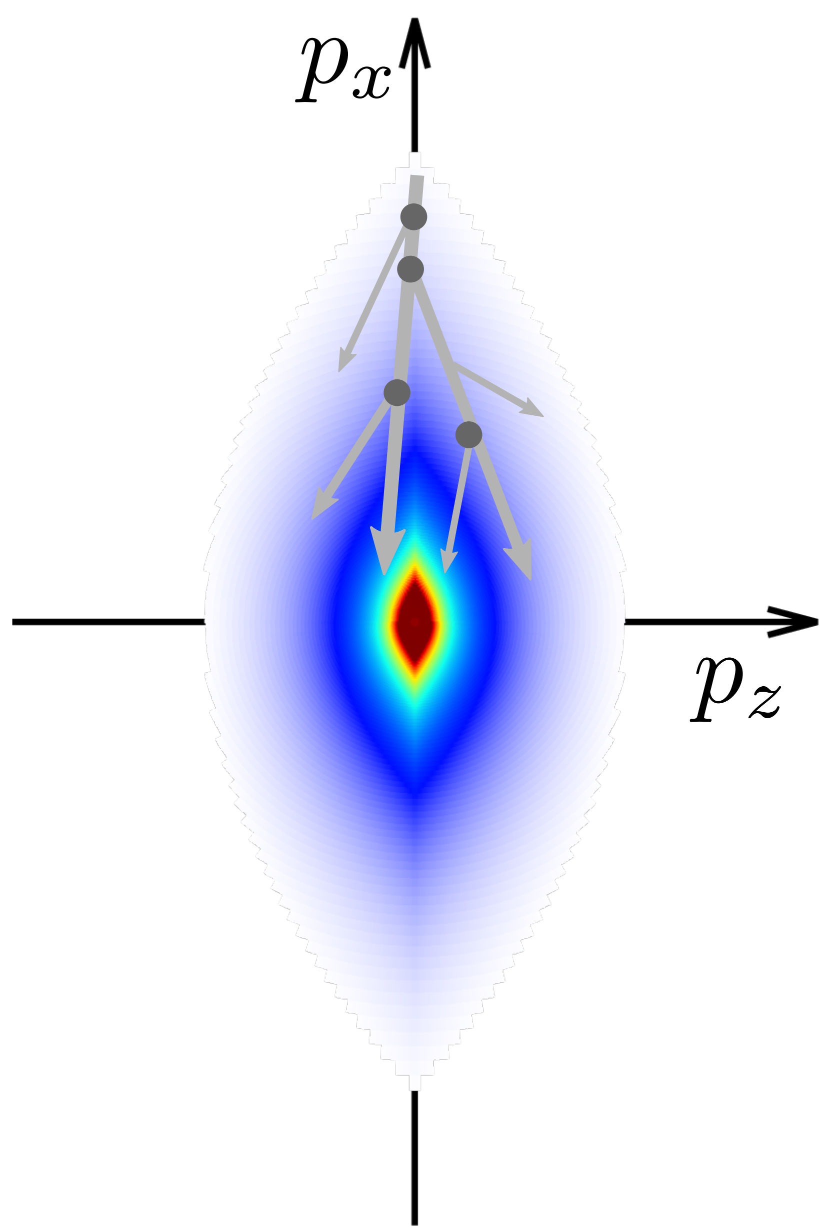
$$n_s \sim \frac{\alpha_s^{1/4} Q_S^3}{(Q_S\,\tau)^{1/2}}$$

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

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

Dominated by soft gluons

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

Soft sector thermalizes

→ Acts like a bath

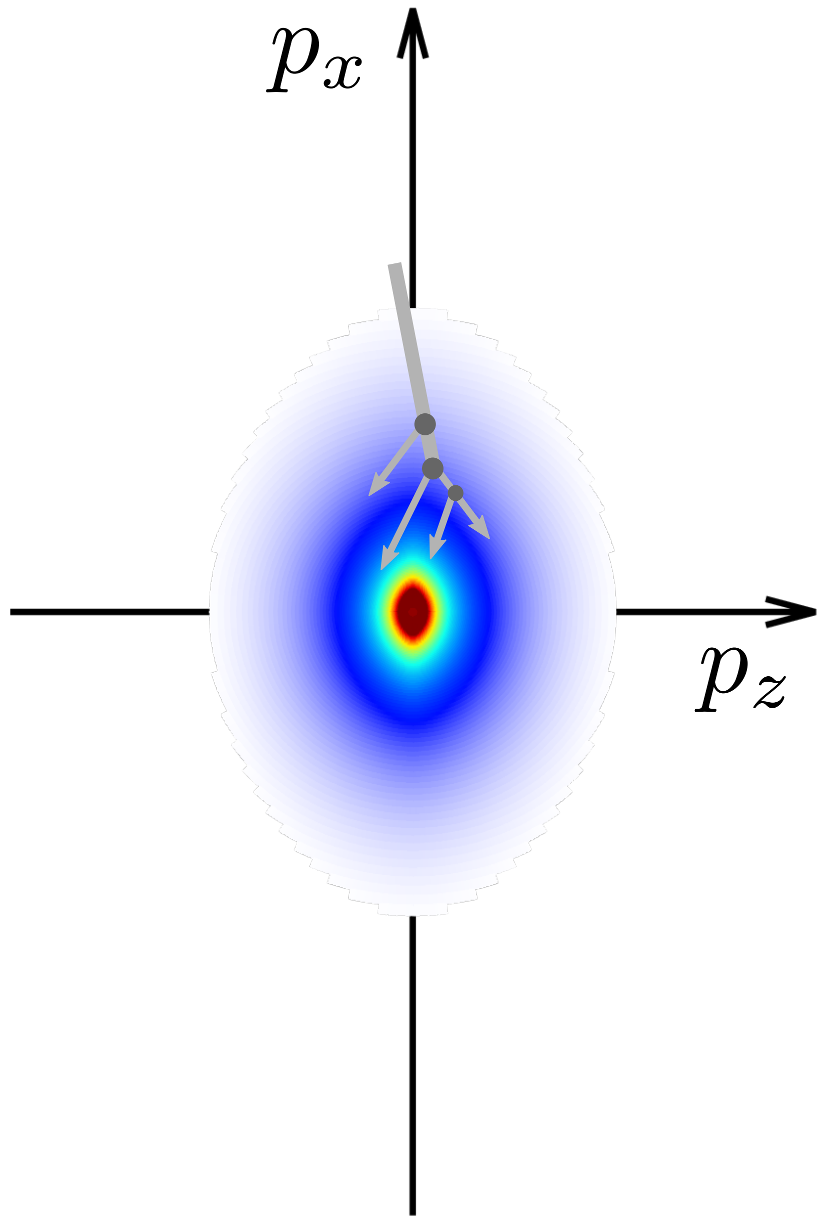
Hard sector looses energy to soft bath

→ Temperature rises as

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

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

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



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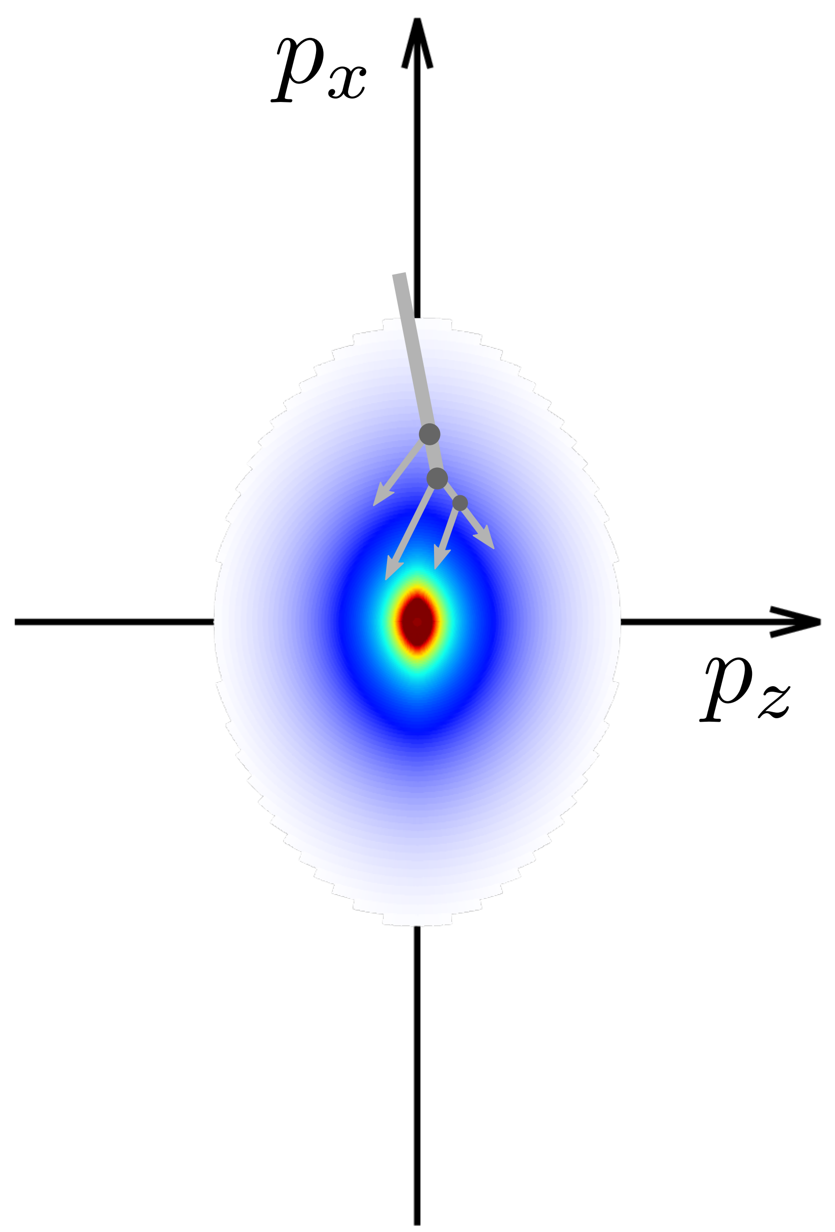
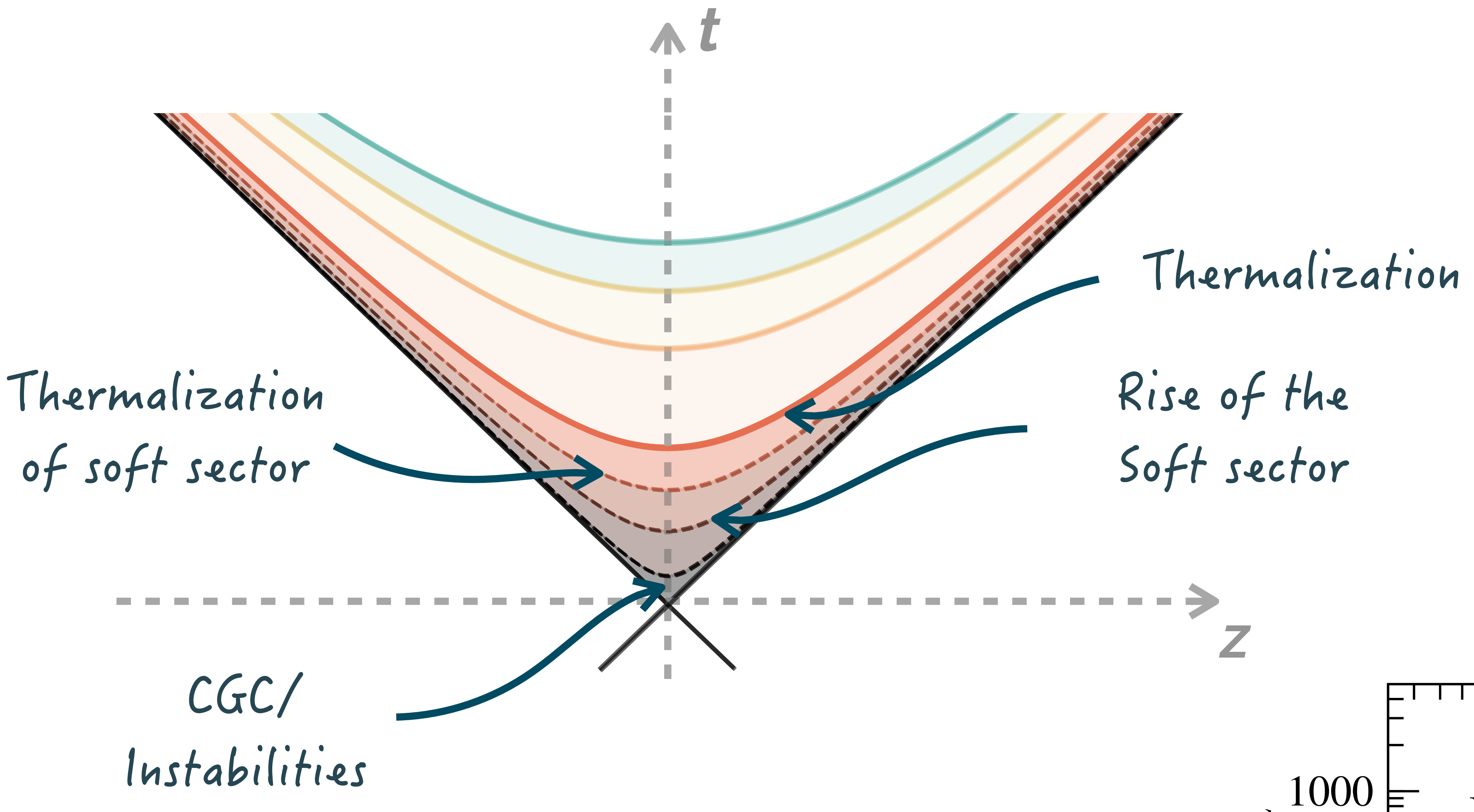


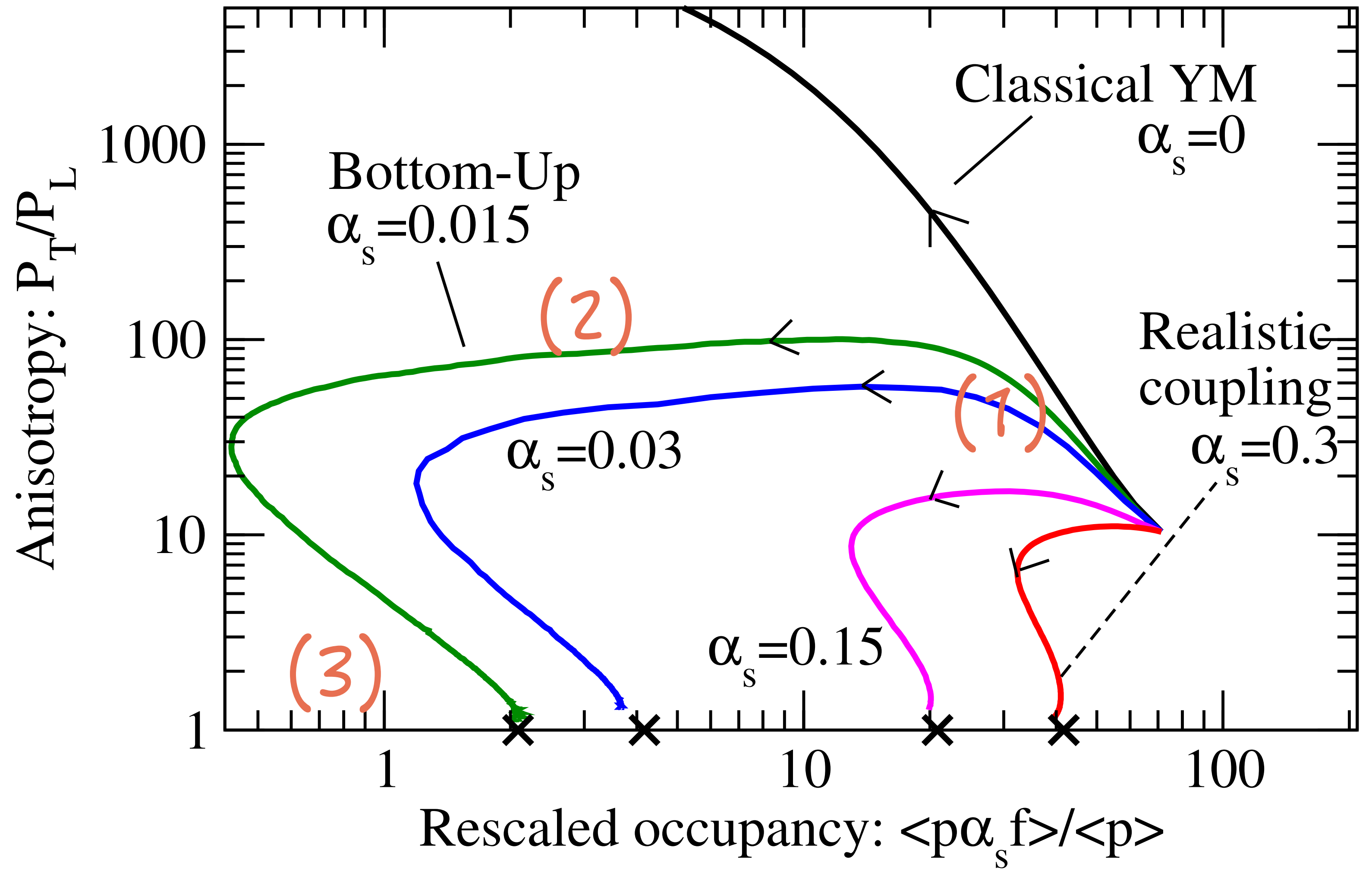
From Kurkela et al.
Phys.Rev. C99 (2019) no.3, 034910

The Standard Model of Heavy Ion Collisions

(revisited)

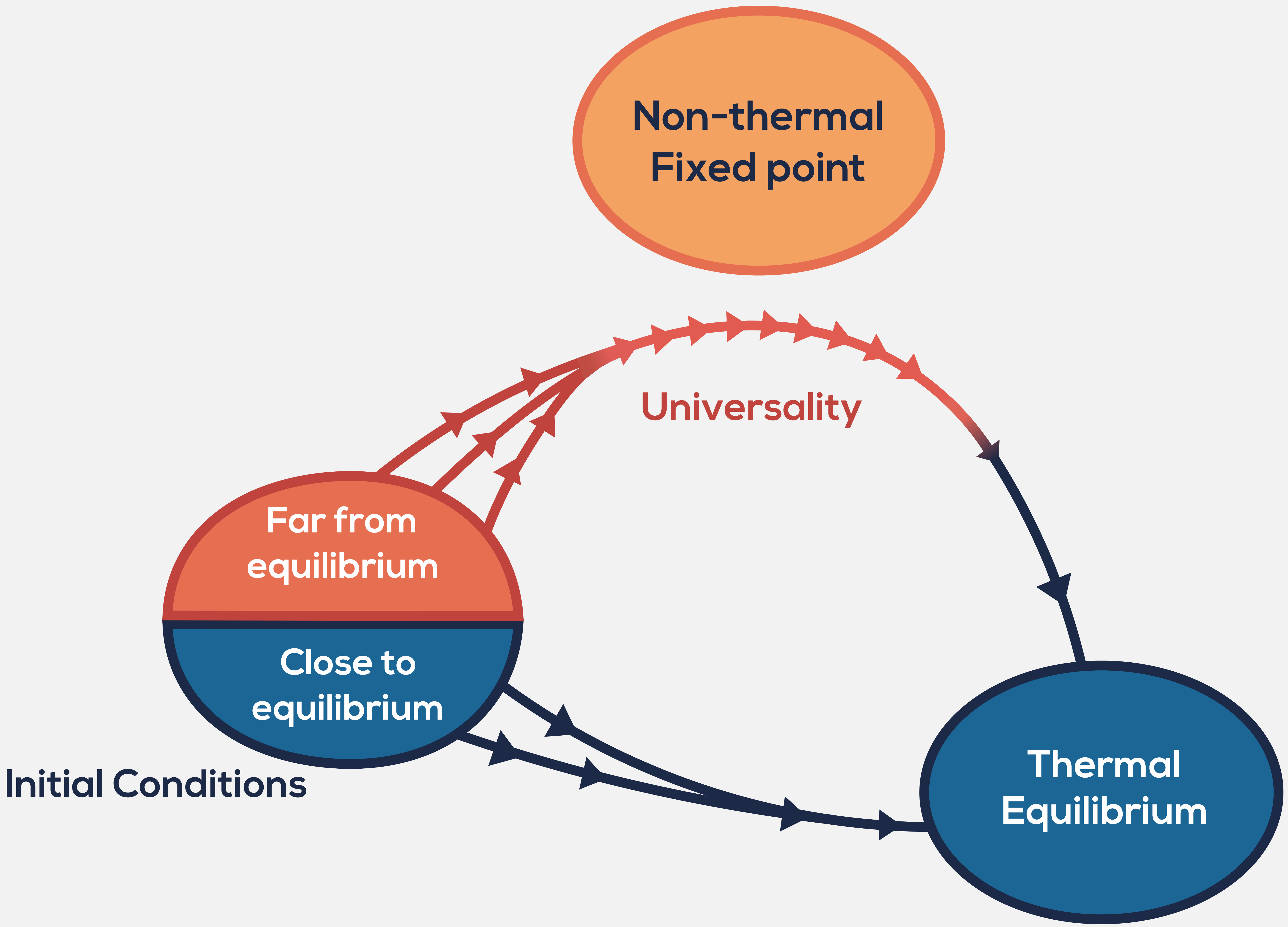


From Kurkela and Zhu
Phys.Rev.Lett. 115 (2015) no.18, 182301



Turbulent thermalization

Of **highly occupied non-abelian** plasmas very far from equilibrium


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

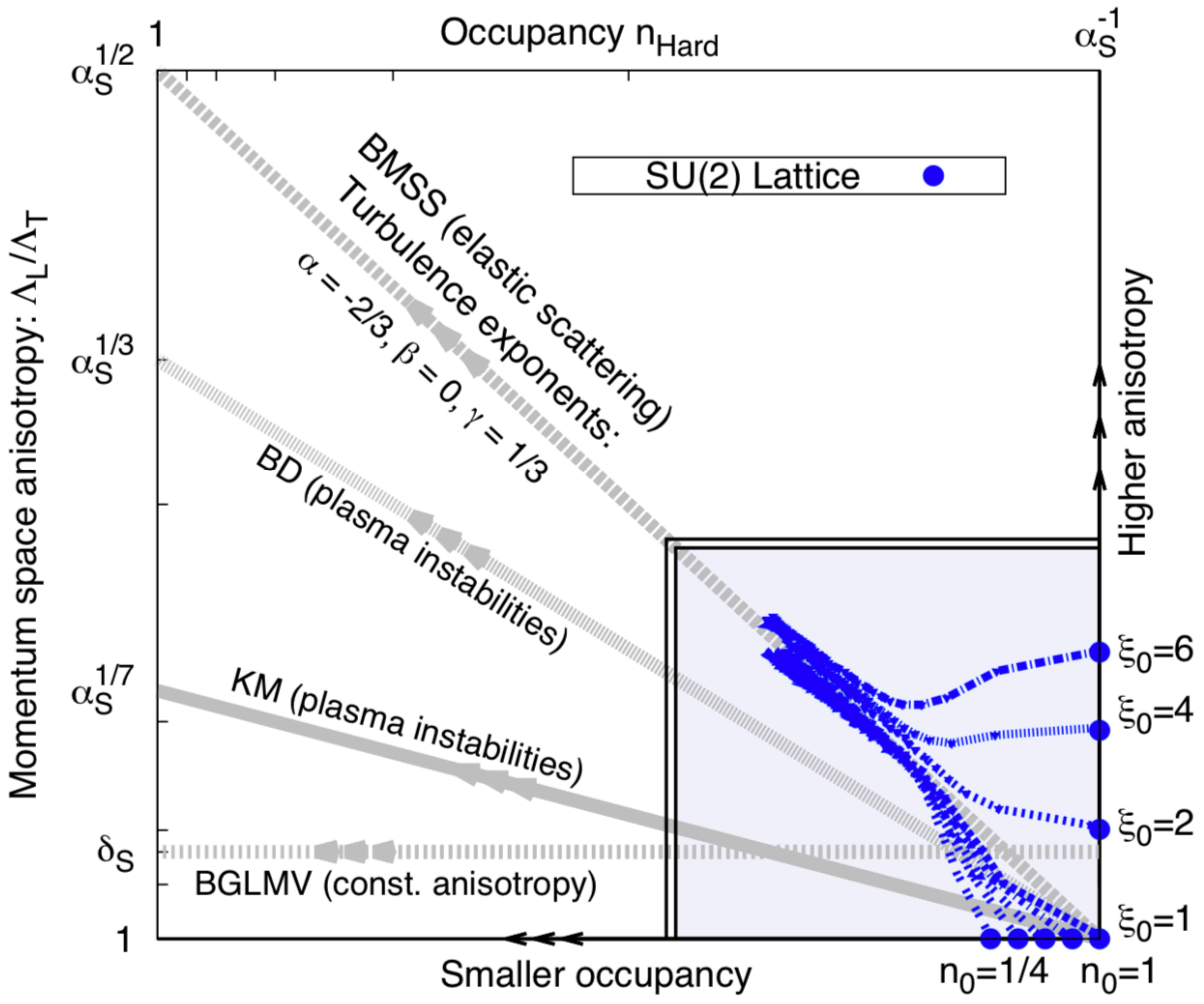
def. distribution function depends on a Universal, time-independent function

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

Transport and Turbulence

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

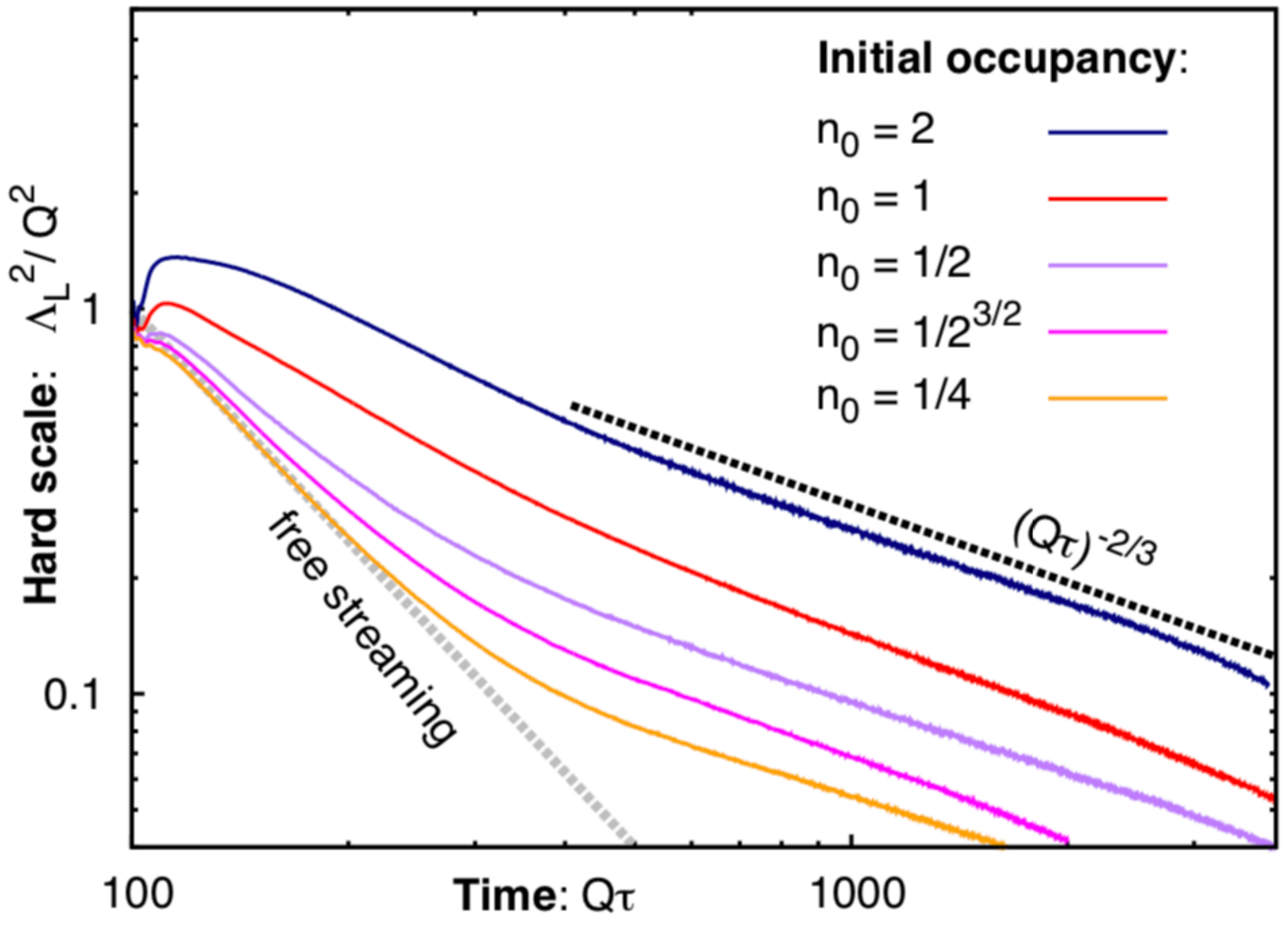
Finding the right scenario



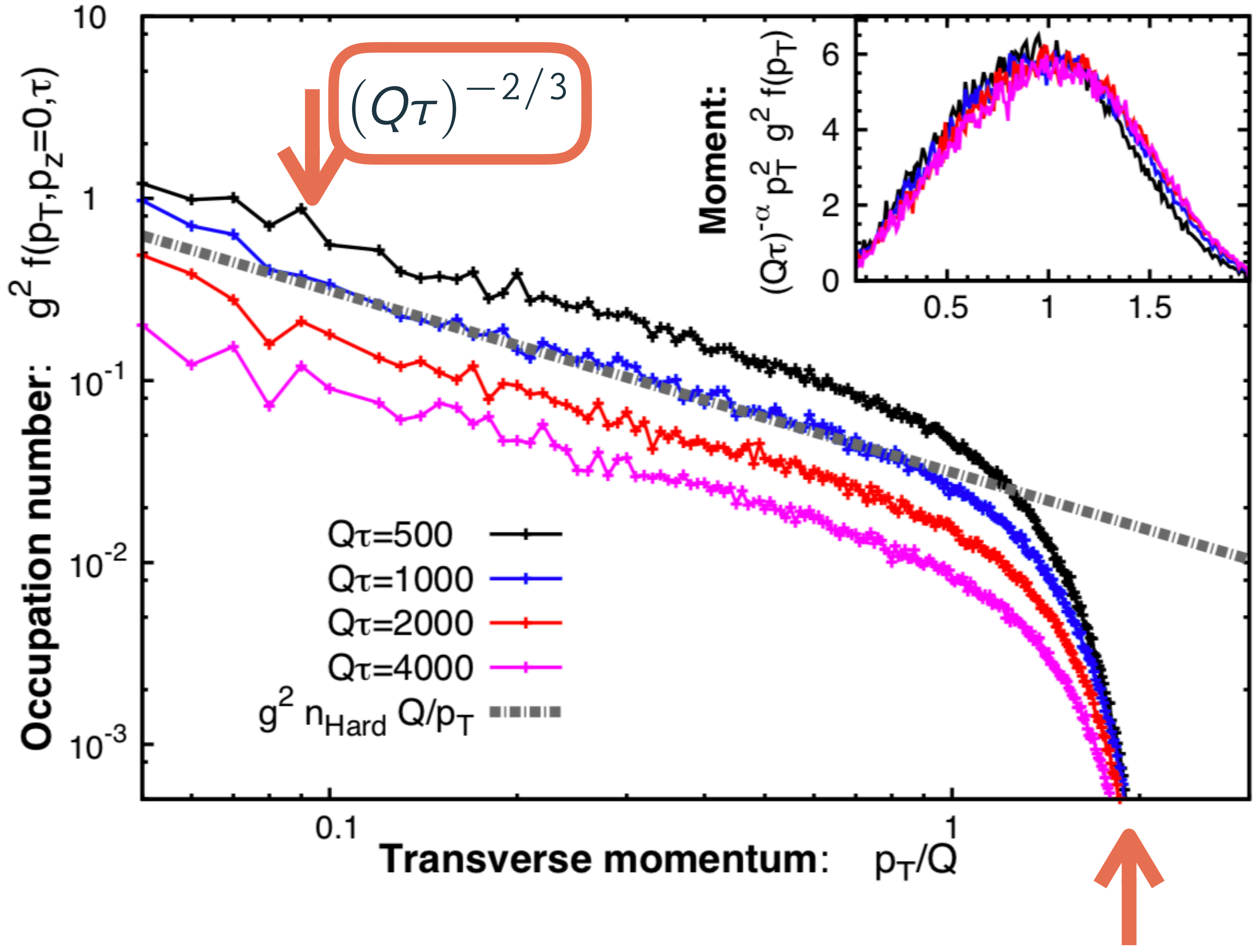
Phys.Rev. D89 (2014) no.11, 114007

Gluon occupation: High

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



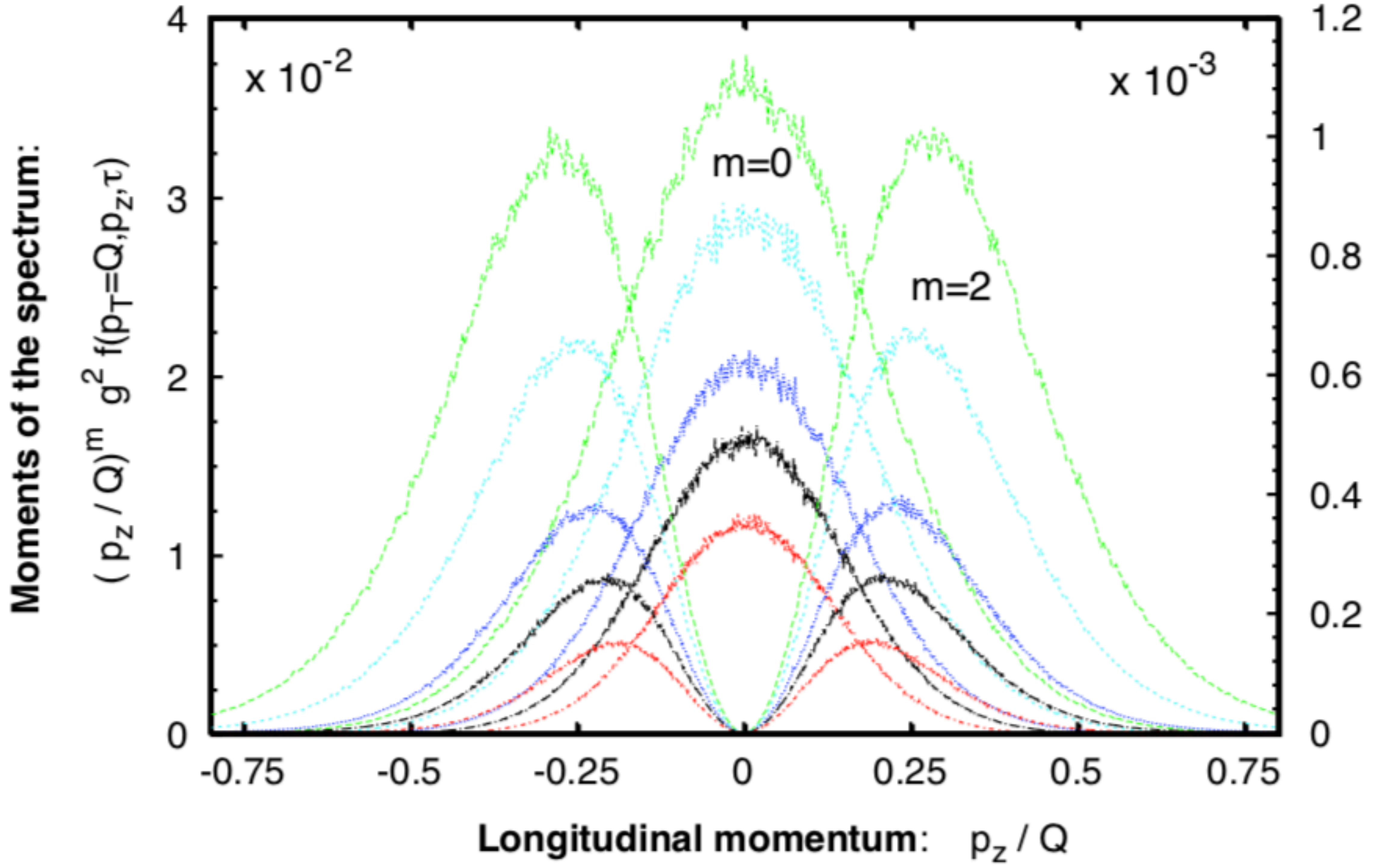
Transverse $p_\perp$



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

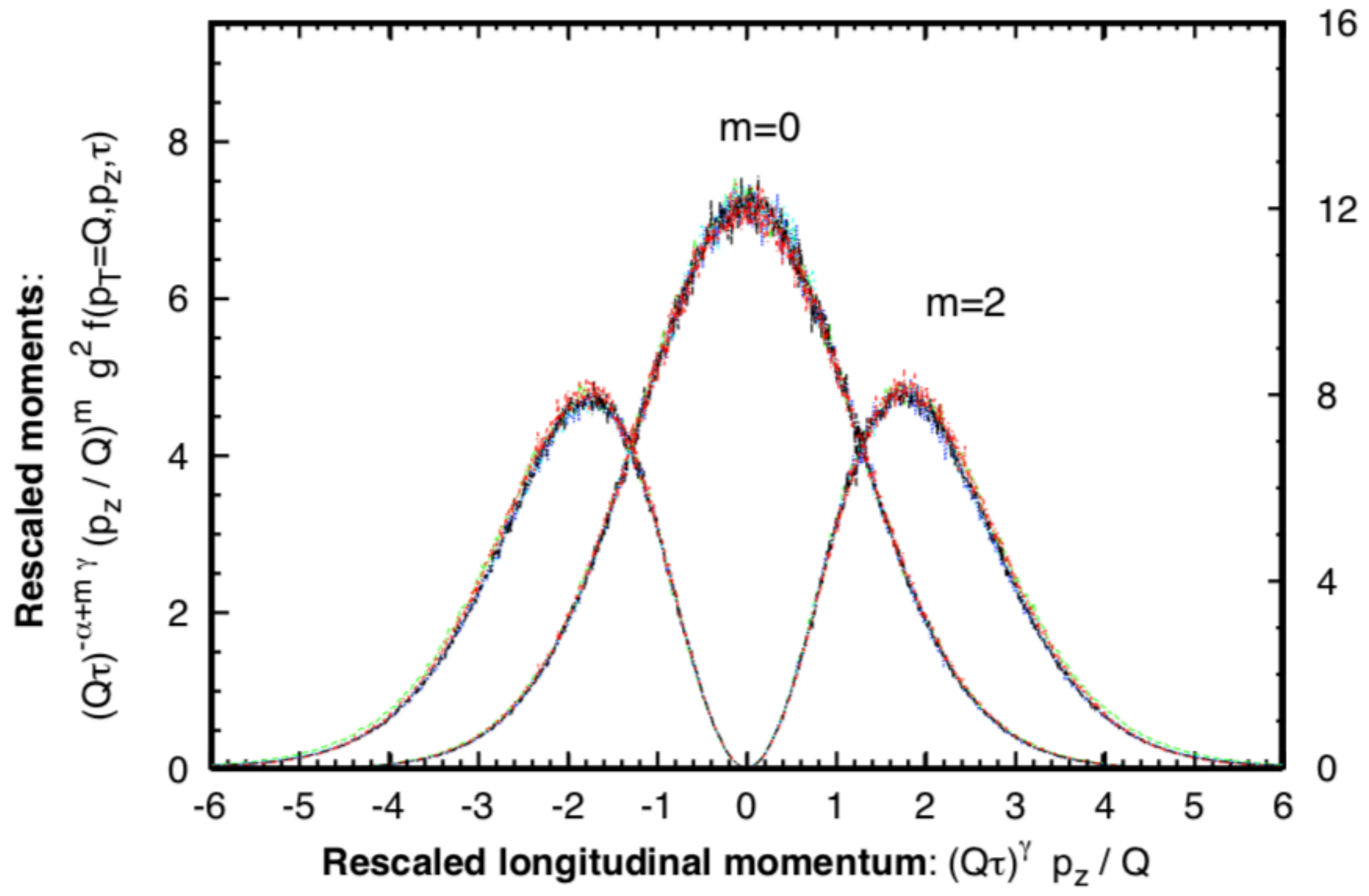
Phys.Rev. D89 (2014) no.11, 114007

Occupancy: p_z



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

Occupancy: p_z



$$\gamma = 1/3$$

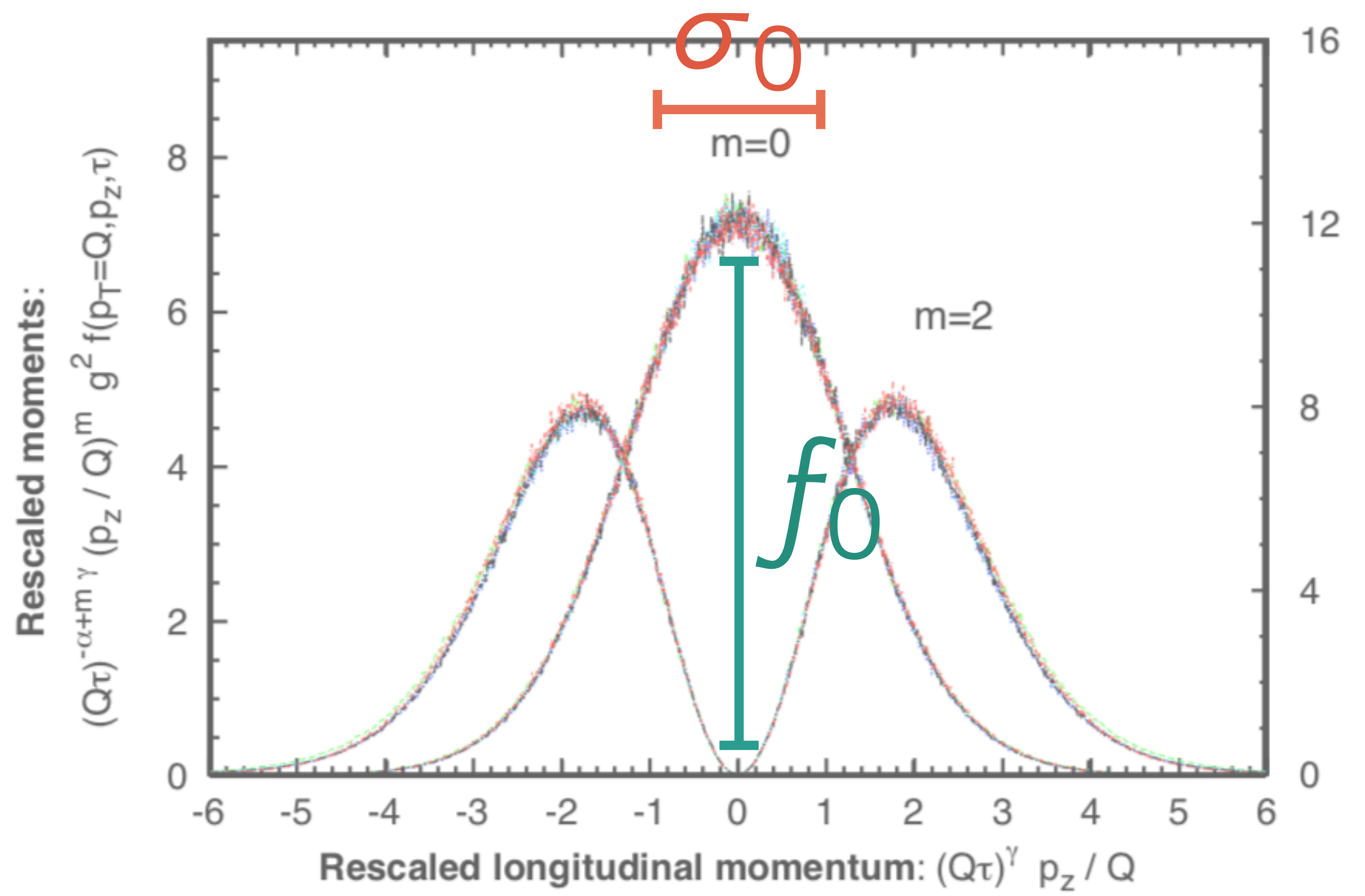
Phys.Rev. D89 (2014) no.11, 114007

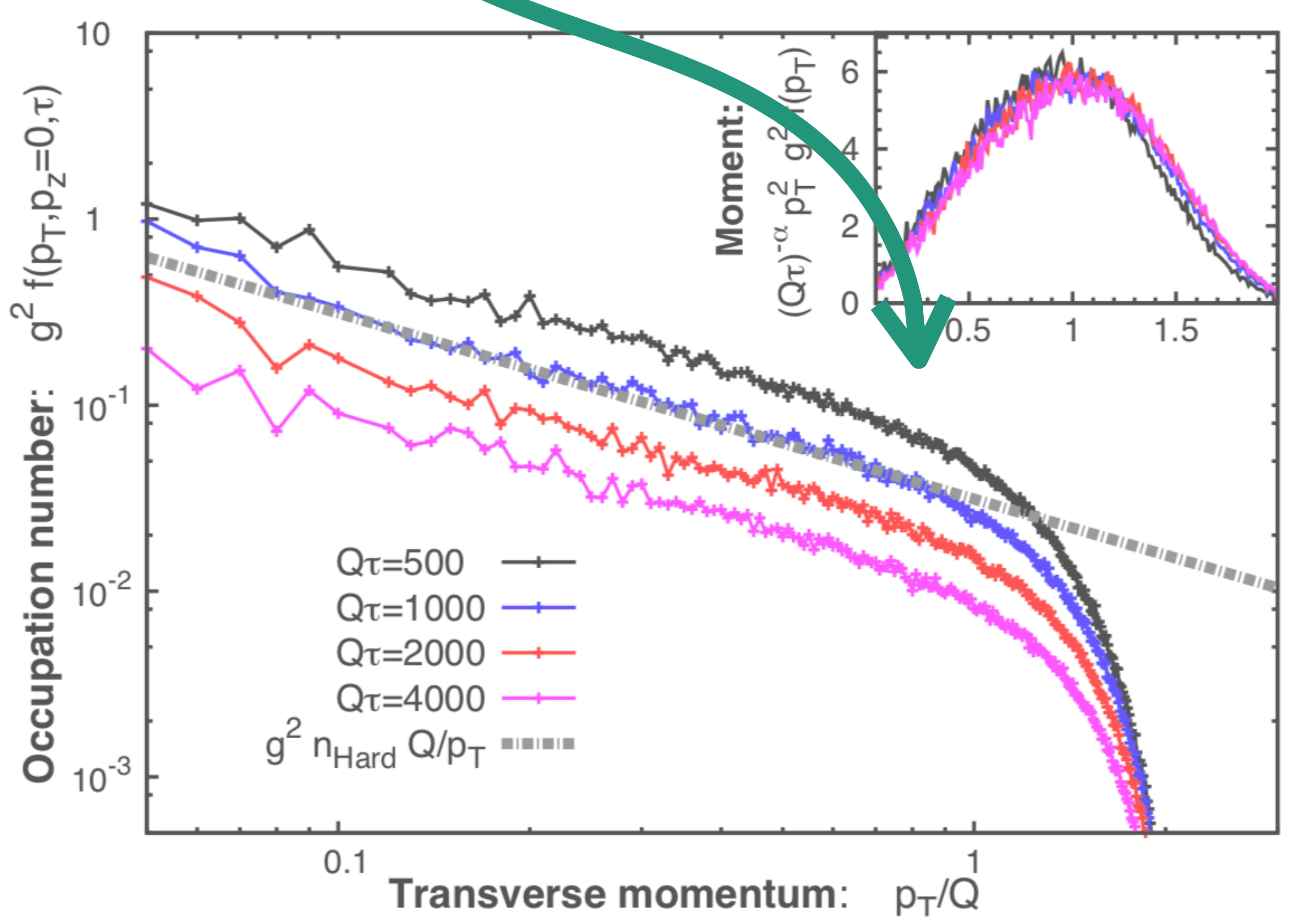
Fit the lattice results

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

with $$f_S\left(p_\perp,\ p_z\right) = f_0 \frac{Q_s}{p_\perp}\, e^{-\frac{1}{2}\left(\frac{p_z}{\sigma_0}\right)^2} W_r(p_\perp - Q_s, r)$$

and $$W_r(p_\perp - Q_s, r) = \theta(Q_s - p_\perp) + \theta(p_\perp - Q_s) e^{-\frac{1}{2}\left(\frac{p_\perp - Q_s}{r\,Q_s}\right)^2}$$





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and $$W_r(p_\perp - Q_s, r) = \theta(Q_s - p_\perp) + \theta(p_\perp - Q_s)\, e^{-\frac{1}{2}\left(\frac{p_\perp - Q_s}{r\,Q_s}\right)^2}$$

Extension

Quark Distribution

Hard dipole approximation → $$f_q\left(\tau, p_\perp, p_z\right) = \alpha_s f_g\left(\tau, p_\perp, p_z\right)$$

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

Phenomenological Matching

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

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%

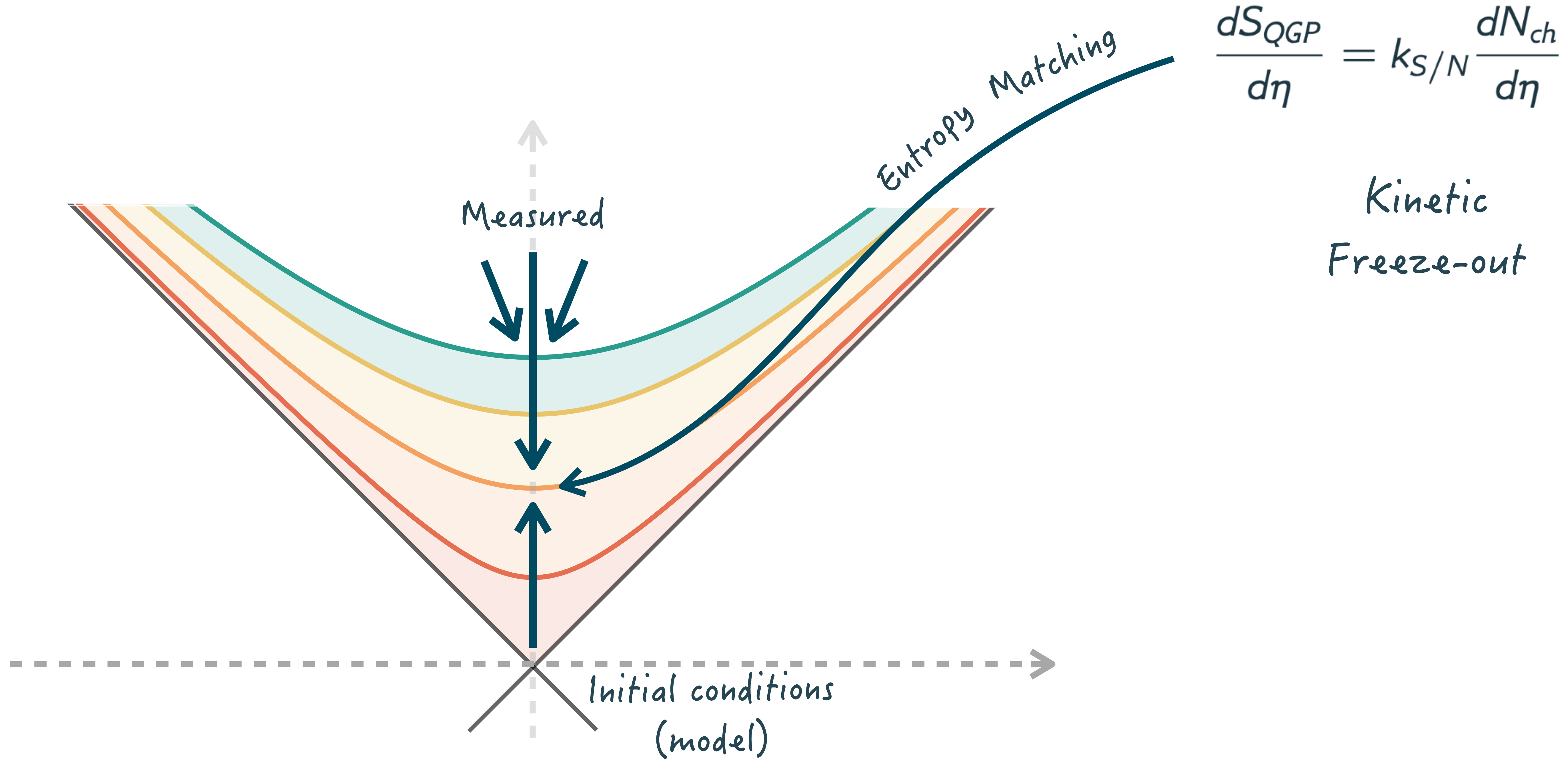
$\langle Q_s^2 \rangle = 2.97\,\mathrm{GeV}^2$ → ALICE, 2.76TeV, 0-20%

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 is transported via

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



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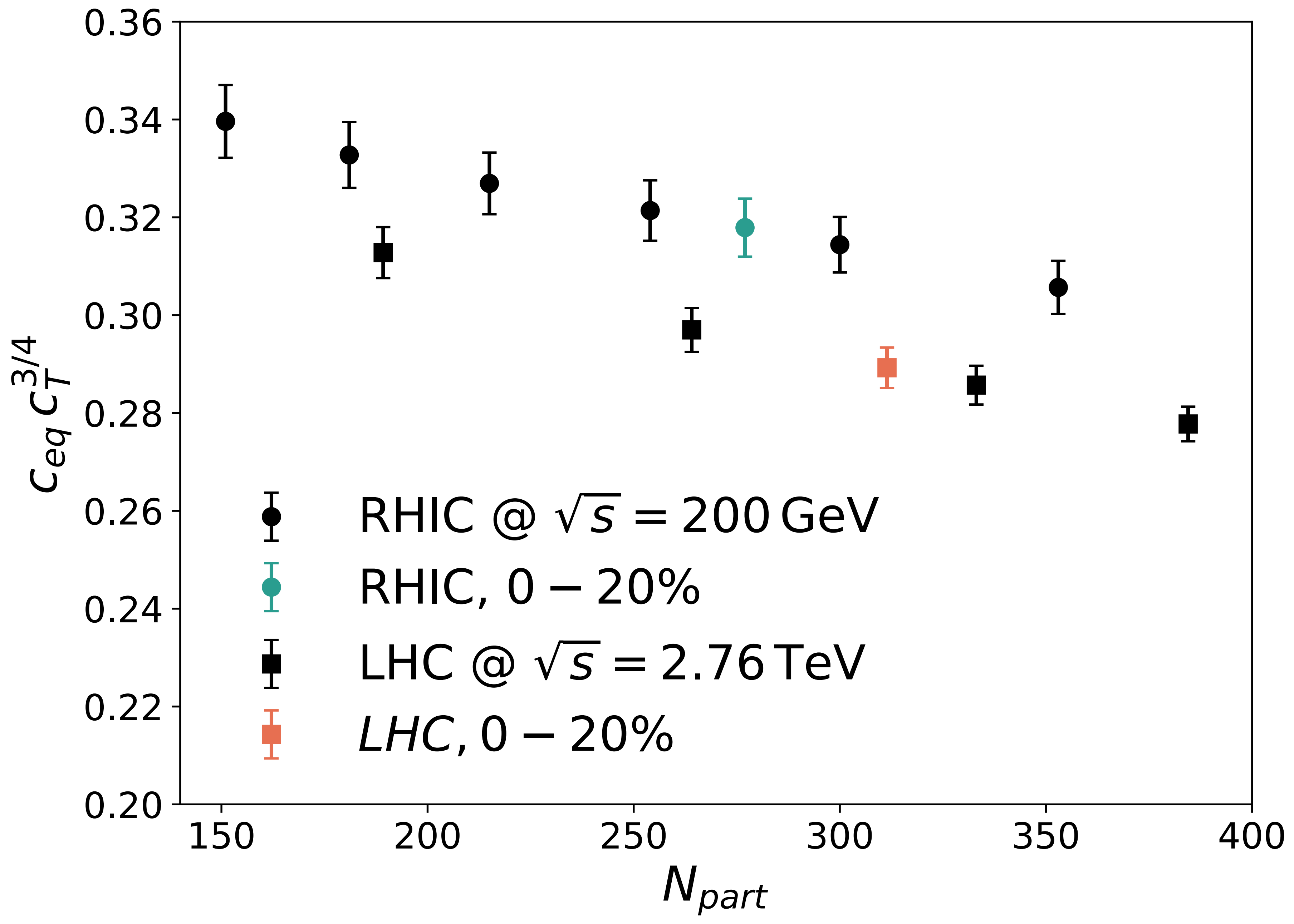


Entropy is transported via

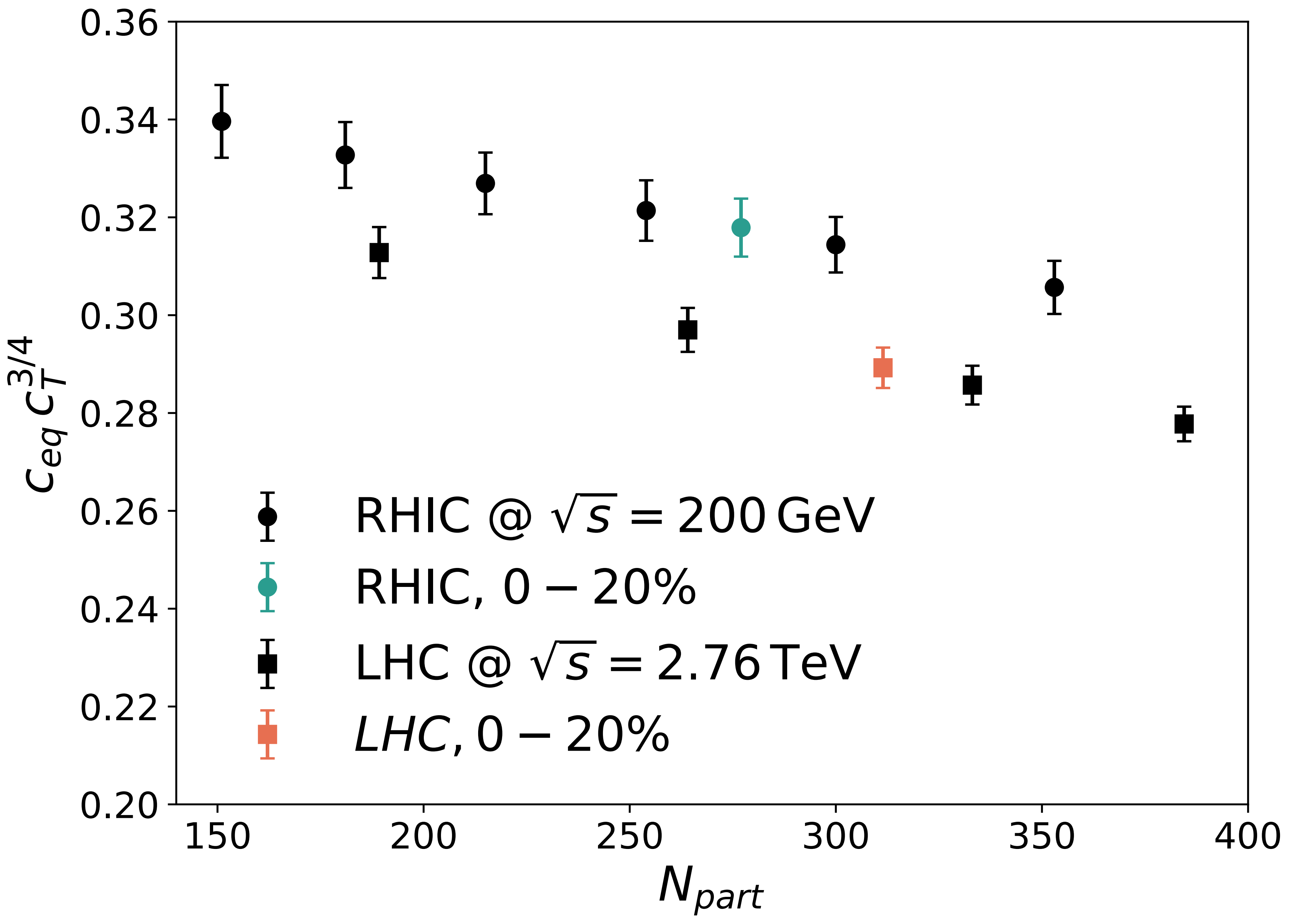
$$\frac{dS_{QGP}}{d\eta} = k_{S/N} \frac{dN_{ch}}{d\eta}$$

C_T known to logarithmic precision

$$C_T = 0.18$$

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 is transported via

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

τ_c is independent of match

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

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