Non-equilibrium photons from thermalizing matter

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Based on: Garcia-Montero. *In preparation*
Berges et al. Phys.Rev. C95 (2017) no.5, 054904

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Contents

Global Goal

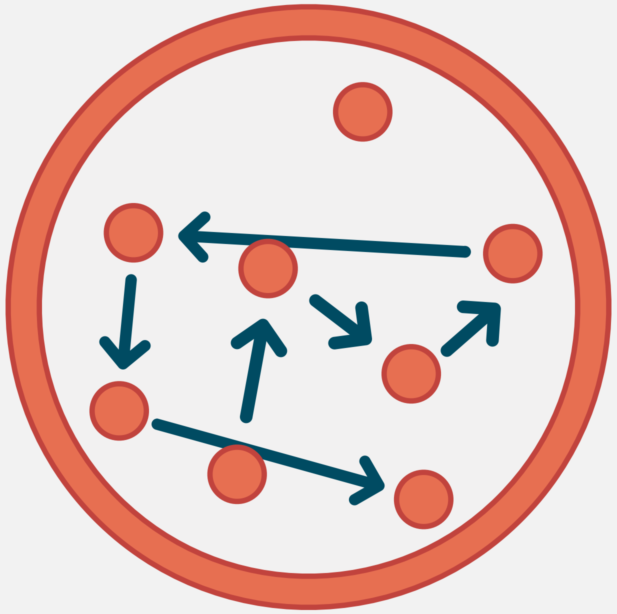
Understand (nuclear) matter under extreme conditions

Local Goal

Use photons as probes of thermalizing nuclear matter

Local Goal

Use photons as probes of
thermalizing nuclear matter



Why photons?

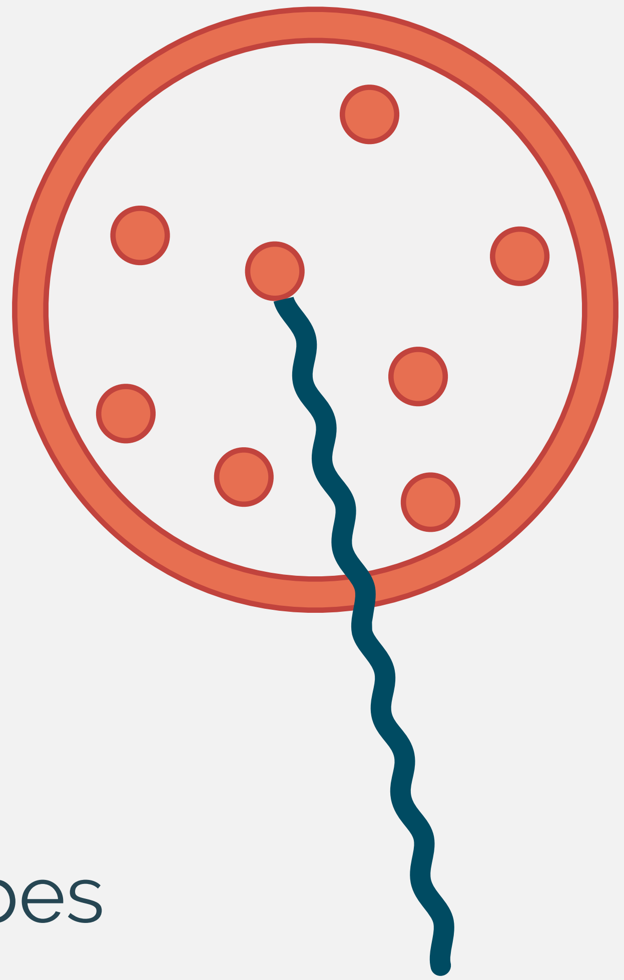
No strong interactions

Local Goal

Use photons as probes of thermalizing nuclear matter

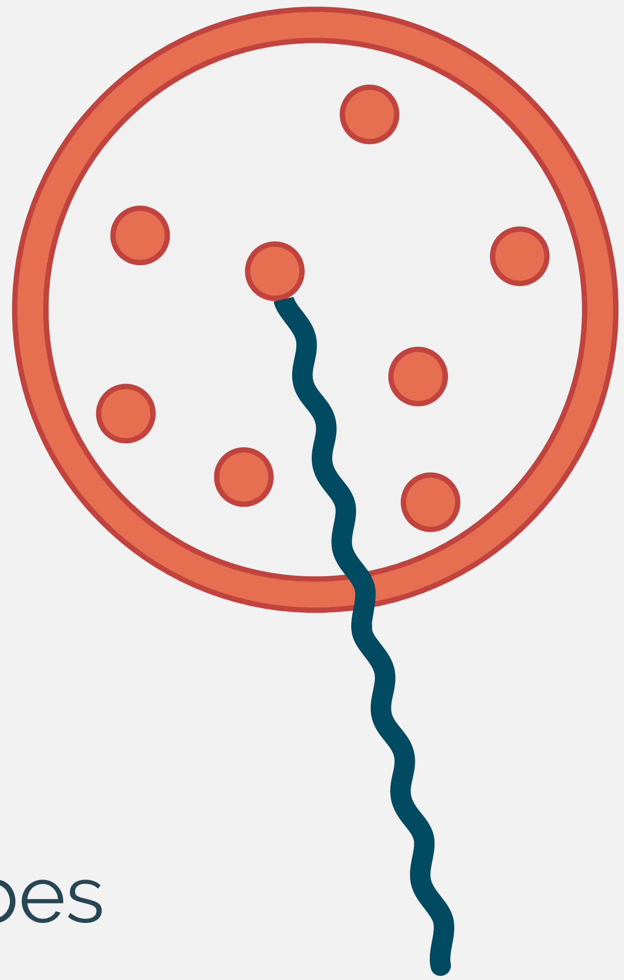
Why photons?

No strong interactions → Clean probes



Local Goal

Use photons as probes of
thermalizing nuclear matter



Why photons?

No strong interactions → Clean probes

Which system?

Ultrarelativistic Nucleus-Nucleus (A+A) Collisions

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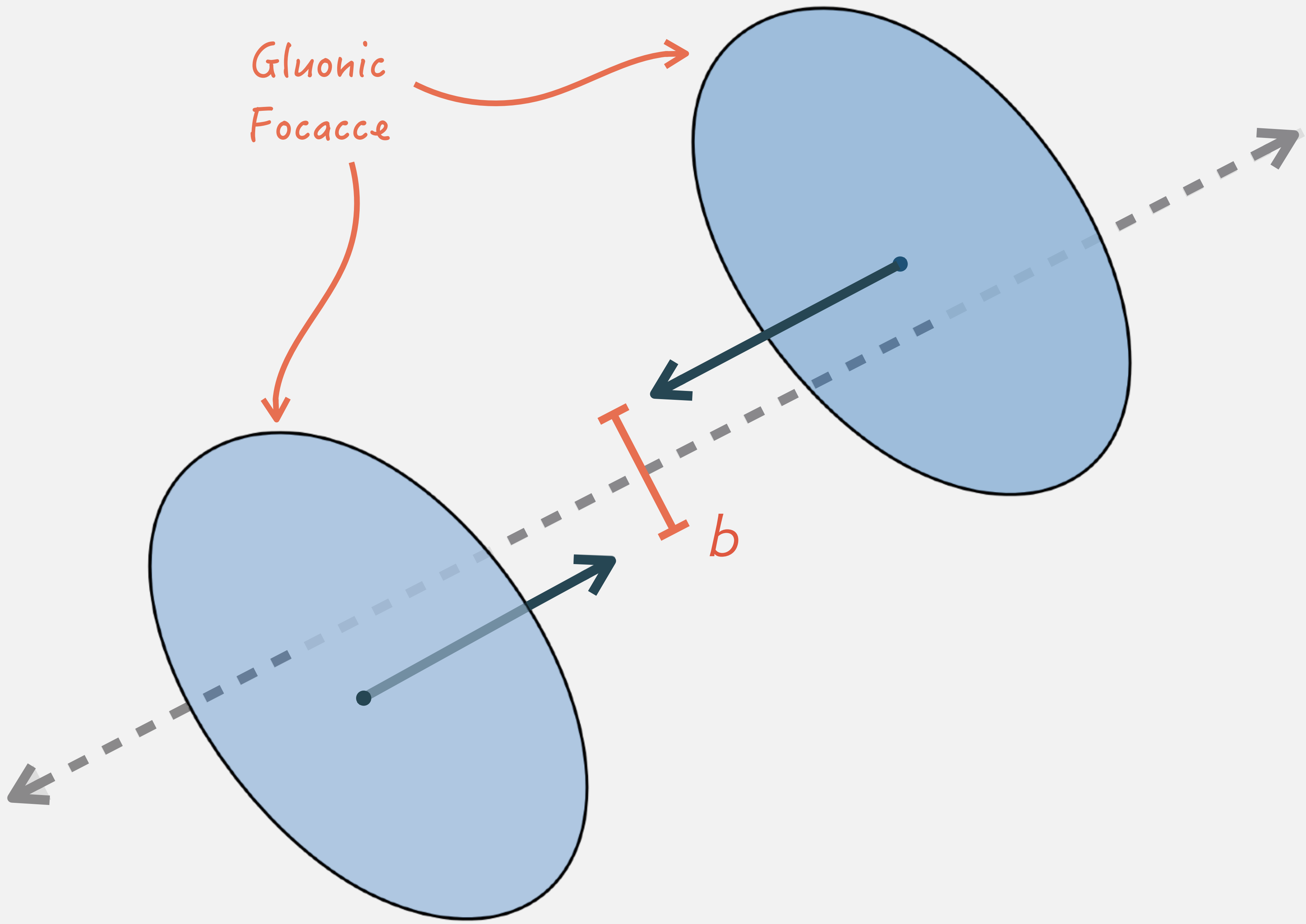
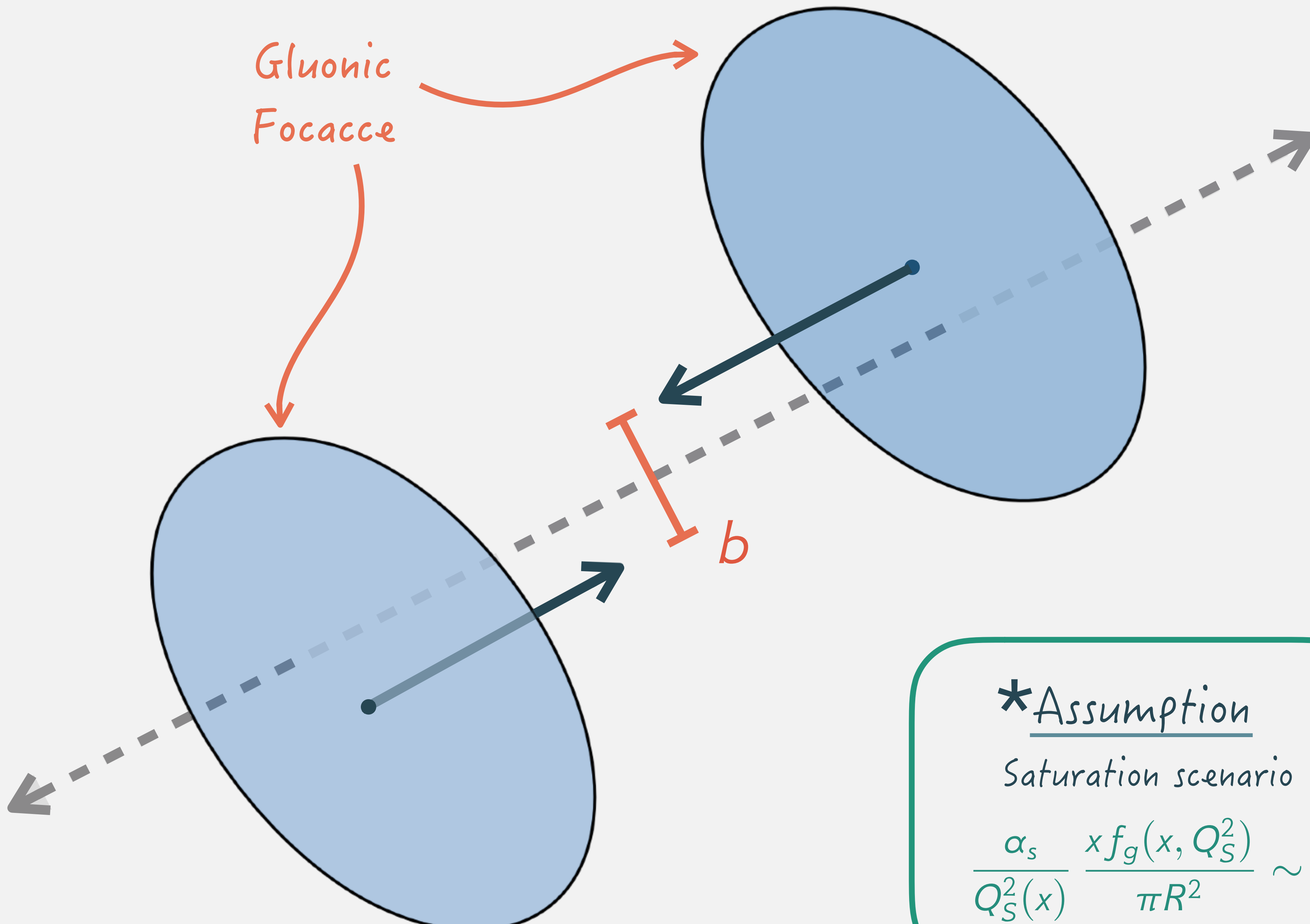


Ultrarelativistic Nucleus-Nucleus (A+A) Collisions

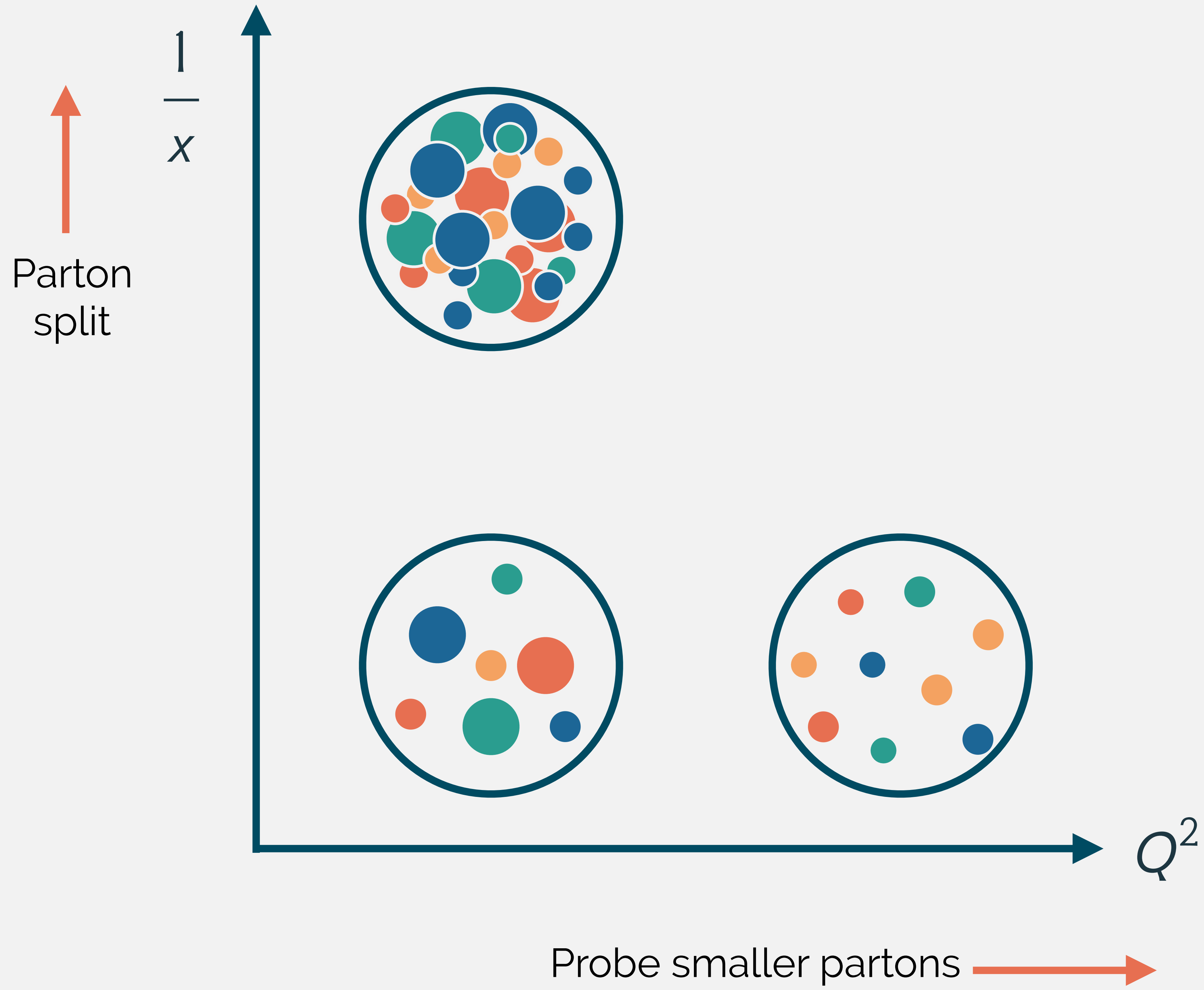


*Assumption

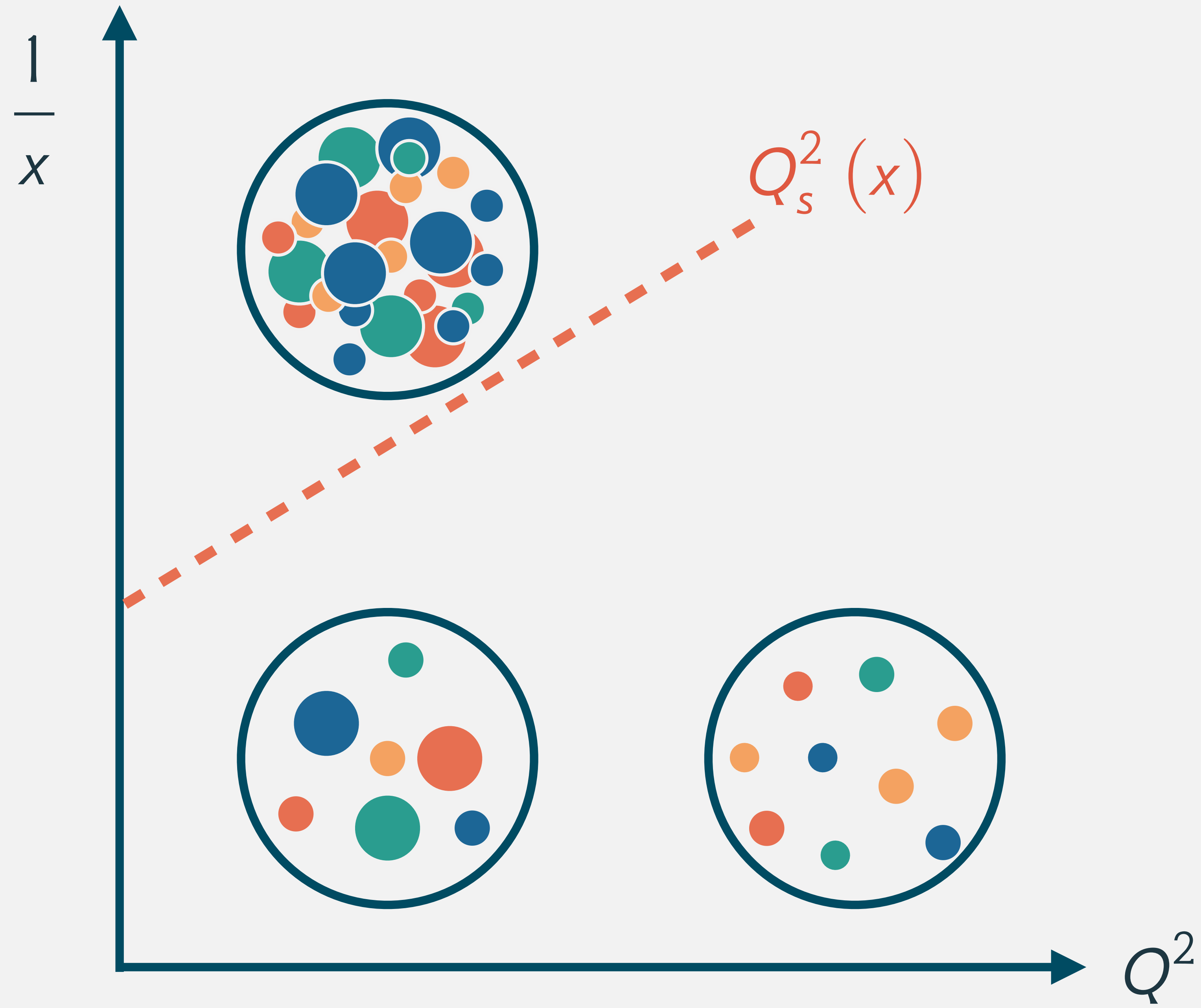
Saturation scenario

$$\frac{\alpha_s}{Q_S^2(x)} \frac{x f_g(x, Q_S^2)}{\pi R^2} \sim 1$$

Saturation



Saturation



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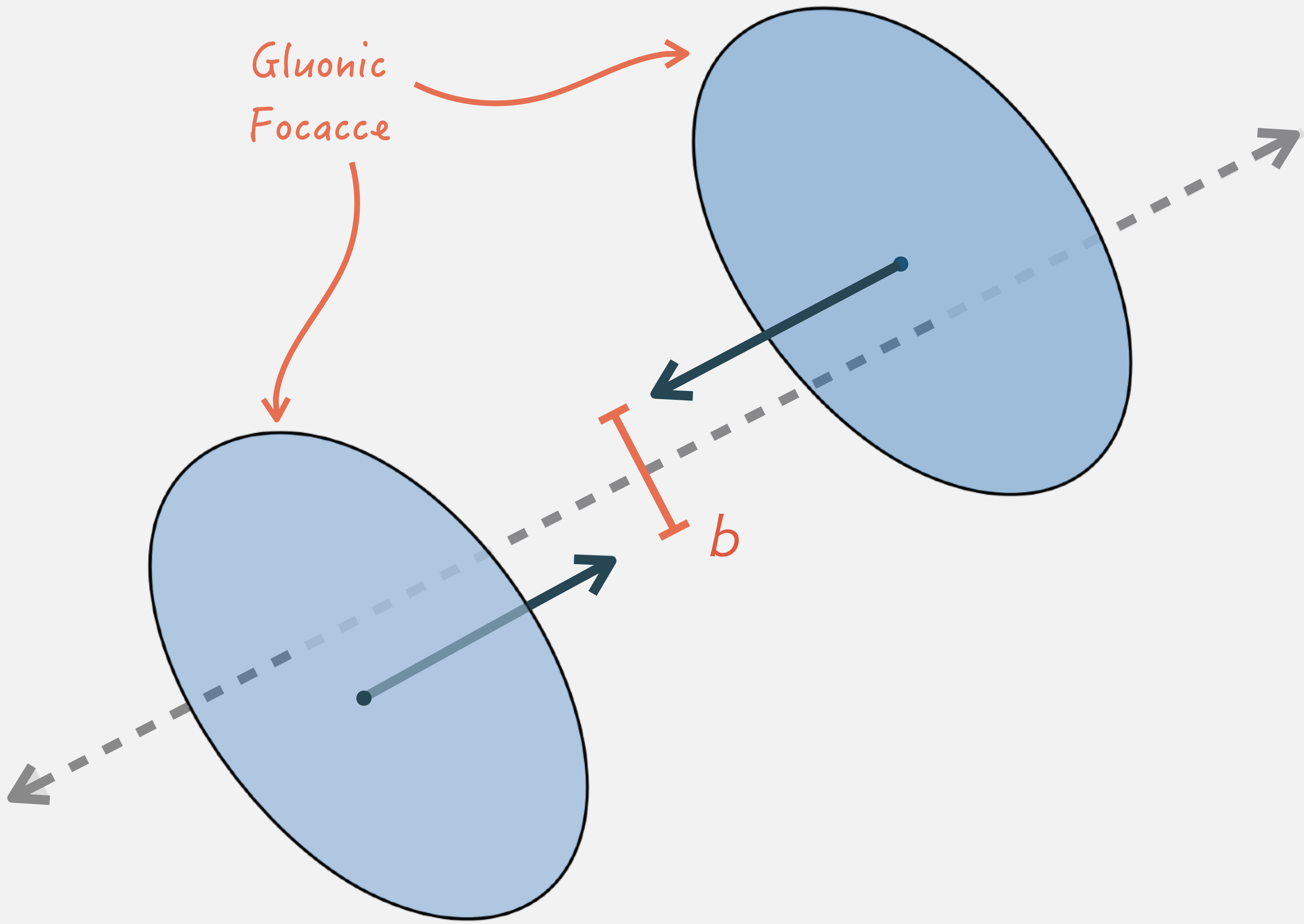

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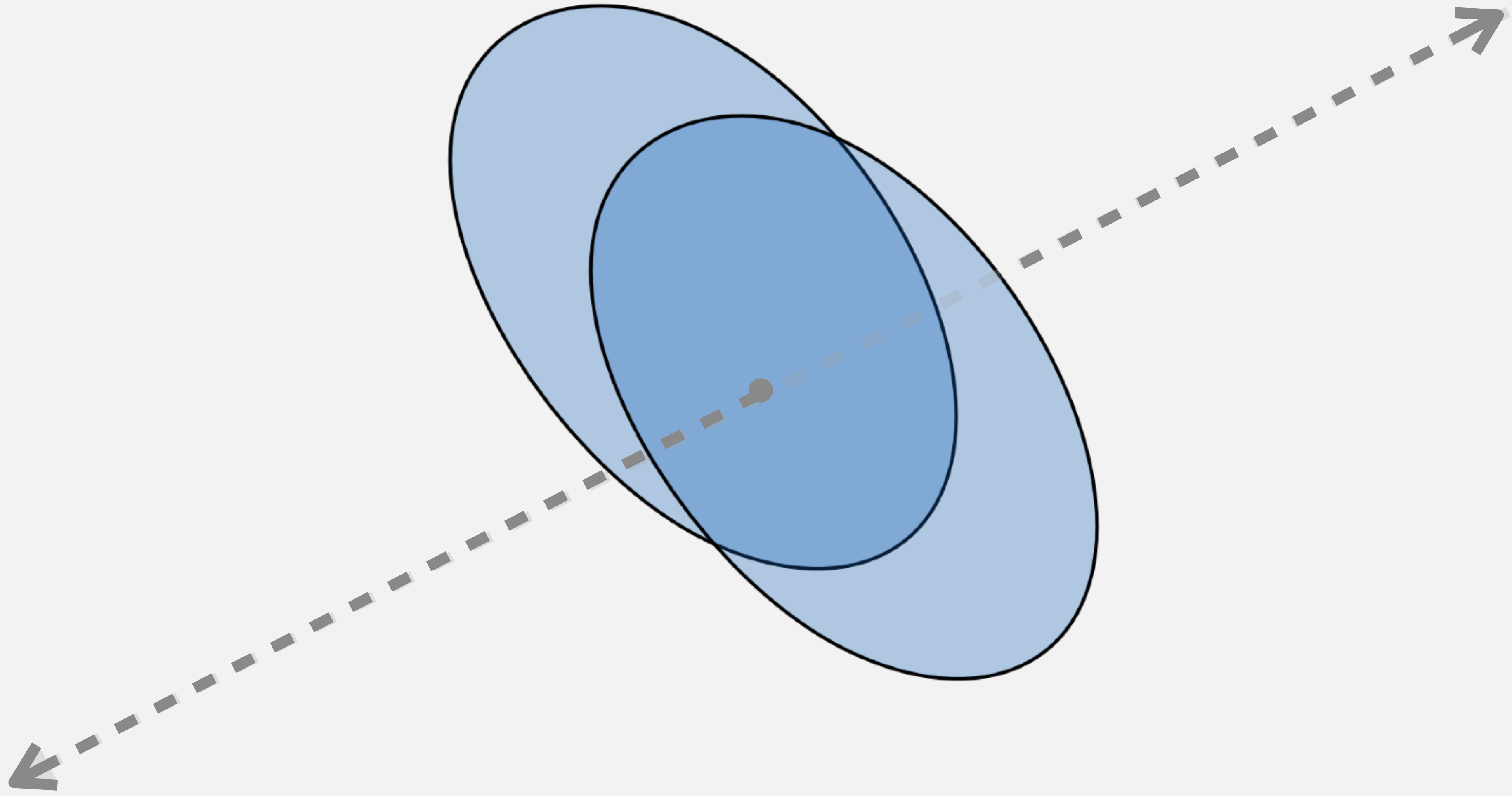

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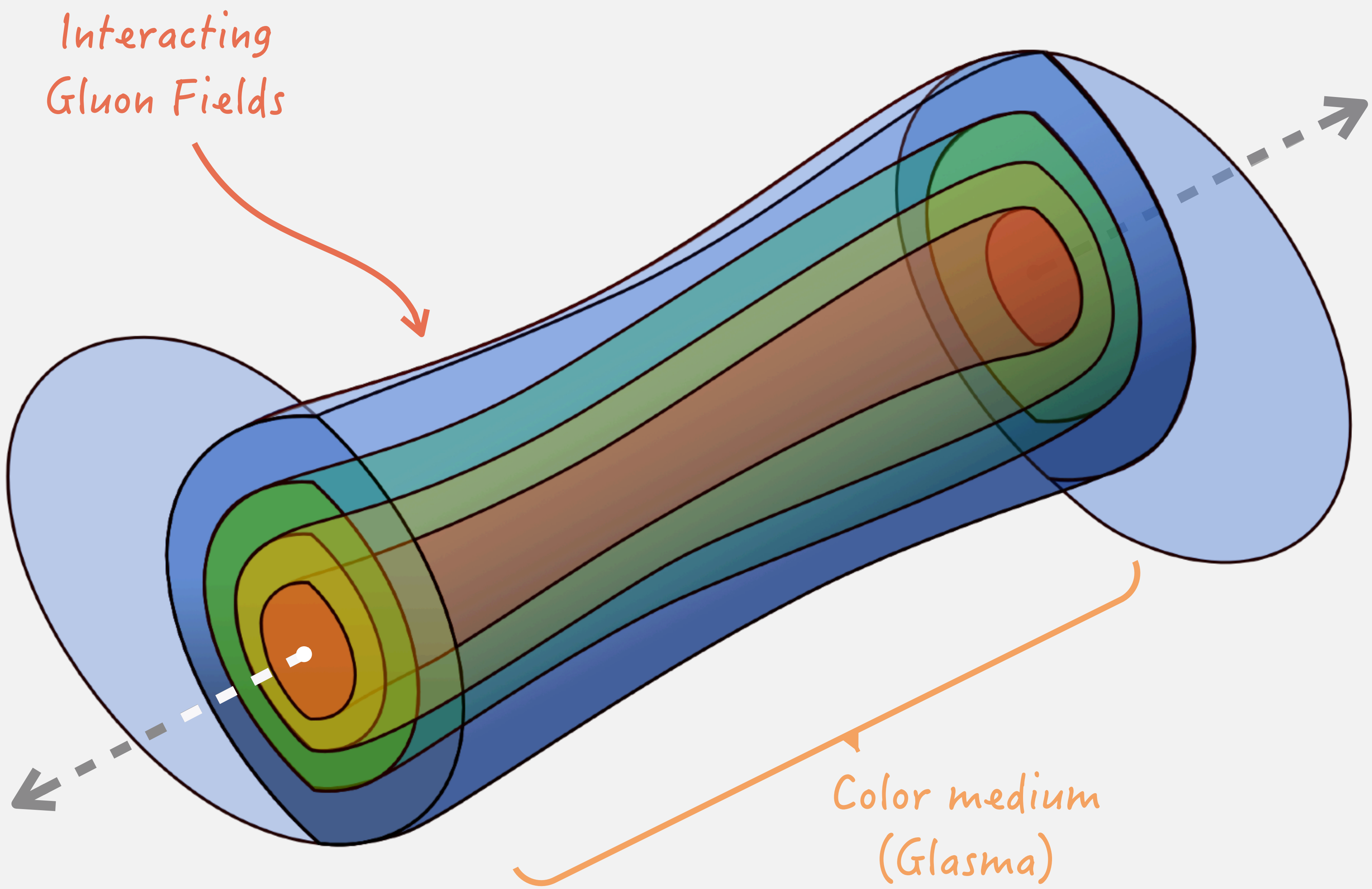
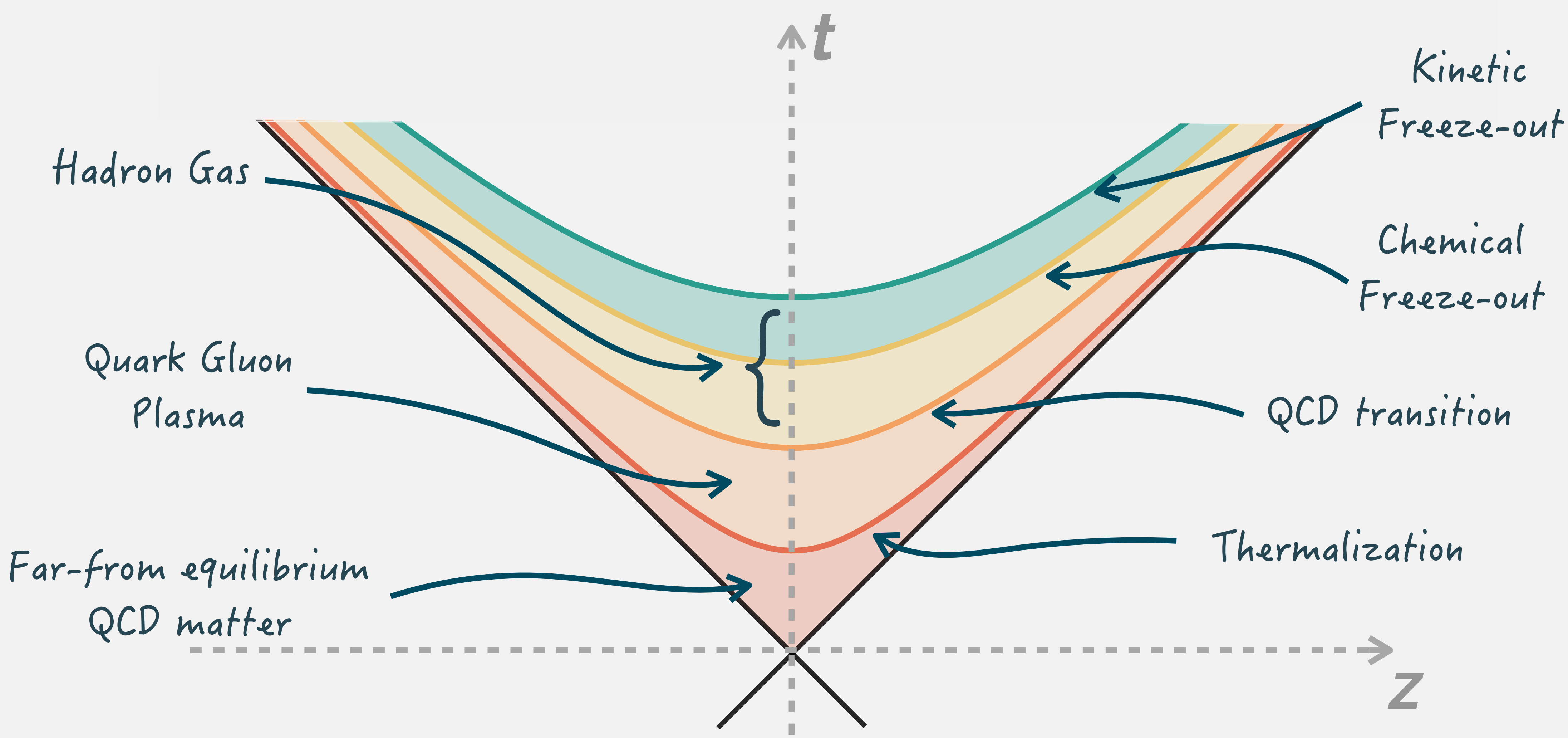


The Standard model of Heavy Ion Collions



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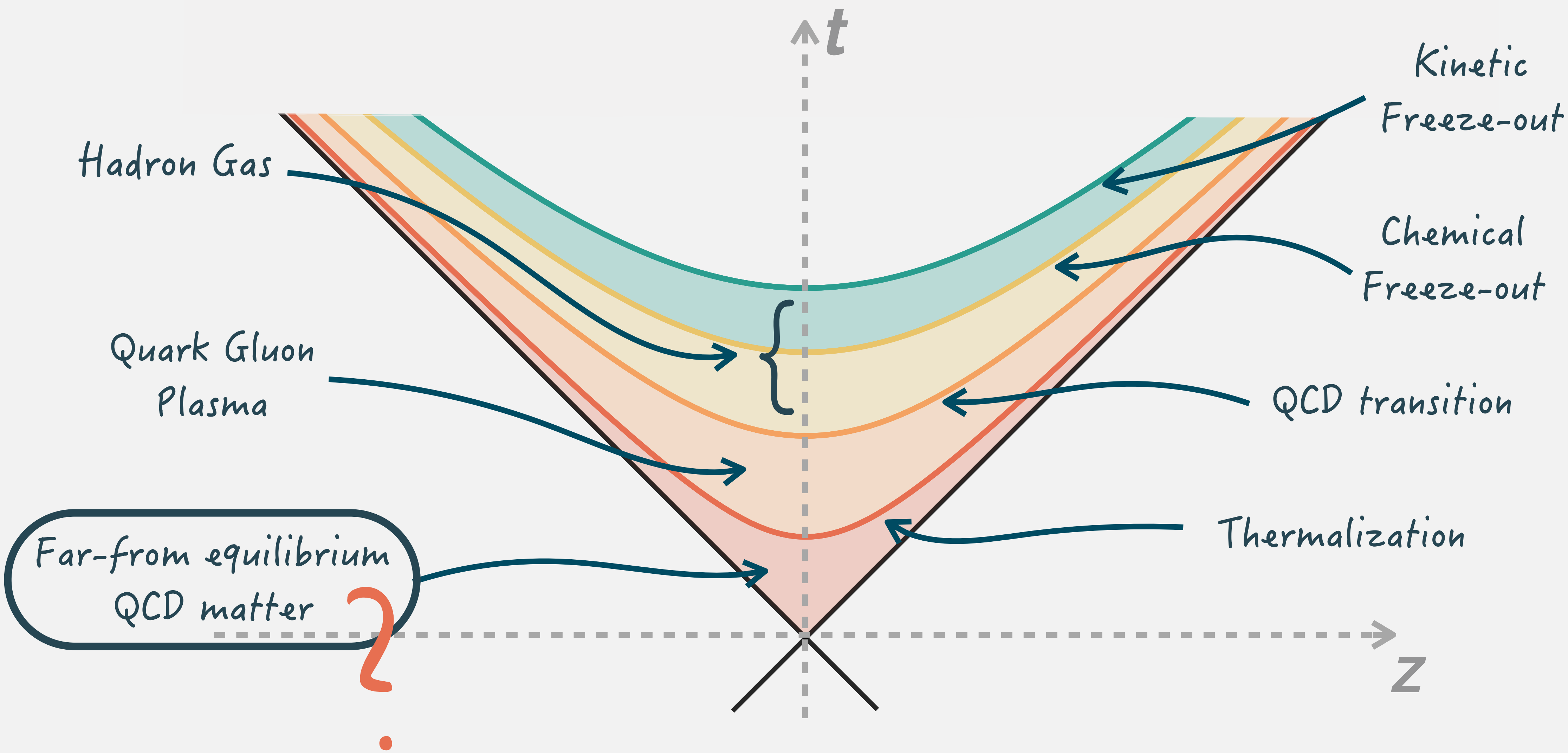
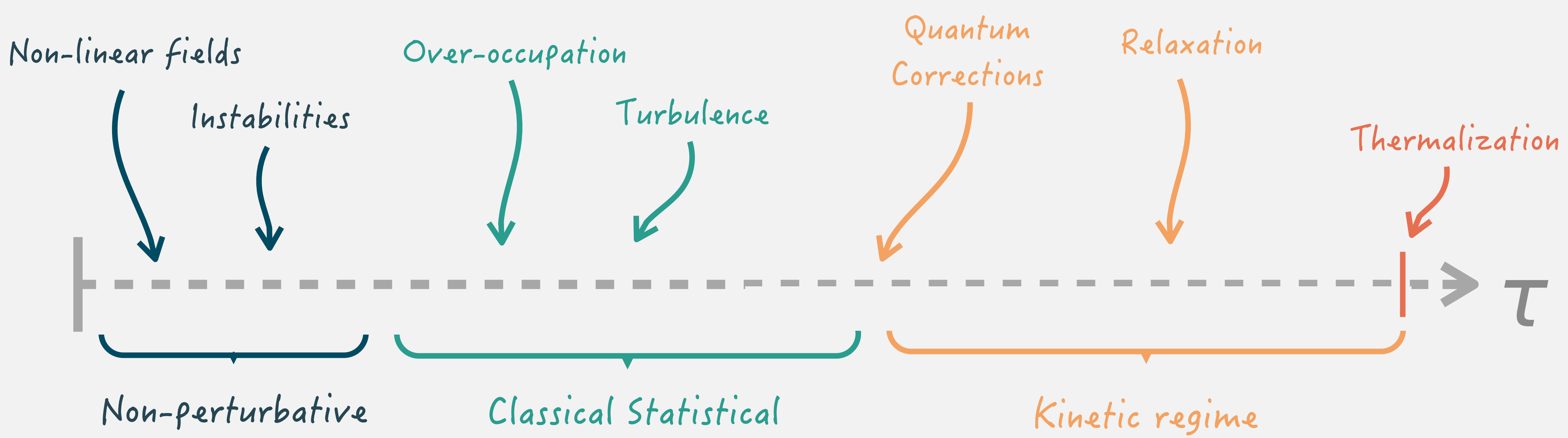
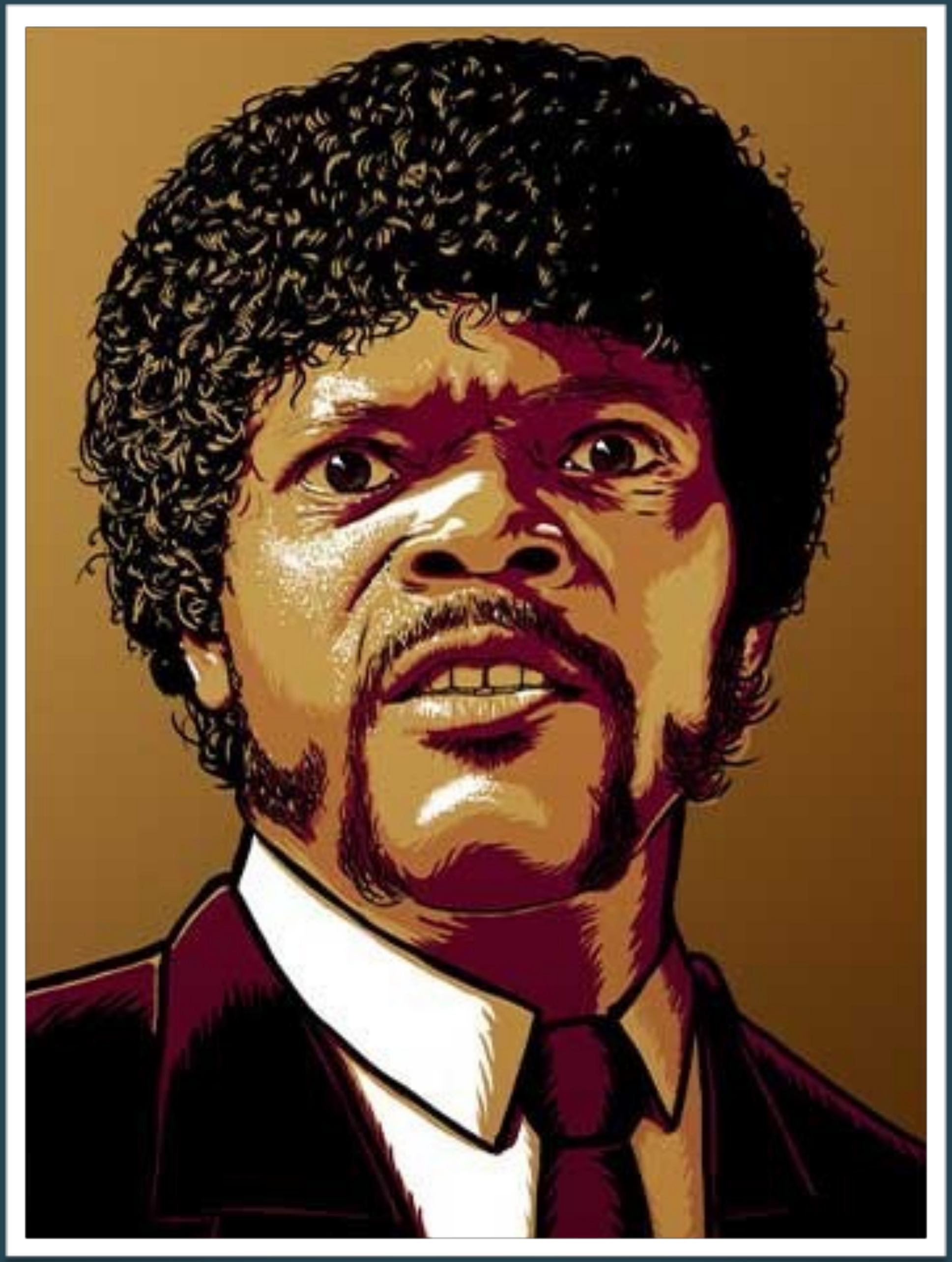


Pre-equilibrium stages





DATA, DO YOU SPEAK IT?

The Observables

$$\frac{dN}{d^2p_\perp dy}$$

The Observables

$$\frac{dN}{d^2p_\perp dy}$$

Invariant
Yield

The Observables

$$\frac{dN}{d^2p_\perp dy} = \frac{1}{2\pi p_\perp}\frac{dN^{iso}}{dp_\perp dy}\left(1+\sum_{n=1}^{\infty} v_n \cos(n\varphi)\right)$$

The Observables

$$\frac{dN}{d^2p_\perp dy} = \boxed{\frac{1}{2\pi p_\perp}\frac{dN^{iso}}{dp_\perp dy}}\left(1 + \sum_{n=1}^{\infty} \boxed{v_n} \cos(n\varphi)\right)$$

The Observables

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The “Photon Puzzle”

$$\frac{dN}{d^2p_\perp dy} = \boxed{\frac{1}{2\pi p_\perp}\frac{dN^{iso}}{dp_\perp dy}}\left(1 + \sum_{n=1}^{\infty} \boxed{v_n} \cos(n\varphi)\right)$$

The inability to calculate both the direct photon’s yield, and it’s anisotropy coefficients with current models

DISCLAIMER

DISCLAIMER

ASSUMPTIONS

Bjorken Expansion

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

Transverse Translation Invariance

$$u = \left(\cosh\eta,\ 0,\ 0,\ \sinh\eta)\right)$$

DISCLAIMER

OBJECTIVE

Solve the “Photon Puzzle”?

NO

↓

So?

↓

Show that NEQ photons are relevant

↓

Change the perspective

Contents

Bottom-up thermalization

Three Stages

I. Early Times

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

II. Onset of thermalization

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

III. Thermalization of the soft sector

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

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

EKT: JHEP 01 (2003) 030

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

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

Dominated by hard gluons

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

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

Inelastic processes produce soft glue $n_s \sim \frac{1}{\alpha_s}\frac{Q^3}{(Q_s\tau)^{4/3}}$

Screening mass $\rightarrow$ $m_D^2 \sim \alpha_s \int \frac{d^3p}{p} f_g \sim \frac{Q_s^2}{Q_S\tau}$

I. Early Times

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

Dominated by hard gluons

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

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

Inelastic processes produce soft glue $\quad n_s \sim \frac{1}{\alpha_s}\frac{Q^3}{(Q_s\tau)^{4/3}}$

Free streaming $\longrightarrow$ $\langle p_z \rangle \sim Q_s\,(Q_s\tau)^{-1}$

Interactions $\longrightarrow$ $\langle p_z \rangle^3 \sim \alpha_s\, n_h$

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

II. Onset of thermalization

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

Occupation of Hard Gluon drops below unity

$$n_h \sim \frac{1}{\alpha_s}\frac{Q^3}{Q_s \tau}$$

Dominated by hard gluons

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

Soft gluons dominate the screening mass

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

Soft avg. mom. $p_s^2 \sim \alpha_s Q_s^2$

Screening mass is dominated by soft sector

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

III. Thermalization of the soft sector

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

Dominated by soft gluons

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

Soft sector thermalizes

Acts like a bath

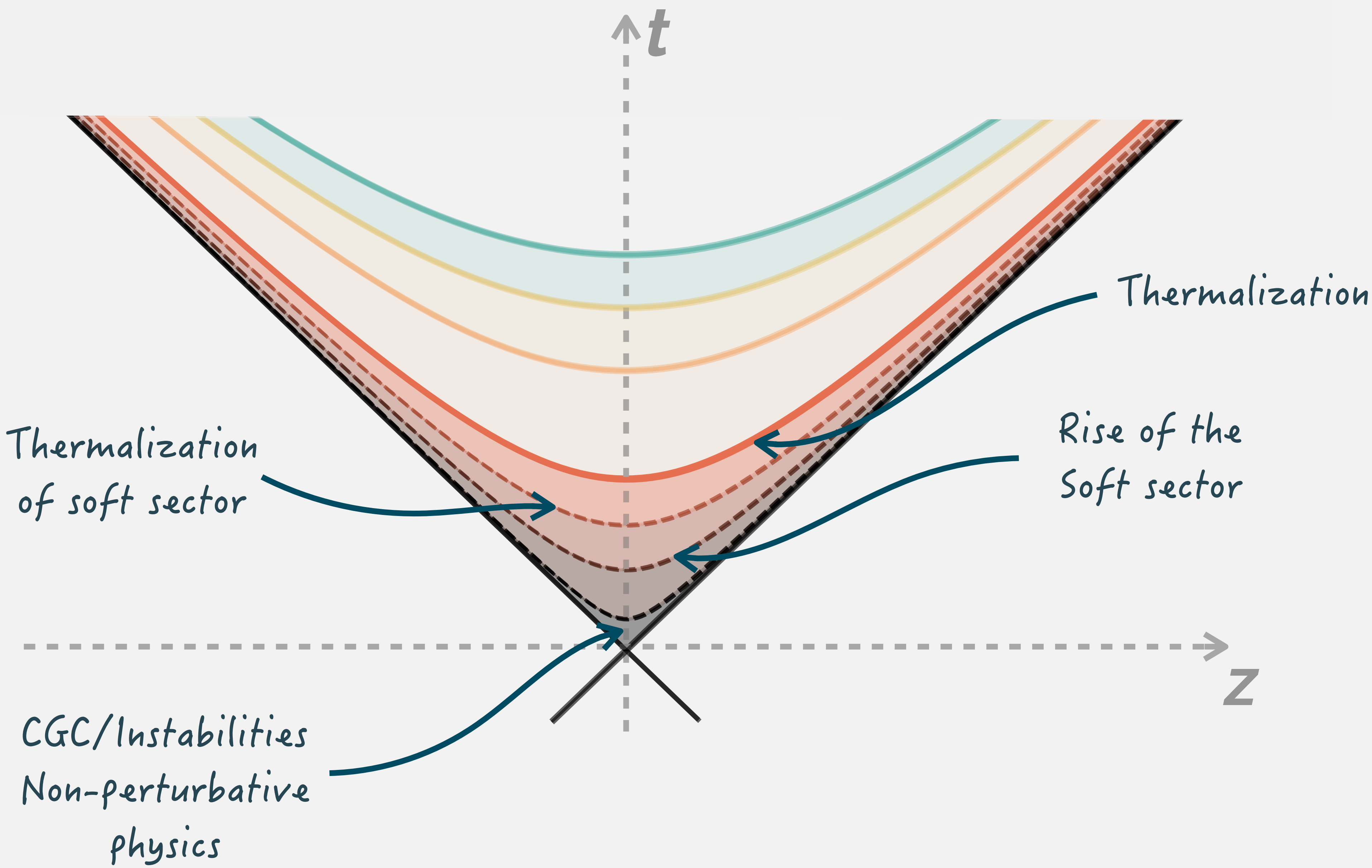
Hard sector looses energy to soft bath

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

$$\boxed{\begin{aligned} \tau_{th} &\sim c_{eq}\, \alpha^{-13/5} Q_S^{-1} \\ T_{th} &\sim c_T\, c_{eq},\, \alpha^{2/5} Q_S \end{aligned}}$$

The Song of of Heavy Ion Collisions

(revisited)



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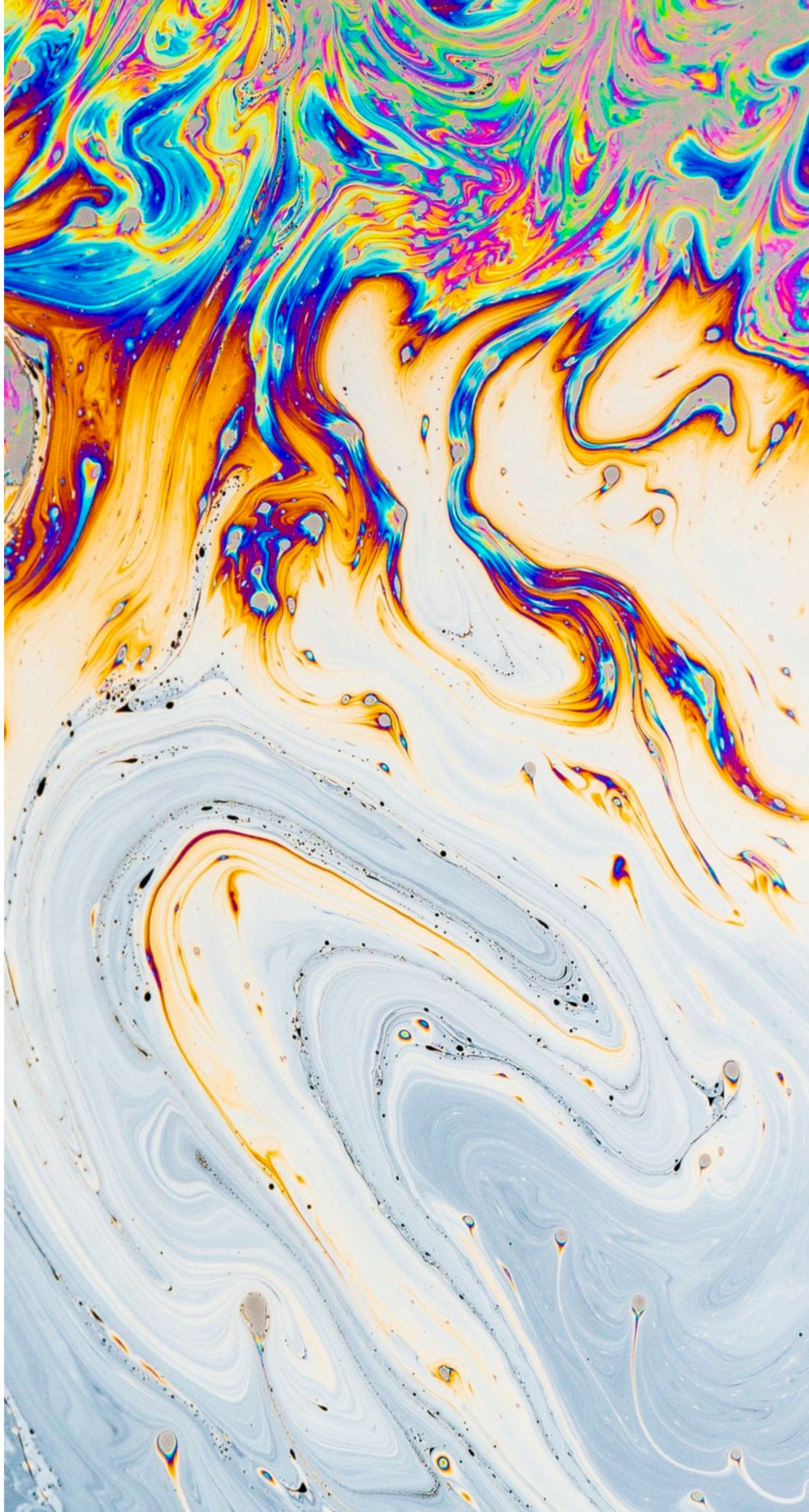
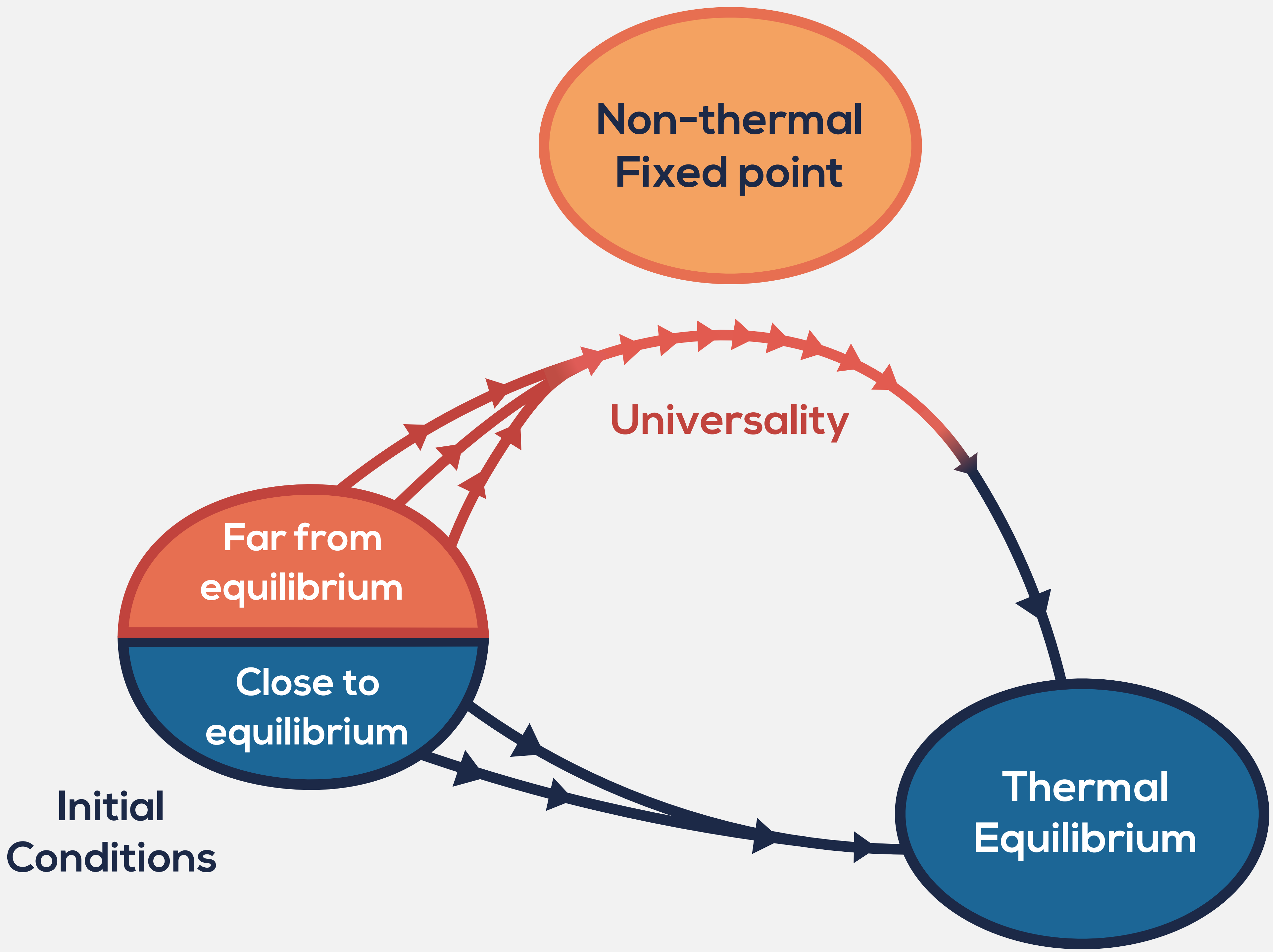


Turbulent thermalization

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

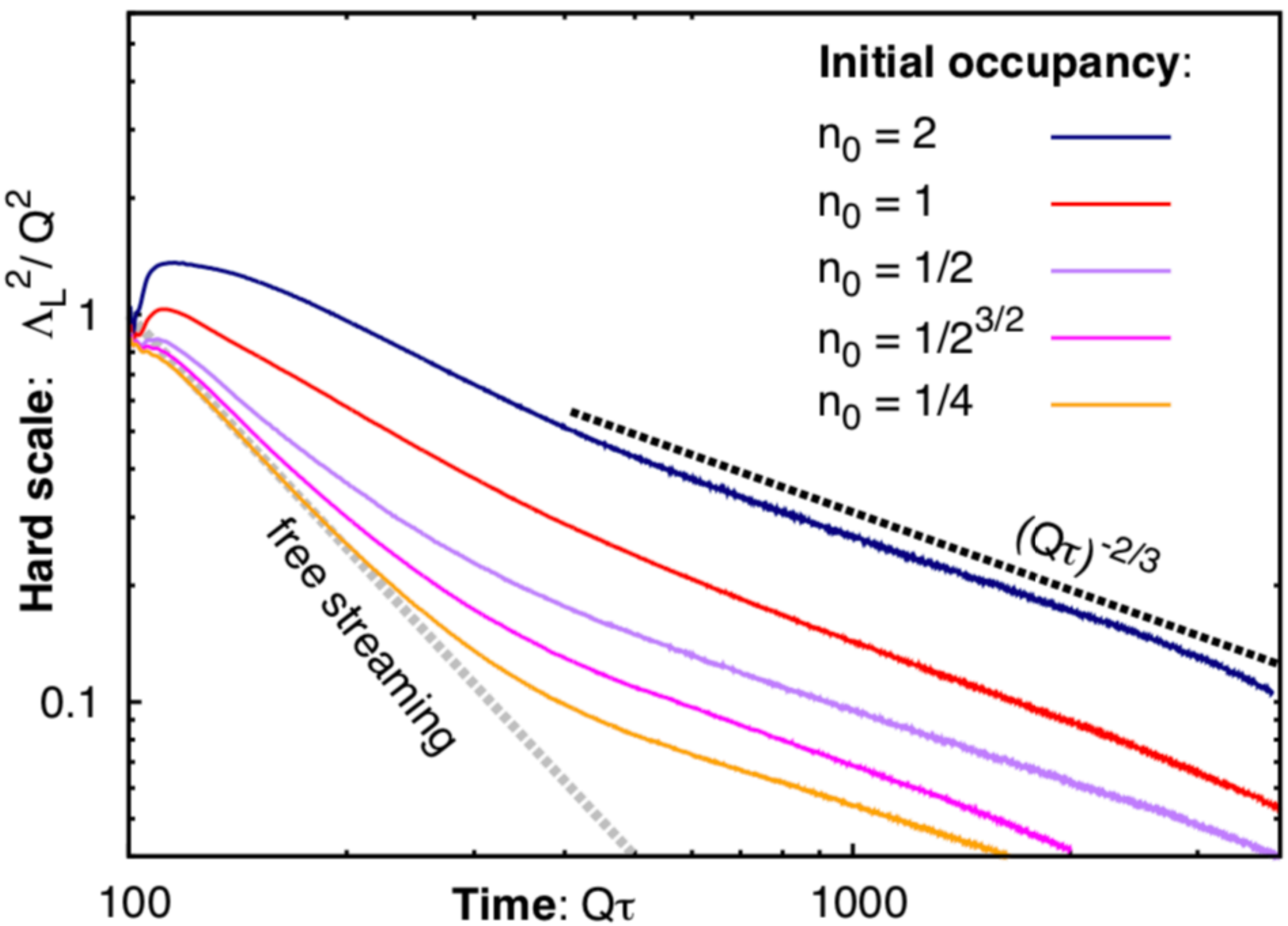
def. distribution function depends on a Universal, time-independent function

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

Transport and Turbulence

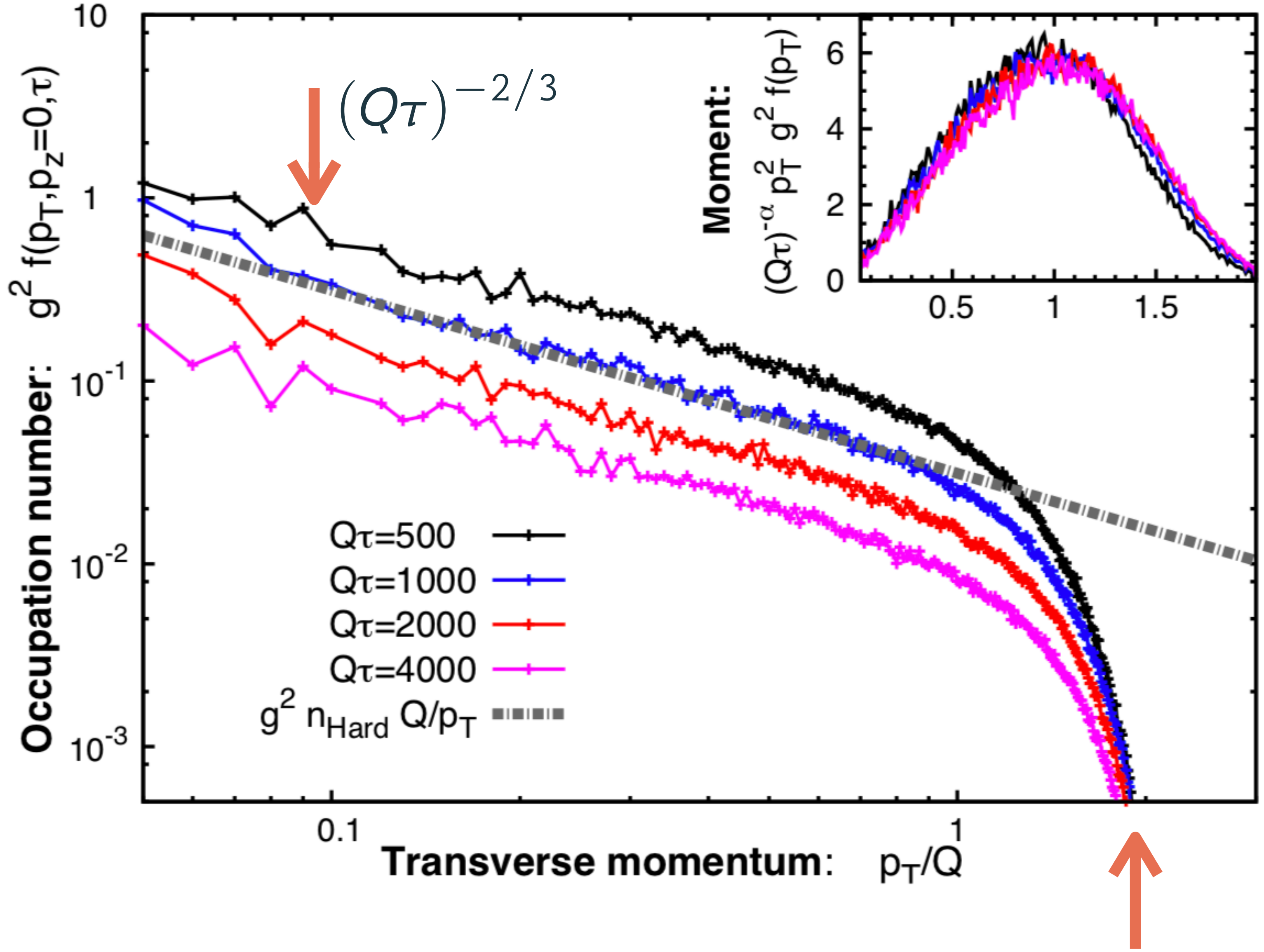
def. Local flow of conserved charges to accommodate better the total corresponding charge. The flow is turbulent when is self-similar

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



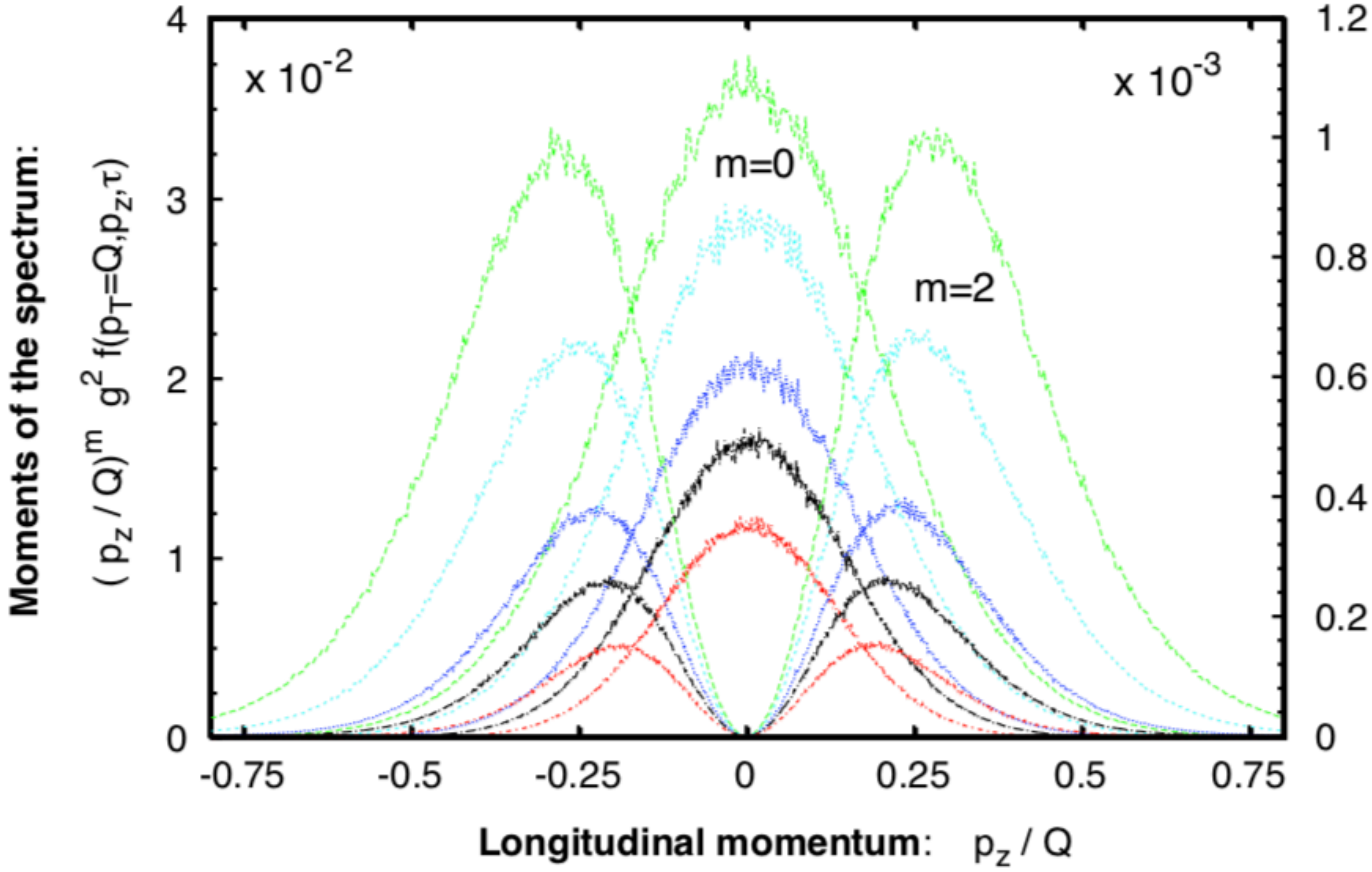
Phys.Rev. D89 (2014) no.11, 114007

Occupancy: $p_\perp$



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

Occupancy: p_z



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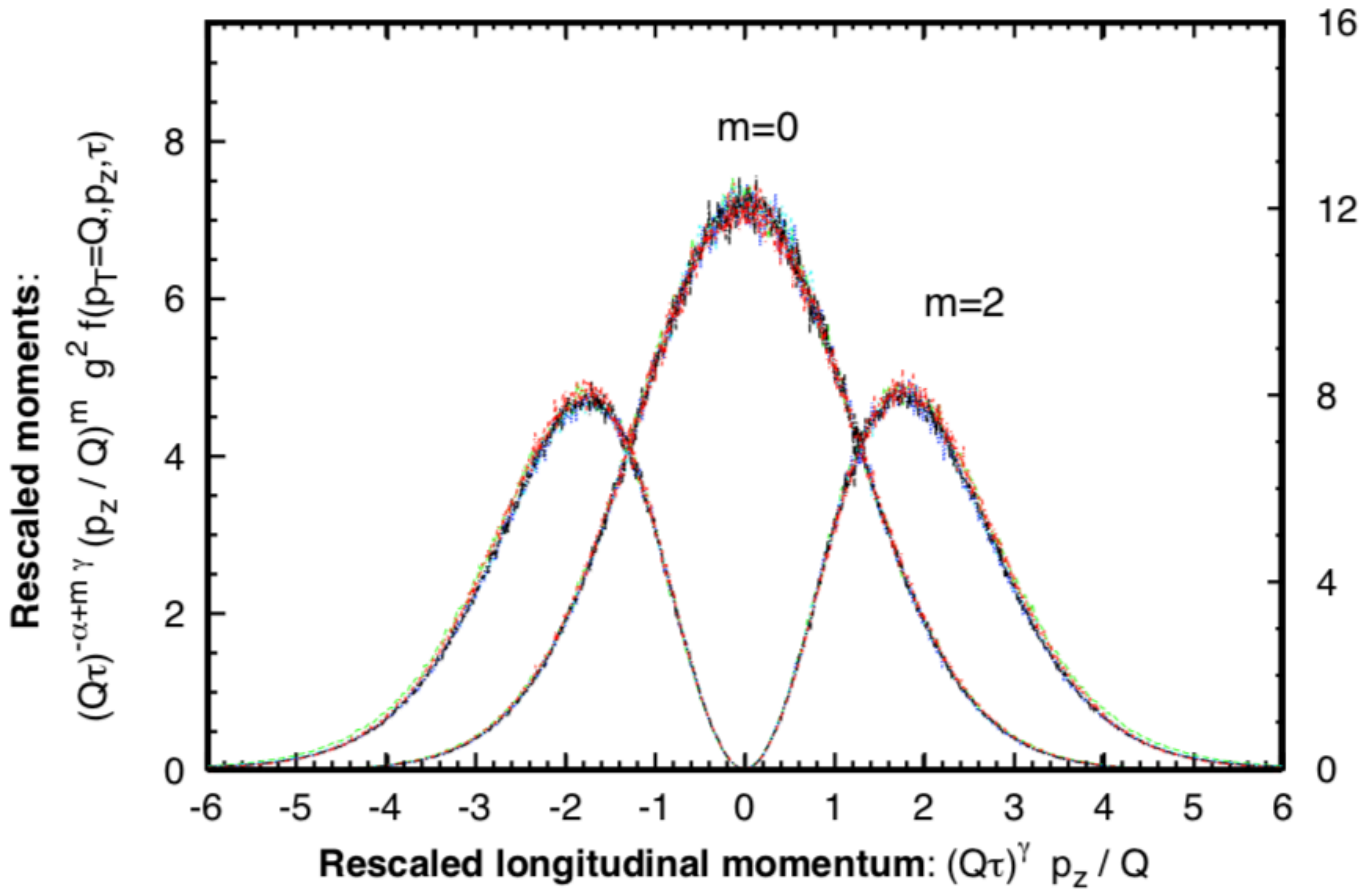
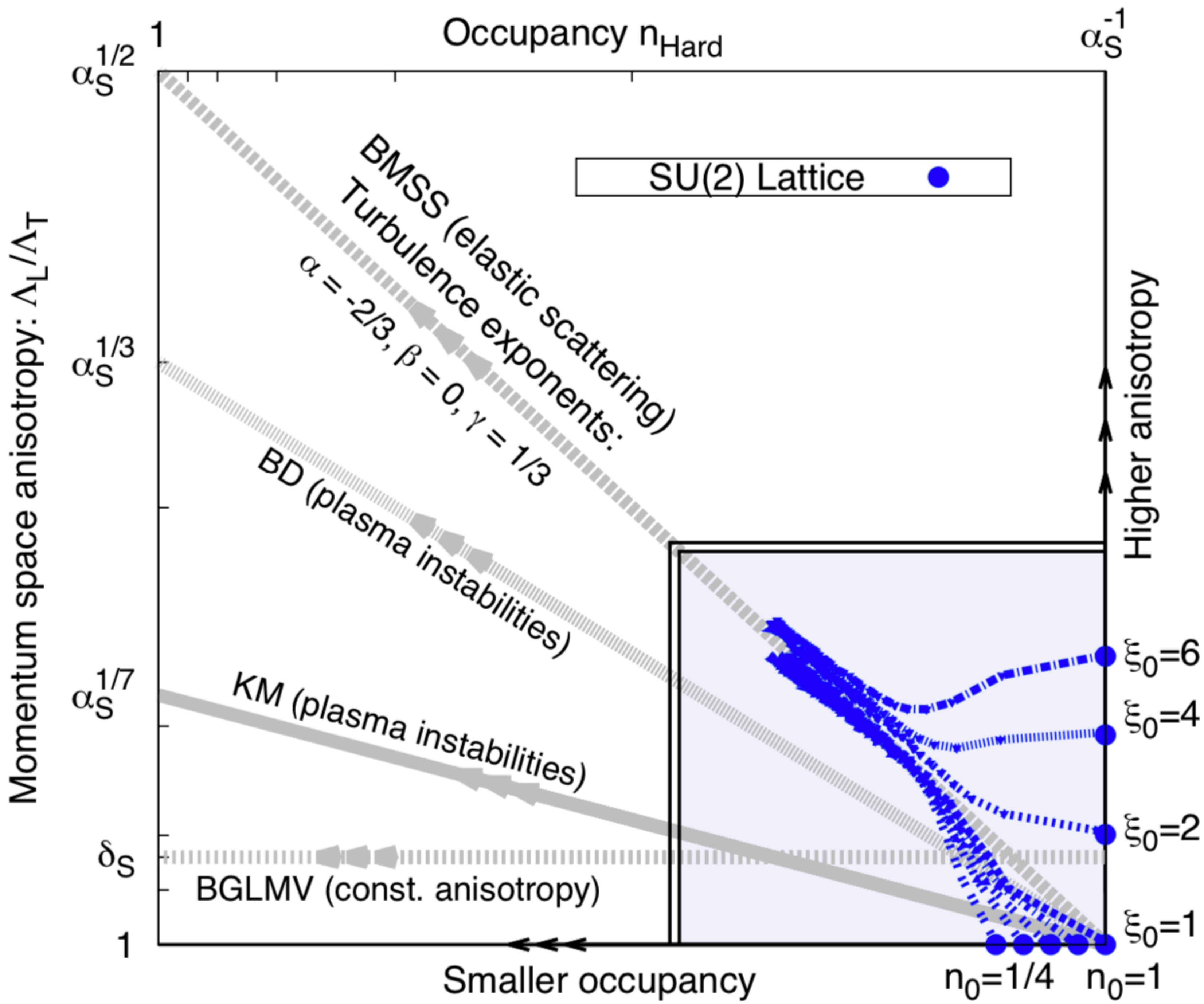
Occupancy: p_z



$$\gamma = 1/3$$

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

Finding the right scenario



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

Fit the lattice results

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

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

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

*Q.Stat. kick in lower than region of interest.

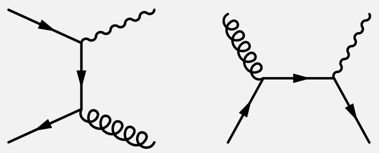
Contents

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

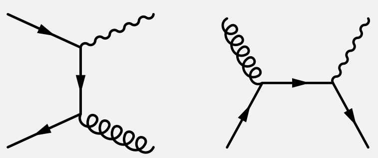
- $2 \leftrightarrow 2$ scatterings



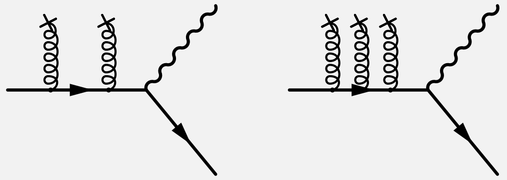
- Momentum transfer: $gT \leftrightarrow T$, $g\,Q_s \leftrightarrow Q_s$

Complete LO

- $2 \leftrightarrow 2$ scatterings



- $1 \leftrightarrow 2$ scatterings



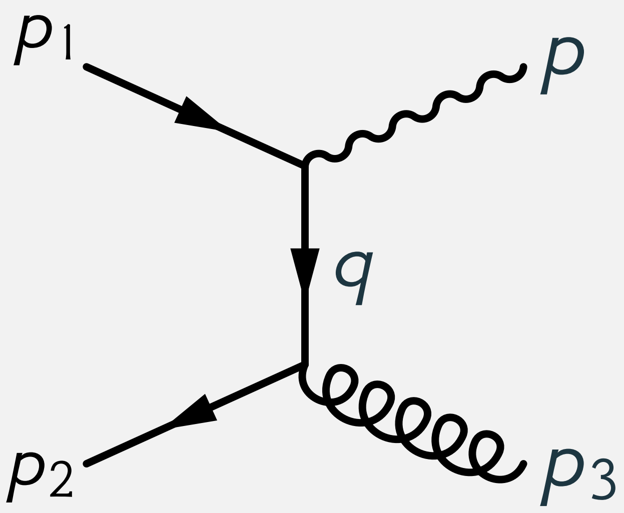
Colinearly enhanced, inelastic processes

LPM

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

EKT: JHEP 01 (2003) 030

Kinetic Rates

$$E\frac{\mathrm{d}N_\gamma}{\mathrm{d}^4X\mathrm{d}^3p} = \frac{1}{2\,(2\,\pi)^{12}}\int \frac{\mathrm{d}^3p_3}{2E_3}\frac{\mathrm{d}^3p_2}{2E_2}\frac{\mathrm{d}^3p_1}{2E_1}\,|\mathcal{M}|^2$$
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Small angle approximation

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

Regulator

EKT: JHEP 01 (2003) 030

Kinetic Rates

$$E\frac{\mathrm{d}N_\gamma}{\mathrm{d}^4X\mathrm{d}^3p} = \frac{1}{2\,(2\,\pi)^{12}}\int \frac{\mathrm{d}^3p_3}{2E_3}\frac{\mathrm{d}^3p_2}{2E_2}\frac{\mathrm{d}^3p_1}{2E_1}\,|\mathcal{M}|^2$$
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$$E\frac{dN}{d^4X\,d^3p} = \frac{40}{9\pi^2}\,\alpha\,\alpha_S\,\mathcal{L}\,f_q(\mathbf{p})\,\boxed{(I_g+I_q)}$$

Screening Masses

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

EKT: JHEP 01 (2003) 030

Thermal Stage

Rate

$$E\,\frac{\mathrm{d}N^{\mathrm{th}}}{\mathrm{d}^4X\mathrm{d}^3p} = \frac{5}{9}\,\frac{\alpha\alpha_s}{2\pi^2}\mathcal{L}\,T^2 e^{-E/T}\,.$$

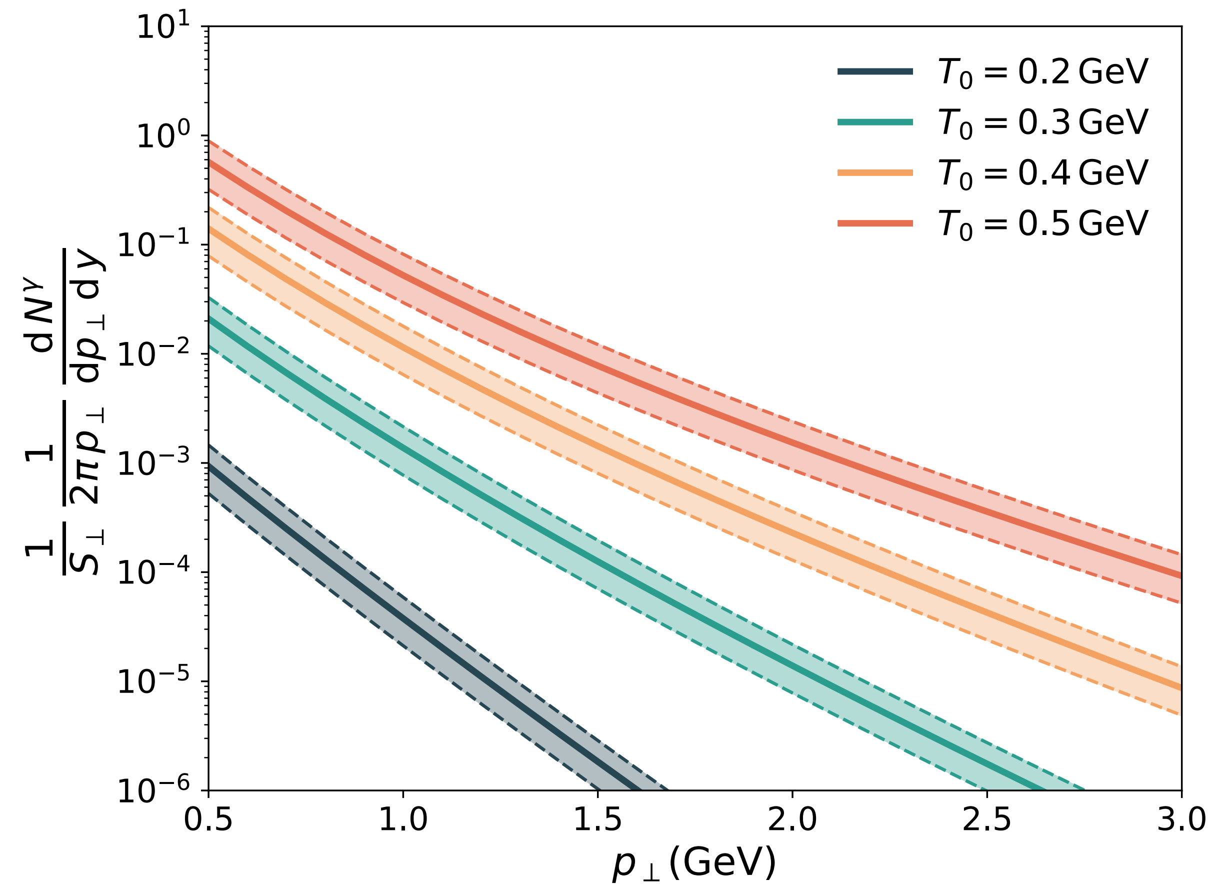
$$T = T_{th}(\tau_{th}/\tau)^{1/3}$$

Inv. Yield

$$\frac{1}{S_\perp}\,\frac{\mathrm{d}N_\gamma}{\mathrm{d}^2p_\perp\mathrm{d}y} = \frac{5}{3}\,\frac{\alpha\,\alpha_s}{\pi^2}\,\tau_{th}^2\,T_{th}^6\,B_{th}(p_\perp)\,.$$

$$B_{th}(p_\perp) = \left\{\beta_{th}^4\left[\frac{K_1(\beta_{th}p_\perp)}{\beta_{th}p_\perp} + 2\frac{K_2(\beta_{th}p_\perp)}{(\beta_{th}p_\perp)^2}\right] - \beta_c^4\left[\frac{K_1(\beta_c p_\perp)}{\beta_c p_\perp} + 2\frac{K_2(\beta_c p_\perp)}{(\beta_c p_\perp)^2}\right]\right\},$$

$$\boxed{\beta = T^{-1}}$$



Total Yield

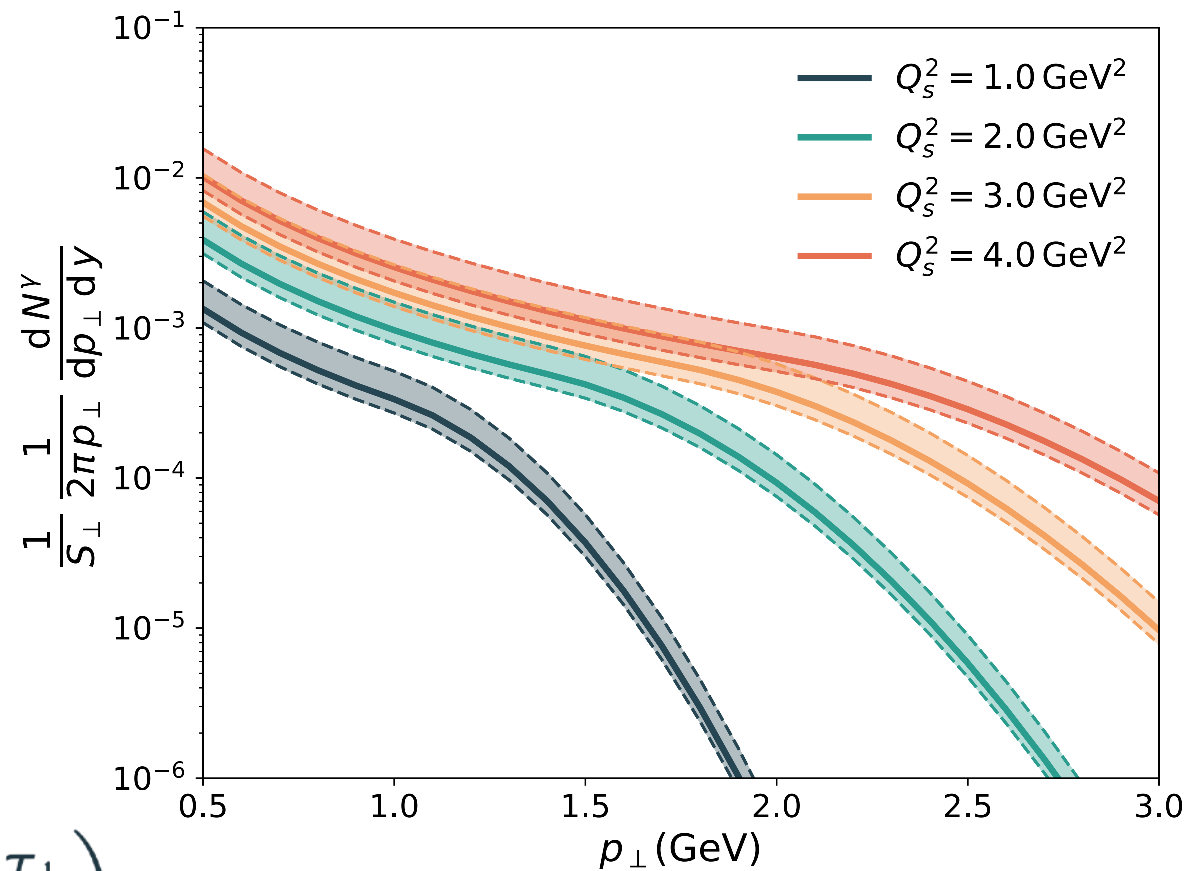
$$\frac{1}{S_\perp}\,\frac{\mathrm{d}N_\gamma}{\mathrm{d}y} = \frac{5}{3}\,\frac{\alpha\,\alpha_s}{\pi}\,\tau_{th}^2\,T_{th}^4\,\left(\frac{T_{th}^2}{T_c^2} - 1\right)\,.$$

Glasma. Stage I

Rate

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

$$\rightarrow \quad I_g(\tau) = \frac{Q_S^2}{4\,\pi^2\alpha_s}\,\frac{\kappa_g}{(Q_S\,\tau)}$$



Inv. Yield

$$\frac{1}{S_\perp}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^2p_\perp\mathrm{d}y} = \sqrt{\frac{\pi}{2}}\,\frac{20}{9\pi^4}\alpha_e\,\kappa_g f_0\,\frac{\sigma_0}{Q_S}\,\log\left(\frac{\tau_1}{\tau_0}\right) \times \frac{Q_S^2}{p_\perp^2}\,W_r[p_\perp - Q_s]$$

Total Yield

$$\frac{1}{S_\perp}\frac{\mathrm{d}N_\gamma}{\mathrm{d}y} = \sqrt{\frac{\pi}{2}}\,\frac{20}{3\pi^3}\alpha_e\,\kappa_g f_0\,\sigma_0\,Q_S\,\frac{2}{3}\log\left(\frac{\tau_1}{\tau_0}\right)\chi_r \quad \longleftrightarrow \quad f_0\,\frac{\sigma_0}{Q_S} = \sqrt{\frac{2}{\pi}}\kappa_q\left[\log\left(\frac{Q_S^2}{\sigma_0^2}\right)\right]^{-1}$$

Glasma. Stage II

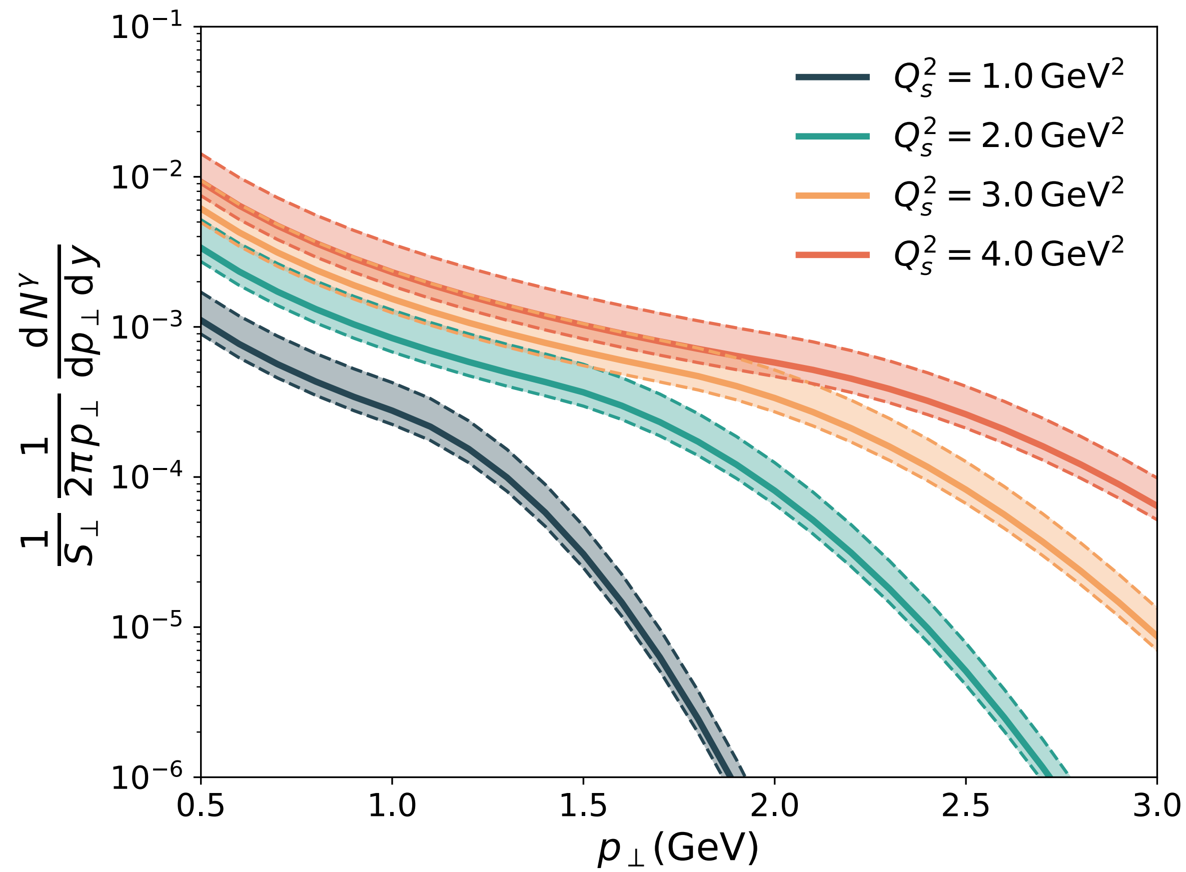
Rate

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

$$\rightarrow \quad I_g(\tau) = \frac{\kappa_g\,\alpha_s^{-1/4}}{4\,\pi^2}\,\frac{Q_S^2}{(Q_S\,\tau)^{1/2}}$$

Inv. Yield

$$\frac{1}{S_\perp}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^2p_\perp\mathrm{d}y} = \sqrt{2\,\pi}\,\frac{20}{9\pi^4}\alpha_e\,\kappa_g\,f_0\,\frac{\sigma_0}{Q_S}\,\frac{Q_S^2}{p_\perp^2} \times W_r[p_\perp - Q_s]\,\left(\alpha_s^{-1/2} - 1\right)$$



Total Yield

$$\frac{1}{S_\perp\,Q_S^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}y} = \sqrt{\frac{\pi}{2}}\,\frac{80}{9\pi^3}\alpha_e\,\mathcal{L}\,\kappa_g\,f_0\,\left(\alpha_s^{-1/2} - 1\right) \quad \leftrightarrow \quad f_0\,\frac{\sigma_0}{Q_S} = \sqrt{\frac{2}{\pi}}\kappa_q\left[\log\left(\frac{Q_S^2}{\sigma_0^2}\right)\right]^{-1}$$

Glasma. Stage III

Rate

$$E\,\frac{\mathrm{d}N^{\mathrm{th}}}{\mathrm{d}^4X\mathrm{d}^3p} = \frac{5}{9}\frac{\alpha\alpha_s}{2\pi^2}\mathcal{L}\,T^2 e^{-E/T}\,.$$

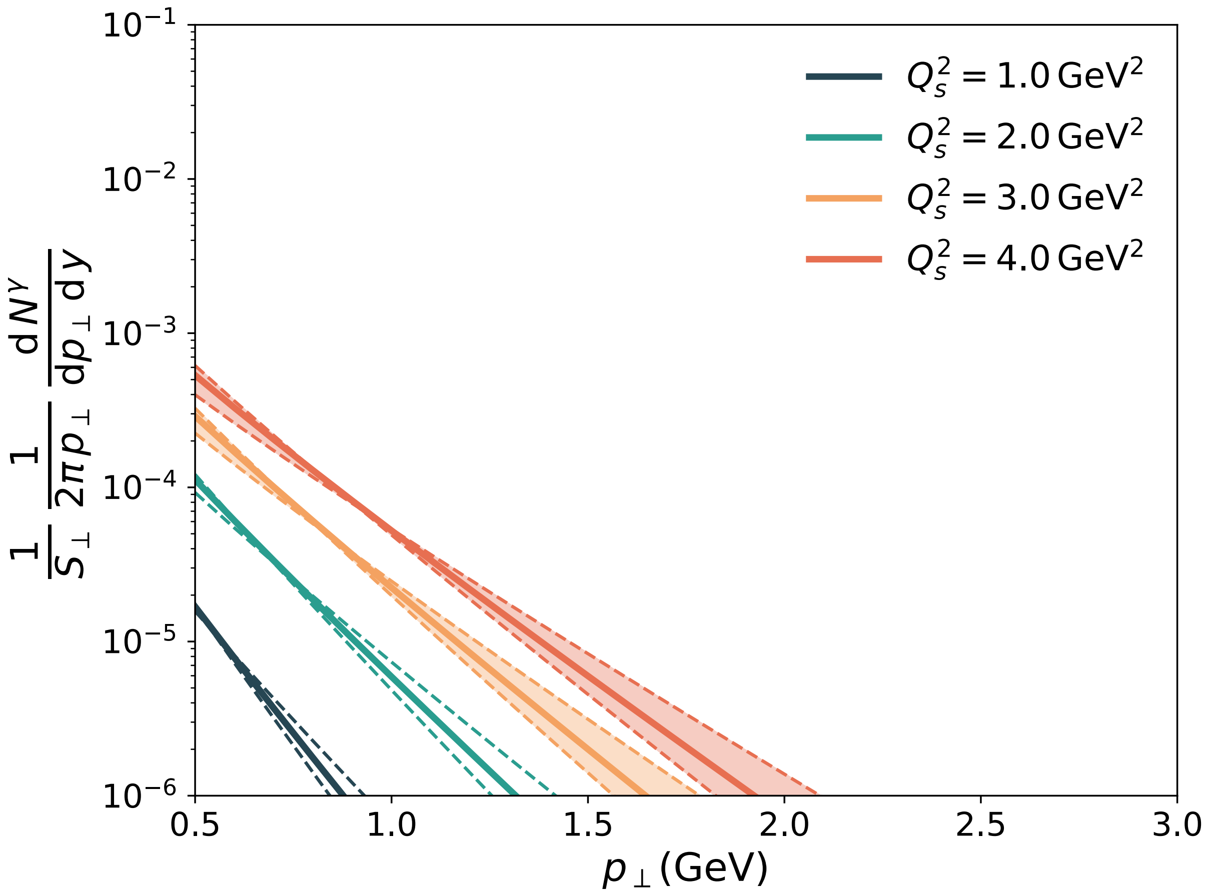
$$T = c_T \alpha_s^{\,3} Q_s (Q_s\tau)$$

Total Yield

$$\frac{1}{S_\perp Q_S^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}y} = \frac{5}{27}\frac{\alpha}{2\pi^2}c_{eq}^6\mathcal{L}\alpha^{-13/5}$$

Inv. Yield

$$\frac{1}{S_\perp}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^2p_\perp\mathrm{d}y} = \sqrt{\frac{\pi}{2}}\,\frac{5}{9}\,\frac{\alpha\,\alpha_s^{-5}}{\pi^2 c_T^2}\frac{p_\perp^4}{Q^4}\frac{32}{945}\mathcal{L}\left(\sqrt{\pi}\mathrm{erf}\left(\sqrt{\frac{p_\perp}{T}}\right) + \sqrt{\frac{T}{p_\perp}}e^{-\frac{p}{T}}\left(1-\frac{1}{2}\frac{T}{p_\perp}+\frac{3}{4}\frac{T^2}{p_\perp^2}-\frac{15}{8}\frac{T^3}{p_\perp^3}+\frac{105}{16}\frac{T^4}{p_\perp^4}\right)\right)\Bigg|_{T_2}^{T_{th}}$$



Phenomenological Matching

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

Glauber

IP-Glasma

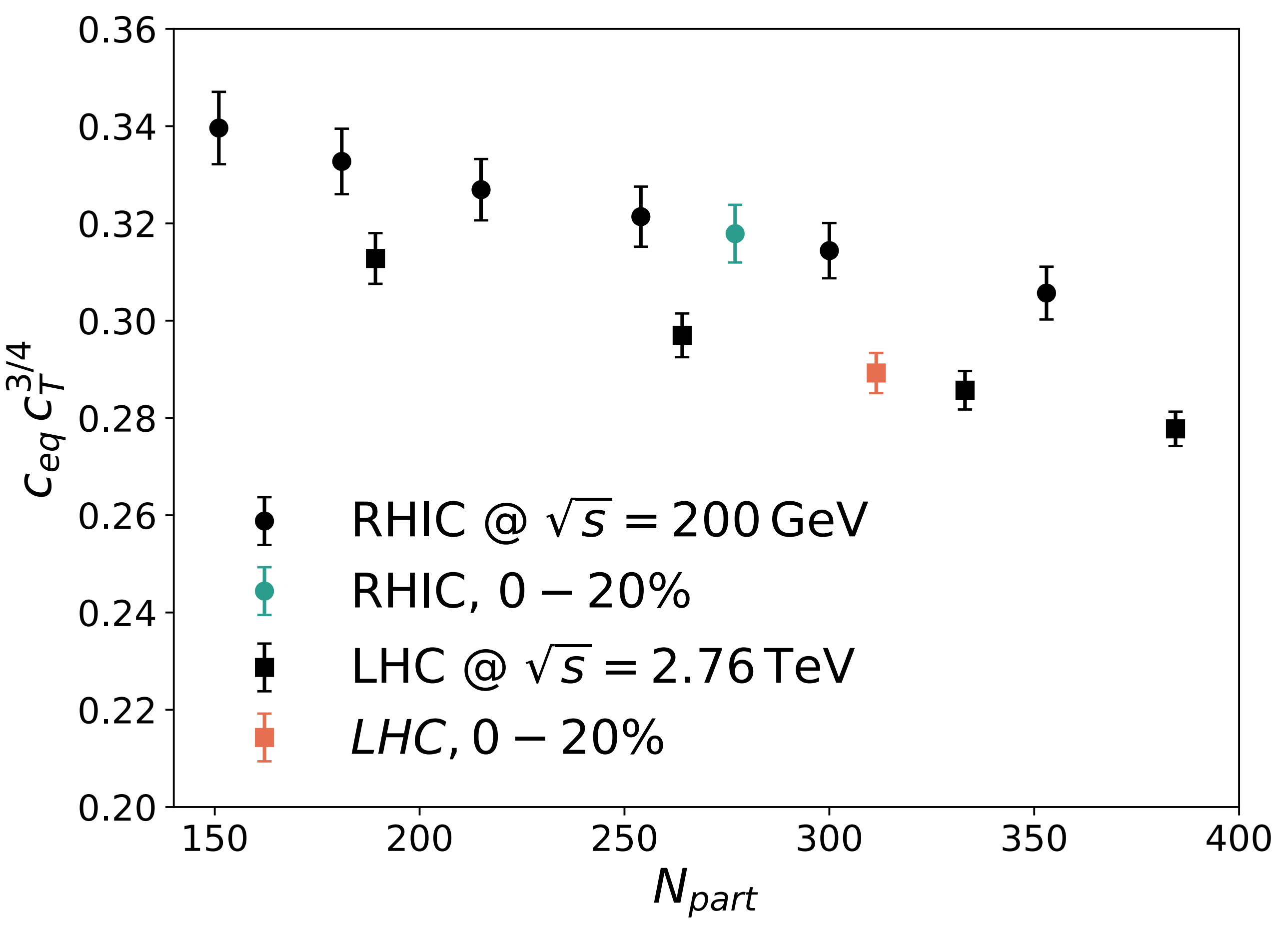
$\langle Q_s^2 \rangle = 2\,\mathrm{GeV}$ $\longrightarrow$ RHIC, 0-5% (Reference)

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

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

Phenomenological Matching

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



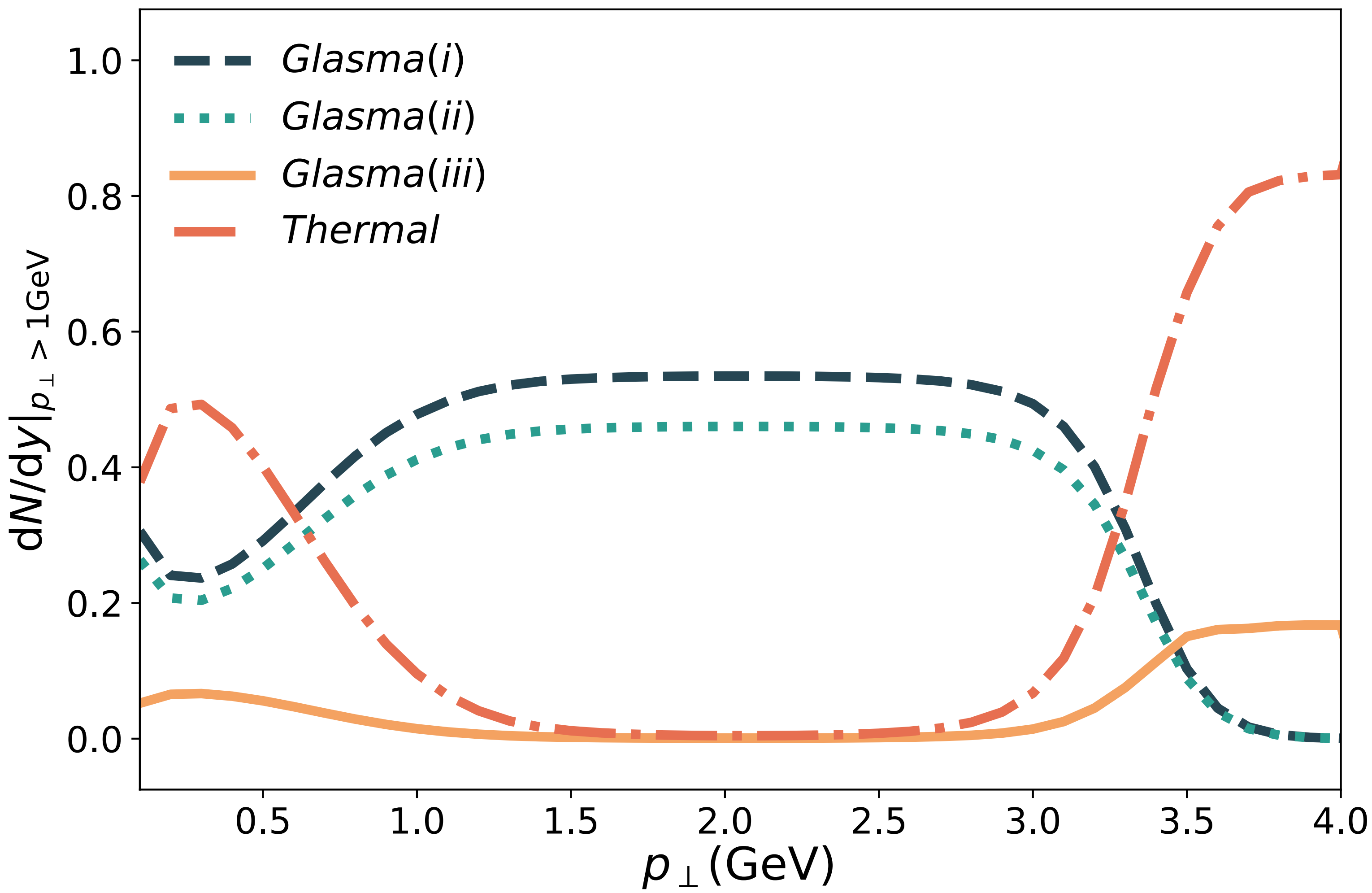
Entropy is transported via

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

C_T known to logarithmic precision

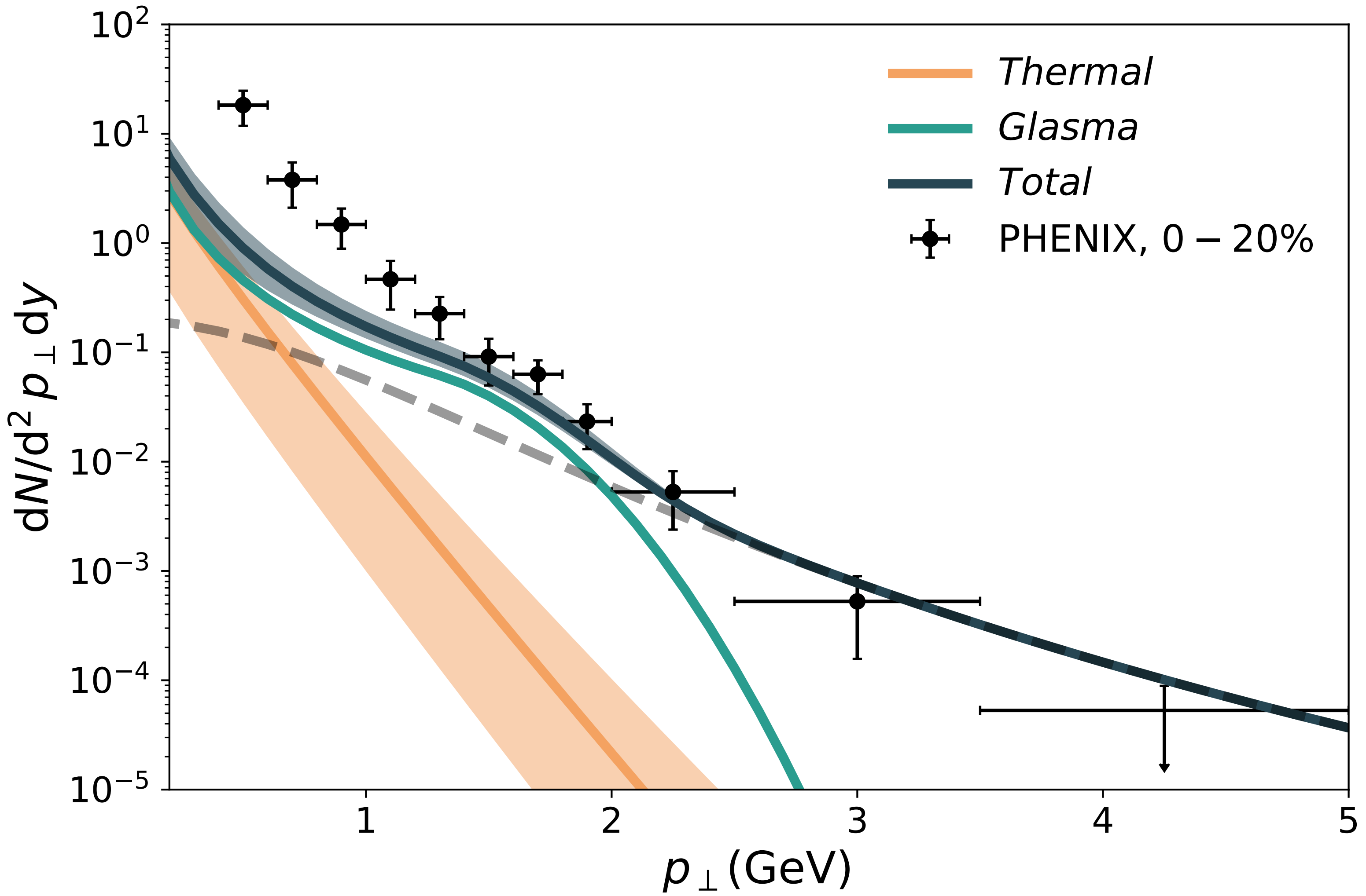
$$C_T = 0.18$$

Contributions



Comparison to data

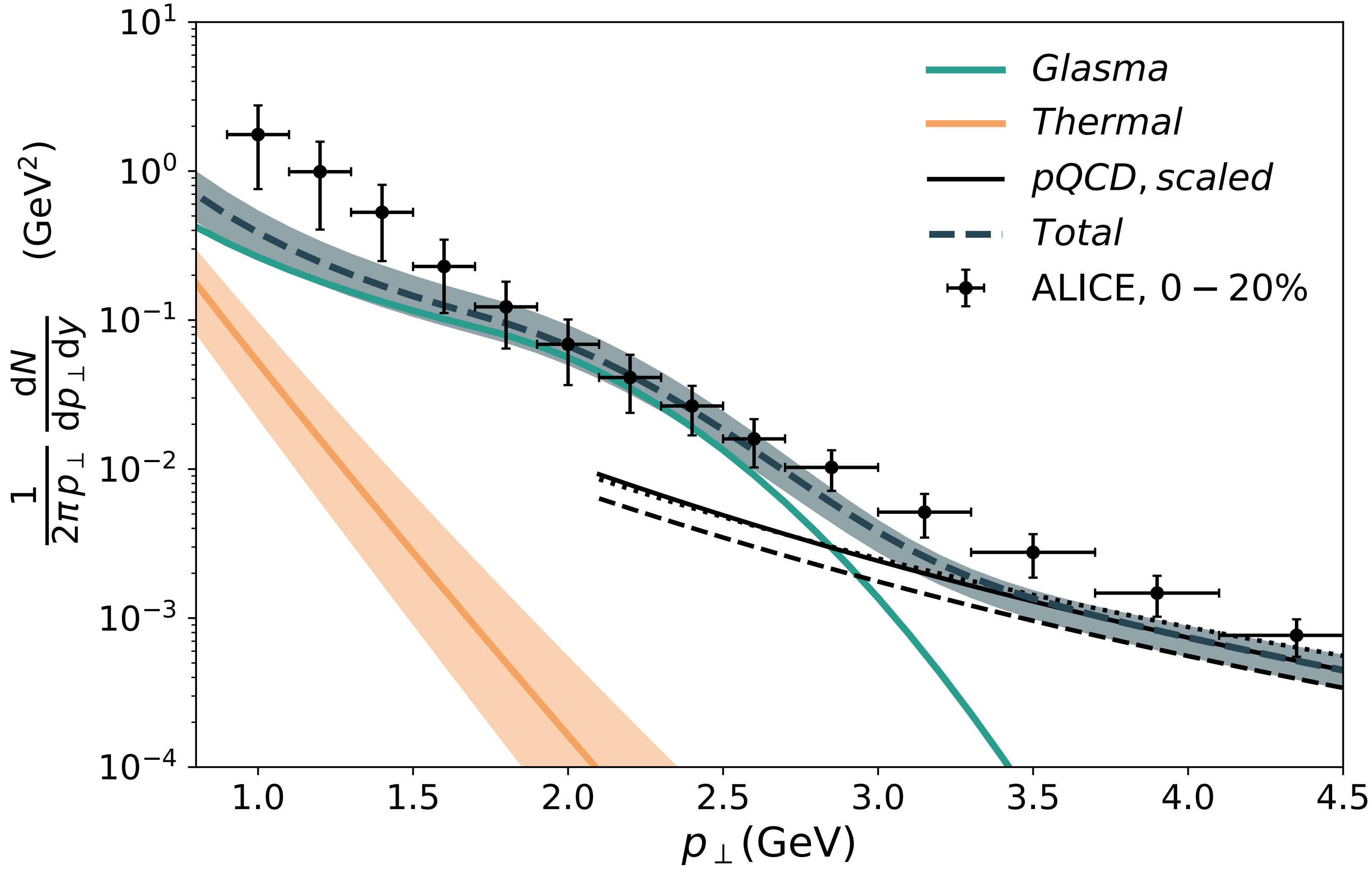
PHENIX



Phys. Rev. C71, 034908 (2005)

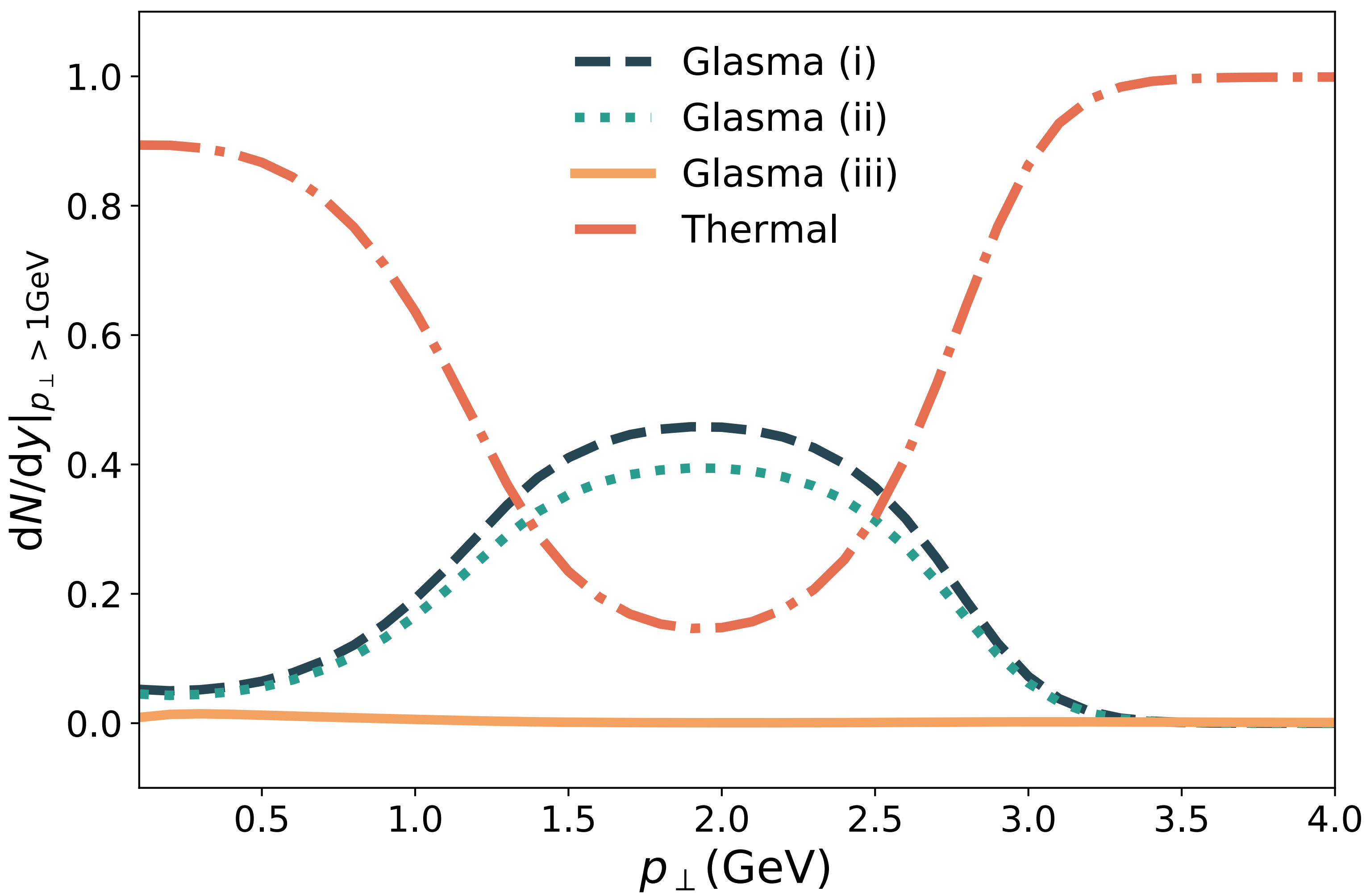
Comparison to data

ALICE



Phys. Lett. B754, 235 (2016),

Contributions
(AMY revisited)

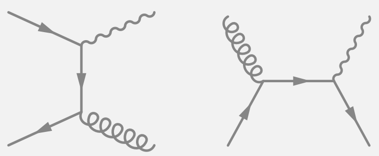


Kinetic Rates

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

Leading Log

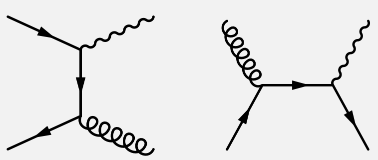
- $2 \leftrightarrow 2$ scatterings



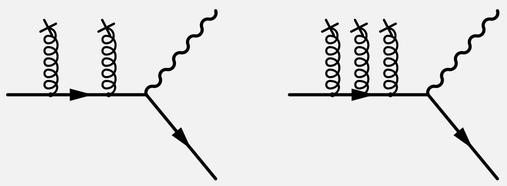
- Momentum transfer: $gT \leftrightarrow T$, $g\,Q_s \leftrightarrow Q_s$

Complete LO

- $2 \leftrightarrow 2$ scatterings



- $1 \leftrightarrow 2$ scatterings

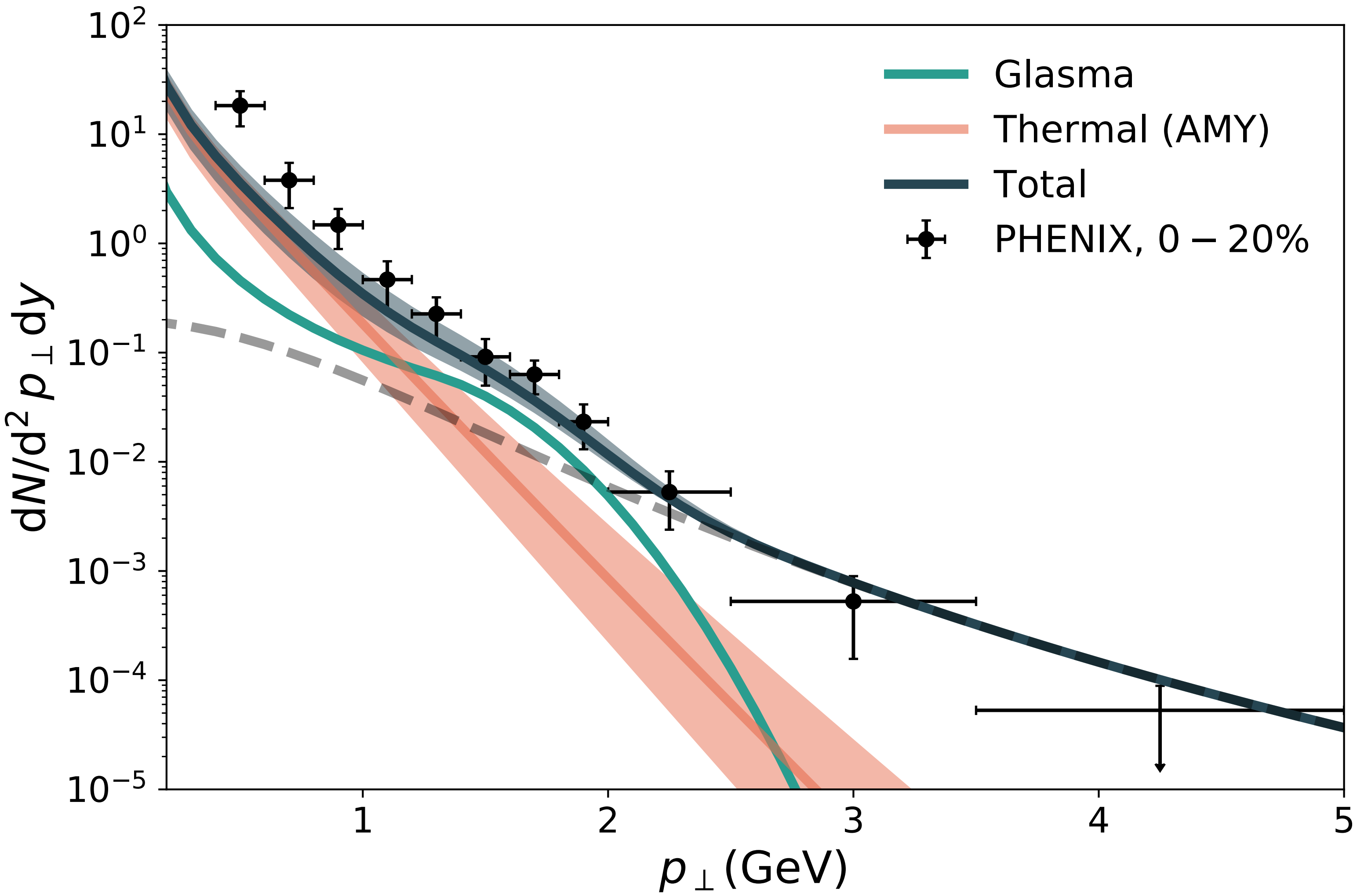


Colinearly enhanced, inelastic processes

LPM

Comparison to data

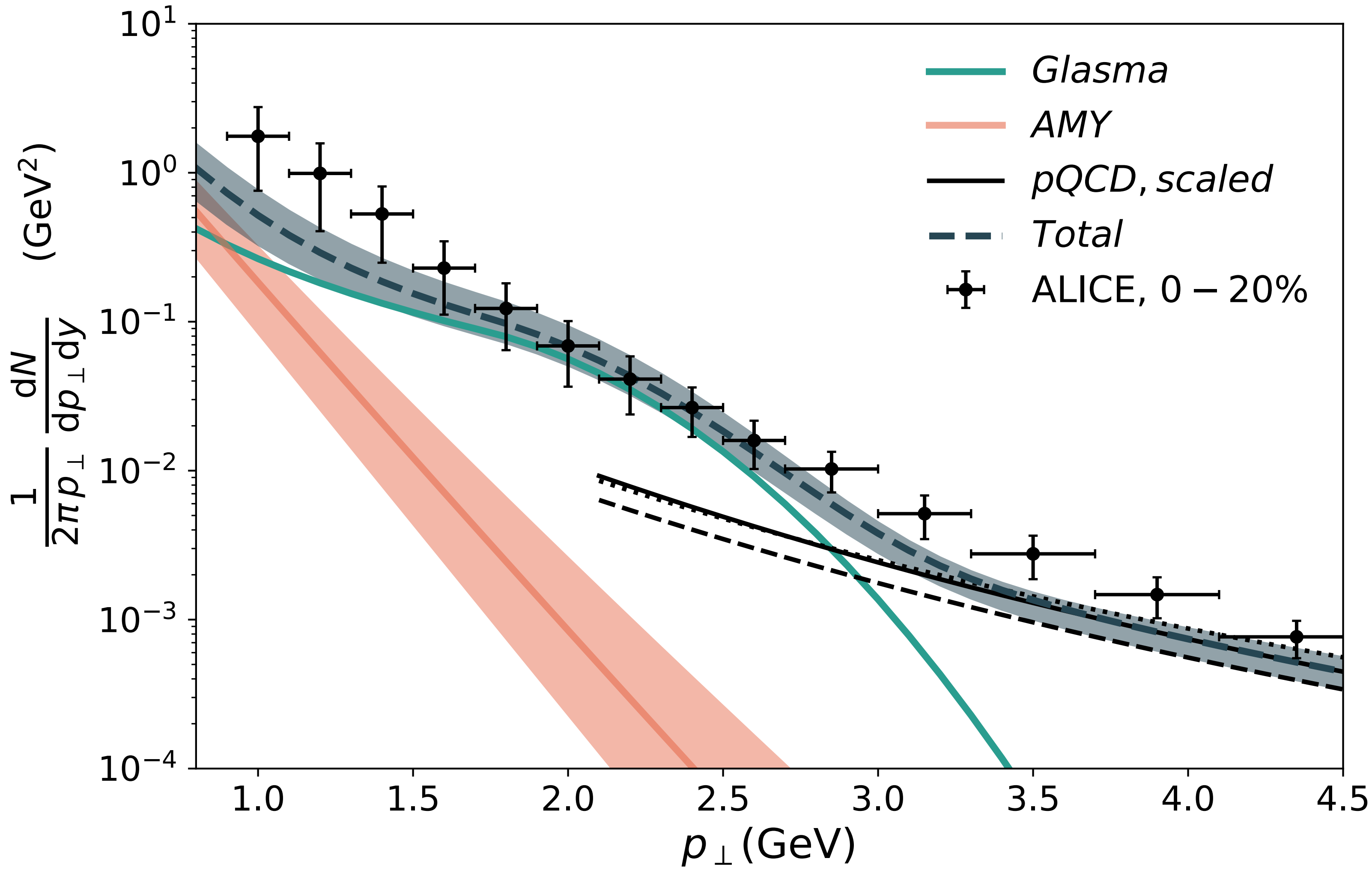
PHENIX (AMY revisited)



Phys. Rev. C71, 034908 (2005)

Comparison to data

ALICE (AMY revisited)



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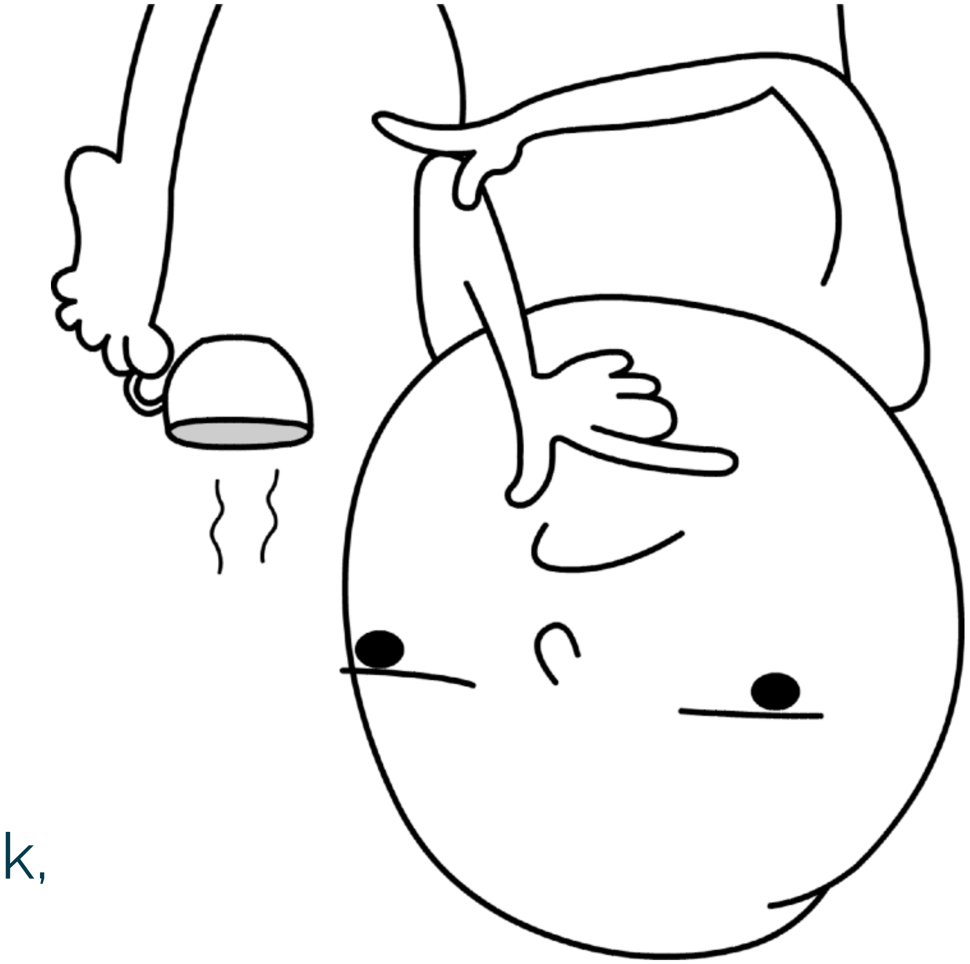
Contents

Caveats

- Simple model
- Pre-equilibrium doesn't account for anisotropies . . . yet.
- Full kinetic approach will account for inelastic terms

→ IR enhancement?

Summary and Outlook



- Photons are our cleanest probes
- BMSS thermalisation is a consistent framework, confirmed by real-time lattice studies
- BMSS photons are relevant at scales relevant for saturation physics
- EKT studies are needed to discriminate, and to account for anisotropies
- Higher correlations (photon HBT) may be particularly sensitive to pre-equilibrium physics