Electroweak probes: Theory

Jean-François Paquet

March 27, 2023

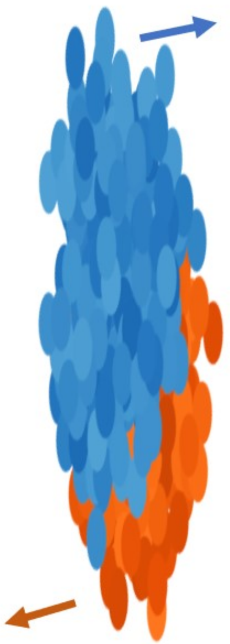
VANDERBILT UNIVERSITY

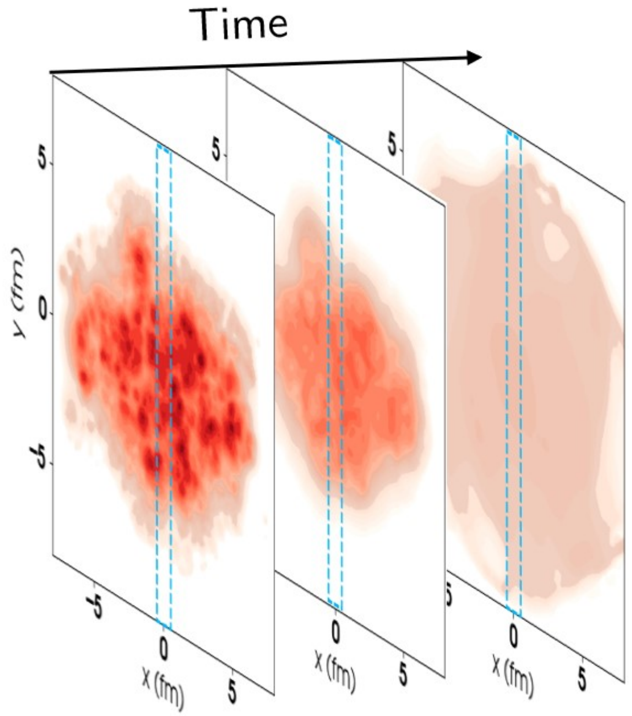
2023 HARD PROBES Aschaffenburg

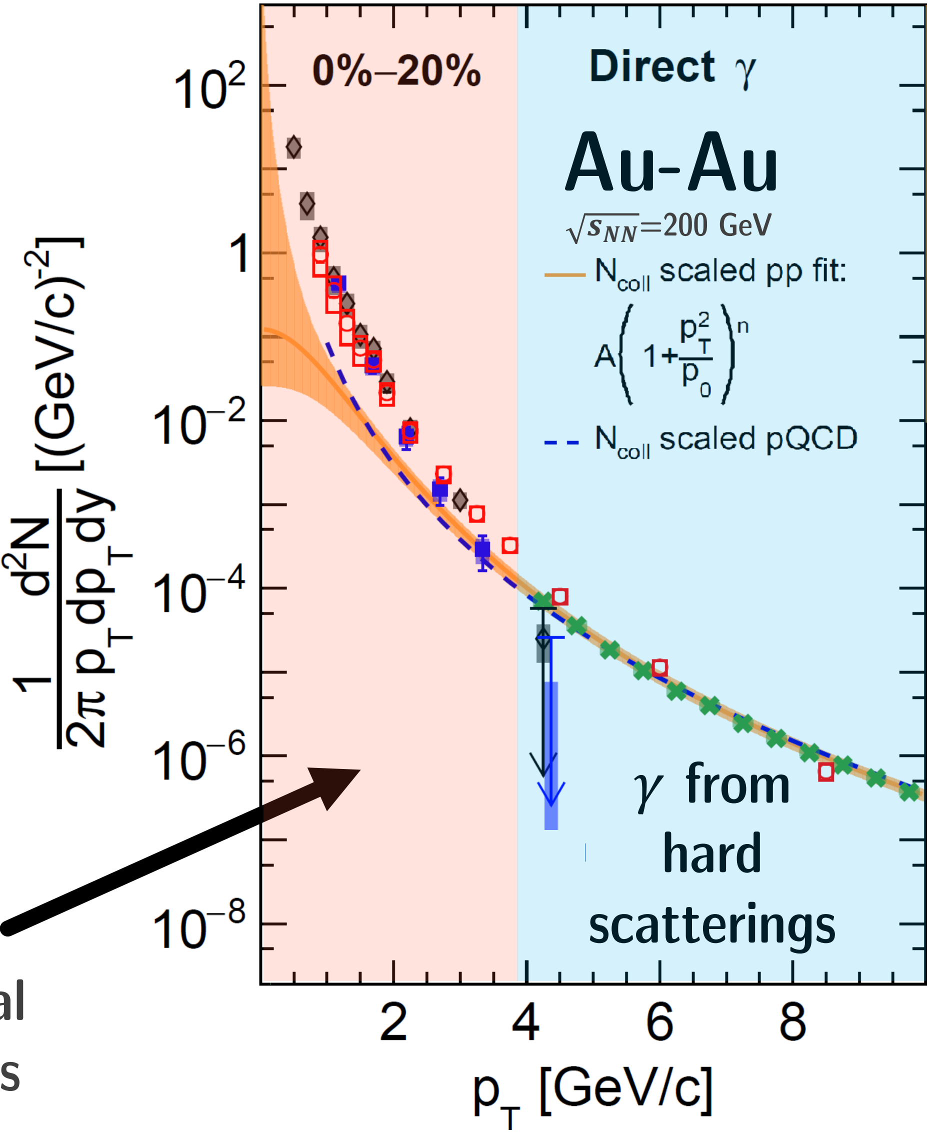
Plasma-induced or plasma-modified γ & l^+l^-

Ref.: PHENIX Collaboration [arXiv:2203.17187]

Figure credit: J-F Paquet and Scott Moreland





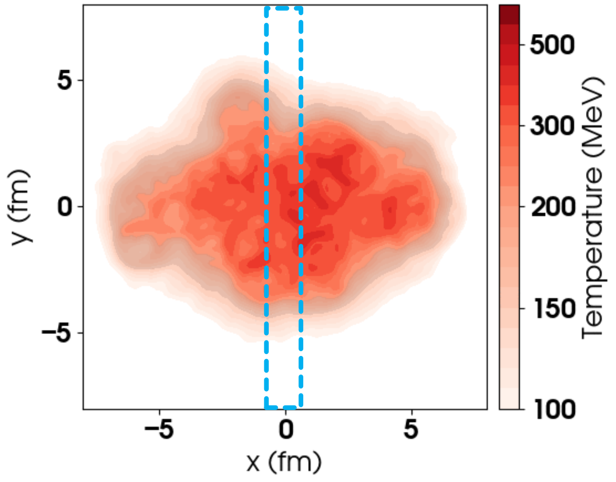


High-energy prompt photons, W/Z bosons, & also UPC studies: next talk by Austin Baty

Thermal photons

Spacetime profile of heavy-ion collisions

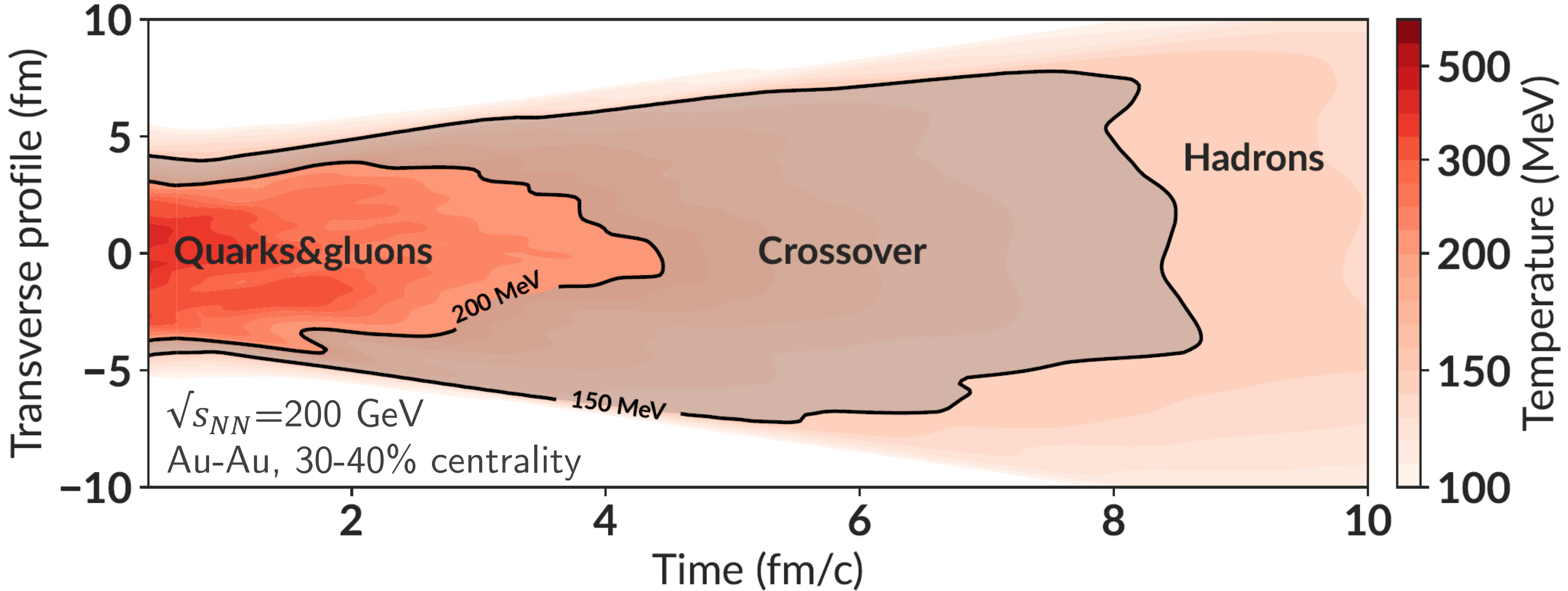
Temperature



$$\frac{d\,Volume}{d\,T} \sim T^{-\left(2c_s^{-2}+1\right)} \sim T^{-9}$$

[c_s^2 is speed of sound]

Figure credit: J-F Paquet and Scott Moreland



Low-energy electromagnetic probes in heavy-ion collisions

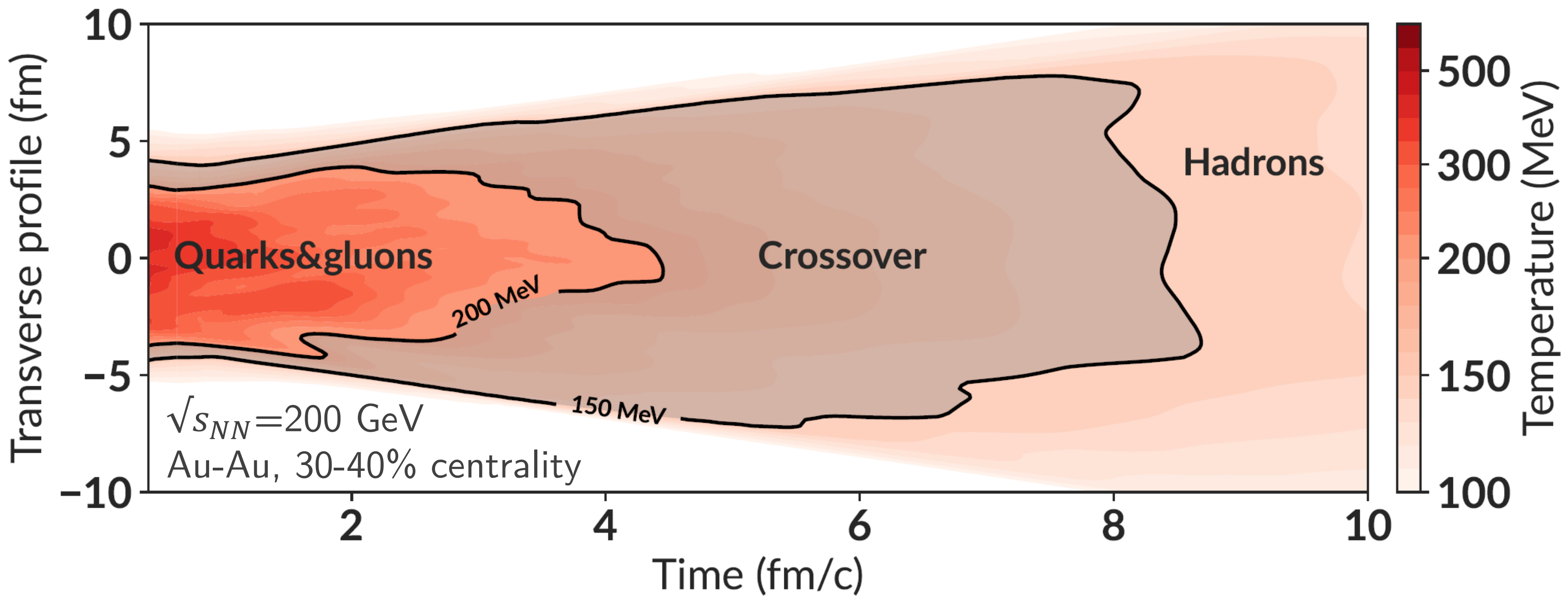
Prompt photons / Drell-Yan dileptons

Pre-equilibrium photons/dileptons

Thermal photons and dileptons

Late-stage photons and dileptons (including hadronic decays)

Other sources have been studied: from magnetic field, from recombination of hadrons, ...

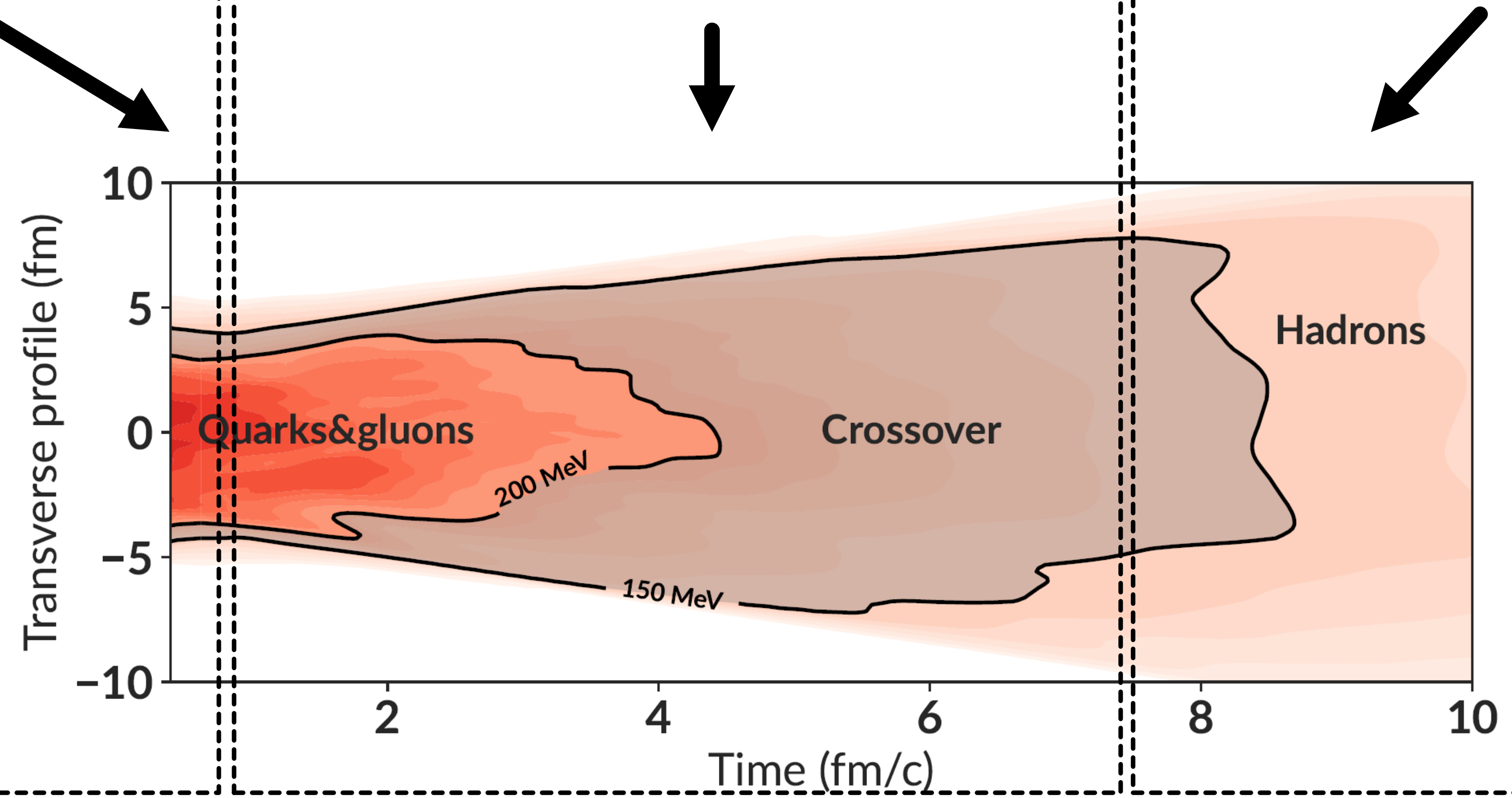


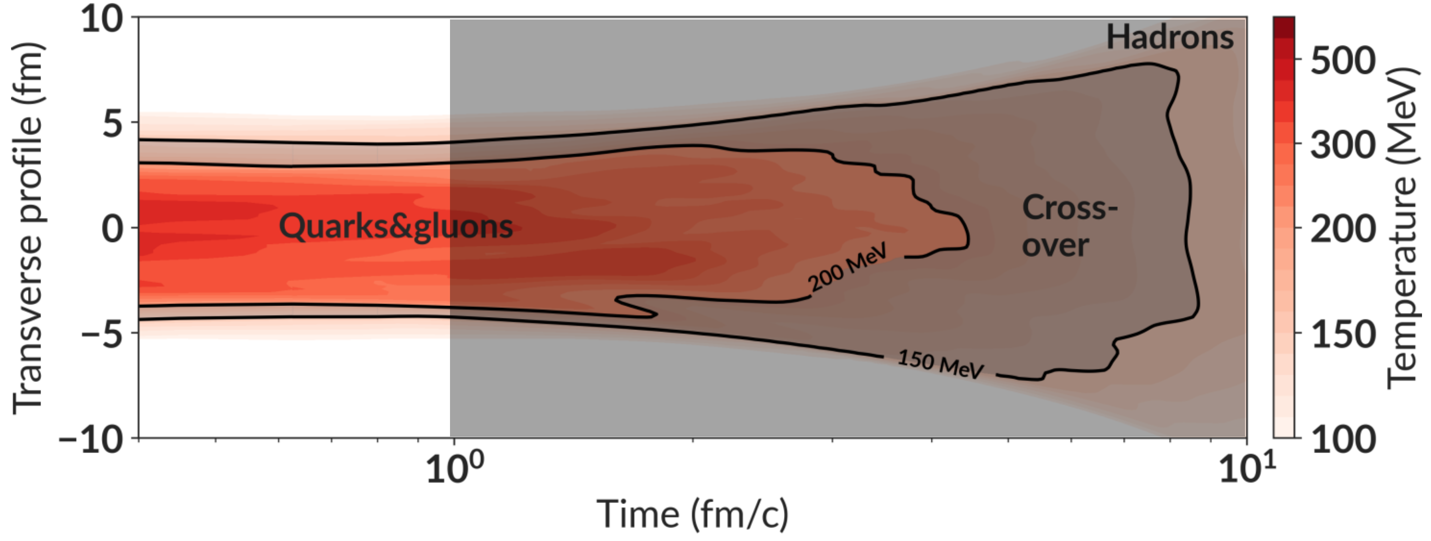
Outline

Part I:
Pre-equilibrium photons/dileptons

Part II:
thermal photons and dileptons

Part III:
Late-stage photons and dileptons



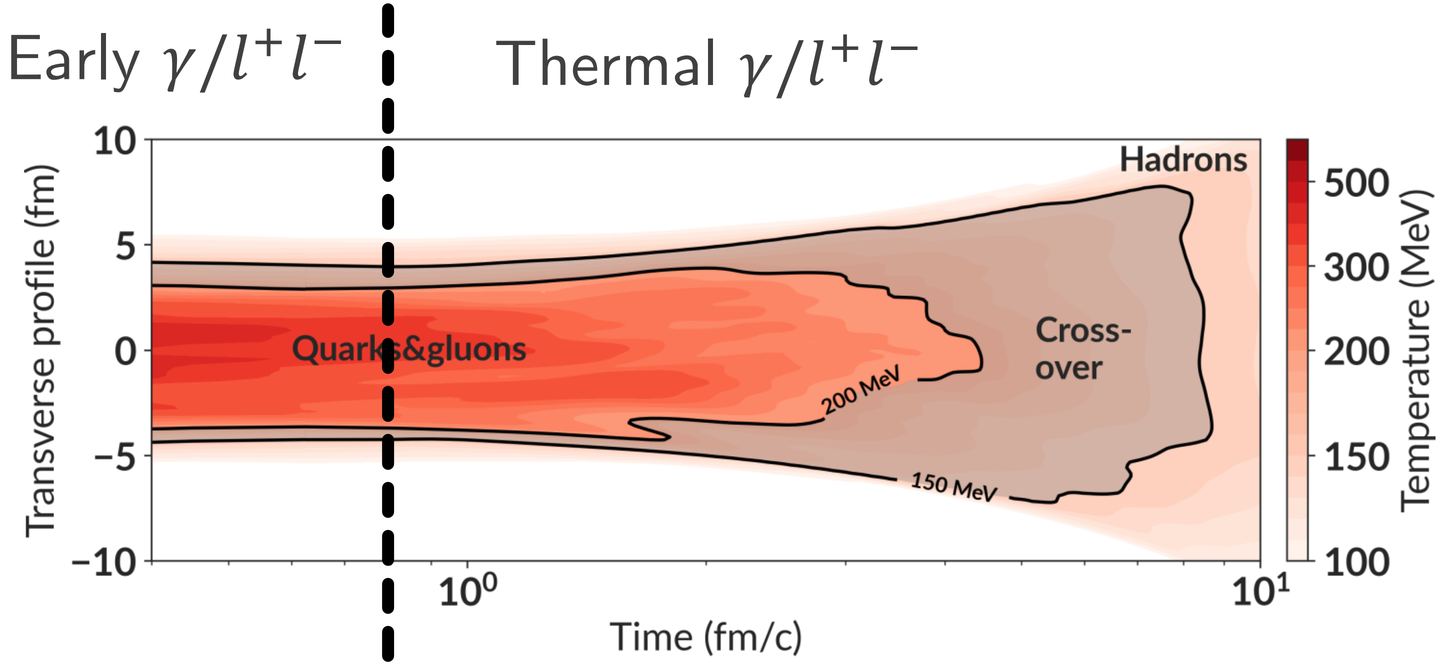


Early-time dynamics itself:
previous talk by Kirill Boguslavski

EARLY-STAGE EMISSION OF γ/l^+l^-

Early-stage emission

- Recent works focused on emission from soft bath of quarks&gluons
- Multiple previous works on emission during formation of soft bath



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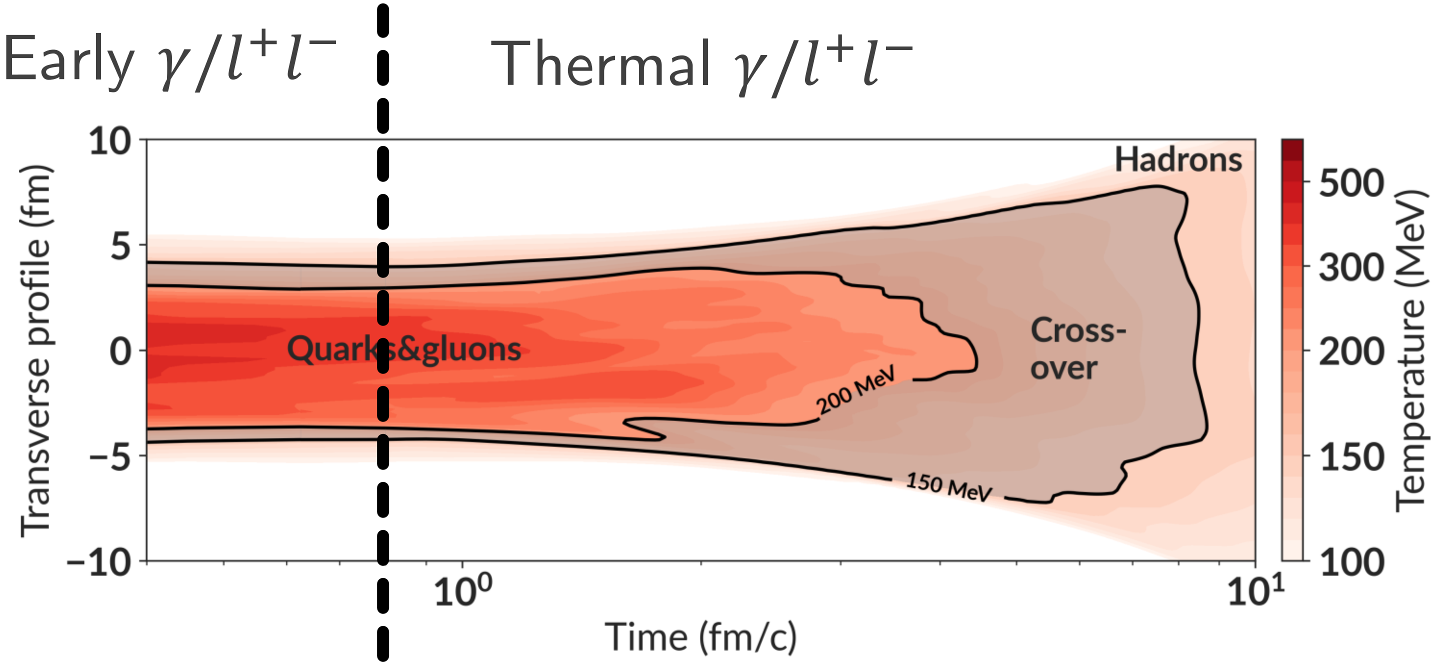


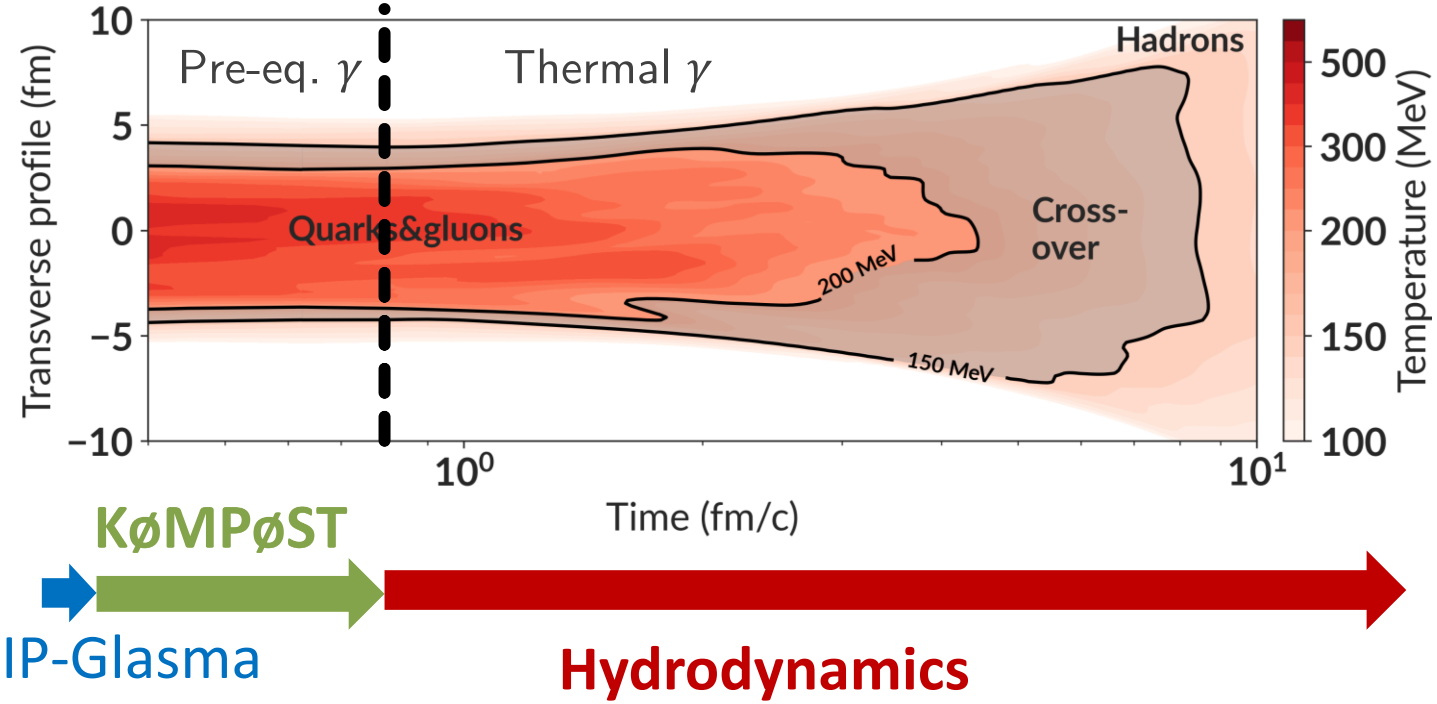
<u>Emission from the soft bath</u>

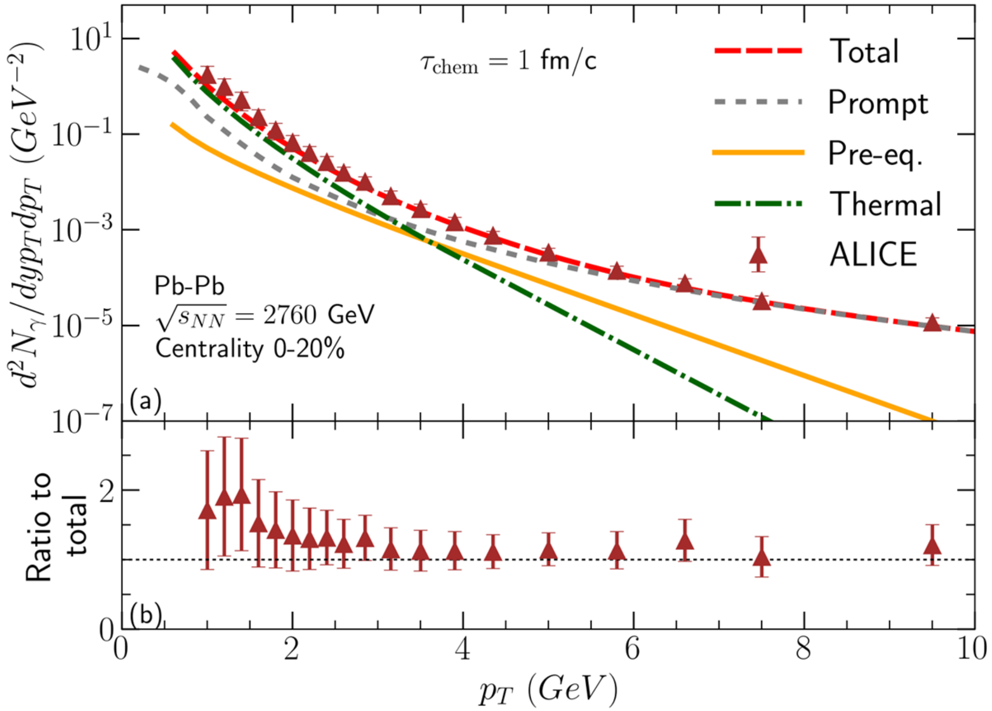
- What is the spatial distribution?
- What is the **rate** of photon and dilepton emission at early times?
  - **Rate** determined by quark/gluon ratio and momentum distributions

    e.g. thermal distributions = equilibrium emission rate ($e^{-\mathrm{energy}/\mathrm{T}}$)

Early-stage photons

Gale, Paquet, Schenke, Shen (2022) PRC

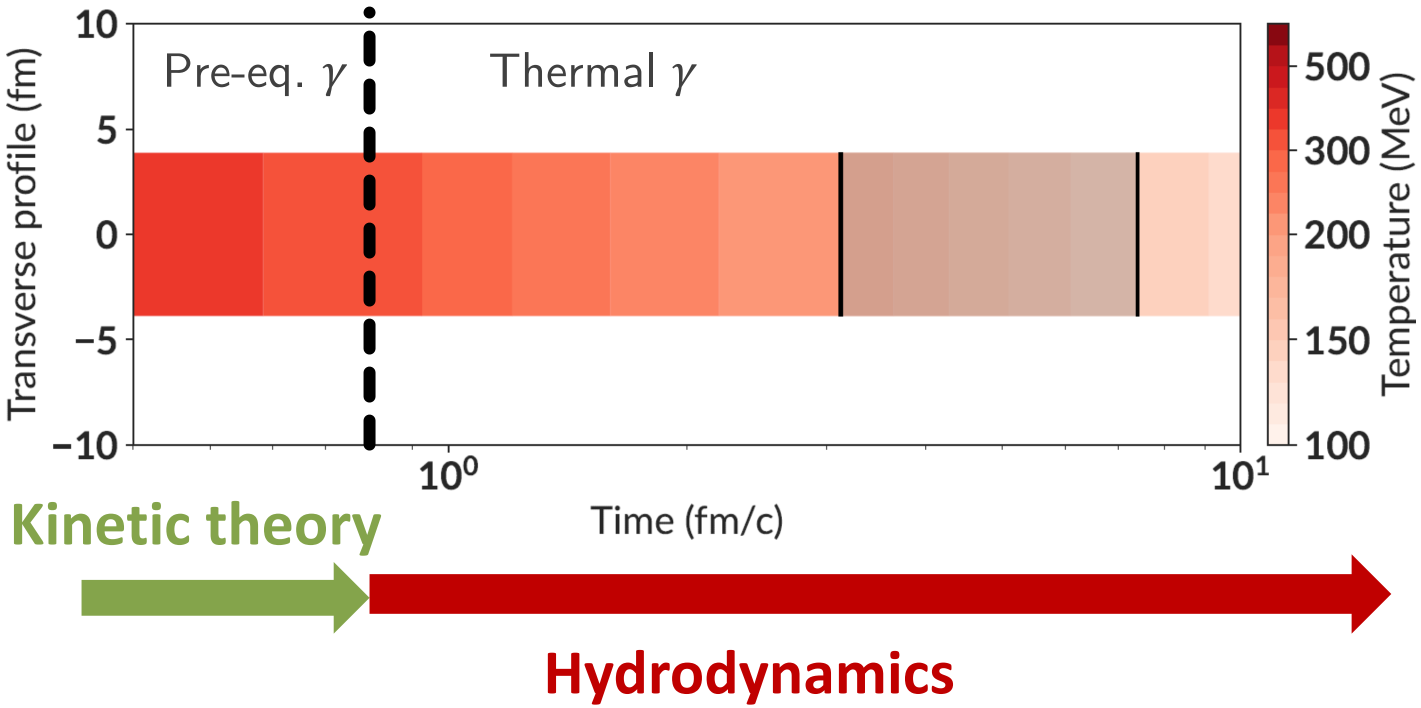




- What is the spatial distribution? IP-Glasma+KøMPøST
- What is the rate of photon emission at early time?
  - Thermal rate w/ viscous corrections + rate suppression factor for chemistry

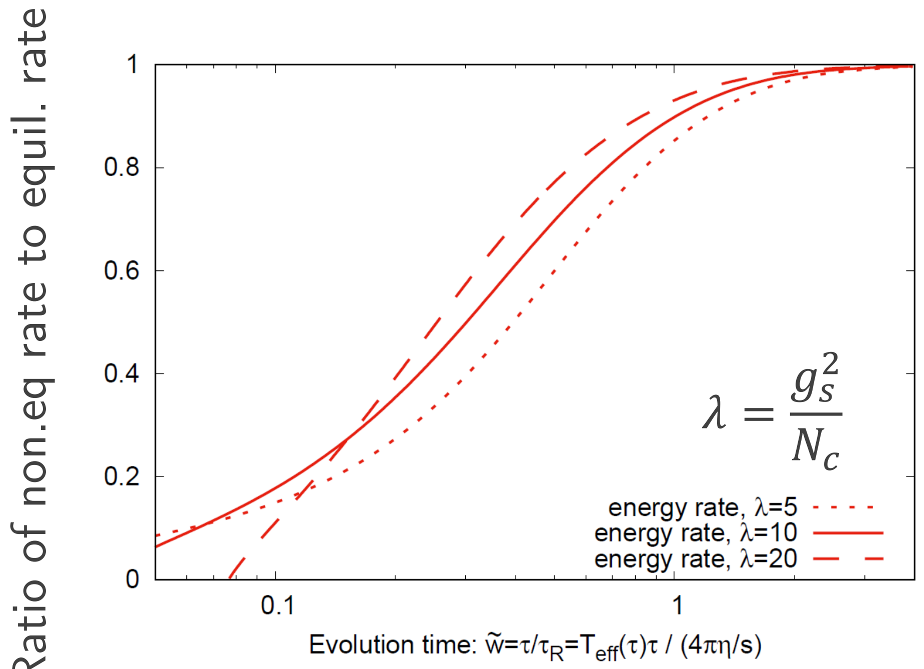
Early-stage photons

Philip Plaschke, Thursday 10:00



Photon emission rate and relaxation to (local) equilibrium calculated consistently

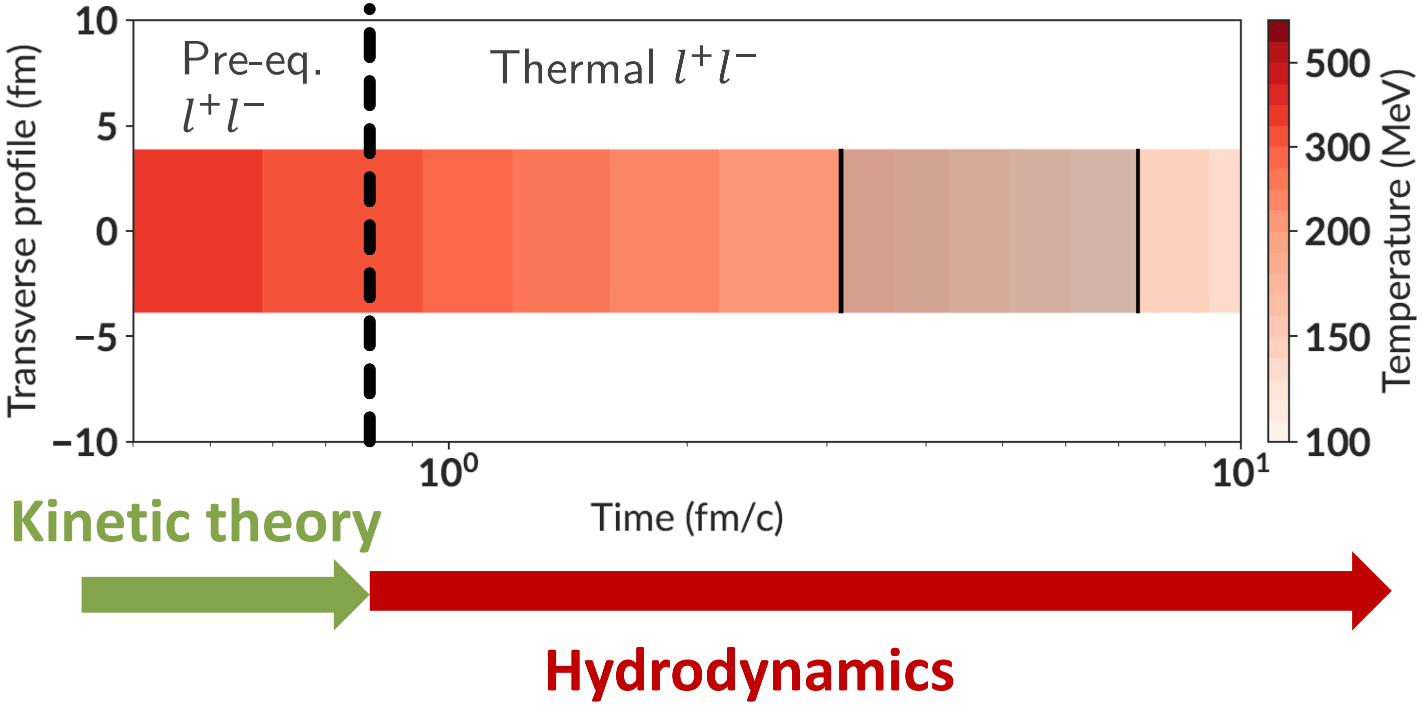
- What is the spatial distribution? Conformal 0+1D boost-invariant
- What is the rate of photon emission at early time?



Evolution time over relaxation time

Early-stage dileptons

Maurice Coquet, Wednesday 10:50



Constraints from photons and dileptons on early-stage momentum anisotropy

- What is the spatial distribution? Conformal 0+1D boost invariant
- What is the rate of dilepton emission at early time?

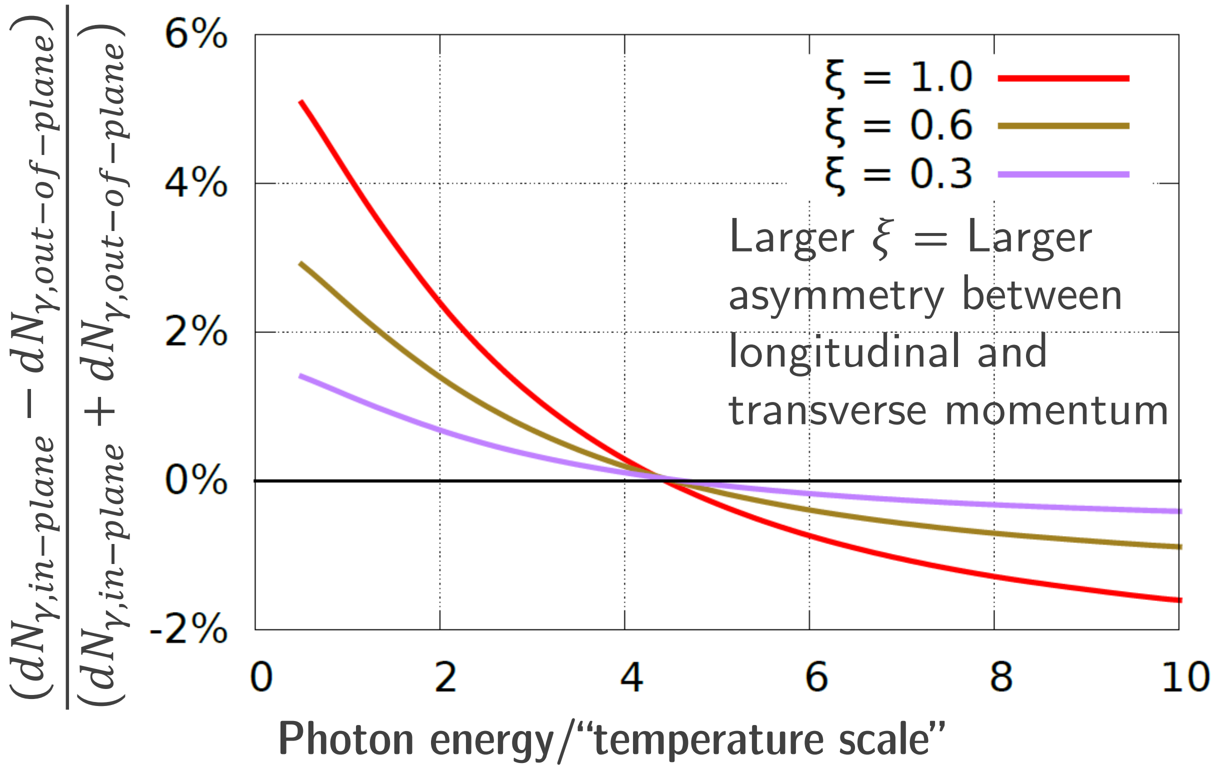
AND

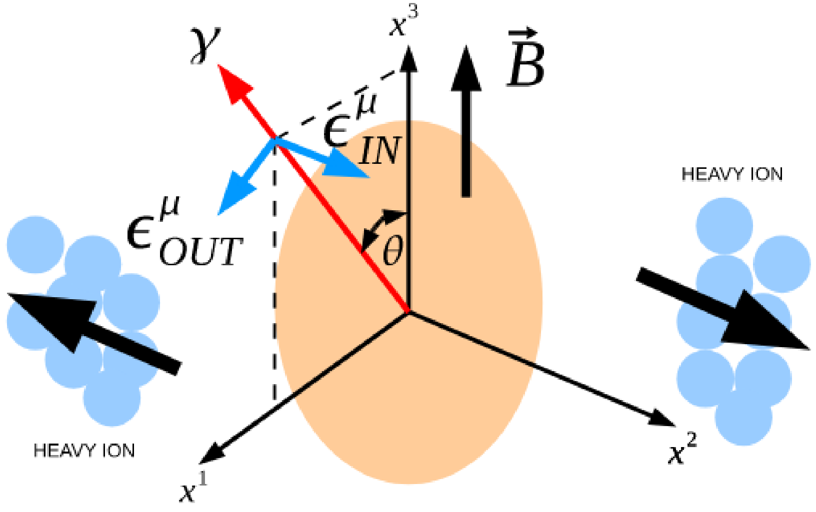
How to differentiate them from other sources, in particular Drell-Yan

⇒ Angular distribution of dileptons

Momentum anisotropy and photon polarization

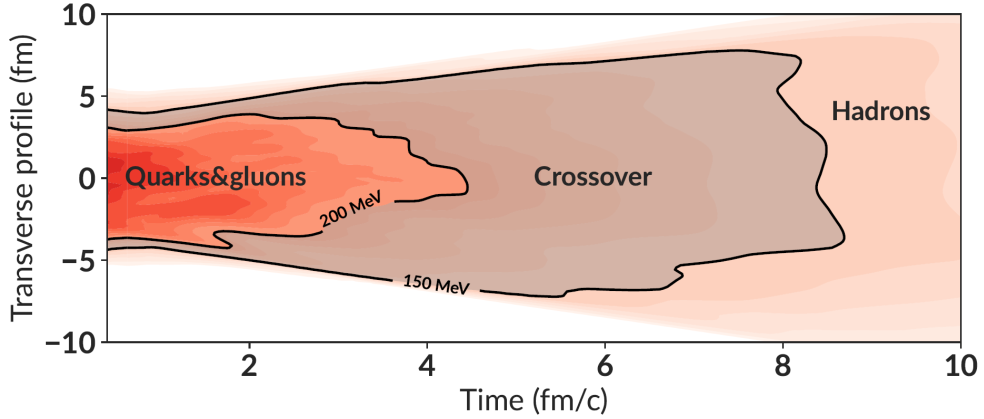
- Previous slides: effect of quark&gluon momentum anisotropy on photon spectrum or dilepton invariant mass spectrum
- **Quark&gluon momentum anisotropy** also **polarizes photons** (& l^+l^-)
  (Full leading-order calculations including bremsstrahlung contributions)





Yee, PRC 2013

Sigtryggur Hauksson, Thursday 9:40



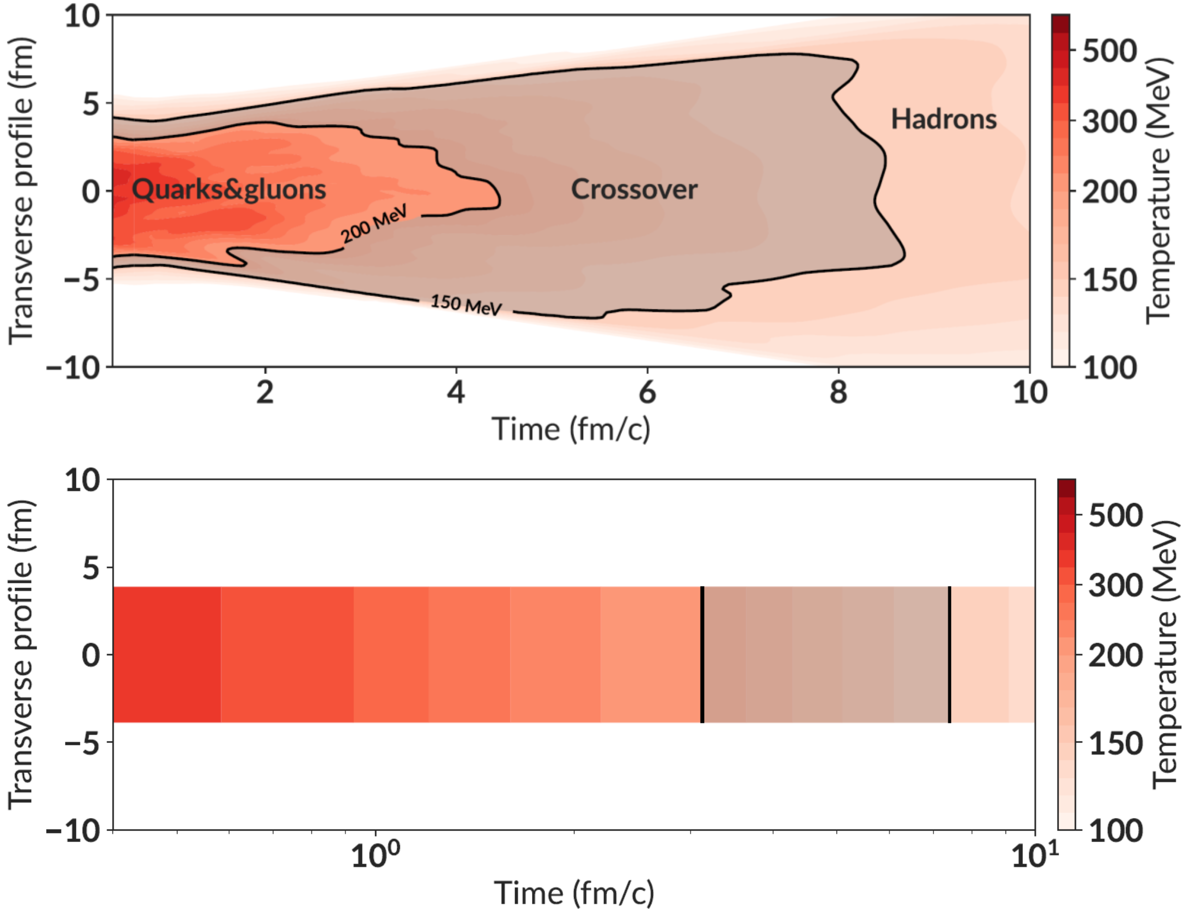
THERMAL AND MEDIUM-MODIFIED PROMPT γ/l^+l^-

Photon emission rate

Photon/l^+l^- emission rate

Spacetime profile of plasma

- Photon production: $$\frac{d^4N_\gamma}{d^4k} = \int d^4X \, \frac{d^4\Gamma_{\gamma/l^+l^-}}{d^3p}(p, T(X), u^\mu(X), \ldots)$$



Photon emission rate

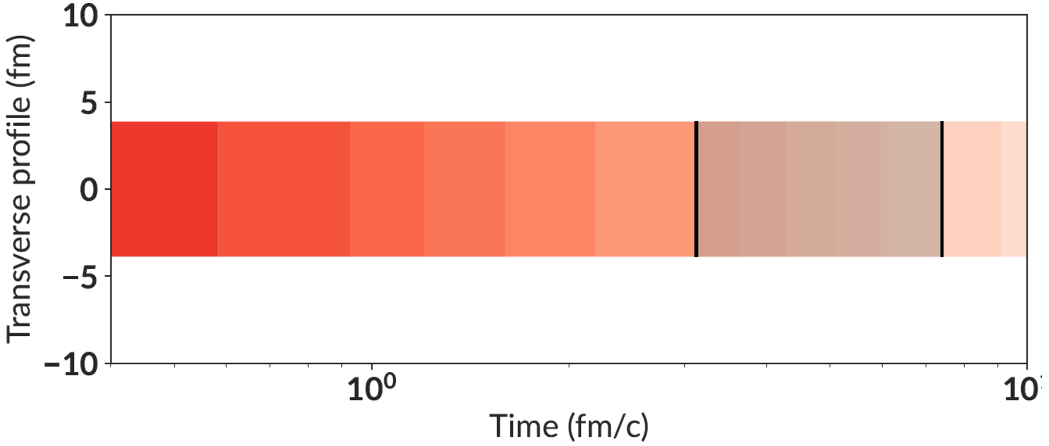
Photon/l^+l^- emission rate

Spacetime profile of plasma

- Photon production: $\frac{d^4N_\gamma}{d^4k} = \int d^4X \frac{d^4\Gamma_{\gamma/l^+l^-}}{d^3p}(p, T(X), u^\mu(X), \dots)$

$$\frac{E\ d^3N_\gamma}{d^3k} \sim \int dT \frac{dV_T}{dT} \sqrt{\frac{2\pi T}{k_T}} \left[k \frac{d^3\Gamma_\gamma(\mathrm{k_T}, \mathrm{T})}{d^3\mathrm{k}}\right]$$

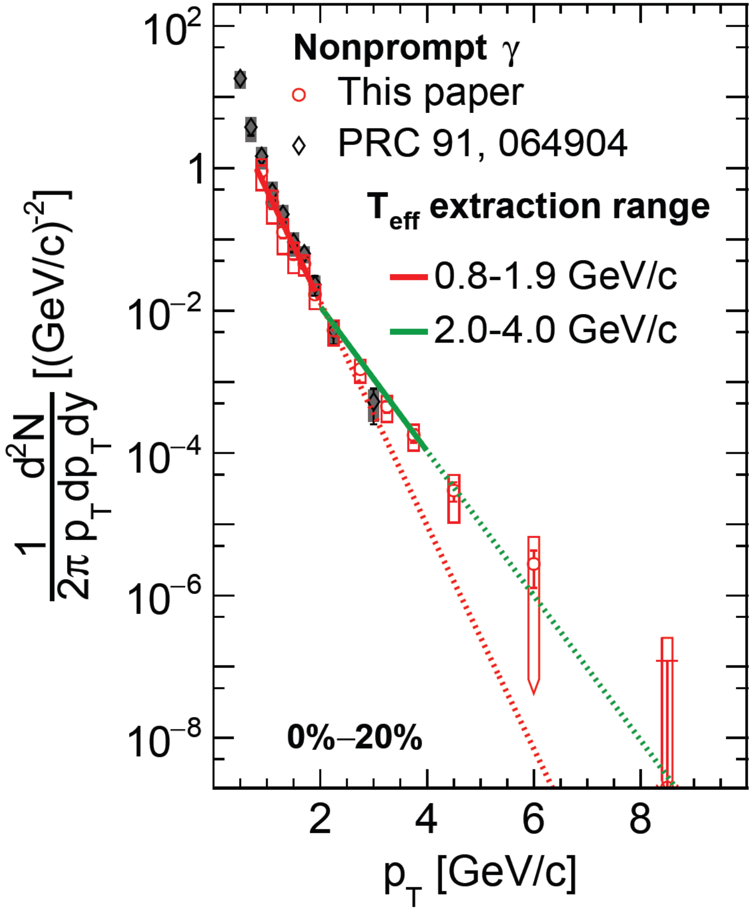
(without effect of transverse flow)



$$T_0 \approx \frac{T_{eff}}{1 - \frac{T_{eff}}{p_T}(cte)}$$

with $(cte) \sim$ 1-2

PHENIX Collaboration (2012) PRL



Corrections from non-conformal speed of sound, non-exp.rate,…: Paquet and Bass, 2022

Photon emission rate

- Photon & l^+l^- production: $$\frac{\mathrm{d}^4 N_\gamma}{\mathrm{d}^4 k} = \int \mathrm{d}^4 X \, \frac{\mathrm{d}^4 \Gamma_{\gamma/l^+l^-}}{\mathrm{d}^3 p}(p, T(X), u^\mu(X), \ldots)$$

Photon/l^+l^- emission rate

Degrees of freedom/Temperatures	Electromagnetic emission rate
Gas of hadrons below $T \approx 150$ MeV	Effective hadronic models
Deconfinement for $T \approx 150 - 200$ MeV	Extrapolated rates from low/high temperatures
Strongly-coupled quark/gluons for $T \sim 200+$ MeV	Lattice QCD, effective models , holography
Weakly-coupled QGP at $T \gg 1$ GeV	Perturbative QCD

Photon emission rate in sQCD

Dibyendu Bala, Tuesday 17:50

- Given transverse and longitudinal spectral function $\rho_T(\omega, k)$ and $\rho_L(\omega, k)$, the rates are

$$\frac{d\Gamma_\gamma}{d^3\vec{k}} = \frac{\alpha_{\rm em} n_B(k)}{\pi^2 k}\left(\sum_{i=1}^{N_f} Q_i^2\right)\rho_T(k, \vec{k}),$$

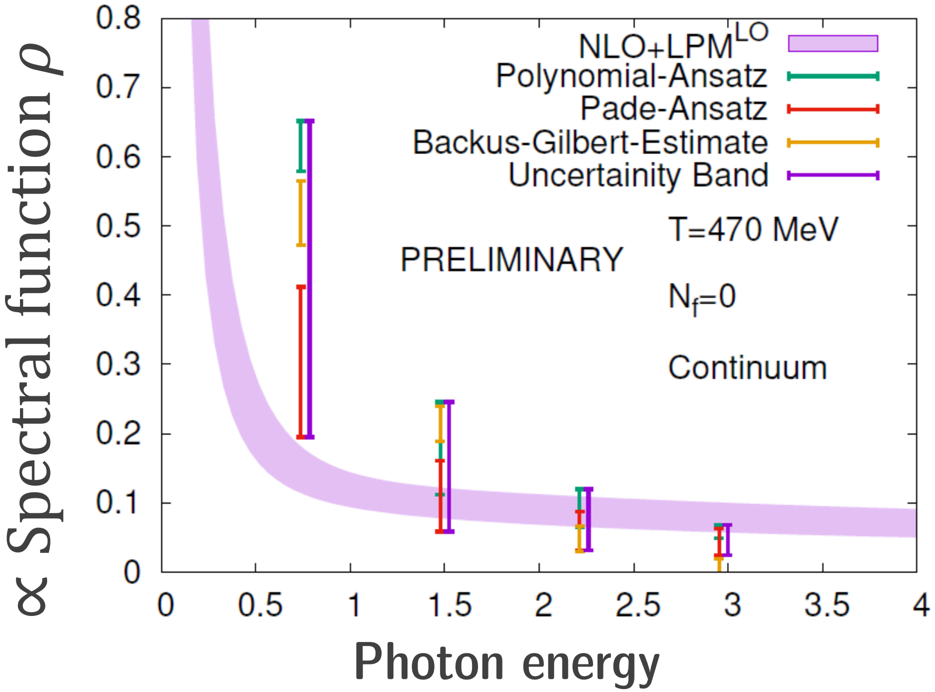
$$\frac{d\Gamma_{l^+l^-}}{d\omega d^3\vec{k}} \simeq \frac{\alpha_{\rm em}^2 n_B(\omega)}{3\pi^2(\omega^2 - k^2)}\left(\sum_{i=1}^{N_f} Q_i^2\right)\left(2\rho_T(\omega, \vec{k}) + \rho_L(\omega, \vec{k})\right)$$

Ref.: Bala, Ali, Francis, Jackson, Kaczmarek, Ueding (2023)

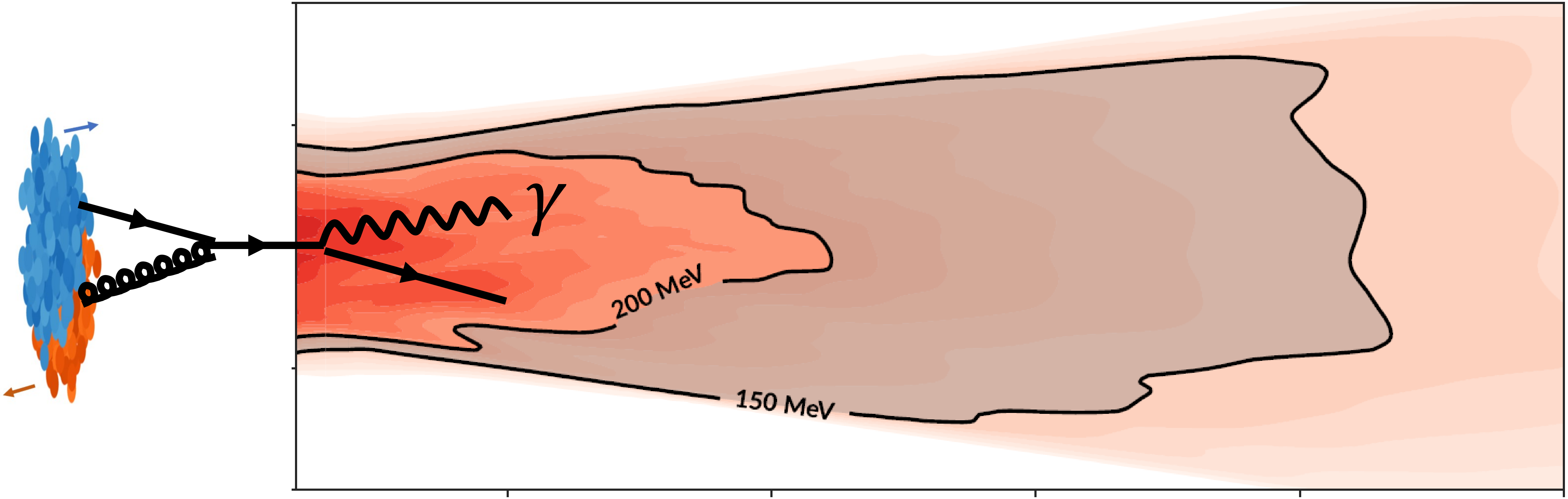
- Lattice constraints from relation

$$G_E(\tau, \vec{k}) = \int_0^\infty \frac{d\omega}{\pi}\,\rho(\omega, \vec{k})\,\frac{\cosh[\omega(1/2T - \tau)]}{\sinh(\omega/2T)}$$

Lattice constraints → Ansatz of spectral function



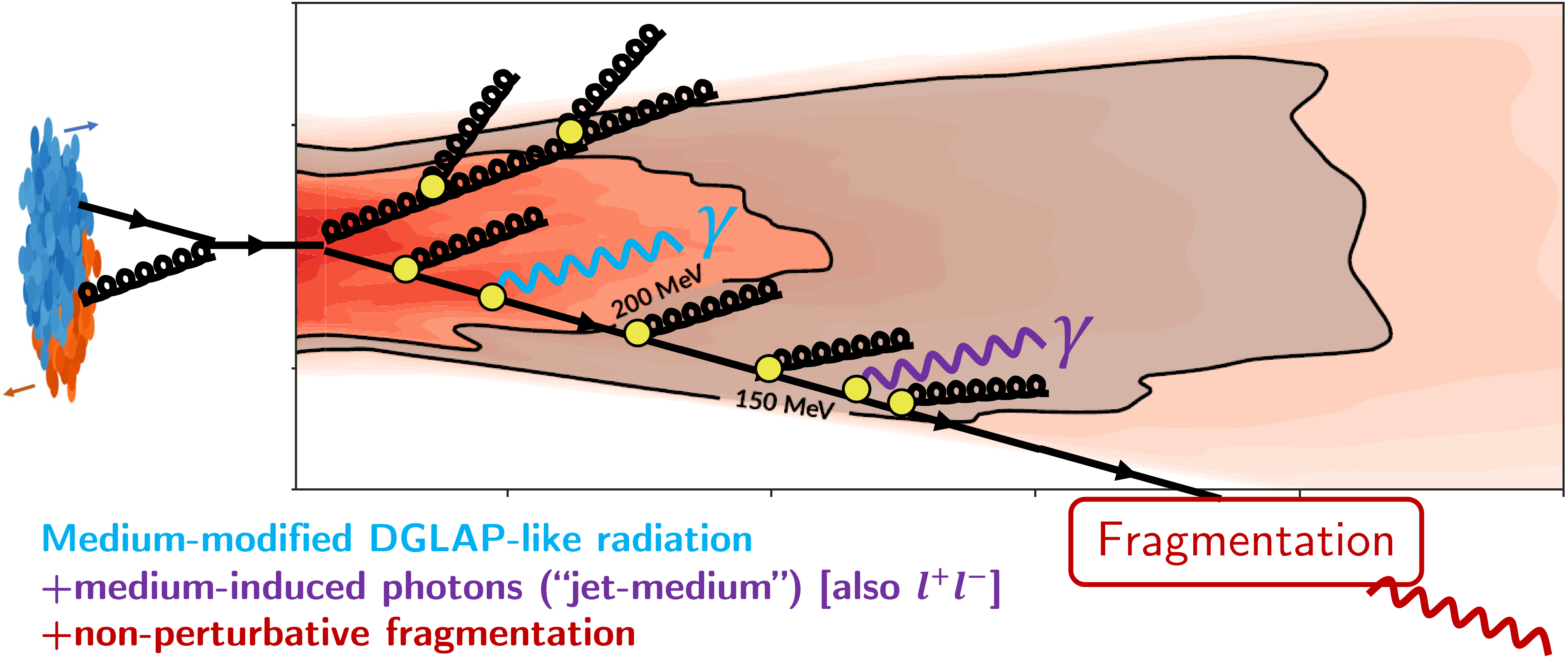
Medium-modified prompt photons



No medium effects on Compton scattering and $q\,\bar{q}$ annihilation

$$q + \bar{q} \rightarrow g + \gamma$$
$$q + g \rightarrow q + \gamma$$
$$q + g \rightarrow q + g + \gamma \ ?$$

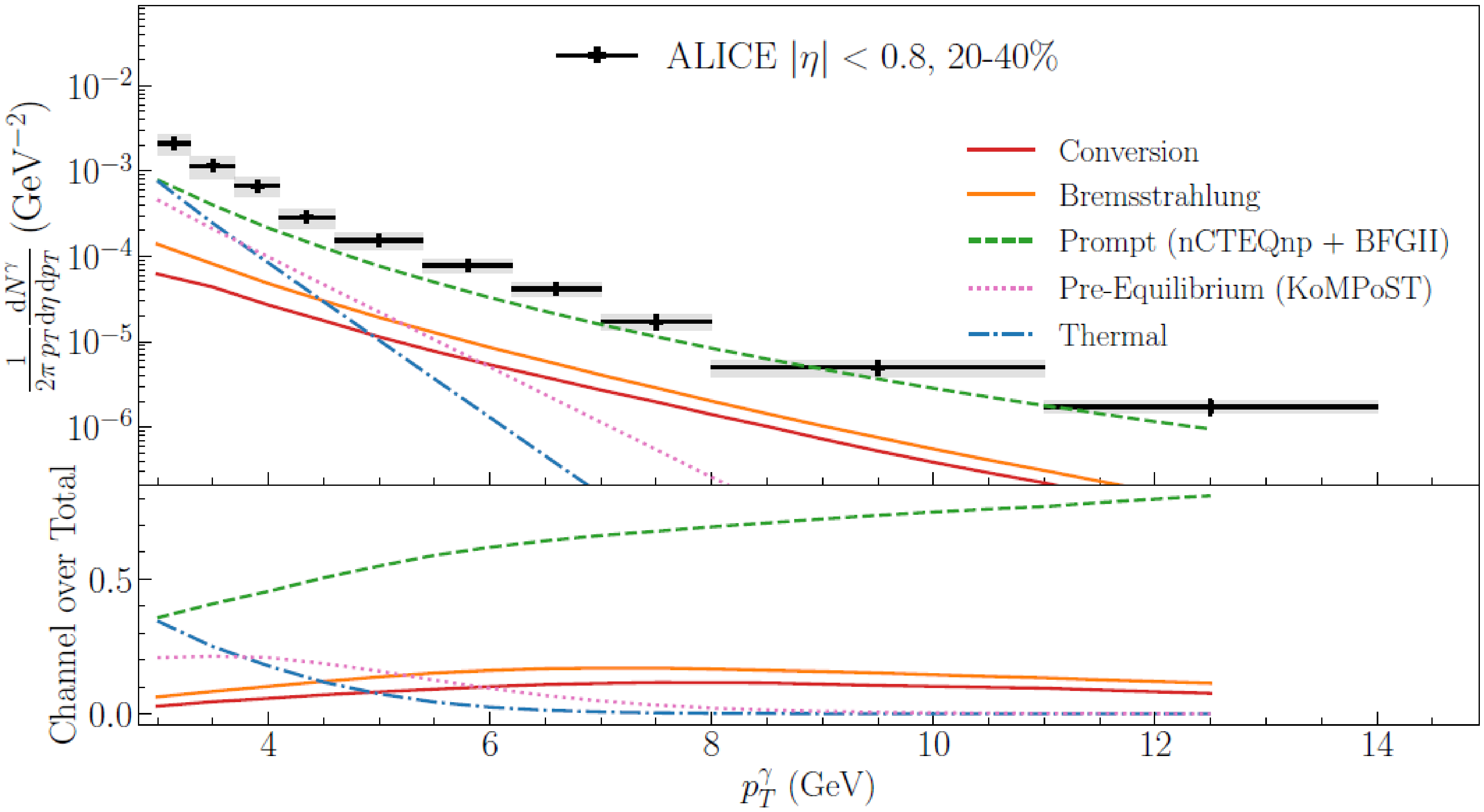
Medium-modified prompt photons



Medium-modified DGLAP-like radiation
+medium-induced photons ("jet-medium") [also l^+l^-]
+non-perturbative fragmentation

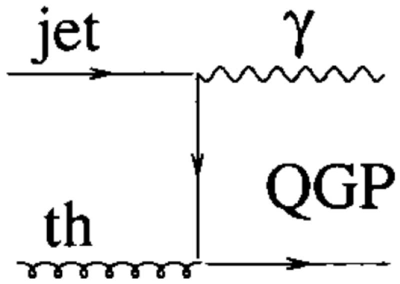
Jet-medium photons

Rouzbeh Modarres-Yazdi, Tuesday 14:40

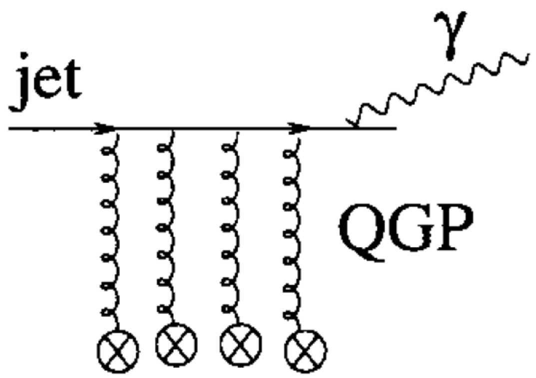


Shi, Modarresi Yazdi, Gale, Jeon (2022)

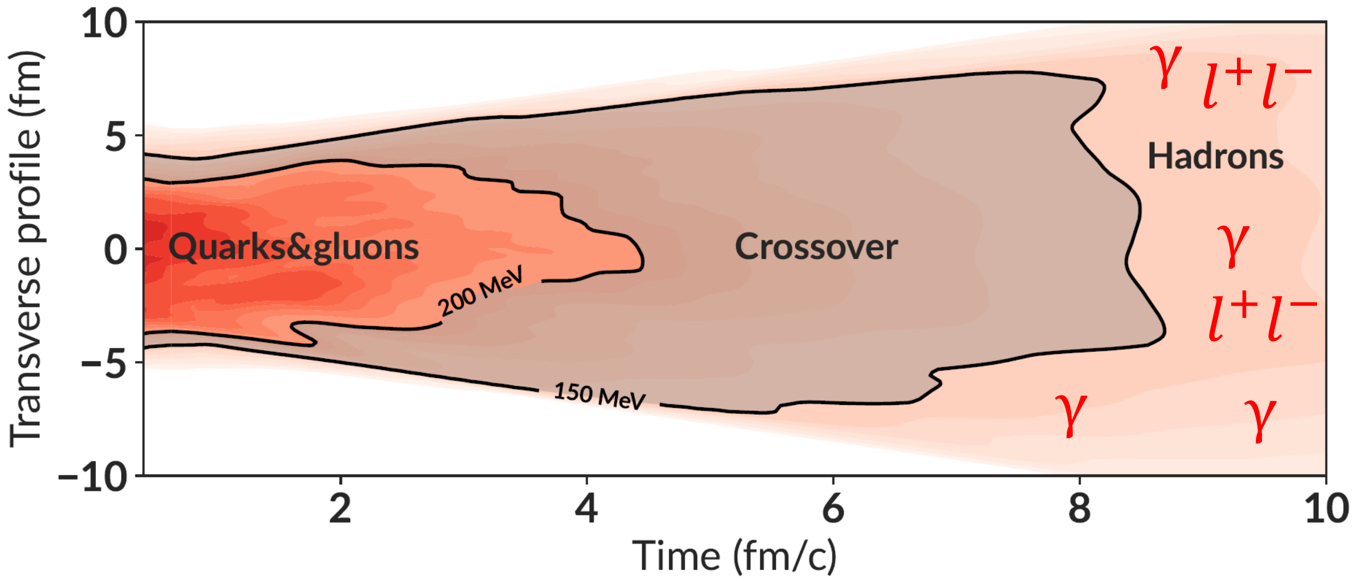
Conversion



Bremsstrahlung



Figures from S.Turbide



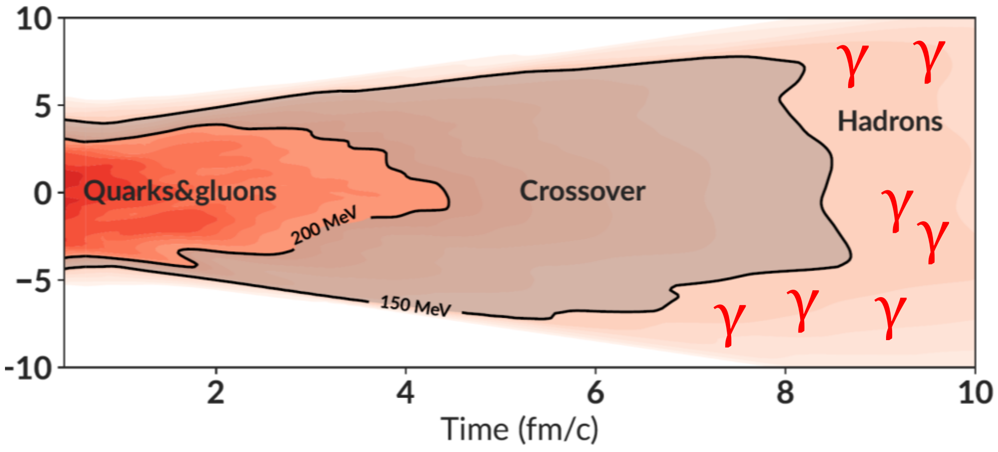
Electromagnetic emission from:

- Hadronic decays
- Hadronic interactions

LATE-TIME EMISSION

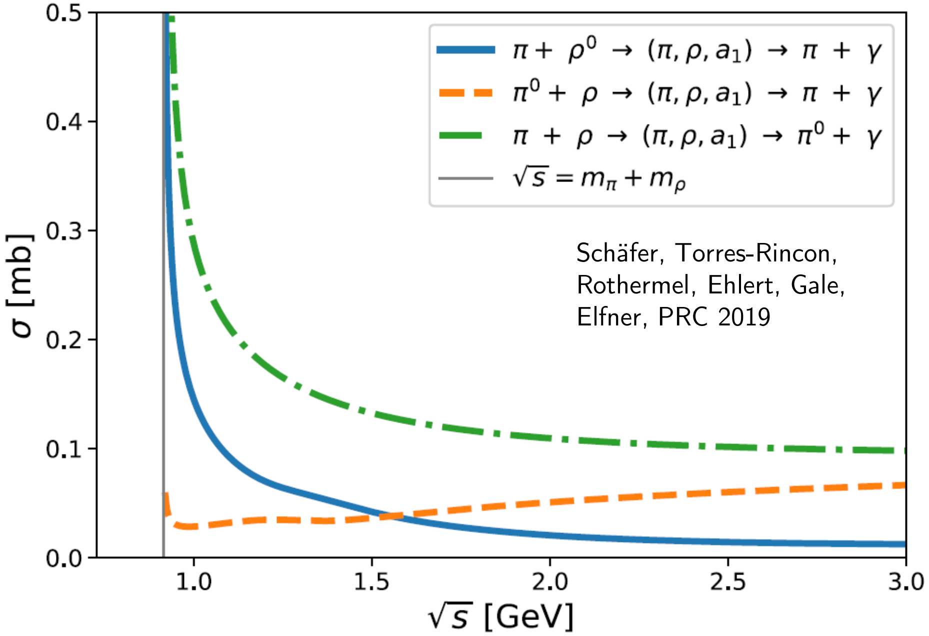
Photons from hadronic interactions

Hannah Elfner, Tuesday 15:20

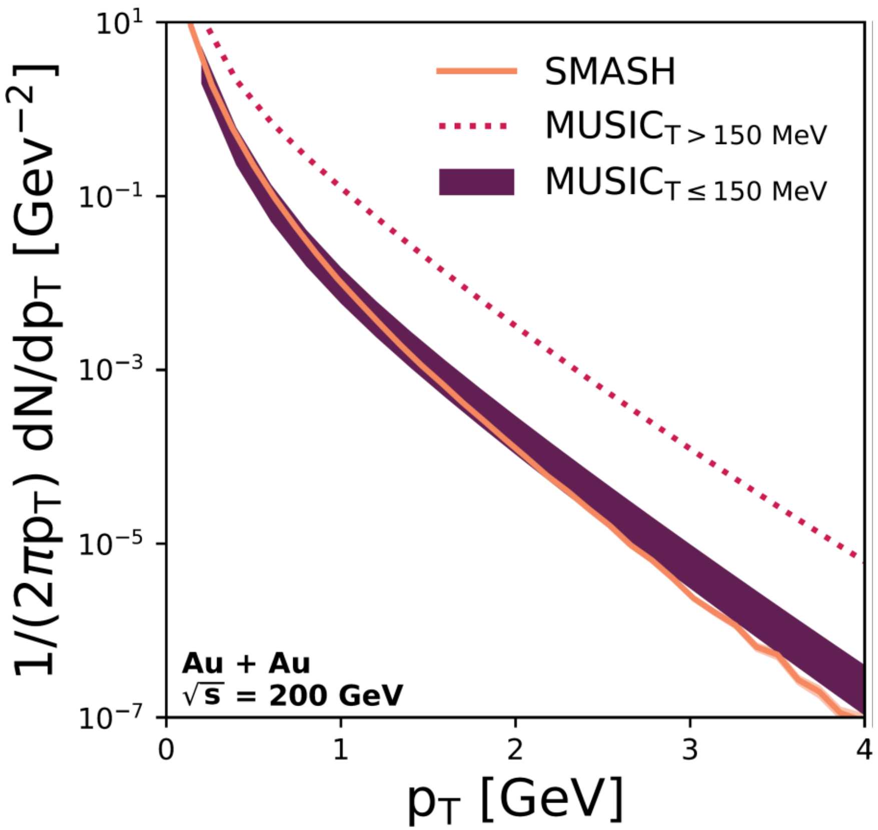


$$\frac{\mathrm{d}^4 N_\gamma}{\mathrm{d}^4 k} = \int \mathrm{d}^4 X \frac{\mathrm{d}^4 \Gamma_{\gamma/l^+l^-}}{\mathrm{d}^3 p}(p, T(X), u^\mu(X), \ldots)$$

Hydro + rate vs hadronic transport



Schäfer, Torres-Rincon, Rothermel, Ehlert, Gale, Elfner, PRC 2019



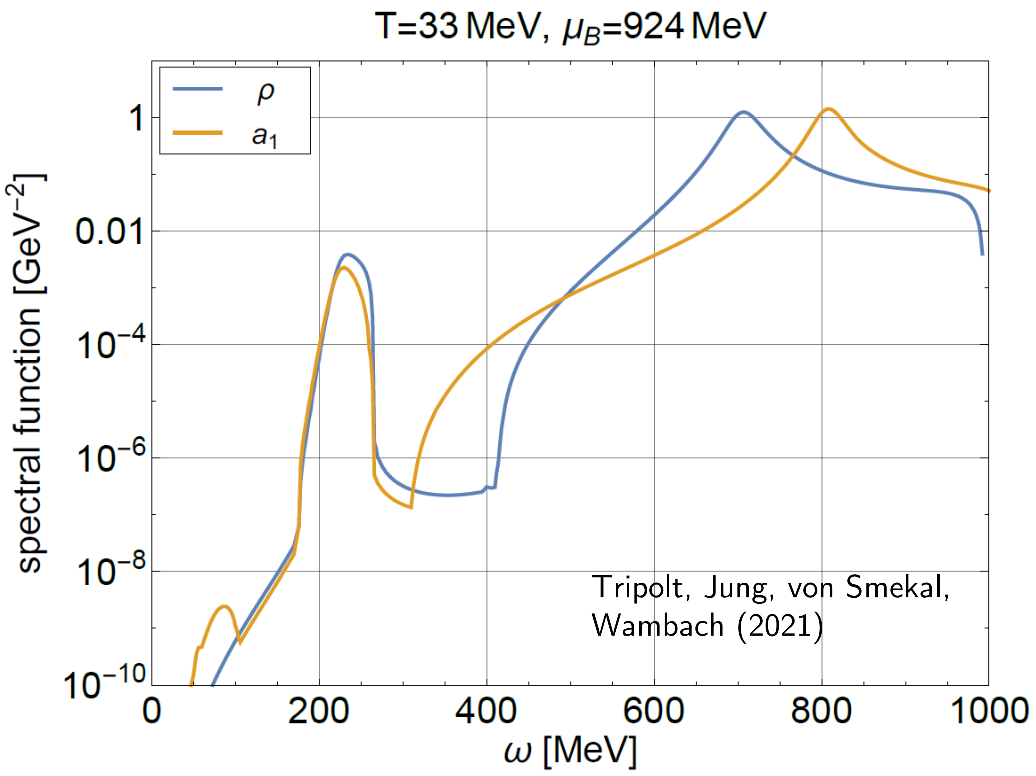
Significant effect on the photon v_2 , see parallel talk

In-medium vector and axial-vector spectral functions

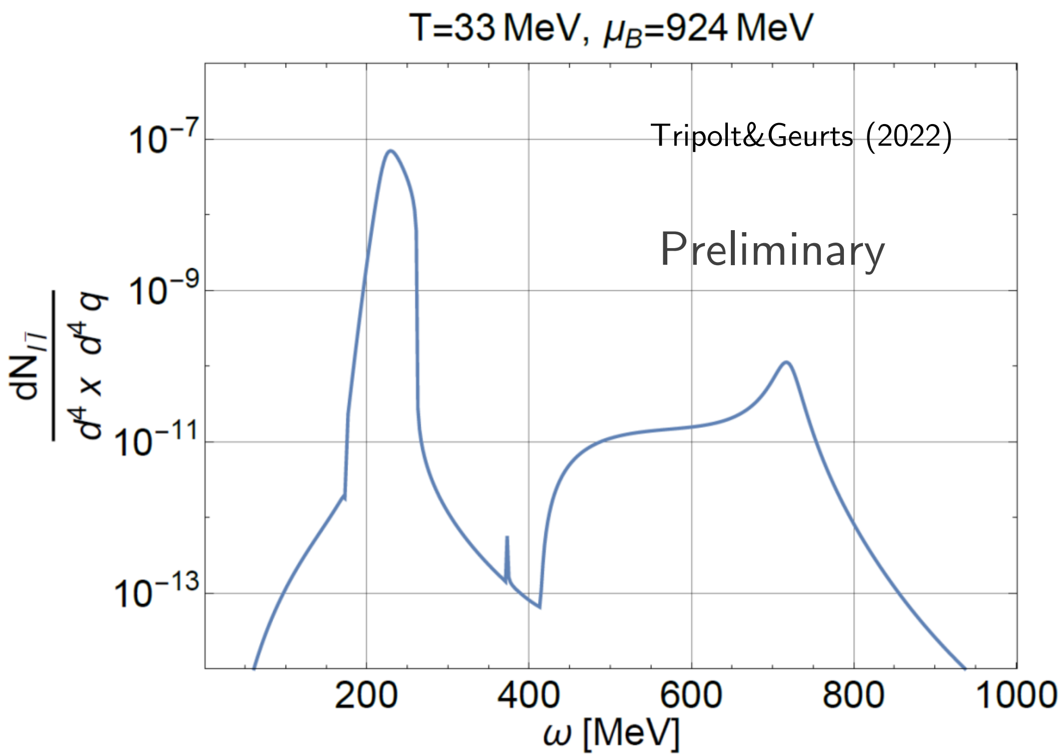
In-medium properties from (analytically continued) Functional Renormalization Group (FRG)

Ralf-Arno Tripolt, Thursday 9:20

$\rho \& a_1$ spectral function at low T&large μ_B

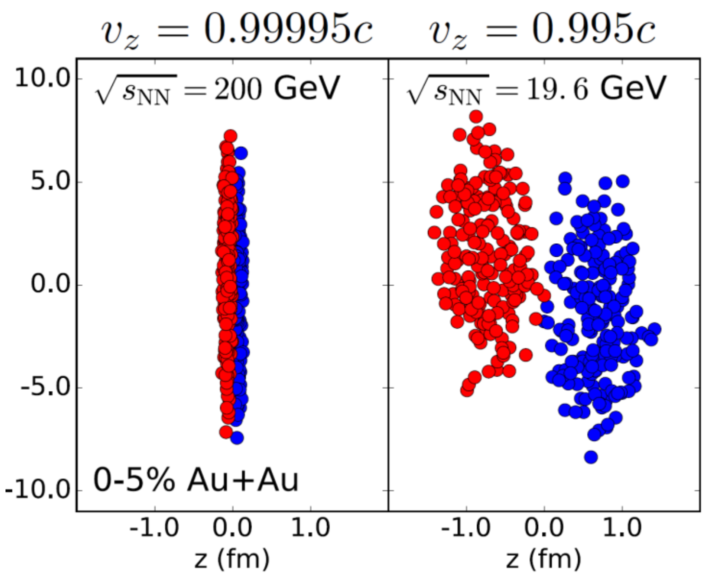


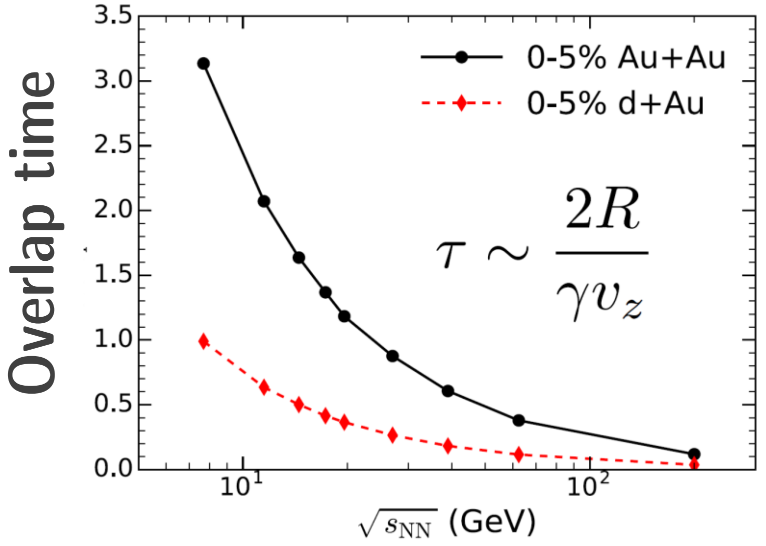
Dilepton rate

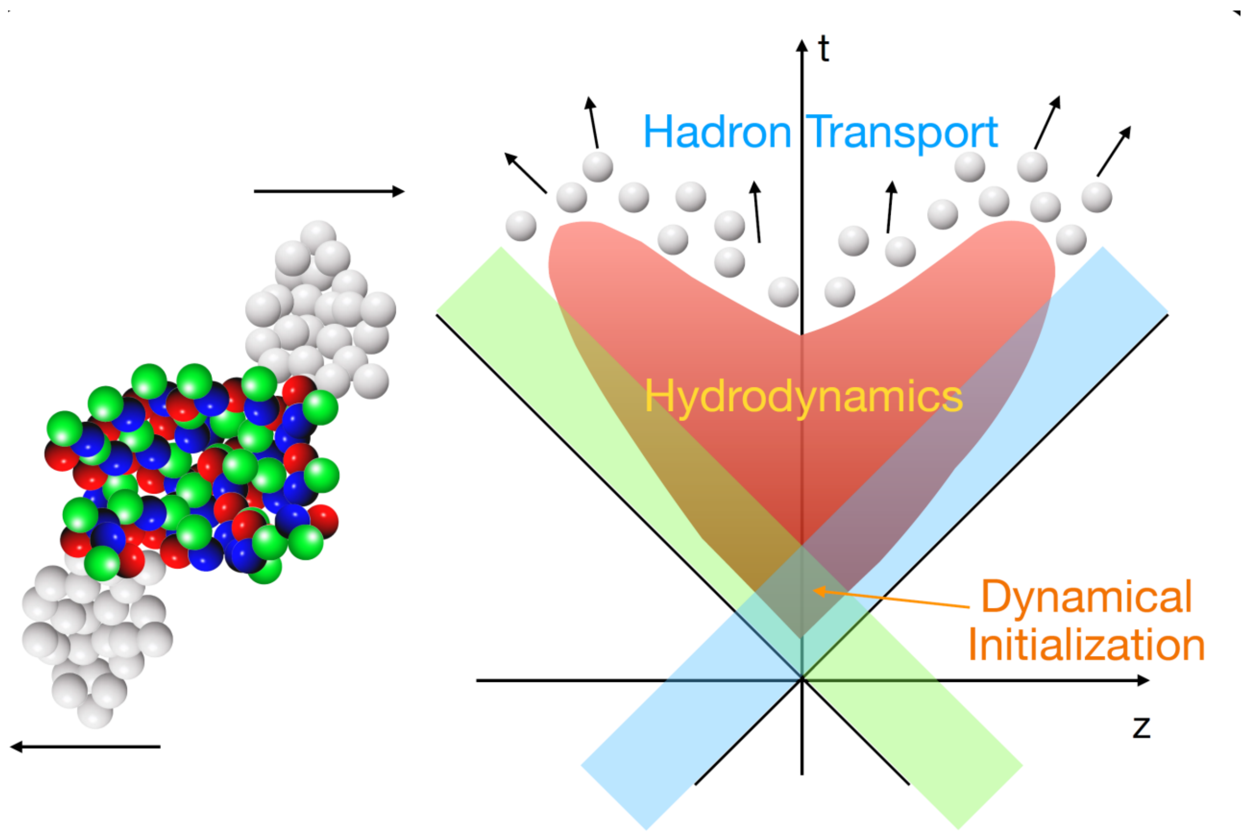


ELECTROMAGNETIC EMISSION AT LOWER BEAM ENERGY

Low-energy collisions: extended "initial conditions"





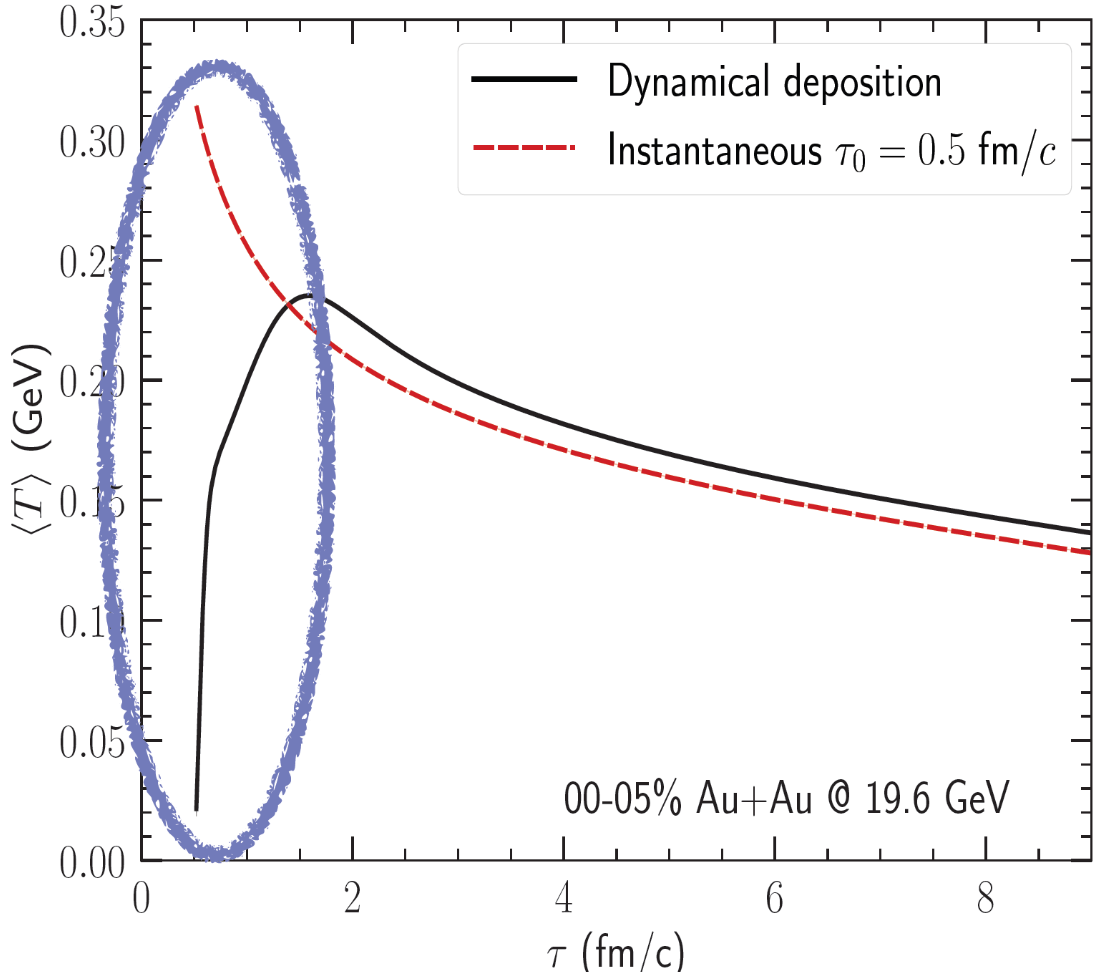


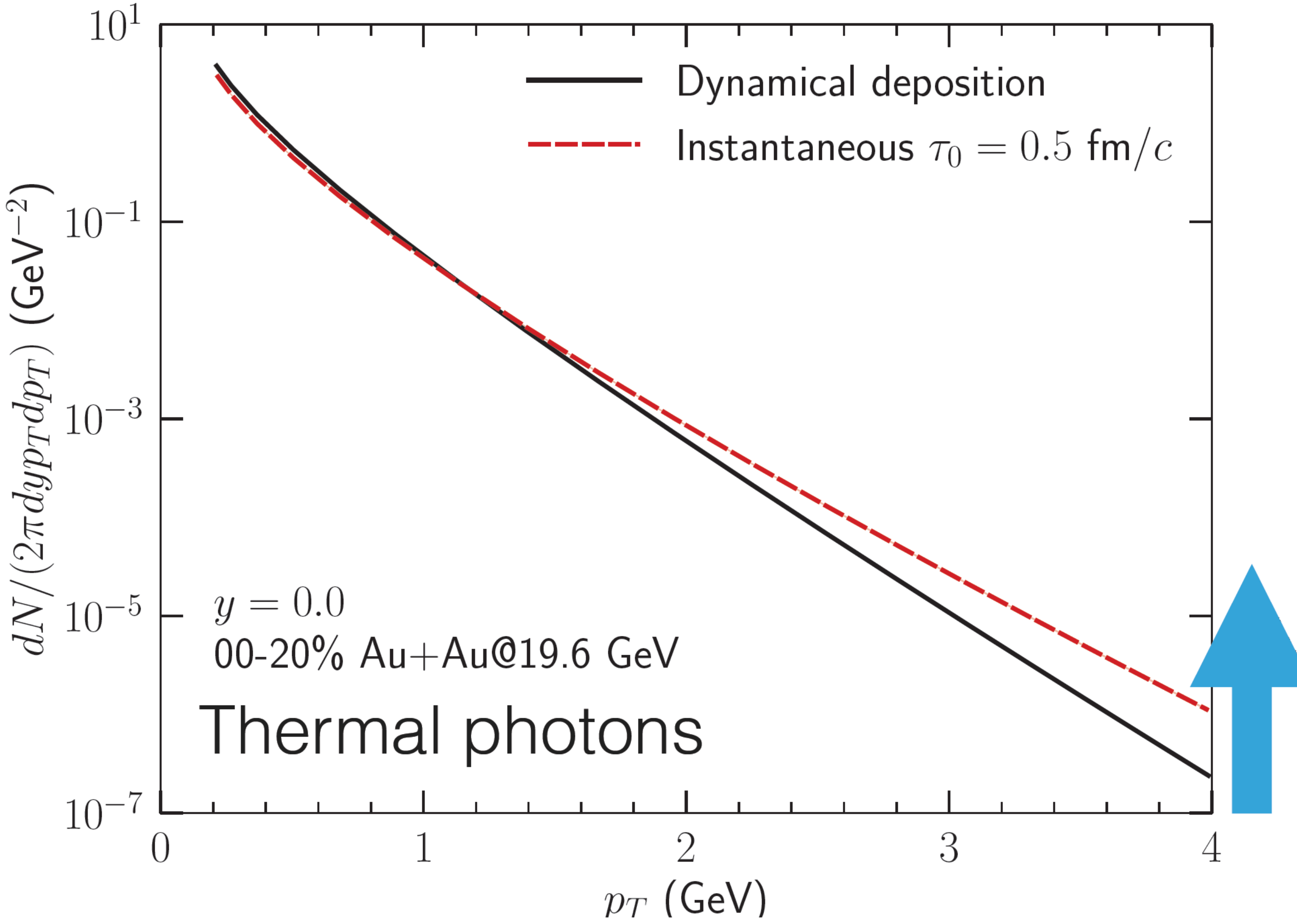
C. Shen and L. Yan, Nucl. Sci. Tech. 31, no.12, 122

Chun Shen, Wednesday 14:20

Low-energy collisions: photons as probes

Chun Shen, Wednesday 14:20



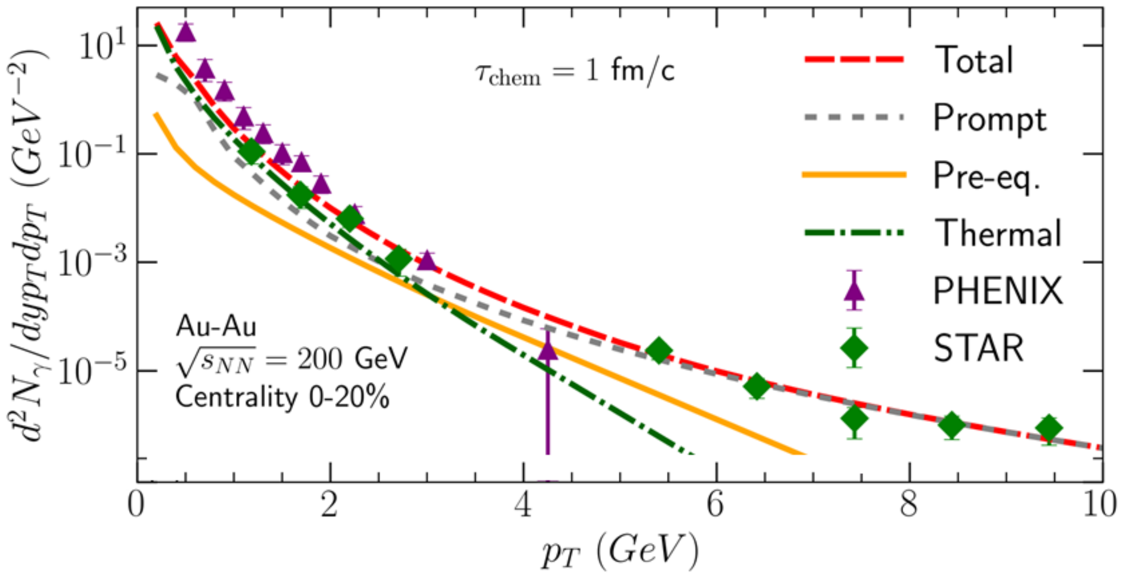


Thermal photons sensitive to energy deposition

SUMMARY

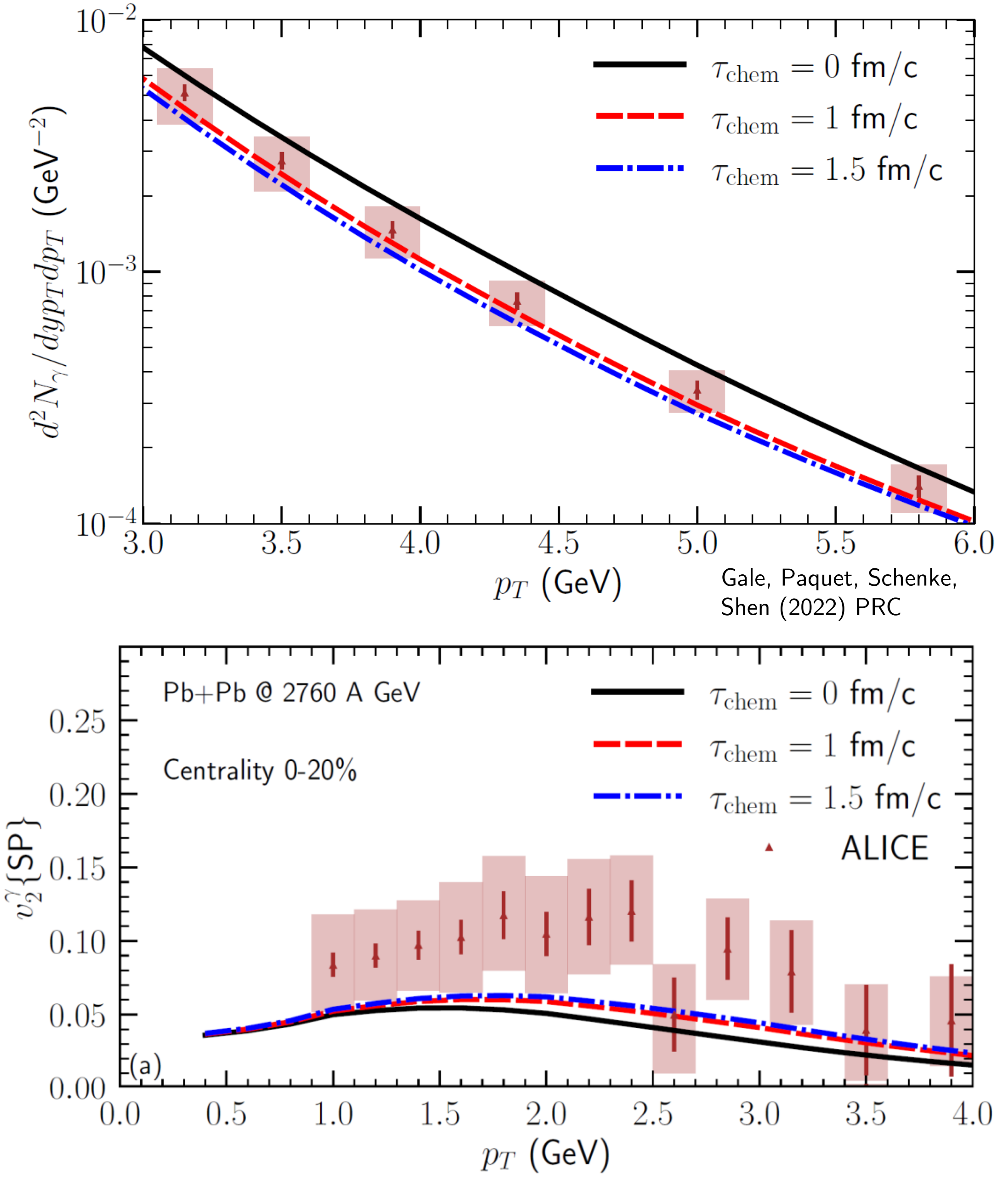
Summary

- Study the early-stage of plasma with photons and dileptons
  - Approach to equilibrium (thermal & chemical) and initial momentum anisotropy
  - New measurements suggested or revisited
  - Early stage increasingly important in small collisions or at lower collision energy
- Constraints on photon emission rate from strongly-coupled QGP ($T \gtrsim 200$ MeV)
- Photons from hadronic transport
- Calculations of photons from jet-plasma interactions



Outlook

- Pre-eq + thermal rate + jet-medium + photons from hadronic transport: effect on photon v_2?
- Other sources of photons and dileptons?
- Important role of dileptons at low collision energies (large μ_B)
- Chiral symmetry restoration
- Lower uncertainties on spectrum and v_n?
- What new measurements are possible?



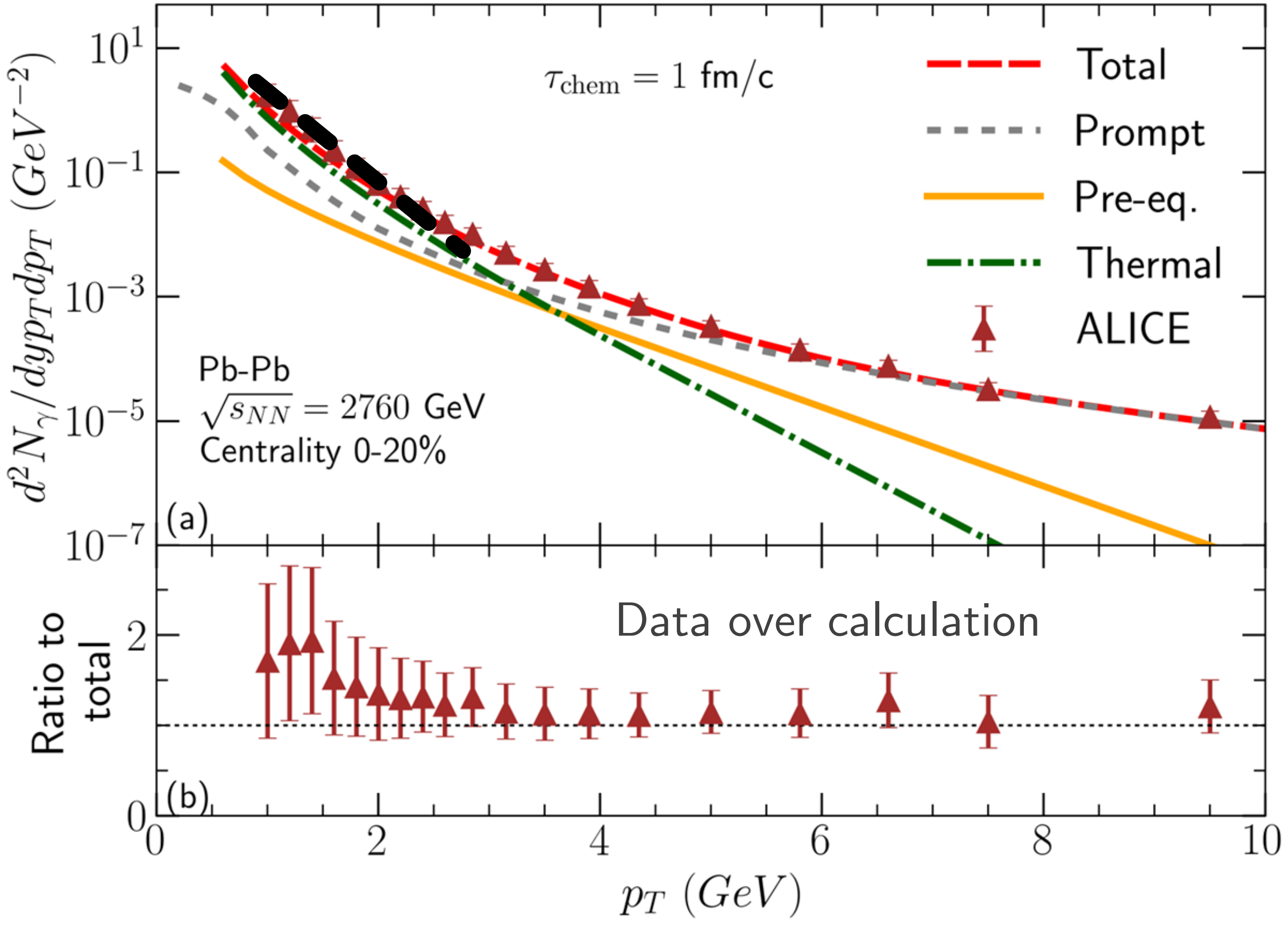
Gale, Paquet, Schenke, Shen (2022) PRC

QUESTIONS?

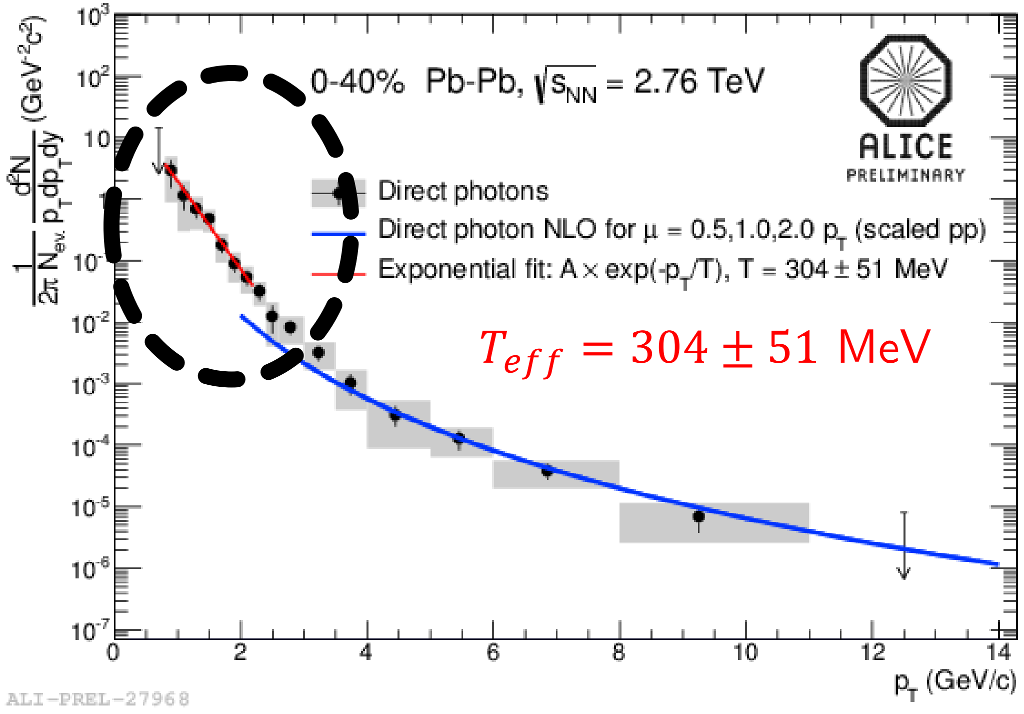
BACKUP

Results: Pb-Pb $\sqrt{s_{NN}}$ =2760 GeV, 0-20%

Gale, Paquet, Schenke, Shen (2022) PRC

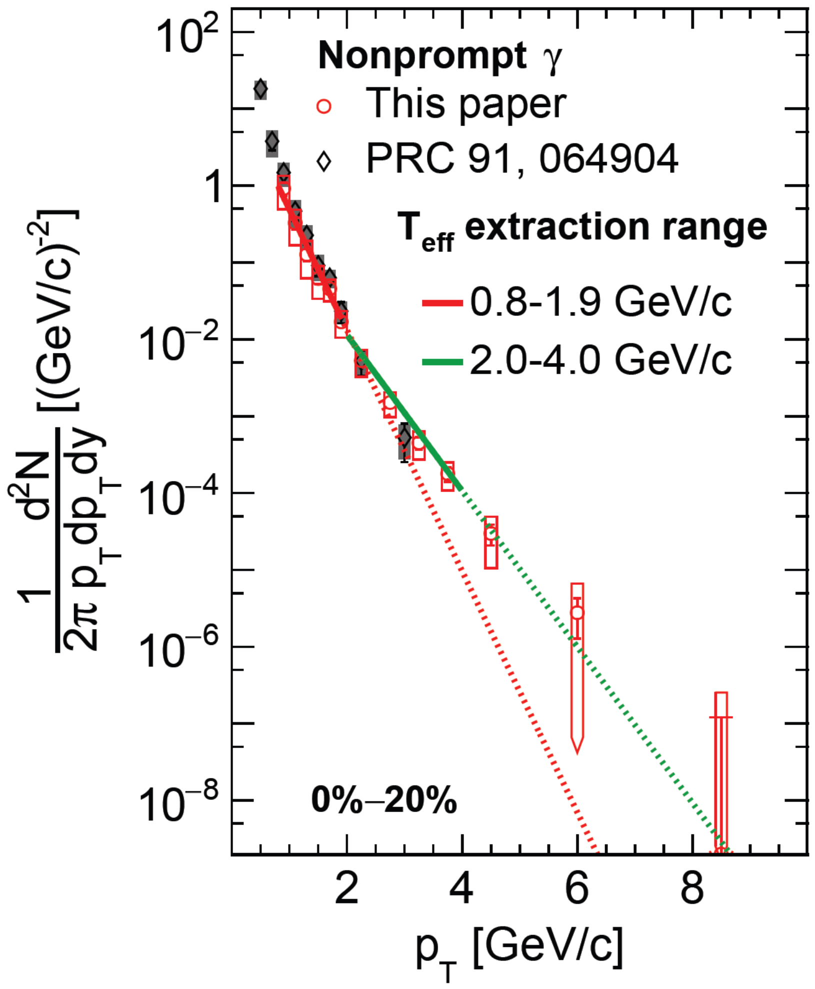


$$\ln\left(\frac{1}{2\pi E}\frac{dN}{dE\,dy}\right) = cte - \frac{E}{T_{eff}}$$



Results: Au-Au $\sqrt{s_{NN}}$ =200 GeV, 0-20%

Ref.: PHENIX Collaboration (2012) PRL



$$\ln\left(\frac{1}{2\pi E}\frac{dN}{dE\,dy}\right) = cte - \frac{E}{T_{eff}}$$

centrality	$T_{\rm eff}$ (GeV/c) $0.8 < p_T < 1.9$ GeV/c	$T_{\rm eff}$ (GeV/c) $2 < p_T < 4$
0%–20%	$0.277 \pm 0.017\ ^{+0.036}_{-0.014}$	$0.428 \pm 0.031\ ^{+0.031}_{-0.030}$
20%–40%	$0.264 \pm 0.010\ ^{+0.014}_{-0.007}$	$0.354 \pm 0.019\ ^{+0.020}_{-0.030}$
40%–60%	$0.247 \pm 0.007\ ^{+0.005}_{-0.004}$	$0.392 \pm 0.023\ ^{+0.022}_{-0.022}$
60%–93%	$0.253 \pm 0.011\ ^{+0.012}_{-0.006}$	$0.331 \pm 0.036\ ^{+0.031}_{-0.041}$

(Prompt photons subtracted before fit)

Thermal photon spectrum: Doppler shift

$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) = \ln\left(\int \mathrm{d}^4X \frac{1}{E}\frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p}(p, T(X), u^\mu(X), \ldots)\right) \sim cte - \frac{E}{T_{eff}}?$$

Photon emission rate: $\frac{1}{\mathrm{E}}\frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p} \sim e^{-\frac{E}{T}}$

Doppler shift

$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx \ln\left(\int \mathrm{d}^4X\, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte = \ln\left(\int d\phi d\eta_s dx_\perp\, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte$$

At midrapidity, $P \cdot u = p_T\left(\cosh(\eta_s)\sqrt{1+u_\perp^2} - u_\perp \cos(\phi)\right)$

Thermal photon spectrum: Doppler shift

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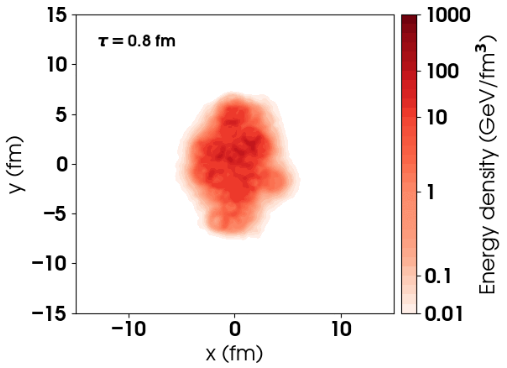


Photon emission rate: $\frac{1}{\mathrm{E}}\frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p} \sim e^{-\frac{E}{T}}$

Doppler shift

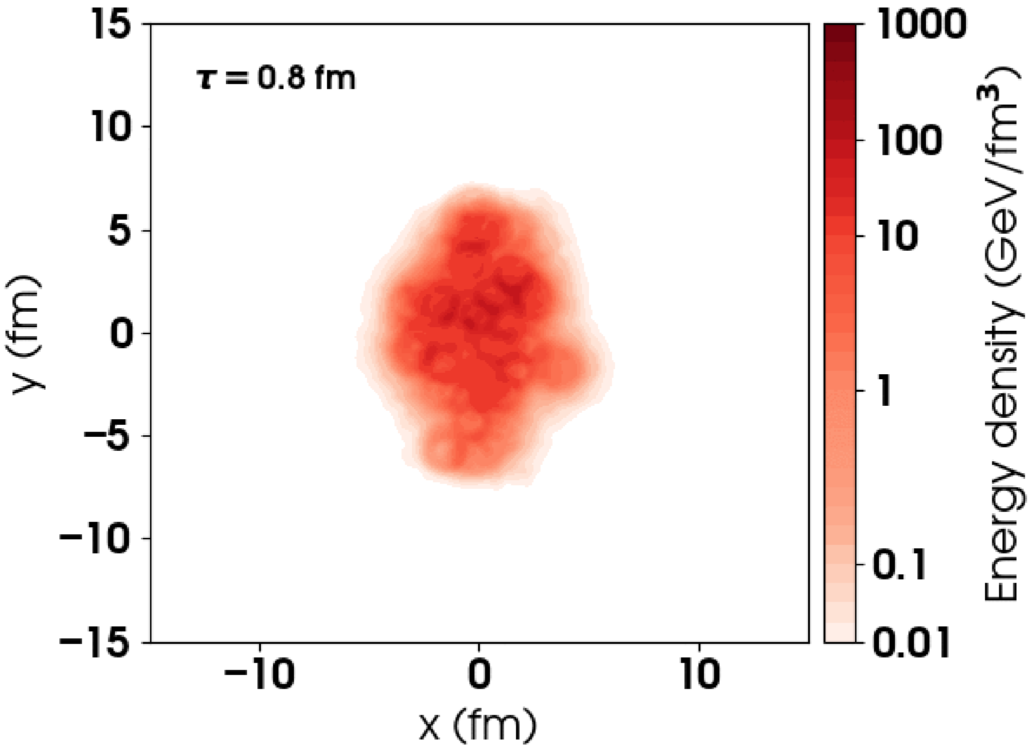
$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx \ln\left(\int \mathrm{d}^4X\, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte = \ln\left(\int d\phi\, d\eta_s\, dx_\perp\, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte$$

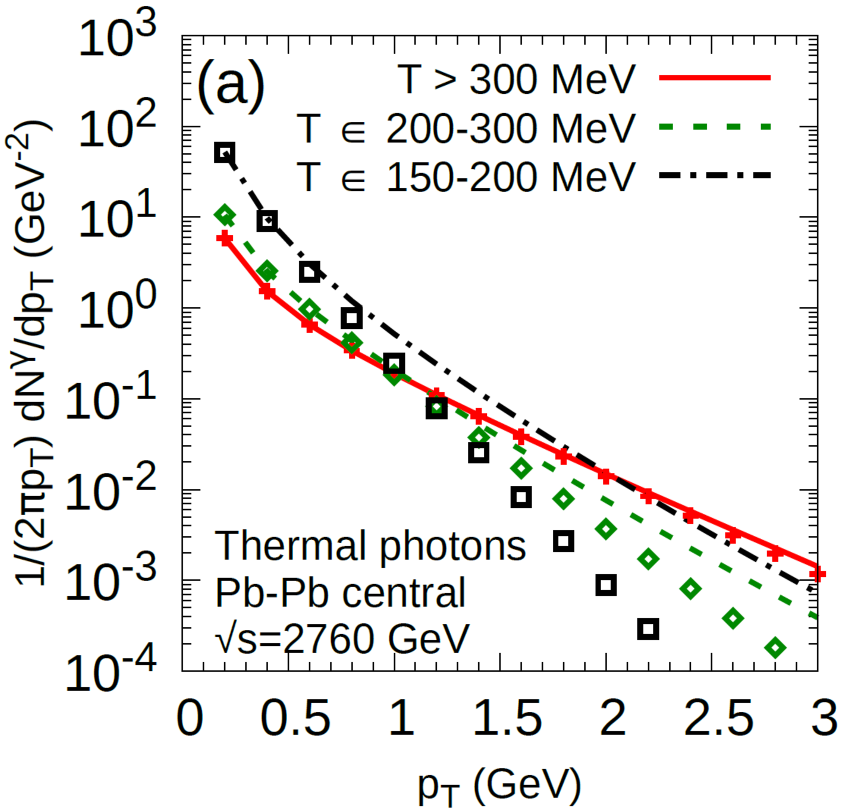
$$\approx \ln\left(\int dx_\perp \exp\left(-\frac{E}{T\left(1+\frac{u_\perp^2}{4E/T}(1+(E/T-2)(E/T))\right)}\right)\right) + cte$$

Thermal photon spectrum: Doppler shift

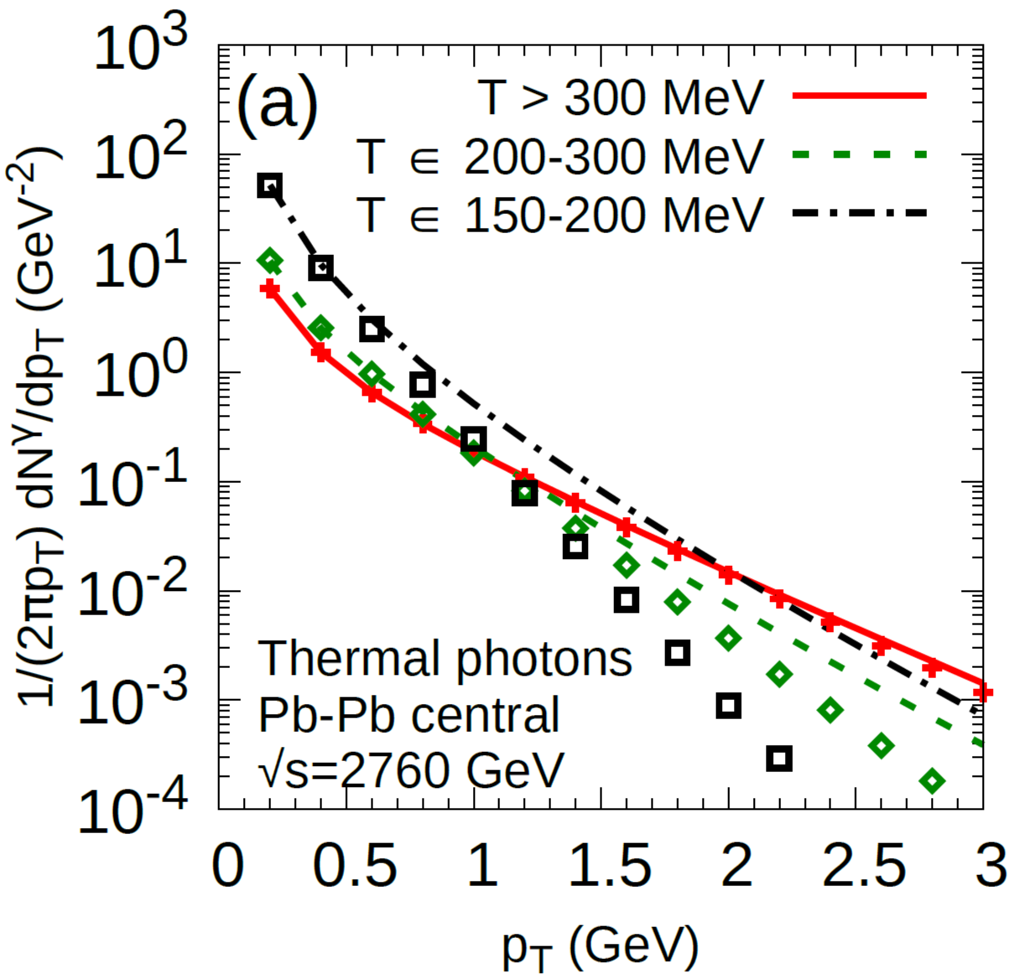
$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx \ln\left(\int dx_\perp \exp\left(-\frac{E}{T\left(1+\frac{u_\perp^2}{4E/T}(1+(E/T-2)(E/T))\right)}\right)\right) + cte$$

Transverse Doppler shift

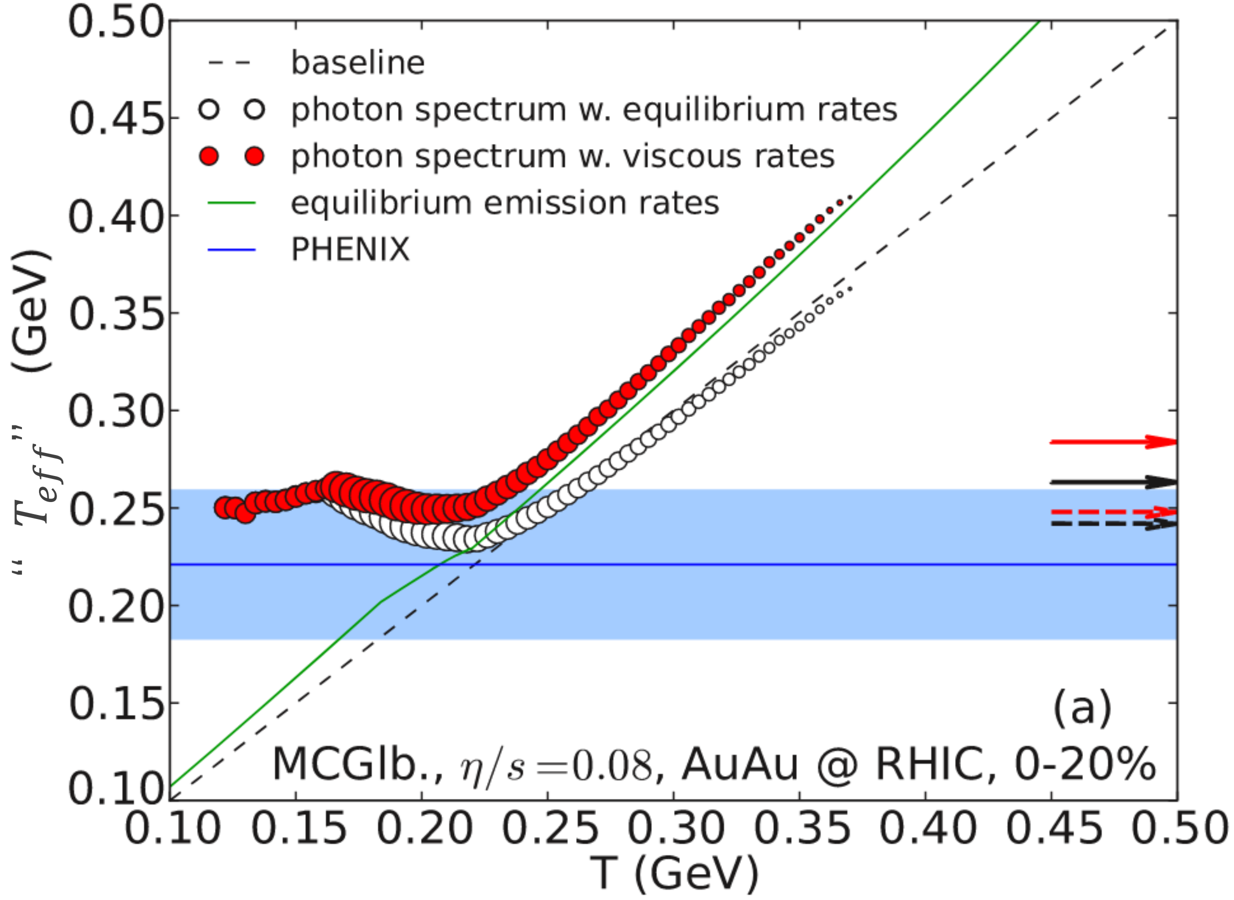




Effect of transverse Doppler shift

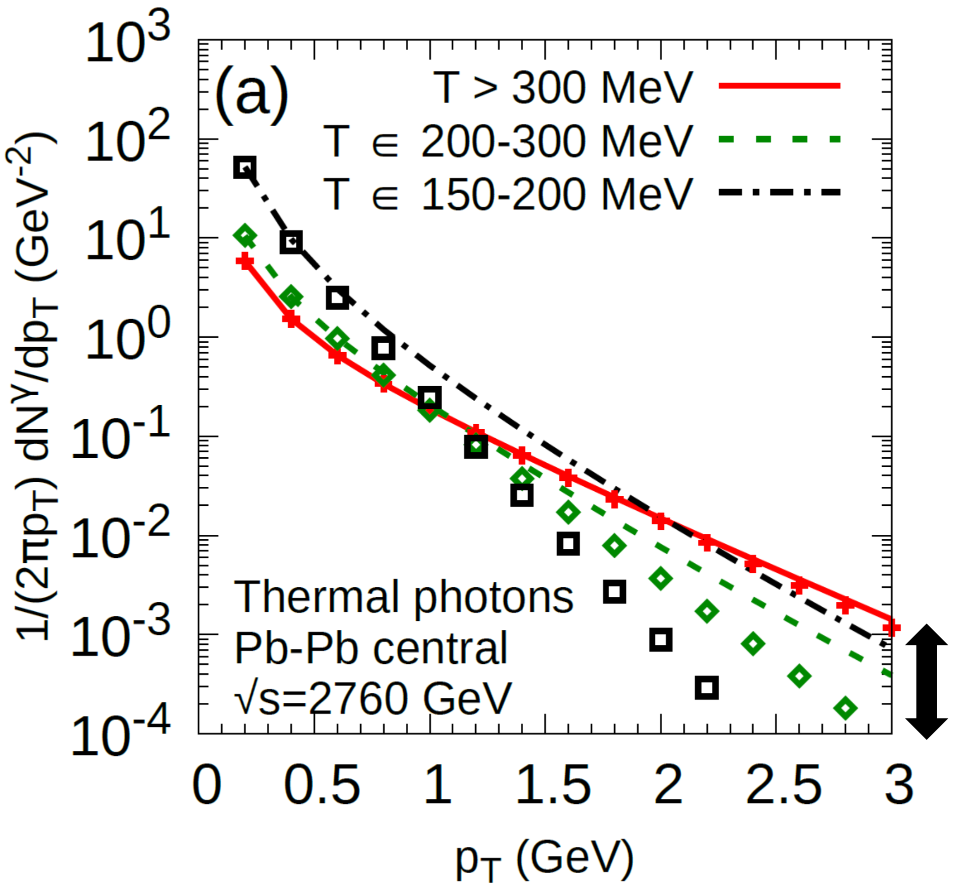


Local effect of Doppler shift

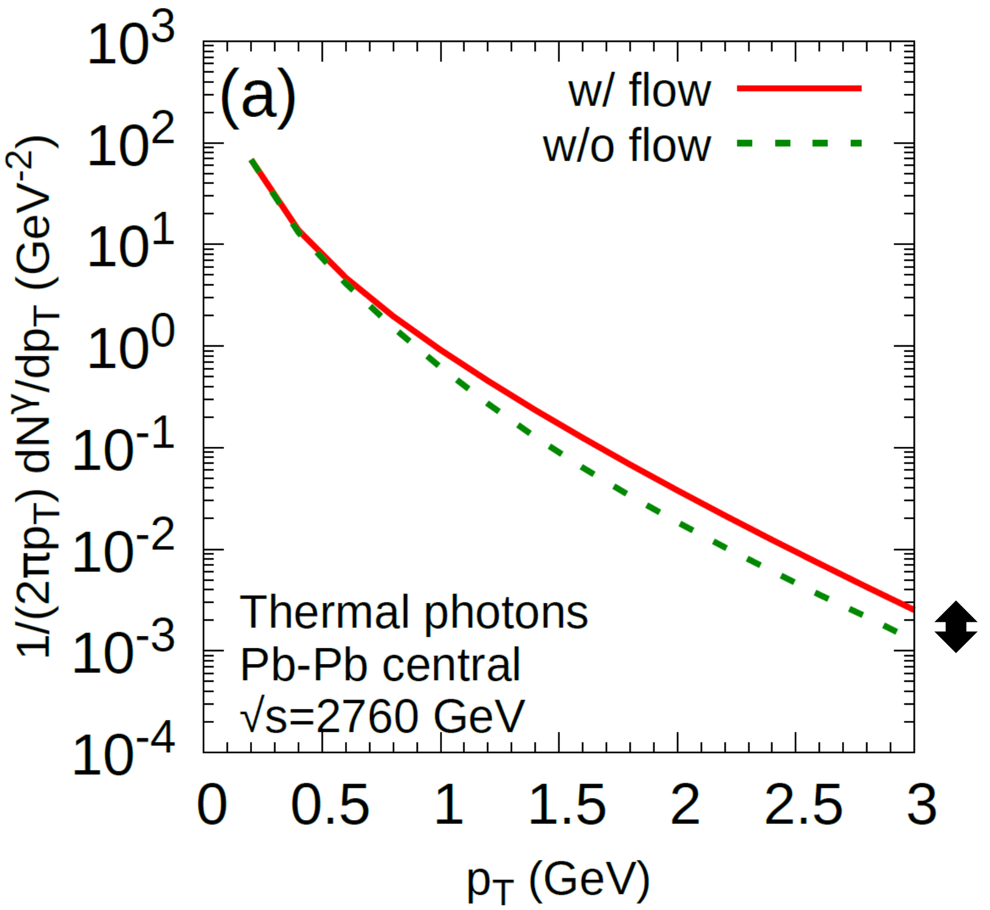


Ref.: Shen, Heinz, Paquet, Gale (2014) PRC;
See also van Hees, Gale, Rapp (2011) PRC

Effect of transverse Doppler shift

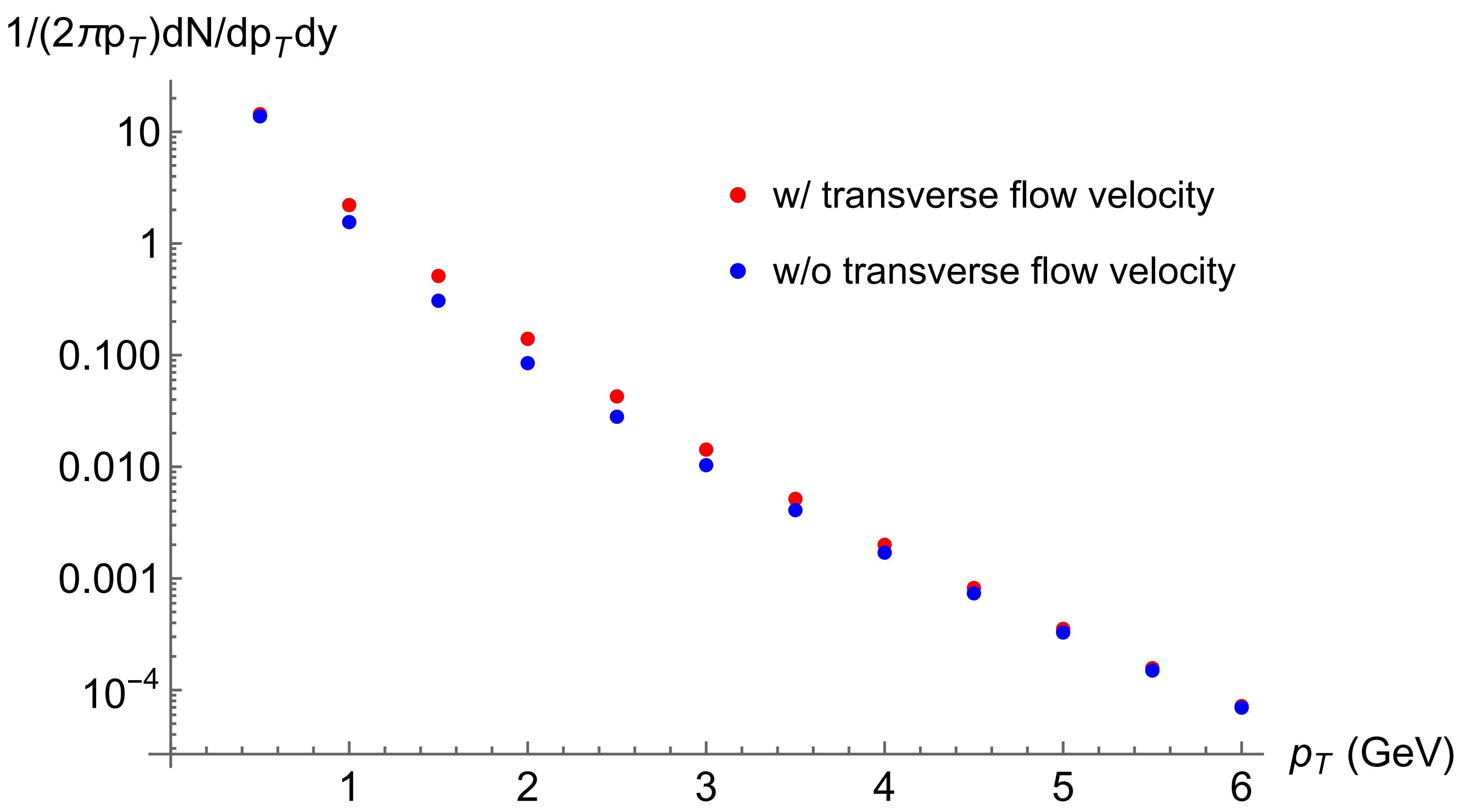


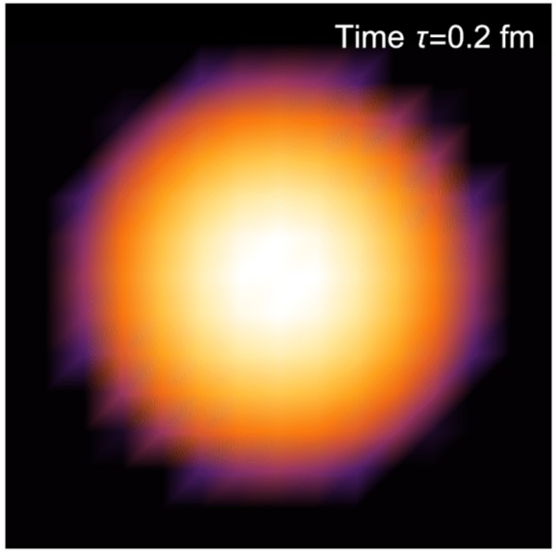
Local effect of Doppler shift



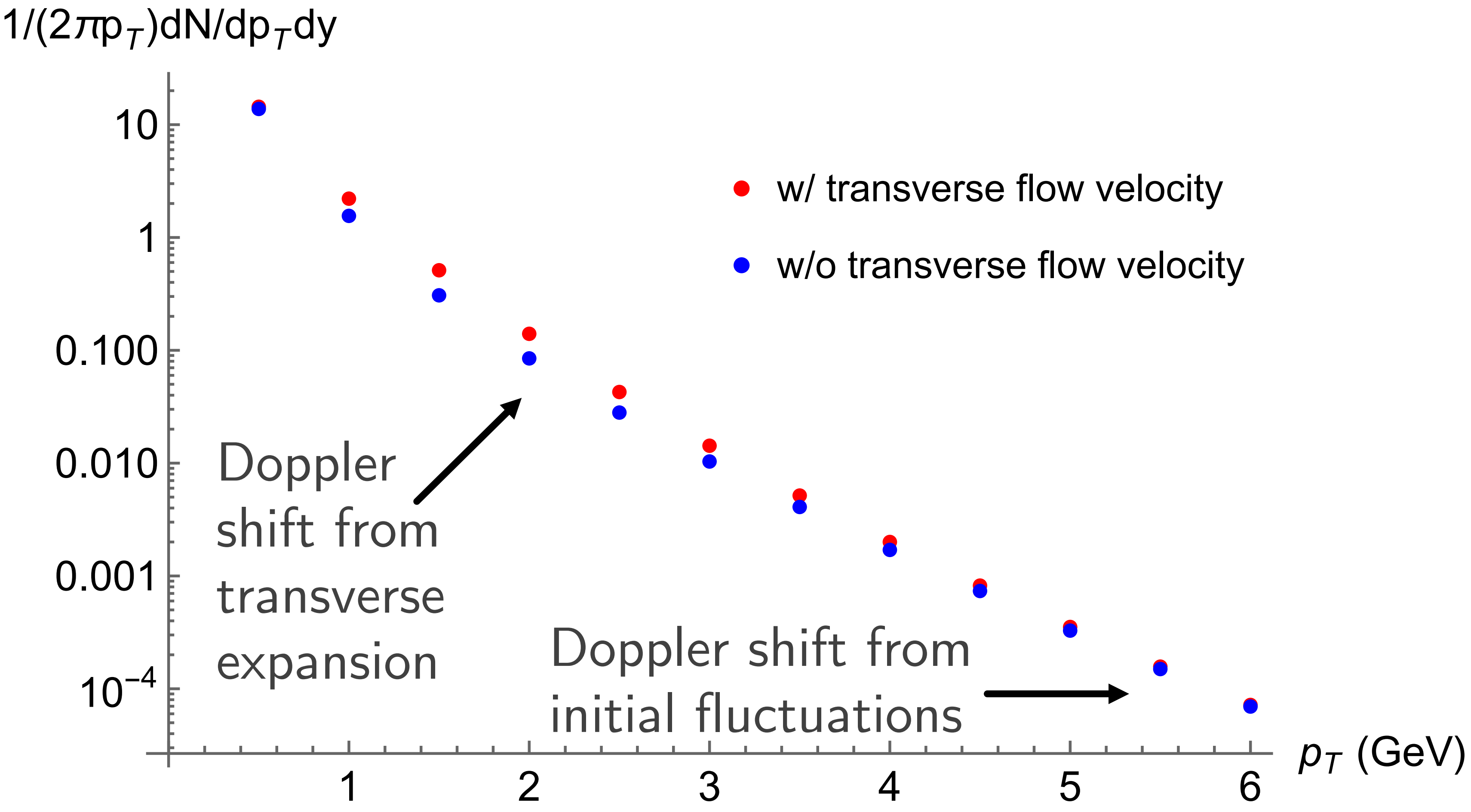
Global effect of Doppler shift

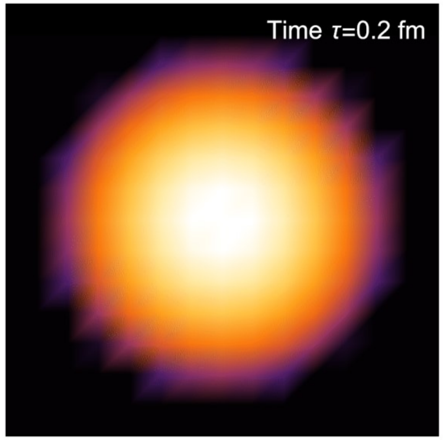
Not all Doppler shifts are equal

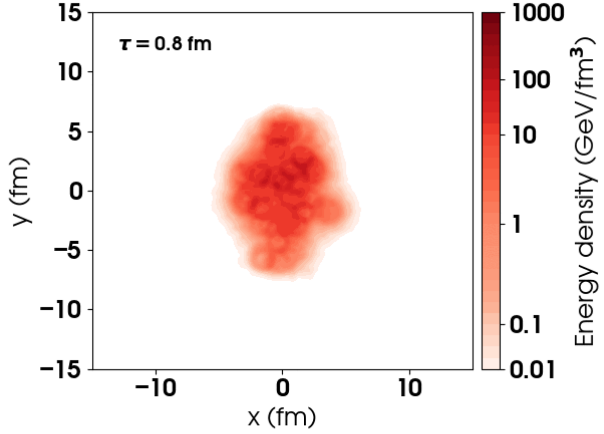




Different origins of the Doppler shift

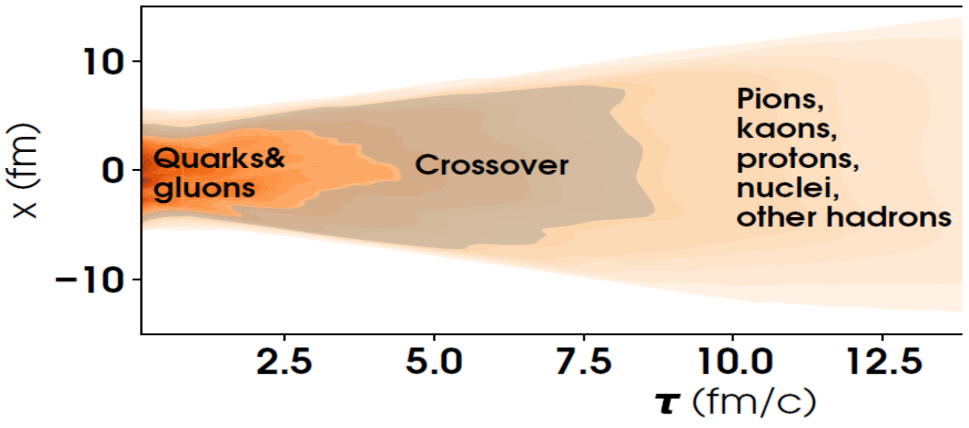






Thermal photon spectrum

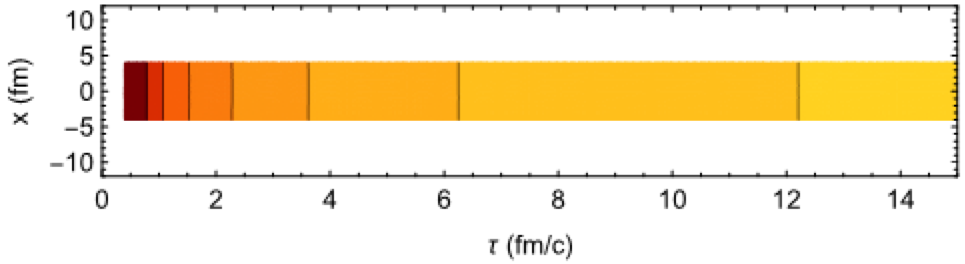
$$\ln\left(\frac{1}{E}\frac{dN_\gamma}{d^3p}\right) \approx \ln\left(\int d\phi d\eta_s dx_\perp e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte$$



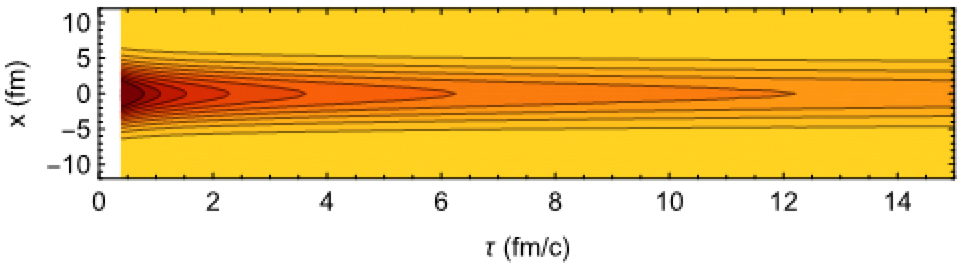
Spacetime profile of plasma: complicated, but can look at simple models

Bjorken hydrodynamics for longitudinal-dominated expansion: $T(\tau) = T_0\left(\frac{\tau_0}{\tau}\right)^{c_s^2}$

➡ Black disk approx: $T(\tau, r<\sigma) = T_0\left(\frac{\tau_0}{\tau}\right)^{c_s^2}$



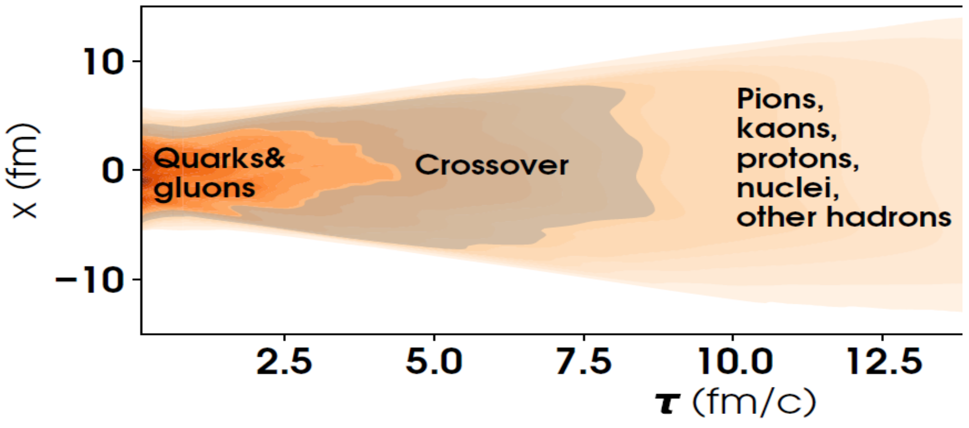
➡ Gaussian approx: $T(\tau, r) = T_0 e^{-\frac{r^2}{2\sigma^2}}\left(\frac{\tau_0}{\tau}\right)^{c_s^2}$



Paquet and Bass [arXiv:2205.12299]

Thermal photon spectrum

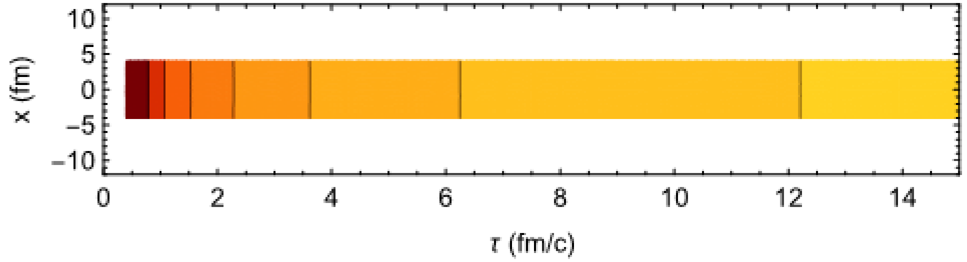
$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx \ln\left(\int d\phi d\eta_s dx_\perp\, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte$$

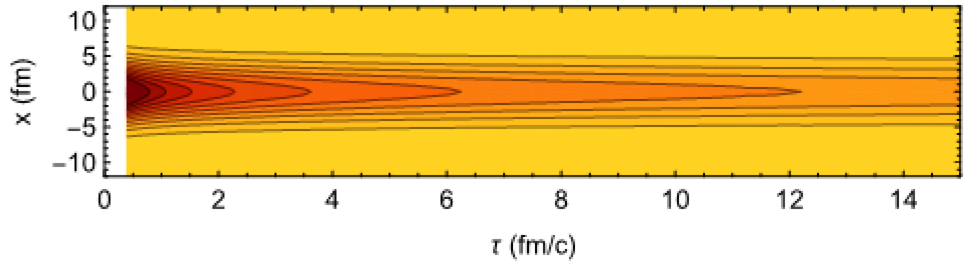


$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx -\frac{E}{T_0} + \frac{3}{2}\log\left(\frac{T_0}{E}\right) + cte + O\left(\frac{T_0}{E}\right)$$

Paquet and Bass [arXiv:2205.12299]

$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx -\frac{E}{T_0} + \frac{5}{2}\log\left(\frac{T_0}{E}\right) + cte + O\left(\frac{T_0}{E}\right)$$



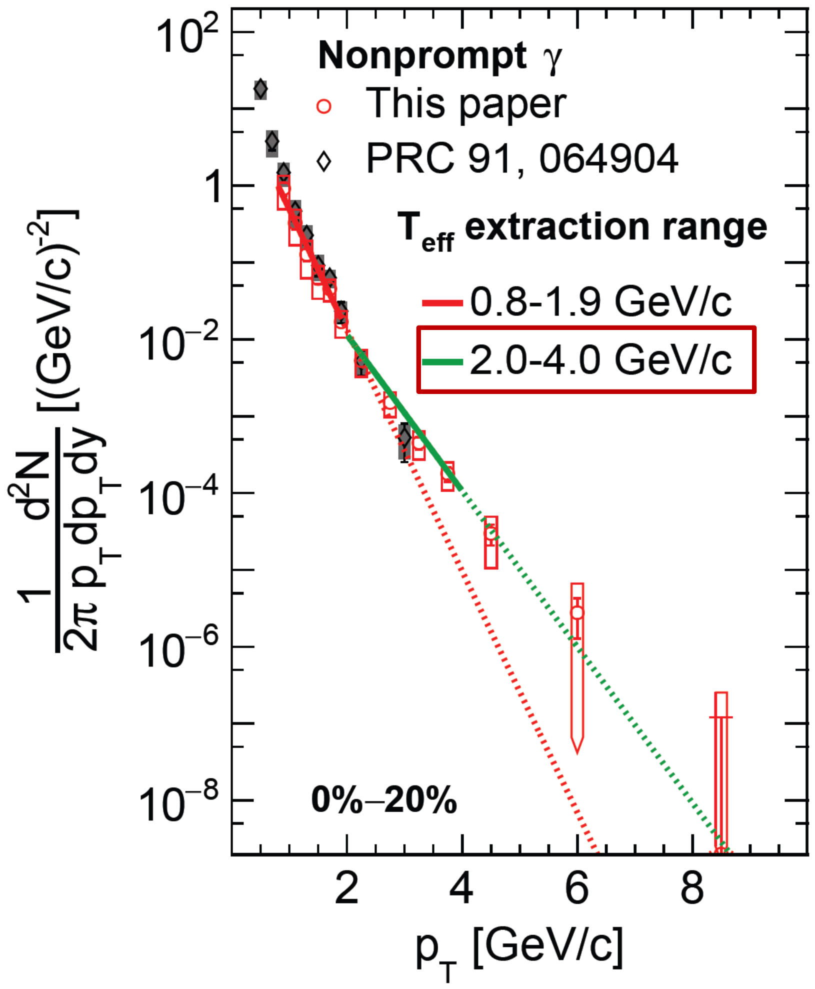


$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx -\frac{E}{T_0} + \mu\log\left(\frac{T_0}{E}\right) + cte \approx -\frac{E}{T_{eff}} + cte$$

$$T_0 \approx \frac{T_{eff}}{1 - \frac{T_{eff}}{E}\mu\ln\mu}$$

Results: Au-Au $\sqrt{s_{NN}}$ =200 GeV, 0-20%

Paquet and Bass [arXiv:2205.12299]



$$\ln\left(\frac{1}{2\pi E}\frac{dN}{dE\,dy}\right) = cte - \frac{E}{T_{eff}}\ ; \quad T_0 \approx \frac{T_{eff}}{1-\frac{T_{eff}}{E}\mu\ln\mu}$$

centrality	$T_0(GeV)$	T_{eff} (GeV/c) $0.8 < p_T < 1.9$ GeV/c	$T_0(GeV)$	T_{eff} (GeV/c) $2 < p_T < 4$
0%–20%	0.48	$0.277 \pm 0.017\ ^{+0.036}_{-0.014}$	0.64	$0.428 \pm 0.031\ ^{+0.031}_{-0.030}$

Non-trivial relation between inverse slope and plasma temperature

Remember: Doppler shift introduces more complications

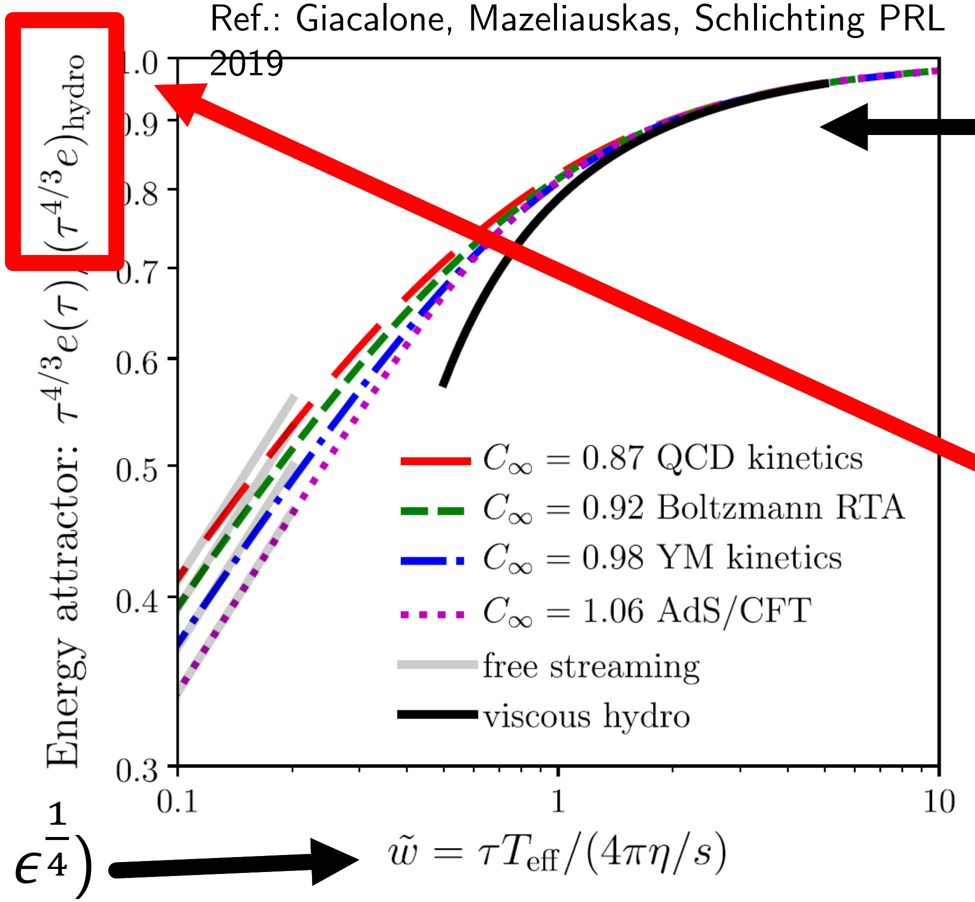
Matching to 0+1D (boost-invariant) hydrodynamics

- In 0+1D hydro, we can characterize $T^{\mu\nu}$ with single component: energy density
- 0+1D dynamical models with smooth transition to hydrodynamics:
  - Kinetic theory (gluons, QCD, RTA) or AdS/CFT

Conclusion:

Properly scaled 0+1D systems approach hydro similarly

Ref.: Giacalone, Mazeliauskas, Schlichting PRL 2019



All systems converge to 0+1D viscous hydro

(note: not all systems have the same final energy density, but this can be rescaled)

Timescale necessary to converge to hydro depends:

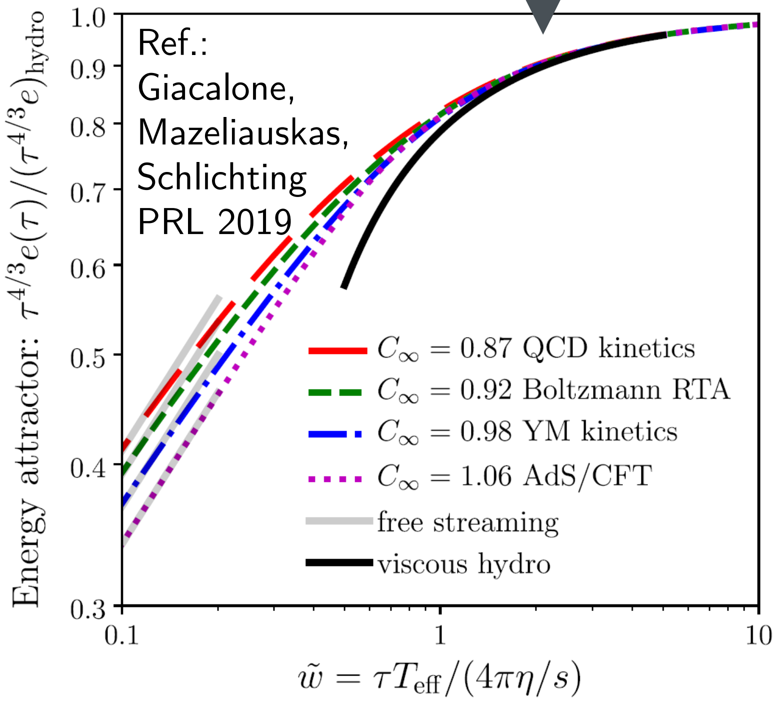
- Strength of interaction $\left(\frac{\eta}{s} \sim \frac{1}{\alpha_s^2}\right)$
- Energy density of the system (or "effective temperature" $T_{eff} \propto \epsilon^{\frac{1}{4}}$)

Matching to 2+1D hydrodynamics: "KøMPøST"

- Take a 2+1D pre-hydro system: how does it approach hydrodynamics?
- Better approximation [KøMPøST]: decompose $T^{\mu\nu}$ in 0+1D background + linear

$$T^{\mu\nu}(\tau_{\mathrm{hydro}}, \mathbf{x}) = \overline{T}^{\mu\nu}_{\mathbf{x}}(\tau_{\mathrm{hydro}}) + \frac{\overline{T}^{\tau\tau}_{\mathbf{x}}(\tau_{\mathrm{hydro}})}{\overline{T}^{\tau\tau}_{\mathbf{x}}(\tau_{\mathrm{EKT}})} \int d^2\mathbf{x}'\, G^{\mu\nu}_{\alpha\beta}(\mathbf{x}, \mathbf{x}', \tau_{\mathrm{hydro}}, \tau_{\mathrm{EKT}})\, \delta T^{\alpha\beta}_{\mathbf{x}}(\tau_{\mathrm{EKT}}, \mathbf{x}')$$

Ref.: Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney PRL2019, PRC2019



Response functions describing evolution of perturbations

- Can be evaluated with QCD kinetic theory
- Also exhibits scaling with interaction strength and energy density of system

[See also Kamata, Martinez, Plaschke, Ochsenfeld, Schlichting, PRD 2020]