Electromagnetic probes in heavy-ion collisions

Jean-François Paquet

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VANDERBILT UNIVERSITY

PROCEEDINGS OF SCIENCE

Electromagnetic probes in heavy-ion collisions: progress and open questions

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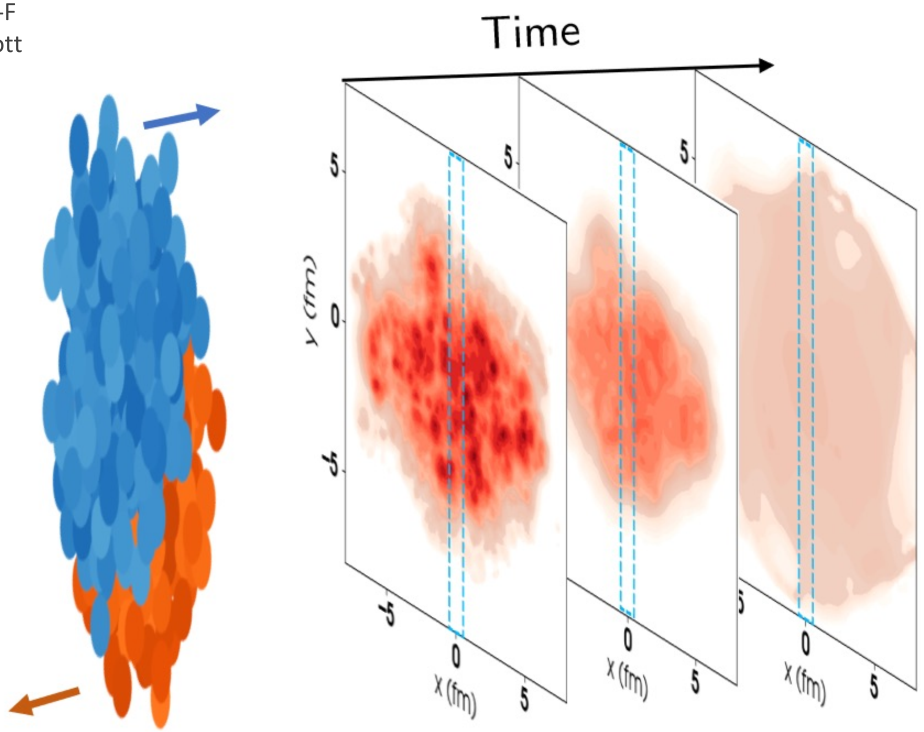
Spacetime profile of heavy-ion collisions

Figure credit: J-F Paquet and Scott Moreland



Spacetime profile of heavy-ion collisions

Temperature

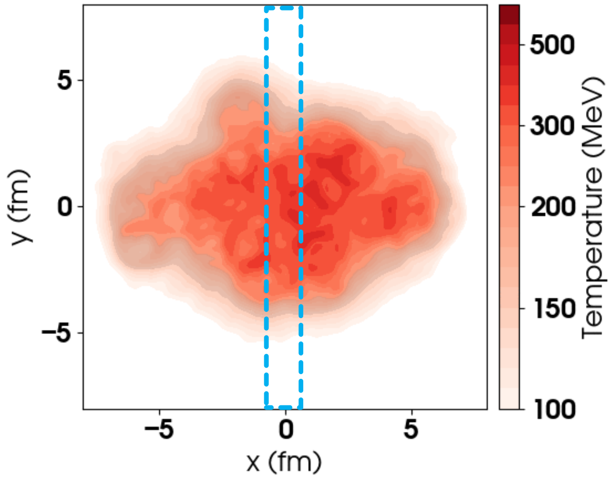
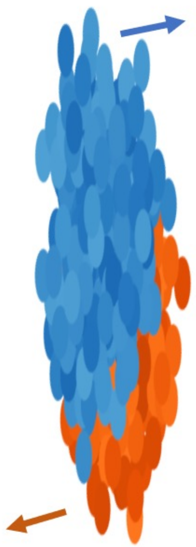
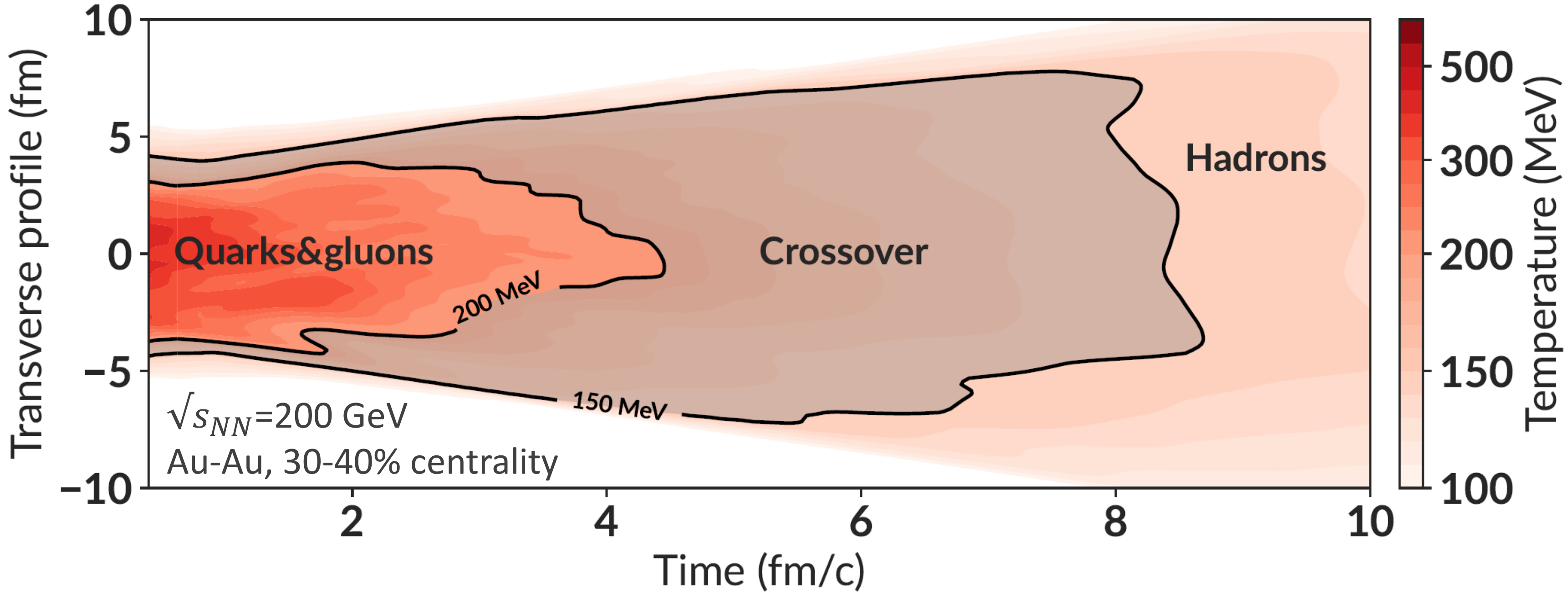


Figure credit: J-F Paquet and Scott Moreland





Electromagnetic probes in heavy-ion collisions

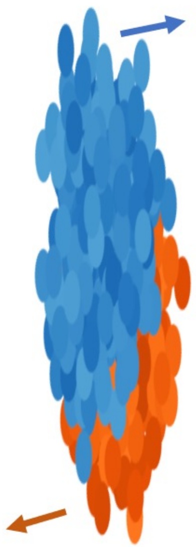
Prompt photons / Drell-Yan dileptons

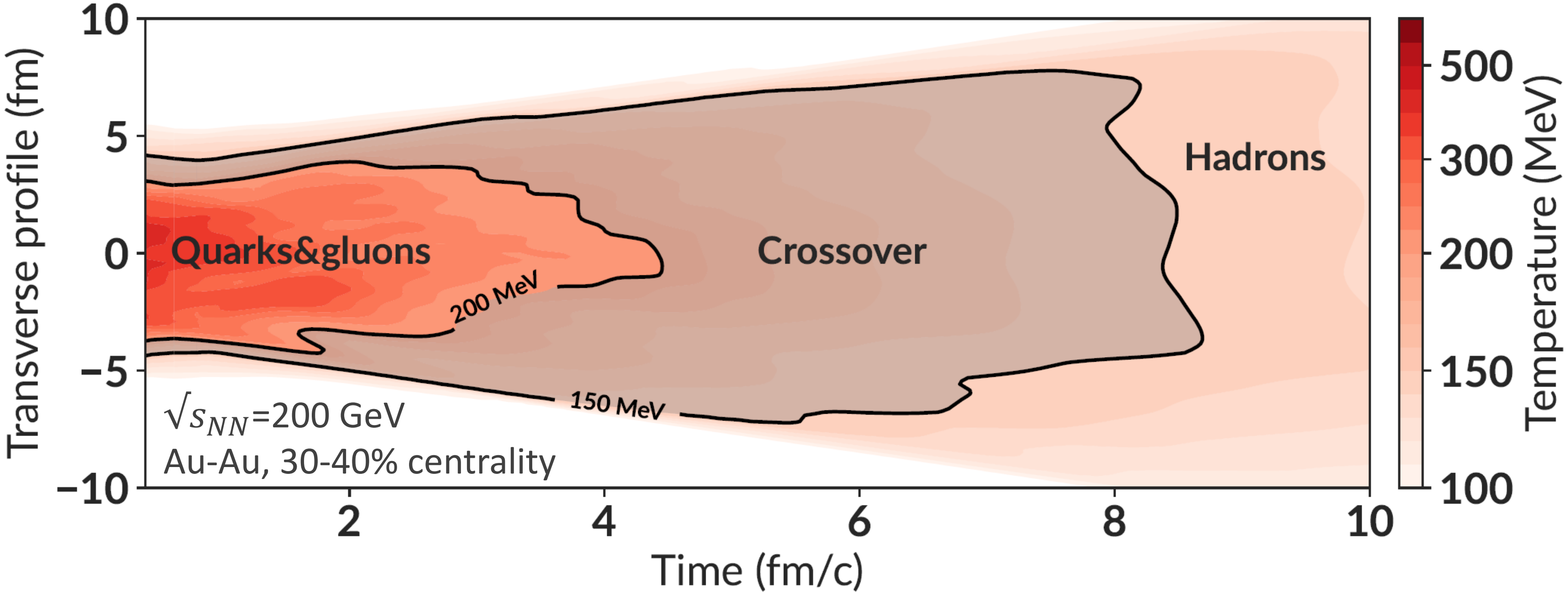
Pre-equilibrium photons/dileptons

Thermal photons and dileptons

Late-stage photons and dileptons (including hadronic decays)

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





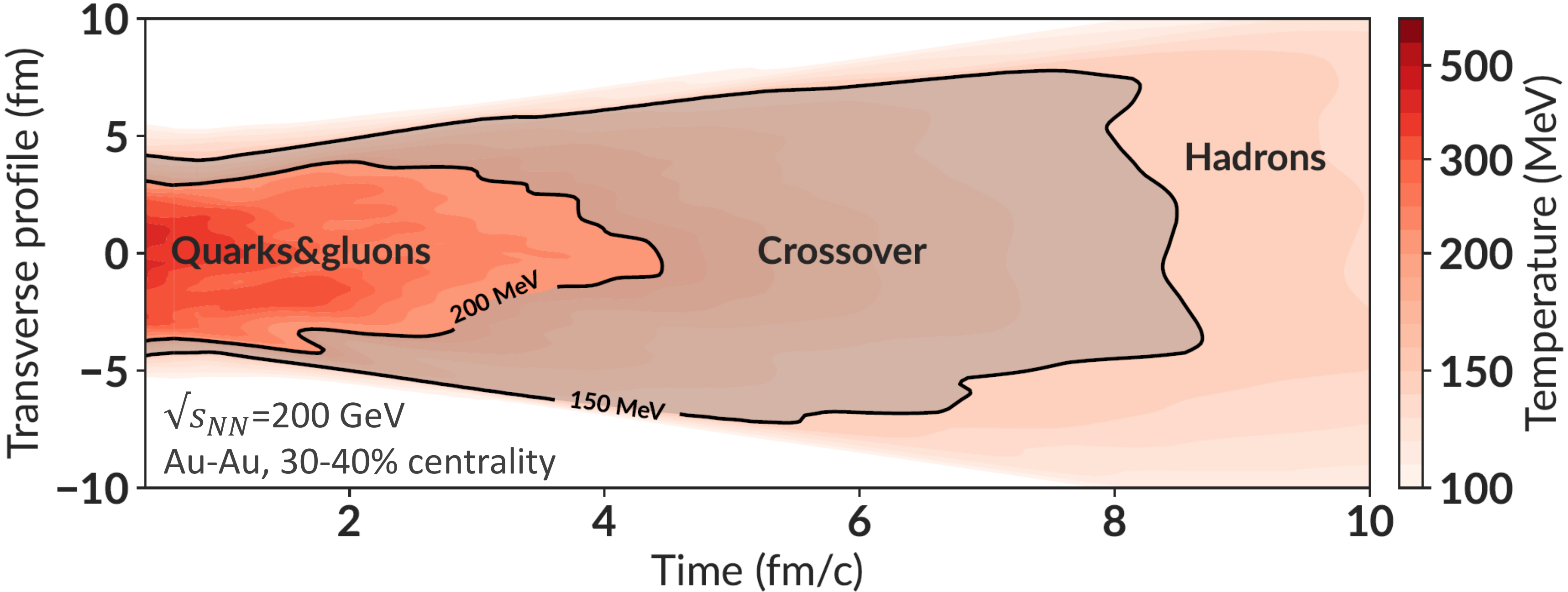
Early stage	Hydrodynamics	Late stage

Interaction strength of nuclear plasma

Early stage	Hydrodynamics	Late stage
Strong?	Strongly-coupled QGP	Weakly-coupled hadron gas

Rate of expansion of nuclear plasma

Early stage	Hydrodynamics	Late stage
Very large longitudinal expansion (~1D)	Longitudinal and transverse expansion (~3D)	Longitudinal and transverse expansion (~3D)



Early stage

Expansion-dominated stage

Interactions: strong
Expansion: extremely rapid

$\tau_{expansion} \gg \tau_{relax}$

Free-streaming?

Hydrodynamics

Interaction-dominated stage

Interactions: stronger
Expansion: slower

$\tau_{expansion} \ll \tau_{relax}$

Hydrodynamics

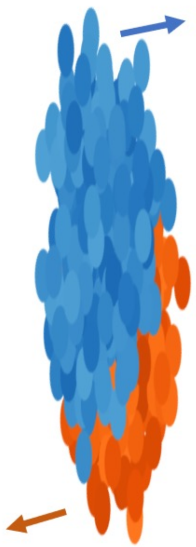
Late stage

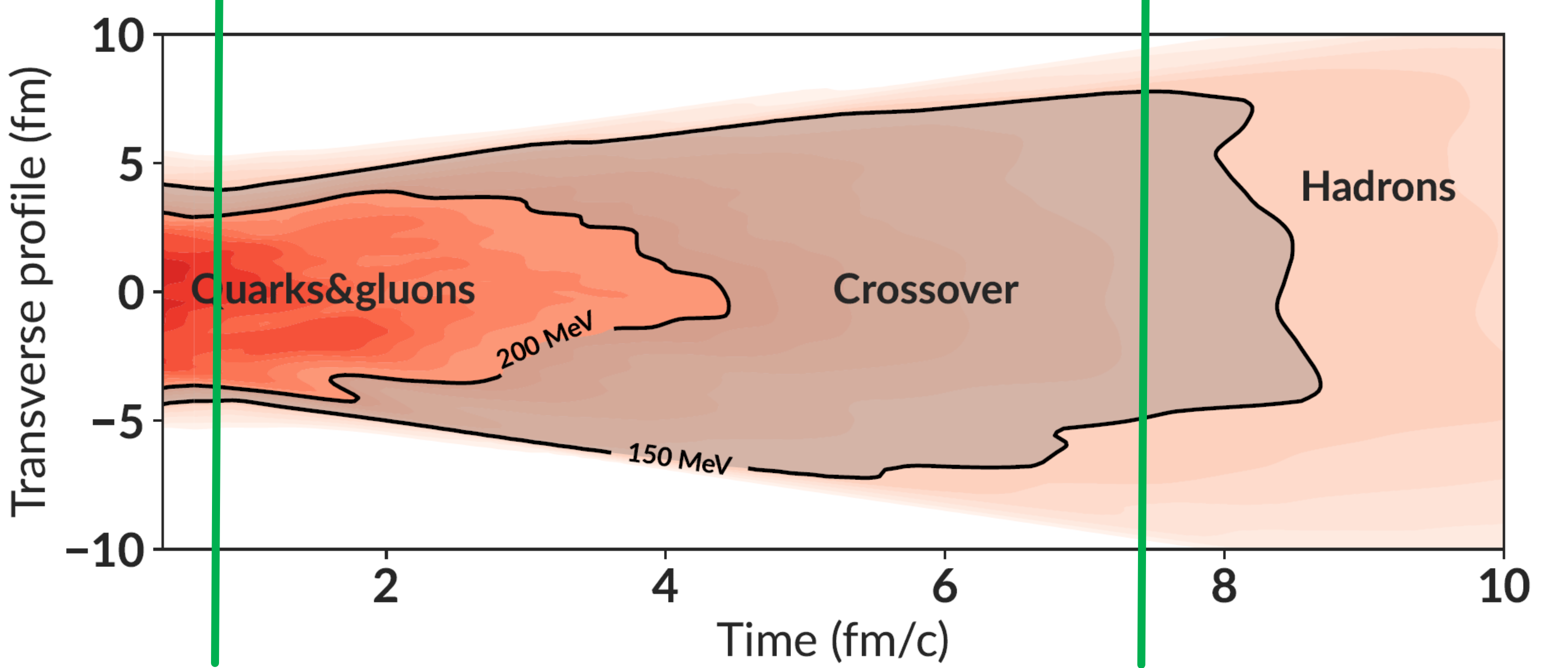
Expansion-dominated stage

Hadron interactions: weaker
Expansion: somewhat slower

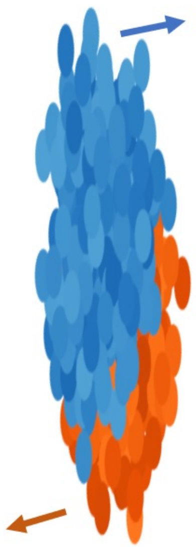
$\tau_{expansion} \gg \tau_{relax}$

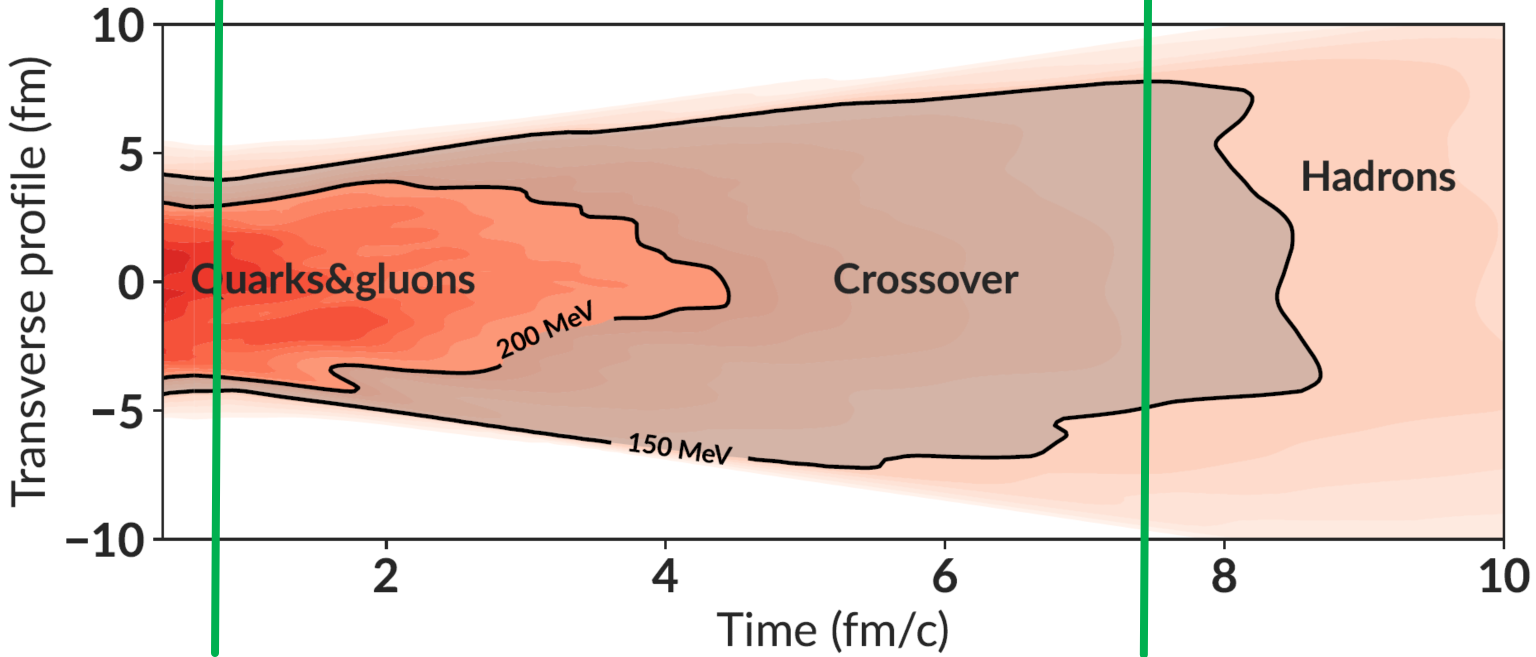
Free-streaming





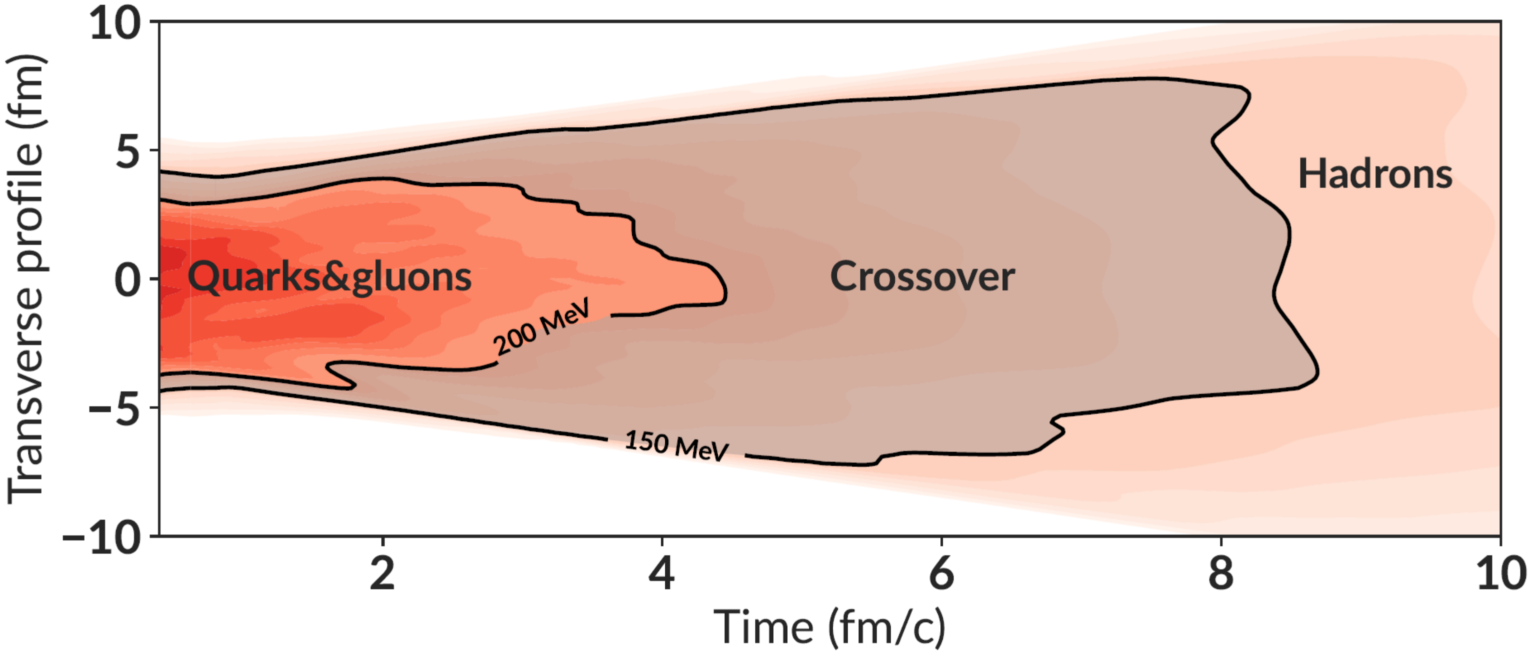
Early stage	Interface	Hydrodynamics	Interface	Late stage
Free-streaming?	Attractors/ hydrody-namization/ thermalization	Relativistic viscous hydrodynamics	Interacting hadron gas (SMASH, UrQMD, …)	Hadrons free-streaming to detectors





Early stage	Interface	Hydrodynamics	Interface	Late stage
Free-streaming?	Attractors/ … thermalization	Relativistic viscous hydrodynamics	Interacting hadron gas	Hadrons free-streaming to detectors
	Pre-equilibrium photons/ dileptons	**Thermal photons and dileptons**	**Late-stage photons and dileptons (including hadronic decays)**	

Prompt photons / Drell-Yan dileptons



Other sources…

Early stage

Free-streaming?

Interface

Attractors/

thermalization

Pre-equilibrium photons/ dileptons

Hydrodynamics

Relativistic viscous hydrodynamics

Thermal photons and dileptons

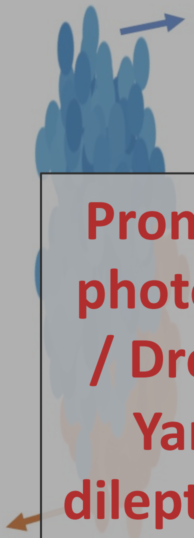
Interface

Interacting hadron gas

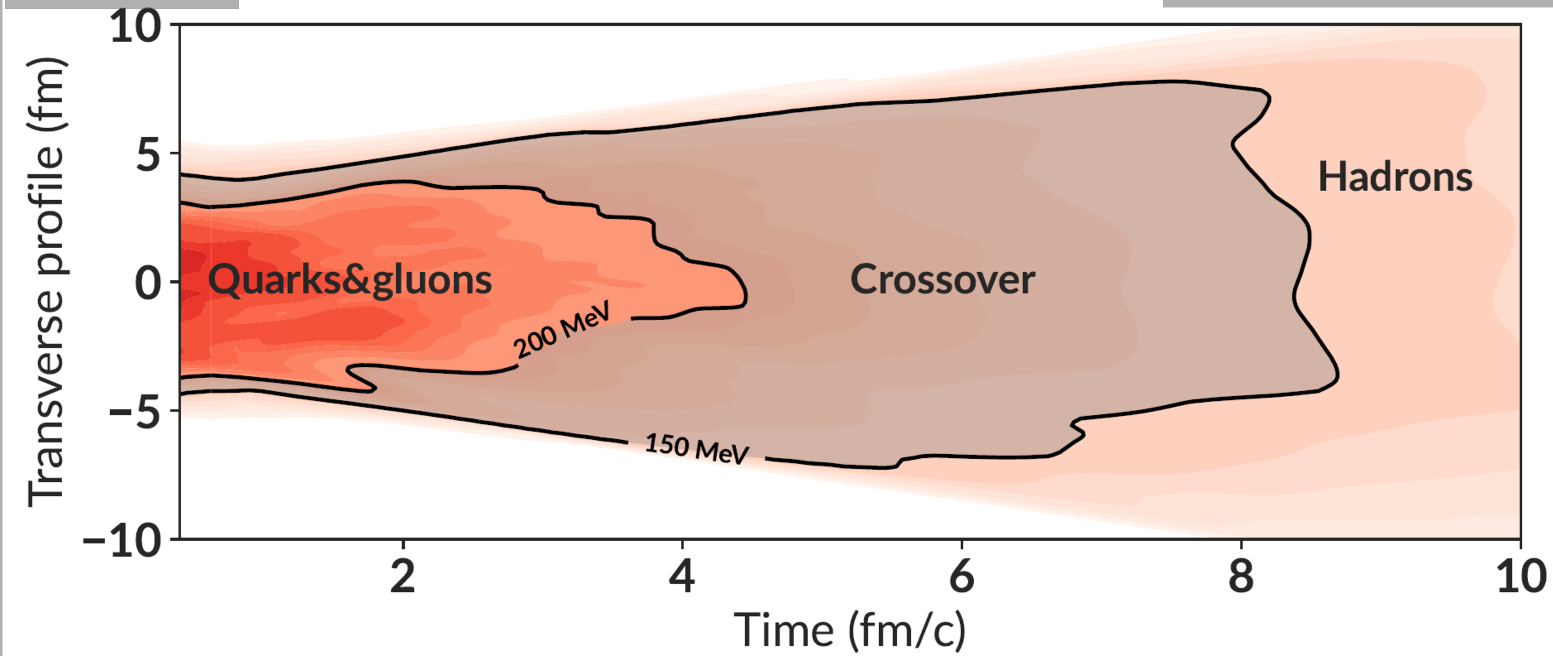
Late stage

Hadrons free-streaming to detectors

Late-stage photons and dileptons (including hadronic decays)



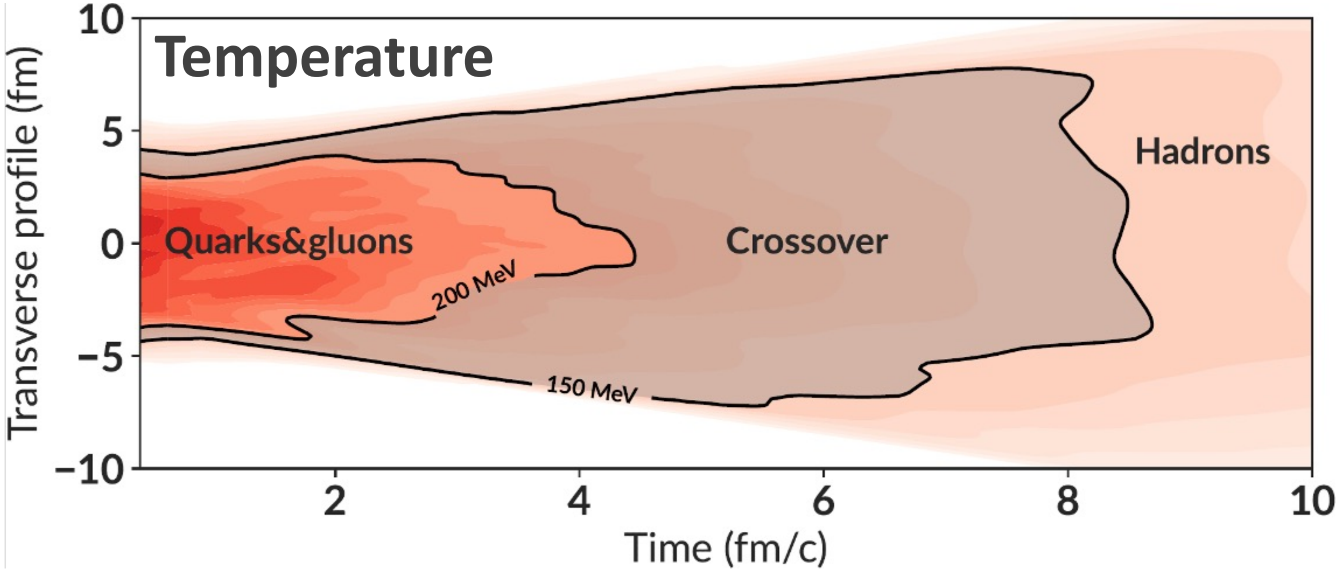
Prompt photons / Drell-Yan dileptons



Other sources...

Photons from deconfined plasma

- What is the spacetime profile of quarks/gluons/hadrons?



- Photon production:

$$\frac{dN_\gamma}{d^3p} = \int d^4X \, \frac{d\Gamma_\gamma}{d^3p}(p, \overbrace{T(X), u^\mu(X), \dots}^{\text{Spacetime profile of plasma}})$$

Photon emission rate

Photon emission rate

Spacetime profile of plasma

- Photon production: $$\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p} = \int \mathrm{d}^4X \, \frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p}(p, \overbrace{T(X), u^\mu(X), \dots}^{\text{Spacetime profile of plasma}})$$

Photon emission rate

State of matter/Temperatures	Photon emission rate
Gas of hadrons below $T \approx 160$ MeV	Effective hadronic models
Deconfinement for $T \approx 160 - 200$ MeV	Extrapolated rates from low/high temperatures
Strongly-coupled quark/gluons for $T \sim 200 - 500$ MeV	Lattice QCD, holography, effective models
Weakly-coupled QGP at $T \gg 1$ GeV	Perturbative QCD

Photon emission rate

Spacetime profile of plasma

- Photon production: $$\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p} = \int \mathrm{d}^4X \, \frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p}\left(p, T(X), u^\mu(X), \dots\right)$$

Photon emission rate

State of matter/Temperatures

Photon emissivity of the quark-gluon plasma: A lattice QCD analysis of the transverse channel

Marco Cè (U. Bern, AEC and Bern U. and CERN), Tim Harris (Edinburgh U.), Ardit Krasniqi (U. Mainz, PRISMA), Harvey B. Meyer (U. Mainz, PRISMA and Helmholtz Inst., Mainz and Darmstadt, GSI), Csaba Török (U. Mainz, PRISMA)

May 5, 2022

26 pages

Weakly coupled QGP at $T \gg 1$ GeV

Photon emission rate

Effective hadronic models

Extrapolated rates from low/high temperatures

Lattice QCD, holography, effective models

Perturbative QCD

Photon emission rate

- Photon production:

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p} = \int \mathrm{d}^4X \, \frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p}\left(p, \overbrace{T(X), u^\mu(X), \text{viscous part (shear and bulk)}}^{\text{Spacetime profile of plasma}}\right)$$

↗ Photon emission rate

State of matter/Temperatures	Equilibrium rate	Non-equilibrium corrections?
Gas of hadrons	Effective hadronic models	Partly known
Deconfinement	Extrapolated rates from low/high temperatures Lattice QCD, holography, effective models	Very limited information
Strongly-coupled QGP		
Weakly-coupled QGP	Perturbative QCD	Partly known

Early stage

Free-streaming?

Interface

Attractors/

thermalization

Pre-equilibrium photons/ dileptons

Hydrodynamics

Relativistic viscous hydrodynamics

Thermal photons and dileptons

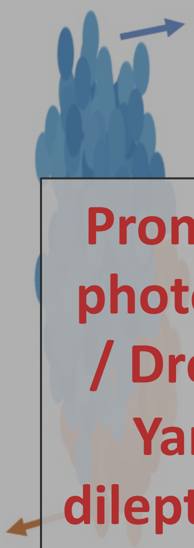
Interface

Interacting hadron gas

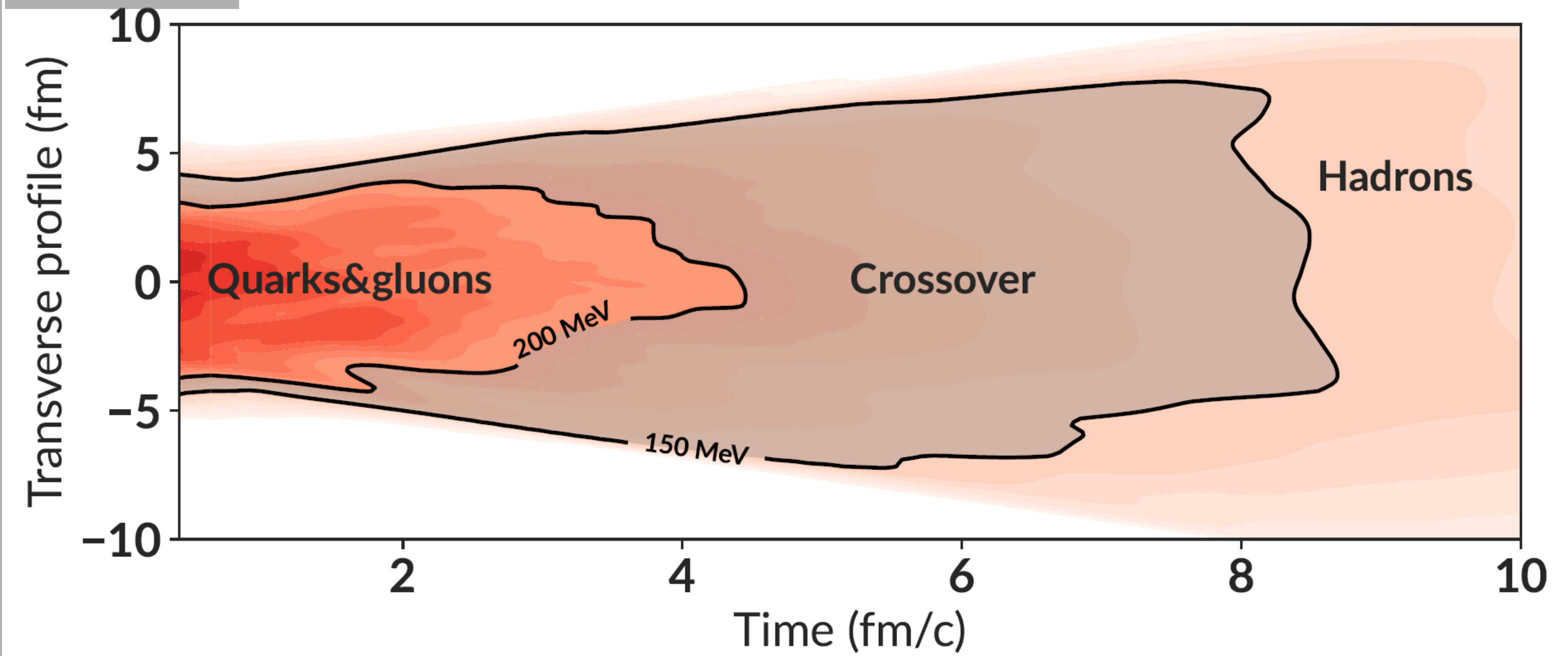
Late stage

Hadrons free-streaming to detectors

Late-stage photons and dileptons (including hadronic decays)

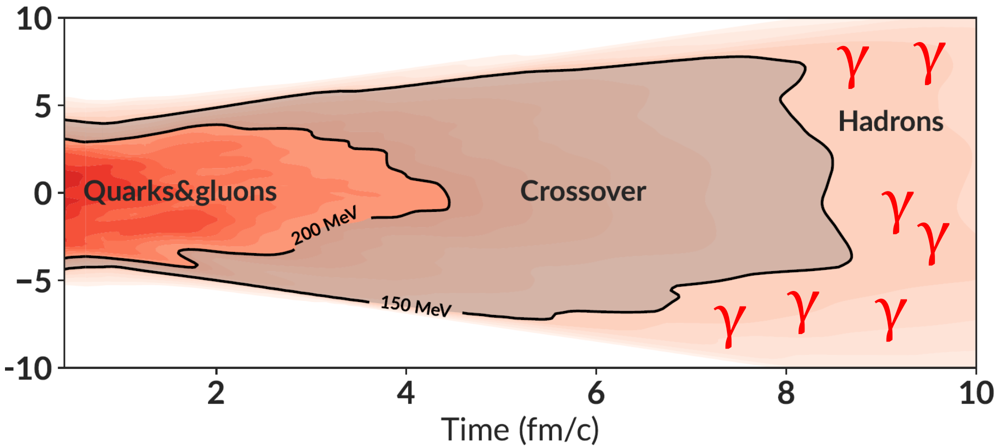


Prompt photons / Drell-Yan dileptons

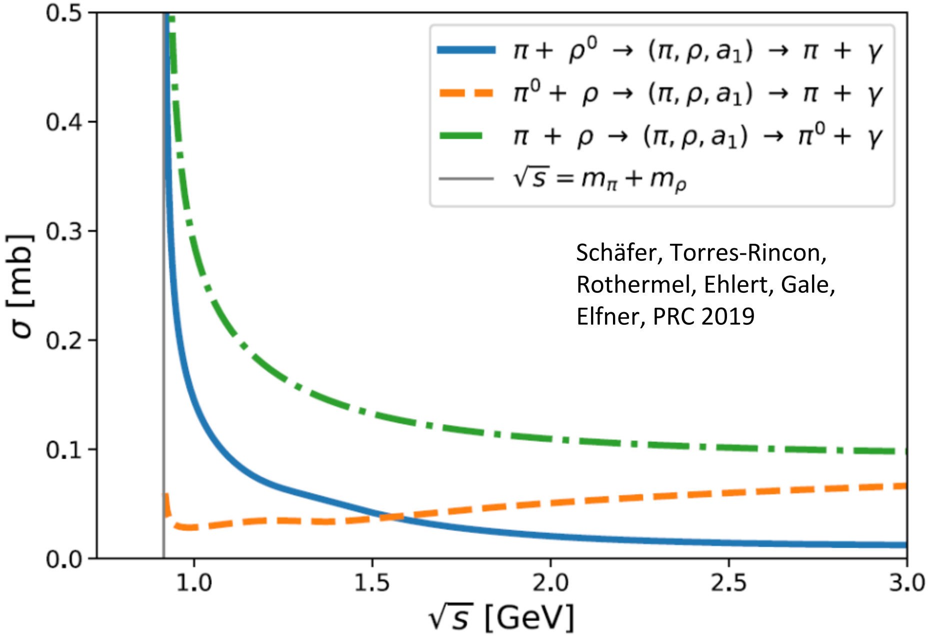


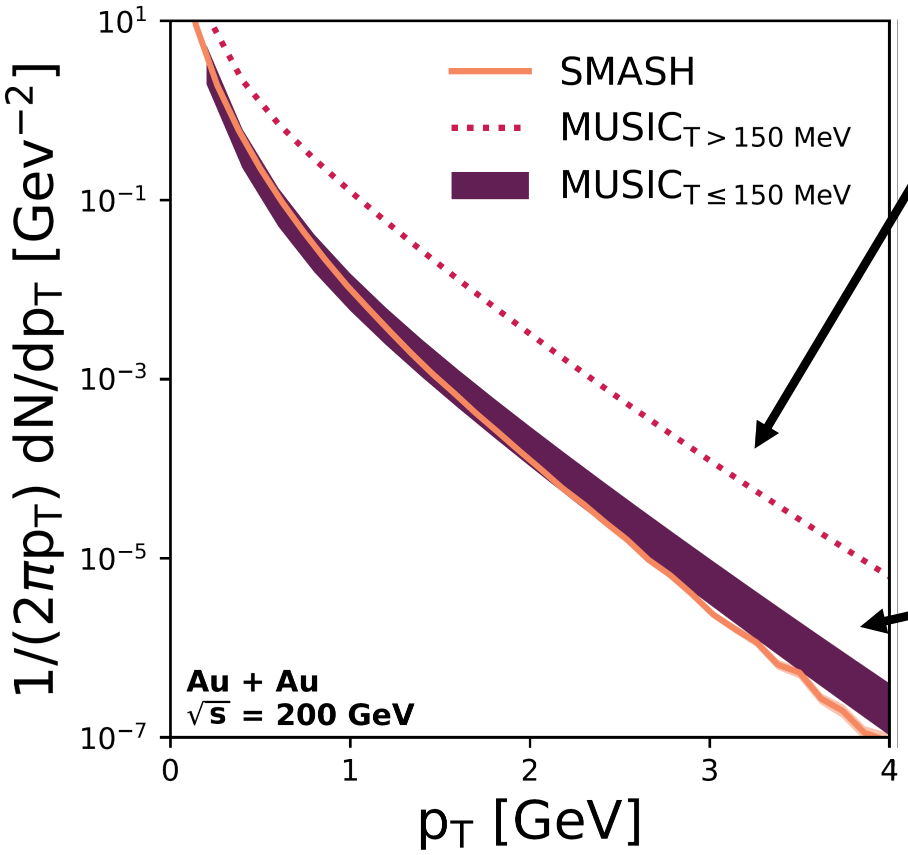
Other sources...

Photons from hadronic interactions



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





Schäfer, Garcia-Montero, Paquet Elfner and Gale (2022) PRC

- Photons from hydrodynamics for T>150 MeV
- Photons from hadronic transport for T<150 MeV

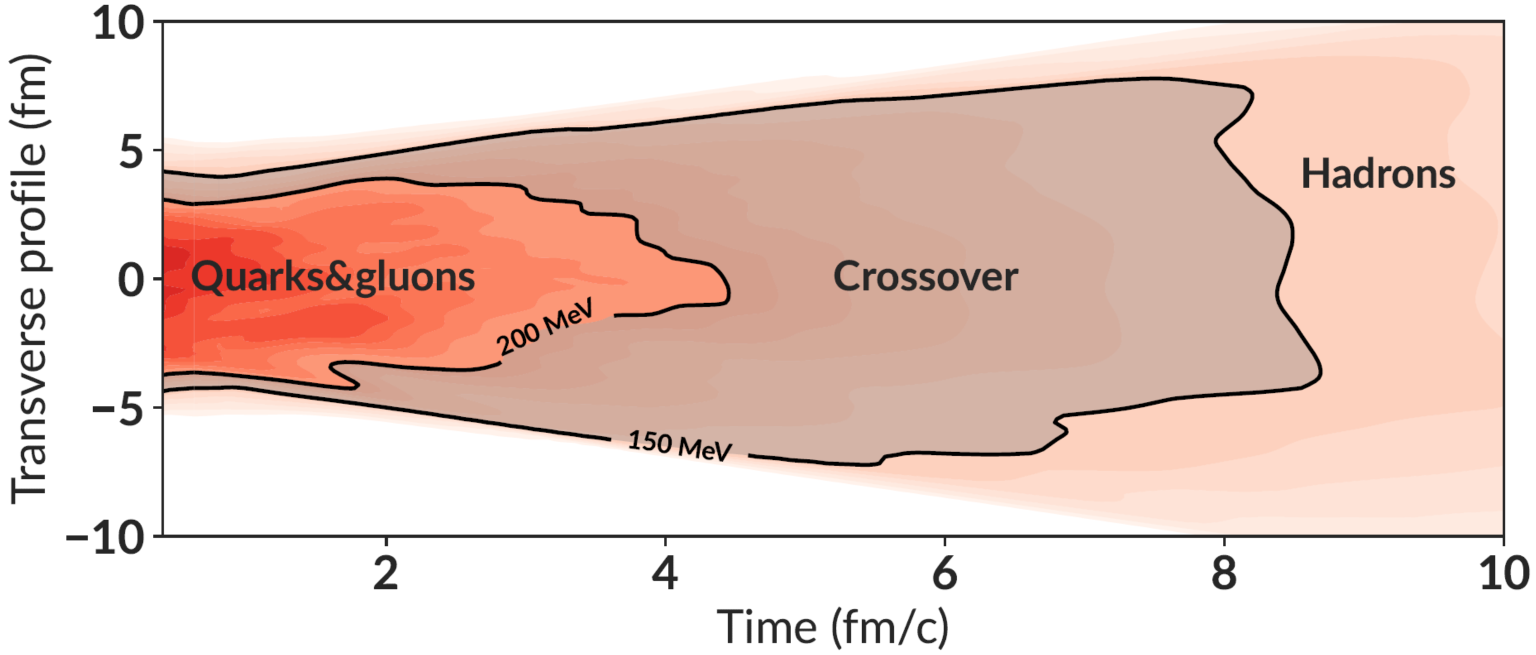
Early stage	Interface	Hydrodynamics	Interface	Late stage
Free-streaming?	Attractors/ hydrodynamization/ thermalization	Relativistic viscous hydrodynamics	Interacting hadron gas	Hadrons free-streaming to detectors

Pre-equilibrium photons/ dileptons

Thermal photons and dileptons

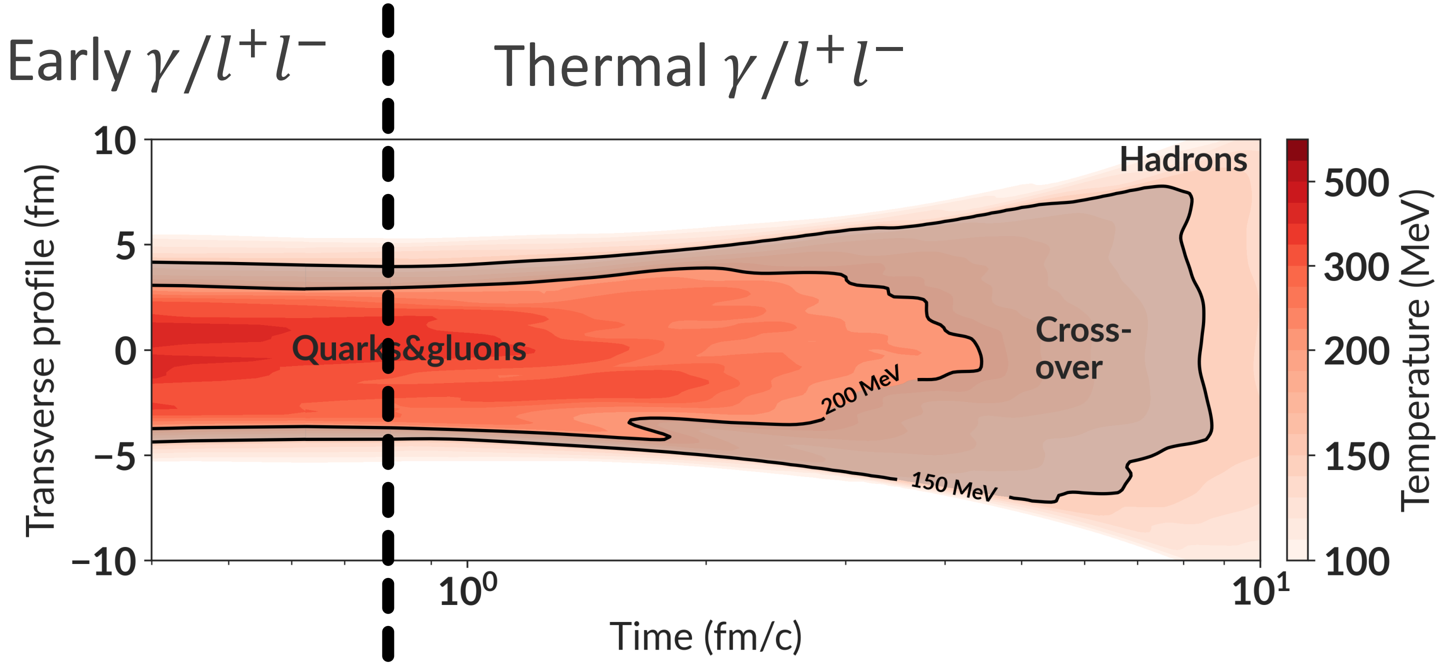
Late-stage photons and dileptons (including hadronic decays)

Prompt photons / Drell-Yan dileptons



Other sources…

Early-stage emission



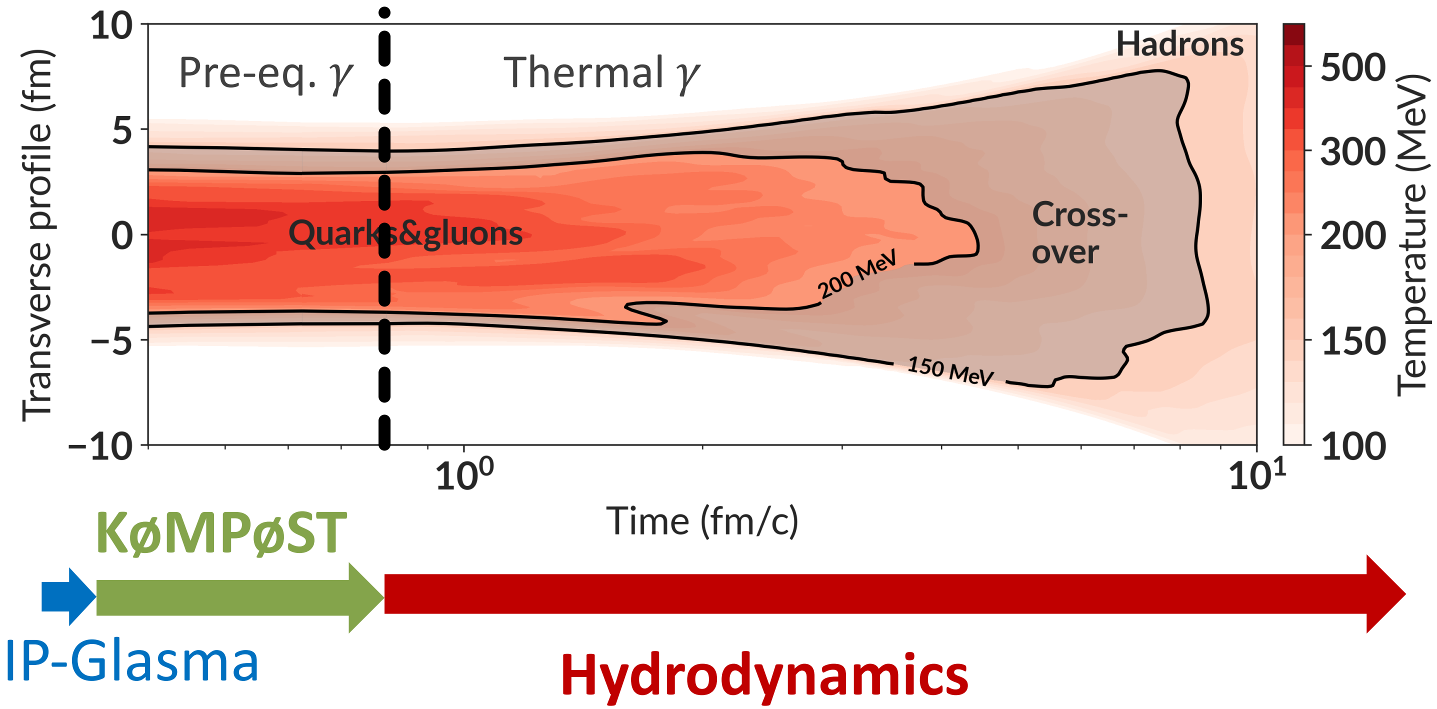
Emission from the soft bath

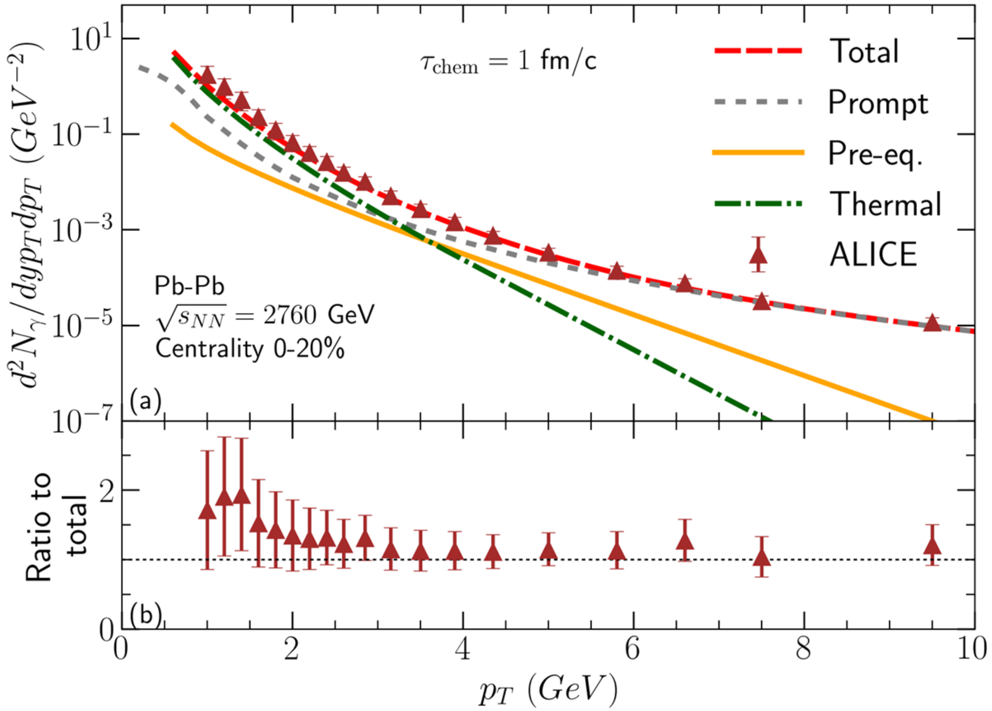
- What is the spatial distribution?
- What is the **rate** of photon and dilepton emission at early times?
  - **Rate** determined by quark/gluon ratio and momentum distributions

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

Early-stage photons

Gale, Paquet, Schenke, Shen (2022) PRC

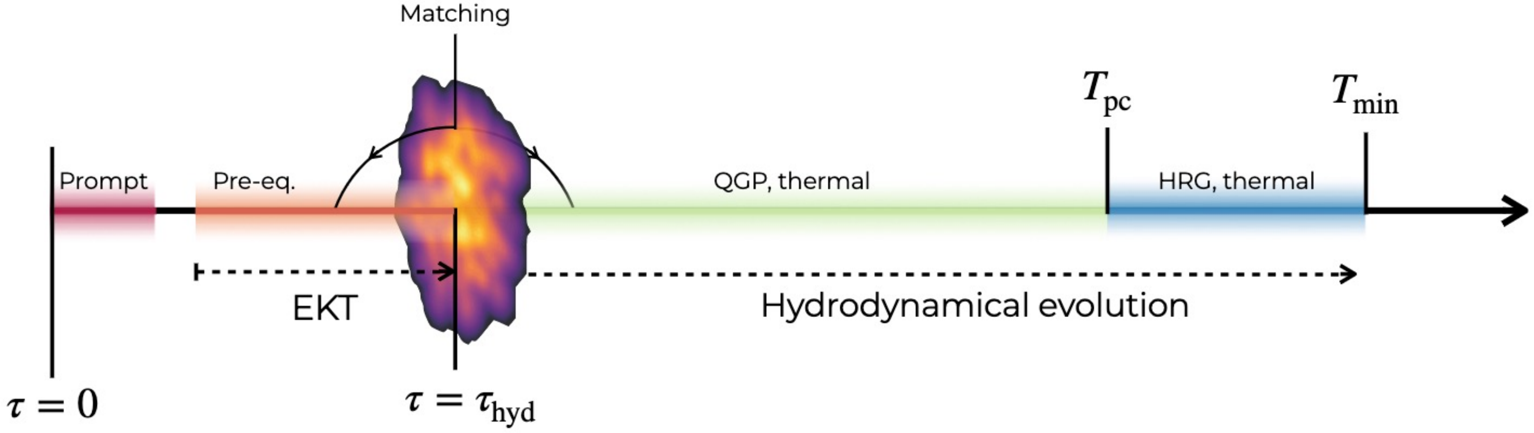


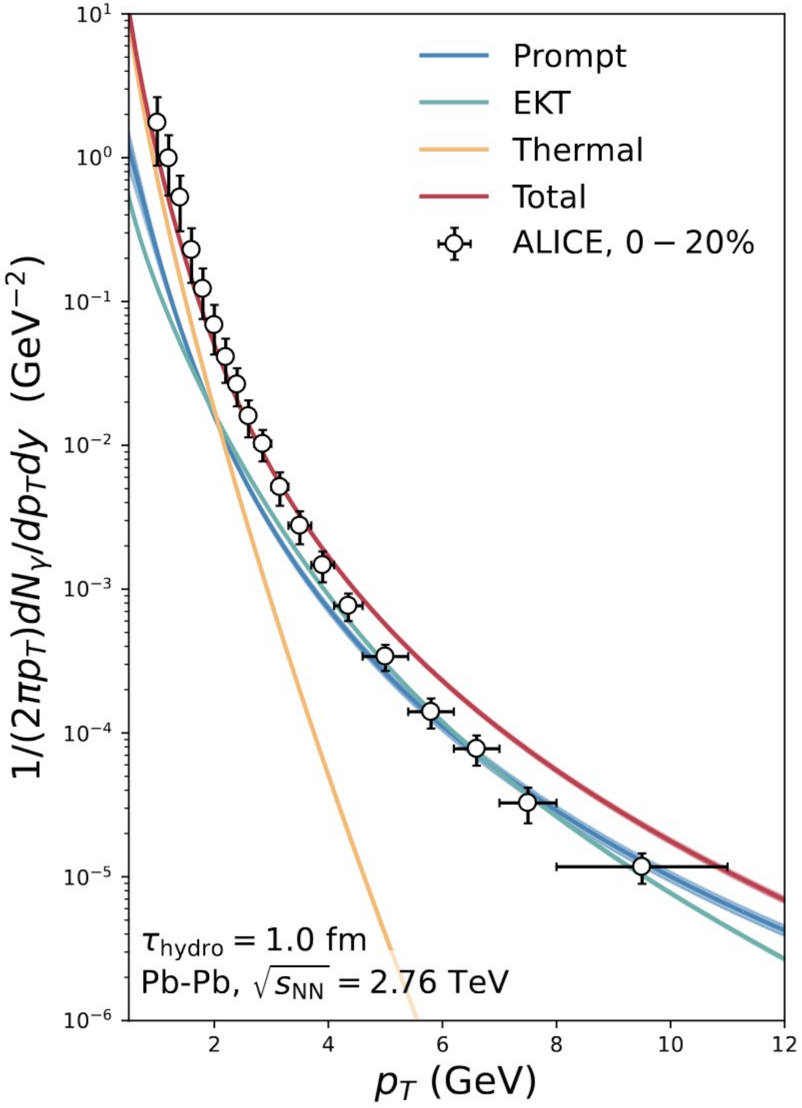


- What is the spatial distribution? IP-Glasma+KøMPøST
- What is the rate of photon emission at early time?
  - Thermal rate w/ viscous corrections + rate suppression factor for chemistry

Early-stage photons

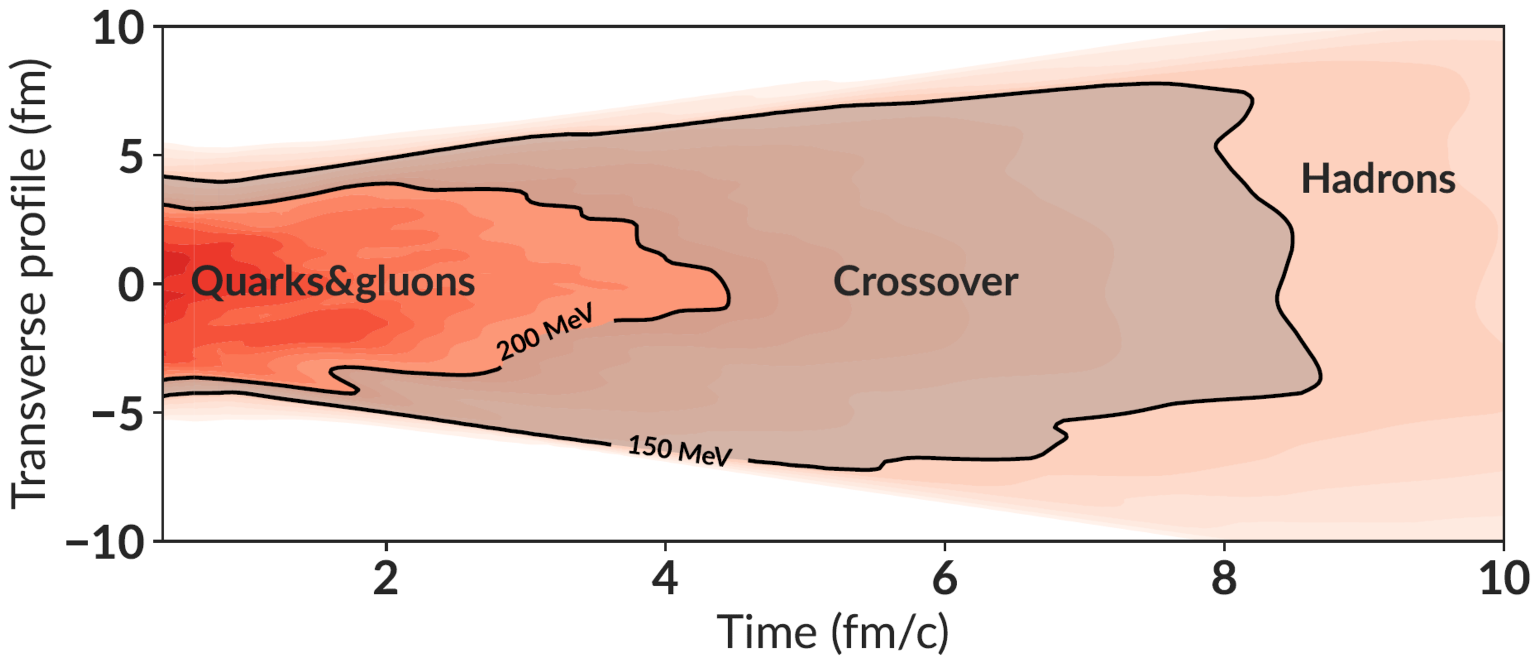
Garcia-Montero, Mazeliauskas, Plaschke, Schlichting [arXiv:2308.09747]





Early stage	Interface	Hydrodynamics	Interface	Late stage
Free-streaming?	thermalization	Relativistic viscous hydrodynamics	Interacting hadron gas	Hadrons free-streaming to detectors
	Pre-equilibrium photons/ dileptons	**Thermal photons and dileptons**	**Late-stage photons and dileptons (including hadronic decays)**	

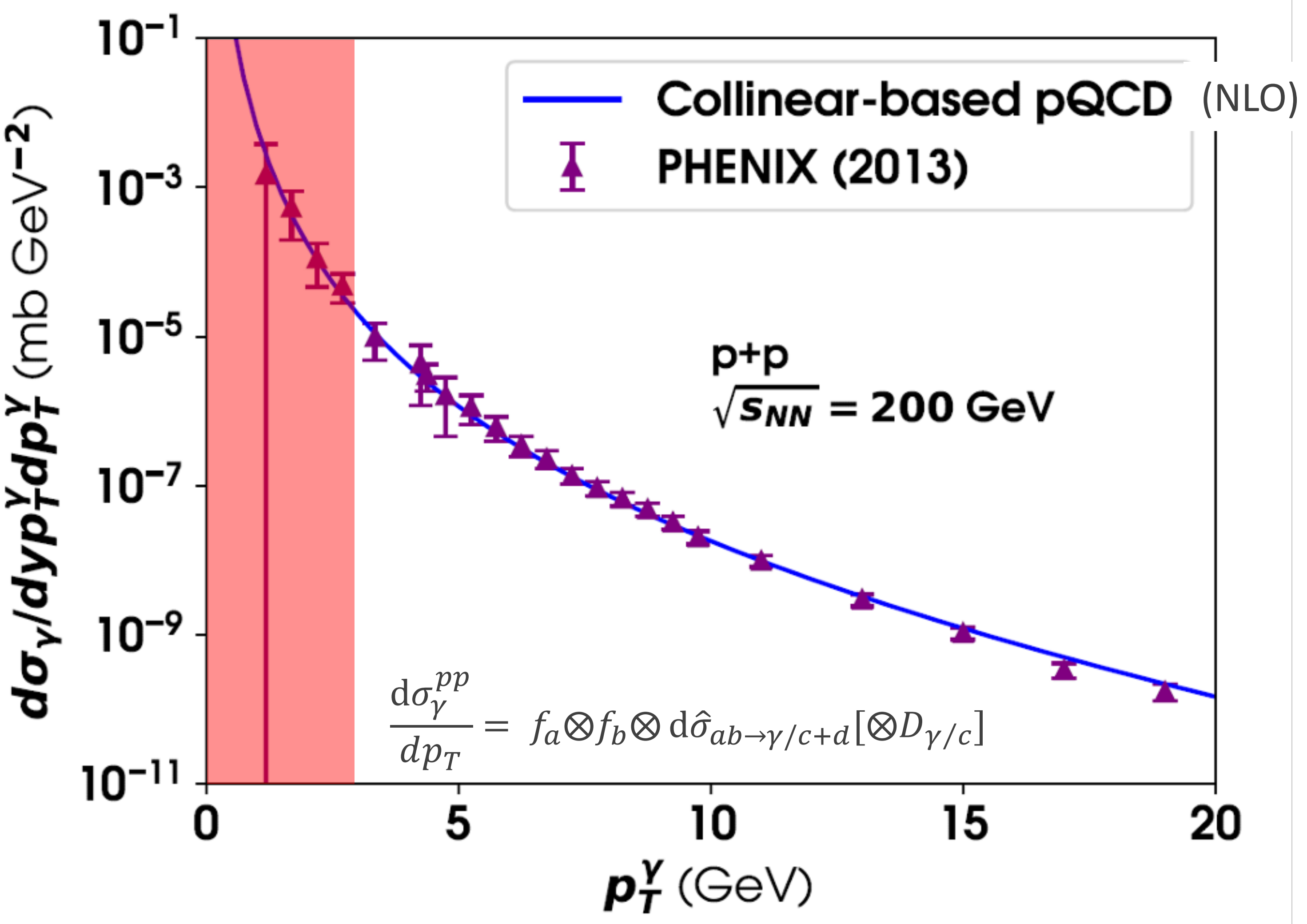
Prompt photons / Drell-Yan dileptons



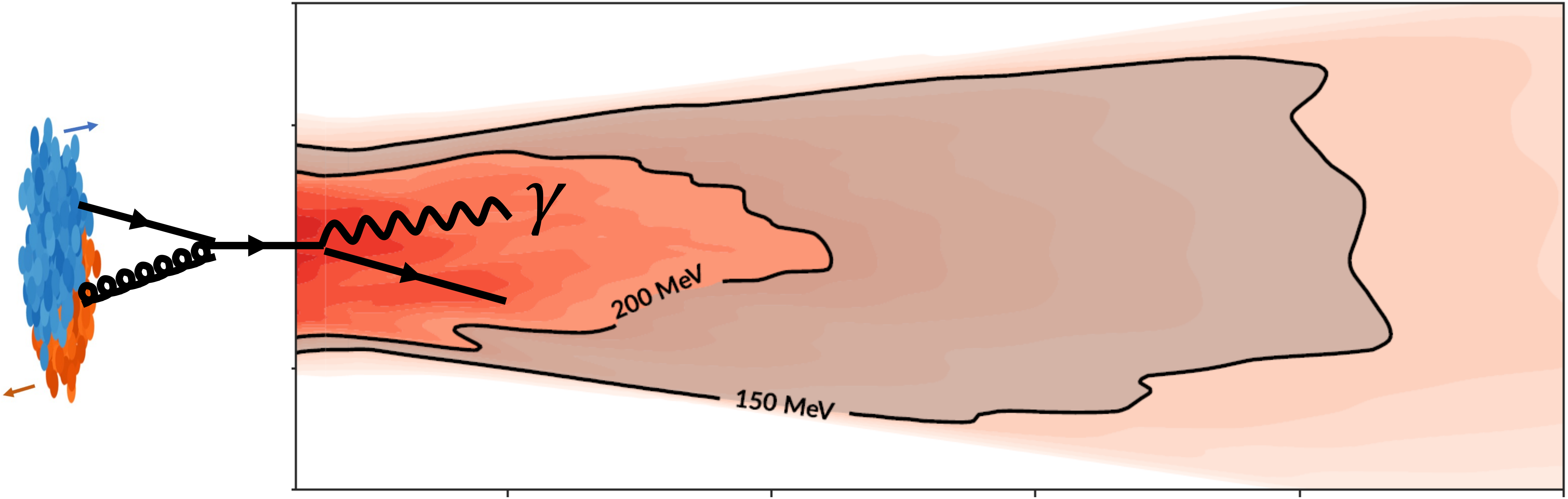
Other sources...

Direct photons in proton-proton collisions: “low” energy

- Low p_T photons:
  - Few measurements (in proton-proton collisions)
  - Difficult to compute from first principles
  - Non-perturbative effects likely significant



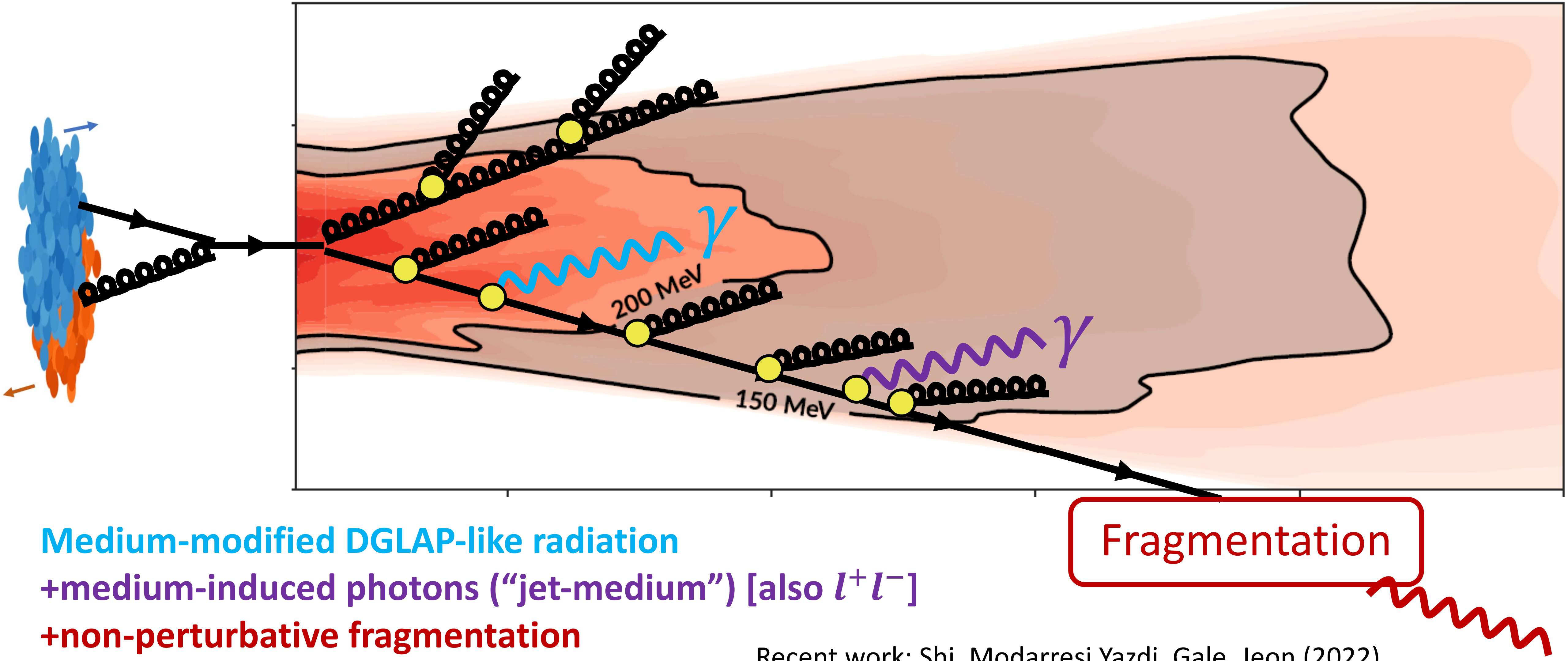
Medium-modified prompt photons



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

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

Medium-modified prompt photons



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

Recent work: Shi, Modarresi Yazdi, Gale, Jeon (2022)

Early stage

Free-streaming?

Interface

Attractors/ thermalization

Pre-equilibrium photons/ dileptons

Hydrodynamics

Relativistic viscous hydrodynamics

Thermal photons and dileptons

Interface

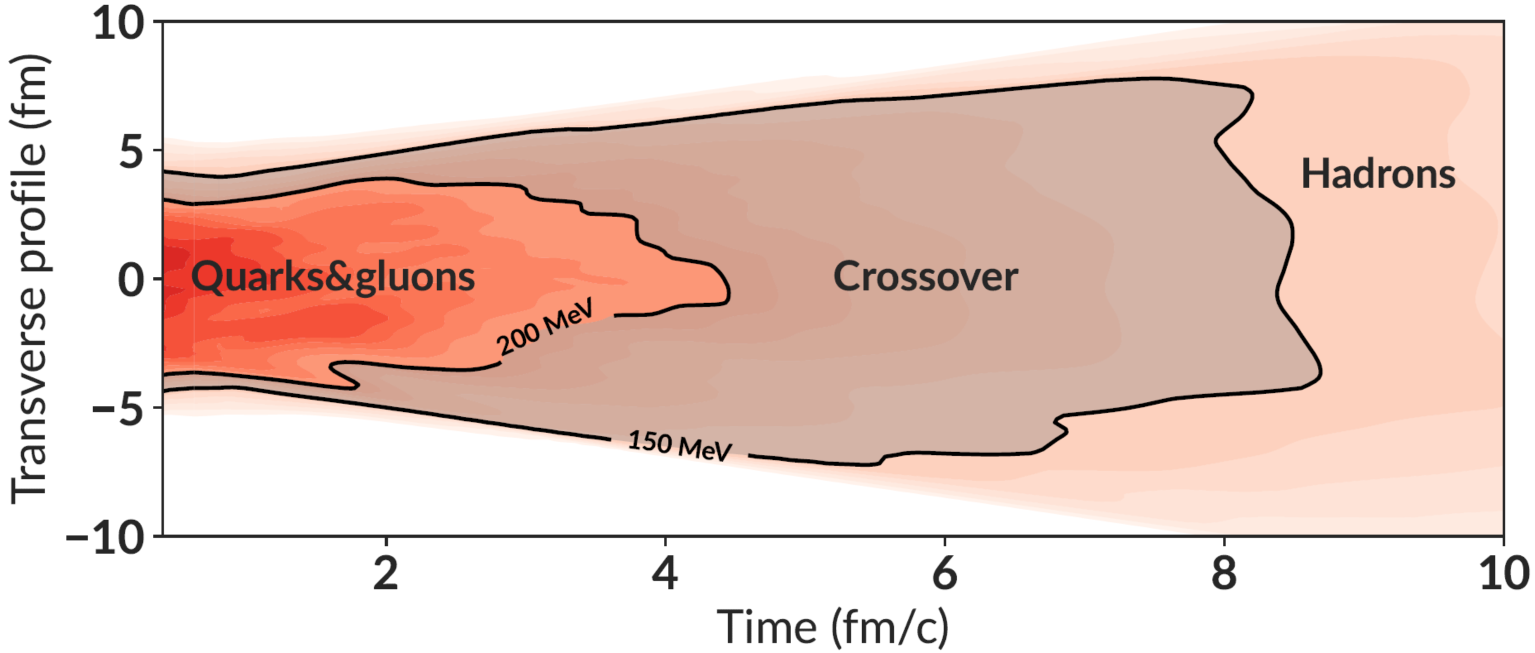
Interacting hadron gas

Late-stage photons and dileptons (including hadronic decays)

Late stage

Hadrons free-streaming to detectors

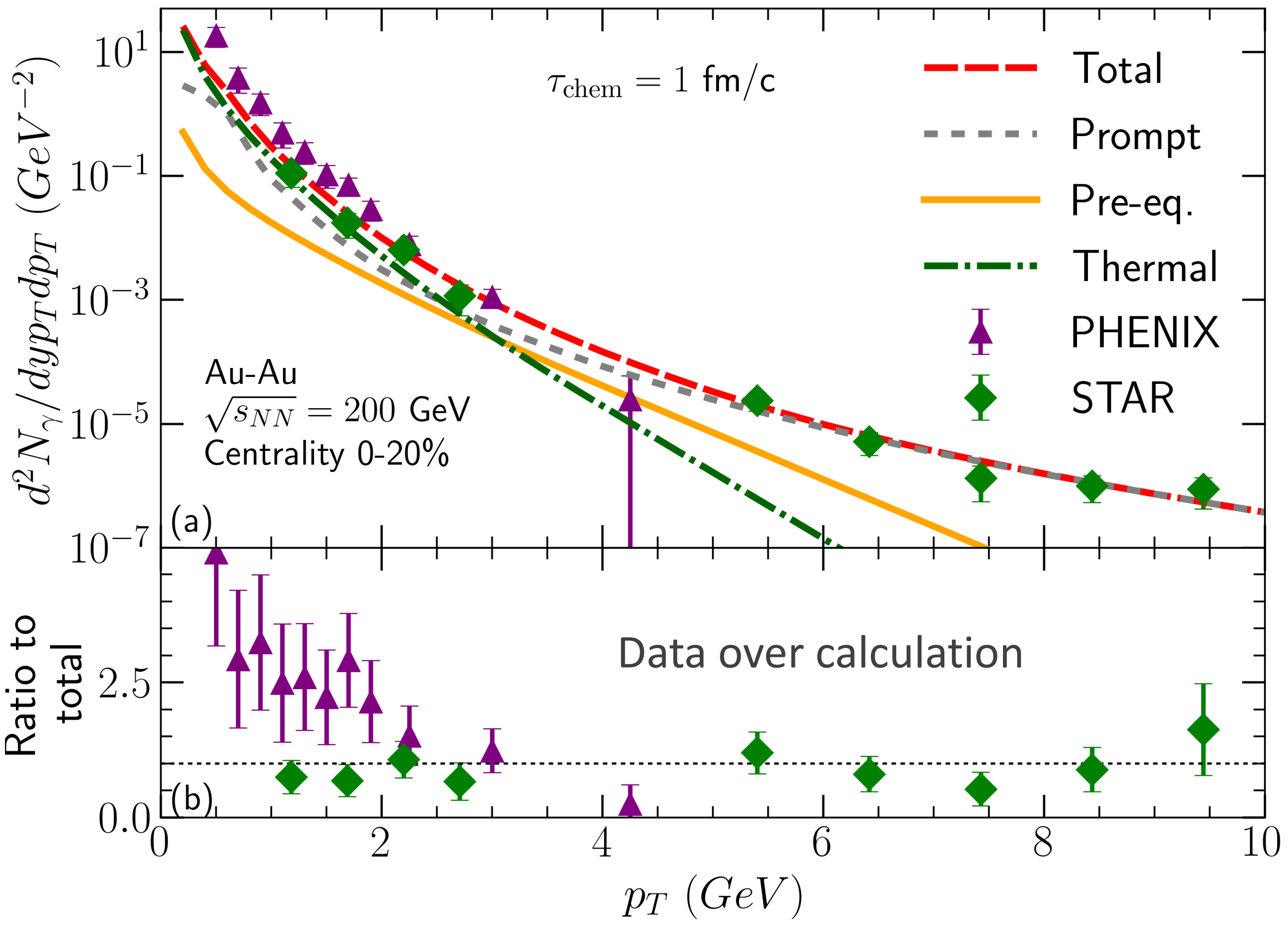
Prompt photons / Drell-Yan dileptons

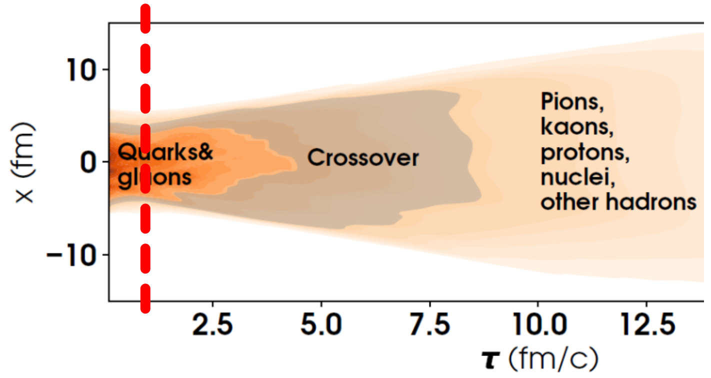


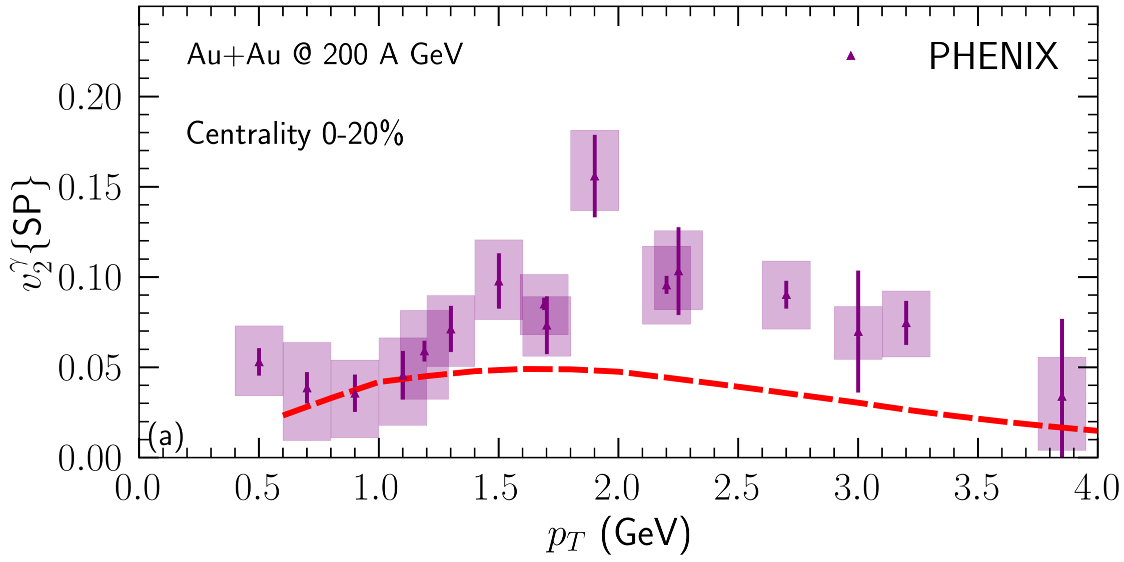
Other sources…

(Non-decay) photons in Au-Au $\sqrt{s_{NN}} = 200$ GeV, 0-20%

Gale, Paquet, Schenke, Shen (2022) PRC

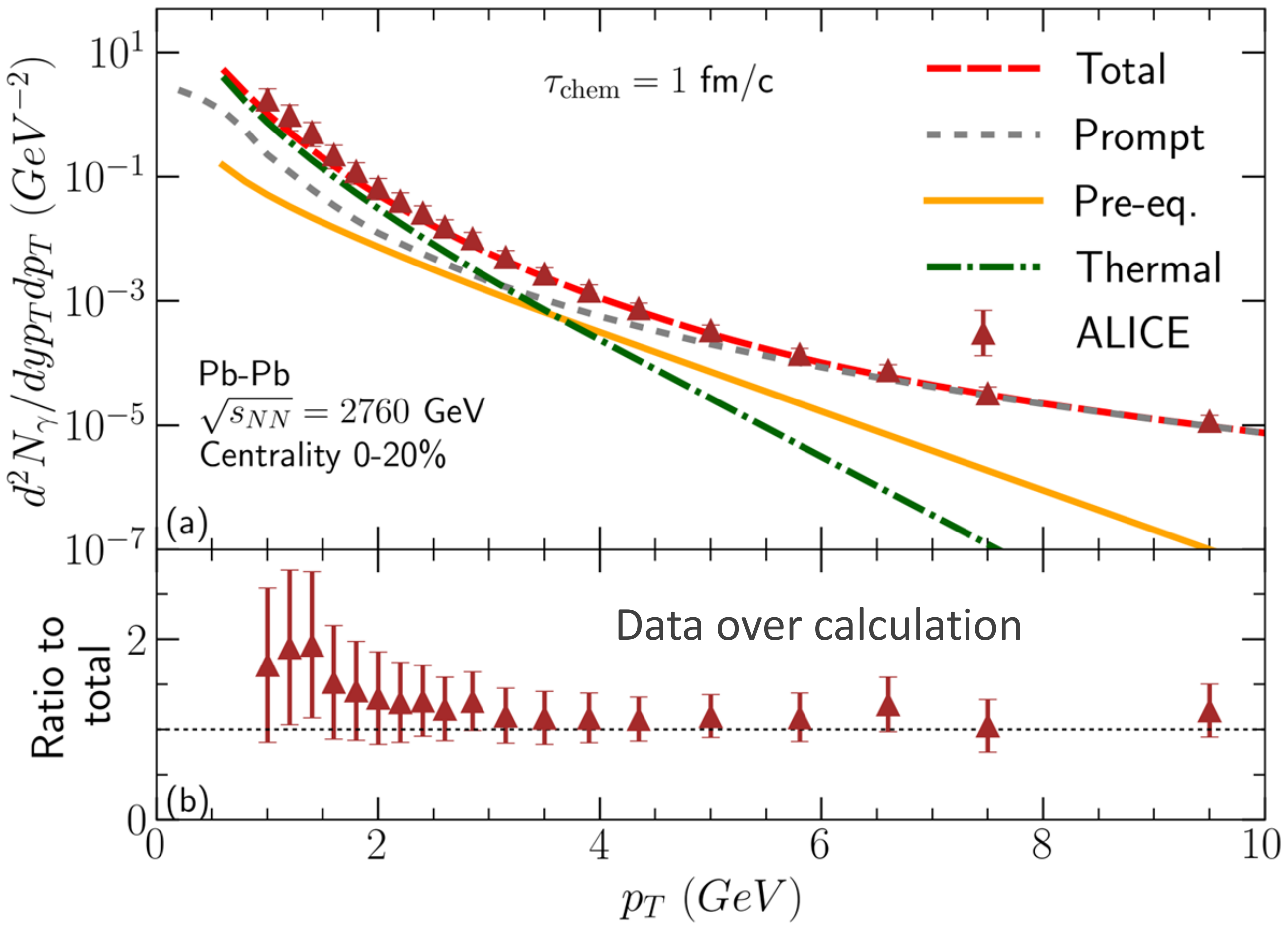


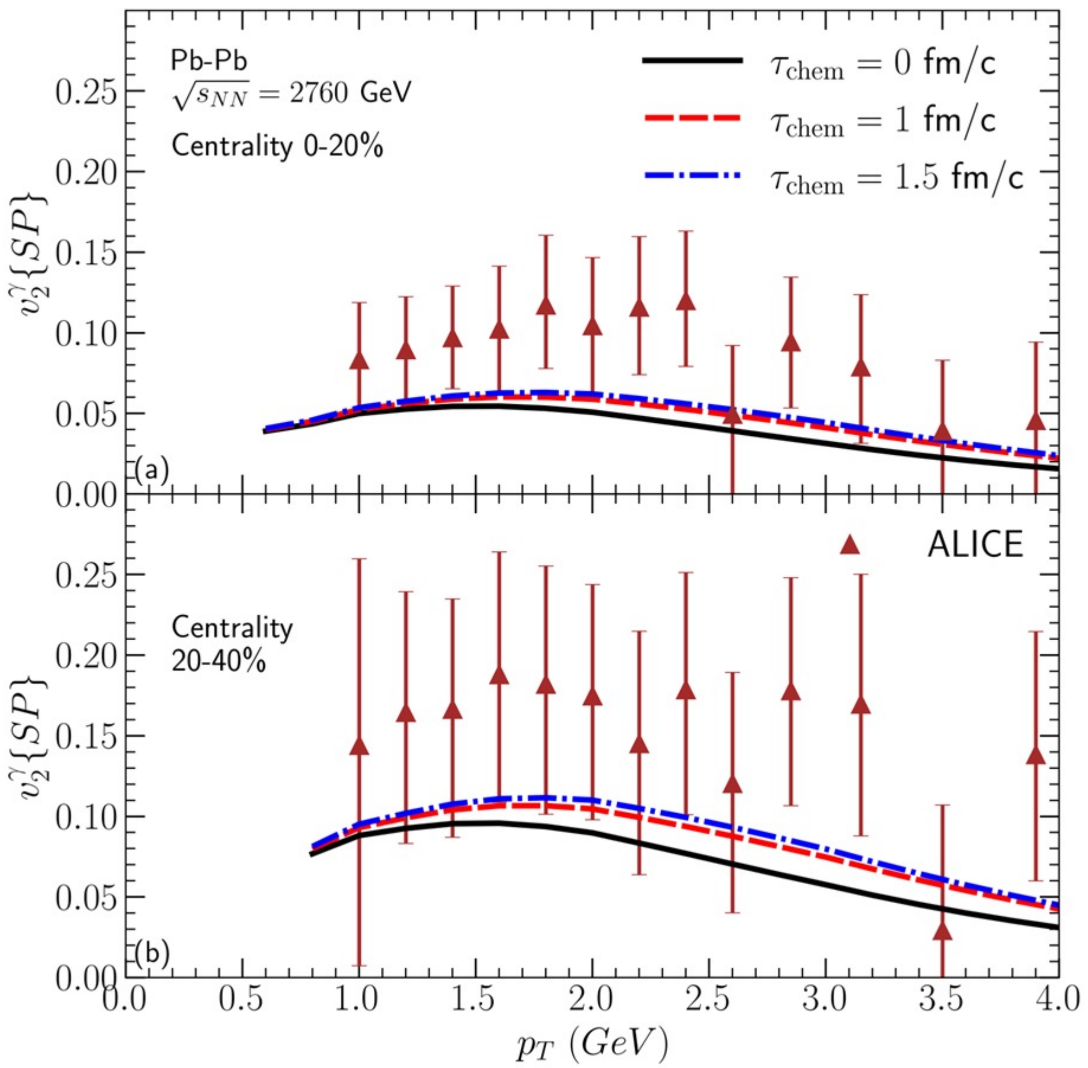




(Non-decay) photons in Pb-Pb $\sqrt{s_{NN}}$ =2760 GeV, 0-20%

Gale, Paquet, Schenke, Shen (2022) PRC





THE TEMPERATURE AND THE SLOPE

Early stage

Free-streaming?

Interf

Pre equilib photo dilept

Interface

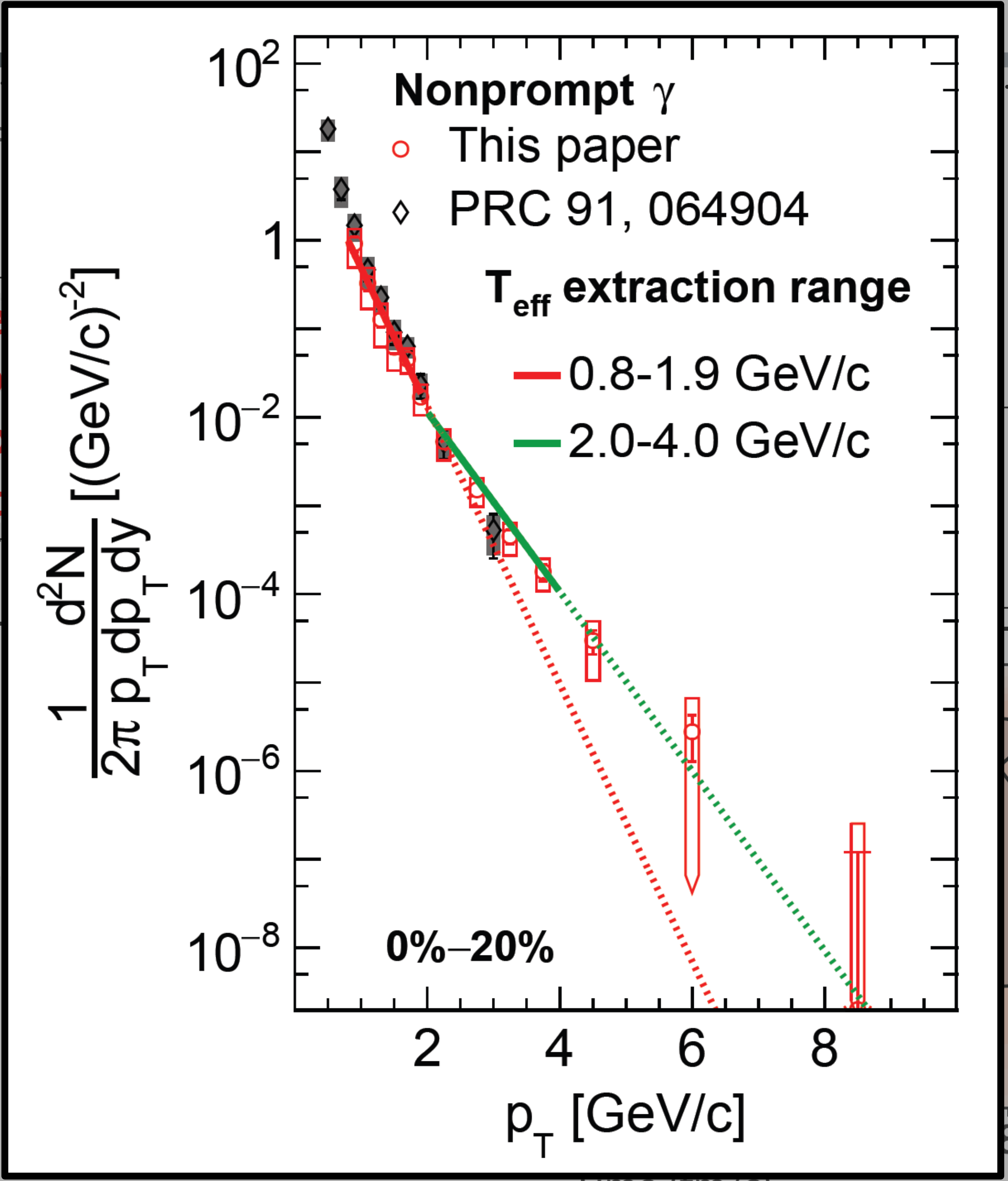
Interacting hadron gas

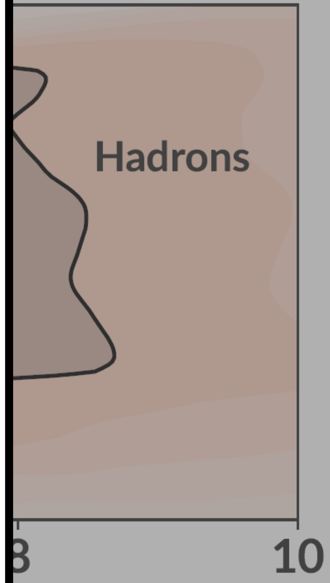
Late stage

Hadrons free-streaming to detectors

Late-stage photons and dileptons (including hadronic decays)

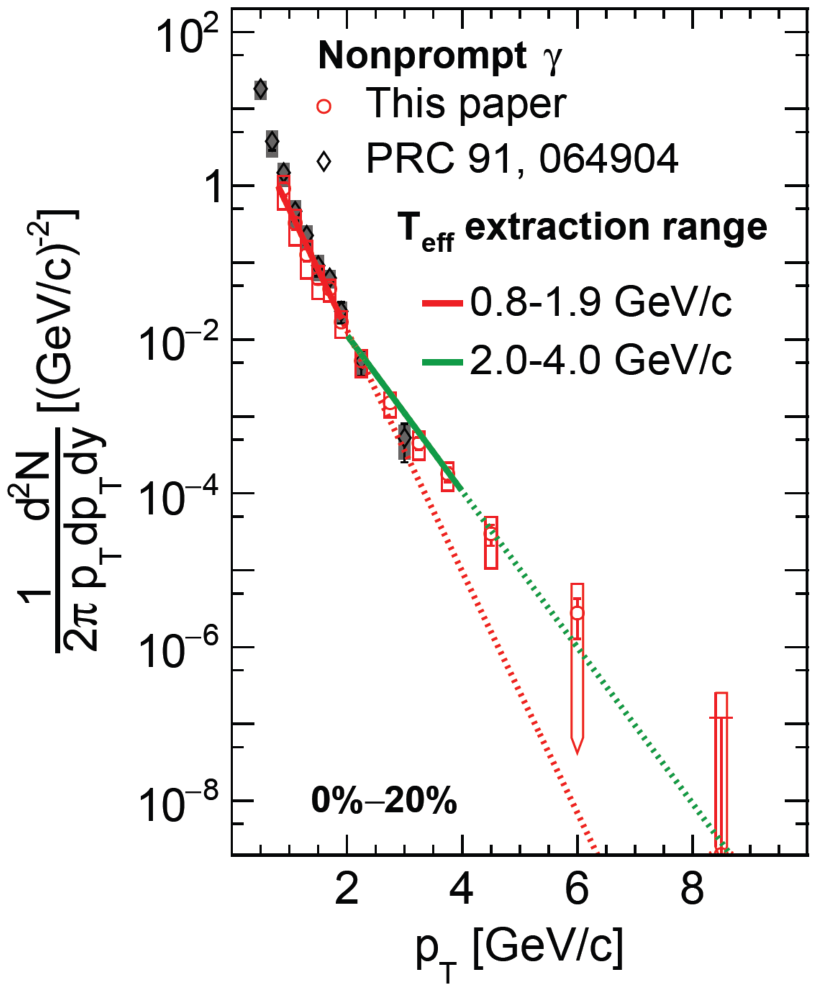
Other sources…





Photon p_T spectrum and inverse slope

Ref.: PHENIX Collaboration [arXiv:2203.17187]



$$\frac{1}{2\pi p_T}\frac{dN_\gamma}{dp_T}\bigg|_{y=0,p_{T,min}<p_T<p_{T,max}} \propto \exp\left(-\frac{p_T}{T_{eff}}\right)$$

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%	$0.253 \pm 0.011\ ^{+0.012}_{-0.006}$	$0.331 \pm 0.036\ ^{+0.031}_{-0.041}$

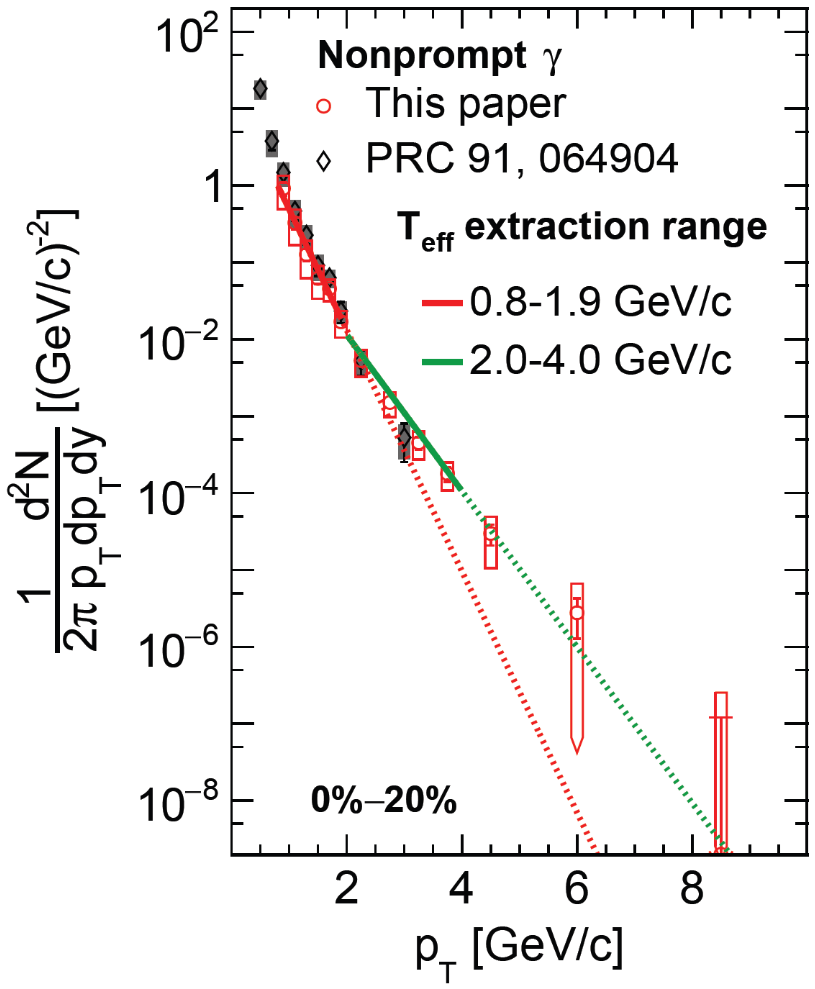
Results at the LHC by the ALICE Collaboration:

Centrality	**T_{eff} (GeV) 0.9 < p_T < 2.1 GeV**	**T_{eff} (GeV) 1.1 < p_T < 2.1 GeV**
0-20%	0.297	-
20-40%	-	0.410

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

Caveats: other sources of photons (e.g. pre-equilibrium), viscosity, ...

Ref.: PHENIX Collaboration [arXiv:2203.17187]



p_T *cut*	T_{eff}	$T_0 = \frac{T_{eff}}{1-\frac{5}{2}\frac{T_{eff}}{p_T}}$
$0.8 < p_T < 1.9$ GeV	277 MeV	570 MeV
$2 < p_T < 4$ GeV	428 MeV	670 MeV

From hydro fit to hadronic data: $T_0 \approx 530$ MeV

[from Gale, Paquet, Schenke, Shen (2022) PRC]

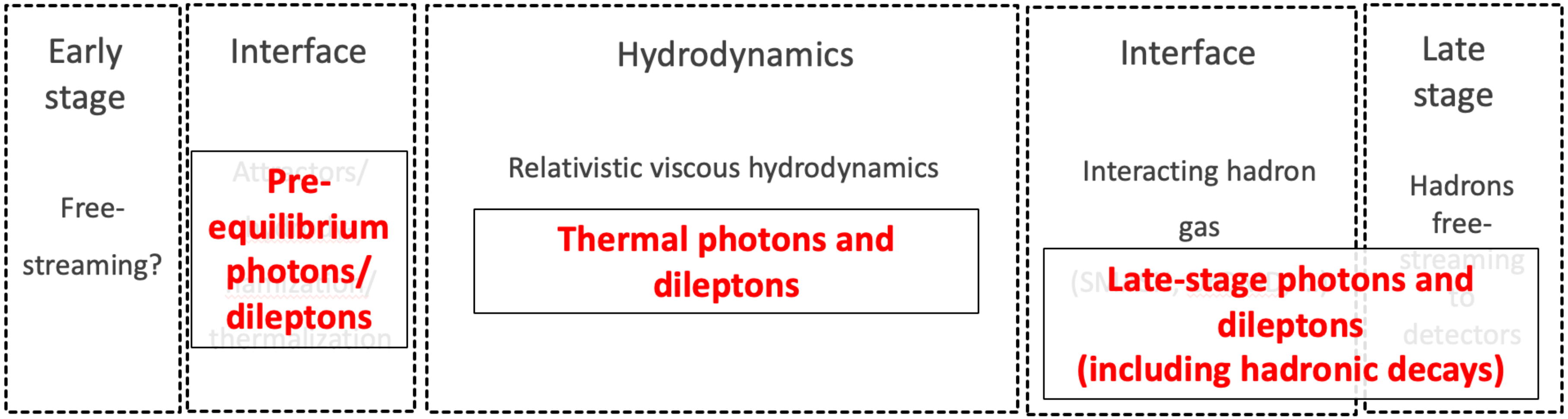
Partly explains large p_T-cut dependence of T_{eff}

Paquet and Bass [arXiv:2205.12299]; Paquet (2023) PRC

SUMMARY

Summary

- Electromagnetic probes are sensitive to all stages of heavy-ion collisions
- Progress at every stage, especially the interfaces; still more to do!



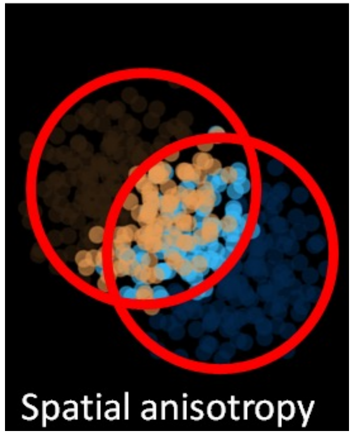
- <u>Lower collisions energy or smaller system size = more interface</u>

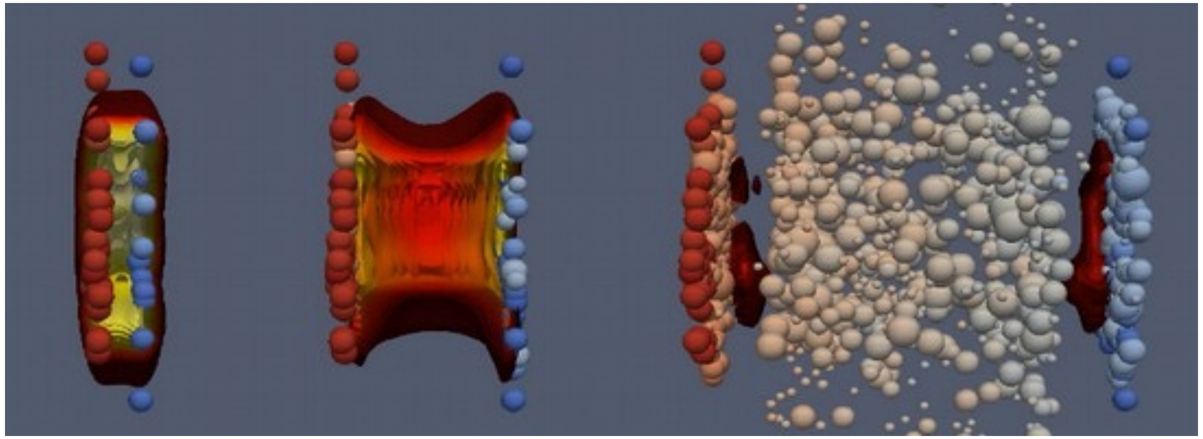
QUESTIONS?

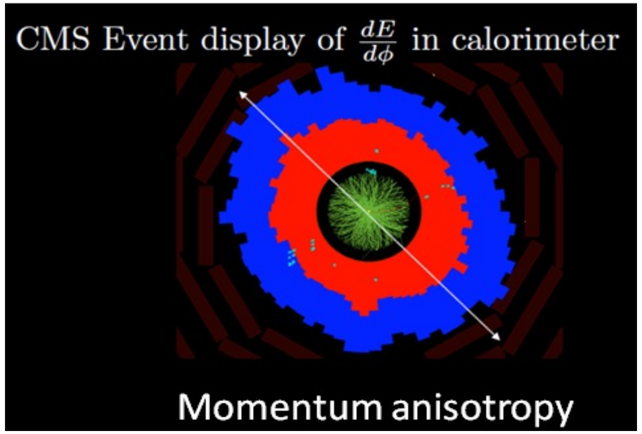
BACKUP

Interaction and expansion

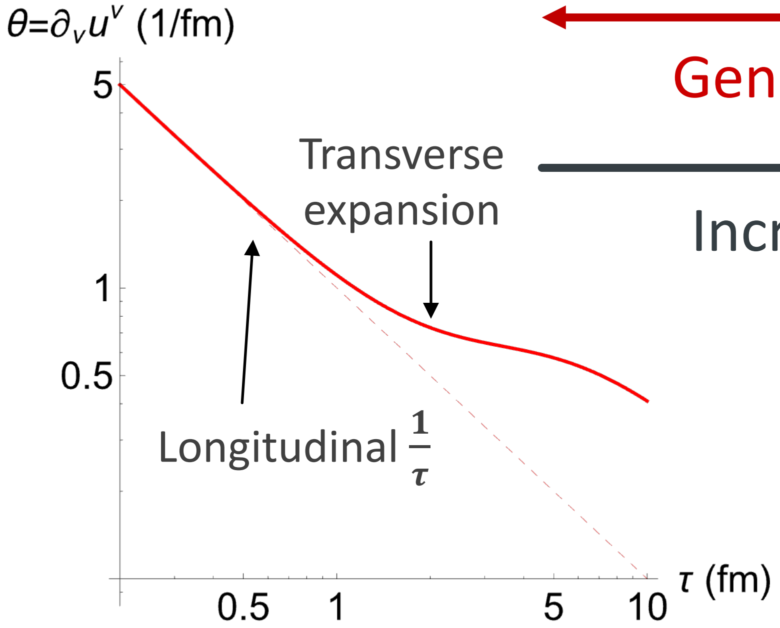
Based on figures by Derek Teaney, CMS Coll., MADAI, H. Elfner and J. Bernhard





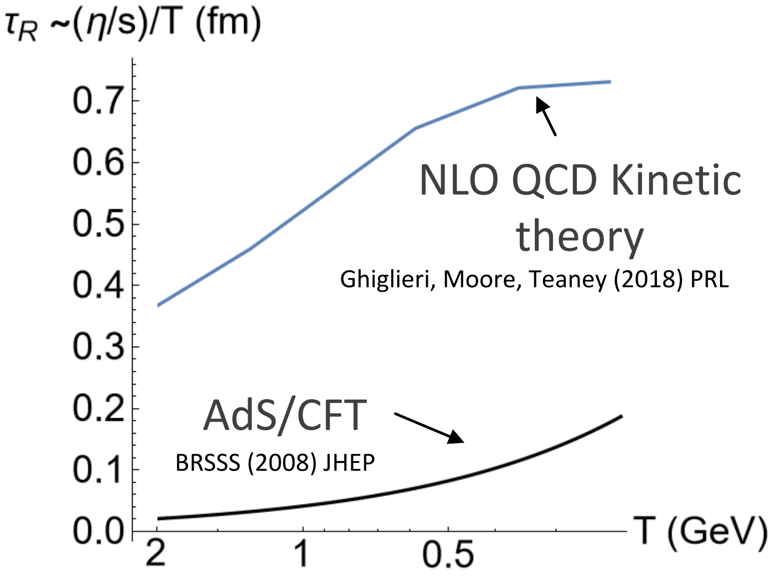


Ref: Review of Particle Physics



General decrease in expansion rate

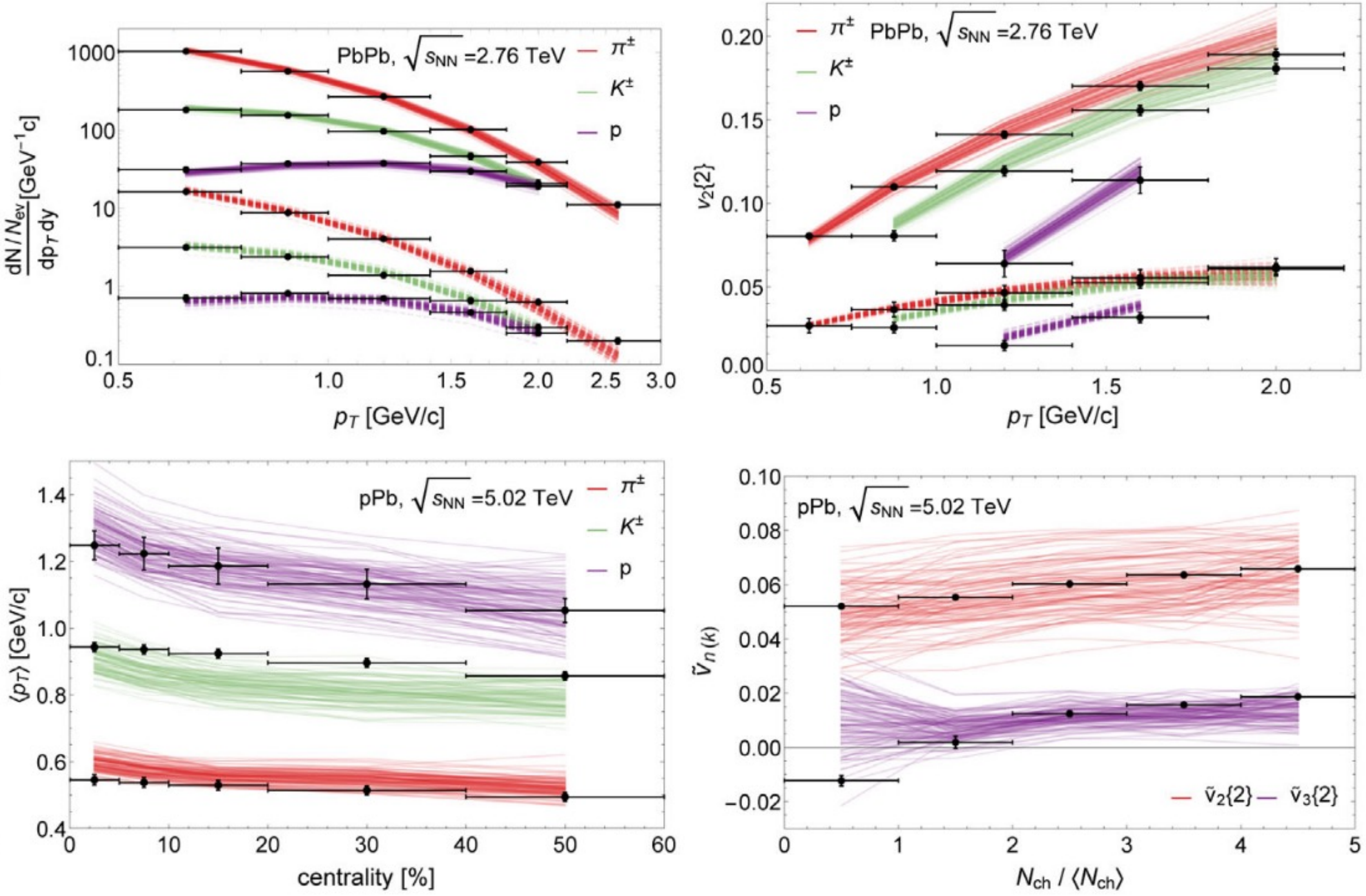
Increase in local equilibration time (relaxation time)



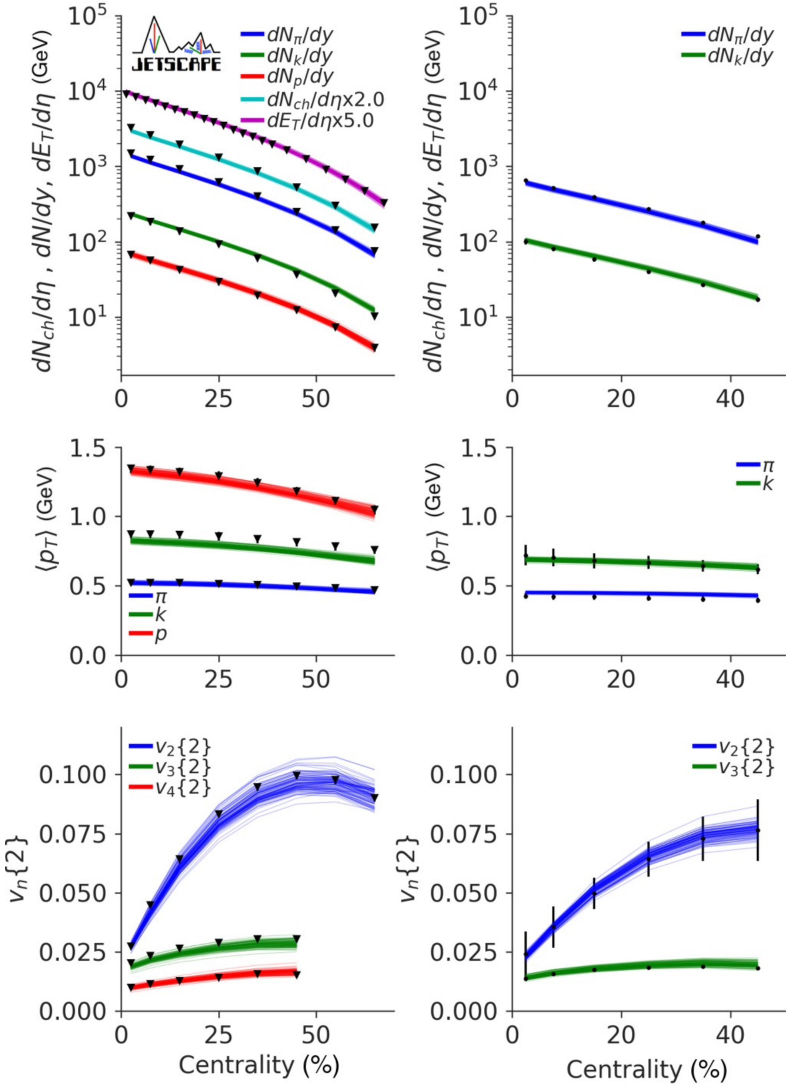
Hydrodynamic-based simulations of heavy ion collisions

- Successful in describing broad sets of measurements

Nijs, van der Schee, Gürsoy, Snellings (2021) PRC, PRL

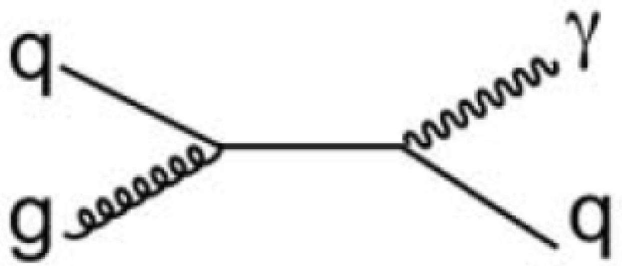


JETSCAPE Collaboration, (2021) PRC, PRL



Direct photons in proton-proton collisions: channels

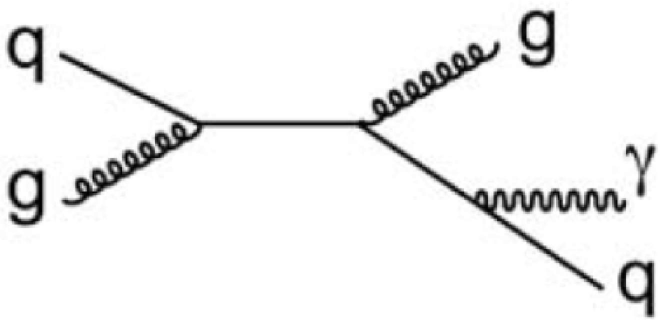
- Hard partonic collisions
  - "Isolated"



(Can be calculated at NNLO)

$$\mathrm{d}\sigma_{\gamma}^{pp}/dp_T = f_a \otimes f_b \otimes \mathrm{d}\hat{\sigma}_{ab\to\gamma/c+d}$$

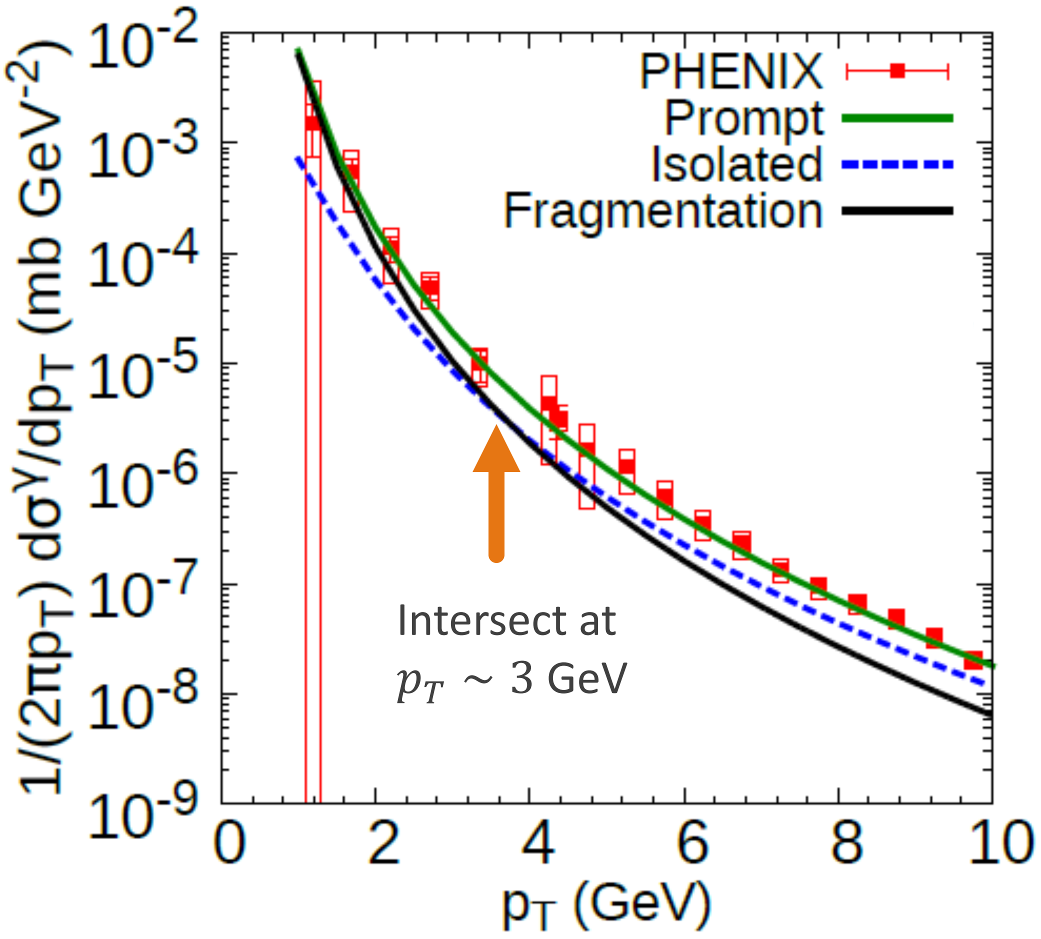
  - Fragmentation



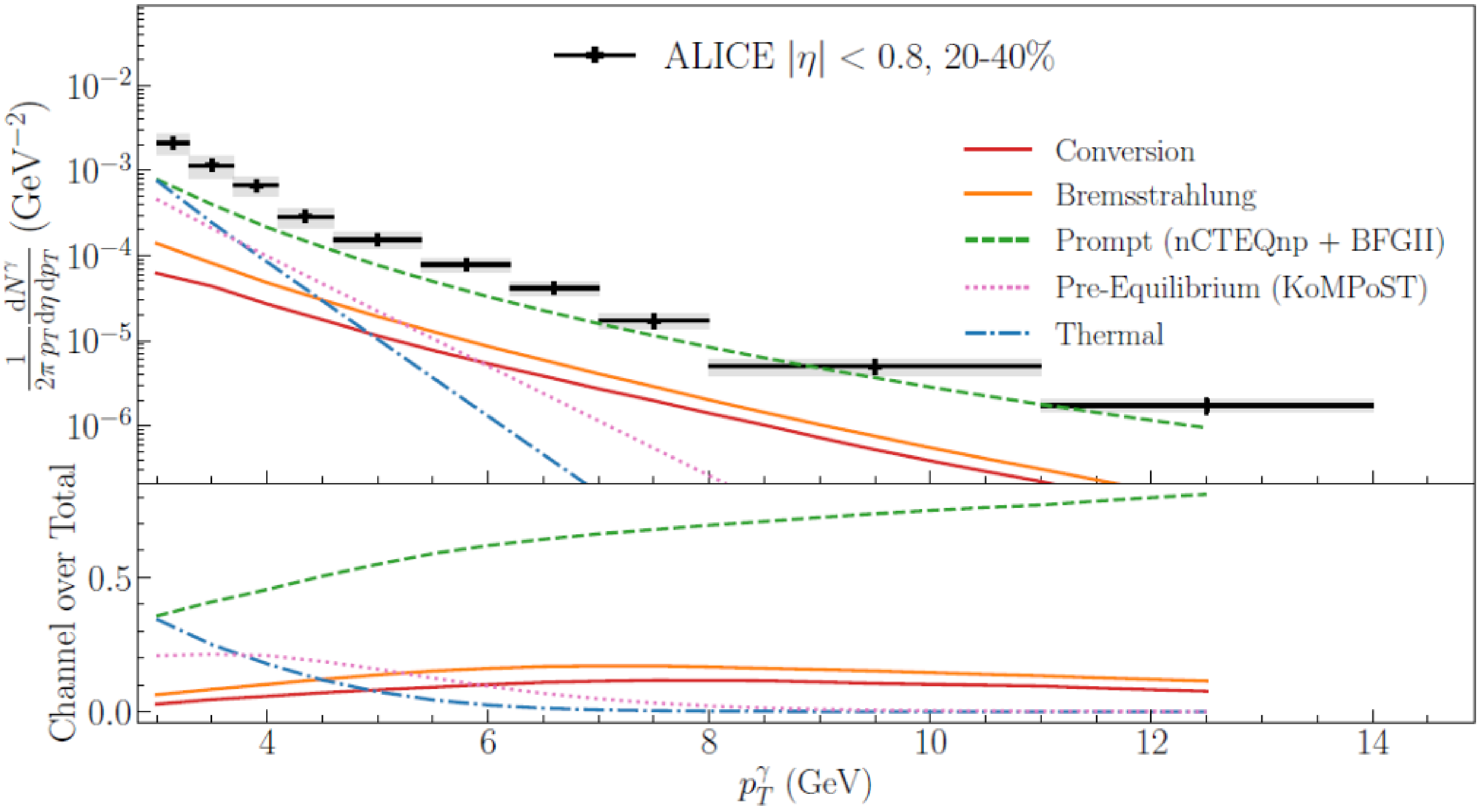
(Fragmentation function unmeasured at NNLO and poorly constrained at NLO)

$$\mathrm{d}\sigma_{\gamma}^{pp}/dp_T = f_a \otimes f_b \otimes \mathrm{d}\hat{\sigma}_{ab\to\gamma/c+d} \otimes D_{\gamma/c}$$

p+p $\sqrt{s}$=0.2 TeV

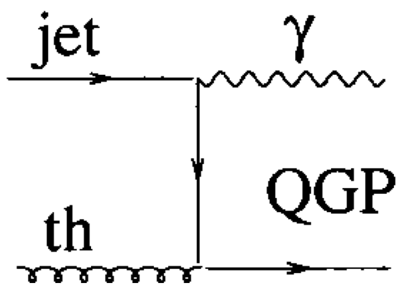


Jet-medium photons

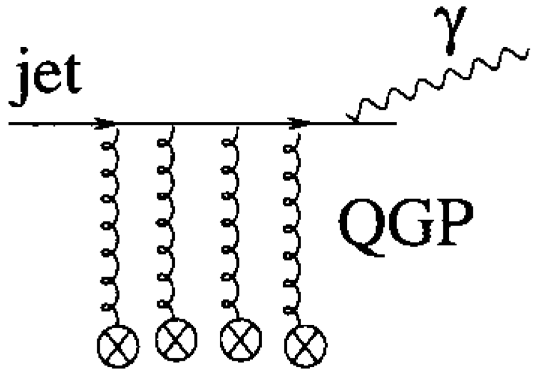


Shi, Modarresi Yazdi, Gale, Jeon (2022)

Conversion



Bremsstrahlung



Figures from S.Turbide

Photon emission rate

Spacetime profile of plasma

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

Photon emission rate

Temperatures	Photon emission rate
$T < 160$ MeV	Effective hadronic models: Texas A&M/McGill rates ("massive Yang-Mills Lagrangian"), Stony Brook rate ("chiral reduction")
$T \approx 160 - 200$ MeV	Lattice QCD: Cè et al (2022) PRD; Jackson&Laine (2019) JHEP; Ghiglieri et al (2016) PRD
$T \sim 200 - 500$ MeV	
$T \gg 1$ GeV	Perturbative QCD: Arnold, Moore, Teaney; Ghiglieri, Moore, Teaney (2013) JHEP

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

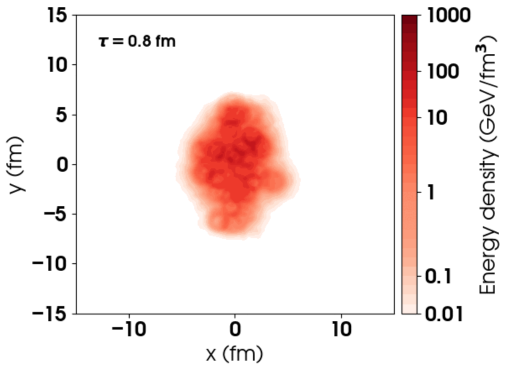
Doppler shift

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

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

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



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

Doppler shift

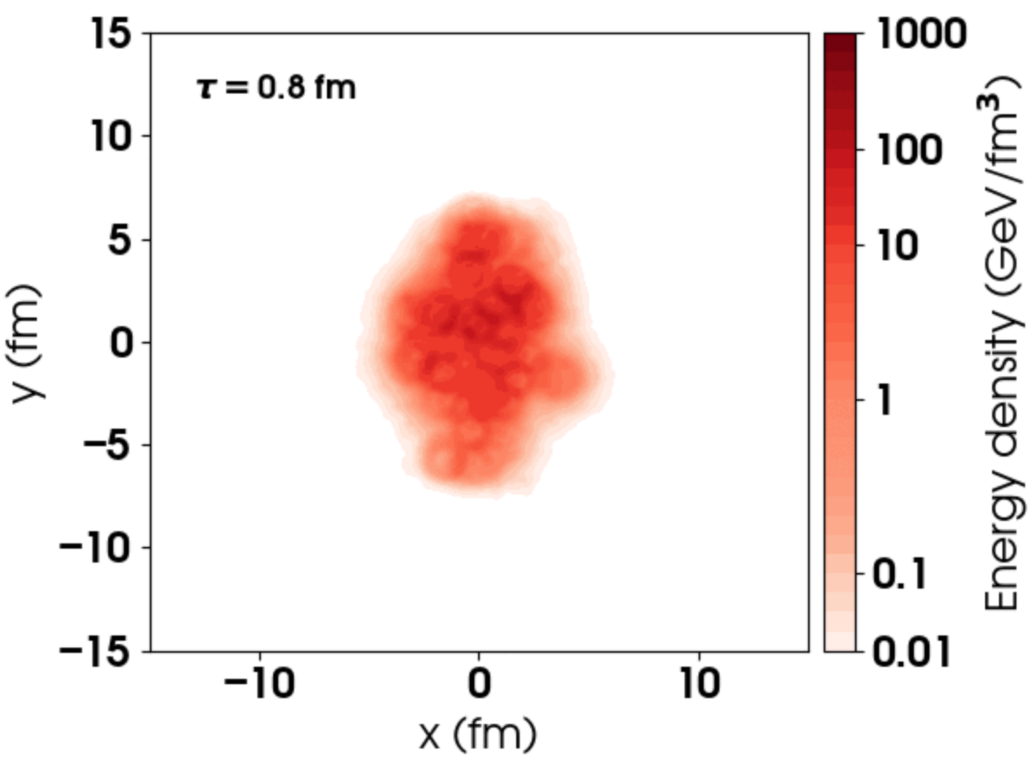
$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx \ln\left(\int \mathrm{d}^4X \, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte = \ln\left(\int d\phi \, d\eta_s \, dx_\perp \, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte$$

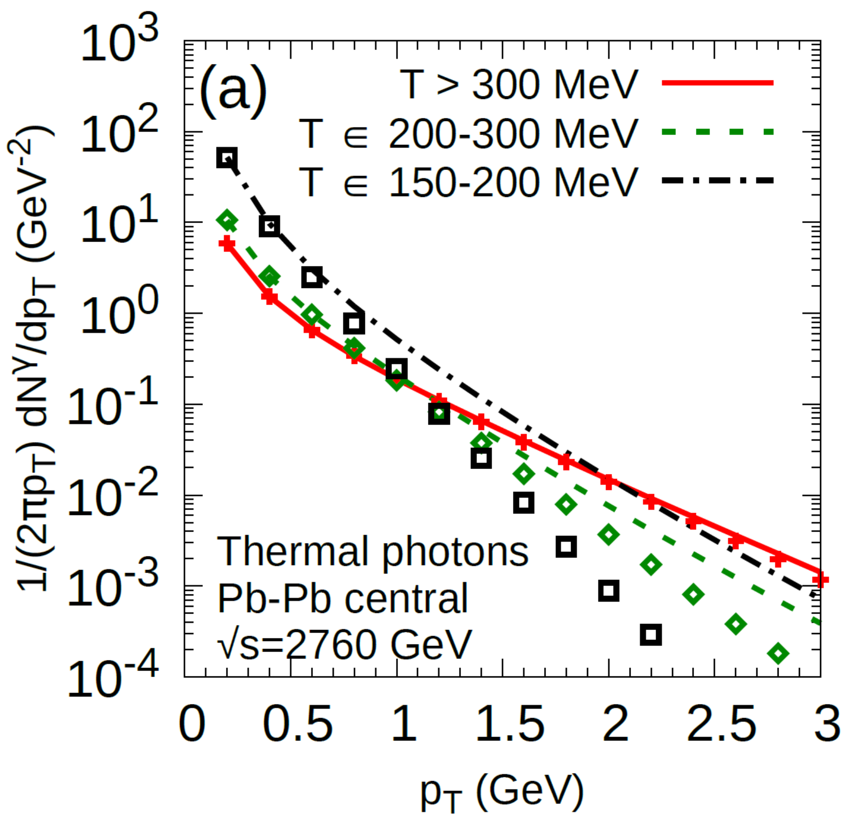
$$\approx \ln\left(\int dx_\perp \exp\left(-\frac{E}{T\left(1+\frac{u_\perp^2}{4E/T}(1+(E/T-2)(E/T))\right)}\right)\right) + cte$$

Thermal photon spectrum: Doppler shift

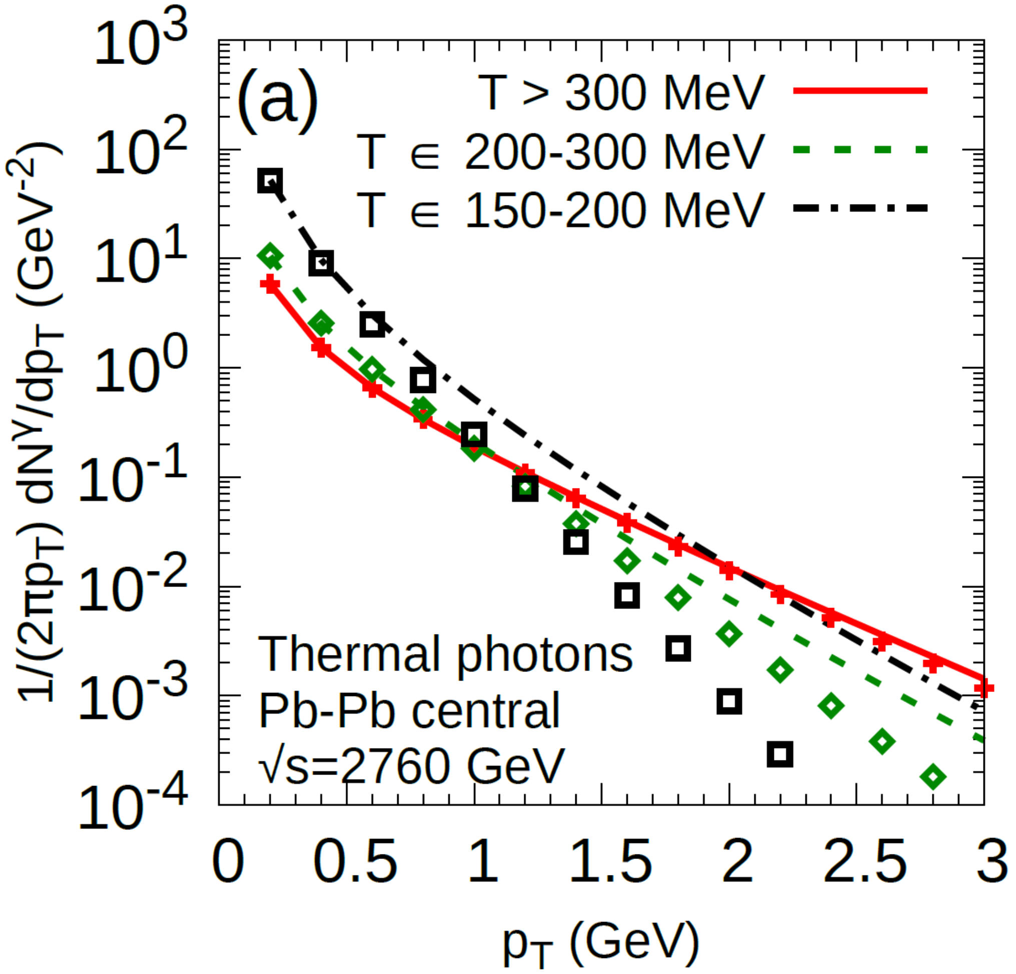
$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx \ln\left(\int dx_\perp \exp\left(-\frac{E}{T\left(1+\frac{u_\perp^2}{4E/T}(1+(E/T-2)(E/T))\right)}\right)\right) + cte$$

Transverse Doppler shift

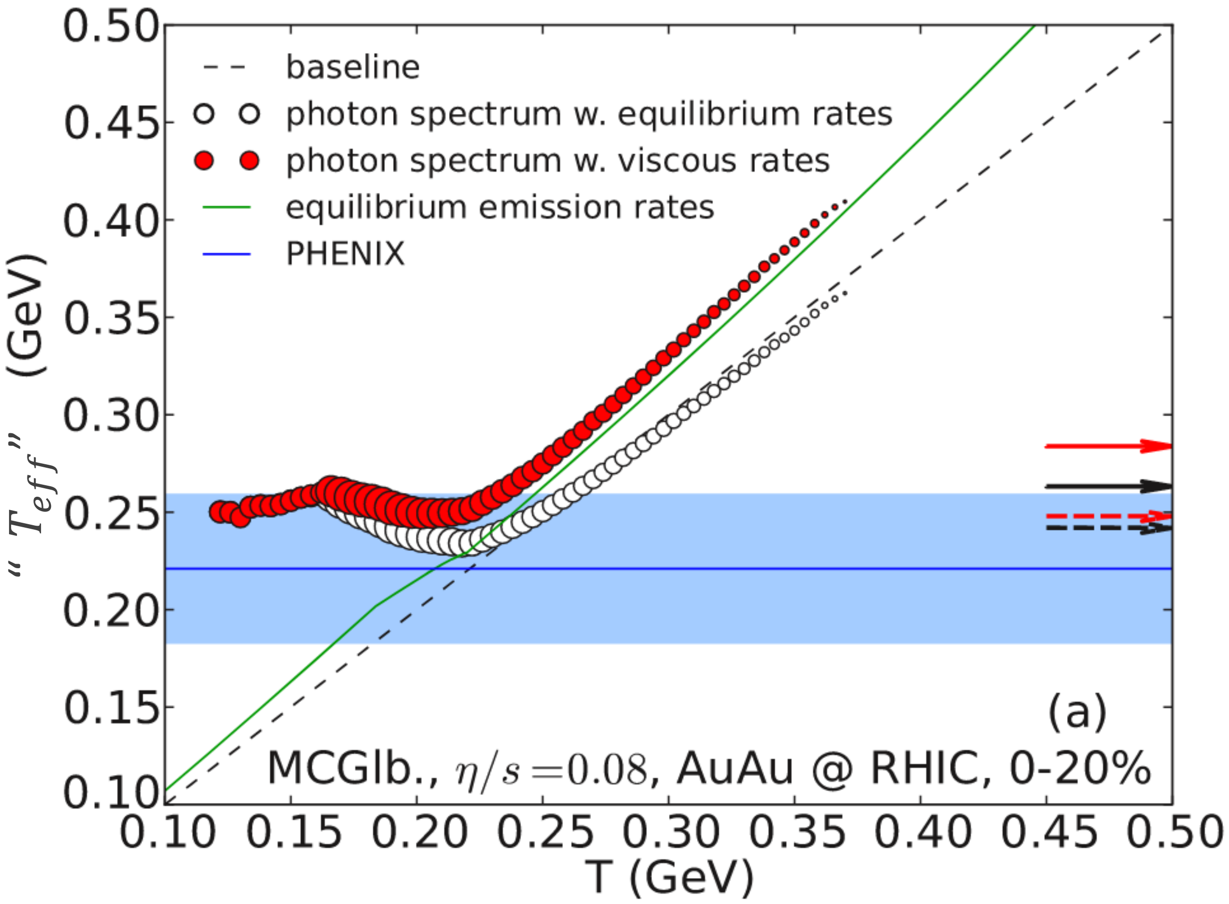




Effect of transverse Doppler shift

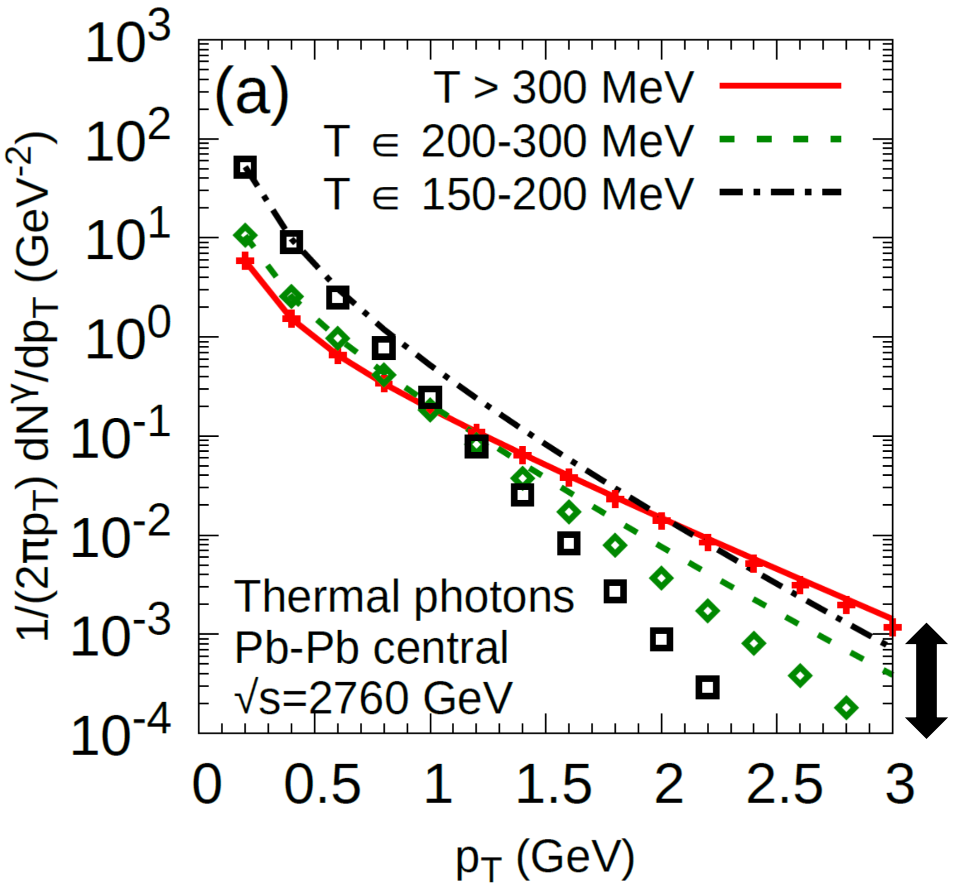


Local effect of Doppler shift

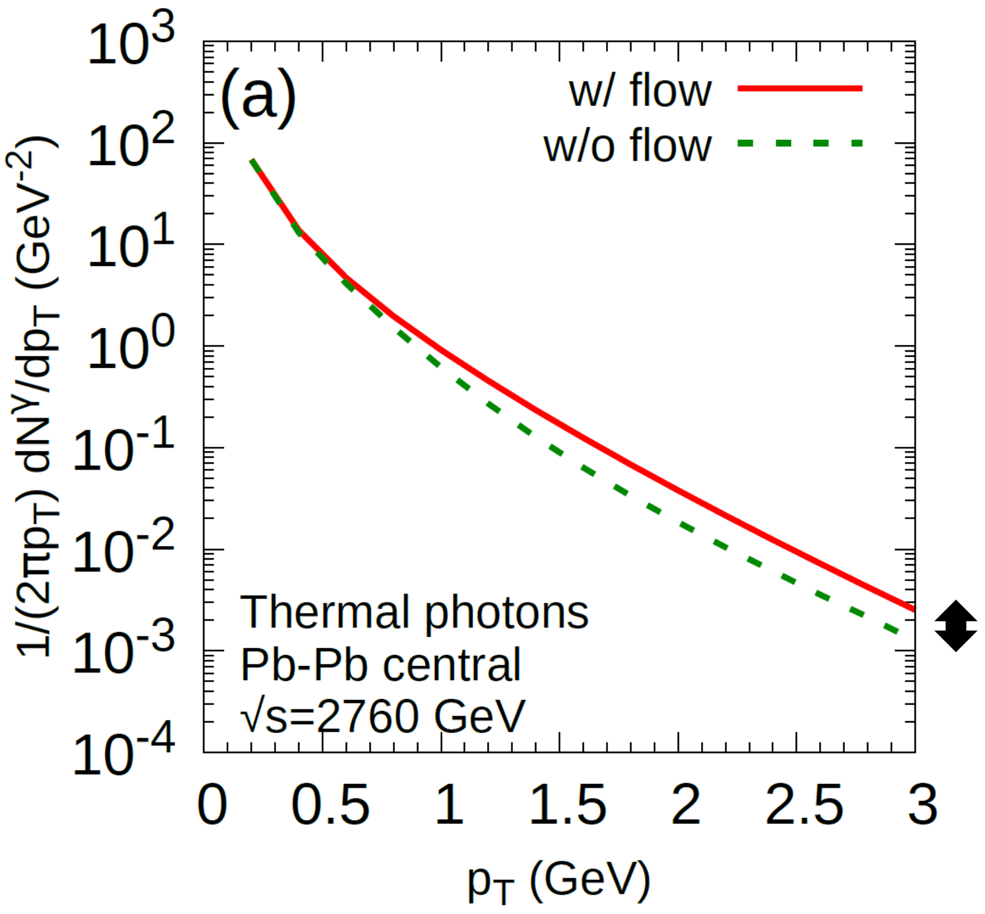


Ref.: Shen, Heinz, Paquet, Gale (2014) PRC;
See also van Hees, Gale, Rapp (2011) PRC

Effect of transverse Doppler shift

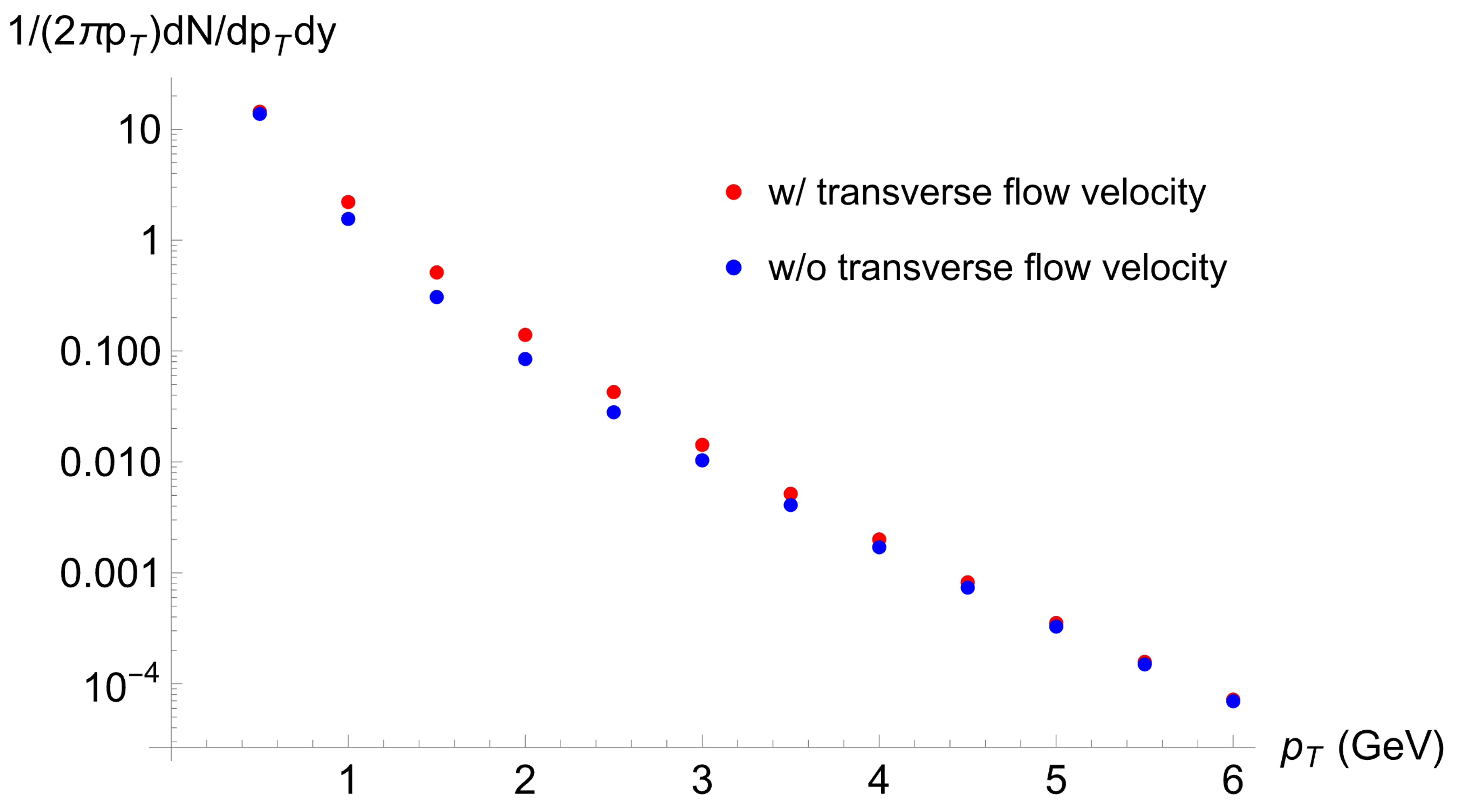


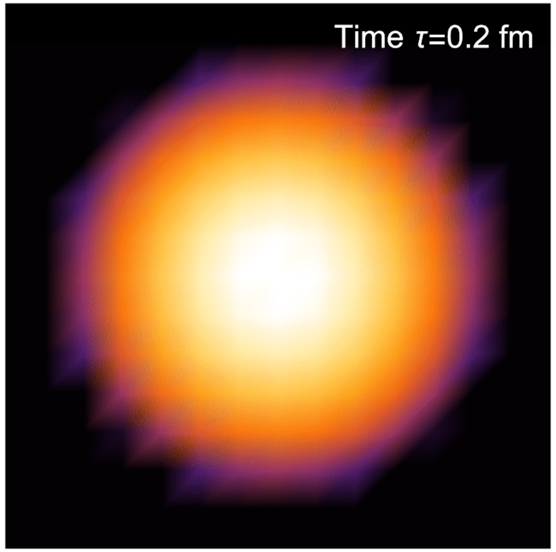
Local effect of Doppler shift



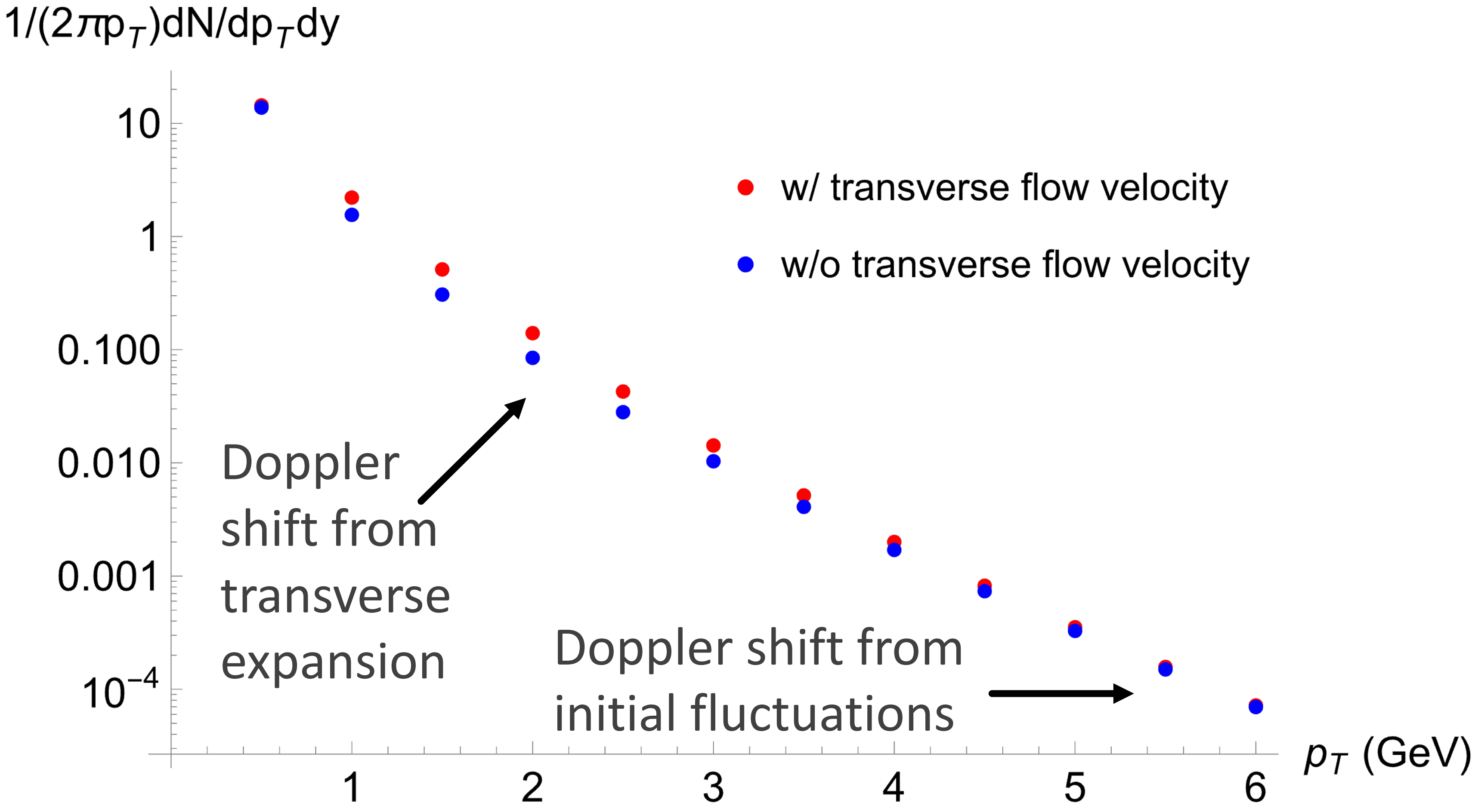
Global effect of Doppler shift

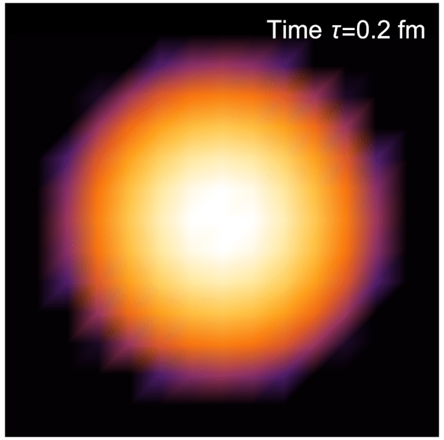
Not all Doppler shifts are equal

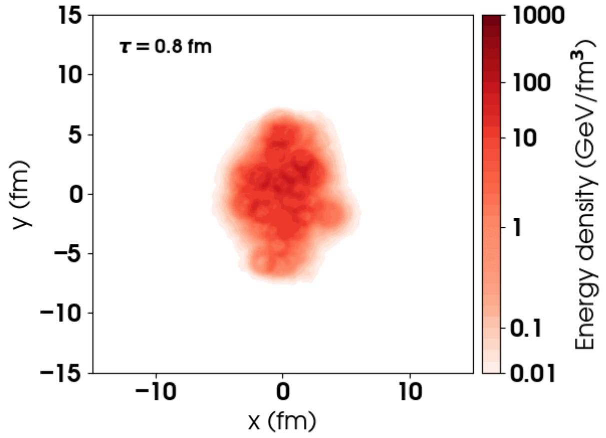




Different origins of the Doppler shift

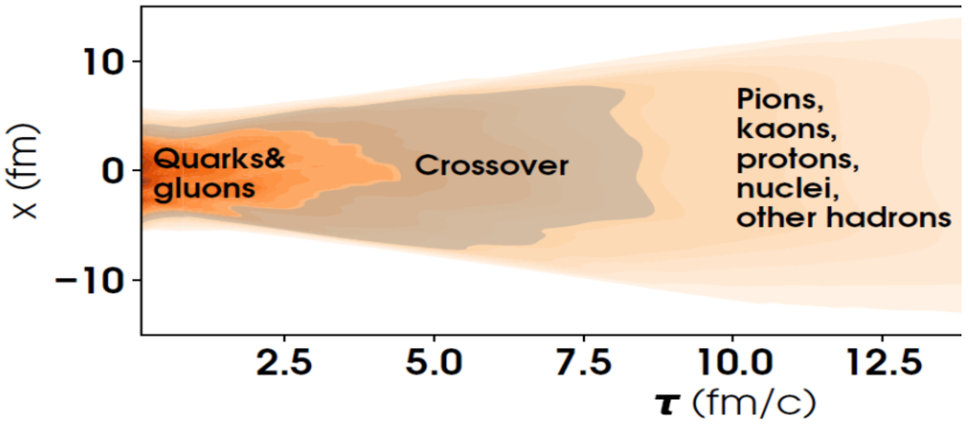






Thermal photon spectrum

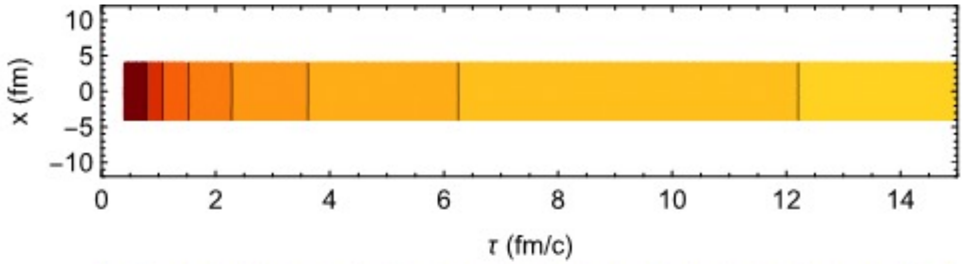
$$\ln\left(\frac{1}{E}\frac{dN_\gamma}{d^3p}\right) \approx \ln\left(\int d\phi d\eta_s dx_\perp\, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte$$



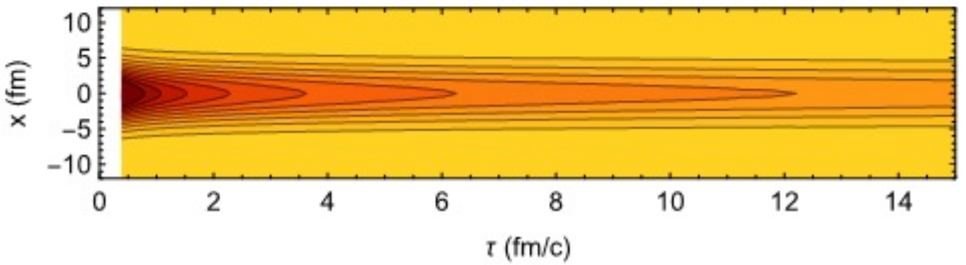
Spacetime profile of plasma: complicated, but can look at simple models

Bjorken hydrodynamics for longitudinal-dominated expansion: $T(\tau) = \mathrm{T}_0\left(\frac{\tau_0}{\tau}\right)^{\mathrm{c}_s^2}$

➡ Black disk approx: $T(\tau, r<\sigma) = \mathrm{T}_0\left(\frac{\tau_0}{\tau}\right)^{\mathrm{c}_s^2}$



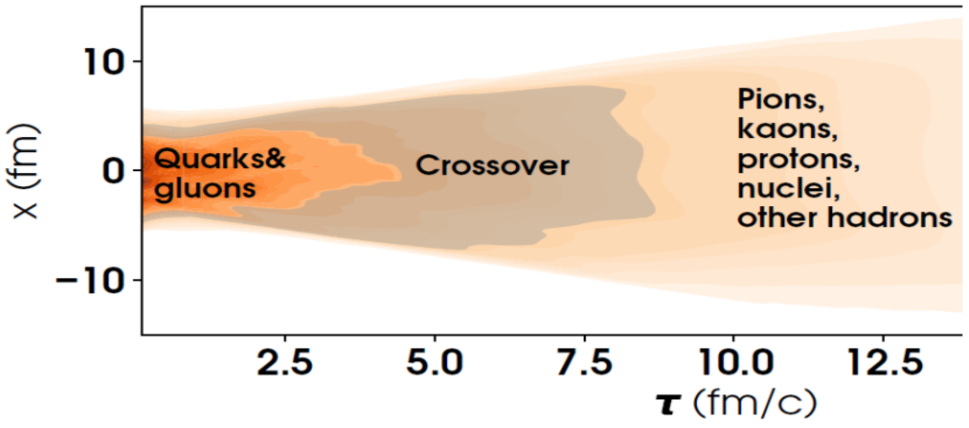
➡ Gaussian approx: $T(\tau, r) = \mathrm{T}_0 e^{-\frac{r^2}{2\sigma^2}}\left(\frac{\tau_0}{\tau}\right)^{\mathrm{c}_s^2}$



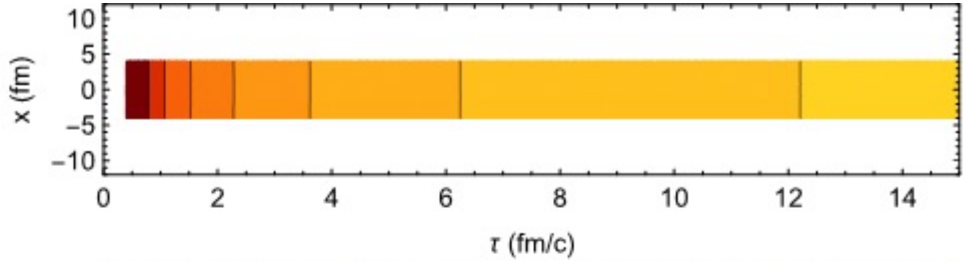
Paquet and Bass [arXiv:2205.12299]

Thermal photon spectrum

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

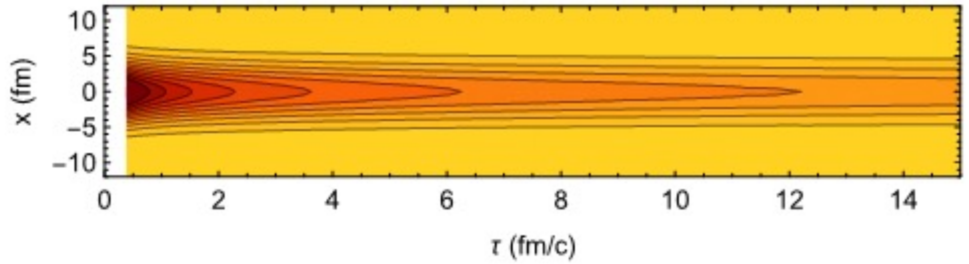


$$\ln\left(\frac{1}{E}\frac{dN_\gamma}{d^3p}\right) \approx -\frac{E}{T_0} + \frac{3}{2}\log\left(\frac{T_0}{E}\right) + cte + O\left(\frac{T_0}{E}\right)$$



Paquet and Bass [arXiv:2205.12299]

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



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

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

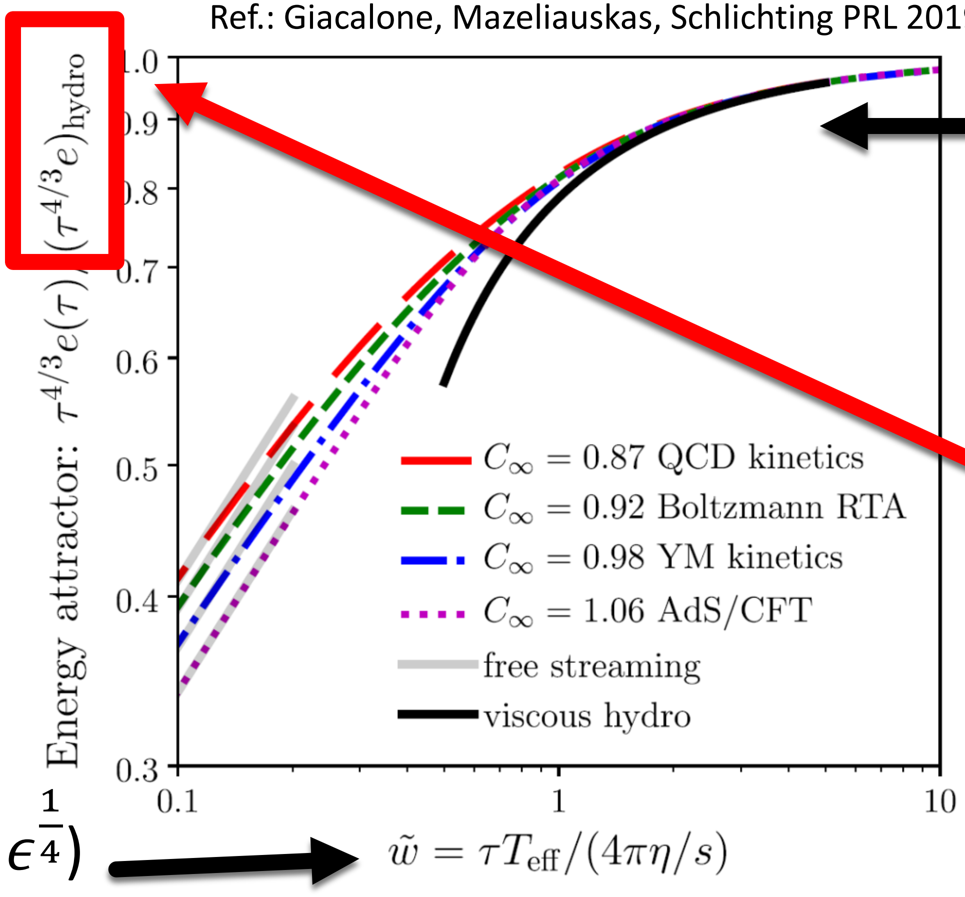
Matching to 0+1D (boost-invariant) hydrodynamics

- 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

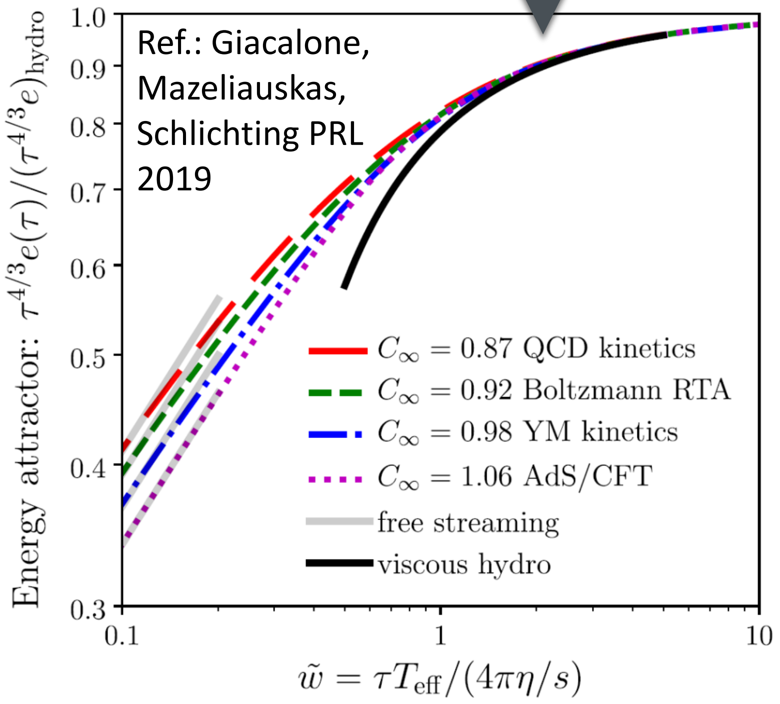
(or "effective temperature" $T_{eff} \propto \epsilon^{\frac{1}{4}}$)

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

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

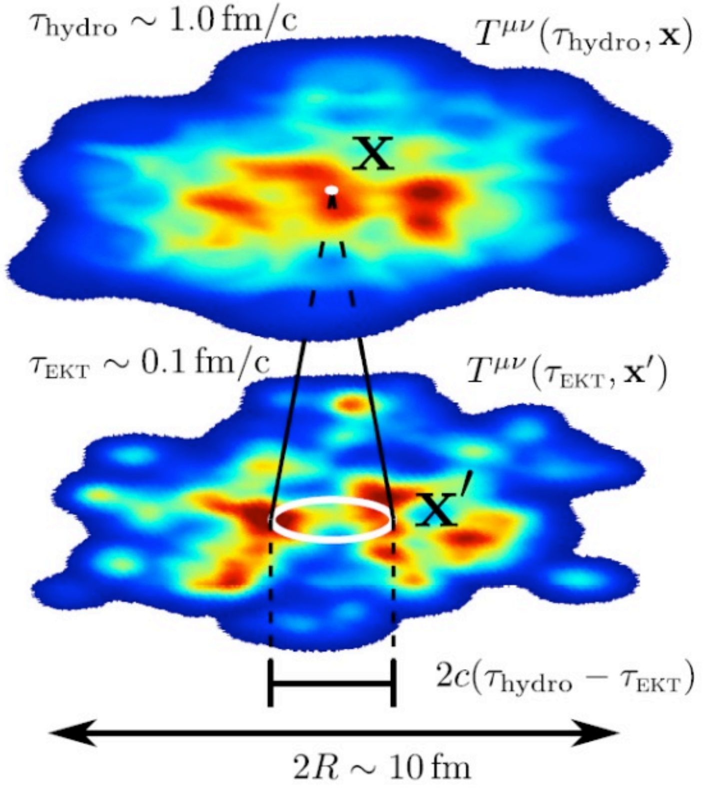
Ref.: Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney PRL2019, PRC2019



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]



Dilepton rate

Figure by Gojko Vujanovic

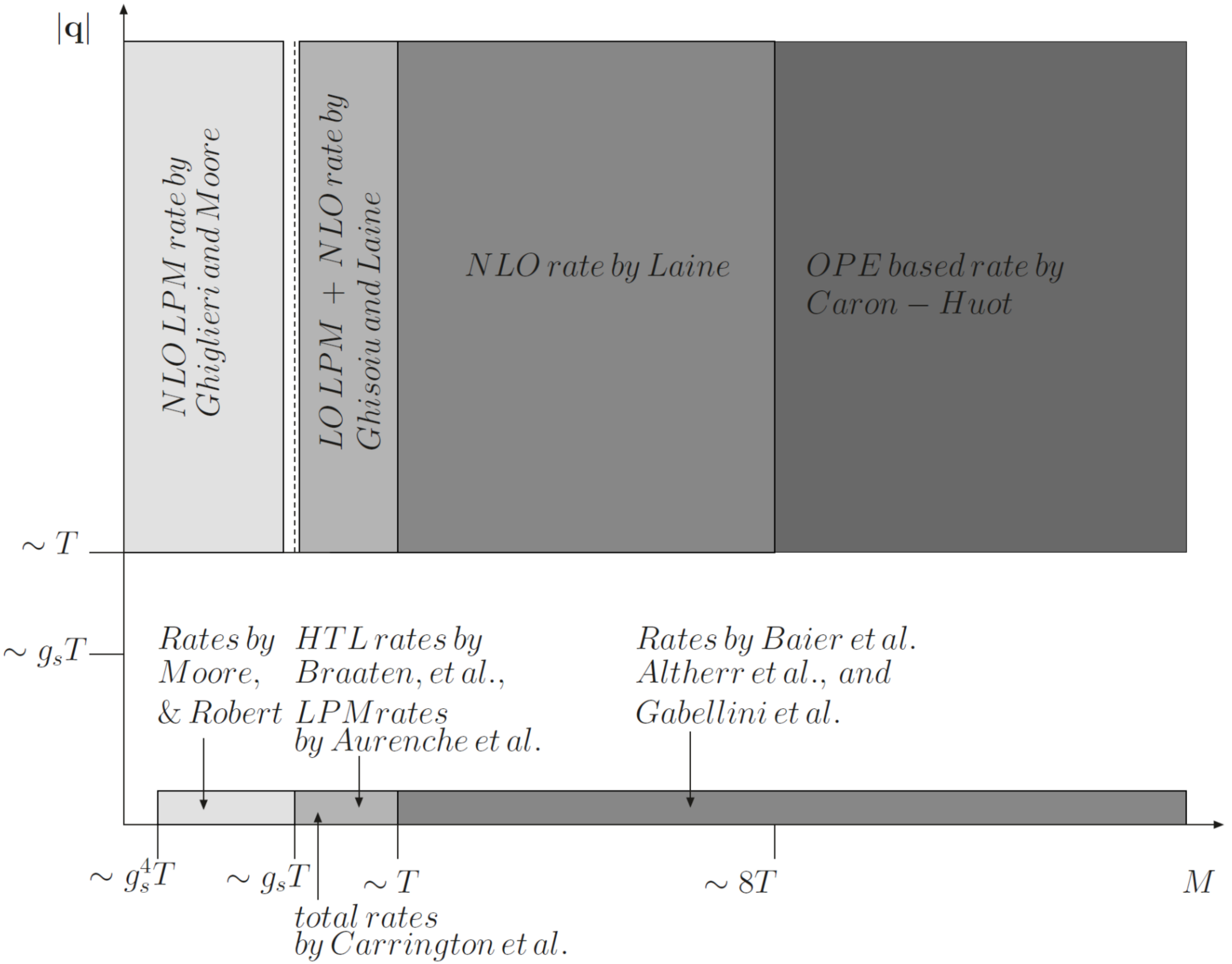
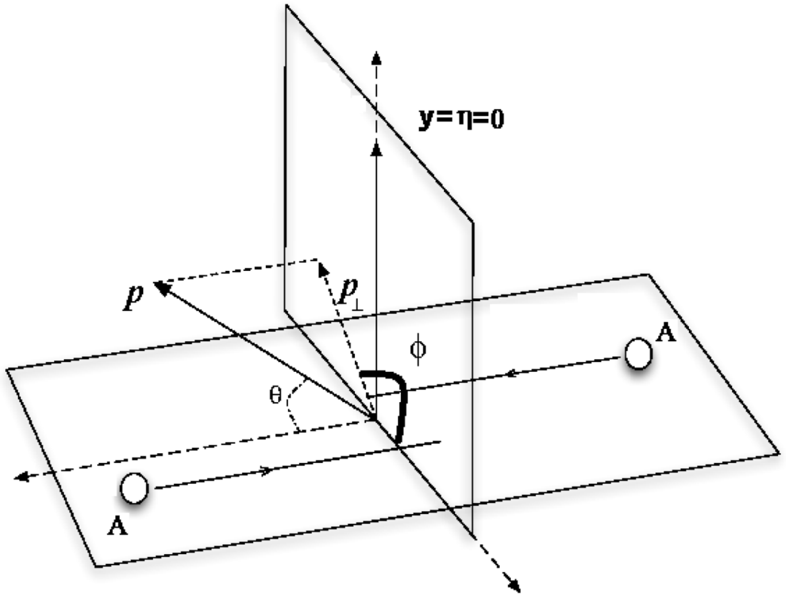
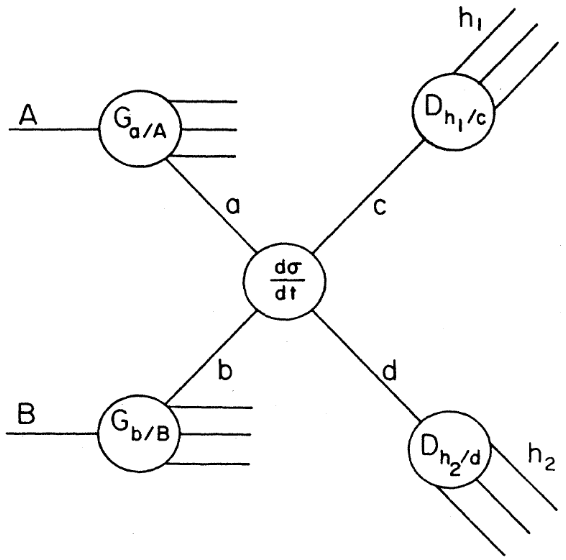


Figure adapted from K. Tuchin (2013) AHEP

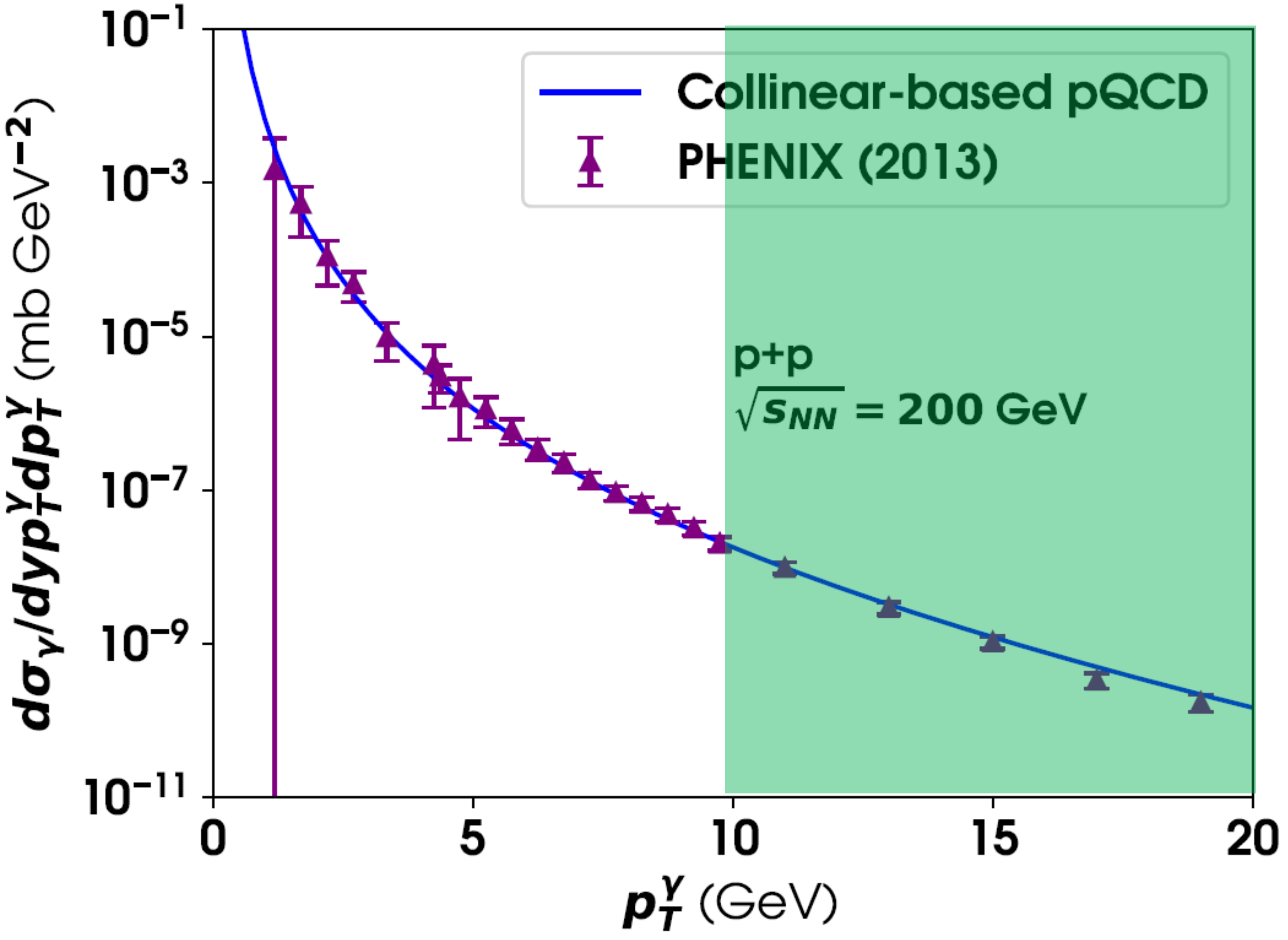




Ref: Owens (1987) RMP

PROTON-PROTON COLLISIONS

Direct photons in p-p collisions: high energy



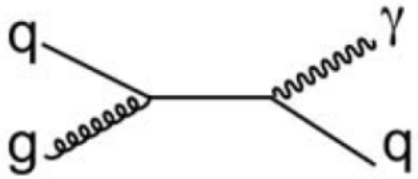
Nuclear Physics B327 (1989) 105–143
North-Holland, Amsterdam

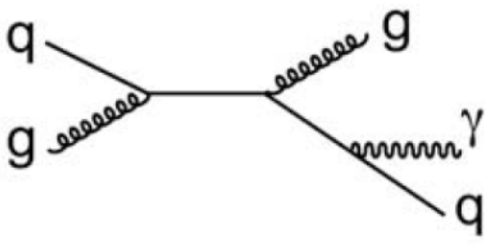
QCD CORRECTIONS TO PARTON–PARTON SCATTERING PROCESSES

F. AVERSA*, P. CHIAPPETTA, M. GRECO*, J.Ph. GUILLET**

- Can be calculated in collinear-factorization based perturbative QCD, up to next-to-leading order

$$\frac{d\sigma_\gamma^{pp}}{dp_T} = f_a \otimes f_b \otimes d\hat{\sigma}_{ab\to\gamma/c+d}[\otimes D_{\gamma/c}]$$

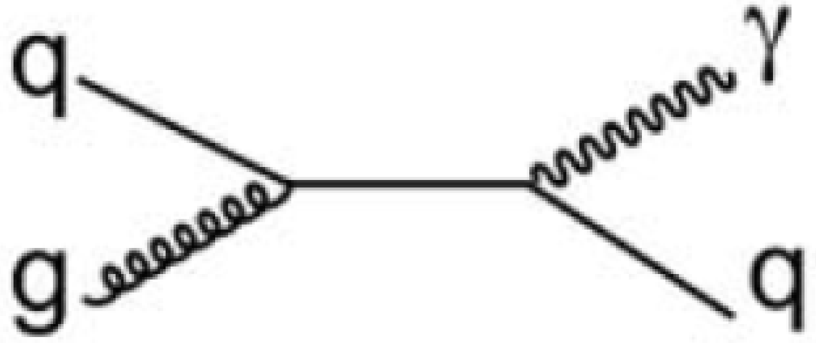




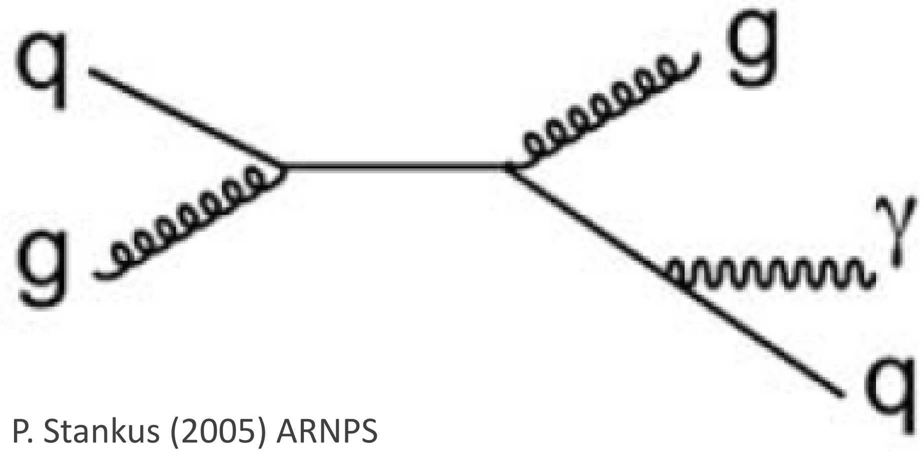
Frag fct: Bourhis, Fontannaz, Guillet (1998) EPJ

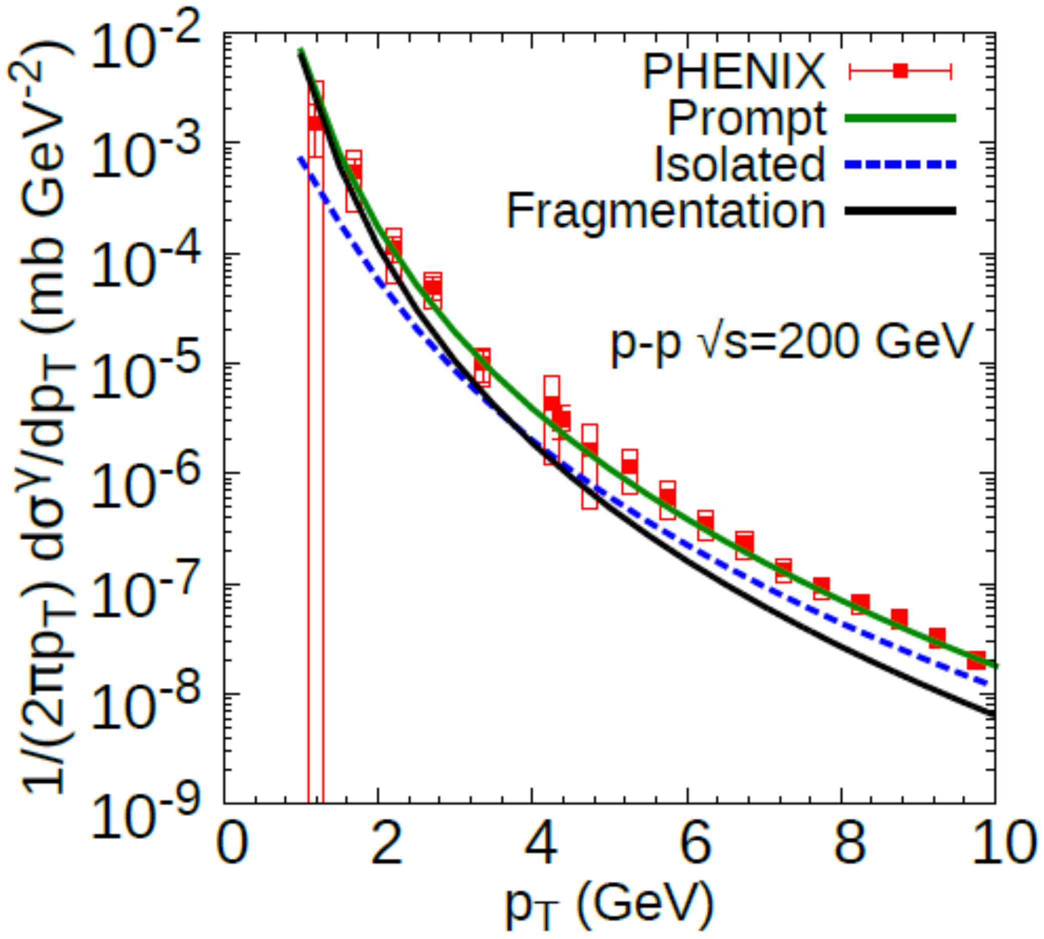
Direct photons in proton-proton collisions: channels

- Hard partonic collisions
  - "Isolated"



  - Fragmentation

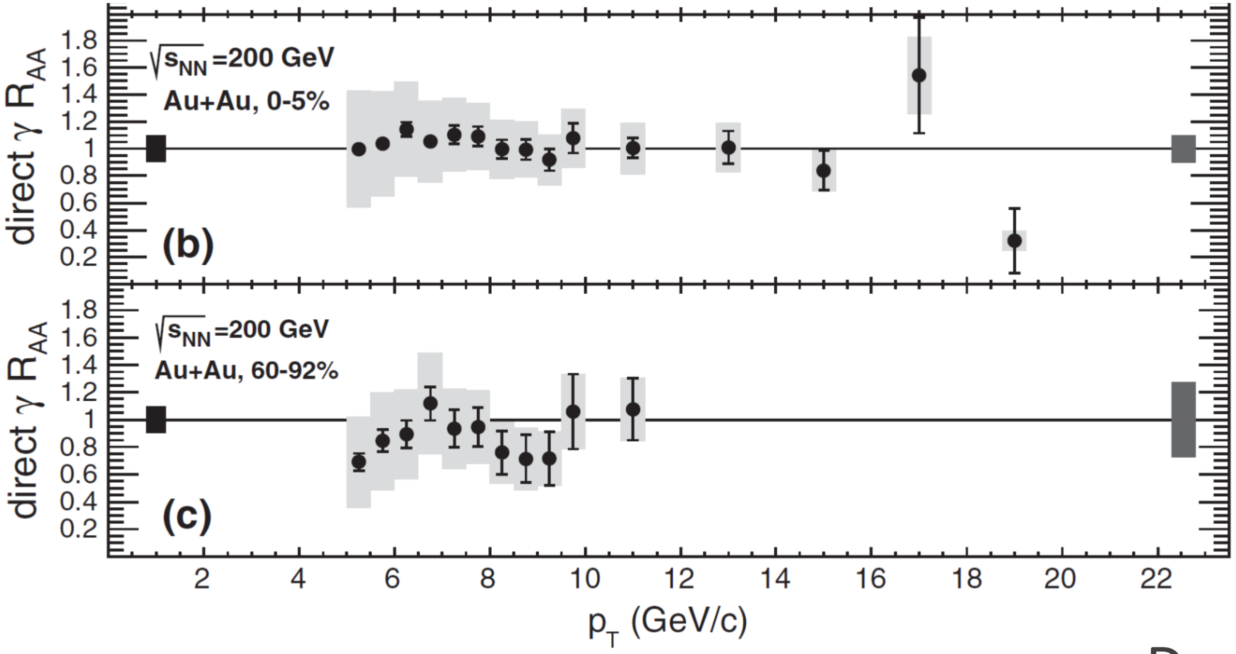




Ref: P. Stankus (2005) ARNPS

Photons in heavy-ion collisions: high p_T

- **Prompt photons** produced as superposition of nucleon-nucleon collisions ("binary scaling")



Ref.: PHENIX Collaboration (2012) PRL

$$R_{AA}^{\gamma} = \frac{\frac{dN_{\gamma}^{AA}}{dp_T}}{\left(\frac{N_{binary}}{\sigma_{pp}^{inel}}\right)\frac{d\sigma_{\gamma}^{pp}}{dp_T}} \approx 1 \qquad \text{(at high } p_T\text{)}$$

Deviations from $R_{AA}^{\gamma} = 1$ originate from:

- Isospin effect (parton content of n vs p)
- Nuclear effects on parton distribution functions
- Parton energy loss [more about this later]