# Nuclear collisions as seen through photons

Jean-François Paquet

November 21, 2022

VANDERBILT UNIVERSITY

Nuclear Physics seminar

MIT Physics

# The higher end of the electromagnetic spectrum

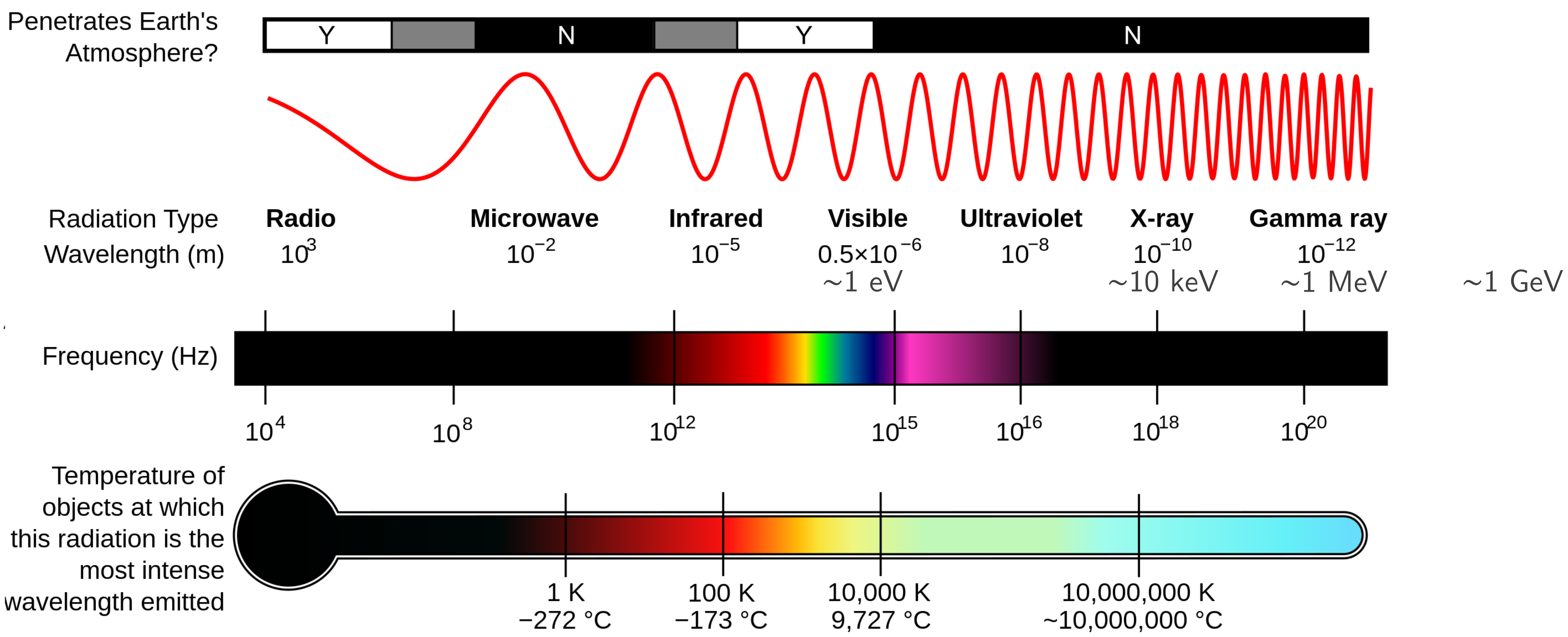
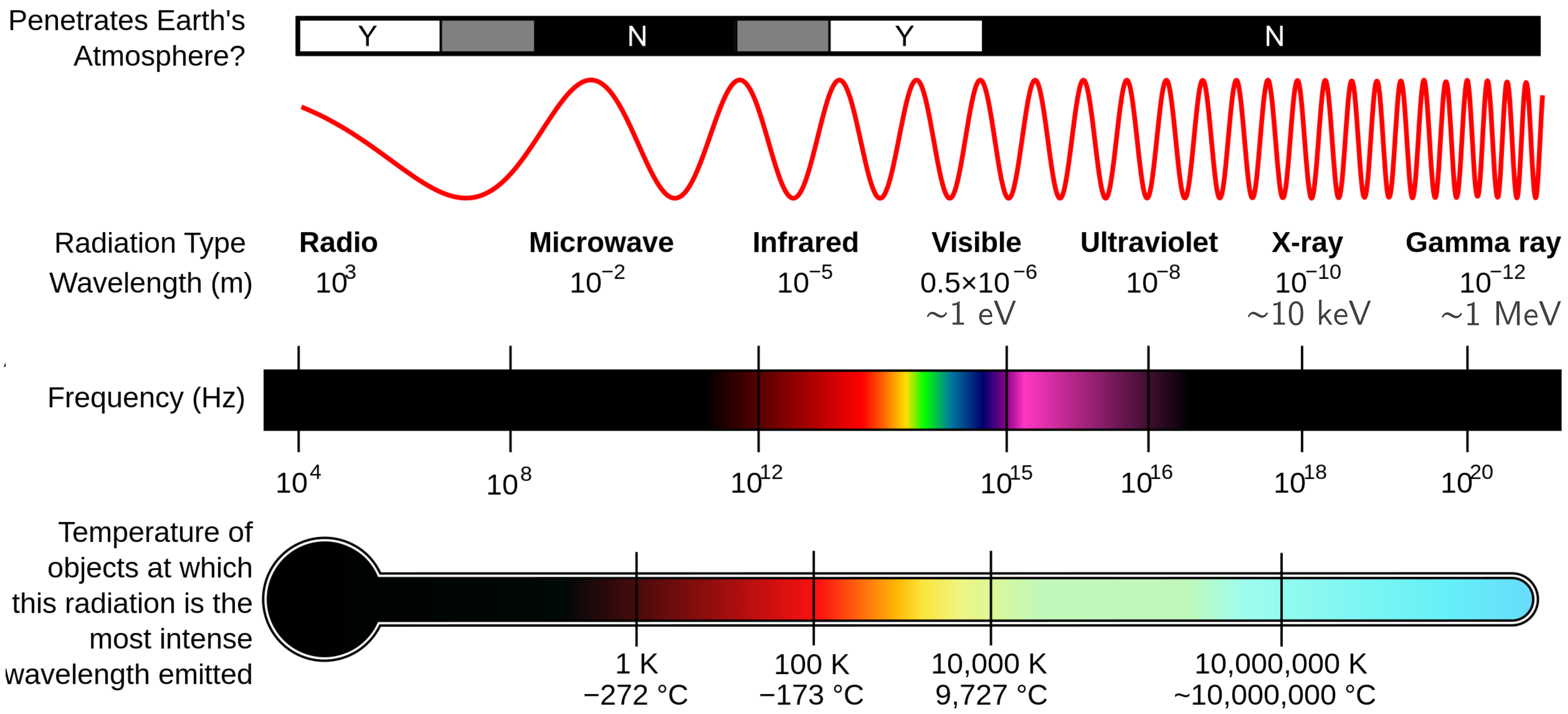



Image modified from Wikimedia

# The higher end of the electromagnetic spectrum



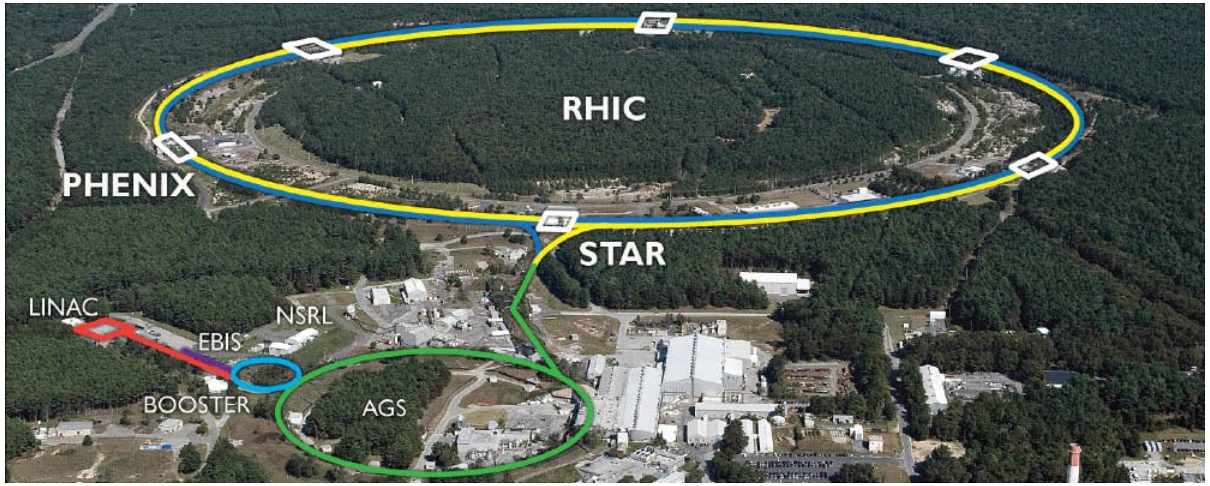

$\sim$1 GeV

$T \sim 10^{12}$K

Image modified from Wikimedia

# RHIC and LHC

**Relativistic Heavy Ion Collider (RHIC)**
**[Brookhaven National Lab, Long Island, NY]**

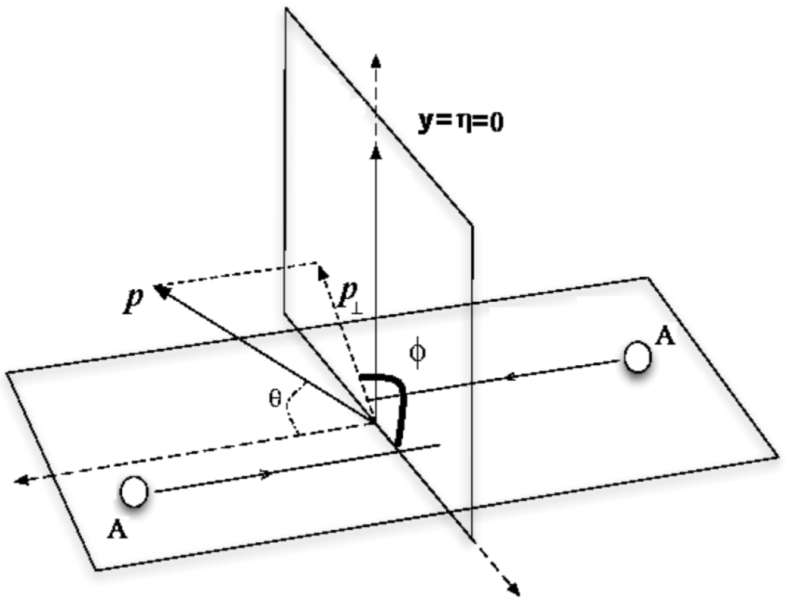


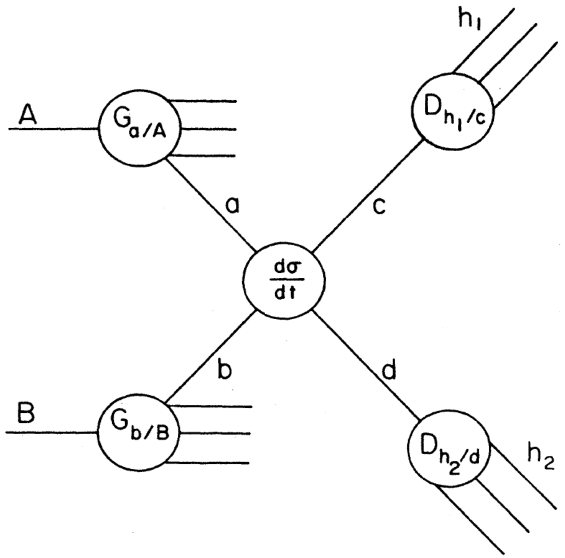

$\sqrt{s_{NN}} \sim 10^2$ GeV

**Large Hadron Collider (LHC)**
**[CERN, Geneva, Switzerland/France]**


$\sqrt{s_{NN}} \sim 10^3$ GeV

Figure adapted from K. Tuchin (2013) AHEP



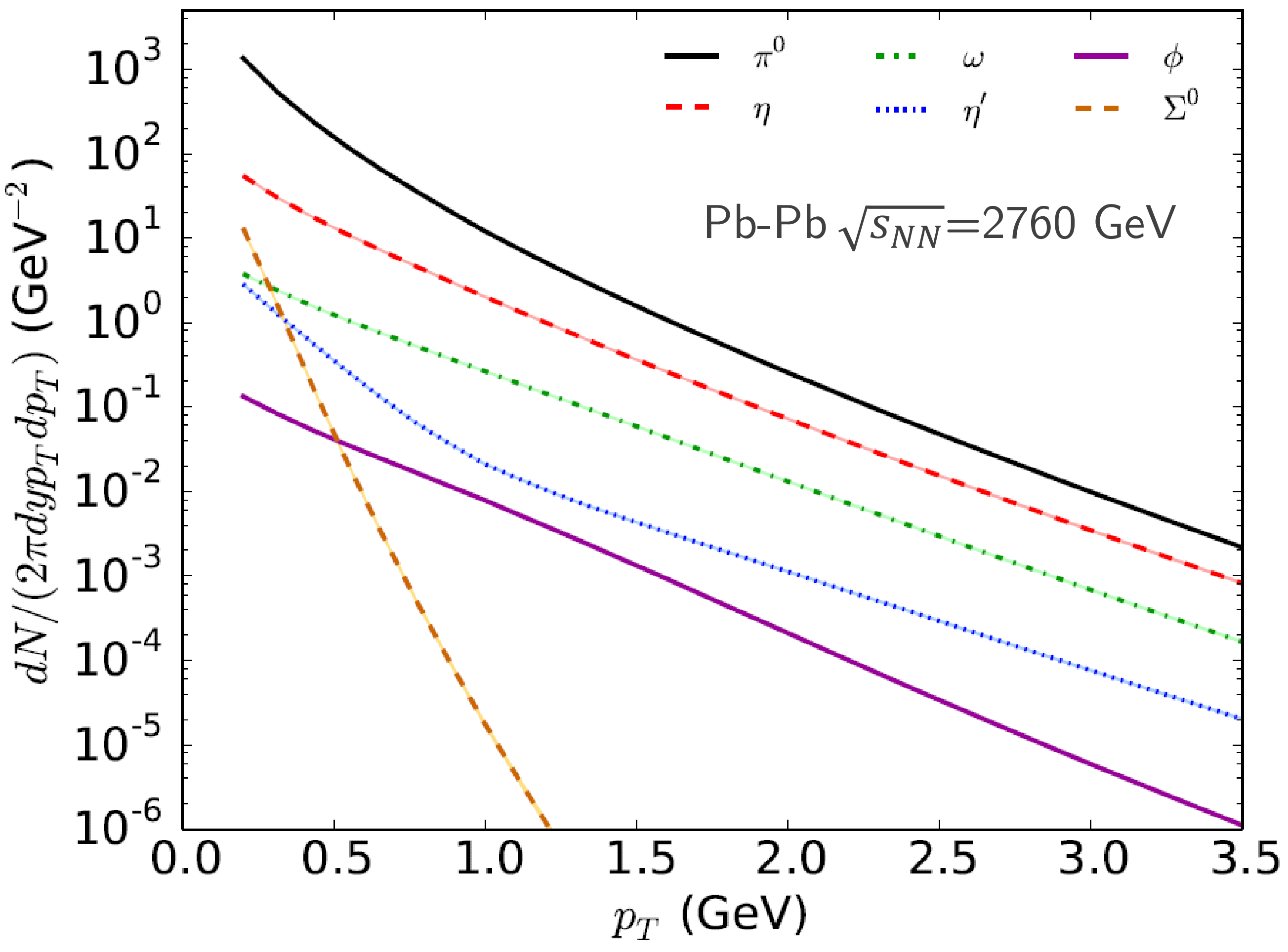

Ref: Owens (1987) RMP

# PROTON-PROTON COLLISIONS

# Hadronic decay photons in nuclear collisions

| particle | mass (MeV) | decay | BR |
|---|---|---|---|
| $\pi^0$ | 134.98 | $\gamma\gamma$ | $9.882 \cdot 10^{-1}$ |
| | | $e^+e^-\gamma$ | $1.174 \cdot 10^{-2}$ |
| $\eta$ | 547.85 | $\gamma\gamma$ | $3.941 \cdot 10^{-1}$ |
| | | $\pi^0\gamma\gamma$ | $2.560 \cdot 10^{-4}$ |
| | | $\pi^+\pi^-\gamma$ | $4.220 \cdot 10^{-2}$ |
| | | $e^+e^-\gamma$ | $6.899 \cdot 10^{-3}$ |
| | | $\mu^+\mu^-\gamma$ | $3.090 \cdot 10^{-4}$ |
| $\eta'$ | 957.66 | $\rho^0\gamma$ | $2.908 \cdot 10^{-1}$ |
| | | $\omega\gamma$ | $2.746 \cdot 10^{-2}$ |
| | | $\gamma\gamma$ | $2.198 \cdot 10^{-2}$ |
| | | $\mu^+\mu^-\gamma$ | $1.080 \cdot 10^{-4}$ |
| $\omega$ | 782.65 | $\pi^0\gamma$ | $8.350 \cdot 10^{-2}$ |
| | | $\eta\gamma$ | $4.600 \cdot 10^{-4}$ |
| | | $\pi^0\pi^0\gamma$ | $7.000 \cdot 10^{-5}$ |
| $\rho^0$ | 775.49 | $\pi^+\pi^-\gamma$ | $9.900 \cdot 10^{-3}$ |
| | | $\pi^0\gamma$ | $6.000 \cdot 10^{-4}$ |
| | | $\eta\gamma$ | $3.000 \cdot 10^{-4}$ |
| | | $\pi^0\pi^0\gamma$ | $4.500 \cdot 10^{-5}$ |

Ref: F. Bock, PhD thesis




Ref: Chun Shen, PhD thesis

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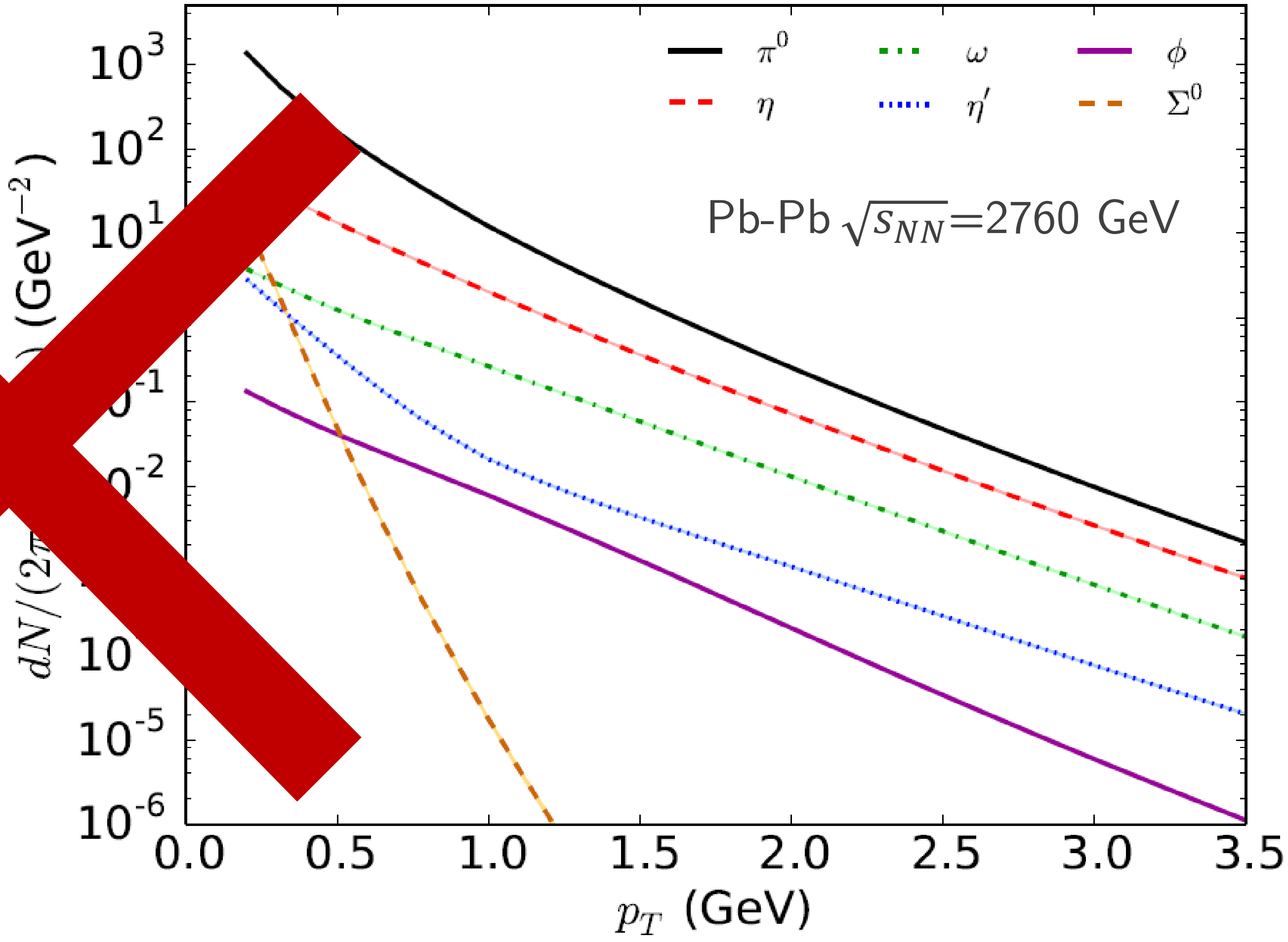


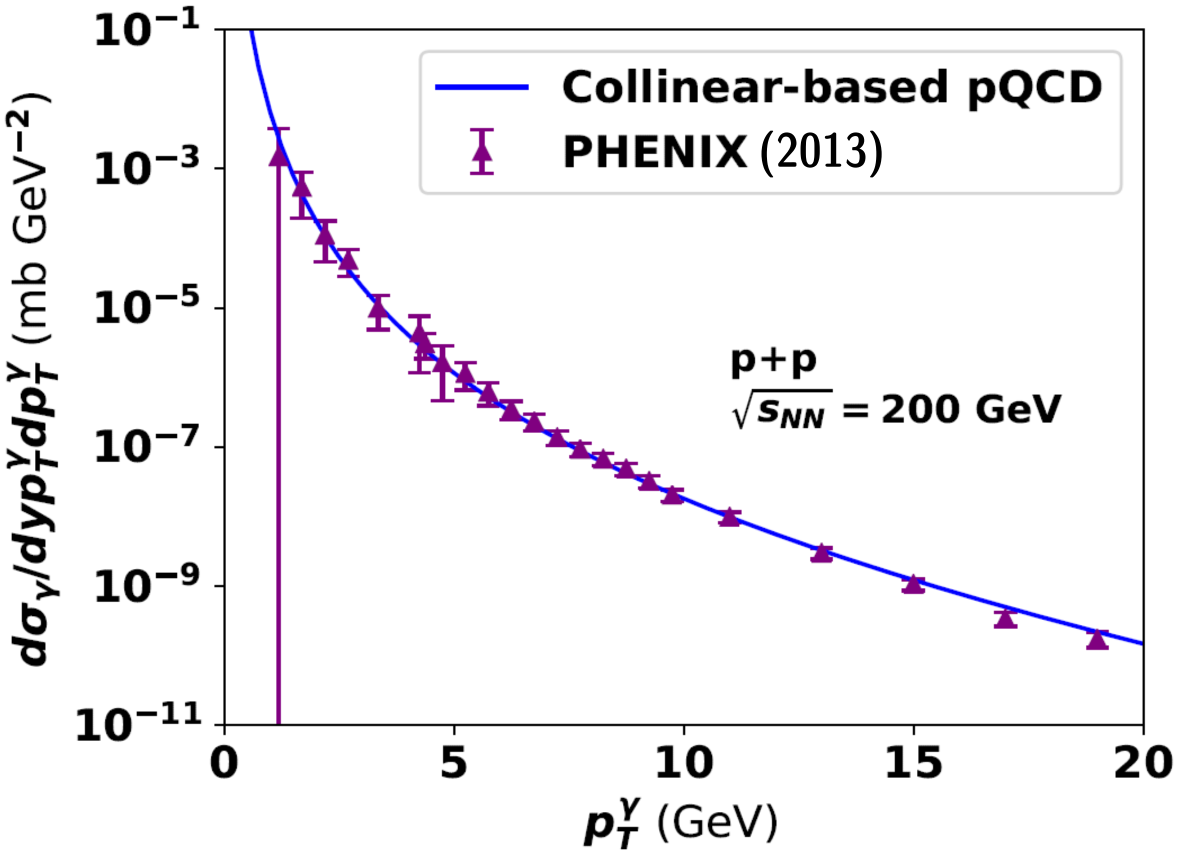

Ref: Chun Shen, PhD thesis

# Direct photons in p-p collisions: high $p_T$

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

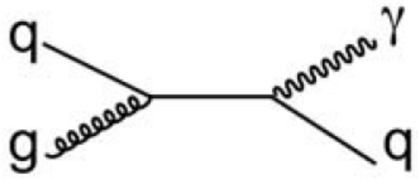
QCD CORRECTIONS TO PARTON–PARTON SCATTERING PROCESSES

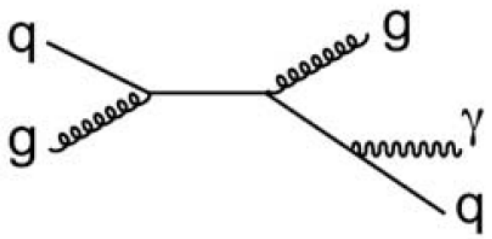
F. AVERSA*, P. CHIAPPETTA, M. GRECO*, J.Ph. GUILLET**




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

$$\frac{d\sigma_\gamma^{pp}}{dp_T} = f_{a/A} \otimes f_{b/B} \otimes d\hat{\sigma}_{ab\to\gamma/c+d}[\otimes D_{\gamma/c}]$$

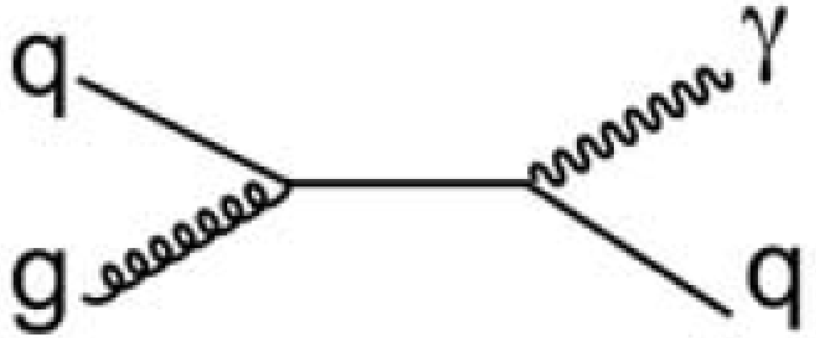


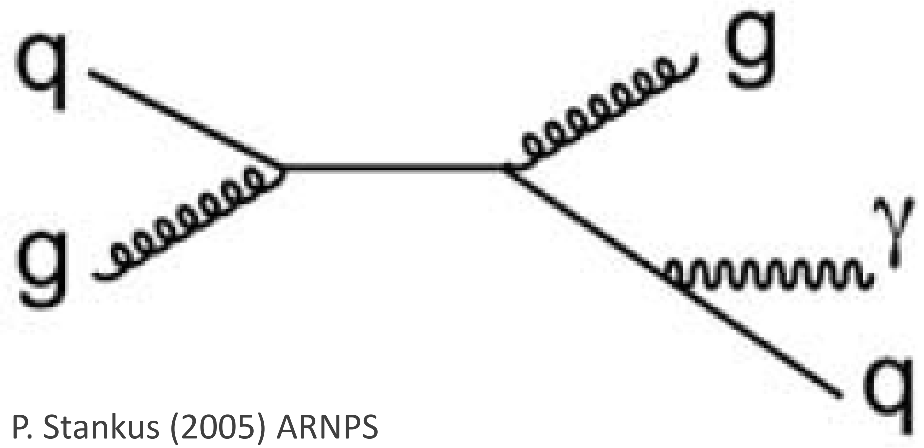

Frag fct: Bourhis, Fontannaz, Guillet (1998) EPJ

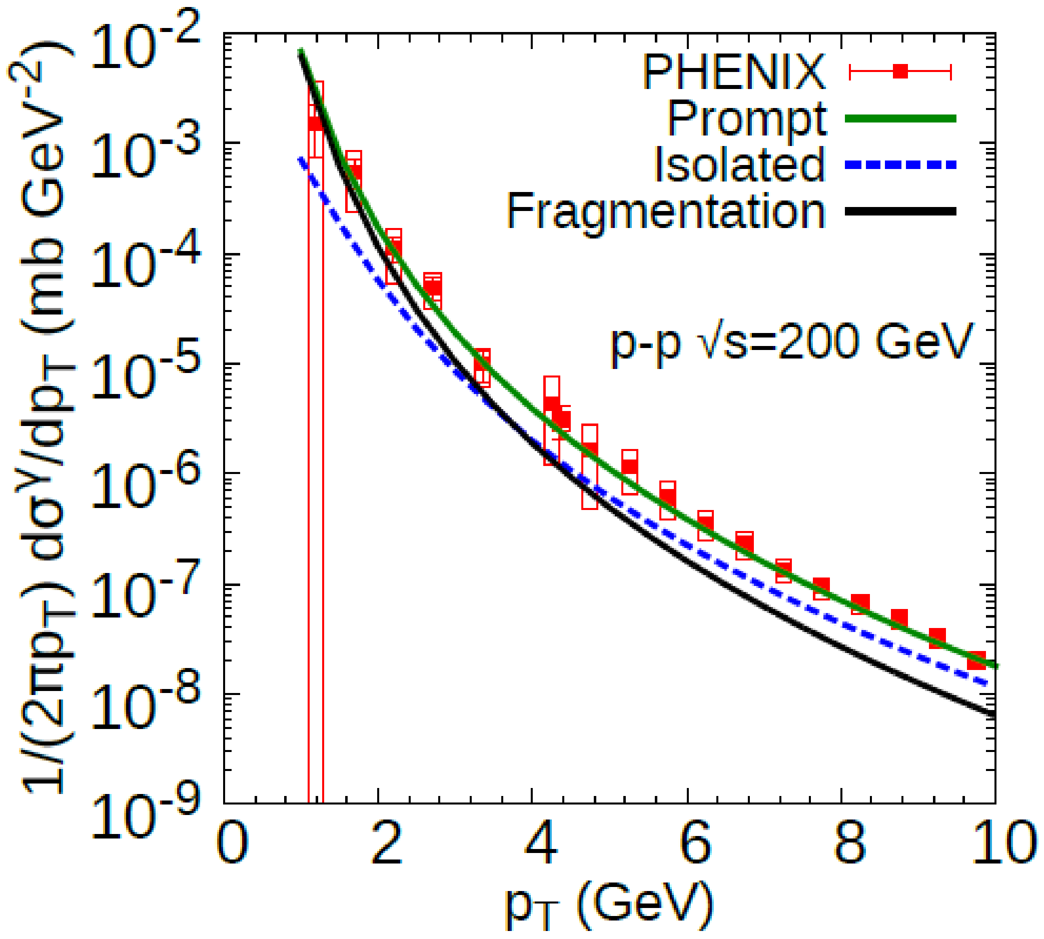
# Direct photons in proton-proton collisions: high $p_T$

- Hard partonic collisions
  - "Isolated"




  - Fragmentation



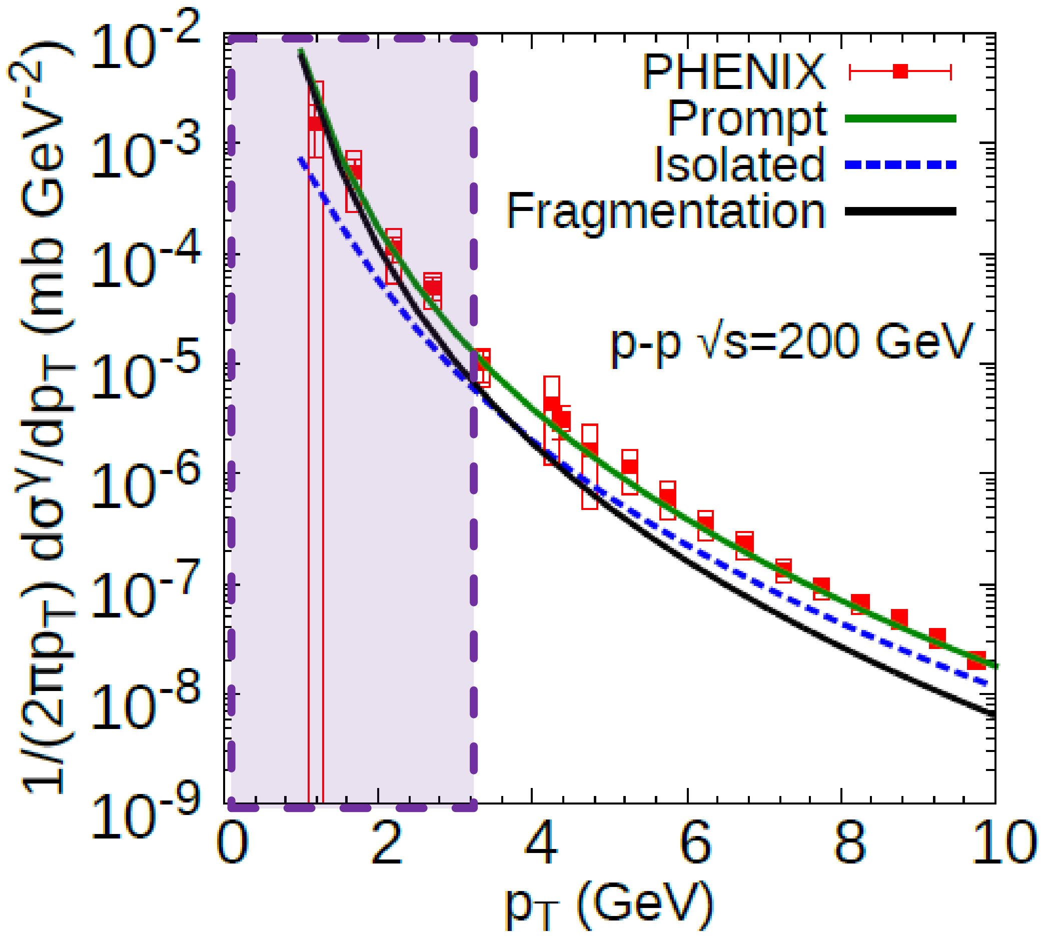



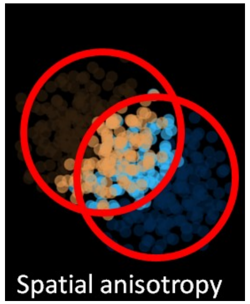

Ref: P. Stankus (2005) ARNPS

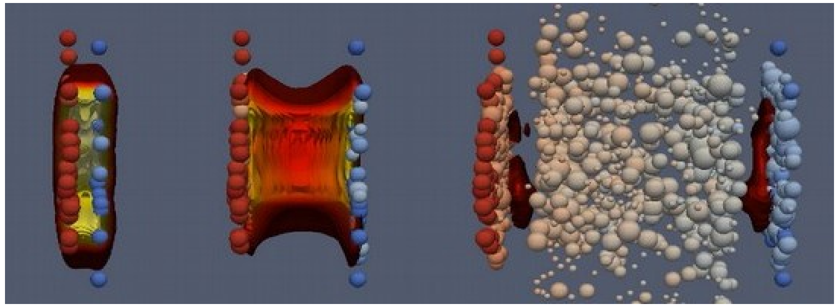
# Direct photons in proton-proton collisions: low $p_T$

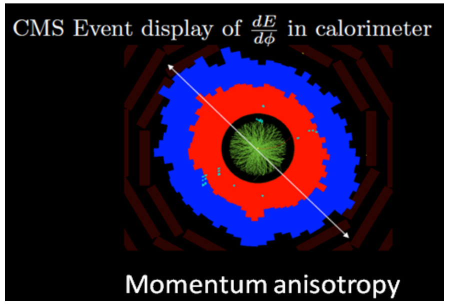
- Lower $p_T$ dominated by fragmentation photons
- Perturbative QCD breaks down eventually at low $p_T$

- **How to compute properly the low-$p_T$ photon spectrum remains an open question**



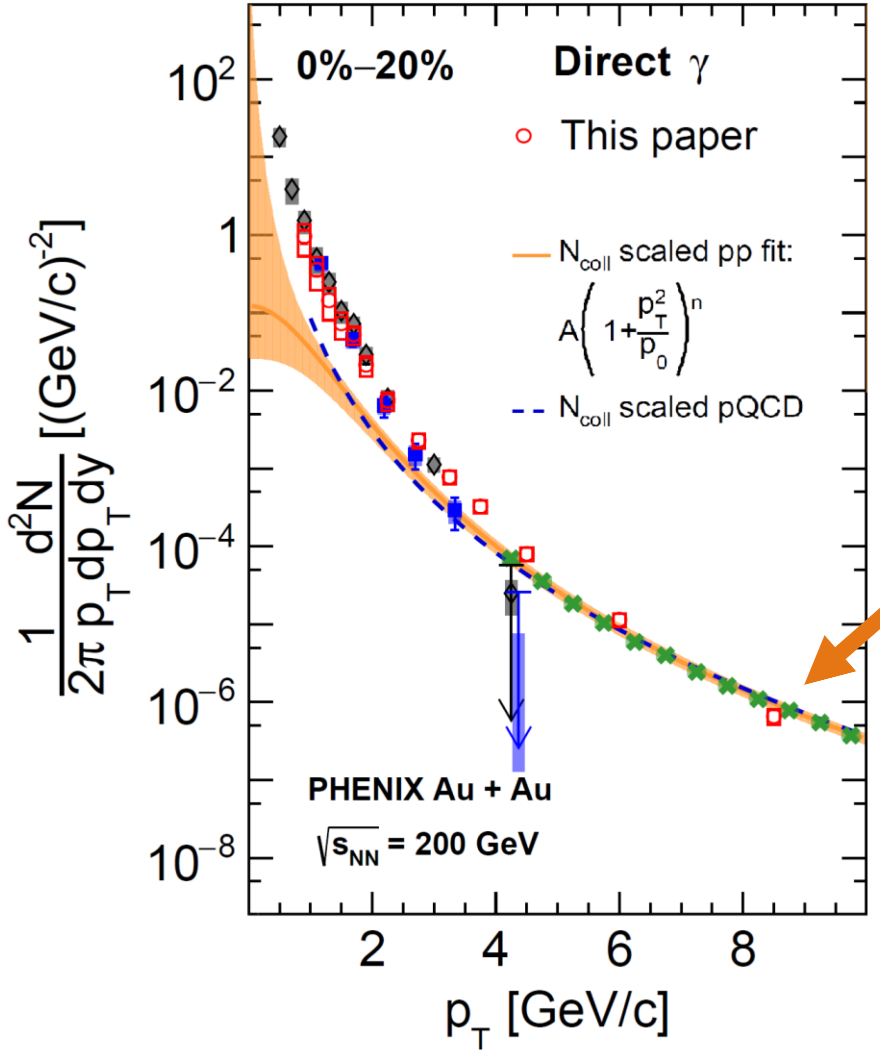





# HEAVY-ION COLLISIONS

# Photon energy spectrum in heavy-ion collisions




- Systematic excess of low energy photons in nucleus collisions

  (also observed by STAR and ALICE Collaborations)

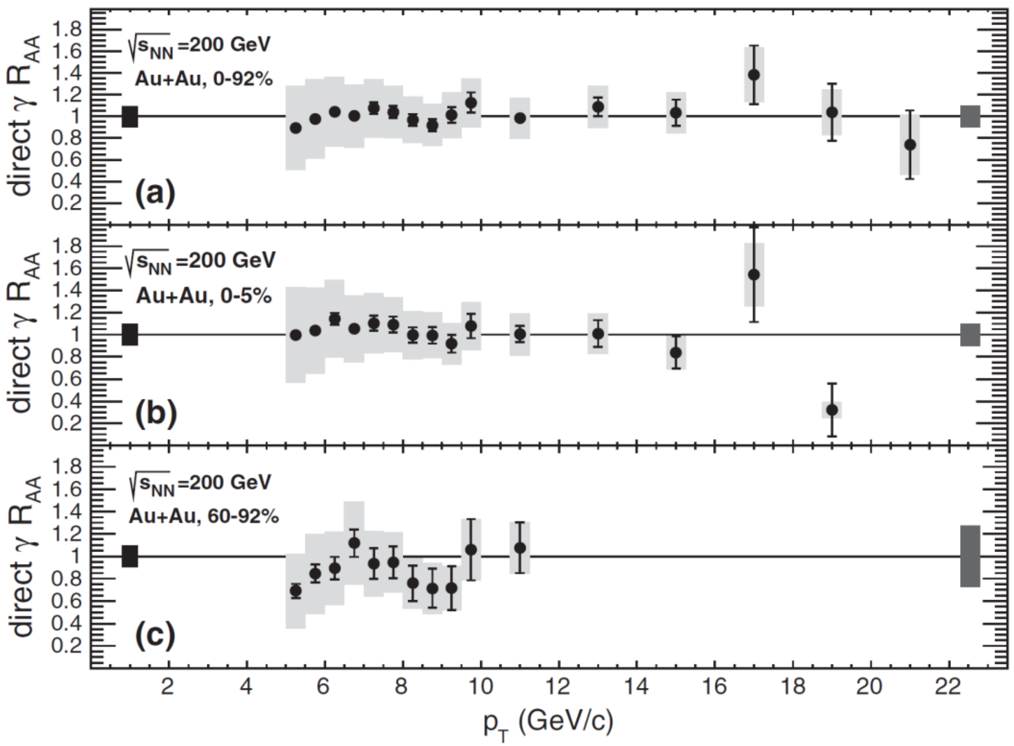
Band is result expected from incoherent superposition of proton-proton collisions

Note: large uncertainty at low $p_T$

Ref.: PHENIX Collaboration [ arXiv:2203.17187 ]

# Photons in heavy-ion collisions: high $p_T$

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




Ref.: PHENIX Collaboration (2012) PRL

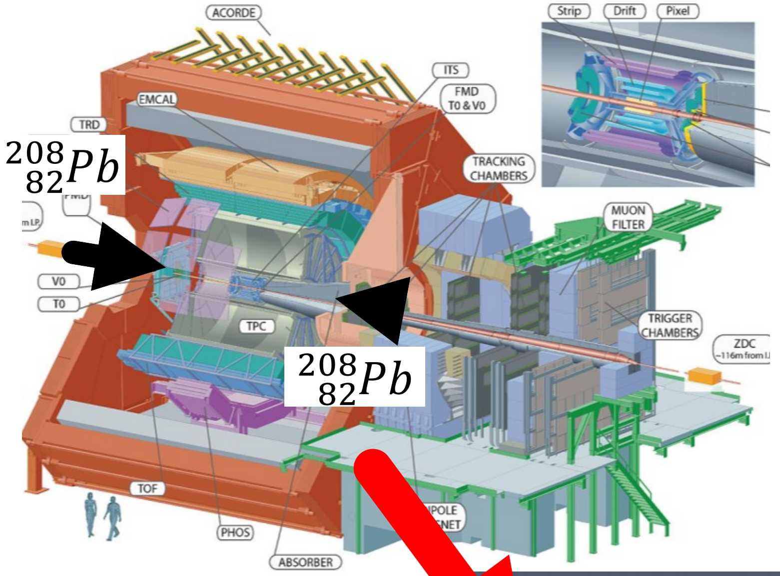
$$R_{AA}^{\gamma} = \frac{\frac{\mathrm{d}N_{\gamma}^{AA}}{dp_T}}{\left(\frac{N_{binary}}{\sigma_{pp}^{inel}}\right)\frac{\mathrm{d}\sigma_{\gamma}^{pp}}{dp_T}} \approx 1 \qquad \text{(at high } p_T\text{)}$$

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

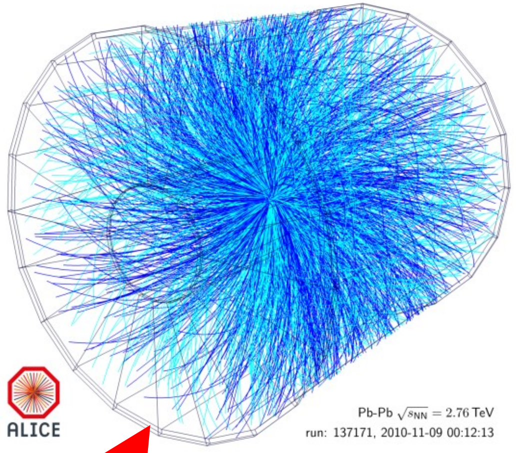
- Isospin effect (parton content of n vs p)
- Nuclear effects on parton distribution functions
- Parton energy loss

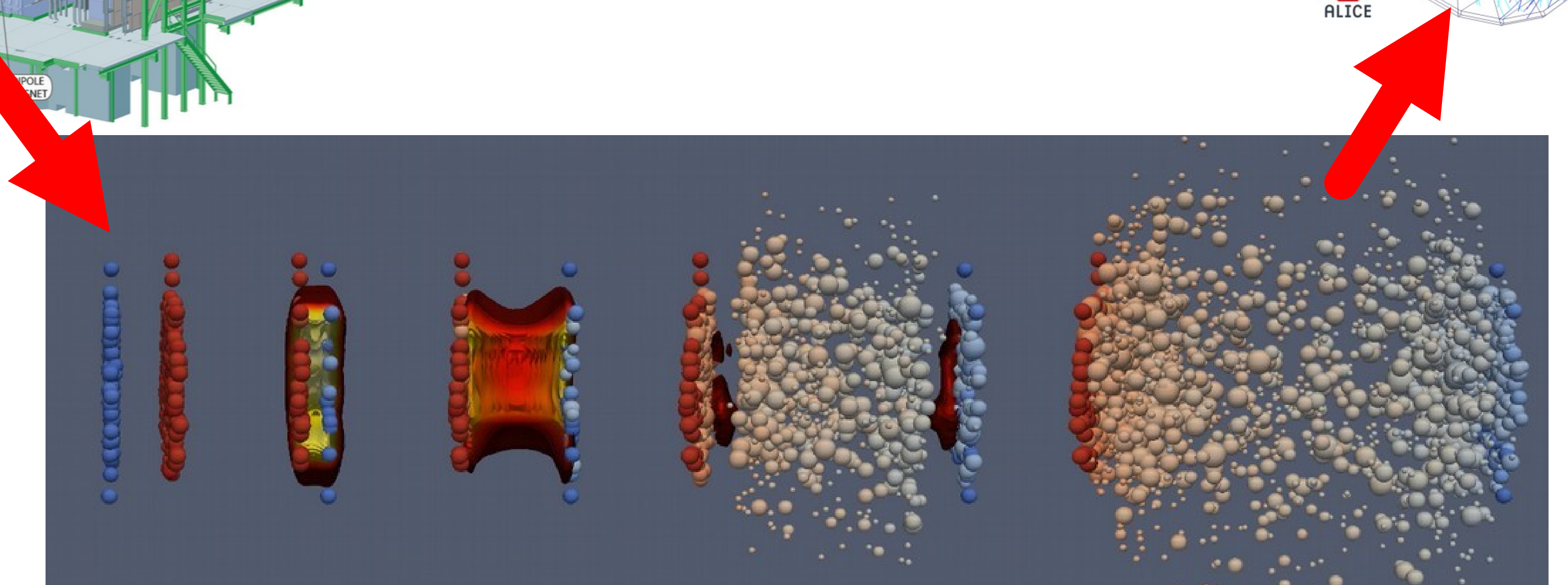
$$\frac{\mathrm{d}N_{\gamma}^{AA}}{dp_T} = \frac{N_{binary}}{\sigma_{pp}^{inel}}\, f_{a/A} \otimes f_{b/B} \otimes \mathrm{d}\hat{\sigma}_{ab\rightarrow\gamma/c+d} [\otimes D_{\gamma/c}]$$

# Heavy-ion collisions

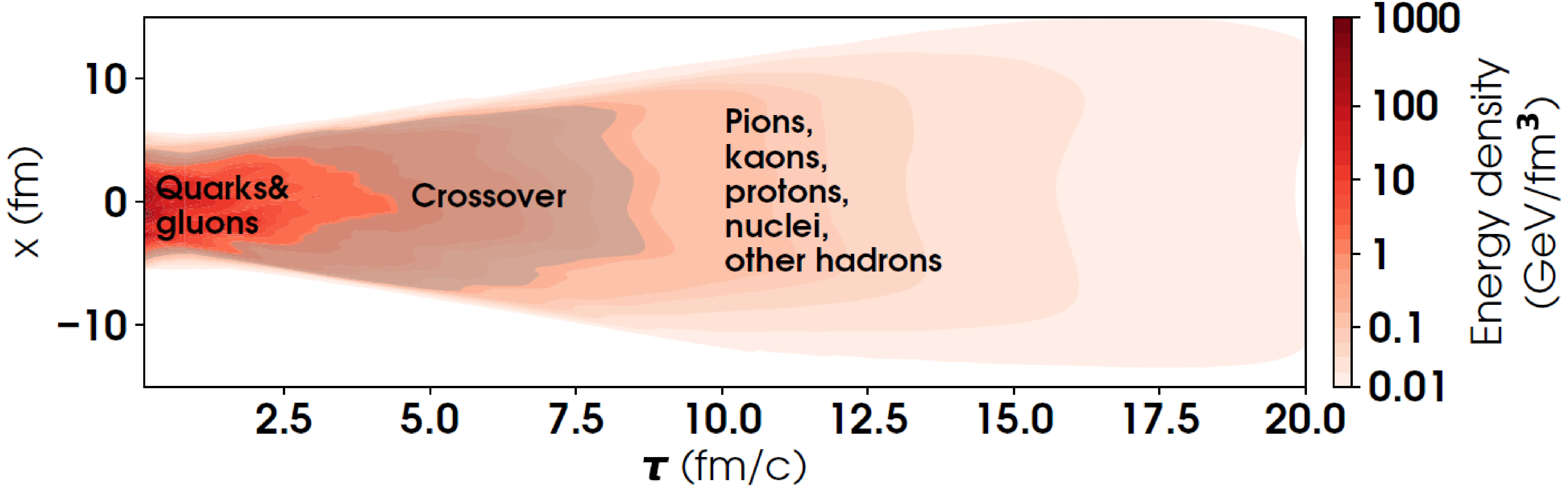


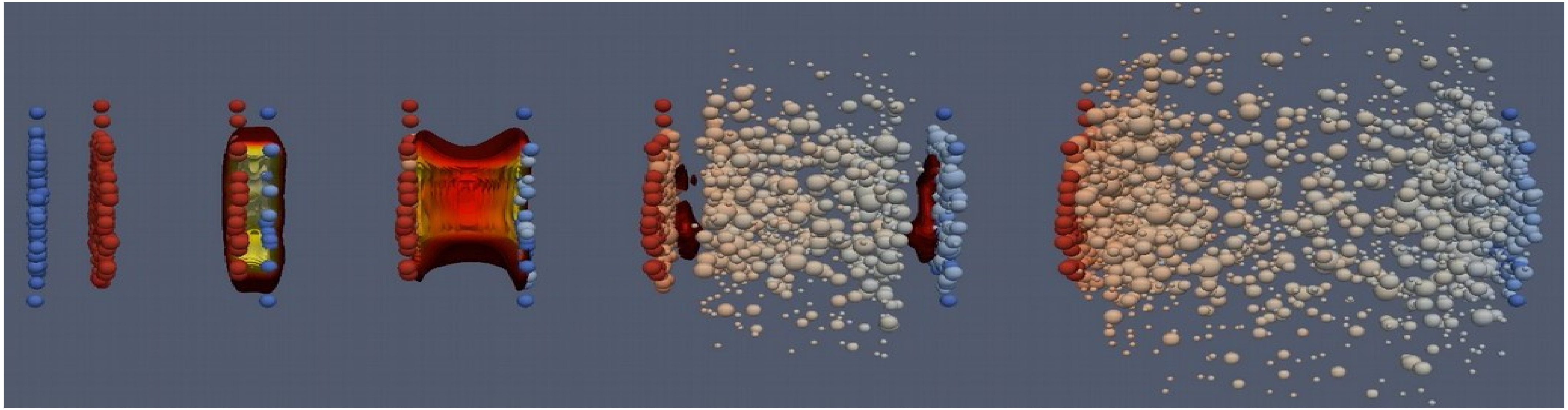

Ref.: ALICE, CERN



Ref: MADAI collaboration, Hannah Elfner and Jonah Bernhard


10
0
−10
x (fm)
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
τ (fm/c)
Quarks&
gluons
Crossover
Pions,
kaons,
protons,
nuclei,
other hadrons
1000
100
10
1
0.1
0.01
Energy density
(GeV/fm³)



# Prompt photons in proton-proton collisions

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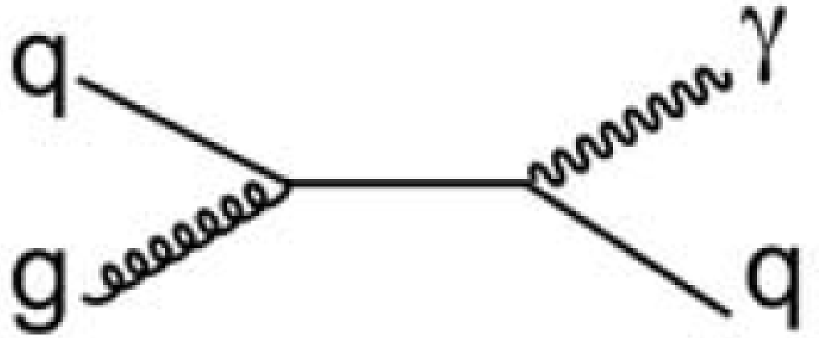
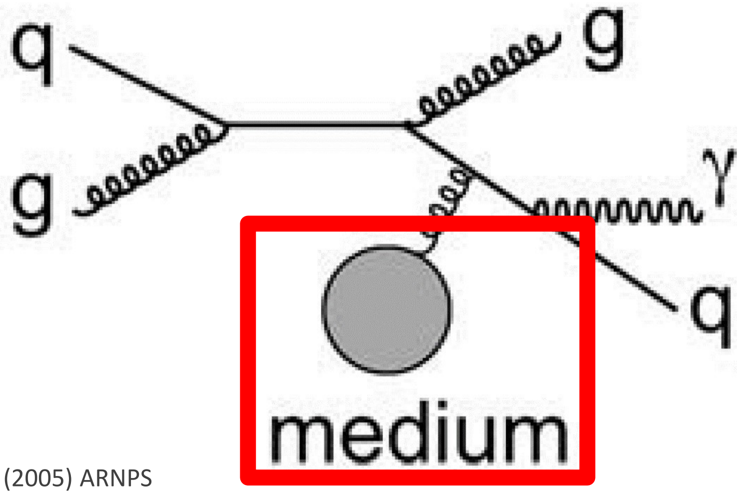
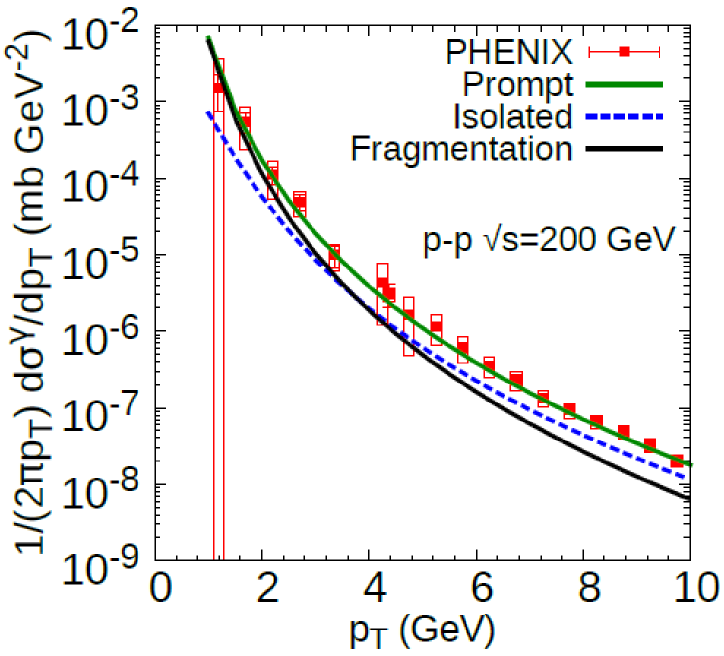
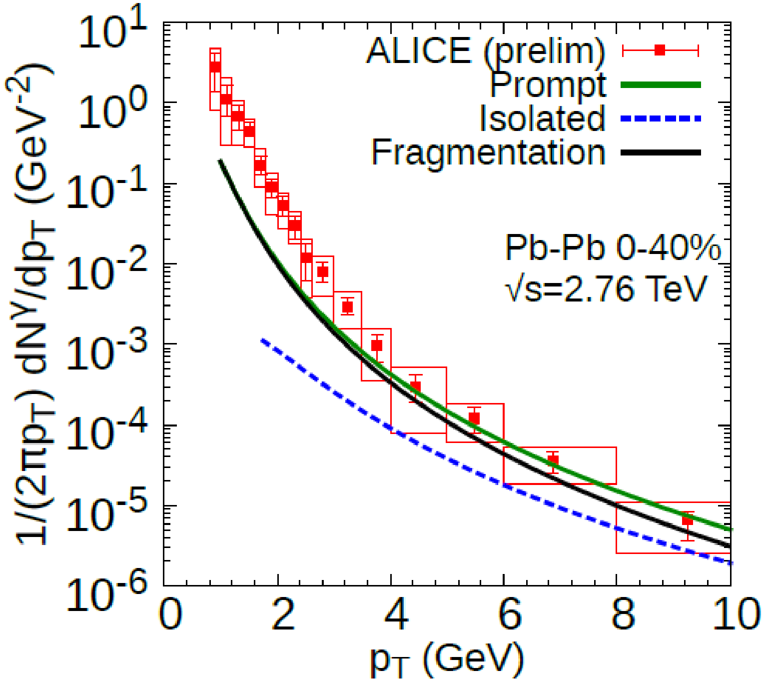
  - "Isolated"

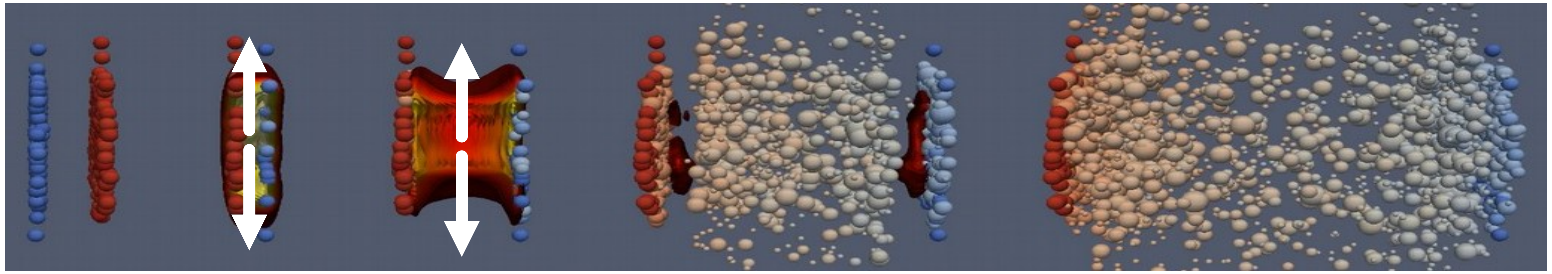



  - Fragmentation



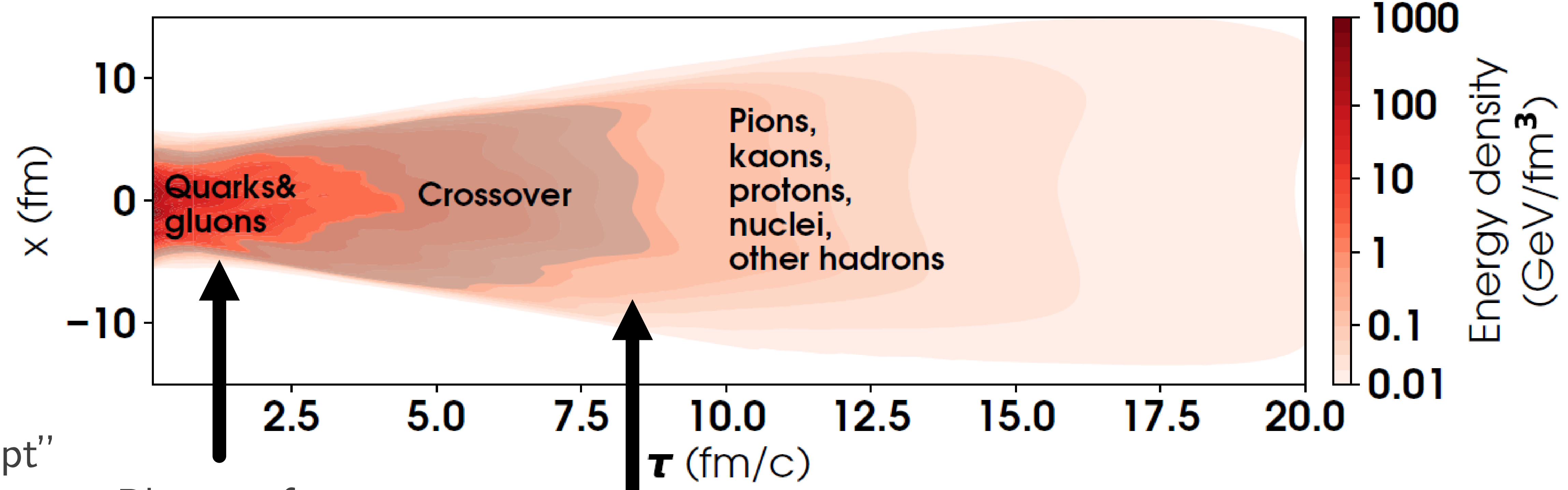



Ref: P. Stankus (2005) ARNPS

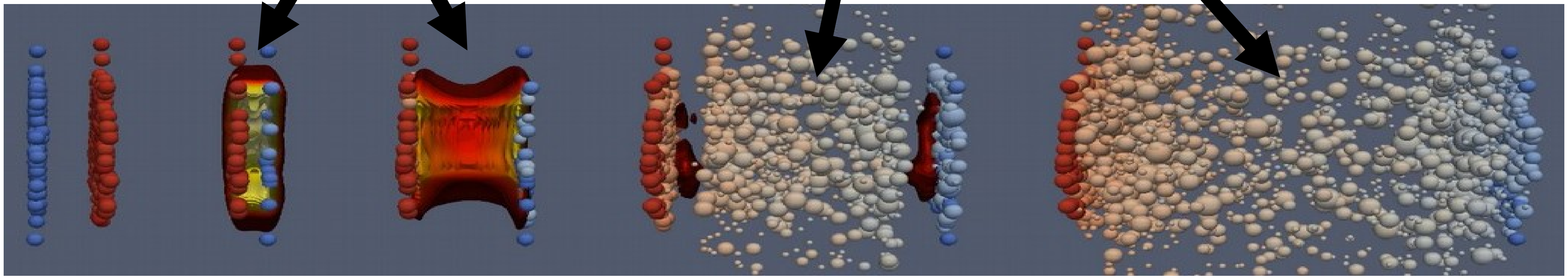
Few recent studies; Modarresi Yazdi, Shi, Gale, Jeon [arXiv:2207.12513]




"Prompt" photons

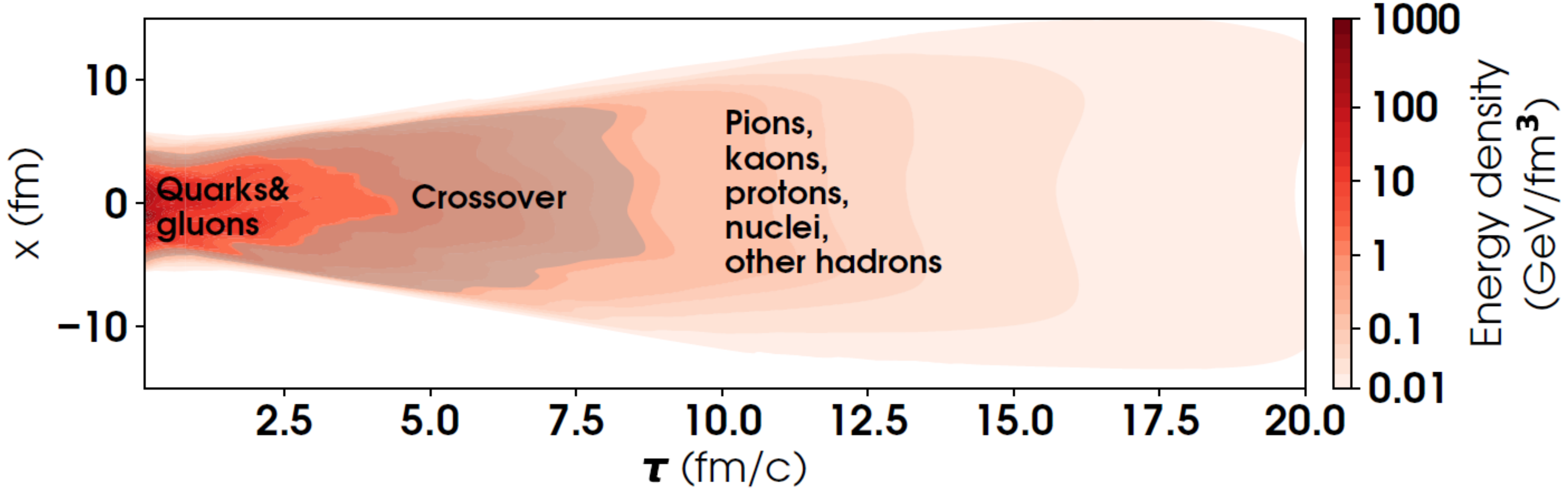
Photons from quark&gluon interactions

- Photons from hadronic interactions
- Photons from hadronic decays



# Photons from deconfined plasma

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




- How much radiation is emitted in each region?

- Note: No clear separation between **quark/gluon** phase and **hadronic** phase

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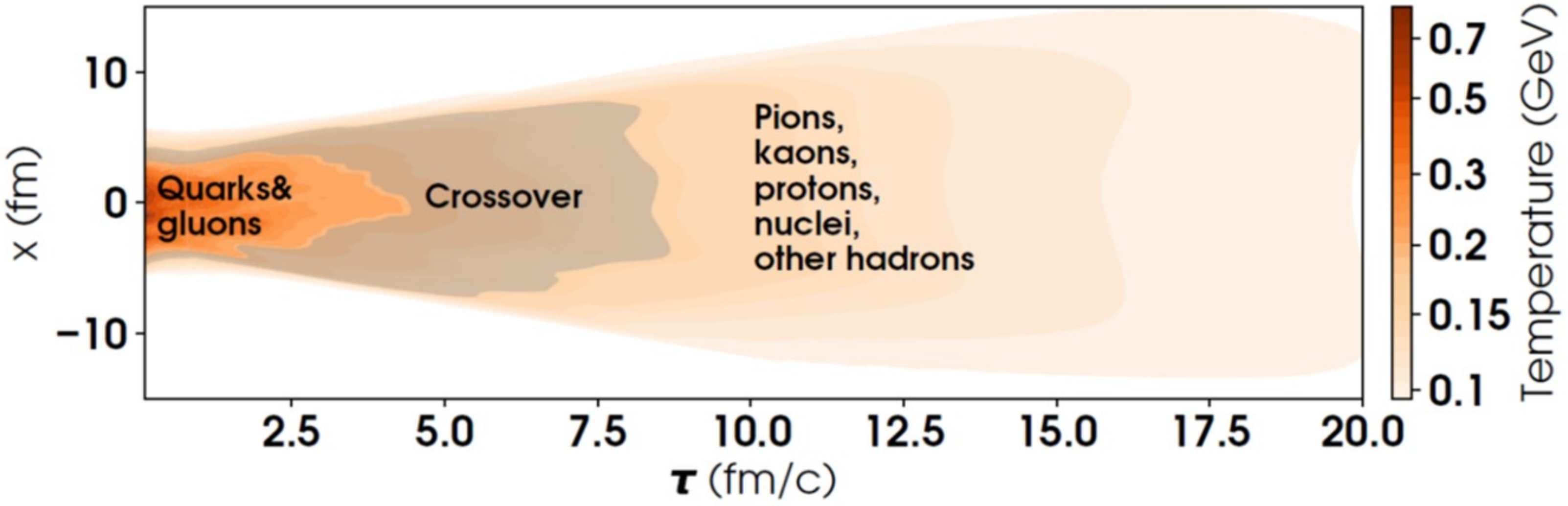


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- Note: No clear separation between **quark/gluon** phase and **hadronic** phase

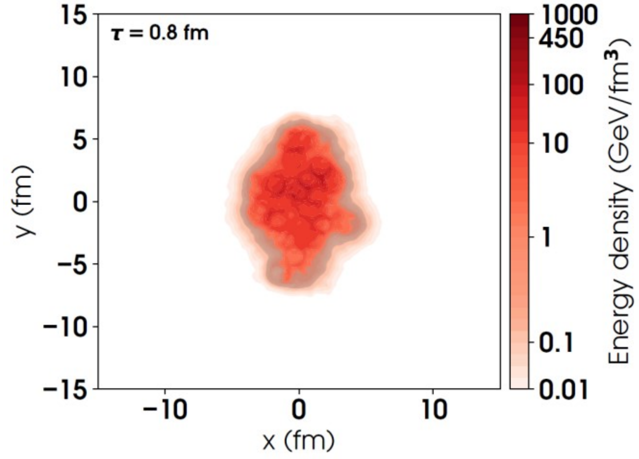
# Relativistic hydrodynamics

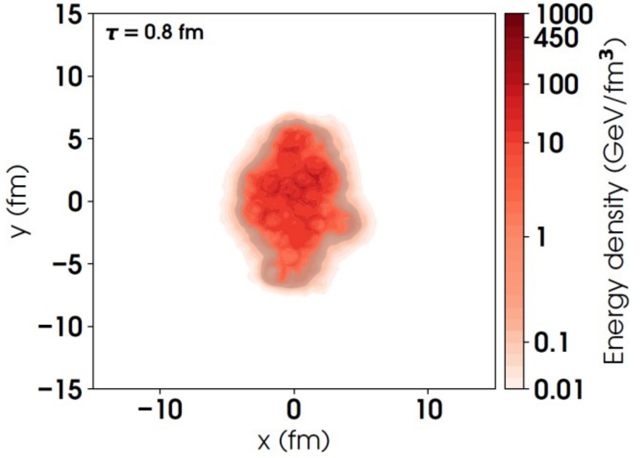
- Evolution of the energy-momentum tensor in space&time

$$T^{\mu\nu} = \epsilon u^{\mu} u^{\nu} - (P + \Pi)(g^{\mu\nu} - u^{\mu} u^{\nu}) + \pi^{\mu\nu}$$

  - $\epsilon$ is the energy density
  - $u^{\mu}$ is the flow velocity (Landau frame: $T^{\mu\nu} u_{\nu} = \epsilon u^{\mu}$)
  - $\Pi$ and are $\pi^{\mu\nu}$ viscous components

Initial conditions



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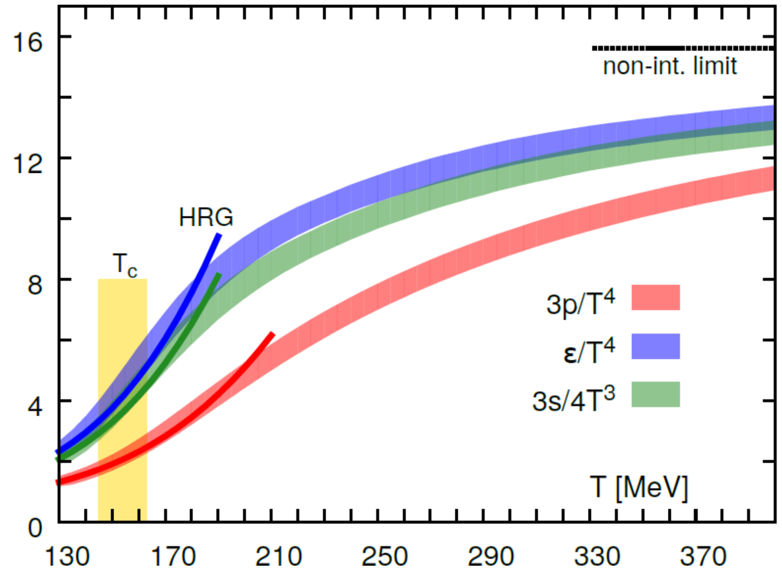
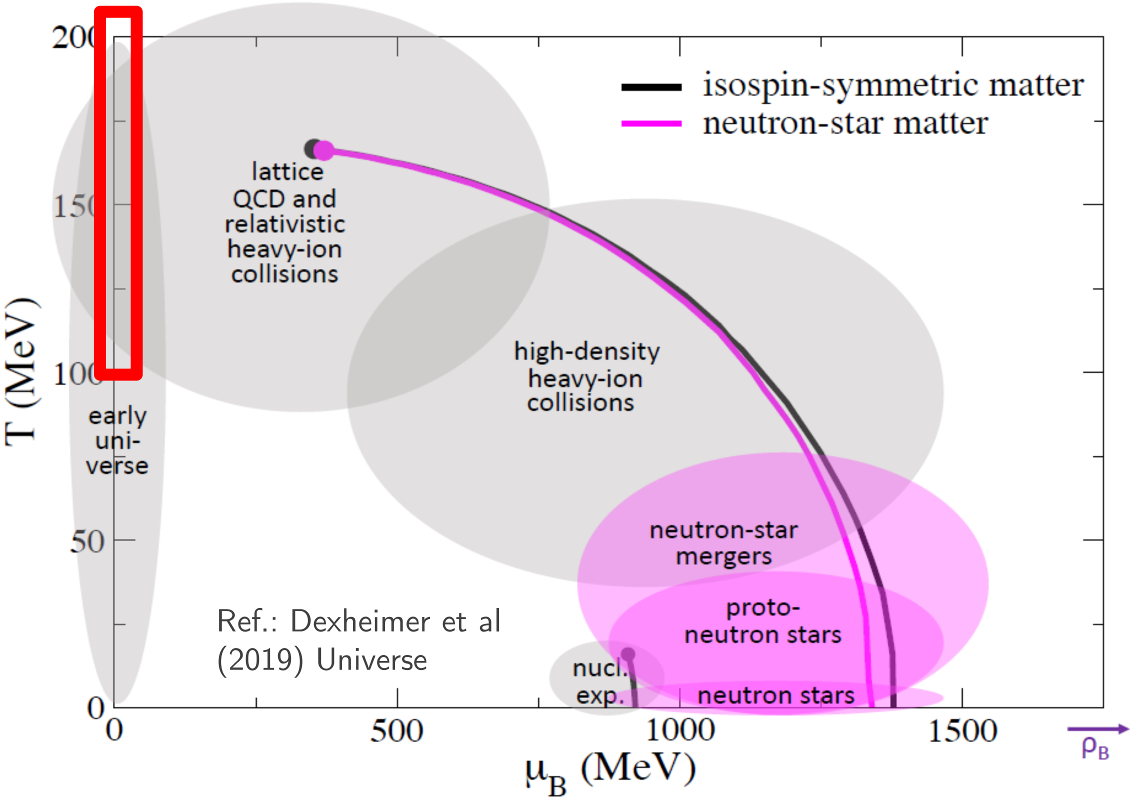
$$T^{\mu\nu} = \epsilon u^{\mu} u^{\nu} - (P + \Pi)(g^{\mu\nu} - u^{\mu} u^{\nu}) + \pi^{\mu\nu}$$

- Conservation of energy and momentum:

$$\partial_{\nu} T^{\mu\nu} = 0$$

- First-principle equation of state



# Relativistic hydrodynamics: viscosity

- Evolution of the energy-momentum tensor in space&time

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (P + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$$

- Conservation of energy and momentum:

$$\partial_\nu T^{\mu\nu} = 0$$

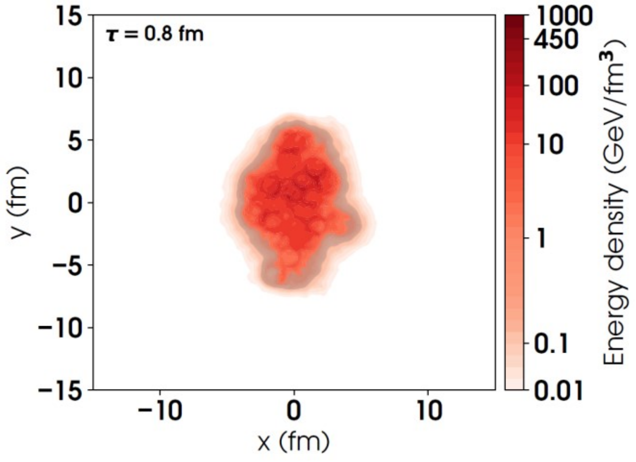
- Mueller-Israel-Stewart relativistic viscous hydrodynamics

$$\tau_\Pi \dot{\Pi} + \boxed{\Pi = -\zeta\, \partial_\mu\, u^\mu} + \text{(2}^{\text{nd}}\text{ order terms)}$$

$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta} \pi^{\alpha\beta} + \boxed{\pi^{\mu\nu} = 2\,\eta(\partial_\mu u^\nu + \cdots)} + \text{(2}^{\text{nd}}\text{ order terms)}$$

Solve hydrodynamics equations numerically (finite volume)

Initial conditions




Mueller (1967) Zeit. fur Phys;
Israel&Stewart (1979) Ann. Phys.

# Photons from deconfined plasma

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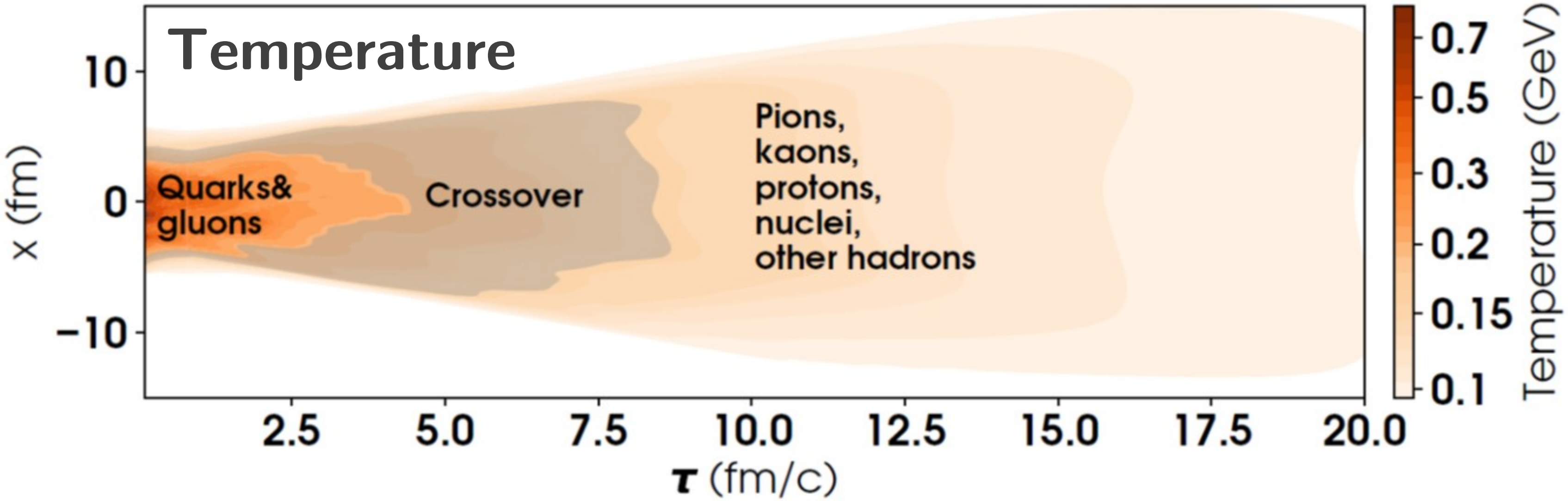



- Photon production: $\frac{dN_\gamma}{d^3p} = \int d^4X \, \frac{d\Gamma_\gamma}{d^3p}(p, \overbrace{T(X), u^\mu(X), \ldots}^{\text{Spacetime profile of plasma}})$

Photon emission rate

# Photon emission rate

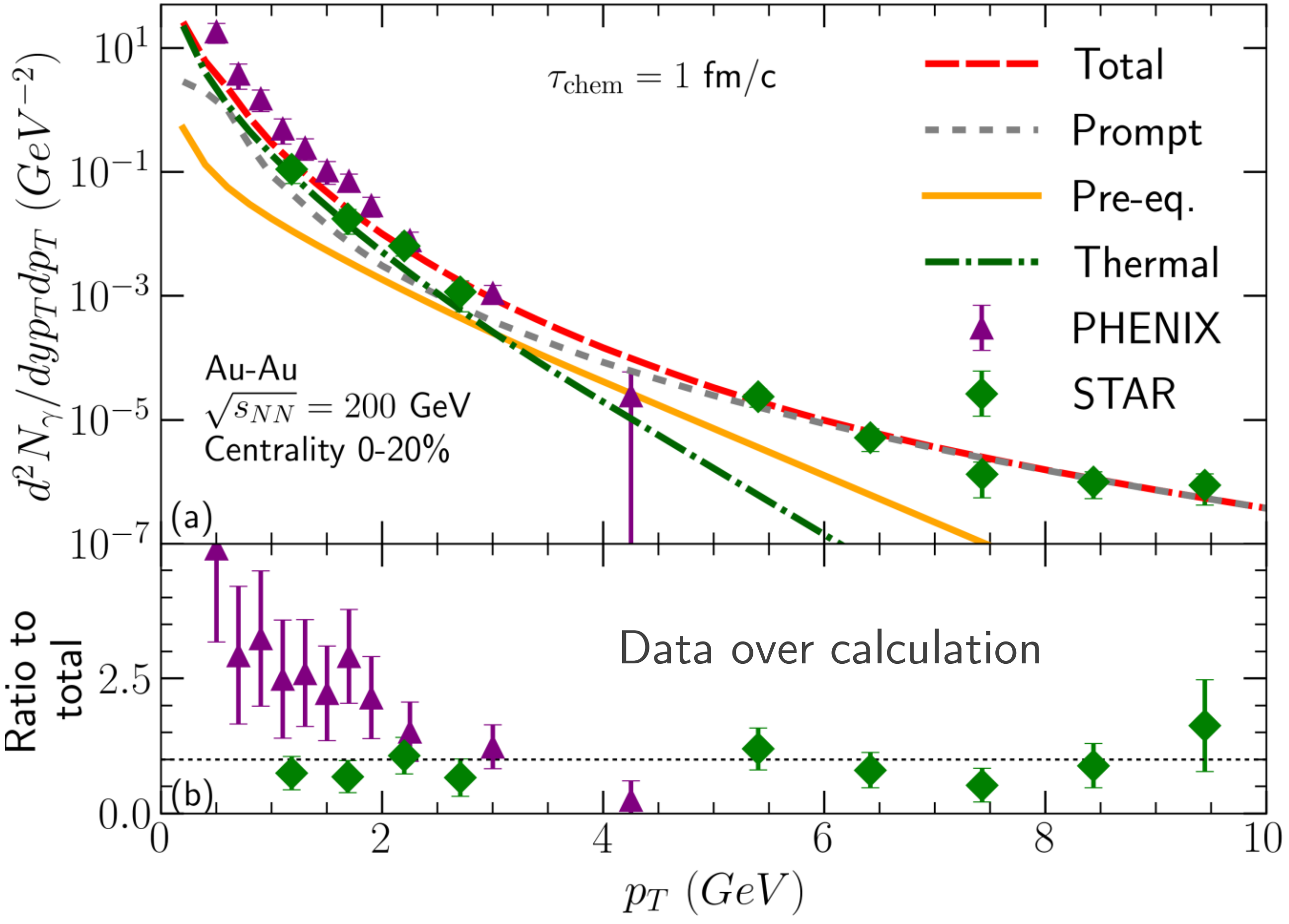
- Photon production: $$\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p} = \int \mathrm{d}^4X \, \frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p}\big(p, \underbrace{T(X), u^\mu(X), \dots}_{\text{Spacetime profile of plasma}}\big)$$

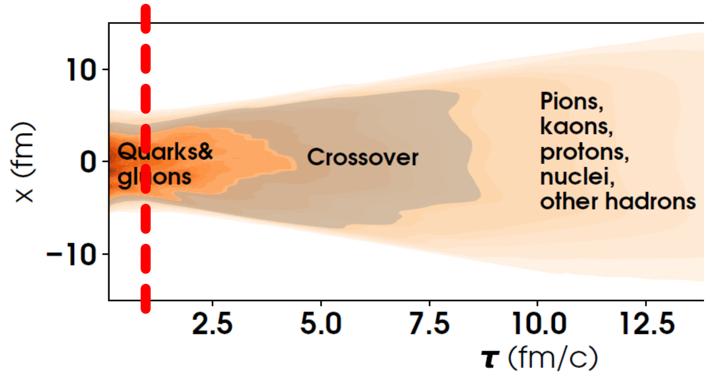
Photon emission rate ($\frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p}$)

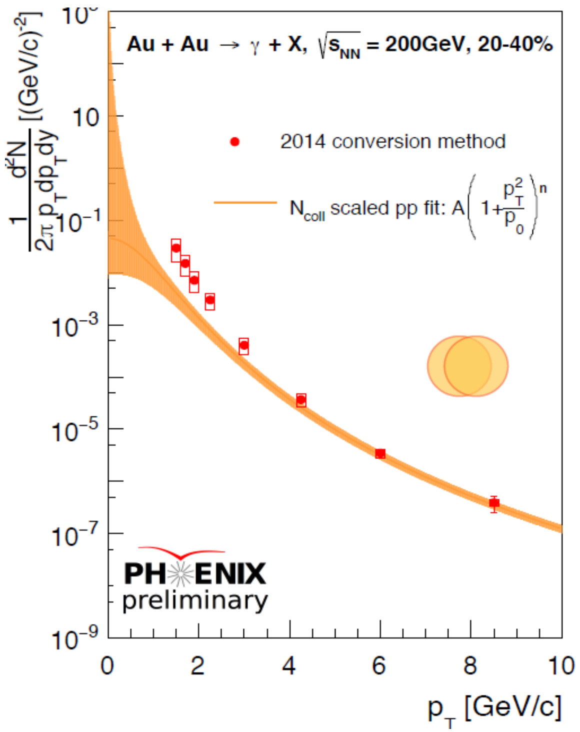
| State of matter/Temperatures | Photon emission rate |
| --- | --- |
| Gas of hadrons below $T \approx 160$ MeV | Effective hadronic models |
| Deconfinement for $T \approx 160 - 200$ MeV | Extrapolated rates from low/high temperatures |
| Strongly-coupled quark/gluons for $T \sim 200 - 500$ MeV | Lattice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

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

Gale, Paquet, Schenke, Shen (2022) PRC

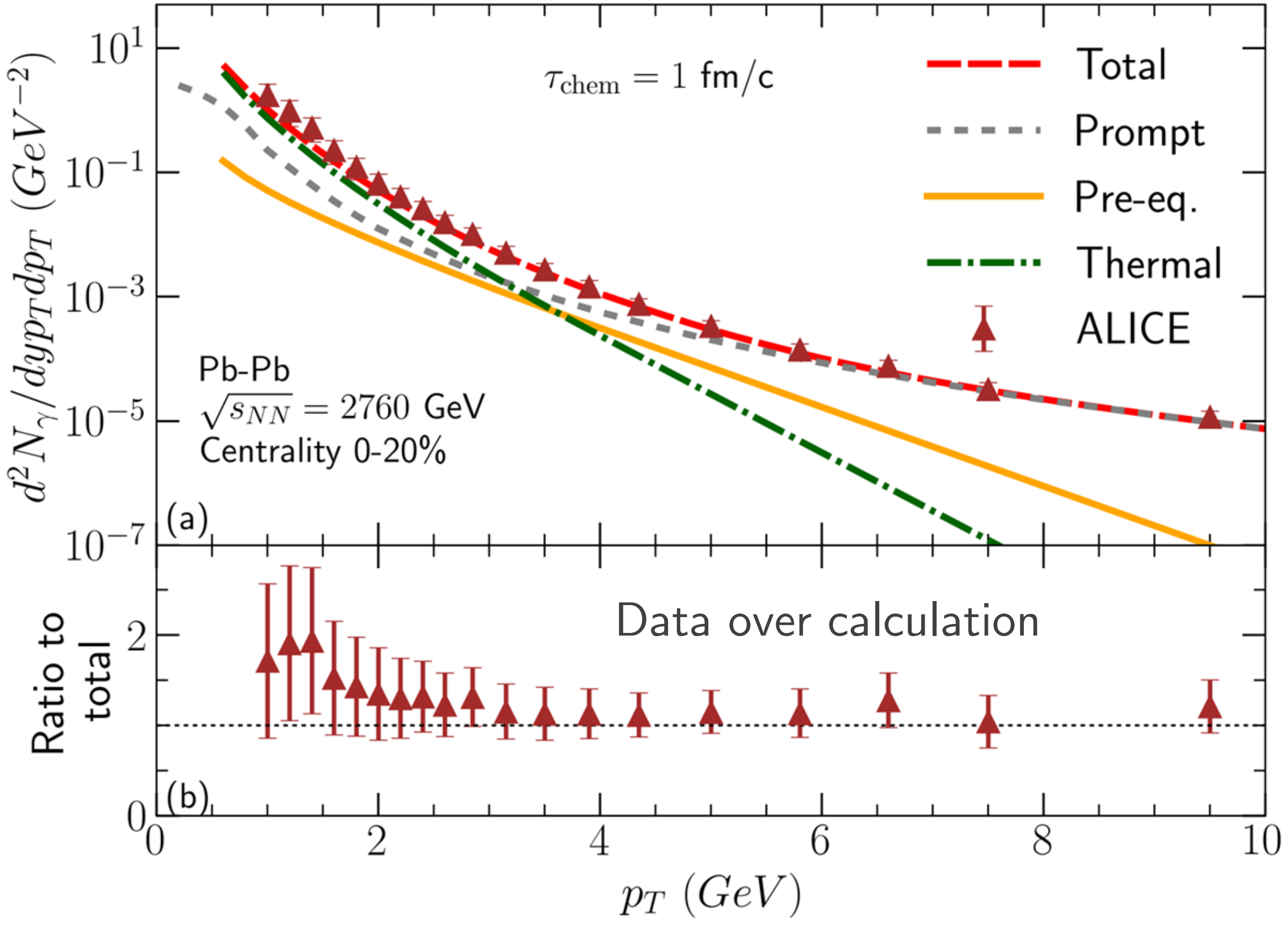


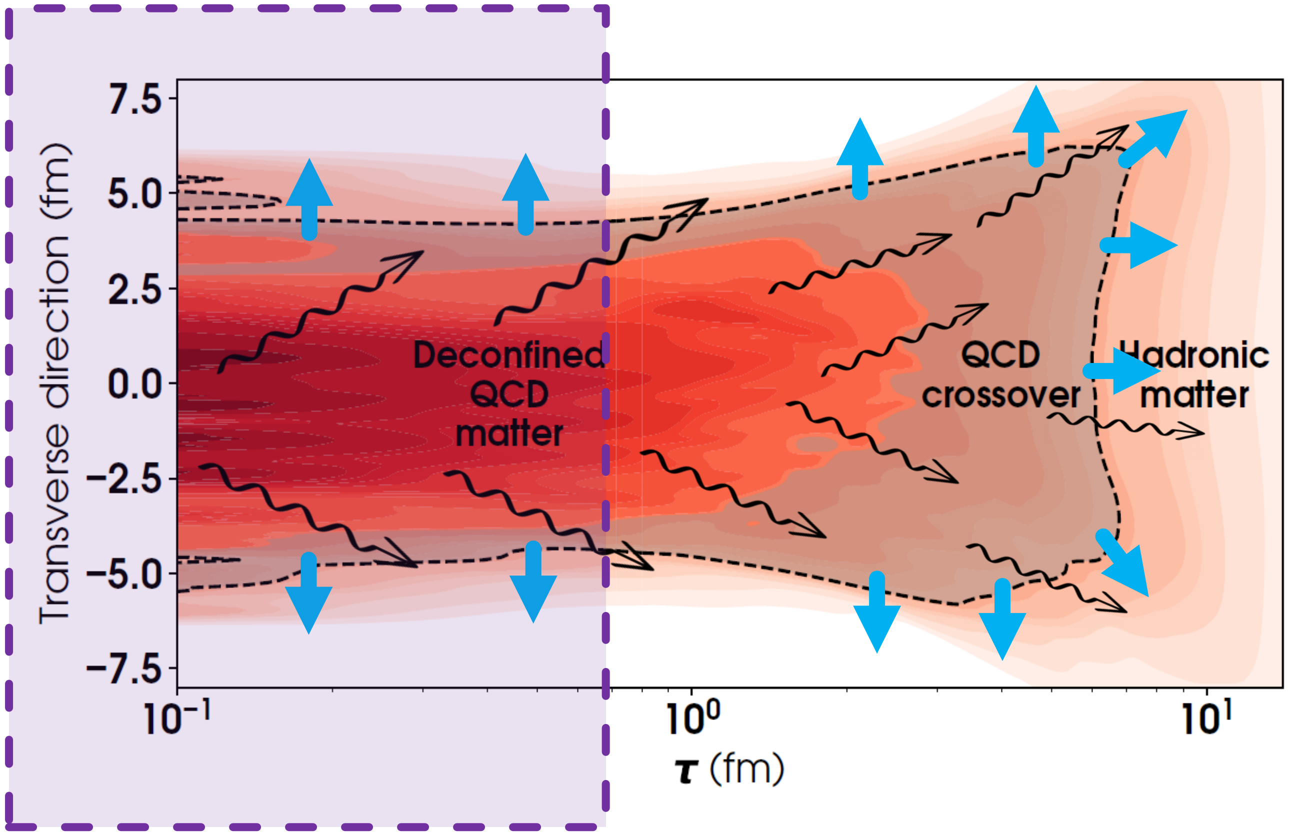
# Results: Pb-Pb $\sqrt{s_{NN}}$ =2760 GeV, 0-20%

Gale, Paquet, Schenke, Shen (2022) PRC

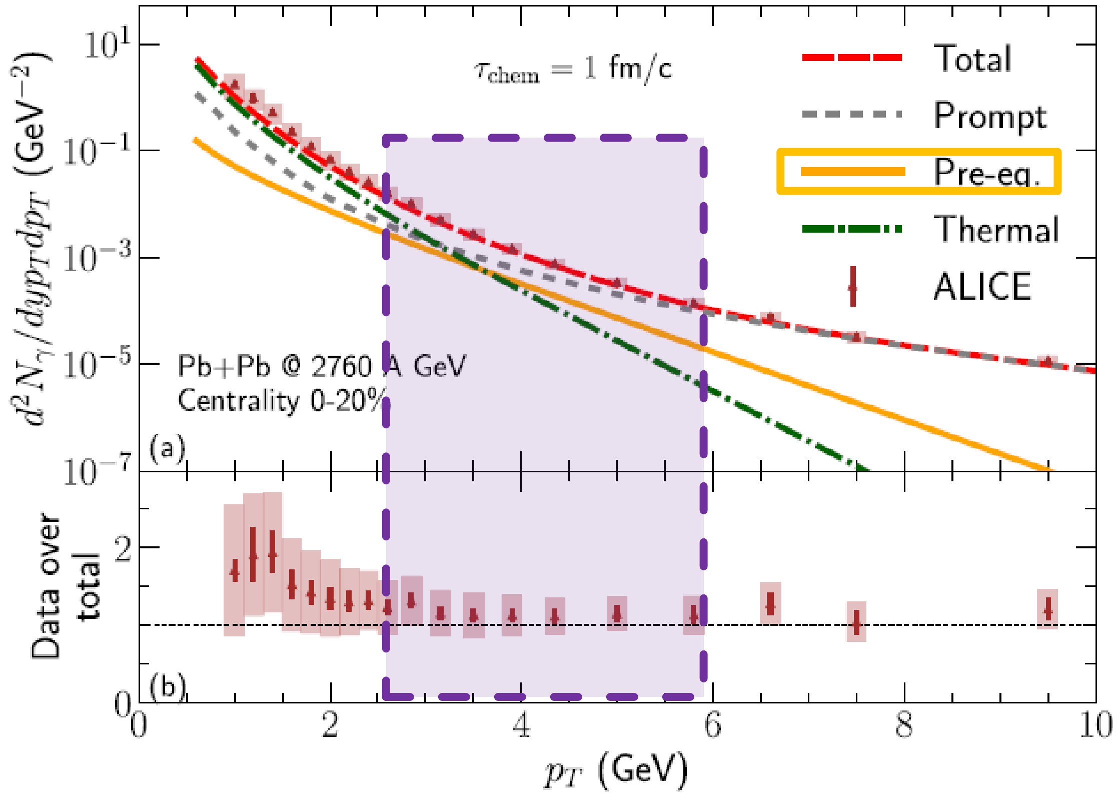



Thermal photons dominate at low energy ($p_T$)

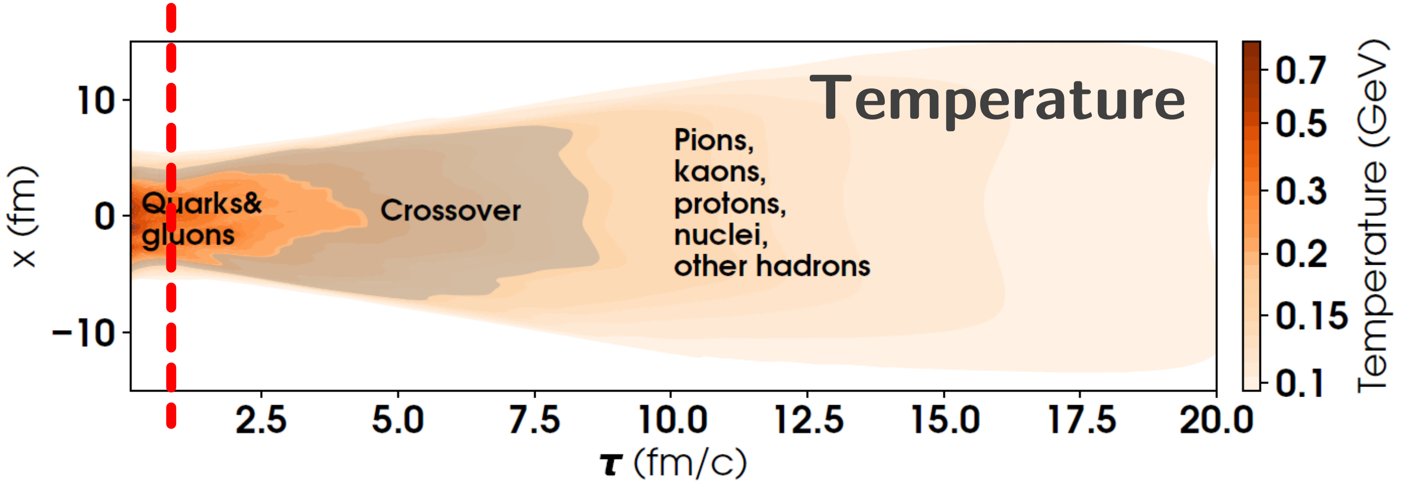
# Photons from the early stage of the collision



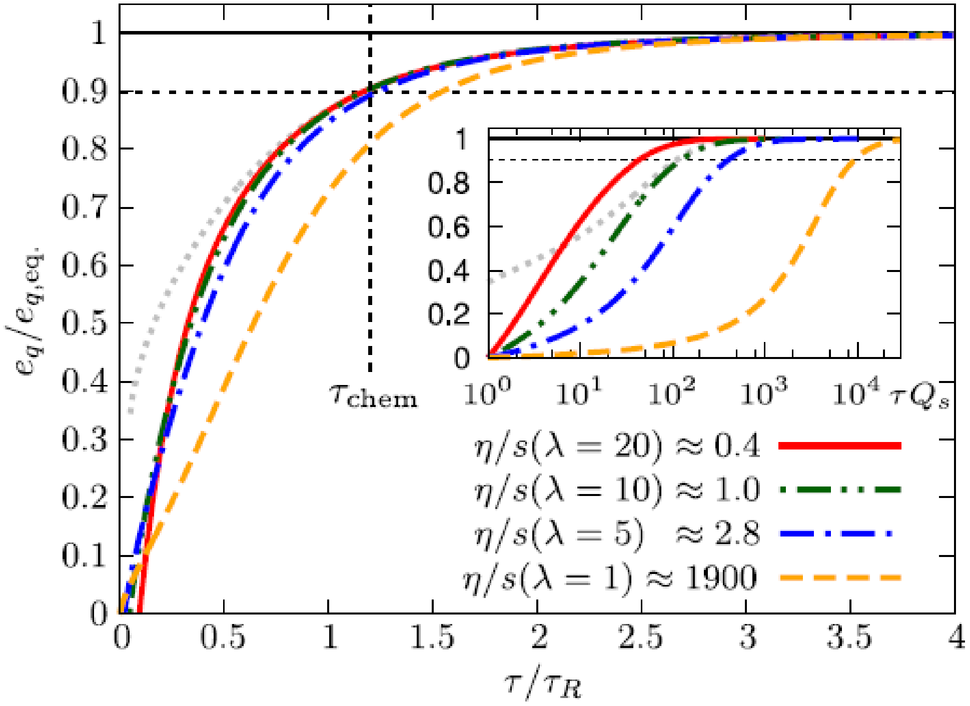

Gale, Paquet, Schenke, Shen (2022) PRC



# Quark-gluon chemical equilibration time



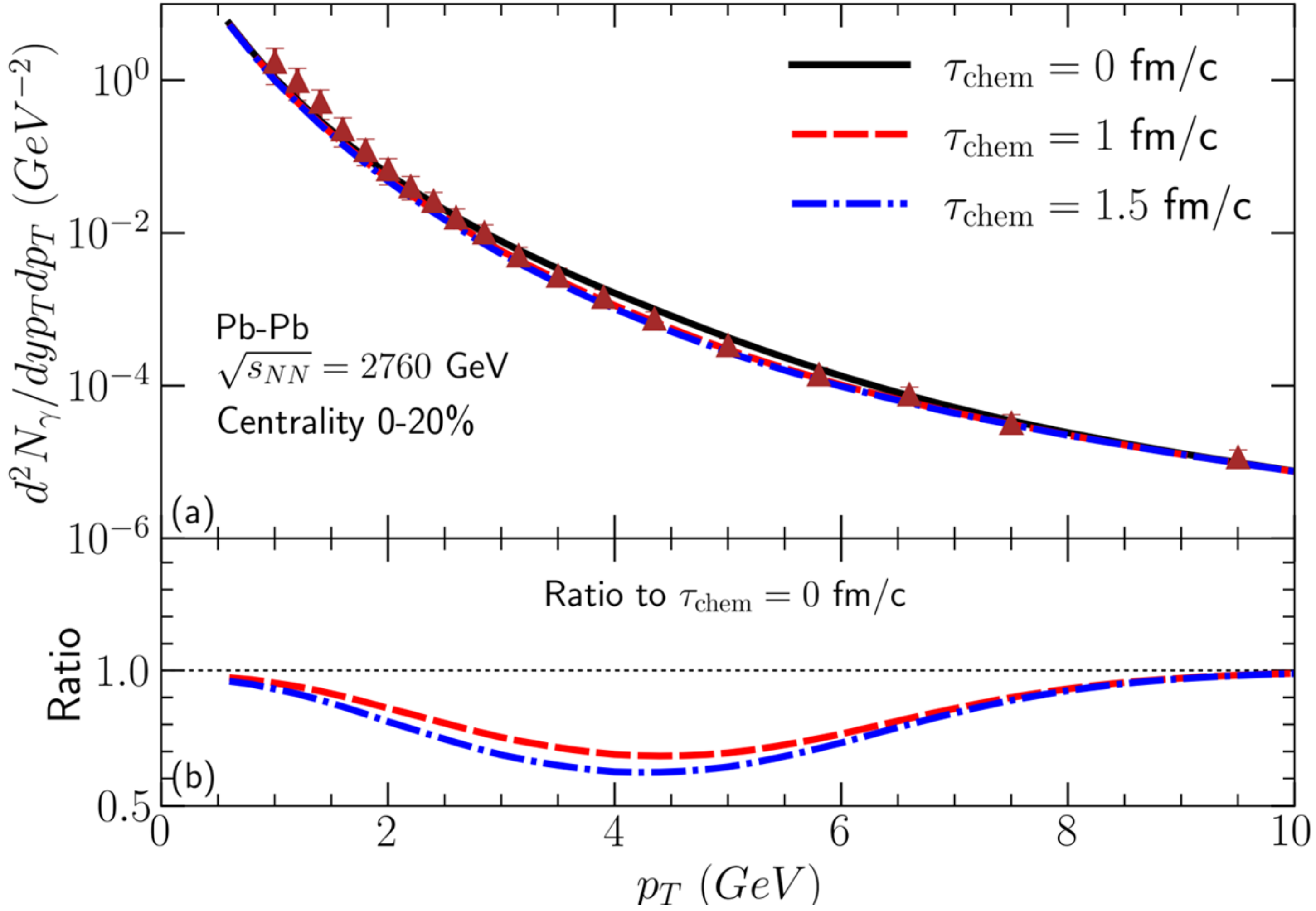

Kurkela and Mazeliauskas (2019) PRL

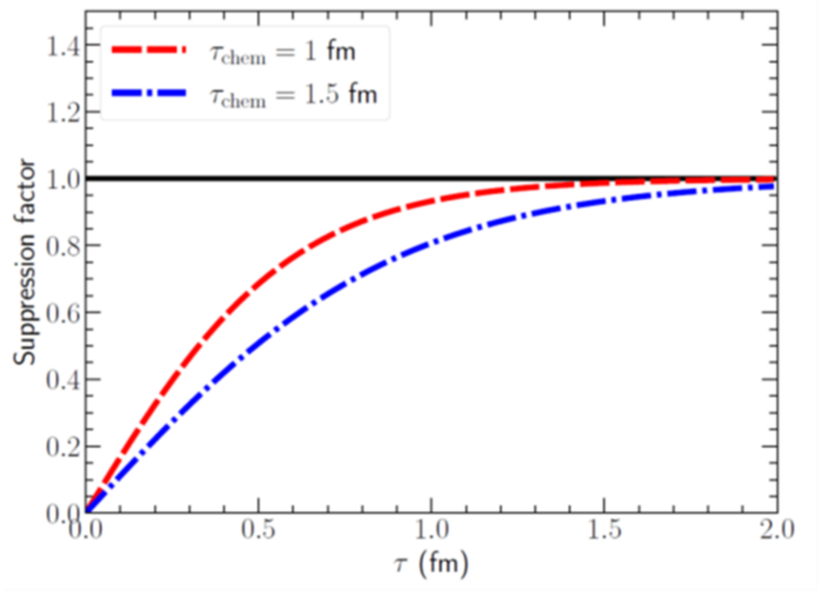



Energy density carried by quarks, compared to that in chemical equilibrium

# Estimating the effect of chemical equilibration time

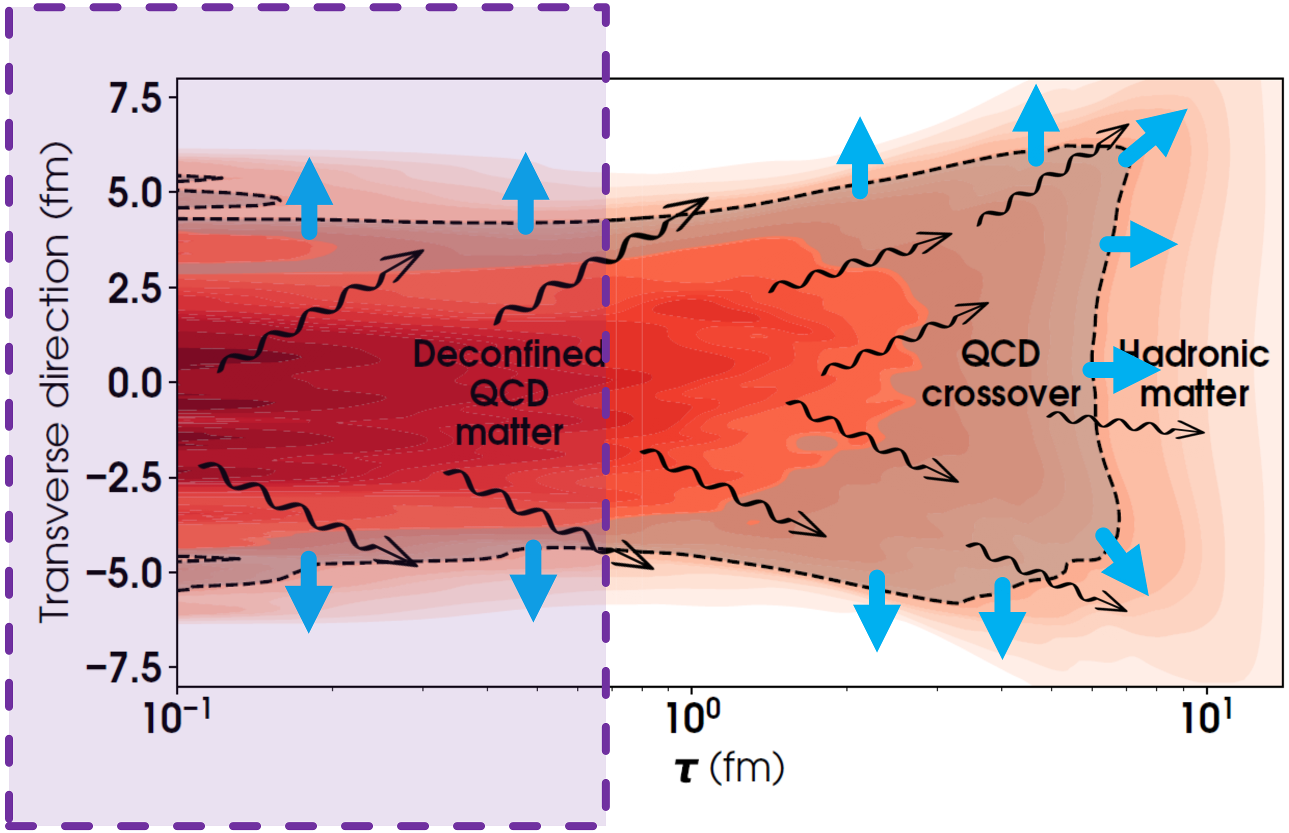
Kurkela and Mazeliauskas (2019) PRL



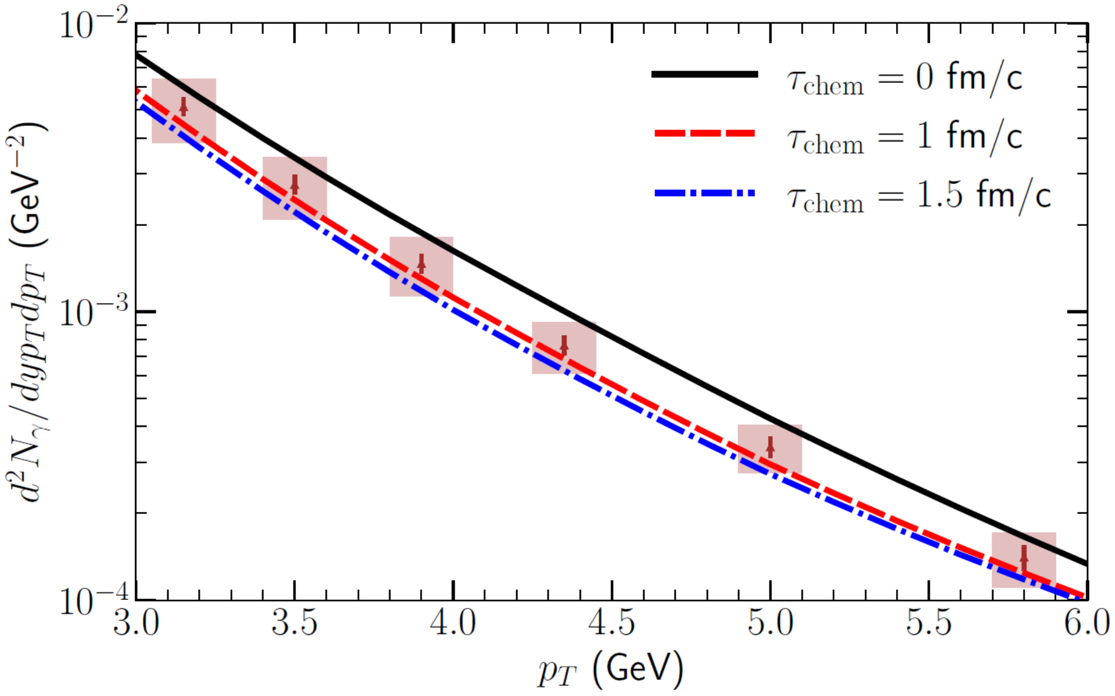




Delayed chemical equilibration:
significant effect on the photon spectra

# Photons from the early stage of the collision




Gale, Paquet, Schenke, Shen (2022) PRC



# Results: momentum anisotropy

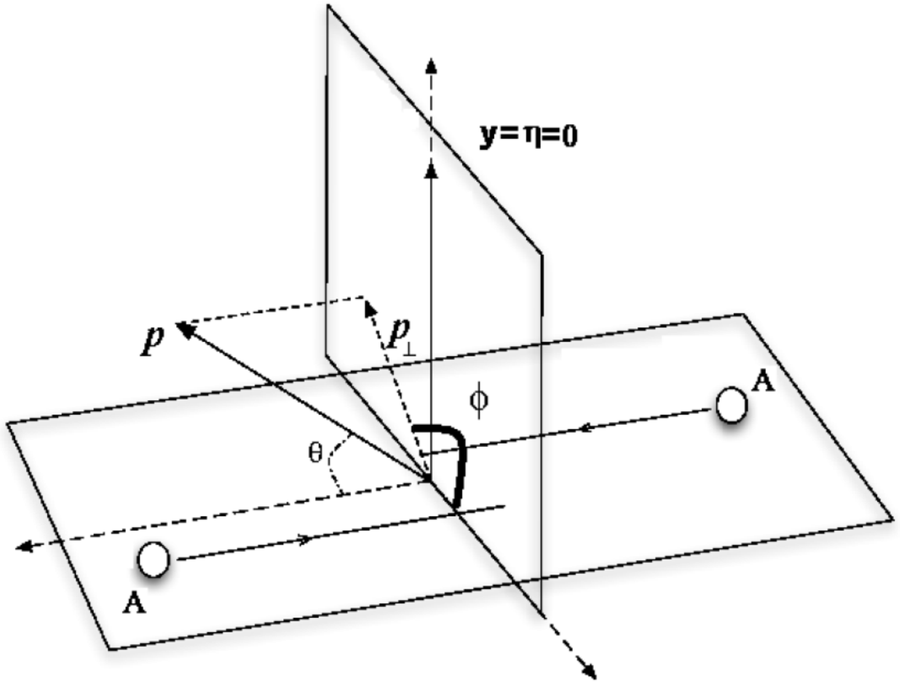


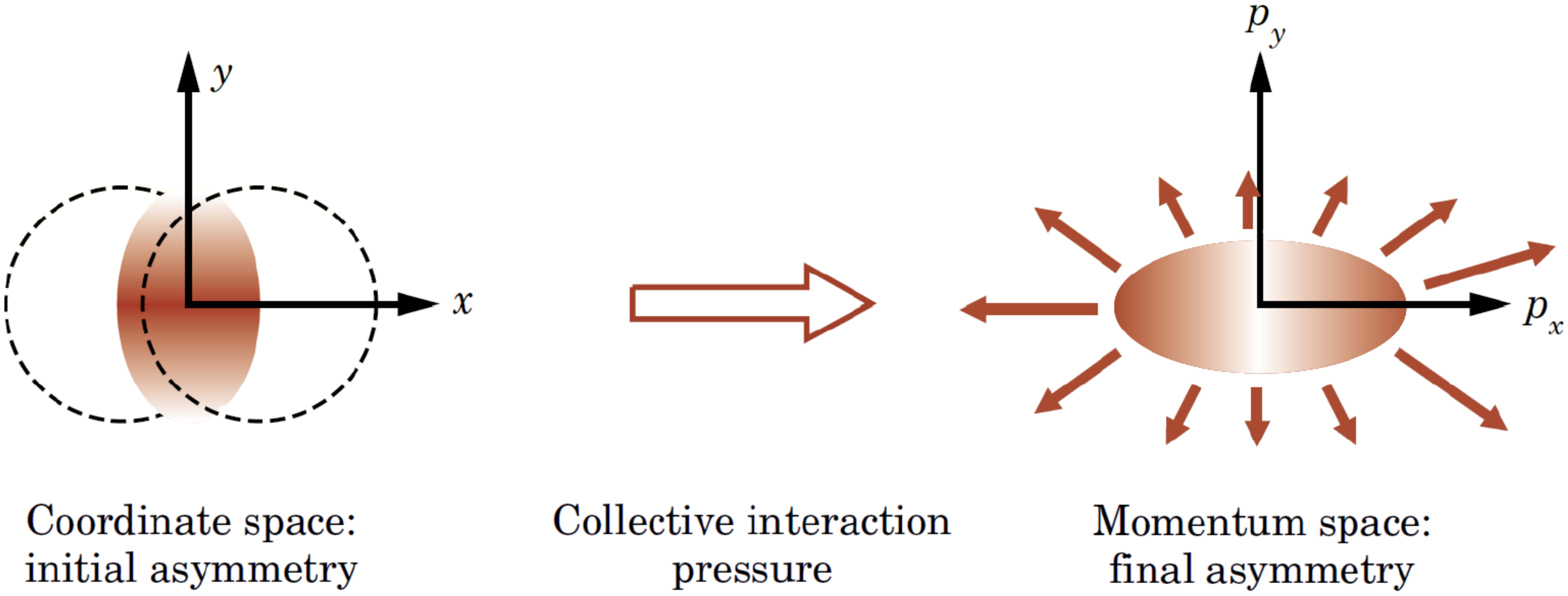

Figure adapted from K. Tuchin (2013) AHEP

$$\frac{1}{2\pi p_T}\frac{dN}{dp_T d\phi} = \left(\frac{1}{2\pi p_T}\frac{dN}{dp_T}\right)\left[1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n))\right]$$

- More precisely:
  momentum anisotropy through photon-hadron correlation

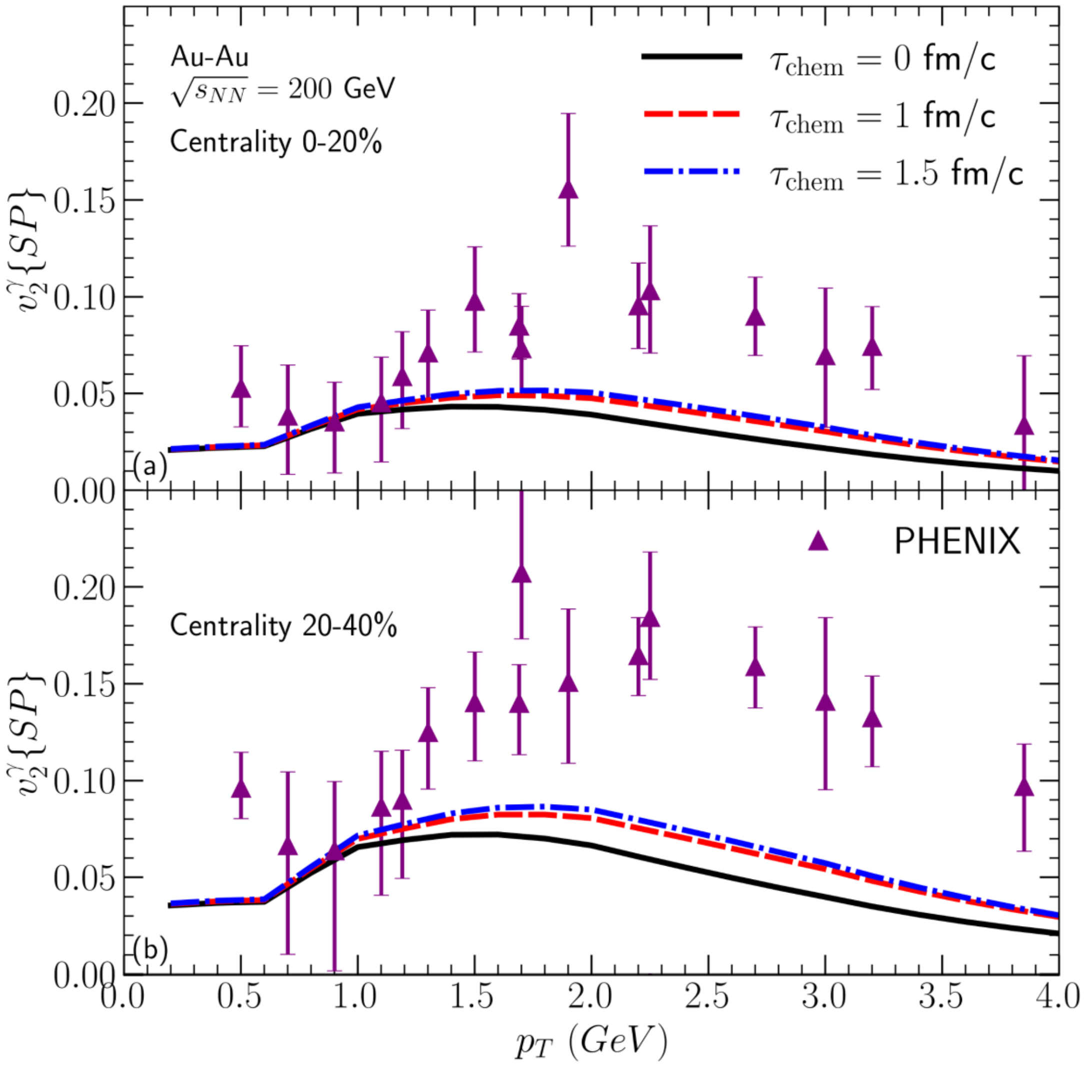
$$v_n\{SP\}(p_T) = \frac{\left\langle v_n^{\gamma}(p_T) v_n^{h} \cos\left(n\left(\Psi_n^{\gamma}(p_T) - \Psi_n^{h}\right)\right) \right\rangle}{\sqrt{\left\langle \left(v_n^{h}\right)^2 \right\rangle}}$$

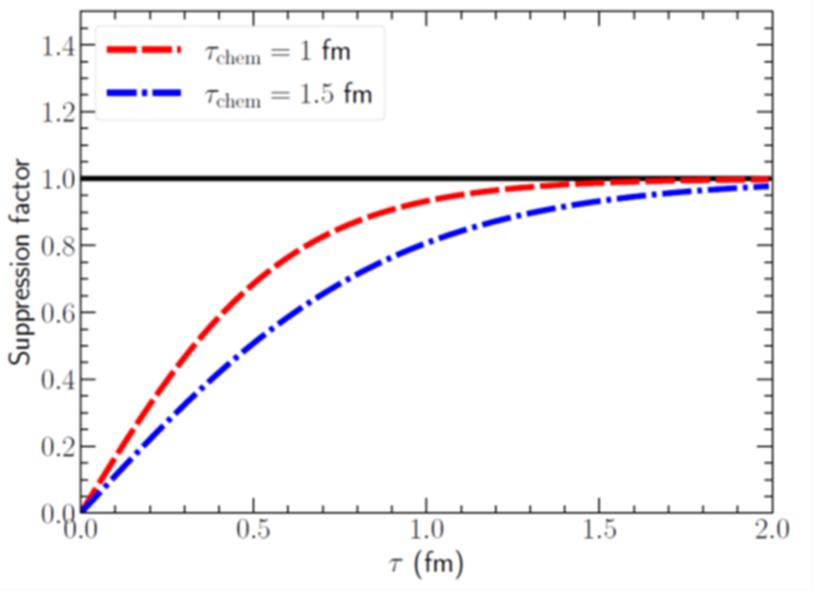
# Momentum anisotropy from geometrical anisotropy




$$\frac{1}{2\pi p_T}\frac{dN}{dp_T d\phi} = \left(\frac{1}{2\pi p_T}\frac{dN}{dp_T}\right)\left[1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n))\right]$$

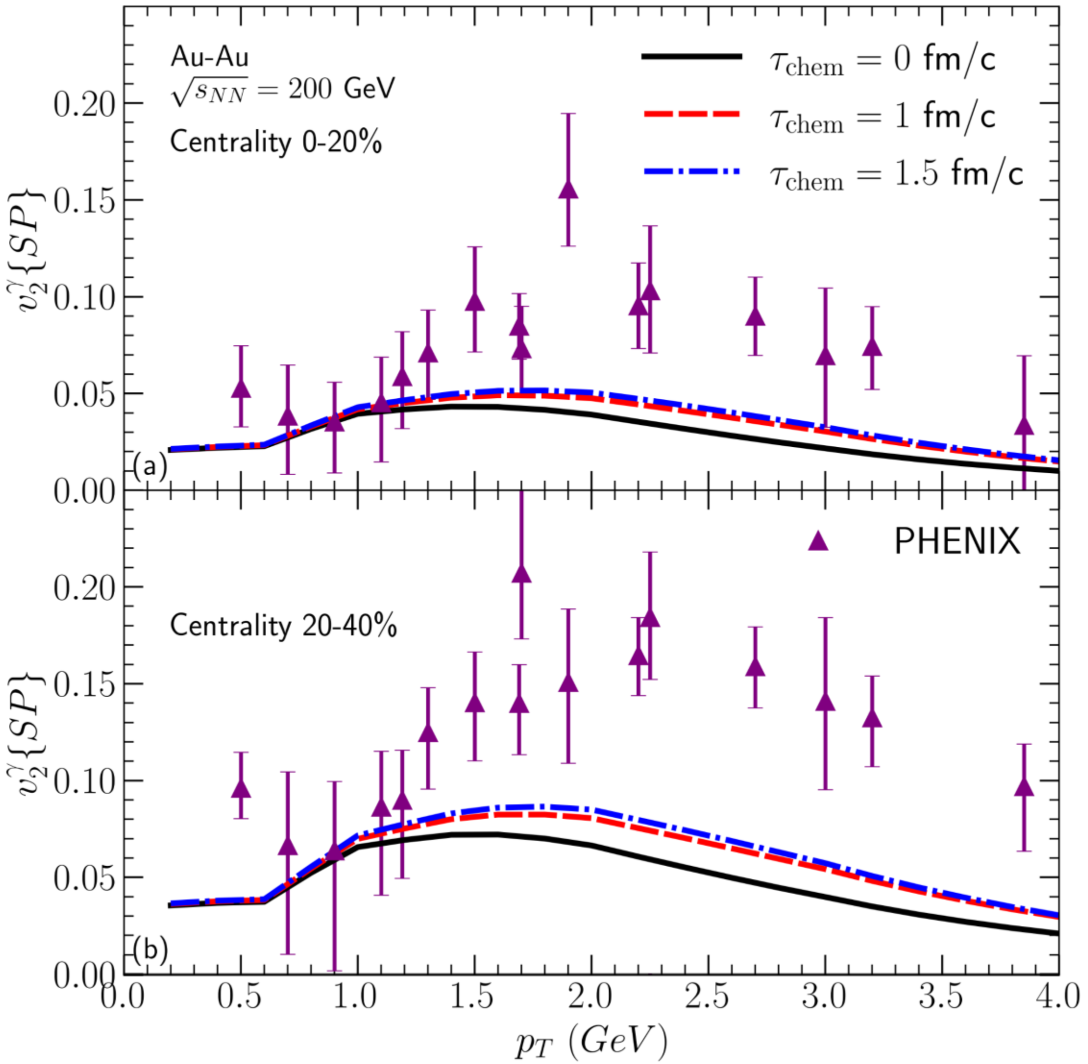
# Results: Au-Au $\sqrt{s_{NN}}$ =200 GeV

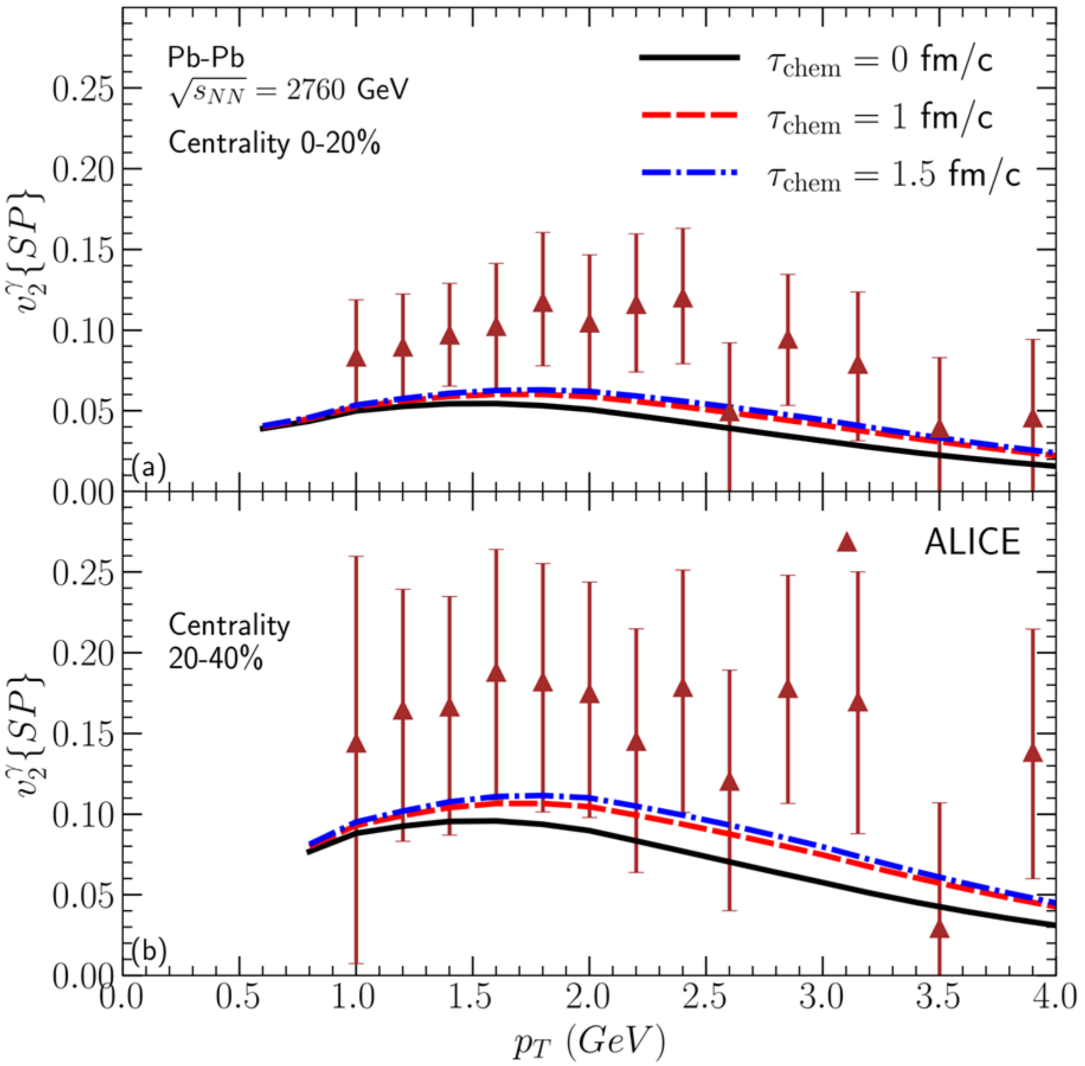


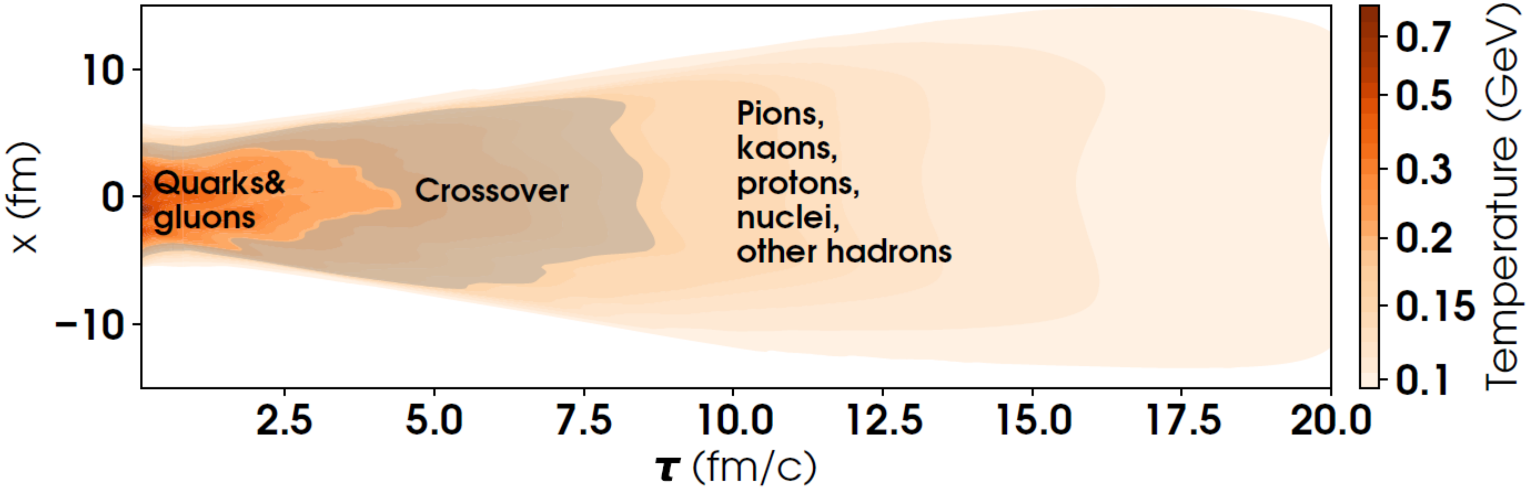



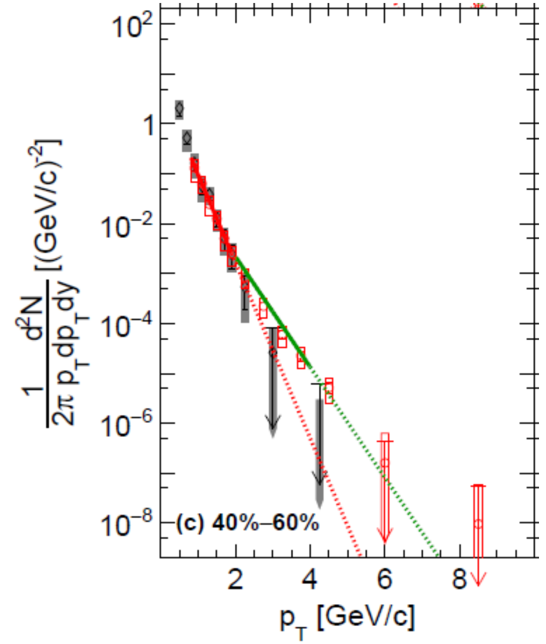

High $p_T$ $v_2^{\gamma}$ increased by delayed chemical equilibration

# The direct photon puzzle



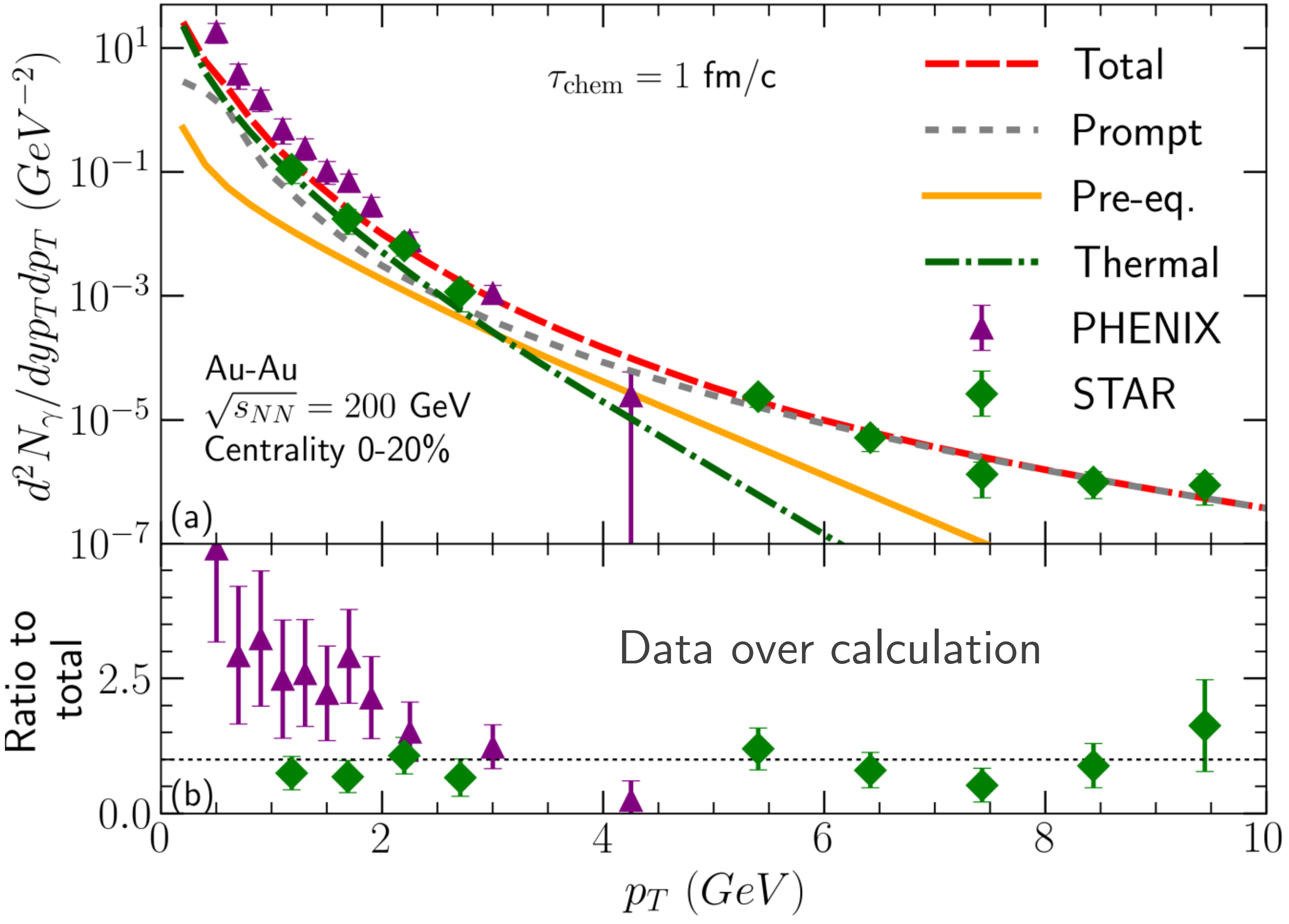


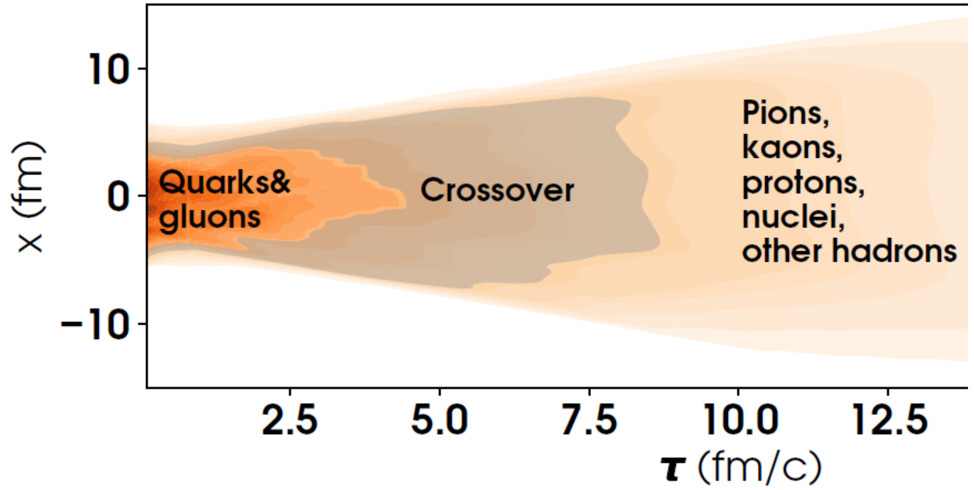




# PLASMA TEMPERATURE FROM PHOTON ENERGY SPECTRUM

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

Gale, Paquet, Schenke, Shen (2022) PRC



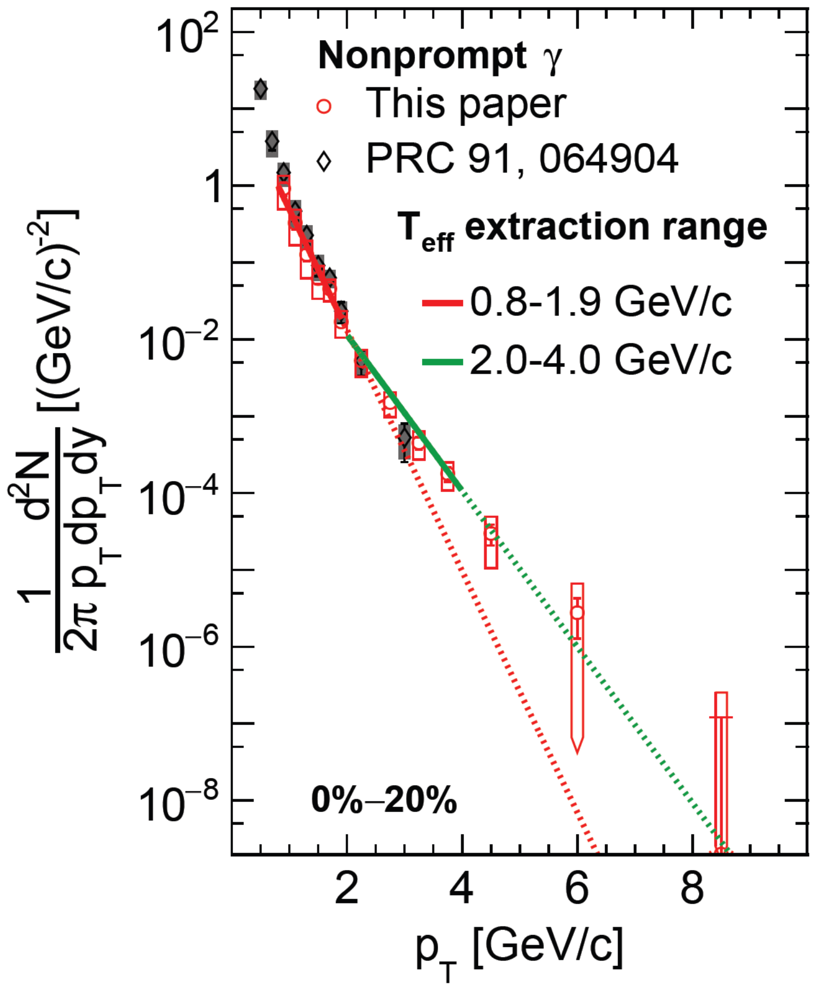




Spacetime profile of plasma

$$\frac{dN_\gamma}{d^3p} = \int d^4X \frac{d\Gamma_\gamma}{d^3p}(p, T(X), u^\mu(X), \dots)$$

Photon emission rate

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




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

| centrality | $T_{\mathrm{eff}}$ (GeV/$c$) $0.8 < p_T < 1.9$ GeV/$c$ | $T_{\mathrm{eff}}$ (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: $\frac{1}{\mathrm{E}}\frac{\mathrm{d}\Gamma_\gamma}{\mathrm{d}^3p} \sim e^{-\frac{E}{T}}$

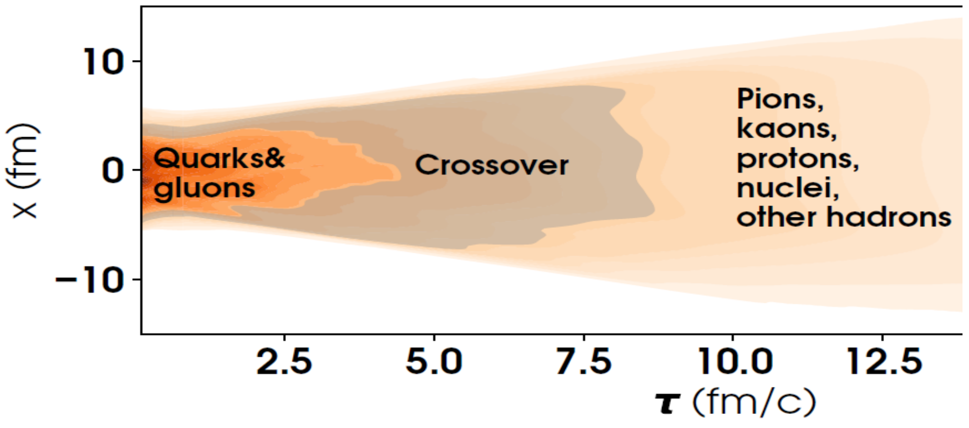
Doppler shift

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

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

# Thermal photon spectrum

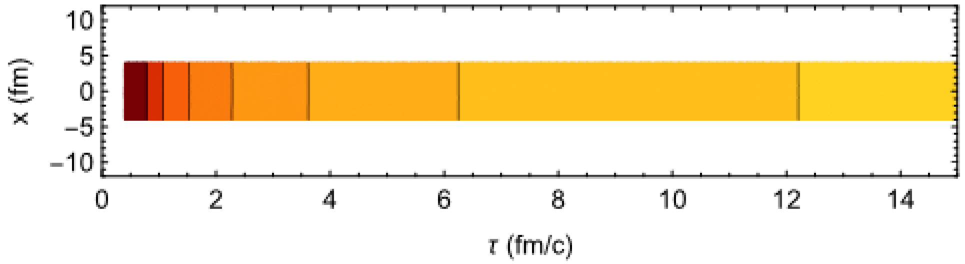
$$\ln\left(\frac{1}{E}\frac{dN_\gamma}{d^3p}\right) \approx \ln\left(\int d\phi\, d\eta_s\, dx_\perp\, e^{-\frac{P\cdot u(X)}{T(X)}}\right) + cte$$



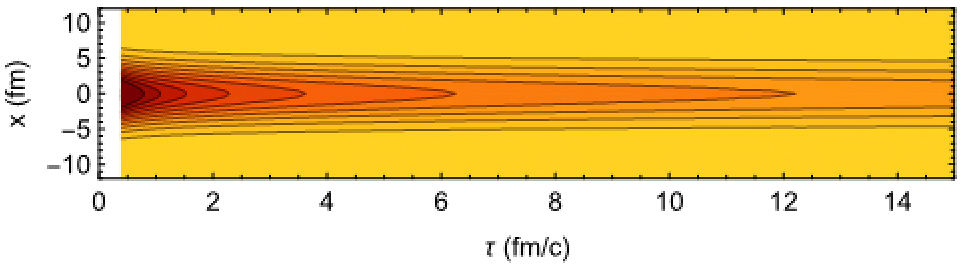

Spacetime profile of plasma: complicated, but can look at simple models

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

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



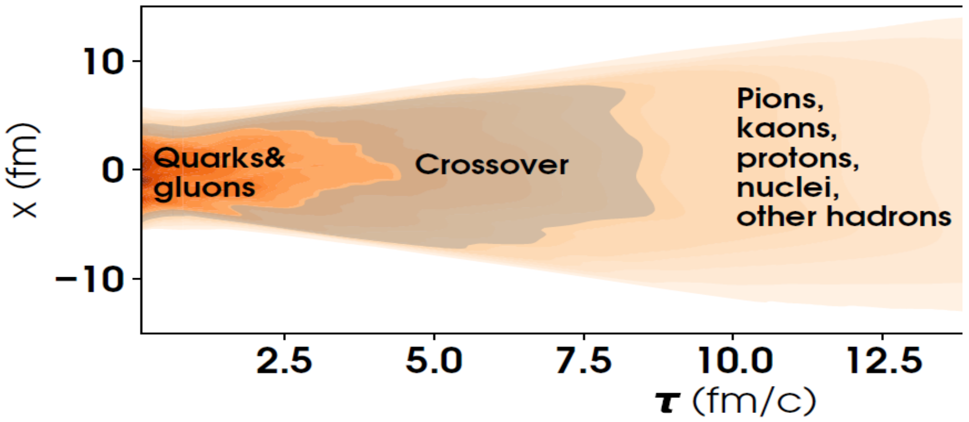

➡ Gaussian approx: $T(\tau, r) = T_0 e^{-\frac{r^2}{2\sigma^2}}\left(\frac{\tau_0}{\tau}\right)^{c_s^2}$



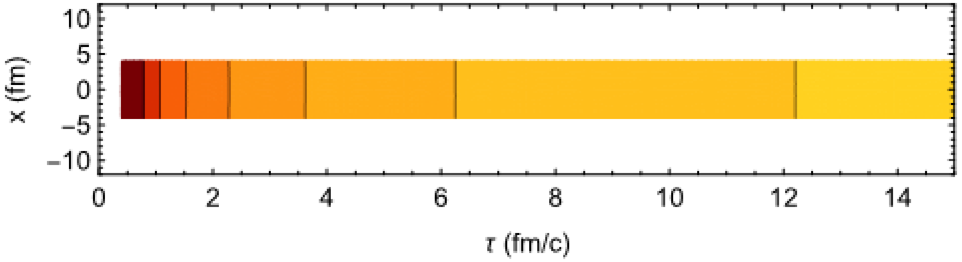

Paquet and Bass [ arXiv:2205.12299 ]

# Thermal photon spectrum

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

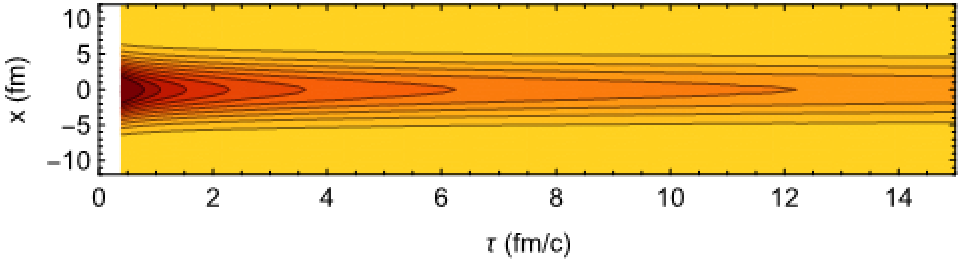



$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx -\frac{E}{T_0} + \frac{3}{2}\log\left(\frac{T_0}{E}\right) + cte + O\left(\frac{T_0}{E}\right)$$




Paquet and Bass [ arXiv:2205.12299 ]

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

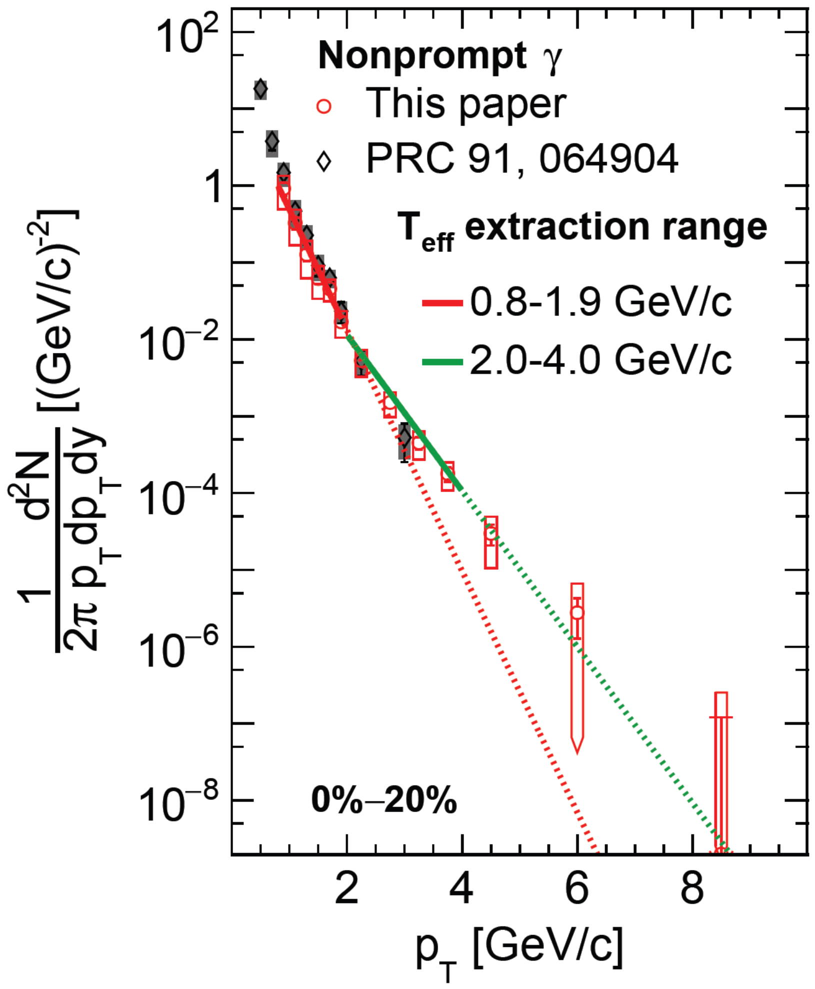



$$\ln\left(\frac{1}{E}\frac{\mathrm{d}N_\gamma}{\mathrm{d}^3p}\right) \approx -\frac{E}{T_0} + \mu\log\left(\frac{T_0}{E}\right) + cte \approx -\frac{E}{T_{eff}} + cte$$

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

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

Paquet and Bass [ arXiv:2205.12299 ]



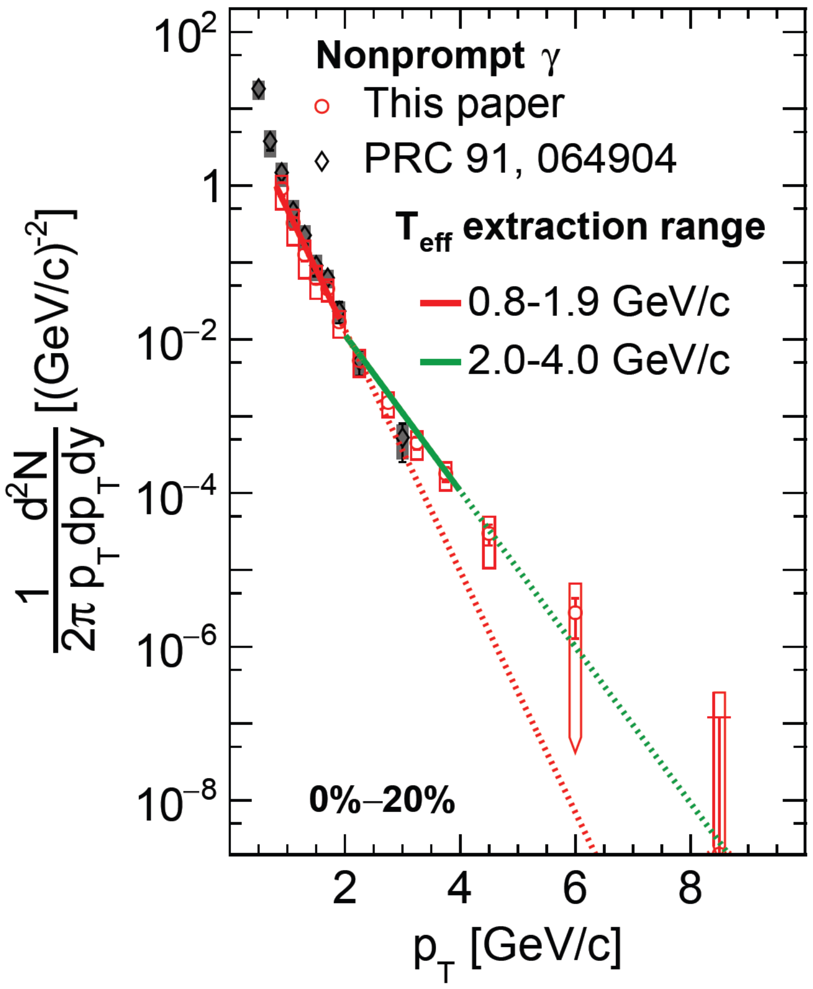

$$\ln\left(\frac{1}{2\pi E}\frac{dN}{dE\,dy}\right) = cte - \frac{E}{T_{eff}}\ ; \qquad T_0 \approx \frac{T_{eff}}{1 - \frac{T_{eff}}{E}\mu \ln \mu}$$

| centrality | $T_0 (GeV)$ | $T_{\text{eff}}$ (GeV/$c$) $0.8 < p_T < 1.9$ GeV/$c$ | $T_0 (GeV)$ | $T_{\text{eff}}$ (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

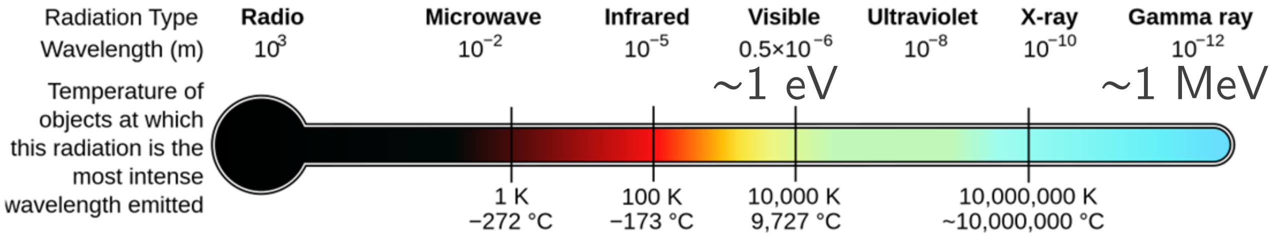
Note: even more complicated due to Doppler shift

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




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

$$T = 500\ MeV = 6 \times 10^{12} K$$




~1 eV

~1 MeV

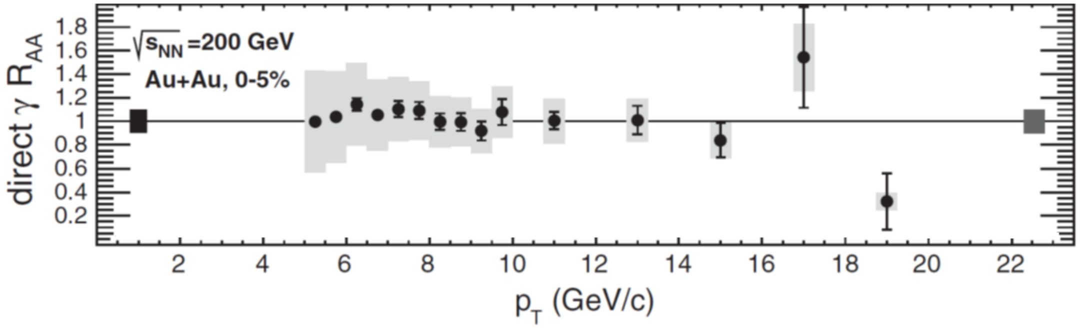
$E_\gamma$ ~1 GeV

$T \sim 10^{12}$K

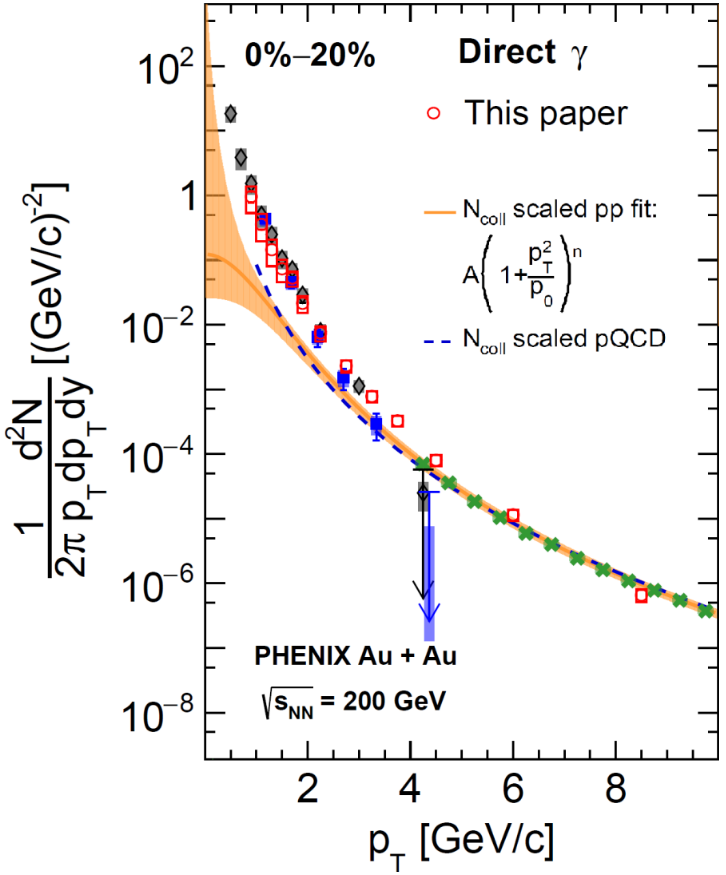
# Summary and outlook

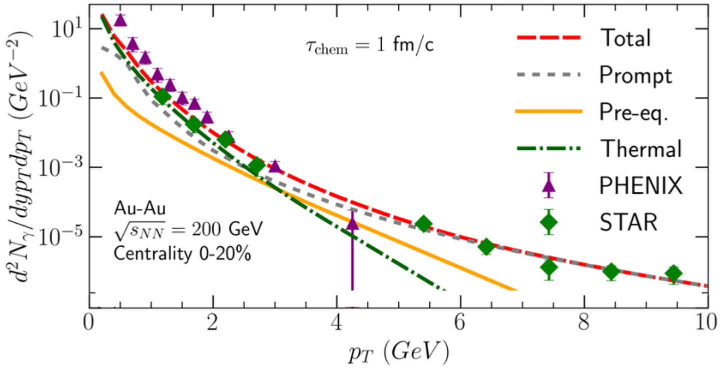
# Summary

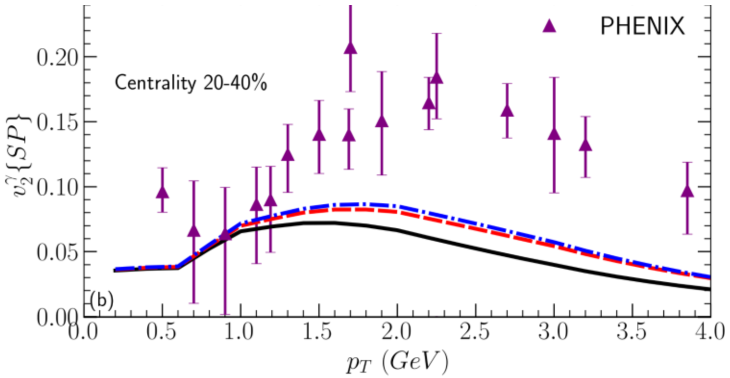
- High-energy photons:
  heavy-ion collisions similar to proton-proton case




- Low-energy photons:
  - Enhancement with respect to proton-proton collisions
  - Exponential spectrum ± consistent with thermal radiation from deconfined plasma
  - Azimuthal anisotropy: tension in model-data comparisons

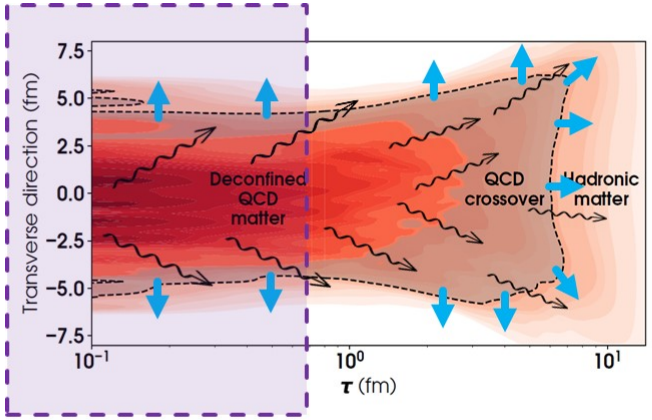


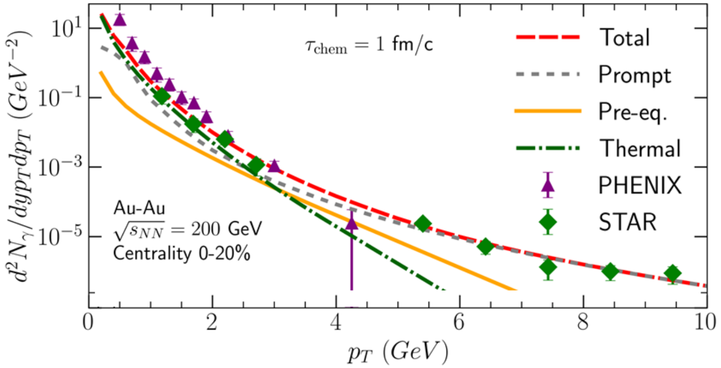



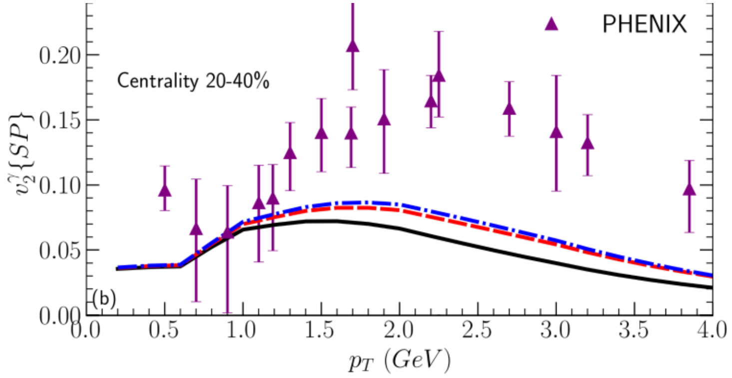
# Outlook

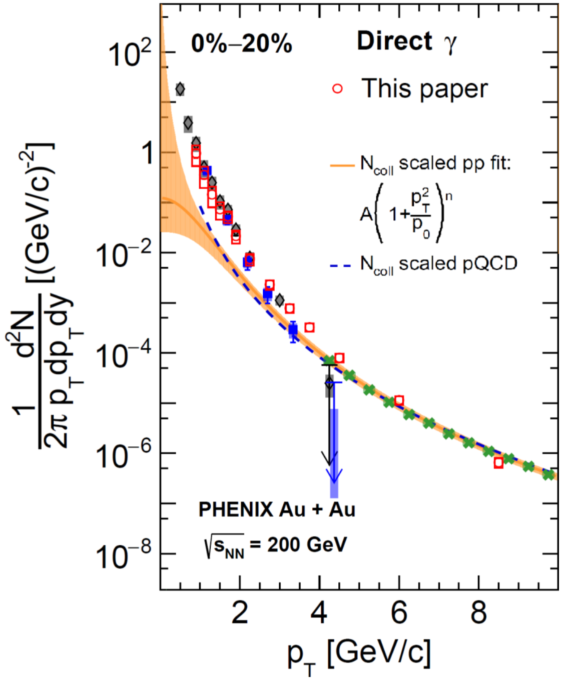
Gale, Paquet, Schenke, Shen (2022) PRC




- Studying the early stage of heavy-ion collisions with photons
- "Multi-messenger" study of heavy-ion collisions
- Better prediction of low $p_T$ photons in proton-proton collisions?




- Many opportunities with dileptons as well