Thermal photons as a quark-gluon plasma thermometer revisited

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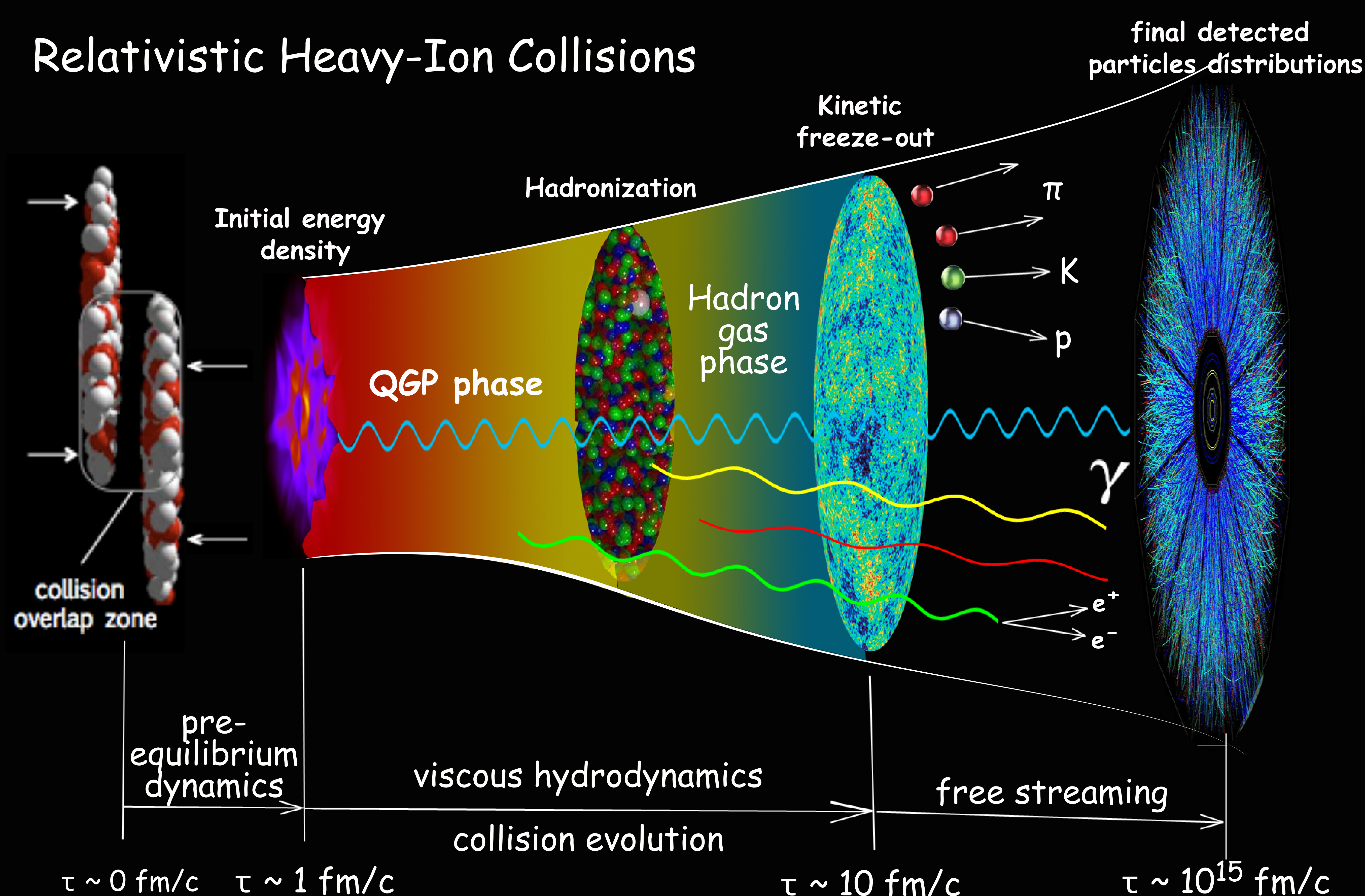
The Ohio State University

In collaboration with Ulrich Heinz, Charles Gale, and Jean-Francois Paquet

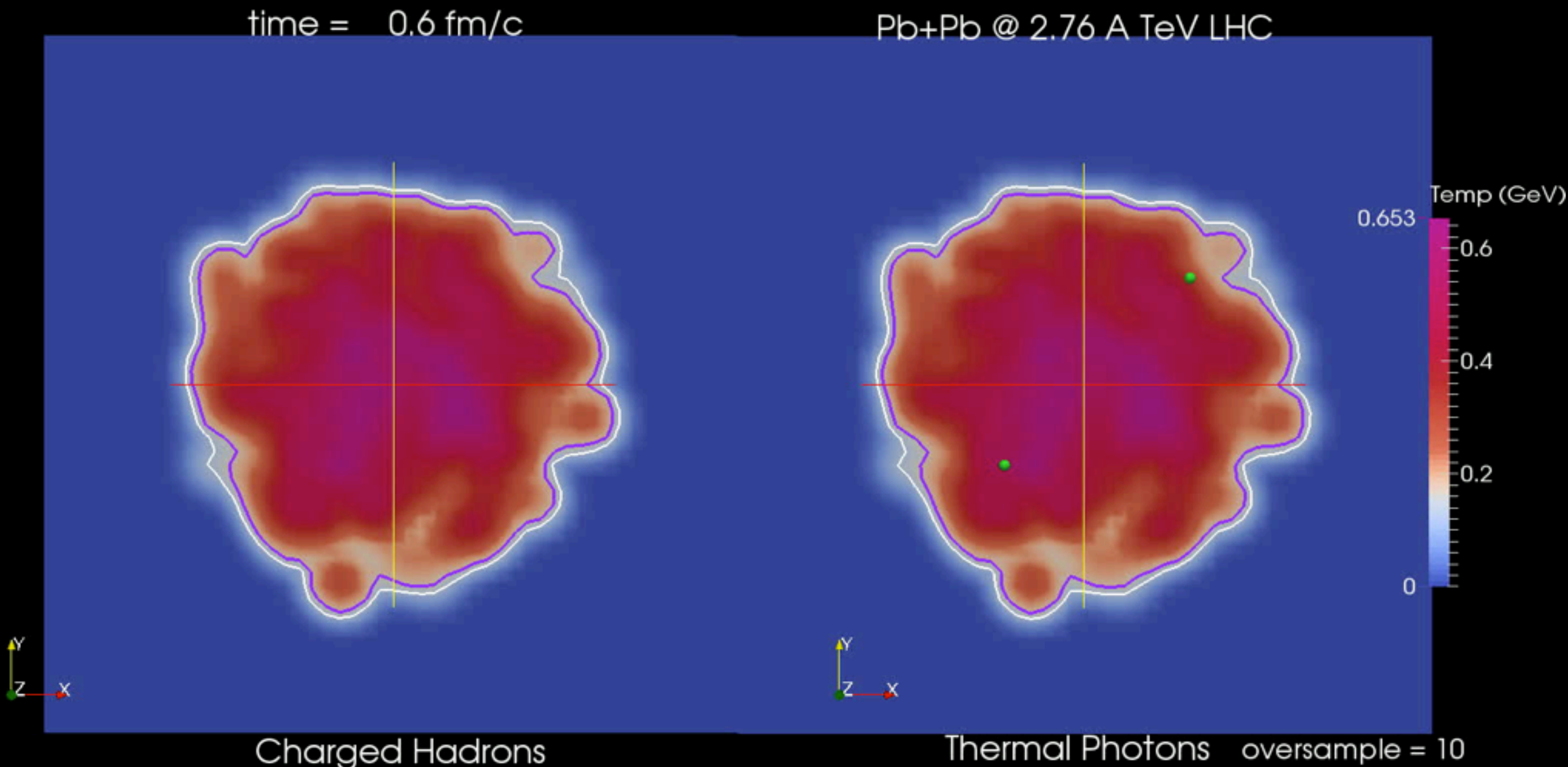
Mar. 7, 2014 Critical Mass Meeting, Toledo

Little Bang



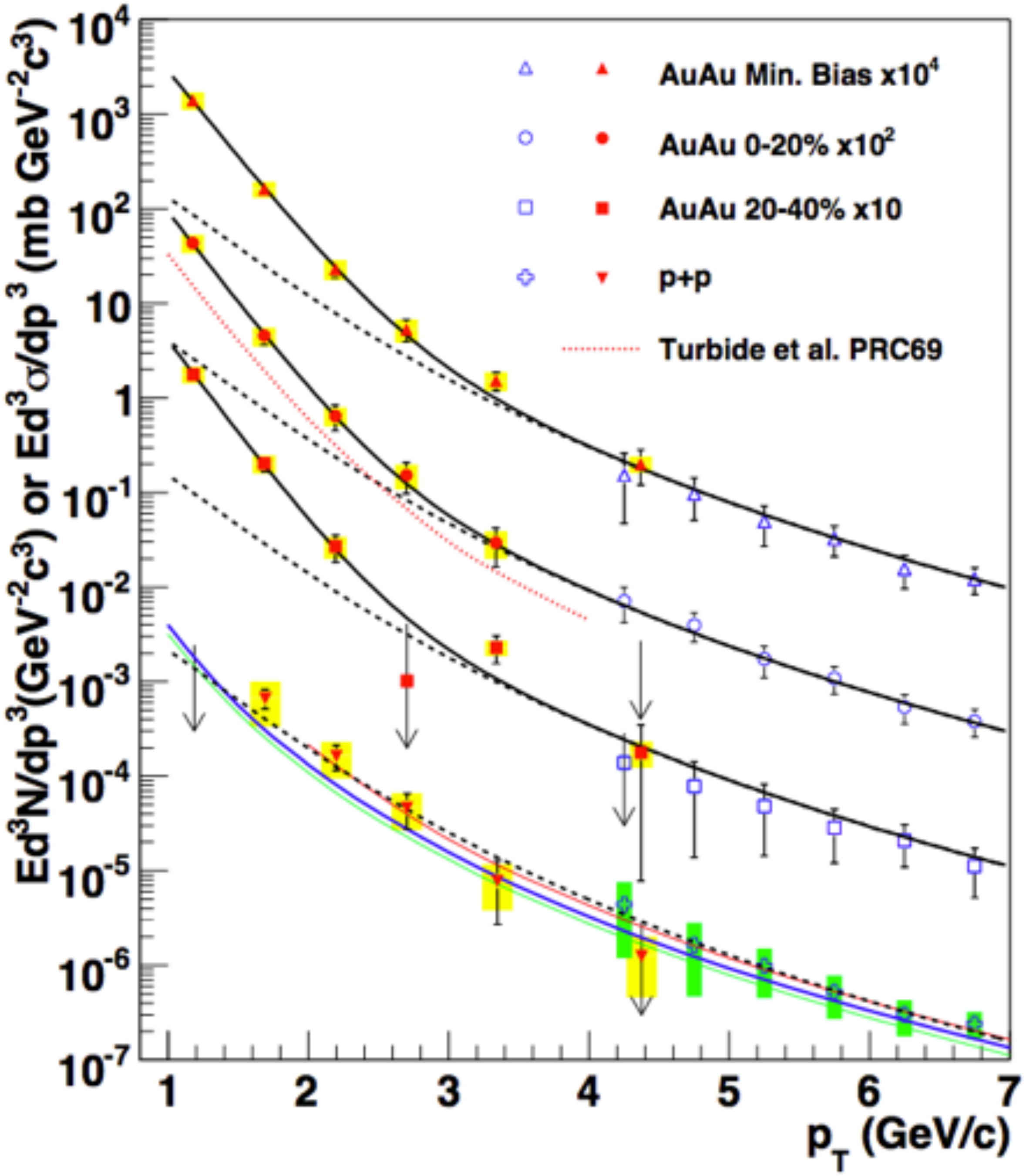
Relativistic Heavy-Ion Collisions
final detected
particles distributions
Kinetic
freeze-out
Hadronization
Initial energy
density
π
K
p
Hadron
gas
phase
QGP phase
γ
e+
e-
collision
overlap zone
pre-
equilibrium
dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

Photons from Heavy-ion Collisions



Fitted T_{eff} from Experiments

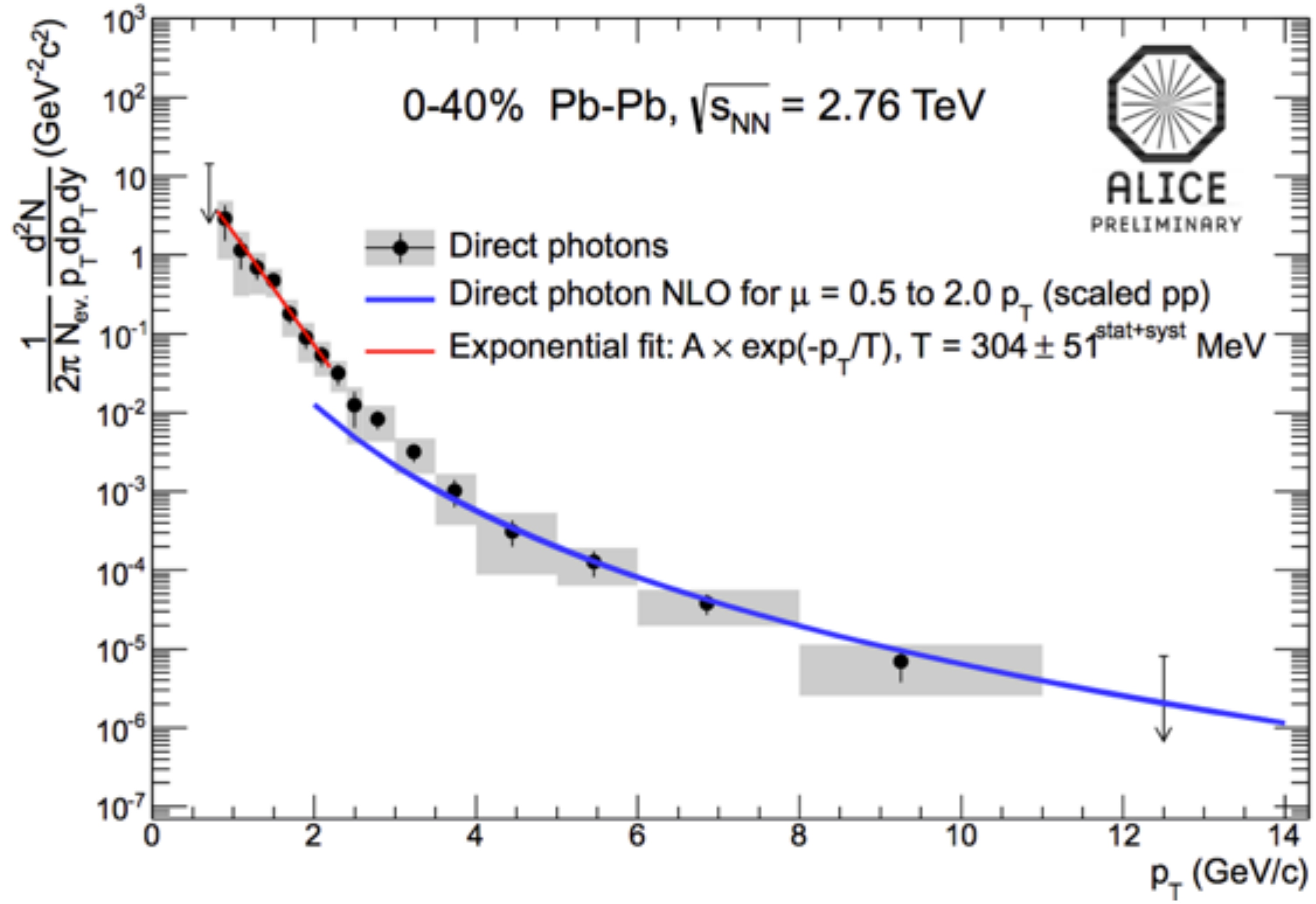
RHIC



$0 - 20\%$

$T = 221 \pm 19 \pm 19\,\mathrm{MeV}$

LHC



fit: $A\exp(-p_T/T)$

$T = 304 \pm 51^{\mathrm{stat+sys}}\,\mathrm{MeV}$

What does this T mean

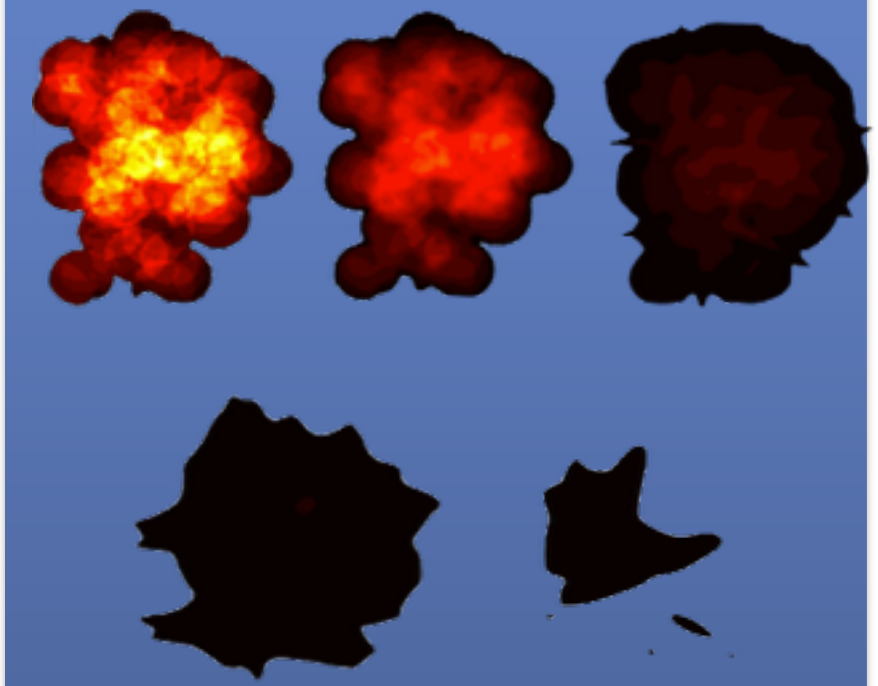
State-of-the-art hydrodynamic modeling

Initial Condition Generators (MC-KLN, MC-Glauber)

https://github.com/chunshen1987/iEBE.git

Thermal Photon Emission Rates

Hydrodynamic Simulations (VISH2+1)



HydroInfo Package

$$e, s, p, T,$$

$$u^\mu, \pi^{\mu\nu}$$

Thermal Photon Interface

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}q_\mu q_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

$$E\frac{dN^\gamma}{d^3p} = \int d^4x q \frac{dR}{d^3q}$$

Hadrons spectra & v_n

Photon spectrum & v_n

State-of-the-art hydrodynamic modeling

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Thermal Photon Emission Rates

viscous corrections

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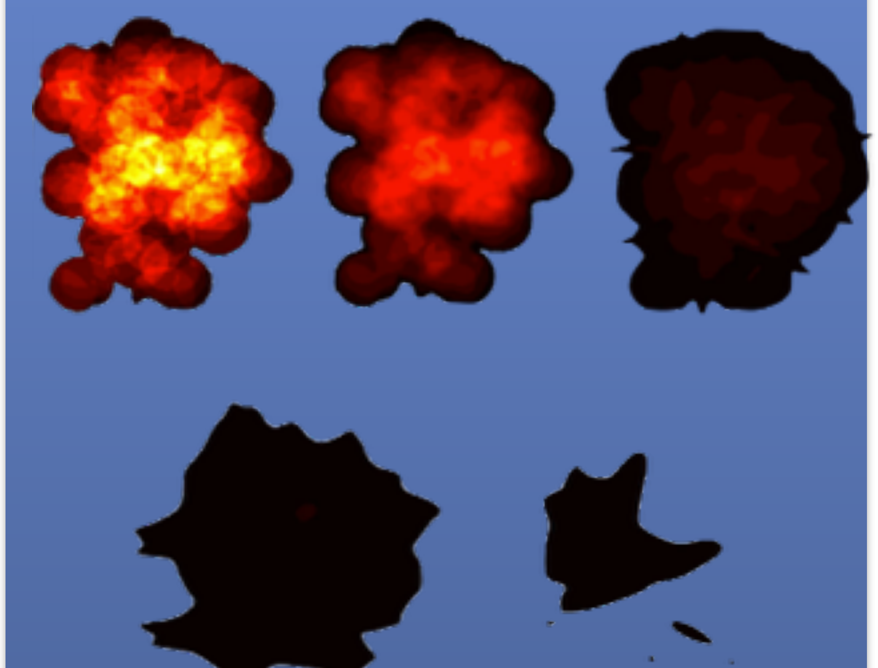

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viscous corrections

Hadrons spectra & v_n

Photon spectrum & v_n

Viscous Photon Emission Rates: General Formalism

Thermal photon emission rates can be calculated by

$$E_q \frac{dR}{d^3q} = \int \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_3}{2E_3(2\pi)^3} \frac{1}{2(2\pi)^3} |\mathcal{M}|^2$$

$$\times f_1(p_1^\mu) f_2(p_2^\mu)(1 \pm f_3(p_3^\mu))(2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - q)$$

With

$$f(p^\mu) = f_0(E) + f_0(E)(1 \pm f_0(E)) \frac{\pi^{\mu\nu} \hat{p}_\mu \hat{p}_\nu}{2(e+p)} \chi\left(\frac{p}{T}\right)$$

We can expand photon emission rates around the thermal equilibrium:

$$\boxed{q \frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu} \hat{q}_\mu \hat{q}_\nu}{2(e+p)} a_{\alpha\beta} \Gamma^{\alpha\beta},}$$

$$a_{\mu\nu} = \frac{3}{2(u\cdot\hat{q})^4} \hat{q}_\mu \hat{q}_\nu + \frac{1}{(u\cdot\hat{q})^2} u_\mu u_\nu + \frac{1}{2(u\cdot\hat{q})^2} g_{\mu\nu} - \frac{3}{2(u\cdot\hat{q})^3} (\hat{q}_\mu u_\nu + \hat{q}_\nu u_\mu).$$

Viscous Photon Emission Rates: General Formalism

Thermal photon emission rates can be calculated by

$$E_q \frac{dR}{d^3q} = \int \frac{d^3p_1}{2E_1(2\pi)^3}\frac{d^3p_2}{2E_2(2\pi)^3}\frac{d^3p_3}{2E_3(2\pi)^3}\frac{1}{2(2\pi)^3}|\mathcal{M}|^2$$

$$\times f_1(p_1^\mu) f_2(p_2^\mu)(1 \pm f_3(p_3^\mu))(2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - q)$$

With

$$f(p^\mu) = \ldots \frac{\pi^{\mu\nu}\hat{p}_\mu\hat{p}_\nu}{\ldots)} \chi\left(\frac{p}{T}\right)$$

$\Gamma_0(q,T) \quad a_{\alpha\beta}\Gamma^{\alpha\beta}(q,T)$

calculated in fluid local rest frame

We can exp… …und the thermal equilibrium:

$$\boxed{q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta},}$$

calculated in lab frame

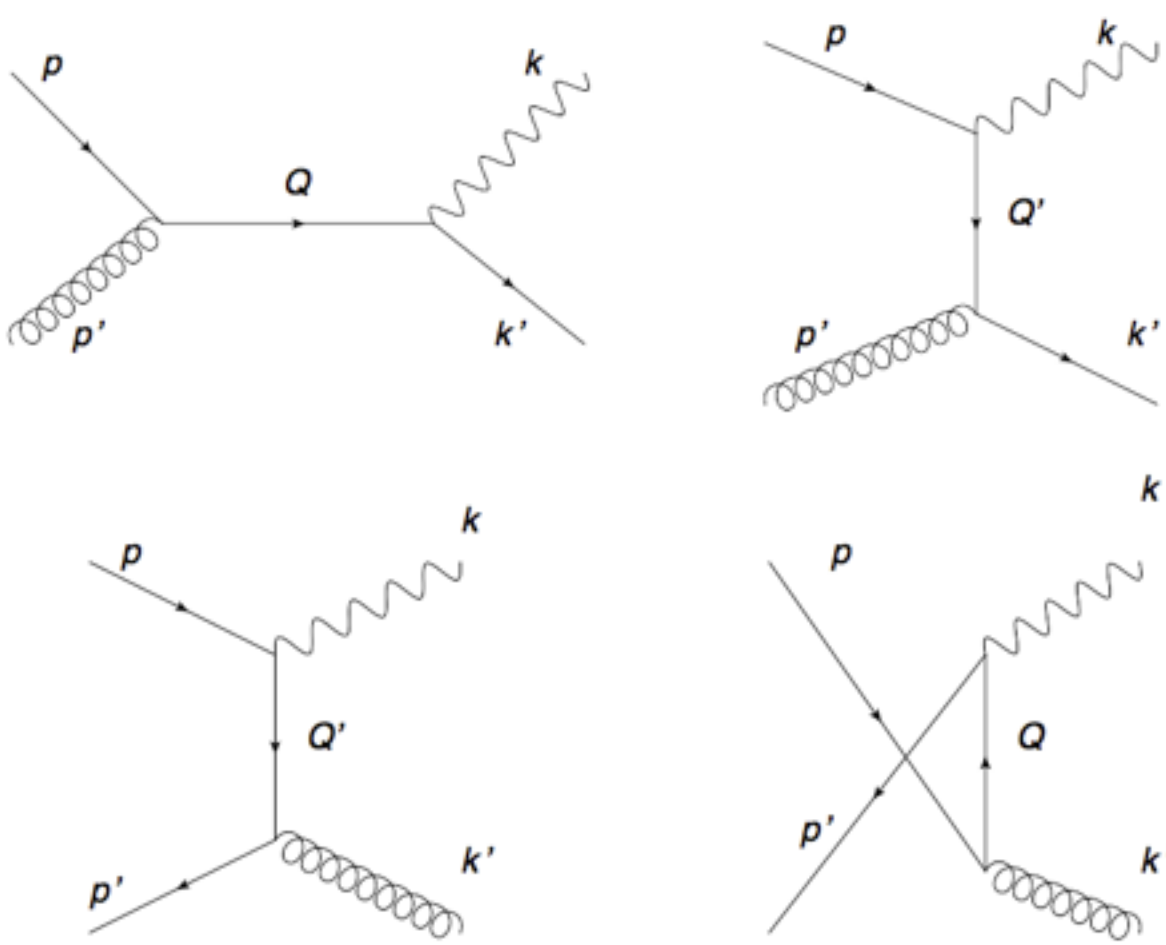
$$a_{\mu\nu} = \frac{3}{2(u\cdot\hat{q})^4}\hat{q}_\mu\hat{q}_\nu + \frac{1}{(u\cdot\hat{q})^2}u_\mu u_\nu + \frac{\ldots}{2(u\cdot\hat{q})^2} \ldots \mu).$$

Viscous Photon Emission Rates: General Formalism

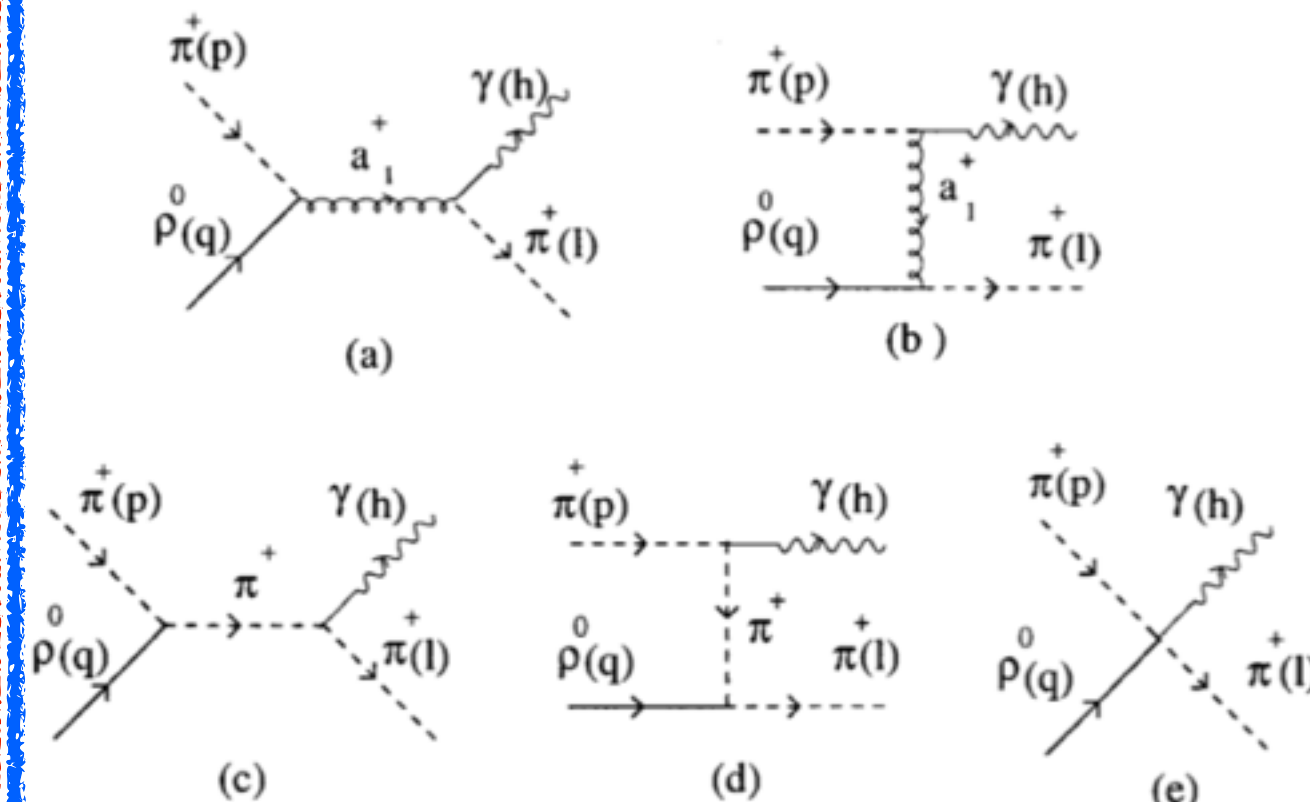
$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)}a_{\alpha\beta}\Gamma^{\alpha\beta}$$

Equilibrium rates

QGP



Hadron Gas



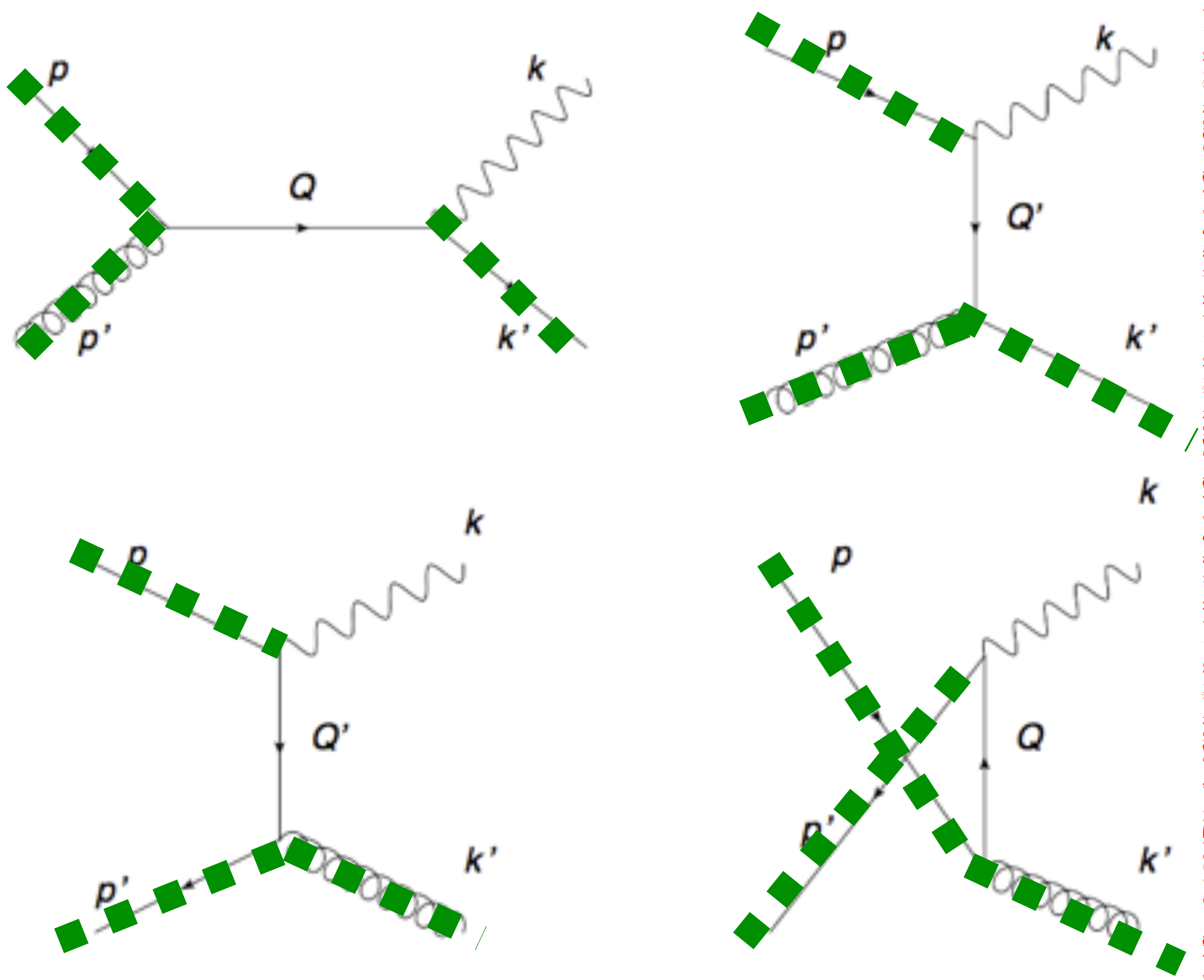
Viscous Photon Emission Rates: General Formalism

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

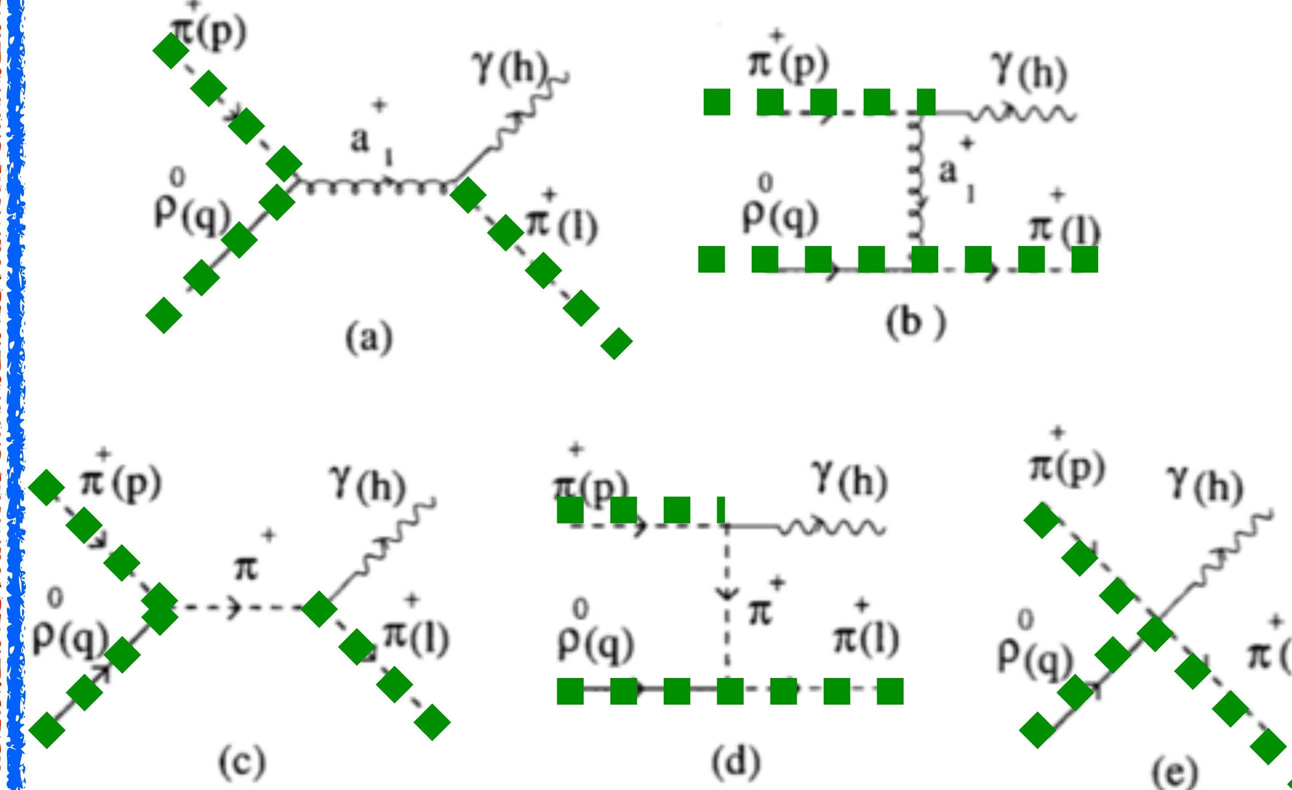
Equilibrium rates

off-equilibrium δf corrections

QGP



Hadron Gas



Viscous Photon Emission Rates: General Formalism

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

Equilibrium rates

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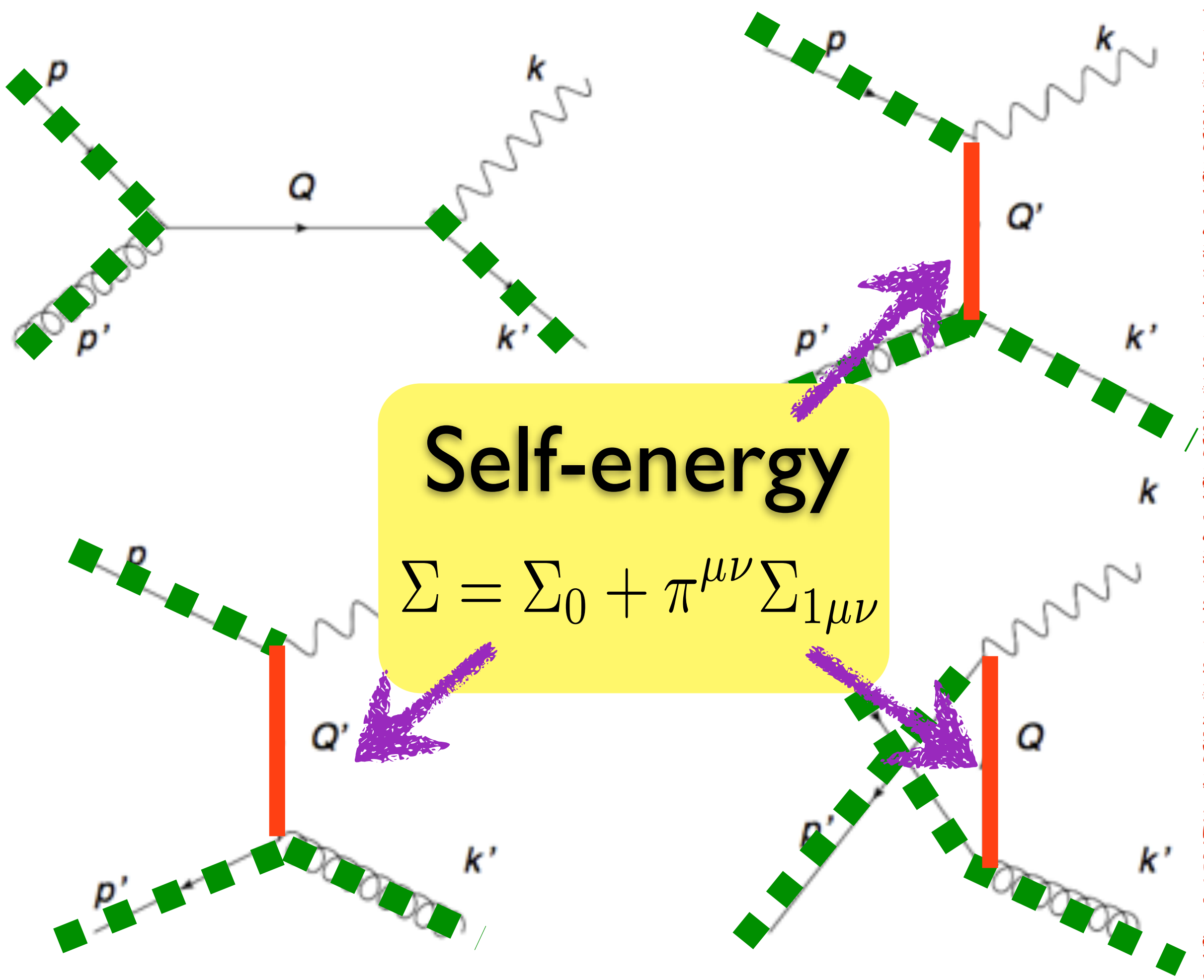
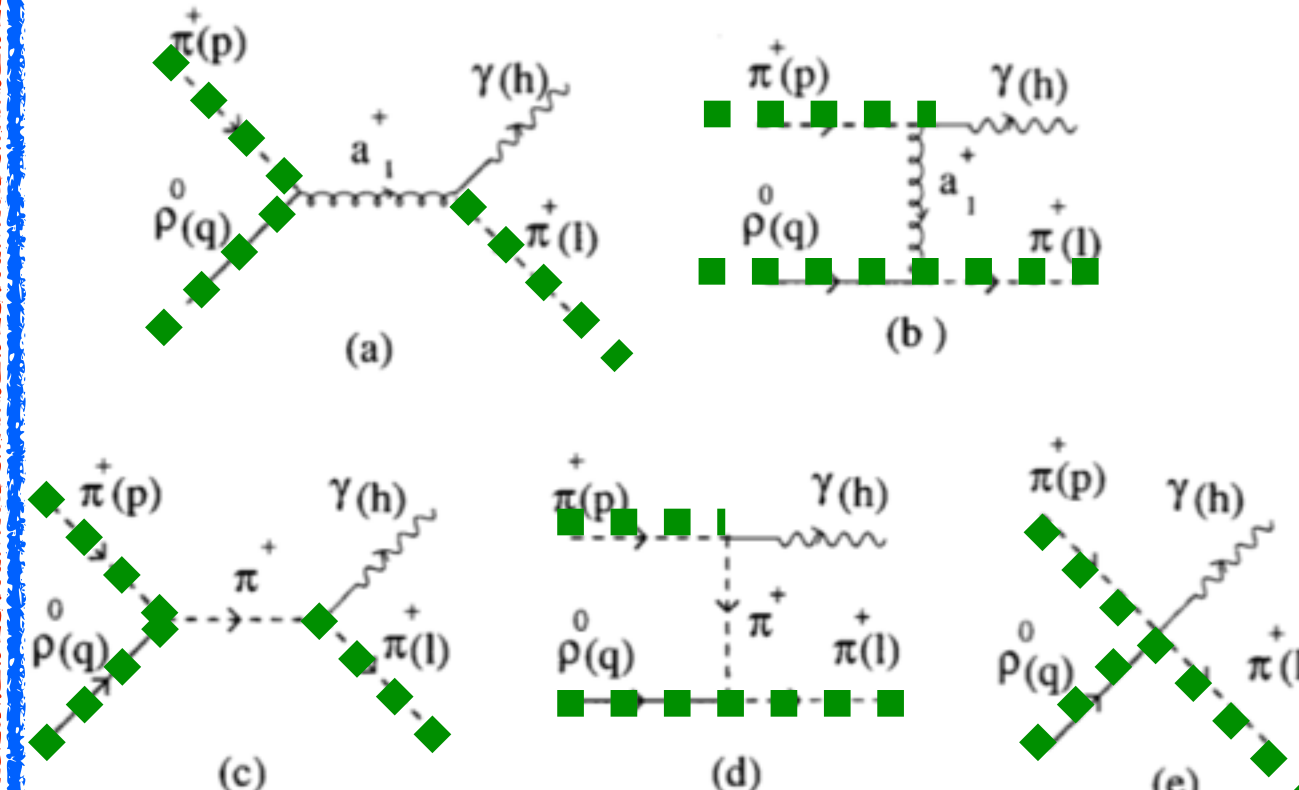


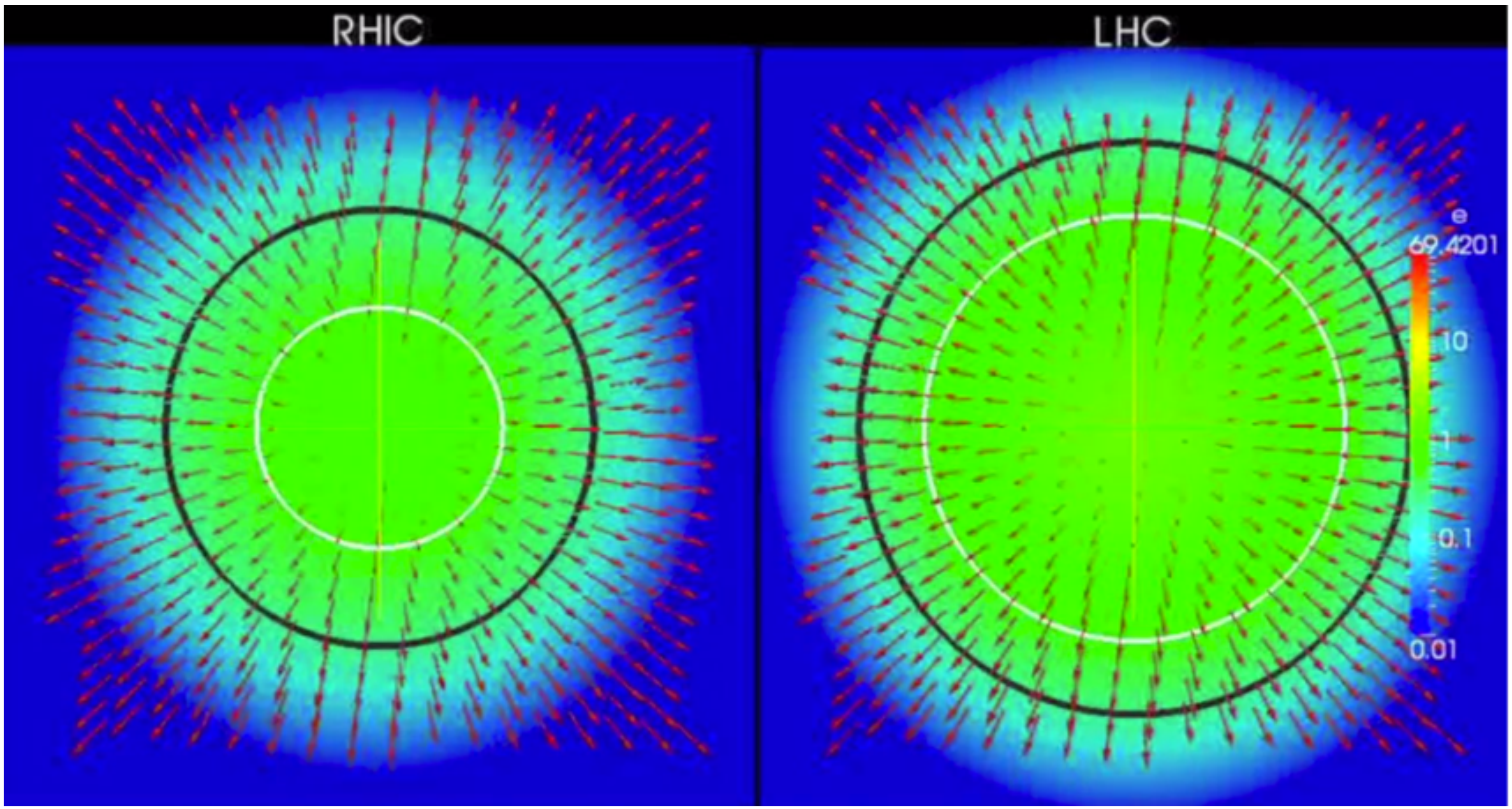
Self-energy

$$\Sigma = \Sigma_0 + \pi^{\mu\nu}\Sigma_{1\mu\nu}$$

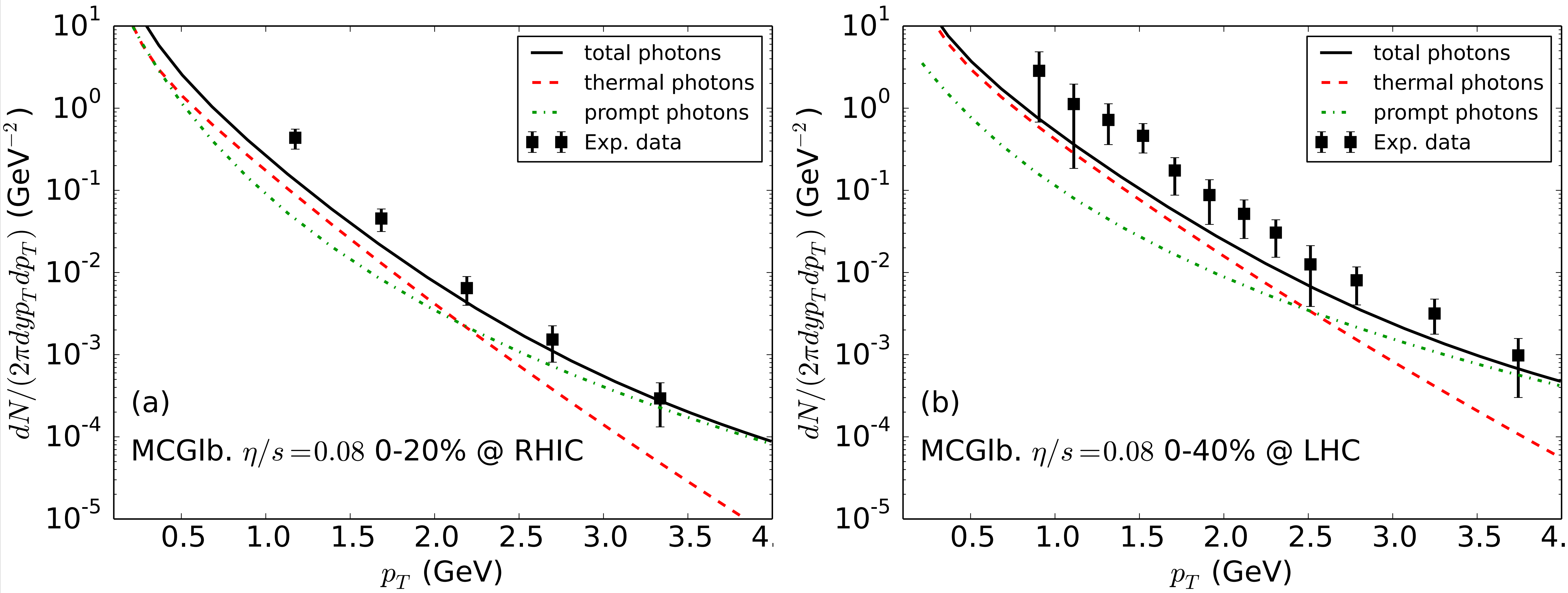
Hadron Gas



Photon spectra and radial flow

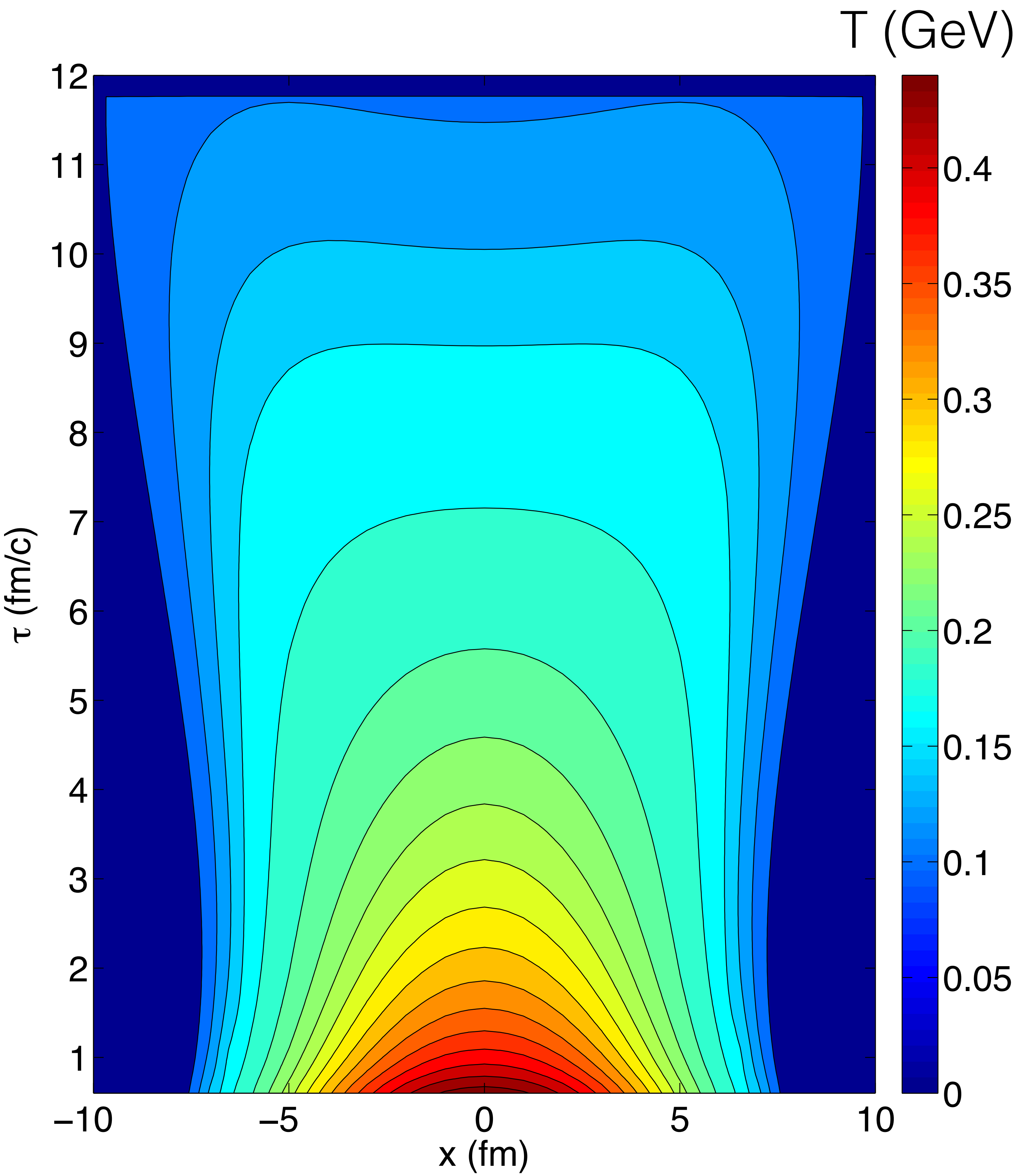


Thermal Photon Spectra

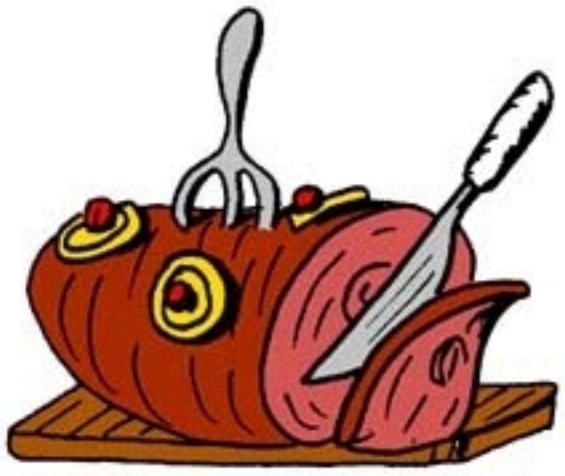


- With all available thermal emission sources, our current calculations still underestimate measured direct photon spectra at low p_T at both RHIC and LHC energies
- Additional emission sources need to be included to improve the agreement between theory and data

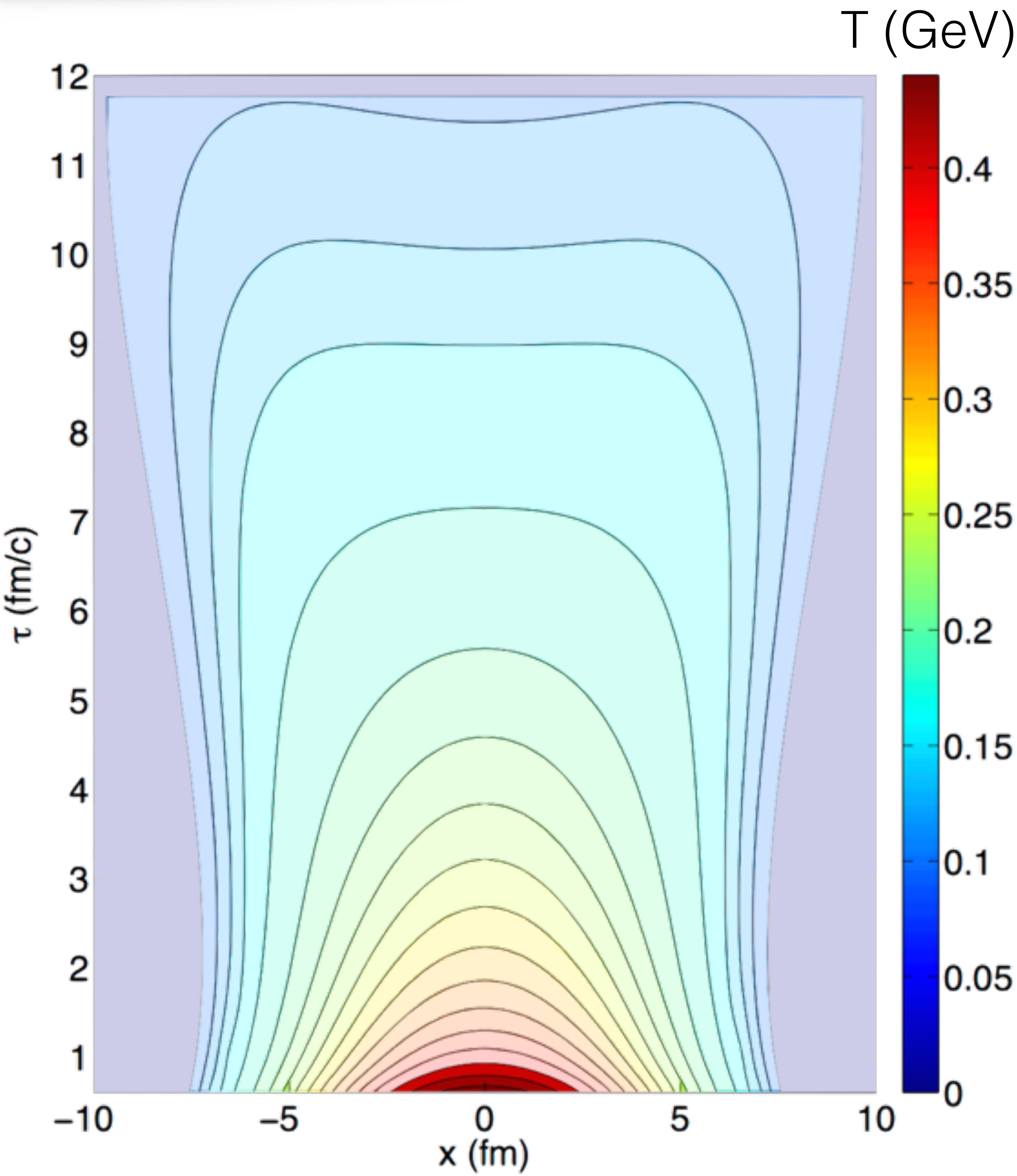
Slope of Photon Spectrum



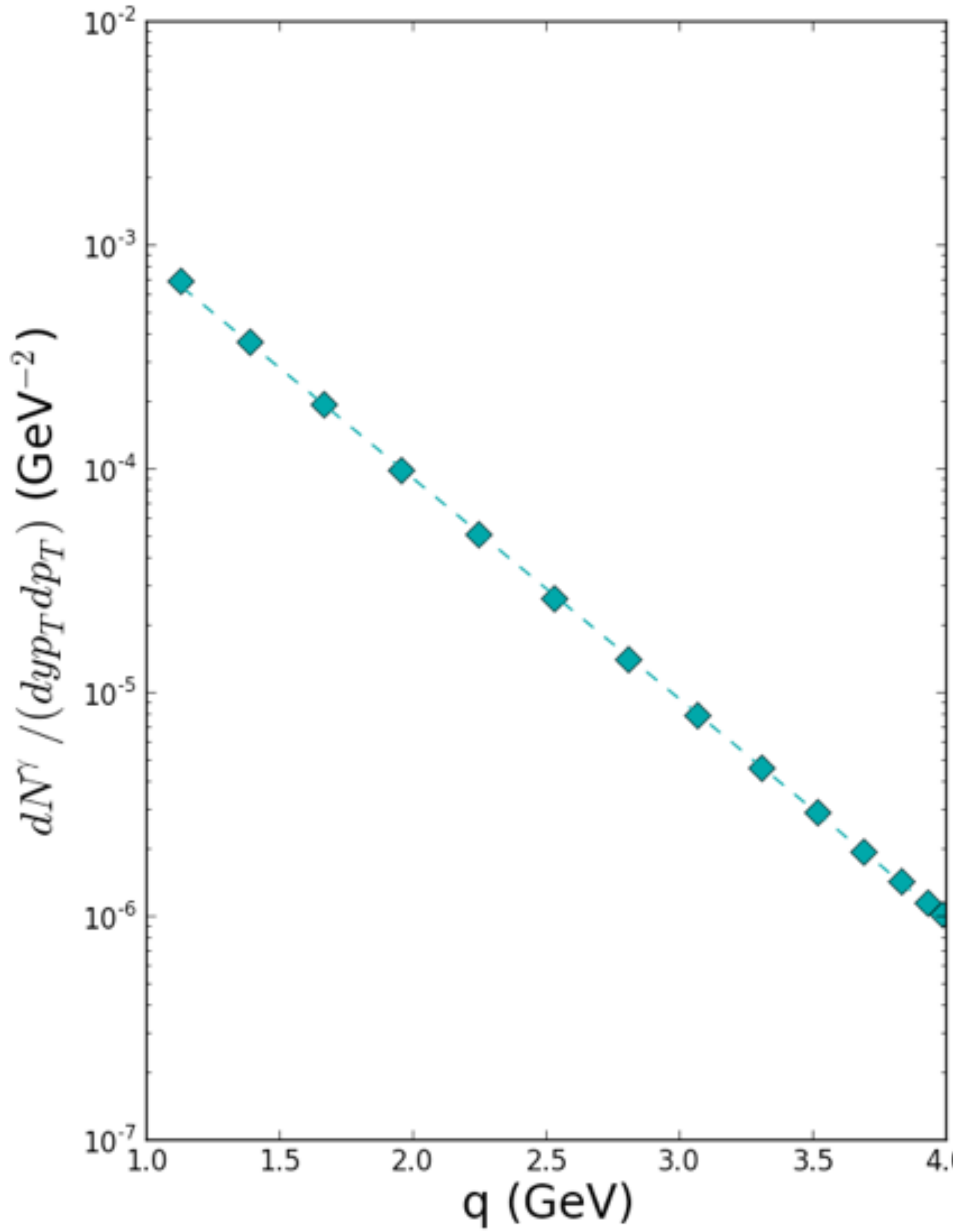
Slicing the hydrodynamic medium



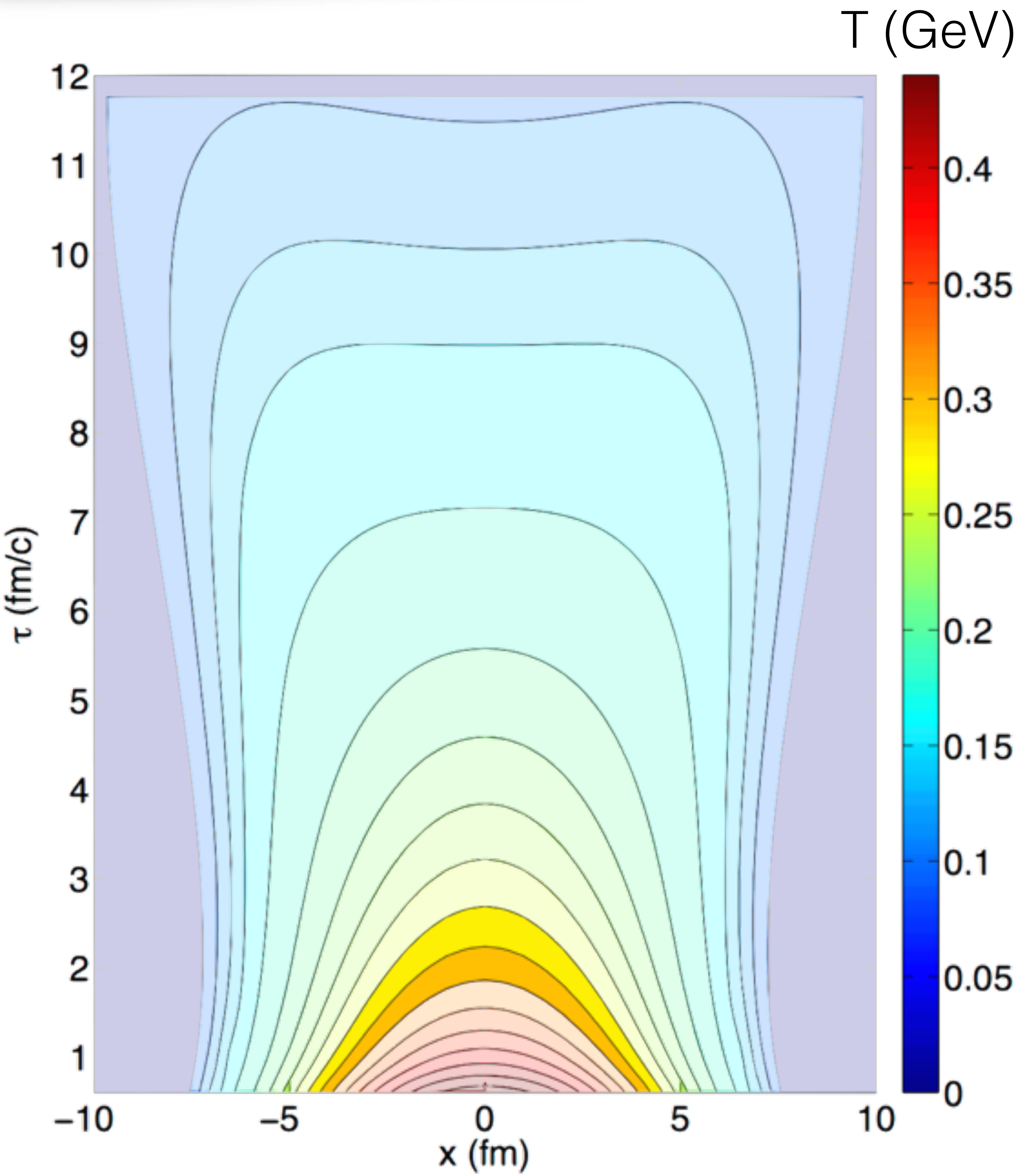
Slope of Photon Spectrum

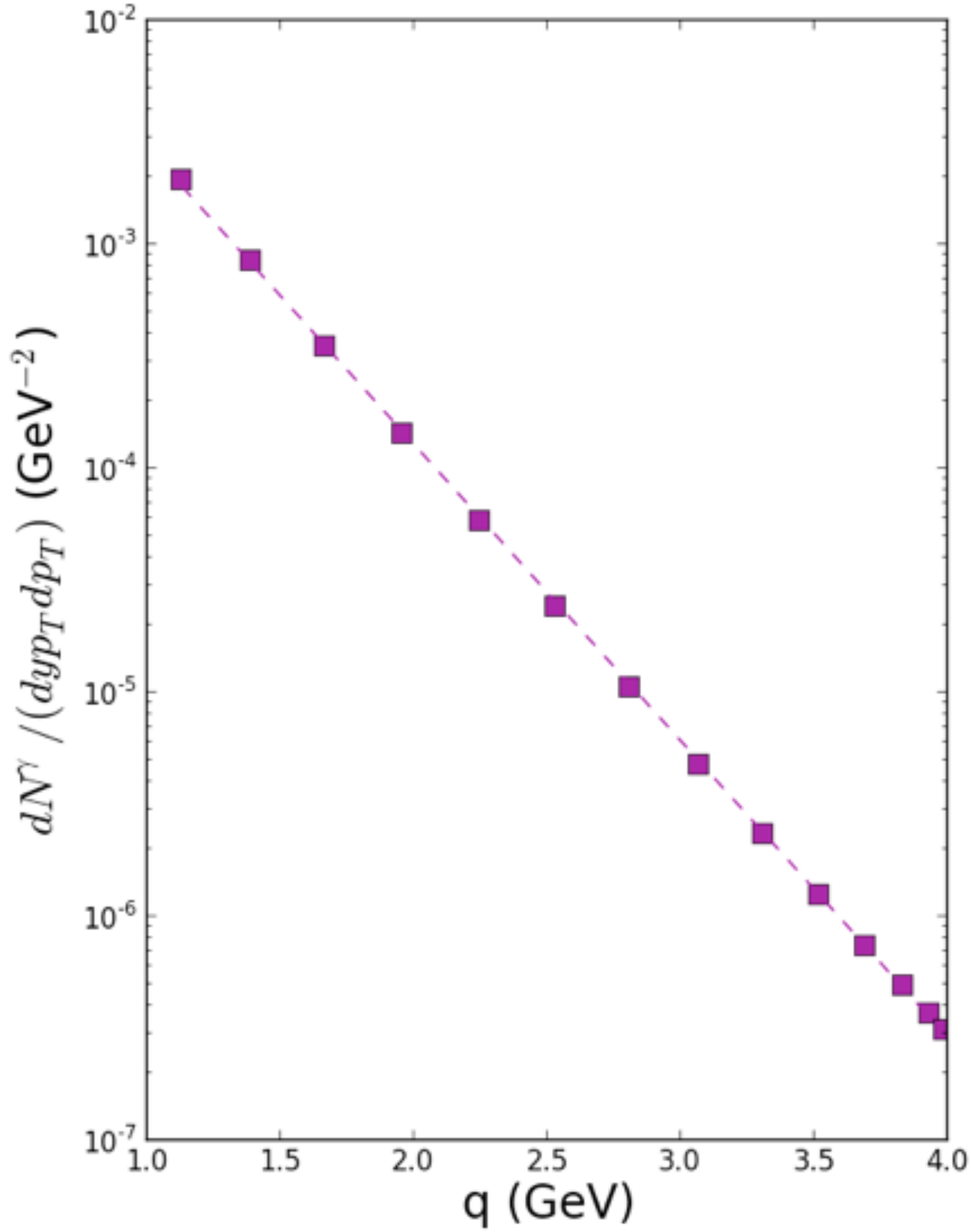


T = 400 MeV

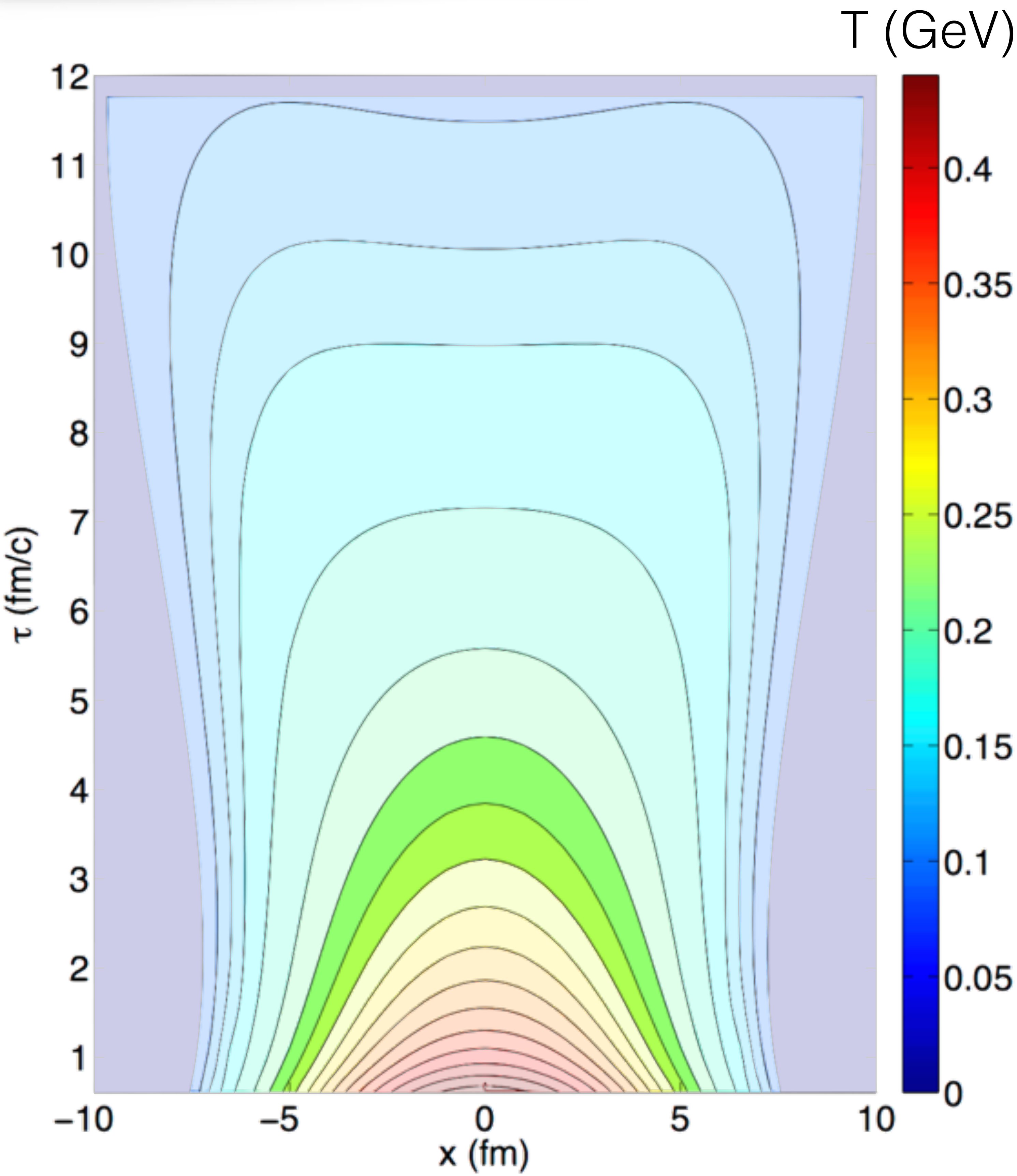


Slope of Photon Spectrum

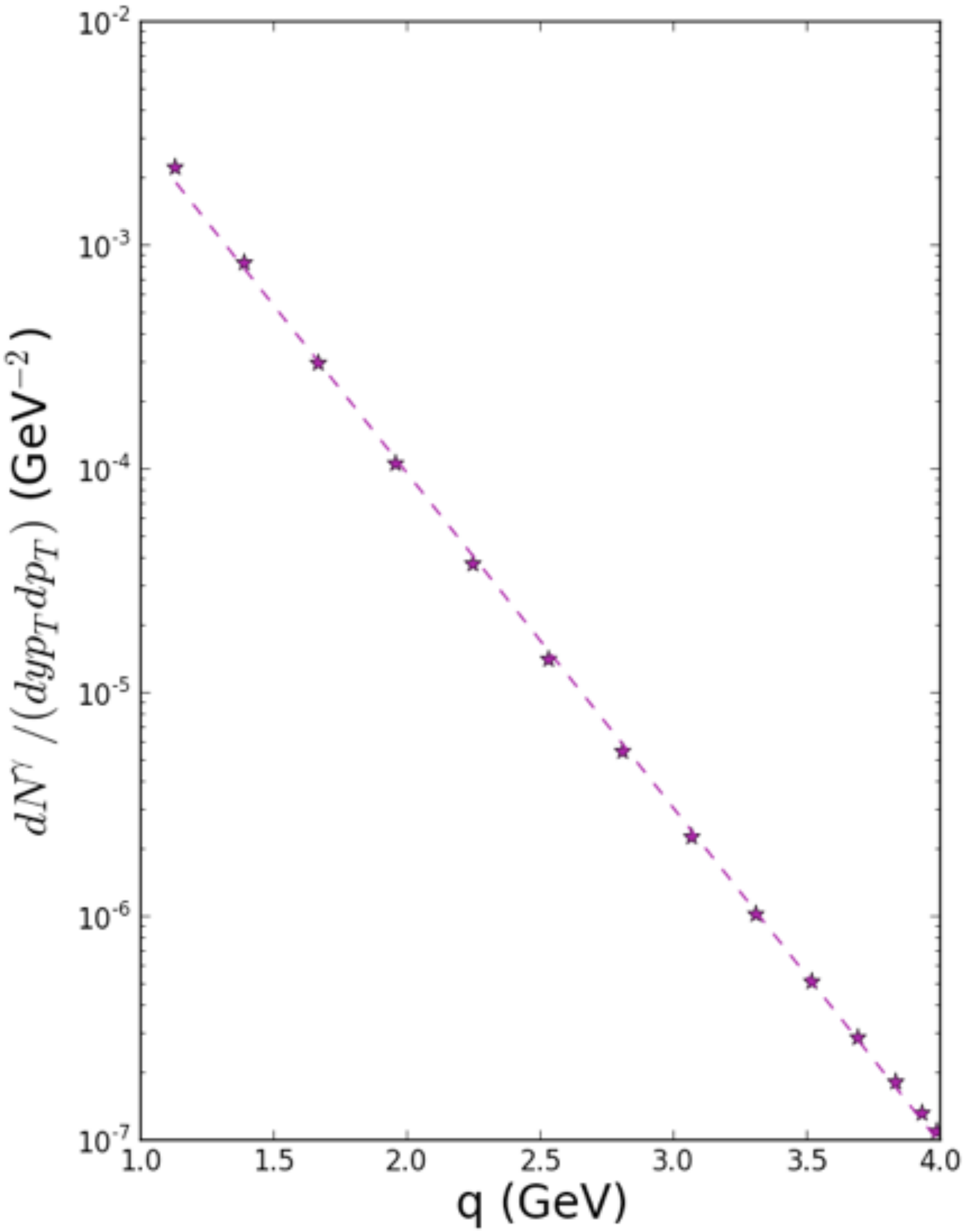




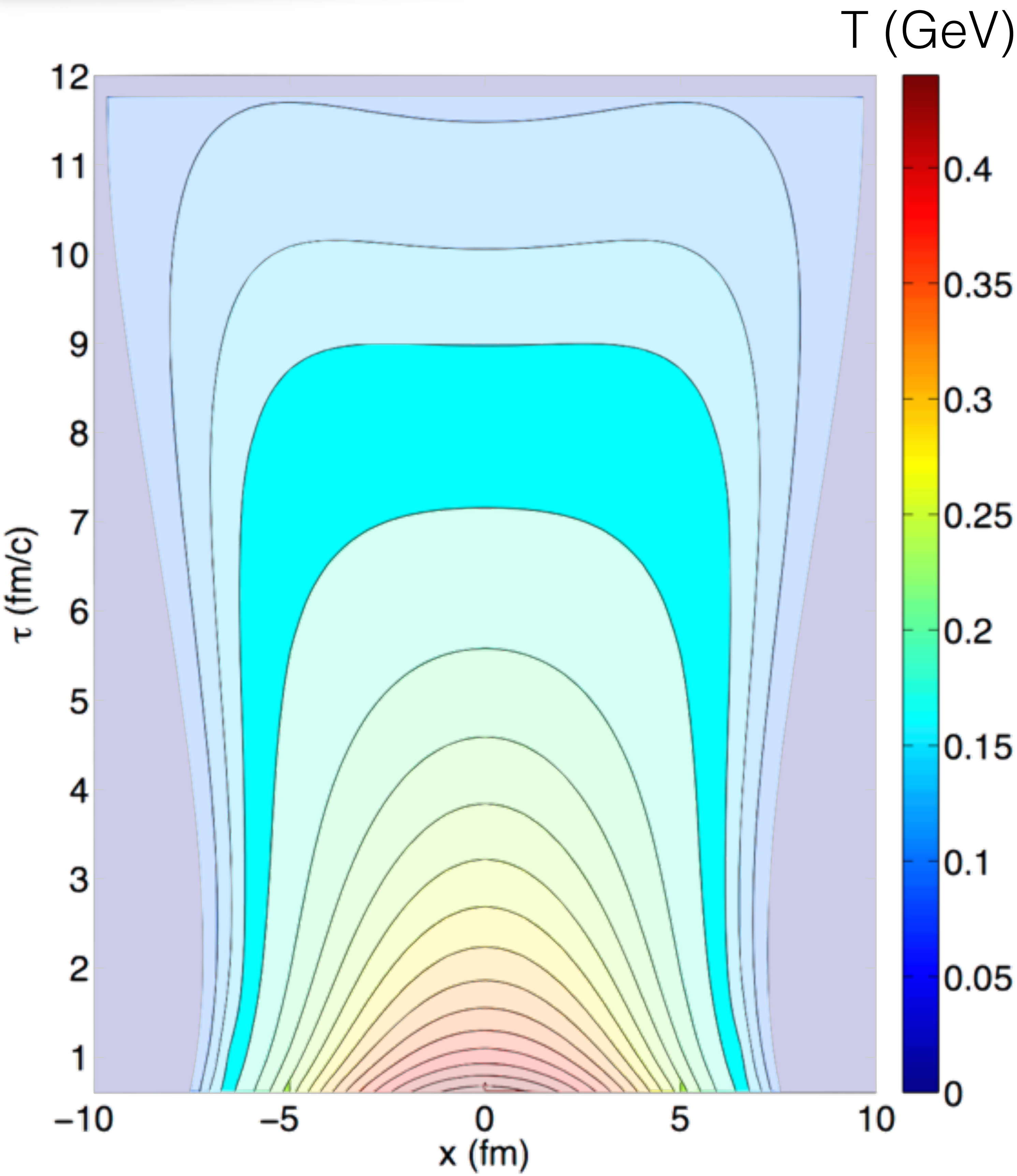
Slope of Photon Spectrum



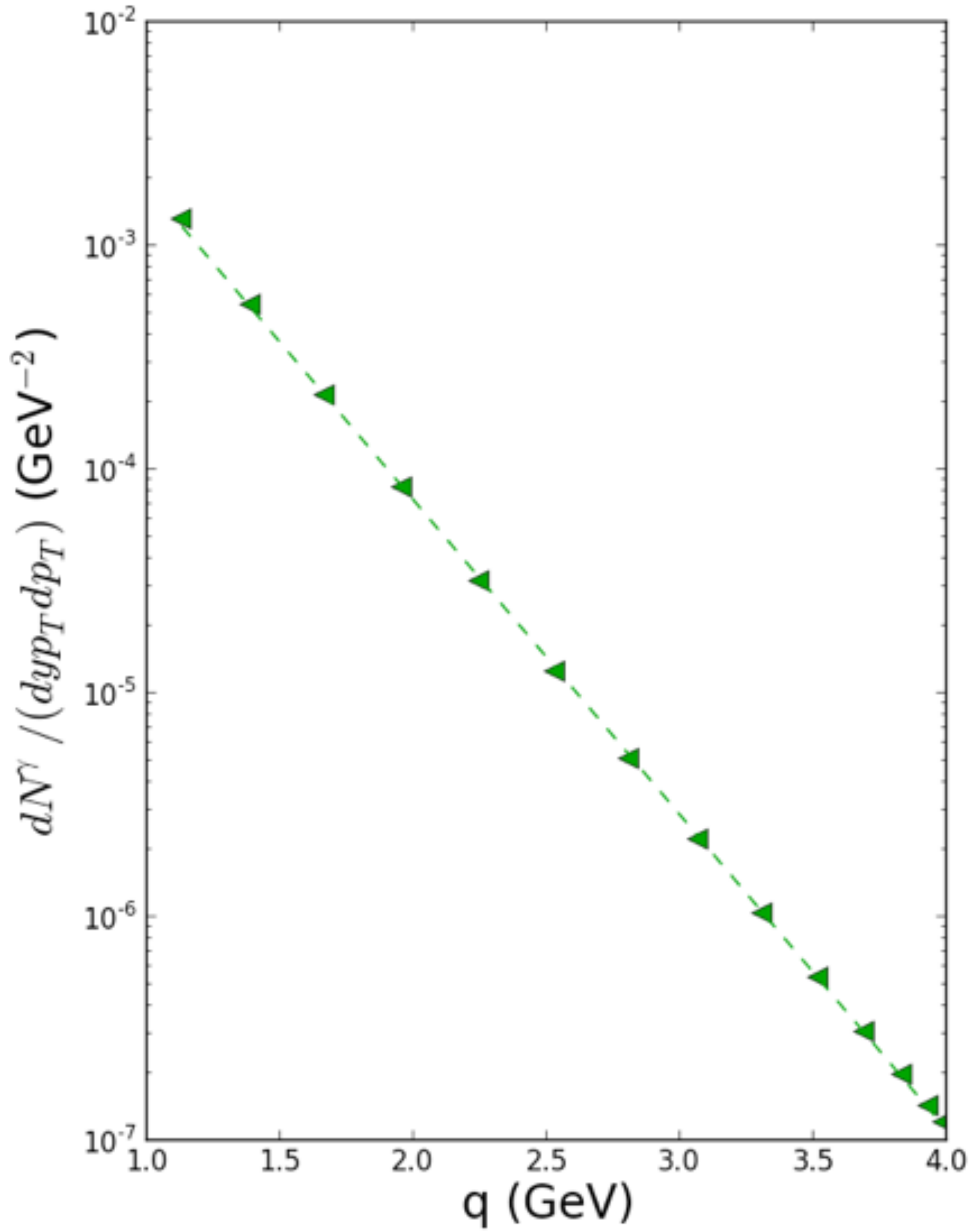
T = 230 MeV



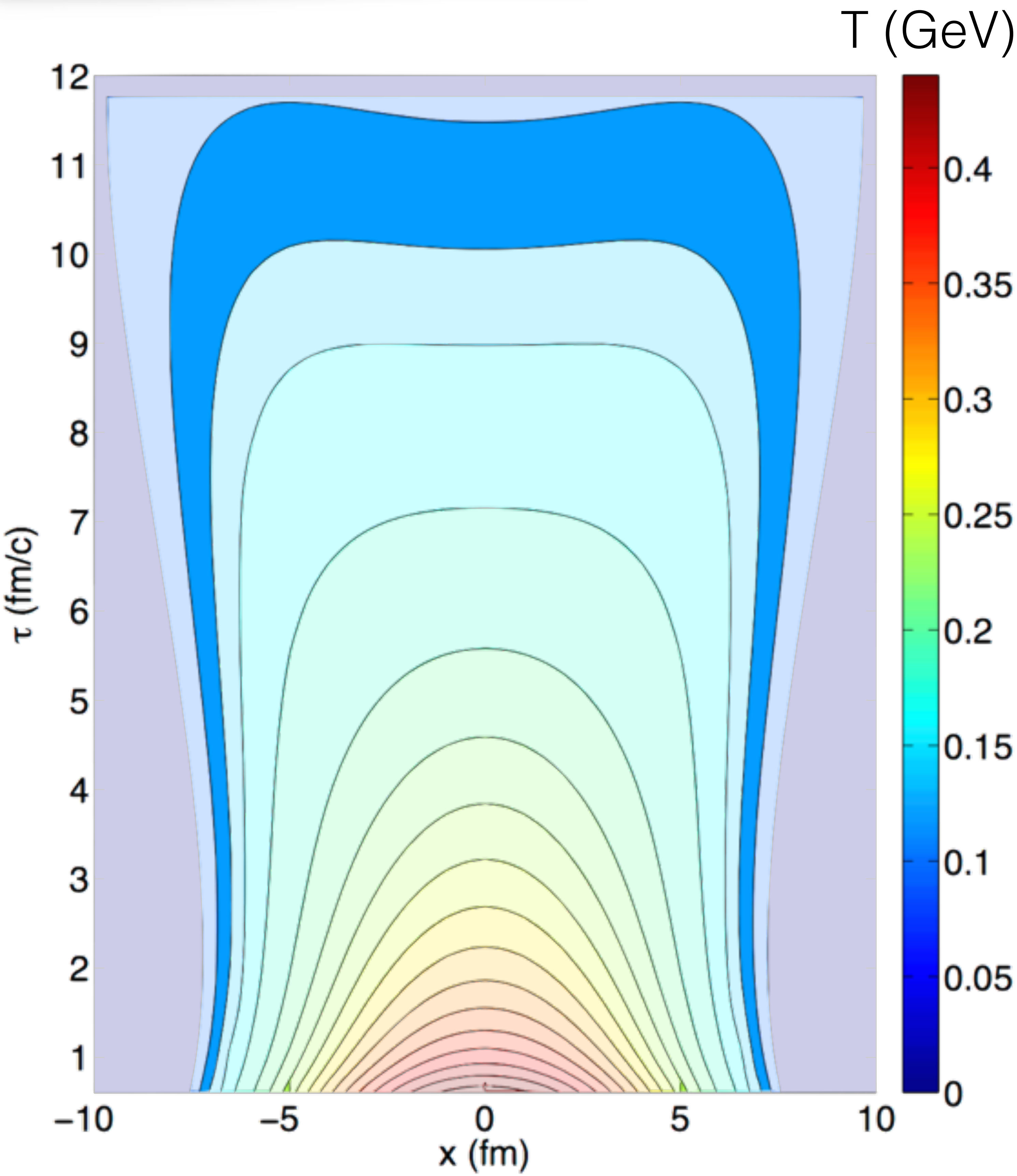
Slope of Photon Spectrum



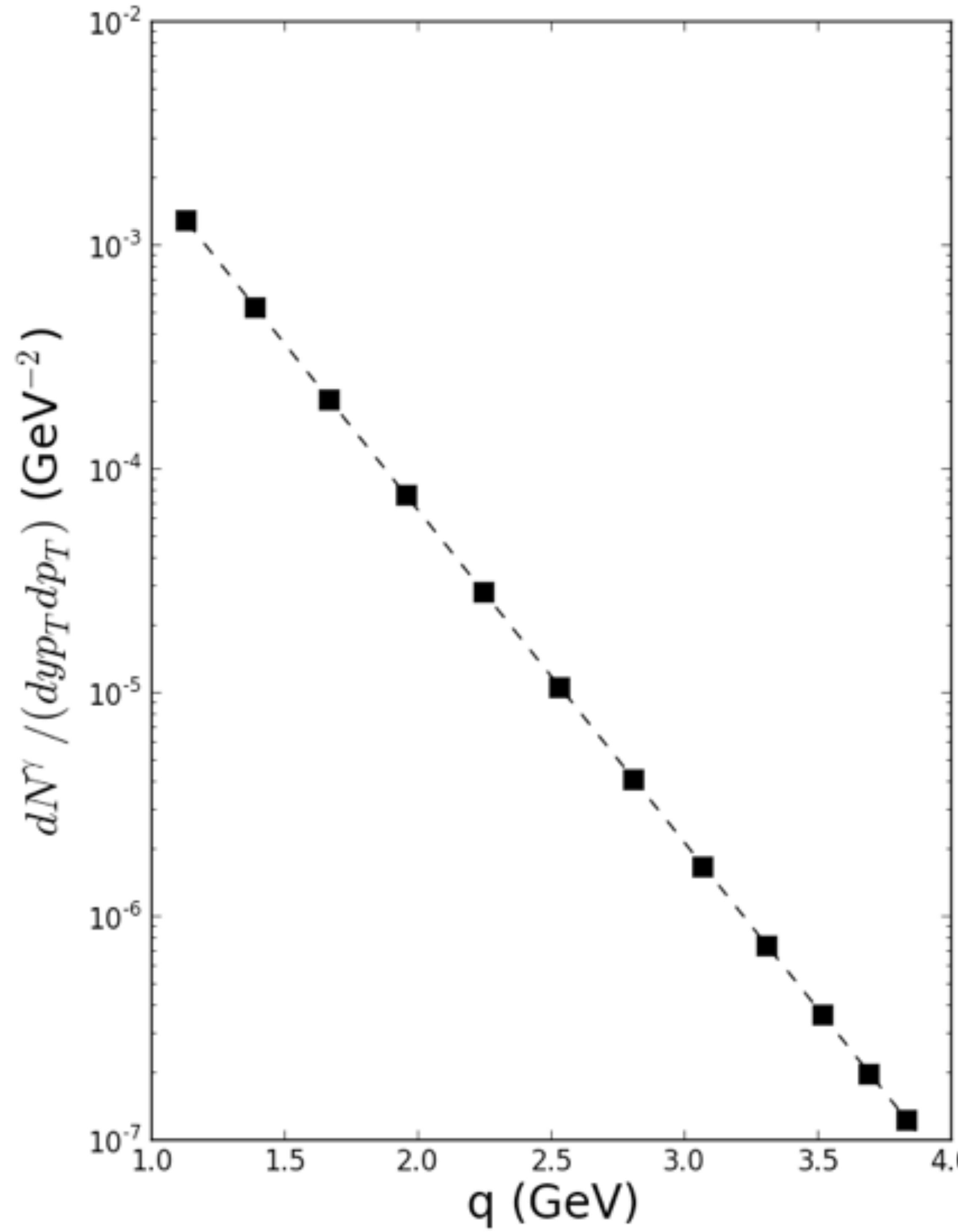
T = 160 MeV



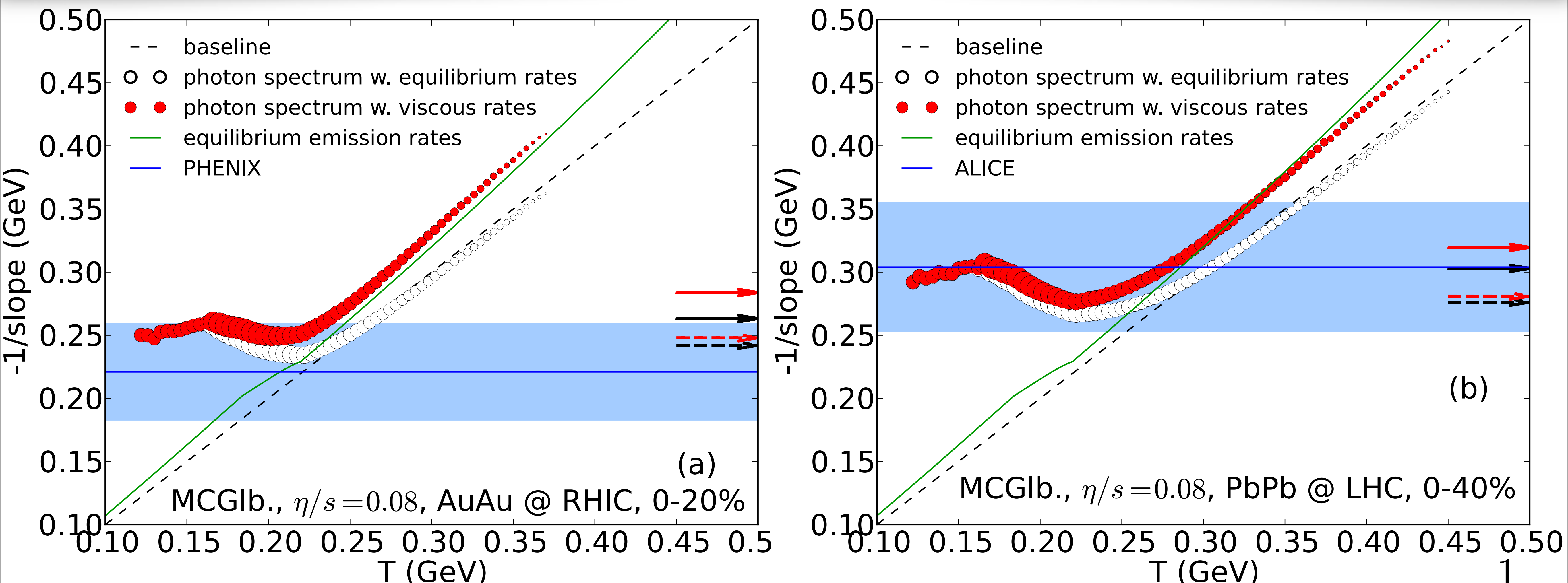
Slope of Photon Spectrum



T = 120 MeV



Fitted T_{eff} vs. True Temperature

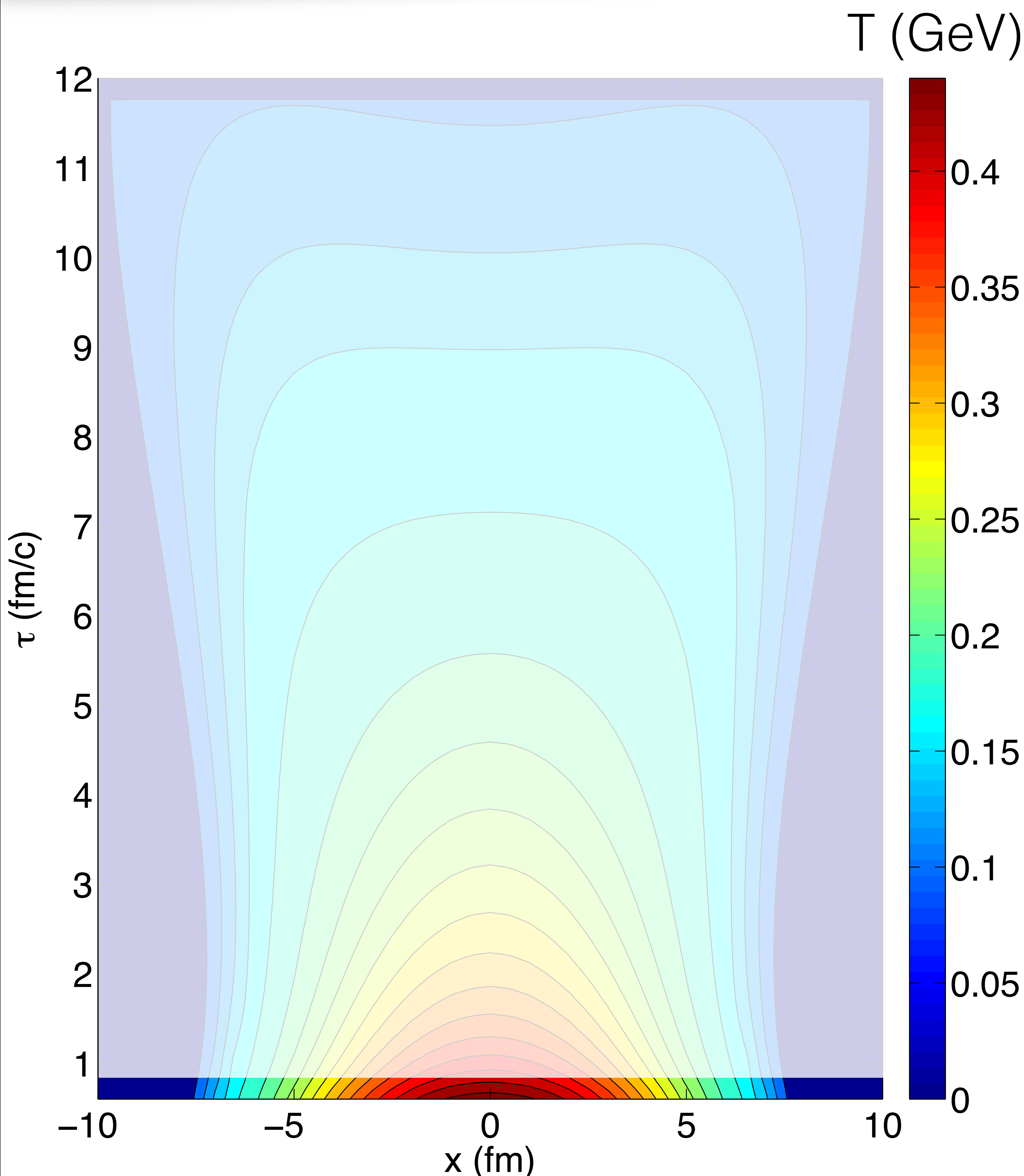


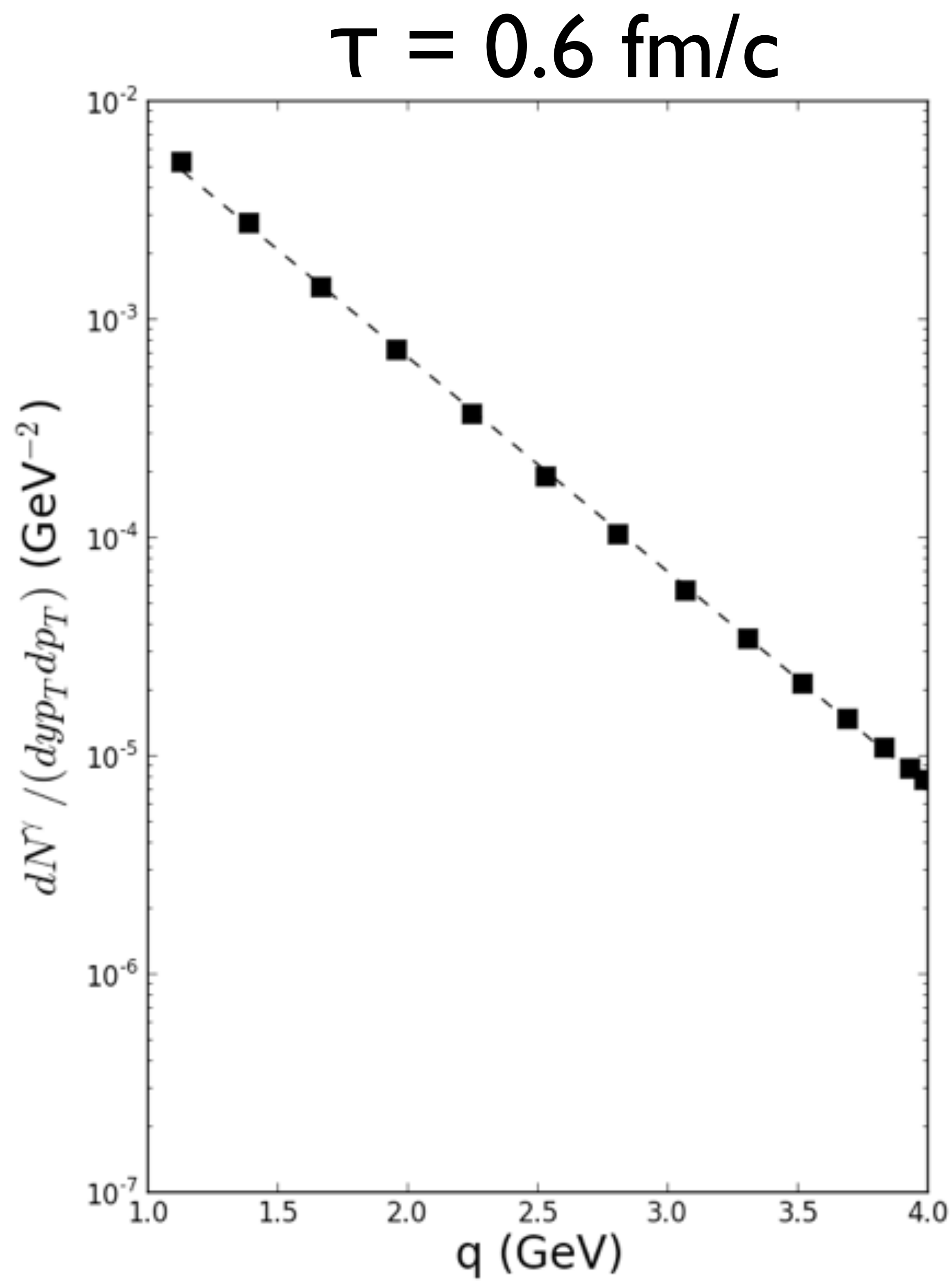
$$T_{\mathrm{eff}} = -\frac{1}{\mathrm{slope}}$$

- Photon emission rates $\propto \exp(-E/T)\log(E/T)$, $T_{\mathrm{eff}} > T$
- **All** photons with T < 250 MeV at RHIC and < 300 MeV at LHC carries T_{eff} within the experimental fitted region
- About **50-60%** of photons are emitted from T = 165~250 MeV, they are strongly blue shifted by radial flow

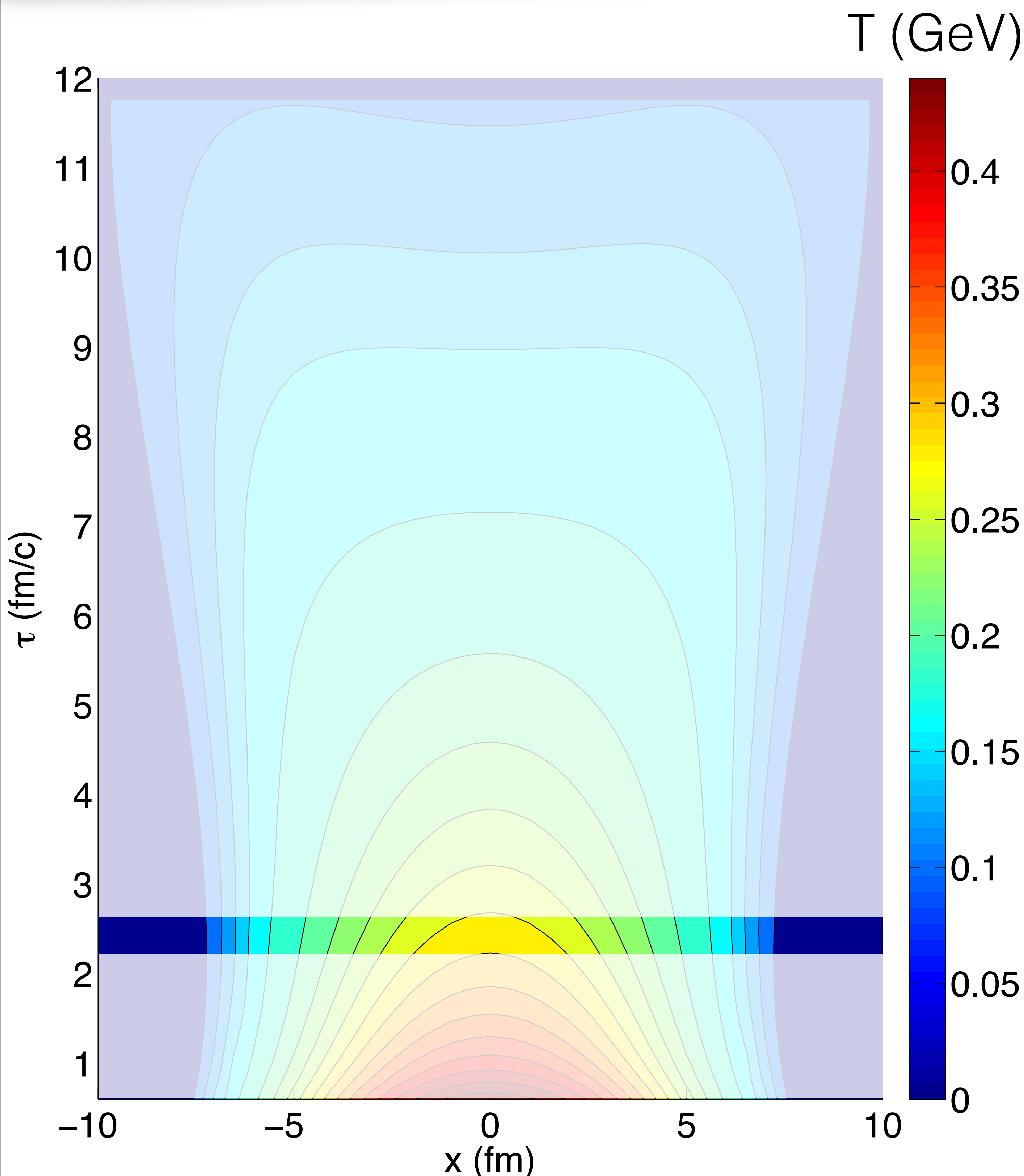
$$T_{\mathrm{eff}} = T\sqrt{\frac{1+v}{1-v}}$$

Slope of Photon Spectrum

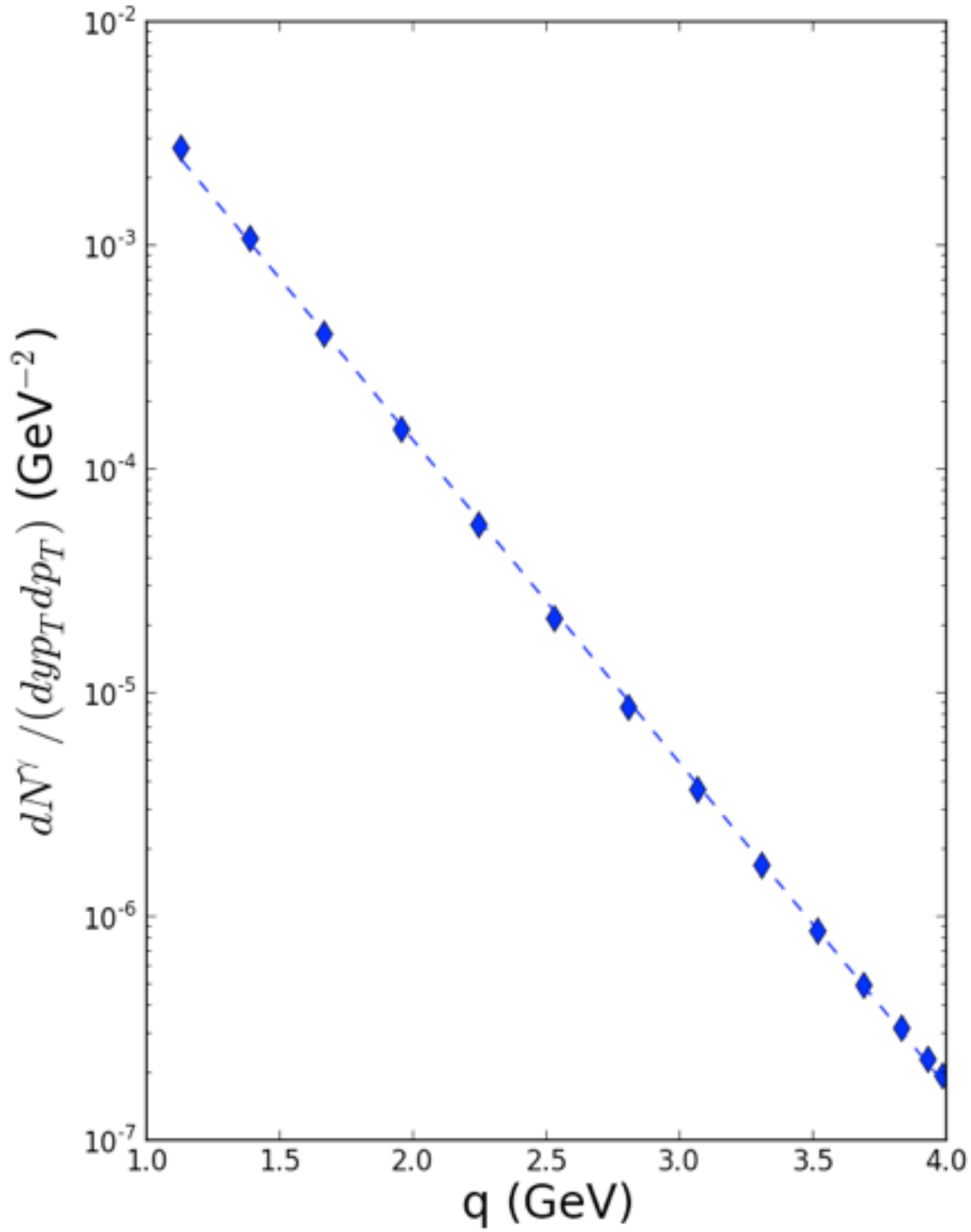




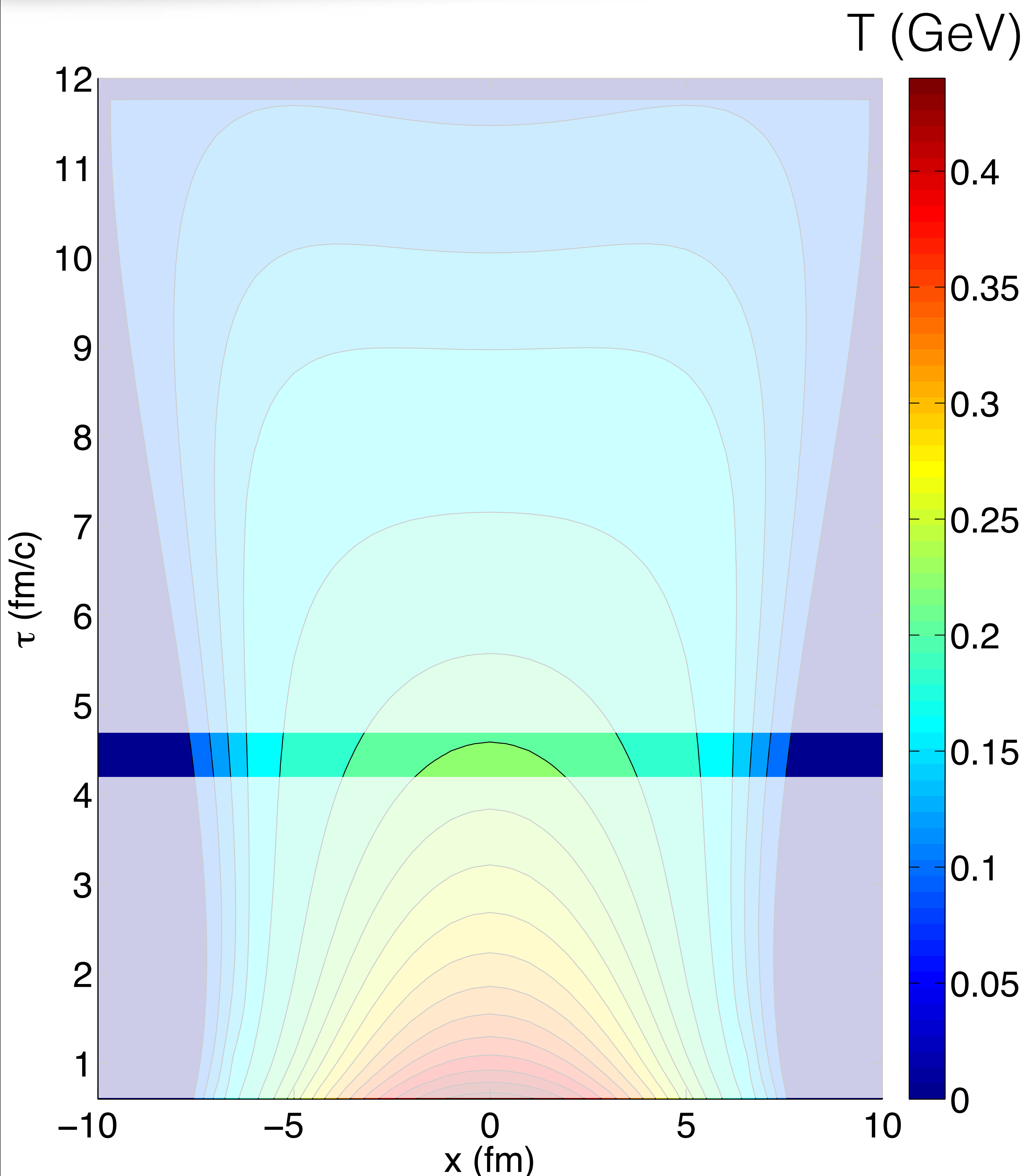
Slope of Photon Spectrum



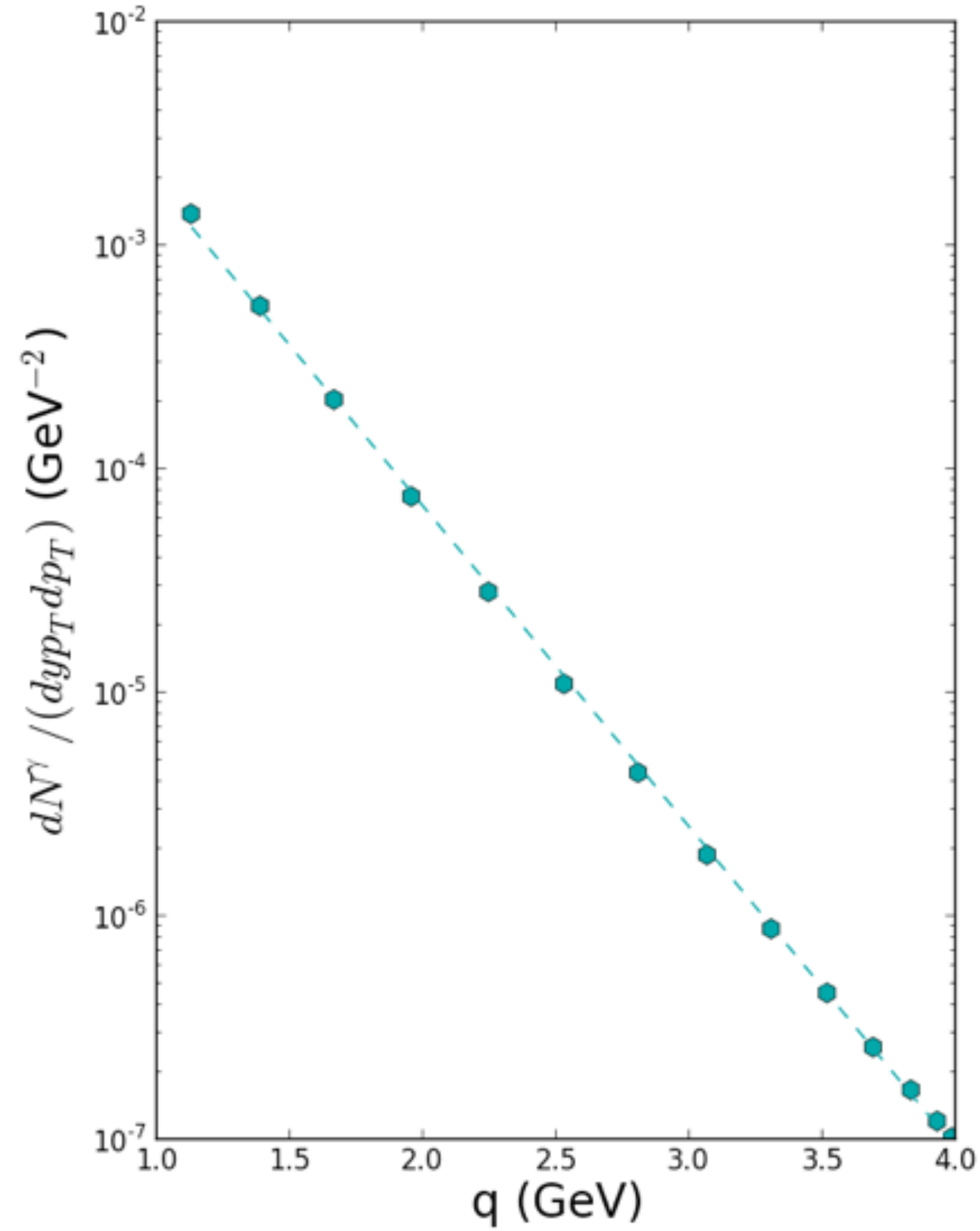
τ = 2.5 fm/c



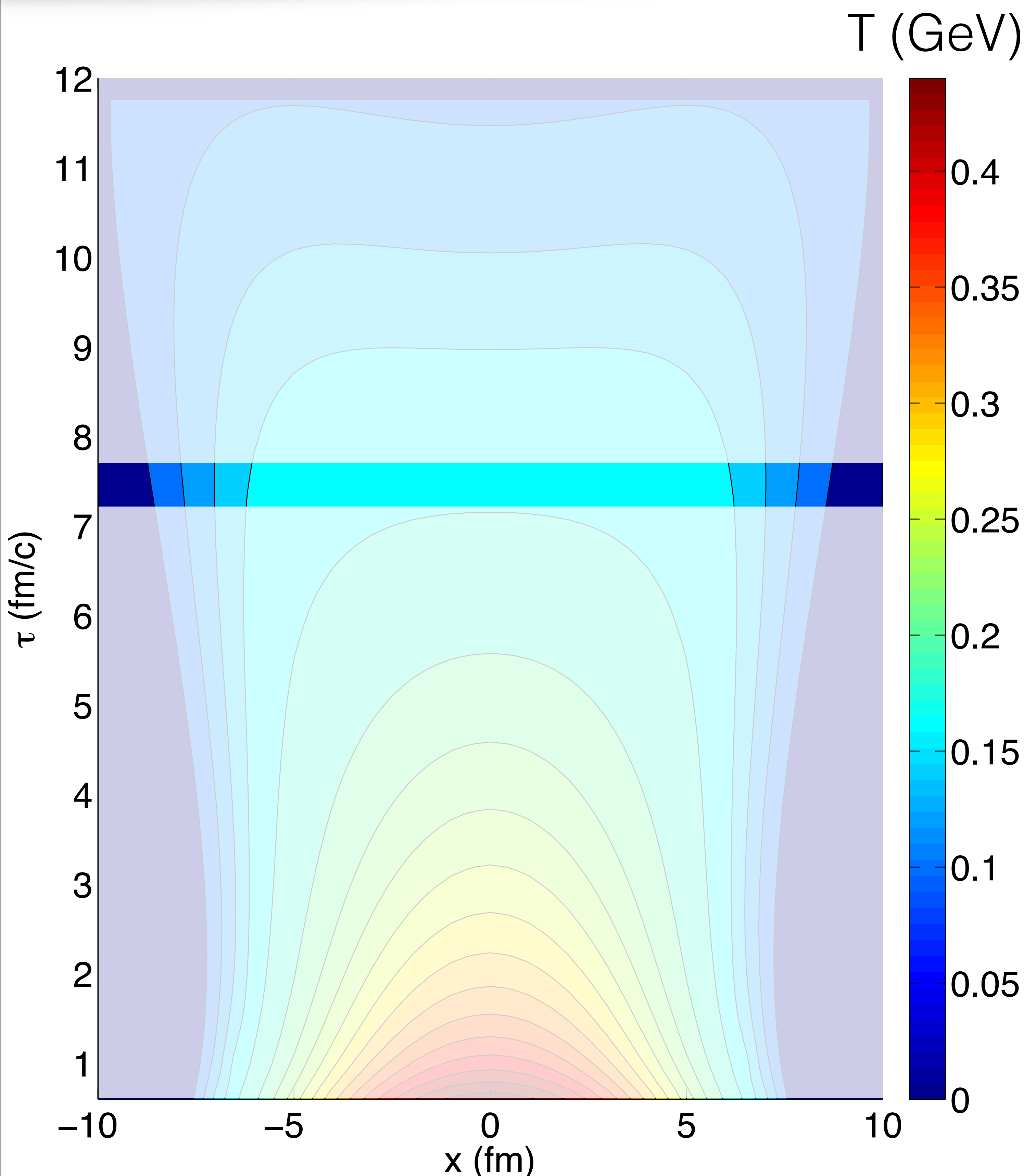
Slope of Photon Spectrum

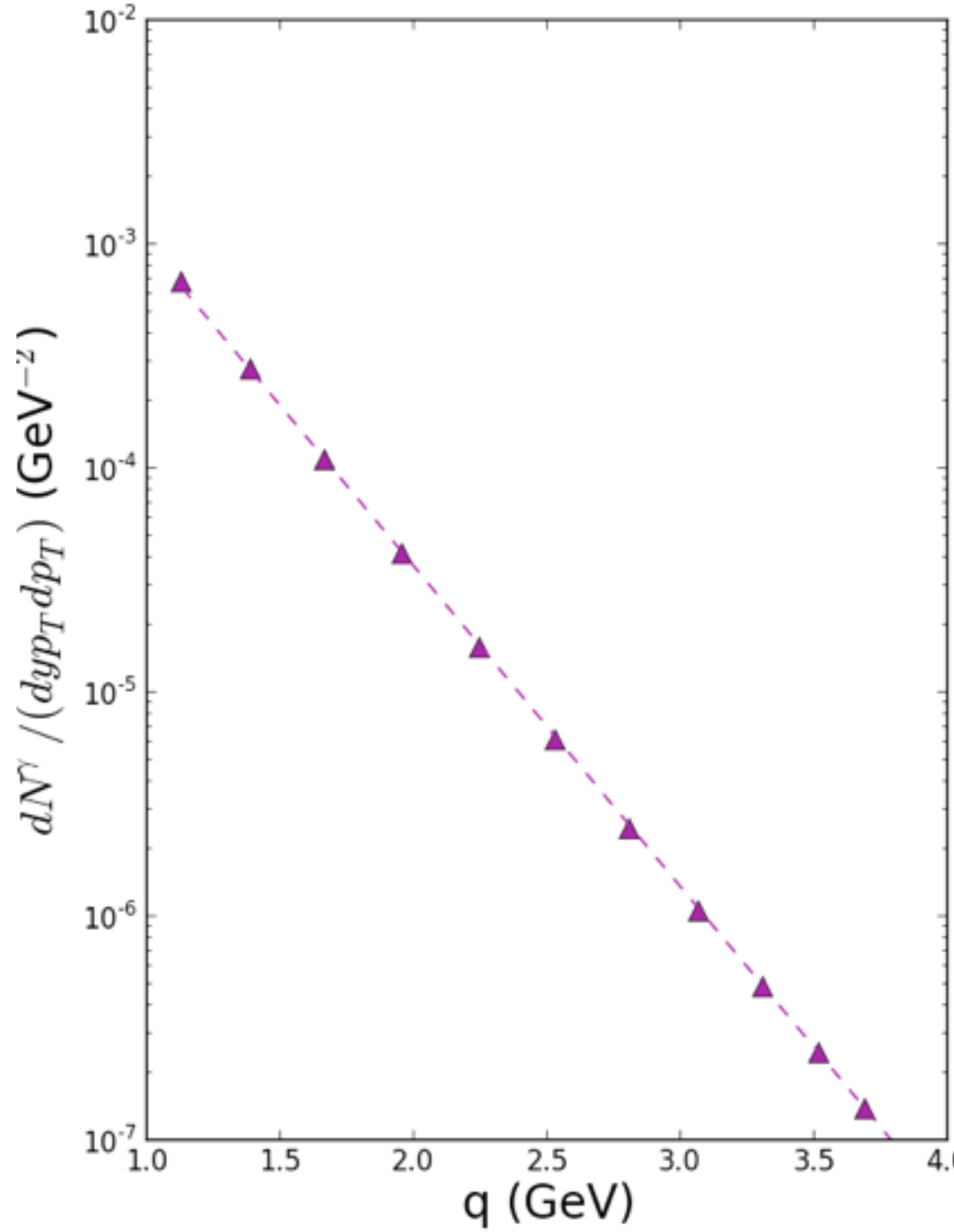


τ = 4.5 fm/c

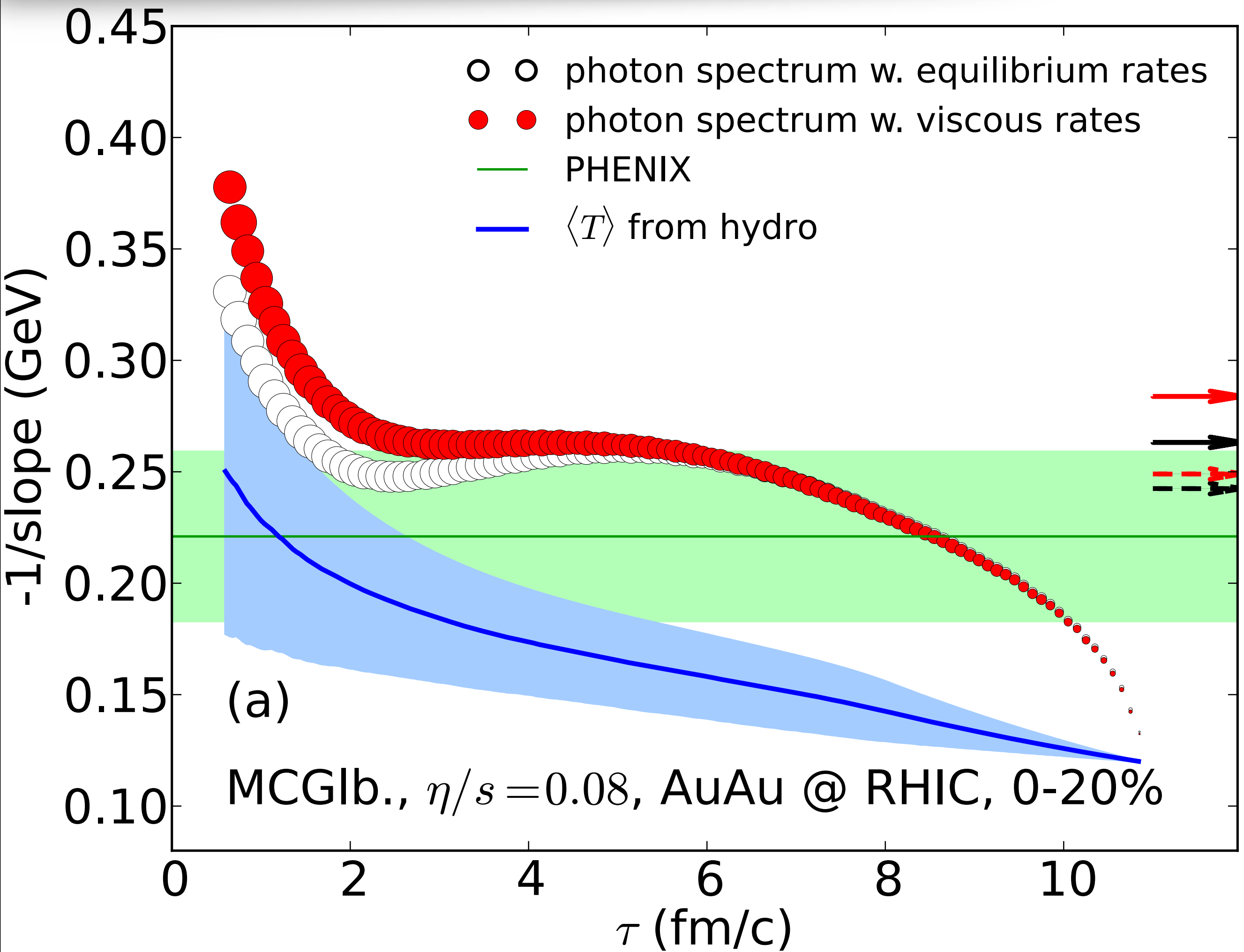


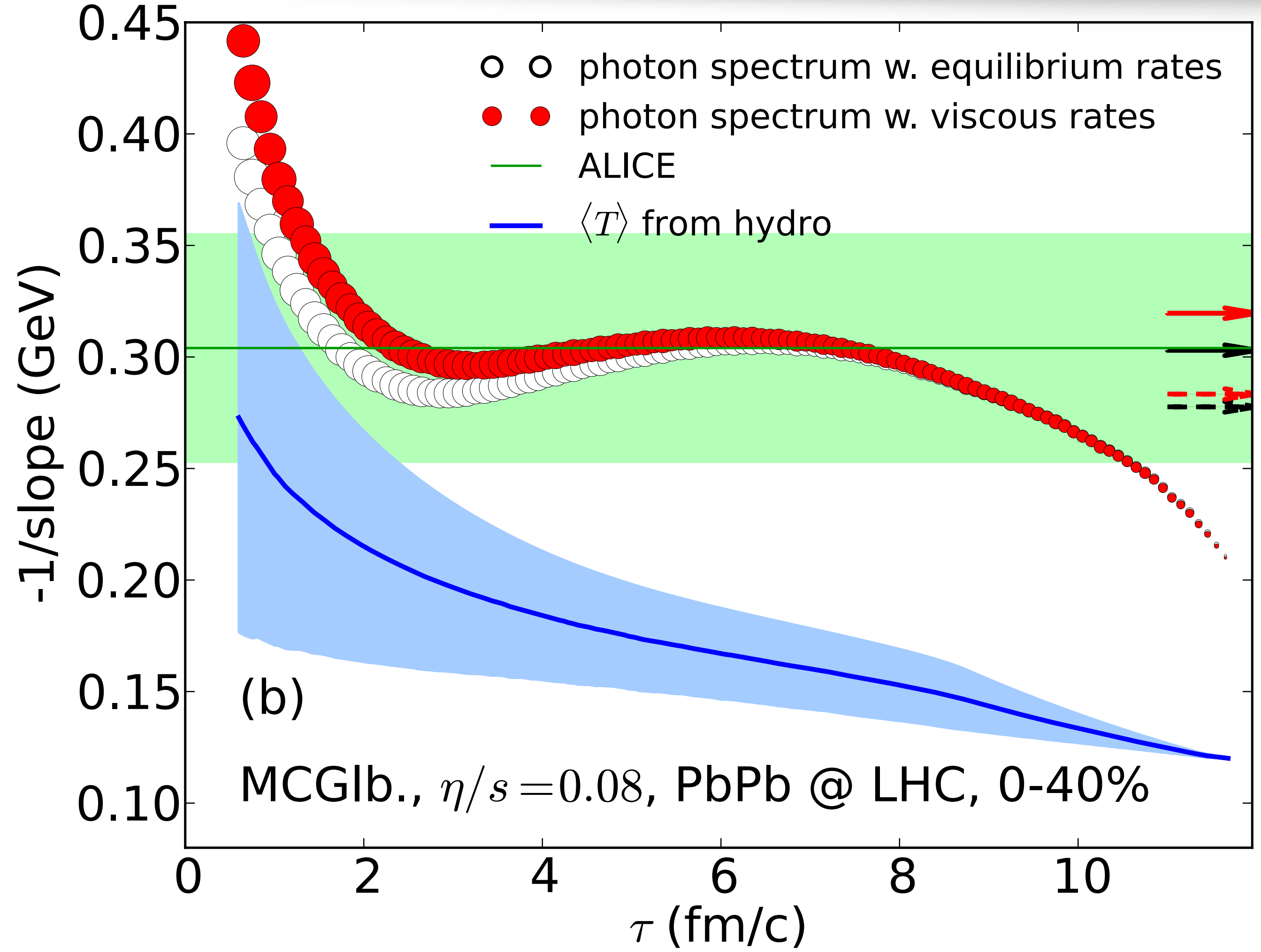
Slope of Photon Spectrum





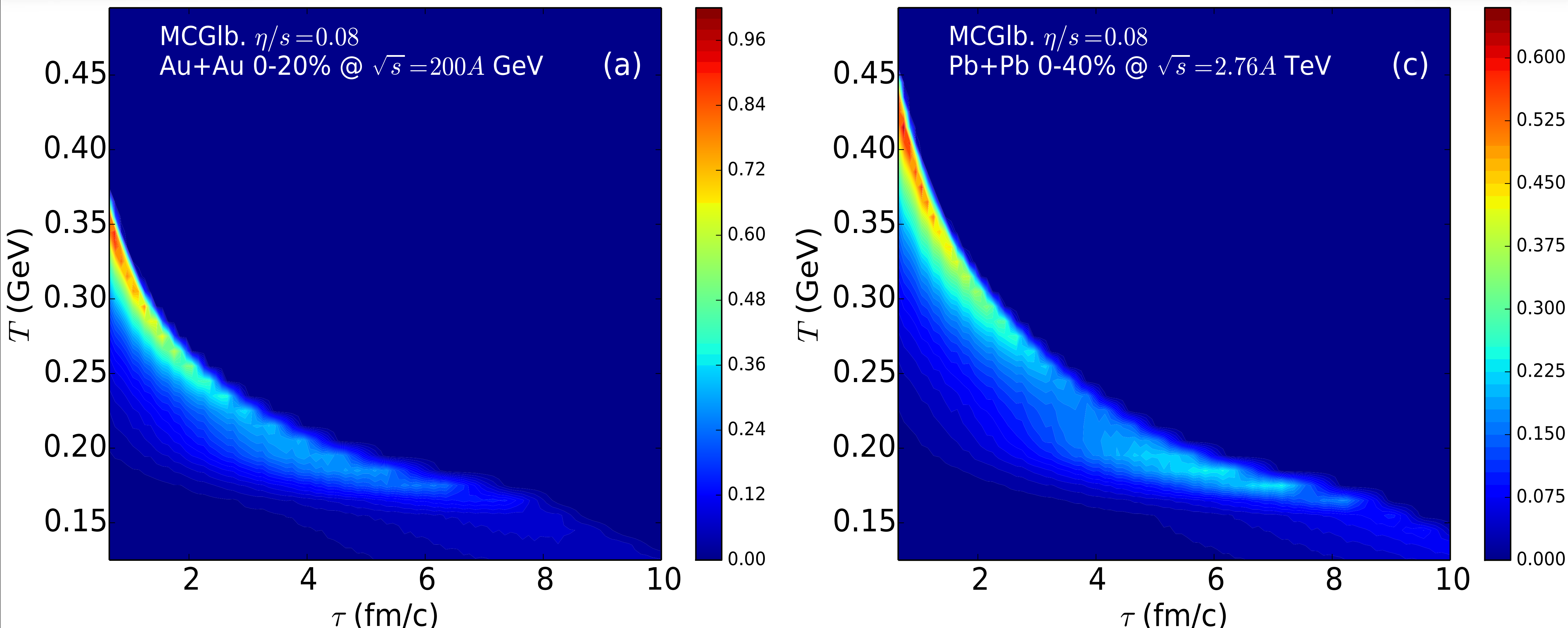
Fitted T_{eff} vs. Emission Time





- About 25% of thermal photons are emitted in the first 2 fm/c
- After 2 fm/c, thermal photons are significantly blue shifted by radial flow
- Viscous corrections to the slope of photon spectra are stronger during the early part of the evolution

Mapping thermal photon emission

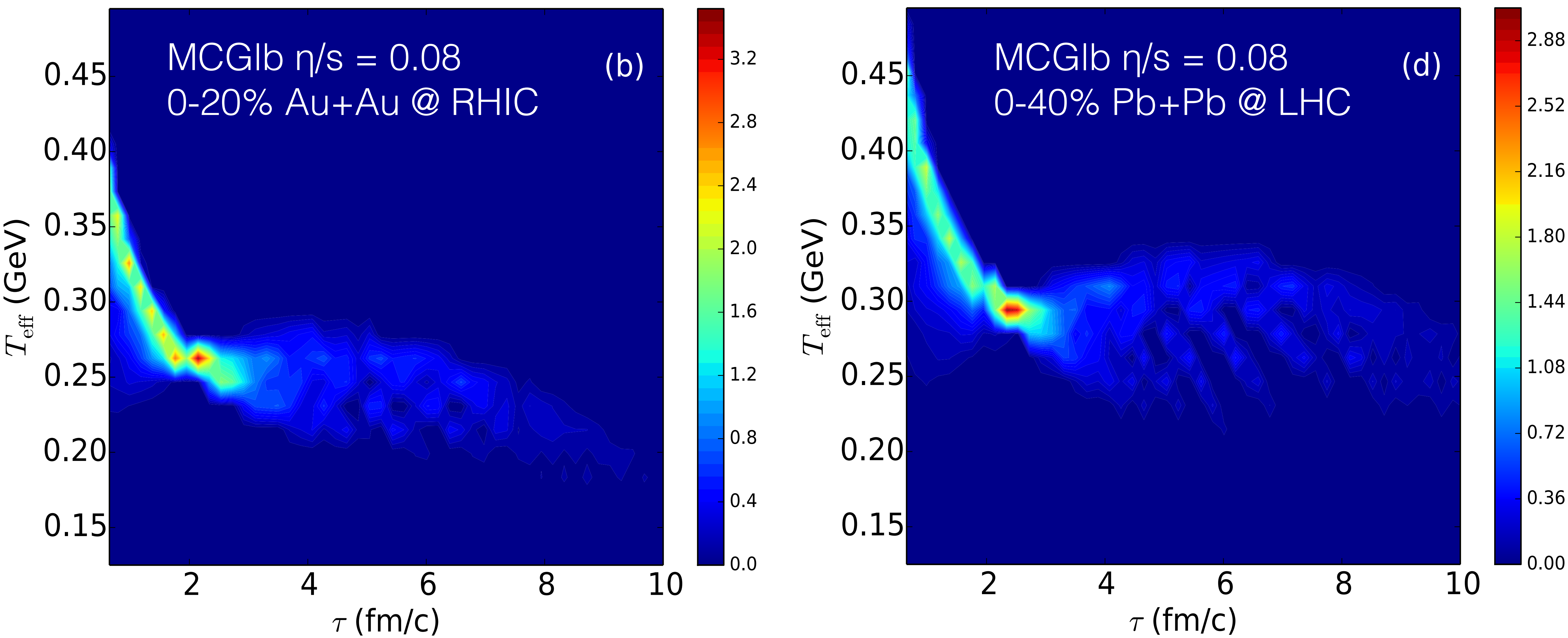


- By cutting hydro medium both in T and tau, we observe a **two-wave** thermal photon production

early time production — high rates at high temperatures

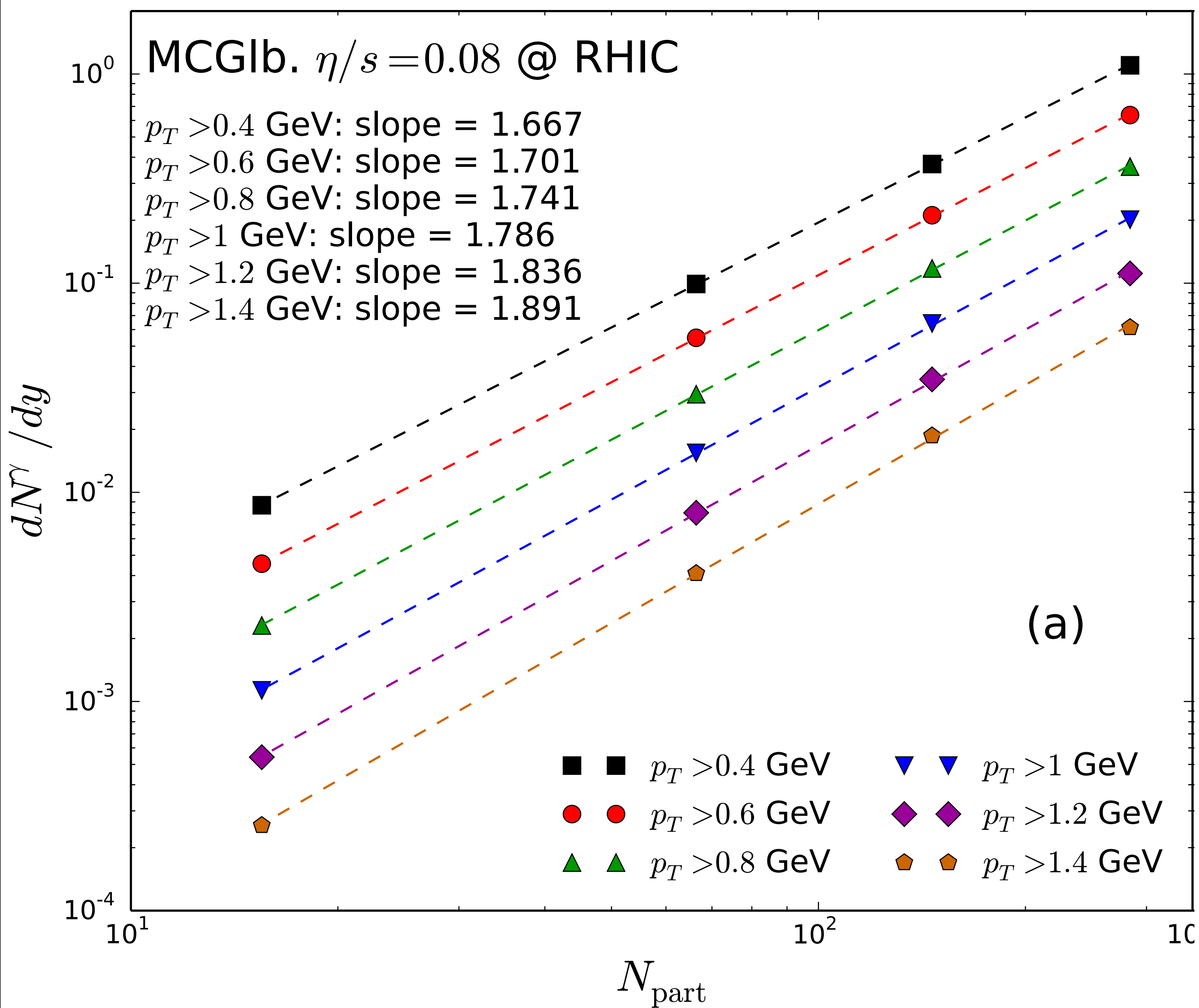
near transition region — growing of space-time volume

Mapping T_{eff}



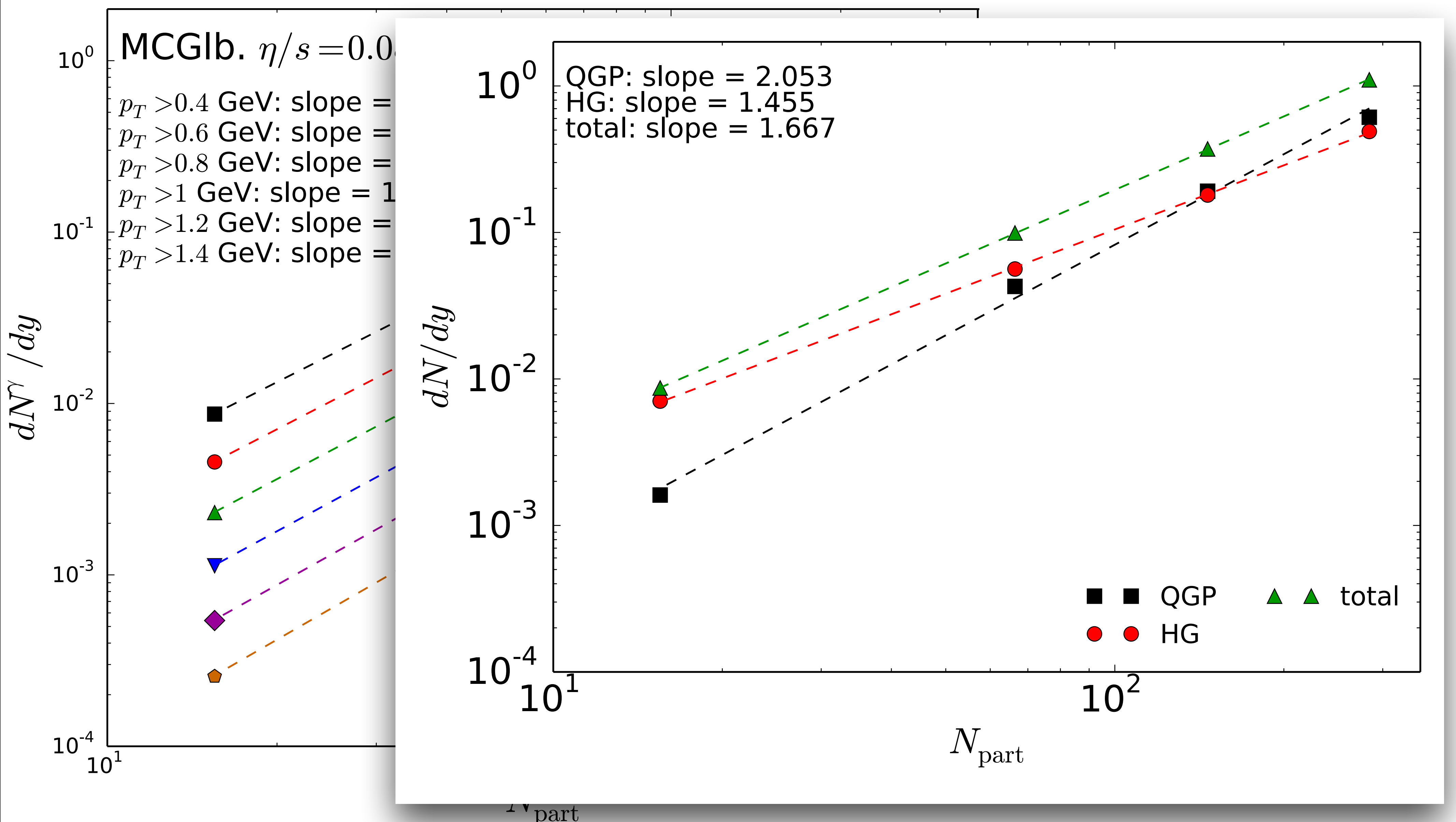
- Hydrodynamic radial flow strongly blue shifts the slopes of photon spectra
- Around 2 fm/c, it greatly shrinks the photon yield distribution in terms of the effective temperature compared to the real temperature

Centrality dependence of photon yield



- Thermal photons from hydrodynamic medium qualitatively reproduce the centrality dependence of the direct excess photon yield at the top RHIC energy

Centrality dependence of photon yield



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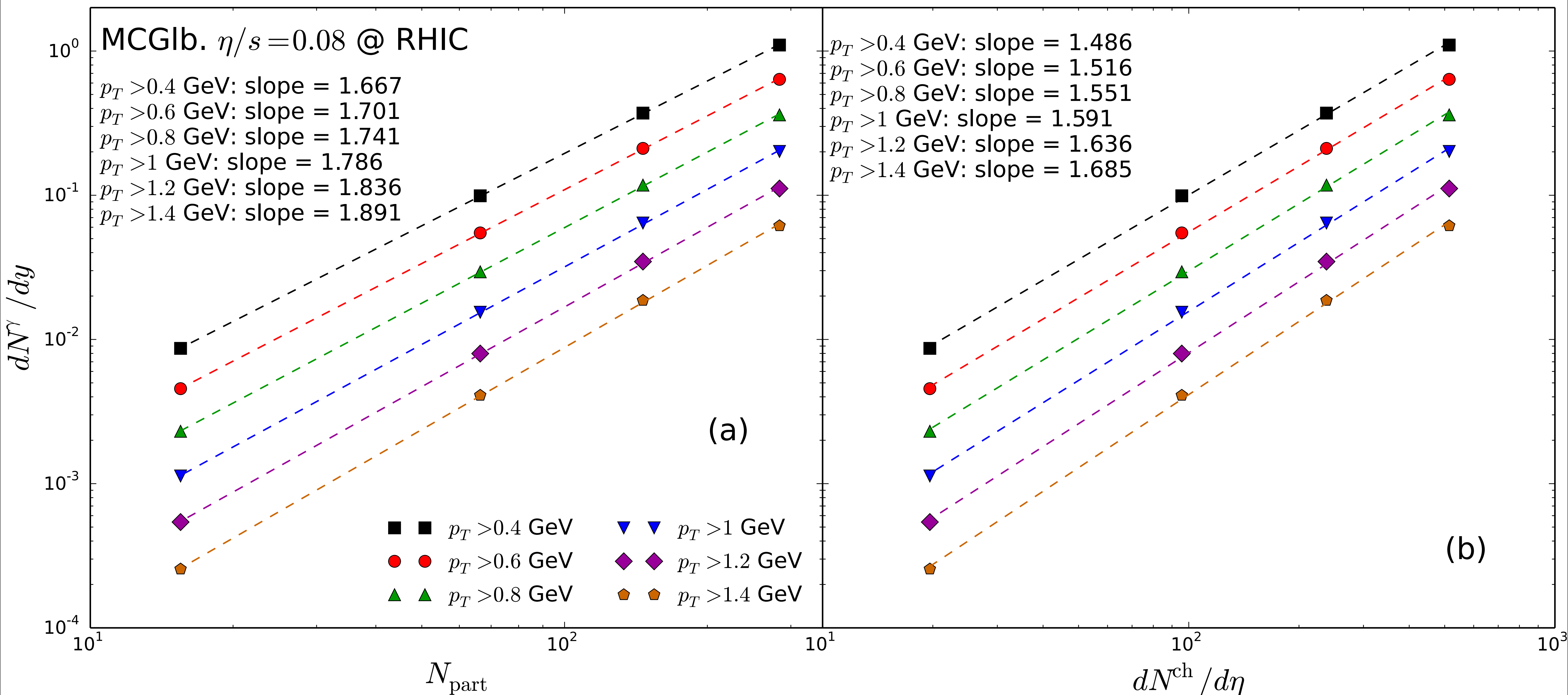

- Thermal photons from hydrodynamic medium qualitatively reproduce the centrality dependence of the direct excess photon yield at the top RHIC energy

dN^γ/dy vs. $dN^{\mathrm{ch}}/d\eta$ → **less model dependent comparison**

Conclusion

- Current theoretical calculation still underestimates the experimental measured direct photon spectra at both RHIC and LHC
- Thermal photon spectra are strongly blue shifted by hydrodynamic radial flow; their inverse slops are **not** reflecting the true underlying temperature of the evolving fireball
- By cutting hydrodynamic space-time volume, we map out thermal photon emission as a function of temperature and emission time
- Thermal photon yields show a stronger centrality dependence than charged hadrons. The extracted exponent suggests a larger emission from late stage of the hydrodynamic evolution in the hadronic phase

arXiv: 1308.2440

https://github.com/chunshen1987/iEBE.git