PHOTONS AS MESSENGERS OF THE NON-EQUILIBRIUM QUARK-GLUON PLASMA

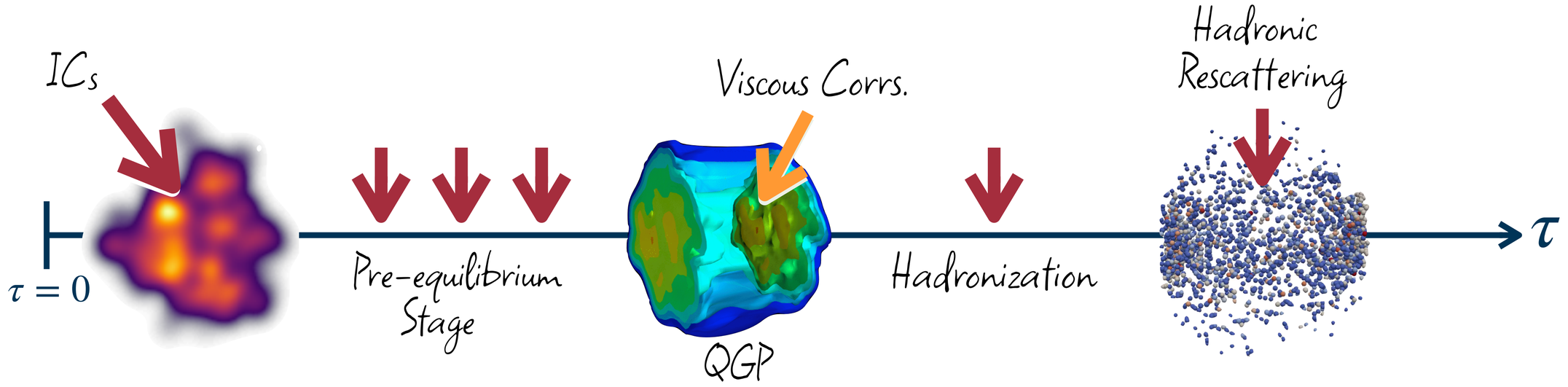
Oscar Garcia-Montero
Fakultät für Physik
Universität Bielefeld
GARCIA@PHYSIK.UNI-BIELEFELD.DE

Bundesministerium für Bildung und Forschung
CRC-TR 211
Strong-interaction matter under extreme conditions
UNIVERSITÄT BIELEFELD
FSP ALICE
Erforschung von Universum und Materie

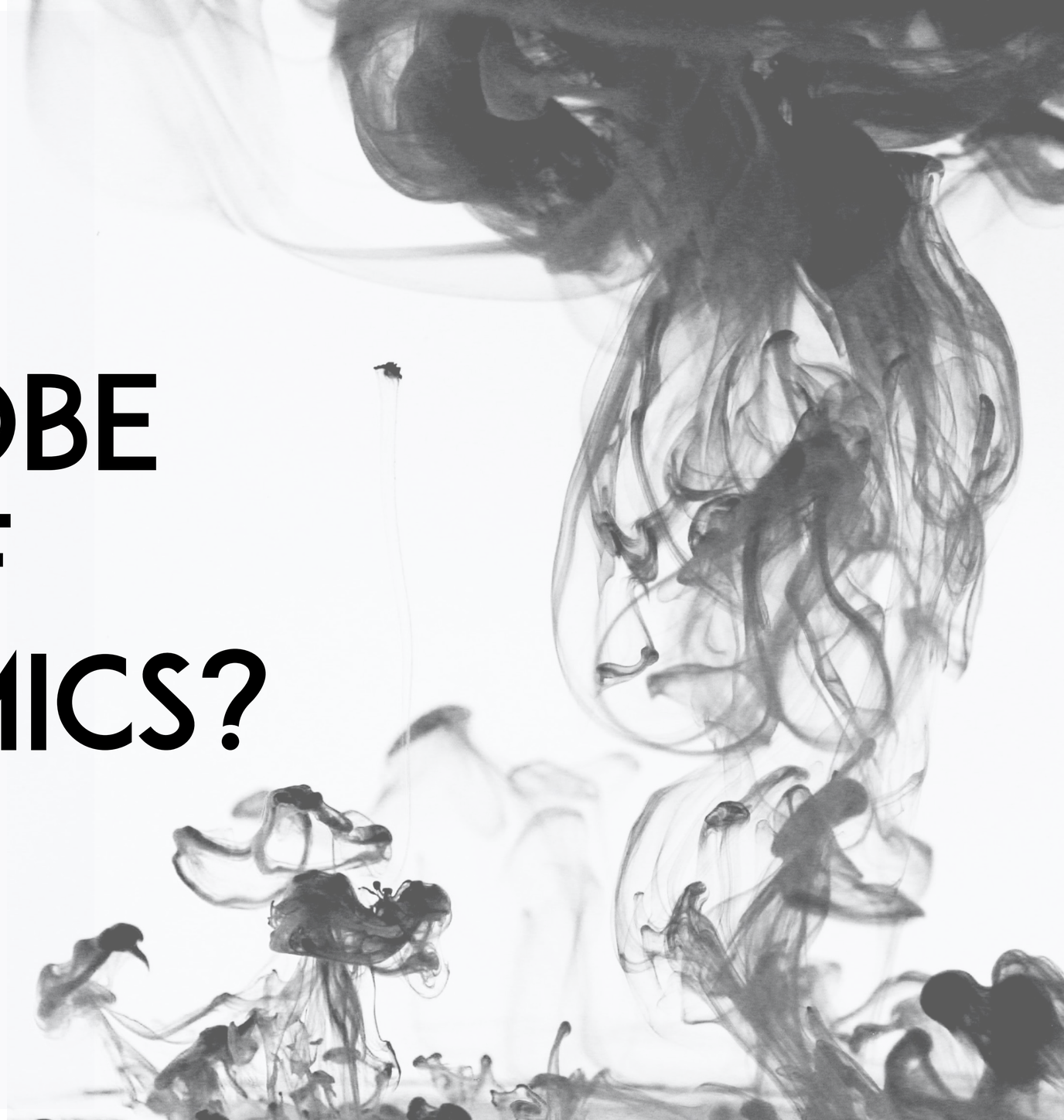
CONTENTS

MOTIVATION

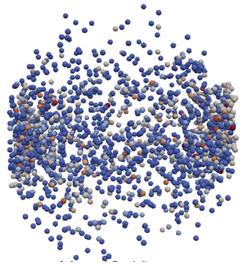
- Heavy-Ion Collisions create an Isolated Quantum System which is
  - Initially far away from any equilibrium
  - Self-interacting
  - Expanding against the vacuum
- A system *battling to thermalize against all odds.*



CAN WE PROBE THE ROLE OF *Non-Eq* DYNAMICS?

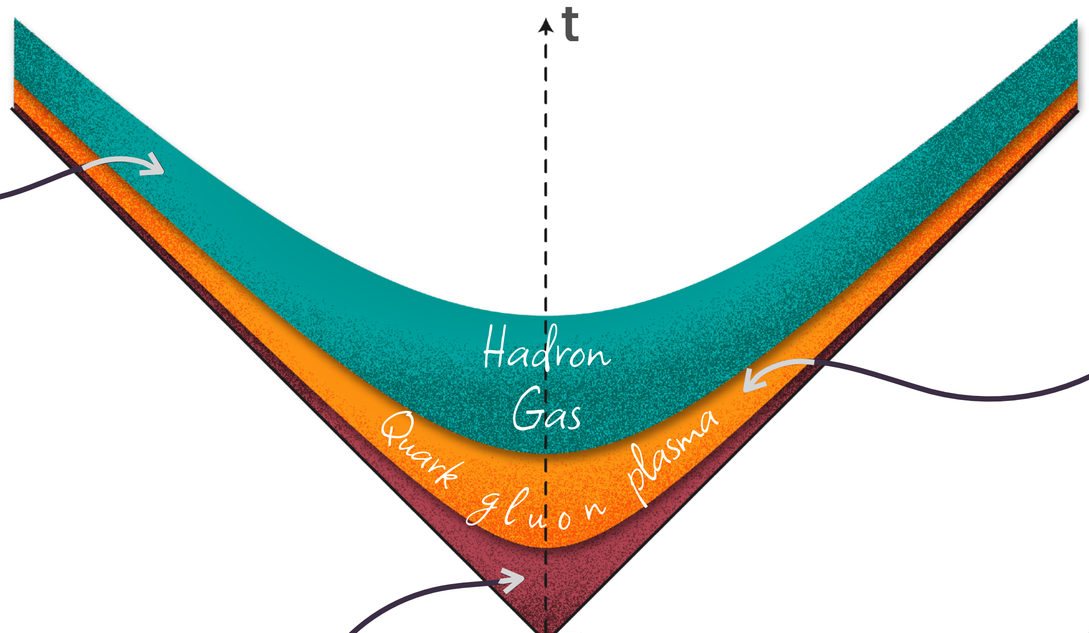


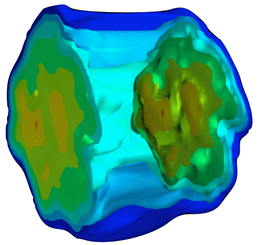
THE STANDARD MODEL OF HEAVY ION COLLISIONS: A HYBRID MODEL



HADRON GAS

SMASH
UrQMD



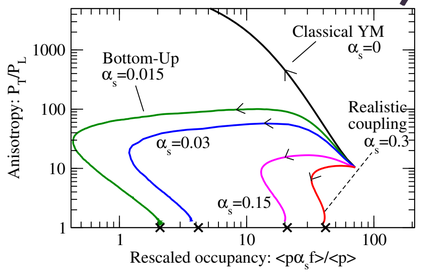


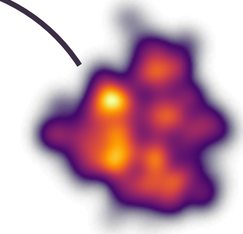
QGP

VISH
MUSIC
vHLLE

PRE-EQUILIBRIUM

AMY EKT
KøMPøST





INITIAL CONDITIONS

TRENTO
IP-Glasma

[1] From Kurkela and Zhu Phys.Rev.Lett. 115 (2015) no.18, 182301

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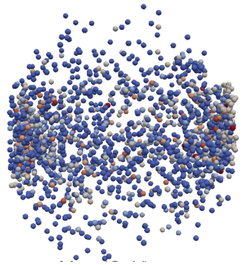

HADRON GAS

SMASH
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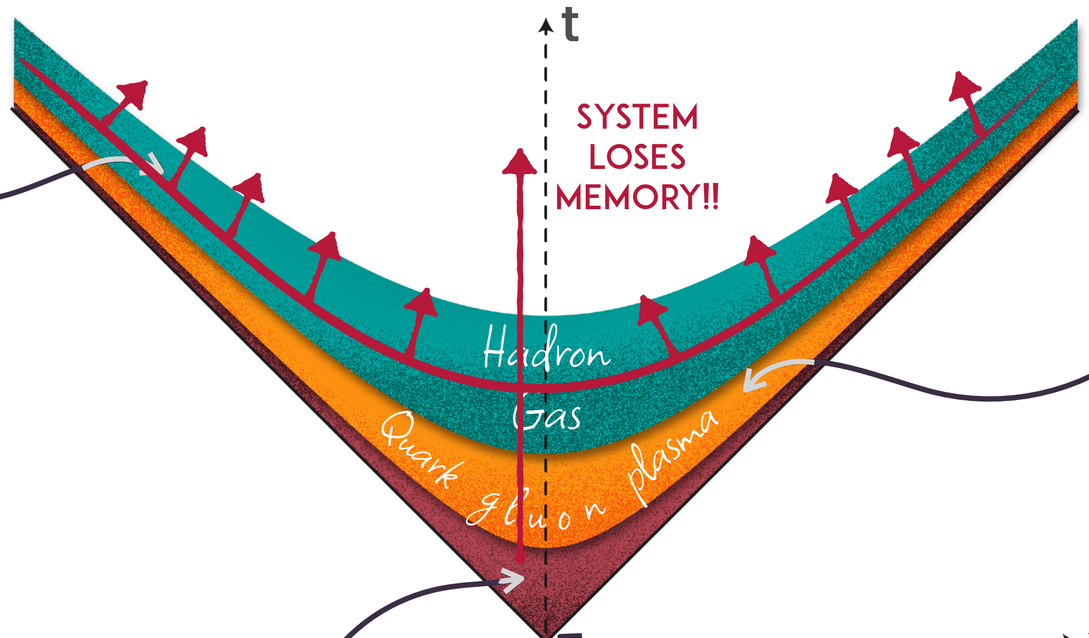

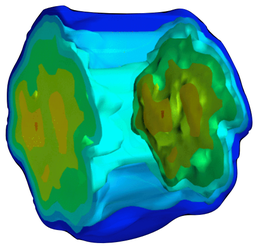

QGP

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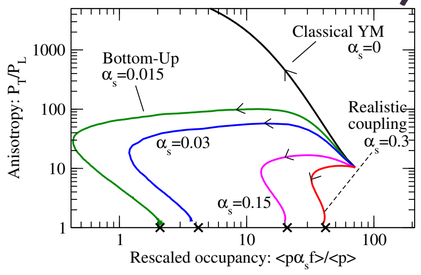

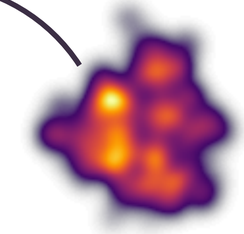

INITIAL CONDITIONS

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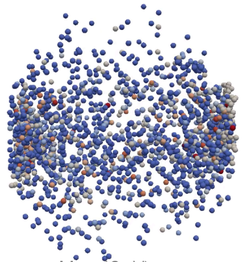
[1] From Kurkela and Zhu Phys.Rev.Lett. 115 (2015) no.18, 182301

THE STANDARD MODEL OF HEAVY ION COLLISIONS: A HYBRID APPROACH



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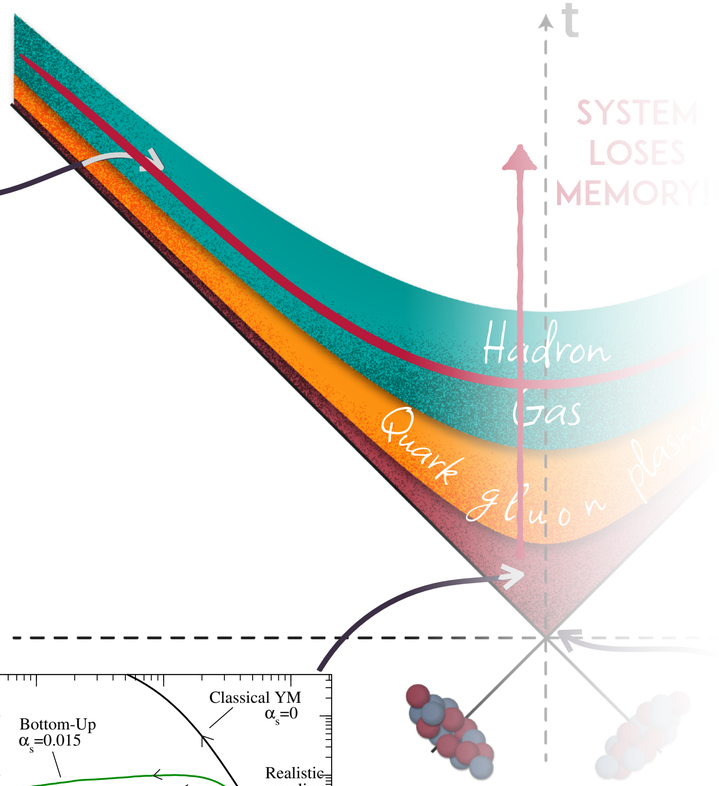

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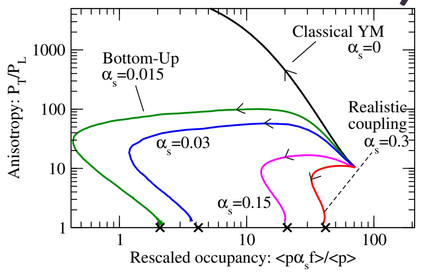

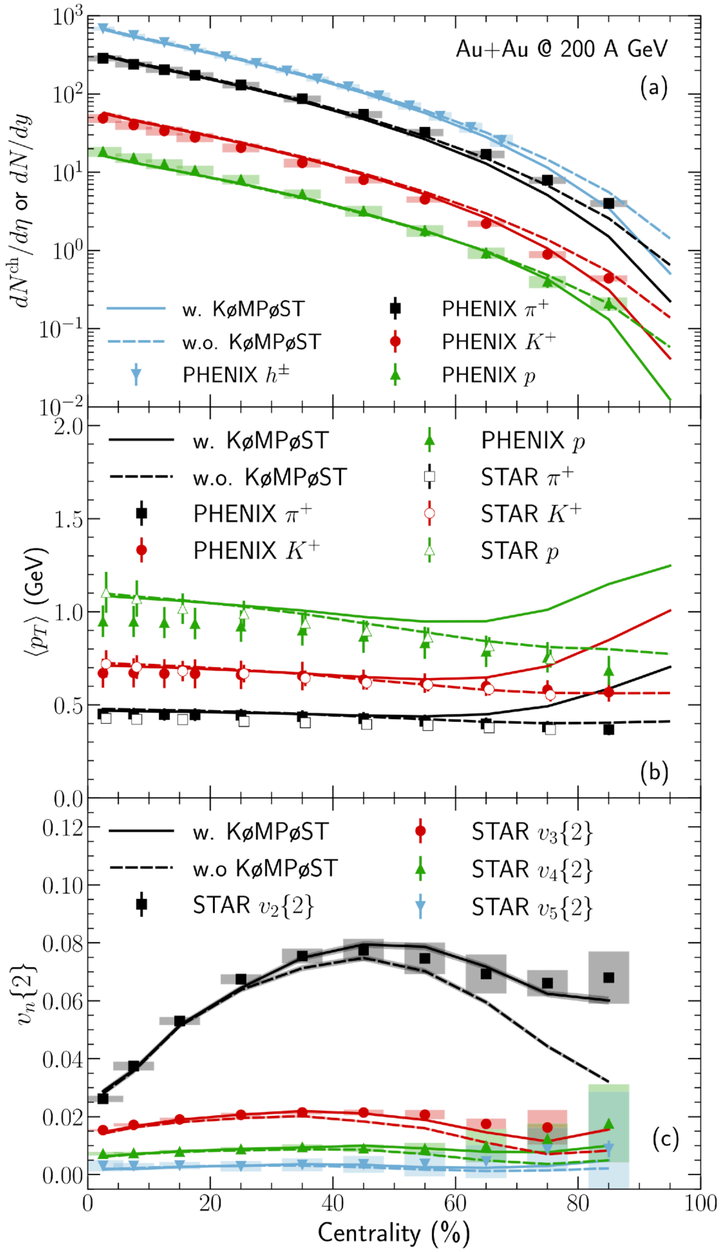

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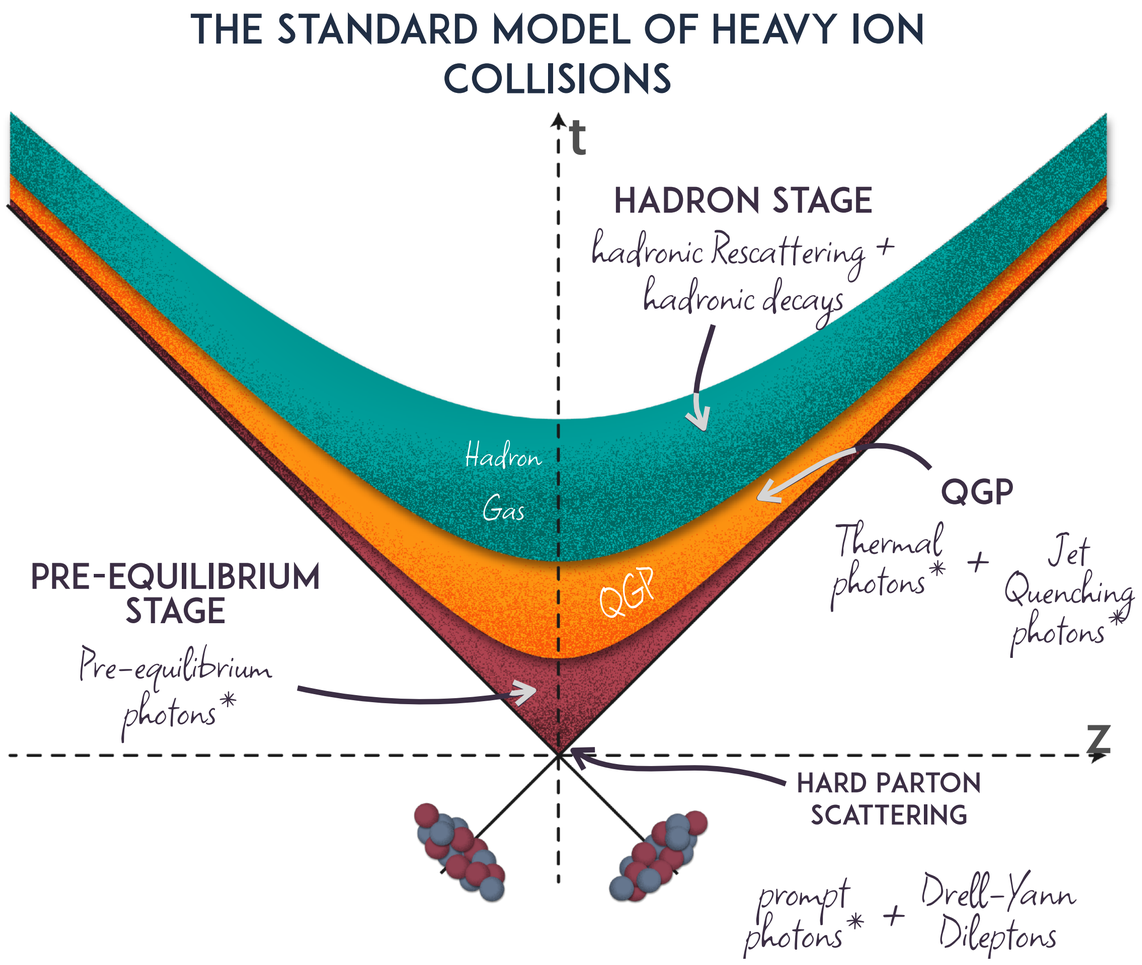
WHAT CAN WE USE TO PROBE THE ROLE OF *Non-Eq* DYNAMICS?

ELECTROMAGNETIC PROBES

- TBU: ***Photons*** and ***dilepton pairs***
- No strong interactions
- Mean free path in medium > medium size
  - Photons escape, virtually unscathed

AS A CONSEQUENCE...

- Different sources through the evolution
- EMPs are particularly sensitive to the evolution of the system
- ***Direct*** Photons* are <u>not</u> produced in decays



Photons* = virtual photons, i.e. dilepton pairs also included in this notation

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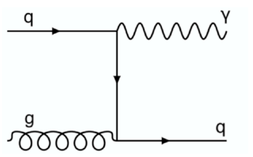
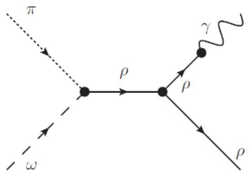
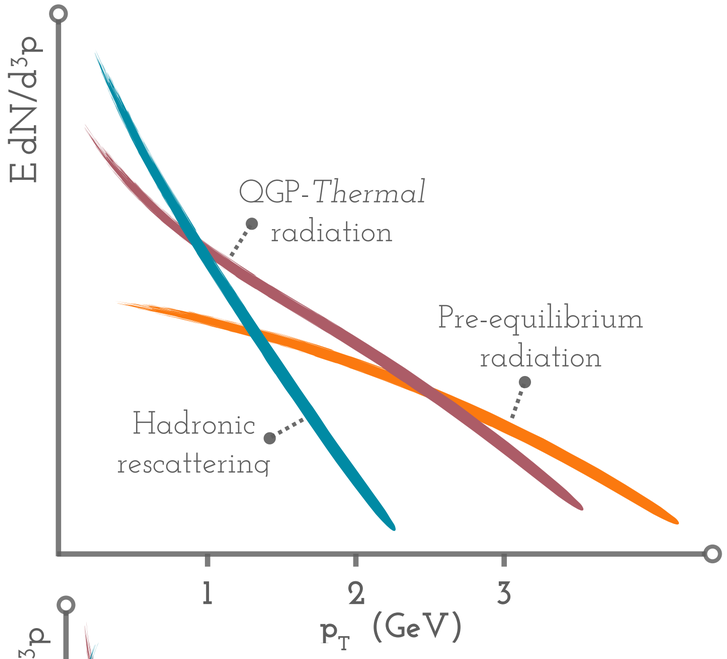
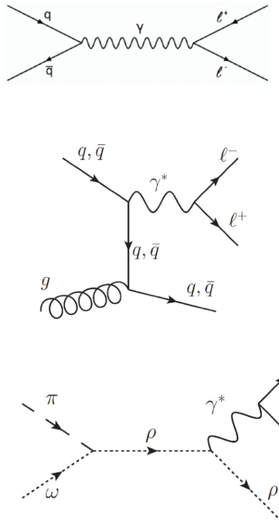
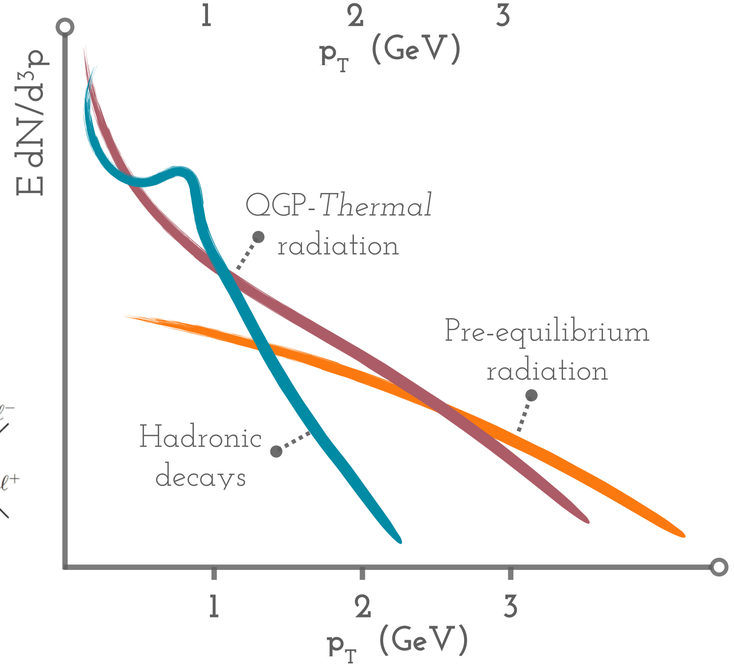
Direct EMPs are not produced through decays





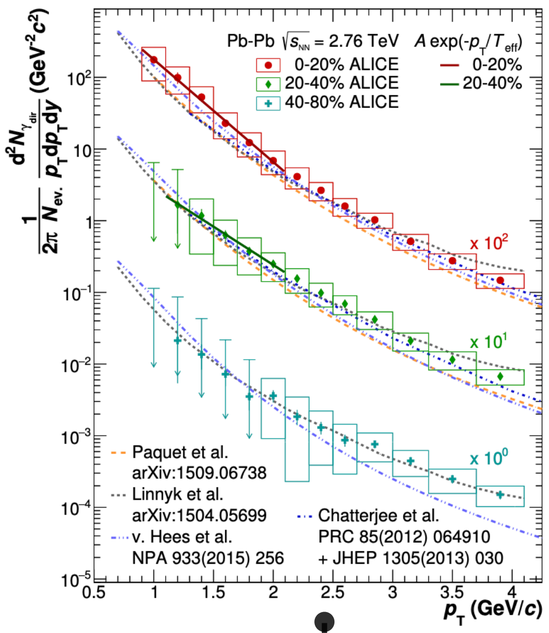






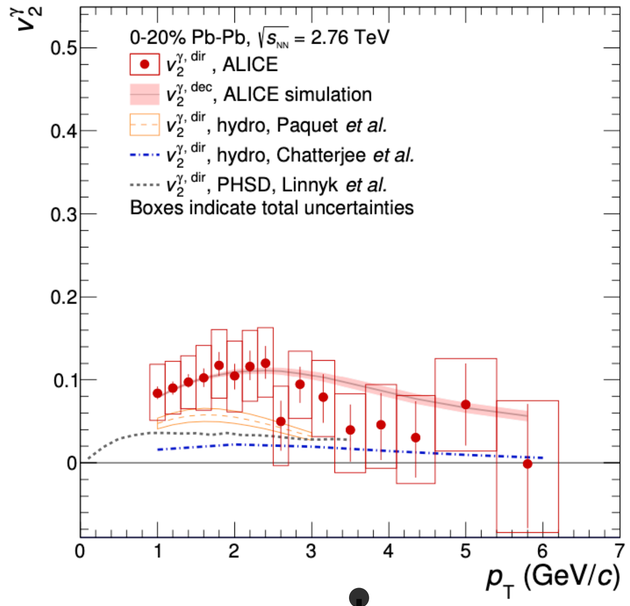
Photons* = virtual photons, i.e. dilepton pairs also included in this notation

HOWEVER, EM probes are yet to be fully understood.



DIRECT PHOTON PUZZLE

"The inability to simultaneously describe both the photon yield and anisotropy."



Yield

Anisotropy coefficients

$$E\frac{dN}{d^3p} = \frac{1}{2\pi p_\perp}\frac{dN}{dp_\perp dy}\left[1+\sum_{n=1}^{\infty} v_n(p_\perp)\cos\left[n(\phi-\Psi_n)\right]\right]$$

Acharya et al. (ALICE), Phys.Lett.B 789 (2019)
Adam et al. (ALICE), Phys. Lett. B754 (2016)

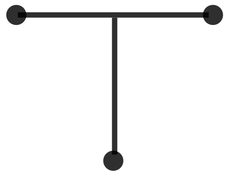
DIRECT EM PROBES

HOWEVER, electromagnetic probes are complicated

Since the yield is given by

$$E\frac{\mathrm{d}N}{\mathrm{d}^3p} = \int_{\tau_0}^{\infty} E\frac{\mathrm{d}N}{\mathrm{d}\tau\,\mathrm{d}^3p} = \sum_i \int_{\tau_i}^{\tau_{i+1}} E\frac{\mathrm{d}N_i}{\mathrm{d}\tau\,\mathrm{d}^3p}$$

This entangles the yields originating in different stages



And the v_n even more (as it is a weighted avg.)

HOW TO DISENTANGLE A LONG EXPOSURE PICTURE?

Correlations.

We'll come back to this.

HBT: Phys. Rev. C80, 0449 (2009)

Recent advances in...

PHOTONS AS MESSENGERS OF EARLIER TIMES

EARLY RADIATION: IS IT RELEVANT?

- Pre-equilibrium photons are computed using approximated 2-to-2 kinetic rates
  - $$E\frac{d^3R}{d^3p} = \frac{40}{9\pi^2}\alpha\alpha_s \underbrace{\mathcal{L}}_{a} \underbrace{f_q(\mathbf{p})}_{b} \underbrace{\int \frac{d^3p'}{(2\pi)^3}\frac{1}{p'}[f_g(\mathbf{p}') + f_q(\mathbf{p}')]}_{c}$$

  a) Regulator
  b) Quark distribution
  c) Related to screening masses

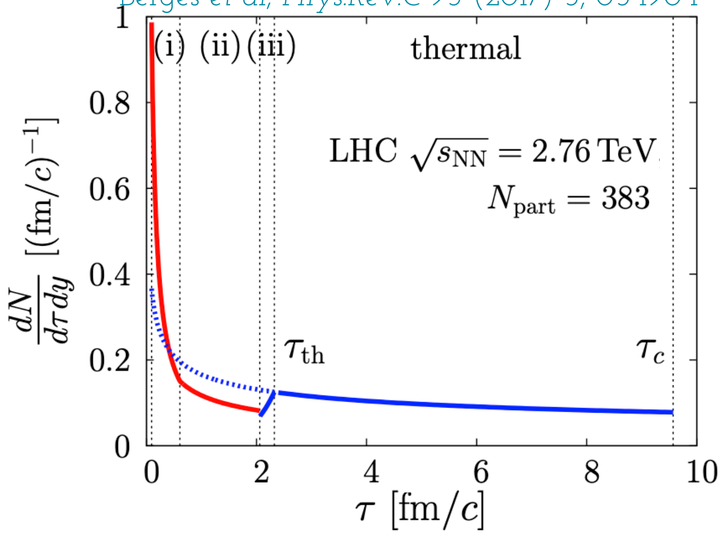
- Space-time evolution to fold the rates with. Use the "bottom-up" thermalization scenario:

  1) Early times: 2-to-2 broadening $1 \ll \tau Q_S \ll \alpha_S^{-3/2}$
  2) Onset of thermalization. $\alpha_S^{-3/2} \ll \tau Q_S \ll \alpha_S^{-5/2}$
  3) Mini-jet quenching $\alpha_S^{-5/2} \ll \tau Q_S \ll \alpha_S^{-13/5}$

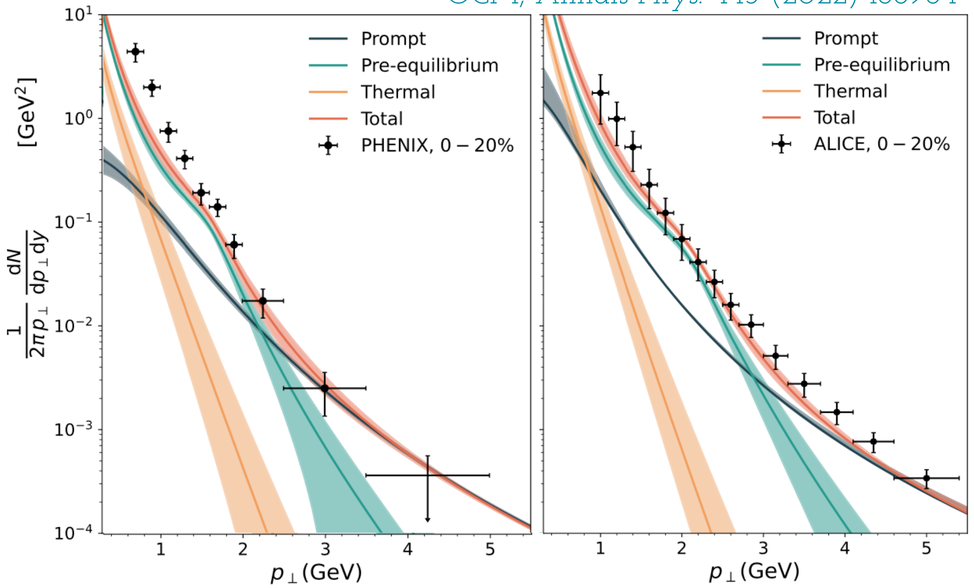
- Input : Gluon distributions from classical statistics
  Pheno. matching for the free parameters, i.e. Q_S

Caveat: pure "bottom-up" gives a long pre-equilibrium stage. These should be taken as ***largest***

Berges et al, Phys.Rev.C 95 (2017) 5, 054904



OGM, Annals Phys. 443 (2022) 168984

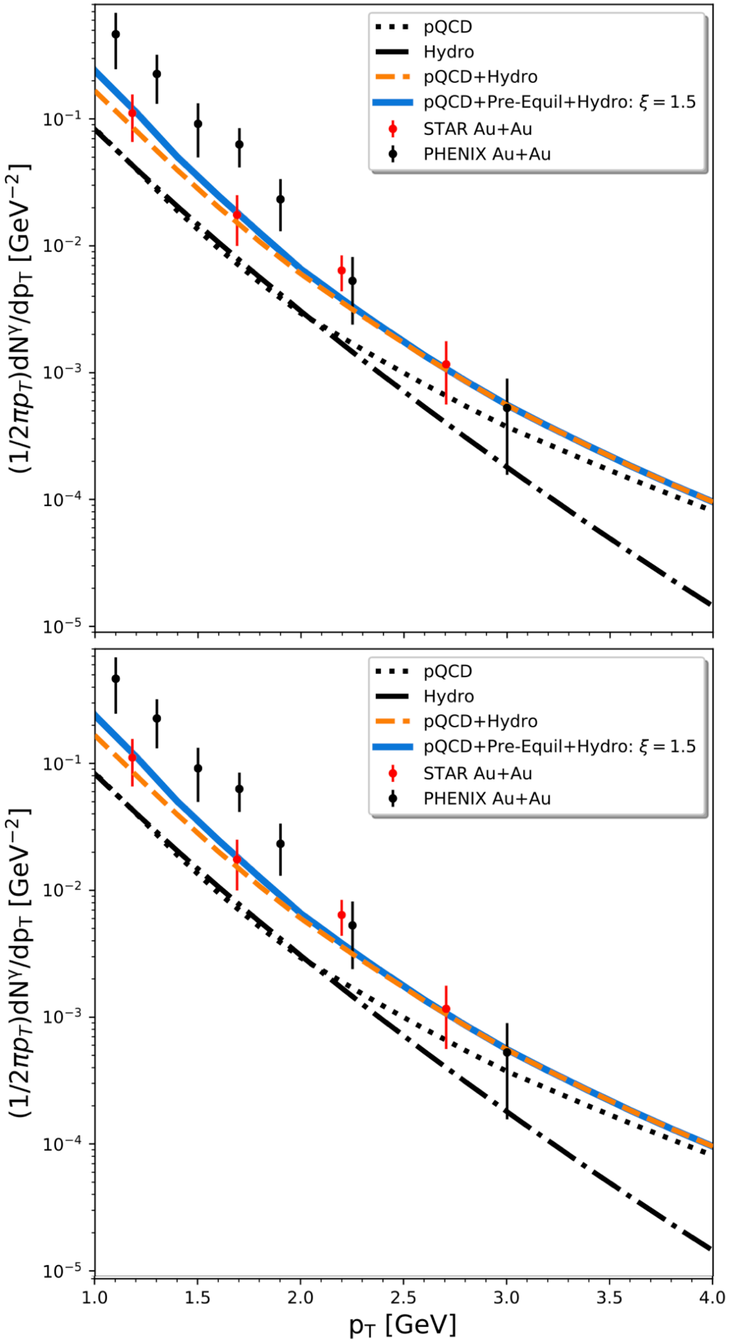


REFINEMENT: KINETIC THEORY

- Pre-equilibrium photons are computed using approximated 2-to-2 kinetic rates
  - $$E\frac{d^3R}{d^3p} = \frac{40}{9\pi^2}\alpha\alpha_s\mathcal{L}f_q(\mathbf{p})\int\frac{d^3p'}{(2\pi)^3}\frac{1}{p'}[f_g(\mathbf{p}') + f_q(\mathbf{p}')]$$
- Distributions are computed in QCD Kinetic theory, using the Fokker-Planck diffusion approximation

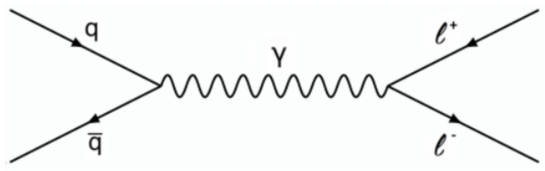
$$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla_x\right)f_{g/q}(t,\mathbf{x},\mathbf{p}) \quad = \quad -\nabla_{\mathbf{p}}\cdot\mathcal{J}_{g/q} + \mathcal{S}_{g/q}$$

- ICs: $f_g(t_0,p) = f_0\,\theta\left(1 - \frac{\sqrt{p_\perp^2 + p_z^2\xi^2}}{Q_s}\right)$ and $f_q(t_0,\mathbf{x},\mathbf{p}) = 0$
- Pheno. matching to energy (multiplicities) $\frac{dE}{d\eta} = 2N_cC_FA_T\frac{f_0Q_s^3}{(2\pi)^2}\frac{1}{\xi}\mathcal{F}(\xi)$
- Gluon number suppressed by large Q_s. Pre-eq. Photons relevant at lower energies.

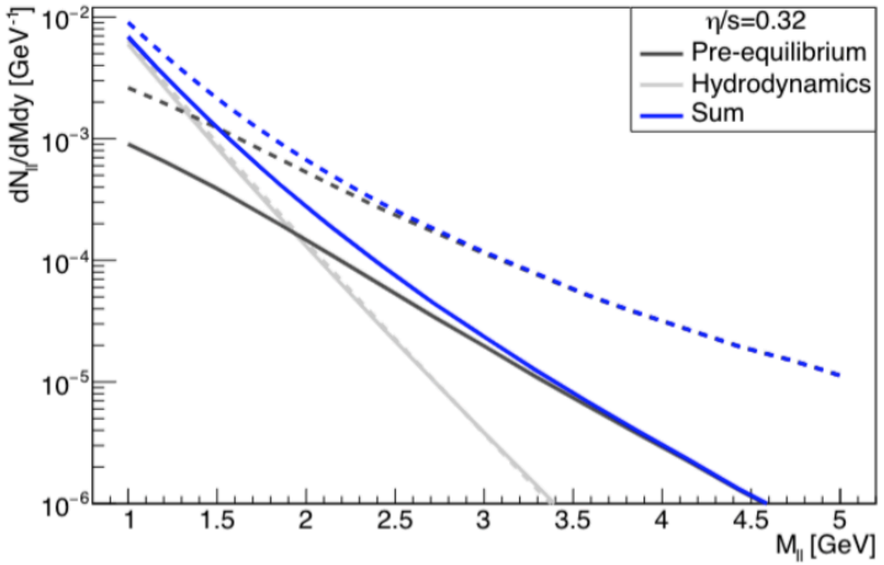


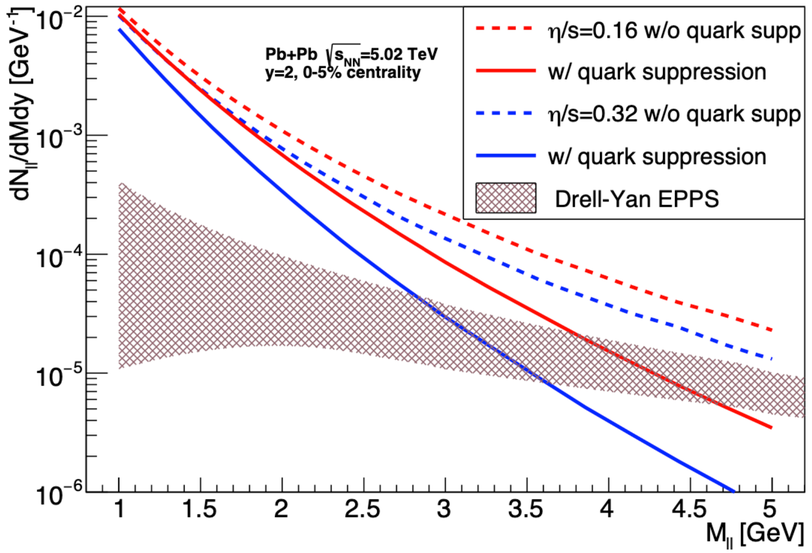
DI-LEPTON PRODUCTION IN HICS

- Di-lepton ($e^+e^-/\mu^+\mu^-$) pairs with invariant mass M~ ***few GeVs*** produced during the initial state; late stage production is suppressed by exp(-M/T)



- Do pre-equilibrium dileptons "out-shine" the Drell-Yann, decay spectra?
  - For some kinematic windows, it may be the case.





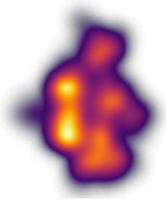
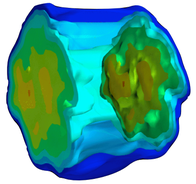
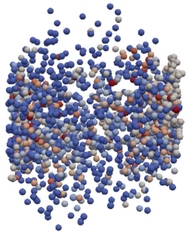
- New window into pre-equilibrium dynamics for 1GeV<M<3GeV accessible with next generation of heavy-ion detectors (ALICE3,LHCb)

Falling out of equilibrium

RESCATTERING DURING THE HADRONIC STAGE

NEQ EFFECTS IN THE HADRONIC STAGE

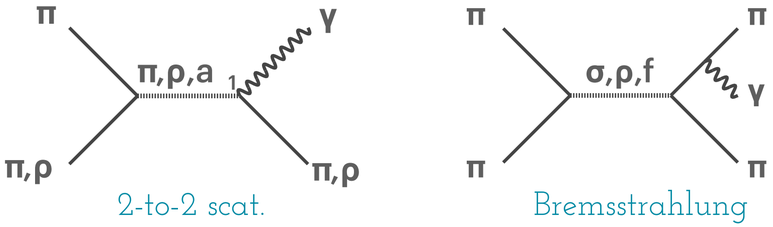
- Hadronic observables are sensitive to end (hadronic) non-equilibrium effects. Are the photons produced also sensitive?

ICs	QGP	AFTERBURNER
		
T_RENTO	(3+1) MUSIC IDEAL HYDRO	SMASH

MODEL A:	THERMAL PHOTONS [T > 150 MeV]	+	AFTERBURNER [microscopic] PHOTONS
MODEL B:	THERMAL PHOTONS [T > 150 MeV]	+	THERMAL PHOTONS [150> T > 120 MeV]

PHOTONS FROM HADRONIC RESCATTERING

Main contributions



Hydrodynamical - Thermal Rates

- Rates obtained from convolution of process amplitude and thermal distribution functions

QGP: AMY, JHEP 0112 (2001) 009

HRG: Turbide *et al*, Phys. Rev. C69, 014903 (2004)

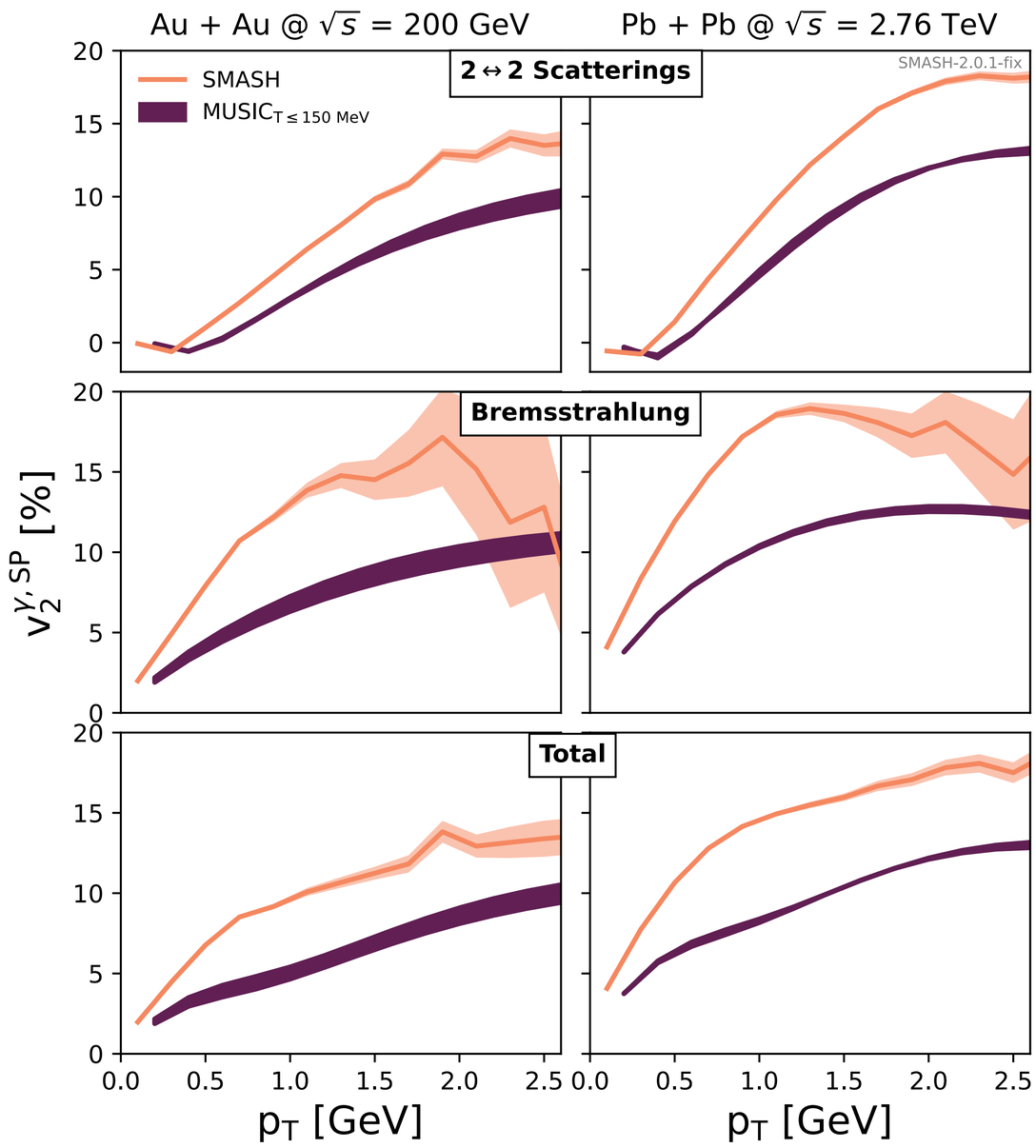
Transport - SMASH photons

- Non-equilibrium production of photons in hadronic matter
- Perturbative production - no backreaction
- Photons are sampled when underlying meson scattering happens

Meson scattering — Schäfer *et al*, *Phys.Rev.D* 99 (2019) 11, 114021

A. Schäfer, OGM, J.F. Paquet, H. Elfner, C. Gale, *Phys.Rev.C* 105 (2022) 4, 044910

Note: Total is weighted average!



EQUILIBRIUM VS NON-EQUILIBRIUM

SOME TECHNICAL DETAILS

Average (smooth) ICs for b = 5 fm

EoS: HoTQCD+SMASH

Transition Temperature T=150

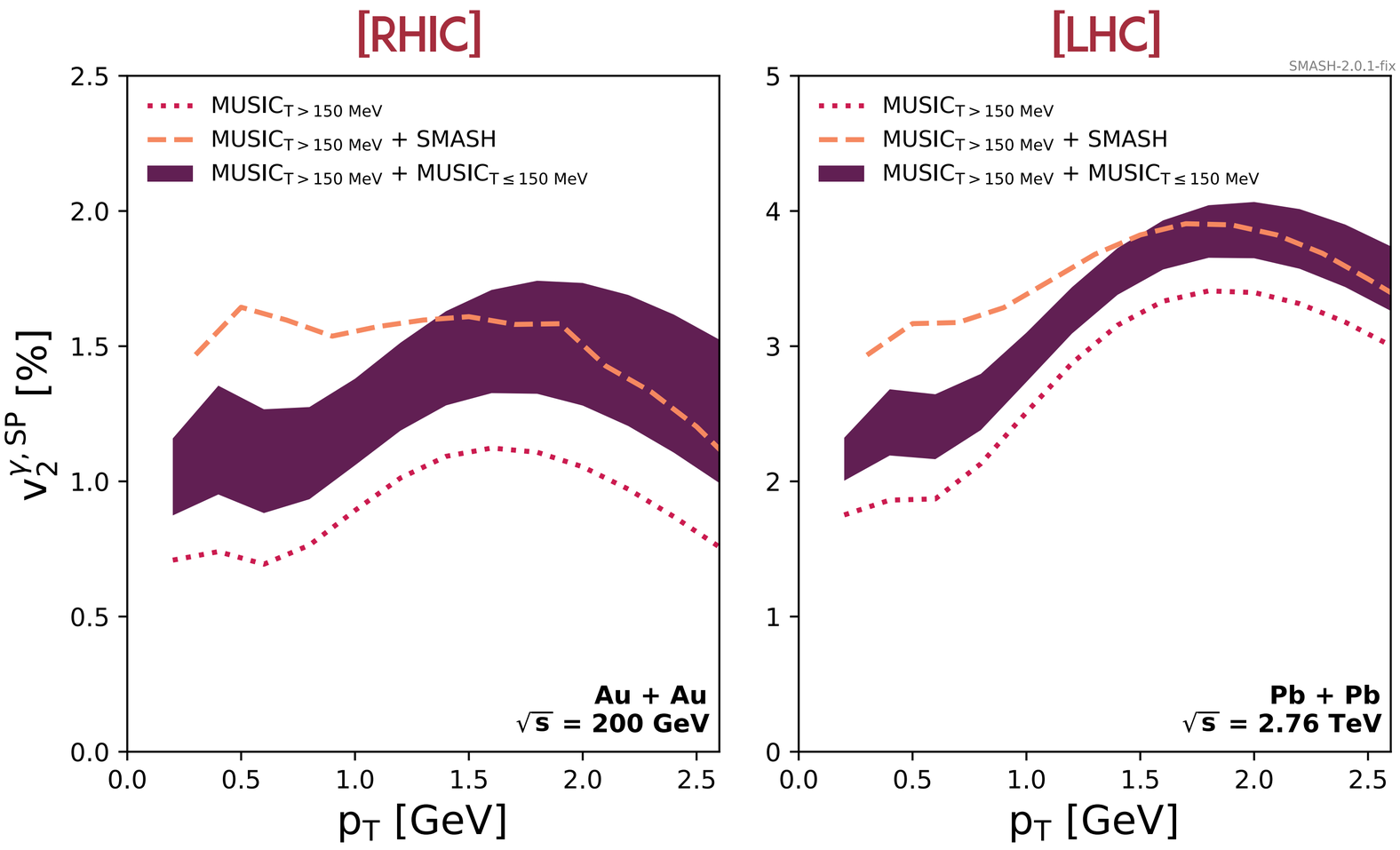
- Checked hadronic observables ✓
- **Comparison:** Model A vs. Model B
  - Computed yield and anisotropy of photons

$$v_2(p_\perp) = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_\perp^2 \rangle}$$

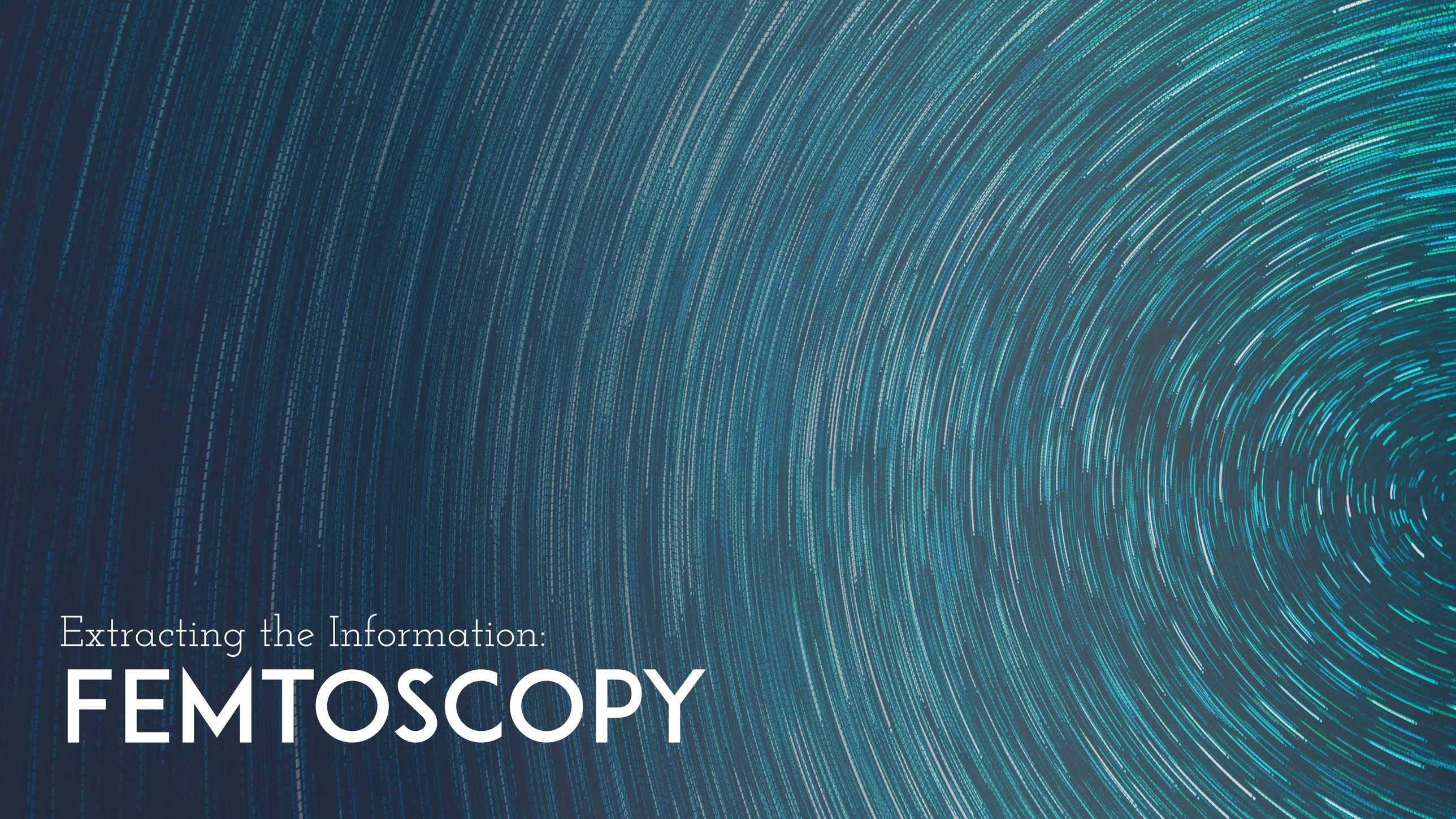
  - Photon anisotropies are measured relative to the hadronic event plane

NON-EQUILIBRIUM EFFECTS ENHANCE PHOTON ANISOTROPIES

QGP VS. HADRONIC MATTER



HADRONIC STAGE IS RELEVANT!
NON-EQ. EFFECTS SHOULD BE ACCOUNTED FOR.

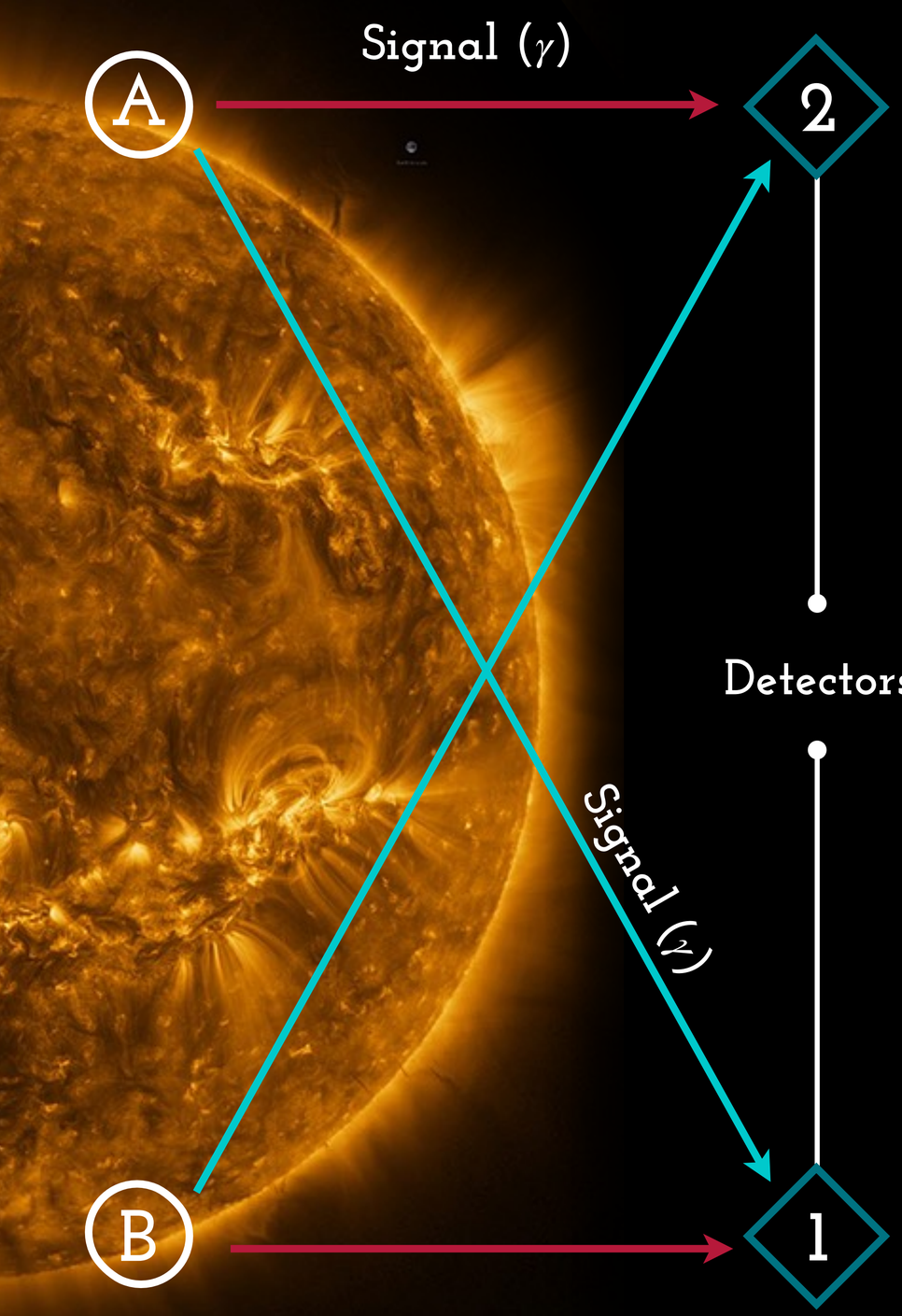


Extracting the Information:

FEMTOSCOPY

PHOTON HBT

Hanbury Brown-Twiss Interferometry

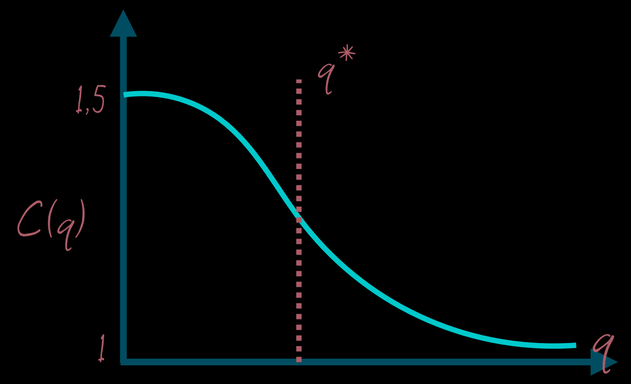


- Originally used to measure the size of astronomical light sources

  i.e. Cassiopeia A and Cygnus A

- How? $\delta x\, \delta p \gg 2\pi\hbar$ *Photons behave classically*

  $\delta x\, \delta p \lesssim 2\pi\hbar$ *Photons behave quantum*



- Quantum effects start at

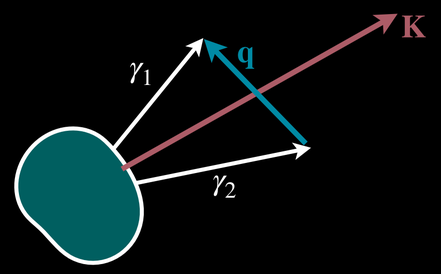
$$\delta x_{max} \sim 2R$$

$$q^* = \frac{\pi\hbar}{R}$$

- Pair variables

$$K^\mu = (K^0, K_\perp, 0, K^z)$$

$$q^\mu = (q^0, q_o, q_s, q_l)$$



A tale of two sources

"Base" Calculation +

Glauber IC's

VISH 2+1 Hydro evolution

Thermal QGP and Hadronic radiation*

Far-from-equilibrium Photons

-*Bottom-up*–like evolution + matching

-Pre-equilibrium photons are computed using kinetic rates , Phys.Rev. C95 (2017) no.5, 054904

OGM. *Annals Phys.* 443 (2022) 168984

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

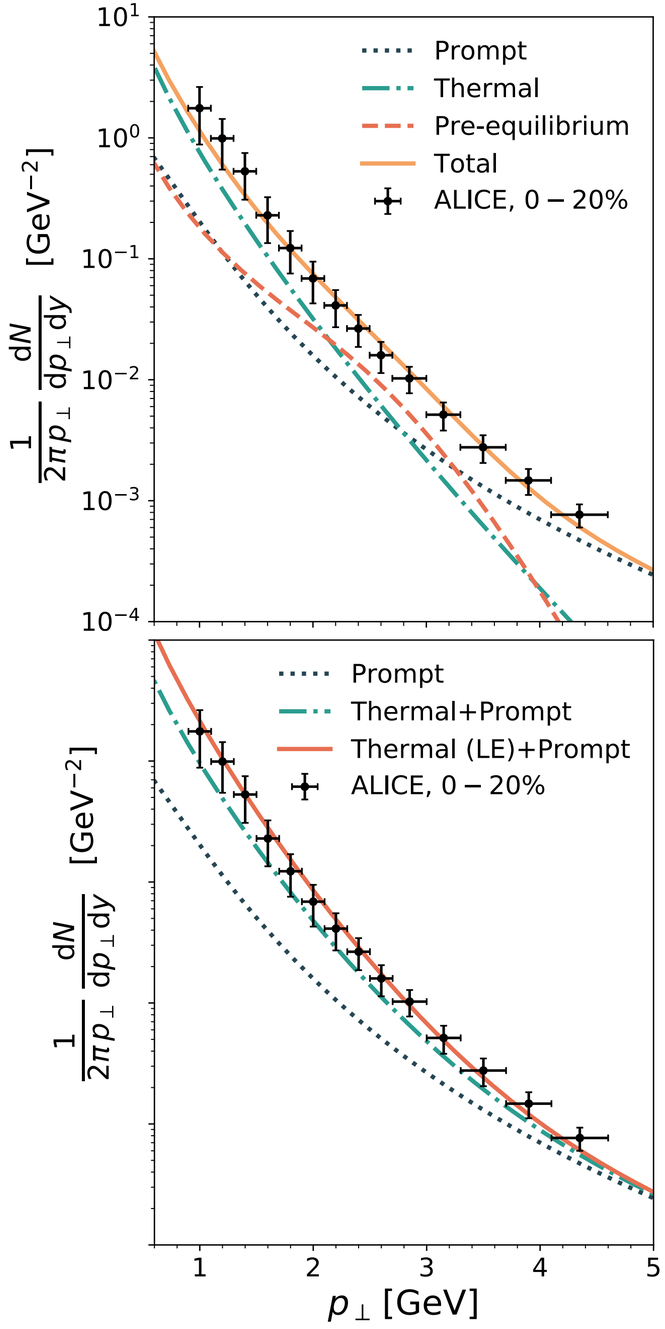
Pseudo-Critical Enhancement

-Phenomenological model.

-At hadronization, non-perturbative rise in partonic cross-sections (Nucl. Phys. A933, 256 (2015))

$$E\frac{\mathrm{d}N_{\mathrm{enh}}}{\mathrm{d}^4x\,\mathrm{d}^3p} \equiv h(T)\,E\frac{\mathrm{d}N_{\mathrm{thermal}}}{\mathrm{d}^4x\,\mathrm{d}^3p} \quad \text{and}$$

$$h(T) = 1 + h_0 \exp\left\{-\frac{(T-T_{pc})^2}{d^2}\right\}$$



*JHEP 12, 009 (2001)
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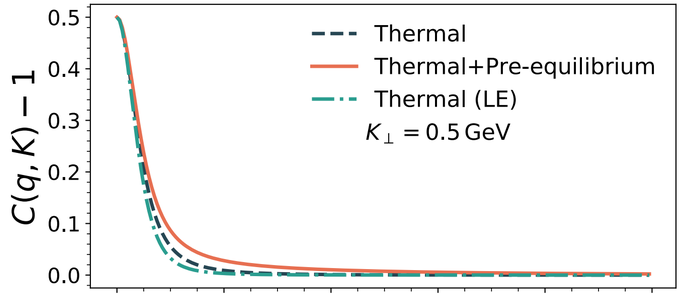
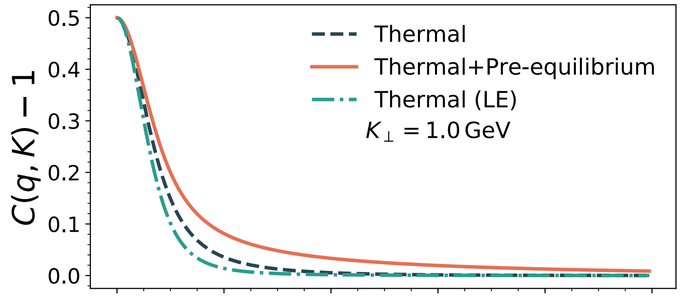
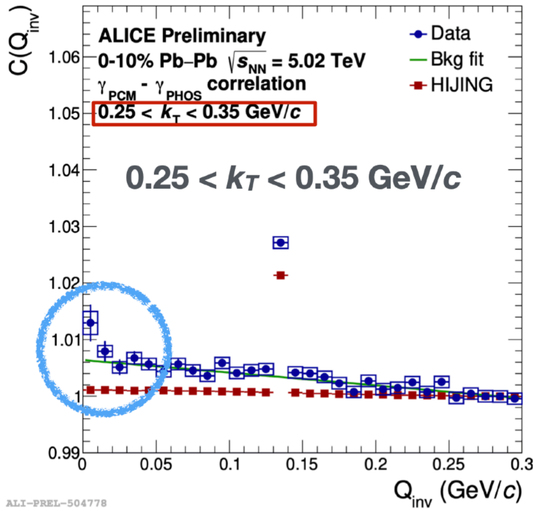




Comparison still needed

Decays dilute signal!



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The HBT-Radii

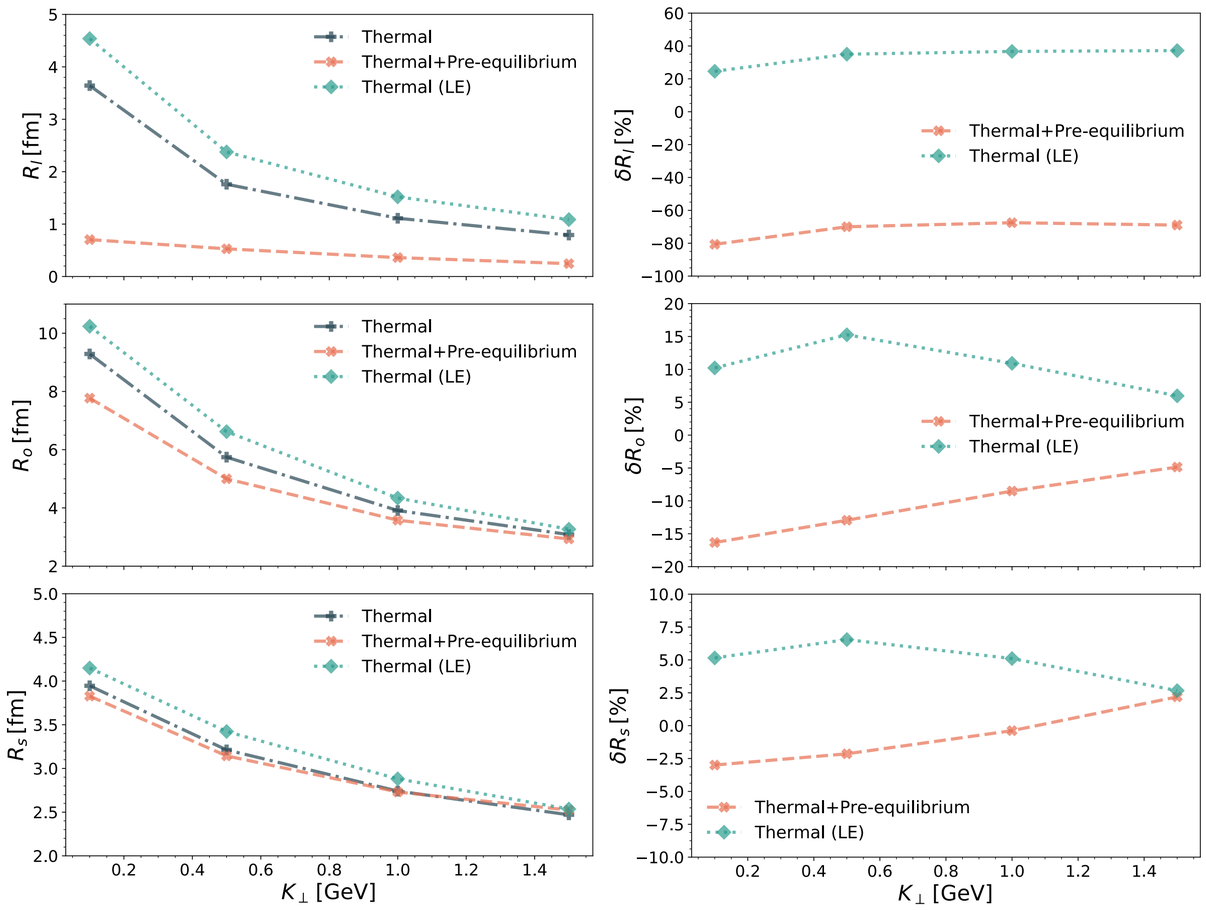
$$\langle\langle q_i q_j \rangle\rangle = \int \mathrm{d}^3 q \, q_i \, q_j \, g(q;K) \equiv \frac{1}{2}(R^{-1})_{ij}$$

$$g(q;K) \equiv \frac{C(q,K)-1}{\int \mathrm{d}^3 q \, [C(q,K)-1]}$$

Longitudinal direction affected the most by the inclusion of the sources.

Early-times production reduces effective radii, while late times increase it.

Are these differences enough to measure it?



SUMMARY

- Electromagnetic probes produced throughout space-time evolution of HICs; escape collision unscathed as they do not interact strongly with the QGP
- EM probes are carry sensitive information about the initial and early stages, which we can use to lear about the early evolution of the medium
- Late time non-equilibrium effects are significant for anisotropy generation
- Non-trivial to resolve the discrepancies in the photon observables
- Photon HBT can be the tool we use to cross-compare different models of photon production