# Direct photons in hot QCD matter what we learned and what we didn't (so far)

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Zimanyi Winter School Dec. 3-7, 2018 Budapest

### Hot QCD matter







Heavy ion collisions

Phase diagram

Initial hard scattering + medium (high p<sub>T</sub>)

"Thermal" radiation (low p<sub>T</sub>)



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#### Stages of a heavy ion collision



Fig. 1: Schematic representation of the various stages of a HIC as a function of time t and the longitudinal coordinate z (the collision axis). The 'time' variable which is used in the discussion in the text is the proper time  $\tau \equiv \sqrt{t^2 - z^2}$ , which has a Lorentz-invariant meaning and is constant along the hyperbolic curves separating various stages in this figure.

E. lancu, 1205.0579

#### Visualization of a heavy ion collision



Three basic photon sources: pQCD, QGP, hadron gas

### Direct photons: penetrating probe



#### Dominant photon sources: p<sub>T</sub> vs time (simplified)



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#### Azimuthal emission pattern – from spatial to momentum anisotropy

Shortest path to surface (vacuum): largest pressure gradient



Flow: Initial spatial anisotropy converts to momentum anisotropy  $(v_2)$ 



Red initial short pathlength Cyan long pathlength

#### $R_{\rm AA}$ wrt. reaction plane ~ $R_{\rm AA}$ wrt. path length

$$egin{aligned} \mathcal{R}_{ ext{AA}}(p_{ ext{T}},\Delta\Phi) &pprox \mathcal{R}_{ ext{AA}}(p_{ ext{T}}) imes rac{\mathcal{N}(p_{ ext{T}},\Delta\Phi)}{\sum_{i}\mathcal{N}(p_{ ext{T}},\Delta\Phi_{i})} \ \mathcal{N}(p_{ ext{T}},\Delta\Phi_{i}) &pprox \mathcal{N}(1+2v_{2}\cos(2\Delta\Phi_{i})) \end{aligned}$$

#### More sources...

Jet fragmentation, Jet-thermal interaction (jet-photon conversion) Initial magnetic field Bremsstrahlung (hadron gas) ...???

Obviously each new source makes the deconvolution from a single, integrated spectrum more difficult



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See e.g., Turbide, Gale, Jeon and

Moore, PRC 72, 014906 (2005)

#### Direct photons: basic processes



0<sup>0</sup>

π

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#### Ways to present direct photon results: spectrum, $\gamma/\pi$ and the $R\gamma$



## Ways to present effects of the medium: $T_{eff}$ , $R_{AA}$ , flow...





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### Some promises of direct, real photons

Binary scaling: proof of sanity  $\rightarrow$  is  $R_{AA}$  a robust observable, is the Glauber model valid? Jet energy scale,  $E_{loss} \rightarrow$  "calibrate" the initial energy of a hard scattered parton Initial temperature  $\rightarrow$  the inverse slope of the spectrum will be dominated by emission at earliest times Thermal radiation from the QGP  $\rightarrow$  does the QGP "outshine" the hadron gas – or vice versa? Time-dependent  $\eta/s \rightarrow ratios$  of Fourier-coefficients of azimuthal asymmetries of emission (not discussed) Initial magnetic field  $\rightarrow$  centrality dependence of emission anisotropies (not discussed) Role of initial state  $\rightarrow$  how fast is thermalization (briefly touched only) Initial geometry  $\rightarrow$  magnitude and centrality dependence of azimuthal asymmetries "Historians" of the entire collision, including expansion dynamics  $\rightarrow$  can various sources be isolated? Provide major surprises  $\rightarrow$  you bet!

#### Testing hot QCD matter: you need a reliable probe (pp)



Data well described by NLO calculations



## The basic question in AA collisions at high $p_T$

This factorization works well in p+p. What is different when relativistic nuclei collide?

Collinear factorization: separation of long and short distances



Are PDFs the same? And the relevant processes? (How) do partons lose energy in the medium? Any other change in the fragmentation? Leading particle: our favorite jet proxy



### High pT (isolated) photons are immune to the medium

In A+A collisions, while hadrons are strongly suppressed, and in a  $p_T$ -dependent way, photons appear to be unaffected

PHENIX PRL 109, 152302 (2012)



PRC 87, 054904 (2013)



Watch out for the slight deviation from unity due to the isospin effect
All right, this is MB, but stay tuned!
(And don't forget: centrality is non-trivial in very asymmetric collisions!)

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#### ATLAS, Pb+Pb

At midrapidity, consistent with 1; fw some depletion PbPb – includes isospin effect (n/p) - EPS09 includes neutron skin effect



ATLAS, PRC 93, 034914 (2016)

#### ATLAS, p+Pb

Photon R<sub>AA</sub> unity even for very asymmetric collisions (some deviation at high rapidity: gluon PDF's?)



### High pT photons: immune to the medium

Hard scattered partons lose energy → fragmentation hadrons are suppressed, but photons are insensitive to medium effects → will be the decisive tool or "centrality" in pA (small-on-large) collisions (*but that's a completely different talk -- GD, Pos(INPC2016)345*)



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### High pT photons: calibrating parton energy loss



Photon triggered hadron-correlations: fragmentation function proxy Dramatic change in Au+Au





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#### Low pT ("thermal") photons – RHIC, Au+Au

PHENIX, PRL 104, 132301 (2010)



Virtual photons. Note that this result is in "tension" with the published STAR result Real photons, measured with external conversion Consistent with virtual photon result (PHENIX)



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 $\left( \begin{array}{c} 0 \end{array} \right)$ 

#### Low pT ("thermal") photons – RHIC, LHC

Everybody sees some excess (apparently exponential) above simple scaled p+p – the argument is only how much is it – and what's the origin?

STAR, PLB 770 (2017) 451





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#### "Thermal" photons: is it really temperature?



Shown in a zillion different versions, same conclusion: direct photon spectra alone, while important, not sufficient constraint on temperature – or "temperature"...

#### Temperature, effective temperature, inverse slope

System evolution followed in a specific hydro model. Apparent inverse slope vs true instantaneous temperature. Size of blobs: instantaneous production rate.



#### *T*<sub>eff</sub>: where do you fit the spectra?

It's hard to argue that a single exponential is a good fit; which region do you fit anyway?



#### T<sub>eff</sub>: where do you fit the spectra?

Rate

**Hadron Gas** 

**sQGP** 

Remember: temperature, radial boost, dominant physics mechanisms – all change with time! Fitting the envelope of this convolved does not give you a simple, ordinary "temperature"!



## "Scaling"

Basic idea: compare photon yields in a wide range of colliding systems and energies; do it in terms of an experimental observable (dN<sub>ch</sub>/dη) rather than Glauber-based N<sub>part</sub> or N<sub>coll</sub>



### "Scaling"

Yields normalized by  $(dN_{ch}/d\eta)^{1.25}$ 



In this narrow range (0.9-2.0 GeV) one single exponential fits well across large range of collision energies



Integrated yields > 1.0 GeV/c From >CuCu to PbPb, 62 to 2760 GeV Large-on-large, very different from pp (or pA)

Most photons produced at late time, which is universal (as opposed to initial state?)

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### Before we get carried away...

We are talking about 2 orders of magnitude in integrated yield, about the same in dN<sub>ch</sub>/dη

Could you (or the data) differentiate between these two curves? (one is  $x^{1.2}$ , the other  $x + x^{4/3}$ suggesting two completely different underlying scenarios)

This second curve is similar to the one suggested by *Feinberg, 1974(!)* 

Also, it could be interpreted as an extra photon source proportional to volume \* lifetime



Principal message: photon production in AA over a large range of sizes and energies can be described empirically with a simple 2-parameter function!

#### The two curves are the two fits in the region of interest



#### Second and third order asymmetries



Higher frequencies are damped faster  $\rightarrow$  ratios of  $v_2/v_3$  for photons (earlier) vs hadrons (later) can provide a clue on viscosity

#### Photon "flow" – PHENIX / RHIC



Three methods, confirmed, now up to very high  $p_{T}$  (no flow, as expected)

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#### Photon "flow" – ALICE / LHC



Large systematics: the measurement lives or dies on  $R_{\gamma}$ 

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## The "direct photon puzzle" in a nutshell high yields and high v2 couldn't be reconciled (so far)

Issue since 2011

PRC 84, 054906 (2011)



#### "Direct photon puzzle" in a nutshell

- Thermal photons (HG+QGP),

#### pQCD with fireball scenario

- H.van Hees, C. Gale, R. Rapp PRC 84 054906 (2011)
- Include finite initial flow at thermalization
- Include resonance decays and hadronhadron scattering
- Blue shift of HG spectrum included

#### - Microscopic transport (PHSD)

- O. Linnyk, W. Cassing, E.L. Bratkovskaya, PRC 89, 034908 (2014)
- Parton-Hadron-String dynamics
- Include large contribution from hadron-hadron interaction in HG using Boltzmann transport
- Include thermal photons from QGP

#### - Enhanced emission from nonequilibrium effects (glasma, etc.)

- C. Gale et al., PRL114, 072301 + priv.comm. with Y Hidaka and J-F. Paquet
- Semi-QGP is the QGP near  $T_{\rm c}$
- Annihilation and Compton processes around hadronization time are naturally included
- Enhanced early emission from

#### magnetic field

- G. Basar, D. E. Kharzeev, V. Skokov, PRL 109 202303 (2012)
- Initial strong magnetic field produces anisotropy of photon emission
- magnetic field + thermal photons (lattice QCD)



### Plenty of new ideas

The main problem is at the heart of the "direct photon promise":

- while *hadronic* observables mostly *constrain* only your *final state* (but not much the dynamics how you got there) *direct photons* force you to get the *entire evolution* rates and expansion right at the same time
- nevertheless, any scenario in the end should explain *hadrons and photons* simultaneously!

*Initial state effects* – including nPDFs, pre-equilibrium processes, glasma, etc. became important players

Radiation from the *hadron phase* (even after decoupling) emphasized more and more

#### Role of the QGP deprecated???

- that's quite ironic: once upon a time we thought it is going to be the dominant source

Whatever the truth, current mainstream models emphasize

- either very early asymmetries and expansion, or very late production, or a combination of both

### *Promise open: "history"* → *differentiating between sources?*



Flow: Initial spatial anisotropy converts to momentum anisotropy  $(v_2)$ 



Cyan long pathlength



Sourc <b>es</b>	<b>p</b> <sub>T</sub>	V <sub>2</sub>	<b>v</b> <sub>3</sub>	v <sub>n</sub> t-dep.	0904.2184
Hadron-gas	$Low p_T$	Positi∨e and sizable	Positi∨e and sizable	$\rightarrow$	here School, Dec. 3-7, 2018 G. David, Stony Brook University
QGP	$Mid \ p_{T}$	Positive and small	Positive and small	~	
Primordial (jets)	High p <sub>⊤</sub>	~zero	~zero	$\rightarrow$	
Jet-Brems.	$Mid \ p_T$	Positive	?		
Jet-photon conversion	Mid p <sub>T</sub>	Negative	?		
Magnetic field	All p <sub>T</sub>	Positive down to p <sub>T</sub> =0	Zero	→ Zimanvi Win	

#### Electromagnetic Radiation from Hot and Dense Hadronic Matter (in pursuit of the "direct photon puzzle")



Castello di Trento ("Trint"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum,

#### Electromagnetic Radiation from Hot and Dense Hadronic Matter Trento, November 26-30, 2018

Main topics Electromagnetic radiation from hot and dense strongly interacting matter Status of our understanding of current experimental methods and results The "photon flow pumle" Progress in photon and dilegton production theory Printer experiments

#### Key-note participants

Yasuyuki Akiba (RIKEN, Japan), Frisderike Bock (CERN), Peter Brum-Minninger (GSI, Germany), Welfgang Cassing (ITP University Gissean, Germany), Araal Drees (Steey Brook University, USA), Hannah Elfare (GSI, Goeths University, FIAS, Germany), Tayana Galatyuk (TU Dammath/ GSI, Germany), Frank Geurs (Rice University, USA), Jacopo Ghiglieri (CERN), Morite Greif (Gooths University, Frankfurt, Germany), Headhi van Baes (Gooths University, Trankfurt, Germany), Norbert Novitzley (University of Turkeba, Japan), Ralf Rapp (Teans A&M University, USA), Klaus Raygere (Heidelberg University, Germany), Lipian Rum (Brookhavan National Laboratory, USA), Takao Sakaguchi (Brookhavan National Laboratory, USA), Johanna Stachal (Haidelberg University, Germany), Itahki Tsernya (Weizmann Institute, Iareal), Ginaluca Usai (University, Germany), Itahki Tsernya (Meizmann Institute, Iareal), Ginaluca Usai (University, Germany), Itahki Tsernya (Meizmann Institute, Iareal), Ginaluca Usai (University, Germany), Itahki Tsernya (Meizmann Institute, Iareal), Ginaluca Usai (University, Germany), Itahki Tsernya (Meizmann Institute, Iareal), Ginaluca Usai (University, Germany), Itahki Tsernya (Meizmann Institute, Iareal), Ginaluca Usai (University, Germany), Itahki Tsernya (Meizmann Institute, Iareal), Ginaluca Usai (University, Germany), Itahki Tsernya (Meizmann Institute, Iareal), Ginaluca Usai (University, Germany), Itahki Tsernya (Meizmann Institute, Iareal), Ginaluca Usai (University, Germany), Itahki Tsernya (Meizmann Institute, Iareal), Ginaluca Usai (University, Germany), Itahki Tsernya (Meizmann Institute, Iareal), Ginaluca Usai (University, Germany), Itahki Tsernya (Meizmann Institute, Iareal), Ginaluca Usai (University, Germany), Itahy)

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Director of the ECT\*. Professor Jochen Wambach (ECT\*

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BNL, 2012	https://www.bnl.gov/trw2012
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BNL, 2014	https://www.bnl.gov/tpd2014/
ECT*, 2015	http://www.ectstar.eu/node/1232
ECT*, 2018	http://www.ectstar.eu/node/4229

Talks: lots of time left for questions

Technical issues discussed in detail

Free discussions: feel free to improvise!

Let's give new momentum to the field: with p/d+A data the plot thickens!

#### ECT\* workshop, Lijuan Ruan (unofficial) PHENIX-STAR discrepancy in low pT photon yields

Slide 2-5: STAR internal conversion compared to PHENIX internal conversion



Plots from Norbert Novitzky.

Errors on STAR data not the same as those in STAR paper.

#### ECT\* workshop, Axel Drees (unofficial) RHIC and LHC same slope between 1-2 GeV

## **Scaled Spectra Divided by Common Fit**

• Data normalized to common fit 0.9 < p<sub>T</sub> < 2.1 GeV



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- Data similar in overlap region below 2 GeV
- Data not truly exponential
- For  $p_T > 2.5$  GeV developing  $\sqrt{s}$  dependence

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ECT\* workshop, Klaus Reygers (unofficial) Due to (correlated) errors the signiicance of non-zero v2 might be small (?)

Significance of the Deviation from the Null Hypothesis  $V_{2,dir} \equiv 0$ 



#### Some promises of direct, real photons

Binary scaling: proof of sanity  $\rightarrow$  *kept* 

Jet energy scale,  $E_{loss} \rightarrow kept$ 

Initial temperature → broken

Thermal radiation from the QGP  $\rightarrow$  **broken** 

Time-dependent  $\eta/s \rightarrow open$ 

Initial magnetic field  $\rightarrow$  open

Role of initial state  $\rightarrow$  open

Initial geometry  $\rightarrow$  open

"Historians" of the entire collision, including expansion dynamics  $\rightarrow$  very model-dependent so far

Provide major surprises → *kept, for sure!* 

# Summary

High p<sub>T</sub> region well understood

- $\rightarrow$  Glauber-model valid in large-on-large collisions
- → Will serve as centrality measure in small-on-large collisions (disclaimer: until now only partially accepted by the community)

Low p<sub>T</sub> region not well understood (extremely hard measurement)

- $\rightarrow$  substantial extra source (over pp) is unquestionable
- → origin (pre-equilibrium? QGP? hadron gas?) unclear
- $\rightarrow$  apparent simple behavior (2 parameters!) in a wide range of systems and energies surprising

Historians of the collision, but deconvolution is extremely hard

No relativistic heavy ion experiment is optimized for low p<sub>T</sub> real photons (not dileptons)

It's a challenging journey – and a dedicated real photon experiment would certainly help...