

# Hot and dense QCD in the LHC era and beyond: recent highlights

Elena G. Ferreiro

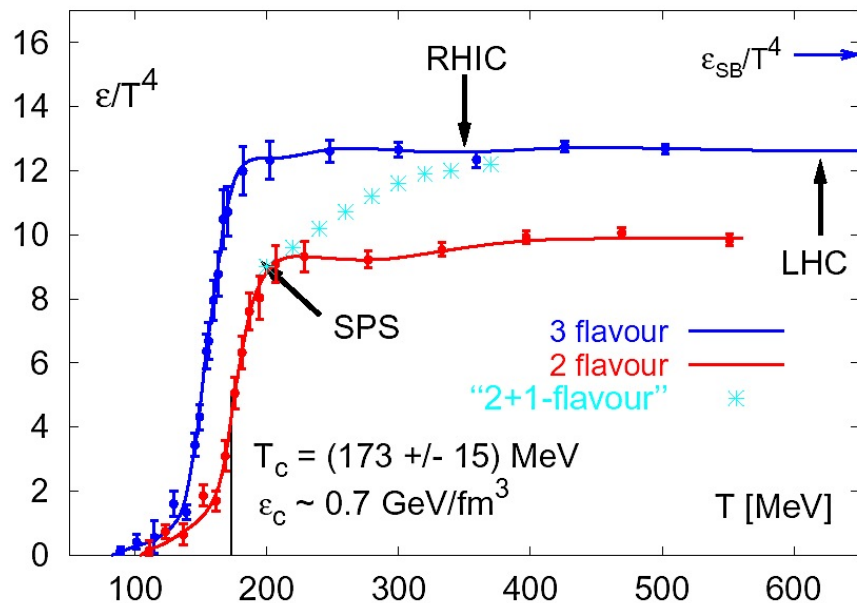
on behalf of Particle Physics Phenomenology Group (RL2)

*IGFAE, Universidade de Santiago de Compostela, Spain*

# Study hot and dense QCD matter: QGP search

- Starting point: Quantum Chromodynamics (QCD)
- QCD asymptotic freedom: Screening of long range confining potential at high  $T$  and/or  $\rho$ , appearance of new degrees of freedom
- Phase transition from “normal” nuclear matter to QGP: Xover, meaning that for temperatures around  $T_c$  the hadronic and QGP phases coexist

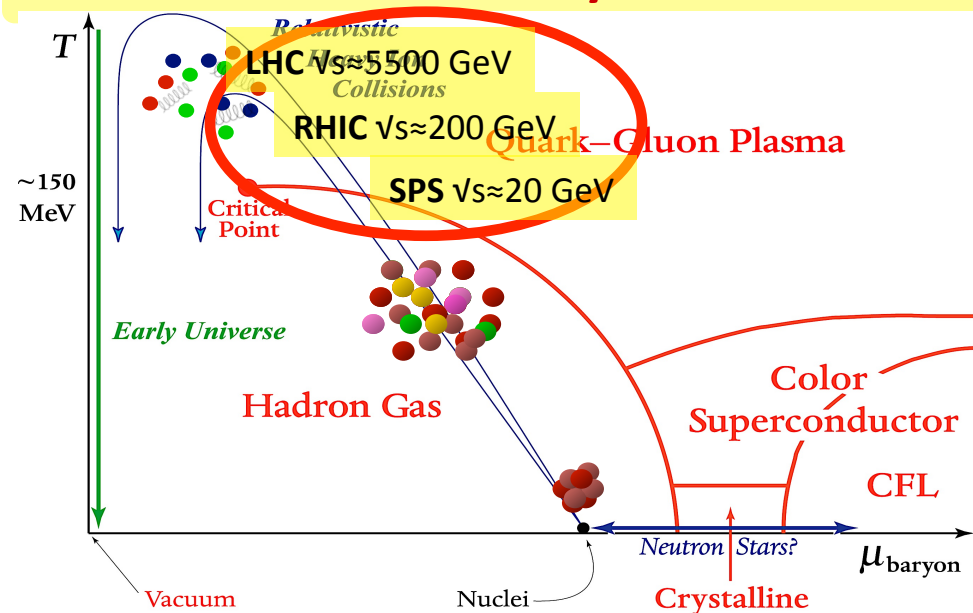
**L QCD: Phase transition  $T \sim 170$  MeV**  
**# d.o.f. increases x10 reaching 80%**  
**of the non-interacting gas limit**



**Where?:**

**in the Universe  $10^{-5}$  s after the Big-Bang**  
**in the core of neutron stars**

**in ultra-relativistic heavy ion collisions**



# QGP search: HIC programs

- First claim: **SPS/CERN (2000)** Pb+Pb @ 17.4 GeV



**A New State of Matter**

**Evidence for a new state of matter**

Home • Press release • Story • Science • Photos • Animations • Experiments

- Second claim: **RHIC/BNL (2006)** Au+Au @ 200 GeV

**Perfect fluid sQGP**



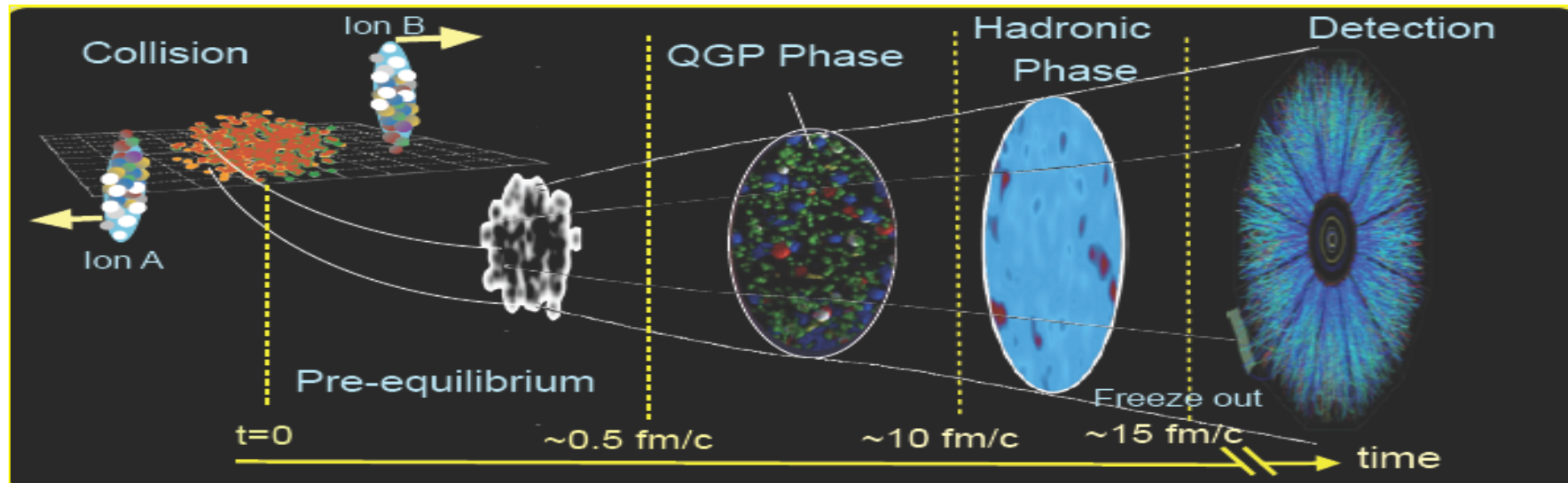
- At present: **LHC/CERN (2010-On)** Pb+Pb @ 2.76 & 5 TeV, p+Pb @ 5 & 8 TeV

**Confirmation & quantitative description**



- **Theoretical goal:** since our main understanding is experimental, we need to build a **coherent and quantitative theoretical picture**

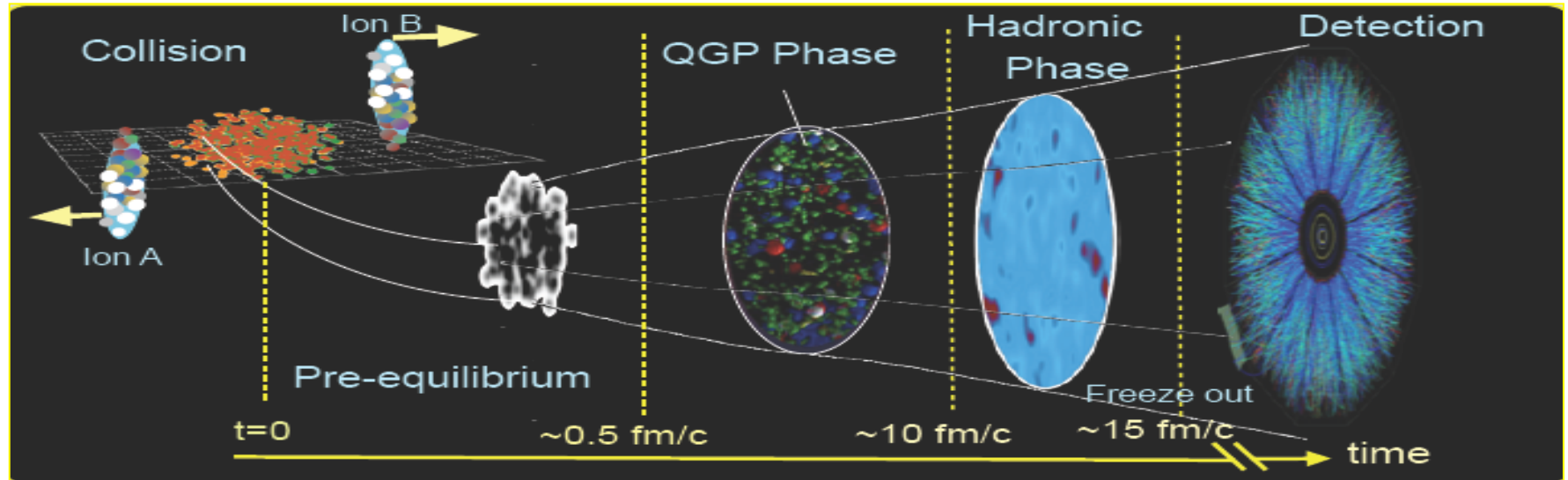
# Space-time picture of heavy ion collisions



The only way we can create the QGP in the laboratory!

- By colliding heavy ions it is possible to create a large ( $\gg 1 \text{ fm}^3$ ) zone of hot and dense QCD matter
- Goal is to create and study the properties of the Quark Gluon Plasma
- Experimentally mainly the final state particles are observed, so the conclusions have to be inferred via models

# Goal of HIC experiments: Study hot and dense QCD matter



**Bulk Observables:  $p \sim \langle p_t \rangle, T$   
~ 99% of detected particles**

Multiplicities

Thermal dileptons & direct photons

Asymmetries, correlations, fluctuations

Collective behavior of the medium

Initial conditions:  $T, \epsilon, \mu$

Thermalization and hydrodynamics

**Hard Probes:  $p \gg \langle p_t \rangle, T$   
~ 1% of detected particles**

Fast quarks and gluons

Jet quenching

Quarkonia dissociation

Medium tomography & diagnosis

Interpretation requires “vacuum”

(p+p) and “cold nuclear” (p+Pb)

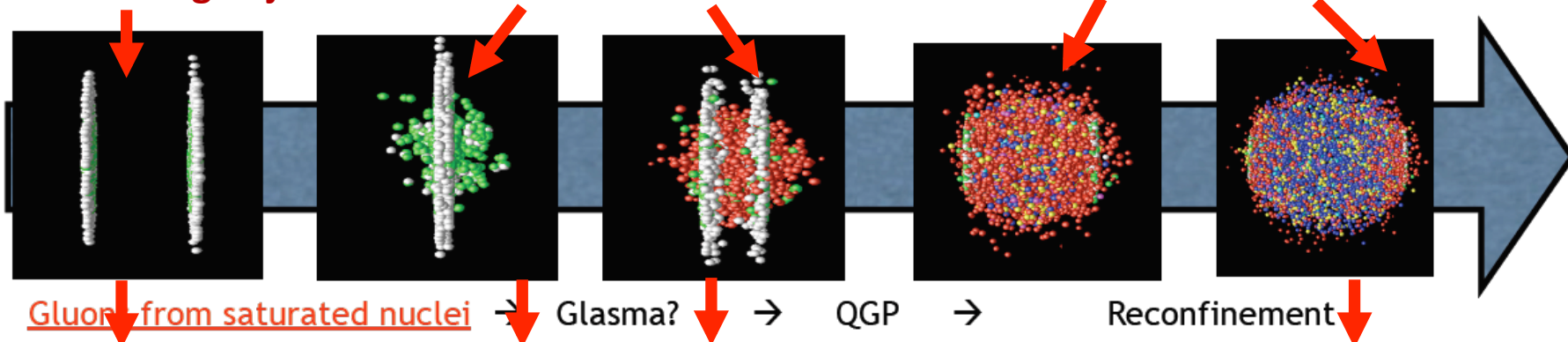
data at the same energy

# Some recent highlights I

The colliding objects

Early stages

Analyzing the medium



Hadron and nuclear wave function: **nPDF**  
Nonlinear evolution and saturation: **CGC**

Correlations (ridge): **CGC** approach and **string/parton** interactions as alternative to hydrodynamics in small systems.

Analysis of the medium through medium modifications of **jets** and **quarkonium**

*EPPS16: Nuclear parton distributions with LHC data*  
Eskola, Paakkinen, Paukkunen Salgado  
**Eur.Phys.J. C77 (2017)**  
& : arXiv:1802.00713

*Correlations and the ridge in the Color Glass Condensate beyond the glasma graph approximation*  
Altinoluk, Armesto, Wertepny  
**JHEP 1805 (2018) 207**

*Probing the time structure of the quark-gluon plasma with top quarks*  
Apolinário, Milhano, Salam, Salgado  
**Phys.Rev.Lett. 120 (2018) 232301**  
*Is bottomonium suppression in p-nucleus and nucleus-nucleus collisions at LHC energies due to the same effects?* Ferreiro, Lansberg **JHEP 1810 (2018) 094**

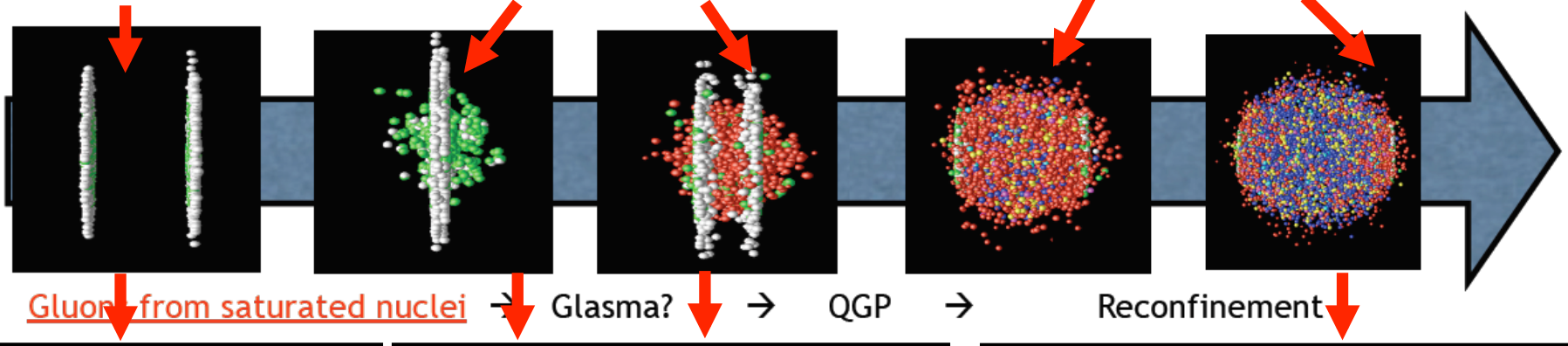


# Some recent highlights II

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Early stages

Analyzing the medium



Gluon from saturated nuclei

→ Glasma? →

QGP →

Reconfinement

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Analysis of the medium through medium modifications of **jets** and **quarkonium**

*Double and triple inclusive gluon production at mid rapidity: quantum interference in p-A scattering*  
Altinoluk, Armesto, Kovner, Lublinsky  
**Eur.Phys.J. C78 (2018) 9**

*Thermal behavior, entanglement entropy and parton distributions*  
Feal, Pajares, Vazquez  
**e-Print: arXiv:1809.04409**  
*Thermal behavior and entanglement in Pb-Pb and p-p collisions*  
**e-Print: arXiv:1805.12444**

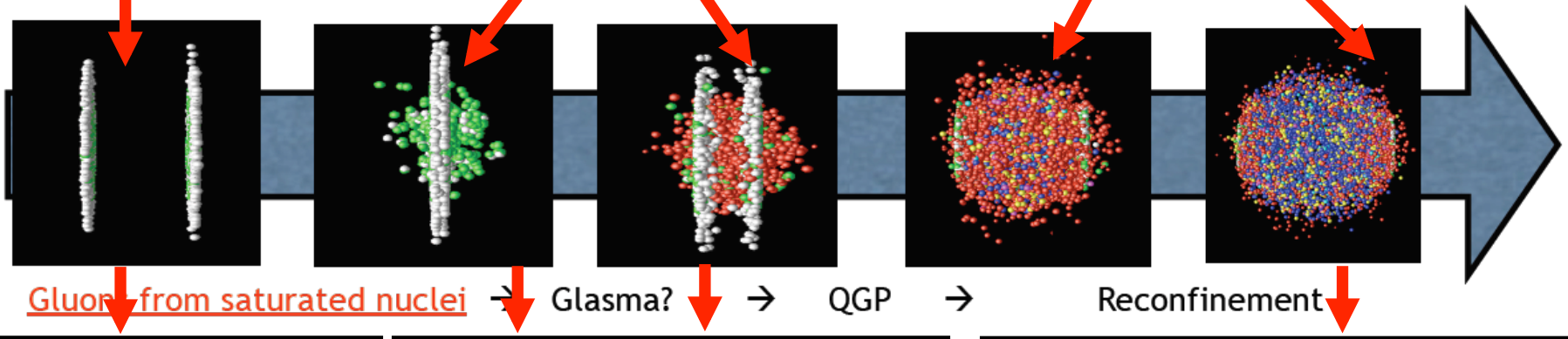
*Intensity of gluon bremsstrahlung in a finite plasma*  
Feal, Vazquez  
**Phys.Rev. D98 (2018) no.7, 074029**  
*Transverse spectrum of bremsstrahlung in finite condensed media*  
**Phys.Rev. D99 (2019) no.1, 016002**

# Some recent highlights: new techniques I

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Gluon from saturated nuclei

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QGP →

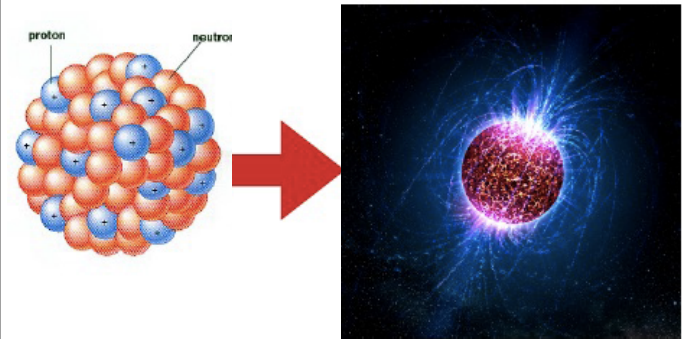
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Analysis of the medium through medium modifications of **jets** and **quarkonium**

Description of nuclear matter, from single nuclei to neutron stars, in effective models as the Skyrme model



*BPS sectors of the Skyrme model and their non-BPS extensions*  
 Adam, Foster, Krusch, Wereszczynski  
**Phys.Rev. D97 (2018) 036002**  
*Roper resonances and quasi-normal modes of Skyrmions*  
 Adam, Haberichter, Romanczukiewicz, Wereszczynski  
**JHEP 1803 (2018) 023**

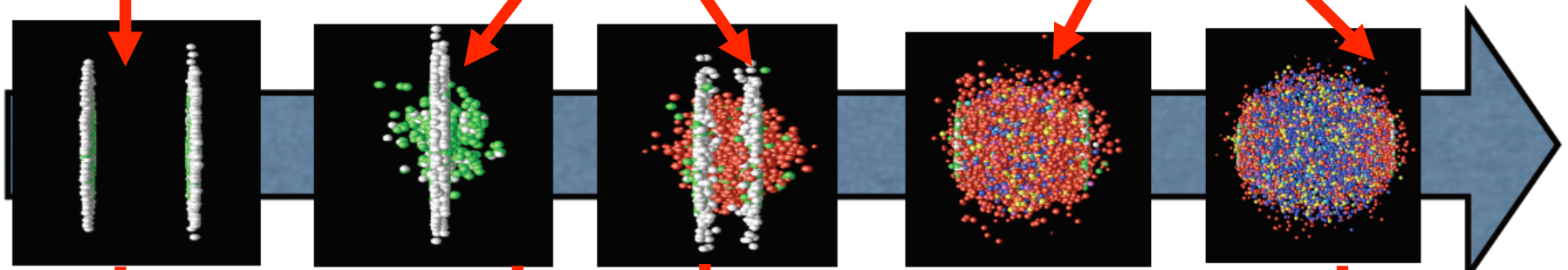


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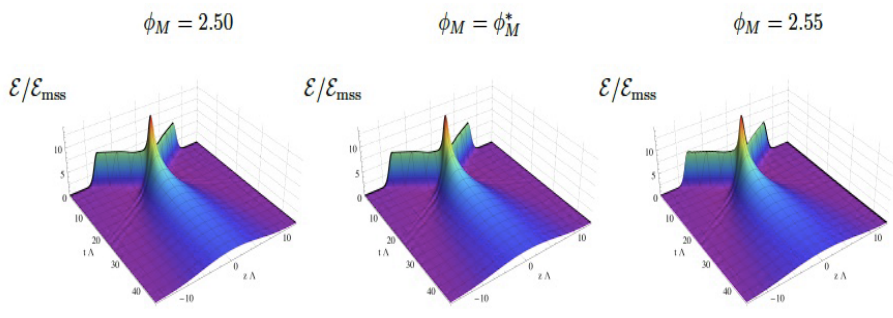
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Holography to analyse relativistic collisions in strongly coupled gauge theories with thermal phase transitions =>  
 \* new hydro formulation  
 \* QCD critical point



Spacetime evolution of the gauge theory energy density resulting from the collisions

*Holographic Collisions across a Phase Transition*  
 Attems, Bea, Casalderrey-Solana, Mateos, Triana, Zilhao  
**Phys.Rev.Lett. 121 (2018) 26, 261601**

- Total number of citations according to inspire: more than 150
- Participation of IACs: Quark Matter, Hard Probes, Initial Stages...
- Plenary talks: Quark Matter 2018, Deep Inelastic Scattering 2018, Hard Probes 2018...
- Participation in the proposals for future experiments:
  - LHeC
  - FCC
  - AFTER@LHC
- *Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams* (Report from Working Group 5 of the Workshop on the Physics of the CERN HL-LHC, and Perspectives at the HE-LHC)
- Outreach: talks in Galician & French high schools, Naukas

# Relations

