DIS2018: Discussion for document preparation for the European Strategy Update for Particle Physics
Kobe, April 17th 2018

# Heavy Ion Theory (addressed in the above facilities)


Néstor Armesto
*Departamento de Física de Partículas and IGFAE*
*Universidade de Santiago de Compostela*
nestor.armesto@usc.es

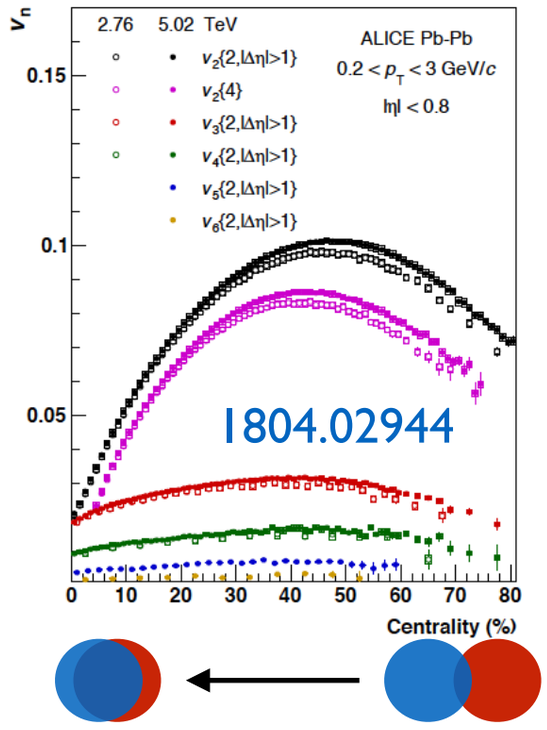


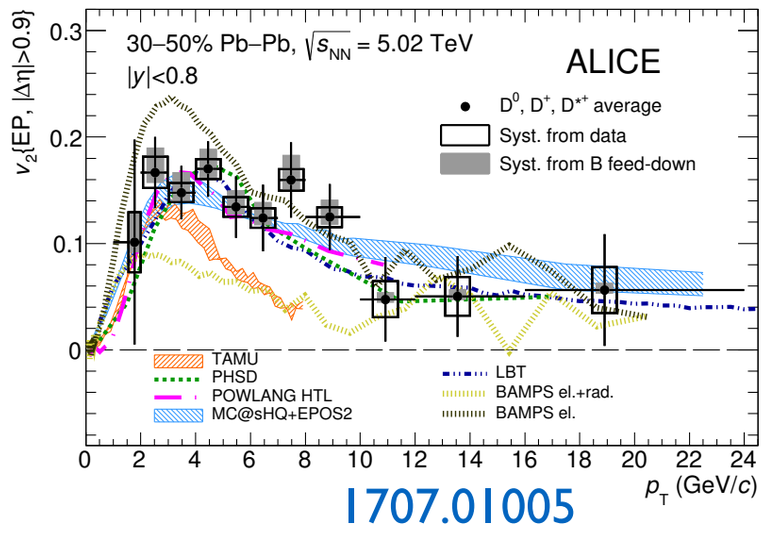
Unión Europea
Fondo Europeo de Desarrollo Regional "Una manera de hacer Europa"
EXCELENCIA MARÍA DE MAEZTU
GOBIERNO DE ESPANA MINISTERIO DE ECONOMIA Y COMPETITIVIDAD
XUNTA DE GALICIA

# Status of Heavy Ions:

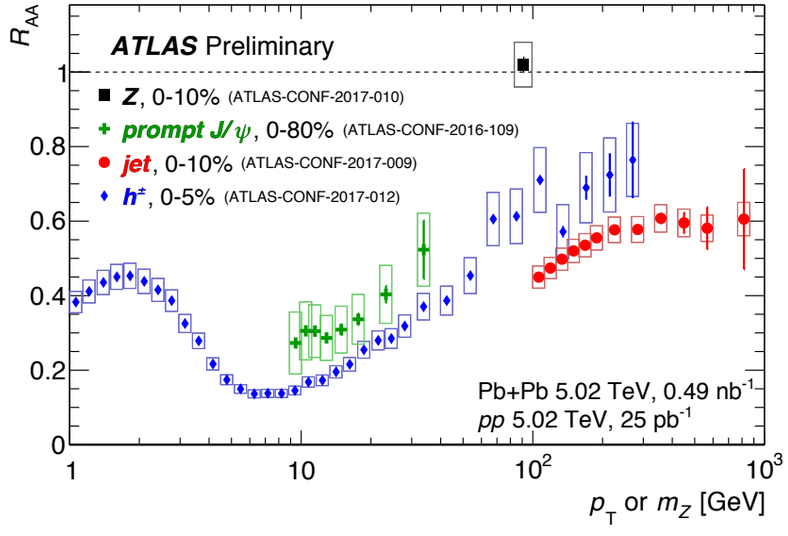
- **HI programme**: QCD at extreme conditions of T & ρ.
- Current status: matter created at RHIC and the LHC, with energy densities > those expected in lattice QCD for deconfinement/χSBR,

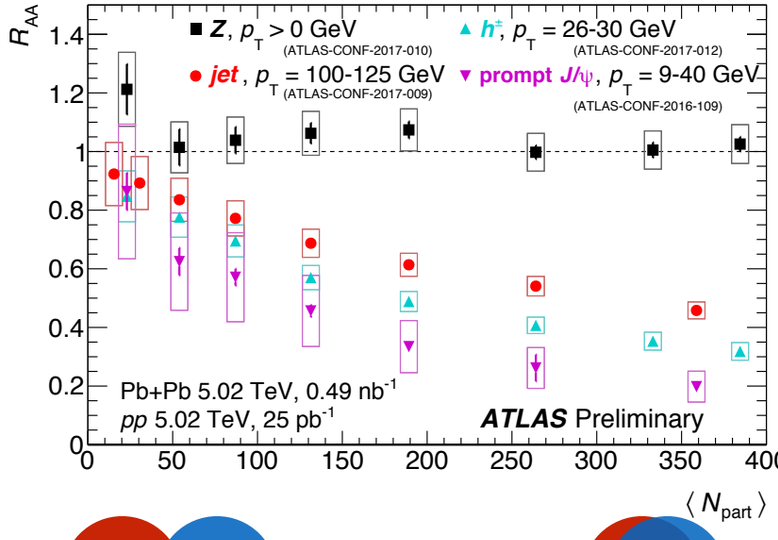
**1)** Shows collective features in the soft sector that are well described by relativistic hydrodynamics if applied very early (≲ 1 fm/c) after the collision, suggesting ≈ equilibration.




**2)** Is very opaque to energetic partons/particles traversing it: strong modification of the yield of hard probes like high-$p_T$ particles, jets, quarkonia.



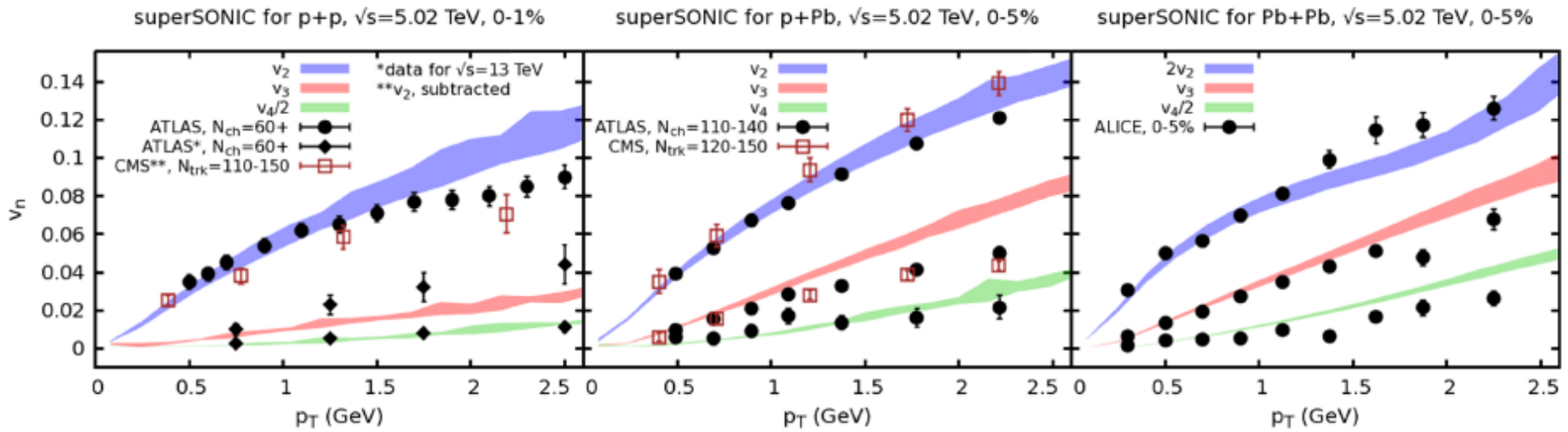
# Open questions:

- Why is the medium describable by hydrodynamics (so early) <u>even in small systems</u> (that show QGP-like features)? [emergence]

1602.09138

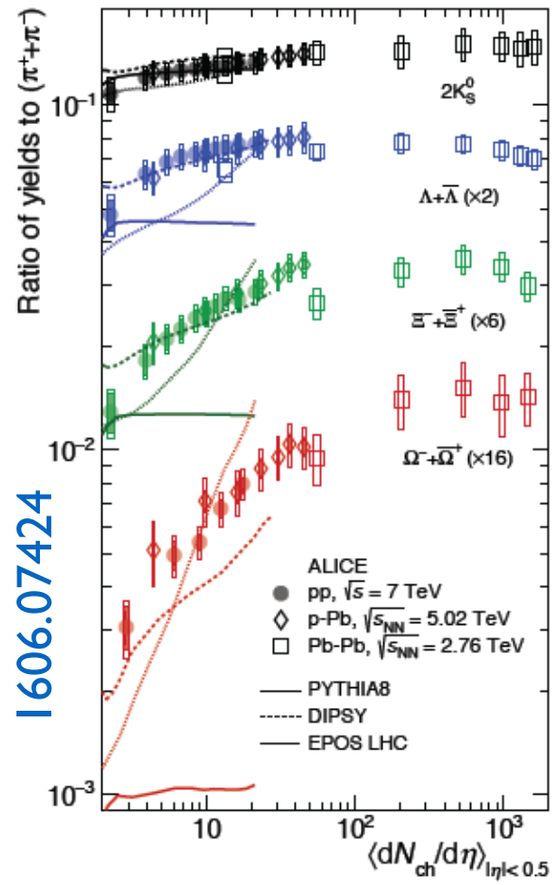
| Observable or effect | PbPb | pPb (at high mult.) | pp (at high mult.) | Refs. |
|---|---|---|---|---|
| Low $p_T$ spectra ("radial flow") | yes | yes | yes | [37–42] |
| Intermed. $p_T$ ("recombination") | yes | yes | yes | [41–47] |
| Particle ratios<br>Statistical model | GC level<br>$\gamma_s^{GC} = 1$, 10–30% | GC level except $\Omega$<br>$\gamma_s^{GC} \approx 1$, 20–40% | GC level except $\Omega$<br>$\gamma_s^{C} < 1$, 20–40% [2] | [48–51]<br>[52] |
| HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$) | $R_{out}/R_{side} \approx 1$ [3] | $R_{out}/R_{side} \lesssim 1$ | $R_{out}/R_{side} \lesssim 1$ | [53–59] |
| Azimuthal anisotropy ($v_n$)<br>(from two part. correlations) | $v_1 - v_7$ | $v_1 - v_5$ | $v_2$, $v_3$ | [25–27]<br>[60–67] |
| Characteristic mass dependence | $v_2$, $v_3$ [4] | $v_2$, $v_3$ | $v_2$ | [67–73] |
| Directed flow (from spectators) | yes | no | no | [74] |
| Higher order cumulants<br>(mainly $v_2\{n\}$, $n \geq 4$) | "$4 \approx 6 \approx 8 \approx$ LYZ"<br>+higher harmonics | "$4 \approx 6 \approx 8 \approx$ LYZ"<br>+higher harmonics | "$4 \approx 6$" [5] | [28, 29, 67]<br>[75–83] |
| Weak $\eta$ dependence | yes | yes | not measured | [83–90] |
| Factorization breaking | yes ($n = 2, 3$) | yes ($n = 2, 3$) | not measured | [91] |
| Event-by-event $v_n$ distributions | $n = 2 - 4$ | not measured | not measured | [92] |
| Event plane and $v_n$ correlations | yes | not measured | not measured | [93–95] |
| Direct photons at low $p_T$ | yes | not measured | not measured [6] | [96] |
| Jet quenching | yes | not observed [7] | not measured [8] | [97–105] |
| Heavy flavor anisotropy | yes | hint [9] | not measured | [106–109] |
| Quarkonia | J/$\psi$ $\uparrow$, $\Upsilon$ $\downarrow$ | suppressed | not measured [8] | [110–116] |

# Open questions:



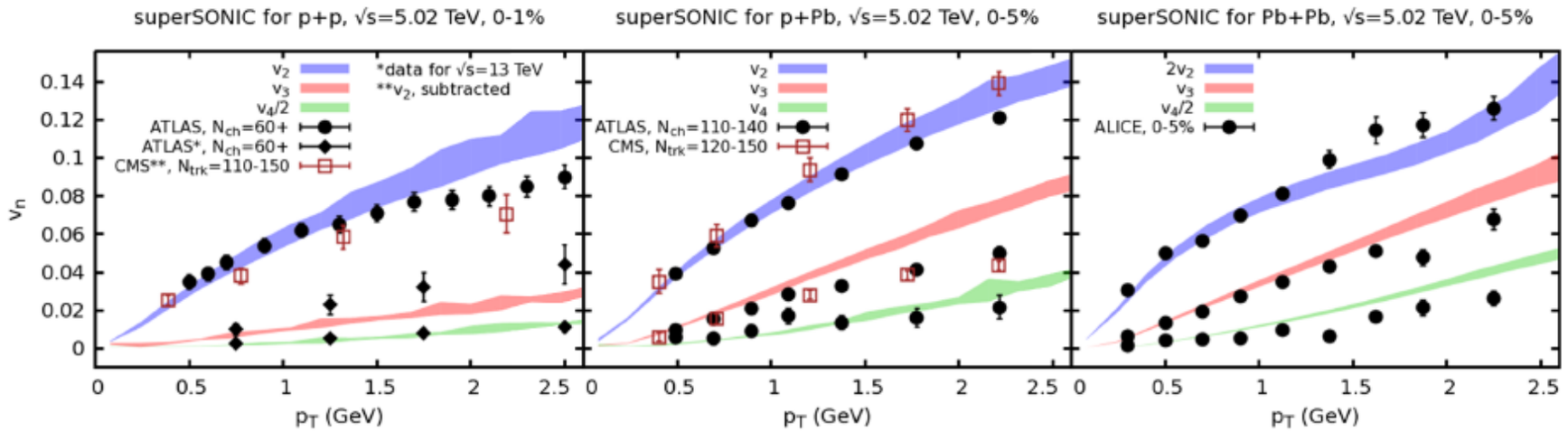

1701.07145, proton as 3 hot spots

FIG. 2. Elliptic ($v_2$), triangular ($v_3$) and quadrupolar ($v_4$) flow coefficients from superSONIC simulations (bands) compared to experimental data from ATLAS, CMS and ALICE (symbols) for p+p (left panel), p+Pb (center panel) and Pb+Pb (right panel) collisions at $\sqrt{s} = 5.02$ TeV [58–62]. Simulation parameters used were $\frac{\eta}{s} = 0.08$ and $\frac{\zeta}{s} = 0.01$ for all systems. Note that ATLAS results for $v_3, v_4$ are only available for $\sqrt{s} = 13$ TeV, while all simulation results are for $\sqrt{s} = 5.02$ TeV.



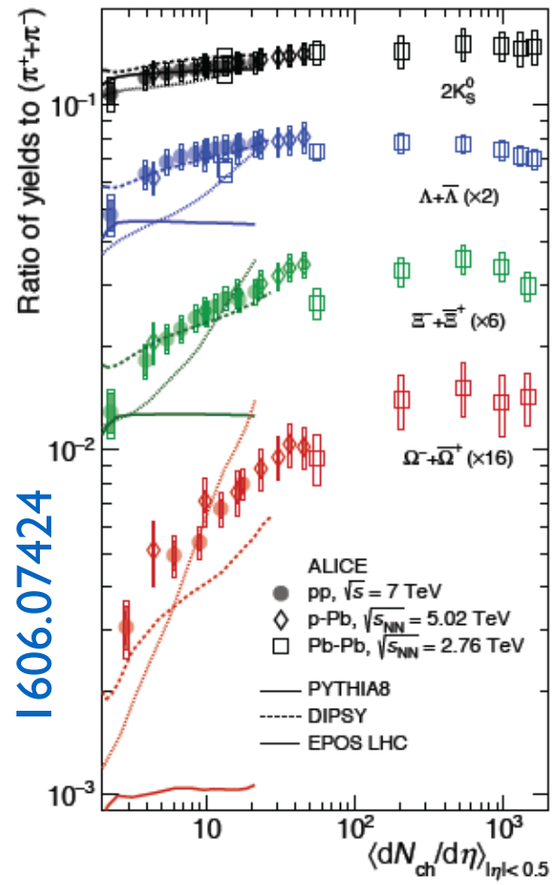

1606.07424

# Open questions:




1701.07145, proton as 3 hot spots

FIG. 2. Elliptic ($v_2$), triangular ($v_3$) and quadrupolar ($v_4$) flow coefficients from superSONIC simulations (bands) compared to experimental data from ATLAS, CMS and ALICE (symbols) for p+p (left panel), p+Pb (center panel) and Pb+Pb (right panel) collisions at $\sqrt{s} = 5.02$ TeV [58–62]. Simulation parameters used were $\frac{\eta}{s} = 0.08$ and $\frac{\zeta}{s} = 0.01$ for all systems. Note that ATLAS results for $v_3, v_4$ are only available for $\sqrt{s} = 13$ TeV, while all simulation results are for $\sqrt{s} = 5.02$ TeV.




1606.07424

- How does it get ≈isotropised? Weak or strong coupling dynamics?
- How to reduce the uncertainty in the extraction of QCD medium parameters?

  ➜ Initial conditions for collective behaviour (nuclear wave function, transverse hadron structure, factorisation - if any - to compute initial parton production,…).

  ➜ Modification of perturbative processes in a medium versus medium response for hard probes.

# Future apart from eA:

B. Müller

- RHIC: RHIC-II, Beam Energy Scan: 10 times statistics, improved vertex and calorimetry, sPHENIX.

| Year | Species | Goals |
|---|---|---|
| 2019 | Au+Au | High Statistics Beam Energy Scan: Search for QCD Critical Point<br>Collider mode: $\sqrt{s_{NN}}$ = 11.5, 14.5, 19.6 GeV<br>Fixed target: 3.0, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV |
| 2020 | Au+Au | High Statistics Beam Energy Scan: Search for QCD Critical Point<br>Collider mode: $\sqrt{s_{NN}}$ = 7.7, 9.1 GeV |
| 2021 | Au+Au<br>p+p/Au | Completion of high statistics beam energy scan (?)<br>Forward measurements in p+p and p+Au (?) |
| 2022 | No run | sPHENIX installation |
| 2023 | Au+Au | sPHENIX Commissioning<br>Single jet, di-jet, photon-tagged jet, *b*-tagged jet spectra<br>Di-jet asymmetry, Upsilon spectra |
| 2024 | p+p<br>p+Au | Reference data for modification of jets, di-jets, *b*-tagged jets<br>Jet $A_{LL}$<br>Reference data for cold nuclear matter effects |
| 2025 | Au+Au | Direct photon measurement<br>Study of flavor dependence of jet observables<br>Modification of jet fragmentation functions, jet splitting functions, other complex jet observables |

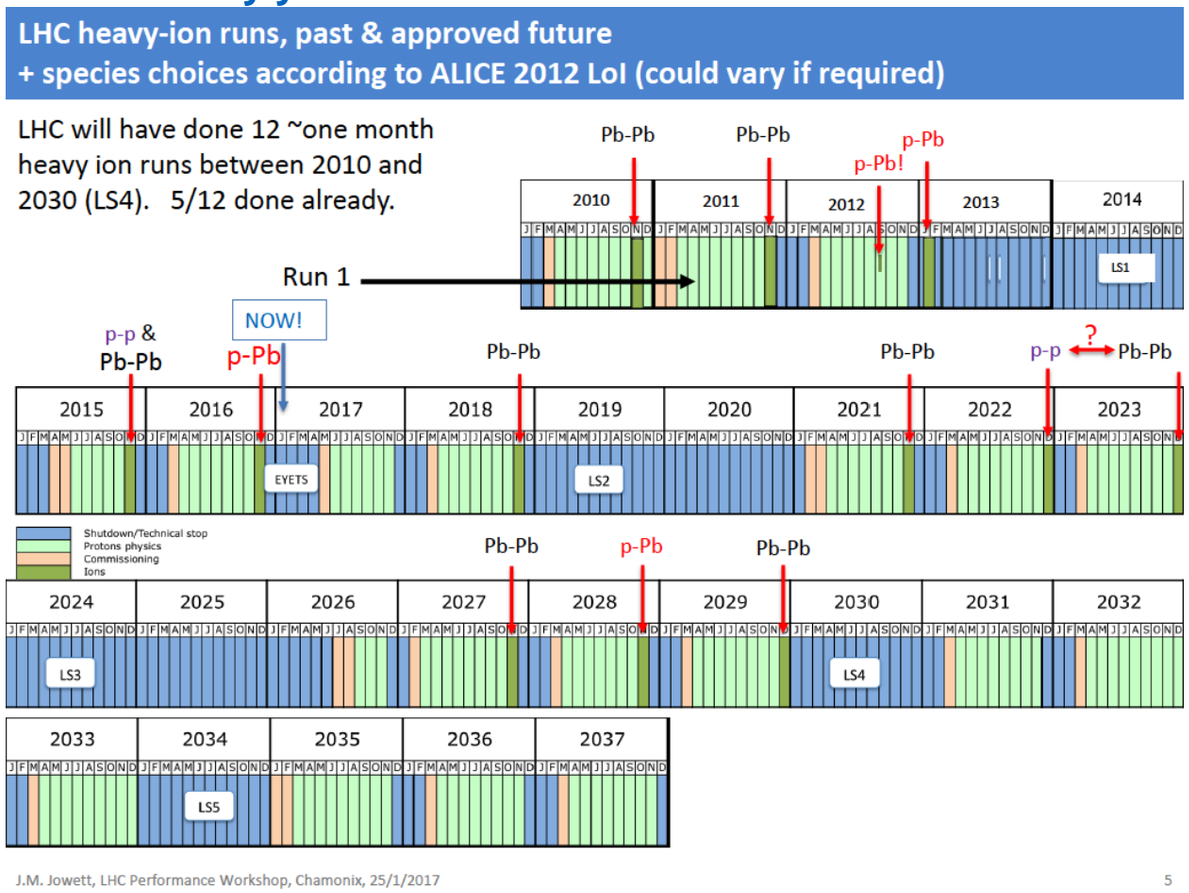
# Future apart from eA:

B. Müller

- RHIC: RHIC-II, Beam Energy Scan: 10 times statistics, improved vertex and calorimetry, sPHENIX.

| Year | Species | Goals |
|---|---|---|
| 2019 | Au+Au | High Statistics Beam Energy Scan: Search for QCD Critical Point<br>Collider mode: $\sqrt{s_{NN}}$ = 11.5, 14.5, 19.6 GeV<br>Fixed target: 3.0, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV |
| 2020 | Au+Au | High Statistics Beam Energy Scan: Search for QCD Critical Point<br>Collider mode: $\sqrt{s_{NN}}$ = 7.7, 9.1 GeV |
| 2021 | Au+Au<br>p+p/Au | Completion of high statistics beam energy scan (?)<br>Forward measurements in p+p and p+Au (?) |
| 2022 | No run | sPHENIX installation |
| 2023 | Au+Au | sPHENIX Commissioning<br>Single jet, di-jet, photon-tagged jet, *b*-tagged jet spectra<br>Di-jet asymmetry, Upsilon spectra |
| 2024 | p+p<br>p+Au | Reference data for modification of jets, di-jets, *b*-tagged jets<br>Jet $A_{LL}$<br>Reference data for cold nuclear matter effects |
| 2025 | Au+Au | Direct photon measurement<br>Study of flavor dependence of jet observables<br>Modification of jet fragmentation functions, jet splitting functions, other complex jet observables |

J. Jowett in Chamonix 2017




- LHC 2018 and Run 3 and 4 (HL-LHC for ions), 10 $nb^{-1}$ integrated luminosity in PbPb per experiment (ALICE, ATLAS, CMS), discussions about how many pp and pPb runs, smaller ions, fixed target program (LHCb, ALICE, AFTER).

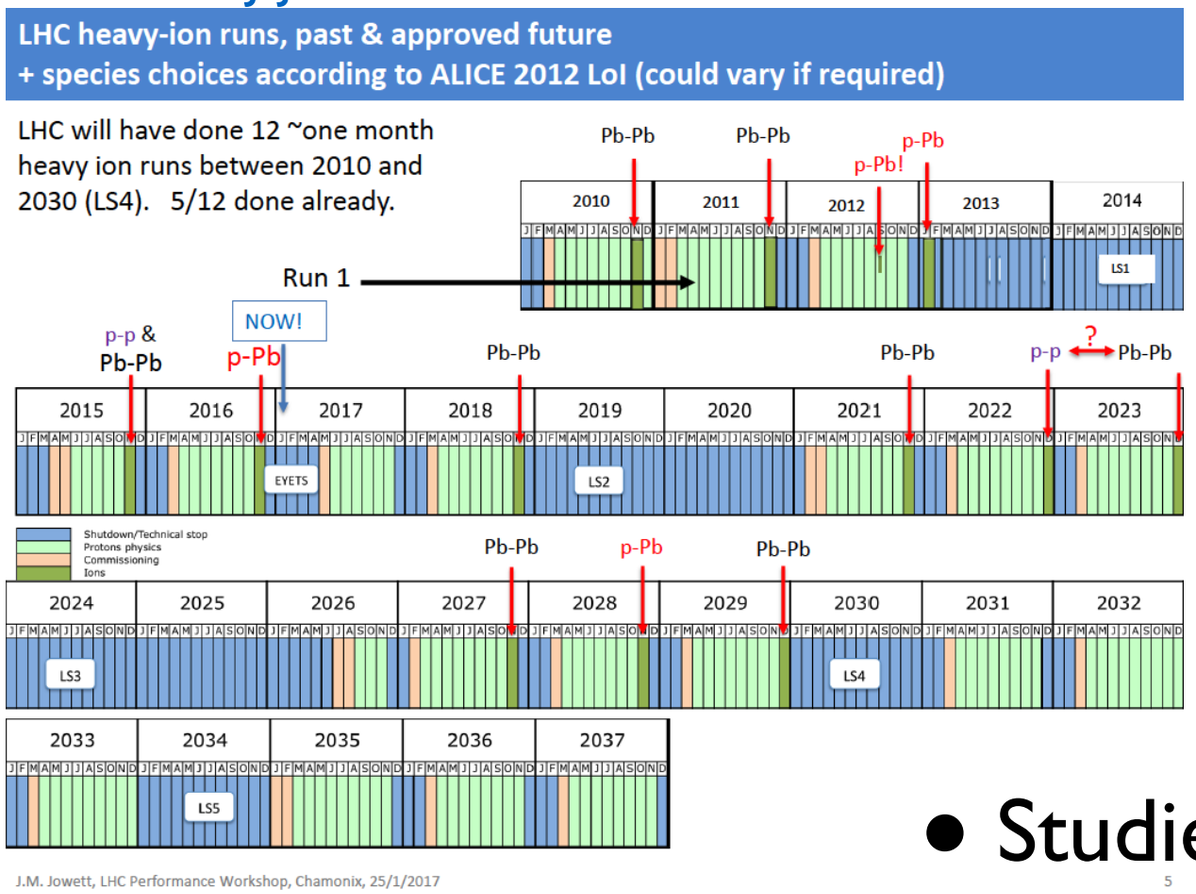
# Future apart from eA:

B. Müller

- RHIC: RHIC-II, Beam Energy Scan: 10 times statistics, improved vertex and calorimetry, sPHENIX.

| Year | Species | Goals |
|---|---|---|
| 2019 | Au+Au | High Statistics Beam Energy Scan: Search for QCD Critical Point<br>Collider mode: $\sqrt{s_{NN}}$ = 11.5, 14.5, 19.6 GeV<br>Fixed target: 3.0, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV |
| 2020 | Au+Au | High Statistics Beam Energy Scan: Search for QCD Critical Point<br>Collider mode: $\sqrt{s_{NN}}$ = 7.7, 9.1 GeV |
| 2021 | Au+Au<br>p+p/Au | Completion of high statistics beam energy scan (?)<br>Forward measurements in p+p and p+Au (?) |
| 2022 | No run | sPHENIX installation |
| 2023 | Au+Au | sPHENIX Commissioning<br>Single jet, di-jet, photon-tagged jet, *b*-tagged jet spectra<br>Di-jet asymmetry, Upsilon spectra |
| 2024 | p+p<br>p+Au | Reference data for modification of jets, di-jets, *b*-tagged jets<br>Jet $A_{LL}$<br>Reference data for cold nuclear matter effects |
| 2025 | Au+Au | Direct photon measurement<br>Study of flavor dependence of jet observables<br>Modification of jet fragmentation functions, jet splitting functions, other complex jet observables |

J. Jowett in Chamonix 2017



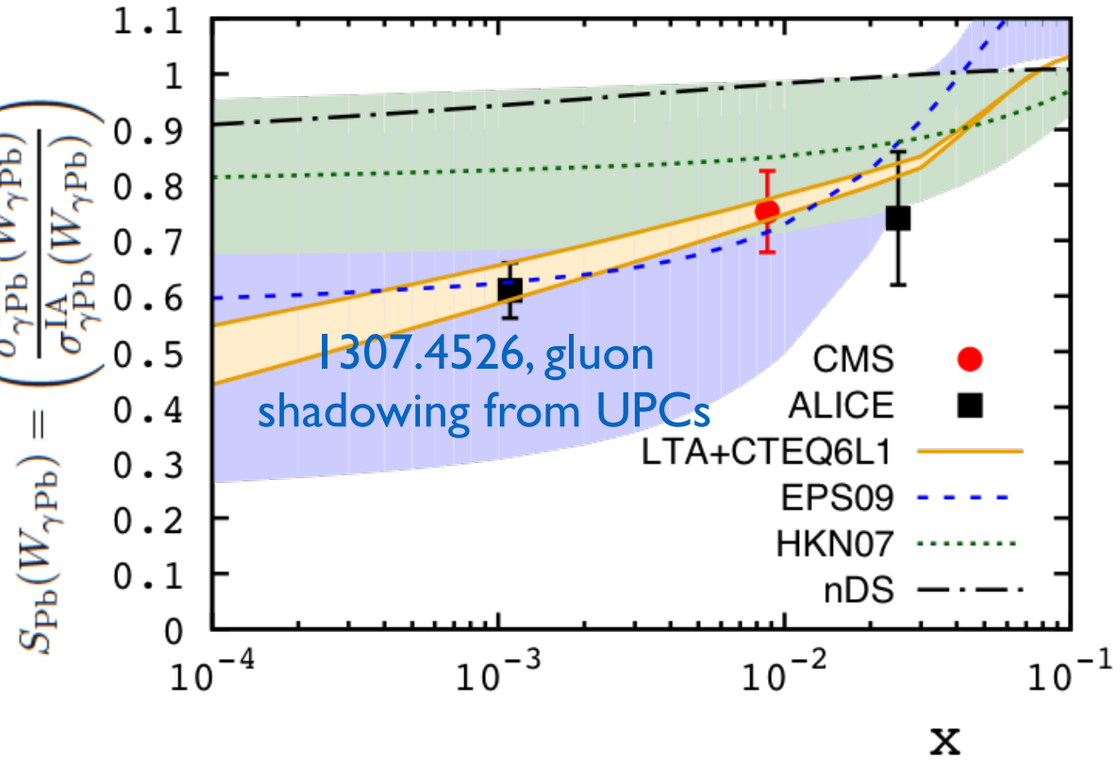

- LHC 2018 and Run 3 and 4 (HL-LHC for ions), 10 $nb^{-1}$ integrated luminosity in PbPb per experiment (ALICE, ATLAS, CMS), discussions about how many pp and pPb runs, smaller ions, fixed target program (LHCb, ALICE, AFTER).
- Studies of AA @ HE-LHC & FCC (1605.01389).

# Future apart from eA:

B. Müller

| Year | Species | Goals |
|---|---|---|
| 2019 | Au+Au | High Statistics Beam Energy Scan: Search for QCD Critical Point<br>Collider mode: $\sqrt{s_{NN}}$ = 11.5, 14.5, 19.6 GeV<br>Fixed target: 3.0, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV |
| 2020 | Au+Au | High Statistics Beam Energy Scan: Search for QCD Critical Point<br>Collider mode: $\sqrt{s_{NN}}$ = 7.7, 9.1 GeV |
| 2021 | Au+Au<br>p+p/Au | Completion of high statistics beam energy scan (?)<br>Forward measurements in p+p and p+Au (?) |
| 2022 | No run | sPHENIX installation |
| 2023 | Au+Au | sPHENIX Commissioning<br>Single jet, di-jet, photon-tagged jet, *b*-tagged jet spectra<br>Di-jet asymmetry, Upsilon spectra |
| 2024 | p+p<br>p+Au | Reference data for modification of jets, di-jets, *b*-tagged jets<br>Jet $A_{LL}$<br>Reference data for cold nuclear matter effects |
| 2025 | Au+Au | Direct photon measurement<br>Study of flavor dependence of jet observables<br>Modification of jet fragmentation functions, jet splitting functions, other complex jet observables |

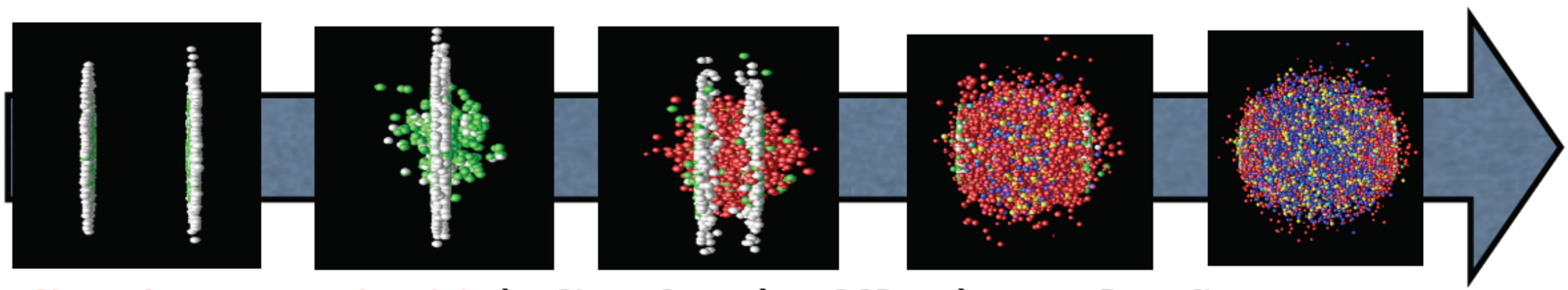
- RHIC: RHIC-II, Beam Energy Scan: 10 times statistics, improved vertex and calorimetry, sPHENIX.




- LHC 2018 and Run 3 and 4 (HL-LHC for ions), 10 $nb^{-1}$ integrated luminosity in PbPb per experiment (ALICE, ATLAS, CMS), discussions about how many pp and pPb runs, smaller ions, fixed target program (LHCb, ALICE, AFTER).
- Studies of AA @ HE-LHC & FCC (1605.01389).
- Present pPb / UPC data do not have a large impact (e.g. on nPDFs in EPPS16; uncertainties?), discussions undergoing (LHCb, ALICE FoCal): forward γ, jets and correlations / jets and exclusive VMs.

# What eA can contribute:

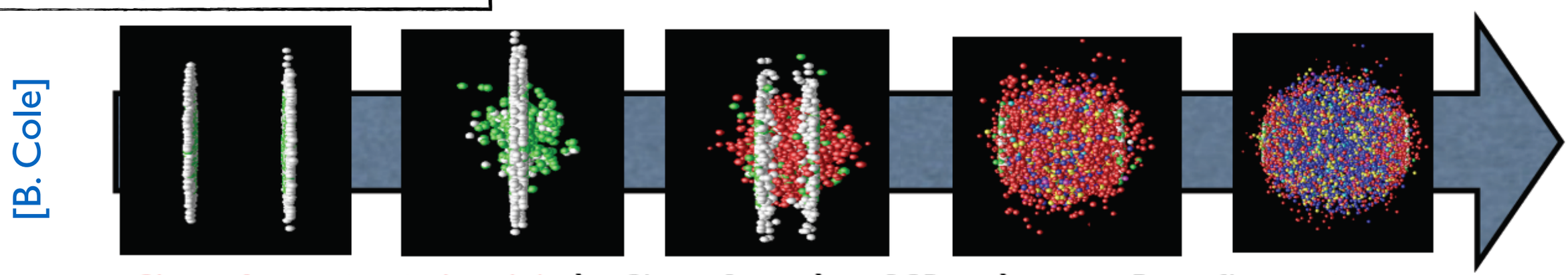
[B. Cole]



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

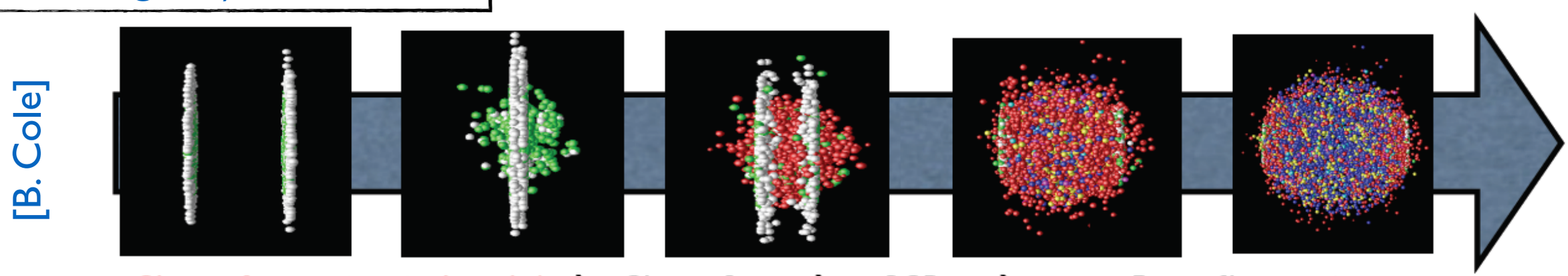
# What eA can contribute:

- Nucleus ≠ Zp+(A-Z)n.
- Particle production at large scales similar to pp (dilute regime).



# What eA can contribute:

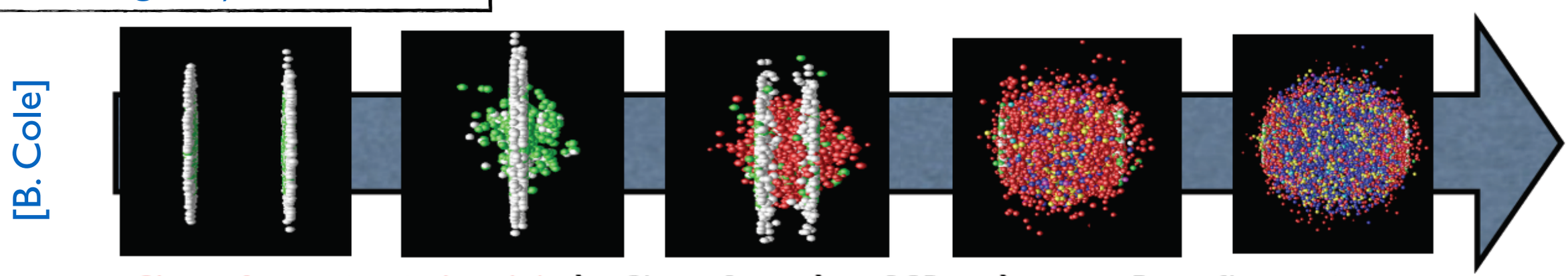
- Nucleus ≠ Zp+(A-Z)n.
- Particle production at large scales similar to pp (dilute regime).




- Lack of information about small-x partons, correlations and transverse structure.
- We do not understand the dense regime.

# What eA can contribute:

- Nucleus ≠ Zp+(A-Z)n.
- Particle production at large scales similar to pp (dilute regime).




- Lack of information about small-x partons, correlations and transverse structure.
- We do not understand the dense regime.

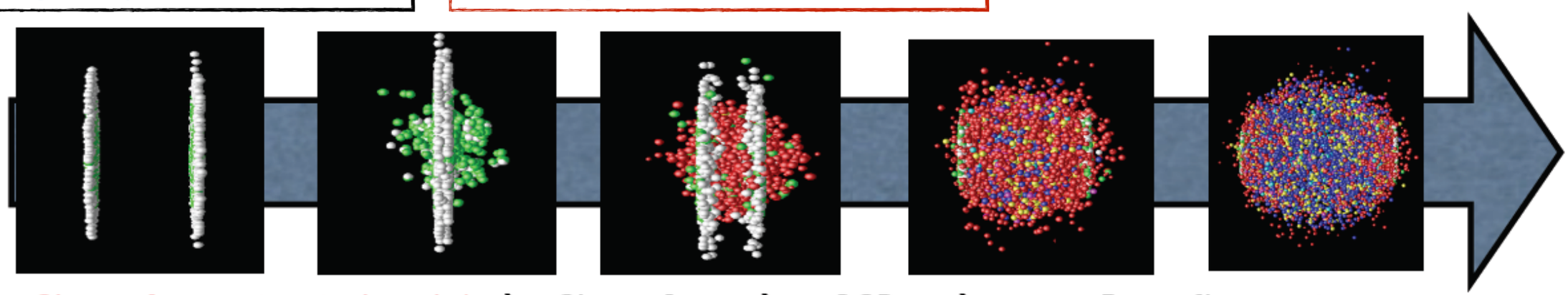
➜ ep and eA: nuclear WF and mechanism of particle production.

# What eA can contribute:

- Nucleus ≠ Zp+(A-Z)n.
- Particle production at large scales similar to pp (dilute regime).

- Medium behaves very early like a low viscosity liquid: macroscopic description.

[B. Cole]



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

- Lack of information about small-x partons, correlations and transverse structure.
- We do not understand the dense regime.

➜ ep and eA: nuclear WF and mechanism of particle production.

- How isotropised the system becomes?
- Why is hydro effective so fast, which dynamics?

➜ ep and eA: initial conditions; how small can a system become and still show 'collectivity'?

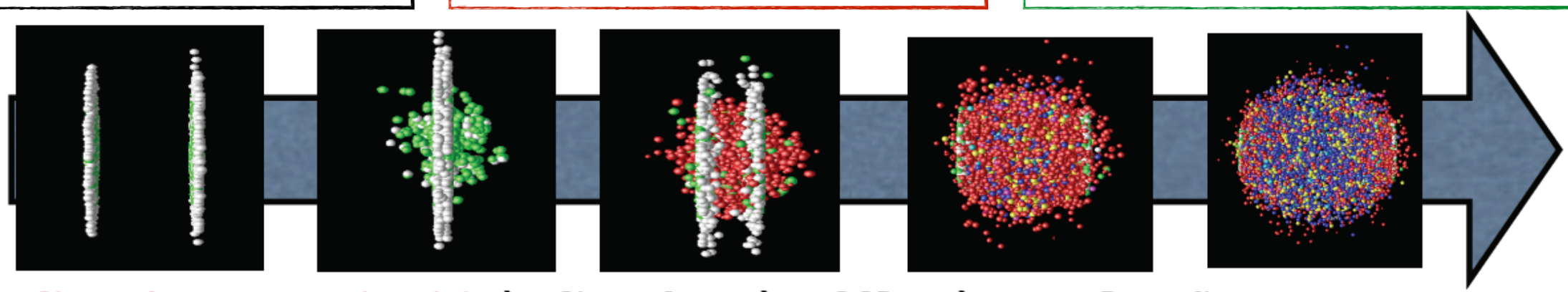
# What eA can contribute:

- Nucleus ≠ Zp+(A-Z)n.
- Particle production at large scales similar to pp (dilute regime).

- Medium behaves very early like a low viscosity liquid: macroscopic description.

- Medium is very opaque to colour.

[B. Cole]



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

- Lack of information about small-x partons, correlations and transverse structure.
- We do not understand the dense regime.

➜ ep and eA: nuclear WF and mechanism of particle production.

- How isotropised the system becomes?
- Why is hydro effective so fast, which dynamics?

➜ ep and eA: initial conditions; how small can a system become and still show 'collectivity'?

- What are the dynamical mechanisms for such opacity? Weak or strong coupling?
- How to extract accurately medium parameters?

➜ ep and eA: in-medium QCD radiation, cold nuclear effects on hard probes.

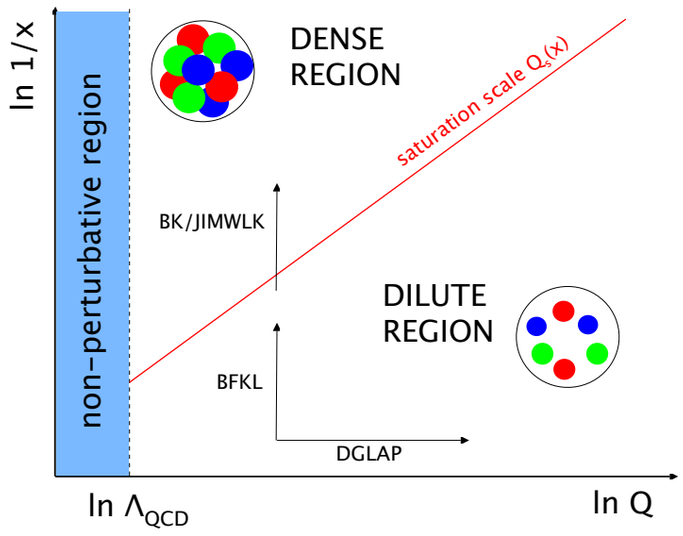
# What we need:

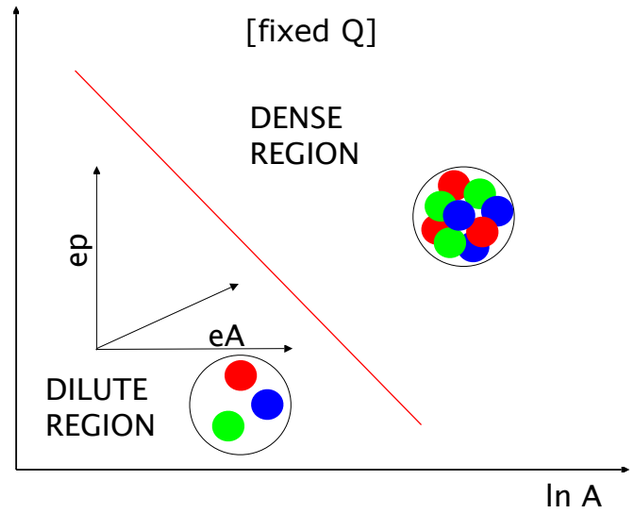
- We need ep and eA:

  ➜ To unravel linear/non-linear dynamics at small x (ep).

  ➜ To establish genuine nuclear effects, p as reference.

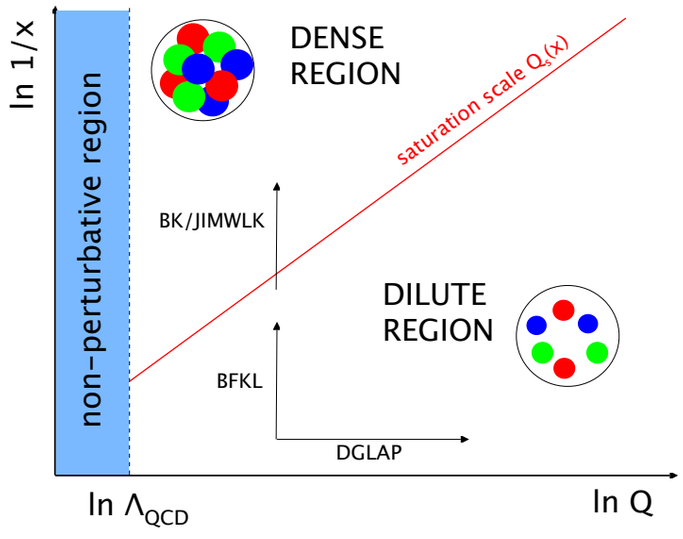
  ➜ To disentangle density (saturation?) from energy (linear resummation?) effects.

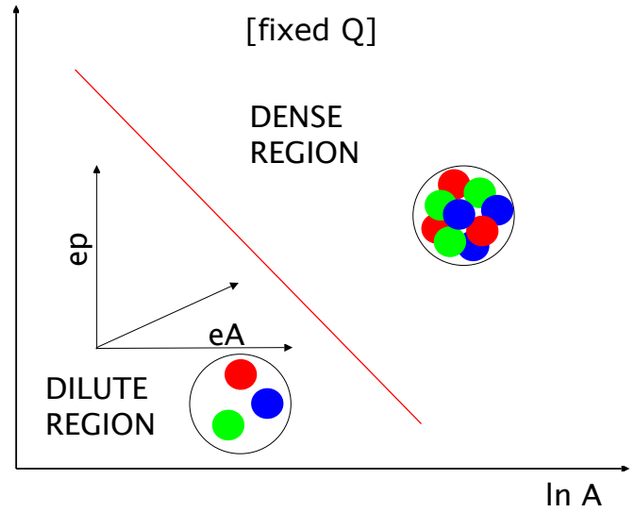


# What we need:

- We need ep and eA:
  - ➜ To unravel linear/non-linear dynamics at small x (ep).
  - ➜ To establish genuine nuclear effects, p as reference.
  - ➜ To disentangle density (saturation?) from energy (linear resummation?) effects.

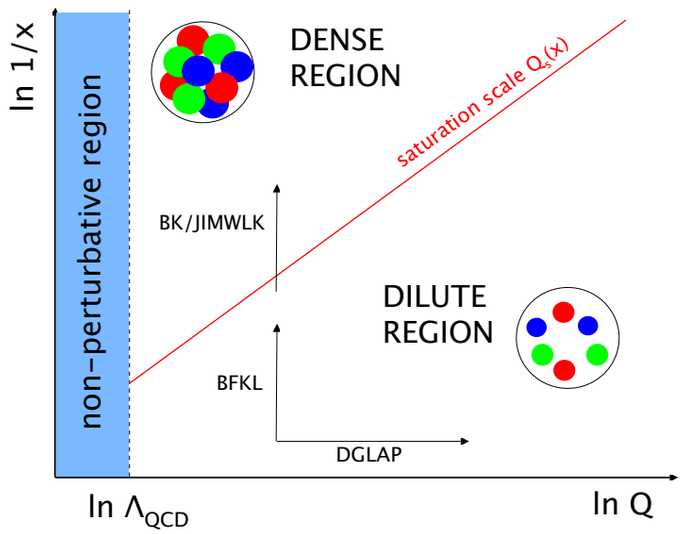


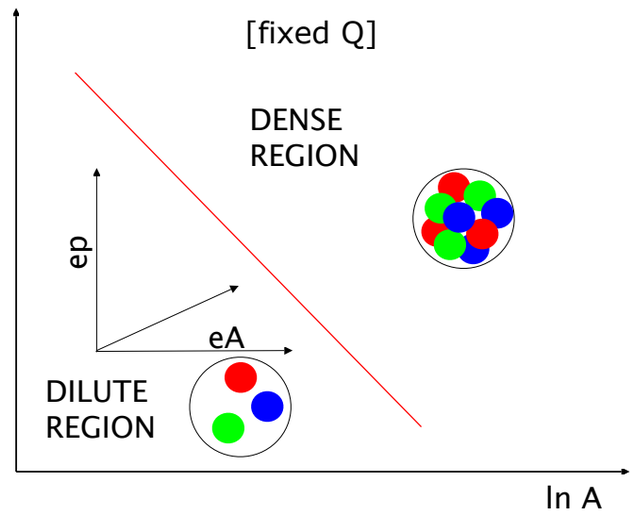




- We need energy:
  - ➜ To determine the partonic structure (nPDFs, transverse profiles) and the validity of factorisation for hh/AA.
  - ➜ To completely unfold nuclear structure as in the proton (Pb/Au PDFs, not ratios): NC+CC, heavy flavours,…
  - ➜ To have lever arm in $Q^2$ at low x.
  - ➜ To explore rarer hard probes (jets, W/Z, tops @ HL/HE-LHC, H @ FCC).

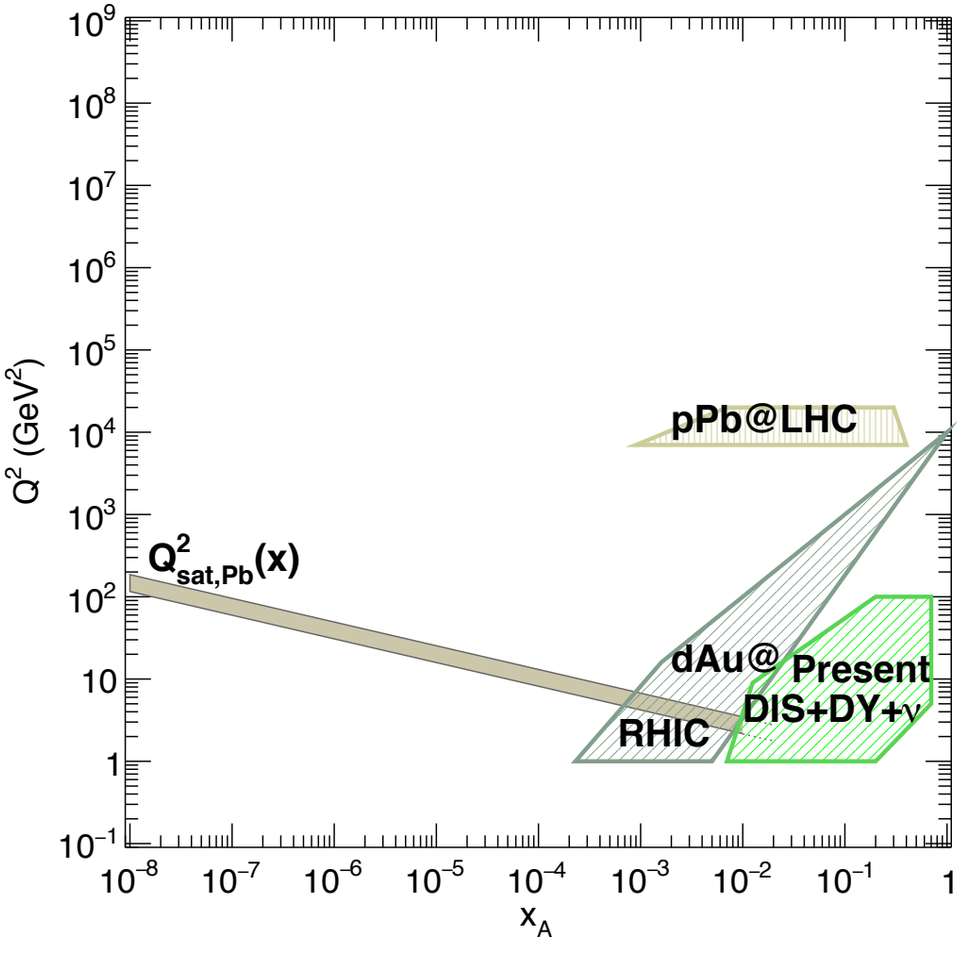
# What we need:

- We need ep and eA:
  - ➜ To unravel linear/non-linear dynamics at small x (ep).
  - ➜ To establish genuine nuclear effects, p as reference.
  - ➜ To disentangle density (saturation?) from energy (linear resummation?) effects.



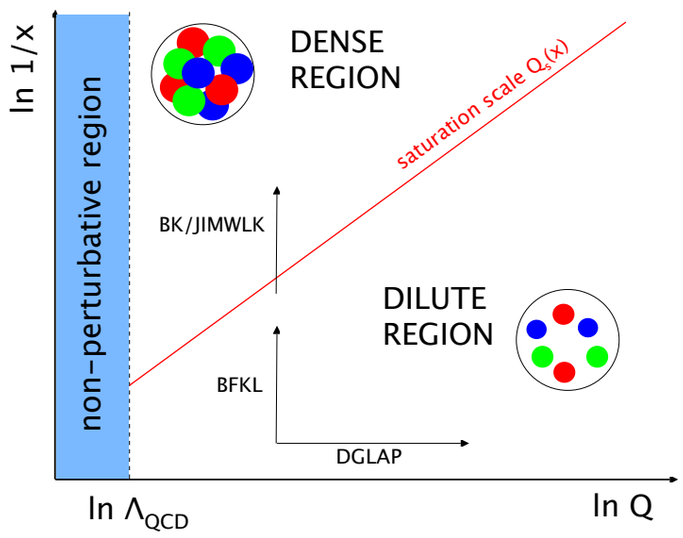



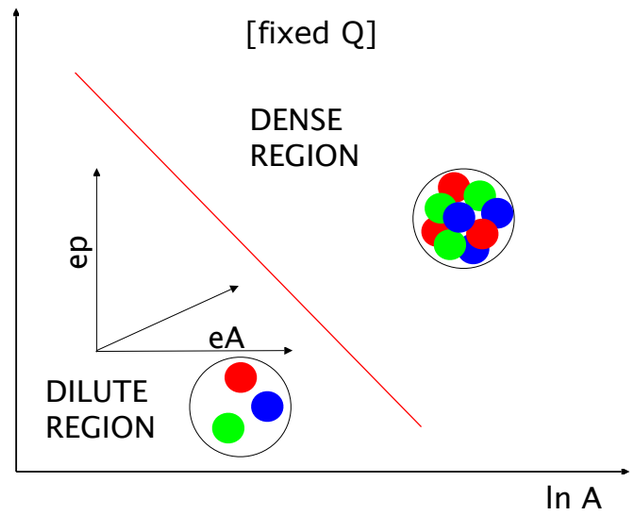

- We need energy:
  - ➜ To determine the partonic structure (nPDFs, transverse profiles) and the validity of factorisation for hh/AA.
  - ➜ To completely unfold nuclear structure as in the proton (Pb/Au PDFs, not ratios): NC+CC, heavy flavours,…
  - ➜ To have lever arm in $Q^2$ at low x.
  - ➜ To explore rarer hard probes (jets, W/Z, tops @ HL/HE-LHC, H @ FCC).



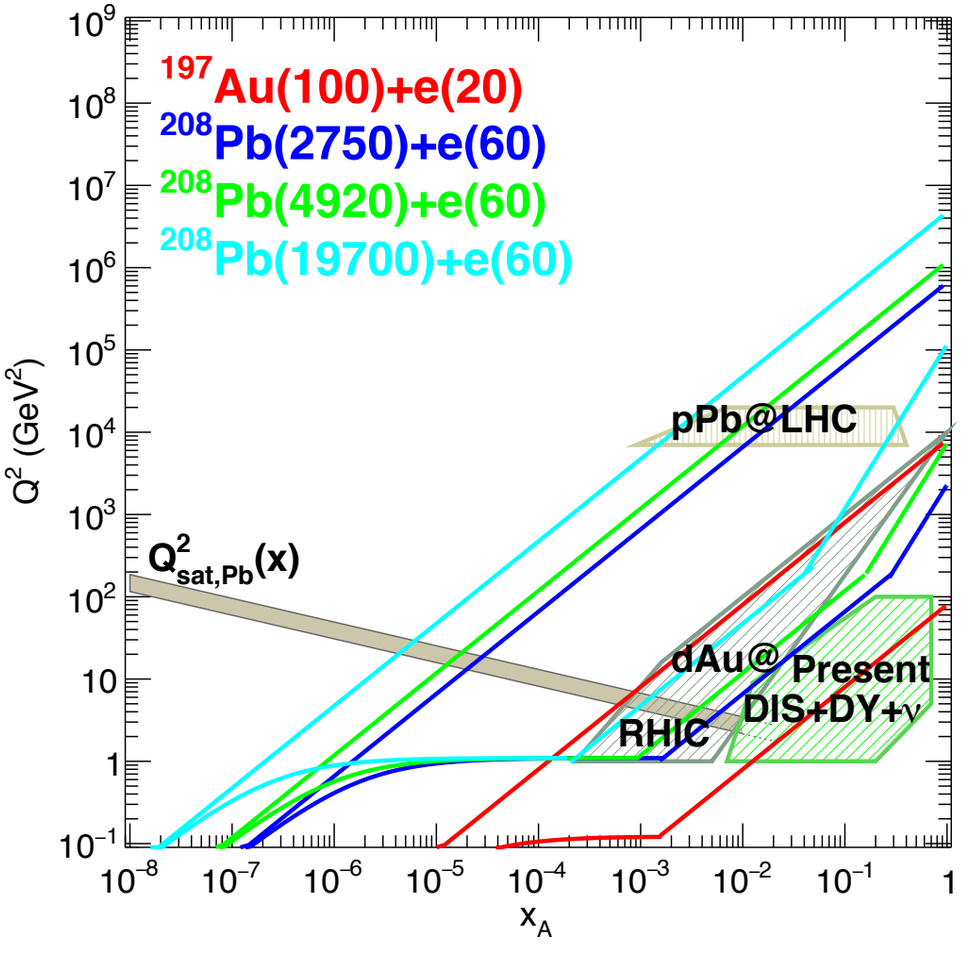
# What we need:

- We need ep and eA:
  - ➜ To unravel linear/non-linear dynamics at small x (ep).
  - ➜ To establish genuine nuclear effects, p as reference.
  - ➜ To disentangle density (saturation?) from energy (linear resummation?) effects.



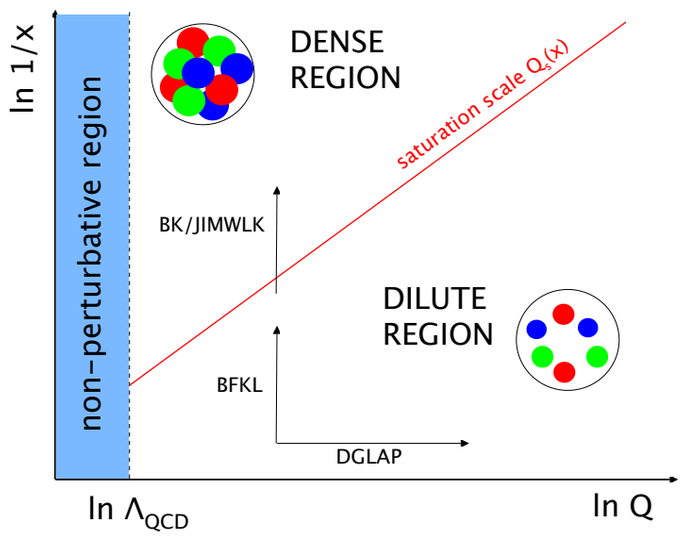



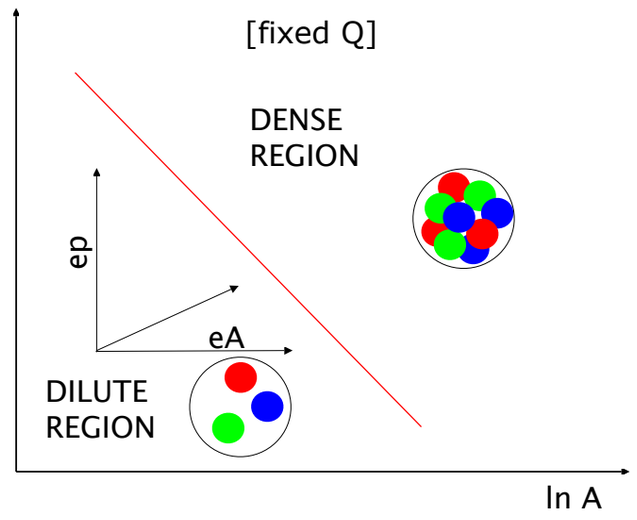

- We need energy:
  - ➜ To determine the partonic structure (nPDFs, transverse profiles) and the validity of factorisation for hh/AA.
  - ➜ To completely unfold nuclear structure as in the proton (Pb/Au PDFs, not ratios): NC+CC, heavy flavours,…
  - ➜ To have lever arm in $Q^2$ at low x.
  - ➜ To explore rarer hard probes (jets, W/Z, tops @ HL/HE-LHC, H @ FCC).



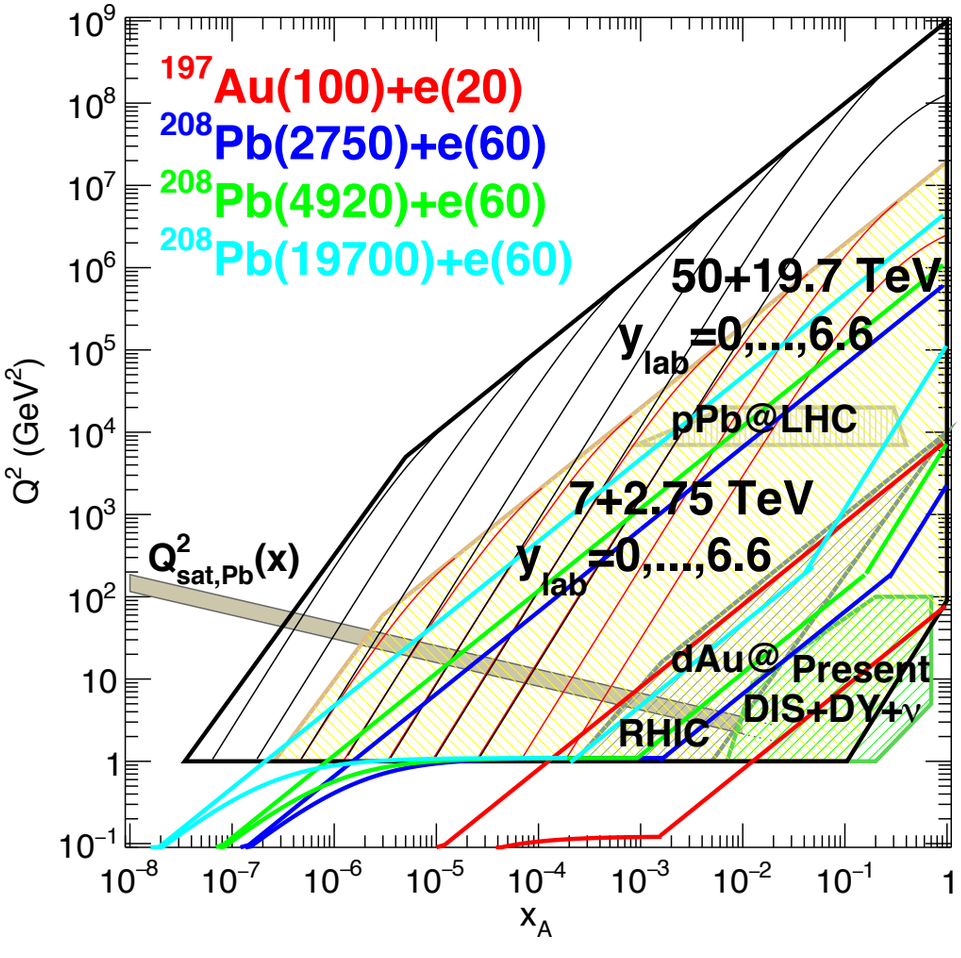
# What we need:

- We need ep and eA:
  - ➜ To unravel linear/non-linear dynamics at small x (ep).
  - ➜ To establish genuine nuclear effects, p as reference.
  - ➜ To disentangle density (saturation?) from energy (linear resummation?) effects.



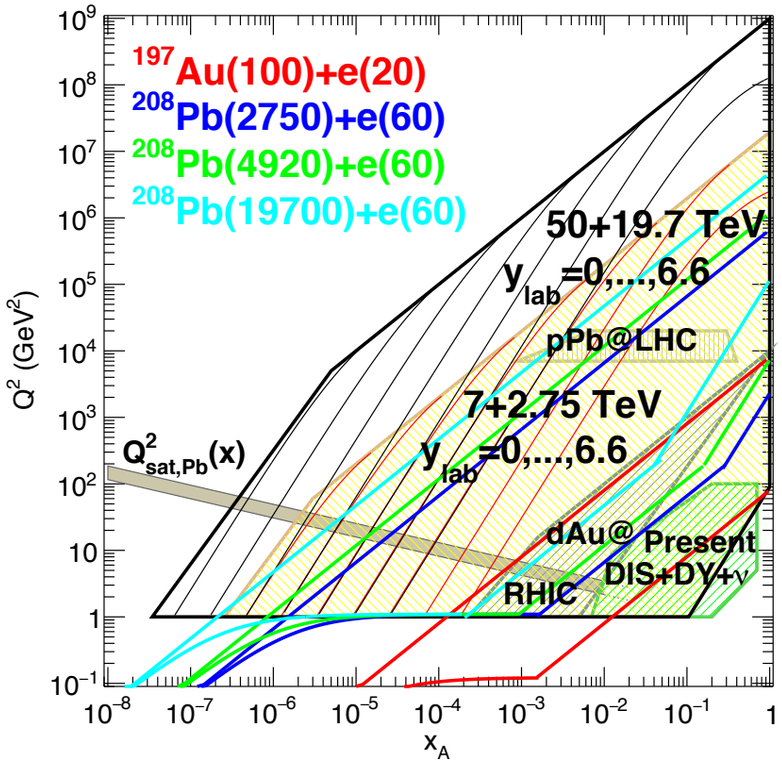




- We need energy:
  - ➜ To determine the partonic structure (nPDFs, transverse profiles) and the validity of factorisation for hh/AA.
  - ➜ To completely unfold nuclear structure as in the proton (Pb/Au PDFs, not ratios): NC+CC, heavy flavours,…
  - ➜ To have lever arm in $Q^2$ at low x.
  - ➜ To explore rarer hard probes (jets, W/Z, tops @ HL/HE-LHC, H @ FCC).



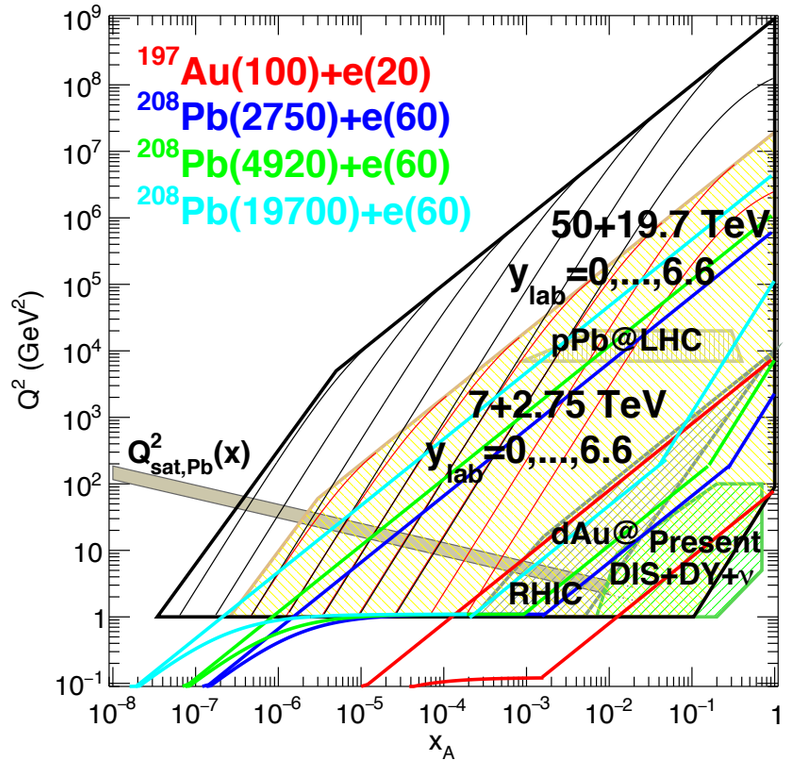
# Summary:

- Some open problems in high-energy heavy ion physics: transition from microscopic dynamics to macroscopic behaviour, collectivity in small systems, determination of medium parameters,…



# Summary:

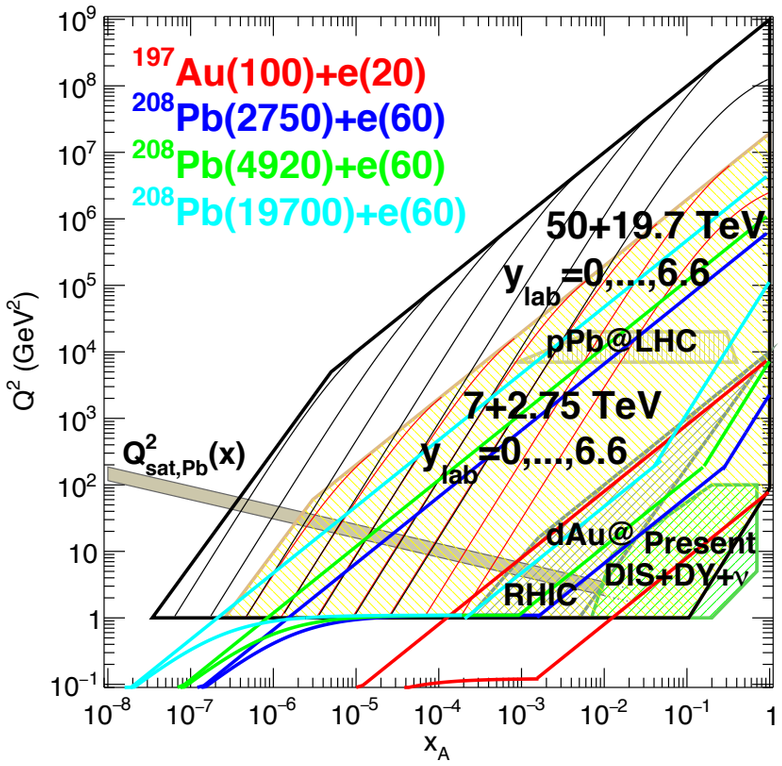
- Some open problems in high-energy heavy ion physics: transition from microscopic dynamics to macroscopic behaviour, collectivity in small systems, determination of medium parameters,…
- ep/eA will provide key information:
  - ➜ Initial conditions for collective behaviour.
  - ➜ The small systems puzzle.
  - ➜ nPDFs and other cold nuclear matter effects for hard probes.
  - ➜ …



# Summary:

- Some open problems in high-energy heavy ion physics: transition from microscopic dynamics to macroscopic behaviour, collectivity in small systems, determination of medium parameters,…

- ep/eA will provide key information:
  - ➜ Initial conditions for collective behaviour.
  - ➜ The small systems puzzle.
  - ➜ nPDFs and other cold nuclear matter effects for hard probes.
  - ➜ …




- **We need**:
  - ➜ ep and eA.
  - ➜ The largest possible lever arm in energy for present and future hh/AA colliders, and for exploring new regimes of QCD.
  - ➜ An EIC (several A's, overlap with FT, precision, versatility) and the LHeC/FCC-eh (large $\sqrt{s_{NN}}$, access to small x and large $Q^2$).
  - ☛ They are complementary, also to pA/UPC at hadron colliders.