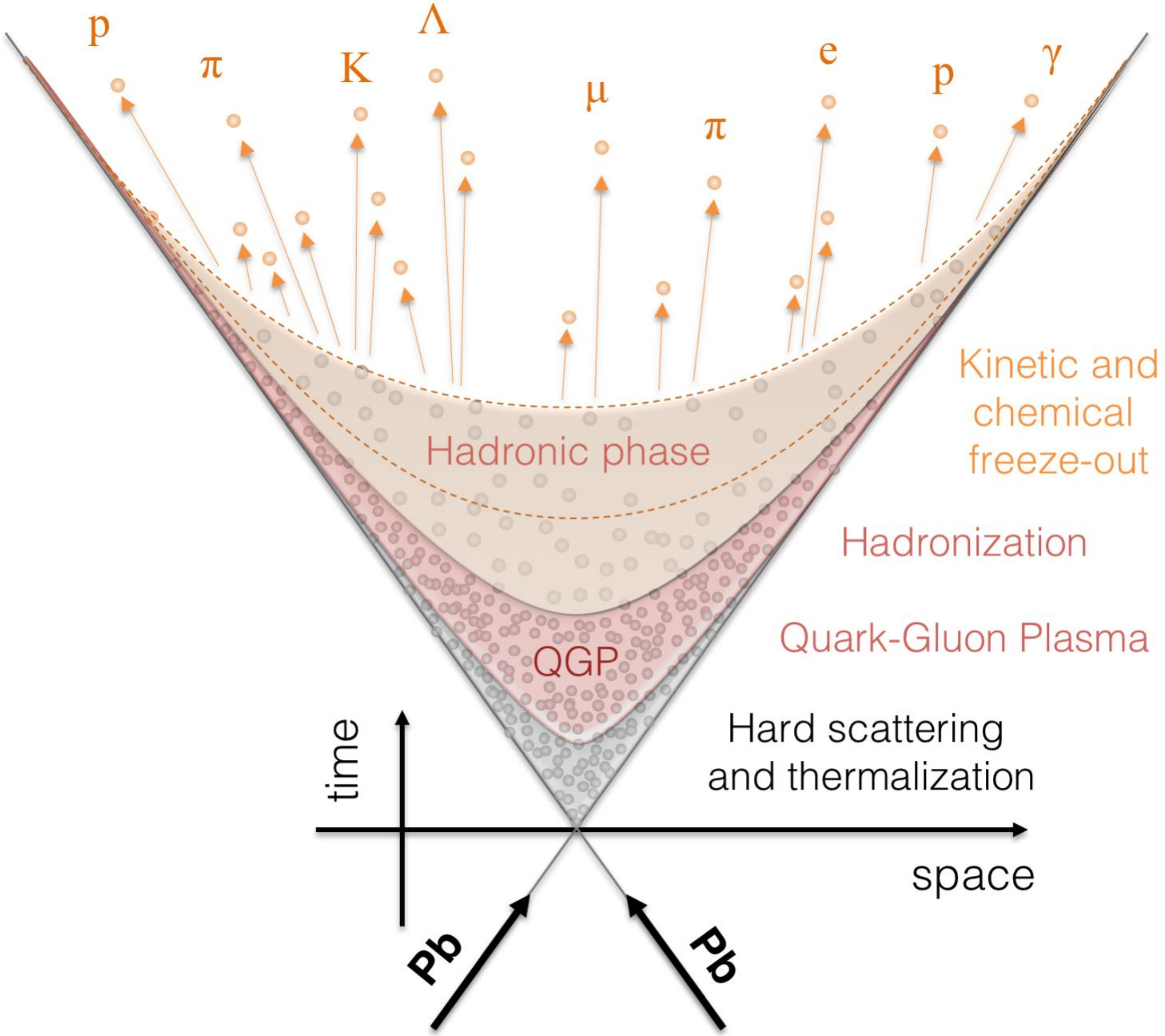
Late Stages

Particlization and Hadronic Phase

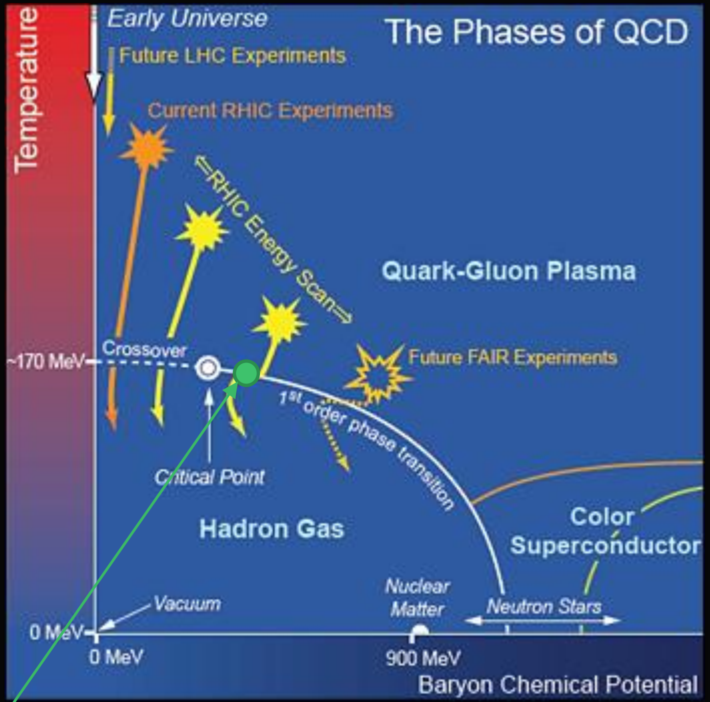
Overview

- We have seen
  - Initial condition generation
  - Pre-equilibrium dynamics
  - Hydrodynamic evolution
- How does the fluid prescription connect to particles?



Hadronization vs Particlization

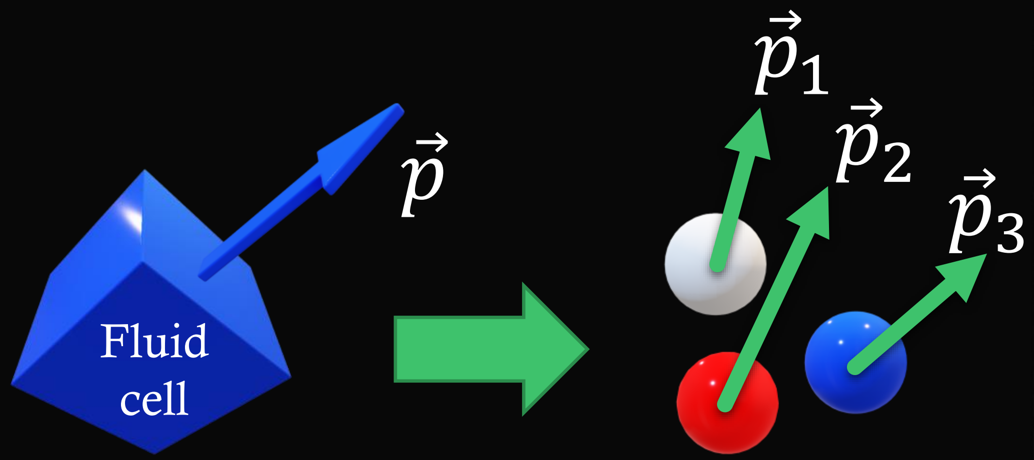
Hadronization



Partons in QGP becomes hadrons

Particlization

- The procedure of transforming fluid cells into hadrons



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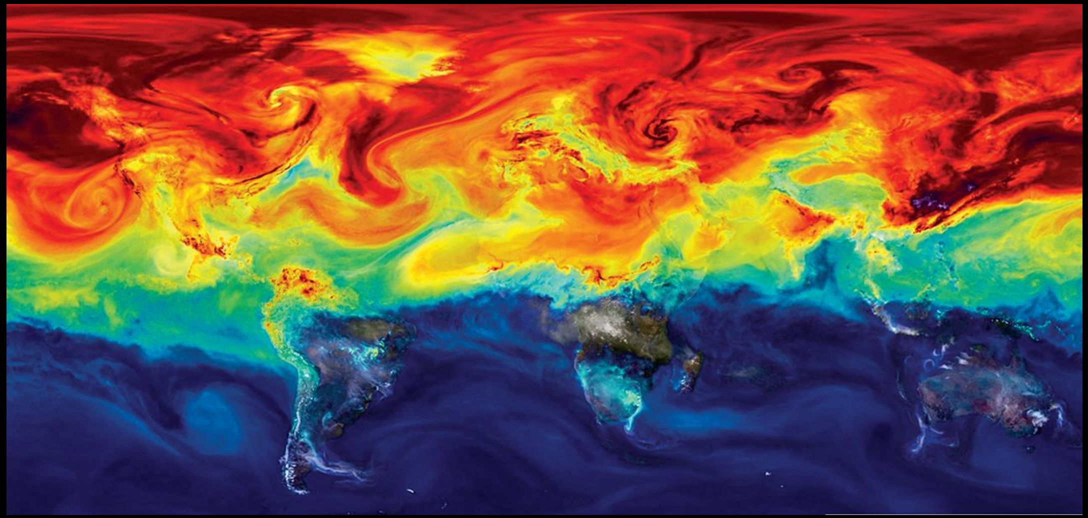

Soden, Collins, Feldman. Science, Vol. 361, Issue 6400, pp. 326-327

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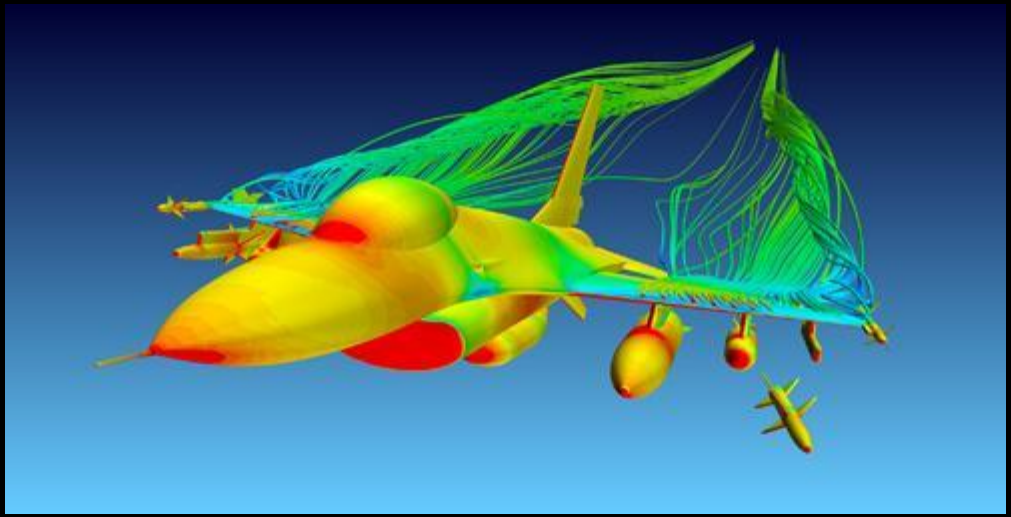

https://www.designnews.com/design-hardware-software/cfd-tool-adds-moving-object-simulation
Accessed on March 11th, 2021

Particlization procedure

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- Particlization is done by exploiting the overlap between Hydrodynamic and **Kinetic Theory** (Hadron gas)

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- Cooper-Frye
  - $E\frac{d^3N}{dp^3} = \int d\sigma_\mu p^\mu f(x,p)$

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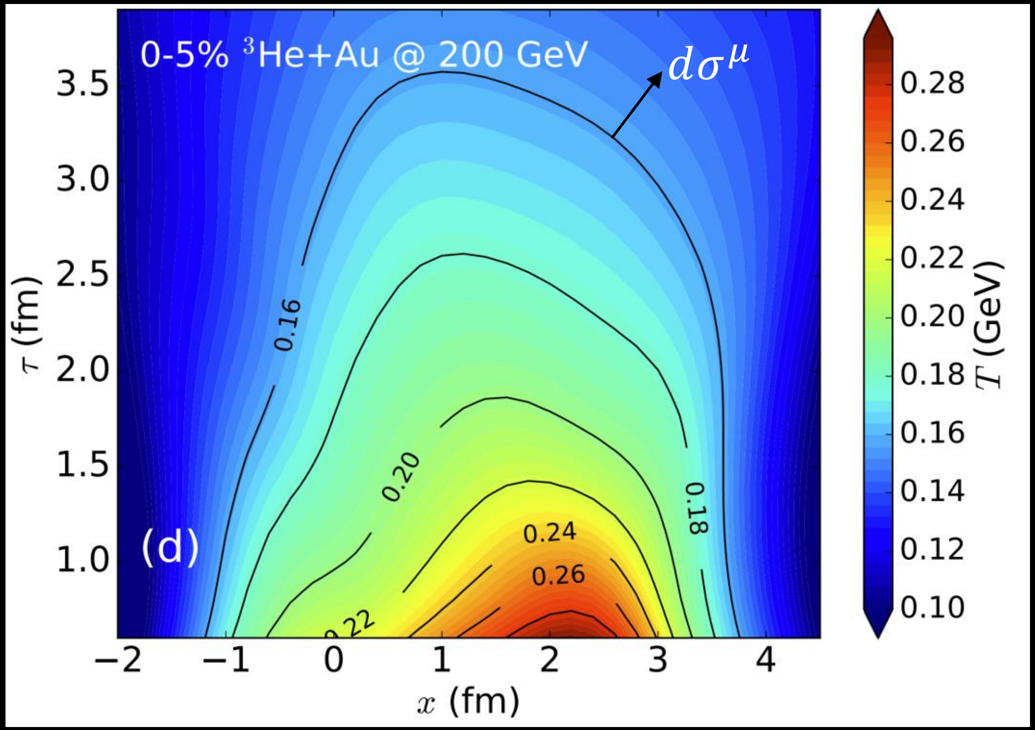

C. Shen, et al. Phys.Rev. C95 (2017) no.1, 014906

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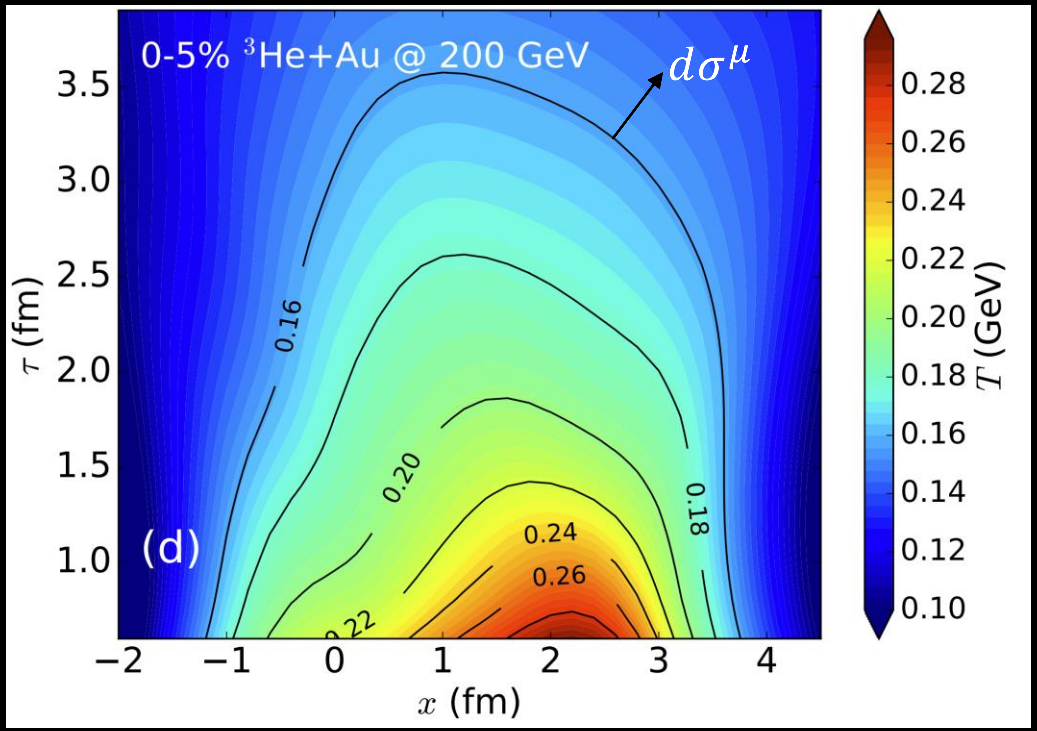

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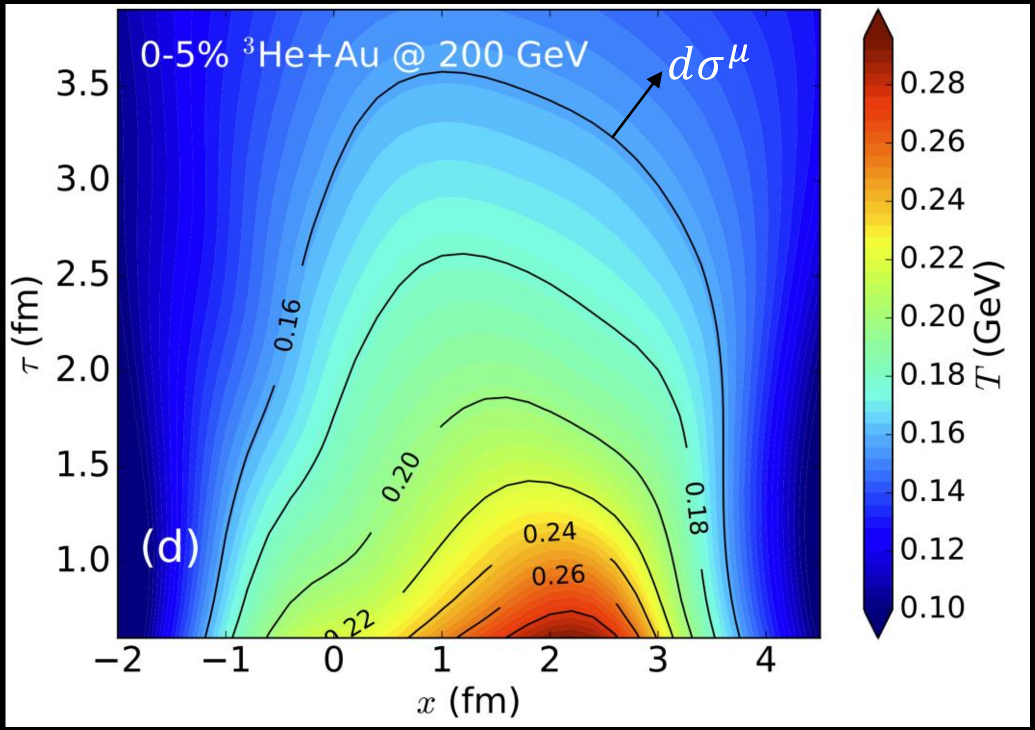
- Particle sampling
  - Particles placed on the place of hypersurface following its momentum distribution



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- References to learn more:
  - [1206.3371] Particlization in hybrid models – Huovinen, Petersen
  - Phys. Rev. D 10, 186 (1974) - Single-particle distribution in the hydrodynamic and statistical thermodynamic models of multiparticle production – Cooper, Frye
  - The iEBE-VISHNU code package for relativistic heavy-ion collisions – Shen et al. – iSS article

Hadron gas - UrQMD

- Up to thousand of particles produced in each collision
- If system is dense enough, hadrons may scatter on each other

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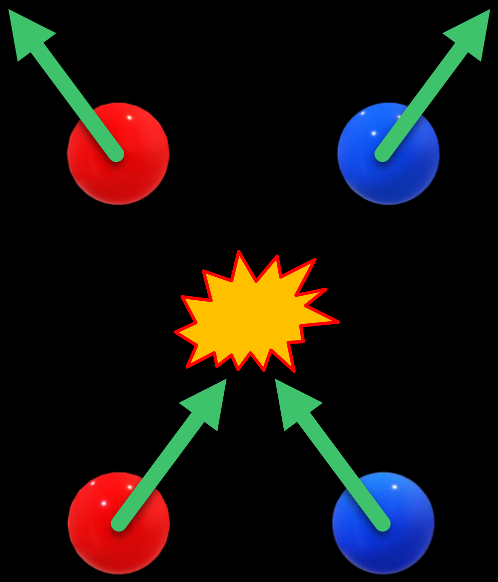

Elastic scattering

- Different kinds of interactions

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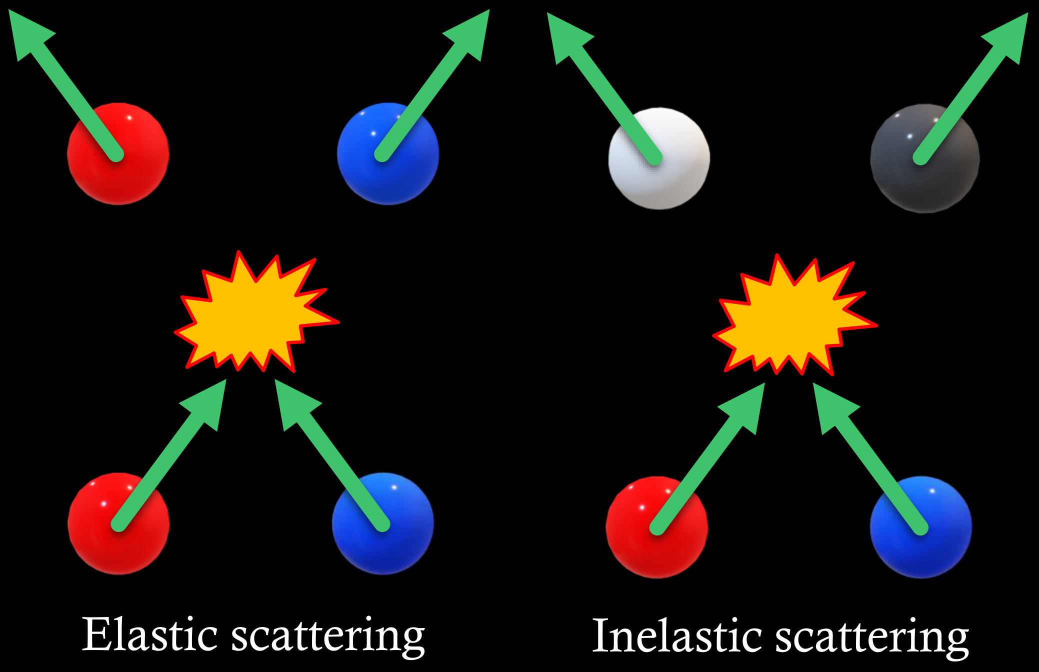

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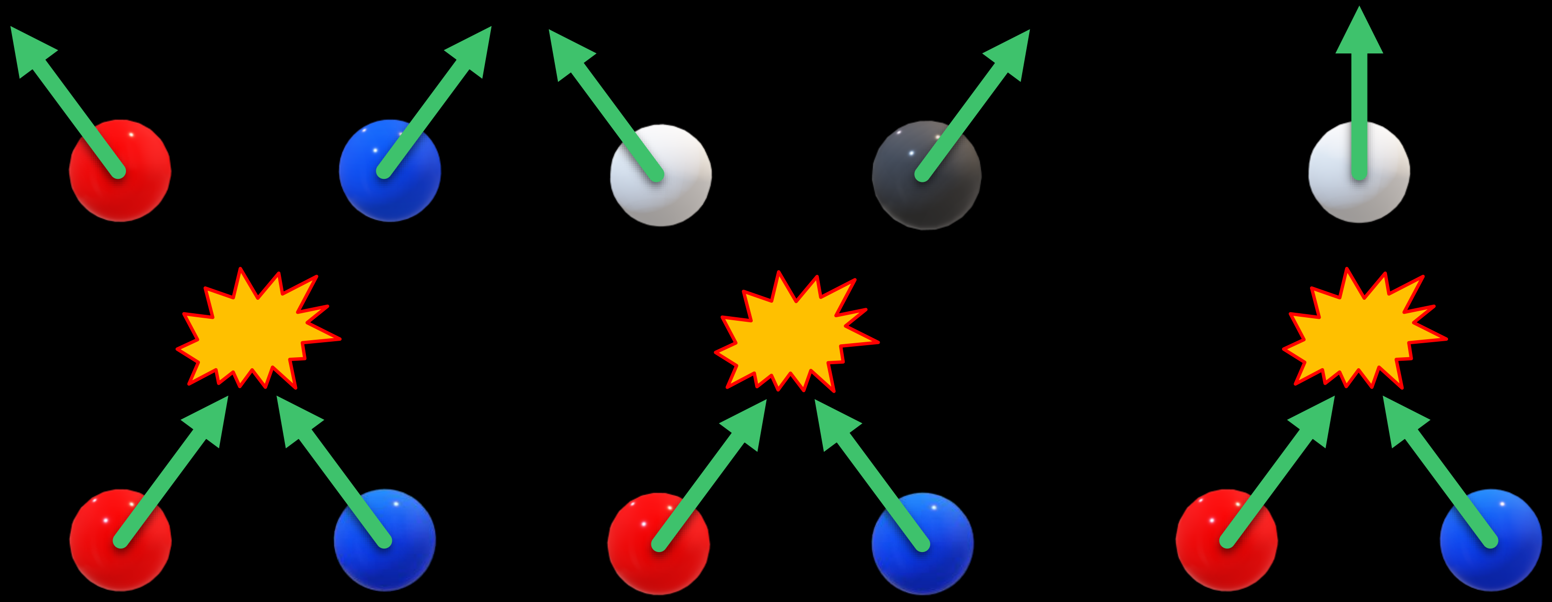

Elastic scattering Inelastic scattering Regeneration

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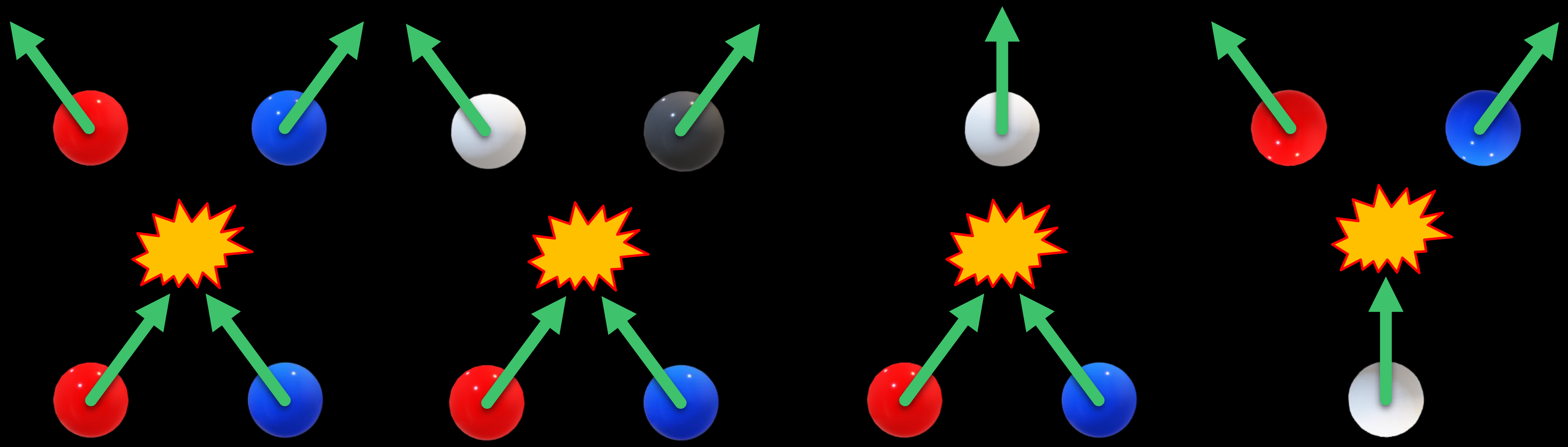

Elastic scattering | Inelastic scattering | Regeneration | Particle decays

Hadron gas - UrQMD

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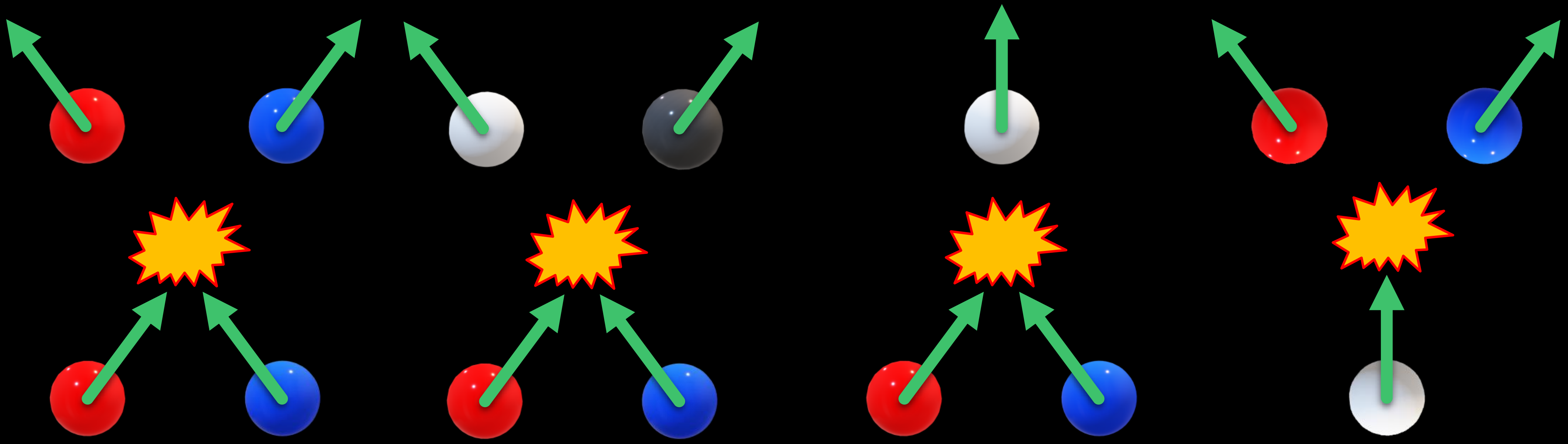
- If system is dense enough, hadrons may scatter on each other
- Different kinds of interactions
- Hadrons travel following classical trajectories
- Interact stochastically following experimental hadron-hadron cross-section



Elastic scattering | Inelastic scattering | Regeneration | Particle decays

Additional References

- [nucl-th/9803035] Microscopic Models for Ultrarelativistic Heavy Ion Collisions – Bass et al.
- [hep-ph/9909407v1] Relativistic Hadron-Hadron Collisions in the Ultra-Relativistic Quantum Molecular Dynamics Model (UrQMD) – Bleicher et al.
- https://urqmd.org/ – UrQMD webpage

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Backups

Wigner functions

Kinetic Theory to Hydrodynamics

- $T^{\mu\nu} = \int \frac{d^3p}{\varepsilon} p^\mu p^\nu f(x,p)$

Quantum Field Theory to Hydrodynamics

- $T^{\mu\nu} = Tr\left(\hat{\rho} : \hat{T}^{\mu\nu}(x) : \right)$

Wigner function (from QFT)

$$W(x,k) = \frac{1}{(2\pi)^4} \int d^4y\, 2\, e^{-ik\cdot y} \langle : \hat{\psi}^\dagger (x + y/2) \hat{\psi}(x - y/2) : \rangle$$

$\langle \cdot \rangle = Tr(\hat{\rho}\, \cdot)$

$f(x,p)$ defined as

$$W^+(x,k) = \theta(k^0) W(x,k) = \int \frac{d^3p}{\varepsilon} \delta^4(k-p) f(x,p)$$