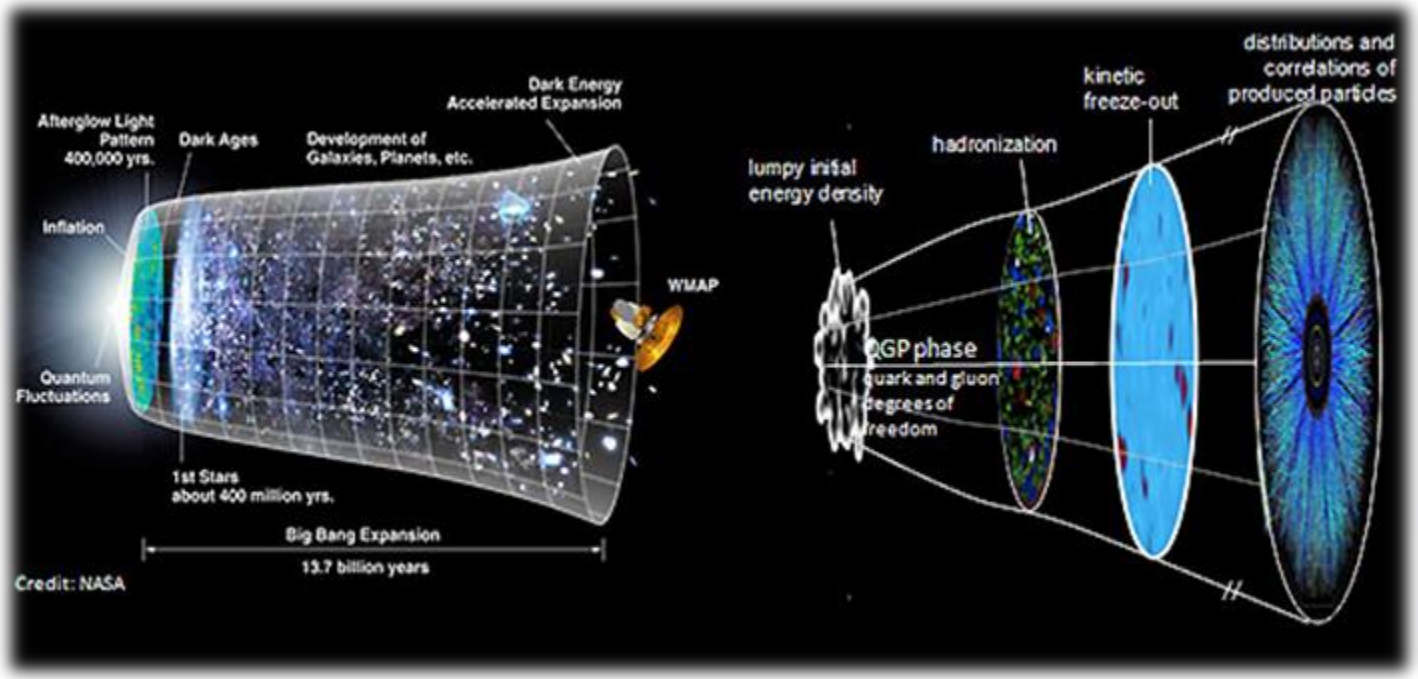
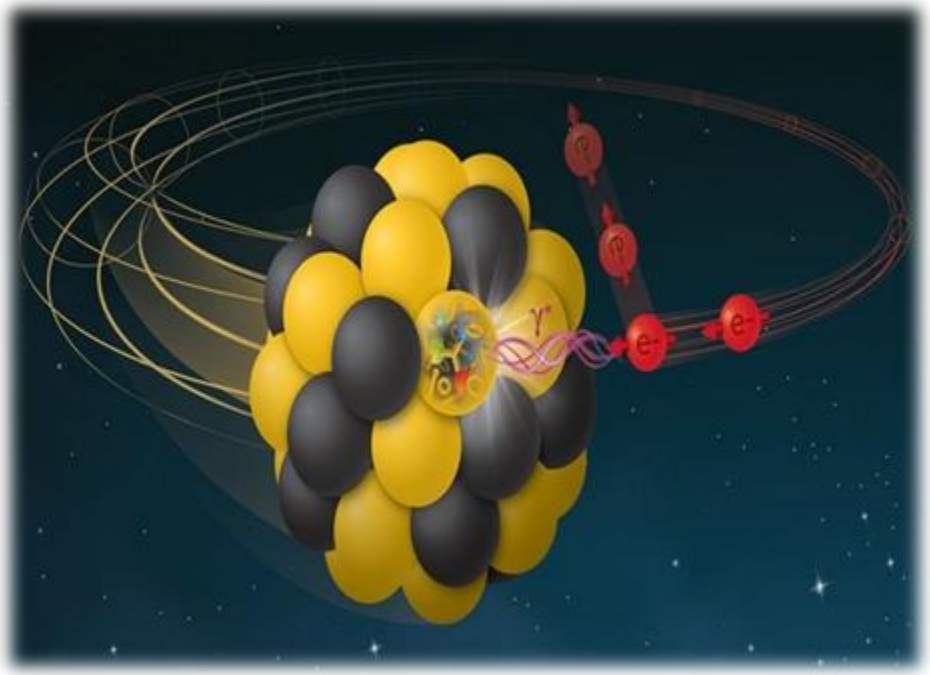
TSU
TEXAS SOUTHERN UNIVERSITY

Brookhaven National Laboratory

The Universe Primordial Soups





Niseem Magdy Abdelrahman
niseem.abdelrahman@tsu.edu

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What is matter made of ?

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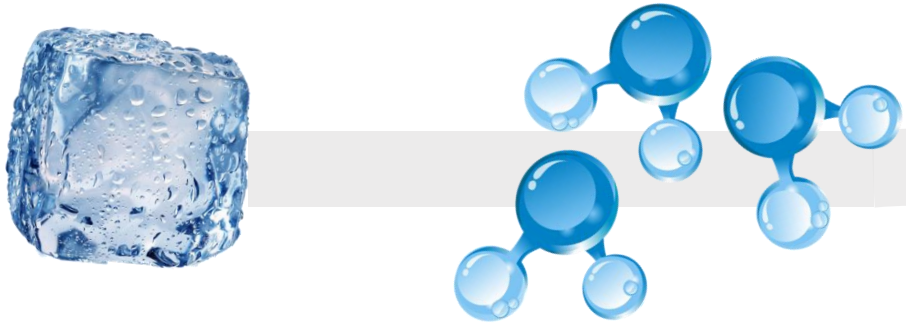

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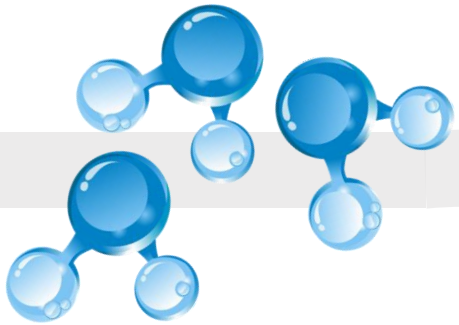

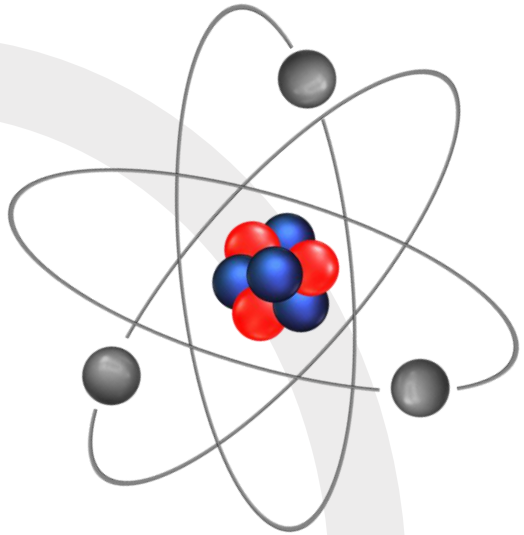

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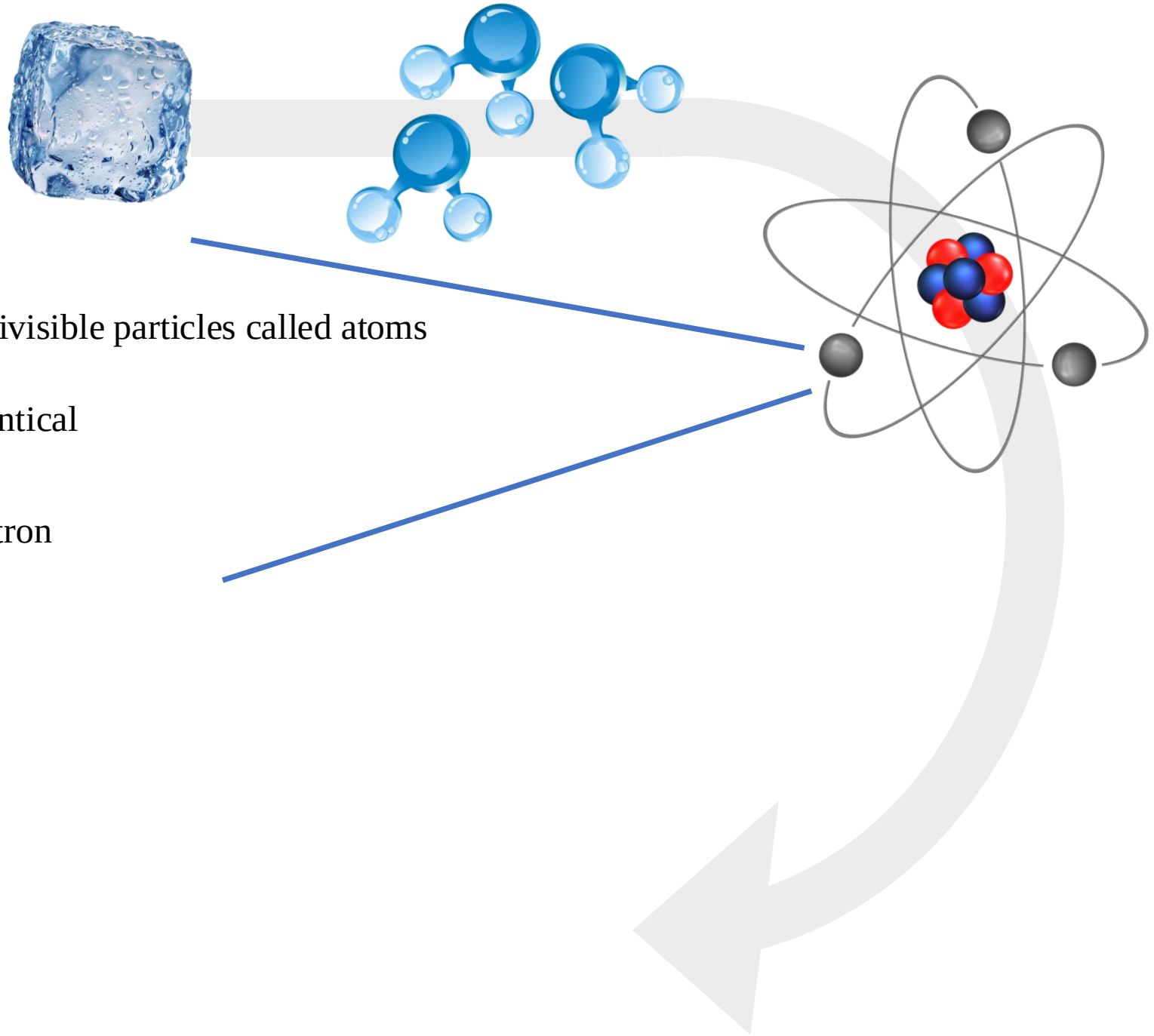

- Ancient Greece:
  - ✓ All matter is composed of tiny, indivisible particles called atoms
- 1803: Dalton's Atomic Theory:
  - ✓ Atoms of the same element are identical
- Late 19th century:
  - ✓ J.J. Thomson: Discovered the electron

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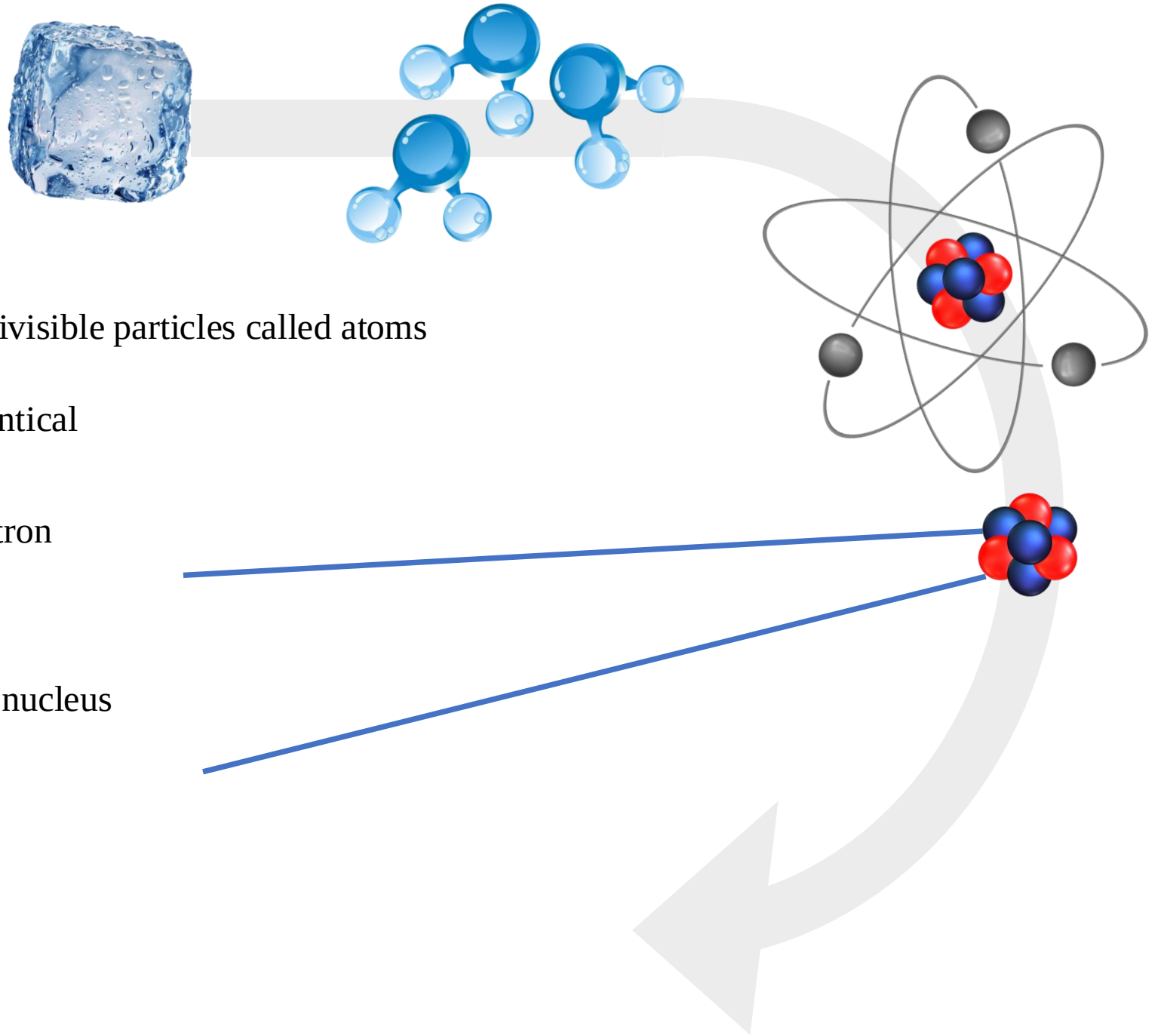

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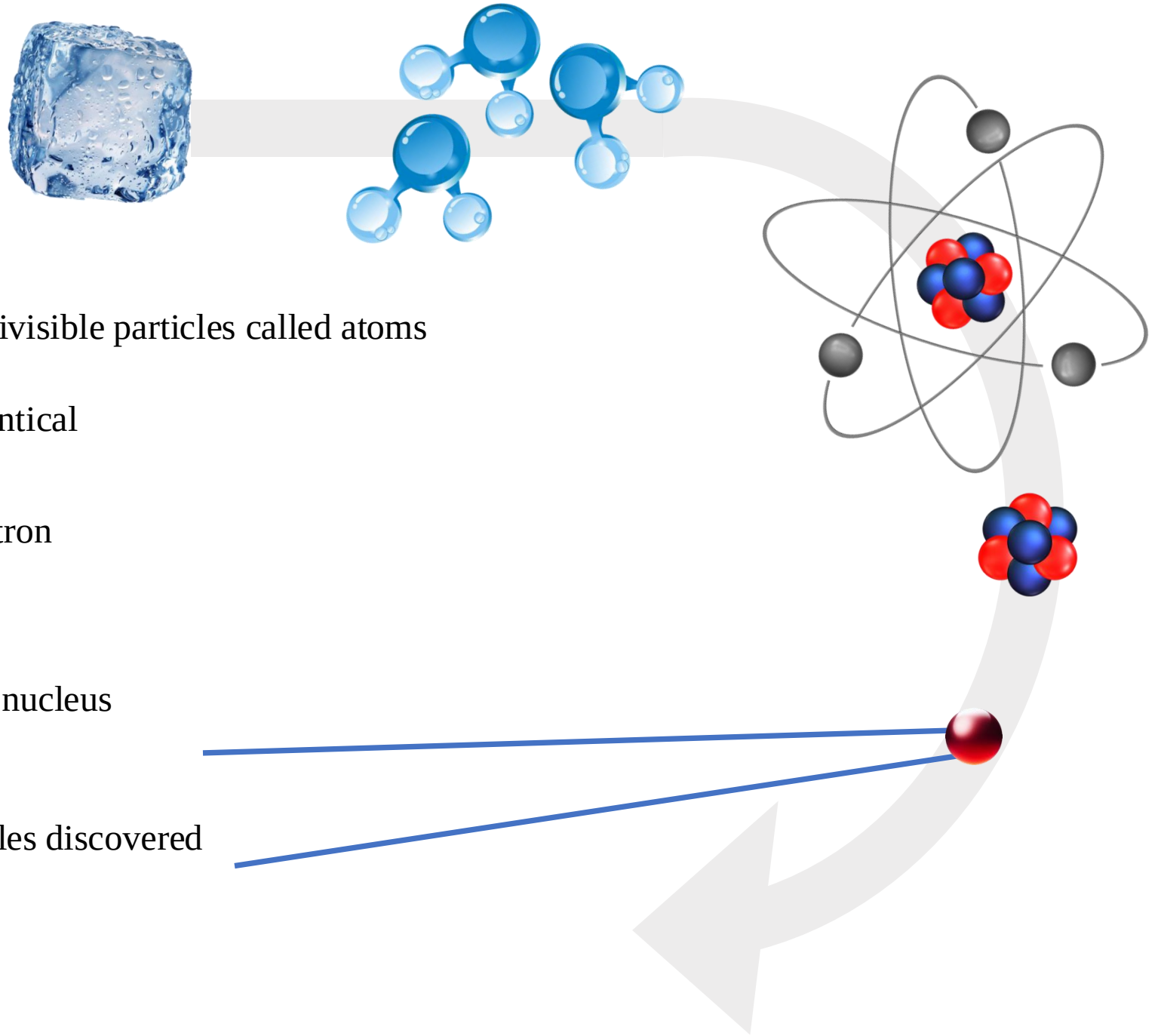

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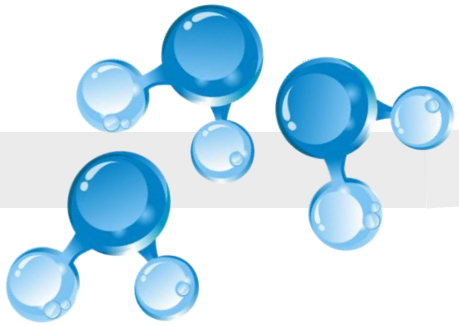

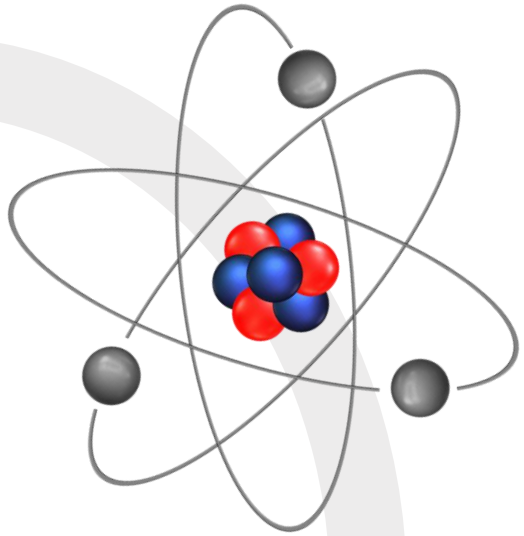

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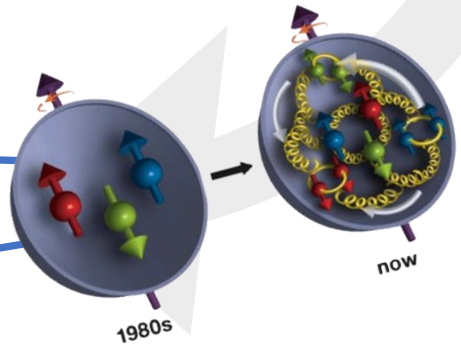
- In the 1960s:
  - ✓ Murray Gell-Mann and George Zweig proposed the existence of quarks



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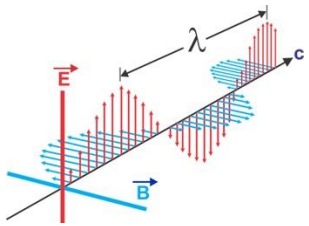
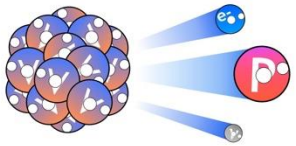
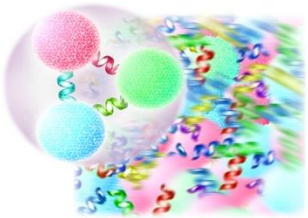


Electromagnetic Force



Weak nuclear Force



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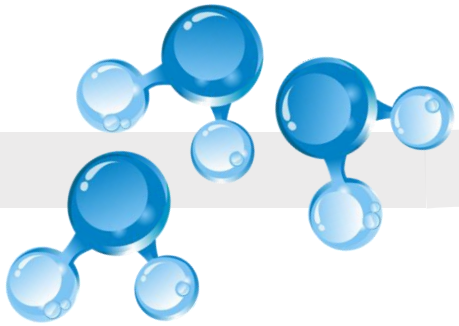

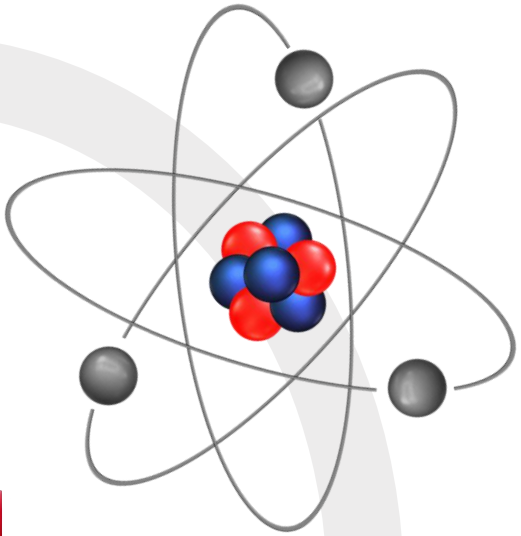

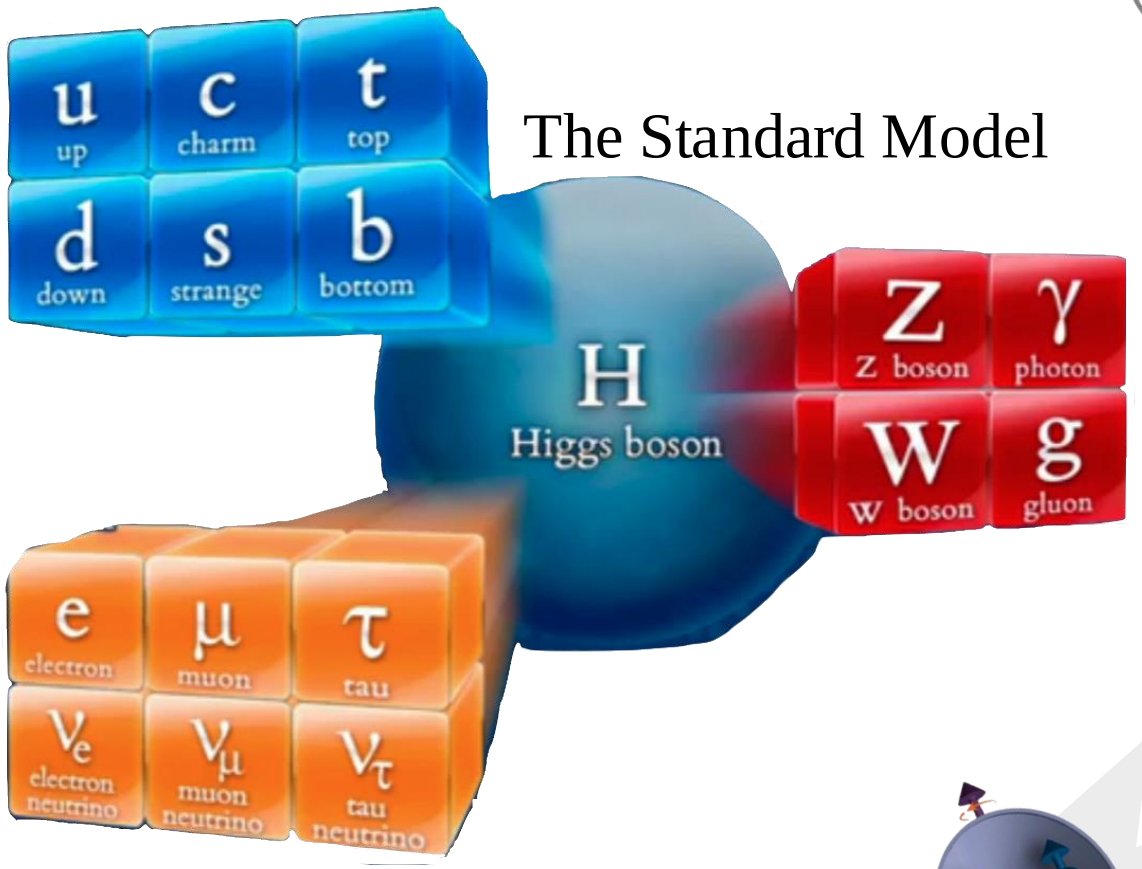

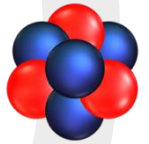

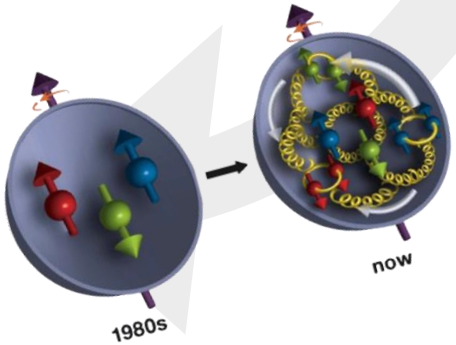

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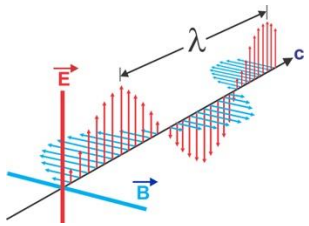

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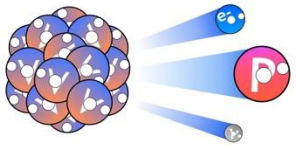

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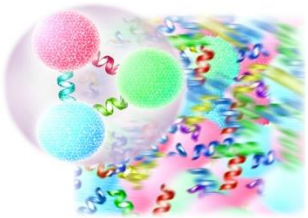

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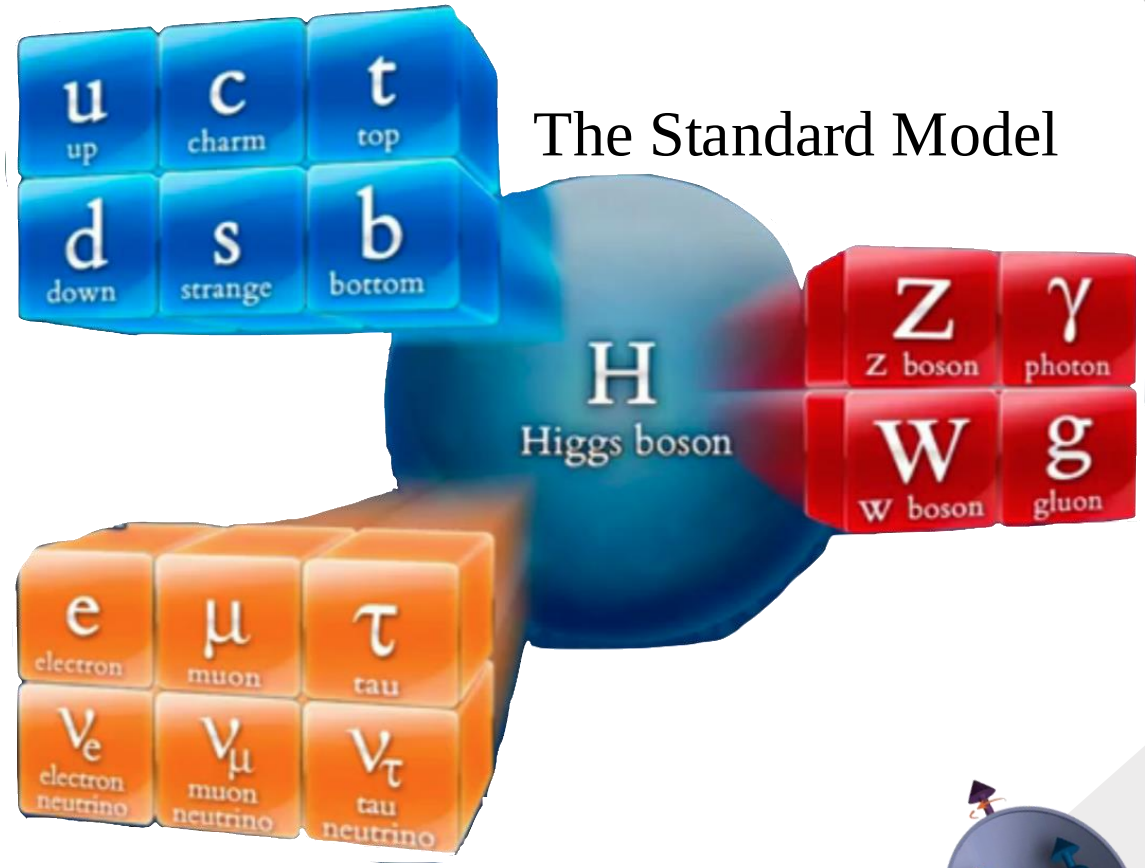
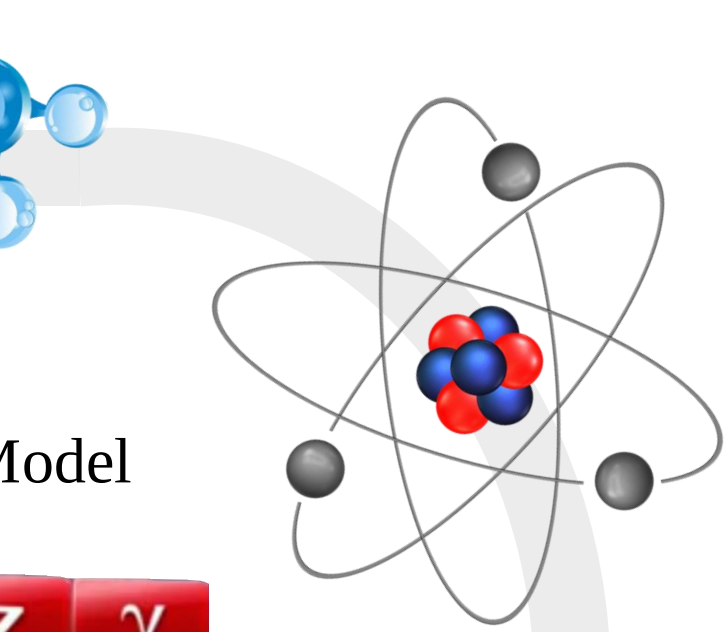
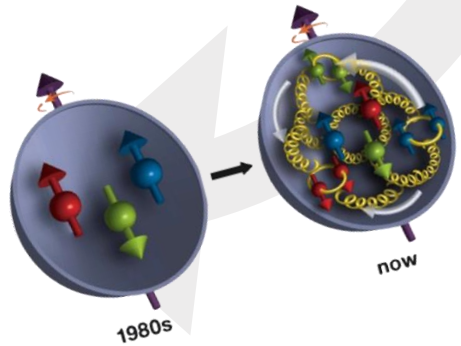


The Standard Model





What is the nature of the quarks and gluons interactions?

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- The bounded quarks and gluons interactions (inside the protons)
  - ✓ Scattering experiment to reflect the bounded state structure

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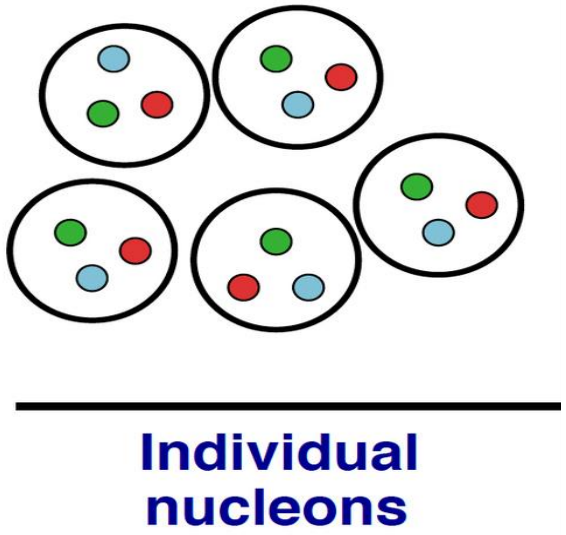

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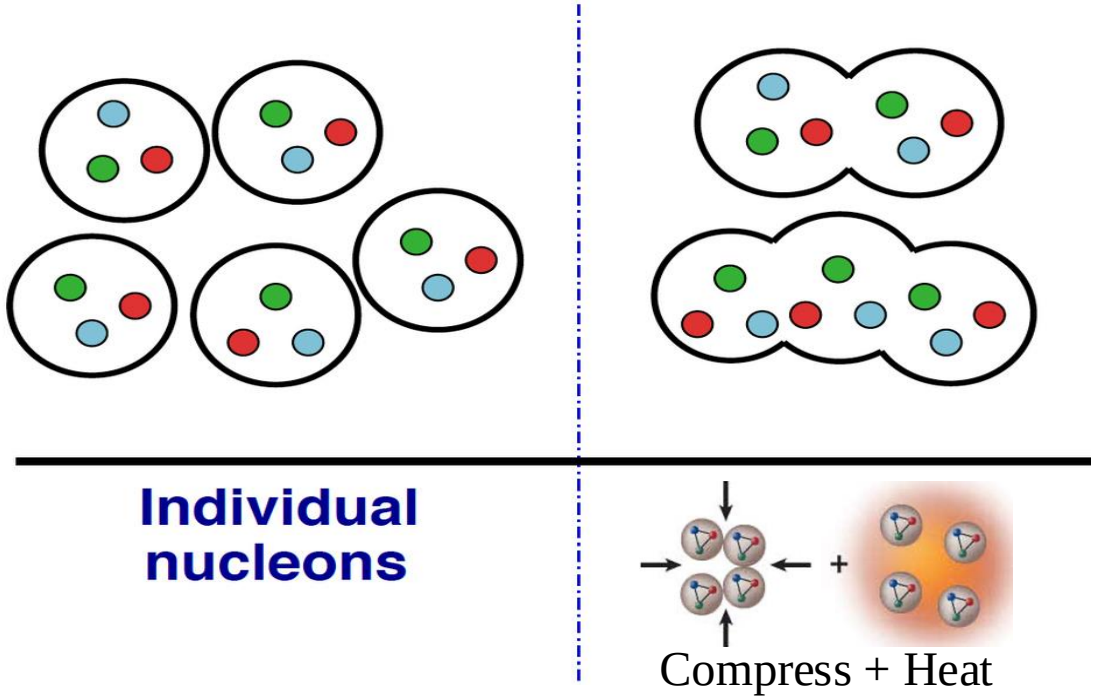

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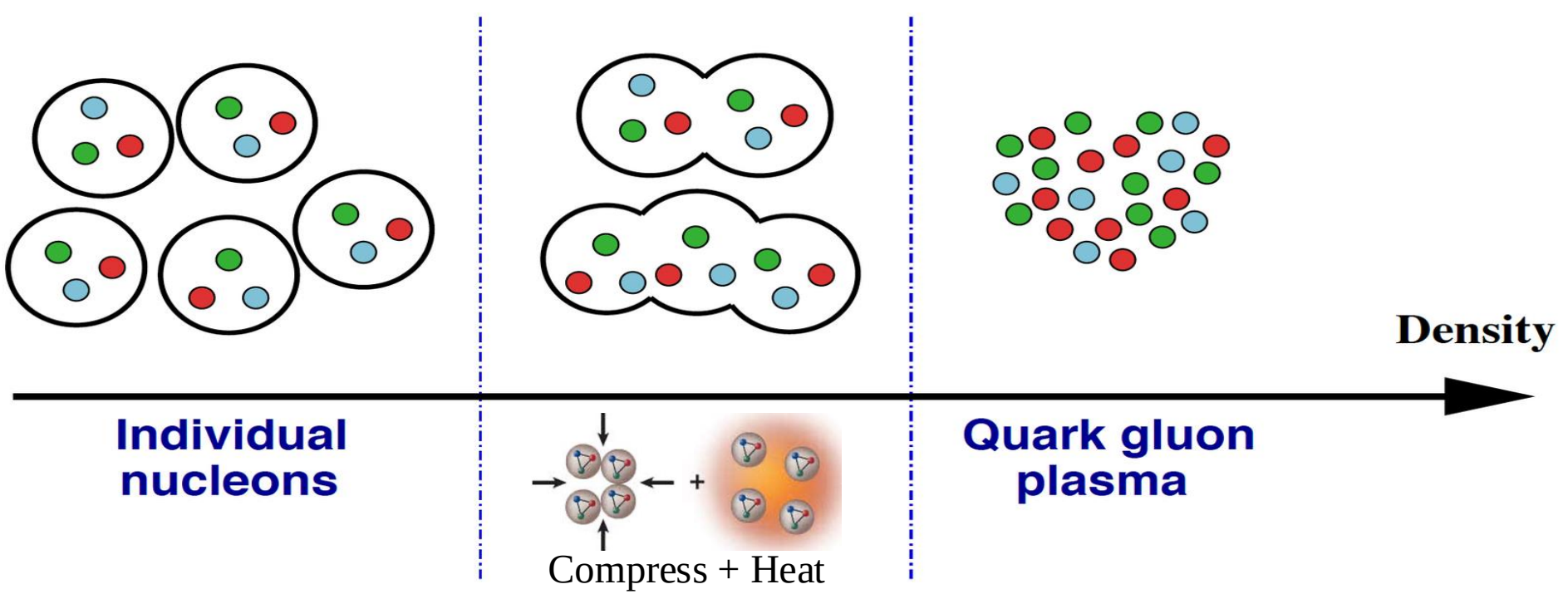

Forming the Quantum chromodynamics matter called Quark Gluon Plasma (QGP)

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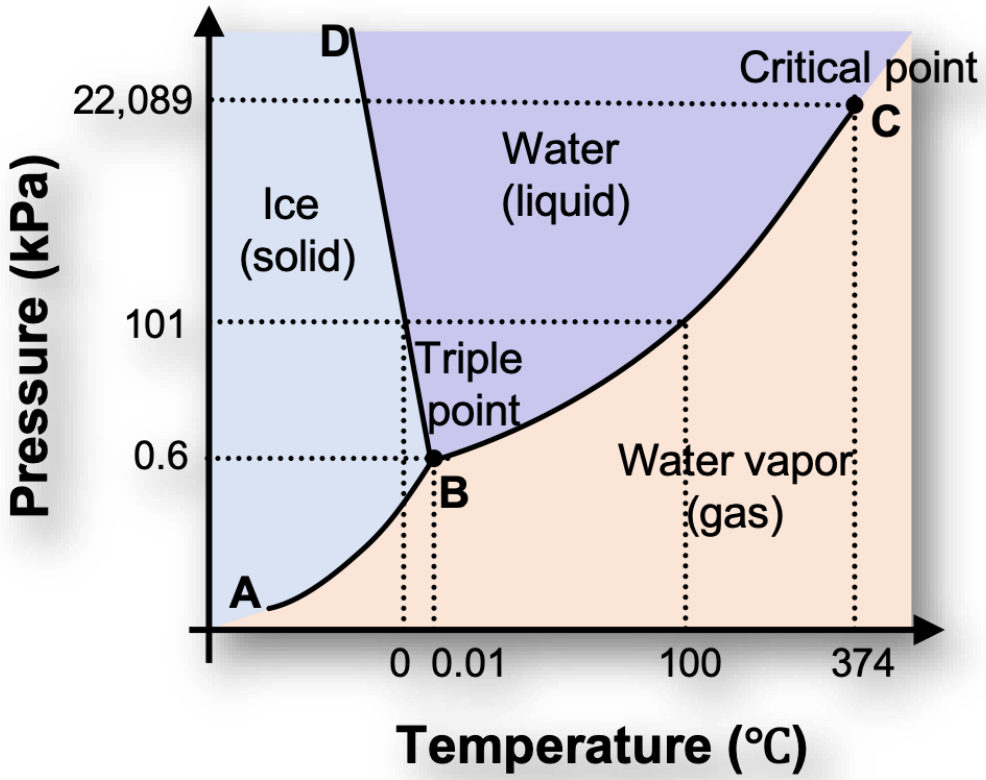

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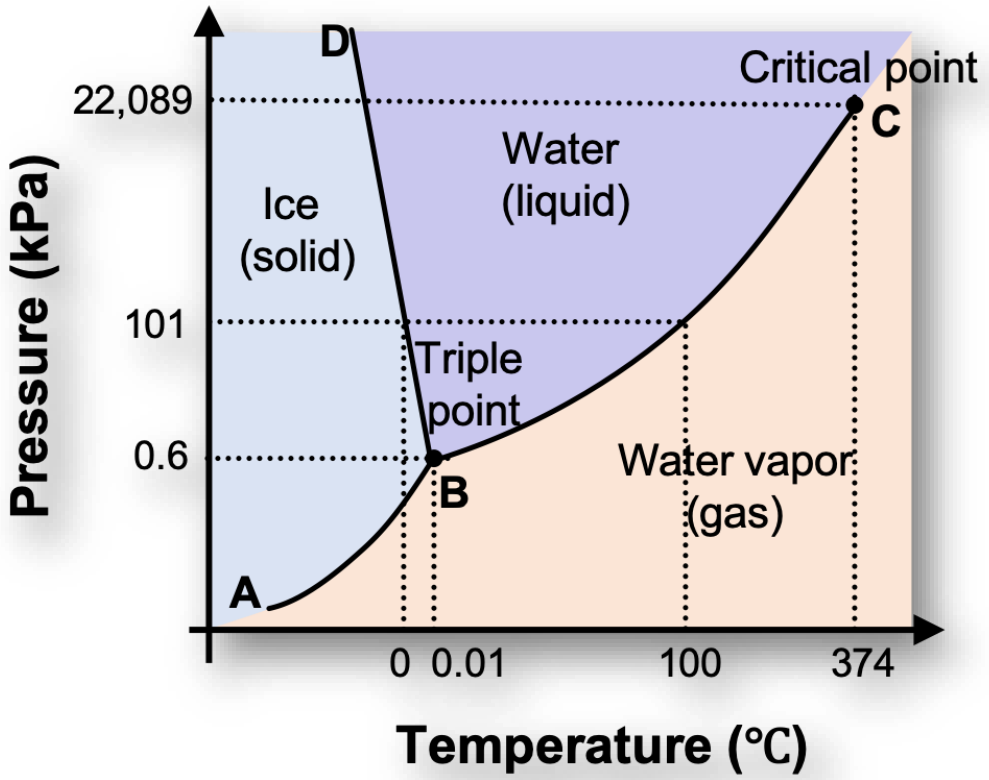

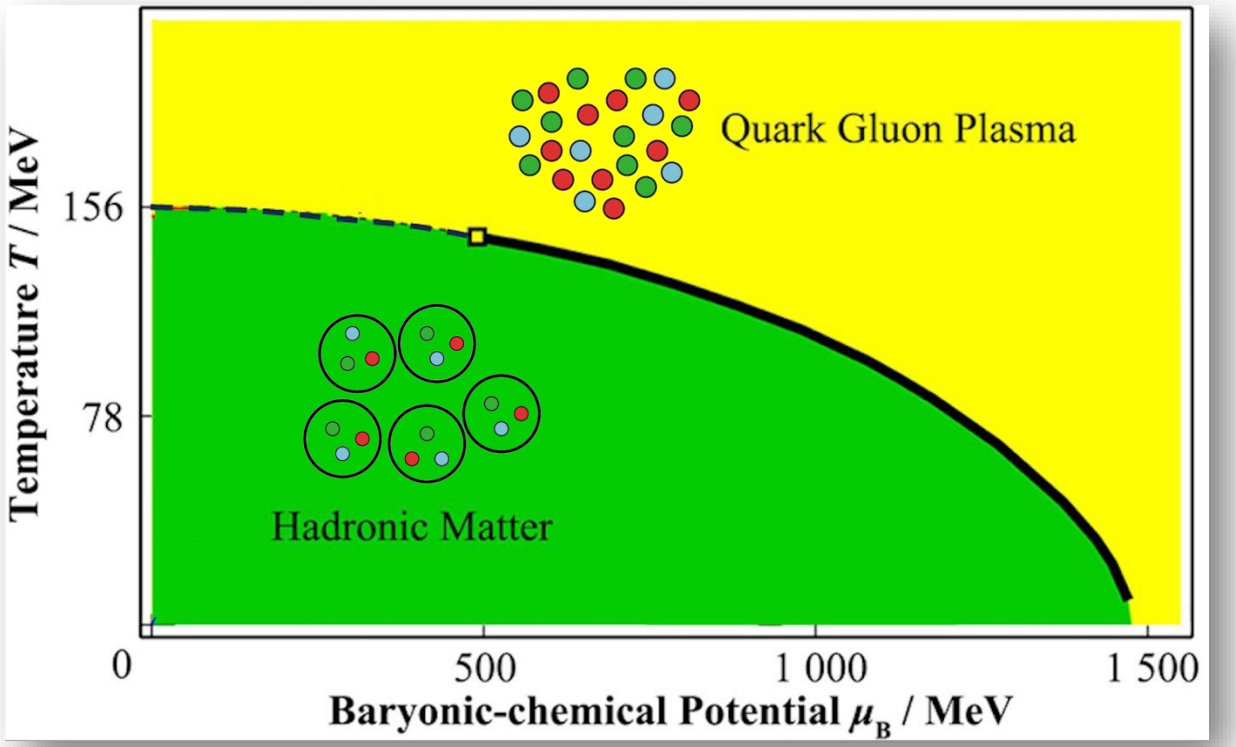

Strong interest in measurements that span a broad μ_B and T domain

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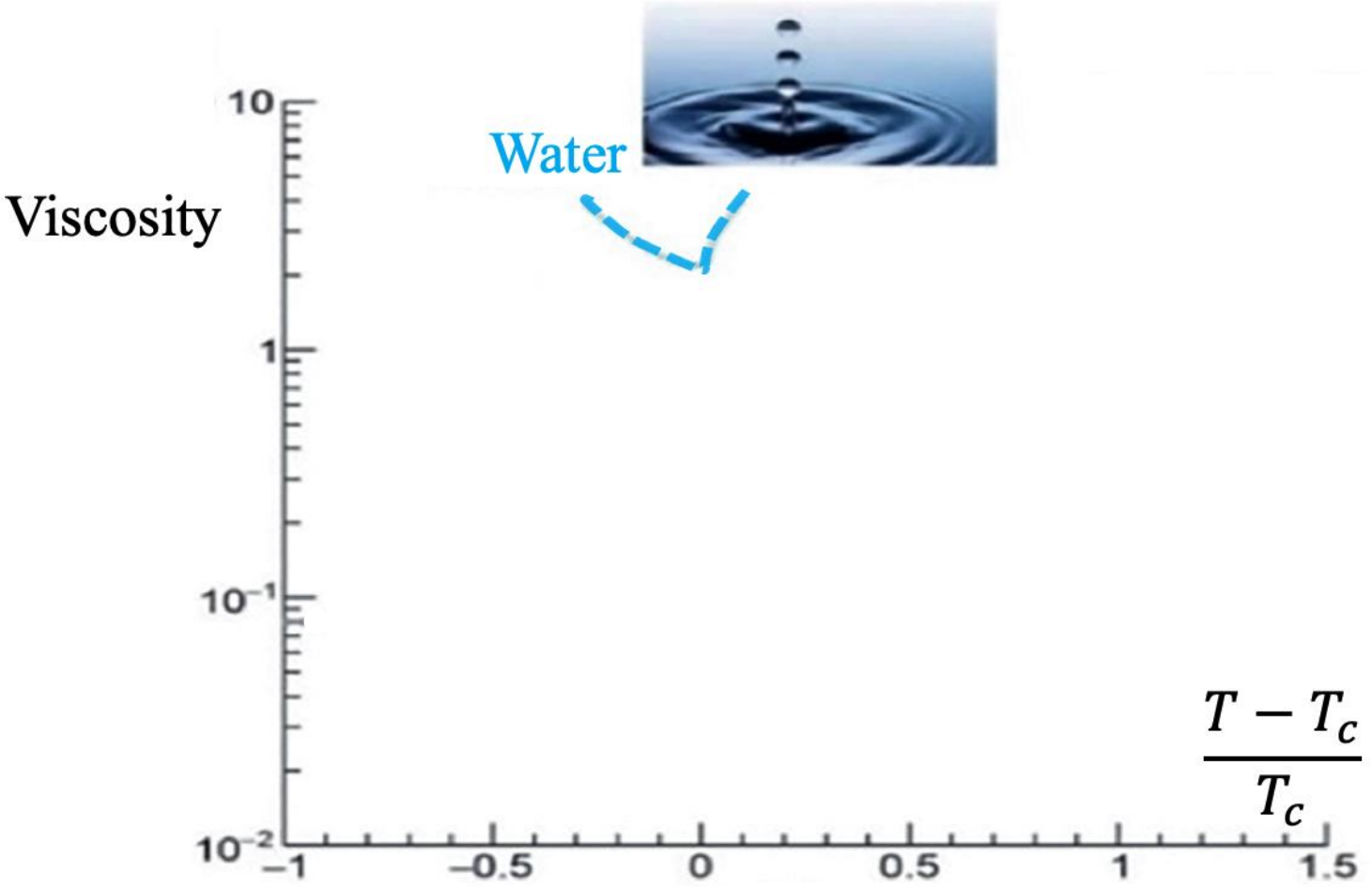

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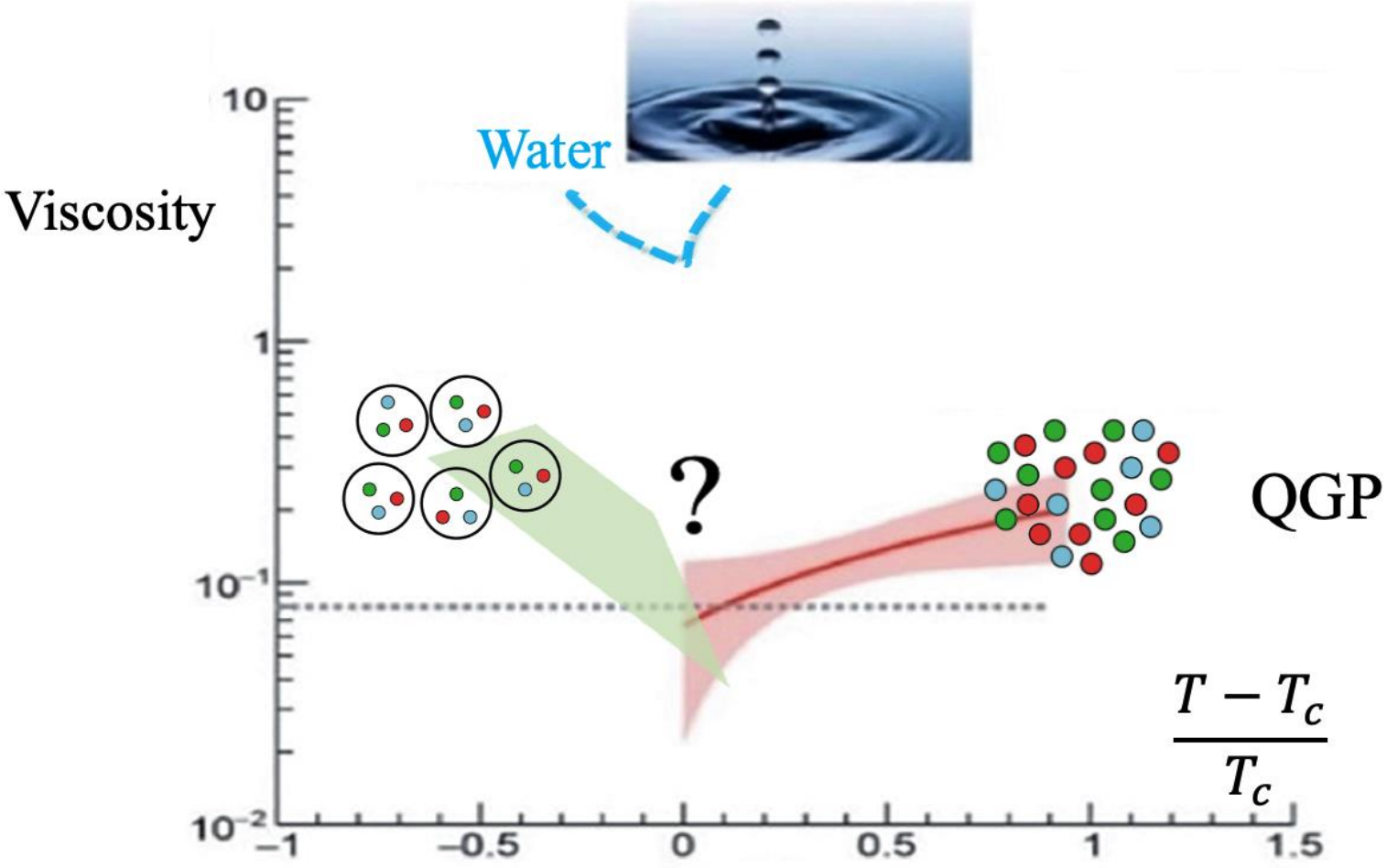

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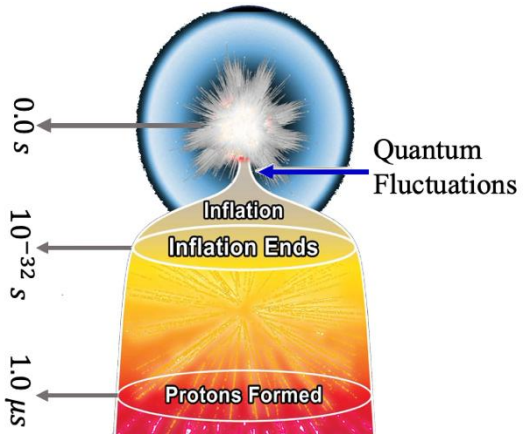
How to reach such extreme conditions?

Early universe



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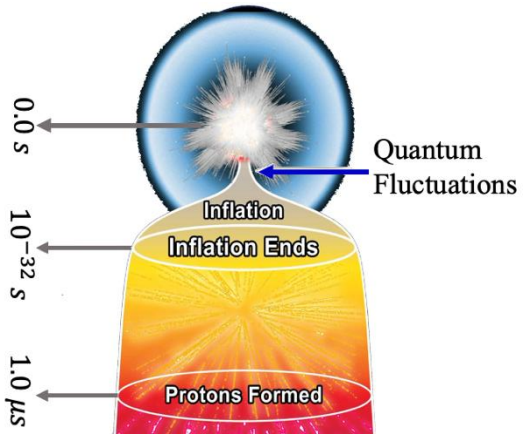
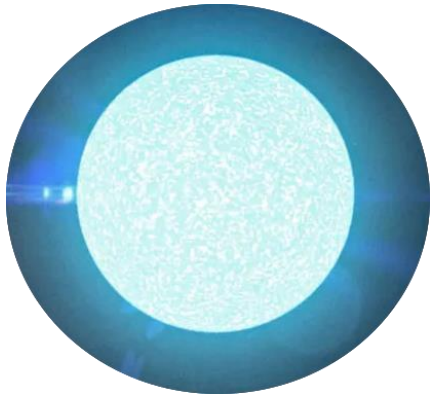


Neutron stars



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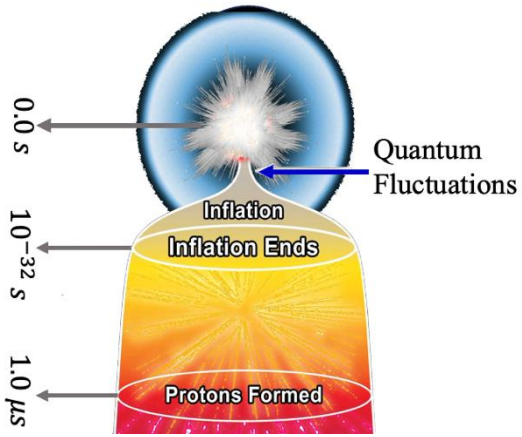

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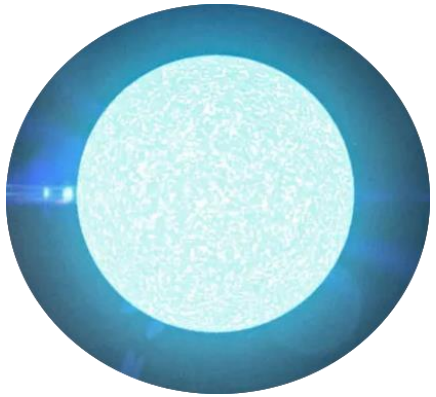
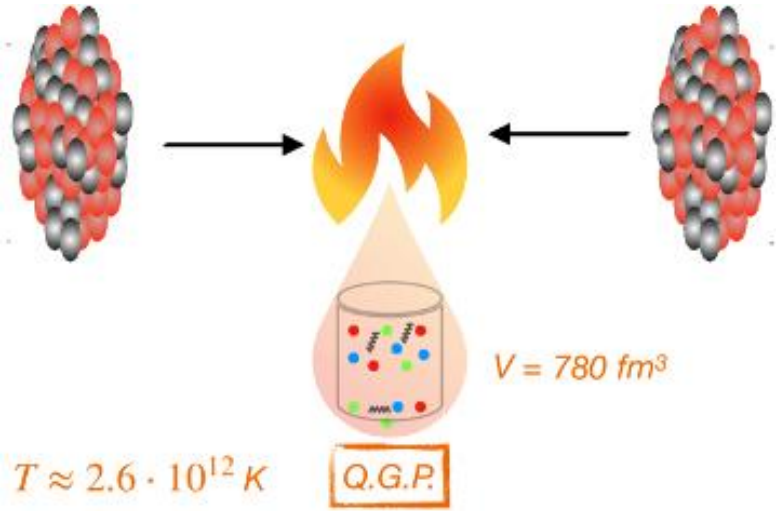


Heavy Ion Collisions (HIC)



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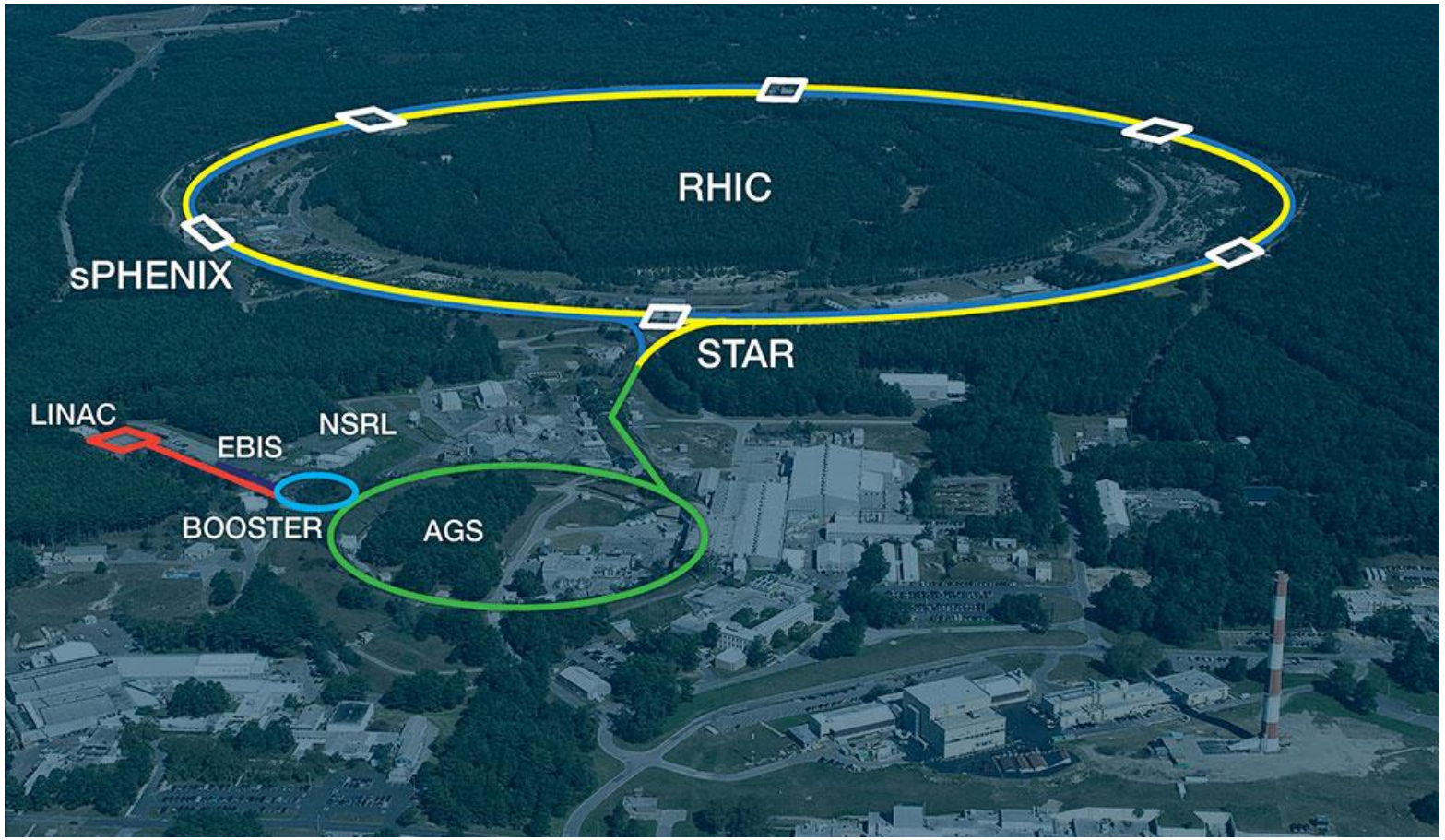

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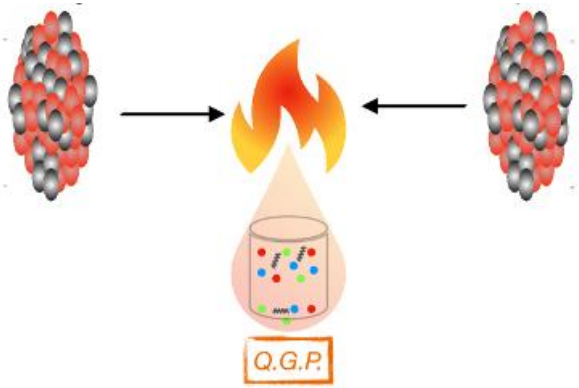

The Quark Gluon Plasma is the ... Hottest

The Quark Gluon Plasma (QGP) can be formed in the laboratory

10^8 times hotter than the sun

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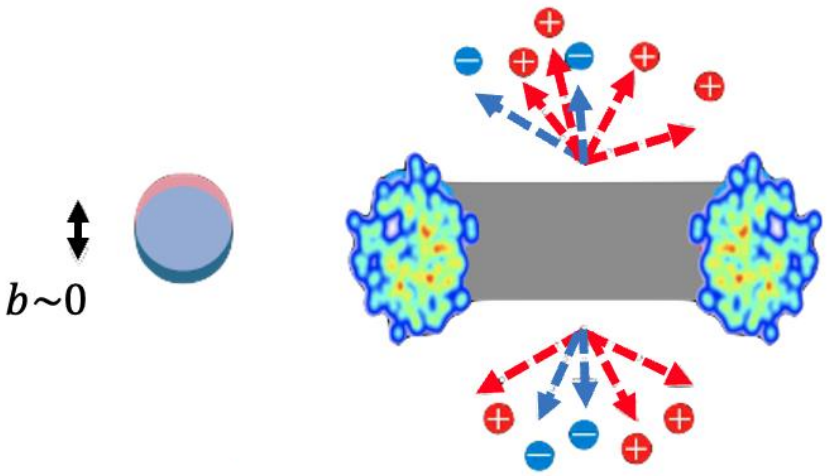

Central event

Big system → Many produced particles

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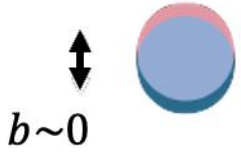

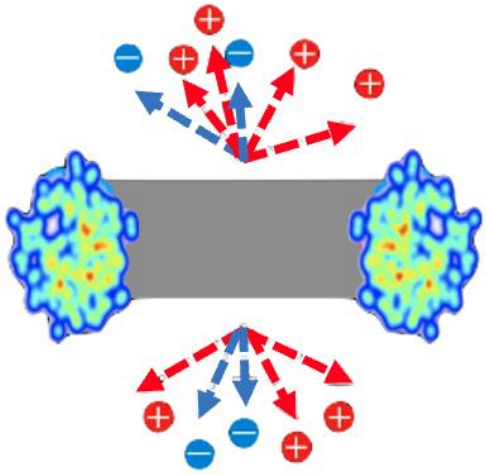

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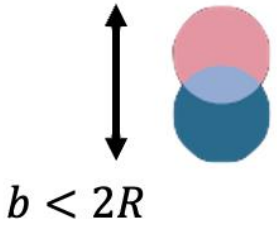
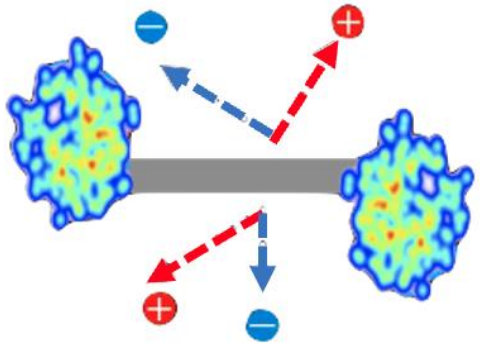
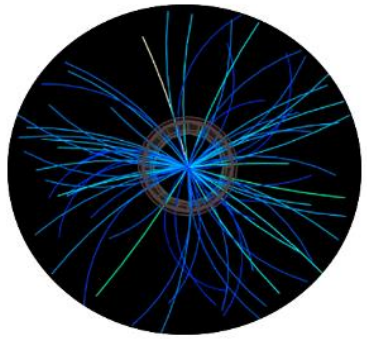




Peripheral event



Small system → Few produced particles

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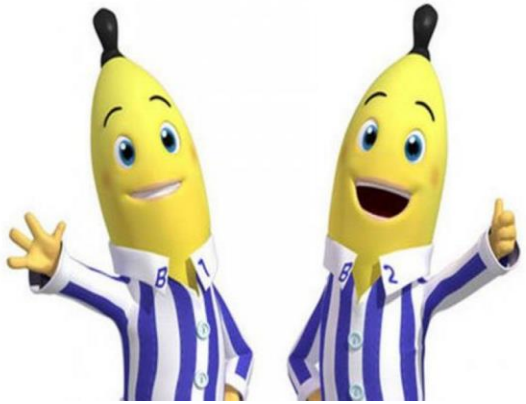
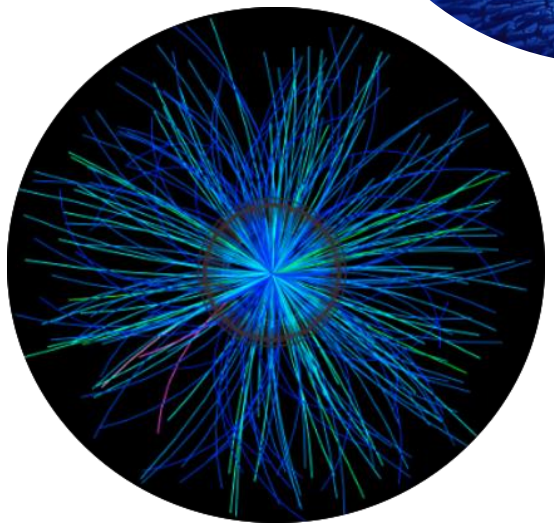
  - Correlations





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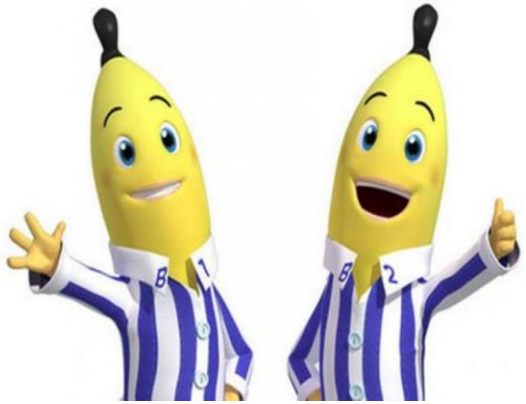
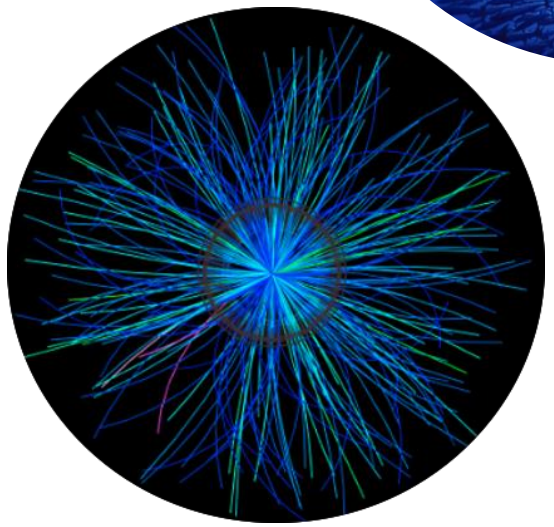
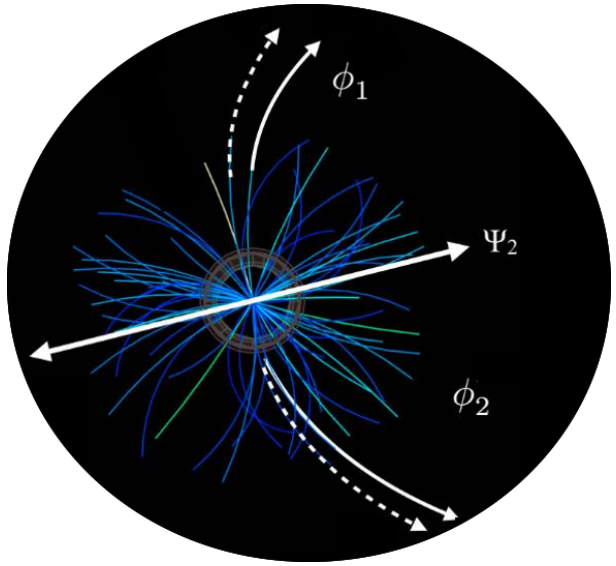




- Collectivity



The observation of a specific pattern or behavior that is followed by most members in a system

What is matter made of ?

What is the nature of the quarks and gluons interactions?

- The unbounded quarks and gluons interactions (not inside the protons)
  - ✓ Extreme conditions of heat and compression to unbound quarks and gluons

Questions in heavy-ion research

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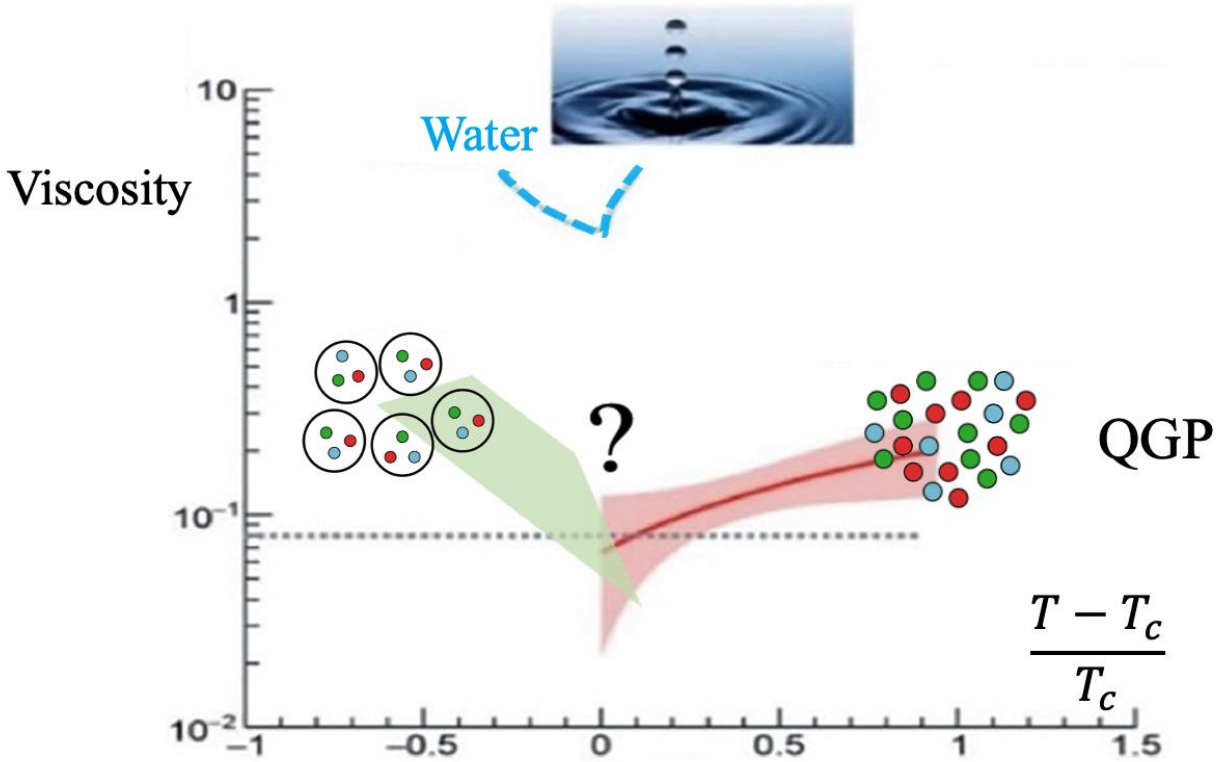
- ✓ What is the nature of the QGP viscosity?



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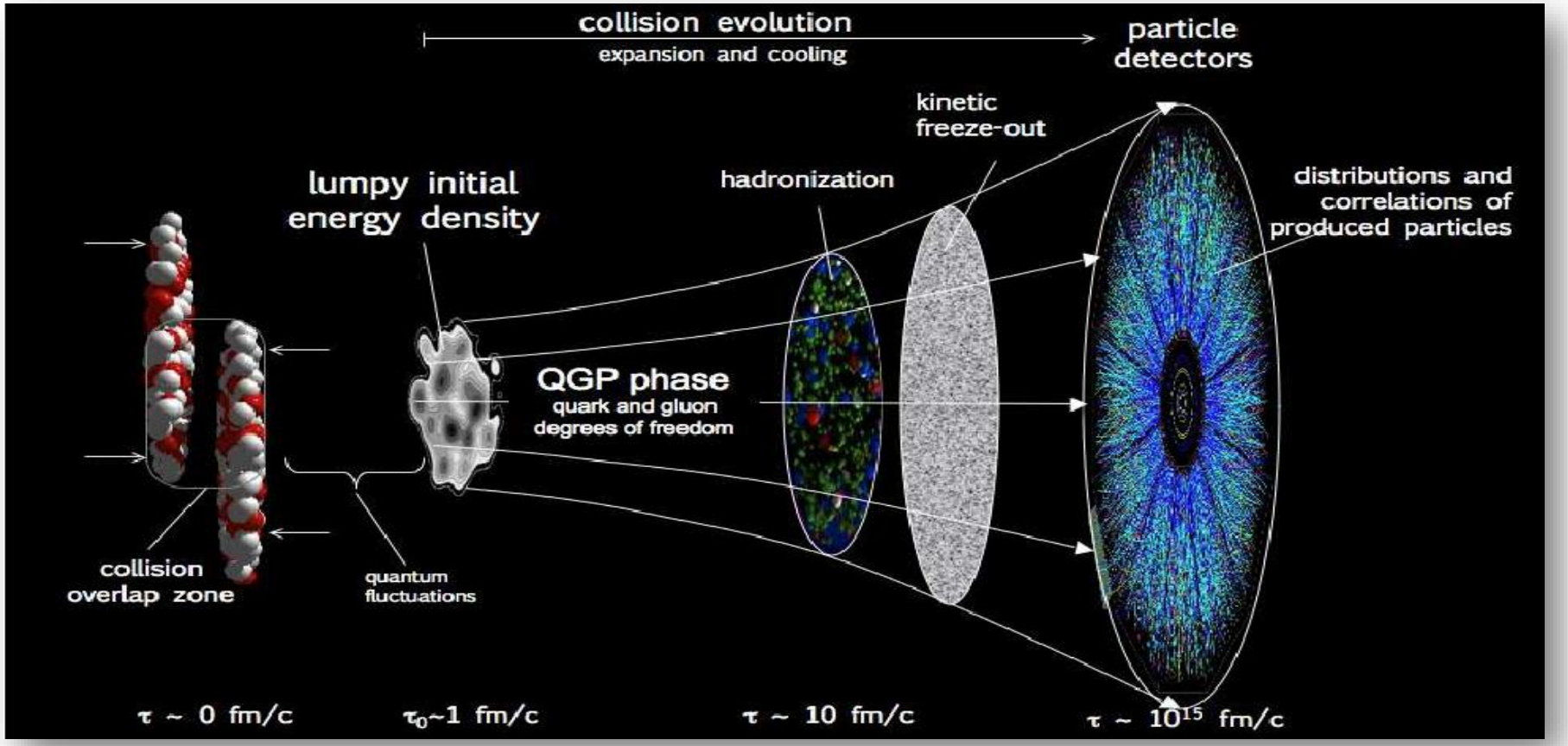
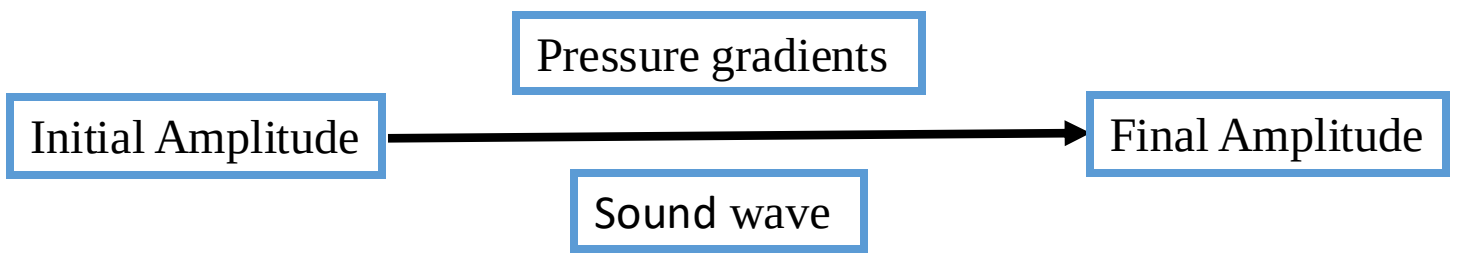
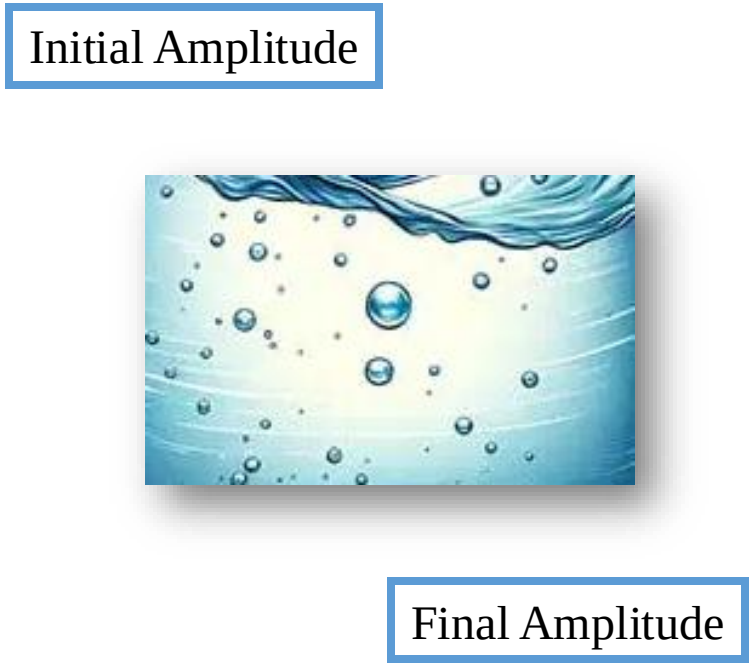


Connecting the initial and final state (Anisotropic flow)

- Sound wave propagation in medium





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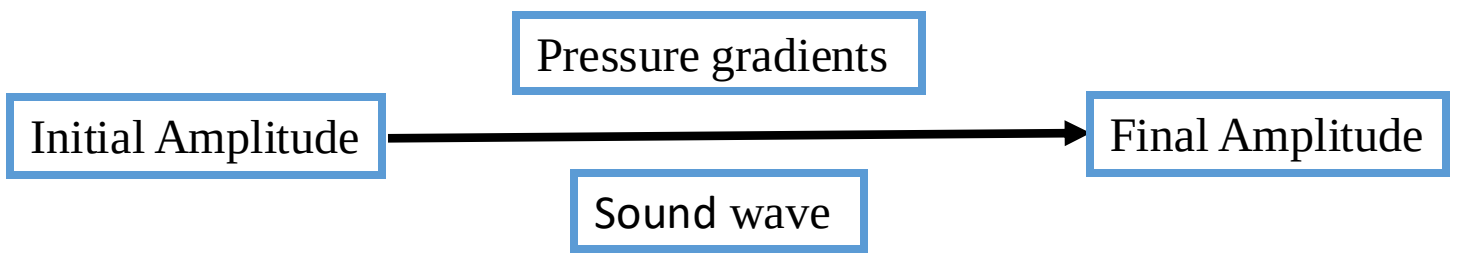

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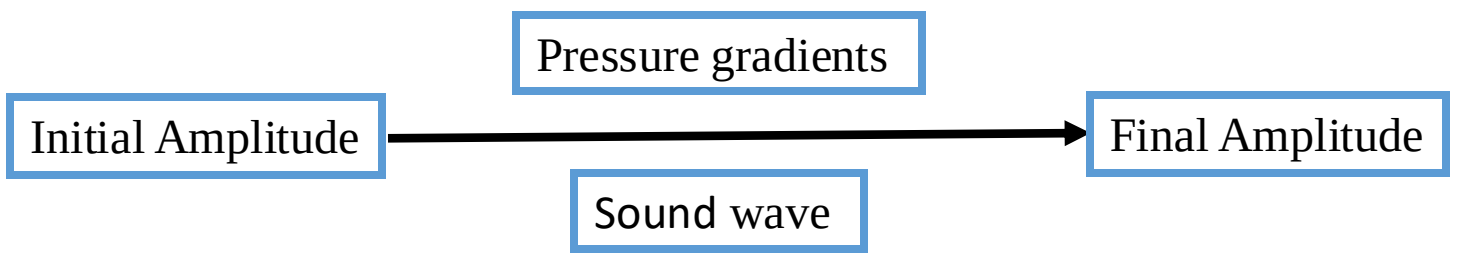

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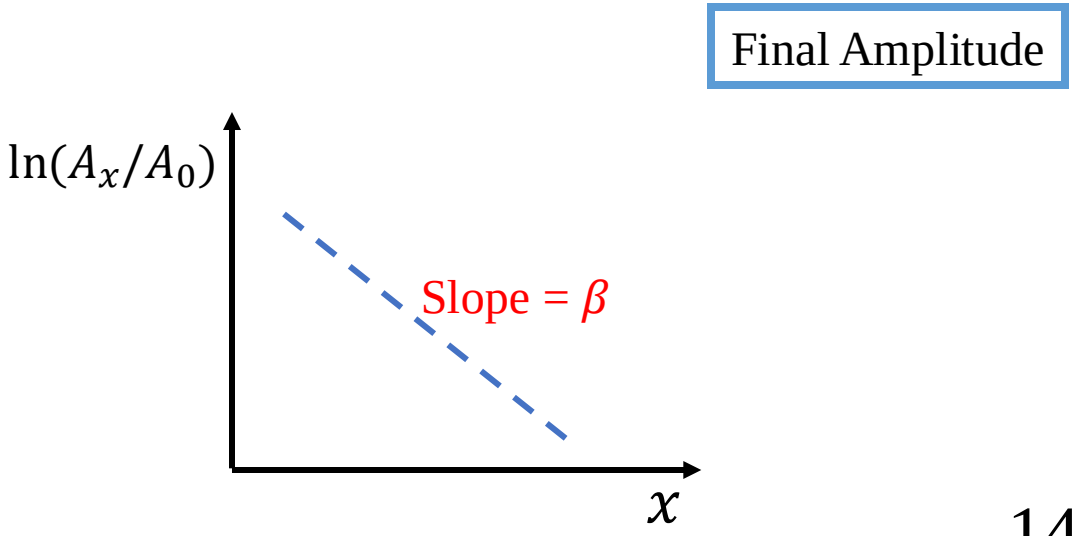

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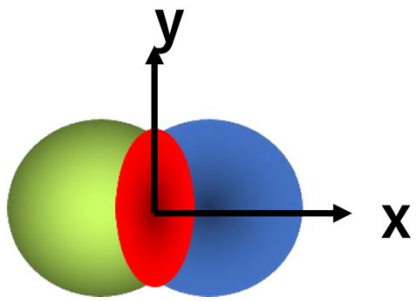

The eccentricity (ε_2) gives the initial spatial anisotropy

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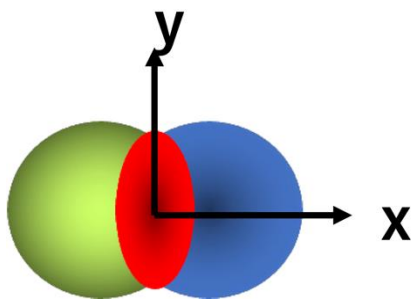

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Pressure gradient

QGP viscosity

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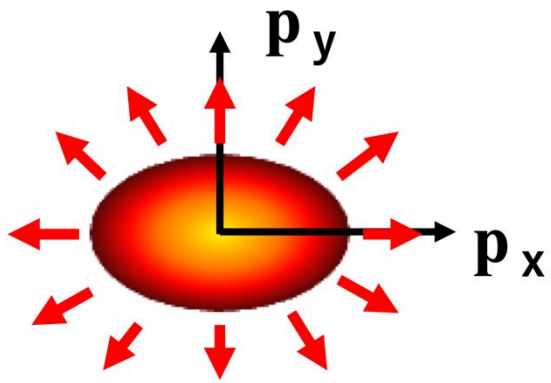

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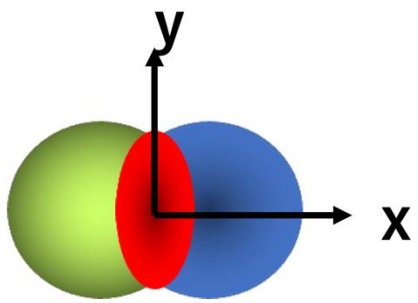

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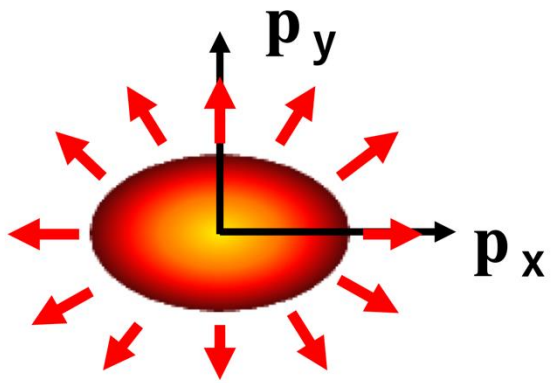

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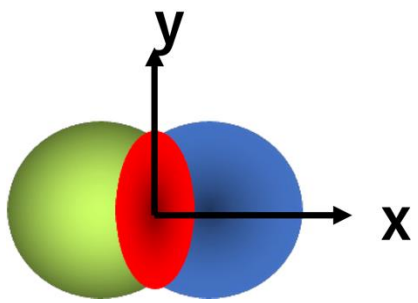

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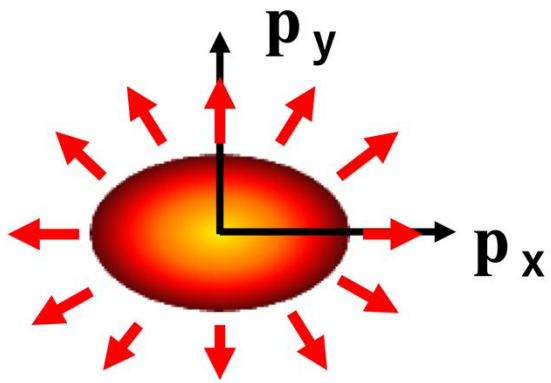

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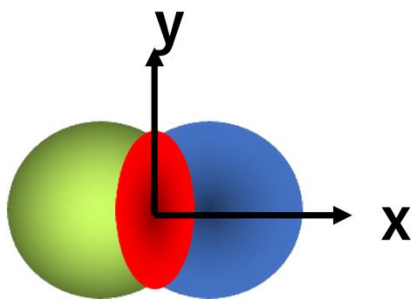

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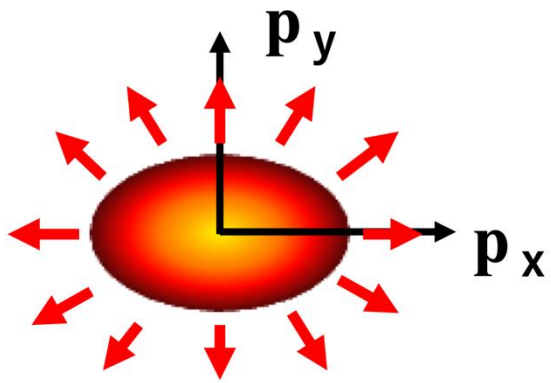

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Models

Connecting the initial and final state (Anisotropic flow)

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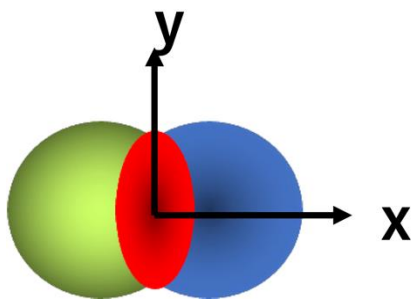

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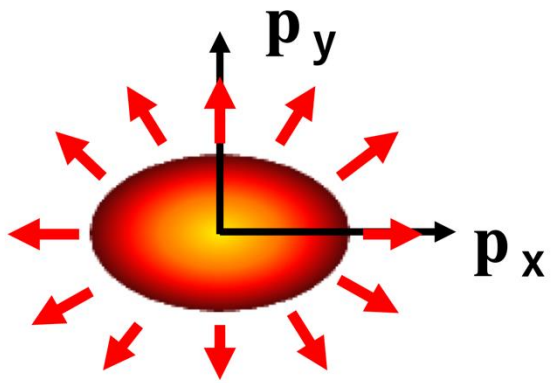

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Models

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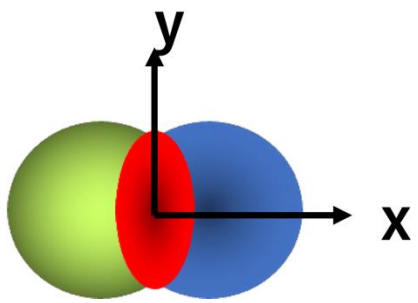

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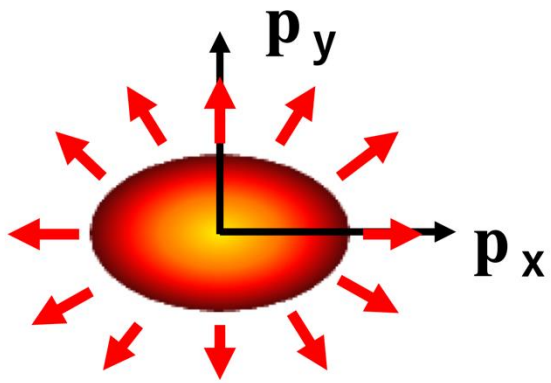

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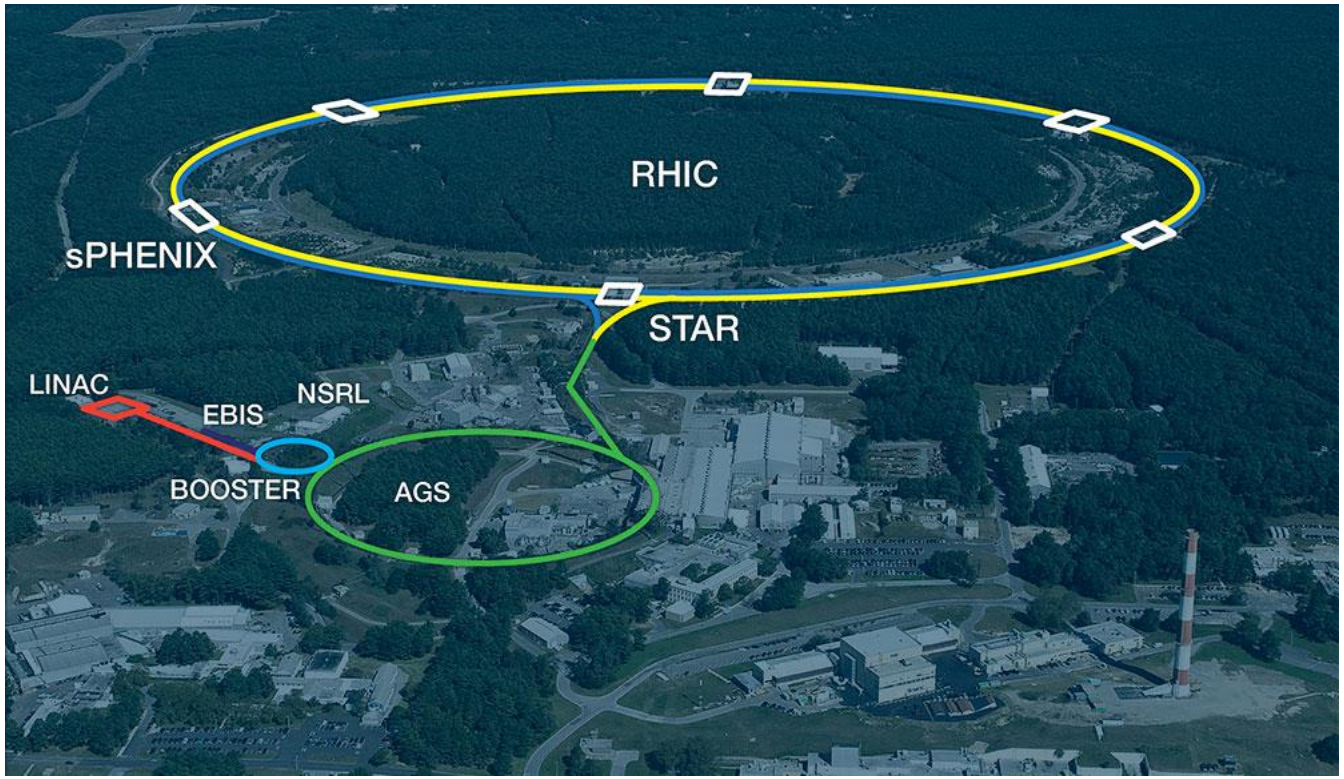
Models

Data

Can we use such an understanding?

Experimental setup

STAR detector at Brookhaven National Laboratory



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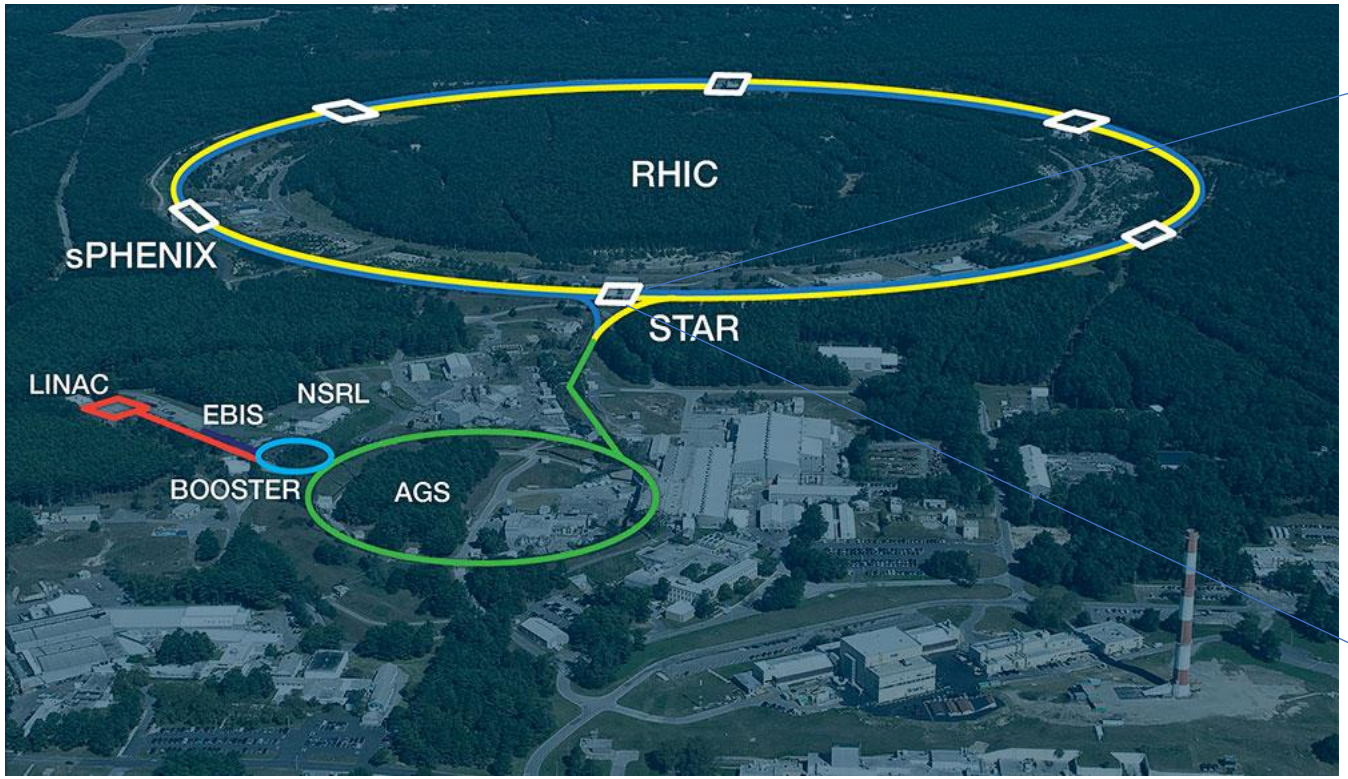

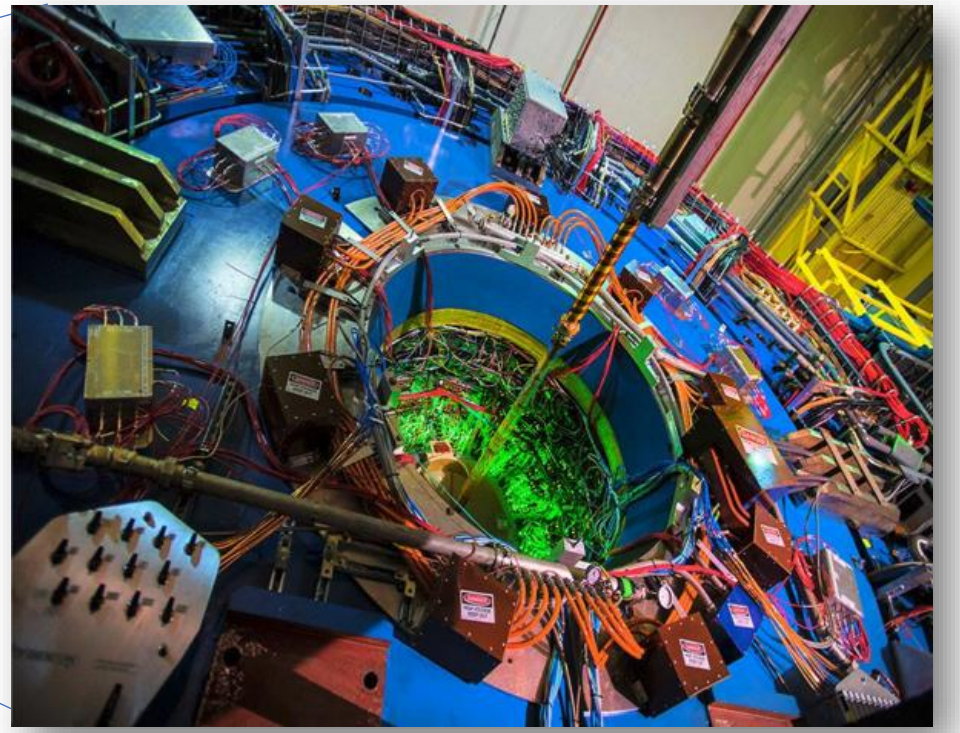

STAR detector provides:

- Capability to access relativistic nuclear collisions of
  - ✓ Au+Au at different beam energies (BES-I and BES-II)
  - ✓ U+U, C+Au, Ru+Ru, Zr+Zr, Cu+Cu, and O+O at 200 GeV

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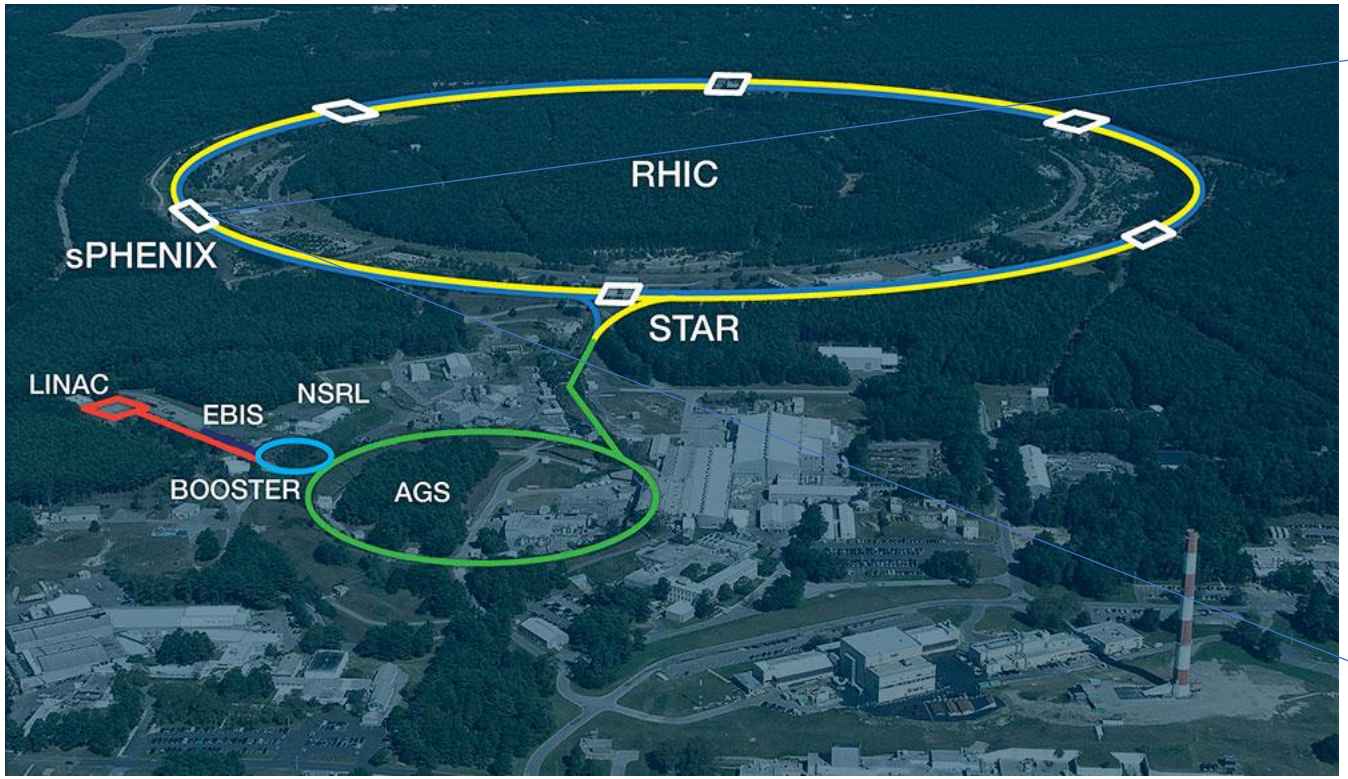
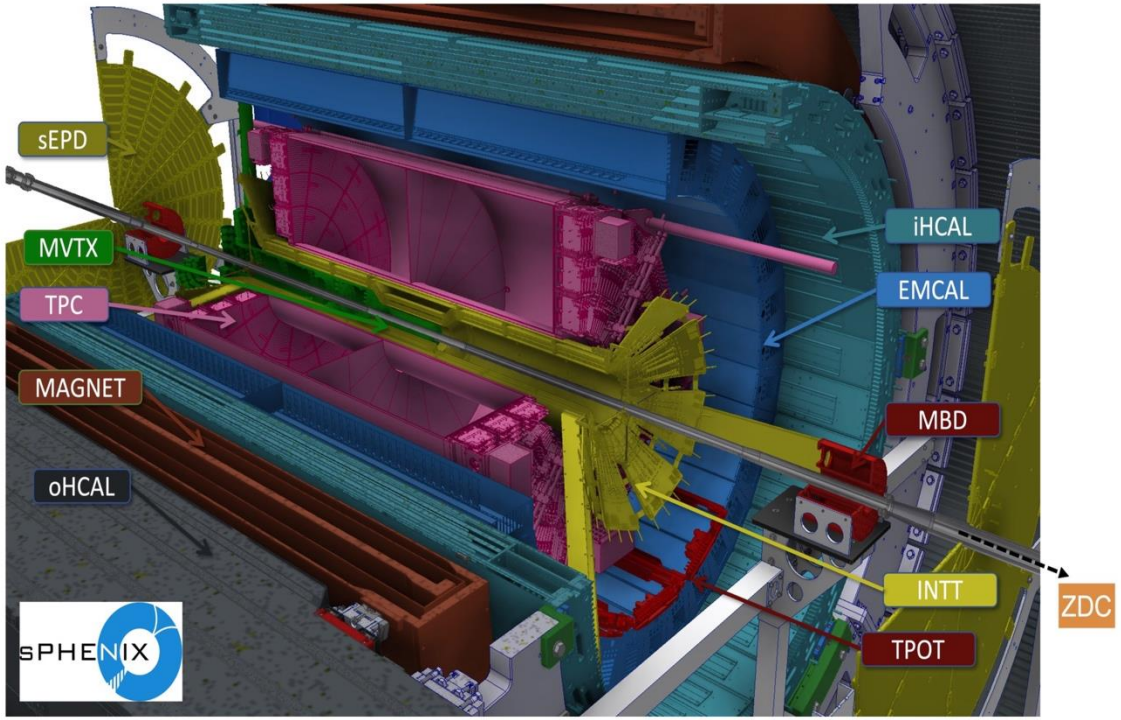


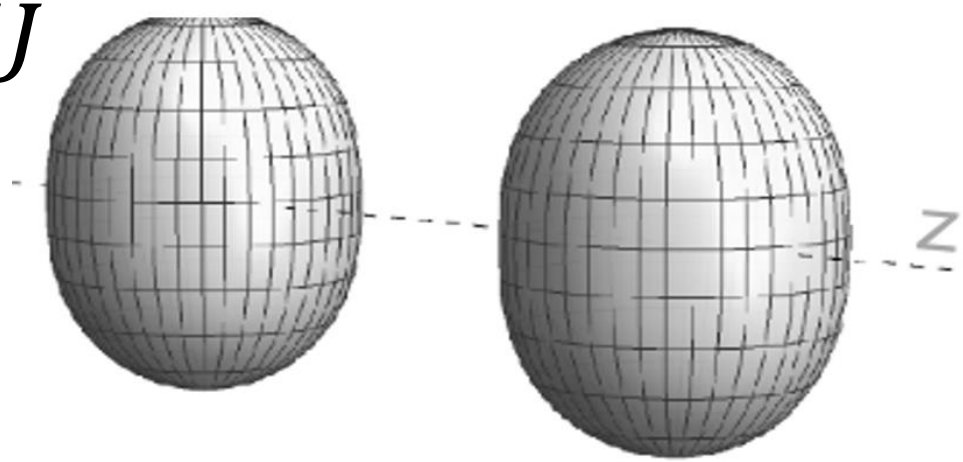


sPHENIX detector:

- New detector

What is the collided nucleus's shape and structure?

^{238}U



STAR Collaboration
Nature 635 (2024) 8037, 67-72

Niseem Magdy
Eur.Phys.J.A 59 3, 64 (2023)

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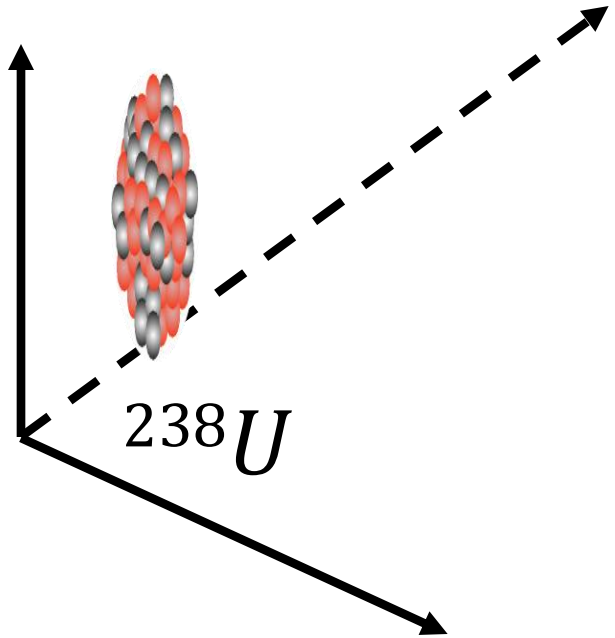

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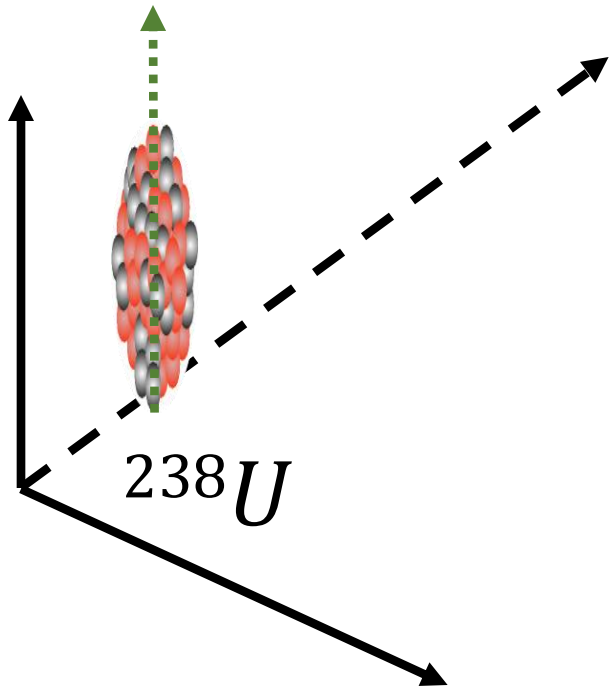

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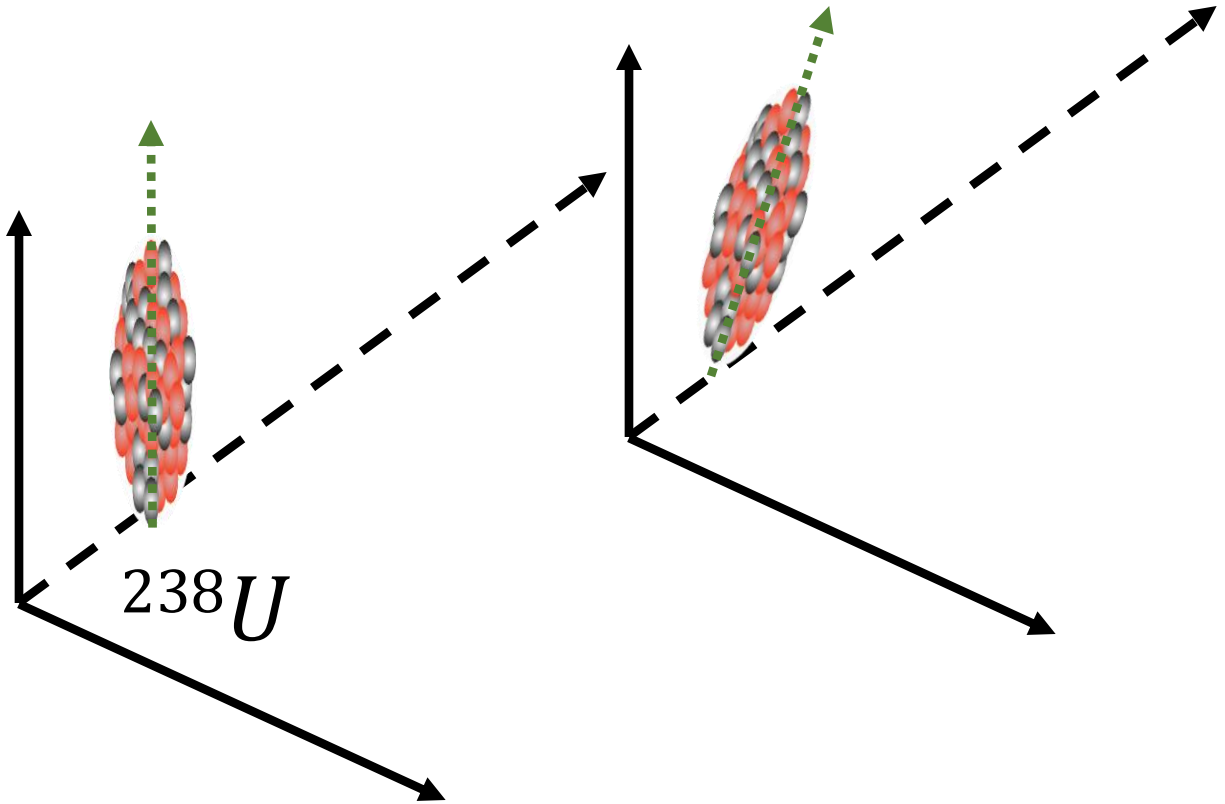

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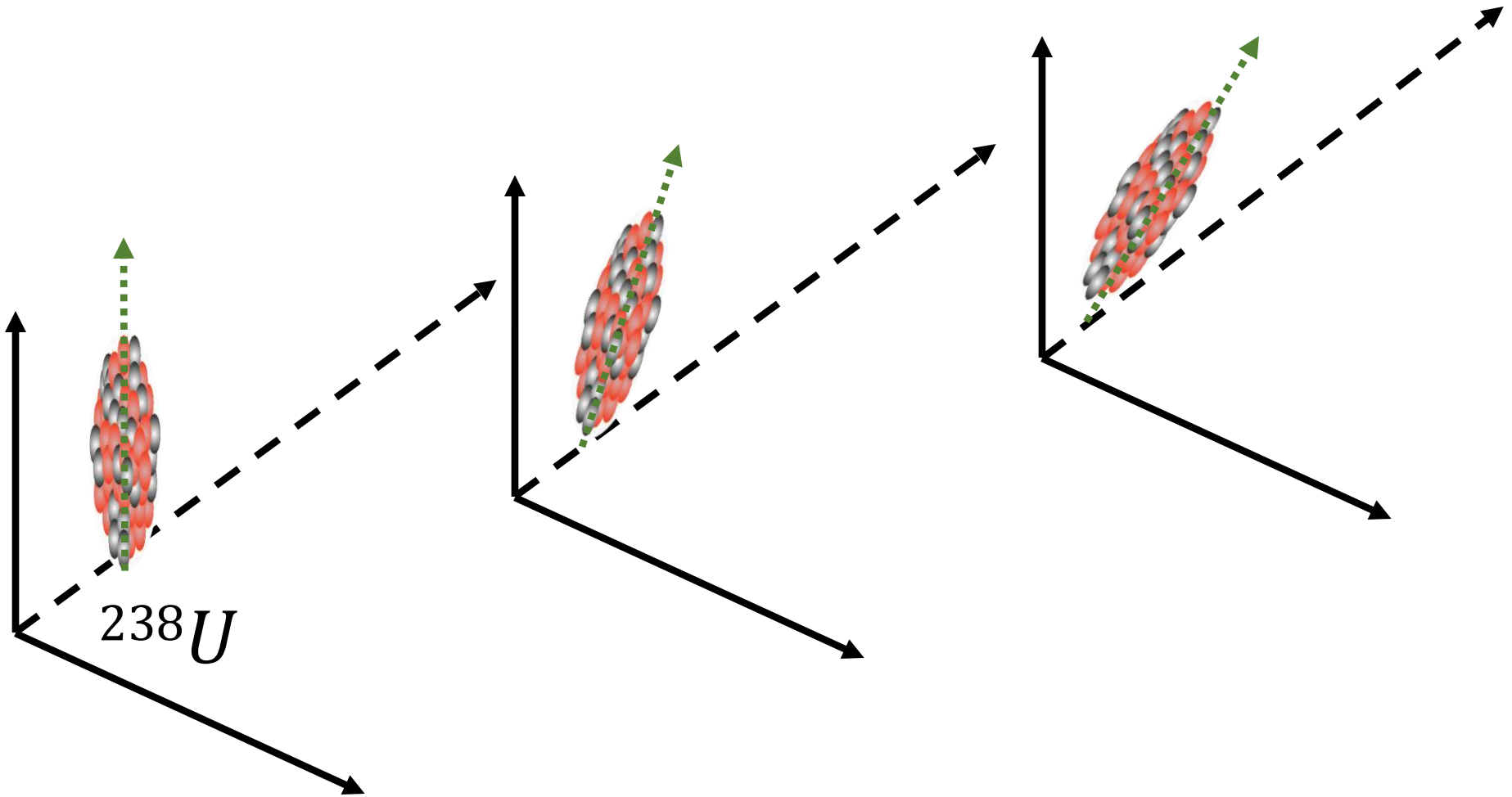

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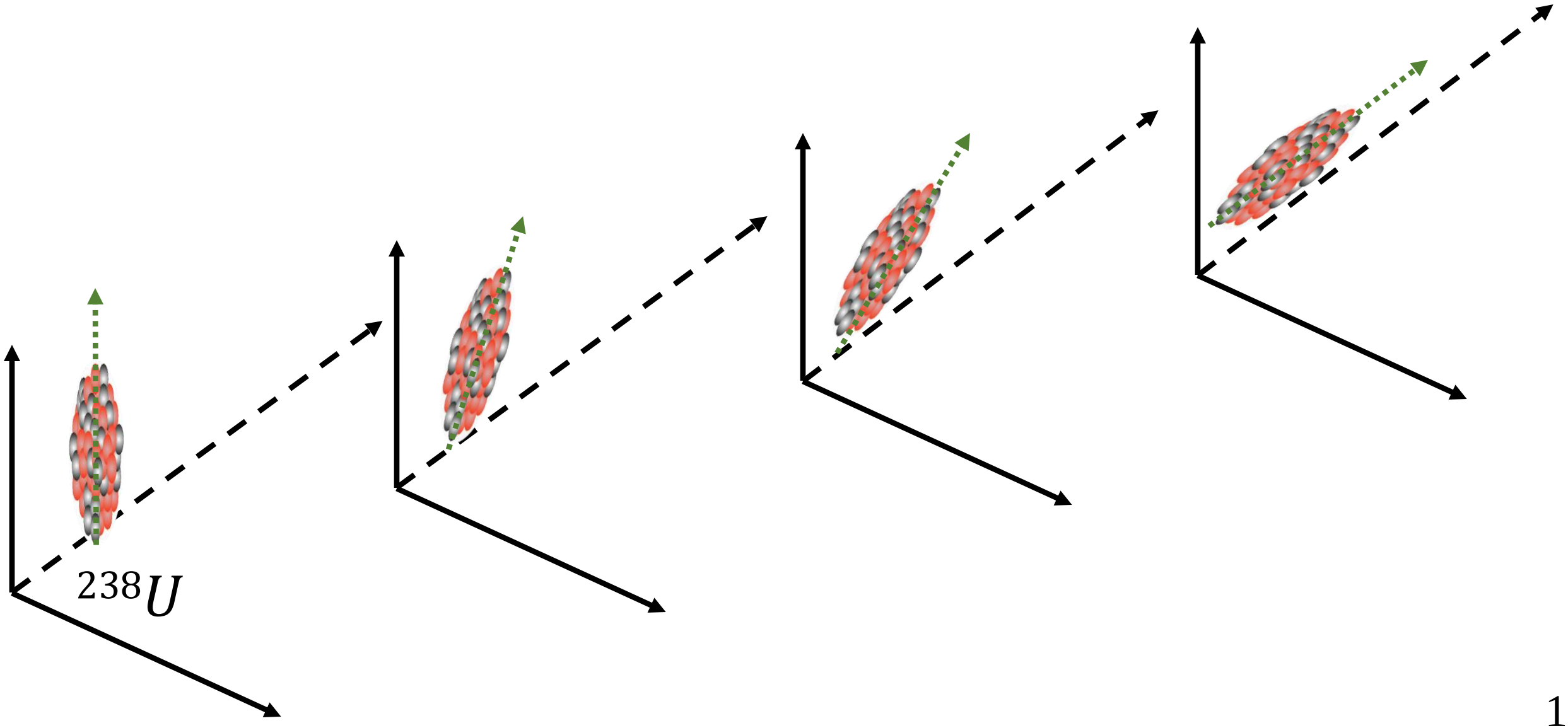

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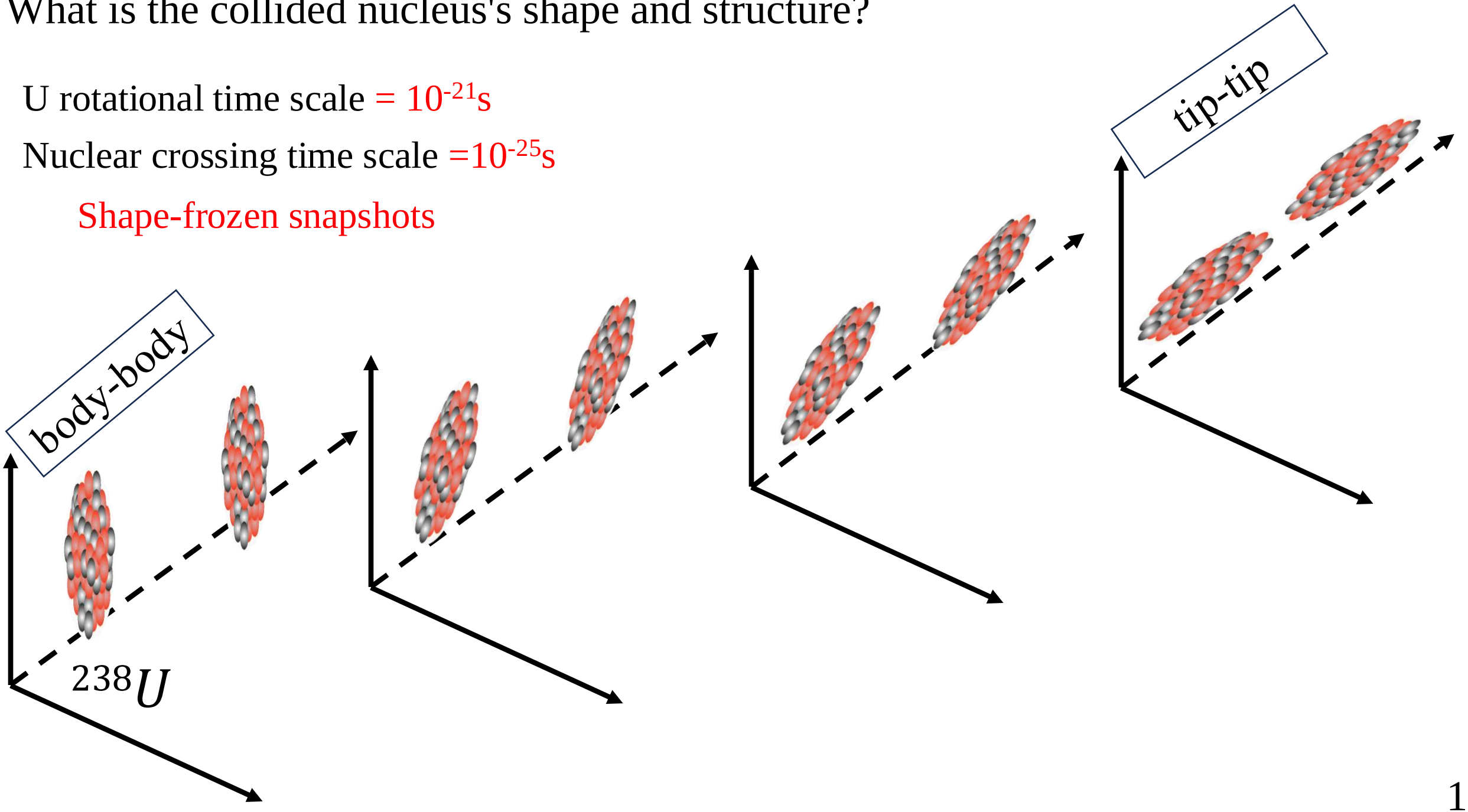
Shape-frozen snapshots



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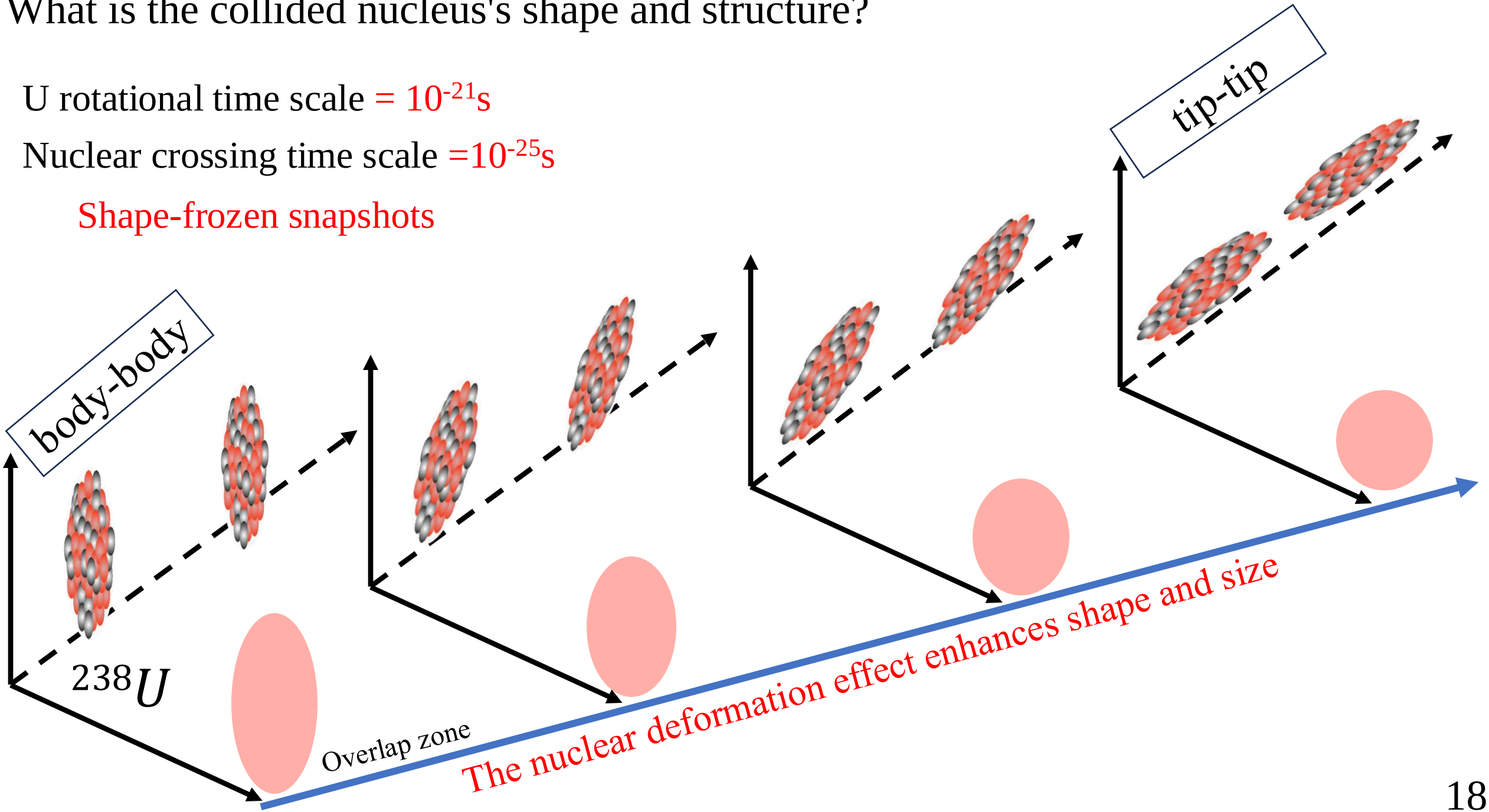

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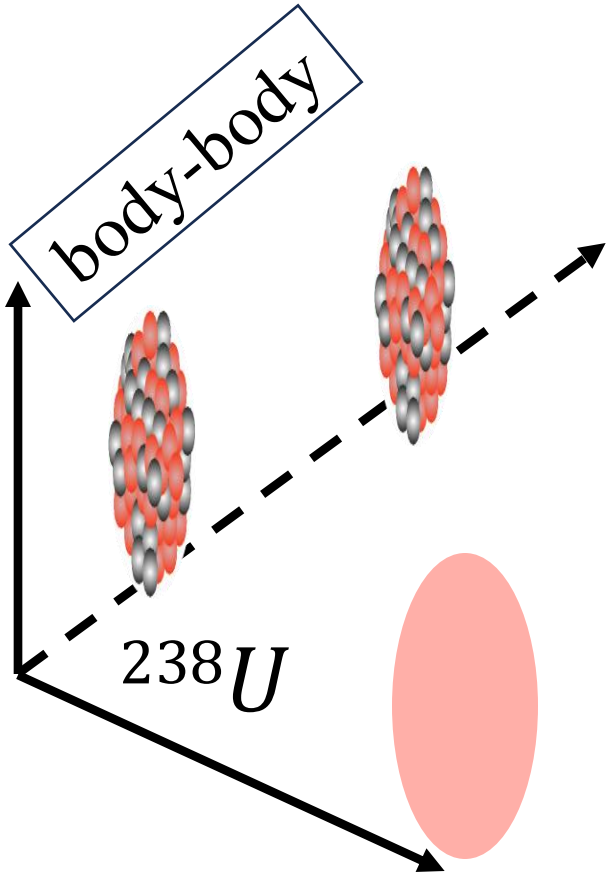

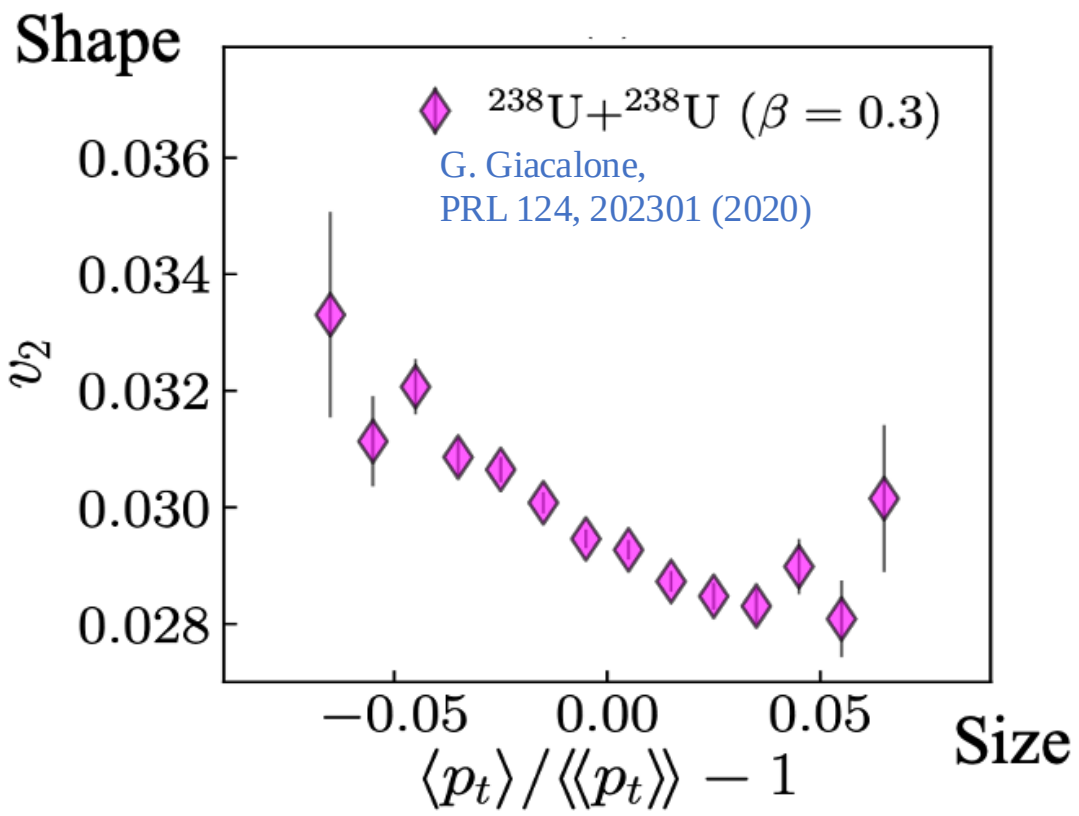

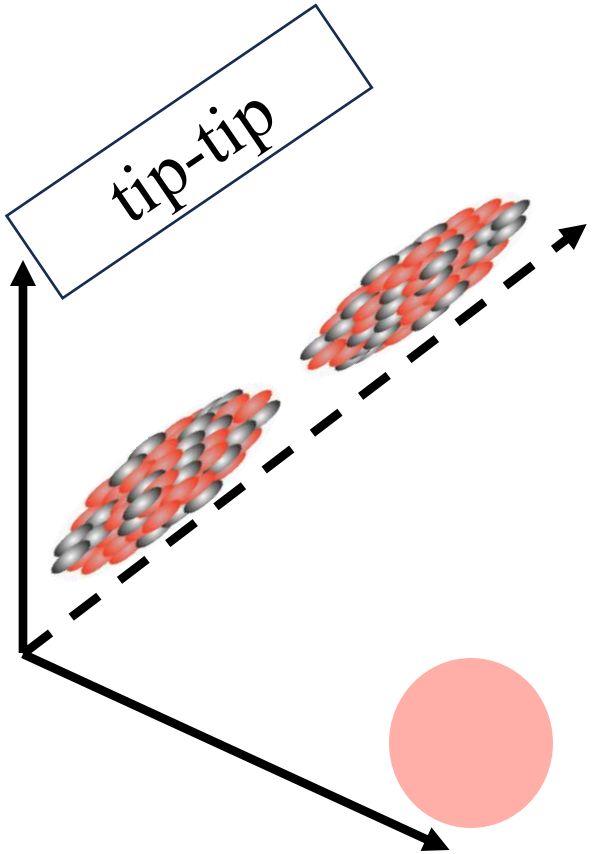

The nuclear deformation effect enhances shape and size

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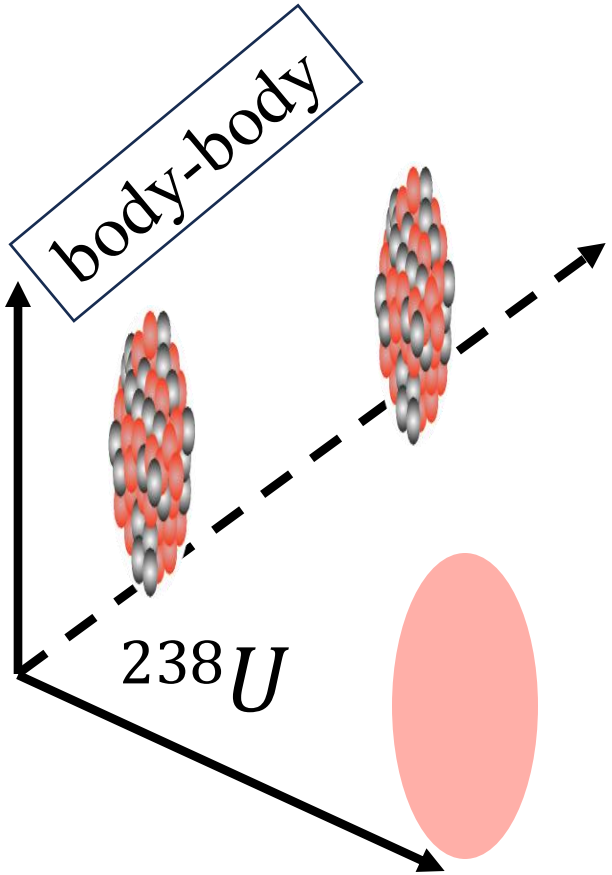
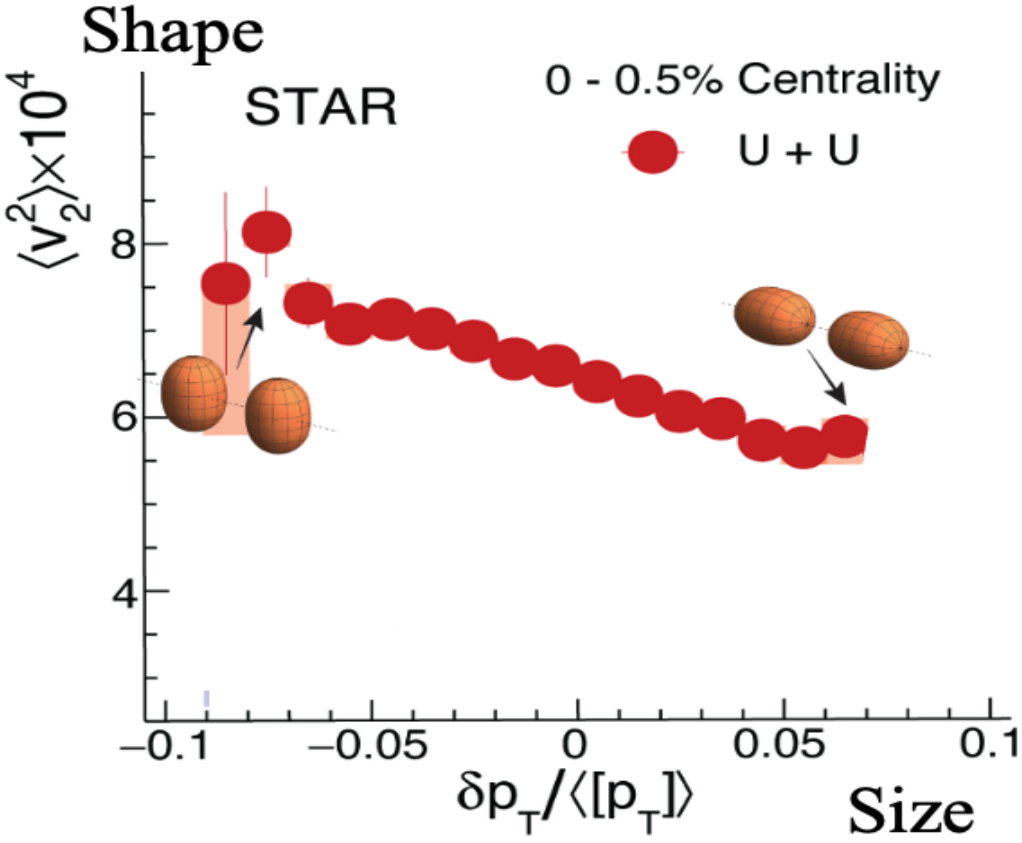
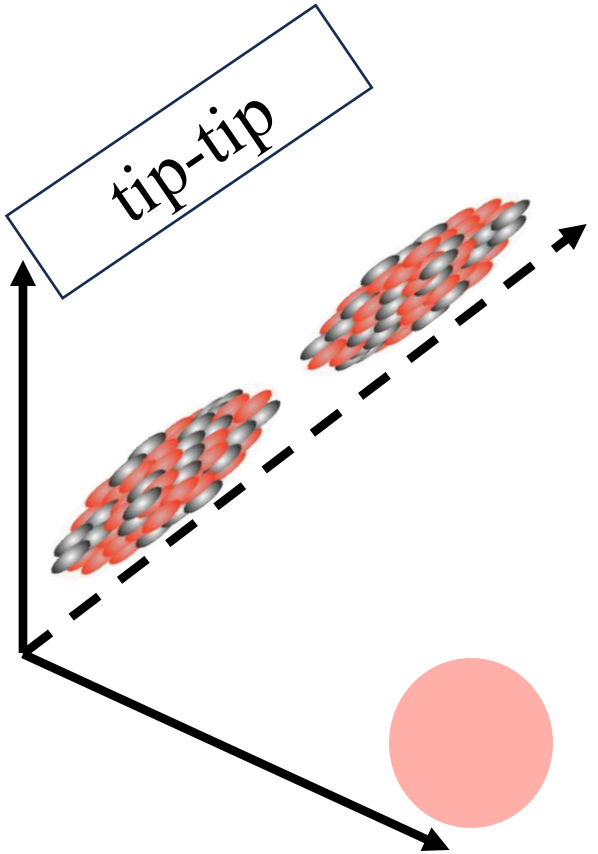






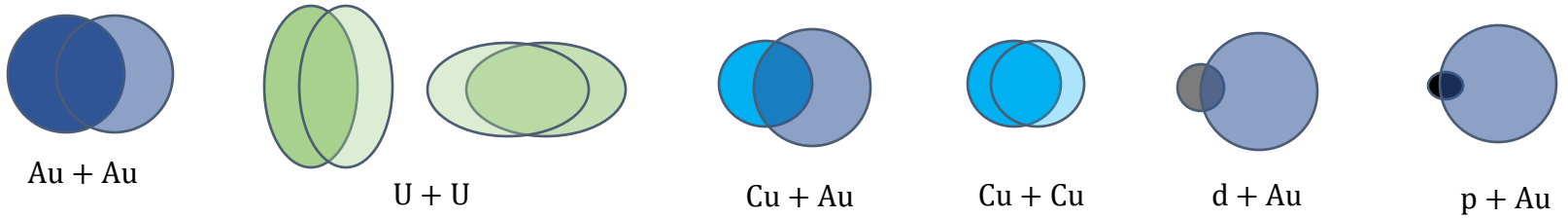
The nuclear deformation effect enhances shape and size

Models must consider the nuclear deformation effect

Can we validate our linear formula?

$$\ln\left(\frac{v_2}{\varepsilon_2}\right) = -\beta''\langle N_{Ch}\rangle^{-1/3}$$

STAR Collaboration
PRL 122 17, 172301 (2019)
PRL 129 25, 252301 (2022)



DOE Highlights,
https://www.energy.gov/science/np/articles/new-findings-flow-particles-heavy-ion-collisions

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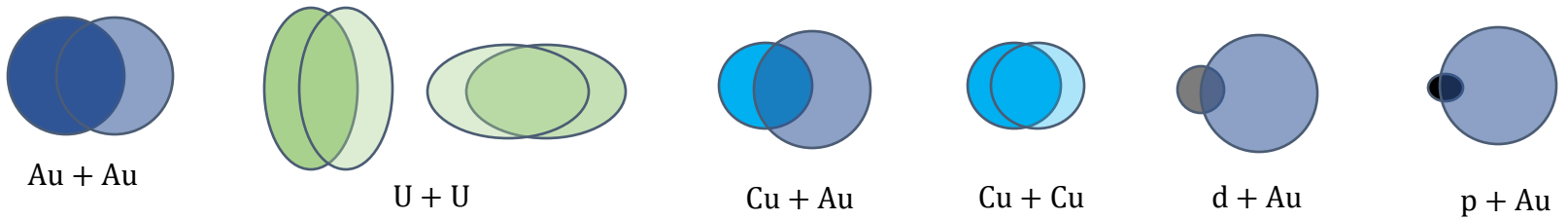
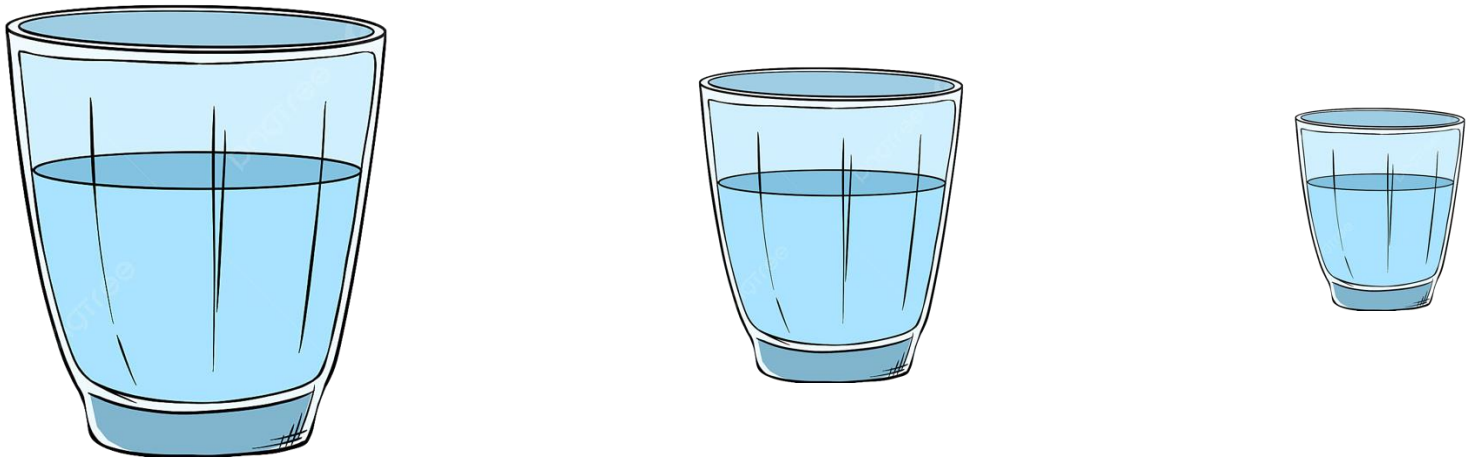


Different shapes and sizes



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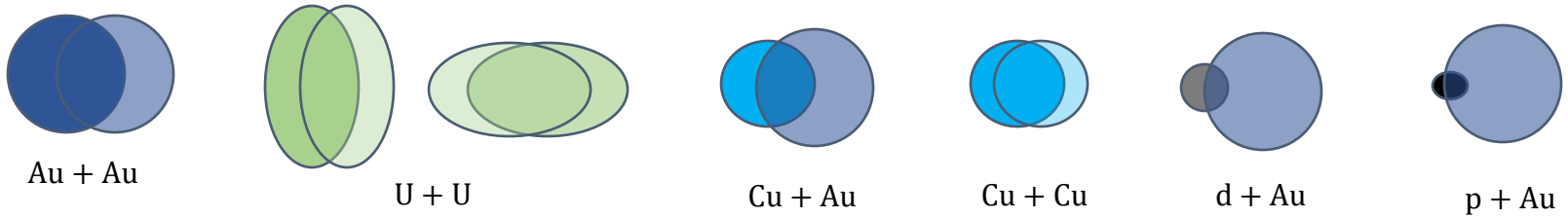

Different shapes and sizes

Similar viscosity

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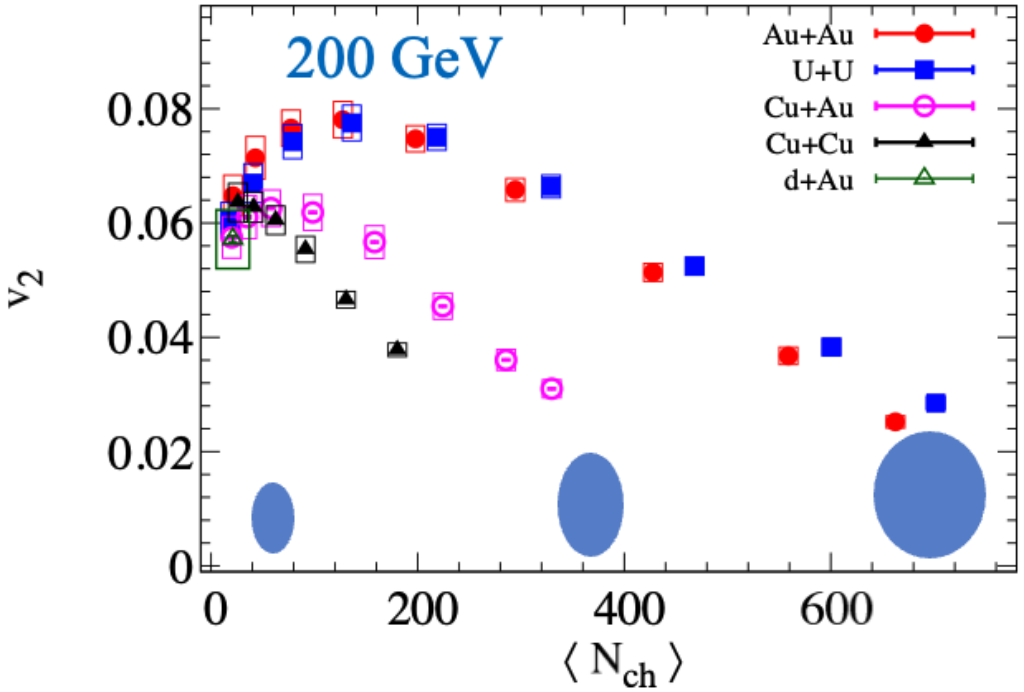

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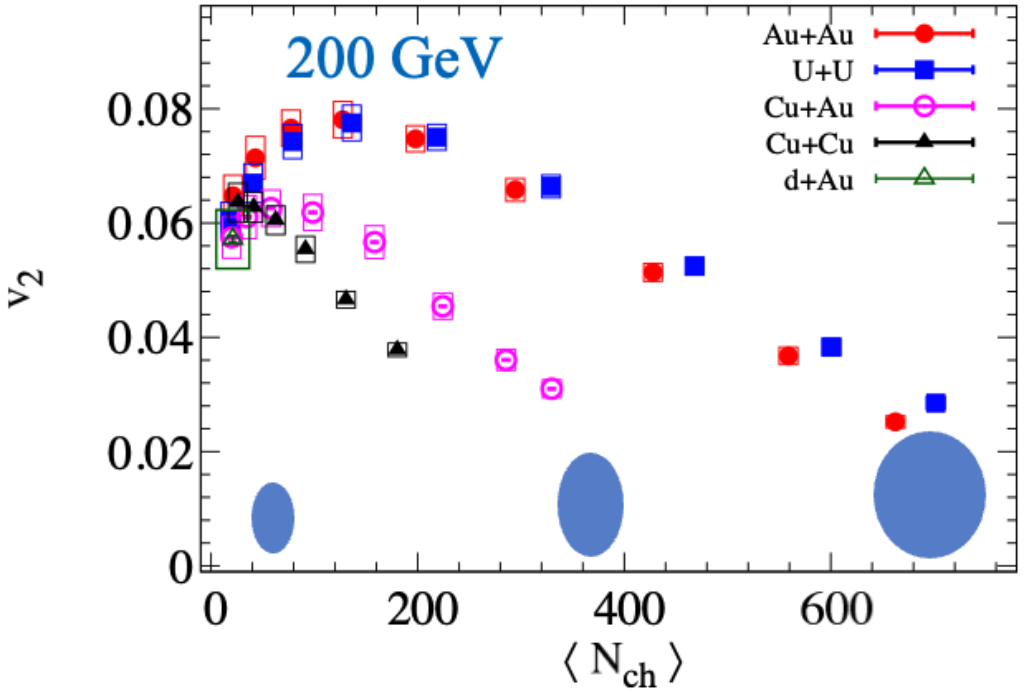
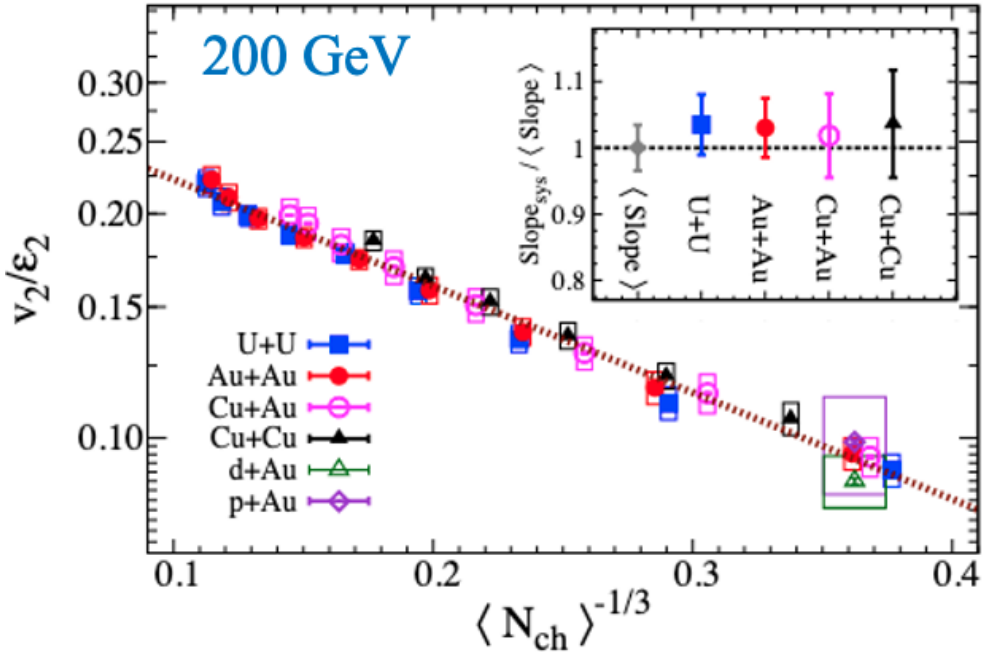
PRL 129 25, 252301 (2022)

Can we validate our linear formula?

$$\ln\left(\frac{v_2}{\varepsilon_2}\right) = -\beta''\langle N_{Ch}\rangle^{-1/3}$$





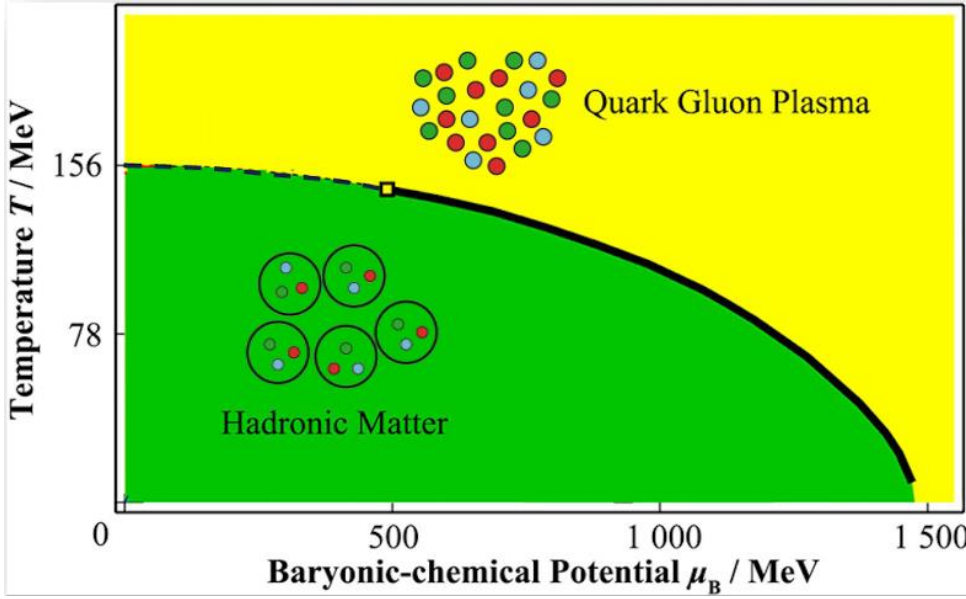
v_2/ϵ_2 for all systems scales to a single curve.

Similar slopes imply similar viscous coefficients for all presented systems

STAR Collaboration
PRL 122 17, 172301 (2019)
PRL 129 25, 252301 (2022)

We can measure the QGP viscosity → β''

$\sqrt{s_{NN}}$ (GeV)	T_{ch} (MeV)	μ_B (MeV)
200	164.3	28
62.4	160.3	70
54.4	160.0	83
39	156.4	103
27	155.0	144
19.6	153.9	188
14.5	151.6	264
11.5	149.4	287
7.7	144.3	398



What is the nature of the QGP viscosity?

$$\ln\left(\frac{v_2}{\varepsilon_2}\right) = -\beta''\langle N_{Ch}\rangle^{-1/3}$$

$\sqrt{s_{NN}}$ (GeV)	T_{ch} (MeV)	μ_{B} (MeV)
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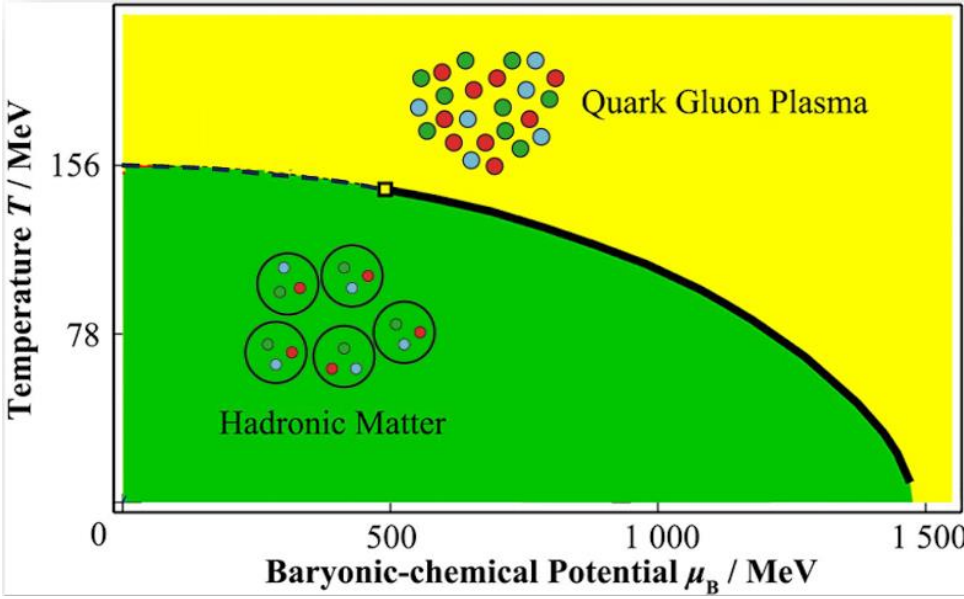

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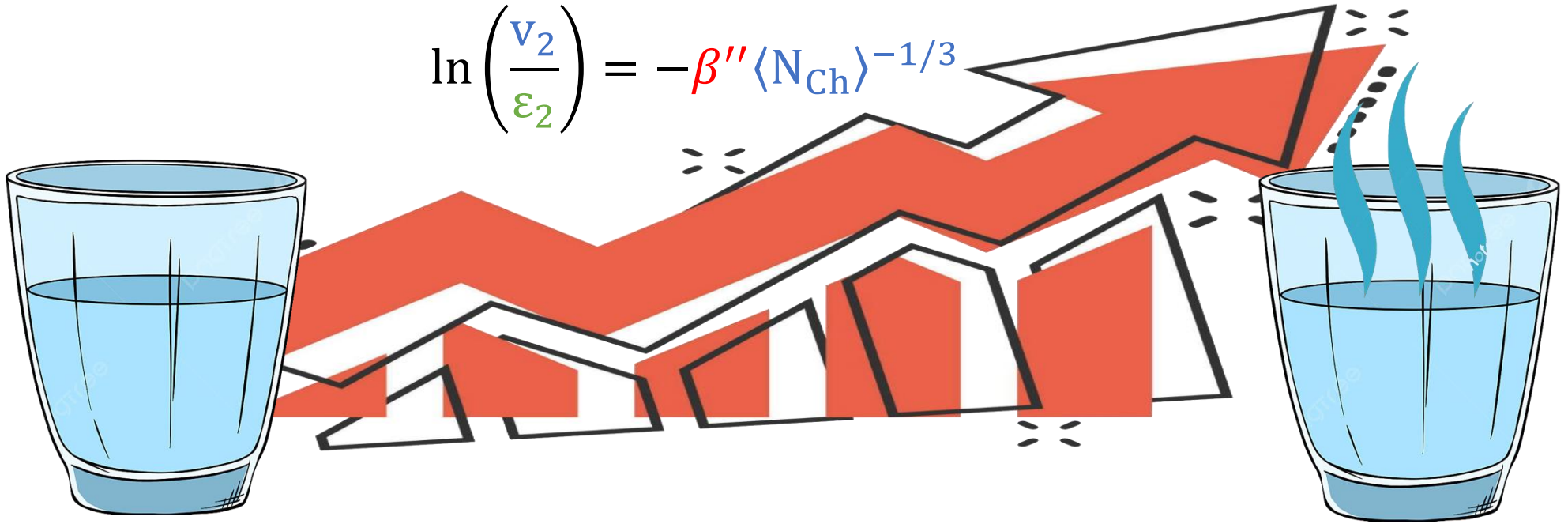

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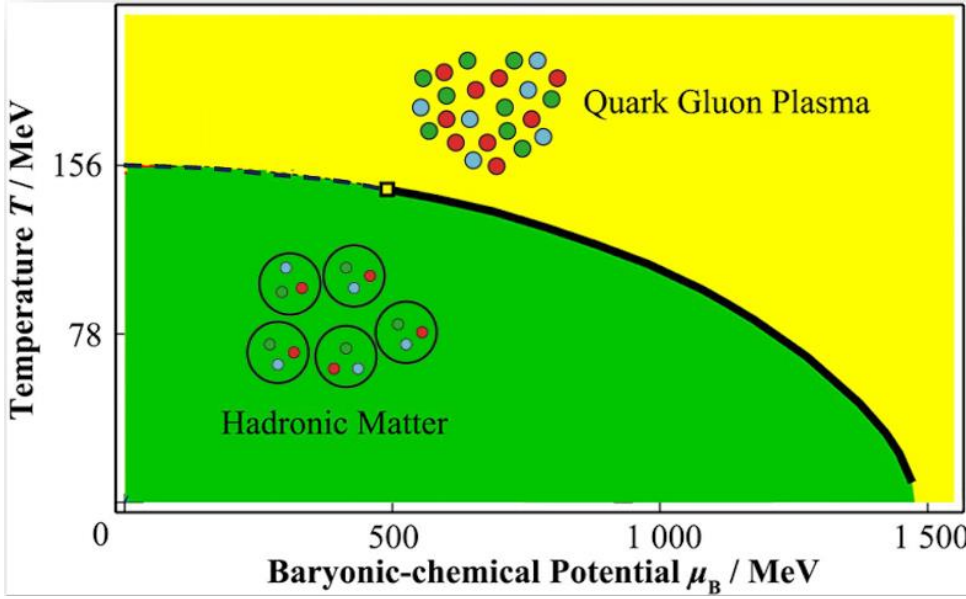
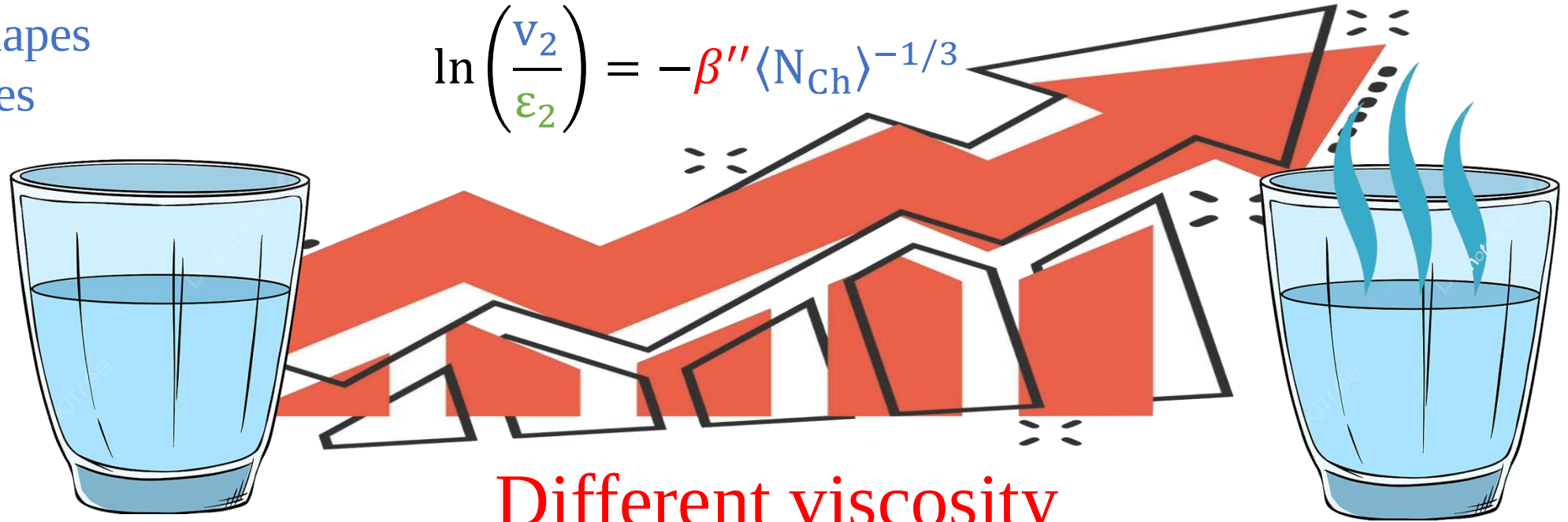


What is the nature of the QGP viscosity?

Similar shapes and sizes

$$\ln\left(\frac{v_2}{\varepsilon_2}\right) = -\beta''\langle N_{Ch}\rangle^{-1/3}$$

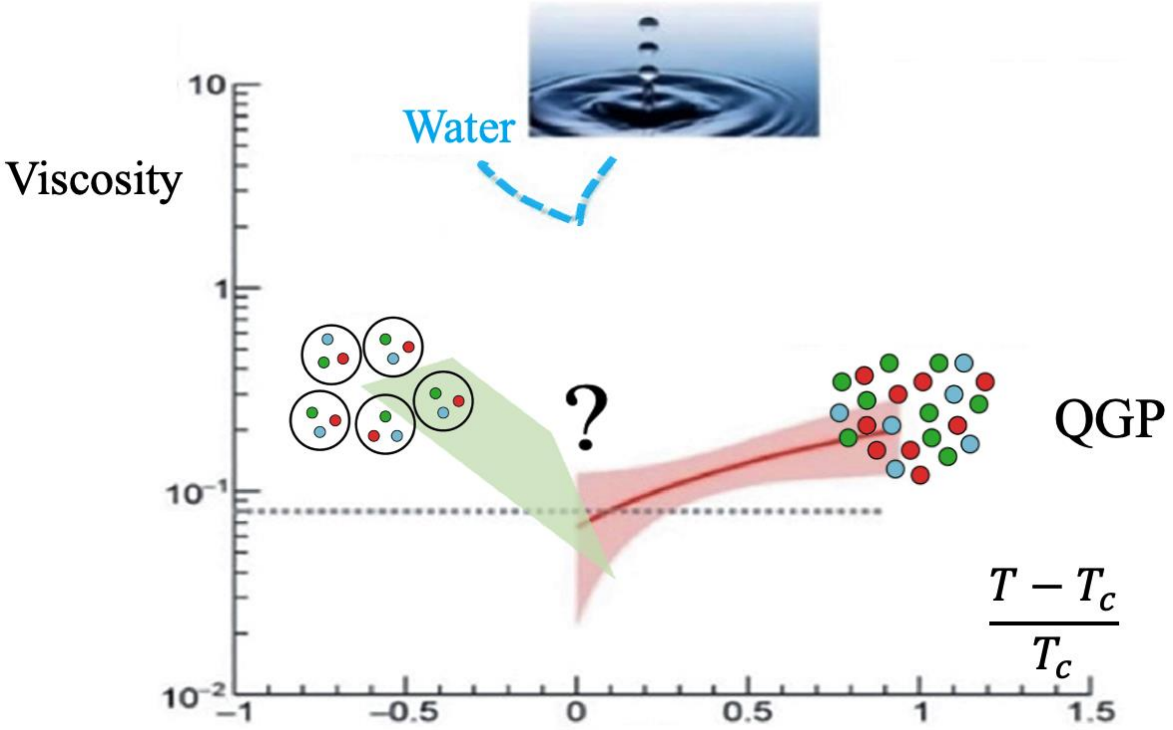


Different viscosity

What is the nature of the QGP viscosity?

STAR Collaboration
PRL 129 25, 252301 (2022)

$$\ln\left(\frac{v_2}{\varepsilon_2}\right) = -\beta''\langle N_{Ch}\rangle^{-1/3}$$



What is the nature of the QGP viscosity?

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PRL 129 25, 252301 (2022)

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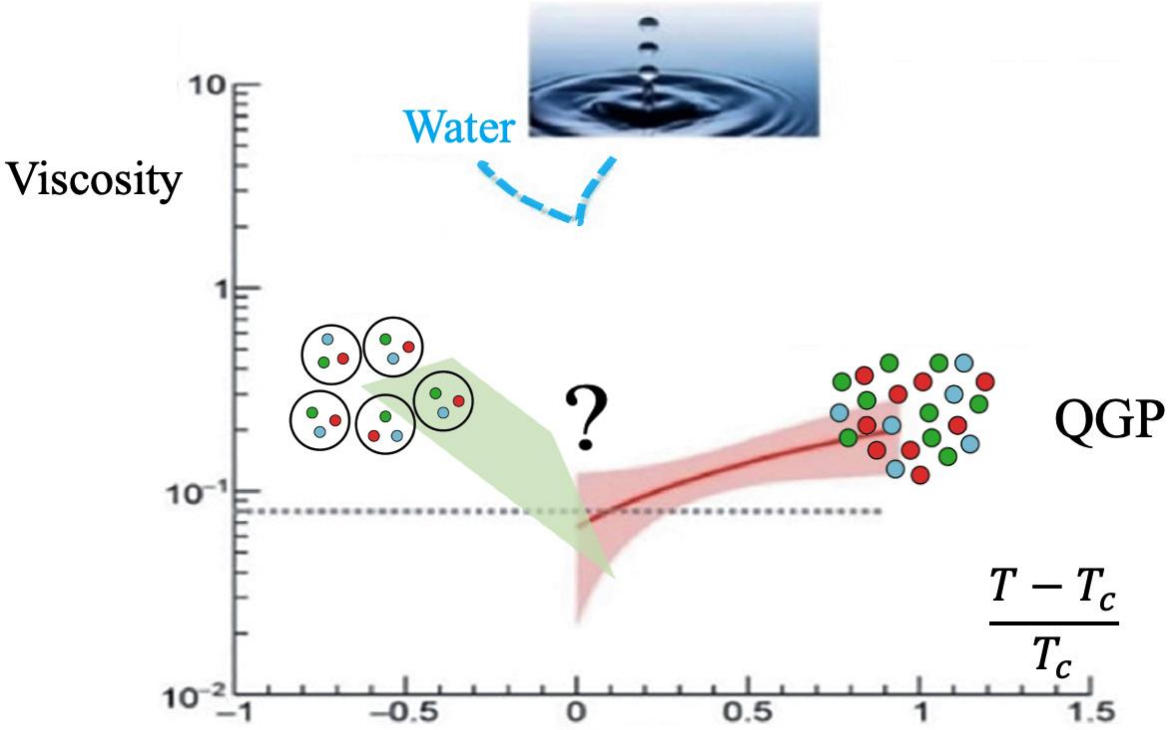

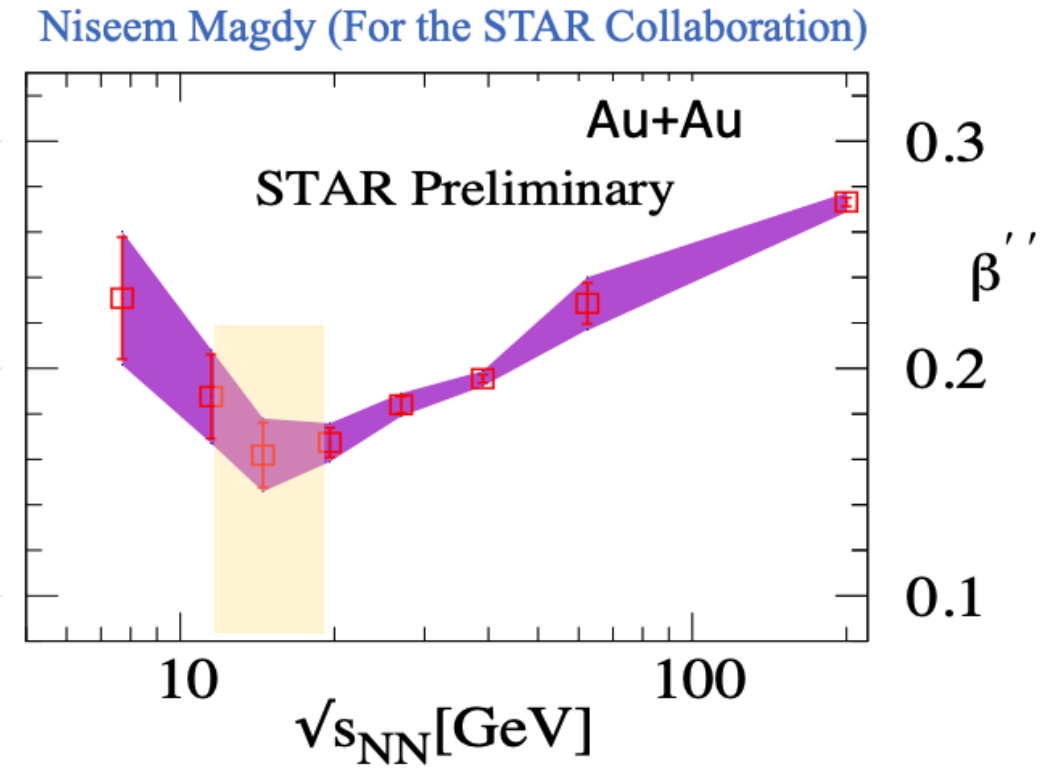

The first experimental measurements of the QGP viscosity

✓ Can the non-monotonic behavior be considered as an indication of the phase transition?

STAR Collaboration
PRL 122 17, 172301 (2019)
PLB 809 135728 (2020)
PRL 129 25, 252301 (2022)
PLB 839 137755 (2023)
arXiv:2401.06625

Niseem Magdy
Phys.Rev.C 106 4, 044911 (2022)
Phys.Rev.C 107 2, 024905 (2023)
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We can understand the nature of the QGP viscosity in HIC

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We can understand the nature of the QGP viscosity in HIC

What is next?

The multi-particle correlations

Niseem Magdy
Phys.Rev.C 106 4, 044911 (2022)
Phys.Rev.C 107 2, 024905 (2023)
Phys.Rev.C 109 2, 024906 (2024)
Phys.Rev.C 110 2, 024906 (2024)

Are sensitive to the interplay between initial- and final-state effects.

Niseem Magdy
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The multi-particle correlations

Are sensitive to the interplay between initial- and final-state effects.

Symmetric Correlations

Asymmetric Correlations

The multi-particle correlations

Niseem Magdy
Phys.Rev.C 106 4, 044911 (2022)
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Phys.Rev.C 109 2, 024906 (2024)
Phys.Rev.C 110 2, 024906 (2024)

Are sensitive to the interplay between initial- and final-state effects.

Symmetric Correlations

- k-even particle correlations
- n-m flow harmonics correlations
- n-order flow harmonic fluctuations
- Differential flow angle fluctuations

Asymmetric Correlations

Analysis Method

Niseem Magdy
Phys.Rev.C 106 4, 044911 (2022)
Phys.Rev.C 107 2, 024905 (2023)
Phys.Rev.C 109 2, 024906 (2024)
Phys.Rev.C 110 2, 024906 (2024)

The multi-particle correlations

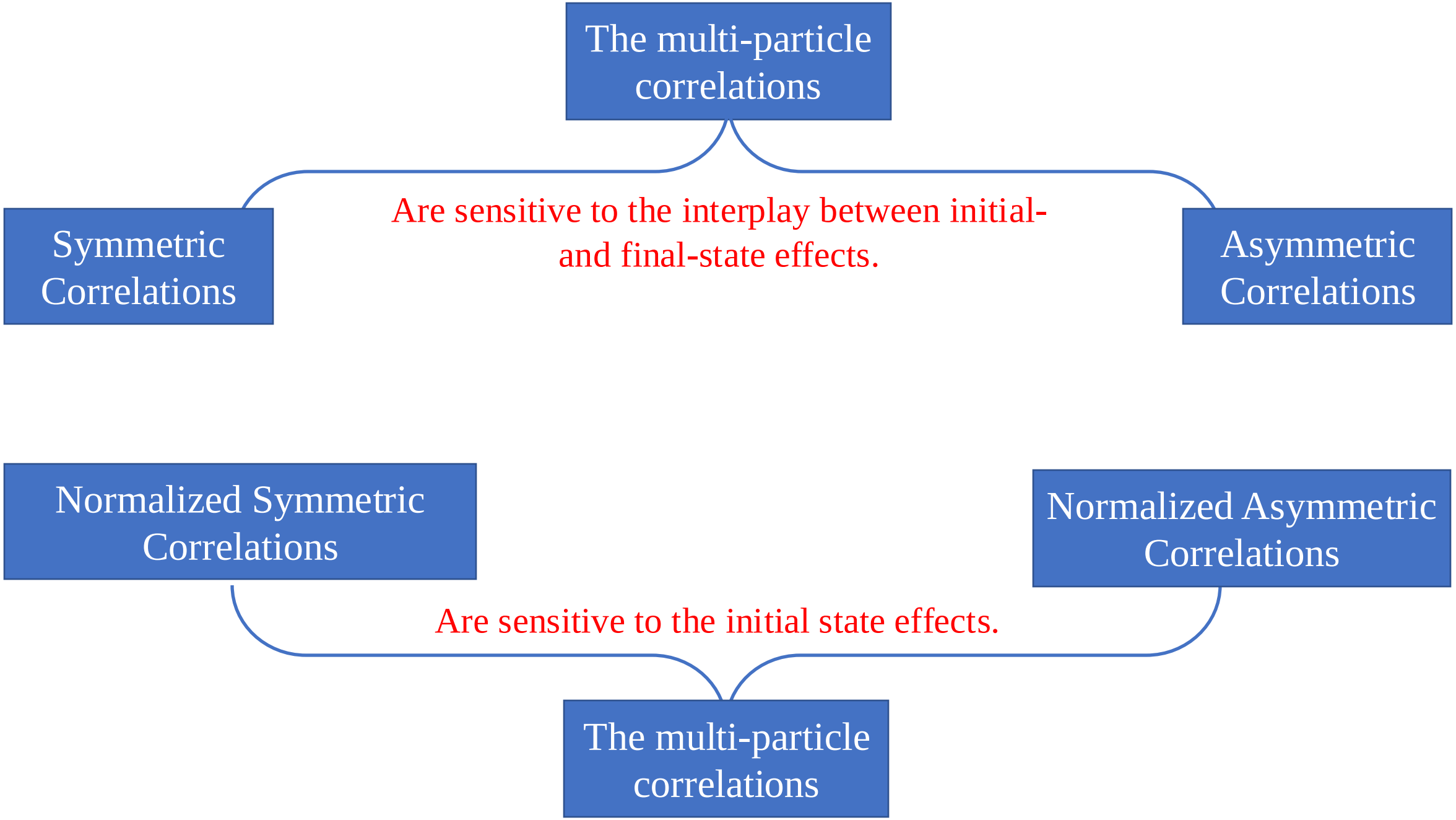
Are sensitive to the interplay between initial- and final-state effects.

Symmetric Correlations

- k-even particle correlations
- n-m flow harmonics correlations
- n-order flow harmonic fluctuations
- Differential flow angle fluctuations

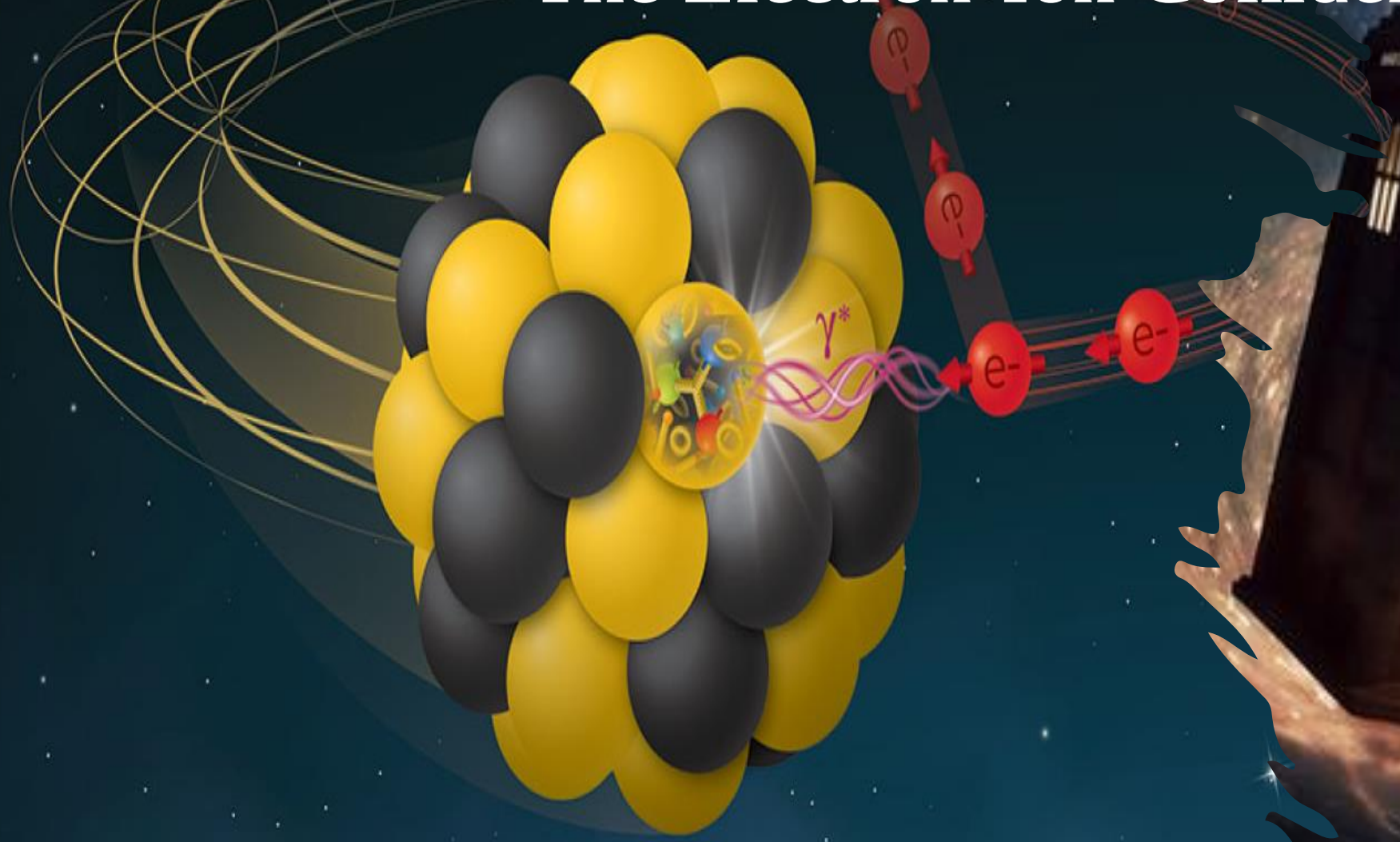
Asymmetric Correlations

- k-odd particle correlations
- n-m mode-coupling
- Event plane angular correlations
- Transverse momentum flow correlations


The multi-particle correlations
Are sensitive to the interplay between initial- and final-state effects.
Symmetric Correlations
Asymmetric Correlations
Normalized Symmetric Correlations
Normalized Asymmetric Correlations
Are sensitive to the initial state effects.
The multi-particle correlations

The world's first nuclear time machine

The Electron-Ion Collider



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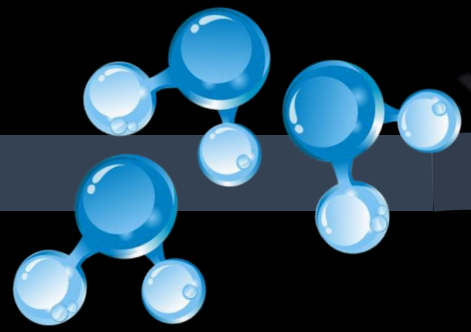
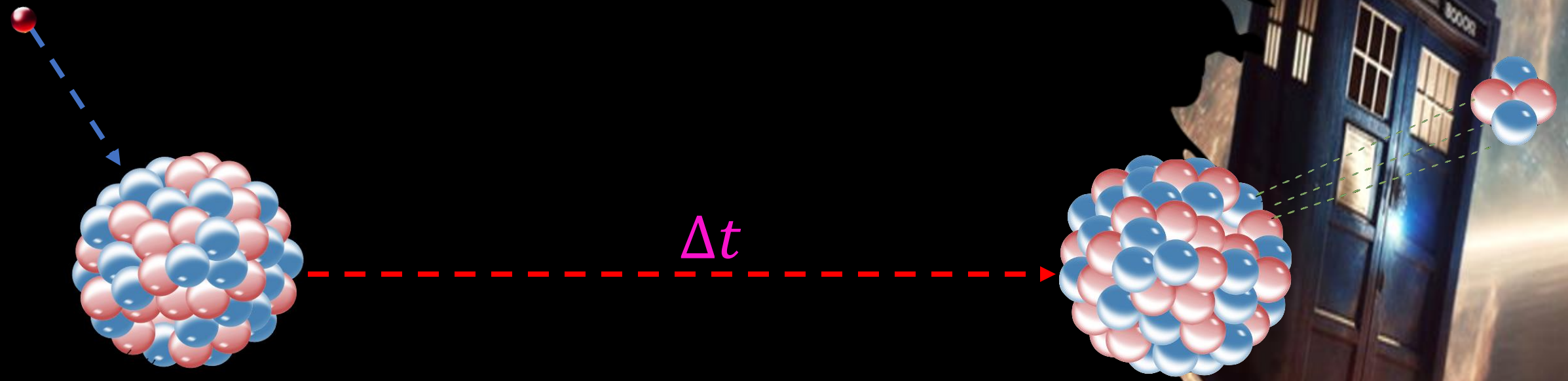
What is matter made of ?



Stable

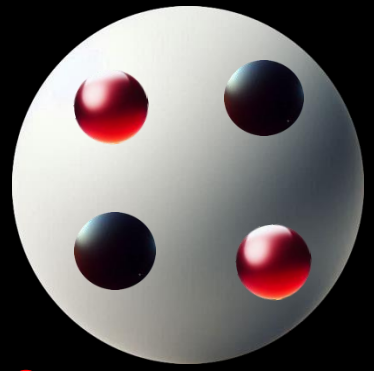
Unstable

Excitation of atomic nuclei



What happens between the excitation and the decay?

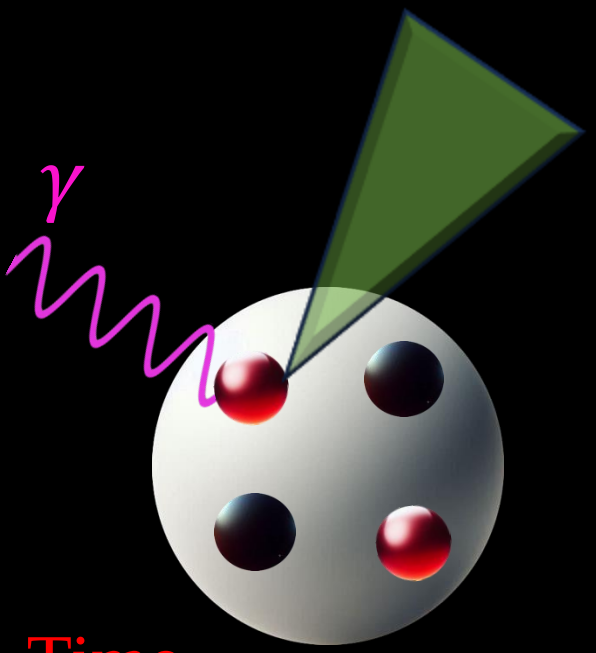
What time machine?



Time

$t \sim 0$ s

What time machine?

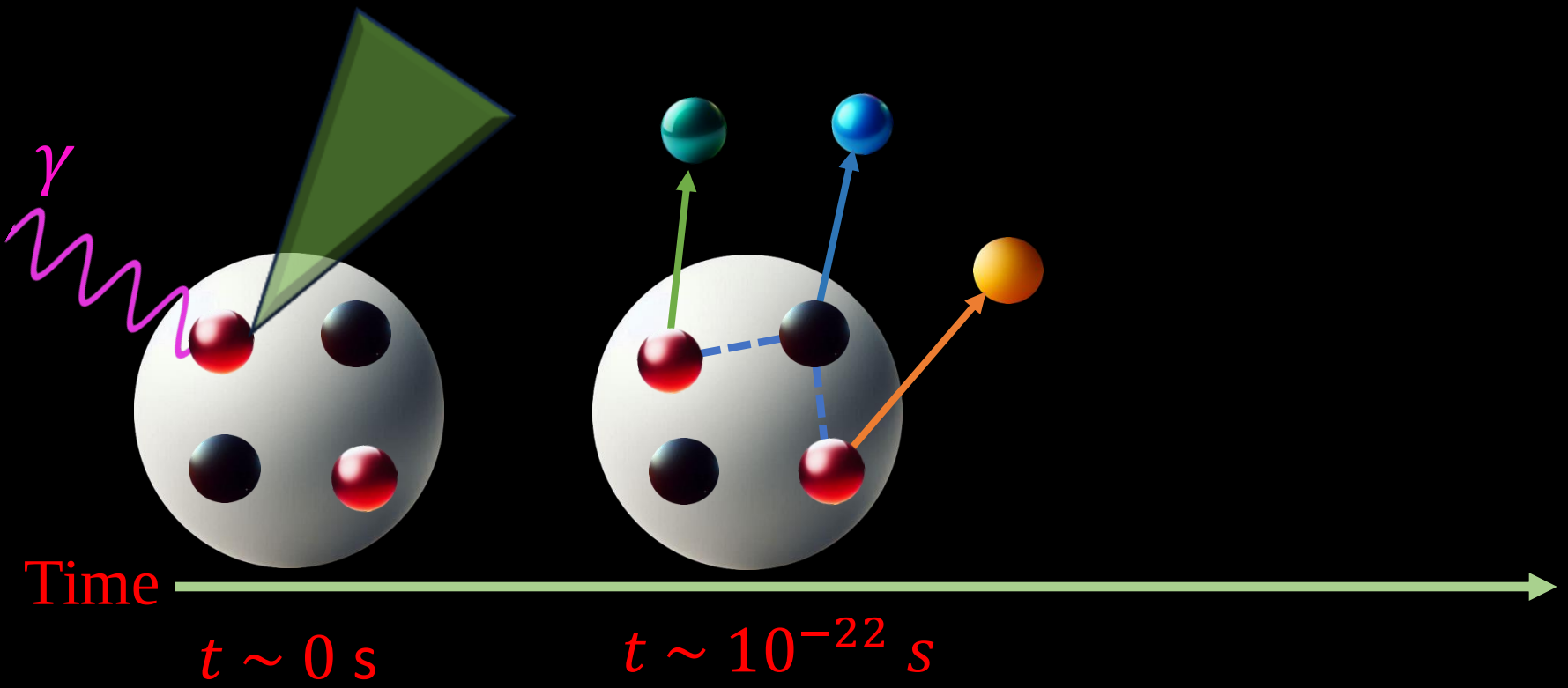


Time

$t \sim 0$ s

First spark

What time machine?



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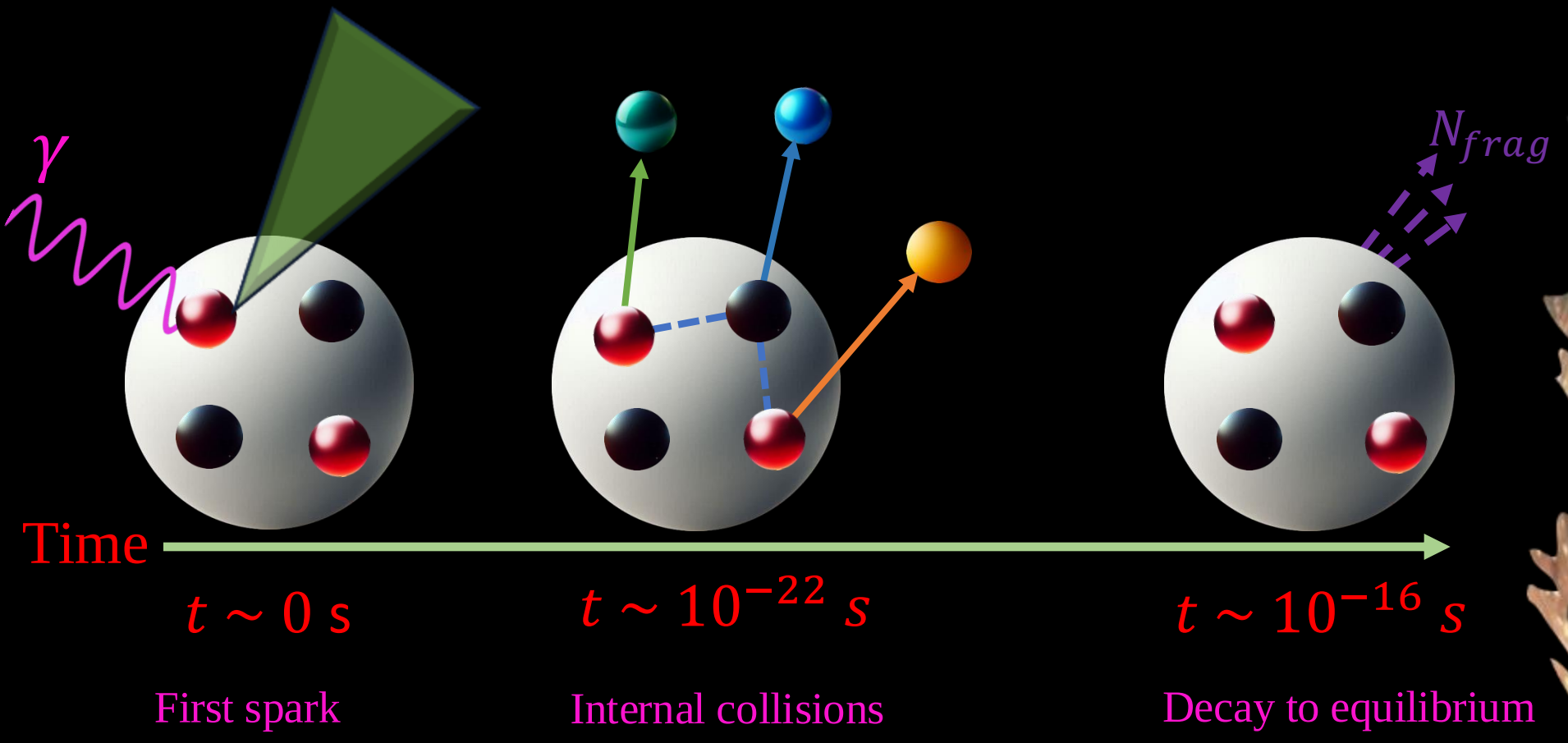

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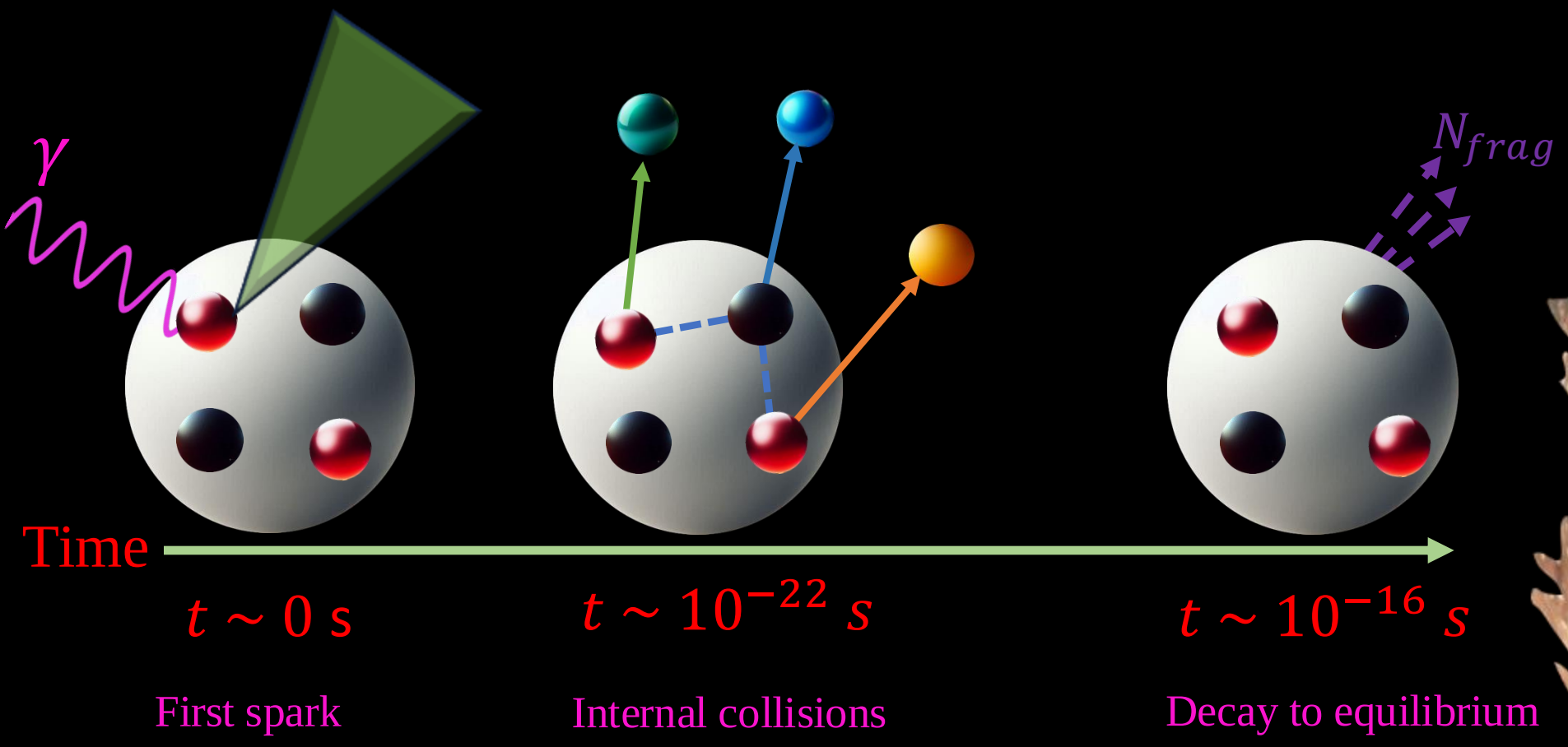


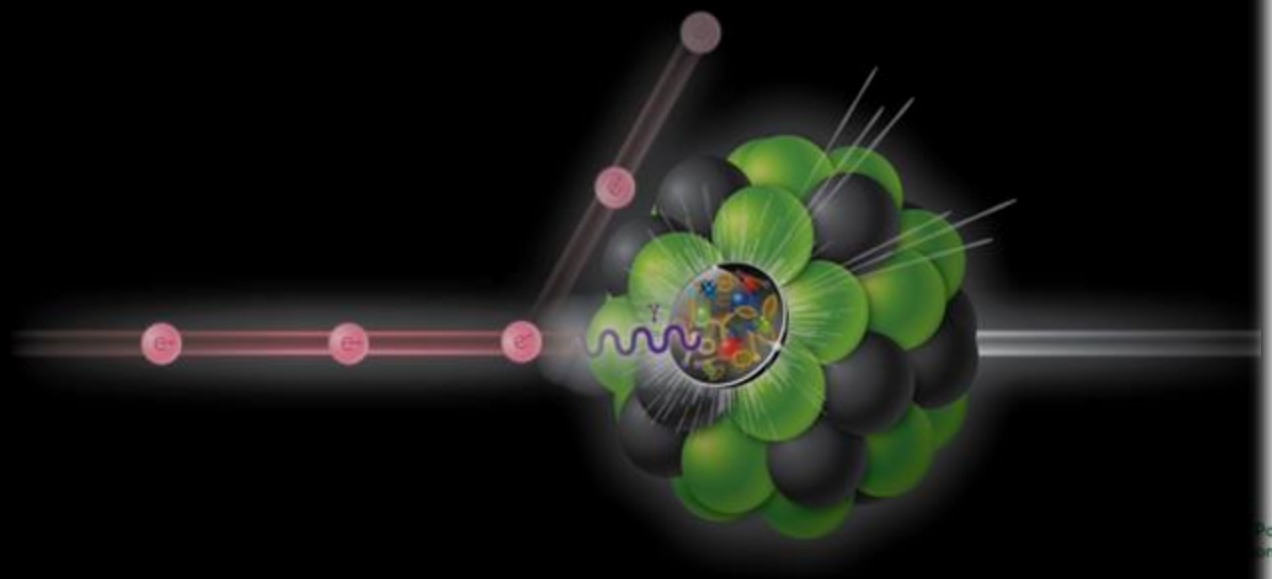
Can we measure this time sequence?

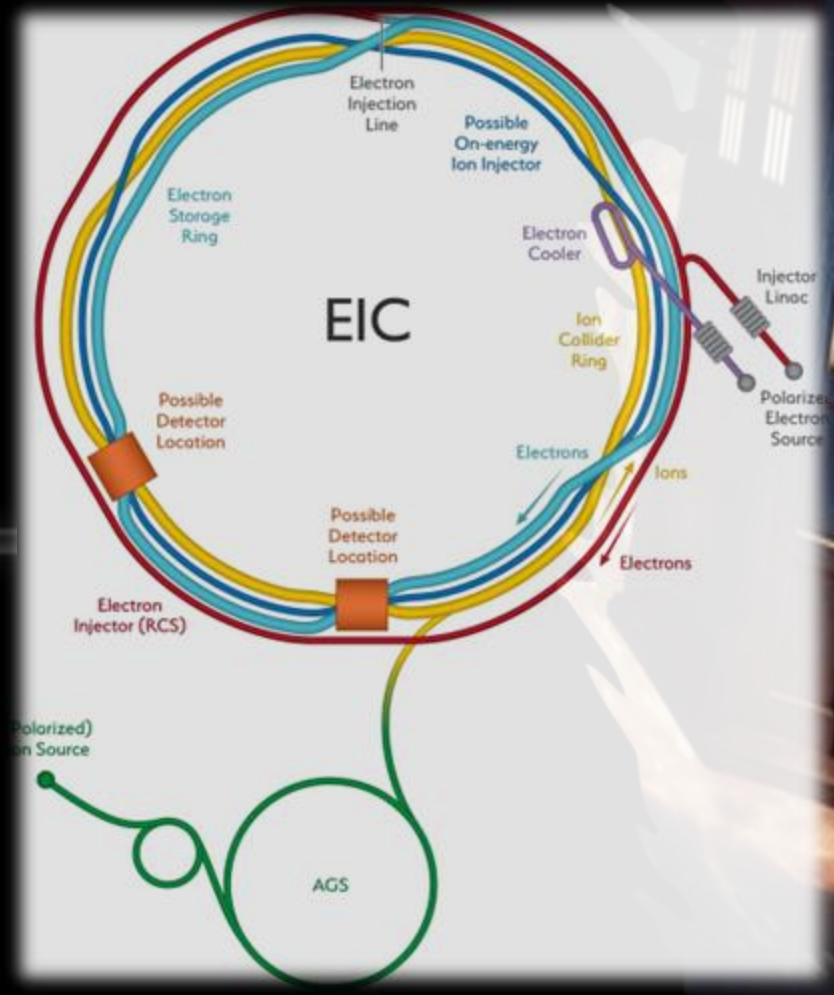
For the first time

Can we measure this time sequence?

For the first time

The Electron-Ion Collider 2030+





Can we measure this time sequence?

For the first time

The BeAGLE model

Wan Chang et al.,
PRD 106, 012007 (2022)

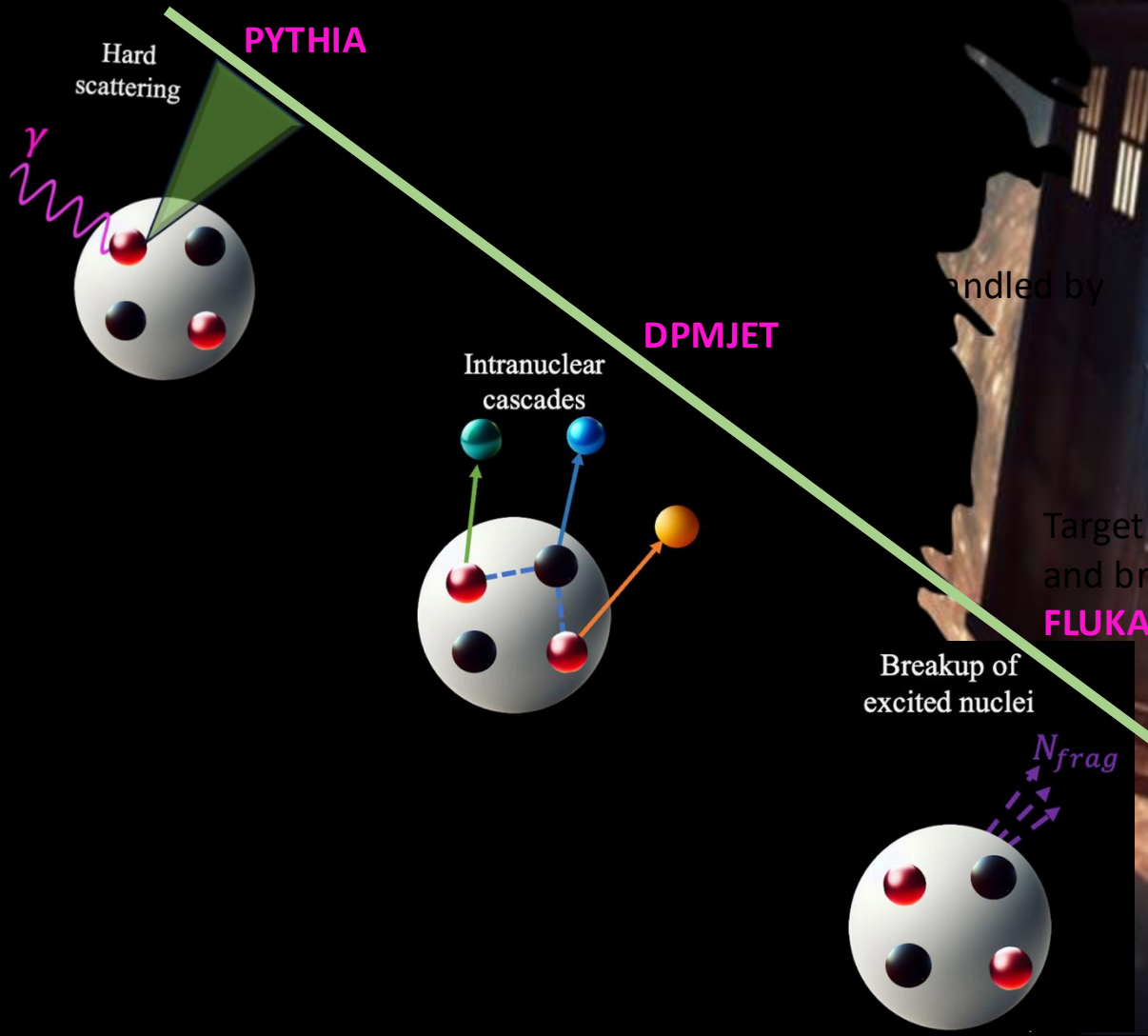
Computer simulations

Can we measure this time sequence?

For the first time

Wan Chang et al.,
PRD 106, 012007 (2022)

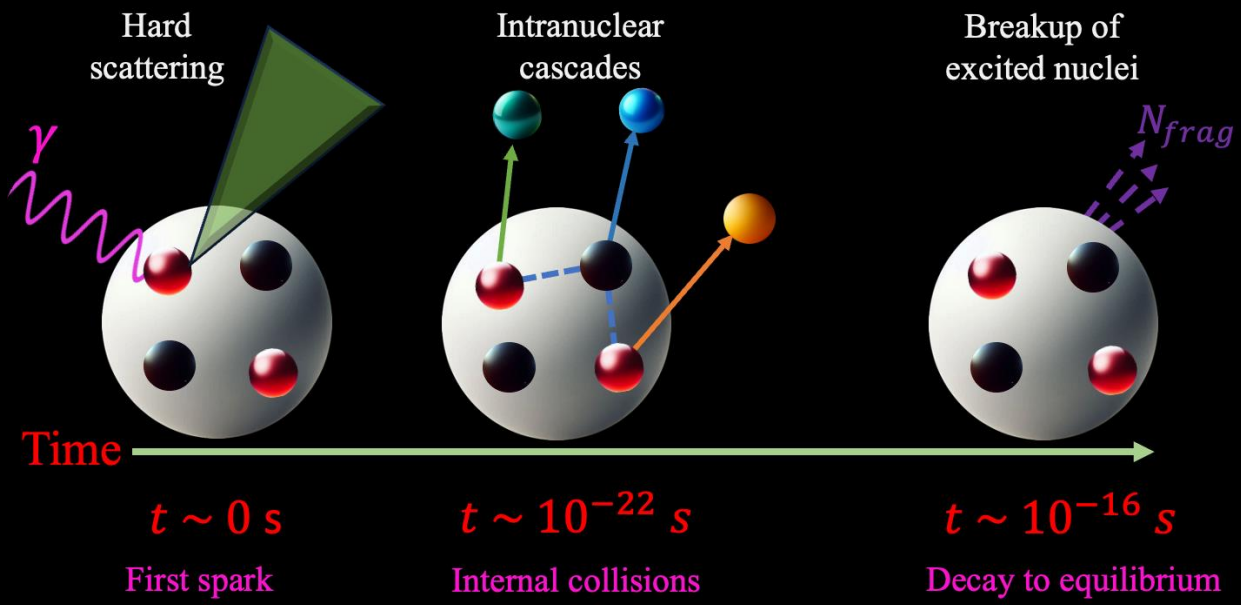
Computer simulations



ndled by

Target remnant evaporation and break up included by **FLUKA**

Can we measure this time sequence?



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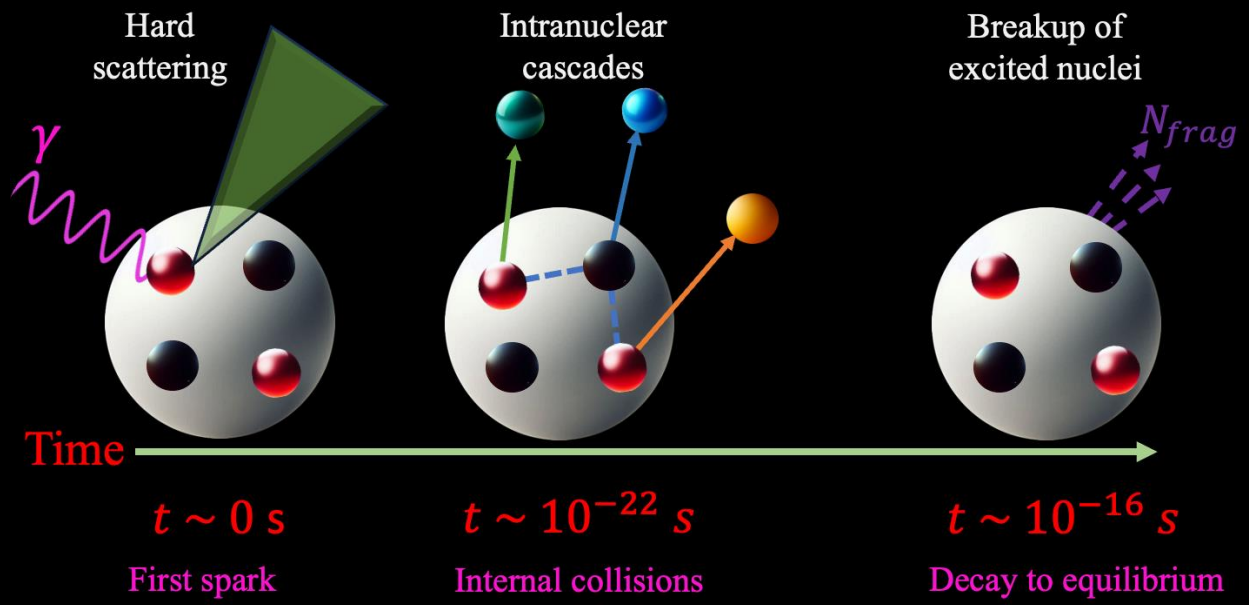

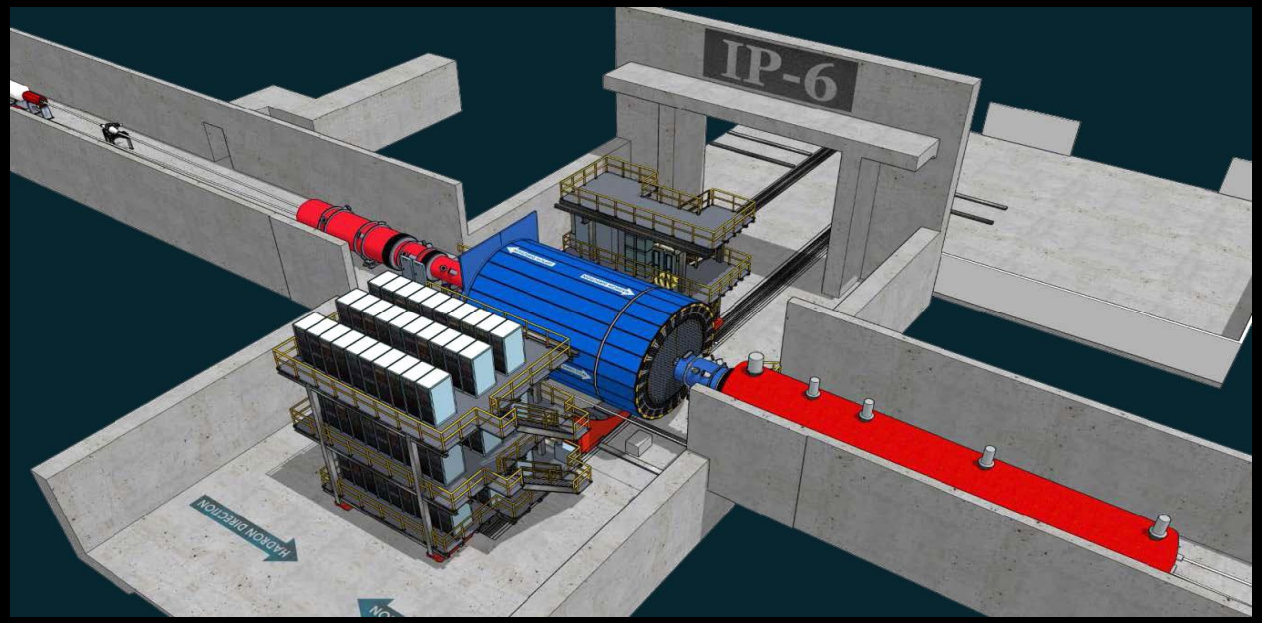

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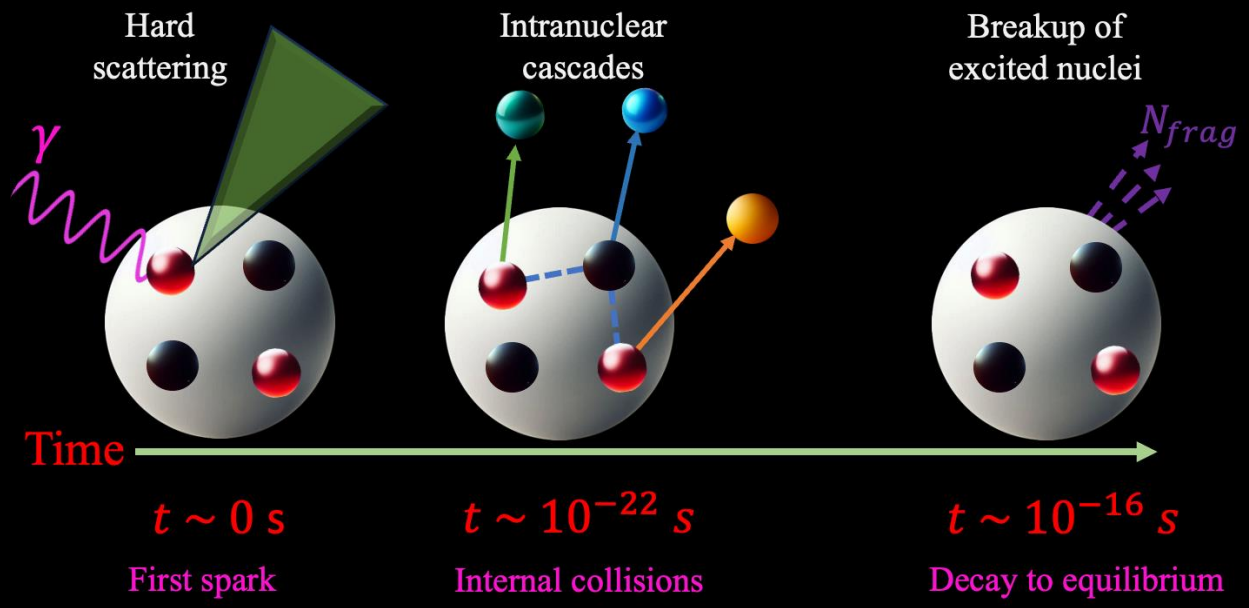

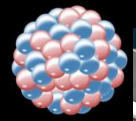

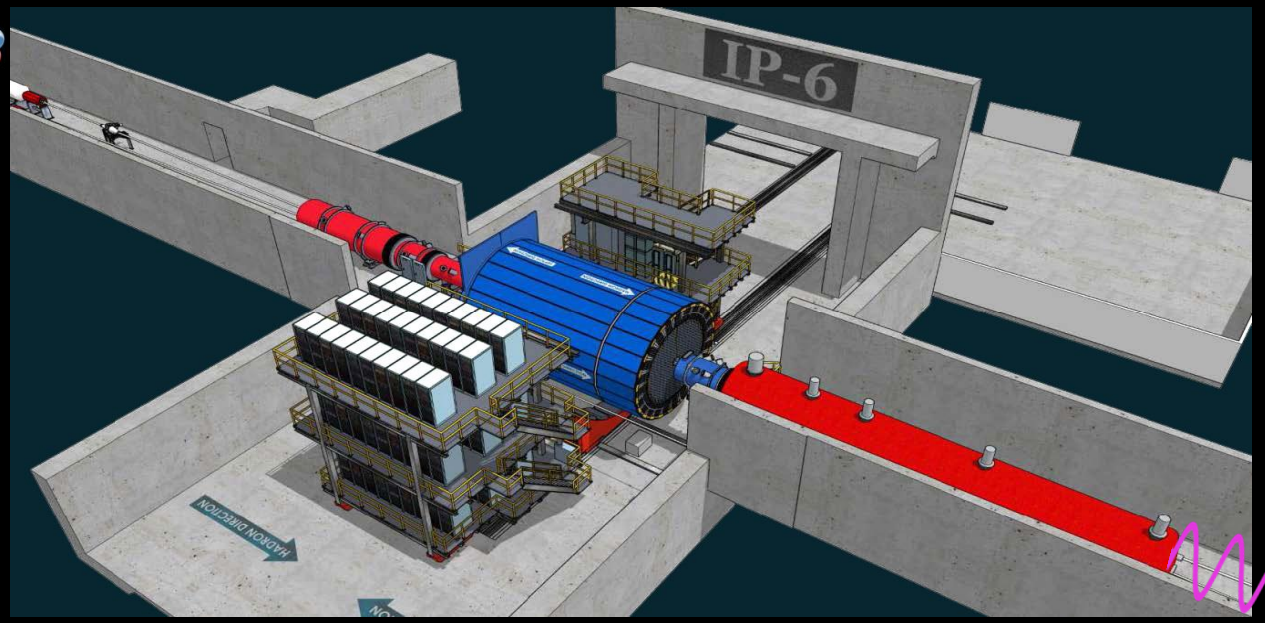

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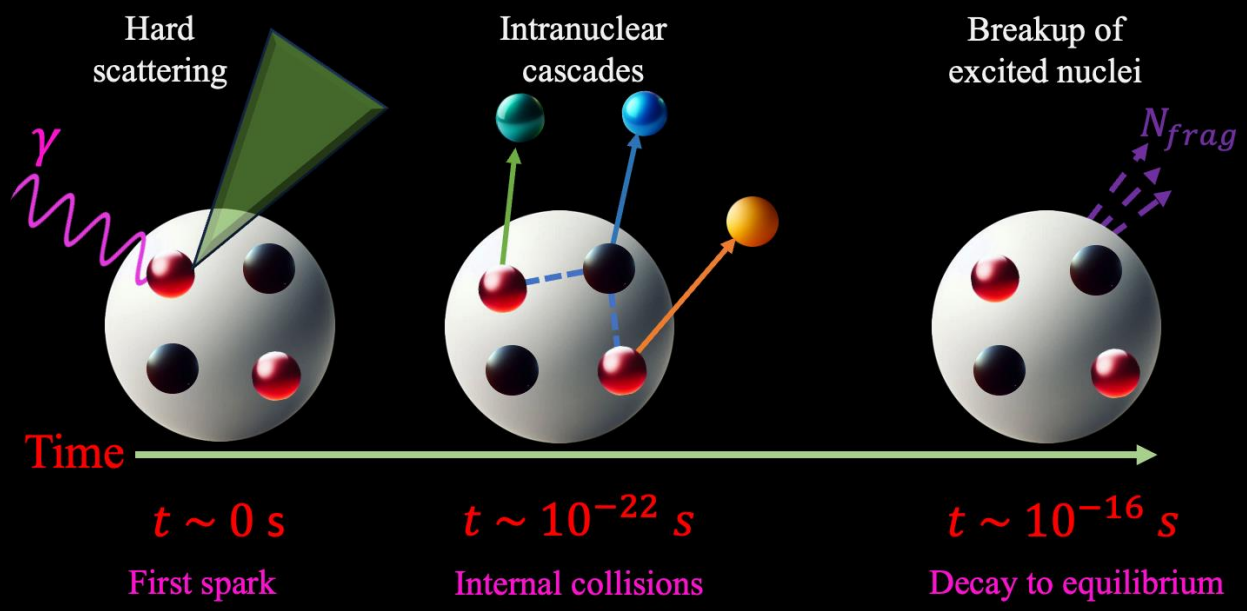

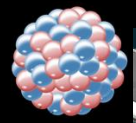

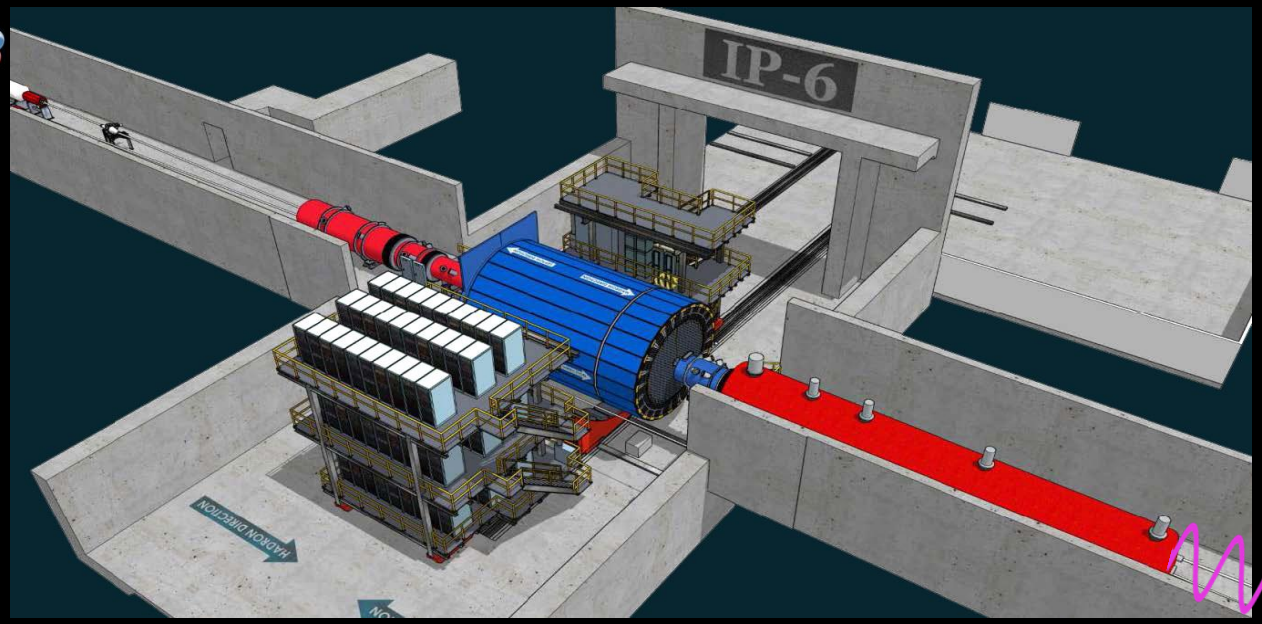

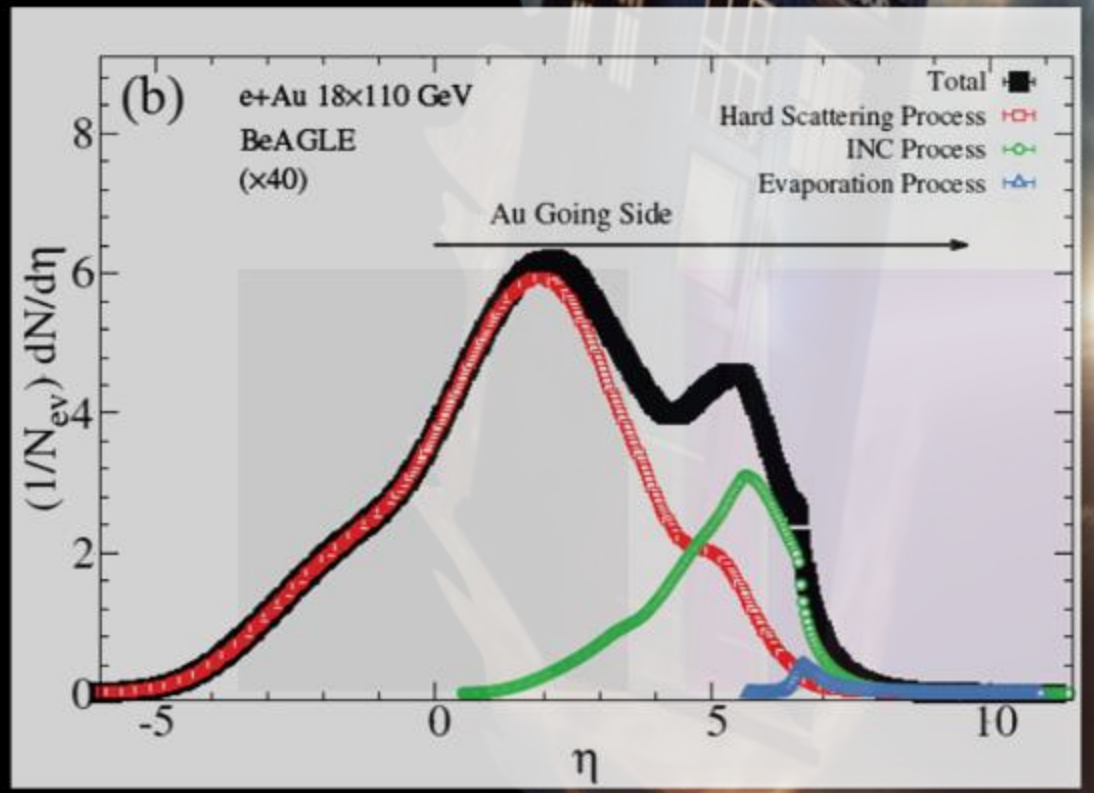

Niseem Magdy et al.
J.Phys.G 52 (2025) 1, 015002

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TSU Physics Podcast: Beyond the Equations

Next Time …

Thank you

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TSU Initiative for Gravity and Experimental-nuclear Research

TSU Physics Podcast: Beyond the Equations

A podcast where scientists from diverse fields of astronomy, nuclear physics, and particle physics come together to explore the story of the universe. We will delve into topics like the Big Bang, particle creation, galaxy formation, and the vast knowledge we've gained about the cosmos. It's a journey through the universe, told by experts in their fields.

Organizers (TSU)

Dr. Michelle Penn-Marshall
Dr. Niseem Abdelrahman
Dr. Mark C. Harvey
Dr. Victor Migenes
Dr. Daniel Vrinceanu

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Symmetric Correlations

Asymmetric Correlations

k-even particle correlations

$$\langle\langle 2m\rangle\rangle_n = \left\langle\left\langle e^{in\sum_{j=1}^{m}(\phi_{2j-1}-\phi_{2j})}\right\rangle\right\rangle$$

$$v_n^2\{2\} = \langle 2\rangle_n$$

$$v_n^4\{4\} = 2\langle 2\rangle^2{}_n - \langle 4\rangle_n$$

$$6\,v_n^6\{6\} = \langle 6\rangle_n - 9\langle 2\rangle_n\langle 4\rangle_n + \langle 2\rangle_n^3$$

Are sensitive to the interplay between initial- and final-state effects.

k-odd particle correlations

$$\langle 3\rangle_{n+m,nm} = \left\langle e^{i(n+m\,\varphi_1 - n\varphi_2 - m\varphi_3)}\right\rangle$$

$$v_{n+2}^{MC} = \frac{\left\langle\left\langle\cos((n+2)\varphi_1^A - 2\varphi_2^B - n\varphi_3^B)\right\rangle\right\rangle}{\sqrt{\langle v_2^2 v_n^2\rangle}}$$

$$v_{n+2}^{Linear} = \sqrt{\left(v_{n+2}^{Inclusive}\right)^2 - (v_{n+2}^{MC})^2}$$

Flow harmonics correlations and fluctuations

$$\langle 4\rangle_{nm} = \left\langle e^{in\,(\phi_1-\phi_2)+im(\phi_3-\phi_4)}\right\rangle$$

$$NSC(n,m) = \frac{\langle 4\rangle_{nm} - \langle 2\rangle_n\langle 2\rangle_m}{\langle 2\rangle_n^{Sub}\langle 2\rangle_m^{Sub}}$$

$$v_n\{4\}/v_n\{2\} \qquad v_n\{6\}/v_n\{4\}$$

Are sensitive to the initial state effects.

Event plane angular correlations

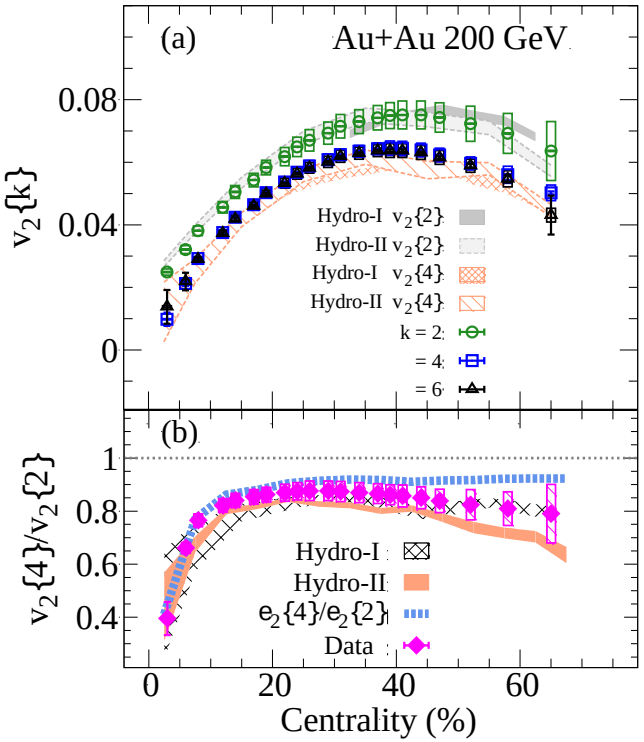
$$\rho_{n+2,2n} = \frac{v_{n+2}^{Non\ Linear}}{v_{n+2}^{Inclusive}}$$

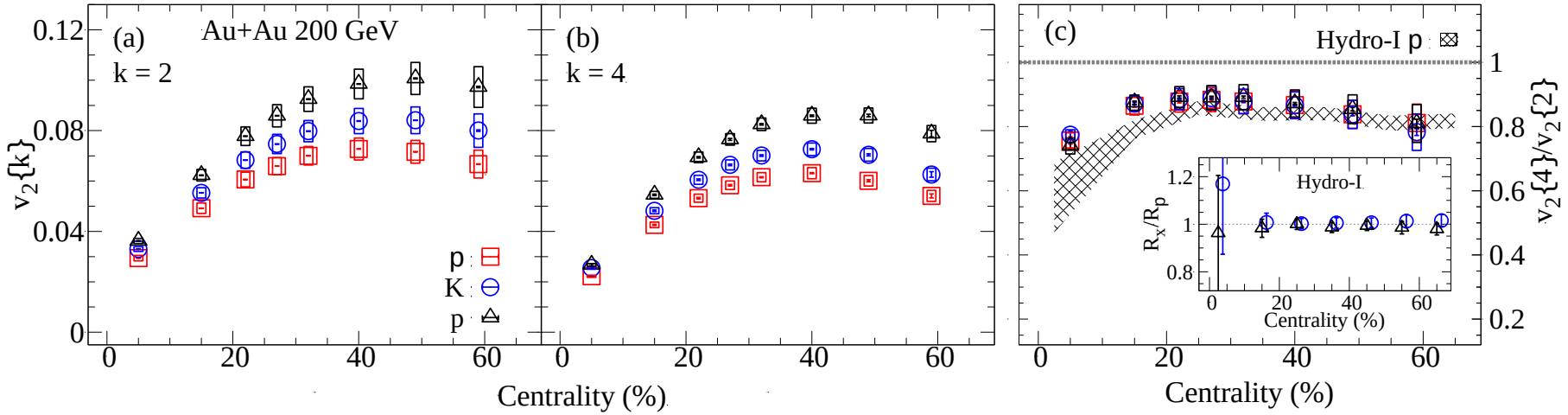
$$\sim\langle\cos((n+2)\Psi_{n+2} - 2\Psi_2 - n\Psi_n)\rangle$$

Anisotropic Flow Fluctuations

STAR Collaboration
PRL 129 25, 252301 (2022)

The $v_2\{k\}$ and $(v_2\{4\}/v_2\{2\})$ centrality dependance





- $v_2\{4\}/v_2\{2\}$ decrees from central to peripheral collisions
- The model calculations:
  - (I) $(v_2\{4\}/v_2\{2\})$ agrees well with the data
  - (II) $(v_2\{4\}/v_2\{2\})$ and $(\epsilon_2\{4\}/\epsilon_2\{2\})$ bracket the data

	Hydro-I	Hydro-II
η/s	0.12	0.05
Initial conditions	IP-Glasma	TRENTO
Contributions	Hydro + Hadronic cascade	Hydro + Direct decays

- $v_2\{4\}/v_2\{2\}$ show weak dependence on particle species.

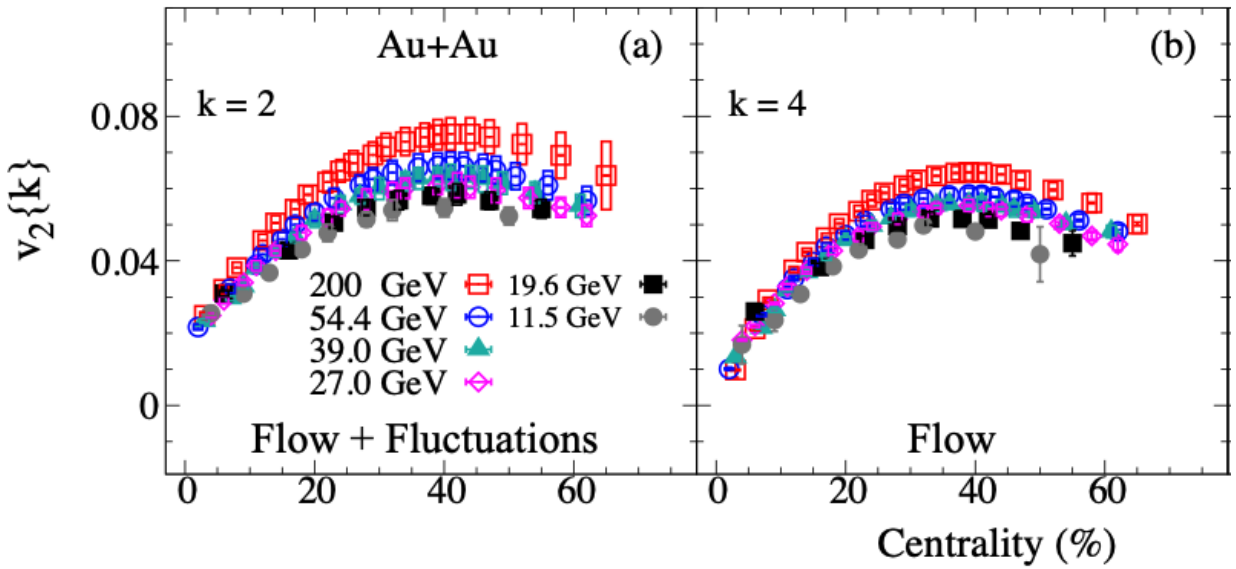
The influence from final-state is less than the one from initial-state **?**

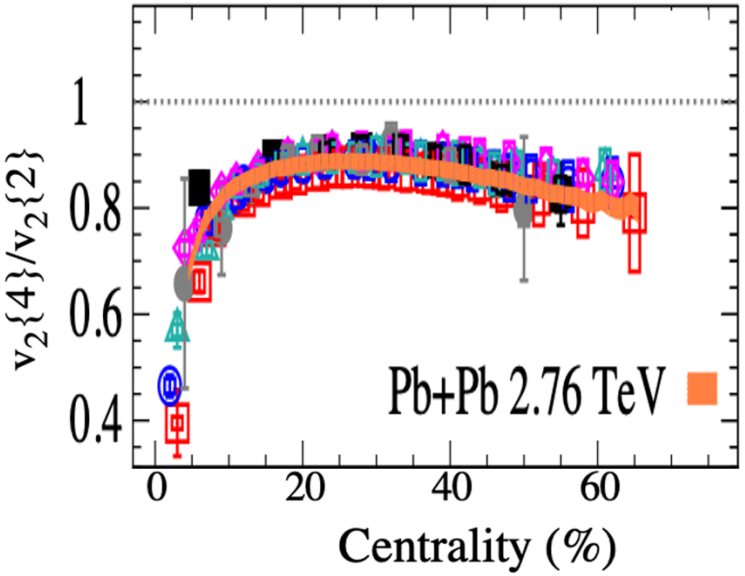
What are the respective roles of the initial/final state effects in the HIC?

Anisotropic Flow Fluctuations

The respective roles of ε_n and ε_n-fluctuations

STAR Collaboration
PRL 129 25, 252301 (2022)





- $v_2\{k\}$ show characteristic BES dependence
- $v_2\{4\}/v_2\{2\}$ show weak dependence on beam energy.

Eccentricity fluctuations do not affect beam energy measurements

✓ Safe to use model-calculated eccentricities with any fluctuations

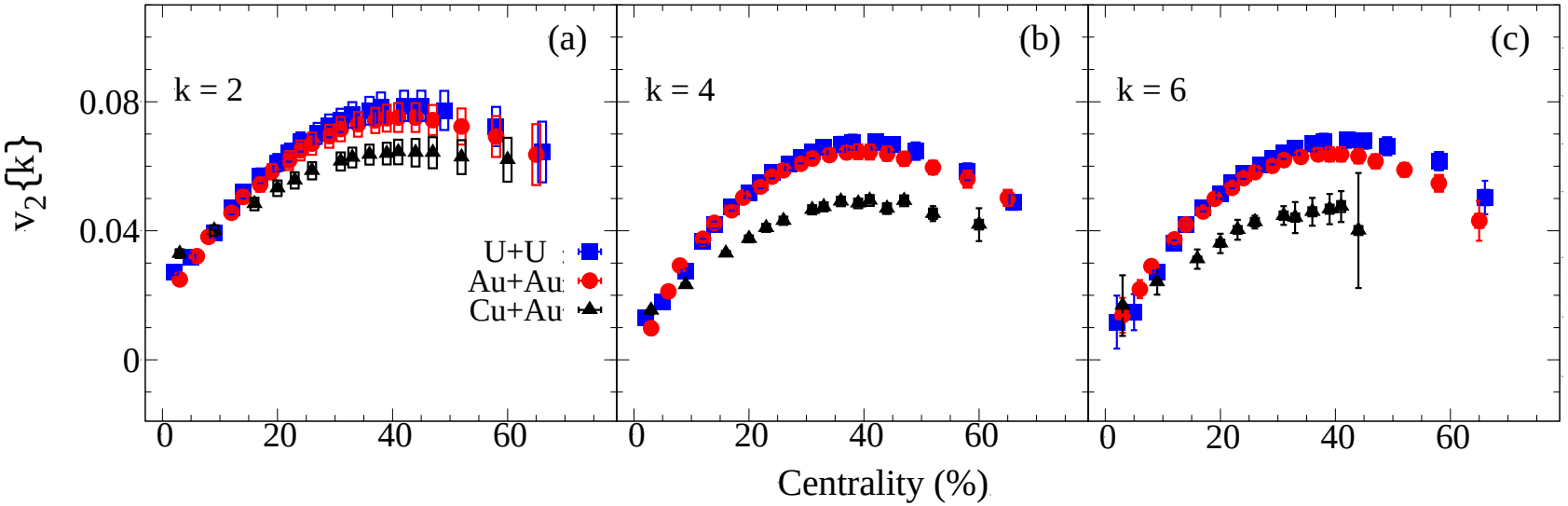
DOE Highlights,
https://www.energy.gov/science/np/articles/new-findings-flow-particles-heavy-ion-collisions

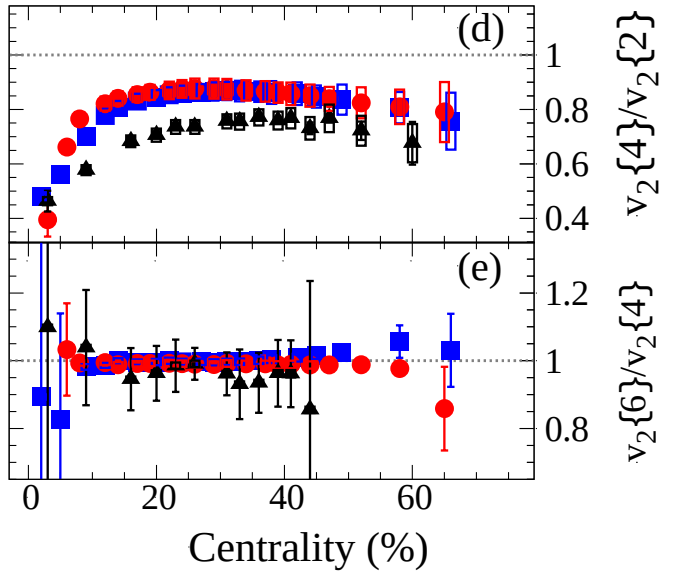
Flow in heavy ion collisions

STAR Collaboration
PRL 129 25, 252301 (2022)

Anisotropic Flow Fluctuations

The respective roles of ε_n, ε_n-fluctuations and the QGP $\frac{\eta}{s}(T, \mu_B)$



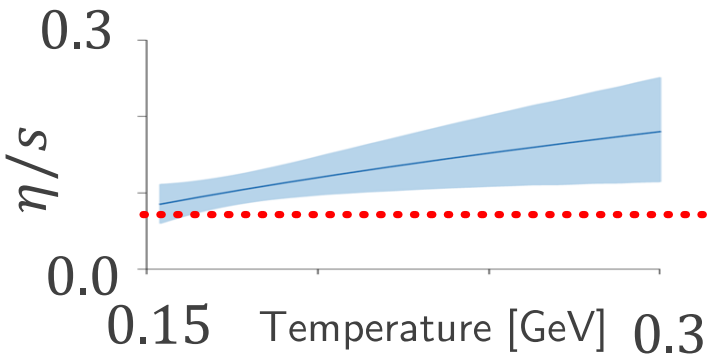


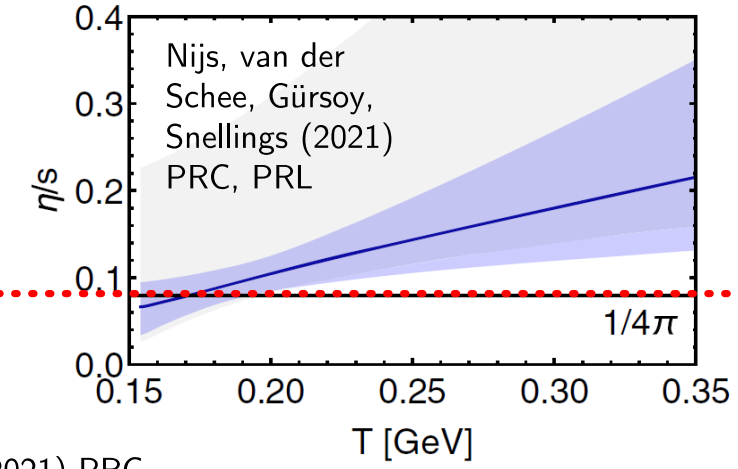
- $v_2\{k\}$ show characteristic system-size dependence.
- $v_2\{4\}/v_2\{2\}$ show a system-size dependence.
- Within uncertainties, $v_2\{6\}/v_2\{4\}$ are consistence with unity

DOE Highlights,
https://www.energy.gov/science/np/articles/new-findings-flow-particles-heavy-ion-collisions

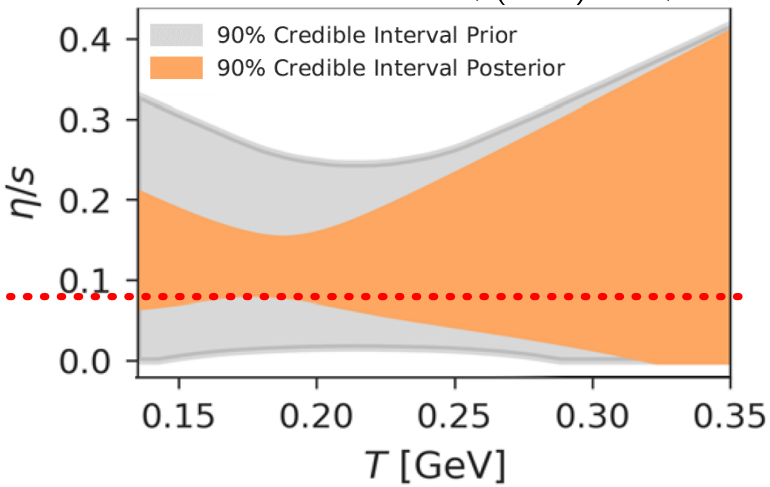
Shear viscosity calibrations

Bernhard, Moreland, Bass (2019) Nat.Phys.





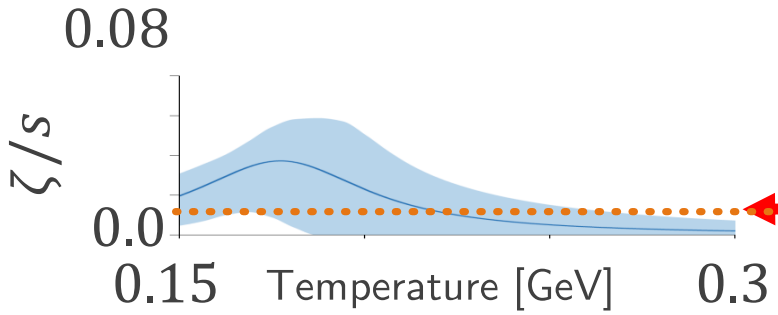
JETSCAPE Collaboration, (2021) PRC, PRL



Similar results from Parkkila, Onnerstad, Kim (2021) PRC

Bulk viscosity calibrations

Bernhard, Moreland, Bass (2019) Nat.Phys.

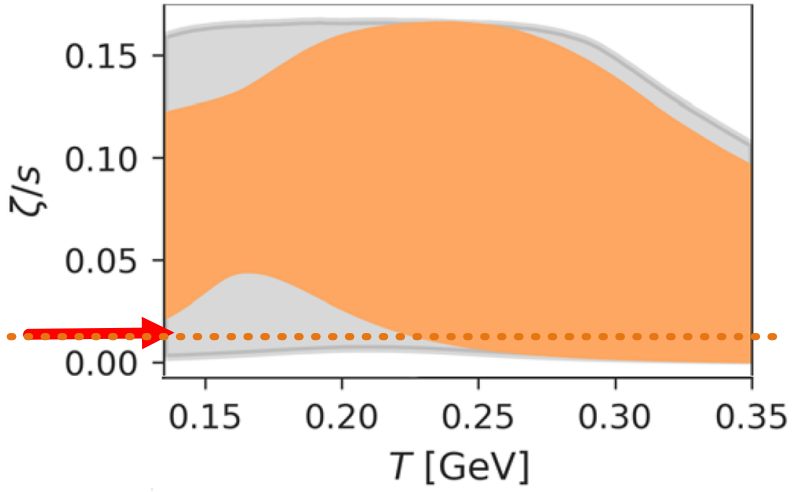


Nijs, van der Schee, Gürsoy, Snellings (2021) PRC, PRL

$\zeta/s < 0.01$

Parkkila, Onnerstad, Kim (2021) PRC: $\zeta/s < 0.03$

JETSCAPE Collaboration, (2021) PRC, PRL



Can we add more constraints on the extraction?

High p_T flow harmonics

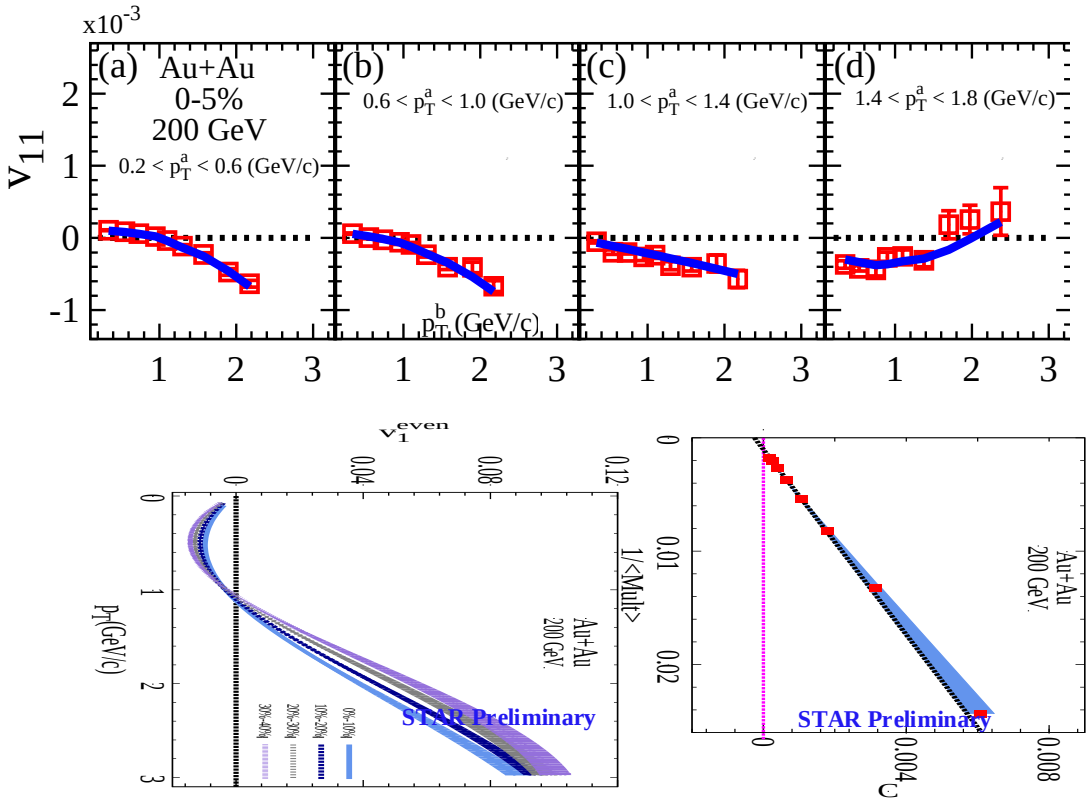
- The two-particle flow harmonics contains short- and long-range non-flow correlations: $v_n^{ab} = v_n^a v_n^b + \delta_{short} + \delta_{long}$
  - ✓ Short-range non-flow effect gets reduced using $|\Delta\eta| > 0.7$ cut
  - ✓ Long-range non-flow effects get reduced using:
    - ✓ Peripheral Subtraction (c_1)
    - ✓ Global Momentum Conservation (GMC)
- Global Momentum Conservation

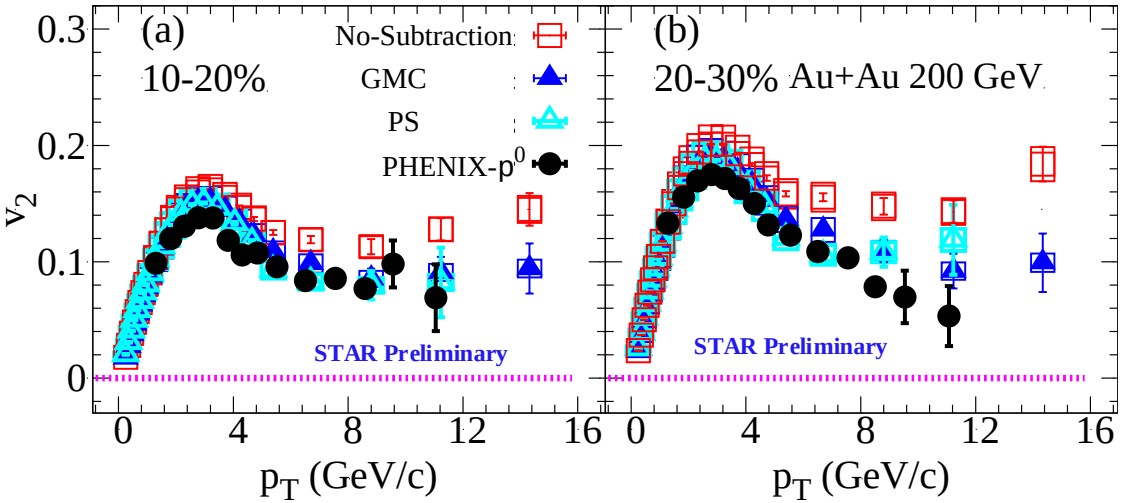
$$v_{nn} = v_{nn}^{flow} - C\,(\bar{v}_{n+1\,n+1} + \bar{v}_{n-1\,n-1})$$

- Peripheral Subtraction

$$v_{nn}^{PS}(p_T) = v_{nn}^{cent\%}(p_T) - \chi^{cent\%}(p_T)\, v_{nn}^{90\%}(p_T)$$

$$\chi^{cent\%}(p_T) = v_{11}^{cent\%}(p_T)/v_{11}^{90\%}(p_T)$$



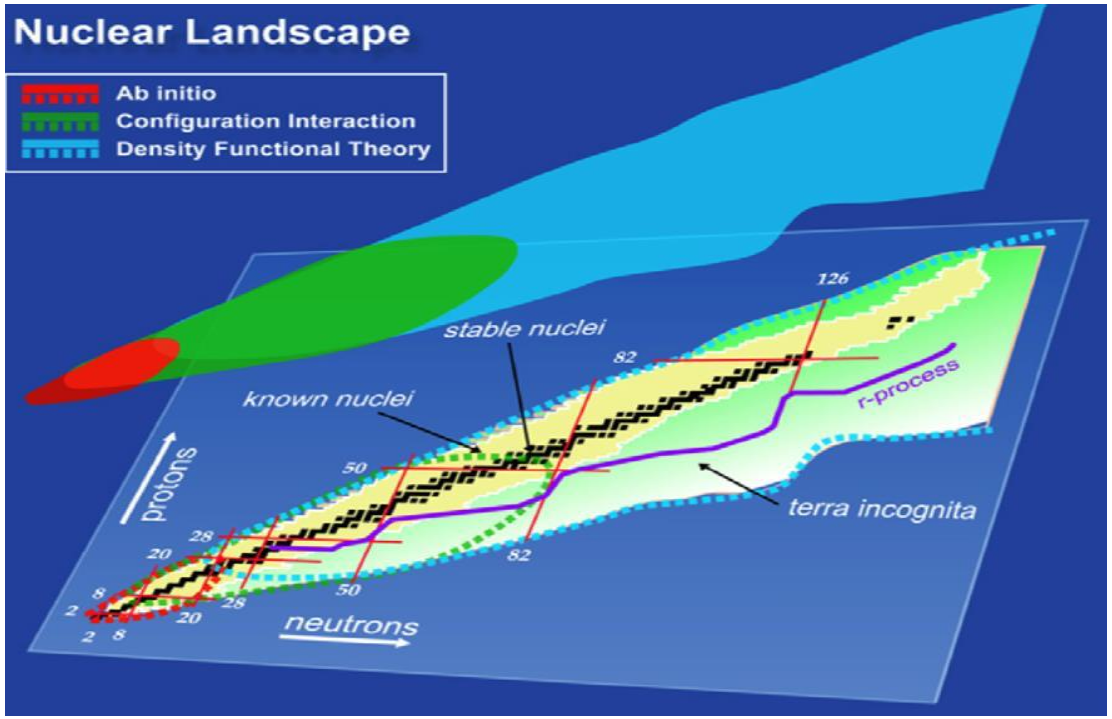


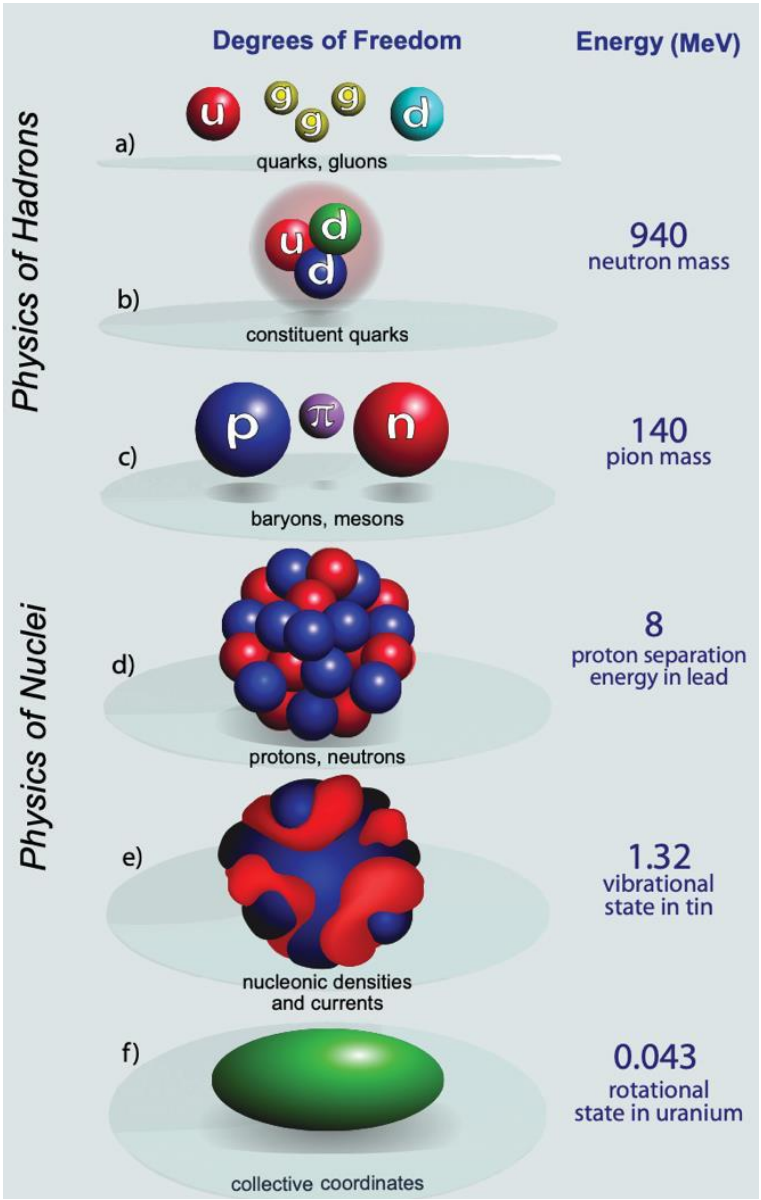
- Good agreement observed between;
  - ✓ GMC and the peripheral subtraction methods
  - ✓ STAR after subtraction and PENIX π^0 measurments

Fathom the fundamental structure of atomic nuclei

Emergent phenomena of the many-body quantum system

- Quadrupole/octupole/hexadecapole deformations
- Clustering, halo, skin, bubble…
- Non-monotonic evaluation with N and Z





Snapshot imaging = tracing the intrinsic nuclear structure?

STAR Collaboration
arXiv:2401.06625
Accepted in Nature

"…figuring out a pocket watch by smashing two together and observing the flying debris"

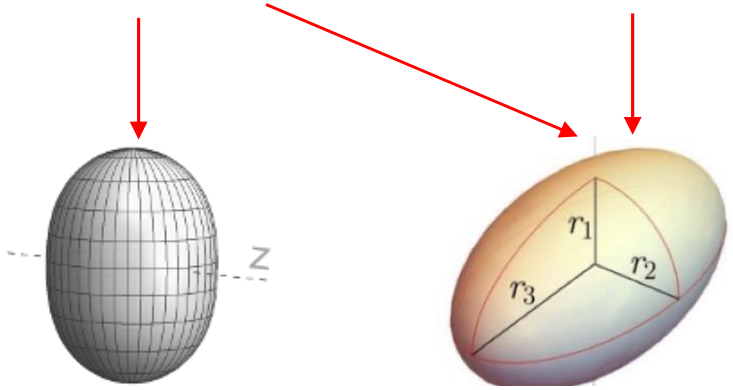
— Richard Feynman

Short-time scale imaging could see detailed shapes?

Nuclear deformation in heavy ^{238}U nucleus

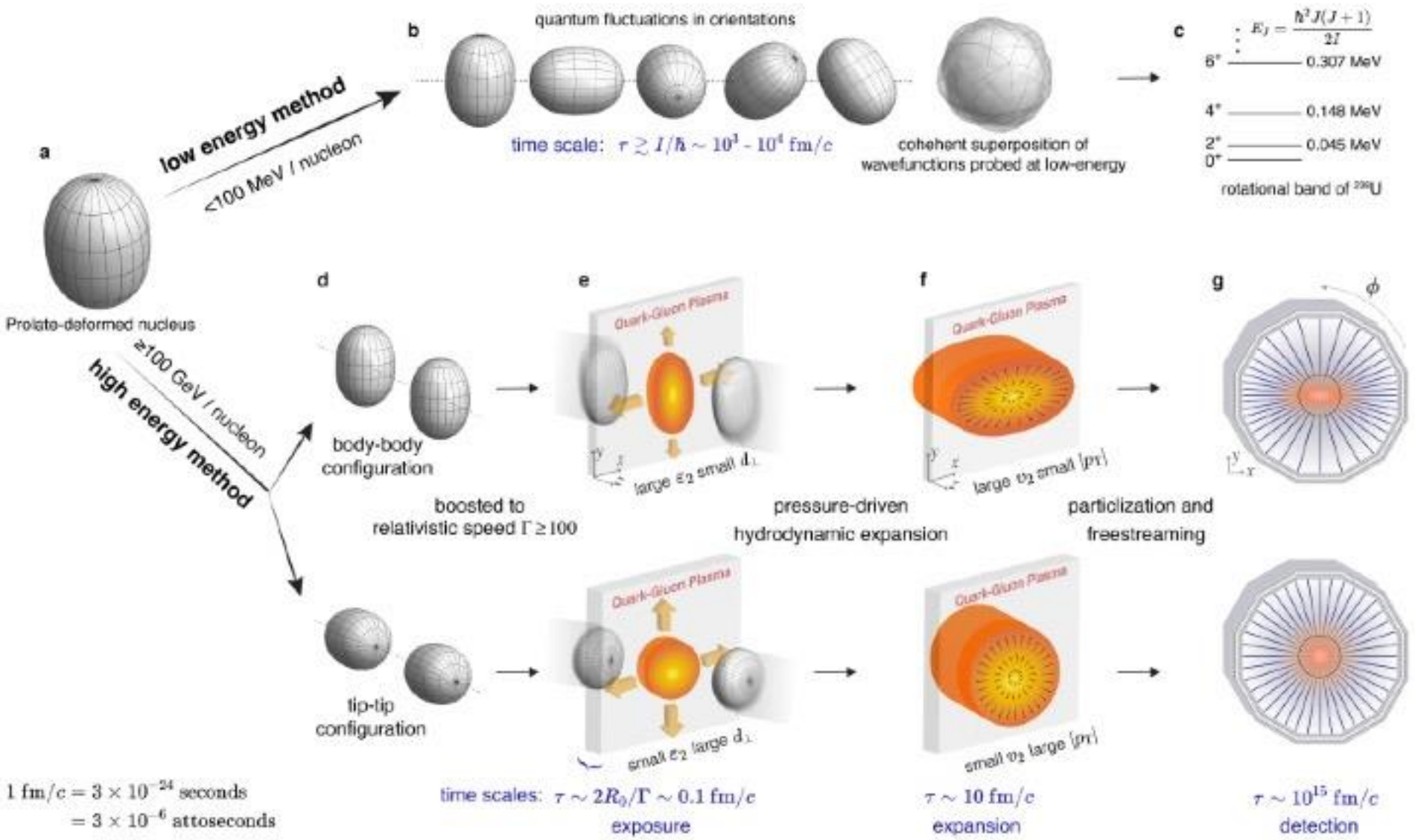
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

$$R(\theta,\phi) = R_0(1+\beta_2[\cos\gamma Y_{2,0}(\theta,\phi) + \sin\gamma Y_{2,2}(\theta,\phi)] + \beta_3 Y_{3,0}(\theta,\phi) + \beta_4 Y_{4,0}(\theta,\phi))$$



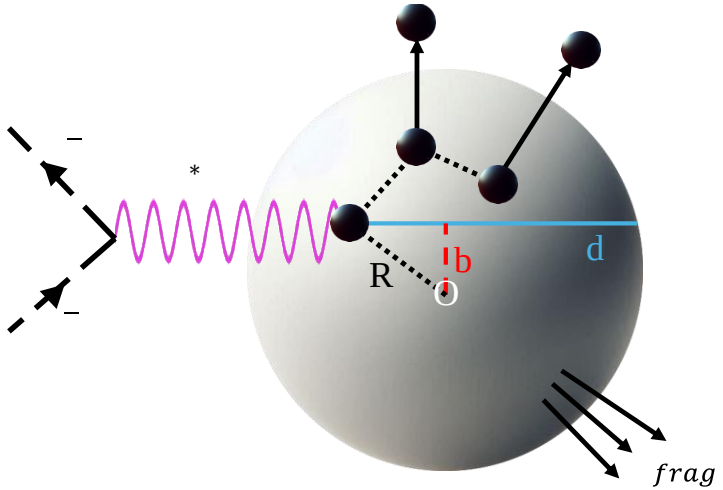
What is the collided nucleus's shape and structure?

STAR Collaboration
arXiv:2401.06625
Accepted in Nature



Shape-frozen snapshots in nuclear crossing (10^{-25}s << rotational time scale 10^{-21}s)

The BeAGLE model

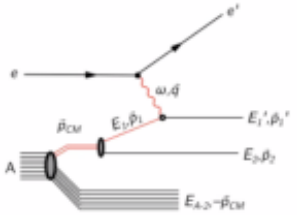


Primary interaction treated by **PYTHIA6** for the hard collision.

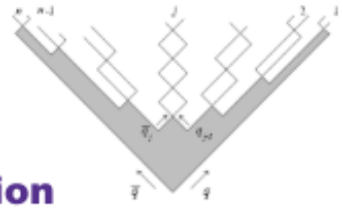
Glauber handled by BeAGLE

PyQM: Nuclear Geometry + optional gluon radiation in medium.

Hadronization handled by **PYTHIA6.**

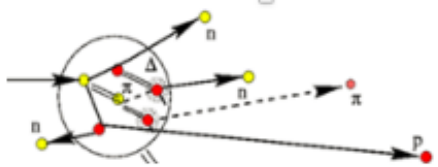


Primary interaction



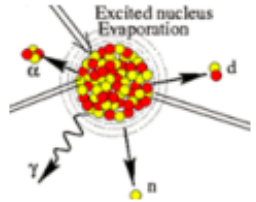
Hadronization

Cascade process handled by **DPMJET.**



Intra-nuclear cascade

Nuclear remnant evaporation and break up by **FLUKA.**



Nuclear remnant evaporation & breakup

- With the BNL and SBU groups, I worked on updating the BeAGLE model version 1.03
- Currently involved in building the next generation of the BeAGLE model “BeAGLE++”