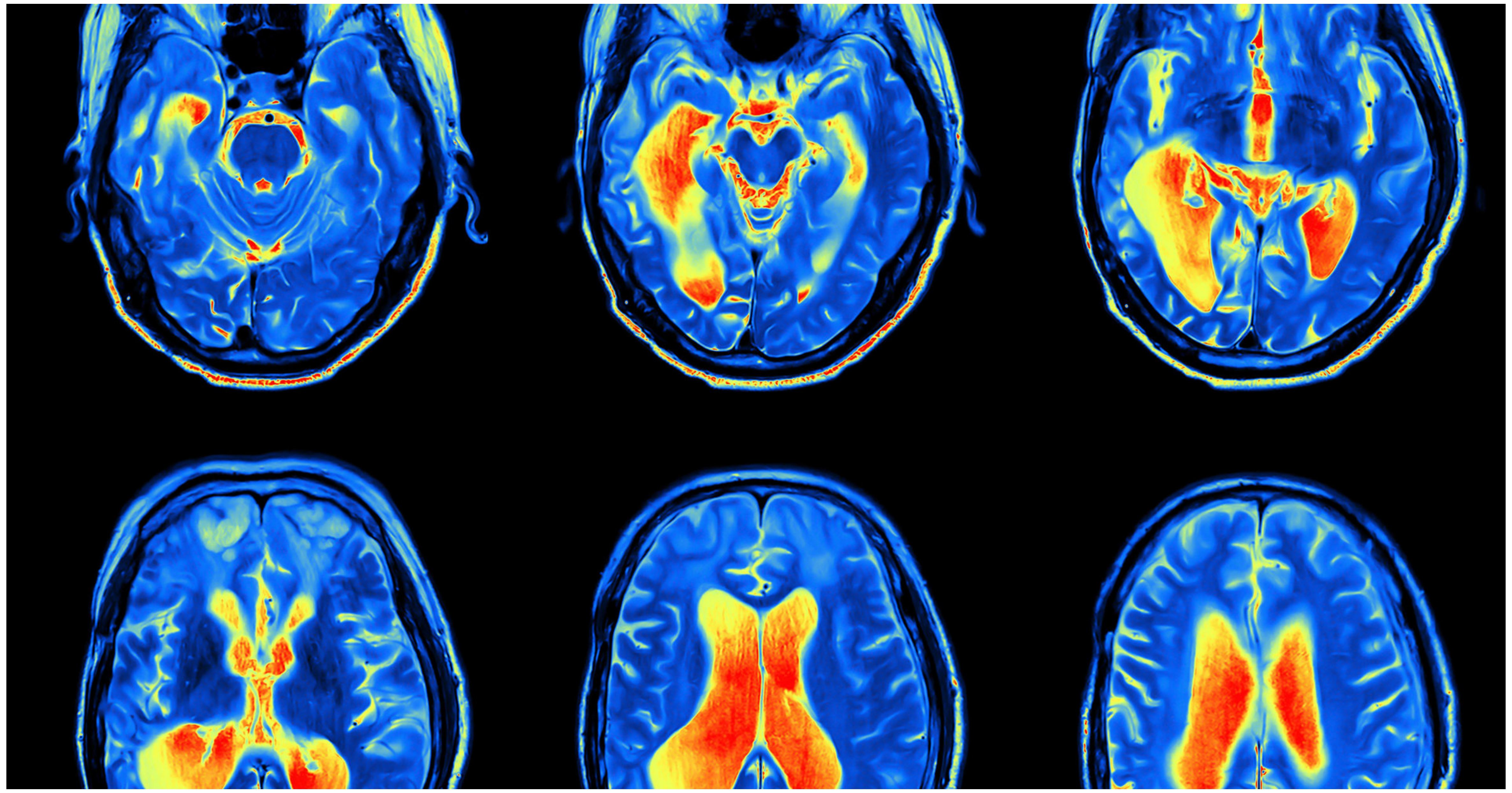
High-energy nuclear physics and heavy ion collisions with CMS

Austin Baty
University of Illinois Chicago
abaty.github.io

July 3, 2024
CMS PURSUE/SPRINT Program
Fermilab

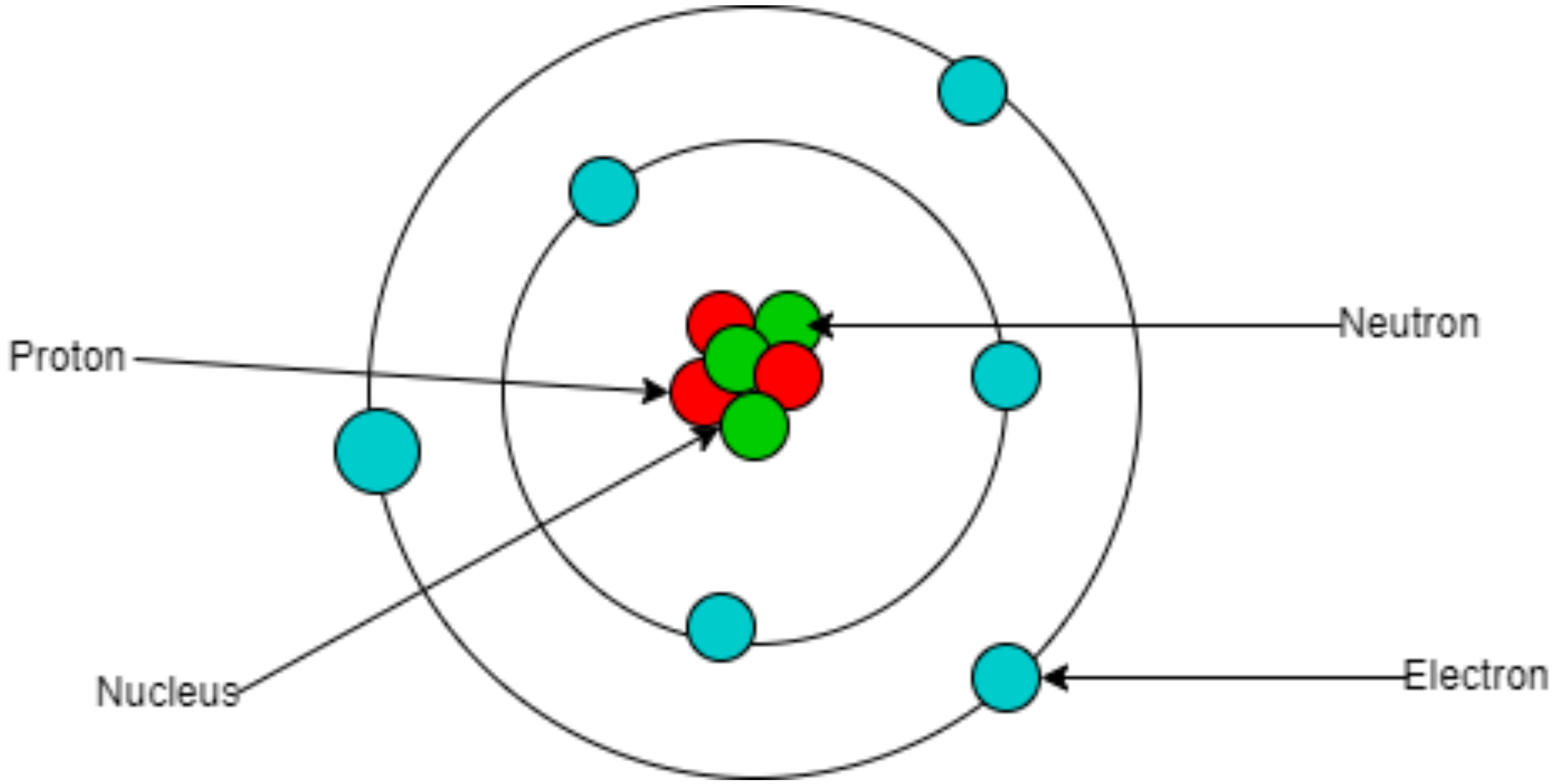
UNIVERSITY OF ILLINOIS CHICAGO

What is nuclear physics?

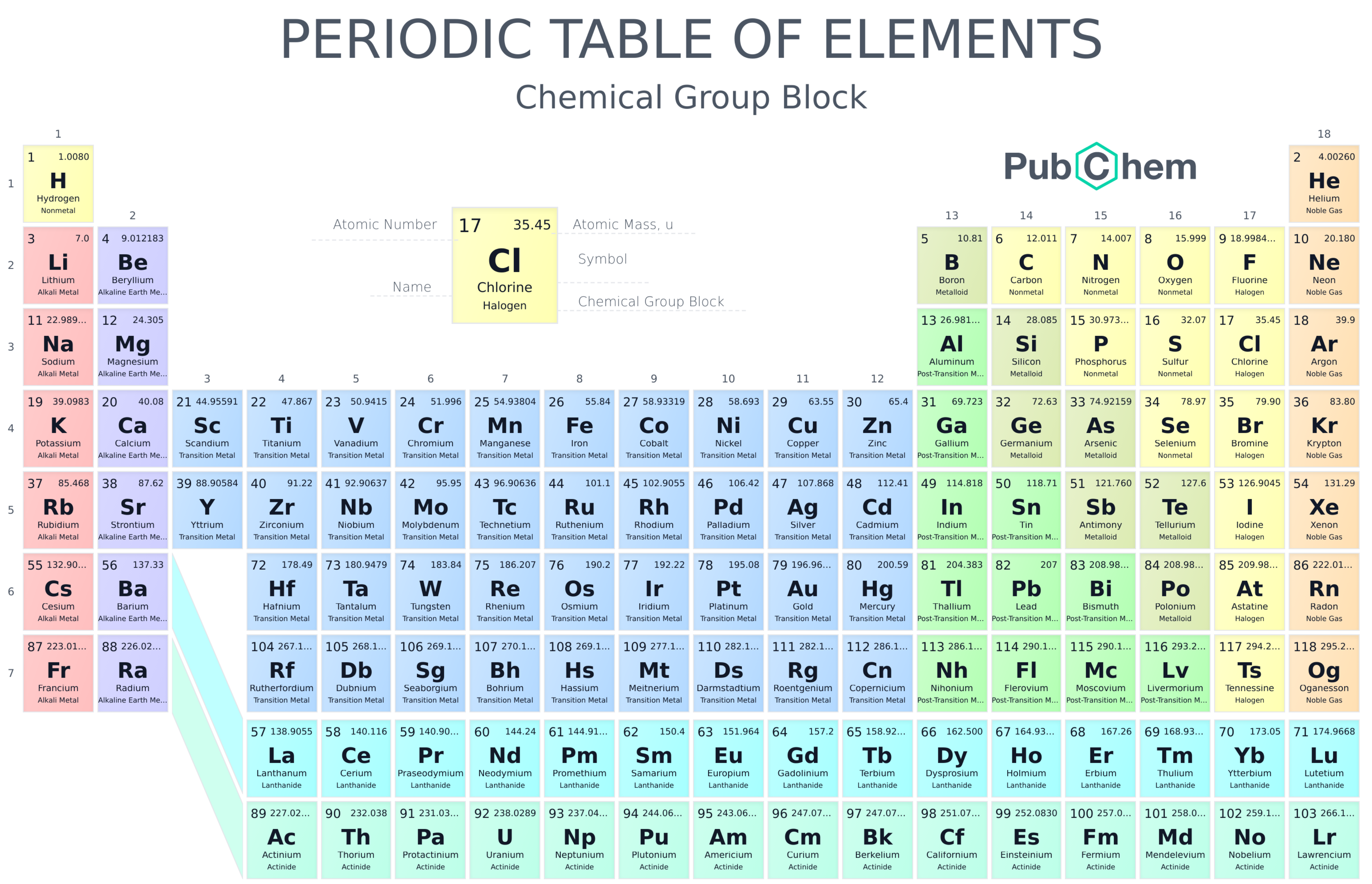


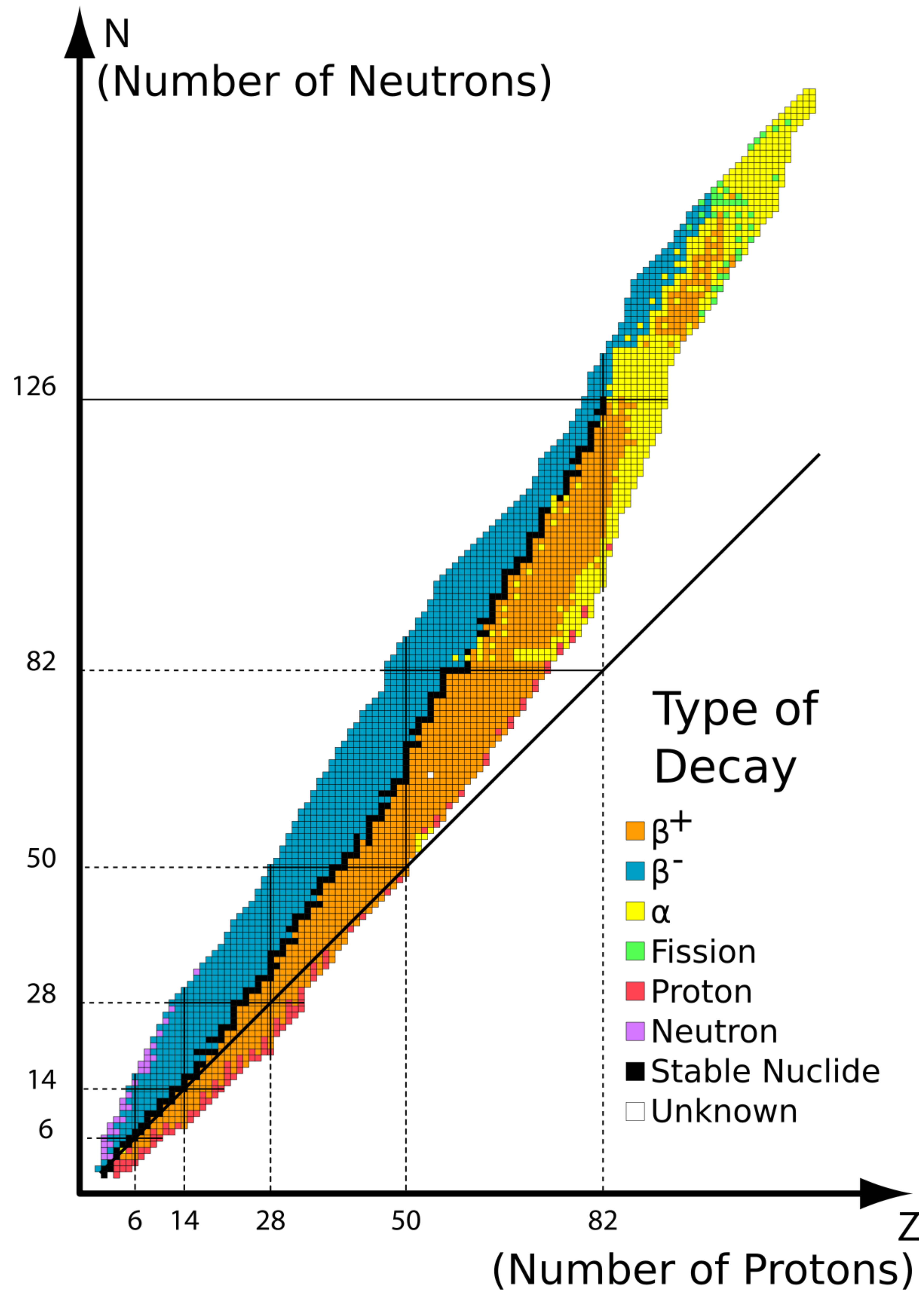
What is nuclear physics?

- **All those applications come from understanding nuclei and the protons/neutrons inside of them**
- **Protons/neutrons form 99% of the visible mass in the universe!**
- **We don’t understand details of what nuclei look like microscopically**



Low energy nuclear physics

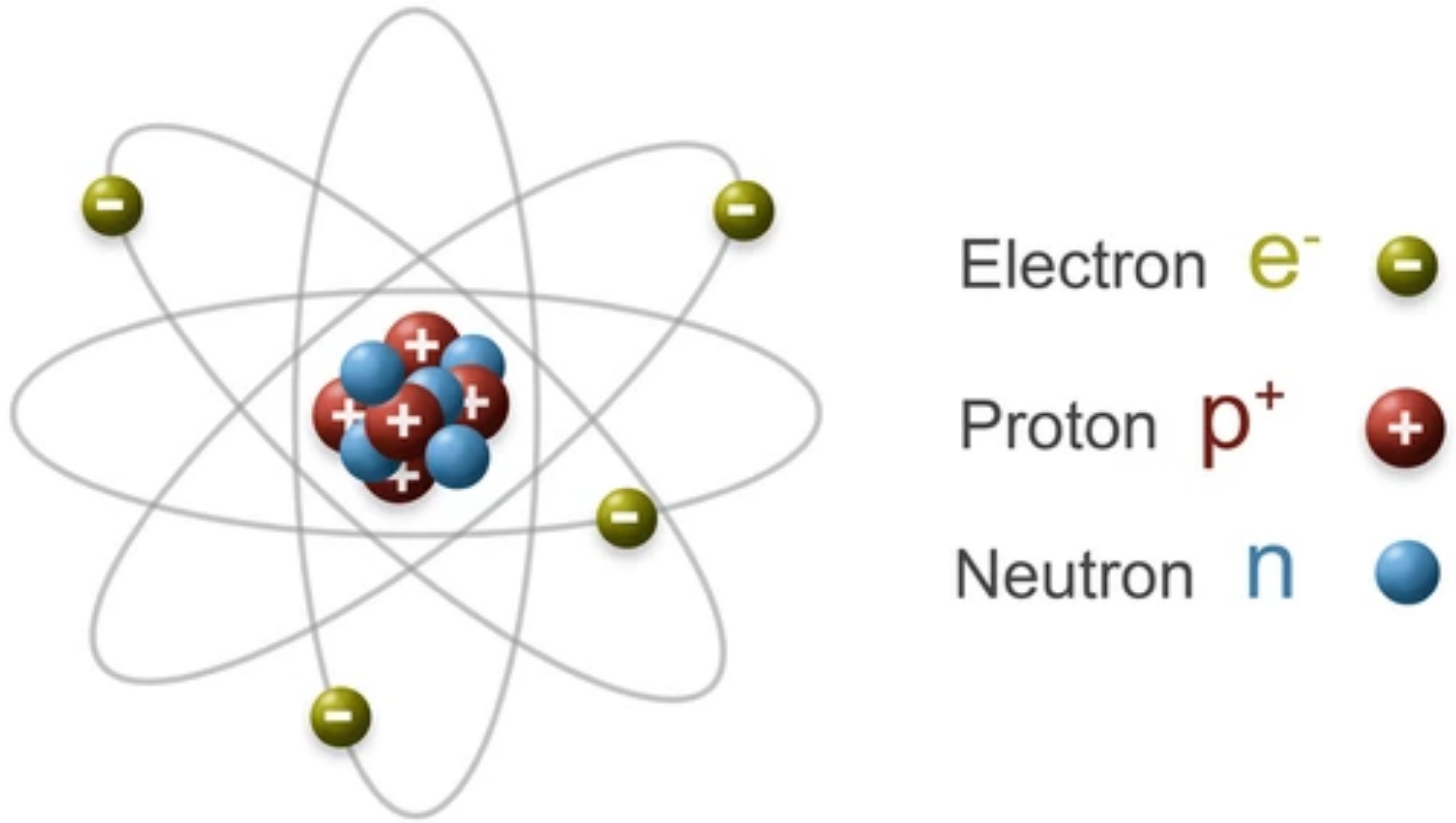


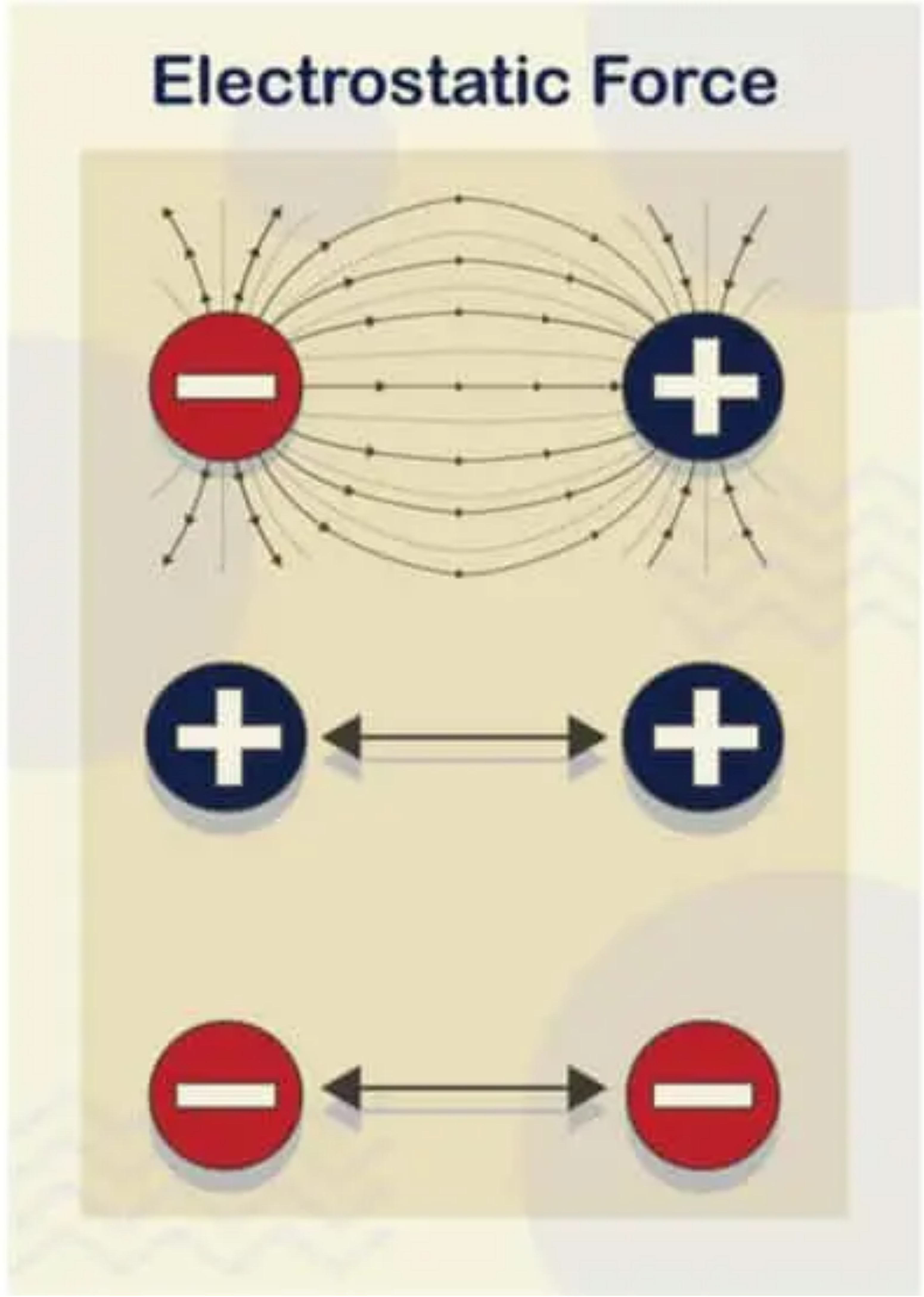


- **Low energy nuclear physics studies how nuclear isotopes can decay**
- **Searching for new elements, etc.**
- **What is ‘high energy’ nuclear physics?**

How are atoms held together?

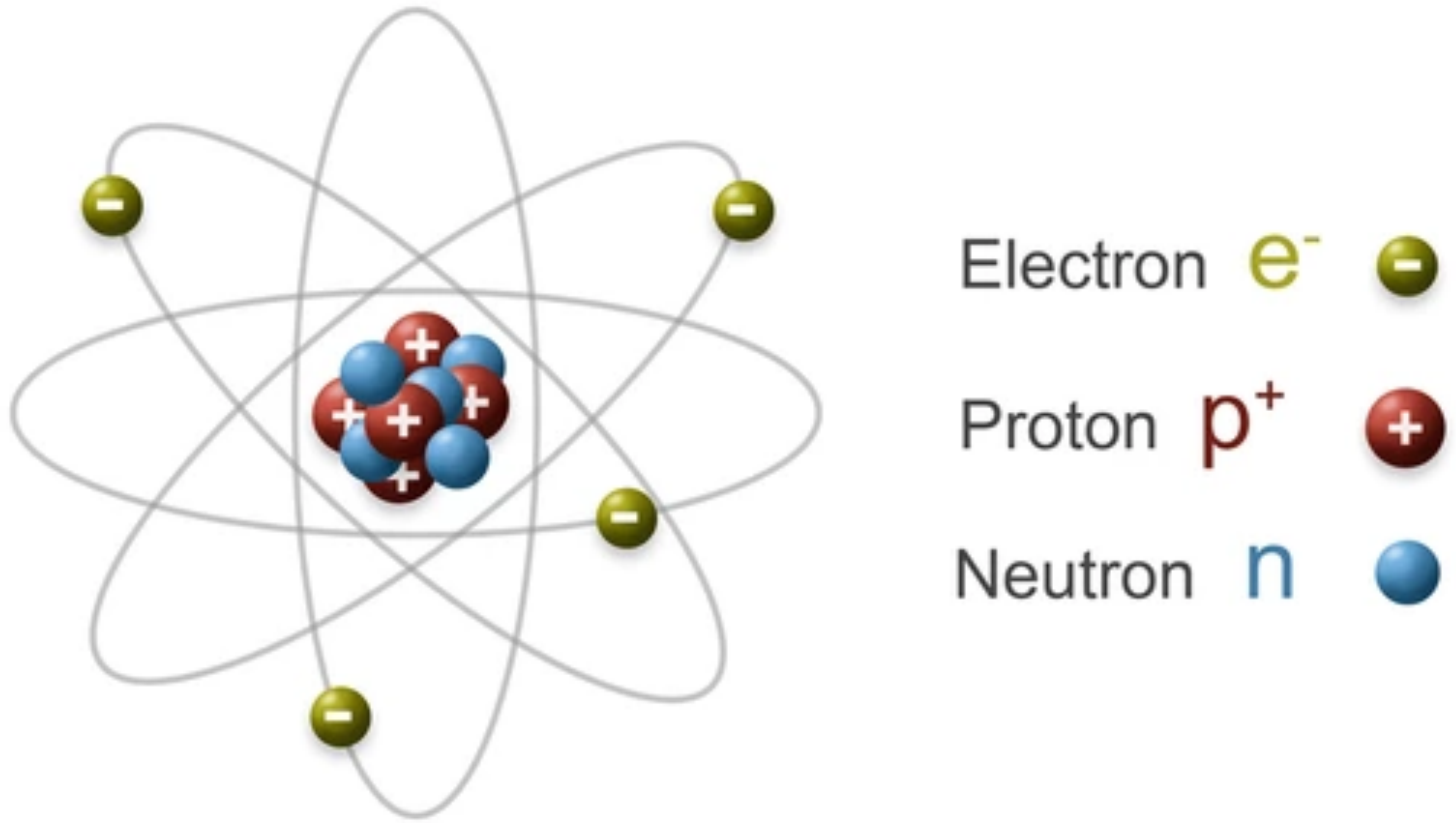
- **Electric (or electromagnetic) force**
  - **Opposite signs attract each other**
  - **Same sign charged repel each other**

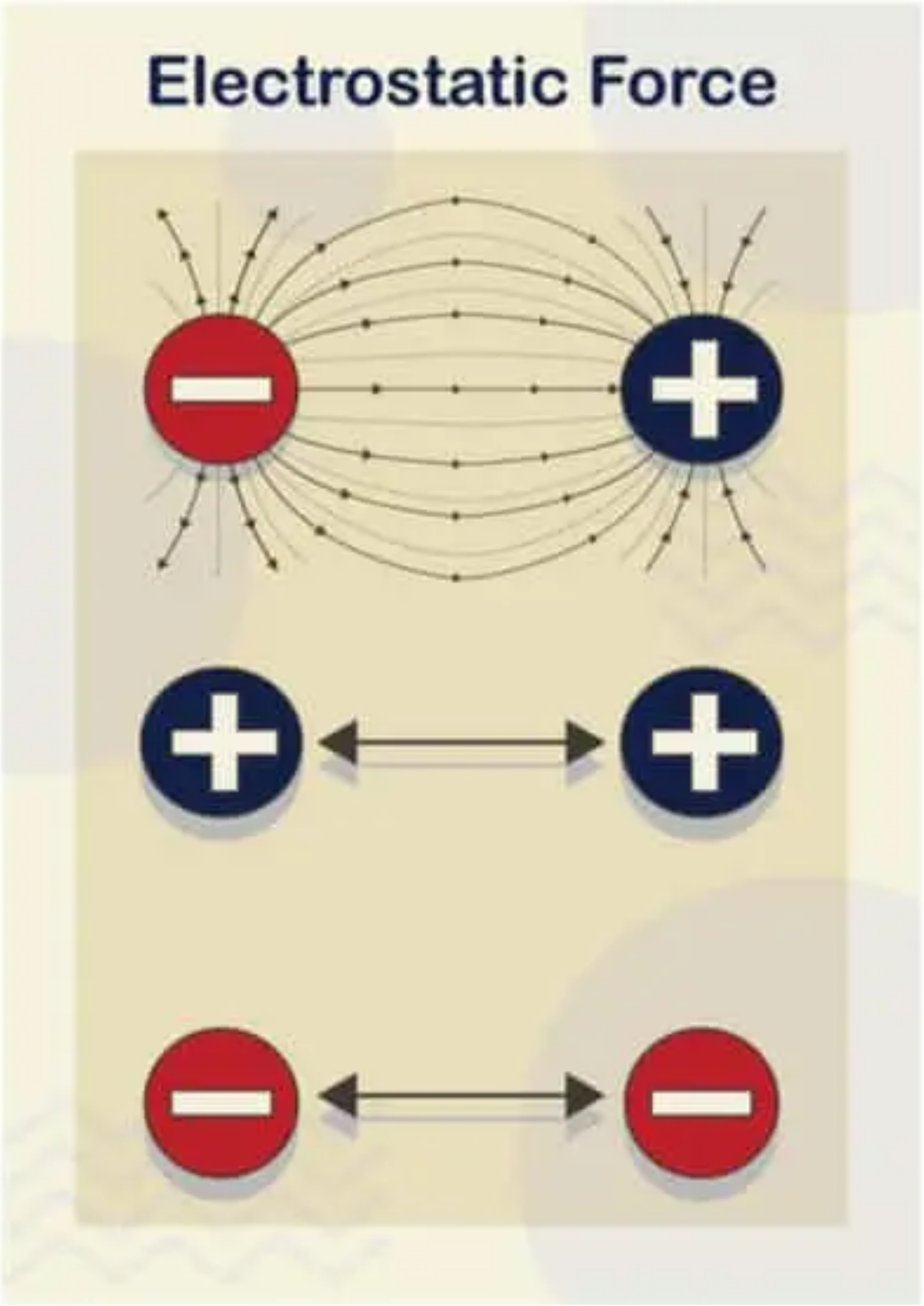




How are nuclei held together?

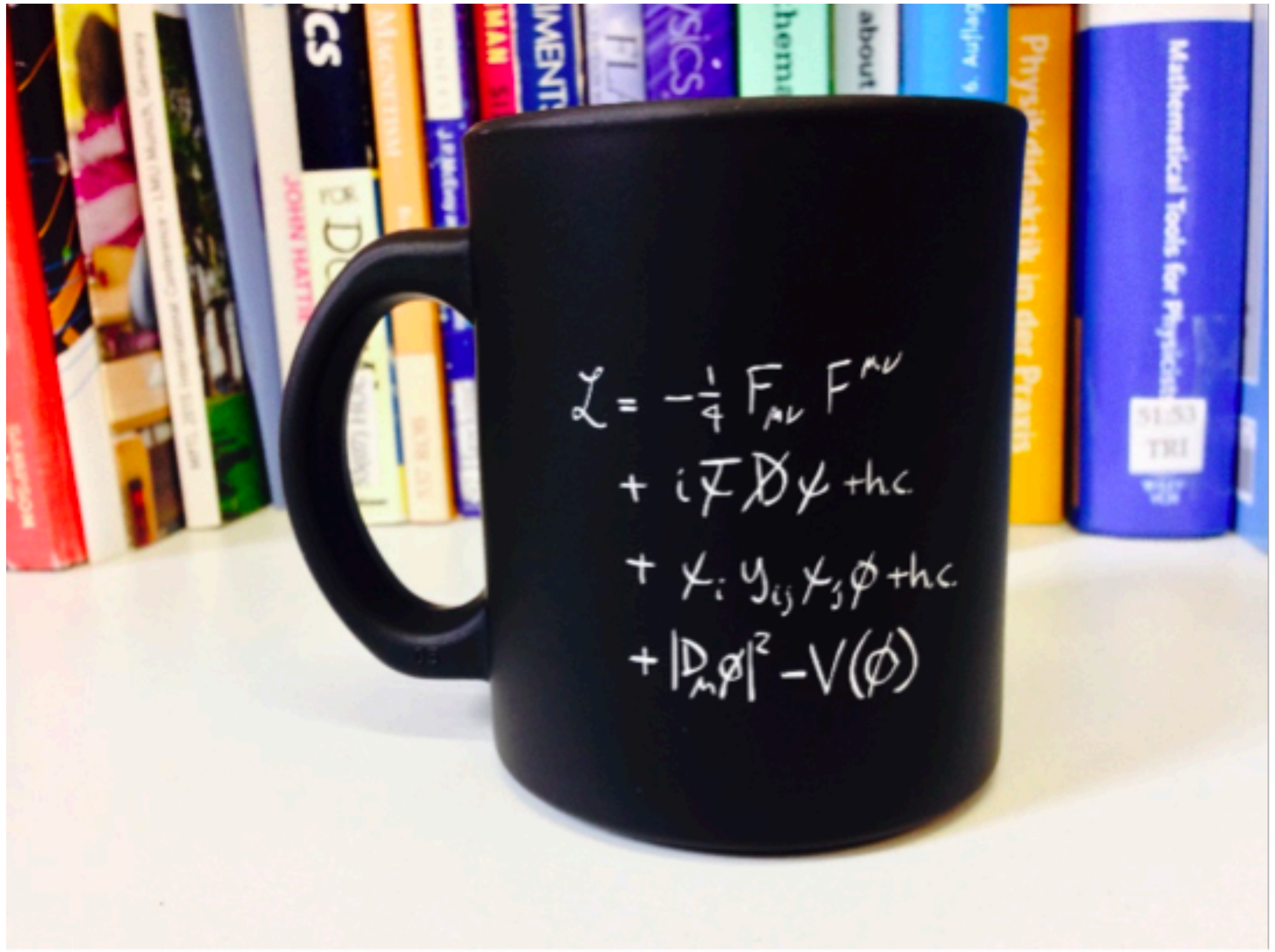
- **All protons have positive charge**
  - **How does the nucleus stay together?**
- **There is another force - the strong force!**



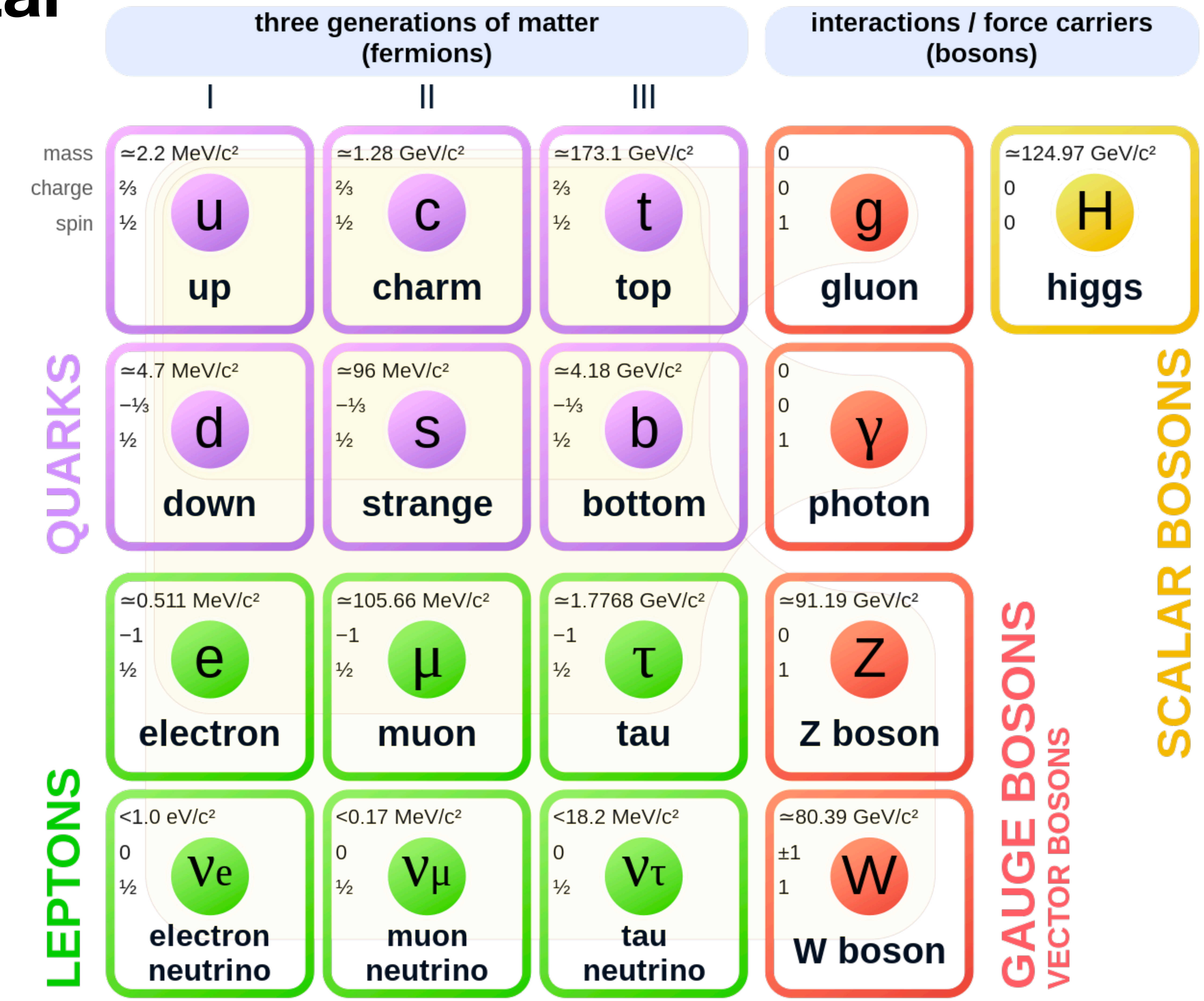


The Standard Model

- **The SM describes 3 fundamental forces of nature**

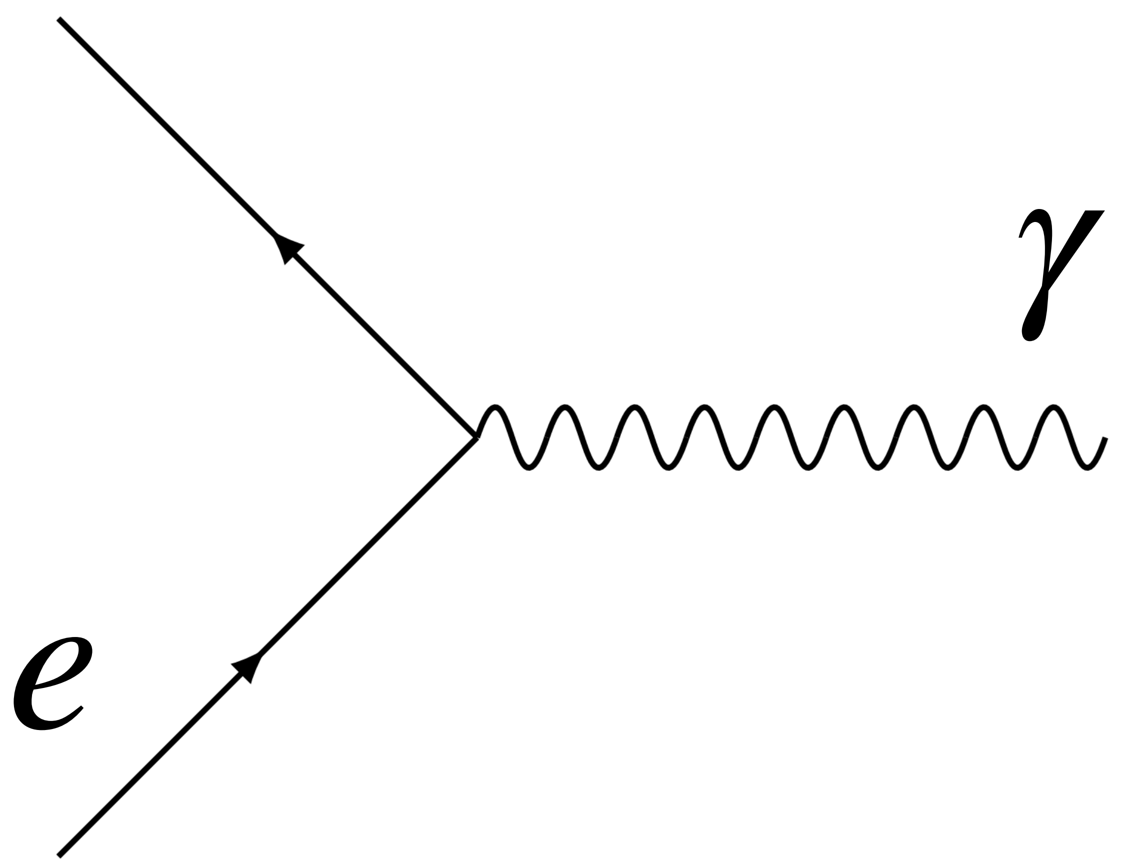


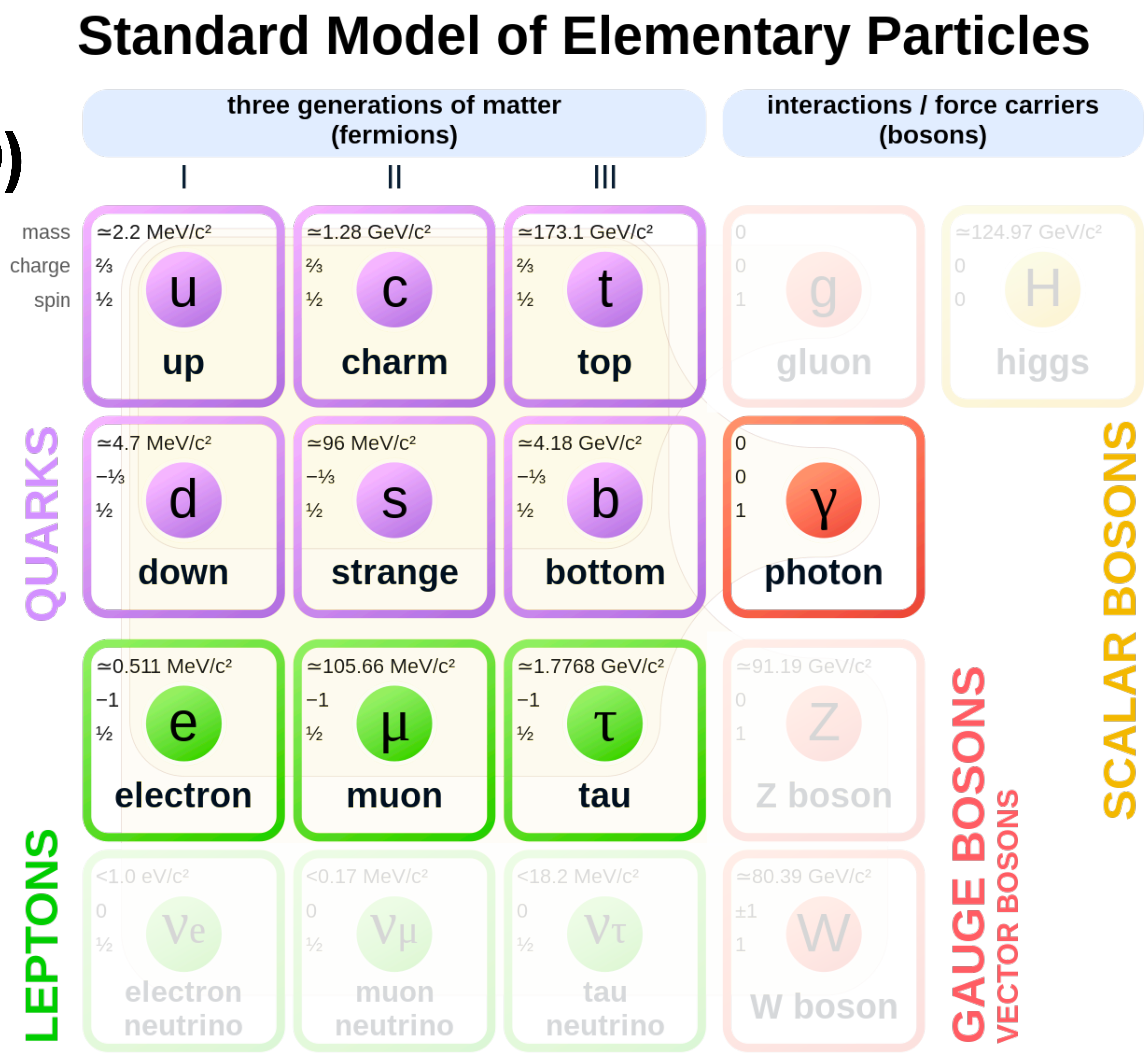
Standard Model of Elementary Particles



Quantum Electrodynamics

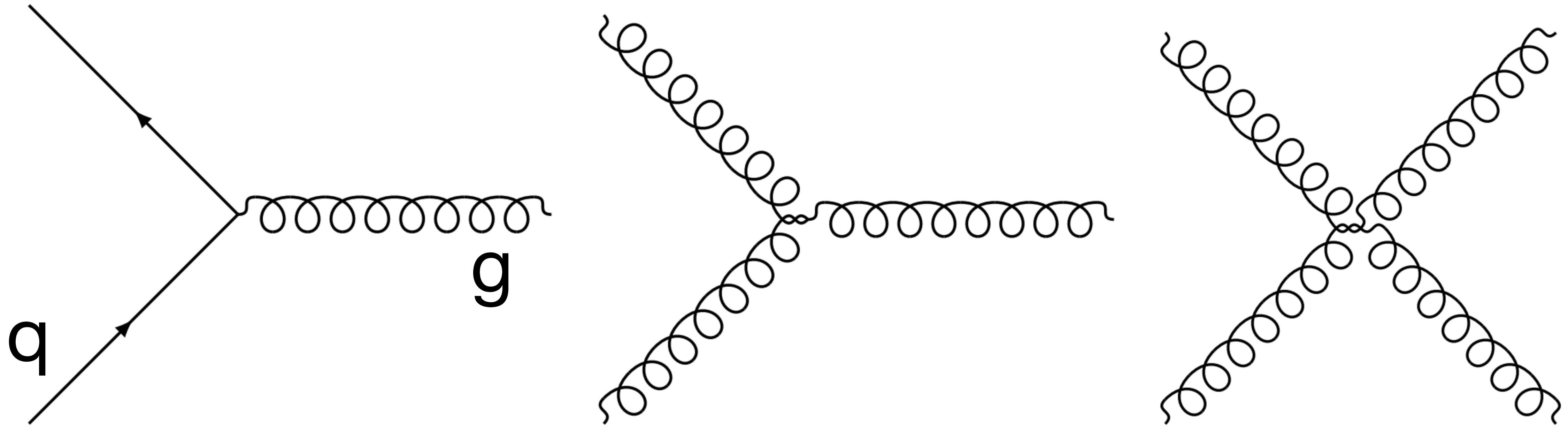
- **Quantum Electrodynamics (QED)**
  - **Fundamental theory of electromagnetism**

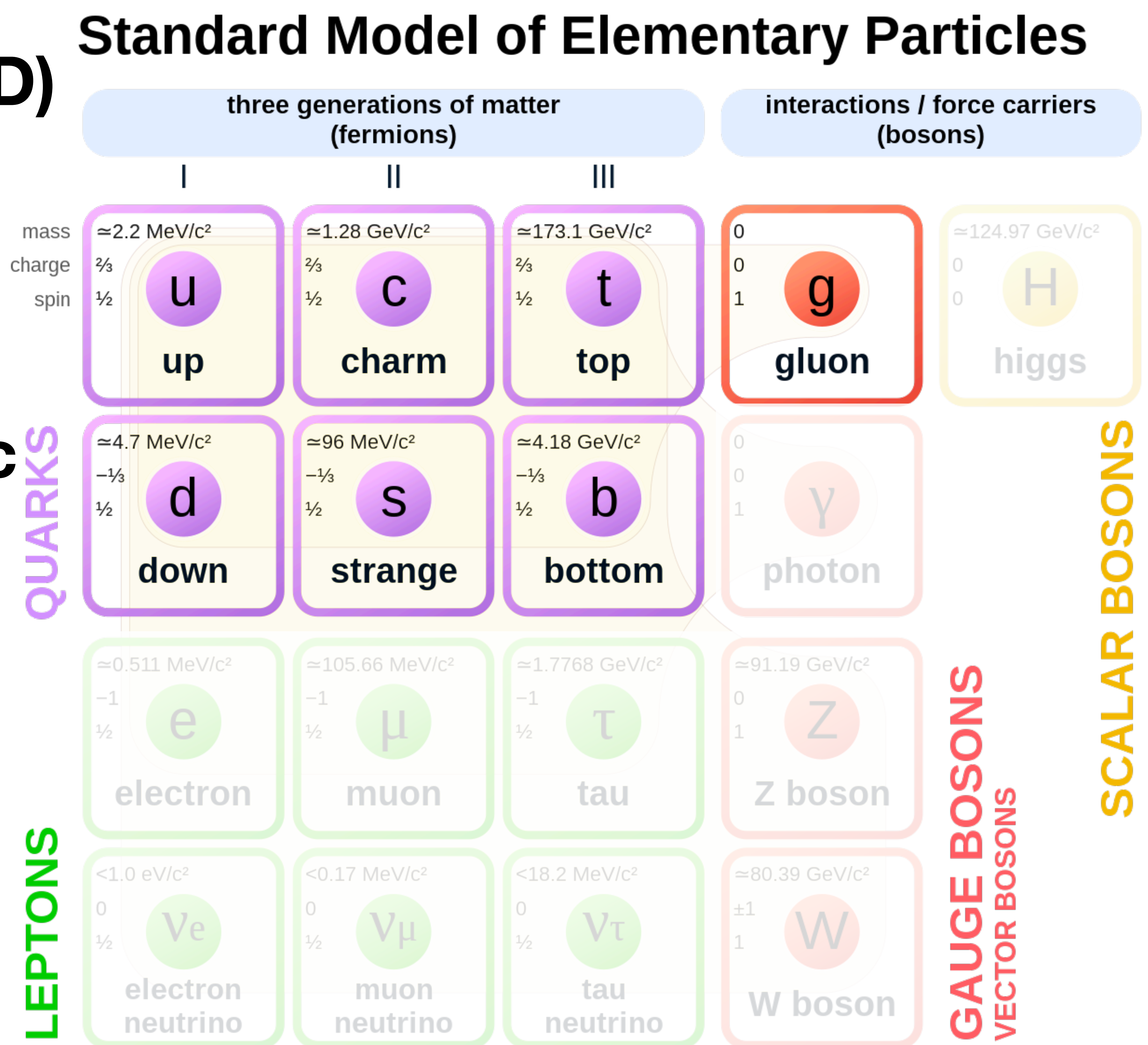




Quantum Chromodynamics

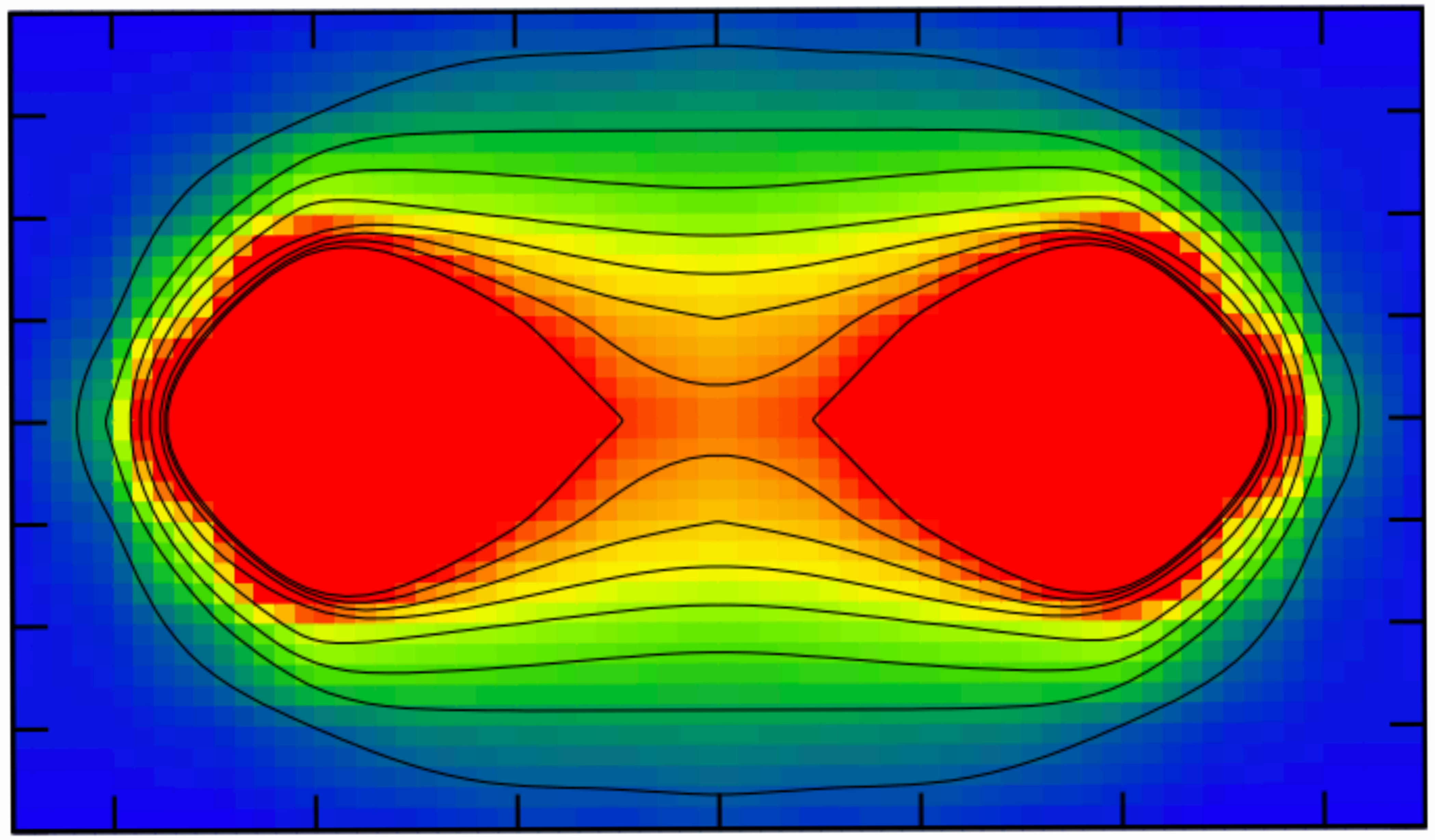
- **Quantum Chromodynamics (QCD)**
  - **Theory of strong force**
  - **Interaction quarks and gluons**
  - **Color charge instead of electric charge**



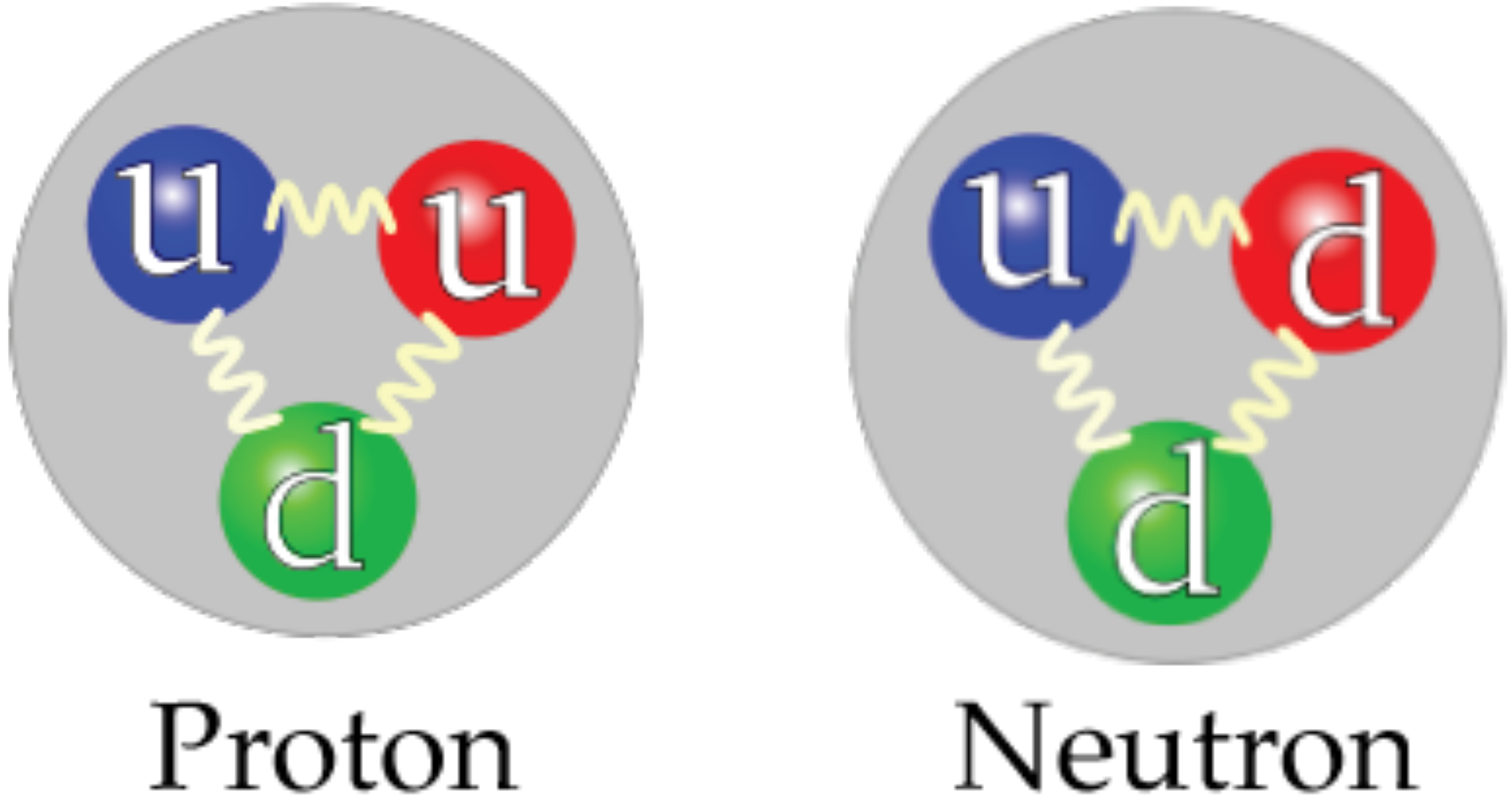


Confinement

- **Quarks are always stuck together by gluons - confined**
- **Protons/neutrons have 3 quarks stuck together**
- **Nuclei are many protons/neutrons stuck together**
  - **High energy nuclear physics wants to understand quarks/gluons**

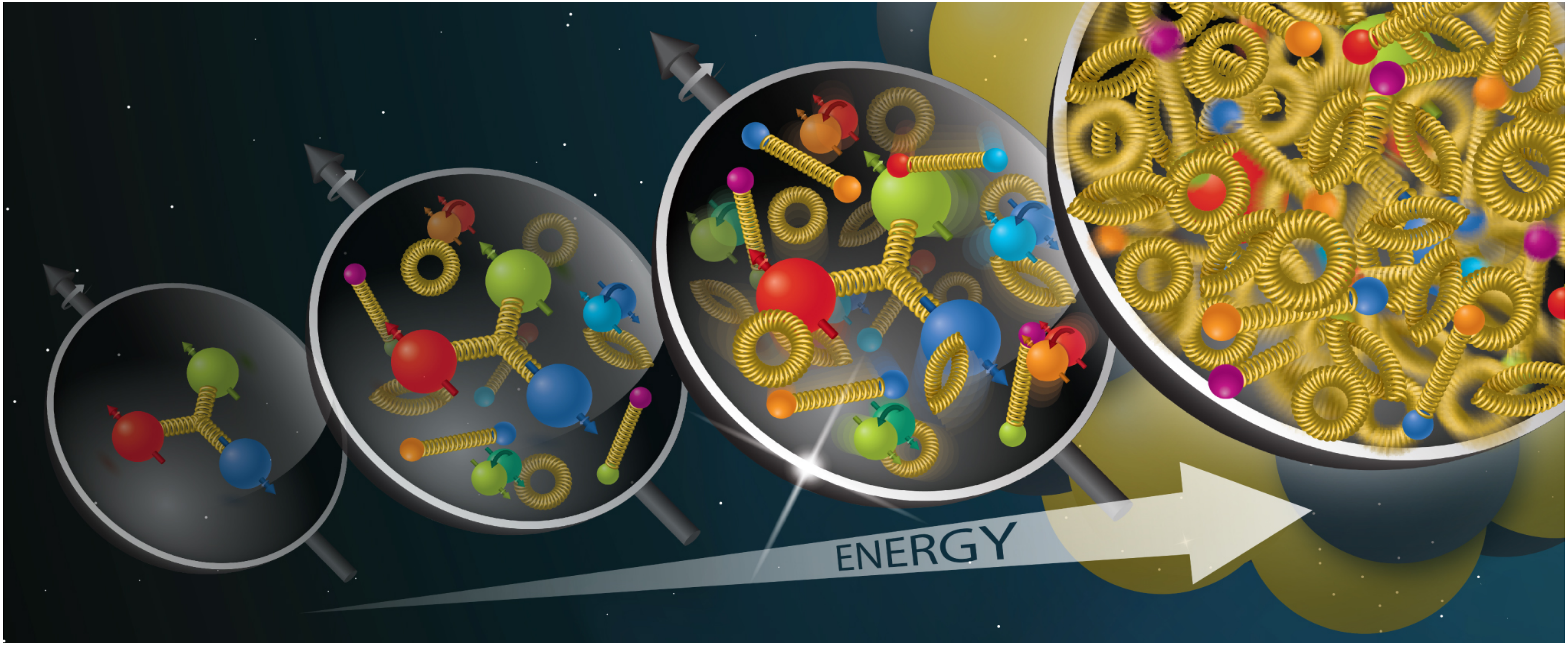


Phys.Rev.D 81:034504,2010



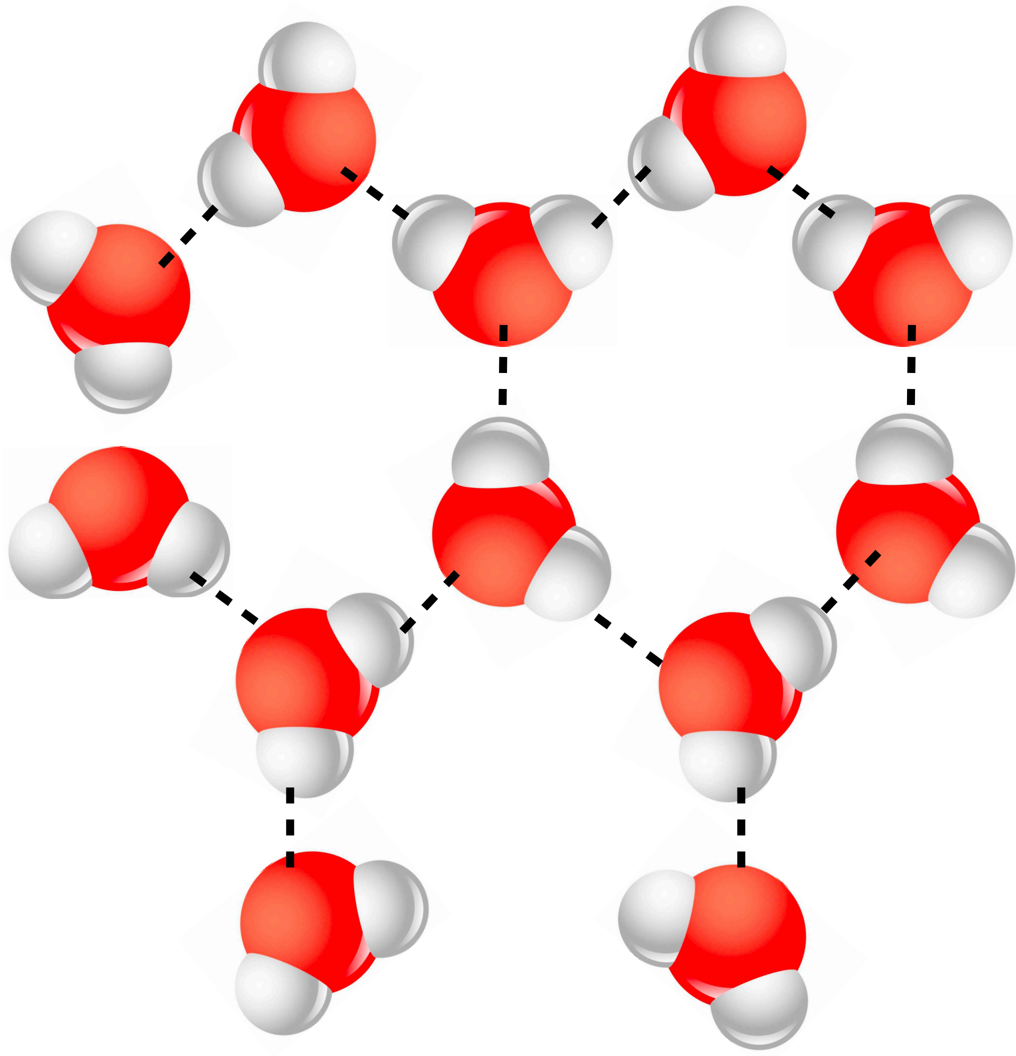
Studying quarks and gluons

- **3 quark picture is simple; gluons important at higher energies!**
- **How can we study quarks and gluons if they are confined?**



Analogy time - Iceworld!

- **Everything is (solid) H_20**
- **Snow-scientists know about molecules and forces between them**

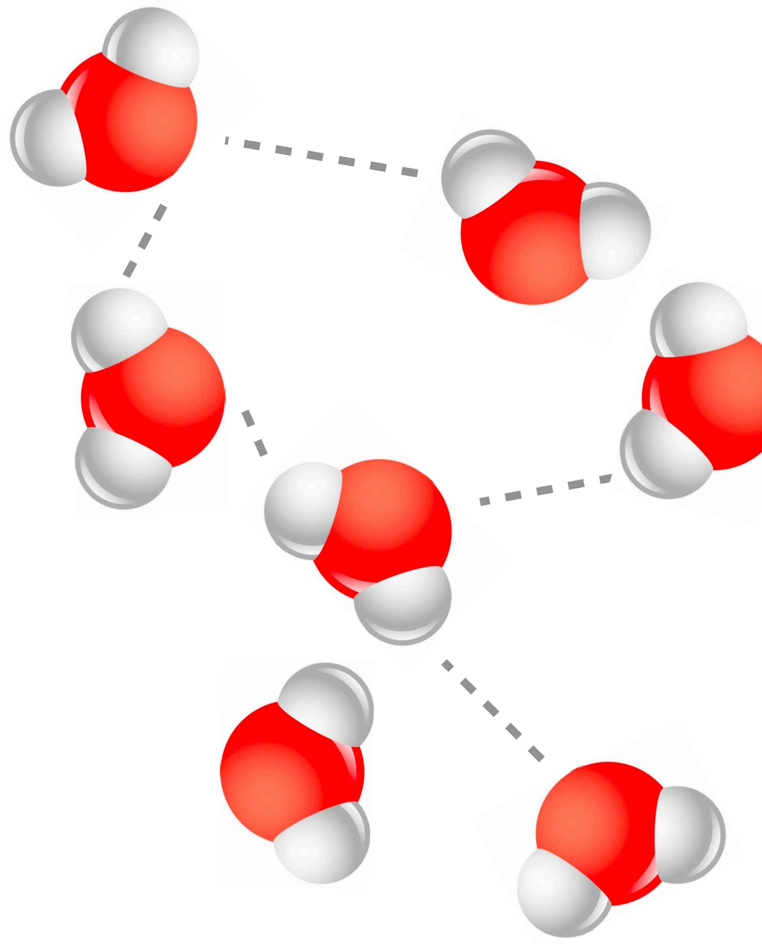


A collision on iceworld!

- **A meteor hits and heats up ice world!**

Discovery of liquid water!

- **Liquid water discovered!**
- **Same molecules**
- **Same force**
- **Different phase of matter**



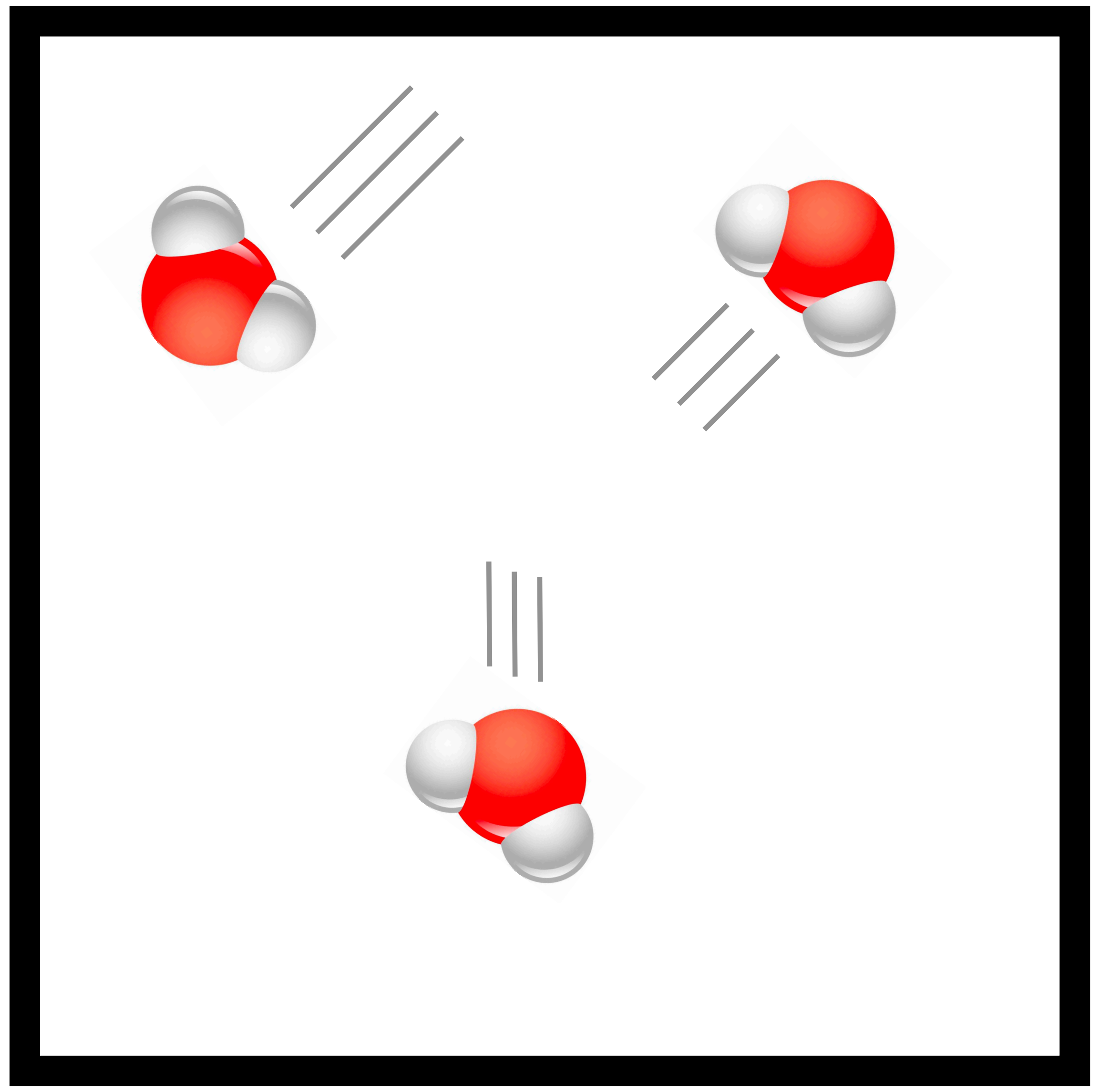
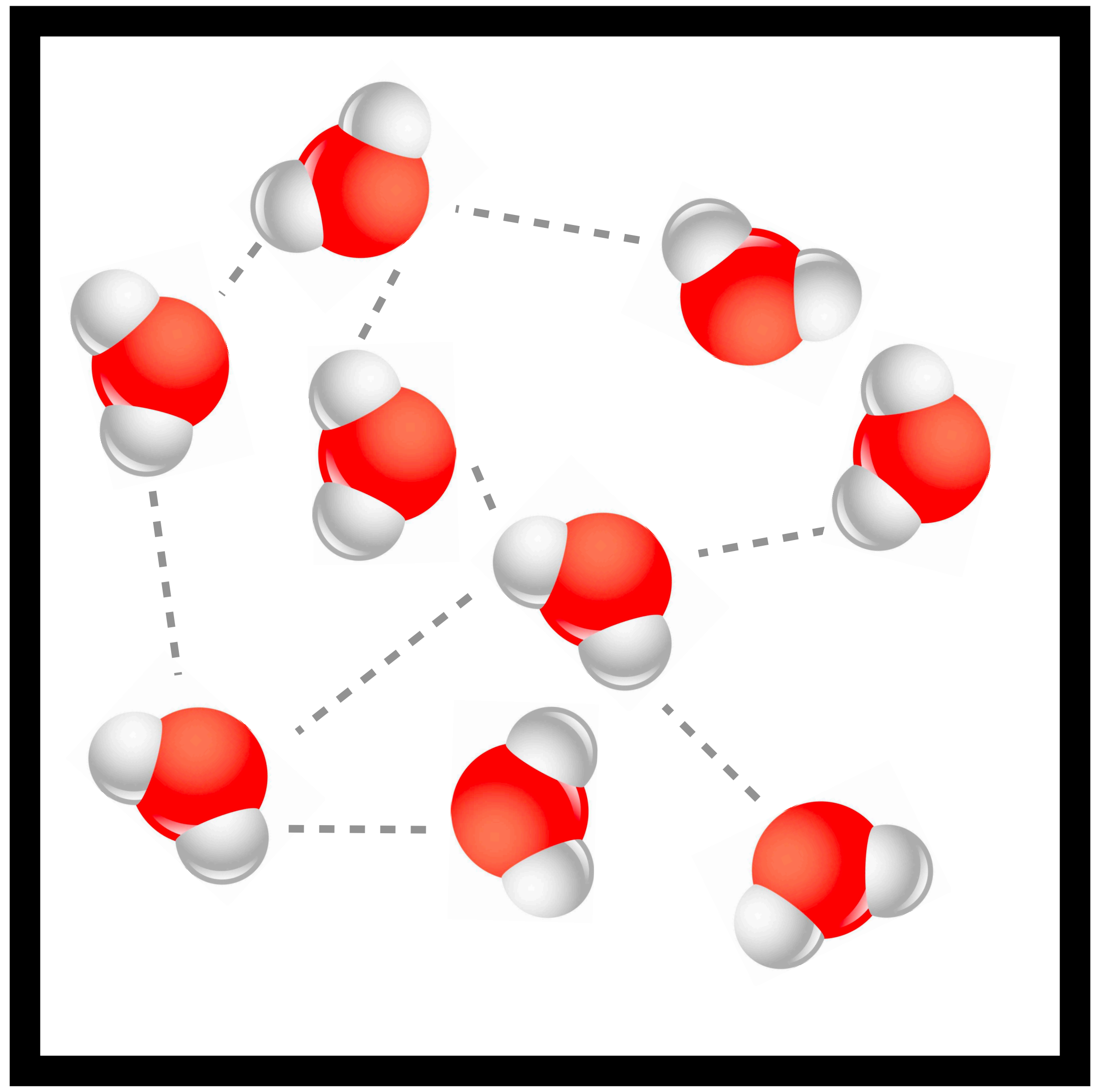
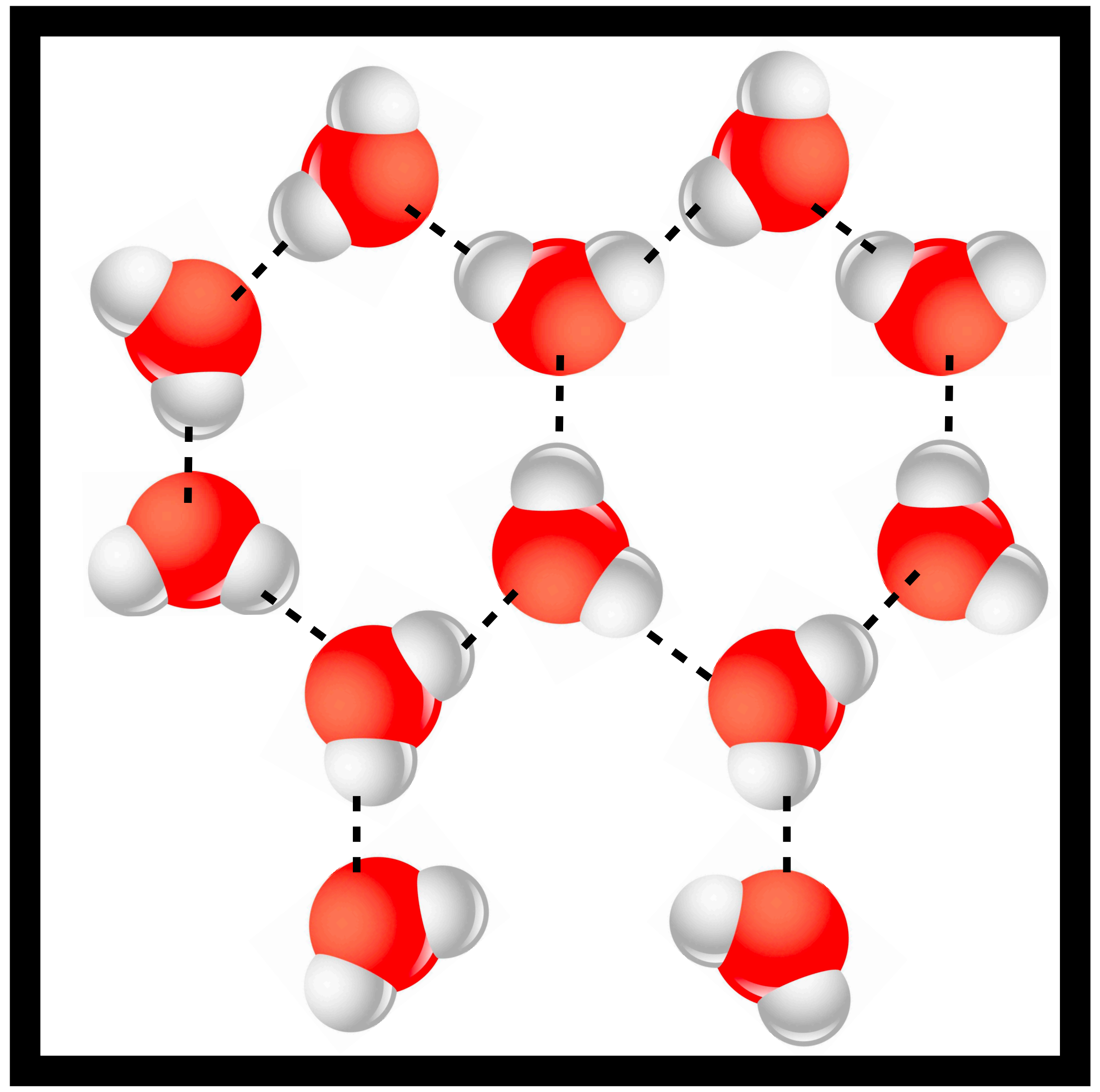
Phases of water

Steam

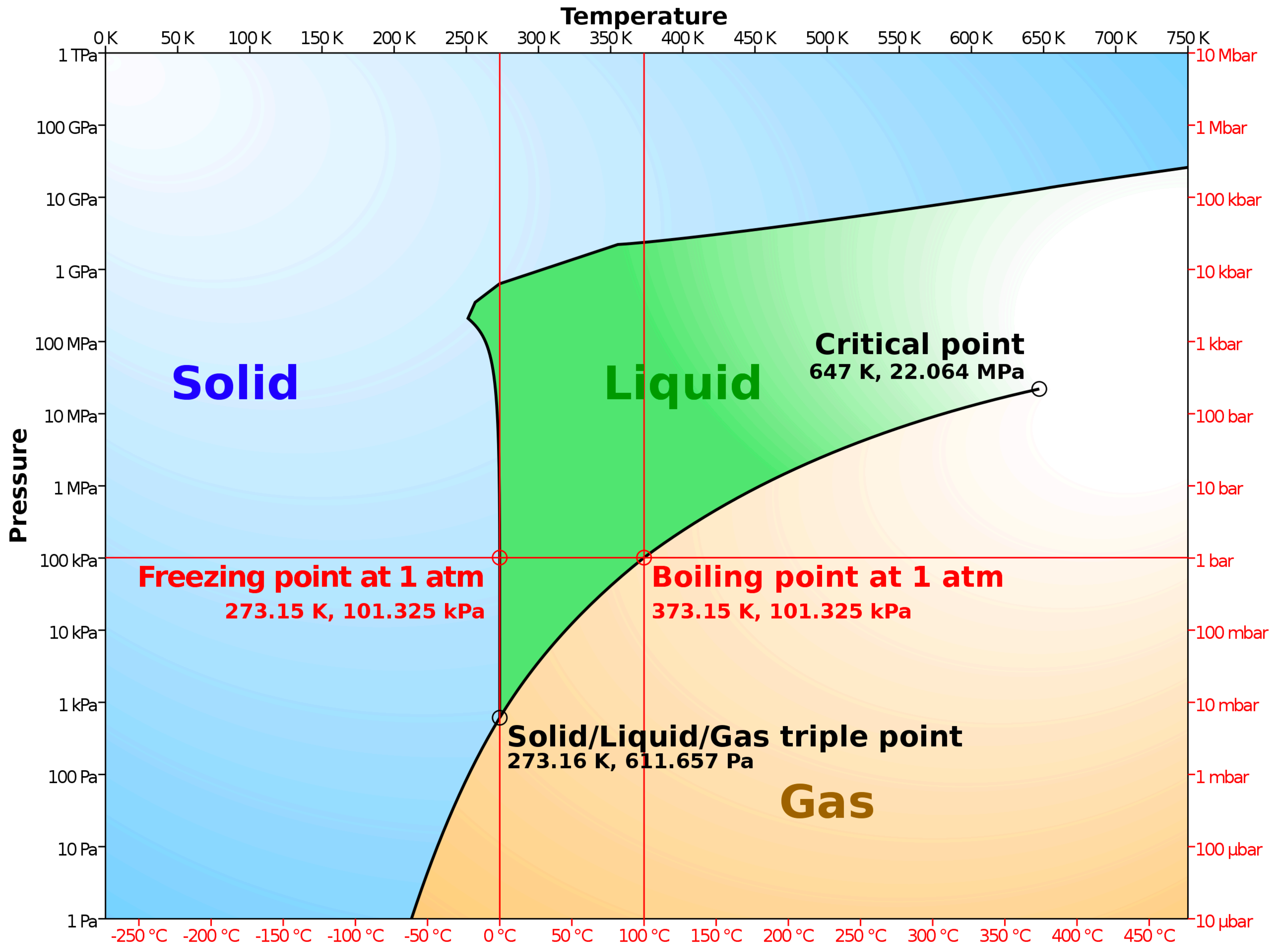
Liquid Water

Ice

Phases of water

Steam	Liquid Water	Ice
		
		

Physicist's view of water



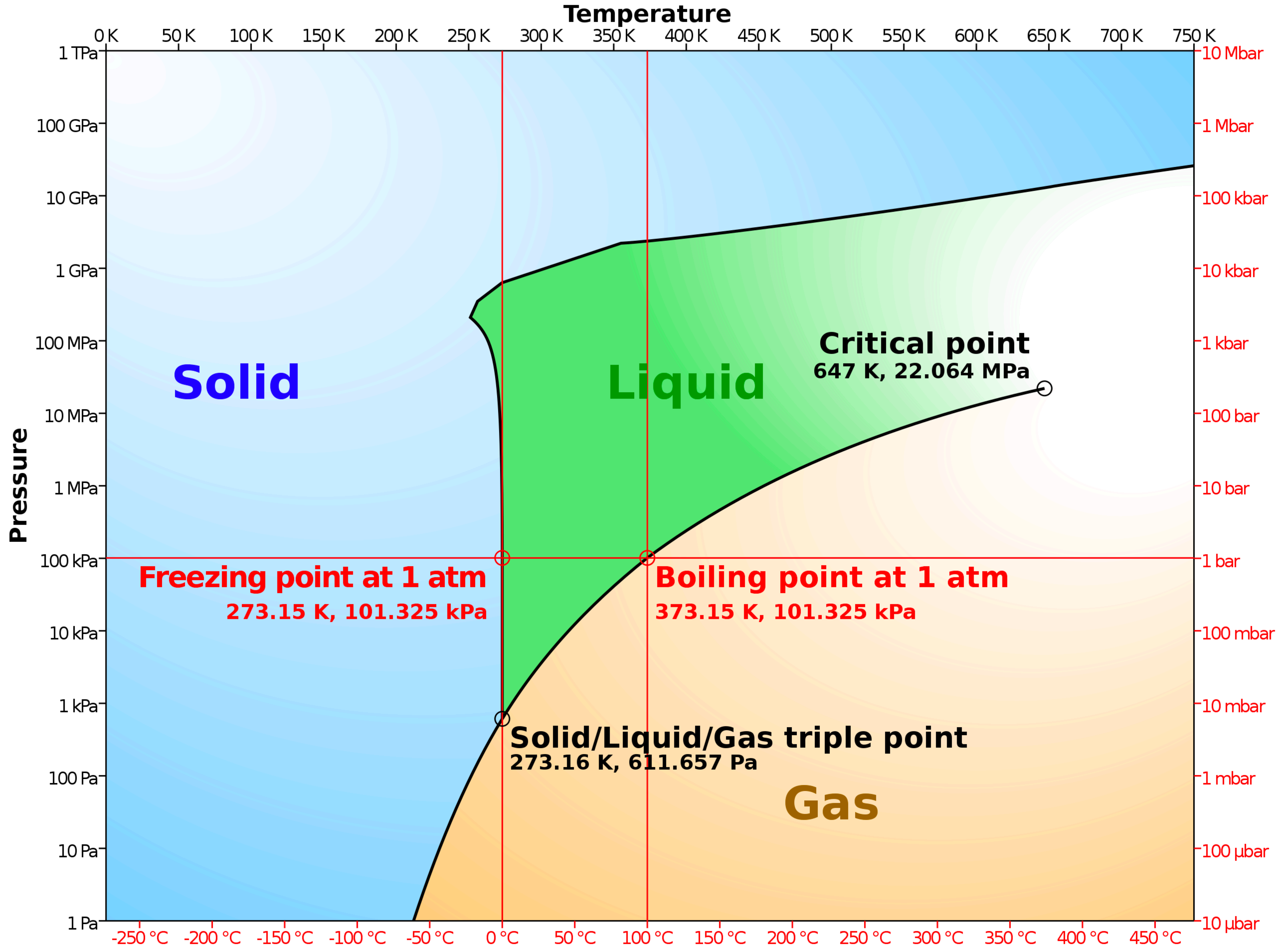
Pressure

Temperature

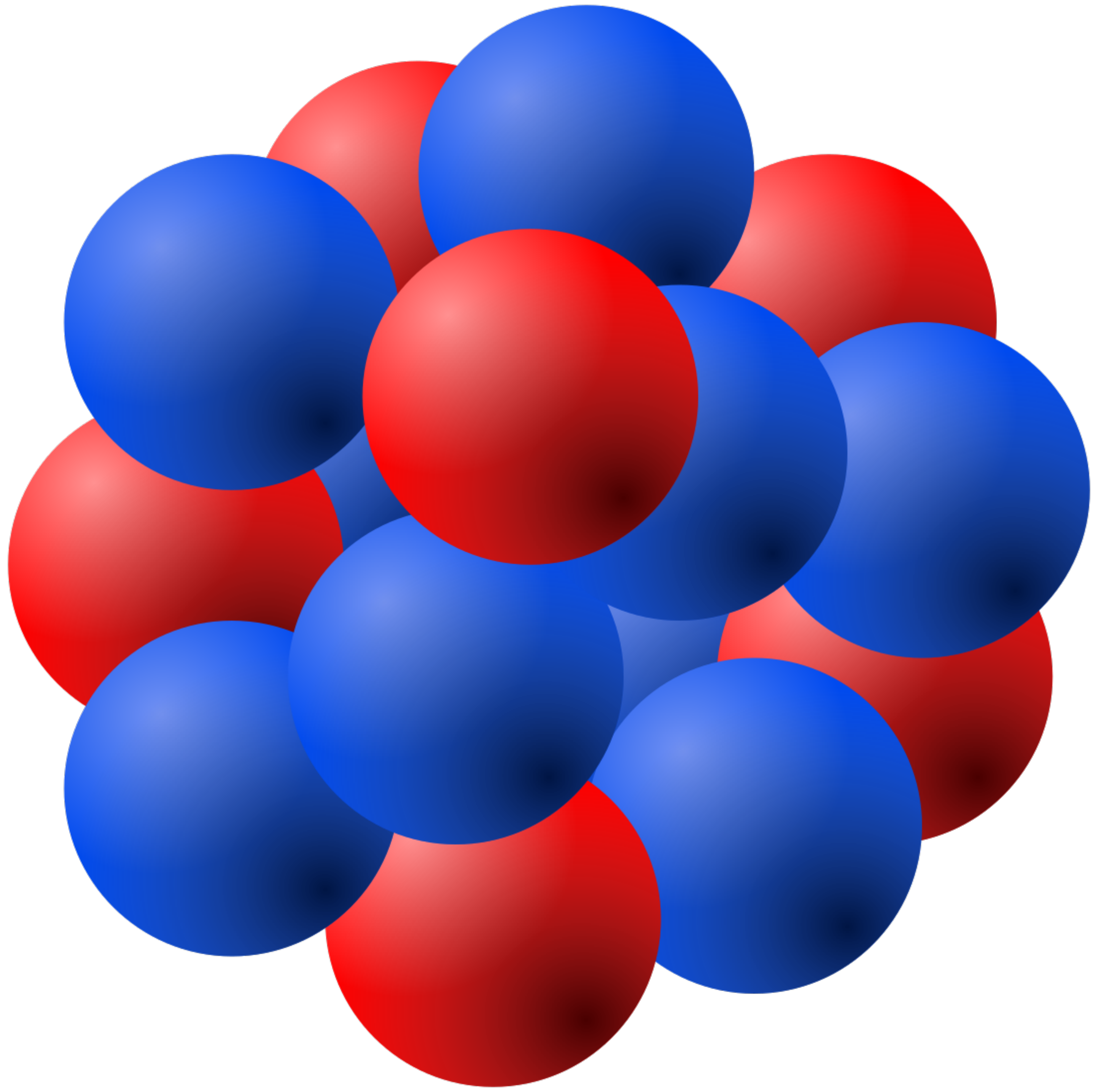
- **Water is very complex!**
- **Electromagnetism is well understood!**

Phase diagram for strong force

- **What does the phase diagram look like for nuclear matter?**

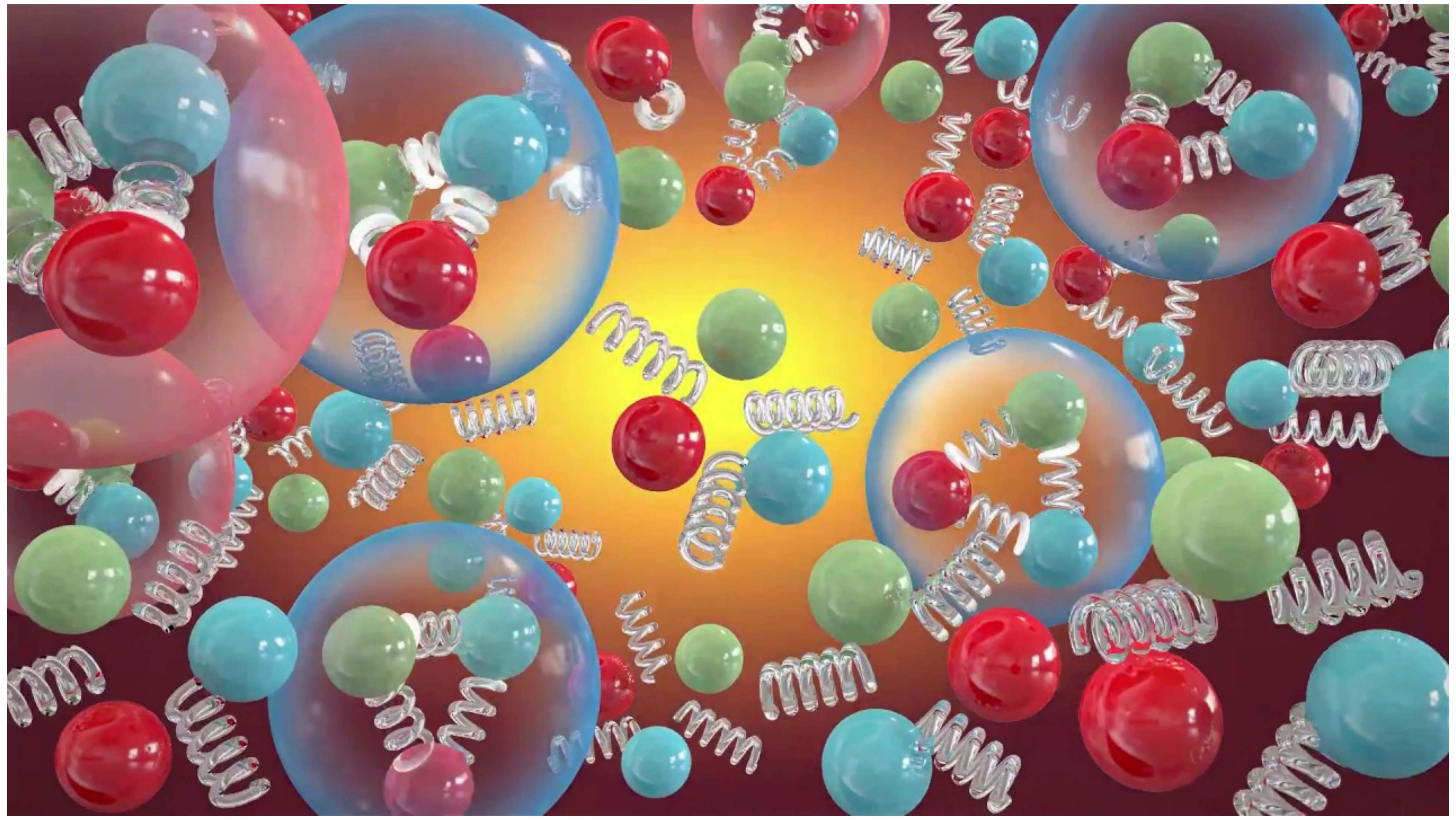


How to study quarks and gluons

 +  = ???

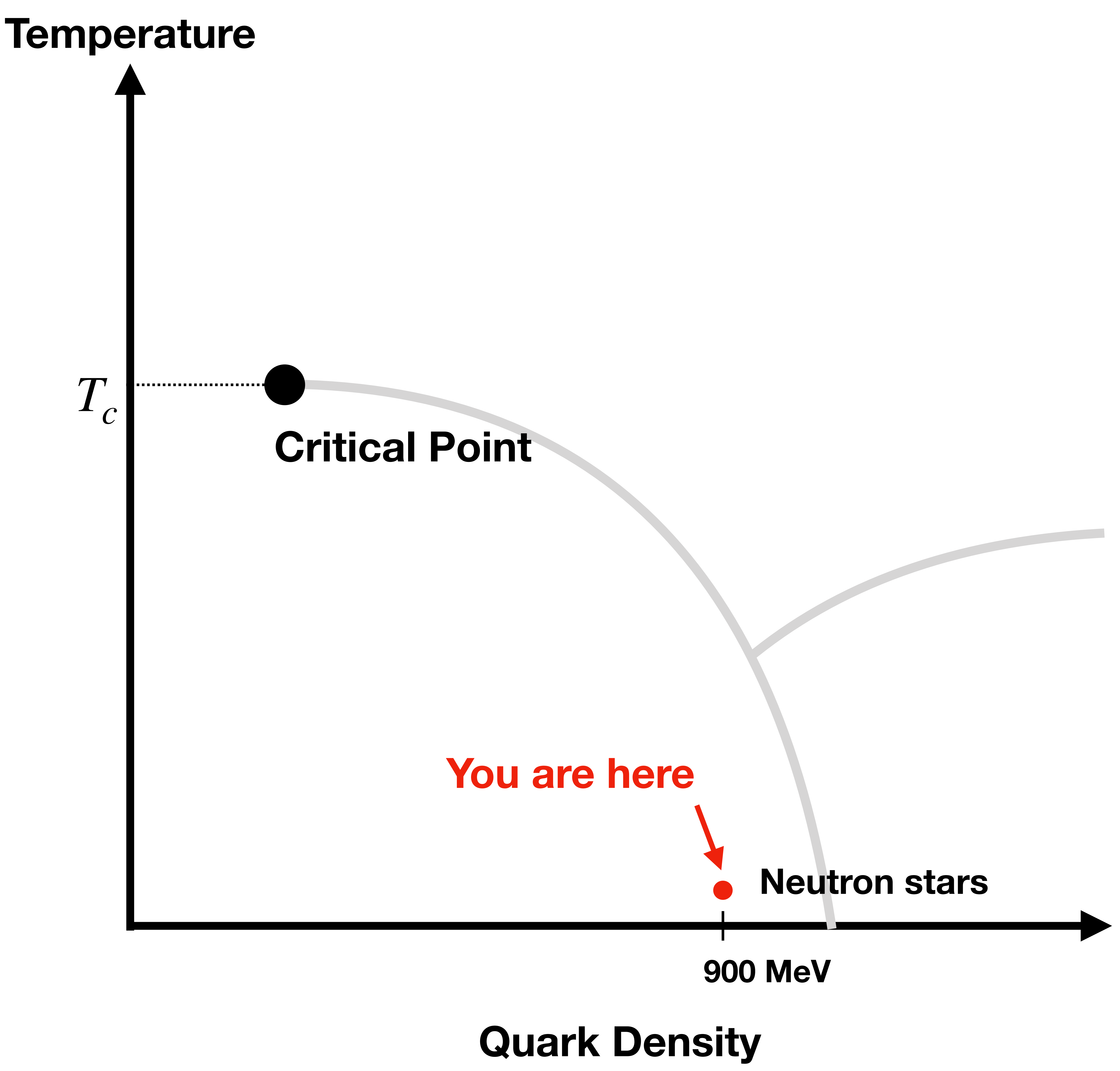
- **If we can heat up nuclei enough, can we ‘melt’ the protons/neutrons into quarks and gluons?**

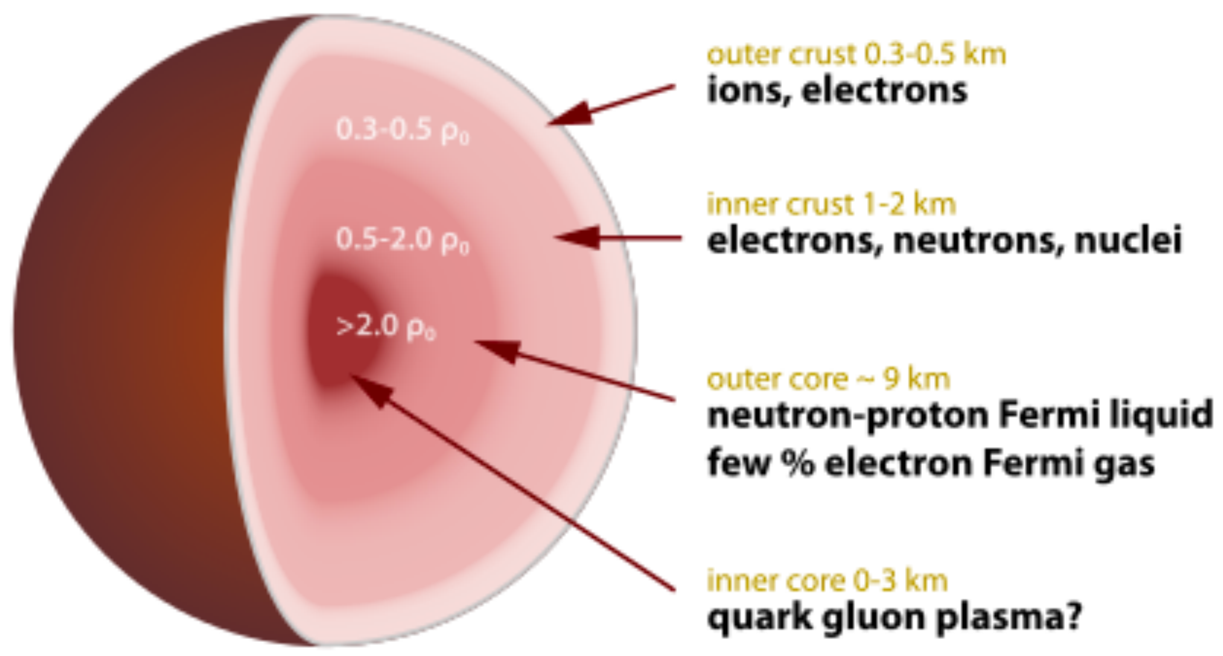
Quark-Gluon plasma



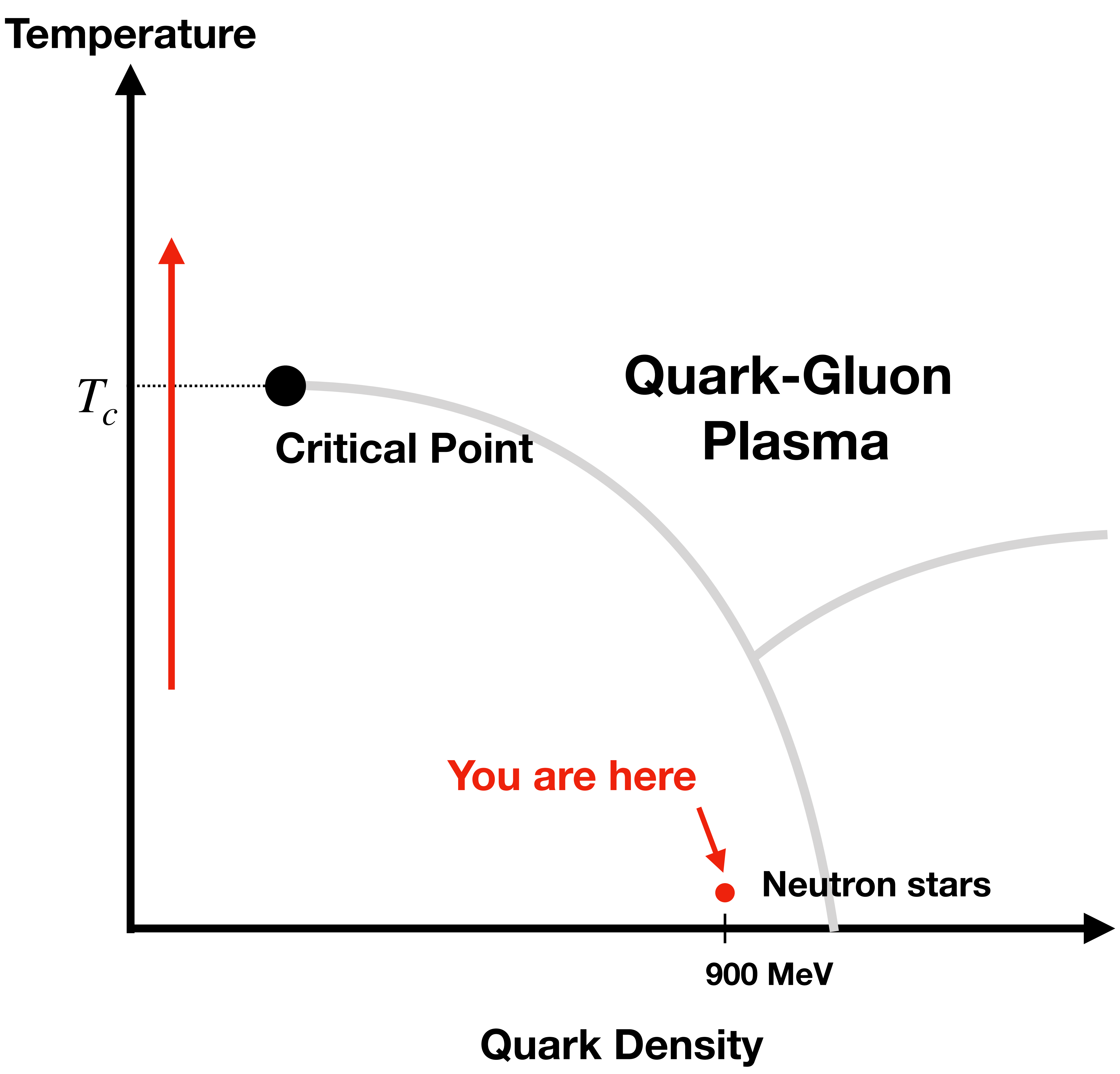
- **Can’t achieve high enough temperatures conventionally**
- **High energy nucleus collisions get very hot**
- **Protons/neutrons melt into a new form of matter**
  - **Quark-Gluon plasma - deconfined!**

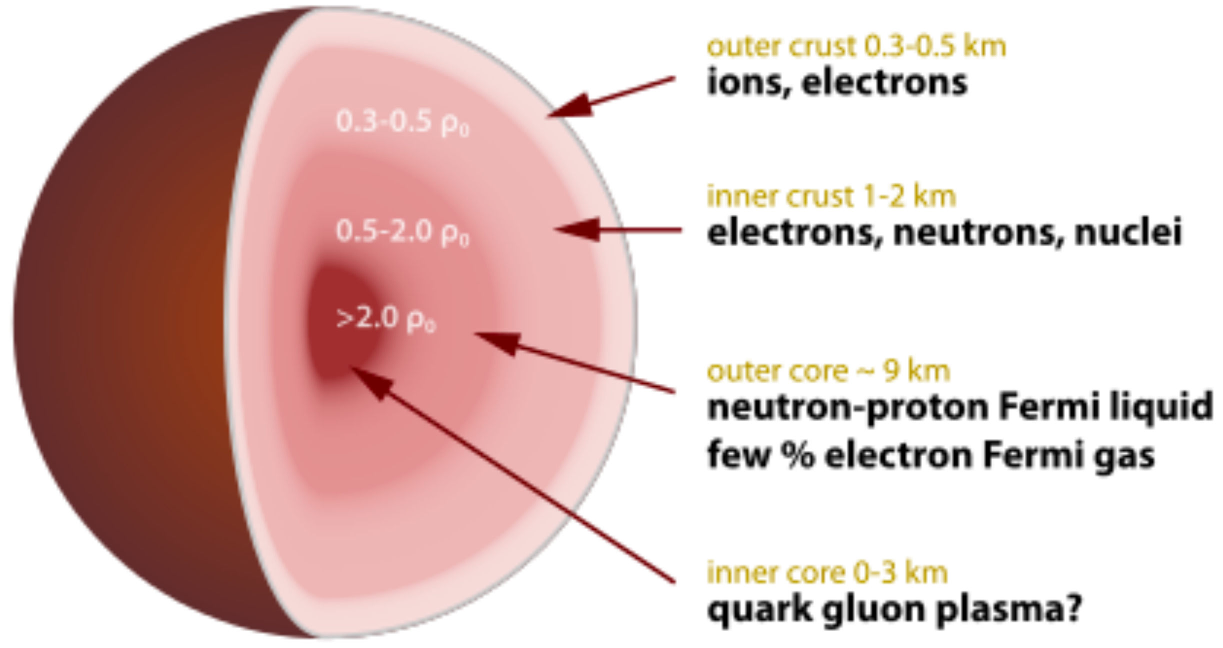
Phase diagram for strong force



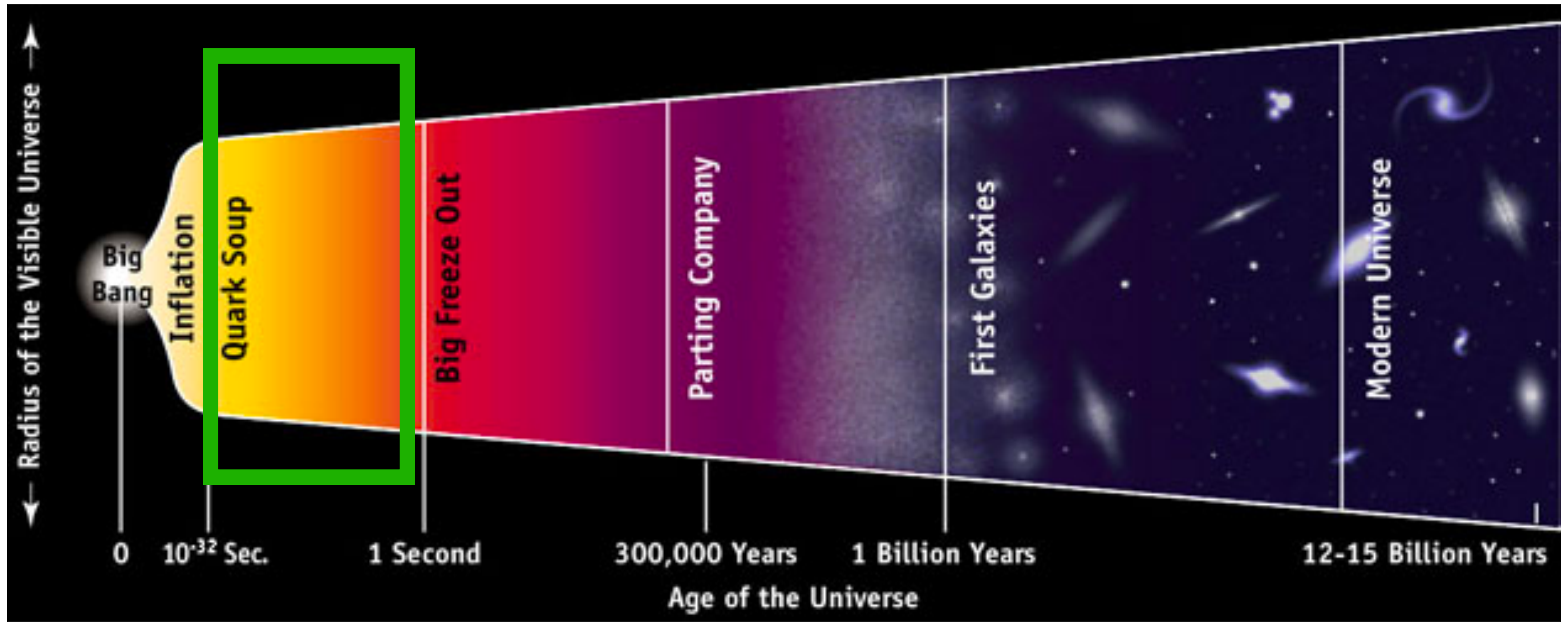


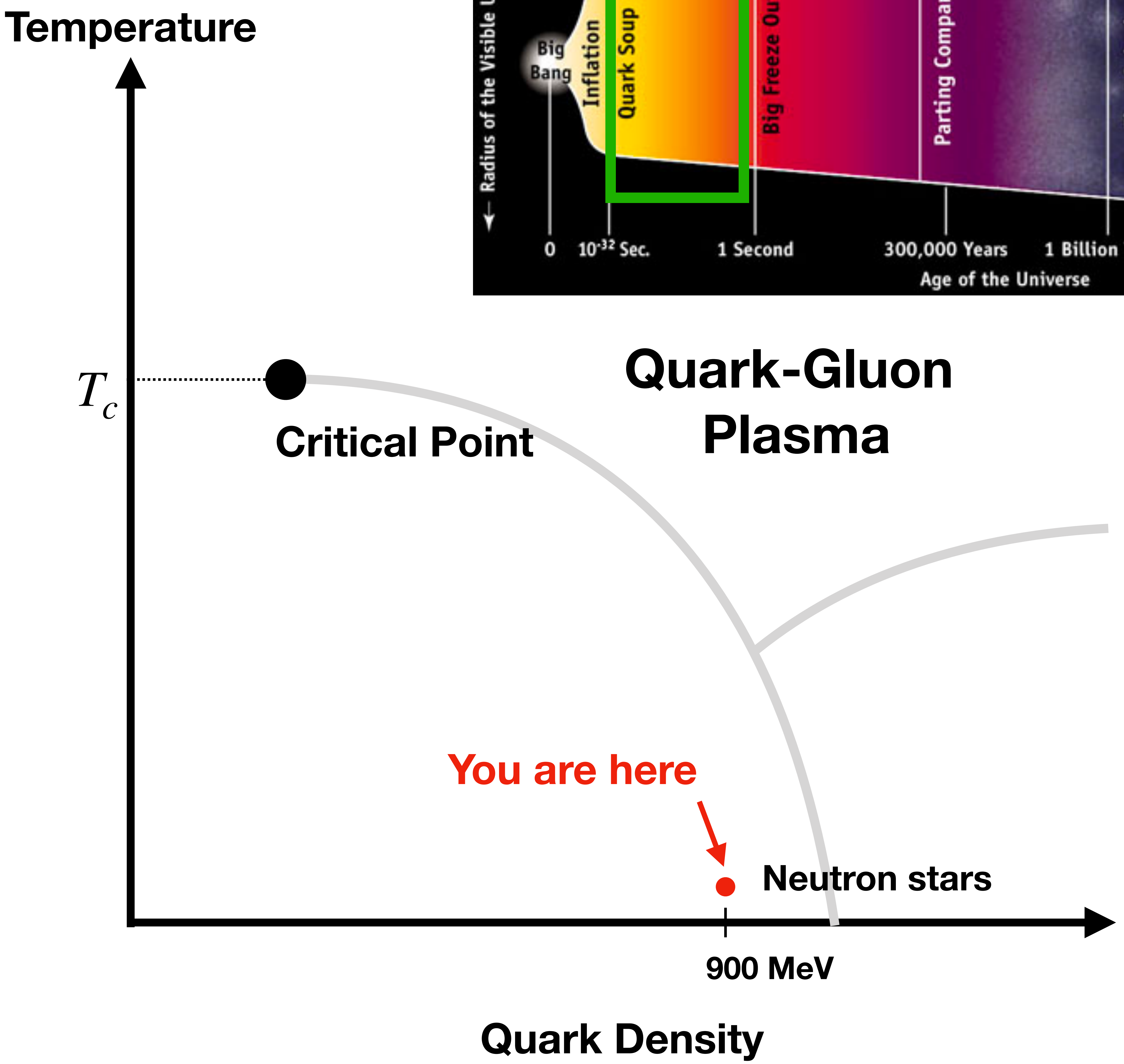
Phase diagram for strong force

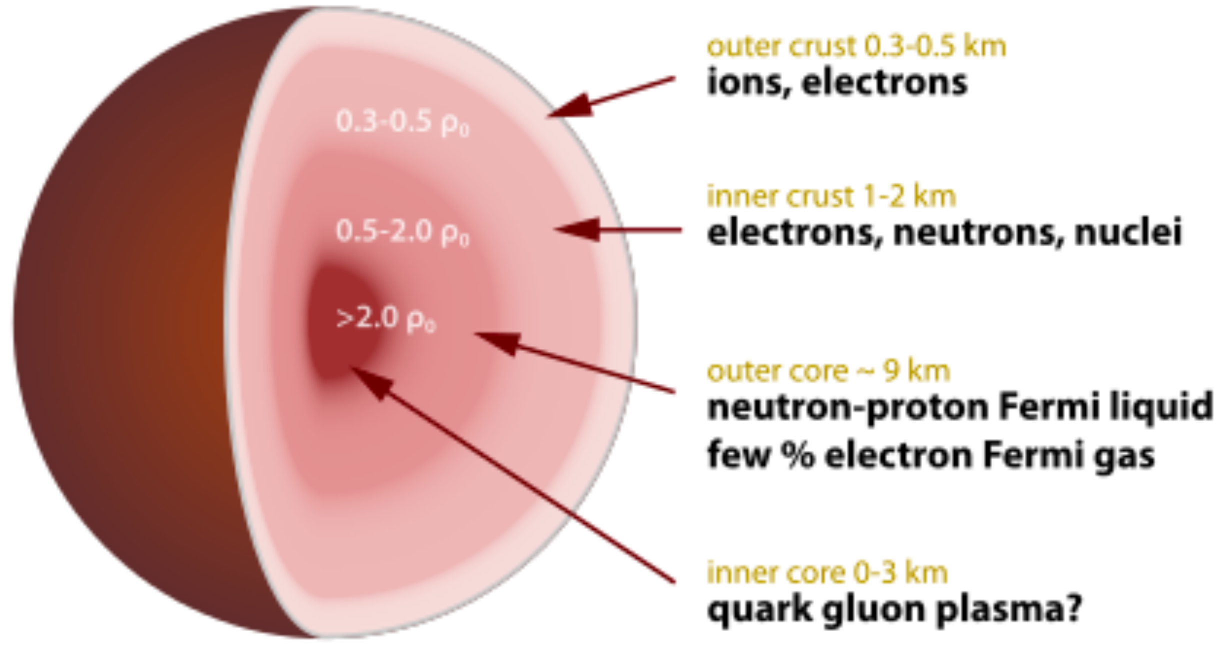




Phase diagram for strong force

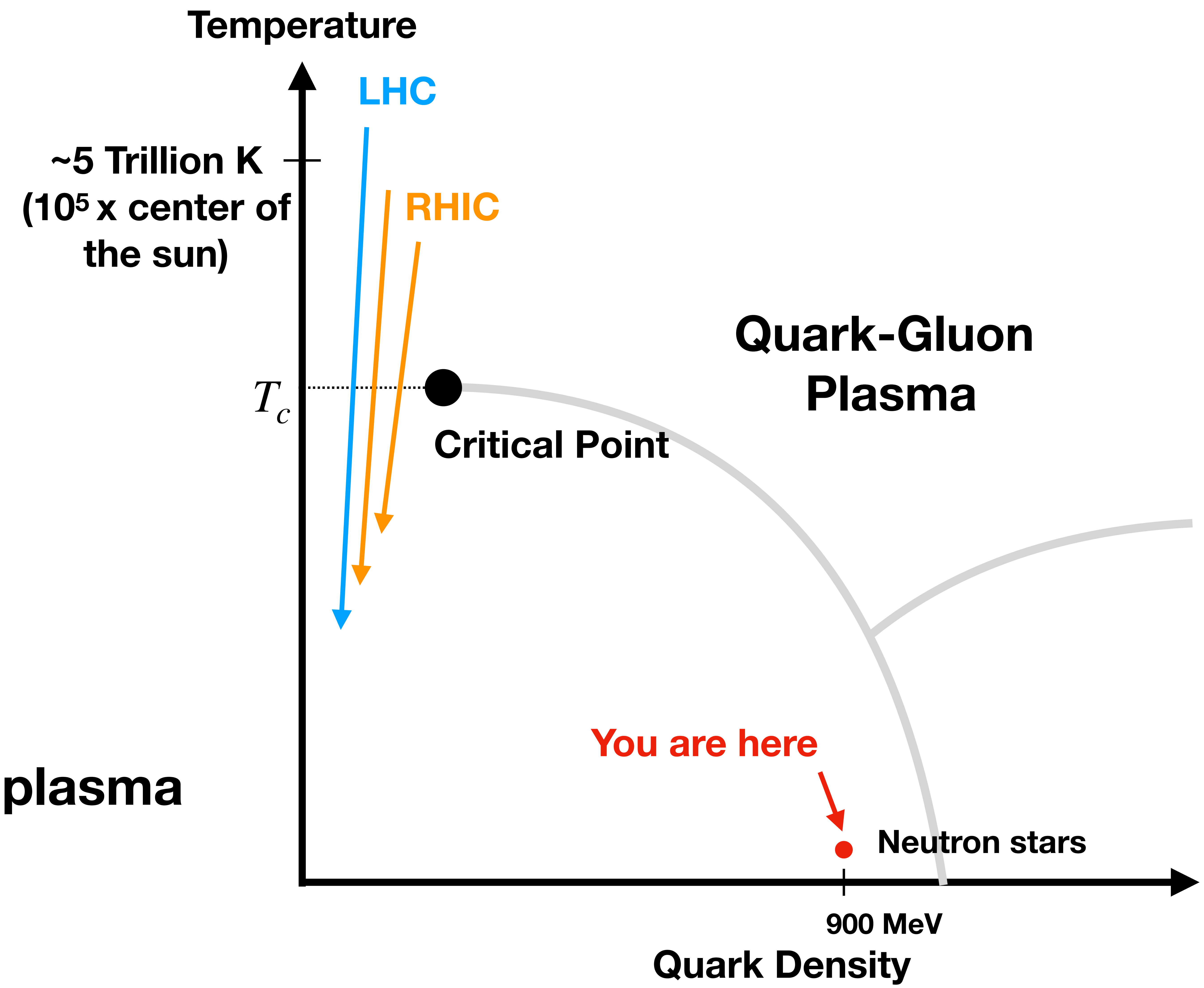






Heavy Ion Collisions

- Created with ion collisions!
- Hottest man-made form of matter
- QGP cools into particles
  - Detect particles, infer quark-gluon plasma properties
- QGP shows very complex behavior!



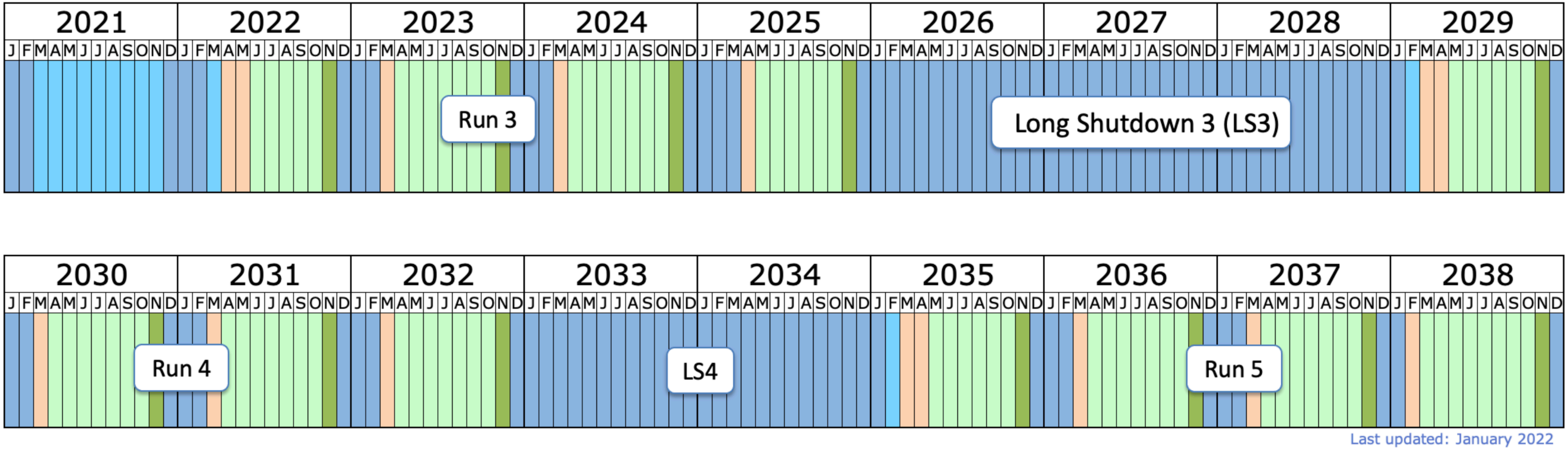
Relativistic Heavy Ion Collider

- Top energy of 200 GeV per nucleon pair
- Can accelerate almost any element

Large Hadron Collider

- **Runs heavy ions ~1 month / year**
- **Top energy of 5.5 TeV per nucleon pair: 1 PeV (0.1 mJ) total collision energy**
- **Accelerates protons, Pb^{208}, Xe^{129}**

LHC Schedule



- **LHC mostly does proton-proton collisions for high-energy physics**
- **Nucleus collisions ~1 month of each year**

Heavy Ion Collisions

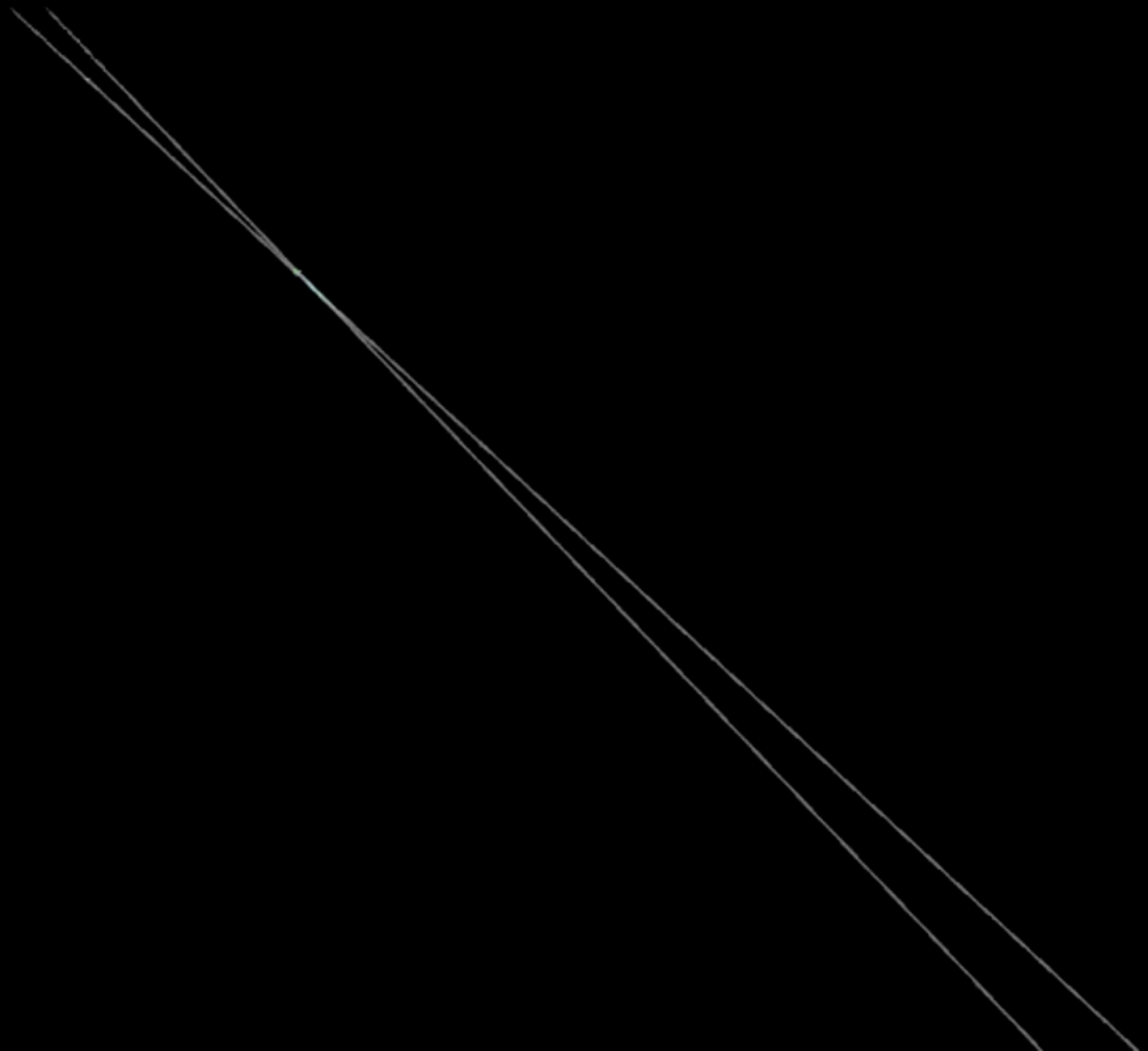
Compact Muon Solenoid

- General purpose experiment
- 50’ tall; 14,000 tonnes
- 3.8 Tesla magnetic field
- >2000 collaborators

pp Event (Not nucleus collision!)

Min-Bias PP (13 TeV)

https://github.com/abaty/OpenGL_LHC



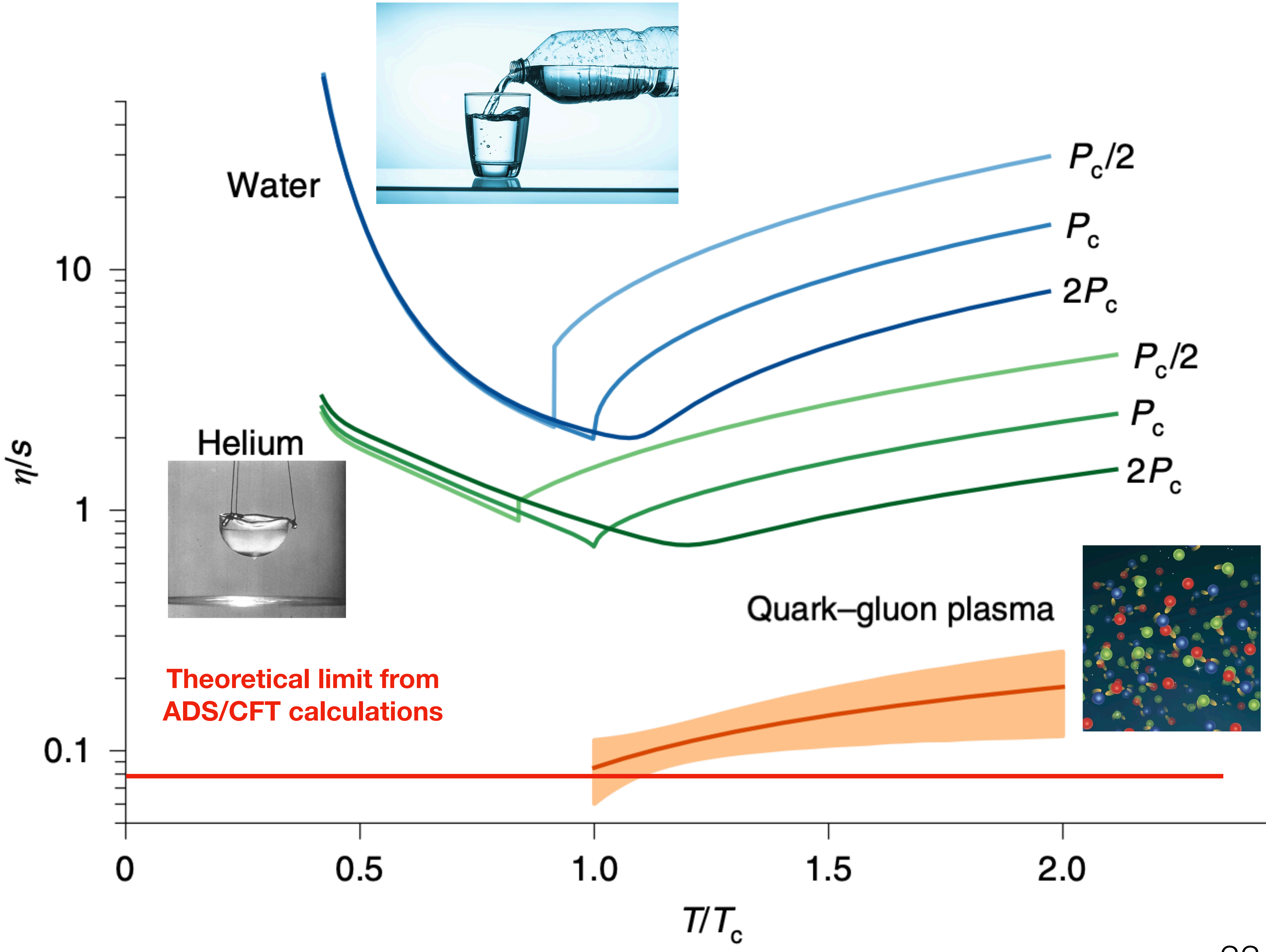
Nucleus-Nucleus (PbPb) Collision

- **Challenging to track all particles**

"Perfect Liquid"

Nature Physics volume 15, 1113–1117 (2019)

- **QGP behaves like a liquid!**
- **Viscosity - 'thickness' of the fluid**
- **QGP 'flows' very easily**

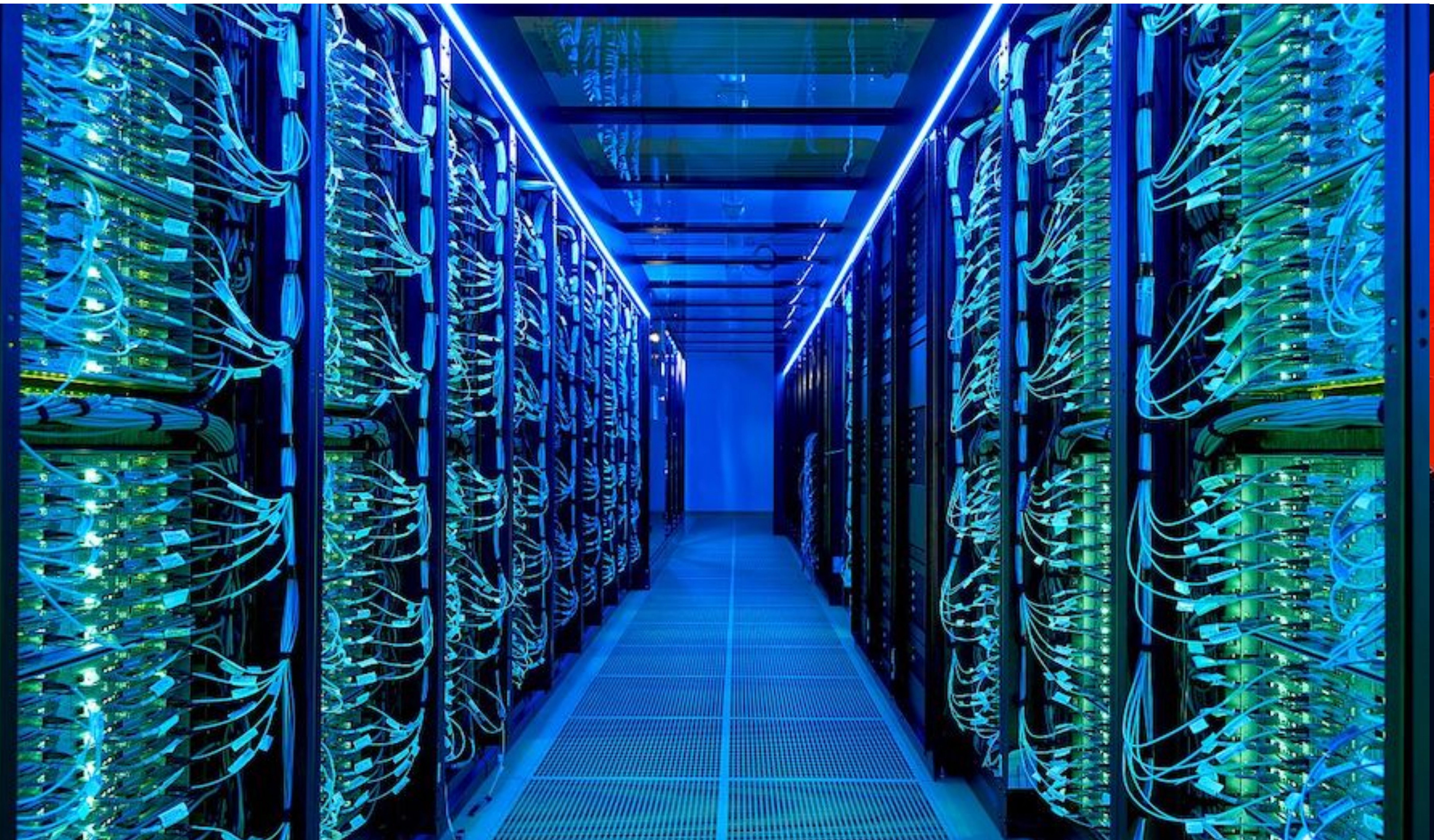
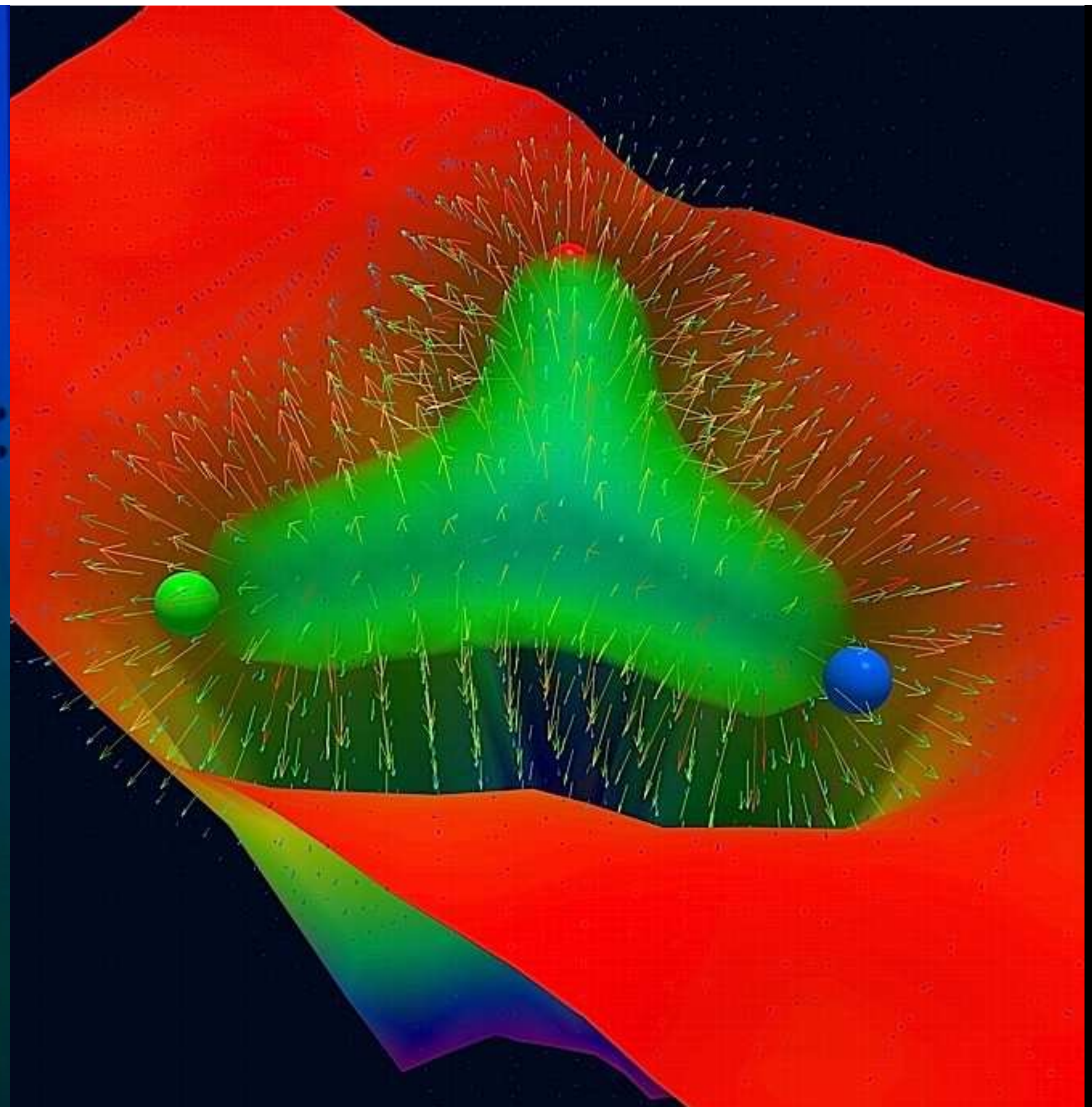
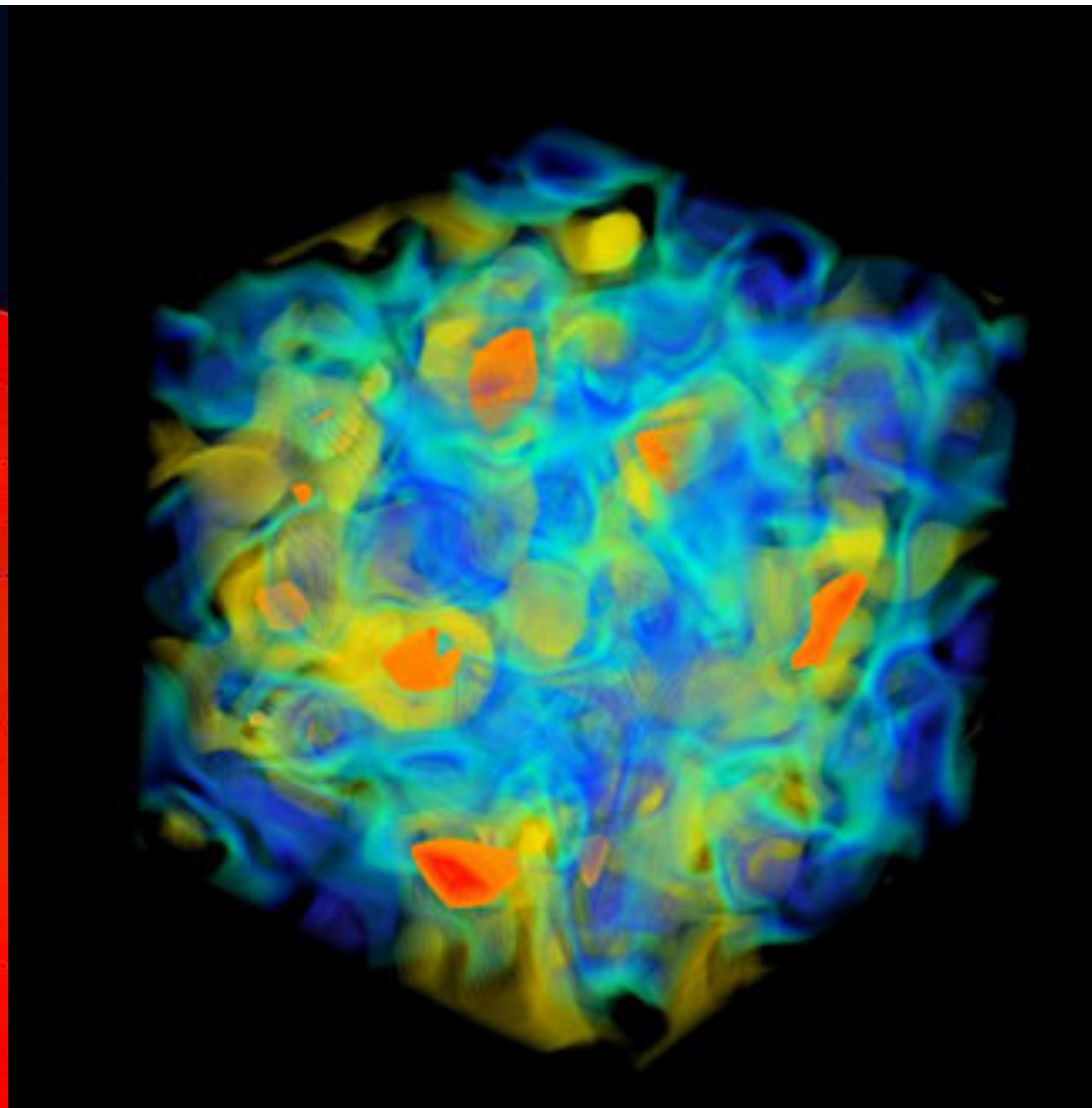


Speed of sound in QGP?

- **How fast do pressure waves travel through the QGP?**
- **How fast do you have to go to make a ‘sonic boom’ in QGP?**

Lattice QCD

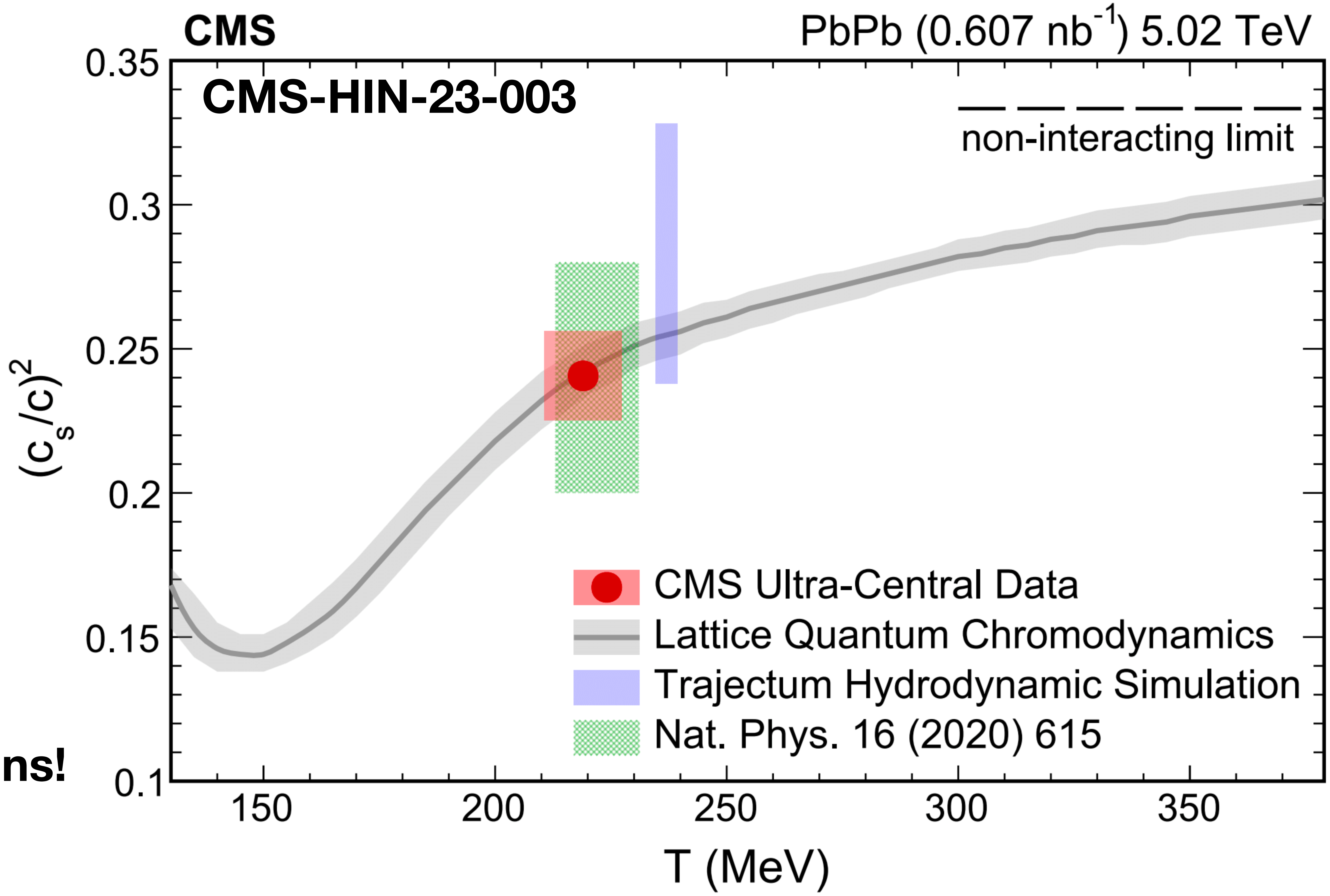
- **Theoretical predictions have been calculated for QGP speed of sound on massive supercomputers**
  - **One of the few things that can be predicted theoretically**
- **Does experiment agree with theory?**

QGP Speed of Sound

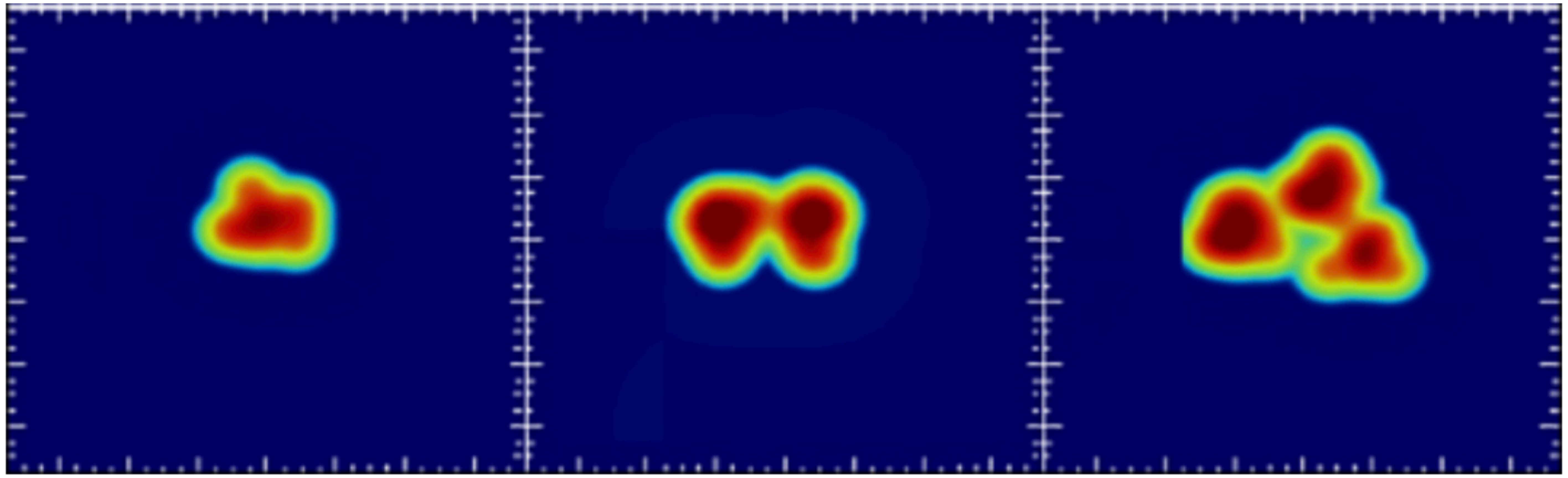
- **In air: 343 m/s**
- **In water: 1500 m/s**
- **In steel: 5000 m/s**
- **In QGP: 150,000,000 m/s**

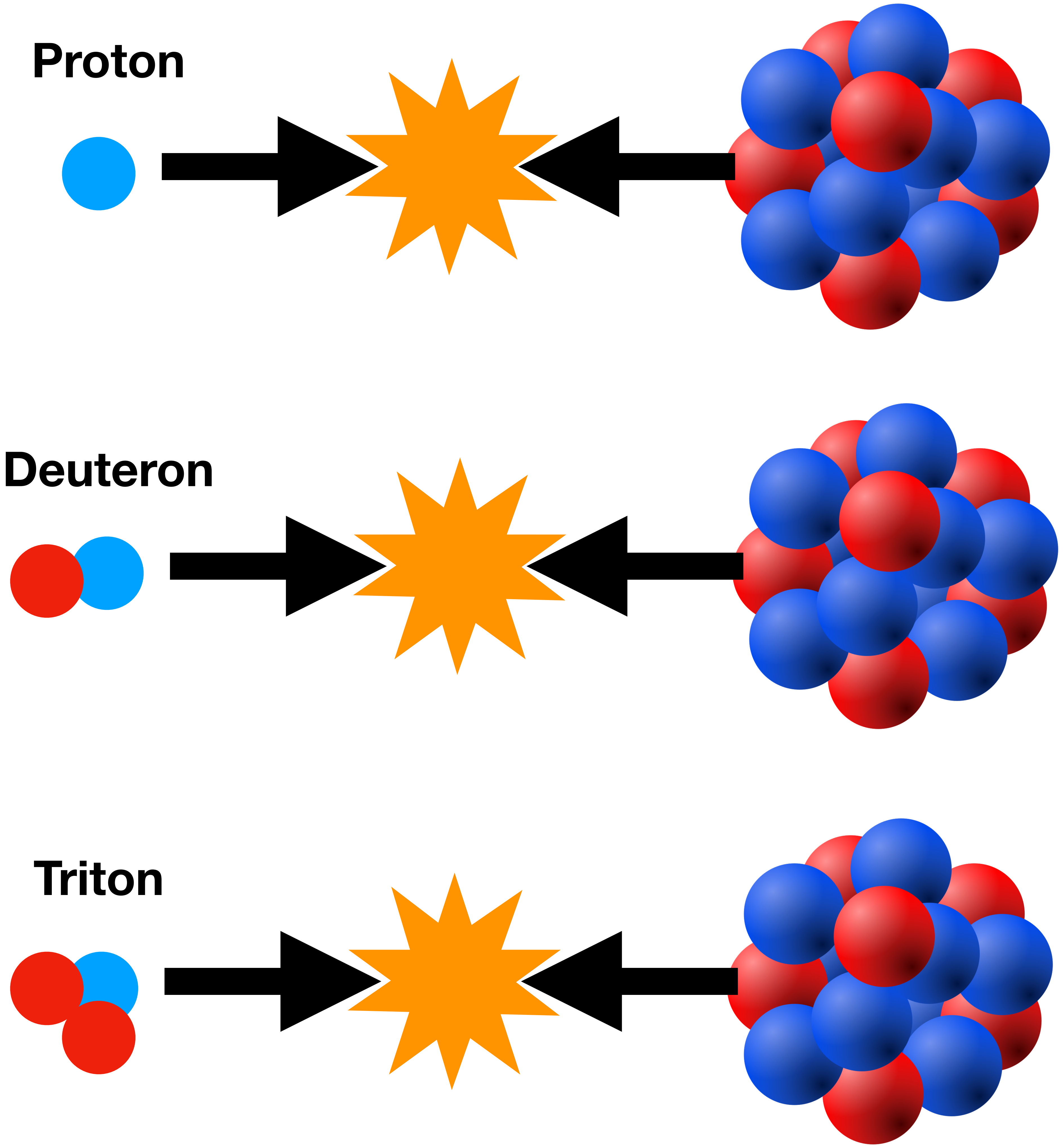
- **Excellent agreement with Lattice QCD!**
- **Testing how well we understand quarks and gluons!**

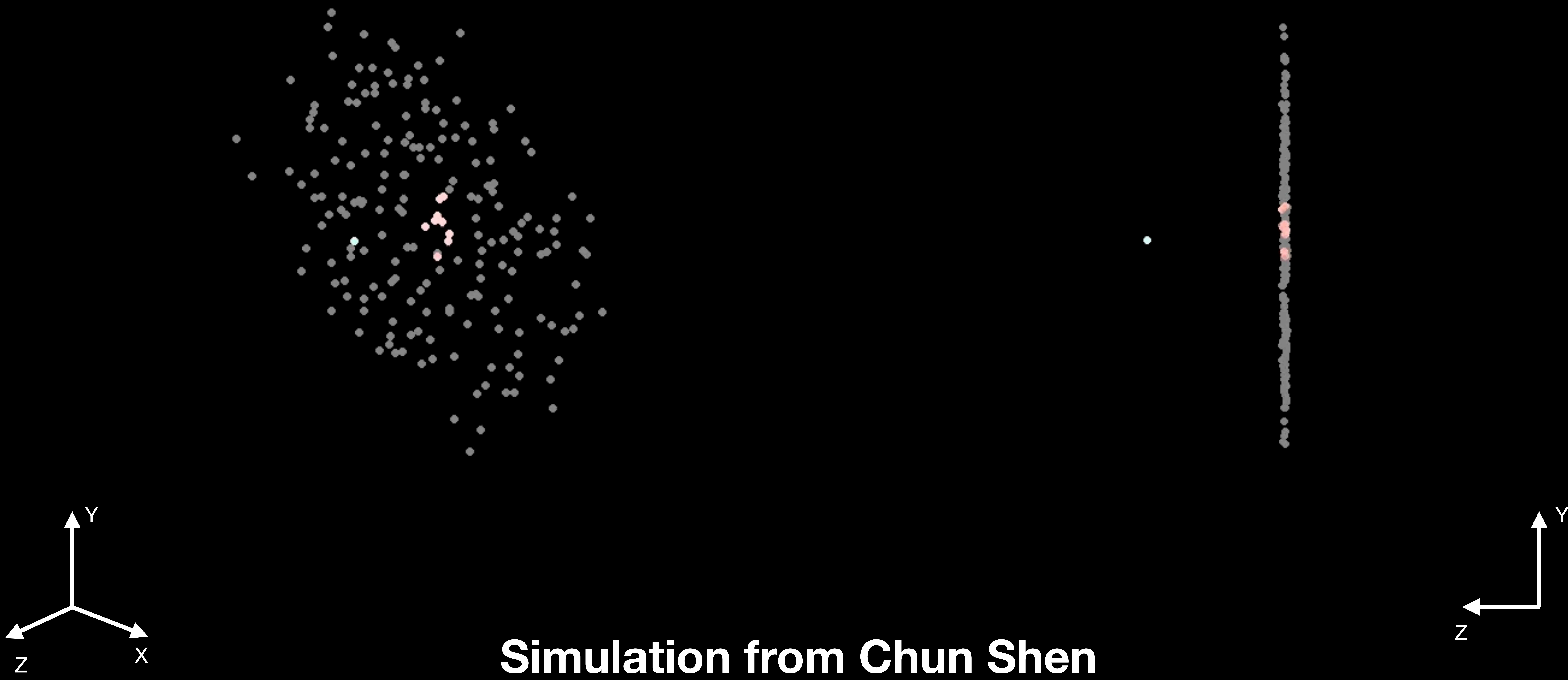


Proton-nucleus collisions

- **Can we make a small ‘droplet’ of QGP in proton-ion collisions?**
- **There seems to be evidence but it is still under debate!**
- **We also study proton-ion collisions at LHC**







Simulation from Chun Shen

The Electron-Ion Collider

A machine that will unlock the secrets of the strongest force in Nature

Graphic from BNL

Large energy range: 20-140 GeV

High luminosities

Polarized electrons/protons

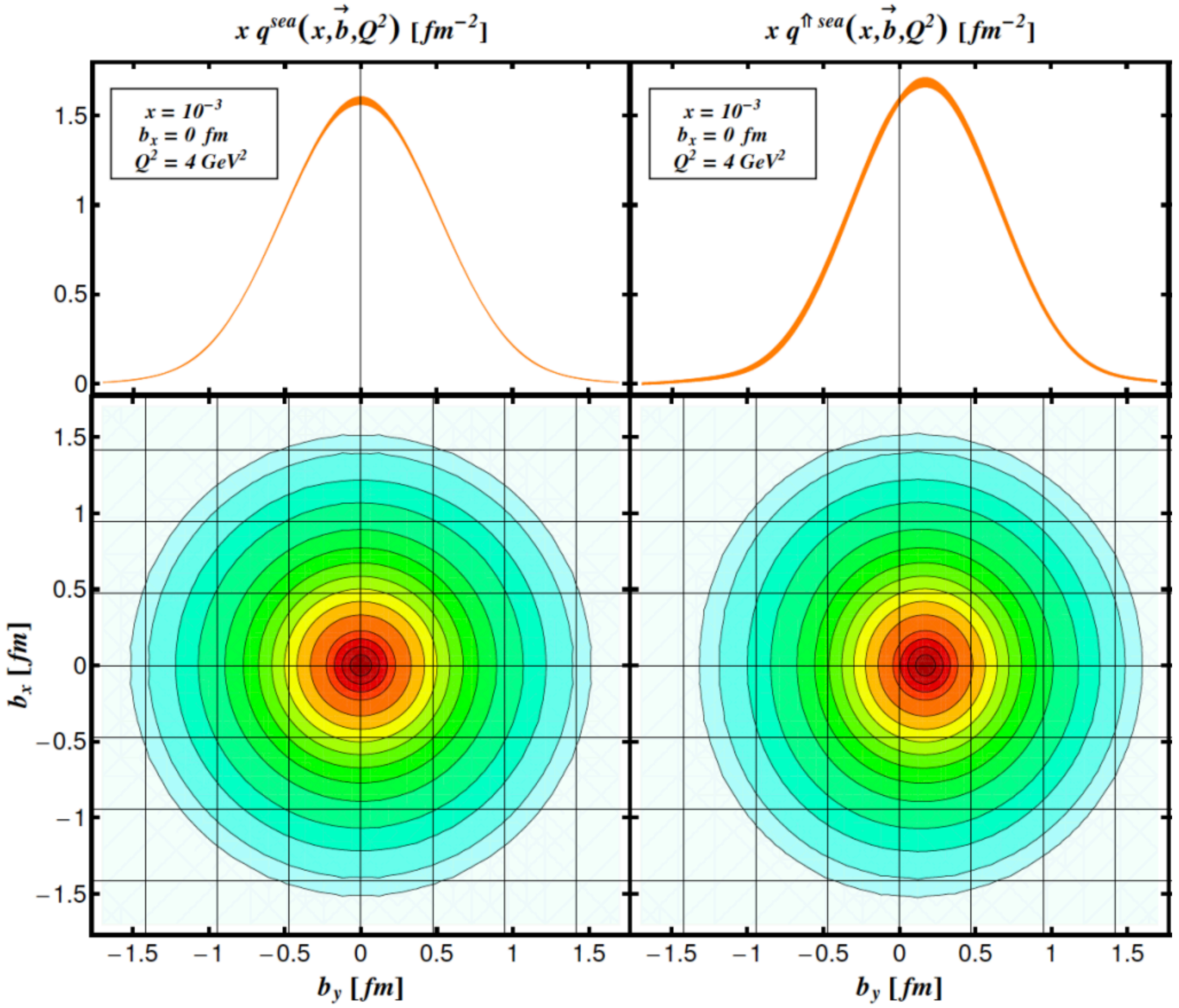
Many ion species: proton - Uranium

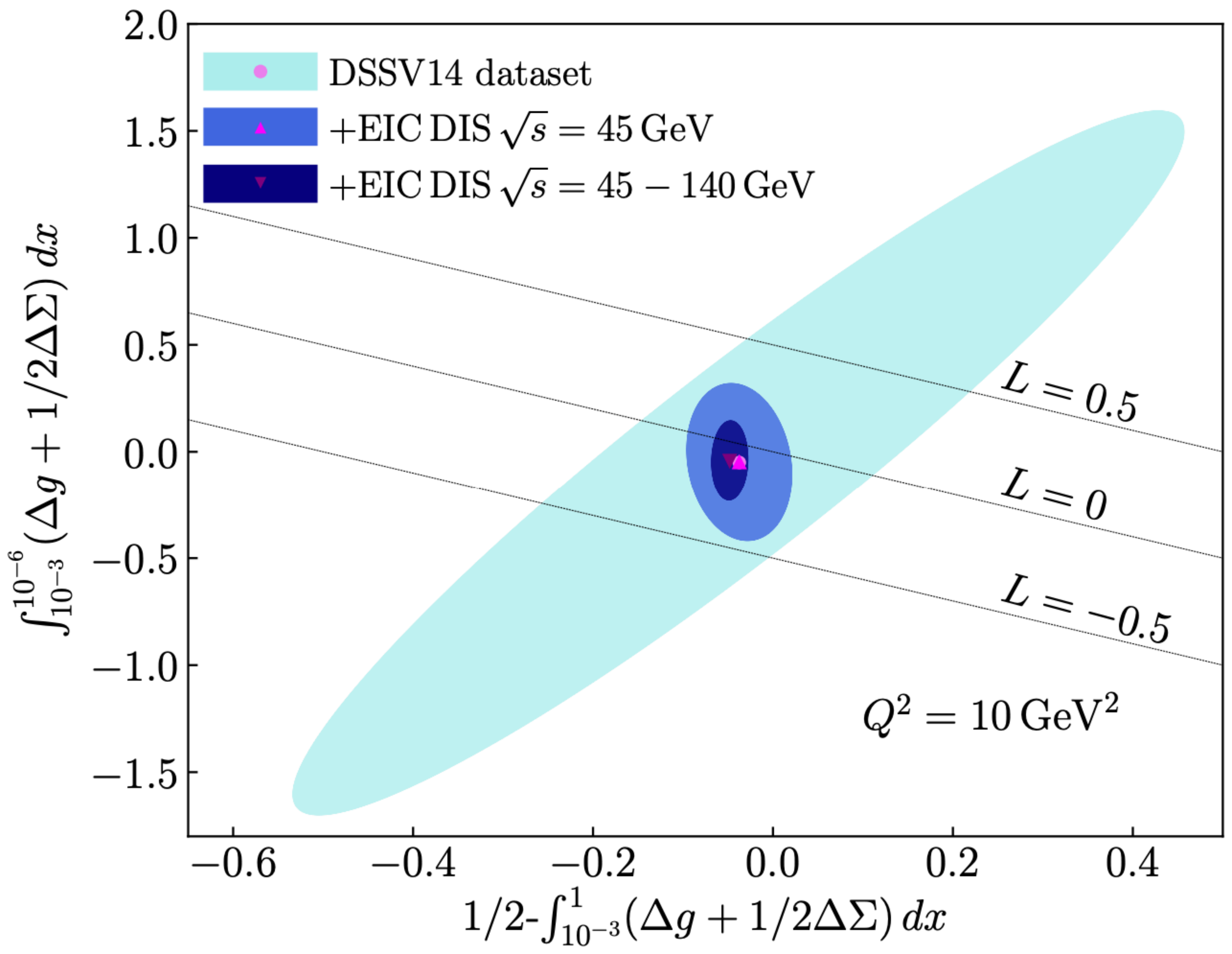
EIC Physics

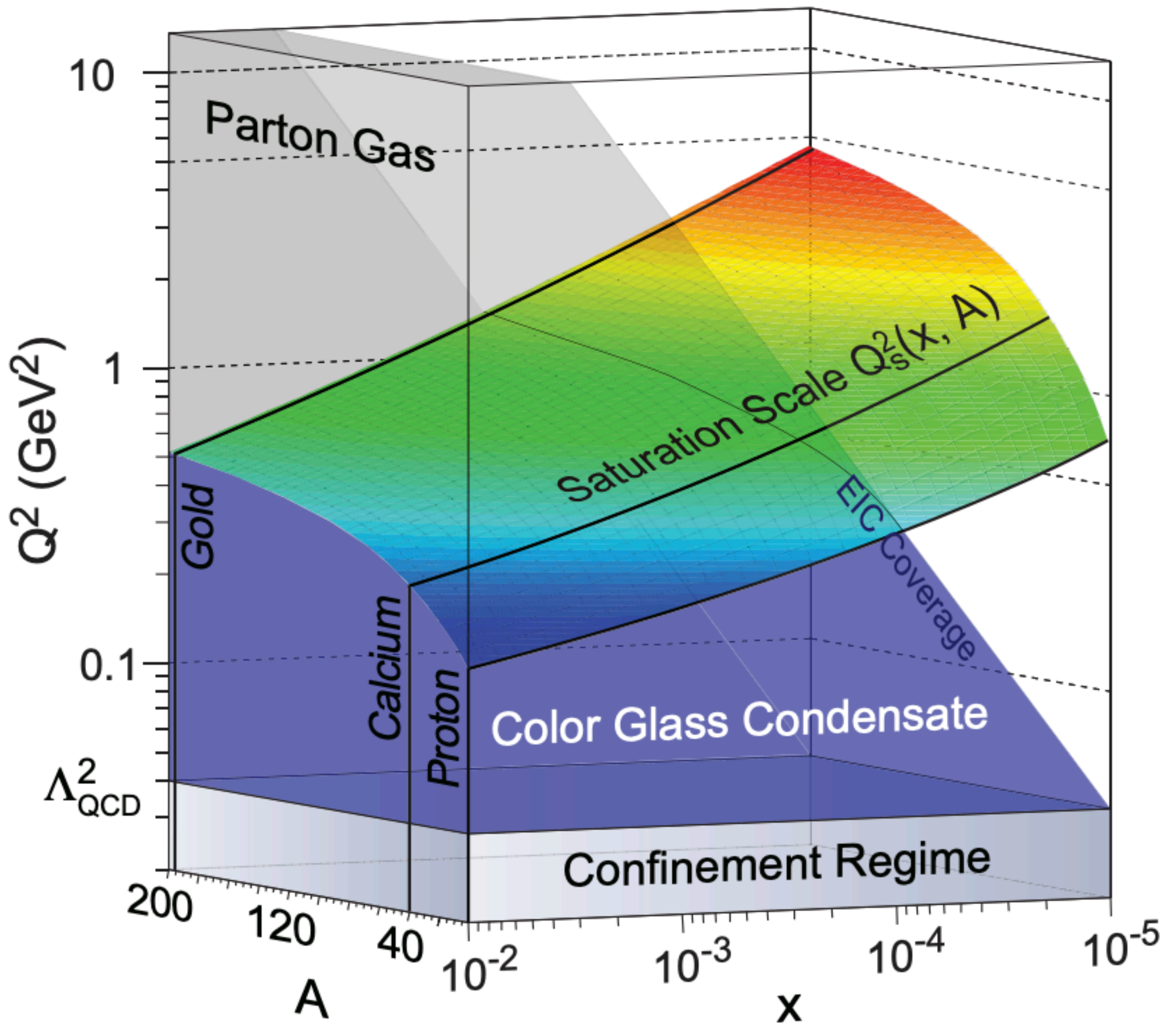
Take pictures of quarks/gluons inside proton/nuclei

How do nuclei spin?

Upper limit on number of gluons in the nucleus?

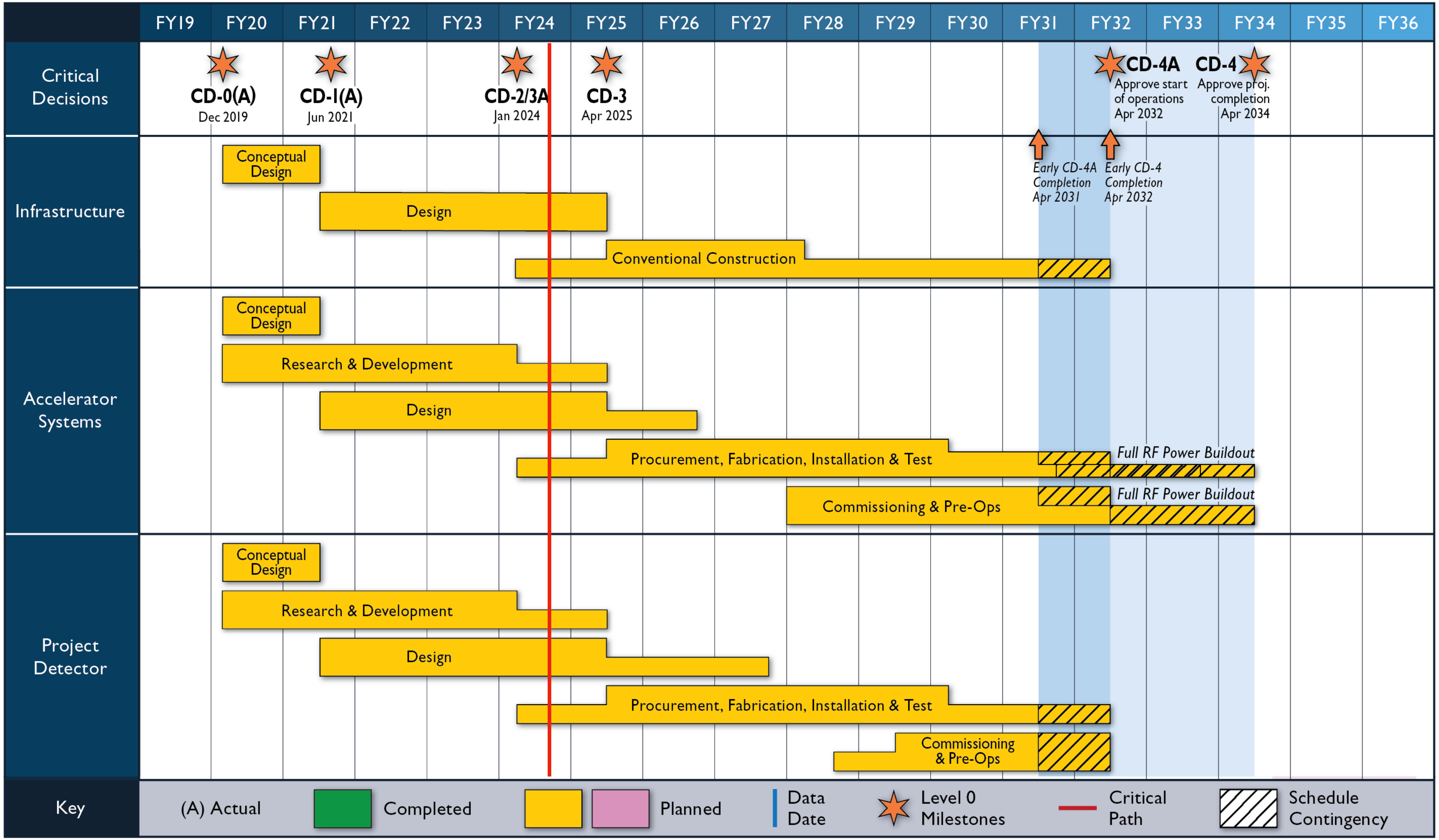


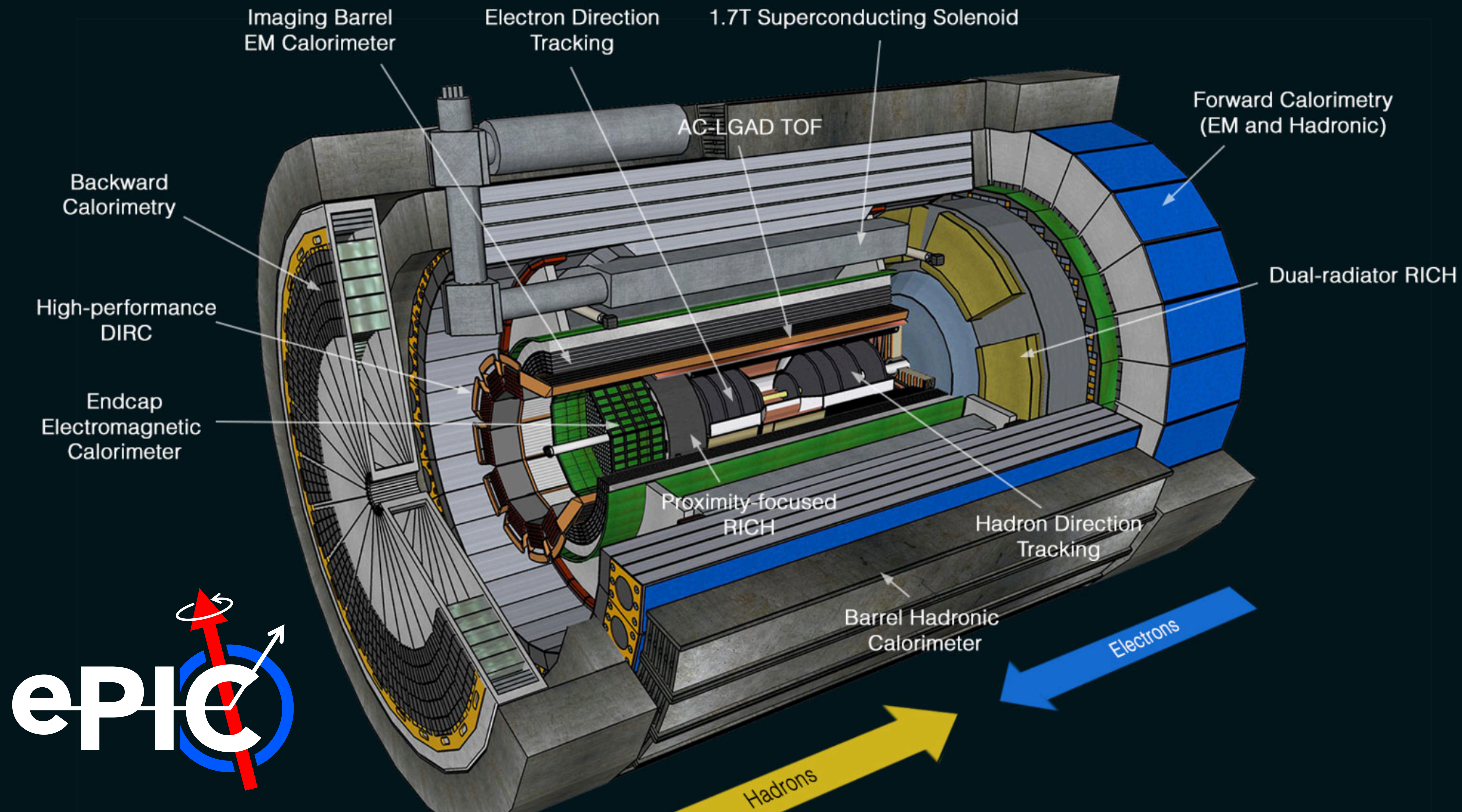




arXiv:2103.05419
Eur. Phys. J. A (2016) 52: 268

EIC Schedule

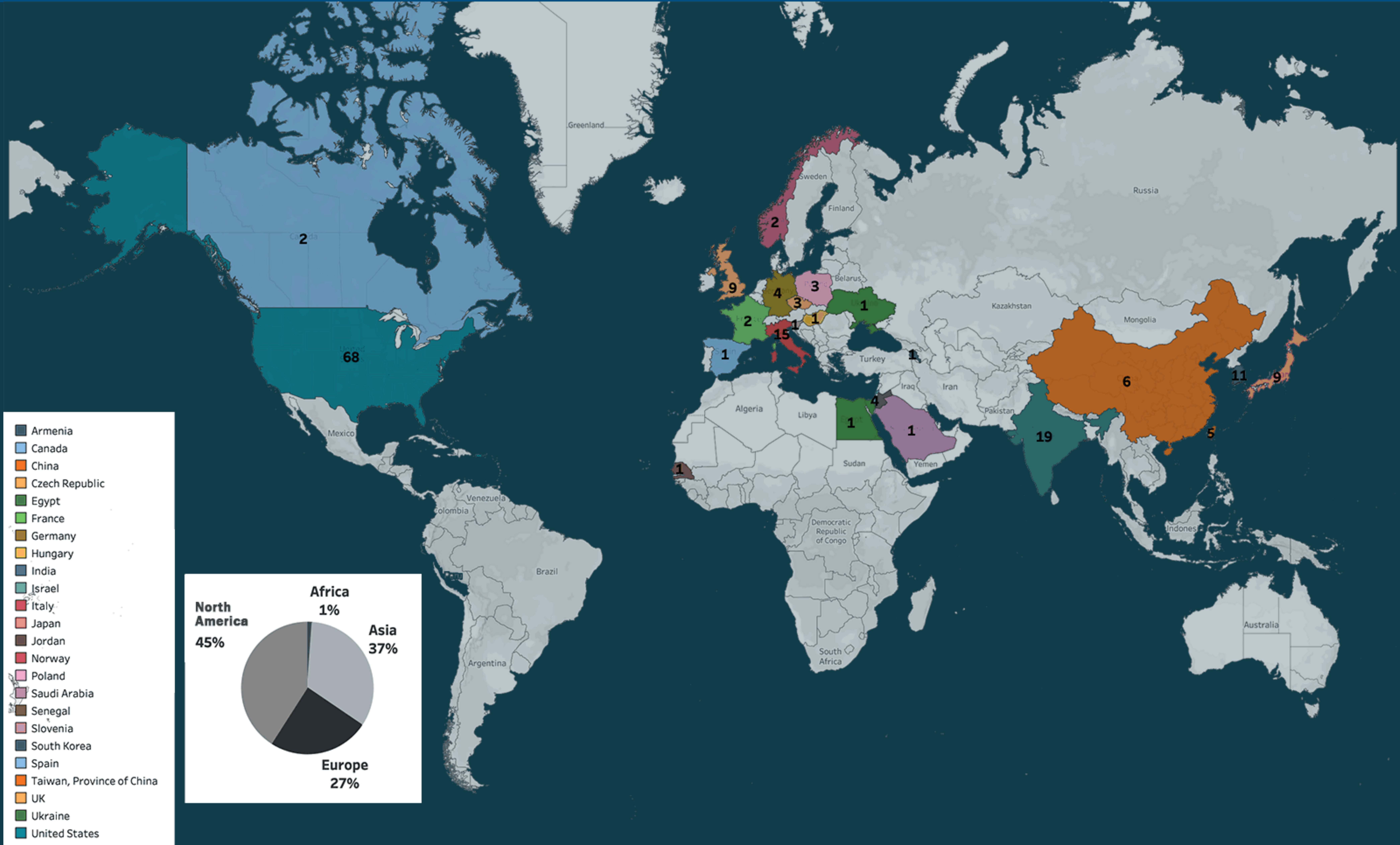




Imaging Barrel EM Calorimeter
Electron Direction Tracking
1.7T Superconducting Solenoid
AC-LGAD TOF
Forward Calorimetry (EM and Hadronic)
Backward Calorimetry
Dual-radiator RICH
High-performance DIRC
Endcap Electromagnetic Calorimeter
Proximity-focused RICH
Hadron Direction Tracking
Barrel Hadronic Calorimeter
Electrons
Hadrons
ePIC


-19.000 ns

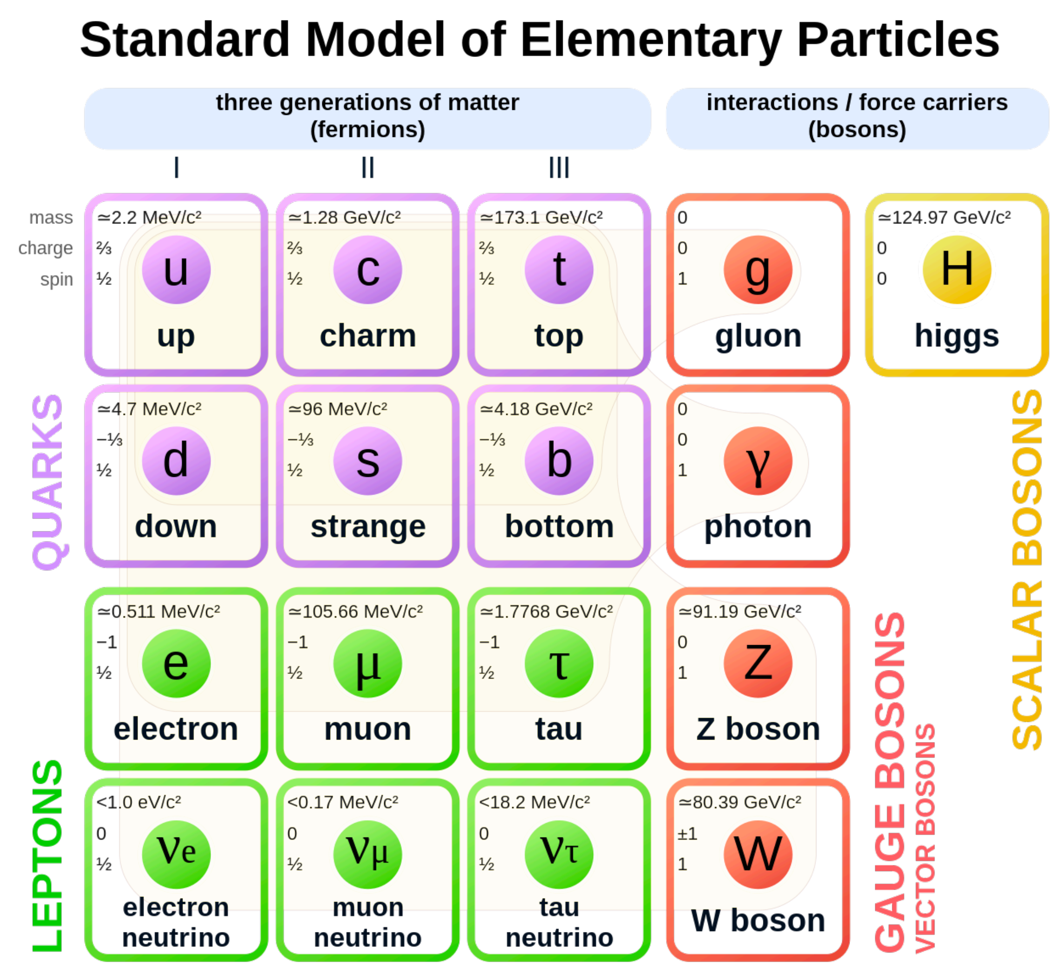
ePIC Collaboration



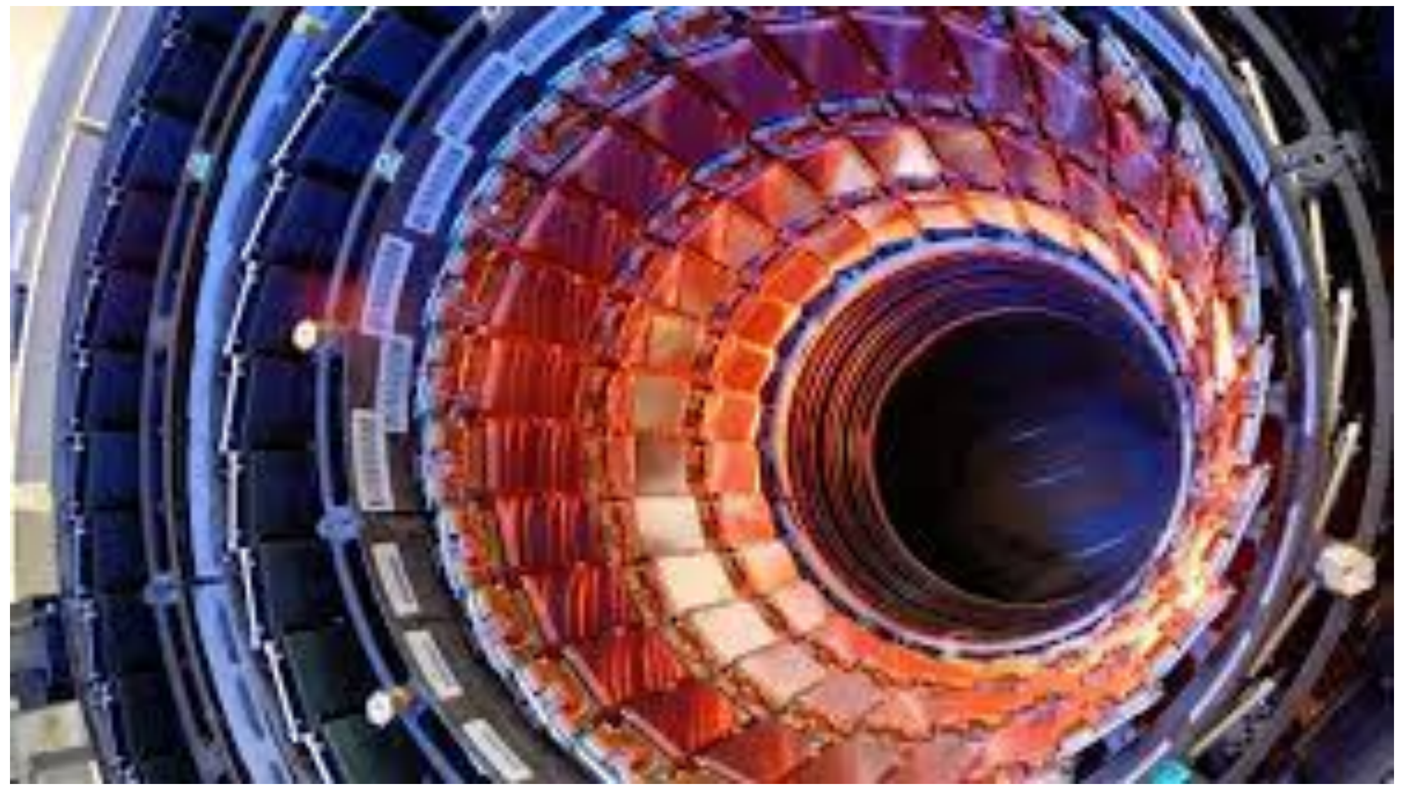
Particle vs Nuclear Physics

- **So how are nuclear and particle physics different?**
  - **Mostly in the questions we try to answer**
- **There is huge overlap in skills!**
- **You can be the next generation of physicists in either field!**

Knowledge of particles



Programming



Particle Detectors

International Collaborations

Summary

- High energy nuclear physics studies the strong force
  - Tells us how nuclei and protons/neutrons are held together
- High-energy nucleus collisions create a hot quark-gluon plasma in the lab
- By studying the QGP we learn more about the strong force

- A new particle collider on US soil (EIC) will do nuclear physics
- You can be the next generation of physicists!