

High-energy nuclear physics and heavy ion collisions with CMS

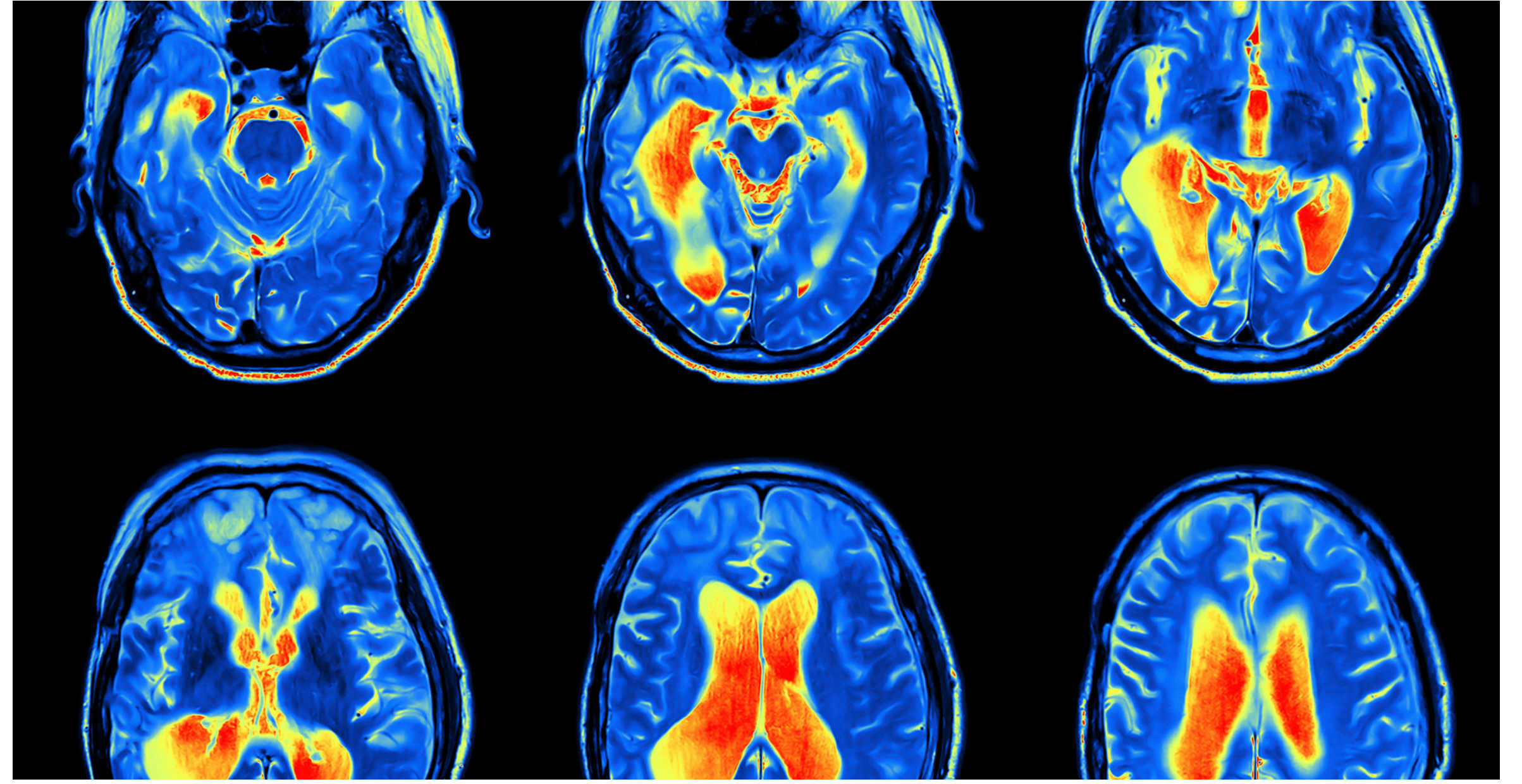
Austin Baty
University of Illinois Chicago
abaty.github.io

July 3, 2024
CMS PURSUE/SPRINT Program
Fermilab



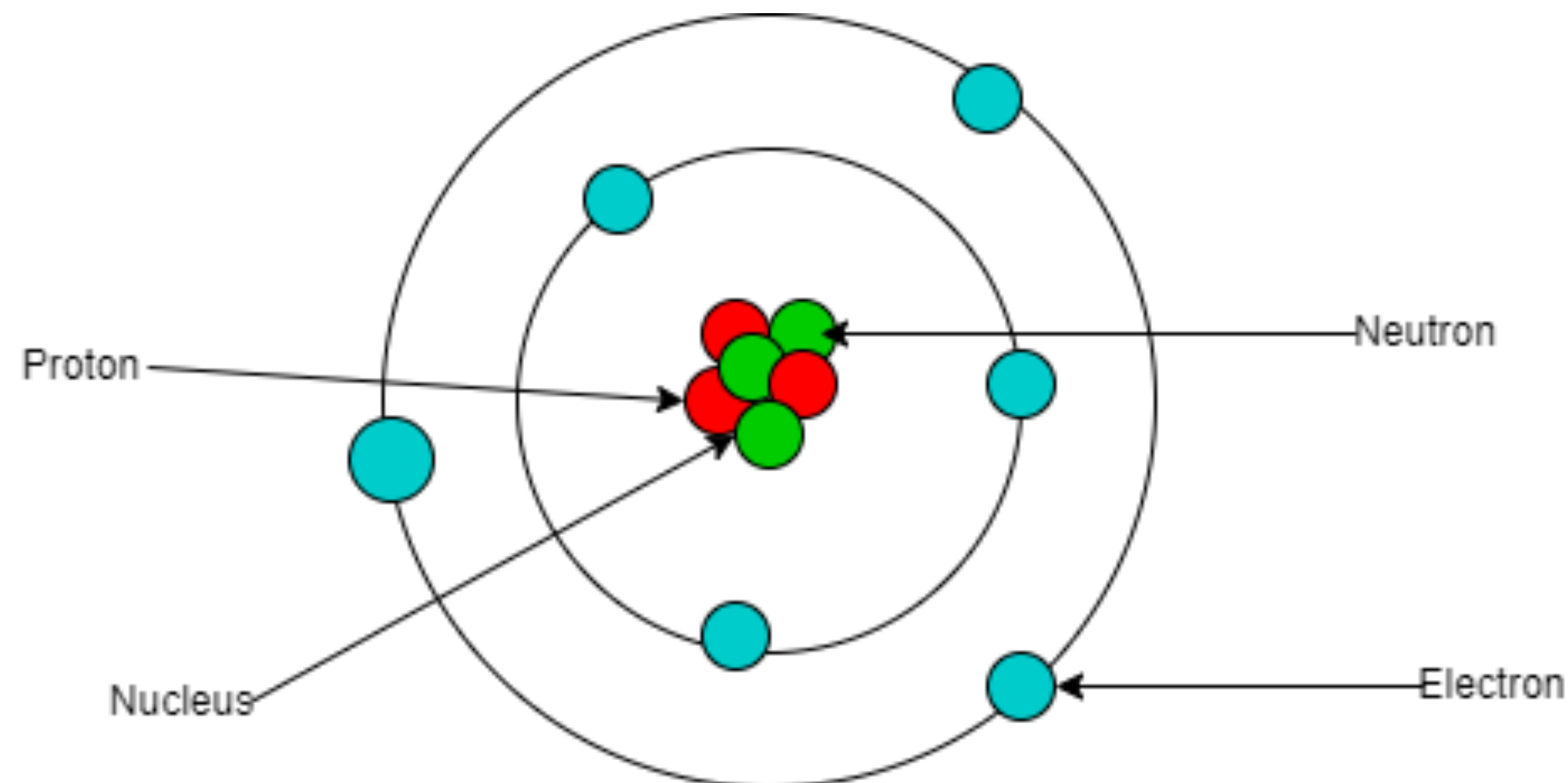
UNIVERSITY OF
ILLINOIS CHICAGO

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**



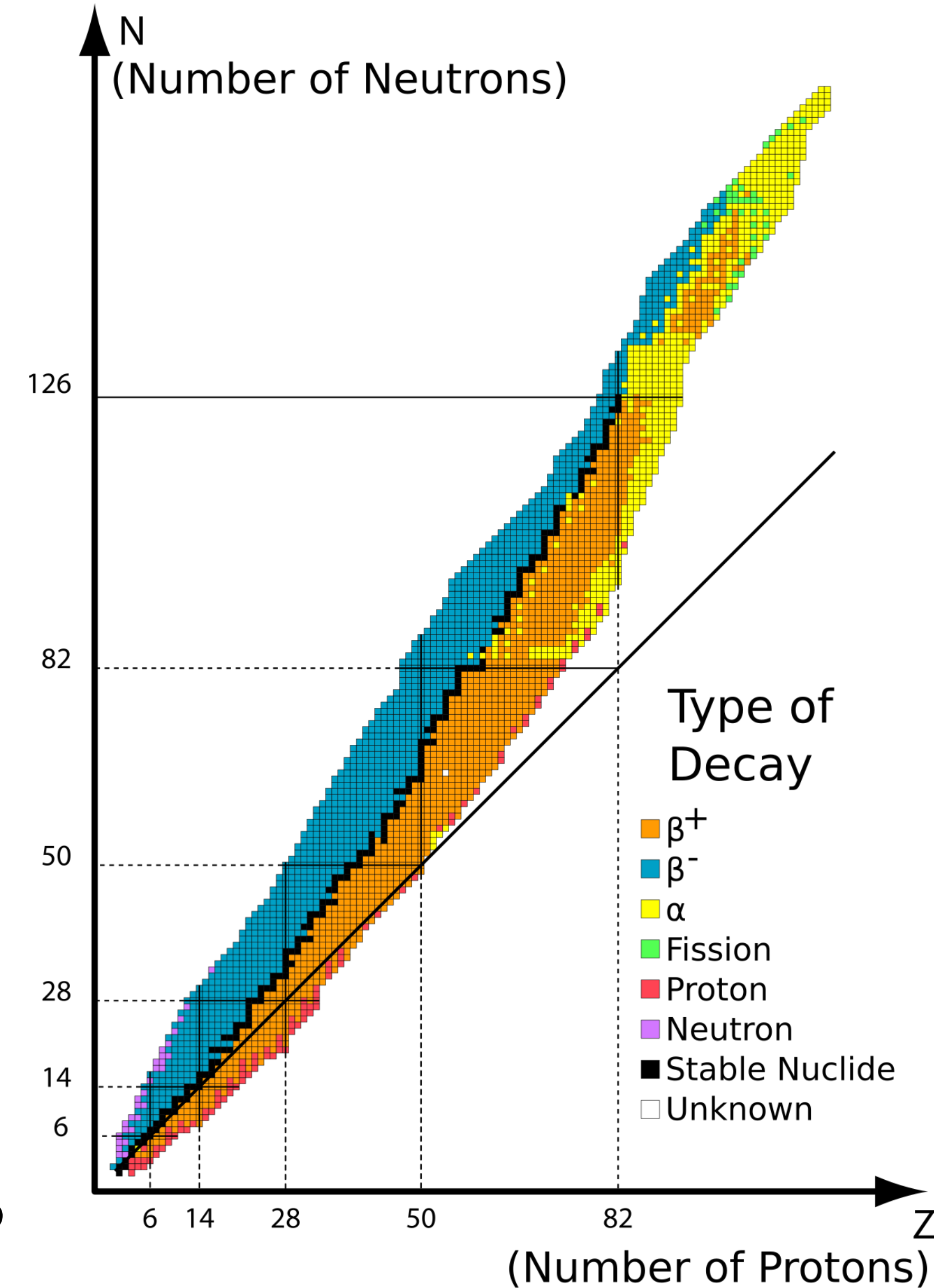
Low energy nuclear physics

PERIODIC TABLE OF ELEMENTS

Chemical Group Block

PubChem

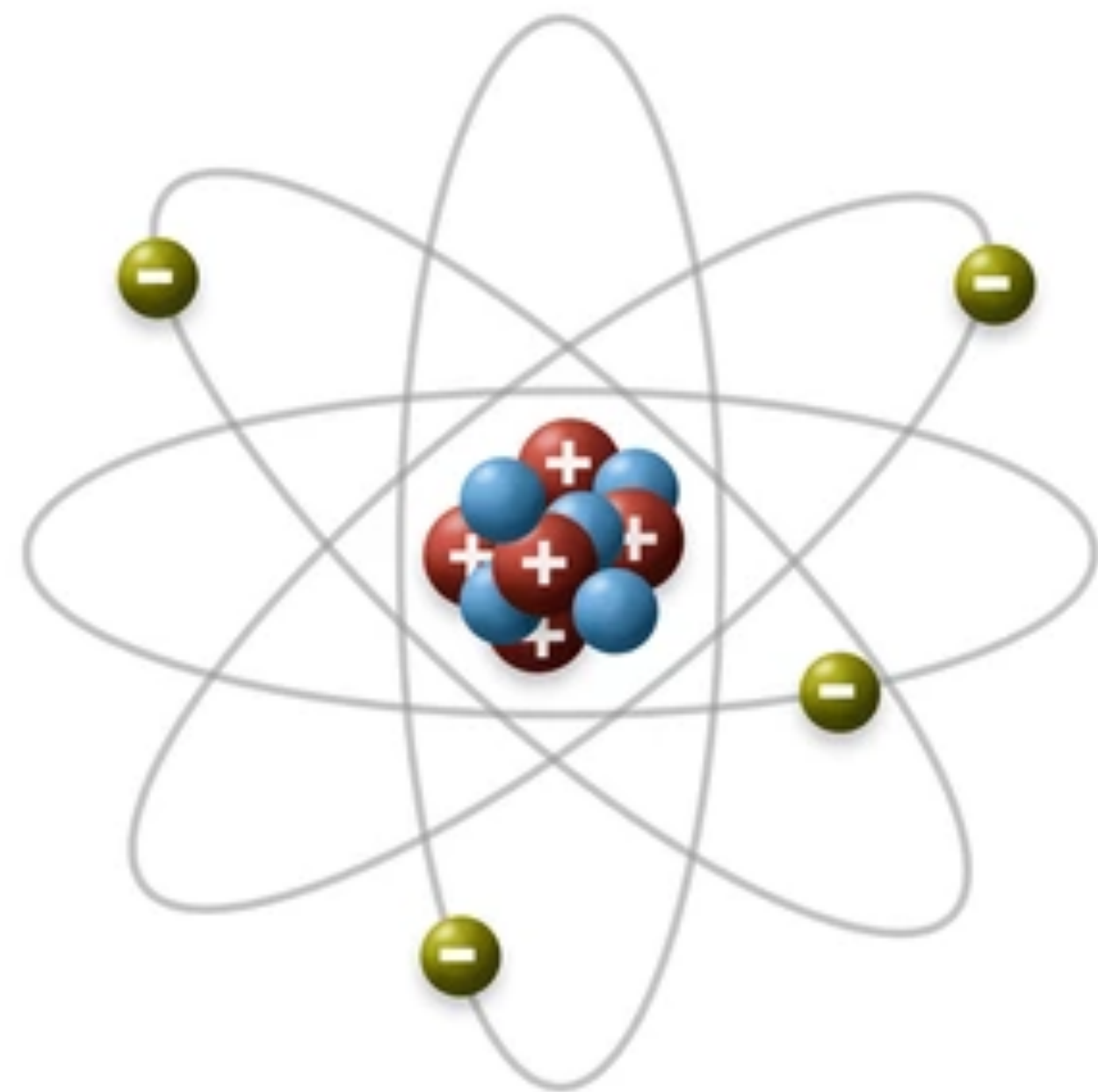
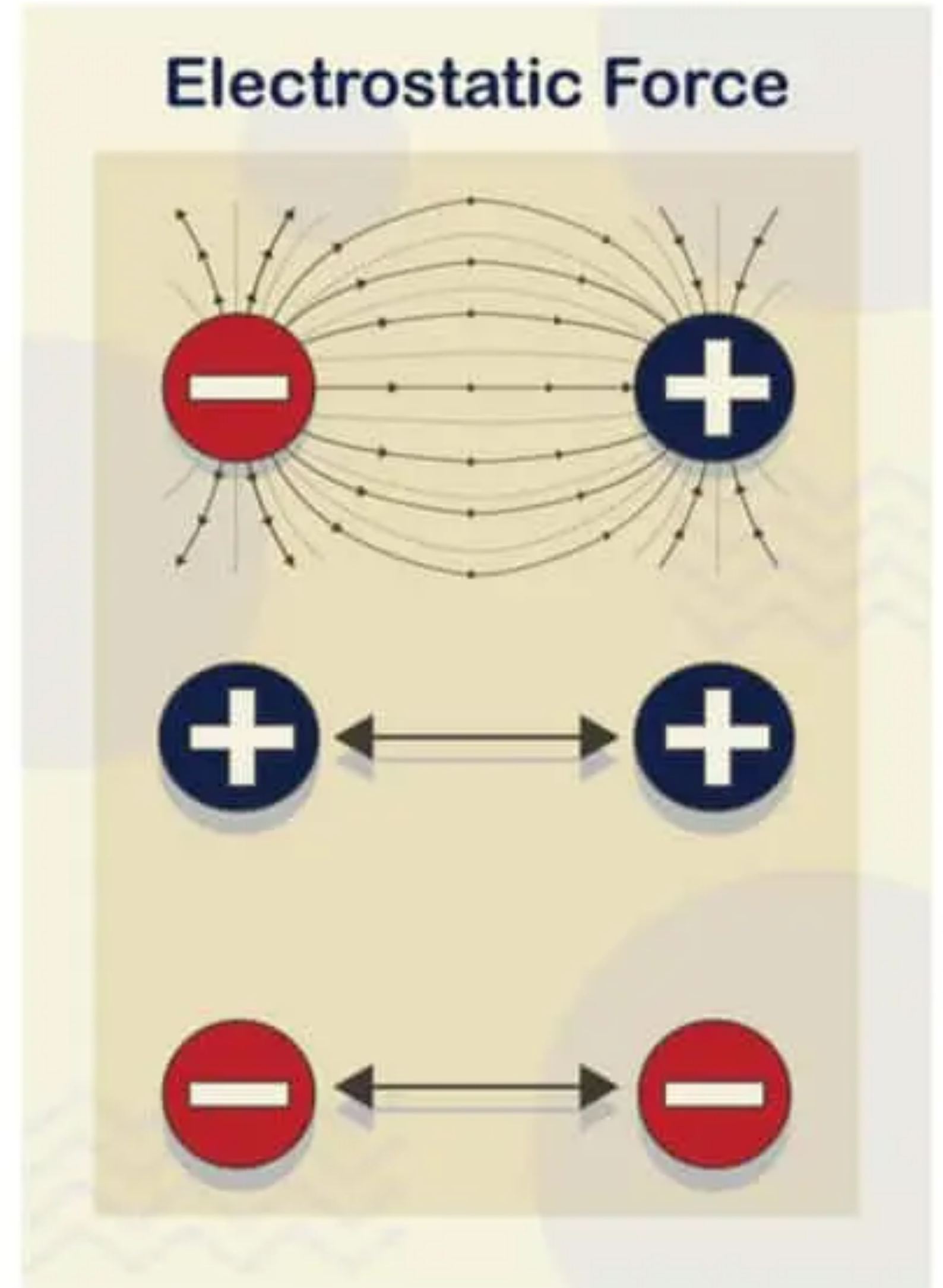
1	2											18					
1 H Hydrogen Nonmetal																	2 He Helium Noble Gas
3 Li Lithium Alkali Metal	4 Be Beryllium Alkaline Earth Me...											10 Ne Neon Noble Gas					
11 Na Sodium Alkali Metal	12 Mg Magnesium Alkaline Earth Me...											18 Ar Argon Noble Gas					
19 K Potassium Alkali Metal	20 Ca Calcium Alkaline Earth Me...	21 Sc Scandium Transition Metal	22 Ti Titanium Transition Metal	23 V Vanadium Transition Metal	24 Cr Chromium Transition Metal	25 Mn Manganese Transition Metal	26 Fe Iron Transition Metal	27 Co Cobalt Transition Metal	28 Ni Nickel Transition Metal	29 Cu Copper Transition Metal	30 Zn Zinc Transition Metal	31 Ga Gallium Post-Transition M...	32 Ge Germanium Metalloid	33 As Arsenic Metalloid	34 Se Selenium Nonmetal	35 Br Bromine Halogen	36 Kr Krypton Noble Gas
37 Rb Rubidium Alkali Metal	38 Sr Strontium Alkaline Earth Me...	39 Y Yttrium Transition Metal	40 Zr Zirconium Transition Metal	41 Nb Niobium Transition Metal	42 Mo Molybdenum Transition Metal	43 Tc Technetium Transition Metal	44 Ru Ruthenium Transition Metal	45 Rh Rhodium Transition Metal	46 Pd Palladium Transition Metal	47 Ag Silver Transition Metal	48 Cd Cadmium Transition Metal	49 In Indium Post-Transition M...	50 Sn Tin Post-Transition M...	51 Sb Antimony Metalloid	52 Te Tellurium Metalloid	53 I Iodine Halogen	54 Xe Xenon Noble Gas
55 Cs Cesium Alkali Metal	56 Ba Barium Alkaline Earth Me...											86 Rn Radon Noble Gas					
87 Fr Francium Alkali Metal	88 Ra Radium Alkaline Earth Me...											118 Og Oganesson Noble Gas					
		57 La Lanthanum Lanthanide	58 Ce Cerium Lanthanide	59 Pr Praseodymium Lanthanide	60 Nd Neodymium Lanthanide	61 Pm Promethium Lanthanide	62 Sm Samarium Lanthanide	63 Eu Europium Lanthanide	64 Gd Gadolinium Lanthanide	65 Tb Terbium Lanthanide	66 Dy Dysprosium Lanthanide	67 Ho Holmium Lanthanide	68 Er Erbium Lanthanide	69 Tm Thulium Lanthanide	70 Yb Ytterbium Lanthanide	71 Lu Lutetium Lanthanide	
		89 Ac Actinium Actinide	90 Th Thorium Actinide	91 Pa Protactinium Actinide	92 U Uranium Actinide	93 Np Neptunium Actinide	94 Pu Plutonium Actinide	95 Am Americium Actinide	96 Cm Curium Actinide	97 Bk Berkelium Actinide	98 Cf Californium Actinide	99 Es Einsteinium Actinide	100 Fm Fermium Actinide	101 Md Mendelevium Actinide	102 No Nobelium Actinide	103 Lr Lawrencium Actinide	



- 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**



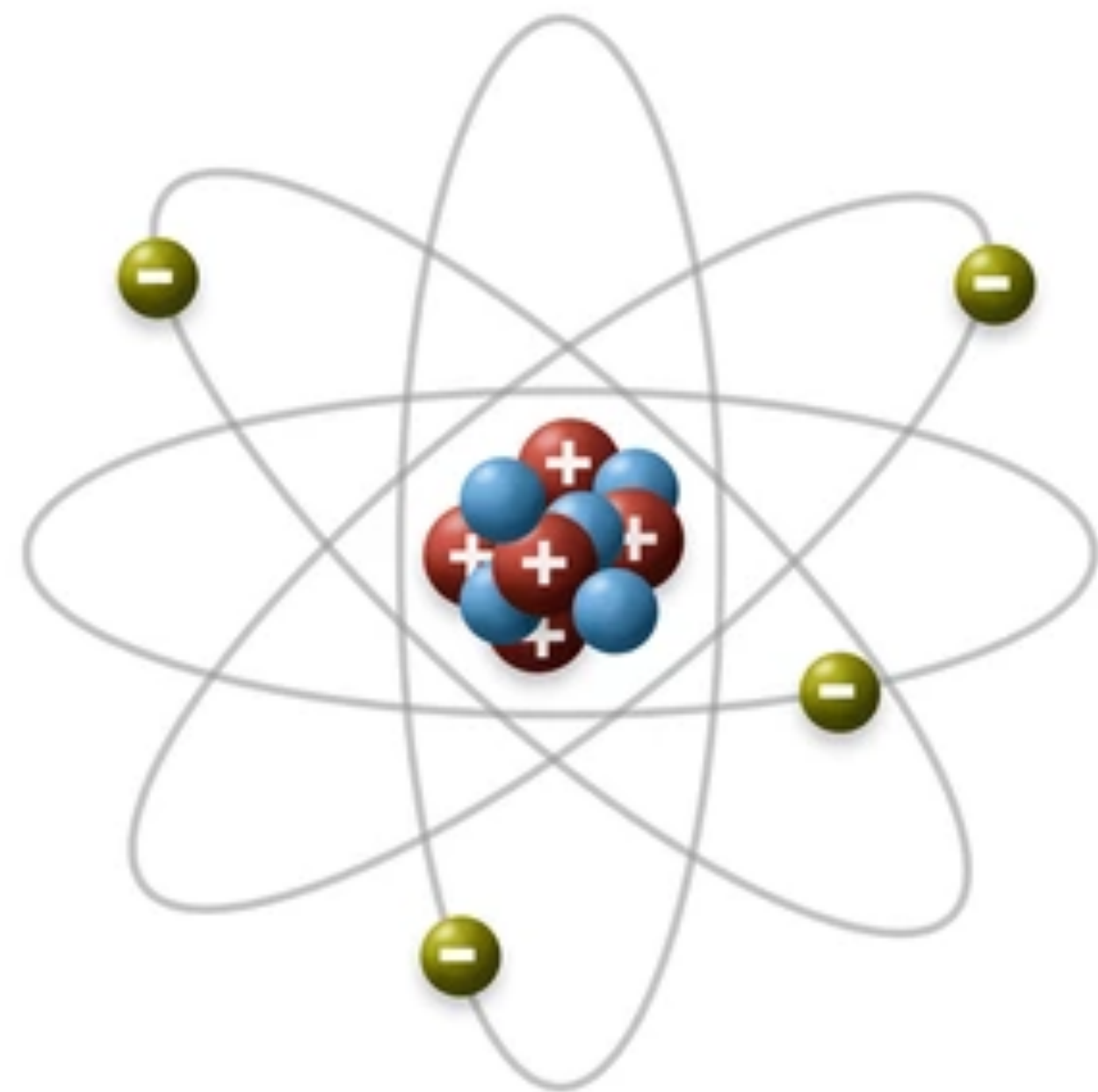
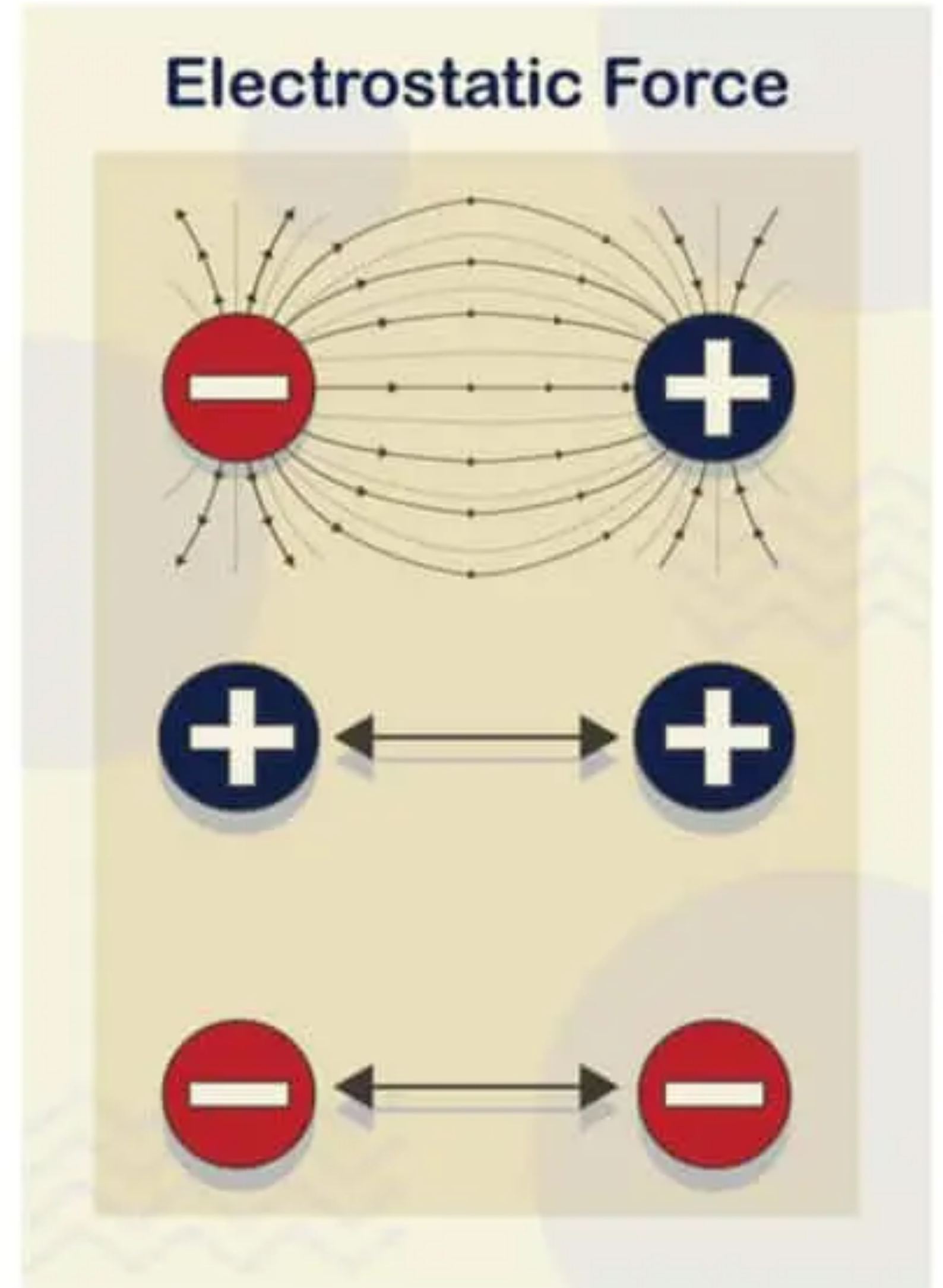
Electron e^- 

Proton p^+ 

Neutron n 

How are nuclei held together?

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



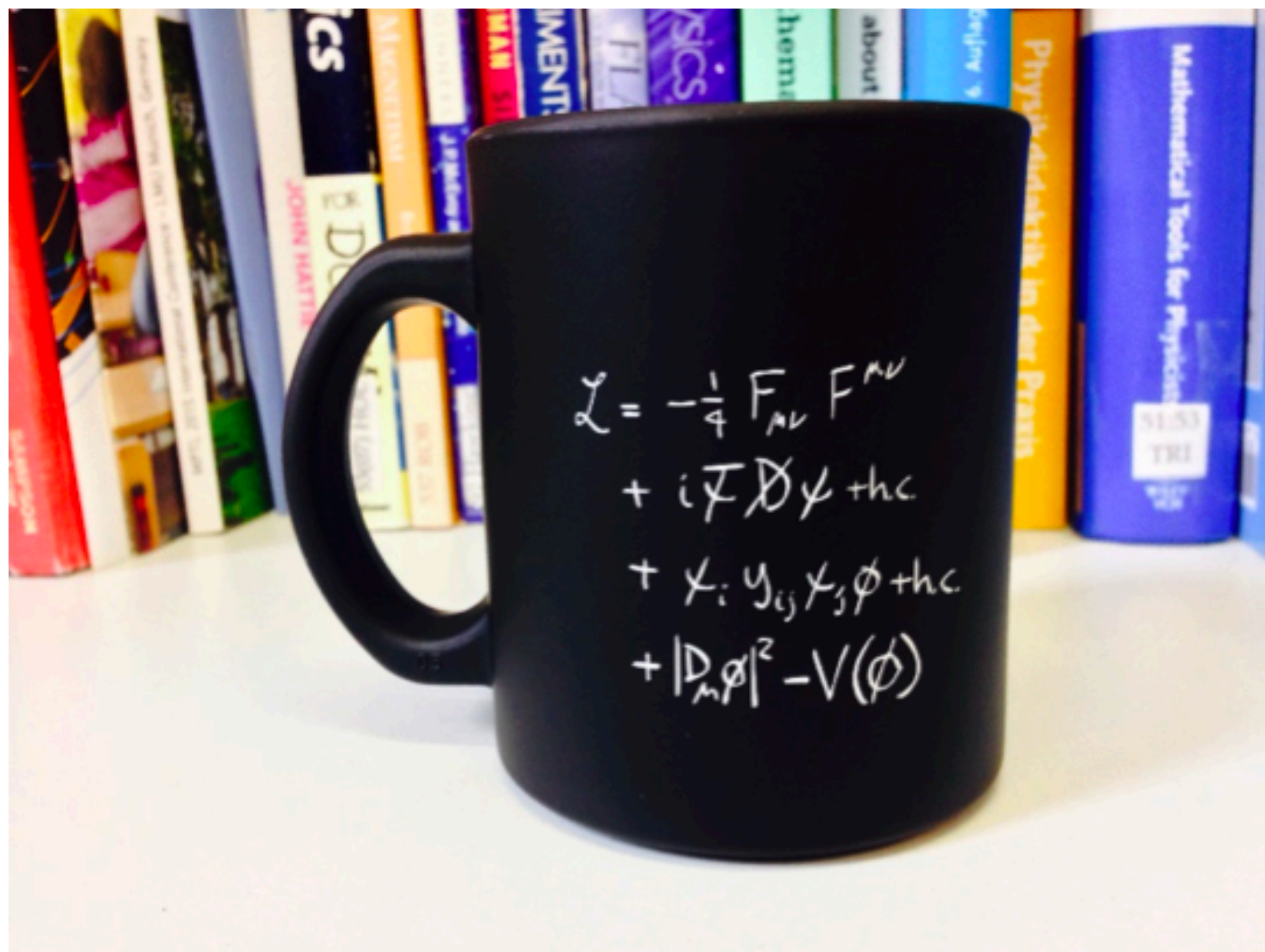
Electron e^- 

Proton p^+ 

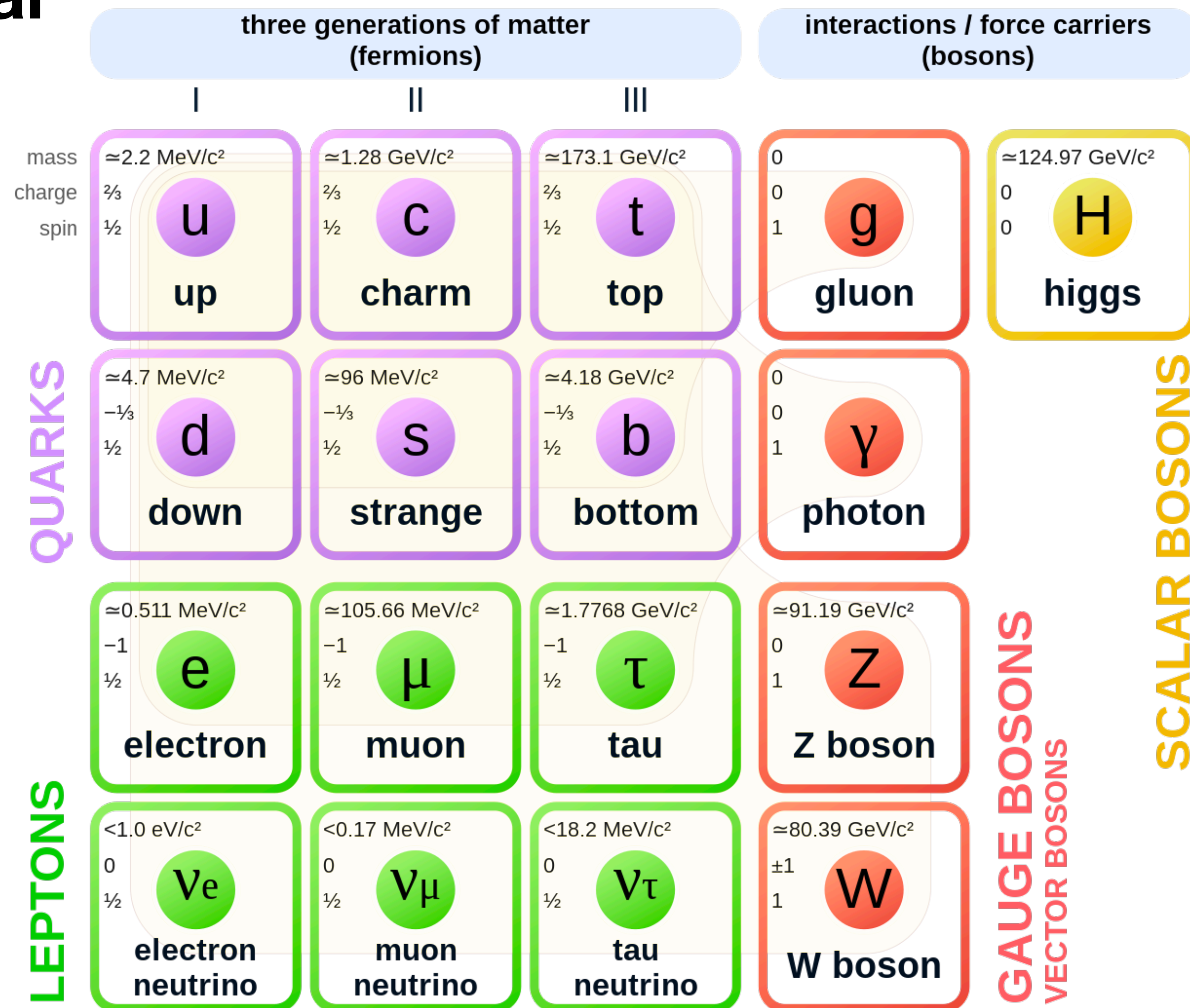
Neutron n 

The Standard Model

- The SM describes 3 fundamental forces of nature

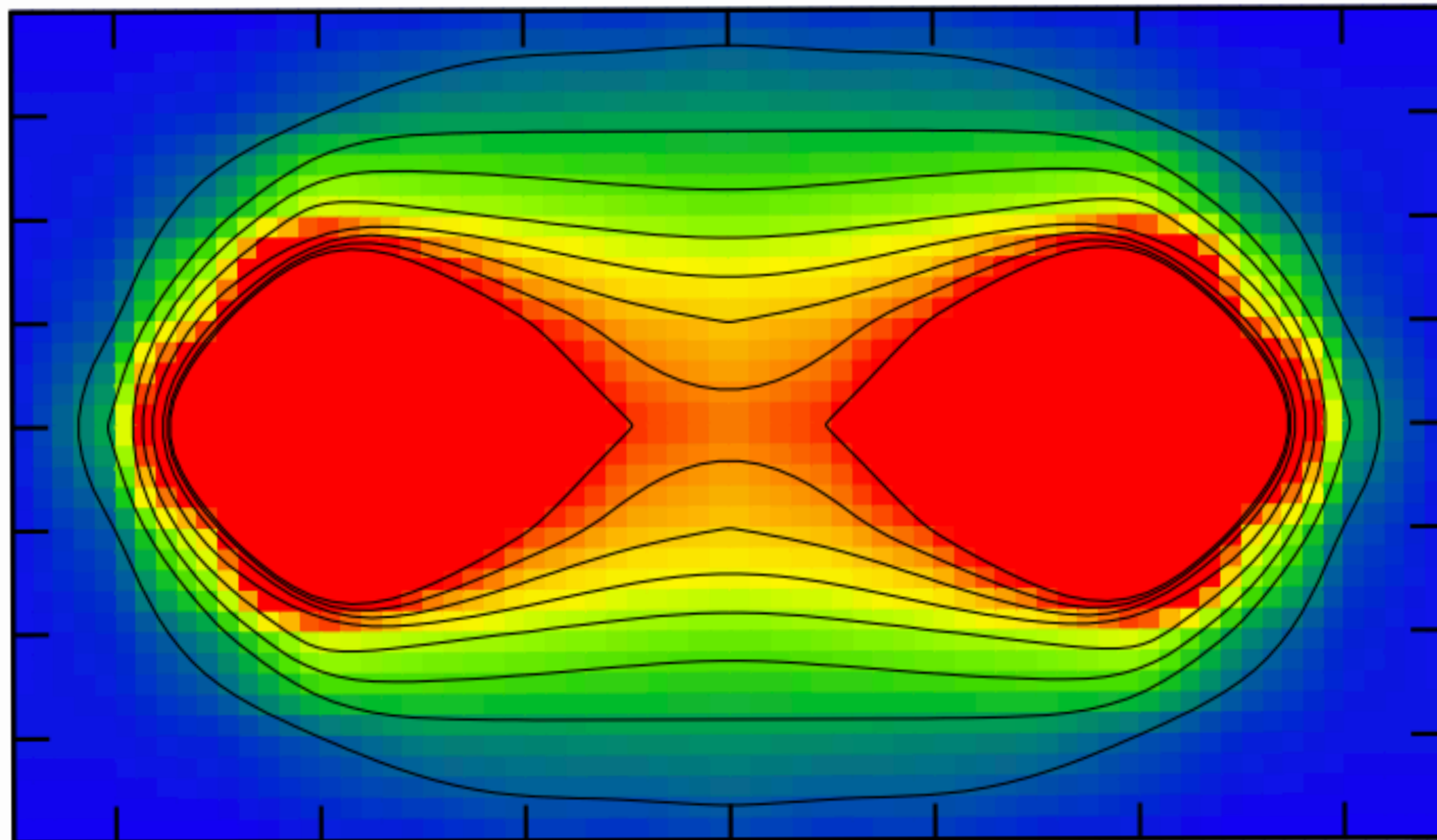


Standard Model of Elementary Particles

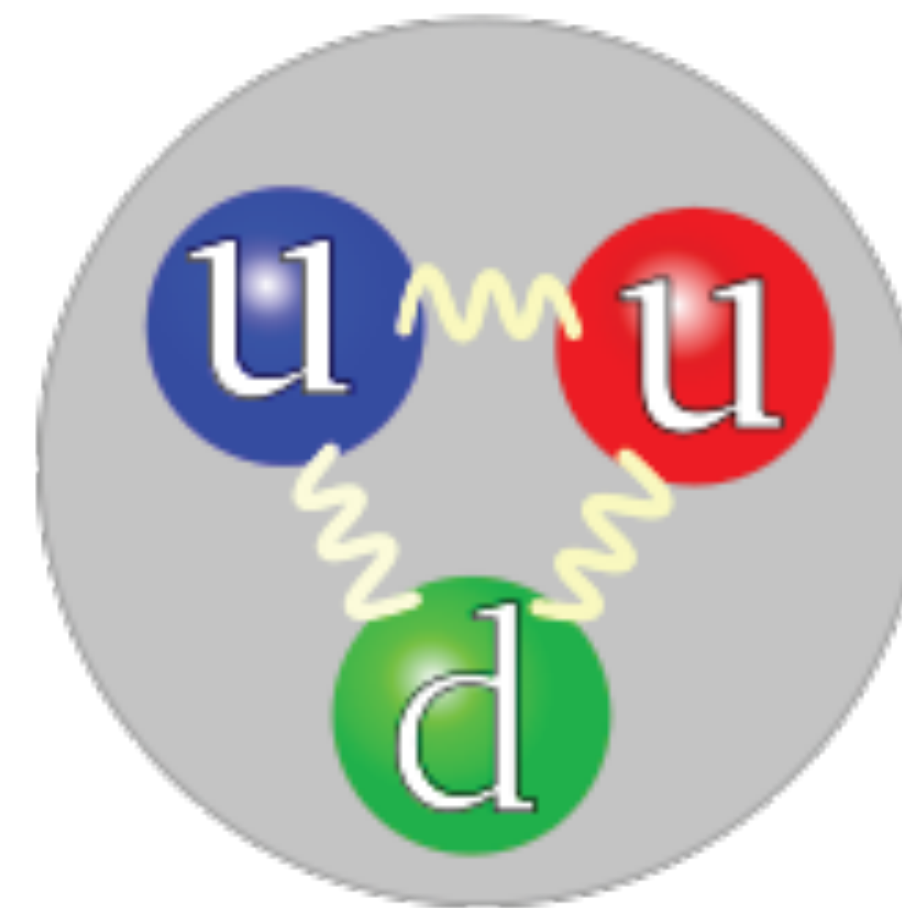


Confinement

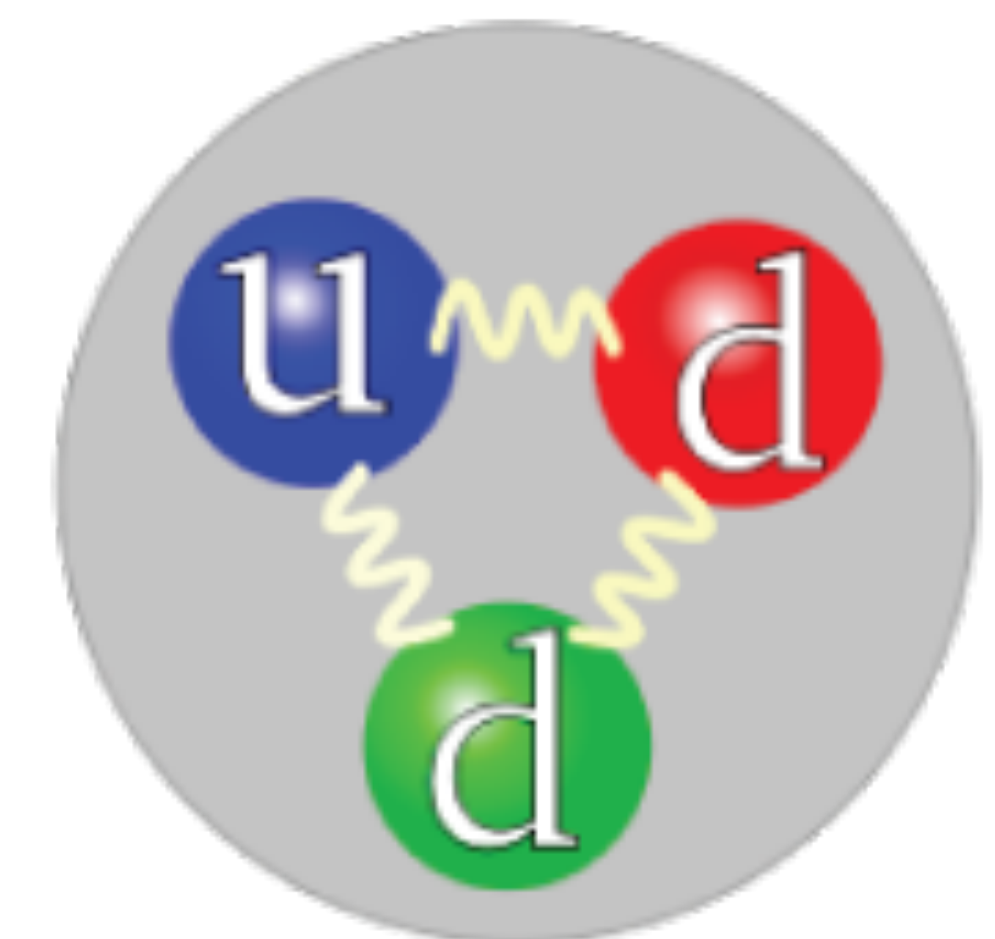
- Quarks are always stuck together by gluons - confined
- Protons/neutrons have 3 quarks stuck together
- Nuclei are many protons/neutrons stuck together
- High energy nuclear physics wants to understand quarks/gluons



Phys.Rev.D 81:034504,2010



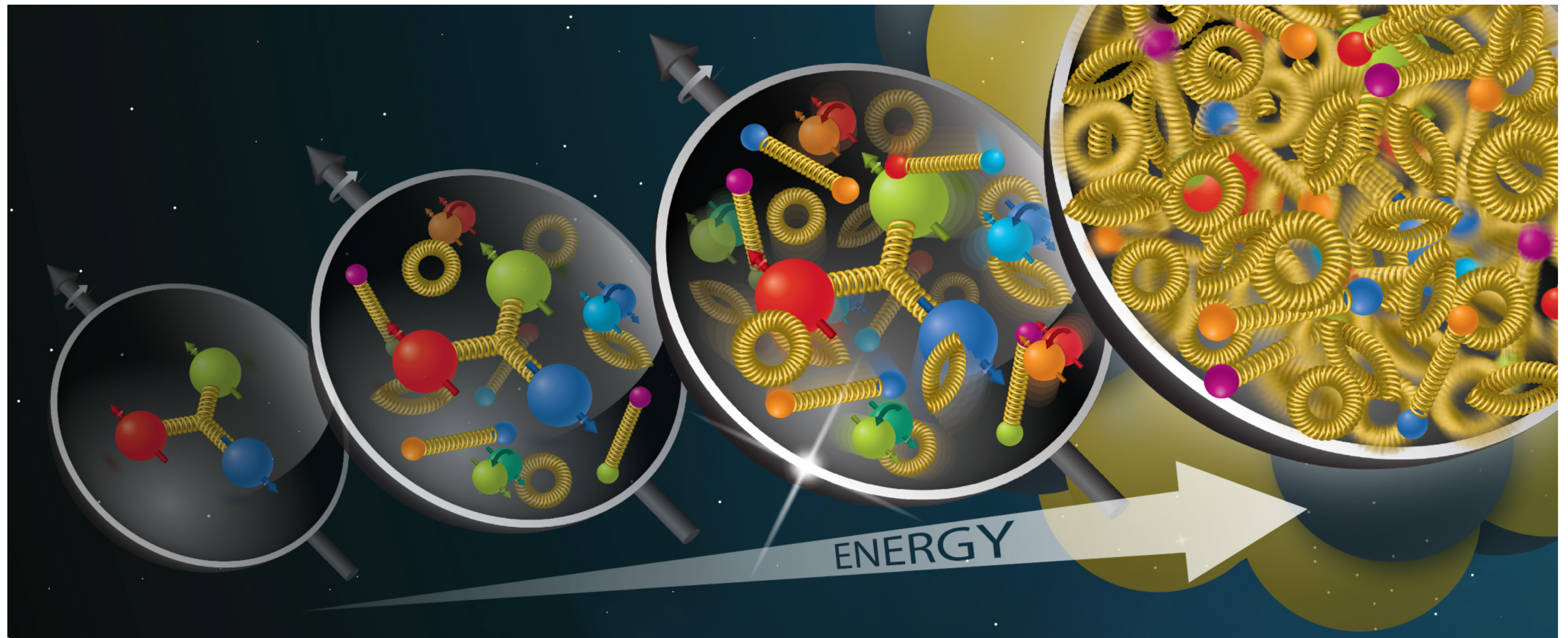
Proton



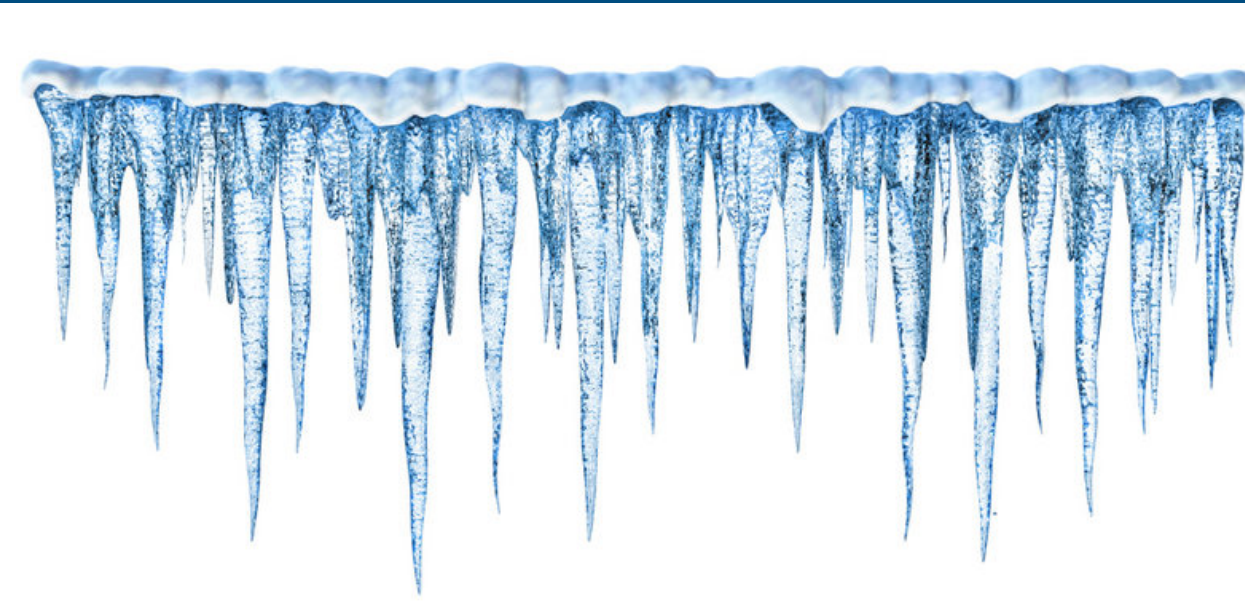
Neutron

Studying quarks and gluons

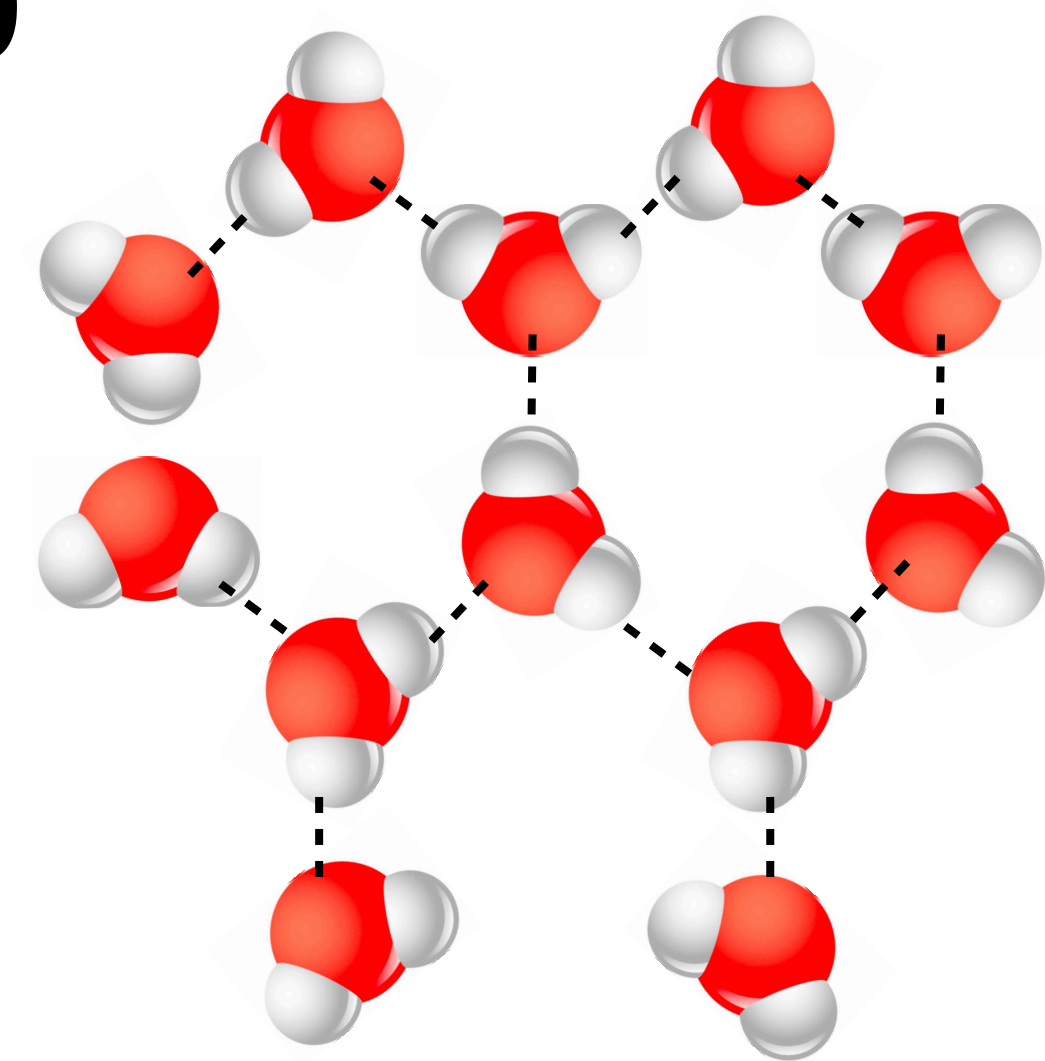
- **3 quark picture is simple; gluons important at higher energies!**
- **How can we study quarks and gluons if they are confined?**



Analogy time - Iceworld!



- **Everything is (solid) H₂O**
- **Snow-scientists know about molecules and forces between them**



A collision on iceworld!

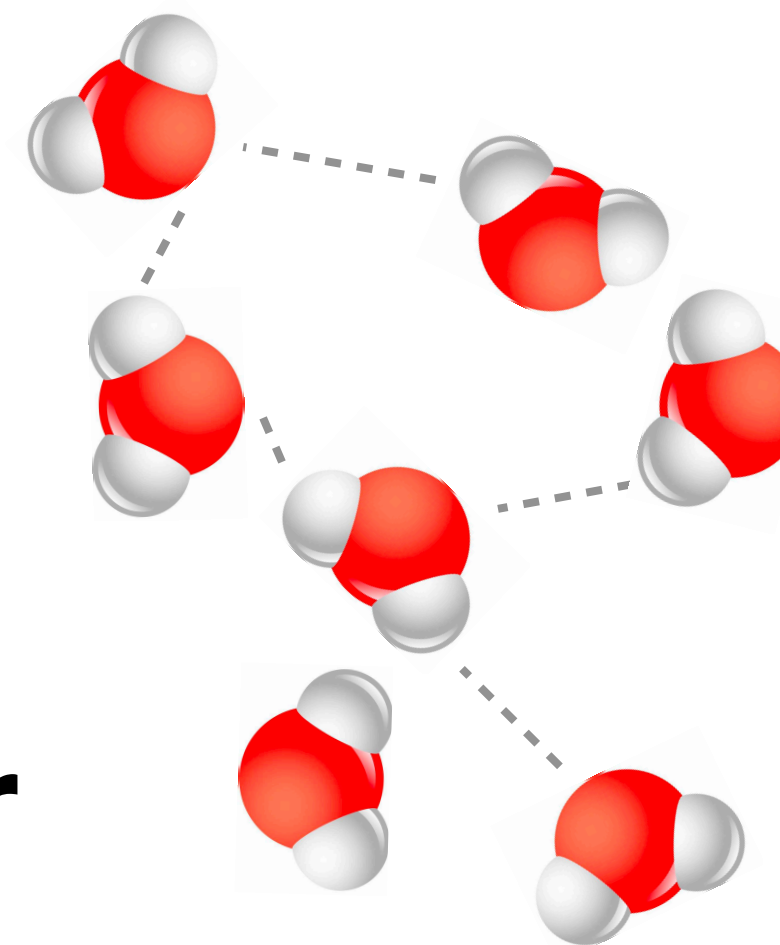


- **A meteor hits and heats up ice world!**

Discovery of liquid water!



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



Phases of water

Steam



Liquid Water

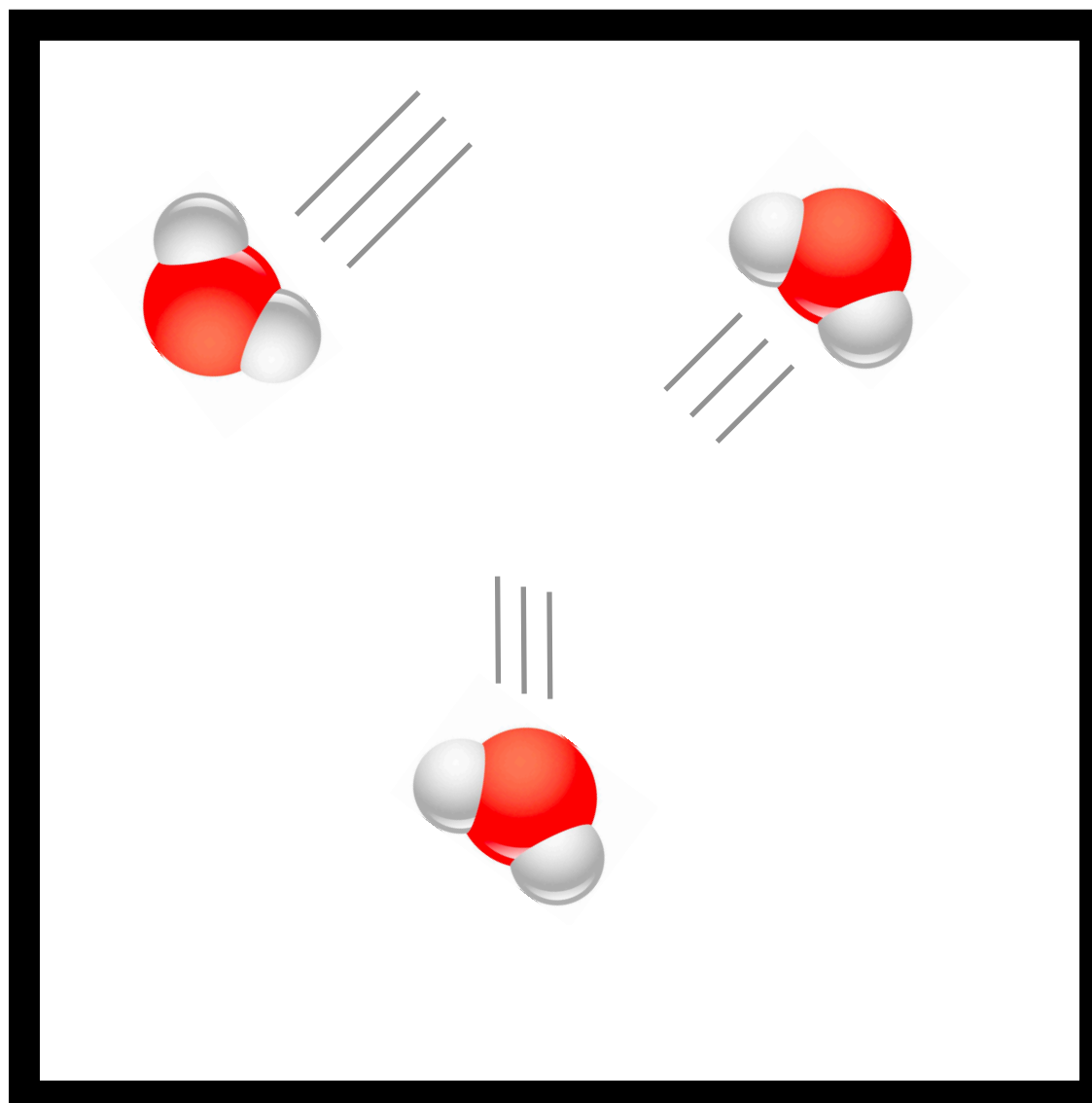


Ice

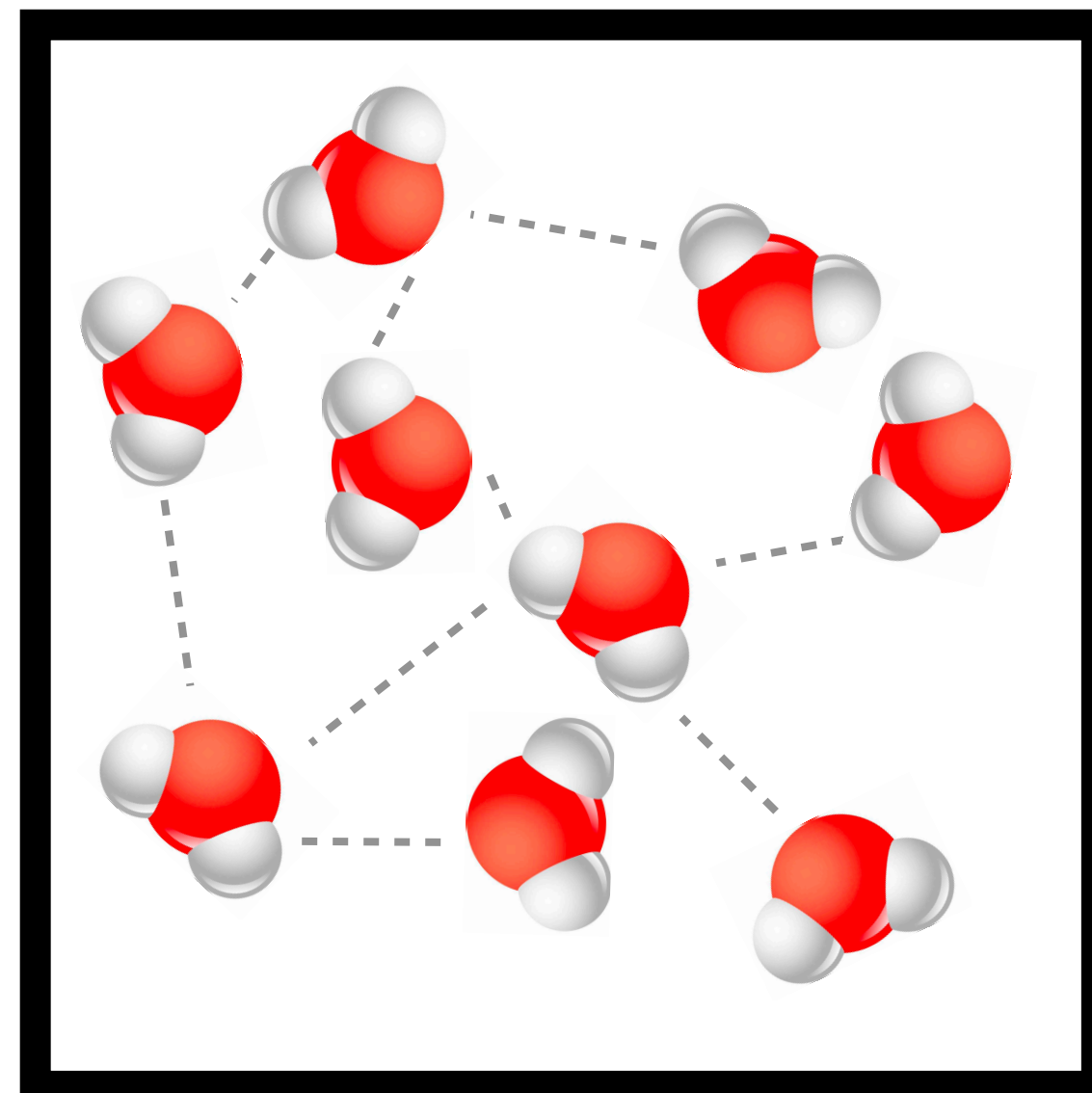


Phases of water

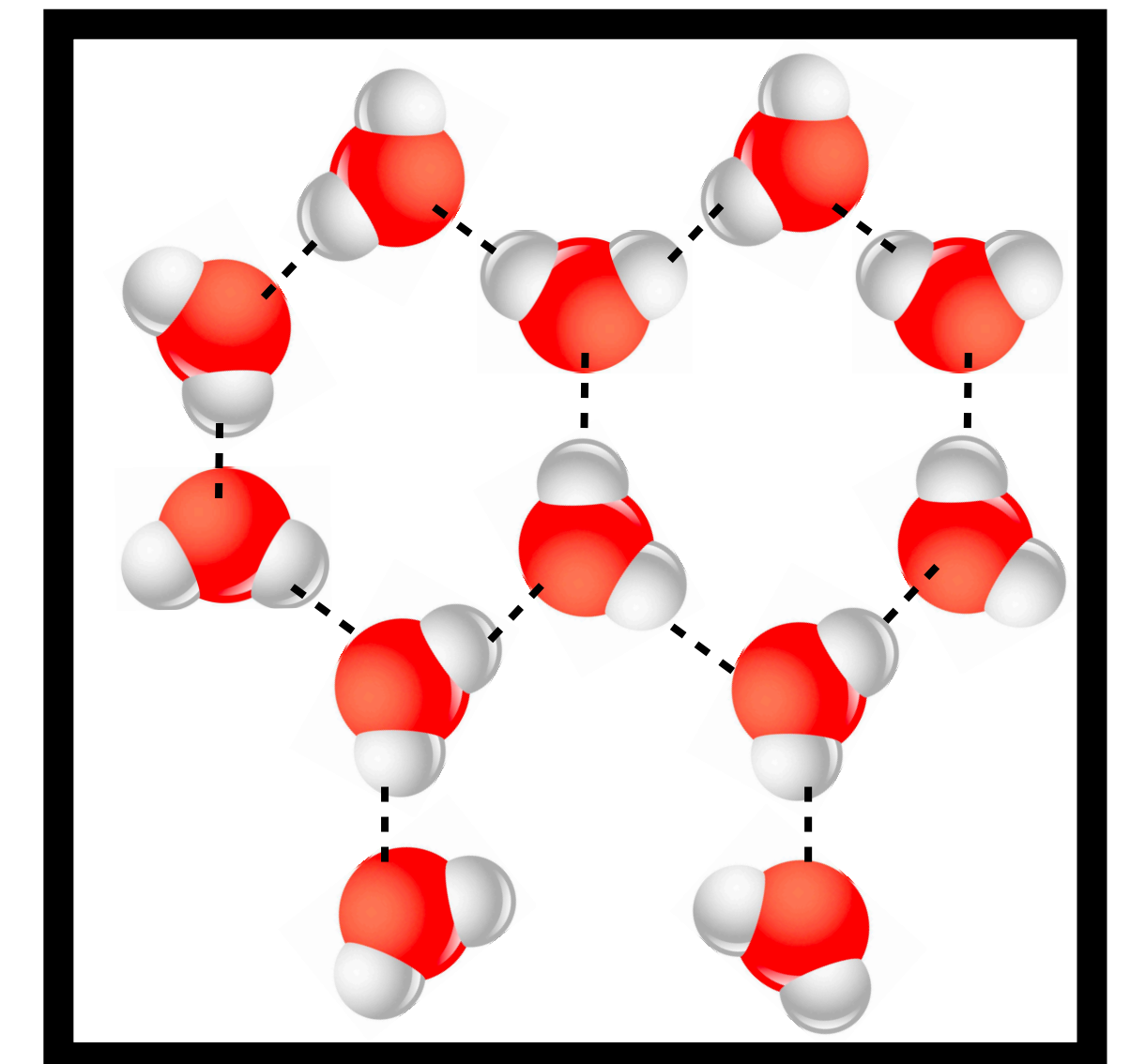
Steam



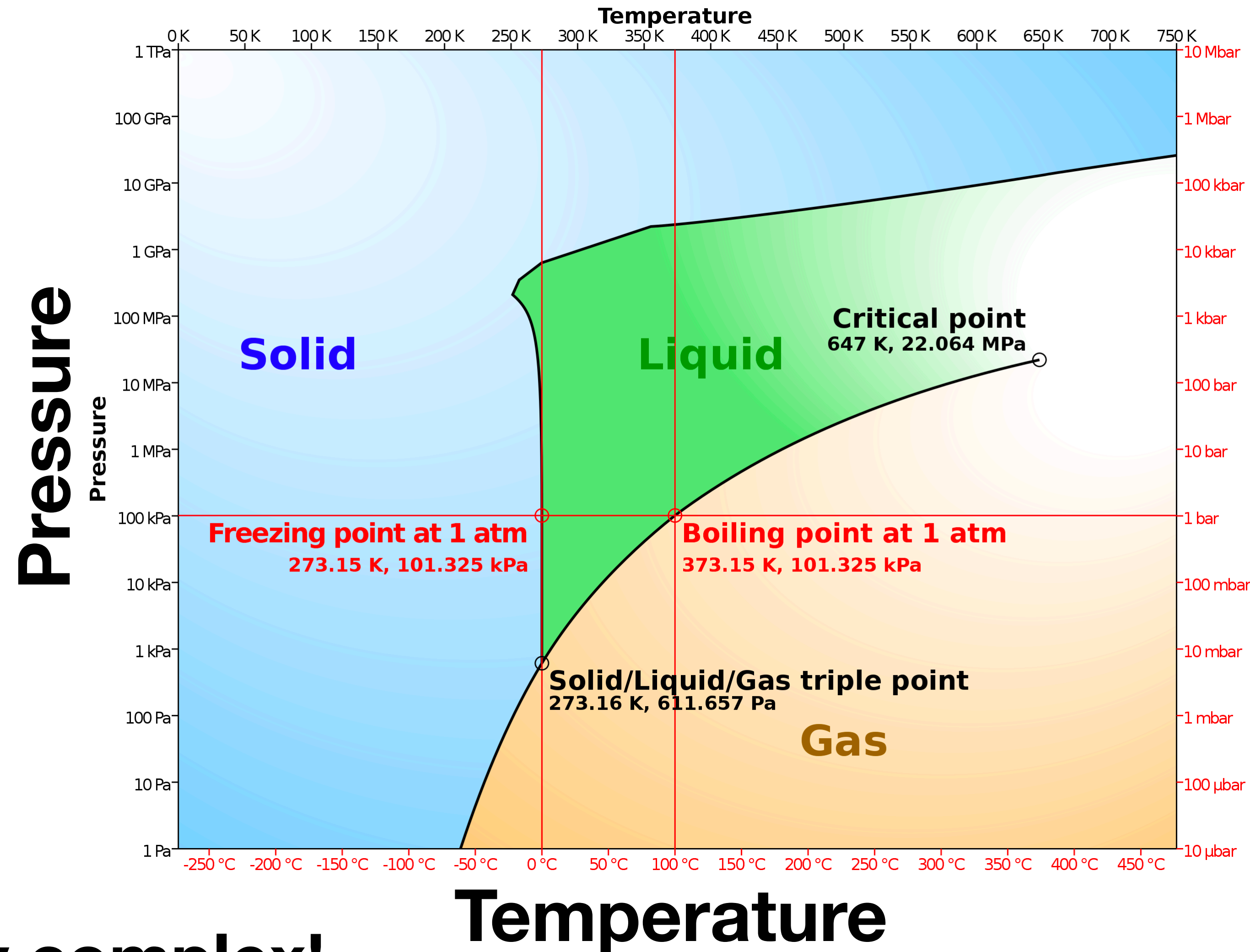
Liquid Water



Ice



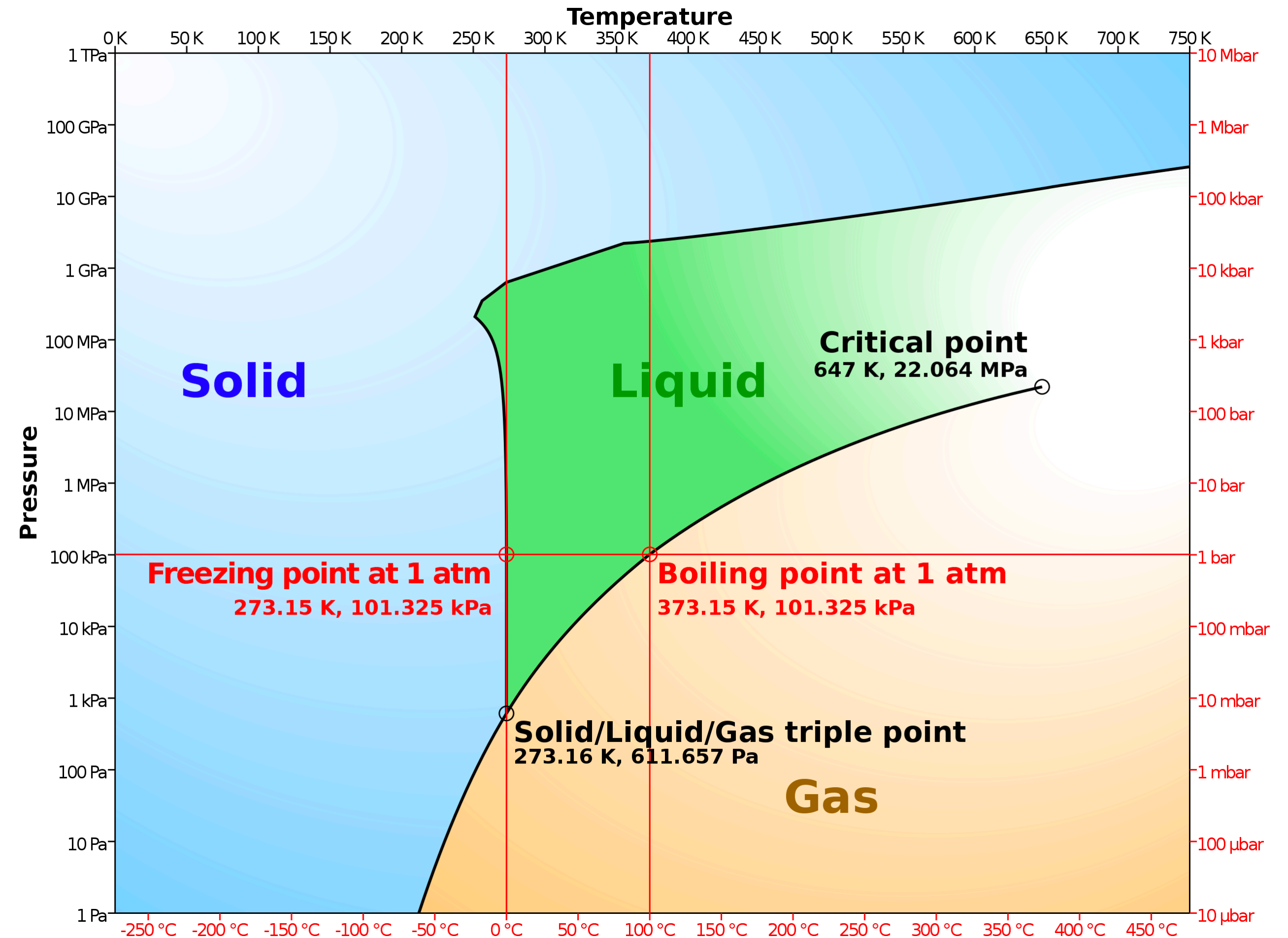
Physicist's view of water



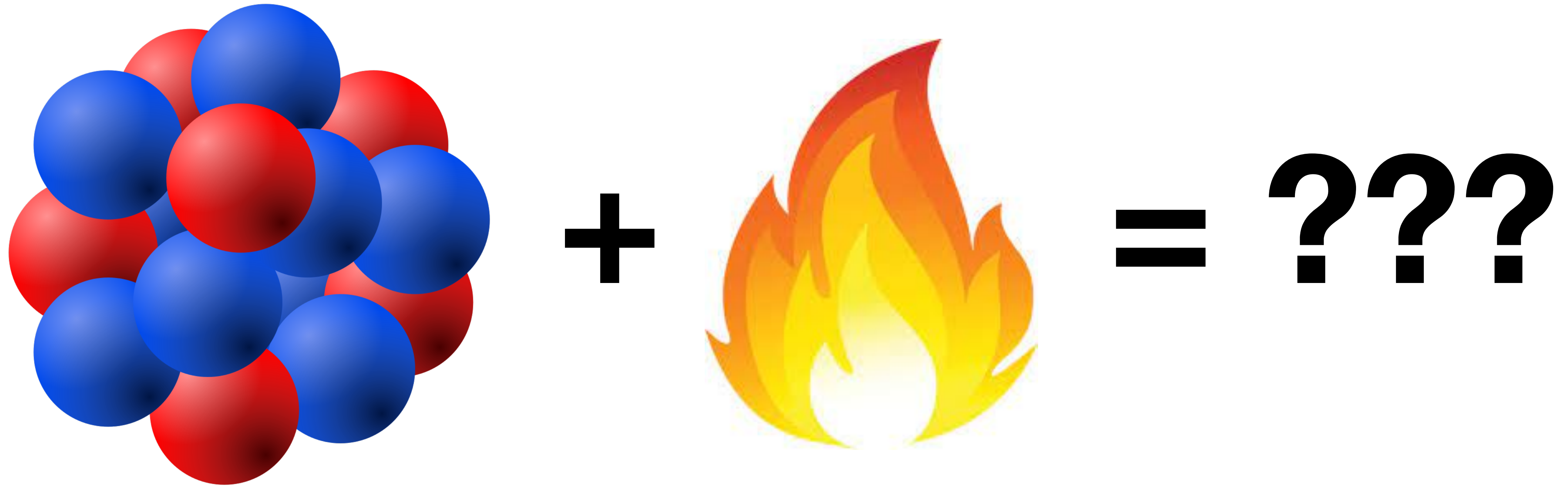
- **Water is very complex!**
- **Electromagnetism is well understood!**

Phase diagram for strong force

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

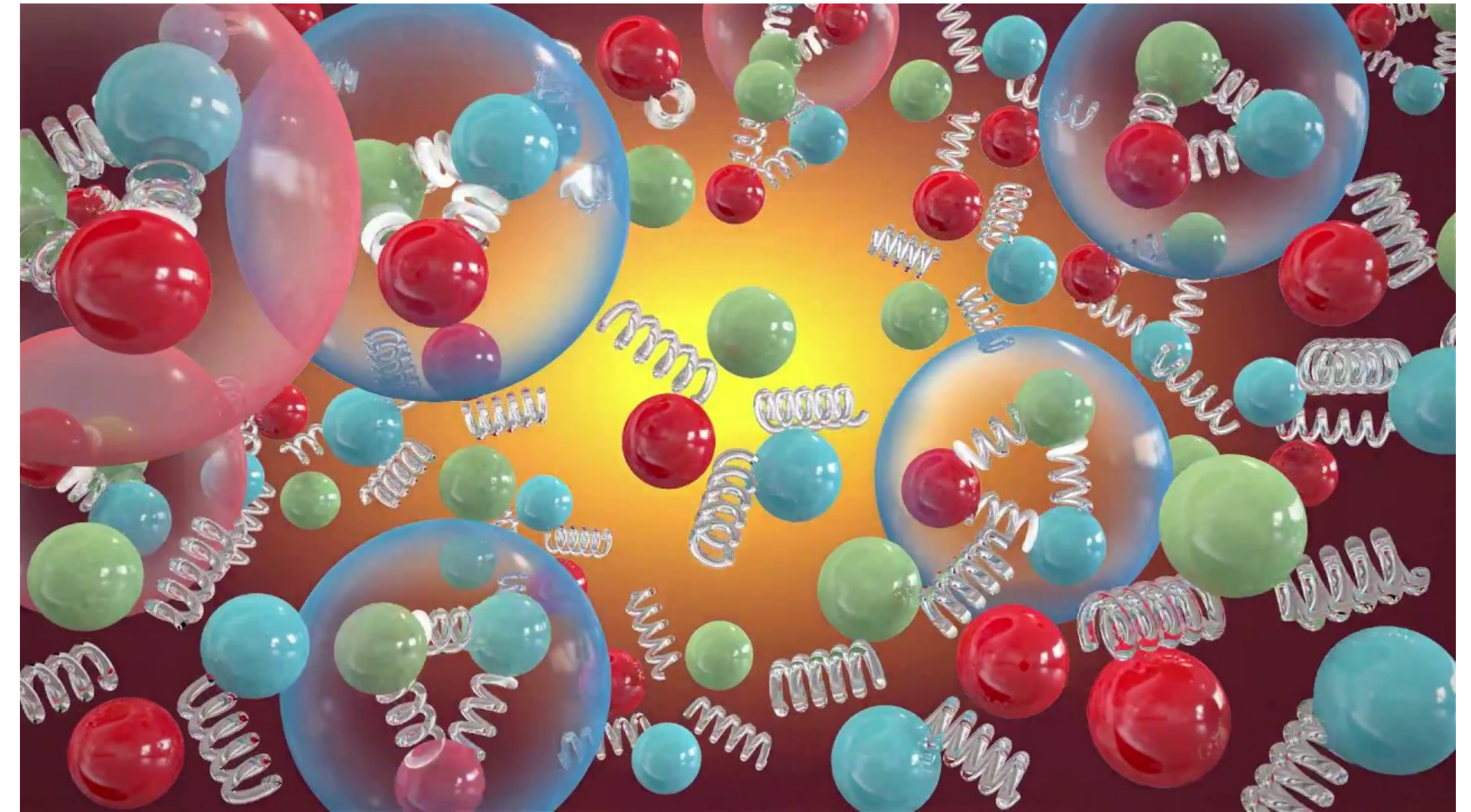
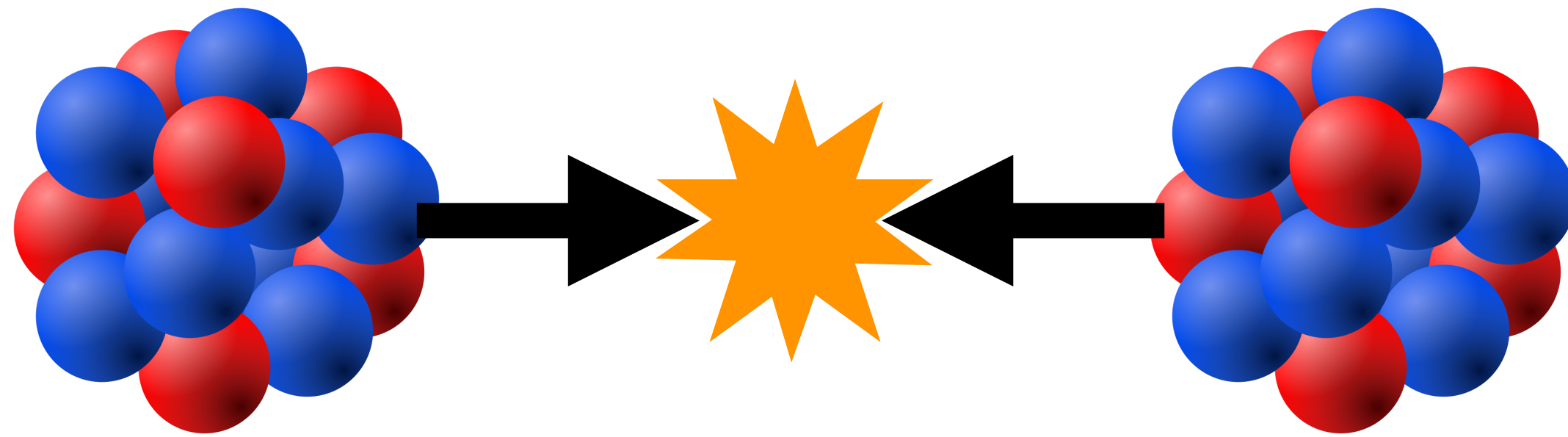


How to study quarks and gluons



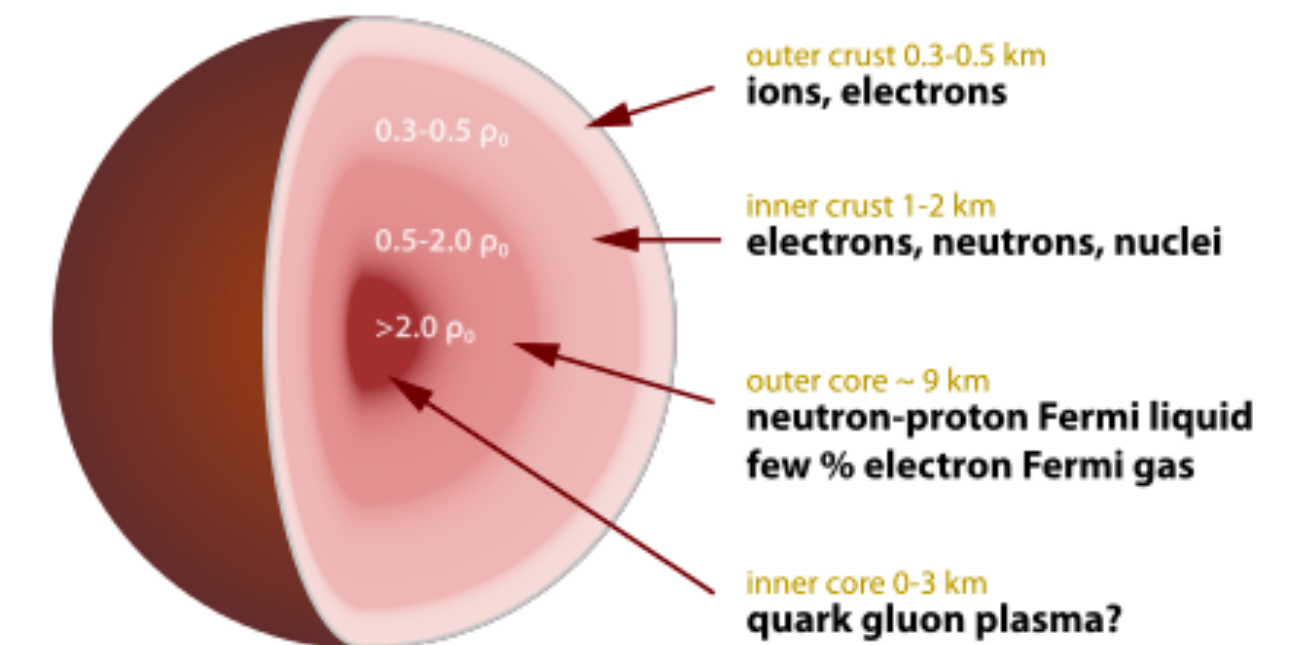
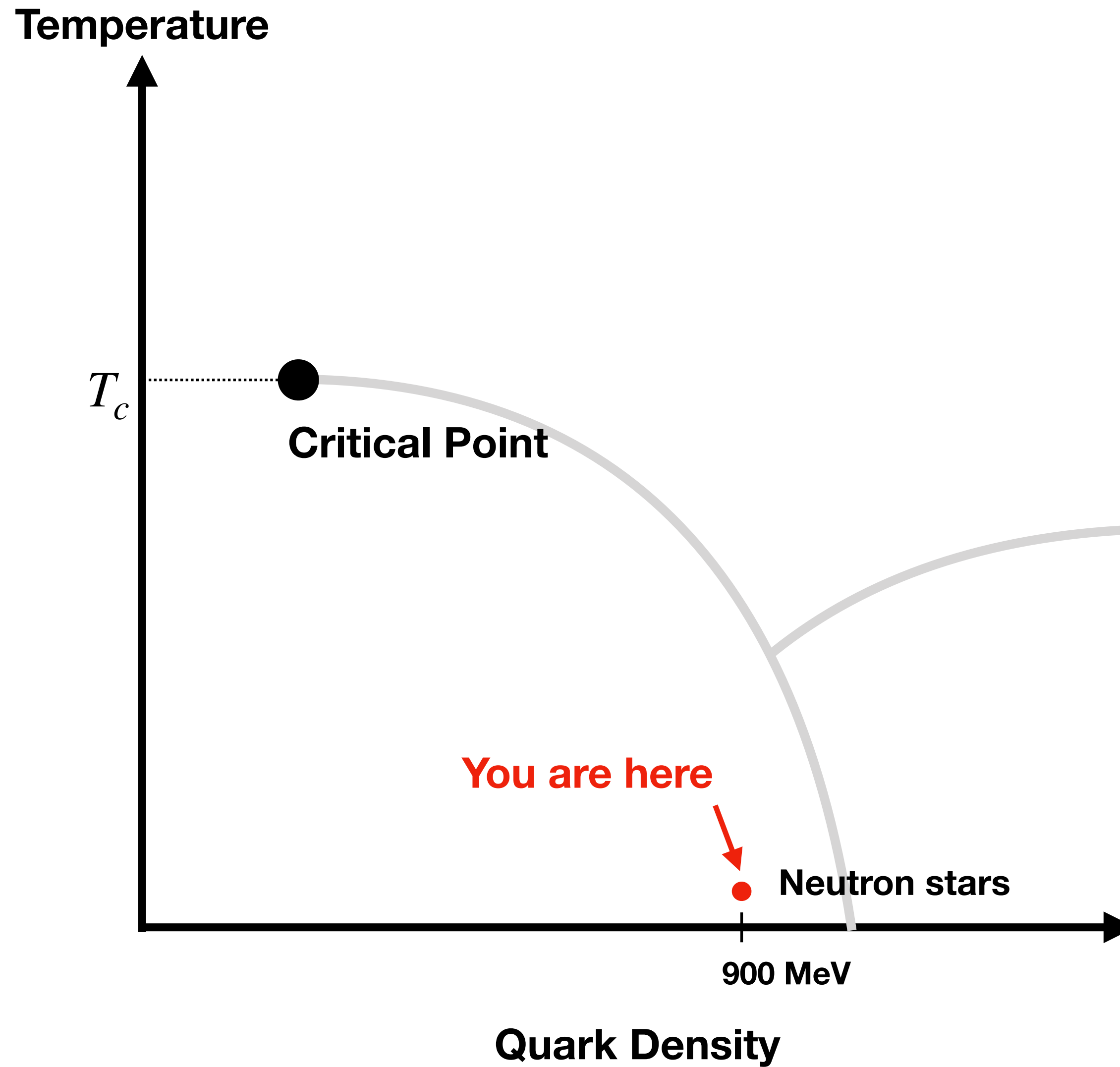
- **If we can heat up nuclei enough, can we ‘melt’ the protons/neutrons into quarks and gluons?**

Quark-Gluon plasma

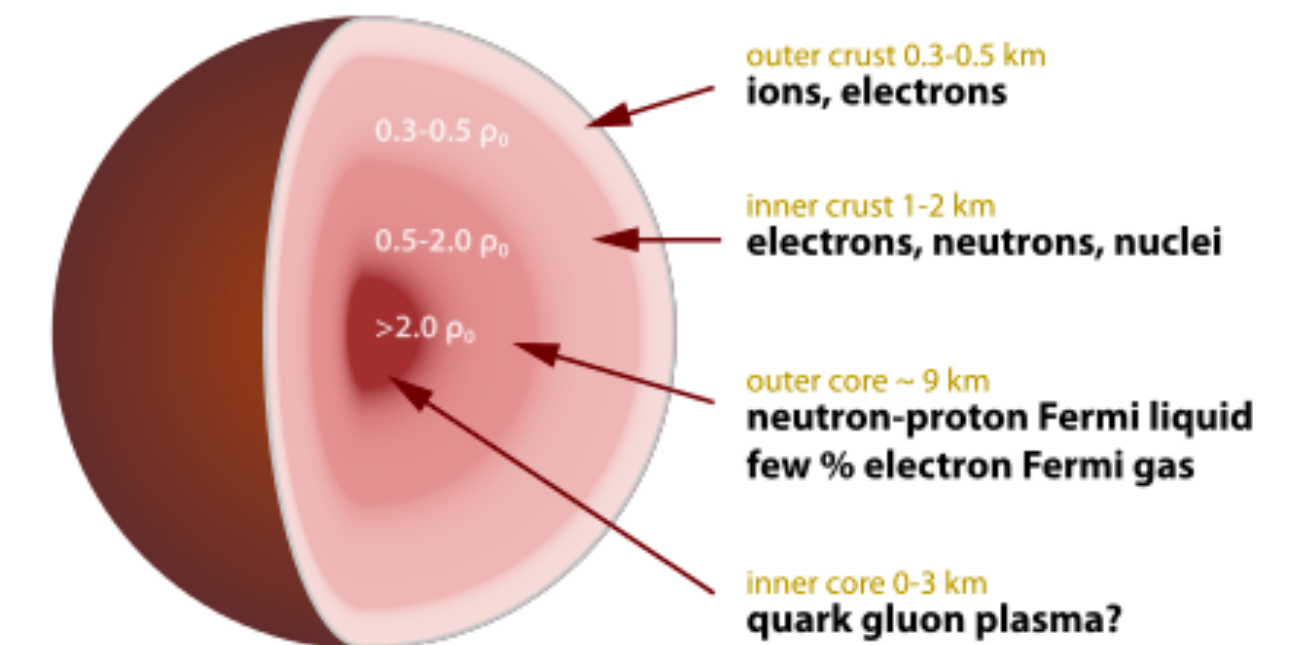
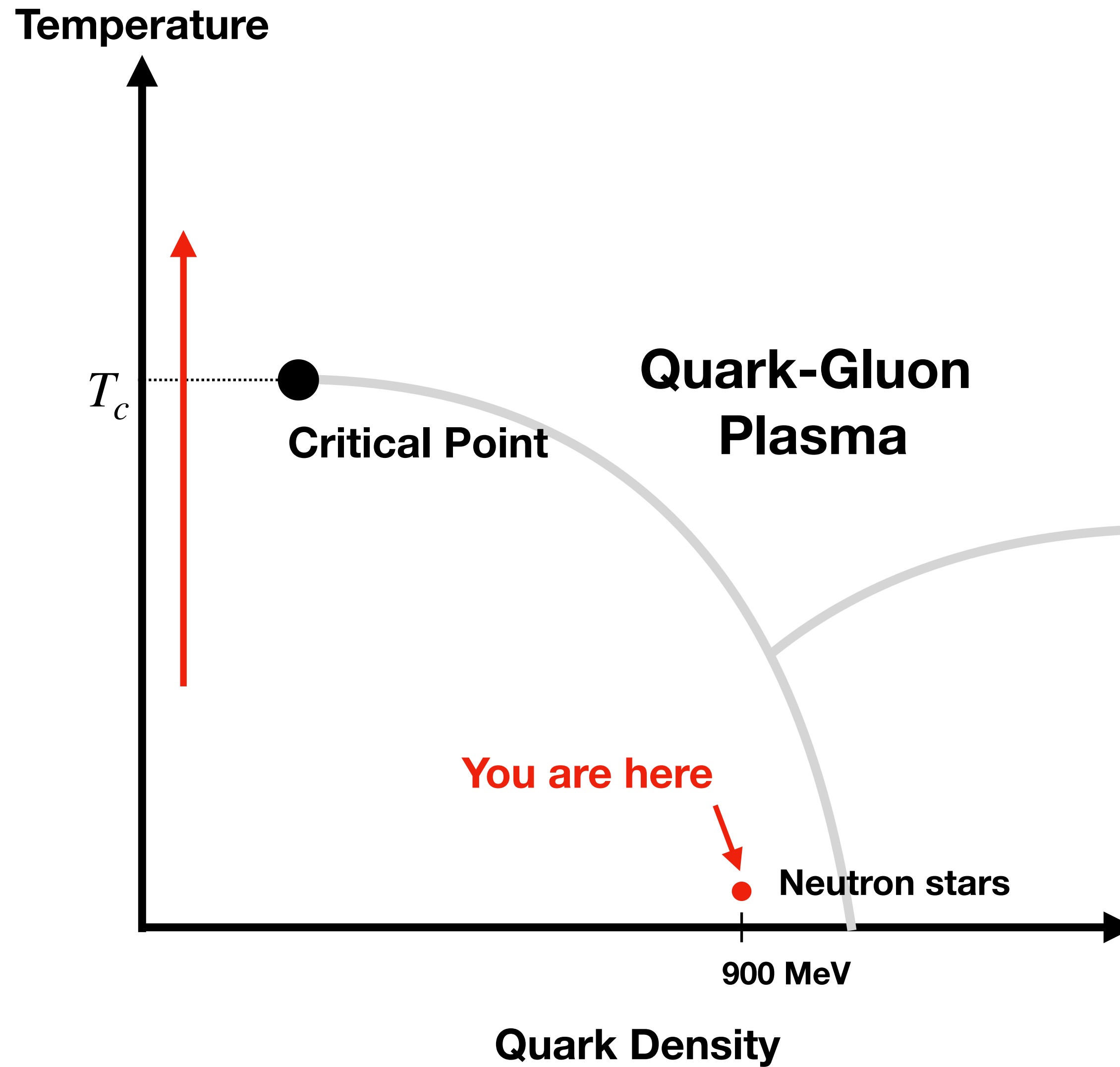


- **Can't achieve high enough temperatures conventionally**
- **High energy nucleus collisions get **very** hot**
- **Protons/neutrons melt into a new form of matter**
- **Quark-Gluon plasma - deconfined!**

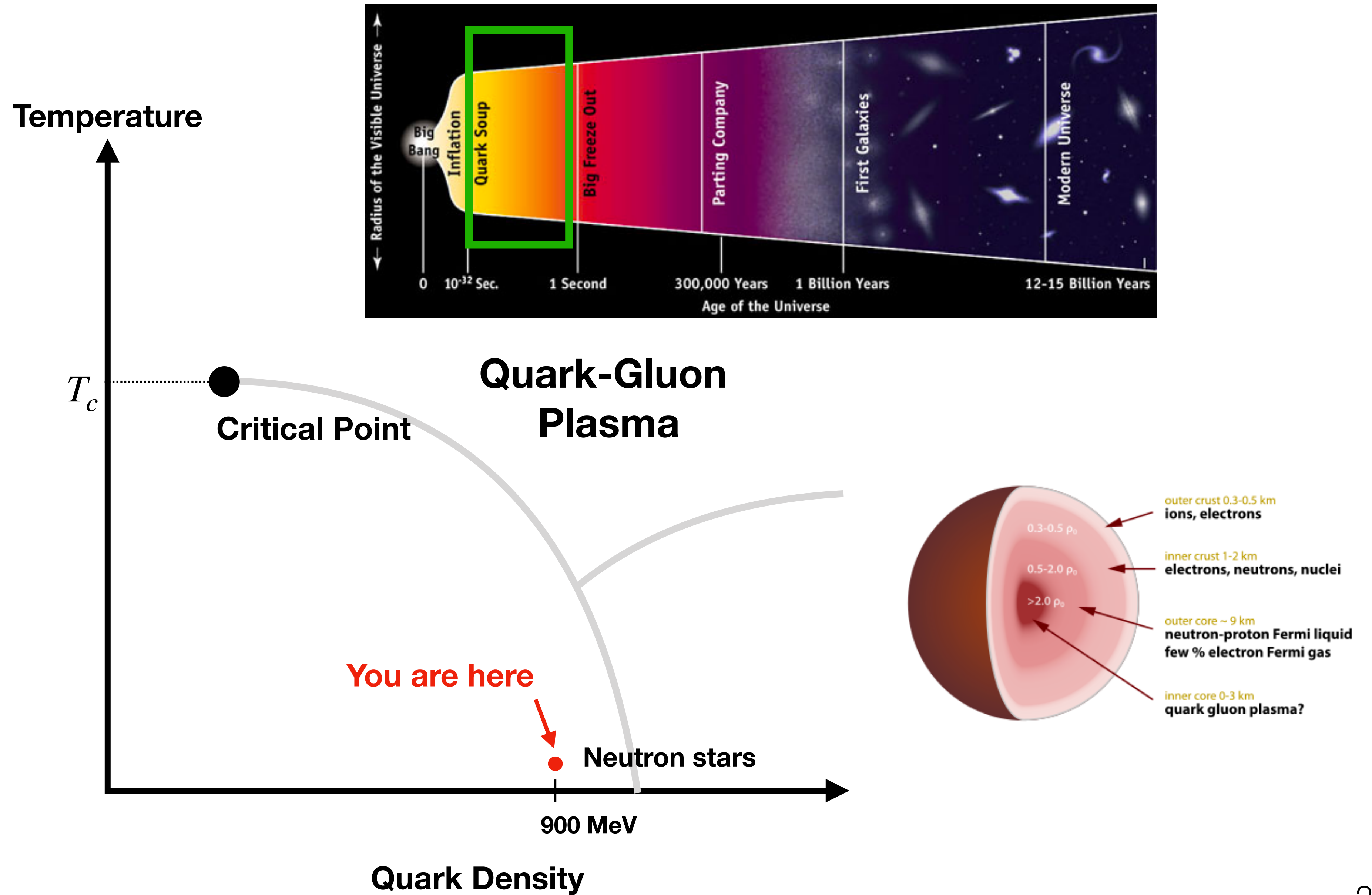
Phase diagram for strong force



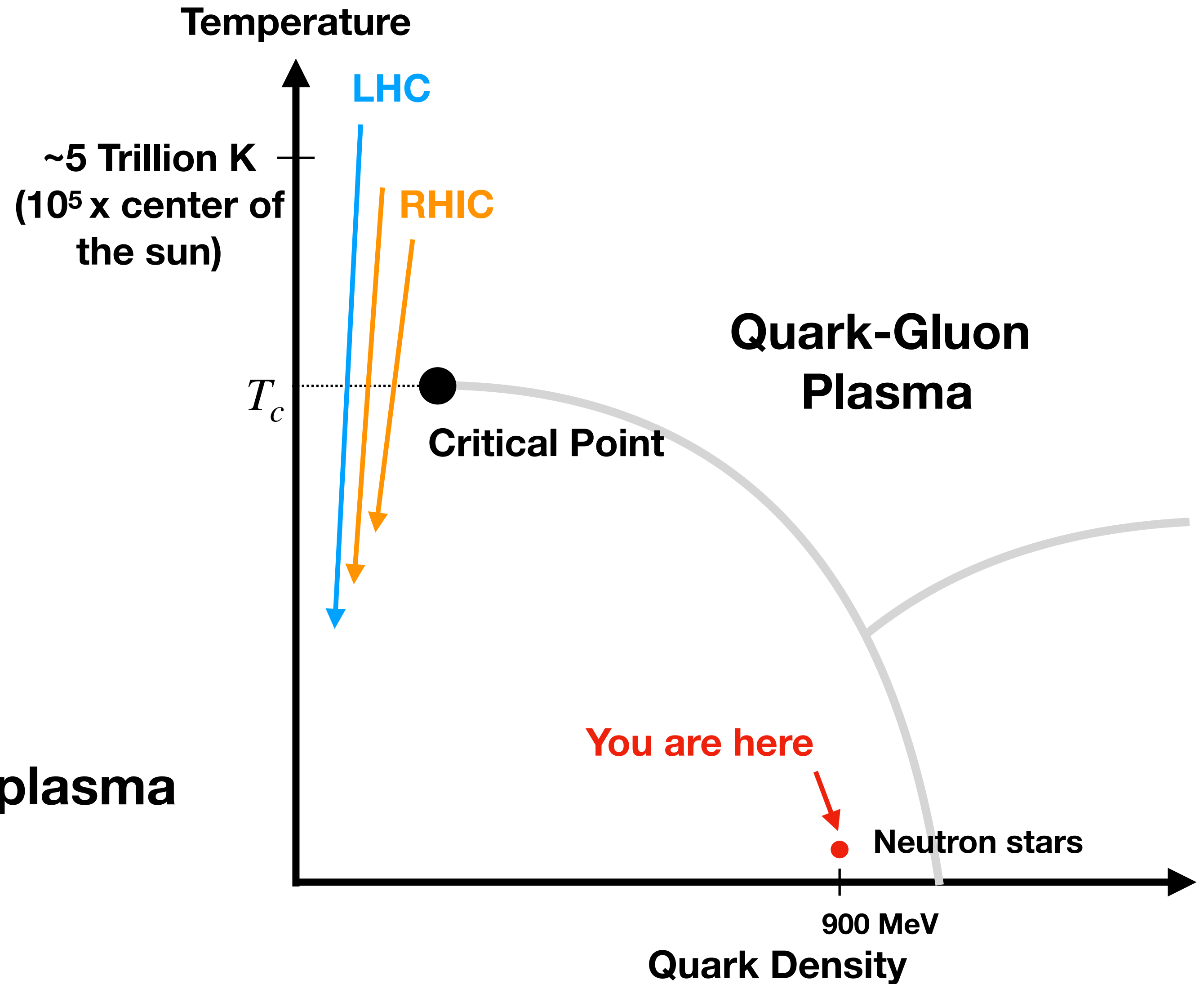
Phase diagram for strong force



Phase diagram for strong force

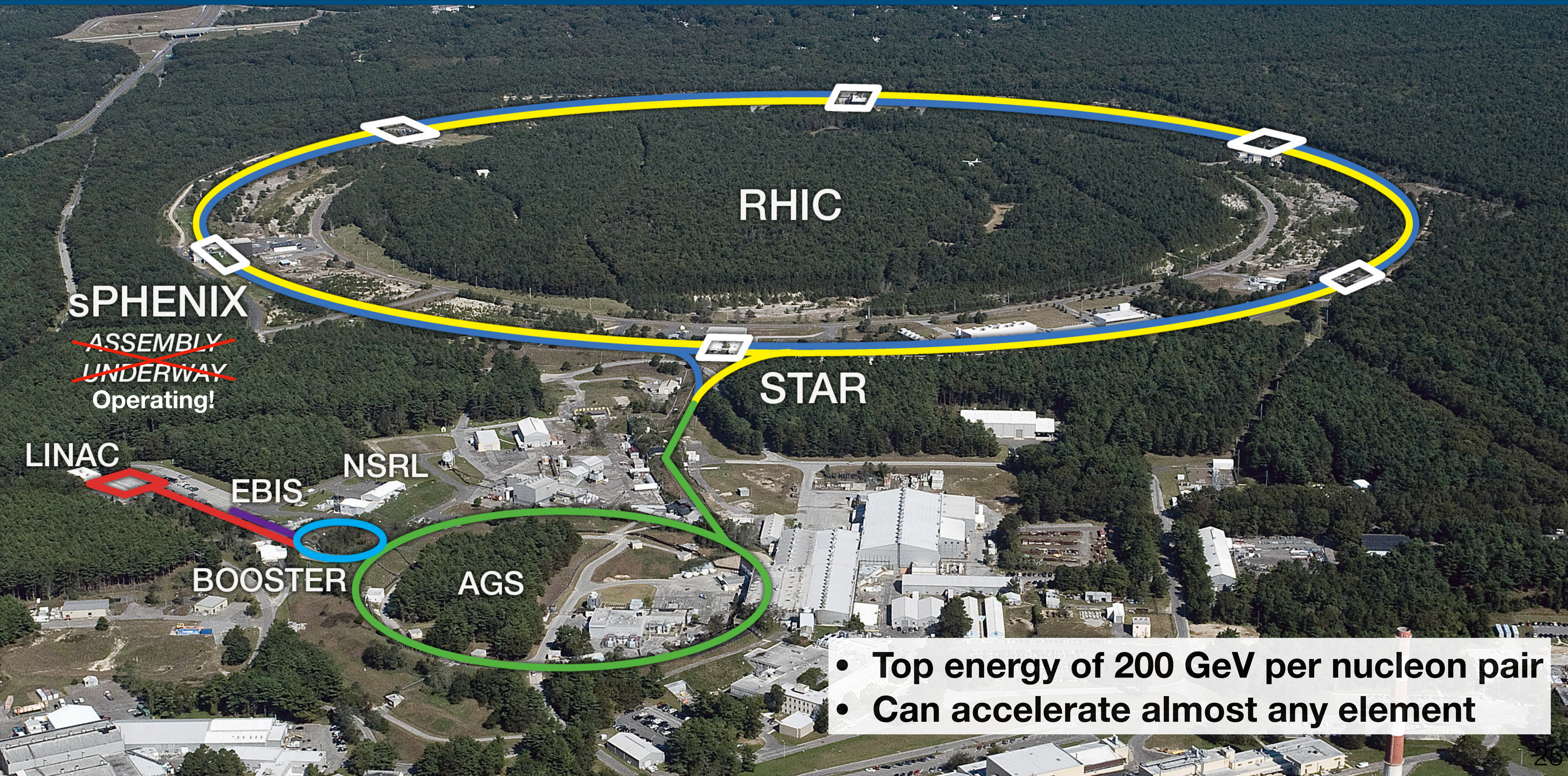


Heavy Ion Collisions



- 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



sPHENIX
~~ASSEMBLY
UNDERWAY~~
Operating!

RHIC

STAR

LINAC

EBIS

NSRL

BOOSTER

AGS

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

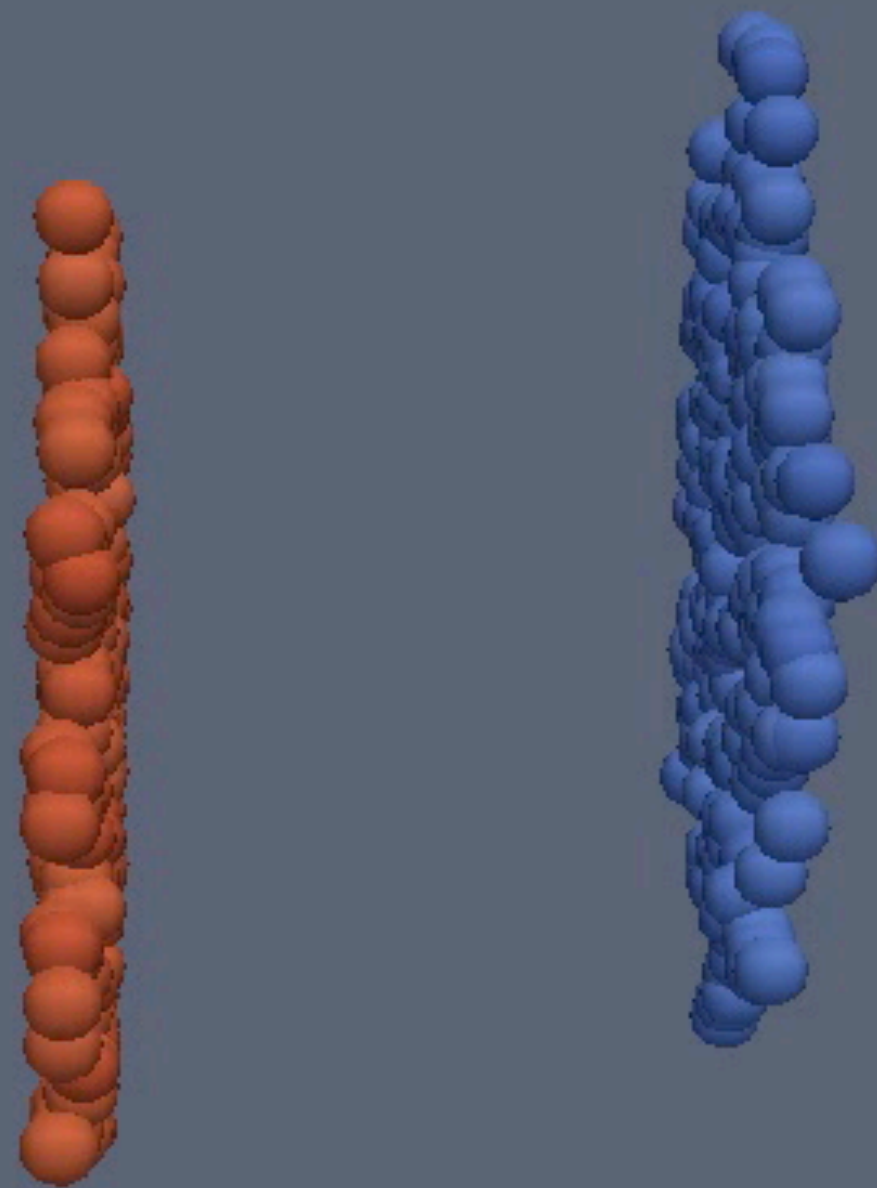
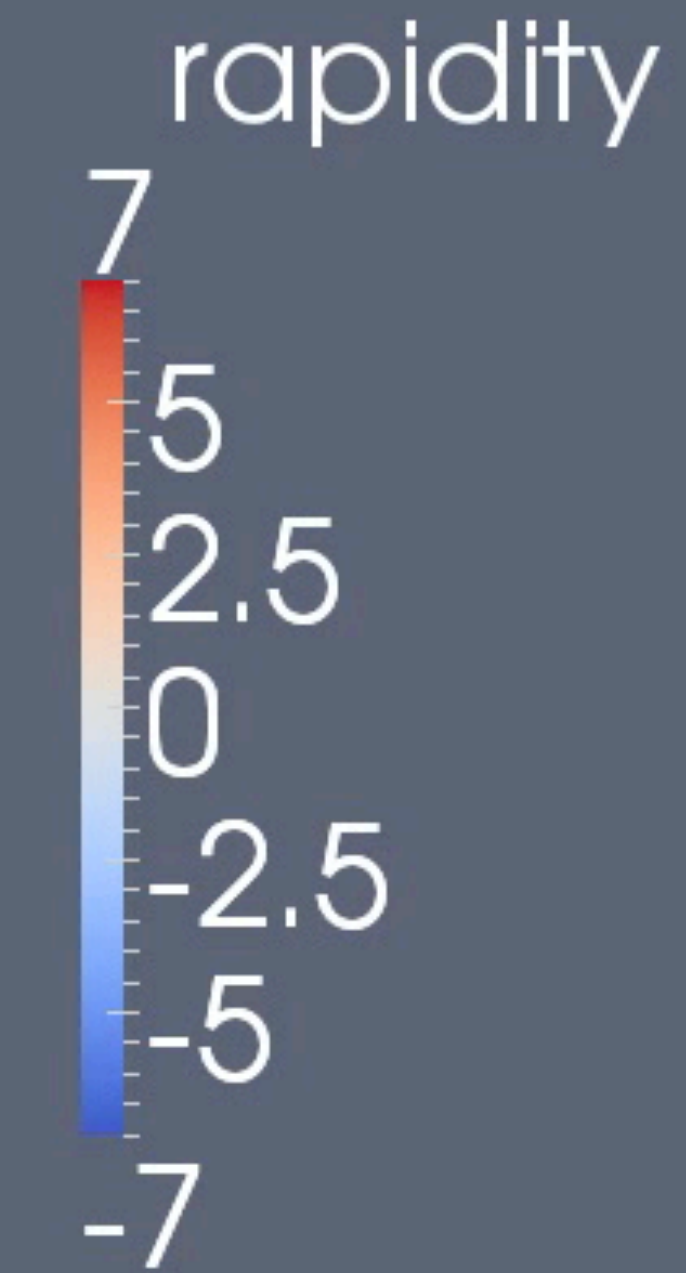
Large Hadron Collider



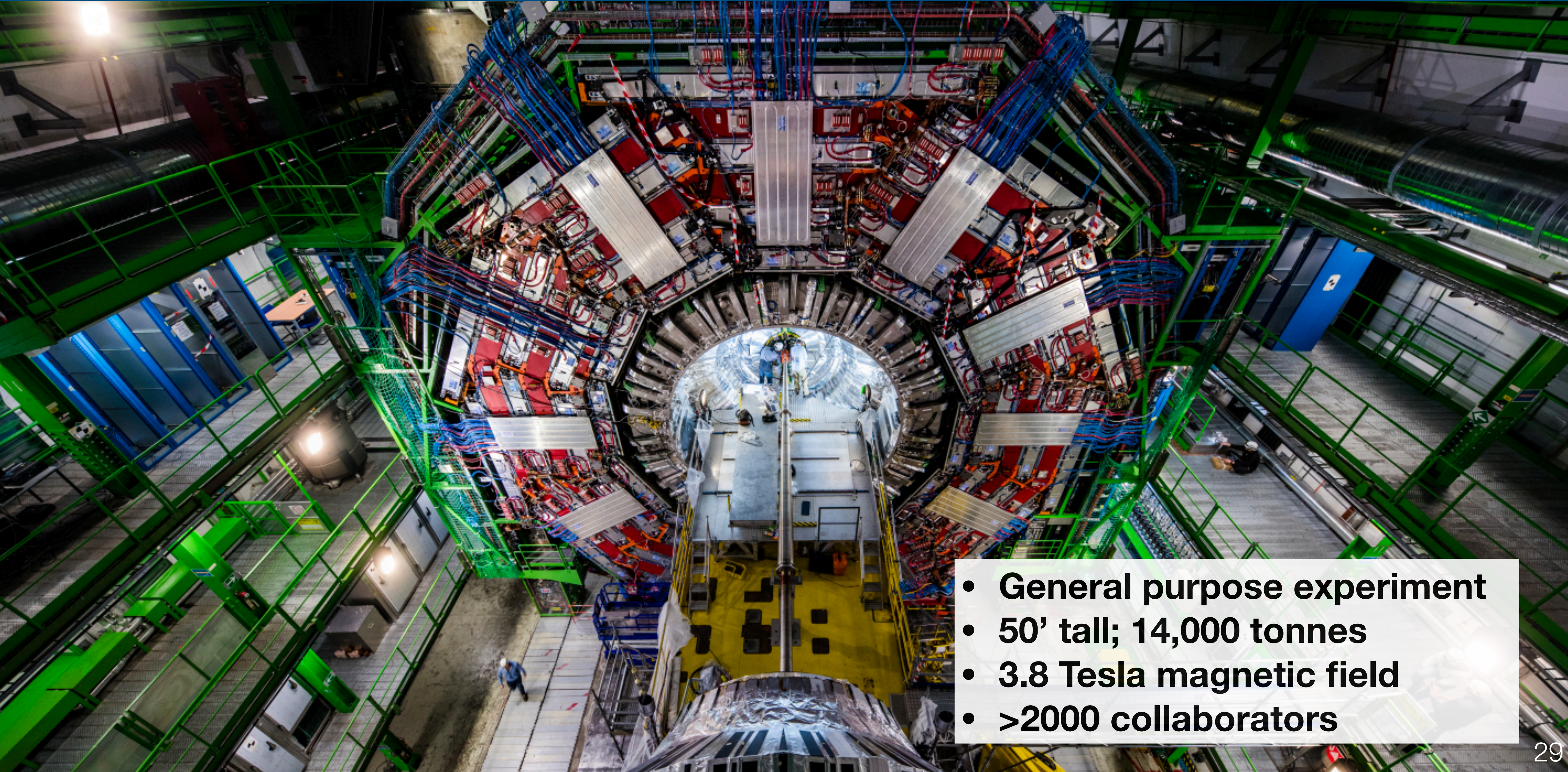
- Runs heavy ions ~1 month / year
- Top energy of 5.5 TeV per nucleon pair: 1 PeV (0.1 mJ) total collision energy
- Accelerates protons, Pb^{208} , Xe^{129}

Heavy Ion Collisions

Time: 0.10

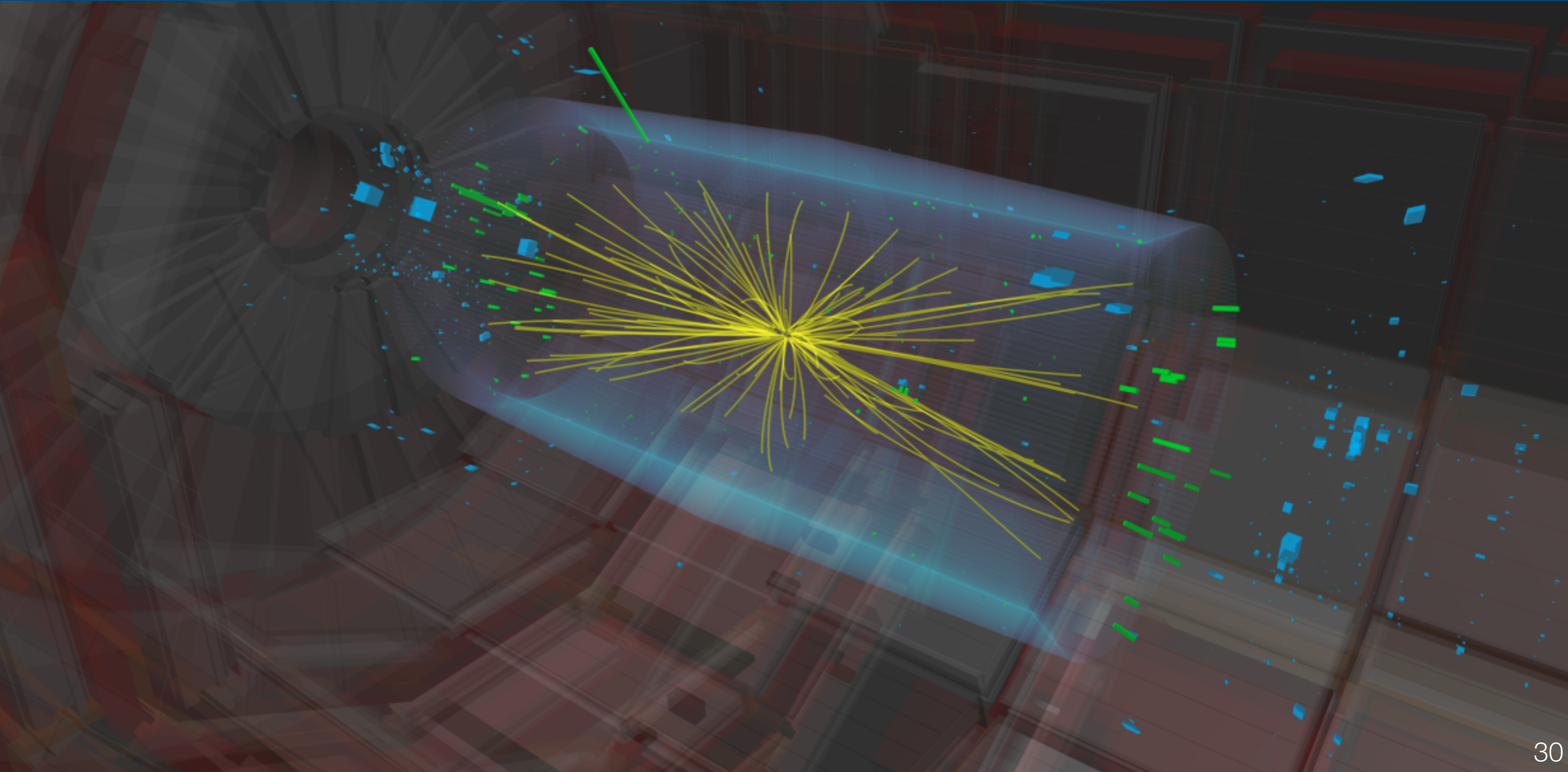


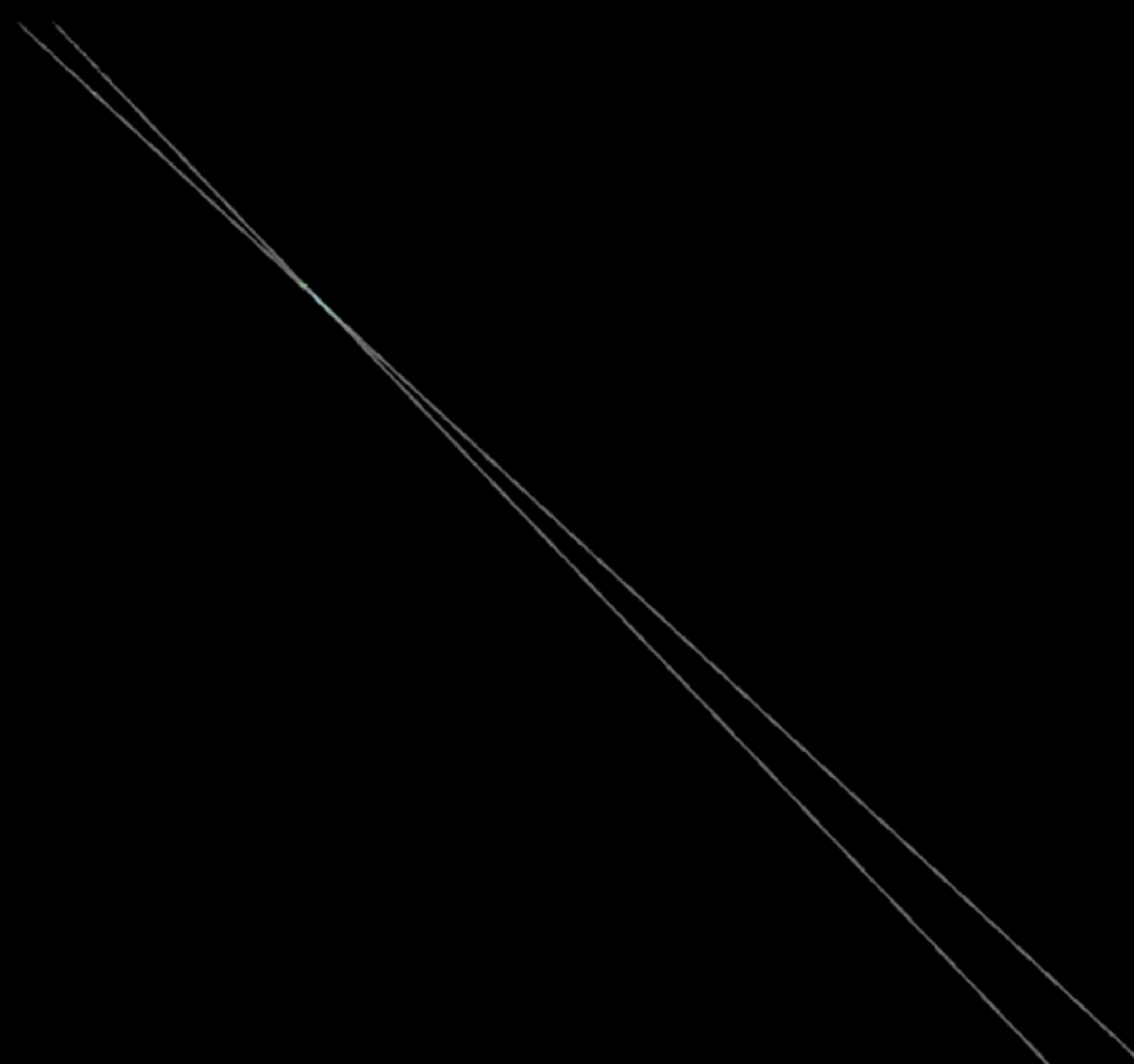
Compact Muon Solenoid



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

pp Event (Not nucleus collision!)





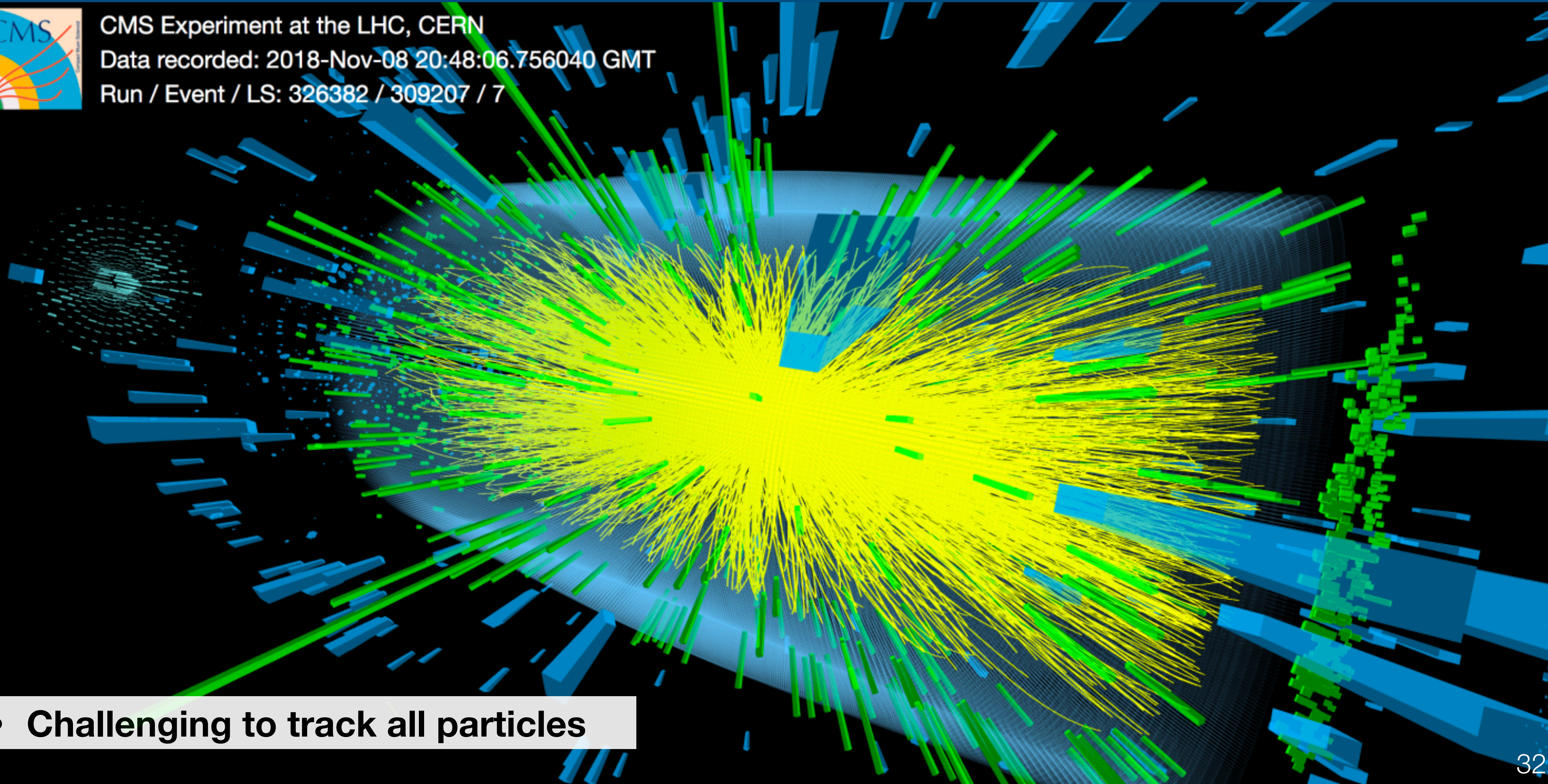
Nucleus-Nucleus (PbPb) Collision



CMS Experiment at the LHC, CERN

Data recorded: 2018-Nov-08 20:48:06.756040 GMT

Run / Event / LS: 326382 / 309207 / 7

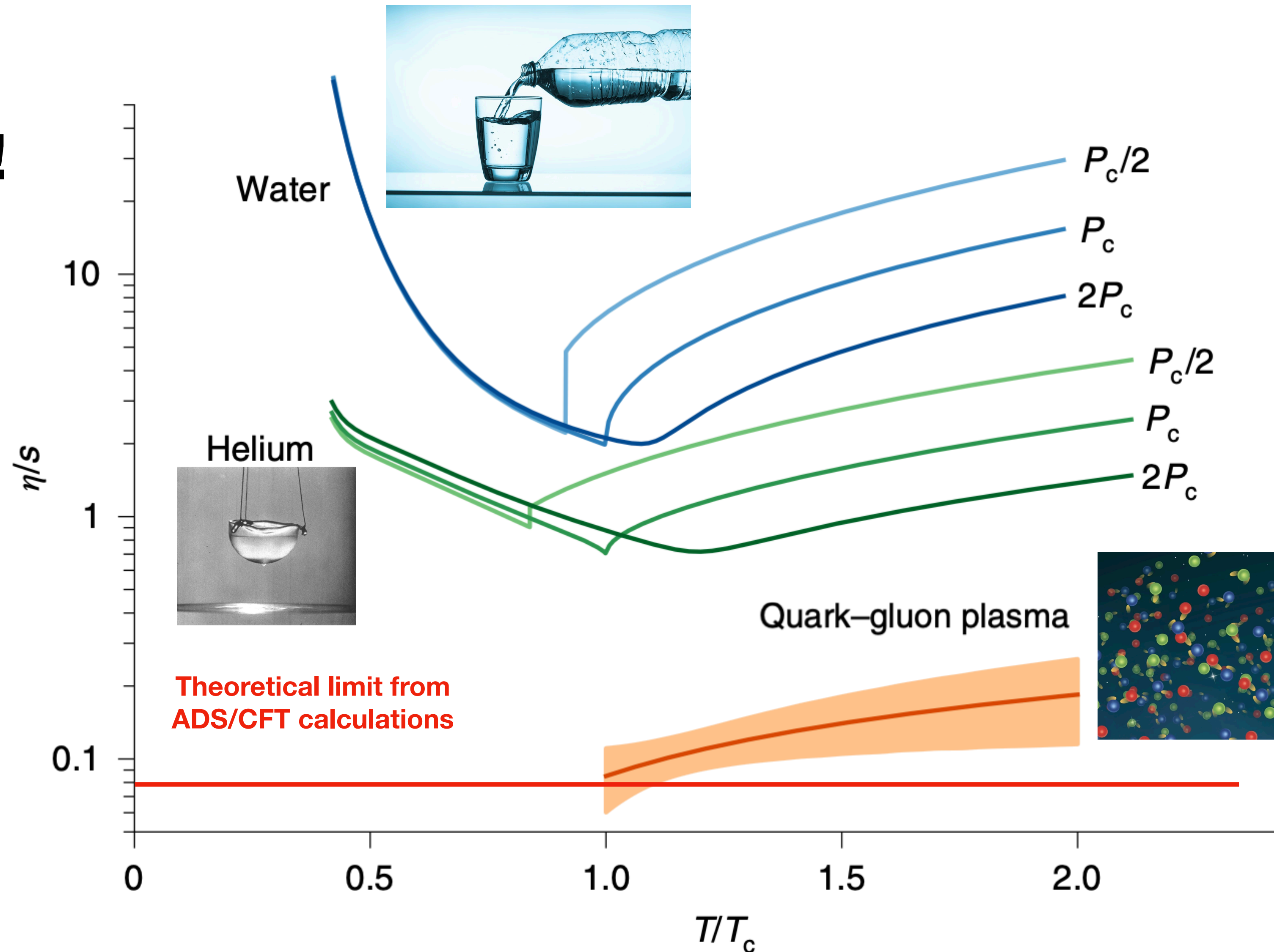


- Challenging to track all particles

“Perfect Liquid”

Nature Physics volume 15, 1113–1117 (2019)

- QGP behaves like a liquid!
- Viscosity - ‘thickness’ of the fluid
- QGP ‘flows’ very easily



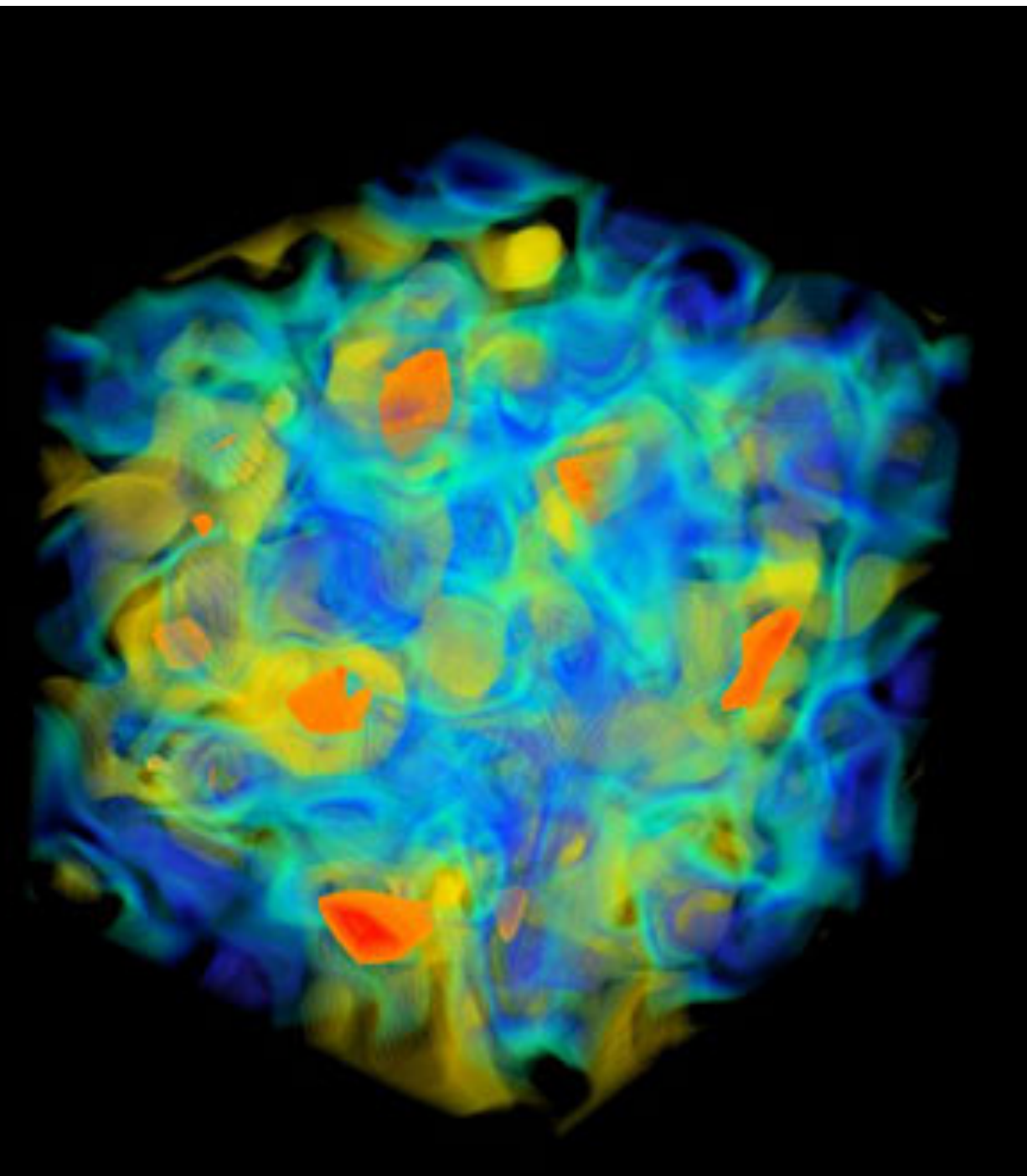
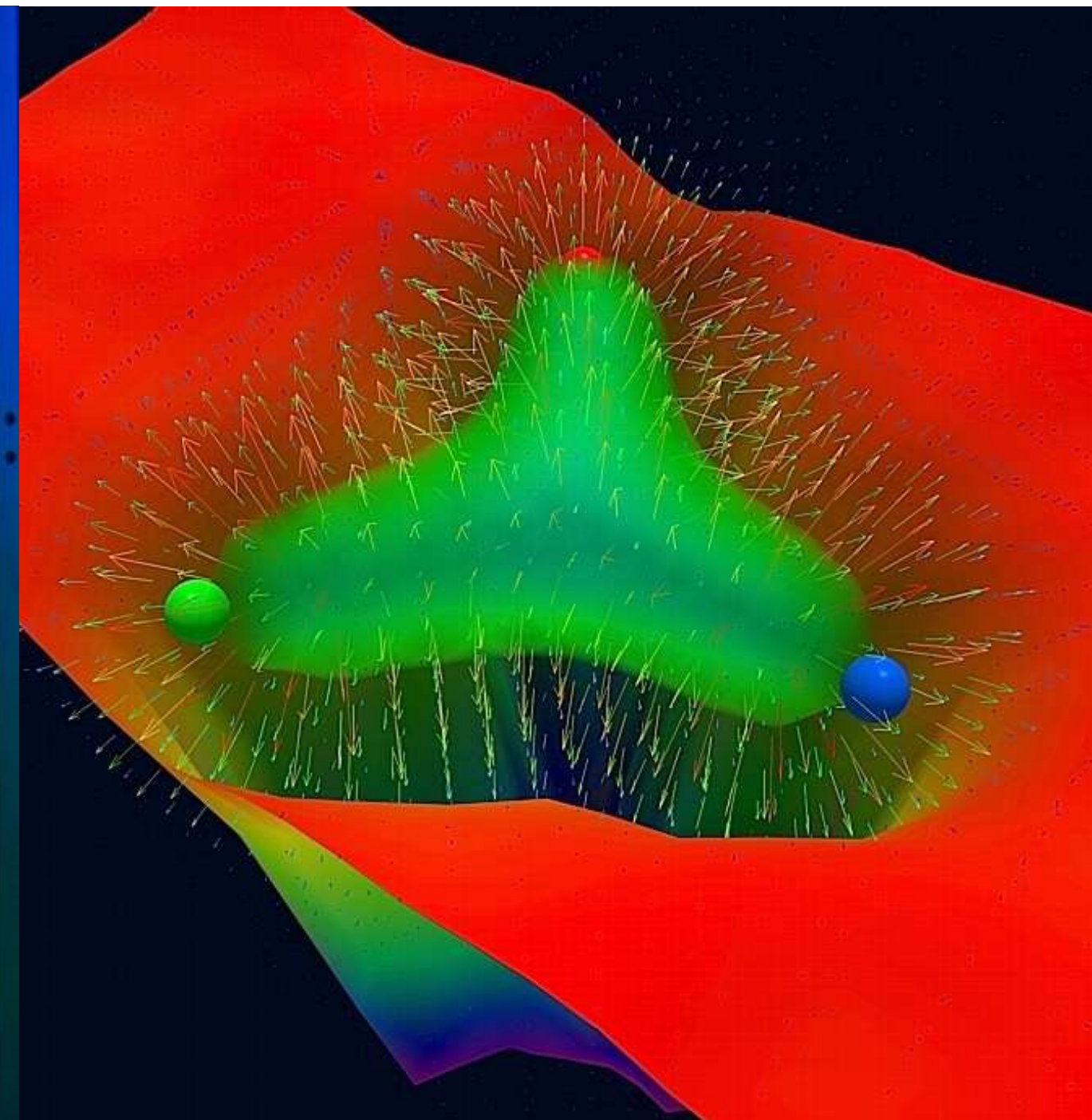
Speed of sound in QGP?

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



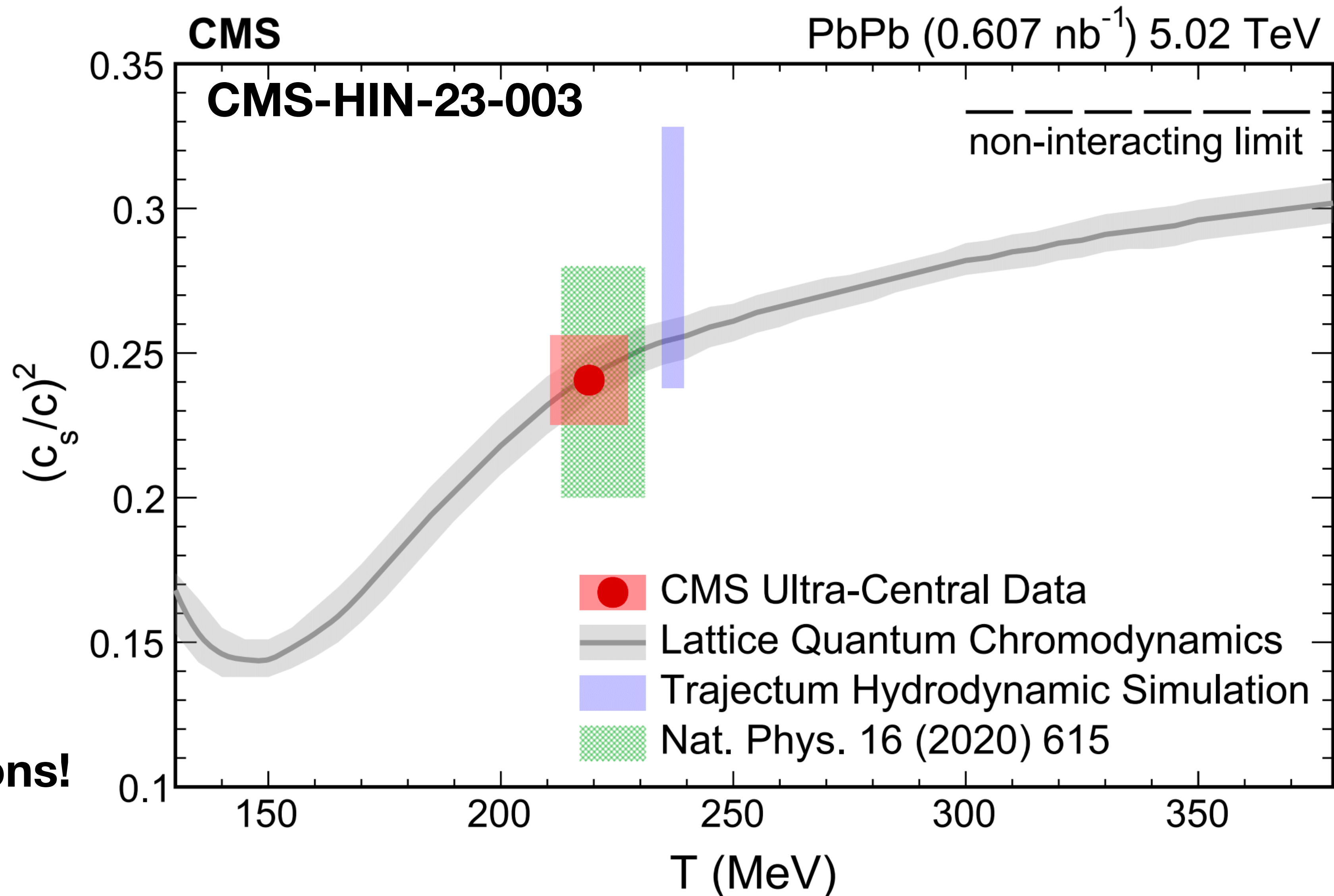
Lattice QCD

- **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?**



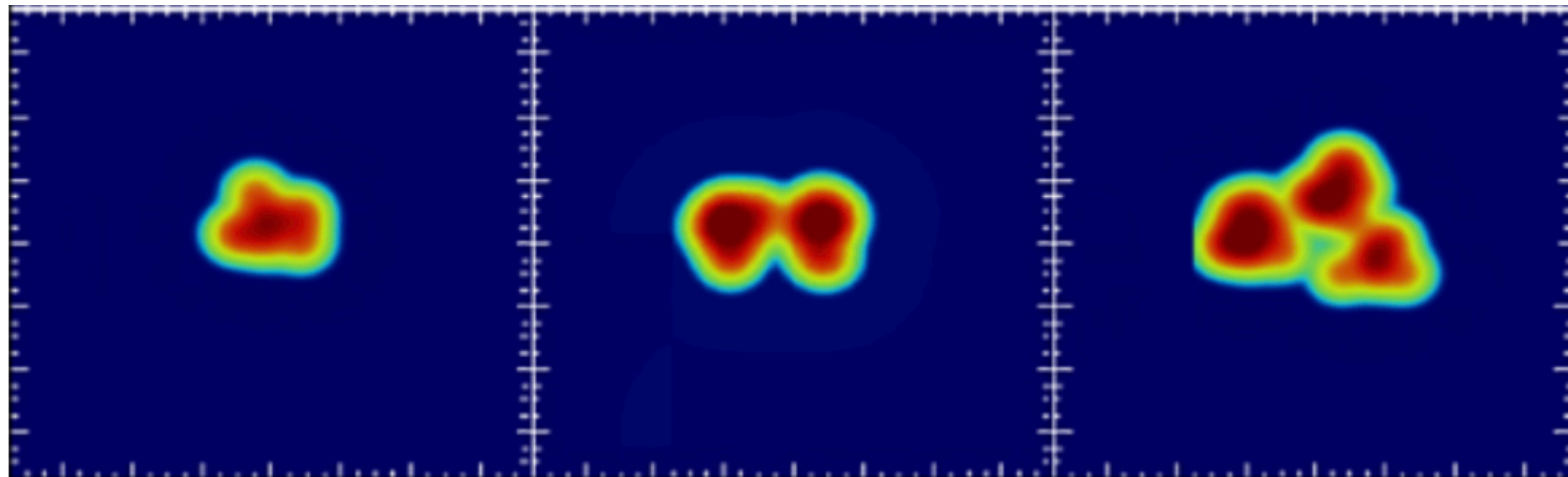
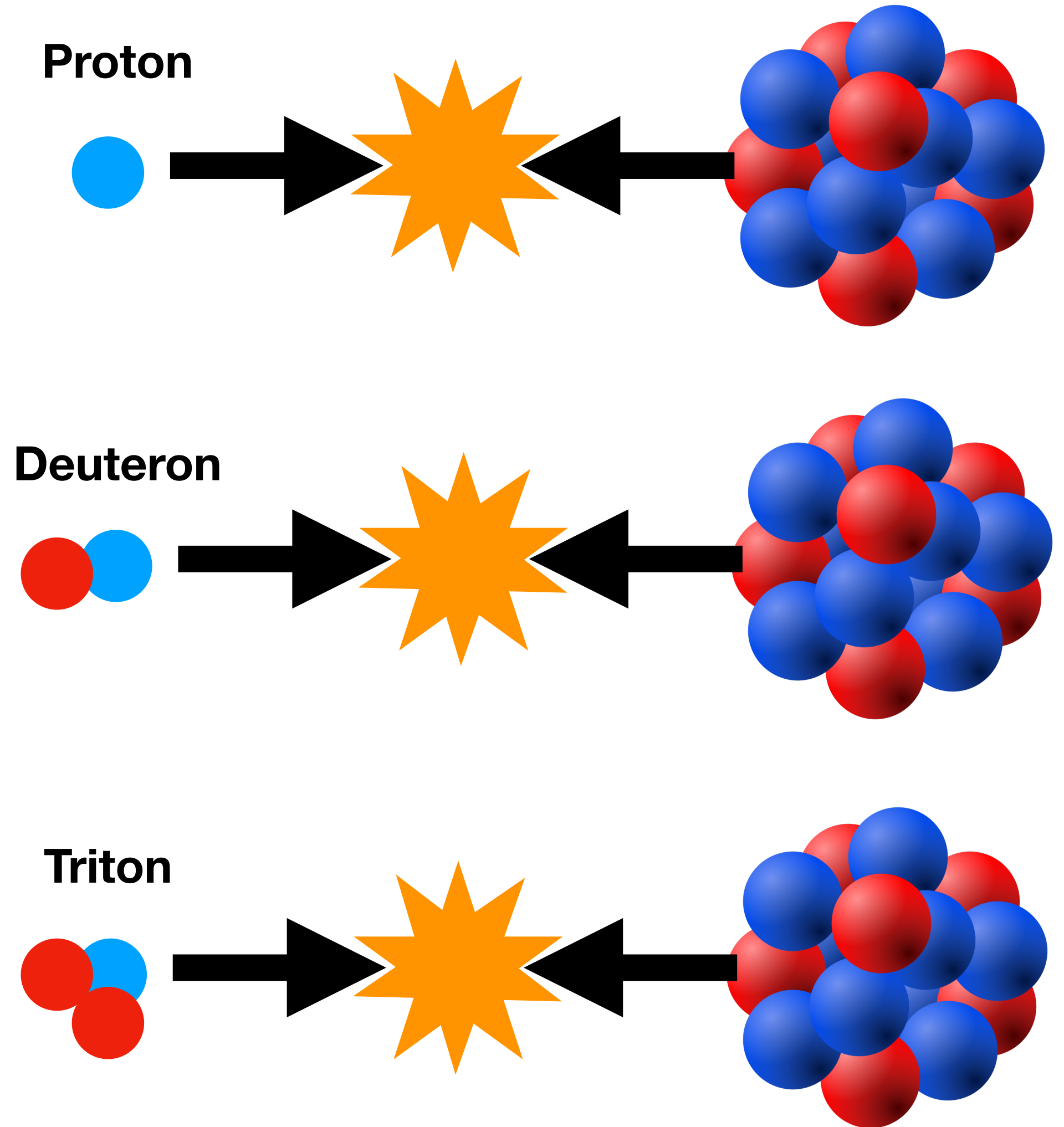
QGP Speed of Sound

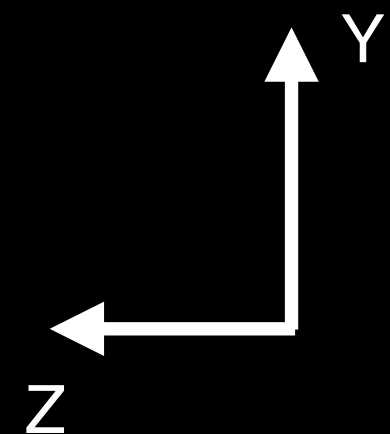
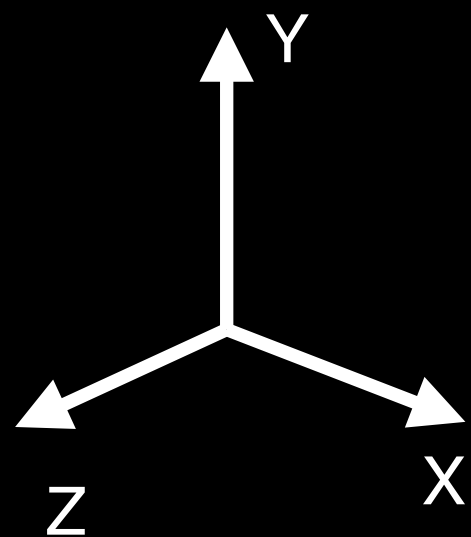
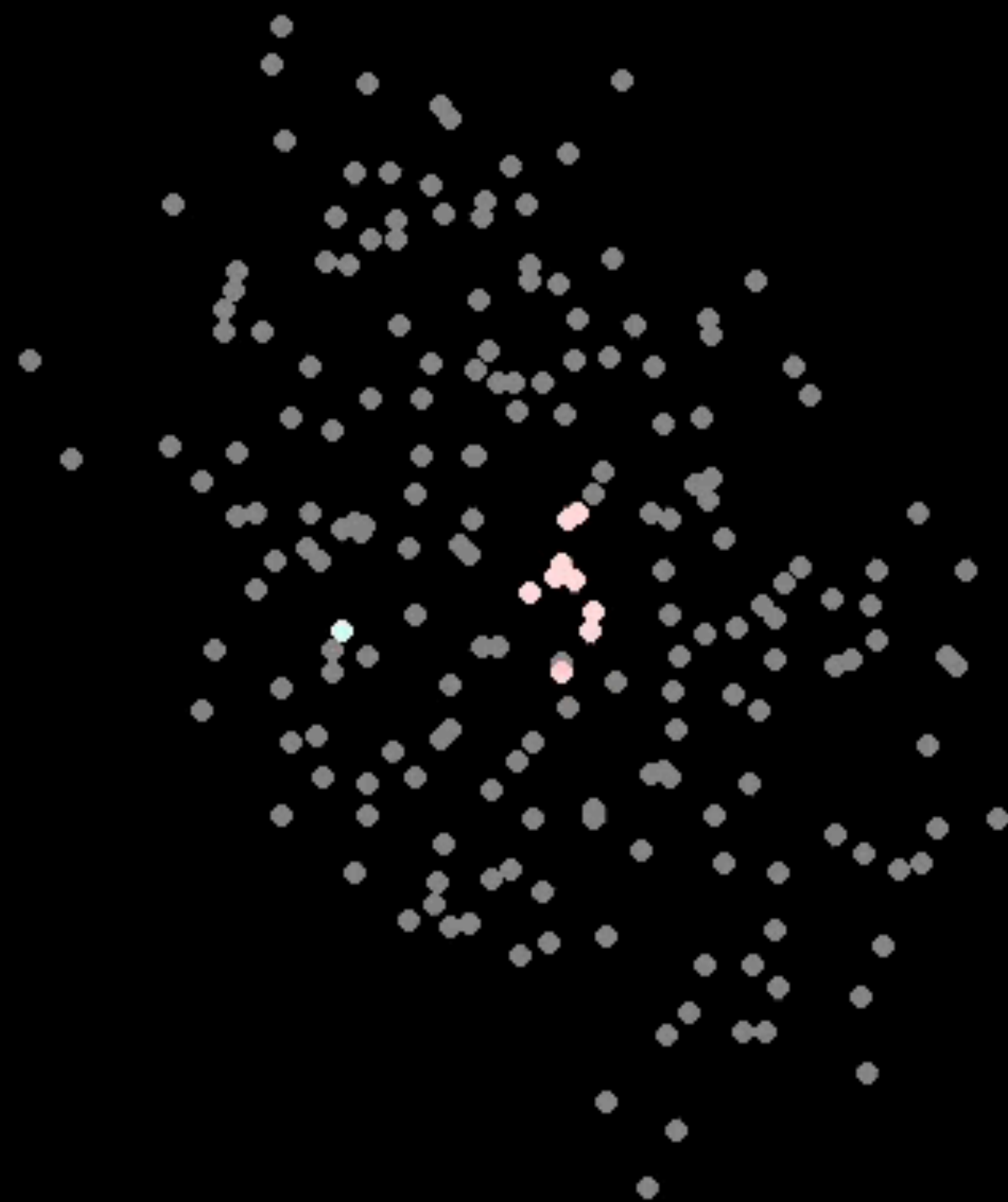
- In air: 343 m/s
- In water: 1500 m/s
- In steel: 5000 m/s
- In QGP: 150,000,000 m/s
- Excellent **agreement** with Lattice QCD!
- Testing how well we understand quarks and gluons!



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



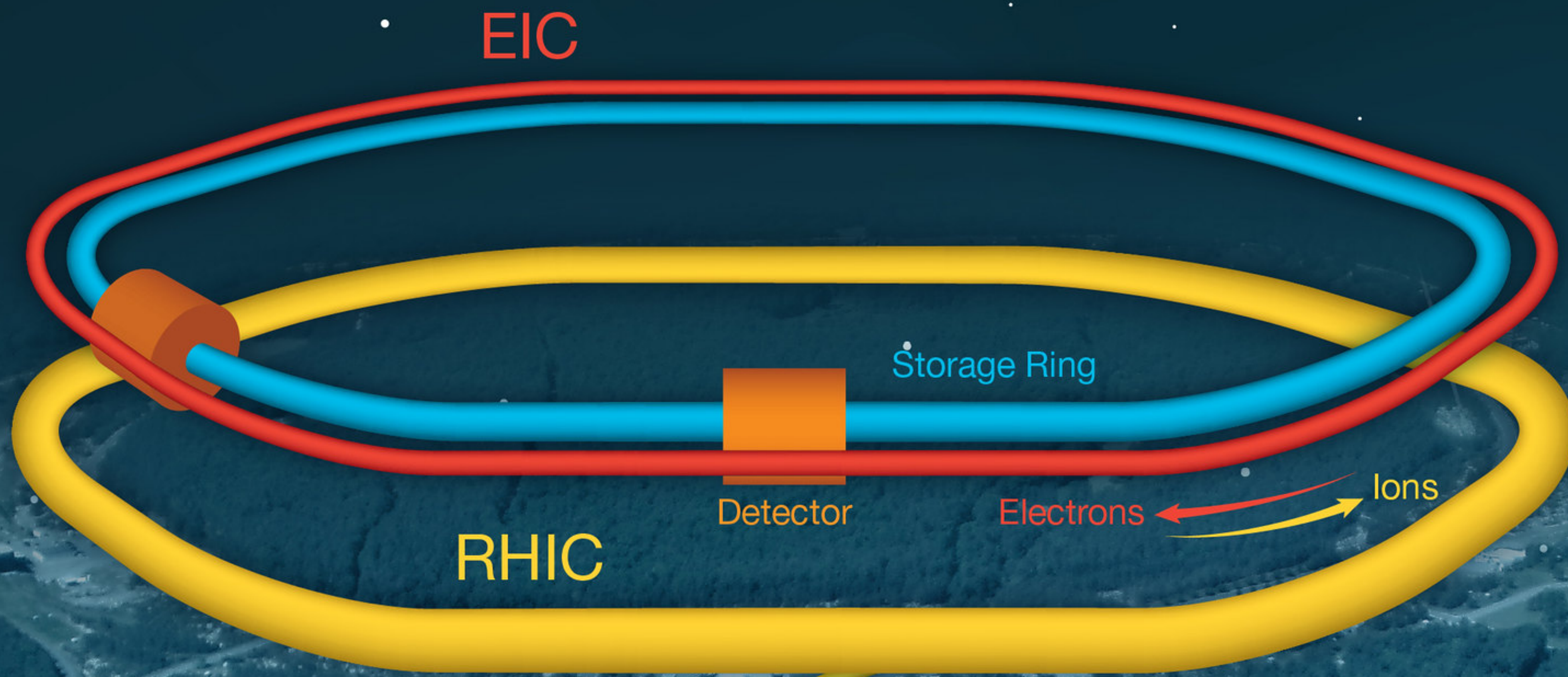


Simulation from Chun Shen

The Electron-Ion Collider

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



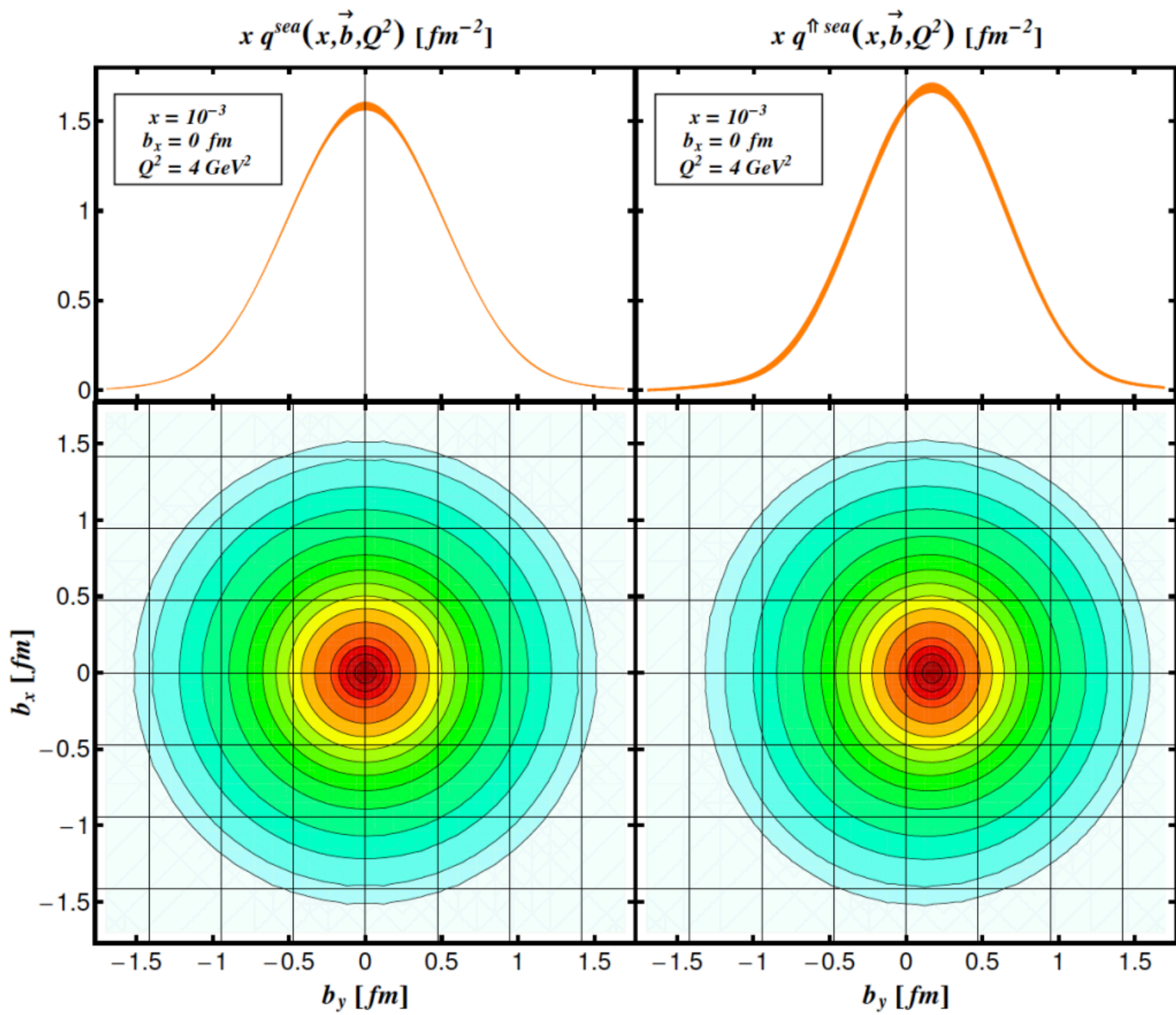


Large energy range: 20-140 GeV
High luminosities
Polarized electrons/protons
Many ion species: proton - Uranium

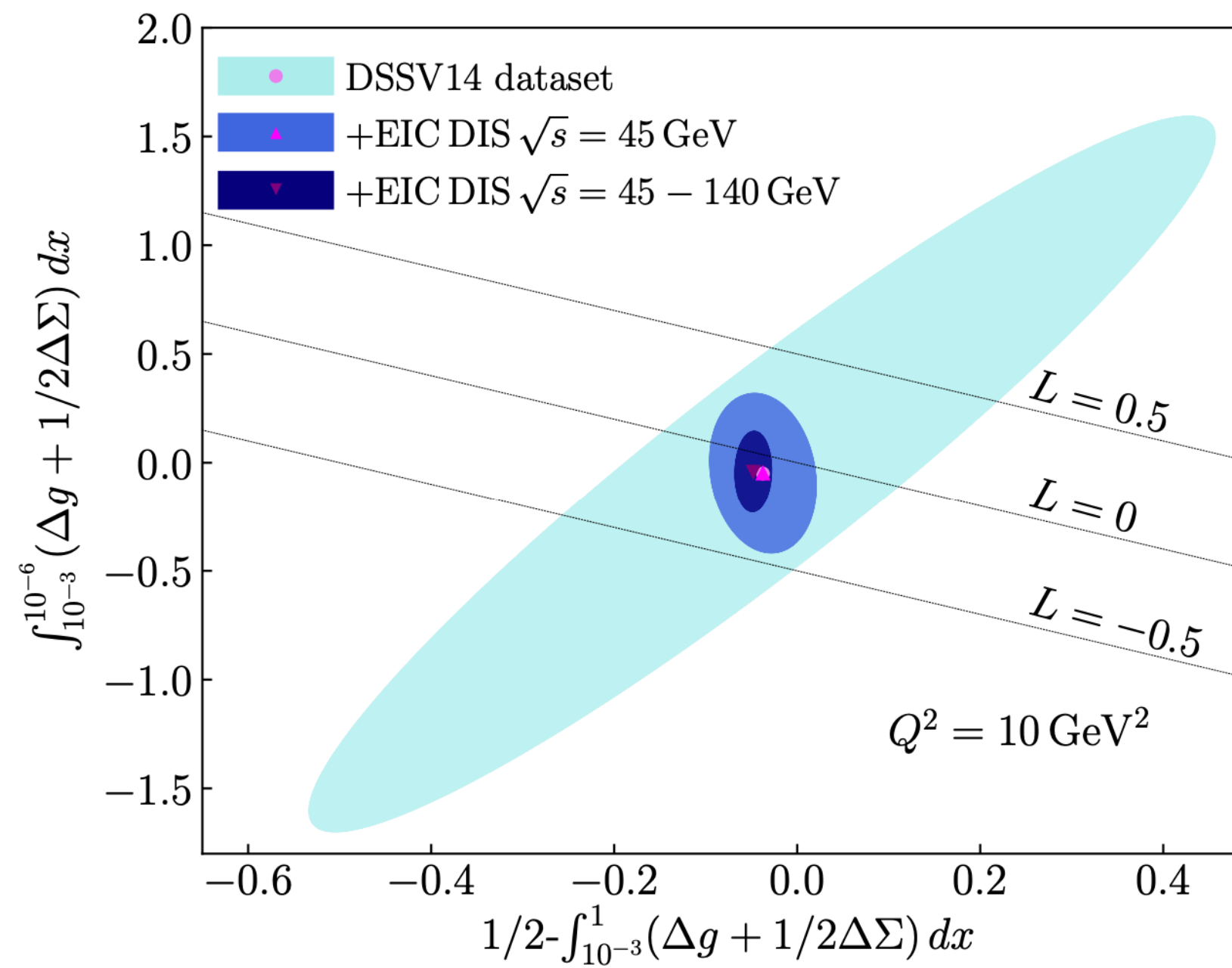
AGS

EIC Physics

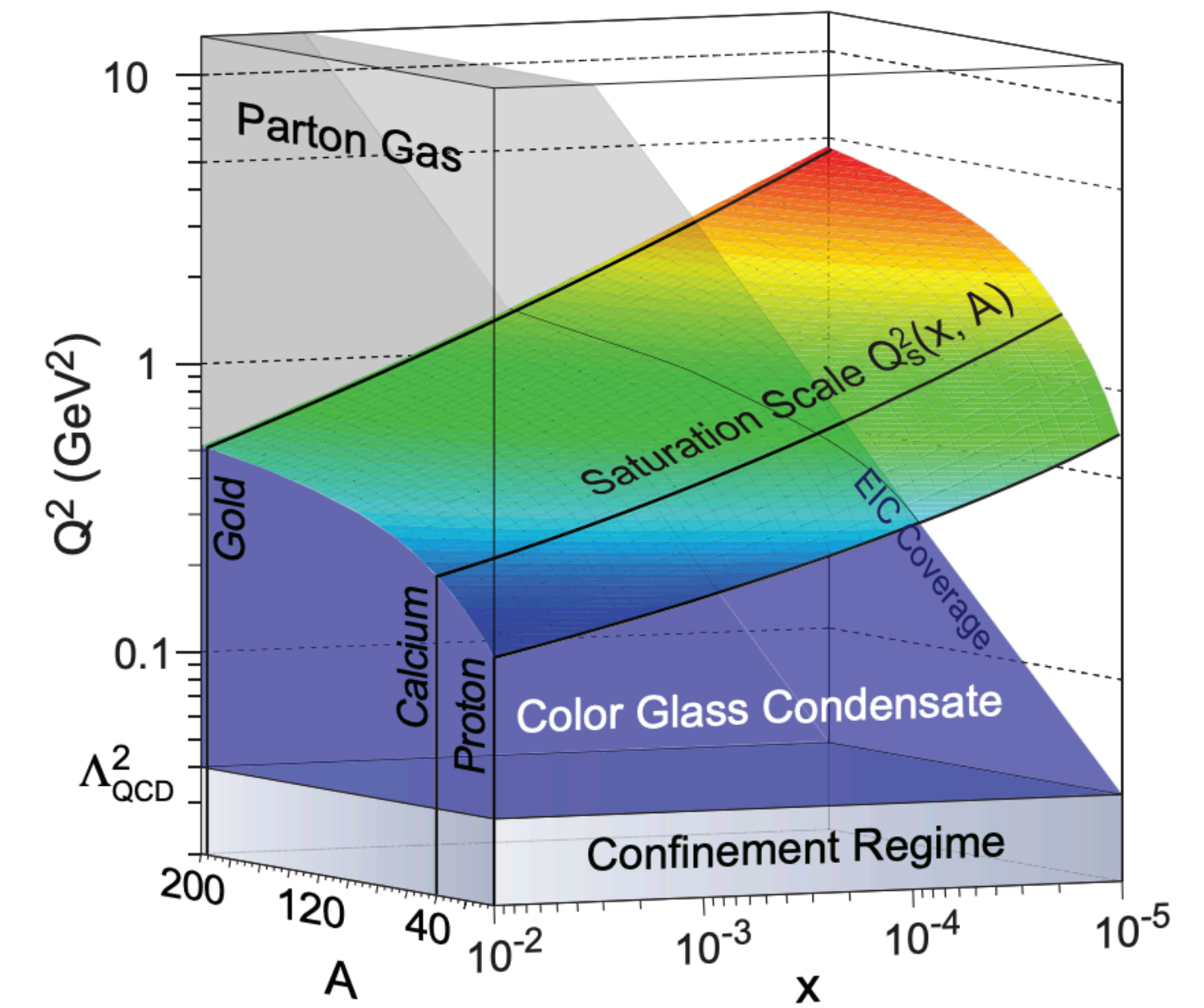
Take pictures of quarks/gluons inside proton/nuclei



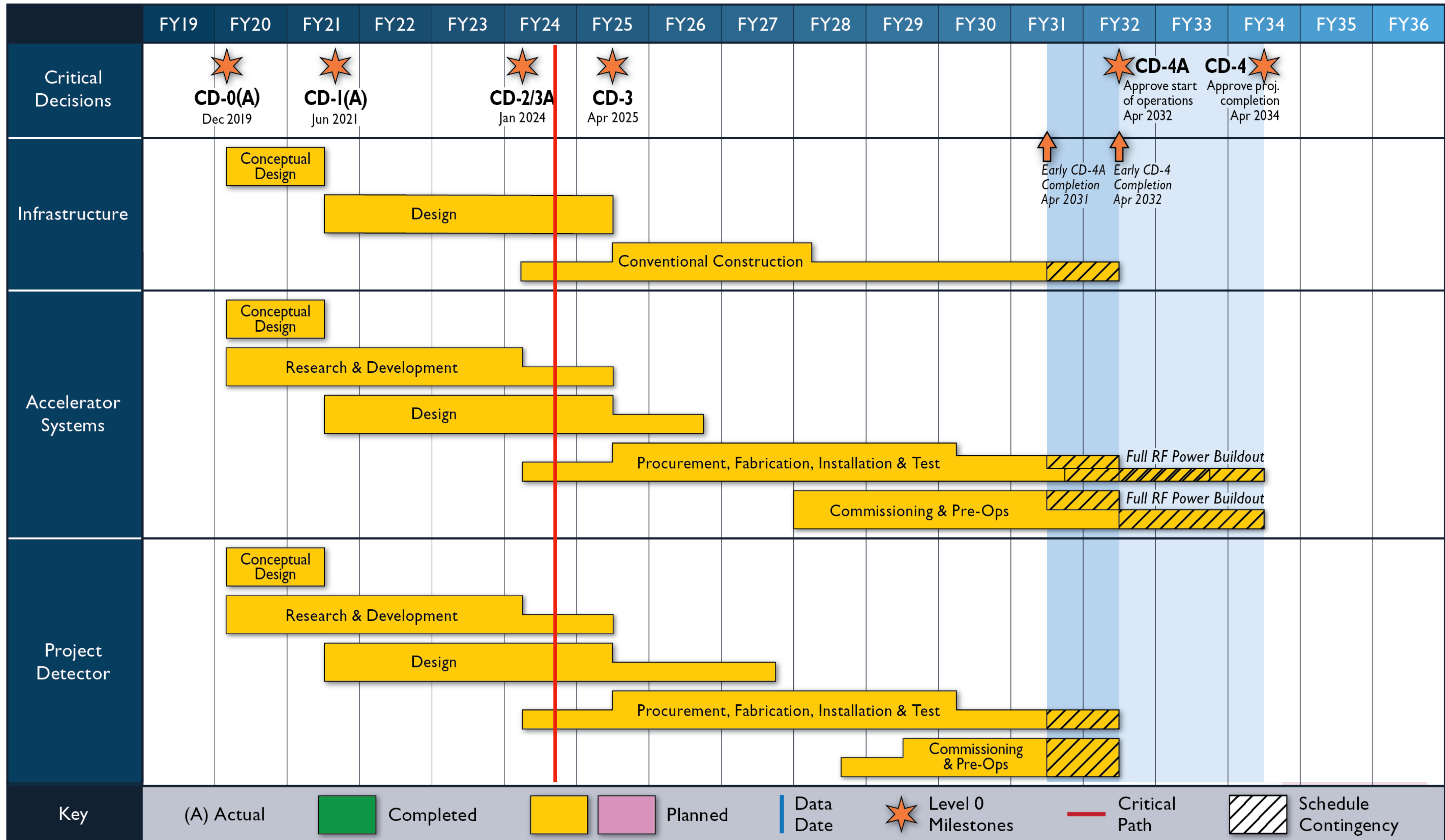
How do nuclei spin?



Upper limit on number of gluons in the nucleus?

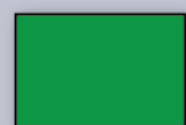


EIC Schedule



Key

(A) Actual



Completed



Planned



Data Date



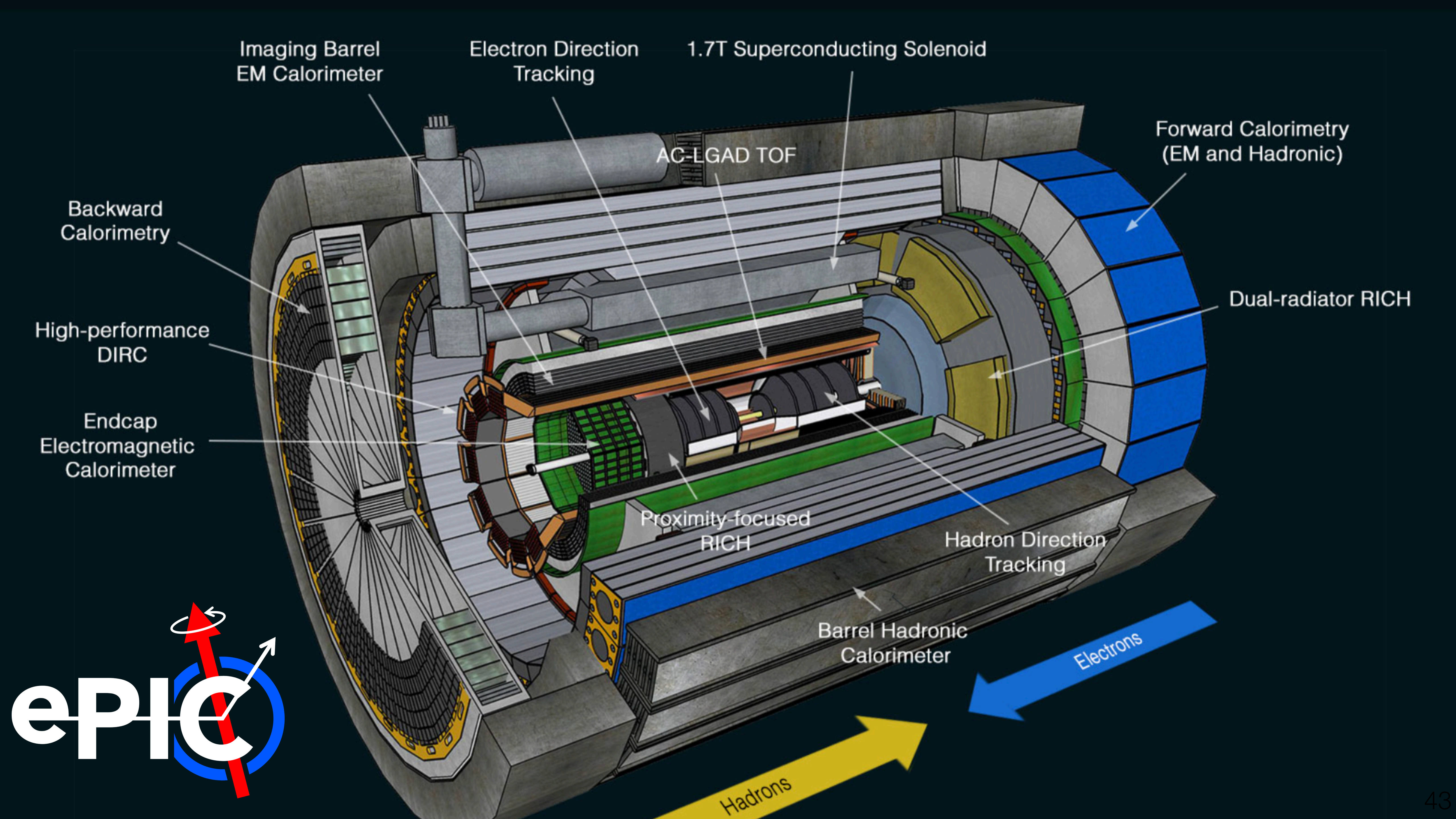
Level 0 Milestones



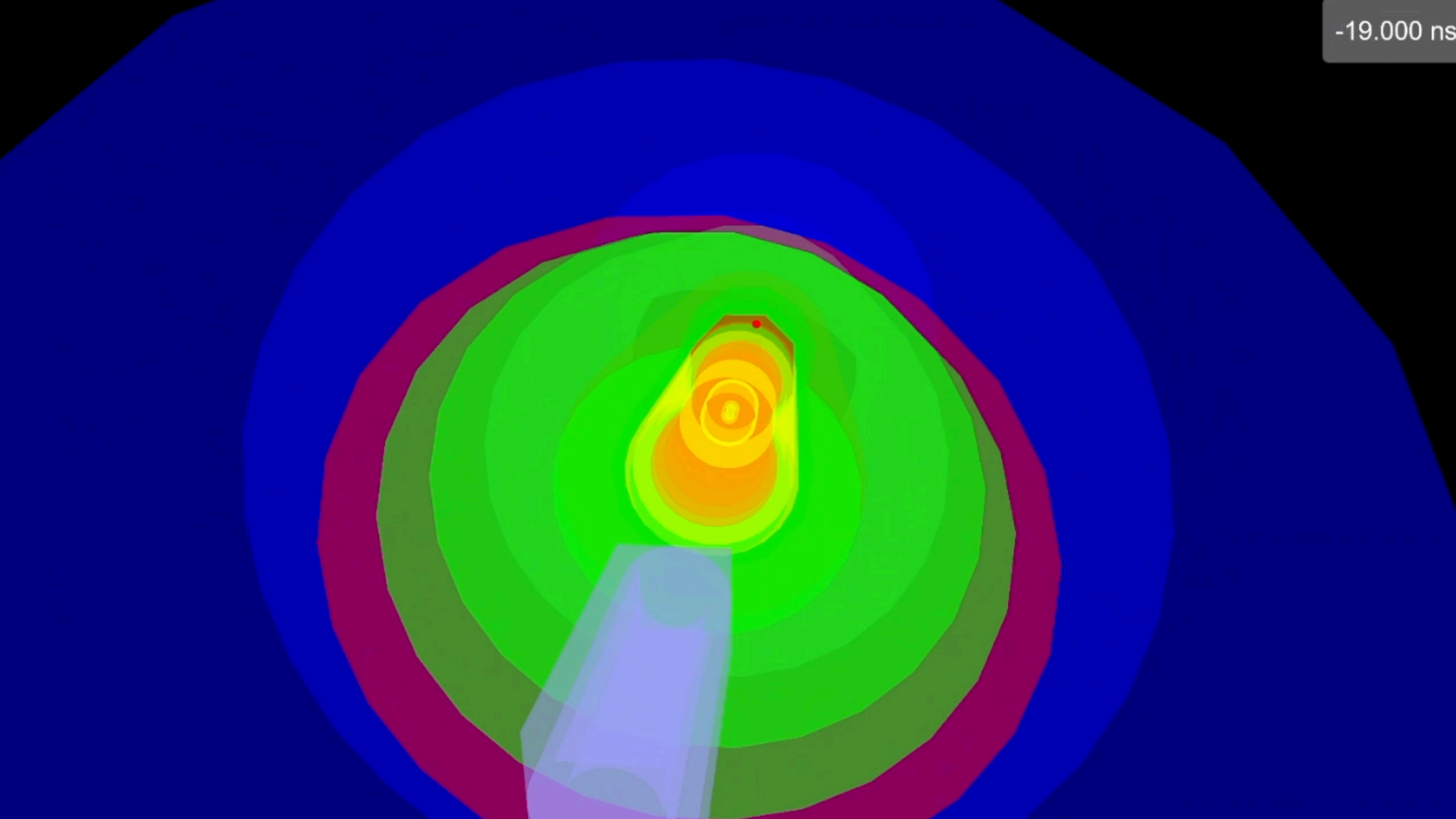
Critical Path



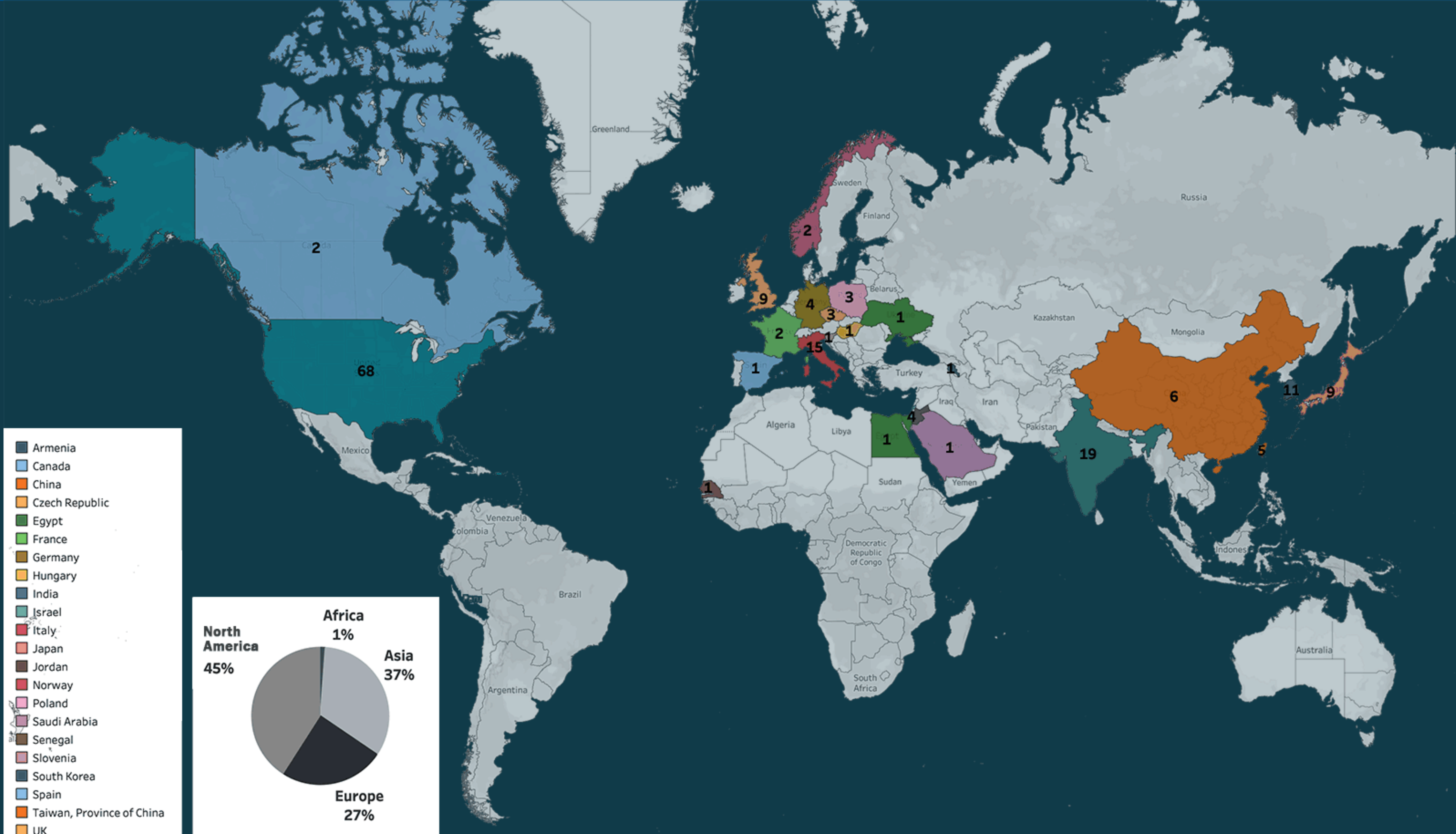
Schedule Contingency



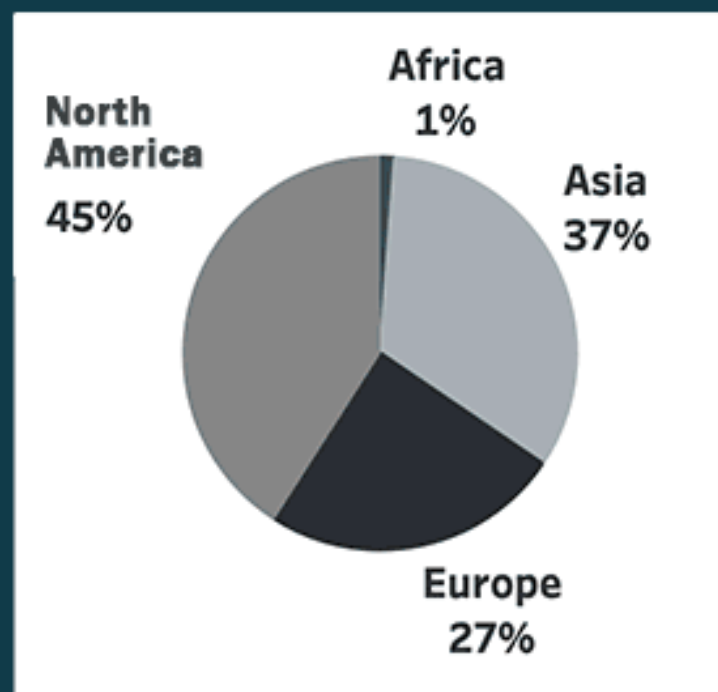
-19.000 ns



ePIC Collaboration



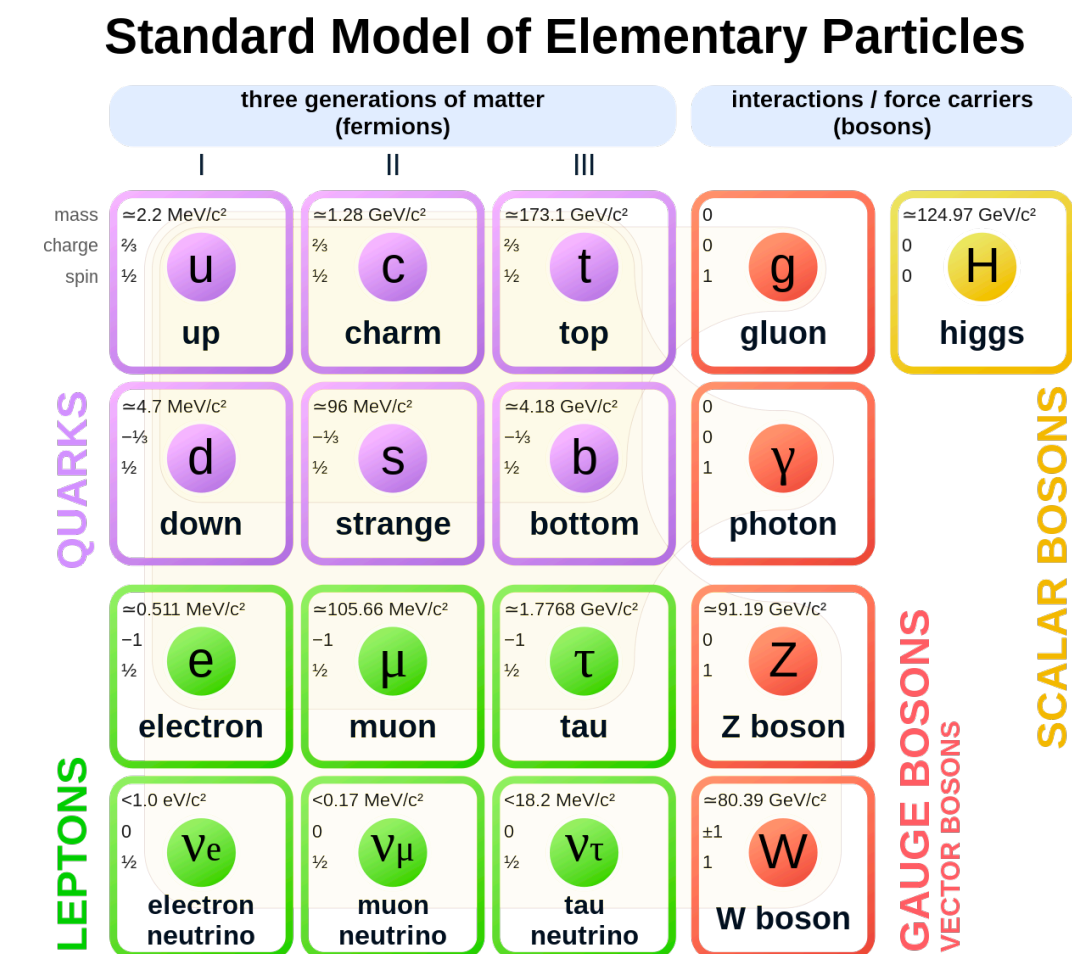
- Armenia
- Canada
- China
- Czech Republic
- Egypt
- France
- Germany
- Hungary
- India
- Israel
- Italy
- Japan
- Jordan
- Norway
- Poland
- Saudi Arabia
- Senegal
- Slovenia
- South Korea
- Spain
- Taiwan, Province of China
- UK
- Ukraine
- United States



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

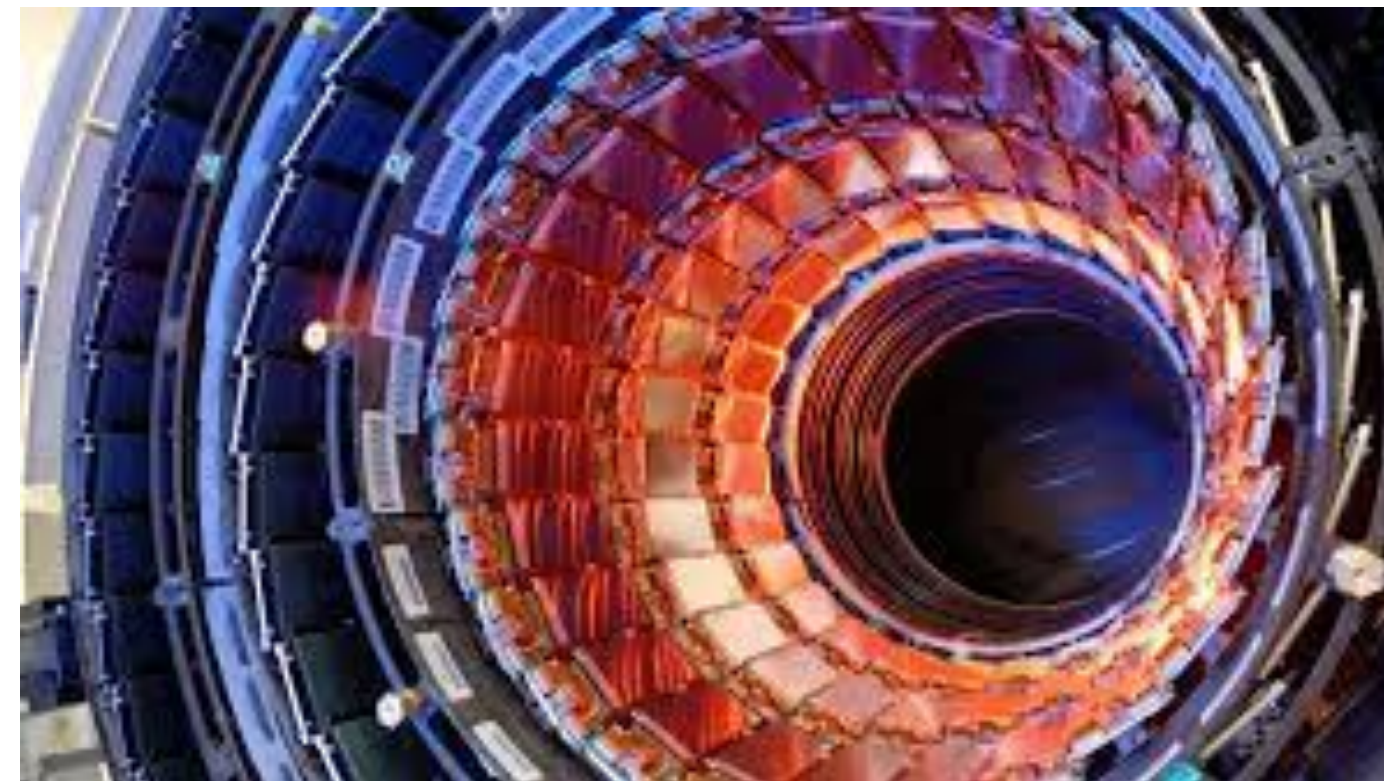


```

7 pub type Matrix4 = Matrix<f32, U4, U4, ArrayStorage<f32, U4, U4>>;
8 pub type Matrix3 = Matrix<f32, U3, U3, ArrayStorage<f32, U3, U3>>;
9 pub type Matrix2 = Matrix<f32, U2, U2, ArrayStorage<f32, U2, U2>>;
10 impl Mul<Tuple> for Matrix4 {
11     type Output = Tuple;
12     fn mul(self, other: Tuple) -> Tuple {
13         Tuple::new(
14             self[(0, 0)] * other.x
15             + self[(0, 1)] * other.y
16             + self[(0, 2)] * other.z
17             + self[(0, 3)] * other.w,
18             self[(1, 0)] * other.x
19             + self[(1, 1)] * other.y
20             + self[(1, 2)] * other.z
21             + self[(1, 3)] * other.w,
22             self[(2, 0)] * other.x
23             + self[(2, 1)] * other.y
24             + self[(2, 2)] * other.z
25             + self[(2, 3)] * other.w,
26             self[(3, 0)] * other.x
27             + self[(3, 1)] * other.y
28             + self[(3, 2)] * other.z
29             + self[(3, 3)] * other.w
30         )
31     }
32 }

```

Programming



Particle Detectors



International Collaborations 46

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!

