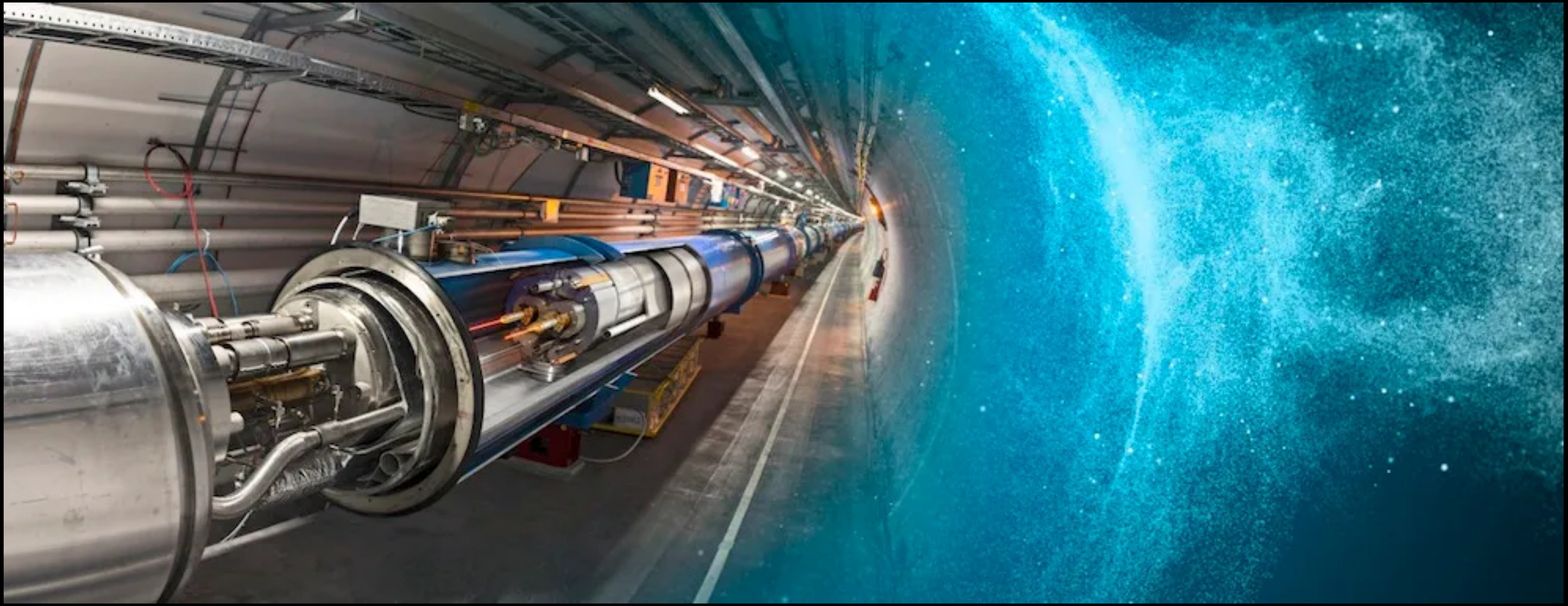
Estudio de la materia en condiciones extremas: del cosmos a los aceleradores de partículas



Alba Soto Ontoso

Seminario de Invitados — Máster en Física

Granada, 8-9th January, 2024

PRELUDIO

Quién soy yo?

Sep 2010-June 2015, **BSc. + MS.c Physics** @University of Sevilla + Granada (Spain)

Sep 2015-June 2018, **Ph.D** @University of Granada (Spain) + Goethe University (Germany) w/ Javier L. Albacete and Hannah Elfner

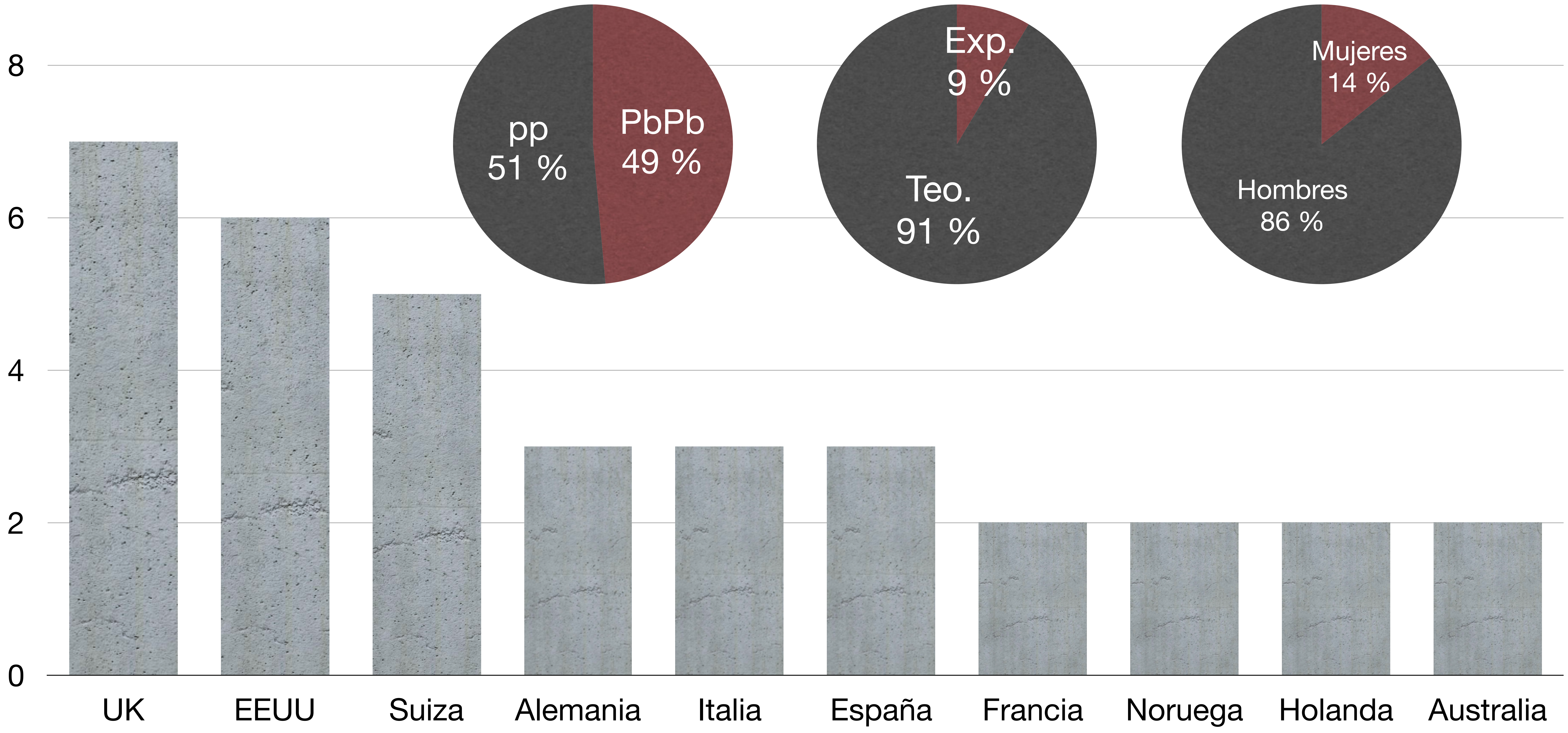
Oct 2018-Oct 2020, **Research Associate** @Brookhaven National Lab (USA) w/ Yacine Mehtar-Tani

Oct 2020-Oct 2022, **Postdoc** @Institute de Physique Theorique (France) w/ Gregory Soyez

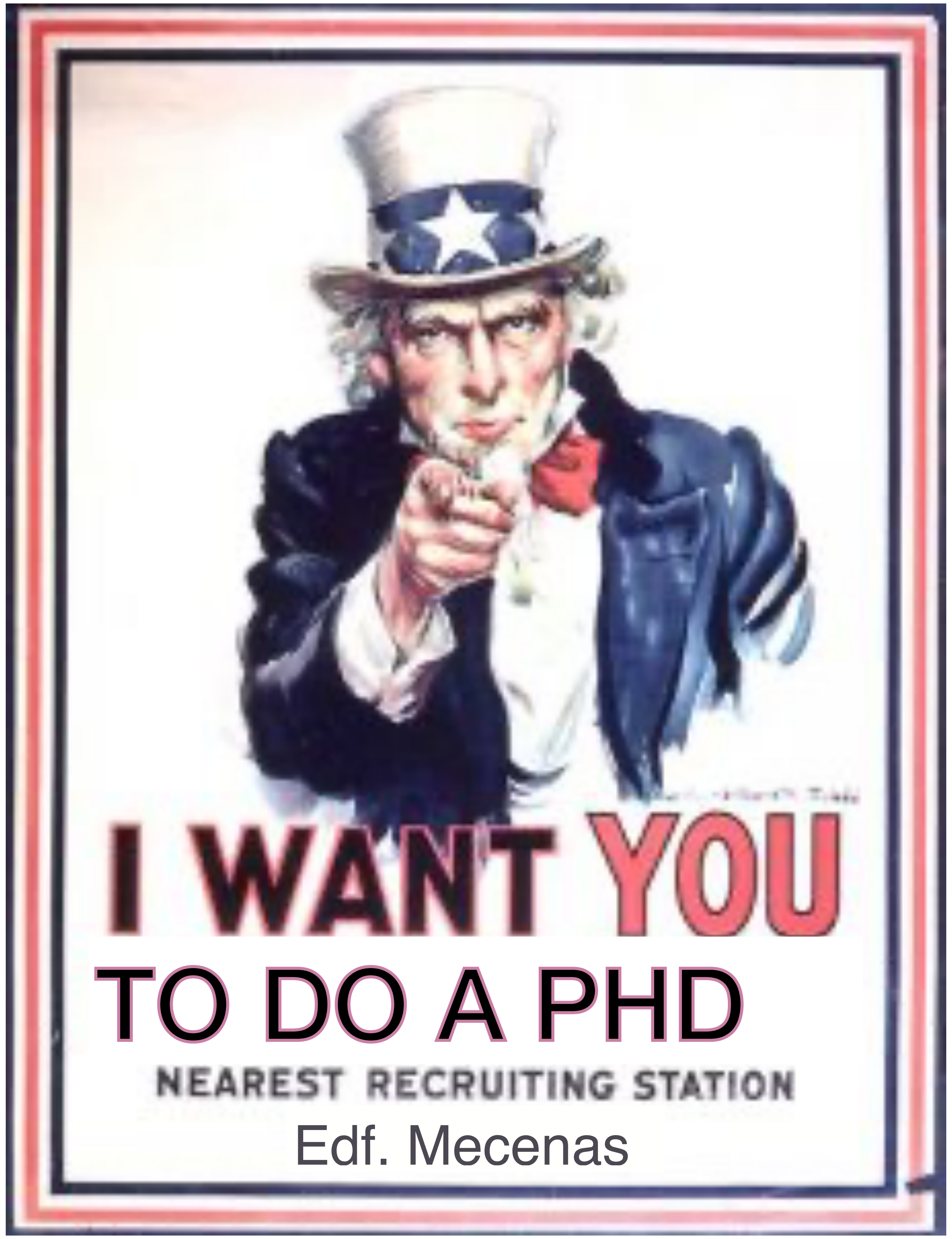
Oct 2022-Sep 2024, **Senior fellow** @CERN (Switzerland)

Sep 2024-$\infty(?)$, **Ramón y Cajal** @University of Granada (Spain)

Mi red de colaboradores/as



Únete

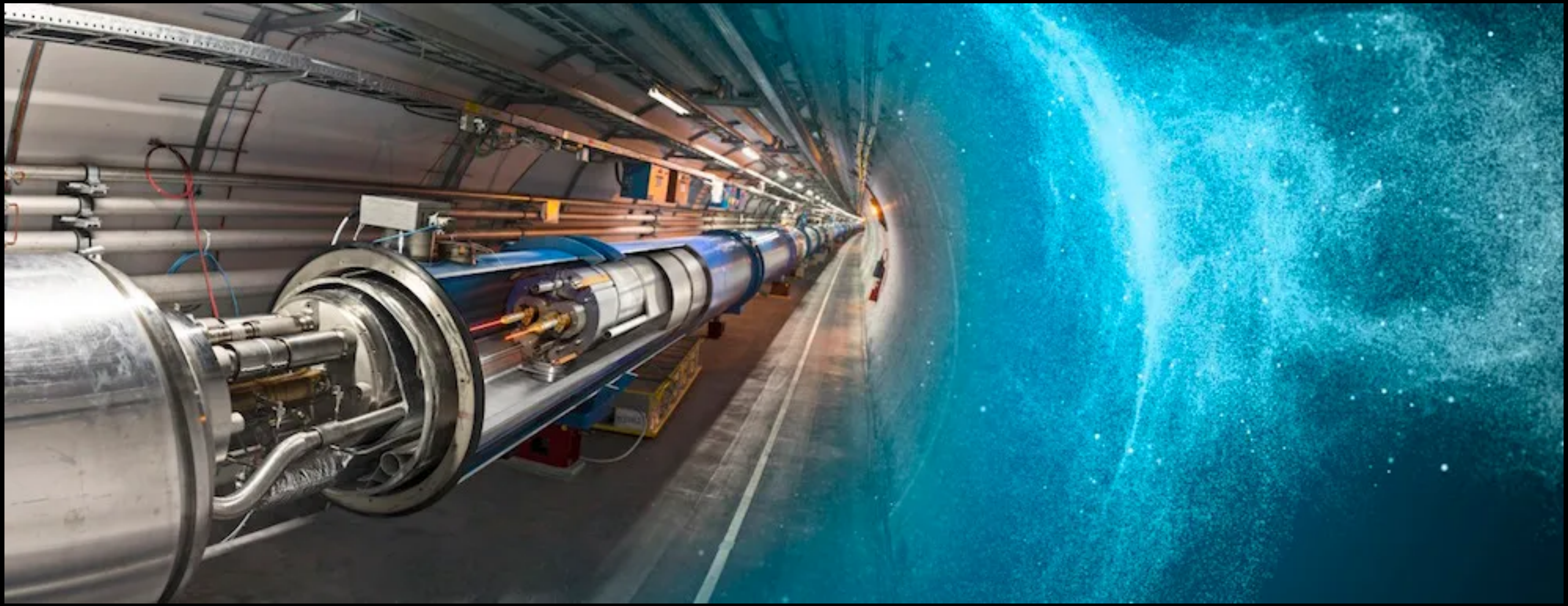


Si estás interesado/a en trabajar conmigo, escríbeme un correo:

alba.soto.ontoso@cern.ch

y hablamos!

Estudio de la materia en condiciones extremas: del cosmos a los aceleradores de partículas



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Plan for the course

Lecture 1: big picture

- The Strong force
- QCD Thermodynamics
- The Quark-Gluon Plasma
- Little and Big Bangs

Lecture 2: early stages

- Spatio-temporal evolution of a heavy-ion collision
- Nuclear PDFs
- Geometry of the collision

Lecture 3: fluid evolution

- Hydrodynamic paradigm
- Connection to nuclear structure
- Small systems puzzle

Lecture 4: jets in the QGP

- Parton shower in vacuum
- Interleaving of vacuum and medium-induced emissions
- Color randomization in the QGP

Plan for the course

Besides these slides, some extra material that we will use can be found in

https://github.com/albaontoso/2024-Granada-heavyion-lectures

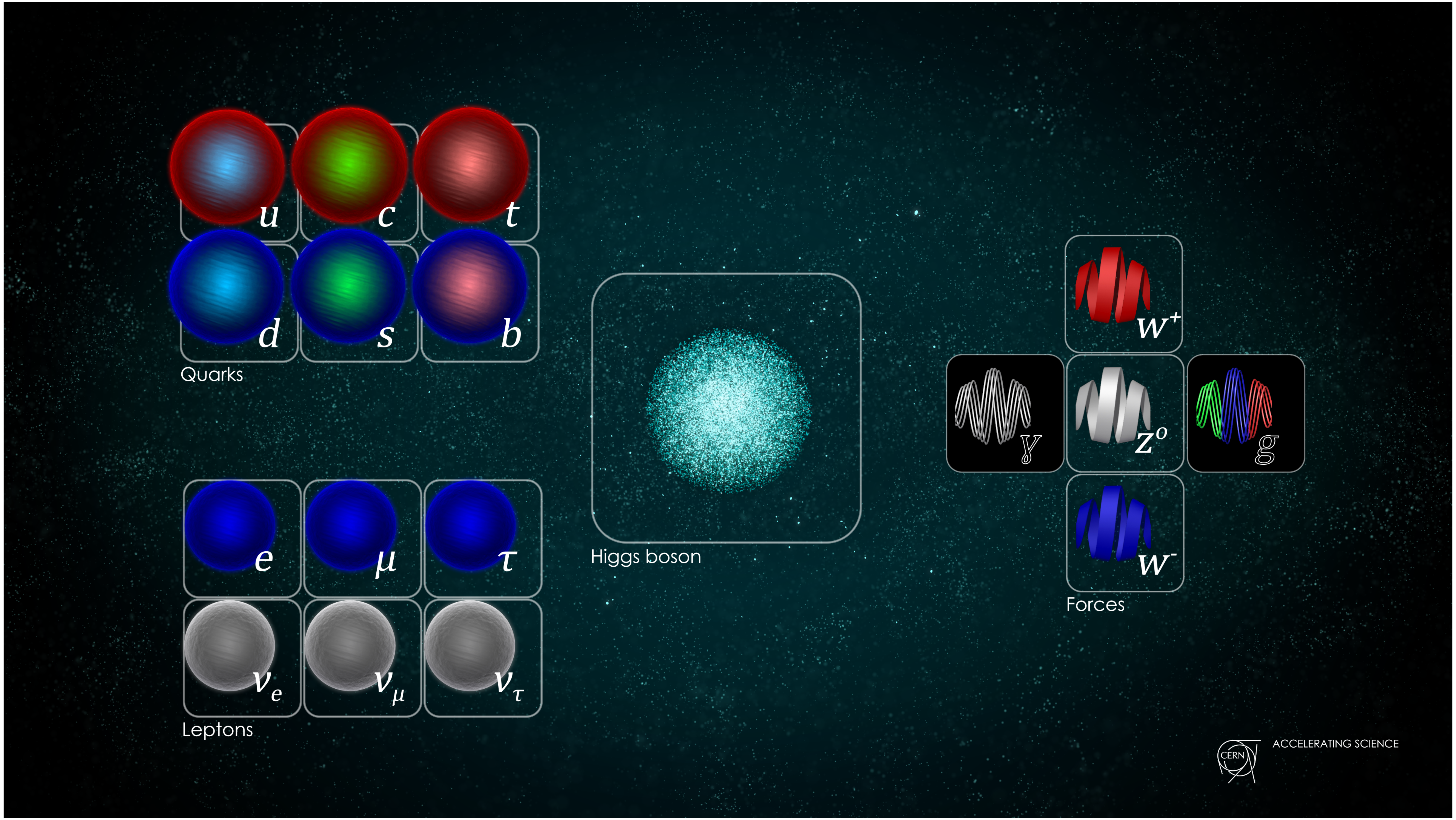
To download it in your computer do

```
git clone git@github.com:albaontoso/2024-Granada-heavyion-lectures.git
```

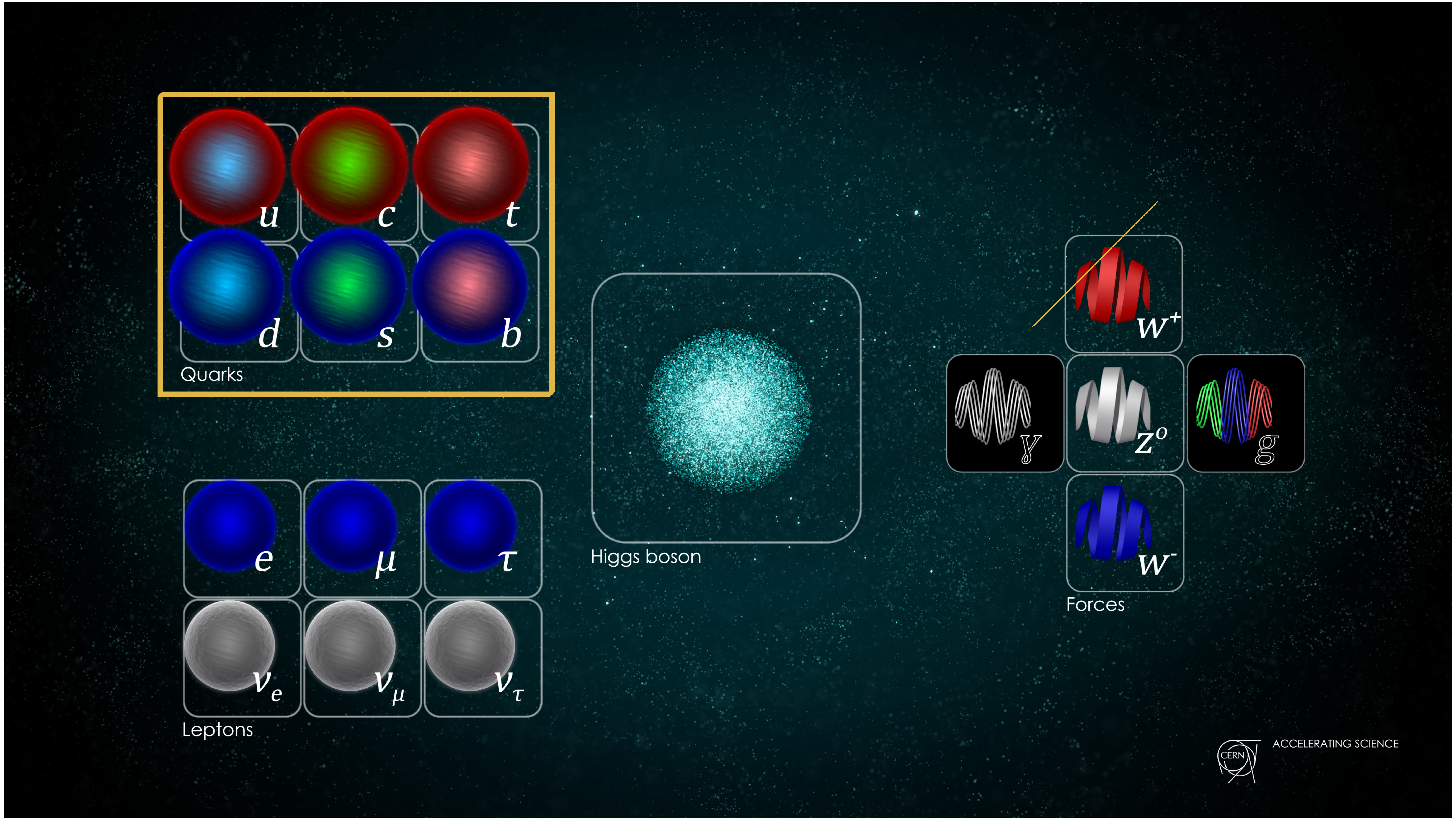
Everything written in `PYTHON`. Few tools to use Jupyter notebooks:

- **Visual studio code** (best editor in my opinion)
- https://colab.research.google.com/
- https://jupyter.org/try

Matter at the femtometer scale

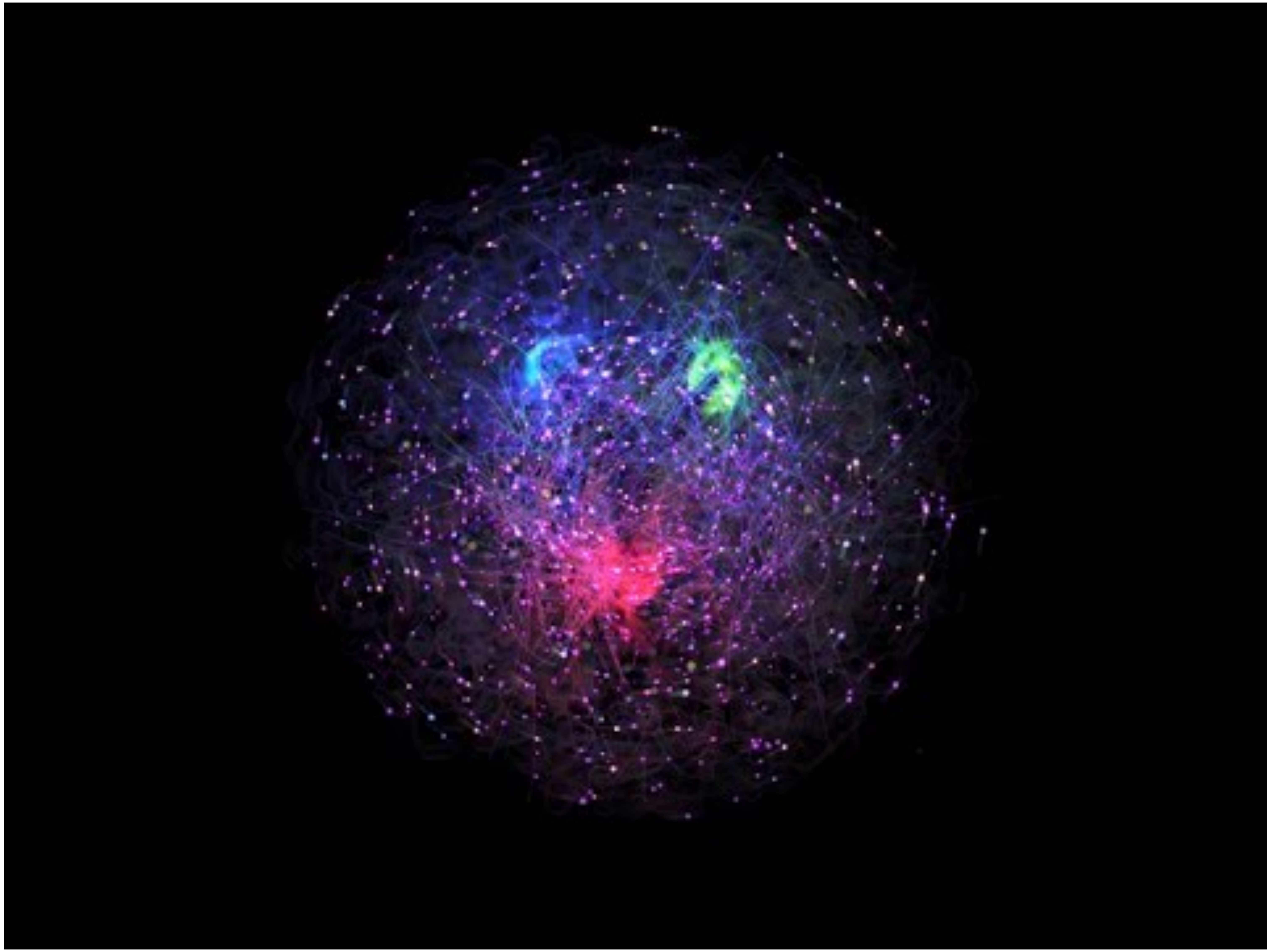


Focus of these lectures: quarks and gluons



Fascinating dynamics inside the proton

[Arts at MIT, https://youtube.com/watch?v=Dt8FZ4ksWiY]



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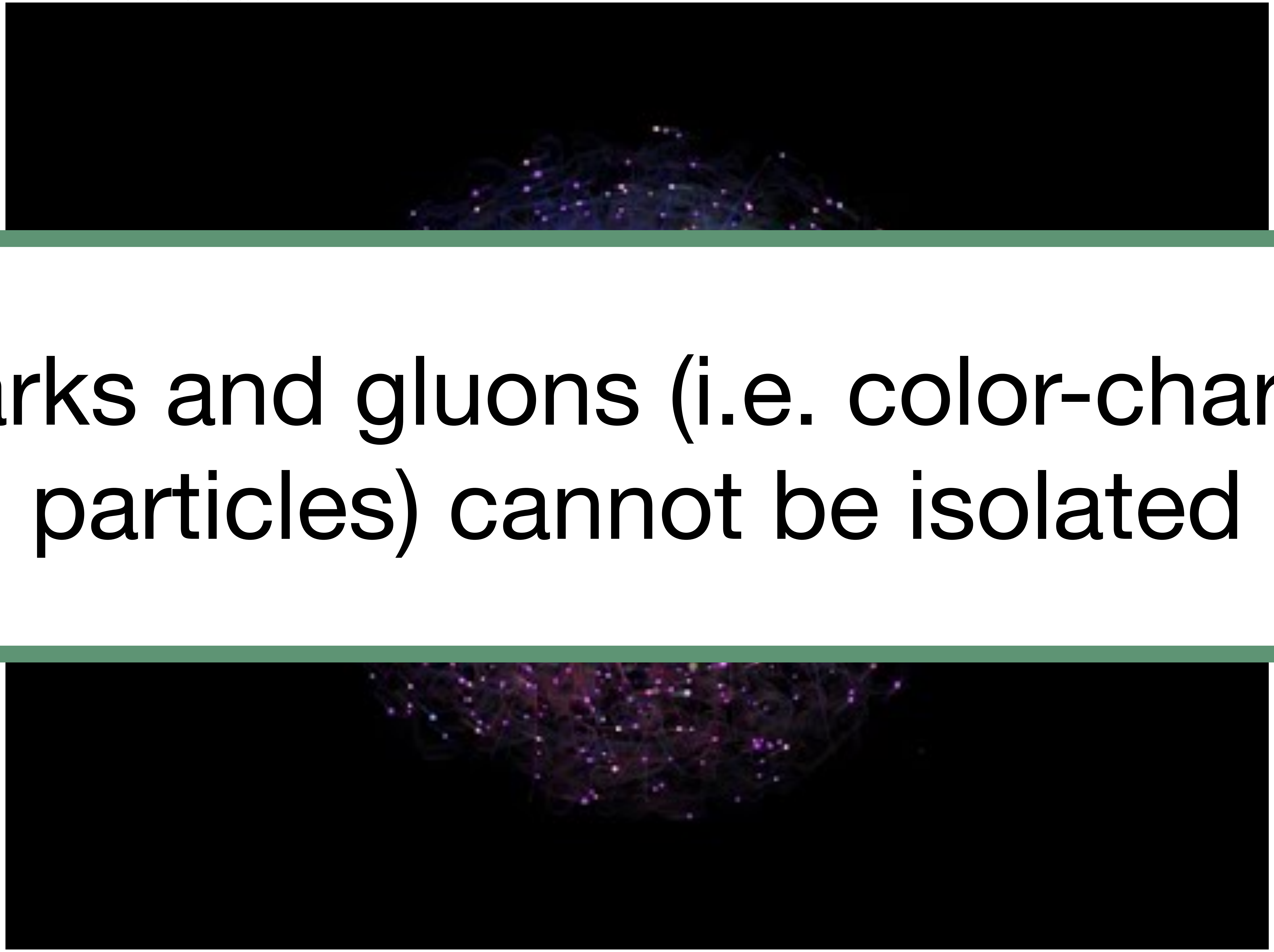


Quarks and gluons (i.e. color-charged particles) cannot be isolated

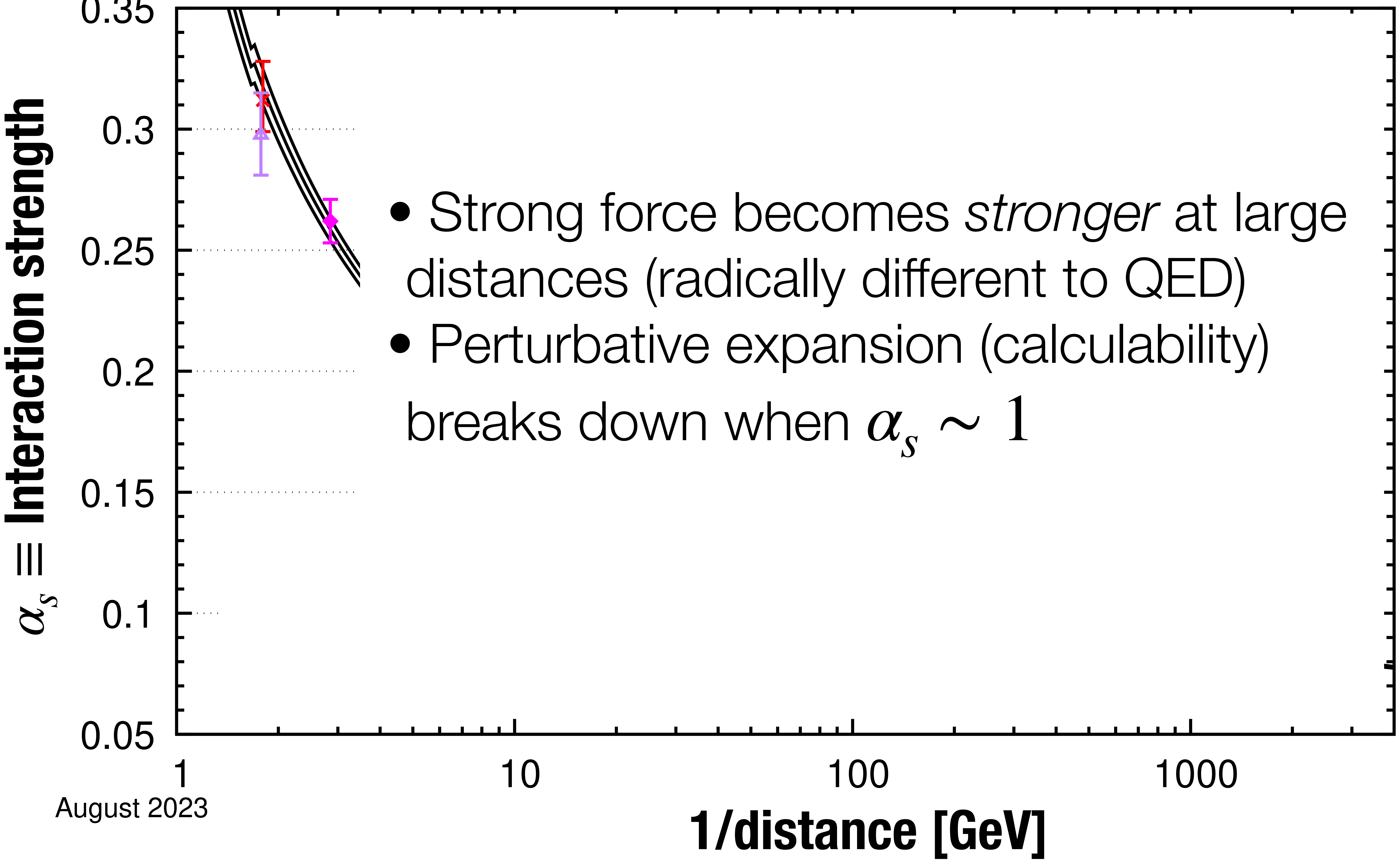
Key aspects of QCD: confinement and asymptotic freedom

$\alpha_s \equiv$ Interaction strength

1/distance [GeV]

Key aspects of QCD: confinement

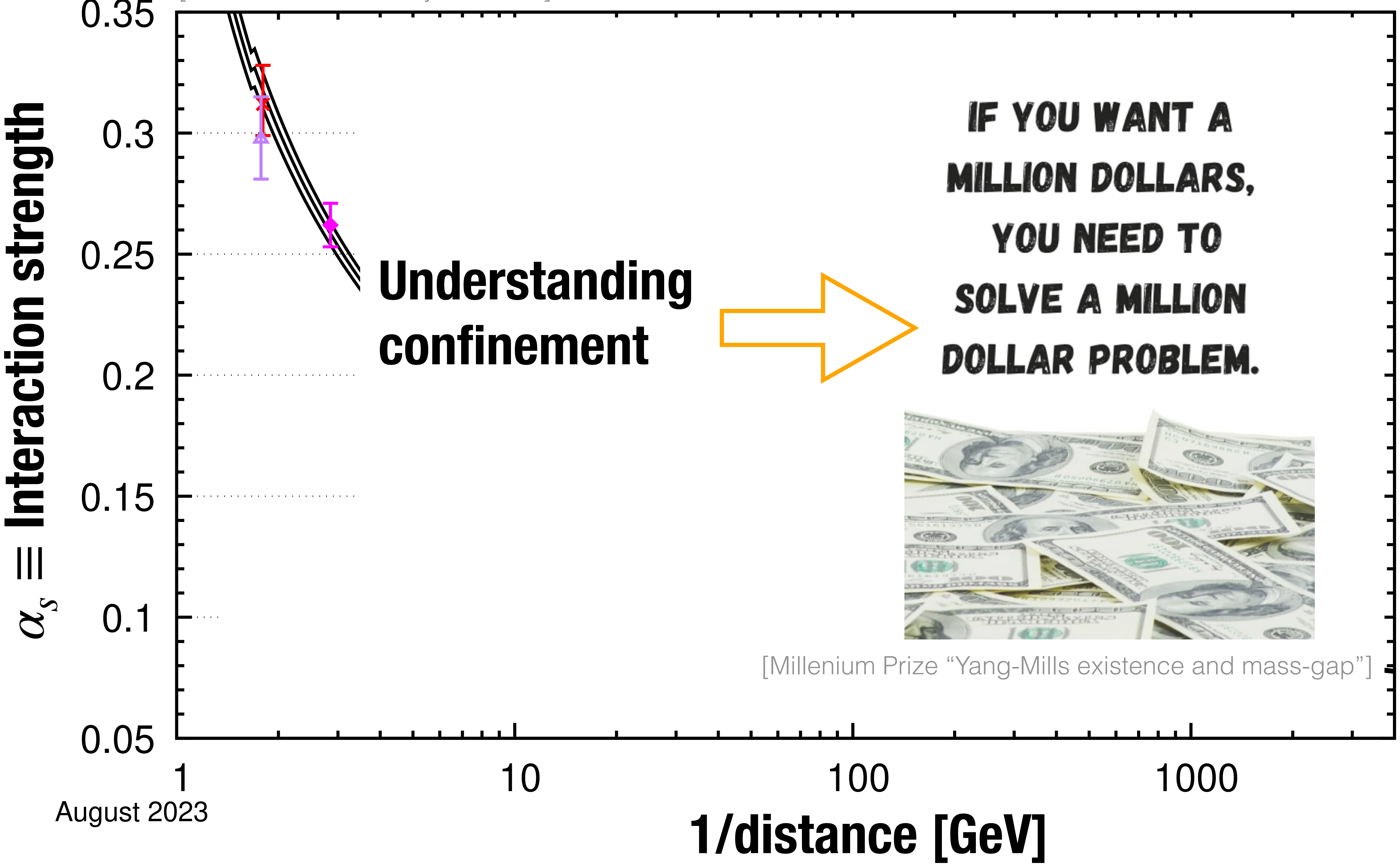
[Review of Particle Physics 2023]



- Strong force becomes *stronger* at large distances (radically different to QED)
- Perturbative expansion (calculability) breaks down when $\alpha_s \sim 1$

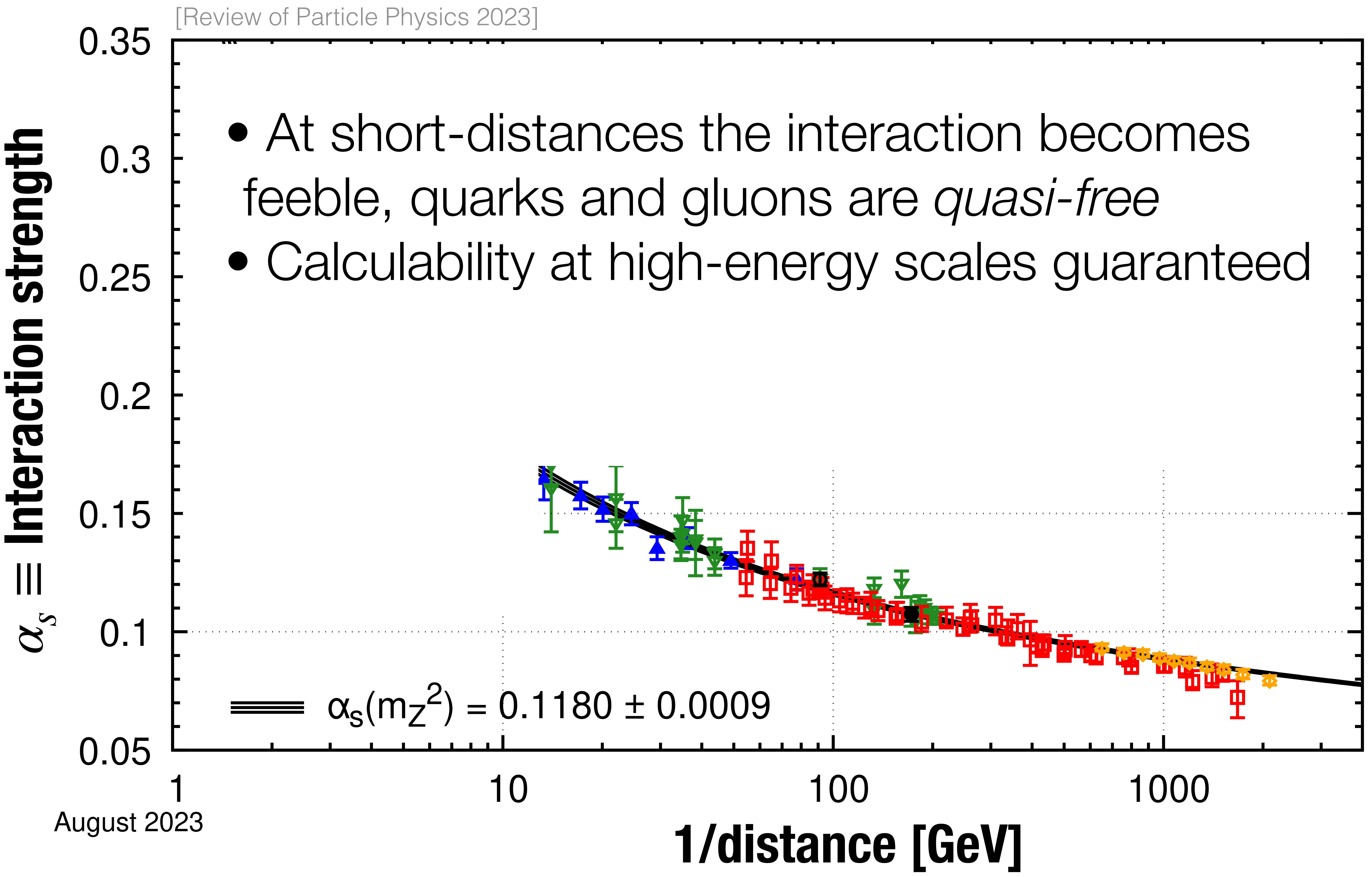
Key aspects of QCD: confinement

[Review of Particle Physics 2023]

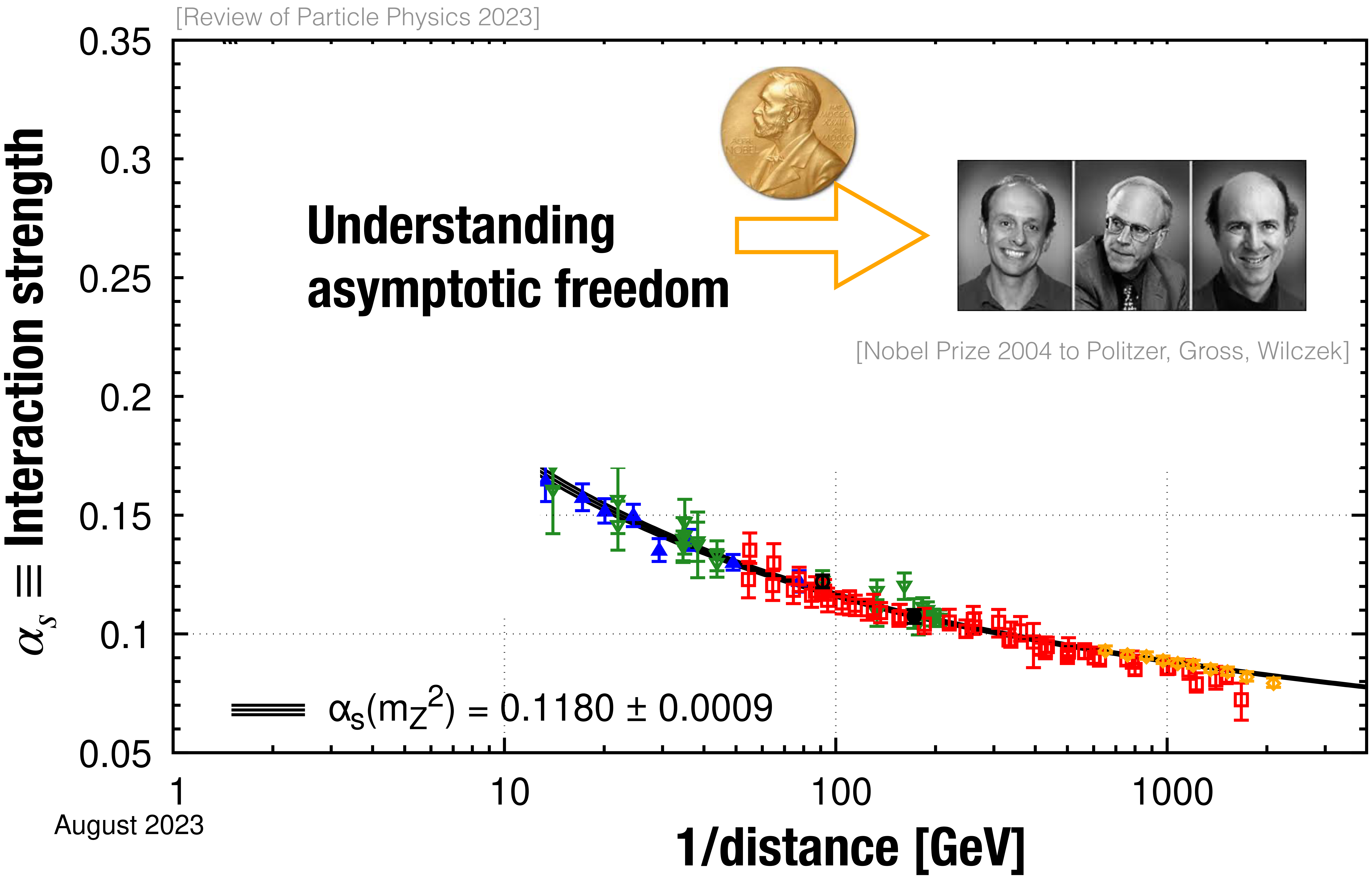


[Millenium Prize “Yang-Mills existence and mass-gap”]

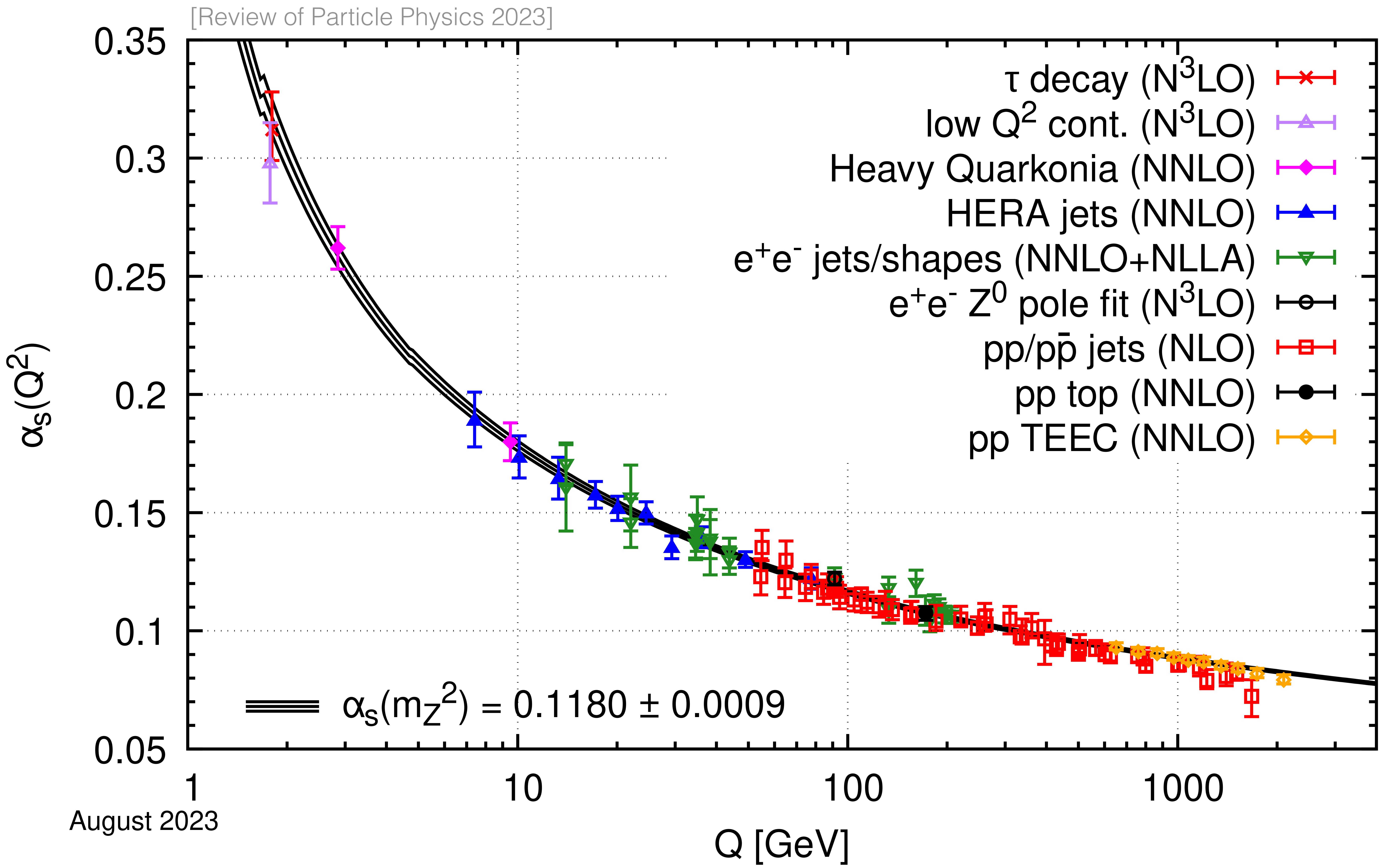
Key aspects of QCD: asymptotic freedom



Key aspects of QCD: asymptotic freedom

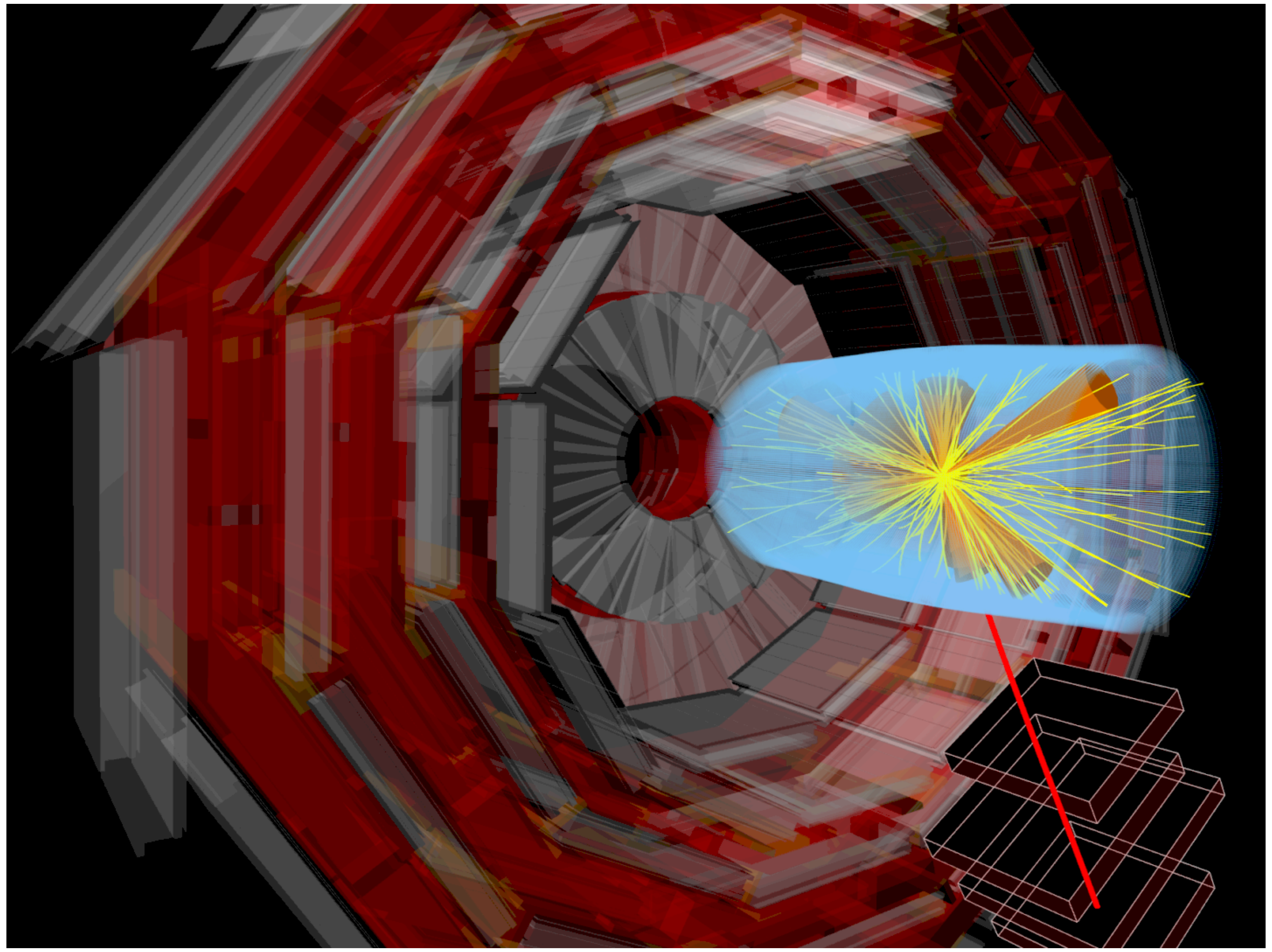


Key aspect of QCD: running of the coupling



Technical (but amazing) point: this behaviour is connected to the gluon self-interaction

Asymptotic freedom opens up the LHC program



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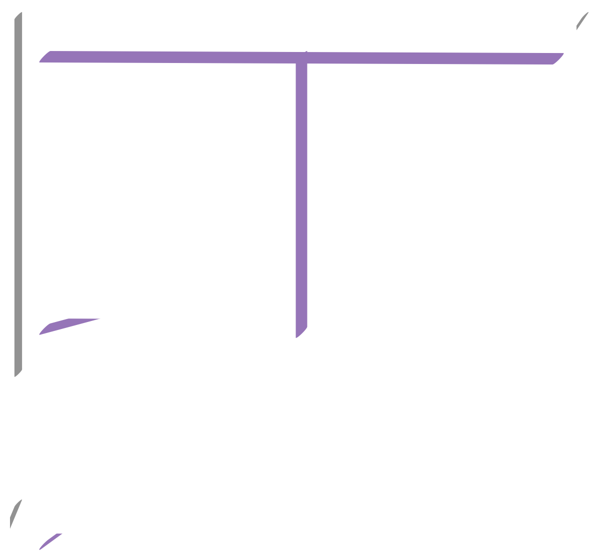


+

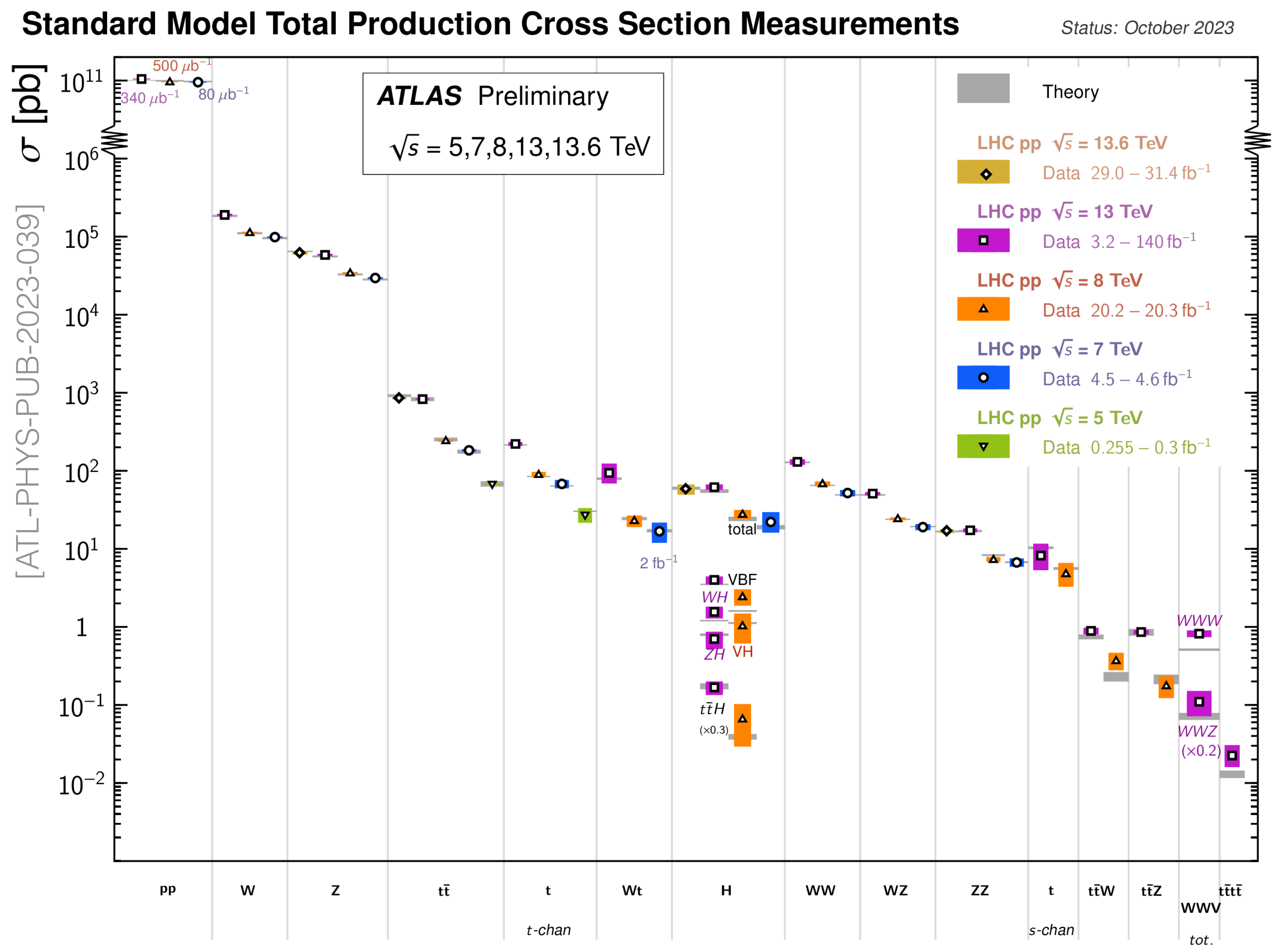
-

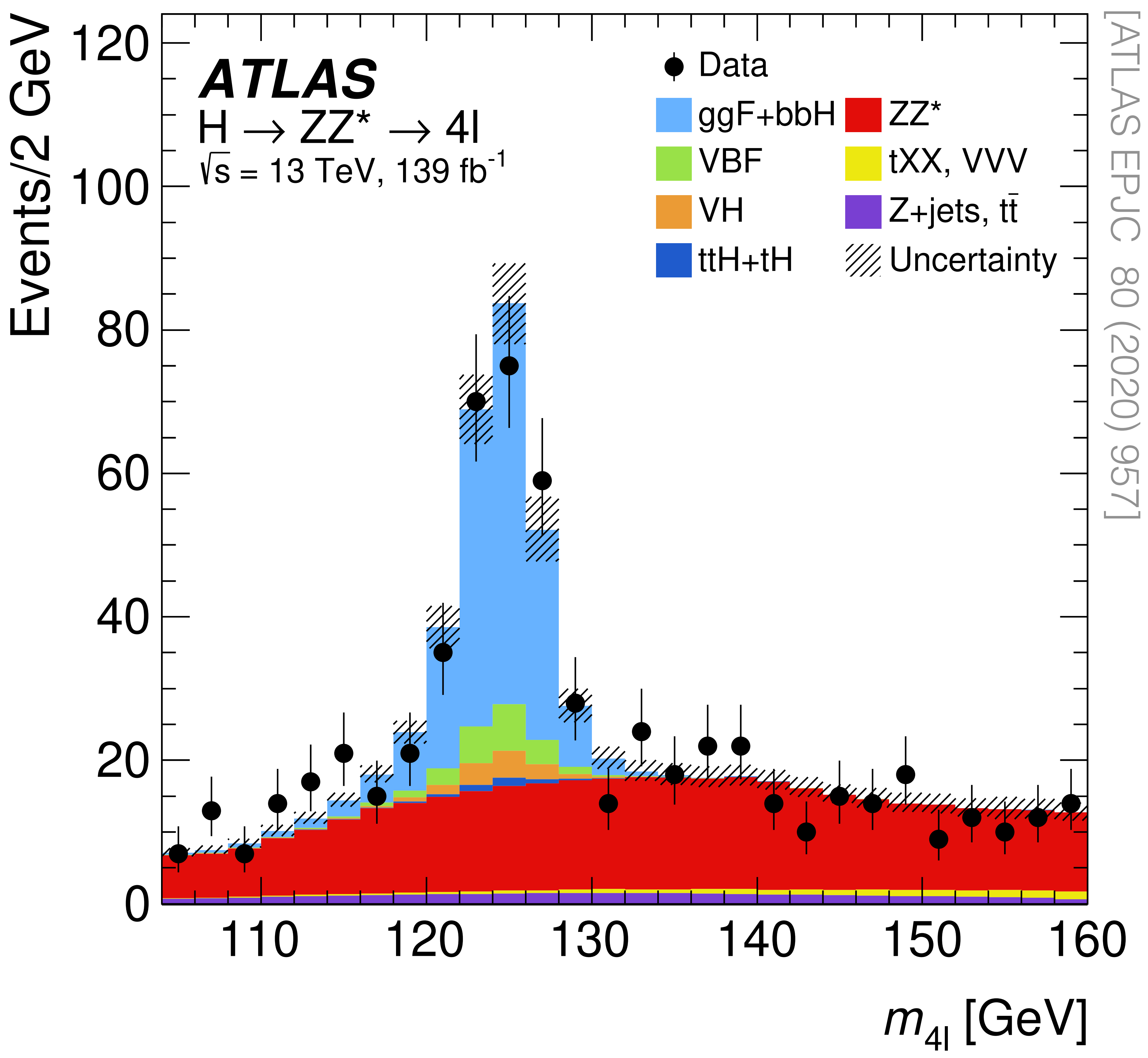
x

$+\mathcal{O}(\alpha_s^3)$

Proton-proton collision computed in terms of Feynman diagrams with quarks and gluons as degrees of freedom

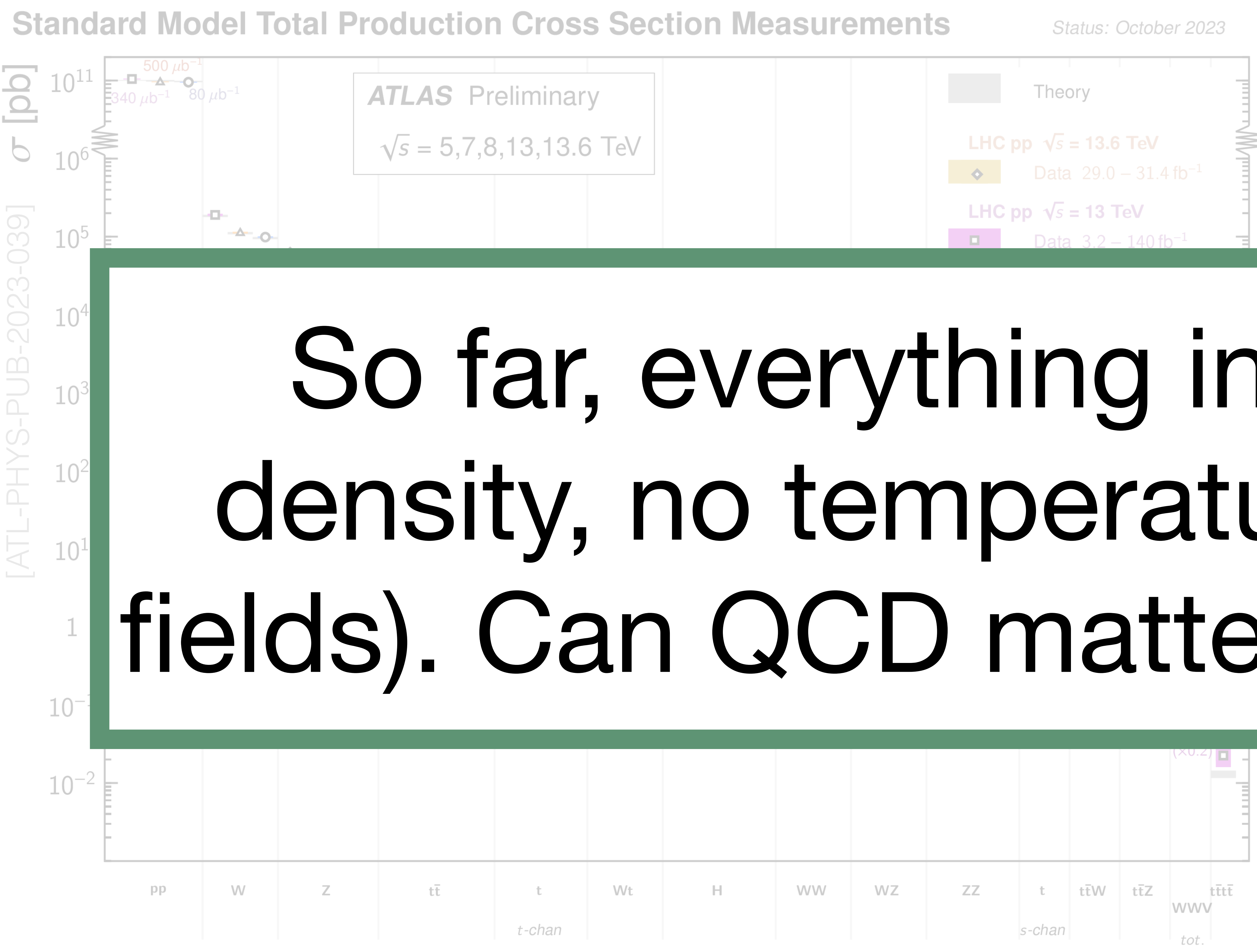
QCD in the real world

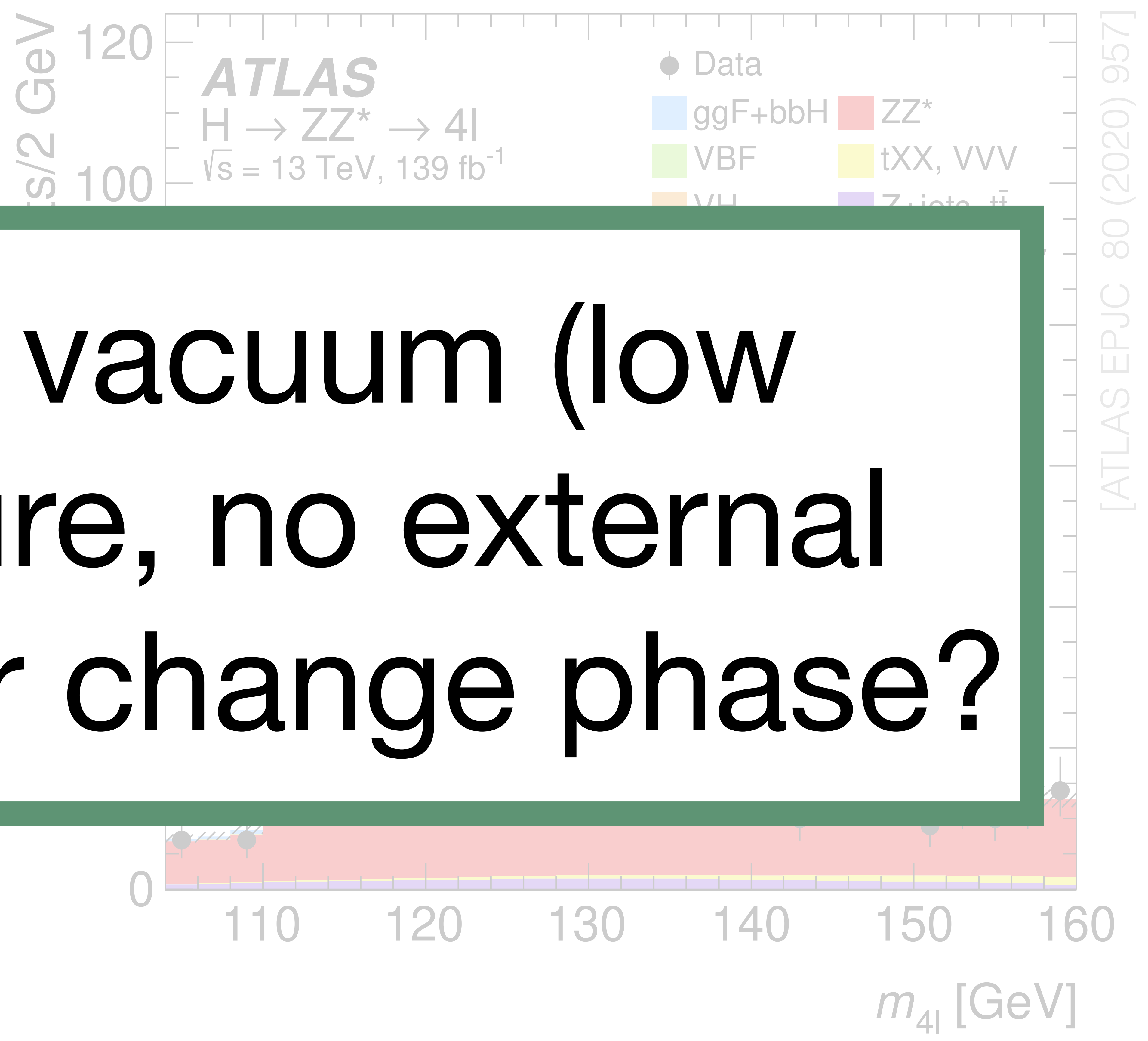




The Higgs wouldn't have been discovered without precise QCD

QCD in the real world

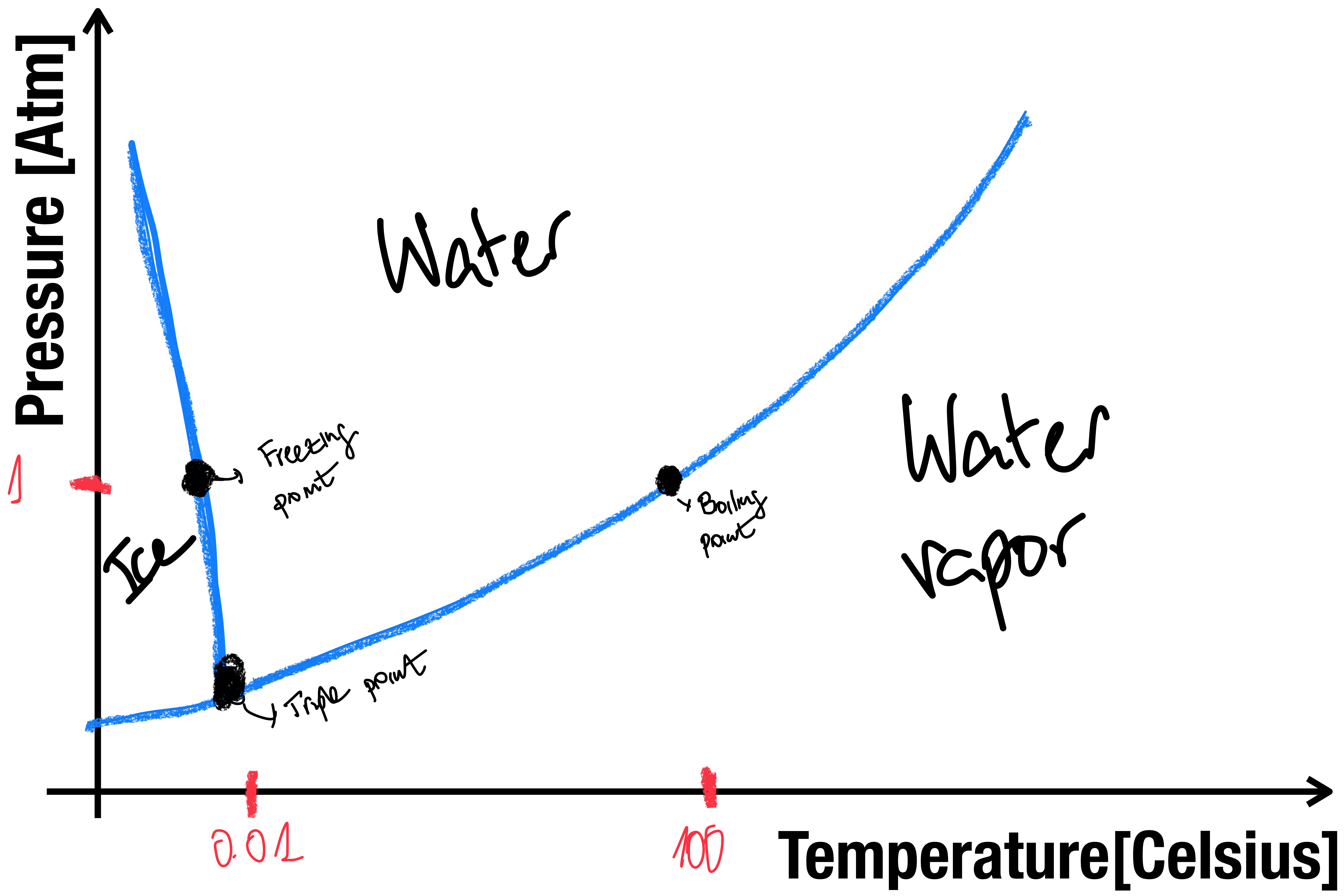




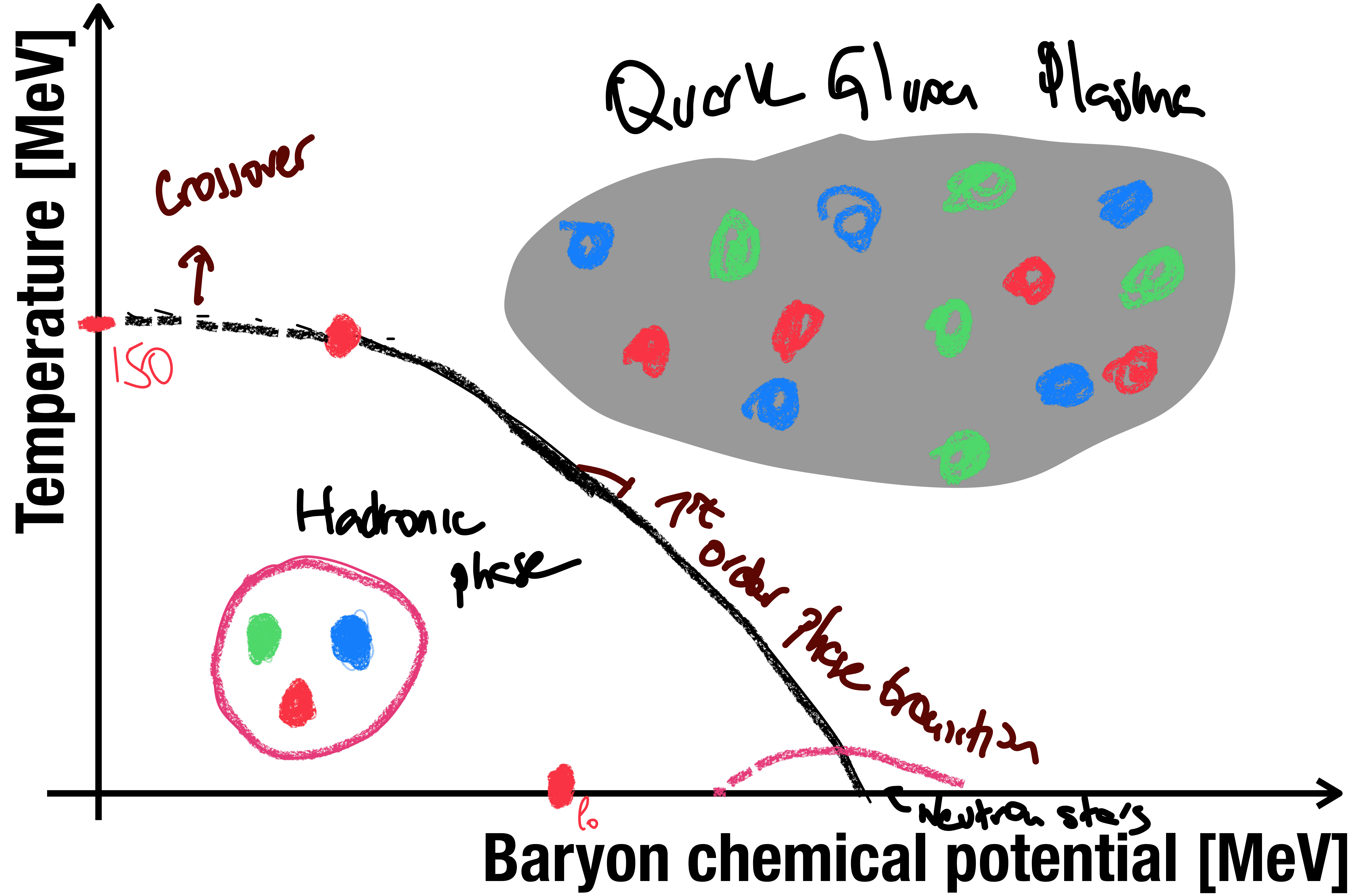
So far, everything in vacuum (low density, no temperature, no external fields). Can QCD matter change phase?

The Higgs wouldn't have been discovered without precise QCD

Reminder: phase diagram of water

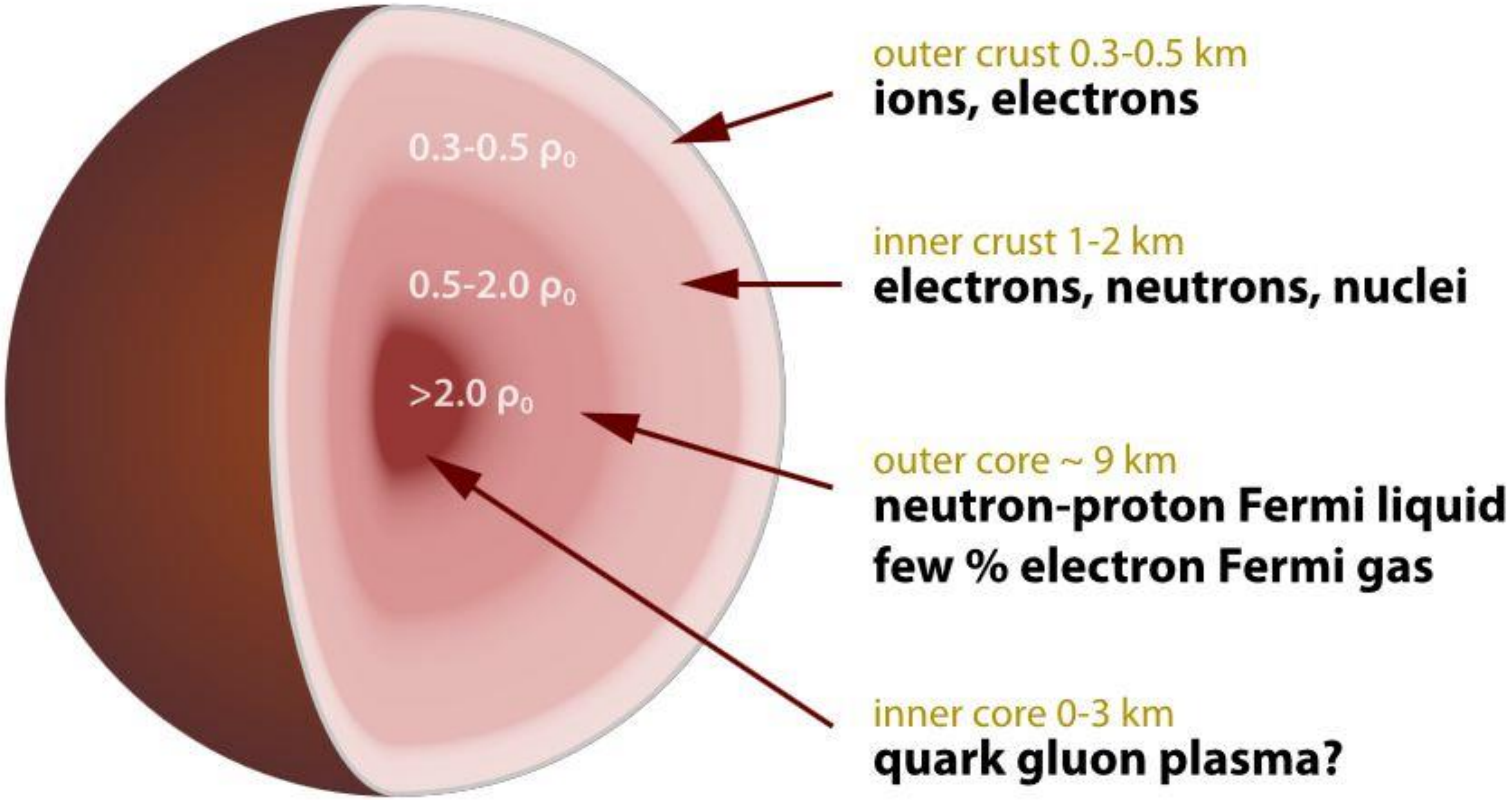


Phase diagram of QCD matter



ρ_0 : nuclear saturation mass density $\rho_0 \sim m_n n_0 = m_n \dfrac{A}{\frac{4}{3}\pi R^3} \sim 900\ \mathrm{MeV}$

Neutron stars: as dense as it gets



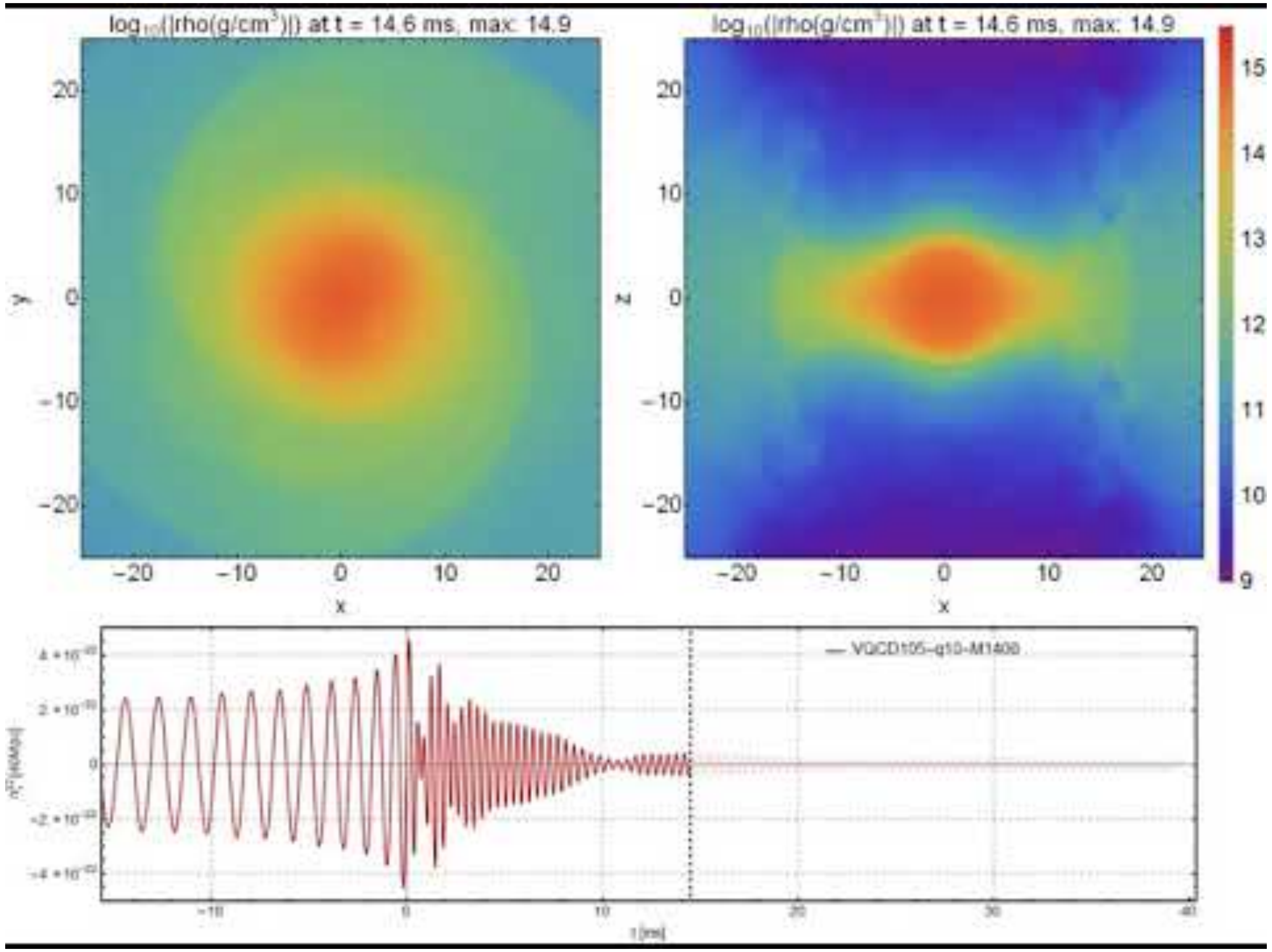
Critical density around 10^{17} kg/m³ ~ put planet Earth into Los Carmenes

Neutron stars produce gravitational waves

[Eckert et al PRD 101 (2020) 10, 103006] https://youtube.com/watch?v=p51XSfYcSb8

Mass density

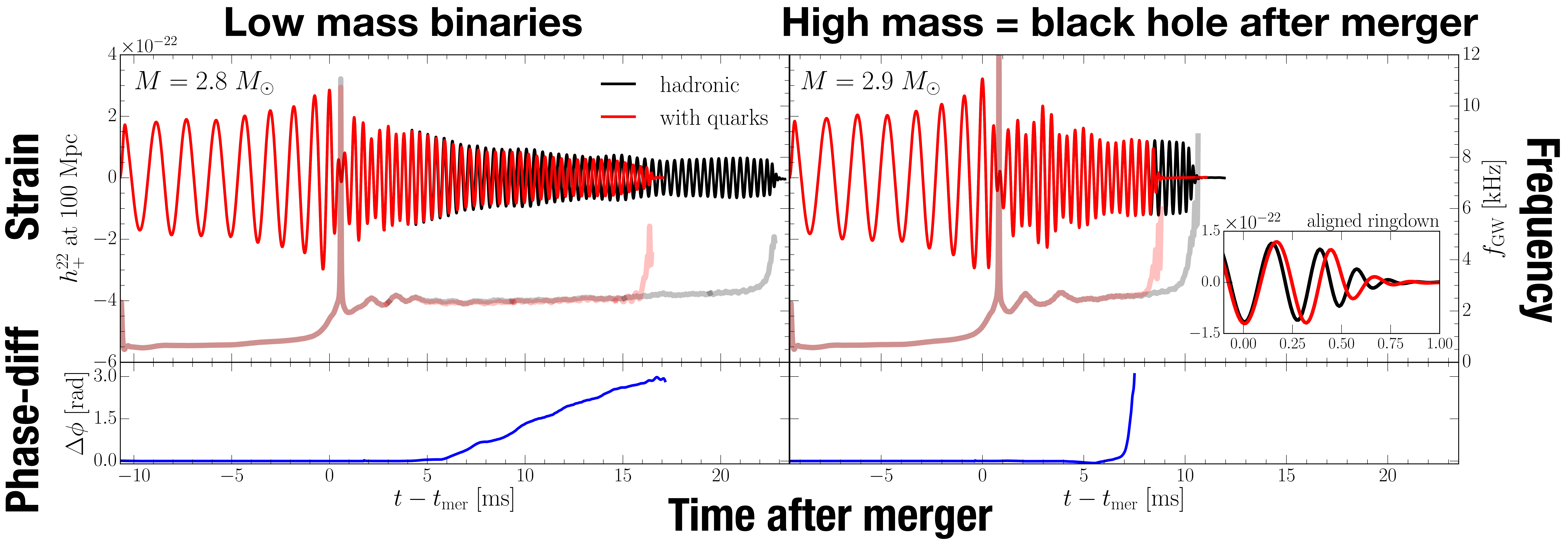
Strain gravitational wave



The merger of 2 neutron stars create gravitational waves measurable at LIGO

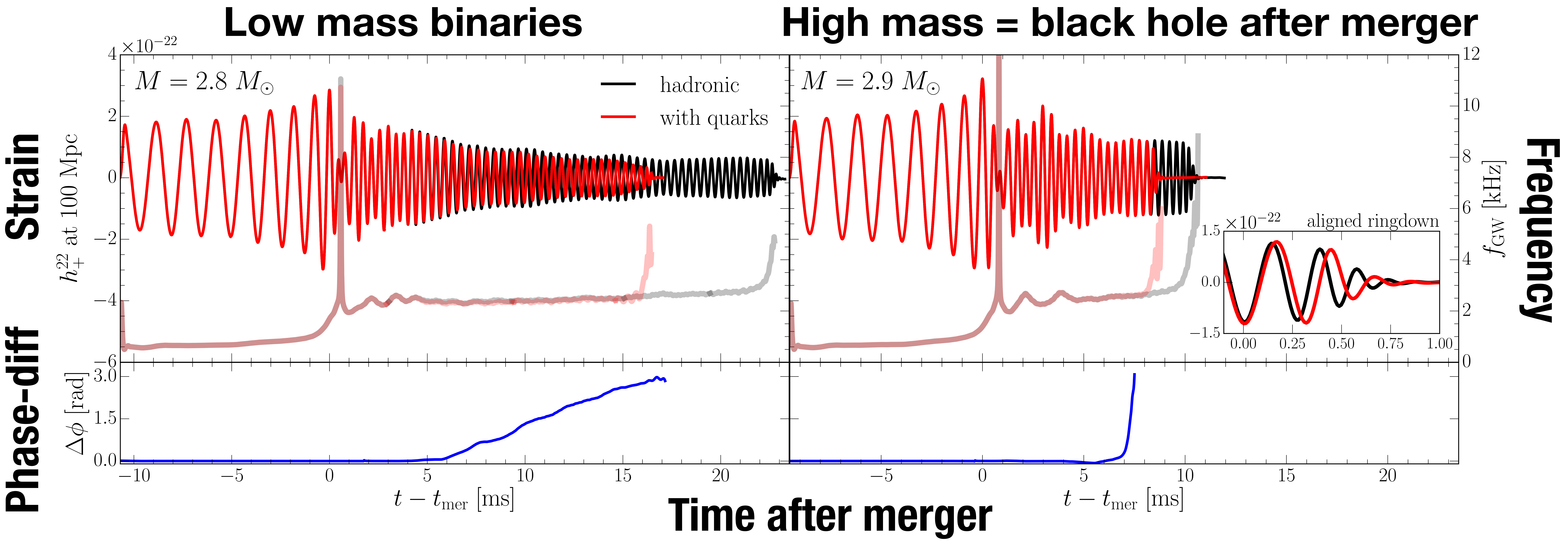
QCD phase-transition imprint into gravitational waves

[Most et al PRL 122 (2019) 6, 061101]



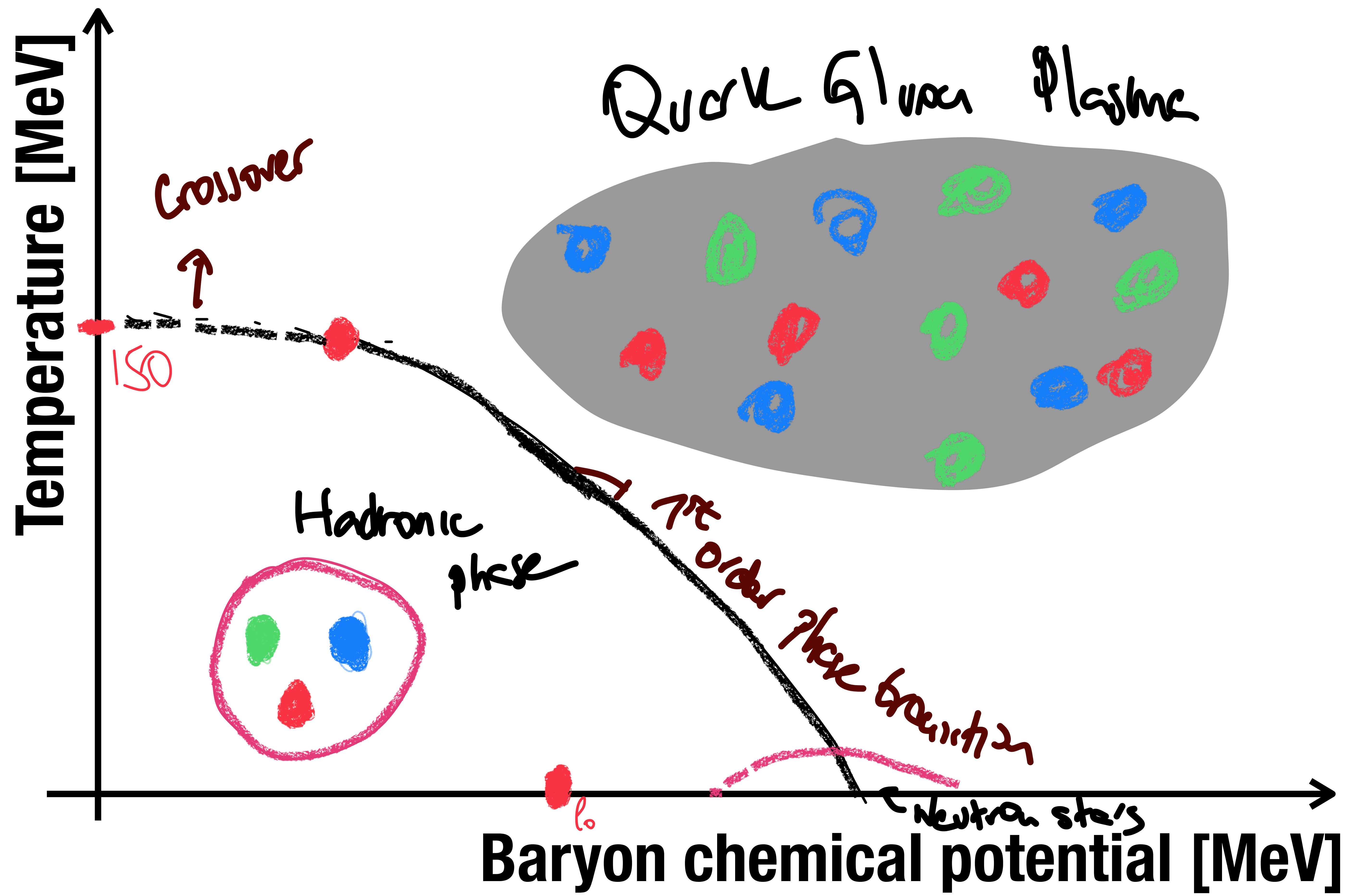
QCD phase-transition imprint into gravitational waves

[Most et al PRL 122 (2019) 6, 061101]



- During inspiral phase no quarks are formed: identical GW signal
- Low mass: post merger spectra sensitive to the presence of quarks
- High mass: signal quickly suppressed by the collapse into a BH

Phase diagram of QCD matter



ρ_0 : nuclear saturation mass density $\rho_0 \sim m_n n_0 = m_n \frac{A}{\frac{4}{3}\pi R^3} \sim 900\ \mathrm{MeV}$

QCD thermodynamics: simple estimates

Consider an ideal gas composed of N_F massless quarks and N_B gluons.
The so-called Stefan-Boltzmann pressure is given by:

$$p(T) = \frac{\pi^2}{90}(N_B + \frac{7}{8}N_F)T^4$$

where

$$N_B = 2 \times 8 \qquad\qquad N_F = 2 \times 2 \times 3 \times 3$$

QCD thermodynamics: simple estimates

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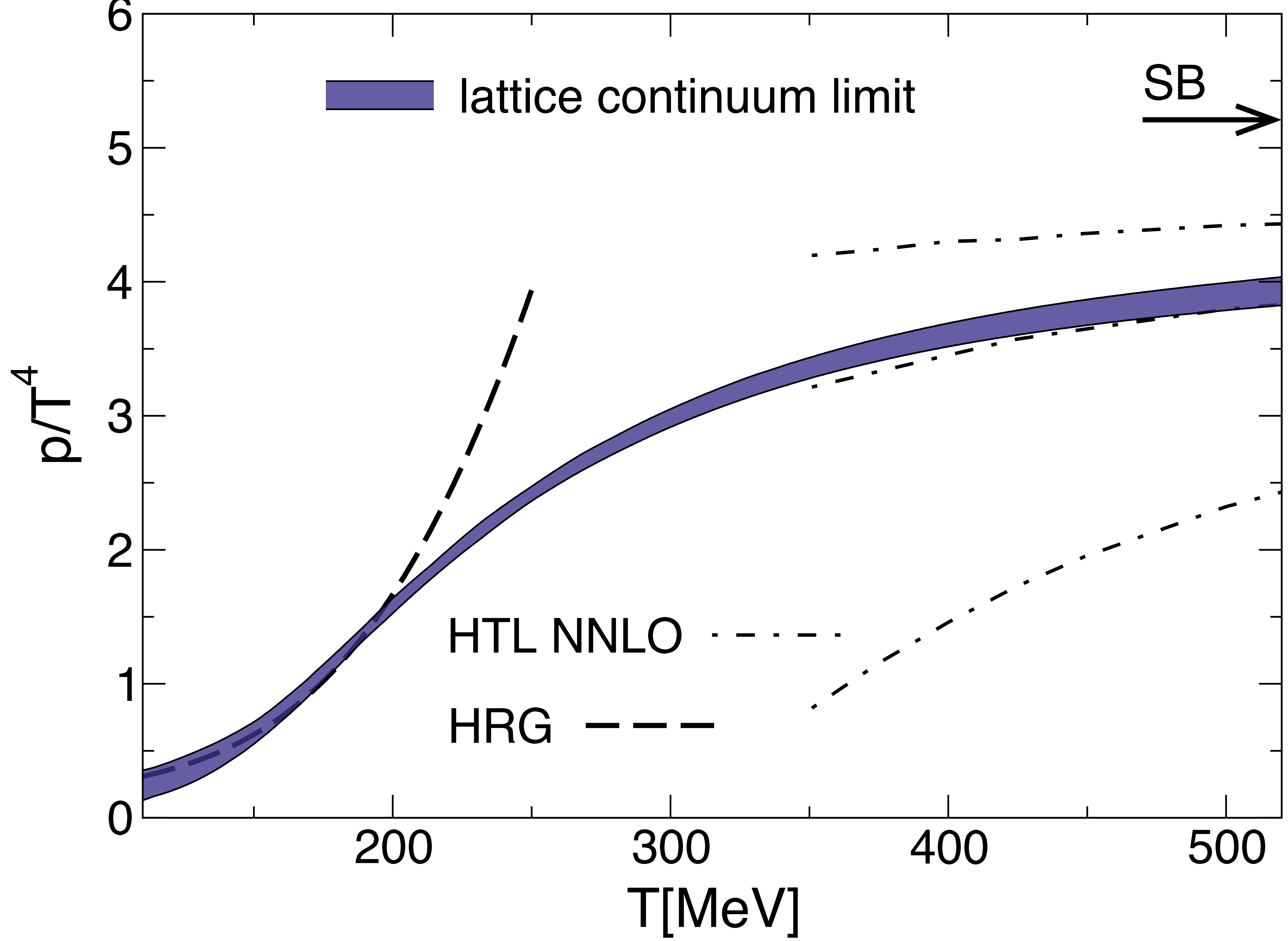
where

$$N_B = \underbrace{2}_{\text{spin}} \times \underbrace{8}_{\text{colour}} \qquad N_F = \underbrace{2}_{\text{spin}} \times \underbrace{2}_{\text{particle/antiparticle}} \times \overbrace{3}^{\text{colour}} \times \overbrace{3}^{\text{flavour (u/d/s)}}$$

QCD thermodynamics: using lattice techniques

[Borsanyi et al PLB 730 (2014) 99-104]



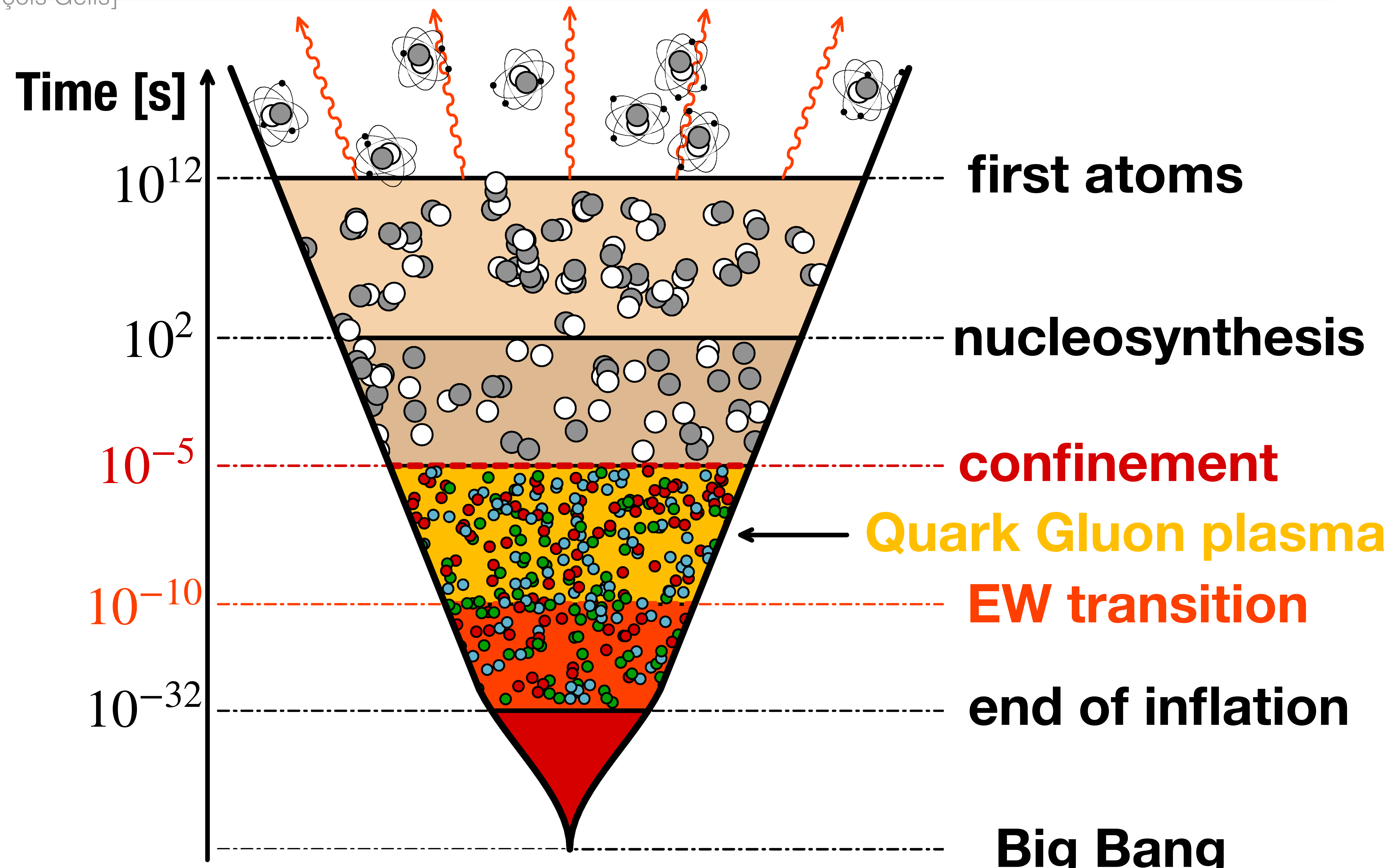
Ideal gas limit

- QGP far from Stefan-Boltzmann limit
- Cross over transition (no sharp rise) from hadrons to quarks and gluons
- Curiosity: lattice result approaches strongly coupled N=4 SYM at high T

Critical temperature around 150 MeV = $10^5 T_{\odot}$ = 2 billion degrees

QGP in the early universe

[Adapted from François Gelis]



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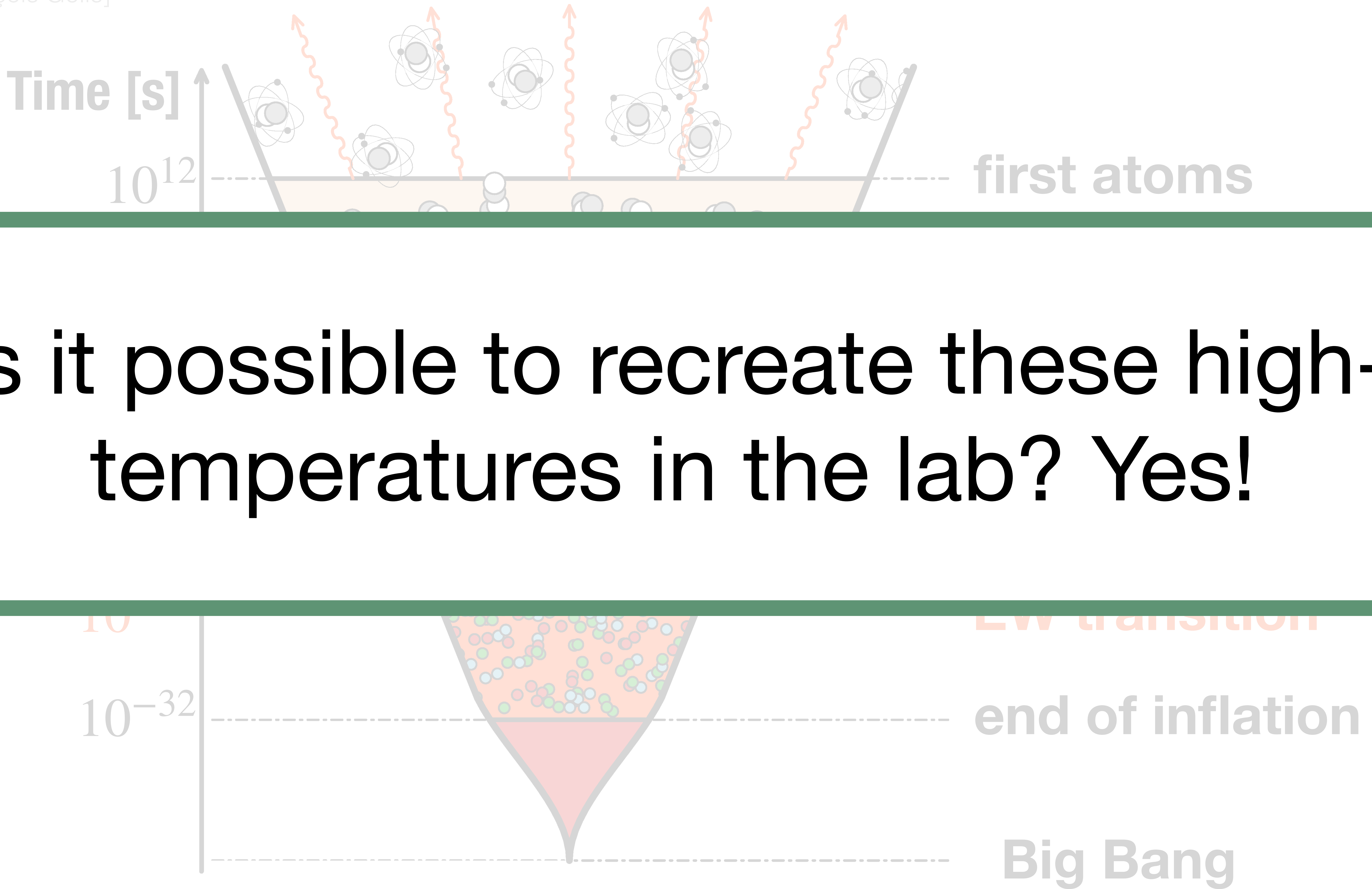
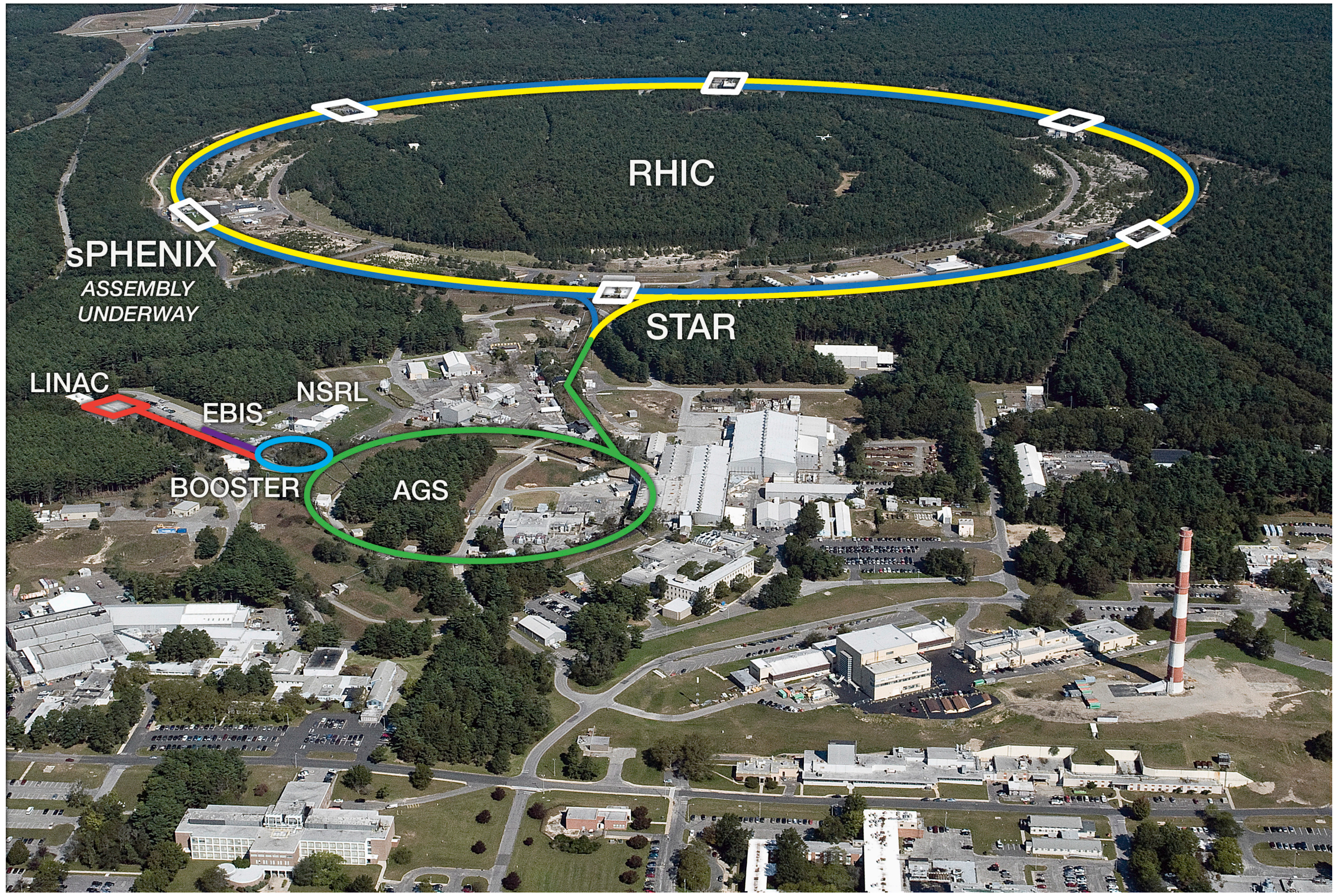


Is it possible to recreate these high-temperatures in the lab? Yes!

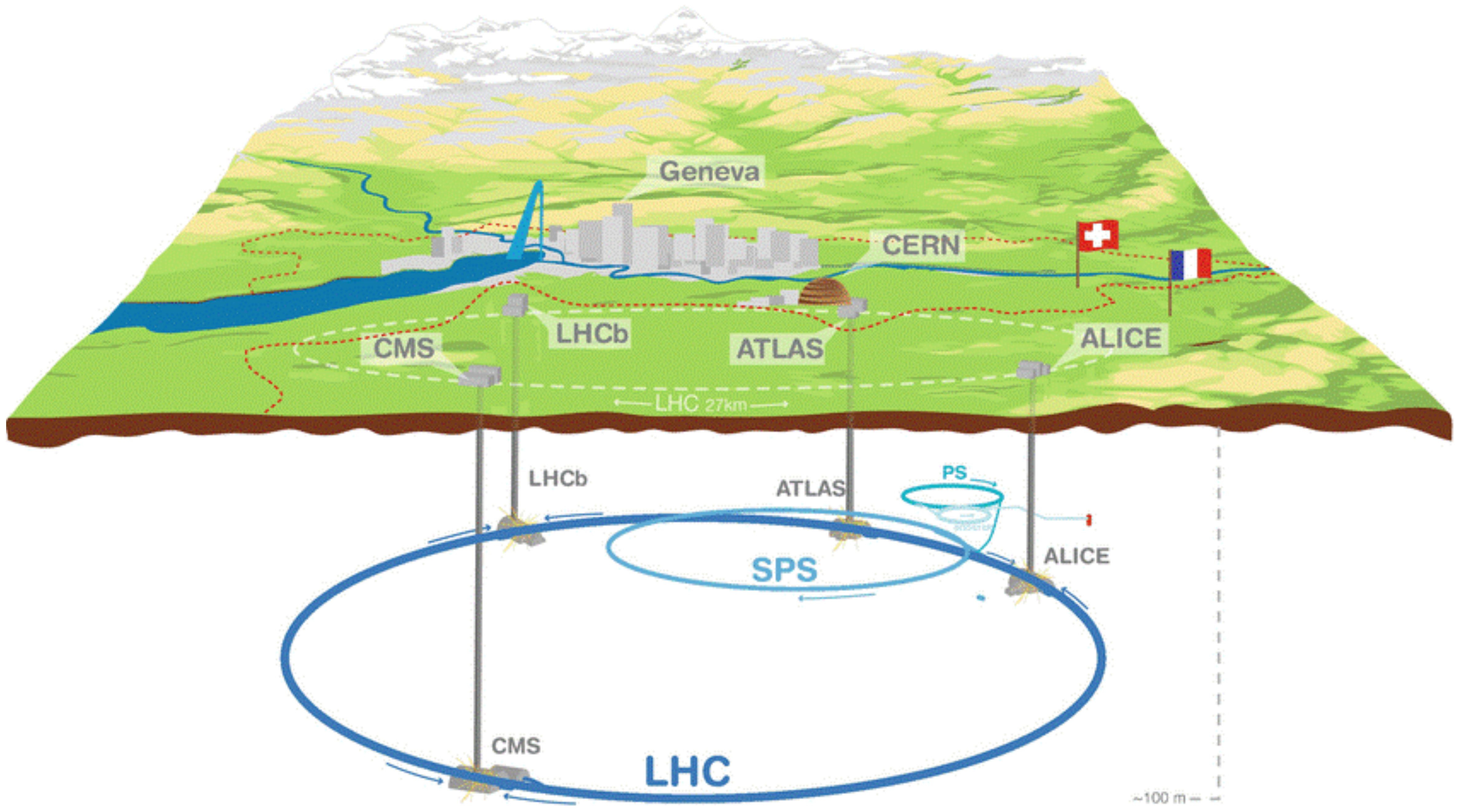
Ultra-relativistic heavy-ion colliders



Relativistic Heavy-Ion Collider

@ Brookhaven National Lab (New York)

$\mathrm{p, Au, U, Zr, Ru} @ 7.7 \leq \sqrt{s_{NN}} \leq 200\ \mathrm{GeV}$



Large Hadron Collider

@ CERN (Geneva)

$\mathrm{p, Pb, Xe, O} @ 2.76 \leq \sqrt{s_{NN}} \leq 6\ \mathrm{TeV}$

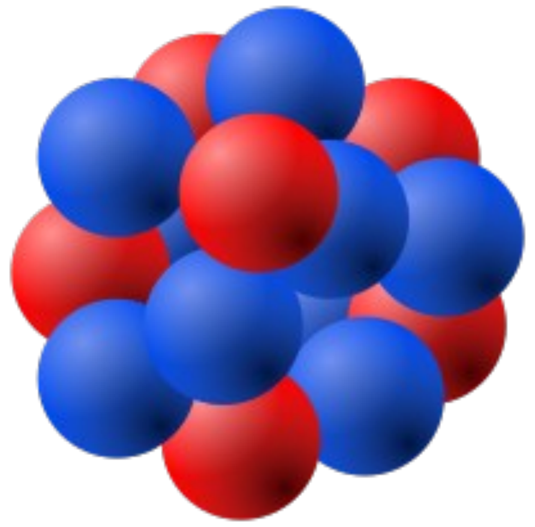
How does a heavy-ion collider work in a nutshell

2 cm, 500 mg
of pure Lead
1$/mg

How does a heavy-ion collider work in a nutshell

2 cm, 500 mg
of pure Lead
1$/mg

vaporise
$T = 500$°C



$^{208}_{82}\mathrm{Pb}$
stable

How does a heavy-ion collider work in a nutshell

2 cm, 500 mg
of pure Lead
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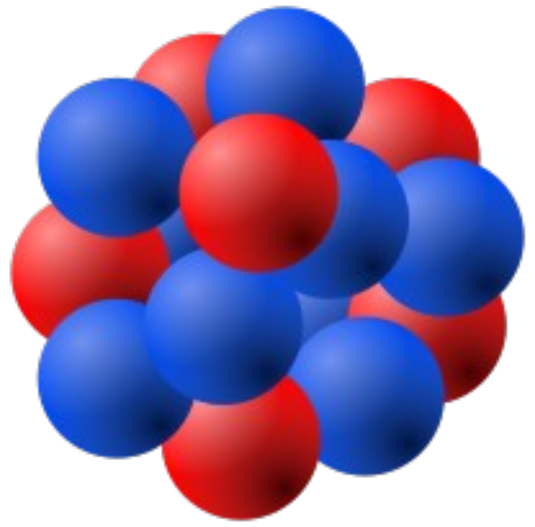
vaporise
$T = 500°\mathrm{C}$



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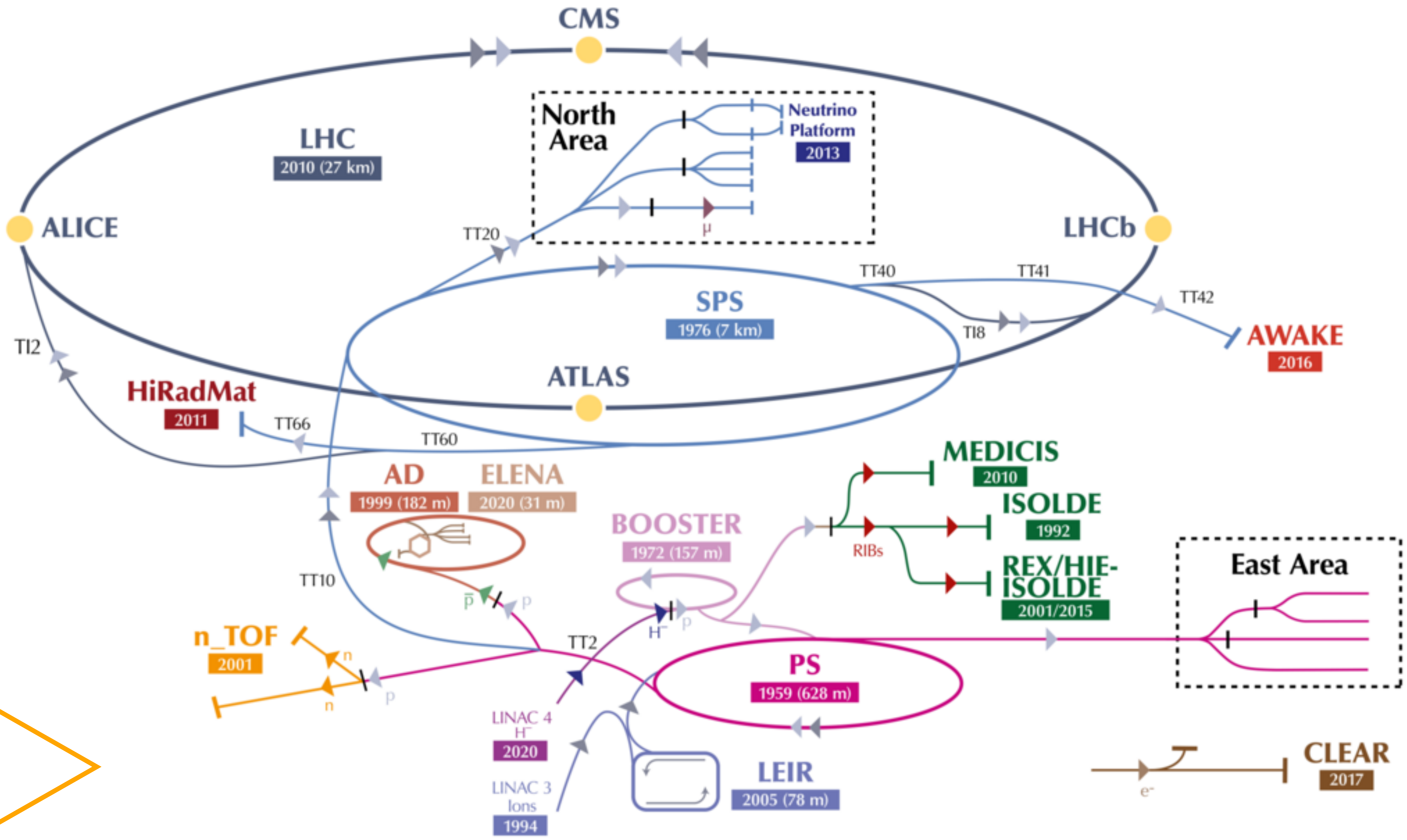
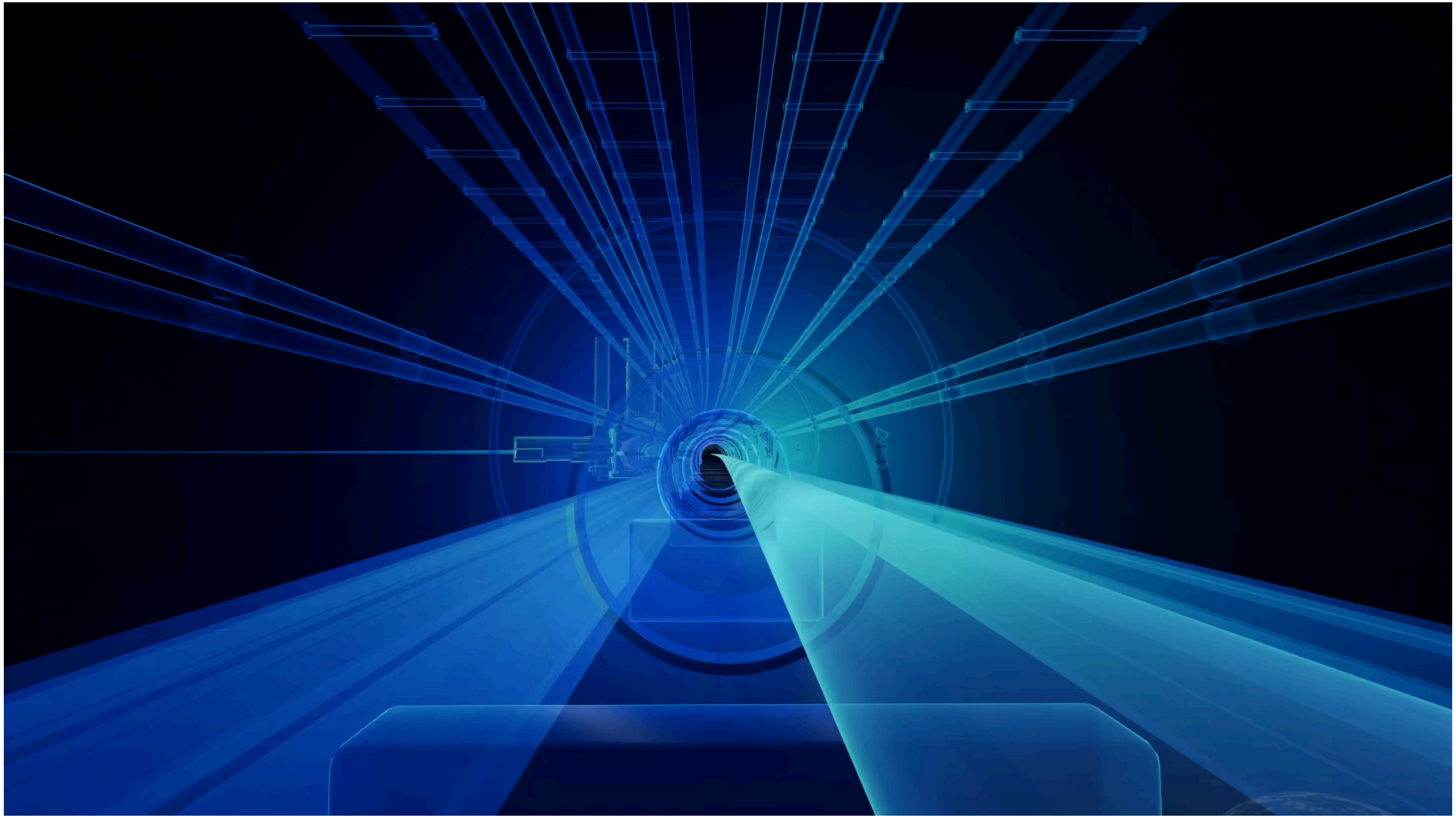


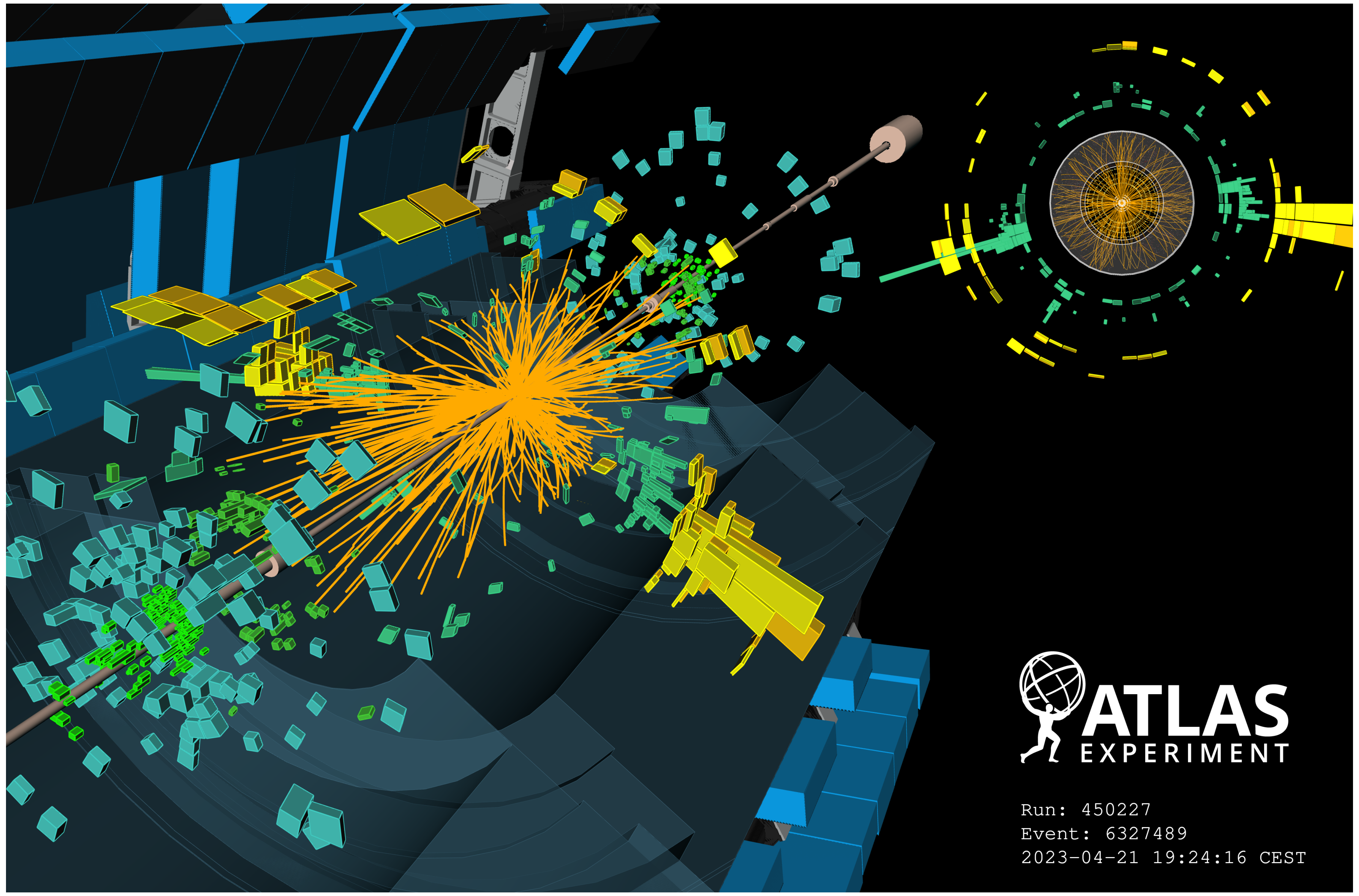
From the Big Bang to the Little Bang

https://home.cern/resources/video/physics/heavy-ion-collision-event-animation

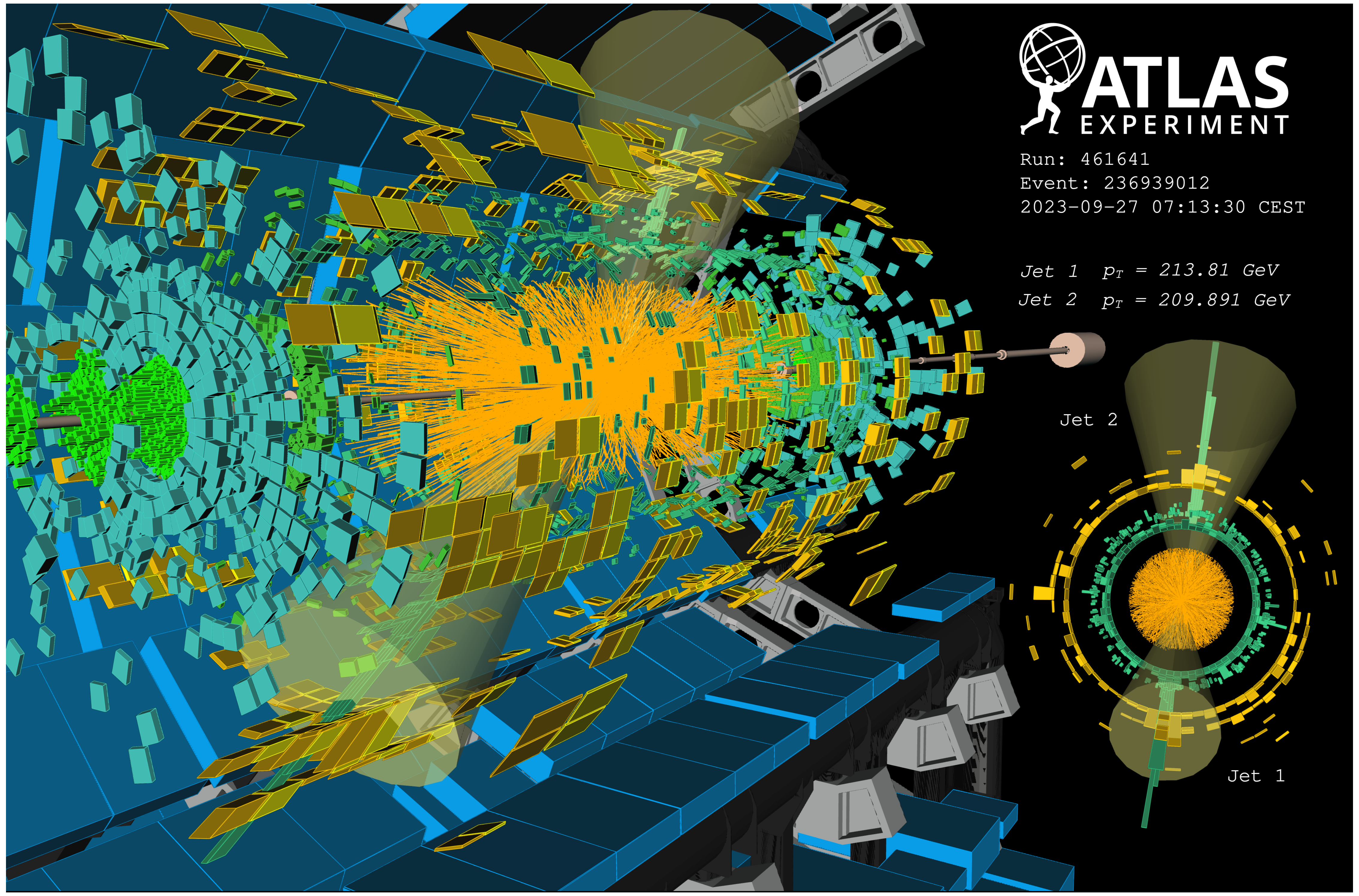


From the Big Bang to the Little Bang

pp@13.6 TeV



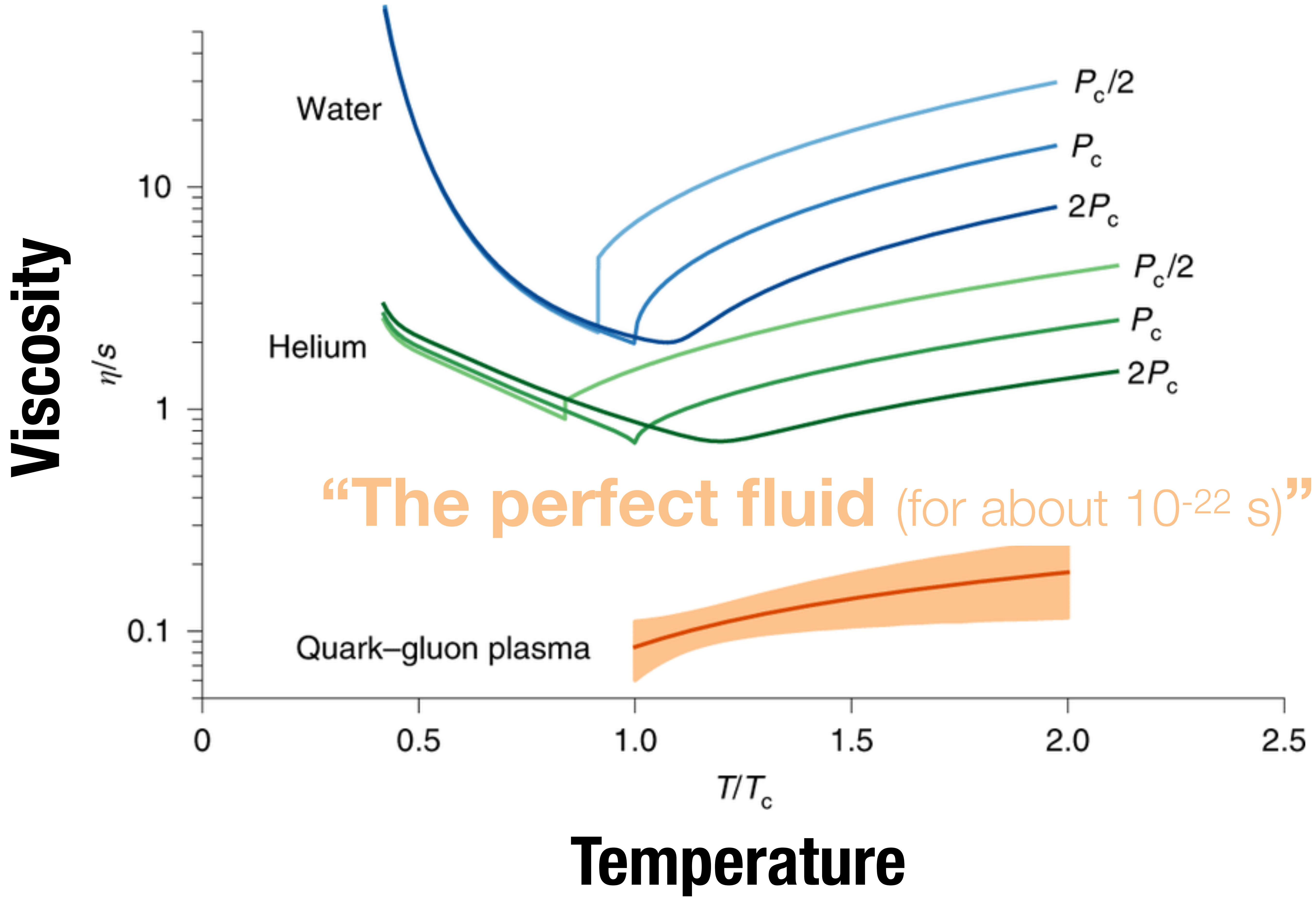
PbPb@5.36 TeV



Challenge: extract QGP properties out of the $\mathcal{O}(10^3)$ detected hadrons

Sneak peek into some of the most fascinating results

[Bernhard et al Nature Phys. 15 (2019) 11, 1113-1117]



[STAR Collab. Nature 548 (2017) 62-65]

Sneak peek into some of the most fascinating unknowns

- How does the QGP emerge from an asymptotically free theory?
- What is the mechanism behind QGP thermalisation in yoctoseconds?
  https://igfae.usc.es/yoctolhc/project/
- How small can a QGP droplet be?
- Why are many bulk phenomena so similar in pp, pPb and PbPb?
- Is there a critical point in the region explored by heavy-ion collisions?
- Which modifications does the QGP induce into a parton shower?