ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Nuclear Physics at UIUC:

Getting to the heart of (the) matter

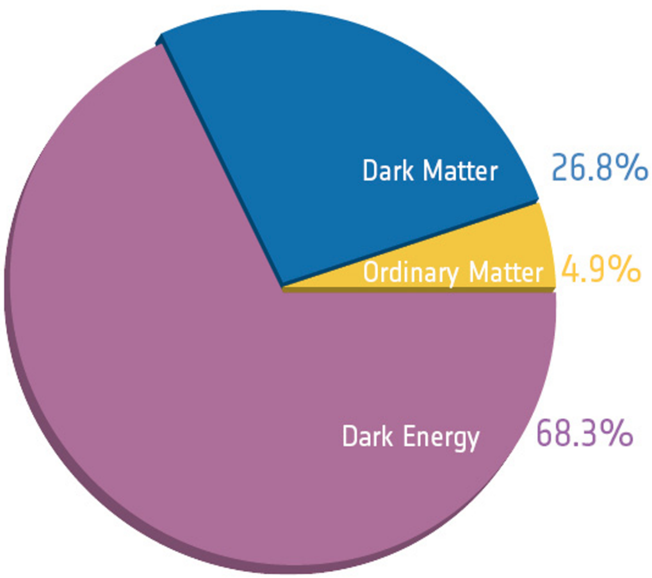
JORGE NORONHA
(on behalf of the Nuclear Physics Group)

Open House Nuclear Physics Seminar – March 2020

Standard Model of Particle Physics

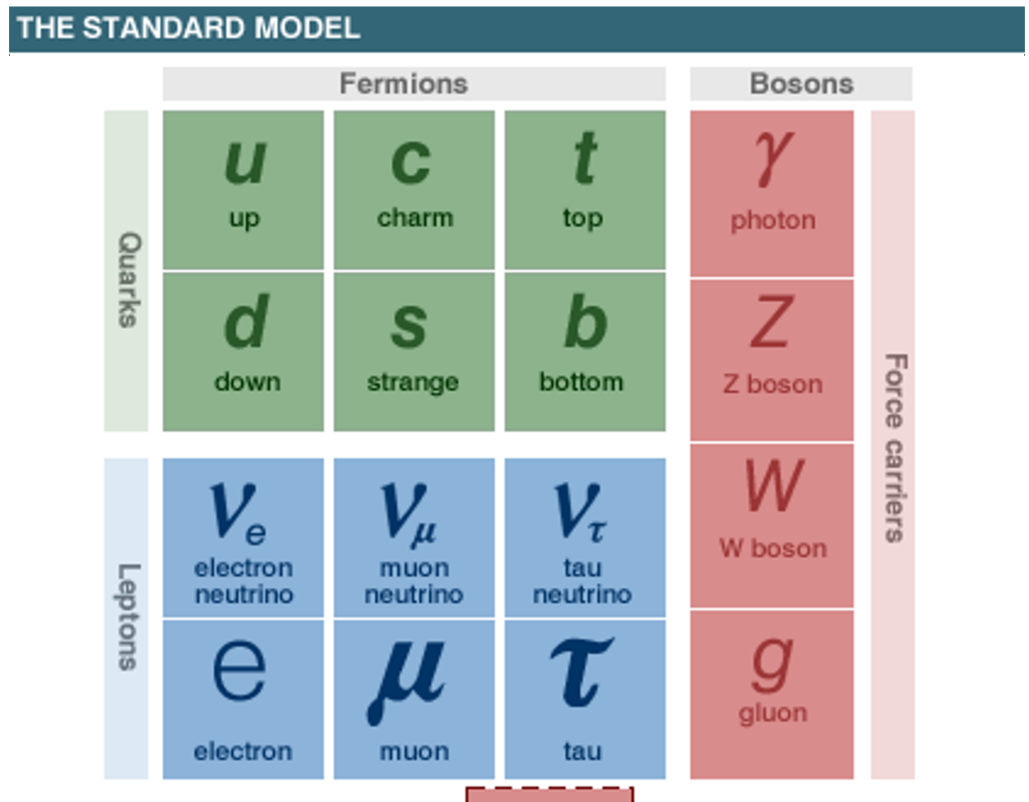
Cosmic Pie Chart

ESA/Planck



Dark matter ?
Dark energy?

Current Status (4.9% of the Universe)



2012

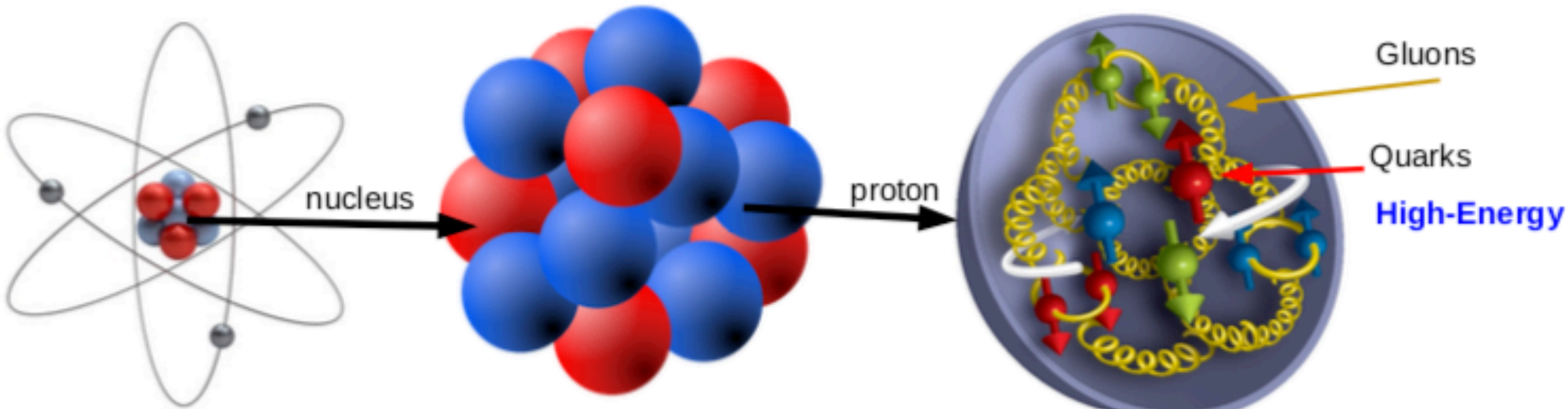
Fundamental Forces of Nature

Interaction	Theory	Mediator	Strength	Range (m)
Strong Force	Quantum Chromodynamics (QCD)	Gluons	10^{38}	10^{-15} (nucleus size)
Electromagnetic	Quantum Electrodynamics (QED)	Photons	10^{36}	Infinity
Weak	Electroweak Theory (EW)	W and Z bosons	10^{25}	10^{-18}
Gravitation	General Relativity (GR)	Gravitons ?	1	Infinity

Main Tool: **Quantum Field Theory**

- Special Relativity + Quantum Mechanics
- Gauge symmetry as underlying principle

Physics at the Smallest Scales



~10^{-10} meters ~10^{-14} meters ~10^{-15} meters

Low-Energy Intermediate-Energy

Natural Units: $\hbar = c = 1$ i.e. $E = Mc^2 \rightarrow E = M$

1 Femtometer [fm] = 10^{-15} [m]

1 [GeV] = 1000 Megaelectron-volt [MeV] = 11 billion [K]

1 [MeV] = $1.79 * 10^{-30}$ [kg]

Nuclear Experiment Faculty

Prof. D. Beck

Fundamental Symmetries

Neutron EDM

Prof. J-C. Peng

Nucleon Structure

Reactor Neutrino Physics

Prof. N. Makins

Nucleon Structure

Nucleon Spin

Head of Physics Department

Prof. M. G. Perdekamp

Heavy Ion Collisions

Nucleon Spin

Prof. A. Sickles

Heavy Ion Collisions

Quark-Gluon Plasma

Jet Physics

Current Nuclear Physics Laboratory Research Staff

Faculty

Doug Beck

Paul Debevec (R)

Naomi Makins

Alan Nathan (R)

Jen-Chieh Peng

Matthias Perdekamp

Anne Sickles

Visiting Scholars

Jaako Koivuniemi
Dipanwita Banerjee
Fabrice Gautheron

Research Physicists

Caroline Riedl
Steve Williamson

Postdocs

Vincent Andrieux
Andrew Chen
Yongsun Kim
Riccardo Longo
Marco Meyer
Tim Rinn
Sebastian Tapia

Technical Support

John Blackburn

Clayton Curry

Javad Khusro

Peter Sobel

Eric Thorsland

Adam Wehe

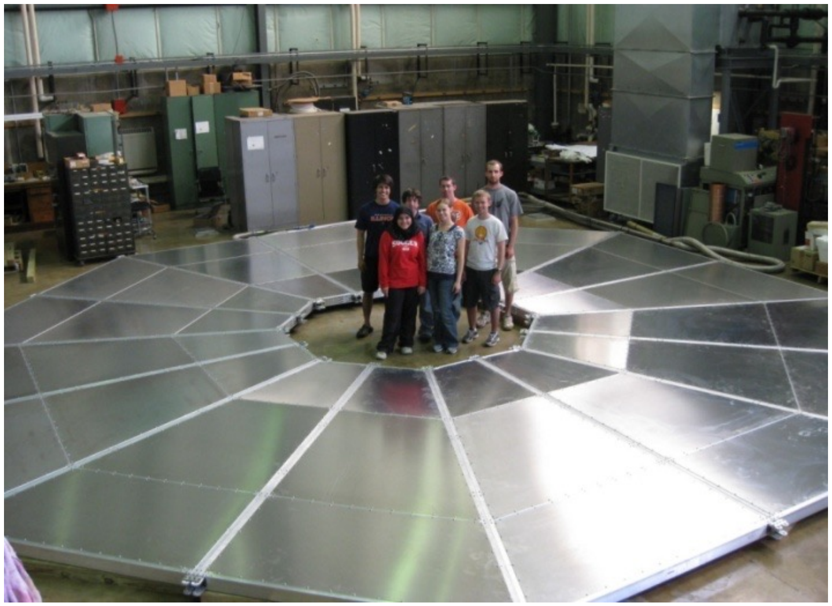
Graduate Students

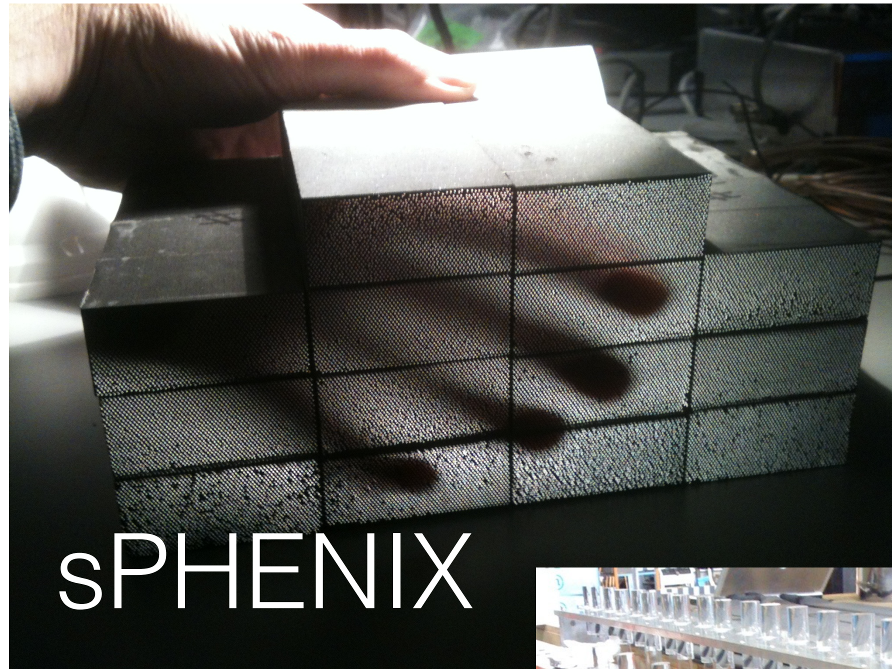
Anabel Romero-Hernandez
April Townsend
Aric Tate
Blake Erickson
Bryan Kerns
Chad Lantz
Dewen Zhong
Greg Mattson
Hugo Leung
Jason Dove
Mike Phipps
Nico Santiago
Sarvagya Sharma
Sheng Yang
Shivangi Prasad
Taylor Shimek
Thomas Rao
Virgina Bailey
Xiaoning Wang

Looking for 3 to 4 students

NPL @ Illinois: detector construction

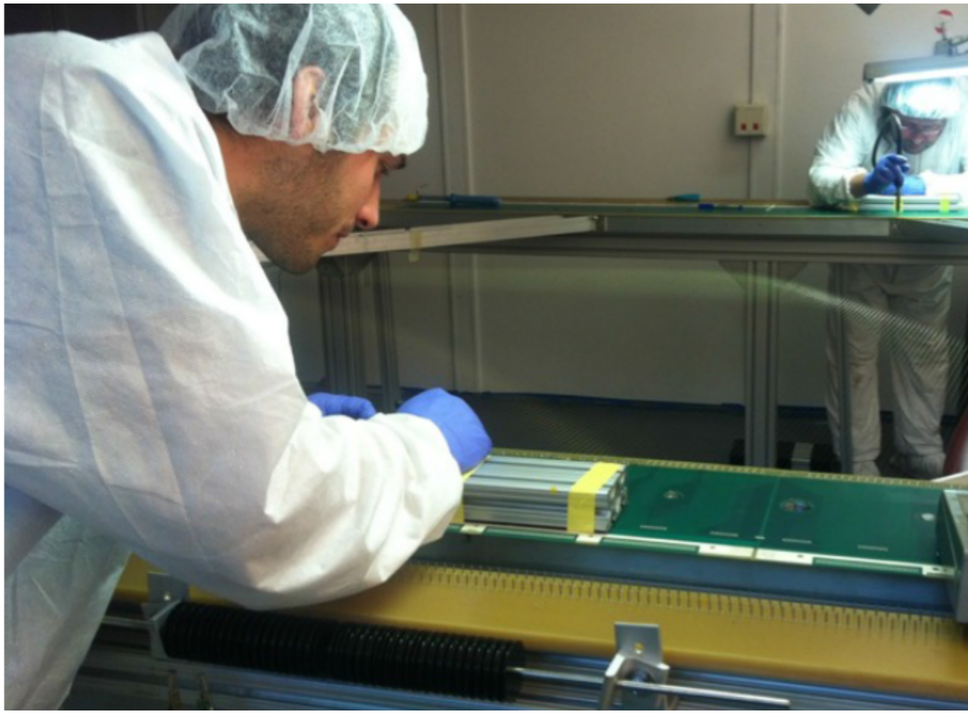
PHENIX RPC



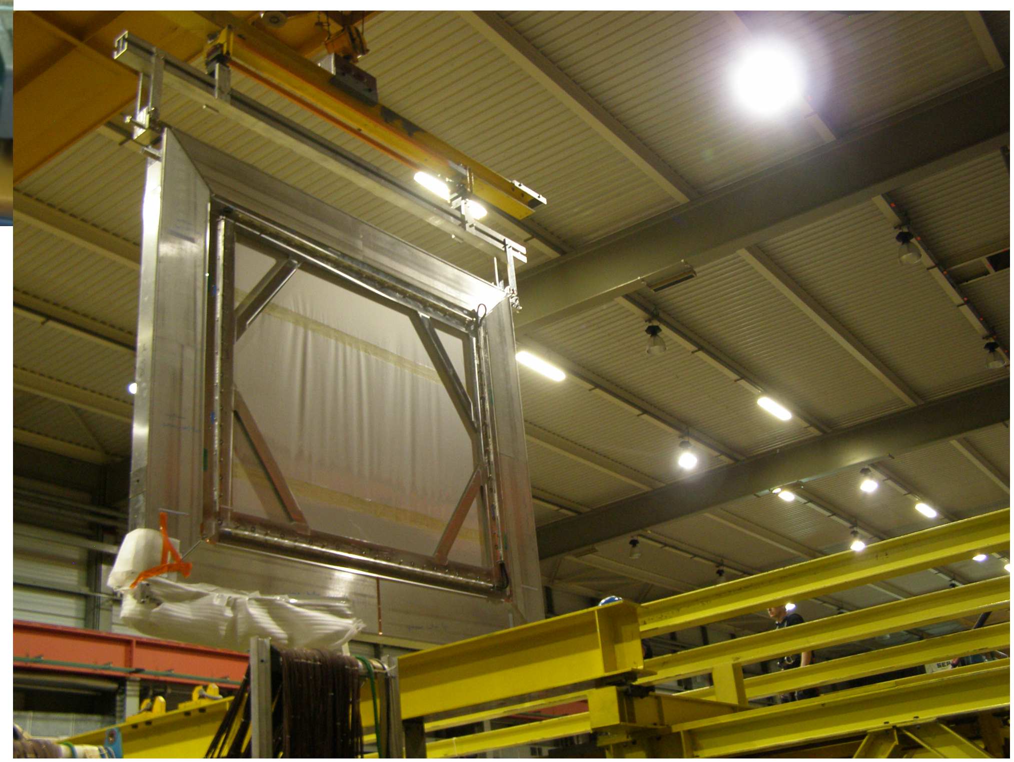


Many local detector construction projects provide unique opportunity for students: sPHENIX calorimeters, COMPASS drift chambers, ATLAS ZDC

COMPASS drift chamber installation



DC construction in Champaign



DC installation at CERN

Participation in Major Experiments

Fundamental Symmetries

Large scale project funded by

- Daya Bay

- nEDM

Quantum Chromodynamics

- sPHENIX (RHIC/BNL)
- SeaQuest (FNAL)
- COMPASS (SPS/CERN)
- ATLAS (LHC/CERN)

Nuclear Theory Faculty

Research Professor
(Professor Emeritus)

Prof. Jorge Noronha

QCD Out of Equilibrium

Neutron Star Mergers

String theory and the Quark-Gluon Plasma

Prof. Jaki Noronha-Hostler

Quark-Gluon Plasma

QCD Equation of State

Computational Fluid Dynamics

Prof. Gordon Baym

Many-Body Physics

Neutron Stars

High Energy Nuclear Theory

Current Nuclear Theory Members

Nuclear Theory Group Expanded in Fall 2019

Faculty

Jorge Noronha

Gordon Baym

Jaki Noronha-Hostler

Postdocs

Matt Sievert

Mauricio Hippert (Fall 2020)

Enrico Speranza (Fall 2020)

Chris Plumberg (Fall 2020)

Graduate Students

Travis Dore

Patrick Carzon

Looking for 5 to 6 students

Current Research Highlights

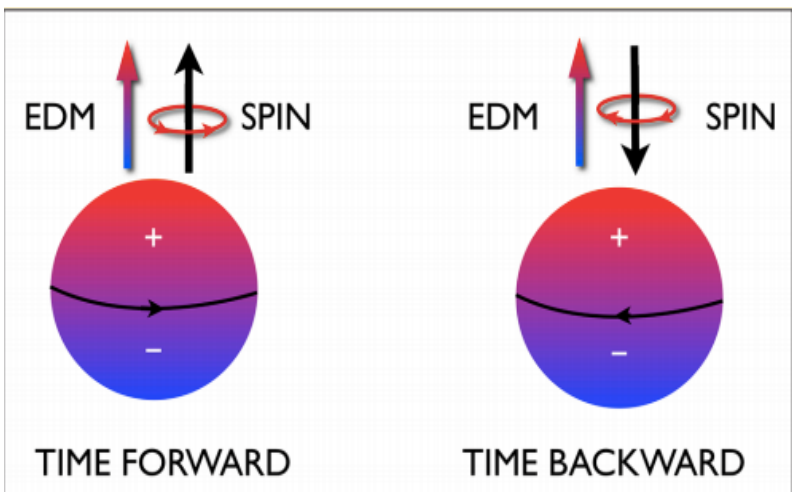
Synergy: Precision ⟷ Discovery

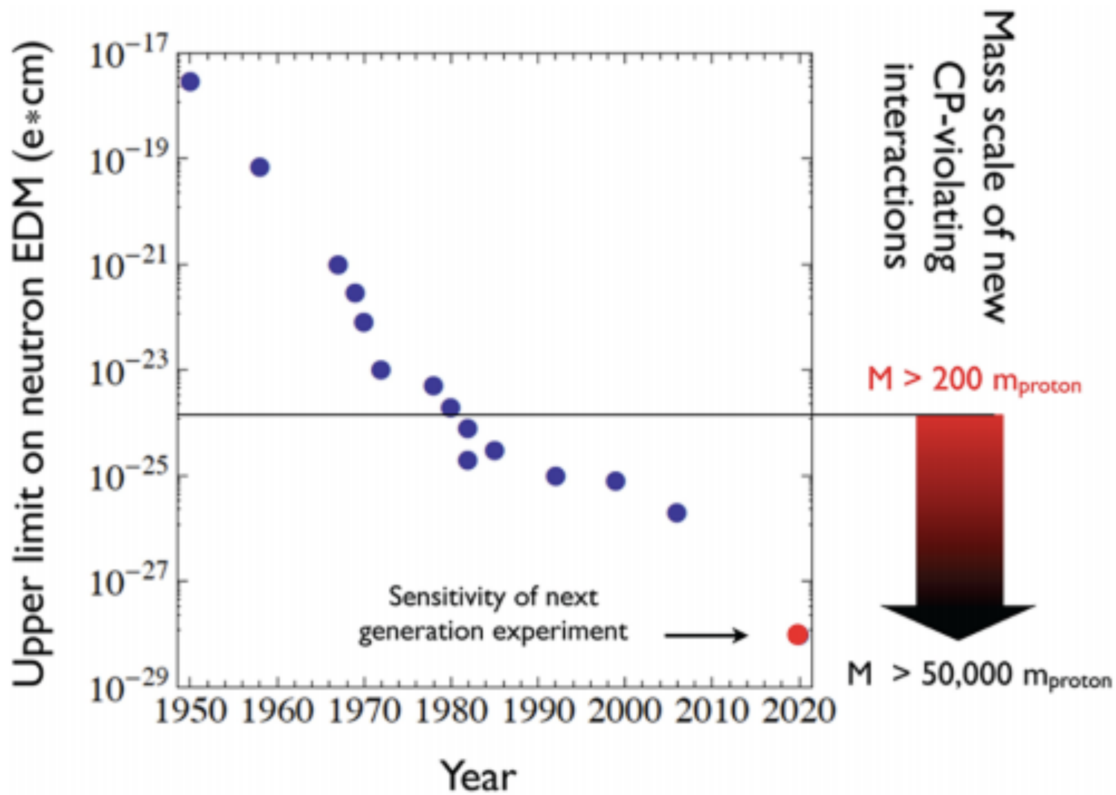
Precision Tests of Fundamental Symmetries

Charge, Parity, Time (CPT) invariance

Observation of Neutron Electric Dipole Moment (EDM) implies time-reversal violation

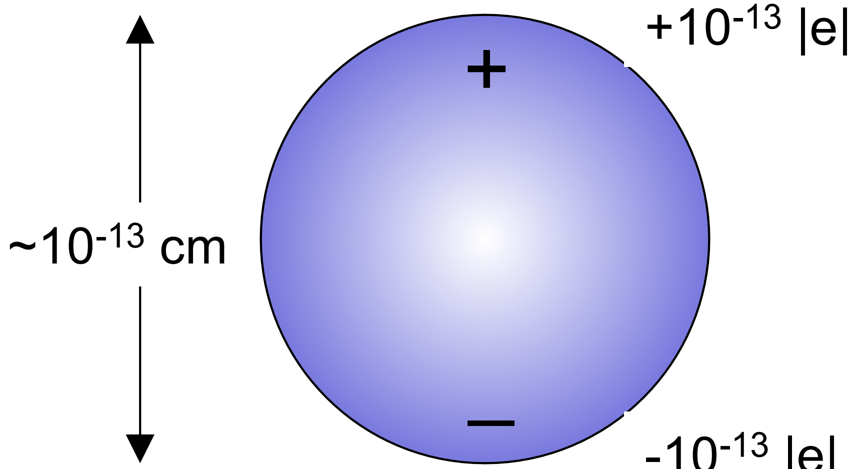
Time-reversal transformation





How Small is Small?

- Current limit on neutron EDM is ~ 10^{-26} e·cm
- Equivalent of 10^{-13} electron charge at neutron N and S poles



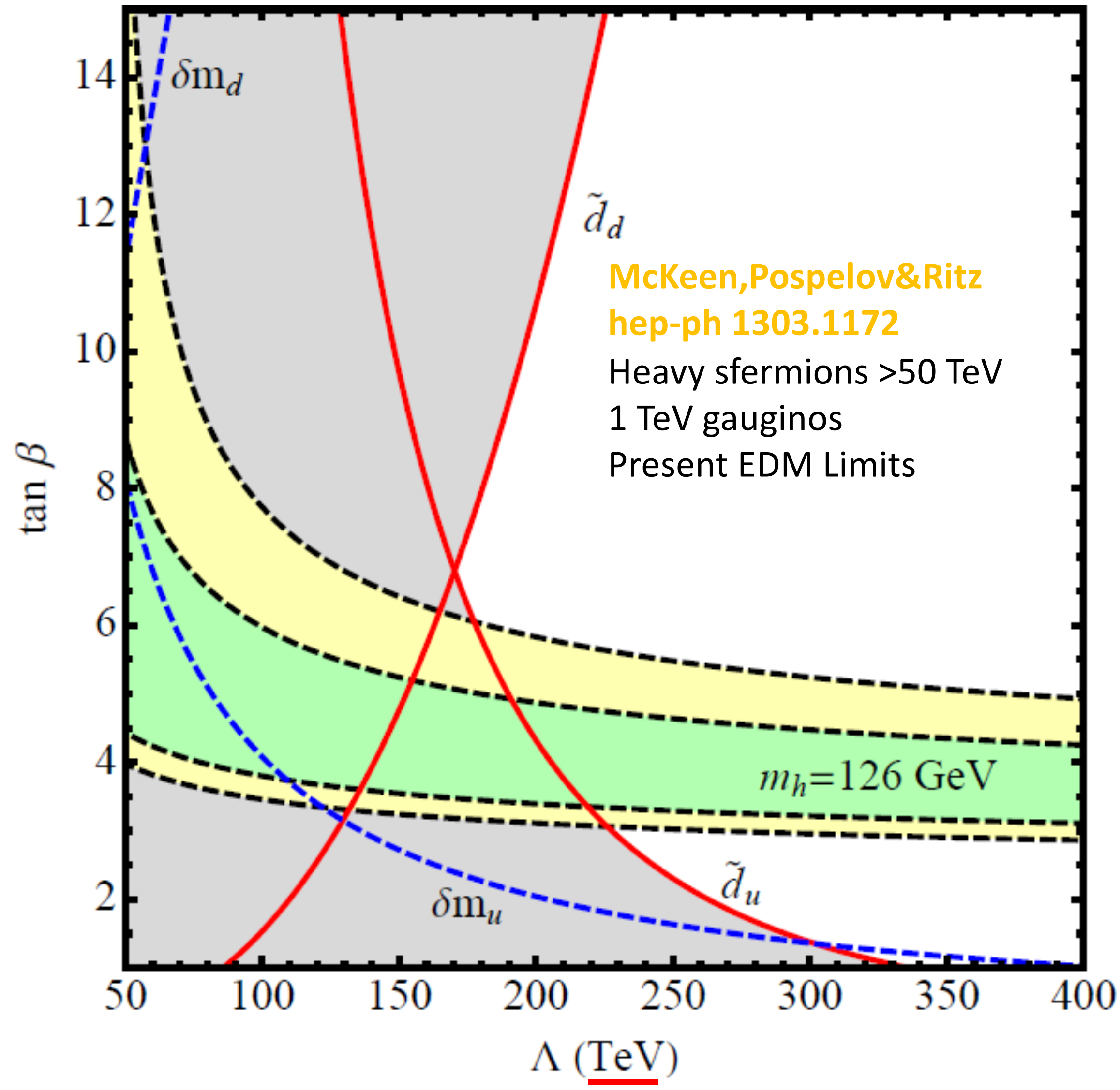
How Does One Trap Neutrons?

- Slow them down! "Ultracold Neutrons" (UCN)
- With kinetic energy of 100 neV (T ~ 1 mK), UCN behave like waves trapped by total internal reflection

Neutron Electric Dipole Moment

Search for physics beyond the Standard Model

- If EDM is non-zero, must be new physics
- Strong constraints on SUSY especially <u>with</u> LHC data
- Improvement of nEDM would push limits off graph



New Measurement: First Phase

- Institut Laue-Langevin, Grenoble (France)

- Currently world's most intense source of ultracold neutrons

Looking for a graduate student

- Nuclear physics (ultra-cold neutrons) ⊕ Atomic physics (magnetometers)

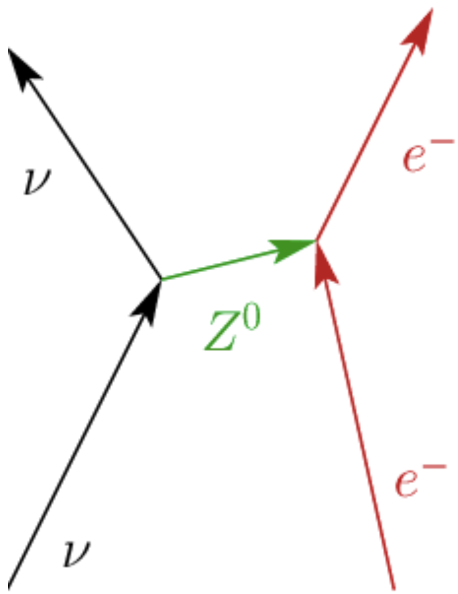
→ Particle/Astrophysics

- Physics beyond the standard model
- Matter-antimatter asymmetry

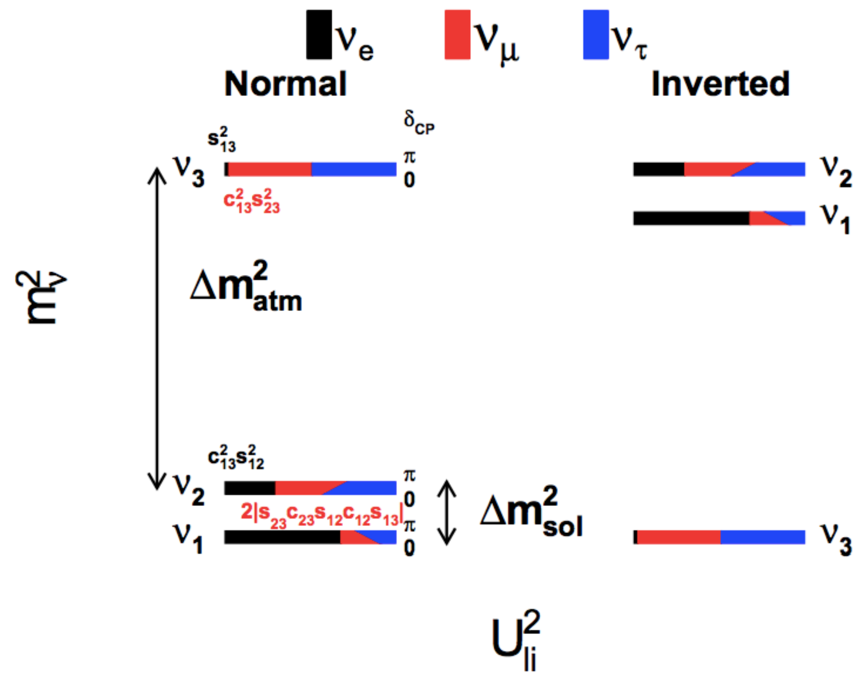
Understanding the Nature of Neutrinos

2015

Weak interactions



Neutrino mass hierarchy

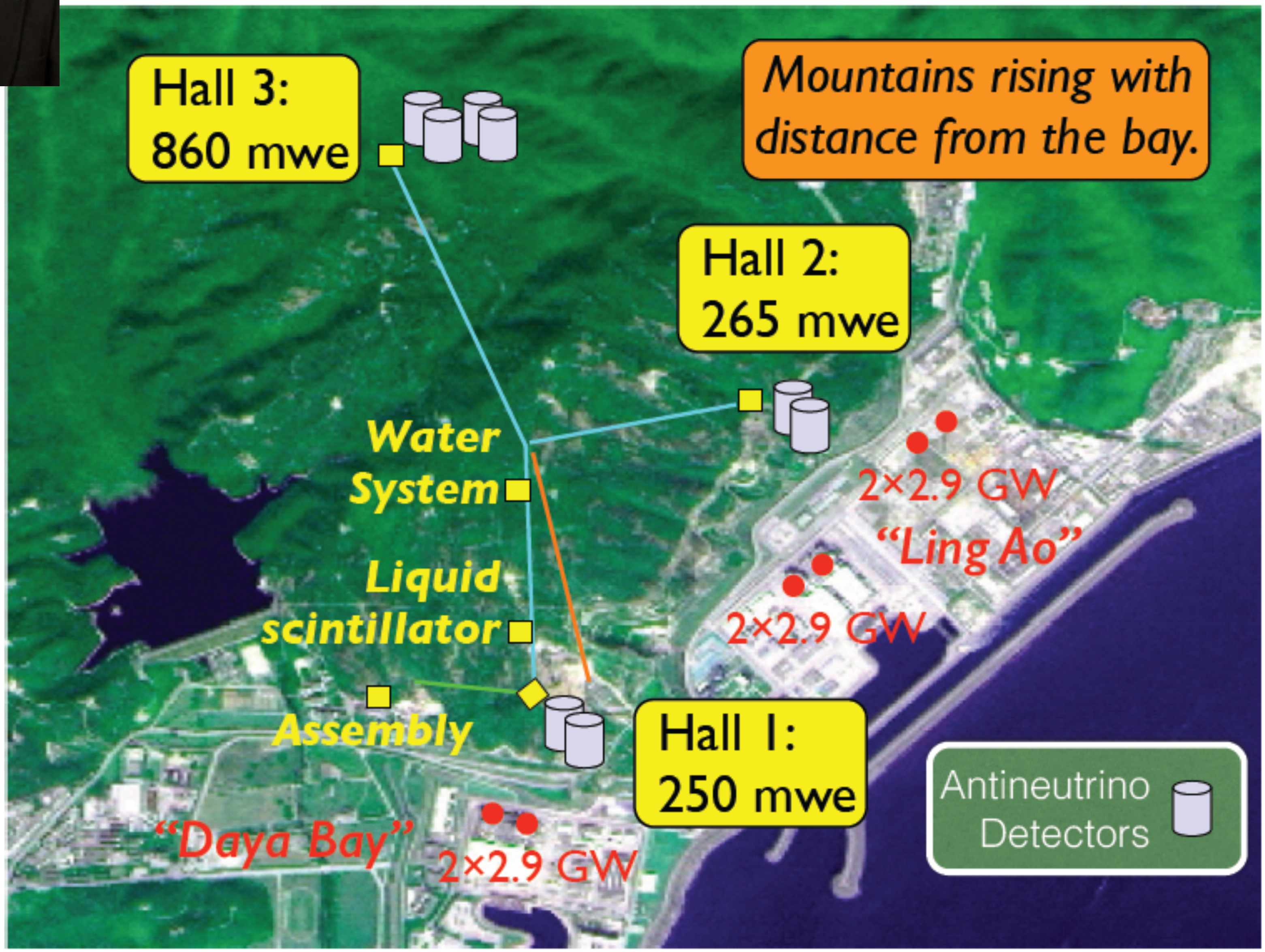


Pontecorvo–Maki–Nakagawa–Sakata (PMNS) Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

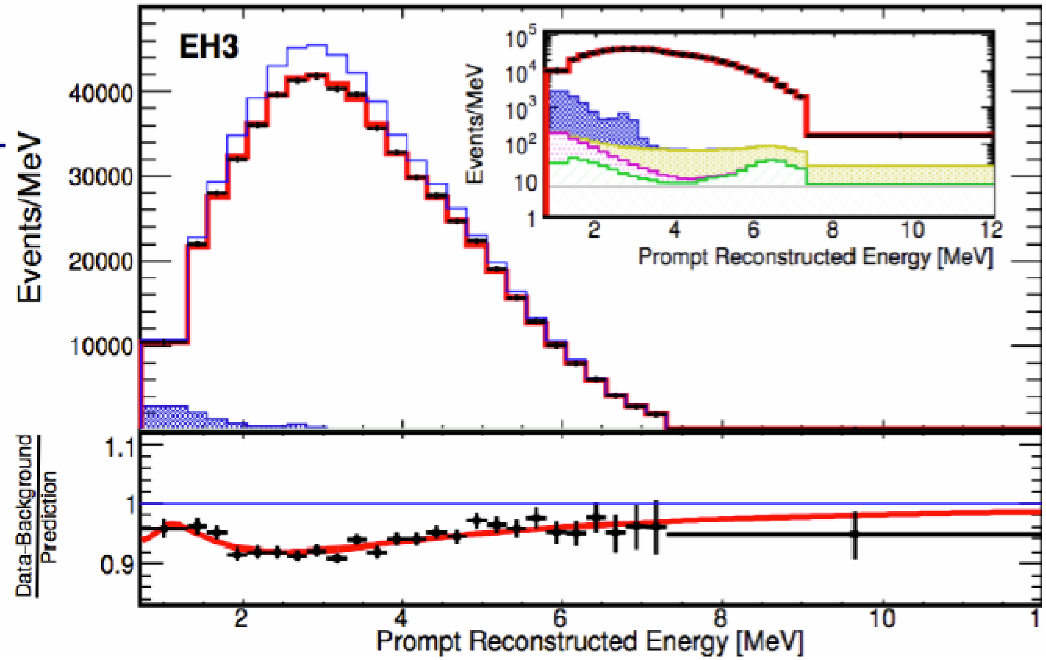
$$\theta_{13}???$$

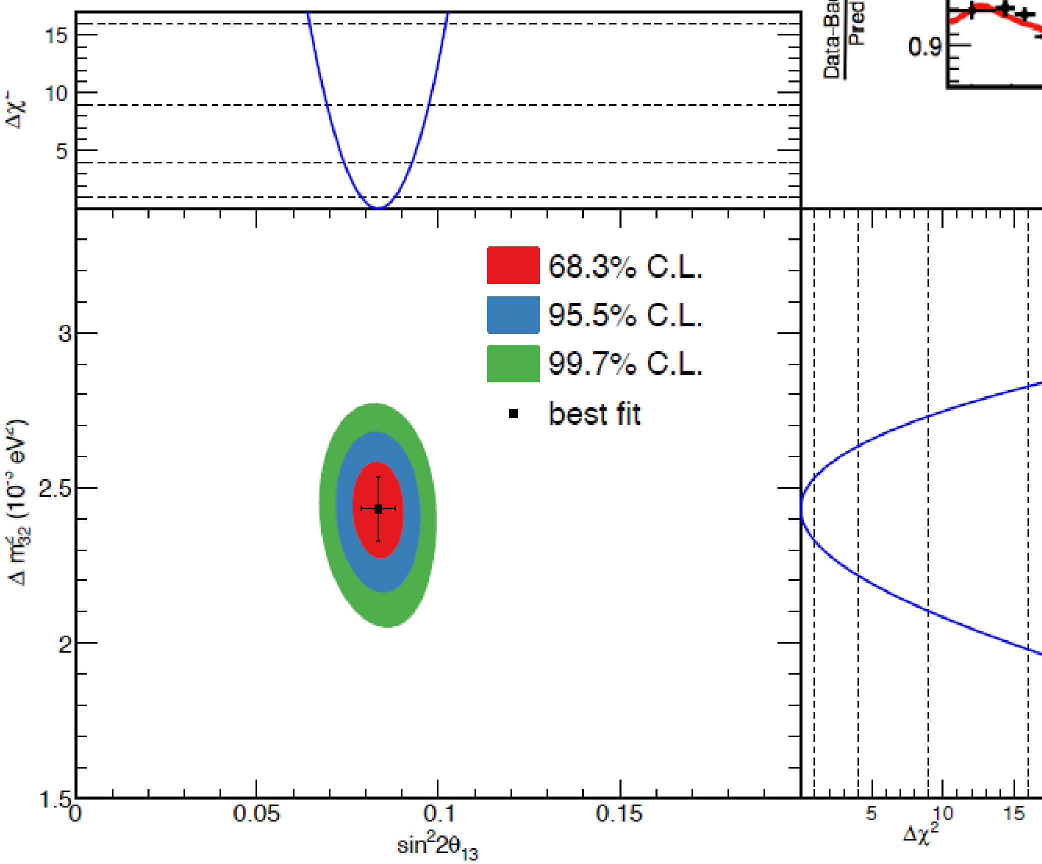
Daya Bay Neutrino Experiment
(search for the θ_{13} mixing angle)



Results

$$\sin^2 2\theta_{13} = 0.084 \pm 0.0047$$
$$\Delta m^2_{32} = (2.433^{+0.102}_{-0.105})\times 10^{-3}\ \mathrm{eV}^2$$
$$\chi^2/NDF = 177.6/205$$





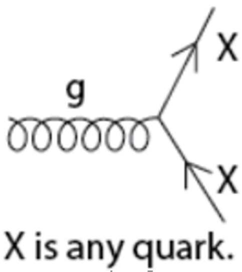
2016 Breakthrough Prize in Fundamental Physics!

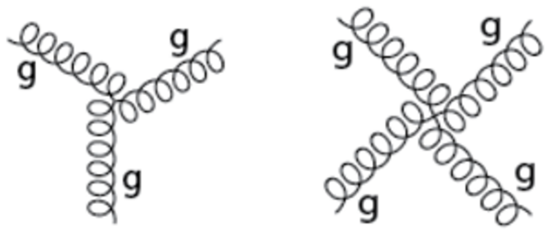
Quantum Chromodynamics (QCD)

2004

The fundamental theory of the strong interactions

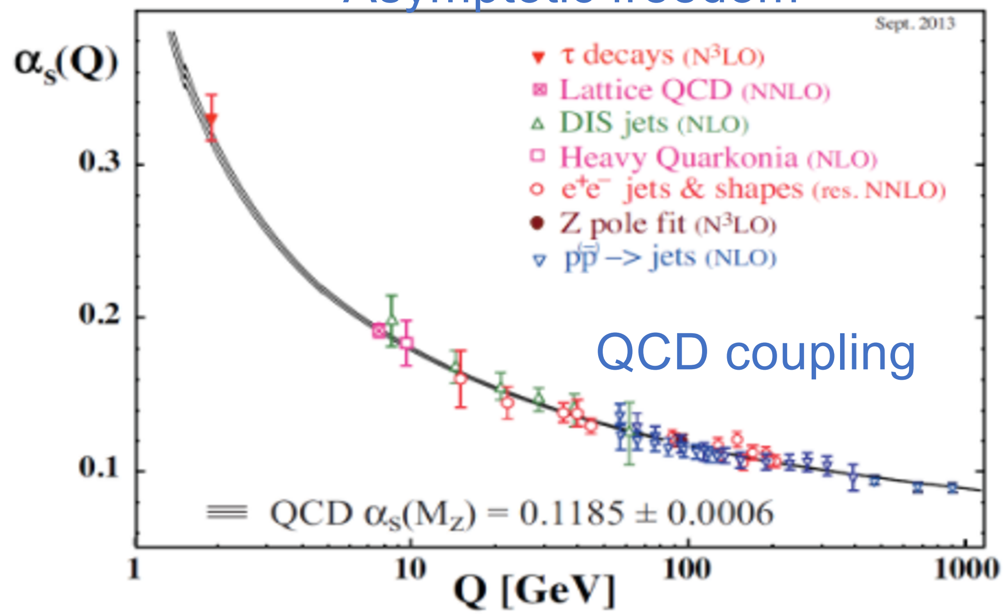
Non-Abelian gauge theory





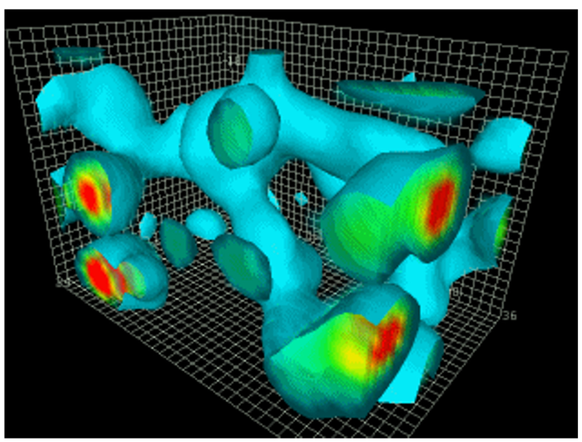
gluon self-interactions

Asymptotic freedom



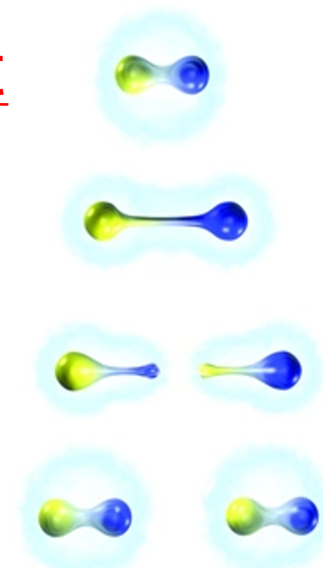
QCD coupling

The QCD vacuum



from D. B. Leinweber

Color confinement



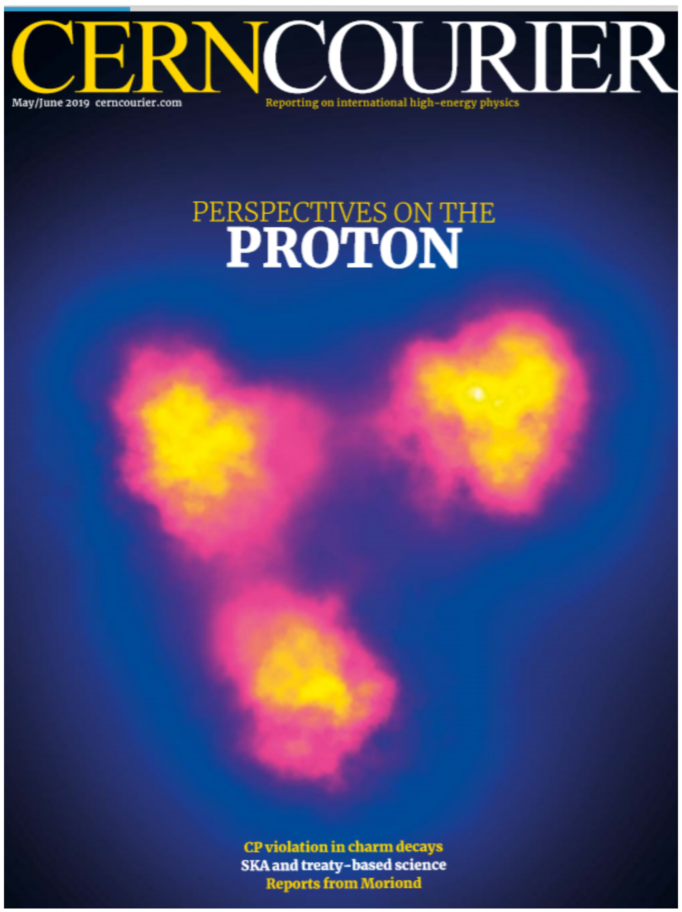
Hadron (pion)

Strong coupling phenomenon !!!

Quarks and gluons can never be truly free

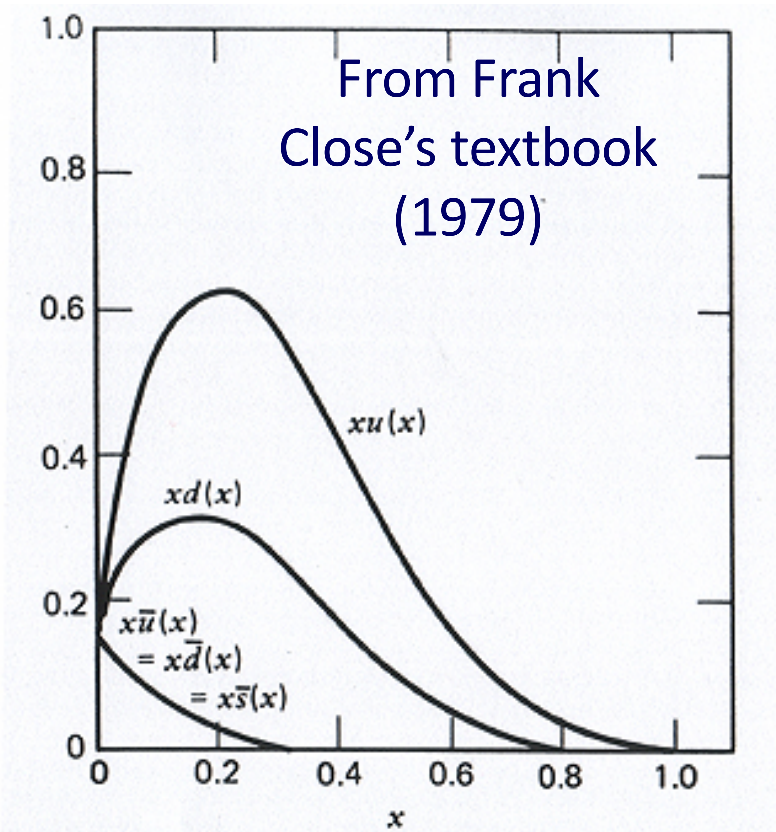
Nucleon Structure

Why is it interesting?



- 99.97% of the visible mass of the Universe is composed of protons and neutrons.
- Quantum Chromodynamics at the confinement scale remains to be understood.
- How does the proton get its spin?

Flavor structure of the parton distributions in the proton



x is the fraction of the proton momentum carried by the quarks/antiquarks ($0 < x < 1$)

Questions

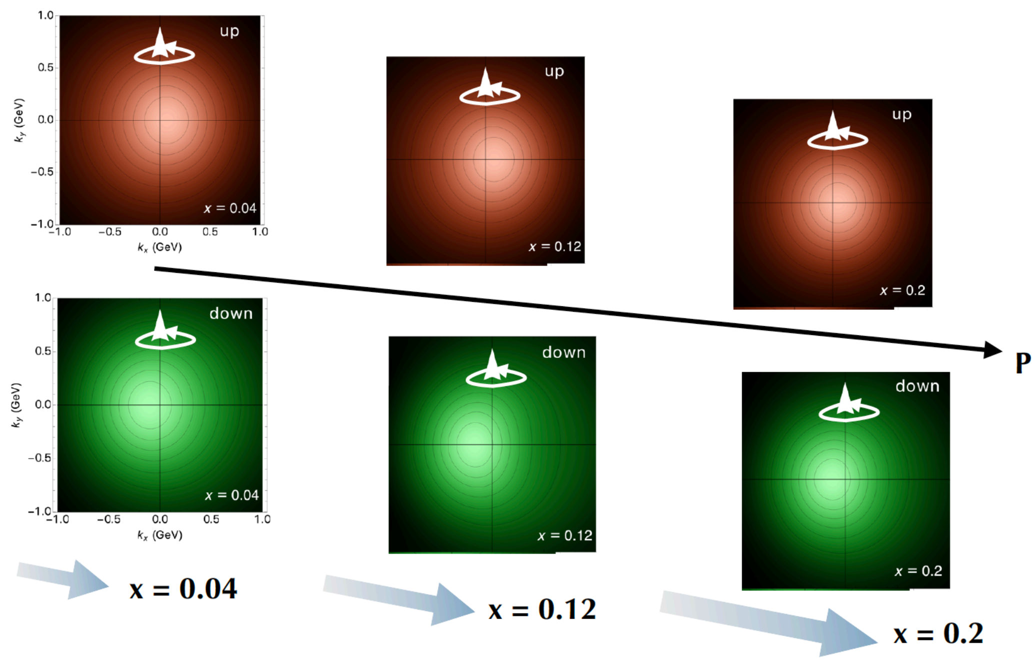
- Is $\bar{u}(x) = \bar{d}(x)$?
- Is $\bar{s}(x) = \bar{u}(x)$?
- Is $\bar{s}(x) = s(x)$?
- Is $\bar{u}_p(x) = \bar{d}_n(x)$?
- Is $u_V(x) = 2d_V(x)$?
- Is $u_p(x) = d_n(x)$?

COMPASS @ CERN: Proton Quark Structure

Matthias Perdekamp

- Fixed Target experiment @CERN SPC (France)
- Uses secondary and tertiary beams at M2 beam-line @CERN SPS

- **Exploring the 3D structure of proton and neutrons**
- Momentum space
  - Drell-Yan process and Semi Inclusive Deep Inelastic Scattering
- Impact parameter space – GPDs
  - Deeply Virtual Compton Scattering



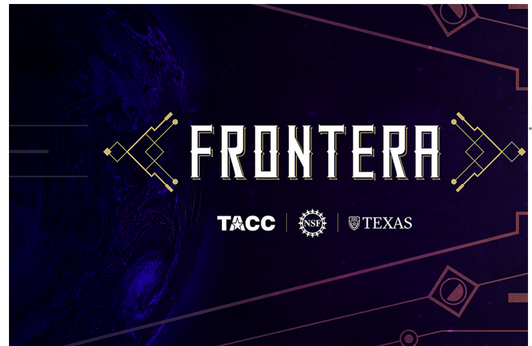
Caroline Riedl

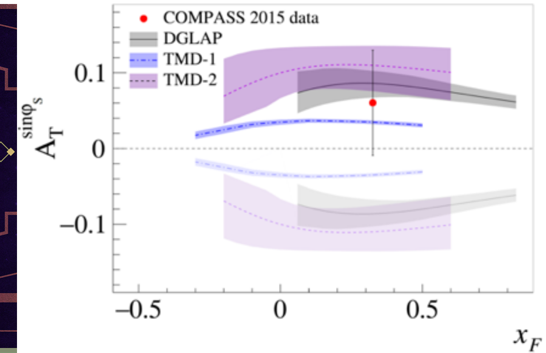
COMPASS Data Analysis on FRONTERA Supercomputer

- Petscale new NSF super-computer: FRONTERA (world's #5 in July 2019)

- 3-23: UIUC COMPASS group received 1.5 Million node hours = 84 Millions core hours

  - PetaByte Data Transfer CERN ➔ Texas
  - Raw data processing
  - Monte Carlo simulation
  - Data analysis



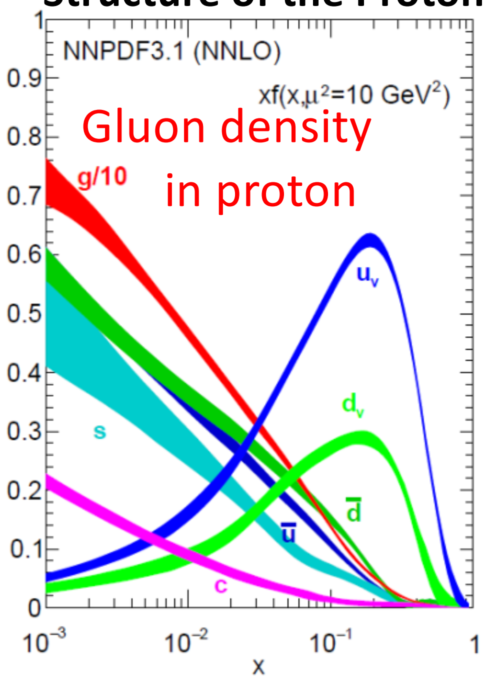


Looking for a graduate student (data analysis)

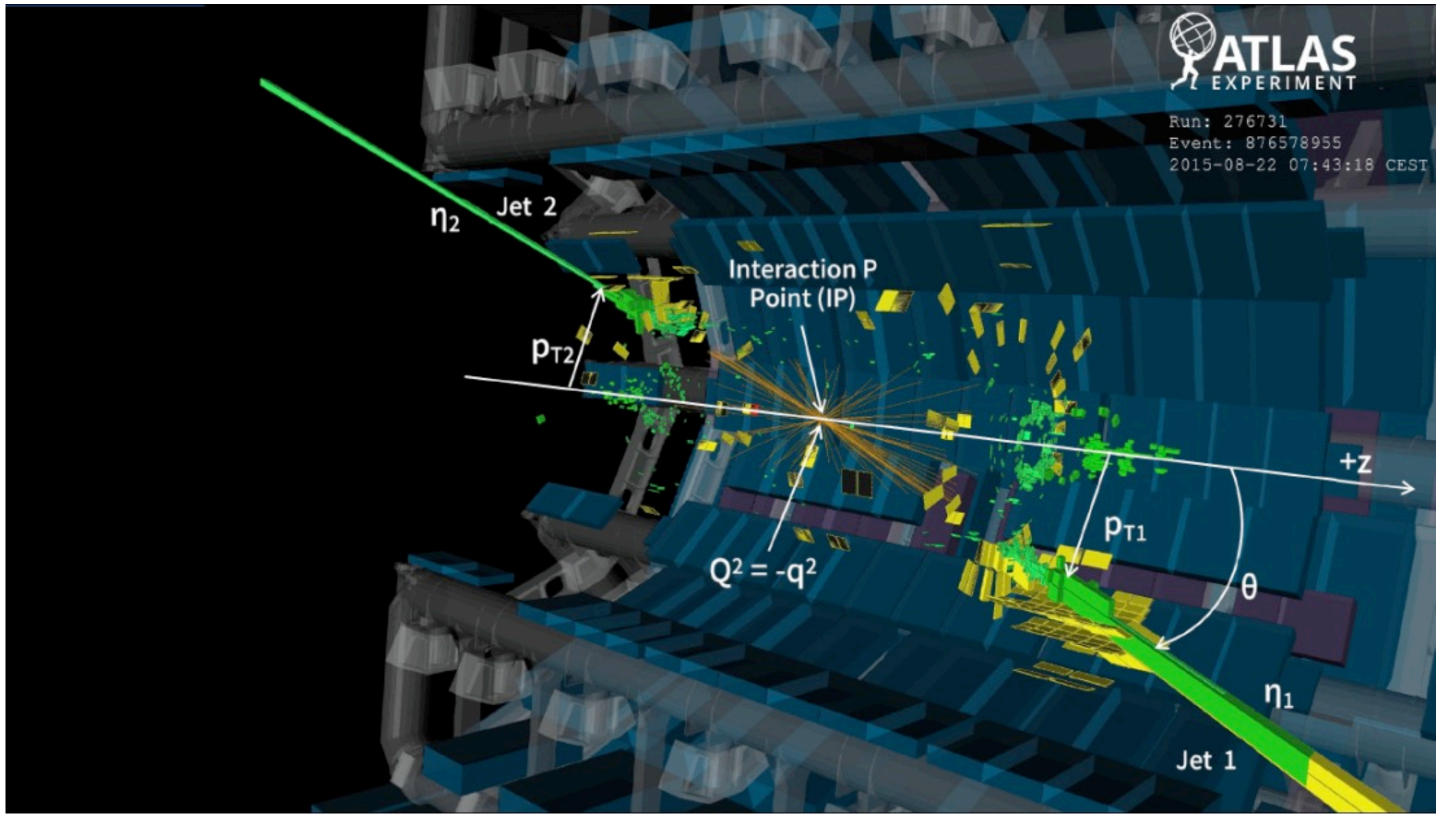
ATLAS: Search for Gluon Saturation + Radiation Hard Zero Degree Calorimeter

Matthias Perdekamp

Gluon and Quark Structure of the Proton

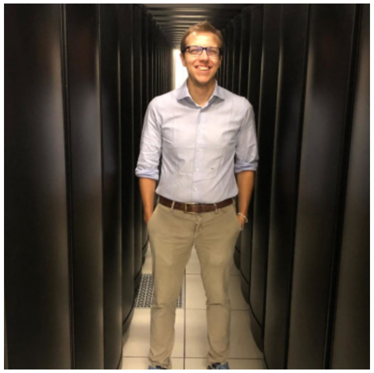


Forward Di-Jets in p-Pb: Testing QCD at Extreme Gluon Densities



Search for saturation effects in the gluon field in the proton

➔ Study QCD at the highest gluon field strengths in p-Pb at LHC !

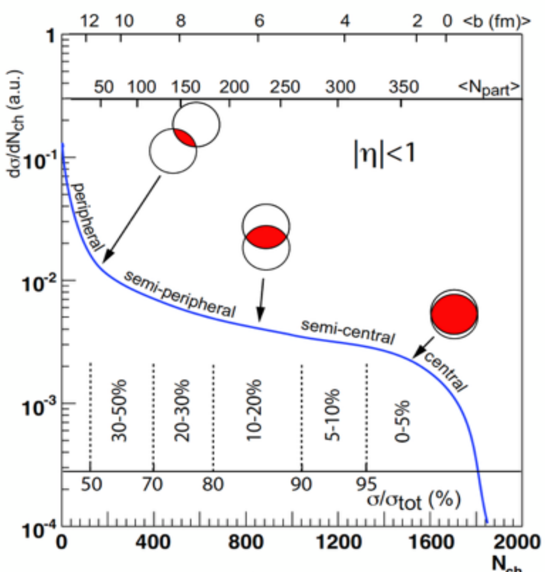


Riccardo Longo

Upgrade of the ATLAS ZDC

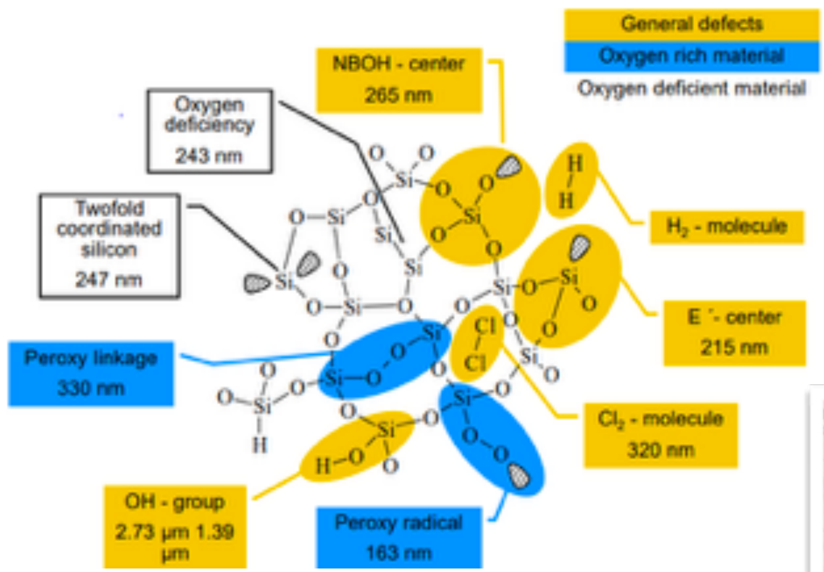
- Improve **radiation hardness** of ZDC for high-Luminosity LHC by factor 10
- ZDCs are located at the highest radiation spot of the LHC!

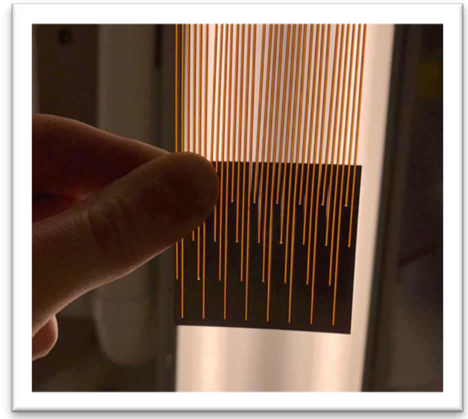
ZDC: Impact Parameter in Pb-Pb collisions at LHC



Ann. Rev. Nucl. Part. Sci. 57 (2007) 205

Material research: Radiation effects in ultra pure silica





Test Beam at CERN and FNAL

Collaboration with CMS, LHC accelerator division and Argonne National Lab

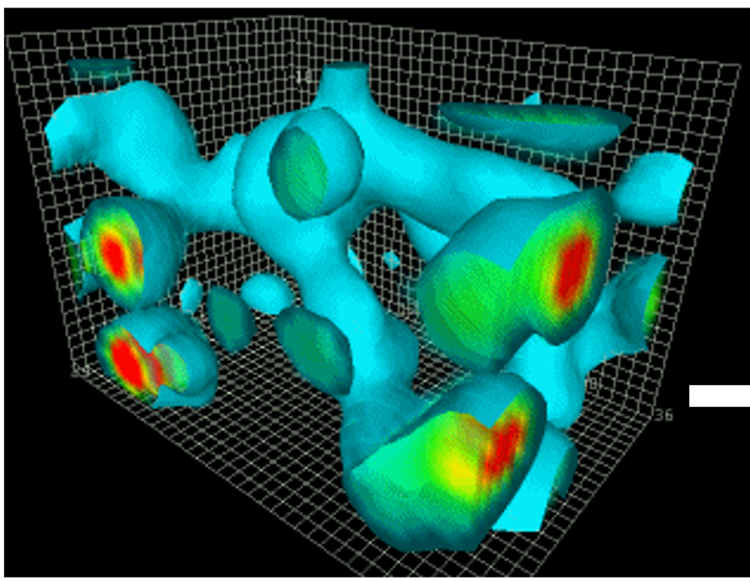
Looking for 1 grad student (p-P data analysis + ZDC R&D)

How does one melt the QCD vacuum?

“In order to study the question of the QCD vacuum, we must turn to a different direction, we should investigate some bulk phenomena by distributing large energy over a large volume.”

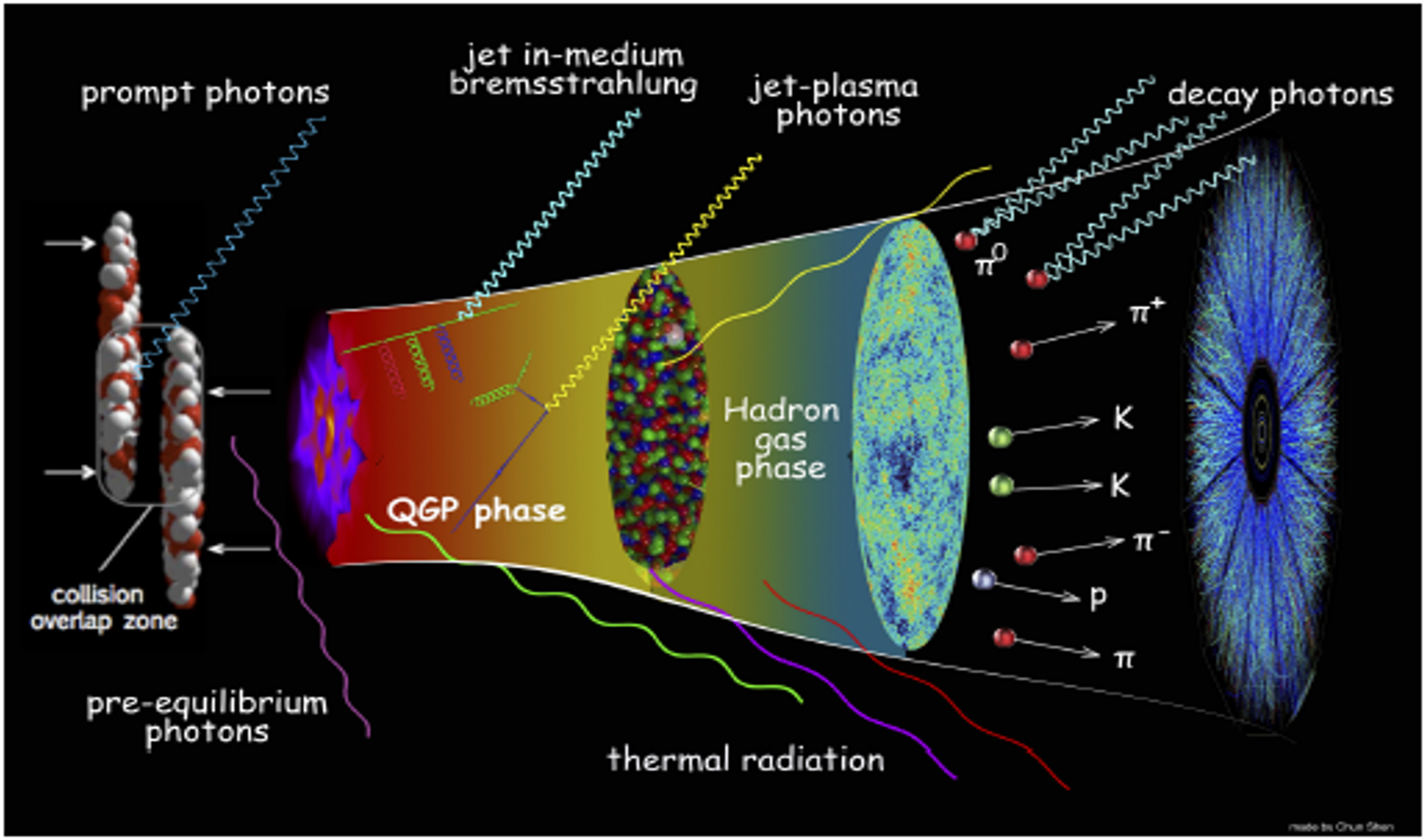
T. D. Lee, Rev. Mod. Phys. 47 (1975)

QCD vacuum T = 0



Heavy-Ion Collisions in a Nutshell – The Little Bang

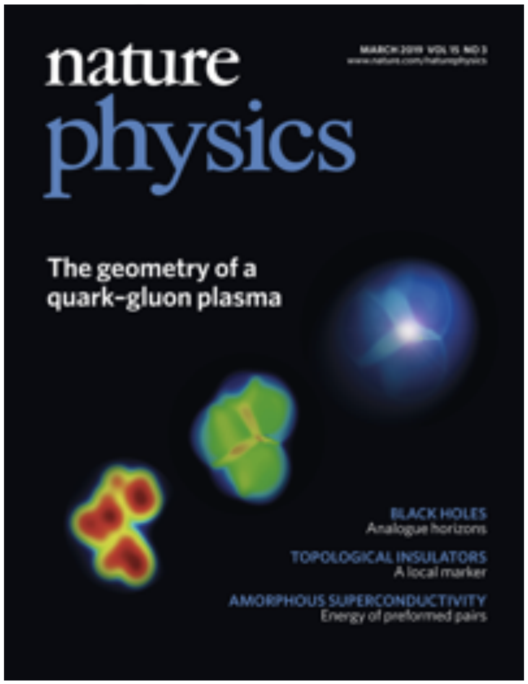
Study deconfinement of quarks and gluons in the lab



QGP = Nature's hottest, smallest, and most perfect fluid

Quark-Gluon Plasma (QGP)
Nature's Most Extreme Liquid

Smallest fluid ever produced



Most vortical liquid- spins 10 billion trillion times faster than the most powerful tornado

Most perfect fluid- 10 times less viscosity than water

Hottest liquid- T~10^{12} Kelvin. LHC won a Guinness World Record.

Quark-Gluon Plasma - Nature's Primordial Liquid existed 10^{-6} sec after Big Bang !!

Large Hadron Collider @ CERN

collide pairs of lead nuclei at 5 TeV / nucleon pair center of mass collision energy

different data than the high energy LHC program but the same experiments are used

~1 month / year of data

~100 of the 3000 ATLAS authors work directly on this physics

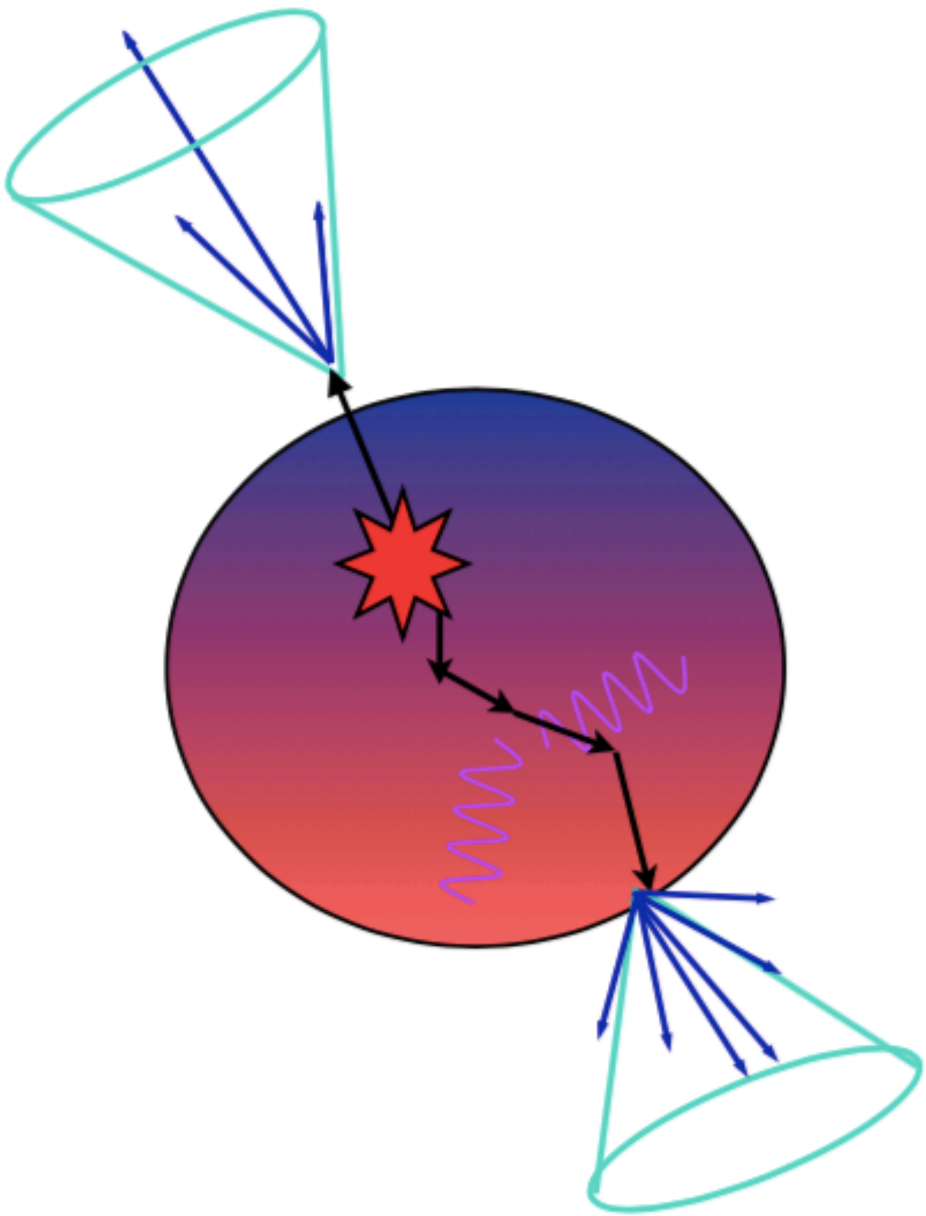
the resulting QGP:
collision energy sets maximum temperature
colliding nuclei set maximum size

$\sim 10^4$ particles created in the most head on collisions

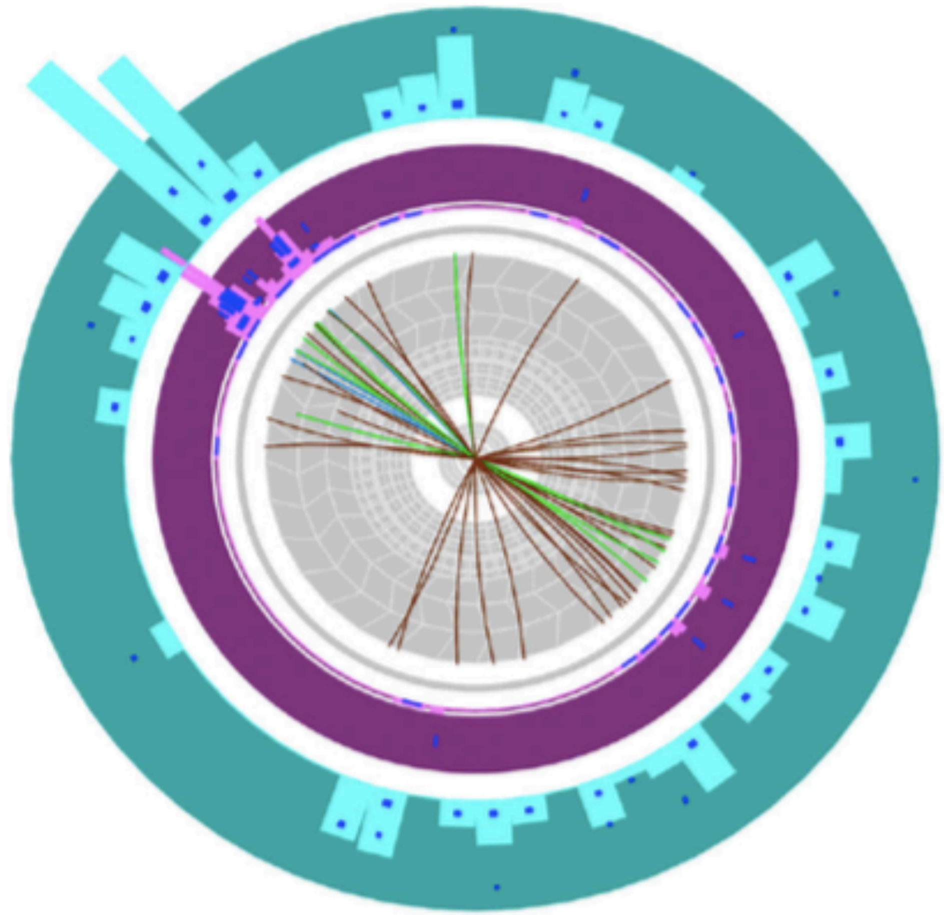
equivalent of $\sim 10^3$ pp collisions at once

jet quenching in action

cartoon



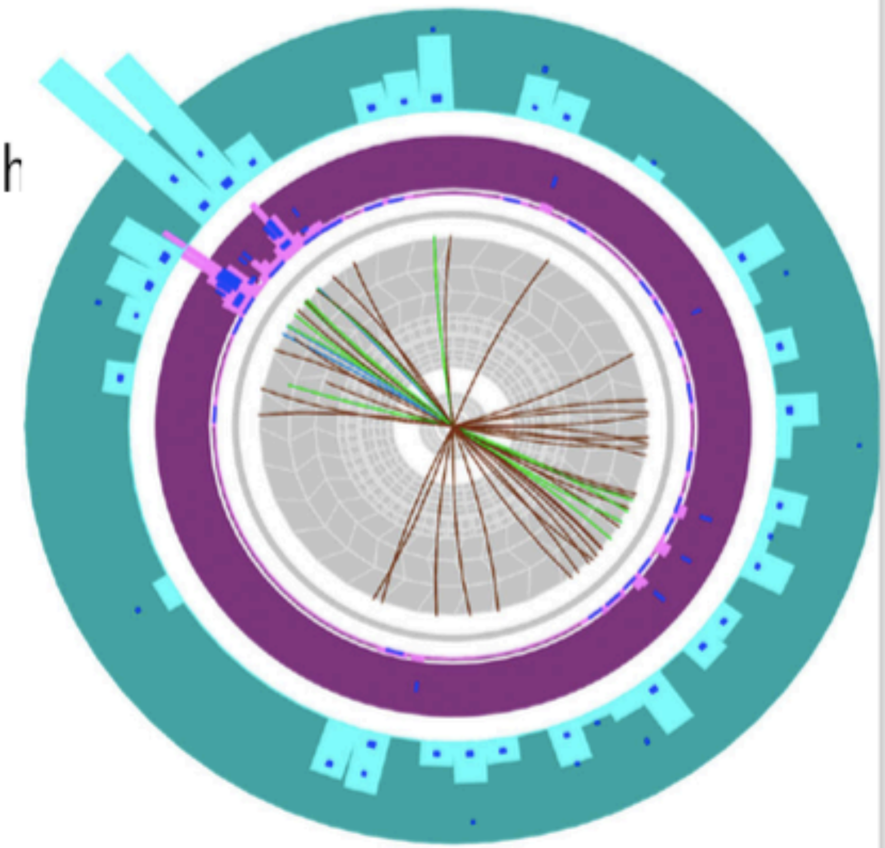
actual event measured in ATLAS



PRL 105 252303

where next?

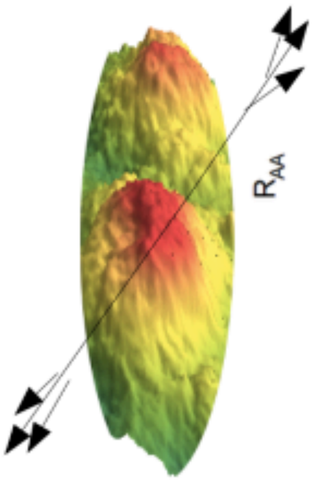
- jets are quenched and their structure is modified by the QGP
  - they are then a probe sensitive to the properties of the QGP
    - other discriminating structure measurements
    - finding the energy lost by the jet
    - changing the QGP the jets go through
      - colliding smaller nuclei
      - lower temperature QGP

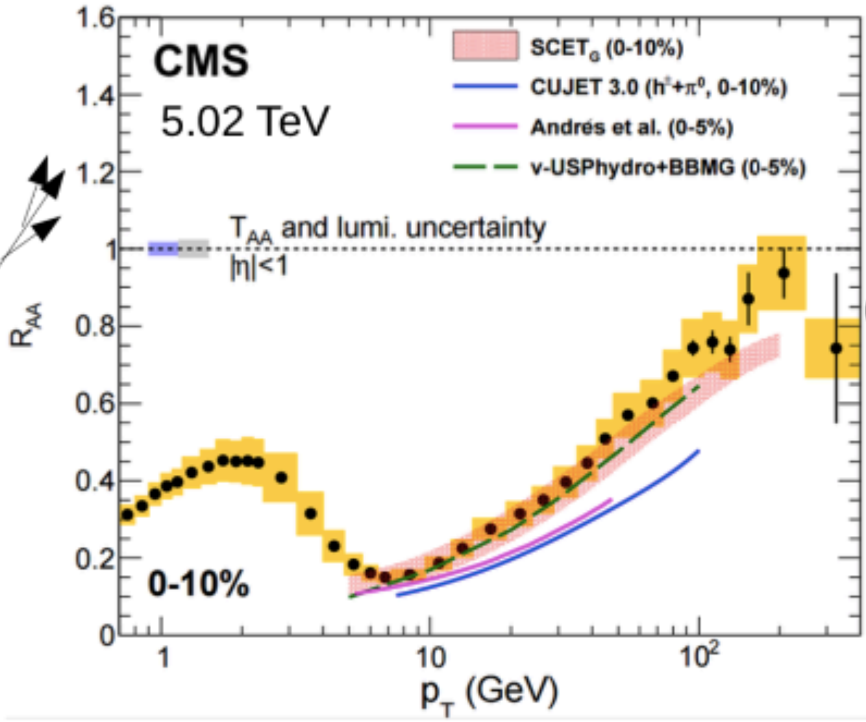


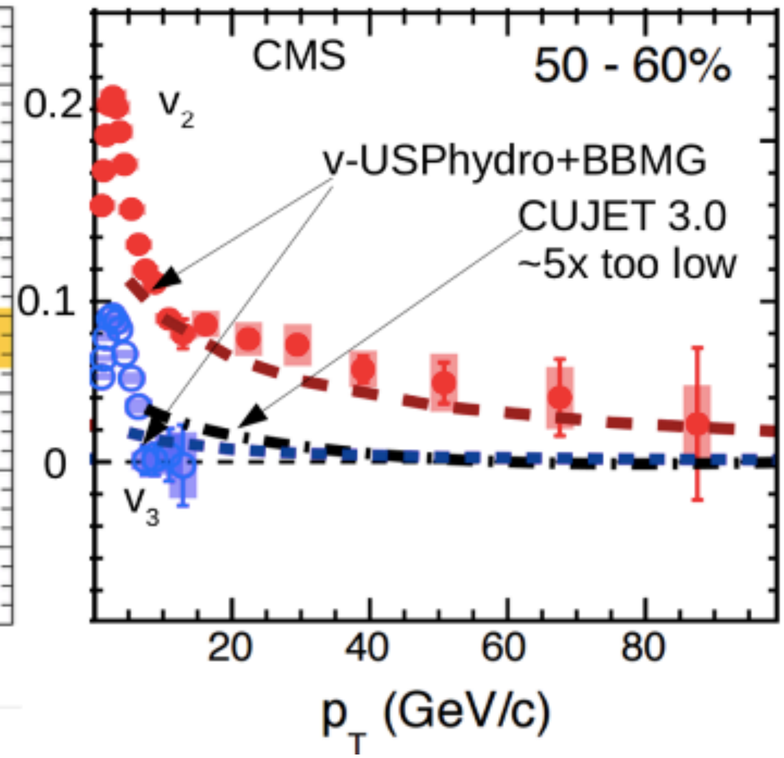
Looking for 1 (or perhaps 2) students

Modelling Jets Plowing Through the Quark-Gluon Plasma

v−USPhydro+BBMG predictions confirmed at LHC run 2



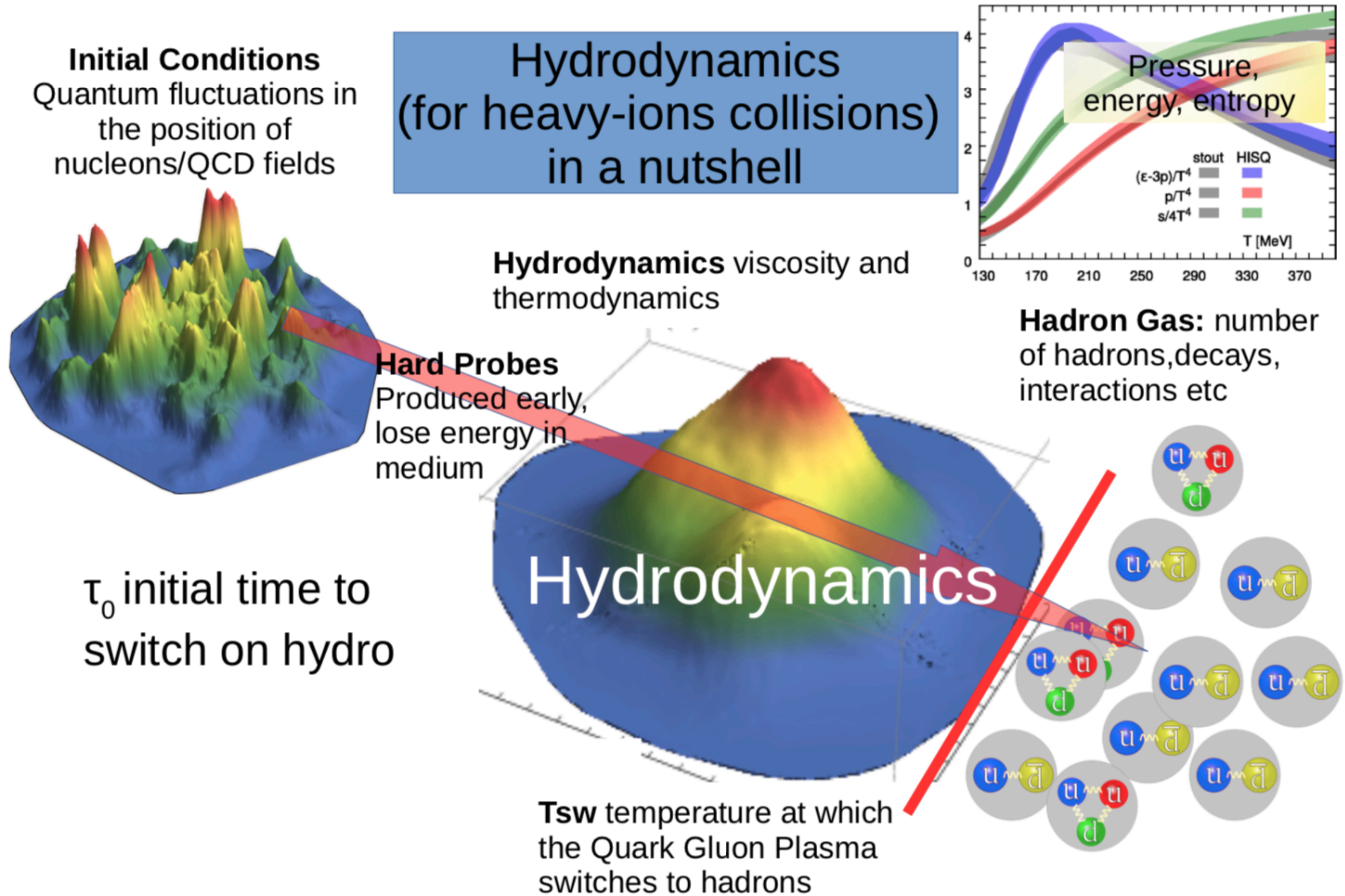




ALFRED P. SLOAN FOUNDATION 1934

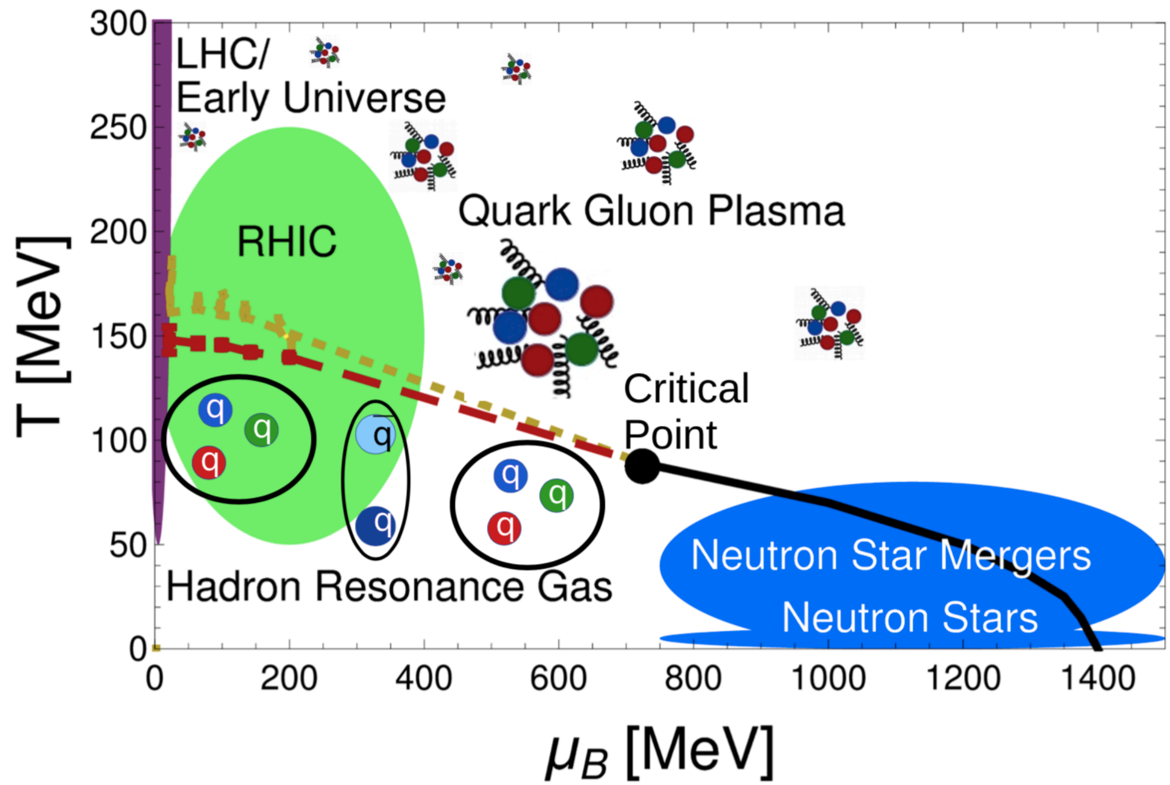
High Performance Computing

Computation Relativistic Fluid Dynamics



Mapping out the QCD phase diagram

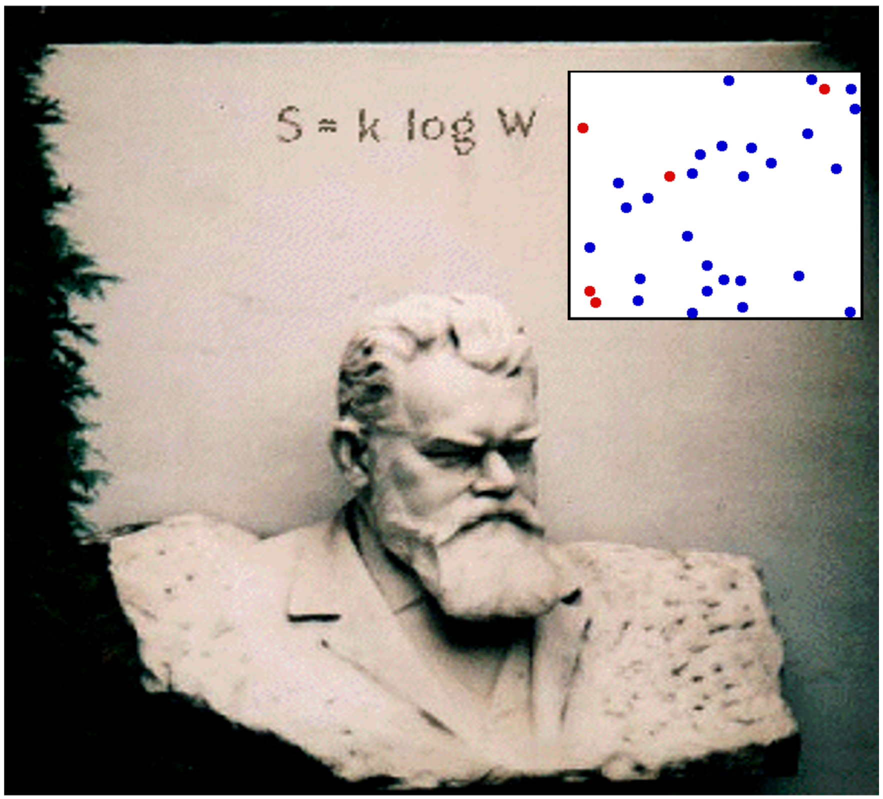
- Lattice QCD/Equation of State
- Relativistic viscous fluid dynamics
- Probing the Quark Gluon Plasma with jets
- Nuclear Structure



Looking for 1-2 students. Interest in computational physics a must!

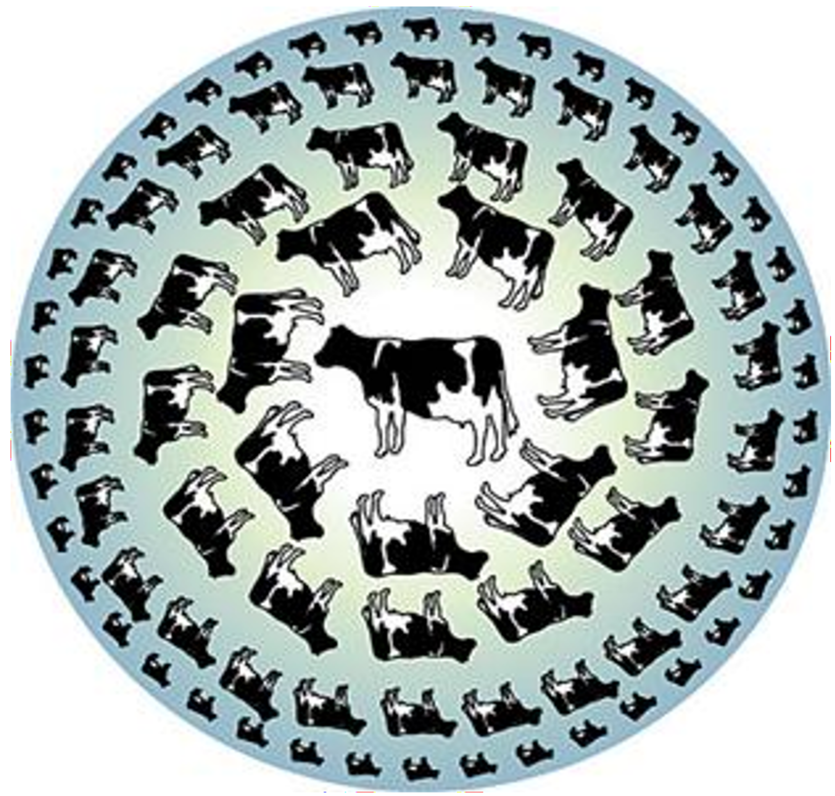
Out-of-Equilibrium Phenomena in Quantum Chromodynamics

Relativistic kinetic theory



QGP at very high temperatures

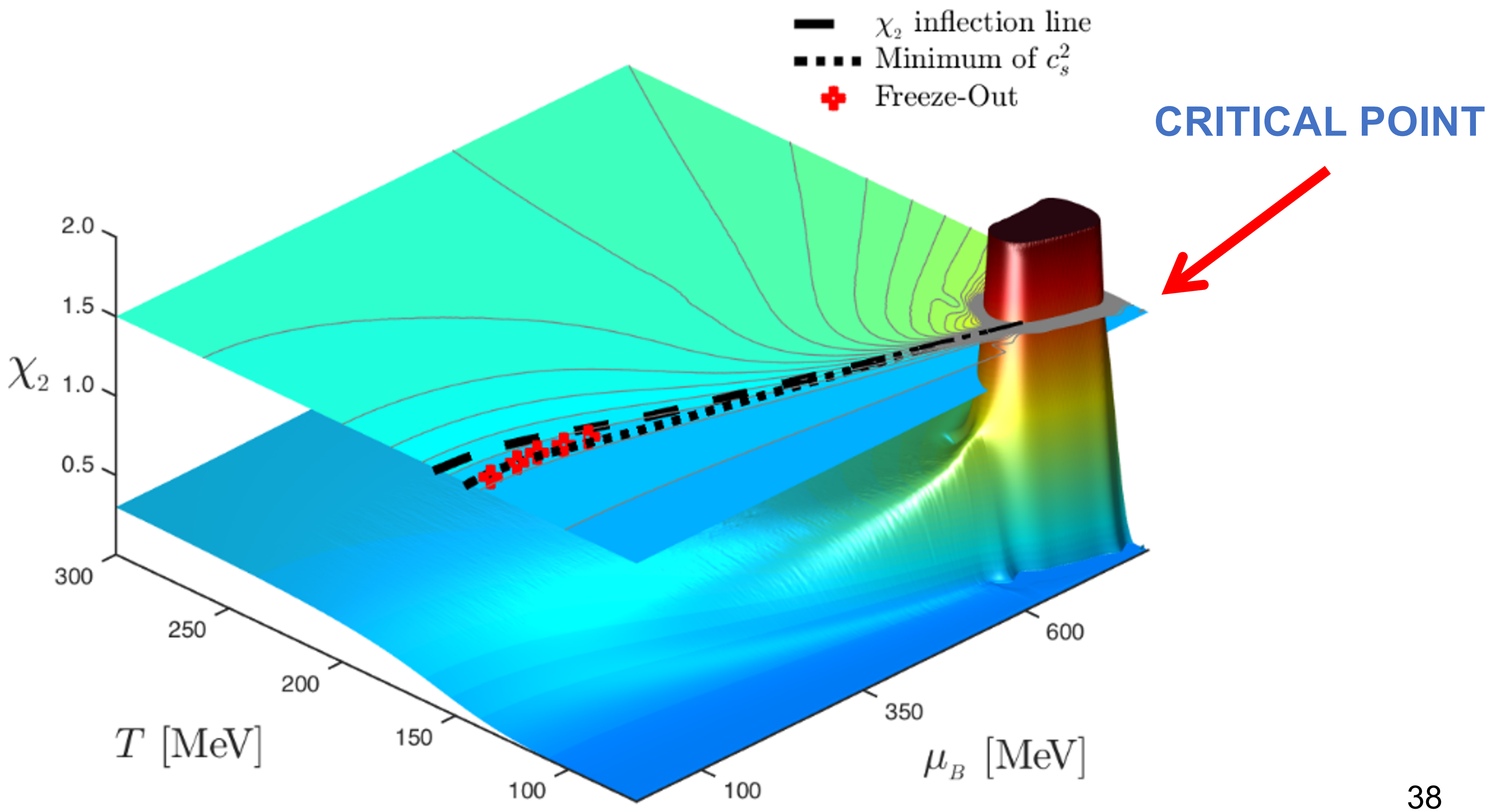
Holographic duality/String Theory



model for strongly coupled QGP

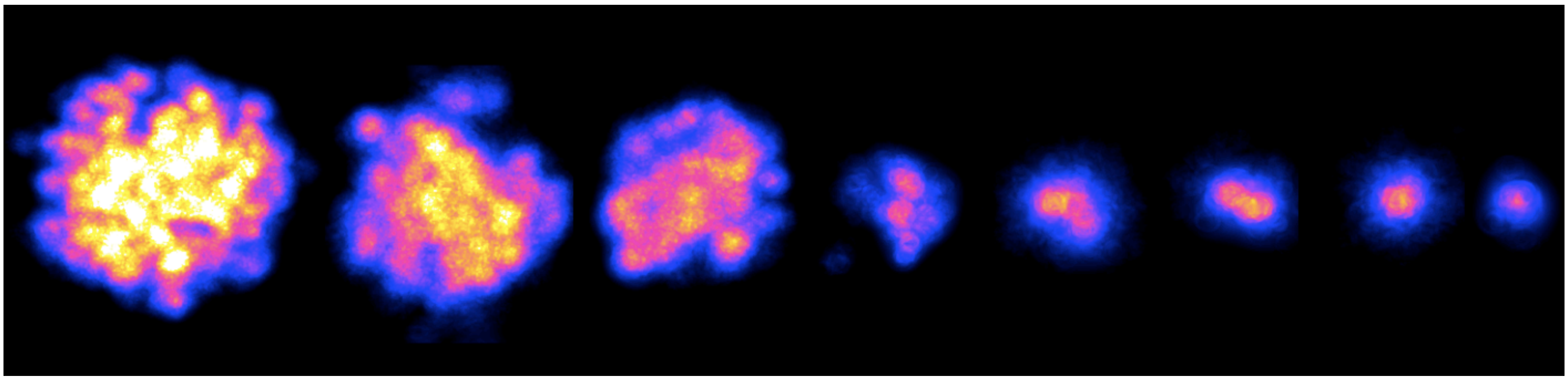
Training String Theory Black holes to Study QCD

QCD critical point: $T_{CEP} = 89 \text{ MeV}, \quad \mu_B^{CEP} = 724 \text{ MeV}$

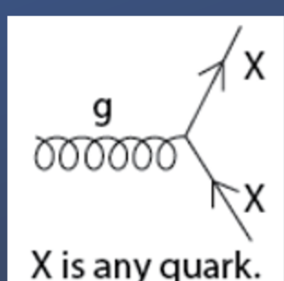


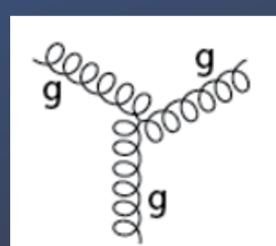
Shrinking the Quark-Gluon Plasma

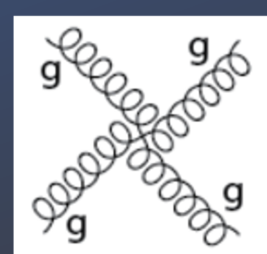
Pb+Pb → **proton+proton**



How does fluid dynamics emerge from





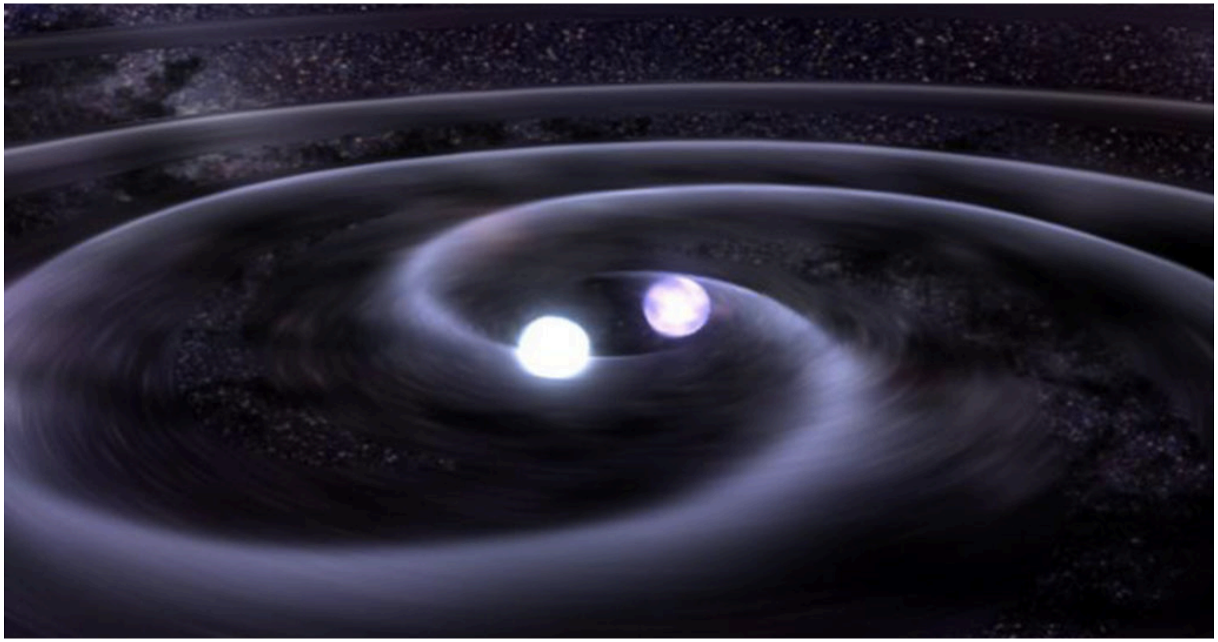


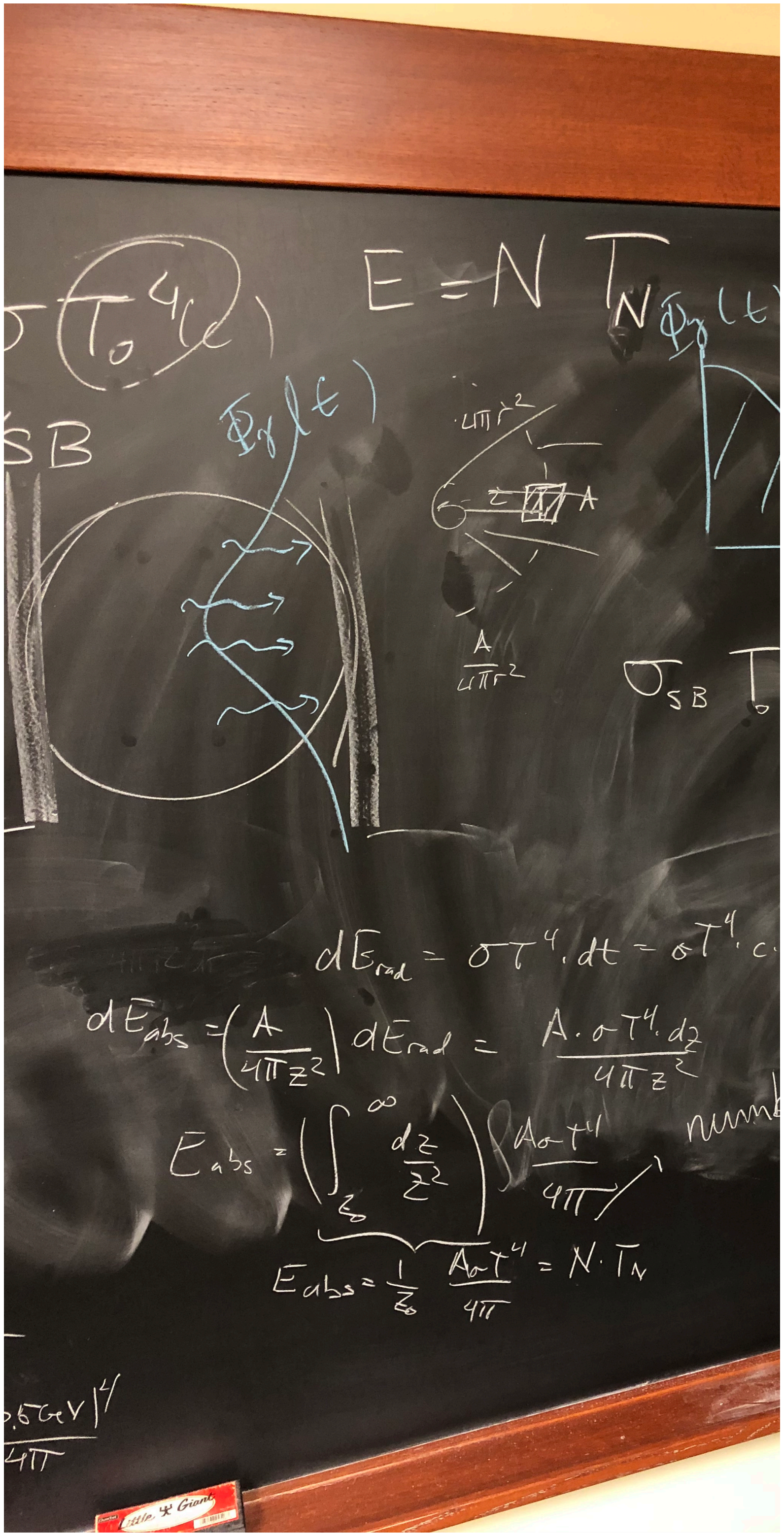
QCD ?

Viscous effects in Neutron Star Mergers

Looking for 1 to 4 students

New research area involving nuclear physics, general relativity, astrophysics, and mathematics





Bi-Weekly Nuclear Physics Journal Club

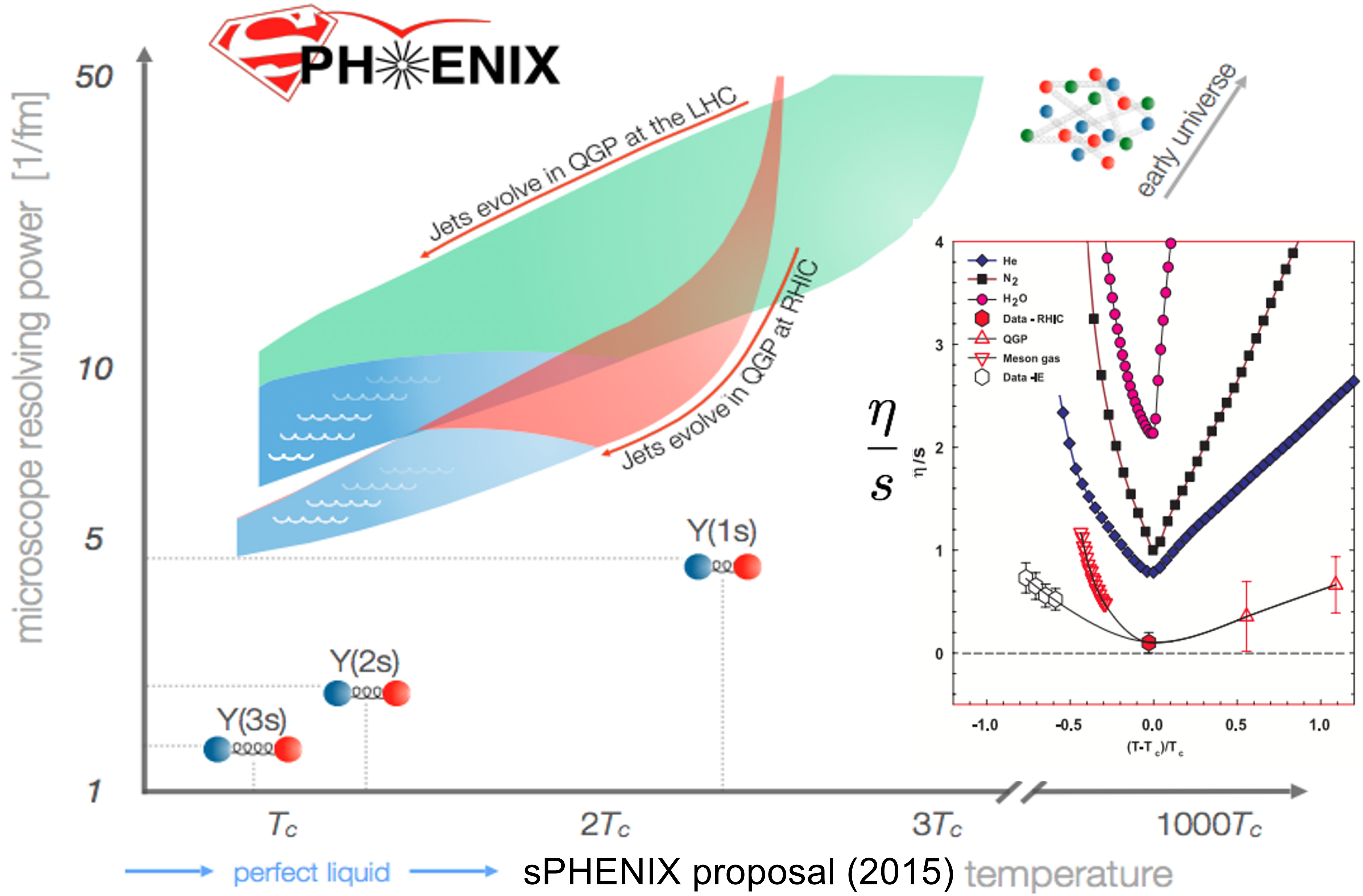
- Students lead the meetings
- Cover hot topics in the field
- In-depth physics discussions between students, postdocs and faculty
- Ideal place for practicing talks

Frontiers of QCD through the next decade

2018+ → Jetting through the QGP (LHC, sPHENIX)

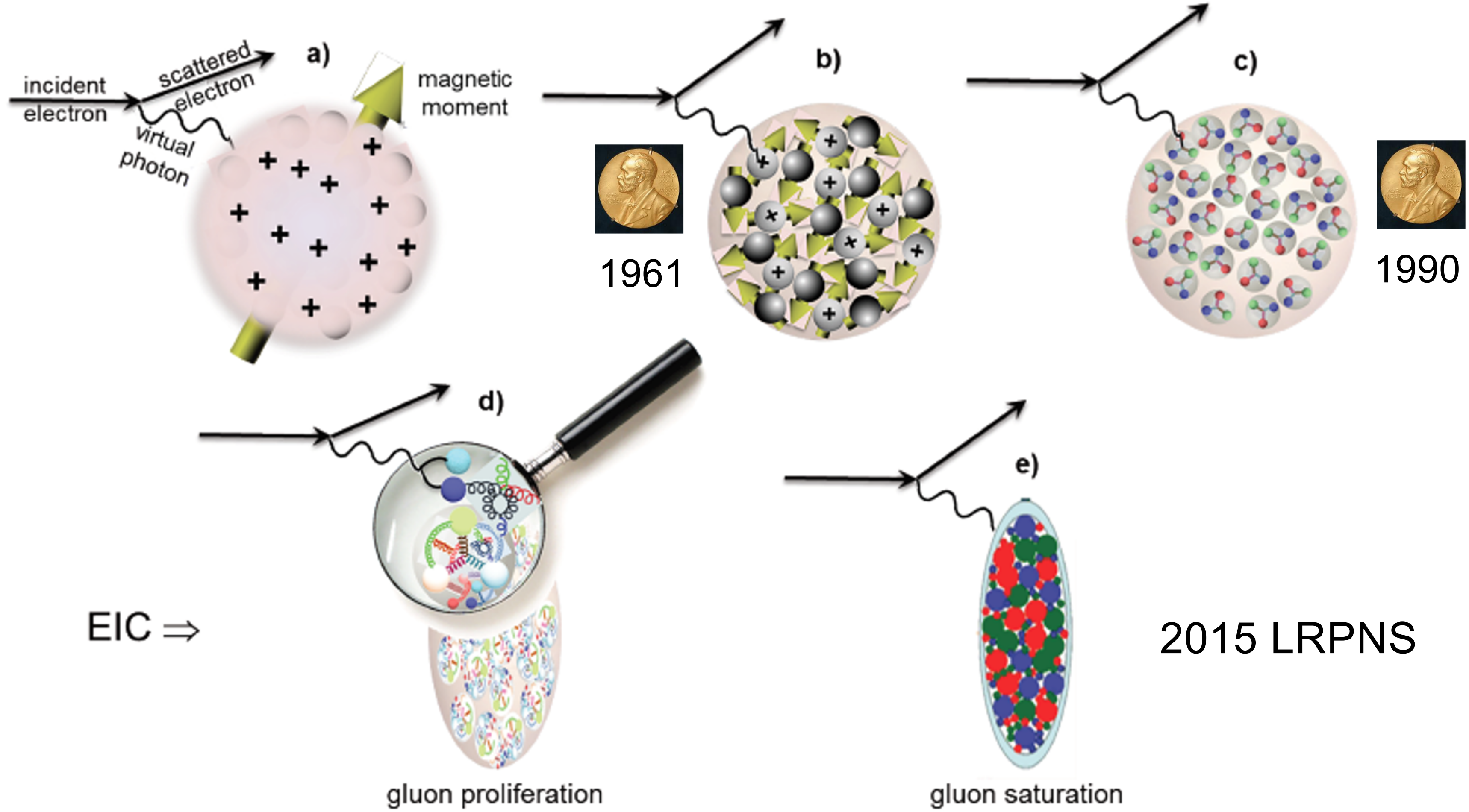
Jets in nucleus-nucleus, proton-nucleus

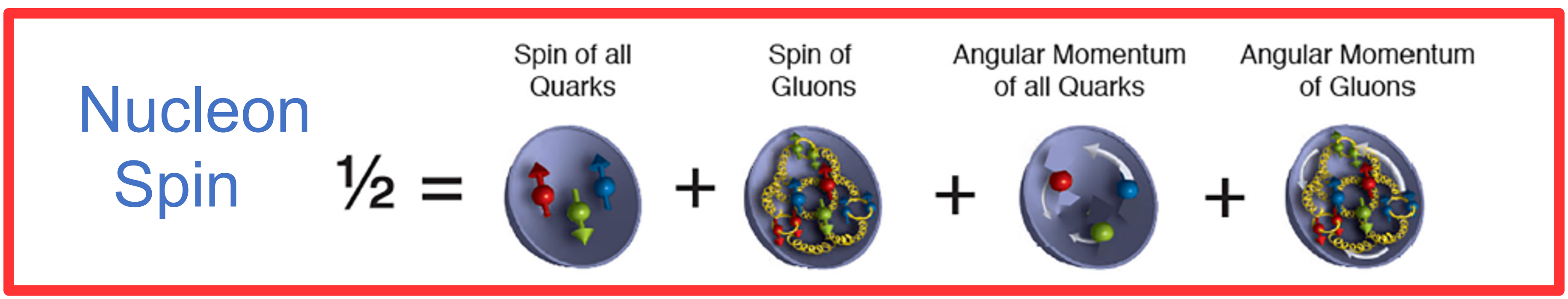
RHIC



sPHENIX proposal (2015)

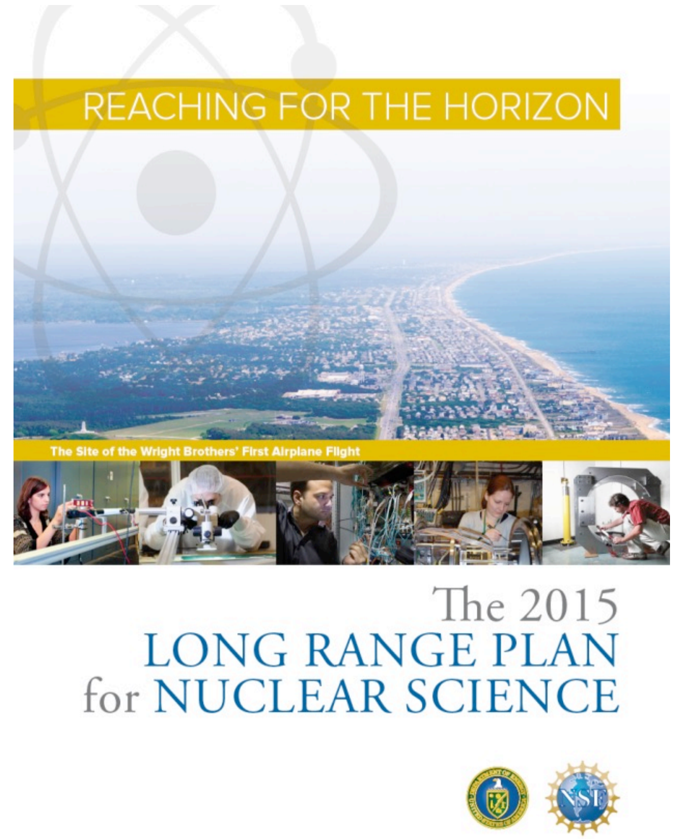
2030's: Electron Ion Collider (EIC)





Big Questions in Nuclear Physics

- How did visible matter come into being and how does it evolve?
- How does subatomic matter organize itself and what phenomena emerge?
- Are the fundamental interactions that are basic to the structure of matter fully understood?
- How can the knowledge and technical progress provided by nuclear physics best be used to benefit society?



The UIUC Nuclear Physics Group has had significant impact in the field and is poised to continue its leadership in the future