The Relativistic Nuclear Collisions Program

at the Lawrence Berkeley Laboratory

An Overview

Presented by
Jim Thomas

5/17/2006

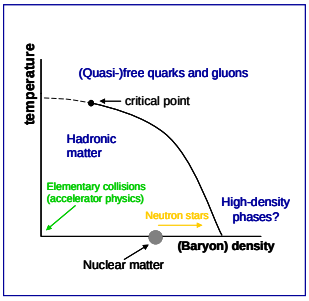
Who we are …

- 9 Scientists
- 2 Retirees
- 6 PostDocs
- 1 Engineer
- 2.5 Computing at PDSF
- 8 Students
- 1 Visiting PD
- 1 Administrator
- and no place to sit down

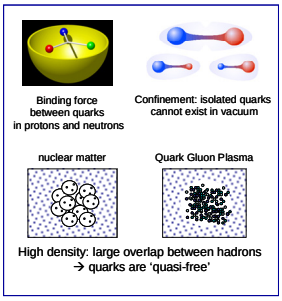
What we do …

- **Create and study hot, dense, nuclear matter in order to search for the quark–gluon plasma and characterize its properties**

Thermodynamic approach
Phase diagram of nuclear matter

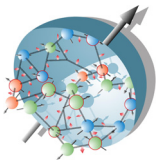


Microscopic picture
The strong interaction (QCD)

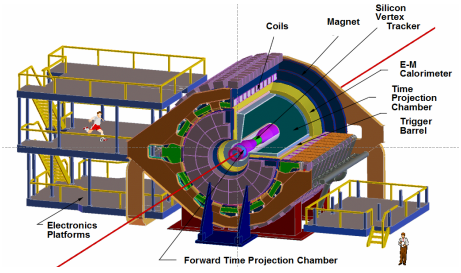


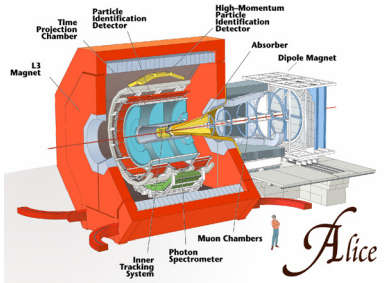
- **Study the spin structure of the nucleon**

$$S_z = \frac{1}{2} = \frac{1}{2}(\Delta u + \Delta d + \Delta s) + \Delta G + \left\langle L_z \right\rangle_{q,G}$$



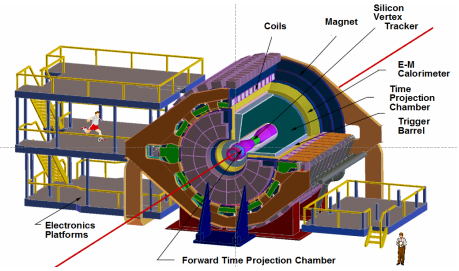
How we do it …

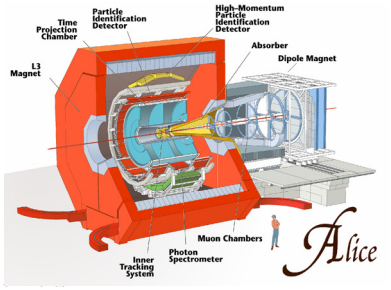




- **STAR is a collider detector at RHIC**
  - **RHIC delivers a variety of heavy ion *and* polarized proton beams at energies up to 200 GeV / A**
- **At its heart is the worlds largest Time Projection Chamber**
  - **Designed and built in Berkeley**
- **STAR Upgrades progressing well**
- **ALICE is a collider detector at the Large Hadron Collider**
  - **The LHC will deliver heavy ion beams, and protons, at energies up to 30x RHIC energies**
- **The ALICE TPC will become the biggest in the world … when it runs**
  - **Based on STAR technology**
- **LBNL and ALICE/USA are providing the EM calorimeter**

What we have learned so far …





- Nuclear Matter produced in Au-Au collisions is 30x denser than normal nuclear matter
- The quarks and gluons that are liberated in a collision are not free streaming particles. They "flow" and "scale" as if engulfed in a dense partonic liquid.
- Au-Au collisions are not a superposition of p-p collisions. The away side jet, in a back to back jet, is suppressed when it passes through the nuclear collision zone.
- Flow, quark scaling, and the high rate of energy loss for jets is a surprise. It suggests a new kind of partonic matter … perhaps a new state of matter at RHIC.
- These discoveries will be explored in more detail: with the STAR upgrades, at low energies in the baryon rich regime at RHIC & GSI, and at high energies with ALICE.

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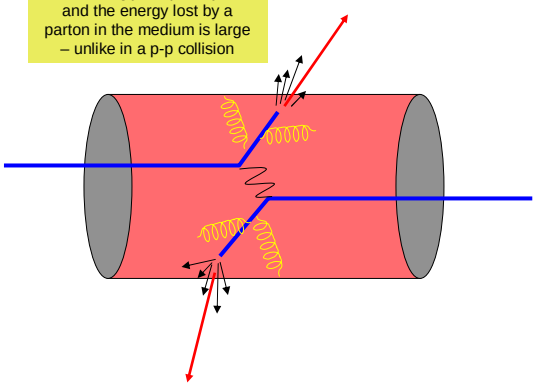
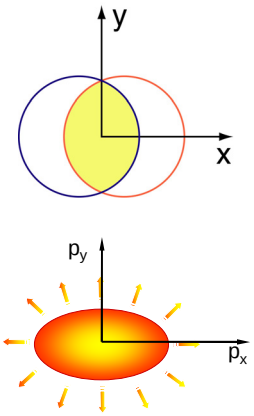
Two Views of a Relativistic HI Collision

Side View

It is a strongly coupled system and the energy lost by a parton in the medium is large – unlike in a p-p collision



End View



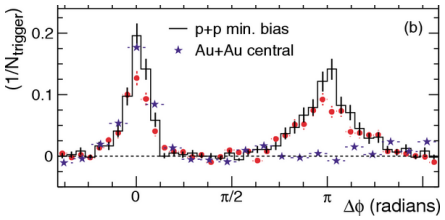
Angular distributions are very revealing

$$1 + 2\,v_1\cos(\phi) + 2\,v_2\cos(2\phi) + \ldots$$

The angular distribution in momentum space is not isotropic

Jim Thomas - LBL

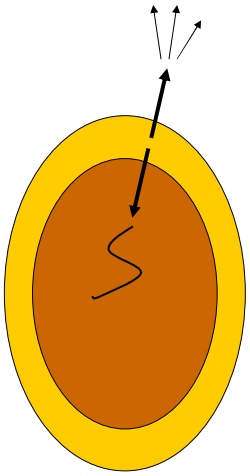
High P_t Jets Probe the Medium



- **The angular distribution of particles, triggered on a jet, shows a clear back-to-back structure in p-p and d-Au collisions**
- **But the away side jet is suppressed in Au-Au collisions**

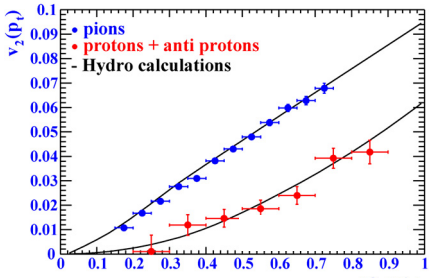
For the new frontiers … see the talk by Marco van Leeuwen

Surface emission



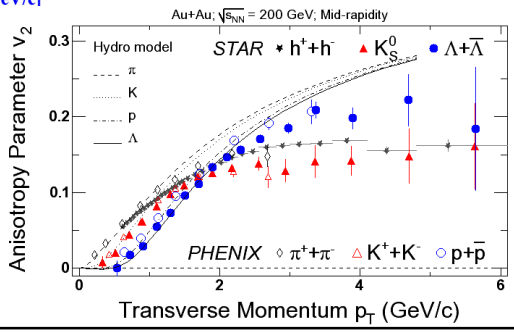
While the backward going jet gets lost in the bulk of the medium

The v_2 Parameter Measures Flow



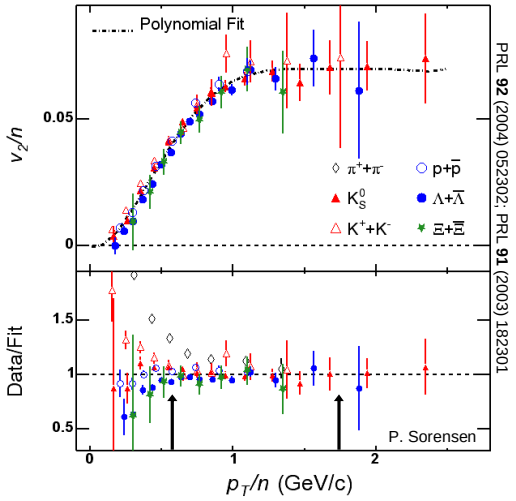
PRL 86, 402 (2001) & nucl-ex/0107003

- **The mass dependence is reproduced by hydrodynamic models**
  - **Hydro assumes local thermal equilibrium**
  - **At early times**
  - **Followed by hydrodynamic expansion**
- **v_2 at high p_t shows meson/baryon differences**



- **A free streaming system of particles does not flow**
- **v_2 is large at RHIC**
- **v_2 persists to high p_t**

Quark Number Scaling

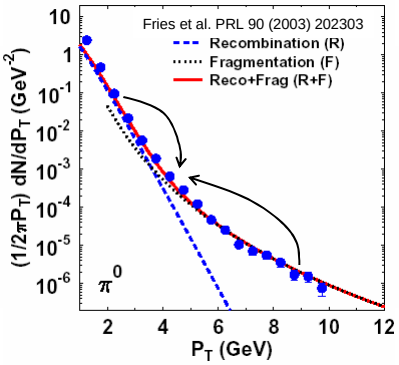


The flow pattern in $v_2(p_T)$ for hadrons is predicted to be simple if flow is developed at the quark level

$p_T \rightarrow p_T/n$

$v_2 \rightarrow v_2/n$,

n = (2, 3) for (meson, baryon)



For the frontiers in energy loss and flow, see the talk by Lijuan Ruan

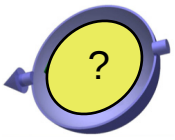
Nucleon Spin Structure

time

1933 Frisch and Stern:

$$\vec{\mu_p} = 2.79 \frac{e\hbar}{mc} \vec{s_p}$$

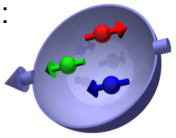
The proton has substructure



~1970 Electron-proton deep-inelastic scattering:

$$2xF_1 = F_2$$

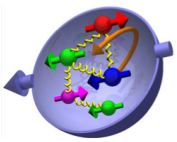
Quarks are spin-1/2



~1985 Polarized deep-inelastic scattering:

$$g_1(x) = \frac{1}{2} \sum e_q^2 (q^{\uparrow\uparrow} - q^{\uparrow\downarrow})$$

Quark spins carry only a small fraction of the nucleon spin.



~2002 For the frontiers in Spin Physics see the talk by E. Sichtermann

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UPC - Ultra Peripheral Collisions

The Lorentz contracted nuclei act as sources of E&M fields.
The interaction is between the exchange particles of the fields.

Electromagnetic Fields – photons
Strong-Force Fields – gluons(mesons/Pomerons)

$A+A \rightarrow A+A+X$

For coherent interactions, the maximum momentum transfer is determined by the nuclear form factor / nuclear size:

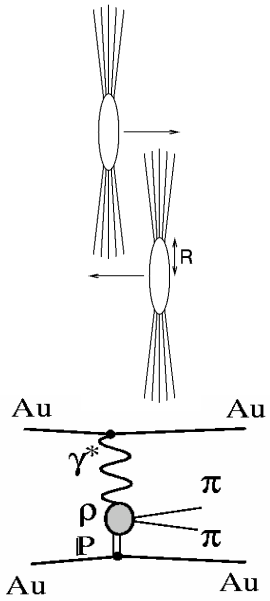
$max(Q) \cong 1/R$

This has two important consequences:

1) The final state will have a low p_T, $p_T \leq 1/R$
2) The maximum photon energy is $\cong \gamma (1/R)$

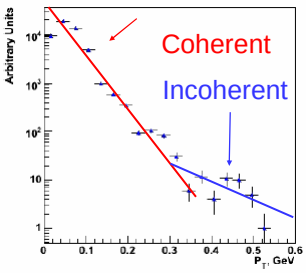
Heavy-Ions are advantageous because $L_{\gamma\gamma} \propto Z^4$

$Z^4 = 4 \cdot 10^7$ for Au



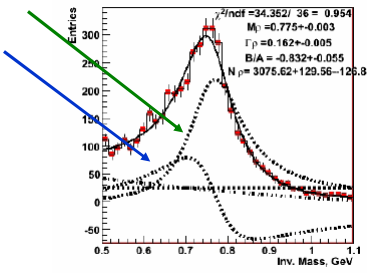
UPC - 200 GeV ρ^0 analysis

- Coherent: $p_T < h/R_A$
  - Entire nucleus is target
  - dN/dt ~ exp(-bt)
    - $b \sim R_A^2$
- Incoherent – individual nucleon is target
  - Can study ρ^0 absorption, etc.
  - dN/dt ~ exp(-bt)
    - $b \sim R_p^2$



ρ^0

Interference Term



- $\pi\pi$ mass spectra show ρ^0, interference with direct pp production
  - Accompanied by mutual Coulomb excitation (MCE)

Top Ten STAR Papers

- **Top Cite 250+**
  - "Elliptic flow in Au + Au collisions at (S(NN))**(1/2) = 130 GeV"
    PRL 86 (2001) 402. Poskanzer, Snellings, Voloshin
  - "Disappearance of Back to Back High Pt Hadron Correlations …"
    PRL 90 (2003) 082302. Hardtke, Miller, Harris
- **Top Cite 100+**
  - "Evidence from d+Au Measurements for Final State Suppression …"
    PRL 91 (2003) 072304. Hardtke, Jacobs, Klay, Putschke, Dunlop, ...
  - "Transverse Momentum and Collision Energy Dependence …"
    PRL 91 (2003) 172302. Jacobs, Klay, Dunlop, Gagliardi, Gans
  - "Centrality Dependence of High Pt Hadron Suppression …"
    PRL 89 (2002) 202301. Filimonov, Jacobs, Klay, Choi, Kunde, …
  - "Identified Particle Elliptic Flow in Au+Au Collisions …"
    PRL 87 (2001) 182301. Poskanzer, Snellings, Tang, Voloshin
  - "Pion Interferometry of s(NN)**(1/2) = 130-GeV Au+Au Collisions at RHIC"
    PRL 87 (2001) 082301. Hardtke, Cramer, Lisa, …
  - "Particle Type Dependence of Azimuthal Anisotropy and Nuclear Modification …"
    PRL 92 (2004) 052302. Sorensen, Xu, Fu, Huang, Lamont, Long
  - "Azimuthal Anisotropy and Correlations in the Hard Scattering Regime at RHIC"
    PRL 90 (2004) 032301. Filimonov, Hardtke, Jacobs, Poskanzer, Snellings, …
  - "Elliptic Flow From Two and Four Particle Correlations in Au+Au Collisions …"
    PRC 66 (2002) 034904. Poskanzer, Snellings,Tang, Keane, Voloshin

LBNL Authors are writing good papers and these papers are being cited frequently

STAR Publications Summary

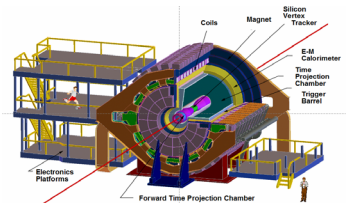
54	publications in the refereed literature (31 PRL, 17 PRC, 5 PLB, 1 NPA)
6	submitted to journals
5	under final review by the collaboration
10	in preparation by editorial committees
75	publications in preparation or published

60% of all STAR publications have primary authors from the RNC group
70% of all STAR PRLs have primary authors from the RNC group

45% of all RHIC citations are from STAR papers (PRL, PRC, PLB, NPA, JPG)
30% of all RHIC citations have primary authors from the RNC group

Average of 103 Citations per PRL from a total of ~3500 citations, to date

STAR Management Roles from within RNC



- STAR Deputy Spokesperson
  - Hans Georg Ritter
- STAR Junior Council Members
  - Sarah Blyth, Lijuan Ruan
- STAR Advisory Board
  - Jim Thomas, Nu Xu
- Co-convenors for UPC, High p_T, and Forward Tracking Working Groups
  - Spencer Klein, Marco van Leeuwen, Ernst Sichtermann
- Trigger Board Members
  - Marco van Leeuwen, Ernst Sichtermann
- STAR Upgrades Committee
  - Howard Wieman, Peter Jacobs, Hans Georg Ritter
- STAR Council Member
  - Nu Xu

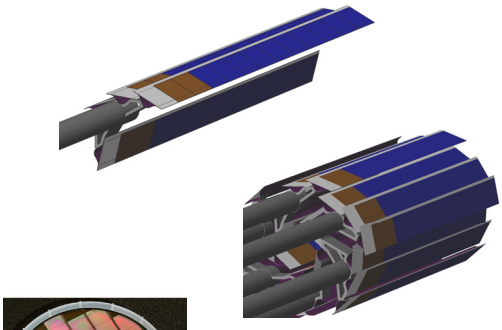
PDSF at LBNL

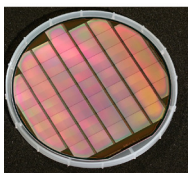
- PDSF - Parallel Distributed Systems Facility
  - Originally acquired from SSC surplus equipment pool
  - 1.8 M$ in FY00-FY03 from NSD equipment funds and from DOE
  - Upgraded and improved each year
  - LDRD funds provide specific intellectual investments such as manpower for GRID development
- Operated by NERSC for STAR and other HE & NP activities
  - MOU between LBNL, STAR, and DOE to cover STAR simulations, embedding*, and analysis activities
  - 500 CPUs, 100 TB of disk, 1000 TB available in HPSS
- Operating funds
  - RNC - 2.5 FTEs
  - ATLAS/Physics - 0.5 FTE
  - NERSC - 2 FTE
  - Yearly mass storage (HPSS) allocation to STAR ~ 1 M$

One half to one third of all STAR computing

Looking to the future

The STAR Heavy Flavor Tracker

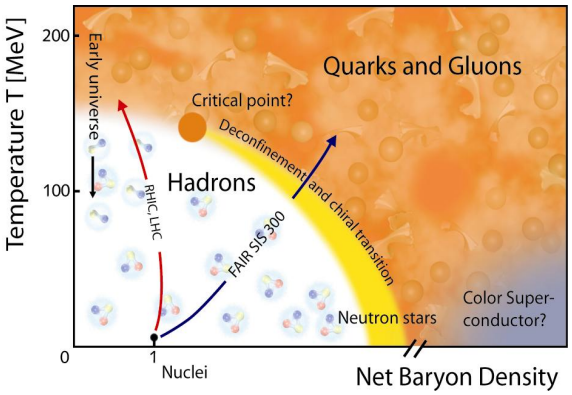




- **A new detector**
  - **30 μm silicon pixels**
- **Direct Topological reconstruction of open Charm hadrons**
  - **Detect charm decays with small cτ, including $D^0 \rightarrow K\,\pi$**
- **New physics**
  - **Charm collectivity and flow to test thermalization at RHIC**
  - **Charm Energy Loss to test pQCD in a hot and dense medium at RHIC**
- **Proposal undergoing review by BNL & STAR**
  - **Prototype `08, complete `10**

For a full discussion of the HFT see the talks by H. Wieman and Nu Xu

Baryon Rich Physics at RHIC and FAIR



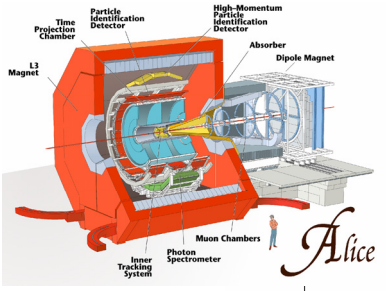
- **Mapping the QCD phase diagram**
- **Search for the boundary between hadronic and partonic worlds**
- **Search for the critical point**
- **Needs theory and experimental collaboration**

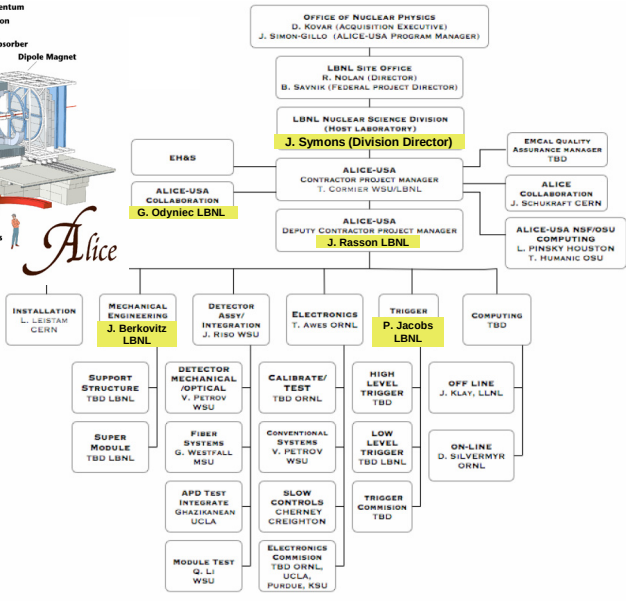
For the frontiers in Baryon Rich Physics, see the talk by Nu Xu

2.1 FAIR 8.1 GeV

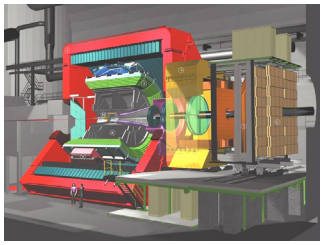
4.6 RHIC 20. GeV

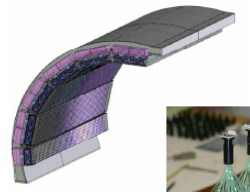
ALICE EMC Management from within RNC

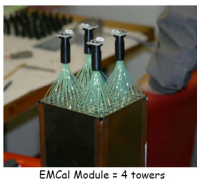




The ALICE EMCal ... a major US Contribution







EMCal Module = 4 towers

- Jet Quenching at the LHC
  - Pb + Pb at 5.5 TeV
- EMCal+ALICE tracking+PID:
  - Full study of jets over huge kinematic range; unique and important probes of QCD matter
- Lead-scintillator sampling calorimeter
  - $|\eta| < 0.7$, $\Delta\phi = 110°$, 13,000 towers
  - Shashlik geometry
- Major Milestones in FY06
  - Fermilab test beam: complete modules tested with final CERN electronics
  - CDR complete: in preparation for CD1
  - Mechanical support structure to be installed summer '06
- Proposed funding assuming an eight super-module scope of work

For a full description of the ALICE program, see the talk by Peter Jacobs

Recent Alumni

- Glenn Cooper, 2000
  - UC Berkeley, Industry
- Milton Toy, 2001
  - UCLA, Industry
- Jinghua Fu, 2002
  - Wuhan U, Faculty Tsinghua U
- Ian Johnson, 2003
  - UC Davis, PD CERN
- Bum Choi, 2003
  - UT Austin, Industry
- Chris Kunz, 2003
  - Carnegie-Mellon, Industry
- Vladimir Morozov, 2003
  - UC Berkeley, Industry
- Xin Dong, 2005
  - USTC, PD USTC
- Heather Gray, 2005
  - Univ. Cape Town, Caltech
- Johanne Gonzalez, 2006
  - UCLA, Industry
- Alexander Wetzler, 2006
  - Frankfurt, Industry
- Joakim Nystrand, 2001
  - Faculty U Bergen
- Fuqiang Wang, 2001
  - Faculty Purdue
- Raimond Snellings, 2002
  - NIKEF
- Masashi Kaneta, 2002
  - Riken BNL
- Aihong Tang, 2002
  - BNL/NIKEF
- David Hardtke, 2003
  - UC Berkeley
- Falk Meissner, 2004
  - Industry
- Jennifer Klay, 2004
  - LLNL & Cal Poly
- Javier Castillo, 2004
  - Orsay
- Fabrice Retiere, 2004
  - TRIUMF
- Kirill Filimonov, 2005
  - UC Berkeley
- Eugene Yamamoto, 2005
  - Industry
- Kai Schweda, 2005
  - Helmholtz Fellow, Heidelberg
- Paul Sorensen, 2005
  - Goldhaber Fellow, BNL
- Markus Oldenburg, 2006
  - CERN Fellow
- Jay Marx, 2006
  - Ligo ED, Caltech

Summary

- A vigorous program of research in Heavy Ion Physics at RHIC
  - PID studies of soft hadronic probes including flow
  - Detailed studies of Jet quenching and energy loss
- We are upgrading STAR to enable new physics opportunities
  - The direct topological reconstruction of open charm with the HFT to probe light quark thermalization and heavy flavor energy loss
- A robust program of Spin measurements with STAR
  - Focus on the gluon contribution to the spin of the nucleon
  - Pursue the individual quark contributions in the future with upgrades
- Exploring new opportunities to study baryon rich matter at RHIC and Fair
  - Locate the phase boundary between hadronic matter and deconfined quarks and gluons
- Also establishing a HI research program at ALICE
  - Building the EM Calorimeter and leading the physics program
- A strong group of young people
  - Training the next generation
  - Doing world class physics

The end