Theoretical initiatives related to the RHIC program

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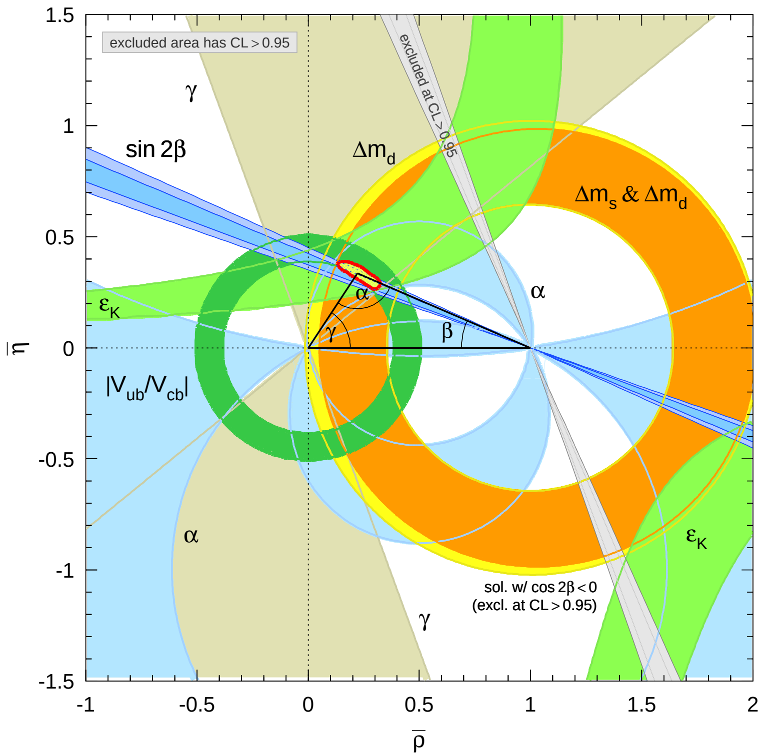
- Where do we stand? What challenges are we facing? (RHIC II, LHC)
- BNL Topical Center LOI "QCD at RHIC Center" (QARC)
- LBNL Topical Center LOI "Hard probes in high energy heavy-ion collisions"
- SciDAC proposal "RHIC Transport Initiative" (RTI)
- QCD Town Meeting White Paper "A Theory Upgrade for RHIC" (RTU)

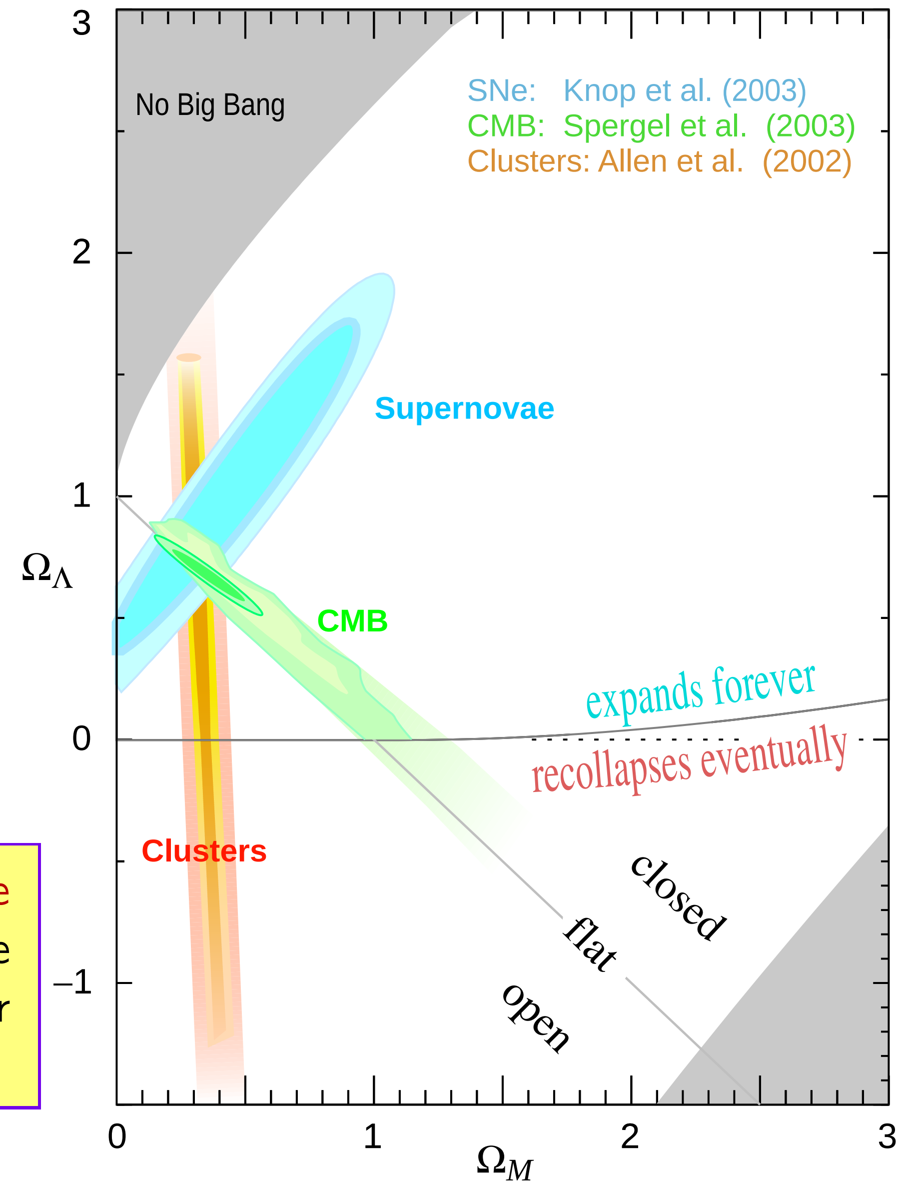
Plots that made the news . . .

From 2006 Review of Particle Properties:

CKM matrix, unitarity triangle:



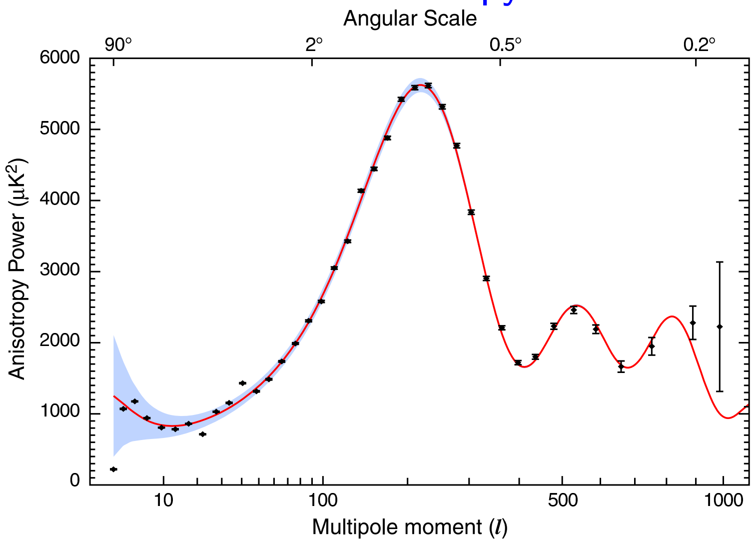
Cosmological parameters:



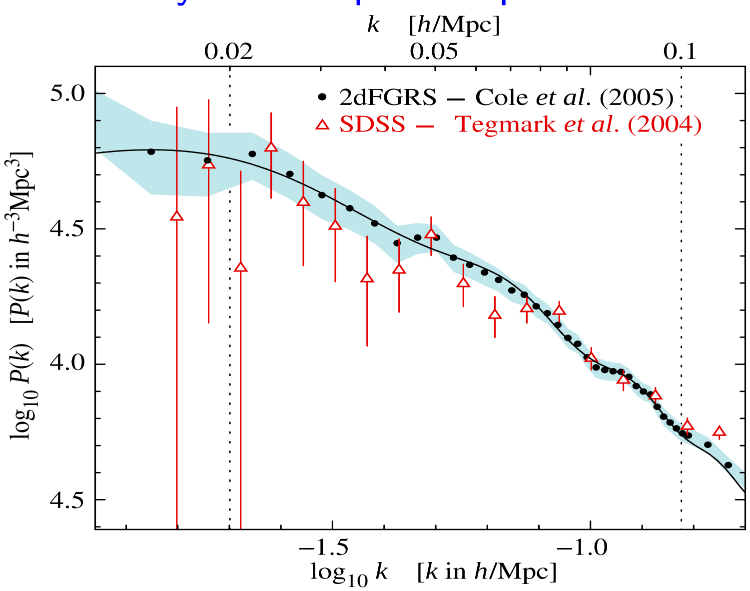
$\Longrightarrow$ precise, quantitative statements, with reliable uncertainty estimates, about the status of the Standard Model and the cosmological state of our Universe

"Money plots" are based on precision data . . .

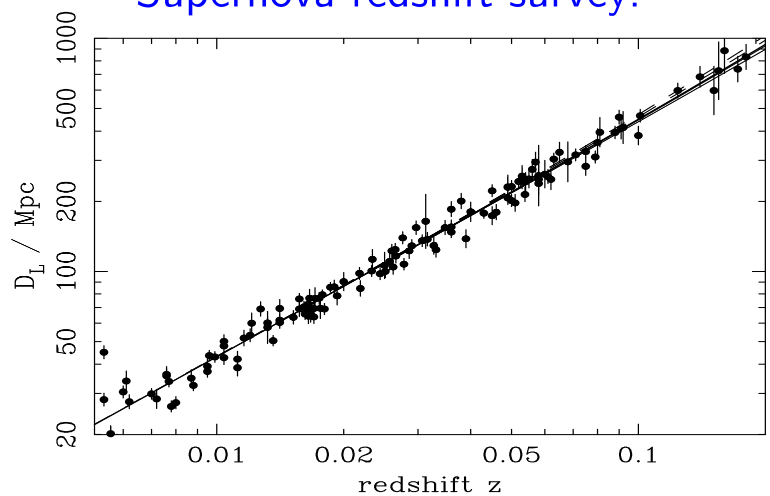
CMB anisotropy:

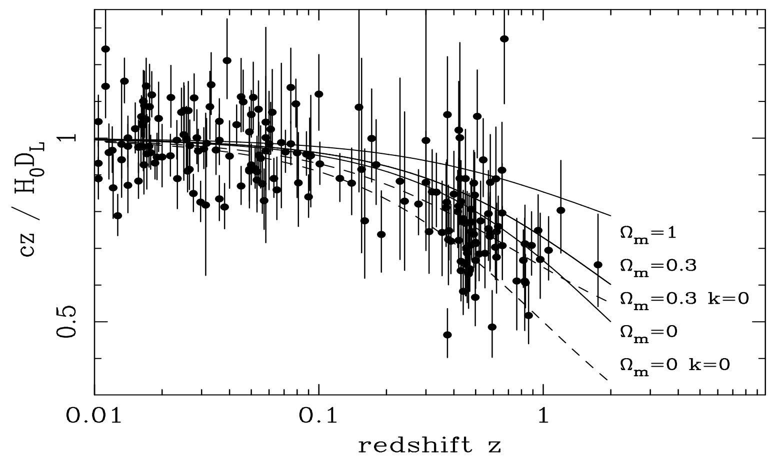


Galaxy cluster power spectrum:



Supernova redshift survey:

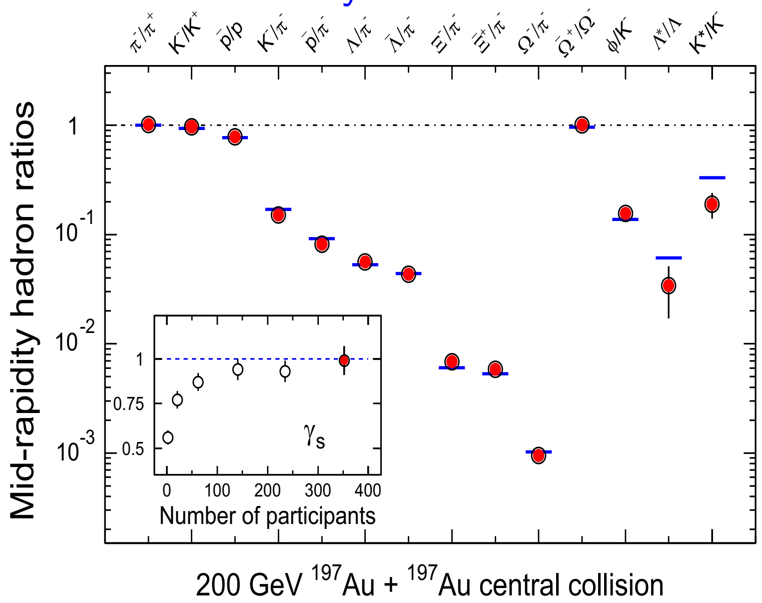




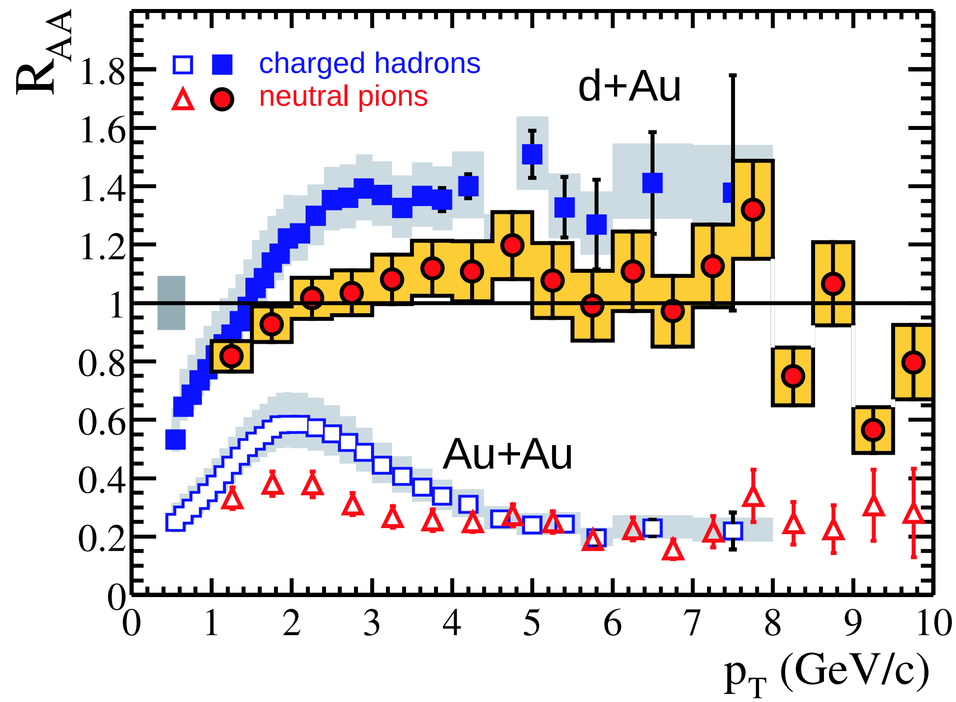
. . . by connecting them through a well-tested, precise dynamical theory for (in this case) the evolution of gravitational disturbances

RHIC, too, produces precision data!

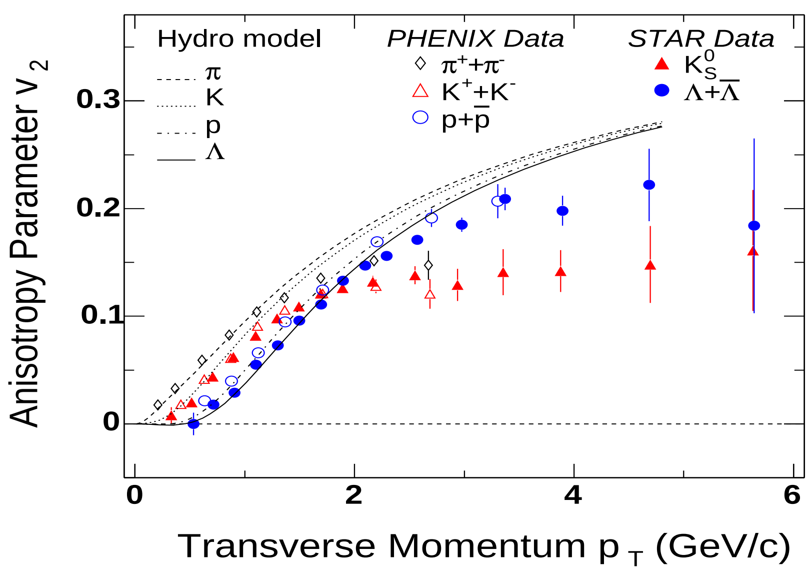
hadron yield ratios:



high-p_T hadron suppression:



identified hadron elliptic flow:

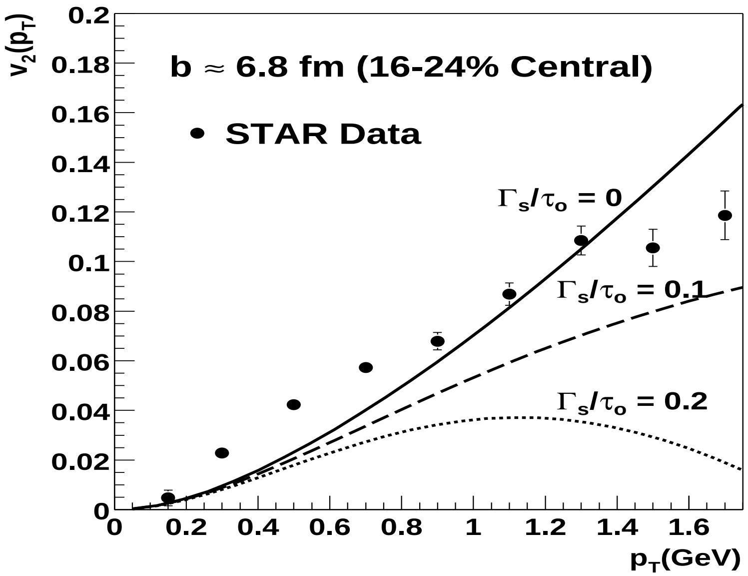


. . . so why aren't we then in the Particle Data book, too?

Two conclusions from first 5 years of RHIC:

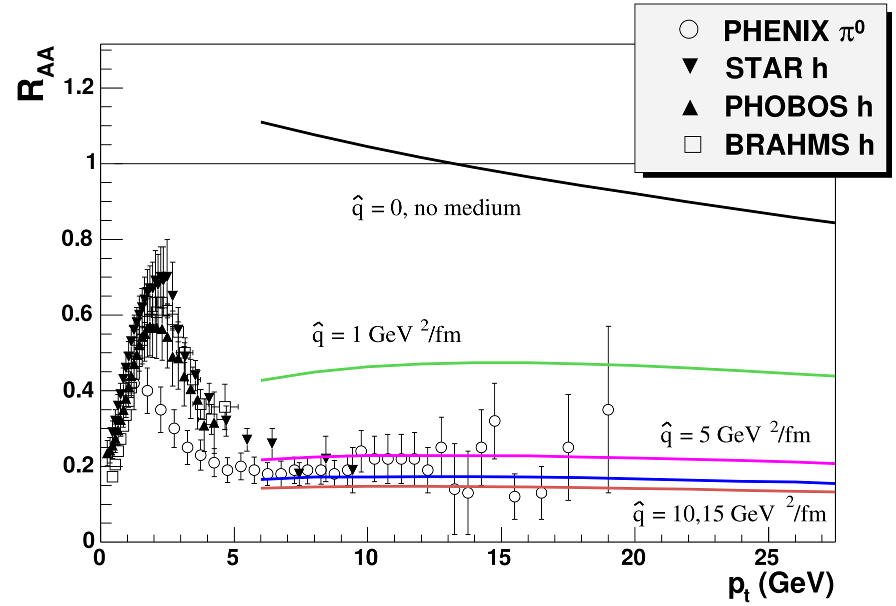
QGP viscosity is small!

(D. Teaney, PRC 68 (2003) 034913)



sQGP is color opaque!

(Eskola et al., NPA 747 (2005) 511)



"sound attenuation length" $\frac{\Gamma_s}{\tau} = \frac{4}{3}\frac{\eta}{s}\frac{1}{T\tau} < 0.1$

$\Longrightarrow$ specific shear viscosity is **close to** Son's **minimum** value $\frac{\eta}{s} = \frac{\hbar}{4\pi}$!

"transport coefficient" $\hat{q} = \frac{\mu_D^2}{\lambda}$ is **large!**

These are **groundbreaking qualitative insights**, but not yet connected with precise hard numbers associated with quantitative uncertainty estimates.

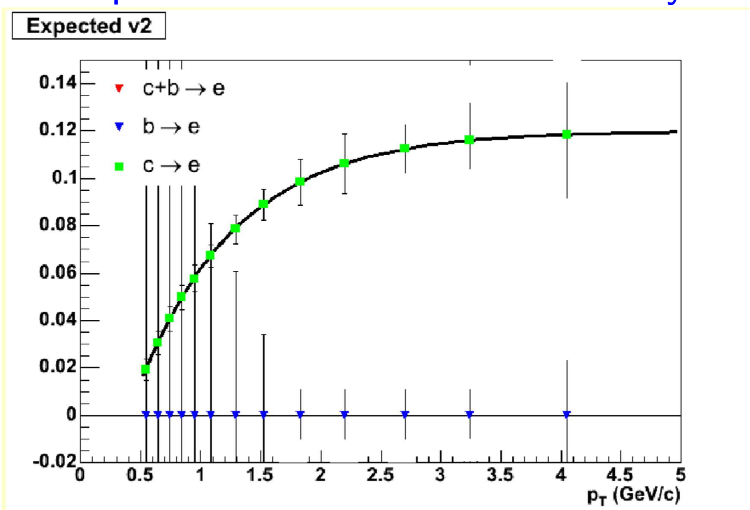
MISSING: A complete, validated and quantitatively reliable theory of heavy-ion collision dynamics.

RHIC II and LHC . . .

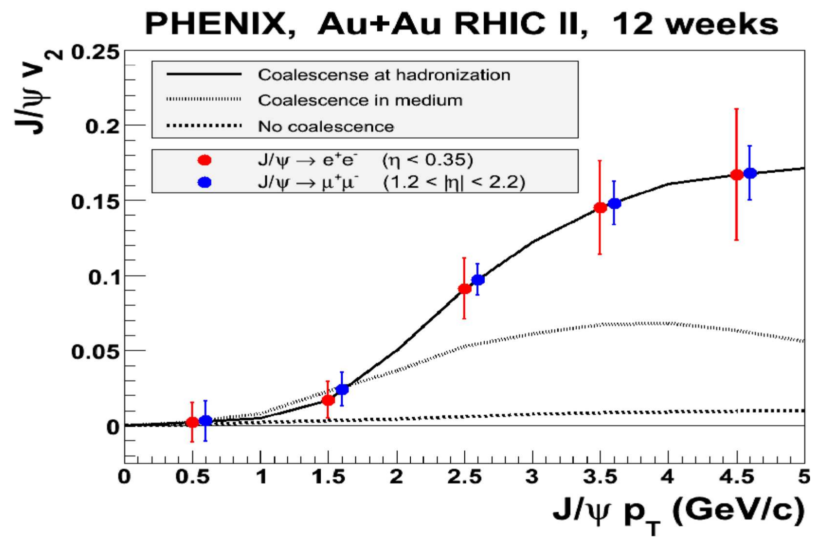
. . . will generate high-quality data in new domains (higher e and T, larger p_T, heavier quarks, rarer and cleaner QGP probes).

Two examples from the **RHIC II Science Working Groups Report**:

elliptic flow of charm and beauty:



J/ψ elliptic flow:



What you **don't** find in that report: **rigorous** estimates of how this will constrain QGP transport coefficients (charm diffusion, shear viscosity, color screening . . .).

To turn the projected measurements at RHIC II and LHC into precise and quantitative estimates of improvements in our knowledge of QCD matter properties requires a commensurate improvement in our theoretical tools for decribing these data.

Theoretical Initiatives

1. QARC: QCD at RHIC Center

BNL/Columbia/(OSU)/Stony Brook/Yale + cooperation with RBRC
Topical Center LOI submitted to DOE early 2006, $600K/year for 5 years

To address 2009 and 2010 theoretical milestones in DOE RHIC performance measures:

2009: "Perform realistic three-dimensional numerical simulations to describe the medium and the conditions required by the collective flow measured at RHIC."

2010: "Complete realistic calculations of jet production in a high density medium for comparison with experiment."

Goals:

- develop tools to perform realistic (3+1)-d numerical hydrodynamical simulations of heavy-ion collisions
- perform realistic calculations of jet production and energy losses in a high-density medium
- perform realistic calculations of charm and J/ψ production

Key research topics:

- detailed description of initial conditions, e.g. from CGC
- detailed LQCD computation of the QGP equation of state
- a (3+1)-d hydrodynamical evolution code, matched to
- a hadronic afterburner for final state hadronic interactions before freeze-out
- comparison with data to constrain kinetic properties and EOS of the QGP
- evaluate possible roles of QGP viscosity
- study backreaction of QCD medium to parton energy loss
- compare light & heavy quark energy loss computed within pQCD and Molecular Dynamics

2. Study of Hard Probes in High Energy Heavy-Ion Collisions

LBNL/Columbia/Duke/Iowa State/LANL/Purdue/Stony Brook/UC Davis

Topical Center LOI submitted to DOE early 2006, $653K/year for 5 years

To address the 2010 DOE RHIC milestones:

2010: "Measure energy and system size dependence of J/ψ production."

2010: "Complete realistic calculations of jet production in a high density medium for comparison with experiment."

Goals:

- turn high-p_T particle production and jet quenching into quantitative probes of the QCD medium
- develop unified framework to integrate many aspects of hard probe physics within a realistic model for the medium dynamics

Key research topics:

- multiple parton scattering & and radiative energy loss
- rescattering of radiated gluons
- intra-jet and inter-jet correlations
- dynamical evolution of the expanding medium
- hadronization via parton recombination and fragmentation
- hadronic rescattering among produced hadrons
- $\gamma+$ jets
- heavy quark suppression (FONLL)
- quarkonium suppression

3. RHIC Transport Initiative (RTI)

Duke/MSU/OSU/Purdue/Minnesota in collaboration with CSEM@Duke and OSC@OSU

DOE SciDAC proposal, March 2006, $905K/year for 5 years (not funded)

Guiding idea: "Full suite of optimized, validated and portable transport codes for the quantitative extraction of QGP and key collision parameters"

Goals:

- compile/develop a suite of optimized, validated, portable, well documented and mutually interfaced transport codes for modelling all dynamical stages of a heavy-ion collision
- develop modular architecture that easily allows to replace dynamical modules for specific stages of fireball evolution by new, more advanced versions
- develop advanced user friendly (3+1)-d visualization tools for RHIC simulations
- extensive modelling and parameter optimization for quantitative extraction of key collision and QGP parameters from data (therm. time, viscosity EOS, chem. fugacities, parton energy loss rates, etc.)

Key ingredients:

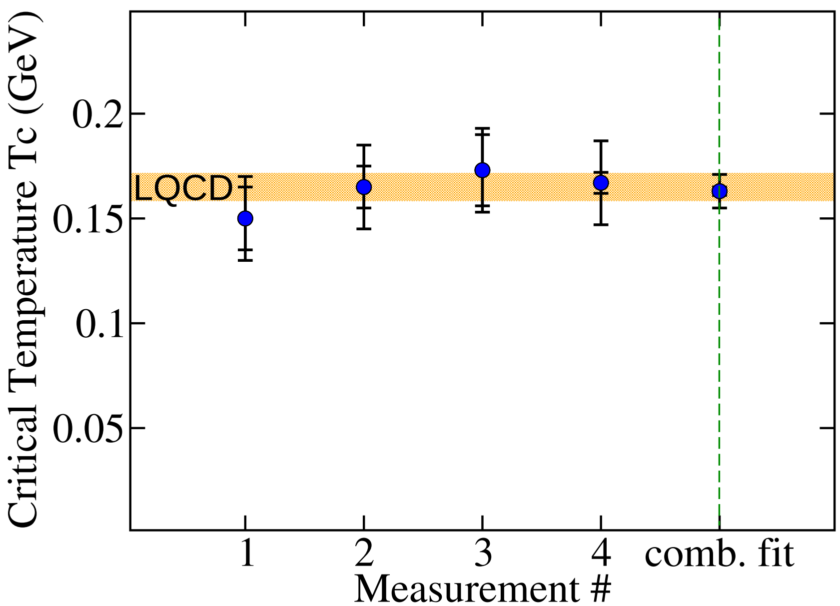
- ideal and viscous (3+1)-d hydrodynamics
- model for CGC thermalization and early pre-equilibrium evolution
- parton kinetic theory models
- hadronic Boltzmann algorithms
- particle correlation afterburners
- parton energy loss and electromagnetic radiation modules
- parameter optimization routines, extraction of EOS and viscosity
- universal code interfaces (XML standards)
- (3+1)-d graphical visualization tools ("RHICview")

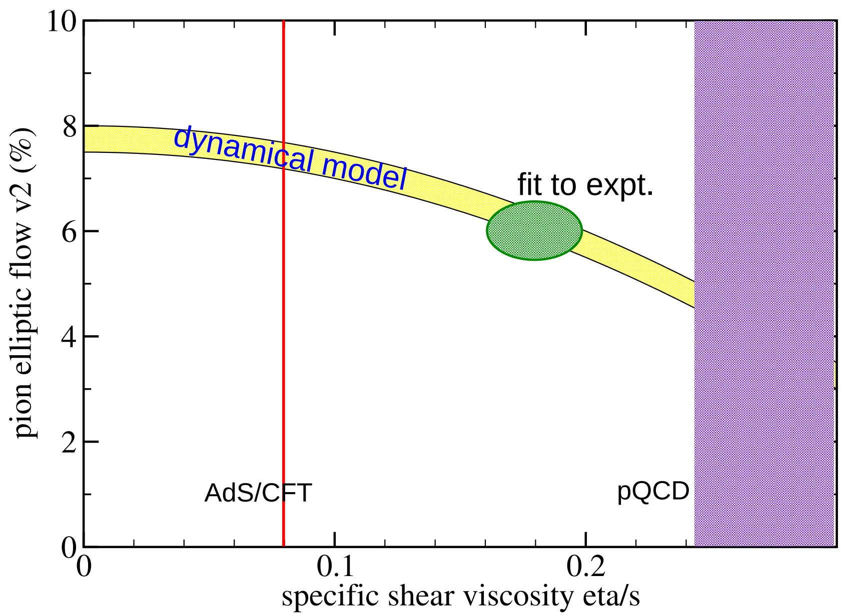
Comparing the dynamical model with experimental data

- Each module of the dynamical model contains parameters that are either not reliably calculable from QCD or for which one wants to verify accuracy of QCD prediction (i.e. eliminate alternate values)
  $\Longrightarrow \sim 2$ dozen parameters $(Q_s,\ T_c,\ c_s(T),\ \eta,\ \zeta,\ \tau_{\rm therm},\ \tau_{\rm chem},\ e_0, \hat{q},\ D_c,\ \Delta m_\rho, \Delta\Gamma_\rho,\ \ldots)$
- Optimization problem $\Longleftrightarrow$ systematic solution, avoiding unphysical minima
  $\Longrightarrow > 10^{19}$ flops per $\sqrt{s}$ and b

This is unavoidable if we want to present the community with accurate results for key parameters, including error bars.

Errors can not be reliably estimated without passing parameter sets through complete dynamical model.





4. A Theory Upgrade for RHIC (RTU)

"Towards a quantitative understanding of
relativistic heavy-ion collision dynamics and QGP properties"

White Paper prepared for this Town Meeting, with broad community support

- Builds on the realization that DOE funding base for the Nuclear Theory program is not strong enough to address the challenges associated with deriving rigorous and quantitative conclusions from precision RHIC and LHC data.

- Proposes collaborative effort by experimental and theoretical RHIC communities to initiate and lead to completion a targeted 5-year "Theory Upgrade" project, on par with planned RHIC II detector and accelerator upgrades and funded outside the base Nuclear Theory program, to develop, validate, document, and prepare for general use a complete set of modeling tools to quantitatively analyze RHIC/LHC data.

- Proposes creation of a virtual center, with broad participation of groups at universities and national labs as well as the experimental collaborations, to develop and maintain codes, improve and extend theoretical methods for calculating dense matter probes, coordinate the modeling and data interpretation effort, and run workshops to assist the greater community in contributing to and making use of the modeling infrastructure.

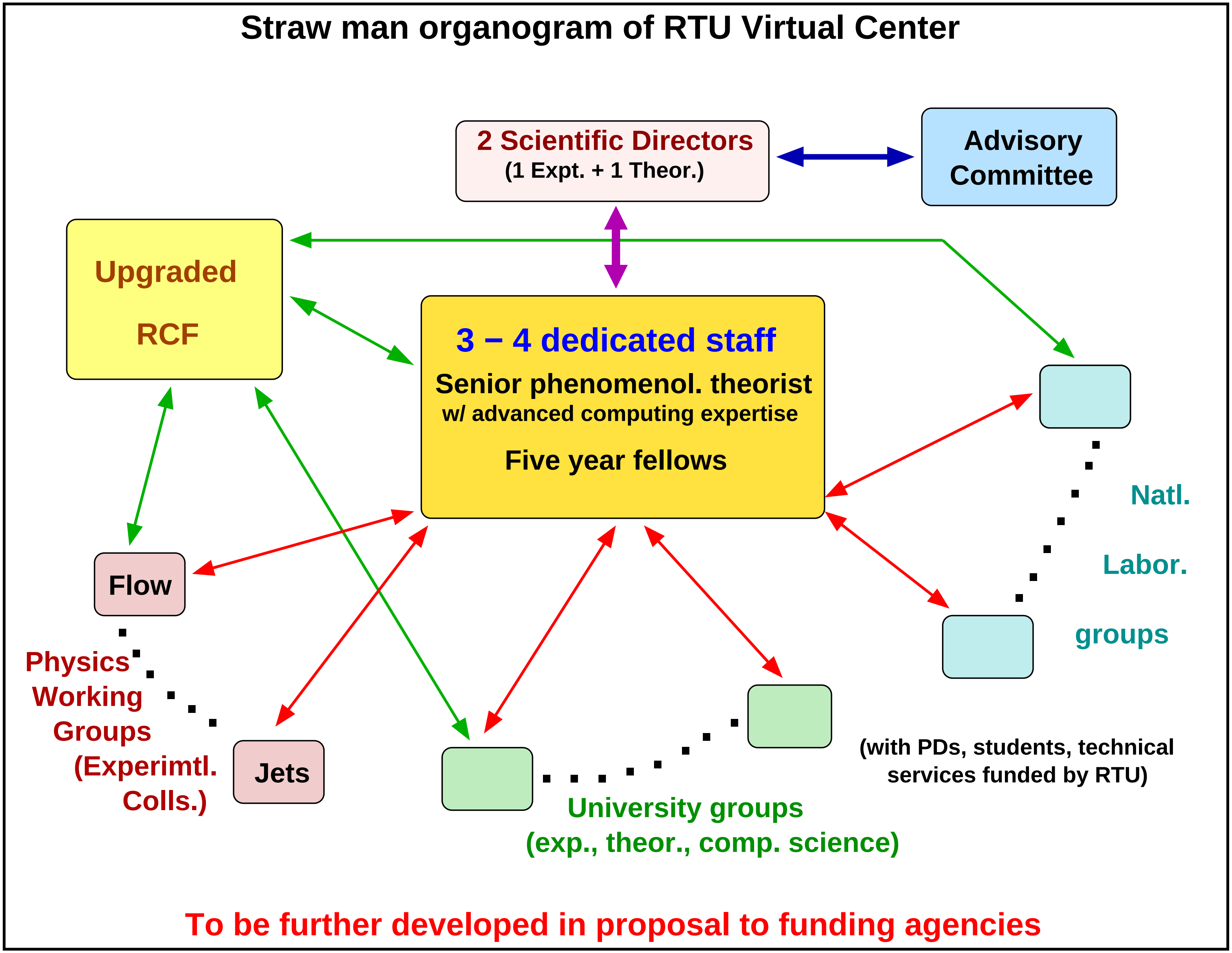
- After the 5-year development period, the experimental RHIC community takes full ownership of the project as part of the ongoing data analysis effort, with continued theory support funded through the base NT program.

A Theory Upgrade for RHIC (RTU) (contd.)

Key contributions to a comprehensive dynamical approach:

- descriptions of energy and baryon number stopping as initial conditions for the dynamical evolution;
- nonperturbative evolution of classical color fields with Color Glass Condensate initial conditions, including space-time evolution of plasma instabilities;
- dynamical models for the initial thermalization stage based on classical or quantum kinetic theory, including the interaction of colored particles with strong color fields;
- (2+1)- and (3+1)-dimensional viscous relativistic hydrodynamics to describe the dynamical expansion of an approximately thermalized quark-gluon fluid;
- Boltzmann models for the evolution of the late hadronic stage, including mean fields;
- jet production and quenching, and parton energy loss in a dynamically evolving background, including back reaction of the medium to the lost energy;
- three-dimensional jet tomography at all rapidities;
- modification of jet fragmentation functions by a dynamically evolving medium;
- the solution of rate equations for strangeness and heavy flavor production and for chemical equilibration among quarks and gluons in a dynamically evolving locally thermalized medium;
- the modeling of hadron production at intermediate transverse momenta by quark recombination from an expanding partonic medium;
- production and propagation of heavy quarkonia, including dissociation and recombination in the evolving medium, as well as energy loss of heavy quarks;
- emission of electromagnetic radiation (photons and dileptons) from a dynamically evolving medium, either by using the temperature and flow history of the dynamical models above, or by including photon production rates into the kinetic codes;
- afterburners to compute correlation and fluctuation spectra and for performing two- and three-particle interferometry from the output of the dynamical models.

$\Longrightarrow$ **community wide effort!**


Straw man organogram of RTU Virtual Center
2 Scientific Directors
(1 Expt. + 1 Theor.)
Advisory Committee
Upgraded
RCF
3 – 4 dedicated staff
Senior phenomenol. theorist
w/ advanced computing expertise
Five year fellows
Flow
Jets
Physics Working Groups (Experimtl. Colls.)
Natl.
Labor.
groups
(with PDs, students, technical services funded by RTU)
University groups
(exp., theor., comp. science)
To be further developed in proposal to funding agencies