Questions and Lessons from the Work of John, PHENIX, and others

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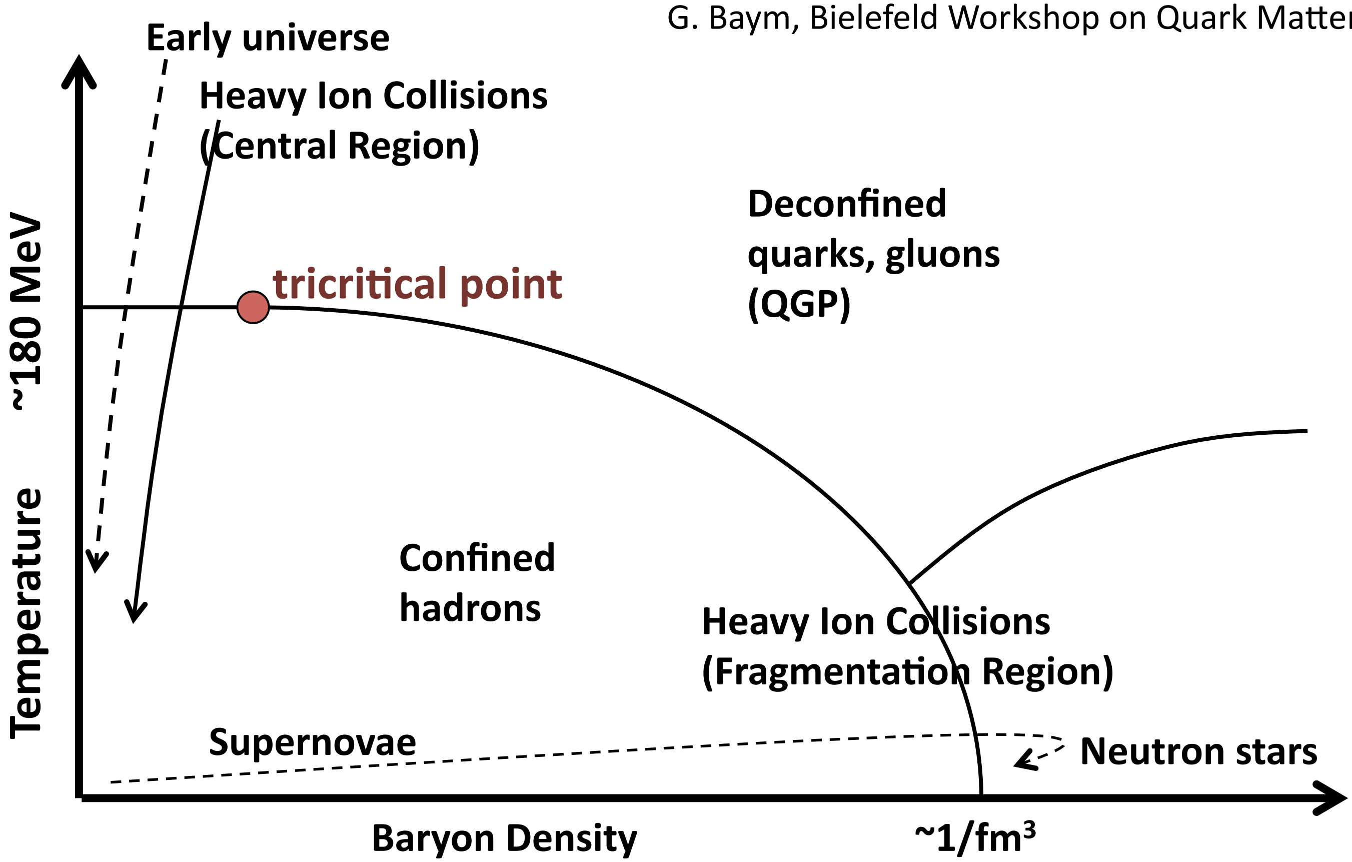
noun

1. that which one learns when one's attempt to find the answer doesn't succeed

Nuclear Matter Phase Diagram

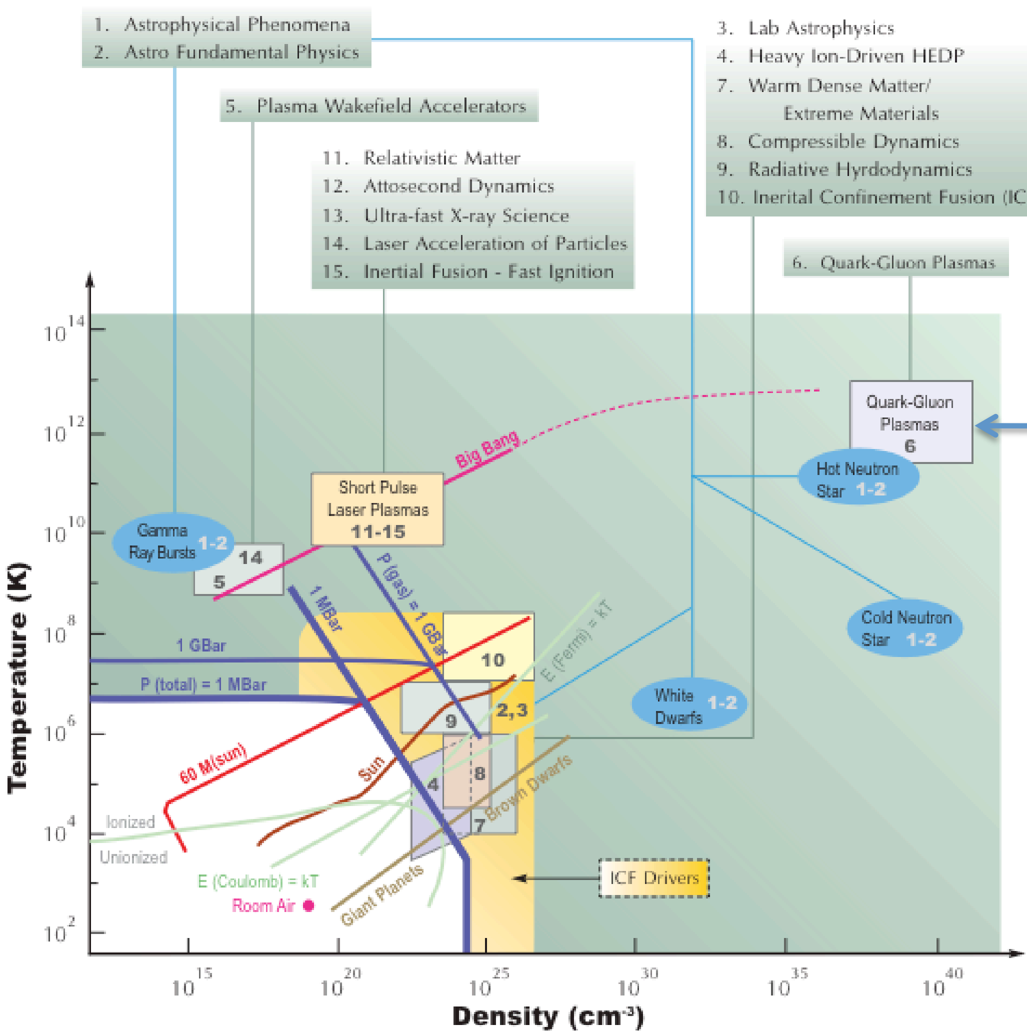
G. Baym, Bielefeld Workshop on Quark Matter, 1983



"to see ourselves as others see us"

Robert Burns, *To A Louse*

Map of the HED Universe

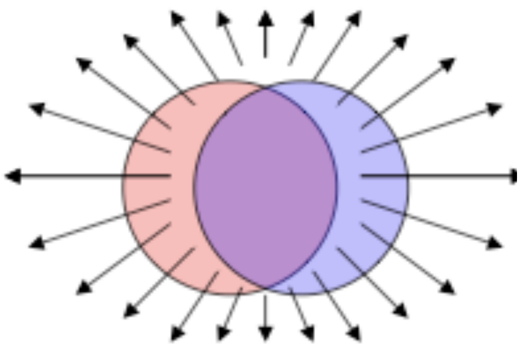


- HEDP 2004 Task Force

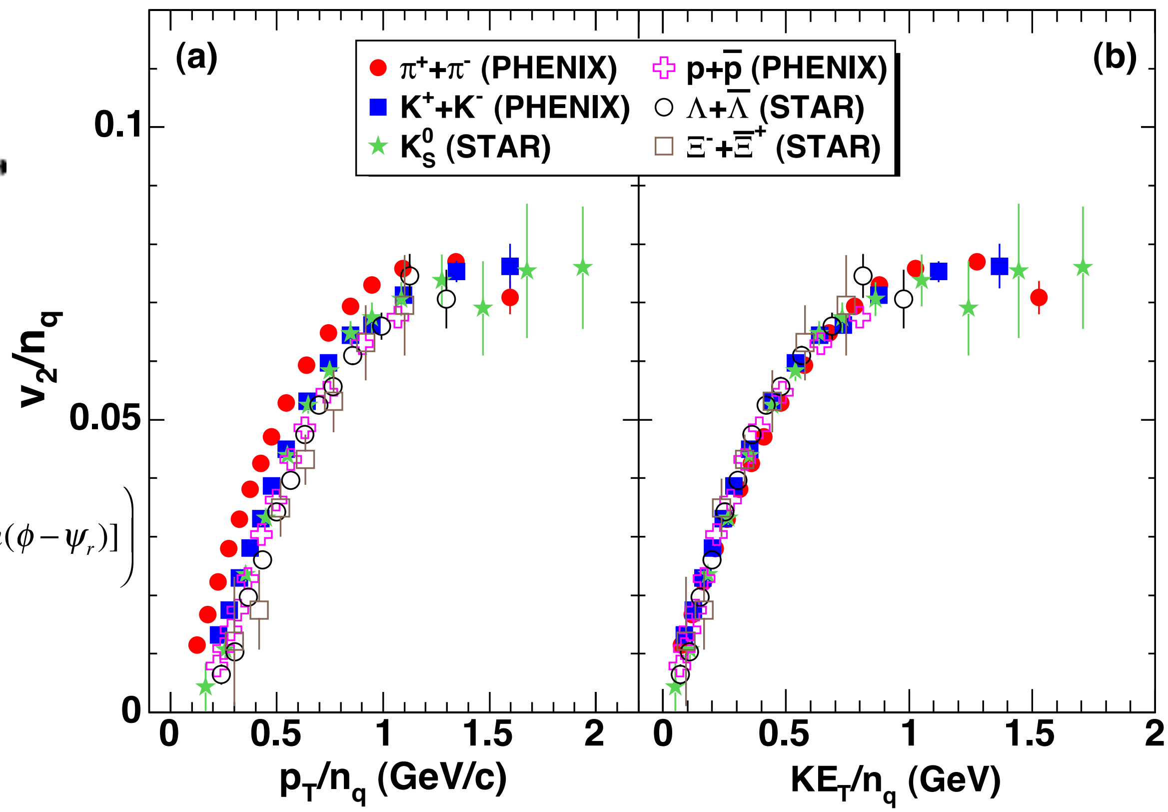
- Quark Gluon Plasma !
- What simple, compelling evidence do we have ?

Stunning (data-only) results (1)

- Elliptic Flow = v_2 = momentum anisotropy, pressure gradients
  - divide both axes by valence quark number

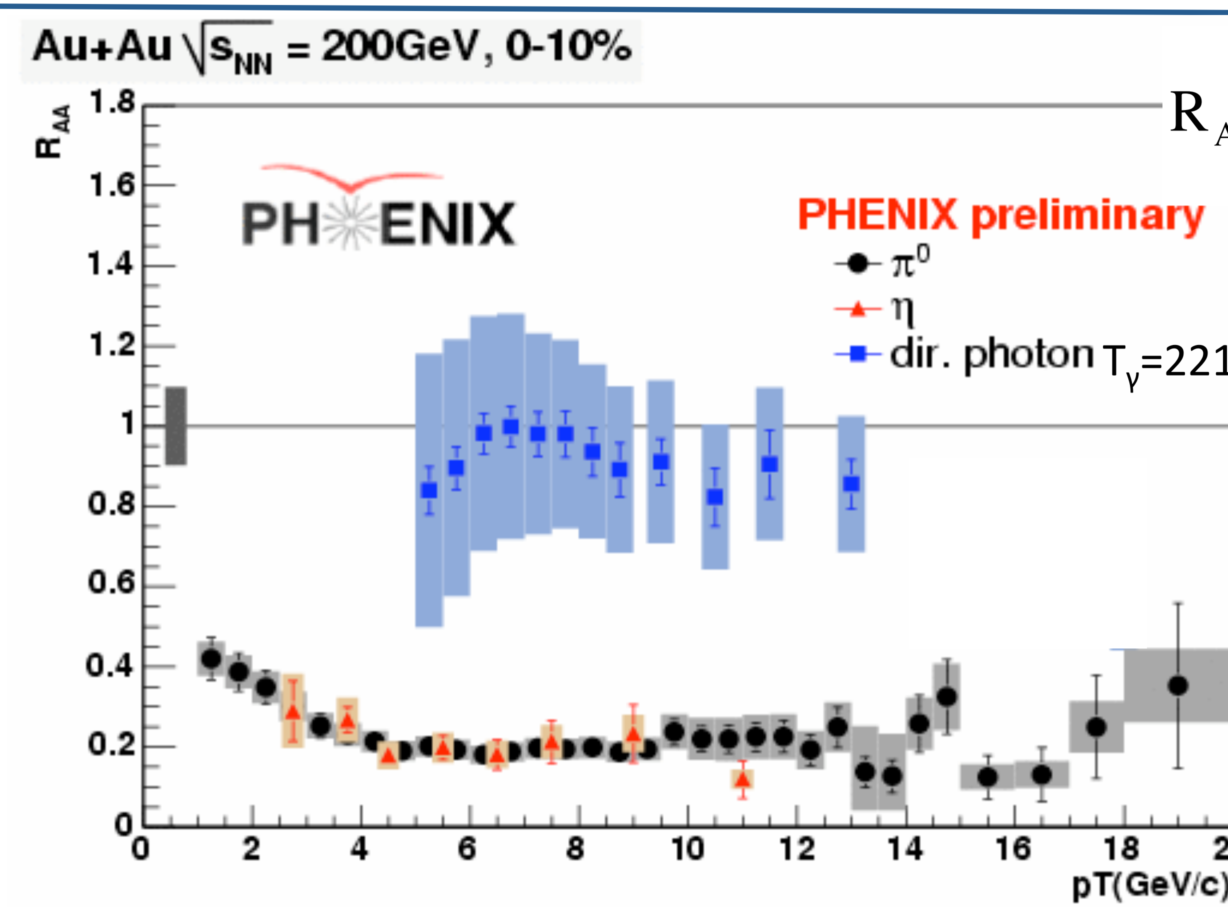


$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{i=1}^{n} 2v_n \cos[n(\phi-\psi_r)]\right)$$



Sensitive to early time pressure gradients, Flow exhibits partonic DoF

Stunning data-only results (2)



$$R_{AA} = \frac{Yield_{AA}/\langle N_{binary}\rangle_{AA}}{Yield_{pp}}$$

T_γ=221 +/- 19 +/- 19 MeV

some theoretical work still required

(se arxiv:0810.3194)
Shadowing, Cronin, ...

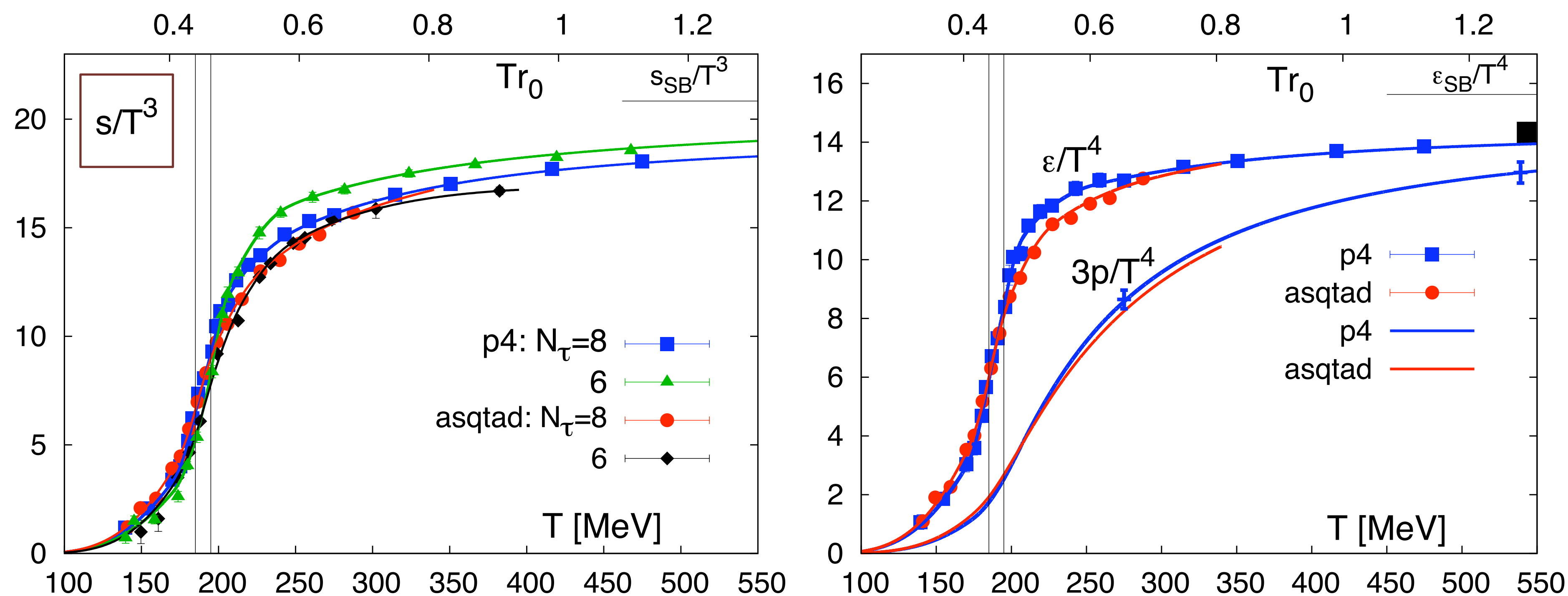
QGP medium opaque to high p_T mesons (from jets), but not direct photons

Understanding space-time

- John's work (& mine) focused on measuring space-time
  - Q: Why?
  - A: Because we can ... (necessary, but not sufficient)
- Initial expectations (static calculations) for large/long-lived source to accompany large entropy change in EoS
- Subsequent (hydro-)dynamic calculations w/ 1st order phase transition also predicted long-lived source

Note that initial LQCD calculations were quenched => 1st order phase transition.

Entropy, Pressure, Energy density

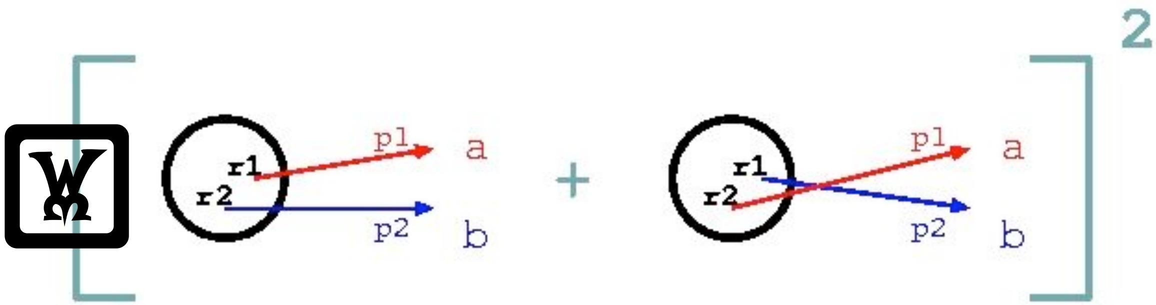


PRD 80, 014504 (2009)

- Recent calculations w/ improved staggered fermion action on N_τ=8 lattices
- Deconfinement transition in the range 185-195 MeV

Measuring QGP & Stellar Radii

$P(p_1,p_2) =$



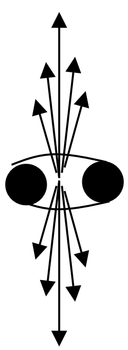
$= $ [illegible] $dx_1 dx_2\{1 + \cos[(\mathbf{p_1}-\mathbf{p_2})(\mathbf{x_1}-\mathbf{x_2})]\}$

$P(p_1,p_2)/P(p_1)P(p_2) = 1 + |$ [illegible] $(\mathbf{p_1} - \mathbf{p_2})|^2$

Gaussian source in x_i yields Gaussian correlation in conjugate variable $q_i = p_{1i} - p_{2i}$

Phil. Mag., 45:663 (1954), Nature, 178:1046 (1956)

p+p

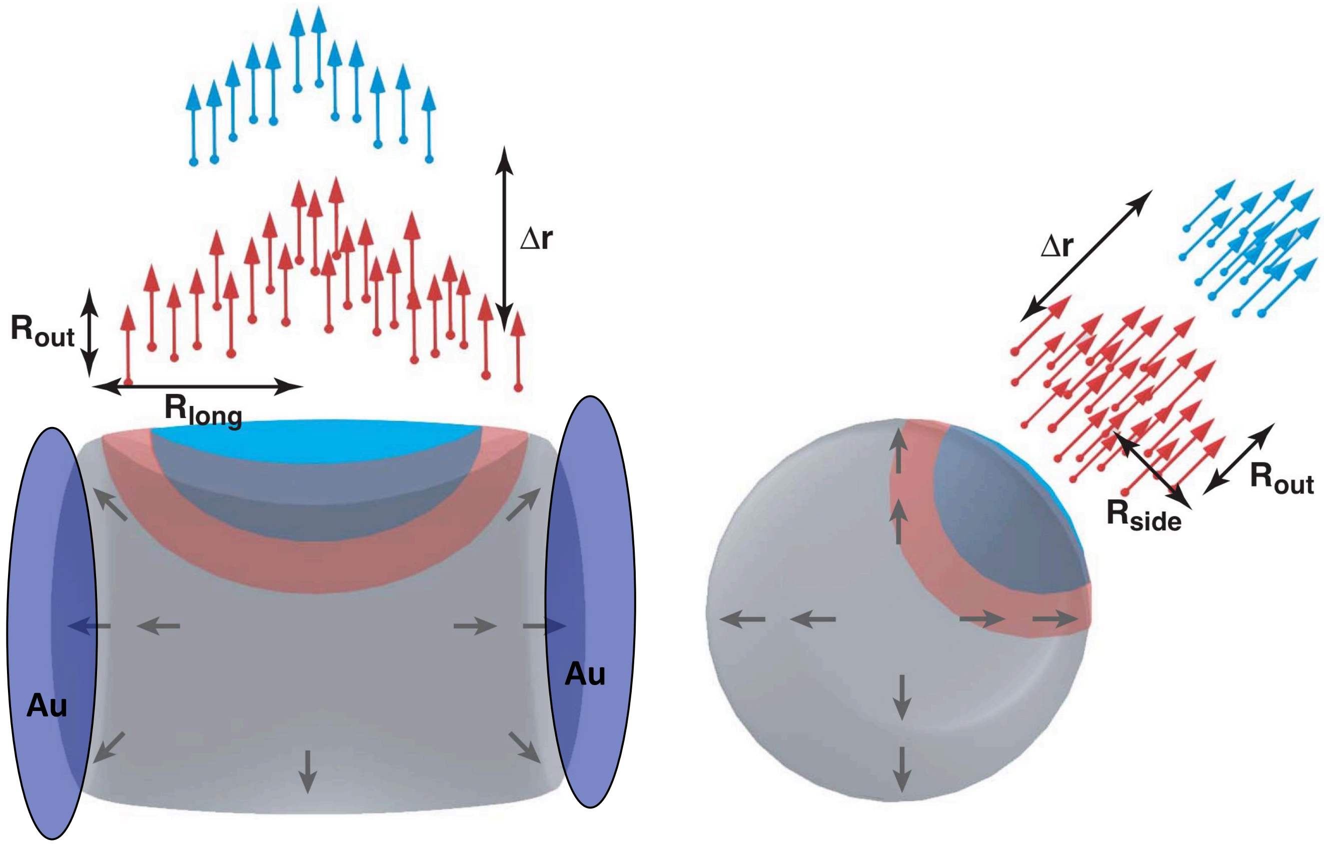


Interference of electric field intensity (plane waves) from source:

- HBT reference is to Hanbury Brown and Twiss, who developed theory and performed first measurements of stellar radii
- First application to particle physics, Goldhaber, Goldhaber, Lee, Pais (GGLP).

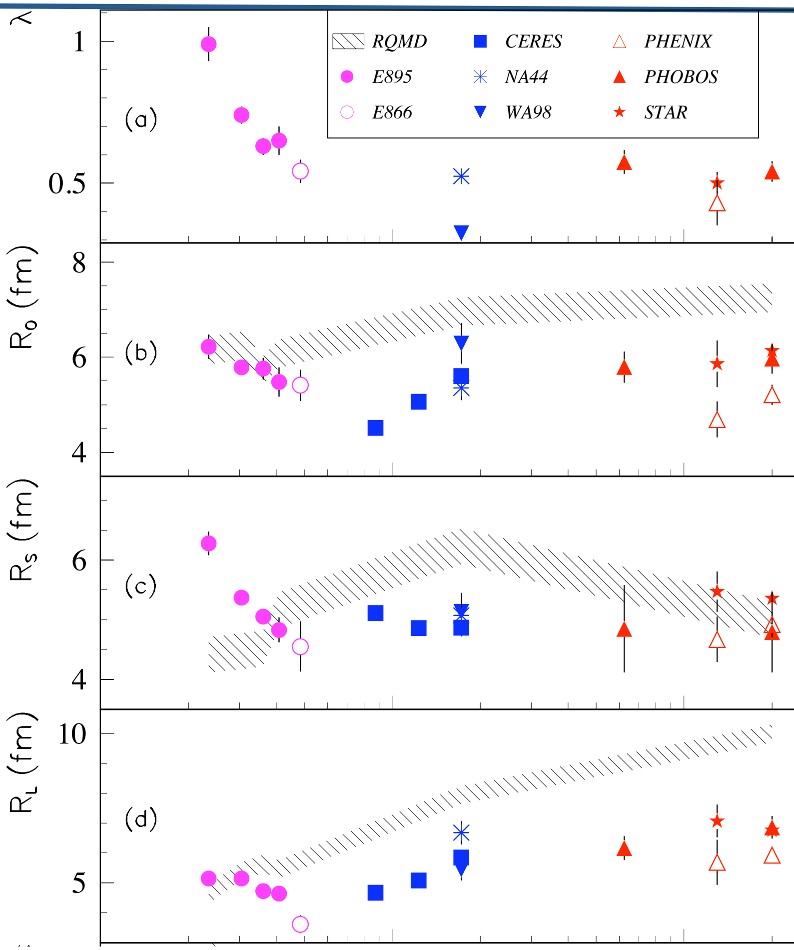
PRL 120, 300 (1960)

Measuring Space-Time in Collision

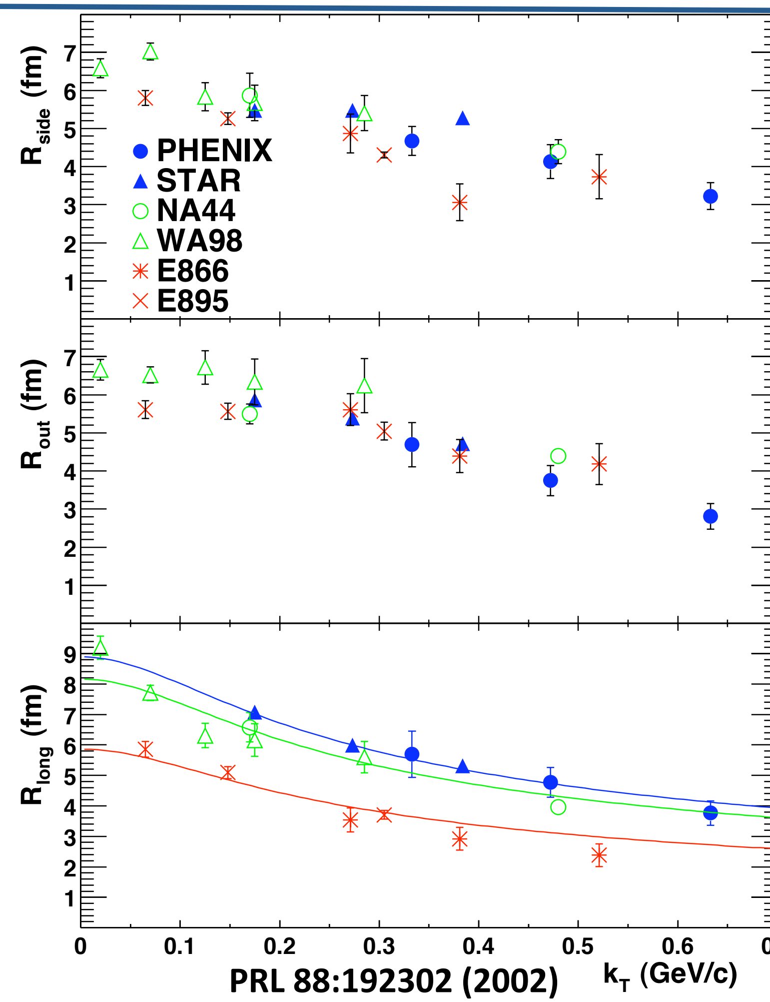


1. Flow (dynamical correlations) reduce *visible source* at higher pair momenta
2. Outwards direction is extended by duration of emission
3. Ratio of out to side radius (Rout/Rside) indicative of emission duration (QGP)

HBT Puzzle 1 (data-only)



Ann. Rev. 55, 357 (2005), PRL 87, 082301 (2001)



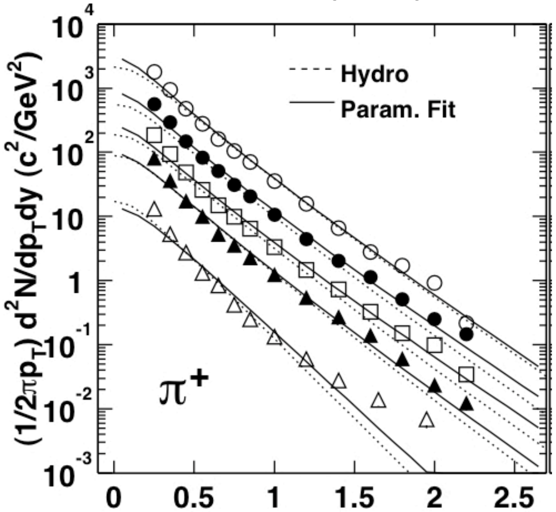
PRL 88:192302 (2002)

Radii show smooth evolution from fixed-target to collider energies

HBT Puzzle 2 (model-comparisons)

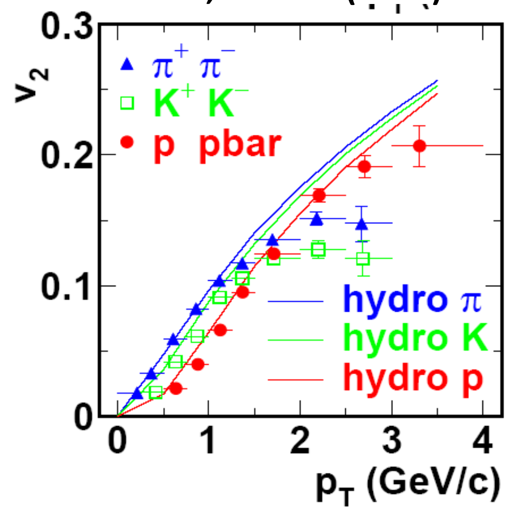
Spectra dN/dp_T

PRC 64, 02904 (2004)



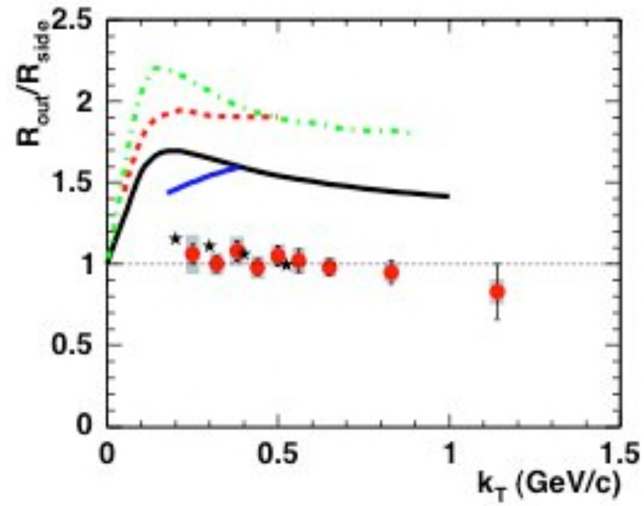
Flow

PRL 91, 182301 (2003)



Space-time

PRL 93, 152302 (2004)



- Hydro models are 2 for 3:
  - tune for spectra
  - match flow
  - neglect space-time (most difficult & least sensitive)

HBT Puzzle Solution (1)

- Stage set …

Quantum Opacity, the RHIC Hanbury Brown–Twiss Puzzle, and the Chiral Phase Transition

John G. Cramer, Gerald A. Miller, Jackson M. S. Wu, and Jin-Hee Yoon*
Department of Physics, University of Washington, Seattle, WA 98195-1560, USA
(Received 27 August 2004; published 18 March 2005)

We present a relativistic quantum-mechanical treatment of opacity and refractive effects that allows reproduction of observables measured in two-pion Hanbury Brown–Twiss (HBT) interferometry and pion spectra at RHIC. The inferred emission duration is substantial. The results are consistent with the emission of pions from a system that has a restored chiral symmetry.

DOI: 10.1103/PhysRevLett.94.102302 PACS numbers: 25.75.-q

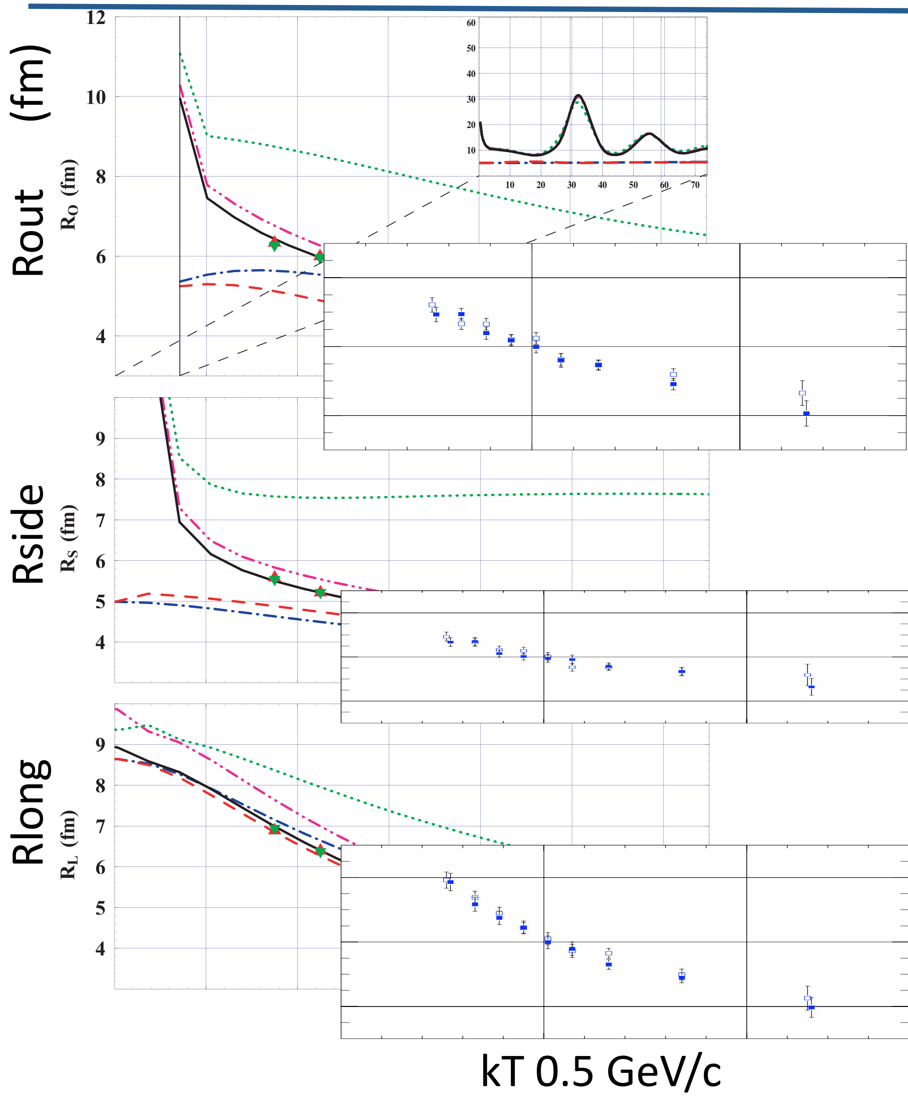
- Adopt hydro-inspired “blast-wave” source
- Optical potential for medium interaction
    - revisit plane wave assumption
    - assume chiral symmetry to guide form of potential
- Fit parameters for blast wave + potential

$$S_0(x, K) = S_0(\tau, \eta) B_\eta(\mathbf{b}, \mathbf{K}_T)/(2\pi)^3$$

$$S_0(\tau, \eta) \equiv \frac{\cosh\eta}{\sqrt{2\pi(\Delta\tau)^2}} \exp\left[-\frac{(\tau-\tau_0)^2}{2(\Delta\tau)^2} - \frac{\eta^2}{2\Delta\eta^2}\right]$$

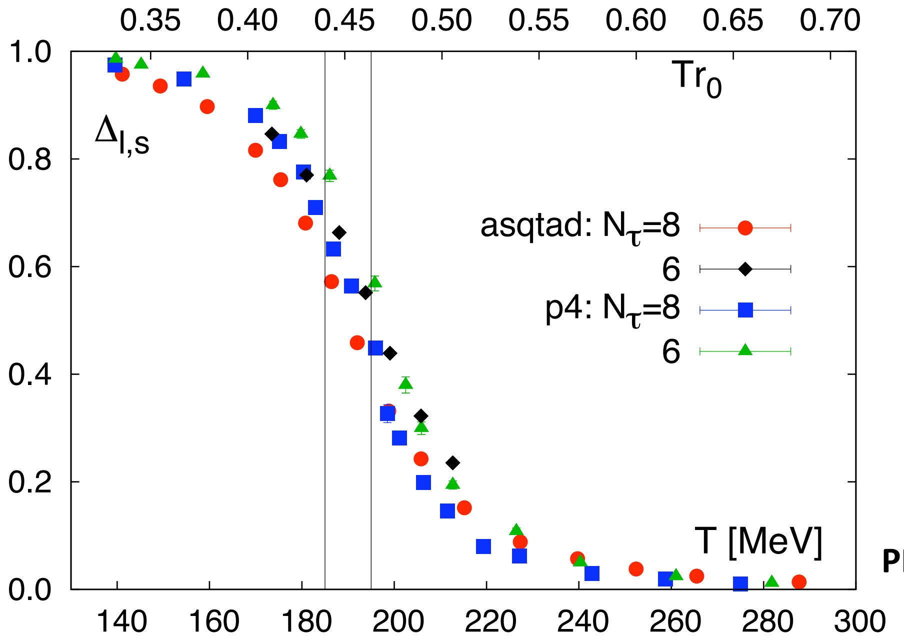
$$B_\eta(\mathbf{b}, \mathbf{K}_T) \equiv M_T \frac{1}{\exp[(K\cdot u - \mu_\pi)/T] - 1}\rho(b),$$

Quantum Opacity Model Results



- Lessons…don't be afraid to:
  - generate a complete solution, even if it requires 10 parameters
  - revisit standard (plane-wave) assumptions
  - cross the blood-brain barrier that too often separates theorists and experimentalists

And what of chiral symmetry?



$$\Delta_{l,s}(T) = \frac{\langle\bar{\psi}\psi\rangle_{l,T} - \frac{m_l}{m_s}\langle\bar{\psi}\psi\rangle_{s,T}}{\langle\bar{\psi}\psi\rangle_{l,0} - \frac{m_l}{m_s}\langle\bar{\psi}\psi\rangle_{s,0}}$$

PRD 80, 014504 (2009)

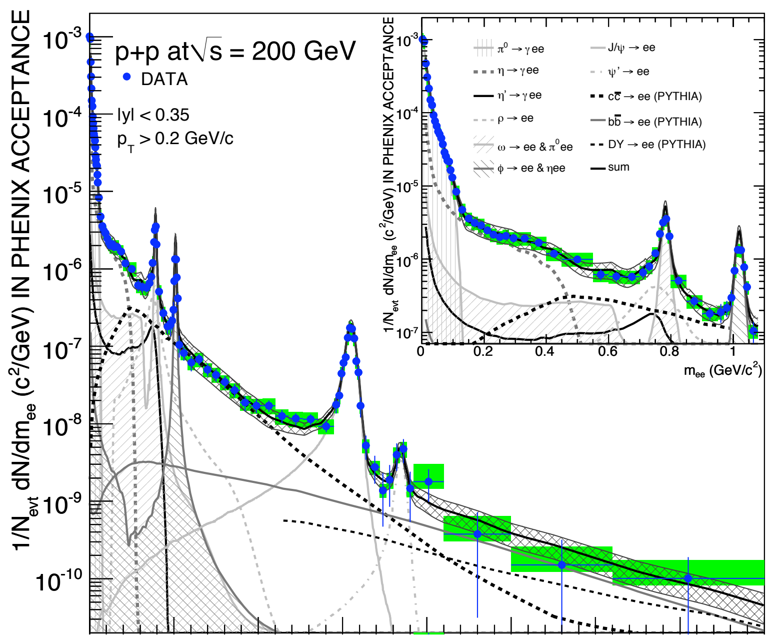
Subtacted chiral condensate exhibits transition in same range as deconfinement

- some calculations predict significantly lower chiral transition **PLB 643, 46 (2006)**
- but both fermion actions violate discrete chiral symmetry (recovered in cont.)

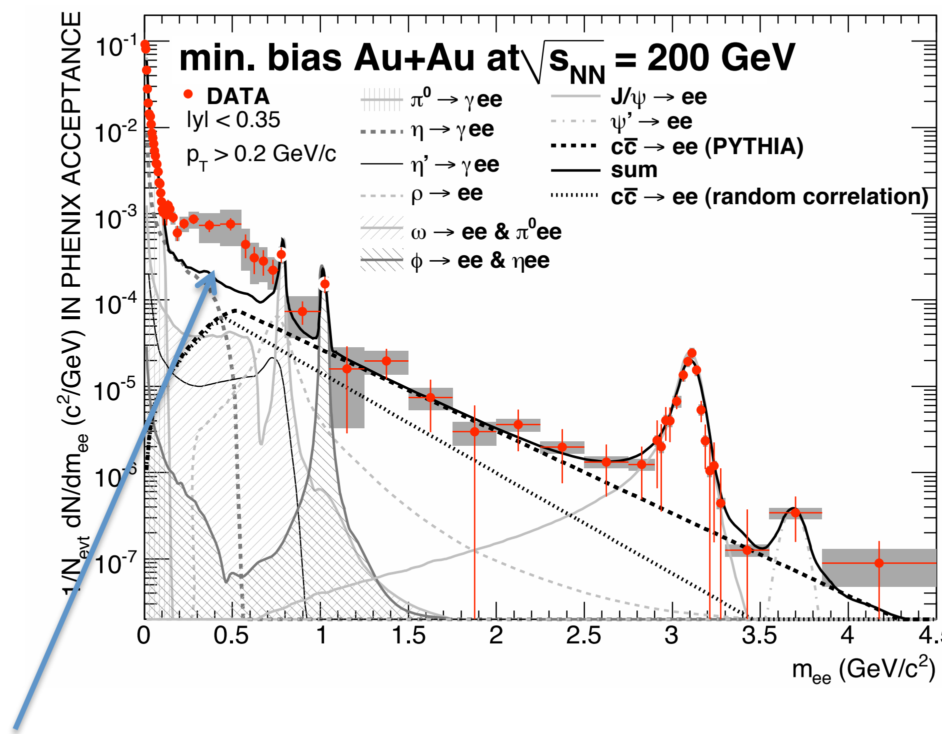
Calculations on N_τ=12 lattices underway
Calculations with DWF (preserves discr. chiral) just a petaFlop away

Chiral Sym. to an Experimentalist

PLB 670:313 (2009)



arxiv 0706.3034



- QGP spectral broadening vs. rescattering effects

New detectors for STAR & PHENIX will soon improve statistics and systematics

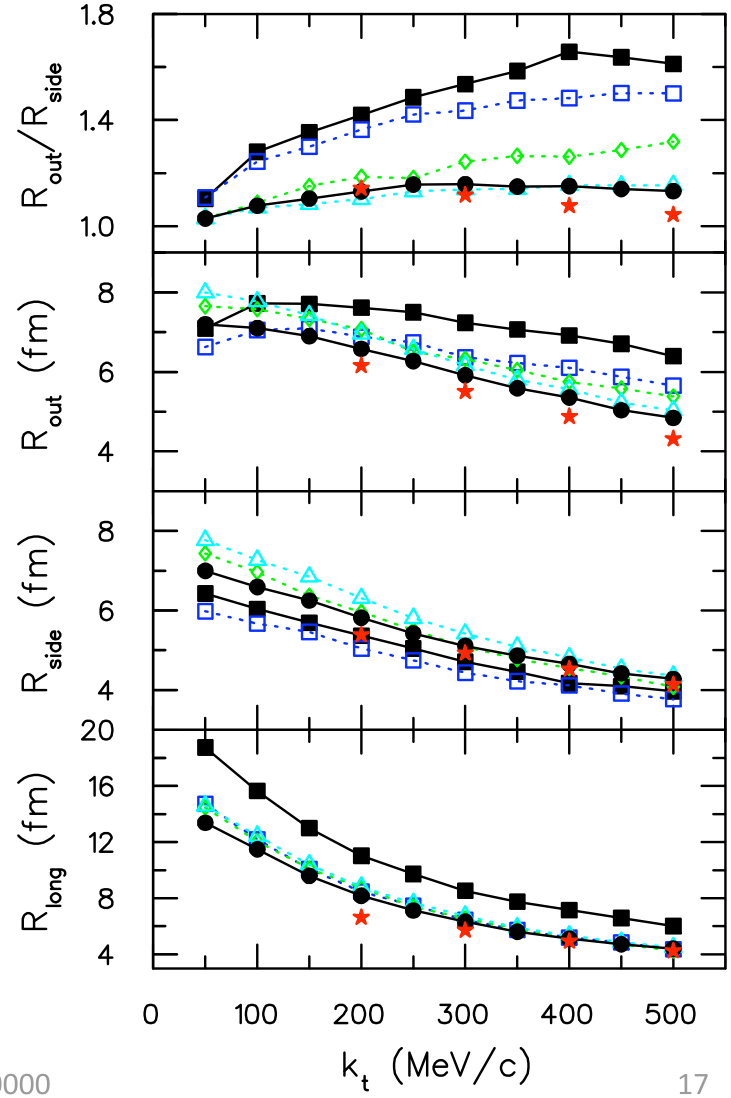
HBT Puzzle Solution (2)

- Recent breakthrough by Vredevoogd and Pratt
  1. Boost Invariant Longitudinal Flow **PRC 79 044915 (2009)**
  2. Traceless stress energy tensor
  3. Stress energy tensor anisotropy independent of transverse coordinate
- Explains large Rside and k_T dependence
- *If correct,* addresses large uncertainty in setting initial conditions of hydrodynamics

HBT Puzzle Solution in 1D

PRC 78 054906 (2008)

- Comparison to pion Radii
  - a series of 10% effects
    1. pre-equ. flow
    2. LQCD EoS
    3. viscosity
    4. improved wave fns.
  - also works for kaons
  - still only 2/3 (no flow)
  - working on 3/3 with Scott using vh2 code by Luzum & Romatschke



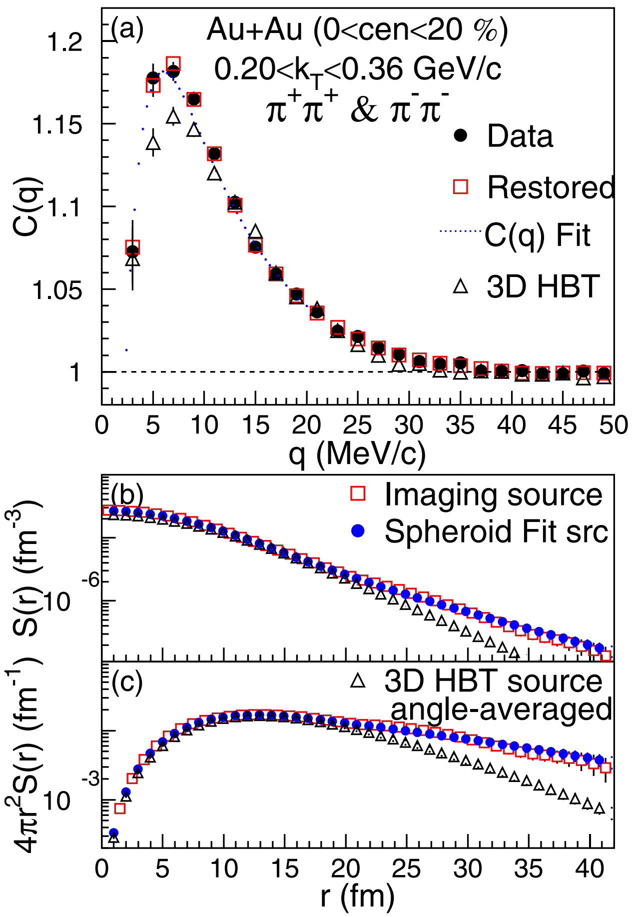
PHENIX HBT Tails

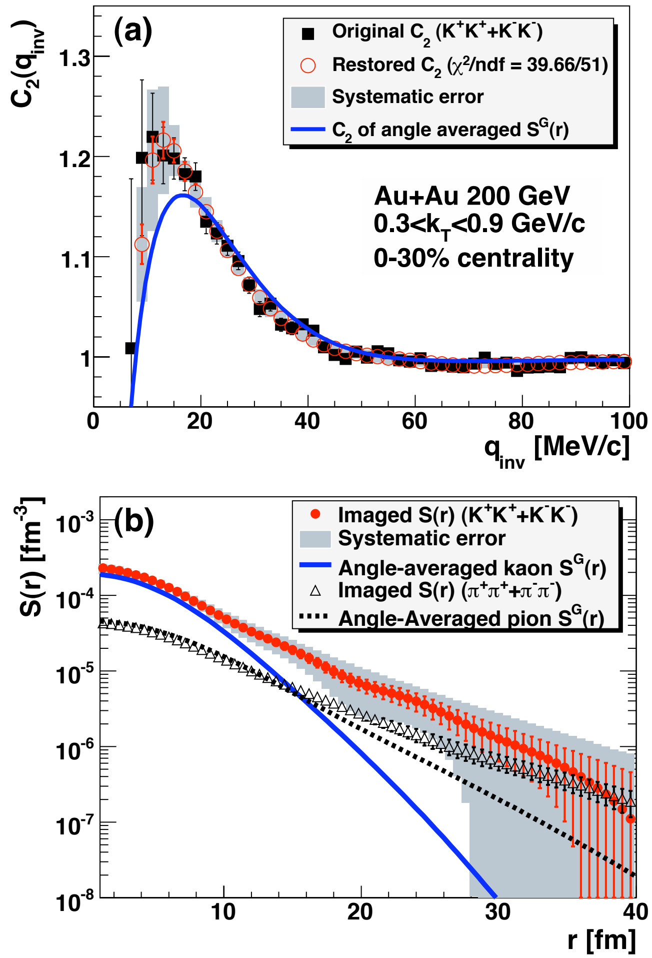
- Beyond Gaussian parameterizations -> rescattering or QGP?

arxiv 0903.4863

PRL 98 132301 (2006)

Pions





Kaons

Lesson

- John's refusal to live/work within self-imposed, arbitrary boundaries has benefitted the field, science, and sets an example for the rest of us.

Happy Birthday

Backup LQCD Material

$$U_{-\mu}(n+\mu+\nu) = e^{iga\left[-A_\mu(n) - a\partial_\nu A_\mu(n) + O(a^2)\right]}$$ <u>1st Taylor series</u>

$$U_{-\nu}(n+\nu) = e^{iga\left[-A_\nu(n)\right]}$$

$$U_\nu(n+\mu) = e^{iga\left[A_\mu(n) + a\partial_\mu A_\nu(n) + O(a^2)\right]}$$

<u>2nd Taylor series</u>

$$\Box = e^{iga^2(\partial_\mu A_\nu - \partial_\nu A_\mu) - ig[A_\mu, A_\nu]} = e^{ia^2 g F_{\mu\nu}} = 1 - \frac{a^4 g^2}{2}\left(F_{\mu\nu}F_{\mu\nu} + O(a^2)\right)$$

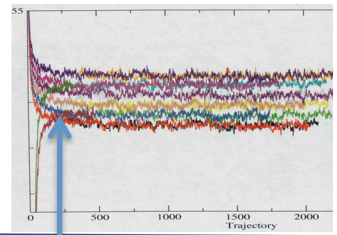
$$S_\Box = \sum_{n,\mu<\nu} Tr\left[F_{\mu\nu}F_{\mu\nu}\right] + const.$$

$$\xrightarrow[a=0]{} \frac{1}{4}\int_V d^3x \int_0^{1/T} Tr\left[F_{\mu\nu}F_{\mu\nu}\right] = S_{gluon}$$

$$U_\mu(n) = e^{igaA_\mu(n)}$$

fermion field

LQCD Analysis



(plaquette histories)

- Apply thermalization cut, remove autocorrelations
- Construct Trace Anomaly (deviation from massless ideal gas)

$$\frac{\varepsilon-3p}{T^4}=\frac{\Theta_F^{\mu\mu}(T)}{T^4}+\frac{\Theta_G^{\mu\mu}(T)}{T^4}=R_\beta(\beta)N_\tau^4\Delta\langle s\rangle \qquad R_\beta(\beta)=T\frac{d\beta}{dT}=-a\frac{d\beta}{da}$$

$$\frac{\Theta_F^{\mu\mu}(T)}{T^4}=-R_\beta R_m N_\tau^4\left(2\hat{m}_l\Delta\langle\bar{\psi}\psi\rangle_l+\hat{m}_s\Delta\langle\bar{\psi}\psi\rangle_s\right)$$

$m_l=0.1m_s(LCP)$
Lines of Constant Physics

$$\frac{\Theta_G^{\mu\mu}(T)}{T^4}=R_\beta N_\tau^4\left(\Delta\langle s_G\rangle-R_u\left(6\beta'_{rt}\Delta\langle R\rangle+4\beta'_{pg}\Delta\langle C\rangle+\frac{1}{4\beta}\Delta\left\langle Tr\left((2D_l^{-1}+D_s^{-1})\frac{dM}{du_0}\right)\right\rangle\right)\right)$$

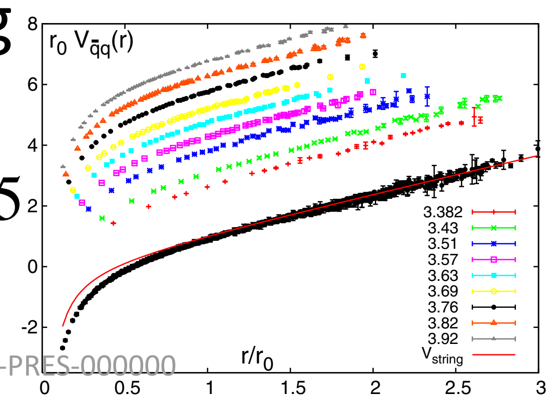
asqtad terms

- Temperature Scale Setting

heavy quark potential ϒ(2S-1S)

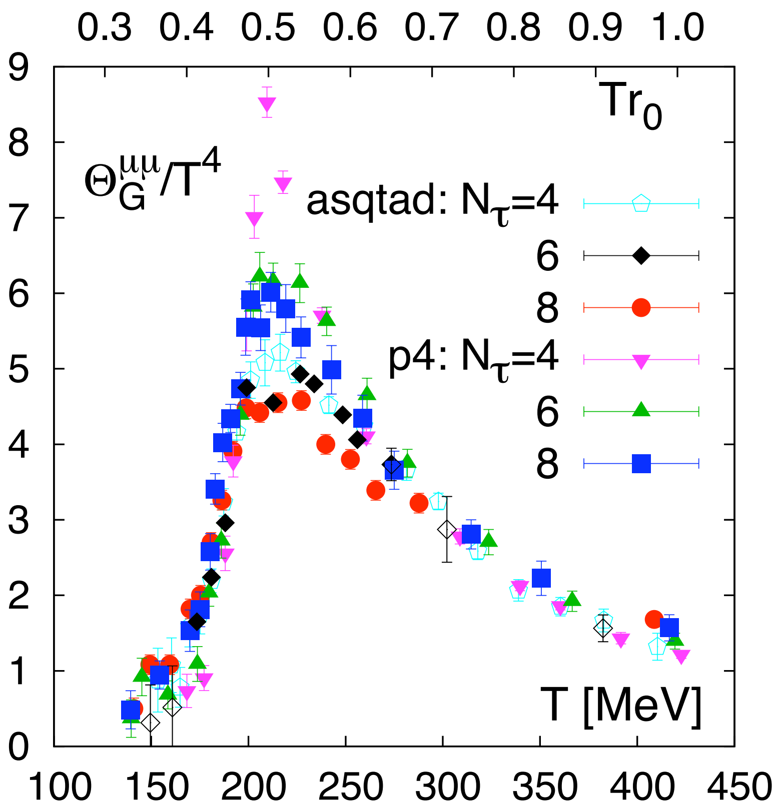
$$\left(r^2\frac{dV_{q\bar{q}}(r)}{dr}\right)_{r=0.469(7)}=1.65$$

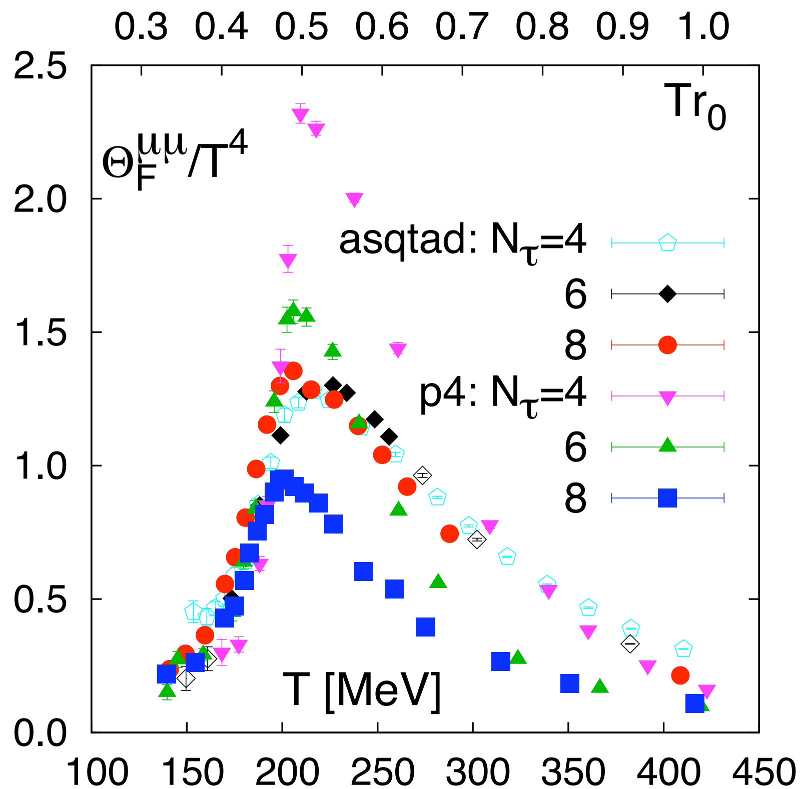
A. Gray, et al, PRD, 72:094507, 2005



M. Cheng, et al, PRD, 77:014511, 2008

Θ fermionic/gluonic contributions





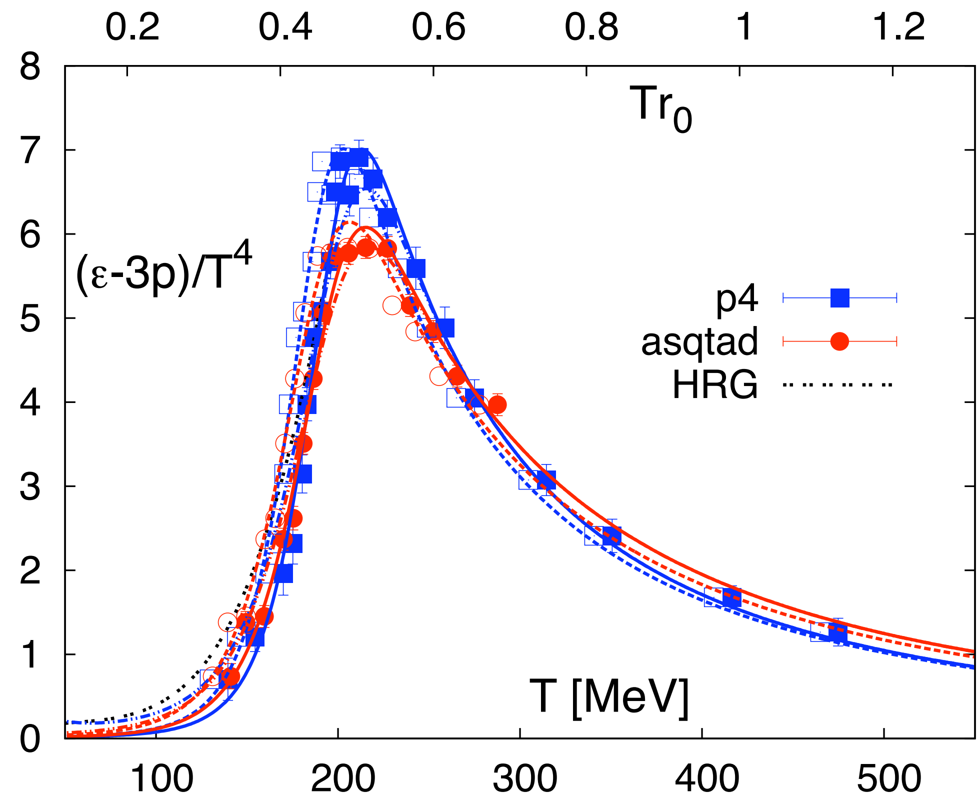
- trace anomaly 85% gluonic (+ fermion interactions)
- larger cutoff effects for p4 fermions from LCP R_m

$\Theta^{\mu\mu}_{reprise}$: Hydro Parametrization

- physically constrains high-T region
- reasonably describes peak, low-T
- single function avoids fluctuations
- few parameters (easy to transfer)

$$\left(1-\frac{1}{\left[1+e^{(T-c_1)/c_2}\right]^2}\right)\times\left(\frac{d_2}{T^2}+\frac{d_4}{T^4}\right)$$

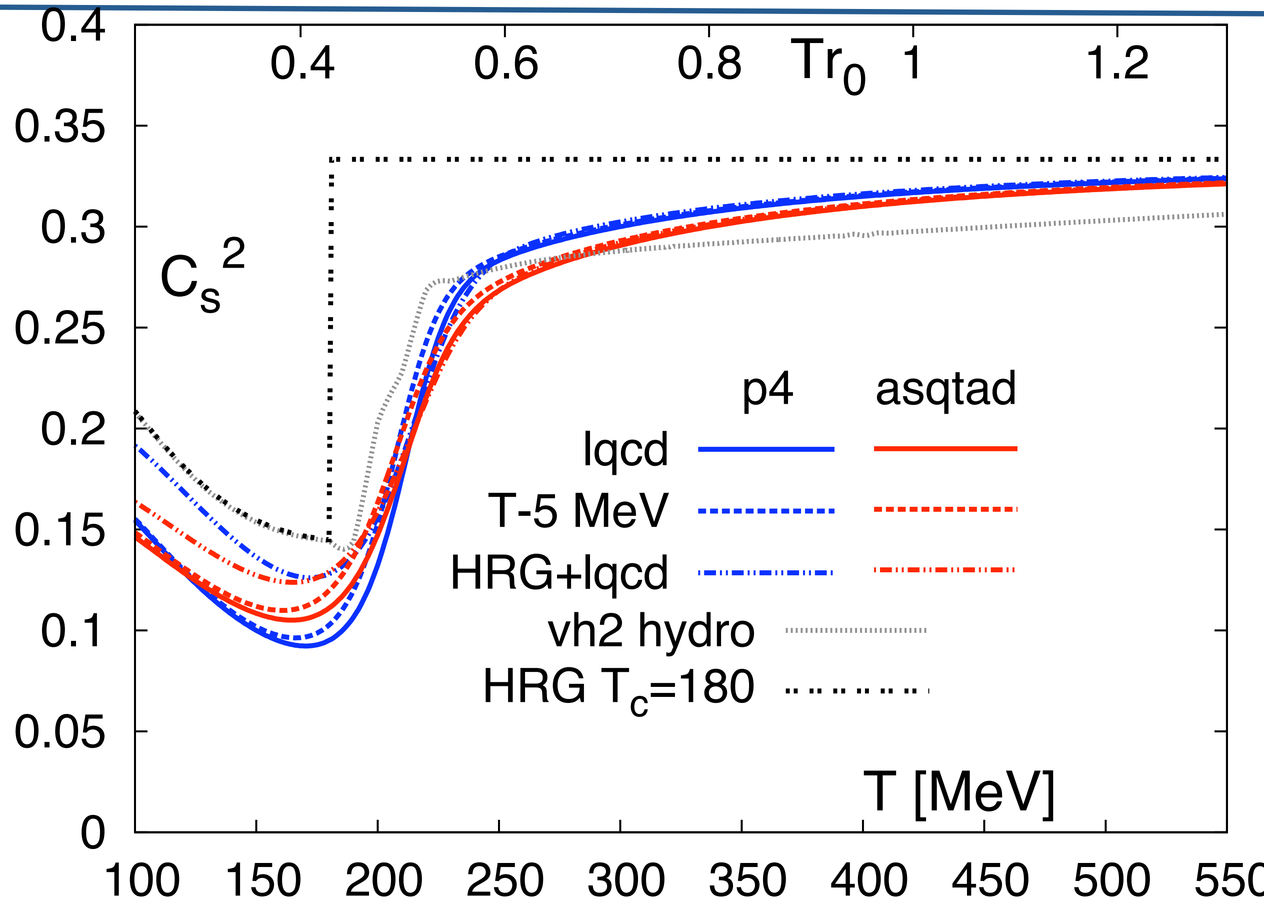
Data	d_2 [GeV]^2	d_4 [GeV]^4	c_1 [GeV]	c_2 [GeV]
p4	0.24(2)	0.0054(17)	0.2038(6)	0.0136(4)
p4-10 MeV	0.241(6)	0.0035(9)	0.1938(6)	0.01361(4)
HRG+p4	0.24(2)	0.0054(17)	0.2073(6)	0.0172(3)
asq	0.312(5)	0.00	0.2024(6)	0.0162(4)
asq-10 MeV	0.293(6)	0.00	0.1943(6)	0.01670(4)
HRG+asqtad	0.312(5)	0.00	0.2048(6)	0.0188(4)



- Three fits each action (p4, asqtad)
  1. lattice data (solid)
  2. lattice data and HRG from 100-130 MeV (double-dot)
  3. lattice-10 MeV shift to approx. chiral/continuum shifts (dash)

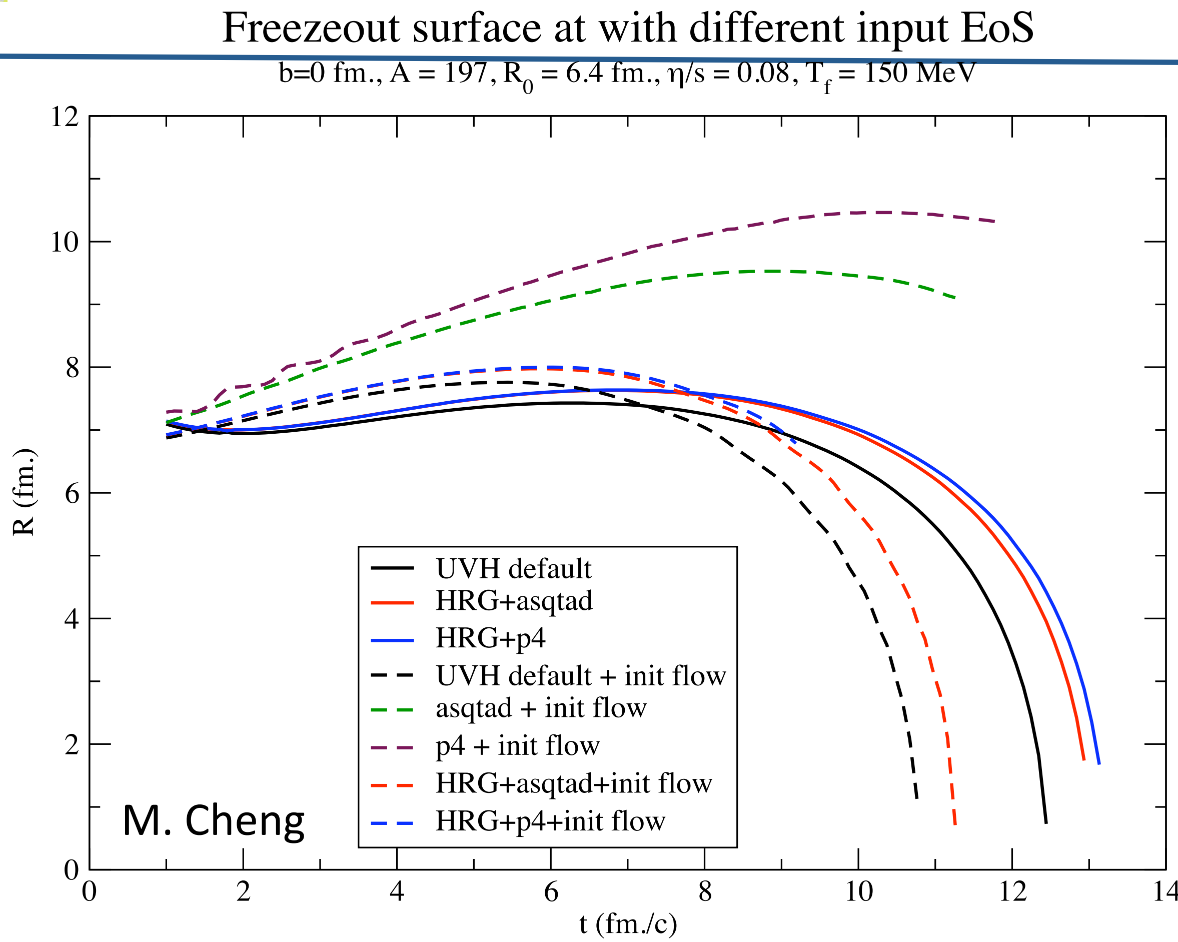
see also poster by P. Huovinen

Speed of Sound in Hydro



1. ready for hydro: smooth approx. to HotQCD EoS w/HRG
2. able to propagate systematic variation through models

Results with VH2 (viscous 2D+1)



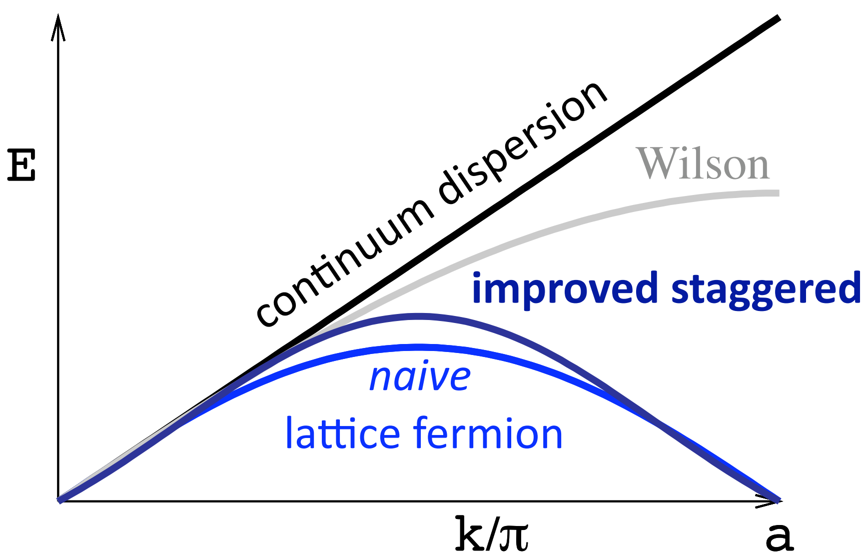
M. Luzum and P. Romatschke, PRC, 78:034915, 2008

- Beginning to propagate EOS thru Hydro
- Preparing to add cascade afterburner->spectra/flow/HBT

trouble with (discrete) fermions

- 1D Dirac Eq. $\frac{\partial\psi}{\partial t} = -\frac{i}{2a}\gamma_5[\psi(n+1)-\psi(n-1)]$ has $E = \pm\frac{\sin(ka)}{a}$
- degenerate fermion states $\left(2^d n_f\right)$

Wilson action lifts degenerate states, breaks chiral symmetry, not widely used in thermodynamics



Staggering Dirac spinor states along 4-corners thins degeneracy by 4

- preserves a discrete chiral symmetry
- additional terms *improve* cutoff effects

p4 [O(a^2)+fat link smearing]
M. Cheng, et al, PRD, 77:014511, 2008

asqtad [O(a^2)+tadpole coefficients]
C. Bernard et al, PRD, 75:094505, 2007

B-W [stout link smearing]
Y. Aoki, et al, PLB643:46, 2006

- all have Symanzik gauge improvements O(a^2)
- all *should* converge as a→0