Bottomonia in A-A

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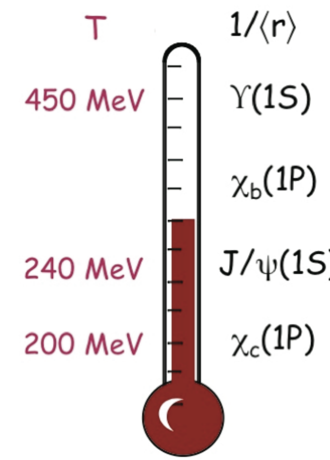
Sapore Gravis Workshop 2014
``Heavy flavour and quarkonium production in high-energy heavy-ion collisions''

Why Bottomonia in A-A?

- Heavy quark effective theory on surer footing
- Cold nuclear matter (CNM) effects are expected to be much smaller than for the charmonia
- Caveat: At very forward/backward rapidities CNM effects on bottomonia might still be important
- The masses of bottomonia are much higher than the temperature (T < 1 GeV) generated in HICs → bottomonia production dominated by initial hard scatterings



A. Mocsy, P. Petreczky, and MS, 1302.2180

- Since bottom quarks and anti-quarks are relatively rare in LHC HICs, the probability for regeneration of bottomonia through statistical recombination is much smaller than for charm quarks
[see e.g. E. Emerick, X. Zhao, and R. Rapp, arXiv:1111.6537]
- Caveat: Still could be some "correlational recombination"

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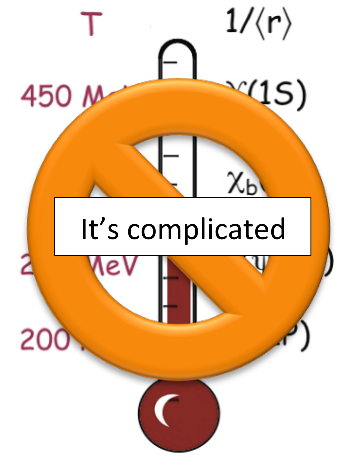

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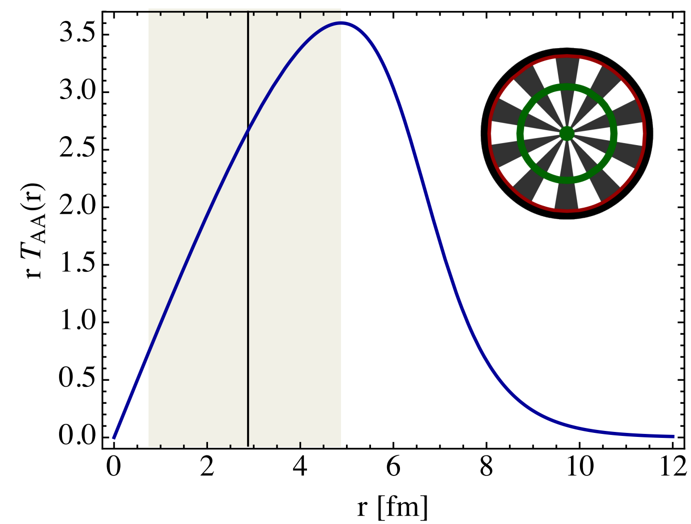
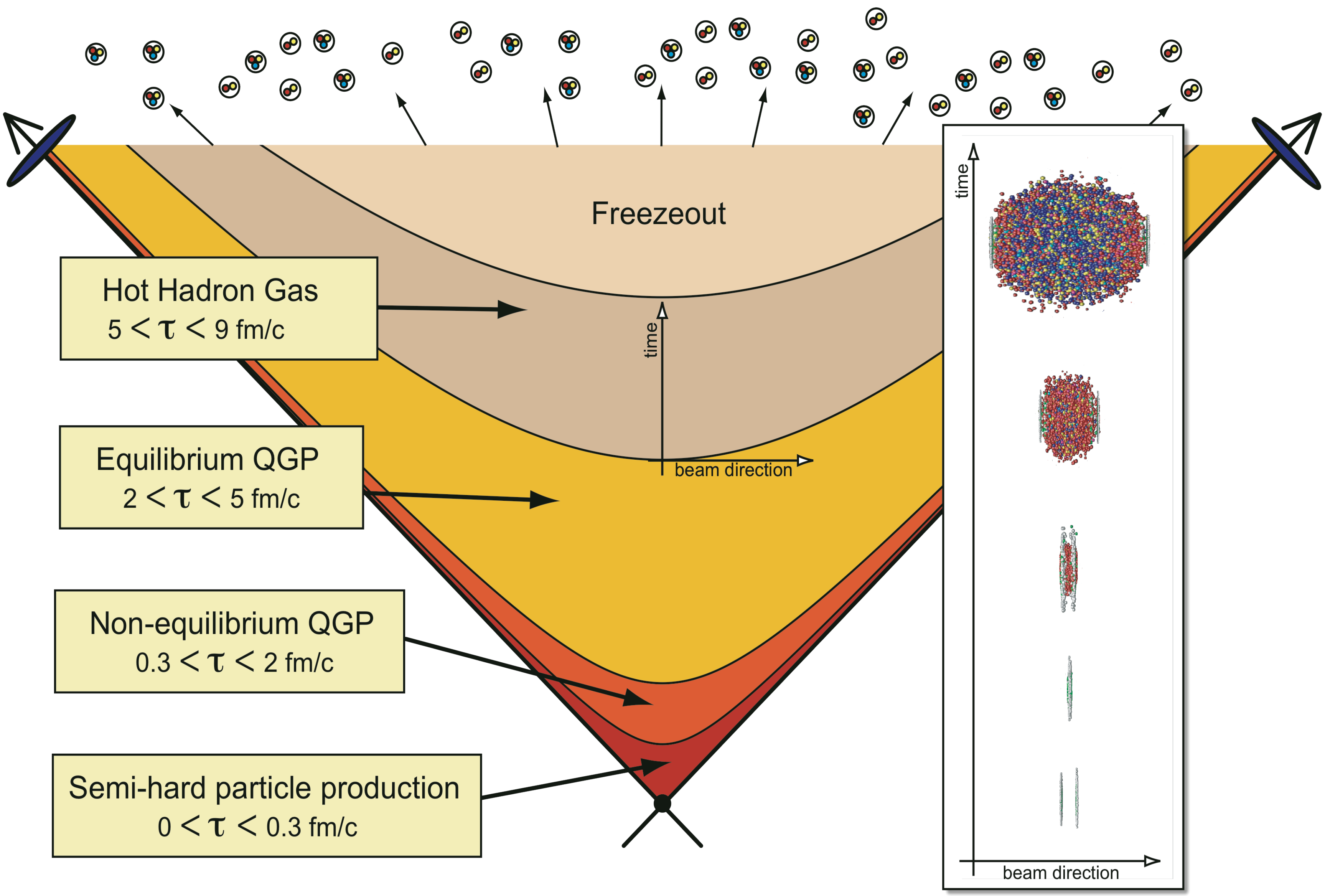
Good news and bad news

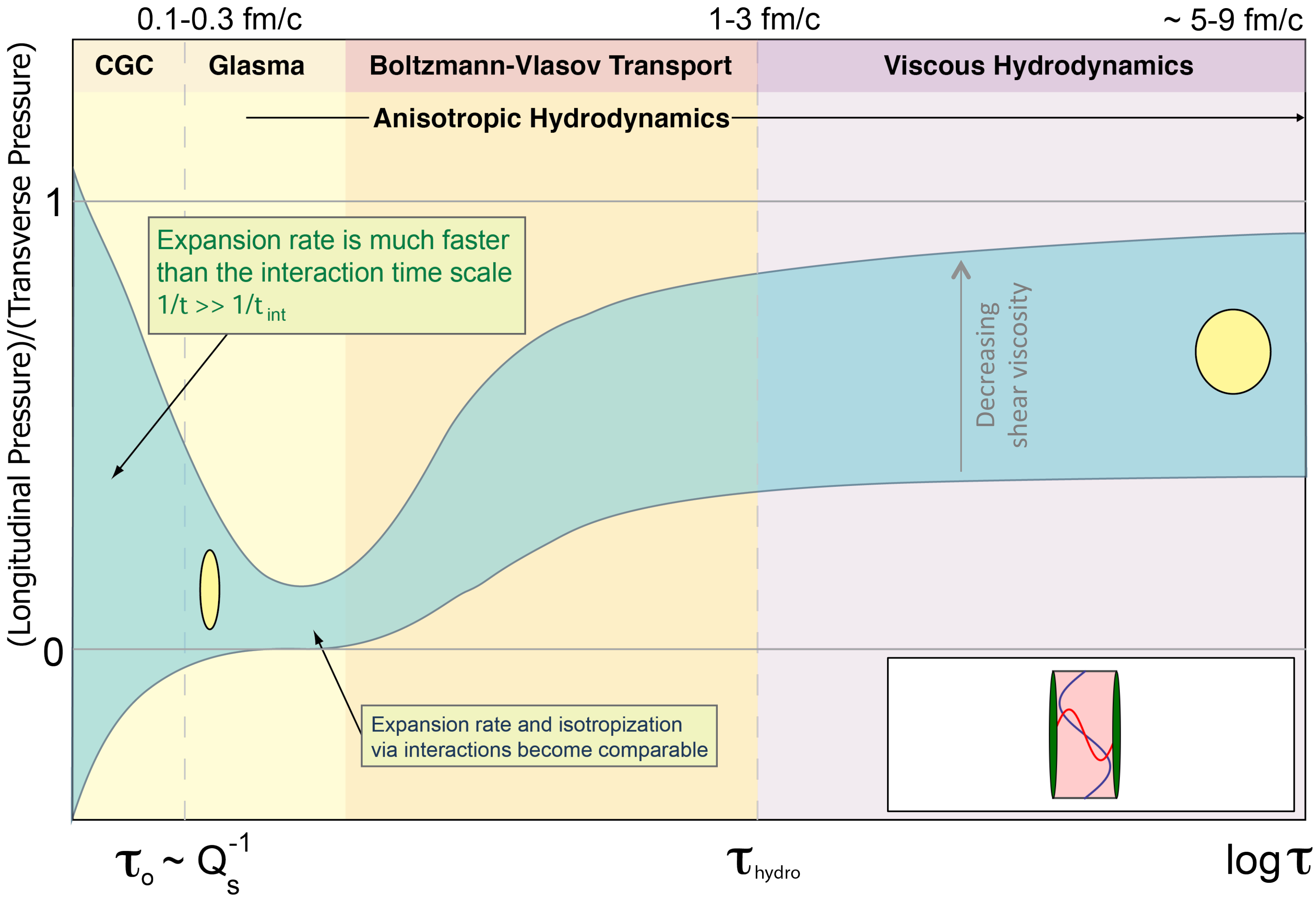
- Large binding energies → short formation times
- Formation time for Υ(1s), for example, is ~ 0.2 fm/c
- This comes at a cost: **We need to reliably model the early-time dynamics since quarkonia are born into it**
- In addition, production vertices can be anywhere in the transverse plane, not just the central hottest region
- For example, for a central collision the most probable <r> ~ 3.2 fm
- **Therefore, we also need to reliably describe the dynamics in the full transverse plane**



LHC Heavy Ion Collision Timescales

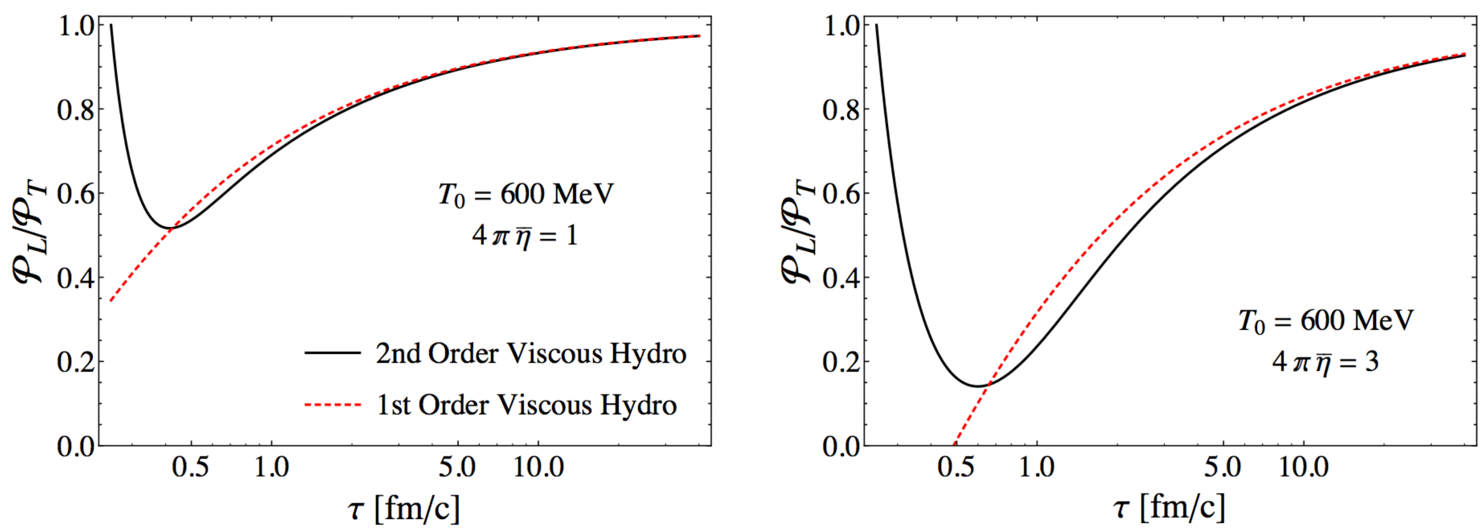


QGP momentum anisotropy cartoon



Estimating Early-time Pressure Anisotropy

- CGC @ leading order predicts negative → approximately zero longitudinal pressure
- QGP scattering + plasma instabilities work to drive the system towards isotropy on the fm/c timescale, but do not fully restore it
- Viscous hydrodynamics predicts early-time anisotropies ≤ 0.35 → 0.5
- AdS-CFT dynamical calculations in the strong coupling limit predict anisotropies of ≤ 0.3



Estimating Early-time Pressure Anisotropy

- CGC @ leading order predicts negative → approximately zero longitudinal pressure
- QGP scattering + plasma instabilities work to drive the system <u>towards</u> isotropy on the fm/c timescale, but do not fully restore it
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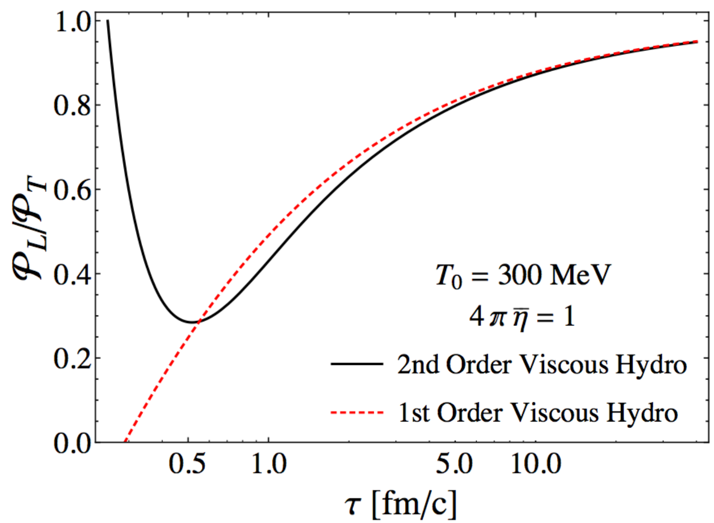
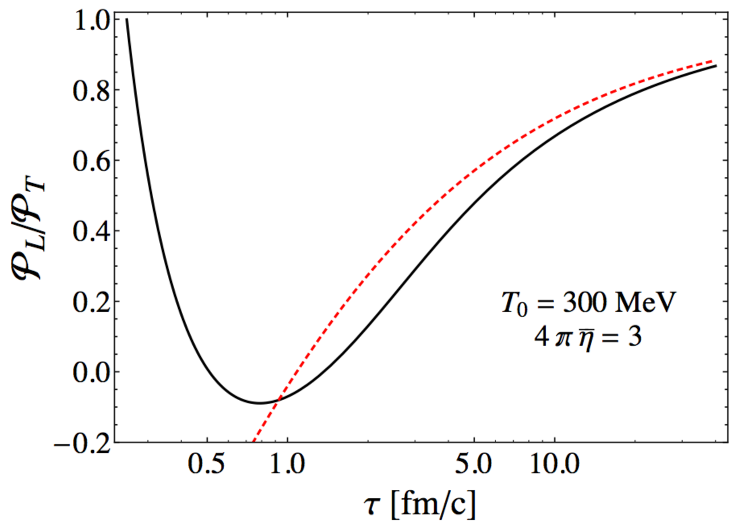




Estimating Anisotropy – AdS/CFT

- In the 0+1d case there are numerical solutions of Einstein's equations to compare with.
  Heller, Janik, and Witaszczyk, 1103.3452
  see also Chesler and Yaffe, 1011.3562

- They studied a wide variety of initial conditions and found a kind of universal lower bound for the thermalization time.

RHIC 200 GeV/nucleon:
T_0 = 350 MeV, τ_0 > 0.35 fm/c

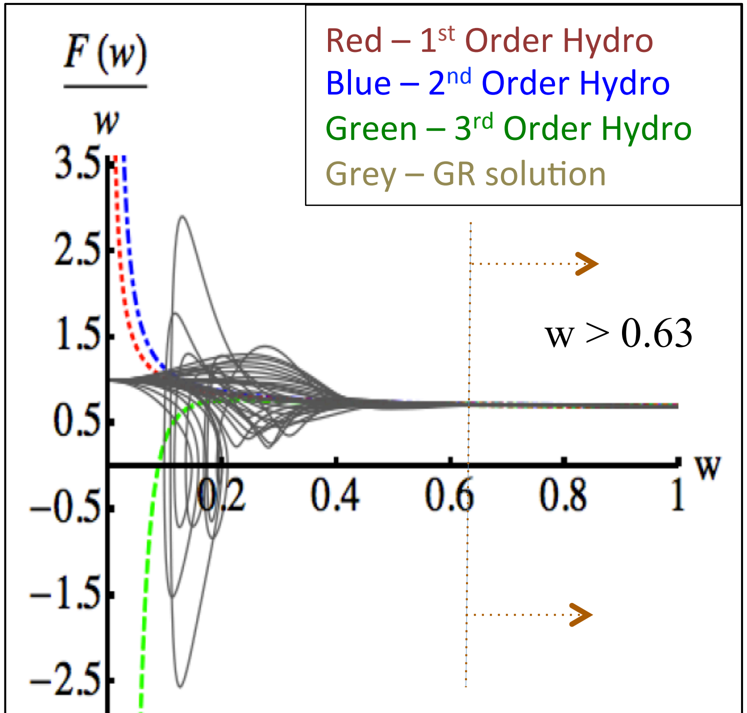
LHC 2.76 TeV/nucleon:
T_0 = 600 MeV, τ_0 > 0.2 fm/c

$$\langle T_{\tau\tau}\rangle \equiv \varepsilon(\tau) \equiv N_c^2 \cdot \frac{3}{8}\pi^2 \cdot T_{eff}^4 \cdot$$

$$w = T_{eff} \cdot \tau$$

$$\frac{\tau}{w}\frac{d}{d\tau}w = \frac{F_{hydro}(w)}{w},$$

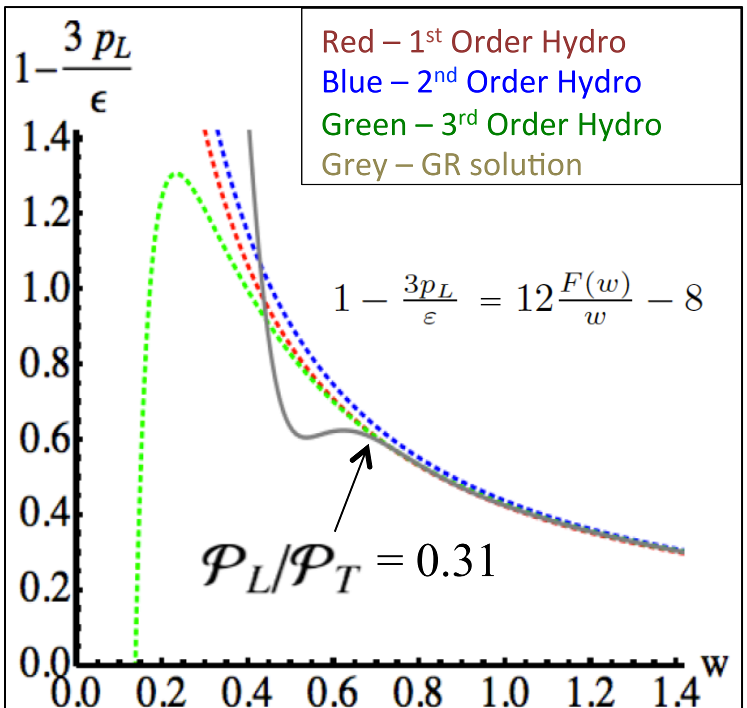
F_{hydro} known up to 3rd order hydro analytically



Heller, Janik, and Witaszczyk, 1103.3452

N=4 SUSY using AdS/CFT

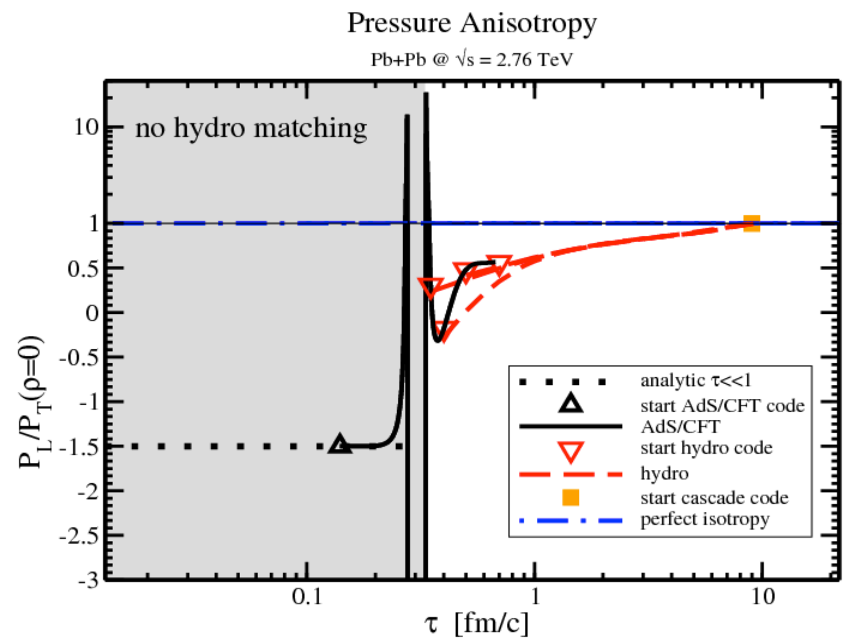
However, at that time the system is not isotropic and it remains anisotropic for the entirety of the evolution



Heller, Janik, and Witaszczyk, 1103.3452

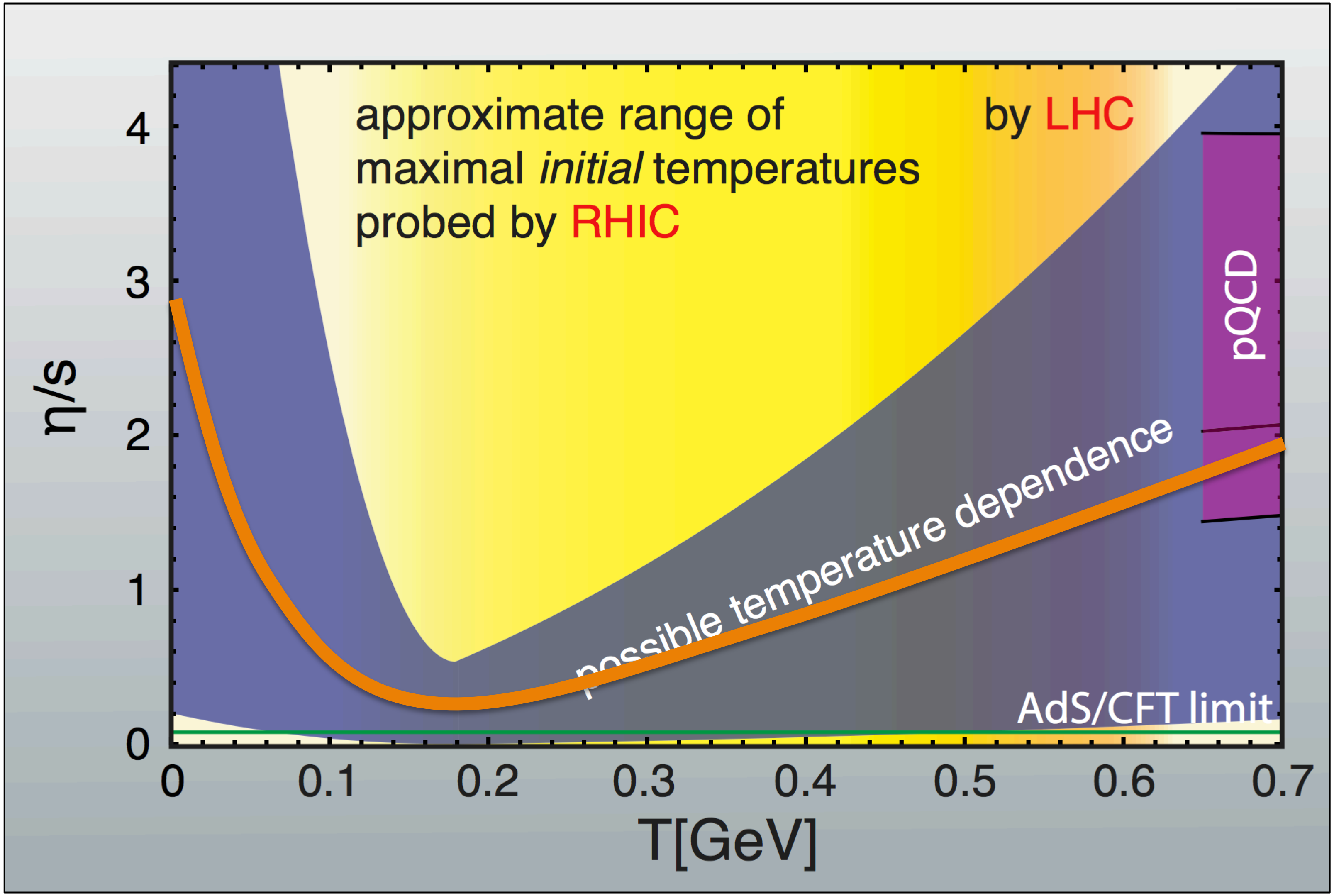
Other AdS/CFT numerical studies which include transverse expansion reach a similar conclusion

van der Schee et al. 1307.2539



See also J. Casalderrey-Solana et al. arXiv: 1305.4919

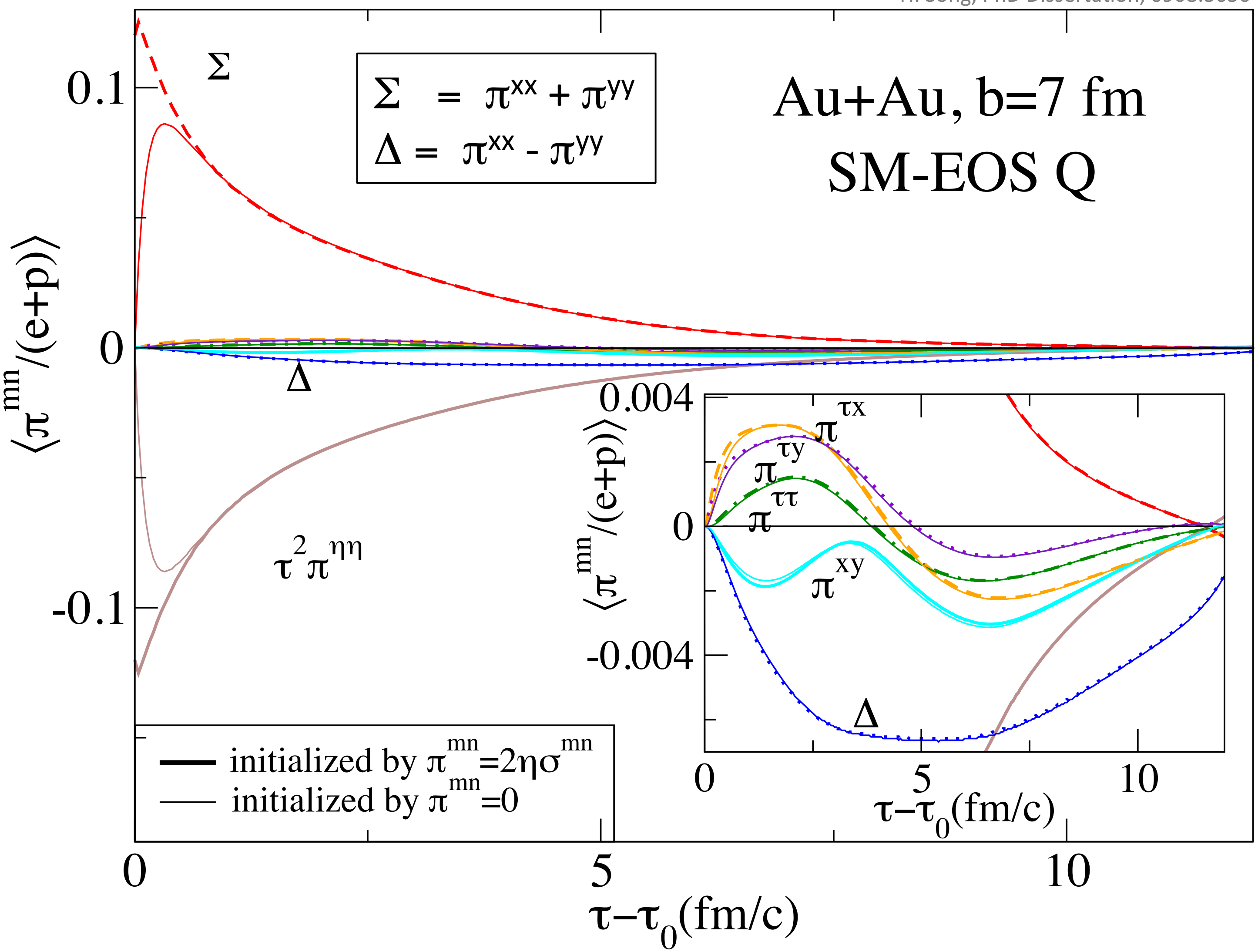
Temperature dependence of η/S



Hot and Dense QCD Matter, Community Whitepaper 2014

Hints from Viscous Hydro

H. Song, PhD Dissertation, 0908.3656



Anisotropic Hydrodynamics Basics

M. Martinez and MS, 1007.0889
W. Florkowski and R. Ryblewski, 1007.0130

Viscous Hydrodynamics Expansion

$$f(\tau,\mathbf{x},\mathbf{p}) = \underline{f_{\rm eq}(\mathbf{p},T(\tau,\mathbf{x}))} + \delta f$$

Isotropic in momentum space

Anisotropic Hydrodynamics Expansion

Treat this term "perturbatively"

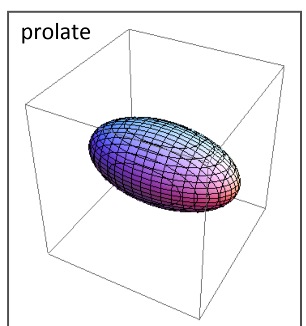
D. Bazow, U. Heinz, and MS, 1311.6720

$$f(\tau,\mathbf{x},\mathbf{p}) = f_{\rm aniso}(\mathbf{p}, \underbrace{\Lambda(\tau,\mathbf{x})}_{T_\perp}, \underbrace{\xi(\tau,\mathbf{x})}_{\text{anisotropy}}\,) + \delta\tilde{f}$$

→ "Romatschke-Strickland" form in LRF

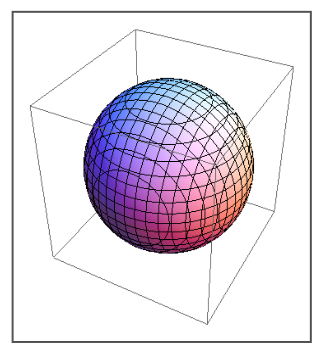
$$f_{\rm aniso}^{LRF} = f_{\rm iso}\left(\frac{\sqrt{\mathbf{p}^2+\xi(\mathbf{x},\tau)p_z^2}}{\Lambda(\mathbf{x},\tau)}\right)$$

$$\xi = \frac{\langle p_T^2\rangle}{2\langle p_L^2\rangle} - 1$$



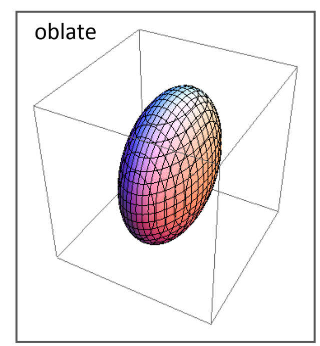
$-1 < \xi < 0$

$\mathcal{P}_L > \mathcal{P}_T$



$\xi = 0$

$\mathcal{P}_L = \mathcal{P}_T$



$\xi > 0$

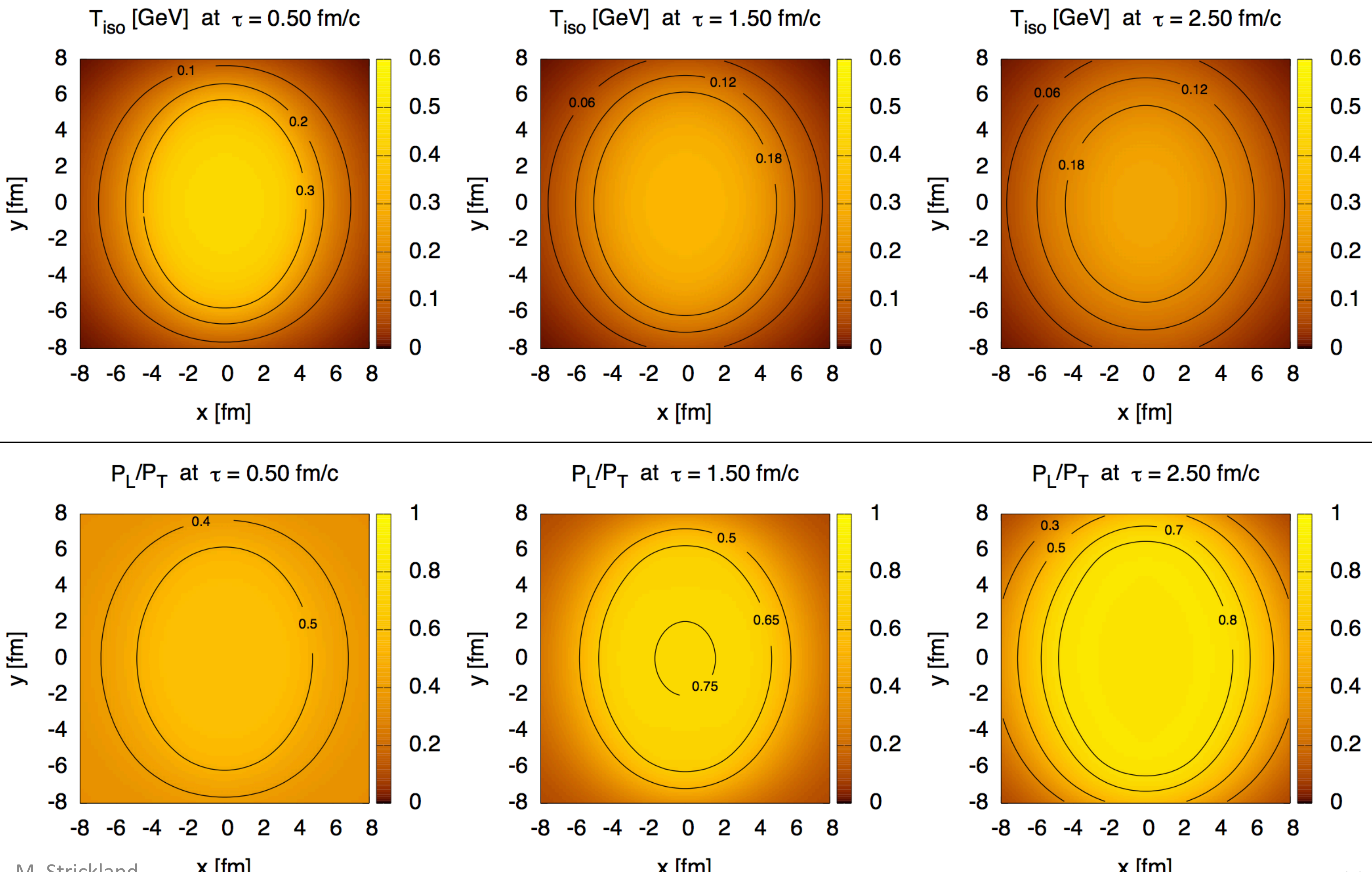
$\mathcal{P}_L < \mathcal{P}_T$

Transverse Dynamics

M. Martinez, R. Ryblewski, and MS, 1204.1473

Pb-Pb @ 2.76 TeV
T_0 = 600 MeV
τ_0 = 0.25 fm/c
b = 7 fm

$$\frac{\eta}{\mathcal{S}} = \frac{1}{4\pi}$$



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M. Martinez, R. Ryblewski, and MS, 1204.1473

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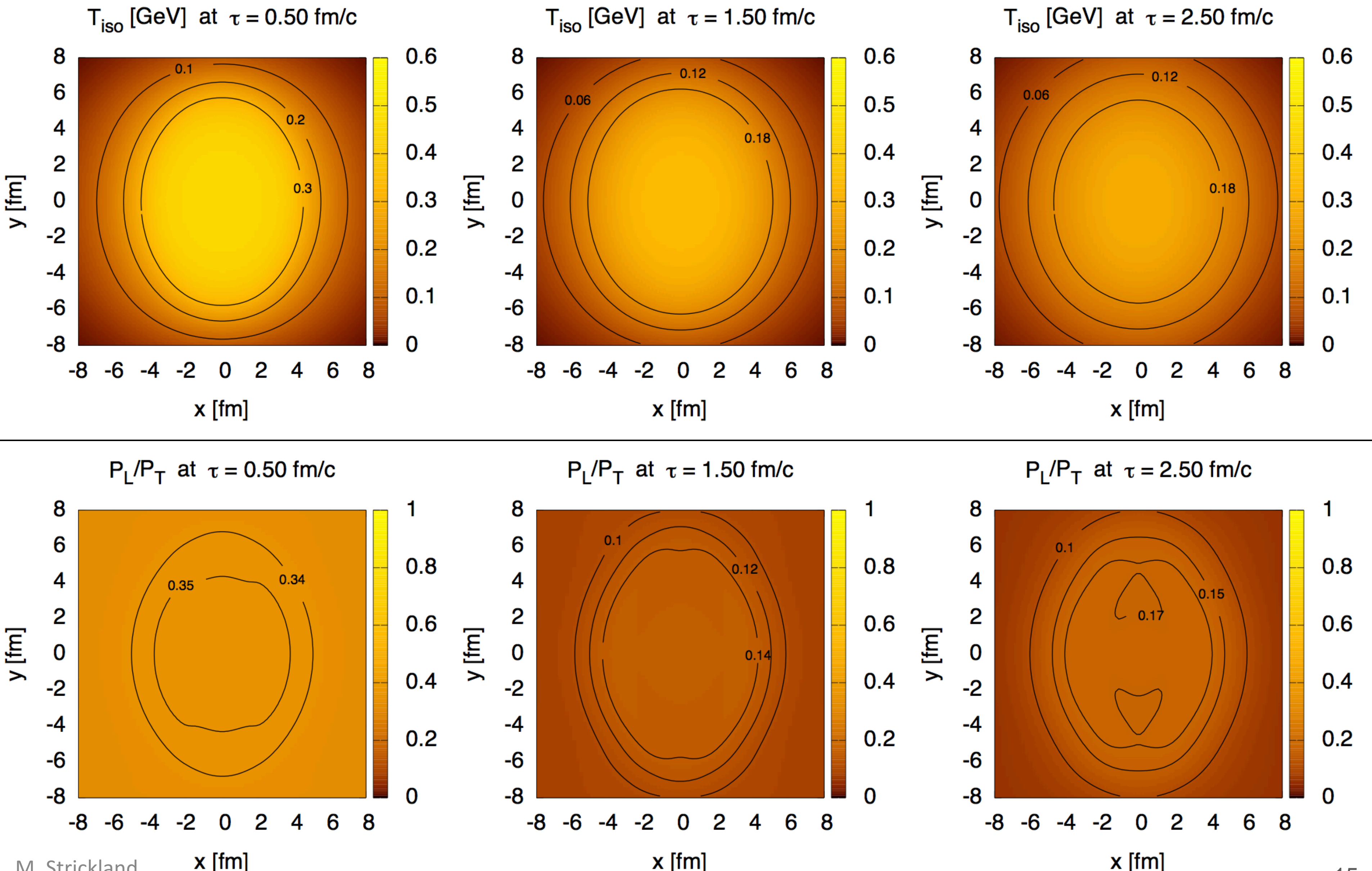

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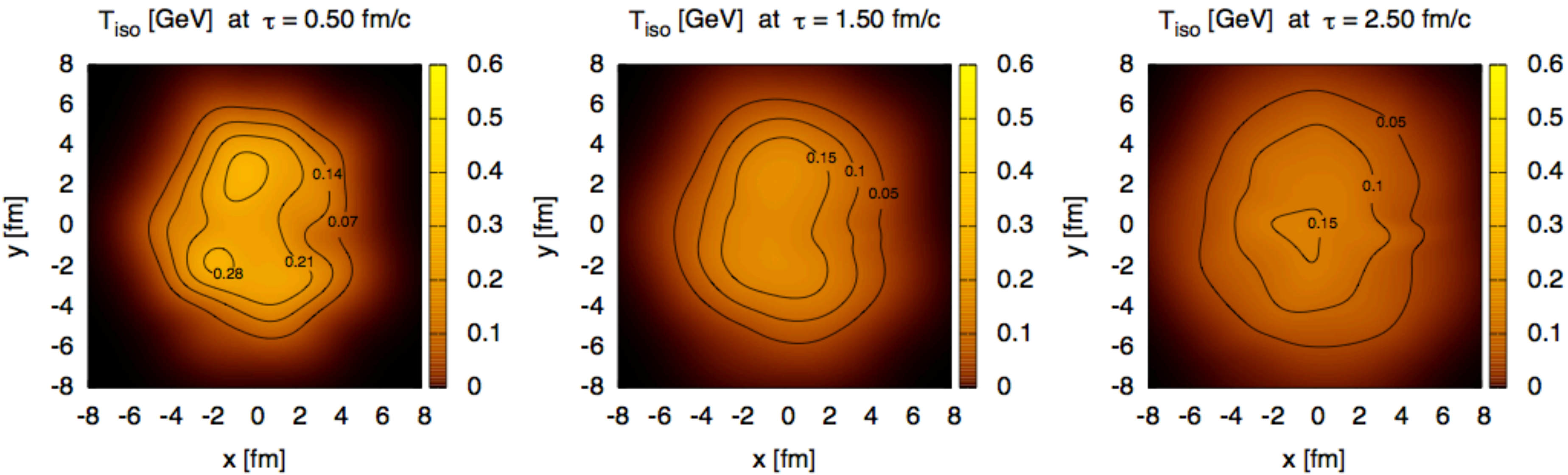
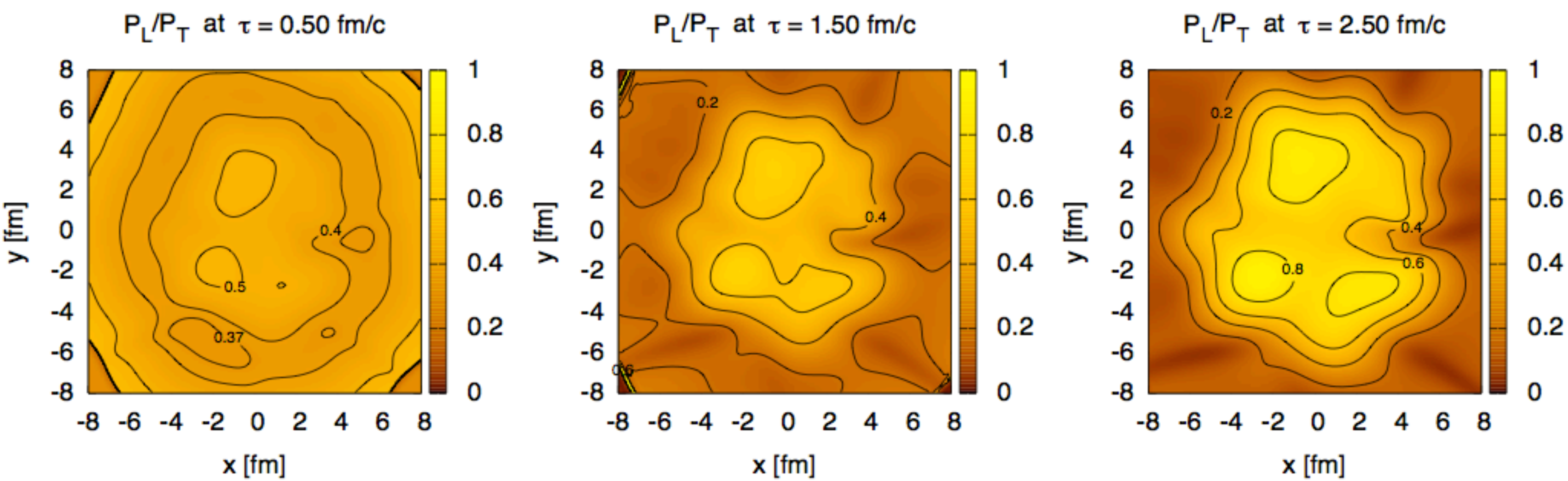




Anisotropic Heavy Quark Potential

Using the real-time formalism one can express the potential in terms of the *static* advanced, retarded, and Feynman propagators

$$V(\mathbf{r},\xi) = -g^2 C_F \int \frac{d^3\mathbf{p}}{(2\pi)^3}\,(e^{i\mathbf{p}\cdot\mathbf{r}}-1)\frac{1}{2}\left(D^{*L}_{R} + D^{*L}_{A} + D^{*L}_{F}\right)$$

Real part can be written as

$$\mathrm{Re}[V(\mathbf{r},\xi)] = -g^2 C_F \int \frac{d^3\mathbf{p}}{(2\pi)^3}\,e^{i\mathbf{p}\cdot\mathbf{r}}\,\frac{\mathbf{p}^2 + m_\alpha^2 + m_\gamma^2}{(\mathbf{p}^2 + m_\alpha^2 + m_\gamma^2)(\mathbf{p}^2 + m_\beta^2) - m_\delta^4}$$

With <u>direction-dependent masses</u>, e.g.

$$m_\alpha^2 = -\frac{m_D^2}{2p_\perp^2\sqrt{\xi}}\left(p_z^2 \arctan\sqrt{\xi} - \frac{p_z \mathbf{p}^2}{\sqrt{\mathbf{p}^2+\xi p_\perp^2}}\arctan\frac{\sqrt{\xi}p_z}{\sqrt{\mathbf{p}^2+\xi p_\perp^2}}\right)$$

Anisotropic potential calculation: Dumitru, Guo, and MS, 0711.4722 and 0903.4703
Gluon propagator in an anisotropic plasma: Romatschke and MS, hep-ph/0304092

Full anisotropic potential

- Result can be parameterized as a Debye-screened potential with a direction-dependent Debye mass
- The potential also has an imaginary part coming from the Landau damping of the exchanged gluon!
- This imaginary part also exists in the isotropic case
  Laine et al hep-ph/0611300
- Used this as a model for the free energy (F) and also obtained internal energy (U) from this.

$$V_{\rm screened}(r,\theta,\xi,\Lambda) = -C_F \alpha_s \frac{e^{-\mu(\theta,\xi,\Lambda) r}}{r}$$

D Bazow and MS, 1112.2761; MS, 1106.2571.

Internal Energy

$$V_{\rm R}(\mathbf{r}) = -\frac{\alpha}{r}\,(1+\mu\,r)\exp\left(-\mu\,r\right) + \frac{2\sigma}{\mu}\left[1-\exp\left(-\mu\,r\right)\right] - \sigma\,r\,\exp(-\mu\,r) - \frac{0.8\,\sigma}{m_Q^2\,r}$$

Dumitru, Guo, Mocsy, and MS, 0901.1998

$$V_{\rm I}(\mathbf{r}) = -C_F \alpha_s p_{\rm hard}\left[\phi(\hat{r}) - \xi\left(\psi_1(\hat{r},\theta)+\psi_2(\hat{r},\theta)\right)\right]$$

Dumitru, Guo, and MS, 0711.4722 and 0903.4703
Burnier, Laine, Vepsalainen, arXiv:0903.3467 (aniso)

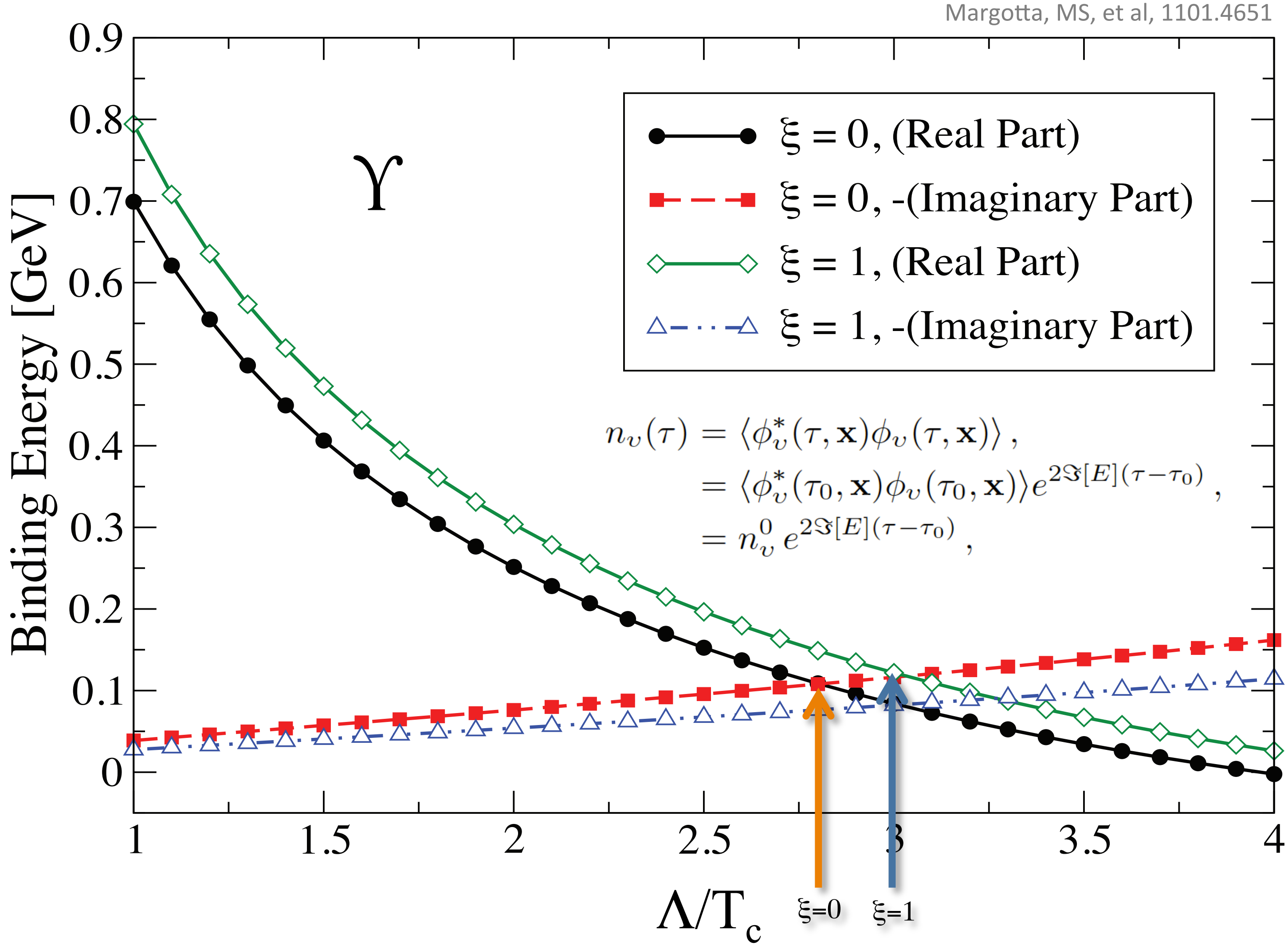
Solve the 3d Schrödinger EQ with complex-valued potential

Margotta, MS, et al, 1101.4651

Obtain real and imaginary parts of the binding energies for the $\Upsilon(1s)$, $\Upsilon(2s)$, $\Upsilon(3s)$, χ_{b1}, and χ_{b2}

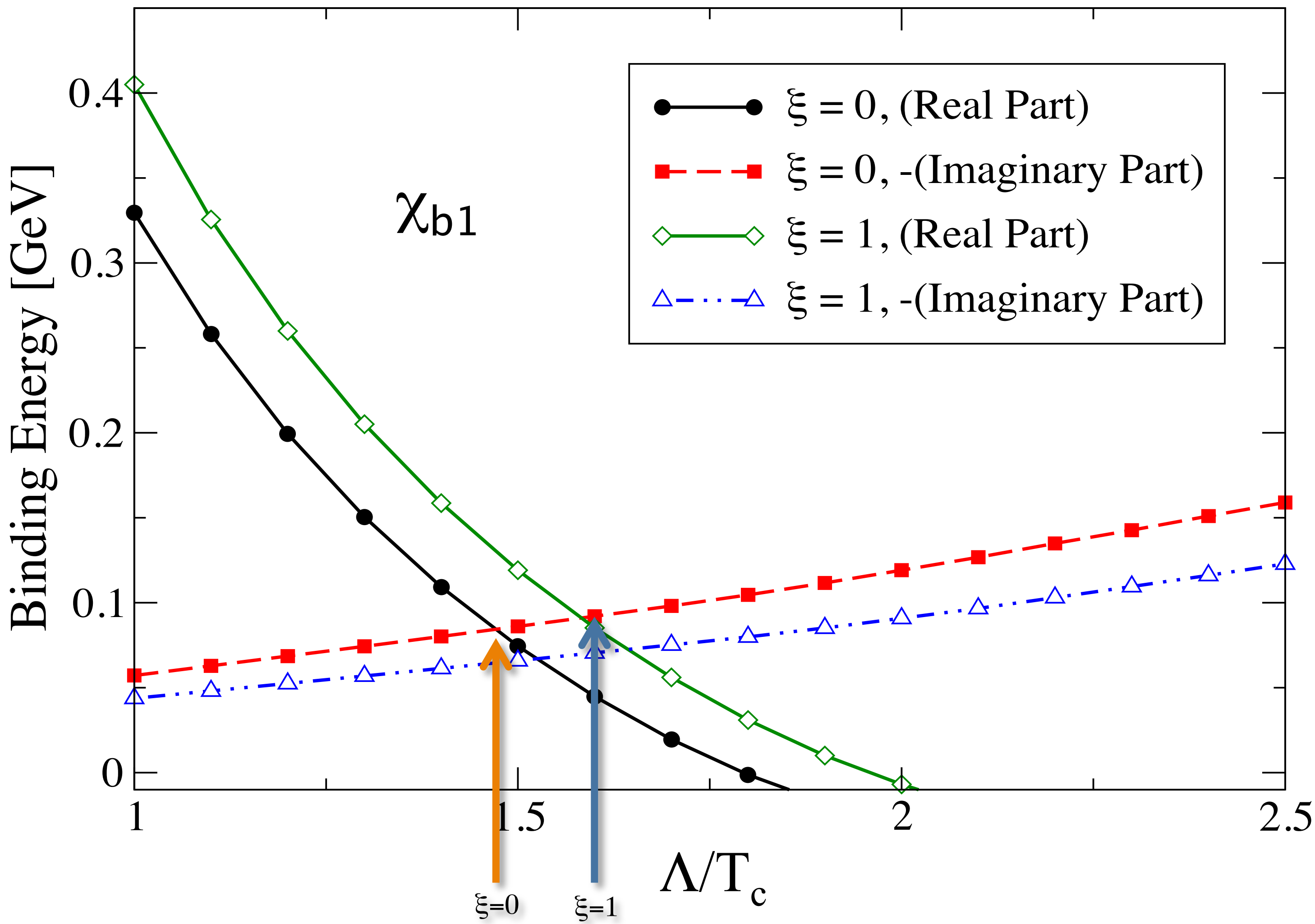
Results for the Υ(1s) binding energy

Margotta, MS, et al, 1101.4651



Results for the χ_{b1} binding energy

Margotta, MS, et al, 1101.4651

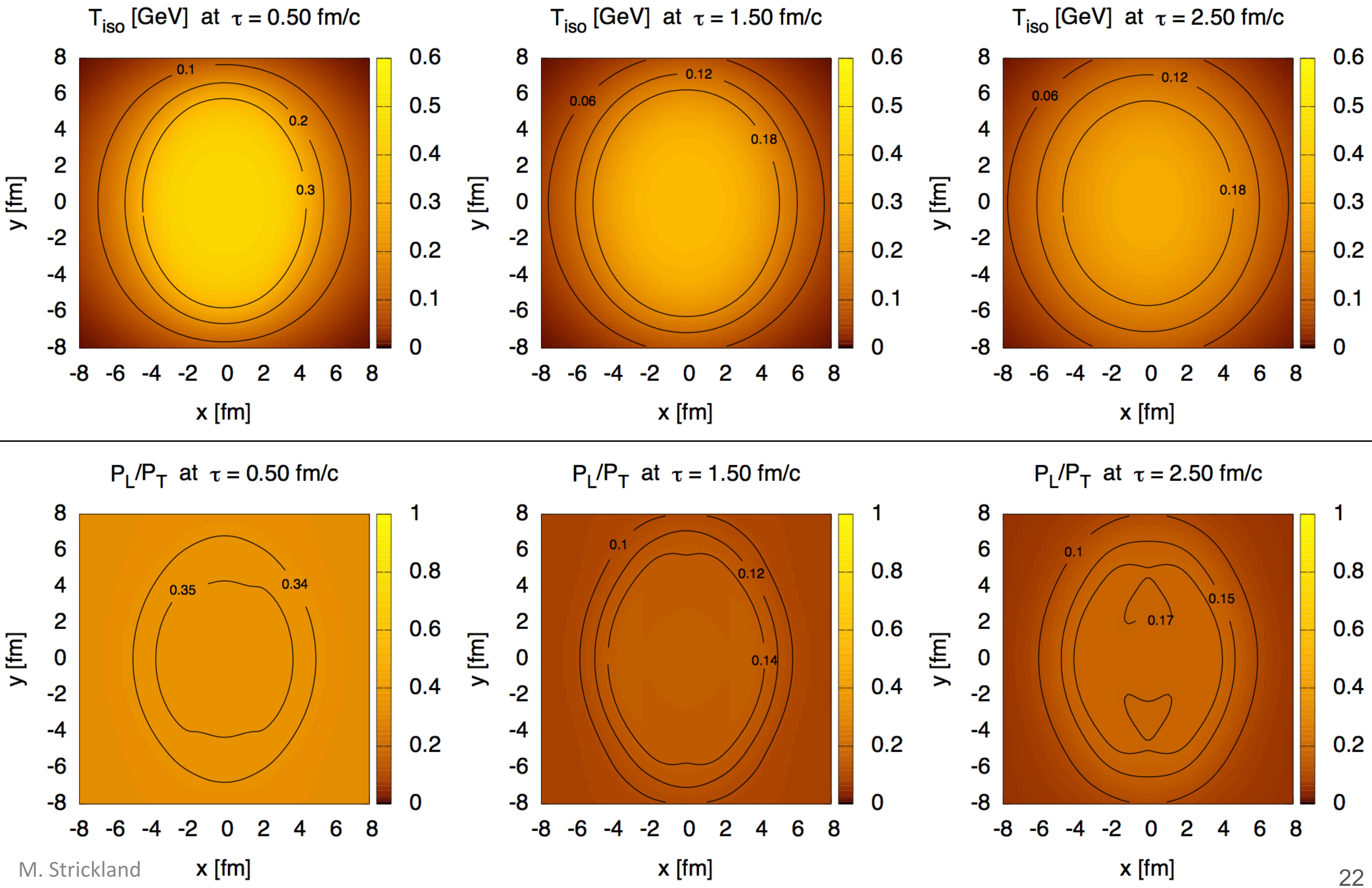


Spatiotemporal Evolution

M. Martinez, R. Ryblewski, and MS, 1204.1473

Pb-Pb @ 2.76 TeV
T_0 = 600 MeV
τ_0 = 0.25 fm/c
b = 7 fm

$$\frac{\eta}{\mathcal{S}} = \frac{10}{4\pi}$$



The suppression factor

- Resulting decay rate $\Gamma_T \equiv -2\,\mathrm{Im}[E_{bind}]$ is a function of τ, $x_\perp$, and ς (spatial rapidity). First we need to integrate over proper time

$$\bar{\gamma}(\mathbf{x}_\perp, p_T, \varsigma, b) \equiv \int_{\max(\tau_{\rm form}(p_T),\tau_0)}^{\tau_f} d\tau\, \Gamma_T(\tau, \mathbf{x}_\perp, \varsigma, b)$$

- From this we can extract R_{AA}

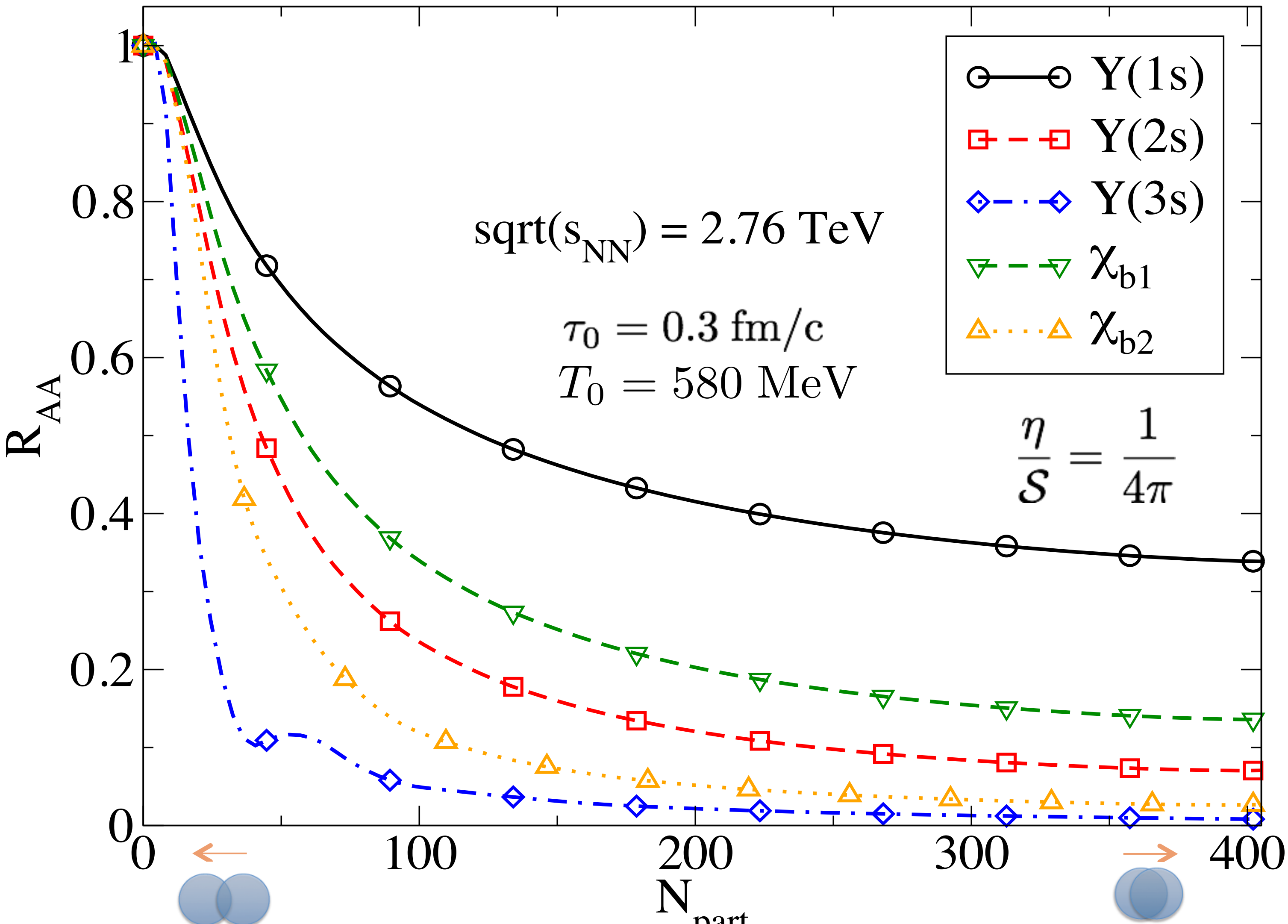
$$R_{AA}(\mathbf{x}_\perp, p_T, \varsigma, b) = \exp(-\bar{\gamma}(\mathbf{x}_\perp, p_T, \varsigma, b))$$

- Use the overlap density as the probability distribution function for quarkonium production vertices and geometrically average

$$\langle R_{AA}(p_T, \varsigma, b)\rangle \equiv \frac{\int_{\mathbf{x}_\perp} d\mathbf{x}_\perp\, T_{AA}(\mathbf{x}_\perp)\, R_{AA}(\mathbf{x}_\perp, p_T, \varsigma, b)}{\int_{\mathbf{x}_\perp} d\mathbf{x}_\perp\, T_{AA}(\mathbf{x}_\perp)}$$

State Suppression Factors, $R_{AA}{}^{i}$

D Bazow and MS, Nucl. Phys. A 879, 25 (2012); MS, PRL 107, 132301 (2011).



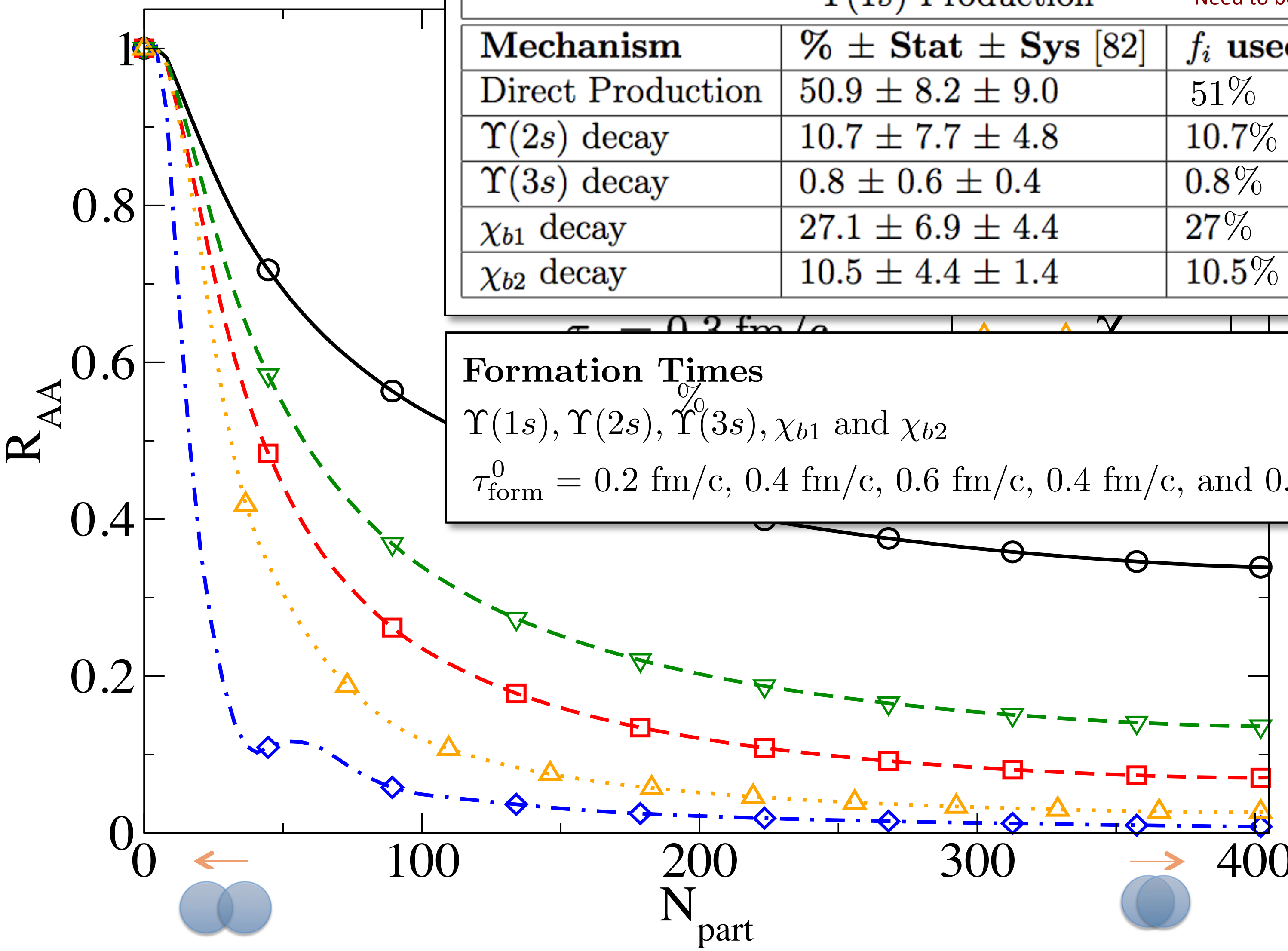
State Suppression Factors, $R_{AA}{}^{i}$

$\Upsilon(1s)$ Production		Need to be updated now!
Mechanism	**% ± Stat ± Sys [82]**	**f_i used herein**
Direct Production	50.9 ± 8.2 ± 9.0	51%
$\Upsilon(2s)$ decay	10.7 ± 7.7 ± 4.8	10.7%
$\Upsilon(3s)$ decay	0.8 ± 0.6 ± 0.4	0.8%
χ_{b1} decay	27.1 ± 6.9 ± 4.4	27%
χ_{b2} decay	10.5 ± 4.4 ± 1.4	10.5%

Formation Times

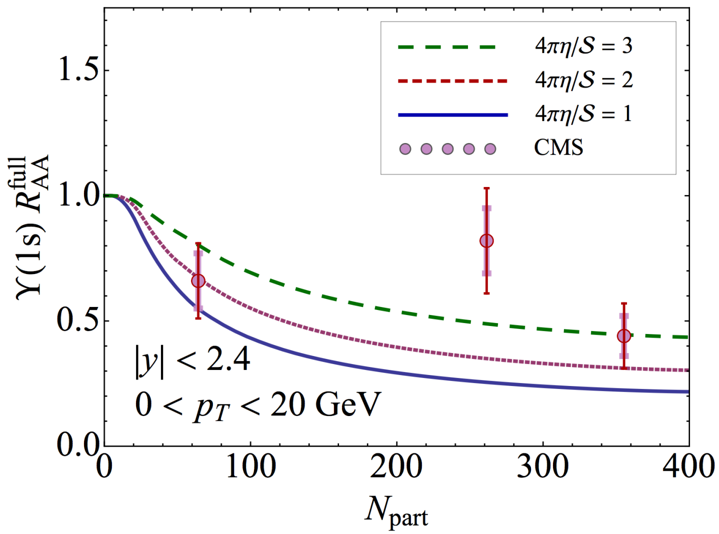
$\Upsilon(1s)$, $\Upsilon(2s)$, $\Upsilon(3s)$, χ_{b1} and χ_{b2}

$\tau^0_{\rm form}$ = 0.2 fm/c, 0.4 fm/c, 0.6 fm/c, 0.4 fm/c, and 0.6 fm/c

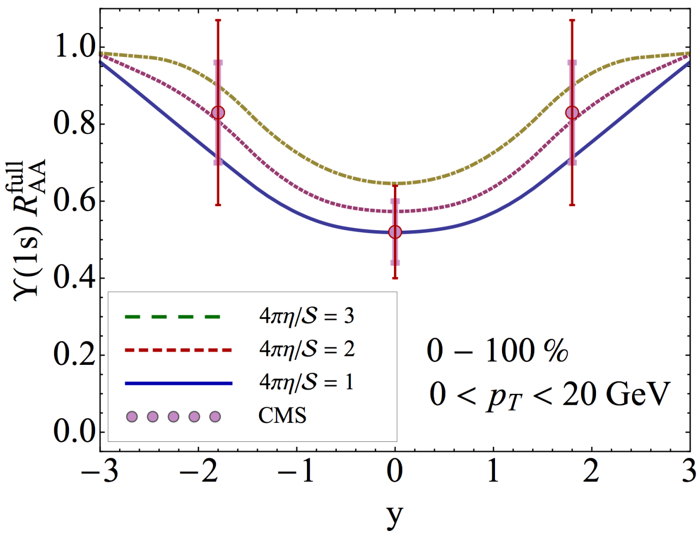


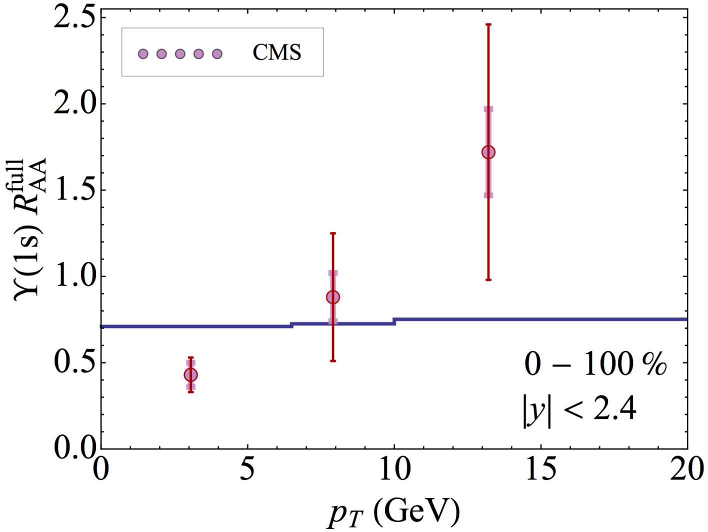
Inclusive Bottomonium Suppression

MS, PRL, arXiv:1106.2571



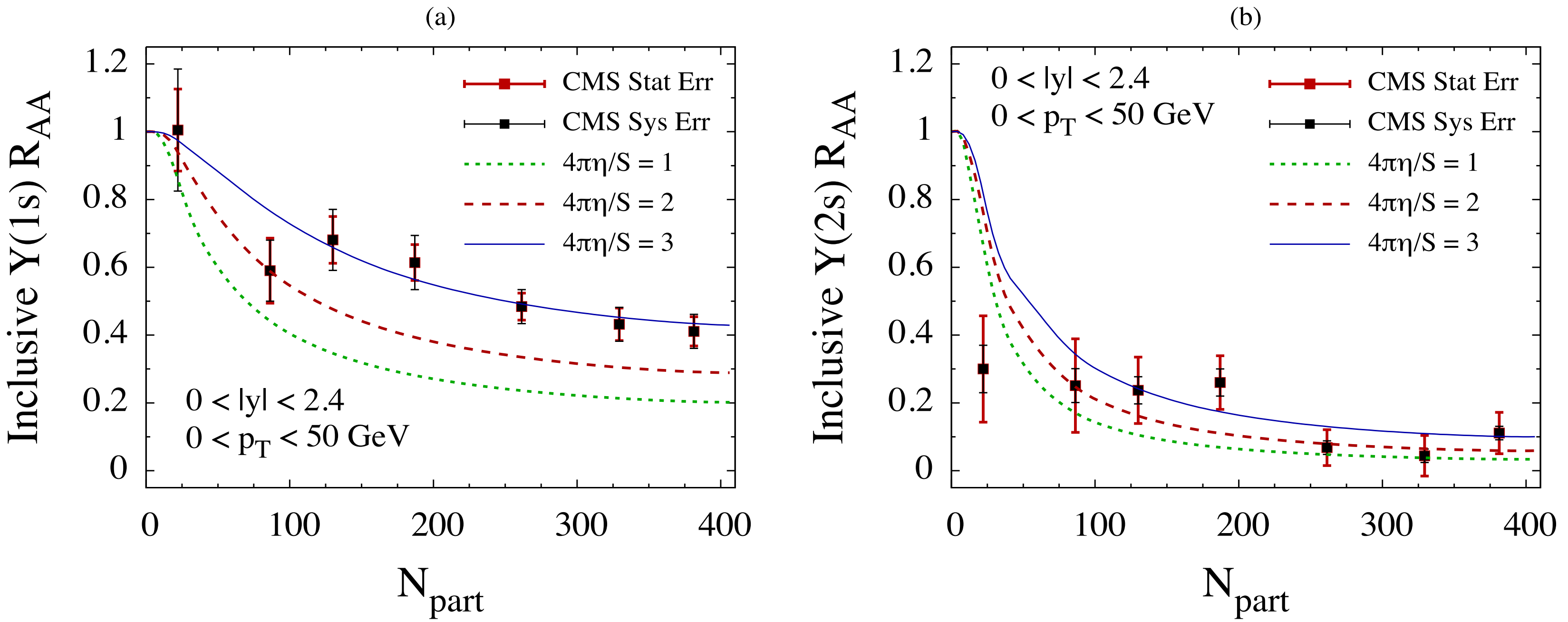
- Comparison with CMS 2010 data
- Initial temperature taken from Schenke hydro simulation fits to v_2
- For each η/S I adjusted the initial temperature to keep the final particle multiplicity fixed



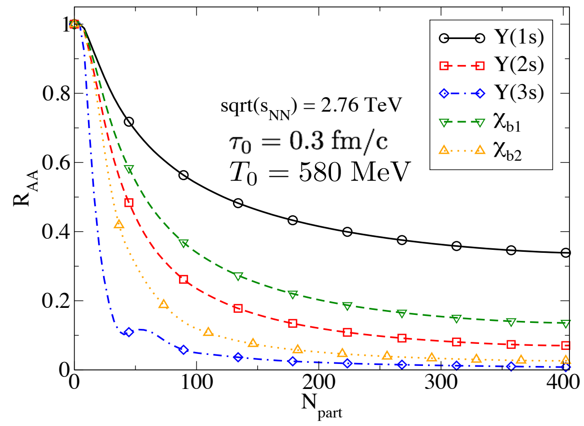


Inclusive Bottomonium Suppression

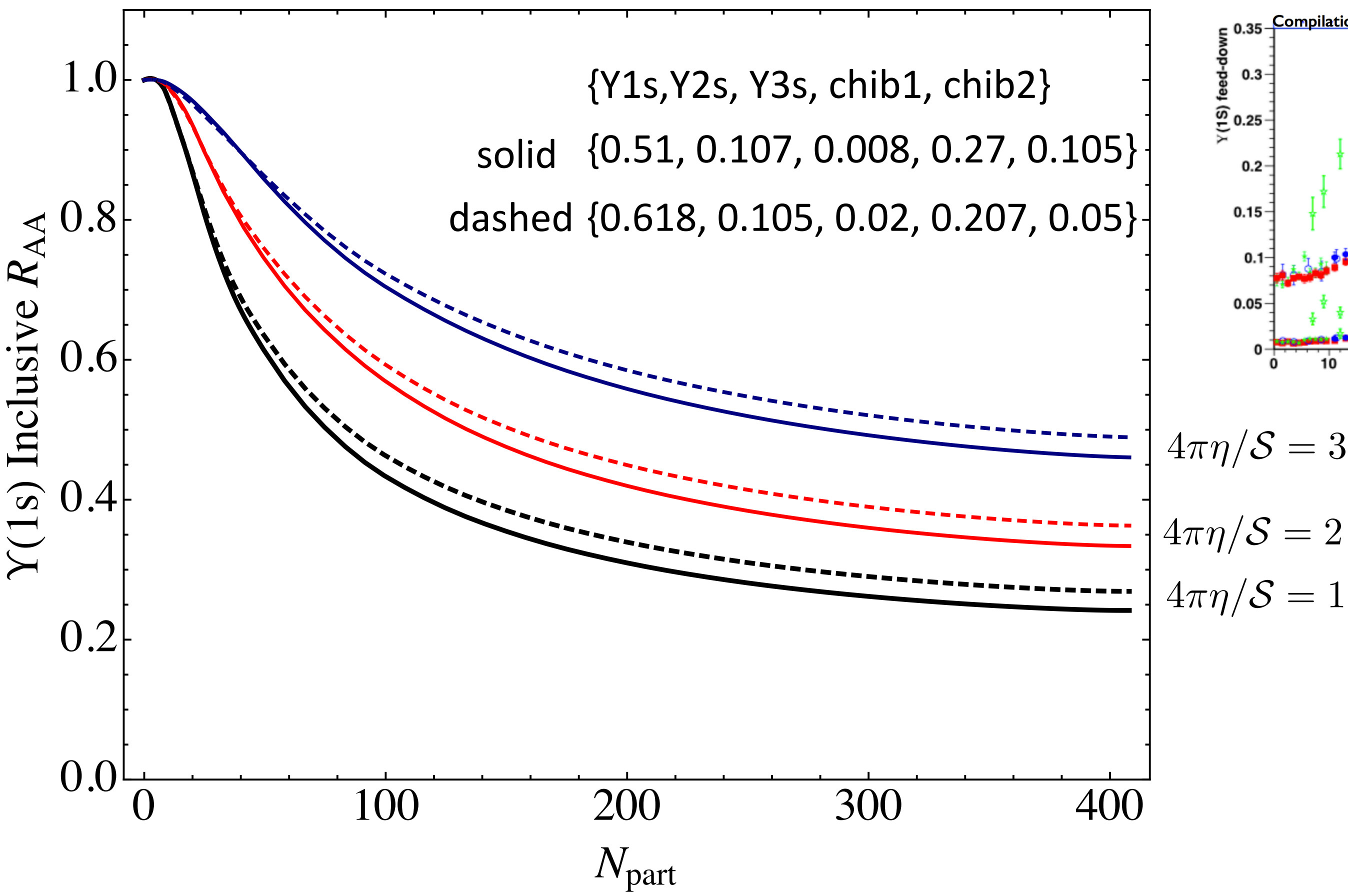
MS, arXiv:1207.5327; MS and D. Bazow, arXiv:1112.2761; MS arXiv:1106.2571

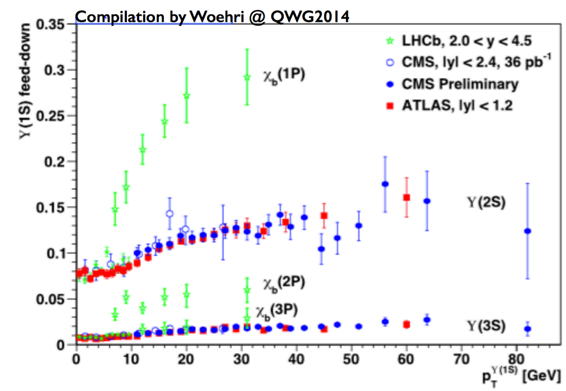


- Comparison with CMS 2011 data
- More Υ(1s) data with smaller error bars
- Υ(2s) data as well
- Would be nice to have rapidity and transverse momentum dependence from CMS

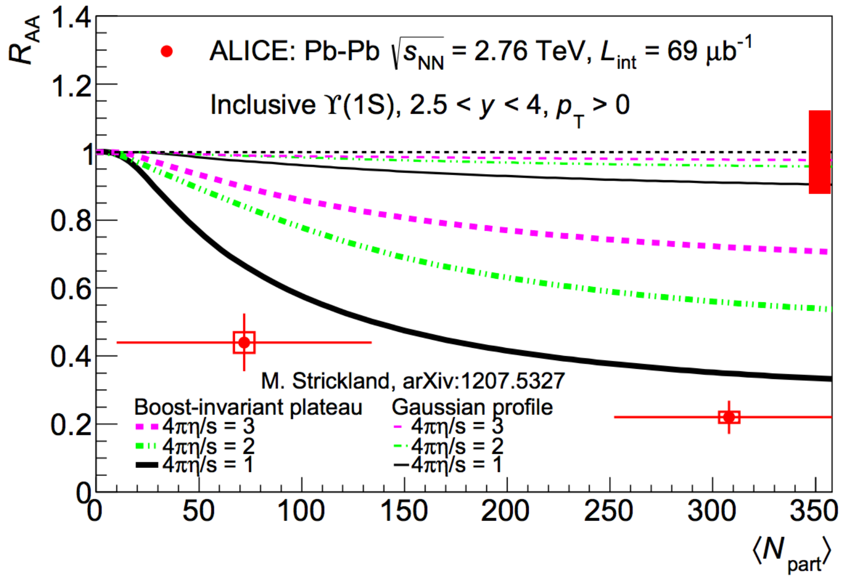


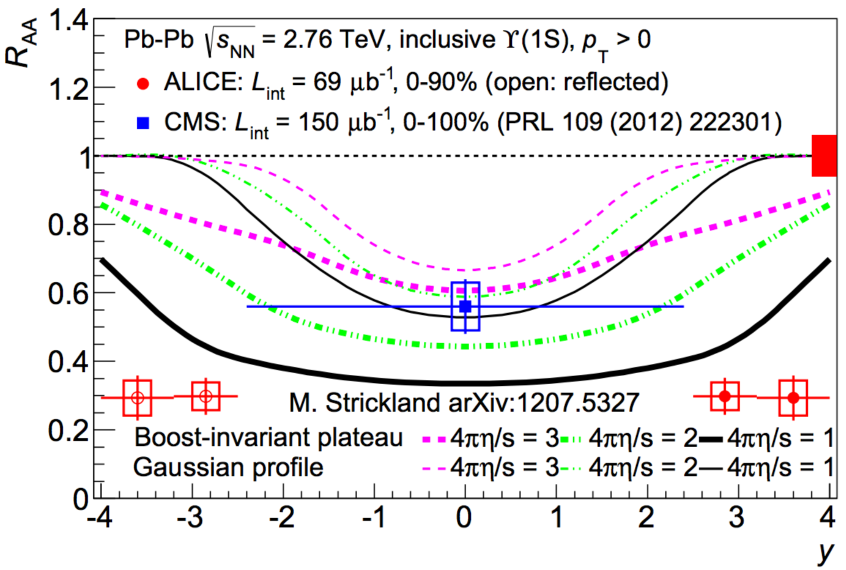
Updated feed down fractions





Conflict with ALICE forward data



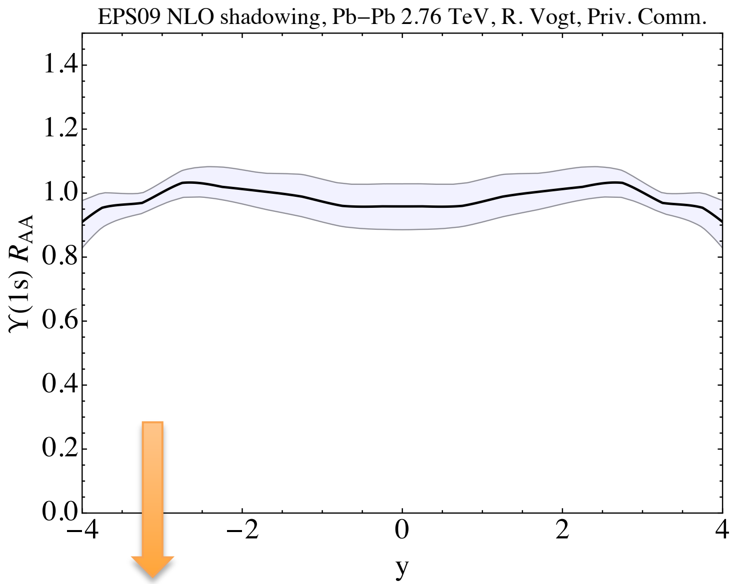


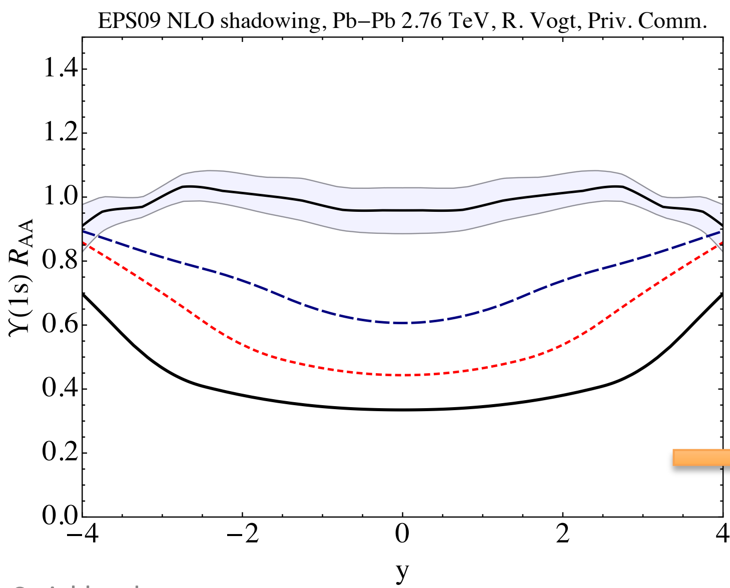
- Thermal suppression model has R_{AA} approaching 1 at forward/ backward rapidity since there one has T → 0
- Using a Gaussian rapidity profile (*Landau-hydro inspired*) does not even come close to the data
- Using a Bjorken-like rapidity profile gives enhanced suppression, **but also doesn't describe what is seen by ALICE!**
- **p-p reference?**

(Some of) the problems with my first calculation

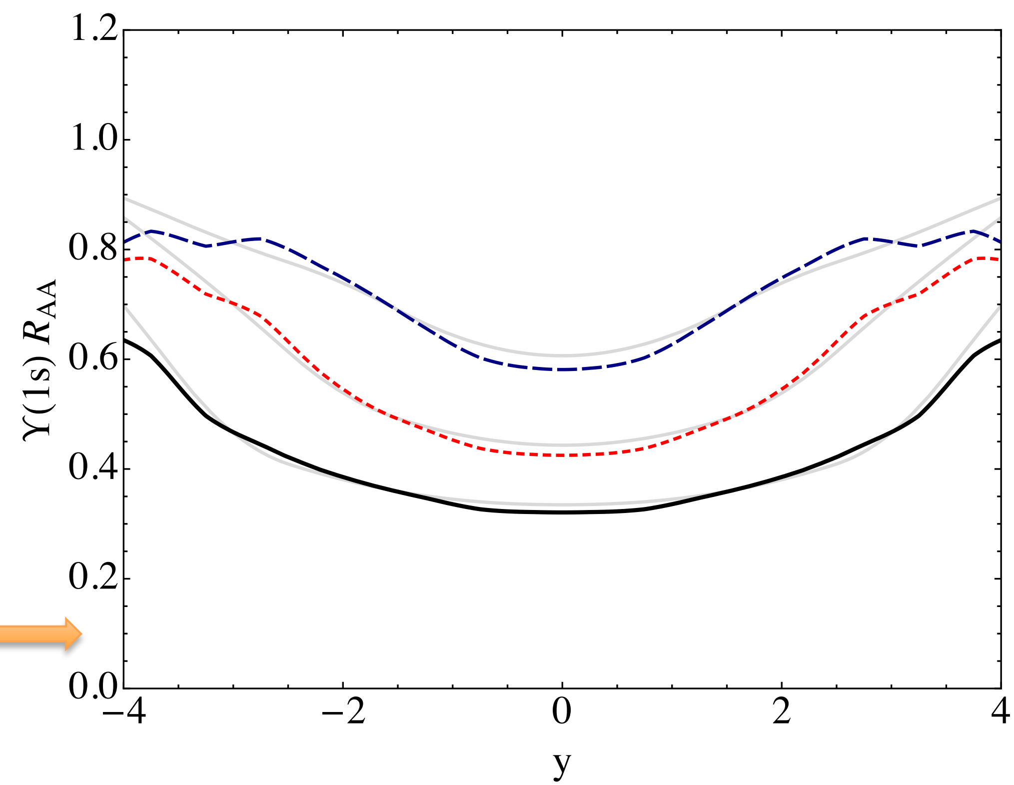
- Small anisotropy expansion used for the imaginary part of the potential [unknown level of theoretical error; IN PROGRESS]
- Dynamics was not 3+1d and I used smooth initial conditions [could be important; 3+1 with fluctuations IMPLEMENTED and being tested as we speak]
- No regeneration included [expected to be small effect <~ 10%; IN PROGRESS]
- No CNM effects [can be included straightforwardly, small effect, see next slide]
- No singlet/octet transition in Im[V] [affects all rapidities; ?]
- Simplistic model of how the anisotropy affects the long range part of the potential [unknown level of theoretical error; IN PROGRESS]
- **Speculation**: At RHIC μ_B ~ 200 MeV @ |y| ~ 3 based on statistical model fits to BRAHMS data [see e.g. Biedron and Broniowski, nucl-th/0610083]
  → increased Debye mass and enhanced suppression at forward rapidity even though T is lower
  [could be important; need experimental and theoretical input to further constrain the magnitude of the baryo-chemical potential at LHC energies]

Estimate CNM effect on Bottomonium in A-A





- Estimate of CNM using EPS09 NLO shadowing provided by R. Vogt
- Effect seems to be quite small
- This is good news for isolating the medium effect we are after, but doesn't help to explain the ALICE forward "anomaly"

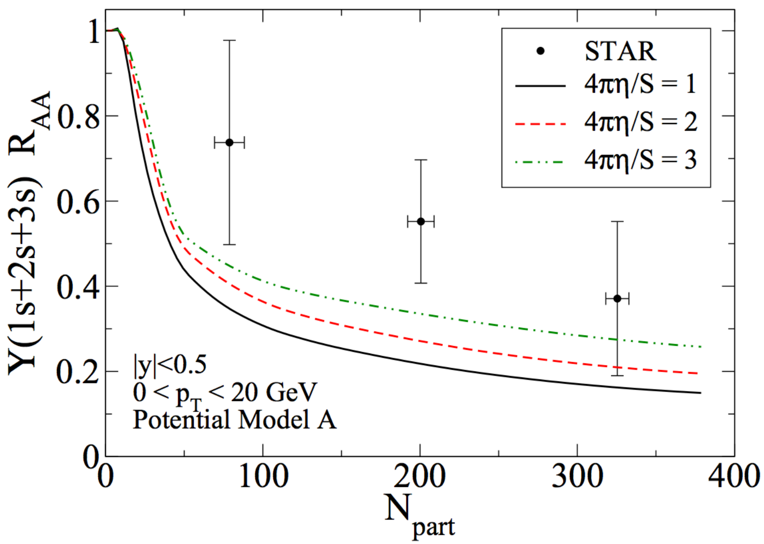


Conclusions

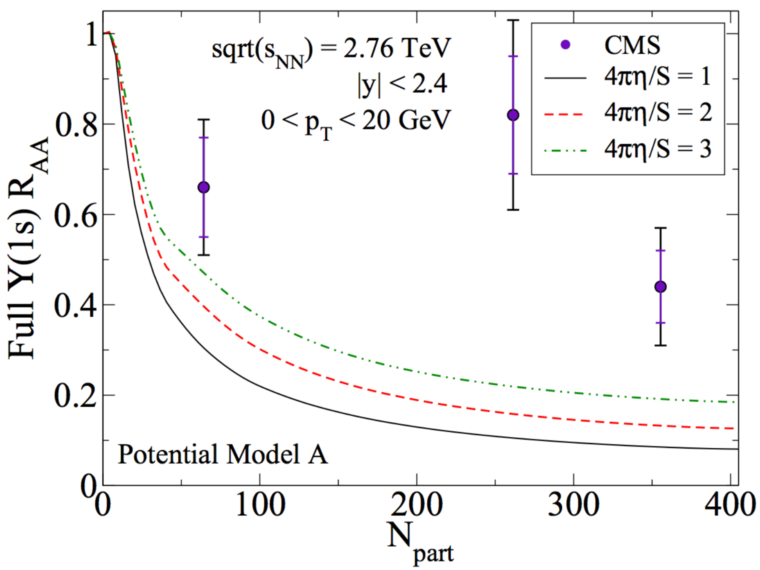
- All signs point to an momentum-space anisotropic QGP → need to self-consistently calculate rates including this fact of life
- At central rapidities, the aHydro+screening model seems to work reasonably well
- CNM effects are quite small
- For the 1s state, there is a large dependence on the assumed value of η/s
- This offers the possibility to constrain η/s using bottomonia R_{AA}
- The strong suppression seen at forward rapidities is a challenge for the "thermal" model as I first implemented it, but there is substantial room for improvement

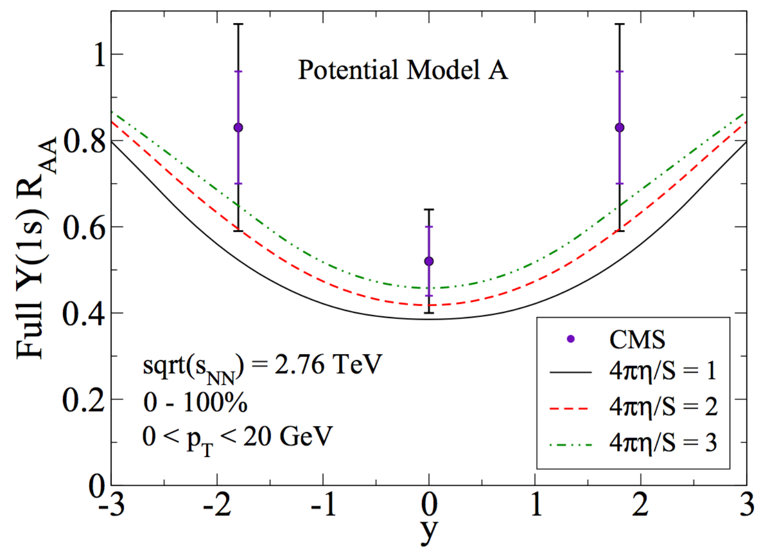
- Backup slides -

Free Energy vs Internal Energy



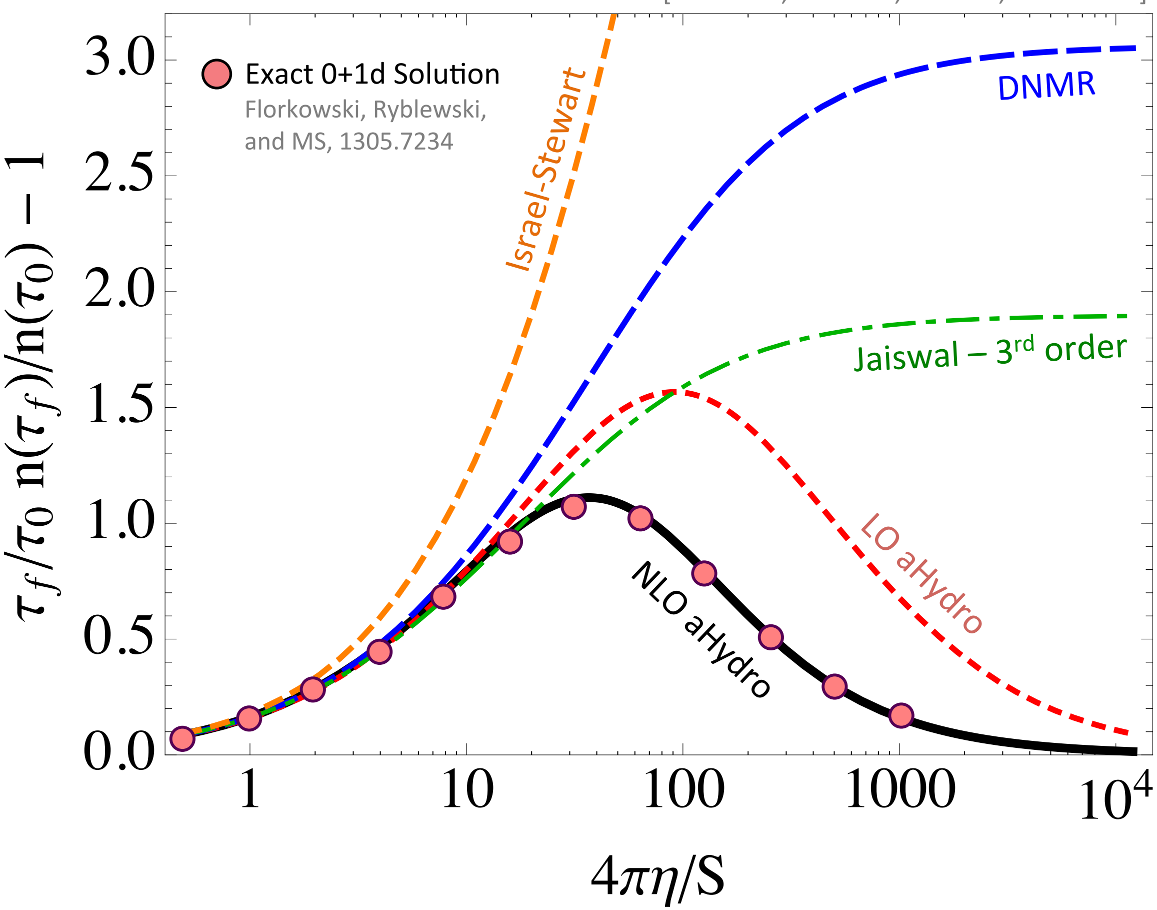
- Free energy based potential predicts far too much suppression compared to data at both RHIC and LHC energies





Example: Entropy Generation

[D. Bazow, U. Heinz, and MS, 1311.6720]



- Number (entropy) production vanishes in two limits: ideal hydrodynamic and free streaming limits
- In the conformal model which we are testing with, number density is proportional to entropy density

Non-boost-invariant aHydro

Martinez and MS, 1011.3056