Core meets corona: Λ and $\bar{\Lambda}$ polarization in peripheral high-energy heavy-ion collisions

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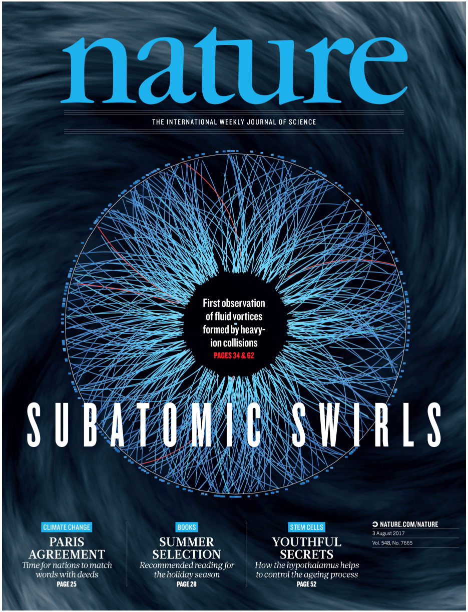
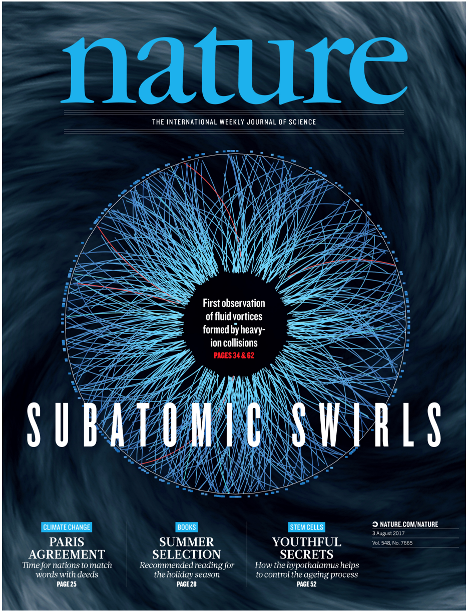
Hot, dense, **swirling** QCD matter



Global Λ hyperon polarization in nuclear collisions: evidence for the most vortical fluid.
STAR Collaboration
Nature 548 (2017)

$$\omega \approx (9 \pm 1) \times 10^{21}\ \mathrm{s}^{-1}$$

Hot, dense, **swirling** QCD matter



$$\omega \approx (9 \pm 1) \times 10^{21}\ \mathrm{s}^{-1}$$

How **swirly** is this?

Superfluid nanodroplets $10^{7}\ \mathrm{s}^{-1}$

Turbulent flow in superfluid He-II $10^{2}\ \mathrm{s}^{-1}$

Rotating, heated soap bubbles used to model climate change $10^{2}\ \mathrm{s}^{-1}$

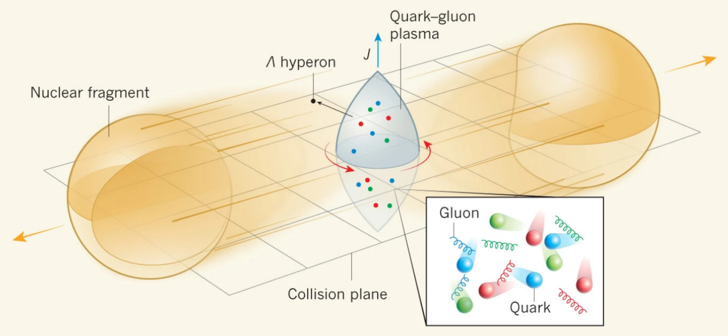
Supercell tornado cores $10^{-1}\ \mathrm{s}^{-1}$

The Great Red Spot of Jupiter $10^{-4}\ \mathrm{s}^{-1}$

Large-scale terrestrial atmospheric patterns $10^{-7} - 10^{-5}\ \mathrm{s}^{-1}$

Solar subsurface flow $10^{-7}\ \mathrm{s}^{-1}$

Hot, dense, swirling QCD matter in HICs

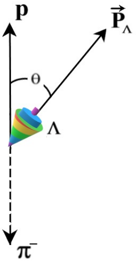


Non-central collisions have large angular momentum $L \sim 10^5 \hbar$.
Shear forces in initial condition introduce vorticity to the QGP.

Spin-orbit coupling: spin alignment, or polarization, along the direction of the vorticity - on average - parallel to J.

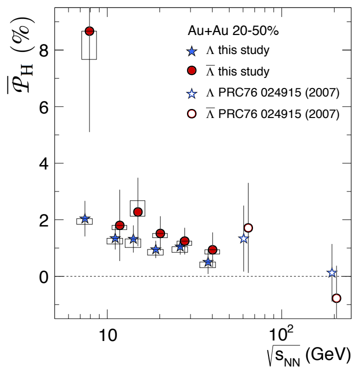
Good swirling-ness probe in HICs: Λ hyperon

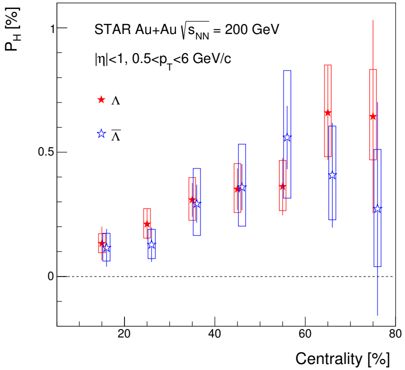
- Particle Data Group:
  - $m_\Lambda = 1115.683 \pm 0.006$ MeV
  - $\tau = 2.632 \pm 0.020 \times 10^{-10}$ s (~ 7.9 cm at c)
  - $\Gamma_1(\Lambda \to p\pi^-) = (63.9 \pm 0.5)\%$
  - $\Gamma_2(\Lambda \to n\pi^0) = (35.8 \pm 0.5)\%$
- Advantages:
  - lightest hyperon with s content
  - long lifetime: good for fiducial track/reco
  - parity-violating weak decay - sort of self-analyzing
  - decay dist not-isotropic: p going off in the direction of Λ spin



Vorticity from global Λ polarization

Meassurement of angular momentum retained at mid-rapidity. In most central collisions: no initial angular momentum, no polarization.





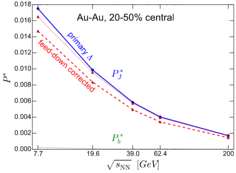
STAR Collaboration, Nature 548 (2017); Phys.Rev.C 98 (2018) 014910

Global Λ polarization models

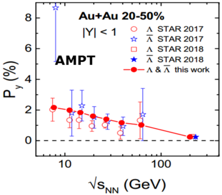
v-Hydro, partonic/hadronic transport, etc.

If the system is in thermal equilibrium, then equilibrium of spin degrees of freedom (spin and orbital angular momentum)

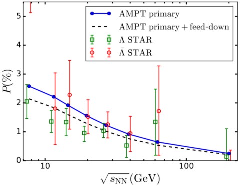
(Karpenko-Becattini EPJC2016)



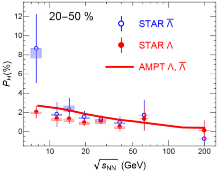
(Wei-Deng-XGH PRC2019)



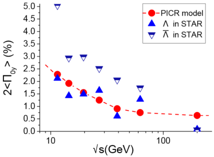
(Li-Pang-Wang-Xia PRC2017)



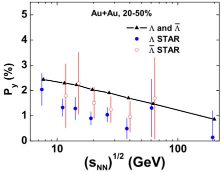
(Shi-Li-Liao PLB2018)



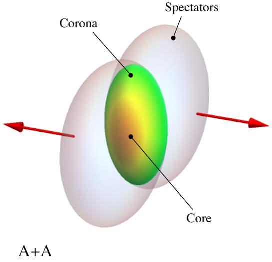
(Xie-Wang-Csernai PRC2017)

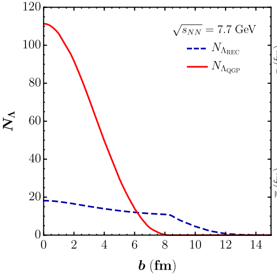


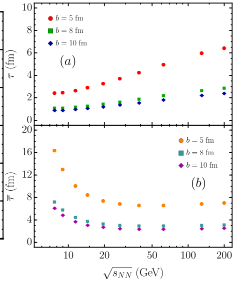
(Sun-Ko PRC2017)

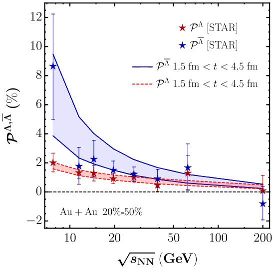


In a nut shell



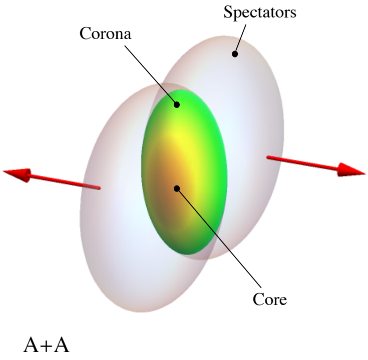






$\Lambda/\bar{\Lambda}$ global polarization from a two-component source

Non-central heavy-ion collision of a symmetric system:
$\Lambda/\bar{\Lambda}$s from core via QGP processes
$\Lambda/\bar{\Lambda}$s from corona via n + n reactions



$$N_\Lambda = \overbrace{N_{\Lambda\,\mathrm{QGP}}}^{core} + \overbrace{N_{\Lambda\,\mathrm{REC}}}^{corona}$$

Polarization asymmetry -spin alignment asymmetry- of any baryon species produced in high-energy reactions

$$\mathcal{P} = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

$N^\uparrow$ and $N^\downarrow$ baryons with spin aligned and opposite to a given direction.

$\Lambda/\bar{\Lambda}$ polarization

$$\mathcal{P}^{\Lambda} = \frac{(N^{\uparrow}_{\Lambda\,\mathrm{QGP}} + N^{\uparrow}_{\Lambda\,\mathrm{REC}}) - (N^{\downarrow}_{\Lambda\,\mathrm{QGP}} + N^{\downarrow}_{\Lambda\,\mathrm{REC}})}{(N^{\uparrow}_{\Lambda\,\mathrm{QGP}} + N^{\uparrow}_{\Lambda\,\mathrm{REC}}) + (N^{\downarrow}_{\Lambda\,\mathrm{QGP}} + N^{\downarrow}_{\Lambda\,\mathrm{REC}})},$$

$$\mathcal{P}^{\bar{\Lambda}} = \frac{(N^{\uparrow}_{\bar{\Lambda}\,\mathrm{QGP}} + N^{\uparrow}_{\bar{\Lambda}\,\mathrm{REC}}) - (N^{\downarrow}_{\bar{\Lambda}\,\mathrm{QGP}} + N^{\downarrow}_{\bar{\Lambda}\,\mathrm{REC}})}{(N^{\uparrow}_{\bar{\Lambda}\,\mathrm{QGP}} + N^{\uparrow}_{\bar{\Lambda}\,\mathrm{REC}}) + (N^{\downarrow}_{\bar{\Lambda}\,\mathrm{QGP}} + N^{\downarrow}_{\bar{\Lambda}\,\mathrm{REC}})}.$$

After a bit of straightforward algebra, we can express the Λ and $\bar{\Lambda}$ polarization as

$$\mathcal{P}^{\Lambda} = \frac{\left(\mathcal{P}^{\Lambda}_{\mathrm{REC}} + \frac{N^{\uparrow}_{\Lambda\,\mathrm{QGP}} - N^{\downarrow}_{\Lambda\,\mathrm{QGP}}}{N_{\Lambda\,\mathrm{REC}}}\right)}{\left(1 + \frac{N_{\Lambda\,\mathrm{QGP}}}{N_{\Lambda\,\mathrm{REC}}}\right)}, \quad \mathcal{P}^{\bar{\Lambda}} = \frac{\left(\mathcal{P}^{\bar{\Lambda}}_{\mathrm{REC}} + \frac{N^{\uparrow}_{\bar{\Lambda}\,\mathrm{QGP}} - N^{\downarrow}_{\bar{\Lambda}\,\mathrm{QGP}}}{N_{\Lambda\,\mathrm{REC}}}\right)}{\left(1 + \frac{N_{\bar{\Lambda}\,\mathrm{QGP}}}{N_{\bar{\Lambda}\,\mathrm{REC}}}\right)}$$

where

$$\mathcal{P}^{\Lambda}_{\mathrm{REC}} = \frac{N^{\uparrow}_{\Lambda\,\mathrm{REC}} - N^{\downarrow}_{\Lambda\,\mathrm{REC}}}{N^{\uparrow}_{\Lambda\,\mathrm{REC}} + N^{\downarrow}_{\Lambda\,\mathrm{REC}}}, \quad \mathcal{P}^{\bar{\Lambda}}_{\mathrm{REC}} = \frac{N^{\uparrow}_{\bar{\Lambda}\,\mathrm{REC}} - N^{\downarrow}_{\bar{\Lambda}\,\mathrm{REC}}}{N^{\uparrow}_{\bar{\Lambda}\,\mathrm{REC}} + N^{\downarrow}_{\bar{\Lambda}\,\mathrm{REC}}}.$$

$\Lambda/\bar{\Lambda}$ polarization

- Notice that $\mathcal{P}^{\Lambda}_{\rm REC}$ and $\mathcal{P}^{\bar{\Lambda}}_{\rm REC}$ refer to the polarization along the global angular momentum produced in the corona.
- Although nucleons colliding in the corona partake of the vortical motion, reactions in cold nuclear matter are less efficient to align the spin in the direction of the angular momentum than in the QGP.
- As a working approximation we set $\mathcal{P}^{\Lambda}_{\rm REC} = \mathcal{P}^{\bar{\Lambda}}_{\rm REC} = 0$ to write

$$\mathcal{P}^{\Lambda} = \frac{\left(\frac{N^{\uparrow}_{\Lambda\,{\rm QGP}} - N^{\downarrow}_{\Lambda\,{\rm QGP}}}{N_{\Lambda\,{\rm REC}}}\right)}{\left(1 + \frac{N_{\Lambda\,{\rm QGP}}}{N_{\Lambda\,{\rm REC}}}\right)}, \quad \mathcal{P}^{\bar{\Lambda}} = \frac{\left(\frac{N^{\uparrow}_{\bar{\Lambda}\,{\rm QGP}} - N^{\downarrow}_{\bar{\Lambda}\,{\rm QGP}}}{N_{\bar{\Lambda}\,{\rm REC}}}\right)}{\left(1 + \frac{N_{\bar{\Lambda}\,{\rm QGP}}}{N_{\bar{\Lambda}\,{\rm REC}}}\right)}.$$

$\Lambda/\bar{\Lambda}$ polarization

- Since reactions in the core are more efficient to align particle spin to global angular momentum, one expects that the **intrinsic** global Λ and $\overline{\Lambda}$ polarizations, namely,

$$
\begin{aligned}
z &= \frac{(N^{\uparrow}_{\Lambda\,\mathrm{QGP}} - N^{\downarrow}_{\Lambda\,\mathrm{QGP}})}{N_{\Lambda\,\mathrm{QGP}}} \\
\bar{z} &= \frac{(N^{\uparrow}_{\overline{\Lambda}\,\mathrm{QGP}} - N^{\downarrow}_{\overline{\Lambda}\,\mathrm{QGP}})}{N_{\overline{\Lambda}\,\mathrm{QGP}}} \simeq \frac{(N^{\uparrow}_{\overline{\Lambda}\,\mathrm{QGP}} - N^{\downarrow}_{\overline{\Lambda}\,\mathrm{QGP}})}{N_{\Lambda\,\mathrm{QGP}}},
\end{aligned}
$$

  are finite, albeit small, where we used that in the QGP one expects $N_{\overline{\Lambda}\,\mathrm{QGP}} \simeq N_{\Lambda\,\mathrm{QGP}}$.
- Therefore,

$$
\mathcal{P}^{\Lambda} = \frac{z\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1 + \frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}, \qquad \mathcal{P}^{\overline{\Lambda}} = \frac{\bar{z}\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\overline{\Lambda}\ \mathrm{REC}}}}{\left(1 + \frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\overline{\Lambda}\ \mathrm{REC}}}\right)}.
$$

$\Lambda/\bar{\Lambda}$ polarization

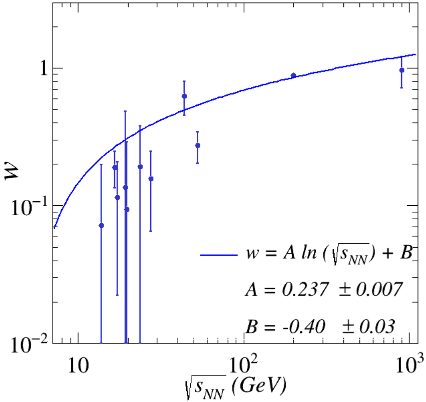
- Cold nuclear matter collisions in the corona are expected to produce more Λs than $\bar{\Lambda}$s, since these processes are related to p + p reactions, where three anti-quarks coming from the sea are more difficult to produce than only one s. Then we can write $N_{\bar{\Lambda}\,\mathrm{REC}} \equiv w N_{\Lambda\,\mathrm{REC}}$.
- In contrast, given the assumption that $N_{\bar{\Lambda}\ \mathrm{QGP}} \simeq N_{\Lambda\ \mathrm{QGP}}$, **no such suppression factor** similar to w needs to be introduced in the QGP (core) region. Thus

$$\mathcal{P}^{\Lambda} = \frac{z \frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1 + \frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}, \quad \mathcal{P}^{\bar{\Lambda}} = \frac{\left(\frac{\bar{z}}{w}\right) \frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1 + \left(\frac{1}{w}\right) \frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)},$$

- The energy dependent coefficient w is expected to be $w < 1$.

Corona features

Cold nuclear matter (less dense than core): model as p + p collisions

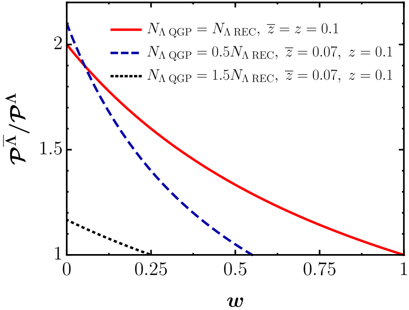


- Experimental data on the ratio $w = N_{\overline{\Lambda}\,\mathrm{REC}}/N_{\Lambda\,\mathrm{REC}}$ obtained from p + p collisions at different energies
- $w = N_{\overline{\Lambda}\,\mathrm{REC}}/N_{\Lambda\,\mathrm{REC}}$ is smaller than 1 except for the largest collision energy considered

M. Gazdzicki and D. Rohrich, Z. Phys. C **71** (1996); J. W. Chapman *et al.*, Phys. Lett. B **47**, 465 (1973); C. Höhne, CERN-THESIS-2003-034; J. Baechler *et al.* (NA35 Collaboration), Nucl. Phys. A **525** (1991); G. Charlton *et al.*, Phys. Rev. Lett. **30** (1973); F. Lopinto *et al.*, Phys. Rev. D **22** (1980); F. W. Busser *et al.*, Phys. Lett. B **61** (1976); D. Brick *et al.*, Nucl. Phys. B **164** (1980); H. Kichimi *et al.*, Phys. Rev. D **20** (1979); S. Erhan, *et al.* Phys. Lett. B **85** (1979); B. I. Abelev *et al.* (STAR Collaboration), Phys. Rev. C **75** (2007); E. Abbas *et al.* (ALICE Collaboration), Eur. Phys. J. C **73** (2013).

Proof of principle

- Although $\bar{z}$ is expected to be smaller than z, **the amplifying effect from the factor $1/w > 1$ produces that $\mathcal{P}^{\bar{\Lambda}} > \mathcal{P}^{\Lambda}$ for a range of w values.**



- In the extreme situation where $\bar{z} = z$ and $N_{\Lambda\,\mathrm{QGP}}/N_{\Lambda\,\mathrm{REC}} = 1$, $\mathcal{P}^{\bar{\Lambda}}/\mathcal{P}^{\Lambda}$ is always larger than 1 for $0 < w < 1$.
- For a more realistic scenario with $\bar{z} < z$ and with $N_{\Lambda\,\mathrm{QGP}}/N_{\Lambda\,\mathrm{REC}} < 1$, there is still a range of w values for which $\mathcal{P}^{\bar{\Lambda}}/\mathcal{P}^{\Lambda} > 1$.

$\Lambda/\bar{\Lambda}$ production in QGP vs REC

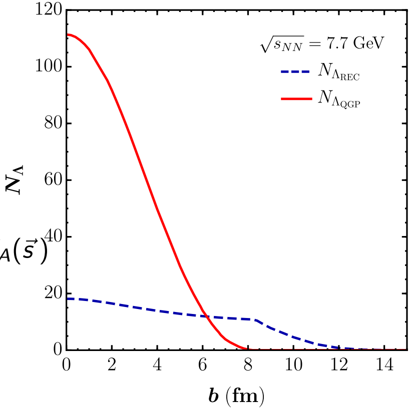
Number of Λs produced in the core $\propto$

$$N_{\mathrm{p\,QGP}} = \int d^2s\ n_{\mathrm{p}}(\vec{s},\vec{b})\,\theta\left[n_{\mathrm{p}}(\vec{s},\vec{b}) - n_c\right]$$

Number of Λs produced in the corona

$$\propto \quad N_{\Lambda\,\mathrm{REC}}\underbrace{\sigma^{\Lambda}_{NN}\left(\sqrt{s_{NN}}\right)}_{\Lambda\ p+p\ xsec}\int d^2s\ T_B(\vec{b}-\vec{s})\,T_A(\vec{s})$$

$$\times\,\theta\left[n_c - n_{\mathrm{p}}(\vec{s},\vec{b})\right]$$



$$\mathcal{P}^{\Lambda} = \frac{z\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}}{\left(1+\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\Lambda\ \mathrm{REC}}}\right)}, \qquad \mathcal{P}^{\bar{\Lambda}} = \frac{\frac{\bar{z}}{w}\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\bar{\Lambda}\ \mathrm{REC}}}}{\left(1+\frac{1}{w}\frac{N_{\Lambda\ \mathrm{QGP}}}{N_{\bar{\Lambda}\ \mathrm{REC}}}\right)}$$

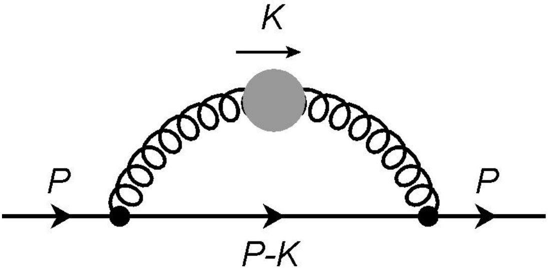
Need to compute z and $\bar{z}$: couple thermal vorticity to spin in a thermal field theoretical framework

$$
\begin{aligned}
\overline{\omega}_{\mu\nu} &= \frac{1}{2}\left(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu\right) \\
\beta_\mu &= u_\mu(x)/T(x)
\end{aligned}
$$

- For a quark spin directed along the $\hat{z}$-axis and a constant angular velocity ω and constant temperature T

$$
\overline{\omega}_{\mu\nu}\sigma^{\mu\nu} \propto \omega/T
$$

Relaxation time: inverse of imaginary part of self-energy with vorticity-spin interaction



$$\Gamma(p_0) = \tilde{f}(p_0)\mathrm{Tr}\left[\gamma^0 \mathrm{Im}\Sigma\right]$$

$\tilde{f}(p_0)$: Fermi-Dirac distribution.

Effective vertex: $\lambda_a^\mu = g\frac{\sigma^{\alpha\beta}}{2}\overline{\omega}_{\alpha\beta}\gamma^\mu t_a$

Gluon propagator at finite T and μ_B

- In a covariant gauge, the Hard Thermal Loop (HTL) approximation to the effective gluon propagator is given by

$$^*G_{\mu\nu}(K) = {}^*\Delta_L(K)P_{L\,\mu\nu} + {}^*\Delta_T(K)P_{T\,\mu\nu}$$

- $P_{L,T\,\mu\nu}$ are the polarization tensors for three dimensional longitudinal and transverse gluons.
- The gluon propagator functions for longitudinal and transverse modes, $^*\Delta_{L,T}(K)$, are

$$^*\Delta_L(K)^{-1} = K^2 + 2m^2\frac{K^2}{k^2}\left[1 - \left(\frac{i\omega_n}{k}\right)Q_0\left(\frac{i\omega_n}{k}\right)\right],$$

$$^*\Delta_T(K)^{-1} = -K^2 - m^2\left(\frac{i\omega_n}{k}\right)\left\{\left[1 - \left(\frac{i\omega_n}{k}\right)^2\right]Q_0\left(\frac{i\omega_n}{k}\right) + \left(\frac{i\omega_n}{k}\right)\right\}$$

Gluon propagator at finite T and μ_B

$$Q_0(x) = \frac{1}{2} \ln \frac{x+1}{x-1}$$

- m is the gluon thermal mass

$$m^2 = \frac{1}{6} g^2 C_A T^2 + \frac{1}{12} g^2 C_F \left(T^2 + \frac{3}{\pi^2} \mu^2 \right)$$

- μ is the quark chemical potential, g is the strong coupling $C_A = 3$ and $C_F = 4/3$ are the Casimir factors for the adjoint and fundamental representations of $SU(3)$, respectively. We take $\alpha_s = g^2/4\pi = 1/3$.

Imaginary part of self-energy

- The **intermediate quark line is taken as a bare quark propagator** such that the inverse of the interaction rate corresponds to the **relaxation time for the spin and vorticity alignment for quarks that are originally not thermalized.**
- The sum over Matsubara frequencies involves products of the propagator functions for longitudinal and transverse gluons ${}^*\Delta_{L,T}$ and the Matsubara propagator for the bare quark $\tilde{\Delta}_F$The term that depends on the summation index is

$$S_{L,T} = T\sum_n {}^*\Delta_{L,T}(i\omega_n)\tilde{\Delta}_F(i(\omega_m - \omega_n)).$$

- The sum is more straightforward evaluated introducing the spectral densities $\rho_{L,T}$ and $\widetilde{\rho}$ for the gluon and fermion propagators, respectively. The imaginary part of S_i, $i = L, T$ is

$$\text{Im } S_i = \pi\left(e^{(p_0-\mu_q)/T}+1\right)\int_{-\infty}^{\infty}\frac{dk_0}{2\pi}\int_{-\infty}^{\infty}\frac{dp_0'}{2\pi} f(k_0)\widetilde{f}(p_0'-\mu)\delta(p_0-k_0-p_0')\rho_i(k_0)\widetilde{\rho}(p_0')$$

Spectral densities

- The spectral density corresponding to a bare quark is given by

$$\widetilde{\rho}(p_0') = 2\pi\epsilon(p_0')\delta(p_0'^2 - E_p^2),$$

where $E_p^2 = (p-k)^2 + m_q^2$ with m_q the quark mass.

- The gluon spectral densities are

$$\rho_L(k_0,k) = \frac{x}{1-x^2}\frac{2\pi m^2\theta(k^2-k_0^2)}{\left[k^2+2m^2\left(1-(x/2)\ln\left|\frac{(1+x)}{(1-x)}\right|\right)\right]^2+[\pi m^2 x]^2}$$

$$\rho_T(k_0,k) = \frac{\pi m^2 x(1-x^2)\theta(k^2-k_0^2)}{\left[k^2(1-x^2)+m^2\left(x^2+(x/2)(1-x^2)\ln\left|\frac{(1+x)}{(1-x)}\right|\right)\right]^2+[(\pi/2)m^2x(1-x^2)]^2}$$

The interaction rate

- The interaction rate for a massive quark with energy p_0 to align its spin with the thermal vorticity is given by

$$\Gamma(p_0)=\frac{\alpha_s}{4\pi}\left(\frac{\omega}{T}\right)^2\frac{C_F}{\sqrt{p_0^2-m_q^2}}\int_0^\infty dkk\int_{\mathcal{R}}dk_0[1+f(k_0)]\tilde{f}(p_0+k_0-\mu_q)$$
$$\times\sum_{i=L,T}C_i(p_0,k_0,k)\rho_i(k_0,k),$$

- $\mathcal{R}$ is the region

$$\sqrt{\left(\sqrt{p_0^2-m_q^2}-k\right)^2+m_q^2}-p_0\leq k_0\leq\sqrt{\left(\sqrt{p_0^2-m_q^2}+k\right)^2+m_q^2}-p_0$$

Polarization coefficients

- The polarization coefficients $C_{L,T}$ come from the contraction of the polarization tensors $P_{L,T}^{\mu\nu}$ with the trace of the factors involving Dirac gamma matrices from the self-energy. After implementing the kinematical restrictions we get

$$
\begin{aligned}
C_T(p_0, k_0, k) &= 8(p_0 + k_0)\left(\frac{k^2 - 2k_0 p_0 - k_0^2}{2k\sqrt{p_0^2 - m_q^2}}\right)^2 \\
C_L(p_0, k_0, k) &= -8(p_0 + k_0)\left[\left(\frac{k^2 - 2k_0 p_0 - k_0^2}{2k\sqrt{p_0^2 - m_q^2}}\right)^2 - \frac{1}{2}\right] \\
&- 8\frac{p_0 k^2}{k_0^2 - k^2}\left(\frac{k^2 - 2k_0 p_0 - k_0^2}{2k\sqrt{p_0^2 - m_q^2}}\right)^2
\end{aligned}
$$

Relaxation time

- The total interaction rate is obtained by integrating over the available phase space

$$\Gamma = V \int \frac{d^3p}{(2\pi)^3} \Gamma(p_0)$$

where V is the volume of the overlap region in the collision

$$V = \frac{\pi}{3}(4R + b)(R - b/2)^2$$

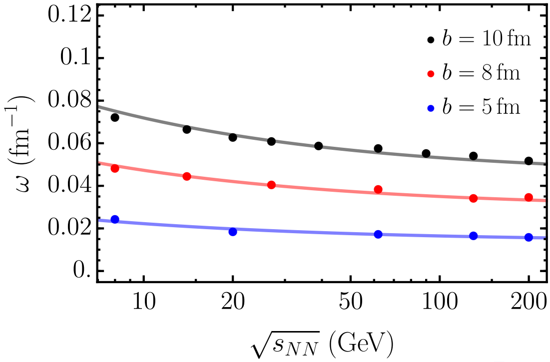
- The relaxation time for spin and vorticity alignment is

$$\tau \equiv 1/\Gamma$$

Initial angular velocity ω

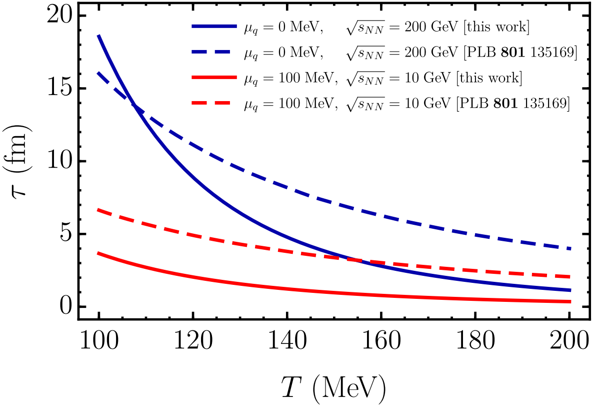
- Initial angular velocity ω for Au+Au collisions at impact parameters $b = 5, 8, 10$ fm as functions of collision energy $\sqrt{s_{NN}}$. Solid lines are the fit of the UrQMD results ($V_N = (4\pi/3)R^3$)

$$\omega = \frac{b^2}{2V_N}\left[1 + 2\left(\frac{m_N}{\sqrt{s_{NN}}}\right)^{1/2}\right]$$



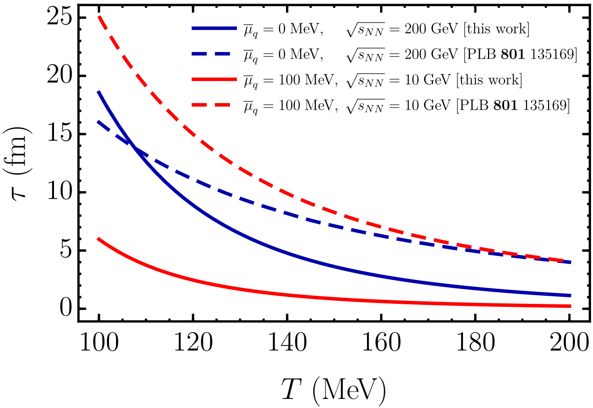
Relaxation time **quarks**, $b = 10$ fm

- Dashed lines, **massless quarks** for $\sqrt{s_{NN}} = 10, 200$ GeV with $\omega \simeq 0.12, 0.10$ fm^{-1}, respectively.
- Solid lines, **massive quarks ($m_s = 100$ MeV)** for $\sqrt{s_{NN}} = 10, 200$ GeV with $\omega \simeq 0.12, 0.10$ fm^{-1}, respectively,



Relaxation time **antiquarks**, $b = 10$ fm

- Dashed lines, **massless antiquarks** for $\sqrt{s_{NN}} = 10, 200$ GeV with $\omega \simeq 0.12, 0.10$ fm^{-1}, respectively.
- Solid lines, **massive antiquarks ($m_{\bar{s}} = 100$ MeV)** for $\sqrt{s_{NN}} = 10, 200$ GeV with $\omega \simeq 0.12, 0.10$ fm^{-1}, respectively,



Intrinsic polarizations z and $\bar{z}$

- The number of particles N in the original state varies as a function of time t as

$$N = N_0 \exp(-t/\tau)$$

- The number of particles coming out from this state (which corresponds to the number of particles that align their spins with the vorticity) is

$$N' = N_0[1 - \exp(-t/\tau)]$$

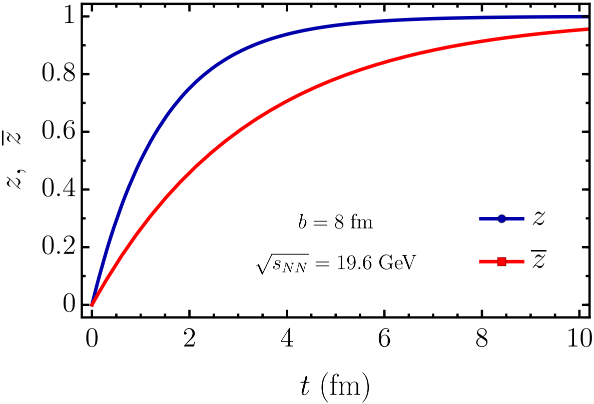
- The factor

$$z = [1 - \exp(-t/\tau)]$$

can be properly called the **intrinsic global polarization.**

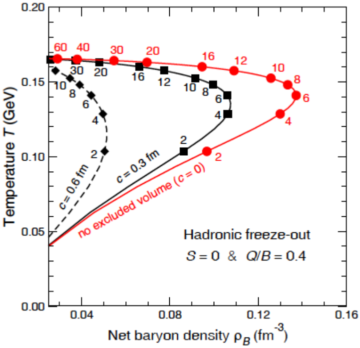
Intrinsic polarizations z and $\bar{z}$

- Intrinsic global polarization for quarks (z) and antiquarks ($\bar{z}$) as functions of time t for semicentral collisions at an impact parameter $b = 8$ fm for $\sqrt{s_{NN}} = 19.6$ GeV. Notice that $\bar{z} < z$, however, both intrinsic polarizations tend to 1 for $t \simeq 10$ fm.



Maximum freeze-out density,

J. Randrup and J. Cleymans, Phys. Rev. **C** 74, 047901 (2006)



$$
\begin{aligned}
T(\mu_B) &= 166 - 139\mu_B^2 - 53\mu_B^4 \\
\mu_B(\sqrt{s_{NN}}) &= \frac{1308}{1000 + 0.273\sqrt{s_{NN}}}
\end{aligned}
$$

Intrinsic global polarization from relaxation times

Relaxation time for quark/antiquark spin and thermal vorticity alignment in a quark-gluon plasma at finite temperature and quark chemical potential

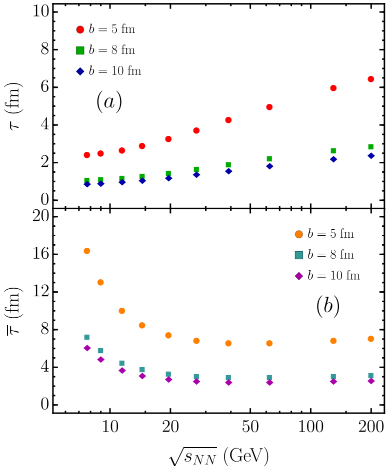
A. Ayala. D. de la Cruz, L. A. Hernández, and J. Salinas, PRD **102**, 056019 (2020).

The interaction between the thermal vorticity and the quark spin is modeled by means of an effective vertex $\to \Gamma \to \tau = 1/\Gamma$

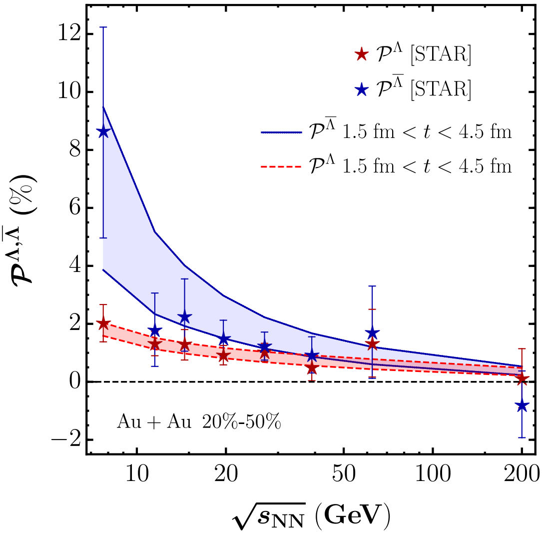
$$z = 1 - \exp\left(-t/\tau\right)$$

$$\bar{z} = 1 - \exp\left(-t/\bar{\tau}\right)$$

as functions of the Λ and $\overline{\Lambda}$ formation time t within the QGP.



$\Lambda/\bar{\Lambda}$ global polarization



Au + Au 20-50% Λ and $\overline{\Lambda}$ polarization from core-corona model

bands: Λ and $\overline{\Lambda}$ formation time in QGP range 1.5 fm $< t <$ 4.5 fm

vs

data STAR-BES Nature 548 (2017)

Conclusions

- Two component source explains the excitation function of Λ and $\overline{\Lambda}$ polarization.
- Essential ingredient the **intrinsic** Λ and $\overline{\Lambda}$ polarization.
- Field theoretical calculation of quark self-energy in a thermal QCD medium with an effective coupling between thermal vorticity and spin can be used to compute the relaxation times and from these the intrinsic polarizations.
- For the future, implement model in a MC analysis to test capablities to measure Λ and $\overline{\Lambda}$ polarizations at MPD-NICA.

¡GRACIAS!