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QM QUARK MATTER KRAKÓW 2022

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

# Modelling particle polarization with spin hydrodynamics

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**Quark Matter 2022**

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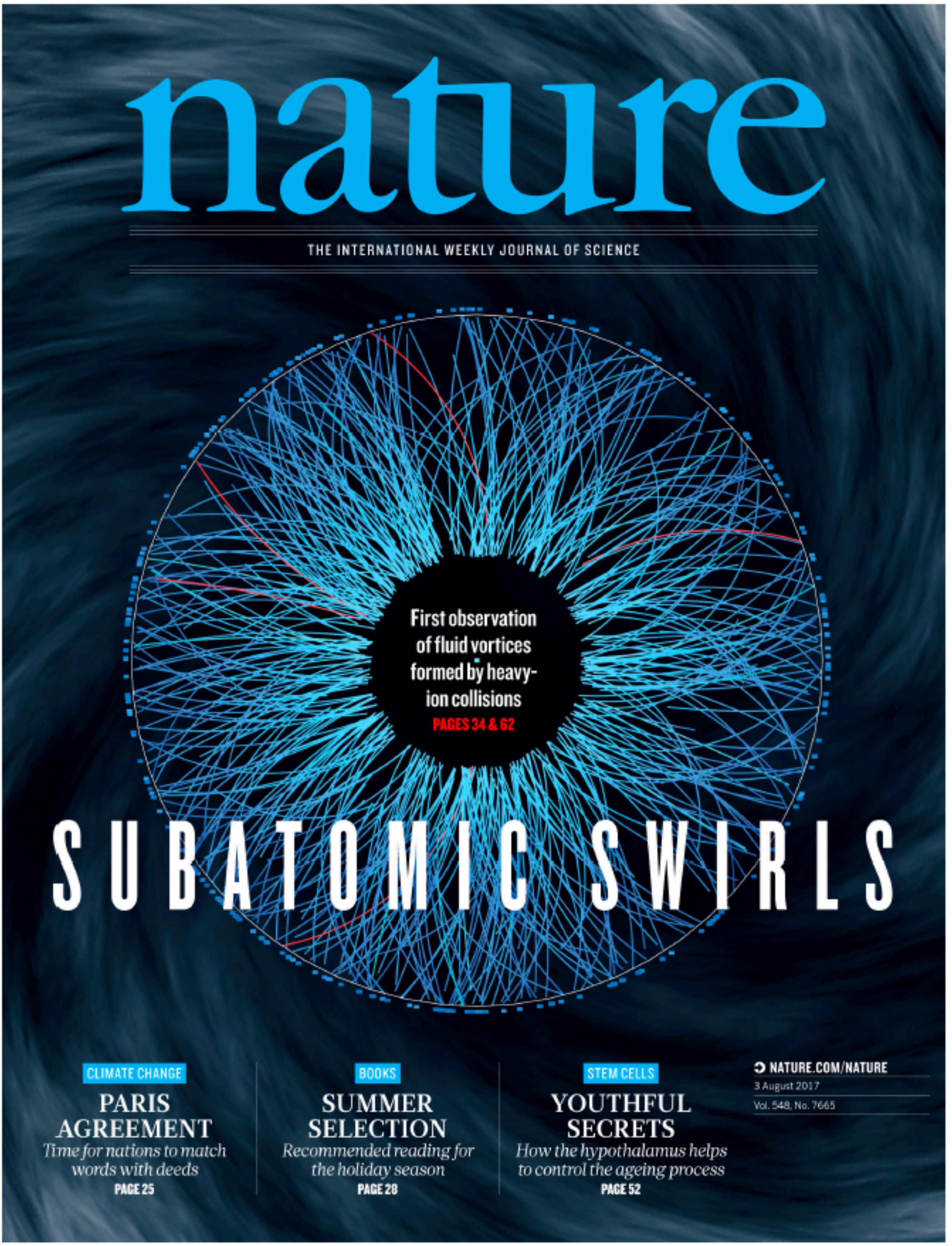
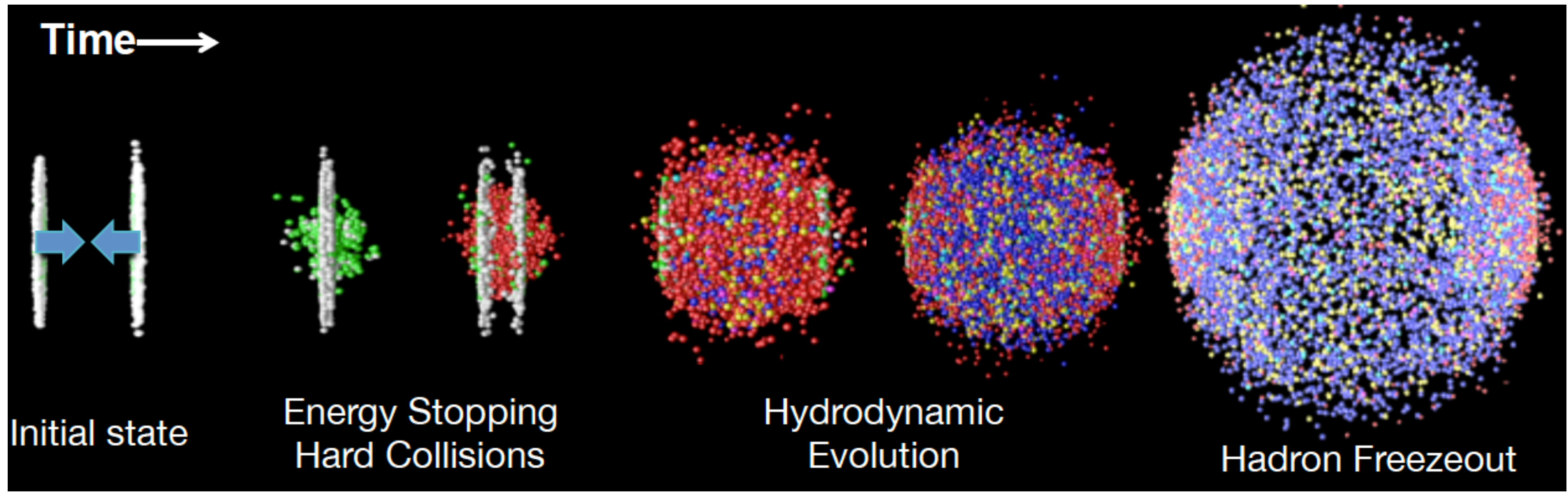



**Relativistic fluid dynamics forms the basis of HIC models**



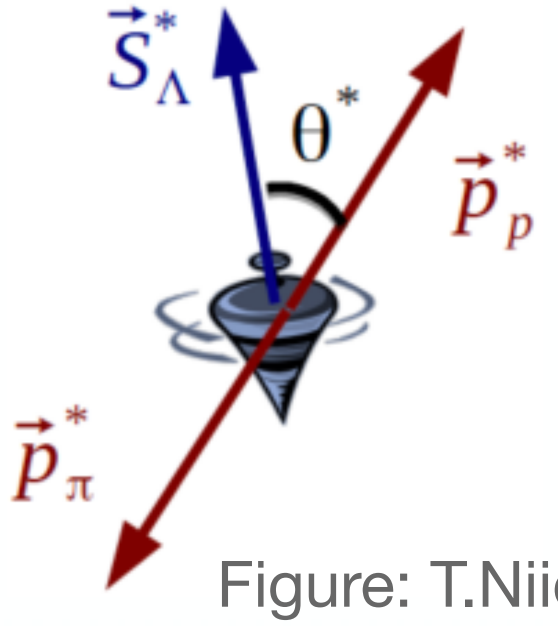




Figure: T.Niida

# Spin polarization in heavy-ion collisions: A new sensitive probe!

Non-central heavy-ion collisions create fireballs with large global orbital angular momenta

F. Becattini, F. Piccinini, J. Rizzo, PRC 77 (2008) 024906

$$\boldsymbol{L}_{\text{init}} \sim 10^5 \hbar$$

Part of the angular momentum can be transferred from the orbital to the spin part

$$\boldsymbol{J}_{\text{init}} = \boldsymbol{L}_{\text{init}} = \boldsymbol{L}_{\text{final}} + \boldsymbol{S}_{\text{final}}$$

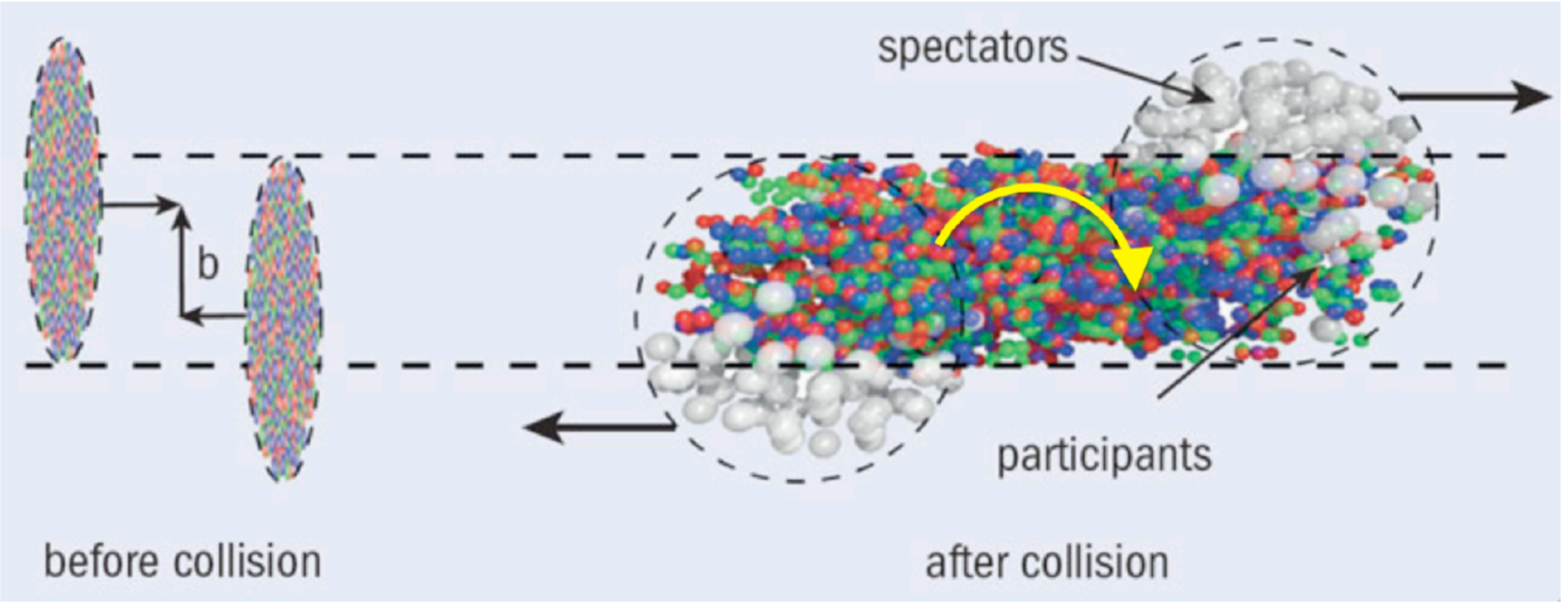
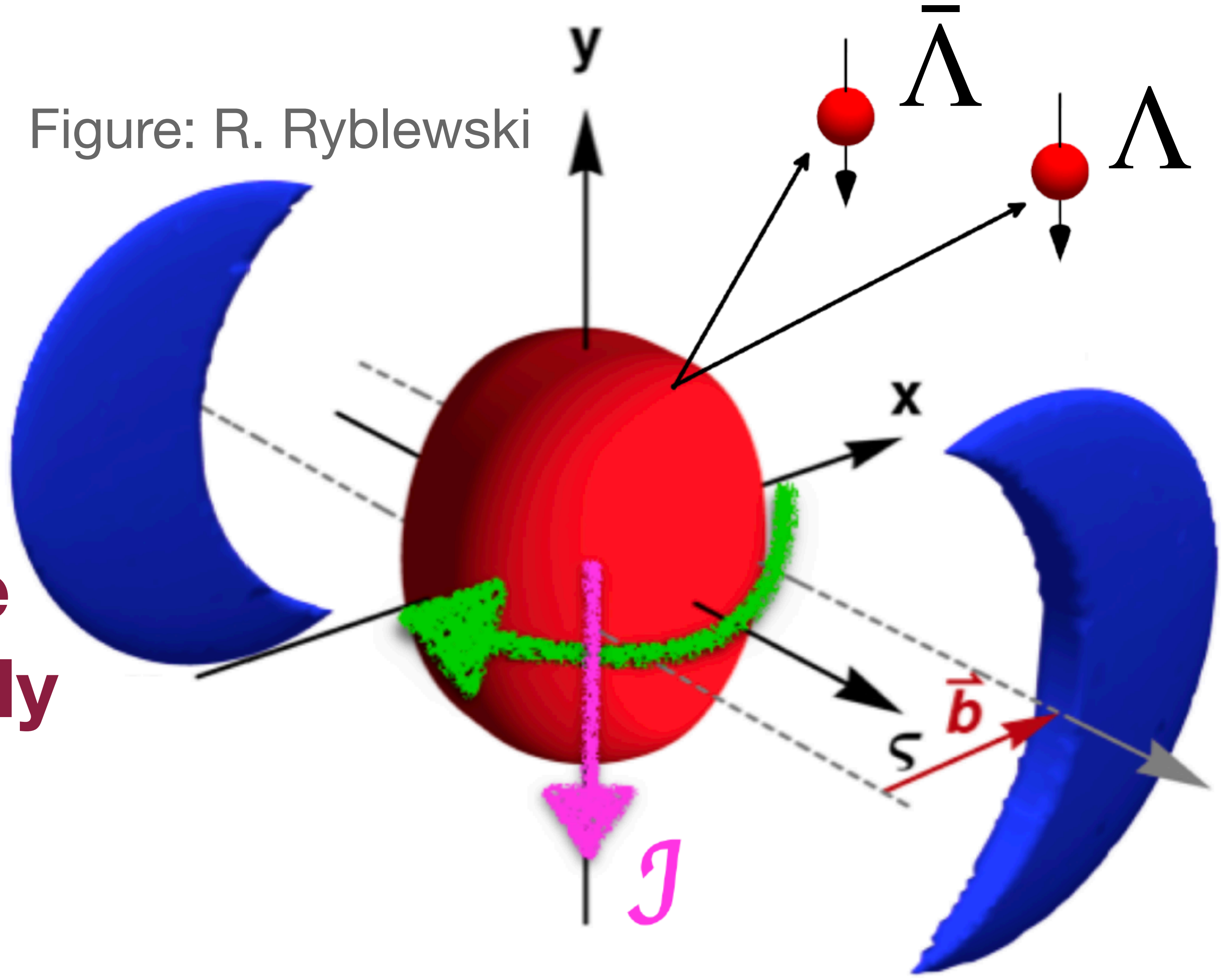
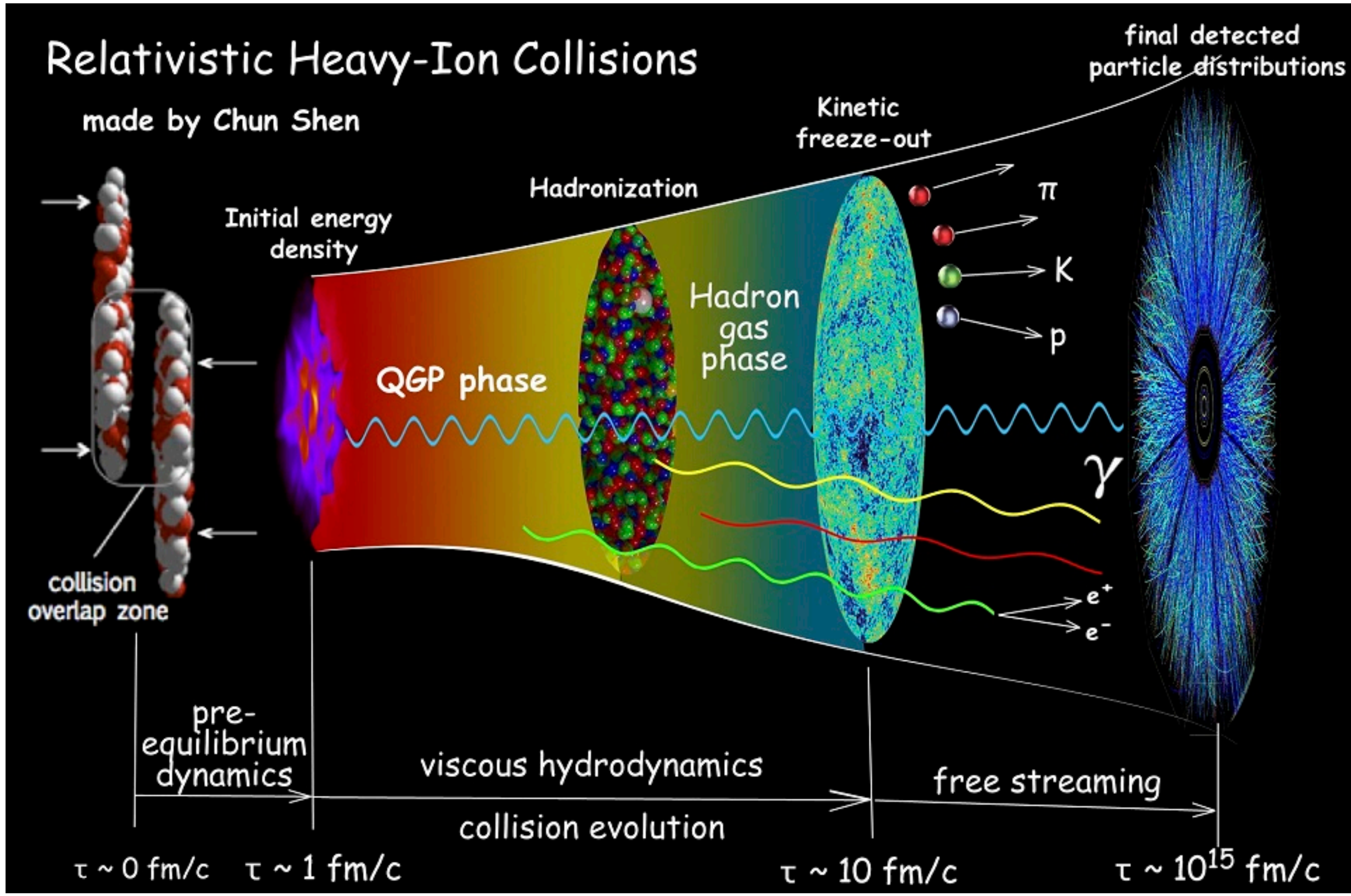



Figure: M. Lisa, talk @ "Strangeness in Quark Matter 2016"

Figure: R. Ryblewski



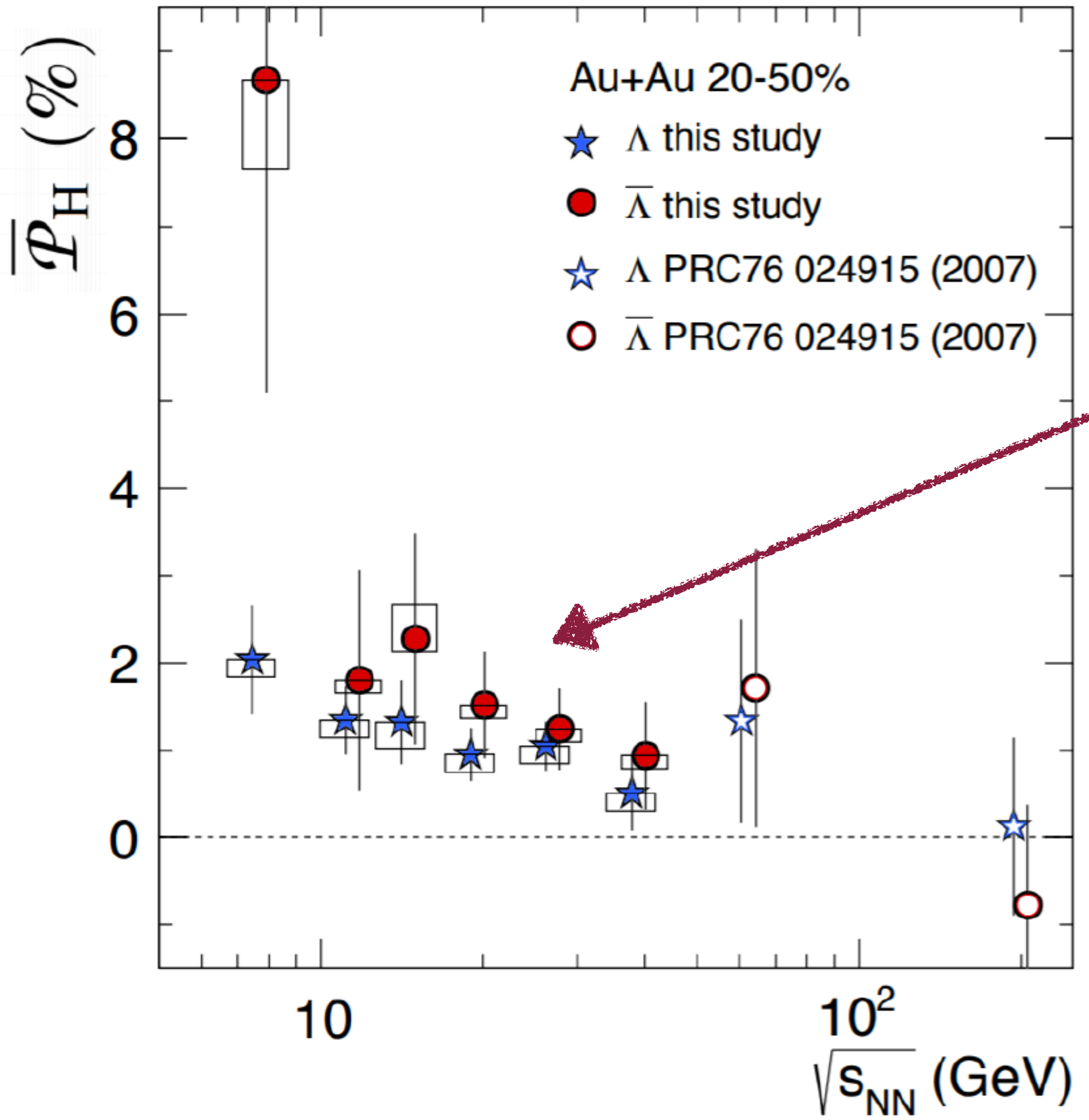

Emitted particles are expected to be globally polarized along the system's angular momentum

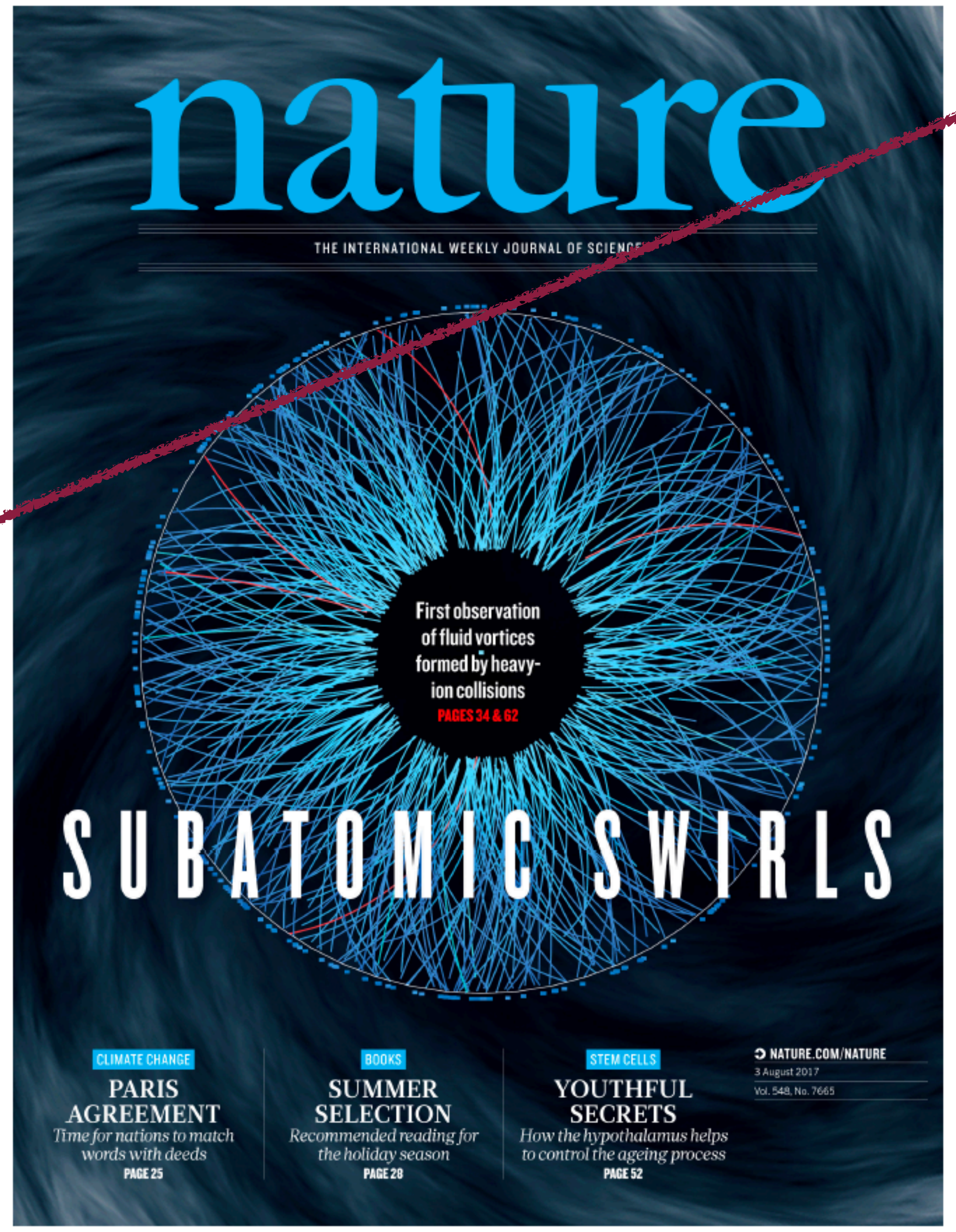


# Experimental measurement of $\Lambda(\bar{\Lambda})$ spin polarization in heavy-ion collisions

L. Adamczyk et al. (STAR) (2017), Nature 548 (2017) 62-65

**~2% - small but measurable effect**




**Self-analysing parity-violating hyperon weak decay allows to measure polarization of $\Lambda$**

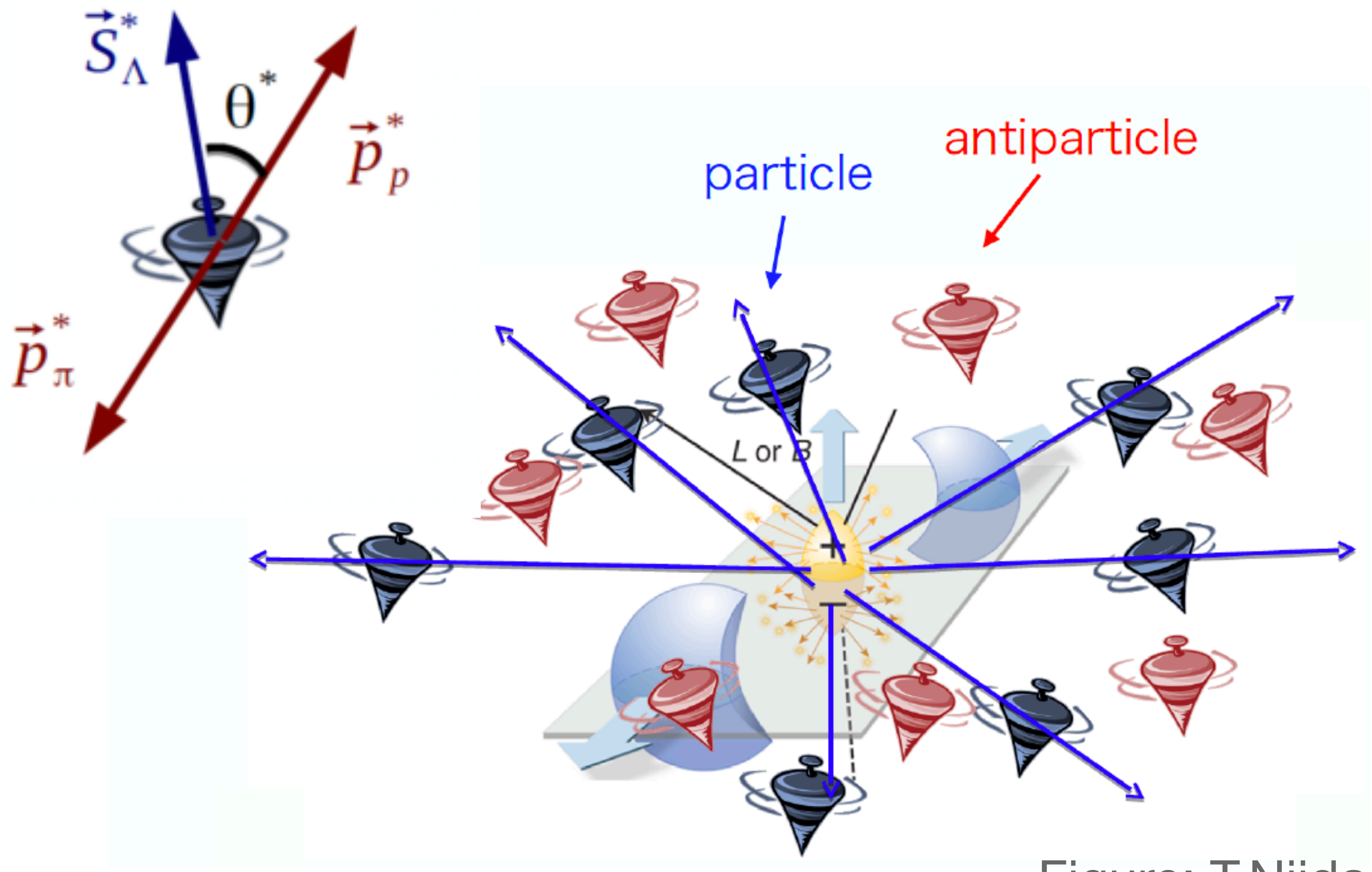



Figure: T.Niida

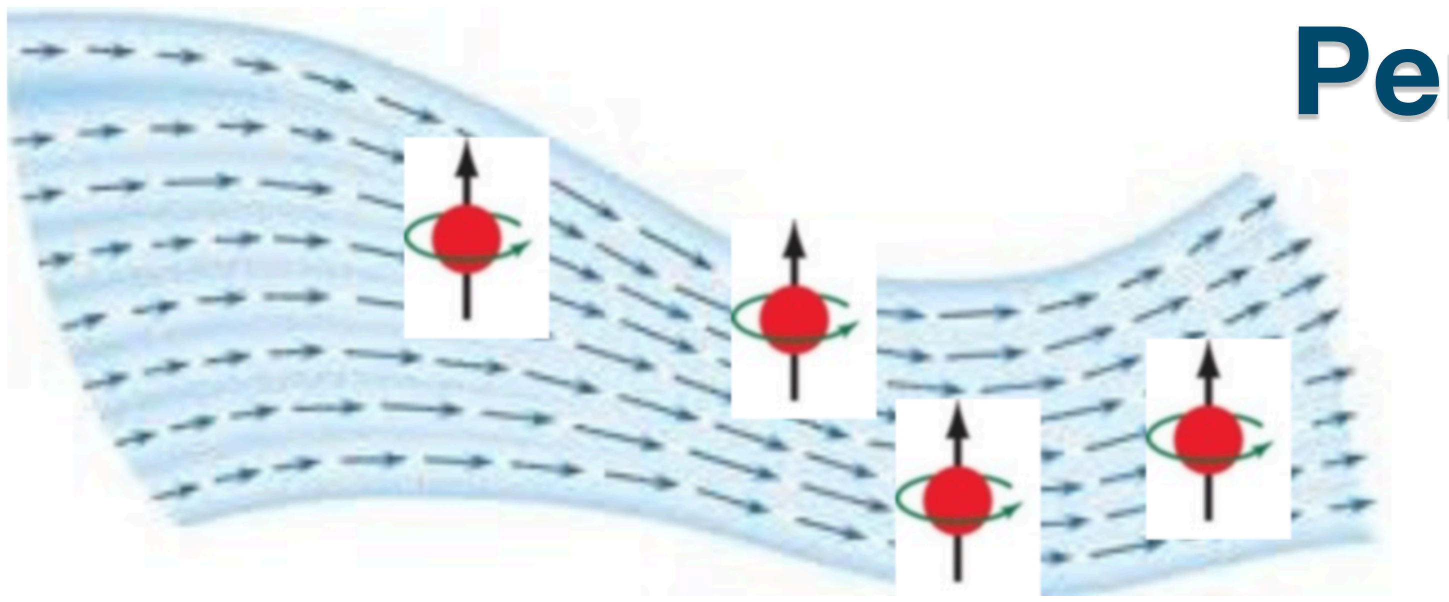
**QGP is the *hottest*, *least viscous,* and *most vortical* fluid ever produced**

$$\omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 0.6 - 2.7 \times 10^{22}\ \mathrm{s}^{-1}$$

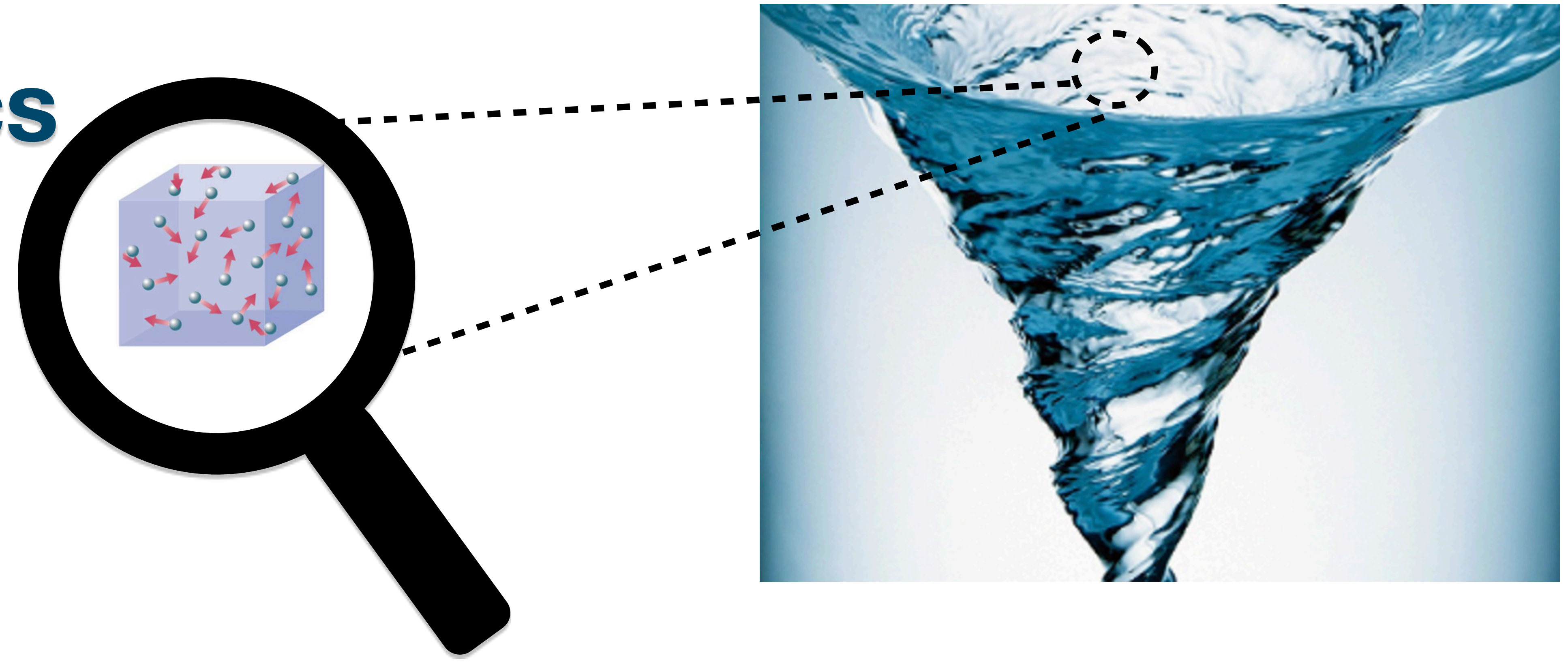
$$P_\Lambda \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T} \qquad P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_{\mathrm{H}}\mathbf{P}_{\mathrm{H}} \cdot \mathbf{p}^*_{\mathbf{p}}\right)$$

$P_\Lambda \approx P_{\bar{\Lambda}}$ → **first direct observation of spin**

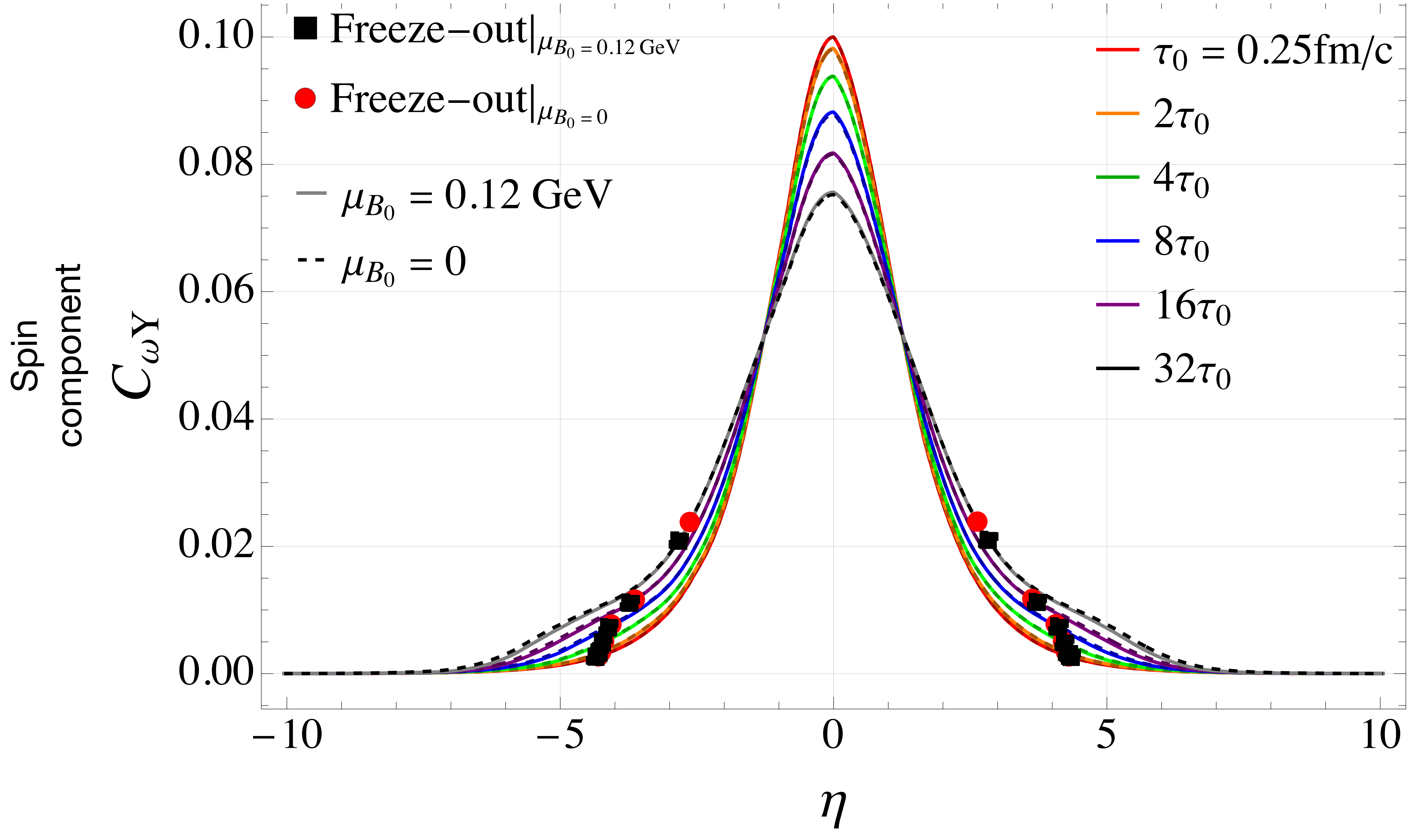


# Perfect-fluid spin hydrodynamics



**Relativistic kinetic theory formulation of ideal fluid**

**For dilute systems, the derivation of fluid dynamics can be done starting from the underlying kinetic theory**




**Quantum RKT**

$$\left(\gamma_\mu K^\mu - m\right)\mathscr{W}(x,k) = C[\mathscr{W}(x,k)]$$

$$K^\mu = k^\mu + \frac{i}{2}\left(\hbar\partial^\mu\right)$$

$$\rightarrow \quad k^\mu\partial_\mu \mathscr{F}_{\mathrm{eq}}(x,k) = 0 \qquad k^\mu\partial_\mu \mathscr{A}^\nu_{\mathrm{eq}}(x,k) = 0 \quad \rightarrow \quad \partial_\mu N^\mu = 0 \quad \partial_\nu T^{\mu\nu} = 0 \quad \partial_\lambda S^{\lambda,\mu\nu} = 0$$

**semi-classical expansion** **moments method**

# Classical spin treatment - perfect fluid

W. Florkowski, R. Ryblewski, A. Kumar, Prog. Part. Nucl. Phys. 108 (2019) 103709
J.-W. Chen, J.-y. Pang, S. Pu, Q. Wang, PRD 89 (9) (2014) 094003

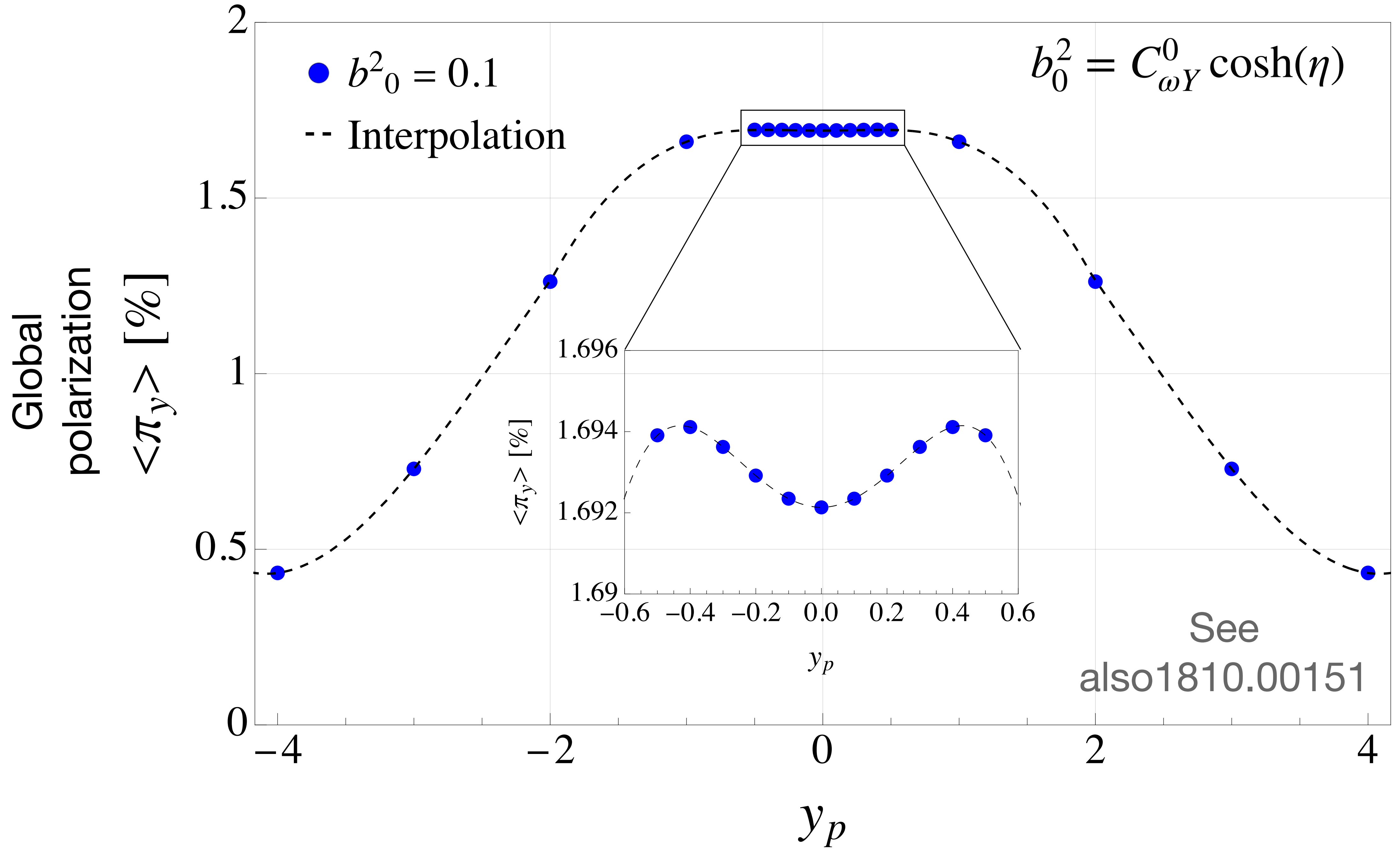
$$f^{\pm}_{\rm eq}(x,p,s) = \exp\left(-p\cdot\beta(x) \pm \xi(x) + \frac{1}{2}\omega_{\alpha\beta}(x)s^{\alpha\beta}\right)$$

$$\int dS \ldots = \frac{m}{\pi \mathfrak{s}} \int d^4s\, \delta(s\cdot s + \mathfrak{s}^2)\, \delta(p\cdot s) \ldots$$

$$N^{\mu}_{\rm eq} = \int dP \int dS\, p^{\mu} \left[f^{+}_{\rm eq}(x,p,s) - f^{-}_{\rm eq}(x,p,s)\right]$$

$$T^{\mu\nu}_{\rm eq} = \int dP \int dS\, p^{\mu}p^{\nu} \left[f^{+}_{\rm eq}(x,p,s) + f^{-}_{\rm eq}(x,p,s)\right]$$

$$S^{\lambda\mu\nu}_{\rm eq} = \int dP \int dS\, p^{\lambda}\, s^{\mu\nu} \left[f^{+}_{\rm eq}(x,p,s) + f^{-}_{\rm eq}(x,p,s)\right]$$




W. Florkowski, A. Kumar, R. Ryblewski, R. Singh, *Phys.Rev.C* 99 (2019) 4, 044910
R. Singh, G. Sophys, R. Ryblewski, *Phys.Rev.D* 103 (2021) 7, 074024
R. Singh, M. Shokri, R. Ryblewski, *Phys.Rev.D* 103 (2021) 9, 094034
W. Florkowski, R. Ryblewski, R. Singh, G. Sophys, *Phys.Rev.D* 105 (2022) 5, 054007

## Explicit constitutive relations

$$N^{\alpha}_{\rm eq} = n u^{\alpha}$$

$$T^{\alpha\beta}_{\rm eq}(x) = \varepsilon u^{\alpha}u^{\beta} - P\Delta^{\alpha\beta}$$

$$S^{\lambda,\mu\nu}_{\rm eq} = S^{\lambda,\mu\nu}_{\rm GLW} = \mathcal{C}\left(n_0(T)u^{\lambda}\omega^{\mu\nu} + S^{\lambda,\mu\nu}_{\Delta\rm GLW}\right)$$

$$S^{\alpha,\beta\gamma}_{\Delta\rm GLW} = \mathcal{A}_0\, u^{\alpha}u^{\delta}u^{[\beta}\omega^{\gamma]}_{\ \delta} + \mathcal{B}_0\left(u^{[\beta}\Delta^{\alpha\delta}\omega^{\gamma]}_{\ \delta} + u^{\alpha}\Delta^{\delta[\beta}\omega^{\gamma]}_{\ \delta} + u^{\delta}\Delta^{\alpha[\beta}\omega^{\gamma]}_{\ \delta}\right)$$

**For $|\omega_{\mu\nu}| < 1$ one obtains the formalism that agrees with that based on the quantum description of spin (in the GLW version).**

$$\langle\pi_{\mu}\rangle = \frac{\int dP \langle\pi_{\mu}\rangle_p E_p \frac{d\mathcal{N}(p)}{d^3p}}{\int dP E_p \frac{d\mathcal{N}(p)}{d^3p}} \equiv \frac{\int d^3p\, \frac{d\Pi^{\star}_{\mu}(p)}{d^3p}}{\int d^3p\, \frac{d\mathcal{N}(p)}{d^3p}}$$