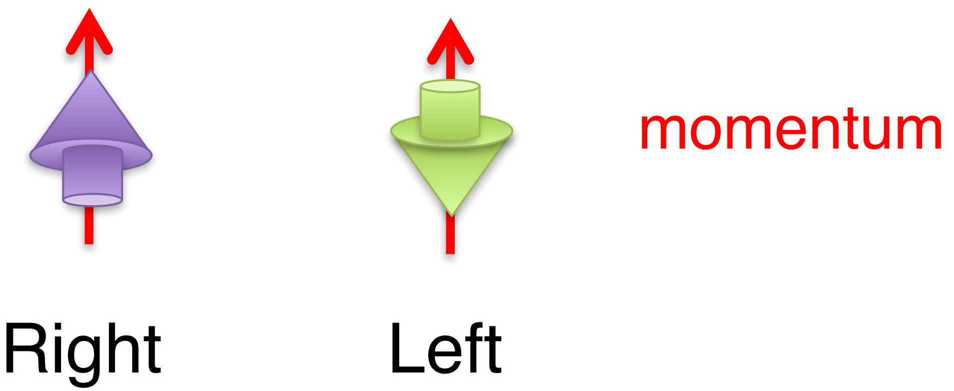
Theoretical overview on the search of anomalous chiral effects

Yuji Hirono

Stony Brook → BNL(Apr. 2016 -)

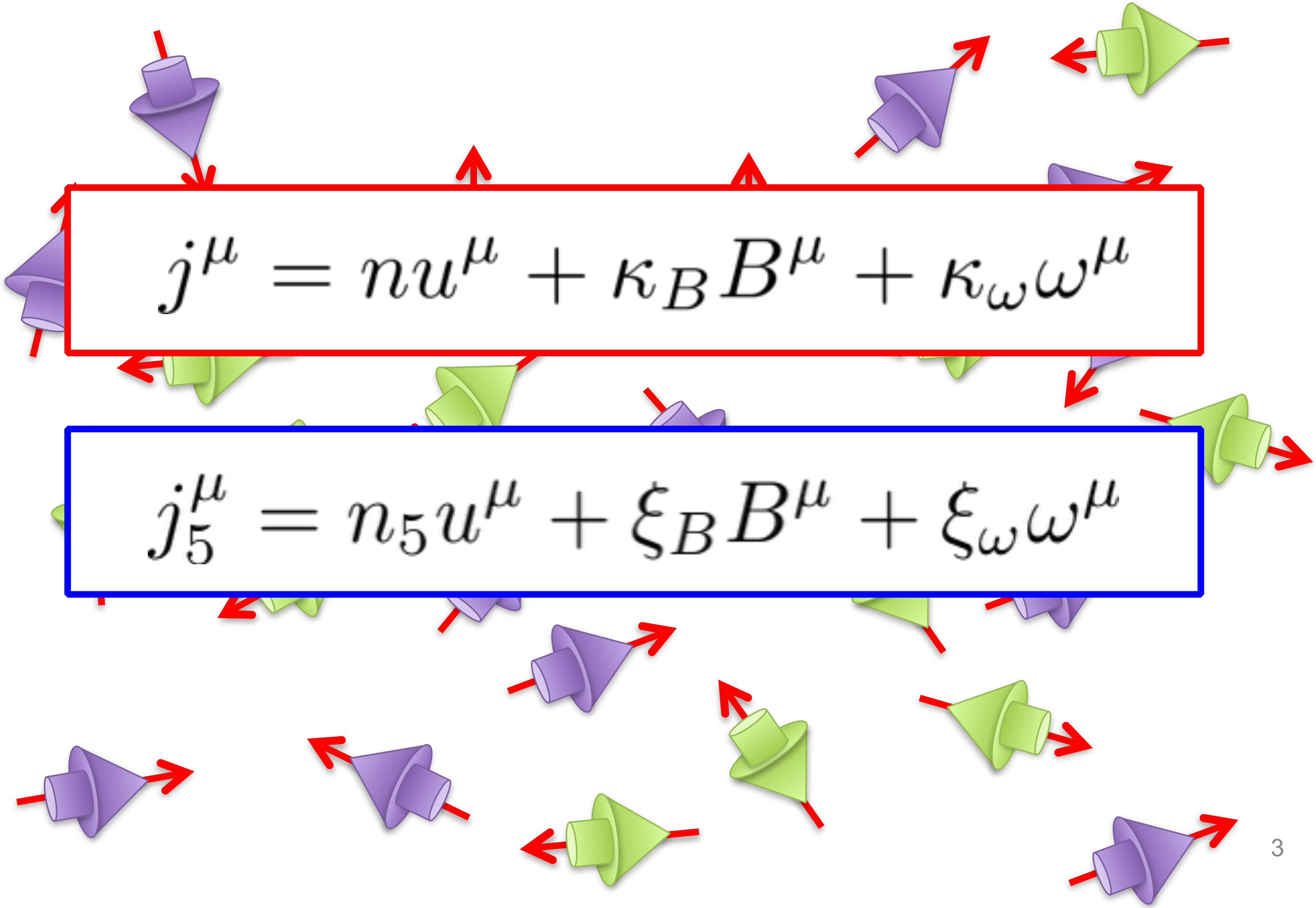
Anomalous chiral effects



$$\partial_\mu j_5^\mu = C E_\mu B^\mu$$

$$j_5^\mu = j_{\mathrm{R}}^\mu - j_{\mathrm{L}}^\mu$$

Anomalous chiral effects



$$j^\mu = n u^\mu + \kappa_B B^\mu + \kappa_\omega \omega^\mu$$

$$j_5^\mu = n_5 u^\mu + \xi_B B^\mu + \xi_\omega \omega^\mu$$

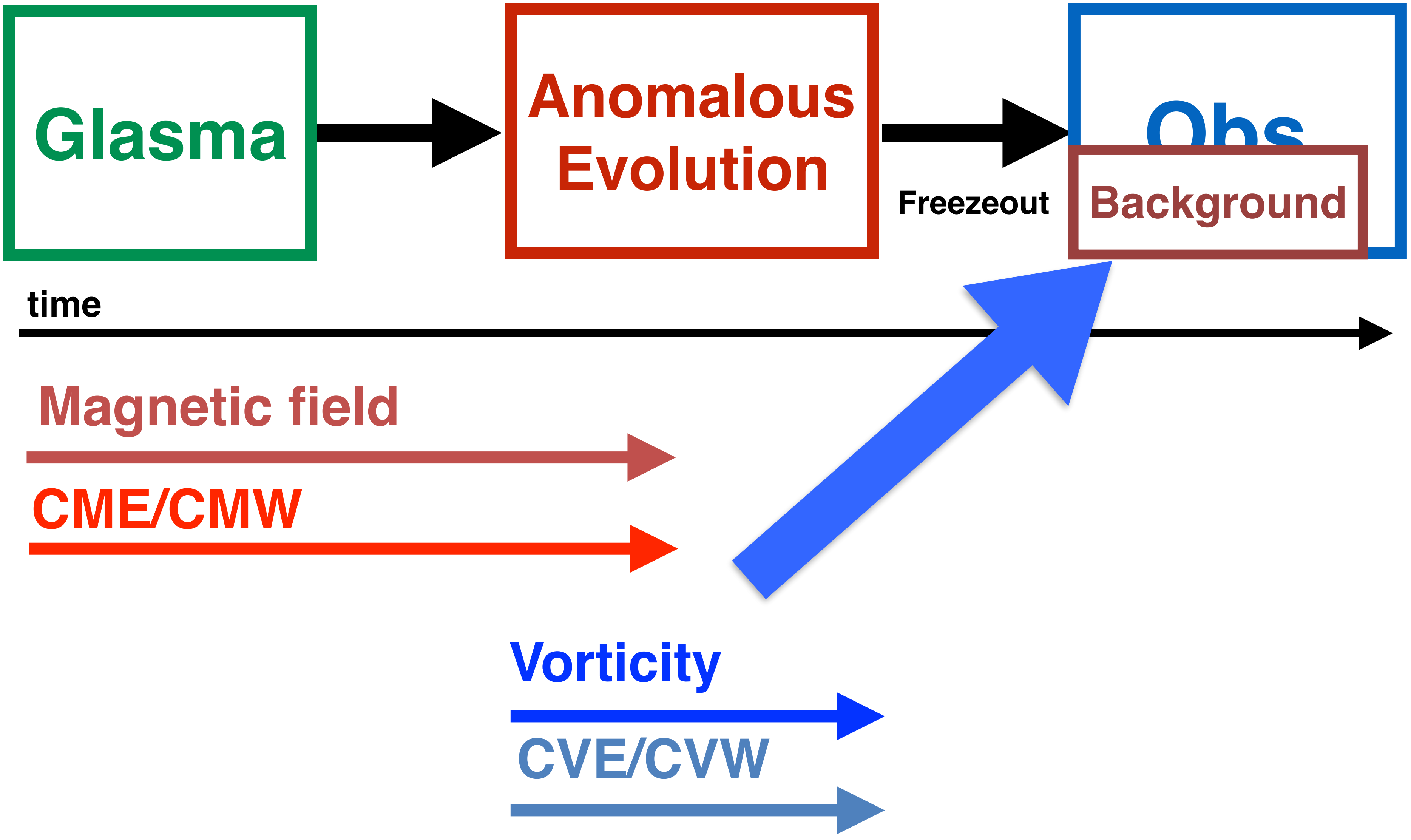
Theoretical frameworks

- **Anomalous hydrodynamics**

  [Son-Surowka 2009; …]

- **Chiral kinetic theory**

  [Son-Yamamoto; Stephanov-Yin; …]

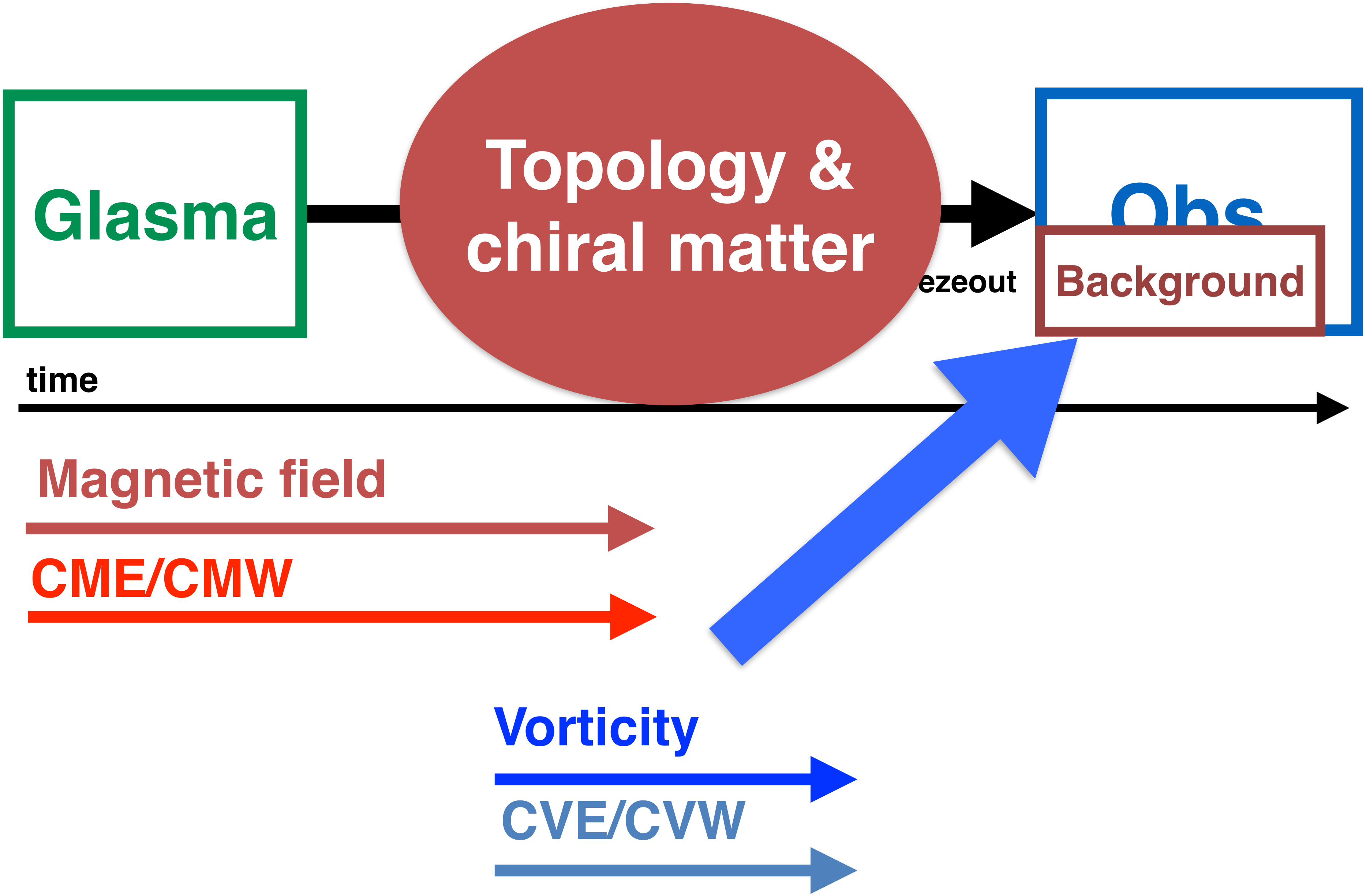

Glasma
Anomalous
Evolution
Obs
Background
Freezeout
time
Magnetic field
CME/CMW
Vorticity
CVE/CVW

Anomalous

Recent theoretical developments

Dynamical modeling of anomalous chiral effects

Outlook for future efforts


Glasma
Topology &
chiral matter
Obs
ezeout
Background
time
Magnetic field
CME/CMW
Vorticity
CVE/CVW

Magnetic & fermionic helicities

$$\partial_\mu j_A^\mu = C_A \boldsymbol{E} \cdot \boldsymbol{B}$$

$$\Rightarrow \boxed{\frac{d}{dt}\left[\mathcal{H} + \mathcal{H}_F\right] = 0}$$

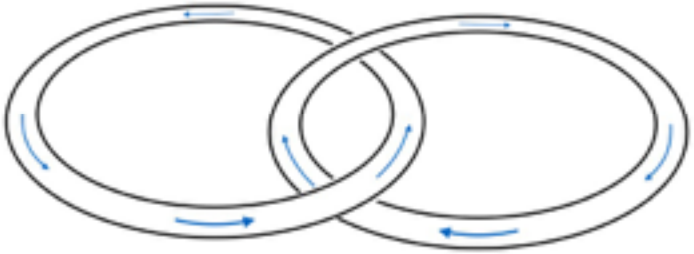
$$\mathcal{H} = \int d^3x \boldsymbol{A} \cdot \boldsymbol{B} \qquad \mathcal{H}_F = \frac{2}{C_A}\int d^3x \, n_A$$

Magnetic helicity

Fermionic helicity

Magnetic helicity knows topology

$$\mathcal{H} = \int d^3x \, \boldsymbol{A} \cdot \boldsymbol{B}$$

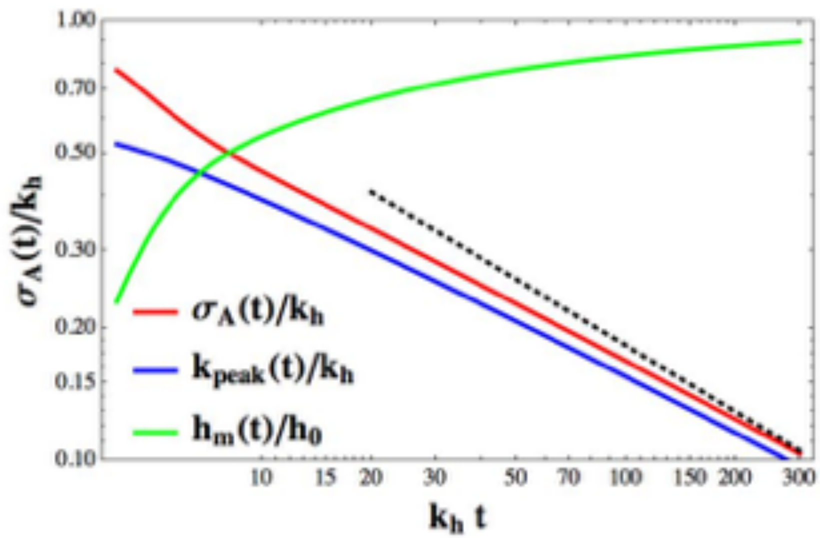


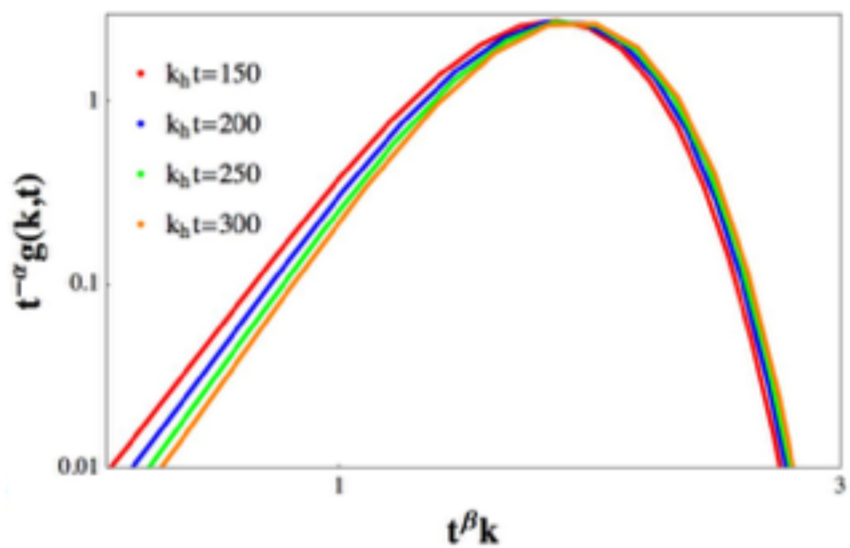
$$= \sum_i \mathcal{S}_i \varphi_i^2 + 2 \sum_{i,j} \mathcal{L}_{ij} \varphi_i \varphi_j$$

Self-linking number **Linking number**

Self-similar inverse cascade of magnetic fields

[Hirono-Yin-Khazeev 1509.07790]



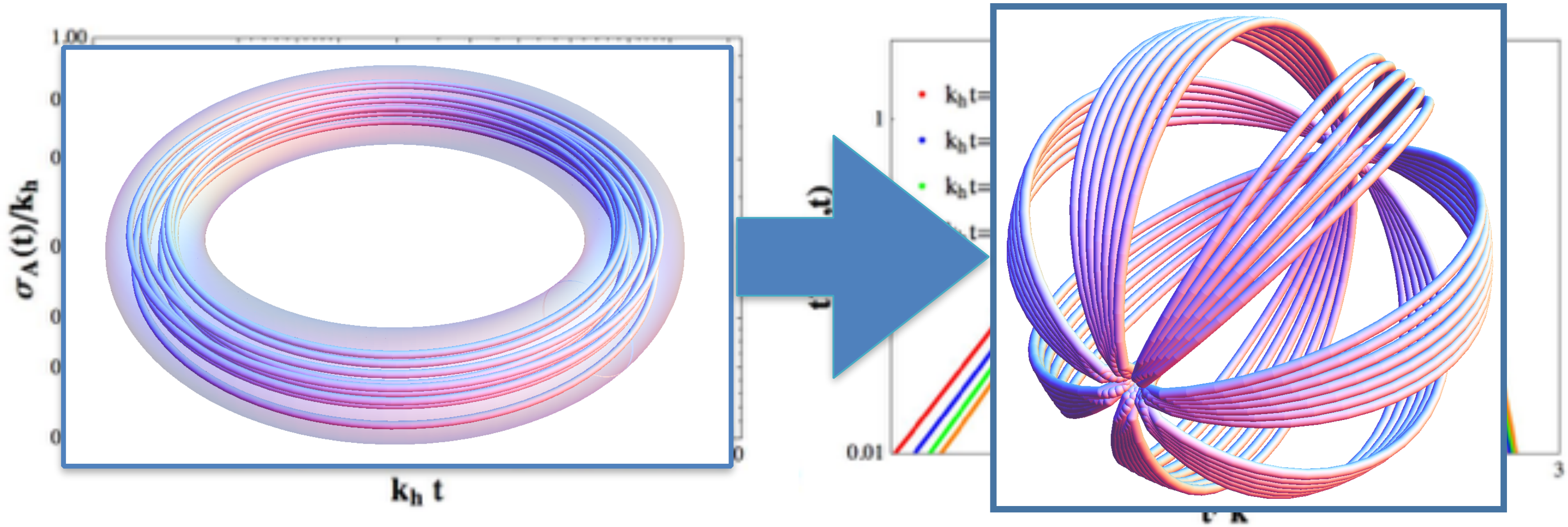


Solved Maxwell-Chern-Simons equations

$$g(k,t) \sim t^{\alpha} \tilde{g}(t^{\beta} k) \quad \alpha = 1, \quad \beta = 1/2$$

Self-similar inverse cascade of magnetic fields

[Hirono-Yin-Khazeev 1509.07790]



Solved Maxwell-Chern-Simons equations

$$g(k,t) \sim t^{\alpha} \tilde{g}(t^{\beta} k) \quad \alpha = 1, \quad \beta = 1/2$$

Anomalous Maxwell equations for inhomogeneous chiral plasma

E. V. Gorbar,[1,2] I. A. Shovkovy,[3] S. Vilchinskii,[1,4] I. Rudenok,[1] A. Boyarsky,[5] and O. Ruchayskiy[6]

[1603.03442]

- Chiral kinetic theory in relaxation time approx.
  - Expansion in B, E//, and derivatives

CME — Ohmic conductivity — Hall current — Diffusion current

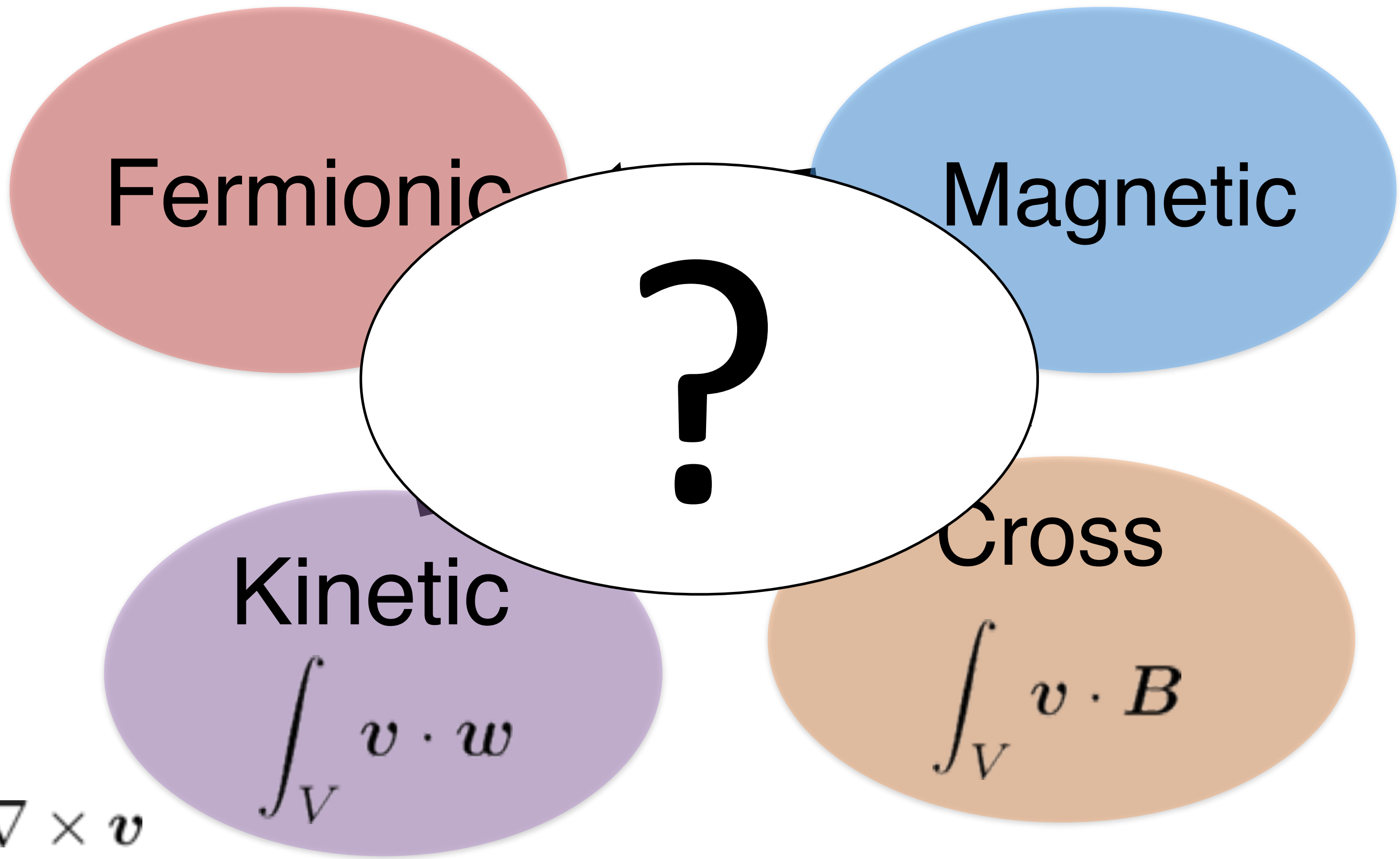
$$\mathbf{j} = \frac{e\mathbf{B}\mu_5}{2\pi^2 c} + \frac{\tau T^2}{9c}\left(1 + \frac{3(\mu^2+\mu_5^2)}{\pi^2 T^2}\right)\left(e\mathbf{E} - \frac{\partial \mu}{\partial \mathbf{x}}\right) + \frac{e^2\tau^2\mu}{3\pi^2}\mathbf{E}\times\mathbf{B} - \frac{2e\tau\mu\mu_5}{3\pi^2 c}\frac{\partial \mu_5}{\partial \mathbf{x}}$$

$$+\frac{e\tau^2\mu}{3\pi^2}\left(\mathbf{B}\times\frac{\partial \mu}{\partial \mathbf{x}}\right) + \frac{e\tau^2\mu_5}{3\pi^2}\left(\mathbf{B}\times\frac{\partial \mu_5}{\partial \mathbf{x}}\right) - \frac{e\tau^2 T^2}{9c}\left(1 + \frac{3(\mu^2+\mu_5^2)}{\pi^2 T^2}\right)\frac{\partial \mathbf{E}}{\partial t} - \frac{e\tau\mu_5}{6\pi^2 c}\frac{\partial \mathbf{B}}{\partial t} - \frac{e\tau}{6\pi^2}\mathbf{E}\times\frac{\partial \mu_5}{\partial \mathbf{x}}$$

New terms including derivatives

Chiral-magnetohydrodynamics

- 4 helicities



$\boldsymbol{\omega} = \nabla \times \boldsymbol{v}$

Self-similar solutions in chiral MHD

Scaling laws in chiral hydrodynamic turbulence

Naoki Yamamoto [1603.08864]

$$\bar{n}_5(t) = \bar{n}_5(t_s)\left(\frac{t_s}{t}\right)^{\frac{1}{2}}$$

$$\xi_B(t) = \xi_B(t_s)\left(\frac{t}{t_s}\right)^{\frac{1}{2}}$$

magnetic correlation length

$$\xi_v(t) = \xi_v(t_s)\left(\frac{t}{t_s}\right)^{\frac{1}{2}}$$

kinetic correlation length

Self-similar inverse cascade in chiral MHD

Exponents differ btw. zero & finite fluid helicities

Quantized chiral magnetic current from the change of topology

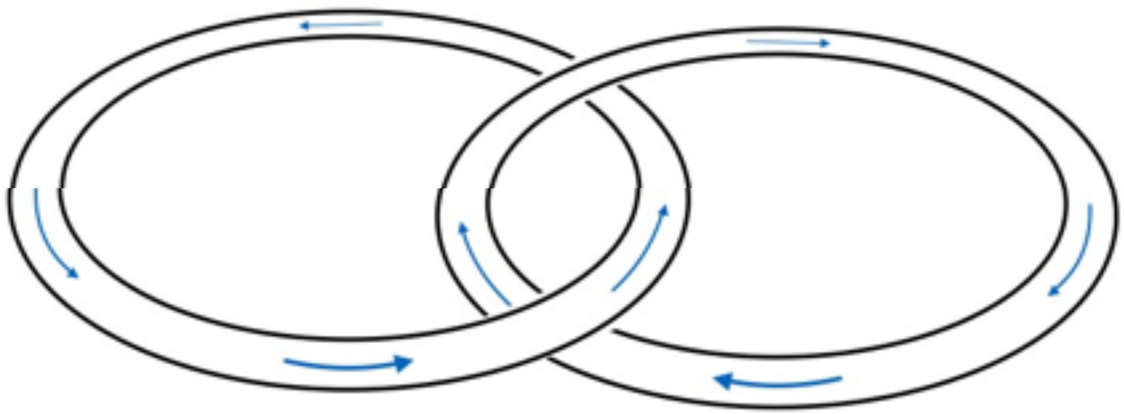
[Hirono-Khazeev-Yin, in prep.]

$$\sum_i \oint_{C_i} \Delta \boldsymbol{J} \cdot d\boldsymbol{x} = -\frac{e^3}{2\pi^2} \Delta \mathcal{H}$$

Change of topology induces CME currents!

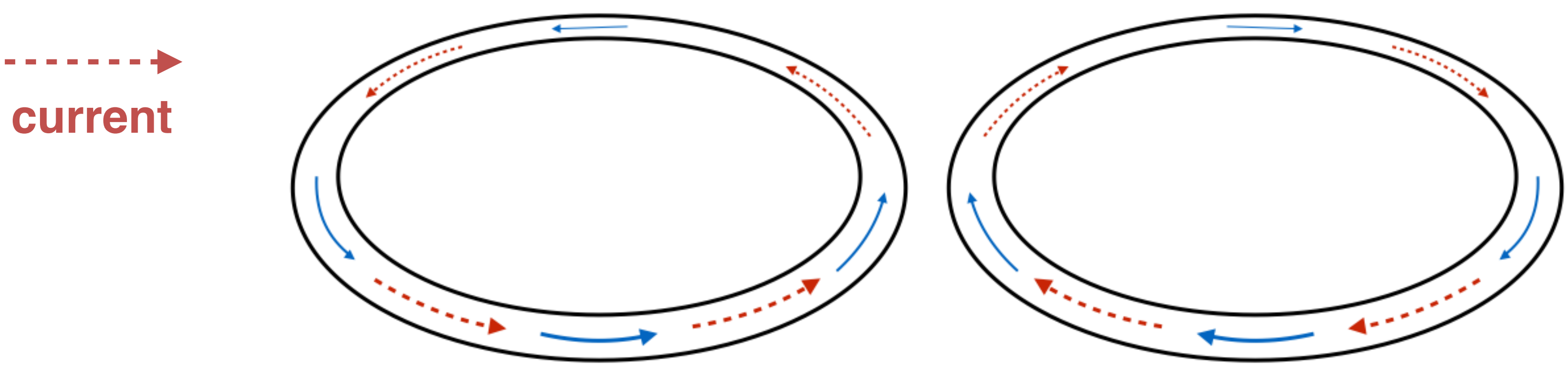
Quantized chiral magnetic current from the change of topology

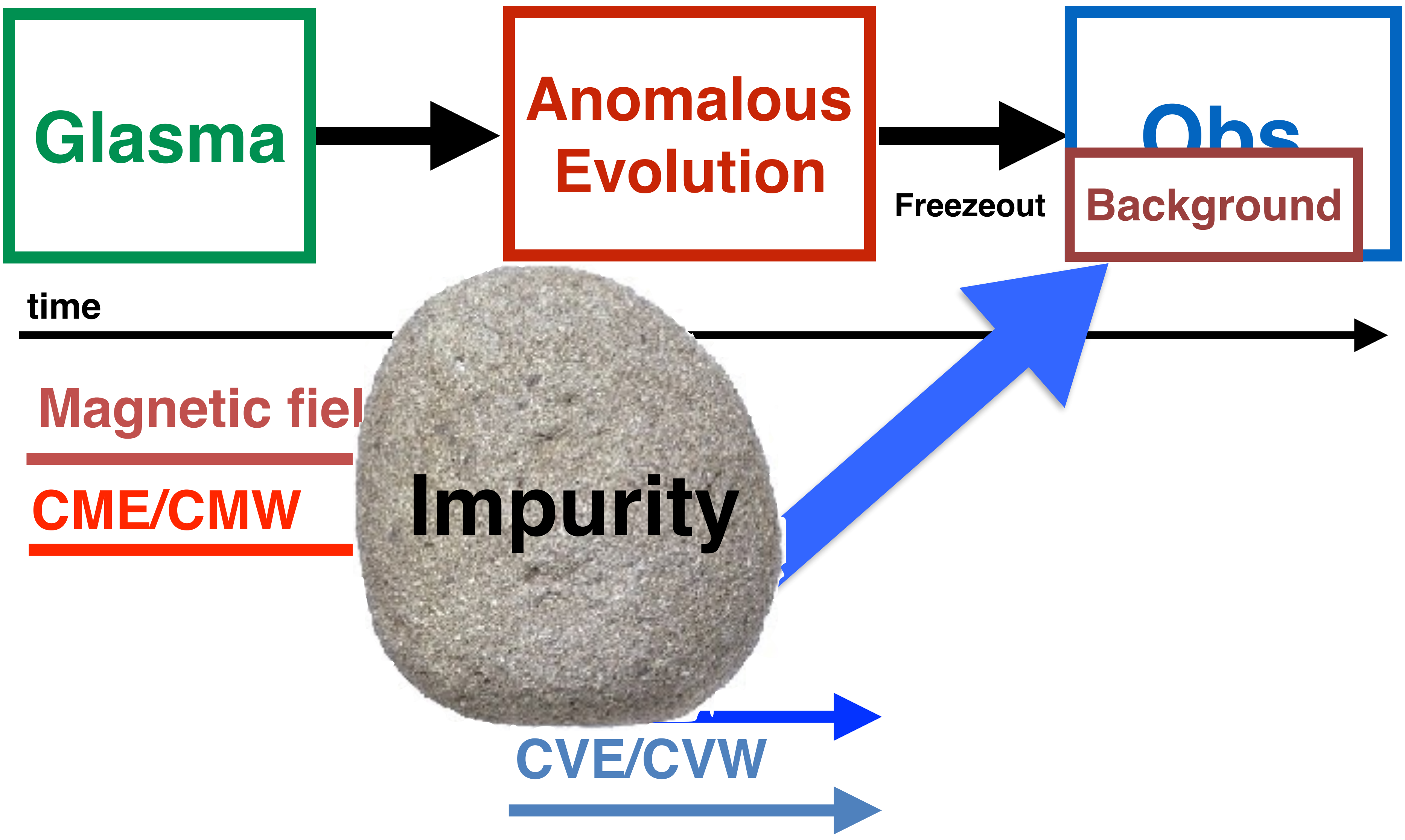
[Hirono-Khazeev-Yin, in prep.]



$$\sum_i \oint_{C_i} \Delta \boldsymbol{J} \cdot d\boldsymbol{x} = -\frac{e^3}{2\pi^2} \Delta \mathcal{H}$$

$$\Delta \mathcal{H} = -2\varphi^2$$





Glasma
Anomalous Evolution
Obs
Background
Freezeout
time
Magnetic fiel
CME/CMW
Impurity
CVE/CVW

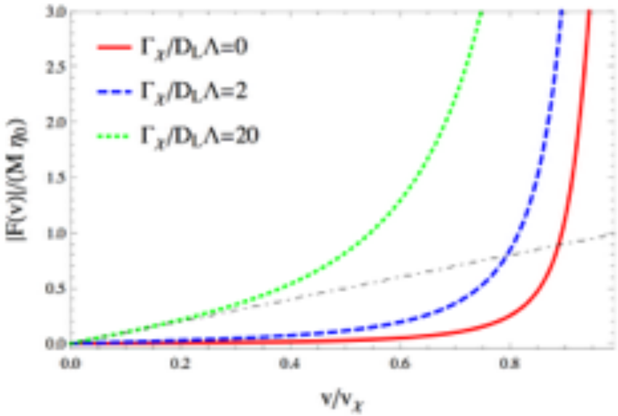
Impurity in chiral fluid

Drag force on heavy quarks from CME in holography

[Rajagopal-Sadofyev 1505.07379]

Absence of drag force due to Landau zero modes

[Sadofyev-Yin 1511.08794]



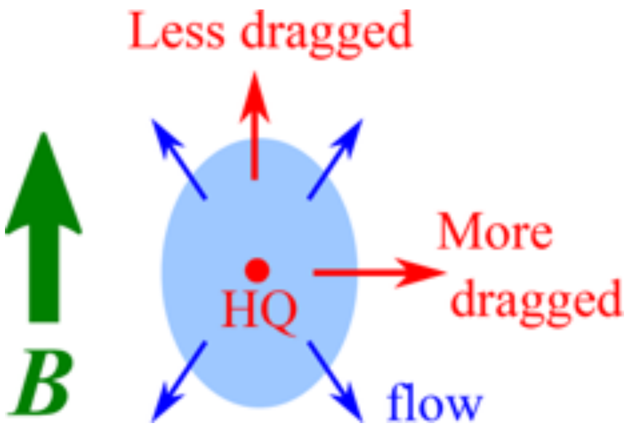
"No drag frame" **[Stephanov-Yee 1508.02396]**

a velocity frame in which:

- drag force takes a simple form
- transport coefficients are just polynomial of T & mu

Drag force under B at weak coupling

[Fukushima-Hattori-Yee-Yin 1512.03689]



$$\frac{dp_z}{dt} = -\eta_{\parallel} p_z + \xi_z$$

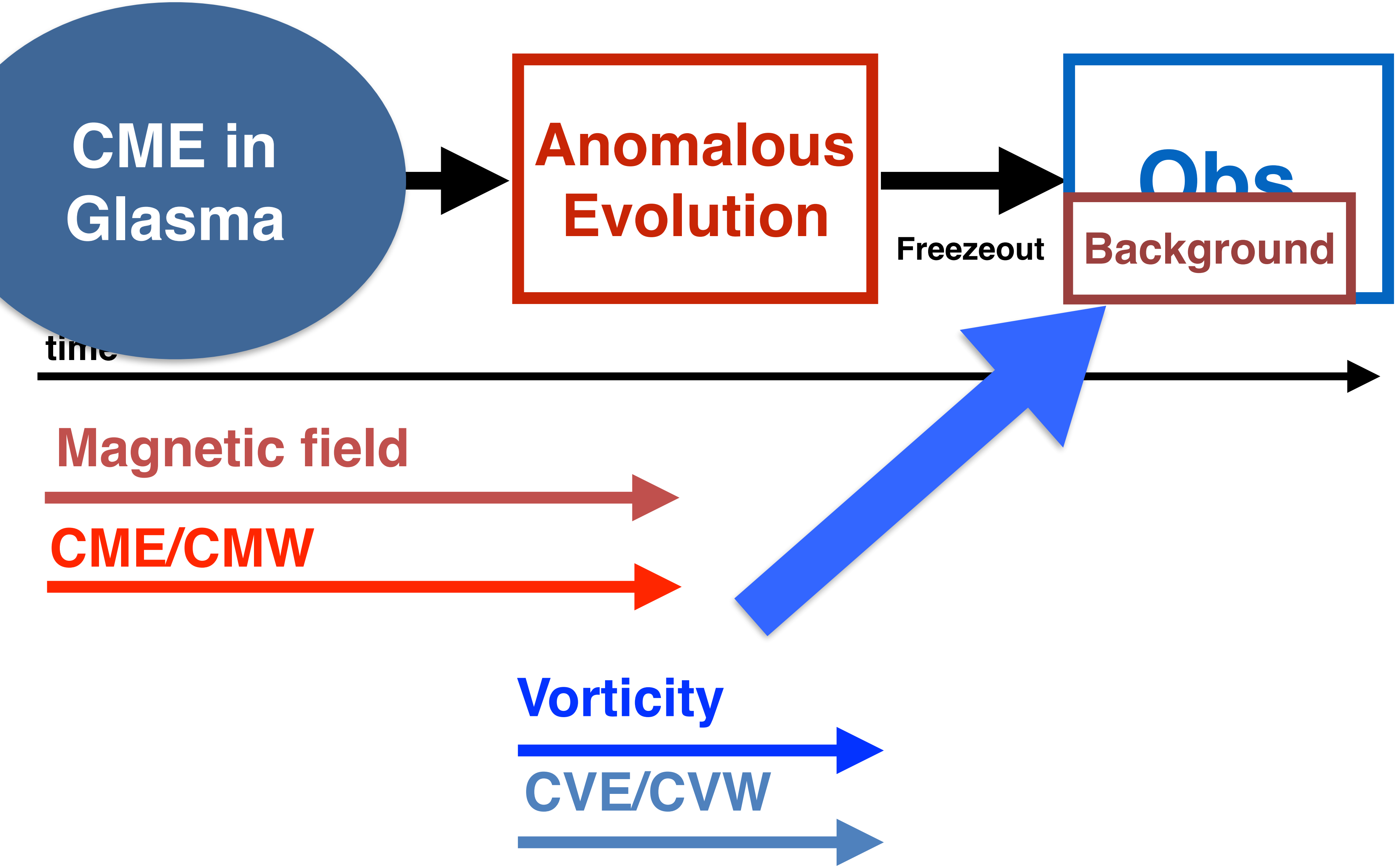
$$\frac{d\boldsymbol{p}_\perp}{dt} = -\eta_\perp \boldsymbol{p}_\perp + \boldsymbol{\xi}_\perp$$

Drag force calculated perturbatively

Longitudinal drag force is suppressed

$$\frac{\eta_{\parallel}(B)}{\eta_\perp(B)} = \frac{\kappa_{\parallel}(B)}{\kappa_\perp(B)} \sim \frac{T^2}{eB} \ll 1$$

[Obs] D meson v2?


CME in Glasma
Anomalous Evolution
Freezeout
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time
Magnetic field
CME/CMW
Vorticity
CVE/CVW

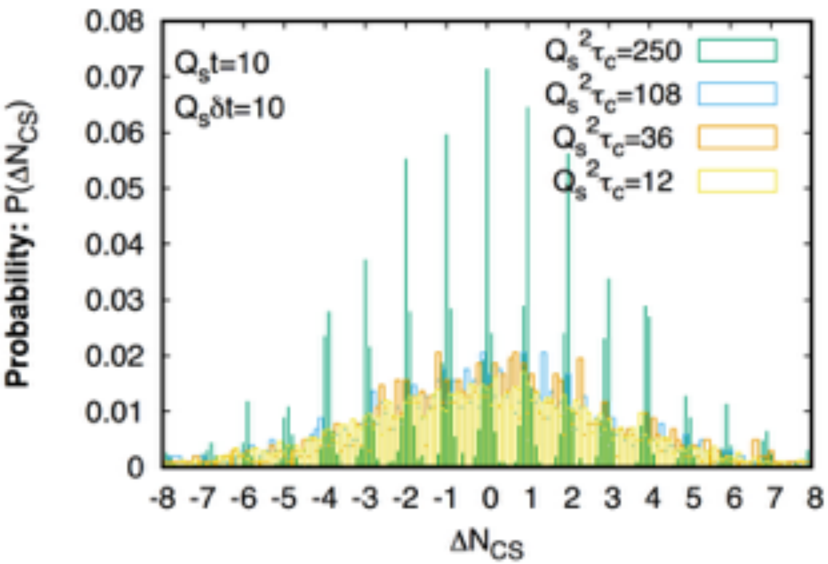
Sphaleron rates in glasma

[1601.07342]

Off-equilibrium sphaleron transitions in the Glasma

Mark Mace,[1,2] Sören Schlichting,[2] and Raju Venugopalan[2,3]

[Talk by Mace on Tue.]



Probability dist. of ΔN_{CS}

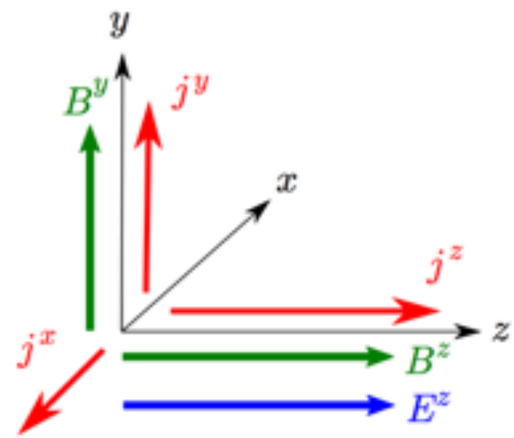
Glasma evolution in classical YM

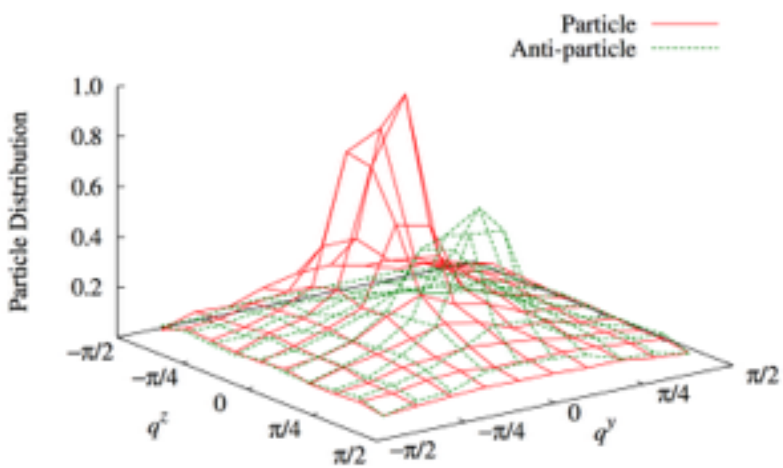
Enhancement of sphaleron rate compared to eq. value

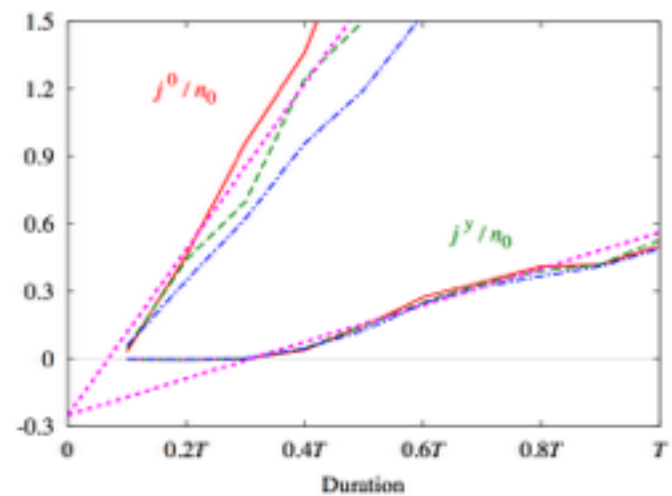
Real-time CME in glasma

[Fukushima 1501.01940]

Particle & current production from CP-breaking background



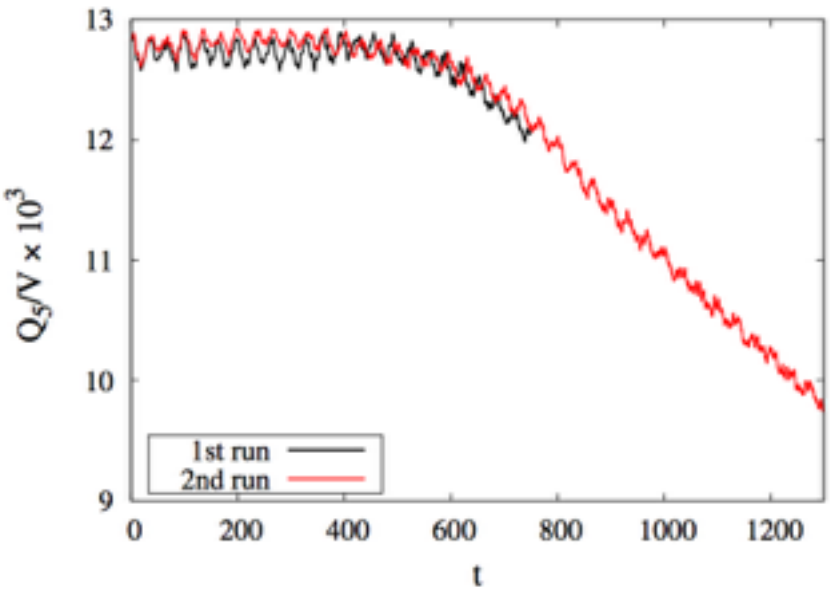


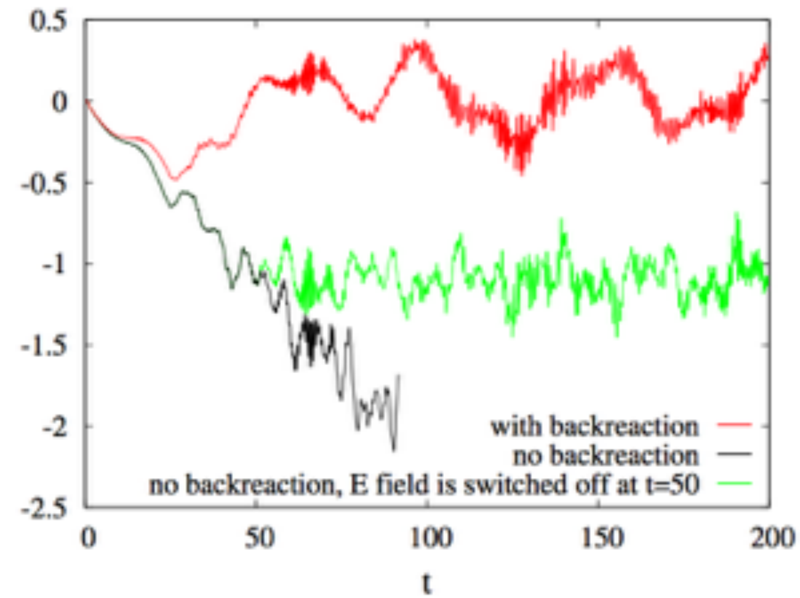


Charge separation

CME in EM fields with real-time lattice

[Buividovich-Ulybyshev 1509.02076]





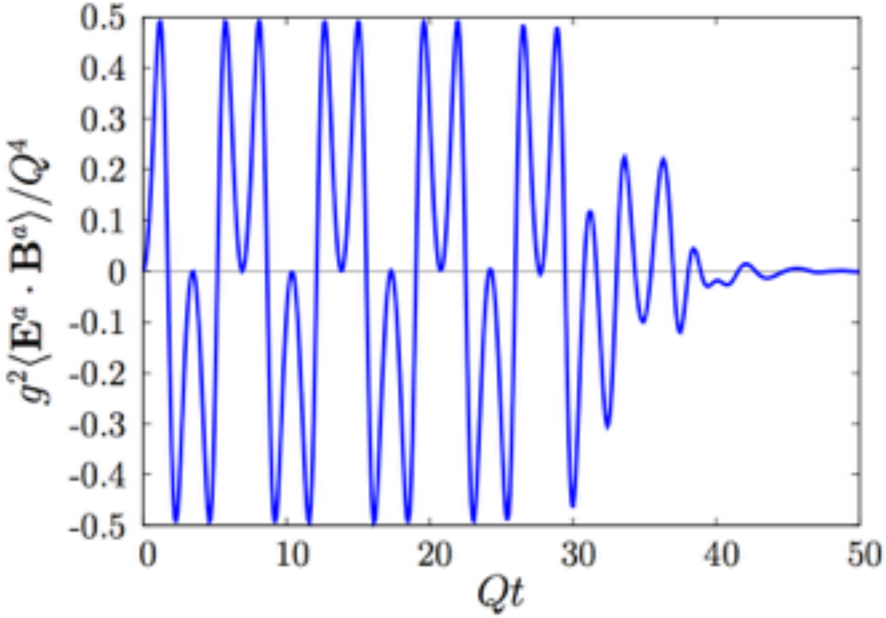
Chirality pumping
with/wo backreaction

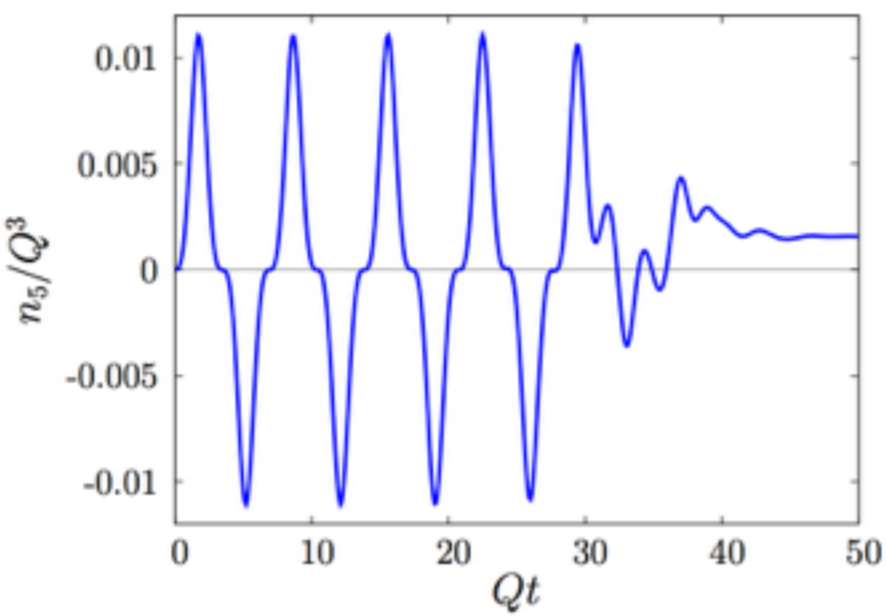
Backreaction of fermions prevents the system from acquiring large chirality imbalance

Real-time n5 production in glasma

[Tanji-Mueller-Berges 1603.03331]

Real-time lattice simulation with back reaction from fermions

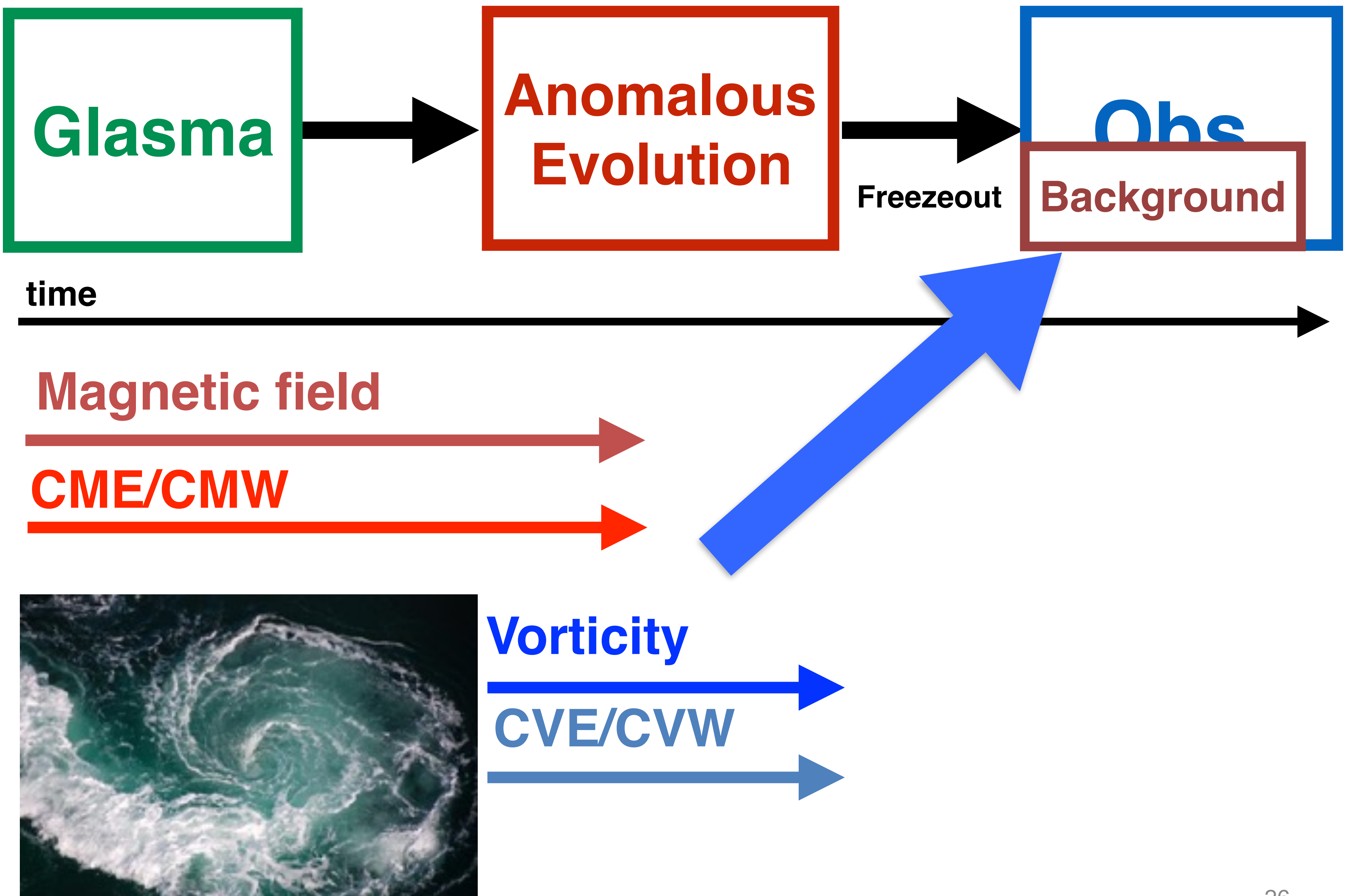




Production of n5 from color E dot B

Particle & current production in classical gauge fields on lattice

	Fukushima [1501.01940]	Buividovich & Ulybyshev [1509.02076]	Tanji et. al [1603.03331]
Gauge field	**U(1) [bg]**	**U(1)**	**SU(2)**
Backreaction	**No**	**Yes**	**Yes**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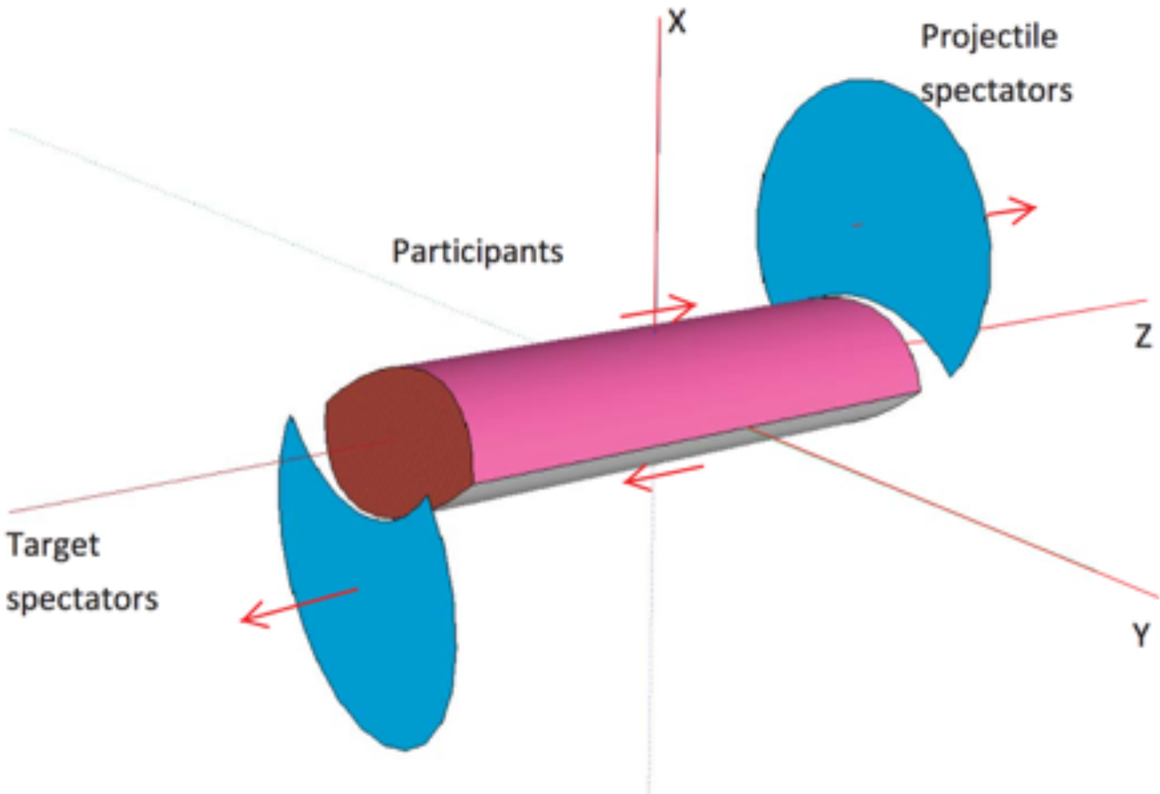
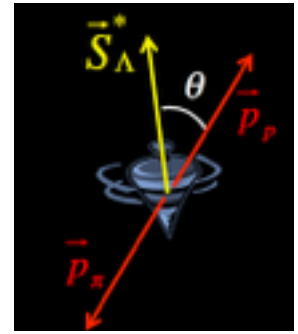
CME/CMW
Vorticity
CVE/CVW

Vorticity in off-central collisions



Figures taken from [Csernai-Magas-Wang 1302.5310]

Λ polarization & vorticity



Taken from Mike Lisa's talk @UCLA 2016

Polarization probes of vorticity in heavy ion collisions

Barbara Betz,[1,2] Miklos Gyulassy,[1,3,4] and Giorgio Torrieri[1,3] [0708.0035]

Flow Vorticity in Peripheral High Energy Heavy Ion Collisions

L.P. Csernai[1], V.K. Magas[2], and D.J. Wang[1] [1302.5310]

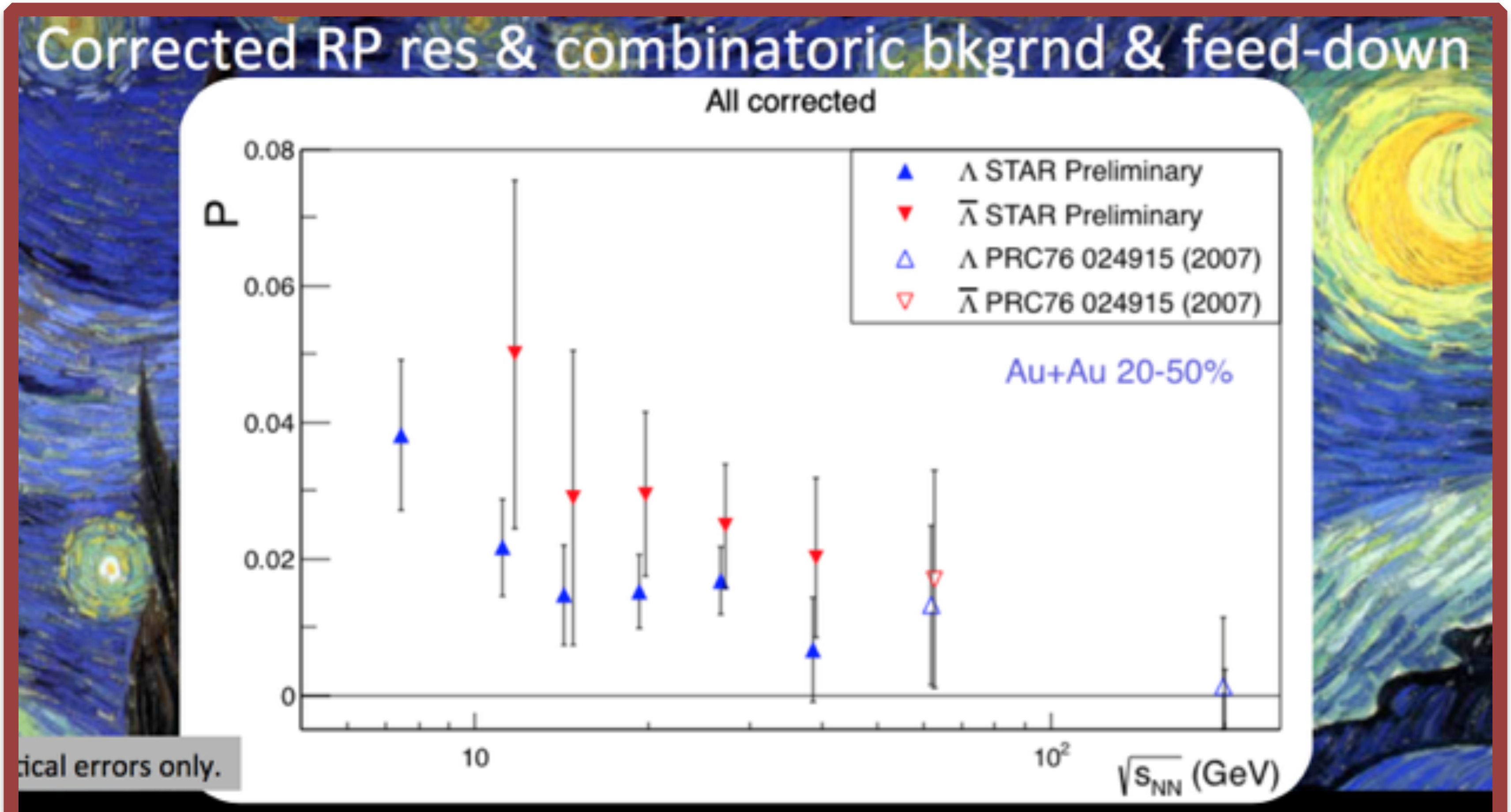
Lambda Polarization in Peripheral Heavy Ion Collisions

F. Becattini[1,2], L.P. Csernai[3], D.J. Wang[3,4] [1304.4427]

A study of vorticity formation in high energy nuclear collisions [1501.04468]

F. Becattini,[1,2] G. Inghirami,[3,1] V. Rolando,[4,5] A. Beraudo,[6]
L. Del Zanna,[1,2,7] A. De Pace,[6] M. Nardi,[6] G. Pagliara,[4,5] and V. Chandra[8]

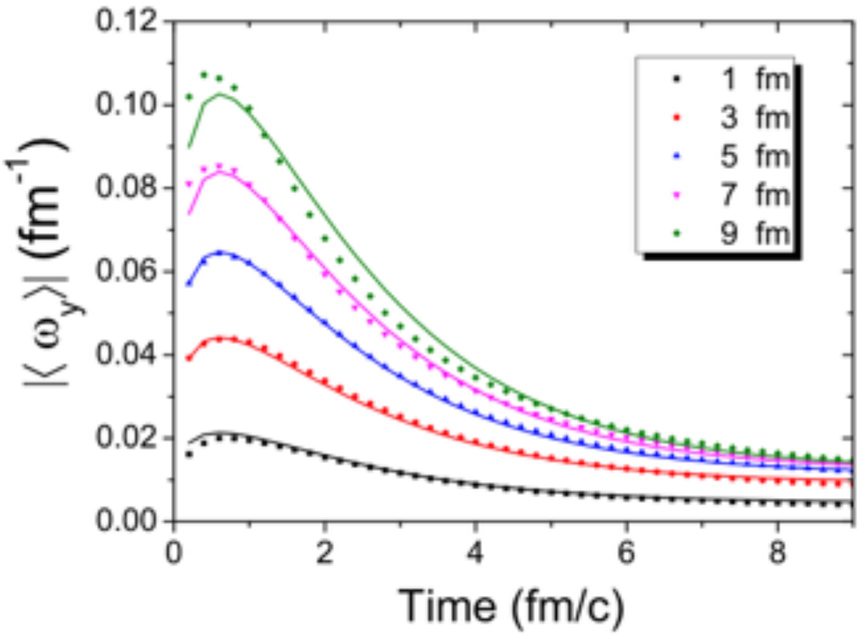
Polarization of Lambdas



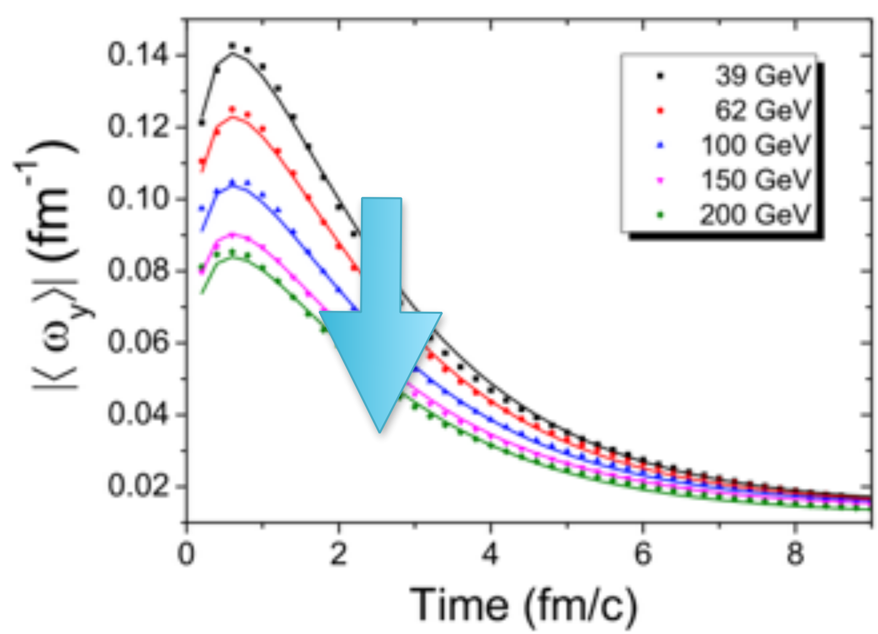
Taken from Mike Lisa's talk@UCLA 2016

Vorticity from AMPT

[Jiang-Lin-Liao 1602.06580]
[Talk by Jiang on Tue.]



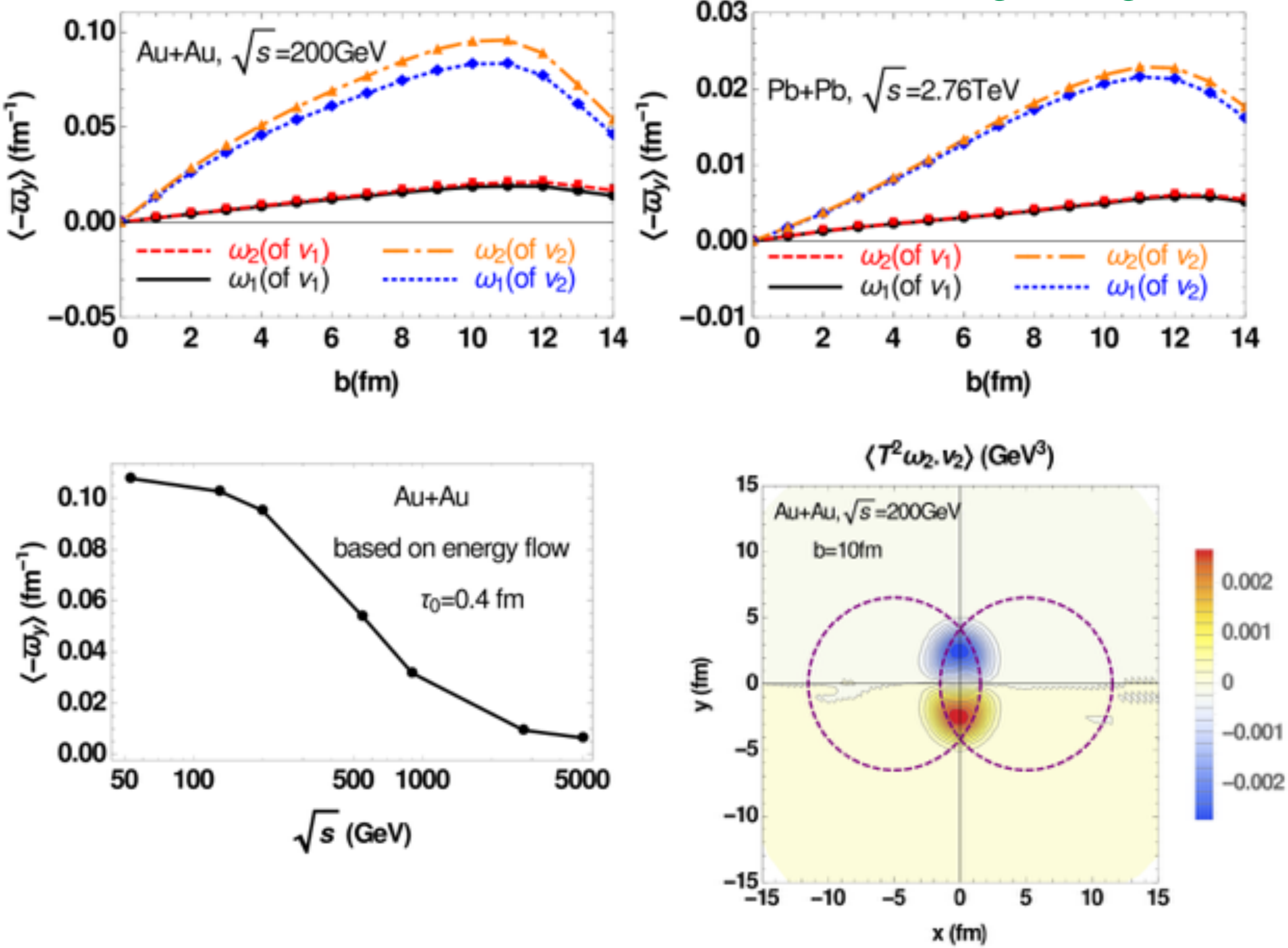
Impact parameter dep.

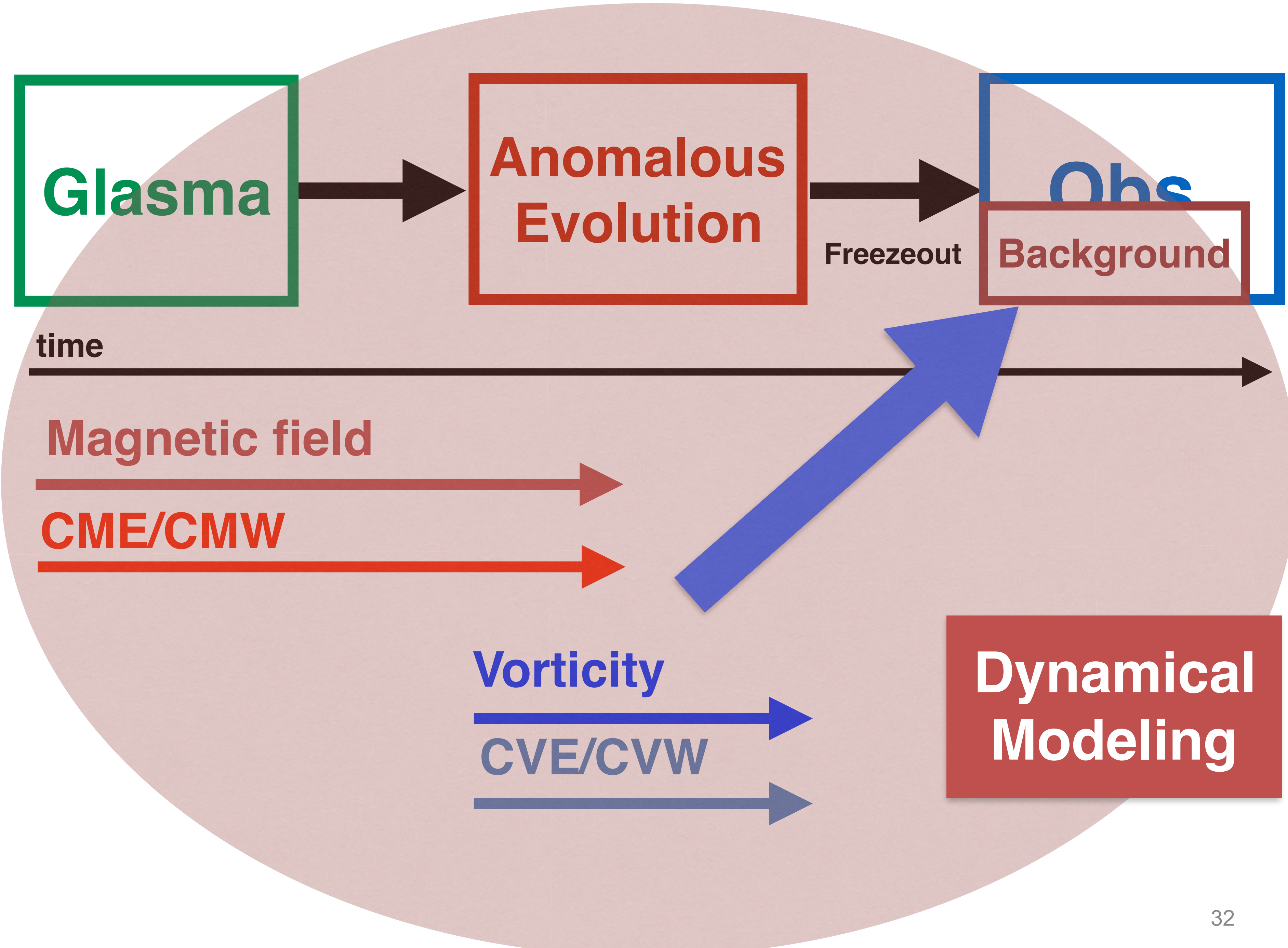


Collision energy dep.

Initial fluid vorticity from HIJING

[Deng-Huang 1603.06117]

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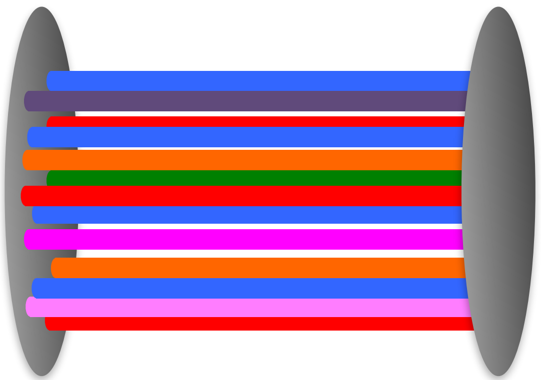
Dynamical
Modeling

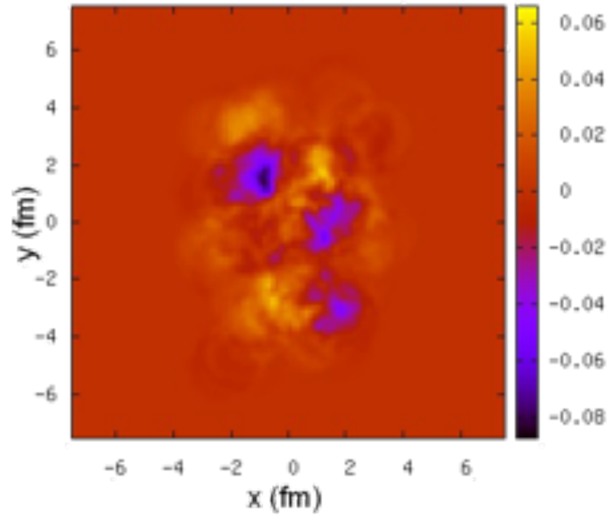
Event-by-event anomalous hydro

[Hirono-Hirano-Khazeev 1412.0311]

- 3+1D Ideal anomalous hydro with CME/CSE with EM fields(no backreaction)

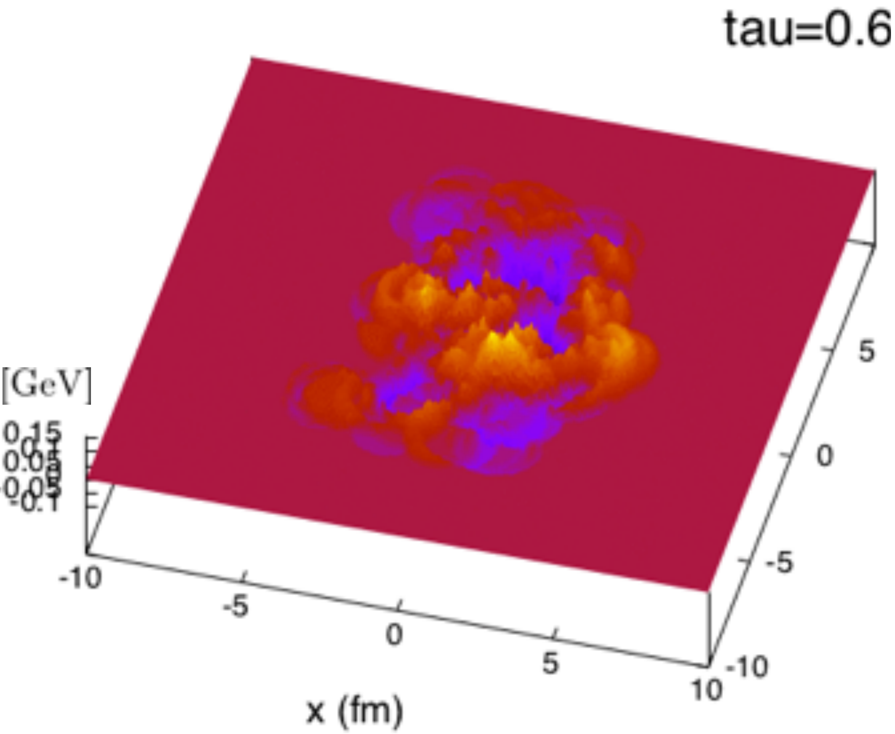


- Event-by-event
- Model of initial axial charge based on flux-tube picture

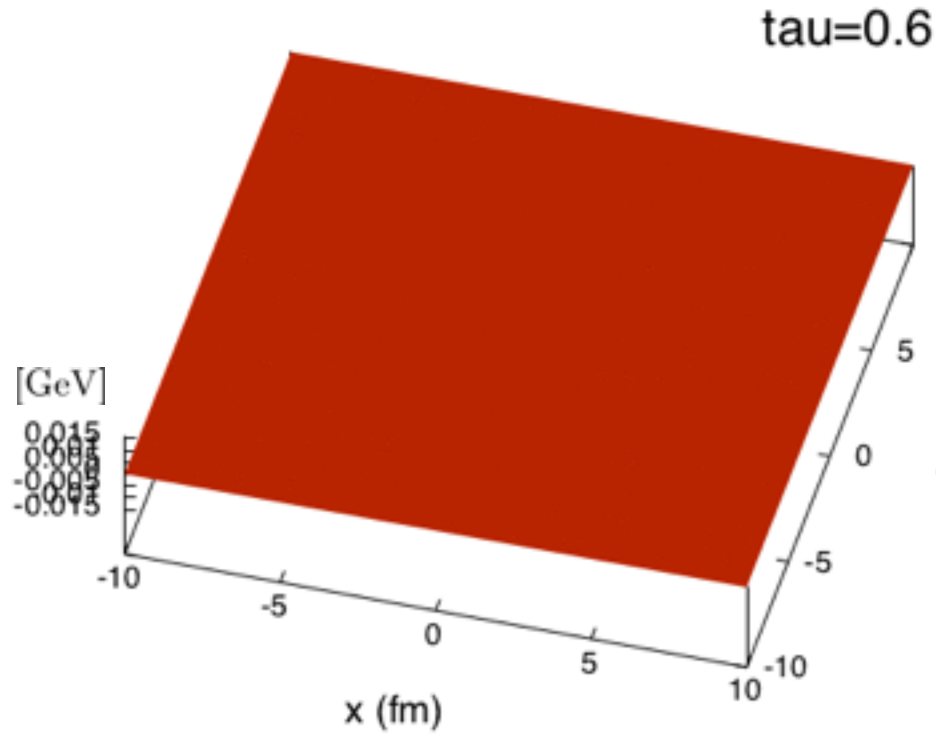


Event-by-event anomalous hydro

[Hirono-Hirano-Khazeev 1412.0311]



μ_5

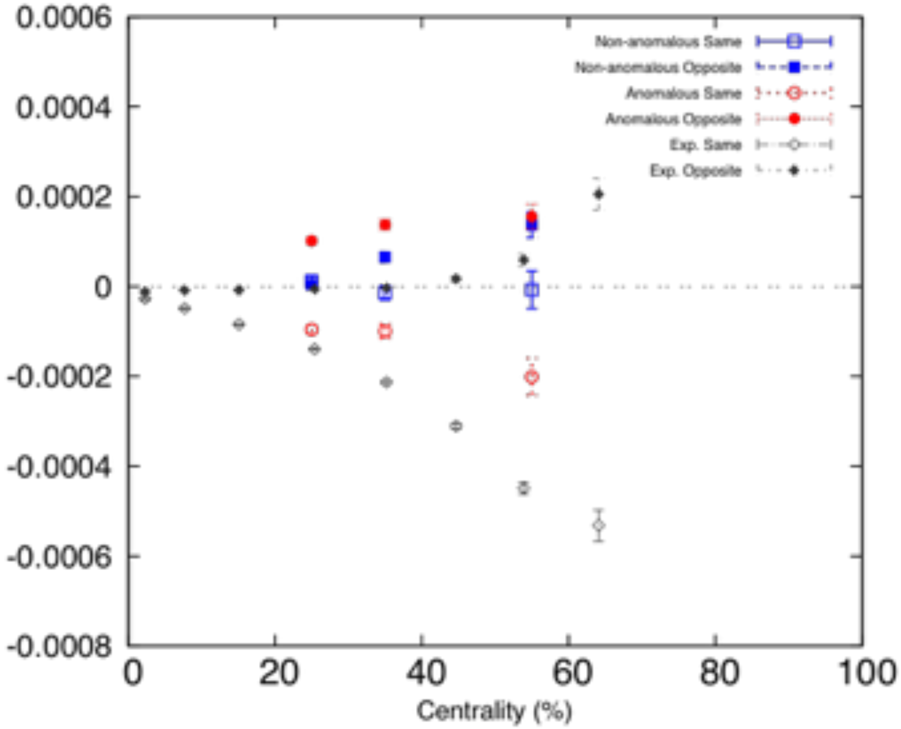


μ

Event-by-event anomalous hydro

[Hirono-Hirano-Khazeev 1412.0311]

$$\gamma_{\alpha\beta} =< \cos(\phi_i + \phi_j - 2\psi_{\mathrm{RP}}) >_{\alpha\beta}$$



Gamma correlations are indeed sensitive to CME/CSE

Values are similar to experimental ones

Hydrodynamics with chiral anomaly and charge separation in relativistic heavy ion collisions

Yi Yin[1,*] and Jinfeng Liao[2,3,†] [1504.06906]

- Charge transport from CME/CSE is solved on top of the solution of 2+1D viscous hydro (VISH)
- Quantify the effects of transverse momentum conservation (TMC)
- Same-charge correlation is calculated

Hydrodynamics with chiral anomaly and charge separation in relativistic heavy ion collisions

Yi Yin[1,*] and Jinfeng Liao[2,3,†]

[1504.06906]

$$\gamma_{\alpha\beta} = < \cos(\phi_i + \phi_j - 2\psi_{\rm RP}) >_{\alpha\beta} \qquad \delta_{\alpha\beta} = < \cos(\phi_i - \phi_j) >_{\alpha\beta}$$

$$\gamma^{\rm data}_{\alpha,\beta} \simeq \boxed{\gamma^{CME}_{\alpha,\beta}} + \gamma^{TMC}_{\alpha,\beta} \;, \quad \delta^{\rm data}_{\alpha,\beta} \simeq \boxed{\delta^{CME}_{\alpha,\beta}} + \delta^{TMC}_{\alpha,\beta}$$

$$(\gamma + \delta)^{\rm data} \approx (\gamma + \delta)^{\rm TMC}$$

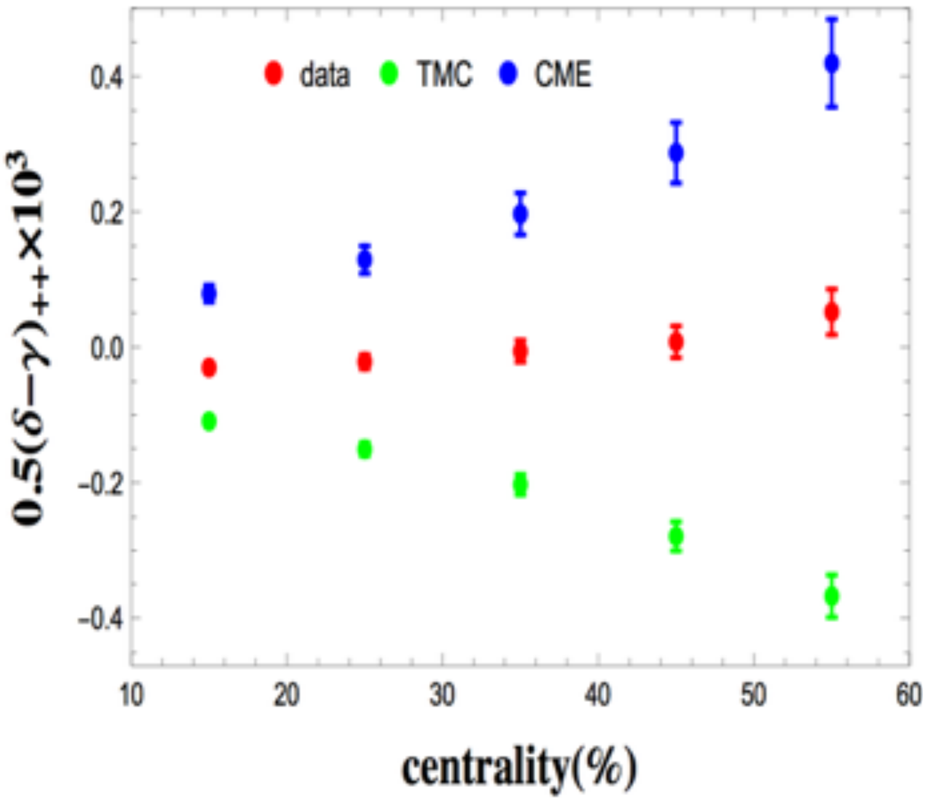
$$\delta^{\rm TMC}_{\alpha\beta} \pm \gamma^{\rm TMC}_{\alpha\beta} = \frac{[\langle p_\perp \rangle_\alpha (1 \pm \bar{v}_{2,\alpha})][\langle p_\perp \rangle_\beta (1 \pm \bar{v}_{2,\beta})]}{N_{TMC} \langle p_\perp^2 \rangle (1 \pm \bar{\bar{v}}_2)}$$

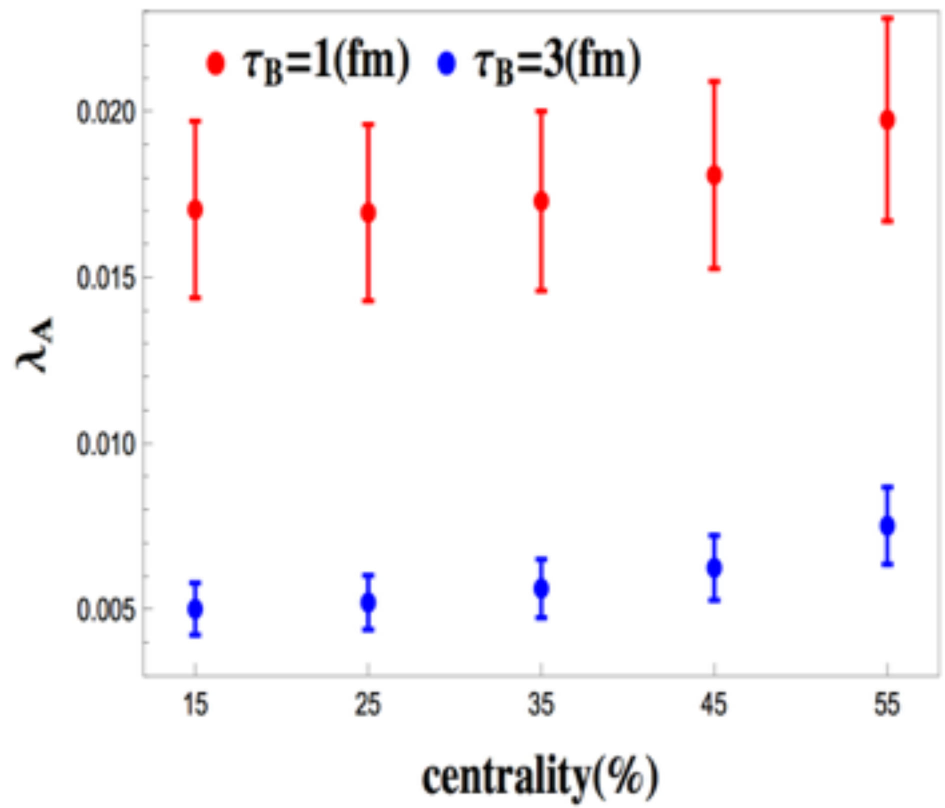
[Bzdak-Koch-Liao 1008.4919]

Hydrodynamics with chiral anomaly and charge separation in relativistic heavy ion collisions

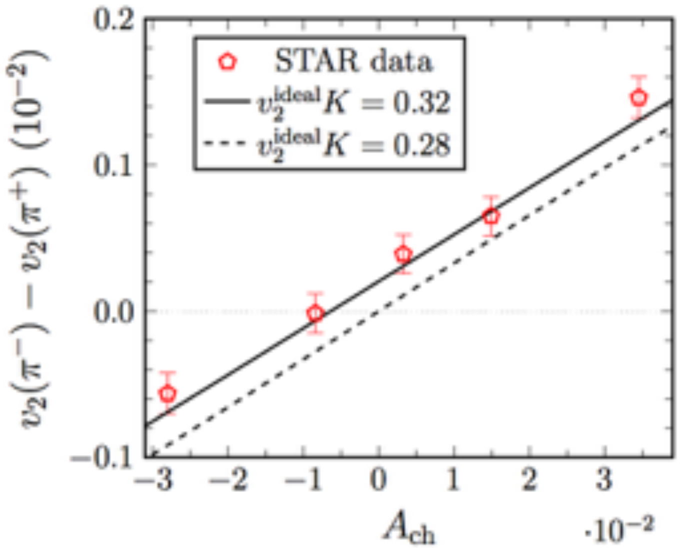
Yi Yin[1,*] and Jinfeng Liao[2,3,†]

[1504.06906]

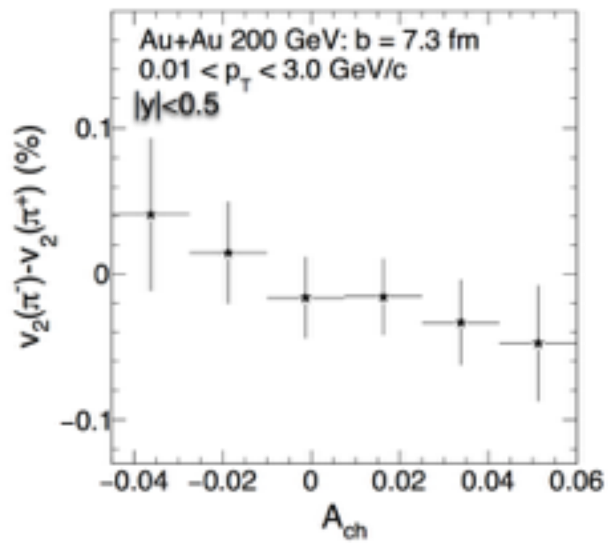




CMW observable $\Delta v_2(A)$



Background from viscosity
[Hatta-Monnai-Xiao 1507.04690]



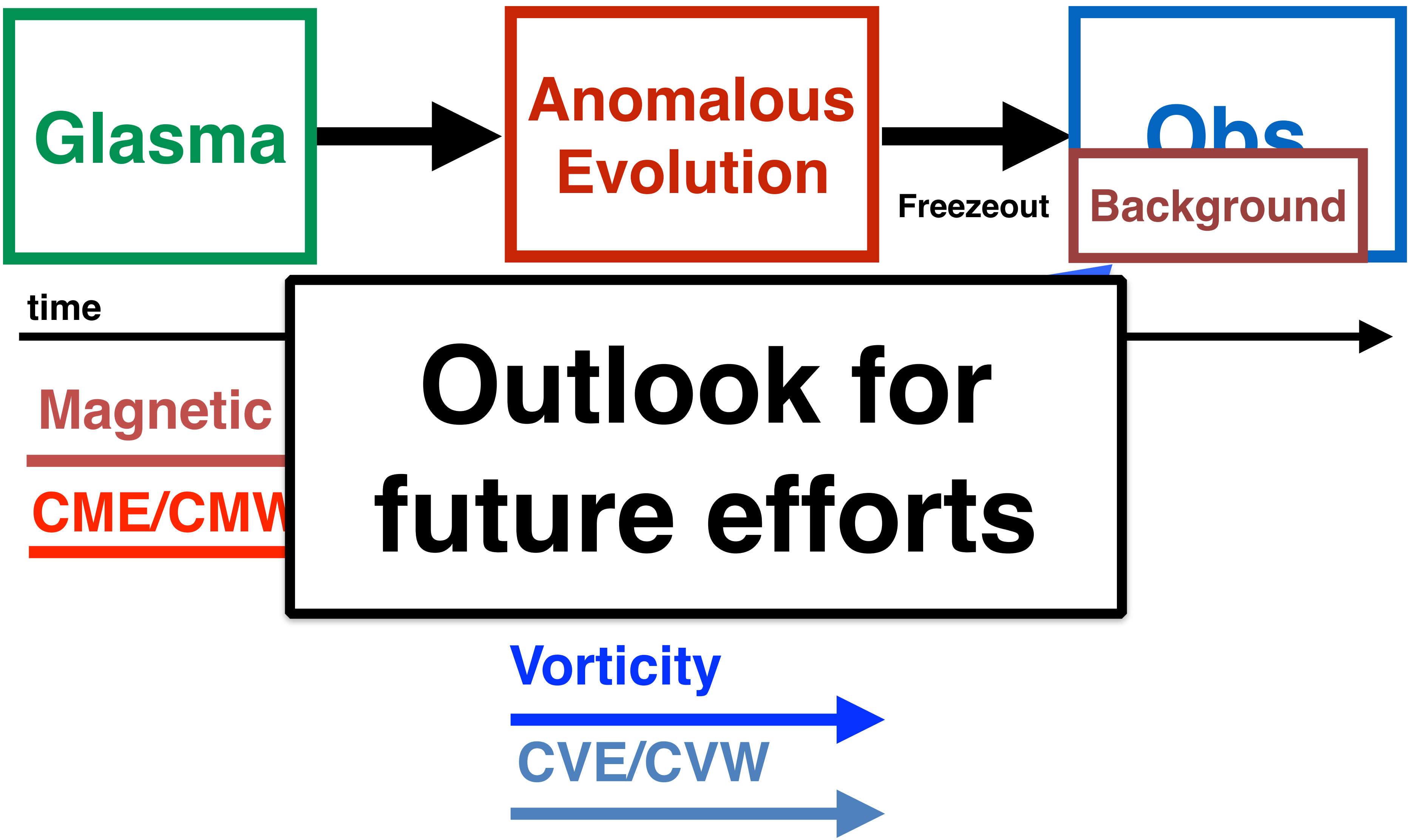
Study in AMPT model
[Talk by Shi @ UCLA 2016]

Quantum statistics [Hong-Hirono-Hirano 1309.2823]

Intercept $\Delta v_2(A = 0)$ is sensitive

slope can come from the choice of particle statistics in Cooper-Frye formula

Outlook for future efforts



Toward the detection of anomalous effects

- **Challenges**
  - Lifetime of B
  - Initial axial charge density & CME current
  - Initial charge densities
  - Vorticity profile
  - Modeling of background effects like LCC

- **Chiral magnetohydrodynamics**
  - Solve anomalous hydro + Maxwell equation consistently

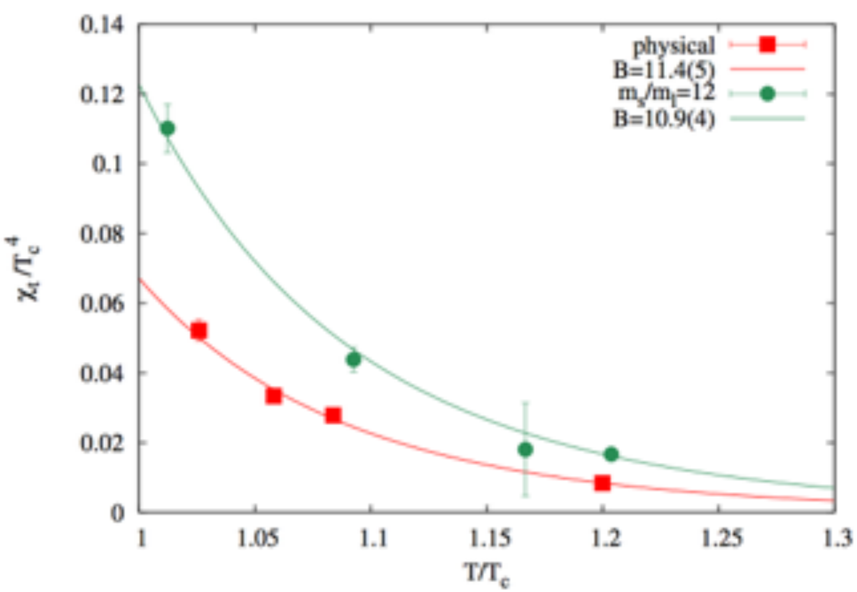
- **Collaborations**
  - Initial condition of axial charge from glasma
  - Topological susceptibility from lattice QCD
  - …

Lattice calc. of topological suscep.

[1602.02197]

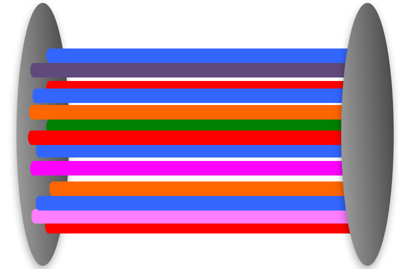
The topological structures in strongly coupled QGP with chiral fermions on the lattice

Sayantan Sharma[a], Viktor Dick[b], Frithjof Karsch[a,b], Edwin Laermann[b], Swagato Mukherjee[a]



EOS from lattice is an important input for anomalous hydro!

Initial conditions inspired by glasma simulations



[Bjoern-Hirono-Kharzeev-Mace, discussing]

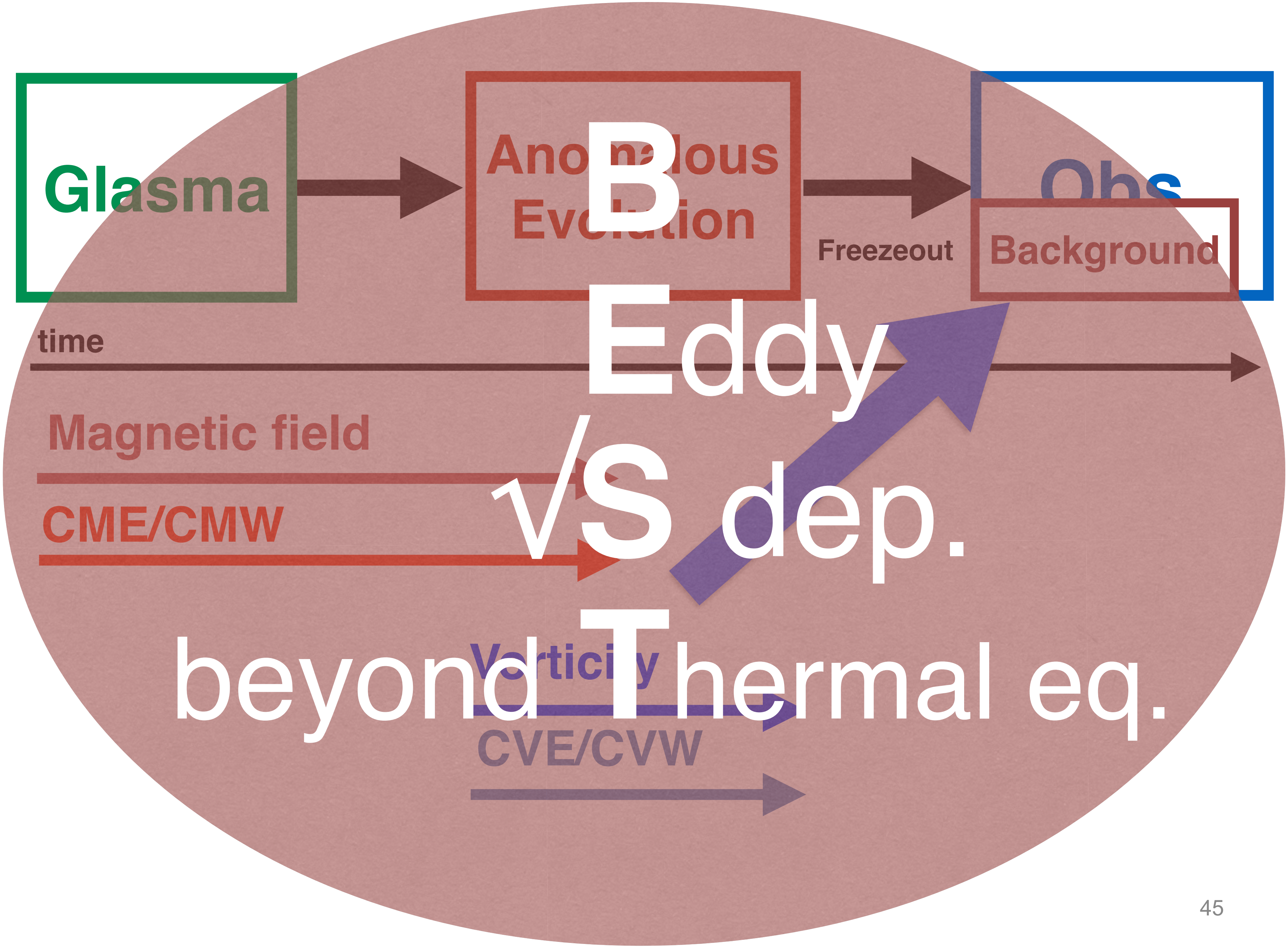
- Axial-charge & CME currents in glasma
  - Important input for anomalous hydro
- 3+1D is essential to have sphalerons
  - No sphaleron in 2+1D

$$\pi_3(SU(N_c)) = \mathbb{Z} \quad \pi_2(SU(N_c)) = \{e\}$$

- Use off-eq sphaleron rate from glasma sim. as an input for the model of initial axial charge density for anomalous hydro

Vorticity comes in handy

- Vorticity decays with hydrodynamic scale
- Larger at lower energy collisions
  - BES


Glasma
Anomalous Evolution
Freezeout
Obs
Background
time
Magnetic field
CME/CMW
Vorticity
CVE/CVW
B
Eddy
√S dep.
beyond Thermal eq.