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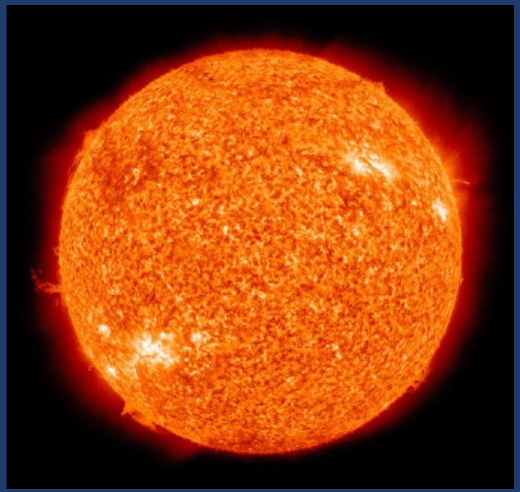
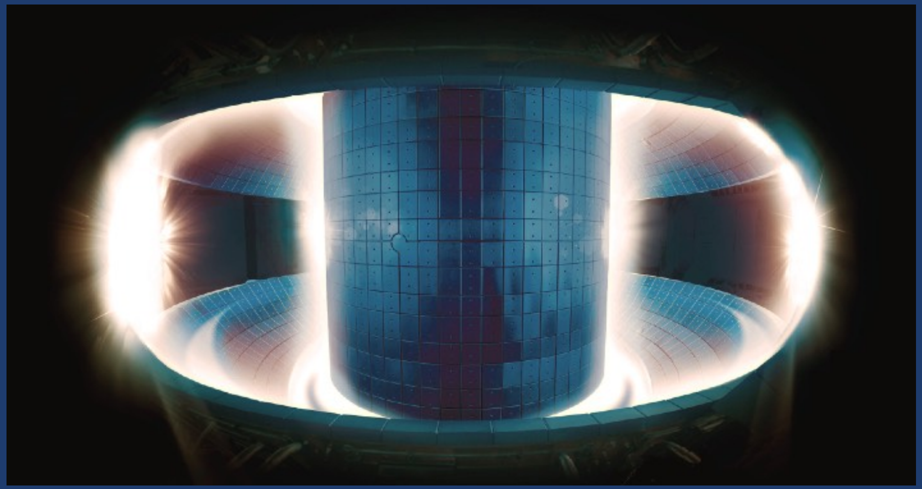
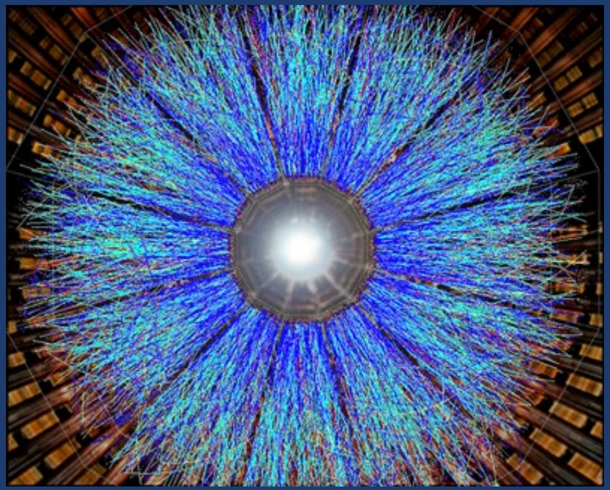
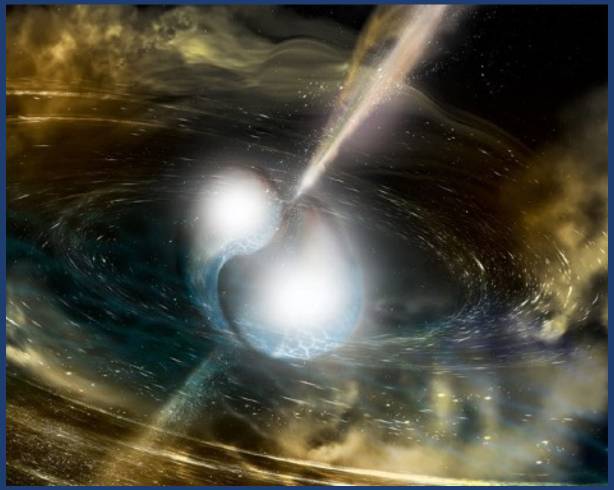
STRONG-FIELD MAGNETOHYDRODYNAMICS

ASU THEORETICAL PHYSICS
COLLOQUIUM, 26.4.2023









microscopic UV physics
(QFT, EFT, holography)

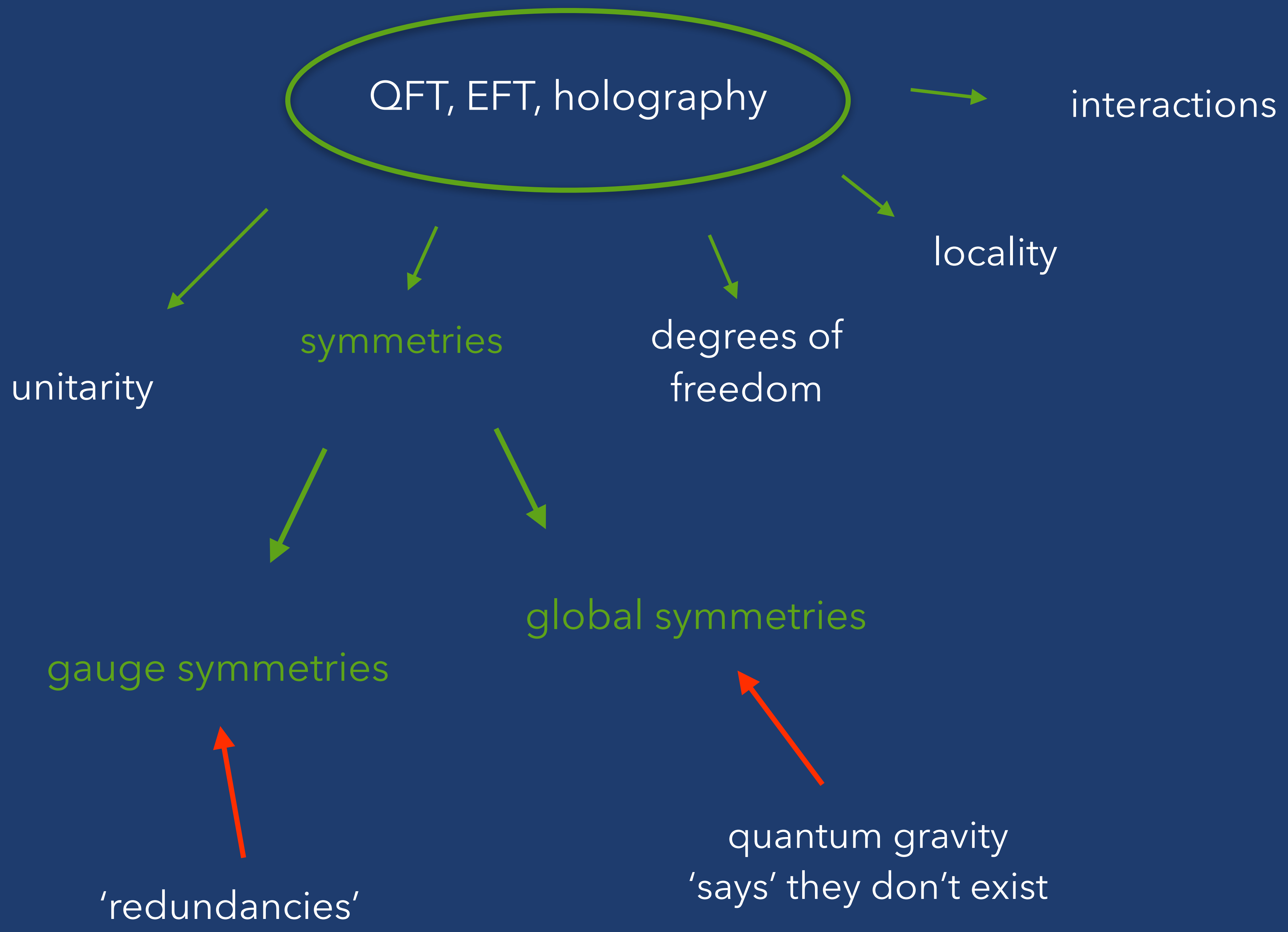
strongly magnetised fluid: PLASMA
magnetohydrodynamics

OUTLINE

- higher-form symmetries
- magnetohydrodynamics
- holographic magnetohydrodynamics
- new application: magnetic diffusion in neutron stars
- summary and future directions

HIGHER-FORM SYMMETRIES

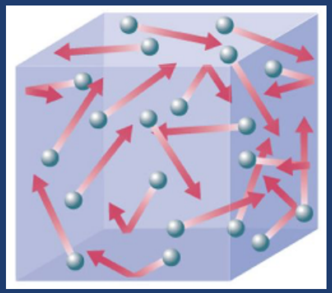
SYMMETRIES IN QFT AND EFT



GLOBAL HIGHER-FORM SYMMETRIES

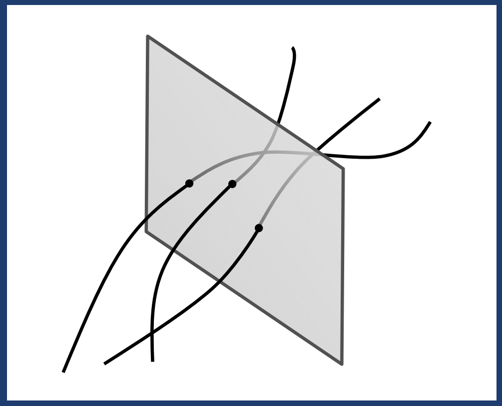
- zero-form symmetry (one-form conserved current)

$$\mathcal{O}(x) \to e^{iq\Lambda}\mathcal{O}(x) \qquad\qquad \partial_\mu J^\mu = 0$$



- one-form symmetry (two-form conserved current)
  [Gaiotto, Kapustin, Seiberg, Willet (2014)]

$$W(C) \to \exp\left(iq\int_C \Lambda\right) W(C) \qquad\qquad \partial_\mu J^{\mu\nu} = 0$$



- *p*-form symmetries count higher-dimensional objects

$$Q = \int_{S_{d-p}} \star J_{p+1}$$

- EM without matter

$$J^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma} \qquad\qquad \tilde{J}^{\mu\nu} = F^{\mu\nu}$$

- EM coupled to matter (e.g., QED)

$$J^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$$

- symmetry is tautological in vacuum

$$\partial_\mu J^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma}\partial_\mu\partial_\rho A_\sigma = 0$$

HIGHER-FORM SYMMETRIES

- continuous symmetries are Abelian, discrete symmetries can be non-Abelian
- SSB and Goldstone bosons [see Hofman, Iqbal (2018); Lake (2018)]

$$\text{zero-form symmetry}: \quad \theta \to \theta + c\,, \qquad S_{IR} \sim \int d\theta \wedge \star d\theta = \int d^4x\, \partial_\mu \theta \partial^\mu \theta$$

$$\text{one-form symmetry}: \quad A \to A + d\alpha, \quad S_{IR} \sim \int dA \wedge \star dA = \int d^4x\, F_{\mu\nu} F^{\mu\nu}$$

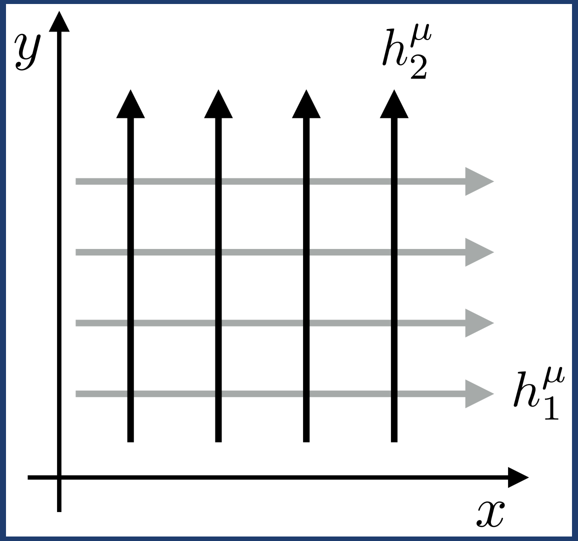
- Goldstone boson of a broken symmetry is the photon
- the phase we are most familiar with is the broken phase
- order parameters of SSB

$$\begin{aligned}
&\text{zero-form symmetry}: && \text{unbroken:} && \langle \mathcal{O}^\dagger(x)\mathcal{O}(y)\rangle \sim \exp\{-m|x-y|\} \\
& && \text{broken}: && \langle \mathcal{O}^\dagger(x)\mathcal{O}(y)\rangle \sim \langle \mathcal{O}^\dagger(x)\rangle\langle \mathcal{O}(y)\rangle \\
&\text{one-form symmetry}: && \text{unbroken:} && \langle W_C\rangle \sim \exp\{-T\,\text{Area}[C]\} \\
& && \text{broken}: && \langle W_C\rangle \sim \exp\{-T\,\text{Perimeter}[C]\}
\end{aligned}$$

- analogy with confinement

HIGHER-FORM SYMMETRIES

- many theories have higher-form symmetries:
  abelian Higgs model, centre symmetries, various condensed matter systems
- another example: (visco)-elasticity
  [Grozdanov, Poovuttikul, PRD (2018); Armas, Jain, JHEP (2019)]



- the language and formalism underpinning these symmetries has been quite thoroughly developed
- new concepts associated with this endeavour:
  2-group, non-invertible symmetries that incorporate anomalies, etc.

MAGNETOHYDRODYNAMICS (MHD)

MAGNETOHYDRODYNAMICS

MHD = Navier-Stokes + Maxwell (EM)

generalise

$$\frac{\partial \epsilon}{\partial t} + \nabla \cdot (\epsilon \vec{v}) = 0$$

continuity

$$\epsilon \left(\frac{\partial}{\partial t} + \vec{v} \cdot \nabla \right) \vec{v} = -\nabla p + \vec{J} \times \vec{B}$$

Euler (or Navier-Stokes)

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J}$$

$$\nabla \cdot \vec{B} = 0$$

~~$\nabla \cdot \vec{E} = 0$~~

Maxwell

$$\vec{E} + \vec{v} \times \vec{B} = 0 \,, \quad (\sigma \to \infty)$$

Ohm's law (ideal)

$$\left(\frac{\partial}{\partial t} + \vec{v} \cdot \nabla \right) \left(\frac{p}{\epsilon^{\gamma}} \right) = 0$$

equation of state

- avoid mixing macroscopic and microscopic concepts
- what are the symmetries?
- general equation of state

  $$B/T^2 \ll 1, \quad g \ll 1$$

- correct number of transport coefficients?
- quantum effects:
  pair-creation, Landau levels?

HYDRODYNAMICS

- low-energy limit of QFTs – a Schwinger-Keldysh effective field theory
  [SG, Polonyi (2013); Crossley, Glorioso, Liu (2015); Haehl, Loganayagam, Rangamani (2015); …]
- conservation laws (equations of motion) of globally conserved operators

$$\nabla_\mu T^{\mu\nu} = 0 \qquad \nabla_\mu J^\mu = 0$$

- tensor structures (symmetries, gradient expansions) and transport coefficients (QFT)

$$T^{\mu\nu} = \sum_{n=0}^{\infty} \left[\sum_i^N \lambda_i^{(n)} \mathcal{T}^{\mu\nu}_{(n)} \right] \xrightarrow[u^\mu \sim T \sim e^{-i\omega t + iqz}]{\nabla_\mu T^{\mu\nu} = 0} \omega(q) = \sum_{n=1}^{\infty} \alpha_n q^n$$

$$\partial u^\mu \sim \partial T \ll 1 \longrightarrow \omega / T \sim q / T \ll 1$$

equilibrium temperature

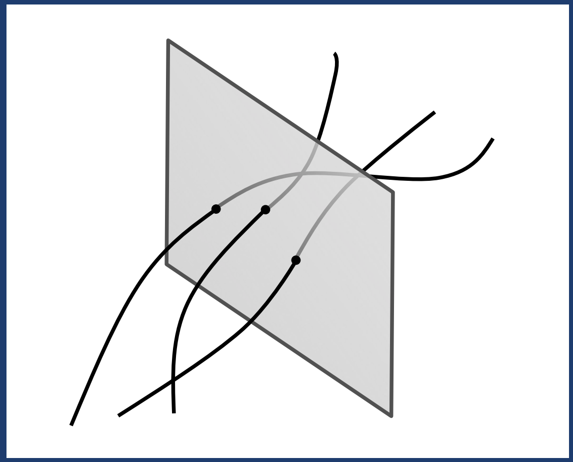
$q = \sqrt{\mathbf{q}^2}$

- first-order truncation = Navier-Stokes equations
- dispersion relations:

shear diffusion	sound
$\omega = -iDq^2$	$\omega = \pm v_s q - i\Gamma q^2$

HIGHER-FORM SYMMETRIES AND MHD

- plasma is a phase with an unbroken one-form symmetry and no IR massless photons (Debye screening)



counting # of magnetic flux lines crossing a 2*d* surface

- $\partial_\mu J^{\mu\nu} = 0$ – Ward identity becomes powerful
- magnetohydrodynamics (MHD) is the IR EFT
- IR dynamics encoded in conservation laws

$$\partial_\mu T^{\mu\nu} = 0$$
$$\partial_\mu J^{\mu\nu} = 0$$

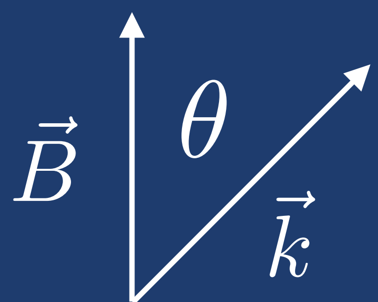
$$J^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$$

- general formulation for any plasma (EoM level) [Grozdanov, Hofman, Iqbal, PRD (2017)]
- any equation of state $P(B,T)$
- transport coefficients (2+3 viscosities and 2 resistivities) →
- electric field ***E*** is induced at derivative level

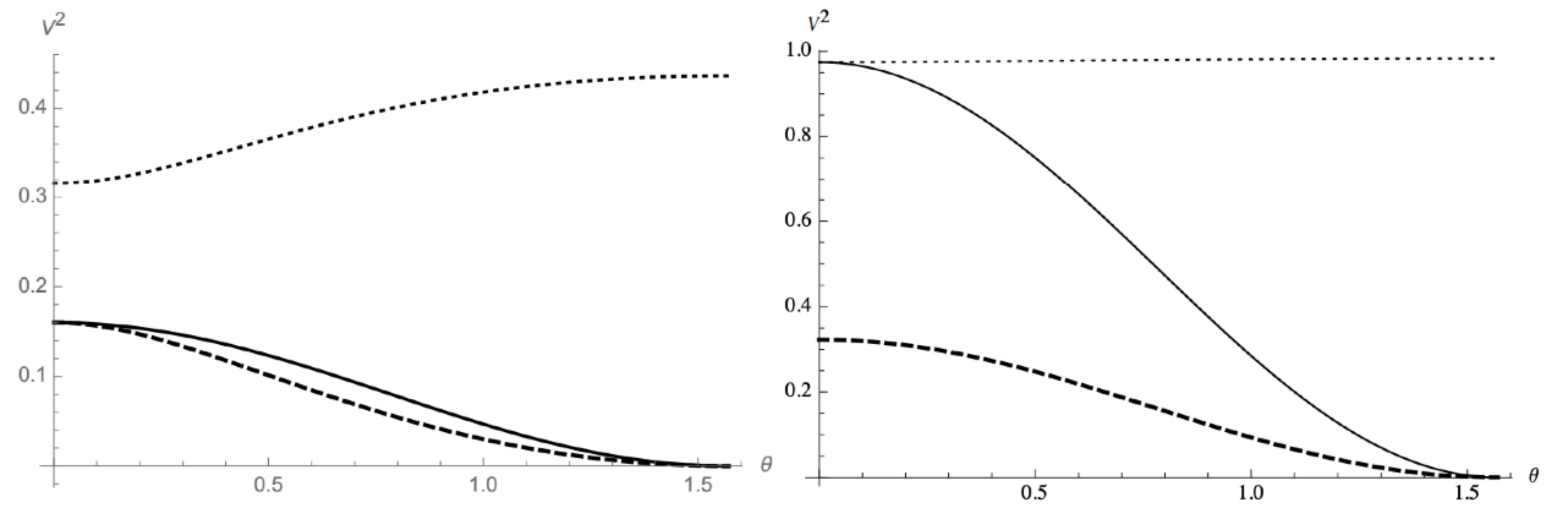
functions of *B* and *T*	
$\eta_\perp \geq 0$	$\eta_\parallel \geq 0$
$r_\perp \geq 0$	$r_\parallel \geq 0$
$\zeta_\perp \geq 0$	$\zeta_\perp \zeta_\parallel \geq \zeta_\times^2$

HIGHER-FORM SYMMETRIES AND MHD

- strong-***B*** dispersion relations



speeds of waves



a) Velocities from high temperature equation of state (4.26) with $\mu/T^2 = 0.4$, $a = g = \beta = 1$.

b) Velocities from high field equation of state (4.31) with $T^2/\mu = 0.4$, $a' = g' = \beta' = 1$.

- Kubo formulae for resistivities (also *wip* with Frangi)

$$r = 1/\sigma\ (?)$$

$$r_\parallel = \lim_{\omega\to 0}\lim_{k^z\to 0}\frac{\langle J^{xy}(-\omega,-k^z)J^{xy}(\omega,k^z)\rangle_R}{-i\omega}$$
$$r_\perp = \lim_{\omega\to 0}\lim_{k^z\to 0}\frac{\langle J^{xz}(-\omega,-k^z)J^{xz}(\omega,k^z)\rangle_R}{-i\omega}$$

- symmetry-enhanced (non-dissipative) *T = 0* limit due to SO(1,1) boost symmetry along the strings (flux lines)
- example: Alfvén waves

$$\omega = \pm k\cos\theta$$

HIGHER-FORM SYMMETRIES AND MHD

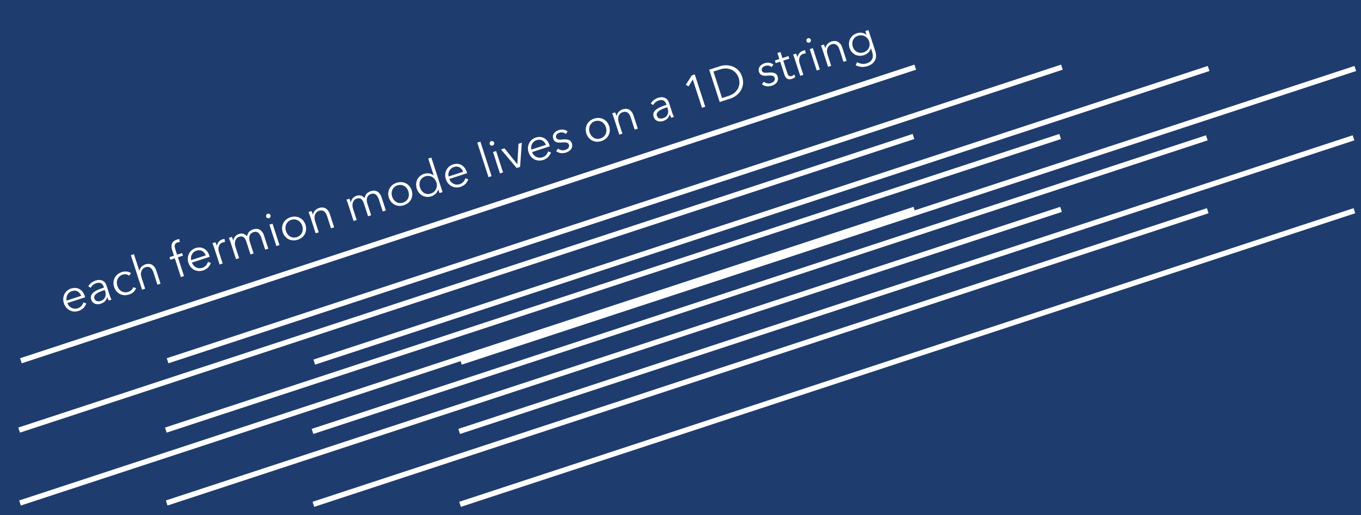
- old theories are special limits of new generalised MHD
- can be easily systematically extended using our formalism

first-order expansion in $B/T^2 \ll 1$ → standard, textbook ideal MHD with new dissipative terms

$$P(B,T) = \frac{a}{4}T^4 + \frac{g^2}{2}B^2 + \frac{\beta}{4}\frac{B^4}{T^4} + \cdots$$

zero-temperature limit: $T = 0$

- massless lowest Landau level fermion in a strong, dynamical magnetic field + *2d* bosonisation



- force-free electrodynamics and corrections [Glorioso, Son (2018)]
  Maxwell's equations
  + constraint

$$\mathbf{E} \cdot \mathbf{B} = 0$$

EXAMPLE: LEADING-ORDER CORRECTED NON-RELATIVISTIC MHD

$$\begin{aligned}
\partial_i B^i &= 0 \\
\partial_t B^i &= -\varepsilon^{ijk}\partial_j E_k, \qquad E^i = -(\vec{v}\times\vec{B})^i + j^i_{diss} \\
\partial_t \varepsilon + \partial_i(\varepsilon v^i) &= 0 \\
\varepsilon(\partial_t + \vec{v}\cdot\nabla)v^i &= -\partial^i p + (\vec{B}\cdot\nabla)B^i + \partial_i \Pi^{ij}_{visc} \\
p(T,B) &= \text{the equation of state}
\end{aligned}$$

extremely complicated equations are systematically generated from the simpler higher-form language

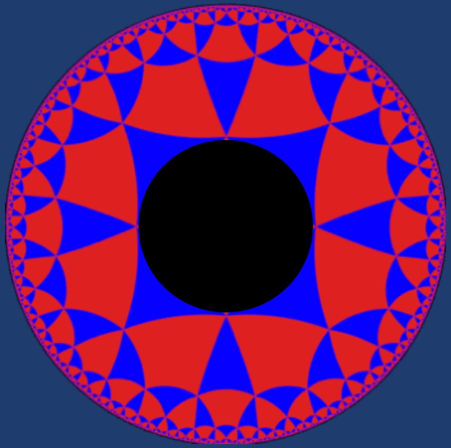
$$j^i_{diss} = r_\perp \frac{T}{B^2}\varepsilon^{ijk}\left[B^n\partial_j\left(\frac{\mu_B B_n}{T}\right) - \vec{B}\cdot\nabla\left(\frac{\mu_B B_j}{T}\right)\right]B_k + r_\parallel\left(\frac{\mu_B B^i}{B}\right)B_p\epsilon^{pmn}\partial_m\left(\frac{B_n}{B}\right)$$

$$\begin{aligned}
\Pi^{ij}_{diss} = \eta_\perp&\left[\left(\mathcal{S}^{ij} - \delta^{ij}(\nabla\cdot\vec{v})\right) + \frac{B^iB^j}{B^2}(\nabla\cdot\vec{v}) + \delta^{ij}\frac{\vec{B}\cdot(\vec{B}\cdot\nabla)v}{B^2} - \frac{1}{B^2}\left(B^i(\vec{B}\cdot\nabla)v^j + B^j(\vec{B}\cdot\nabla)v^i\right)\right] \\
&+ \eta_\parallel\left[\frac{1}{B^2}\left(B^i\mathcal{S}^{jk}B_k + B^j\mathcal{S}^{jk}B_k - \frac{2B^iB^j}{B^4}B^kB^l\mathcal{S}_{kl}\right)\right] + \left[\delta^{ij} - \frac{B^iB^j}{B^2}\right]\delta f + \frac{B^iB^j}{B^2}\delta\tau
\end{aligned}$$

$$\begin{aligned}
\mathcal{S}^{ij} &= \partial^i v^j + \partial^j v^i \\
\delta f &= -\zeta_\perp\left((\nabla\cdot\vec{v}) - \frac{\vec{B}\cdot(\vec{B}\cdot\nabla)\vec{v}}{B^2}\right) - \zeta_\times\left(\frac{\vec{B}\cdot(\vec{B}\cdot\nabla)\vec{v}}{B^2}\right) \\
\delta\tau &= -\zeta_\times\left((\nabla\cdot\vec{v}) - \frac{\vec{B}\cdot(\vec{B}\cdot\nabla)\vec{v}}{B^2}\right) - \zeta_\parallel\left(\frac{\vec{B}\cdot(\vec{B}\cdot\nabla)\vec{v}}{B^2}\right)
\end{aligned}$$

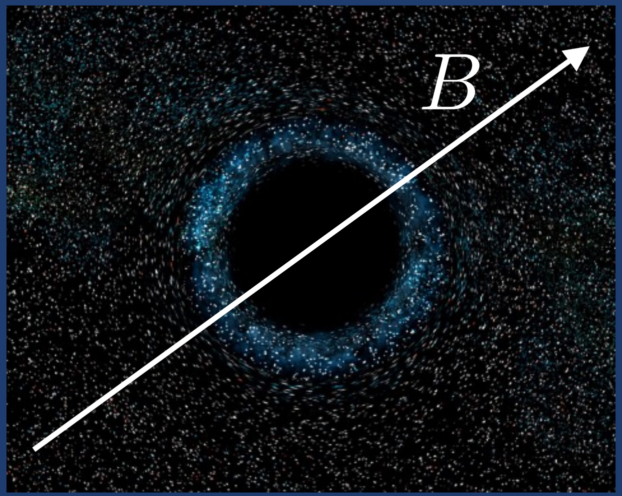
HOLOGRAPHIC MHD

HOLOGRAPHIC MHD



- holographic duality:

some QFTs in 4d = gravity (string theory) in 5d



- holographic dual of a magnetised plasma
  [Grozdanov, Poovuttikul, JHEP (2017); Hofman, Iqbal, SciPost (2017)]

- generating functional

$$W\left[g_{\mu\nu}, b_{\mu\nu}\right] = \left\langle \exp\left[i \int d^4x \sqrt{-g} \left(\frac{1}{2} T^{\mu\nu} g_{\mu\nu} + J^{\mu\nu} b_{\mu\nu} \right) \right] \right\rangle$$

- theory of gravity and two-form gauge field ($H = db$) in 5d

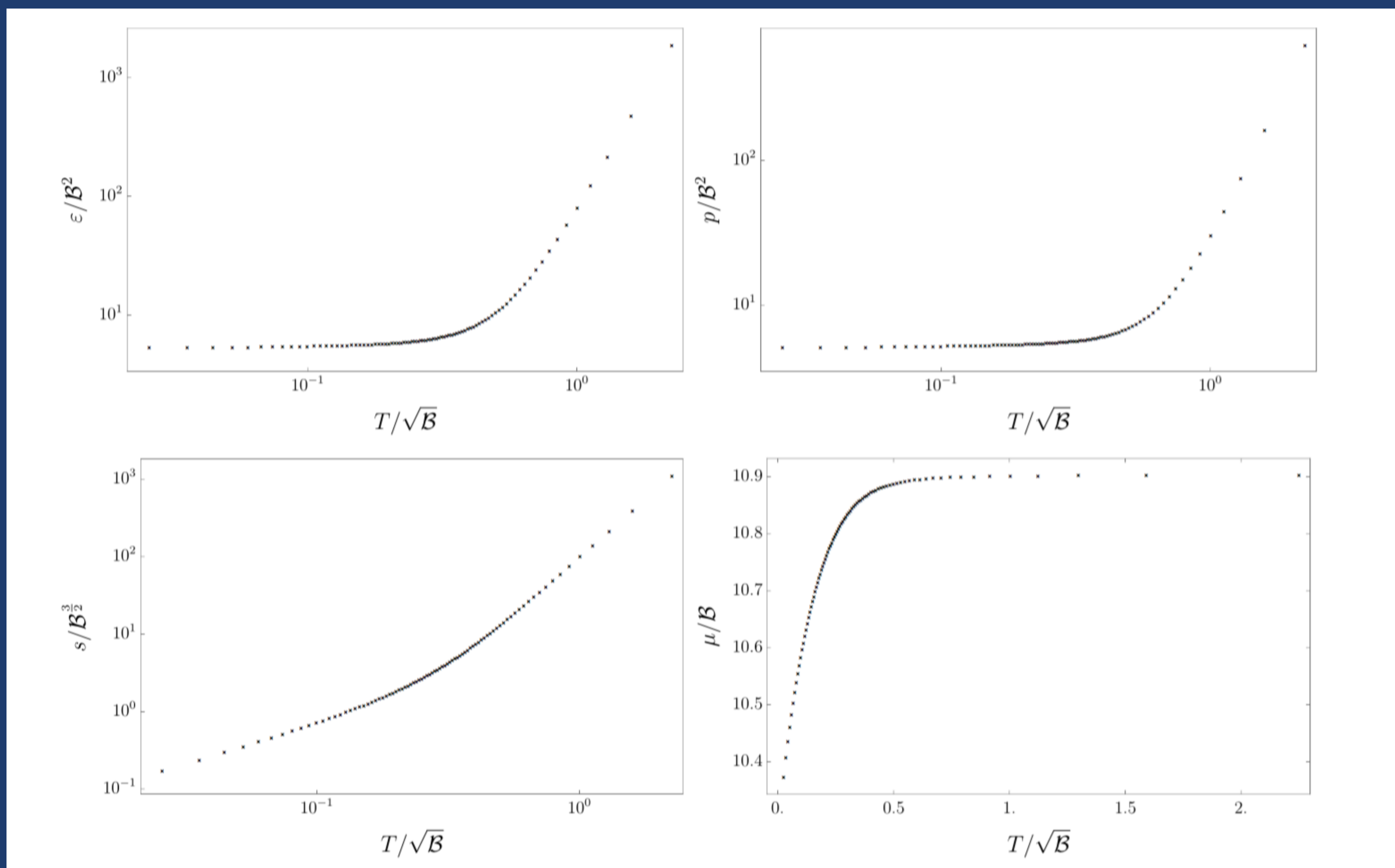
$$S = \frac{N_c^2}{8\pi^2} \left[\int d^5x \sqrt{-g} \left(R + 12 - \frac{1}{3e^2} H_{\mu\nu\rho} H^{\mu\nu\rho} \right) + \int_{\partial M} d^4x \sqrt{-\gamma} \left(2\,\mathrm{tr} K - 6 + \frac{1}{e^2} \mathcal{H}_{ab} \mathcal{H}^{ab} \ln \mathcal{C} \right) \right]$$

+ mixed boundary conditions

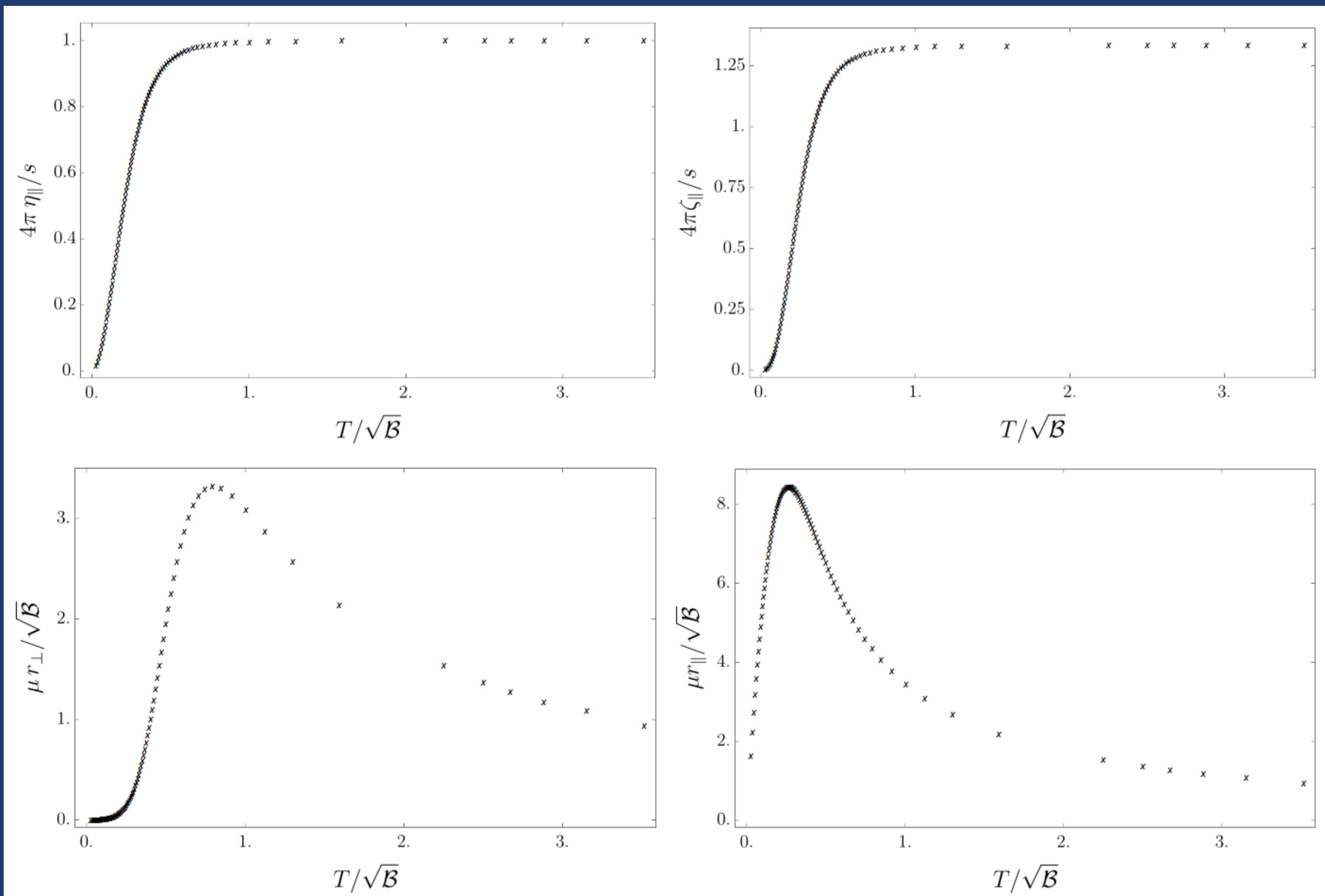
- holographic model with dynamical electromagnetism (gauged U(1) R-symmetry)

HOLOGRAPHIC MHD EQUATION OF STATE

	weak field ($T/\sqrt{\mathcal{B}} \gg 1$)	strong field ($T/\sqrt{\mathcal{B}} \ll 1$)
ε	$\frac{N_c^2}{2\pi^2}\left(74.1 \times T^4\right)$	$\frac{N_c^2}{2\pi^2}\left(5.62 \times \mathcal{B}^2\right)$
p	$\frac{N_c^2}{2\pi^2}\left(25.3 \times T^4\right)$	$\frac{N_c^2}{2\pi^2}\left(5.32 \times \mathcal{B}^2\right)$
s	$\frac{N_c^2}{2\pi^2}\left(99.4 \times T^3\right)$	$\frac{N_c^2}{2\pi^2}\left(7.41 \times \mathcal{B}\,T\right)$
μ	$\frac{N_c^2}{2\pi^2}\left(10.9 \times \mathcal{B}\right)$	$\frac{N_c^2}{2\pi^2}\left(2.88 \times \mathcal{B}\right)$



HOLOGRAPHIC MHD TRANSPORT COEFFICIENTS



	weak field ($T/\sqrt{\mathcal{B}} \gg 1$)	strong field ($T/\sqrt{\mathcal{B}} \ll 1$)
$\eta_\perp$	$\frac{s}{4\pi}$	$\frac{s}{4\pi}$
$\eta_\parallel$	$1.00 \times \frac{s}{4\pi}$	$\frac{s}{4\pi}\left(21.32 \times \frac{T^2}{\mathcal{B}}\right)$
$\zeta_\perp$	$0.33 \times \frac{s}{4\pi}$	$\frac{s}{4\pi}\left(16.34 \times \frac{T^3}{\mathcal{B}^{3/2}}\right)$
$\zeta_\parallel$	$1.33 \times \frac{s}{4\pi}$	$\frac{s}{4\pi}\left(65.37 \times \frac{T^3}{\mathcal{B}^{3/2}}\right)$
$\zeta_\times$	$-0.66 \times \frac{s}{4\pi}$	$-\frac{s}{4\pi}\left(32.69 \times \frac{T^3}{\mathcal{B}^{3/2}}\right)$
$r_\perp$	$\frac{\mathcal{B}}{\mu}\left(3.37 \times \frac{1}{T}\right)$	$\frac{\sqrt{\mathcal{B}}}{\mu}\left(4.7 \times \frac{T^3}{\mathcal{B}^{3/2}}\right)$
$r_\parallel$	$\frac{\mathcal{B}}{\mu}\left(3.37 \times \frac{1}{T}\right)$	$\frac{\sqrt{\mathcal{B}}}{\mu}\left(62.3 \times \frac{T}{\sqrt{\mathcal{B}}}\right)$

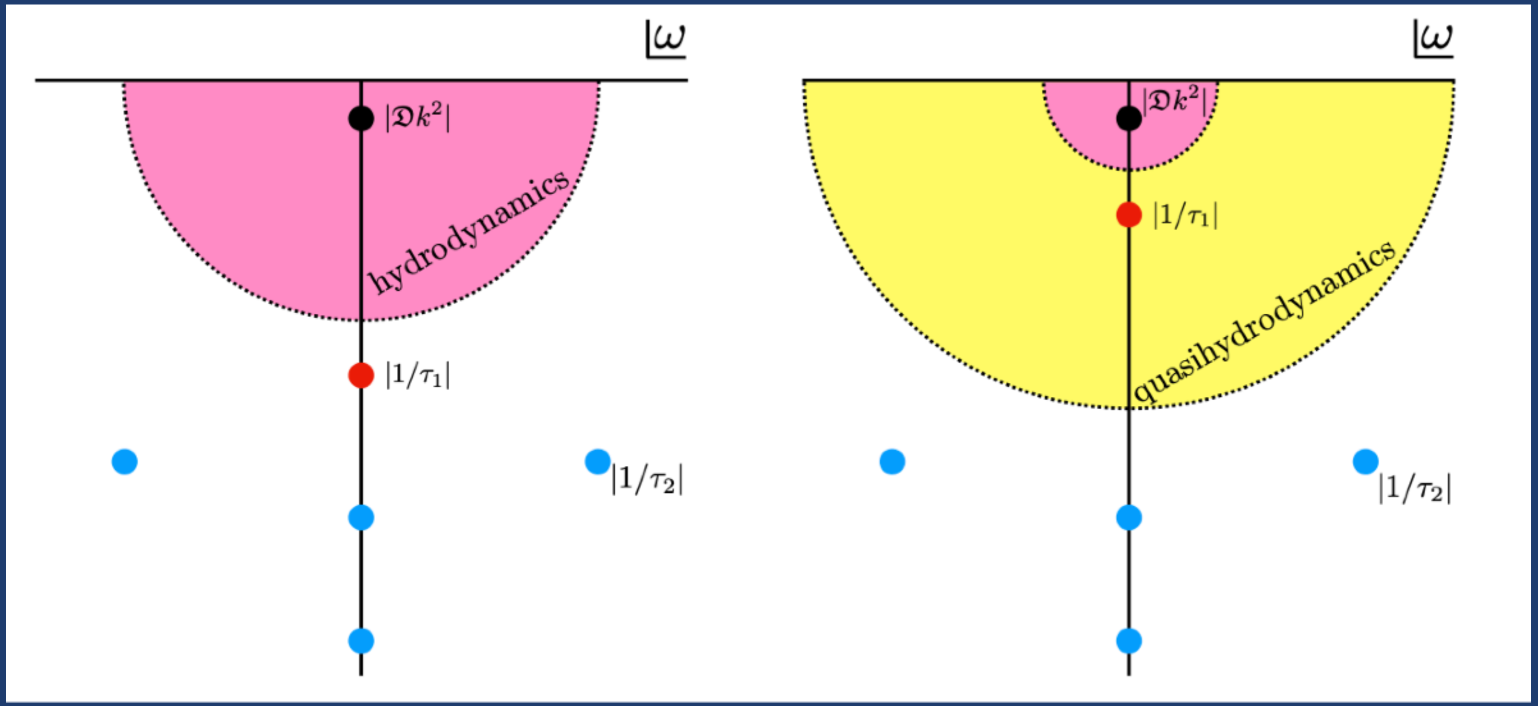
- maximal resistivity
- bulk viscosities

$$\zeta_\perp \zeta_\parallel = \zeta_\times^2$$

reminiscent of Kovtun-Son-Starinets and Haack-Yarom – minimisation of entropy [see Grozdanov, Starinets, JHEP (2014)]

- all transport coefficients must vanish at *T = 0*
  [Grozdanov, Hofman, Iqbal, PRD (2017)]
- holography agrees
  [Grozdanov, Poovuttikul, JHEP (2017)]

BEYOND MHD



- *quasihydrodynamics* [Grozdanov, Lucas, Poovuttikul, PRD (2018)]
- screened photons
- dynamical electric fields
- Ampere's law

$$\partial_t \mathbf{E} - \#\nabla \times \mathbf{B} = -\frac{1}{\tau}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) + O(\partial^2)$$

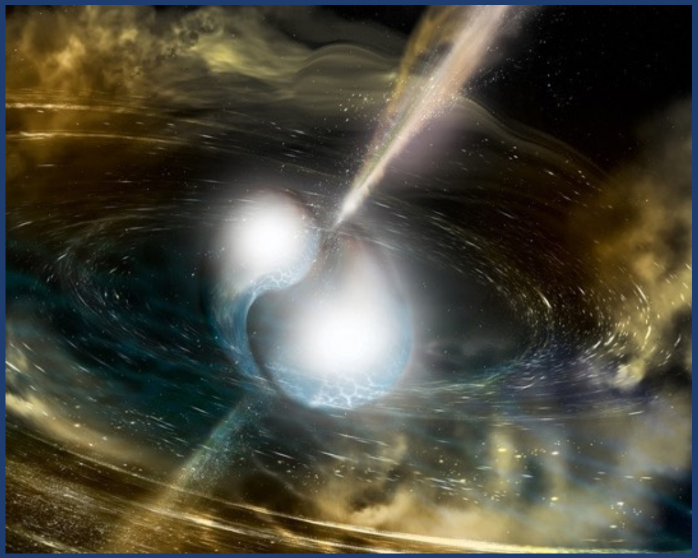
- Müller-Israel-Stewart theory structure

$$J^{\mu\nu} = 2\rho u^{[\mu} h^{\nu]} + \mathcal{J}^{\mu\nu}, \quad u^\lambda \nabla_\lambda \mathcal{J}^{\mu\nu} + \ldots = -\frac{1}{\tau}\mathcal{J}^{\mu\nu}$$

- systematic construction of EFTs beyond the MHD limit
- study of plasma instabilities

NEW APPLICATION: MAGNETIC DIFFUSION IN NEUTRON STARS

[GROZDANOV, LEUTHEUSSER, LIU, VARDHAN, 2022 AND 2023]



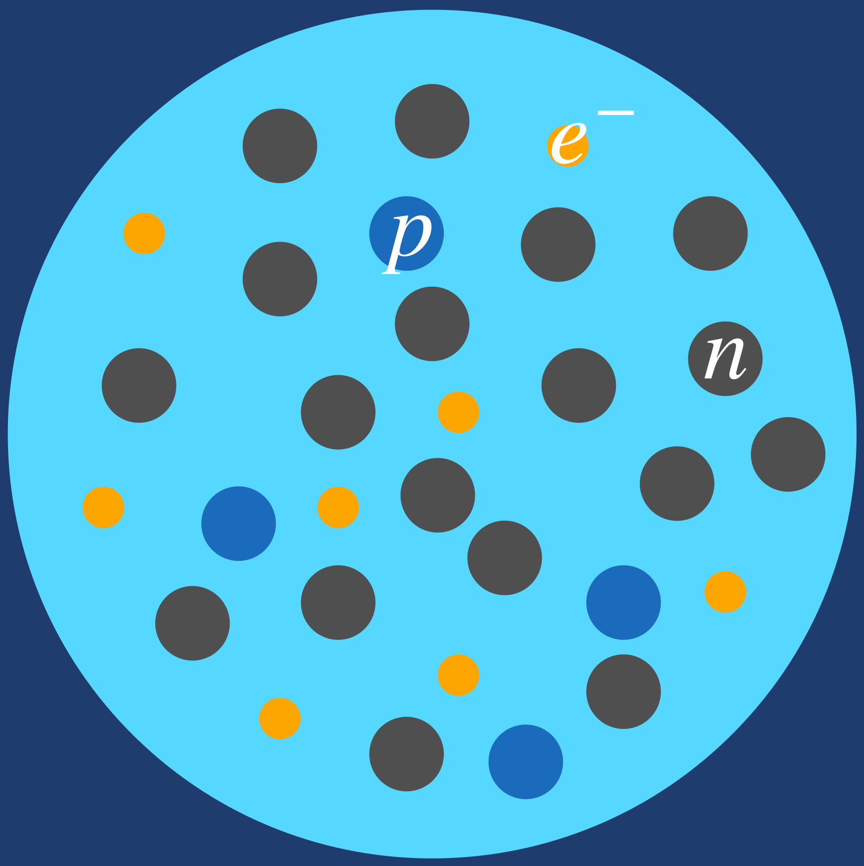
dynamics of strong magnetic fields in neutron stars

old: microscopic model of Goldreich and Reisenegger (1992)

new approach: higher-form symmetries and EFT

MAGNETIC DIFFUSION IN NEUTRON STARS

- theory of magnetic field evolution [Goldreich and Reisenegger (1992)]
- neutron star is a fluid made of neutrons, electrons and protons



$$\mu_n + m_n \psi = \text{constant}$$

$$m_p \frac{\partial \boldsymbol{v}_p}{\partial t} + m_p (\boldsymbol{v}_p \cdot \nabla) \boldsymbol{v}_p = -\nabla \mu_p - m_p \nabla \psi + e\left(\boldsymbol{E} + \frac{\boldsymbol{v}_p}{c} \times \boldsymbol{B}\right) - \frac{m_p \boldsymbol{v}_p}{\tau_{pn}} - \frac{m_p(\boldsymbol{v}_p - \boldsymbol{v}_e)}{\tau_{pe}},$$

$$m_e^* \frac{\partial \boldsymbol{v}_e}{\partial t} + m_e^* (\boldsymbol{v}_e \cdot \nabla) \boldsymbol{v}_e = -\nabla \mu_e - e\left(\boldsymbol{E} + \frac{\boldsymbol{v}_e}{c} \times \boldsymbol{B}\right) - \frac{m_e^* \boldsymbol{v}_e}{\tau_{en}} - \frac{m_e^*(\boldsymbol{v}_e - \boldsymbol{v}_p)}{\tau_{ep}}.$$

$$\Delta\Gamma \equiv \Gamma(p + e^- \to n + \nu_e) - \Gamma(n \to p + e^- + \bar{\nu}_e) = \lambda \Delta\mu$$

weak interactions influence continuity equations

$$\frac{\partial \boldsymbol{B}}{\partial t} = -c\nabla \times \left(\frac{\boldsymbol{j}}{\sigma_0}\right) + \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \left(\frac{m_p/\tau_{pn} - m_e^*/\tau_{en}}{m_p/\tau_{pn} + m_e^*/\tau_{en}}\right) \nabla \times \left(\frac{\boldsymbol{j} \times \boldsymbol{B}}{n_c e}\right)$$

$$\sigma_0 = n_c e^2 \left(\frac{1}{\tau_{ep}/m_e^*} + \frac{1}{\tau_{pn}/m_p + \tau_{en}/m_e^*}\right)^{-1} \qquad \frac{\boldsymbol{v}_p + \boldsymbol{v}_e}{2} = \boldsymbol{v} - \left(\frac{m_p/\tau_{pn} - m_e^*/\tau_{en}}{m_p/\tau_{pn} + m_e^*/\tau_{en}}\right) \frac{\boldsymbol{j}}{2n_c e} \qquad \boldsymbol{j} = \frac{c\nabla \times \boldsymbol{B}}{4\pi}$$

MAGNETIC DIFFUSION IN NEUTRON STARS

- theory of magnetic field evolution [Goldreich and Reisenegger (1992)]
- neutron star is a fluid made of neutrons, electrons and protons
- phenomenological considerations give MHD evolution equations for magnetic diffusion
- coefficients are determined in terms of microscopic quantities

$$\nabla \cdot \mathbf{B} = 0, \quad \partial_t \mathbf{B} = -\nabla \times \mathbf{E}$$

$$\mathbf{E} = \eta\, \mathbf{j} + c_a\, (\mathbf{j} \times \mathbf{B}) \times \mathbf{B} + c_H\, \mathbf{j} \times \mathbf{B}$$

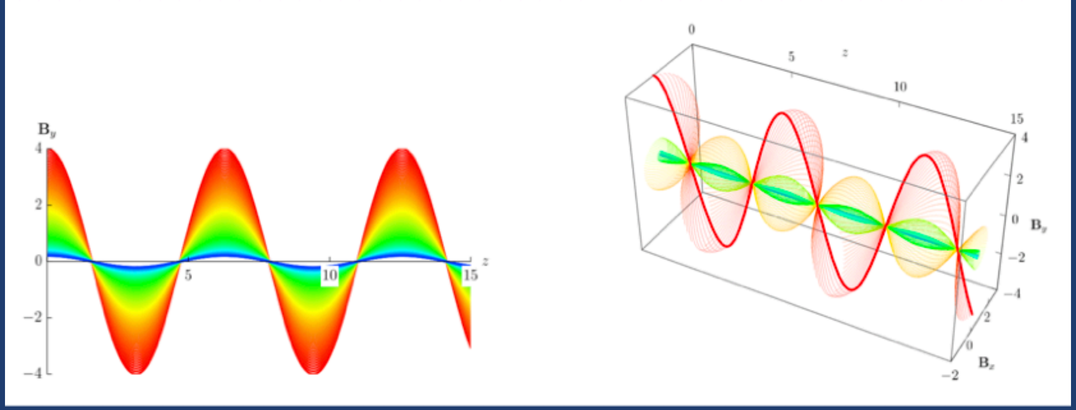
$$\mathbf{j} \equiv \nabla \times \mathbf{B}, \quad \eta,\, c_a,\, c_H = \text{const.}$$

standard diffusion

$$\partial_t \mathbf{B} = \eta \nabla^2 \mathbf{B}$$

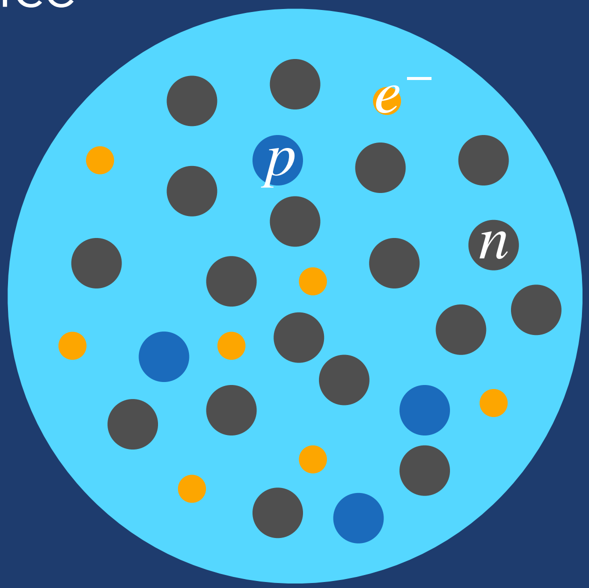
ambipolar diffusion

Hall drift



MAGNETIC DIFFUSION IN NEUTRON STARS

- EFT (CTP formalism) for the one-form symmetry with broken *C*-invariance
  [Grozdanov, Leutheusser, Liu, Vardhan, 2207.01636 & *to appear*]



$$J^{0i} = a\, G_{0i} - \beta_0 (c\, \delta_{ij} + \tilde{c}\, G_{0i} G_{0j}) \partial_0 G_{0j} + h \epsilon_{ijn} G_{0n} \partial_0 G_{0j} + m \delta_{ij} \epsilon_{kln} G_{0n} H_{jkl}$$

$$J^{ij} = -2\beta_0 (d\, \delta_{ik} \delta_{jl} + \tilde{d}\, \epsilon_{ijm} \epsilon_{kln} G_{0m} G_{0n}) \partial_0 G_{kl} - m \epsilon_{lij} \partial_l G_{0k}^2 + 2p \delta_{k[i} \epsilon_{j]ln} G_{0n} \partial_0 G_{kl}$$

- new magnetic diffusion equation

$$\nabla \cdot \mathbf{B} = 0, \quad \partial_t \mathbf{B} = -\nabla \times \mathbf{E}$$

$$\mathbf{E} = \eta\, \mathbf{j} + c_a\, (\mathbf{j} \times \mathbf{B}) \times \mathbf{B} + c_H\, \mathbf{j} \times \mathbf{B} - c_H (\nabla \ln a(\mathbf{B}^2) \times \mathbf{B}) \times \mathbf{B} - c_\eta \nabla \ln a(\mathbf{B}^2) \times \mathbf{B} + \nabla f$$

$$\eta = c_\eta + c_a \mathbf{B}^2, \; c_\eta = \frac{2\beta_0 d}{a}, \; c_a = \frac{4\beta_0 \tilde{d}}{a^3}, \; c_H = -\frac{p}{a^2}$$

all functions of ***B***

- one can compute all correlation functions of ***B*** and ***E*** from auxiliary higher-form variables – a much more 'natural' description

MAGNETIC DIFFUSION IN NEUTRON STARS

- magnetic field dependence of susceptibilities

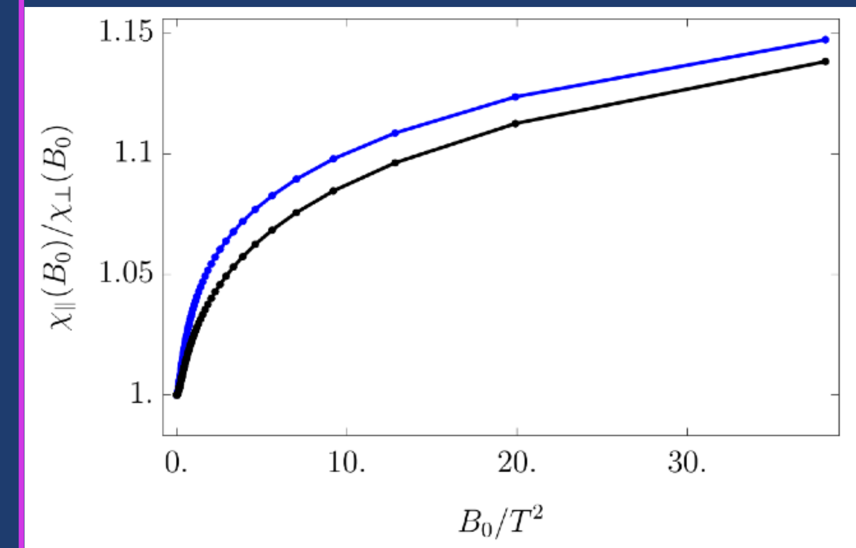
$$\chi_\parallel = a + \tilde{a} B_0^2, \quad \chi_\perp = a, \quad \tilde{a} = 2a'(B_0^2)$$

- Kubo formulae:

$$\chi_\parallel = \lim_{\mathbf{k}\to 0}\lim_{\omega\to 0} G^R(B_z, B_z), \quad \chi_\perp = \lim_{\mathbf{k}\to 0}\lim_{\omega\to 0} G^R(B_x, B_x)$$

→

holography

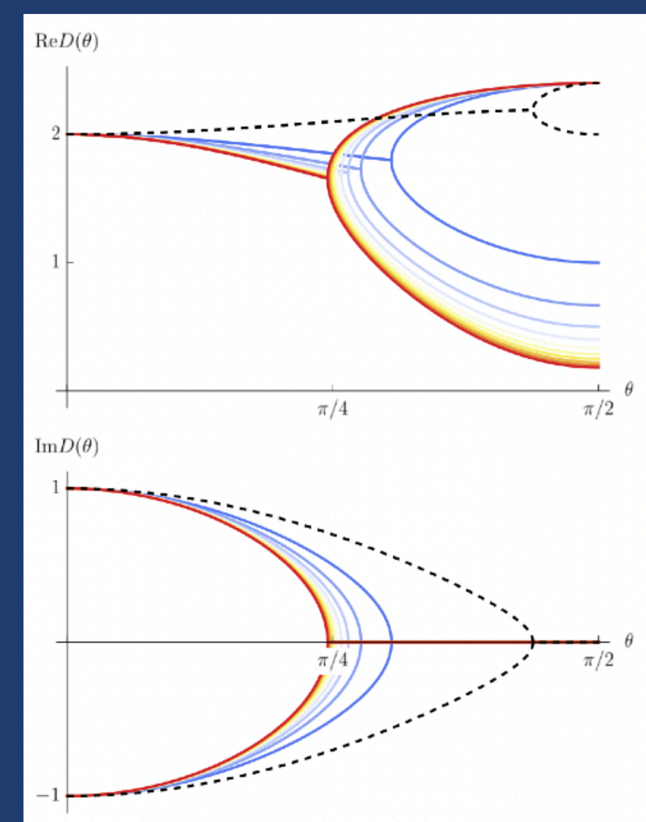


$$\sigma^\parallel = \lim_{\omega\to 0}\lim_{\mathbf{k}\to 0} \frac{1}{i\omega} G^R(E_z, E_z), \quad \sigma_1^\perp = \lim_{\omega\to 0}\lim_{\mathbf{k}\to 0} \frac{1}{i\omega} G^R(E_x, E_x), \quad \sigma_2^\perp = \lim_{\omega\to 0}\lim_{\mathbf{k}\to 0} \frac{1}{i\omega} G^R(E_x, E_y)$$

- 'corrected' diffusive dispersion relation

$$\omega = -i\frac{\sigma_1^\perp}{\chi_\perp} k_z^2 - \frac{i}{2}\left(\frac{\sigma^\parallel}{\chi_\perp} + \frac{\sigma_1^\perp}{\chi_\parallel}\right) k_\perp^2 \mp \frac{i}{2}\sqrt{\left(\frac{\sigma^\parallel}{\chi_\perp} - \frac{\sigma_1^\perp}{\chi_\parallel}\right)^2 k_\perp^4 - 4\left(\frac{\sigma_2^\perp}{\chi_\perp}\right)^2 \left(k_z^2 + \frac{\chi_\perp}{\chi_\parallel} k_\perp^2\right) k_z^2}$$

→



$$\omega = -iD(\theta)k^2$$

SUMMARY AND FUTURE DIRECTIONS

- formal approach to QFTs enables new physical insights
- plasma can be understood as a string fluid
- higher-form symmetries and new developments in EFTs allow for a new, general formulation of magnetohydrodynamics applicable to strong ***B*** fields
- new predictions, including a new theory of magnetic diffusion in neutron stars
- next step: non-linear evolution of the (diffusion) equation (best variables?)
- include other effects: superfluidity, …
- how large are new effects in realistic neutron stars or other realistic plasmas?

THANK YOU!