Project B04:
The electroweak response of hot and dense QCD matter

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

CRC-TR 211 Strong-interaction matter under extreme conditions

TECHNISCHE UNIVERSITÄT DARMSTADT

DFG

UNIVERSITÄT BIELEFELD

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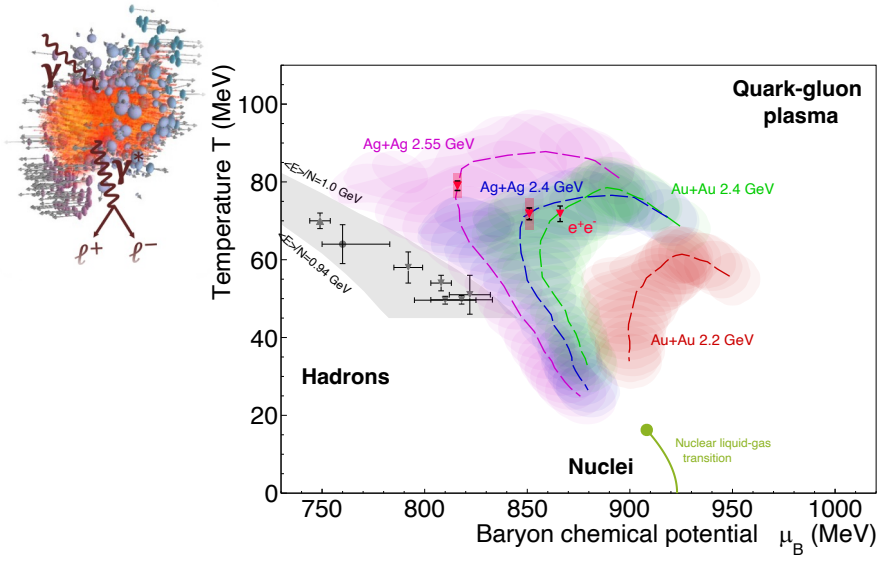
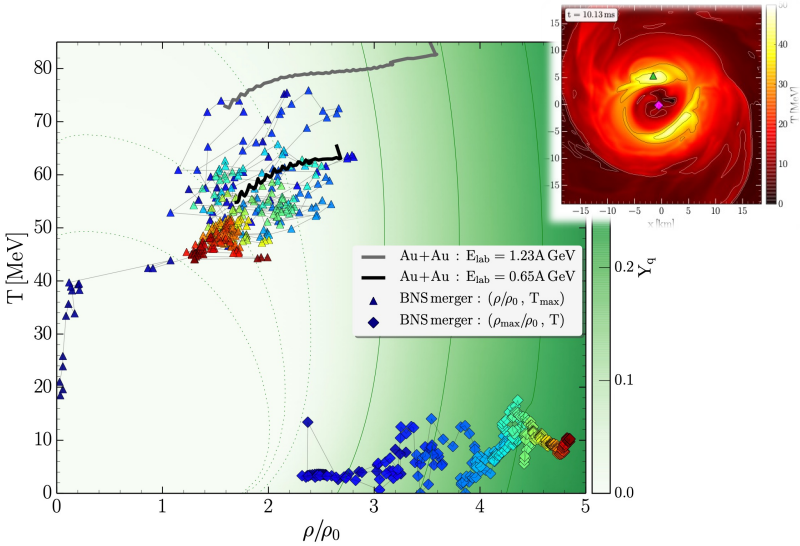
Central goal

Realistic effective description using the **functional renormalization group (FRG)** and **renormalization-group invariant mean-field theory (RG-MF)** to compute the relevant **thermodynamic properties** and **electroweak response** of QCD matter

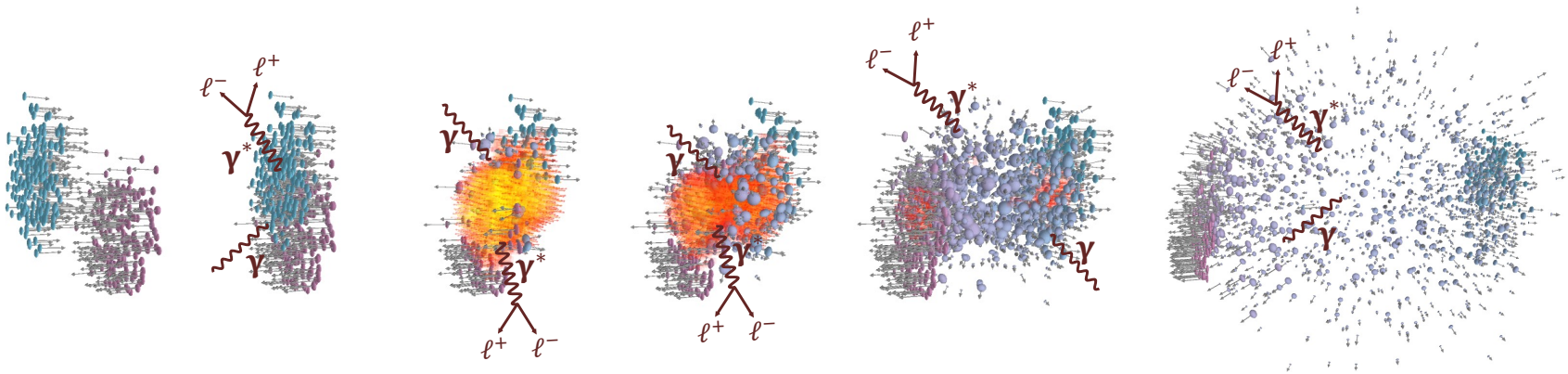




FO curve: Cleymans, Redlich, NPA 661 (1999) 379
Nuclear liquid-gas: Recchi, von Smekal, Wambach, [arXiv:2511.07226 [nucl-th]]
Au+Au 2.4 GeV data: HADES, Nature Phys. 15(2019) 1040
Ag+Ag data: HADES in preparation

Hanauske *et al.*, Particles 2 (2019) no.1
Rezzolla *et al.*, PRL 122 (2019) no. 6, 061101

EM radiation as multi-messenger of fireball



electromagnetic radiation (γ, γ^*)

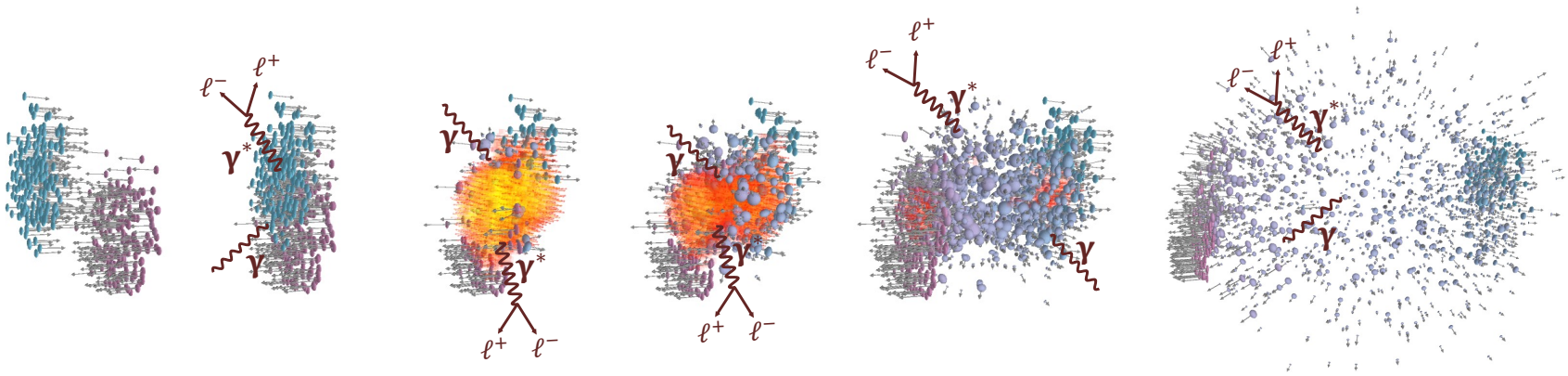
reflect the whole history of a collision

no strong final state interaction
$\rightsquigarrow$ leave reaction volume undisturbed

encodes information on matter properties enabling unique measurements

- degrees of freedom of the medium
- fireball lifetime, temperature $\langle T \rangle$, acceleration (T_{eff}), polarization
- transport properties
- restoration of chiral symmetry

EM radiation as multi-messenger of fireball



- **Dileton rates**:

$$\frac{dN_{ll}}{d^4q d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^B(q_0,T)\mathrm{Im}\Pi_{em}(M,q,T,\mu_B)$$

McLerran - Toimela formula, PRD 31 (1985) 545

- **Transport properties** of the medium - electrical conductivity:

$$\sigma_{el}(T,\mu_B) = -e^2 \lim_{q_0\to 0}\frac{1}{q_0}\mathrm{Im}\Pi_{em}(q_0, q=0; T,\mu_B)$$

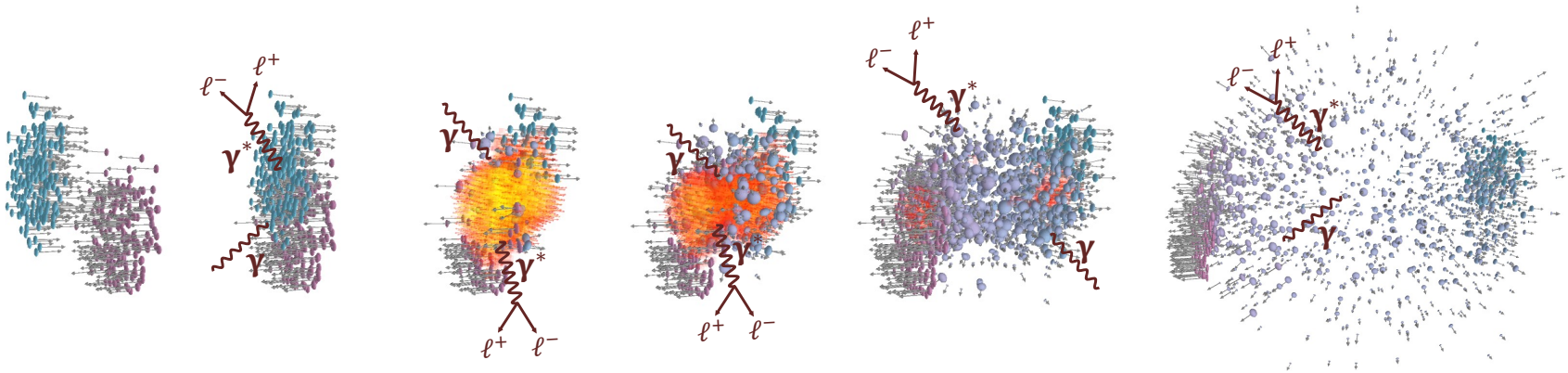
- **Polarization** encodes the mechanisms that underlie EM emission:

$$\lambda_\theta = \frac{\varrho_T - \varrho_L}{\varrho_T + \varrho_L}$$

- Integrate rates over **evolving fireball**:

$$\frac{dN_{ll}}{dM} = \int d^4x \frac{M d^3q}{q_0}\frac{dN_{ll}}{d^4q d^4x}$$

EM radiation as multi-messenger of fireball



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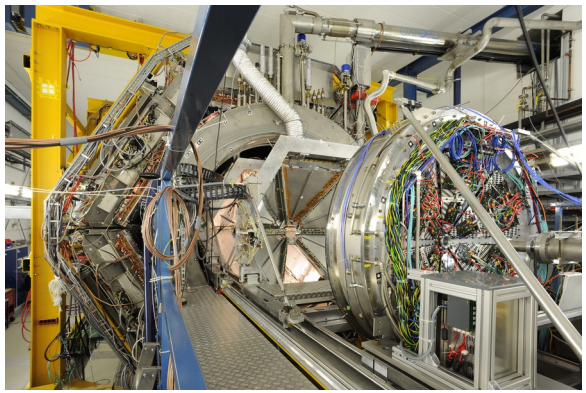
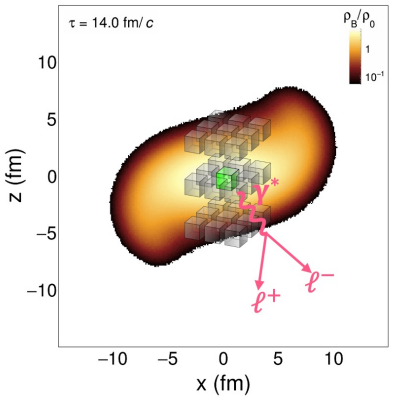
compare to exp. data

HADES at GSI

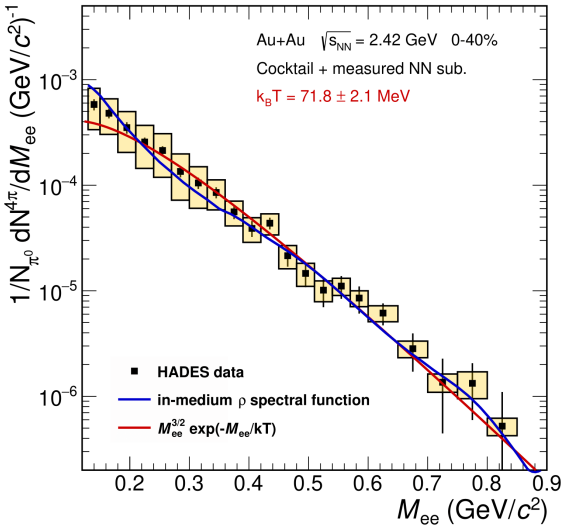


Thermal dileptons HADES systematics

➥ **very good agreement between experiment and theory (Coarse-Grained transport approach) for excess radiation**



Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



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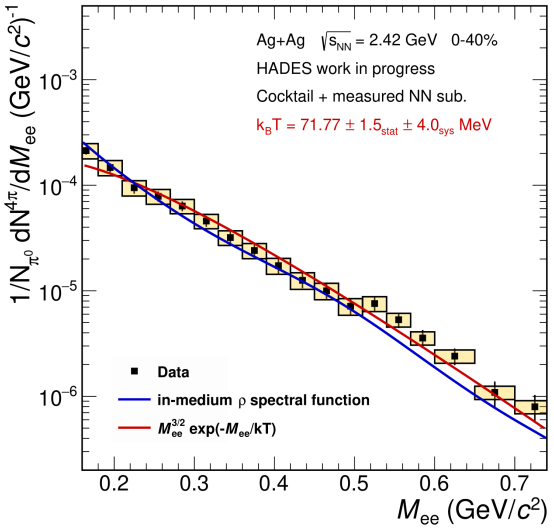
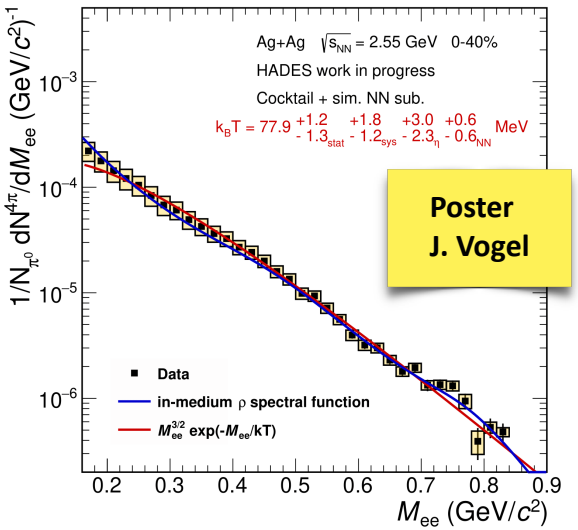


Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV



Poster J. Vogel

- in-medium spectral function from many-body theory consistently describes SIS18, SPS, RHIC, LHC energies Rapp and Wambach, Adv.Nucl.Phys. (2000) 25
- ρ-meson peak undergoes a strong broadening in medium, baryonic effects are crucial

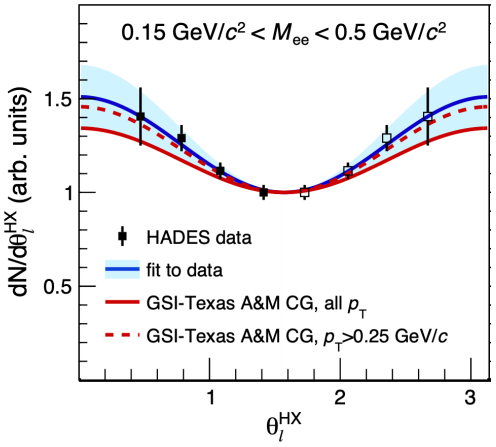
Virtual photon polarization

- Decompose spectral function using projectors for a spin-1 particle
  $\rho_{EM}^{\mu\nu} = \rho_L\, P_L^{\mu\nu} + \rho_T\, P_T^{\mu\nu}$ with $g_{\mu\nu}\,\rho_{EM}^{\mu\nu} = \rho_L + 2\rho_T$
- Angular distribution of single lepton in γ^* rest frame depends on polarization of γ^*

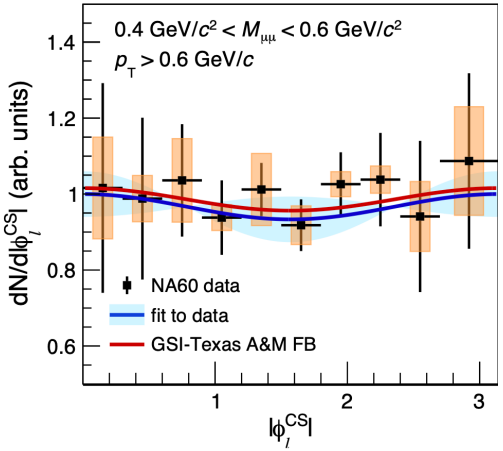
$$\frac{dN}{d^4x d^4q d\Omega} = \mathcal{N}(1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi^\perp \sin^2\theta \sin 2\varphi + \lambda_{\theta\varphi}^\perp \sin 2\theta \sin\varphi)$$

- Different virtual photon **production mechanisms** imprint different anisotropy parameters $\boldsymbol{\lambda}$
- $\boldsymbol{\lambda}$ coefficients related to **difference** between **longitudinal and transverse** spectral function components $\boldsymbol{\lambda_\theta} = \frac{\varrho_T - \varrho_L}{\varrho_T + \varrho_L}$

HADES



NA60

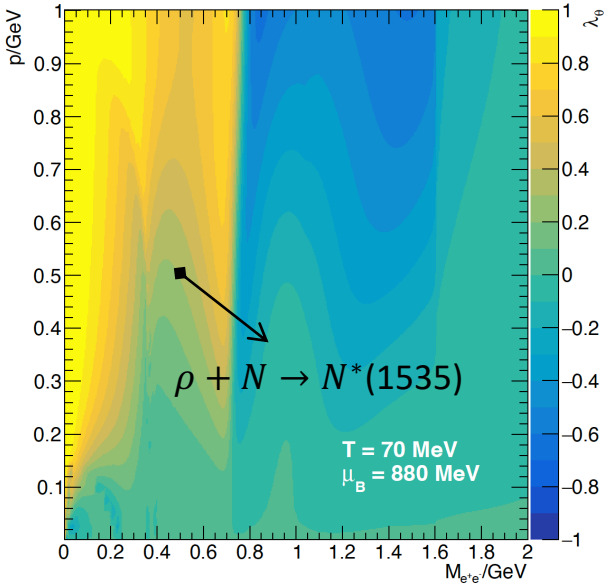


Seck *et al.*, Phys.Lett.B 861 (2025) 139267

HADES, PRC 84 (2011) 014902
NA60, PRL 102 (2009) 222301

Talk F. Seck

Vector meson polarization from the FRG-PDM spectral function



Wiest, PhD thesis, TU Darmstadt 2025

B04 Objectives

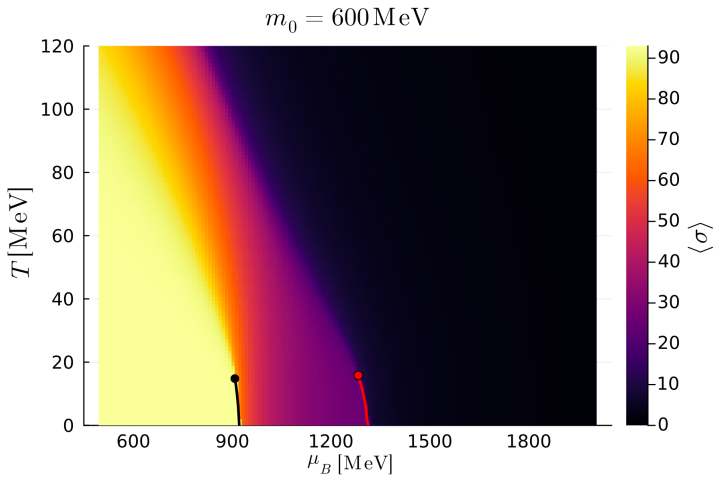
- further develop and utilise a **realistic chirally-symmetric effective hadronic theory** for symmetric and asymmetric nuclear matter, including strangeness
- **consistently compute EW spectral functions** at high baryon densities and T
- infer EM signals of **chiral symmetry restoration in HIC** and compare to data
- **predict neutrino production** and **propagation** in neutron-star merger events

Effective hadronic theory for nuclear & neutron matter

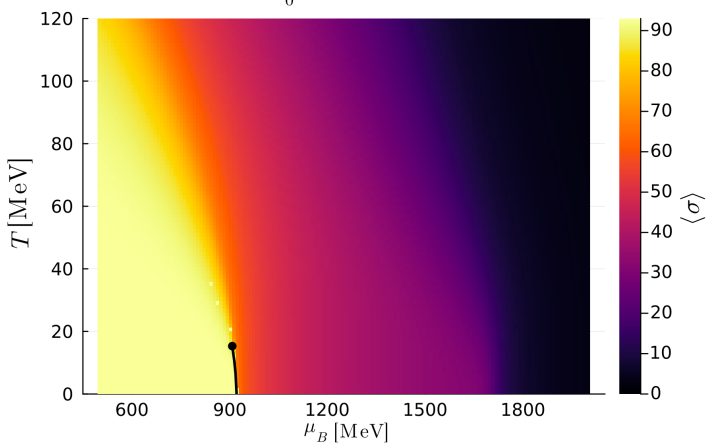
Talk M. Recchi

Recchi, von Smekal, Wambach, [arXiv:2511.07226 [nucl-th]]

Renormalization-group invariant parity-doublet model



with fermionic vacuum fluctuations



see also, Eser, Blaizot, PRC 109 (2024) 045201

EoS and thermodynamics:

- use chiral parity-doublet models (PDM) with baryons and mesons as effective hadronic theory for chiral symmetry restoration in dense matter

Pion-baryon couplings and axial charges:

- **kinetic mixing** to fix the electroweak response of the model
- two mixing angles plus pseudovector coupling h_v ⇝ independently adjust

$$g_A = \frac{\cos(\theta_1+\theta_2)}{\cos(\theta_1-\theta_2)} + 4h_v \frac{\sin\theta_1\cos\theta_2}{\cos^2(\theta_1-\theta_2)}$$

$$g_A^* = \frac{\cos(\theta_1+\theta_2)}{\cos(\theta_1-\theta_2)} + 4h_v \frac{\cos\theta_1\sin\theta_2}{\cos^2(\theta_1-\theta_2)}$$

Kummer, Leupold, von Smekal, [arXiv:2512.03894 [hep-ph]]

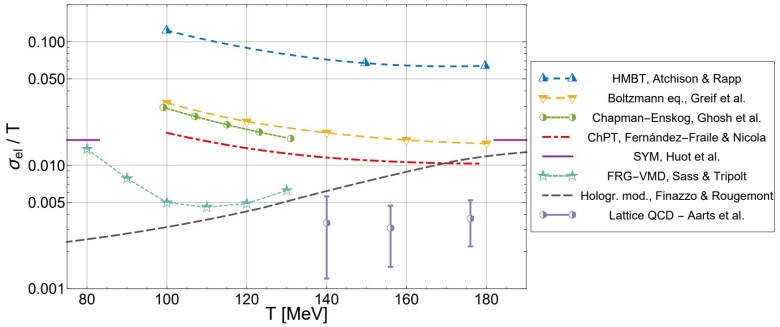
Strangeness:

- extend RG-MF formulation of PDM to 2+1 flavors in collaboration **with B09** for charge neutral, β-equilibrated matter

Electroweak response of dense QCD matter

EW currents:

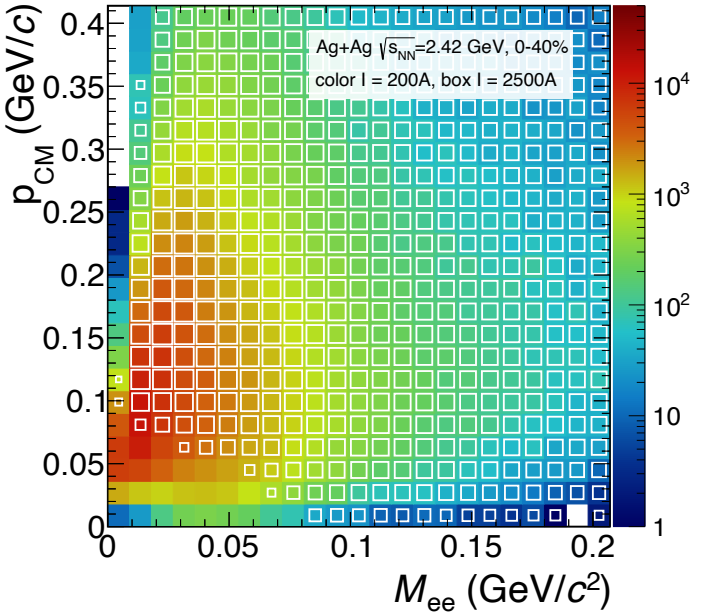
- gauge extended PDM with kinetic mixing and (axial-)vector mesons (minimal spin) to construct EW currents
- go beyond one-loop structures of present aFRG flows ⇝ use effective two-loop setup to calculate EW response from Kubo relations
- calculate transport coefficients, low invariant mass SFs and polarization observables



Geurts, Tripolt, PPNP 128 (2023) 104004

EM spectral functions:

- apply in Coarse-Grained transport approach
- compare to HADES data



Non-monotonic trend of σ_{el} as the nuclear LG critical point?

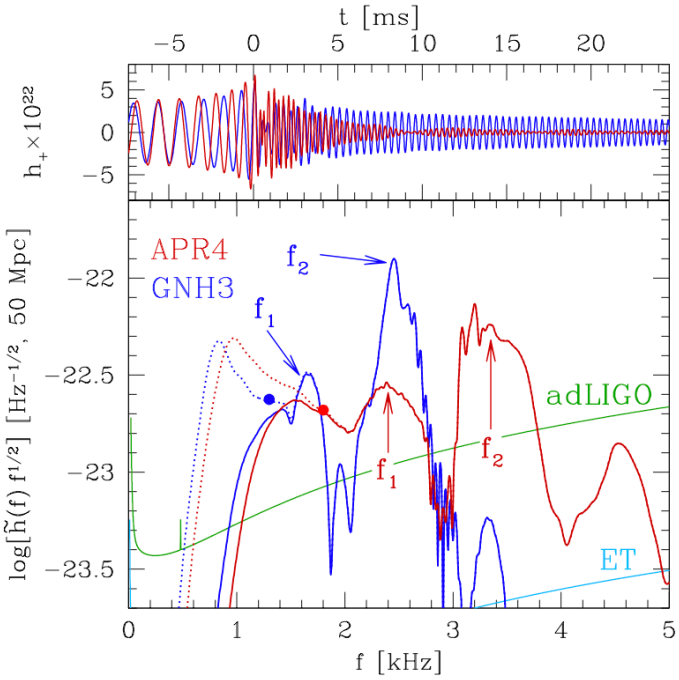
Color superconductivity predicted to manifest itself in an enhanced yield of low-energy dileptons?

Nishimura *et al.*, PTEP 2022 (2022) 9, 093D02

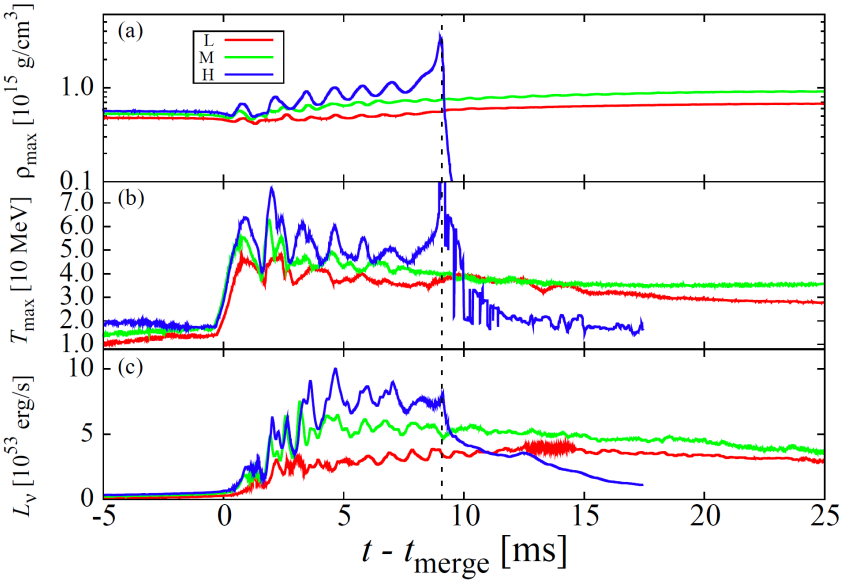
EW SFs and neutrinos

Method: couple the parity-doublet model to the electroweak field (SU(2)×SU(2) gauging) and compute the EW response functions of dense matter, together with the corresponding EoS, to predict:

- observational consequences in BNS merger events for GW profiles
- thermal production of neutrinos in the post-merger remnant (emissivity (time-like) and propagation (space-like)



Hinderer, Rezzolla, Baiotti, "The Physics and Astrophysics of Neutron Stars", Springer (2019)



Sekiguchi *et al.*, PRL 107, 051102 (2011)

The Bigger Bang

Thank you for your attention!