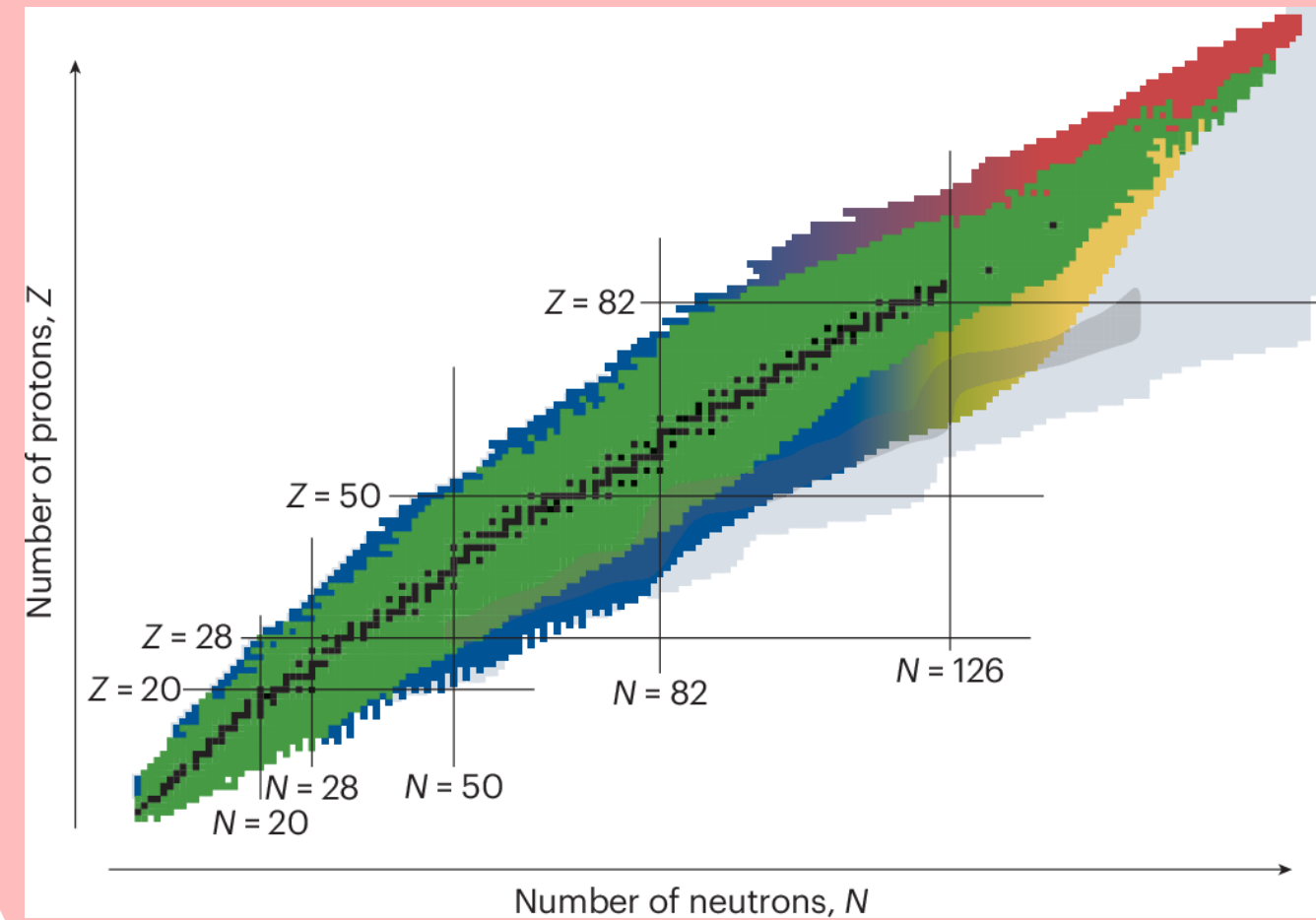
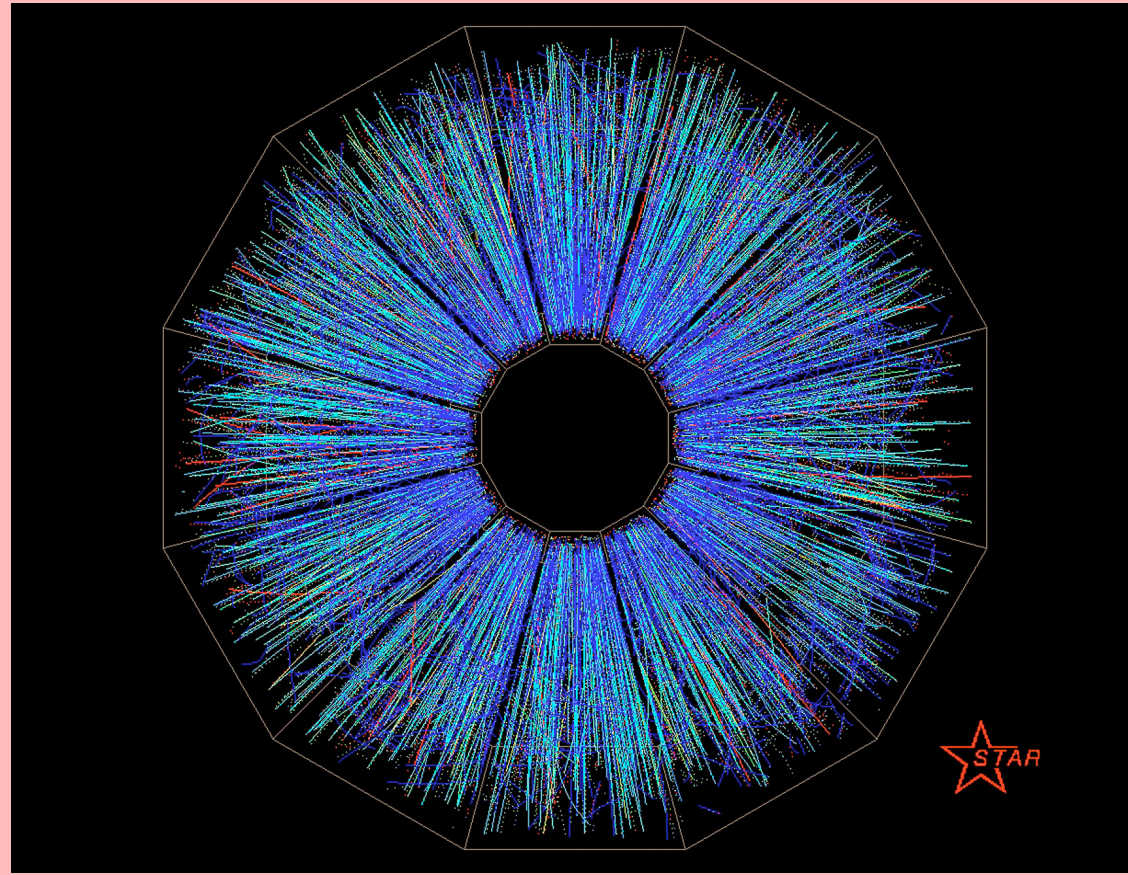


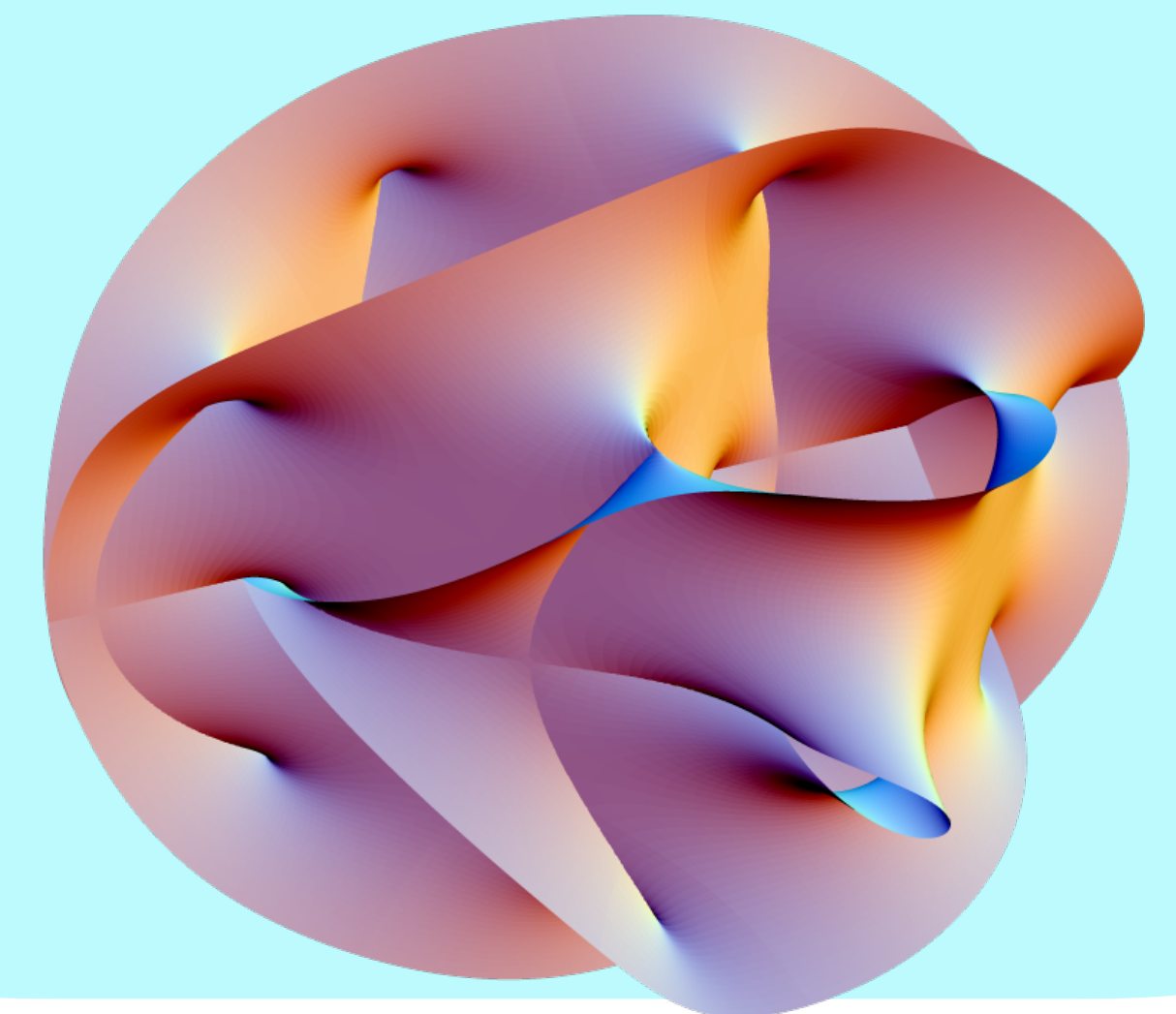
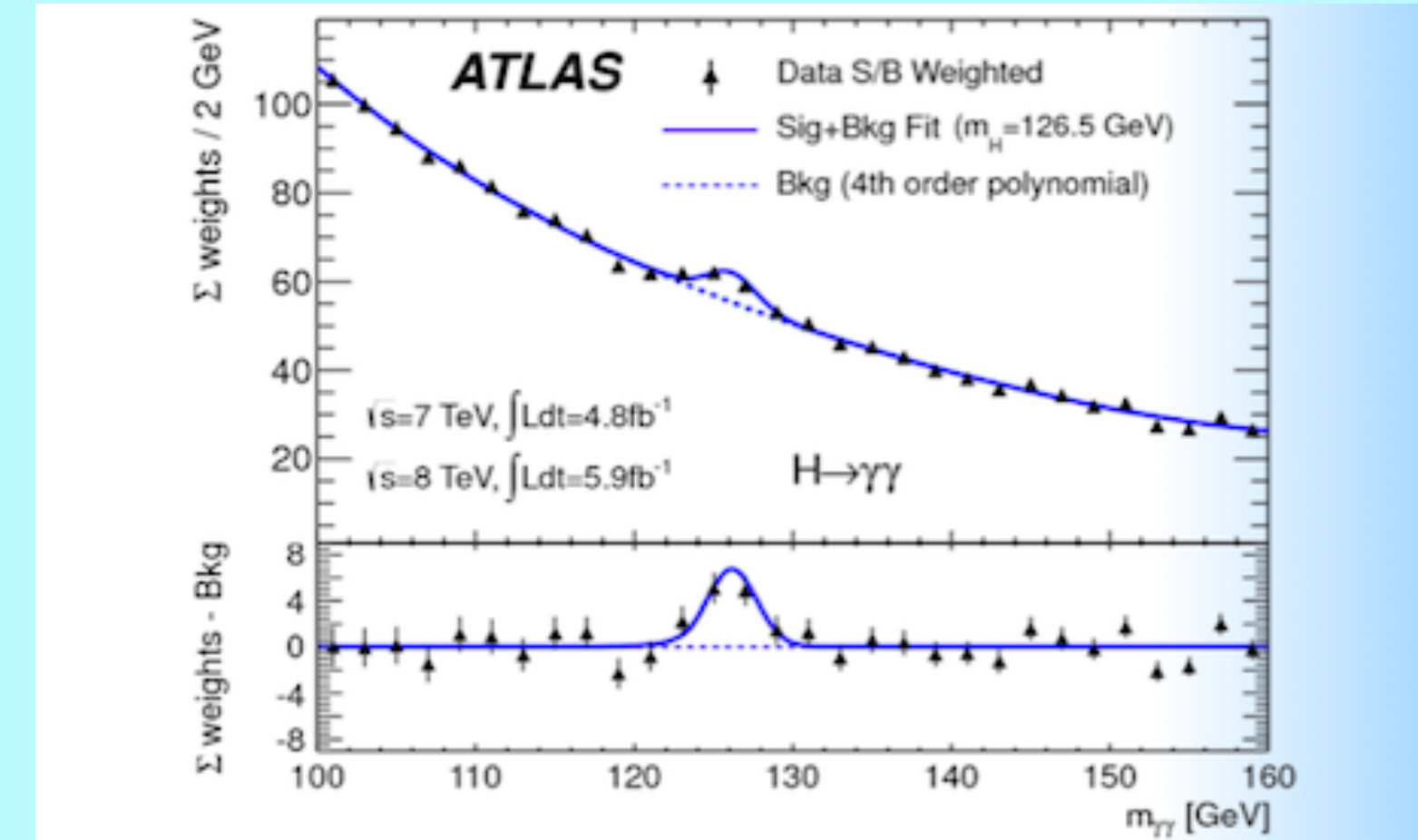
Synergy: Theory

NP



M. Thoennessen, A. Gade

HEP



QCD, SM, BSM



Tools: QFT, Lattice, χ PT, EFT
large N_c , AdS/CFT...

Theory: Detectors, targets, stars



accelerator experiments, astro-
physical constraints of BSM physics,
precision tests of symmetries + ...

Nuclear physics today:

Structure, reactions and dynamics of nuclei, nuclear astrophysics

Spectrum, matrix elements, dynamic correlation functions, electroweak nuclear form factors

Properties of neutron stars, nucleosynthesis, kilo- and super-novae from multi-messenger signals

Hot & cold QCD

QCD phase diagram, heavy ion collisions, low-x physics, hadronic tomography and matrix elements, lattice QCD, effective field theory

Fundamental symmetries, neutrons and neutrinos

Precision tests of BSM physics: P, T, CP, L-violation; neutrino flavor physics

...but again, false boundaries

Fundamental symmetries, neutrons and neutrinos

The physics program:

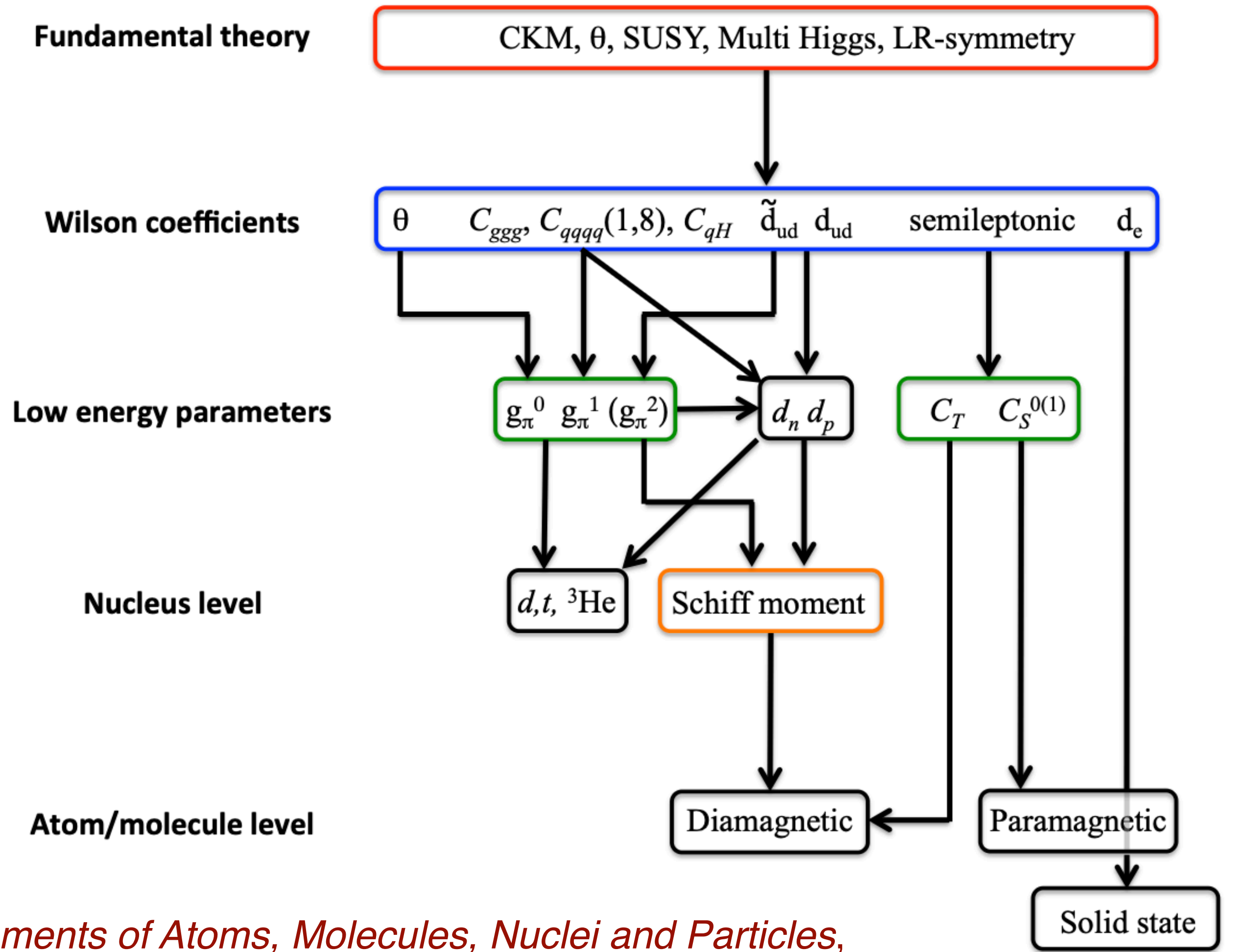
- electron and neutrino interactions with the nucleus, EW nuclear form factors
critical for DUNE to realize discovery potential: central to NP/HE synergy (previous talk)
- neutron decay
3- σ “Cabibbo anomaly” in CKM angles
- nuclear matrix elements for $0\nu\beta\beta$ decay
BSM models of lepton masses, leptogenesis
- CP-violating electric dipole moments & other manifestations of P, CP, T-violation
BSM models of CP violation, baryogenesis
- ν self-interactions, flavor mixing
supernovae - how they work and what we will see
- ...

Fundamental symmetries, neutrons and neutrinos

Tests of BSM physics at the precision frontier is a **multi-scale endeavor** requiring collaborative theory input over a wide energy range

Example: CP violating electric dipole moments leptons and quarks

- BSM model builders
- SMEFT
- Lattice QCD
- χ PT
- Nuclear matrix elements
- Atomic, solid state physics...



TE Chupp, P Fierlinger, MJ Ramsey-Musolf, *Electric Dipole Moments of Atoms, Molecules, Nuclei and Particles*, **Rev. Mod. Phys. 91, 015001 (2019)**.

Nuclear astrophysics

- Neutrinos power supernovae, flavor oscillations play a key role
 - μ , τ neutrinos have longer mean free path in shock wave; oscillations in ejecta can alter nucleosynthesis
- Neutrino pair conversion can provide fast flavor evolution
 - Supernovae (and early universe) provide neutrino-dense environments where ν - ν interactions and pairwise flavor conversion can be important
- Stars, supernovae, compact objects provide dark matter laboratories with multi-messenger signals
 - Cooling rates are sensitive to emission of light, weakly interacting particles — providing more stringent bounds than accelerator experiments
 - Dark matter halos constrained by gravitational wave signals in n-star mergers

A few examples of synergy from nuclear astrophysics:

L Johns, H Nagakura, GM Fuller, A Burrows,
Fast oscillations, collisionless relaxation, and spurious evolution of supernova neutrino flavor,
Phys. Rev. D 102, 103017 (2020), arXiv:2009.09024

I Tamborra, S Shalgar,
New Developments in Flavor Evolution of a Dense Neutrino Gas,
Ann. Rev. Nucl. Part. Sci. 71, 165 (2021), arXiv:2011.01948

AE Nelson, S Reddy, D Zhou,
Dark Halos Around Neutron Stars and Gravitational Waves,
JCAP 07, 012 (2019), arXiv:1803.03266

M Buschmann, C Dessert, JW Foster, AJ Long, BR Safdi,
Upper Limit on the QCD Axion Mass from Isolated Neutron Star Cooling,
Phys. Rev. Lett. 128, 091102 (2022), arXiv:2111.09892

Hot and cold QCD

- Lattice QCD plays a key role in precision studies of hadron structure and matrix elements

A key focus in recent years has been to minimize hadronic theory uncertainties in interpretation of μ (g-2) results

LQCD making progress in parton distribution functions

Tetraquarks, pentaquarks & glue excitations: light exotic hadron studies [$a_0(980)$, $\kappa(800)$, $f_0(980)$] complement the heavies [$X(3872)$, ... $Y(4260)$..., Z ..]

Matrix elements for neutron oscillations, proton decay

- LQCD studies of light nuclei inform anthropic arguments, nature of strange quark matter

How does deuteron binding depend on quark masses? Is the H-dibaryon bound?

- Chiral perturbation theory is being extended to include the nonperturbative physics of nuclei... which in turn is incorporated in state-of-art nuclear structure

Novel applications of nonperturbative effective field theory, following program initiated by Weinberg

A few examples from **cold** QCD:

LJ Broussard et al.,
Baryon Number Violation: From Nuclear Matrix Elements to BSM Physics,
J. Phys G 52, (2025) 8, 083001, arXiv:2504.16983
Summary of INT workshop INT-25-91W

AD Hanlon et al.,
Investigating the Role of Tetraquark Operators in Lattice QCD Studies of the a_0 and κ Resonances,
arXiv:2603.19192

M. Constantinou et al.,
Parton distributions and lattice-QCD calculations: Toward 3D structure,
Prog. Part. Nucl. Phys. 121 (2021) 103908, arXiv:2006.08636

Hot and cold QCD

- Relativistic heavy ion collisions probe QCD at high temperature and low baryon density

Mapping out the QCD phase diagram

Related properties of quark-gluon plasma to $N=4$ SYM plasma through AdS/CFT (viscosity, shock-waves, heavy quark energy loss...)

Application of energy-energy correlation/CFT technology from HE physics

From gluon radiation to gravitational radiation

A few examples from **Hot** QCD:

P Kovtun, DT Son, AO Starinets,

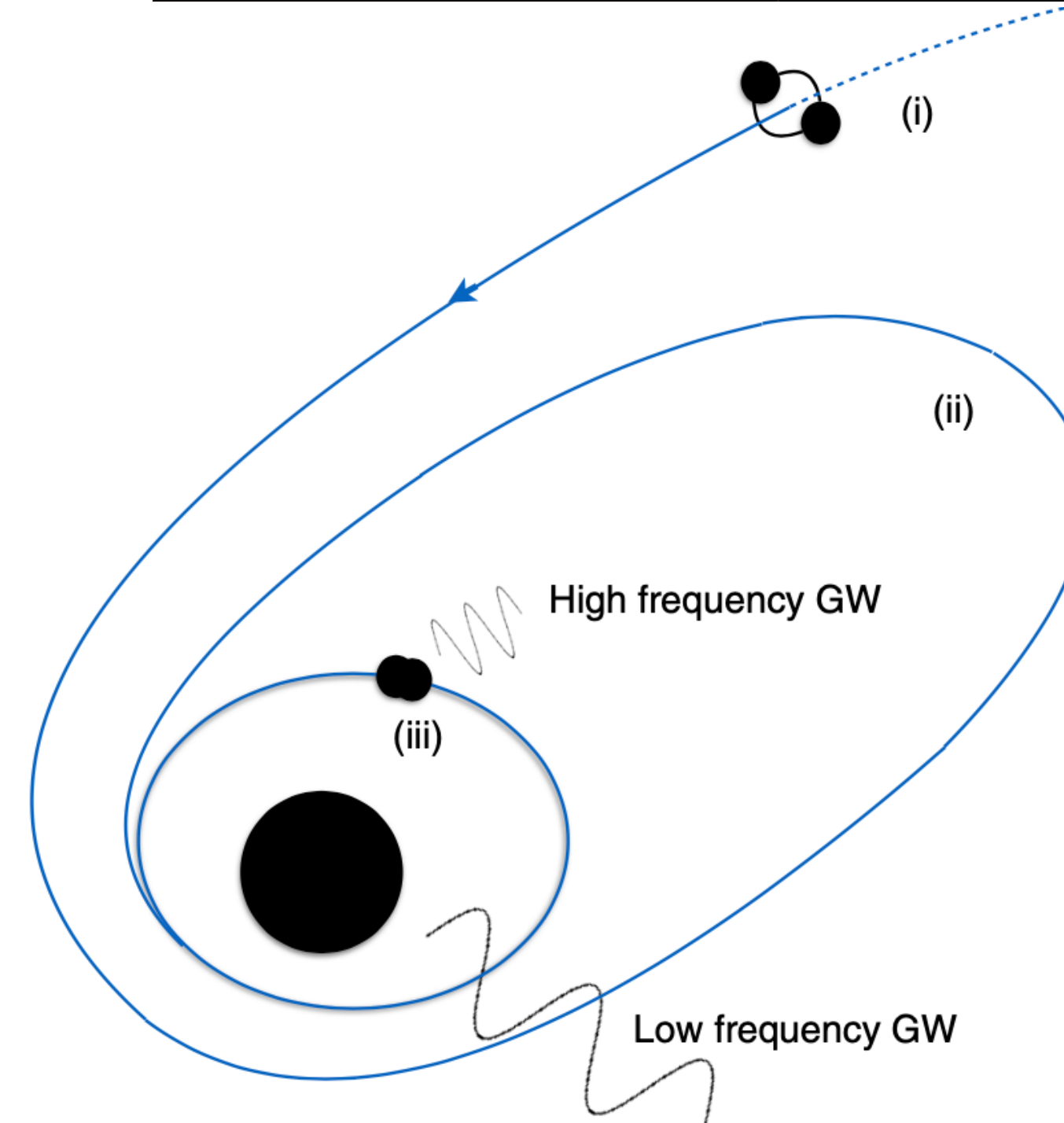
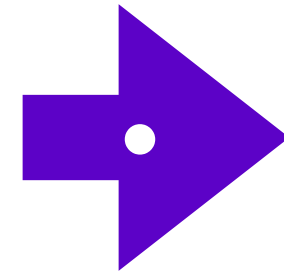
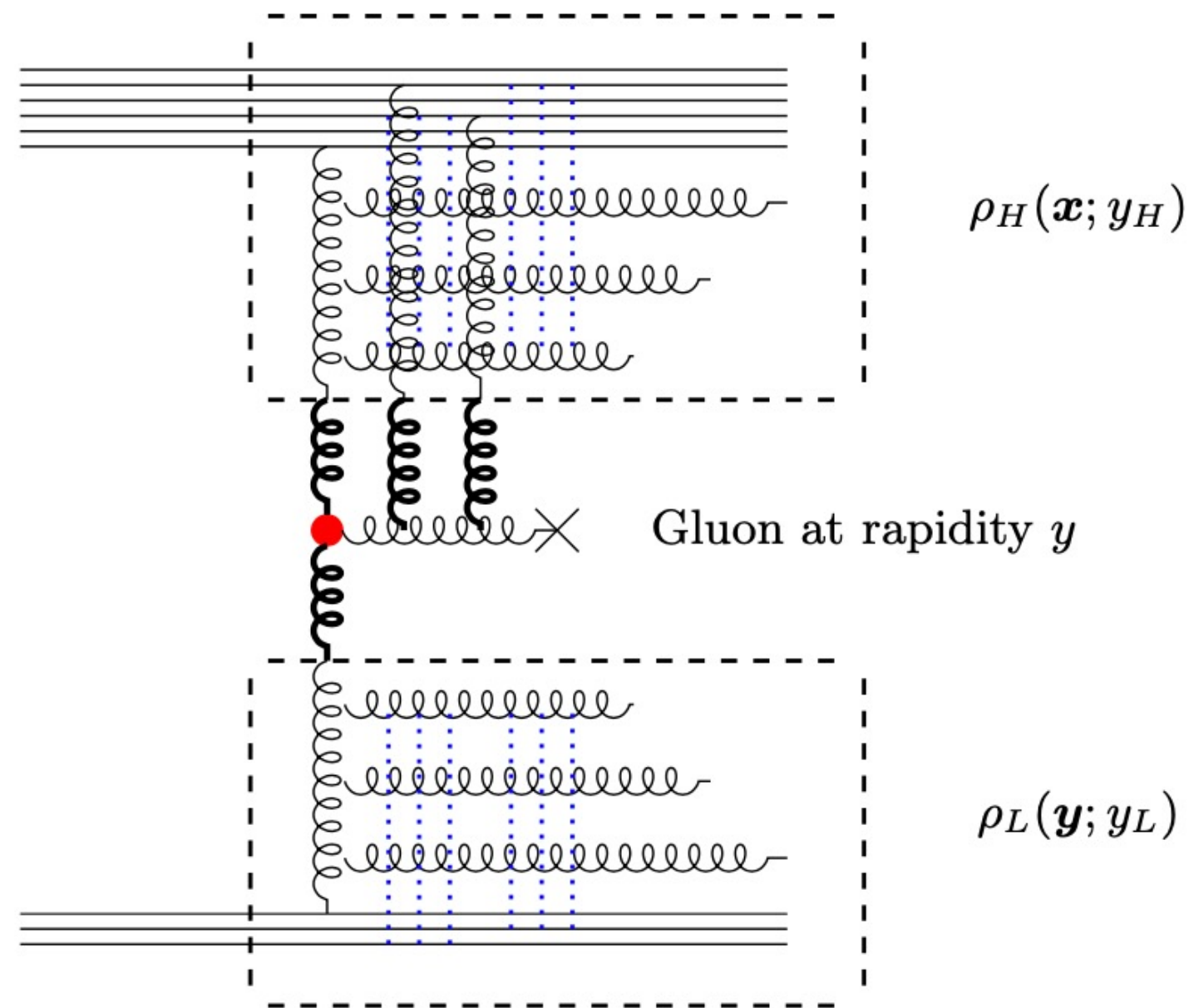
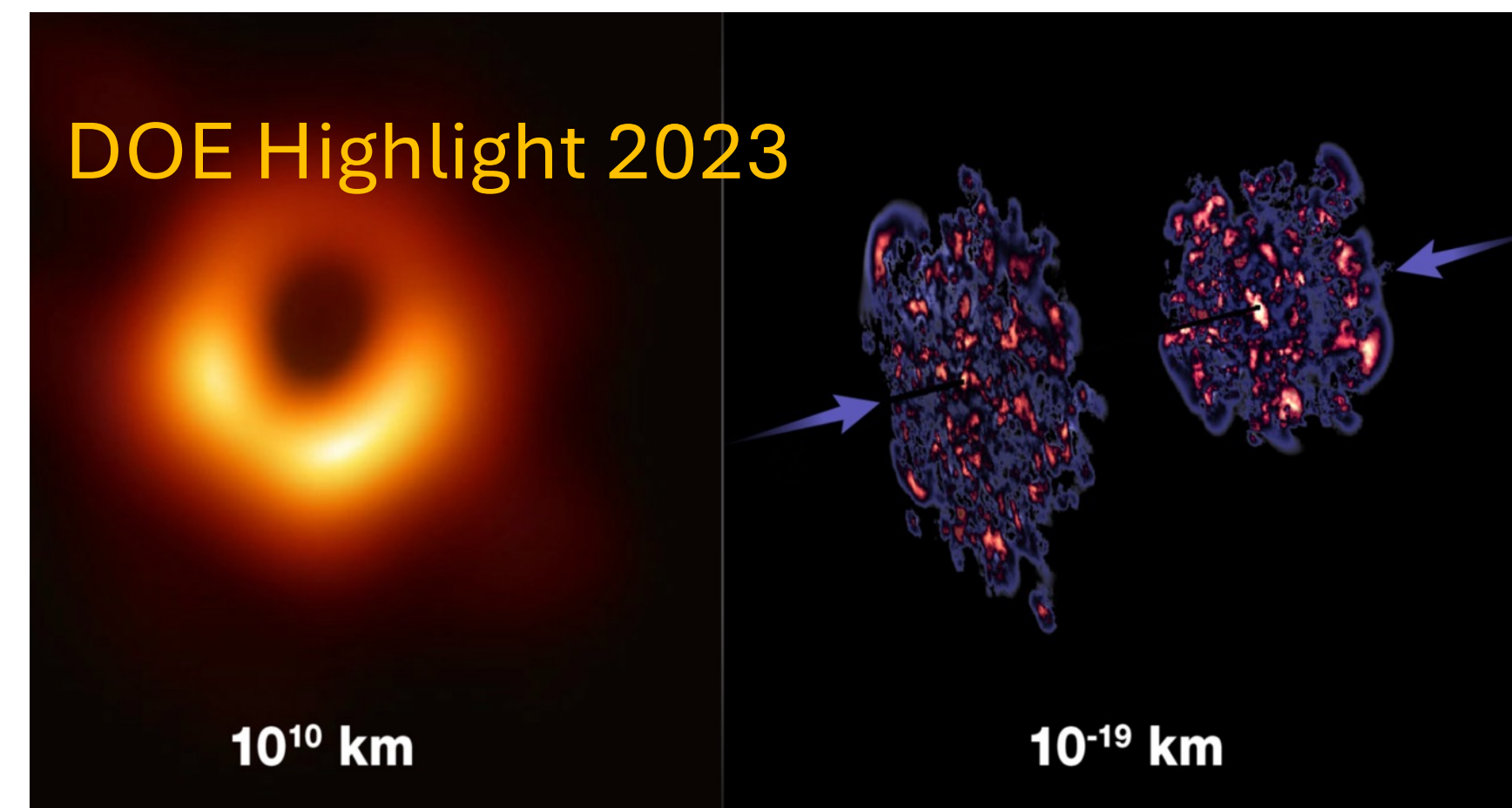
Viscosity in Strongly Interacting Quantum Field Theories from Black Hole Physics,
Phys. Rev. Lett. 94 (2005) 111601, hep-th/0405231

J Barata, MV Kuzmin, I Mout, AV Sadofyev, JM Silva,

Hydrodynamics and Energy Correlators,
arXiv:2604.21971, (2026)

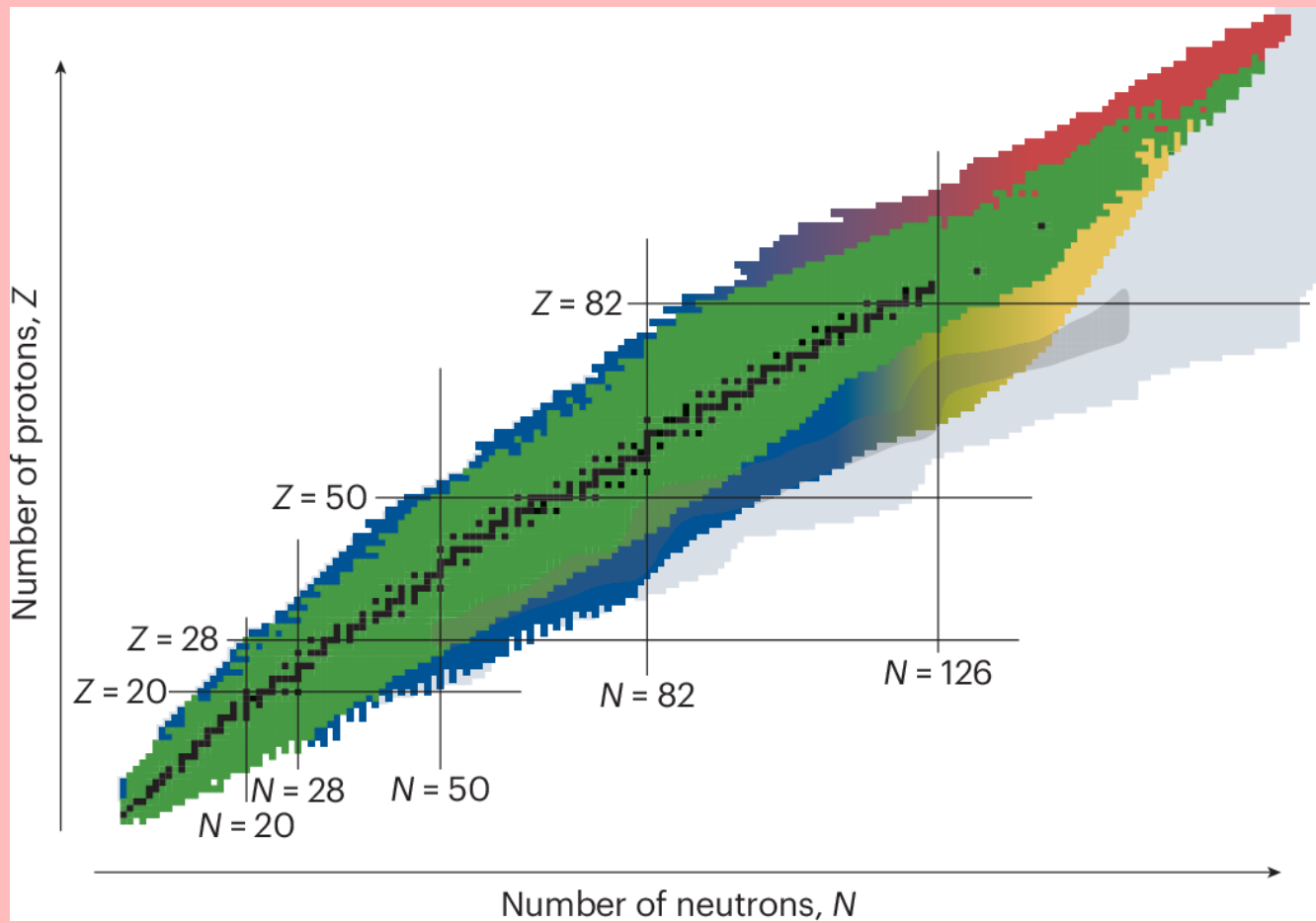
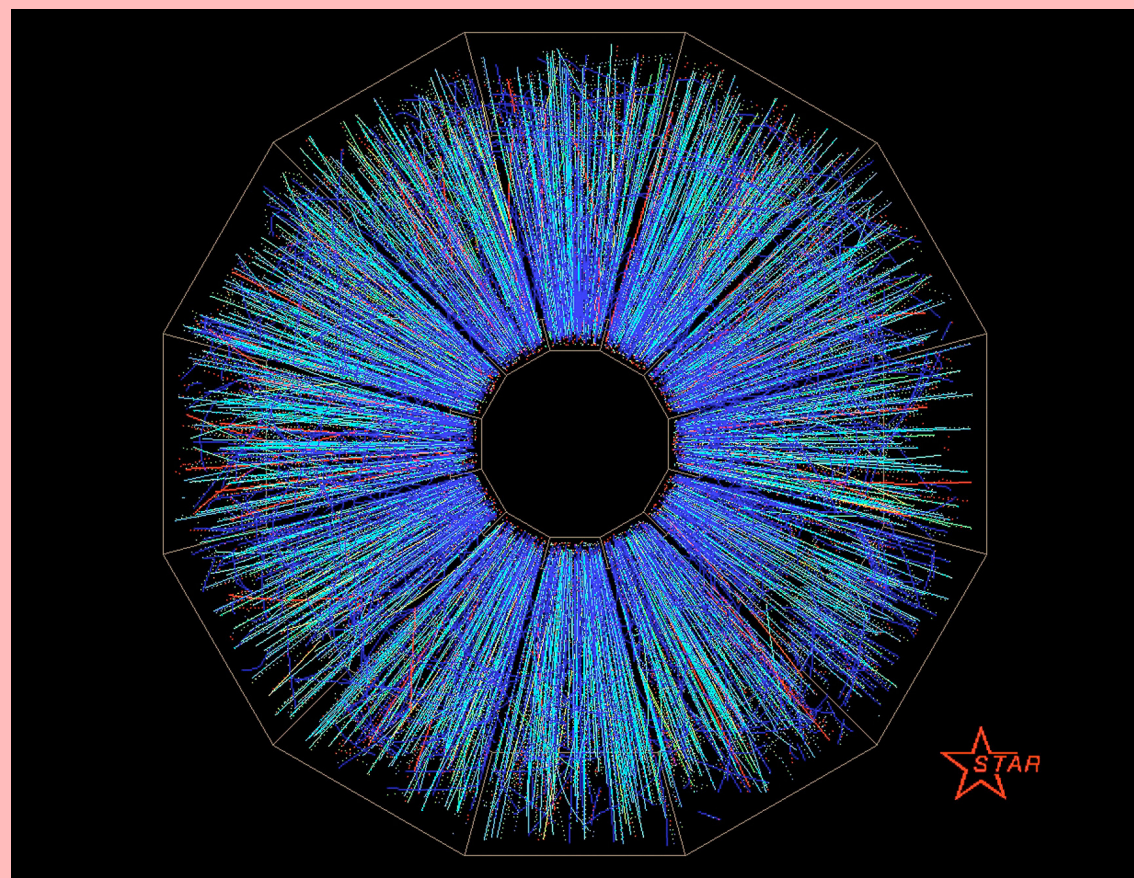
Another example:

Theory of strong-field gluon radiation in heavy ion collisions can be adapted to compute gravitational wave signals from inspiraling compact objects of very different masses

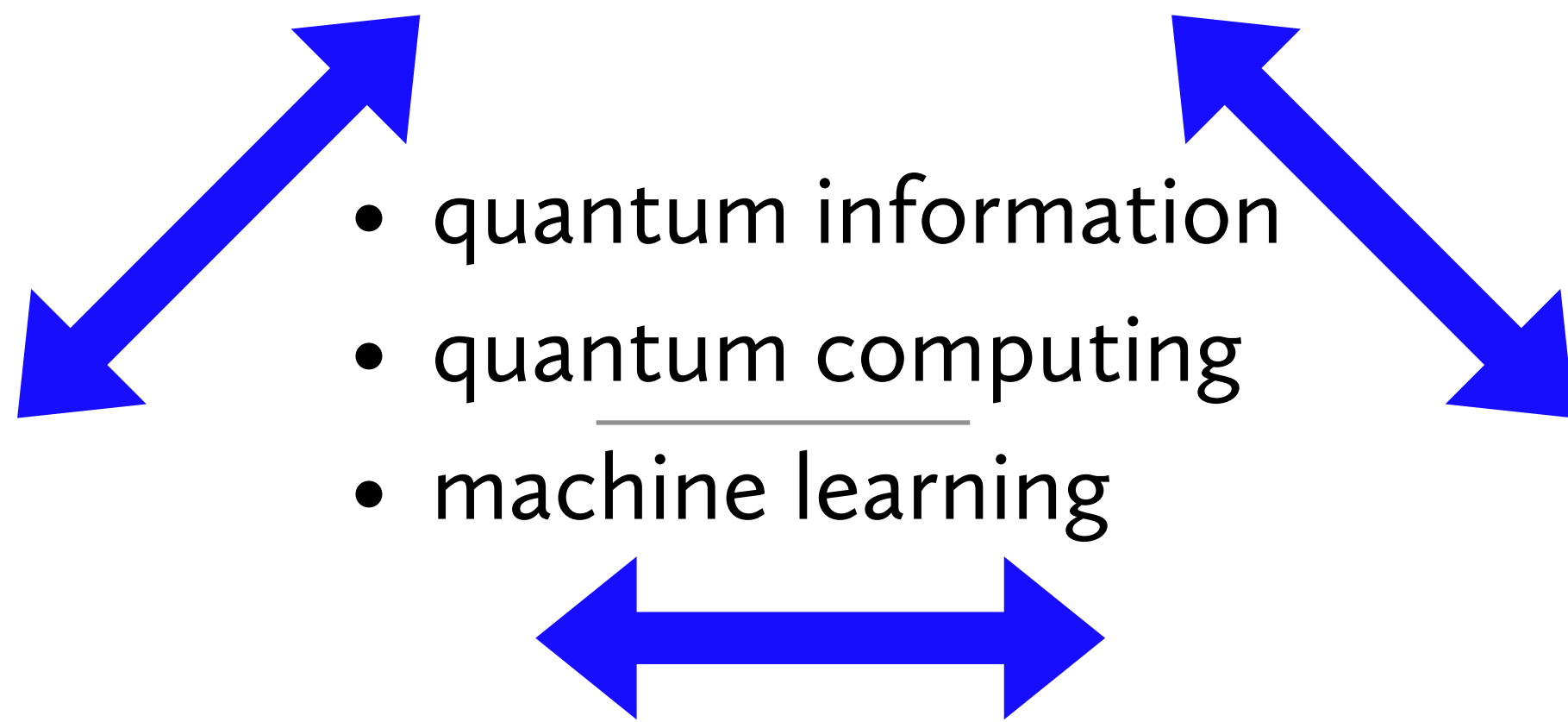


AM Stasto, H Raj, R Venugopalan, *Squeezed State Radiation in Shock-Wave Scattering: QCD-Gravity Double Copy*, arXiv: 2605.03038 (2026)

NP



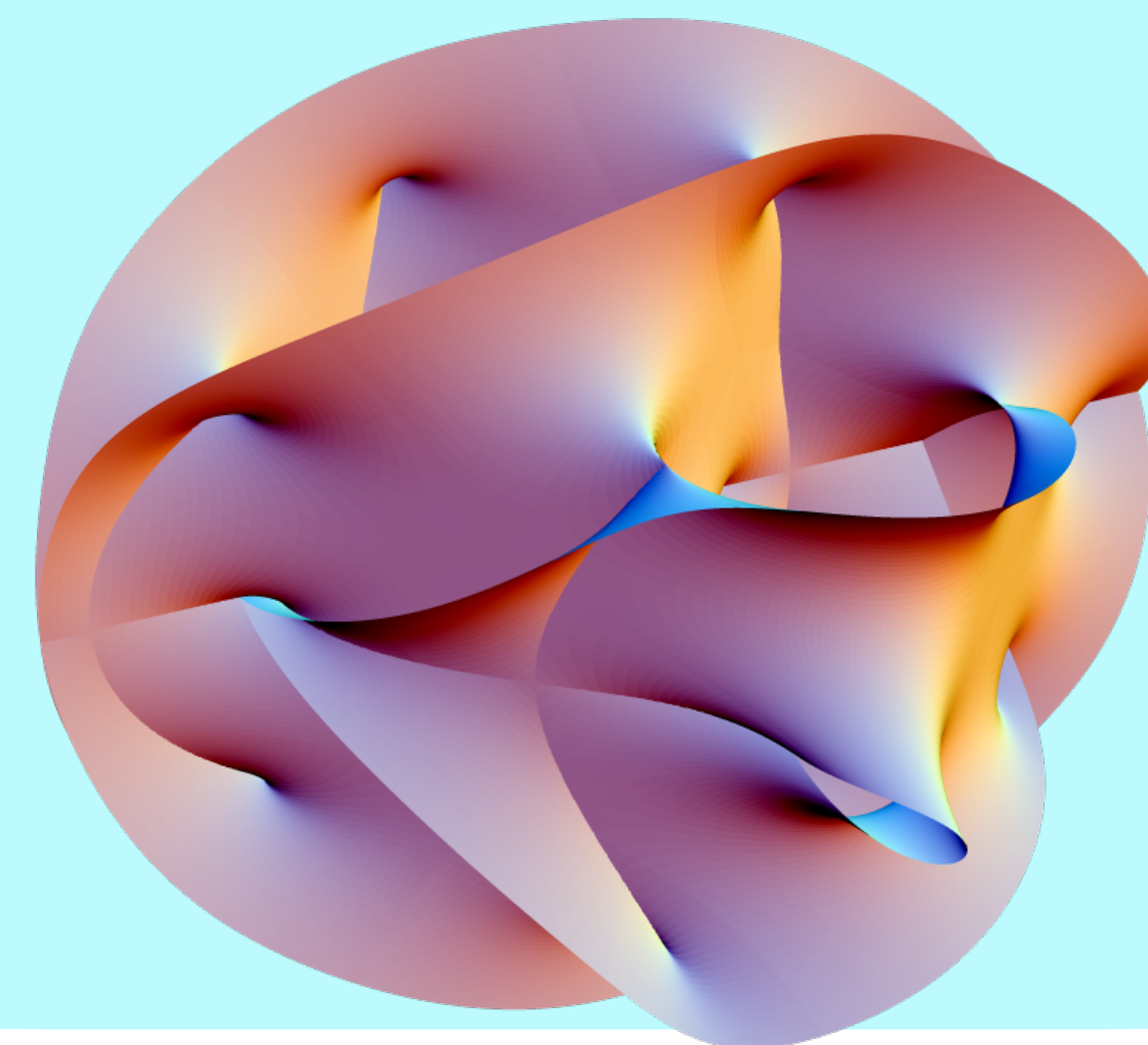
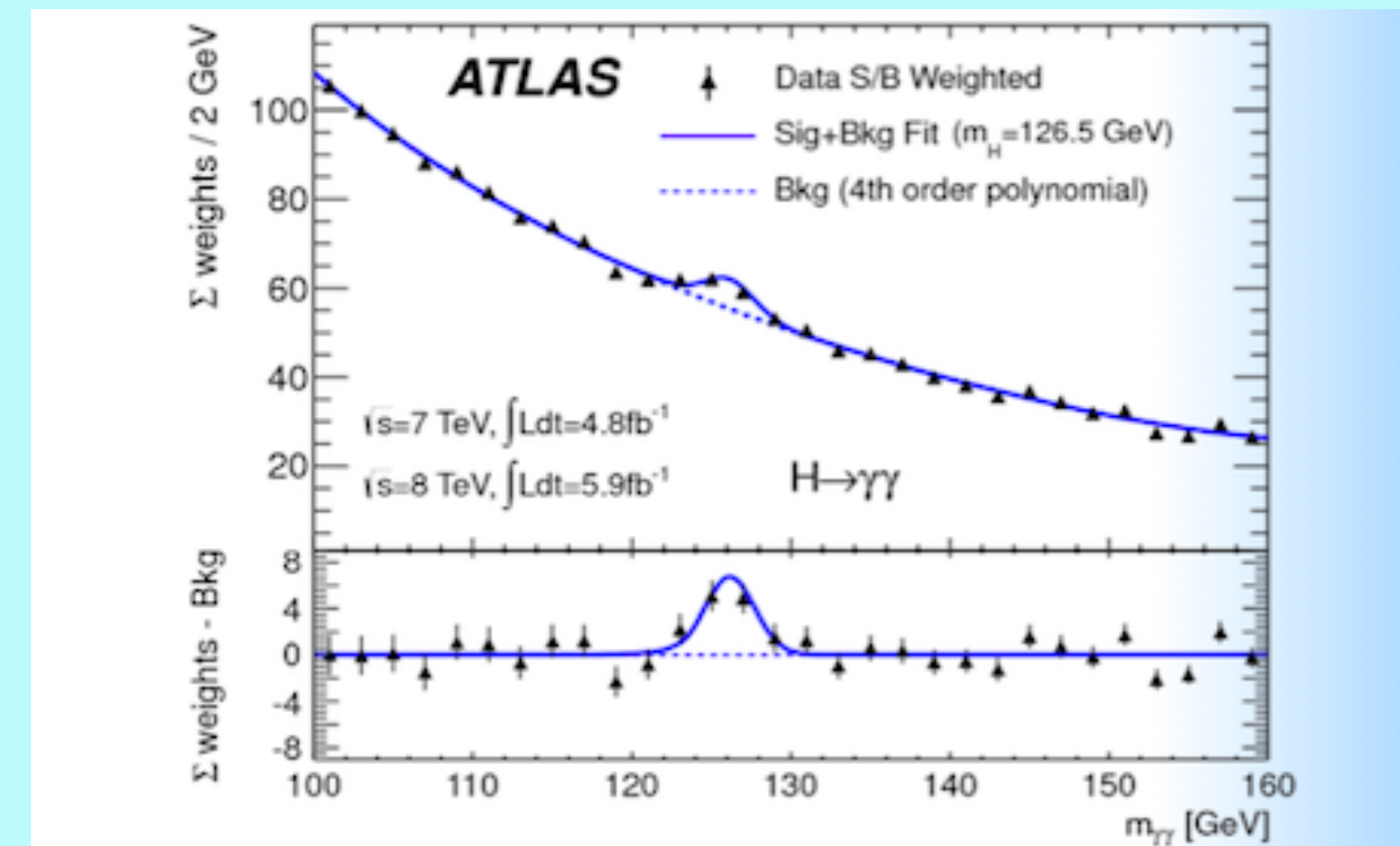
M. Thoennessen, A. Gade



- quantum information
- quantum computing
- machine learning

- beating computational sign problems
- role of entanglement for symmetry, thermalization
- accelerating discovery with machine learning

HEP



A few examples illustrating the breadth of the NP effort in quantum/machine learning

R Weiss, A Baroni, J Carlson,
Solving Reaction Dynamics with Quantum Computing Algorithms,
Phys. Rev. C 111 06004 (2025), arXiv:2404.00202

CEP Robin, MJ Savage,
Quantum Complexity and New Directions in Nuclear Physics and High Energy Physics Phenomenology,
arXiv:2604.26376

MS Albergo, G Kanwar, P Shanahan,
Flow Based Generative Models for Markov Chain Monte Carlo in Lattice Quantum Field Theory
Phys. Rev. D 100 (3) 034515 (2019), arXiv: 1904.12072

S. Beane, DB Kaplan, N Klco, MJ Savage,
Entanglement Suppression and Emergent Symmetries of Strong Interactions
Phys. Rev. Lett. 122 (10) 102001 (2019), arXiv: 1812.03138

Synergy between NP/HE theory is not aspirational — it is happening

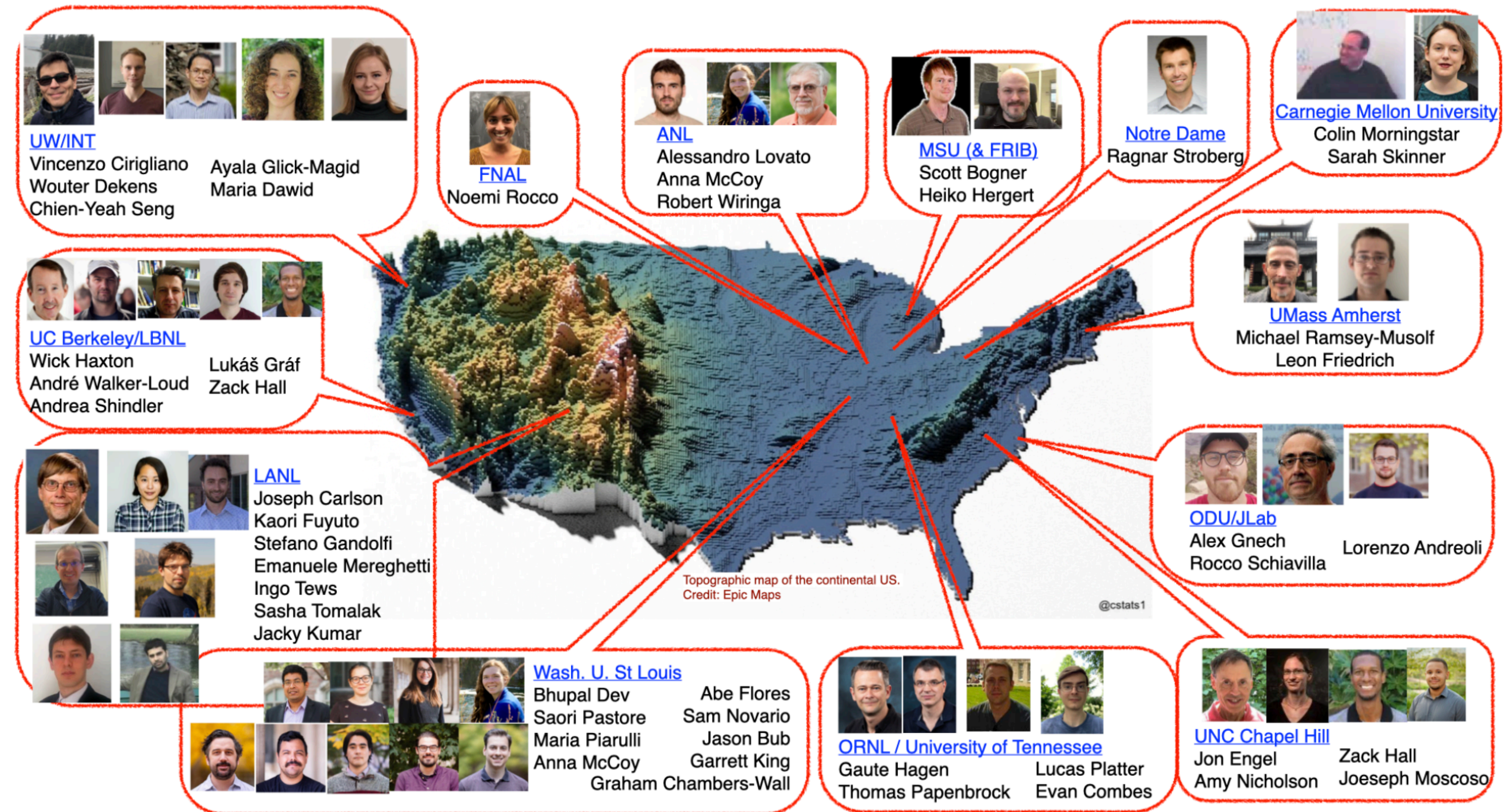
Many collaborations exist across NP + HE to address specific scientific problems and to pool resources

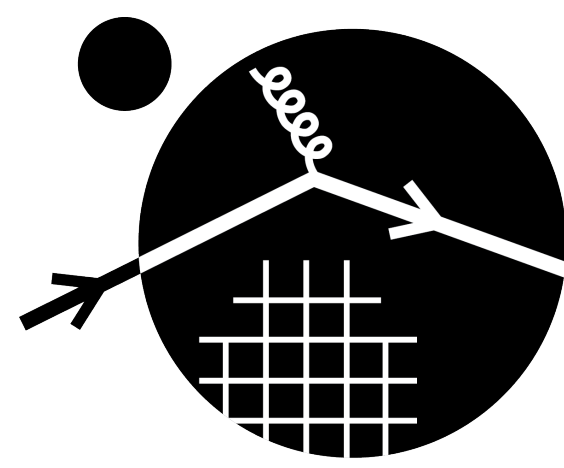
A few examples:

- USQCD — created 1999 — virtually all US lattice effort in HE and NP
- NTNP — Nuclear Theory for New Physics — 14 institutions, cofunded by HE/NP
- Neutrino Theory Network — 28 institutions, HE + NP
- N₃AS — Network for Neutrinos, Nuclear Astrophysics, and Symmetries — 12 institutions, NP + HE
- Double Beta Decay Topical Theory Alliance — 6 institutions, many-body theory + lattice +EFT
- Simons Collaboration on Confinement and QCD Strings — 13 institutions, expertise from string theory to relativistic heavy ion collisions

Example: NTNP: Electric dipole moments — β decay — neutrino-nucleus scattering

Members of the NTNP Collaboration





INSTITUTE for
NUCLEAR THEORY

Synergy is the mission: A theory center for community-driven workshops

- INT mission: dissolving boundaries; identifying and solving pressing problems
- Connections to nuclear theory are very broadly defined, from quantum chaos to AdS/CFT.

Workshops selected by our National Advisory Committee of eminent international physicists, theory + experiment, in NP, HE, Astro, and Computational physics

(former NAC members include DPF Sakurai Prize winners Lepage, Manohar, Mueller, Wilczek, Wise, as well as many Bonner, Bethe, Feshbach prize winners)

Historically ~400 workshop participants/yr

The INT is a user facility for the collision of ideas

- visit us and be stimulated
- propose a workshop and move **physics** forward