THEORY FRONTIER

COMMUNITY PLANNING 2021

Town Hall @ CSS Seattle
July 24, 2022

TF Logo: Flip Tanedo

Theory Frontier

GOALS:

- Articulate the role/vibrancy/importance of theory within HEP, both in relation to projects and on its own right

- Highlight important developments over the past and exciting new directions/opportunities over the next decade

- Theory cross-cutting - every frontier has (as usual) own theory representation, TF should help facilitate theory related activities in and across other frontiers

Theory Frontier Organization


Nathaniel Craig
UCSB


Csaba Csaki
Cornell


Aida El-Khadra
UIUC

Topical Group		**Topical Group co-Conveners**			
TF01	String theory, quantum gravity, black holes	Daniel Harlow	Shamit Kachru	Juan Maldacena	
TF02	Effective field theory techniques	Patrick Draper	Ira Rothstein		
TF03	CFT and formal QFT	David Poland	Leonardo Rastelli		
TF04	Scattering amplitudes	Zvi Bern	Jaroslav Trnka		
TF05	Lattice gauge theory	Zohreh Davoudi	Taku Izubuchi	Ethan Neil	
TF06	Theory techniques for precision physics	Radja Boughezal	Zoltan Ligeti		
TF07	Collider phenomenology	Fabio Maltoni	Shufang Su	Jesse Thaler	
TF08	BSM model building	Patrick Fox	Graham Kribs	Hitoshi Murayama	
TF09	Astro-particle physics and cosmology	Dan Green	Joshua Ruderman	Ben Safdi	Jessie Shelton
TF10	Quantum information science	Simon Catterall	Roni Harnik	Veronika Hubeny	
TF11	Theory of Neutrino Physics	André de Gouvêa	Irina Mocioiu	Saori Pastore	Louis Strigari

Theory Frontier: liaisons

Energy Laura Reina (Florida State U)	**Neutrino Physics** Irina Mociouiu (Penn State U) & Kaladi S. Babu (Oklahoma State U)
Rare Processes and Precision Alexey Petrov (Wayne State)	**Cosmic** Flip Tanedo (UC Riverside)
Theory	**Accelerator** Lian-Tao Wang (U Chicago)
Instrumentation	**Computational** Steven Gottlieb (Indiana U)
Underground Facilities	**Community Engagement** Devin Walker (Dartmouth)
Early Carreer Rotating	

TF: Events

- TF Conference at KITP February 2022 - hybrid with ~ 100 in person participants
- 4 days of dedicated TF parallel session talks at CSS
- Cross frontier sessions with EF, CF, CompF, RPF
- Participated in EF, RPF conferences, large participation in CPM fall 2020

White papers

- 138 White papers submitted to TF out of total 510 (second most after EF 150)
- Official numbers per topical group:
- Actual numbers higher

TF	16
TF01	9
TF02	6
TF03	11
TF04	3
TF05	9
TF06	8
TF07	32
TF08	11
TF09	18
TF10	6
TF11	9

TF01

Daniel Harlow,
Shamit Kachru,
Juan Maldacena
conveners

One central development in quantum gravity — with implications for field theory and general quantum systems — has been the derivation of powerful bounds on the transfer of information.

Question: How quickly do black holes scramble information at their horizon?

$\updownarrow$ related by holography

Question: How does the "butterfly effect" manifest itself in thermal quantum systems?

To answer the second question, study correlation functions measuring the effect of slightly changing insertion times of operators. You can think of this as slightly changing initial conditions and comparing results.

4-pt correlator measuring butterfly effect $\longrightarrow$

$$C(t) \sim e^{2\lambda_L t}$$

$$\text{Bound}: \lambda_L \leq 2\pi T$$

Maldacena, Shenker, Stanford 2015;.....

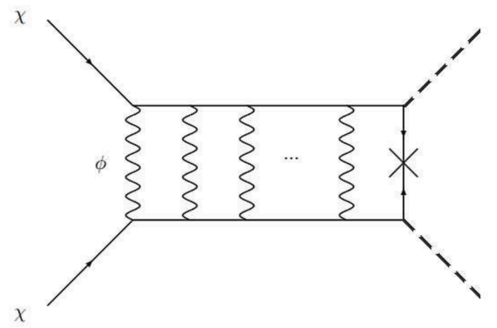
The bound has been loosely proved for large N quantum systems. It is conjectured that systems which saturate the bound are dual to Einstein gravity theories. This provides a sharp criterion for which quantum systems "emerge" gravity.

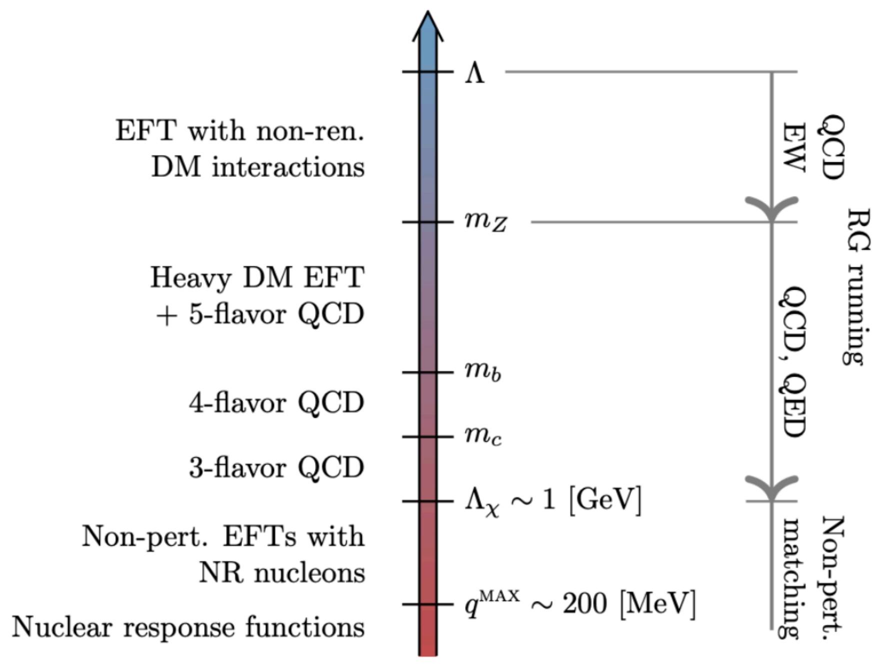
TF02

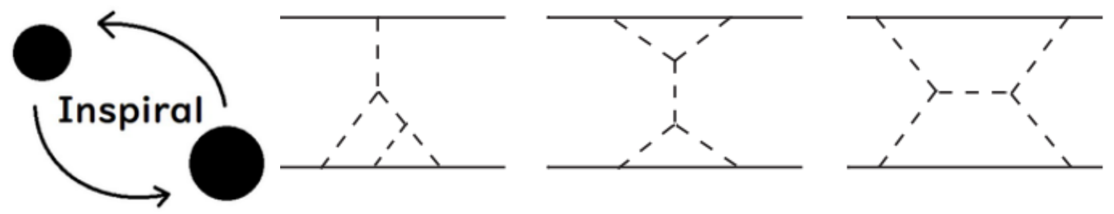
Patrick Draper and Ira Rothstein conveners

Theory $\Longleftrightarrow$ EFT $\Longleftrightarrow$ Observation

- Development of new EFTs and applications
  - interactions of dark matter with nuclei, annihilation rates, …
  - cosmological parameter measurement from LSS data, bounds on nongaussianities, …
  - understanding exotic states of condensed matter systems
  - gravitational wave spectra from binary inspirals
  - precision collider probes of BSM physics via SMEFT

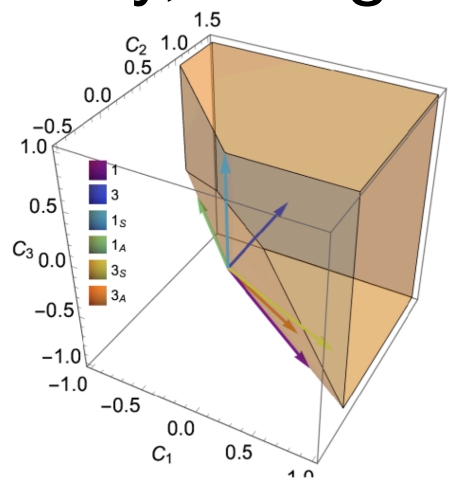


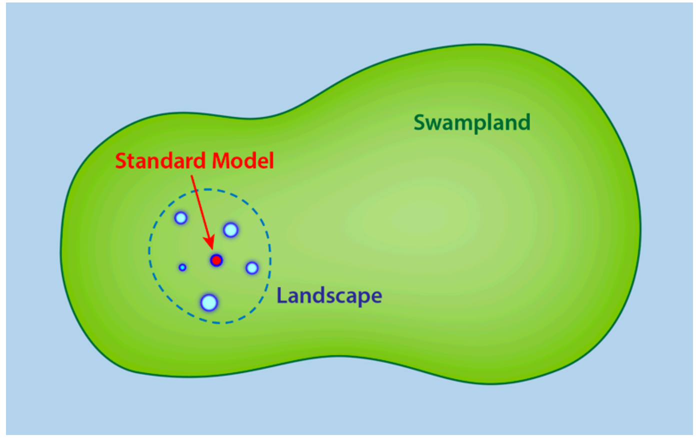




		g^3X^3	H^6	H^4D^2	$g^2X^2H^2$	$y\psi^2H^3$	$gy\psi^2XH$	ψ^2H^2D	ψ^4
		1	2	3	4	5	6	7	8
g^3X^3	1	g^2	0	0	1	0	0	0	0
H^6	2	$g^6\lambda$	λ, g^2, y^2	$g^4, g^2\lambda, \lambda^2$	$g^6, g^4\lambda$	$\lambda y^2, y^4$	0	$\lambda y^2, y^4$	0
H^4D^2	3	g^6	0	g^2, λ, y^2	g^4	y^2	g^2y^2	g^2, y^2	0
$g^2X^2H^2$	4	g^4	0	1	g^2, λ, y^2	0	y^2	1	0
$y\psi^2H^3$	5	g^6	0	g^2, λ, y^2	g^4	g^2, λ, y^2	$g^2\lambda, g^4, g^2y^2$	g^2, λ, y^2	λ, y^2
$gy\psi^2XH$	6	g^4	0	0	g^2	1	g^2, y^2	1	1
ψ^2H^2D	7	g^6	0	g^2, y^2	g^4	y^2	g^2y^2	g^2, λ, y^2	y^2
ψ^4	8	g^6	0	0	0	0	g^2y^2	g^2, y^2	g^2, y^2

- How do fundamental principles sculpt the space of physical EFTs?
  - impact of coupling to quantum gravity: lessons from string theory, holography, semiclassical gravity
  - powerful constraints from unitarity, analyticity, causality
  - naturalness as a pragmatic guide to BSM model building & experiment



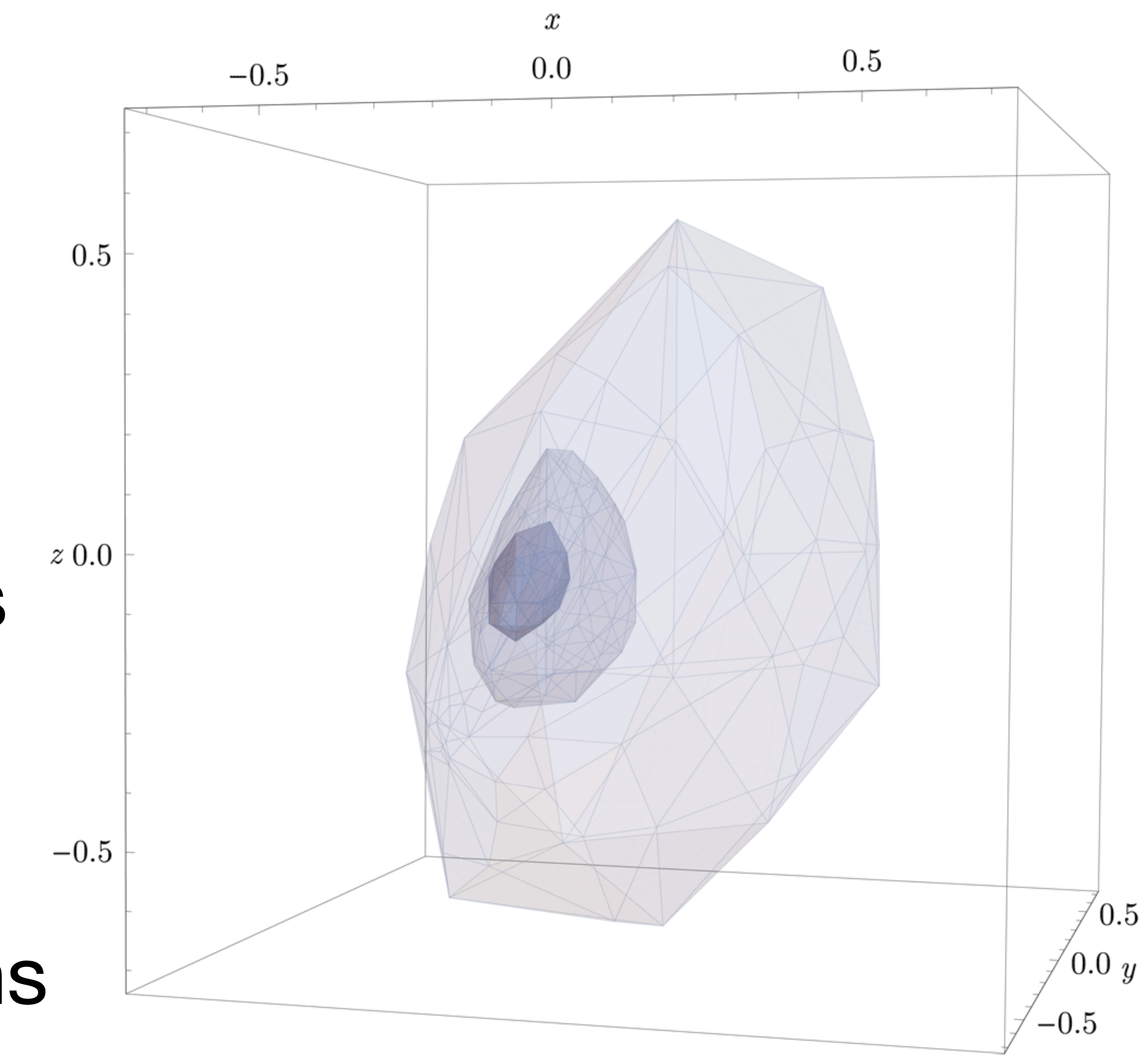


	Strong CP Problem	CC Problem	Hierarchy Problem
Cts. symmetry	$U(1)_{PQ}$	SUSY	SUSY, global
Disc. symmetry	P/CP	$E \to -E$	$\mathbb{Z}_2$
Relaxation	Axion	Abbott	Relaxion
Anthropics	Tied to CC?	Structure formation	Atomic principle
UV/IR mixing	?	Holography	WGC/NCQFT/...

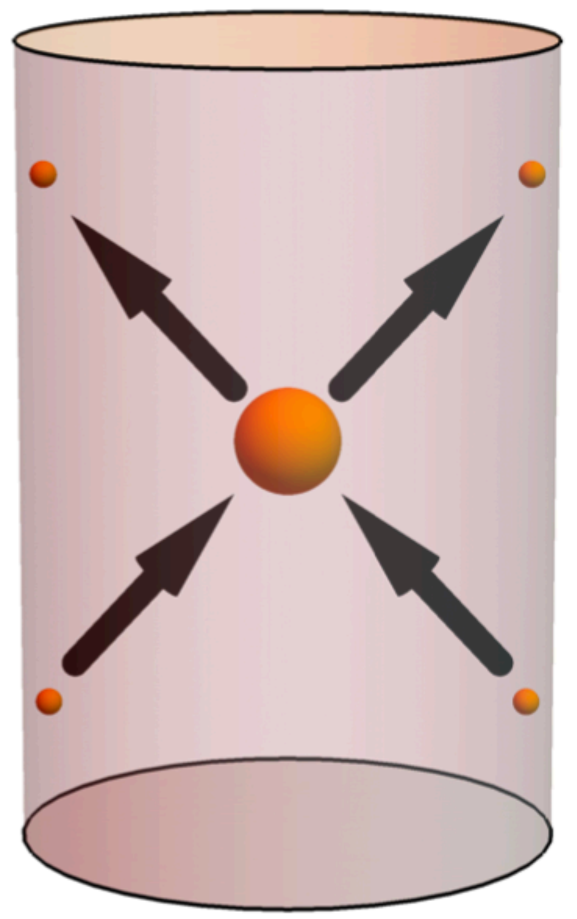
Applied EFT research plays a vital role across many experimental programs.
Formal EFT research provides new tools for attacking some of the deepest questions in HEP.

TF03: CFT and formal QFT

David Poland and Leonardo Rastelli



- **What is QFT and where are its boundaries?**
  - Traditionally, QFT = theory of quantized fields w/ explicit Lagrangian
  - More general framework needed to capture rich structures — many axiomatic approaches
- **New strategies for charting theory space**
  - Many bootstrap programs (CFT/S-Matrix/String/…): observables w/ consistency conditions
  - Key role of symmetry principles — many generalizations of the idea of symmetry
  - Progress in classification of SCFTs using both algebraic and geometric methods
- **Many deep connections**
  - Quantum gravity, especially via holography
  - Increasing role of information theory (entanglement properties of QFT)
  - Mathematics



TF04: Scattering Amplitudes

Zvi Bern and Jaroslav Trnka conveners

Motivations

- Develop new efficient methods to calculate scattering amplitudes.
- Apply to important physical problems, e.g. collider physics, gravitational wave physics.
- Use the S-matrix as probe to study new structures in quantum field theory.

White Papers:

1. Computational Challenges for Multi-Loop Collider Phenomenology
   Cordero, von Manteuffel and Neumann

2. Functions Beyond Multiple Polylogarithms for Precision Collider Physics
   Bourjaily, Broedel, Duhr, Frellesvig, , Chaubey,Hidding, . Marzucca, McLeod, Spadlin, Tancredi, Vergu, Volk, Volovich, von Hippel, Weinzierl, Wilhelm, Zhang

3. Solving Scattering in $\mathcal{N} = 4$ Super-Yang-Mills Theory
   Arkani-Hamed, Basso, Dixon, McLeod, Spradlin, Trnka, Volovich.

4. The Double Copy and its Applications Adamo, Carrasco, Carrillo-Gonzalez, Chiodaroli, Elvan, Johansson, O'Connell, Roiban, Schlotterer

5. Gravitational Waves and Scattering Amplitudes Buonanno, Khalil, O'Connell, Roiban, Solon, Zeng

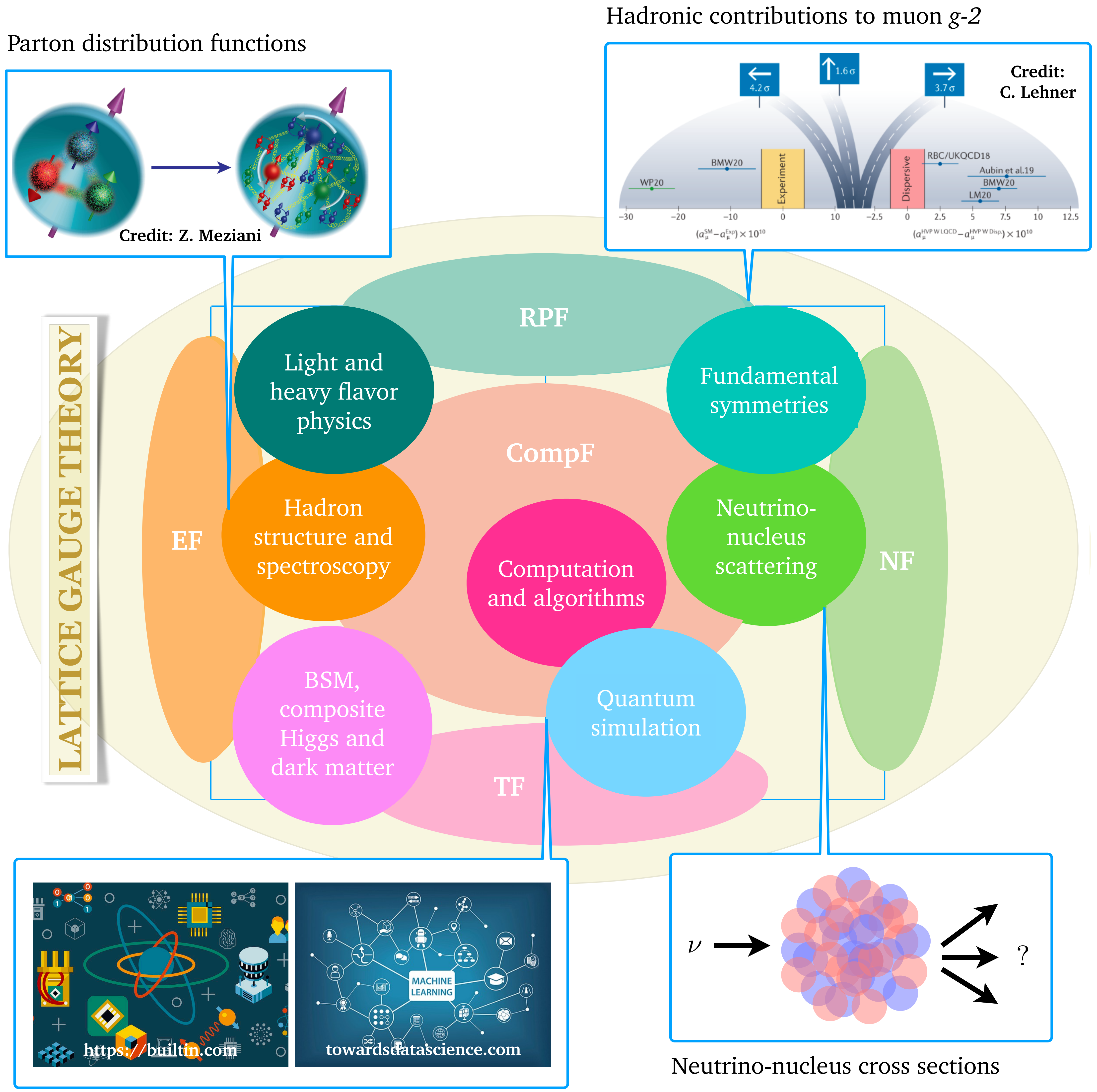
TF04: Scattering Amplitudes

6. SMEFT at the LHC and Beyond — Shepherd
7. String Perturbation Theory — Berkovits, D'Hoker, Green, Johansson, Schlotterer
8. UV Constraints on IR Physics — de Rham, . Kundu, Reece, Tolley, Zhou
9. S-matrix Bootstrap — Kruczenski, Penedones, van Rees
10. The Deepest Problem: Some Perspectives on Quantum Gravity — Giddings
11. The Cosmological Bootstrap — Baumann, Green, Joyce, Pajer, Pimentel, Sleight, Taronna.

Scattering amplitudes is a thriving subfield of particle theory, with many directions

TF05 - Lattice Gauge Theory

Zohreh Davoudi, Taku Izubuchi and Ethan Neil conveners



New strategies in computing and simulation, e.g., machine learning and quantum computing

- Precision lattice QCD is an essential input for disentangling electroweak or BSM physics in experiments with hadrons - e.g. muon (g-2)
- Lattice calculations as a “numerical laboratory” push the boundaries of our knowledge of strongly-coupled physics - e.g. holography tests in N=4 SYM
- Lattice theorists also drive advances in computation: new algorithms and methods for extreme-scale computing, as well developing tools in emerging areas - e.g. machine learning, quantum computing

See plenary talks by A. Kronfeld and Z. Davoudi (Mon afternoon), parallel session (Thu morning)

TF06 : Theory Techniques For Precision Physics

Conveners: R. Boughezal, Z. Ligeti

Precision calculations enable the stringent tests of the Standard Model needed to interpret experimental data and search for new physics. They constitute an essential component of the theory infrastructure underpinning the success of HEP experimental program.

Important future directions highlighted by community contributions

- Establishing the SM at the 1% level will require extending the precision QCD frontier to the N3LO level.
- All-orders understanding of QCD through advances in resummation is important for the high-luminosity era at the LHC and future colliders.
- Parton showers play a central role in the planning and interpretation of HEP experiments, and must continue to advance toward a more accurate representation of QCD.

- Study of the SMEFT beyond dimension-6 is needed to understand how such higher order effects impact the interpretation of current and future data.
- Future flavor physics measurements have the potential to probe energy scales far beyond those directly accessible; fully realizing this potential relies upon precise theory calculations.

TF07: Collider phenomenology

Fabio Maltoni
Shufang Su
Jesse Thaler

$$\sigma_{\rm obs} \simeq \frac{1}{2E_{\rm CM}^2} \sum_{n=2}^{\infty} \int {\rm d}\Phi_n \, |\mathcal{M}_{AB\to 12\ldots n}|^2 f_{\rm obs}(\Phi_n) \longmapsto \text{interpretation}$$

beam

sum over final-state multiplicity

integrate over phase space

scattering amplitude

observable

interpretation

- deep learning
- public collider data

Observables
- Kinematic features
- ML-based observables
- Jet substructures
- Multi-point energy correlators
- Optimal transport
- Quantum algorithms

Calculations
- Precision of EW/H/top physics
- Precision calculations for LC
- Resummation techniques
- Study of elusive signatures
- Extracting SM parameters
- EW radiation

Event Generators
- Multi-purpose or ML based event generators
- Extending applicability/reducing uncertainties
- Computational challenge

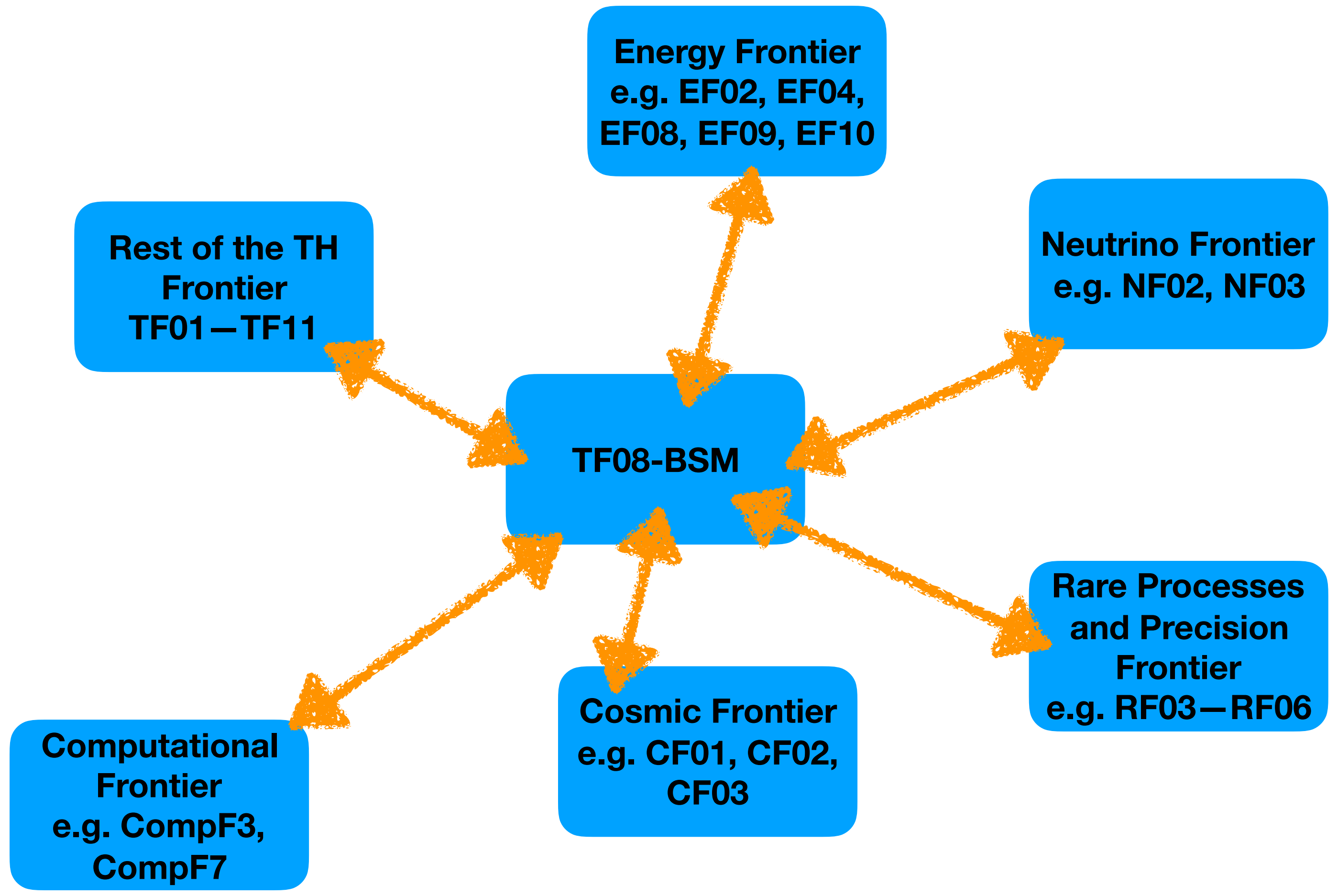
Interpretation Tools
- Anomaly detection
- Effective field theory
- Data and analysis preservation

Physics at Future Colliders (EF)

Search Strategies
- Cascade decay signatures
- Dark sectors/Low mass scalars ….

TF08 BSM Model Building: Selected Highlights

Conveners: Patrick Fox, Graham Kribs, Hitoshi Murayama



Selected developments in BSM model building in the past decade motivated by:

- Neutral Naturalness
  - Higgs naturalness through a new symmetry which relates the SM quarks to colorless partners, where the SM Higgs boson often acquires new, or exotic, decay modes; and signals from the confining group in the hidden sector can include displaced decays back into the SM, leading to striking signatures at current and upcoming colliders.

- Dark Sector Creativity
  - New interaction mechanisms including freeze-in, cannibalism, atomic, asymmetric, inelastic, …
  - Emphasis on dark matter model building that naturally spans a broader range of possible dark matter mass, including ultralight (axion) dark matter, light dark matter, and very heavy strongly-coupled dark matter.

- Testable Baryogenesis
  - New (low scale) baryogenesis models that can produce new signals accessible at ongoing collider experiments, allowing for a multi-prong search for new physics.

- Experimental Anomalies
  - Muon g-2; lepton flavor universality violation in charged current (b -> clv) and neutral current (b -> sll), …

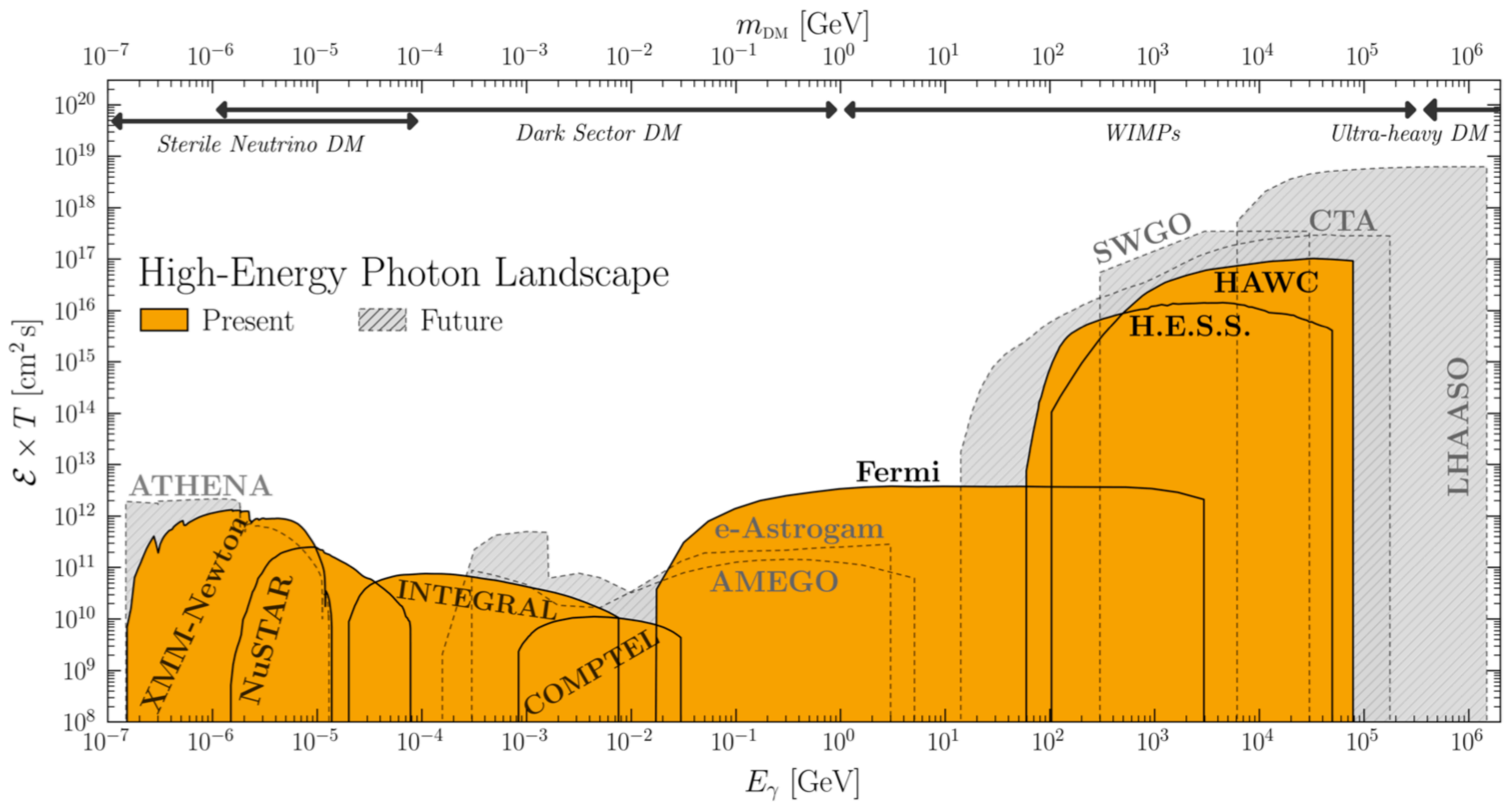
BSM model building transforms the “why?” questions of the SM and beyond into “how?” answers.

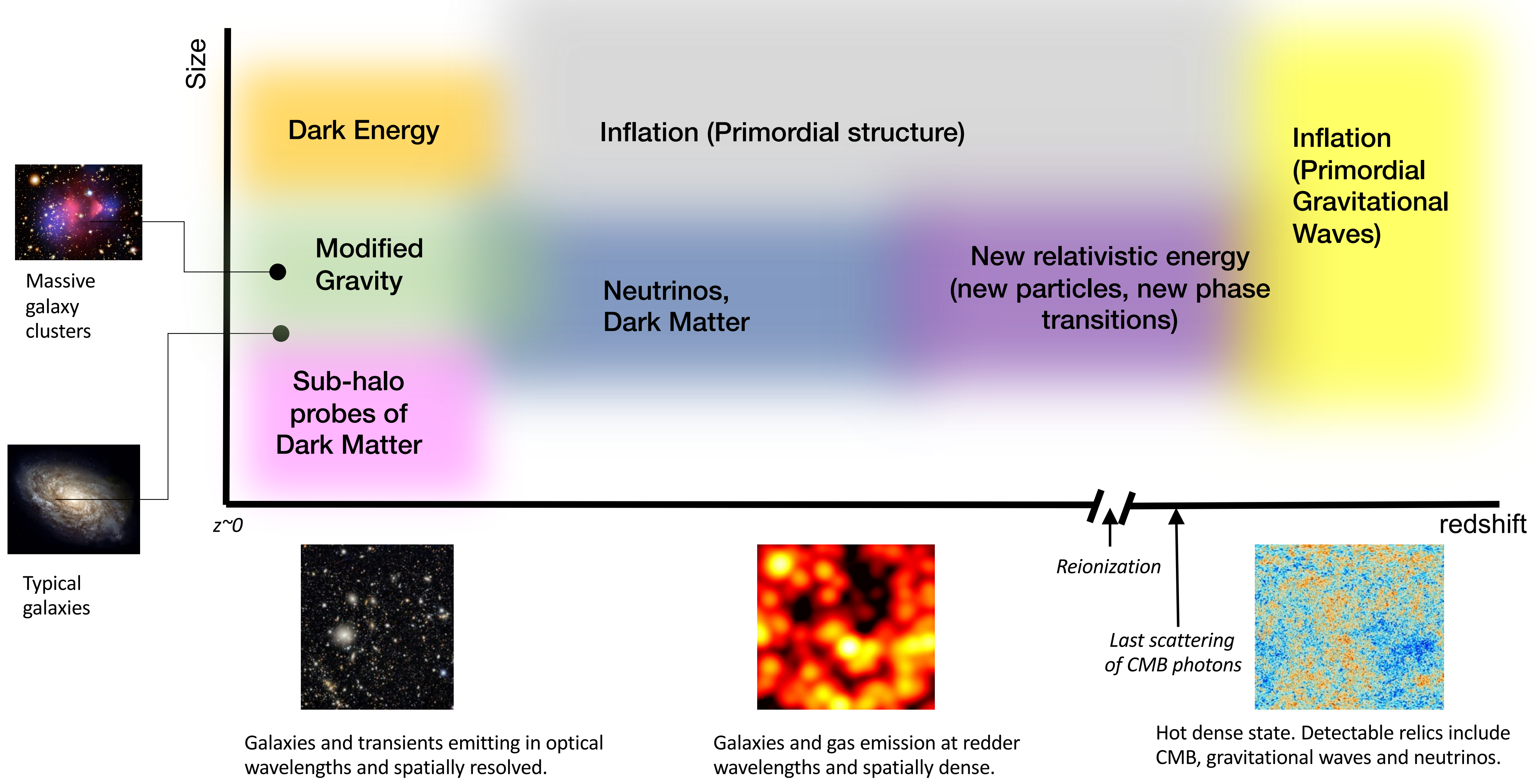
TF09: Astroparticle Physics and Cosmology

Conveners: Daniel Green, Ben Safdi, Jessie Shelton, Josh Ruderman

Exciting directions building to the next decade:

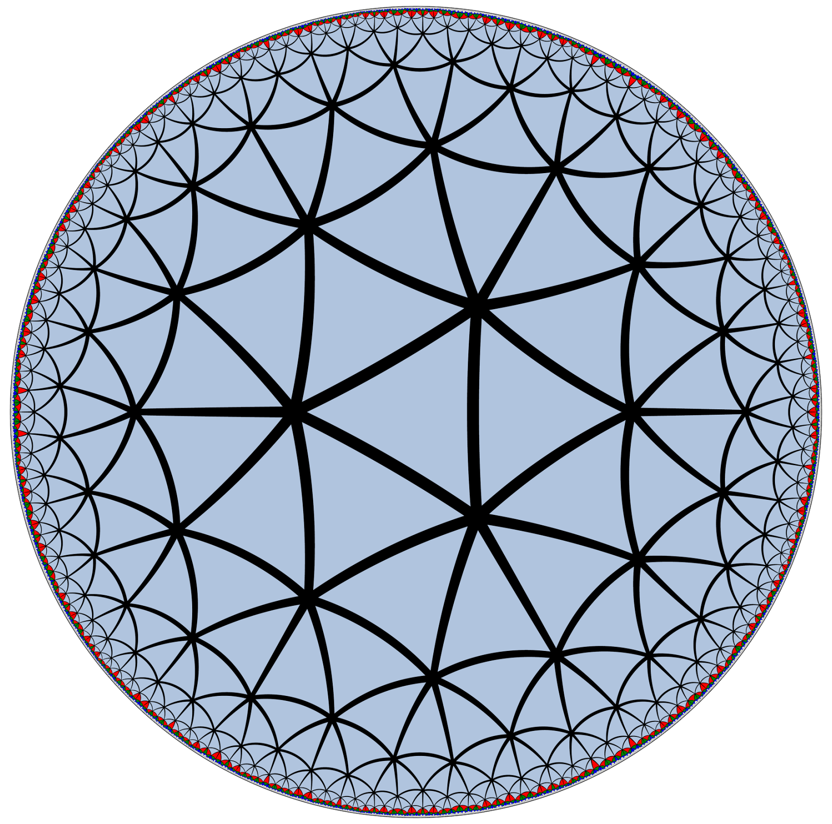
- **New experiments** probe wide range of dark matter models
  - theory leading explosion of new techniques
- **Novel astrophysical searches** for dark matter
  - theory leading to new measurements across the EM spectrum
  - gravitational waves emerging a new testbed for light dark matter
- **Progress in Large Scale Structure** Data Analysis
  - new analyses, competitive / complementary to the CMB, have been made possible by theoretical insights
  - same techniques will be essential for next generation surveys
- **Cosmology and fundamental physics** intertwined
  - interplay between bootstrap, EFT and cosmological observables
  - exciting directions connecting quantum information and the physics of de Sitter space / inflation





Astroparticle physics and cosmology is where theory, observations, and experiments unite!

TF10: QIS for HEP

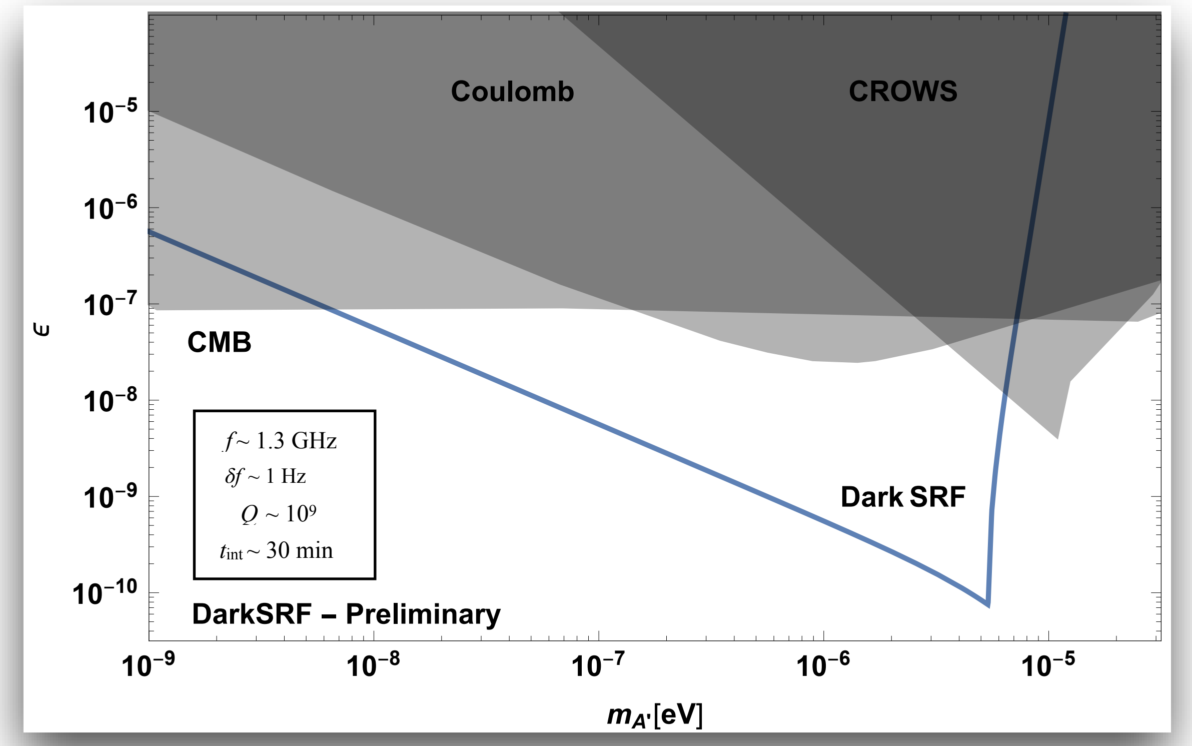


Quantum Sensing and searched for new physics

Quantum Computaion and Simulation

Entanglement and connections to holography/gravity

- 38 LOIs. 6 white papers with TF10 as primary (additional cross lists with Comp/TF05/TF01) Draft summary: 14+10 pages.



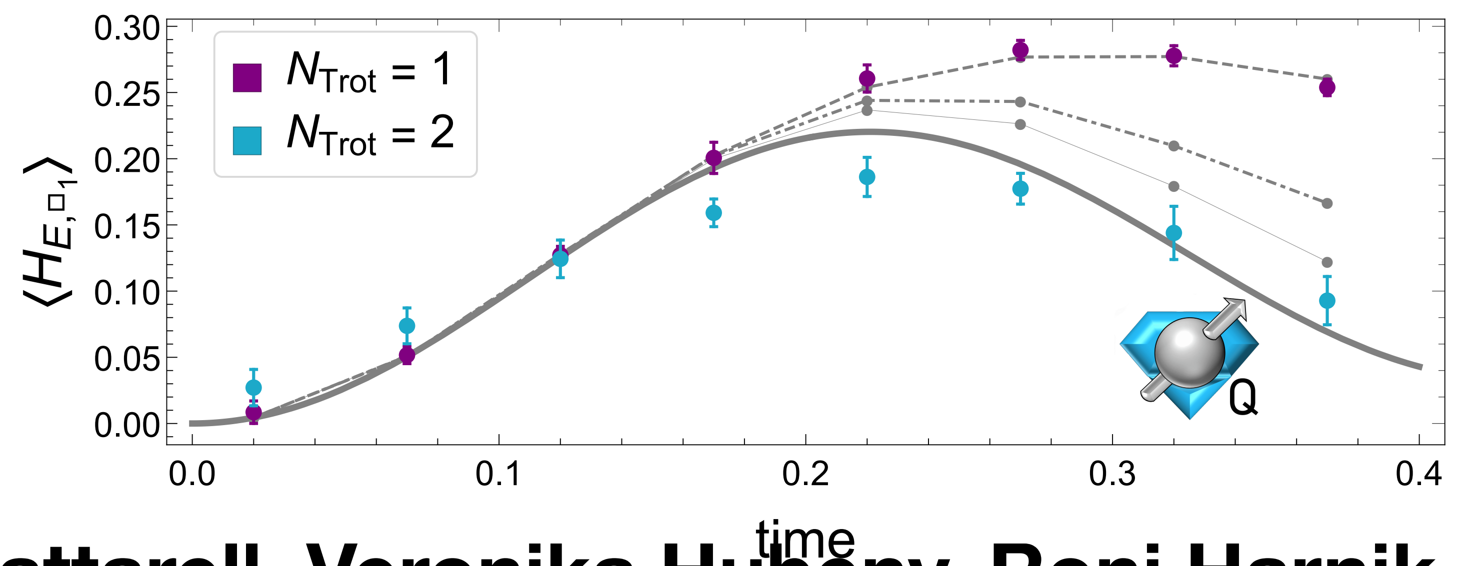
Highlight: Quantum Simulation :

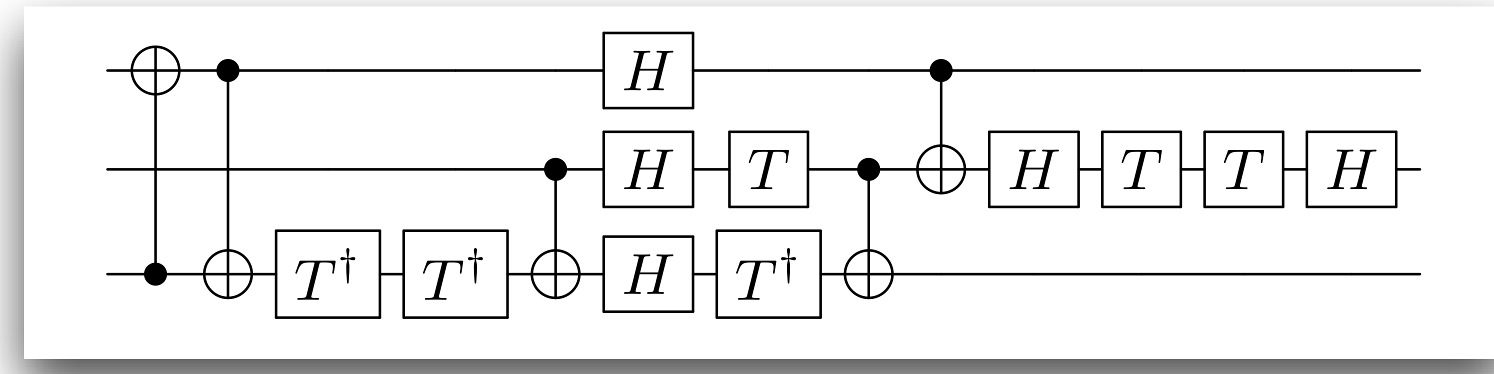
Hamiltonian Lattice Gauge Theory

Tensor Networks

Discrete holography

Ex: 1+1 SU(2) gauge theory
2 plaquettes, j=1/2 truncation
IBM-Tokyo
Klco 2020, 110 citations





Conveners: Simon Cattarell, Veronika Hubeny, Roni Harnik

TF11/NF08 TG Neutrino Theory

André de Gouvêa, Irina Mocioiu, Saori Pastore, and Louis Strigari

Highly interdisciplinary across frontiers

Theory of Neutrino Physics

1. What is the origin of nonzero neutrino masses? How do we learn more?
2. Is there a theory of flavor? What is it? How do we learn more?
3. Solving current (and future!) neutrino puzzles, including the short-baseline anomalies.

Theory for Neutrino Physics

1. Simulating astrophysics sources of neutrinos and computing neutrino transport in these environments;
2. BSM neutrino physics in early universe cosmology;
3. Computing neutrino-nucleon and neutrino-nucleus scattering, from low-energy scattering solar and supernova neutrinos up to DIS, including implementation (and validation against electromagnetic data);
4. Neutrino and non-neutrino phenomenology for neutrino experiments. Impact of different neutrino properties and BSM and how these can be explored in future neutrino experiments (oscillations, CEvNS, solar, atmospheric, SN, and UHE neutrinos, direct detection experiments, etc);
5. Computing matrix elements for neutrinoless double-beta decays.

Exceptional **breadth of energy scales** (eV to EeV**)** **probes** (neutrino oscillations, neutrino scattering, colliders, nuclear processes, charged-leptons, astrophysical objects, cosmology) **along with specialized, unique tools** (oscillations, nuclear physics, many-body physics, EFTs, model-building, etc.)

Theory Frontier Documents

First drafts of topical group summaries and the frontier summary are available now.

Frontier and topical group summaries

https://bit.ly/3cnOT2Y

Feedback on summaries

https://bit.ly/3aItHEc

The Theory Frontier Report

Executive Summary

Theory is essential to the field of particle physics, producing transformative science both in connection to projects and in its own right. It is central to the motivation, analysis, and interpretation of experiments; lays the foundations for future experiments; and advances our understanding of Nature in regimes that experiments cannot (yet) reach. Theory underlies our understanding of the most basic building blocks of Nature, unifying the frontiers of particle physics and connecting them to gravity, cosmology, astrophysics, nuclear physics, condensed matter physics, and mathematics. Theory extends the boundaries of our knowledge of Nature, incorporates new perspectives (such as quantum information), and develops new techniques relevant to experiment. Theory is responsive, pinpointing novel directions based on recent experimental data, proposing future experiments, and developing the precision tools necessary to interpret them, all with the aim of maximizing experimental impact. Theorists play a leading role in disseminating new ideas to a wider public and serve as role models for aspiring young scientists.

The theory community is vibrant. Together, fundamental theory, computational theory, and phenomenology form a balanced and interconnected scientific ecosystem closely aligned with experiment. The past decade has witnessed significant advances across the many facets of the field, with immense promise in the years to come. In fundamental theory, new perturbative and non-perturbative techniques (ranging from the double copy structure of scattering amplitudes to the advent of diverse bootstrap methods) have vastly expanded our knowledge of quantum field theory, in tandem with complementary advances in lattice field theory quantifying non-perturbative properties in theories of interest. A deeper understanding of holography and insights from quantum information have breathed new life into the longstanding quest for a complete theory of quantum gravity. New effective field theories have facilitated applications of QFT to high-energy scattering, Higgs physics, large-scale structure, inflation, dark matter detection, and gravitational waves. In phenomenology, the search for physics beyond the Standard Model has broadened considerably with the advent of novel concepts like neutral naturalness or cosmological selection of the electroweak vacuum. Dark matter theory is undergoing a renaissance with the exploration of the full range of allowed dark matter masses, numerous portals to dark sectors, and novel interaction mechanisms. Advances in dark matter phenomenology have gone hand in hand with new proposals for dark matter experiments leveraging quantum sensing, often envisioned and implemented by theorists. The discovery of gravitational waves has catalyzed rapid progress in precision calculations via scattering amplitudes and inspired the use of gravitational waves to study particle physics inaccessible via planned colliders. Cross-fertilization between fundamental theory, computational theory, and phenomenology has led to significant advances in precision collider physics essential for the LHC. Precision flavor physics has been the cradle of many of our most powerful effective field theory tools including heavy quark effective theory and soft-collinear effective theory. Taking advantage of the large amount of experimental data, they are now enabling advanced theoretical analyses to obtain constraints on promising BSM candidate theories, maximizing the discovery potential of the experiments. An explosion of theoretical activity in collider phenomenology has led to many new collider observables including many forms of jet substructure and the emerging field of multi-point correlators, employing widespread innovations in computational theory to leverage machine learning and artificial intelligence. A theory-driven, coordinated program combining nuclear effective theory, lattice QCD, perturbative QCD, and event generation to quantify the multi-scale nuclear cross sections at the needed precision level has been launched, that will allow us to unlock the full potential of the present and future neutrino physics program. In computational theory, lattice QCD has become a powerful tool for precision physics, yielding precise SM predictions that reveal surprising new tensions in quark flavor physics and for the muon $g-2$. The scope of lattice QCD is undergoing a rapid expansion, promising to provide quantitative access in the coming decade to important new observables. Innovations in the theory of ML developed to accelerate lattice field theory computations may have transformational impact on the field. Recent dedicated efforts to develop the methods and theoretical foundations for quantum simulations of quantum field theories relevant to high energy theory are already yielding intriguing results on currently available hardware, with great promise in the decades to come. The US theory community has played a leading role in all of these endeavors, and will sustain its position of international leadership with continued support.

The Theory Frontier Report
Executive Summary

Theory is:

- Producing transformational science

- Projects
- Own right

- Central to the motivation, analysis, and interpretation of experiments

- Lays the foundations for future experiments

- Advances our understanding of Nature in regimes that experiments cannot (yet) reach

Theory:

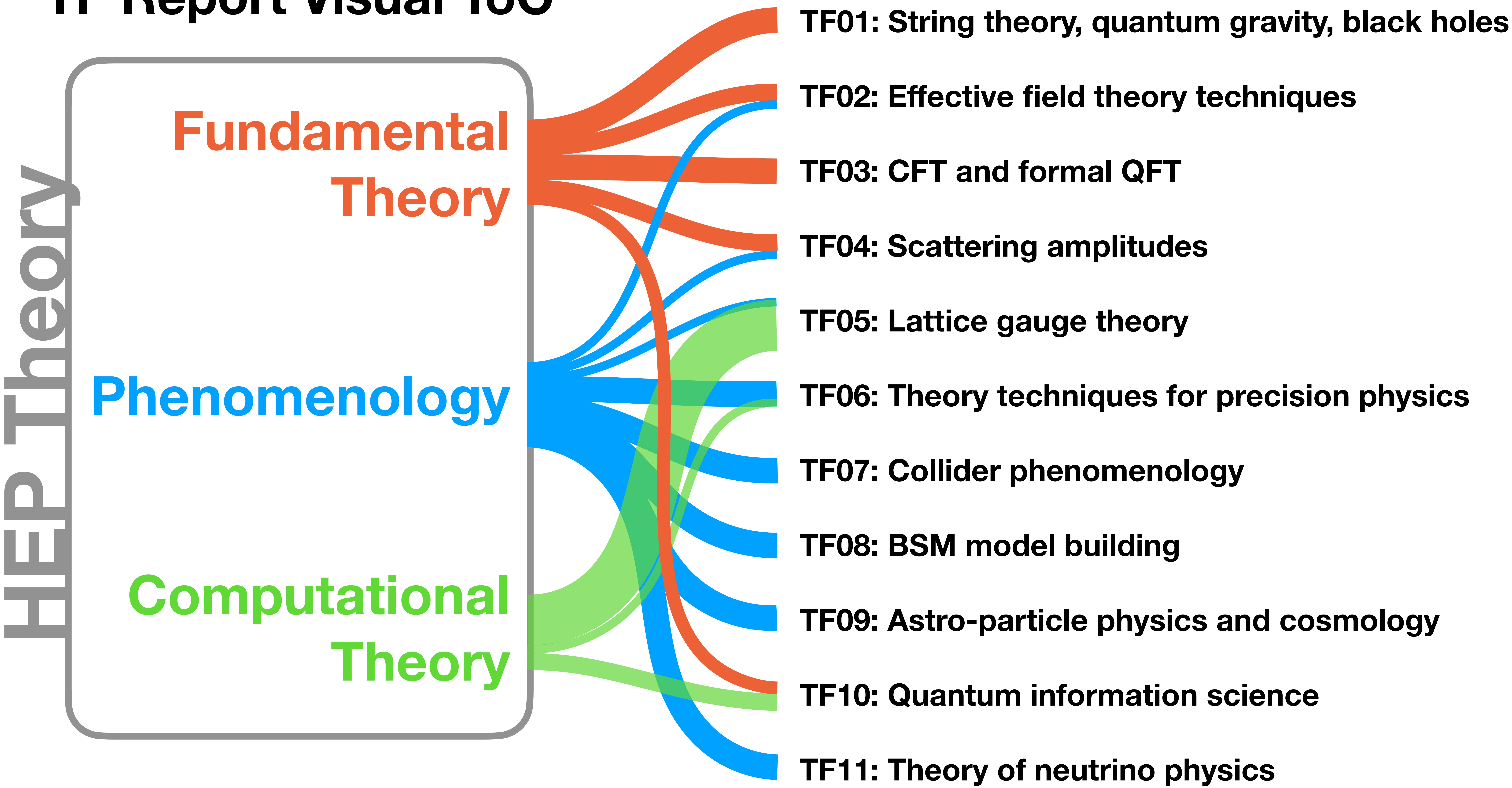
- Unifies the frontiers of particle physics
- Connects to gravity, cosmology, astrophysics, nuclear physics, condensed matter physics, and mathematics
- Extends the boundaries of our knowledge, incorporates new perspectives such as QI
- Responsive:
  - Proposing new directions based on data
  - Proposing/leading new experiments
  - Developing new analysis tools

Theory:

- Fundamental theory
- Phenomenolgy
- Computational theory

- form a balanced and interconnected scientific ecosystem closely aligned with experiment

TF Report Visual ToC



Highlights from last decade

Fundamental theory

- New perturbative and non-perturbative techniques (ranging from the double copy structure of scattering amplitudes to the advent of diverse bootstrap methods) have vastly expanded our knowledge of quantum field theory

- A deeper understanding[22] of holography and insights from quantum information have breathed new life into the [23] longstanding quest for a complete theory of quantum gravity

Fundamental theory

- New effective field theories have facilitated applications of QFT to high-energy scattering, Higgs physics, large-scale structure, inflation, dark matter detection, and gravitational waves

Phenomenology

- Search for physics beyond the Standard Model has broadened considerably with the advent of novel concepts like neutral naturalness or cosmological selection of the electroweak vacuum

Phenomenology

- Dark matter theory is undergoing a renaissance with the exploration of the full range of allowed DM masses, numerous portals to dark sectors, and novel interaction mechanisms. Advances in dark matter phenomenology have gone hand in hand with new proposals for dark matter experiments leveraging quantum sensing, often envisioned and implemented by theorists.

- The discovery of gravitational waves has catalyzed rapid progress in precision calculations via scattering amplitudes and inspired the use of gravitational waves to study particle physics inaccessible via planned colliders.

Phenomenology

- In precision collider theory the calculation of cross sections to the NNLO and beyond in QCD has now become possible, unlocking the door to unprecedented tests of the SM.

- Precision flavor physics has been the cradle of many of our most powerful effective field theory tools including HQET, SCET, now enabling advanced theoretical analyses to obtain constraints on promising BSM candidate theories.

- Collider phenomenology has led to many new collider observables including many forms of jet substructure and the emerging field of multi-point correlators, and is employing widespread innovations in computational theory to leverage machine learning and artificial intelligence.

Phenomenology

- Neutrino physics program for multi-scale nuclear cross sections at the needed precision level that will allow us to unlock the full potential of the present and future neutrino experiments.

Computational theory

- Lattice QCD has become a powerful tool for precision physics, yielding precise SM predictions that reveal surprising new tensions in quark flavor physics and for the muon g-2.

Computational theory

- Efforts to develop the methods and theoretical foundations for quantum simulations of quantum field theories relevant to high energy theory are already yielding intriguing results on currently available hardware, with great promise in the decades to come.

Theory Frontier

Nathaniel Craig
Csaba Csaki
Aida El-Khadra

THEORY FRONTIER
COMMUNITY PLANNING 2021

- A statement of support of the essential role of theory similar to (and at least as strong as) the European Strategy.
- Theory is an essential component of particle physics, both in relation to Projects and in its own right.
- Research should be included in P5 alongside projects:
  Ideally P5 will recommend maintaining a balanced program of Projects and Research, both are essential to the health of the field.