New Models and Methods for Particle Physics

From Neutrinos to Quantum Computing

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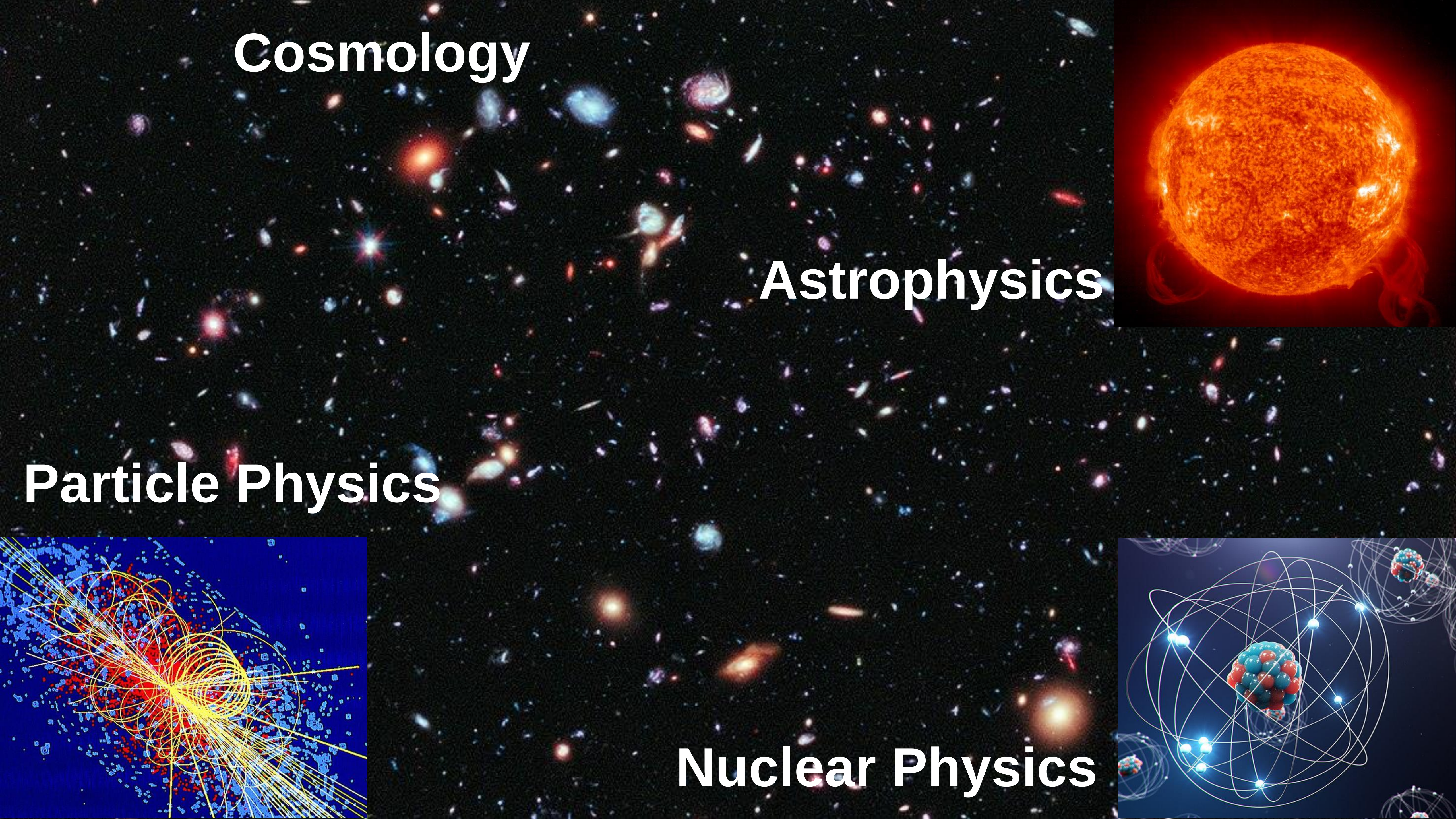
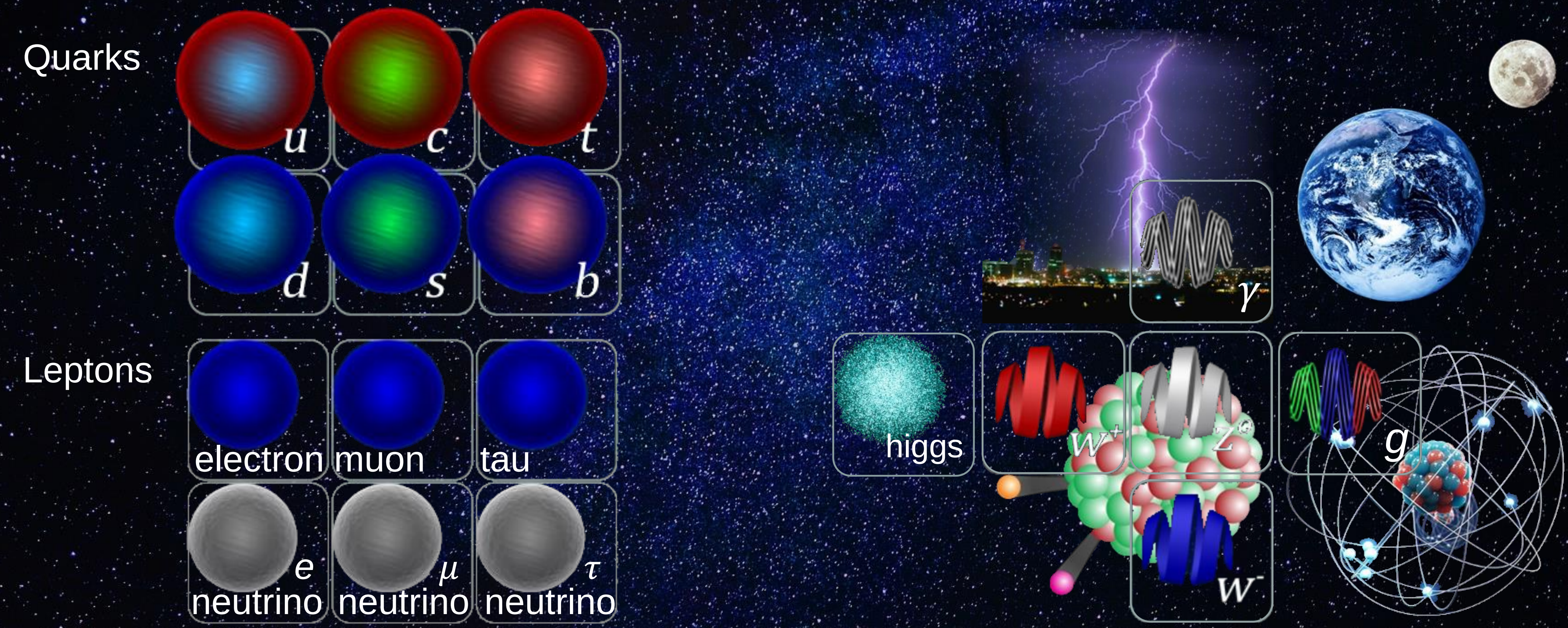
MPP Colloquium, 26 November 2024


Cosmology
Astrophysics
Particle Physics
Nuclear Physics

“Standard Model” of Particle Physics

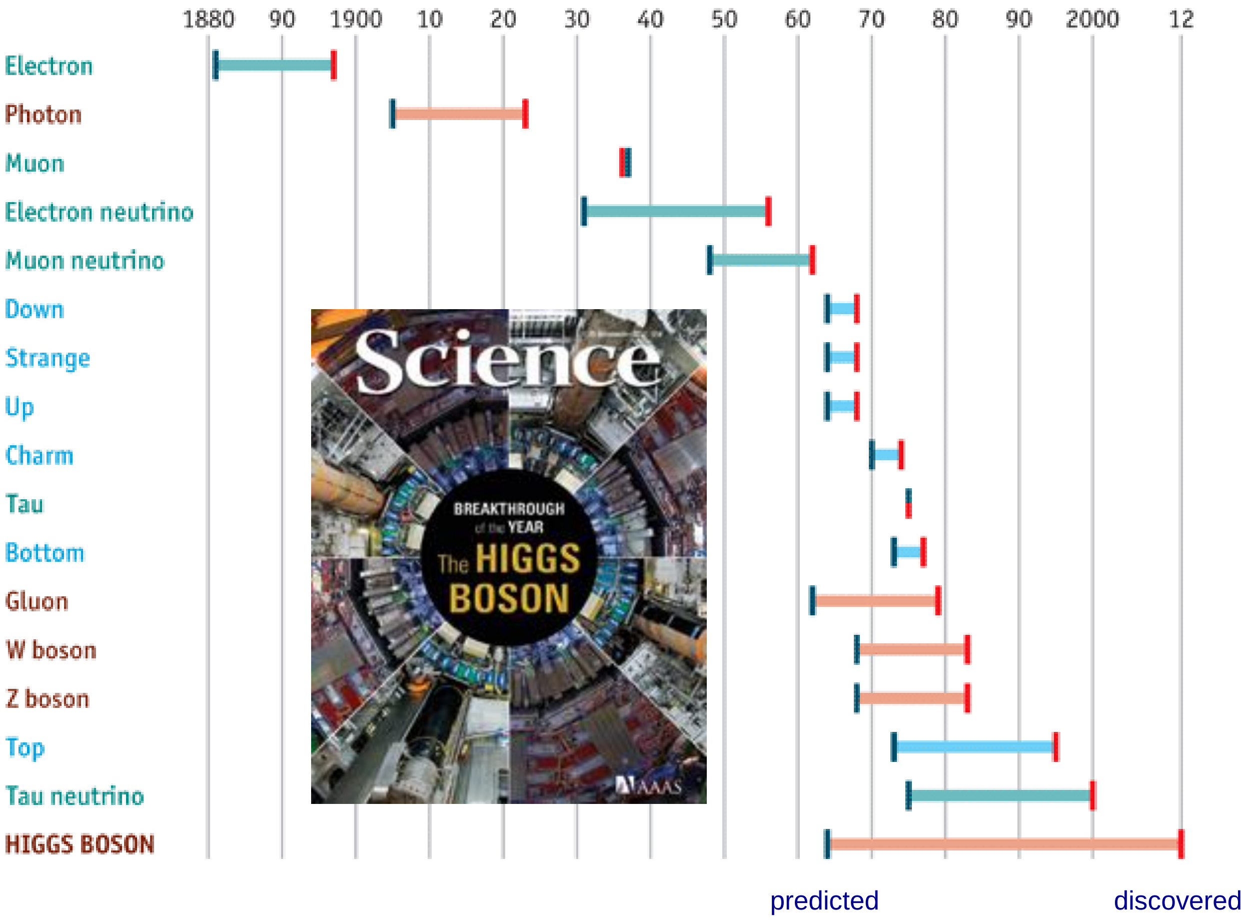
Matter (+ Antimatter)

Forces



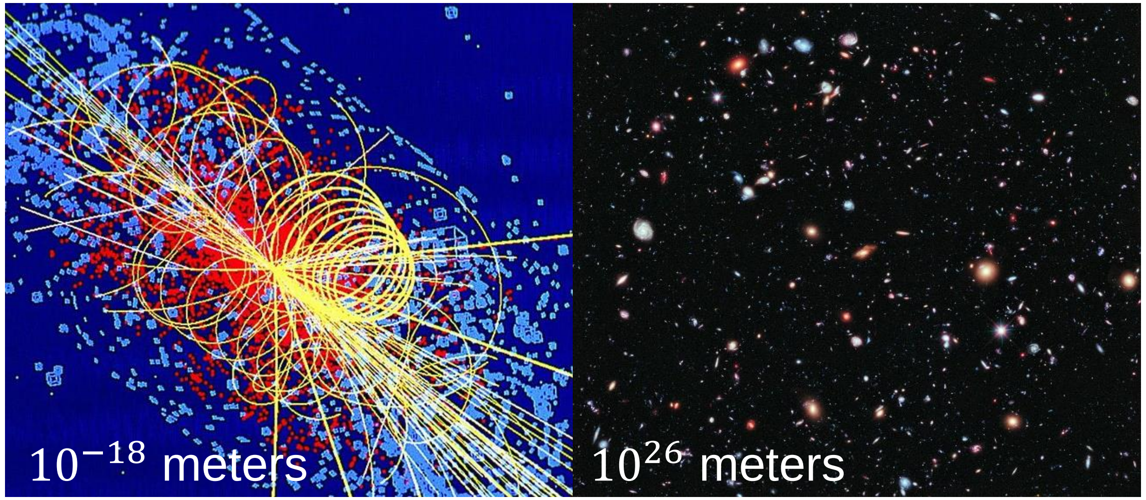
The success of the "Standard Model"

Every predicted particle was eventually discovered:



Content: all particles & forces (except for gravity)

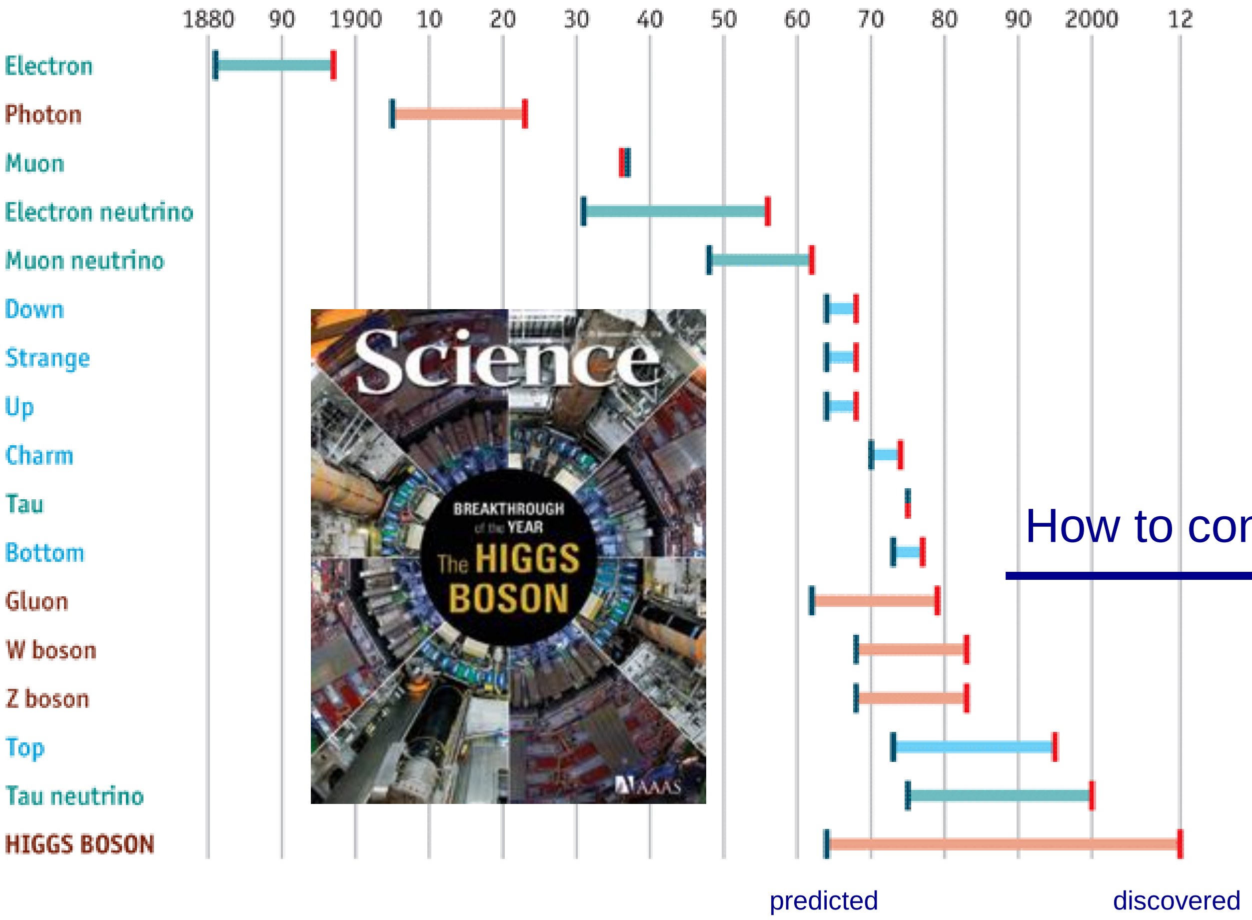
Range:



Precision: up to 0.00000000001 (electron g-factor)

Open questions of the “Standard Model”

Every predicted particle was eventually discovered:



Why do neutrinos have masses?

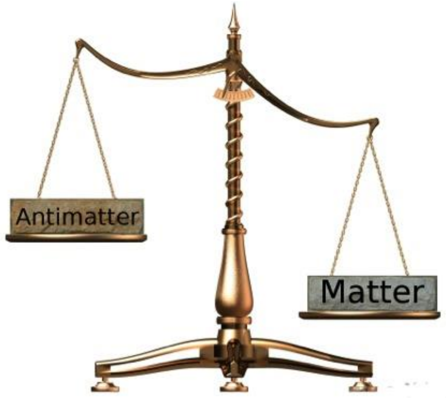
Why is there more matter
than antimatter in the universe?

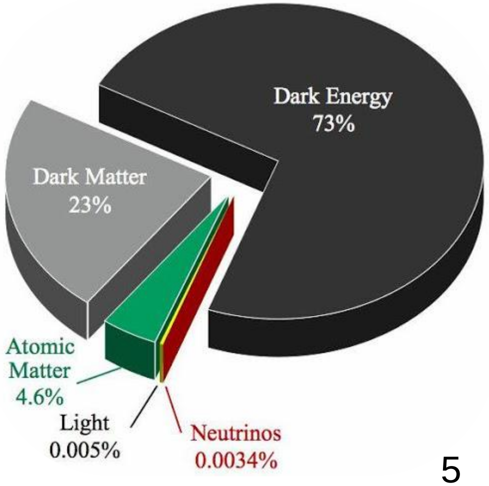
Why has no strong CP violation been observed?

What are dark matter and dark energy?

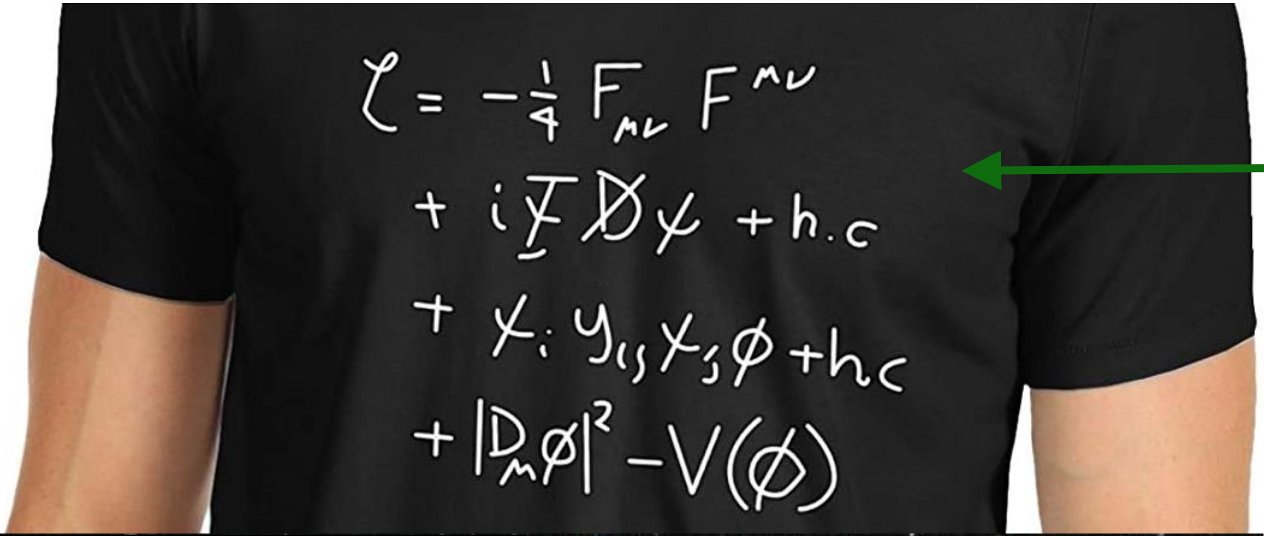
...

How to continue?



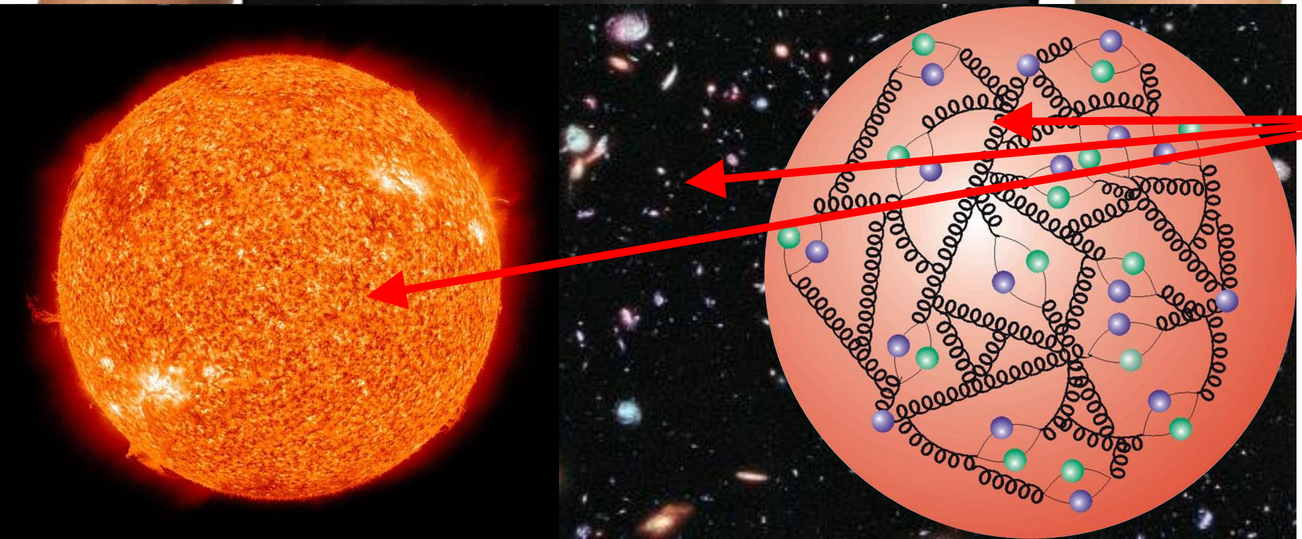


How can we answer these open questions?



Simple equation

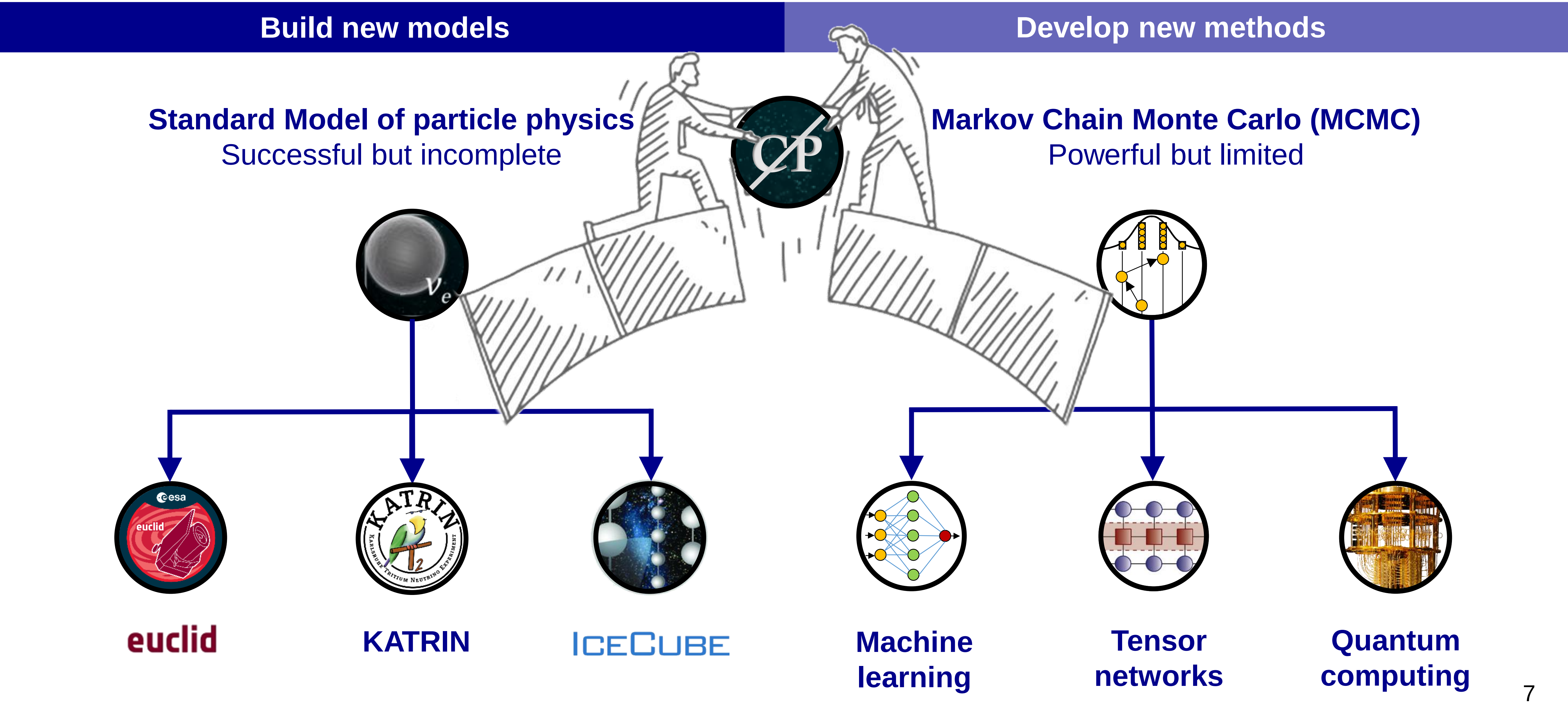
Beautiful but incomplete!
Need new equations → ***new models***



Complex phenomena

Emergent structures!
Need numerical simulations → ***new methods***

New models and methods for particle physics



New models and methods for particle physics

Build new models | **Develop new methods**

Standard Model of particle physics
Successful but incomplete

ν_e

- euclid
- KATRIN
- IceCube

Markov Chain Monte Carlo (MCMC)
Powerful but limited

- Machine learning
- Tensor networks
- Quantum computing

How to build new models?

Neutrino mass model	History of Universe

Standard Model

Masses of particles are generated in the early universe →

Problem

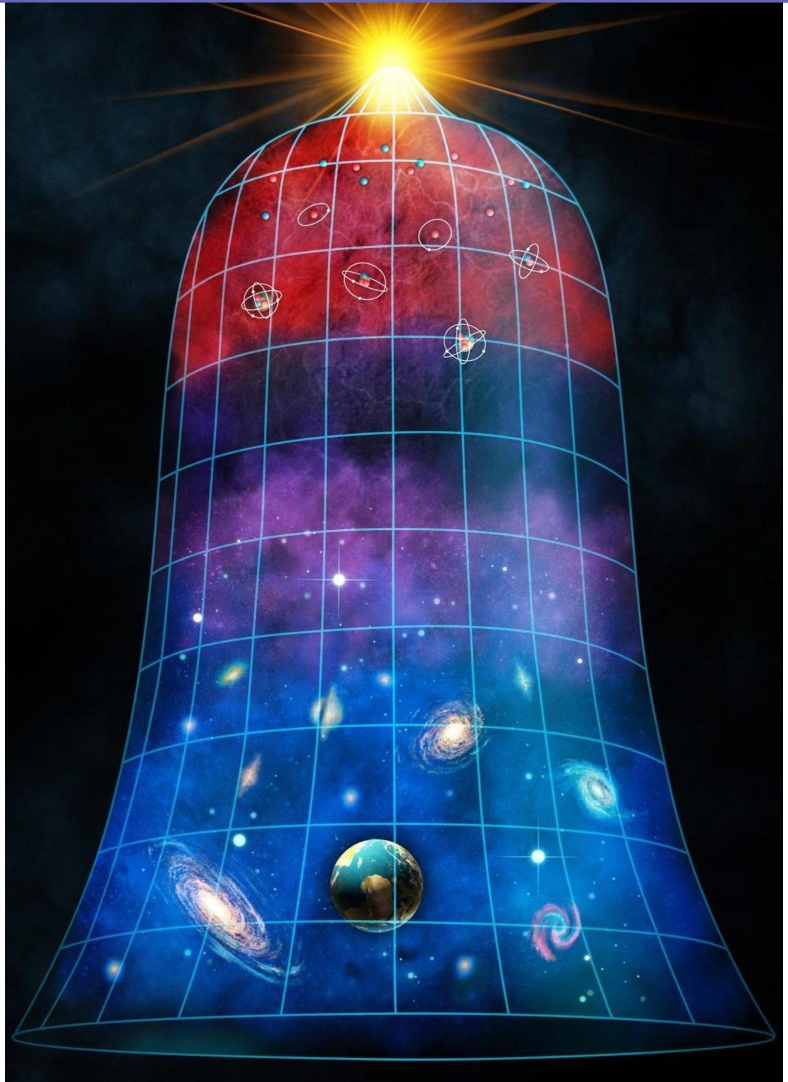
Neutrino masses: predicted $= 0$ but measured $\neq 0$

Our model [1]

Neutrinos can become massive in the late Universe →

Key prediction

Neutrino condensation → flavor symmetry breaking



[1] Dvali, **LF**, *PRD* (2016a)

New neutrino physics hiding at low energies

New low-energy model [1]

Idea

Small neutrino masses from gravitational anomaly
→ Standard Model + gravity

New concept

Neutrino condensate and effective masses
→ at new low-energy gravitational scale

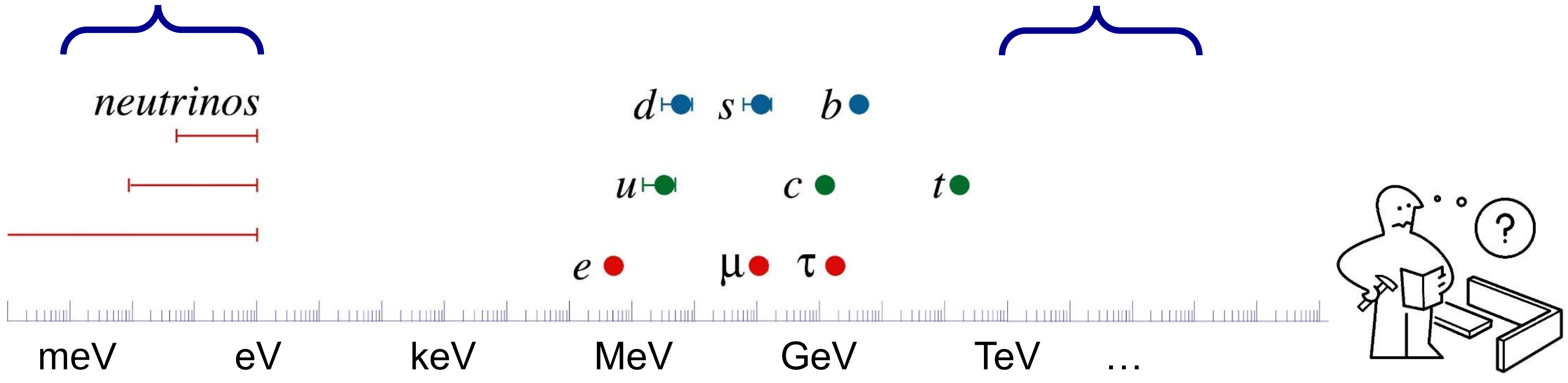
Common high-energy models

Ideas

“Seesaw” mechanisms, large extra dimensions, …
→ Standard Model + new particles, symmetries, …

Unifying concept

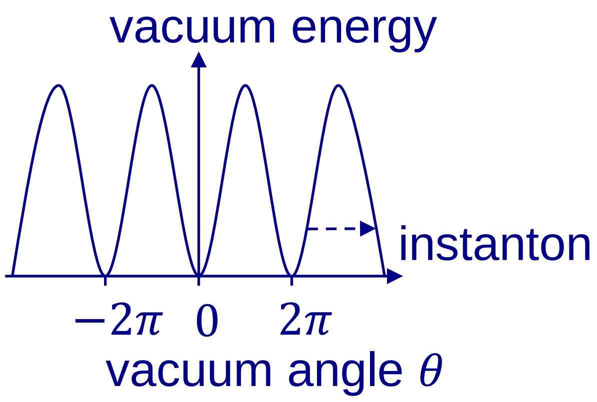
Neutrino masses from Higgs condensate
→ suppressed by new high-energy physics

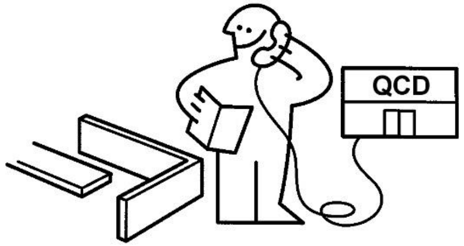


[1] Dvali, **LF**, *PRD* (2016a)

Analogy: Non-perturbative QCD vacuum

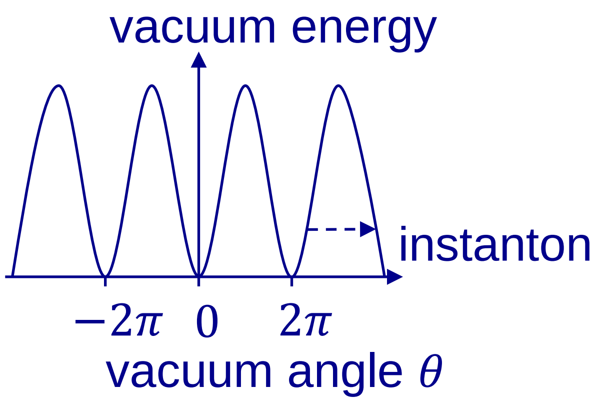
Quantity	QCD with 3 quarks	Gravity with 3 neutrinos
Fermion flavor symmetry	$U(3)_L \times U(3)_R \to U(3)_V$	$U(3)_L \times U(3)_R$ exact if $m_\nu = 0$
(Pseudo) Goldstone bosons	$1(\eta') + 8(\pi, K, \eta)$	
Axial anomaly	$\partial_\mu j_5^\mu = G\tilde{G} + m_q \bar{q}\gamma_5 q$	
Topological susceptibility	$\langle G\tilde{G}, G\tilde{G}\rangle_{p\to 0} \neq 0 \to \langle \bar{q}q \rangle \neq 0$	

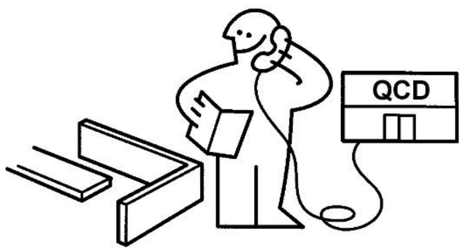




Analogy: Non-perturbative QCD vacuum

Quantity	QCD with 3 quarks	Gravity with 3 neutrinos
Fermion flavor symmetry	$U(3)_L \times U(3)_R \to U(3)_V$	$U(3)_L \times U(3)_R \to U(1)^3$? [1]
(Pseudo) Goldstone bosons	$1(\eta') + 8(\pi, K, \eta)$	$1(\eta_\nu) + 14(\phi_k)$ [1]
Axial anomaly	$\partial_\mu j_5^\mu = G\tilde{G} + m_q \bar{q}\gamma_5 q$	$\partial_\mu j_5^\mu = R\tilde{R} + m_\nu \bar{\nu}\gamma_5 \nu$
Topological susceptibility	$\langle G\tilde{G}, G\tilde{G}\rangle_{p\to 0} \neq 0 \to \langle \bar{q}q\rangle \neq 0$	$\langle R\tilde{R}, R\tilde{R}\rangle_{p\to 0} \neq 0$? $\to \langle \bar{\nu}\nu\rangle \neq 0$ [1]





[1] Dvali, **LF**, *PRD* (2016a)

The model: Neutrino condensation

Pure gravity	Gravity coupled to neutrinos

Starting point

Non-perturbative topological effects in pure gravity

Assumption

Non-zero topological vacuum susceptibility $\rightarrow \theta$-term

Consequence [1]

New low-energy gravitational scale Λ_G

Anomaly

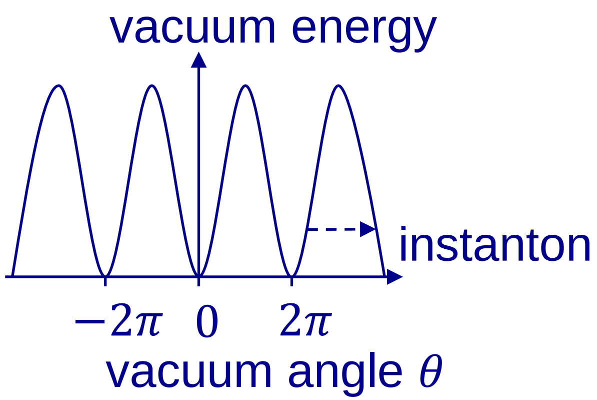
Neutrino flavor symmetry breaking via chiral anomaly

Condensation [1]

Neutrino condensation below scale Λ_G: $\langle \bar{\nu}\nu \rangle \neq 0$

New particles [1]

Emergence of η_ν and 14 massless Goldstones ϕ_k



[1] Dvali, **LF**, *PRD* (2016a)

The model: Neutrino masses

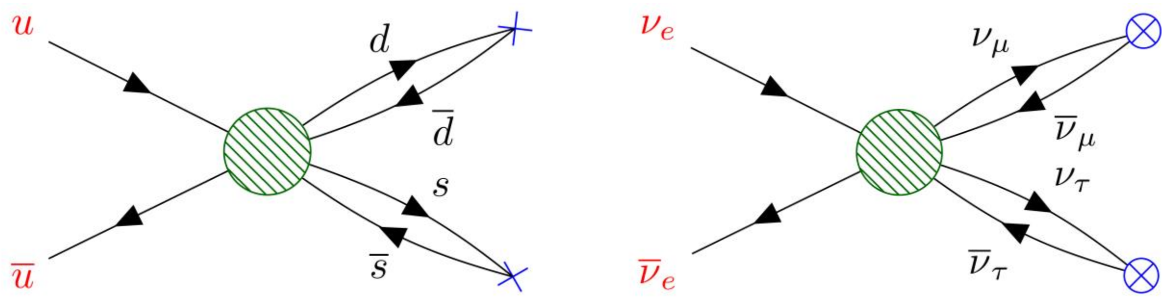
Non-perturbative origin	Properties

Effective masses [1]

Generated via non-perturbative coupling to condensate

QCD analogy

Coupling analogous to `t Hooft vertex in QCD [2]



Effective potential [1]

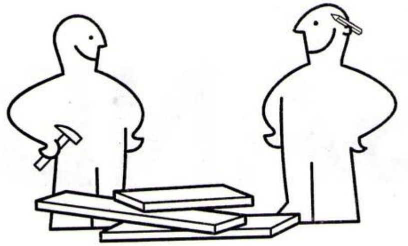
$V(\hat{X}) = \sum_n \frac{1}{n} c_n \mathrm{Tr}\left[\left(\hat{X}^+\hat{X}\right)^n\right]$ with $\hat{X}_{\alpha_L}^{\alpha_R} \equiv \langle \bar{\nu}_{\alpha_L} \nu_{\alpha_R} \rangle$

Mass hierarchy [1]

$\hat{X} = \mathrm{diag}(m_1, m_2, m_3)$ determined by minimum $\frac{\partial V}{\partial m_i} = 0$

Dirac vs. Marjoana [1]

Model works for both natures: $\langle \bar{\nu}_L \nu_R \rangle$ or $\langle \nu_L^T C \nu_L \rangle$



[1] Dvali, **LF**, *PRD* (2016a), [2] Computation of topological up-quark mass contribution with Lattice QCD: Alexandrou, Finkenrath, **LF**, et al., *PRL* (2020)

The model: Theory summary

Neutrino mass model

Standard Model

Masses of particles are generated in the early universe

Problem

Neutrino masses: predicted $= 0$ but measured > 0

Our model [1]

Neutrinos can become massive in the late universe

Key prediction

Neutrino condensation → flavor symmetry breaking

[1] Dvali, **LF**, *PRD* (2016a)

How to constrain this model?

Neutrino mass model	Constraints

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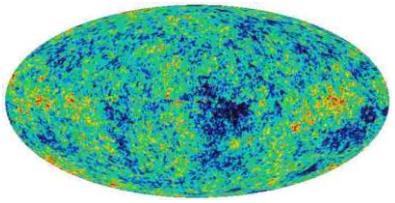
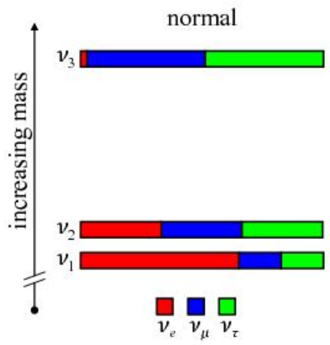
Condensate $|\langle\bar{\nu}\nu\rangle| \sim$ scale $\Lambda_G^3 \sim$ temperature T_{SSB}^3

Λ_G

$\sim 0.3\ \mathrm{eV}$ — Upper bound from SM and cosmology



$\sim 4\ \mathrm{meV}$ — Lower bound from Δm_ν and gravity



[1] Dvali, **LF**, *PRD* (2016a)

How to test this model?

Neutrino mass model	Implications for dark energy

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Numerical coincidence [1]

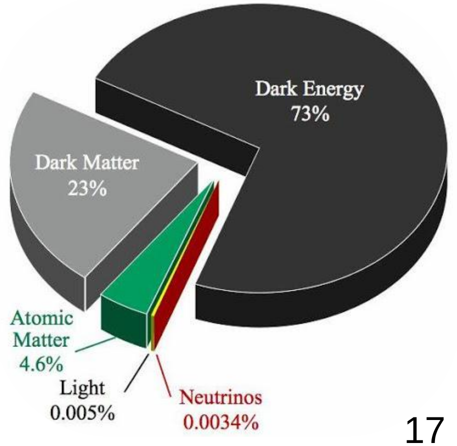
Condensate $\langle\bar{\nu}\nu\rangle$ on dark energy scale, $\rho_{\mathrm{DE}} \sim (\mathrm{meV})^4$
→ connected to fundamental new energy scale Λ_G

Cosmological constant? [2]

Excluded by S-matrix formulation of quantum gravity

Dynamical dark energy? [3]

Predicted time dependence, e.o.s. parameter $w \neq -1$



[1] Dvali, **LF**, *PRD* (2016a);
[2] Dvali, Gomez, *JCAP* (2014); [3] Dvali, Freche, **LF**, *manuscript in preparation*

How to test this model?

Neutrino mass model

Standard Model

Masses of particles are generated in the early universe

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Neutrinos can become massive in the late universe

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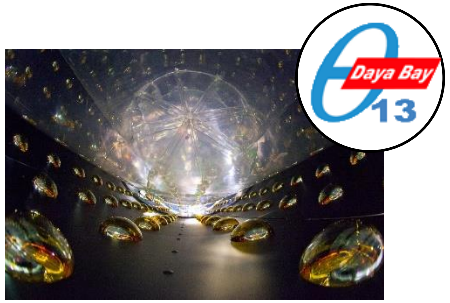
Predictions for cosmic neutrinos

Topological defects emerge from phase transition [2]



Cosmic neutrinos disappear after phase transition [1,3]

→ no mass detection at   only at

[1] Dvali, **LF**, *PRD* (2016a);
[2] Dvali, **LF**, Vachaspati, *PRL* (2023); [3] Lorenz, **LF**, et al., *PRD* (2019), (2021); ongoing work with Brinckmann (Euclid Collaboration)

How to test this model?

Neutrino mass model

Standard Model

Masses of particles are generated in the early universe

Problem

Neutrino masses: predicted = 0 but measured > 0

Our model [1]

Neutrinos can become massive in the late universe

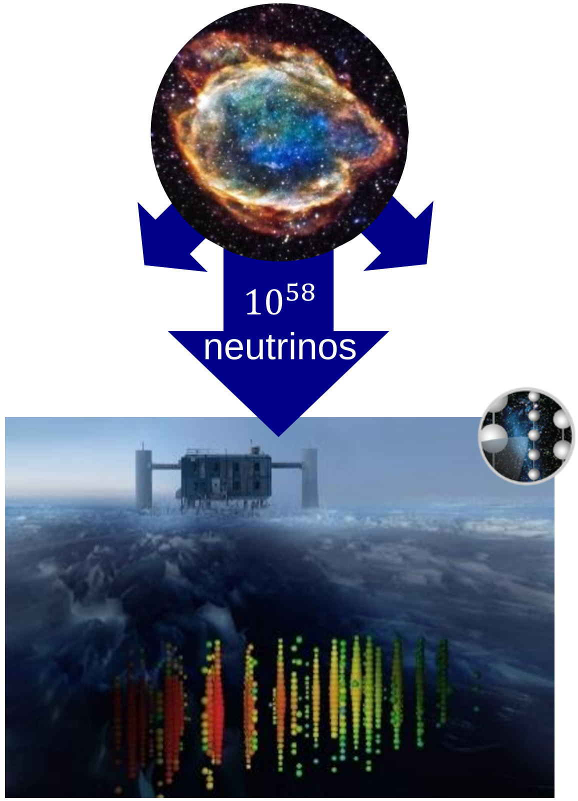
Key prediction

Neutrino condensation → flavor symmetry breaking

Predictions for astrophysical neutrinos

Heavier neutrinos decay into lightest: [1] $\nu_i \to \phi_k + \nu_j$ or $\bar{\nu}_j$

Discover: neutrino = or ≠ antineutrino? [2]



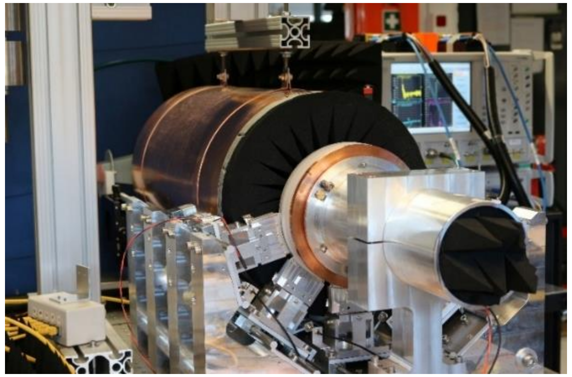
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

[1] Dvali, **LF**, *PRD* (2016a);
[2] **LF**, Raffelt, Vitagliano, *PRD* (2020)

How to test this model?

Neutrino mass model	Predictions for axion-search experiments
Standard Model	**Standard Model**
Masses of particles are generated in the early universe	Weak force distinguishes matter from antimatter
Problem	**Problem**
Neutrino masses: predicted = 0 but measured > 0	Strong force doesn't! Need new particle: axion?
Our model [1]	**Our model** [1]
Neutrinos can become massive in the late universe	New axion-like particles η_ν and ϕ_k → testable at …
Key prediction	
Neutrino condensation → flavor symmetry breaking	

… ALPS II experiment [2]

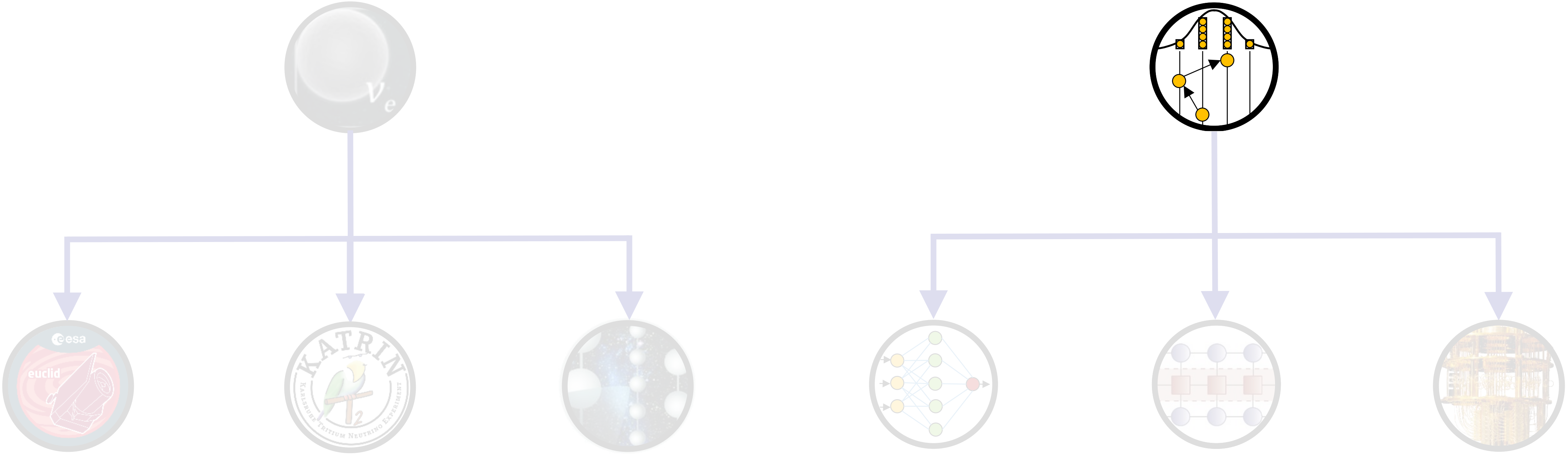


… MADMAX experiment? [3]

[1] Dvali, **LF**, *PRD* (2016a);
[2] Dvali, **LF** (2016b); [3] ongoing discussions with Dvali, Zhang, et al.

New models and methods for particle physics

Build new models	Develop new methods
Standard Model of particle physics Successful but incomplete	**Markov Chain Monte Carlo (MCMC)** Powerful but limited



euclid

KATRIN

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Machine learning

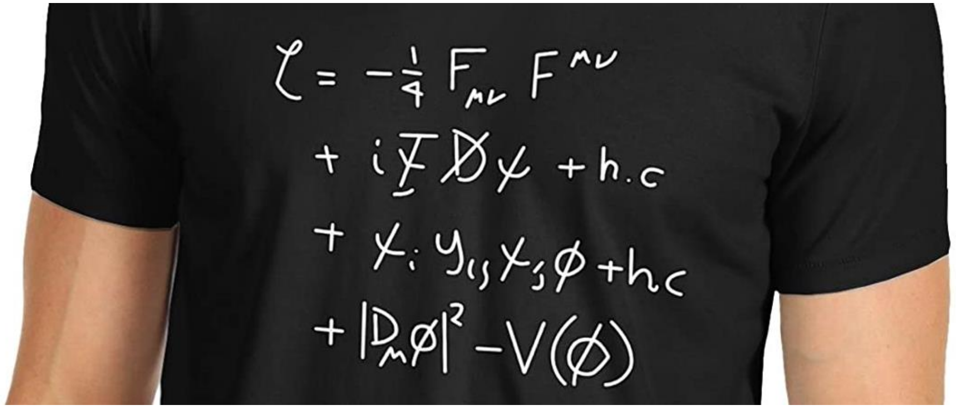
Tensor networks

Quantum computing

Why do we need numerical methods?

$\int$

Integrate



$$\boldsymbol{dF\, d\psi\, d\phi}$$

over forces (F), matter (ψ), Higgs field (ϕ)

Too complex:
no exact computation!

→

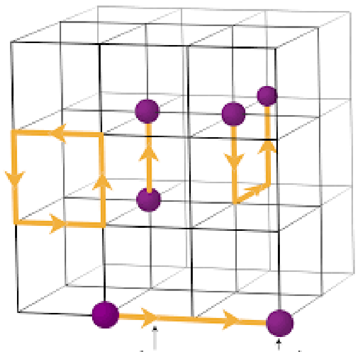
Way out:
approximation!

Which methods do we currently use?

Particle physics	Cosmology
Markov Chain Monte Carlo (MCMC) method	**MCMC method**
“Lattice” QCD: quarks and gluons on spacetime grid	Cosmological parameter estimation: age of Universe, …
Our work[1]	**Our work**[2]
Falsified $m_u = 0$ solution to strong CP problem → axion	Studied time-dependent cosmological neutrino masses

$\int$

Integrate



common methods for particle physics, cosmology, condensed matter physics, chemistry, biology, …

$\int$

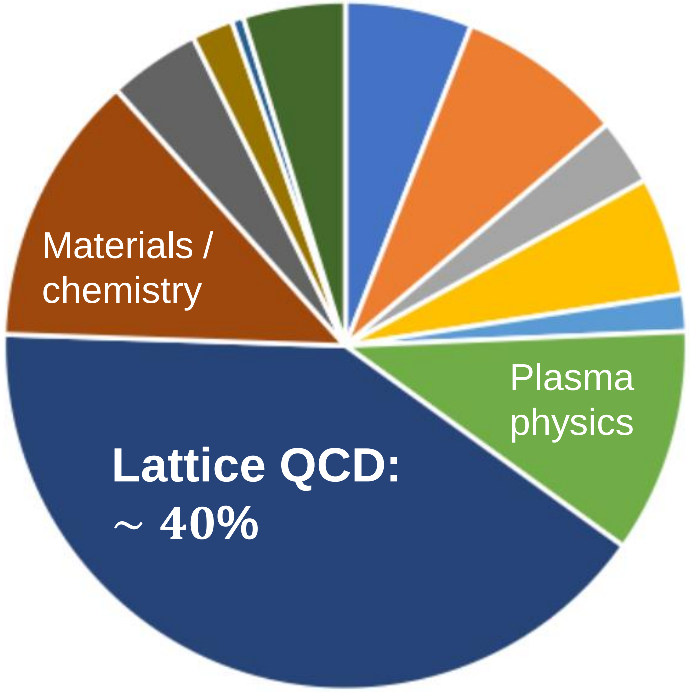
Integrate

[1] Alexandrou, Finkenrath, **LF**, et al., *PRL* (2020); [2] Lorenz, **LF**, et al., *PRD* (2019), (2021), ongoing work with Brinckmann (Euclid Collaboration)

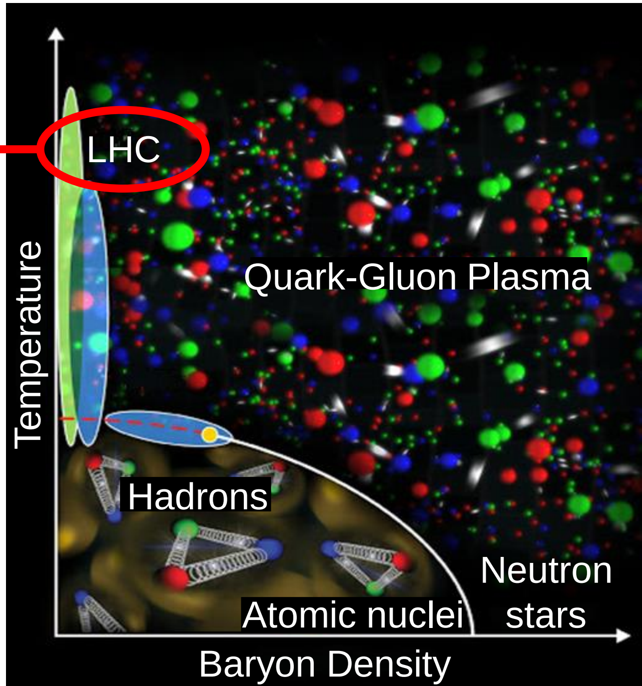
Why do we need new methods?

Computational costs of MCMC	Computational challenges of MCMC

E.g. "Lattice QCD": dominant supercomputer usage (INCITE 2019) → *machine learning* [1]



Cannot directly compute free energy, entropy, … → *machine learning* [1]



[1] White Paper: Boyda, Cali, Foreman, **LF**, et al. (2022); Nicoli, Anders, **LF**, et al., *PRL* (2021); …
[2] **LF**, et al., *PRD* (2023); **LF** et al., *PRD* (2020); Nakayama, **LF**, et al., *PRD* (2022); …
[3] **LF**, et al., *Quantum* (2021); **LF**, et al., *PRA* (2022); Di Meglio, et int., **LF**, et al. (QC4HEP Working Group), *PRX Quantum* (2023); …

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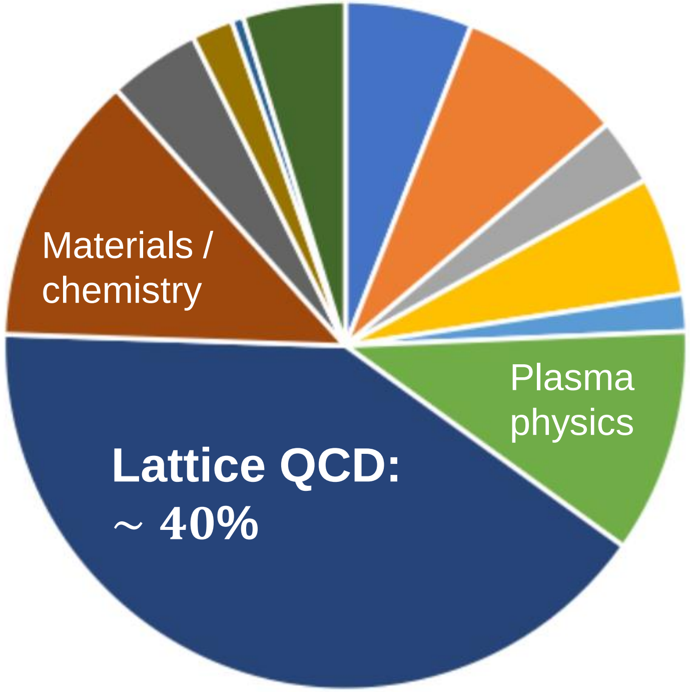
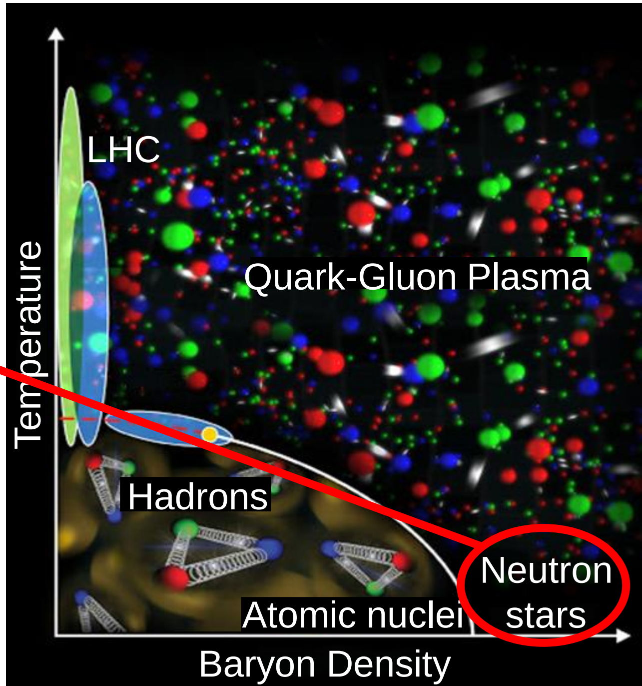


Computational challenges of MCMC

Cannot directly compute free energy, entropy, … → *machine learning* [1]

Cannot simulate large θ-term, chemical potential, … → *tensor networks* [2]



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[3] **LF**, et al., *Quantum* (2021); **LF**, et al., *PRA* (2022); Di Meglio, et int., **LF**, et al. (QC4HEP Working Group), *PRX Quantum* (2023); …

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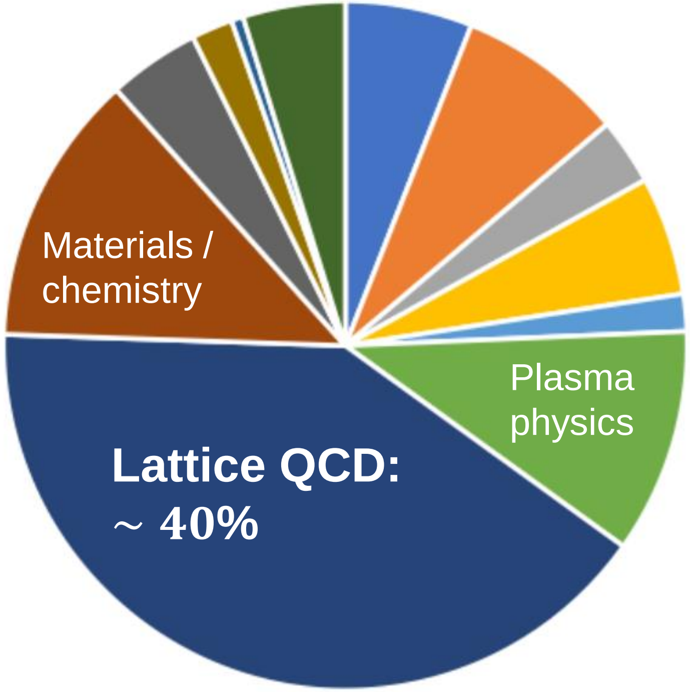

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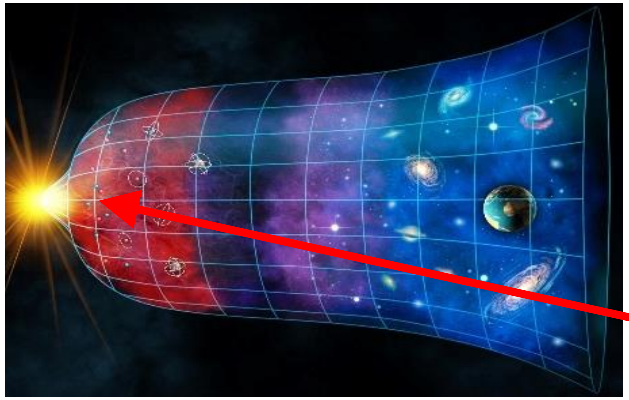

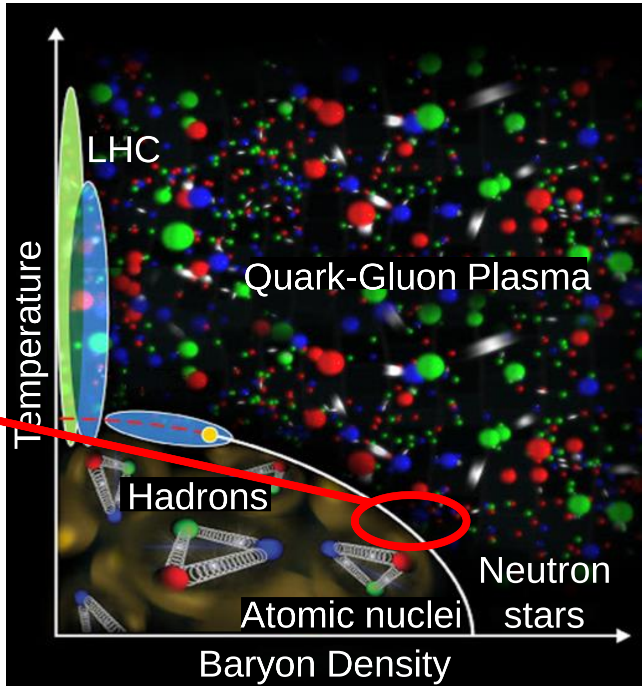

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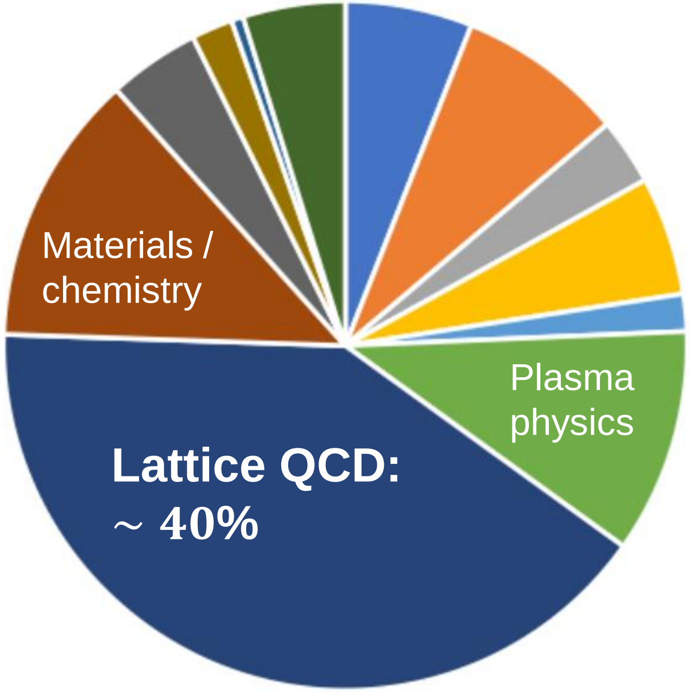

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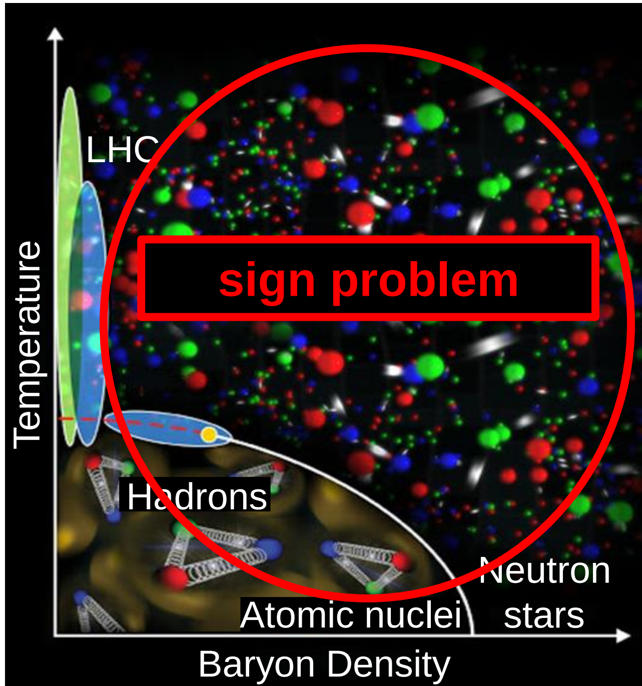

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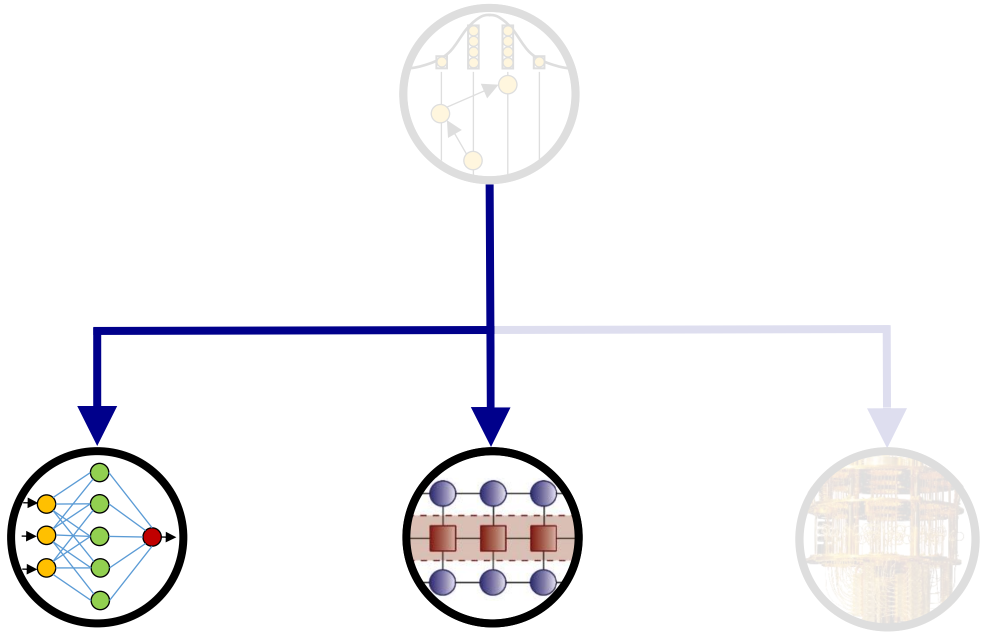
Standard Model of particle physics Successful but incomplete	**Markov Chain Monte Carlo (MCMC)** Powerful but limited

euclid KATRIN ICECUBE



Machine learning **Tensor networks** **Quantum computing**

How to tackle MCMC challenges with new methods?

Standard method: MCMC for Lattice QCD

Concept

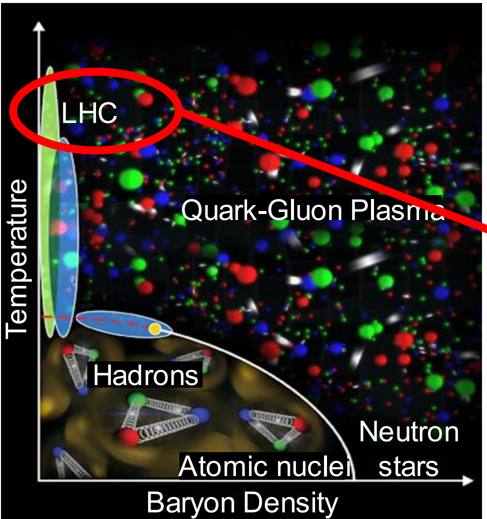
Compute observables: $\langle O \rangle = \frac{1}{Z} \int D\phi e^{-S(\phi)} O(\phi)$

Sample: $\langle O \rangle \approx \frac{1}{N} \sum O(\phi_i)$, where $\phi_i \sim p(\phi) = \frac{1}{Z} e^{-S(\phi)}$

Problem

Sequential, correlated sampling of ϕ_i → slow and costly

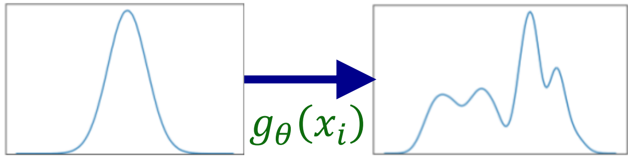
No *direct* computation of free energy → large errors



New method: machine learning

Concept

Train deep neural network:



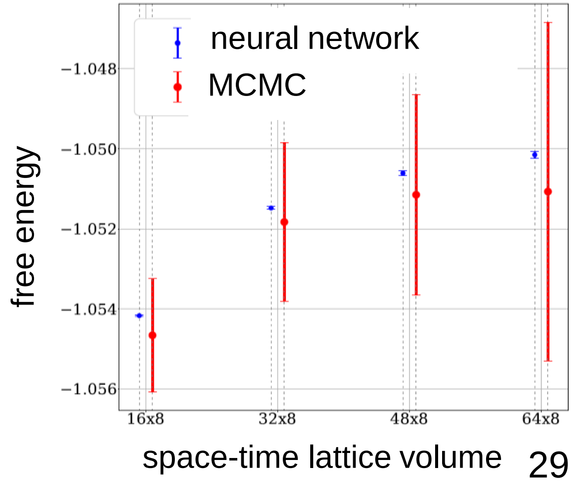
Results

Parallel, uncorrelated sampling of x_i → get $\phi_i = g_\theta(x_i)$

Direct computation of free energy in 1+1D Higgs model [1]

Future

Observables in 2+1D [2] & 3+1D [3]



[1] Nicoli, Anders, **LF**, et al., *PRL* (2021), *PoS Lattice* (2022), *PoS Lattice* (2024);
[2] Ongoing work with Nicoli, Schuh, et al.; development of software package NeuLat;
[3] White Paper: Boyda, Cali, Foreman, **LF**, et al. (2022)

How to tackle MCMC challenges with new methods?

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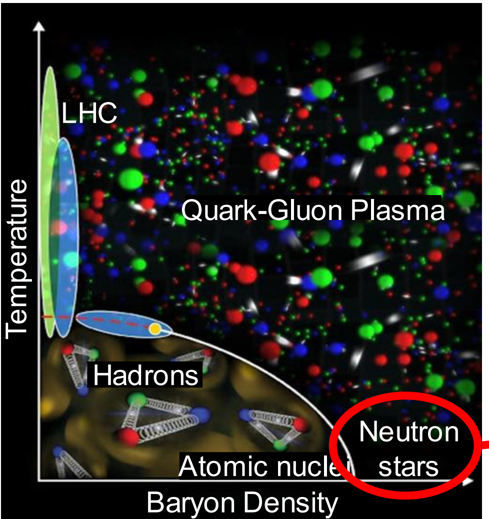
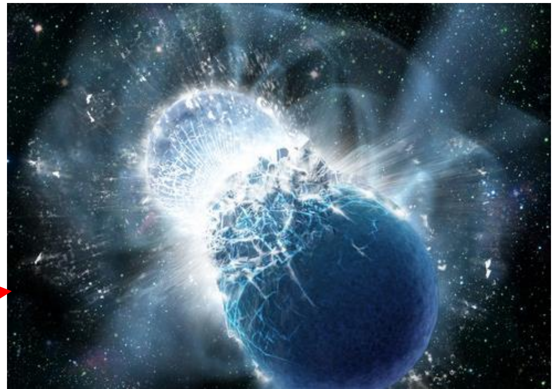
Sample: $\langle O \rangle \approx \frac{1}{N} \sum O(\phi_i)$, where $\phi_i \sim p(\phi) = \frac{1}{Z} e^{-S(\phi)}$

Problem

Complex action for $\theta-$term and chemical potential μ

→ "sign problem" → no simulations for large θ or μ





New method: tensor networks

Concept

Compute observables: $\langle O \rangle = \langle \psi | O | \psi \rangle$, approximate $|\psi\rangle$

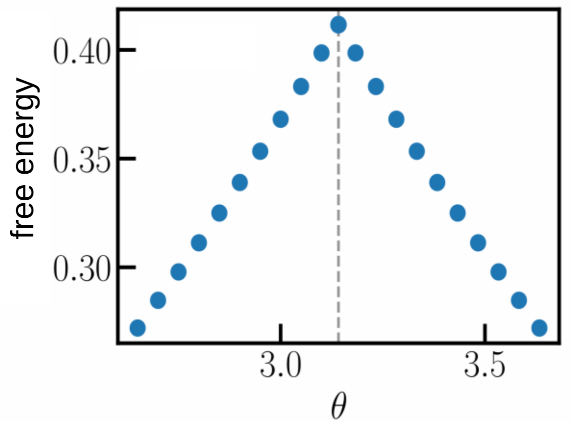
E.g.: $|\psi\rangle = \sum c_{i_1 \cdots i_n} |i_1\rangle \cdots |i_n\rangle \approx \sum A^1_{i_1} \cdots A^n_{i_n} |i_1\rangle \cdots |i_n\rangle$

Results

Simulations of phase transitions for large θ or μ in 1+1D[1]

Future

Phase transitions in 2+1D and 3+1D[2]



[1] **LF**, et al., *PRD* (2020); Nakayama, **LF**, et al., *PRD* (2022); **LF**, et al., *PRD* (2023);
[2] Kühn, Gerken, **LF**, et al., *PRB* (2023); Crippa, Romiti, **LF**, et al. (2024);
Crane, et int., **LF**, et al. (2024); ongoing work with Diamantini, et al.

What are the prospects and challenges of new methods?

New method: machine learning

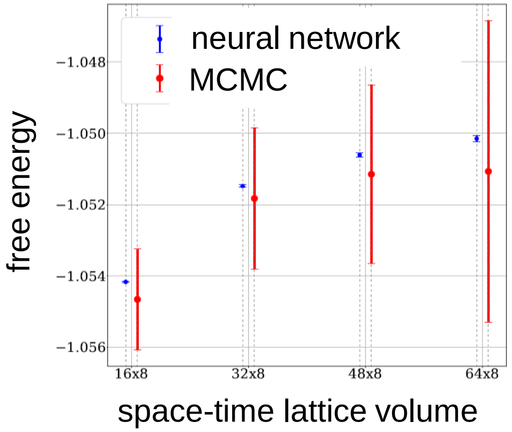
Prospects

- ✓ Direct computation of free energy, entropy, … [1]
- ✓✗ Mitigate sign problem [2]

Challenges

- ✗ Mode collapse [3]
- ✓✗ Focus on 1+1D, first ansatzes in 2+1D & 3+1D

→ roadmap to QCD [4]



New method: tensor networks

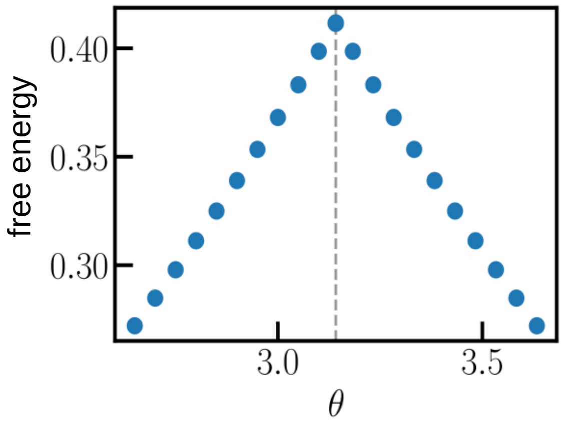
Prospects

- ✓ Direct computation of free energy, entropy, … [5]
- ✓ Evade sign problem [5]

Challenges

- ✗ Approximation inefficient for highly entangled states
- ✓✗ Focus on 1+1D, first ansatzes in 2+1D & 3+1D [6]

→ competition with quantum computing [7]



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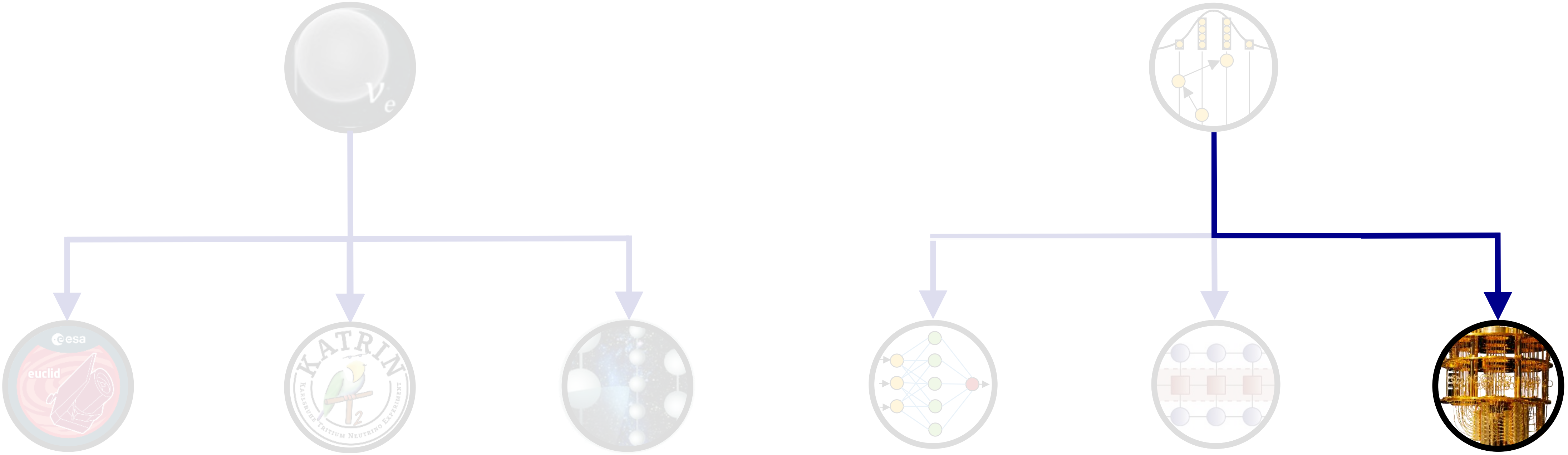
New models and methods for particle physics

Build new models	Develop new methods
Standard Model of particle physics Successful but incomplete	**Markov Chain Monte Carlo (MCMC)** Powerful but limited



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How to tackle MCMC challenges with new methods?

Standard method: MCMC for Lattice QCD	New method: quantum algorithms

Standard method: MCMC for Lattice QCD

Concept

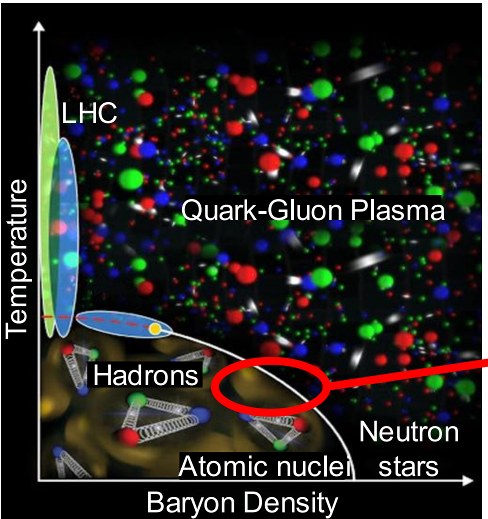
Compute observables: $\langle O \rangle = \frac{1}{Z} \int D\phi e^{-S(\phi)} O(\phi)$

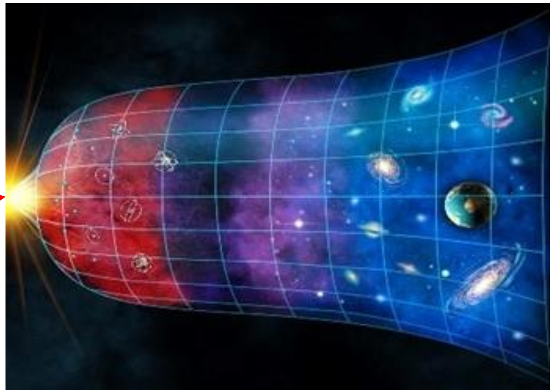
Sample: $\langle O \rangle \approx \frac{1}{N} \sum O(\phi_i)$, where $\phi_i \sim p(\phi) = \frac{1}{Z} e^{-S(\phi)}$

Problem

Euclidean action $S(\tau = it) \rightarrow$ no real-time evolution

$\rightarrow$ can be exponentially hard for tensor networks





New method: quantum algorithms

Concept

Compute $|\psi(t)\rangle = e^{-iHt}|\psi(0)\rangle$, encode 2^n basis states

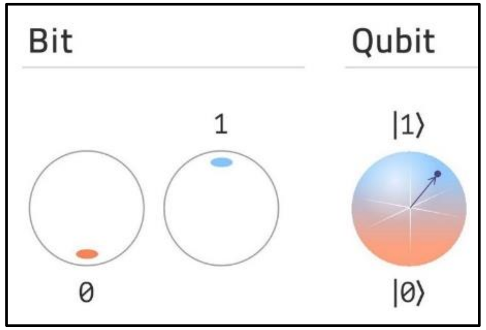
First step

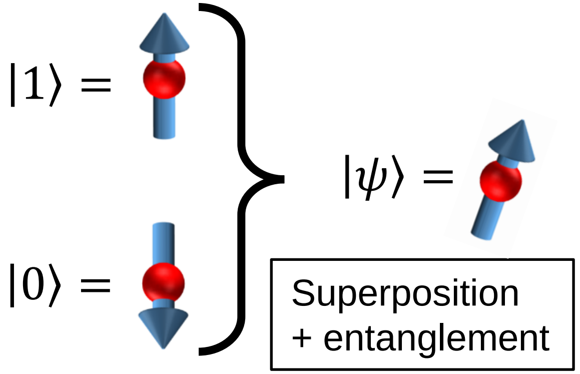
Focus on ground-state preparation: $\min_{\alpha} E_\alpha = \langle \psi_\alpha | \mathcal{H} | \psi_\alpha \rangle$

Hybrid quantum-classical algorithms

Classical optimization of quantum gate parameters $\boldsymbol{\alpha}$

$\rightarrow$ use machine learning [1]





[1] Nicoli, Anders, **LF**, et al., *NeurIPS* (2023), Anders, et int., **LF**, et al., *ICML* (2024)

Quantum Computing for High-Energy Physics
State of the Art and Challenges
Summary of the QC4HEP Working Group

Alberto Di Meglio,[1,*] Karl Jansen,[2,3,†] Ivano Tavernelli,[4,‡] Constantia Alexandrou,[5,3] Srinivasan Arunachalam,[6] Christian W. Bauer,[7] Kerstin Borras,[8,9] Stefano Carrazza,[10,1] Arianna Crippa,[2,11] Vincent Croft,[12] Roland de Putter,[6] Andrea Delgado,[13] Vedran Dunjko,[12] Daniel J. Egger,[4] Elias Fernández-Combarro,[14] Elina Fuchs,[1,15,16] Lena Funcke,[17] Daniel González-Cuadra,[18,19] Michele Grossi,[1] Jad C. Halimeh,[20,21] Zoë Holmes,[22] Stefan Kühn,[2] Denis Lacroix,[23] Randy Lewis,[24] Donatella Lucchesi,[25,26,1] Miriam Lucio Martinez,[27,28] Federico Meloni,[8] Antonio Mezzacapo,[6] Simone Montangero,[25,26] Lento Nagano,[29] Voica Radescu,[30] Enrique Rico Ortega,[31,32,33,34] Alessandro Roggero,[35,36] Julian Schuhmacher,[4] Joao Seixas,[37,38,39] Pietro Silvi,[25,26] Panagiotis Spentzouris,[40] Francesco Tacchino,[4] Kristan Temme,[6] Koji Terashi,[29] Jordi Tura,[12,41] Cenk Tüysüz,[2,11] Sofia Vallecorsa,[1] Uwe-Jens Wiese,[42] Shinjae Yoo,[43] and Jinglei Zhang[44,45]

Quantum computers offer an intriguing path for a paradigmatic change of computing in the natural sciences and beyond, with the potential for achieving a so-called quantum advantage—namely, a significant (in some cases exponential) speedup of numerical simulations. The rapid development of hardware devices with various realizations of qubits enables the execution of small-scale but representative applications on quantum computers. In particular, the high-energy physics community plays a pivotal role in accessing the power of quantum computing, since the field is a driving source for challenging computational problems. This concerns, on the theoretical side, the exploration of models that are very hard or even impossible to address with classical techniques and, on the experimental side, the enormous data challenge of newly emerging experiments, such as the upgrade of the Large Hadron Collider. In this Roadmap paper, led by CERN, DESY, and IBM, we provide the status of high-energy physics quantum computations and give examples of theoretical and experimental target benchmark applications, which can be addressed in the near future. Having in mind hardware with about 100 qubits capable of executing several thousand two-qubit gates, where possible, we also provide resource estimates for the examples given using error-mitigated quantum computing. The ultimate declared goal of this task force is therefore to trigger further research in the high-energy physics community to develop interesting use cases for demonstrations on near-term quantum computers.

How can we quantum simulate* lattice field theories?

Overview	Sign-problem-afflicted regimes

Current technology

$\mathcal{O}(100 - 1000)$ noisy qubits with error mitigation

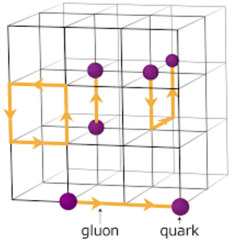
State of the art

First quantum simulations of 1+1D gauge theories [1]

Next steps

Efficient lattice fermion implementations [2]

Hybrid MCMC-quantum simulations of gauge theories [3]



* Note: quantum simulate or tensor-network-approximate

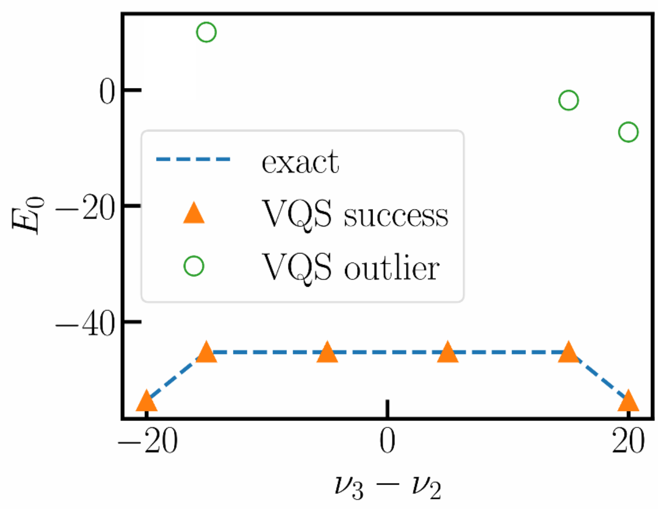
Topological terms

1+1D gauge theories with θ-term [4] and dynamical axion [5]

2+1D gauge theories with Chern-Simons term [6]

Chemical potentials

1+1D gauge theories with chemical potentials ν_f [7]



[1] Reviews: **LF**, et al., *PoS Lattice* (2023); Di Meglio, et int., **LF**, et al. (QC4HEP Working Group), *PRX Quantum* (2023); [2] Angelides, **LF**, et al., *PRD* (2023); [3] Crippa, Romiti, **LF**, et al. (2024); Avkhadiev, **LF**, et al. (2024); [4] Crane, et int., **LF**, et al. (2024); [5] ongoing work with Halimeh et al.; [6] Peng, Diamantini, **LF**, et al., (2024); [7] Schuster, Kühn, **LF**, et al., *PRD* (2024); …

Outlook: how can we address the sign problem in 3+1D?

Example: U(1) lattice gauge theory with θ-term

Goal

Study phase transition at $\theta = \pi$ and large $g = \beta^{-1/2}$

Theoretical requirements

Derive 3+1D θ-term in Hamiltonian lattice formulation [1]

Develop quantum algorithms for 1+1D,[2] 2+1D,[3] and 3+1D

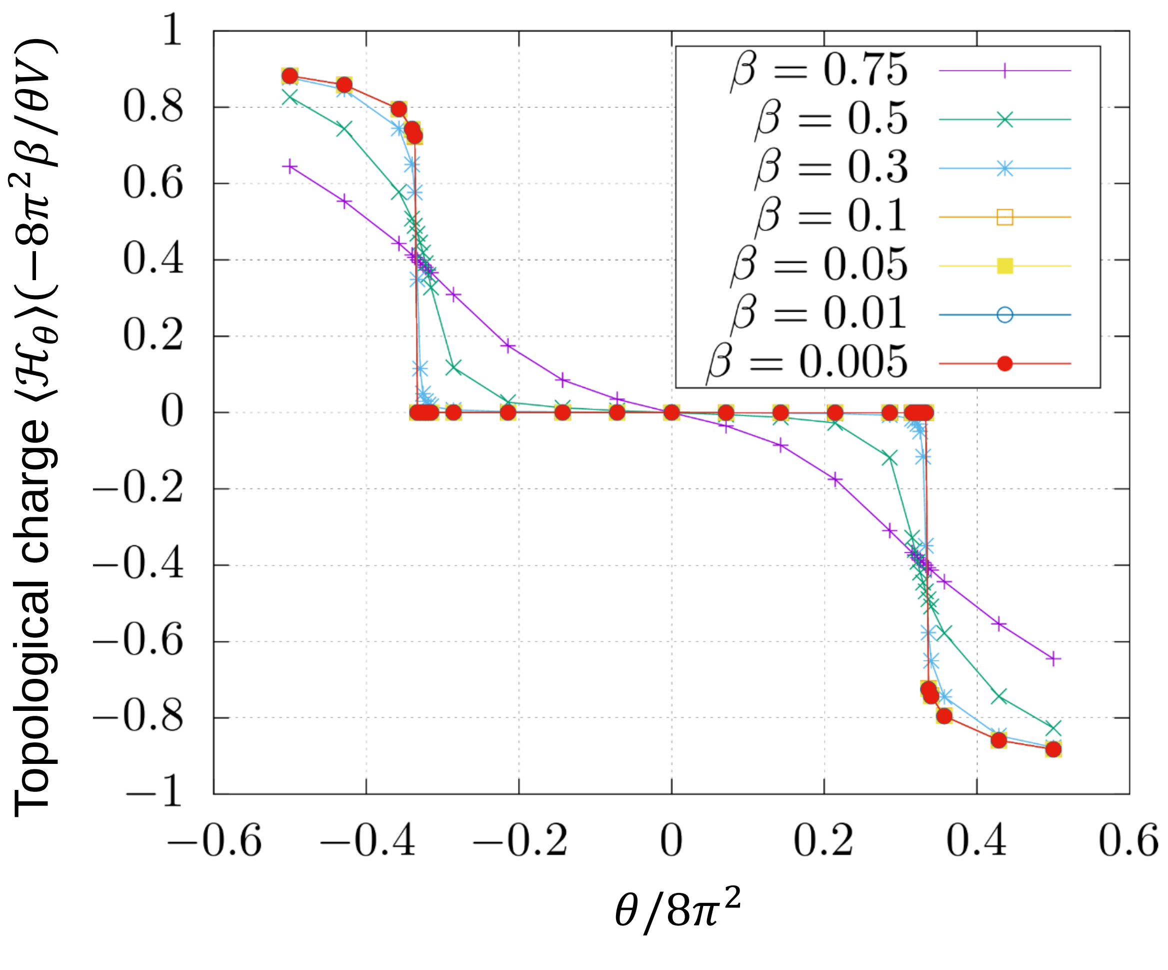
First classical computations

Study phase transition with exact diagonalization [1]

Future work

Larger volumes: tensor-network & quantum computations

First classical results for a single cube



[1] Kan, **LF**, et al., *PRD* (2021);
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[3] Crippa, Romiti, **LF**, et al. (2024); Crane, et int., **LF**, et al. (2024); …

Outlook: the future of quantum computing

The path to go…	A rough sketch…

State of the art *

First quantum simulations of 1+1D lattice theories [1]

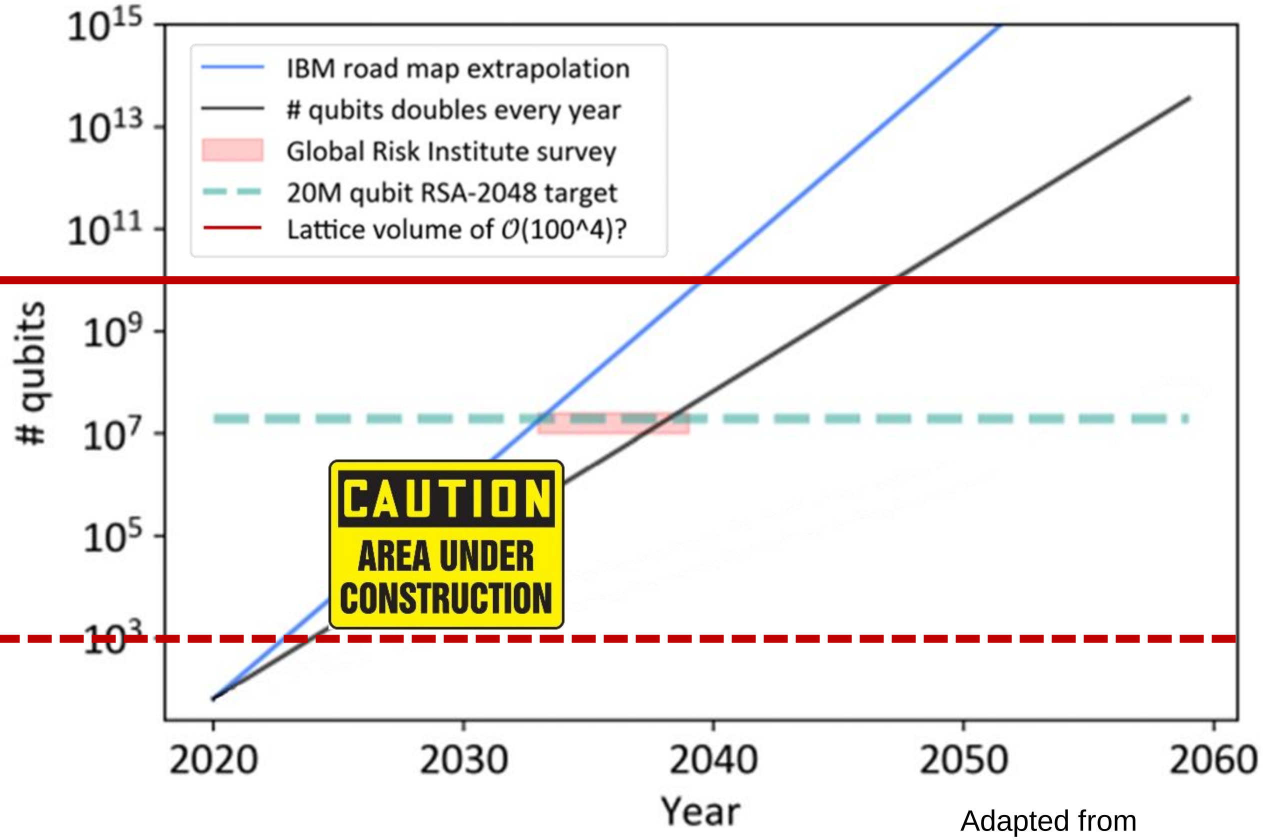
Noise mitigation, [2] circuit optimization, [3] new algorithms [4]

Future goals *

Quantum simulations for 2+1D & 3+1D theories

To evade sign problem, … of Lattice QCD and beyond

Analogous to Lattice QCD from 1980s to 2020s?



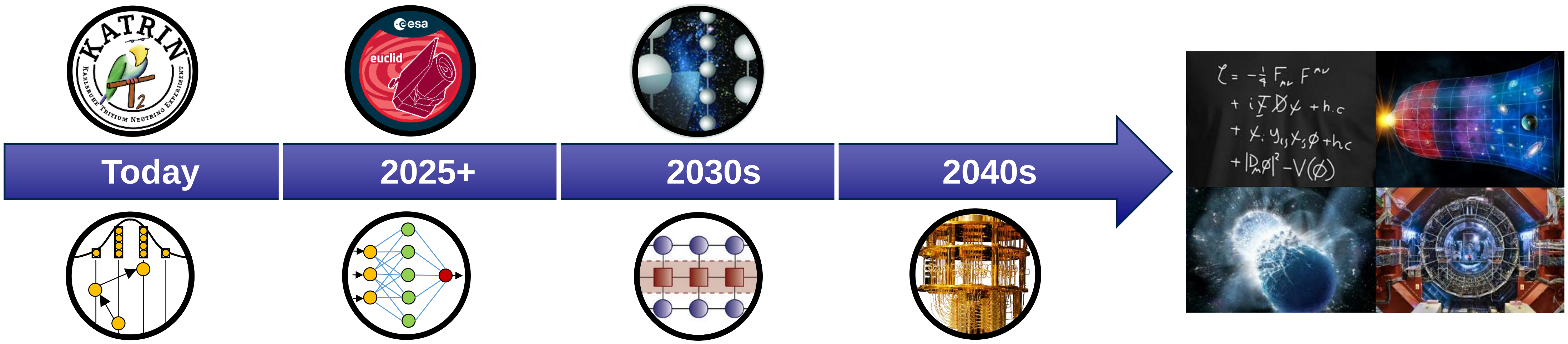
Adapted from Groenland (2024)

* Focus on algorithms: usable also for tensor networks

[1] Reviews: **LF**, et al., *PoS Lattice* (2023); Di Meglio, et int., **LF**, et al. (QC4HEP Working Group), *PRX Quantum* (2023);
[2] **LF**, et al., *PRA* (2022), …, [3] **LF**, et al., *Quantum* (2021), **LF**, et al., *IEEE ICWS* (2021), …, [4] Angelides, **LF**, et al., *PRD* (2023); Crippa, Romiti, **LF**, et al. (2024); …

Summary: new models and methods for particle physics

New models	New methods
State of the art	**State of the art**
Low-energy avenue of model building: [1] m_ν, ρ_{DE}, ϕ_k, …	Testing (B)SM physics with MCMC, [2] new methods [3]
Future goals	**Future goals**
Further developing and testing new low-energy models	Application of new methods to (B)SM phenomena



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[2] Lorenz, **LF**, et al., *PRD* (2021); Alexandrou, Finkenrath, **LF**, et al., *PRL* (2020); [3] **LF**, et al., *Quantum* (2021), **LF**, et al., *PRA* (2022), **LF**, et al., *PRD* (2023); Avkhadiev, **LF**, et al. (2024); …

Thanks to my collaborators


Gia Dvali
(MPP, LMU)


Georg Raffelt
(MPP)


Karl Jansen
(DESY)


Phiala Shanahan
(MIT)


Jesse Thaler
(MIT)


Christine Muschik
(Perimeter Inst.)


Tanmay Vachaspati
(Arizona State U.)


Philipp Stratmann
(Intel Munich)


Ivano Tavernelli
(IBM Zurich)


Stefan Kühn
(DESY)


Carsten Urbach
(Bonn U.)


Sofia Vallecorsa
(CERN)


Erminia Calabrese
(Cardiff U.)


Steven Girvin
(Yale U.)

and many more…

Special thanks

… to my research group:

… for support and funding:

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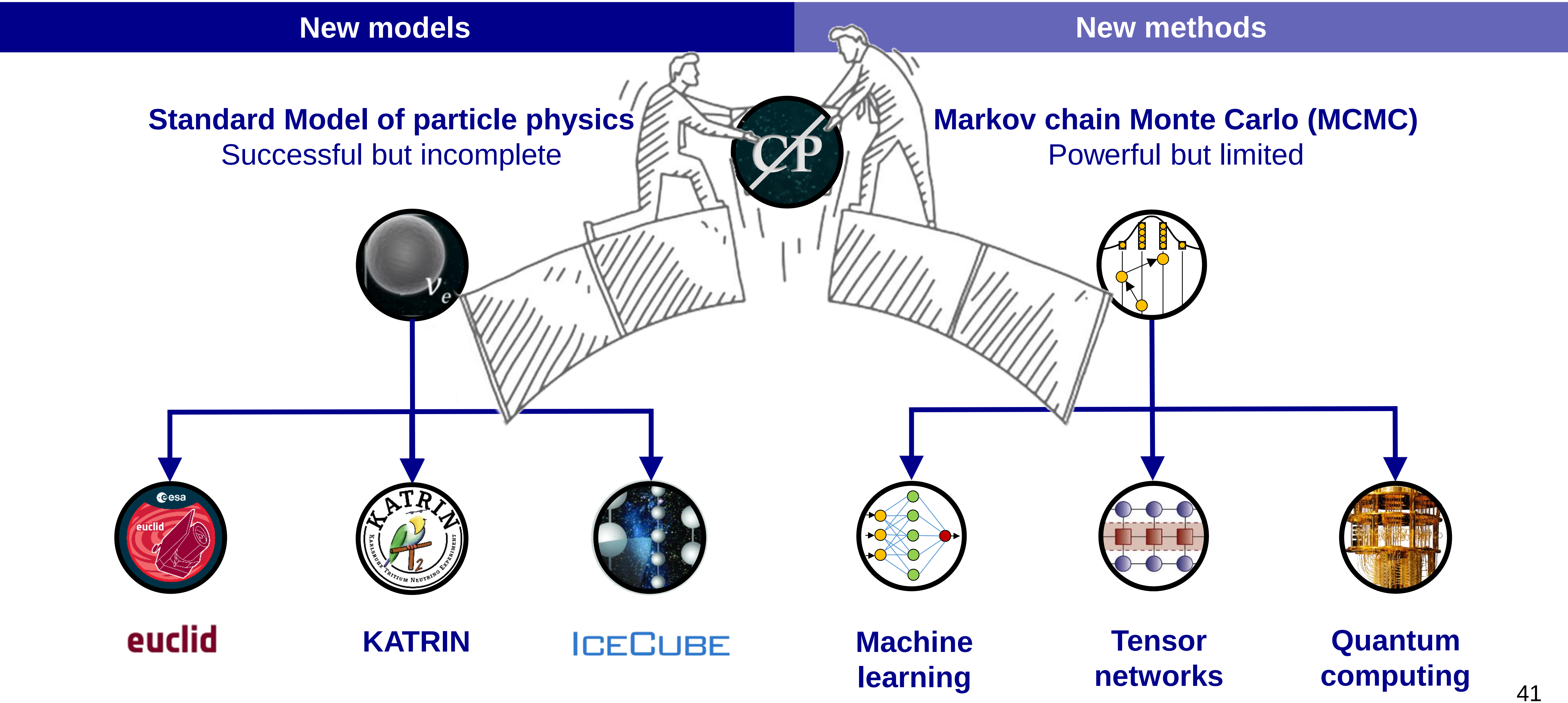
INSTITUTE FOR MACHINE LEARNING AND ARTIFICIAL INTELLIGENCE

… for computing time:

UNIVERSITÄT BONN HPC/A-LAB

IBM Q™ rigetti intel

Thanks to you for listening! Any questions on … ?



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