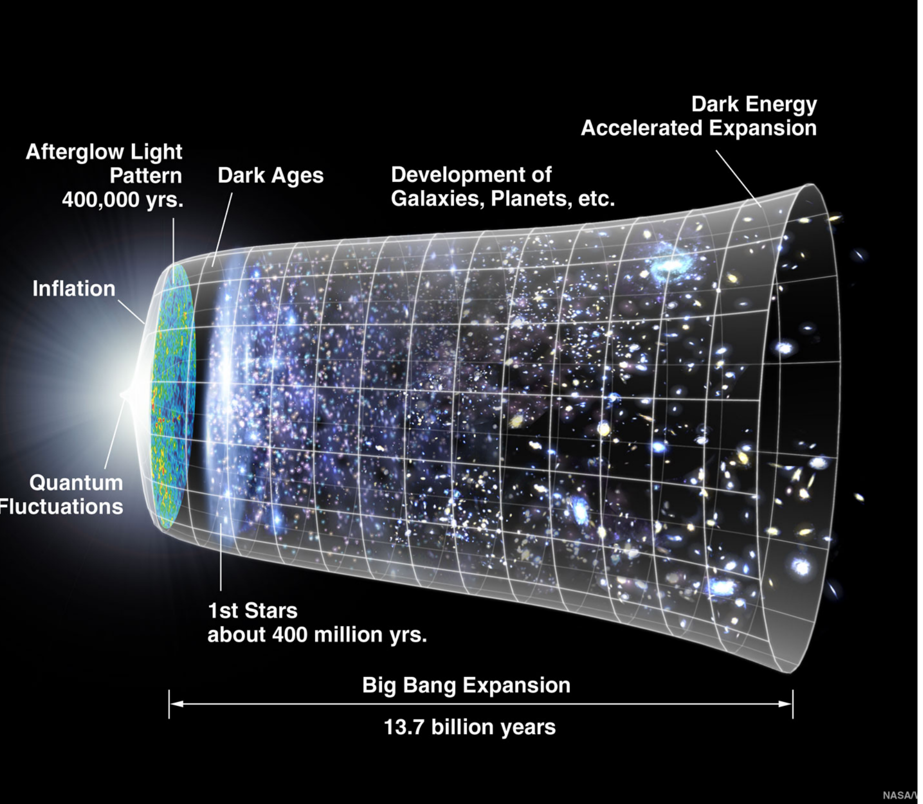
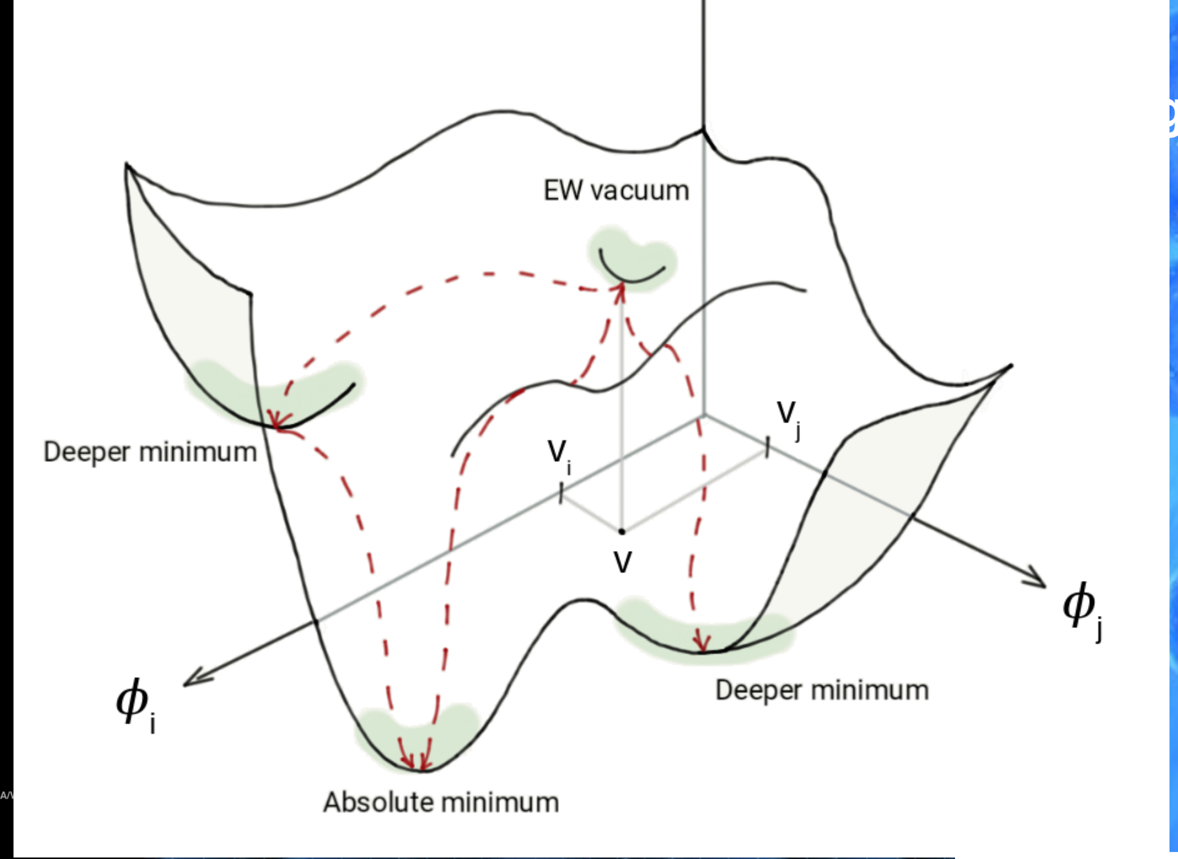
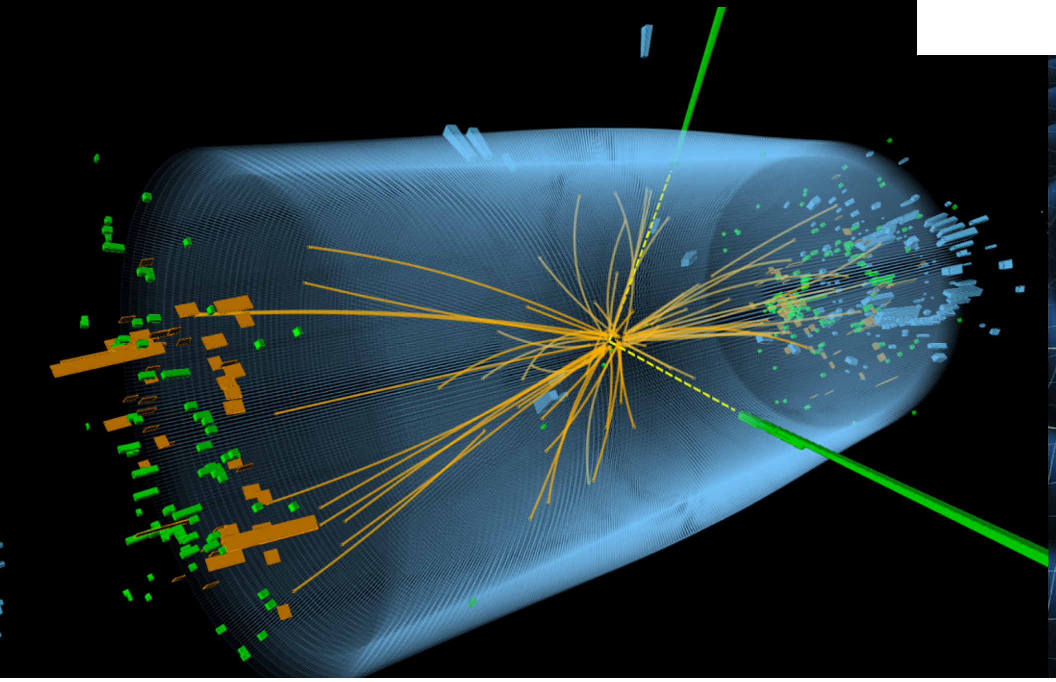
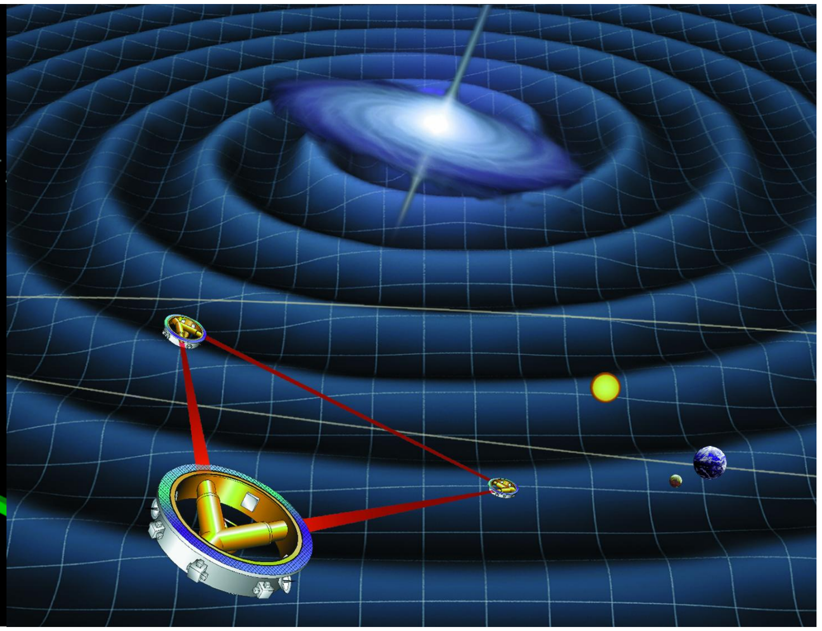
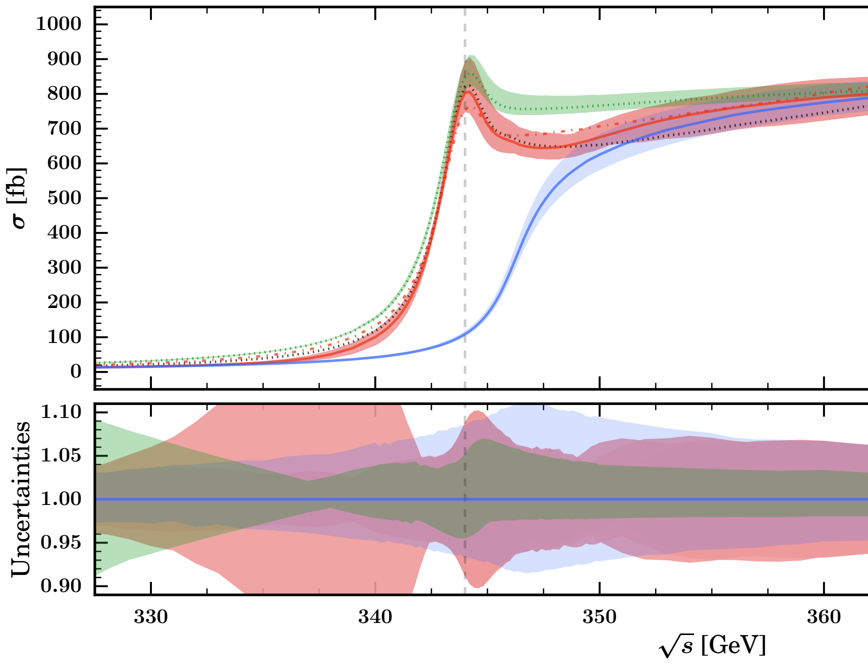










Theory plans (DESY): phenomenology

Georg Weiglein, DESY & UHH

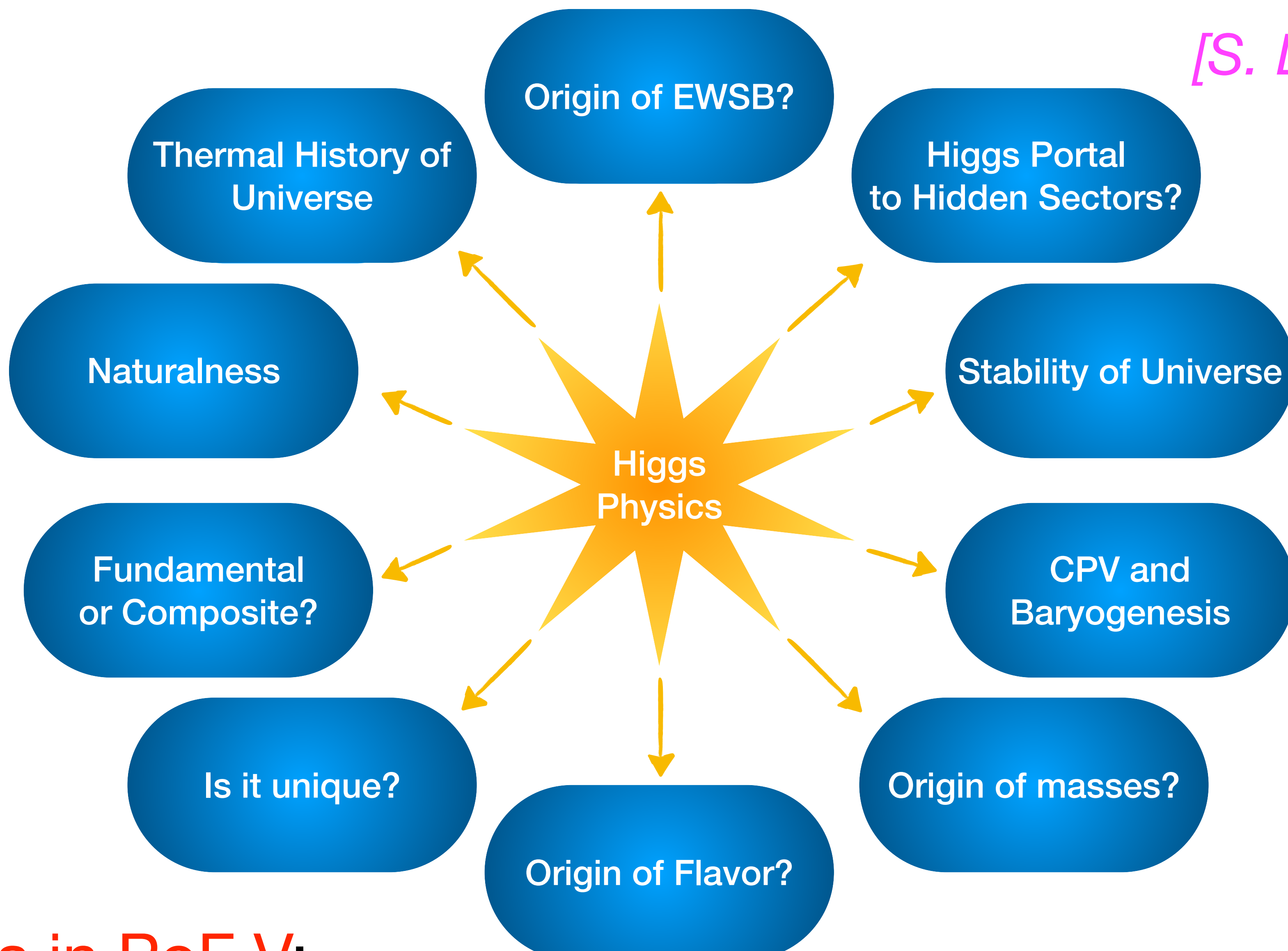
DESY, 06 / 2025

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE
DESY.

Higgs physics

Most of the open questions of particle physics are directly related to Higgs physics and in particular to the Higgs potential

[S. Dawson et al. '22]



Particular focus in PoF V:
Higgs pair (triple) production, Higgs self-couplings, precision predictions, new signatures, guidance for searches, model building, model distinction, …

Higgs potential: the "holy grail" of particle physics

Crucial questions related to electroweak (EW) symmetry breaking: what is the form of the Higgs potential and how does it arise?

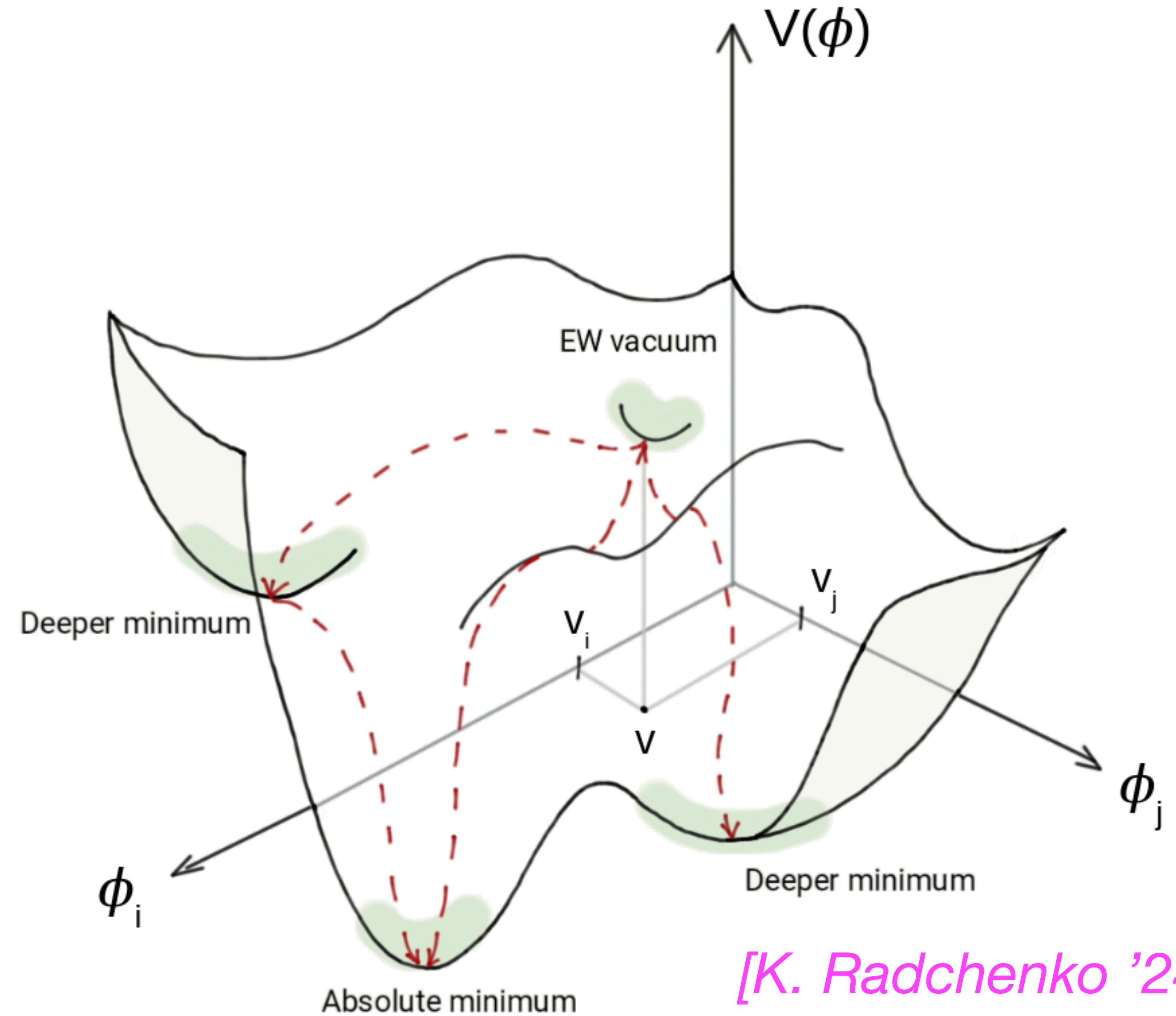
Trilinear coupling → Quartic coupling → Possible couplings involving additional scalars

$$V = 1/2\, m_h^2\, h^2 + v\, \lambda_{hhh}\, h^3 + \lambda_{hhhh}\, h^4 + \ldots + v\, \lambda_{hhH}\, h^2 H + v\, \lambda_{HHH}\, H^3 + \ldots$$

Known so far:
(h: detected Higgs at 125 GeV)

Distance of EW minimum from origin of field space: v

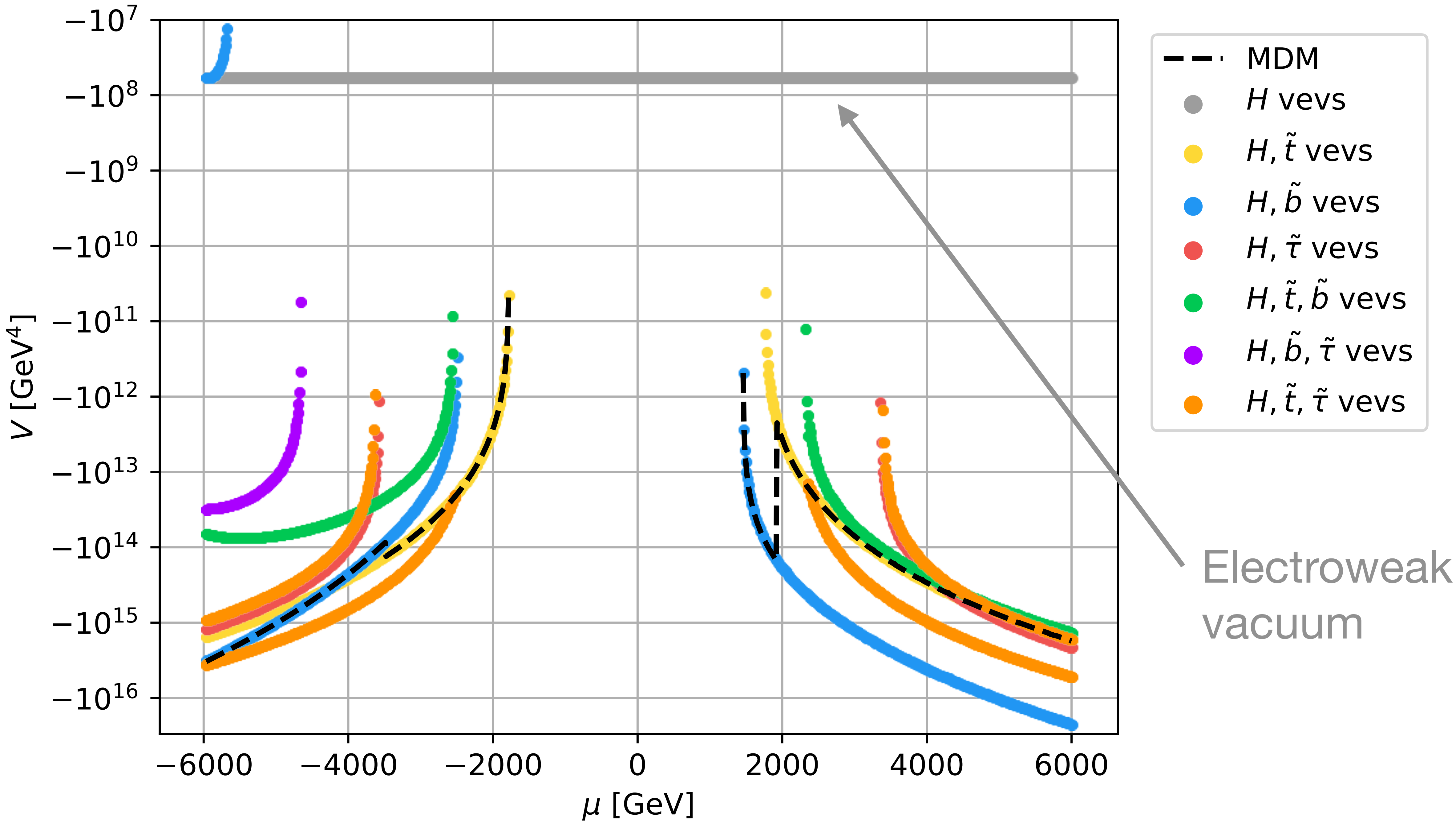
Curvature of the potential around the EW minimum: m_h



[K. Radchenko '24]

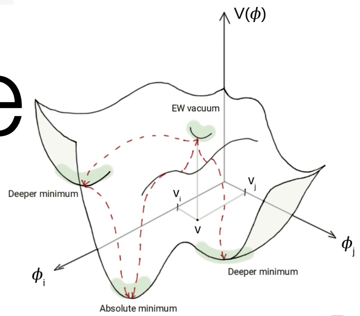
Vacuum stability: possible tunnelling into deeper minima of the Higgs potential

Example: potential along a direction through SUSY parameter space:



⇒ Most dangerous minimum (MDM) often differs from the global minimum and also from the one that is closest in field space

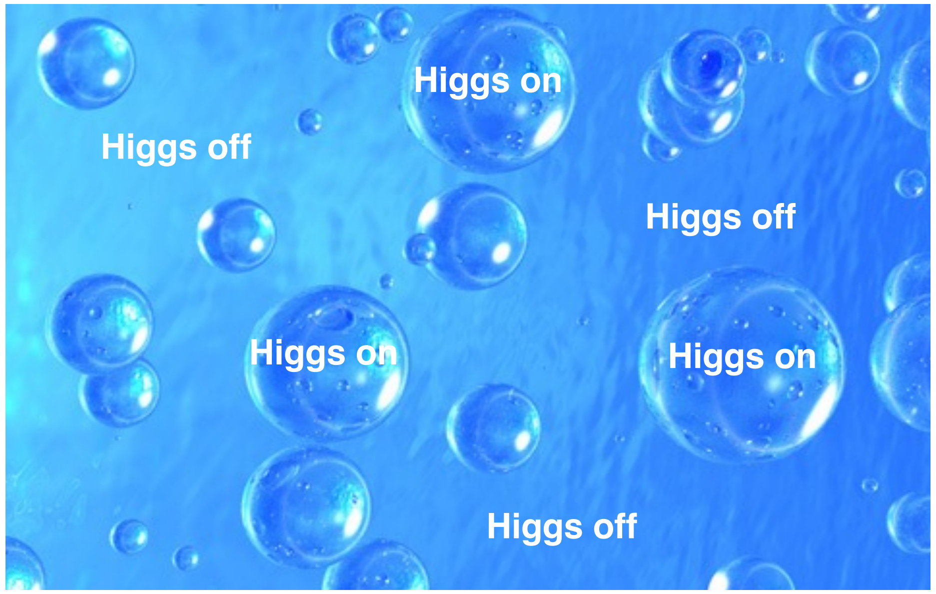
The Higgs potential and the electroweak phase transition (EWPT)



[D. Gorbunov, V. Rubakov]

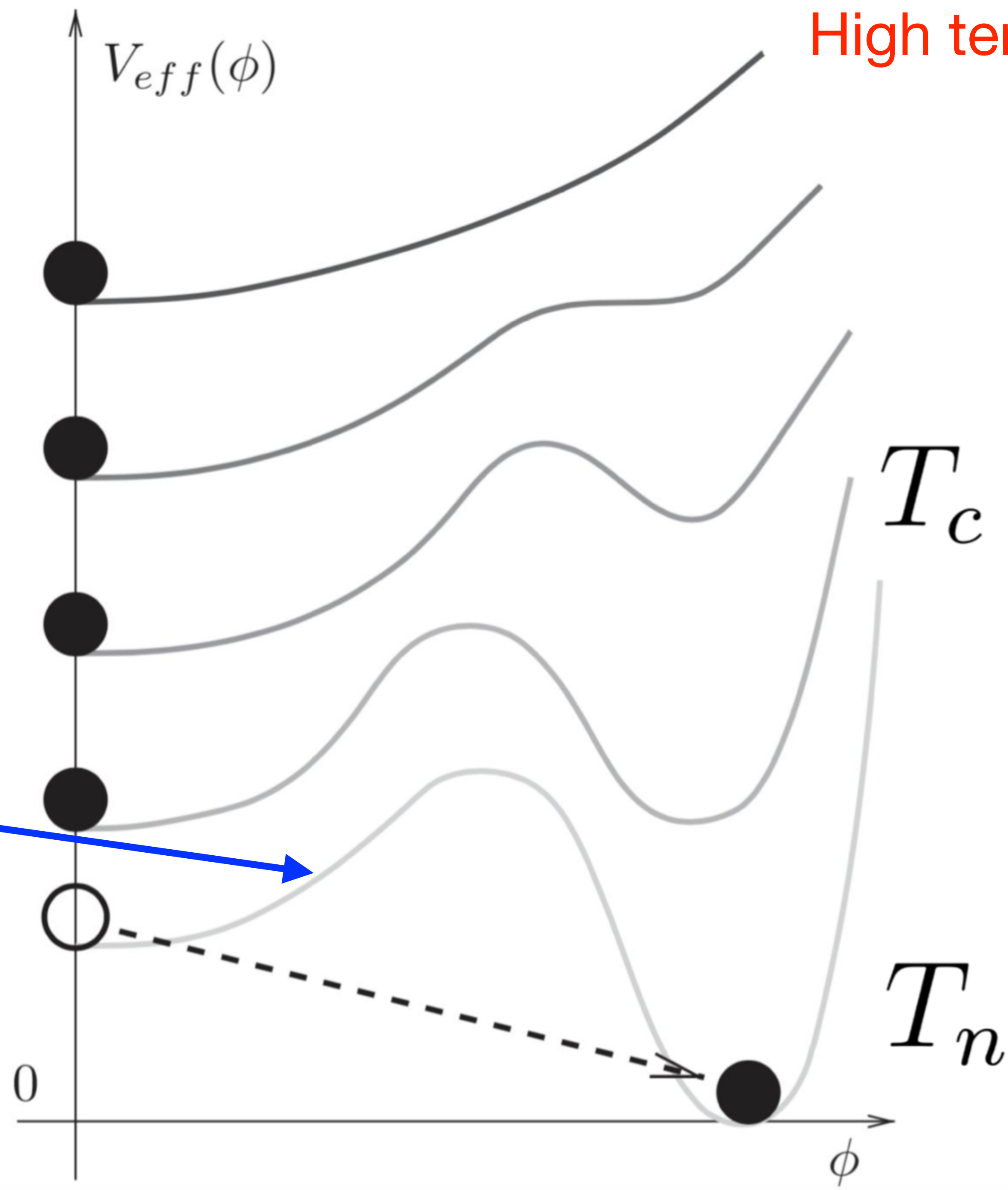
Temperature evolution of the Higgs potential in the early universe:

$$V(\phi, T) = V_0(\phi) + V^{loop}(\phi, T)$$



Potential barrier depends on trilinear Higgs coupling(s)

EW baryogenesis: creation of the asymmetry between matter and antimatter in the universe requires strong first-order EWPT



High temperature

Critical temperature (degenerate minima)

Transition temperature (strong first-order EWPT)

Probing additional sources of CP violation; strong CP problem

Machine Learning for CP sensitivity at the LHC and future colliders

Global fits of Electric Dipole Moments in Effective Field Theories as complementary CP information

CP-mixing and interference effects in BSM Higgs searches

Applications of new ideas on generalised/non-invertible symmetries to address open puzzles of the SM, in particular the hierarchy problem and the strong CP problem

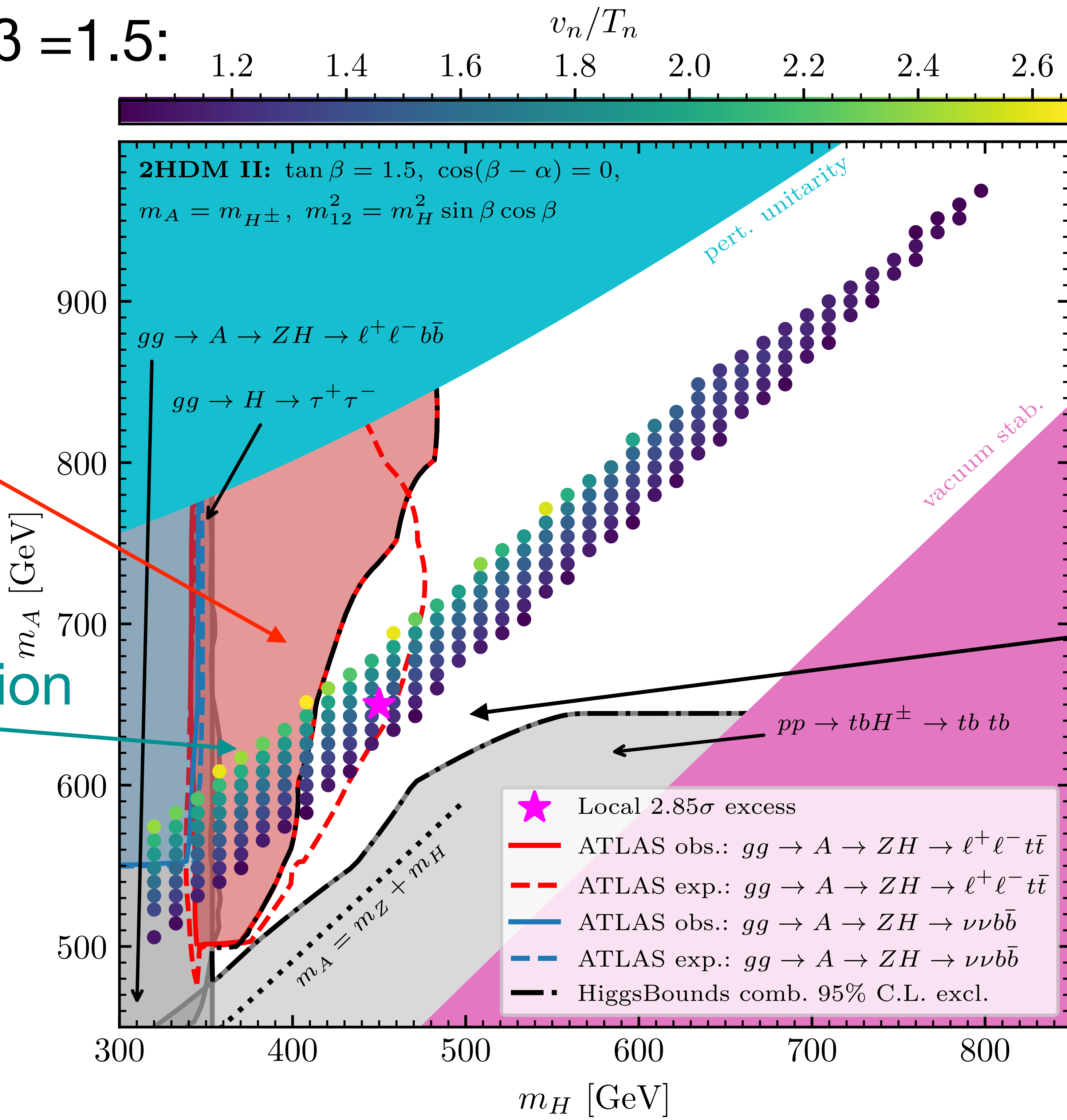
…

Probing the electroweak phase transition with the "smoking gun" signature pp → A → ZH → Ztt

2HDM, tanβ =1.5:

[ATLAS Collaboration '23]

Strongest phase transition



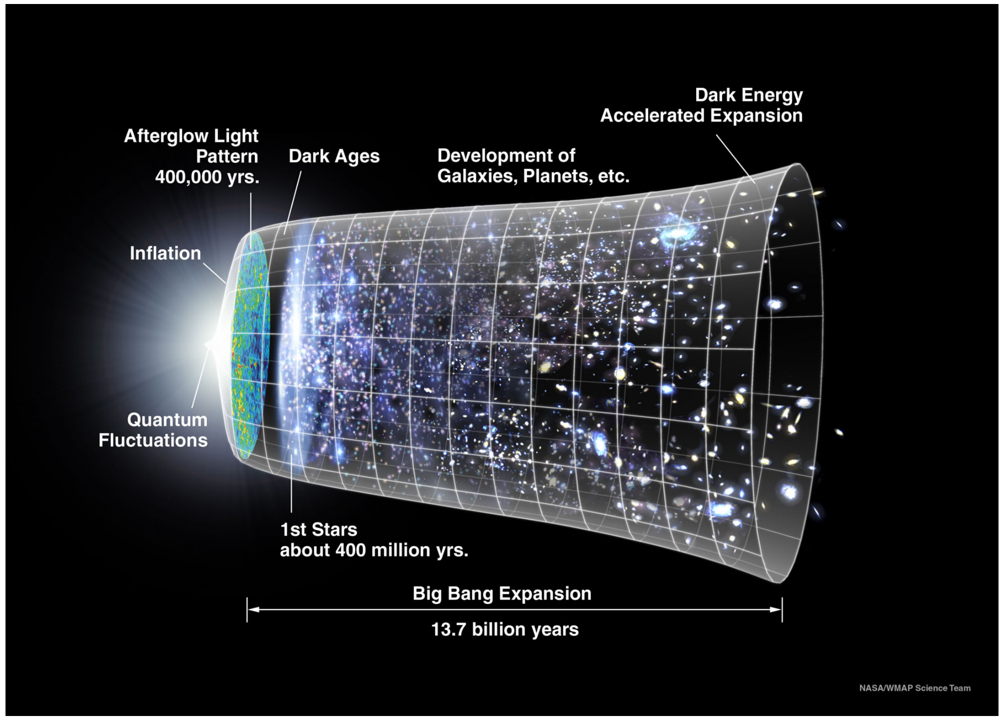
2.85 σ local excess at (m_A, m_H) = (650, 450) GeV

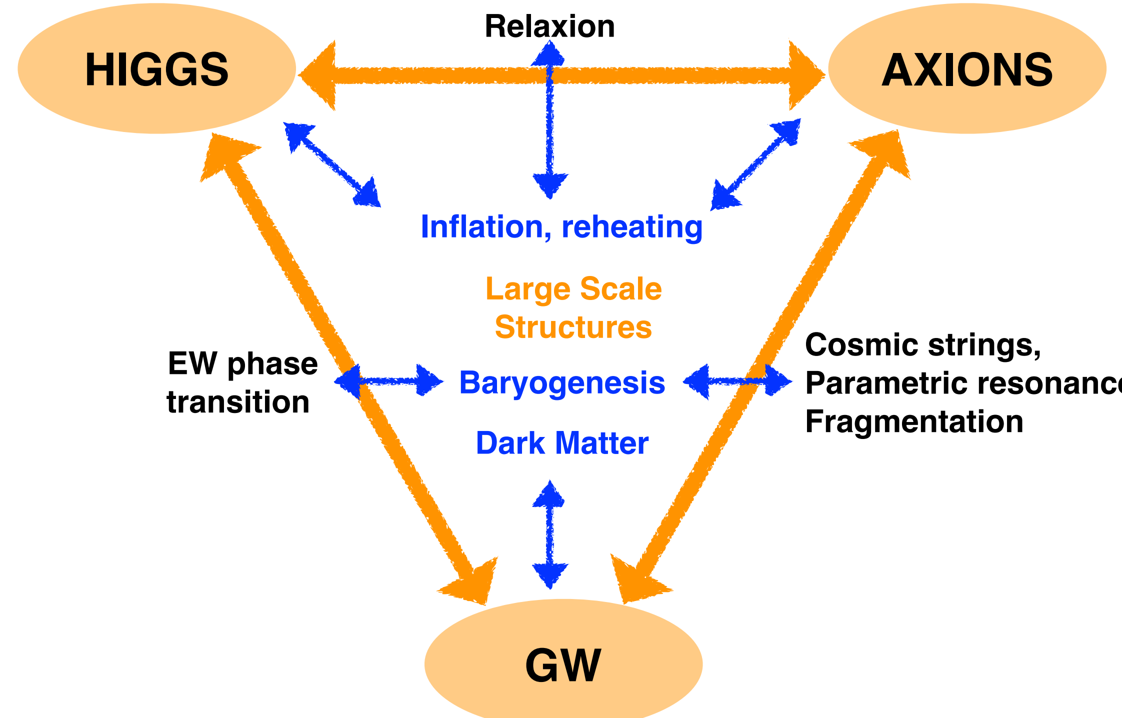
not confirmed by CMS

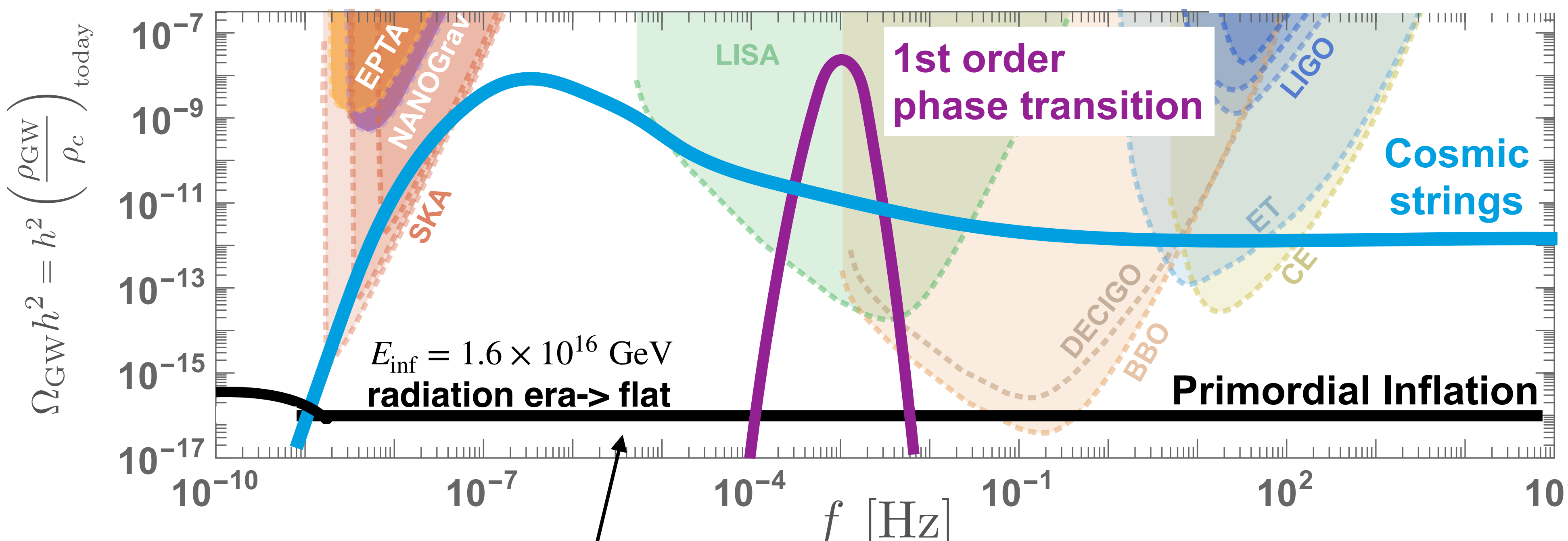
[CMS Collaboration '24]

⇒LHC searches start to probe the region giving rise to a strong FOEWPT

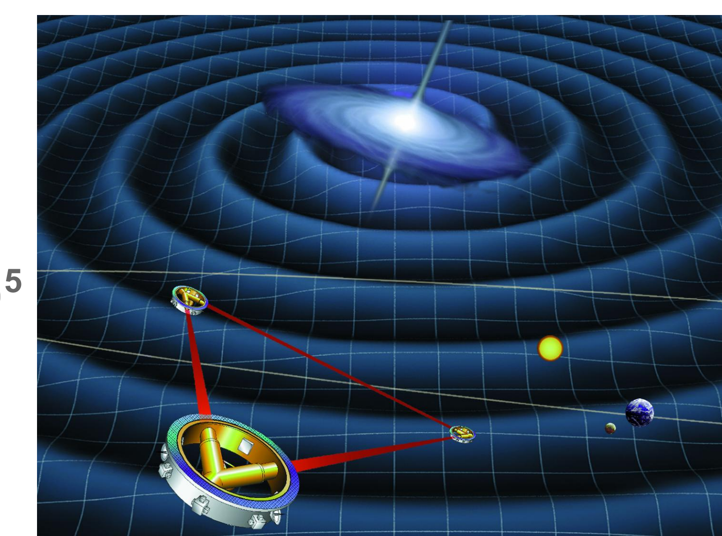
Gravitational waves as a probe of the early universe







LISA:



Irreducible GW background from amplification of initial quantum fluctuations of the gravitational field during inflation

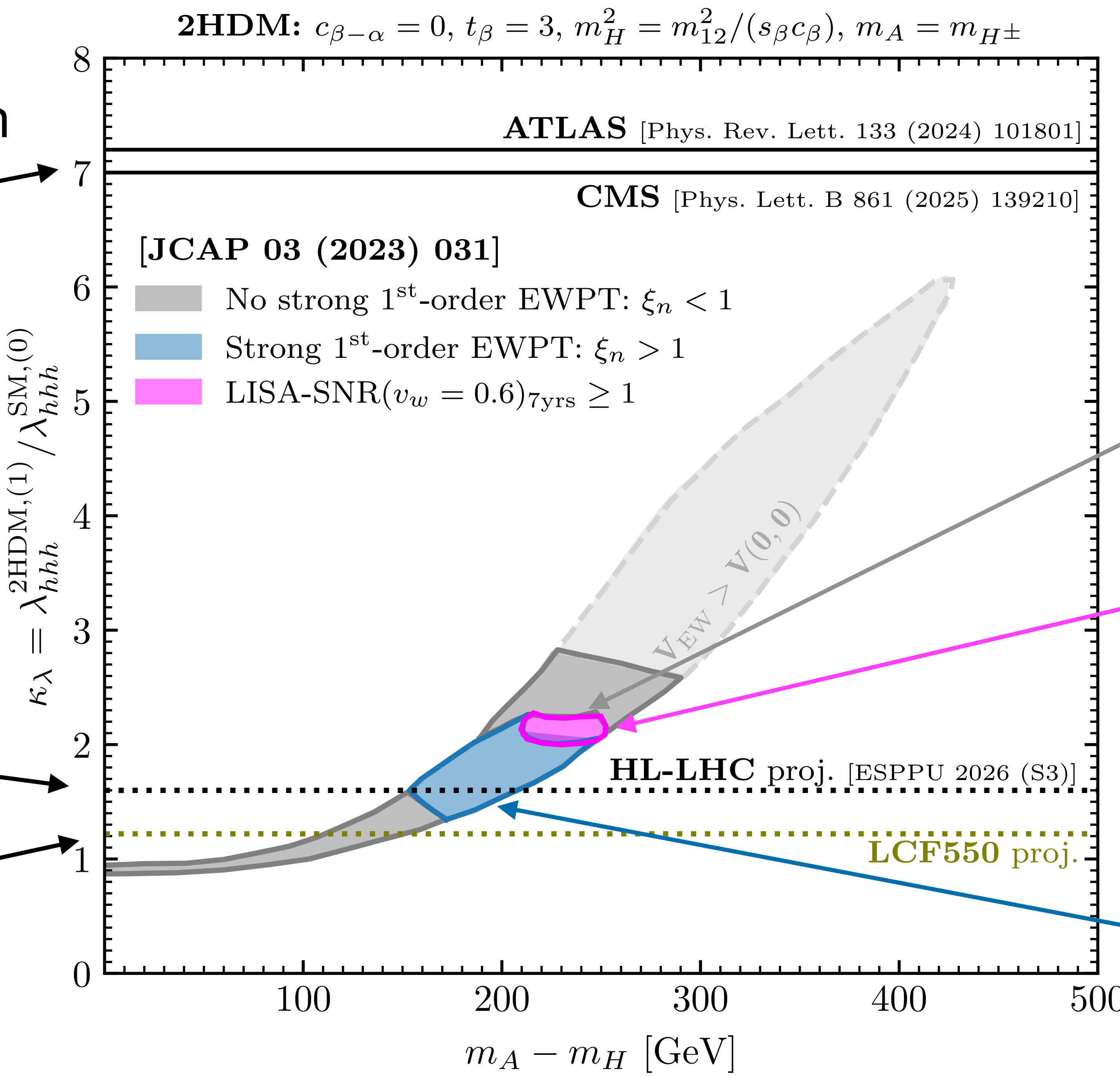
Relation between trilinear Higgs coupling and strong first-order EWPT with potentially observable GW signal

alignment limit,
tanβ = 3,
1-loop prediction

current bound

HL-LHC sensitivity

LC550 sensitivity



excluded because of "vacuum trapping"

region with potentially observable gravitational wave (GW) signal

region with strong first-order EWPT

⇒ Region with strong first-order EWPT and potentially detectable GW signal is correlated with significant deviation of $\varkappa_\lambda$ from SM value

Precision physics of the ew and strong interactions

Quantitative understanding of QCD is vital for interpretation of data at the LHC and future colliders, often presents a limiting factor for physics impact of measurements

Goals:
- push precision of predictions by developing new methods and concepts; extend predictions to new processes / observables
- more systematic understanding and treatment of theoretical uncertainties
- develop systematic frameworks for improving and quantifying precision of predictions
- implement developed methods into public tools for the high-energy community; focus on accuracy of results and efficient use of computing resources

Examples:
theory uncertainties: concept of nuisance parameters; apply factorisation formulae to new processes/observables, include sub-leading effects; concepts/methods: parton shower algorithms; tools: event generators, evolution and manipulation of PDFs

QCD + electroweak contributions

LHC physics: multi-boson physics with polarisation, NLO QCD+EW corr. For BSM models (extended Higgs models, SMEFT etc.), off-shell ttbar + X, pp → bblvlv + {A, AA, Z, H, ...} etc., Top threshold effects

MC generators: NNLO EW in collinear and soft subtraction, matching to showers, development for the tt threshold scan (NLO EW, NNLO QCD threshold matching, matching to soft gluon shower etc.), GPU offloading and ML for phase-space sampling (cross-link to SciComp and MT-DMA)

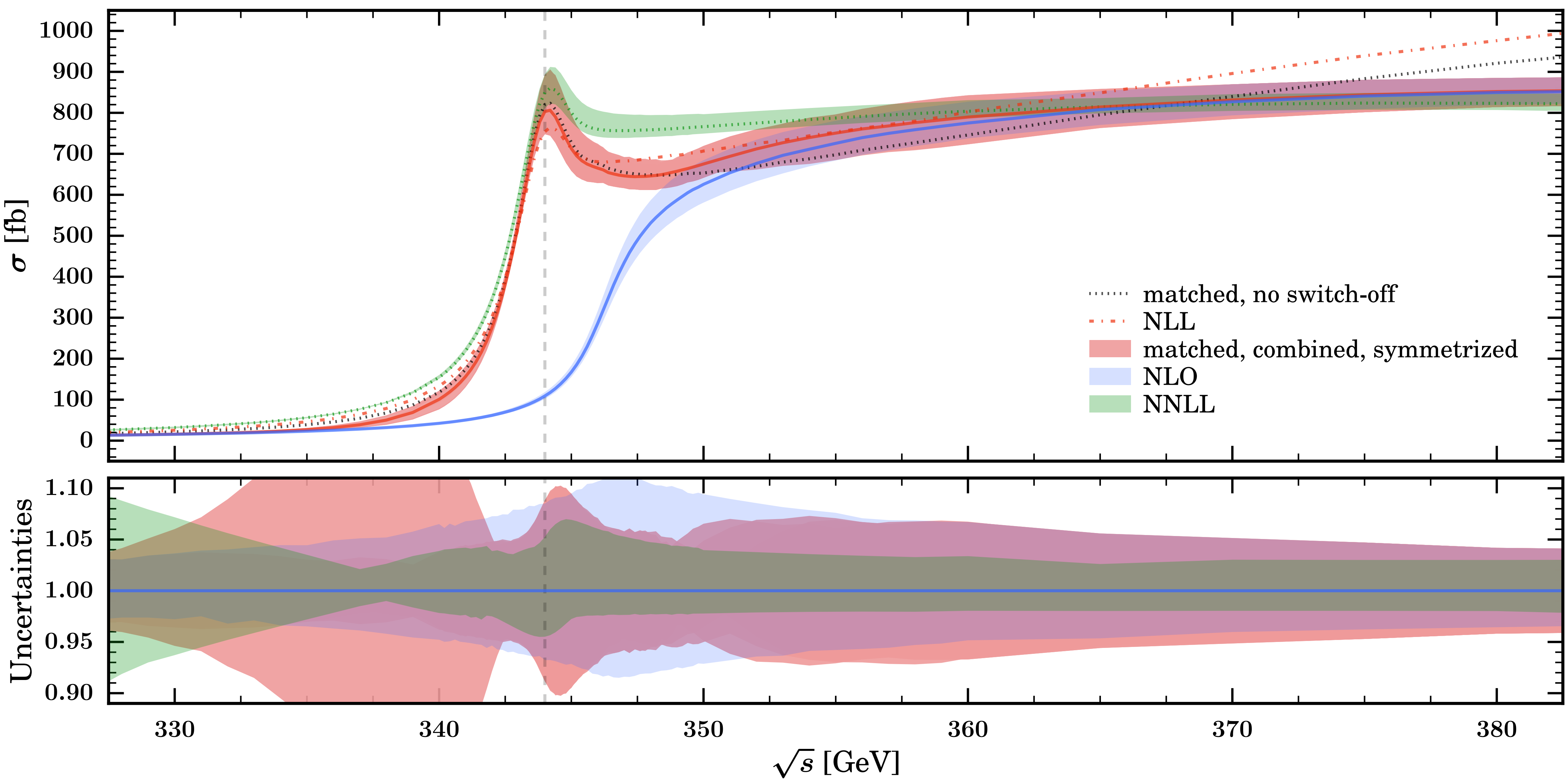
Electroweak physics at highest energies (MuC, FCC-hh etc.): electroweak factorisation, EW PDFs, matching to EW showers and fragmentation

Physics at photon colliders and physics program at LUXE (pheno + simulation tools)

NLO EW calculations/simulations for Higgs physics / BSM models at e+e- colliders (FCC-ee, LCF, etc.)

Example: e+e- → tt, projection for future matching

Future matching of NNLO QCD contribution in the continuum and NNLL tt threshold resummation:



Effective field theory analyses and future collider studies

Effective Field Theory: classification of physical impacts of dimension-8 operators on EW and Higgs measurements; theoretical constraints from unitarity and causality (swampland and positivity); small instanton effects on axion and axion-like particle interactions with SM degrees of freedom

Future colliders: demonstrate the potential of precision EW and Higgs measurements to probe new physics at high energy as well as at low coupling. The study will combine effective field theory analyses and model-specific studies for instance in the context of grand-unification scenarios.

Probing the dark sector

Collider signatures of dark sectors

Dark matter production mechanisms

Constraining new physics with cosmological probes such as BBN and CMB

Dark matter spikes around black holes

Primordial black holes

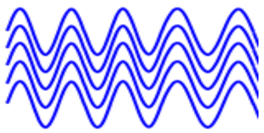
Signatures and models of self-interacting dark matter

Novel experimental probes for ultralight dark matter

Using quantum sensors to search for (ultra)light DM

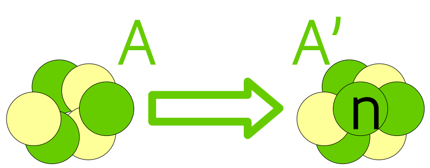
[see talk by S. Worm]

Simple SM extension: ultralight scalar ϕ → DM candidate

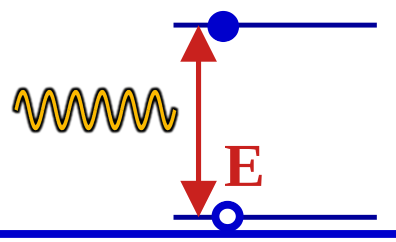
Ultralight ($m_\phi \lesssim 10\,\mathrm{eV}$) → DM as classical, coherently oscillating field $\phi(t) \approx \phi_0 \cos(m_\phi t)$ 

→ induces **oscillations** of α_{em} and fermion masses
→ oscillations of electron levels in atoms and ions: testable by frequency ratios of (atomic) clocks

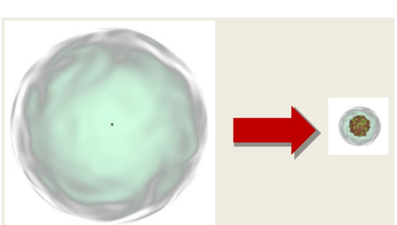
Isotope shifts for Dark Mediator



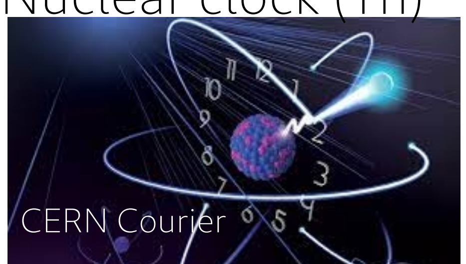
Atom/ion clocks



Highly charged ions



Nuclear clock (Th)



Enhanced sensitivity to ULDM ϕ

Additional directions

- **Cavities** for axions and High-Frequency Gravitational Waves
- **Atom interferometers** for ULDM and Gravitational Waves
- **Quantum Information Theory** for optimizing detection schemes
- **Non-minimal models**

Close interaction between experiment and theory!

Conclusions

Precise predictions, theory input for enhancing the sensitivity of experimental analyses to BSM effects and to the discrimination between different realisations of the underlying physics

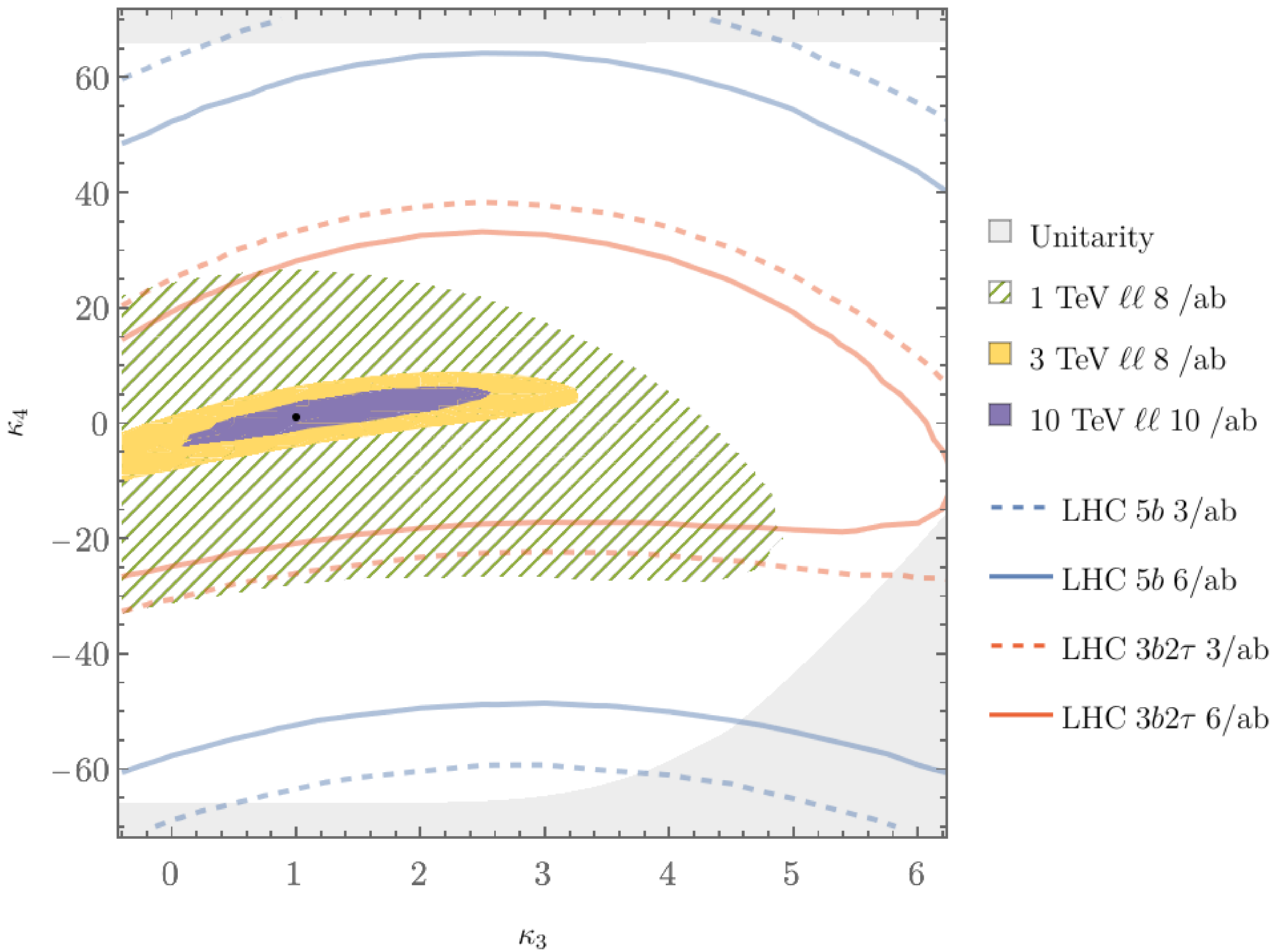
Exploit and improve machine-learning methods, make use of new mathematical / theoretical developments

Interplay between collider physics, the evolution of the early universe and the physics of gravitational waves

Close interaction between experiment and theory, build on successful track record of common publications and joint projects

Backup

Triple Higgs production: HL-LHC vs. lepton colliders



HL-LHC is comparable to 1 TeV lepton collider for $\varkappa_\lambda \approx 1$

Higher-energetic lepton colliders have better sensitivity

Particle Cosmology @ DESY

Géraldine SERVANT
DESY/U.Hamburg

PoF V MU-FPF Retreat, June 20 2025

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Universität Hamburg

Permanent Staff

Konstandin

Schmidt-Hoberg

Westphal

Servant

Ringwald's replacement

+ two 5-year junior staff

+ recent new associate with UHH

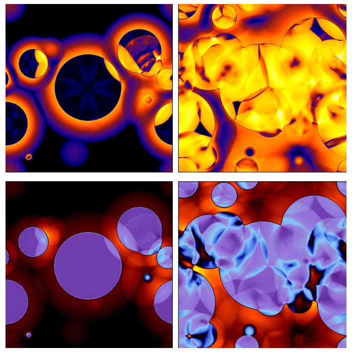
Witte

Team strongly embedded into the Quantum Universe cluster

Higgs cosmology

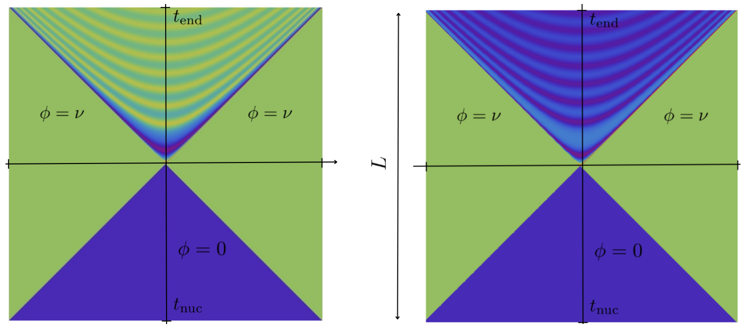
-Non standard Higgs thermal histories

-Higgs & inflation



-Electroweak phase transition

-Electroweak baryogenesis

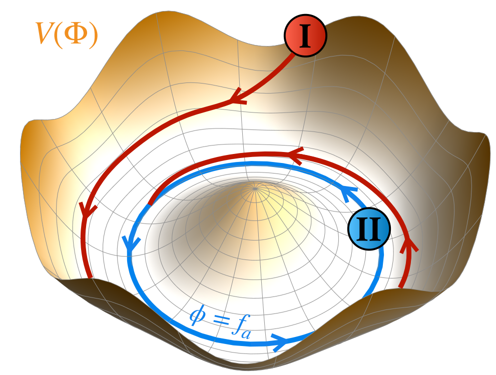


-Cosmological solutions to the hierarchy problem

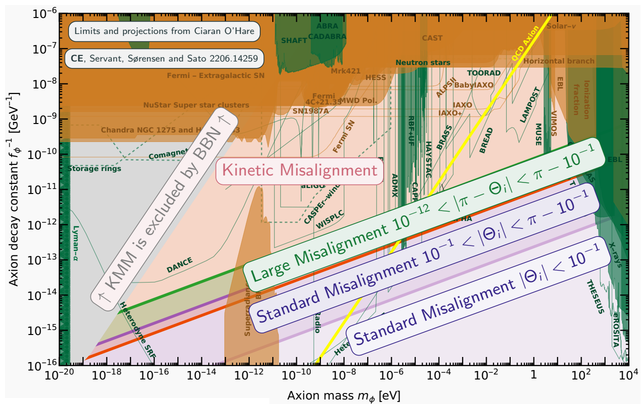
-Higgs partners cosmology

Axion cosmology & axion dark matter

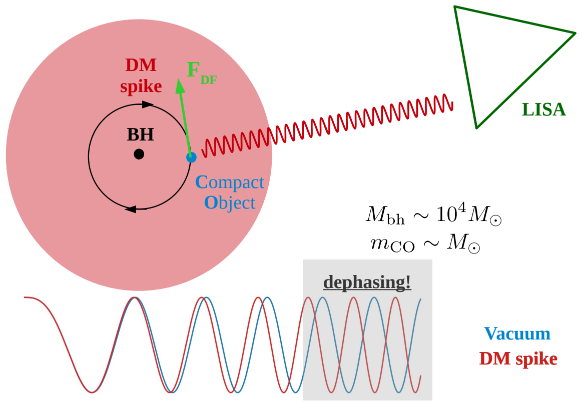
-Early cosmology of the Peccei-Quinn sector



-Axion dark matter production mechanism



-Gravitational signatures of axion dark matter



-Late cosmology of ultra-light dark matter

-Signatures of axion spectator during inflation

-Axion-Higgs cosmological interplay

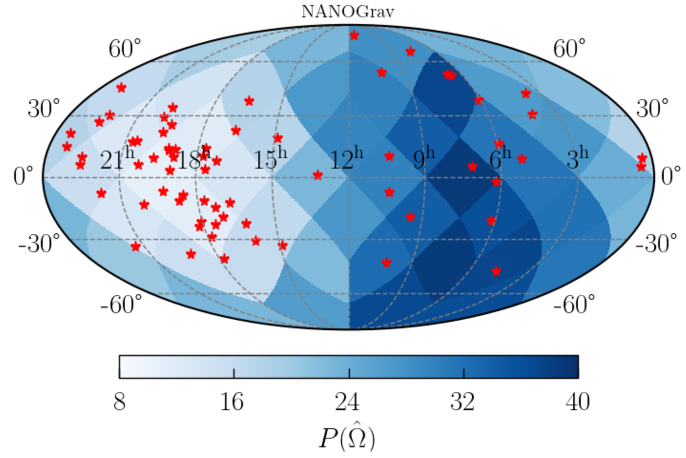
Primordial gravitational waves

-LISA Science

-Next-to-LISA space mission

-Einstein Telescope Science

-PTA Science



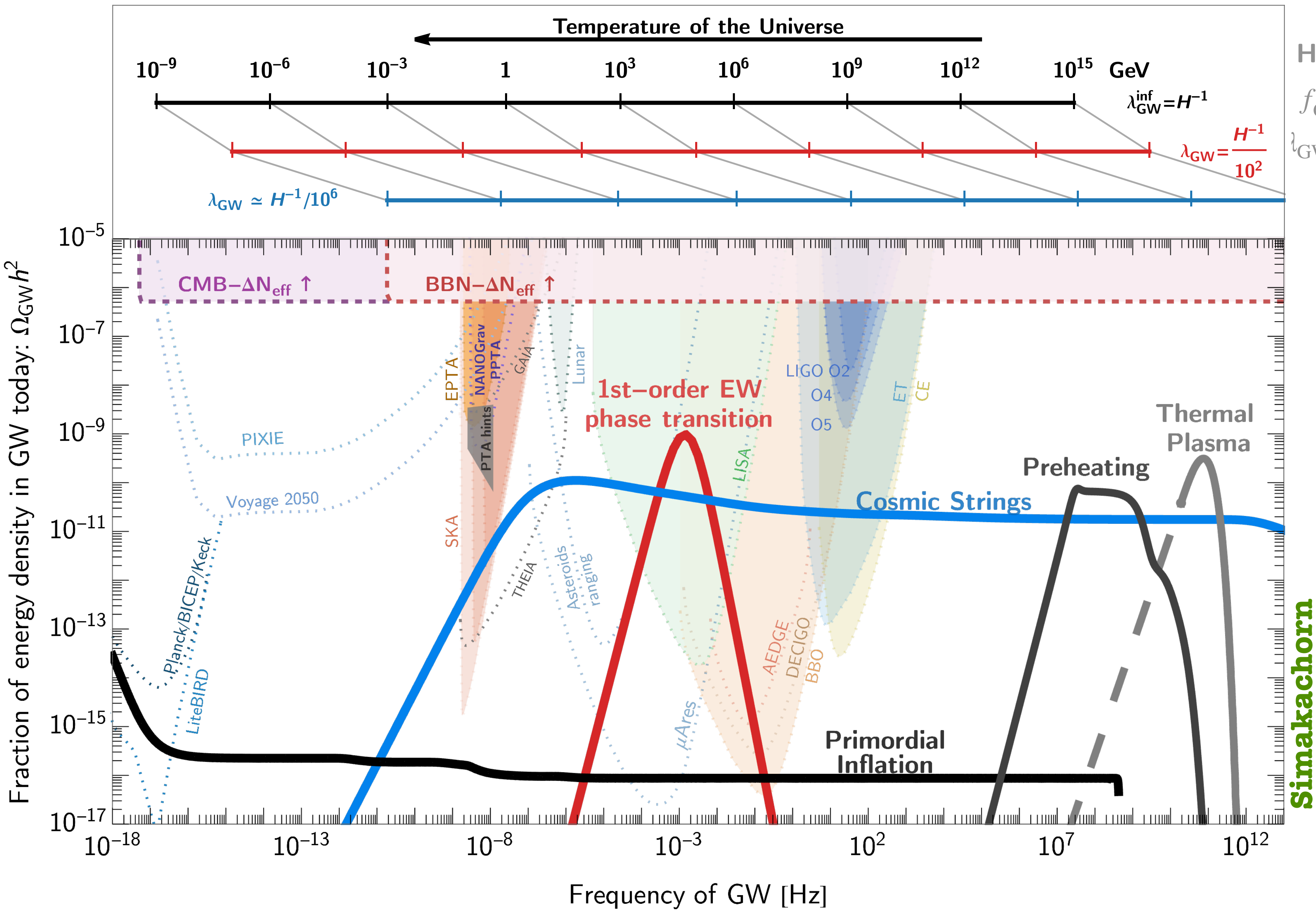
Reading the cosmological history in the GW frequency spectrum

GW frequency $f_{\mathrm{GW},0} \simeq \lambda_{\mathrm{GW}}^{-1} \left(\frac{a_{\mathrm{prod}}}{a_0} \right)$

Low-freq. lim

$f_{\mathrm{GW}}^{\min} \simeq H_0^{-1}$

$\simeq 10^{-18}$ Hz

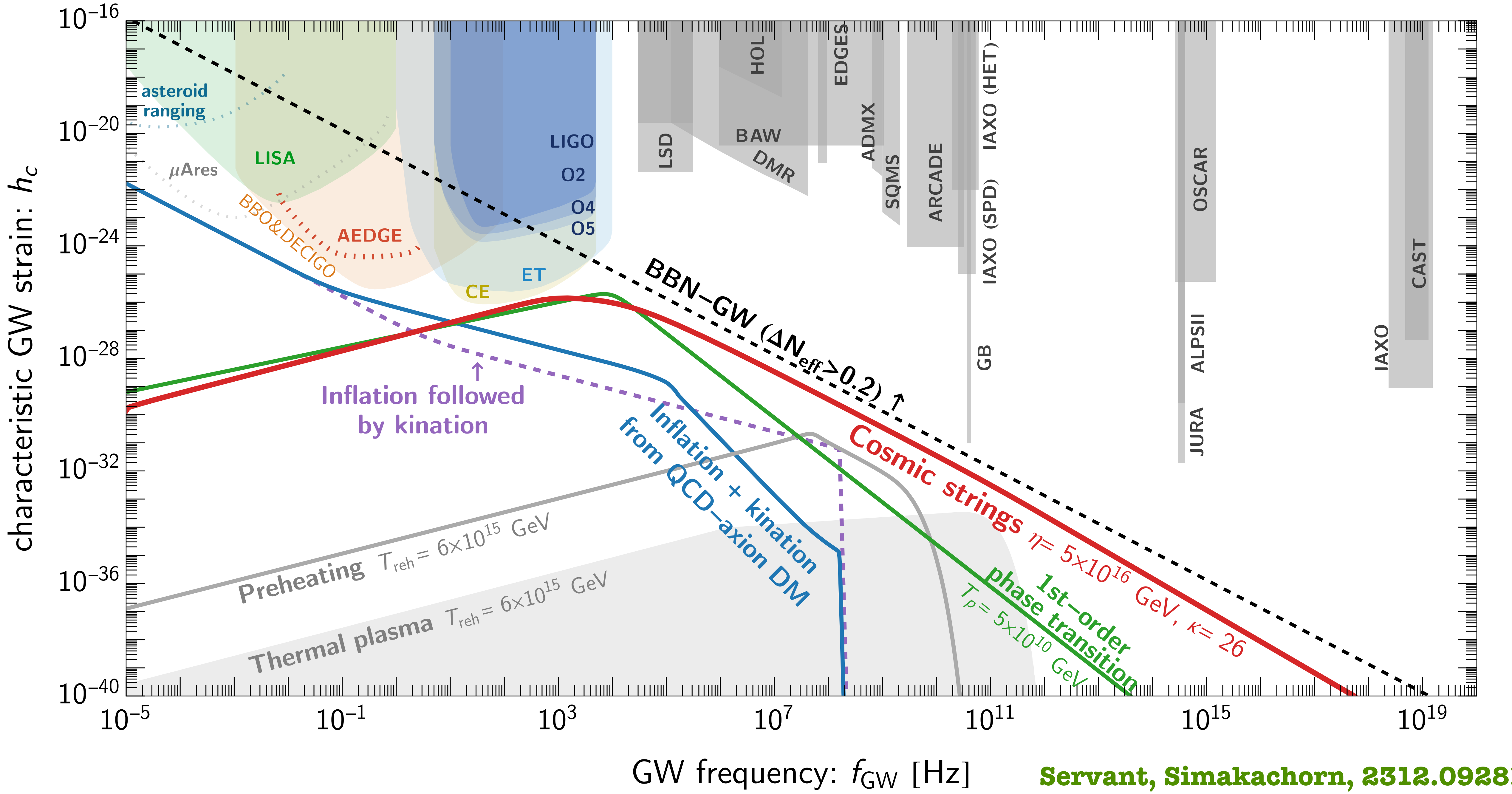


High-freq. limit

$f_{\mathrm{GW}}^{\max} \simeq 10^{13}$ Hz

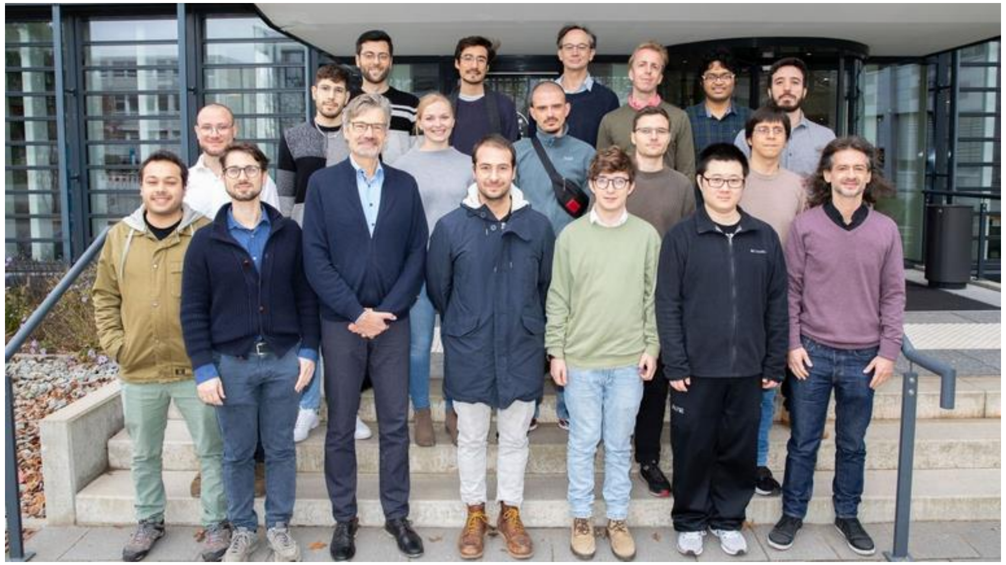
$\lambda_{\mathrm{GW}} \sim H^{-1} \sim M_{\mathrm{pl}}^{-1})$

Ultra-high-frequency primordial GW



Servant, Simakachorn, 2312.09281
PRD Editor selection

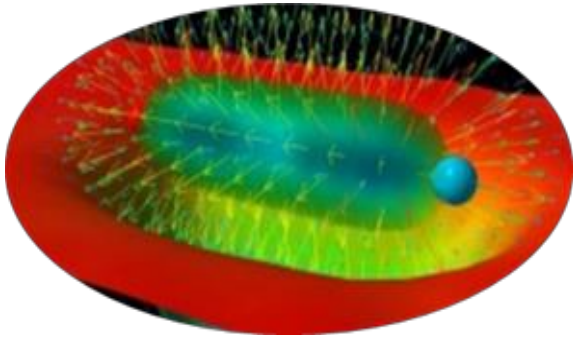
String Theory and Mathematical Physics



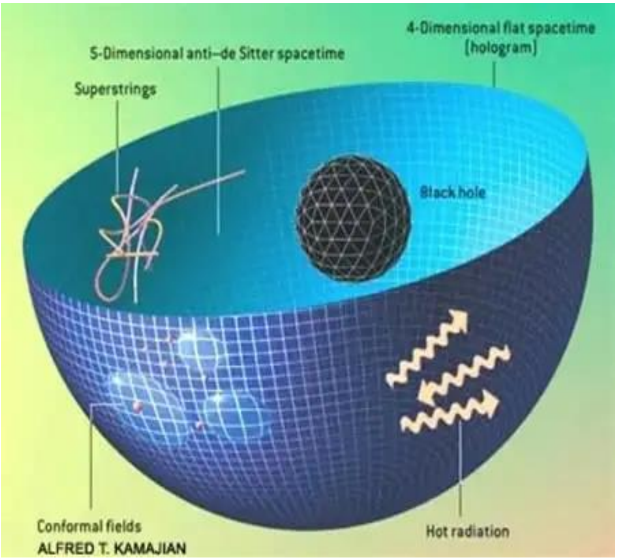
String Theory and Mathematical Physics

Scientific Goals

Main Theme: Study of Quantum Field Theory, i.p. Gauge Theories, deep in the (non-perturbative, strongly coupled) quantum regime.



- Explore space of QFTs; focus on fixed points of renormalization group
- Establish new paradigms for QFT i.p. through exactly solvable models
- Compute novel (non-local) observables at zero and finite temperature.



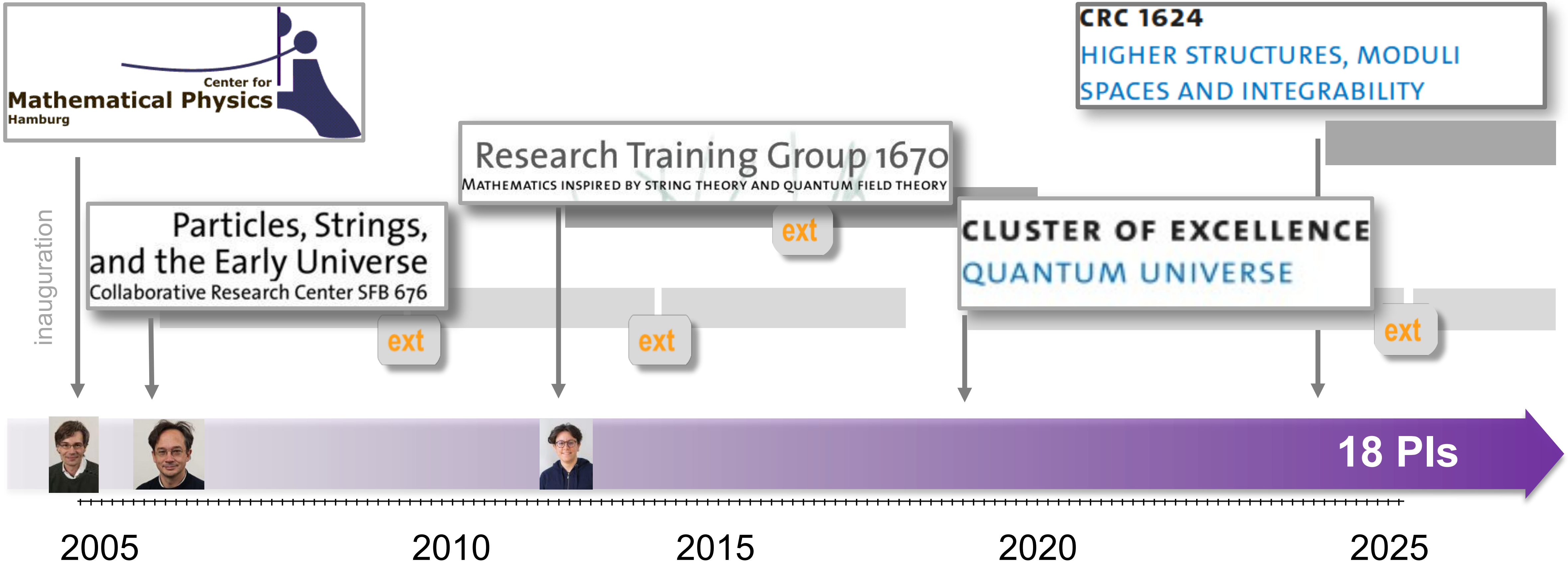
Through holography obtain new tools to study quantum gravity and in particular the quantum physics of black holes.

Mostly Fundamental Interactions a bit dark universe

String Theory and Mathematical Physics

The Center for Mathematical Physics (ZMP)

15 PIs, ~ 60 ECRs



ZMP grew into world-class center for Mathematical Physics a unique facility in Germany

CRC 1624

HIGHER STRUCTURES, MODULI SPACES AND INTEGRABILITY

- Explore space of QFTs; focus on fixed points of renormalization group
- Establish new paradigms for QFT i.p. through exactly solvable models
- Compute novel (non-local) observables at zero and finite temperature.

Moduli Spaces

Integrability

Higher Structures

String Theory and Mathematical Physics

Maintaining the unique Center

As a founding member of ZMP, DESY‘s contributions remain key to success

- Funds about 50% of the research within physics side of ZMP
- Crucial for the embedding of ZMP into physics program

e.g. Quantum Universe

During the expected runtime of the SFB 1624 (2024-2036) two of the DESY funded PIs (Schomerus, Teschner*) need replacement in order to maintain a critical physics contribution/link.

Also one PI at UHH (Arutyunov)

The Wolfgang Pauli Centre

WOLFGANG
PAULI
CENTRE

Interdisciplinary centre
for theoretical physics

The Wolfgang Pauli Centre for Theoretical Physics

Developments during PoF IV

2017 First concept paper

2018-2020 Comprehensive strategy paper by UHH/DESY

→ WPC strategy paper

2020 High level scientific evaluation of the WPC strategy

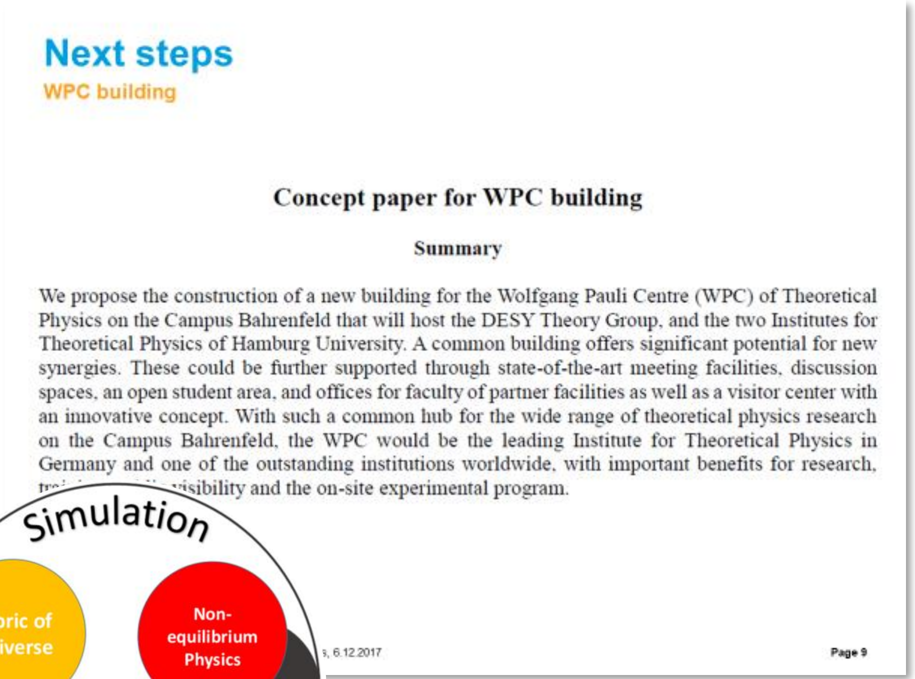
→ WPC evaluation report

2022 UHH and DESY sign cooperation agreement

Construction costs explode after Russian invasion

2023 Decision to rent space in Notkestrasse (Doppel H)

2024-2025 Planning for refurbishment of new location



Next steps

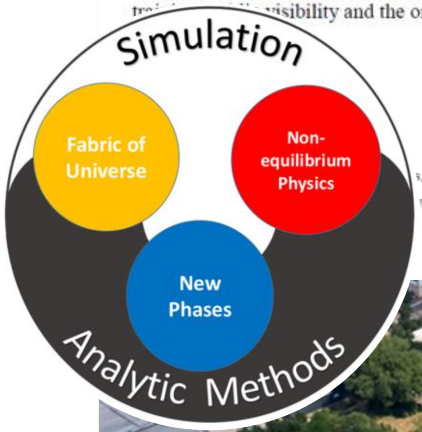
WPC building

Concept paper for WPC building

Summary

We propose the construction of a new building for the Wolfgang Pauli Centre (WPC) of Theoretical Physics on the Campus Bahrenfeld that will host the DESY Theory Group, and the two Institutes for Theoretical Physics of Hamburg University. A common building offers significant potential for new synergies. These could be further supported through state-of-the-art meeting facilities, discussion spaces, an open student area, and offices for faculty of partner facilities as well as a visitor center with an innovative concept. With such a common hub for the wide range of theoretical physics research on the Campus Bahrenfeld, the WPC would be the leading Institute for Theoretical Physics in Germany and one of the outstanding institutions worldwide, with important benefits for research, visibility and the on-site experimental program.

6.12.2017 Page 9



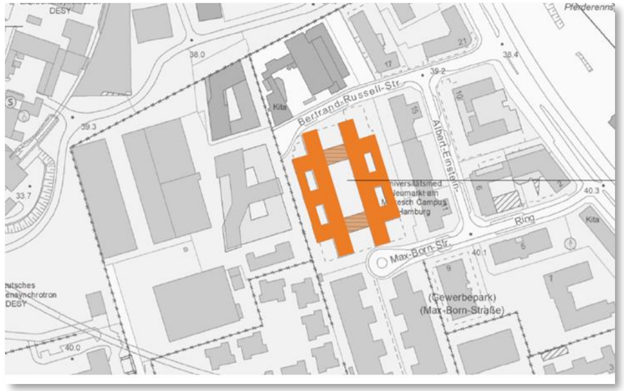
The Wolfgang Pauli Centre

WPC in Doppel-H

~ 4600 m2 to be rented and refurbished for the needs of WPC (co-working, meeting facilities..)

According to current optimal timeline, building could be fully operational in 2029.

Given issues with current office spaces on campus and promises made for PoF IV it seems crucial that plans for WPC in current form are realized w/o delay



The Wolfgang Pauli Centre

New Scientific Measures

Research hostel can host up to 6 new YIGs

extends fellow program to senior postdocs

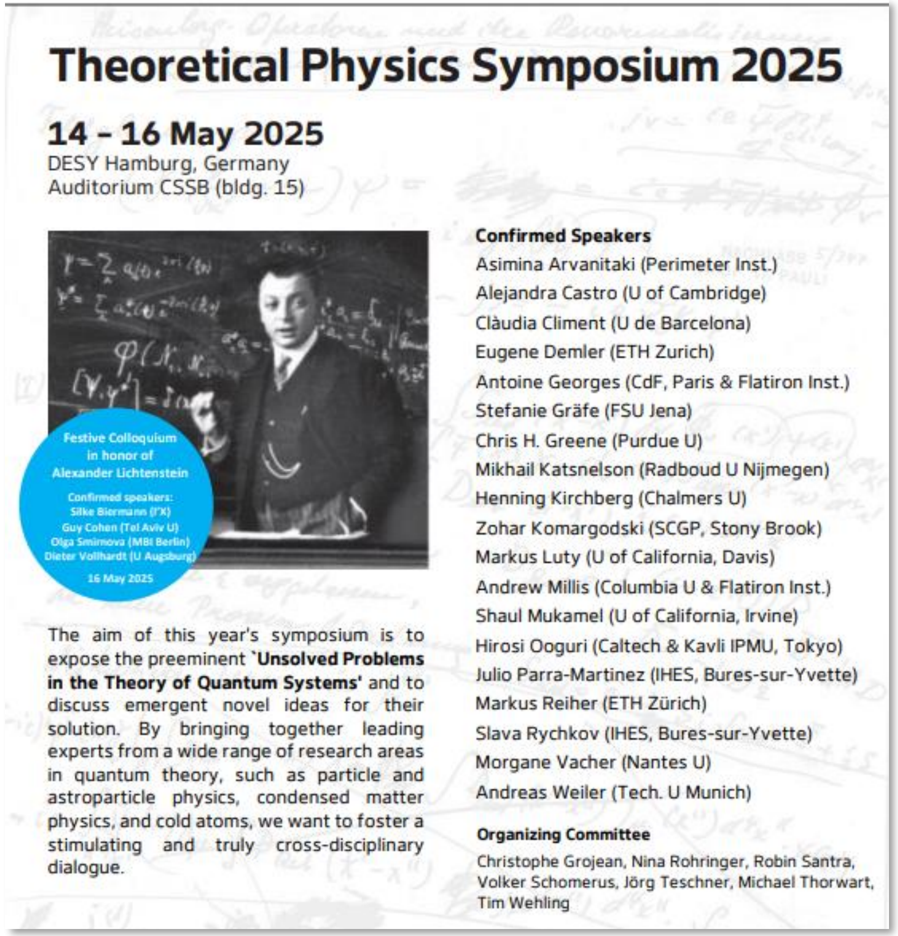
- transition to faculty positions

New thematic visitor program with ~20 visitors

Once fully operational requires ~ 400 K Euro/year

about 50 % is funded from DESY and UHH(QU)

WPC is designed as a facility for interaction across divisions, photon science & astrophysics.



Quotations from Review

``I fully endorse the WPC's visionary proposal and I am convinced that the WPC will become an internationally-recognized center of scientific excellence and a source of inspiration for the physics community and the public alike.''

Gian Giudice, Head of the Theoretical Physics Department, CERN

``The WPC is well conceived and is truly impressive in its scope and broad vision. [….] Hamburg is an ideal place for this center thanks to the well-established activity in multiple institutions in all five pillars, and to the proximity of unique experimental capabilities at DESY and the European XFEL.'' *Shaul Mukhamel, University of California, Irvine, USA*

``I wholeheartedly endorse this exciting proposal to expand and enhance the WPC.[…] I can well imagine that this initiative will raise the WPC to become Germany's leading institute for theoretical physics and a recognized leader on the world stage.'' *Robert Myers, Director, Perimeter Institute, Waterloo, Canada*

``I express my strong support for the WPC effort, and I see potential for a unique interdisciplinary environment for theoretical physics to develop, based on existing strengths in Hamburg.''

Peter Zoller, Research Director, University of Innsbruck, Austria

``Hamburg has a long tradition as a power house in theoretical physics. Now WPC brings not only the local talents together but also conducts thematic programs that bring in international leaders. In addition, it maintains proximity to experimental activities. The proposal makes perfect sense, and WPC is poised to become a formidable foe of all the other centers around the world.'' *Hitoshi Murayama, University of California, Berkeley, USA*