

# Theory and GGI

Stefania De Curtis  
INFN Firenze



**ECFA**

European Committee for Future Accelerators





THEORY & THE GALILEO GALILEI INSTITUTE  
FOR THEORETICAL PHYSICS (GGI)



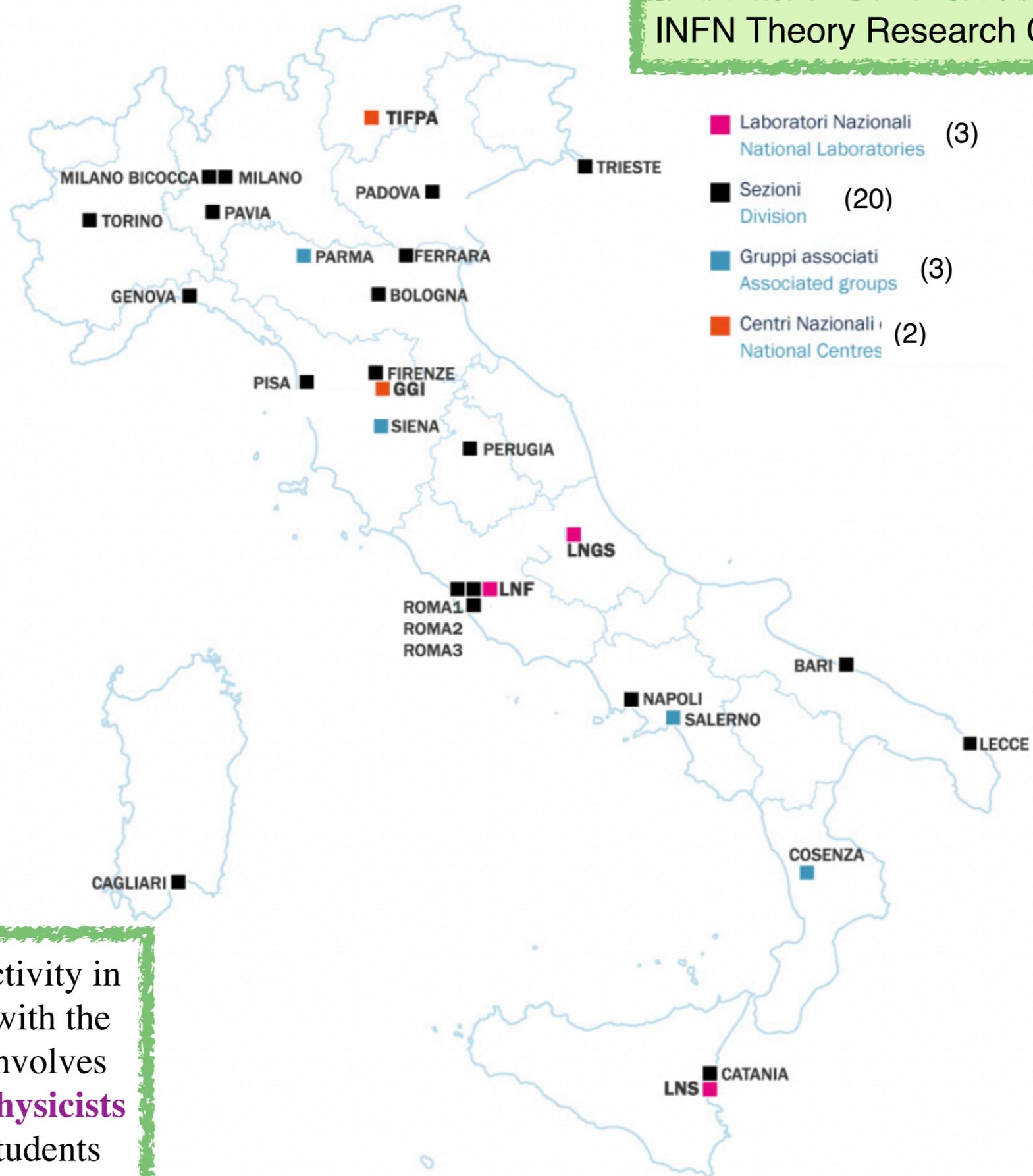
Stefania De Curtis  
INFN Firenze

and

Fulvio Piccinini  
INFN Pavia

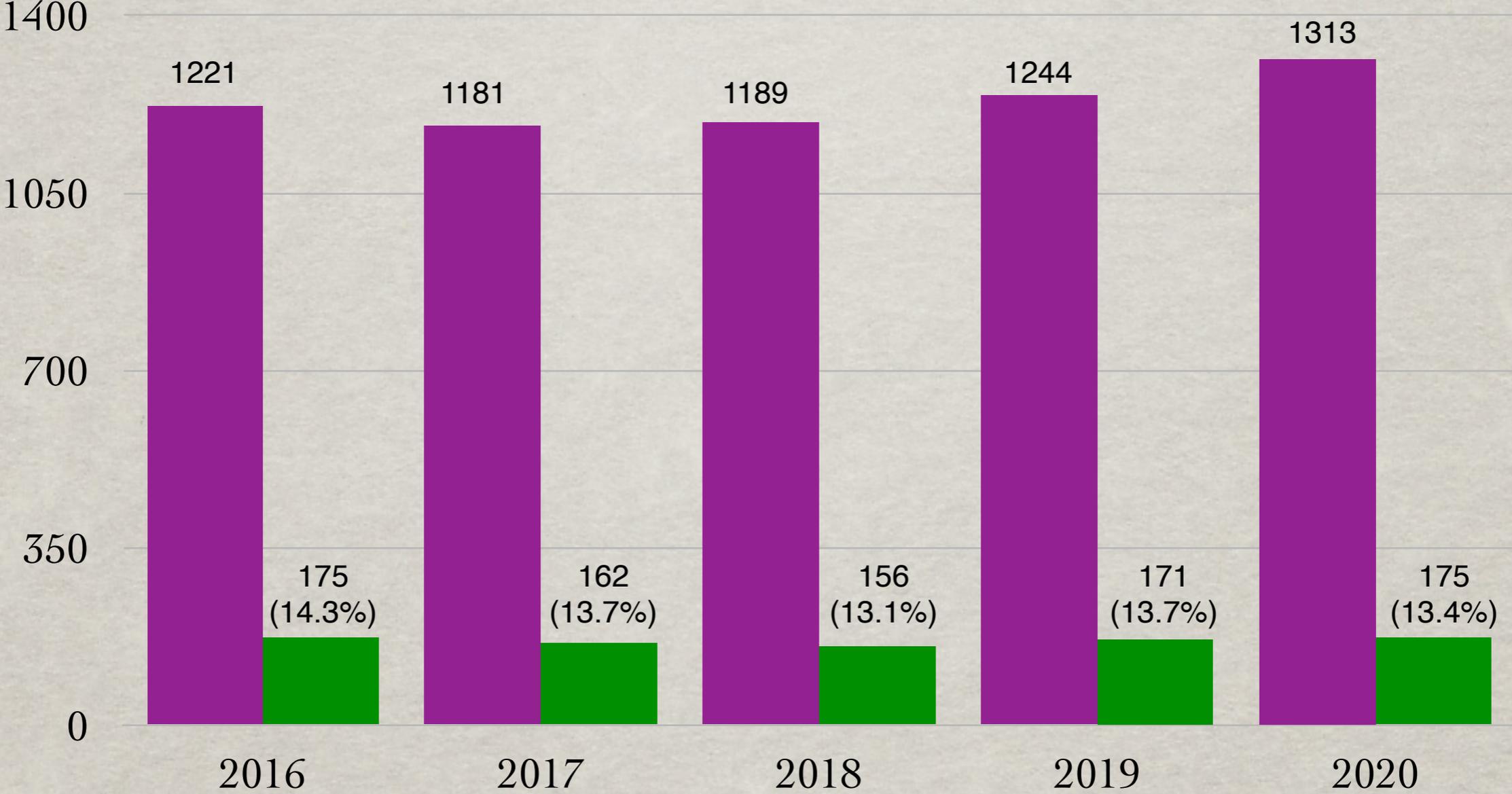
rECFA Meeting - Rome, March 4, 2022

## INFN Theory Research Community



Theory research activity in **close connection** with the **academic world** involves **more than 1300 physicists** (including PhD students and post-docs)

# Researchers in Theoretical Physics 2016 - 2020



Researchers in Theoretical Physics



Women Researchers in Theoretical Physics - less than 14%

INFN Theory Research Activities are coordinated by the CSN4 and organised in 6 areas / lines

**L1: String and Field Theory**

String Theory, M-Theory, Supergravity, D-Branes, AdS/CFT, Quantum Gravity, Lattice Gauge Theories, Confinement, Cosmology

**L2: Particle Phenomenology**

Standard Model Physics and Beyond, Collider Phenomenology, Higgs Physics, Flavour Physics

**L3: Hadron and Nuclear Physics**

Quark Gluon Plasma, Heavy Ion Collisions, Hadronic Physics, Spin Physics, Nuclear Structure

**L4: Mathematical Methods**

Foundations of Quantum Physics, Quantum Computing, Quantum Cryptography, Chaos, Integrable Models

**L5: Astroparticle Physics and Cosmology**

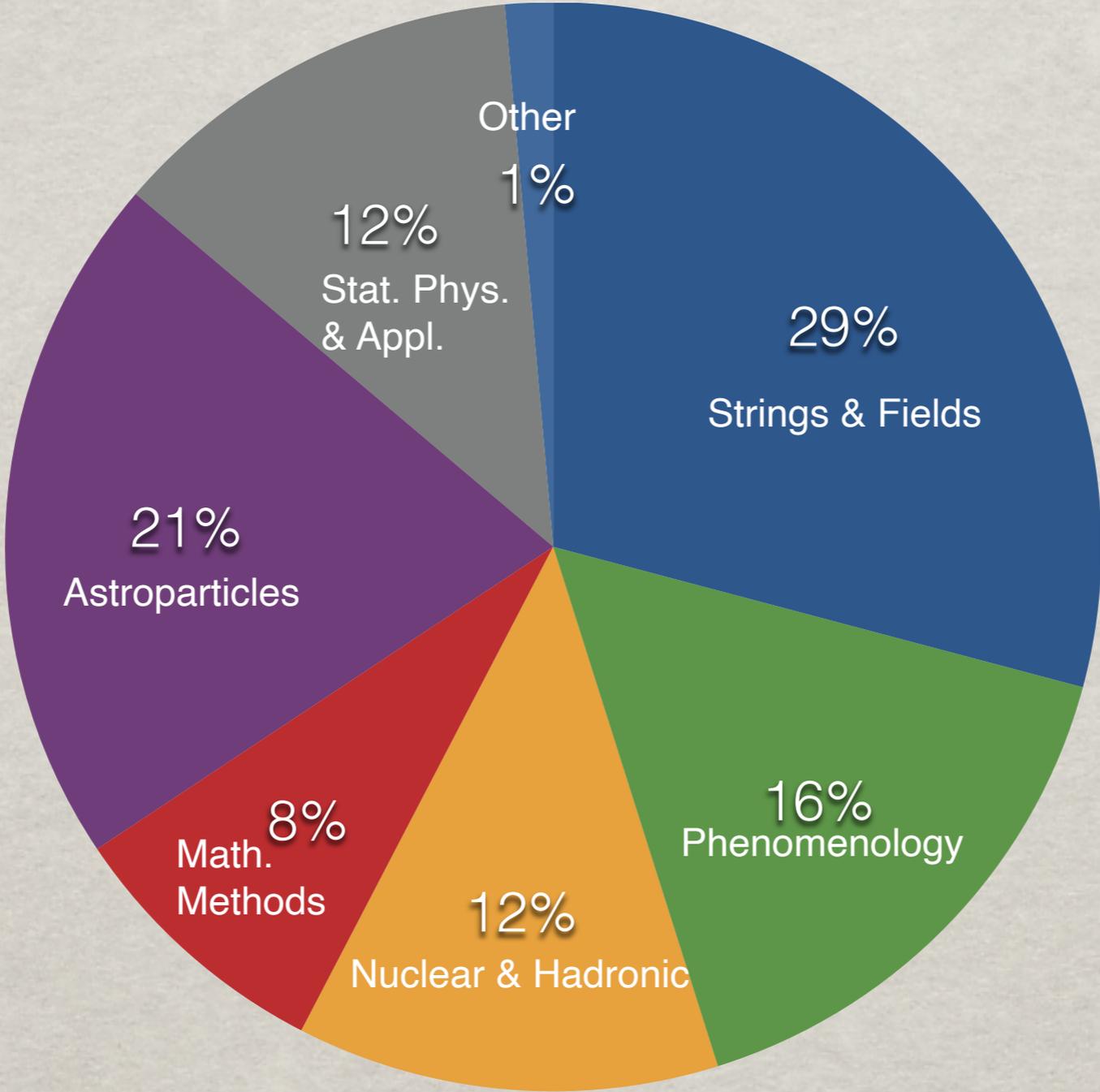
Neutrino Physics, Dark Matter, Dark Energy, Gravitational Waves, Nuclear Astrophysics, Modified Theories of Gravity

**L6: Statistical and Applied Field Theory**

Spin Glasses, Computation Biology, Condensed matter, Nanostructures, Complex Systems, Turbulence

The INFN TH Community is organised in **35 research projects** evaluated every 3 years by external referees

FTE distribution per Research Line (2020)



A large portion of the TH investigations is **deeply entangled with the experimental research** in particle, nuclear, astroparticle physics

Which are the main directions in TH Physics? Highlight of the recent scientific activities 

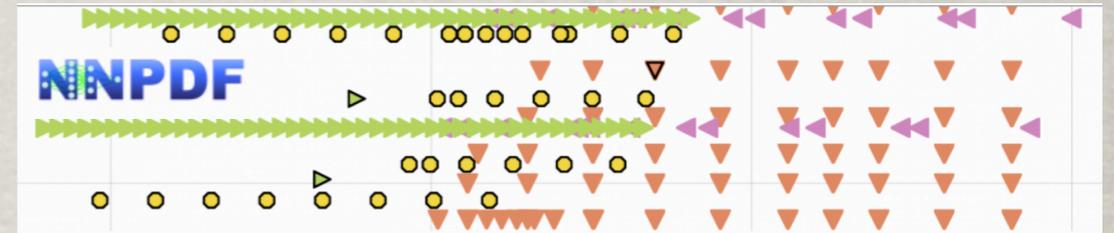
## Precision Standard Model Physics at the LHC

### ✓ SM precision calculations and Monte Carlo event generators

simulation of high energy pp collision at high momentum transfer: PDFs (**NNPDF** collaboration provides the most used ones), scattering amplitudes, final state jet substructure (also using ML techniques). MC generators like POWHEG-BOX, MG5\_aMC@NLO are the baseline for simulations at LHC

### ✓ Perturbative calculation techniques

new results on the multi-loop integral calculation with internal massive lines, analytic treatment of soft and collinear radiation

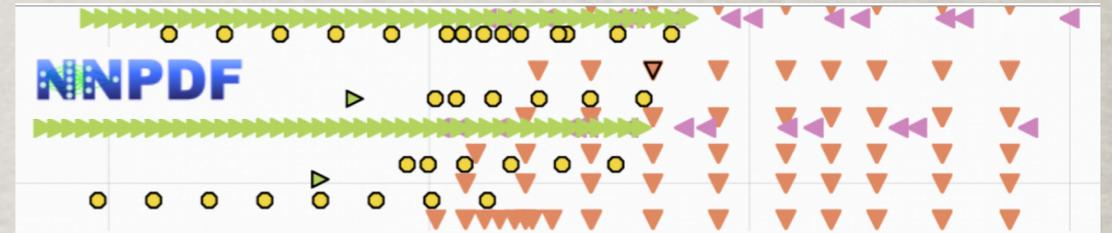


Several consultant experts for the LHC experiments and coordinators to the **CERN Physics WGs within LPCC**

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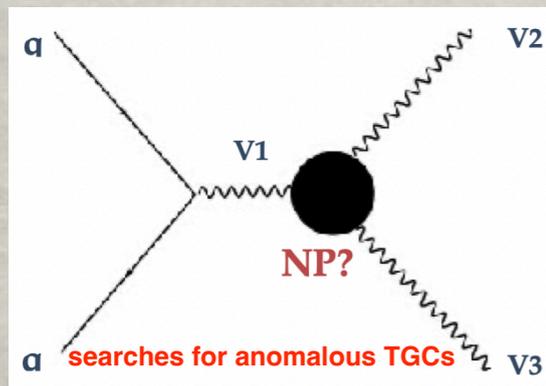


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## Physics Beyond the SM and Dark Matter



### ✓ Effective Field Theory approach to NP

extend the SM with higher-dim operators to parametrise the discrepancies in a model-independent way, systematic development of **SMEFT** in simulation tools and pheno studies to improve the sensitivity to the Wilson coeff. of dim-6 operators

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6}$$

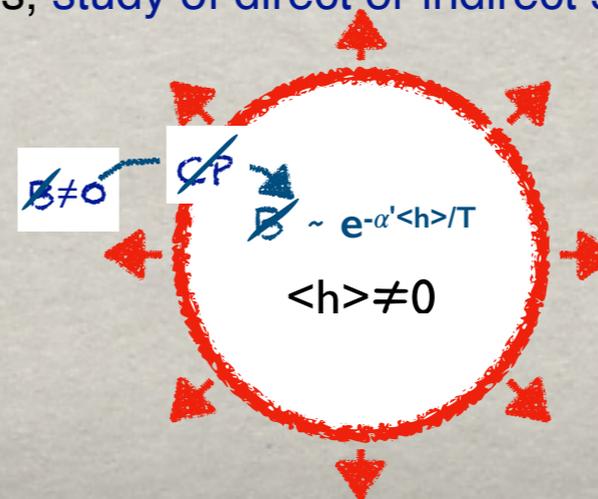
BSM       $\mathcal{O}_i^{d=6}$

### ✓ BSM investigations and connections with astroparticle and cosmology

open questions of the SM: Dark Matter, Dark Energy, matter-antimatter asymmetry ..... : several scenarios are considered: WIMPS, axions, ALPs, primordial black holes, **study of direct or indirect signatures at present and future experiments**

### ✓ Interplay of the Higgs and DM sectors

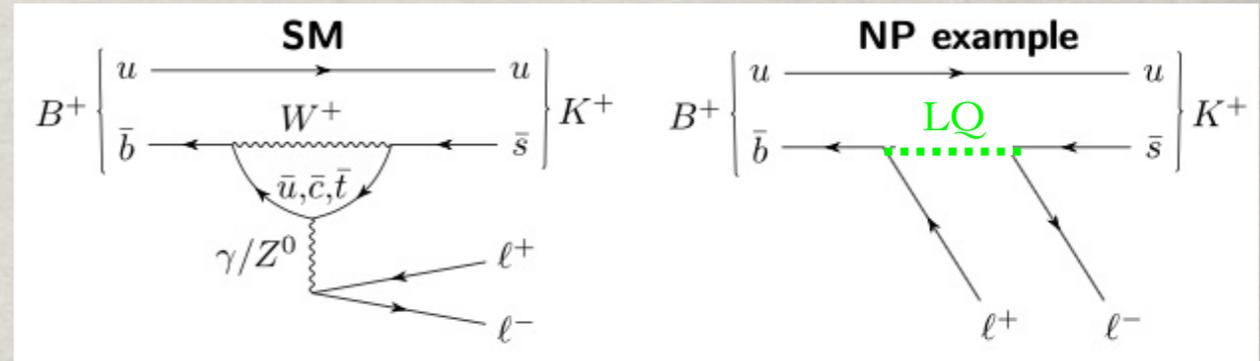
strongly interacting theories for first-order EW phase transitions, baryogenesis, composite DM, stochastic GW signals  $\Rightarrow$  **collider-cosmology synergy**



# Flavour Physics

## ✓ Flavour structure of the SM and connection to NP

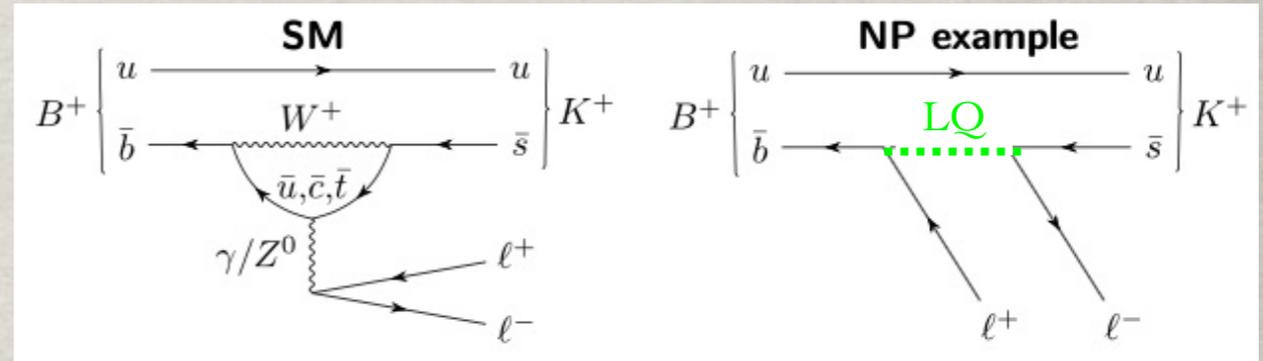
Anomalies in the decay of charmed mesons and recently in rare B-meson decays pointing to a violation of lepton flavour universality. Global analysis of LHCb data in the EFT framework. Theoretical work to understand the structure of the exotic states (tetraquarks, pentaquark)



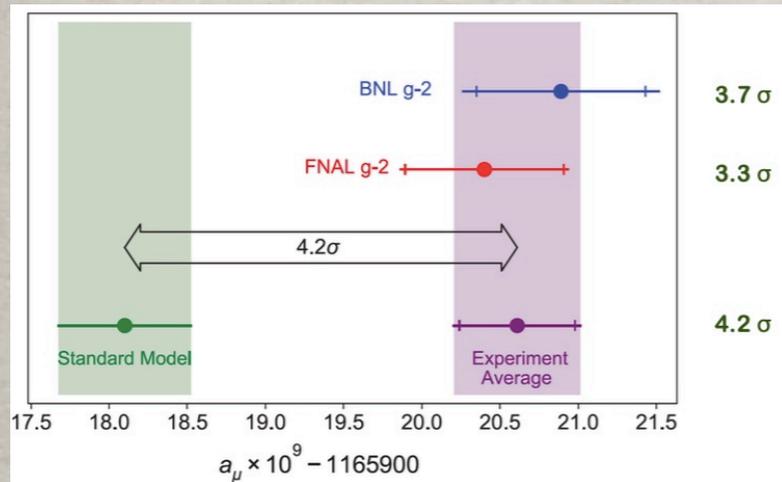
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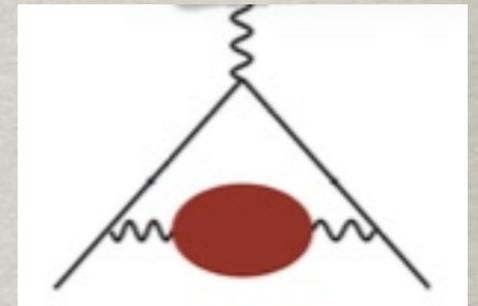


## Muon g-2 anomaly in connection with the 2021 FNAL result



## ✓ Involvements in the (g-2) Theory group for up-to-date SM predictions

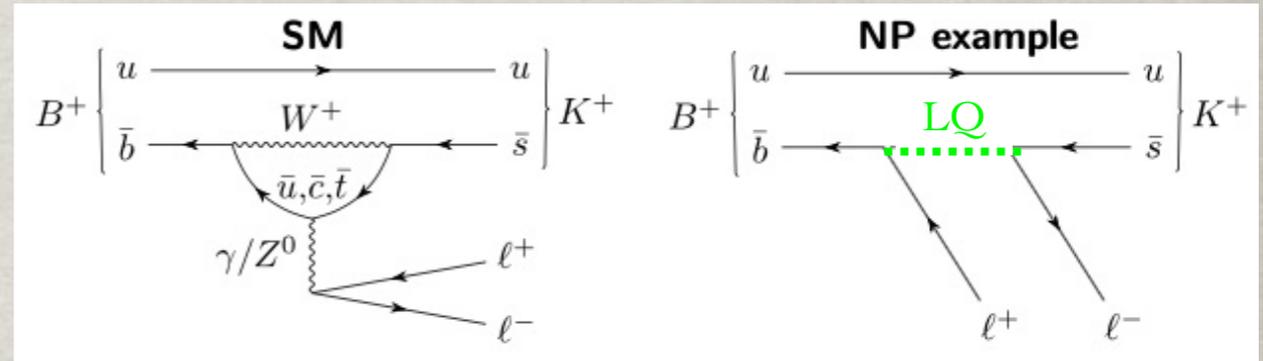
Investigations on possible BSM scenarios, Lattice QCD for ab-initio calculation of the **hadronic contribution to the photon vacuum polarisation**, very high precision study of the muon-electron scattering for the proposed MuonE experiment to reduce the main theoretical uncertainty on the **hadronic corrections**



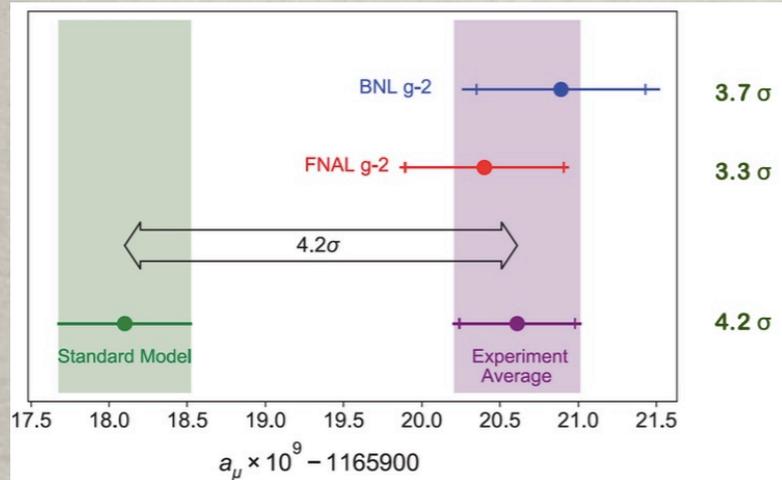
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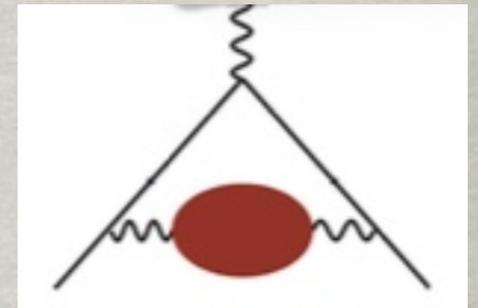


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## Future colliders

### ✓ After the ESPP Update 2020 new TH activities

Study of the physics potential of future high-energy leptonic and hadronic colliders for example for the Higgs boson after HL-LHC, new studies on the potential of a high-energy muon collider (Higgs self-interactions, BSM particle production). New event generators for leptonic machines

Many contributions of INFN TH-members to the ECFA workshops on e+e- Higgs/EW/Top factory; to (inter)national muon collider studies; to the WG's and write up of the FCC CDR's as well as of the 2018 CLIC summary report

**First FCC-Italy Workshop - Rome, March 21-22, 2022**

## Hadronic and Nuclear Physics

### ✓ Exploration of 3D structures of nucleons through Transverse Momentum Dependent and Generalised parton distributions

the TMD factorization framework includes perturbative corrections to the hard part at NNLO and the resummation of soft-gluon radiation at NNNLL, quantitative study of different methods to solve the evolution equations in QCD

### ✓ Study of the properties of strongly interacting matter at high temperature and density

developments of the theoretical tools necessary to perform realistic simulations of the dynamics of heavy ion collisions, phenomenological studies devoted to the interpretation of the measurements performed at LHC, RHIC, FAIR and NICA



### ✓ Structure and dynamics of few-body systems including light nuclei and hypernuclei, and study of the hadronic reactions of interest for astroparticle physics

Synergy with national labs activities on nuclear physics

Active participation by the hadronic physics community to the Electron Ion Collider working groups

## Astroparticle Physics and Cosmology

### ✓ Theoretical Astroparticle Physics

neutrino physics, dark matter and dark energy, axion phenomenology, baryon asymmetry of the universe, physics of high-energy cosmic and gamma rays and their connections with GWs in a multimessenger context

### ✓ Theory of Gravitational Wave Sources

Modelling gravitational wave sources via both **semi-analytical** and **numerical** methods, study of the dynamics of black hole formation, study of strong-field phenomena in modified gravity theories

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## ✓ Compact stars and dense nuclear matter

dramatic evolution after the [event of August 2017 when the merger of two compact stars was observed for the first time](#), equation of state at finite temperature for the study of mergers and supernovae explosions; study of condensates and their impact on the thermal and rotational evolution of stars, study of the effect of hyperons and delta resonances

## ✓ Inflation, Dark Matter and the Large-Scale Structure of the Universe

aspects of the standard cosmological model, its extensions, and connection with particle physics, [models of inflation in the early Universe](#), nature of dark matter and dark energy, gravitational waves and the viability of modified gravity models, cosmological information from GWs at present and future interferometers. [Numerical codes for N-body simulations including ML techniques](#)

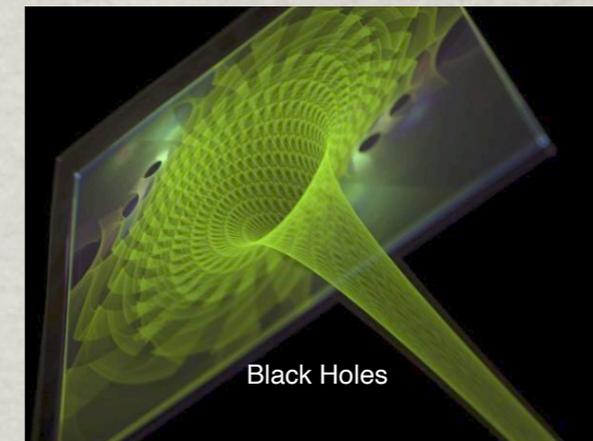


Many contributions to the 2020 ESPPU, including neutrino, non-accelerator DM, ALPs, data analysis and activity with working groups within several experimental collaborations e.g. PLANCK (in the past), VIRGO, Einstein Telescope, EUCLID, LISA, LiteBIRD, GAPS



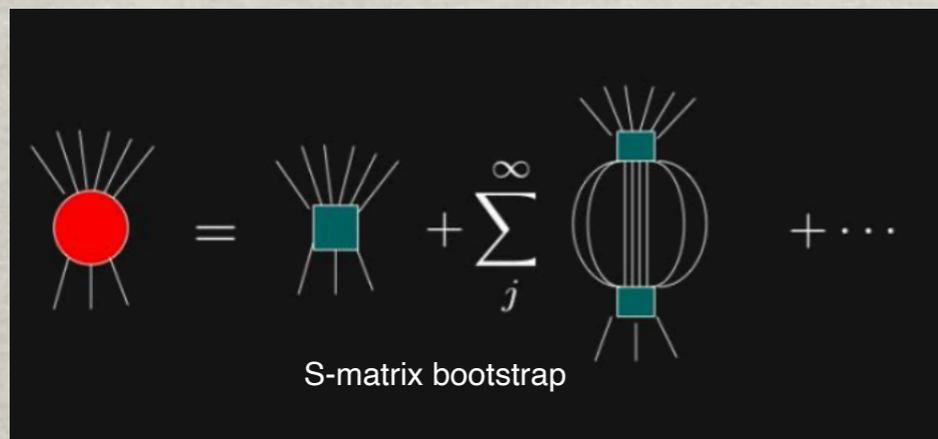
## ✓ Fundamental aspects of Gravity and Cosmology

modification of QFT in curved spacetimes, physical aspects of Black Holes, effective theory of gravity for phenomena at astro and cosmo scales not explained by GR



## ✓ Strings and Gauge Field Theory

basic principles behind quantum theories of gravity, models for unification of fundamental interactions, non perturbative effects in QFT, AdS/CFT correspondence and holography, string phenomenology and string cosmology, bootstrap to construct a bridge between weak and strong coupling behaviour

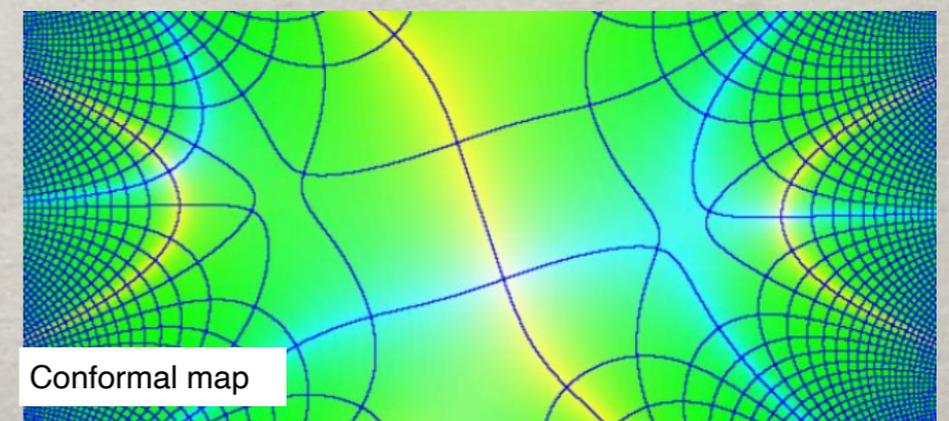


## ✓ Non-Perturbative Quantum Chromodynamics

large distance properties of QCD investigated with lattice, functional integral techniques and chiral effective theories, new results on color confinement and flux tubes, topological properties of Y-M theories

## ✓ Statistical Field Theory

exactly solvable models in 2-dim: conformal field theories, integrable systems, statistical properties of quantum systems out-of-equilibrium, entanglement in quantum extended systems, new phases of matter with topological features



## Mathematical Methods

### ✓ Mathematical methods of non linear physics

Classification/construction of integrable systems from physical models and by algebraic/geometric methods

### ✓ Dynamics and non equilibrium states of complex systems

Non-linear effects, disorder and non standard topologies at the origin of anomalous transport properties and complex collective dynamical regimes

### ✓ Geometry and Symmetry in Quantum Field Theory

Quantum spacetimes, Quantum group symmetries, Non-commutative geometry, Algebraic and Topological QFT, Geometrical methods in statistical physics and complex systems

### ✓ Quantum Systems: entanglement, simulations, information

Investigation of typical quantum mechanical effects and phenomena via entanglement and other quantum correlations; quantum simulation; quantum control

### ✓ Foundations and applications of quantum physics, quantum computation and quantum algorithms

open quantum systems, quantum/gravity interplay, axiomatic approaches in QM, QFT and QG, theoretical inputs for new experiments, towards quantum technologies



Synergy with new INFN projects on quantum technologies



Participation to the Superconducting Quantum Materials & Systems Center of Fermilab and U.S. Department of Energy

## Statistical and Applied Field Theory

### ✓ Equilibrium and non-equilibrium statistical mechanics of disordered systems

collective excitations, transport phenomena and other many-body properties of low dimensional systems

### ✓ Computational Biophysics

study of the properties of biological matter at the system-level by using quantitative methods of theoretical physics, construction of predictive, testable models by using methods and concepts from statistical mechanics and field theory, supported by advanced computer simulations

**Sibylla Biotech** is a spin-off of INFN (one of the founders is from TIFPA)

### ✓ Dynamics and statistics of complex networks .....

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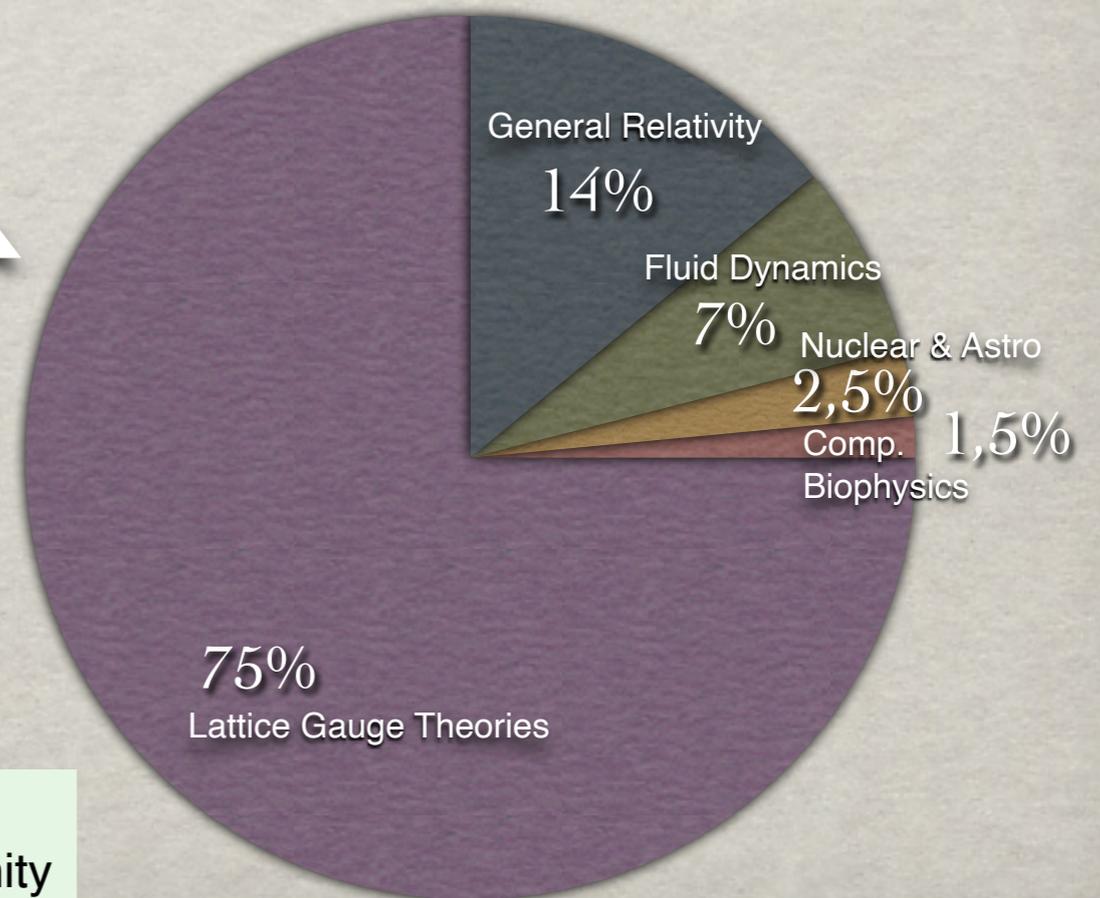
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## Computing @ INFN - Theory

a common denominator to different research area

**needs are increasing !**

	2018	2019	2020
LGT: hadron physics	54	108	180
LGT: QGP and BSM	207	432	648
LGT: flavor physics	117	234	387
Colliders phenomenology	1	2	3
General relativity	142	182	227
Cosmology and Astroparticle physics	3	4	6
Nuclear Theory	18	27	36
Fluid Dynamics	50	80	110
Quantitative Biology	9	18	27
Disordered systems	4	6	8
Condensed matter	2	4	6
<b>Grand Total (Mcore-h)</b>	<b>607</b>	<b>1097</b>	<b>1638</b>
<b>Grand Total (Eq. Pflops)</b>	<b>4.6</b>	<b>8.4</b>	<b>12.5</b>



INFN has been assigned the funding of a pre-exascale machine within EuroHPC, an opportunity also for the INFN-Theory Community

## INFN Post-Doc Positions - Theory

✓ Action due to the pandemics - additional post-doc positions with the residual budget

— 2022 total of 34 fellows in place — 2023 total of 35 fellows in place

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✓ Milla Baldo Ceolin Prize  
Women in Theoretical Physics

to the best Master thesis in theoretical physics by women students in Italian universities  
(action aimed at improving the gender balance in Th-physics)



the ceremony held at the GGI

**THE GALILEO GALILEI INSTITUTE  
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**ARCETRI - FIRENZE**



**SIMONS FOUNDATION**

# THE GALILEO GALILEI INSTITUTE FOR THEORETICAL PHYSICS

ARCETRI - FIRENZE

The GGI is a research hub dedicated to organising and hosting **long-term (6-8 weeks) programs** and **(2-3 weeks) PhD schools** to foster breakthroughs in the fundamental understanding of the universe



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Since its birth, in 2005, the GGI has achieved an impressive record of high-level activities and, in 2018, it has been established as a **National Centre for Advanced Studies of INFN**



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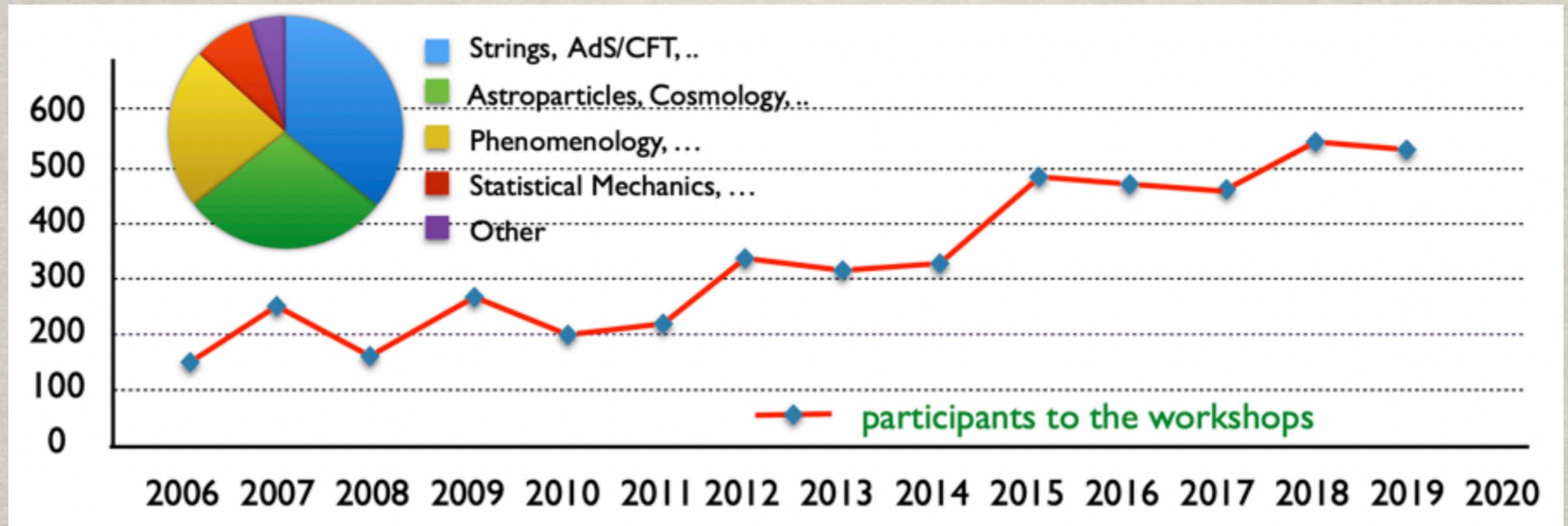
Invited speakers and other contributors to the GGI activities are **equally considered** regardless of **gender, nationality and ethnic or social origin**. The GGI actively welcomes interactions among the participants, providing a comfortable and professional work environment



SIMONS FOUNDATION



To date, **44 workshops** have been held at the GGI, with an ever-increasing number of participants, covering all the areas of theoretical physics that are of interest to the INFN and **encouraging links between the various topics** and the scientific interaction of researchers with different skills



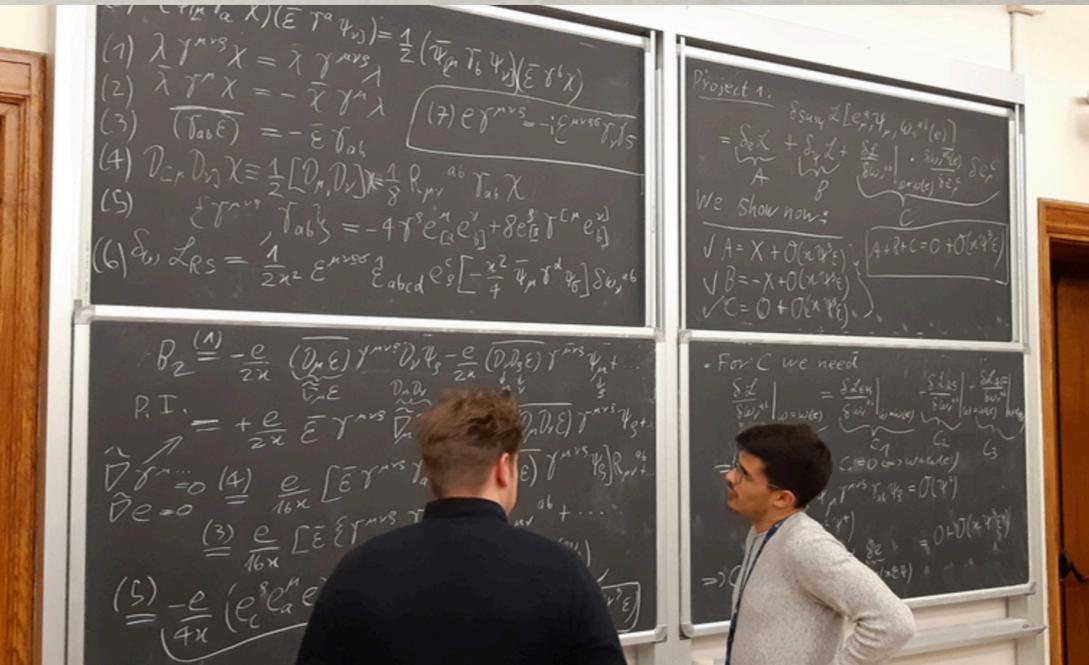
Contacts with experimental research associated with the subject of the workshops are particularly encouraged thus fostering the **synergy between the theoretical and experimental communities**

The GGI is the ideal place for “contamination” between the various areas of research. Ex: the forthcoming workshop on **Machine Learning** (Aug. 22 - Sept. 30, 2022) will deal with applications to a wide variety of topics from high energy physics, astrophysics, cosmology to condensed matter and statistical physics

# PhD Schools @ GGI

Since 2014 the GGI organises also **5 international schools for PhD students** every year. These include advanced lectures in:

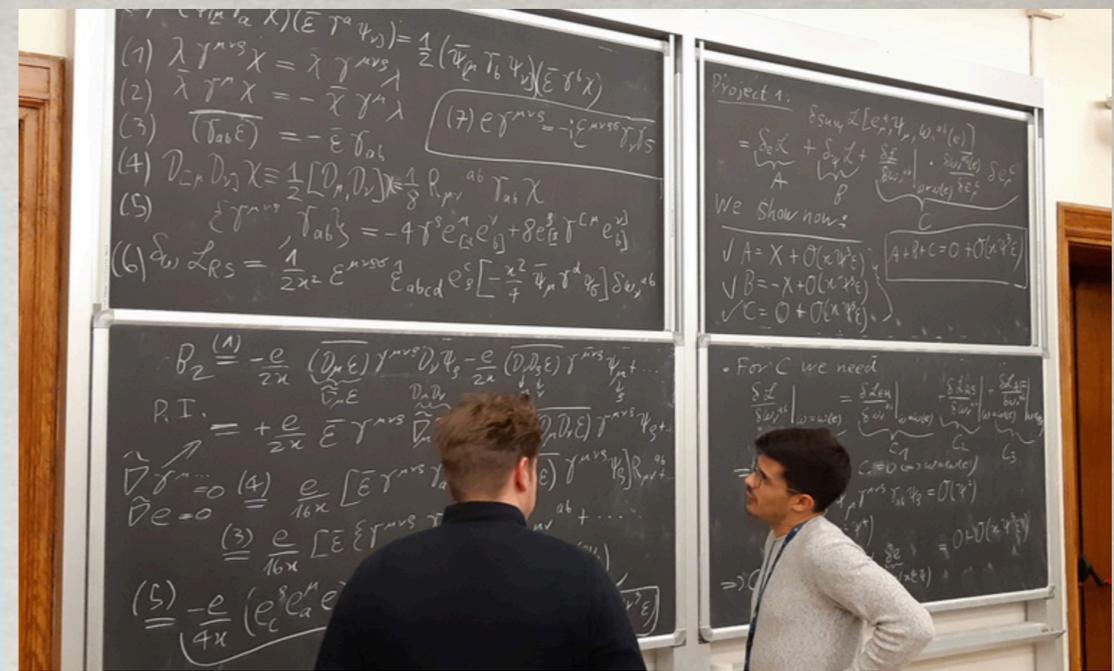
- Field and string theory
- Theory of fundamental interactions
- Statistical field theory
- Nuclear and hadronic physics
- Astro-particle physics



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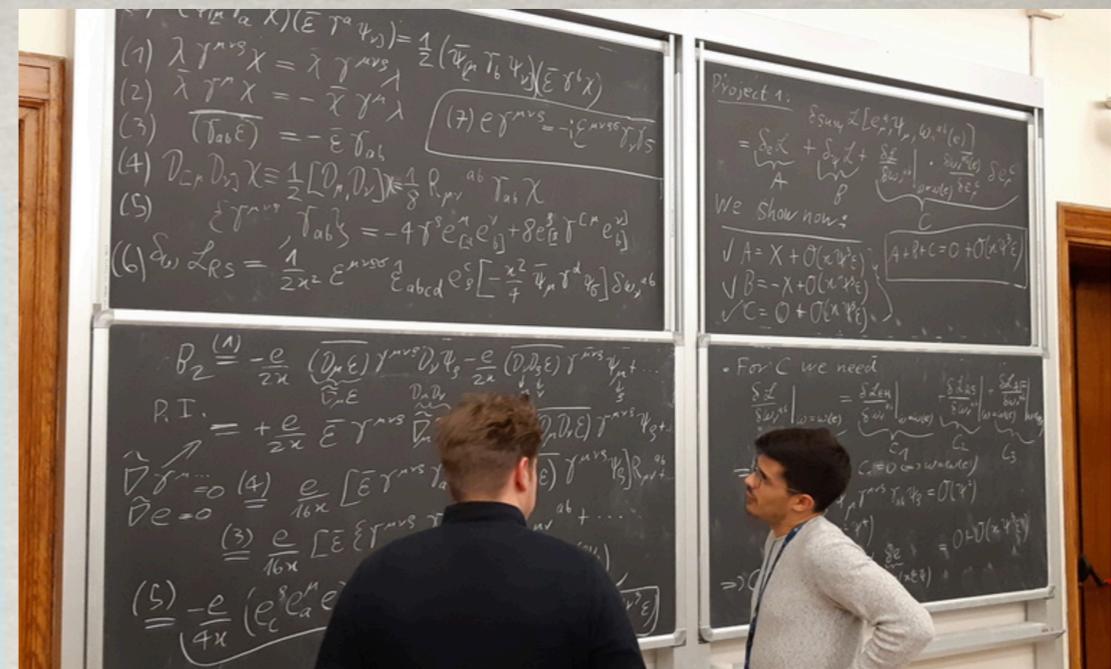
~60 students are selected for each school (approximately 40% foreigners) organised over 2-3 weeks of full immersion with lectures at the blackboard, and discussions in a very informal and stimulating atmosphere



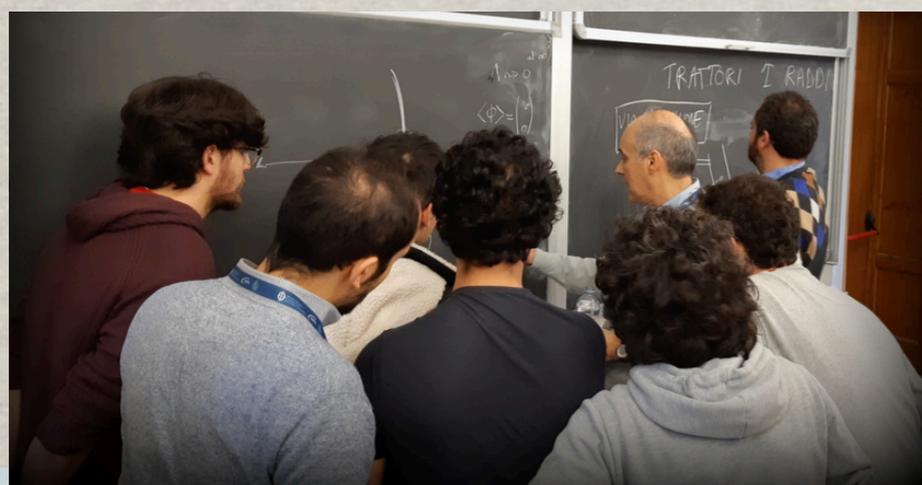
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All the lectures are video-recorded and available **an archive of absolute value for young researchers!**

Eight Lectures on Exotic Hadrons  
 Luciano Maiani  
 CERN, Geneva, Switzerland

Galileo Galilei Institute, Firenze, february 21-25, 2022

**Summary**

1. The overall panorama
2. Constituent Quark Model and masses of conventional mesons and baryons.
3. Light and Heavy Tetraquarks. First comparison with hadron molecules.
4. Tetraquarks and the EightFold Way.
5.  $X(3872)$  and its missing partners.
6. Born-Oppenheimer approximation for double charm baryons and tetraquarks.
7. Multiquark states in  $N$  colours, in the limit  $N \rightarrow \infty$ .
8. Tetraquarks vs. molecules: the Weinberg criterium for  $X(3872)$  and the double charm  $\mathcal{T}_{cc}^+(3875)$ .

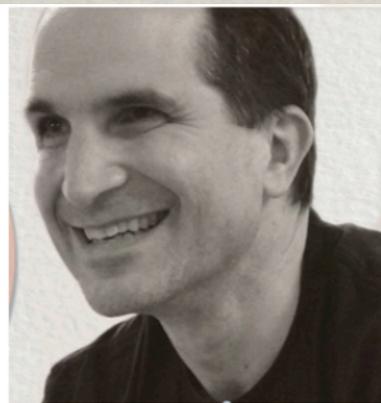
Feb. 21-25, 2022 6:39 / 1:48:19 L. Maiani, Exotic Hadrons. 1

## The INFN Galileo Galilei Medal Award

Established in 2018, it is assigned every two years to **one or more scientists** who, in the 25 years before the date of the award, have achieved **outstanding results in theoretical physics**

The first recipient was **Juan Martin Maldacena** for *"his ground-breaking ideas in theoretical physics, and especially for the discovery of duality between gravity and ordinary quantum field theory, with far-reaching implications"*

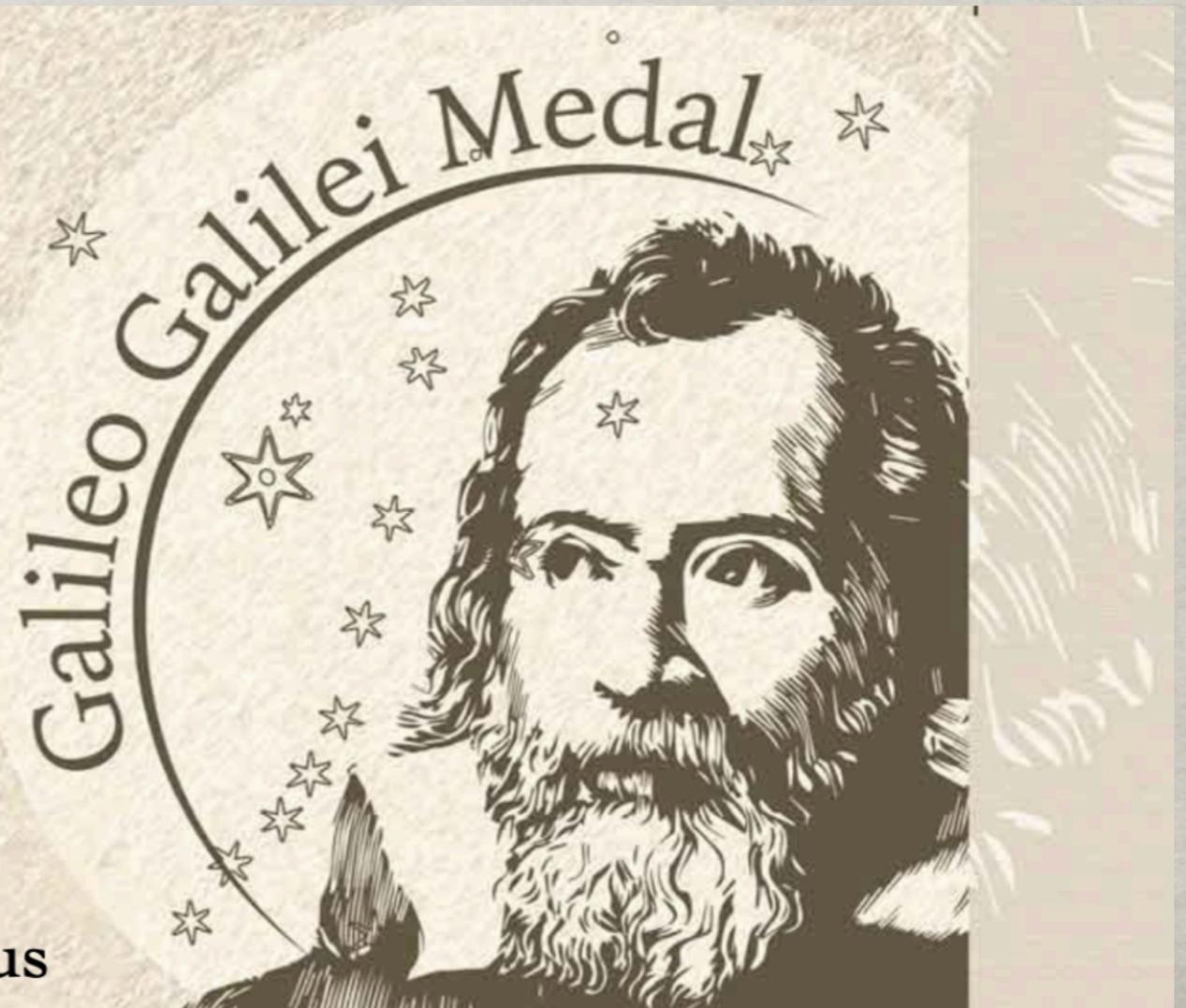
The 2021 Galileo Galilei Medal went to **Alessandra Buonanno, Thibault Damour** and **Frans Pretorius** for *"the fundamental understanding of sources of gravitational radiation by complementary analytic and numerical techniques, enabling predictions that have been confirmed by gravitational wave observations and are now key tools in this new branch of astronomy"*



2019 Maldacena



2021 Buonanno, Damour, Pretorius





GGI SEMINARS



# GGI TEA BREAKS SPECIAL EDITION



## STEVEN WEINBERG AND HIS LEGACY

DATE  
19-01-2022, 3PM CET

ABSTRACT

THE GALILEO GALILEI INSTITUTE CELEBRATES STEVEN WEINBERG, A FOUNDING FATHER OF THE THEORY OF FUNDAMENTAL INTERACTIONS AND ONE OF THE GREATEST THEORETICAL PHYSICISTS OF THE LAST CENTURY, WITH A SPECIAL EDITION OF THE GGI TEA BREAKS.

RICCARDO BARBIERI (SNS, PISA)

THE STANDARD MODEL OF PARTICLE PHYSICS

HOWARD M. GEORGI (HARVARD UNIVERSITY)

EFFECTIVE FIELD THEORIES AND THE LOW-ENERGY LIMIT OF STRONG INTERACTIONS

EDWARD WITTEN (IAS PRINCETON)

ON THE ROLE AND MEANING OF SYMMETRIES IN FIELD THEORY

NIMA ARKANI-HAMED (IAS PRINCETON)

GRAVITY AS AN EFFECTIVE FIELD THEORY AND THE COSMOLOGICAL CONSTANT

### ORGANIZING COMMITTEE

ROBERTO CONTINO  
(SAPIENZA U. & INFN ROME 1)

GUIDO D'AMICO  
(UNIV. & INFN PARMA)

FRANCESCO D'ERAMO  
(UNIV. & INFN PADOVA)

DAVID MARZOCCA  
(INFN TRIESTE)

DOMENICO ORLANDO  
(INFN TORINO)

ALESSANDRO SFONDRINI  
(UNIV. & INFN PADOVA)

ANDREA TESI  
(INFN FIRENZE)

RICCARDO TORRE  
(INFN GENOVA)

VALENTINA FORINI  
(LONDON CITY U. & HUMBOLDT U. BERLIN)

ENRICO TRINCHERINI  
(SNS PISA)



The "**GGI Tea Breaks**" is a web-seminar series on the theory of fundamental interactions covering a wide spectrum of arguments

It includes **Theory-Colloquia** given by established experts as well as **Focus -Meetings** on special topics given by two or more scientists with different expertise

The aim is to discuss the open questions in fundamental physics while offering to researchers and PhD students an introduction to some of the hottest topics in the field. Ample space to questions and discussion is allocated at the end of the seminars

The special edition on "**Steven Weinberg and his legacy**" has more than 5,000 visualisation on YouTube

The hill of Arcetri, where the GGI is located, was designated a **Historic Site** by the **EPS**, the European Physical Society, on 17 May 2013

In 1921 the Institute of Physics was opened and Antonio Garbasso succeeded in setting up a school, known as the **school of Arcetri**

It was here that Enrico Fermi wrote his fundamental article on the statistics of half-integer spin particles, which are now known as fermions

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**The GGI wants to keep the school of Arcetri alive**



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2019 - In the cloister of Arcetri during the Workshop "Next Frontiers in the search for Dark Matter"