VERSO LA EUROPEAN STRATEGY FOR PARTICLE PHYSICS
CSN4 A FERRARA

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PER GLI ASSOCIATI ALLA CSN4 INFN

INFN, sezione di Ferrara

6 novembre 2024

Dal sito web dell’INFN:

“La CSN4 coordina le ricerche in fisica teorica, che sviluppano ipotesi, modelli e teorie fisiche per spiegare i risultati sperimentali già acquisiti e aprire nuovi scenari per la fisica del futuro.
[…]
Tali studi teorici si avvalgono, da un lato dei risultati sperimentali prodotti dagli acceleratori di particelle e dagli esperimenti di fisica astroparticellare, e dall'altro di metodi matematici e tecniche formali e numeriche.”

https://home.infn.it/it/csn4-fisica-teorica

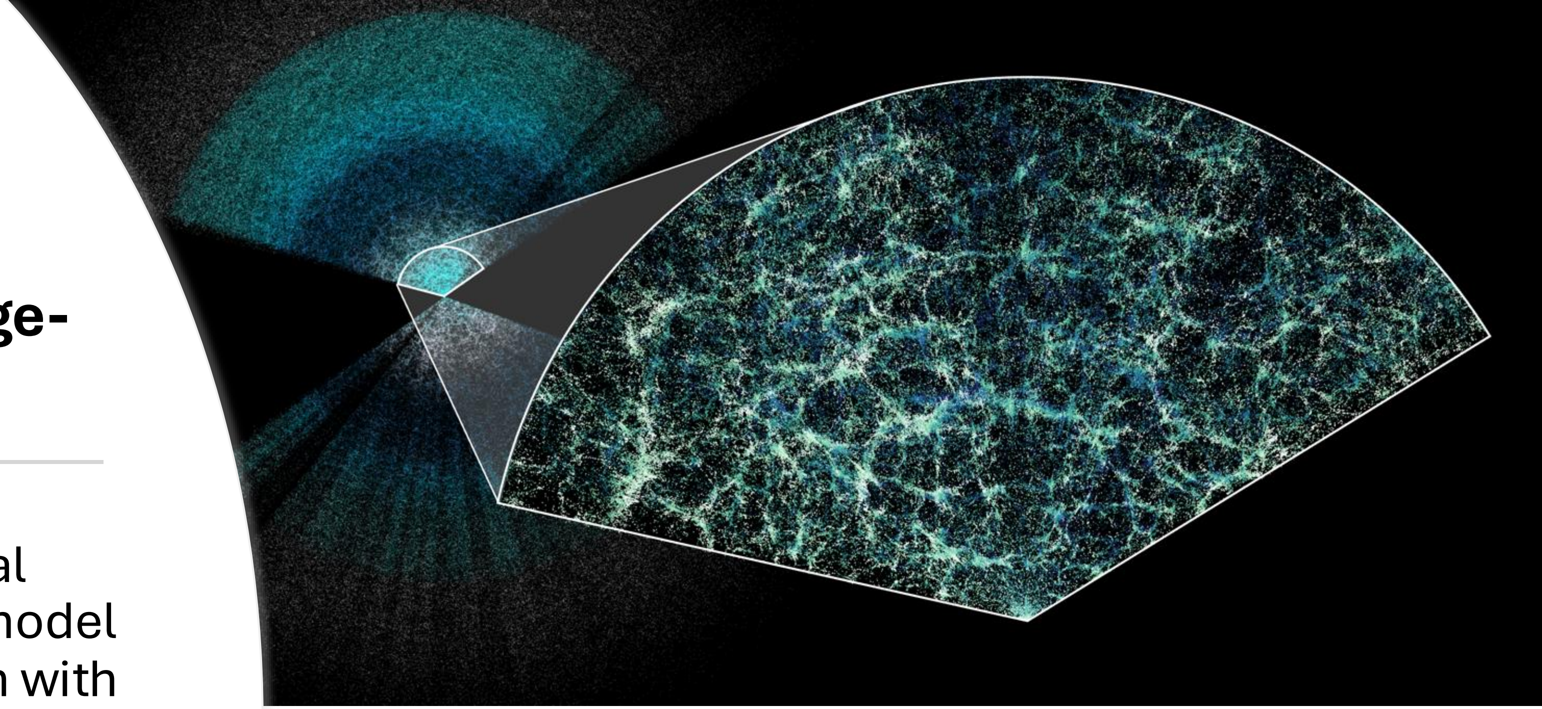
L’attività di CSN4 si articola in sigle nazionali chiamate *iniziative specifiche*.

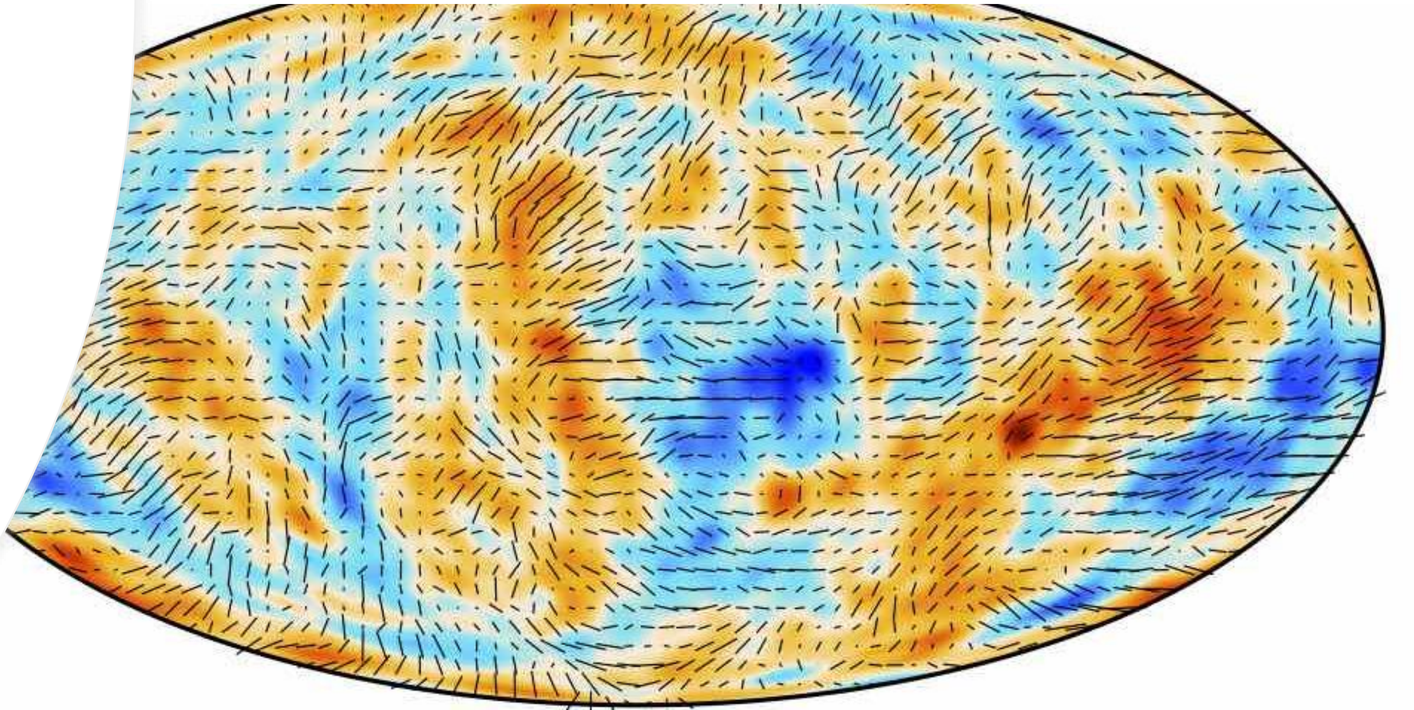
4 IS di CSN4 presenti a Ferrara:

- InDark – Cosmologia (RL e RN M. Lattanzi)
- NEUMATT – Materia nucleare in oggetti compatti (RL e RN G. Pagliara)
- NPQCD – QCD su reticolo (RL S.F. Schifano, RN C. Bonati (PI))
- TAsP – Fisica Astroparticellare (RL I. Masina, RN F. Donato (TO))

InDark

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

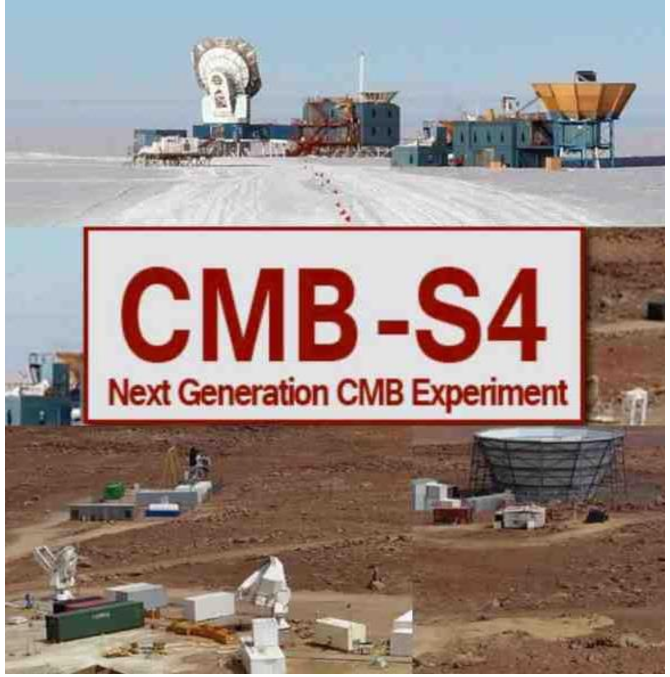


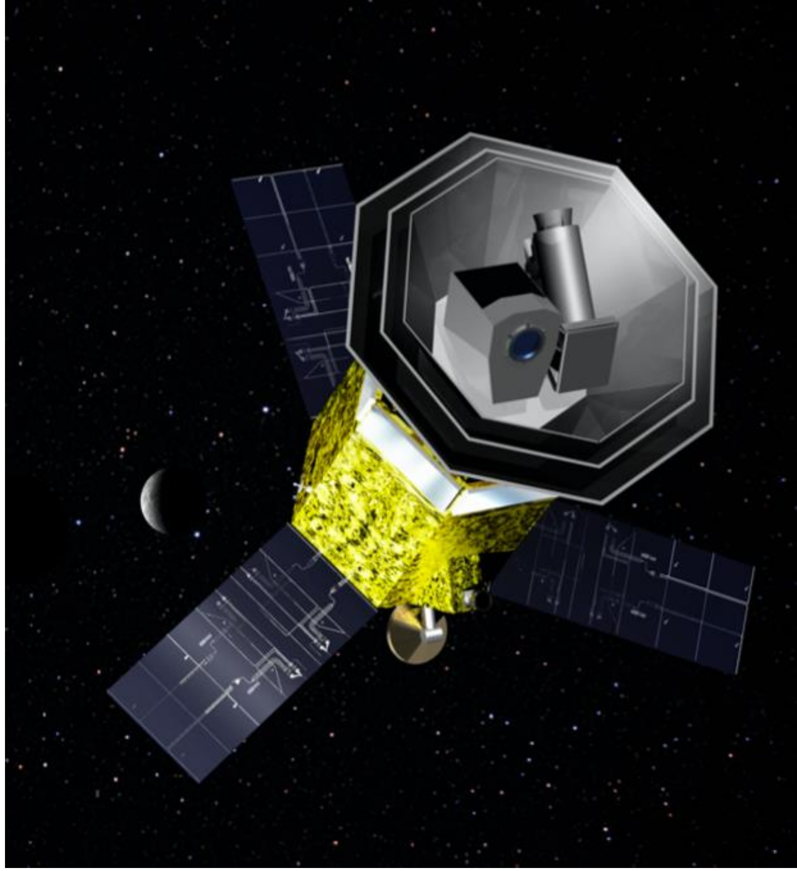


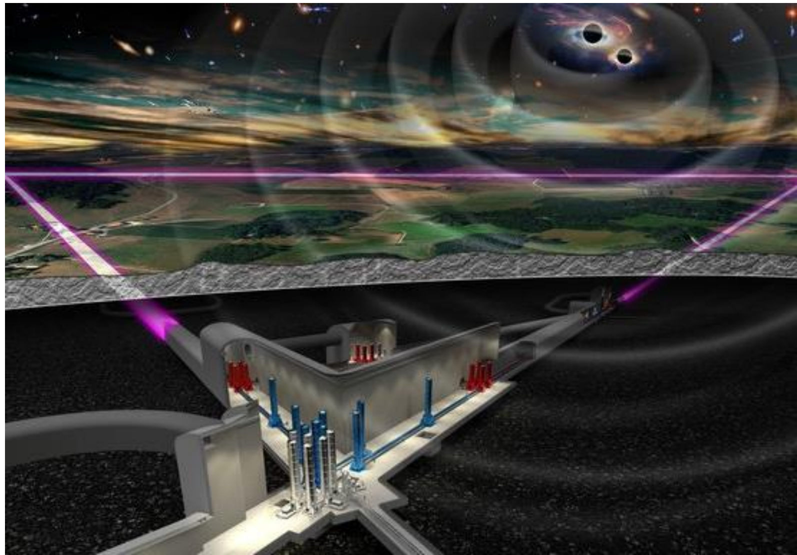
- InDark focuses on investigating crucial aspects of the standard cosmological model and its extensions, and their connection with particle physics:
  - Inflation and the early Universe
  - Dark matter and dark energy
  - Neutrinos and light relics (e.g. axions and ALPs)
  - Modified gravity

Related experimental efforts

- Cosmic Microwave Background observations from both space and ground (LiteBIRD, CMB-S4)
- Galaxy surveys (Euclid)
- Gravitational wave interferometers (ET)







NEUMATT Particles physics with compact stars: new phases of strongly interacting matter

What is the ground state of matter at high densities and “small” temperatures?
A rather robust theoretical prediction (based on QCD and Cooper pairs instability):
the Color Flavor Locked phase (Nucl.Phys.B 1999, Alford, Rajagopal, Wilczek)

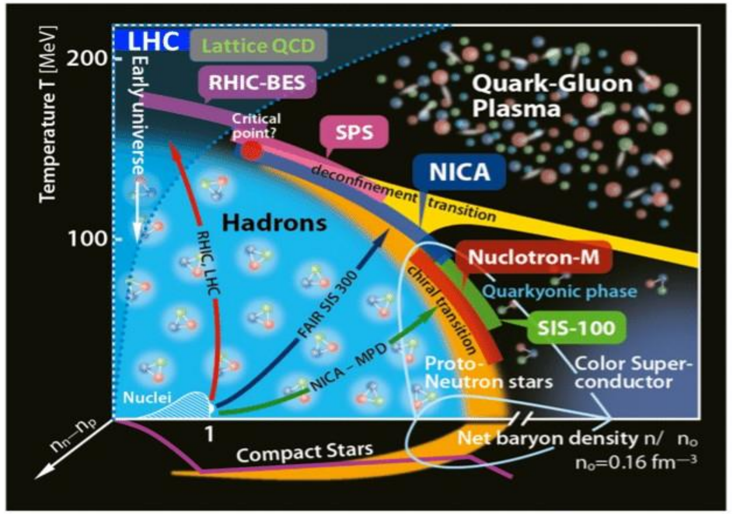
- three flavour color superconducting quark matter
- chiral symmetry broken
- superfluid
- massive gluons
- appearance of Goldstone bosons

$$\langle \psi_i^\alpha C\gamma_5 \psi_j^\beta \rangle \propto \Delta_{\rm CFL}(\kappa+1)\delta_i^\alpha\delta_j^\beta + \Delta_{\rm CFL}(\kappa-1)\delta_j^\alpha\delta_i^\beta$$

Simmetry breaking pattern:

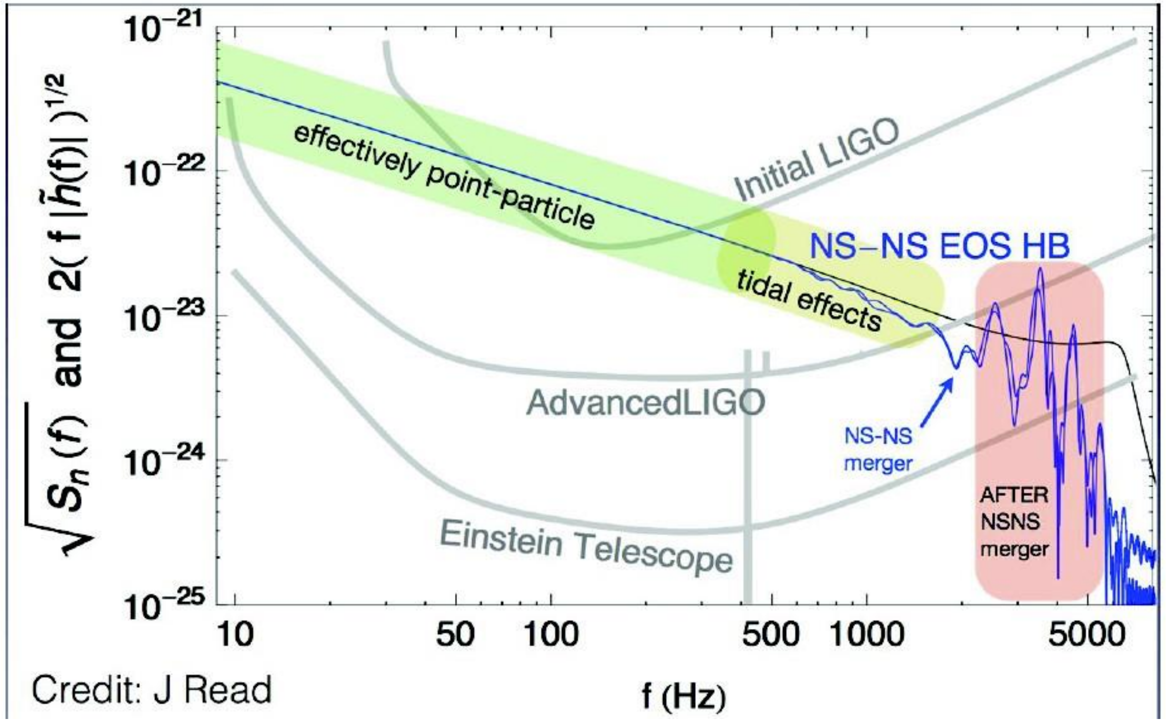
$$[SU(3)_c] \times U(1)_B \times \underbrace{SU(3)_L \times SU(3)_R}_{\supset [U(1)_Q]} \rightarrow \underbrace{SU(3)_{c+L+R}}_{\supset [U(1)_{\tilde{Q}}]} \times \mathbb{Z}_2$$

Thermodynamical conditions in compact stars:
Temperature T < few tens of MeV
Density n > few times the nuclear saturation density.
Compact stars are the right systems in which this phase (and several other phases) might take place.



Slide from G. Pagliara

The most promising/exciting future experiment: Einstein Telescope



ET will allow to access the postmerger GW signals: the remnant is a hot and very massive rotating (differential rotation) compact star. New phases of strongly interacting matter are expected to form in those objects. If they are stable or they eventually collapse to a BH is an open question which is related to different properties of the equation of state of matter (stiffness, transport properties, neutrino interactions, etc...)

Slide from G. Pagliara

NPQCD: Non Perturbative Quantum Chromodynamics

The main interest of NPQCD research group is the study of the non-perturbative features of strongly interacting gauge theories, and most notably of Quantum Chromodynamics (QCD).

Sedi partecipanti: Bari, Cosenza, Ferrara, Pisa

RN: Claudio Bonati (Pisa)

Research activities:

- The color confinement mechanism
- Theta dependence and QCD axion
- QCD in extreme conditions
- Dual formulations of lattice models
- **High performance computing and quantum computing**
- Strongly coupled lattice models
- Quantum Computing

Slide from F. Schifano

NPQCD: Non Perturbative Quantum Chromodynamics

Computing simulation requires large and powerful computing systems

The research activities of Ferrara are focused on:

- Efficient use of recent GP-GPU systems (e.g. GH200)
- Optimization of lattice-based (LQCD, LBM and Spin Glasses) codes for multi-core and many-core architectures
- Experimenting with Quantum Computing:
  - Variational Quantum Eigensolver,
  - Quantum Graph Neural Networks,
  - Optimization Algorithms (Graph coloring, etc)

Slide from F. Schifano

Reference document is ESPP 2020:

https://cds.cern.ch/record/2721370/files/CERN-ESU-015-2020%20Update%20European%20Strategy.pdf

Slide from I. Masina

I.Masina's areas of current research in theoretical particle physics

My reasearch interest cover various areas of theoretical physics, in particular, following a somewhat chronological order:

1- Particle physics within and beyond the Standard Model

1.1 Phenomenological aspects of the Mass, Flavor and CP problems:

neutrinos; fermion masses and mixings; rare decays; fermion electric and magnetic dipole moments; ...

1.2 Model building and phenomenology in various frameworks:

running couplings; Grand Unification; proton decay; Supersymmetry; Technicolor; ...

➡ 1.3 Stability and metastability of the electroweak vacuum

2- Astro-particle physics and cosmology beyond the Standard Model

2.1 leptogenesis and baryon asymmetry of the Universe

2.2 cosmic microwave background, dipole and Earth motion, anomalies

2.3 cosmic rays

➡ 2.4 primordial inflation and the Higgs field

➡ 2.5 evaporating primordial black holes, dark matter and dark radiation

These activities are supported by CSN4 within TAsP (Theoretical Astroparticle Physics)

Points of ESPP 2020 that I.Masina would like to be kept and further emphasized in future documents:

A. Since the recommendation in the 2013 Strategy to proceed with the programme of upgrading the luminosity of the LHC, the HL-LHC project, was approved by the CERN Council in June 2016 and is proceeding according to plan. In parallel, the LHC has reached a centre-of-mass energy of 13 TeV, exceeded the design luminosity, and produced a wealth of remarkable physics results. Based on this performance, coupled with the innovative experimental techniques developed at the LHC experiments and their planned detector upgrades, a significantly enhanced physics potential is expected with the HL-LHC. The required high-field superconducting Nb_3Sn magnets have been developed. ***The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.***

B. Theoretical physics is an essential driver of particle physics that opens new, daring lines of research, motivates experimental searches and provides the tools needed to fully exploit experimental results. It also plays an important role in capturing the imagination of the public and inspiring young researchers. The success of the field depends on dedicated theoretical work and intense collaboration between the theoretical and experimental communities. ***Europe should continue to vigorously support a broad programme of theoretical research covering the full spectrum of particle physics from abstract to phenomenological topics. The pursuit of new research directions should be encouraged and links with fields such as cosmology, astroparticle physics, and nuclear physics fostered. Both exploratory research and theoretical research with direct impact on experiments should be supported, including recognition for the activity of providing and developing computational tools.***

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A (necessarily incomplete) list of open problems/observational targets:

- Origin of neutrino masses
- Inflation
- Strong CP violation (QCD axion)
- Dark matter and dark energy
- Cosmological light relics
- Behaviour of gravity at large scales or in extreme regimes
- Origin of matter/antimatter asymmetry
- Stability and metastability of the EW vacuum
- Violation of “fundamental” symmetries
- QCD in extreme conditions
- ……

BUT…. Theoretical physics is not just about suggesting "new" physics target for experiments. It is also about "known" physics that enters intepretation of experimental results and should be kept under control, such as

- Nonlinear effects in cosmological structure formation
- Infrared EW corrections at accelerators
- Lattice QCD and axion properties
- Nuclear matrix elements for 0nu2beta decay
- Role of loops in the computation of inflationary observables

+ developing methods for making these kind calculations faster and more reliable and remember…

All models are wrong…

and remember…

All models are wrong…

… still, some of them are useful