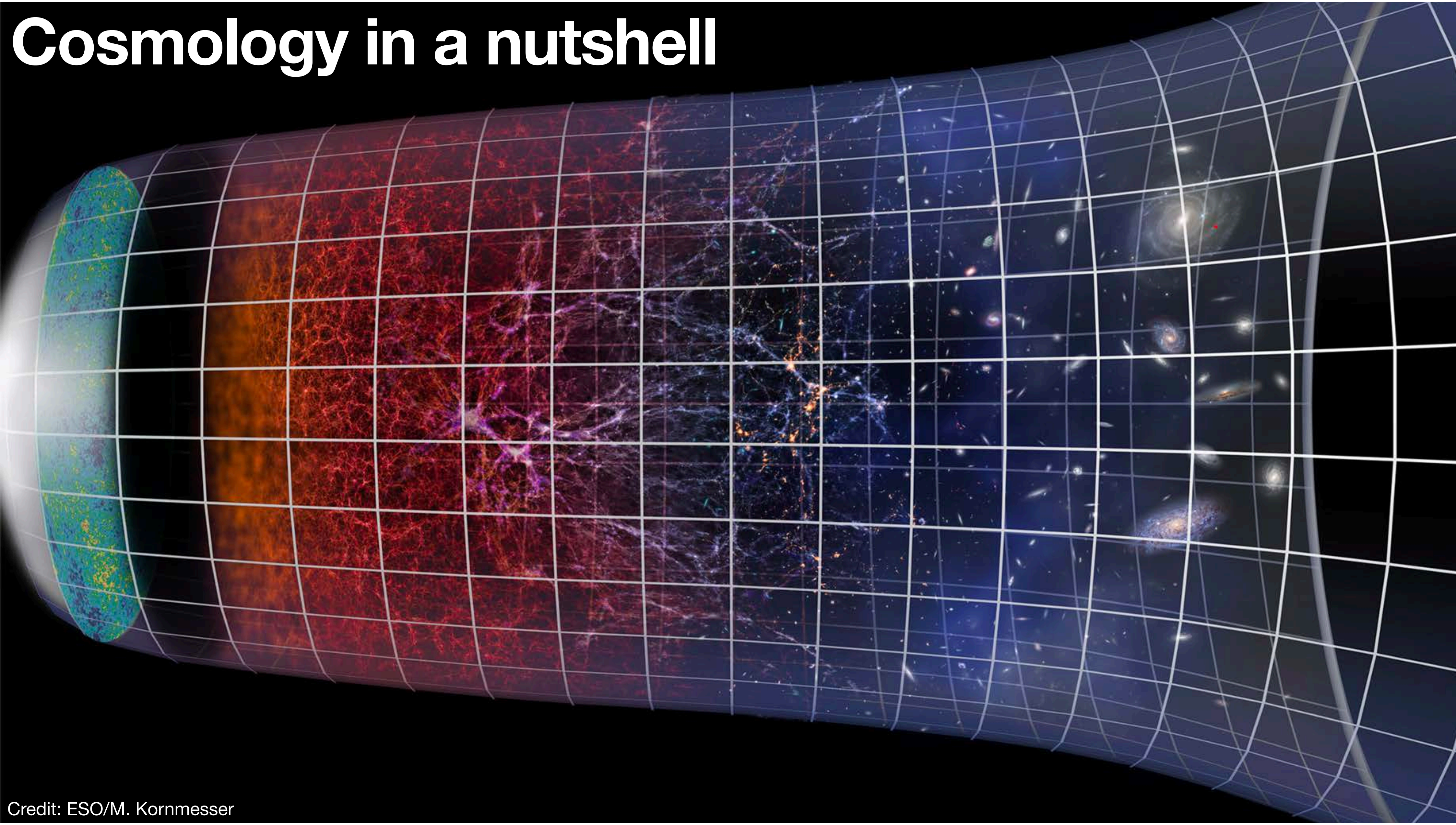
Theoretical Cosmology

Conseil Scientifique de l'IN2P3

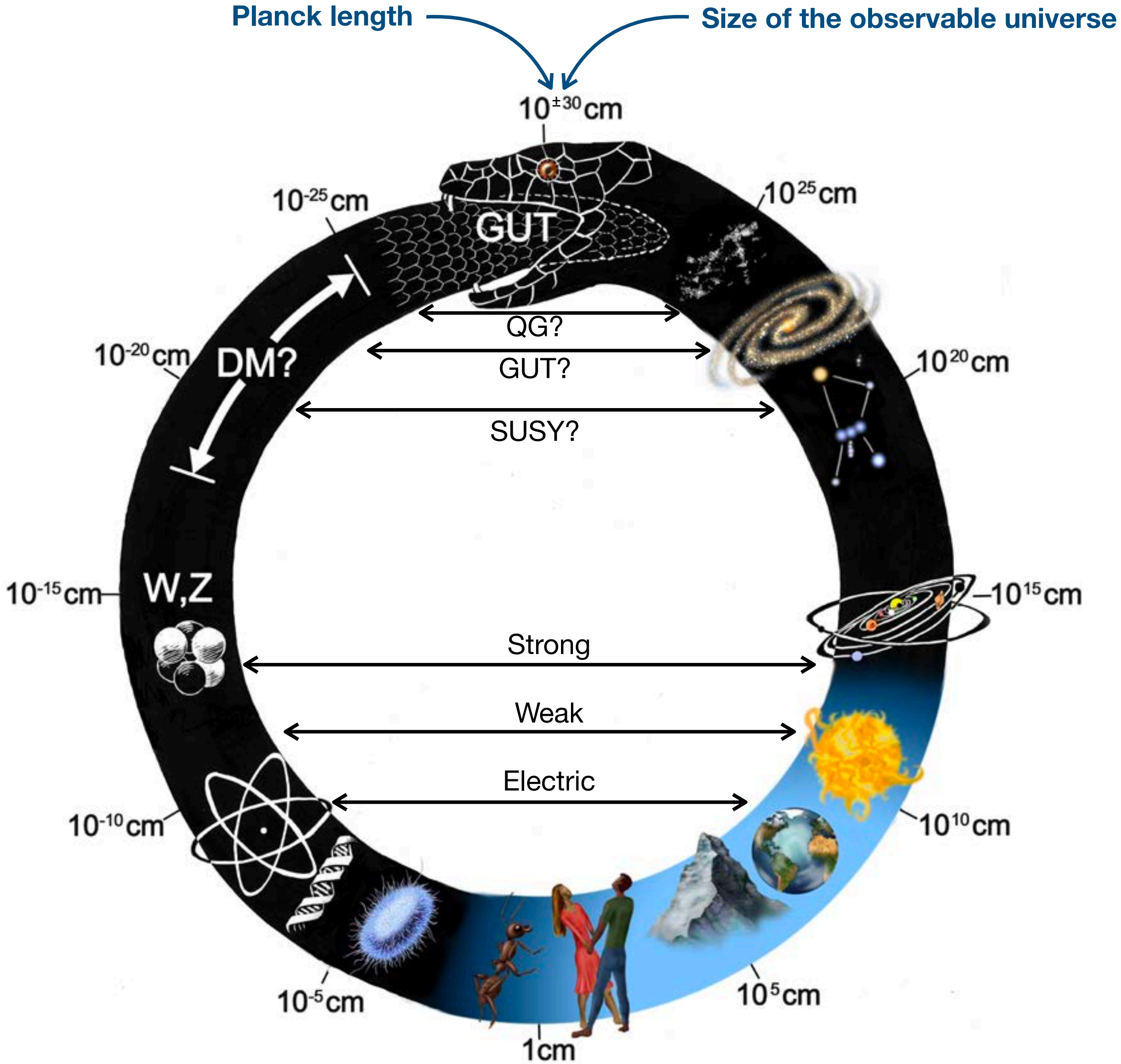
Vincent Vennin, 29th June 2021

Cosmology in a nutshell



Credit: ESO/M. Kornmesser

Cosmology in a nutshell



The cosmic Uroboros

Summary of the workshop:

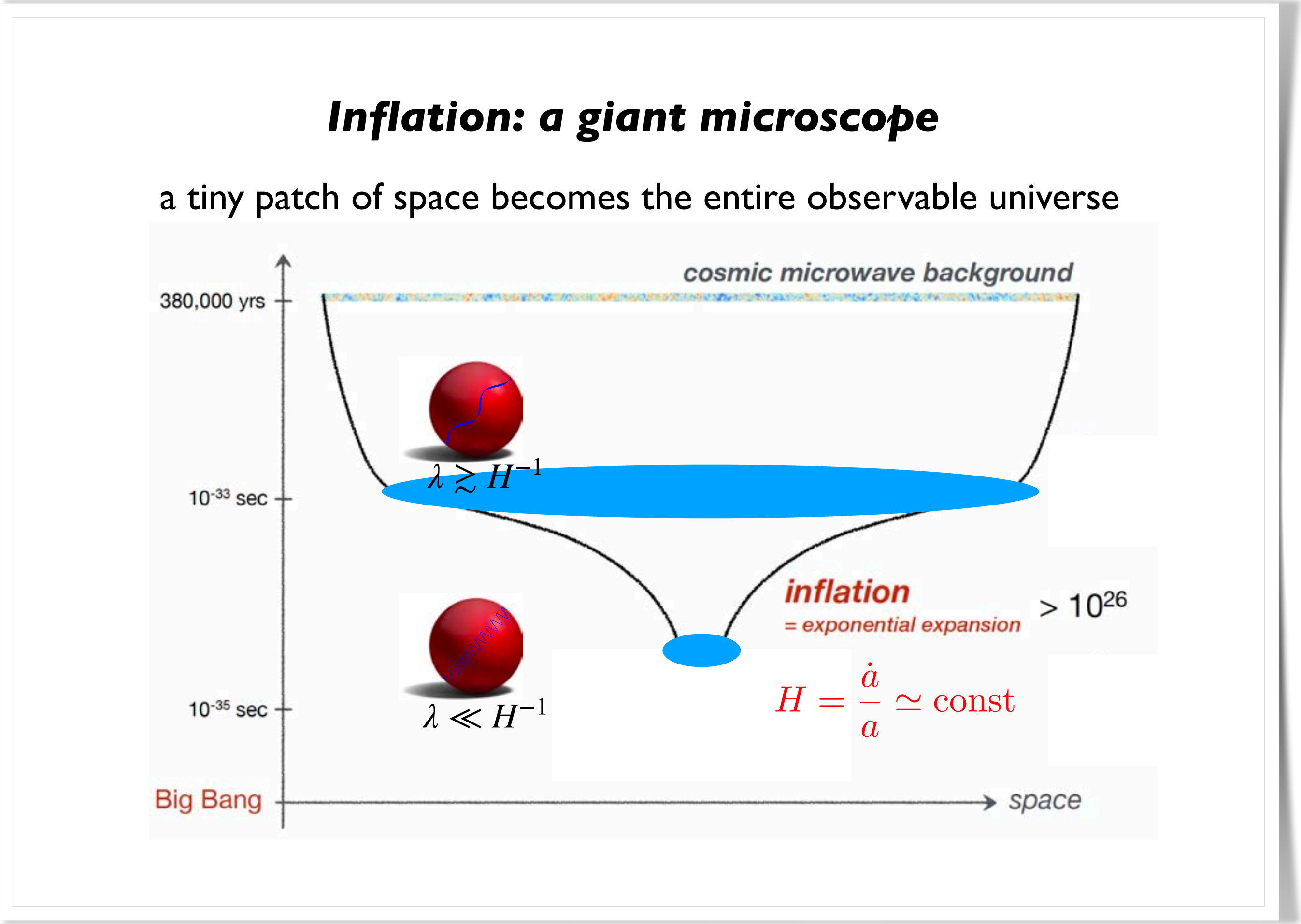
Physique Théorique des ∞ .

A SELECTION OF TOPICS IN THEORETICAL COSMOLOGY

Program and slides available at: https://indico.in2p3.fr/event/23540/overview

See written report for further details about specific contributions from IN2P3 researchers

Early Universe



<u>Open issues:</u>

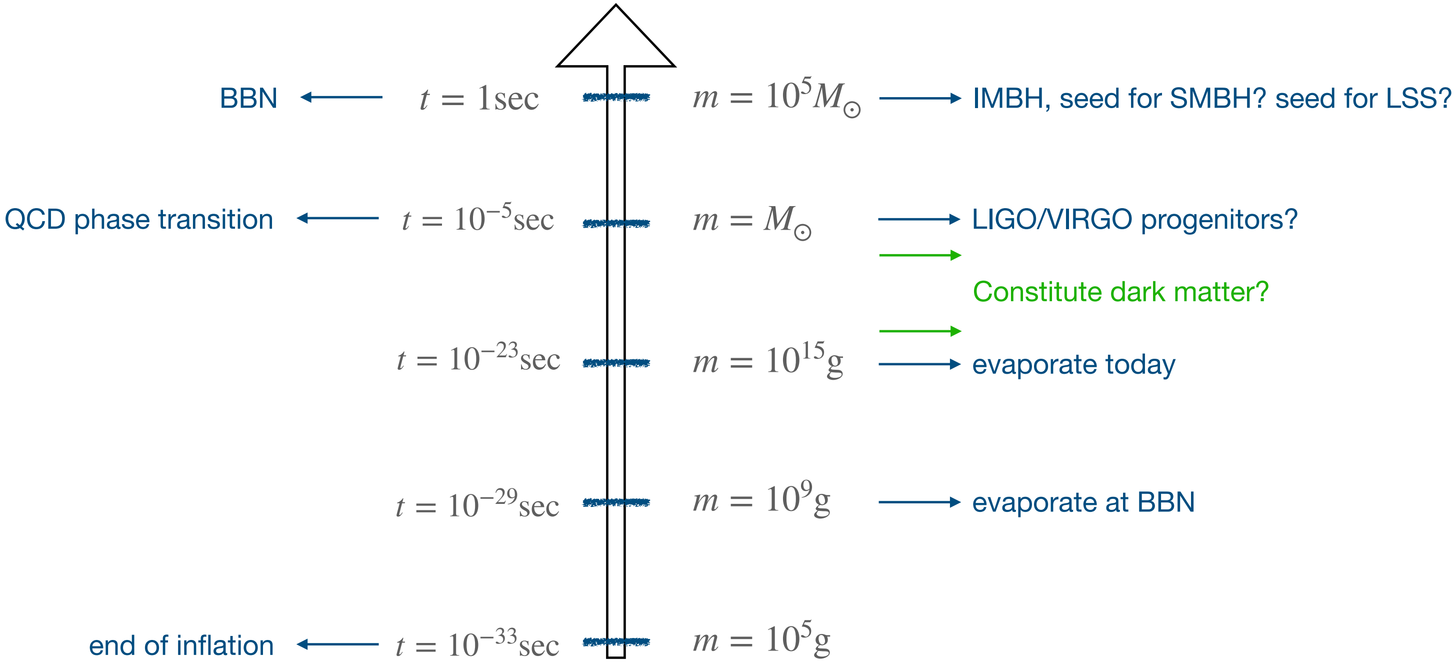
- What is the inflaton?
- To which extension of the standard model does it belong?
- At which energy did inflation occur?
- How did the inflaton transfer its energy to the standard model particles?
- Was it the only field around?
- Did super-Planckian degrees of freedom play a role?
- What does inflation tell us about the nature of Quantum Mechanics, and about the interplay between Quantum and Gravitational physics?
- What about alternatives to inflation?
- How to best constrain inflation from the CMB / LSS / GWs / etc?

c.f. presentation by Sébastien Renaux-Petel (Institut d'Astrophysique de Paris): "Early Universe Cosmology"

Primordial Black Holes

Possible origins:
- Collapse of large primordial over densities
- Phase transitions
- Collapse of topological defects

$$m_{\mathrm{PBH}} \sim m_{\mathrm{Pl}} \frac{t}{t_{\mathrm{Pl}}} \sim 10^{38}\mathrm{g}\frac{t}{\mathrm{sec}}$$



Open issues:

- Formation mechanisms?
- How to compute their abundance?
- Role of Hawking evaporation?
- Testing GR?
- …

c.f. presentation by Alexandre Arbey (Institut de Physique des 2 infinis de Lyon): “Primordial Black Holes”

Modified gravity

- So far, **GR** seems compatible with all observations.
- Several motivations for exploring **modified gravity**
  - Quantum gravity effects
  - Understand cosmological acceleration (or possibly dark matter)
  - Explore alternative gravitational theories
  - **Testing gravity**
- Modified gravity actively studied in two main contexts:
  - In cosmology (alternative to the cosmological constant, exotic early Universe models)
  - In astrophysics: compact objects (black holes, neutron stars)

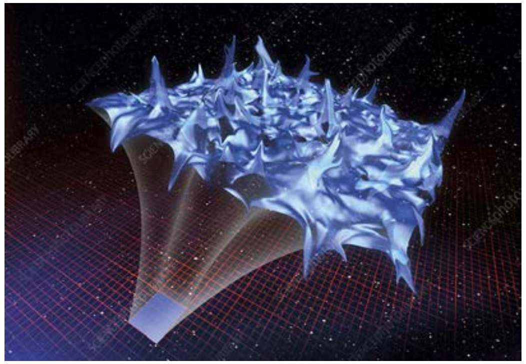
It is rather difficult to modify gravity:

1. The theory must be **internally consistent** (e.g. no problematic instabilities)
2. The theory **must look like GR** in all regimes where GR has been tested
   Lab tests, Solar system, Binary pulsars (and now binary BH)
3. Hopefully (but not necessarily), the theory should **account for the observed acceleration** and exhibit some **distinctive signatures**.

<u>Possible signatures</u>
- Speed of GWs different from *c*
- Evolution of cosmological perturbations different from GR
- GWs from binary merger with different waveforms (quasi normal modes)
- Different internal structures for compact objects (strong-field regime)

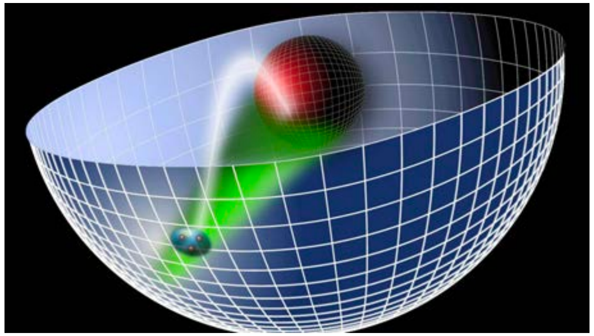
c.f. presentation by David Langlois (Laboratoire Astroparticules et Cosmologie): Modified Gravity in Cosmology and Astrophysics

Quantum gravity



Problem:
- We do not know how to combine gravitational and quantum physics
- There are a number of places in cosmology where both play a role
- Need to modify GR? QM? Both?

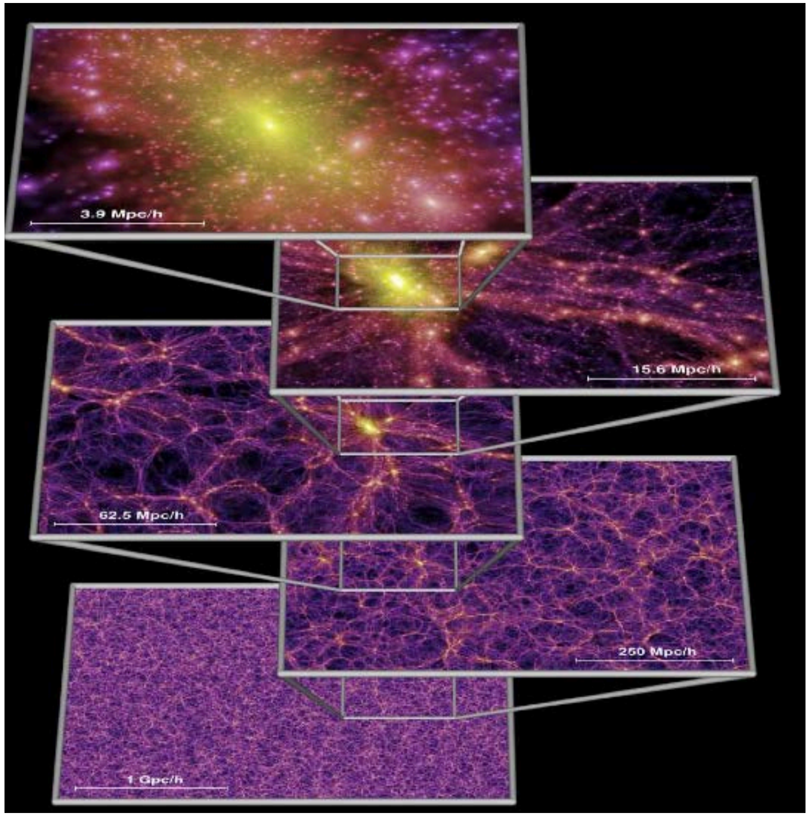
Various approaches:
- String theories
- Loop quantum gravity
- Approaches inspired by the holographic principle, AdS/CFT, emergent gravity etc
- …



Possible applications: a better understanding of
- Inflation
- Dark energy
- Black holes
- …

c.f. presentation by Elias Kiritsis (Laboratoire Astroparticules et Cosmologie): Emergent Gravity and Cosmology

Cosmological Structure Formation



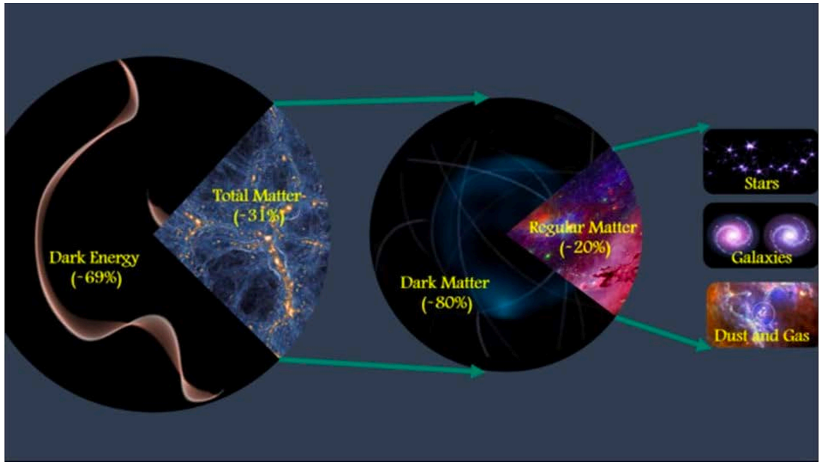
To account for the organisation of matter (visible and dark)
on the largest scales (roughly: galactic scales upwards 0.1 - 10 Mpc)

Goals:
- Account for the formation of structures in our Universe
- Constrain cosmology (cosmological parameters, theory of gravity, etc)
- Reconstruct initial conditions (primordial fluctuations) and thus constrain early Universe

Technical challenges:
- Role of baryonic & AGN feedback
- Role of non-linearities
- Heavy numerical methods (N-body codes tested with scale-free models, large volumes, MCMC with many realisations)
- Statistical characterisation of the cosmic web (clustering, intrinsic alignment, etc): what should be measured?

c.f. presentation by Michael Joyce (Sorbonne Université): Non-linear cosmological structure formation

Dark matter

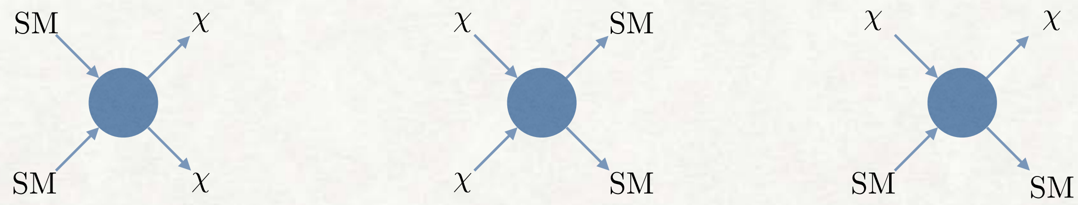


Technical challenges:
- extract “cosmological” & “particle physics” information from large surveys with large astrophysical uncertainties.
- Broad phenomenology: complementarity of probes over a wide-variety of scales and times.
- accurate modeling of small-scale physics + statistical analysis. *N*-body? EFT of LSS?
- Do σ_8 and H_0 tensions point towards interactions/decays in the dark sector?

Many gravitational clues for the existence of Dark Matter on a variety of scales.
Description “CDM” is purely parametric: can we probe the nature of DM?

An analogy with the WIMP

Production | Annihilation | Scattering



in particle physics

Collider | Indirect detection | Direct detection

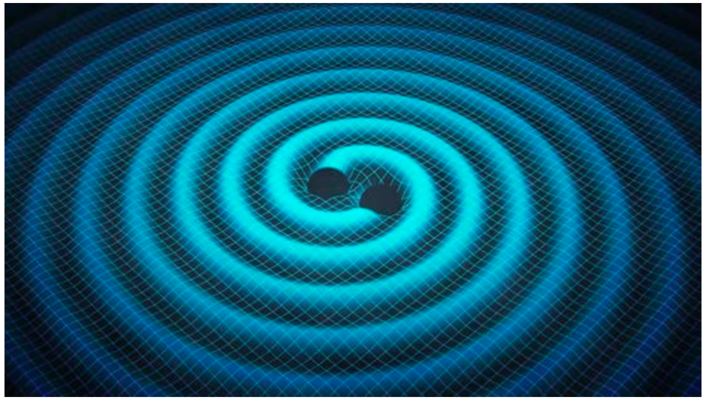
in cosmology

Relic abundance | Energy injection | Momentum transfer

The strength of cosmology is its ability to constrain many different scenarios
via the complementarity of various probes
(WIMP, axions, sterile neutrinos, Primordial Black holes…)

c.f. presentation by Vivian Poulin (Laboratoire Univers et Particules, Montpellier): Dark matter in cosmology

Gravitational Waves Cosmology



Goal: Use GW observations to probe the cosmic expansion and test different cosmological scenarios / models

<u>Standard Sirens:</u> GW events that can be used as absolute cosmological distance indicators

- Luminosity distance estimated from GW signal
- Redshift obtained from EM observations or features in the mass distribution of GW sources

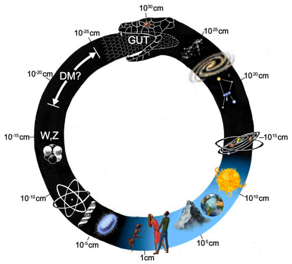
<u>Fit the distance-redshift relation</u>

- Constrain cosmological parameters
- Test GR on cosmological scales
- Probe inhomogeneities?

Example of multi-messenger astronomy

c.f. presentation by Nicola Tamanini (Laboratoire des deux infinis Toulouse): Gravitational-waves cosmology, a new arena to test the dark universe

Specific aspects of the field



Scientific coverage:
- Spans a large range of scales —> multidisciplinary, interface-driven
- Strong interactions with all other components of IN2P3: formal theoretical physics, particle physics, nuclear physics, astroparticles etc

Methodological coverage:
- Wide spectrum of methods: algebraic, analytical, topological, geometrical, QFTs, EFTs, numerical, statistical, etc…
- Fosters mobility of researchers across topics
- Stimulates research at the interface

Institutional coverage:
- Various IN2P3-affiliated laboratories
- Laboratories with other main affiliations (INP, INSU)
- Hiring from different CNRS sections: 01 (IN2P3), 02 (INP), 17 (INSU); besides university positions
- Substantial amount of collaborators based abroad, which results into various international partnerships. Research without borders!

- **APC Paris** (Chiara Caprini, Nathalie Deruelle, Eric Huguet, Elias Kiritsis, David Langlois, Jihad Mourad, Francesco Nitti, Jacques Renaud, Julien Serreau, Danele Steer, Vincent Vennin, Cristina Volpe)
- **IJCLab Orsay** (Eugeny Babichev, Christos Charmousis, Yann Mambrini, Karim Noui, Bartjan Van Tent)
- **IP2I Lyon** (Hubert Hansen, Jerome Margueron, Alexandre Arbey)
- **IPHC Strasbourg** (Michel Raush de Traubenberg)
- **L2IT Toulouse** (Nicola Tamanini)
- **LAAP Annecy** (Tania Regimbau)
- **LPNHE Paris** (Michael Joyce)
- **LPSC Grenoble** (Aurelien Barrau, Killian Martineau)
- **LUPM Montpellier** (Karsten Jedamzik, Julien Larena, Julien Lavalle, Vivian Poulin)

- **INP**: LAPTH Annecy, L2C Montpellier, CPT Marseilles, LPTHE Paris, LPENS Paris
- **INSU**: IAP Paris, LUTH Meudon, IAS Orsay

Specific aspects of the field

- Large amount of topics being covered in spite of moderate number of involved scientists
- Various connection with experimental projects
- Strong international visibility
- Pronounced ability to embrace new topics, and to show versatility in a quickly-developing field
- High potential for breakthrough, wide impact across communities (3 out of the last 4 Nobel prizes were given to Cosmology!)

- Interaction rate within the French community is sometimes limited (too few recruitments to cross the critical-mass threshold in some topics given growing activity and broad scope of the field; lack of theory-specific national platform)
- Performance with funding applications sometimes suffers from schemes being not adapted to theory, and theory being dispatched across several items