Introduction:
Theoretical Physics

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Andreas Goudelis
LPC – Clermont Ferrand

One slide on theoretical physics

Randomly googling, one finds *e.g.* :

> *The description of natural phenomena in mathematical form.*

Collins dictionary

> *A branch of physics that employs mathematical models and abstractions of physical objects and systems to rationalize, explain and predict natural phenomena.*

Wikipedia

Key elements:

- Abstraction.
- Qualitative understanding.
- Mathematical/quantitative description.

Today on the menu:

- Lattice QCD
- Dark Matter

Topic No 1:

Lattice Quantum Chromodynamics

Quantum fields and Lagrangians

The world of microscopic relativistic physics is described by quantum field theory:

$$\boxed{\text{particles} \rightarrow \text{excited states of fields}}$$

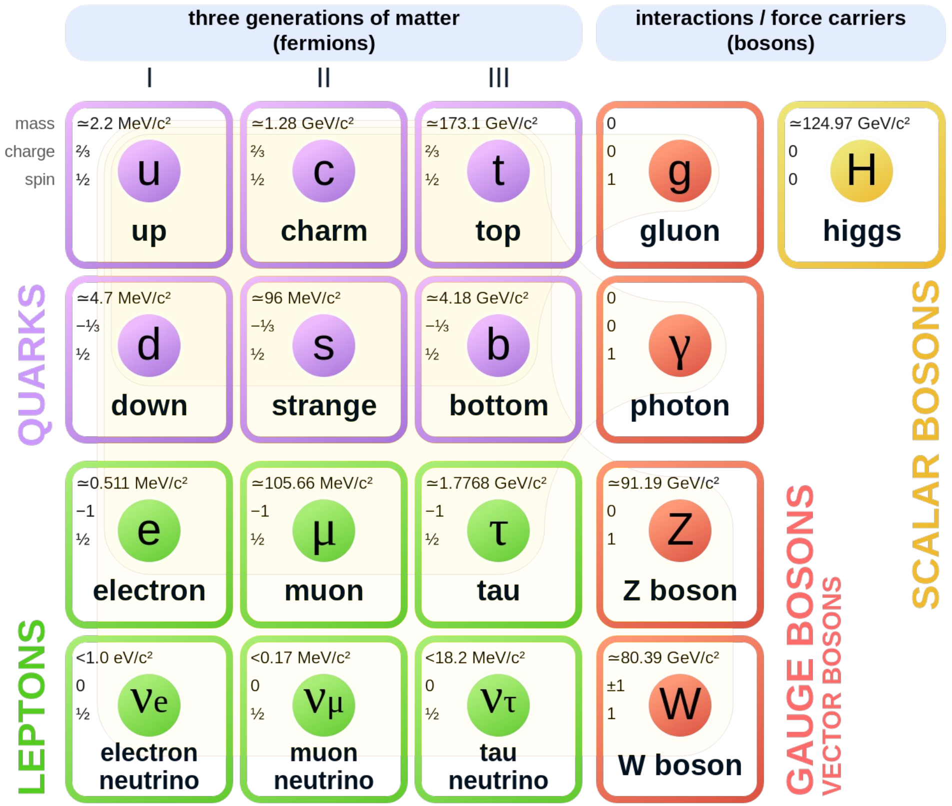
Operator functions of spacetime

The interactions between fields are described by Lagrangians. Consider *e.g.* a real scalar field φ. A Lagrangian for this field would look something like:

$$\mathcal{L} = \underbrace{(\partial_\mu \phi)(\partial^\mu \phi)}_{\text{Kinetic term}} - \underbrace{\frac{m^2}{2}\phi^2}_{\text{Mass term}} + \underbrace{\frac{a}{3!}\phi^3}_{\text{Interaction of 3 } \varphi\text{'s among them}} + \underbrace{\frac{\lambda}{4!}\phi^4}_{\text{Interaction of 4 } \varphi\text{'s among them}}$$

The Standard Model and QCD

The known elementary particles are described by the Standard Model of particle physics:



Standard Model of Elementary Particles

The masses of these particles, their interactions etc are also described by a Lagrangian.

But a bit lengthier than the one we just saw

The strong interactions, in particular, concern a subset of these particles:

- The gluons (spin-1 force carriers)
- The quarks (spin-1/2 matter fields)

The underlying theory is caled *Quantum Chromodynamics* (QCD).

Note: the strength of the SM interactions is not fixed. It varies with energy. In particular, at low energies the strong interactions can become *strong*!

Observables and path integrals

In quantum physics observables are represented by operators. So how can we compute measurable quantities (cross-sections, decay rates etc), *i.e.* expectation values of such operators in QFT?

The basic object that we (often, silently) employ is the *path integral*.

$$\langle \mathcal{O} \rangle \propto \int \mathcal{D}\phi \; e^{i \int d^4x \mathcal{L}[\phi]} \; \mathcal{O}[\phi]$$

L, O: generalisations of functions called "functionals"

So the path integral is an integral over

· All field configurations

· All spacetime points

→ Infinite number of integrals!

In general, we don't know how to calculate such objects

Solution Nº1: perturbation theory

Consider a simple Lagrangian:

$$\mathcal{L} = \underbrace{(\partial_\mu \phi)(\partial^\mu \phi) - \frac{m^2}{2}\phi^2}_{\text{Free part}} + \underbrace{\frac{\lambda}{4!}\phi^4}_{\text{Interacting part}}$$

And remember what we want to calculate:

$$\langle \mathcal{O} \rangle \propto \int \mathcal{D}\phi \; e^{i \int d^4x \mathcal{L}[\phi]} \; \mathcal{O}[\phi]$$

Assuming λ is small (*i.e.* that the λ-term is just a *perturbation* over the free theory), then we can:

- Separate the free from the interacting part
- Taylor-expand the exponential in powers of λ

Or be more rigorous and actually use functional methods

It turns out that usually we *do* know how to calculate the resulting integrals, order-by order in the expansion :)

Yayyyyy :) !!!

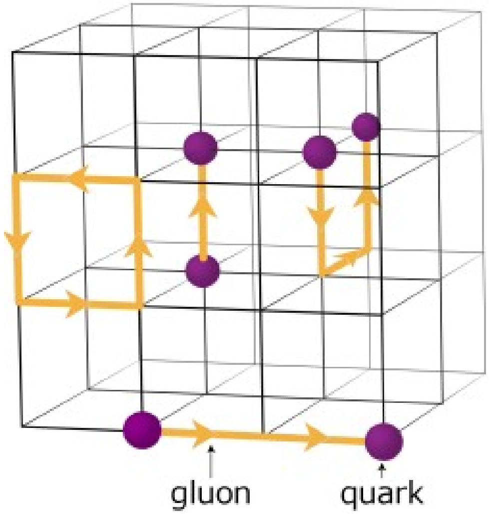
Solution N°2: lattice gauge theory

But what if *e.g.*, λ is not small? Such a situation occurs, *e.g.*, in low-energy QCD.

And QCD is part of the Standard Model!

The general idea: discretise the problem

- Consider a finite volume of spacetime and discretise the spacetime coordinates
- Properly define matter fields (fermions) to live on the lattice sites and link them with interactions (gauge fields)
- Monte-Carlo – integrate discretised version of the path integral
- Properly recover the continuum limit



Many applications, *e.g.* in flavor physics (form factors), understanding of low-energy QCD (confinement), BSM physics (technicolor), precision measurements (muon g-2) …

Cf Letizia Parato's talk :) !

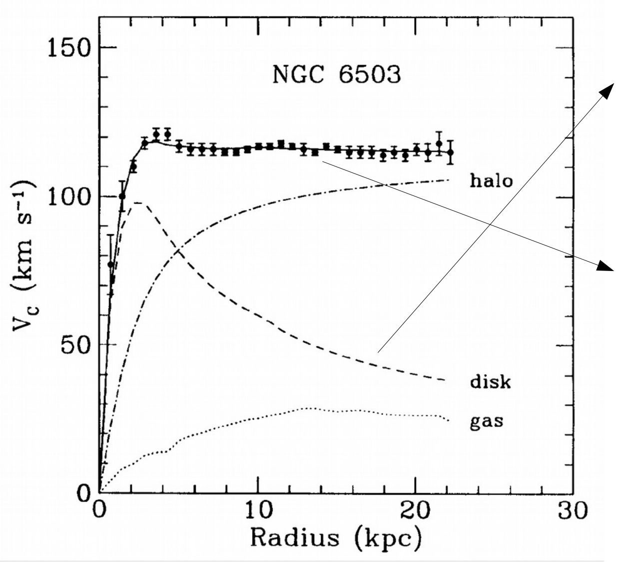
Topic No 2:

Dark matter

What is dark matter ?

I wish I knew... But it really seems to exist: Evidence @ multiple distance scales

Galaxies (rotation curves)



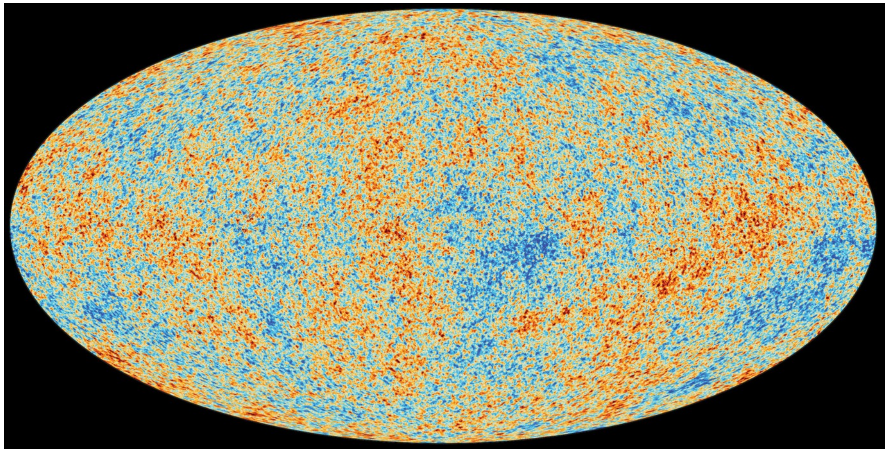
Predicted from luminous disk

Visible

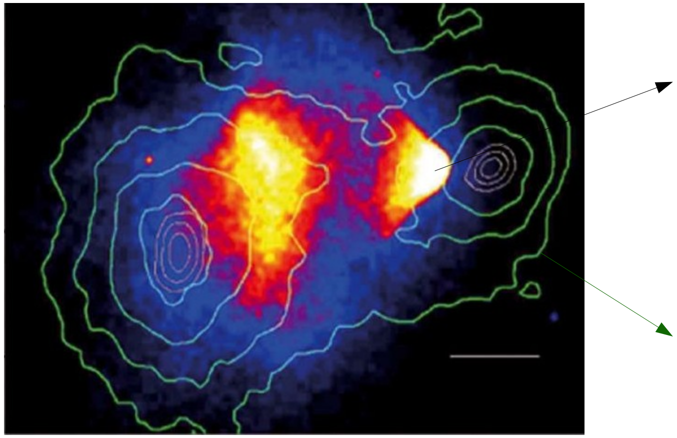
Observed

Total

Cosmic Microwave Background



Galaxy clusters (lensing VS spectroscopy)



Spectroscopy-deduced matter distribution

Visible

Lensing-deduced matter distribution

Total

· Measure tiny anisotropies in otherwise almost perfect blackbody spectrum.

Planck 2018:

$$\Omega_b h^2 = 0.02242 \pm 0.00014$$

$$\Omega_c h^2 = 0.11933 \pm 0.00091$$

arXiv:1807.06209

What do we know about dark matter ?

All the pieces of evidence for the existence of dark matter rely on gravity...

No information about its (particle?) nature!

Some general things that we *do* know about dark matter :

· It gravitates.

· It must be cold-ish (for structure formation) → It cannot be neutrinos.

· It must be stable on cosmological timescales + E/M neutral.

· It constitutes ~85% of the matter content of the Universe (CMB).

→ *We do have a number!*

· Can we explain why $\Omega_{\mathrm{DM}}/\Omega_{\mathrm{baryons}} \sim 5$?

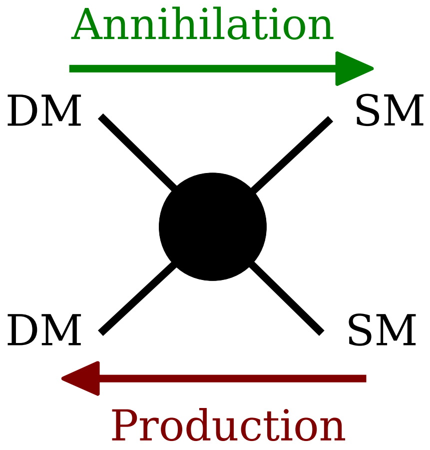
· Can we detect it non-gravitationally ?

Dark matter abundance in the Universe

Imagine that at first only the SM particles exist in the expanding Universe.

We know that the Universe expands!

Assume also that the DM-SM communication takes place through processes like :



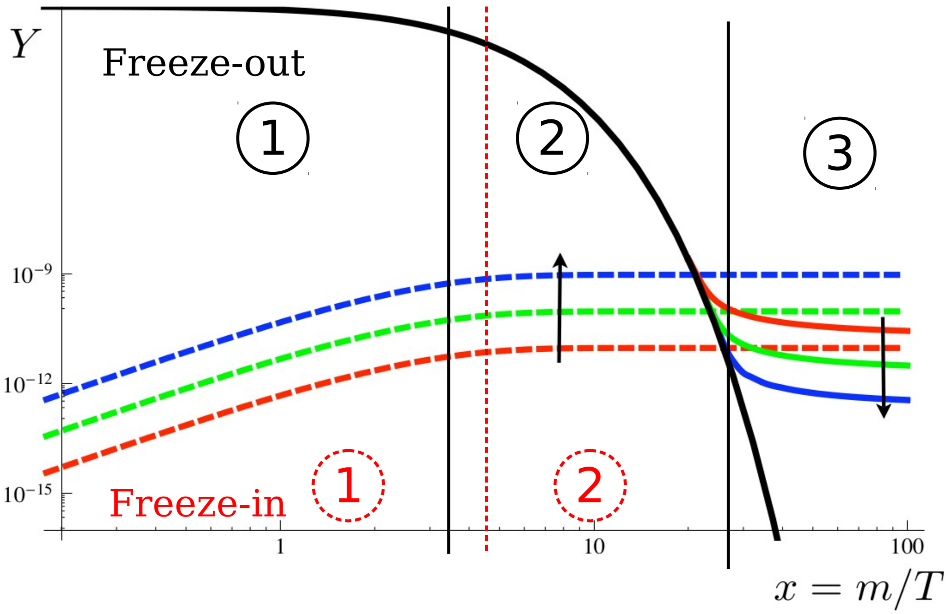
Three points to keep in mind :

- Early times: high temperature, high density.
- Cosmic expansion: → temperature drops, → particles get diluted
- Annihilation rates scale as $n^2 <\sigma v>$.

Tip of the day:
You can fill in empty space in slides with kouign amann!

Dark matter abundance in the Universe

In practice: solve Boltzmann equation taking into account all relevant processes.



Tweaked from arXiv:0911.1120

Strong enough interactions

1) The two sectors equilibrate rapidly.

2) Cooling: DM production shuts down.

3) Dilution: DM abundance “freezes”.

Thermal freeze-out picture

Extremely weak interactions

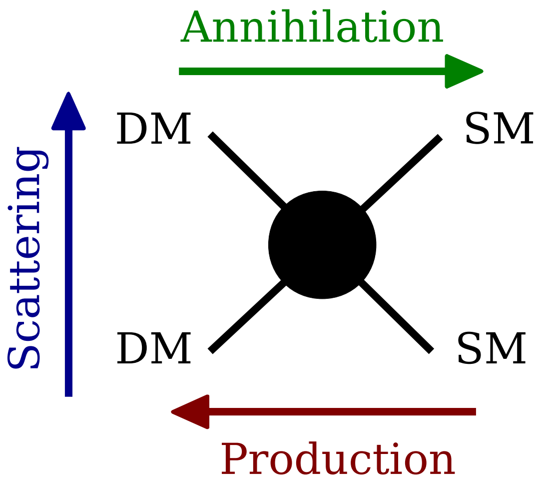
1) The two sectors never equilibrate.
DM too dilute: it never annihilates.

2) Cooling: DM production shuts down.

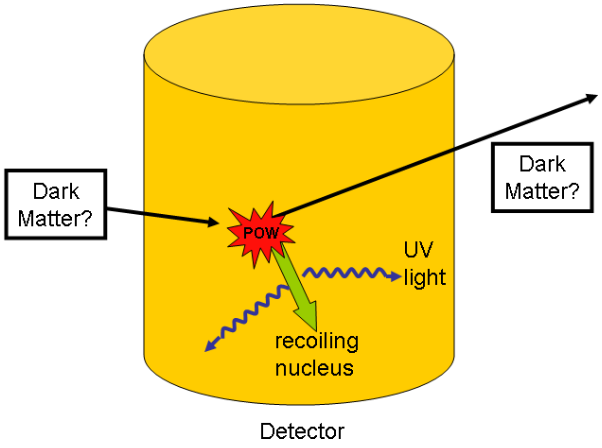
Freeze-in picture

So how can we detect dark matter ?

By rotating this picture, we can get three ideas:

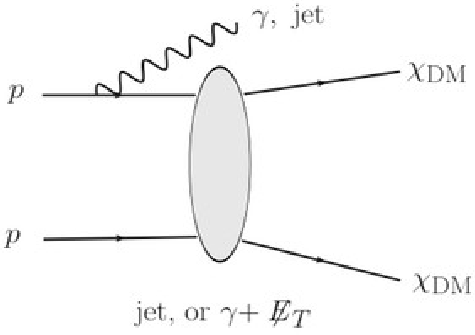


Direct detection

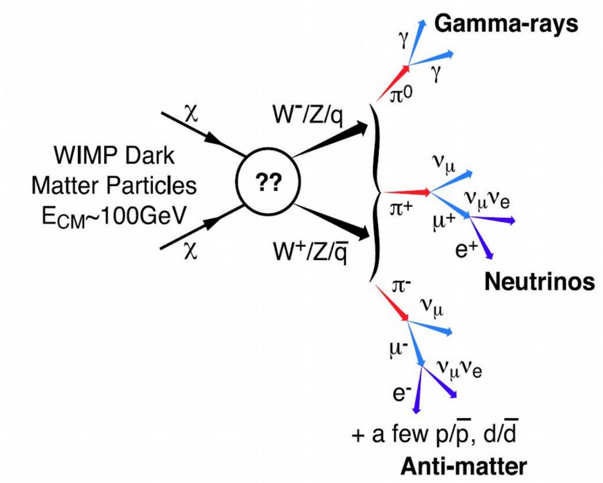


Cf Ali Mjallal’s talk :) !

Collider searches



Indirect detection



Cf Celine Armand’s talk :) !

Summary

· Theoretical physics is great.

And theoretical physicists are cool.

· It is *not* just a mental exercise: even in its most speculative forms, it is *physics, i.e.* it studies and tries to make sense out of the physical world.

· It is *useful.*

Think of all the theory that goes into programs like GEANT

Dark matter physics proposes new experimental signatures

The Higgs boson and gravitational waves began as theoretical predictions

Lattice QCD computes quantities that are crucial for experiments

Have fun in the session!