Theory Session

Jonathan Kriewald

Jožef Stefan Institute

JRJC 2024

Theory Session

What is theoretical Physics?

Field of theoretical physics is incredibly broad:

- Methods and Phenomena strongly depend on **Energy scale**
- In general: try to find mathematical means to ***model*** phenomena in Nature
- Theory ⇔ **Testable** mathematical description of Nature

  ⇒ Make **new predictions**, **test** predictions in experiments

Example: Einstein's **General** theory of **Relativity**

⇒ Explain Perihelion of **Mercury,** **not** possible with Newtonian Mechanics

⇒ Test GR in **bending of light around the Sun**

⇒ predict **gravitational red-shift** **and** **gravitational waves**

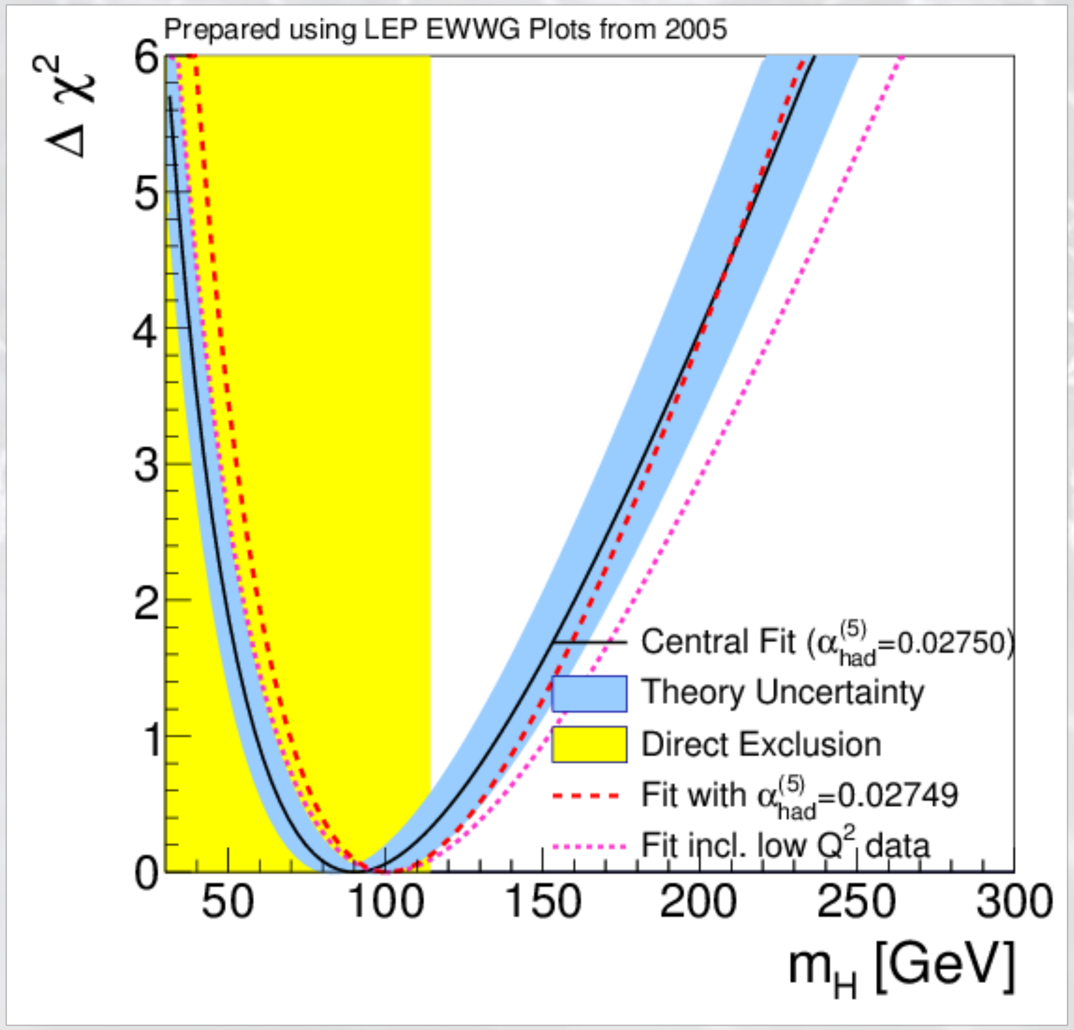
What is theoretical high-energy Physics?

Let’s divide in two categories:

“Pure” Theory

- Develop **Mathematical Foundations**: Quantum Field Theory, String Theory, Renormalisation, …
- Develop **Computational Methods:** Feynman Diagrams, Perturbation Theory, Lattice Field Theory, …
- Predict **New Phenomena** by demanding **mathematical consistency**: Symmetries, Gauge Theory, …

What is theoretical high-energy Physics?



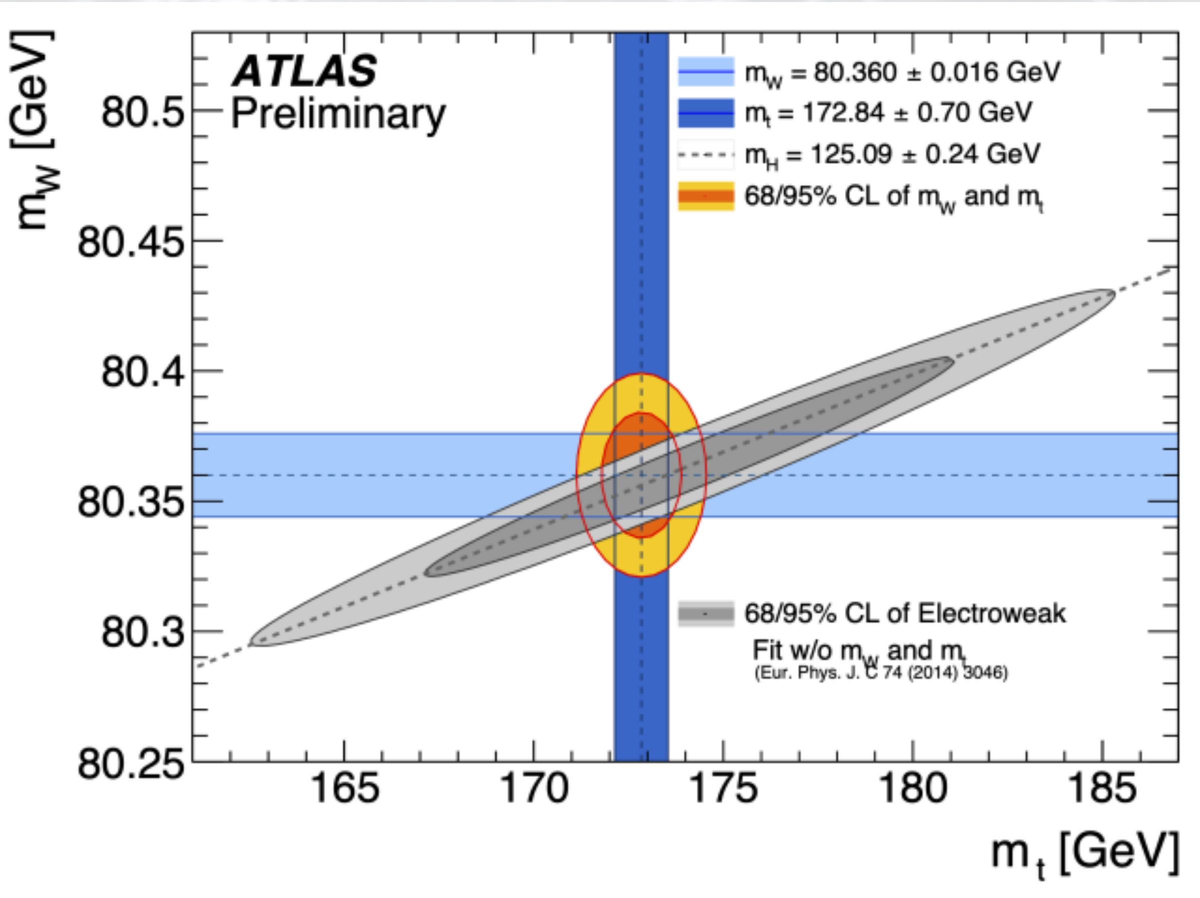
No lose "theorem"

Phenomenology

- *Apply* QFT to develop Models of Nature: Shell Model, Fermi Theory, Standard Model, Effective Field Theories, …
- Fit Models to **Data** and predict Observables to **test** models
- Construct new models to describe ***"anomalous data"***

What is theoretical high-energy Physics?

Let’s divide in two categories:



Phenomenology

- *Apply* **QFT** to develop Models of Nature: Shell Model, Fermi Theory, Standard Model, Effective Field Theories, …
- Fit Models to **Data** and predict Observables to **test** models
- Construct new models to describe ***“anomalous data”***

No lose “theorem”

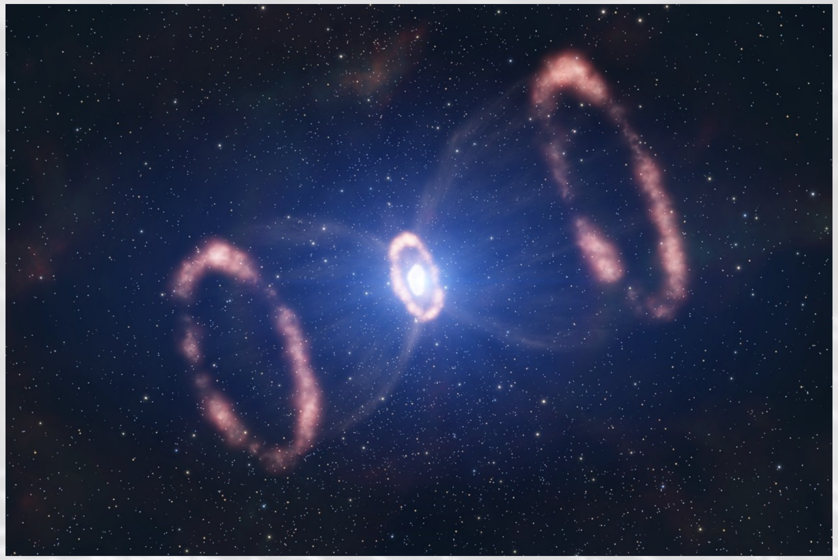
Why do we need Theory?

Why do we need Theory?

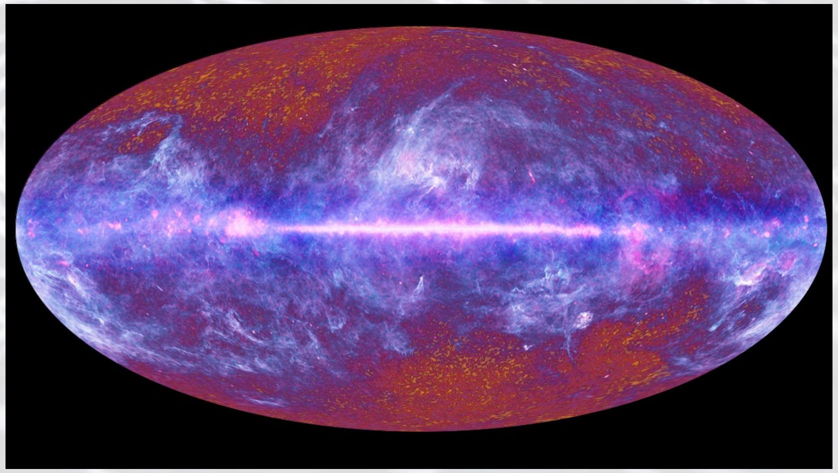
Ehhhh…. Because it’s fun 🤠??

The fun today:

- **Axion** emission from **Strange Matter** in Core Collapse **Supernovae** (Maël Cavan)



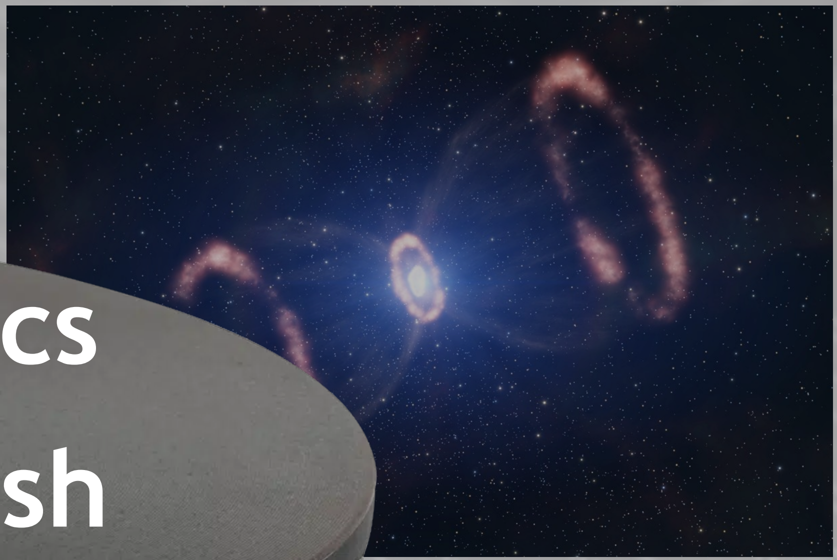
- Cosmological and astrophysical constraints on resonant s-wave **Dark Matter annihilation** (Margaux Jomain)



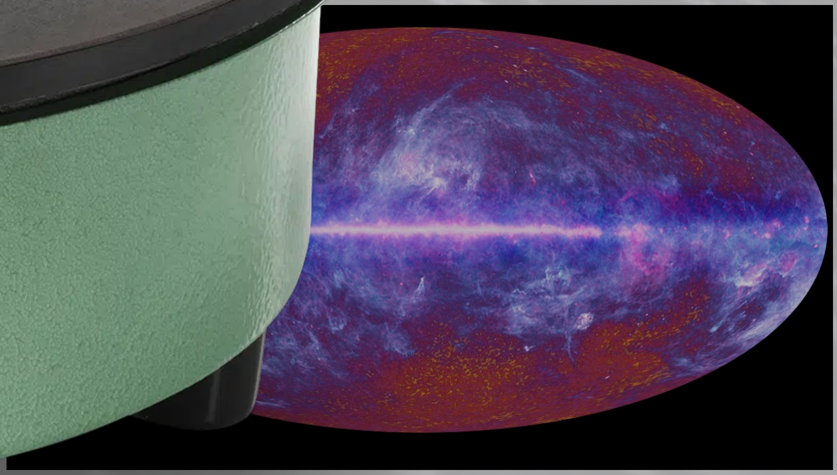
- **Giant Dipole Resonances** and pygmy Resonances within the **Large Scale Nuclear Shell Model** approach (Oscar Le Noan)

(picture unrelated)

The fun today:



- **Axion** emissi
  Coll

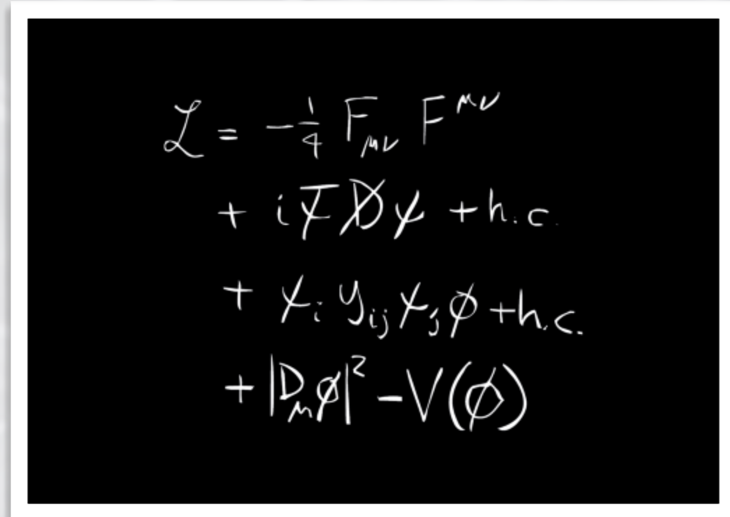


- Cosm
  constrai
  Matter ann

- Giant Dipole Resonances and pygmy Resonances within the Large Scale Nuclear Shell Model approach (Oscar Le Noan)

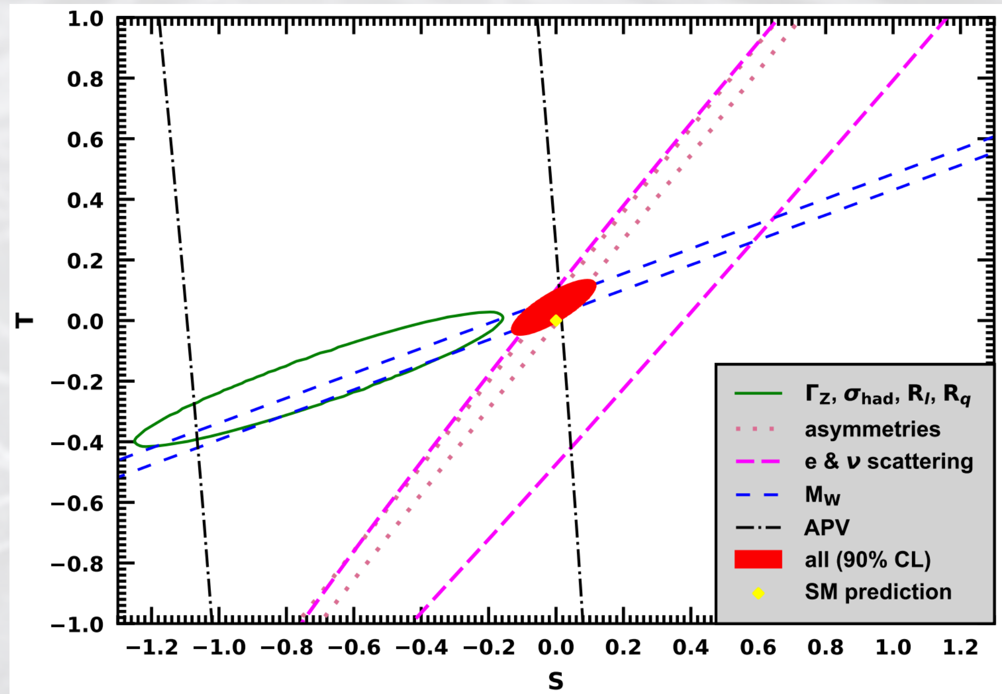
(picture unrelated)

The Standard Model — A success story

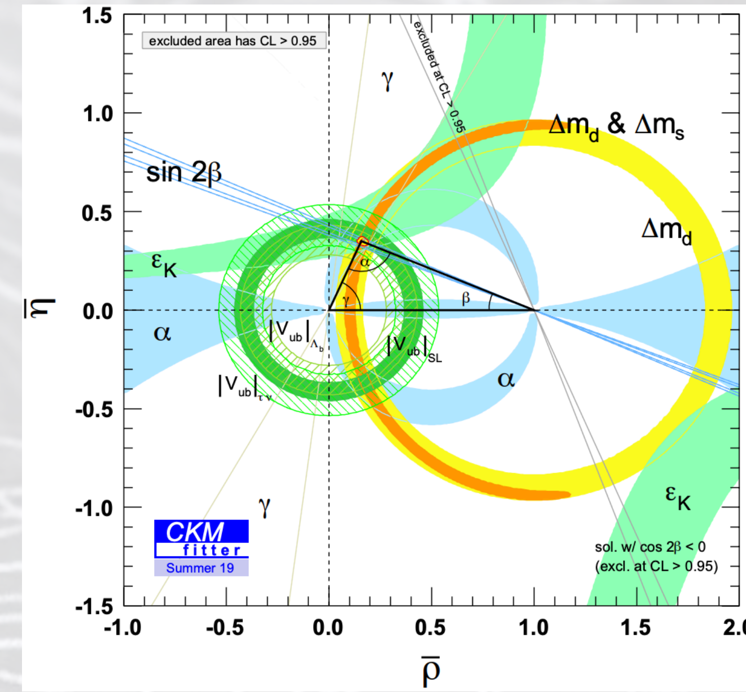


$\mathcal{G}_{SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

\+ some ***accidental* symmetries**

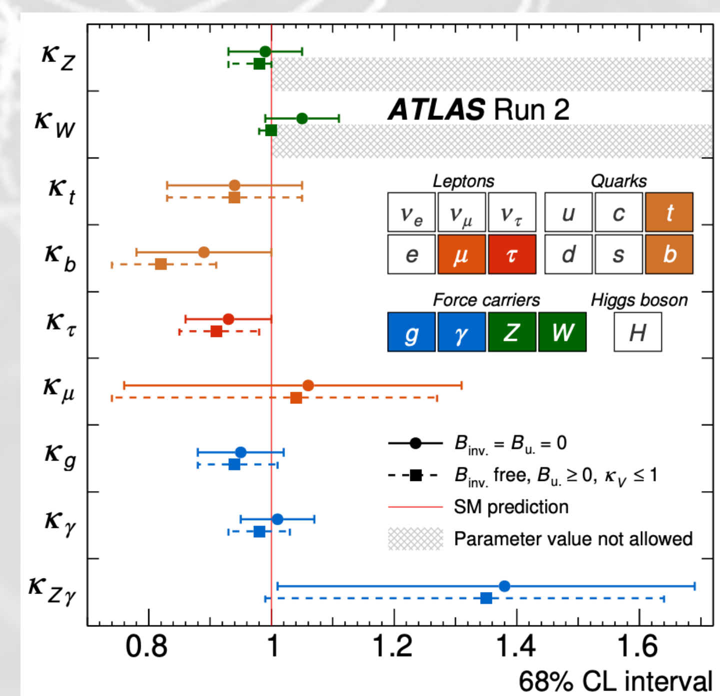


Electroweak fit



CKM paradigm of flavour mixing

> **Hundreds of experimental measurements overwhelmingly confirm the SM!**

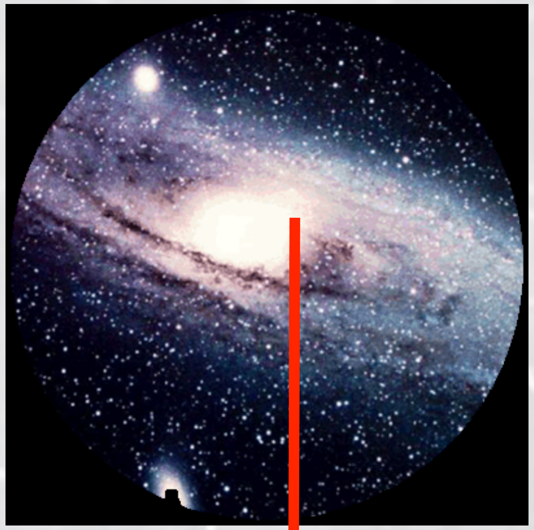


Higgs couplings

⇒ Just need to completely understand the Higgs sector now?

Strong arguments in f(l)avour of New Physics!

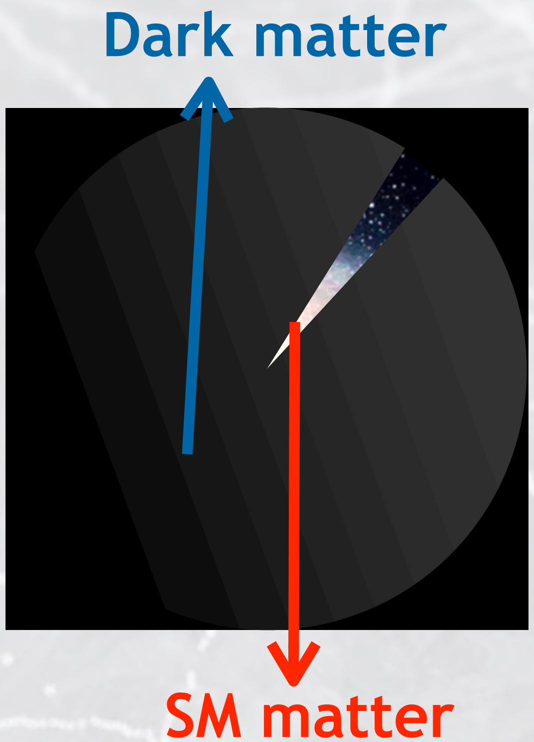
Some remaining puzzles of Nature:



SM matter

Strong arguments in f(l)avour of New Physics!

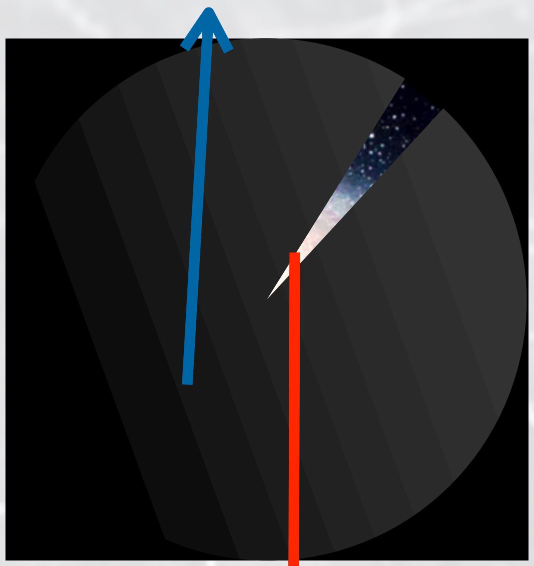
Some remaining puzzles of Nature:



Strong arguments in f(l)avour of New Physics!

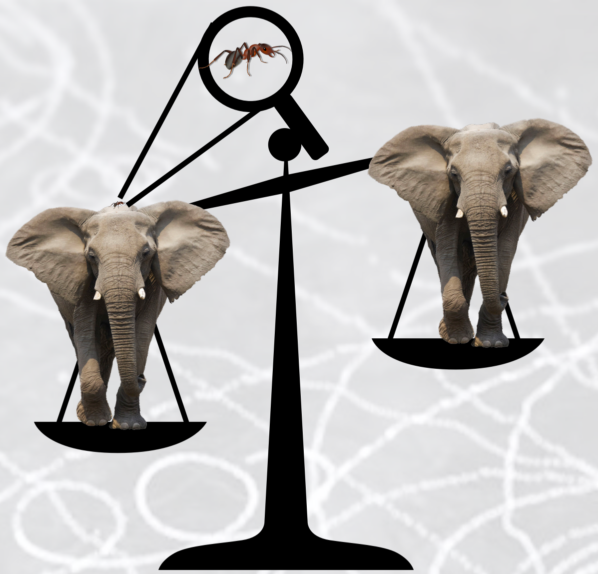
Some remaining puzzles of Nature:

Dark matter



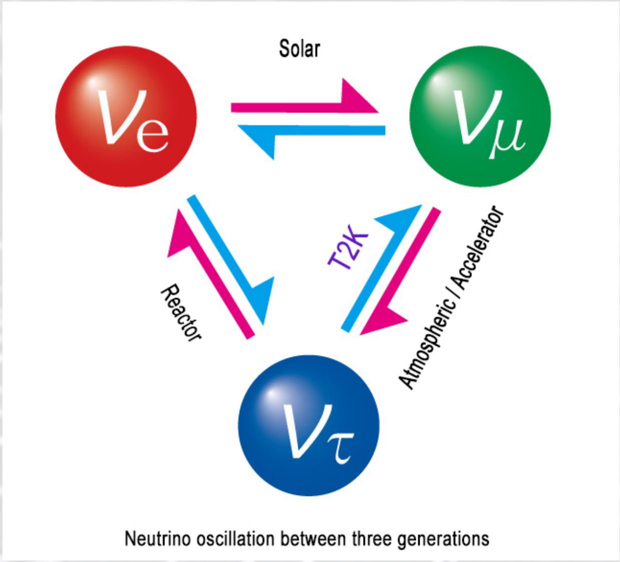
SM matter

Baryon asymmetry of the Universe



$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \mathcal{O}(10^{-10})$$

ν-oscillations



Some "*theoretical*" issues:

- **Quantum theory of Gravity**
- **Flavour puzzle**
- **"Hierarchy problem":** why is the Higgs so light and the Planck-scale so high?
- **"Strong CP problem":** what is the mechanism behind the absence of $G\tilde{G}$?

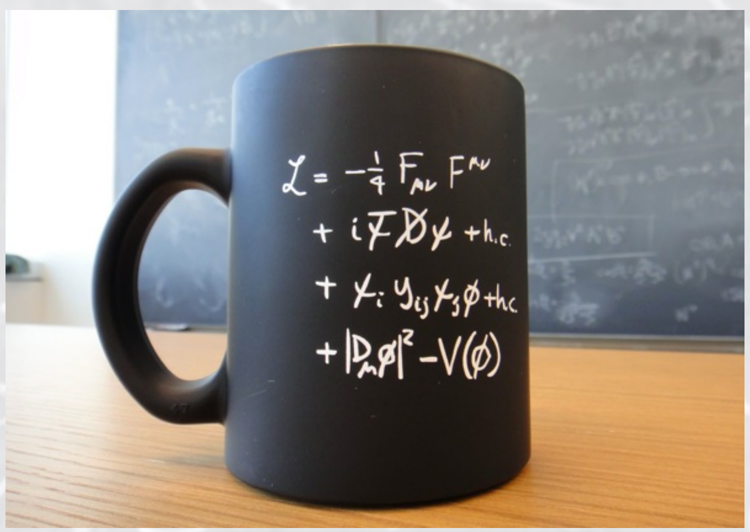
Axions & Supernovae

The strong CP problem

Quantum ChromoDynamics (QCD) symmetry is $SU(3)$

Non-abelian symmetries allow for “special” term in the Lagrangian:

(For $SU(2)$ the term can be re-absorbed in the W fields)



$$+\theta \frac{g}{32\pi} G_{\mu\nu} \tilde{G}^{\mu\nu} \text{ with } \tilde{G}_{\mu\nu} = \varepsilon_{\alpha\beta\mu\nu} G^{\alpha\beta}$$

$\Rightarrow G\tilde{G}$ term is CP violating

Measurements of neutron EDM:

$$\bar{\theta} = \theta - \arg\det Y_u Y_d \lesssim 10^{-10}$$

Coincidence?

Axions and the strong CP problem

Technical Naturalness à la 't Hooft: a given parameter is allowed to be small if it enhances the symmetry of the Theory

Give Symmetry origin to a small $\bar{\theta}$? e.g. Left-Right symmetry, many approaches …

(QCD-) Axions:

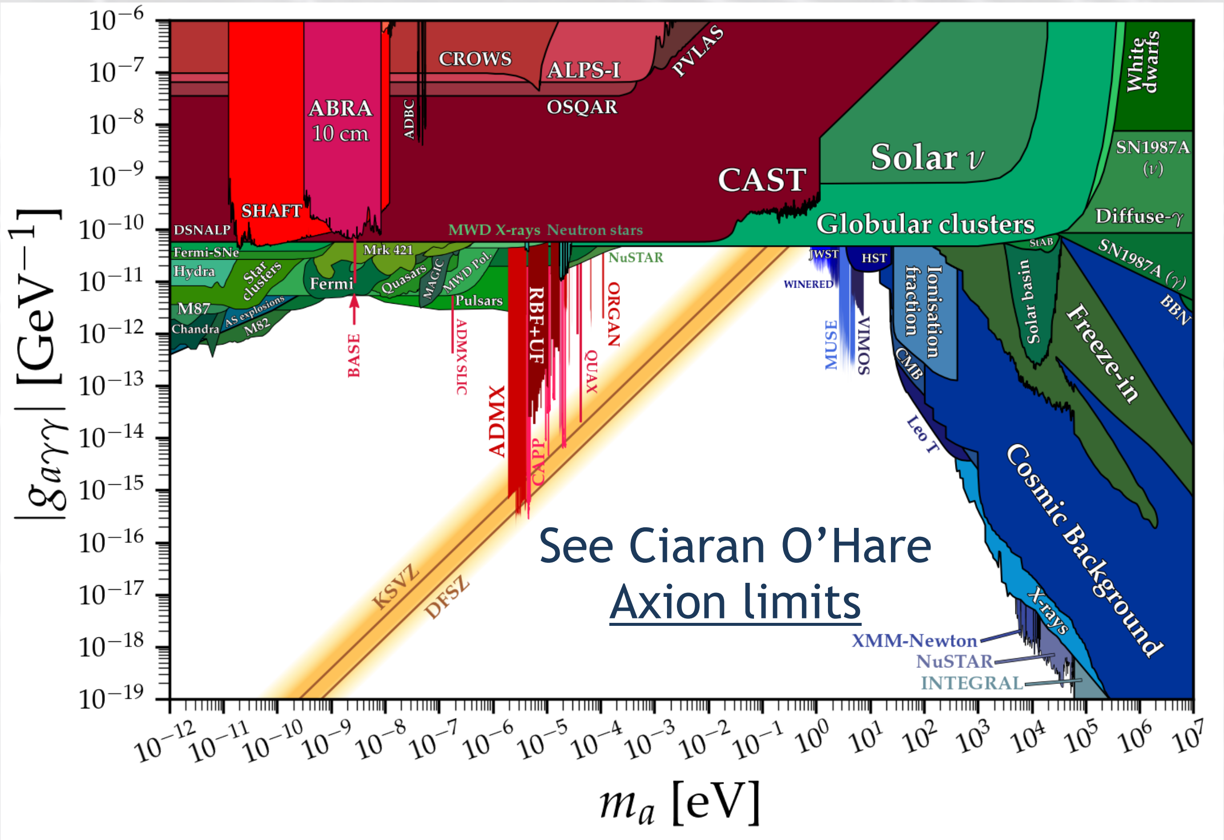
$$\mathscr{L} \supset \left(\frac{a}{f_a} + \theta\right) \frac{1}{32\pi^2} G\tilde{G}$$

Symmetry: $a \to a + \alpha f_a \,, \theta \to \theta - \alpha$

Generate other couplings via **RGE**:

$$\mathscr{L} \supset \frac{\partial_\mu a}{f_Q} Q^\dagger \sigma^\mu Q$$

Many technical details to UV origin, here just few comments on axion EFT…



For a proper intro axions see e.g. the TASI lecture notes by Anson Hook

Axions and the strong CP problem

Technical Naturalness à la ’t Hooft: a given parameter is allowed to be small if it enhances the symmetry of the Theory

Give Symmetry origin to a small $\bar{\theta}$? e.g. Left-Right symmetry, many approaches …

(QCD-) **Axions**:

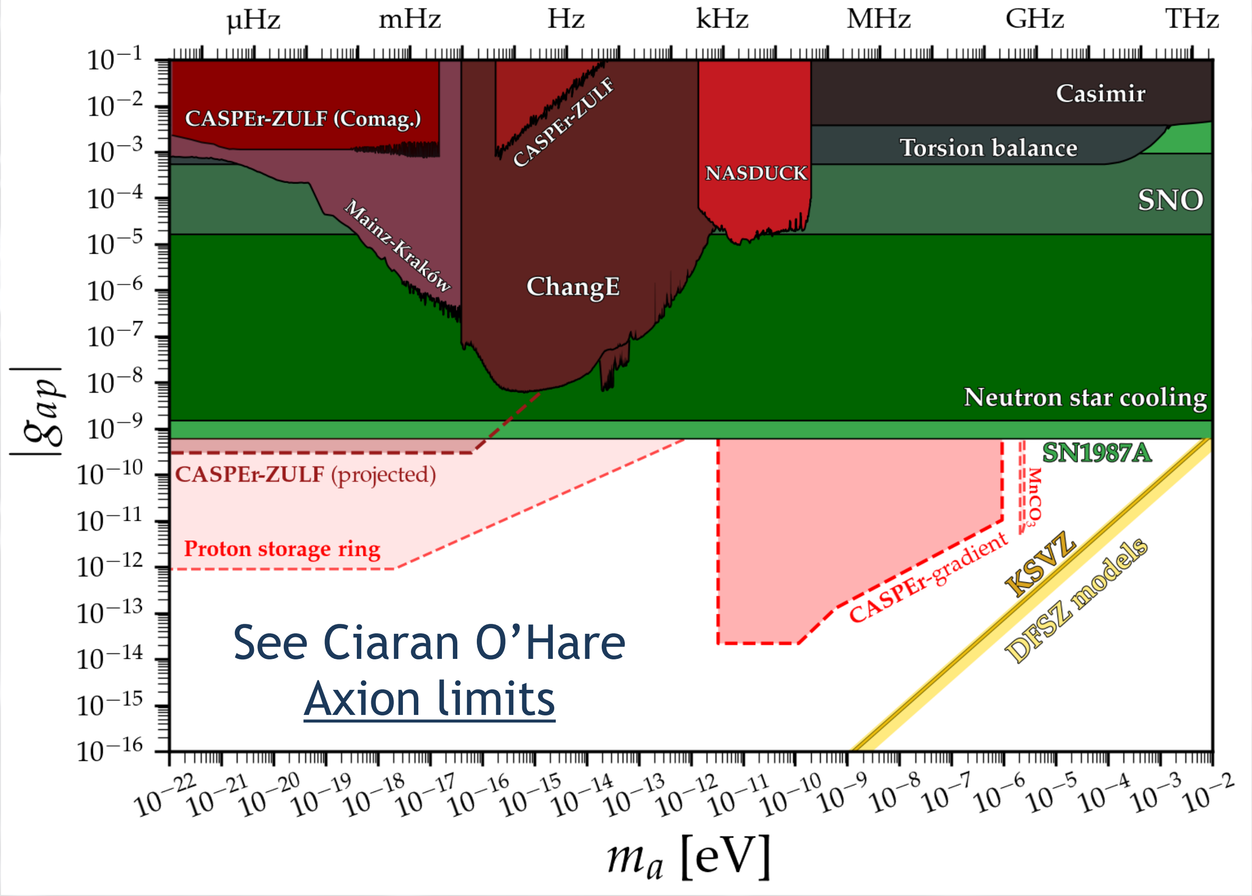
$$\mathscr{L} \supset \left(\frac{a}{f_a} + \theta\right)\frac{1}{32\pi^2}G\tilde{G}$$

Symmetry: $a \to a + \alpha f_a \,, \theta \to \theta - \alpha$

Generate other couplings via **RGE**:

$$\mathscr{L} \supset \frac{\partial_\mu a}{f_Q} Q^\dagger \sigma^\mu Q$$

Many technical details to UV origin, here just few comments on axion EFT…



For a proper intro axions see e.g. the TASI lecture notes by Anson Hook

Supernovae

Some fun facts:

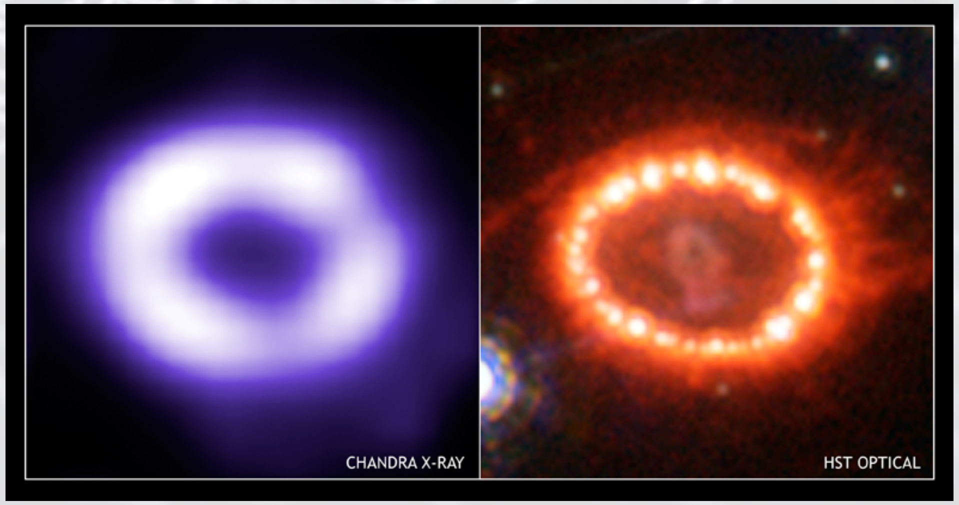
(For everything else see Cosmo-session and Mael's talk)

- Use Type Ia Supernovae e.g. as Standard Candles for distance measurements

  Maaaaany observations

- Observed **1 (one)** supernova with Neutrino burst: **SN 1987A**
- Supernova 1987A was a **Core collapse Supernova (Type II)**
- $\sim 10^{58}$ were neutrinos emitted, 25 observed

  TWENTY-FIVE

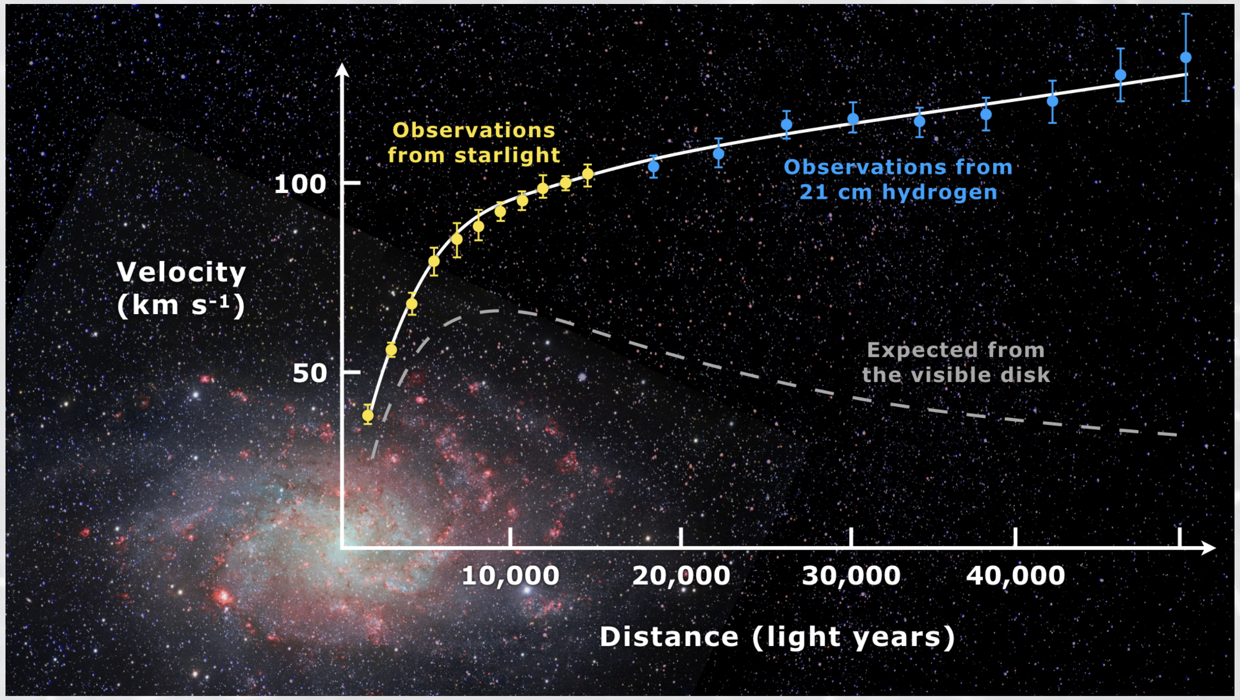


- Also spectral measurements
- Supernova models rely on this data
- Use Supernovae as Ultra-high-luminosity particle physics laboratories

Dark Matter & Astrophysics

Evidence for Dark Matter

- Galaxy rotation curves do **not** follow expectations for visible matter

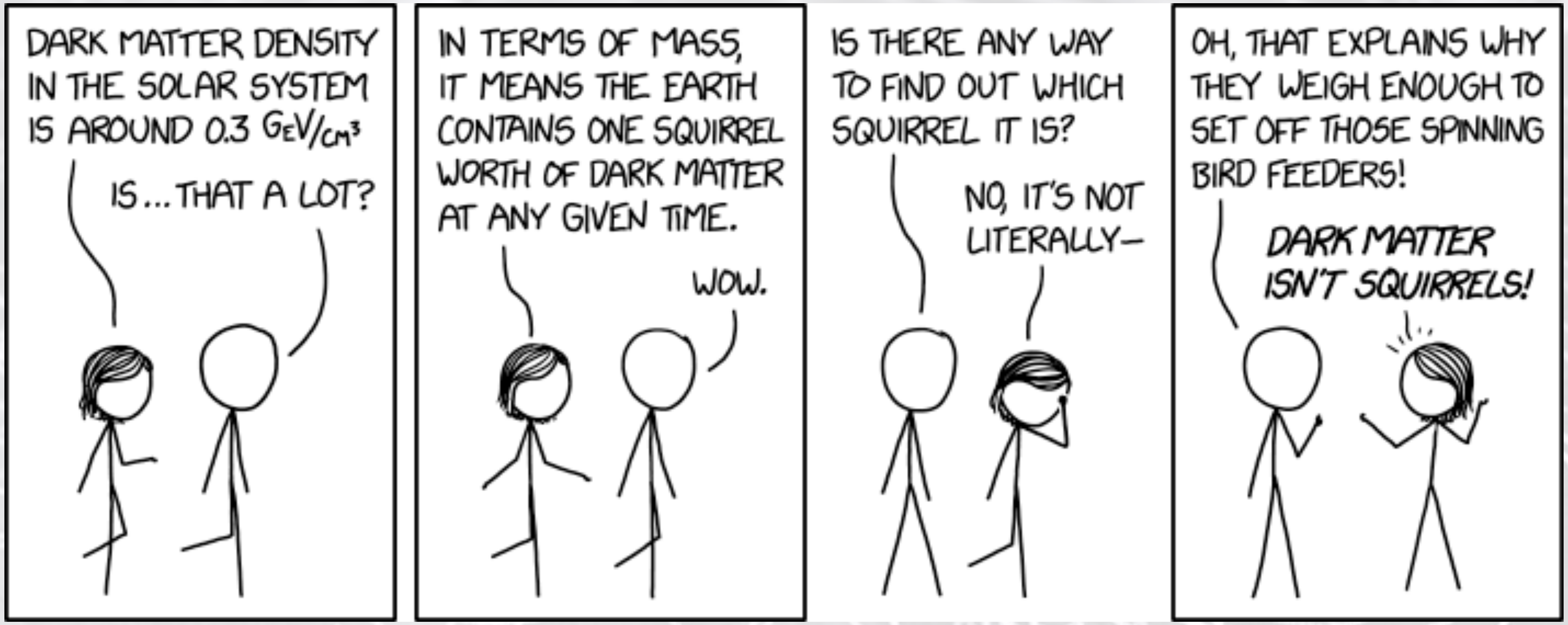


- **Bullet Cluster**: Colliding galaxies visible matter does not explain result

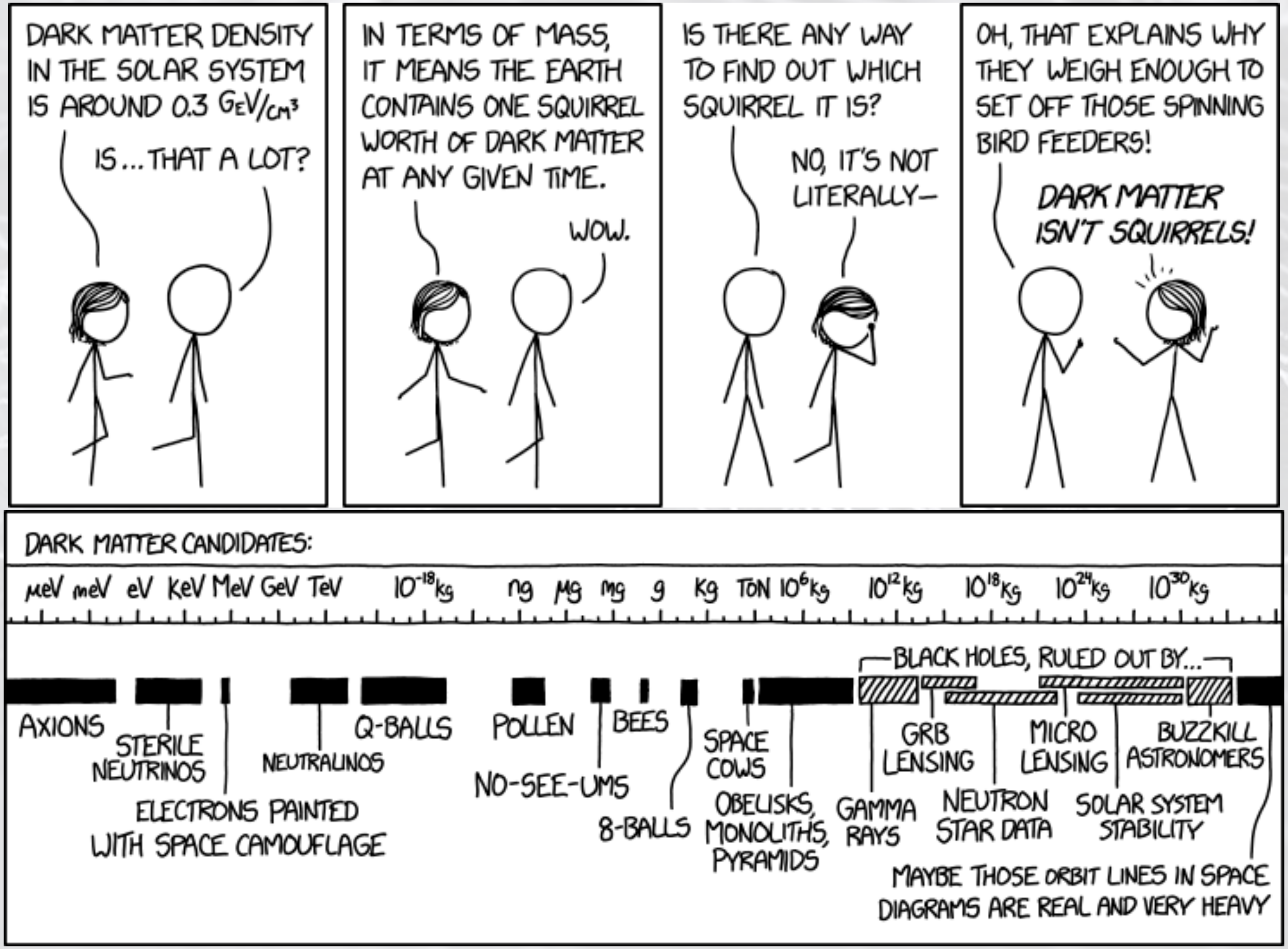
- (Large) Structure formation does not work with visible matter
- **CMB** multipole spectrum, **BAO's**, **Redshift** distortions, Lyman-α forrest, …

Some of these (but not all) are explainable with modified gravity, or MOdified Newtonian Dynamics (**MOND**)

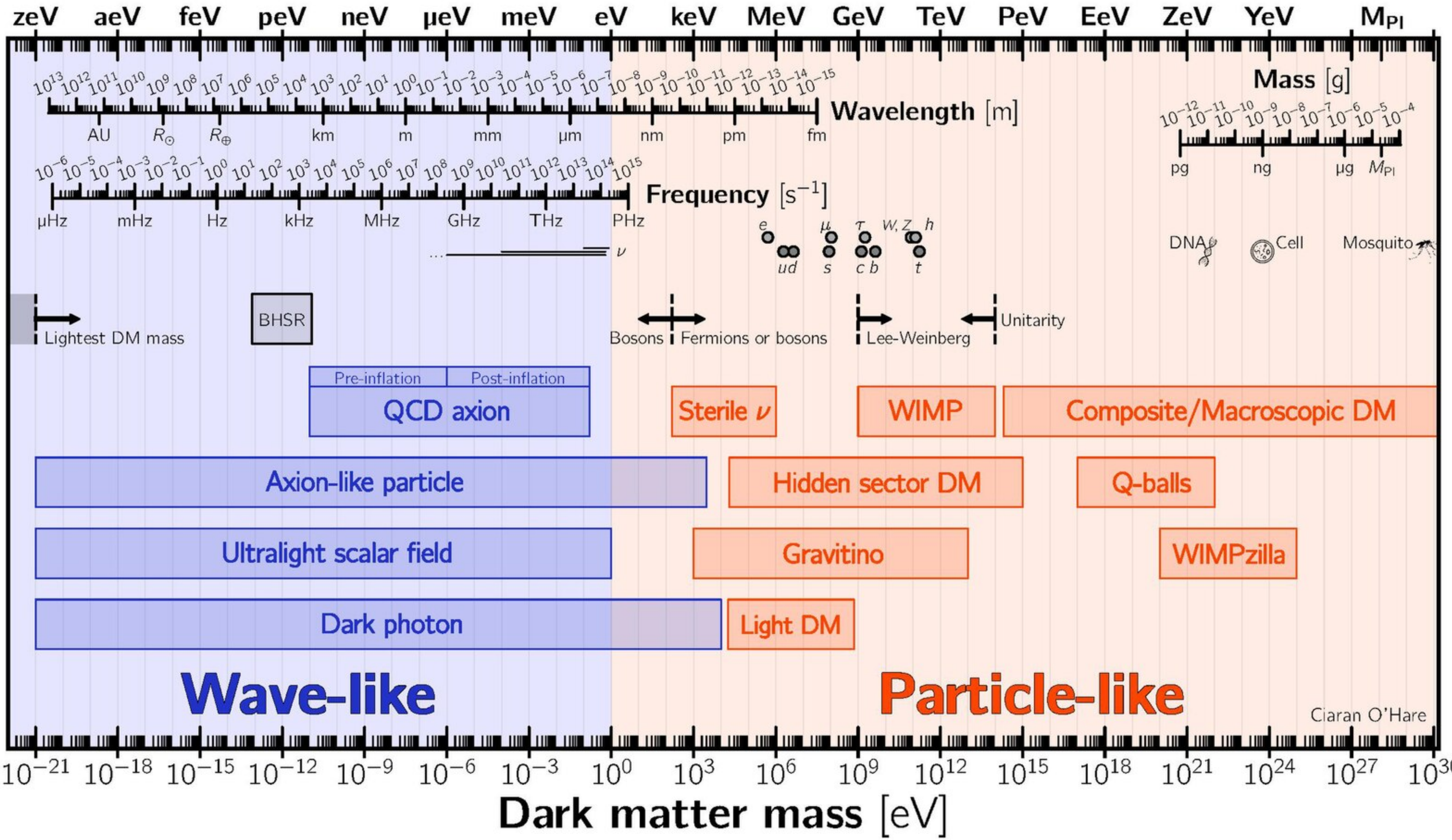
What is Dark Matter?



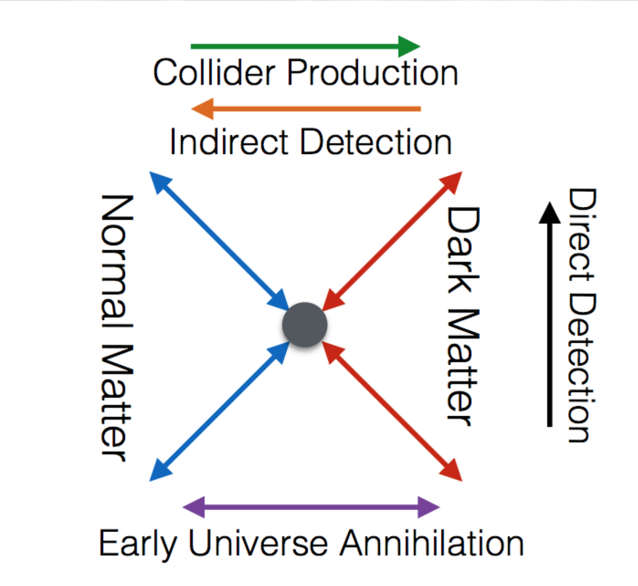
What is Dark Matter?

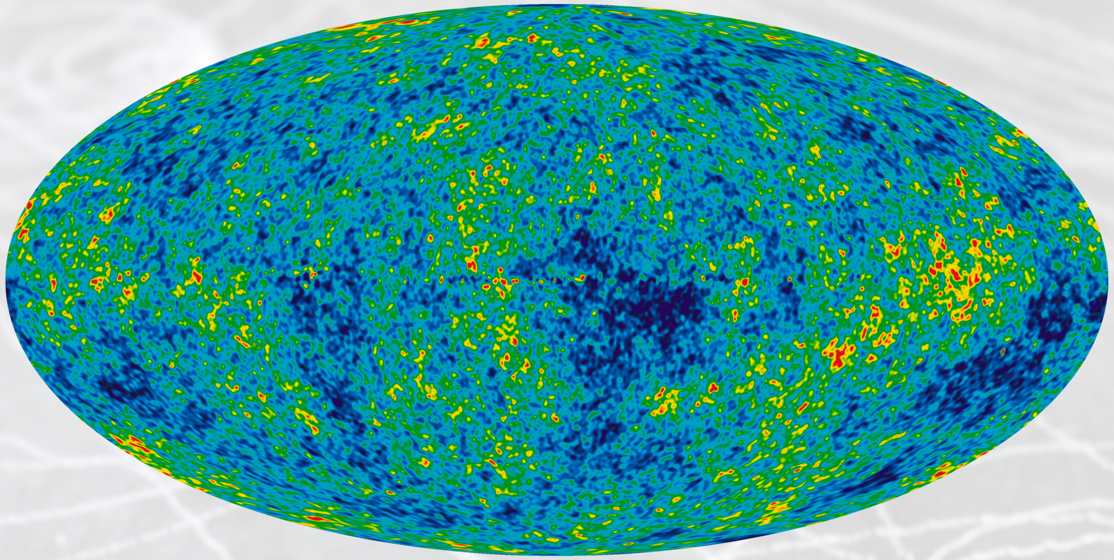


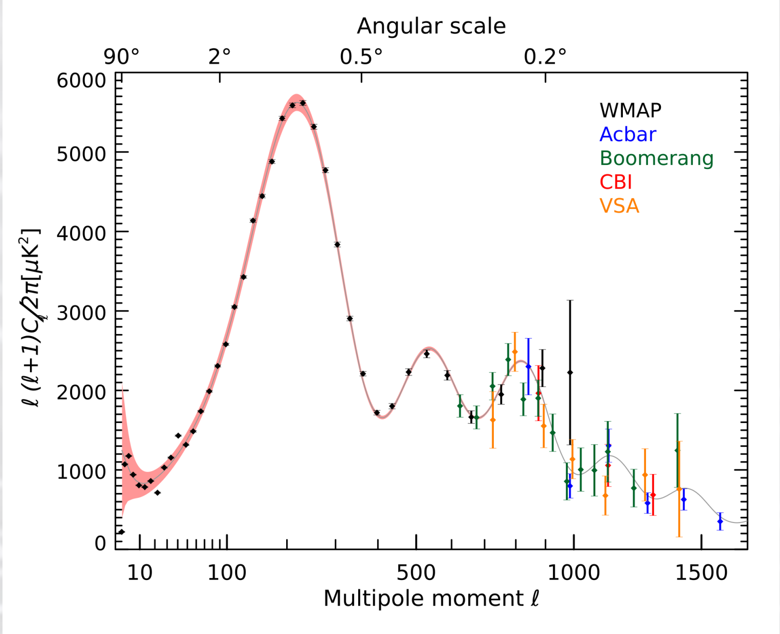
What is Dark Matter?



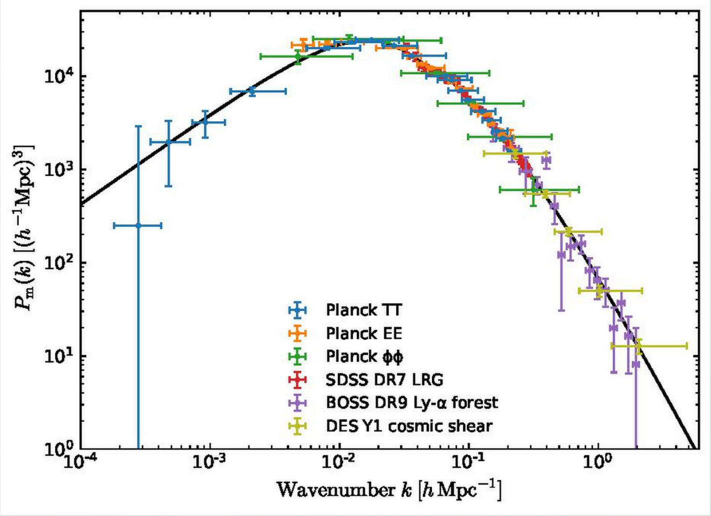
How do we find Dark Matter?



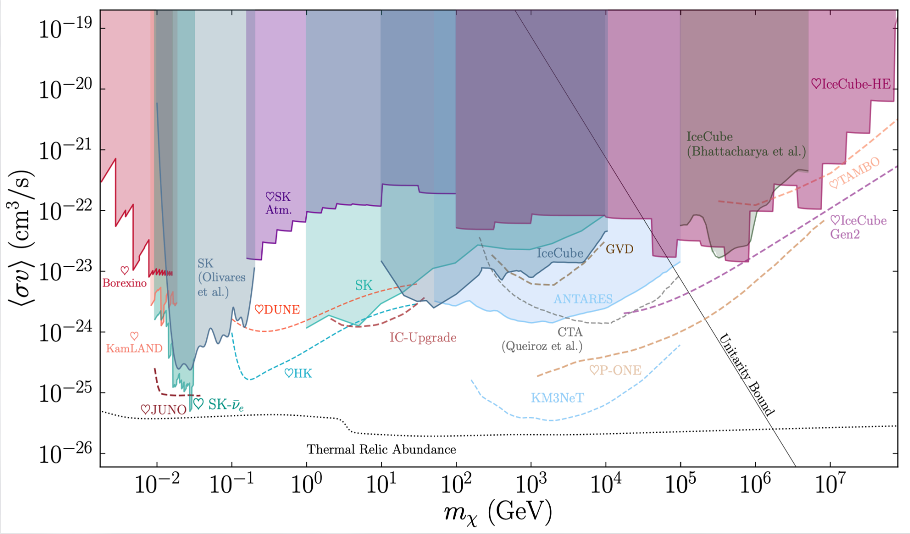




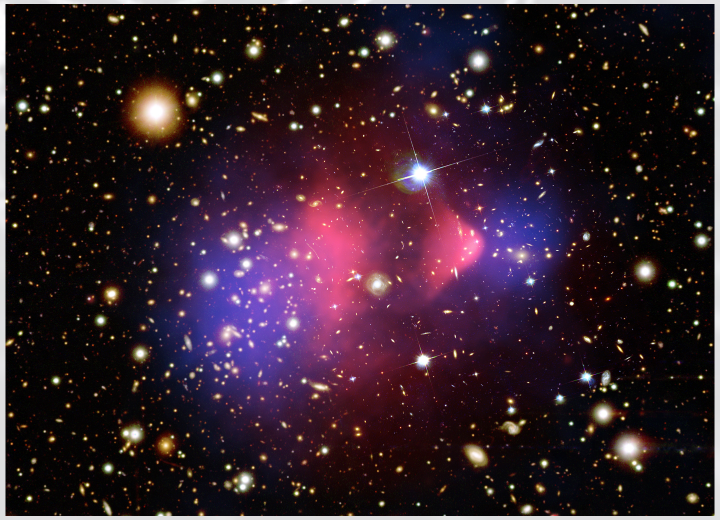
Structure formation: Cold or warm DM?



Detection on Earth?



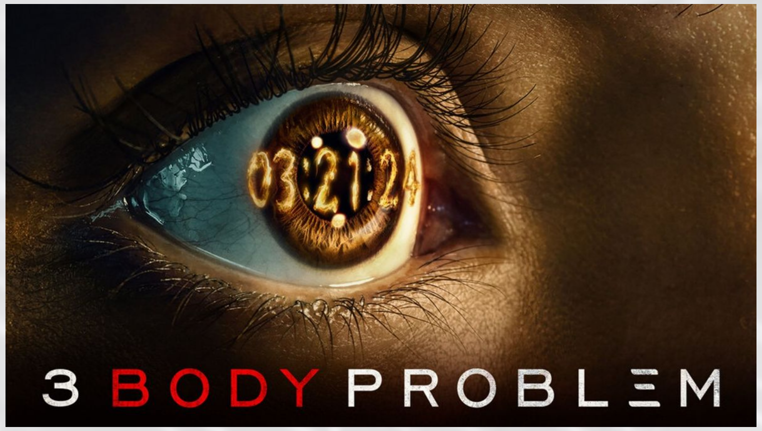
Bullet Cluster: Self-interactions?



Today: Indirect detection of Dark Matter (and how to escape it): Margaux's talk

Nuclear Theory

Nuclear Theory in a nutshell



The problem: **many body interactions**

Few particles: $2 \to 2$, $2 \to N$ scatterings, $1 \to N$ decays

Many many particles: Describe ***collective behaviour***

⇒Statistical Mechanics: **Gases, Fluids, Plasmas**, …

⇒ Low energy: **condensed matter, soft matter, crystals**, …

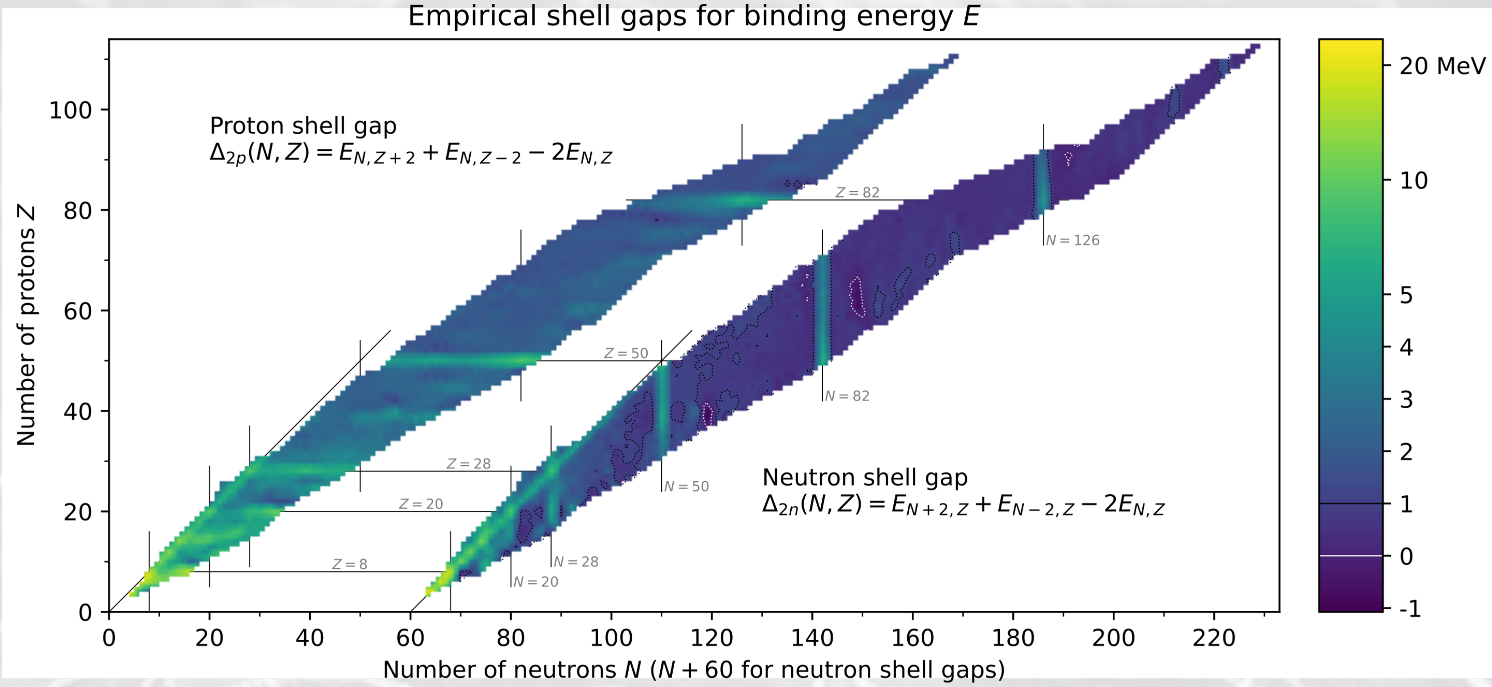
Nuclear Physics somewhere in between …

Need to model **strong interactions** between **(many)** nucleons

Require ***large-scale*** computations (expensive)

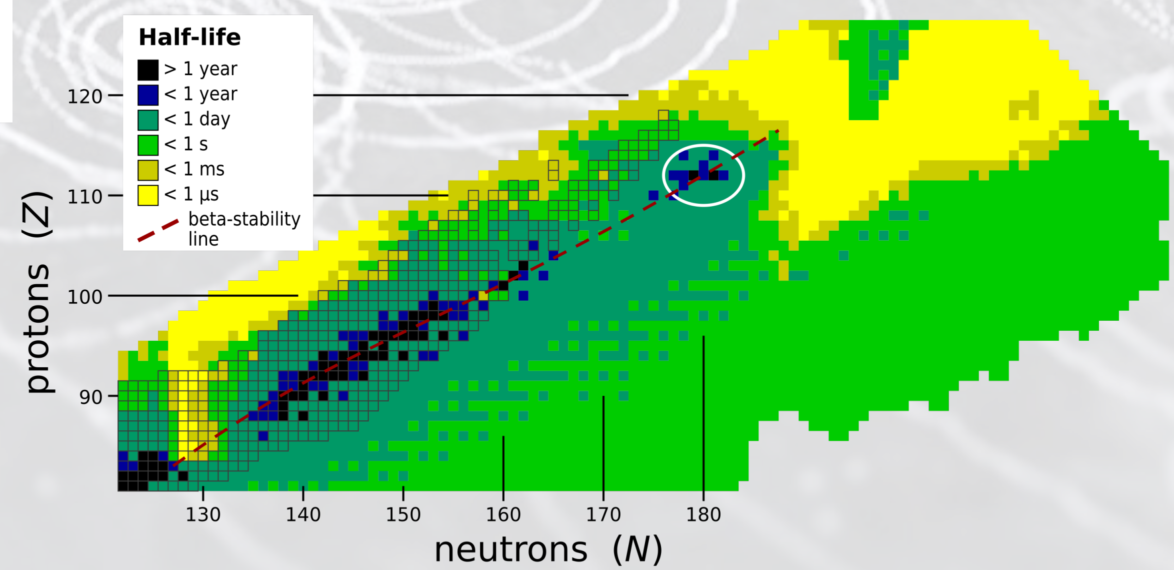
Shell model

Explain **Magic Numbers:** 2 , 8 , 20 , 28 , 52 , 82 , 126, …



…184 ???

Describe basic Nuclear structure



Predict "Island of Stability"

Many more (and more advanced approaches):

Large Scale Shell Model (LSSM), (Relativistic) (Quasi) Random Phase Approximation, Open Quantum Systems, …

(For everything else see Nuclear session and Oscar's talk)

Why Nuclear Theory?

Experimentalists and Theoreticians across all Energy scales rely on Nuclear Theory:

- Cosmology: Big Bang Nucleosynthesis (BBN)
- Astrophysics: Theory of Stars, Supernovae, etc, …
- Particle Physics: Neutrino Experiments @ Nuclear Reactors, test SM in Nuclear transitions, β-decay experiments, …
- Industry/everyday life: Nuclear Reactors, Imaging technologies for Medicine, Radiotherapy, …

Why theoretical high-energy Physics ?

because it is *fun*, duh! 🥳

Why theoretical high-energy Physics ?

Ok it's also useful:

- Describe an make sense of phenomena across all settings and **energy scales**
- Even if abstract, it is **physics**, think e.g. about the **no-lose "theorem"**
- Necessary for experiments: think of all the theory in **GEANT4, Pythia, …**

Enjoy the session :)