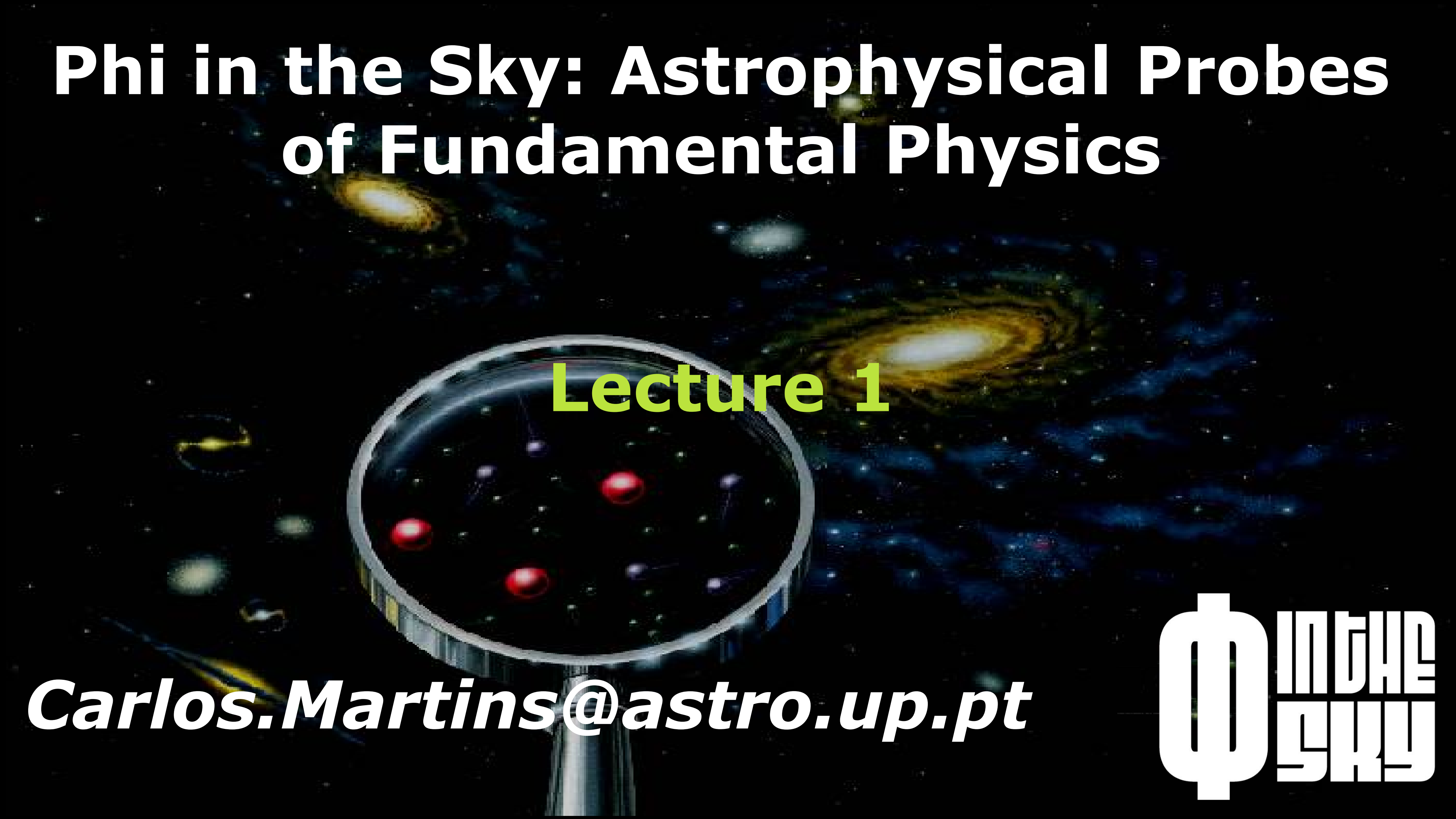

Phi in the Sky: Astrophysical Probes of Fundamental Physics

Lecture 1

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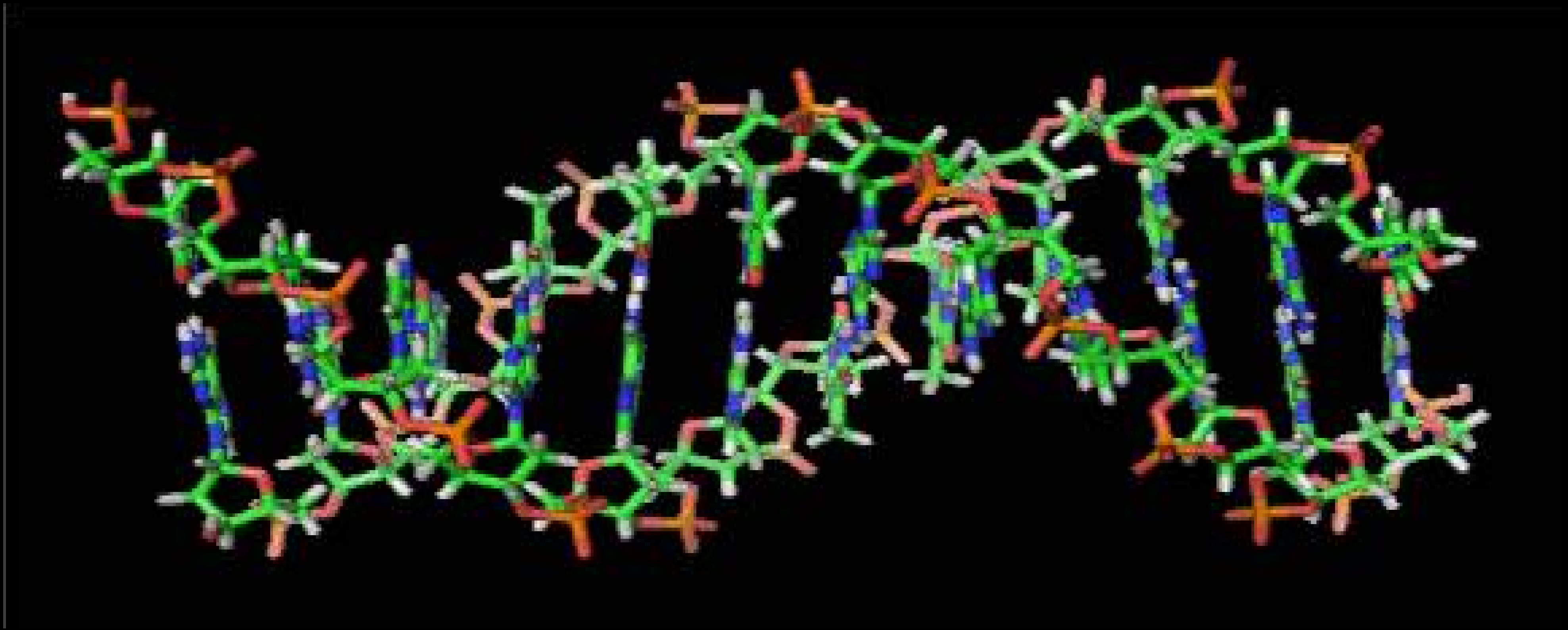
Is this a dog?

Is this a dog?

Precision Taxonomy



So What's Your Point?

Acceleration of the universe shows that our theories of cosmology and particle physics are incomplete (and possibly incorrect)

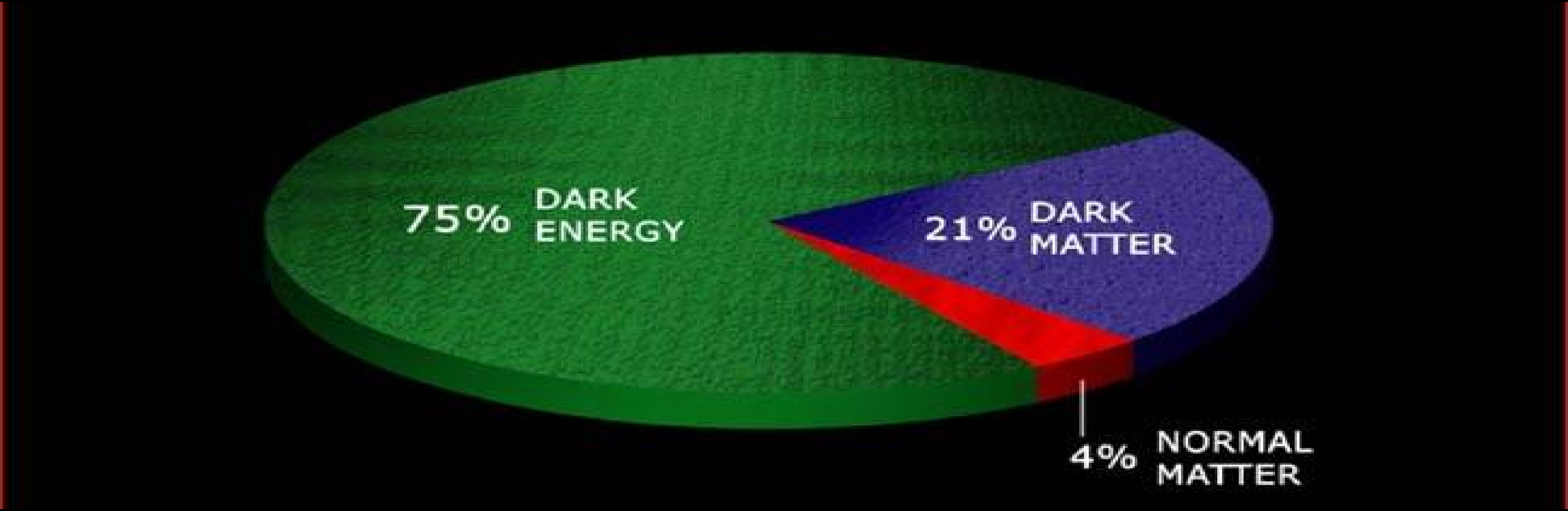
Is dark energy a cosmological constant (i.e. vacuum energy)?

- If yes, it's 10^{many} times below Quantum Field Theory expectations
- If no, the Einstein Equivalence Principle is violated

New physics is out there, waiting to be discovered; we must search for, identify and characterize this new physics

I will highlight the current role of high-resolution spectroscopy in this quest, and the requirements to keep it competitive in the 2030s

The Dark Universe: a new Neptune or a Vulcan?



Further Hints of New Physics

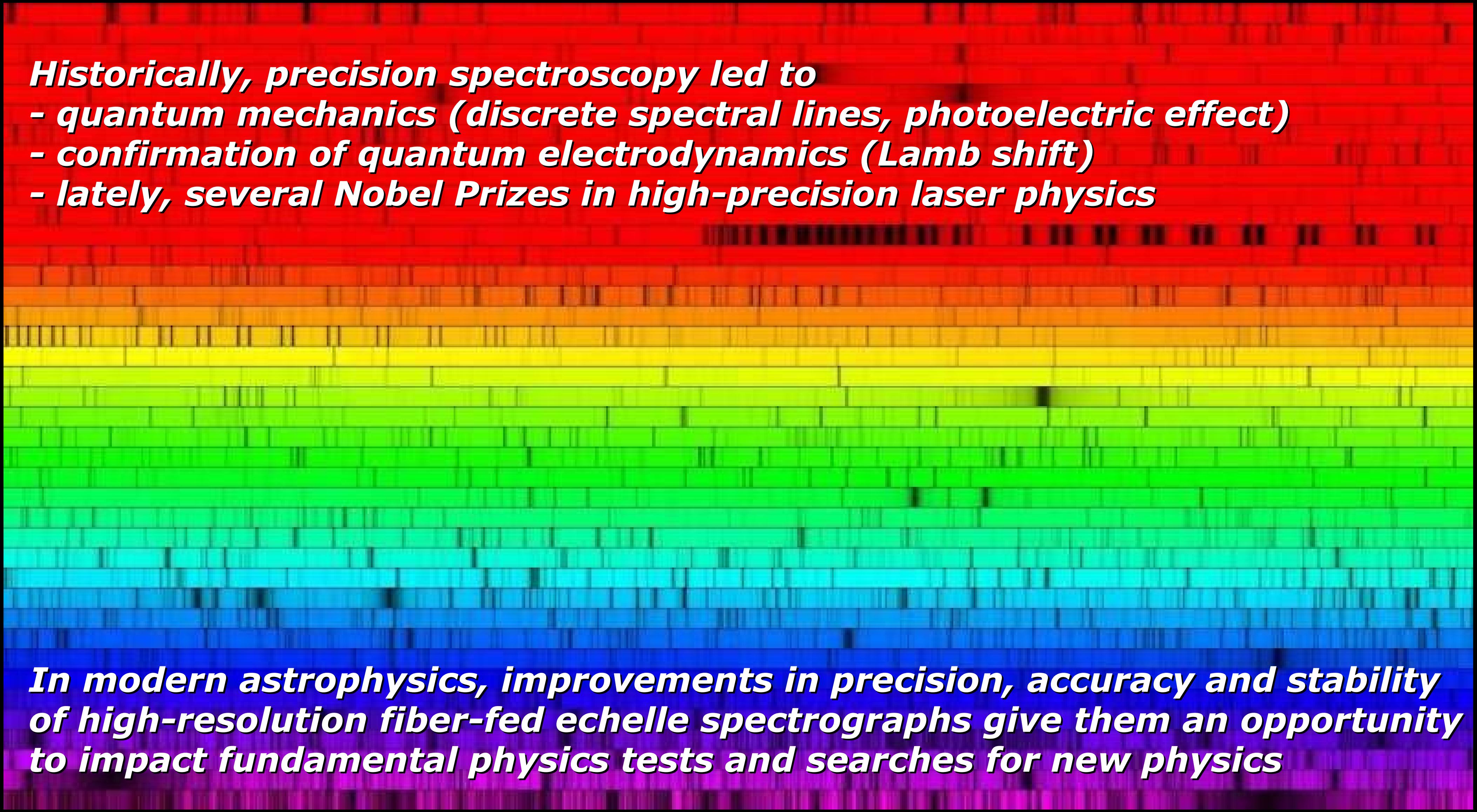
Three firmly established facts which the standard model of particle physics can't explain:

- Neutrino masses: Key recent result in particle physics, needs new ad-hoc conservation law or phenomena beyond current framework.
- Dark matter: no Standard Model object or particle can account for all the dark matter required by observations.
- Size of baryon asymmetry: A BAU mechanism does exist, but fails given the measured values of the parameters controlling it.

Our confidence in the standard model that leads us to the expectation that there must be new physics beyond it

- All have obvious astrophysical and cosmological implications

Progress in fundamental particle physics increasingly depends on progress in observational cosmology

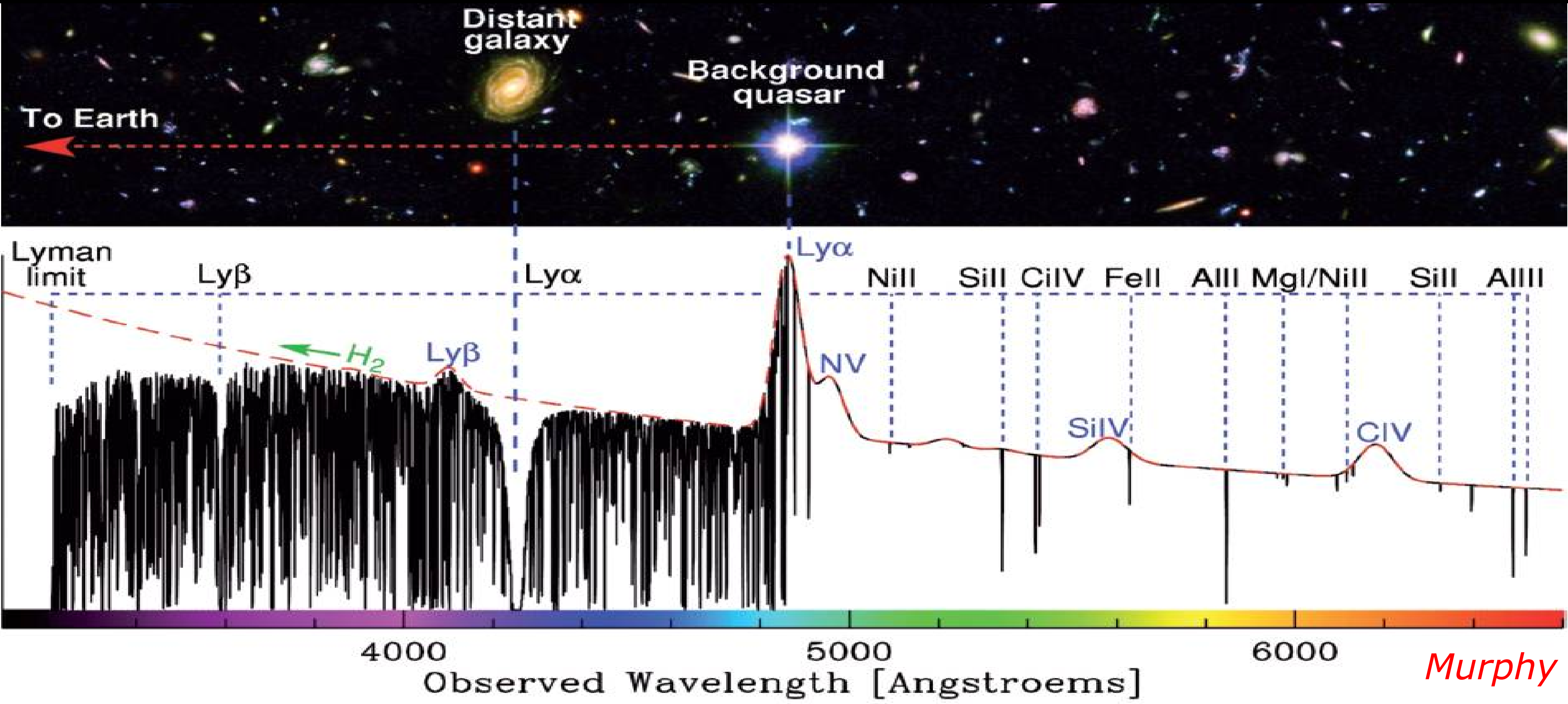


Historically, precision spectroscopy led to

- *quantum mechanics (discrete spectral lines, photoelectric effect)*
- *confirmation of quantum electrodynamics (Lamb shift)*
- *lately, several Nobel Prizes in high-precision laser physics*

In modern astrophysics, improvements in precision, accuracy and stability of high-resolution fiber-fed echelle spectrographs give them an opportunity to impact fundamental physics tests and searches for new physics

Precision Spectroscopy in Astrophysics



Murphy

What is Fundamental Physics?

Tests of fundamental laws and symmetries

- Equivalence Principle, Laws of Gravity, Spacetime structure and dimensionality, Foundations of quantum mechanics, etc.

Characterization of fundamental constituents

- Scalar fields (Higgs, dark energy, …), new particles for dark matter, magnetic monopoles, fundamental strings, etc.

Fundamental theories (string theory, quantum gravity, etc) generically lead to violations of standard principles

- Fundamental couplings dynamical, violating Einstein Equivalence Principle
- Gravitational laws modified, impacting expansion history of the Universe
- Space-time structure (sometimes) modified, violating Lorentz Invariance

Scalars, Because They Are There

We know since 2012 (thanks to the LHC) that fundamental scalar fields are among Nature's building blocks

Cosmological scalar fields will naturally couple to the rest of the model, leading to long-range forces and 'varying constants'*

- Well-known result [Dicke 1964, Carroll 1998, Damour & Donoghue 2010, …]

E.g., electromagnetic sector couplings yield spacetime variations of the fine-structure constant, with multiple testable fingerprints

- Even (improved) null results are important, and often very competitive

** Any scalar field couples to gravity; it couples to nothing else if a global symmetry suppresses other couplings. But quantum gravity effects don't respect global symmetries, and string theory has no unbroken global symmetries [Banks & Dixon 1988].*

Scalars, Because They Are There

Does the Higgs have a cosmological counterpart?

  - Scalar fields are popular in cosmology because they can take a VEV while preserving Lorentz invariance
  - Vector fields or fermions would break Lorentz Invariance and give you problems with Special Relativity

Scalar fields play a key role in most paradigms of modern cosmology:

- Exponential expansion of the early universe (inflation)
- Cosmological phase transitions & their relics (cosmic defects)
- Dynamical dark energy powering current acceleration phase
- Varying fundamental couplings (rolling in time, rambling in space)

More important than each of these is the fact that they don't occur alone: this allows key consistency tests

Basics of Equivalence Principles

Two kinds of mass can be ascribed to a body:

- Inertial mass: proportionality factor between a force applied to it and the acceleration it acquires in response, in an inertial laboratory
- Gravitational mass: measures its ability to attract (active mass) or be attracted by (passive mass) any other body

Newton’s Equivalence Principle: $m_i \propto m_g$

  - whence the Universality of Free Fall: local acceleration of gravity is the same for all bodies, regardless of their mass and composition

Einstein noted this implies that the effect of gravitation is locally equivalent to the effect of an accelerated frame, and can be locally canceled – the Weak Equivalence Principle

The Einstein Equivalence Principle

WEP: The trajectory of a freely falling test body is independent of its mass, internal structure and composition (hence Universality of Free Fall)

LLI: In a local freely falling frame, non-gravitational physics is independent of the frame's velocity

LPI: In a local freely falling frame, non-gravitational physics is independent of the frame's location

In higher-dimensional theories, new interactions naturally appear which violate the Equivalence Principle at some level, including among others

- Massless scalar fields from string theory
- Vector fields from SUSY-inspired standard model extensions
- Lorentz invariance breaking from deviations from space-time continuum

Consequences

Theories obeying EEP are metric theories of gravity

- Space-time endowed with symmetric metric
- Freely falling bodies follow geodesics of this metric
- In local freely falling frames, non-gravitational physics laws are those of SR

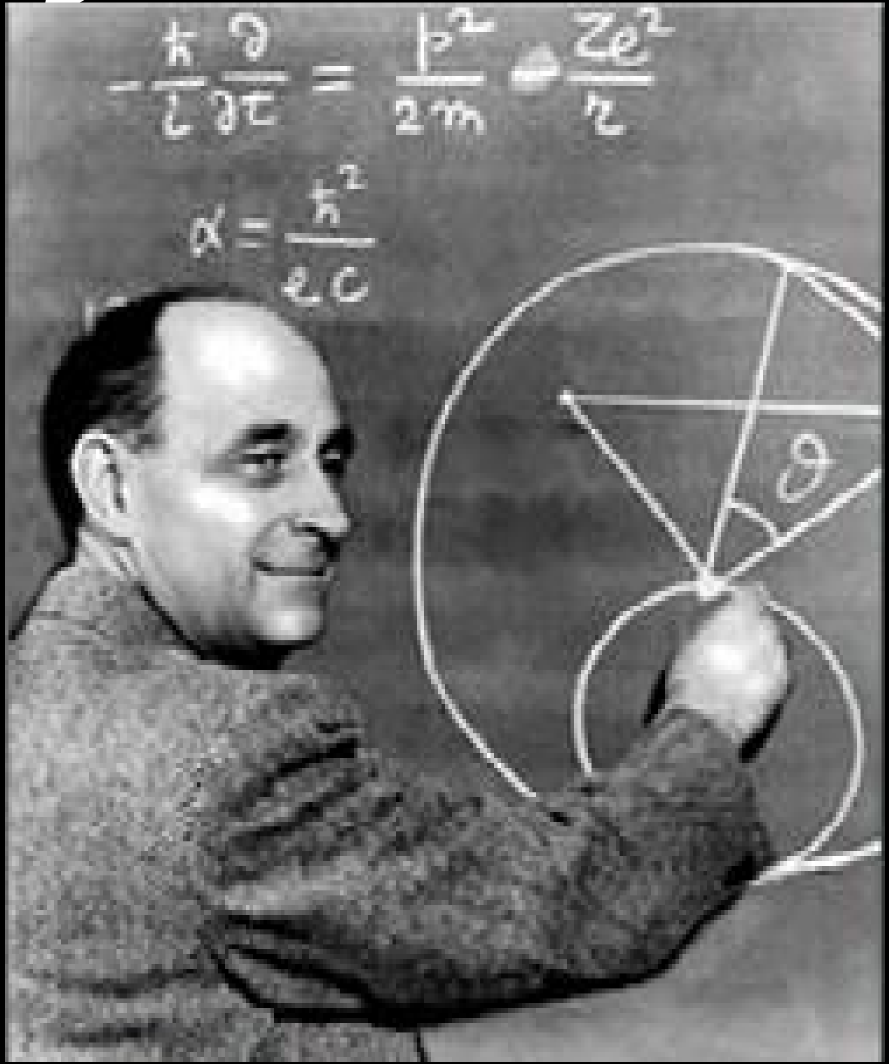
If EEP holds, the effects of gravity are identical to those of living in a curved space-time (i.e., gravity is a fictitious force)

- SEP contains EEP: special case where gravitational interactions are ignored
- If SEP holds there's one and only one gravitational field in the universe

GR and (plain vanilla) Brans-Dicke are metric theories of gravity, but superstring theory isn't

  - ...neither is any theory where varying non-gravitational couplings are associated with dynamical fields coupling to matter

Varying Fundamental Couplings



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Review

The status of varying constants: a review of the physics, searches and implications

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Constant? Fundamental? Varying?

Nature is characterized by some physical laws and dimensionless couplings, which we have assumed to be spacetime-invariant

- For the former, this is a cornerstone of the scientific method
- For latter, a simplifying assumption without further justification
- If they vary, all the physics we know is incomplete

We have no ‘theory of constants’ and do not know what role they play in physical theories

Improved null results are important and theoretically very useful; a detection would be revolutionary

Classification

An unsolved issue: no 'theory of constants' exists! *[Duff et al. 2002, Martins 2002, …]; a* useful classification is *[Lévy-Leblond 1979]*

- Type A: Properties of particular physical objects, e.g. masses and moments of fundamental particles
- Type B: Characteristics of classes of physical phenomena, e.g. coupling constants
- Type C: Universal constants, e.g. speed of light, Planck constant
- Type D: Invisible constants, e.g. isotropy of space, ratio of inertial and gravitational mass
- Type E: Constants indistinguishable from zero, e.g. mass of photon, neutrality of matter

The classification of some constants changes with time, and may be different in different theories!