Variation of fundamental constants:

Search for new physics around a supermassive black hole

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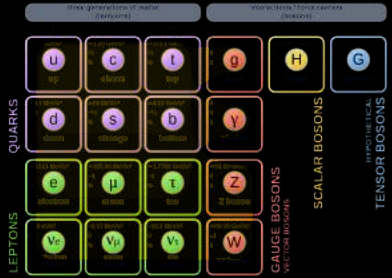
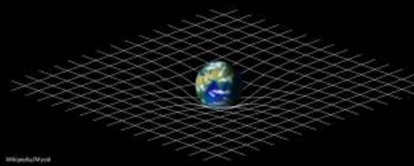
Current theory of the Universe



Standard Model: Quantum theory of particles + interactions

- Predicted new particles (W/Z bosons, quarks)
- Correctly predicts electron magnetic moment to 15 digits!



General Relativity: Einstein's theory of gravitation, space-time

- From precession of Mercury to gravitational waves at LIGO
- Tested from tiny (10^{-5} m) to extra-galactic length scales

However, all is not well...

Extraordinarily successful, however, several deep problems:

Matter–Anti-matter asymmetry

- The Big Bang should have created equal amounts of matter and antimatter.
- So why is there far more matter than antimatter in the universe?

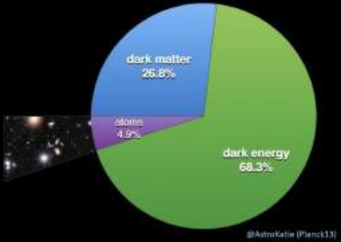
General Relativity + Quantum Mechanics: incompatible

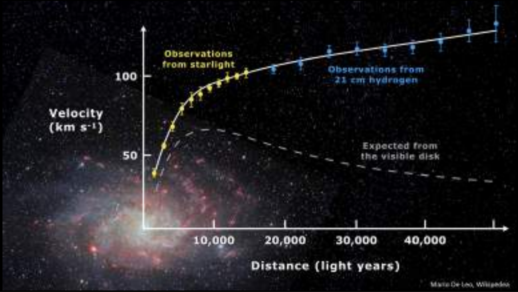
- Standard Model and general relativity are not compatible
- No working quantum theory of gravitation

Dark matter and dark energy

- Make up most ($\sim$ 95%) of the Universe – unexplained

- $\sim 80\%$ of matter in the universe
- Rotation curves + velocity dispersion
- Bullet cluster
- Gravitational lensing
- Structure formation

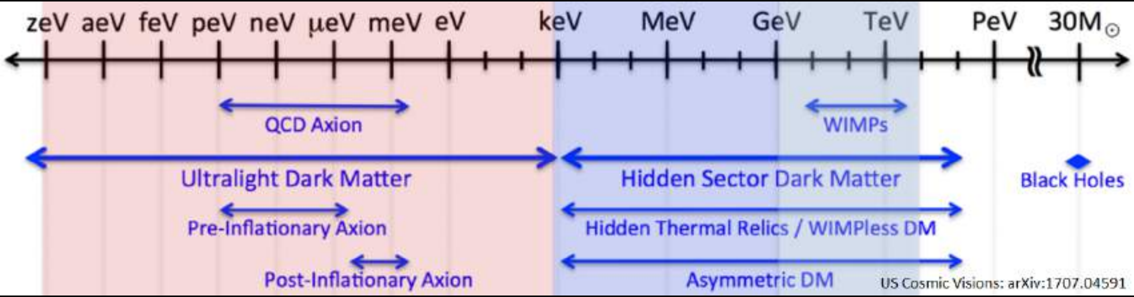




Dark matter: what we *don't* know

...everything else

- Possible mass range: spans 90(!!) orders-of-magnitude

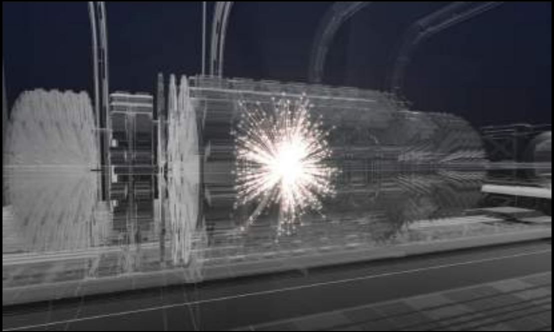


- Very strong evidence for some kind of new particles/fields – but we have no idea where to look

Search for physics *beyond* the Standard Model

Search for specific theories

- Other theories make *slightly* different predictions from SM+GR
- Dedicated experiment to test specific theories
- Targeted and precise: but narrow in scope
- Example: Large Hadron collider, CERN
- So far: no luck



CERN

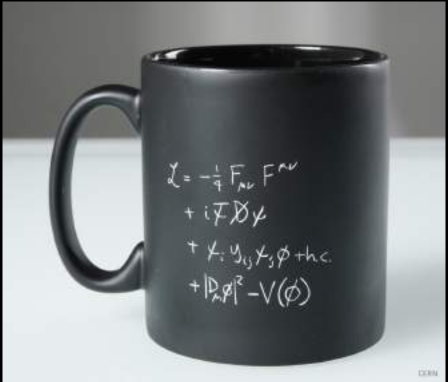
Search for strange/exotic signals: expect to find zero

- Look for physics not included in SM+GR
- Non-zero measurement is sign of new physics
- Example: Equivalence principal (laws of nature are the same everywhere)

Variation of Fundamental Constants

Are the laws of nature the same everywhere in the Universe?

Fundamental Constants



Not predicted by theory: have to be measured

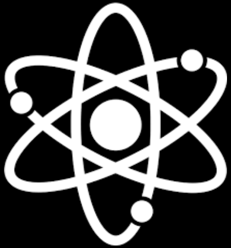
- Electron masses: $m_e \approx 9.109... \times 10^{-31}$ kg
- Electron charge: $-e \approx -1.602... \times 10^{-19}$ C
- Speed of light: $c = 299\,792\,458$ m/s

Some questions

- Why do they take their specific values?
- Fine tuning problem: if even slightly different: no atoms, no life (no one to ask this question)
- **Have they always had the same value? Are they the same everywhere?**

Fundamental Constants: not so constant?

- Issue: ambiguity from units



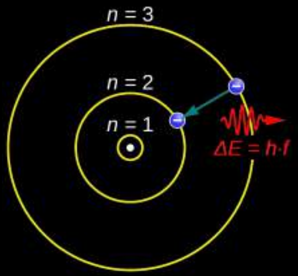
Unit-less ratios

- Mass ratio: $m_p/m_e \approx 1836.15267343$
- **Fine structure constant**
  - Determines strength of electromagnetic interactions

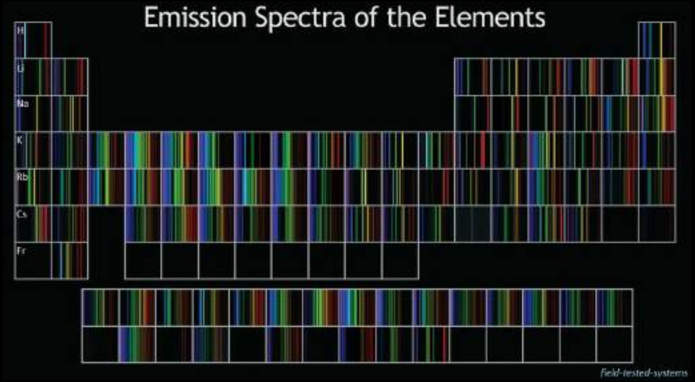
$$\alpha = \frac{e^2}{4\pi\epsilon_0\,\hbar c} \approx \frac{1}{137}$$

Atomic Transitions

- Atomic electrons occupy specific orbitals
- Electrons can jump between orbitals: absorb/emit photons of light
- Transition only occurs at specific frequency matches energy gap: $f = \Delta E / h$
- Energy, and thus frequency, depend on **fundamental constants**



JabberWok/Wikipedia

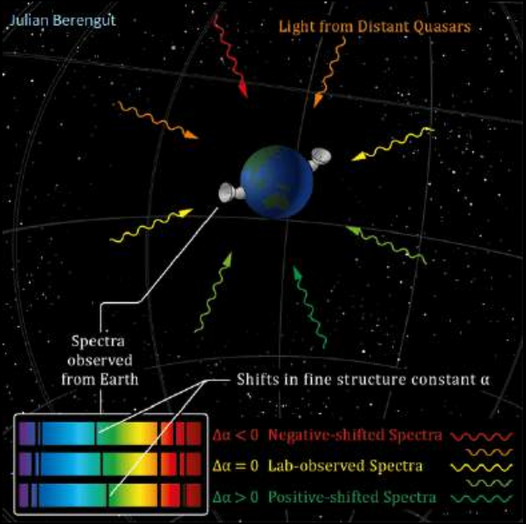


Fundamental Constants – how to observe

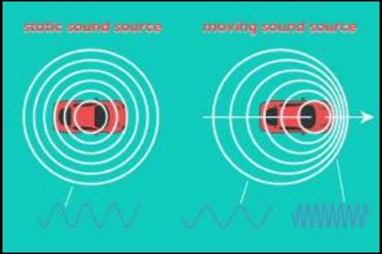
- Observe spectra from distant stars
- Compare to measurements on Earth
- Wavelengths (frequencies) differ: variation in α?

- **Problem:** What about red-shift?

- Universe expansion (+ motion of stars)
- Wavelengths *will* be different (Doppler effect)



Sensitivity Coefficients

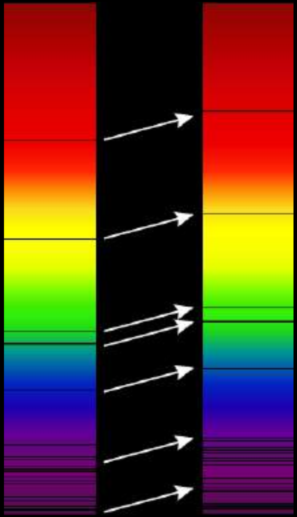


Brad Williams/soundfly.com

- Each transition depends on α *differently*

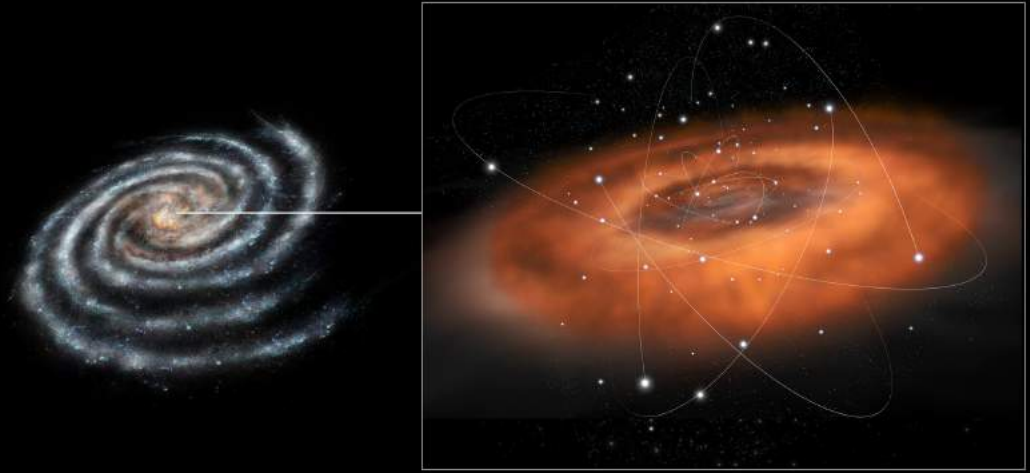
$$\boxed{\frac{\delta f}{f} = K \frac{\Delta \alpha}{\alpha}}$$

- K (sensitivity coeficient) must be *calculated*
- Need to observe multiple spectra
- K larger for heavy atoms



Wikipedia/Georg Wiora

Fundamental Physics with the Super-massive black hole



ESA / C. Carreau

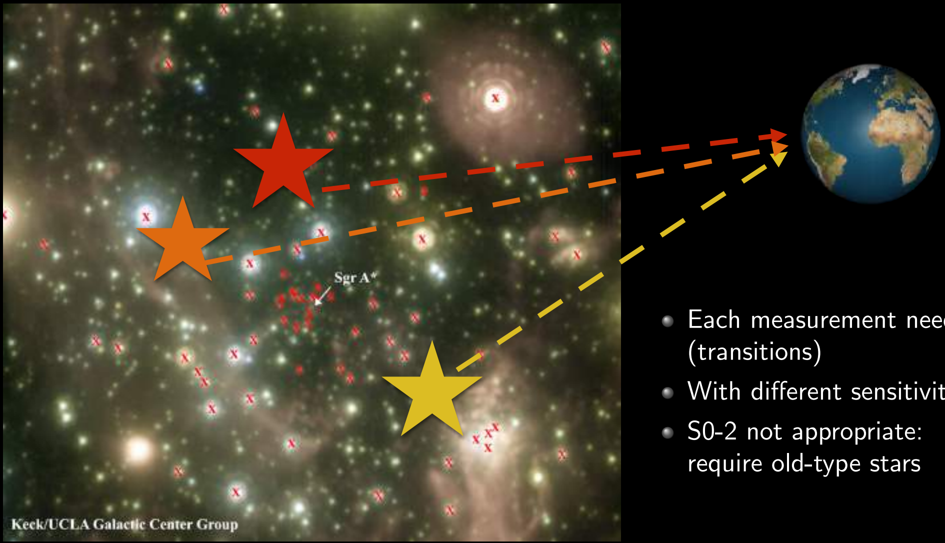
Observing super-massive black hole

- with UCLA Galactic Centre Group
  - Observations led by Tuan Do
  - Andrea Ghez: Awarded 2020 Nobel prize for discovery of black hole
- Keck telescope in Hawaii
- Motion of $\sim$1000 stars tracked
- Precise spectroscopy for many stars

ethantweedie.com/

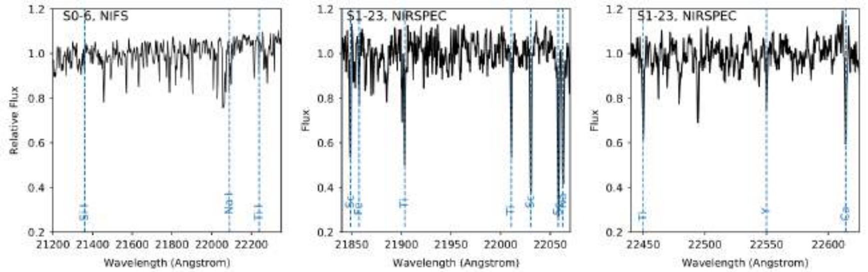
- High gravitational potential
- Possibly large concentration of dark matter
- Could this affect fundamental constants?

Search for variation in α close to Black Hole at Galactic Centre

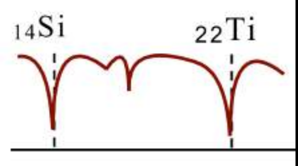


- Each measurement needs 2 lines (transitions)
- With different sensitivity to α (K)
- S0-2 not appropriate: require old-type stars

Spectroscopy in high gravity



- Thousands of transitions observed: require clear extraction
- Identified 15 suitable transitions in 6 stars
- Compute K sensitivity coefficients
- Fit for red-shift and variation in α simultaneously



• Hees, Do, Roberts, Ghez *et al.* Phys. Rev. Lett. 124, 081101 (2020).

Results and future improvements

- Didn't find significant deviation from zero:

$$\frac{\Delta\alpha}{\alpha_0} = (1.0 \pm 5.8) \times 10^{-6}$$

- Can constrain specific models (no deviation from GR found):

$$\frac{\Delta\alpha}{\alpha_0} = \beta\frac{\Delta U}{c^2} \quad \Longrightarrow \quad \beta = 3.6 \pm 12$$

- Current: incidental data
- Dedicated measurements: more transitions, better statistics
- Stars closer to the Black Hole (higher gravity)
- More favourable atoms (higher sensitivity)
- Improvements in spectroscopic instruments
- $\Longrightarrow$ up to 4 orders-of-magnitude improvement in future

$$\frac{\Delta\lambda}{\lambda} = \frac{\overbrace{\lambda(z,\alpha)}^{\text{Observed}} - \overbrace{\lambda(z=0,\alpha_0)}^{\text{Earth value}}}{\lambda(z=0,\alpha_0)} = \overbrace{z}^{red-shift} - \underbrace{K}_{sensitivity}(1+z)\frac{\overbrace{\Delta\alpha}^{Target}}{\alpha}$$