Search for a Variation of the Fine Structure Constant around the Supermassive Black Hole in Our Galactic Centre

Benjamin M. Roberts (UQ)

Aurelien Hees (SYRTE), Tuan Do (UCLA)
UCLA Galactic Center Group (Andrea Ghez *et al.*)
National Astronomical Observatory of Japan Team

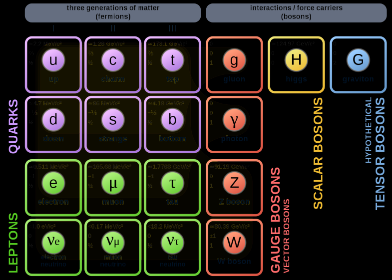
AIP2022 – Australian Institute of Physics Congress

Adelaide, Australia

16 December 2022

Current theory of the Universe

- **Standard Model + General Relativity**



Extraordinarily successful, however, several deep problems:

Matter–Anti-matter asymmetry

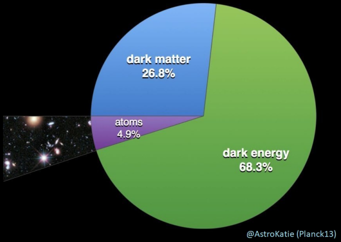
- The Big Bang should have created equal amounts of matter and antimatter.
- So why is there far more matter than antimatter in the universe?

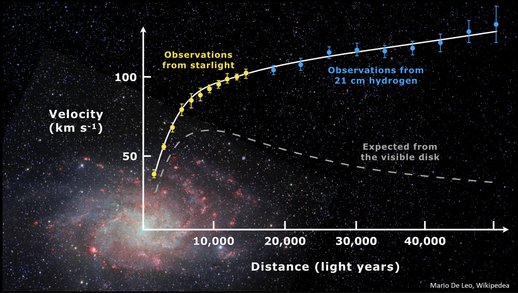
Dark matter and dark energy

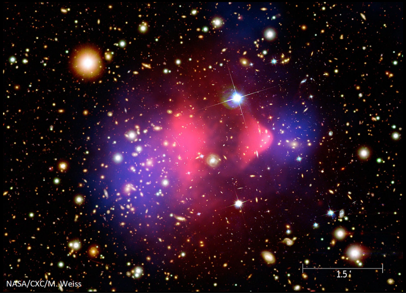
- Make up most ($\sim 95\%$) of the Universe – unexplained

Dark Matter: what we know

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



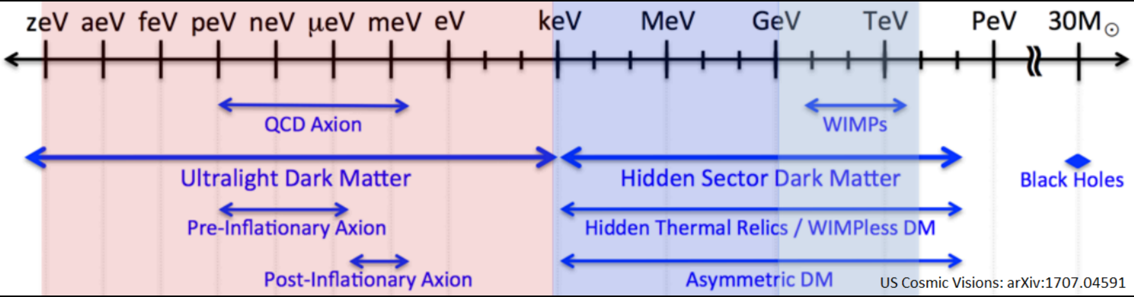




Dark matter: what we *don't* know

...everything else

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

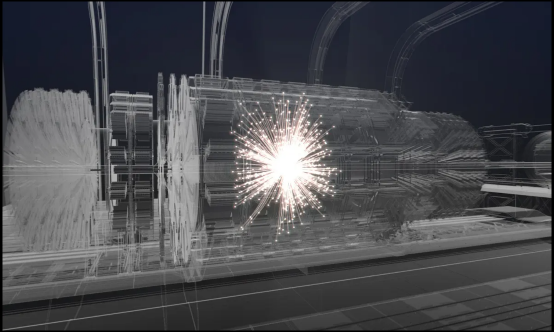


- Very strong evidence for some kind of new particles/fields – but we have no idea where to look

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



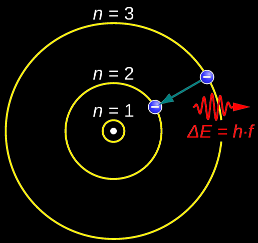
CERN

Search for strange/exotic signals: expect to find zero

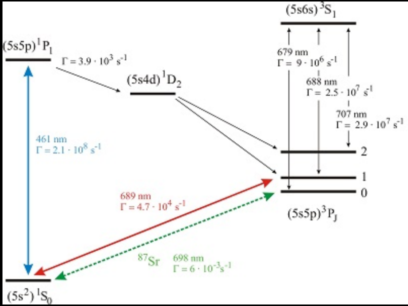
- Look for physics not included in SM+GR
- Non-zero measurement is sign of new physics
- Example: Equivalence principal (laws of nature are the same everywhere)

Variation of Fundamental Constants: Atomic Transitions

- Energy, and thus frequency, depend on **fundamental constants**



JabberWok/Wikipedia



$$\omega^A = \underbrace{F_A(\alpha)}_{\text{Transition-specific}} \times \underbrace{m_e c^2 \alpha^2}_{\text{Units}}$$

- Unit-dependence cancels in ratios – must measure dimensionless ratios

Dzuba, Flambaum, Webb, PRL**82**, 888 (1999); Kozlov, Budker, Ann.Phys. 1800254 (2018).
Savalle, Hees, Frank, Cantin, Pottie, BMR, Cros, McAllister, Wolf, PRL**126**, 051301 (2021)

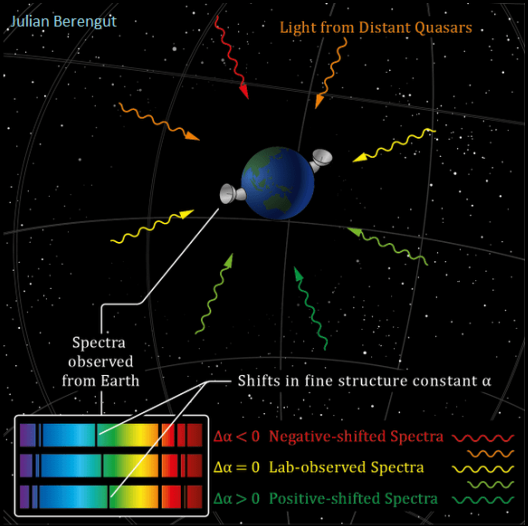
Fundamental Constants – how to observe

- Observe spectra from distant stars
- Compare to measurements on Earth
- Wavelengths (frequencies) differ: variation in α?
- **Problem:** What about red-shift?

- Each transition depends on α *differently*

$$\frac{\delta\omega}{\omega} = K\frac{\Delta\alpha}{\alpha}$$

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



Calculating Sensitivity Coefficients

- Large-scale many-body calculations of complex atoms
- Must be fully relativistic, account for electron correlations
- Calculate $\delta\omega/\delta\alpha$

$$H\Psi_A = E_A\Psi_A$$

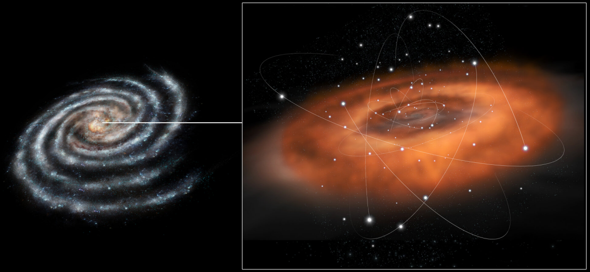
Side result:

- Possibly most accurate calculation to date of 4-valent Si
- High accuracy calculations of notoriously difficult 8-valent Fe
- Made possible by efficient calculation scheme in AMBiT/CI+MBPT

AMBIT (open source): Kahl, Berengut, Comp. Physics. Communications, 2019
Based on CI+MBPT: Dzuba, Flambaum, Kozlov, Phys. Rev. A 54, 3948 (1996).

Observing super-massive black hole

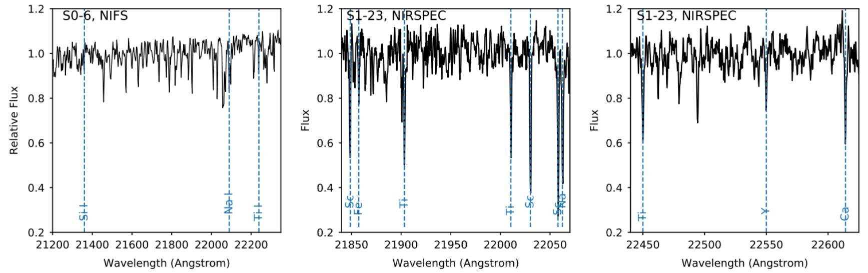
- with UCLA Galactic Centre Group
  - Observations led by Tuan Do
  - Andrea Ghez: Awarded 2020 Nobel prize for discovery of black hole
- Keck telescope in Hawaii
- Motion of $\sim$1000 stars tracked
- Precise spectroscopy for many stars



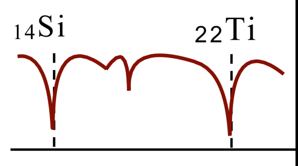
ESA / C. Carreau

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

Spectroscopy in high gravity: initial search, existing data



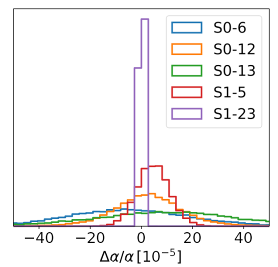
- Thousands of transitions observed: require clear extraction
- Identified 15 suitable transitions in 6 stars
- Compute K sensitivity coefficients
- S0-2 not appropriate: require old-type stars



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

- Fit for red-shift and variation in α simultaneously

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



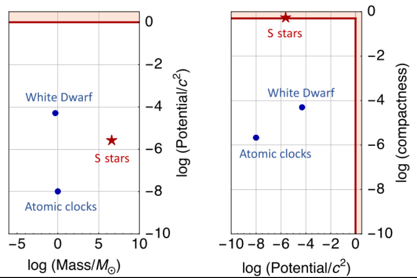
- No significant deviation from zero:

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

Constraints on post-GR theories

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

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

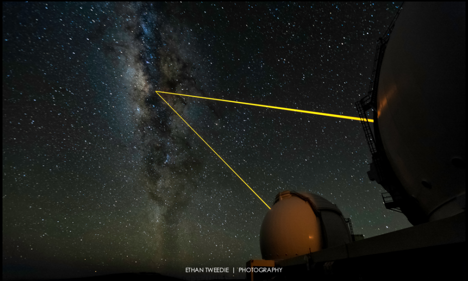


- 6 order of magnitude less stringent that atomic clocks
- 1 order of magnitude less stringent than the white dwarf
- But for the first time around a BH
- And: Current: incidental data
- $\implies$ several orders-of-magnitude improvement in future

- Hees, Do, Roberts, Ghez *et al.* Phys. Rev. Lett. 124, 081101 (2020).
- Ashby, Parker, Patla, Nat. Phys. **14**, 822 (2018).
- Berengut *et al.* Phys. Rev. Lett. **111**, 010801 (2013); Hu *et al.*, Mon. Not. R. Astron. Soc. (2020).

Summary and Future

- Observed wavelengths 15 atomic lines in 6 old-type stars
- Compute sensitivity to $\delta\alpha$
- Constrain $\delta\alpha$ and $\delta\alpha \propto U$
- First time around a black hole
- Demonstrate new ways Galactic Center can be used to probe fundamental physics.



ethantweedie.com/

Upcoming improvements

- Tuan Do (UCLA): awarded dedicated time on Keck
- Improved spectroscopy: better resolution
- Many more stars and lines: improved statistics (from 15)
- Hope: more favourable transitions (larger sensitivity K)
- Closer to the Black Hole (larger ΔU) – sensitivity to β
- Potential for several order-of-magnitude improvement

- Hees, Do, Roberts, Ghez *et al.* Phys. Rev. Lett. 124, 081101 (2020). [arXiv:2002.11567]

Upcoming postdoc position – UQ, Brisbane

- Atomic Parity Violation: Probing standard model at low energies with atomic physics

- Funding for postdoc
- Know a great candidate?
- Not advertised yet, but put people in touch
- j.ginges @ uq.edu.au, b.roberts @ uq.edu.au