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

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DSU2022 – The Dark Side of the Universe

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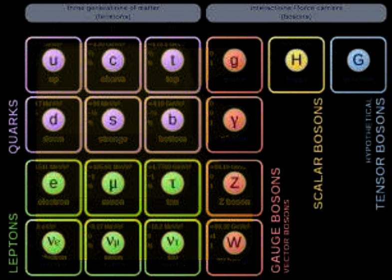
- **Standard Model + General Relativity**



Extraordinarily successful, however, several deep problems:

Matter–Anti-matter asymmetry

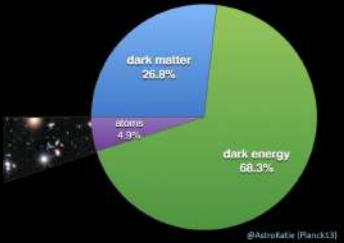
- The Big Bang should have created equal amounts of matter and antimatter.
- So why is there far more matter than antimatter in the universe?

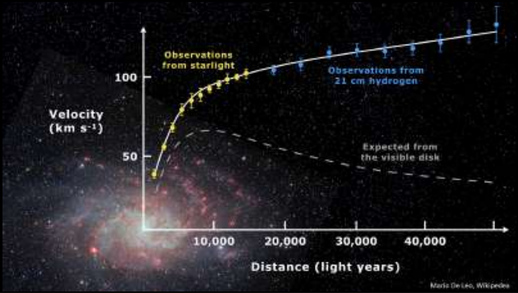
Dark matter and dark energy

- 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

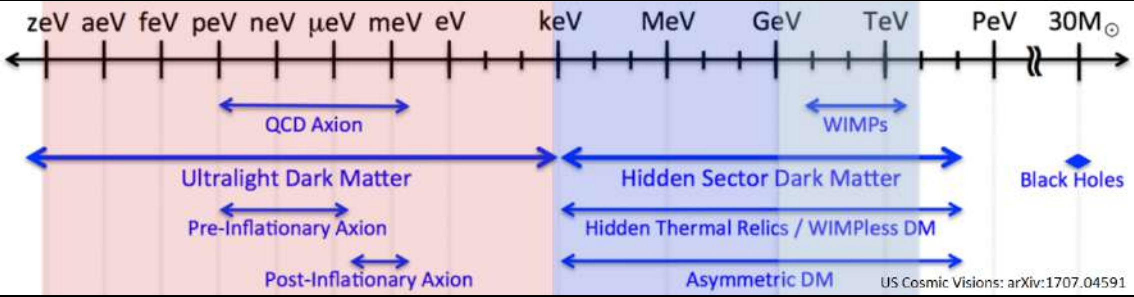




Dark matter: what we *don't* know

...everything else

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

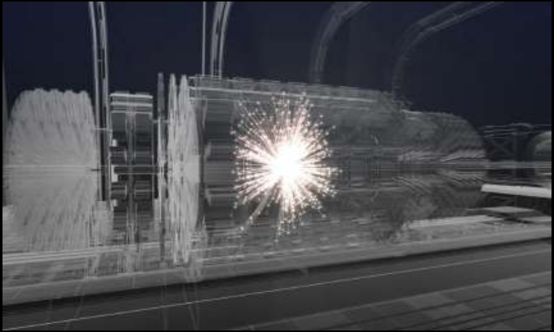


- Very strong evidence for some kind of new particles/fields – but we have no idea where to look

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

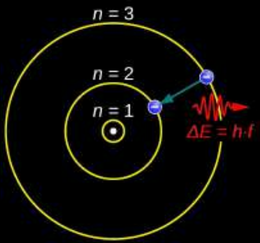
Are the laws of nature the same everywhere in the Universe?

$$\alpha \approx 1/137.036....$$
$$= \alpha(\boldsymbol{x}, t)?$$

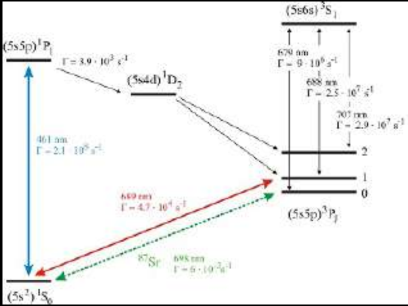
See talk by Leonardo Giani – Thursday evening

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)

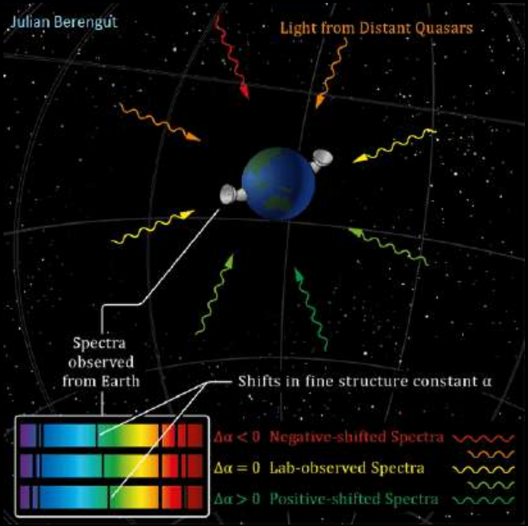
Fundamental Constants – how to observe

- 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 $\delta\omega/\delta\alpha$

$$H\Psi_A = E_A\Psi_A$$

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

Result: accurate k for many systems

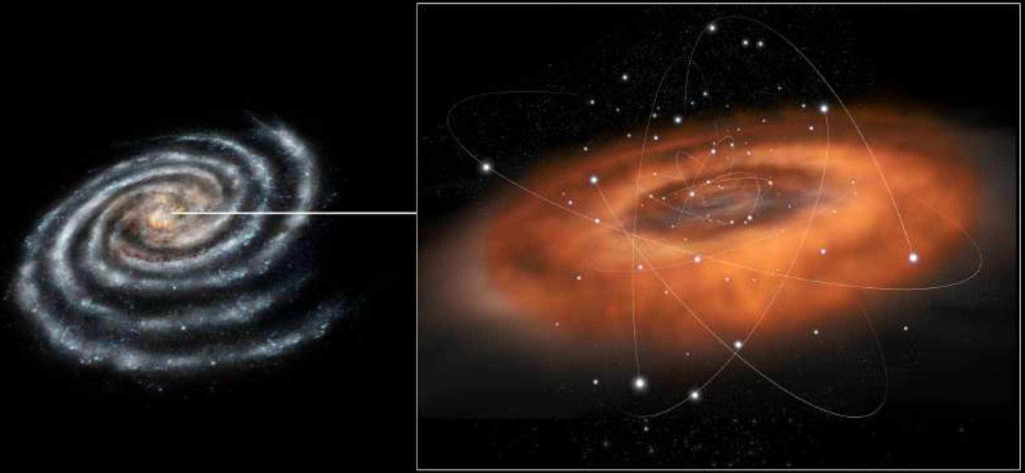
TABLE I. Atomic properties of the absorption lines used in this analysis. The wavelengths λ are experimental values reported in [46]. The sensitivity to the fine structure constant k_α is computed from *ab initio* calculation using the AMBiT software [45], see the discussion in Sec. I from the Supplemental Material [40]. The last column indicates which instrument has been used to measured each line with the following: (a) NIFS spectrograph, (b) IRCS spectrograph, (c) NIRSPEC order34, (d) NIRSPEC order35.

	Lower		Upper		λ [Å]	k_α	instrument
$_{14}$Si	$3s^23p4p$	$^1D_2$	$3s^23p5s$	$^1P^o_1$	21 360.027	0.013(9)	a
$_{11}$NaNa	$4s$	$^2S_{1/2}$	$4p$	$^2P^o_{1/2}$	22 089.728	0.004(2)	a,b
$_{22}$Ti	$3d^34s$	$^5P_2$	$3d^24s4p$	$^5D^o_2$	22 238.911	−0.34(10)	a
$_{22}$Ti	$3d^34s$	$^5P_2$	$3d^24s4p$	$^5D^o_1$	22 450.025	−0.37(10)	c
$_9$Y	$4d^25s$	$^4F_{7/2}$	$4d5s5p$	$^4F^o_{7/2}$	22 549.938	−0.88(6)	c
$_{20}$Ca	$4s4d$	$^3D_1$	$4s4f$	$^3F^o_2$	22 614.115	−0.03(1)	c
$_{21}$Sc	$3d^24s$	$^4F_{3/2}$	$3d4s4p$	$^2D^o_{3/2}$	21 848.743	−0.23(3)	b,d
$_{39}$Fe	$3d^64s^2$	$^3D_3$	$3d^64s4p$	$^3P^o_2$	21 857.345	0.56(28)	d
$_{22}$Ti	$3d^34s$	$^5P_2$	$3d^24s4p$	$^5D^o_3$	21 903.353	−0.30(10)	b,d
$_{22}$Ti	$3d^34s$	$^5P_1$	$3d^24s4p$	$^5D^o_2$	22 010.501	−0.31(9)	b,d
$_{21}$Sc	$3d^24s$	$^4F_{5/2}$	$3d4s4p$	$^2D^o_{3/2}$	22 030.179	−0.25(4)	b,d
$_{21}$Sc	$3d^24s$	$^4F_{9/2}$	$3d4s4p$	$^4D^o_{7/2}$	22 058.003	−0.29(4)	d
$_{11}$Na	$4s$	$^2S_{1/2}$	$4p$	$^2P^o_{3/2}$	22 062.485	0.007(2)	b,d

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

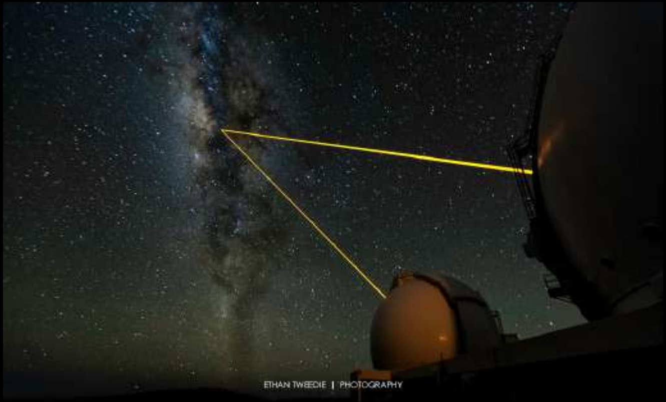
Fundamental Physics with the Super-massive black hole



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 ∼1000 stars tracked
- Precise spectroscopy for many stars



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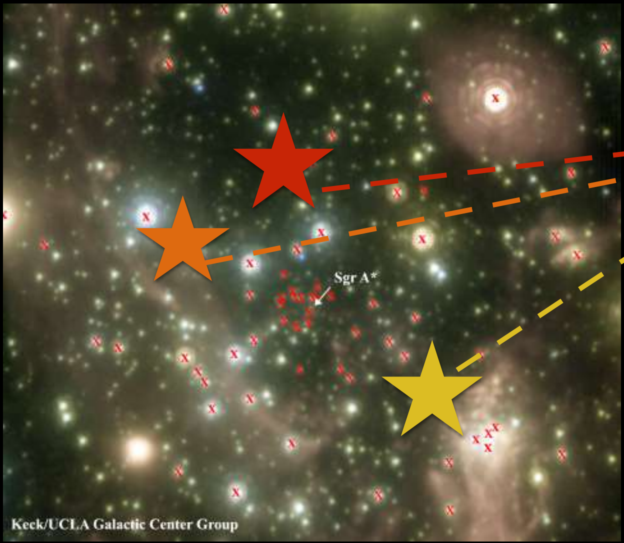
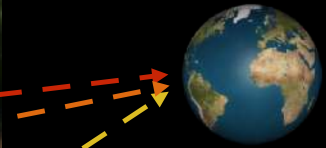
- High gravitational potential
- Possibly large concentration of dark matter
- Could this affect fundamental constants?

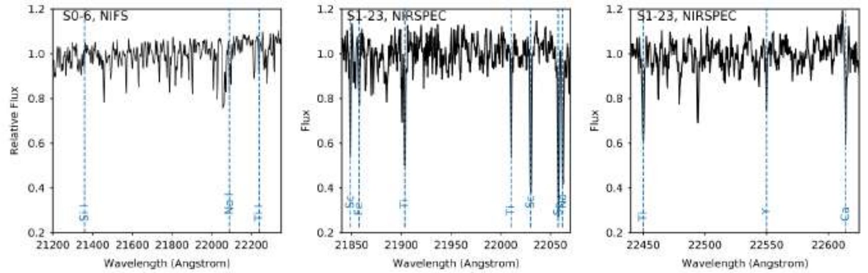
Search for variation in α close to Black Hole at Galactic Centre



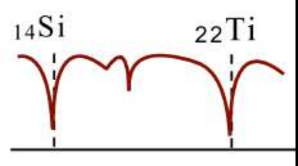


- Each measurement needs 2 lines (transitions)
- With different sensitivity to α (K)
- S0-2 not appropriate: require old-type stars

Spectroscopy in high gravity: initial search, existing data



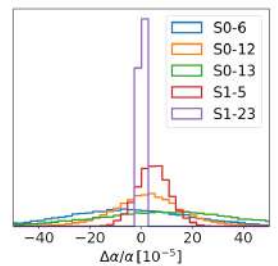
- Thousands of transitions observed: require clear extraction
- Identified 15 suitable transitions in 6 stars
- Compute K sensitivity coefficients
- Fit for red-shift and variation in α simultaneously



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

- Fit for red-shift and variation in α simultaneously

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



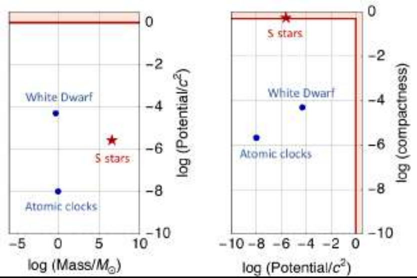
- No significant deviation from zero:

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

Constraints on post-GR theories

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

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

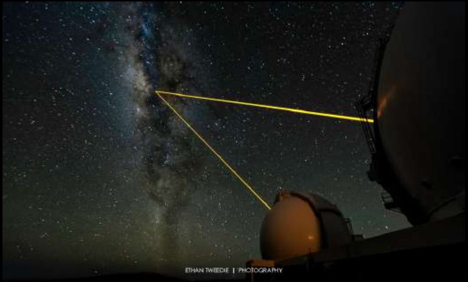


- 6 order of magnitude less stringent that atomic clocks
- 1 order of magnitude less stringent than the white dwarf
- But for the first time around a BH
- And: Current: incidental data
- $\Longrightarrow$ several orders-of-magnitude improvement in future

- 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.



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

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

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