Variation of fundamental constants: Search for new physics around a supermassive black hole

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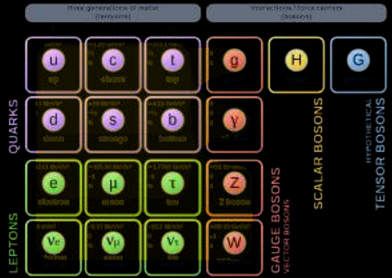
Current theory of the Universe

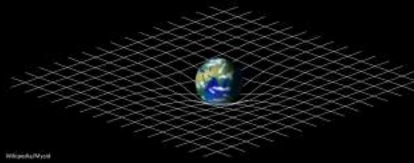
Standard Model: Quantum theory of particles + interactions

- Predicted new particles (W/Z bosons, quarks)
- Correctly predicts electron magnetic moment to 10 digits!
- Discovery of Higgs boson



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

- From precession of Mercury to gravitational waves at LIGO
- Tested from small to extra-galactic length scales



- However...

Several deep inconsistencies

Matter–Anti-matter asymmetry

- Why is there far more matter than antimatter in the universe?
- Not enough CP-violation in the Standard Model to explain this

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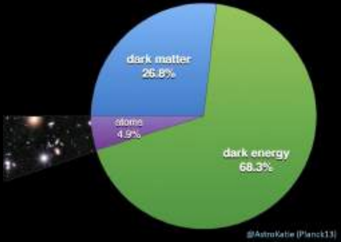
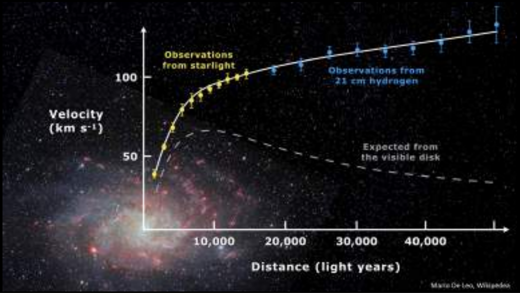
Dark matter and dark energy

- Dark energy: accelerated expansion
- Dark matter: galactic rotation curves etc.
- 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
- Cosmic Microwave background
- Gravitational lensing
- Structure formation

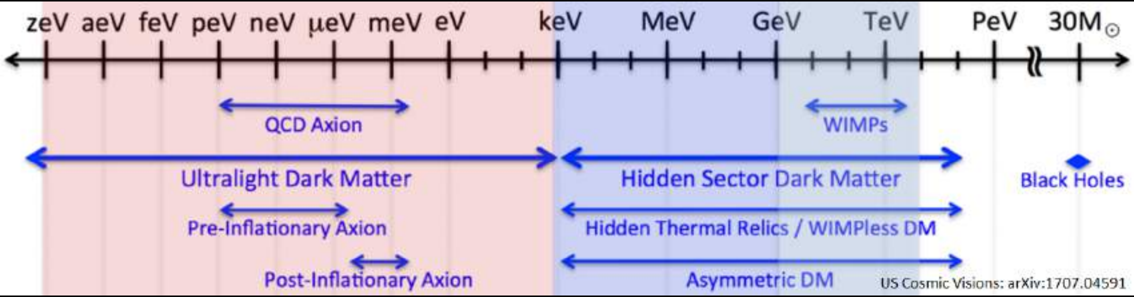




Dark matter: what we *don't* know

...everything else

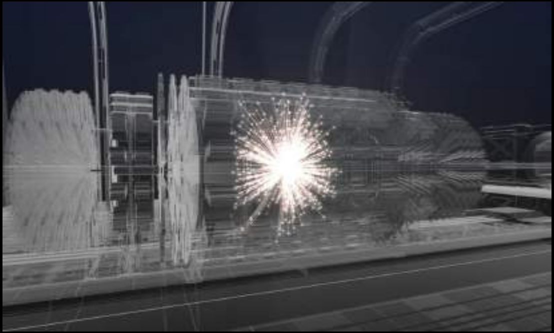
- Possible mass range: spans 90(!!) orders-of-magnitude



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

Search for 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

Alternative approach:

- General search for violations of the deep assumptions of above theories

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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)

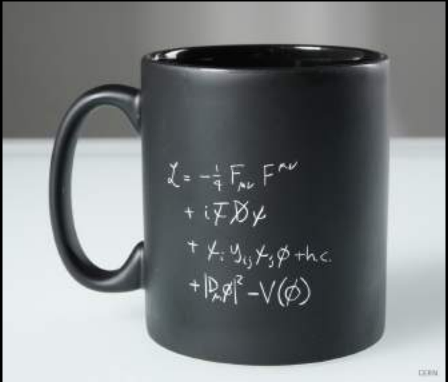
- Such violations arise naturally in many beyond-Standard-Model theories

Variation of Fundamental Constants

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

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

Fundamental Constants



Not predicted by theory: have to be measured

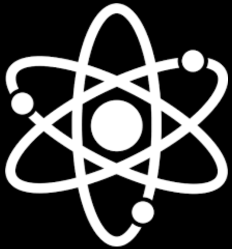
- Electron masses: $m_e \approx 9.109... \times 10^{-31}$ kg
- Electron charge: $-e \approx -1.602... \times 10^{-19}$ C
- Speed of light: $c = 299\,792\,458$ m/s

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



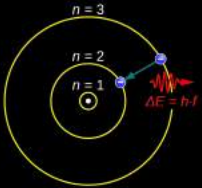
Unit-less ratios

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

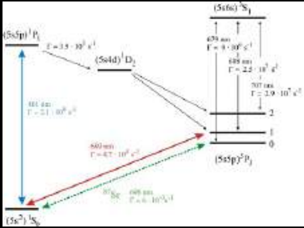
$$\alpha = \frac{e^2}{4\pi\epsilon_0\,\hbar c} \approx \frac{1}{137}$$

Variation of constants – atomic transitions

- Atomic energy levels (and therefore transition frequencies) depend on **fundamental constants**
- Shift in transition frequency may be due to change in constants



JabberWok/Wikipedia



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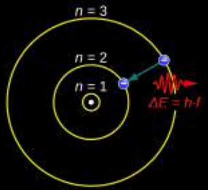

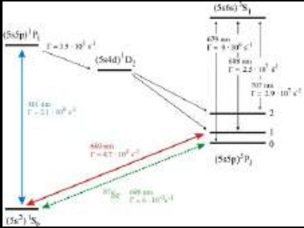

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Specific level sensitivity:

$$\frac{\Delta\omega}{\omega} = K \frac{\Delta\alpha}{\alpha} \qquad \left(K \equiv \frac{\partial\omega}{\partial\alpha}\frac{\alpha_0}{\omega} \right)$$

Variation of constants – meaningful?

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Example: transitions in H

$$\omega_{\rm SI} = \frac{m_e c^2\alpha^2}{2}\left(\frac{1}{n^2} - \frac{1}{n'^2}\right)F(Z\alpha) \qquad \omega_{\rm atomic} = \frac{1}{2}\left(\frac{1}{n^2} - \frac{1}{n'^2}\right)F(Z\alpha)$$

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Problem: I can change dependence on α by changing units!

Even though α in dimensionless, issue remains

Which unit system is correct? (Obviously nonsense question)

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- K only uniquely defined up to additive constant

Variation of constants – meaningful? Yes (with caution)!

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Solution: frequency ratios:

$$\frac{\delta\left(\omega_A/\omega_B\right)}{\left(\omega_A/\omega_B\right)} = K_A\frac{\delta\alpha}{\alpha} - K_B\frac{\delta\alpha}{\alpha} = (K_A - K_B)\frac{\delta\alpha}{\alpha}$$

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- Unit ambiguity cancels in ratios
- Must have two lines (minimum) at each spacetime location
  - Not enough to have one line at two different locations
- $K_A - K_B$ non-zero only due to relativistic corrections

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)

Searching for Variation of Fundamental Constants

Variation of 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?

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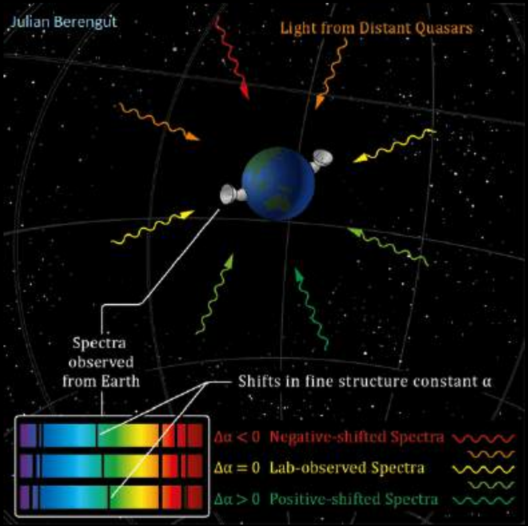
- **Problem:** What about red-shift?

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

- 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).

Configuration Interaction + MBPT

- Separate "core" and "valence" electrons
  - Energy to excite core $\gg$ Energy to excite valence
  - Core stays static (to leading approx.)
  - e.g., Mg : Ne-like core + $3s^2$

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CI part:

- Allow 1 and 2 particle excitations from "leading configuration" - e.g., Mg:

$$\Psi = c_1|3s^2\rangle + c_2|3s4s\rangle + c_3|3s3d\rangle + c_4|4s^2\rangle \ldots$$

- Not exact, because expansion isn't infinite: N terms
- Solve Schrodinger equation: $N \times N$ eigenvalue problem

$$\sum_J \left(\langle I|H|J\rangle - E\delta_{IJ}\right) c_J = 0$$

“Emu CI” with AMBiT

$$\psi = \sum_I c_I |I\rangle$$

$$\langle I|H|J\rangle$$

- Not all configurations I, J equally important

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$$\psi = \sum_I c_I |I\rangle = \sum_A c_A |A\rangle + \sum_B c_B |B\rangle \quad (|c_A| \gg |c_B|)$$

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- Split into two groups: small group of important configurations + rest

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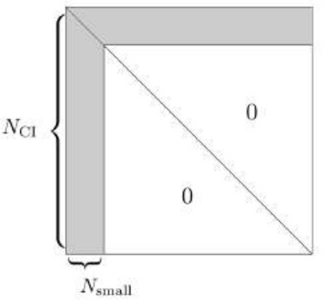
- Not all configurations I, J equally important
- Split into two groups: small group of important configurations + rest
- Include all diagonal elements
- Include all involving important set
- Exclude cross-terms among 'rest'
- Drastically reduces memory required



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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
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$_{11}$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
$_{39}$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
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$_{26}$Fe	$3d^64s^2$	$^3D_3$	$3d^64s4p$	$^3P^o_2$	21 857.345	0.56(28)	d
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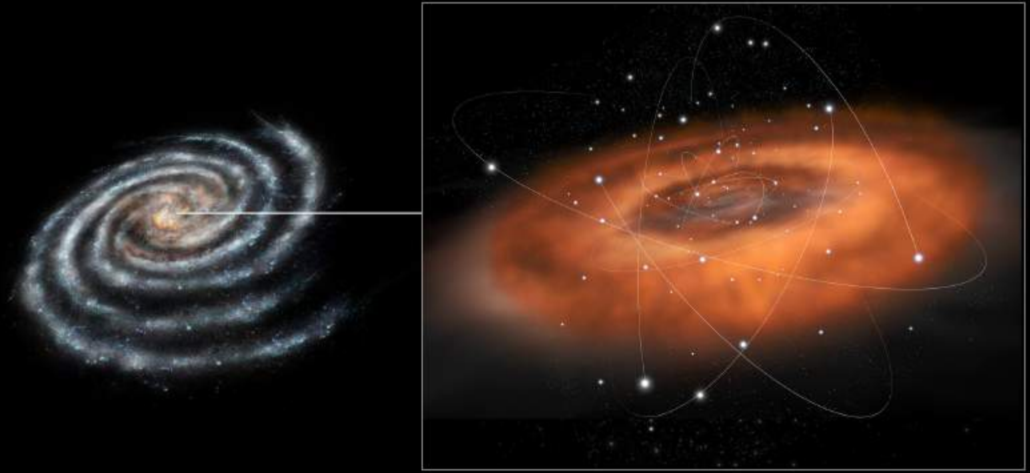
- Hees, Do, Roberts, Ghez *et al.* Phys. Rev. Lett. 124, 081101 (2020). Side result:
  - Possibly most accurate calculation to date of 4-valent Si
  - High accuracy calculations of notoriously difficult 8-valent Fe
  - Made possible by efficient calculation scheme in AMBiT/CI+MBPT

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 $\sim$1000 stars tracked
- Precise spectroscopy for many stars

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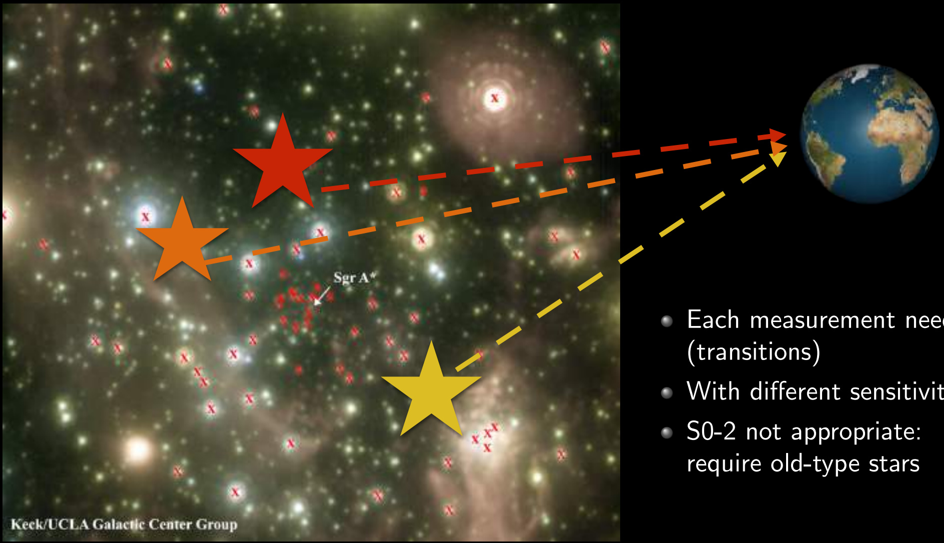
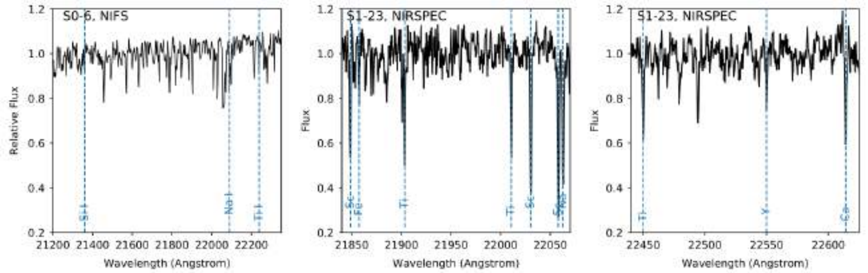
- Extreme environment: ideal candidate
- High gravitational potential
- Possibly large concentration of DM
- Could this affect fundamental constants?

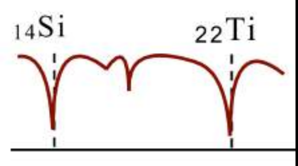
Search for variation in α close to Black Hole at Galactic Centre



- 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





- Hundreds 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

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

Analysis and Results

- Fit for red-shift and variation in α simultaneously

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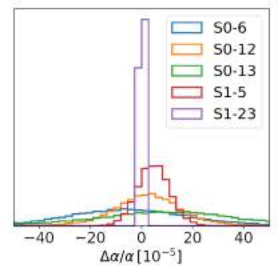


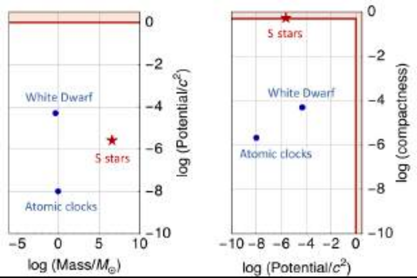
- No significant deviation from zero:

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

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).
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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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Upcoming improvements

- Potential for several order-of-magnitude improvement with dedicated search

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