Search for a variation of the fine-structure constant around the supermassive Black Hole in our Galactic Centre

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- *arXiv:2002.11567*

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Fundamental Physics Probes:

Standard Model + General Relativity: successful, likely incomplete

Two general approaches:

1. Measure known quantity with high precision:
   - Consistent with theory? (e.g., H0)

2. Look for “unkown” signals (expect to find zero)
   - Non-zero measurement: evidence for new physics
   - E.g., Equivalence Principal: *Are the laws of nature the same everywhere in the Universe?*

Fundamental Physics with the Supermassive Black Hole in our Galactic Centre

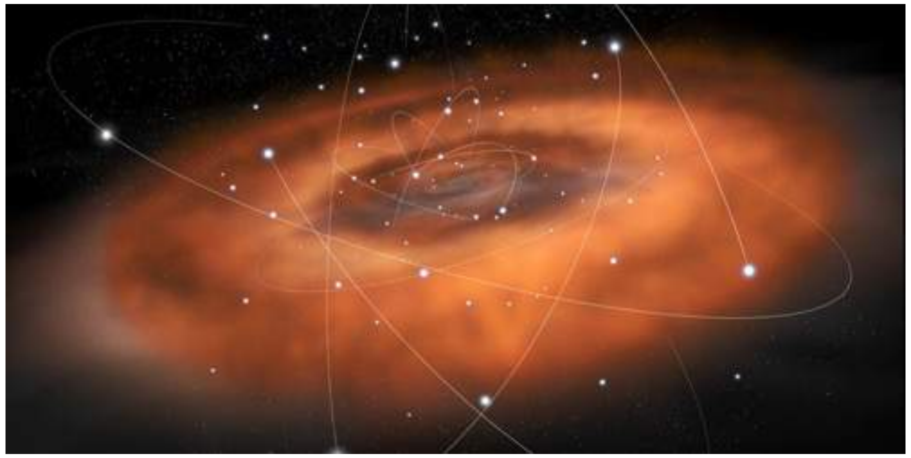


Image: ESA/C. Carreau

Searching for a breaking of the Equivalence Principle can shed light on new physics

Some models of Dark Matter and Dark Energy

see Damour and Polyakov, GRG, 1994
Arvanitaki et al, PRD, 2015

Unification scenarios/ most attempts for a quantum theory of gravity

see e.g. refs in Altschul et al, 2015

Violation of EEP

The "universal" coupling of gravitation seems anomalous compared to other interactions

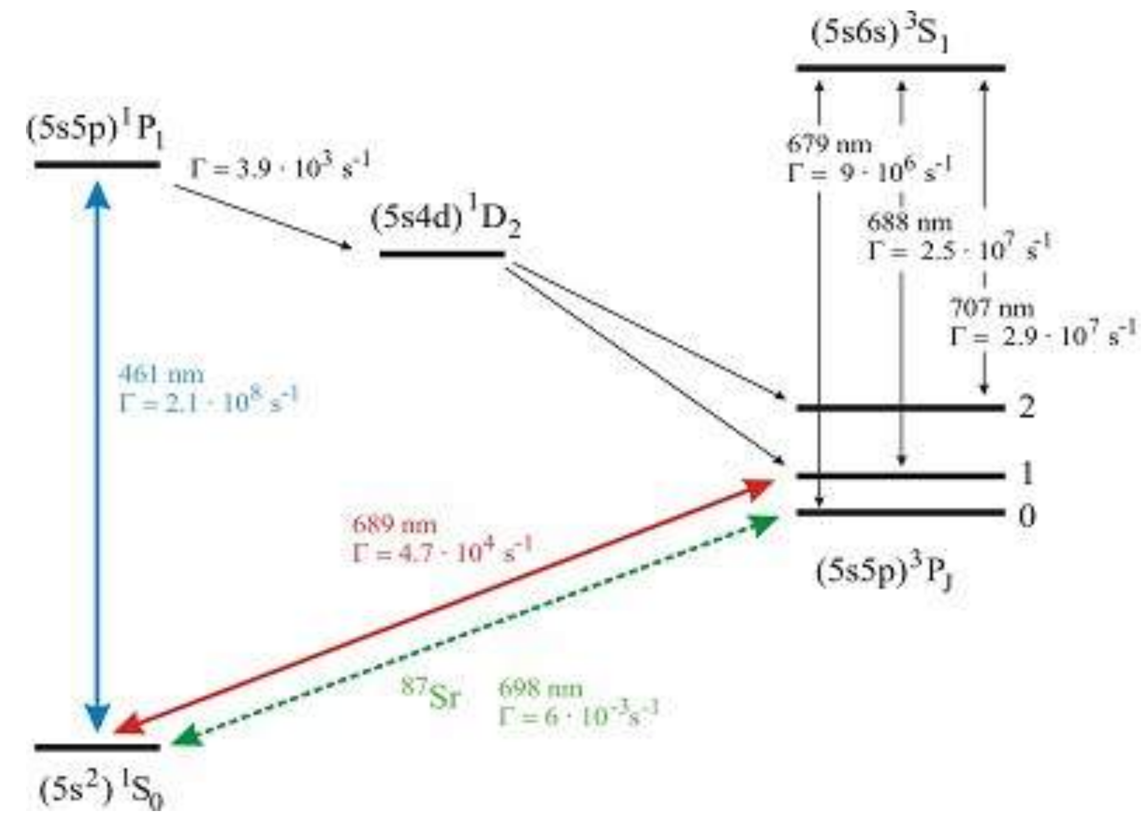
see the discussion in Damour, CQG, 2012

Local dependence of fundamental "constants" of nature

Flambaum 2007,
Pospelov2008, Damour 2012

Access to new physics?

Variation the fine structure constant α



$$E \propto f(\alpha) \implies \omega \propto f(\alpha)$$

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

$$\omega^{(A)} = -\underbrace{F_A(\alpha)}_{\text{transition-specific}} \times \underbrace{m_e c^2 \alpha^{2+\mu}}_{\text{Unit (universal)}} \qquad (2)$$

$$\delta\left(\frac{\omega^{(A)}}{\omega^{(B)}}\right) \Big/ \left(\frac{\omega^{(A)}}{\omega^{(B)}}\right) = K^{(A)}\frac{\delta\alpha}{\alpha} - K^{(B)}\frac{\delta\alpha}{\alpha} = (K^{(A)} - K^{(B)})\frac{\delta\alpha}{\alpha}$$

- Safe, so long as we measure only dimensionless ratios

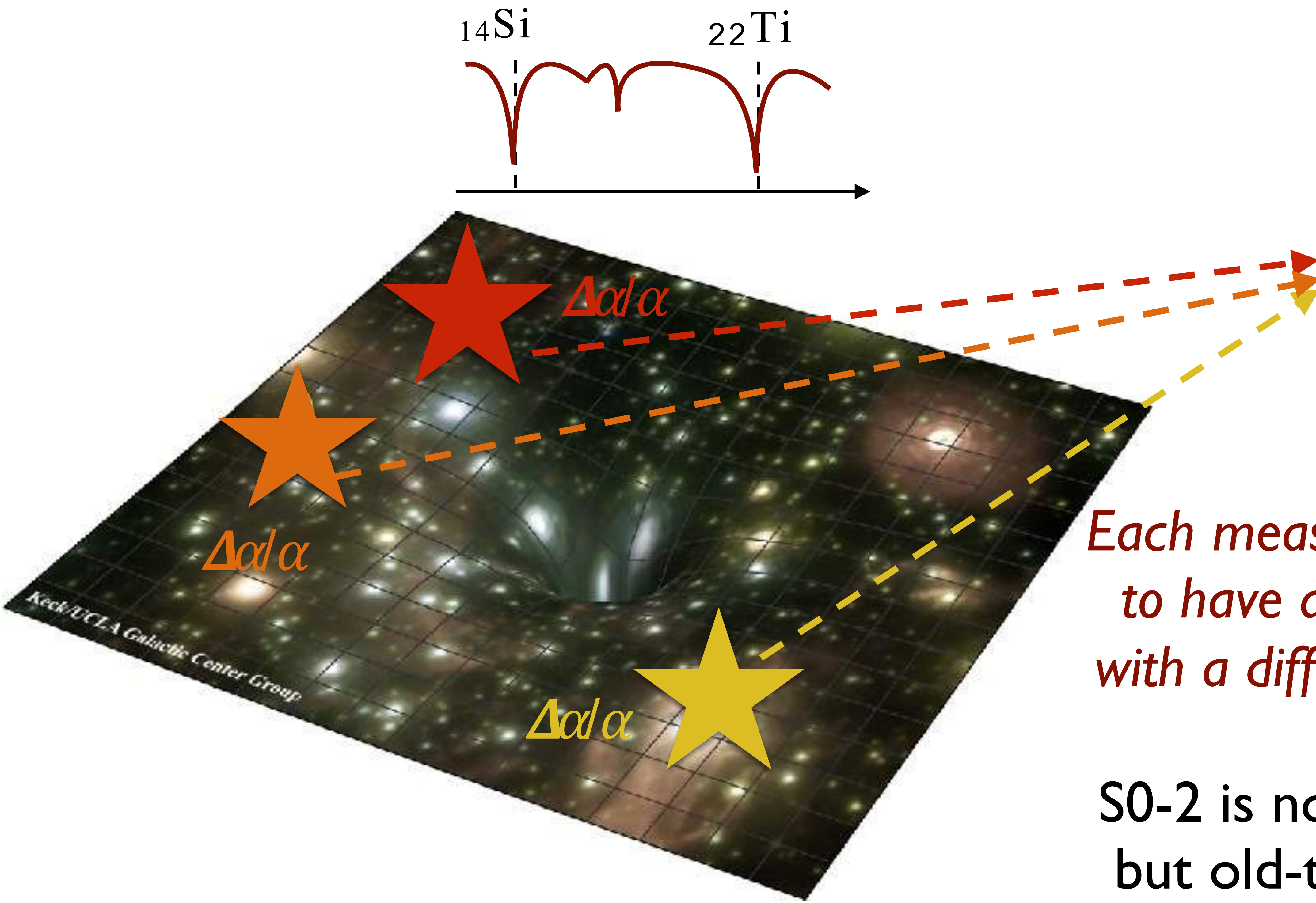
See:

[1] V. A. Dzuba, V. V. Flambaum, and J. K. Webb, Phys. Rev. Lett. **82**, 888 (1999).

[2] M. G. Kozlov and D. Budker, Ann. Phys. 1800254 (2018).

[3] E. Savalle, A. Hees, F. Frank, E. Cantin, P.-E. Pottie, BMR, L. Cros, B. T. McAllister, and P. Wolf, Phys. Rev. Lett. **126**, 051301 (2021).

Spectroscopy measurements in the GC can be used to search for variations in α



Each measurement needs to have at least 2 lines with a different sensitivity to α.

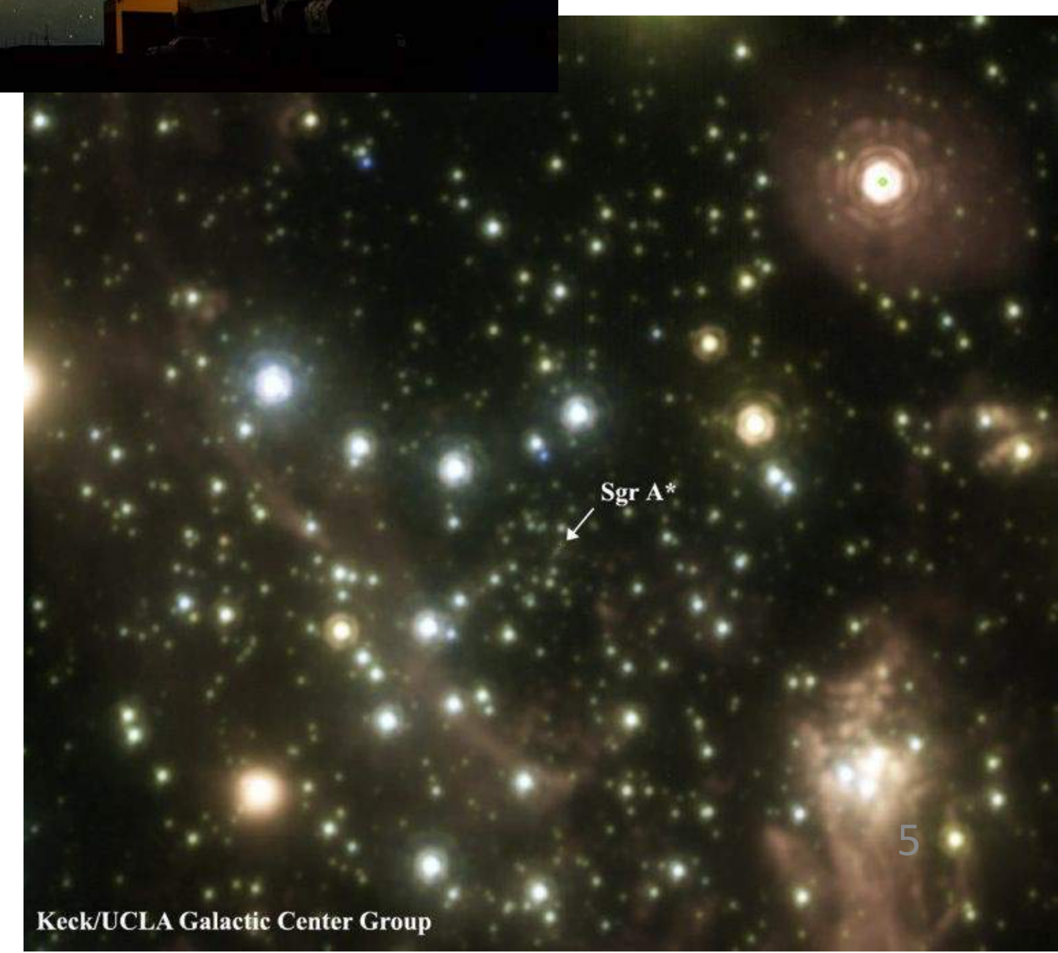
S0-2 is not appropriate but old-type stars are appropriate

Stars orbiting the GC have been observed since 1995

- Keck Observatory:
  - Speckle and Adaptive Optics ***imaging***. *Accuracy @0.15 mas*
  - ***Spectroscopic*** measurements. *Accuracy @20 km/s*
- The motion of ~ 1000ish stars is tracked:
  - construction of an absolute reference frame

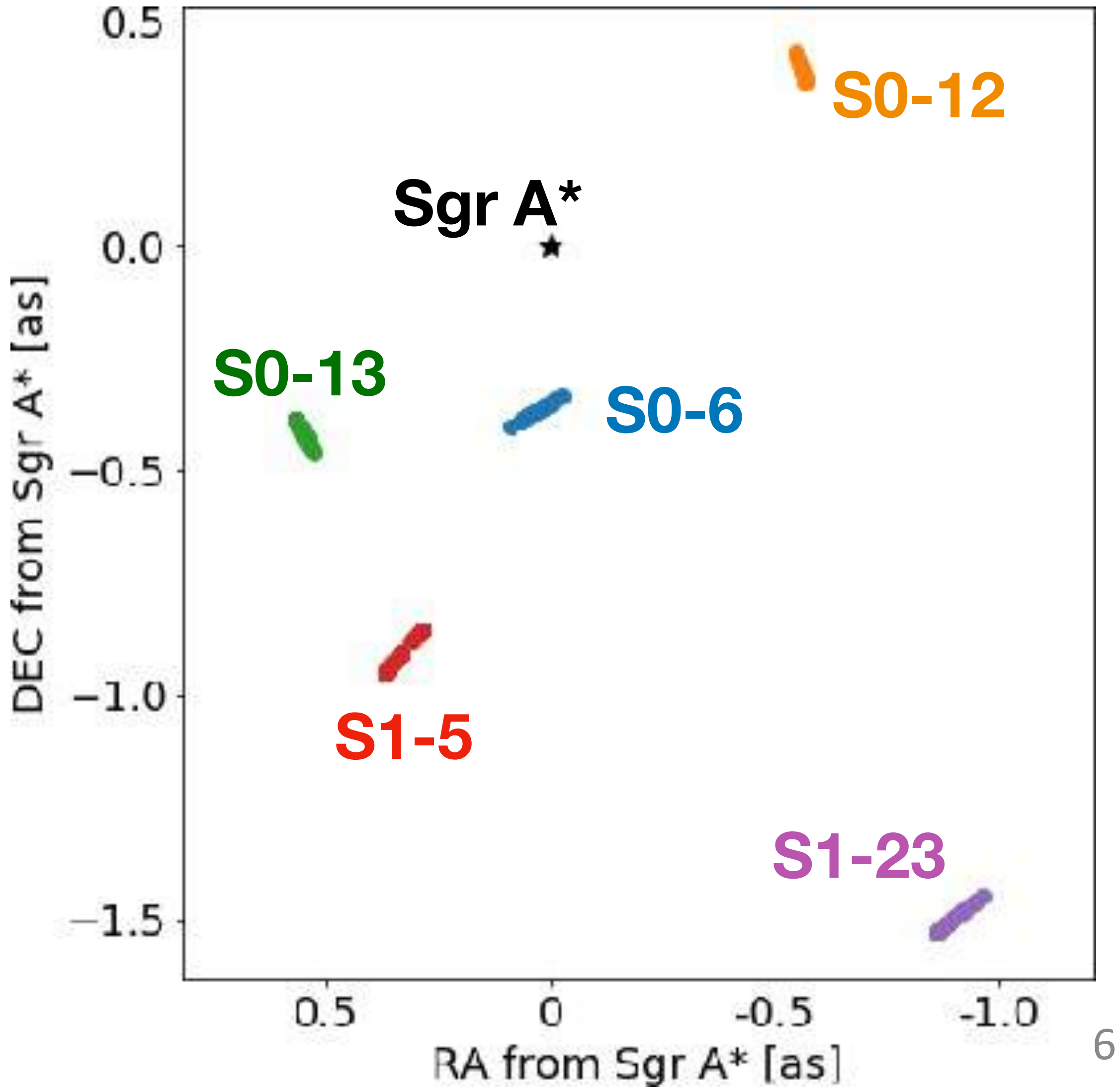
see Sakai et al, ApJ, 2019
Jia et al, ApJ, 2019

- Similar observations have been taken @VLT



Six old-type stars have been identified as promising

- Need many spectral lines (with different sensitivities to α): old-type stars
- Bright, to ensure a high SNR. Magnitude < 15
- Sufficiently in the central region: existence of measurements and probe of α "close" to the BH



- S0-6 - Mag: 14.1
- S0-12 - Mag: 14.3
- S0-13 - Mag: 13.3
- S1-5 - Mag: 12.7

measured by NIFS in 2018

- S1-23 - Mag: 12.7

measured by NIRSPEC in 2016

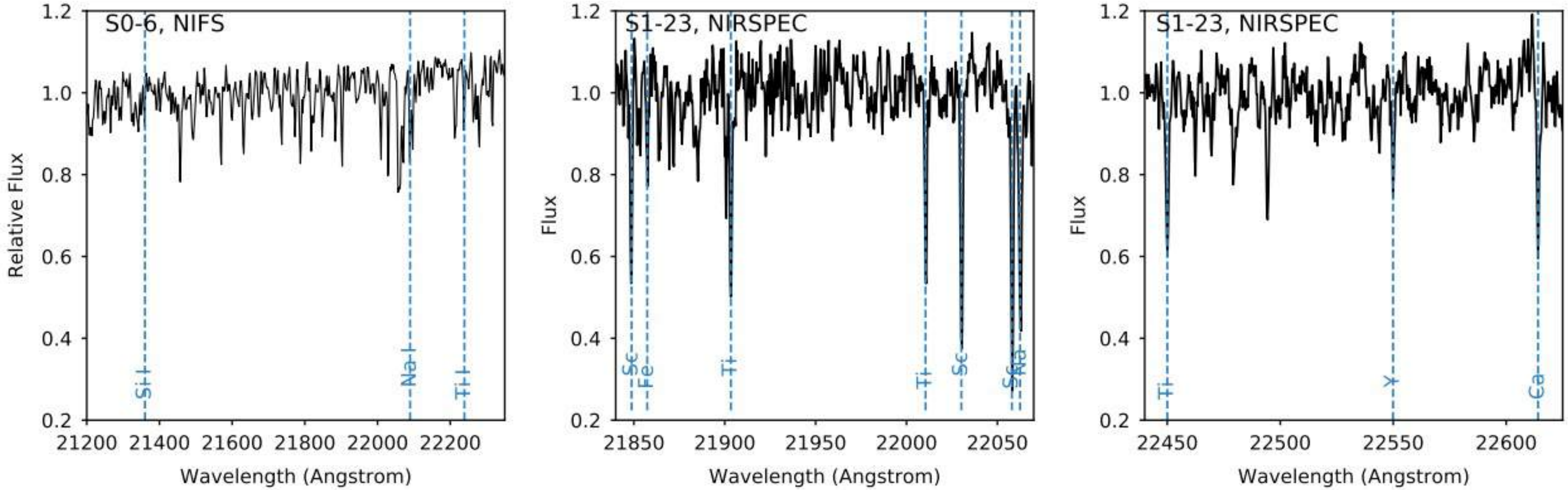


FIG. 3. Example spectra of the stars used in this work. Left: Spectrum of the star S0-6 observed using the NIFS spectrograph with a spectral resolution $R = 5000$. We have identified three lines that are suitable for the fine structure constant analysis. Center and right: Spectra of the star S1-23 observed with the NIRSPEC instrument with $R = 20\,000$. This higher spectral resolution allows us to identify ten atomic lines for use in this experiment.

- For each spectrum (i.e. one star at one epoch t_i)
  - extract N lines (j) independently
- Lines need to be isolated enough to be extracted alone:
  - 15 lines identified

Conceptually easy to infer a mapping of α in the GC

Measurement of the line j at epoch t_i

Value on Earth

Quantity of interest

$$\frac{\Delta\lambda_j}{\lambda_j}=\frac{\lambda_j(z,\alpha)-\lambda_j(z=0,\alpha_0)}{\lambda_j(z=0,\alpha_0)}=z-k_{\alpha,j}(1+z)\frac{\Delta\alpha}{\alpha}$$

RV + relativistic redshift

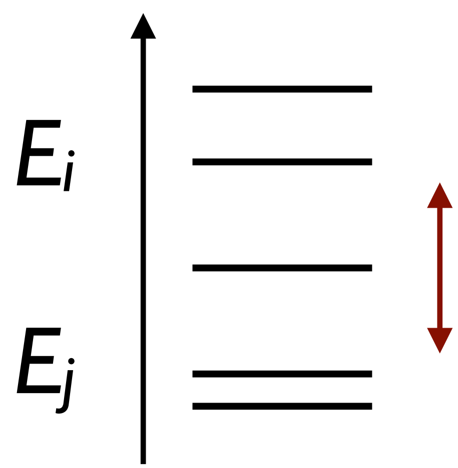
Sensitivity of the line j to α

<u>3 Aspects:</u>

- Observe wavelength (track stars, identify, calibrate etc.) -- T. Do
- Fit with 2 parameters: z_i and $\Delta\alpha/\alpha$ (each line) -- A. Hees
- Know k - need multiple lines with different k -- B. Roberts

Computation of the sensitivity coefficients, K

Energy levels for the electronic configuration



$\omega = (E_i\text{-}E_j)/\hbar$

Energies are computed from first principles

$$H\,|\Psi_k\rangle = E_k\,|\Psi_k\rangle$$

Interaction with the nucleus + interactions of the electrons

Wave function of the N electrons (Slater determinant)

- The sensitivity coefficient is computed numerically $k_\alpha = \dfrac{d\ln\omega}{d\ln\alpha}$

Costly computation done by B. Roberts using AMBIT

AMBIT (open source): Kahl, Berengut, Comp. Physics. Communications, 2019

Based on CI+MBPT: Dzuba, Flambaum, Kozlov, Phys. Rev. A 54, 3948 (1996).

Results: Accurate k's – many different values

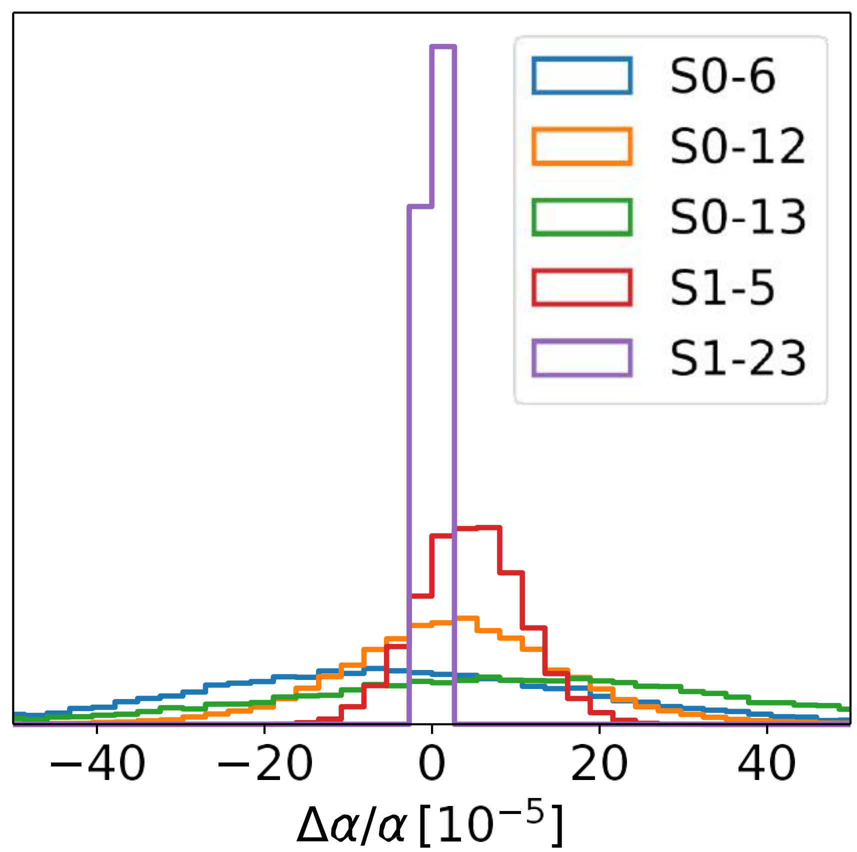
TABLE I. Atomic properties of the absorption lines used in this analysis. The wavelengths λ are experimental values reported in [46]. The sensitivity to the fine structure constant k_α is computed from *ab initio* calculation using the AMBiT software [45], see the discussion in Sec. I from the Supplemental 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.

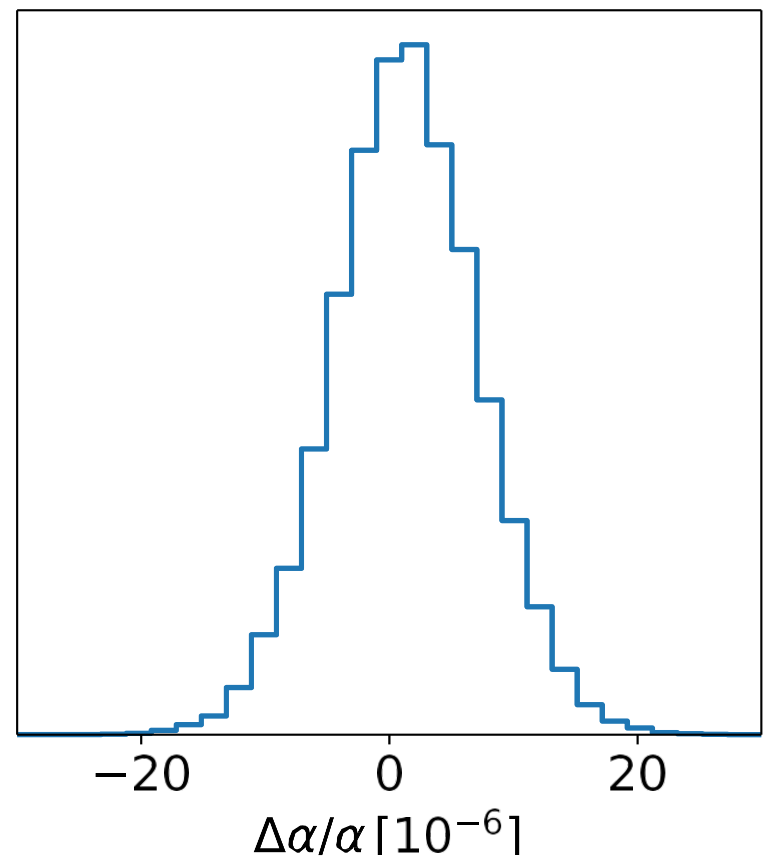
	Lower		Upper		λ [Å]	k_α	instrument
$_{14}$Si	$3s^23p4p$	$^1D_2$	$3s^23p5s$	$^1P^o_1$	21 360.027	0.013(9)	a
$_{11}$NaNa	$4s$	$^2S_{1/2}$	$4p$	$^2P^o_{1/2}$	22 089.728	0.004(2)	a,b
$_{22}$Ti	$3d^34s$	$^5P_2$	$3d^24s4p$	$^5D^o_2$	22 238.911	−0.34(10)	a
$_{22}$Ti	$3d^34s$	$^5P_2$	$3d^24s4p$	$^5D^o_1$	22 450.025	−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

No variations of α detected around Sgr A*





- Variation of the fine structure constant between the GC and Earth constrained

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

- Same order of magnitude as constraints from quasars
- NIRSPEC measurements are the one the most constraining

Constraint on variations of α with respect to the gravitational potential

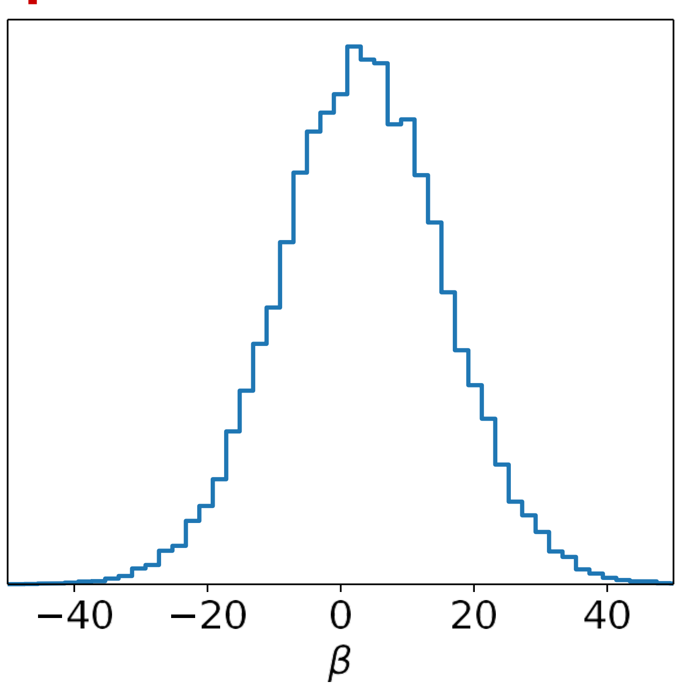
- A parametrization that appears naturally in some tensor-scalar theories of gravitation

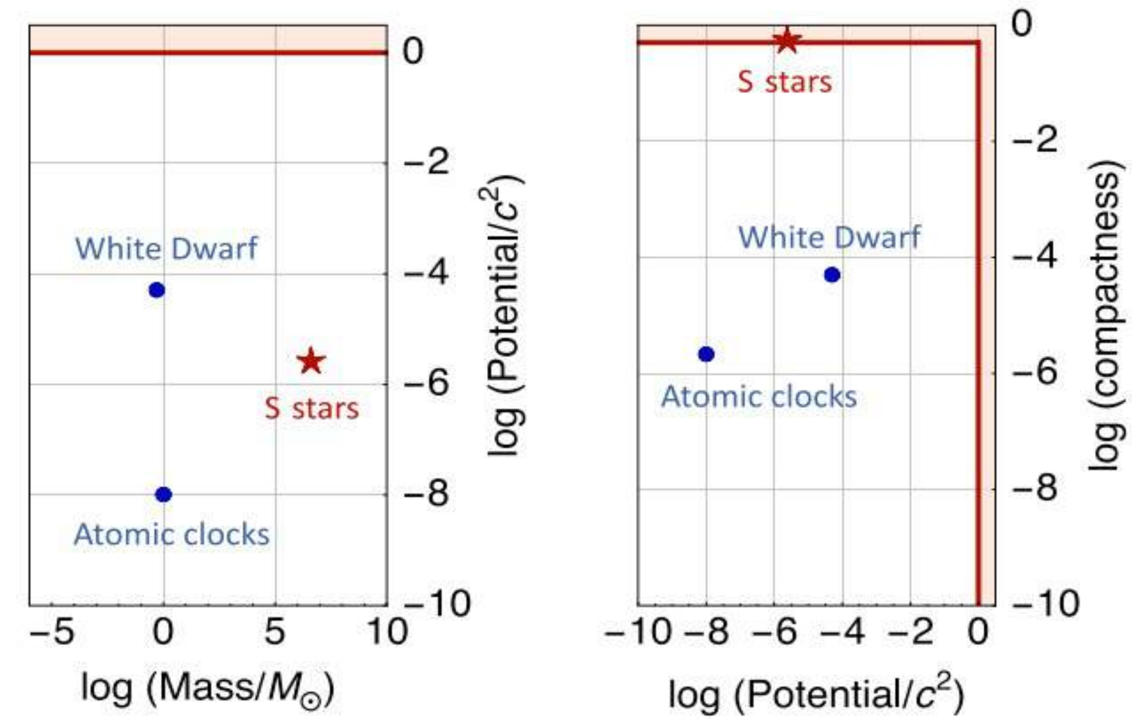
$$\frac{\Delta\alpha}{\alpha} = \beta_\alpha \frac{\Delta U}{c^2},$$

gravitational potential

fundamental parameter

$\beta = 3.6 \pm 12$

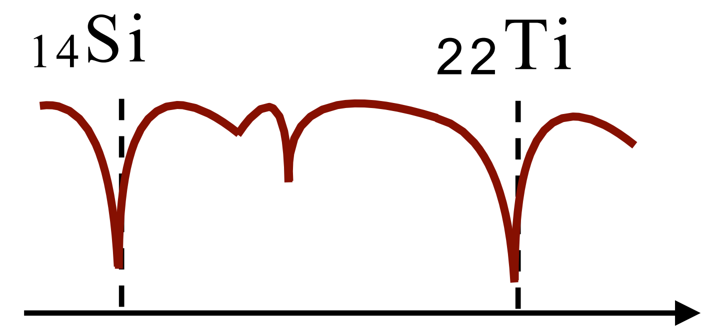




- 6 order of magnitude less stringent that atomic clocks and 1 order of magnitude less stringent than the white dwarf but for the first time around a BH

- N. Ashby, T. E. Parker, and B. R. Patla, Nat. Phys. 14, 822 (2018).
- J. C. Berengut, V. V. Flambaum, A. Ong, J. K. Webb, J. D. Barrow, M. A. Barstow, S. P. Preval, and J. B. Holberg, Phys. Rev. Lett. 111, 010801 (2013); Hu et al., Mon. Not. R. Astron. Soc. (2020).

- Measure absorption wavelength
- 15 atomic lines in 6 old-type stars
- Compute sensitivity to $\boldsymbol{\delta\alpha}$
- Constrain $\boldsymbol{\delta\alpha/\alpha}$ and $\boldsymbol{\delta\alpha} \propto$ U
- First time around a black hole
- Shows new ways the monitoring of stars in the Galactic Center can be used to probe fundamental physics.



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Editors' Suggestion   Featured in Physics

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

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- *arXiv:2002.11567*

- Initial results: incidental data (not dedicated observations)
- Proposal for dedicated measurements (led by Tuan Do) underway
- More stars, more lines, stars closer to GC
  - Goal: up to 5 orders of magnitude improvement in β