Tests of the Einstein Equivalence Principle around the Supermassive Black Hole in our Galactic Center

A. Hees, SYRTE, Paris Observatory
with the UCLA Galactic Center Group (A. Ghez, T. Do et al)
and B. Roberts, University of Queensland

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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
Derevianko's talk

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

Dynamical process to explain "constants" of the Standard Model

see e.g. Damour, CQG, 2012
Derevianko's talk

Access to new physics?

Galactic Center measurements open a new window to search for violations of the EEP

- Stringent tests of the EEP exist in the Solar System:
  - universality of free fall @10^{-14} with MICROSCOPE Touboul et al, PRL, 2017
  - redshift test @10^{-5} with GALILEO Delva et al, PRL, 2018, Herrmann et al, PRL, 2018
  - time variation of constants of Nature with clocks @10^{-16} yr^{-1}

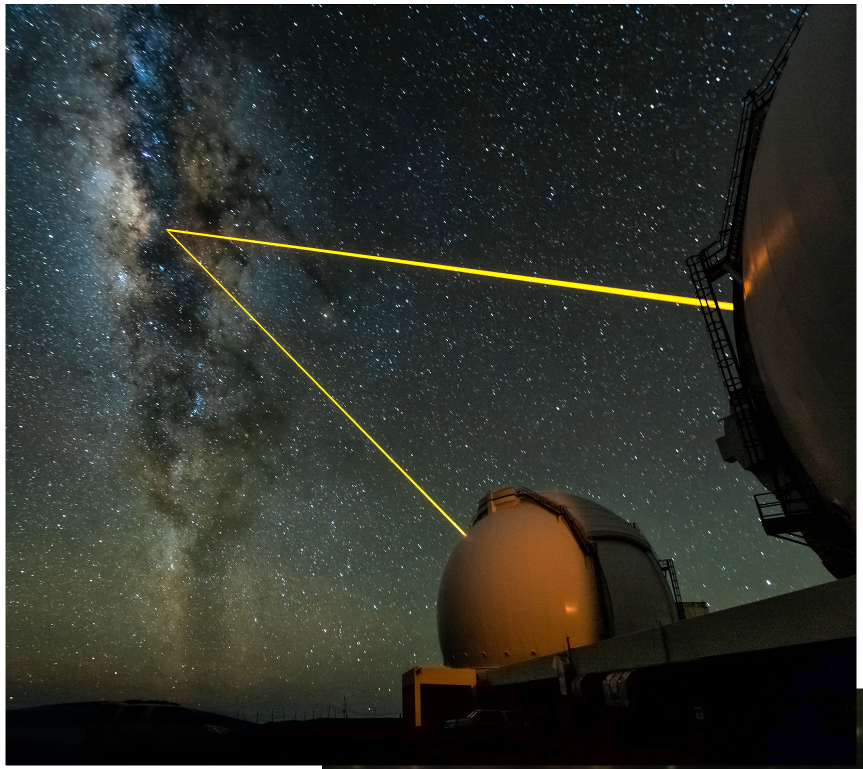
  see e.g. Ashby et al, Nat. Phys., 2018

- Is the gravitational interaction identical somewhere else in the Universe? And in particular around a black hole?

- Deviations from GR can locally be "hidden/screened": chameleons, Vainshtein, symmetron, …

- Deviations from GR can be enhanced around compact objects: scalarization

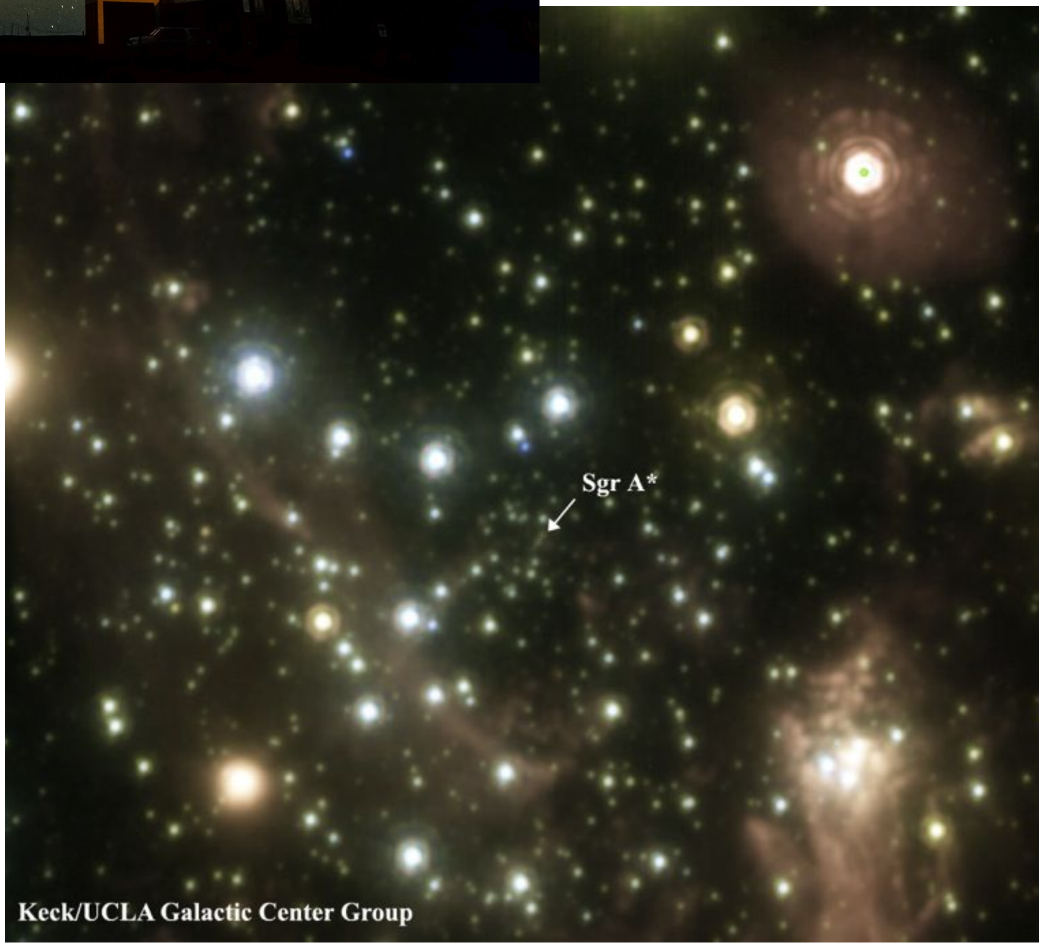
Stars orbiting the GC have been observed since 1995

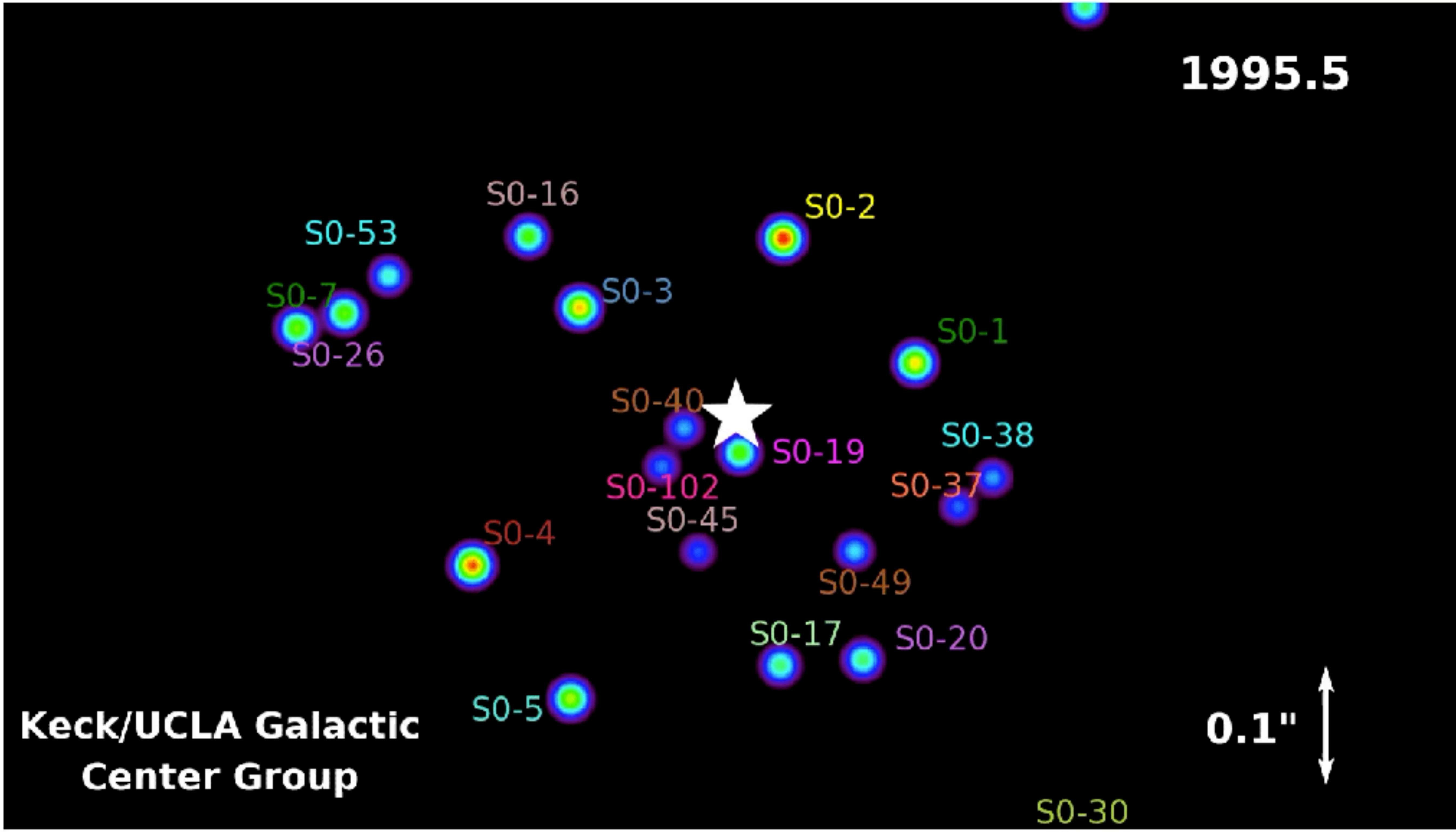


- Keck Observatory:
  - Speckle and Adaptive Optics ***imaging***. *Accuracy @0.15 mas*
  - ***Spectroscopic*** measurements. *Accuracy @20 km/s*
- The motion of ~ 1000ish stars is tracked:
  - construction of an absolute reference frame

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

  - the central arc second: Keplerian motion
- Similar observations have been taken @VLT

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Keck/UCLA Galactic Center Group
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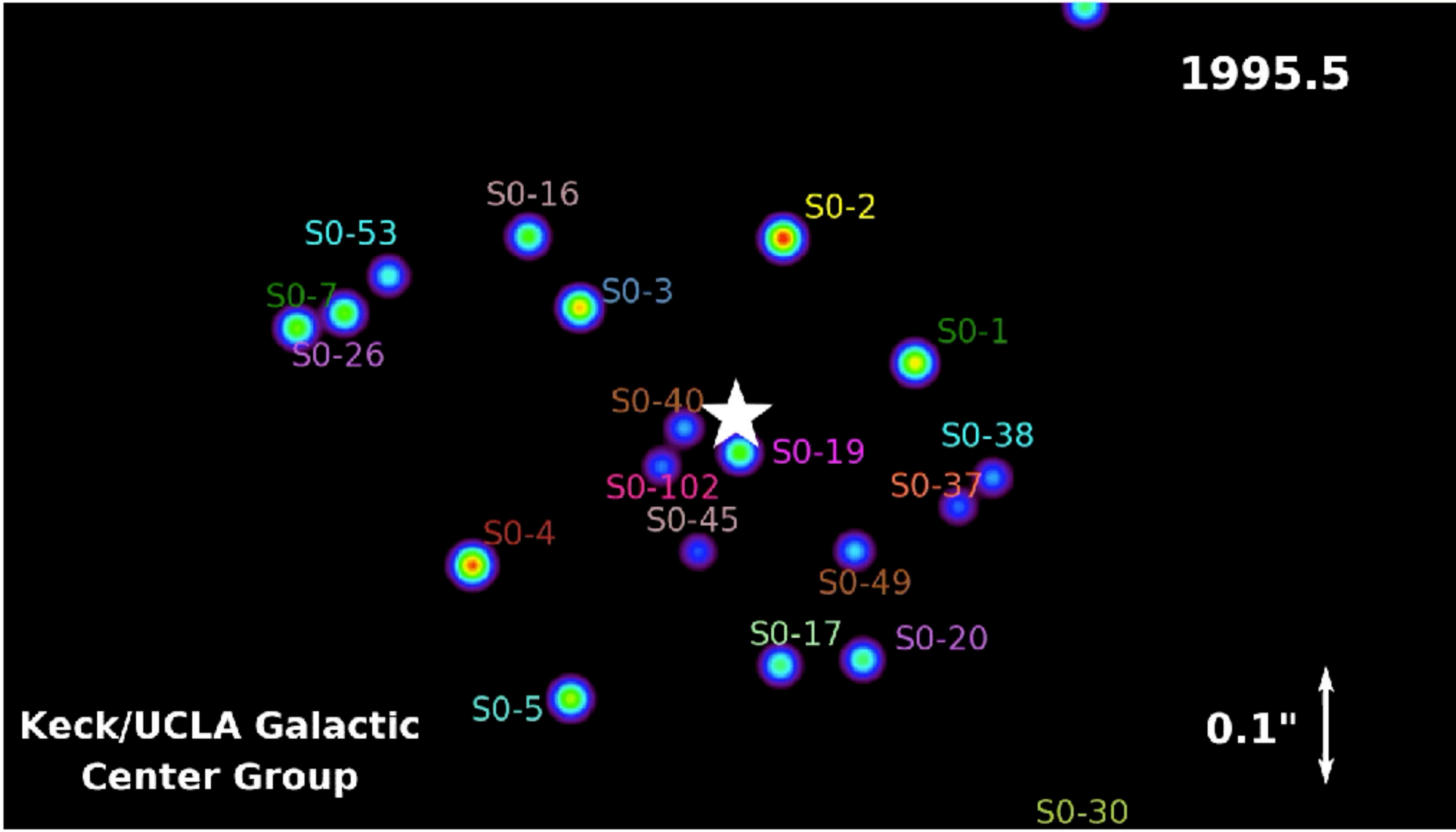
S0-30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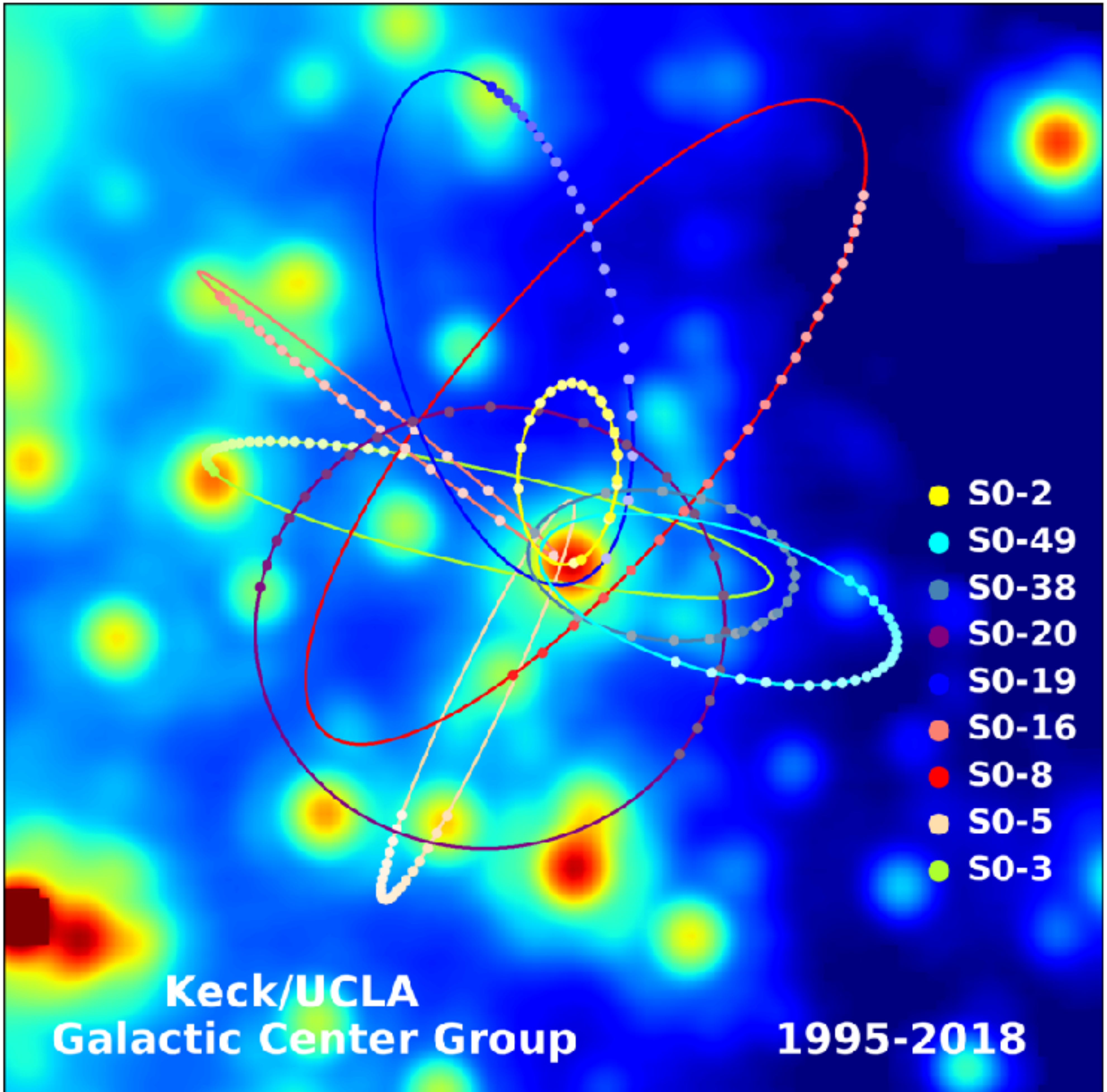
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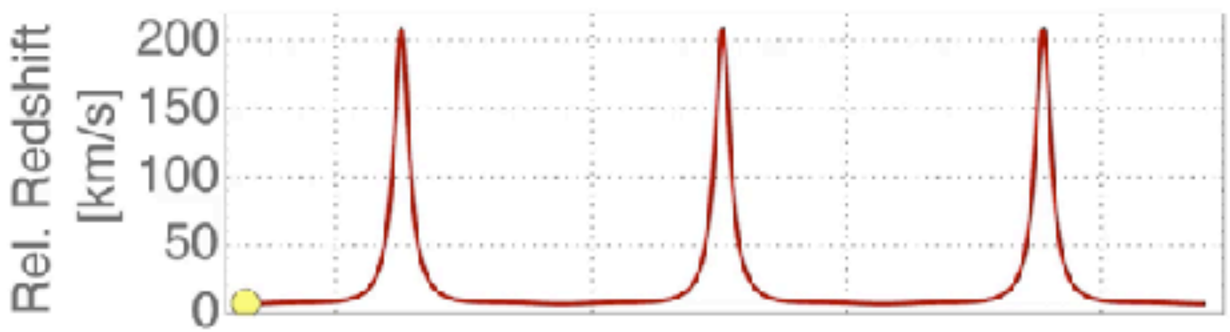
Keck/UCLA
Galactic Center Group
1995-2018

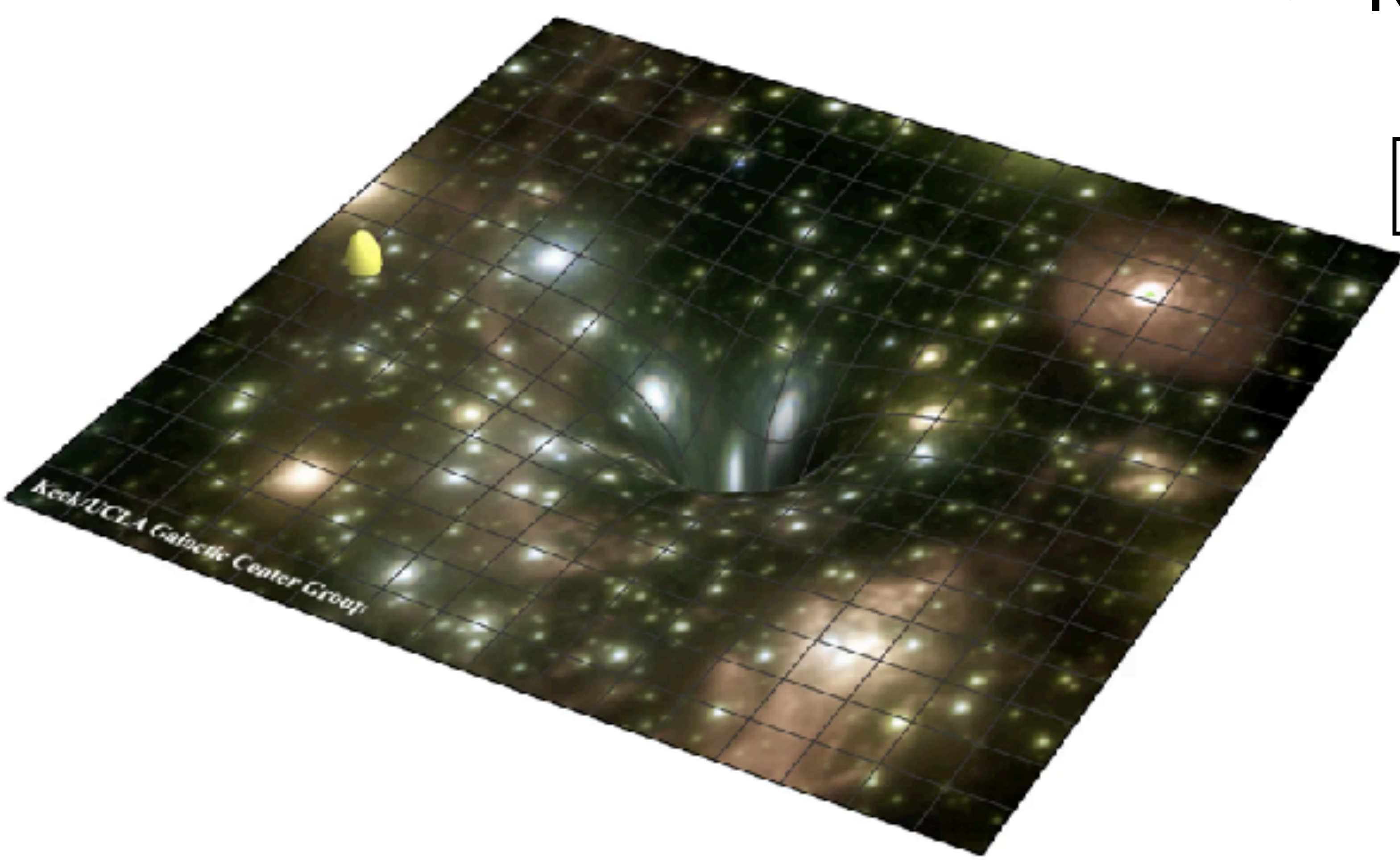
Can these observations be used to probe fundamental physics?

Is the Equivalence Principle valid around a SMBH?

- redshift test
- variation of the fine structure const.

Measurement of the relativistic redshift during S0-2/S2's closest approach in 2018





- Relativistic redshift (eq. principle)

$$[RV]_{\mathrm{rel}} = \frac{v^2}{2c} + \frac{GM}{rc}$$

peak @ ~ 200 km/s

- S0-2/S2 was followed very closely at Keck and at the VLT in 2018

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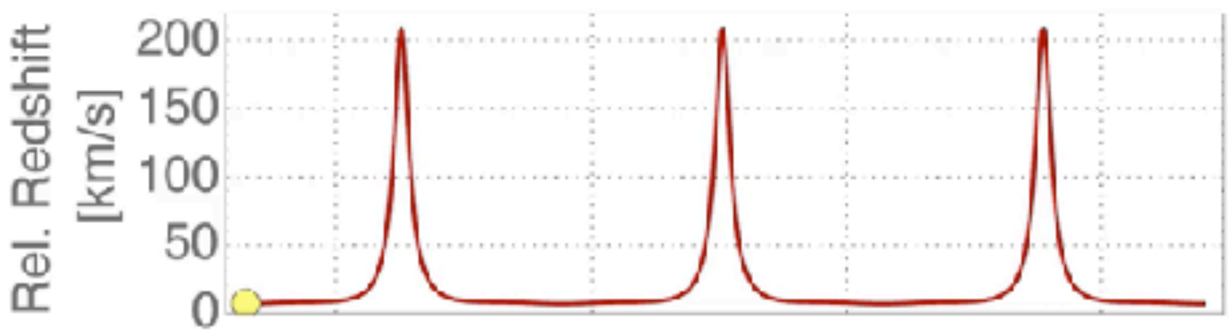

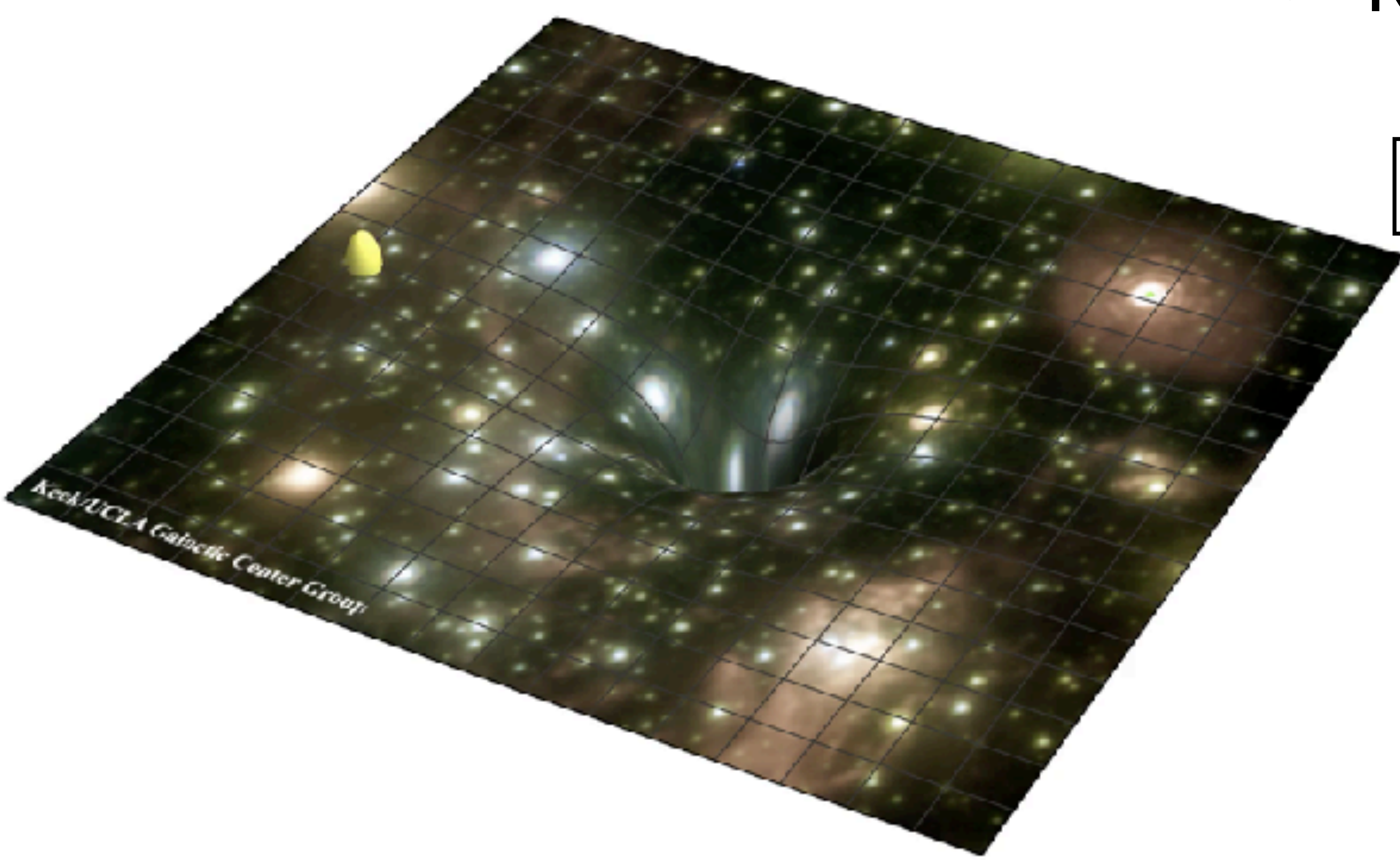

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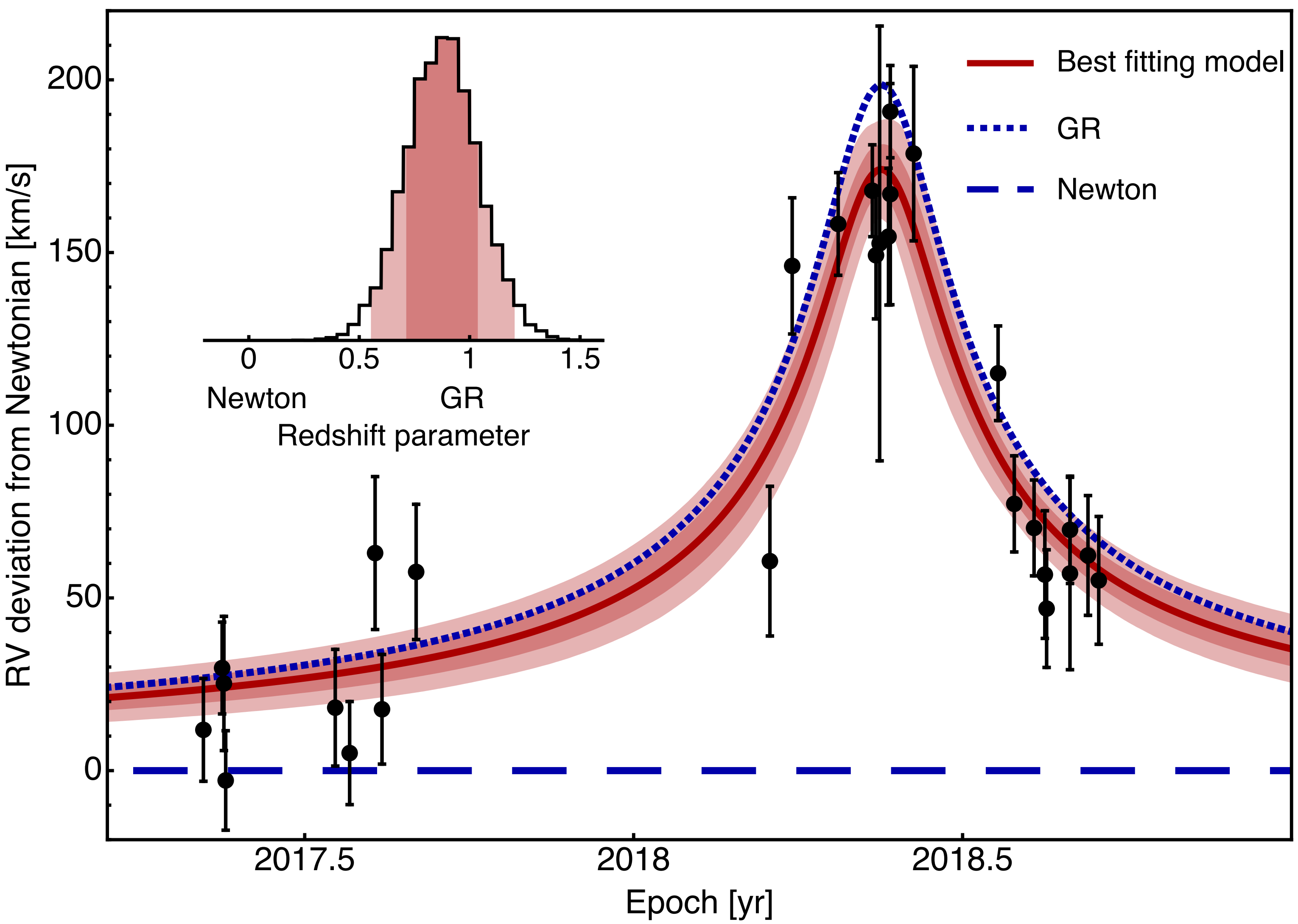
Measuring the redshift requires a careful analysis

- 45 astrometric measurements (from two instruments) and 115 radial velocity (RV) measurements (from 6 instruments - 4 telescopes: Keck, VLT, GEMINI and SUBARU)
- Combined in an orbital fit that includes: SMBH mass, SMBH position/velocity, orbital parameters, + parameters for systematics
- Thorough analysis of systematics:
  - Additional systematic uncertainty
  - Correlation within the astrometric dataset
  - Offset between instruments
  - Use of different telescope to check for possible systematics
  - Measurement of RV standards to check for systematics
  - …

see Do et al, Science, 2019

S0-2's relativistic redshift is consistent with GR

Υ is a parameter that encodes a deviation from relativistic redshift (=1 in GR, =0 in Newton)



$$RV = [RV]_{\mathrm{Newton}} + \Upsilon \left[\frac{v^2}{2c} + \frac{GM}{rc} \right]$$

$$\Upsilon = 0.88 \pm 0.17$$

see Do et al, Science, 2019

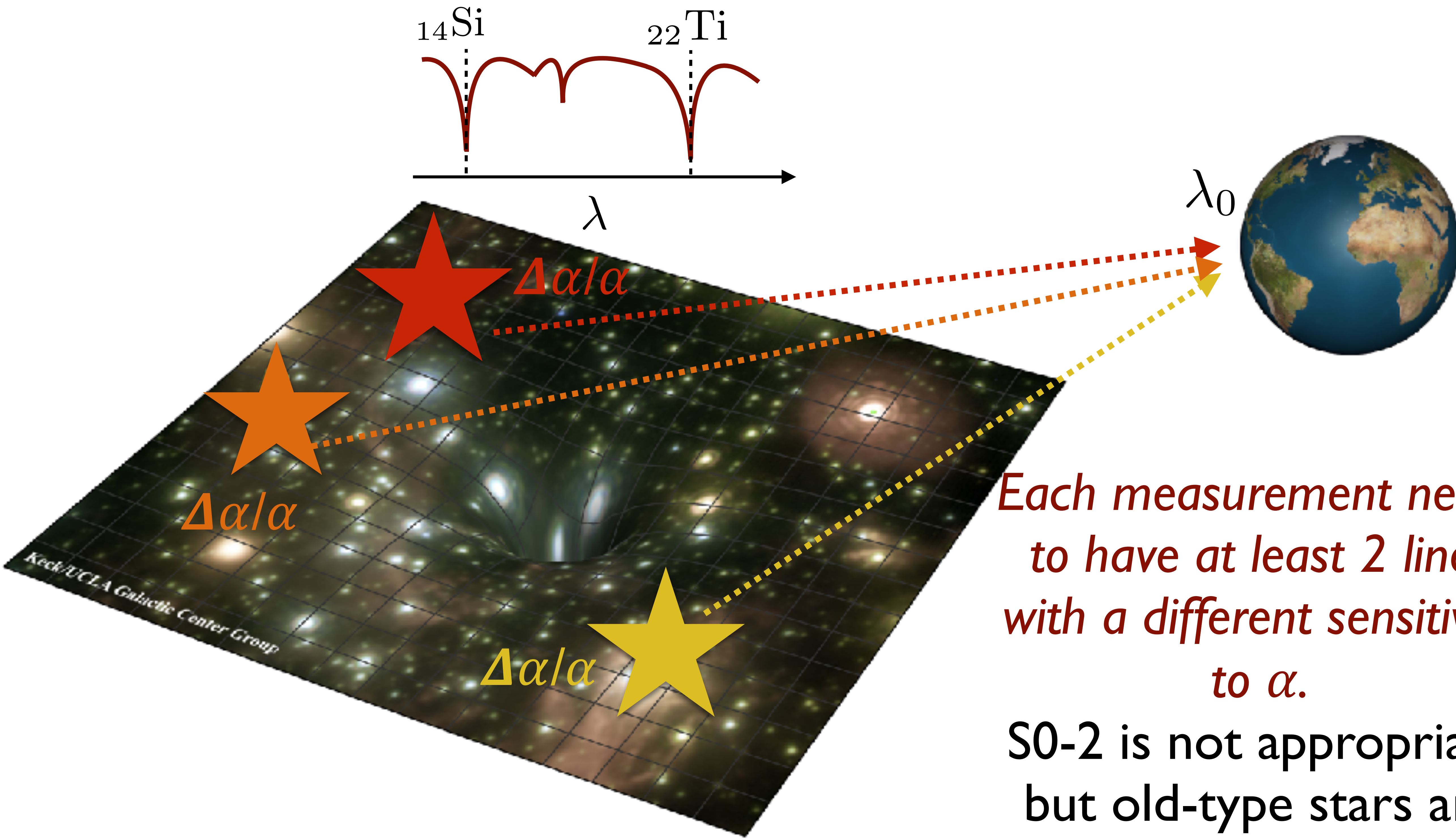
1σ agreement with GR and Newton excluded @5σ

- A similar result has been obtained by GRAVITY

$$\Upsilon = 0.9 \pm 0.06(\mathrm{stat}) \pm 0.15(\mathrm{syst})$$

see GRAVITY coll. , A & A, 2018

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

Six old-type stars have been identified as promising

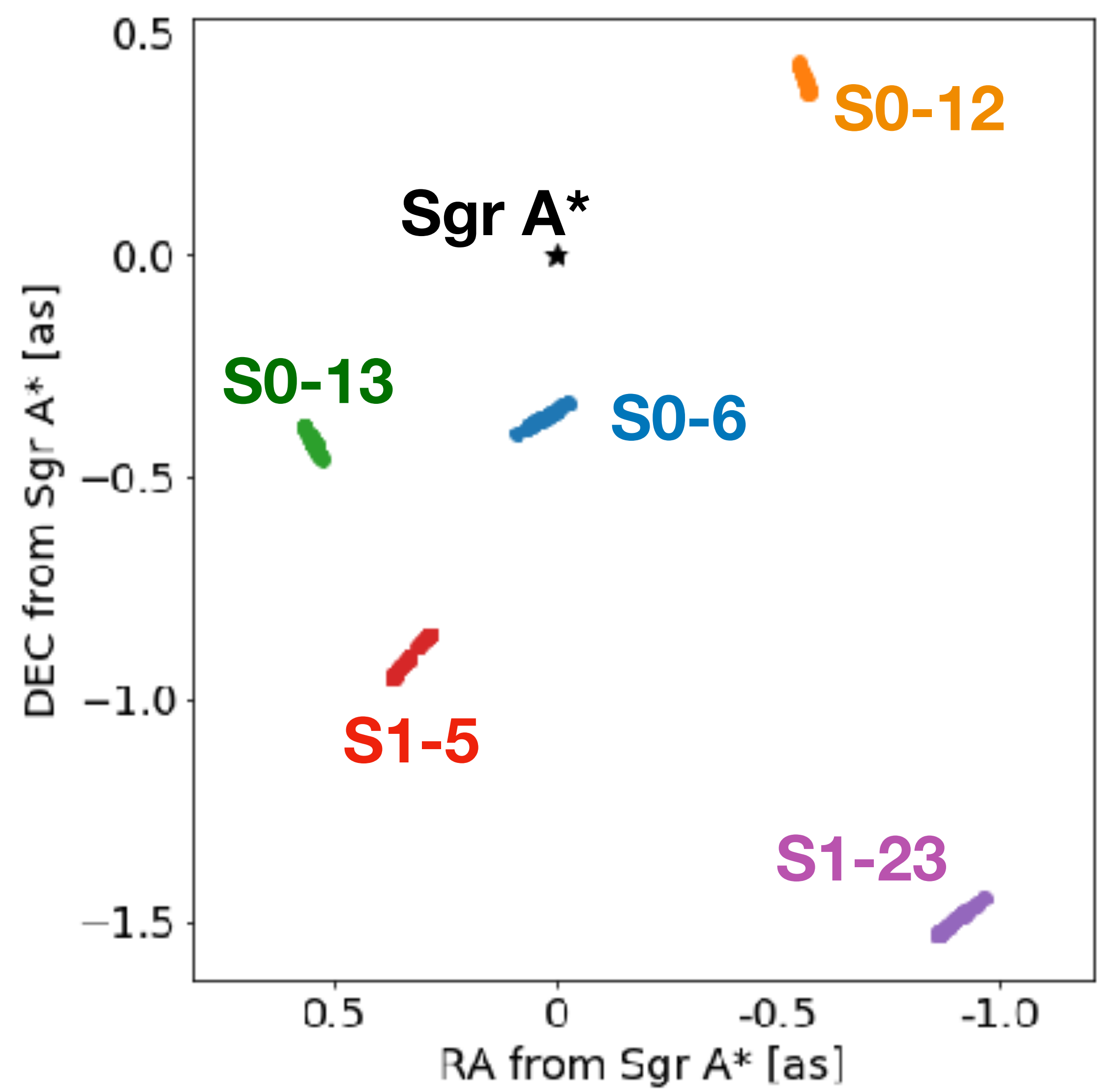
- Needs a lot of spectral lines (with different sensitivities to α): old-type stars
- Bright, to ensure a high SNR. Magnitude < 15
- Sufficiently in the central region: existence of measurements and probe of α “close” to the BH

- 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



Conceptually easy to infer a mapping of α in the GC

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

Measurement of the line j at epoch t_i

Quantity of interest

$$\left.\frac{\Delta\lambda_j}{\lambda_j}\right|_{z_i} = z_i + k_{\alpha,j}\frac{\Delta\alpha}{\alpha}$$

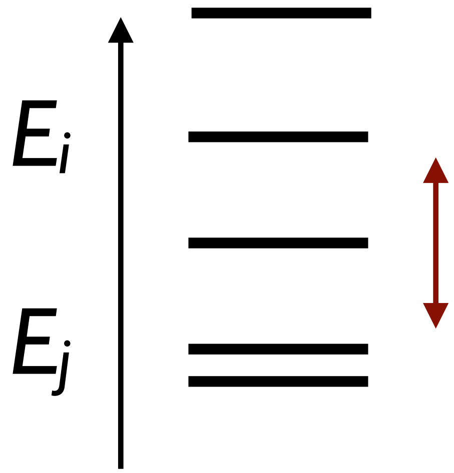
RV + relativistic redshift

Sensitivity of the line j to α (see following slide)

- Fit with 2 parameters: z_i and $\Delta\alpha/\alpha$

The theoretical computation of the sensitivity coefficients is not an easy task

Energy levels for the electronic configuration



$\omega = (E_i - E_j)/\hbar$

Energies are computed from first principles (Hartree-Fock)

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

Interaction with the nucleus + self interaction of the electrons

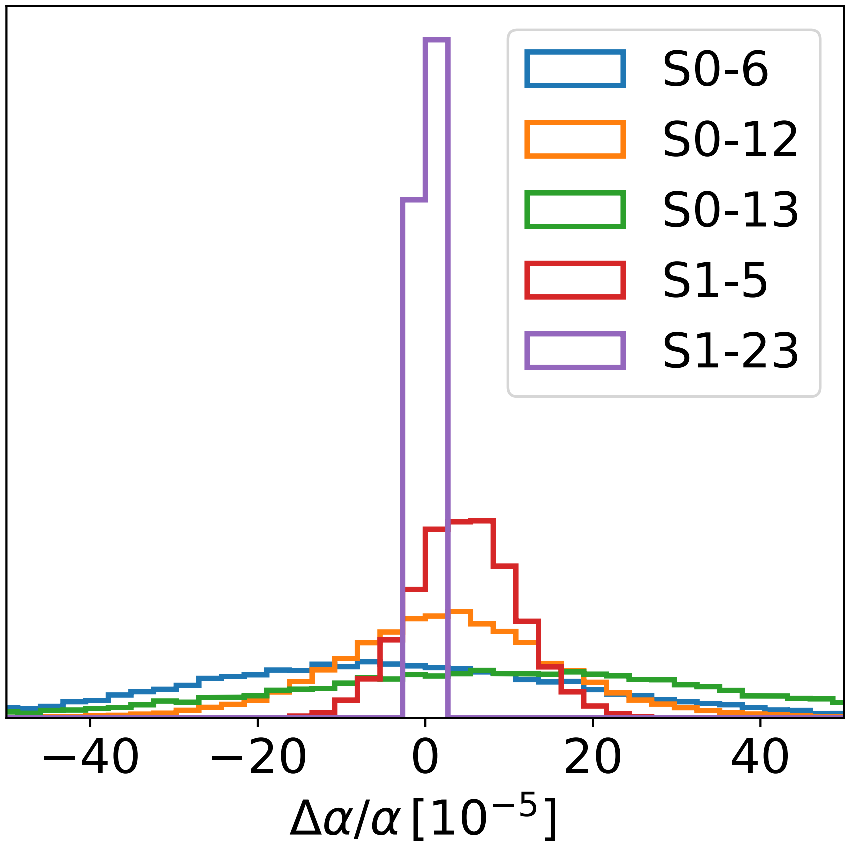
Wave function of the N electrons (Slater determinant)

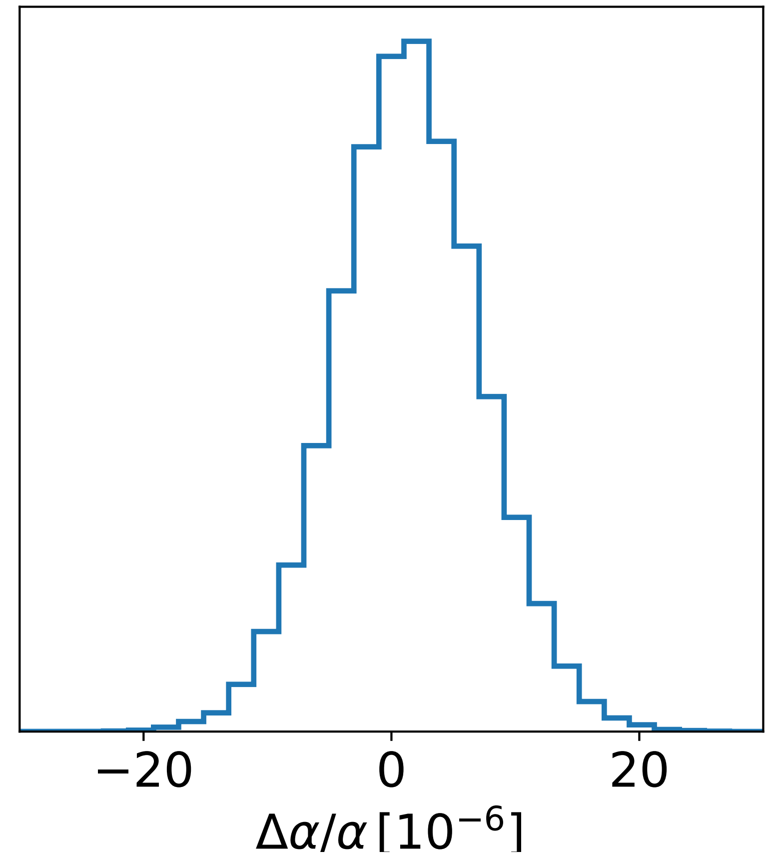
- The sensitivity coefficient is computed numerically $k_\alpha = \dfrac{d\ln\omega}{d\ln\alpha}$

Extremely costly computation done by B. Roberts using AMBIT

For AMBIT see e.g. Kahl and Berengut, Comp. Physics. Communications, 2019

No variations of α detected around Sgr A*





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

$$\frac{\Delta\alpha}{\alpha} = (1.4 \pm 5.8) \times 10^{-6}$$

- 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

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

gravitational potential

fundamental parameter

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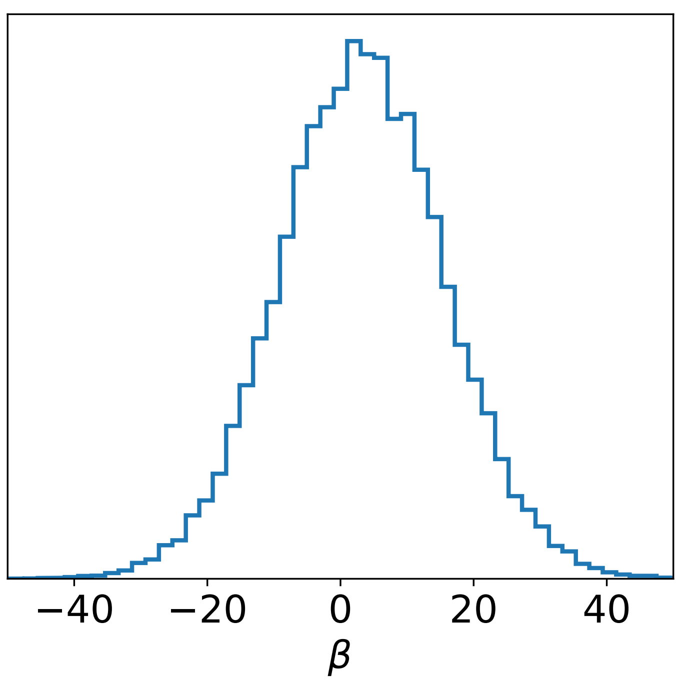
gravitational potential

fundamental parameter

$$\beta = 3 \pm 12$$



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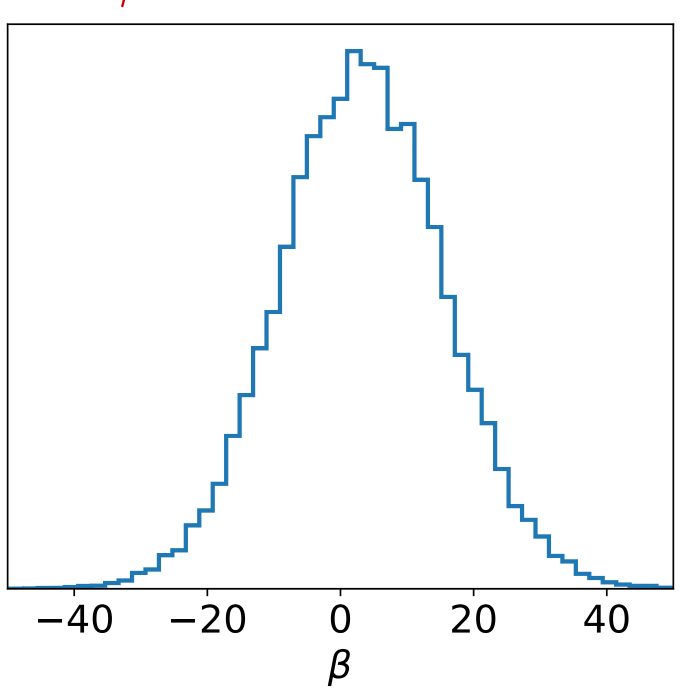

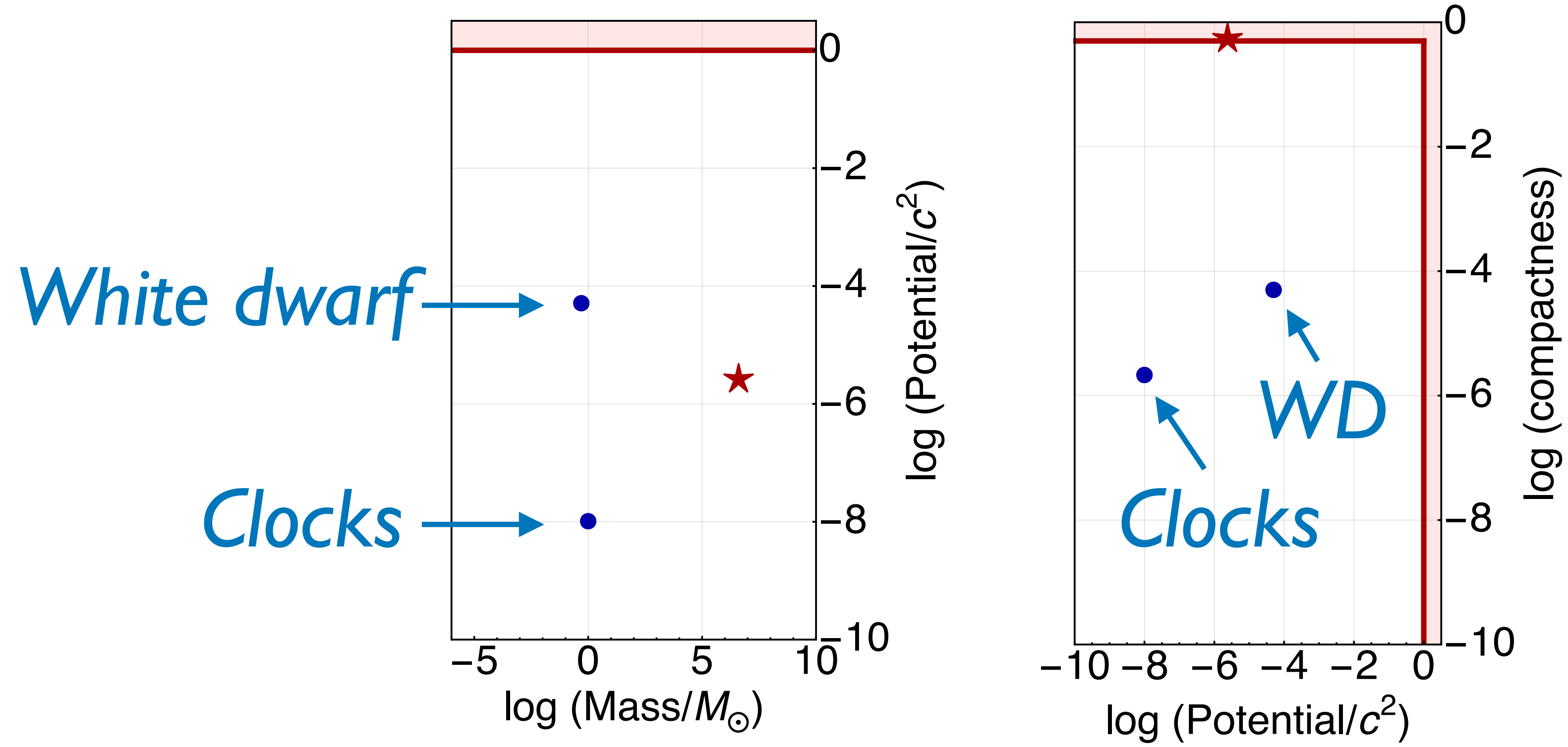

- 6 order of magnitude less stringent that atomic clocks and 1 order of magnitude less stringent than the white dwarf but for the first time around a BH

Conclusion

- Searching for violation of the EEP is one promising way to search for new physics: unification theories, Dark Matter/Dark Energy

- measurements of stars orbiting Sgr A* provide a new opportunity to test the Equivalence Principle
  - gravitational redshift test @30%
  - variation of α @6 x10^{-6}

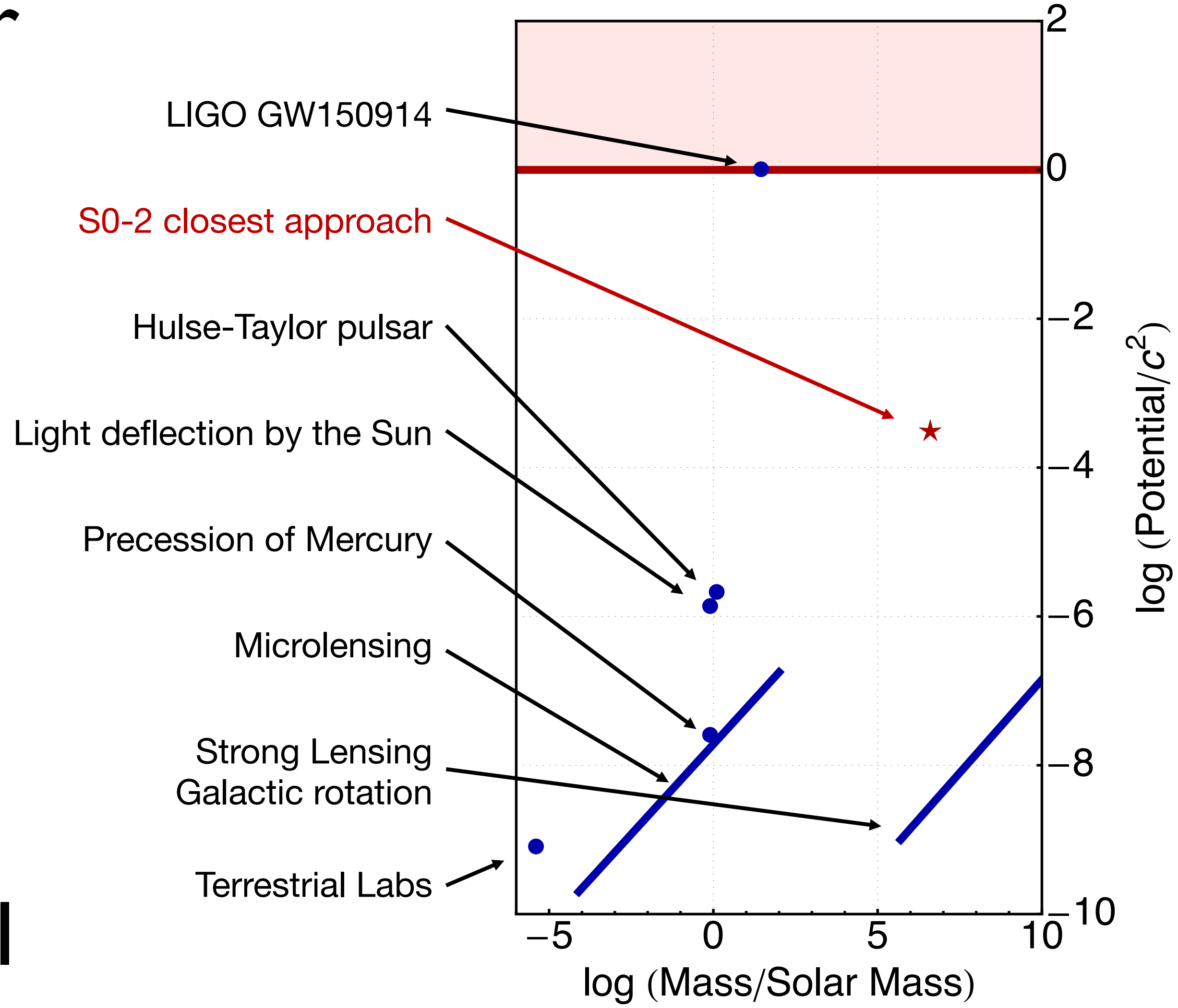

Figure inspired by D. Psaltis, 2004

- Not as stringent as similar tests in the Solar System but:
  - in a different location
  - in a higher gravitational potential
  - around a black hole
  - …

- Improvement and other GR tests expected in the future