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# *The motion of S2 as dark matter detector*

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# Idea and motivation

**Idea:** Constrain an ultralight scalar field cloud around the supermassive Black Hole (BH), ***Sagittarius A****, at the center of the Milky Way using orbital motion of S-stars.

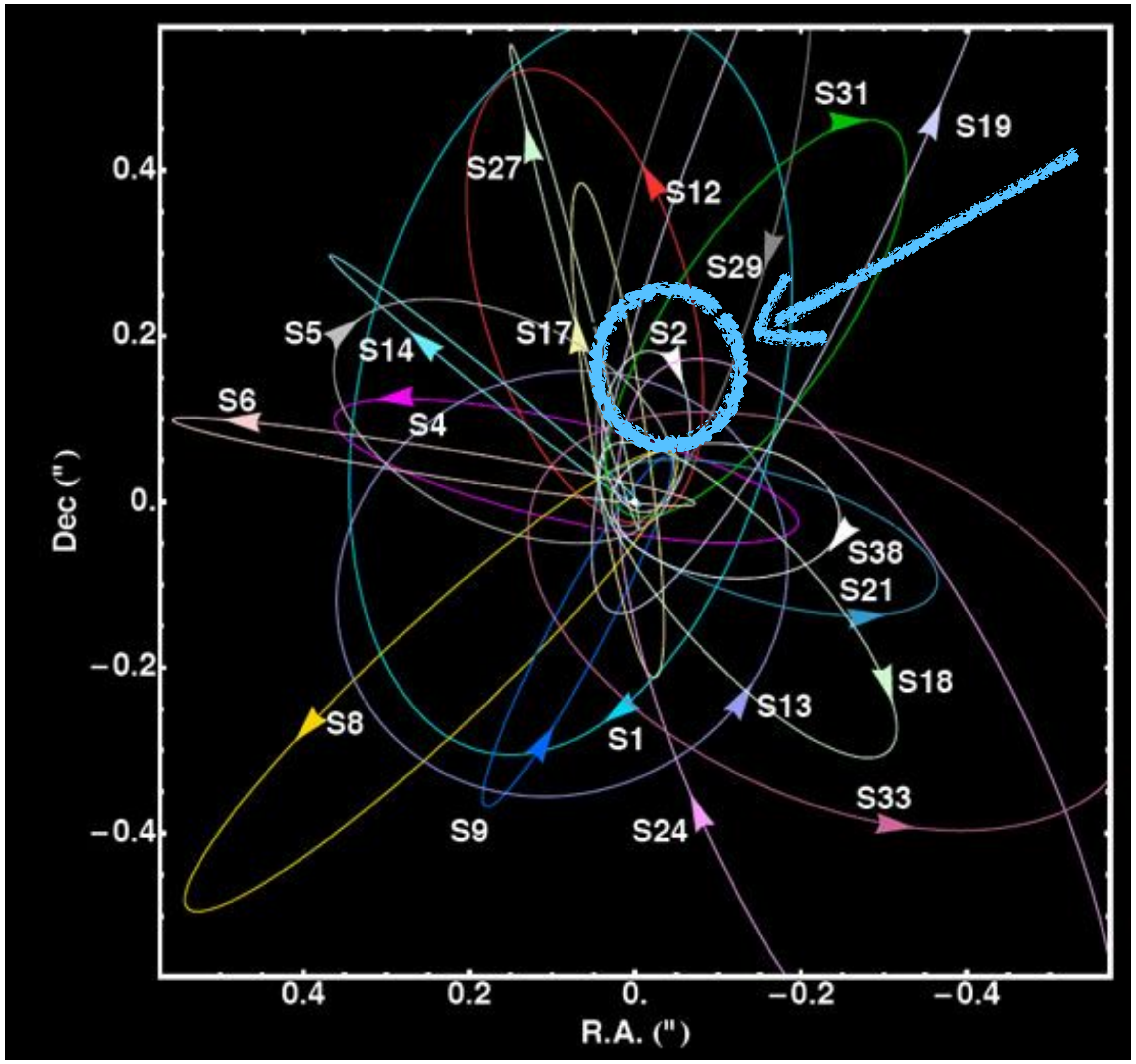
**We will focus on star S2.**

**Data:** We have **astrometry** (positions in the sky) and **spectroscopy** (radial velocity measurements).

**Motivation:** Ultralight bosons are possible candidates for **Dark Matter** (DM).

DM may cluster around supermassive BHs (Sadeghian et al. 2013).

The Galactic Center (GC) is the perfect laboratory to look for it.




Credits to S. Gillessen, GRAVITY Coll., Max Planck Institute

# Theoretical setup

$$S = \int d^4x \sqrt{-g} \left( \frac{R}{16\pi G c^{-4}} - \frac{1}{2} g^{\alpha\beta} \partial_\alpha \Psi^* \partial_\beta \Psi^* - \frac{\mu}{2} \Psi \Psi^* \right) \longrightarrow \begin{cases} G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \\ \square \Psi = \mu^2 \Psi \end{cases} \quad \left( \mu = \frac{m_s c}{\hbar} \right)$$

**Einstein-Klein-Gordon** System of equations

**Mass coupling** $\alpha = r_g \mu = \left[ \frac{GM_\bullet}{c^2} \right] \left[ \frac{m_s c}{\hbar} \right]$

In the limit $\alpha \ll 1$, the fundamental mode of the field $(\ell = m = 1)$ is given by (Brito et al., 2015)

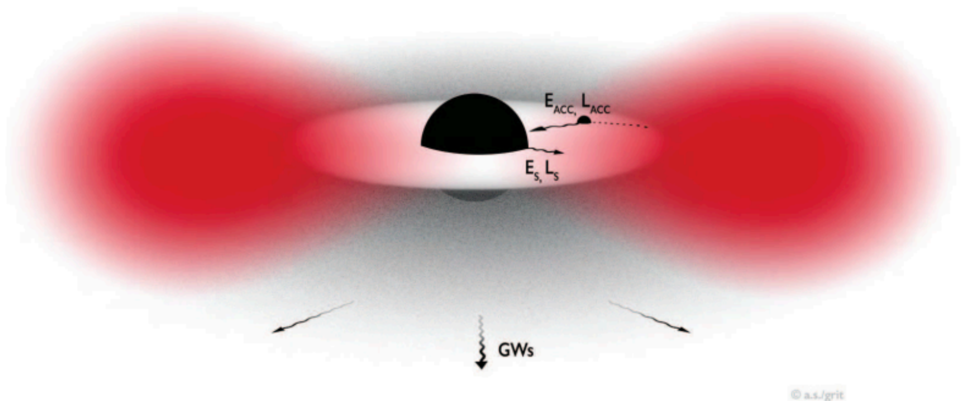
$$\Psi = A_0 e^{-i(\omega_R t - \varphi)} \, r \, \alpha^2 e^{-r\alpha^2/2} \sin\theta \qquad \left( A_0^2 = \Lambda \frac{\alpha^4}{64\,\pi} \right)$$

We compute the energy momentum of the scalar field

$$T_{\mu\nu} = \frac{1}{2} \left( \partial_\alpha \Psi^* \partial_\beta \Psi + \partial_\beta \Psi^* \partial_\alpha \Psi \right) - \frac{1}{2} g^{\alpha\beta} \left( \partial_\sigma \Psi^* \partial^\sigma \Psi + \mu^2 \Psi^* \Psi \right)$$

And we obtain the energy density of the scalar field *in the low energy limit:*

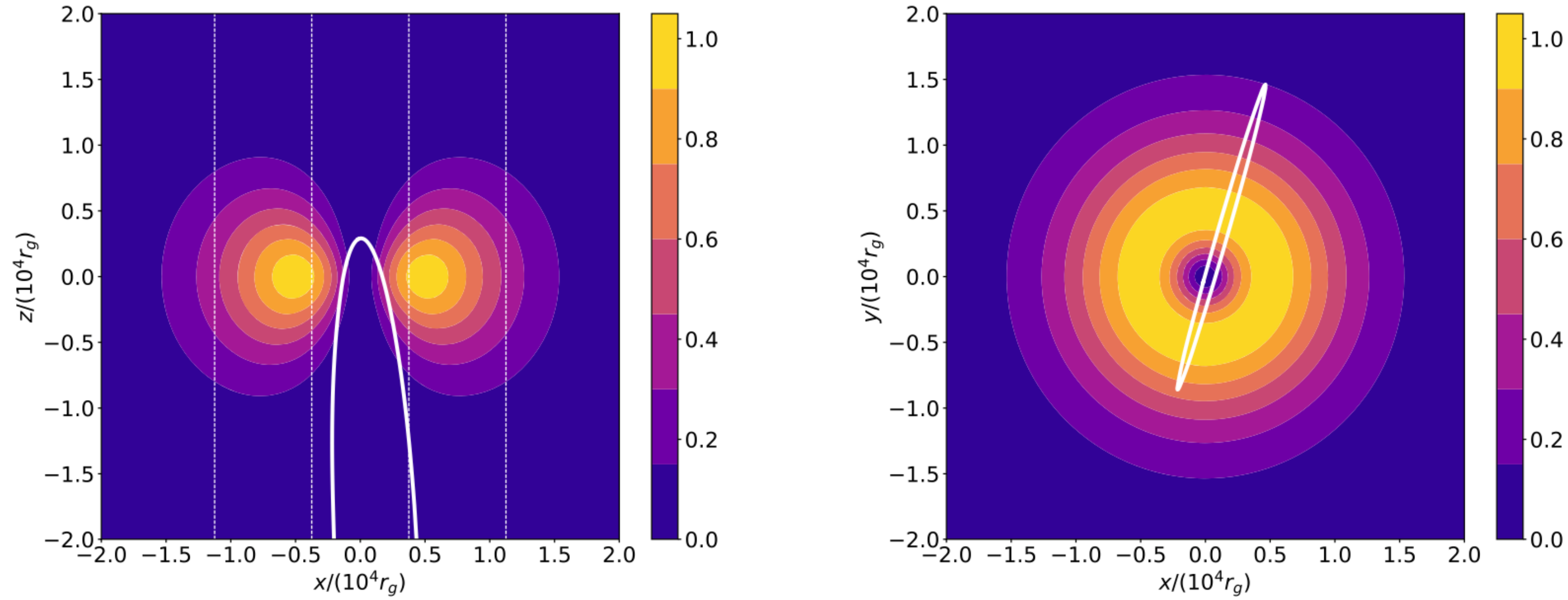
$$\rho = \frac{m_s^2 c^2}{\hbar^2} |\Psi|^2 + \mathcal{O}\left(c^{-4}\right)$$



# Analytical results

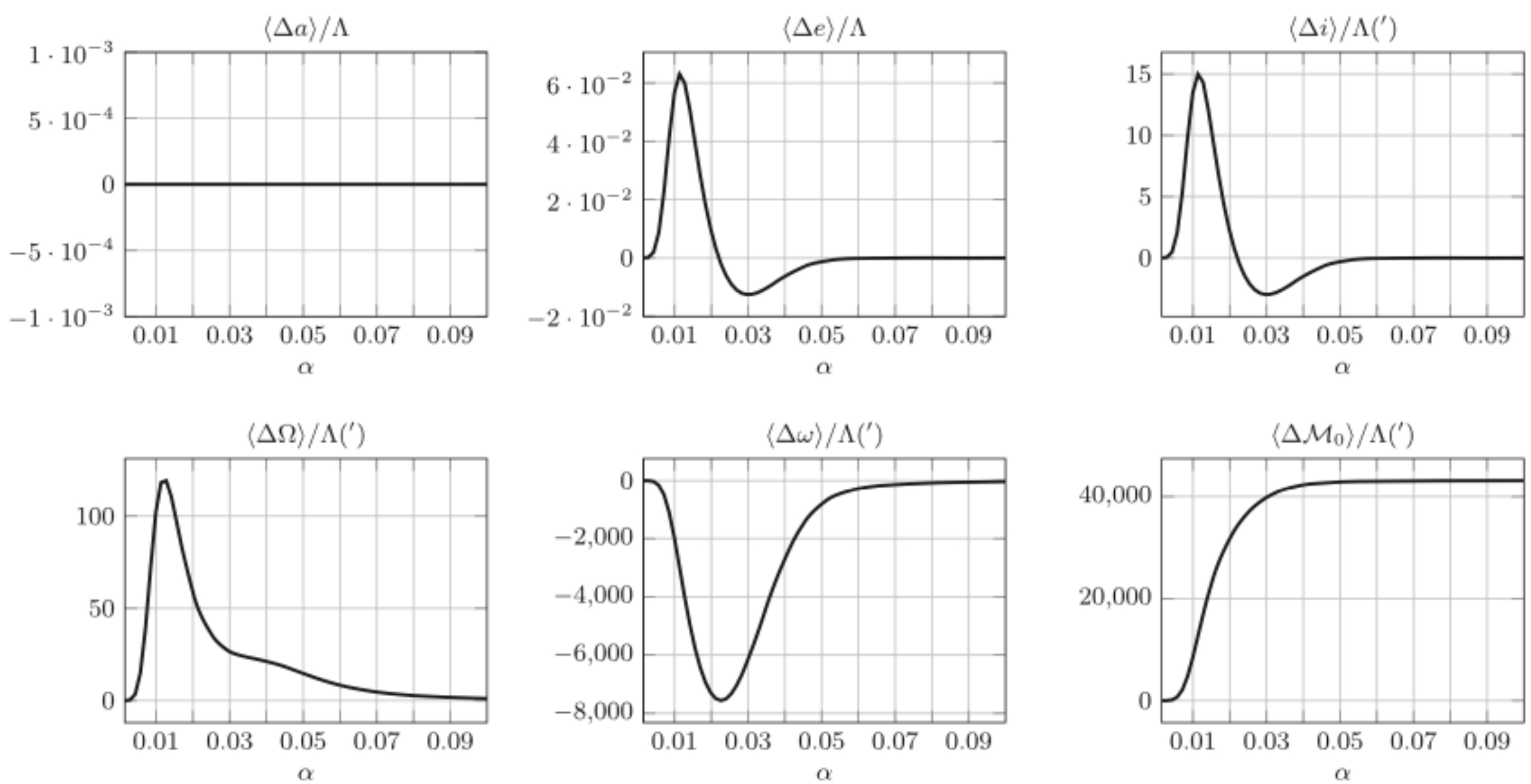
## Distribution of the energy density

$$\rho = \frac{m_s^2 c^2}{\hbar^2} |\Psi|^2$$




$$r_g = \left(\frac{2M_\bullet G}{c^2}\right)$$

Variation of the orbital elements of S2: $\Delta\kappa = \int_{f_0}^{f_0+2\pi} \frac{d\kappa}{dt}\frac{dt}{df'}df'$ with $\kappa \in \{e, a, i, \Omega, \omega, t_p\}$




$$\Lambda = \frac{M_{\rm cloud}}{M_{\rm BH}}$$

$0.001 \lesssim \alpha \lesssim 0.05$ [1]

$\left(10^{-20} \lesssim m_s \lesssim 10^{-18}\right)$ eV/c$^2$


[1] GRAVITY Coll. *et al.*, "Scalar field effects on the orbit of S2 star", MNRAS 489, 4606-4621 (2019)

# The method: Markov Chain Monte Carlo (MCMC)

using emcee (Foreman-Mackey et al., 2013) Python package

We need to *sample* the posterior distribution of a set of parameters $\theta_i$ by means of Bayes' theorem

$$P(\theta|D) \propto P(D|\theta)P(\theta)$$

$D$ = data set

$$\theta_i = \{\underbrace{e, a, \Omega, i, \omega, t_p}_{\text{Keplerian elements}}, \underbrace{R_0, M_\bullet}_{\text{BH Mass and GC distance}}, \underbrace{\alpha, \Lambda}_{\text{Scalar field cloud parameters}}\}$$

**Gaussian likelihood**

$P(D|\theta)$ = Likelihood

$$\log(P(D|\theta)) = -\frac{1}{2}\left[\sum_{i=0}^{N_{\rm data}}\left(\frac{x^i - x^i_{\rm data}}{\sigma^i_x}\right)^2 + \left(\frac{y^i - y^i_{\rm data}}{\sigma^i_y}\right)^2 + \left(\frac{v^i_r - v^i_{r\rm data}}{\sigma^i_{v_r}}\right)^2\right]$$

$P(\theta)$ = Prior distributions of $\theta_i$

**Flat priors**, i.e. uniformly distributed in

$$\left(\theta_i^{\rm true} - \Delta\theta_i^{\rm true}\right) \leq \theta_i \leq \left(\theta_i^{\rm true} + \Delta\theta_i^{\rm true}\right)$$

# Summary and future perspectives

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- We look for ultralight boson in the form of a cloud around the supermassive BH at the center of our Galaxy;

- We know that if the coupling of the field is in the range $0.001 \lesssim \alpha \lesssim 0.05$ then it can leave imprints in the orbital elements of S2 and we have some chances to detect it;

- We focus on this range and we implement a MCMC method to find the best-fit estimates for scalar field parameters $\alpha, \Lambda$;

- Preliminary results show that the same range of $\alpha$ is excluded by observations and we found **no evidences** for a scalar field cloud.

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## Future perspectives

- Extend the same analysis to other S-stars to confirm or reject results on S2;
- Test different matter distributions around Sgr A*, i.e. power law distributions and/or vector clouds;

# Thank you for your attention!