Searching for Ultra-Light Dark Matter Signals with the Stellar Kinematics

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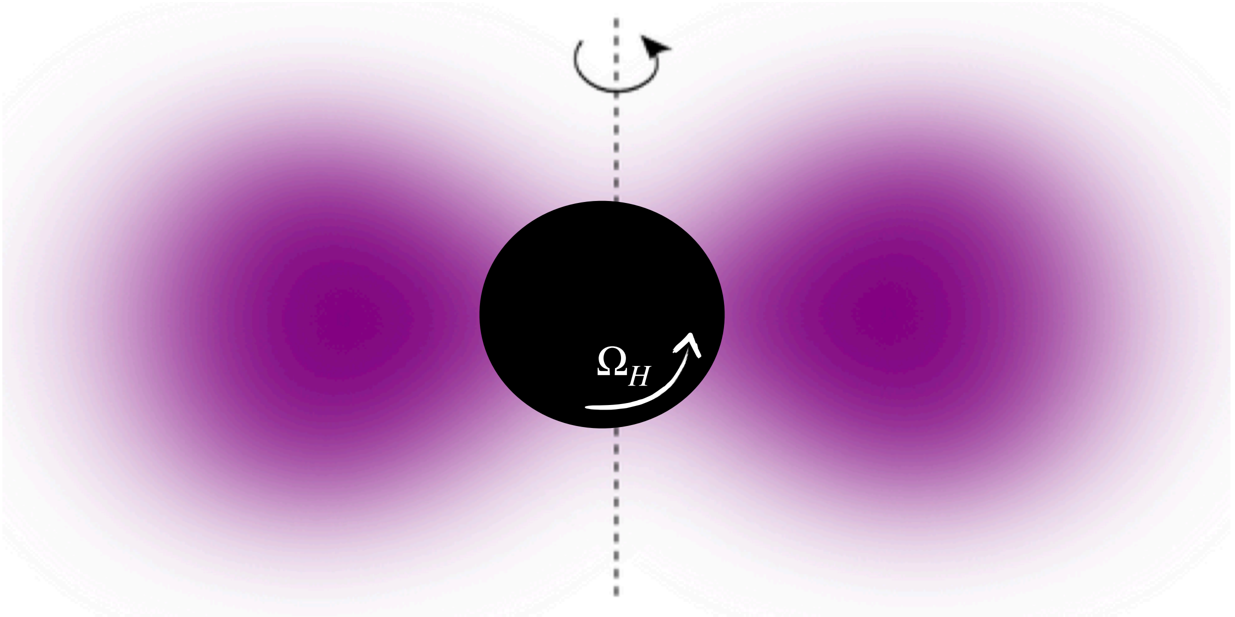
Based on *PRD 106, 103024(2022);*
MNRAS 527, 3196-3207(2024).

4th International FLAG Workshop@Catania
(11/09/2024)

Outlines

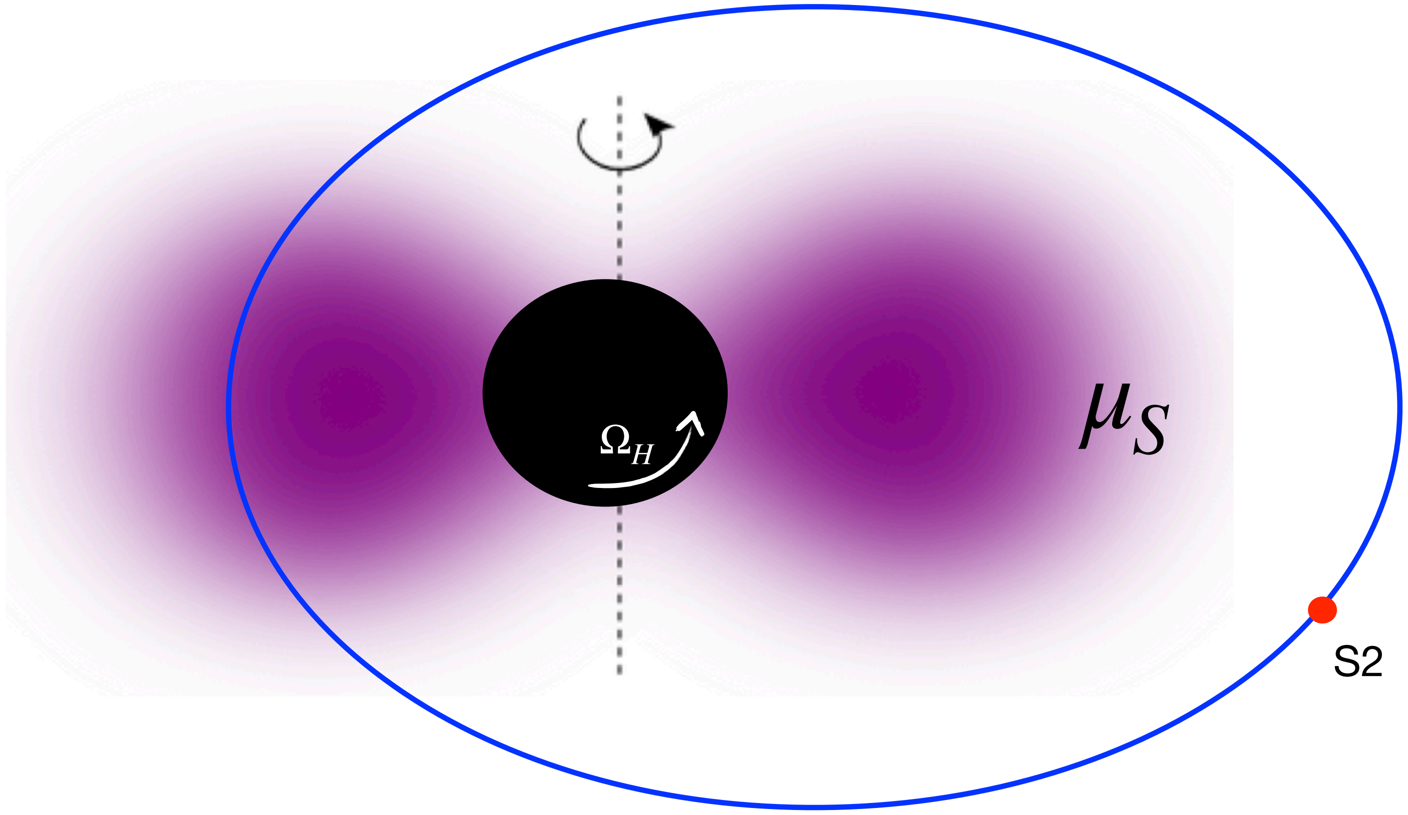
Superradiant scalar clouds growth around Sagittarius A*

- **What** are superradiant clouds?
- **Why** are we interested in them?
- **How** can we constrain their mass at the GC?
- **Results** on the mass of those clouds around Sagittarius A*;



Scalar cloud

Black holes as particle detectors

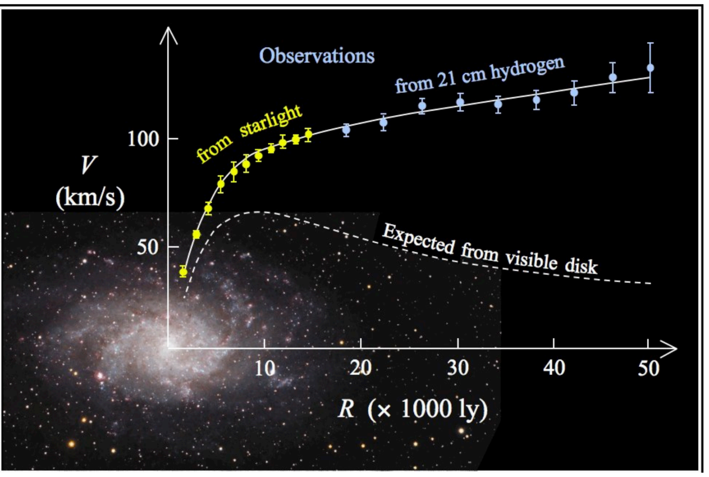


Bosonic waves scattering off a rotating black hole can extract rotational energy from it. For a scalar cloud, the interaction with the black hole's gravitational field leads to the amplification of the field's amplitude with:

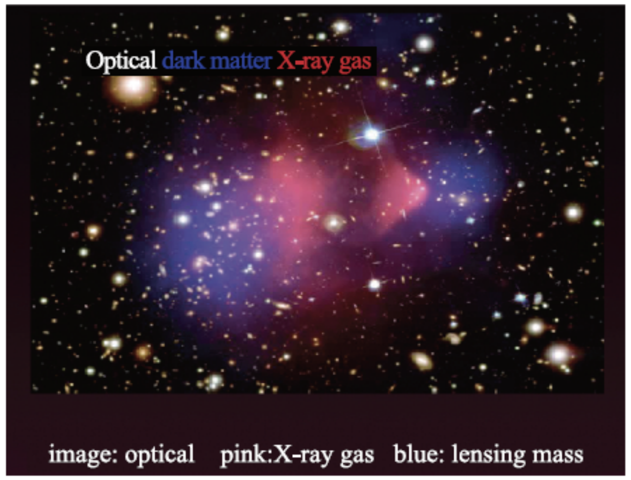
Superradiance condition: $\omega < m\Omega_H$

Richard Brito, Vitor Cardoso, Paolo Pani, Superradiance: New Frontiers in Black hole Physics, *Lect.Notes Phys.(2015)*.

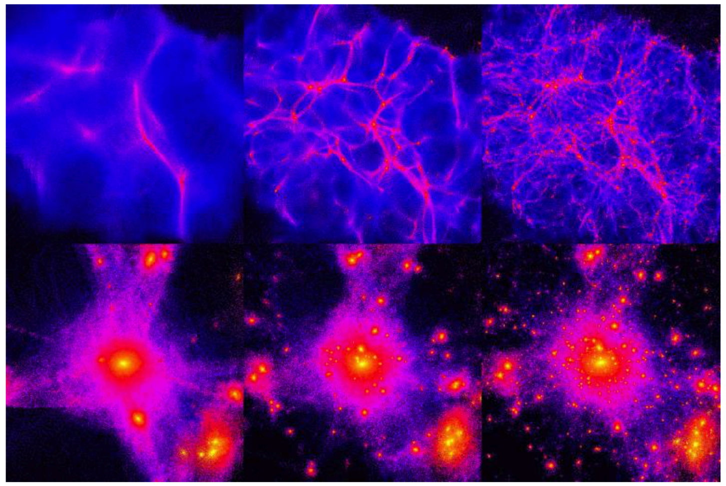
Motivation



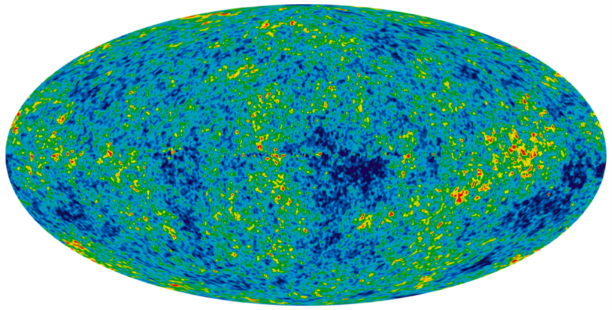
Galactic Rotation Curve



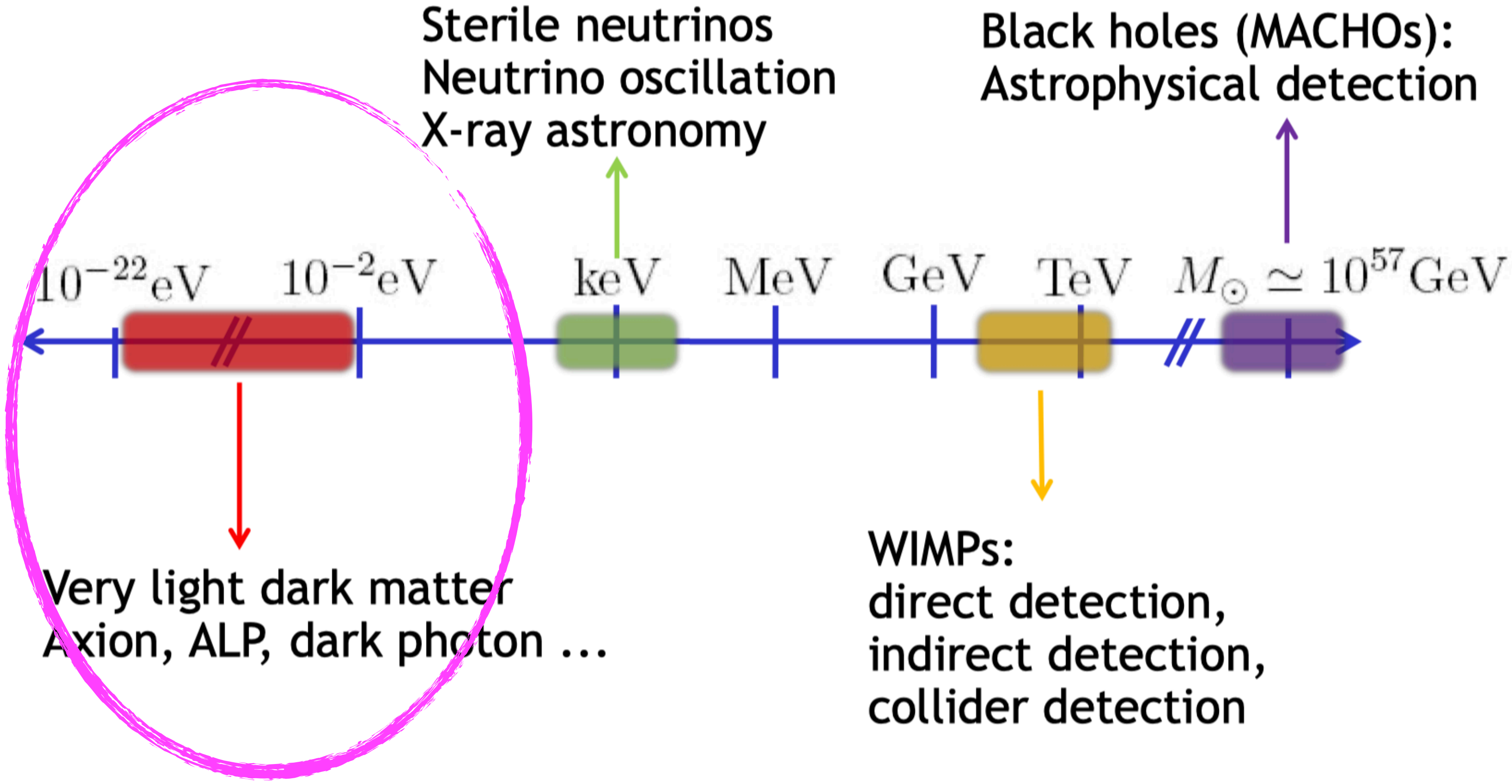
Collisions of Galaxy Clusters



Large Scale Structure



Cosmic Microwave Background



Sterile neutrinos
Neutrino oscillation
X-ray astronomy

Black holes (MACHOs):
Astrophysical detection

Very light dark matter
Axion, ALP, dark photon ...

WIMPs:
direct detection,
indirect detection,
collider detection

Crisis on small scales of LCDM:

Cusp-core problem
Too-big-to-fail problem
Missing satellites problem
Diversity problem

Motivation

Ultralight bosons are good candidates for DM (axions, axion-like particles, dark photons…)

BUT

They are very weakly coupled to SM particles and difficult to detect in the lab

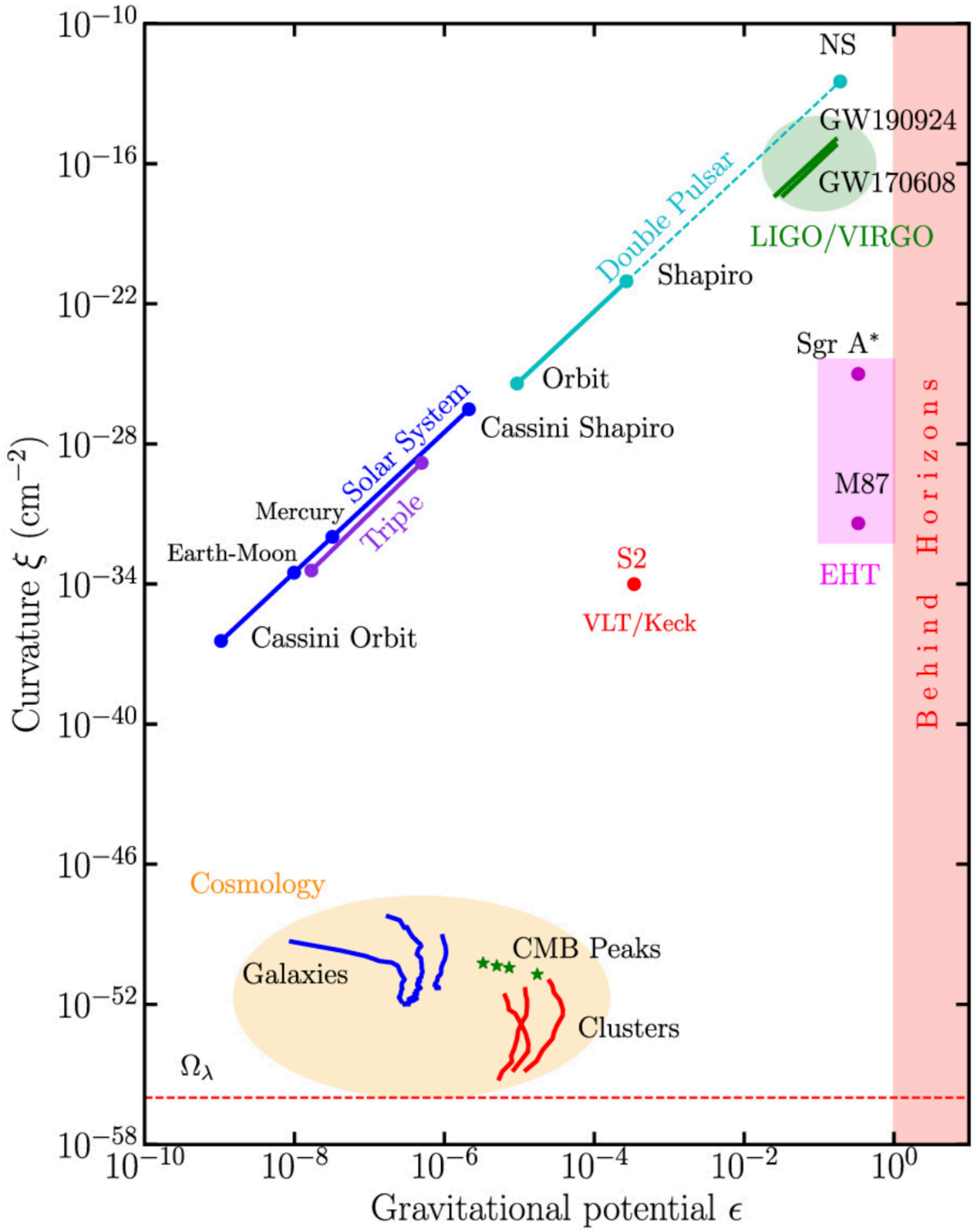
↓

DM would be bounded in strong gravitational field and form a far more dense region around SMBH.

↓

Galactic Center:

a perfect laboratory to test DM around **Sagittarius A*** for their density

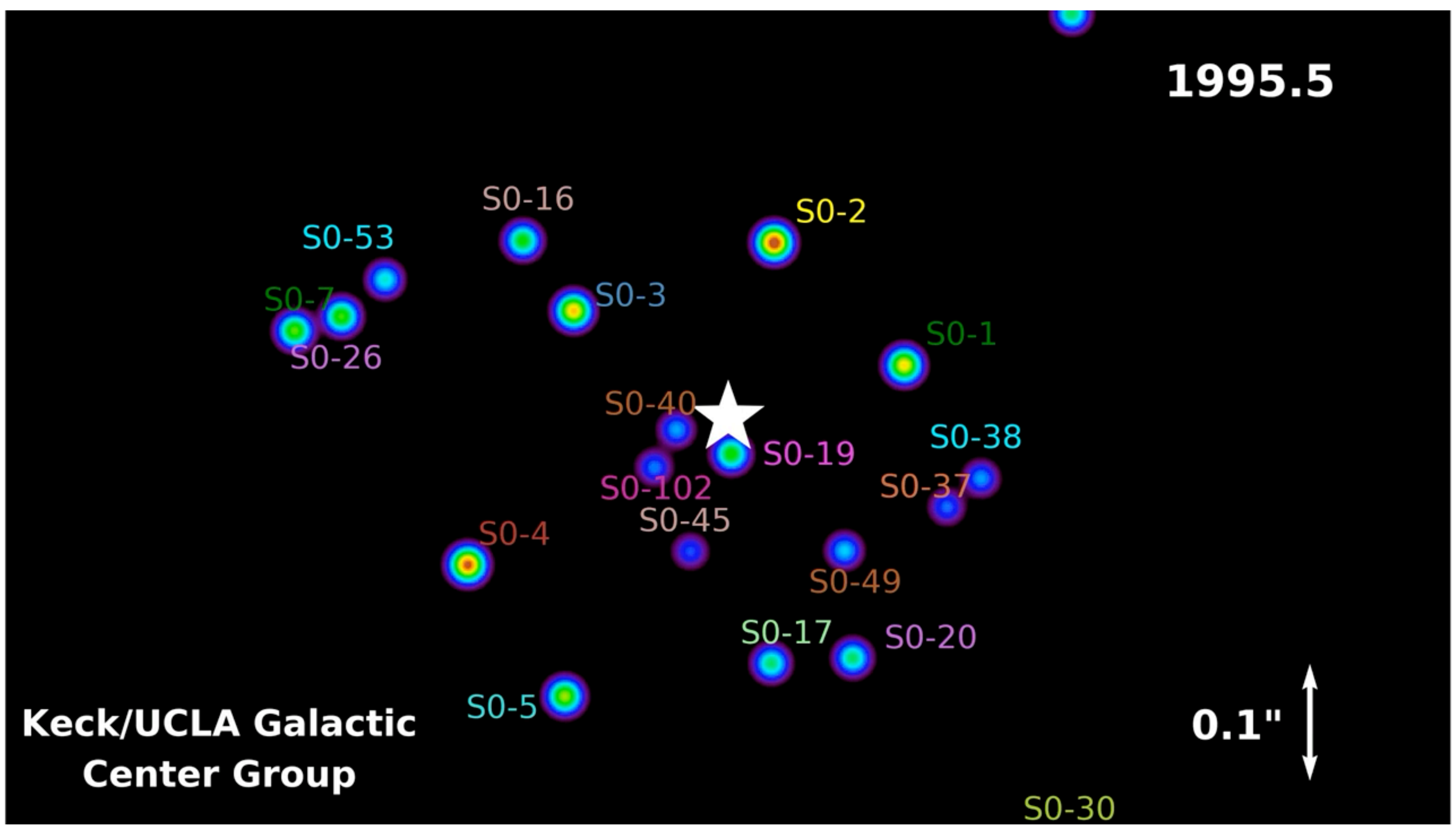


Mariafelicia de Laurentis, et al, The GC as a laboratory for Theories of gravity and dark matter, *Rept.Prog.Phys.(2023)*.

Data sources

Imaging and astrometric measurements @ Keck
Spectroscopy and radial velocity measurements @Keck @VLT

S-stars cluster around SgrA*



Very Large Telescope@MPE

Keck Observatory@UCLA

Data sources

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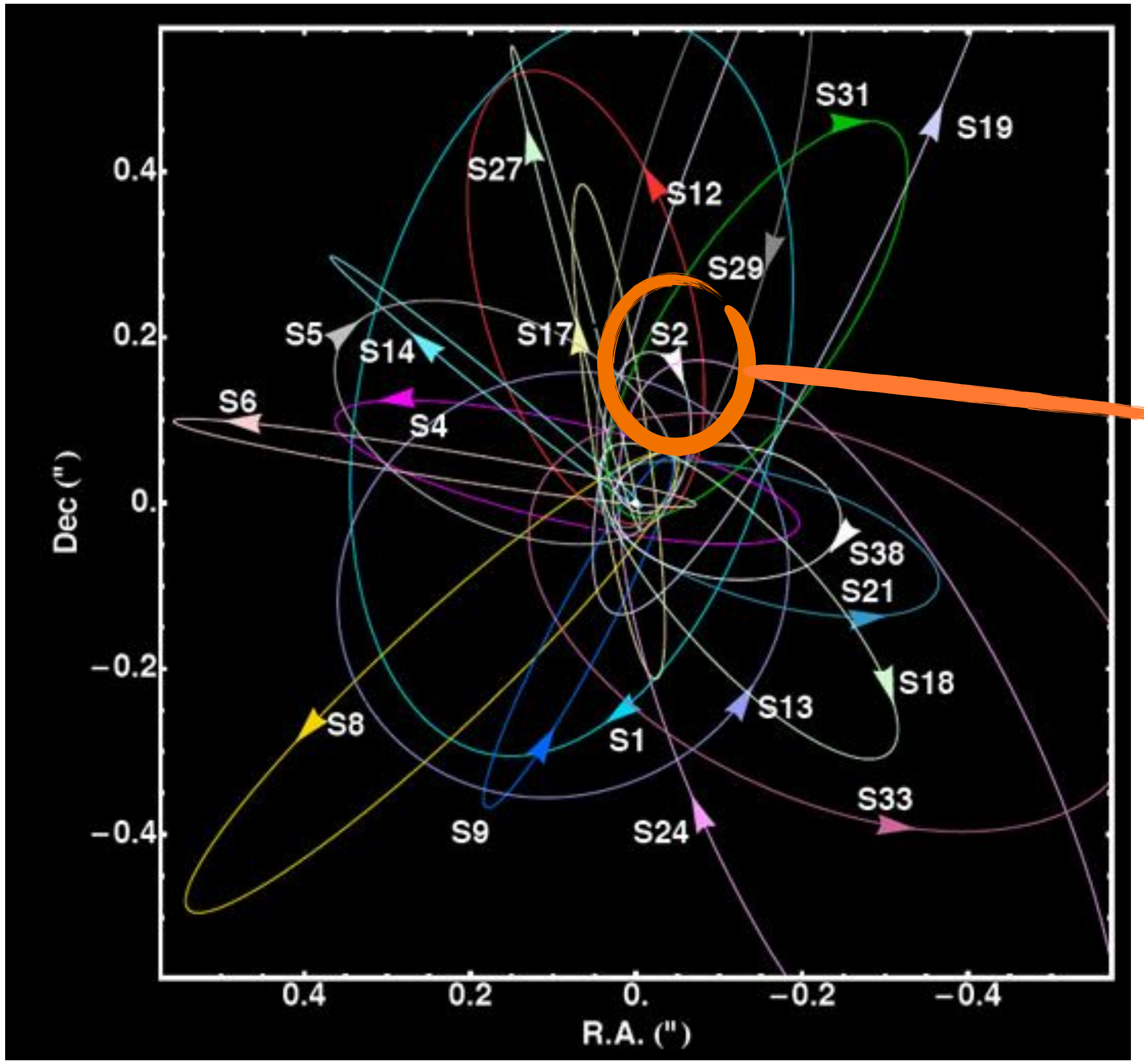
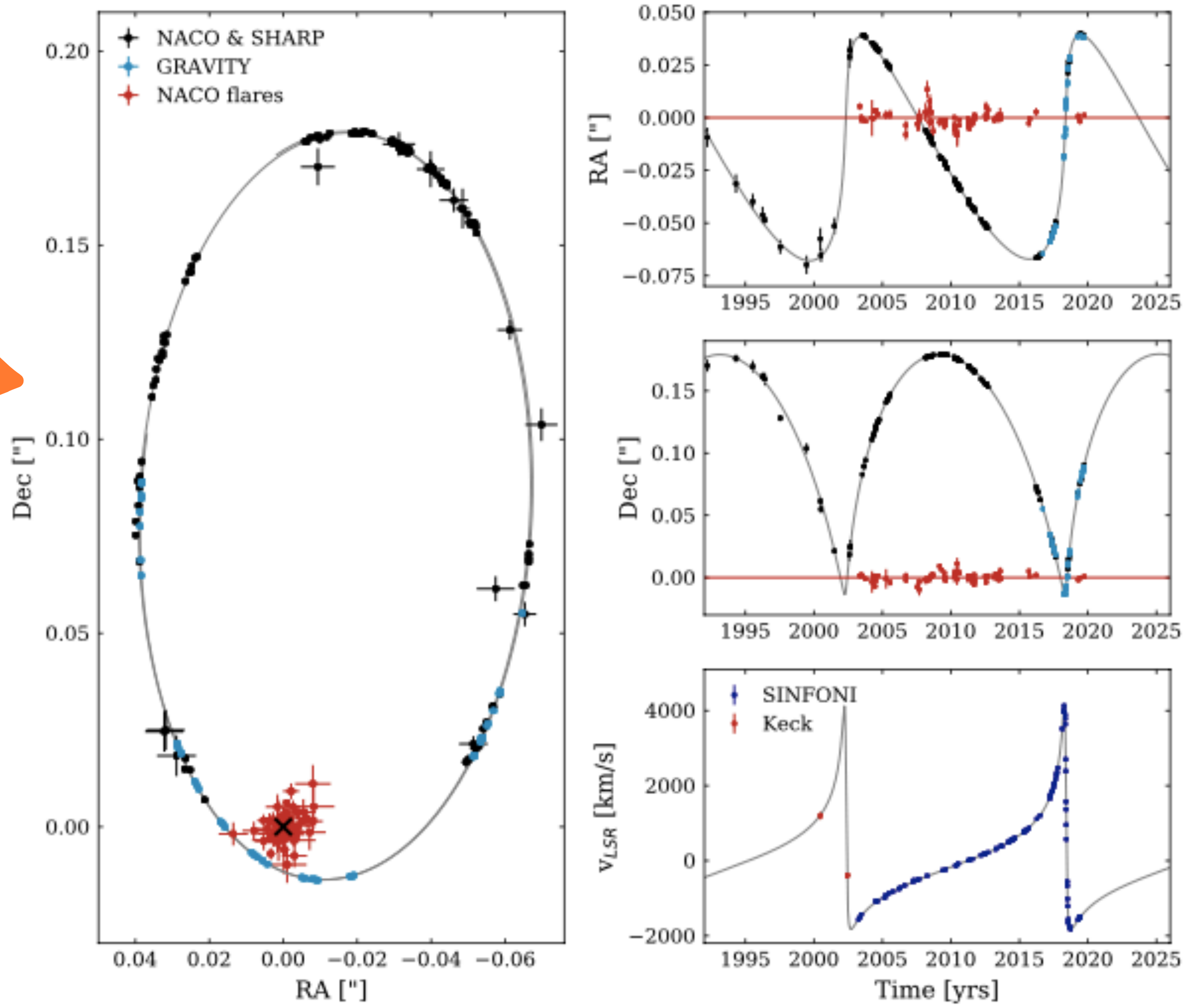
Spectroscopy and radial velocity measurements @Keck @VLT

S-stars cluster



Credit: ESO/MPE

S2 data



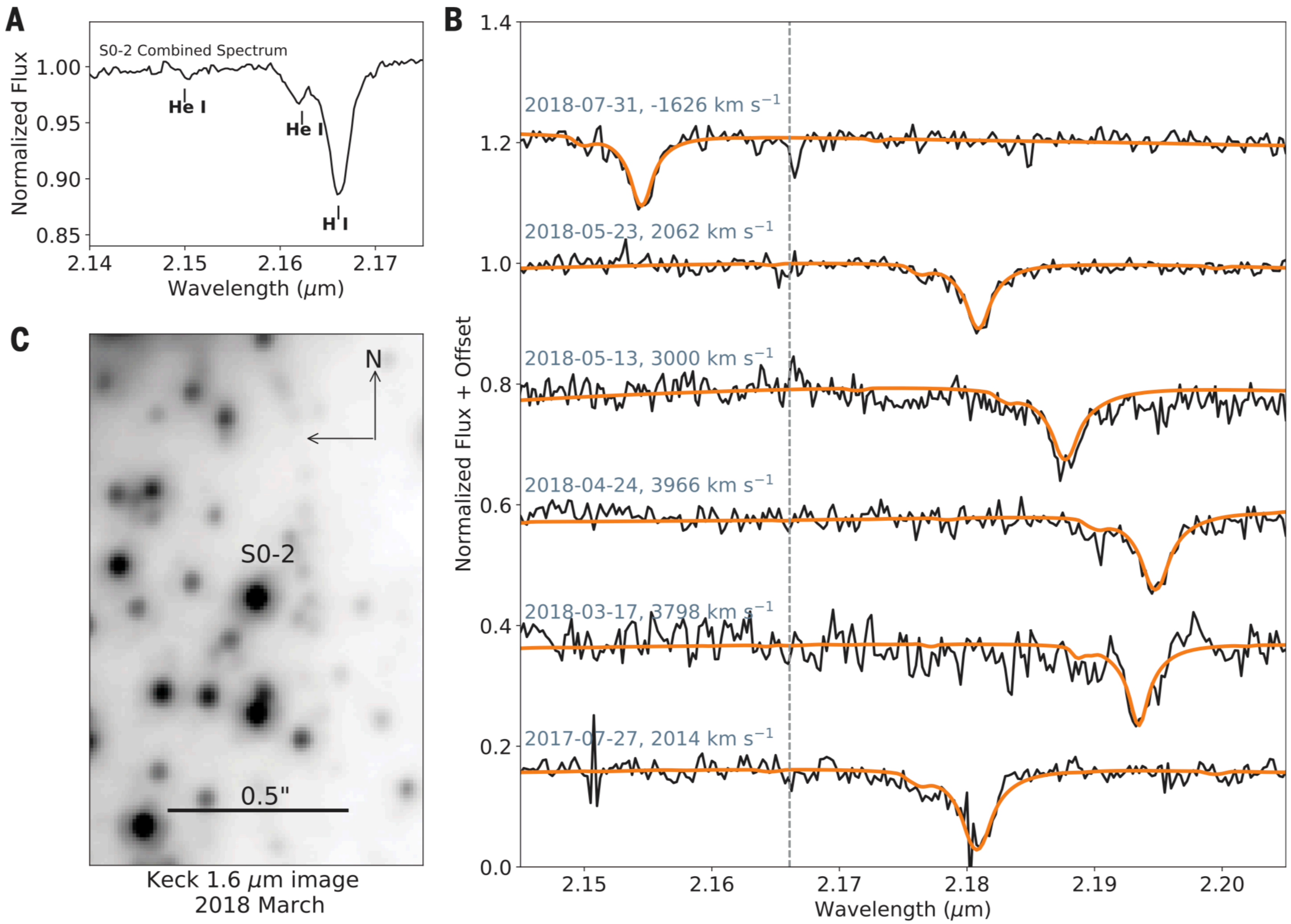
GRAVITY Coll., *2020, A&A 636 L5*

Dataset

Available Data for star S2:

- **Astrometry($\sigma \sim 50\,\mu\mathrm{as}$)**
  - NIRC on Keck I (1995-2005);
  - AO imaging with NIRC2 on Keck II (2005-2018).

- **Spectroscopy and RV ($\sigma \sim 20\ \mathrm{km/s}$)**
  - NIRSPEC/NIRC2/OSIRIS@Keck;
  - SINFONI@VLT.
  - NIFS@Gemini;
  - IRCS@Subaru;



Tuan Do,et al, Science (2019)

Black Hole-Scalar System

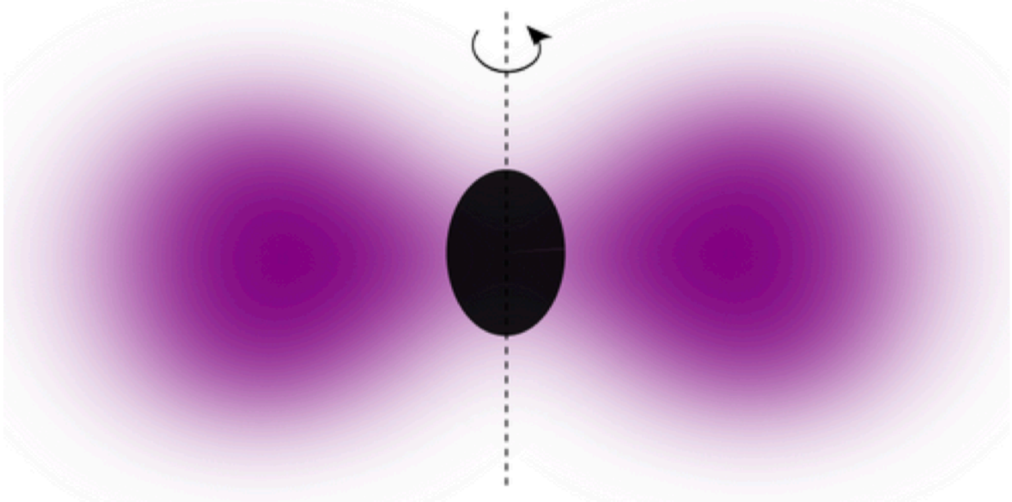
$$S = \int d^4x\sqrt{-g}\left(\frac{R}{16\pi} - \frac{1}{2}g^{\alpha\beta}\Phi^*_{,\alpha}\Phi^*_{,\beta} - \frac{\mu_s^2}{2}\Phi\Phi^*\right),$$

Mass coupling: $\zeta = \frac{r_g}{\lambda_C} = \mu_s M_\bullet \sim \mathcal{O}(10^{-3})$

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

$\left(G = c = \hbar = 1\right)$

$$\Phi = C_0 \mathrm{e}^{-\mathrm{i}(\bar{\omega}_R\bar{t} - \varphi)}\bar{r}\zeta^2 \mathrm{e}^{-\frac{\bar{r}\zeta^2}{2}} \sin\theta.$$



GRAVITY Collaboration, Scalar field effects on the orbit of S2 star, MNRAS(2019)
GRAVITY Collaboration, Motion of S2 and bounds on scalar clouds around SgrA*, MNRAS(2024)

Black Hole-Scalar System

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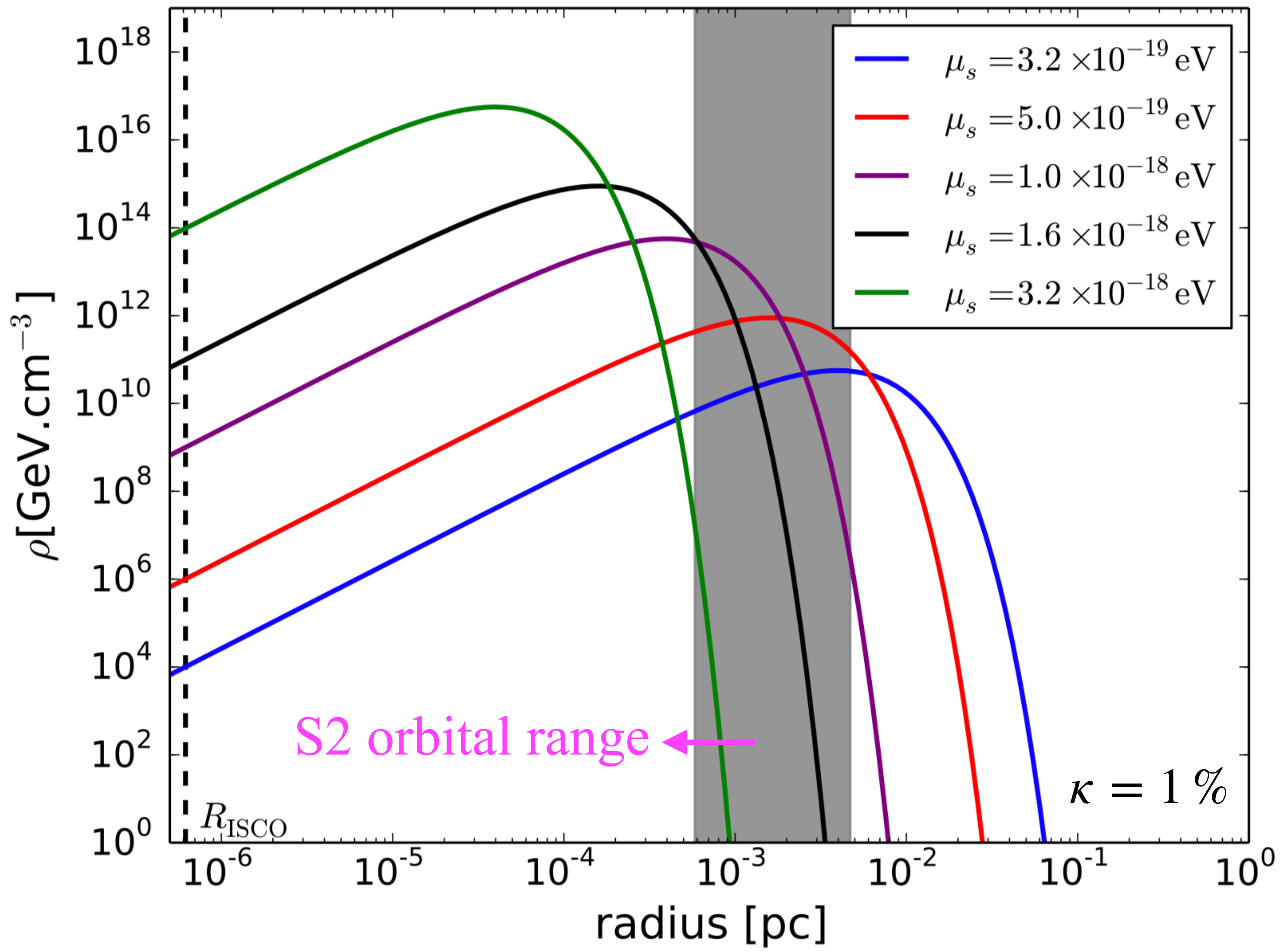
$$\Phi = C_0 \mathrm{e}^{-\mathrm{i}(\bar{\omega}_R\bar{t}-\varphi)}\bar{r}\zeta^2\mathrm{e}^{-\frac{\bar{r}\zeta^2}{2}}\sin\theta.$$

$$\downarrow$$

$$\rho = \frac{1}{2}\mu_s^2|\Phi|^2 = \frac{1}{2}\mu_s^2\left(C_0^2\zeta^4\mathrm{e}^{-\zeta^2\bar{r}}\bar{r}^2\sin^2\theta\right).$$

$$\downarrow$$

$$\boxed{\kappa = \frac{M_{\rm cloud}}{M_\bullet}}$$



Also see A.Foschi's Talk (On behalf of GRAVITY)

Frequency Shift Induced by SM-ULDM Interaction

$$E_n = -\frac{\mu e^4}{2\left(4\pi\epsilon_0\right)^2 \hbar^2}\frac{1}{n^2} \simeq -\frac{m_e c^2}{2}\frac{\alpha^2}{n^2}$$

Higgs portal interaction:

$$\mathcal{L}_{\Phi H} = \beta|\Phi|^2|H|^2,$$

The Higgs vacuum expectation value:

$$v = v_{\mathrm{ew}}\sqrt{1 - \frac{2\beta}{m_H^2}\frac{\rho(r)}{2\mu_s^2}} \approx v_{\mathrm{ew}}\left(1 - \frac{\beta}{m_H^2}\frac{\rho(r)}{2\mu_s^2}\right),$$

$$m_e \approx m_e^{\mathrm{bare}}\left(1 - \frac{\beta}{m_H^2}\frac{\rho(r)}{2\mu_s^2}\right),$$

Energy shift and radial velocity:

$$\left[\frac{\delta V_{mn}}{V_{mn}}(r)\right]_{\Phi H} \approx \frac{\delta m_e}{m_e} \approx \frac{\beta}{m_H^2}\frac{\rho(r)}{2\mu_s^2}.$$

Photon portal interaction:

$$\mathcal{L}_{\Phi\gamma} = \frac{g}{4}|\Phi|^2 F^2,$$

The fine structure constant:

$$\alpha = \alpha_0\left(\frac{1}{1 - g v_\Phi^2}\right) \approx \alpha_0(1 + g\frac{\rho}{2\mu_s^2}).$$

$$\left[\frac{\delta V_{mn}}{V_{mn}}(r)\right]_{\Phi\gamma} \approx \frac{2\delta\alpha}{\alpha} \approx 2g\frac{\rho(r)}{2\mu_s^2}.$$

Method

Corrections to the post-Newtonian equation

[C.M.Will, et al, PRD (2017); Tuan Do, et al. Science (2019)]

$$\frac{dr^2}{dt^2} = -\frac{GM(r)}{r^3}\mathbf{r} + \frac{GM(r)}{c^2r^3}\left(4\frac{GM(r)}{r} - v^2\right)\mathbf{r} + 4\frac{GM(r)(\mathbf{r}\cdot\mathbf{v})}{c^2r^3}\mathbf{v}$$

With enclosed mass $M(r) = M_{\bullet} + M_{\text{cloud}} + Ar^{1.6}$

$$\mathbf{r}(t) \equiv (X(t), Y(t), Z(t)); \mathbf{v}(t) \equiv (V_X(t), V_Y(t), V_Z(t))$$

$$\begin{aligned}
X(t_p) &= -r_p \sin\omega \cos I \sin\Omega + r_p \cos\omega \cos\Omega, \\
Y(t_p) &= r_p \sin\omega \cos I \cos\Omega + r_p \cos\omega \sin\Omega, \\
Z(t_p) &= -r_p \sin\omega \sin I, \\
V_X(t_p) &= -v_p \cos\omega \cos I \sin\Omega - v_p \sin\omega \cos\Omega, \\
V_Y(t_p) &= v_p \cos\omega \cos I \cos\Omega - v_p \sin\omega \sin\Omega, \\
V_Z(t_p) &= -v_p \cos\omega \sin I.
\end{aligned}$$

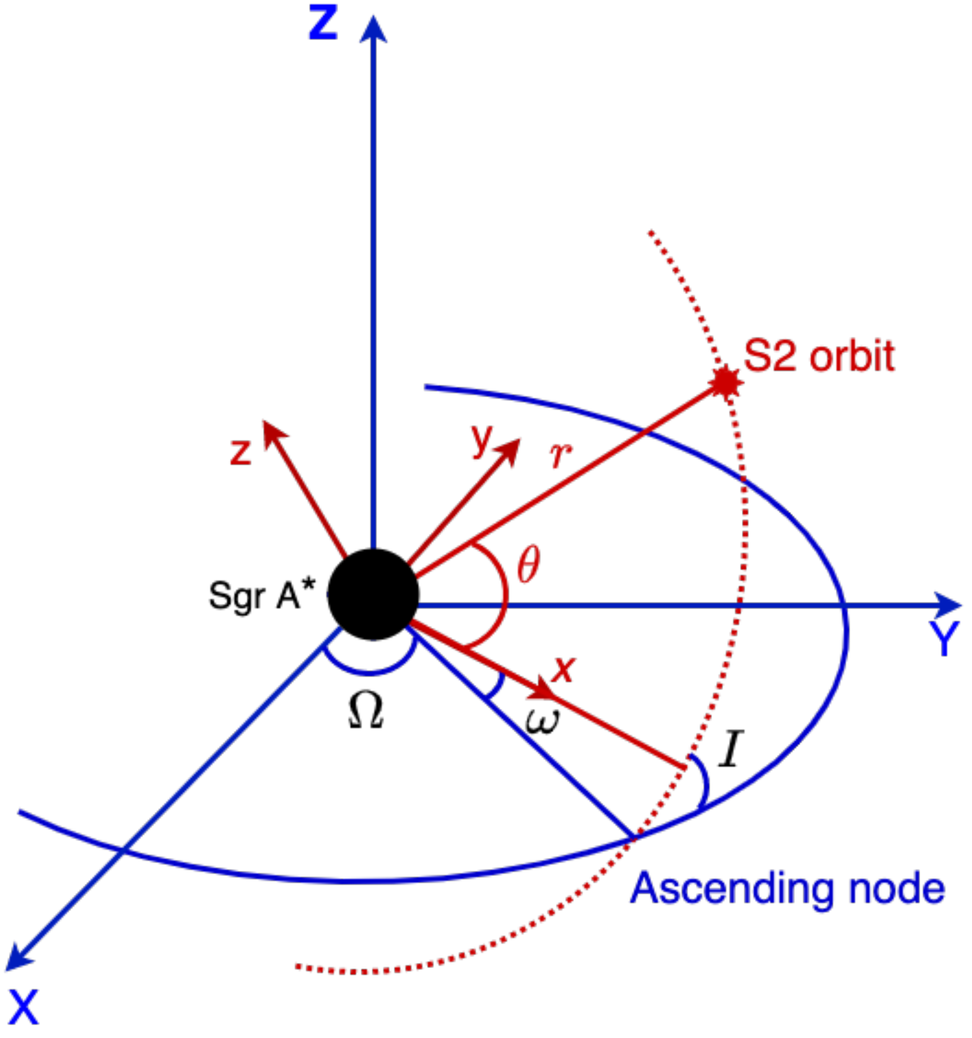
$$t_{\text{em}} = t_{\text{obs}} + \frac{Z(t_{\text{obs}})}{c}.$$

$$\alpha_*(t_{\text{obs}}) = \frac{Y(t_{\text{em}})}{R_0} + \alpha_{\text{BH}} + v_\alpha \cdot (t_{\text{em}} - t_{\text{J2000}}),$$

$$\delta_*(t_{\text{obs}}) = \frac{X(t_{\text{em}})}{R_0} + \delta_{\text{BH}} + v_\delta \cdot (t_{\text{em}} - t_{\text{J2000}}),$$

$$v_r(t_{\text{obs}}) = V_Z(t_{\text{em}}) + v_{r0} + \boxed{\left[\frac{V_Z^2(t_{\text{em}})}{2c} + \frac{GM}{c\,r(t_{\text{em}})}\right]} + \underline{\Delta V_r},$$

the correction of relativity



v_p, r_p are the velocity and radius at time t_p :

$$(a, e, P, I, \Omega, \omega) \longrightarrow (r_p, v_p, t_p, I, \Omega, \omega)$$

Method

Markov Chain Monte Carlo **emcee** (Foreman-Mackey *et al*. 2013) Python package

We need to *sample* $P(\theta \,|\, D) \propto P(D \,|\, \theta) P(\theta)$ for different fixed values of α

D = data set

$$\theta_i = \{\underbrace{M_\bullet, R_0}_{\text{BH Mass and GC distance}}, \underbrace{\alpha_{\mathrm{BH}}, \beta_{\mathrm{BH}}, v_\alpha, v_\beta}_{\text{SMBH Position}}, \underbrace{t_p, r_p, v_p, I, \omega, \Omega}_{\text{Keplerian elements}}, \underbrace{p, \Lambda, \mathrm{offset}}_{\text{System Correction}}, \underbrace{\kappa}_{\text{Cloud's fractional mass}}, \underbrace{\beta}_{\text{SM-ULDM Interaction}}\}$$

Astrometric measurements: $L_{\mathrm{astro}} \propto \dfrac{1}{\sqrt{(|\boldsymbol{\Sigma}_\alpha||\boldsymbol{\Sigma}_\delta|)}} \exp\left[-\dfrac{1}{2}\left(\Delta\boldsymbol{\alpha}^T \boldsymbol{\Sigma}_\alpha^{-1} \Delta\boldsymbol{\alpha} + \Delta\boldsymbol{\delta}^T \boldsymbol{\Sigma}_\delta^{-1} \Delta\boldsymbol{\delta}\right)\right]$

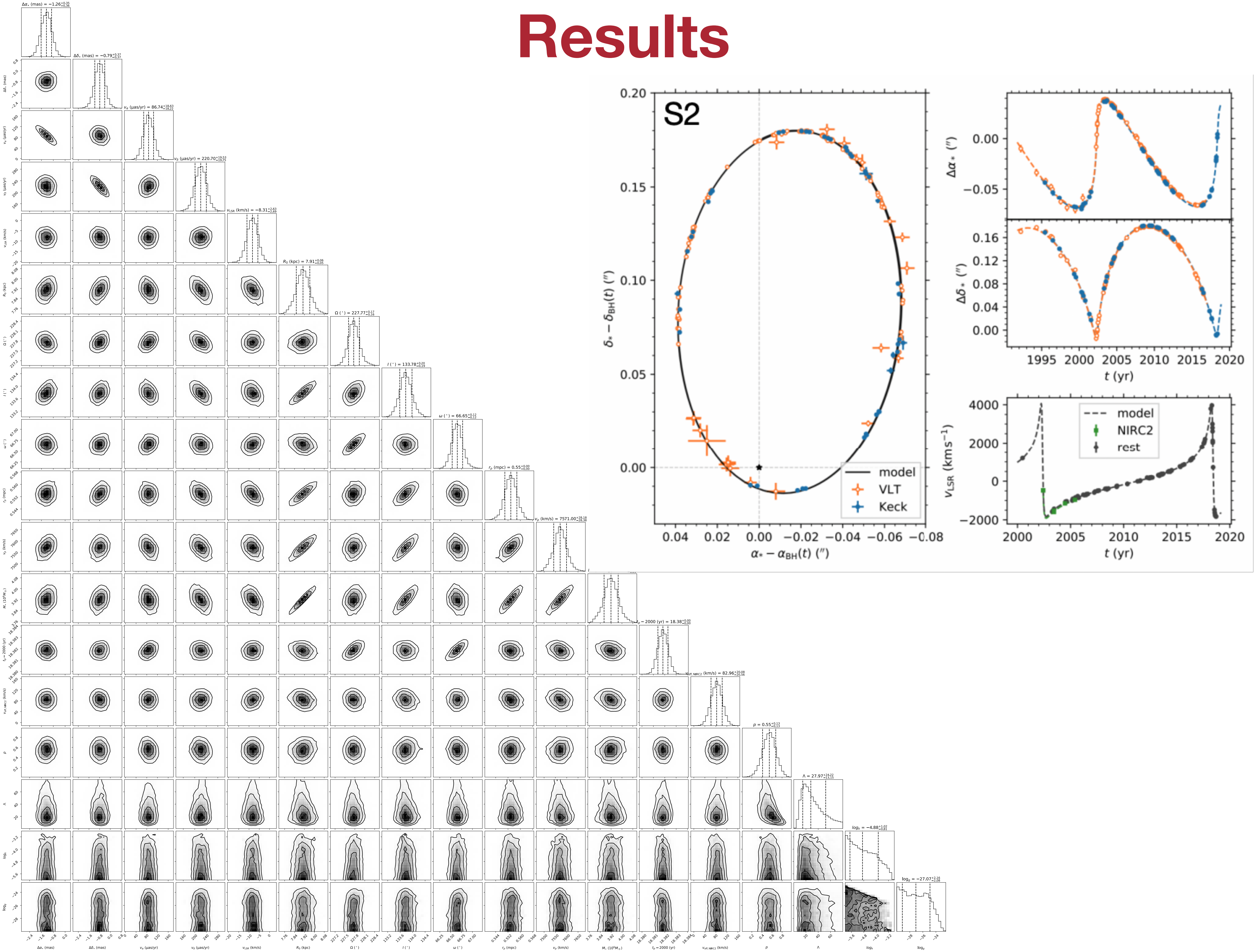
Radial velocities: $-2 \ln L_{\mathrm{RV}} = \chi^2_{\mathrm{RV}} = \sum_j \left(\dfrac{v_{r,j} - \mu_{v_r}(t_j)}{\sigma_{v_r,j}}\right)^2$

$L_{\mathrm{tot}} = L_{\mathrm{astro}} \times L_{\mathrm{RV}}$

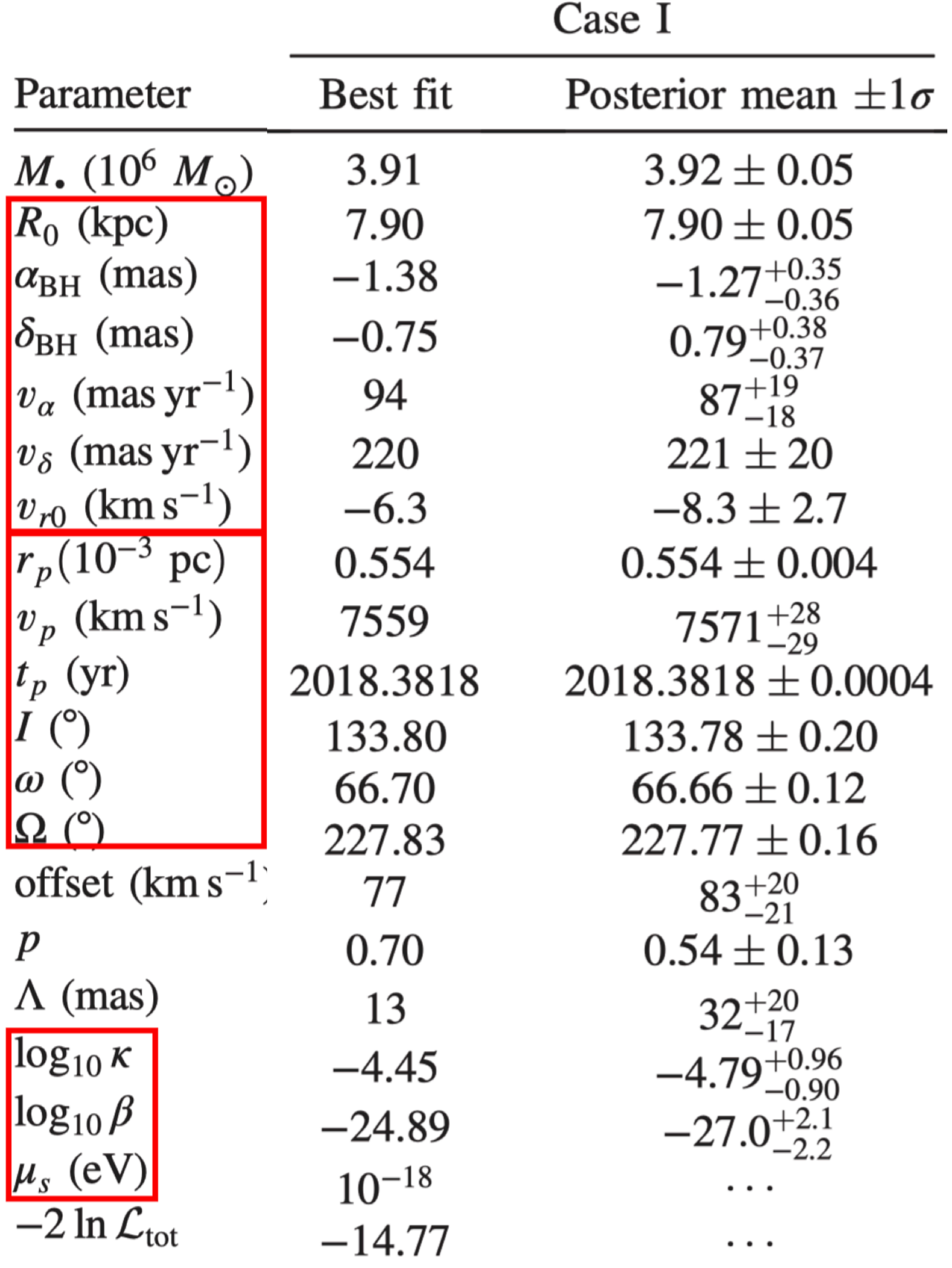
$P(D \,|\, \theta)$ = Gaussian Likelihood

$P(\theta)$ = **Uniform** priors for physical parameters, **Gaussian** priors for SMBH position, Keplerian elements.

Results


$\Delta\alpha_*$ (mas) = $-1.26^{+0.35}_{-0.36}$
$\Delta\delta_*$ (mas) = $-0.79^{+0.37}_{-0.37}$
v_α (µas/yr) = $86.74^{+18.63}_{-18.22}$
v_δ (µas/yr) = $220.70^{+19.53}_{-19.75}$
$v_{\rm LSR}$ (km/s) = $-8.31^{+2.63}_{-2.69}$
R_0 (kpc) = $7.91^{+0.06}_{-0.05}$
Ω (°) = $227.77^{+0.17}_{-0.16}$
I (°) = $133.78^{+0.20}_{-0.19}$
ω (°) = $66.65^{+0.12}_{-0.12}$
r_p (mpc) = $0.55^{+0.00}_{-0.00}$
v_p (km/s) = $7571.00^{+28.18}_{-28.38}$
$t_p - 2000$ (yr) = $18.38^{+0.00}_{-0.00}$
$v_{\rm off,NIRC2}$ (km/s) = $82.96^{+20.08}_{-20.56}$
$p = 0.55^{+0.13}_{-0.13}$
$\Lambda = 27.97^{+24.22}_{-13.15}$
$log_k = -4.88^{+1.02}_{-0.81}$
$\log_g = -27.07^{+2.16}_{-2.08}$
M_* ($10^6 M_\odot$)
S2
$\delta_* - \delta_{\rm BH}(t)$ ('')
$\alpha_* - \alpha_{\rm BH}(t)$ ('')
model
VLT
Keck
$\Delta\alpha_*$ ('')
$\Delta\delta_*$ ('')
t (yr)
$v_{\rm LSR}$ (kms^{-1})
model
NIRC2
rest

Results



Parameter	Case I Best fit	 Posterior mean $\pm 1\sigma$
$M_\bullet$ ($10^6\ M_\odot$)	3.91	3.92 ± 0.05
R_0 (kpc)	7.90	7.90 ± 0.05
$\alpha_{\rm BH}$ (mas)	-1.38	$-1.27^{+0.35}_{-0.36}$
$\delta_{\rm BH}$ (mas)	-0.75	$0.79^{+0.38}_{-0.37}$
v_α (mas yr^{-1})	94	87^{+19}_{-18}
v_δ (mas yr^{-1})	220	221 ± 20
v_{r0} (km s^{-1})	-6.3	-8.3 ± 2.7
r_p (10^{-3} pc)	0.554	0.554 ± 0.004
v_p (km s^{-1})	7559	7571^{+28}_{-29}
t_p (yr)	2018.3818	2018.3818 ± 0.0004
I (°)	133.80	133.78 ± 0.20
ω (°)	66.70	66.66 ± 0.12
Ω (°)	227.83	227.77 ± 0.16
offset (km s^{-1})	77	83^{+20}_{-21}
p	0.70	0.54 ± 0.13
Λ (mas)	13	32^{+20}_{-17}
$\log_{10}\kappa$	-4.45	$-4.79^{+0.96}_{-0.90}$
$\log_{10}\beta$	-24.89	$-27.0^{+2.1}_{-2.2}$
μ_s (eV)	10^{-18}	…
$-2\ln\mathcal{L}_{\rm tot}$	-14.77	…

Case I: the SMBH + scalar field

$$M(r) = M_\bullet + 2\pi \int_{r_{\rm ISCO}}^{r} r'^2 {\rm d}r' \int_0^\pi \sin\theta' {\rm d}\theta' \rho(r', \theta'),$$

Mass distribution of scalar field:

$$\rho = \frac{1}{2}\mu_s^2 |\Phi|^2 = \frac{1}{2}\mu_s^2 \left(C_0^2 \zeta^4 {\rm e}^{-\zeta^2 \bar{r}} \bar{r}^2 \sin^2\theta \right).$$

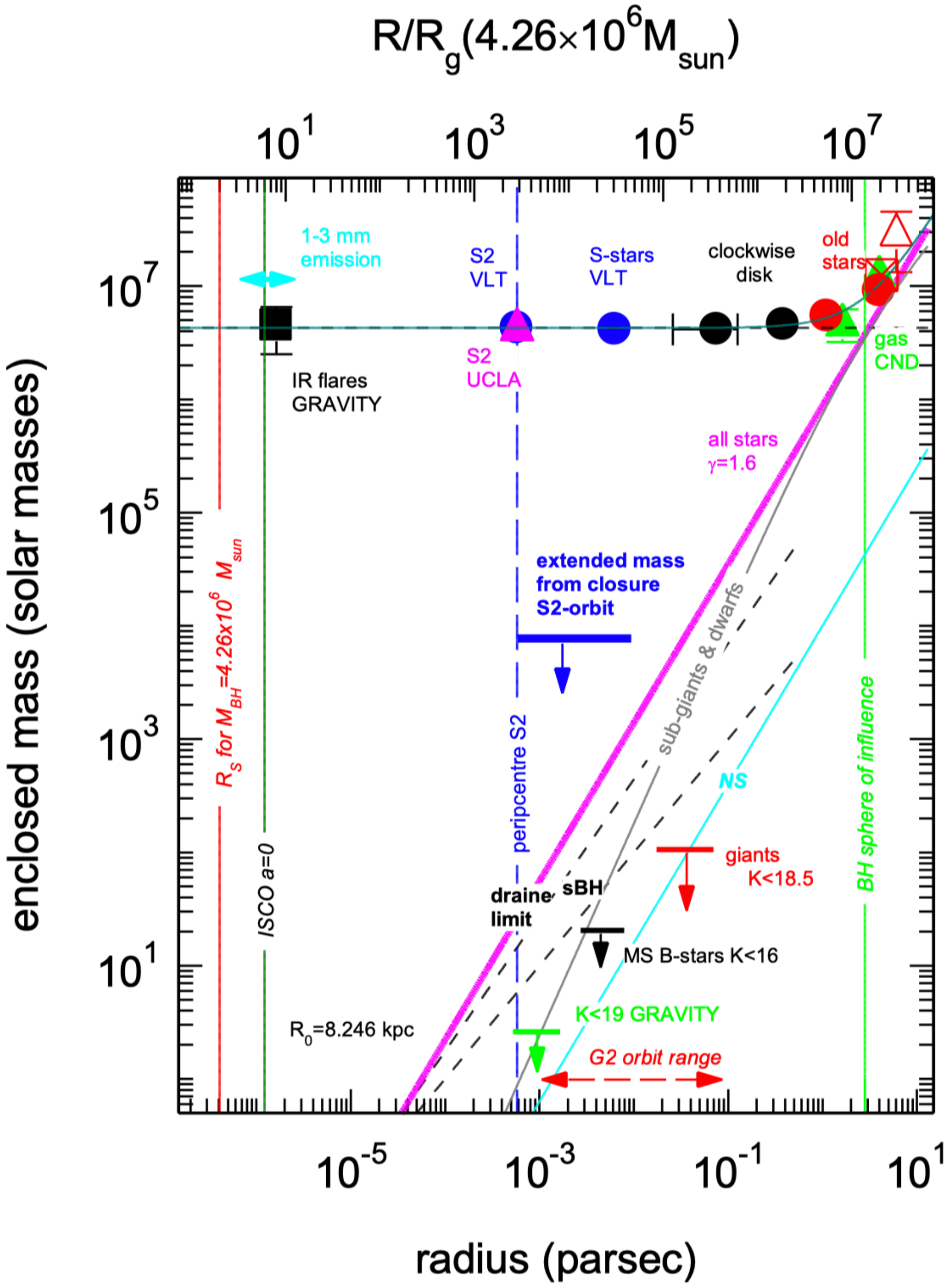
$$\kappa = \frac{M_{\rm cloud}}{M_\bullet} = \frac{\int \rho r^2 \sin\theta d r d\theta d\varphi}{M_\bullet}.$$

Results

	Case II	
Parameter	Best fit	Posterior mean $\pm 1\sigma$
$M_\bullet$ ($10^6\ M_\odot$)	3.90	3.92 ± 0.05
R_0 (kpc)	7.89	7.91 ± 0.05
$\alpha_{\rm BH}$ (mas)	−1.28	-1.22 ± 0.33
$\delta_{\rm BH}$ (mas)	−0.87	-0.75 ± 0.37
v_α (mas yr^{-1})	86	85 ± 18
v_δ (mas yr^{-1})	231	218 ± 19
v_{r0} (km s^{-1})	−8.1	-8.7 ± 2.8
r_p (10^{-3} pc)	0.552	0.554 ± 0.003
v_p (km s^{-1})	7559	7573^{+27}_{-26}
t_p (yr)	2018.3819	2018.3818 ± 0.0004
I (°)	133.70	133.80 ± 0.18
ω (°)	66.65	66.66 ± 0.12
Ω (°)	227.73	227.79 ± 0.17
offset (km s^{-1})	81	83^{+19}_{-20}
p	0.62	$0.54^{+0.14}_{-0.13}$
Λ (mas)	16	31^{+19}_{-17}
$\log_{10}\kappa$	−5.51	$-4.82^{+0.95}_{-0.89}$
$\log_{10}\beta$	−24.88	$-26.81^{+2.11}_{-2.20}$
μ_s (eV)	10^{-18}	…
$-2\ln\mathcal{L}_{\rm tot}$	−14.21	…

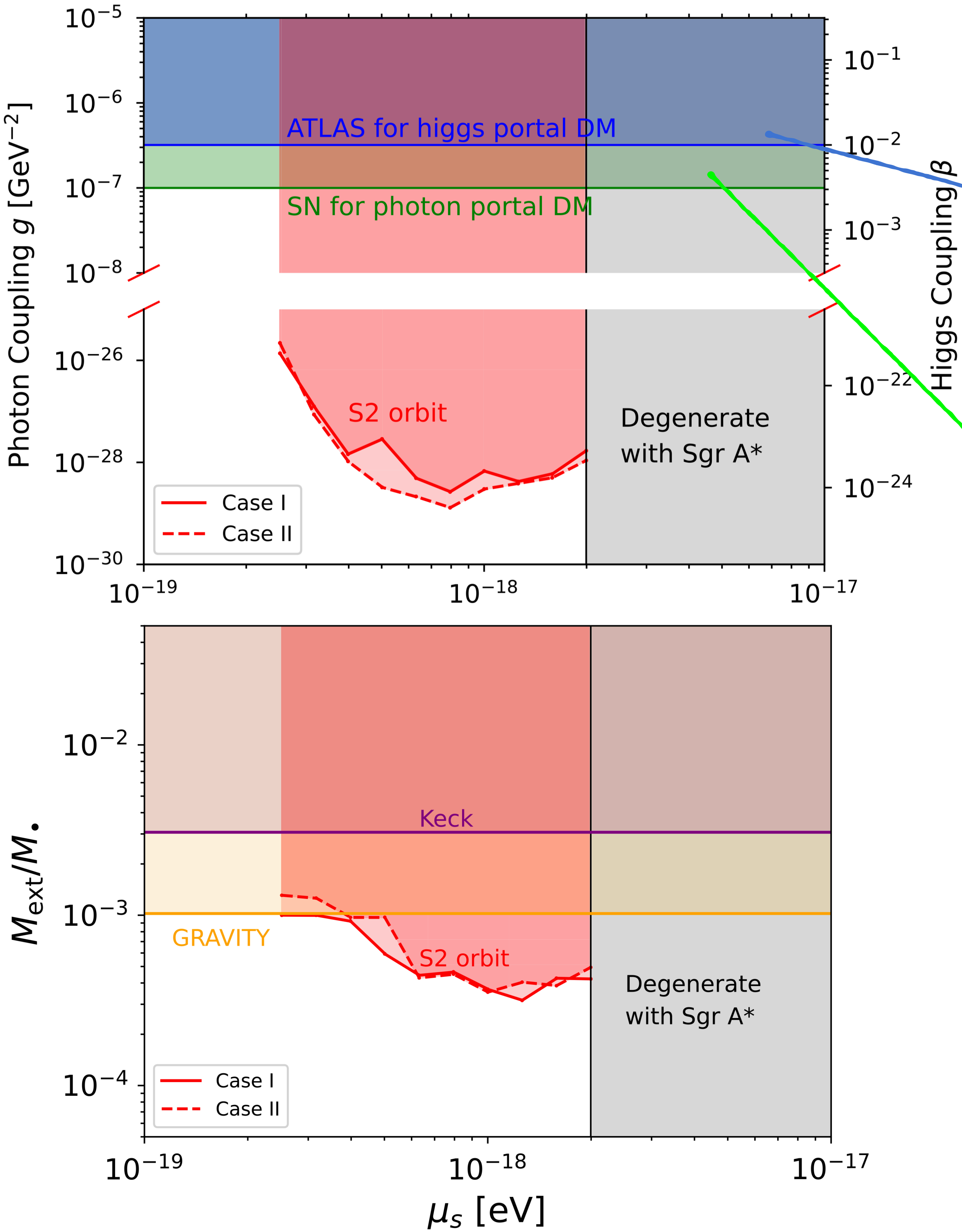
Case II: the SMBH + scalar field
+ astrophysical background

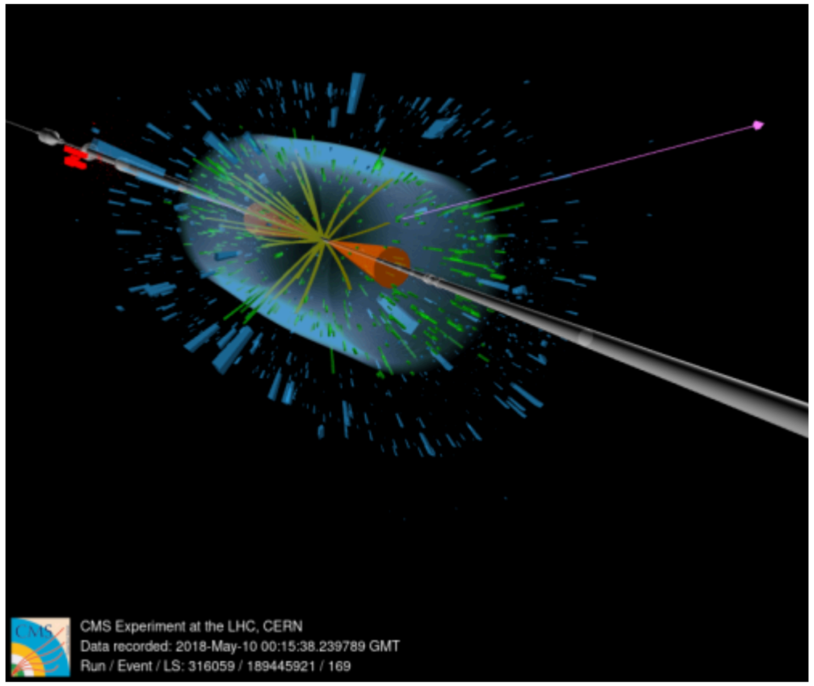
$$M(r) = M_\bullet + Ar^{1.6} + 2\pi \int_{r_{\rm ISCO}}^{r} r'^2 {\rm d}r' \int_0^\pi \sin\theta' {\rm d}\theta' \rho(r', \theta'),$$



Astrophysical background around Galactic center credited by *GRAVITY A&A(2020)*

Results





Searching Higgs Portal from Collider.
CMS, PLB(2019)

Searching Photon Portal from Supernova energy loss.
Y. Stadnik, V.Flambaum, PRL(2015)

Summary of the results

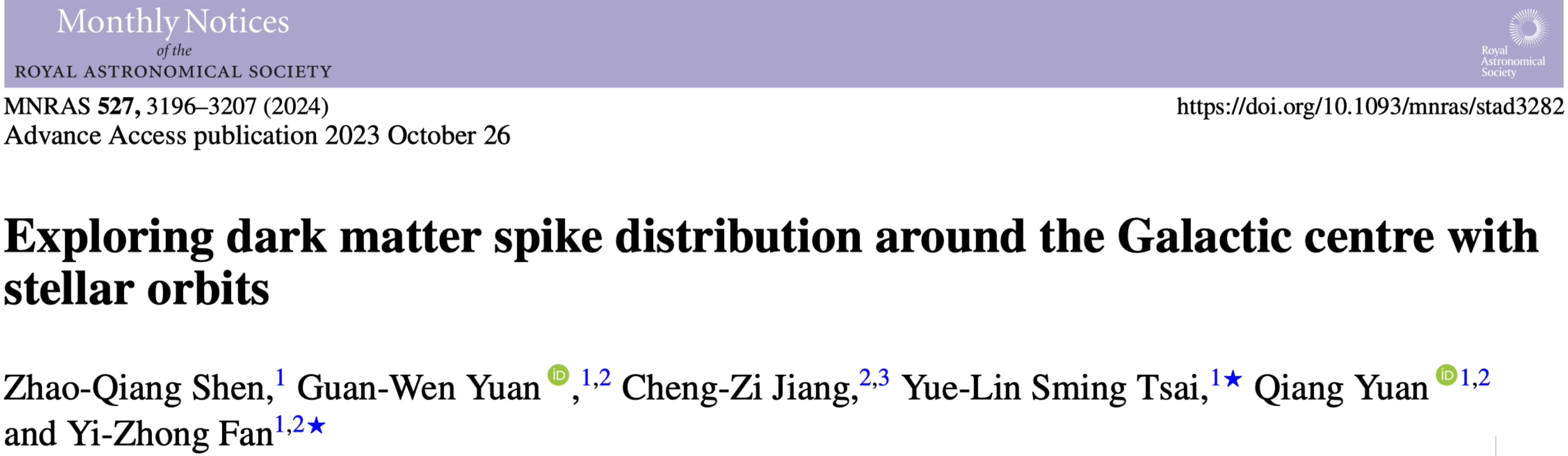
- ULDM is a well motivated candidate for dark matter, S2 orbit only sensitive to constrain the scalar mass window $3.2 \times 10^{-19} \lesssim \mu_s \lesssim 1.6 \times 10^{-18}\mathrm{eV}$

- The Higgs portal coupling 95% upper limit ($\beta < \mathcal{O}(10^{-24})$ at $\mu_s \simeq 10^{-18}$eV) is much stronger than the ATLAS limit

- The photon portal coupling 95% upper limit ($g < \mathcal{O}(10^{-28})\mathrm{GeV}^{-2}$ at $\mu_s \simeq 10^{-18}$ eV) is much stronger than the limit obtained by supernova energy loss arguments

- The upper limits of the extended mass of scalar cloud is $\sim 3 \times 10^{-4} M_\bullet$, which statistically agrees with the scenario of point-like mass of SgrA*

- The astrophysical power law component ($\sim 1200 M_\odot$ enclosed in S2's orbit) only has a relatively small impact on the parameters of ULDM model.



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Exploring dark matter spike distribution around the Galactic centre with stellar orbits

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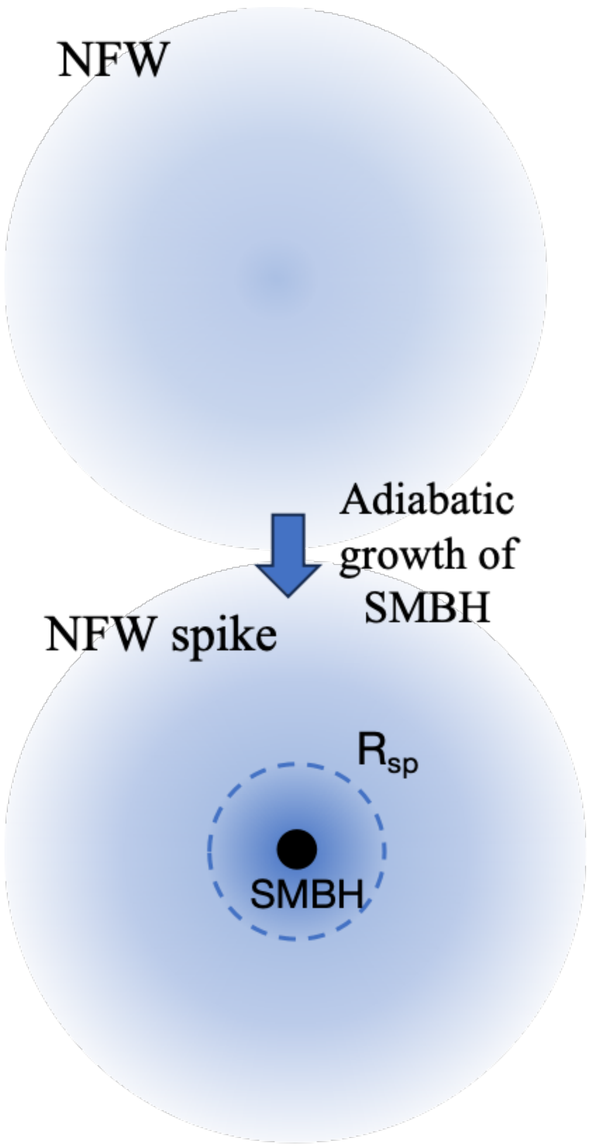
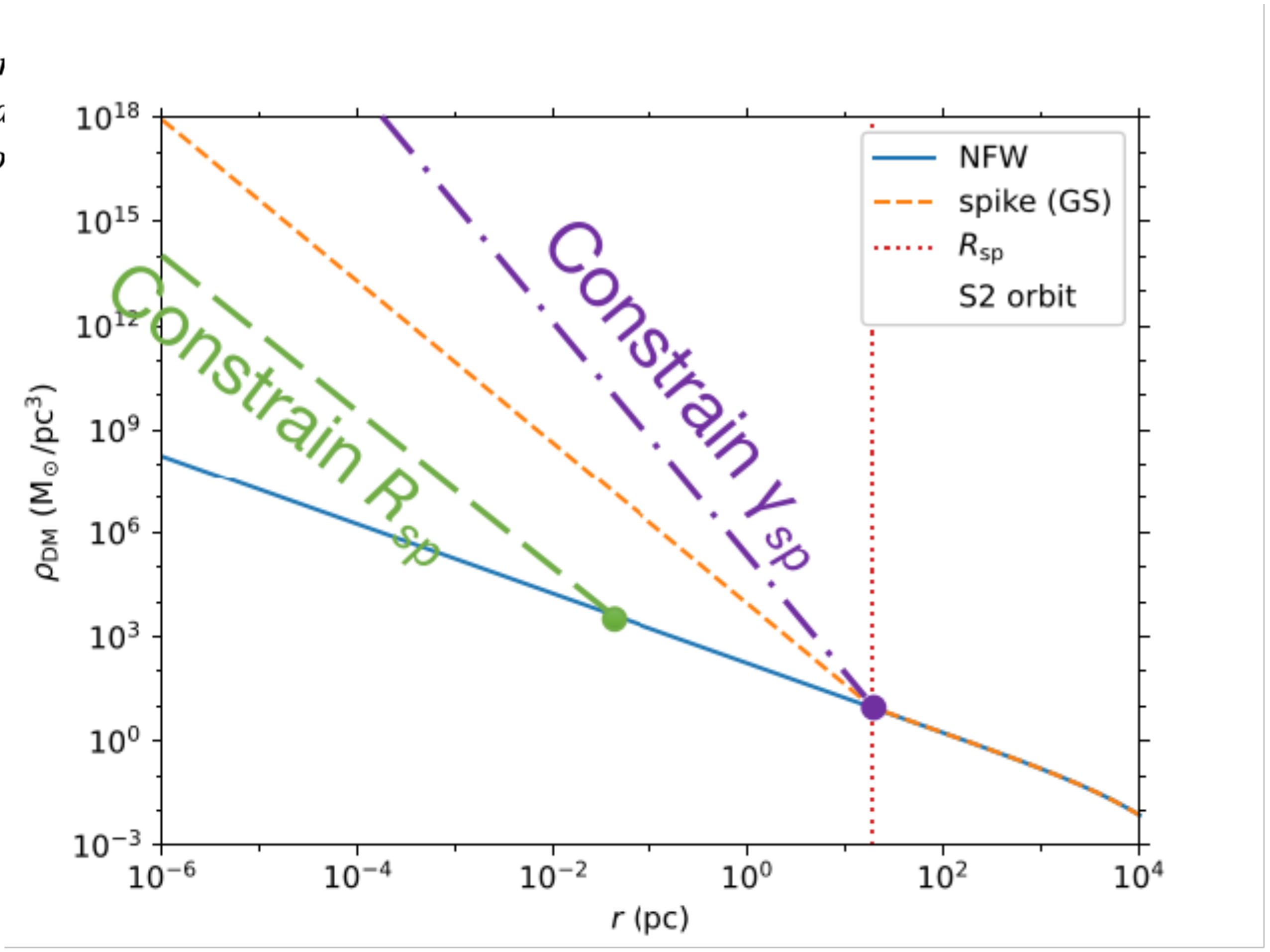
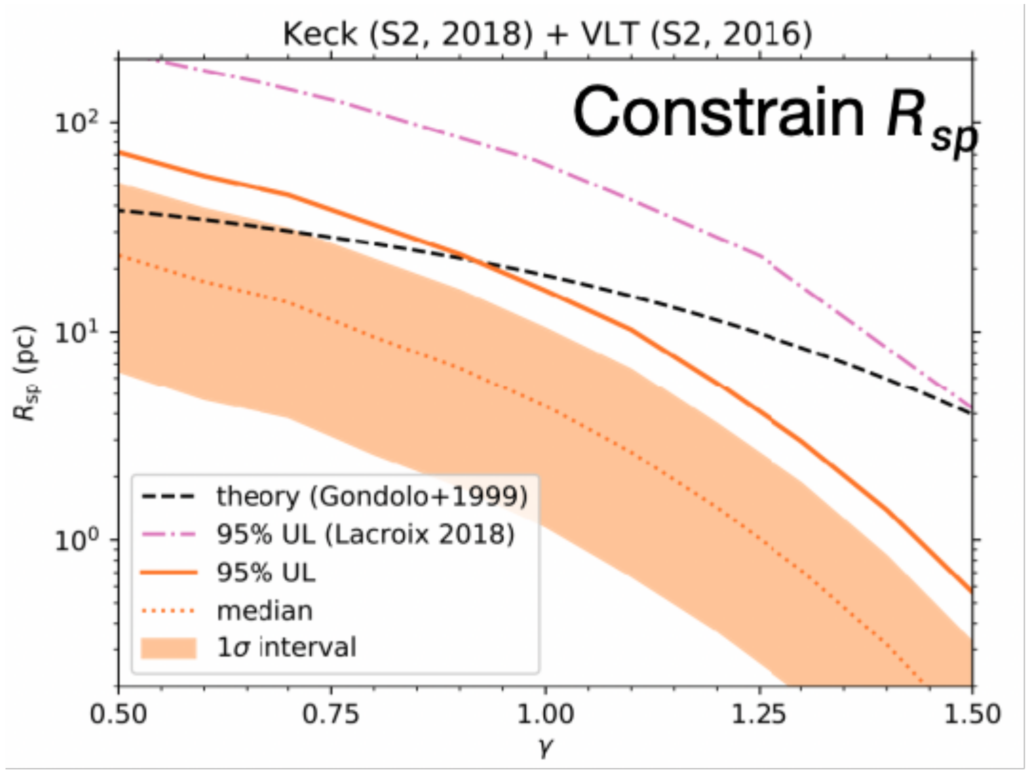


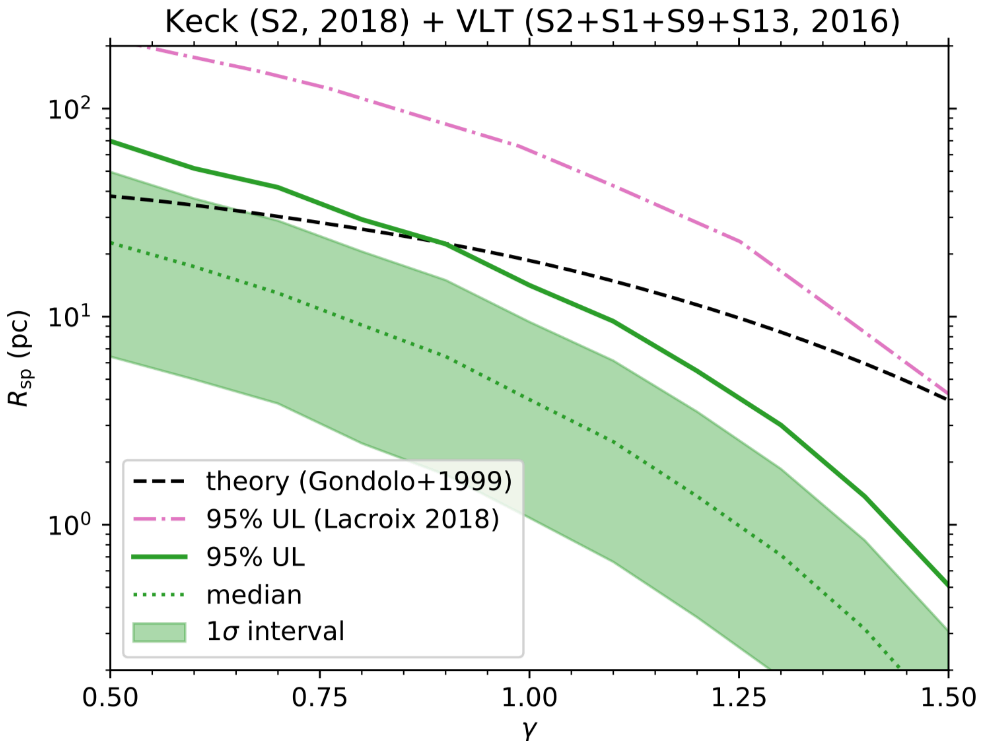


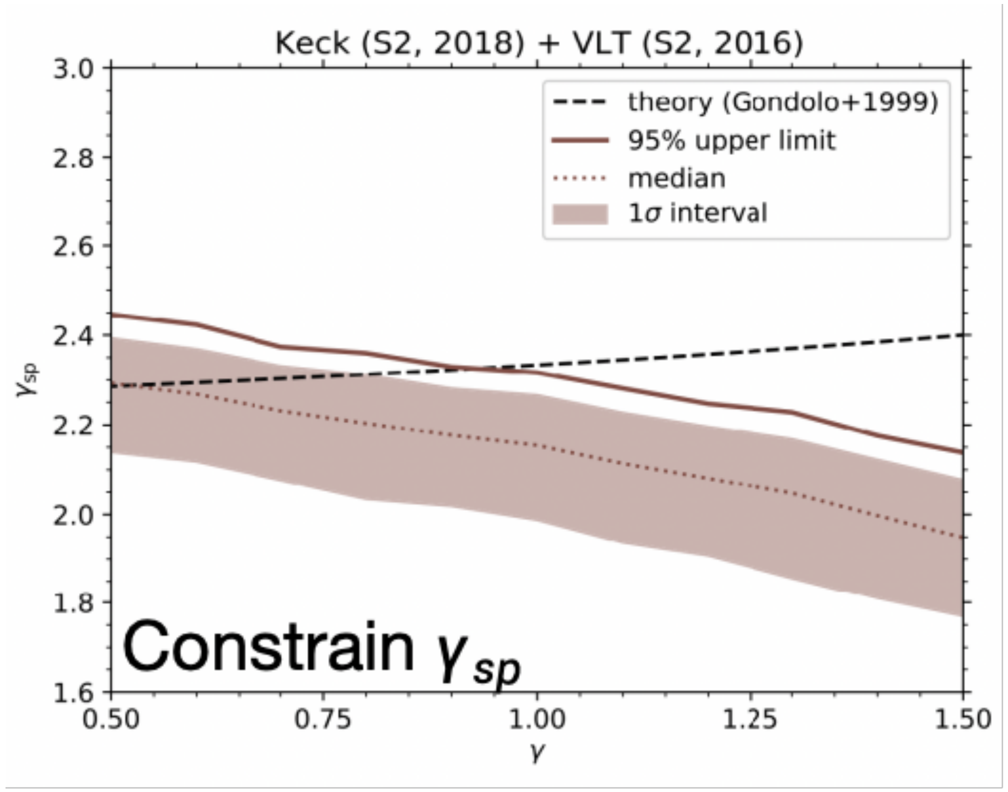
We set two types of constraints:

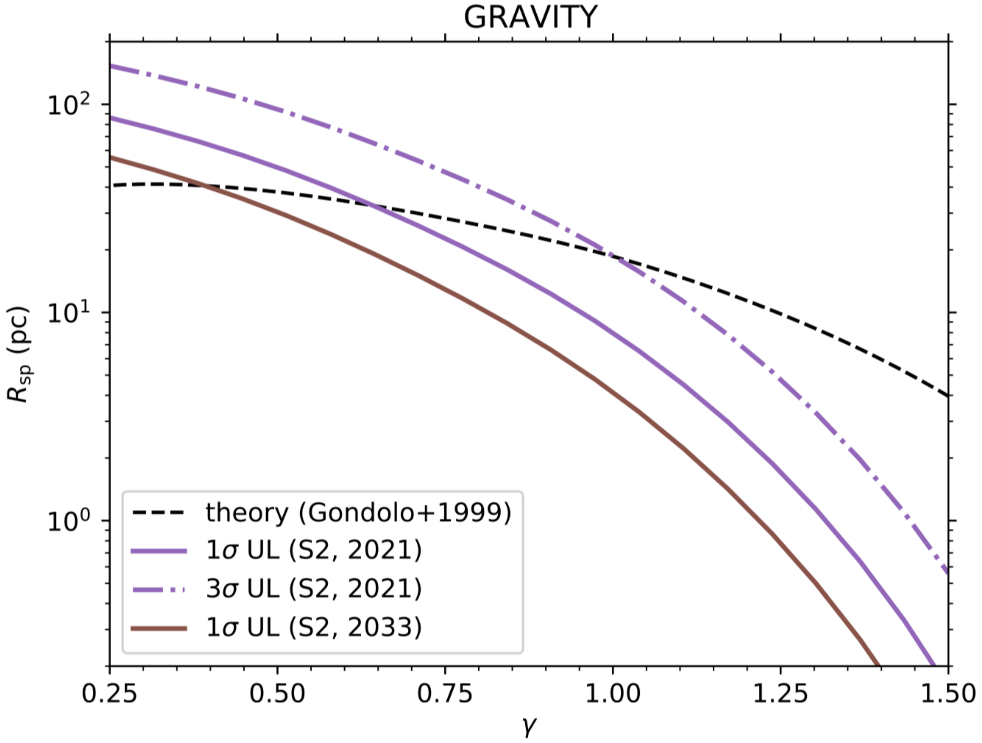
- ○ Constraint the spike radius r_{sp}
- ○ Constraint the spike slope γ_{sp}

Results









- $R_{sp} < 15.7$ pc for NFW spike at 95% CL
- $\gamma_{sp} < 2.32$ for NFW spike at 95% CL
- The GS spike model is disfavoured at 95% when the initial slope $\gamma > 0.92$

- The upper limits on the spike radius R_{sp} between S2 only and the four S-stars are negligible.
- the surviving NFW spike infer the 95% lower limit of $\langle \sigma v \rangle \gtrsim 7.7 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1} \times (m_{\mathrm{DM}}/100\mathrm{GeV})(10\mathrm{Gyr}/\tau_{\mathrm{BH}})$

Summary of the results

- High precision astrometry observation of SMBHs, especially stellar dynamics, provide an unique way to test "new physics" around strong gravity region.
- Different dark matter candidates have predicted different effects, we search for their potential signals by the stellar dynamics around SgrA*.
- Regarding the ULDM, we set very strong constraints for the Higgs/Photon portal coupling, which are much stronger than other limits.
- Regarding the WIMP, we excluded the classic WIMP 'spike' proposed by Gondolo&Silk (1999), one of most import assumption for dark matter detection, with the observations of SgrA*

Thanks for your attention!