Hey! I know you are all tired, BUT

I am Bai

I am Bai

From Weizmann Institute

Phenomenologies associate with

Ultralight Field Backgrounds

- Scalars,
- Vectors…

- Dark Matter
- or non-dark Matter

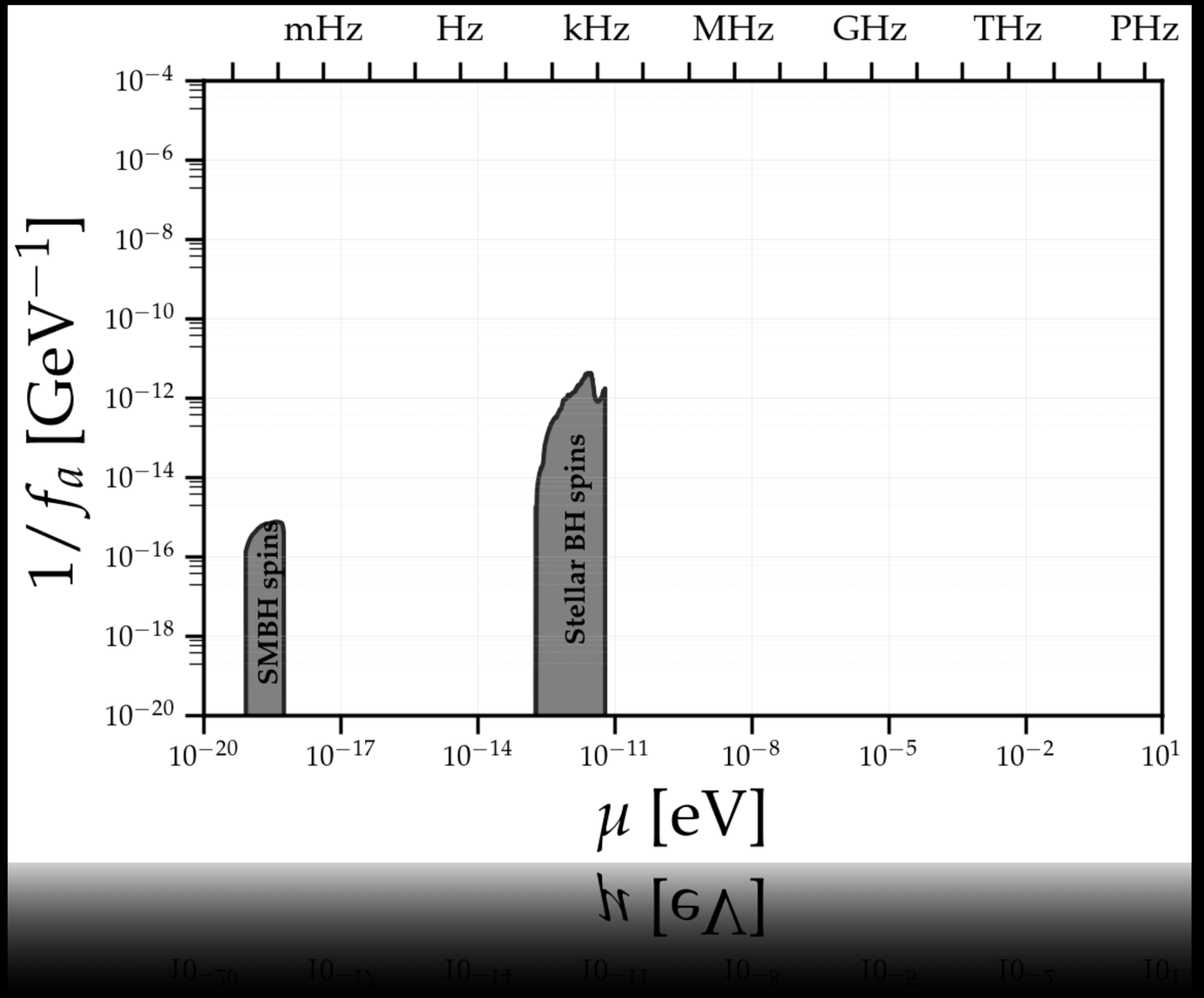
For real…

Superradiance + Spectroscopic

Enhanced Phenomenology

Zhaoyu Bai @ Cargese

2025.07.30


mHz
Hz
kHz
MHz
GHz
THz
PHz
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
$1/f_a$ [GeV^{-1}]
SMBH spins
Stellar BH spins
10^{-20}
10^{-17}
10^{-14}
10^{-11}
10^{-8}
10^{-5}
10^{-2}
10^{1}
μ [eV]

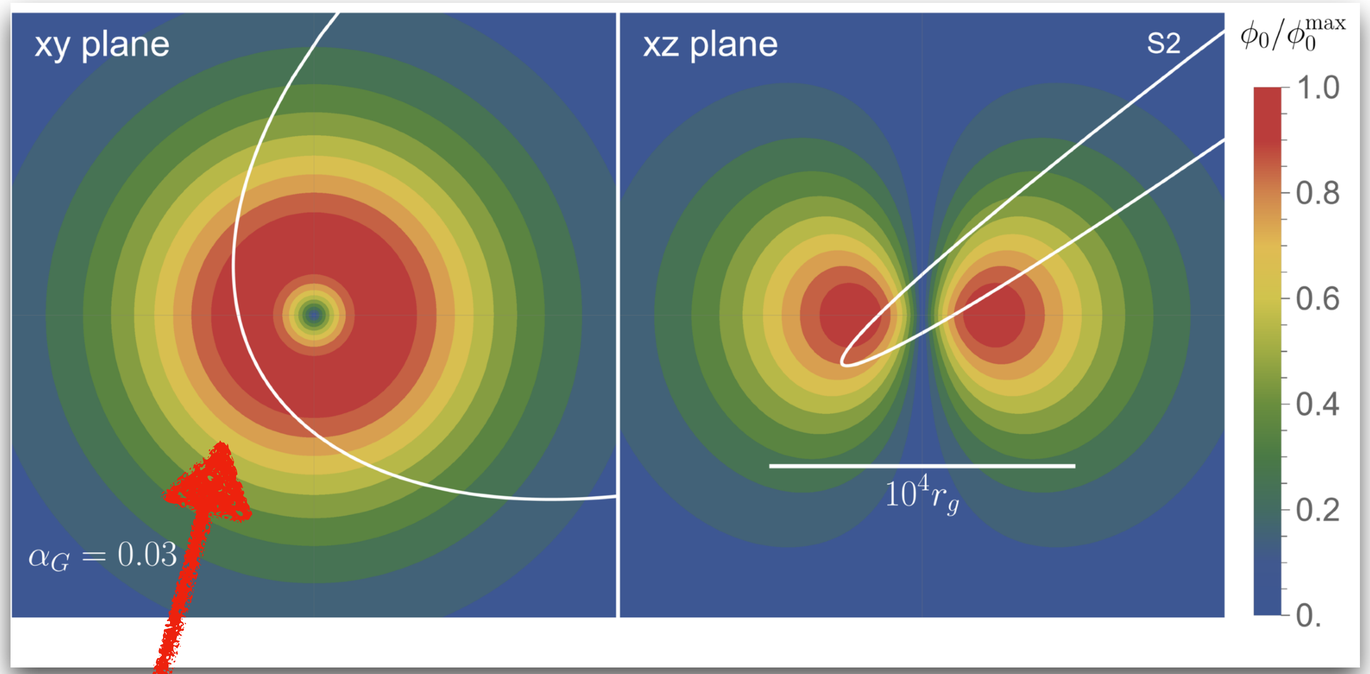
Keep in mind…

Superradiance forms without the assumption of dark matter.

Keep in mind…

And the Amplitude is Huge:

$$\phi_0^{\max} \approx 0.07\,\alpha_G^2 M_{\rm pl}\sqrt{\frac{M_{\rm cloud}}{M_{\rm BH}}} \approx 0.5\,\alpha_G f_\phi$$



Superradiance ⟵ Scalars backgrounds — Axions/ALP/Generic

Ultralight particles

S-Star Spectroscopy

Existing S2 Star Observation — To Future Prospect

- **Cadence** (exposure time): 10 or 15 mins.
- Over a period of **25 days,** Daily averages of **3 hours** of observations.
- Most Relevant Observation Period (2017/2018): **Periastron**
- The median uncertainty for Hydrogen $\frac{\delta\lambda_j}{\lambda_j}$ is 10^{-4} 10km/s uncertainty of RV. $v_{\text{perihelion}} \approx 7,600\,\text{km/s}$
- Future: $\frac{\delta\lambda}{\lambda} \approx 3 \times 10^{-6}$ HISPEC (anticipated in 2026) and MODHIS (2030)
- Future Radial Velocity Precision (with multi-band analysis): ~30 cm/s.

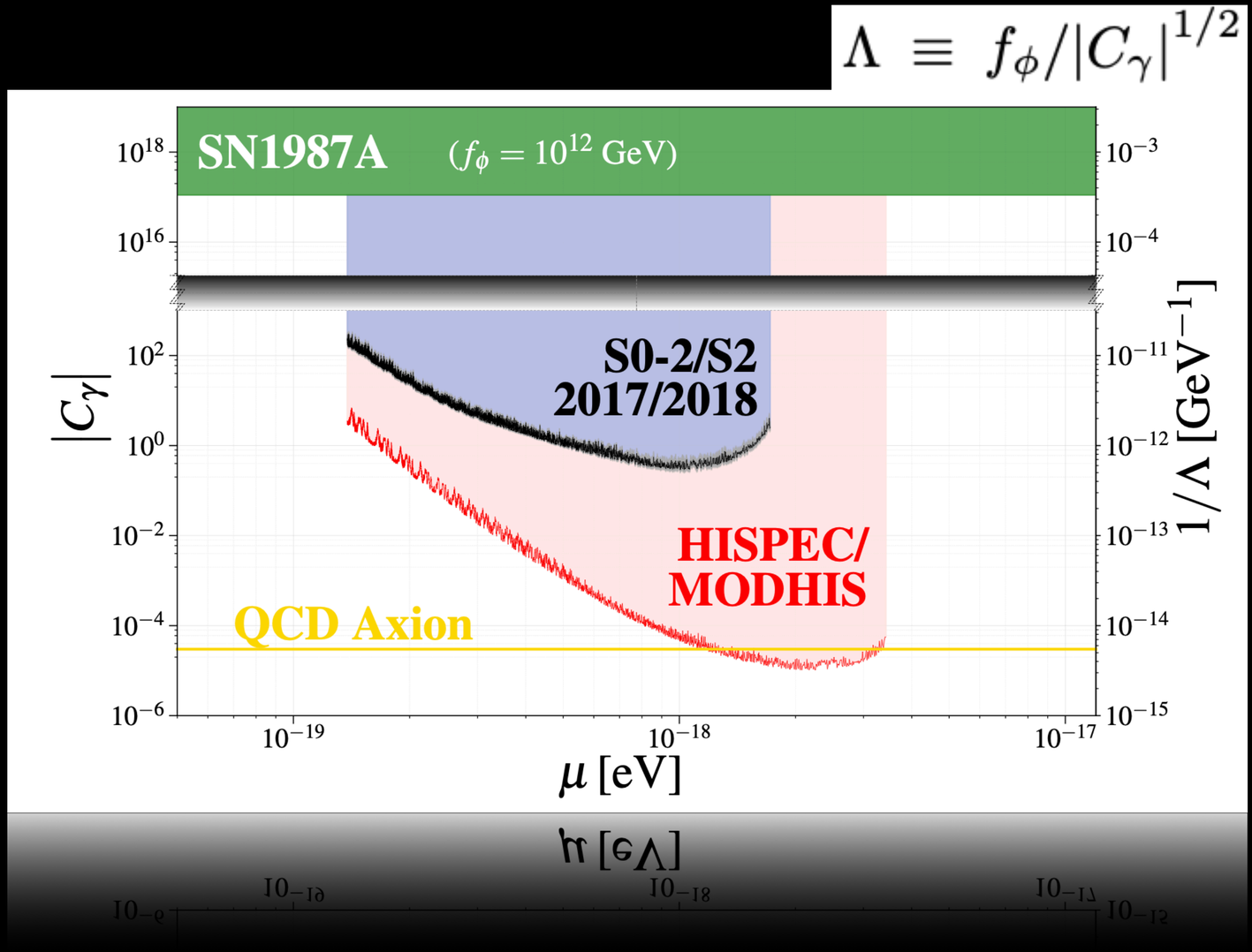
* We primarly focused on the Hydrogen line for S2 Star analysis

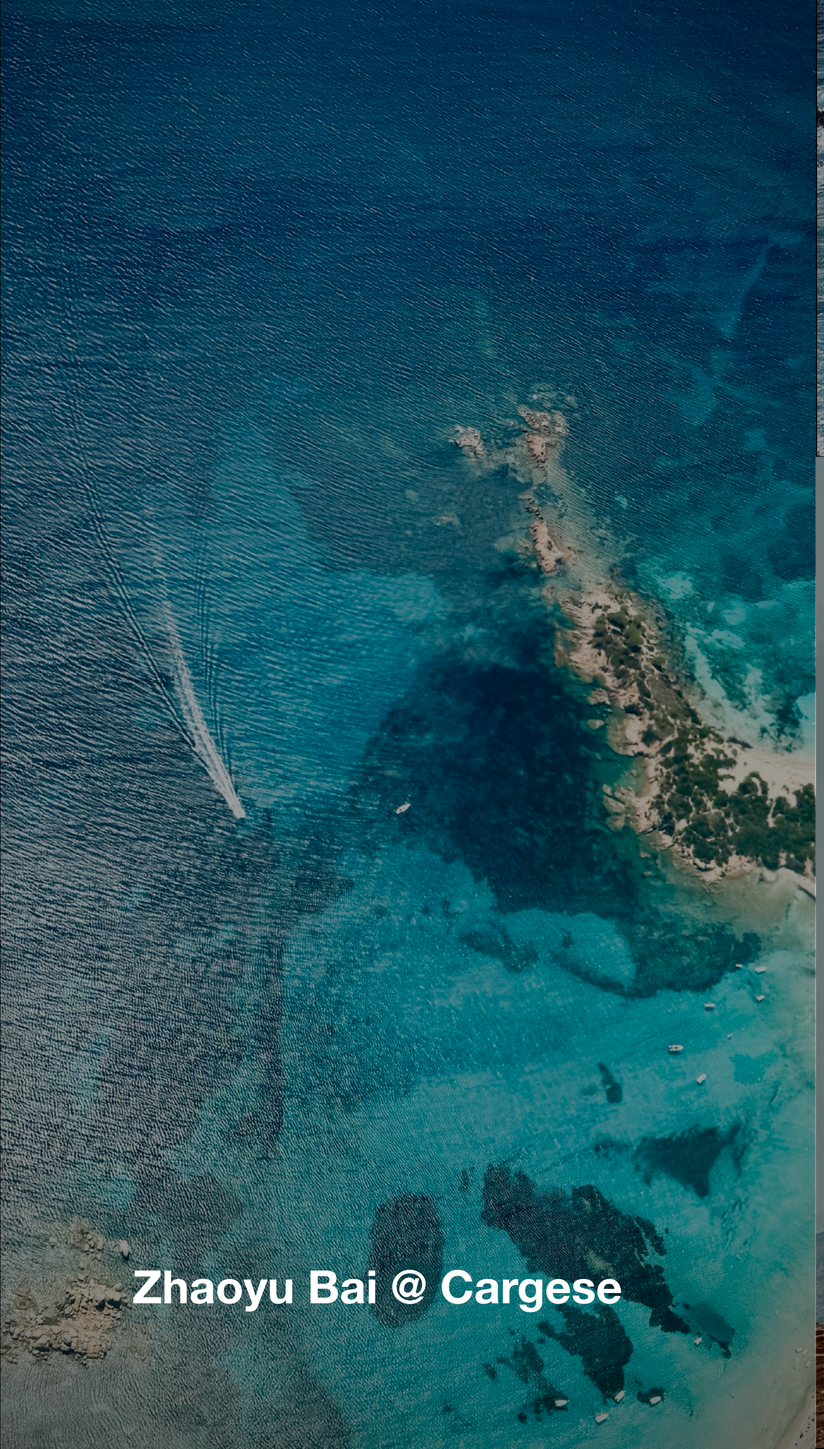
Projected sensitivity on the quadratic scalar–photon coupling

$$\frac{C_\gamma}{4}\frac{\phi^2}{f_\phi^2}F_{\mu\nu}F^{\mu\nu}$$

As a benchmark

$$|C_\gamma| \approx 3 \times 10^{-5}$$





Thanks

More information (Arxiv operates 24/7):
Call 2507.07482

Zhaoyu Bai @ Cargese

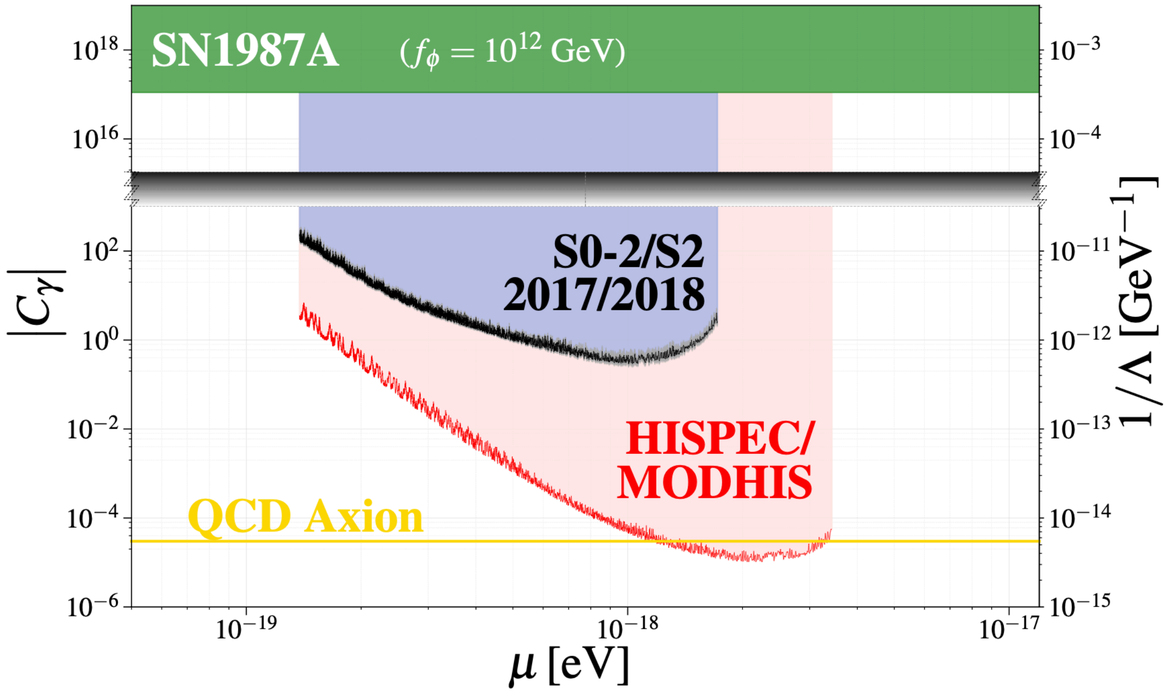
2025.08.02

Results

- **Current data:** Gemini/NIFS over 25 days in 2017–2018.
- **Future prospects:** HISPEC/MODHIS projections incorporating:
  - 10^3 -fold better spectroscopic resolution
  - 1/2 observing cadence
  - 10-fold longer total observation days
  - A late-type star with a semi-major axis 10% that of S2
- Constraint **independent** on f_ϕ

$$\phi_0^{\max} \approx 0.07\,\alpha_G^2 M_{\rm pl}\sqrt{\frac{M_{\rm cloud}}{M_{\rm BH}}} \approx 0.5\,\alpha_G f_\phi$$

$$\frac{C_\gamma}{4}\,\frac{\phi^2}{f_\phi^2}\,F_{\mu\nu}F^{\mu\nu}$$



Projected constraints on the quadratic scalar–photon coupling

$$\Lambda \equiv f_\phi/|C_\gamma|^{1/2} \qquad |C_\gamma| \approx 3\times 10^{-5}$$

Scalar - Photon Quadratic Couplings

Ultralight Bosons

- **Axions/ALPs:** Nonperturbative QCD or explicit UV effects induce
- **QCD axion:** loop calculations yield $|C_\gamma| \sim 3 \times 10^{-5}$ (UV dependent)
- **Generic Scalar Particles:** With Z2 symmetry.
- **Quadratic Coupling Effect:**
  - Operator $\frac{C_\gamma}{4} \frac{\phi^2}{f_\phi^2} F_{\mu\nu} F^{\mu\nu}$ modifies the lagrangian effectively $-\frac{1}{4}\left[1 - \frac{C_\gamma \phi^2}{f_\phi^2}\right] F_{\mu\nu} F^{\mu\nu}$
  - Fine structure constant $\alpha_{\text{eff}} \approx \alpha\left(1 + \frac{C_\gamma \phi^2}{f_\phi^2}\right)$

S-Star Spectroscopy

Summary

- An exposure is around 10 mins.

$$\frac{\delta\alpha_{\rm EM}}{\alpha_{\rm EM}} \simeq C_\gamma \frac{\phi^2}{f_\phi^2}$$

- Modulation at Periastron
- Spectral line shift:

$$\frac{\delta\lambda_j}{\lambda_j} \approx -k_{\alpha,j}\frac{\delta\alpha_{\rm EM}}{\alpha_{\rm EM}} \approx \frac{\delta v}{c}$$

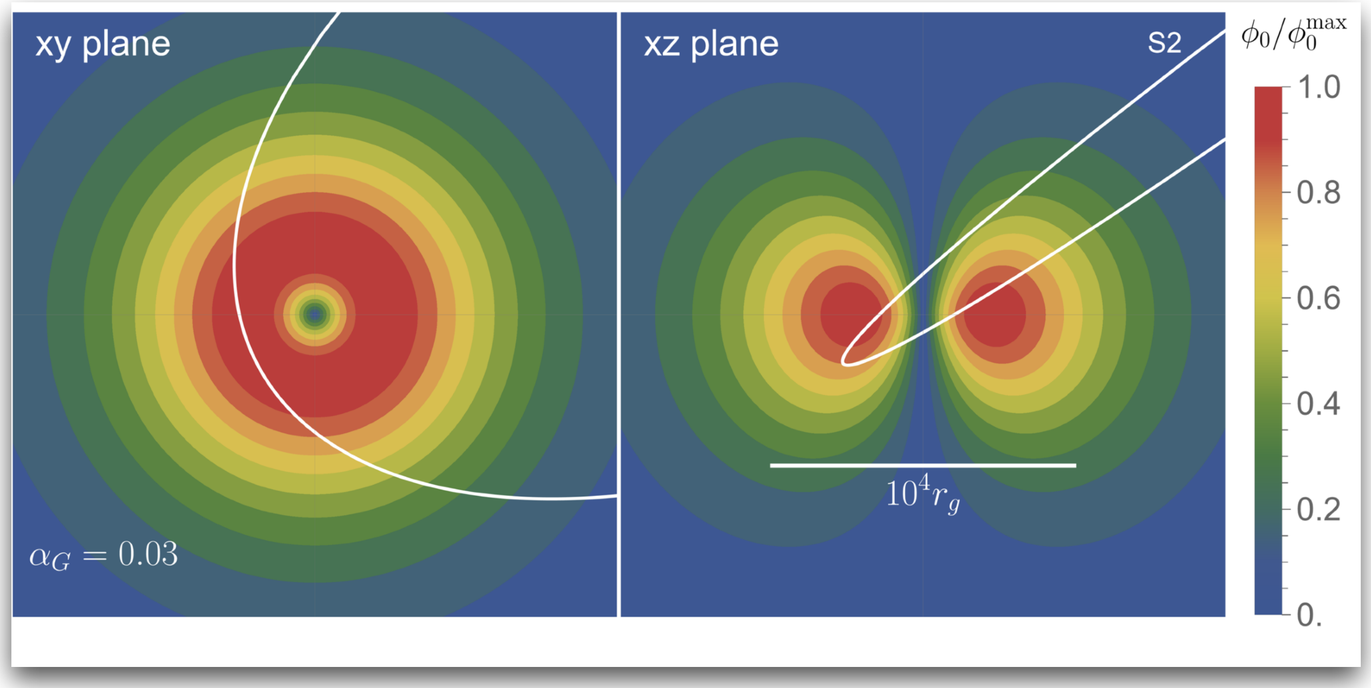
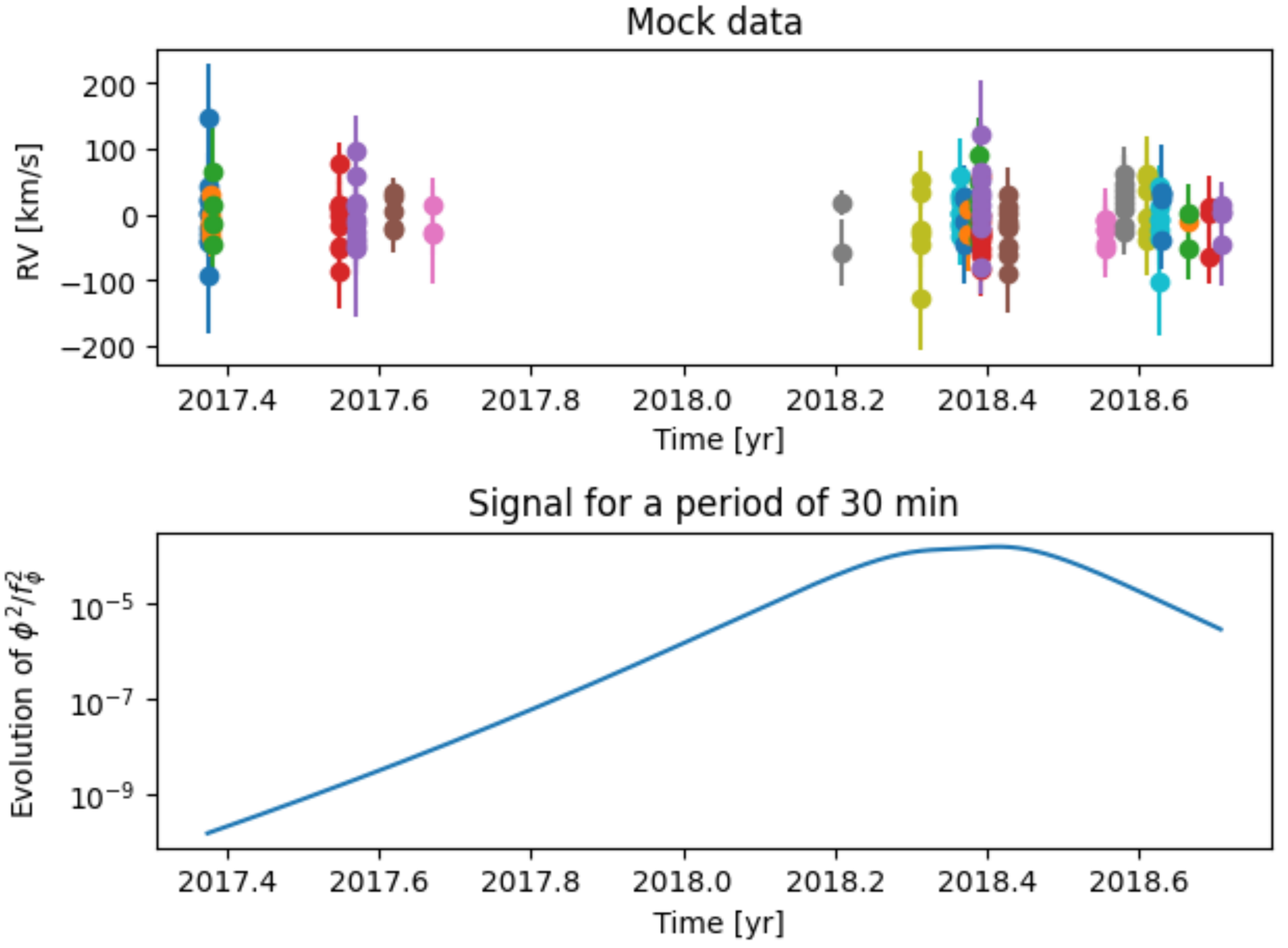


FIG. 1: An example of the normalized axion/scalar cloud density, $\phi_0/\phi_0^{\rm max}$, for $\alpha_G = 0.03$ on the xy-plane (left) and xz-plane (right) in the BH frame, where the BH spin axis is aligned with the $+z$ direction. The projected orbit of the S2 star is also shown on both planes. The transformation of the S2 orbit into the BH frame adopts fiducial values of $i_{\rm BH} = 155°$ and $\Omega_{\rm BH} = 177°$ [66].

*The logic to the Soliton Core DM is the same


Mock data
RV [km/s]
200
100
0
−100
−200
2017.4
2017.6
2017.8
2018.0
2018.2
2018.4
2018.6
Time [yr]
Signal for a period of 30 min
Evolution of ϕ^2/f_ϕ^2
10^{-5}
10^{-7}
10^{-9}
2017.4
2017.6
2017.8
2018.0
2018.2
2018.4
2018.6
Time [yr]