The High Energy X-Ray Probe (HEX-P)

Constraining Black Hole Growth History with population spin measurements

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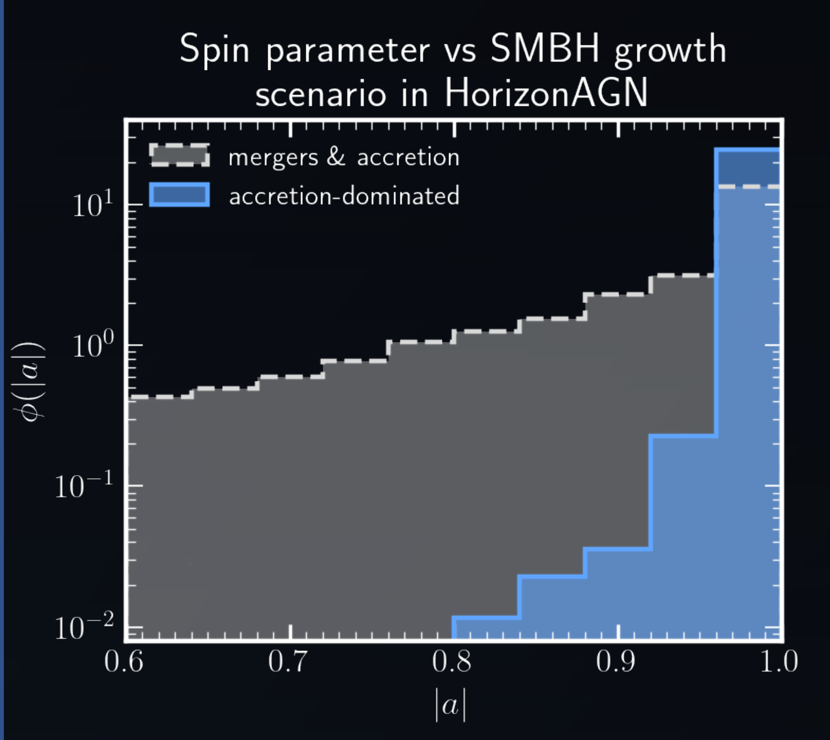
Overview:

HEX-P is a probe-class mission concept that will combine high spatial resolution X-ray imaging (<10 arcsec FWHM) and broad spectral coverage (0.1-150 keV) with an effective area far superior to current facilities (including XMM-Newton and NuSTAR), to enable revolutionary new insights into a variety of important astrophysical problems. Among these, constraining the primary growth channel of supermassive black holes (SMBH) remains one the most actively debated questions in the context of cosmological structure formation. The nature of their growth history dictates the expected SMBH spin distribution, and thus SMBH spin measurements offer a rare observational window into this question. With its broad bandpass and high throughput, HEX-P is an excellent probe for reflection spectroscopy and reverberation mapping, promising to deliver spin measurements for large samples of SMBHs at redshift z=0 and beyond. Here, we investigate the capability of HEX-P to distinguish between different primary SMBH growth channels, based on the distinct mass vs spin distributions predicted for these channels by state-of-the-art cosmological simulations. More information on HEX-P, including the full team list, is available at **https://hexp.org.**

State-of-the-art cosmological simulations track spin parameter evolution in realistic SMBH populations



▵ **A.** *Comparison of spin parameter distributions resulting from two SMBH growth channels in the HorizonAGN cosmological simulation at z~0.06. Data courtesy of* ***Beckmann & Smethurst+2023***

Owing to their rapid increase in sophistication and resolution, hydro-dynamical *cosmological simulations are now capable of following spin parameter evolution in large statistical samples of SMBHs.*

Whether estimated in post-processing (*Berti & Volonteri 2008; Dotti+2013; Beckmann & Smethurst+ 2023*) or calculated on-the-fly (*Bustamante & Springel 2019, Dubois+2021*), the SMBH spin parameter is affected by the accretion and merger history of black holes. Cosmological models hence predict distinct spin parameter distributions for different SMBH growth channels, which, in principle, *can be used to constrain growth histories of black holes in the observable Universe.*

Here we make use of the striking spin parameter differences between accretion- and merger-dominated SMBH histories presented by *Beckmann & Smethurst + 2023*, *to investigate the feasibility of constraining black hole growth with population spin measurements.*

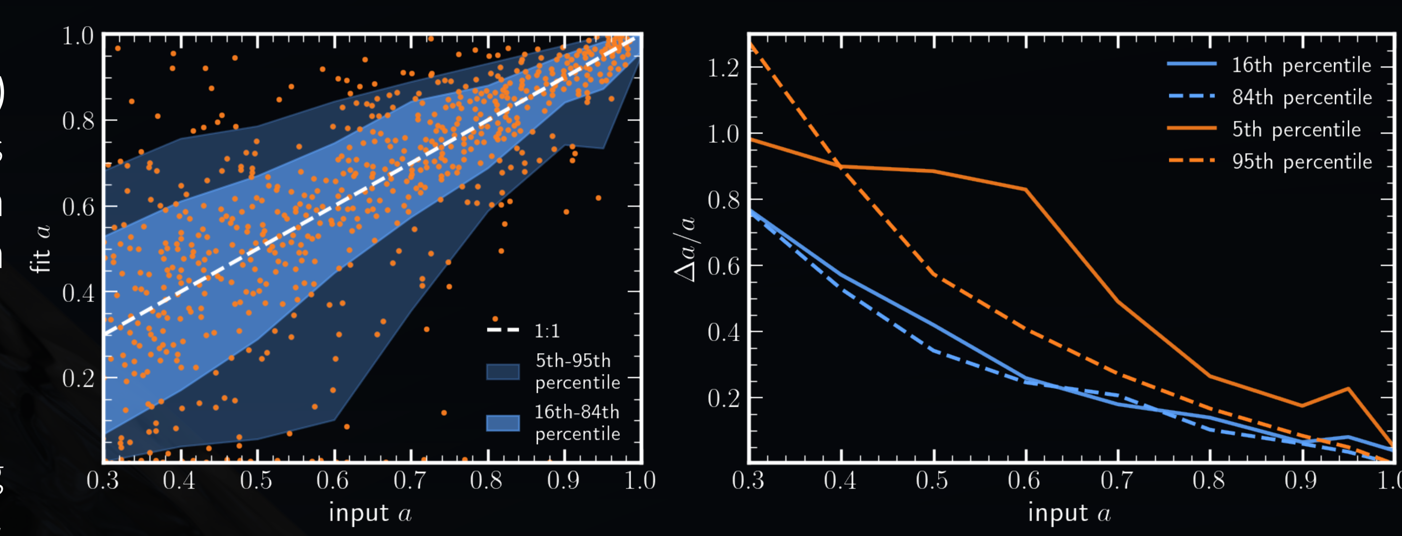
Kologorov-Smirnov test: accounting for luminosity bias and a-dependent measurement uncertainty

We use a *Kolmogorov-Smirnov (K-S) test* to estimate sample sizes required to differentiate between spin parameter distributions shown in Fig. A.

To simulate realistic measurements:

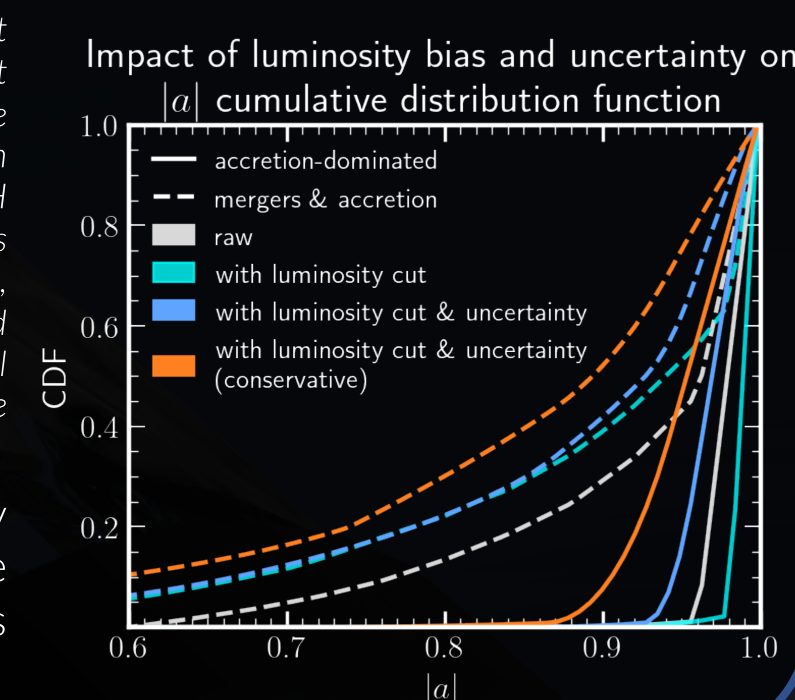
- we *impose a flux limit* (restricting simulated SMBH to top 30% L_{bol} averaged over 100Myr)
- *and account for measurement uncertainty varying with* $|a|$. In lieu of currently on-going HEX-P parameter recovery simulations, we use the baseline model in Parker+2022 to construct an uncertainty model for $|a|$.

For a given sample size N we take a random draw from the flux-limited spin parameter distribution, perturb it within the assumed uncertainty and perform a K-S test against the opposite distribution. We repeat the procedure multiple times and record what fraction of tests differentiates between the two spin parameter distributions.



▵**B.** *a-dependent uncertainty model based on spin parameter recovery study in Fig. 3 of Parker+2022.*

▹**C.** *Impact of mimicking a flux limit (cyan), followed by measurement uncertainty (blue & orange) on the cumulative distribution function of $|a|$ in accretion- and merger-dominated SMBH populations. Although luminosity cut acts to increase differences between the CDFs, this effect is offset by the assumed uncertainty model. 'Conservative' label corresponds to the 5-95th percentile uncertainty model in Fig. B.*



Do you have ideas for how HEX-P would revolutionize your science? Get in touch!

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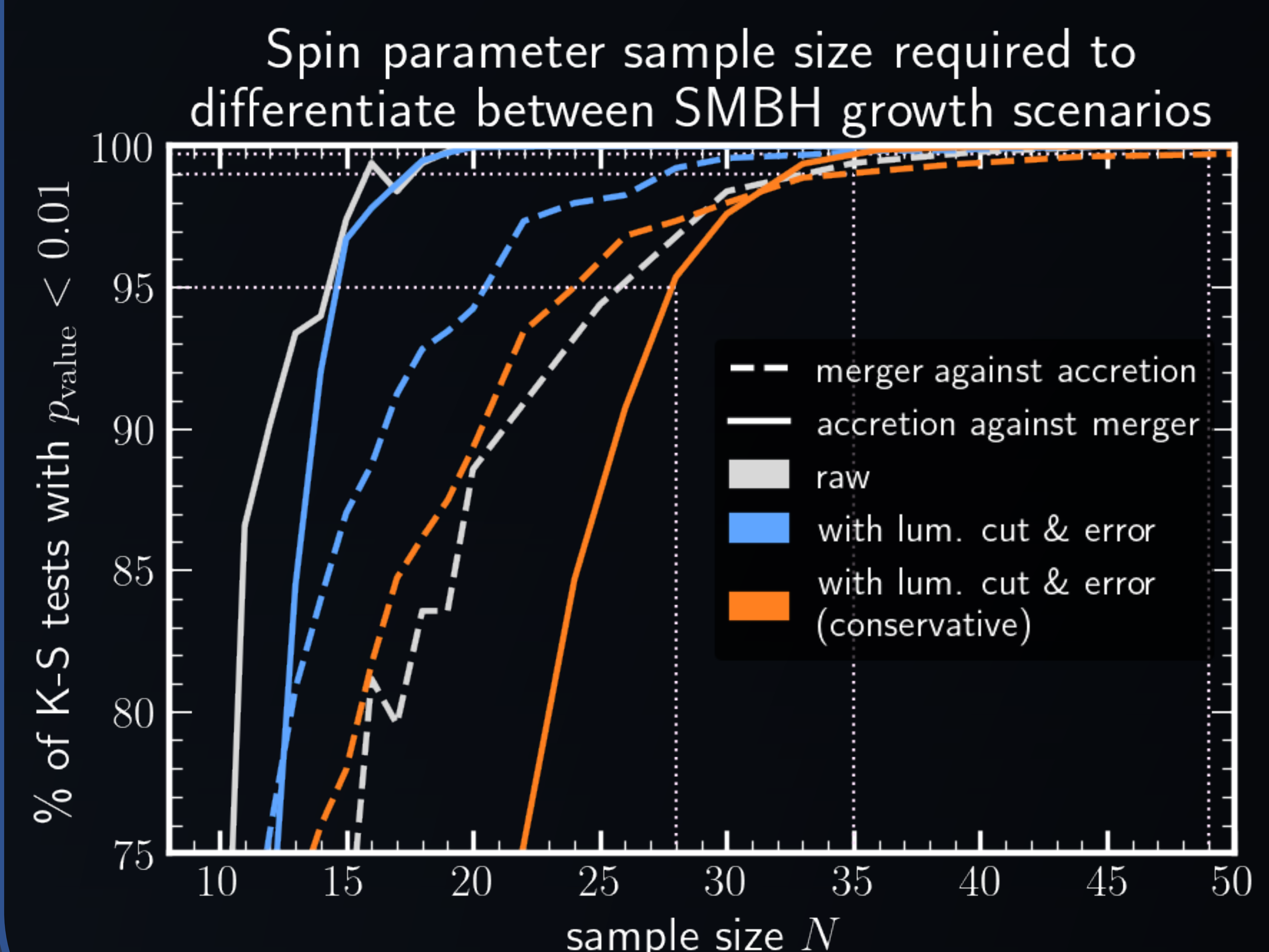
HEX-P will be capable of constraining SMBH growth channels as predicted by cosmological models



As demonstrated in Fig. D, the fraction of K-S tests differentiating between the two distributions ($p_{value} < 0.01$) grows rapidly with the simulated sample size. With the imposed flux limit and assumed uncertainty model, *HEX-P would need to observe at most 35 (49) SMBH for a 99% (99.7%) chance of differentiating between the accretion- and merger-dominated growth channels* as predicted by Beckmann & Smethurst+2023.

Upon completion of HEX-P spin parameter recovery simulations we expect the required sample size to reduce even further, given the differences in instrument capabilities between HEX-P and XMM-Newton, upon which we based our current uncertainty model.

◃ **D.** *Fraction of K-S tests, in percent, differentiating between the two growth scenarios ($p_{value} < 0.01$) as a function of spin measurement sample size. For each N we draw 500 spin values from a given distribution and then perturb each value a 100 times within uncertainties shown in Fig. B (a total of 50 000 K-S tests per N). Dotted vertical lines indicate sample size N required to differentiate between accretion- and merger-dominated growth in 95%, 99% and 99.7% of simulated K-S tests. In the most conservative scenario, HEX-P would need less than 50 measurements to differentiate between the SMBH growth histories.*

HEX-P
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