The XUV environment and evolution of the 45 Myr old super-Neptune DS Tuc Ab

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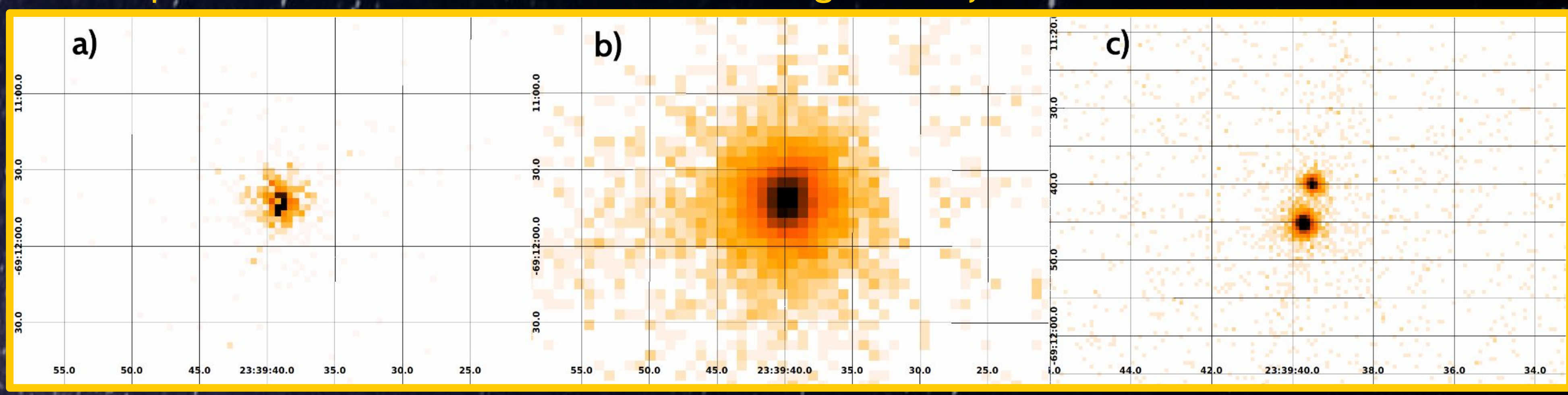
- DS Tuc is a young (45 Myr old) binary star system in the Tuc-Hor moving group. The primary star hosts a 5.7 Earth radii super-Neptune.
- We analysed four Chandra observations to assess the XUV irradiation environment of the planet, and its variation on several different timescales.
- These observations fully separate the flux from the two stars in X-rays for the first time, permitting a significant improvement in accuracy.
- We identified two strong X-ray flares from the primary star, and possible evidence of an activity cycle in its quiescent emission, motivating further observations with Chandra in the future.
- Our simulations of the possible future of the planet reveal a wide range of possible final sizes from Neptune-size to stripped super-Earth. Better mass constraints could narrow this range.

Observations

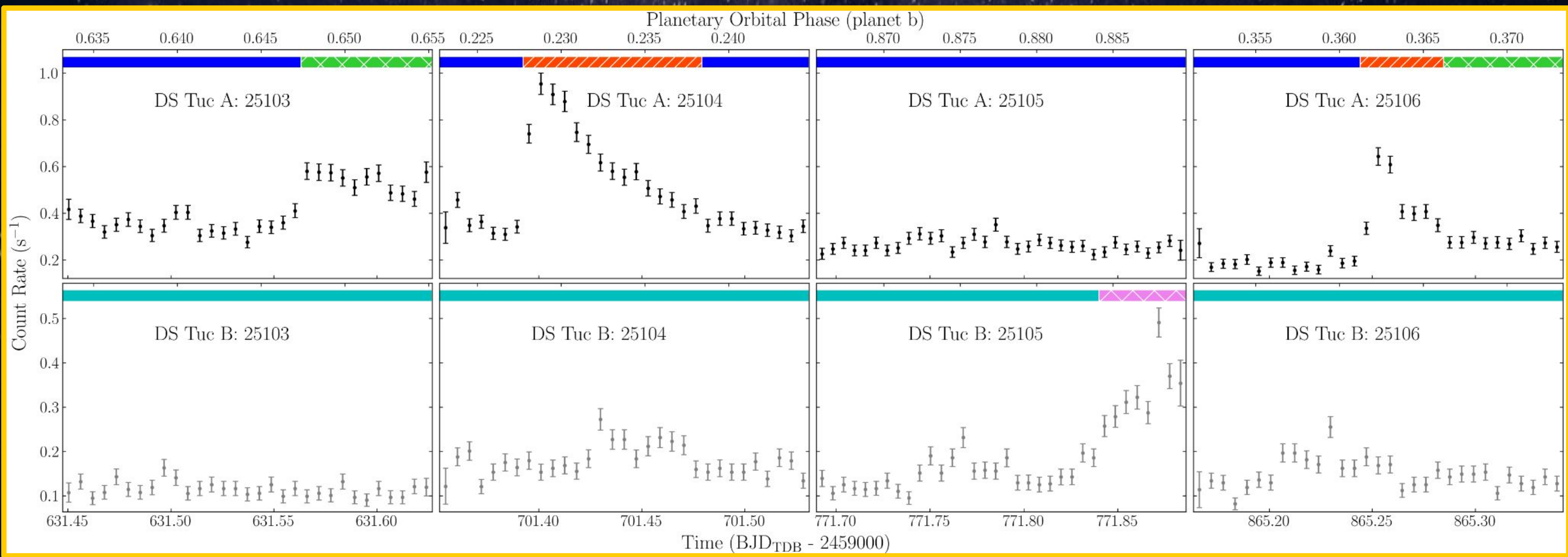
- *Chandra* observed DS Tuc on four occasions in 2022
- 57 ks of exposure time
- Clear advantage in comparing the images with Swift and XMM-Newton on the **right**.
- We improved the accuracy and reliability of the X-ray flux measurements of the two stars in the system by fully separating them in the images.

Comparison of images of the DS Tuc system taken with a) *Swift* XRT, b) *XMM-Newton* EPIC-pn, and c) *Chandra* ACIS-S. The *Chandra* image is from just one of the four observations.



Light Curves

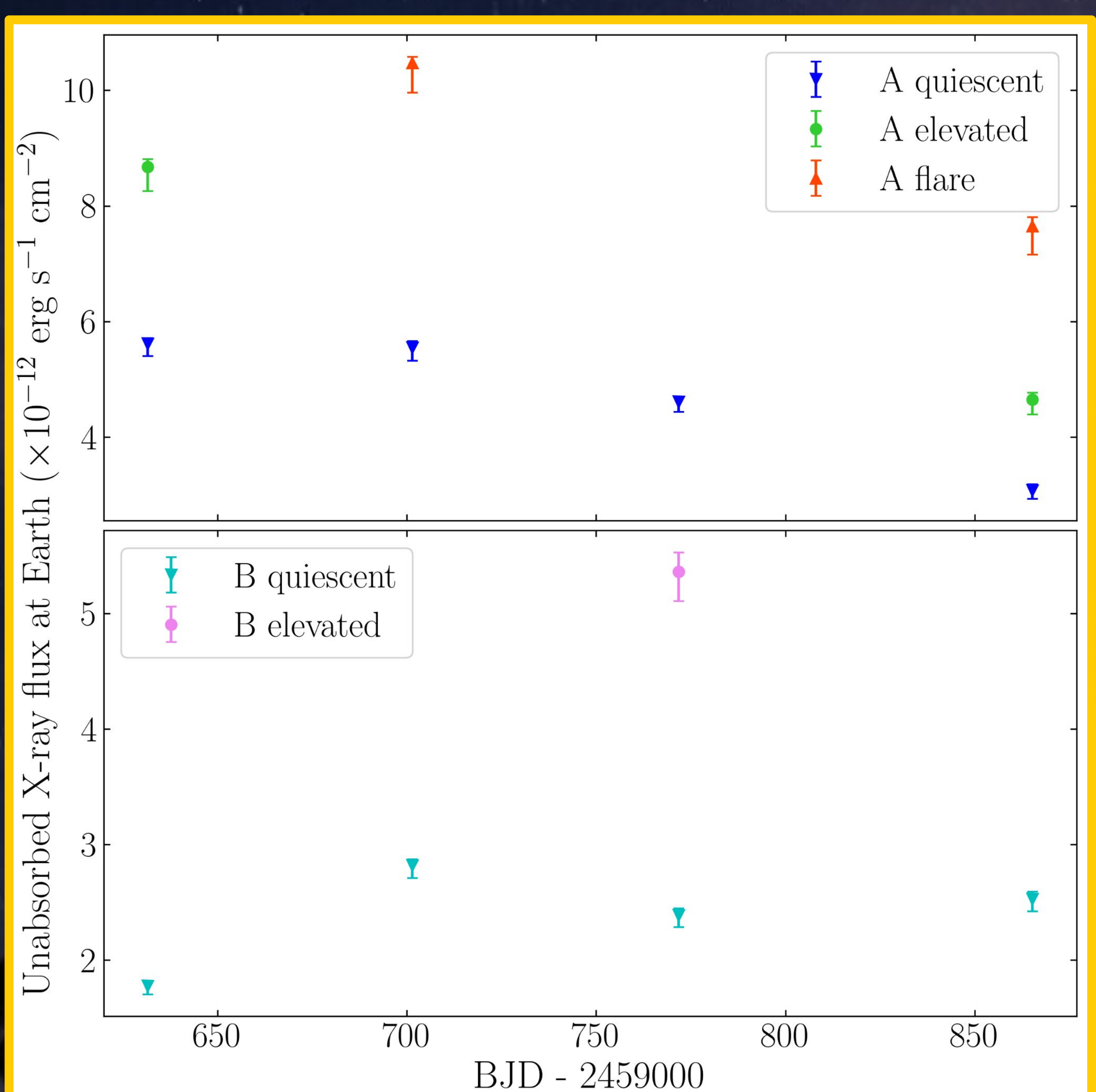
- The *Chandra* light curves for the two stars are shown **below**.
- Both stars show variation, but especially the planet host DS Tuc A, which flared twice in the observations.
- We observed the expected hardening of the in-flare emission in the hardness ratio - a comparison of the soft & hard energy count rates.
- The separate spectra that we extracted based on defining epochs of different activity states (see caption and ribbons on the plot) also showed this hardening during flares clearly.
- Our defined activity epochs also allowed us to measure separate fluxes for the different activity states in each observation.



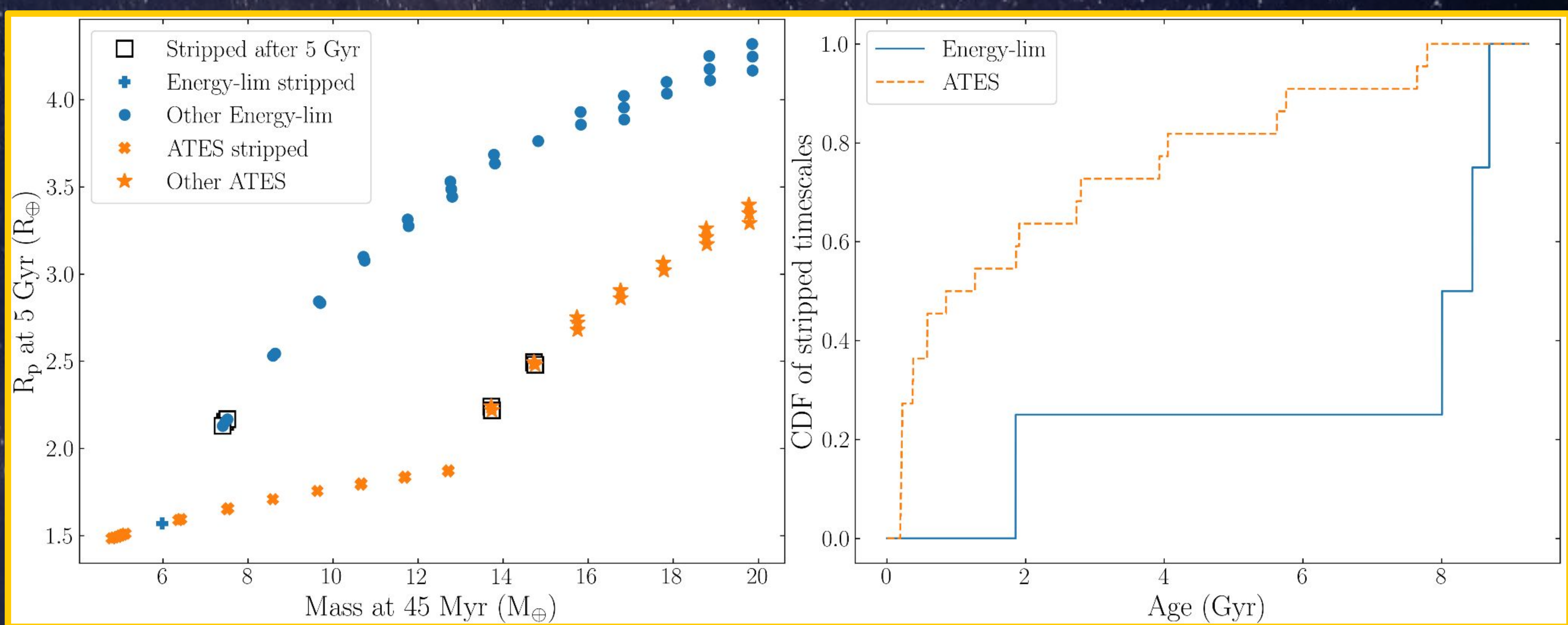
ACIS-S light curves for DS Tuc A (top panels) and DS Tuc B (bottom panels) in each of the four observations. The ribbons at the top of each panel denote periods of quiescence (solid blue and cyan), flaring (red single hatched), and other periods of elevated count rate (green and pink cross hatched). These definitions were used to extract separate spectra.

Longer term variation

- **Below** we plot a light curve of the measured fluxes of both stars
- We observe a decline in the quiescent level of DS Tuc A in the *Chandra* observations which could be a hint of a solar-like coronal activity cycle.
- More observations with *Chandra* in the coming years would be able to determine if this is indeed an activity cycle signature, and its characteristics if so.
- Star B also varies, but without a clear trend



Fluxes across each *Chandra* observation, split into the activity epochs defined from the light curves, showing a clear decline in the quiescent flux of star A across the eight month baseline. Some upper errorbars are smaller than the points. All measurements are for the 0.1 to 2.4 keV band.



Outcome of the simulations. The left panel shows the radii of DS Tuc Ab at 5 Gyr as a function of the implied current mass for the simulations which reproduced the radius at the current age of 45 Myr. For the cases where the planet is stripped, the right panel shows the cumulative distribution function of the timescales on which this happens.

Evolution simulations

- We ran simulations of the evolution of the planet DS Tuc Ab using MESA, with our methods largely as presented in King+2024, based on earlier work by Chen & Rogers 2016, and Malsky & Rogers 2020.
- We used a grid of starting envelope mass fractions and starting masses, together with two methods for estimating the mass loss rate at each step: energy-limited escape (Watson+1981, Erkaev+2007), and ATES (Caldiroli+2022)
- After running the simulations, we deemed **"successful"** all tracks those which reproduced the radius of the planet at the current age of 45 Myr to within 1-σ of the measured value
- The successful simulations largely favour a starting envelope mass fraction of 15 to 20%
- For the successful tracks, **above (left panel)** we plot the radius at a typical field age of 5 Gyr against the mass at 45 Myr. We find a range of different outcomes: Neptune-size, sub-Neptune-size, and stripped super-Earth. Improved future constraints on the planet mass could significantly narrow these possibilities.
- In the corresponding **right panel above** we plot the stripping timescale for those successful tracks which completely lose their primordial envelope in the simulations.
- About half of the cases which are stripped do so within ~1 Gyr, but in a significant minority of cases this happens well past 5 Gyr (highlighted with black boxes in the left panel of the above figure).

References:

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