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Precise determination of circumstellar disk lifetimes

Disk evolution in a single star-forming region

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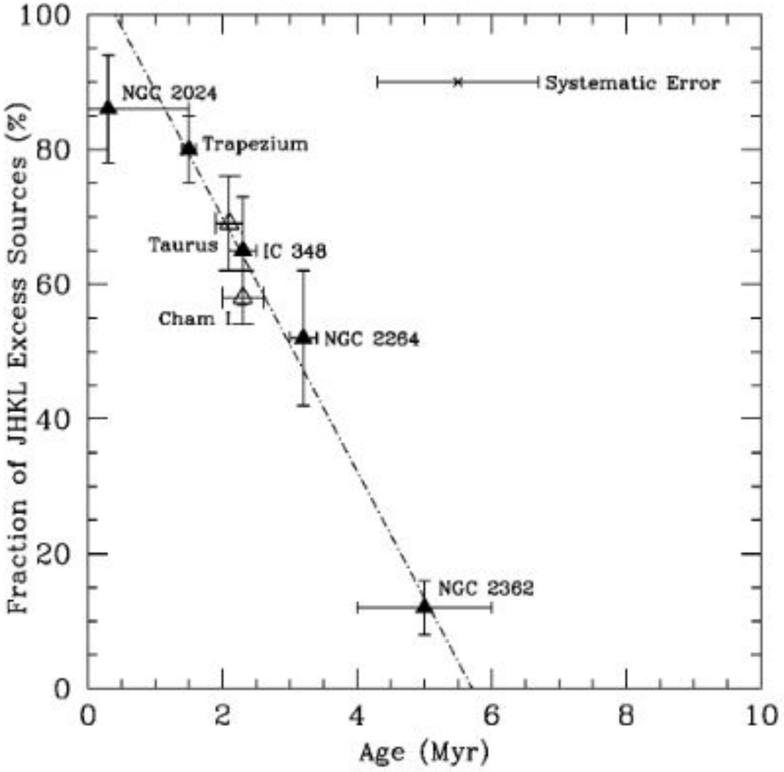
Setting the stage

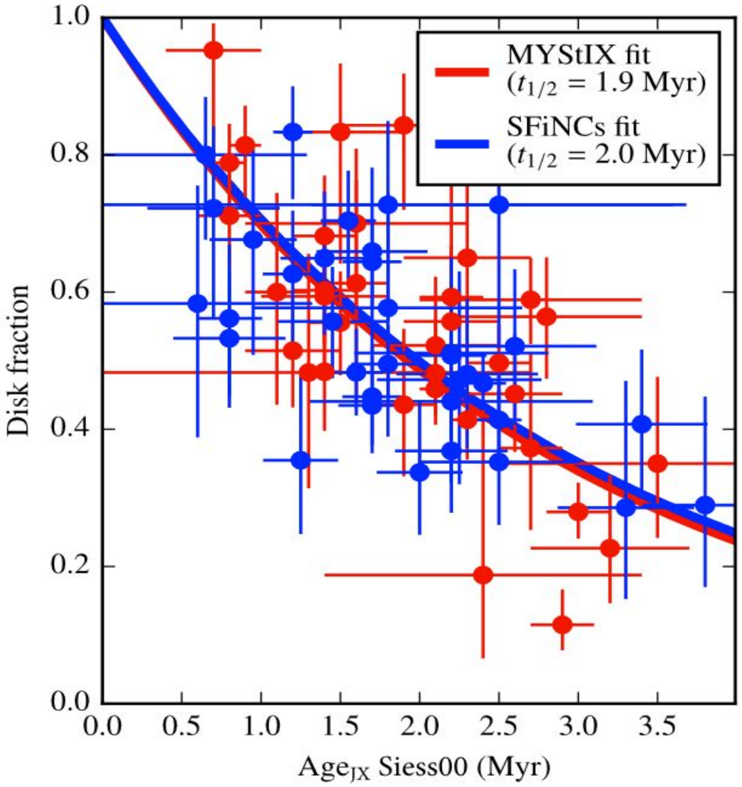
- Circumstellar disks
  - form during stellar formation
  - dissipate after time
  - are the cradles of planet formation
- Disk lifetime estimates as the fraction of stars with a disk versus the age
- Exponential decay models yield results
  - from 2 Myr (Fedele et al. 2010, Ribas et al. 2014, 2015)
  - to 8 Myr (Michel et al. 2021)
- Different methodologies yield similar results



Haisch et al. 2001

Caveats

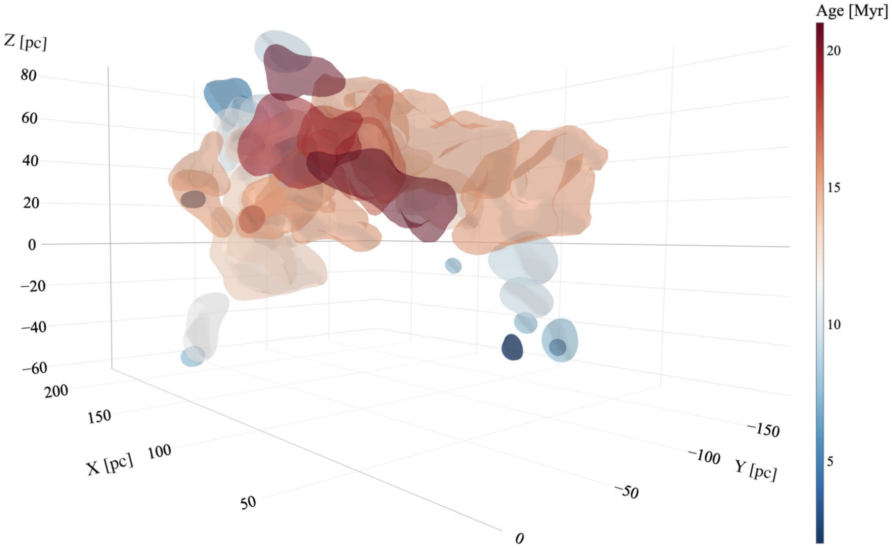
- Need to know
  - Membership of a star to a stellar cluster
  - Precise age estimation
  - Presence of circumstellar disk
- Using different stellar clusters
  - ✓ increases number of data points
  - × mixes different environments
  - × mixes different initial conditions of star formation



Richert et al. 2018

How to overcome these caveats

- Novel clustering algorithm
  - Significance mode Analysis (SigMa, Ratzenböck et al. 2023a)
  - Applied to the Scorpius Centaurus OB association
- Validate through narrow sequences in color-magnitude space
  - Fit isochrones
  - Coherently determined ages (Ratzenböck et al. 2023b)



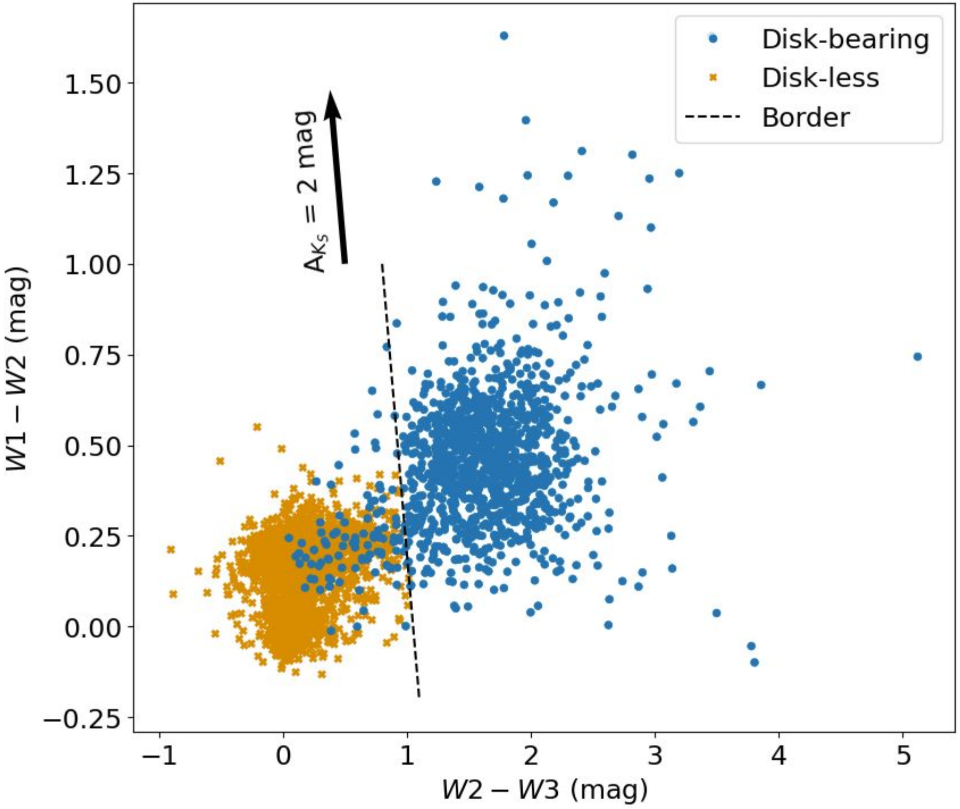
Ratzenböck et al. 2023b

Selection of circumstellar disks

- Detection of circumstellar disks as excess in the infrared (Haisch et al. 2001)
- Use photometric measurements of WISE (mid-) and 2MASS (near-infrared)
- Combined with the stellar cluster information from Gaia and the isochronal ages (PARSEC isochrones)
- Use different approaches and compare dependencies on method
    - Color-color diagrams (CCD)
    - Spectral energy distribution (SED)
    - Selection from the literature (Luhman 2022)

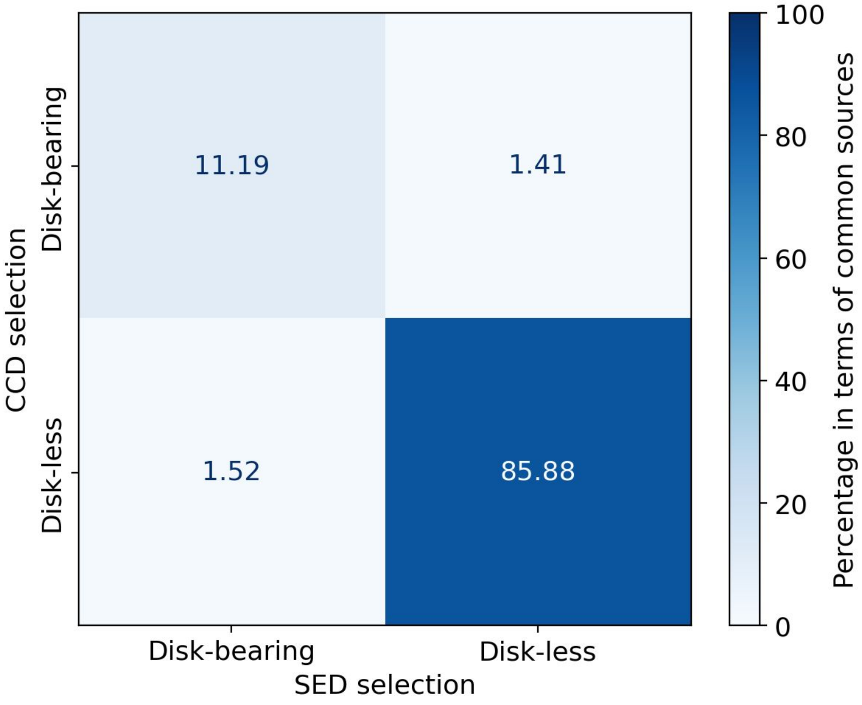
Color-color diagrams

- Four distinct combinations of photometric bands using WISE and 2MASS
- One star can appear in multiple combinations if it fulfills quality criteria for all bands used
- If a star has an excess in one diagram → selected as bearing a circumstellar disk
- More flexible approach



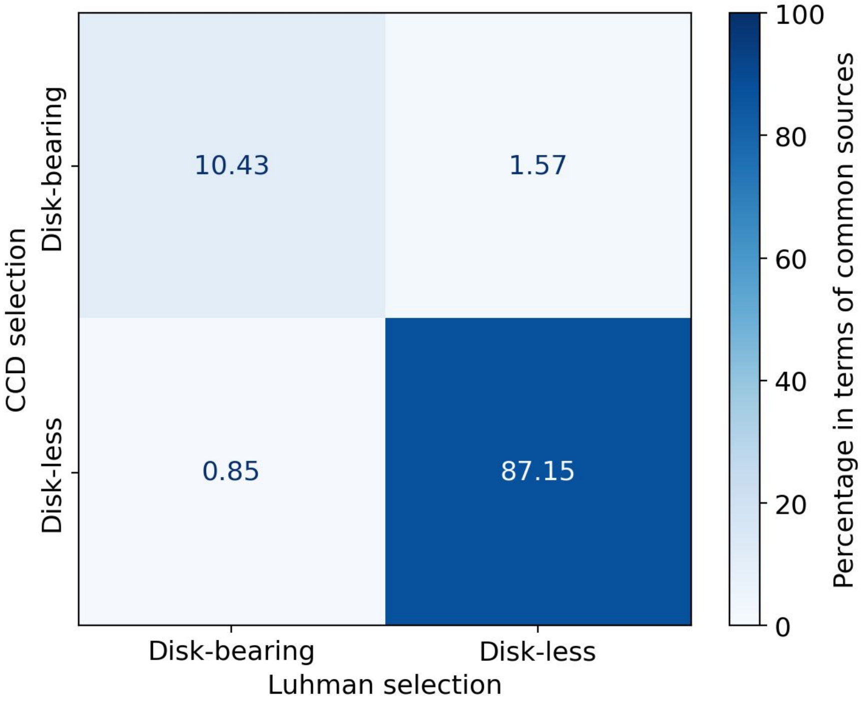
Spectral energy distribution

- Convert photometric measurements to flux
- Perform a linear fit and take the slope as spectral index
- Stars with slope ≥ -2 selected as disk-bearing
- Comparison to CCD selection method, but less flexible
- Little confusion in the selection



Comparison to the literature

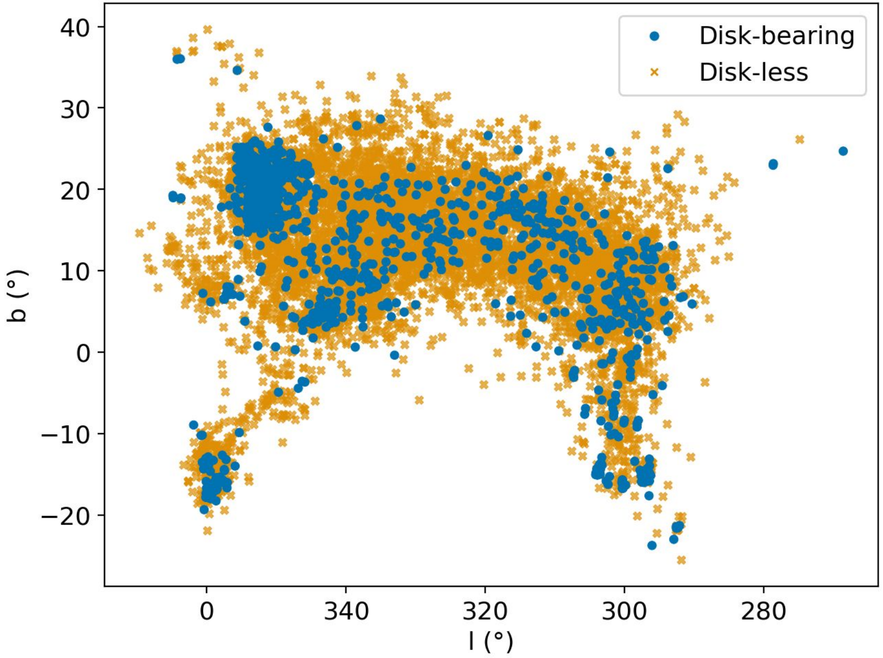
- Luhman 2022 determines types of disks in Sco-Cen
- Smaller region of Sco-Cen is considered → less stars in this sample
- Little confusion in the selection
- Similar distribution to before



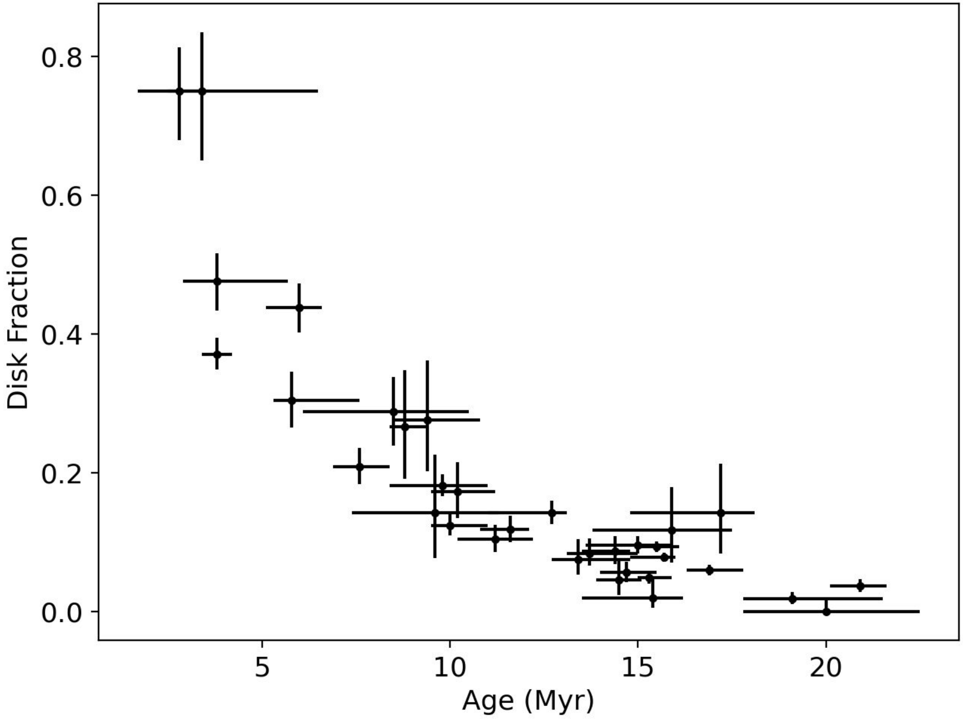
Resulting selection of circumstellar disks

- Disk-bearing stars distributed throughout entire region
- Some overdensities visible
- Disk fraction f_i for each stellar cluster i is computed as

$$f_i = \frac{\#DB_i}{\#DB_i + \#DL_i}$$



The relation of disk fraction versus age



Modeling relation

- Exponential decay visible in the data

$$f(t) = f_0 \cdot e^{-\frac{t-t_0}{\tau}}$$

- Data present in 3-21 Myr for 33 data points
- Shift the function to the right to model this range
- Using Bayesian inference to fit the relation

Statistical Model

- Detecting a disk or not is a Bernoulli process

$$p(k_i \mid f_i,\ N_i) = Binomial(N_i,\ f_i)$$

- We know number of disks and stars in a stellar cluster → invert statement using Bayes formula

$$p(f_i \mid k_i,\ N_i) = \frac{1}{Z} \cdot p(k_i \mid f_i,\ N_i) \cdot p(f_i \mid N_i)$$

- To mitigate outlier effects and unaccounted noise, we use a mixture model

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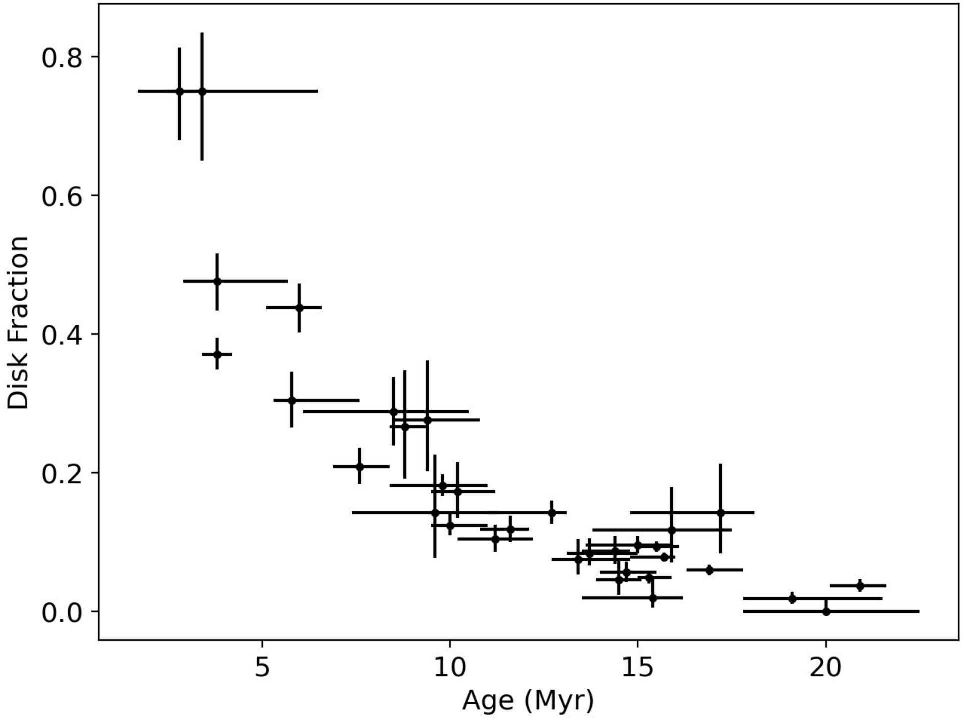

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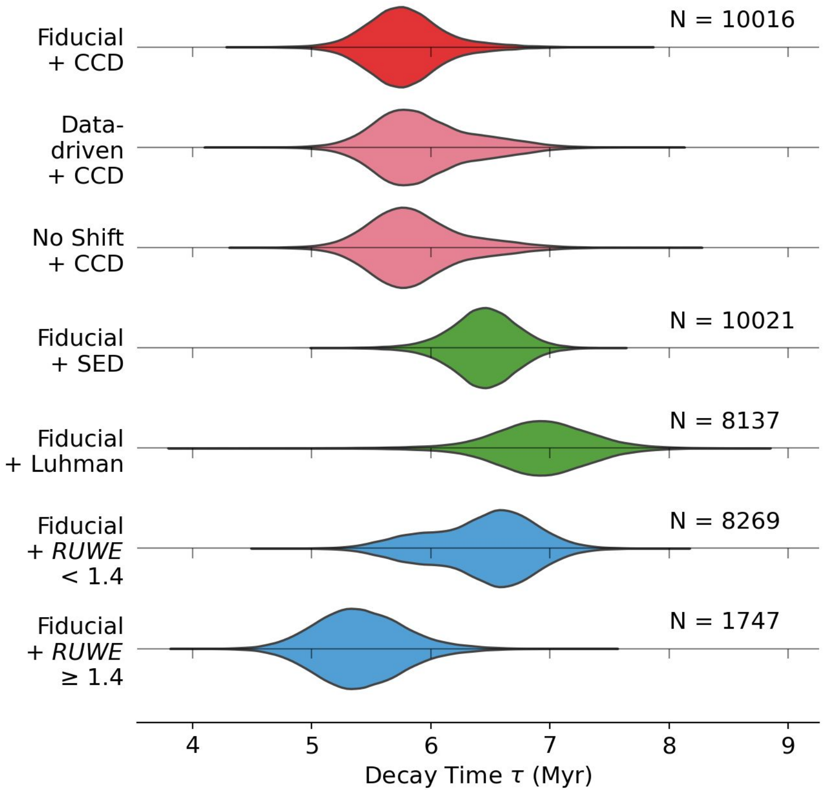
Models and Choices for Priors

- Different model architectures to study the influence of modeling
  - **Fiducial**: Priors constrained to physical values, flat in the range
  - **Data-driven**: No constraints on the flat priors
  - **No-shift**: No constraints on the flat priors and the shift is set to 0
- To study the effect of disk selection, the fiducial model is tested on
  - Selection of disks with Spectral Energy Distribution
  - Selection from Luhman 2022
- The effect of multiple stellar systems on the result is analyzed by
  - Splitting the data in two subsets using Gaia’s RUWE at 1.4
  - Fit the fiducial model

Distribution of the decay time

- Bayesian inference yields posterior distribution for all three parameters
- Modeling approach has no influence
- Disk selection affects result
- Possible multiple stellar systems spread around fiducial result



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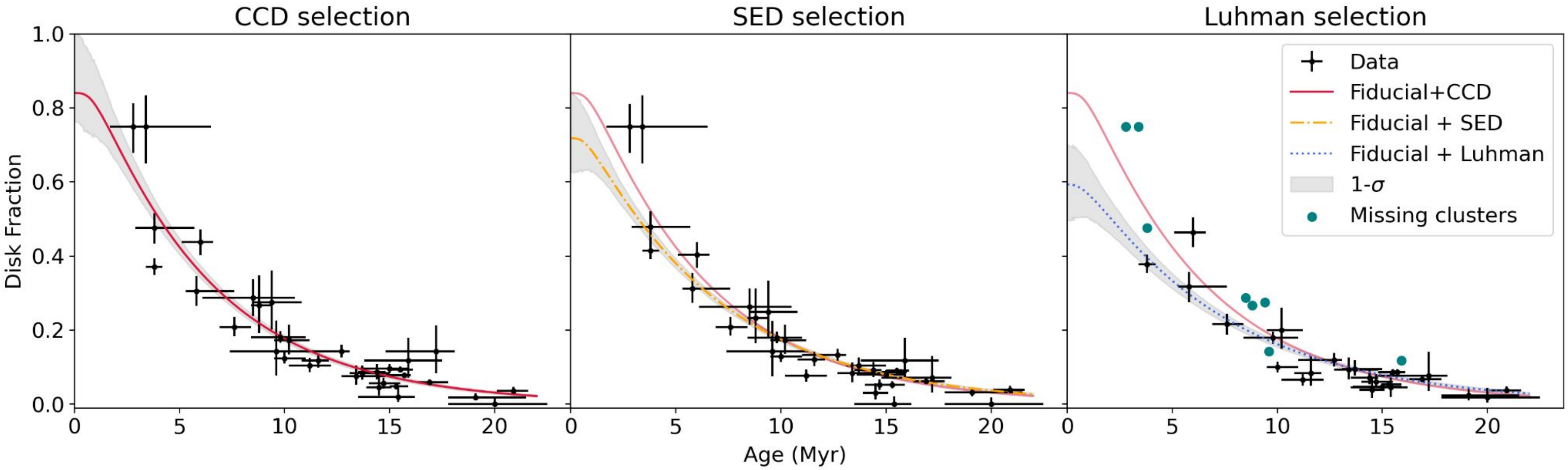
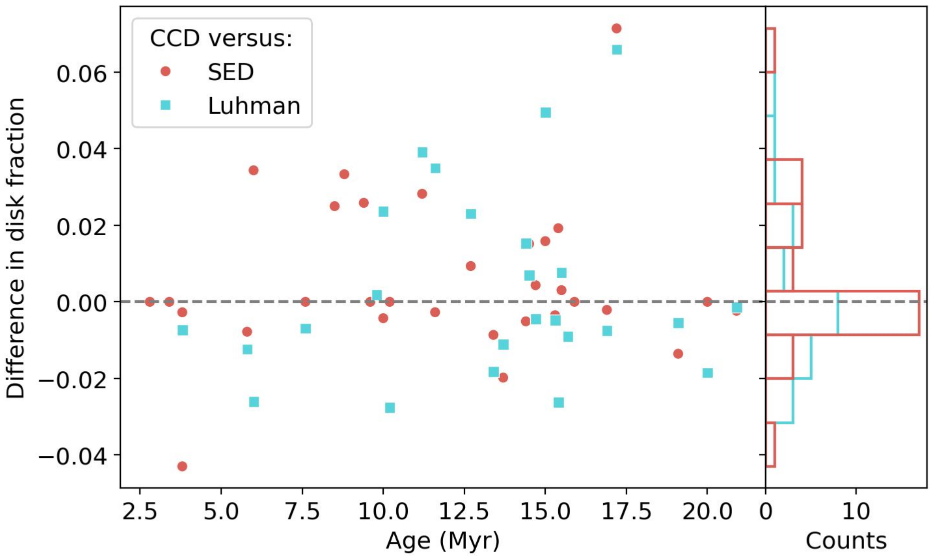


Resulting selection of circumstellar disks

- Difference in decay time between CCD and SED or Luhman selection
- Difference in disk fraction constant over time
- 8 stellar clusters missing in the data from Luhman 2022



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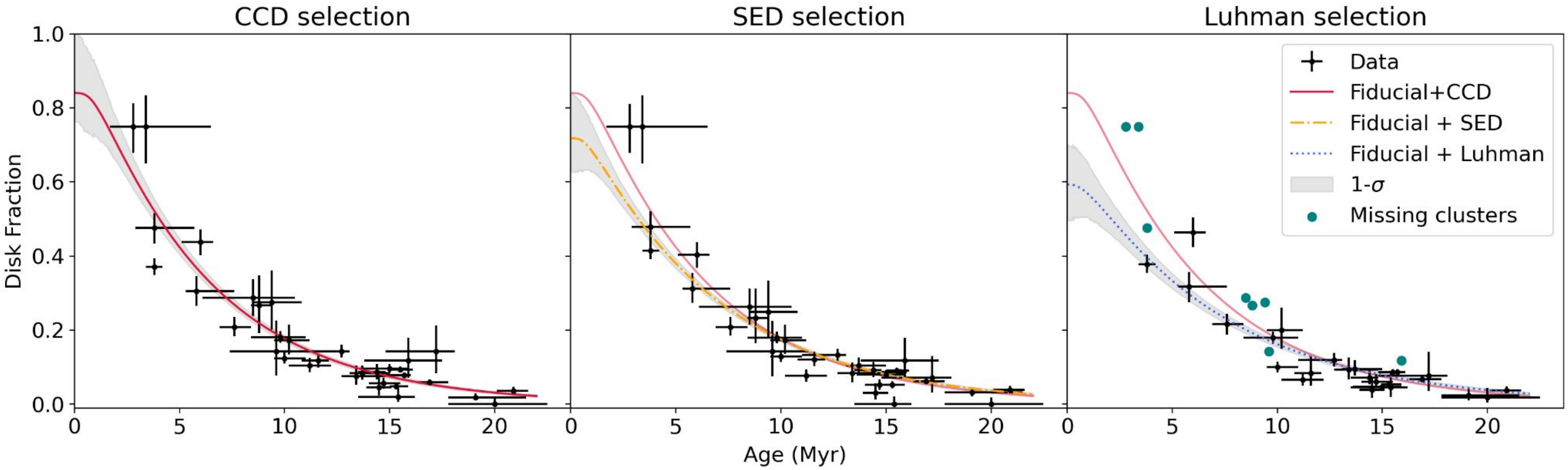
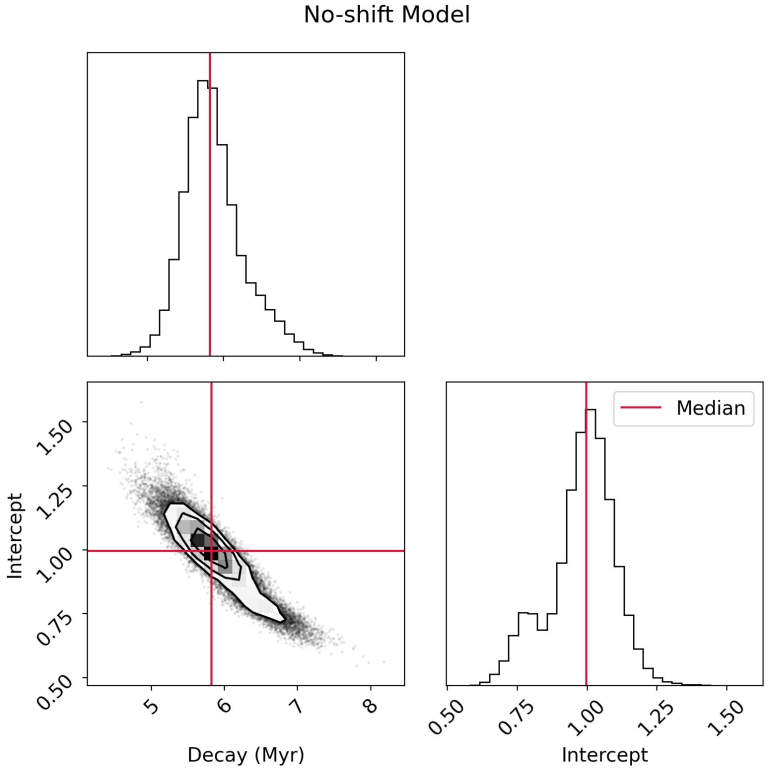


Influence of the shift

- Without the shift, decay time and initial disk fraction have strong correlation
- Decouple these parameters
- Improves model flexibility



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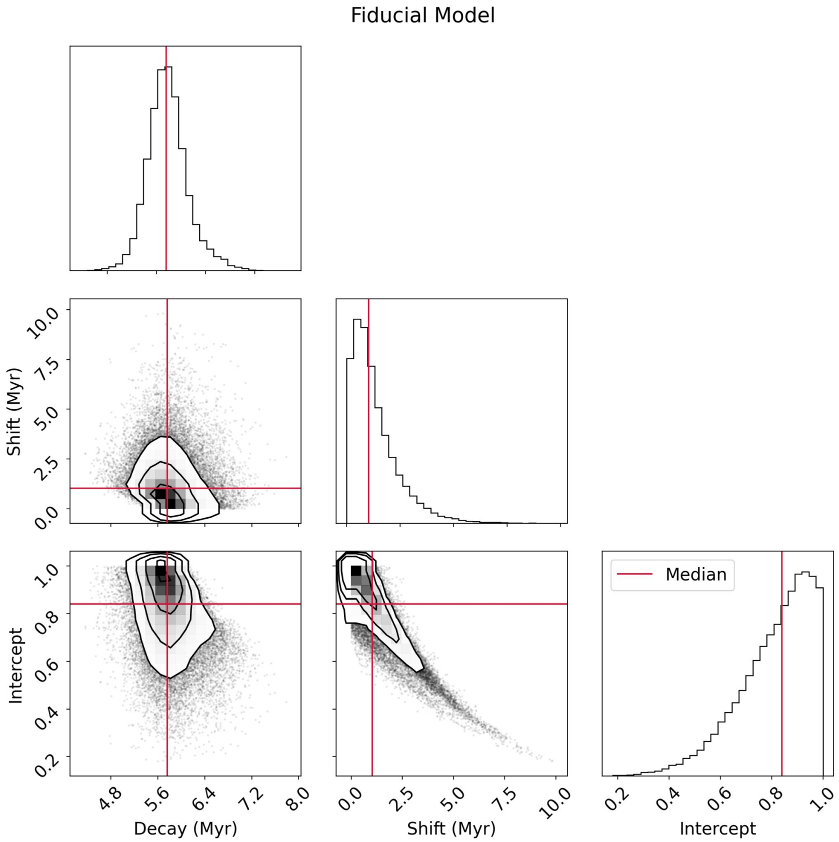


Effect of the stellar mass on the result

- No cut in stellar mass
- Sample from the complete stellar mass function from the hydrogen burning limit to 8 solar masses
- Pfalzner et al. 2022 argue that combining stellar clusters at different distances biases the result towards higher stellar masses
- Marginalize over entire stellar mass range and Gaia selection function at 100-200 pc
- Uncertainty may be increased because of this

Dependency on the age of stellar clusters

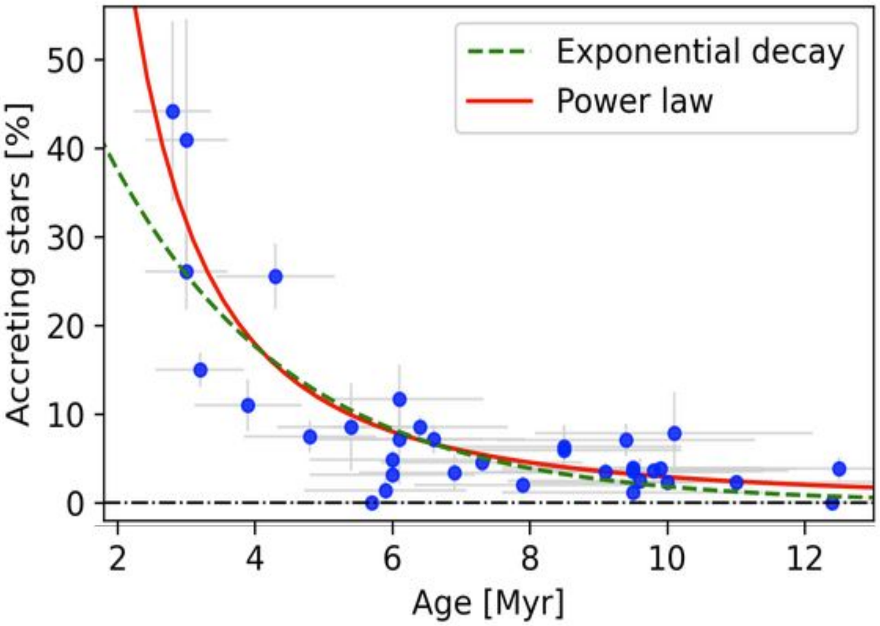
- Do not account for age uncertainty
- Isochronal ages dependent on stellar models
- Miret Roig et al. 2024 find systematic offset between isochronal and dynamical traceback ages
- If data is shifted along the age axis, shift and initial disk fraction are affected

Interpretation of the result

- Median disk decay time is $5.76^{+0.28}_{-0.31}$ Myr
- Why are we getting this larger value?
  - Untangling populations that formed in one environment
  - Sensitive to entire stellar mass range
  - Most stars are low-mass stars
- No data below 3 Myr
  - Sample is based on Gaia selected stellar members
  - Cannot determine the full shape of the functional relation
  - Posterior distribution shaped by prior distribution

Implications of the result

- Fedele et al. 2010
  - Obtain accretion timescale of 2.3 Myr and dispersion timescale of 3 Myr
- Accretion timescale of 2.7 ± 0.4 Myr (Delfini et al. 2025)
- Disk decay time of $5.76^{+0.28}_{-0.31}$ Myr



Delfini et al. 2025

Using Bayesian Modeling and novel clustering and age dating techniques, we can better constrain the lifetime of disks.