Using machine-learning to study the evolution of star clusters

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Astronomický ústav AV ČR
STŘEDOČESKÉ INOVAČNÍ CENTRUM
Středočeský kraj
Co-funded by the European Union
Umělá inteligence pro vědu a společnost

Introduction

About me

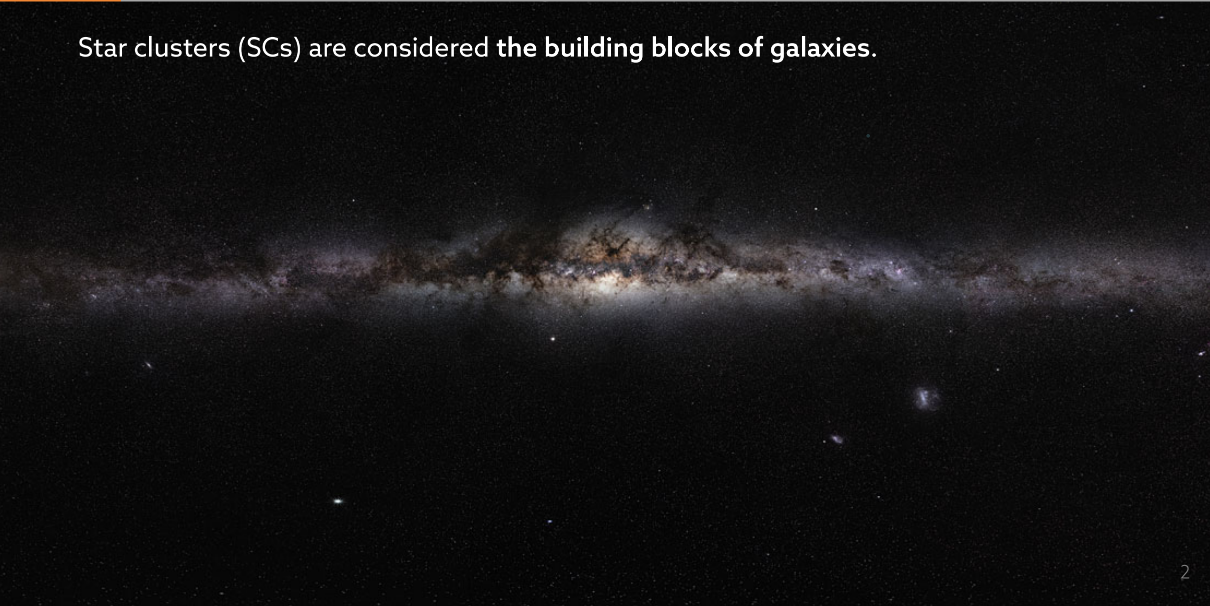
Research:

- 2019: **PhD** at Charles University, Prague
- 2019–2020: **Postdoc** at Astronomical Institute of the Czech Academy of Sciences
- 2020–2022: **Postdoc** at Astronomy Dept., Indiana University Bloomington, USA
- 2022–2023: **Visiting Professor** at Physics Dept., Indiana University Bloomington, USA
- 2024–now: **Marie Skłodowska-Curie Fellow** at Astronomical Institute of the Czech Academy of Sciences (programme *MERIT*)

Very active in public outreach, education of the younger generation, books author, ...

What/where are star clusters?

Star clusters (SCs) are considered **the building blocks of galaxies.**



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10 to 100 stars ($M \lesssim 100\ M_\odot$)
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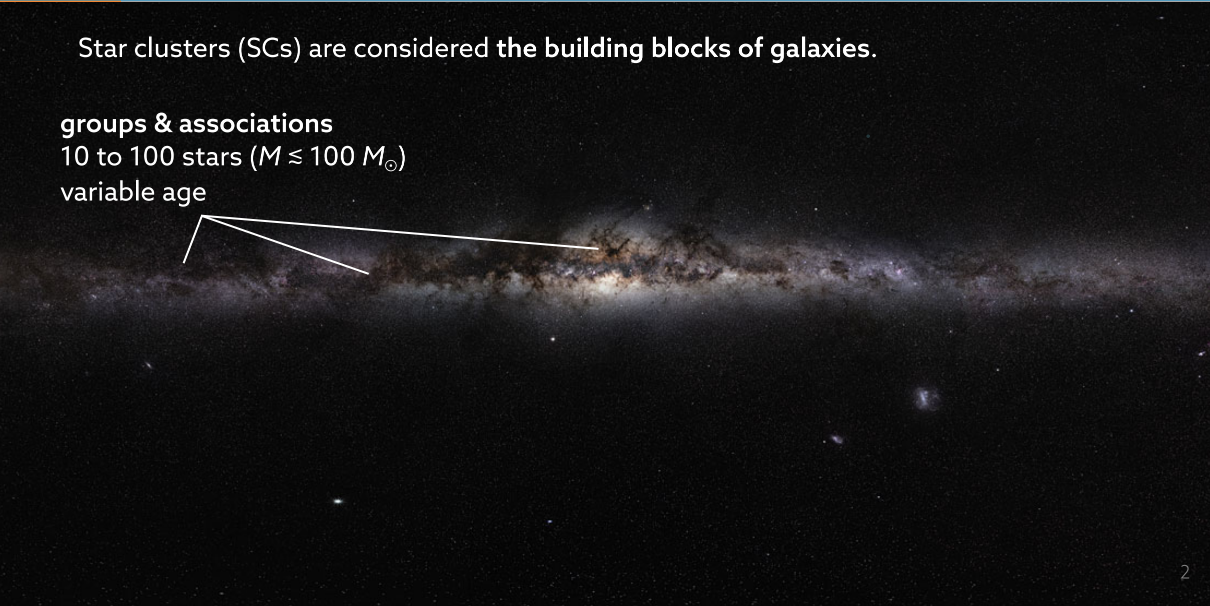

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open clusters
~ 10^3 stars ($M \sim 10^3\ M_\odot$)
~ 100 Myr

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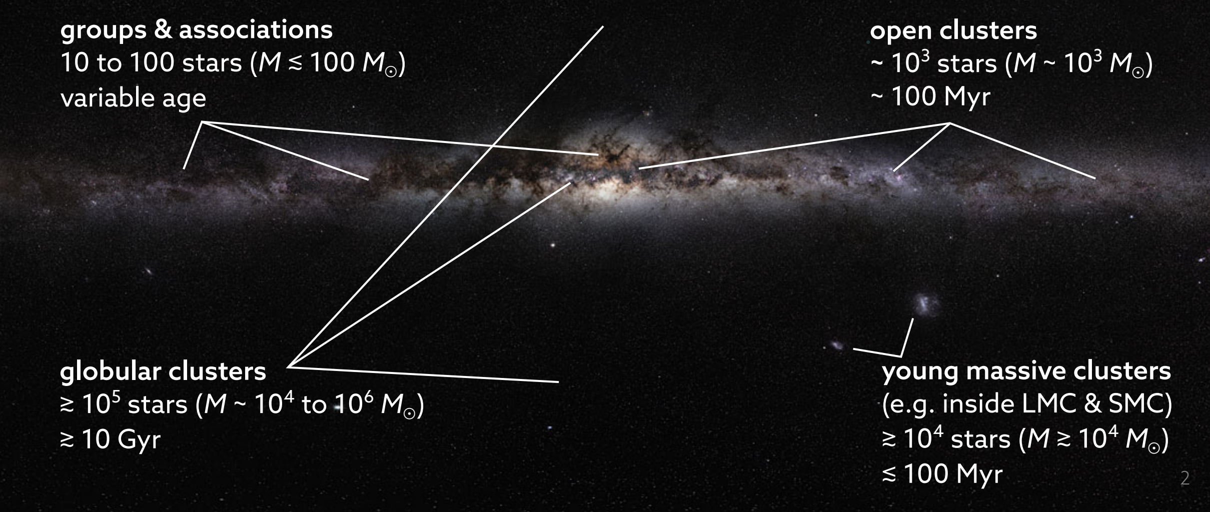

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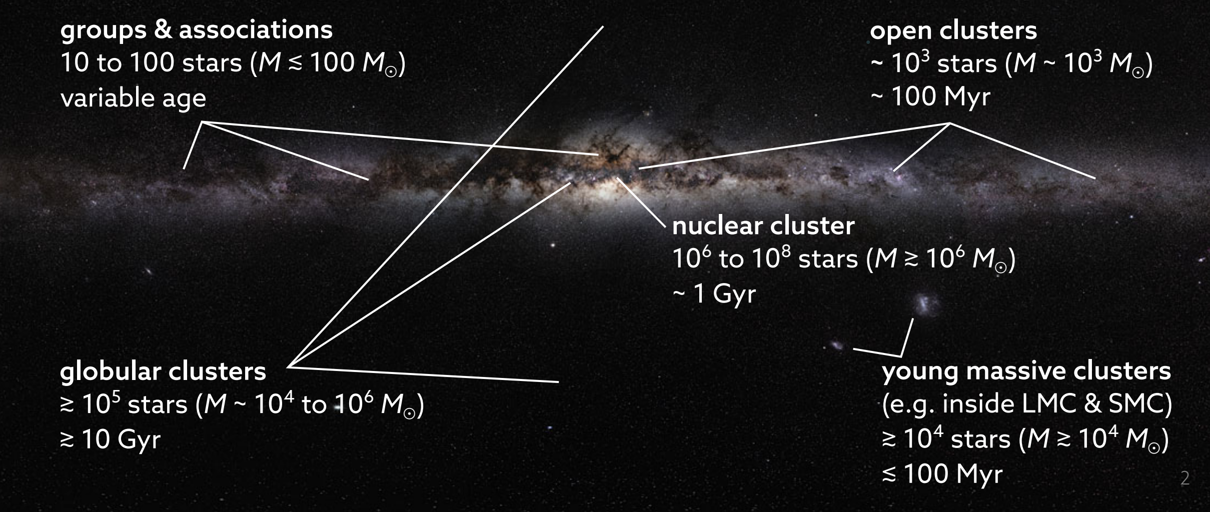
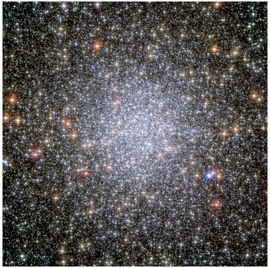


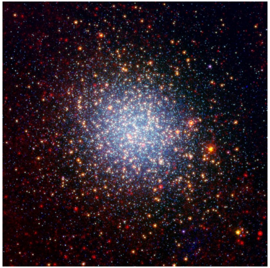
Focus of this lecture

Globular clusters are thought of as

- spherically symmetric
- dynamically relaxed
- containing (almost) no gas

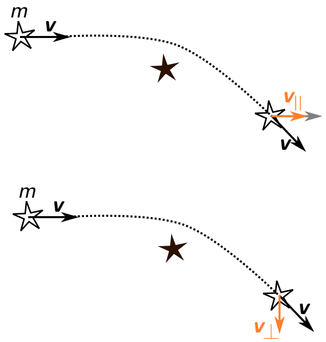
Global dynamical evolution of SCs takes **Myr to Gyr**,
i.e. our observations are only snapshots in a random instant.





Theoretical minimum

Concept of "**two-body relaxation**"
i.e. we can determine some evolutionary properties of SCs from multiple two-body encounters
(e.g. Spitzer 1987; Binney & Tremaine 2008)



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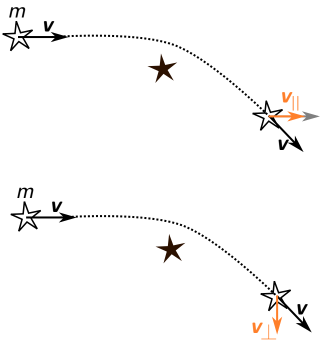

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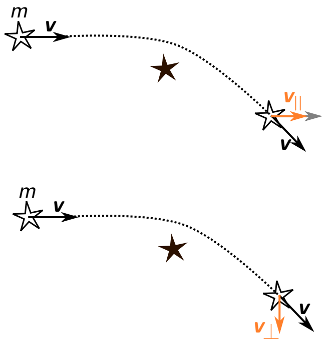

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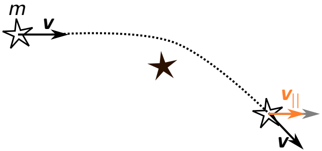
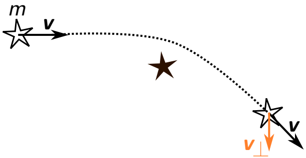
- **crossing time** (from avg. velocity and SC radius) measures the short-term evolution inside SCs





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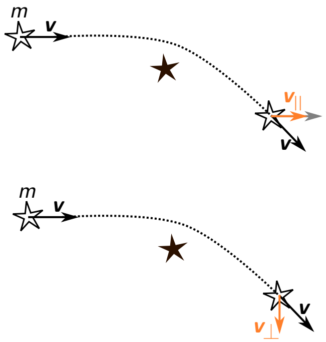
- **mass segregation** (dyn. friction depends on mass)
- **crossing time** (from avg. velocity and SC radius) measures the short-term evolution inside SCs
- **relaxation time** (from the change of $v_{\perp}$) measures the long-term evolution of SCs

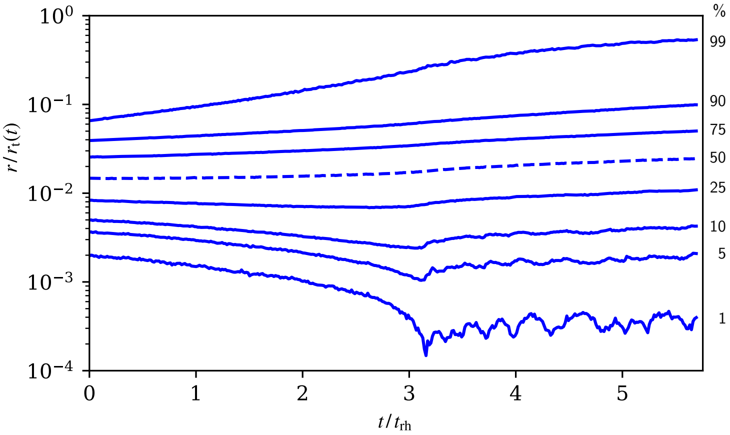
"stars should **forget** their initial conditions after t_{rh}"



Theoretical minimum

Lagrangian radii

= concentric spheres
with fixed mass fractions



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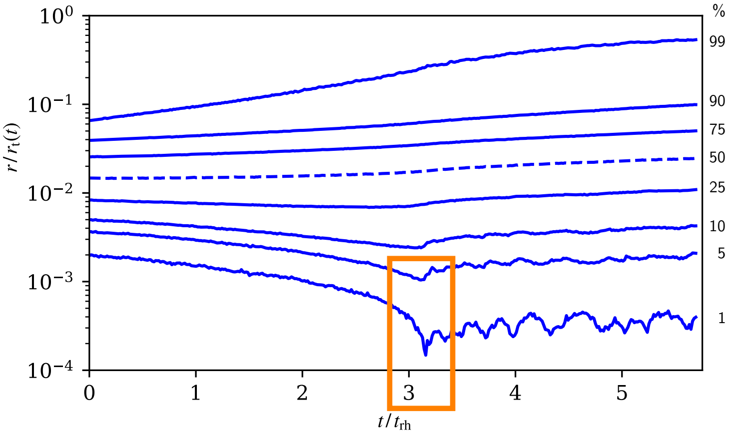
core collapse

- min core radius
- max core density



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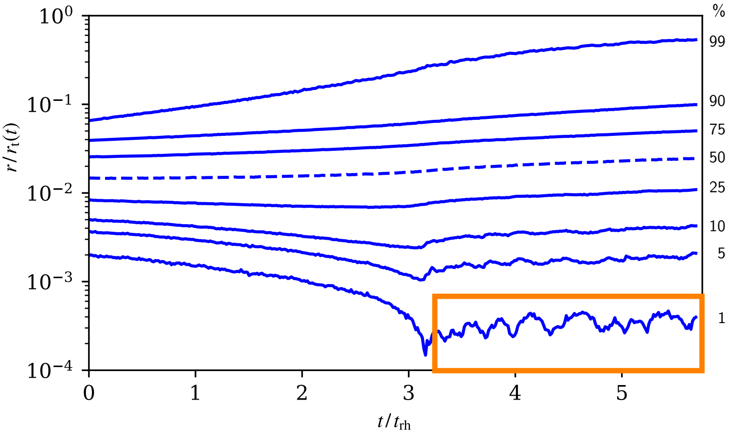
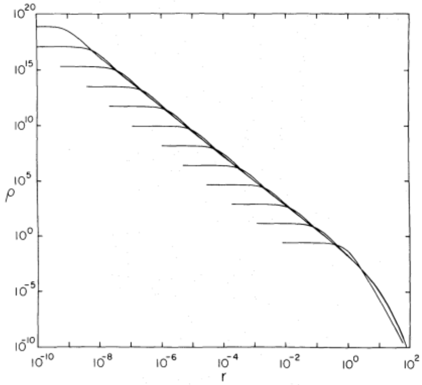
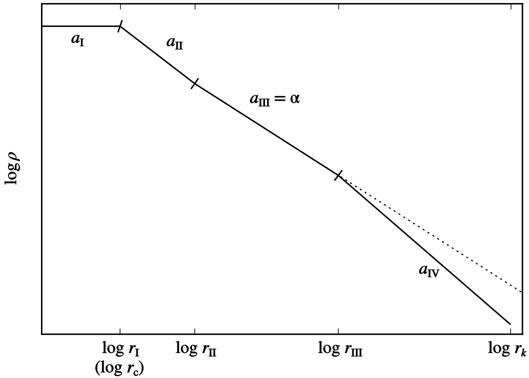
gravothermal oscillations



Theoretical minimum

Radial density profile (plots from Cohn 1980; Pavlík & Šubr 2018)

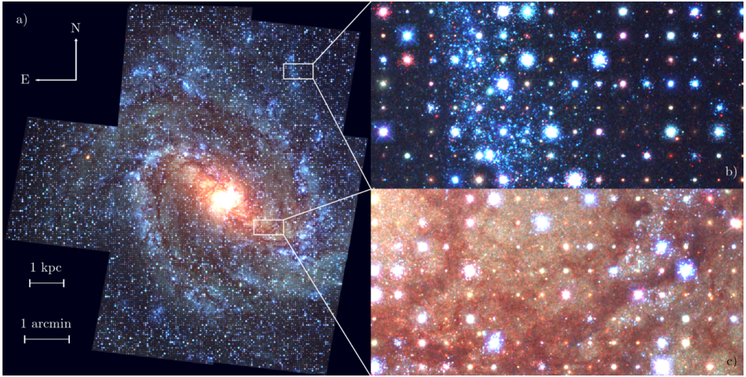




Example of SCs and AI

Searching SCs in spiral galaxy Messier 83 (Bialopetravičius & Narbutis 2020)

- data from the *Hubble Space Telescope* and machine learning
- identification and localisation of SCs, **revealing evolutionary and structural parameters**



Connecting the SC's structure, age, stellar populations, ...

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And some initial conditions are **not forgotten** after t_{rh}!

Machine learning of dynamic model of SC evolution with Matěj Trnka and Václav Šmídl (Czech Technical University)

Problem definition

Initial conditions of SCs – Plummer model (Plummer 1911)

- **spherically symmetric** (similar to real SCs)
- has **analytic description** – e.g. for the radial density profile

$$\rho_{\mathrm{P}}(r) = \frac{3M_{\mathrm{tot}}}{4\pi a_{\mathrm{P}}^3}\left(1 + \frac{r^2}{a_{\mathrm{P}}^2}\right)^{-\frac{5}{2}}$$

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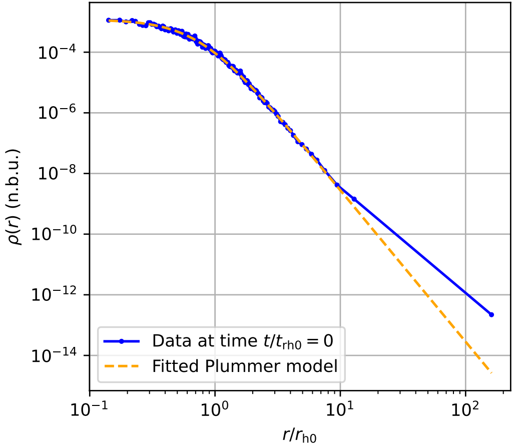
The goal is to find **analytic prescription for evolved SCs** (1st order testing – *N*-body models with 10^4 equal-mass particles).

Initial conditions and evolution

Density profile from the data and a fit with the Plummer profile



time $t/t_{\rm rh0} = 0$, $a_{\rm P} \approx 5.826\,{\rm r}_{\rm h,0}$

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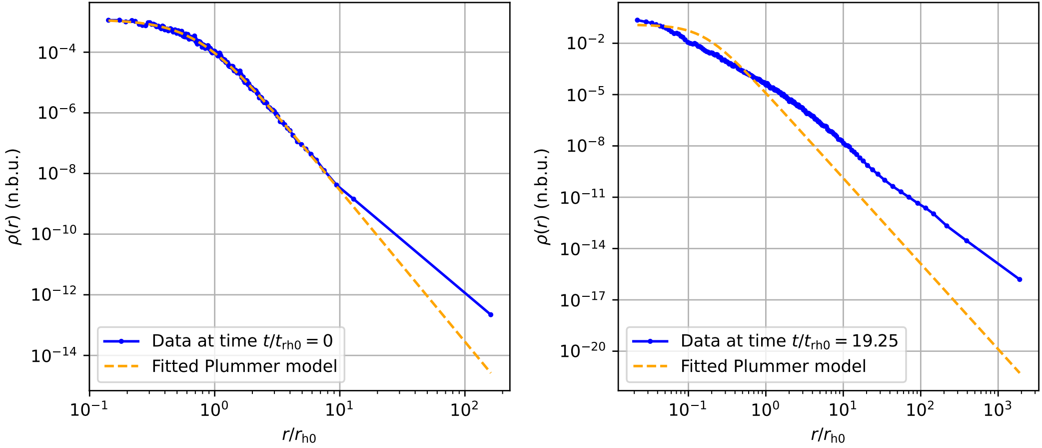

time $t/t_{\rm rh0} = 0$, $a_{\rm P} \approx 5.826\,\mathrm{r_{h,0}}$

time $t/t_{\rm rh0} = 19.25$, $a_{\rm P} \approx 1.249\,\mathrm{r_{h,0}}$

Model GB2

Generalised Beta distribution of the 2nd kind (GB2) probability density

$$f_{\text{PDF}}(x; a, b, p, q) = \frac{|a| x^{ap-1}}{b^{ap} B(p,q) \left(1 + \left(\frac{x}{b}\right)^{a}\right)^{p+q}},$$

where $a, b, p, q > 0$ are parameters giving its shape and $B(p,q)$ is the Beta function.

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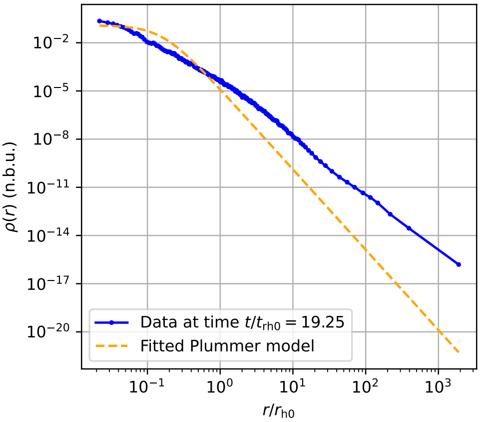
Key properties of GB2:

- analytic function, flexible, can model a wide range of data
- **becomes Plummer** for $a = 2$, $b = a_{\mathrm{P}}$, $p = \frac{3}{2}$, $q = 1$

GB2 results: radial profile



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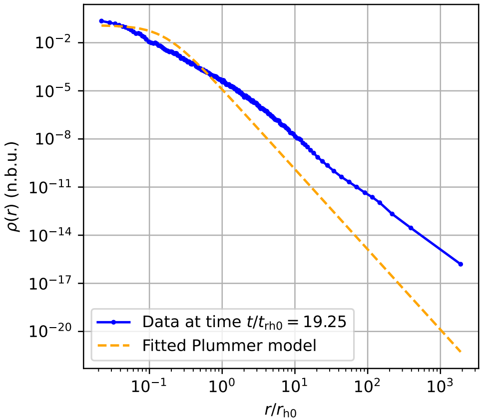

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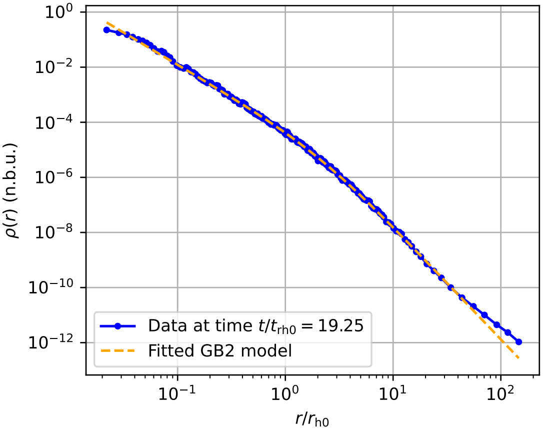
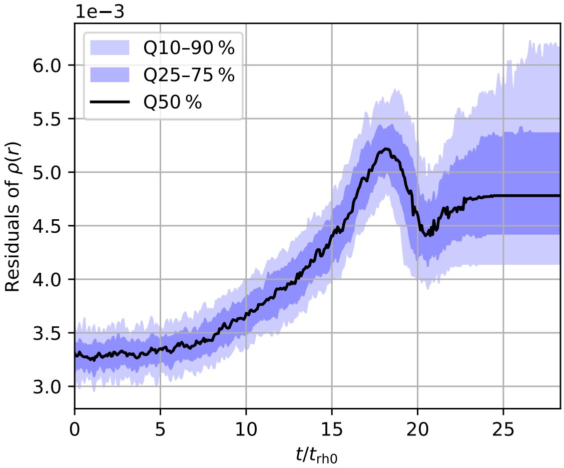


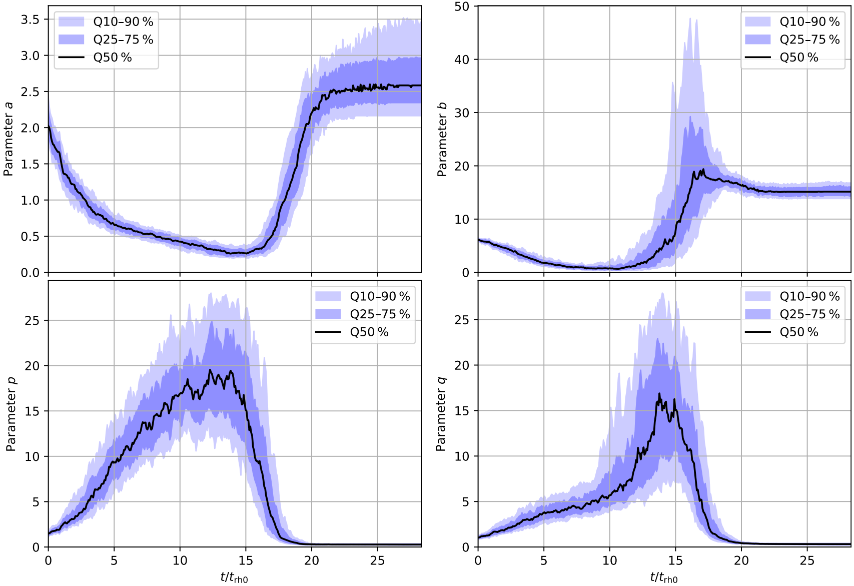
fitting f_{PDF} in log-log space, eliminating the escaping stars

GB2 results: evolution in time

Fitted (with L-BFGS-b optimisation algorithm) in each time snapshot for 100 realisations of the model



GB2 results: parameters



Physical properties and application

Physical properties:

- **core collapse time** visible in the residuals and parameters
- parameters stabilise after core collapse
- the relation between GB2 and the density profile allows to calculate **additional physical properties of the system**

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Application:

- analysis of the time evolution
- calculating the velocity dispersion
- **convert to 2D projection** (important for observations)
- identification of the dynamical age of SCs

Comparison with observations (2D-projected GB2)

Surface density at radius R (line-of-sight integral)

$$\Sigma(R) = \int_{-\infty}^{\infty} \rho\left(\sqrt{R^2 + z^2}\right)\, \mathrm{d}z$$

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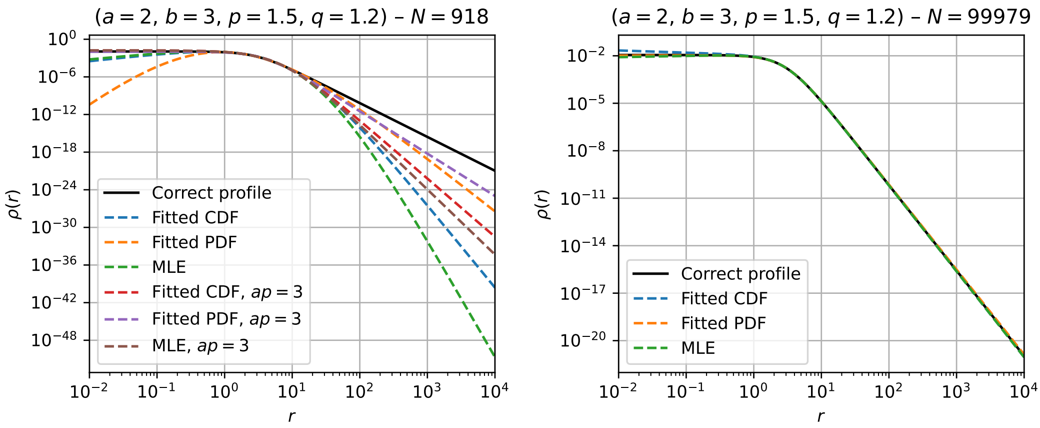
Issues with real SCs:

- few bright/observed stars
- outskirts more difficult to observe
- overcrowding (high central density)

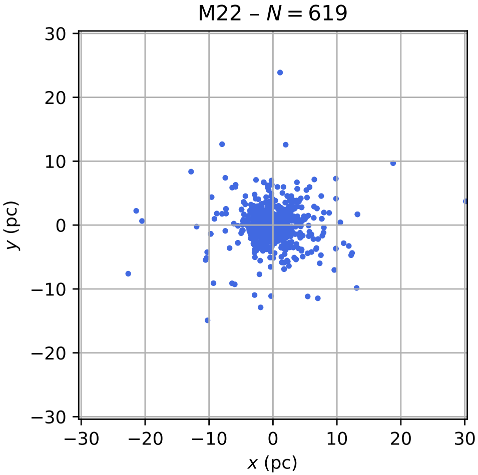
2D projection results: generated data

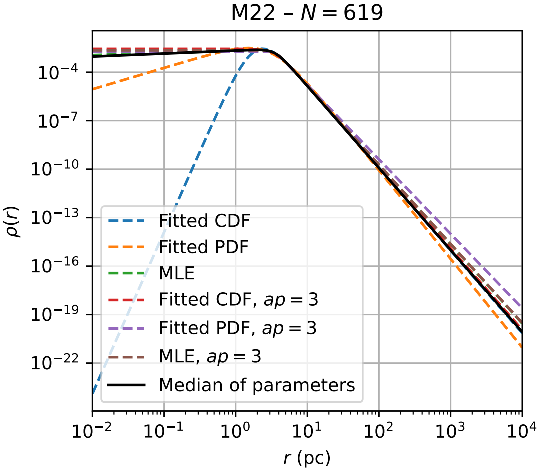


Condition $ap = 3$ gives a 3-parameter model with finite, non-zero density in the core and comparable results in the whole SC

2D projection results: Messier 22

Data of Messier 22 form the Simbad database





Conclusions & Future aims

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Getting to the **interesting evolutionary stages** of SCs (e.g. core collapse), however, **takes time and is costly** even with the state-of-the-art hardware and software.

We are now checking the results with other methods and we are also working towards developing a **better integrator with AI** to speed up the computations.

Thank you for your attention.

Acknowledgement & References

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