Predicting the limits of the ELT

Defensio

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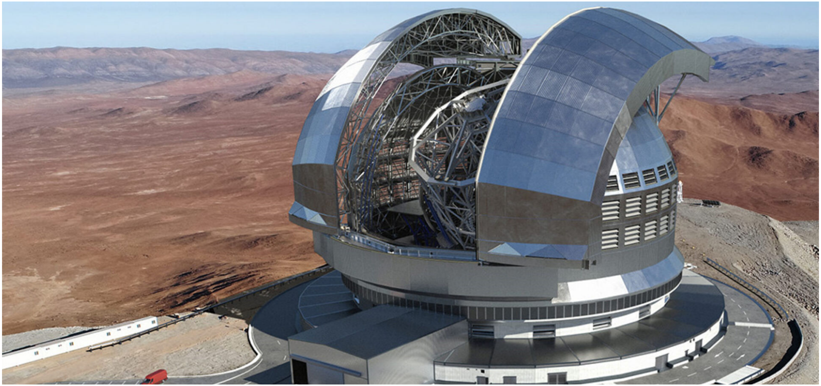
April 22, 2022

Outline

Primary objective

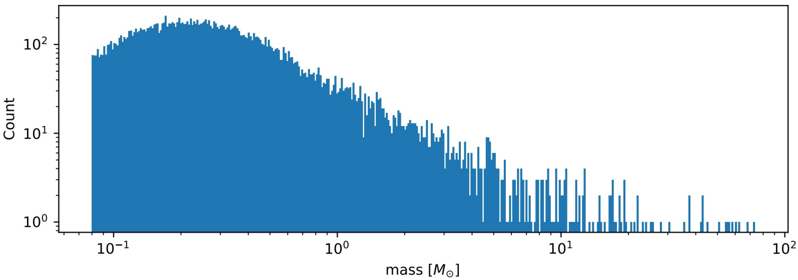
Estimate reliability limit for future IMF studies in the galactic centre using the ELT!

ELT

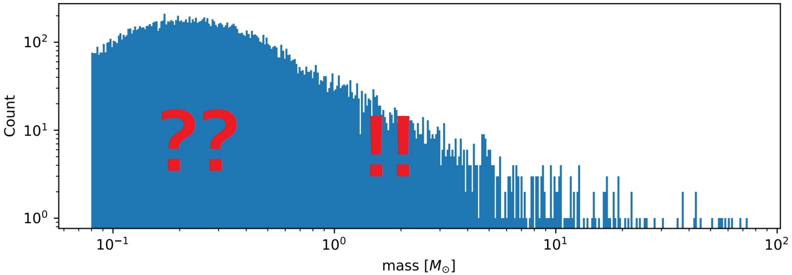


https://cdn.eso.org/images/banner1920/telescope-dome-landing.jpg

IMF



Reliability Limit

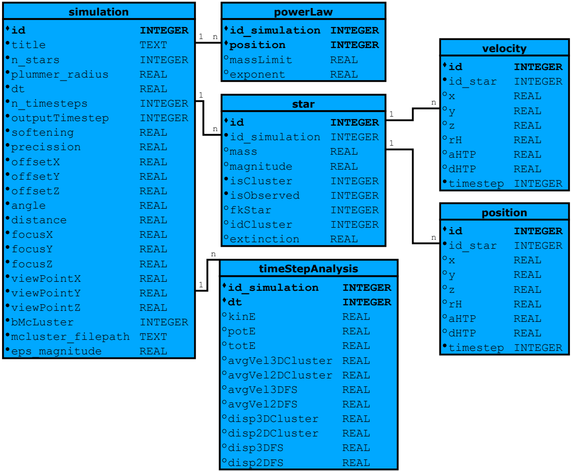


Motivation

- Universal IMF?
- estimate number of lower-mass stars
- understand star formation process
- N-body simulation with $N \gg 1$
- Clustering of time-dependent data

Action Plan

1. Simulate stars
2. Observe stars
3. Analyze
4. Measure performance


simulation
id INTEGER
title TEXT
n_stars INTEGER
plummer_radius REAL
dt REAL
n_timesteps INTEGER
outputTimestep INTEGER
softening REAL
precission REAL
offsetX REAL
offsetY REAL
offsetZ REAL
angle REAL
distance REAL
focusX REAL
focusY REAL
focusZ REAL
viewPointX REAL
viewPointY REAL
viewPointZ REAL
bMcLuster INTEGER
mcluster_filepath TEXT
eps_magnitude REAL
powerLaw
id_simulation INTEGER
position INTEGER
massLimit REAL
exponent REAL
star
id INTEGER
id_simulation INTEGER
mass REAL
magnitude REAL
isCluster INTEGER
isObserved INTEGER
fkStar INTEGER
idCluster INTEGER
extinction REAL
timeStepAnalysis
id_simulation INTEGER
dt INTEGER
kinE REAL
potE REAL
totE REAL
avgVel3DCluster REAL
avgVel2DCluster REAL
avgVel3DFS REAL
avgVel2DFS REAL
disp3DCluster REAL
disp2DCluster REAL
disp3DFS REAL
disp2DFS REAL
velocity
id INTEGER
id_star INTEGER
x REAL
y REAL
z REAL
rH REAL
aHTP REAL
dHTP REAL
timestep INTEGER
position
id INTEGER
id_star INTEGER
x REAL
y REAL
z REAL
rH REAL
aHTP REAL
dHTP REAL
timestep INTEGER
1
n

Parameters

McLuster by Andreas Kuepper with Kroupa, P. & Baumgardt, H.

- Plummer density profile
- virial equilibrium
- Kroupa IMF 0.08 $M_\odot$ to 100 $M_\odot$
- Metallicity in range 0.5 - 2 solar
- No binaries
- N 1.3k - 40.4k

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Time integration

- Direct summation $O(N^2)$
- Barnes-Hut Algorithm $O(N \log(N))$
  - approximate with macro particles
  - $\frac{width}{distance} < \theta_{max}$
- Softening
- Time step size

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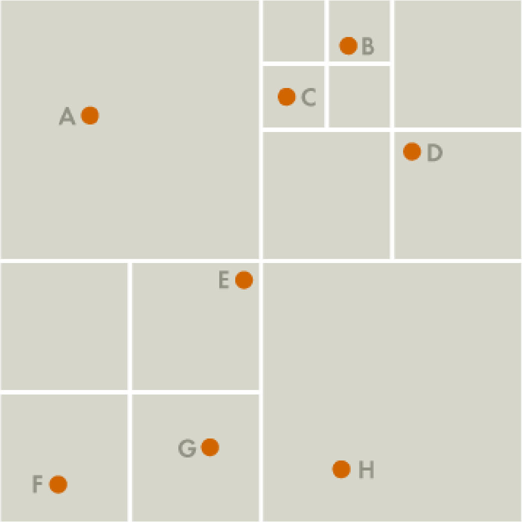
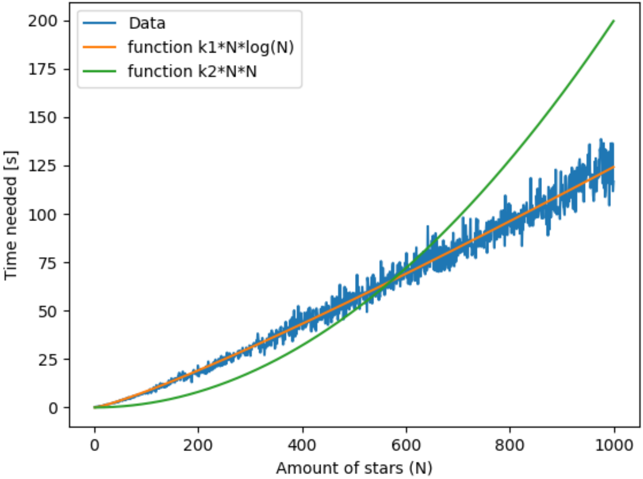
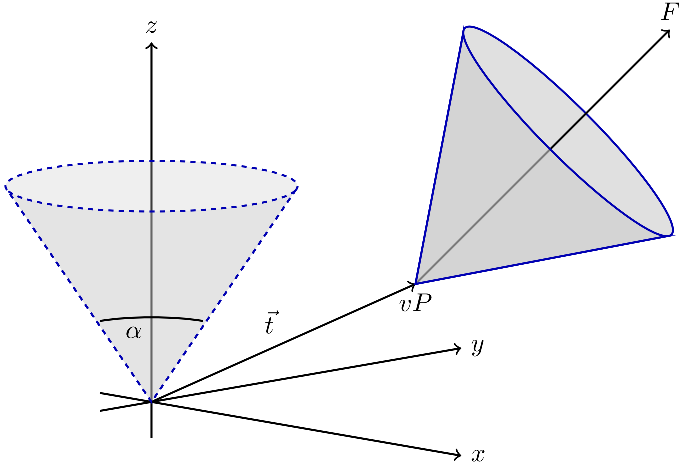


http://arborjs.org/docs/img/example-space.png


Data
function k1*N*log(N)
function k2*N*N
200
175
150
125
100
75
50
25
0
Time needed [s]
0
200
400
600
800
1000
Amount of stars (N)

Multi-component axis-symmetric potential $\Phi(R, z)$

- components
  - Black hole: Keplerian potential $\Phi_{bh}(r)$
  - Disk: Miyamoto Nagai potential $\Phi_{disk}(R, z)$
  - Bulge: Hernquist potential $\Phi_{bulge}(r)$
  - Dark matter halo: Navarro–Frenk–White potential $\Phi_{halo}(r)$
- needed for
  - Force from analytic derivatives
  - Initial conditions for field stars


z
F
α
$\vec{t}$
vP
y
x

Initialize mass (1)

Total mass inside code

$$M = \int_{-R}^{R} \int_{-\sqrt{R^2 - x^2}}^{\sqrt{R^2 - x^2}} \int_{\frac{h}{R} r}^{h} \rho \left(\mathbf{T} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} \right) dzdydx$$

R cone base radius

T transformation matrix

h cone height

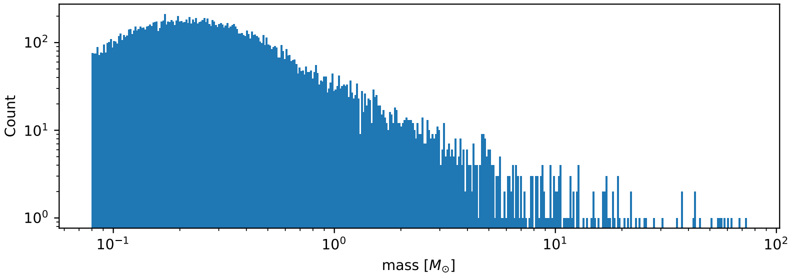
Integration

- GSL: GNU Scientific Library
- Gauss-Kronrod quadrature

Initialize mass (2)

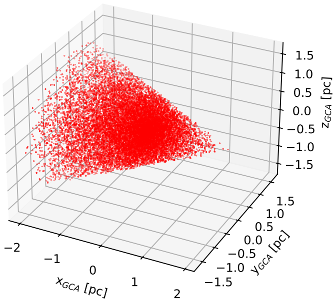
Sample mass functions

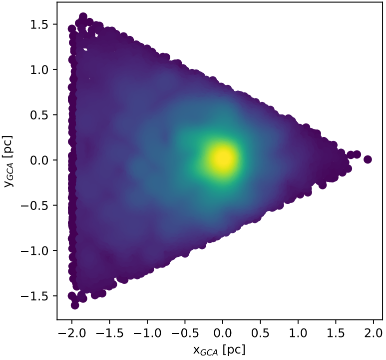
- rejection sampling
- inverse transformation sampling



Positions

1. uniform distribution
2. transformation
3. rejection sampling

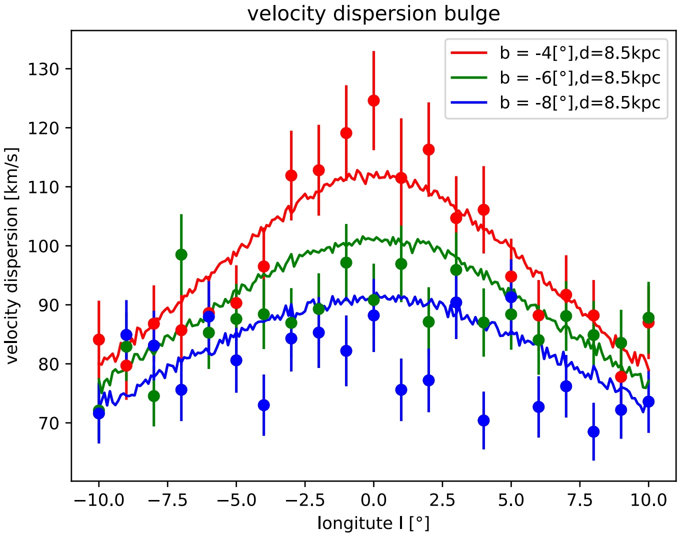




Velocities

Solve Jeans equations

- Disk
  - Epicyclic Approximation
  - average & dispersion
  - Sampled from Gaussian distributions
- Bulge
  - $\sigma_r^2 = \frac{1}{\rho} \int_r^\infty \rho \frac{\partial \Phi}{\partial r} \mathrm{d}r$
  - Lookup table
  - isotropic
  - limited by escape speed


velocity dispersion bulge
b = -4[°],d=8.5kpc
b = -6[°],d=8.5kpc
b = -8[°],d=8.5kpc
velocity dispersion [km/s]
130
120
110
100
90
80
70
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0
longitute l [°]

1. Integrate equations of motion
    - Euler
    - Velocity Verlet
2. Write to Database every x timesteps
3. Test total Energy
4. Boundary conditions?

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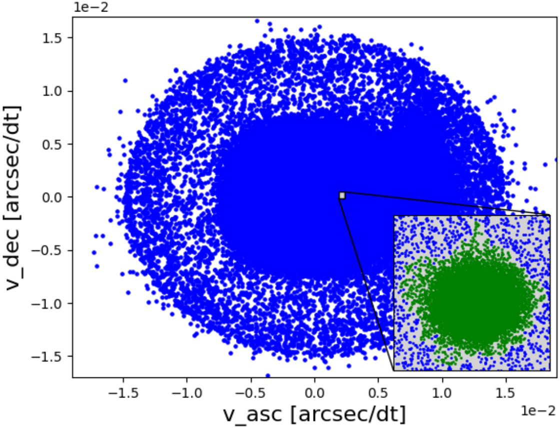

1e−2
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
v_dec [arcsec/dt]
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
v_asc [arcsec/dt]
1e−2

Coordinate Systems

GalPot by Paul McMillan

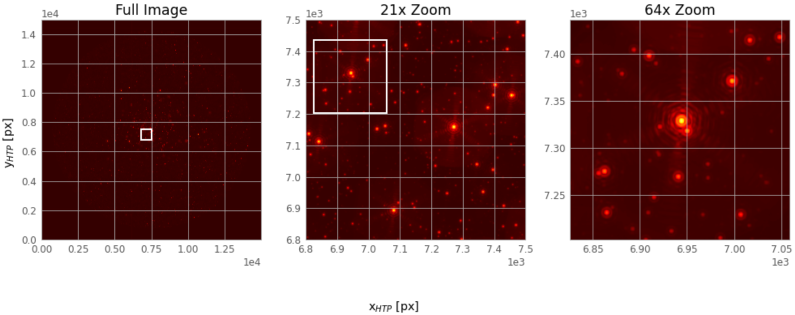
GCA	Galactocentric Cartesian
LSR	Local Standard of Rest
HCA	Heliocentric Cartesian
HTP	Heliocentric Telescope Polar

ScopeSim by Kieran Leschinski

Spectra

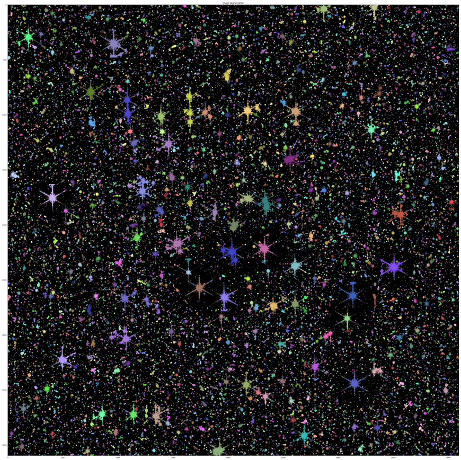
- Spectral type
- Pickles catalogue
- Apparent magnitude
- Extinction
- Weight of spectrum

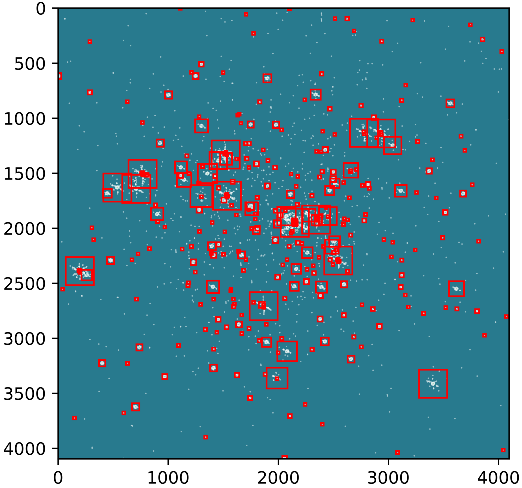
Output FITS files

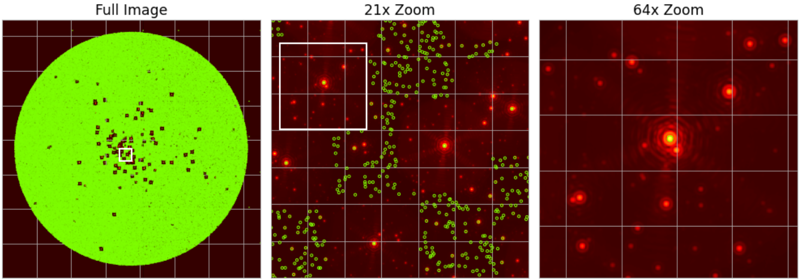

Full Image
21x Zoom
64x Zoom
1e4
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.00
0.25
0.50
0.75
1.00
1.25
1e4
1e3
7.5
7.4
7.3
7.2
7.1
7.0
6.9
6.8
6.8
6.9
7.0
7.1
7.2
7.3
7.4
7.5
1e3
1e3
7.40
7.35
7.30
7.25
6.85
6.90
6.95
7.00
7.05
1e3
y_{HTP} [px]
x_{HTP} [px]

Photutils by Larry Bradley et al.

- DAOStarFinder
    - Threshold
    - 2D Gaussian kernel
    - Roundness
    - Mask
- Image Segmentation
    - Connected pixels
    - Threshold
    - Source Deblending




0
500
1000
1500
2000
2500
3000
3500
4000
0
1000
2000
3000
4000


Full Image
21x Zoom
64x Zoom

mlpack by Ryan Curtin et al.

- Map observed stars
  - Range search
- Velocity approximation
  - Nearest-neighbors search
  - max magnitude difference
  - compare with mapping

DBSCAN Algorithm

Density-based spatial clustering of applications with noise

Pros:

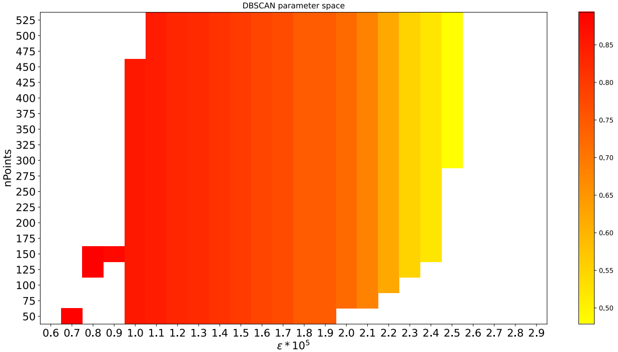
- noise
- amount of clusters

F1 Score

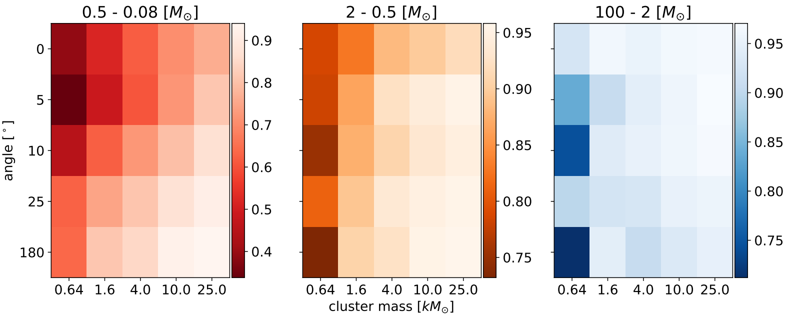
$$F_1 = 2\frac{P \cdot R}{P + R} = \frac{TP}{TP + 0.5(FP + UP + FN)}$$

- TP correctly classified as cluster star
- FP wrongly classified as cluster star
- UP not mapped star classified as cluster star
- FN wrongly classified as field star

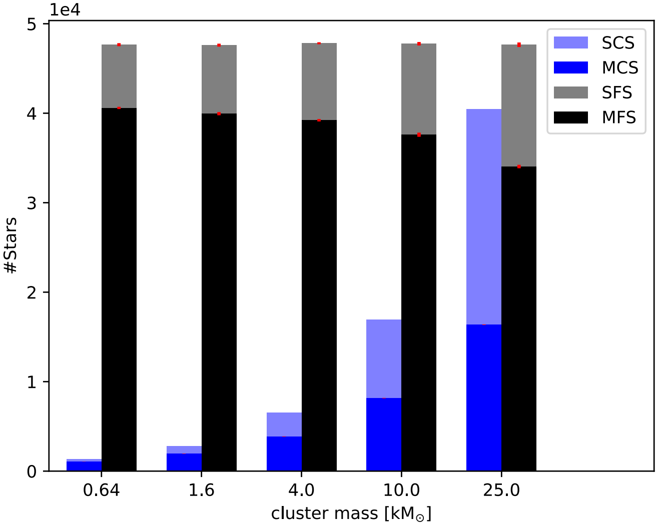
Parameter optimization



Results: F1


0.5 - 0.08 [$M_\odot$]
2 - 0.5 [$M_\odot$]
100 - 2 [$M_\odot$]
angle [°]
0
5
10
25
180
0.64
1.6
4.0
10.0
25.0
cluster mass [$kM_\odot$]
0.9
0.8
0.7
0.6
0.5
0.4
0.95
0.90
0.85
0.80
0.75

Star $M_\odot$	Cluster $kM_\odot$	% Found	F1 Score
<0.5	0.64	41	0.39
<0.5	1.60	40	0.52
<0.5	4.00	40	0.62
<0.5	10.00	35	0.71
<0.5	25.00	28	0.76
0.5 - 2	0.64	81	0.79
0.5 - 2	1.60	80	0.83
0.5 - 2	4.00	76	0.88
0.5 - 2	10.00	63	0.90
0.5 - 2	25.00	54	0.92


1e4
5
4
3
2
1
0
#Stars
SCS
MCS
SFS
MFS
0.64
1.6
4.0
10.0
25.0
cluster mass [kM$_\odot$]

general remarks on performance

- Pass and loop by reference
- Multithreading (OpenMP)
- Choice of language
- Define (mathematical) constants
- C++ : emplace_back VS push_back