Globular clusters' dynamical age determination based on machine learning performed on large number of detailed MOCCA simulations

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Outline

Globular clusters

Globular clusters

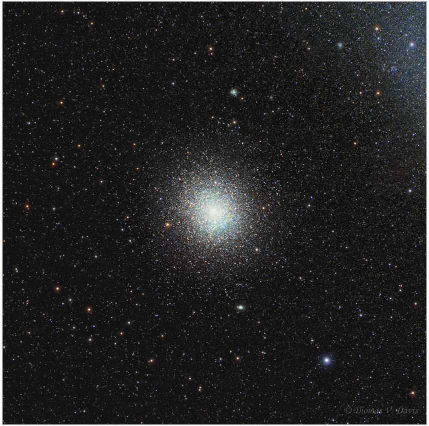

Figure 1: 47Tuc globular star cluster, one of the biggest and oldest in the Milky Way.

- very old (age comparable to the age of the Universe)
- size up to around 100 ly
- a core is clearly visible – best place for creating of many exotic objects: cataclysmic variables, X-ray binaries, black holes, intermediate-mass black holes, blue stragglers
- great laboratories for studying stellar evolution and dynamical interactions between stars
- Milky Way GCs: 50% GC within 5 kpc, the most distant 130 kpc

Dynamical modelling – importance

- may provide basic information to understand the **formation and then the evolution of exotic objects** within star clusters (e.g. hard binaries)
- dynamical interactions between stars may lead to **perturbations, disruptions, collisions and mass transfers** between stars
    - e.g. this may lead to decrease the semi-major axes and allow mergers which would now happen otherwise
    - may lead to formation of exotic binaries, supernova explosions (especially in the initial phase when many of massive stars are present), formation of black holes
- dynamical interactions in GCs may eject a lot of binaries that could be potential **sources of GWs**

MOCCA code

MOCCA – features

- one of the most advanced codes for simulations of real-size star clusters
- based on Monte Carlo method (a few simplifications in comparison to N-body codes, e.g. one radial position)
- agrees very well with N-body codes (Wang et al. 2016)
- provides almost as much details about stars as N-body codes
- simulating the real clusters (M22, M4, 47Tuc etc.)
- exotic objects: blue stragglers, IMBHs, CVs...
- “observations” of simulations vs. real observations (COCOA)
- MOCCA can now handle **dynamical evolution of multiple population**
- very fast, which allows to test whole range of possible initial conditions (MOCCA-SURVEYs)
- data analysis with BEANS

MOCCA-SURVEY-1

- over 2000 detailed models of real size star clusters done with previous version of MOCCA (MOCCA-SURVEY-1)
    - various initial conditions
    - accessible from BEANS alongside with MOCCA-SURVEY-2 (*http://beans.moccacode.net/*)

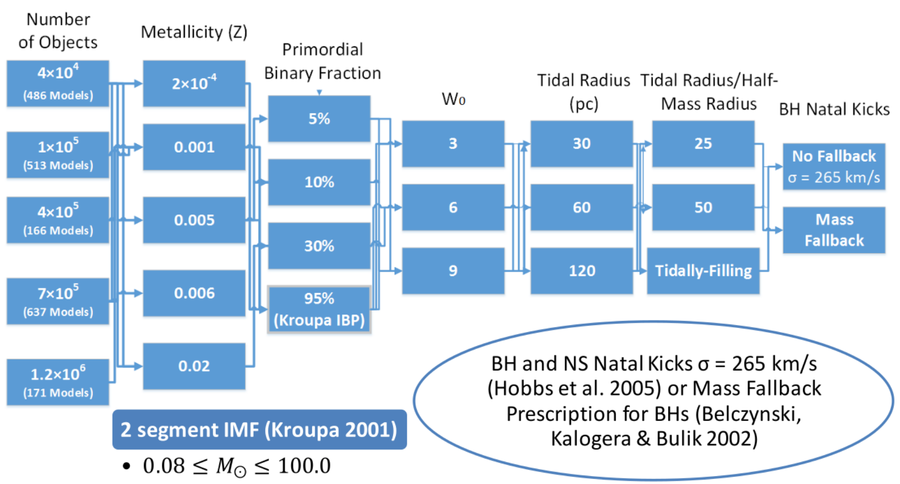

Figure 2: First MOCCA-SURVEY (Askar et al. 2017)

Parameter	FG	SG
N	400k, 600k, 800k, 1.6M	150k, 200k, 300k, 600k
W_0	2, 3, 4, 5, 6	7, 8
M_{max}	150	20, 150
fb	0.1, 0.5, 0.95	
r_g	2, 4, 6, 8	
r_{hFG}	2, 4, 6, 8, TF	
$conc_{pop}$	0.05, 0.1, 0.15, 0.2	

Figure 3: Grid of initial conditions of MOCCA simulations. Note: not all of the combination of the parameters were computed.

- focus on multiple populations
  - → but the simulations are useful for any project
- updated SSE/BSE (Hurley et al. 2002, 2005)

MOCCA-SURVEYs (Survey1, Survey2, and more models in progress

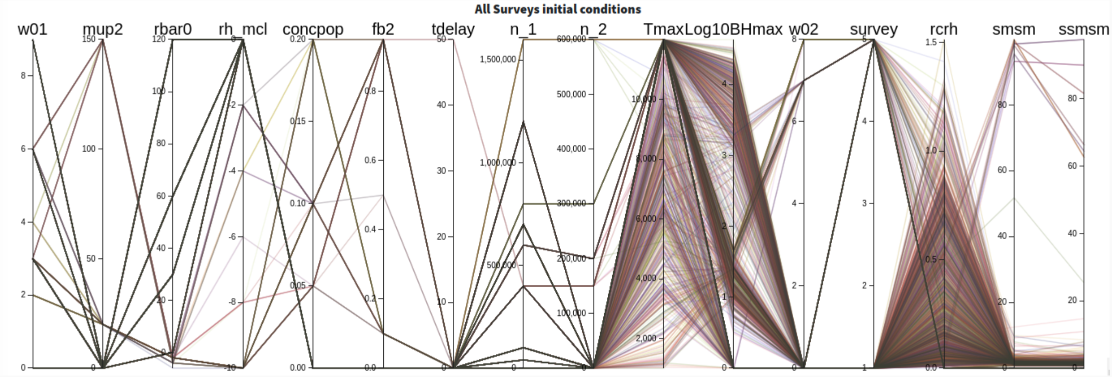

Figure 4: Grid of all MOCCA models from different MOCCA-SURVEY.

Milky Way coverage of initial conditions (MOCCA-SURVEY-2)

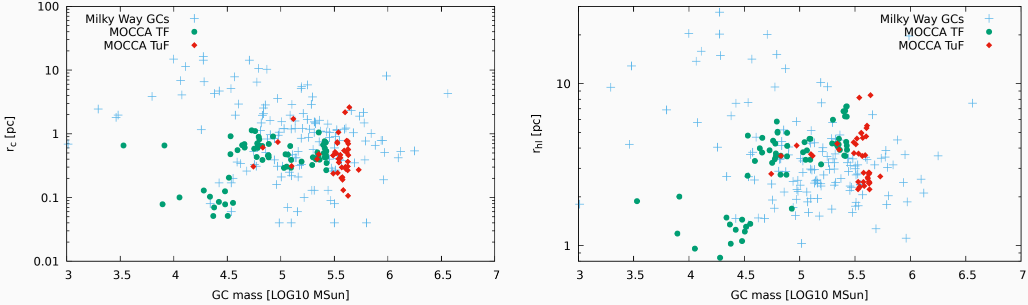

Figure 5: MOCCA simulation r_c, and r_{hl} coverage of Milky Way GCs. MOCCA simulations cover proper ranges of values of Milky Way GCs – it gives some confidence that the results of our work are well representing Milky Way GCs

Motivation

What are blue stragglers?

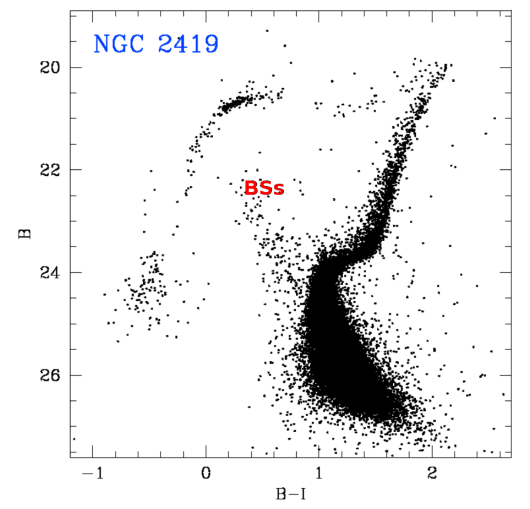

Figure 6: Example BSs in NGC2419

- BSs defined as stars which are brighter and bluer (hotter) than the main sequence turn-off point
- BSs lie along an extension of the main sequence in CMD
- it suggests that these objects got some additional mass
- BSs are present essentially in all star clusters

Two channels of formation: mass transfer and collisions

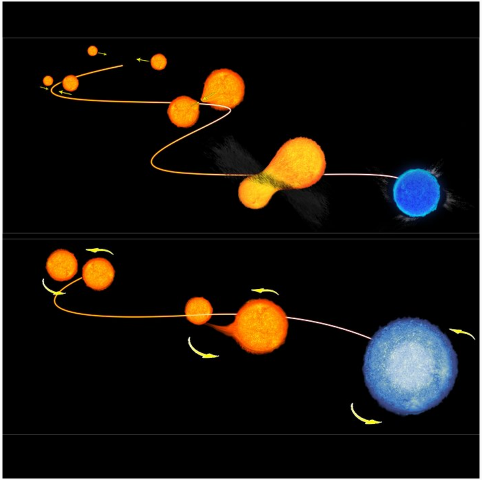

Figure 7: Mass transfer and collisional scenarios of BSs formation

- mass transfer (MT):
  - only for binaries (strong dependence on IMF)
  - BSs exceed only slightly turn-off (mostly)
  - MT leads to merger, which can create BSs too
- collisions (COLL):
  - dynamical interactions
  - important only for some star clusters

Core collapse excess of blue stragglers number – 1 Gyr

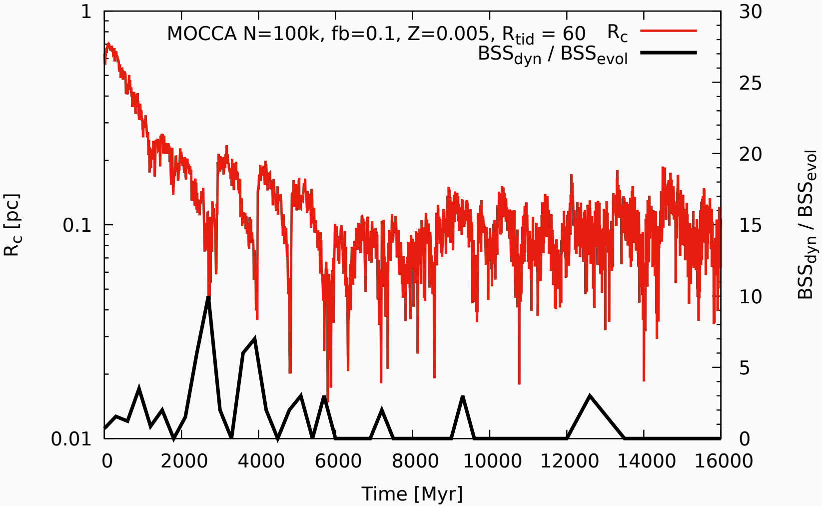

Figure 8: Core collapse vs. dynamical blue straggler excess

Core collapse excess of blue stragglers number – 3 Gyr

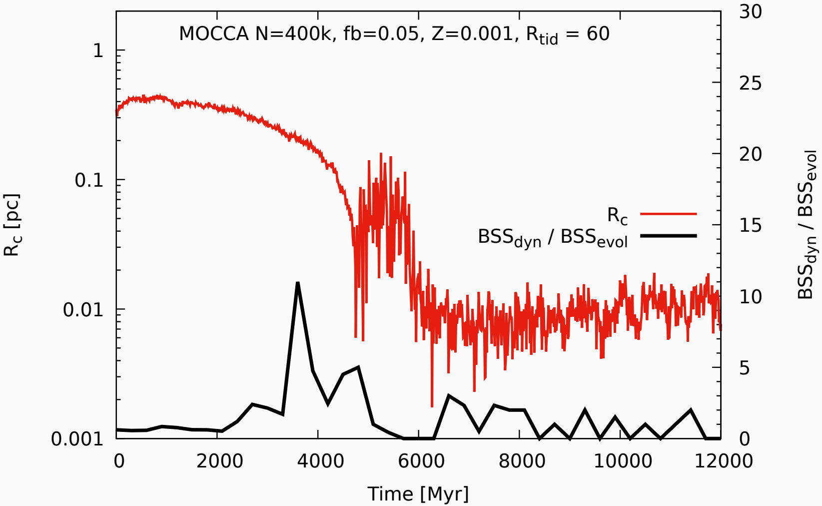

Figure 9: Core collapse vs. dynamical blue straggler excess

Core collapse excess of blue stragglers number – 6 Gyr

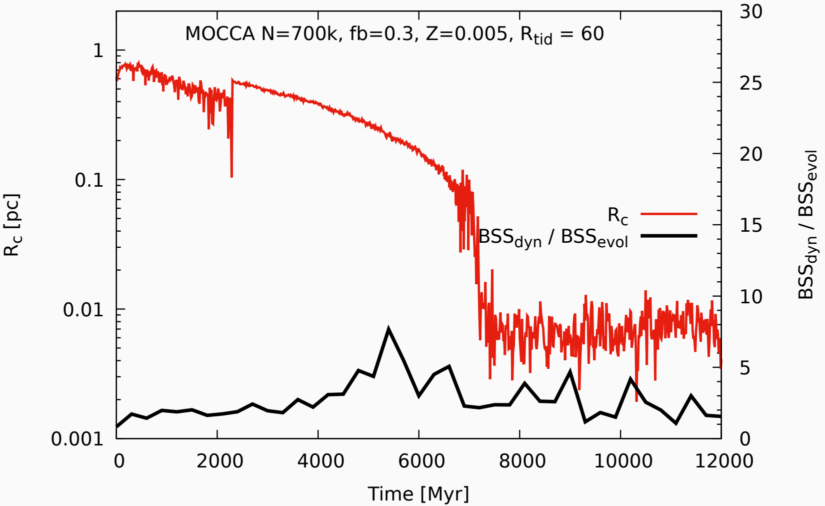

Figure 10: Core collapse vs. dynamical blue straggler excess

Core collapse excess of blue stragglers number – 11 Gyr

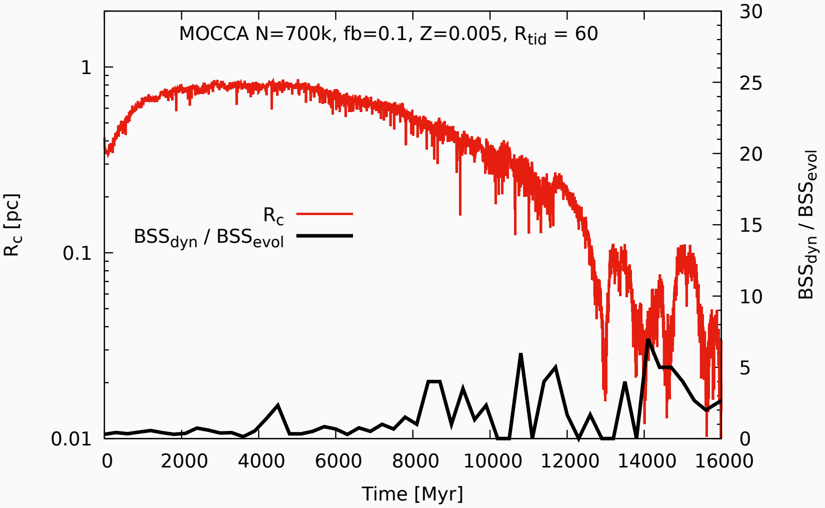

Figure 11: Core collapse vs. dynamical blue straggler excess

Core collapse excess of blue stragglers number for Milky Way

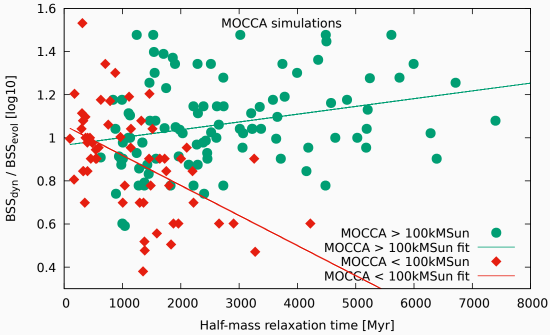

Figure 12: Dynamical BSSs to evolution BSSs fractions function of the half-mass relaxation time

- MOCCA simulations divided into two groups: more massive clusters (green points, $> 100kM_{\odot}$), and less massive clusters (red points, $< 100kM_{\odot}$
- **low and high mass GCs have clearly different slopes for the excess of dynamical BSSs**
- motivation 1: ML to find the core collapse automatically

BEANS code

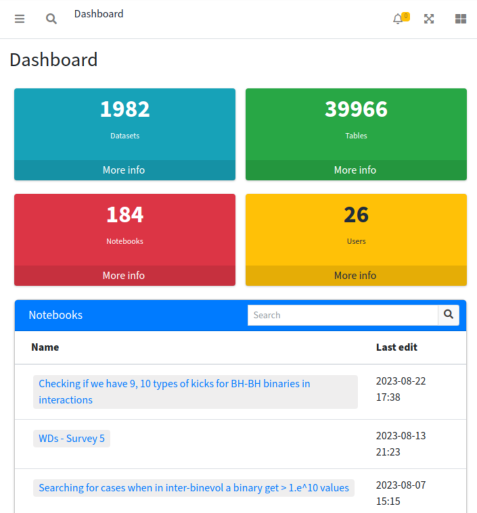

Figure 13: `http://BEANScode.net`

- interactive, distributed data analysis
- web-based
- open source
- data analysis in a form of notebooks (like Jupyter)
- Apache Pig (Apache Hadoop)
- connectors to MOCCA, NBODY codes
- Python, AWK, Gaia plugins
- **access to all simulations from all different MOCCA-SURVEY from BEANS**
- motivation 2: ML plugin

BEANS code

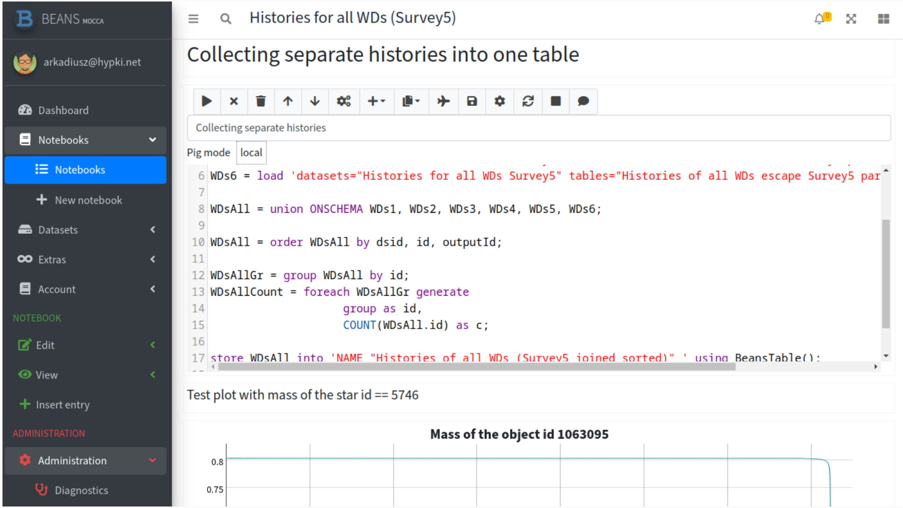

Figure 14: BEANS example notebook (computing histories for all WDs from all MOCCA simulations).

Results

BEANS ML plugin

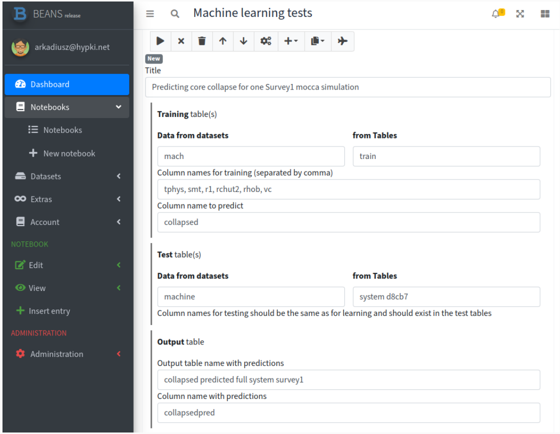

Figure 15: BEANS ML plugin

- ML plugin added to BEANS
  - now we have access to our > 2000 MOCCA simulations
- currently we are using SCIKIT-LEARN
  - e.g. Random Forest Classifier
  - APACHE MAHOUT in plans
- one can easily define which column to use for learning which helps non-technical users
- the output are immediately accessible in BEANS for further analysis

ML accuracy

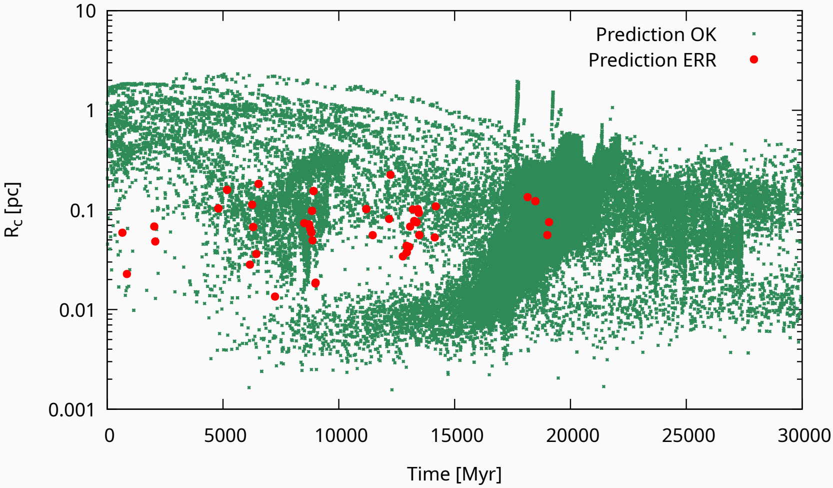

Figure 16: Qualitative ML accuracy for predicting core collapse for a few MOCCA simulations

Finding the core collapse time

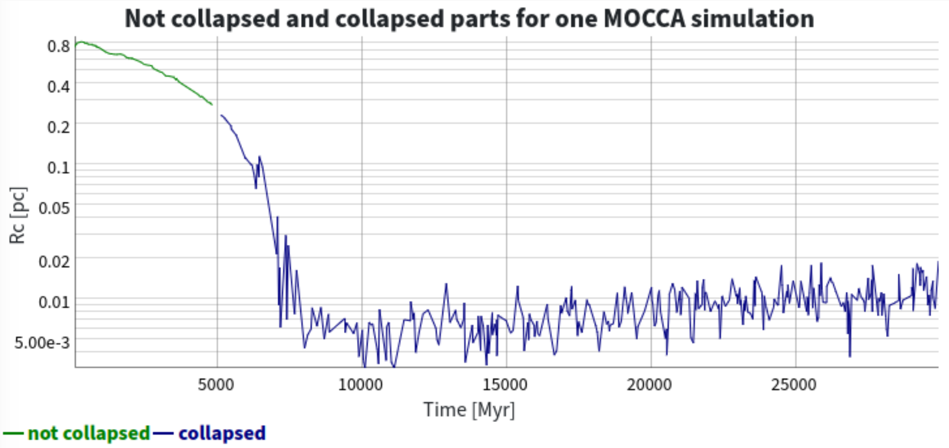

Figure 17: Collapse and not collapsed parts for one selected MOCCA simulation

Last step – using Apache Pig to compute core collapse

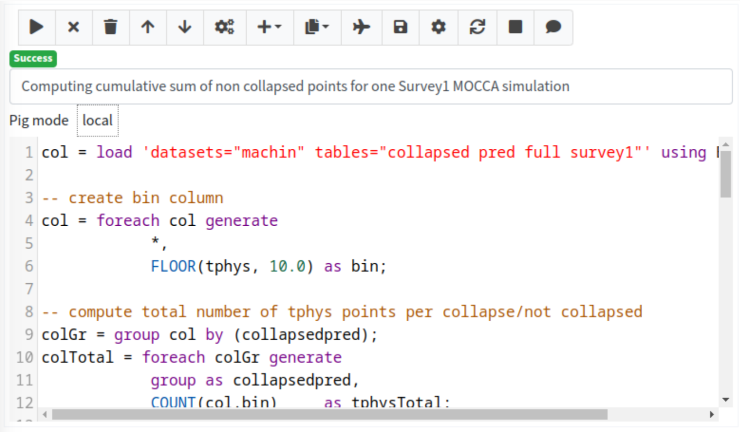

Figure 18: Apache Pig computes cumulative distributions for all MOCCA simulations for collapsed and not collapsed points. The core collapse is when not collapsed closes to 1.0, and not collapsed is still small.

Last step – using Apache Pig to compute cumulative distributions

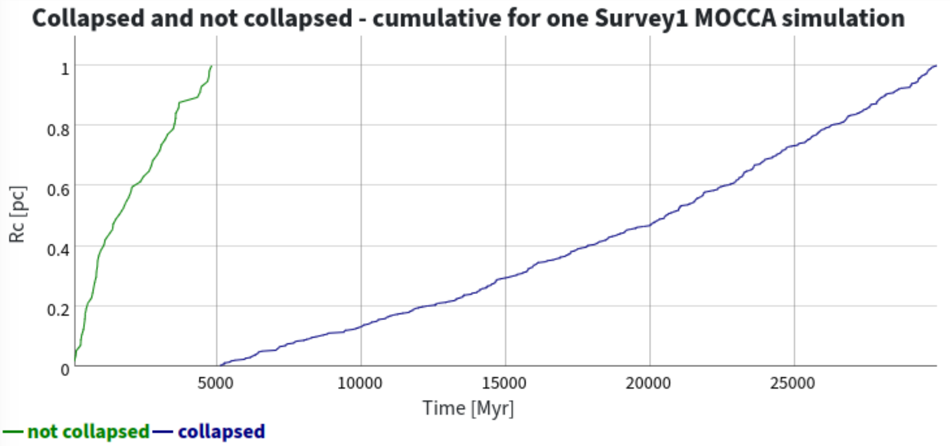

Figure 19: Cumulative plots showing collapsed and not collapsed parts for one MOCCA simulation

Current step – testing different classifiers

Nearest Neighbors 'n_neighbors': 3: accuracy=68.59% precision=37.56% recall=49.07% train_time=18.12333s predict_time=528.67222s

...

Decision Tree 'max_depth': 10: accuracy=67.49% precision=35.26% recall=44.43% train_time=18.15583s predict_time=0.11338s

...

Random Forest 'max_depth': 10, 'max_features': 'sqrt', 'n_estimators': 10: accuracy=67.97% precision=36.28% recall=46.44% train_time=102.94294s predict_time=1.12742s

...

Naive Bayes 'var_smoothing': 1e-07: accuracy=95.29% precision=90.63% recall=89.36% train_time=0.99014s predict_time=0.31822s

QDA 'reg_param': 0.0: accuracy=85.84% precision=79.14% recall=54.67% train_time=2.08210s predict_time=0.48526s

...

Gradient Boosting 'learning_rate': 0.01, 'n_estimators': 50: accuracy=67.49% precision=35.26% recall=44.43% train_time=1294.12376s predict_time=2.26932s

...

Next steps

- check different GCs parameters (or subset of them) to asses whether the predictions would be equally good
- check other ML classifiers:
  - Nearest Neighbors, Decision Tree, Random Forest (different params), Naive Bayes, QDA, Gradient Boosting
- use ML to predict CC, nCC, IMBH-GC, BHs-GC clusters

Conclusions

Figure 20: MOCCA, NCAC, NCN

- BEANS – it is a nice cool toy which allow us to do the full data analysis (+ML) on TBs of data from one place
- machine learning is unbelievable powerful
  - machine learning can automatize many effort with really easily
  - it can be actually easy applied
- astro science: **core collapse in GCs does increases the number of blue stragglers**

MOCCAcode.net | BEANScode.net | Arkadiusz Hypki | ahypki@camk.edu.pl