An investigation of Black Hole formation in Globular Clusters

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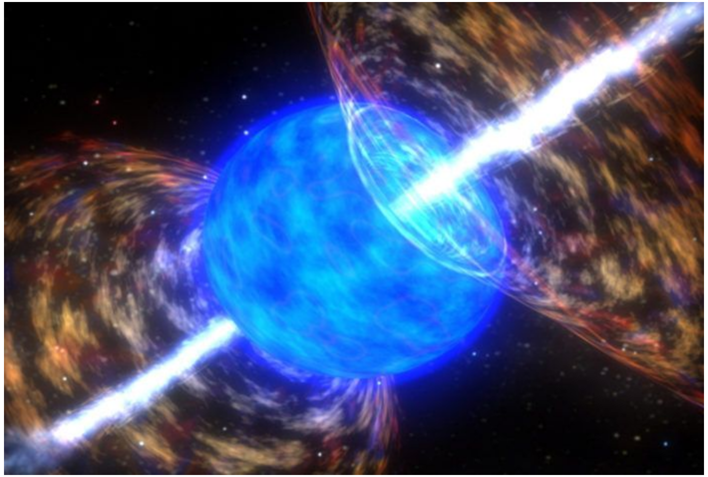
Motivations

How do stellar mergers in young globular clusters affect black hole spin?

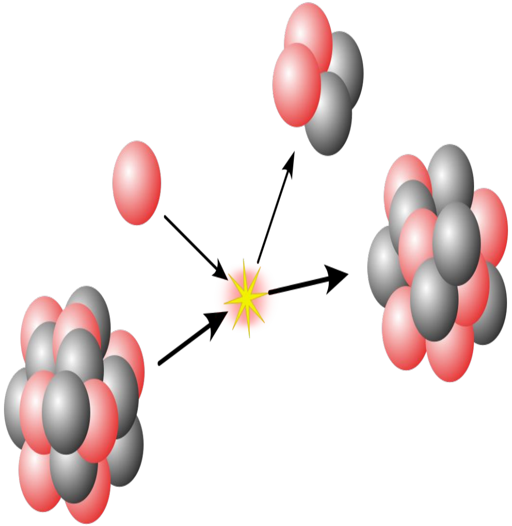


Could explain formation of heavy elements!

-When massive stars merge, angular momentum can transfer to the merger product, potentially creating black holes with non-zero spins

-We can also probe the relations between Spin, metalicity and merger rates with this massive data set

Implications of these black holes



- Some black holes in clusters will be born with non-zero spins, affecting their retention after binary black hole mergers
- These may help grow intermediate-mass black holes in clusters
- These events may produce luminous fast blue optical transients detectable by surveys
- These objects may produce r-process elements, possibly explaining r-process enhancement in some Milky Way globular clusters like M15

My Data

What data are we working with?

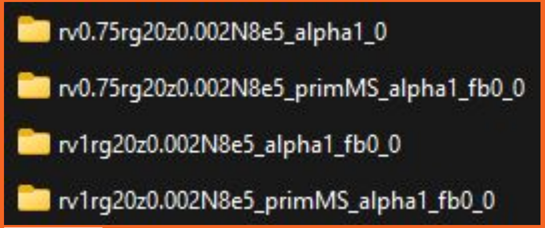
- N-body simulations of stellar clusters using CMC
- Each model has varied parameters such as virial radius and metallicity , almost fully spans parameter space of the milky way
- Individual models
    - Black hole formation data set
        - 1:time 2:r 3.binary? 4:id 5: initial M_progenitor 6:M_progenitor 7:bh mass 8:bh spin
    - Collision data set
        - 1:time 2:interaction type 3: new id 4-5: initial mass ids 6: r 7: stellar types
    - Merger data set
        - 1:time 2:interaction type 3: new id 4-5: initial mass ids 6: r

Original Scope

The project started off relatively small scale

Admittedly maybe a little too small

	Rv = 0.75	Rv = 1
Primordial Mass Seg. true	1	1
Primordial Mass Seg. False	1	1




ASTR 154
WE
HAVE
THE
Data

New scope

N: Number of stars in 100,00
Rv: Virial radius in parsec
Rg: Gravitational Radius
Z: Metallicity

N2.0rv0.5rg2.0Z0.0002	N2.0rv0.5rg2.0Z0.002	N2.0rv0.5rg2.0Z0.02	N2.0rv0.5rg8.0Z0.0002	N2.0rv0.5rg8.0Z0.002
N2.0rv0.5rg8.0Z0.02	N2.0rv0.5rg20.0Z0.0002	N2.0rv0.5rg20.0Z0.002	N2.0rv0.5rg20.0Z0.02	N2.0rv1.0rg2.0Z0.0002
N2.0rv1.0rg2.0Z0.002	N2.0rv1.0rg2.0Z0.02	N2.0rv1.0rg8.0Z0.0002	N2.0rv1.0rg8.0Z0.002	N2.0rv1.0rg8.0Z0.02
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N16rv1.0rg2.0Z0.002	N16rv1.0rg2.0Z0.02	N16rv1.0rg8.0Z0.0002	N16rv1.0rg8.0Z0.002	N16rv1.0rg8.0Z0.02
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N16rv2.0rg2.0Z0.02	N16rv2.0rg8.0Z0.0002	N16rv2.0rg8.0Z0.002	N16rv2.0rg8.0Z0.02	N16rv2.0rg20.0Z0.0002
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N16rv4.0rg8.0Z0.0002	N16rv4.0rg8.0Z0.002	N16rv4.0rg8.0Z0.02	N16rv4.0rg20.0Z0.0002	N16rv4.0rg20.0Z0.002
N16rv4.0rg20.0Z0.02	N32rv1.0rg20.0Z0.0002	N32rv1.0rg20.0Z0.02	N32rv2.0rg20.0Z0.0002	N32rv2.0rg20.0Z0.02

```
Found 145 total models, 71 with rv < 1.1
Discovered 71 models for analysis

Parameter ranges:
N: 2.000 - 32.000
rv: 0.500 - 1.000
rg: 2.000 - 20.000
Z: 0.000 - 0.020
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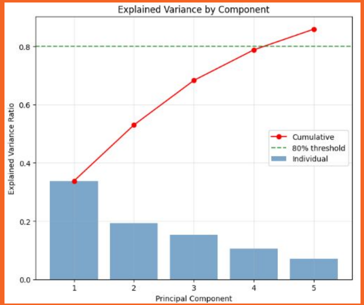
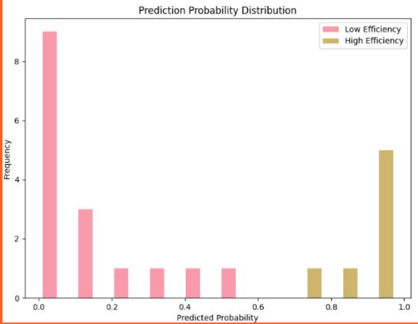
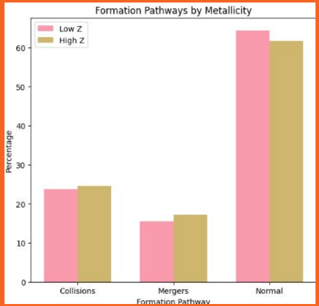
Methods

Tecniques I will use

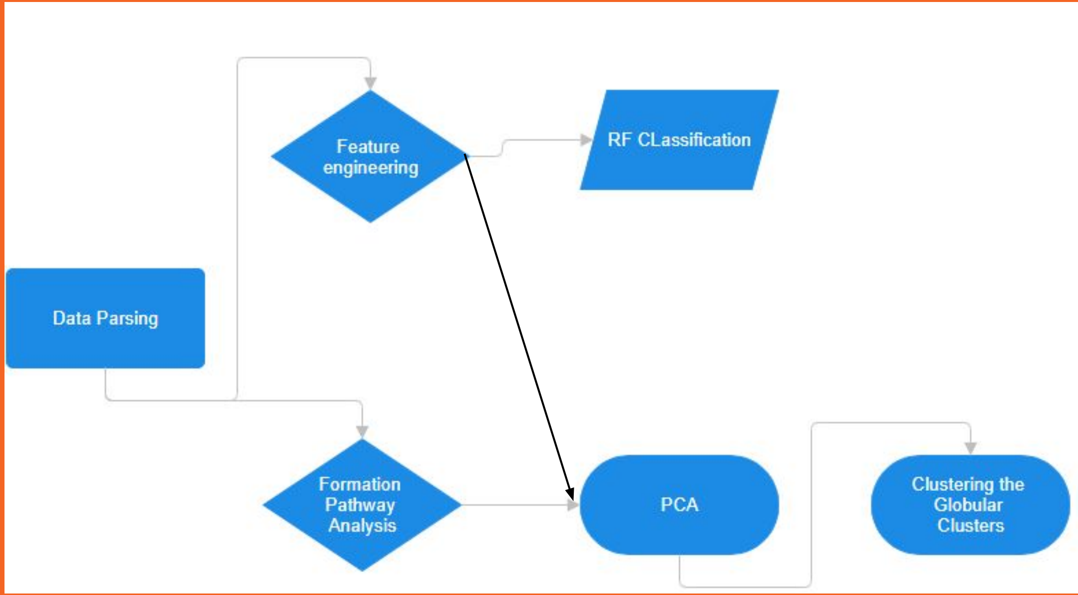
- Scientific Programming(PEP8)
- Data Visualization
- Statistics
- Dimensionality reduction
- Clustering
- Classification







Workflow



Feature engineering
RF CLassification
Data Parsing
Formation Pathway Analysis
PCA
Clustering the Globular Clusters

Steps taken

1. Data Parsing
   a. Loaded and standardized outputs from all simulations
2. Pathway Analysis
   a. Cross-referenced >200,000 BH IDs with collision and merger logs to determine each BH's formation channel
3. Feature Engineering
   a. Computed derived features for each model
      i. Non zero spins, formation pathway fractions, formation location etc
4. Dimensionality Reduction (PCA)
   a. Used Principal Component Analysis to reduce the high-dimensional feature space to a few main axes
5. Clustering
   a. Applied K-means clustering to PCA results to identify distinct "cluster populations"
6. Random Forest Classification
   a. built a Rf classifier with cv splitting to predict which clusters would have high merger-driven BH formation efficiency, using physical parameters as inputs

Results

Metallicity Effects

Z inversely correlates with BH mass

High-Z clusters form 7.8±0.2 M☉ BHs vs 17.1±2.5 M☉ in low-Z

No significant Z effect on collision/merger rates

```
Low Z (Z = 0.000200 - 0.002000):
  Models: 50
  Mean BH count: 1494.0 ± 1197.3
  Collision formation: 23.7% ± 21.7%
  Merger formation: 15.5% ± 7.8%
  Mean BH mass: 17.1 ± 2.5 M☉

High Z (Z = 0.020000 - 0.020000):
  Models: 25
  Mean BH count: 1311.5 ± 1157.0
  Collision formation: 24.6% ± 19.5%
  Merger formation: 17.2% ± 6.9%
  Mean BH mass: 7.8 ± 0.2 M☉
```

```
Correlations with Metallicity:
  BH Count: -0.072
  Collision %: 0.050
  Merger %: 0.102
  Mean BH Mass: -0.935
```

Black Hole Formation Pathways

Mean Collisions: 24.0%

Mean Mergers: 16.1%

Mean Normal Evolution: 63.4%

Collision-formed BHs are 2.3× more massive on average

Spin Distribution Findings

Surprising Result:

Only 5/75 models show non-zero spins (0.009% mean spinning fraction)

Max spin observed: 0.686

	non_zero_spin_mean	high_spin_fraction
count	5.000	75.000
mean	0.686	0.009
std	0.000	0.042

Likely due to no longer looking at cherry picked data set but instead a larger and longer running milky way parameter space

We conclude:

Mergers in clusters rarely produce high-spin BHs

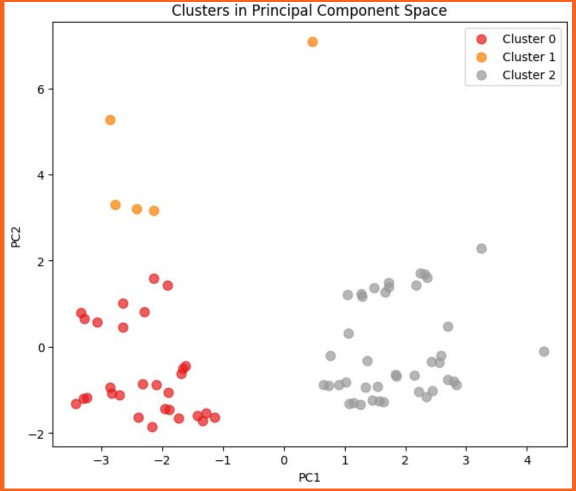
Cluster Subpopulations (PCA)

3 Distinct Evolutionary Pathways Identified

Cluster 0: Low-Z, high collision rates

Cluster 1: High-Z, low BH masses

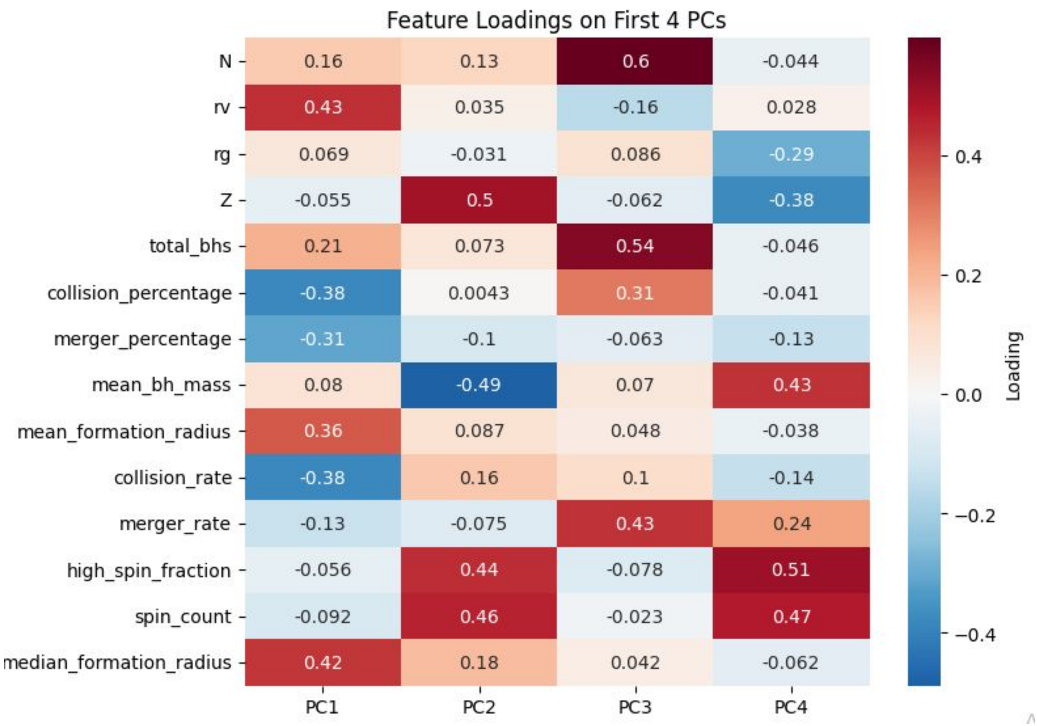
Cluster 2: Mid-Z, efficient mergers

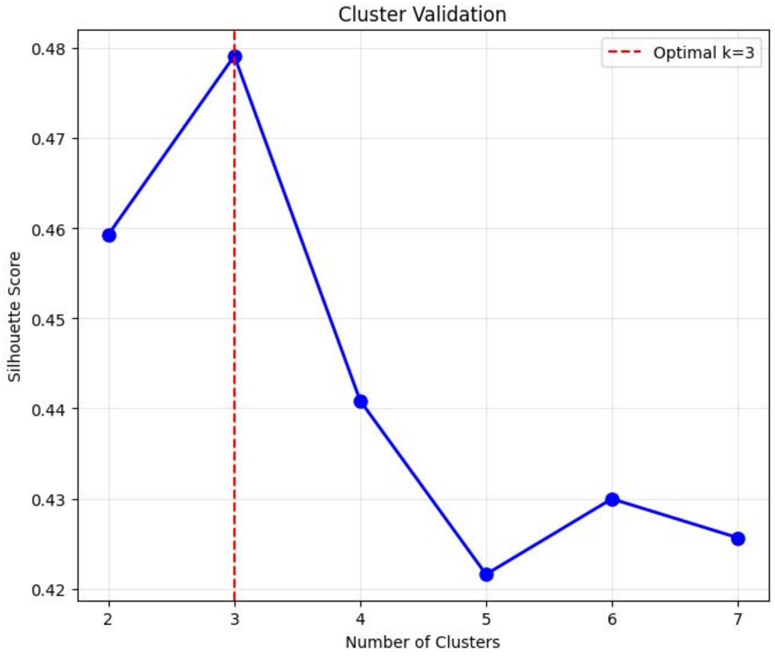



```
PC1 (33.8% variance) - Top loadings:
  rv: 0.433
  median_formation_radius: 0.423
  collision_rate: 0.382
  collision_percentage: 0.382

PC2 (19.2% variance) - Top loadings:
  Z: 0.502
  mean_bh_mass: 0.489
  spin_count: 0.459
  high_spin_fraction: 0.439
```

Bonus PCA and Clustering Visualizations!



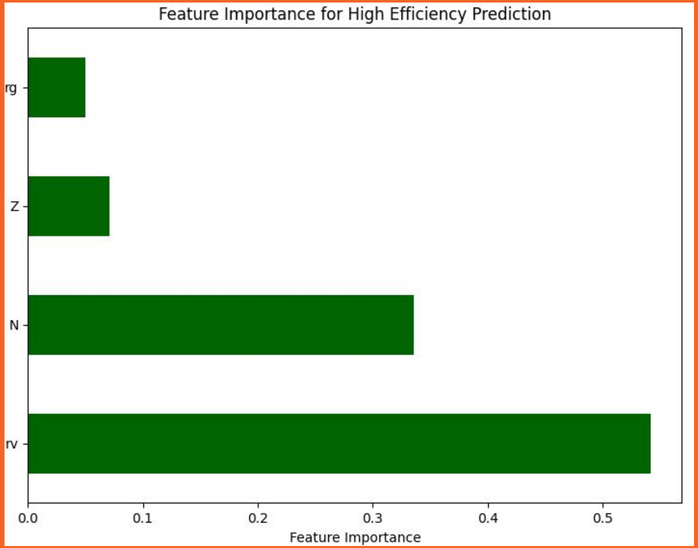


Predictive Modeling

Virial Radius (rv) Most Predictive of High Merger Efficiency

RF Accuracy: 95.7%

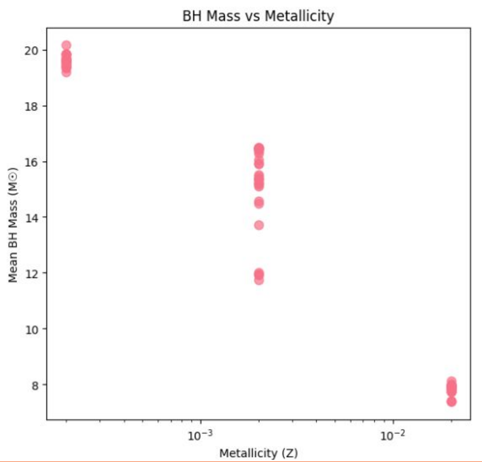
Feature Importance: rv (54%), N (34%), Z (7%), rg (5%)

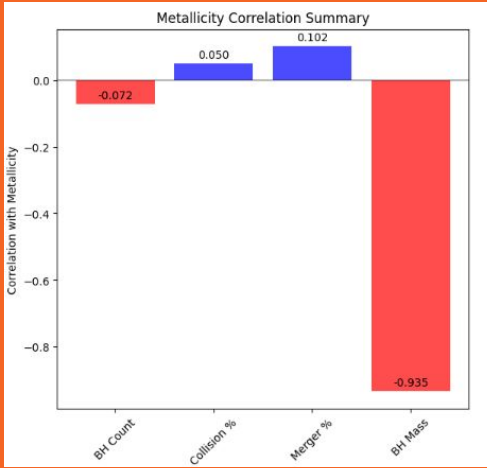


Cluster density > metallicity in determining merger rates

Conclusions/ Confirmations

1. Metallicity drives BH mass more than formation mechanism
2.
3. Current milkway based models underproduce high-spin BHs
4. Virial radius key predictor of merger activity





Next Steps

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- See if I more derived features could lead to interesting results (Adding in the spin fractions as a derived features greatly affected my PCA)
- I'm curious to see if I can get reasonable predictions for spins and merger rates of a cluster given the initial conditions(Quasi-emulation?)
- Try to make PDFs using derived properties

Steps to take before finalizing the report and takeaways

- Clean up my code to align with PEP8 and add in comments and documentation
- Make a Git repository
- If I had to tell myself one piece of advice when starting this , it would be to MAKE EVERYTHING A FUNCTION.

Thank You