AI in Astronomy workshop – USC8
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INAF-OACT

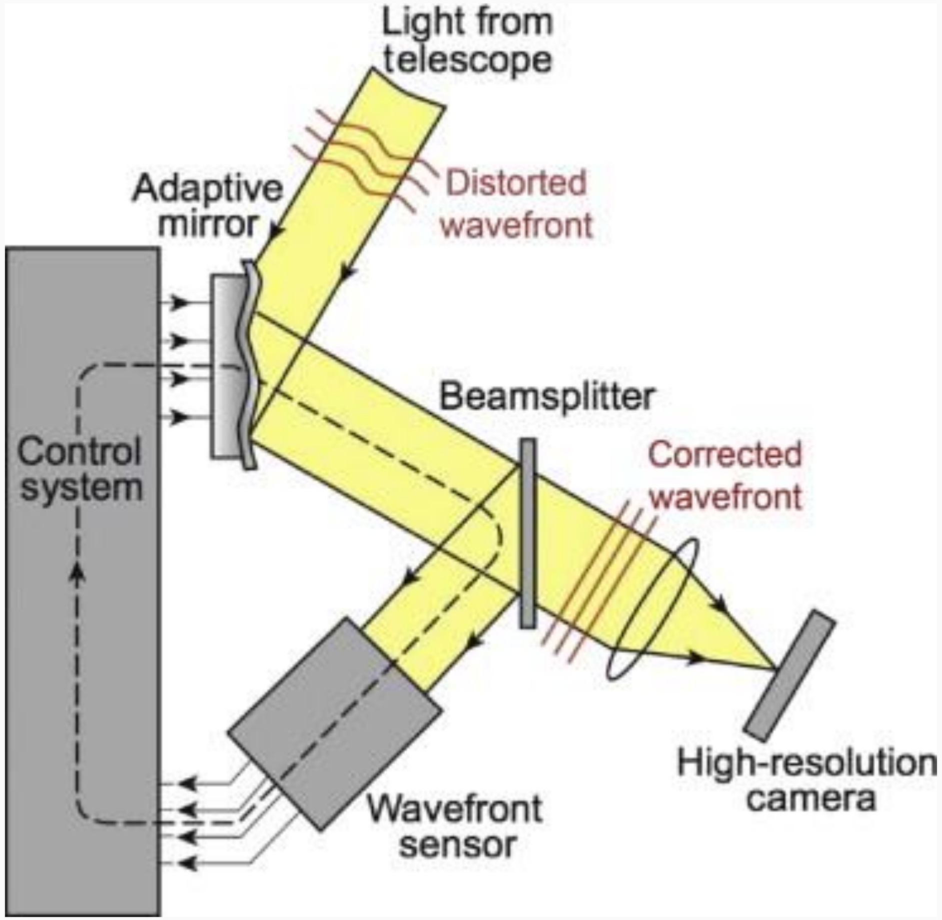
Machine learning for asterism selection in adaptive optics

Fabio Rossi

INAF - Osservatorio Astrofisico di Arcetri

Adaptive Optics

- Enabling Technology for ground based VLT/ELT telescopes
- Atmospheric Turbulence Correction
- Point Spread Function quality measures
  - Strehl
  - FWHM (Full Width at Half Maximum)



taken from “INTRODUCTION TO ADAPTIVE OPTICS AND ITS HISTORY”, Claire Max

What is MAVIS?

MCAO
ASSISTED
VISIBLE
IMAGER &
SPECTROGRAPH

See [3] as a reference.

Uses VLT UT4 AO Facility

- Existing deformable secondary
- Existing laser guide star facility

AO Module (AOM)

- Visible (VRI, UB goal)
- 30” Ø field of view corrected
- FWHM < 26mas (V band - faint)
- Strehl ratio > 10% (V band - bright)
- Sky coverage > 50% @ Gal. pole

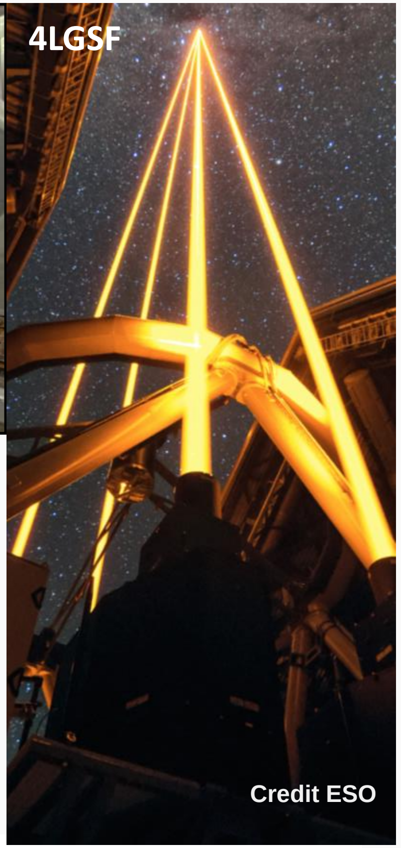
Imager

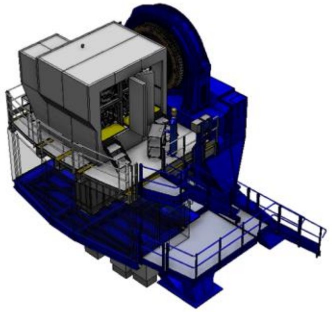
- 30”x30” FoV
- ~ 7mas/pixel
- Wide + narrow band filters

IFU Spectrograph

- 25 mas and 50 mas spaxels
    - 6”x6” and 3”x3” FoV respectively
- ~4000 and ~15000 spectral resln modes
- 4 interchangeable VPH gratings

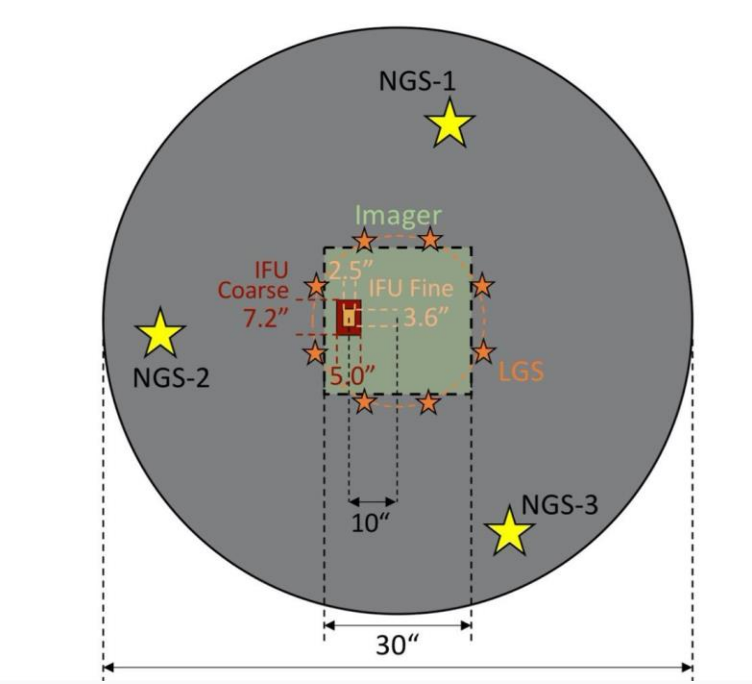
Credit ESO

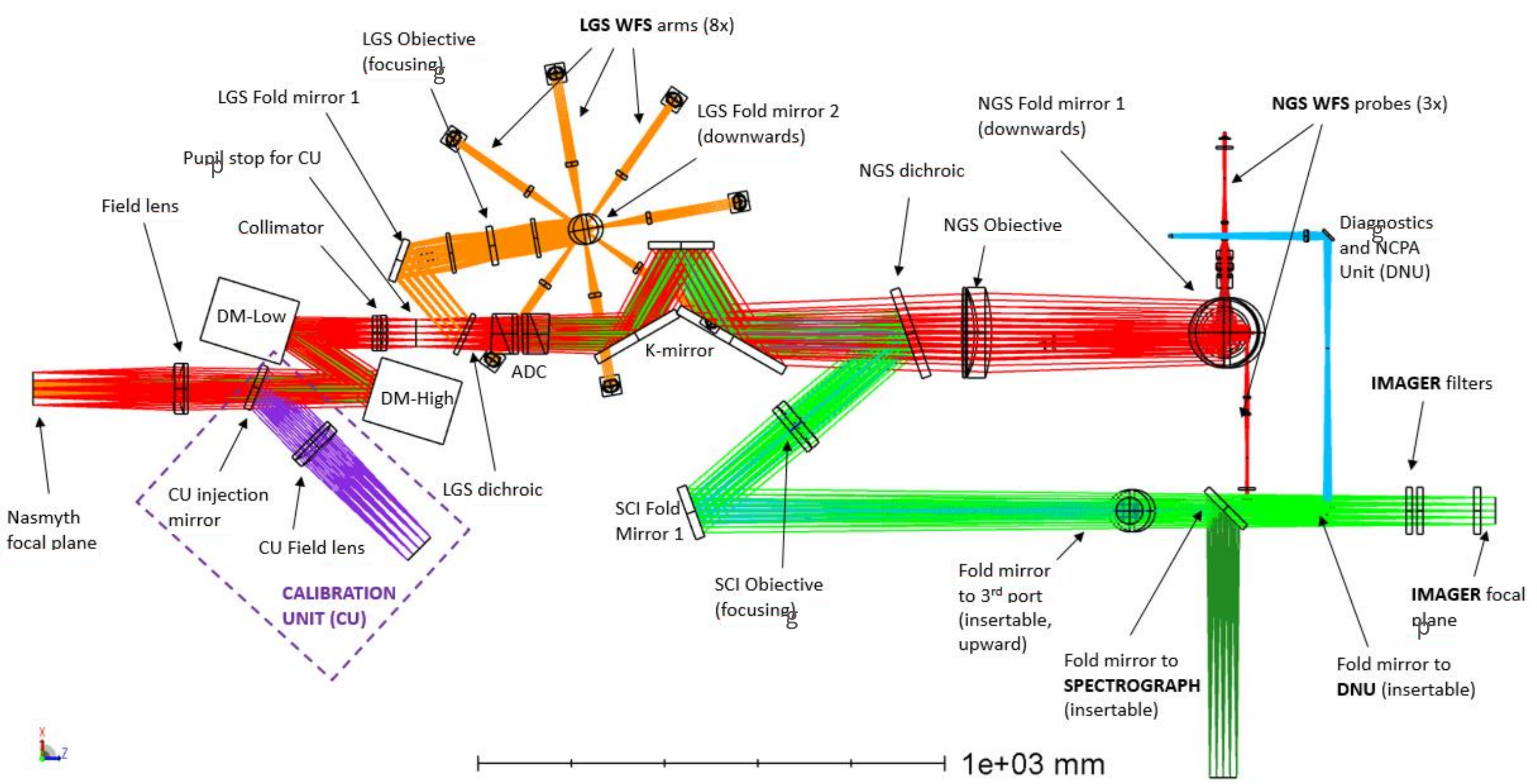




MAVIS AO

- Multi Conjugate AO
- 8 Laser Guide Stars (High Order Modes correction)
- 3 Natural Guide Start (Low Order correction)
- 3 Deformable Mirrors conjugated at different altitudes → Atmospheric Turbulence Tomography





TIPTOP

- Simulation Tool developed by LAM and Arcetri [2]
- https://tiptop.readthedocs.io/en/main/
- Can predict the AO performance by producing the expected PSF
  - for different types of AO systems, MCAO included
- Analytical approach in Fourier domain
  - not and End-To-End like [1] simulator but almost as accurate
- Variable atmospheric and operating conditions
- Fast computation time
  - order of $\mathbf{T_A}$ = 0.15 seconds to evaluate one asterism with GPU acceleration
- Currently being integrated in the Exposure Time Calculator at ESO for the ERIS/VLT instrument
  - Next for MAVIS, MORFEO

Asterism Selection: the problem

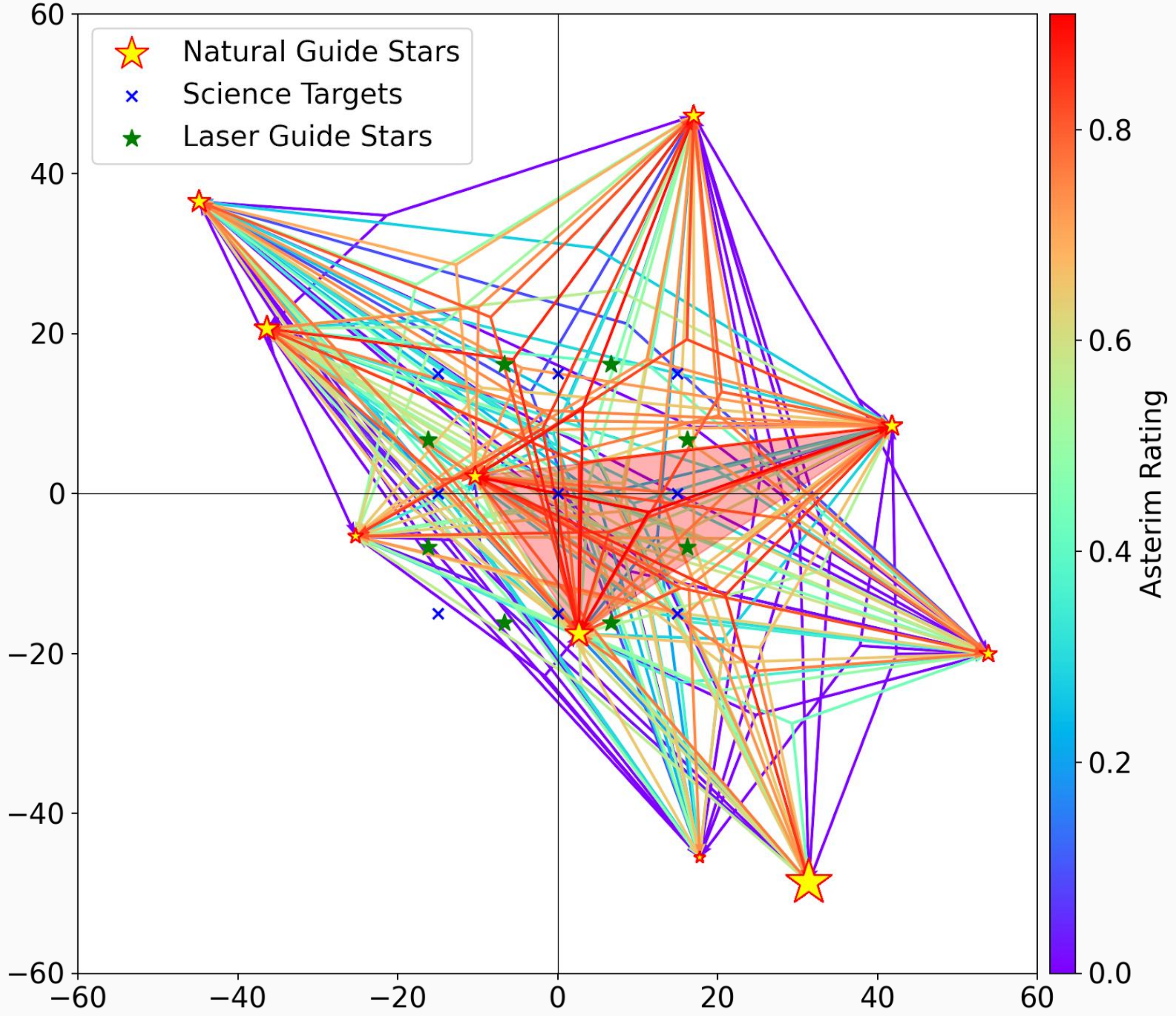
- How to choose the 3 Natural Guide Stars?
- Given a scientific target, the possible candidates must
  - Fit in the FoV of the AO system
  - Have a minimum magnitude
- Bright and close stars are better, but there is no simple heuristic
- With TIPTOP we can brute force compute all the cases, but how many options we have?
- Given n candidate stars we have the combinations of k=3 elements:

$$\binom{n}{k} = \frac{n!}{k! \cdot (n-k)!}$$

  - 10 stars = 120 asterisms → **18 seconds**
  - 20 stars = 1140 asterisms → 171 seconds or **2 minutes 51 seconds**
  - 30 stars = 4060 asterisms → 609 seconds or **10 minutes 9 seconds**
- **Goal: a reliable estimate of the best asterism in about 1second**
  - Use case: the astronomer using the ETC (Exposure Time Calculator) GUI

Asterism Selection

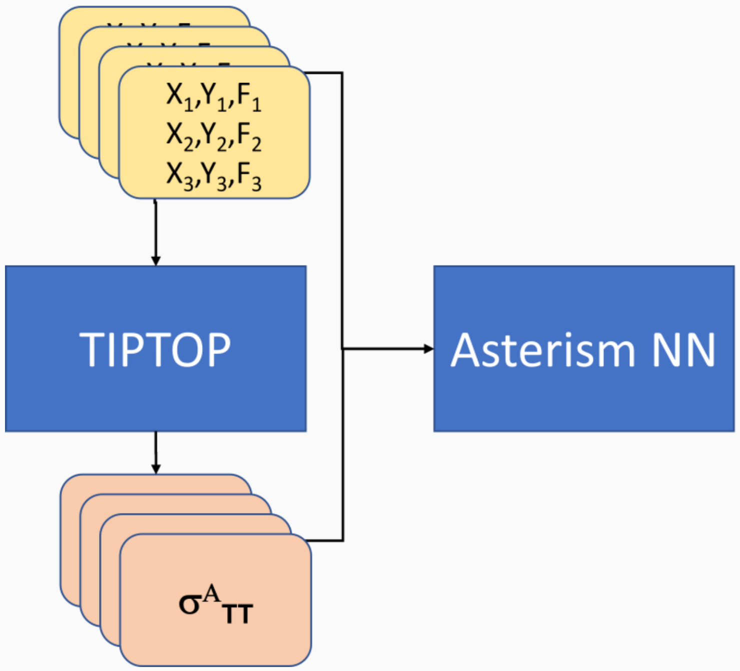
- Our inputs are the coordinates and the magnitude of each star
- The output for each asterism is the residual (not corrected) wavefront RMS
- A polynomial model can be used for the ERIS case, where the choice is a single NGS
- **For the MAVIS case we can use a Neural Network to quickly rank all the possible asterisms**



An example of Asterism visualization in TIPTOP, 9 stars, 84 asterisms. Here we draw 3 barycentric vector for each asterism, colored with the level of LO residual (rescaled). The best asterism is drawn as a red triangle.

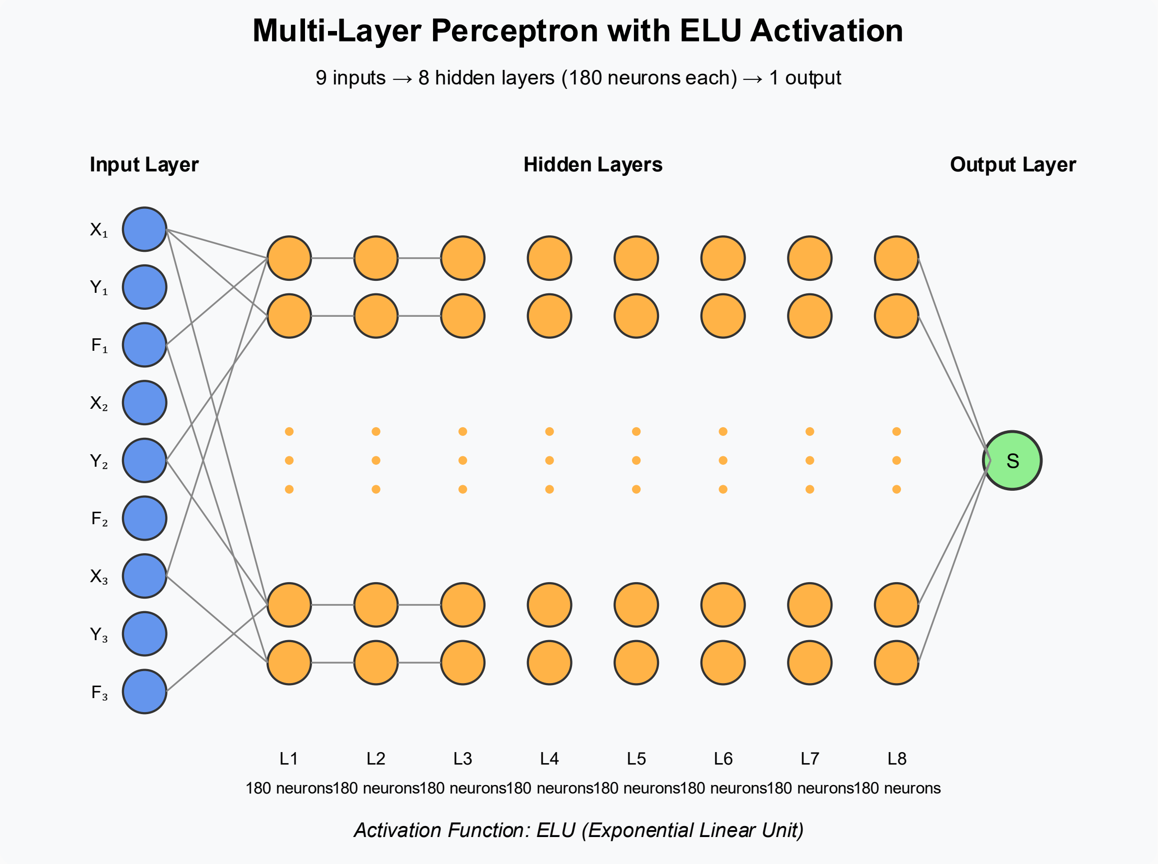
Asterism Neural Network – Training Set

- Since the High Order (HO) part of the simulation is fixed, we can select the best asterism based only the Tip Tilt Jitter residual σ^{A}_{TT}, which is computed by the Low Order (LO) part of the simulation (even if this requires in as input the HO part output: the PSD of the high order modes residuals).
- Training Data
  - compute a large number of simulations (thousands) for the specific case, with randomly generated asterisms (varying positions and magnitudes of the NGSs): for each triple of stars, we have a value of σ^{A}_{TT}.



Asterism Neural Network – Network Structure

- First tests with Classical Multi-Layer perceptron
- Usual hyper-parameters optimization (number of layers, layers width, different activation functions)

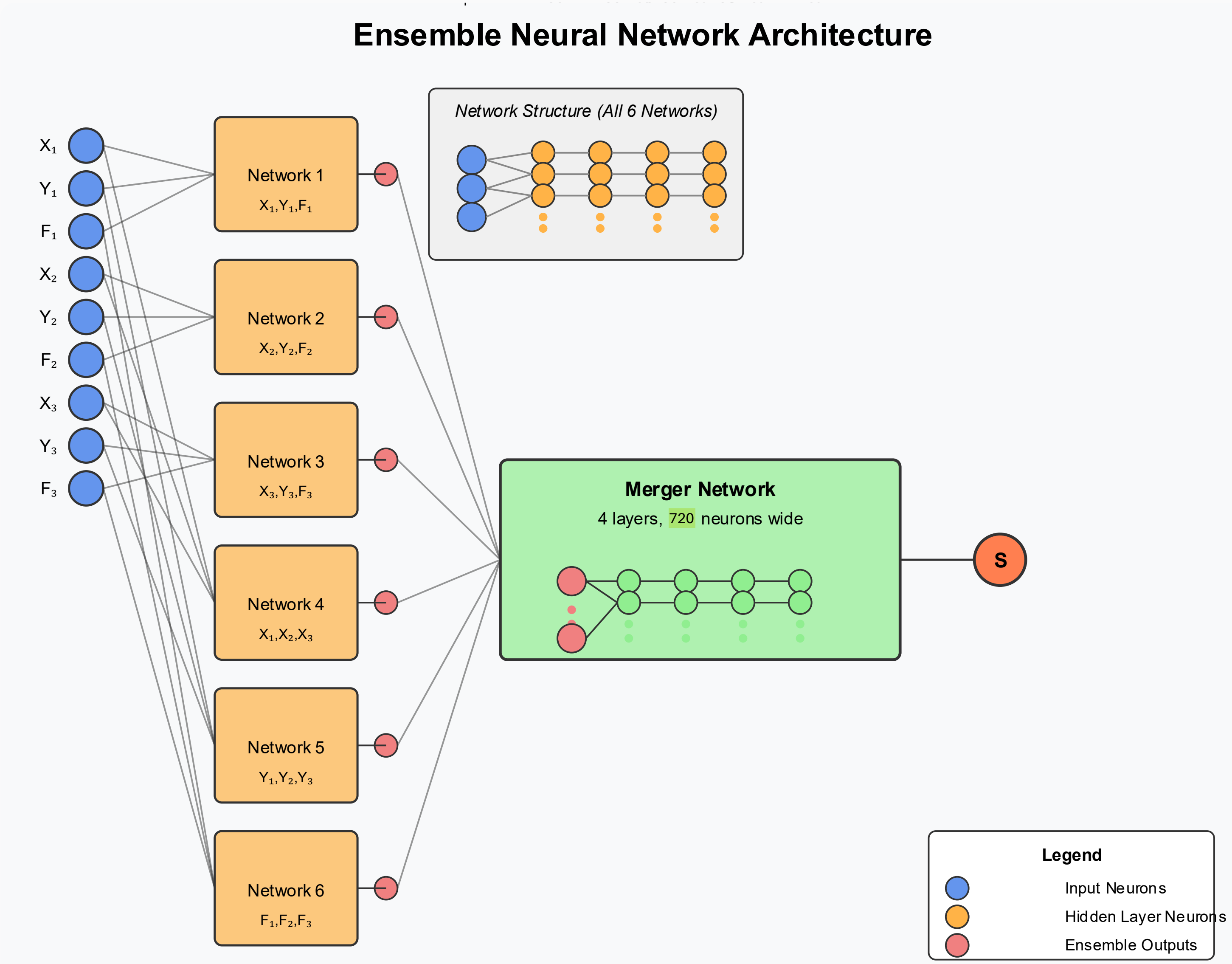


Ensemble methods

- Ensemble learning combines the predictions from multiple neural network models to reduce the variance of predictions and reduce generalization error.

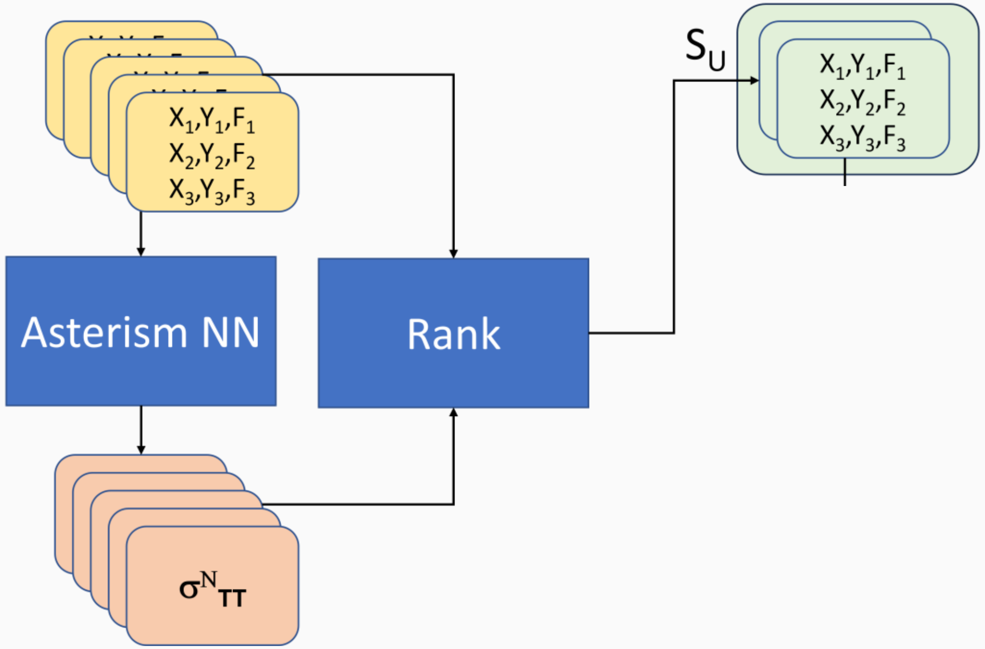
- Noticeable improvement by using ensemble-like method in out problem
  - 3 Networks, each learning about each star data
  - 3 Networks, each learning about all of the corresponding data (Xs,Ys, fluxes)
  - One Network merging the results from the 6 above
  - Lower number of connections to achieve better performances!

Asterism Neural Network – MLP Ensemble Structure



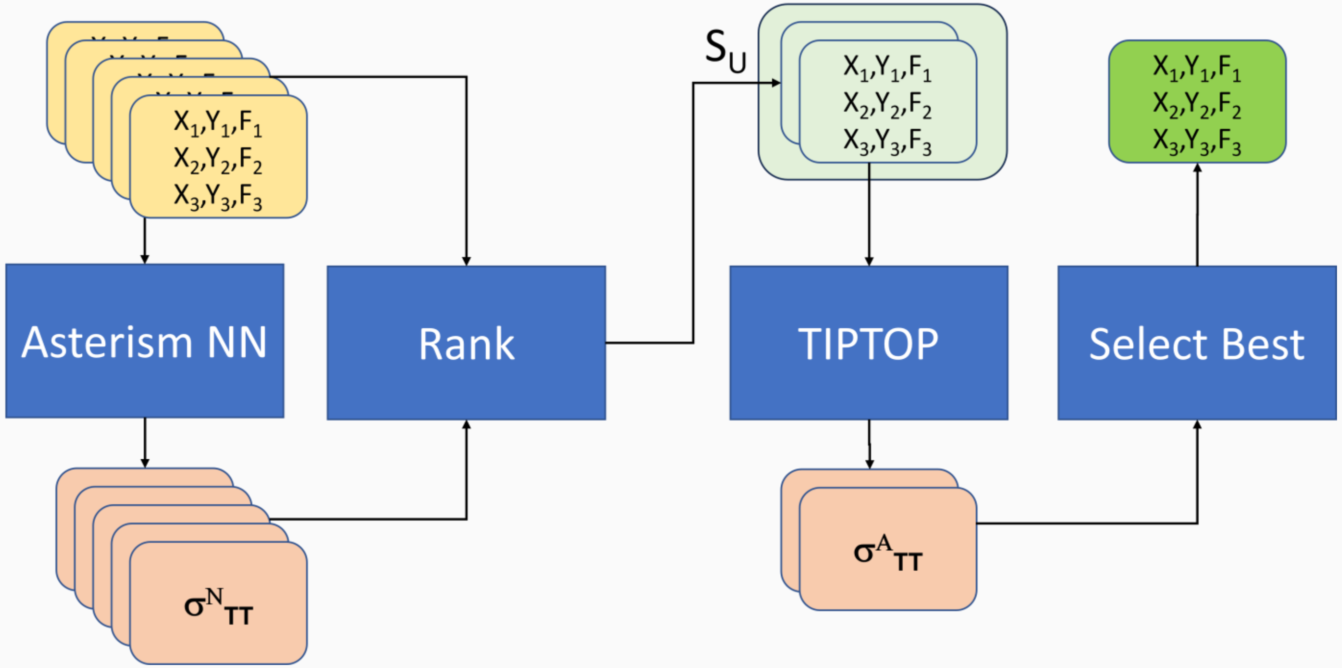
Ranking and accuracy (1)

- Train a Neural Network model to perform the regression from the input asterism features (9 scalar values: X, Y coordinates and Flux on the NGS sensors, for each of the 3 stars) to the associated output $\boldsymbol{\sigma^{N}_{TT}}$.
  - Asses the NN uncertainty in prediction U_N:
    - $E_\sigma = (\sigma^{A}_{TT} - \sigma^{N}_{TT})/\ \sigma^{A}_{TT}$
    - $U_N = 1.6 * \mathbf{RMS}(E_\sigma)$
  - Rank all of the possible asterisms based on $\boldsymbol{\sigma^{N}_{TT}}$
  - Define the set of asterisms S_U for which:
    - $\sigma^{N}_{TT} < \min(\sigma^{N}_{TT})\times(1+U_N)$
    - **Add the 3 best ranking ones anyway**



Ranking and accuracy (2)

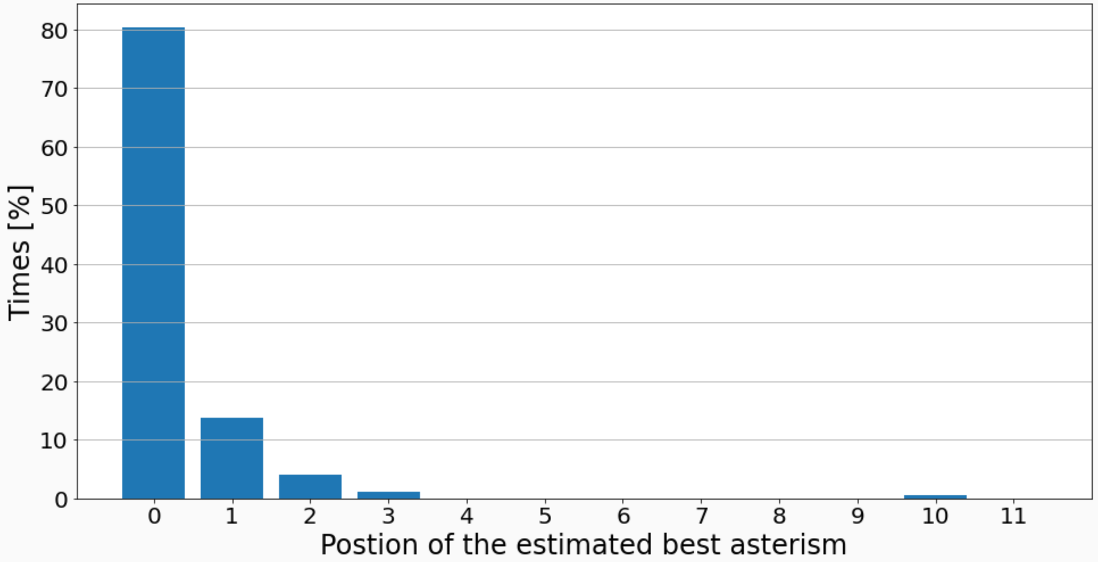
- Finally, to check how well the NN estimation worked
  - Compute σ^{A}_{TT} for the asterisms in S_U using TIPTOP, select the one yielding $\min(\sigma^{A}_{TT})$



Results

- Implementation integrated as an extension of TIPTOP, based on **pytorch**
- Training set: ~40K Ast. (960 Fields)
- Test set ~5K Ast. (120 Fields)
- Validation set ~5K Ast. (120 Fields)
  - 8/7 stars on average per field
- U_N = 0.112 (or 12.2% error)
- Share of Ast. in S_U: 8.8% computation time saved: **~91.2%**
- In about 96% of case the best asterism ranked in the first 3 positions by the NN model.

- **Wrong Asterism Selections: 0**
  - **Achieved by a max computation time is 10*T_A ≈ 1.5s**



Thanks for your attention!

Any question?

References

1. G. Agapito et al., ‘PASSATA - Object oriented numerical simulation software for adaptive optics’, Proc. SPIE Vol. 9909 (2016)
2. B. Neichel et. al., ‘TIPTOP: a new tool to efficiently predict your favorite AO PSF’, Proc. SPIE Vol. 11448, Adaptive Optics Systems VII (2021)
3. F. Rigaut et. Al., ‘MAVIS on the VLT: A Powerful, Synergistic ELT Complement in the Visible.’ The Messenger, 2021, 185, pp.7-11.
4. Rossi, F.; Agapito, G.; Plantet, C.; Neichel, B.; Rigaut, F., “Efficient asterism selection for wide field adaptive optics systems with TIPTOP”, Proceedings of SPIE - The International Society for Optical Engineering, 2024 | Conference paper, DOI: 10.1117/12.3020159, EID: 2-s2.0-85206106132