Graduate School Seminar
Warszawa, Poland

A family tree of galaxies

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November 30, 2022

Outline

Based on the work of:

Pearson, Suelves, et al (2022) (published in A&A)

Suelves, Pearson, & Pollo (2022) (published in A&A)

Intro to the Tree and the Merging of galaxies

Merging galaxies identified on images

Merging galaxies identified on photometric meassurements

Sky background error

Conclusions

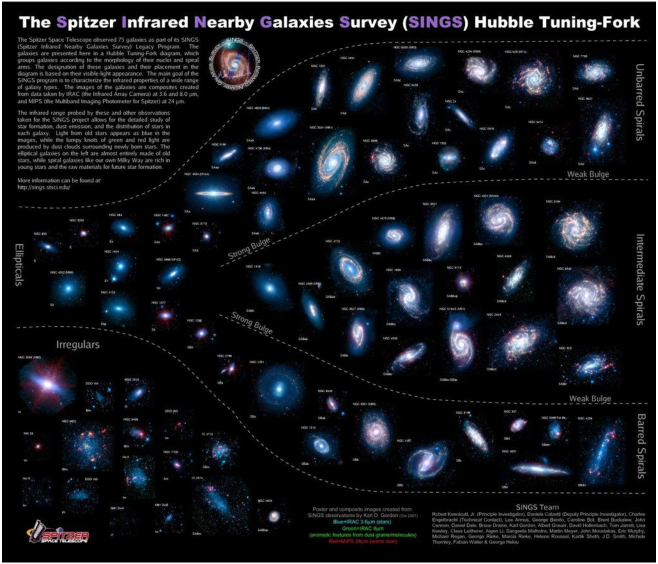
Galaxies

NGC 1300

Credit: HST, NASA/ESA

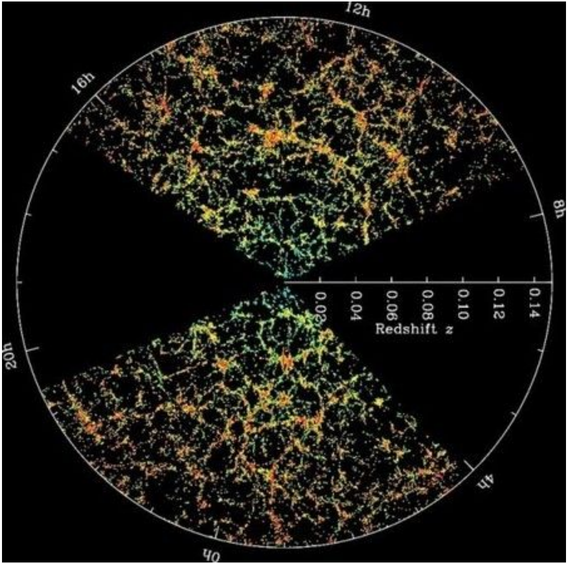
- Stars
- Gas
- Dust
- Planets

A whole Zoo of Galaxies



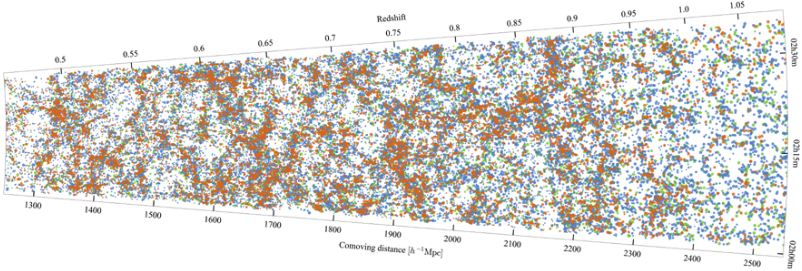
Credit: NASA/JPL-Caltech/K. Gordon (STScI) and SINGS Team

Large scale structure



Credit: SDSS

Large scale structure



Credit: VIPERS colaboration

How has the galactic zoo originated?

The two more common types

Elliptical vs Spiral galaxies

The two more common types

The two more common types

Ellipticals

- Old stars
- Not much gas, not much star formation
- Massive and redder

The two more common types

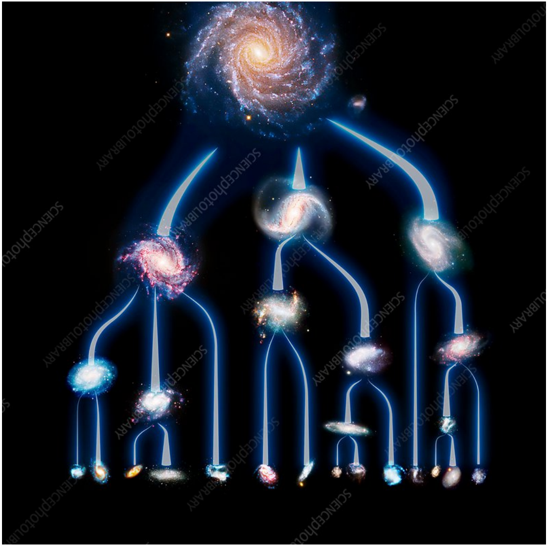
Spirals

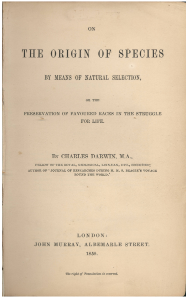
- Young and old stars
- With gas that keeps forming new ones
- Less massive and bluer

Ellipticals

- Old stars
- Not much gas, not much star formation
- Massive and redder

On the origin of galaxies





ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

By CHARLES DARWIN, M.A.,

FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES;
AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

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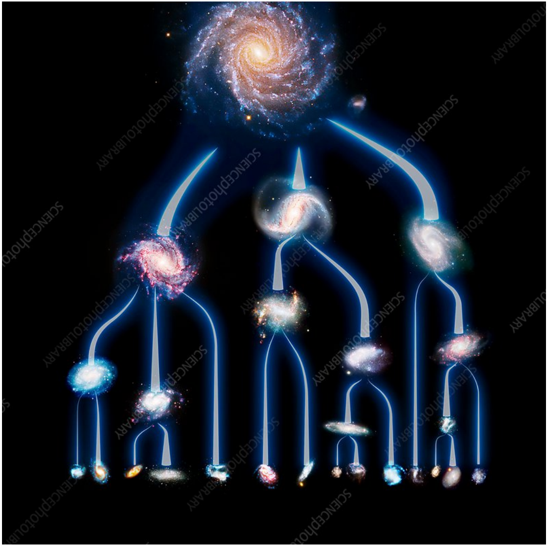
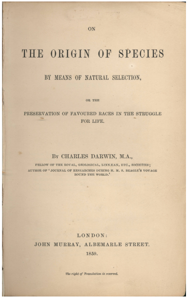
On the origin of galaxies

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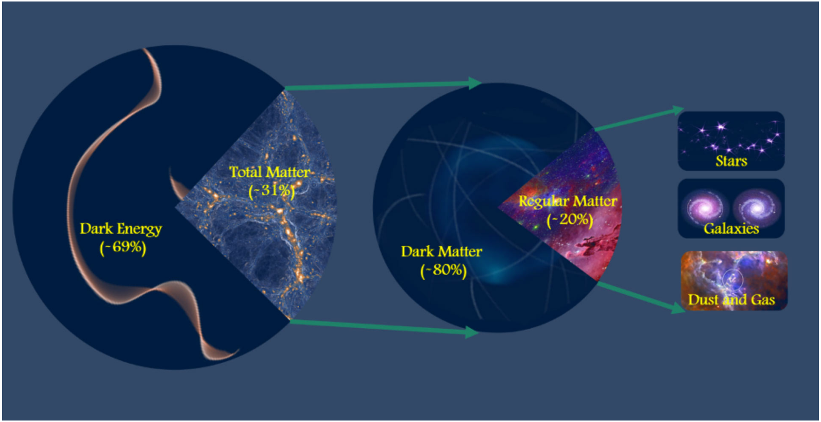
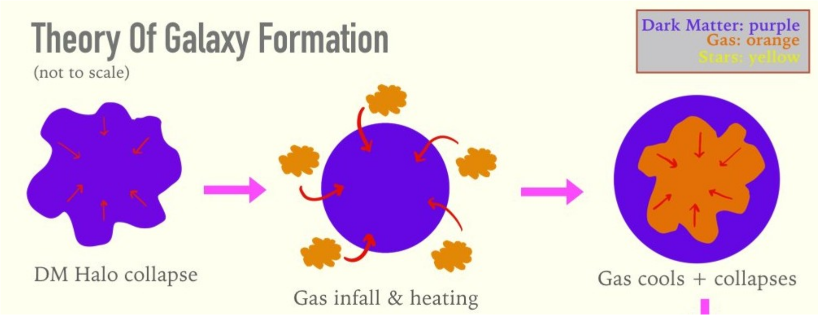
Nature or **Nurture?**

Universe's Components

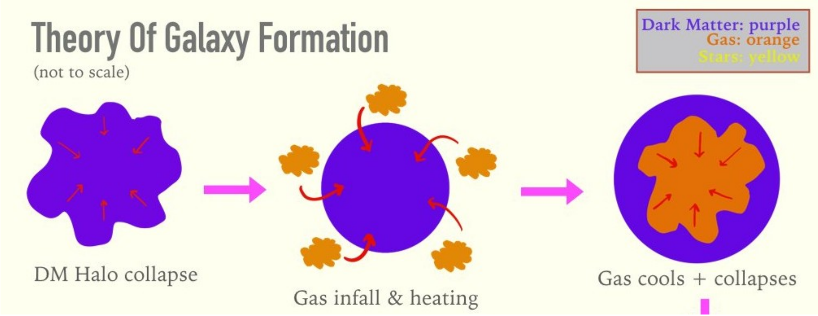


Credit: M. Abdullah, University of California Riverside



Dark Matter collapsed in Haloes

Dark Matter dynamics depend only on gravity



Dark Matter collapsed in Haloes

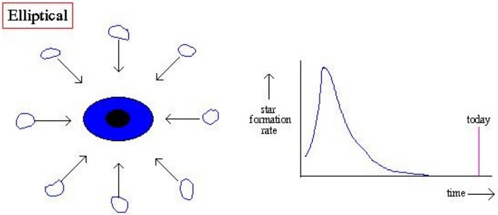
Dark Matter dynamics depend only on gravity

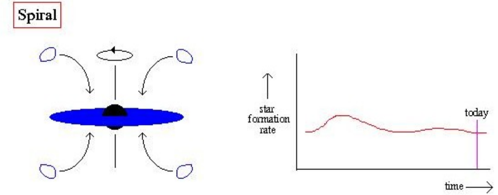
Baryonic matter fell into the Haloes

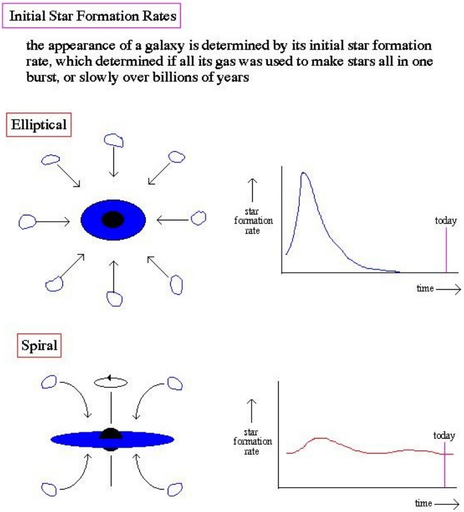
Baryonic matter dynamics driven by self-interactions that heat and cool the gas

Initial Star Formation Rates

the appearance of a galaxy is determined by its initial star formation rate, which determined if all its gas was used to make stars all in one burst, or slowly over billions of years

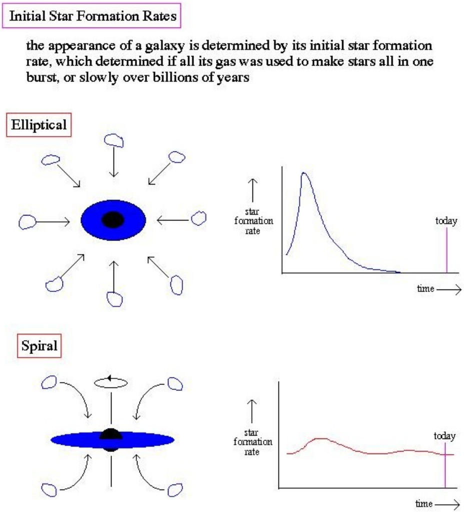






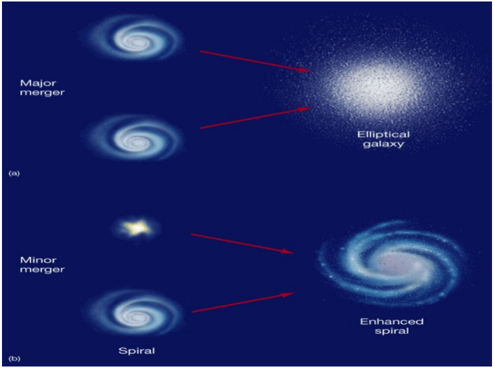
Ellipticals

- Massive haloes gathered gas fast
- Haloe's spherical symmetry is maintained
- Strong gas consumption in stars
- Strong winds and SNe expelling gas
- Surrounding environment with other overdensities around



Spirals

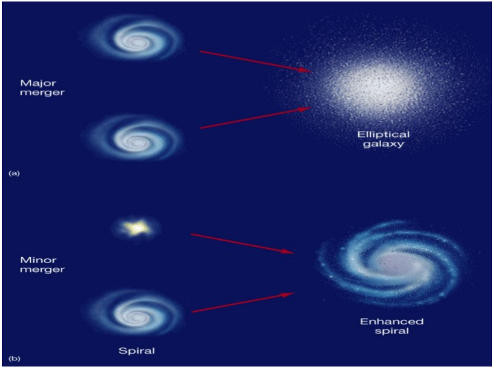
- Halo attracted gas slowlier
- Slow gas interactions allowed **L** to form a disk
- Gas used and expelled less aggressively
- Surrounding environment less overcrowded



Credit: Eric J. Chaisson course at Harvard

Ellipticals

- Evidence: two massive spirals of similar mass merge into an elliptical galaxy



Credit: Eric J. Chaisson course at Harvard

Spirals

- Evidence: an spiral feeds on gas of the small galaxy

Milky Way known merging history: 6 confirmed, maybe even 7?!
Credit: Gaia Data Release 3

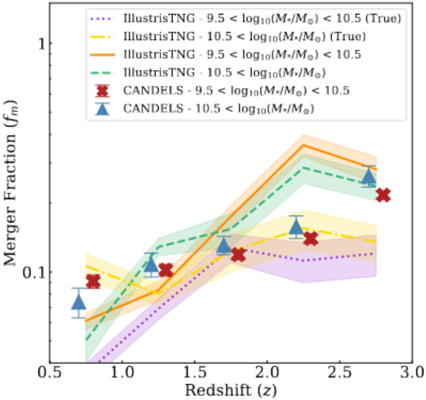
Galaxy Mergers

Credit: HST, NASA/ESA

Galaxy Mergers

Credit: HST, NASA/ESA

A vogage in time

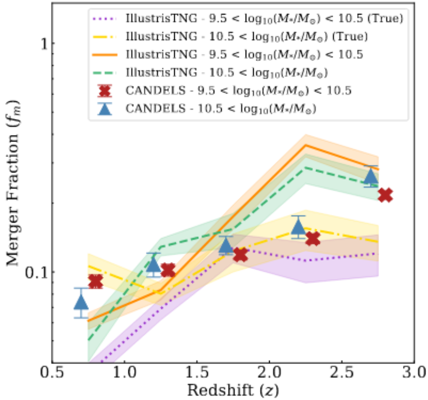


Credit: Whitney+21

Telescopes are our astronomical Beagle

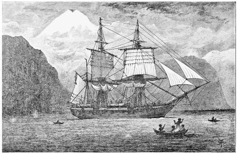
Looking back in time through the sky, we find mergers were more frequent in the past!

A vogage in time



Credit: Whitney+21

Telescopes are our astronomical HMS Beagle



Looking back in time through the sky, we find mergers were more frequent in the past!

However, mergers are still found nowadays,
how could Hubble telescope get such pics?!

Main work: Merger Identification!!

Problems

Credit: JWST, Stephan's Quintet

Contamination

Credit: JWST, Stephan's Quintet

Intro to the Tree and the Merging of galaxies

Merging galaxies identified on images

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Sky background error

Conclusions

Visual Inspection

Professionals look at astronomical frames

Merger Identification Methods

Visual Inspection

Professionals look at astronomical frames

Close Pairs

Pairing sky-neighbours at similar radial distance

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Morphological Analysis

Parameters that quantify shape distortions

Merger Identification Methods

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Close Pairs

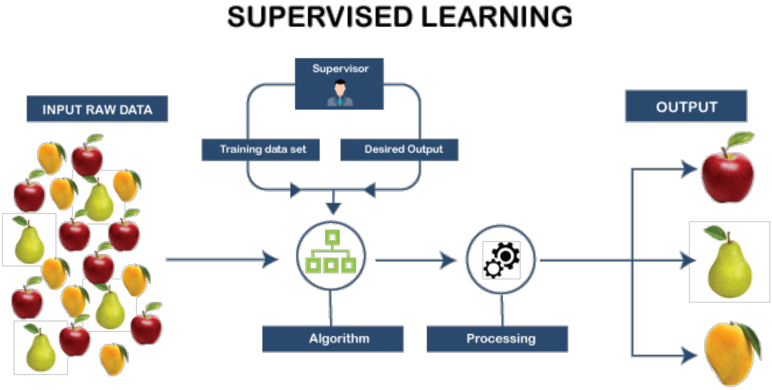
Pairing sky-neighbours at similar radial distance

Morphological Analysis

Parameters that quantify shape distortions

Convolutional Neural Networks (CNN)

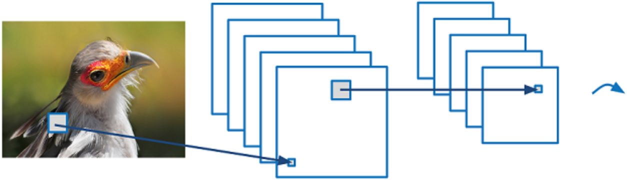
Models that learn properties that characterize pre-classified galaxies **from the images**



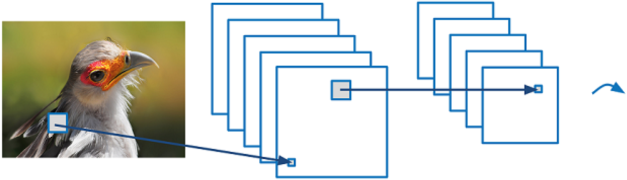
Credit: nhadep247.net

- Training dataset
- Model type and structure

CNN



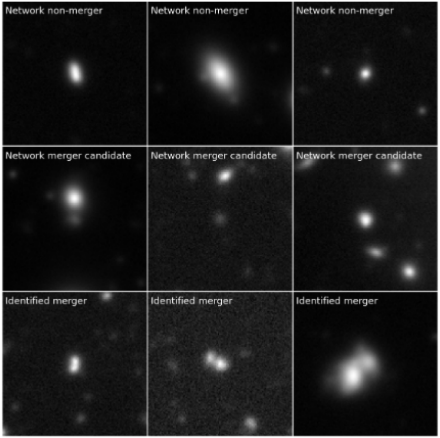
CNN



Plastic bag
100% confidence

CASSIOPEIA
Polaris
CEPHEUS
URSA MINOR
Thuban
BIG DIPPER
North Ecliptic Pole
DRACO
Deneb
HERCULES
CYGNUS
Vega
LYRA

Subaru's Hyper Supreme-Cam (HSC)
r-band optical frames



Credit: Pearson et al. (2022)

- Network's non-mergers: 24 069
- Network's merger candidates: 10 195

Visual Inspection by Pearson & Suelves:

- Identified mergers: 2 109

Visual Inspection results:
miss-classification due to **contamination** by no physically associated companion and blended sources

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Main merger tracer:
the morphological parameters that examine the **asymmetry** of the light distribution

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Catalogue:
of 2 109 mergers in the North Ecliptic Pole

Visual Inspection results:
miss-classification due to **contamination** by no physically associated companion and blended sources

Main merger tracer:
the morphological parameters that examine the **asymmetry** of the light distribution

Catalogue:
of 2 109 mergers in the North Ecliptic Pole

and now, these galaxies and more can be visually classified by anybody in Galaxy Zoo!!

Citizen Science project for visual classification of galaxies

Result: merger vote fraction f_{M}

Mergers

- from Darg et al (2010), by Visual Inspection of high f_{M}
- primary source of merging pairs

Non-Mergers

- from Galaxy Zoo's low f_{M}

Class-Balanced Dataset

- Training: 2 680 Mergers + 2 680 Non-mergers
- Distance: redshift $z \in [0.01, 0.1]$
- Nearest neighbour match in [r-band magitude, redshift] space

Credit: SDSS DR9, Aladin[1], Darg et al (2010)

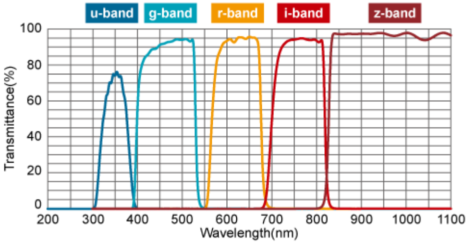
ML method using, only Photometry?

Saving time and resources
&
Learning new properties

Training dataset, Inputs

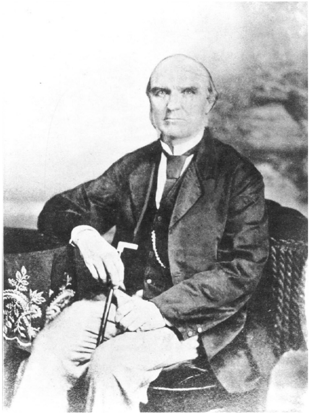
Input Information

- Magnitudes, colors and errors
- Multiple flux calc. methods
- Five optical bands



What is photometry?

What is magnitude in astronomical context?



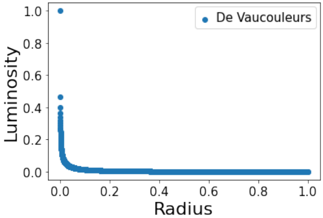
Credit: Wikipedia

1856, Norman R. Pogson defined:

magnitude from flux

$$m_1 = -2.5 \log F_1 \ .$$

Model Magnitudes for Ellipticals
Surface Brightness

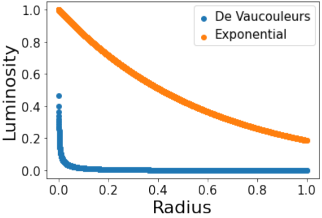


de Vaucouleurs

$$I(r) = I_0 \exp\left[-7.67\left(\frac{r}{r_0}\right)^{\frac{1}{4}}\right] ,$$

Fluxes are calculated from integrating the Brightness Model (or Intensity Profile)

$$F \sim 2\pi \int_0^r I(r) r dr \ .$$

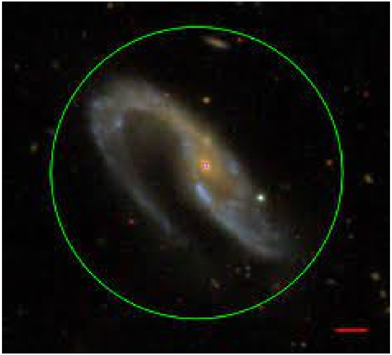


Exponential

$$I(r) = I_0 \exp\left[-1.68\frac{r}{r_0}\right] \quad ,$$

Fluxes are calculated from integrating the Brightness Model (or Intensity Profile)

$$F \sim 2\pi \int_0^r I(r) r dr \ .$$



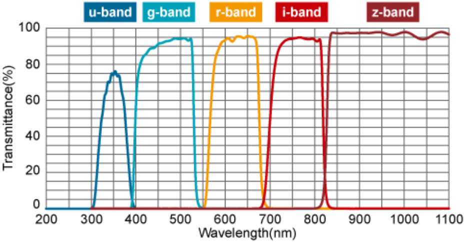
Counts in the pixels within the aperture

Magnitude inside the fiber's 3 arcsec ϕ aperture

Training dataset, Inputs (again xd)

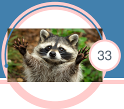
Input Information

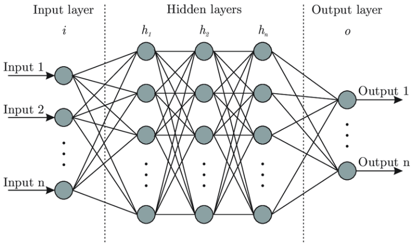
- Magnitudes, colors and errors
- Model and Aperture flux calc. methods
- Five optical bands



COLORS?! the substraction between two bands' magnitude $\rightarrow$ *r*-*g*

Neural Network





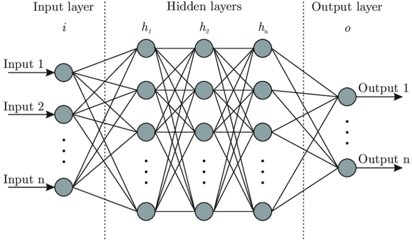
Classification method using internal layers of mathematical connections

Input: Photometric information
→ Training Data

Internal layers: trained parameters

Output: Binary Classification
→ Labels: Merger or Non-Merger

Neural Network



Classification method using internal layers of mathematical connections

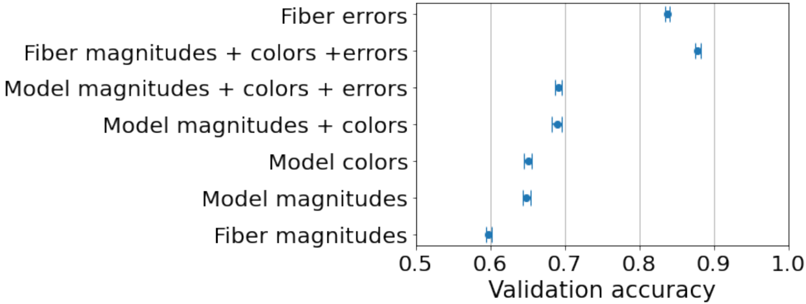
Input: Photometric information
→ Training Data

Internal layers: trained parameters

Output: Binary Classification
→ Labels: Merger or Non-Merger

- Automatized method
- Learning Properties: already-known and new ones!

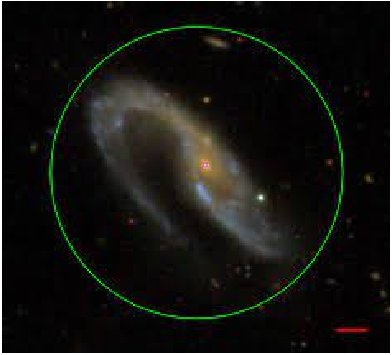
Photometric results



Credit: Suelves et al. +22

Fiber magnitude and errors

Magnitude inside the fiber's 3 arcsec ϕ aperture

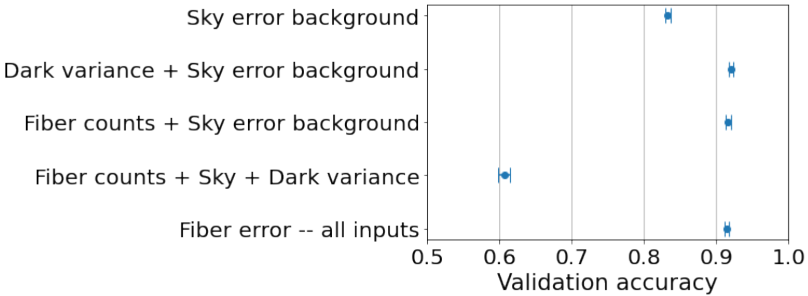


The fiber error depends on 4 parameters:

- Aperture counts
- Dark current variance
- Sky background
- Sky background error

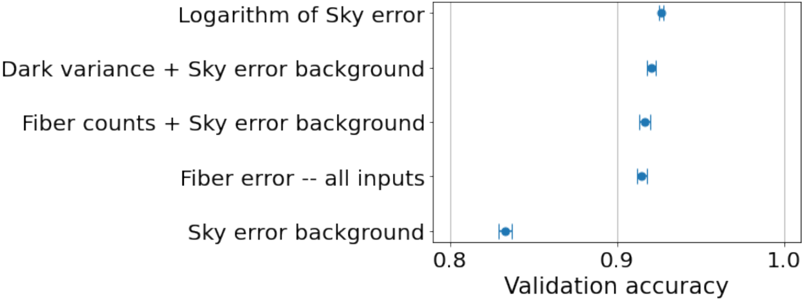
Fiber error input’s results

SDSS’s fibers



Credit: Suelves et al. +22

Logarithmic skyErr

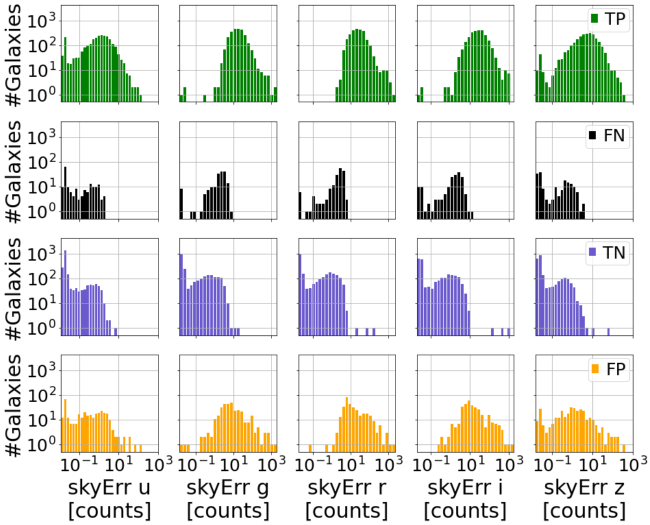


Credit: Suelves et al. +22

Logarithmic 5-bands sky error accuracy:

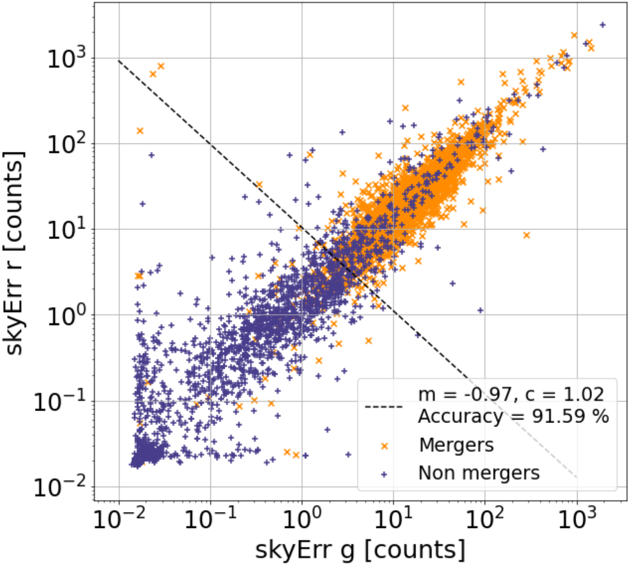
- Validation: 92.64 ± 0.15 %
- Test: 92.36 ± 0.21 %

Logarithmic skyErr, feature space



Credit: Suelves et al. +22

Decision Boundary



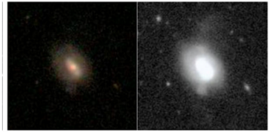
Credit: Suelves et al. +22

Sky background error

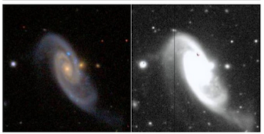
Physics

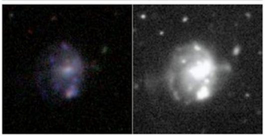
- sky error traces structures of too low S/N.

Merger remnants at different deepness: SDSS (color *g*-*r*-*i*) vs SDSS Stripe 82 (*r*)

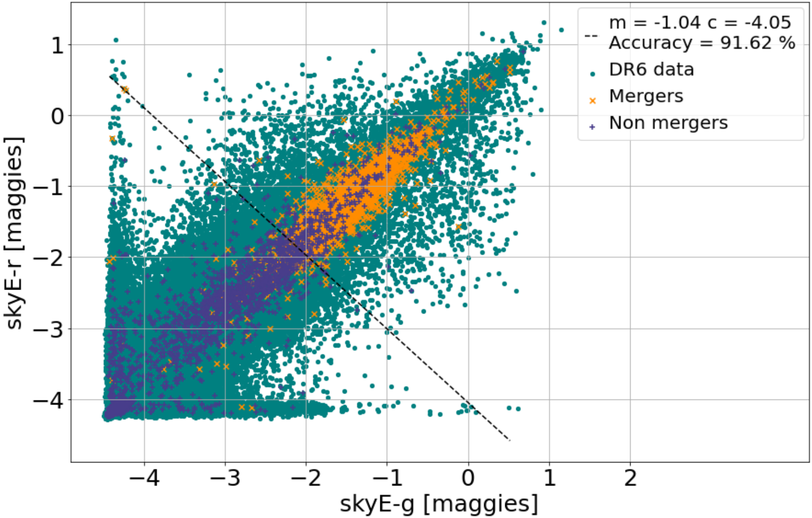


Credit: Kaviraj+14

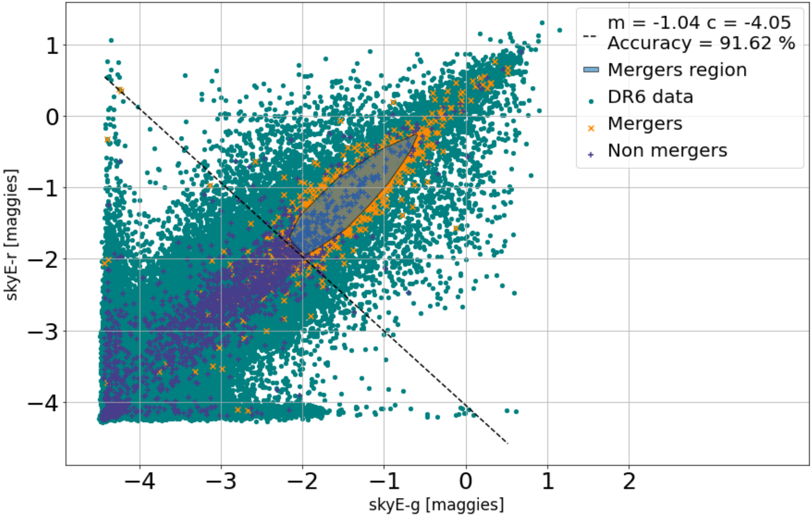




NOTE: Darg et al (2010) is a catalog of **merging pairs**, we still need to find merger remnants!



Total galaxies: 286 616   Mergers: 37 586   Merger Rate: 13.11%



Total galaxies: 286 616 Mergers: 24 756 Merger Rate: 8.64%

Current Work
SDSS DR6 mergers

Intro to the Tree and the Merging of galaxies

Merging galaxies identified on images

Merging galaxies identified on photometric meassurements

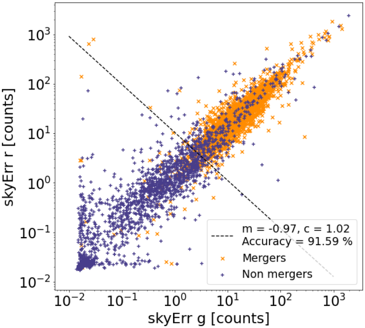
Sky background error

Conclusions

Conclusions

Future Work

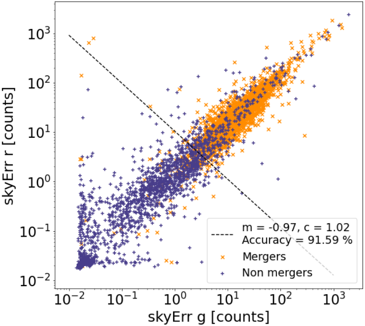
- Build a merger catalog of SDSS DR6 through skyErr *g*-*r* area
- Extend it to deeper images: NEP, comparing to Pearson et al. +22 catalog, and to future Galaxy Zoo: Cosmic Down results
- Extend it to deeper images, LSST!
- Apply a CNN on galaxy residuals: Dawid Chudy, from UJ, is testing it



Summary

Take-home message

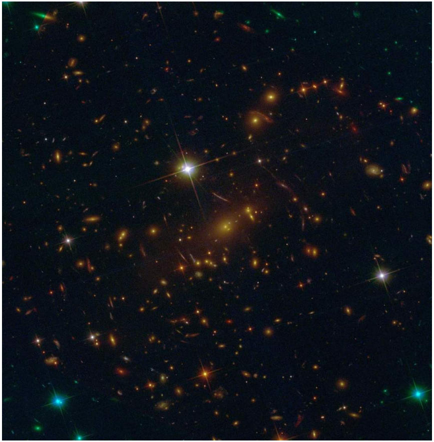
- **MIND THE ERRORS! There is where the physics are!**
- Catalog of Mergers in the North Elipctic Pole wide field
- NN led to discover an unknown property!
- Sky error as trace of merging processes



Thank you!

Galaxy Zoo: Cosmic Down

https://www.galaxyzoo.org/

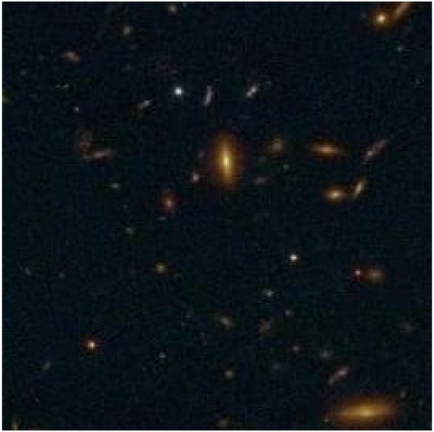


HST

JWST

HST vs JWST sky background?Zoom

Appendix 1



HST

JWST

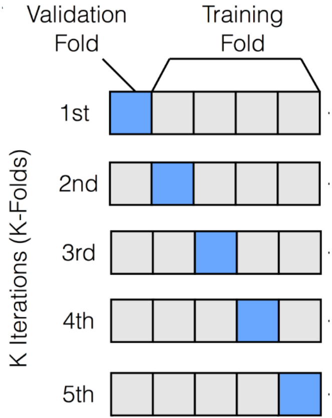
Binary Classification: labels Merger or Non-Merger

- 2 Dense layers of 16 neurons
- ReLU activation function
- 0.2 dropout rate
- Output: softmax probability
- Min-max normalization $x_{norm} = (x - min(x))/(max(x) - min(x))$

```
class photo_model(tf.keras.Model):
    def __init__(self):
        ## Im trying to name each layer and see if the loading is managed through it
        super(photo_model, self).__init__()
        self.drop_rate = 0.1

        self.fuco1 = tf.keras.layers.Dense(16,name='dens_1')
        self.batn1 = tf.keras.layers.BatchNormalization(name='btchn_1')
        self.drop1 = tf.keras.layers.Dropout(self.drop_rate,name='drop_1')

        self.fuco5 = tf.keras.layers.Dense(16,name='dens_2')
        self.batn5 = tf.keras.layers.BatchNormalization(name='btchn_2')
        self.drop5 = tf.keras.layers.Dropout(self.drop_rate,name='drop_1')

        self.y_out = tf.keras.layers.Dense(NO_CLASS, activation='softmax',name='out')
```

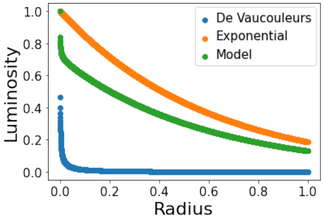
Adam training method

5-fold Validation



Model Magnitudes, Surface Brightness

Appendix 4



*

$frac_{DeV} = 0.3$

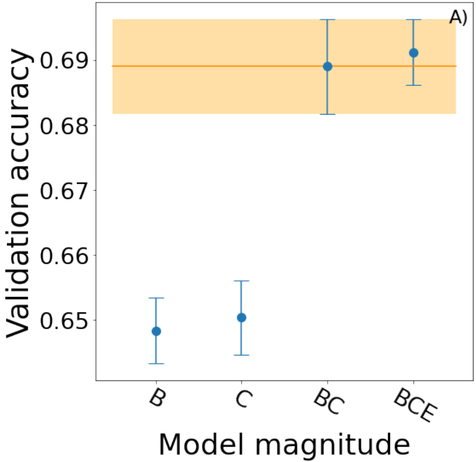
Model magnitude in SDSS

$$F_{\mathrm{model}} = frac_{DeV}\, F_{deV} + (1 - frac_{DeV})\, F_{exp} \ ,$$

Fluxes are calculated from integrating the Brightness Model (or Intensity Profile)

$$F \sim 2\pi \int_0^r I(r) r dr \ .$$

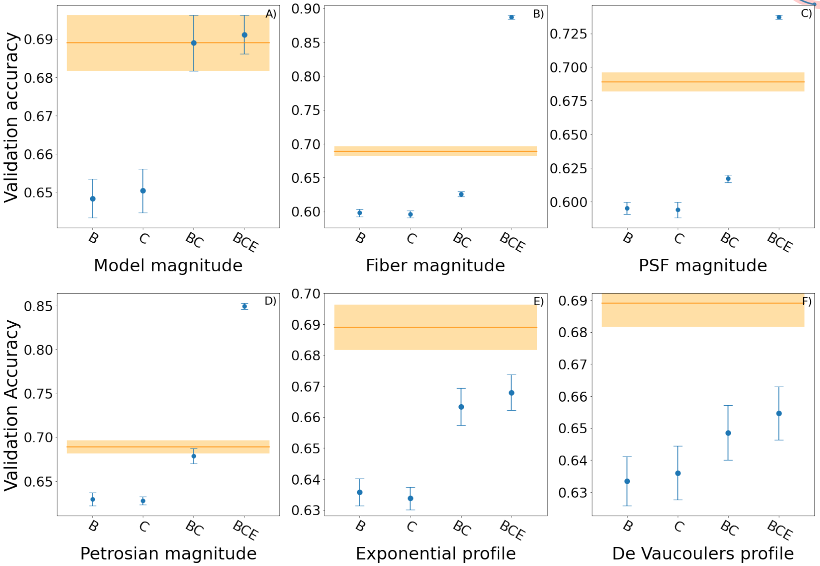
NN training over different Inputs
Appendix 5



Credit: Suelves et al. +22

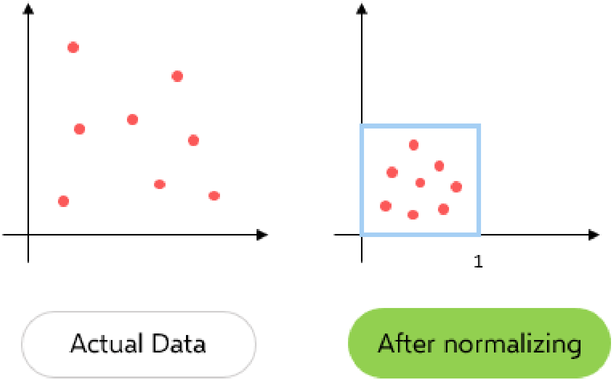
NN training over different Inputs

Appendix 5

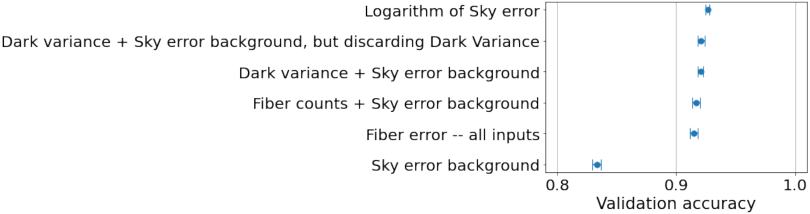


Feature X^{g} normalized to $x^{\mathrm{g}} \in [0,1]$ for **each galaxy**

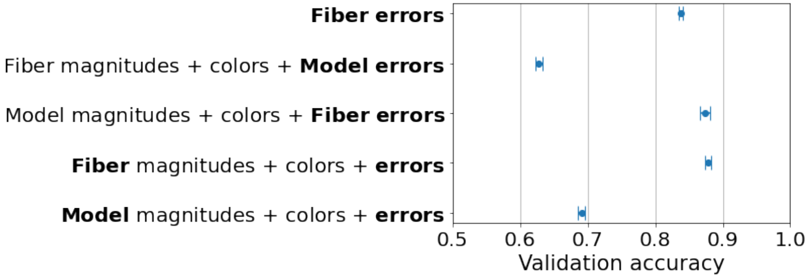
$$x^{\mathrm{g}} = \frac{X^{\mathrm{g}} - \min(X^{\mathrm{g}})}{\max(X^{\mathrm{g}}) - \min(X^{\mathrm{g}})}$$



Normalization importance
Appendix 7



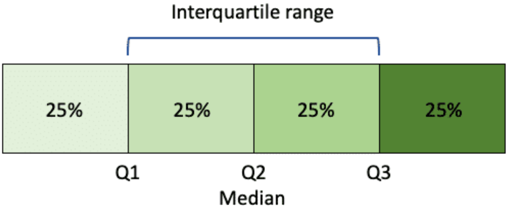
Credit: Suelves et al. +22



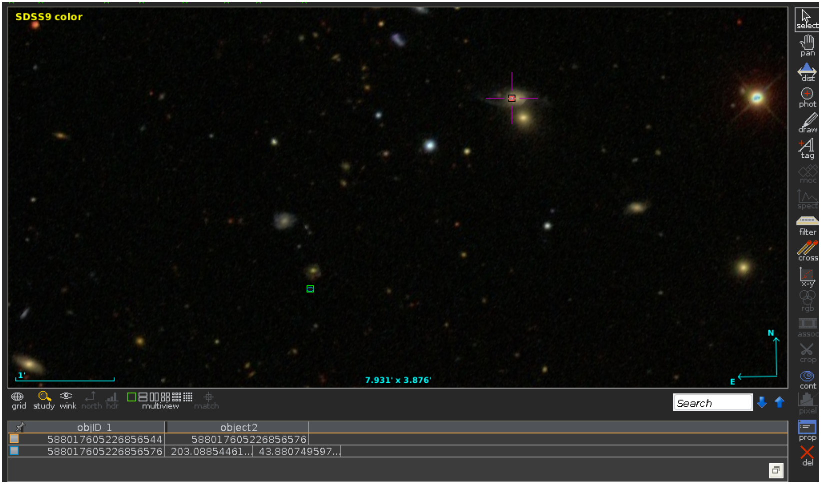
Credit: Suelves et al. +22

Calculation

- detections flagged as bright are subtracted (above 60σ)
- background clipped median, interpolation between 256x256 pix boxes centered every 128



This is a merger from Darg et al. (2010), **does it have a pair companion??**



SDSS9 color
1'
7.931' x 3.876'
N
E
select
pan
dist
phot
draw
tag
moc
spect
filter
cross
x-y
rgb
assoc
crop
cont
pixel
prop
del
grid
study
wink
north
hdr
multiview
match
Search
objID 1
object2
588017605226856544
588017605226856576
588017605226856576
203.08854461...
43.880749597...

Fiber error calculation

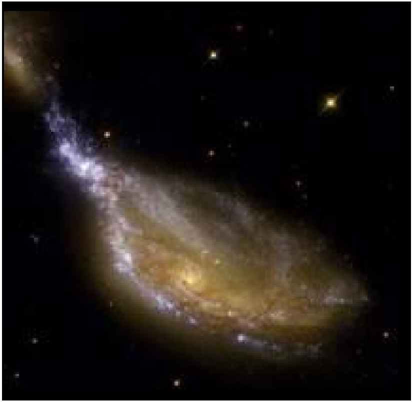
Appendix 10

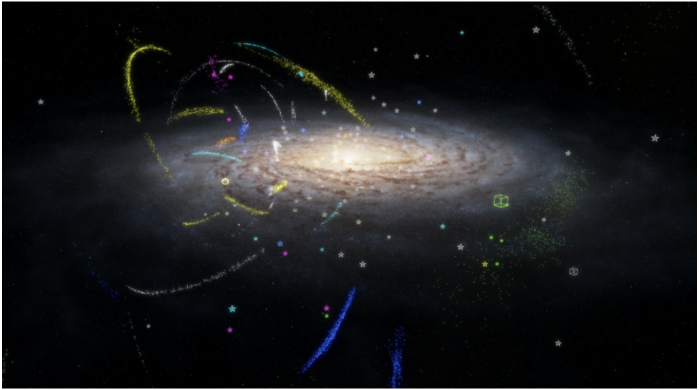
Magnitude error

$$\sigma_m^{\mathrm{new}} = \frac{2.5}{\ln 10} \frac{\sigma_{\texttt{counts}}}{f_0} \frac{1}{\sqrt{4b^2 + \left(\frac{f}{f_0}\right)^2}} \ , \tag{1}$$

Counts error

$$\begin{aligned} \sigma_{\texttt{counts}}^{\mathrm{new}} = \Bigg[& \frac{\texttt{counts} + (\texttt{sky} \cdot A_{\mathrm{pixels}})}{\mathrm{gain}} + \\ & A_{\mathrm{pixels}} \cdot (\texttt{dark variance} + \texttt{skyErr}^2) \Bigg]^{1/2} \ . \end{aligned} \tag{2}$$





Credit: Max Planck Institute

- Halo contains the oldest stars in the galaxy
- The dynamics of the halo stars archive of the Milky Way's interactions with its surroundings
- Stellar Streams: associations of stars that were torn apart and stretched out by tidal forces
- (7th mergers is possible to be within the data)