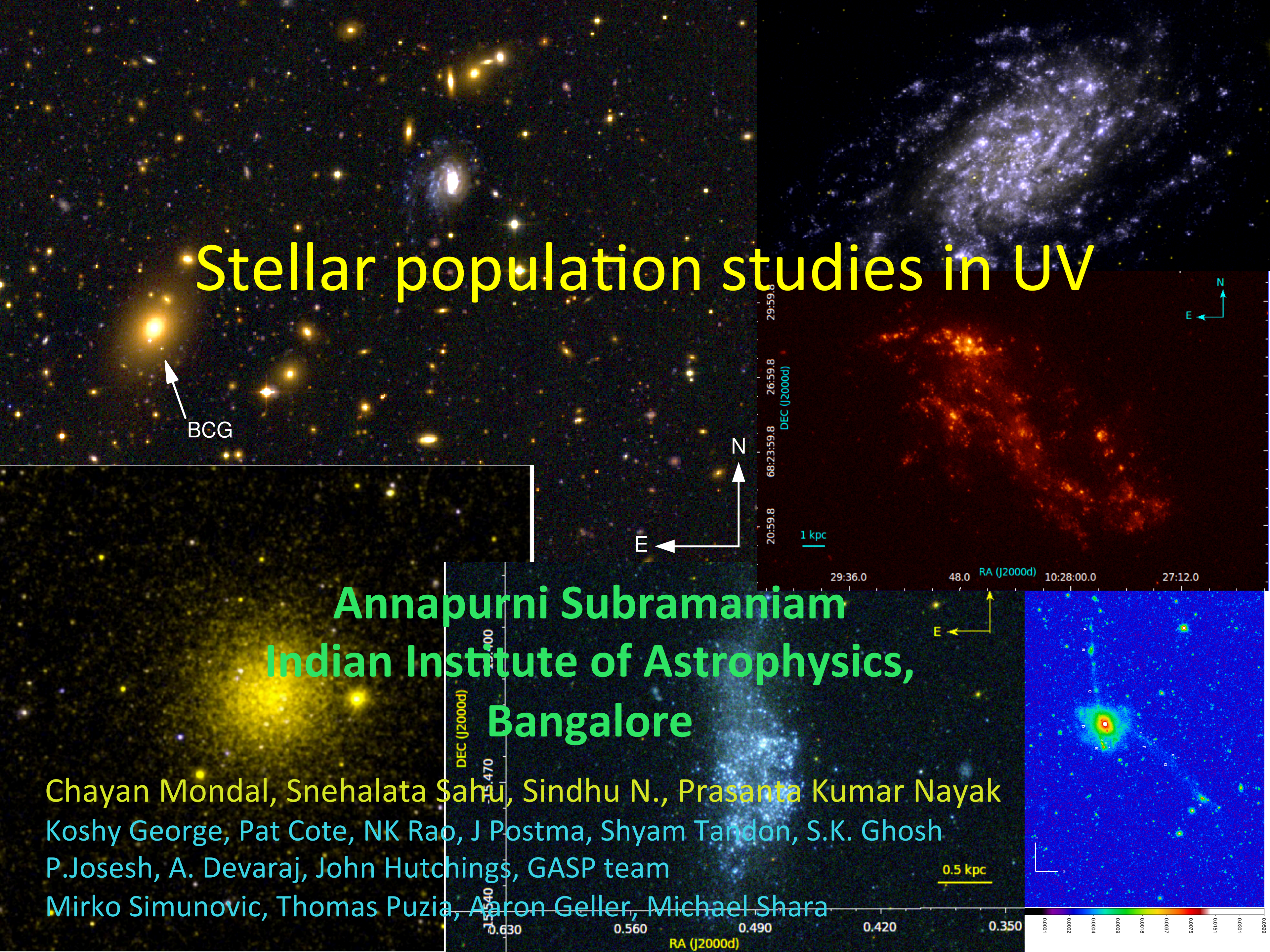


Stellar population studies in UV

Annapurni Subramaniam
Indian Institute of Astrophysics, Bangalore

Chayan Mondal, Snehalata Sahu, Sindhu N., Prasanta Kumar Nayak
Koshy George, Pat Cote, NK Rao, J Postma, Shyam Tandon, S.K. Ghosh
P.Josesh, A. Devaraj, John Hutchings, GASP team
Mirko Simunovic, Thomas Puzia, Aaron Geller, Michael Shara

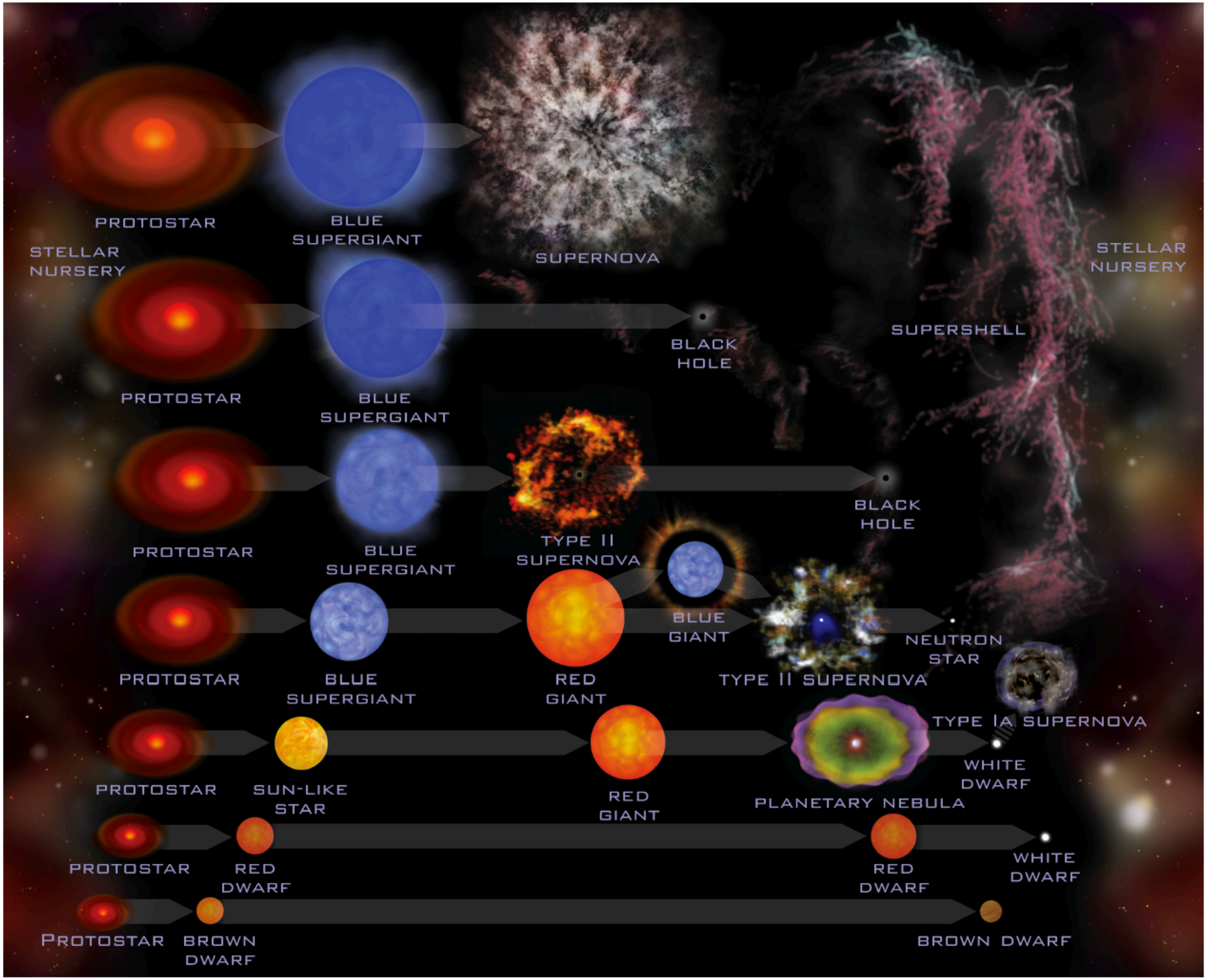
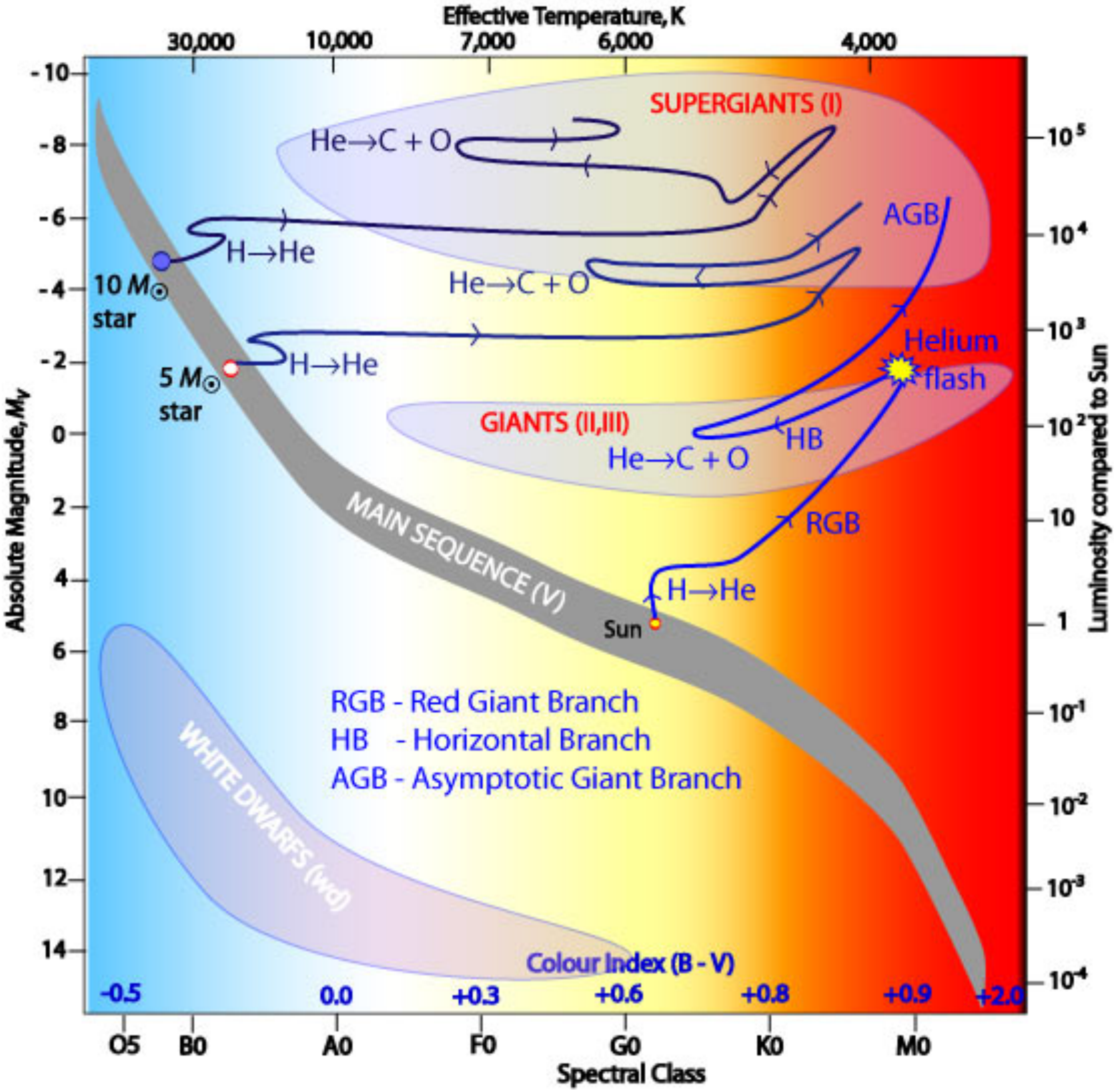
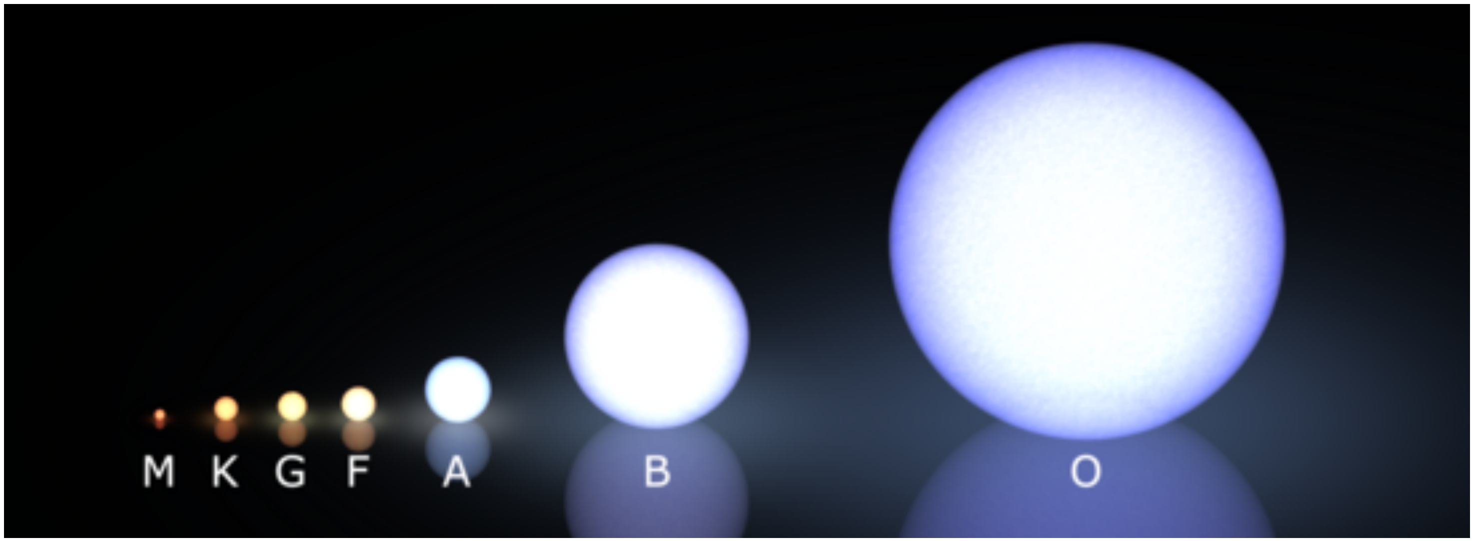


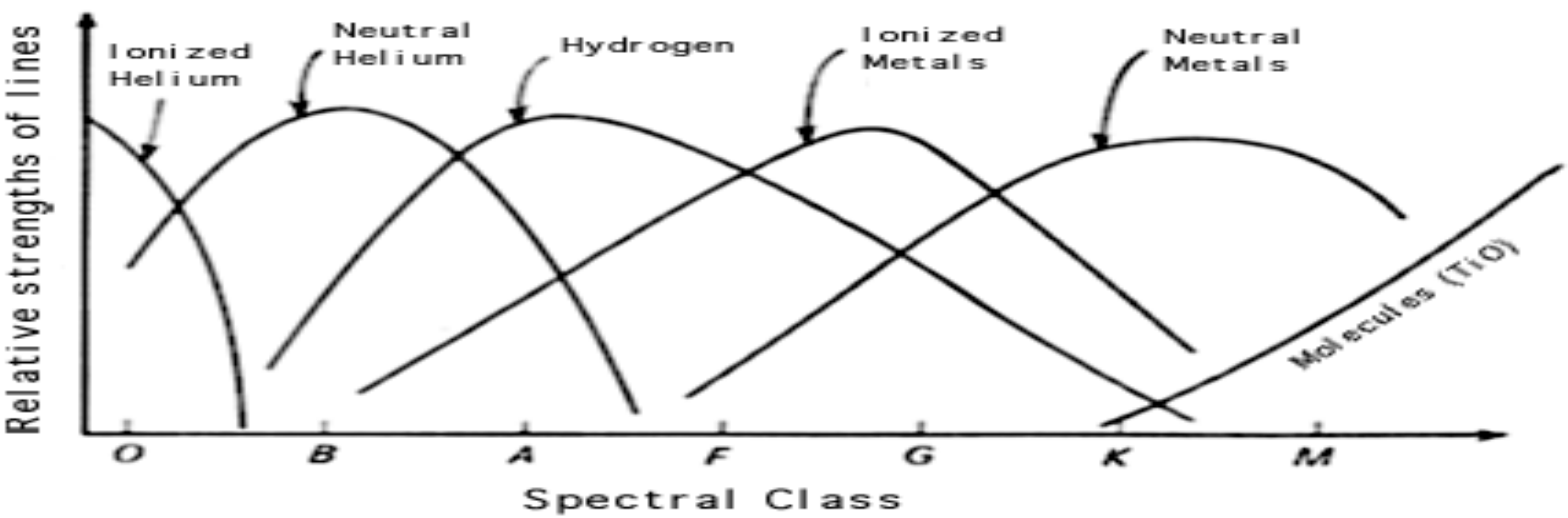
Figure 1.1: Image depicting birth, evolution and death of stars. The mass of the star increases on the y-axis and the time evolution is represented on the x-axis, from left to right. Credit: Jet Propulsion Laboratory.

Evolutionary Tracks off the Main Sequence



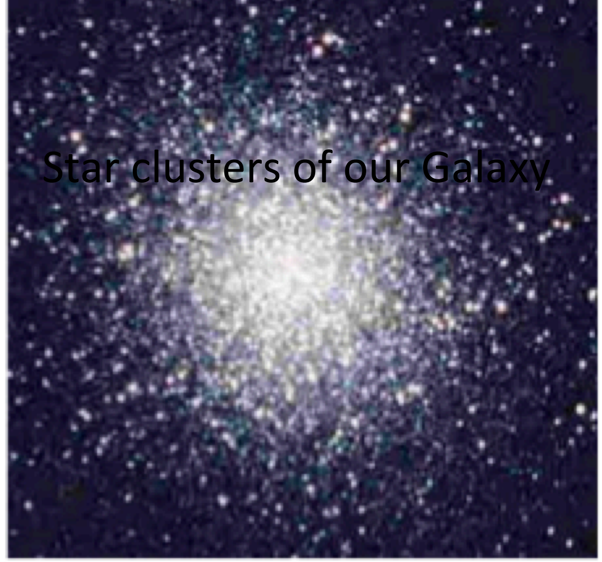
Stars of different colors





Star clusters of our Galaxy

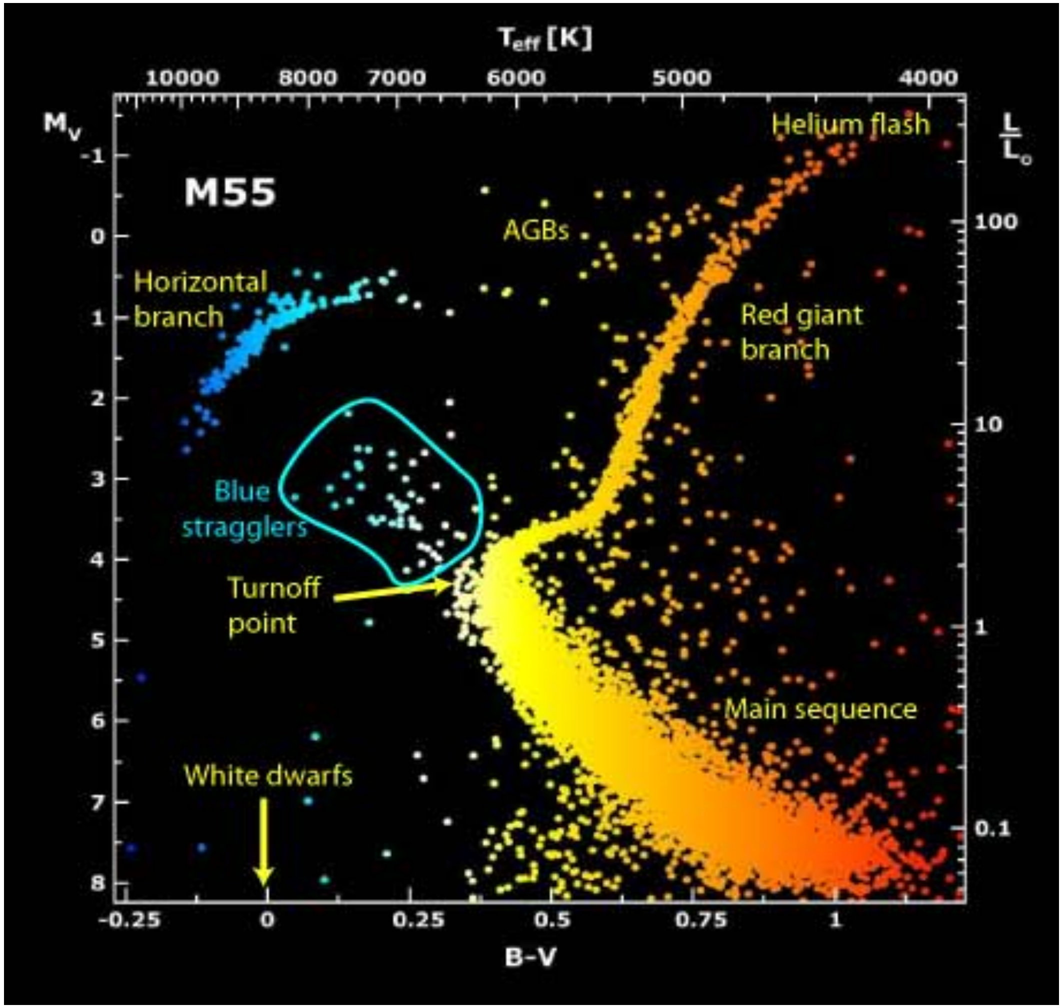
Open cluster



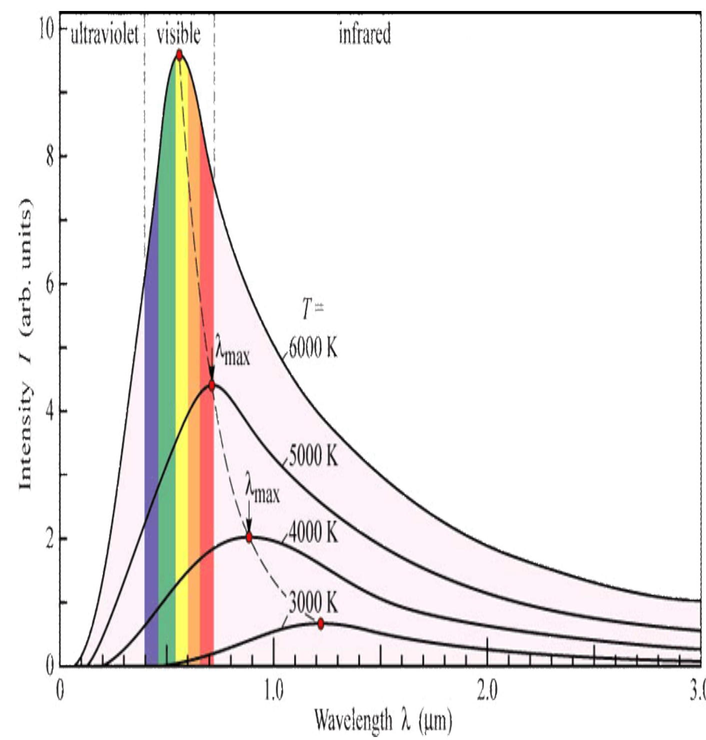
Globular Cluster

OB associations

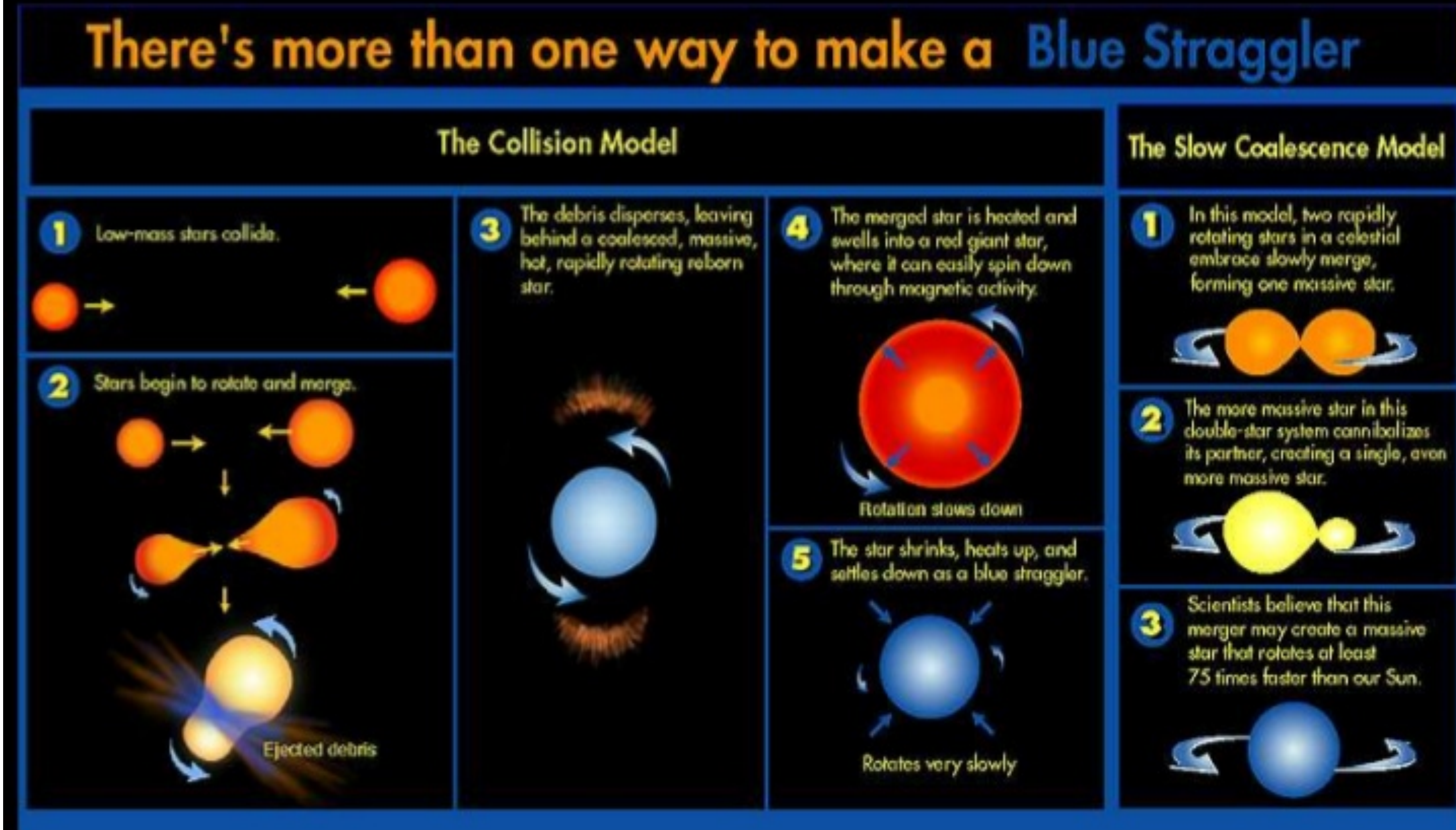
NGC 1300



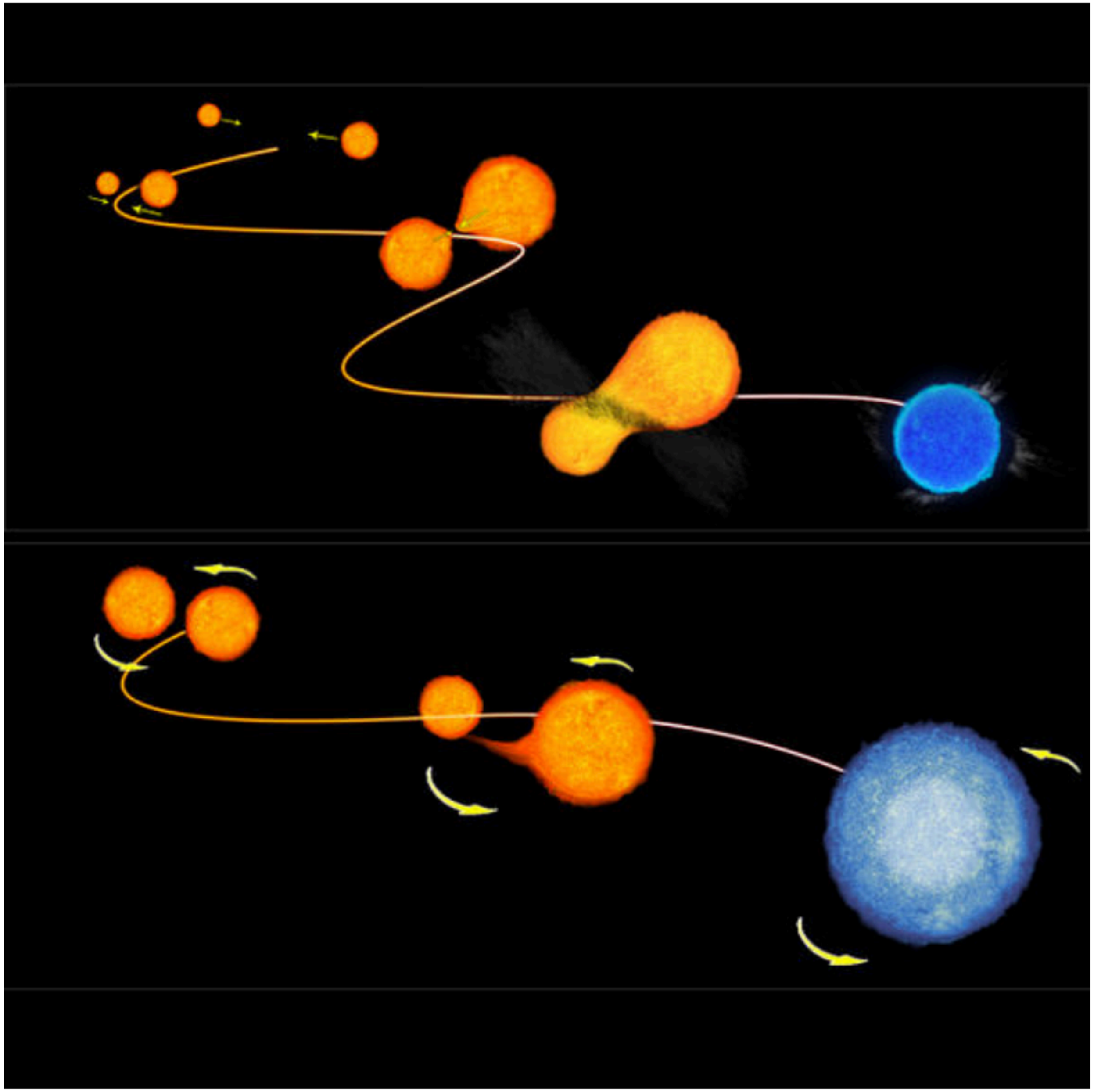
T_eff [K]
10000
8000
7000
6000
5000
4000
M_V
L/L☉
M55
Helium flash
AGBs
Horizontal branch
Red giant branch
Blue stragglers
Turnoff point
Main sequence
White dwarfs
-1
0
1
2
3
4
5
6
7
8
100
10
1
0.1
-0.25
0
0.25
0.5
0.75
1
B-V



ultraviolet
visible
infrared
Intensity I (arb. units)
T =
6000 K
5000 K
4000 K
3000 K
λmax
λmax
0
2
4
6
8
10
0
1.0
2.0
3.0
Wavelength λ (μm)



There's more than one way to make a Blue Straggler
The Collision Model
The Slow Coalescence Model
1 Low-mass stars collide.
2 Stars begin to rotate and merge.
Ejected debris
3 The debris disperses, leaving behind a coalesced, massive, hot, rapidly rotating reborn star.
4 The merged star is heated and swells into a red giant star, where it can easily spin down through magnetic activity.
Rotation slows down
5 The star shrinks, heats up, and settles down as a blue straggler.
Rotates very slowly
1 In this model, two rapidly rotating stars in a celestial embrace slowly merge, forming one massive star.
2 The more massive star in this double-star system cannibalizes its partner, creating a single, even more massive star.
3 Scientists believe that this merger may create a massive star that rotates at least 75 times faster than our Sun.



An artist's conception of how a blue straggler may form from a binary system. Credit: NASA/ESA

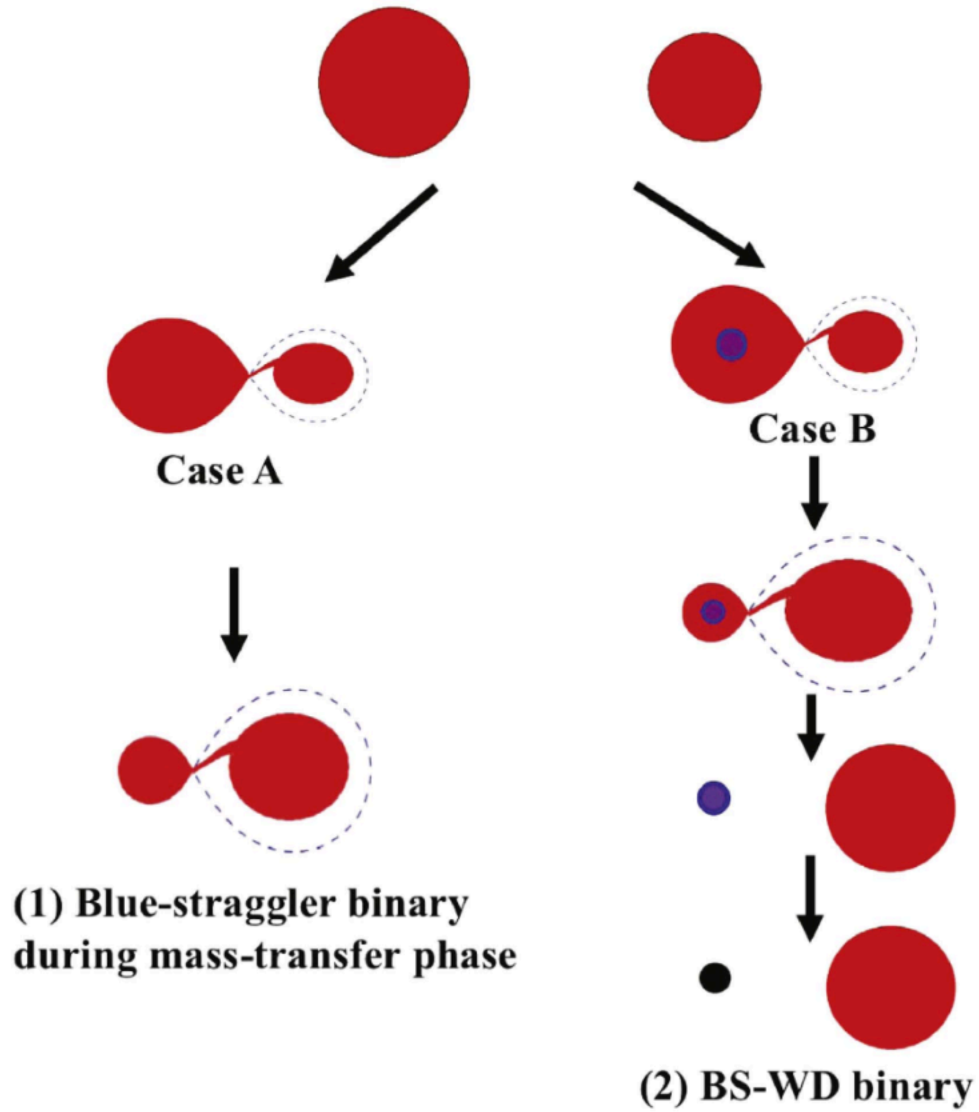
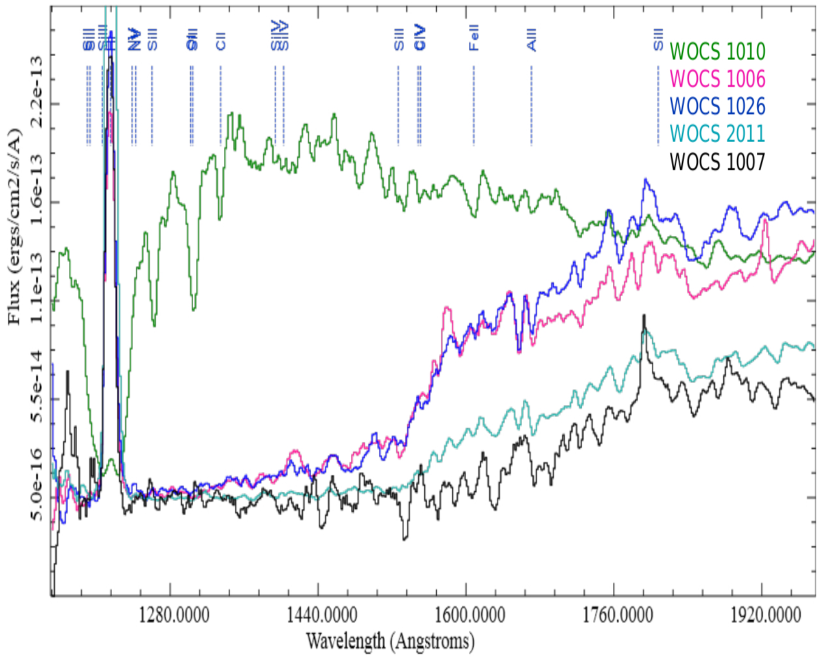


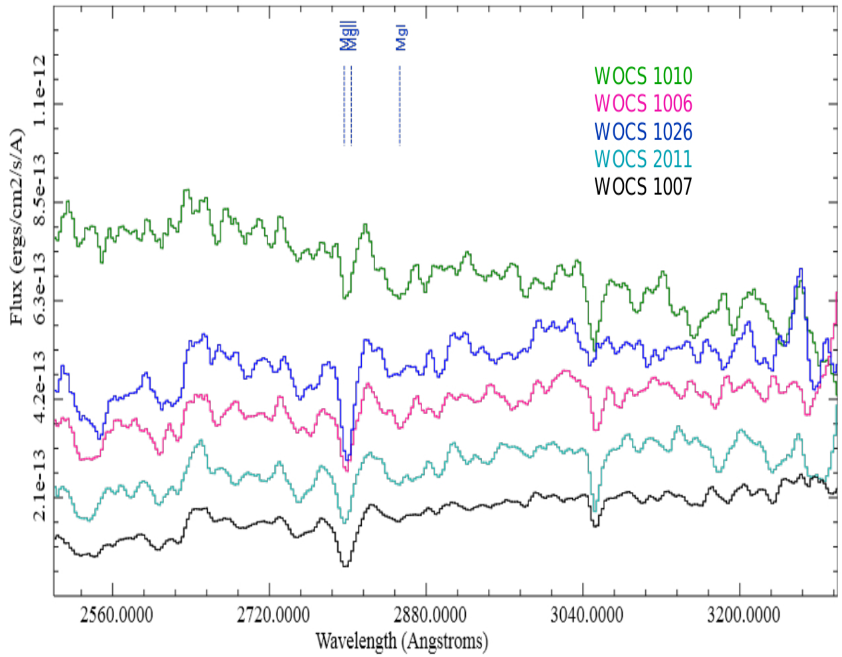
Figure 1. Schematic view of the evolutionary paths of binaries that produce two kinds of blue-straggler binaries. (1) Case A binary evolution may produce blue straggler binaries that are experiencing mass transfer. (2) Case B binary evolution may produce blue-straggler binaries that have finished mass transfer and have a blue straggler orbiting a white dwarf (the BS–WD binaries).

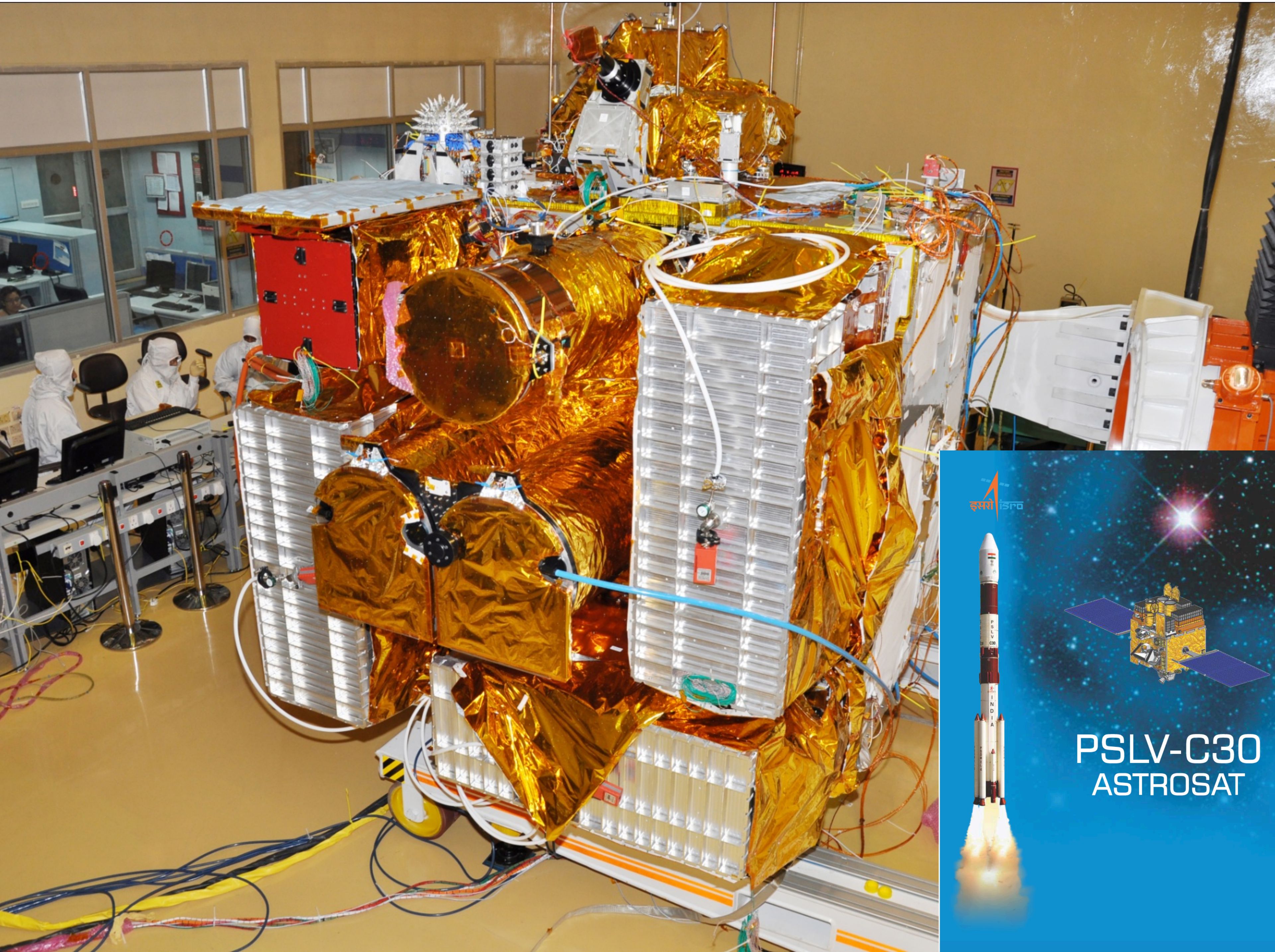
Sources UV flux

- Young O/B Stars
- White Dwarfs
- Hot spots on contact and semi-detached binaries
  - Hot Spots with temperature 4000 to 11000 K (Kouzuma 2018)
- Flairs – Transient
- Chromospheric Activity – Low Temperature ~8000 K (Hall 2008)
- Coronal emissions – Low density, Low Flux
- Note: Hot spots, very hot WD, flairs, coronal activity also produce X-rays

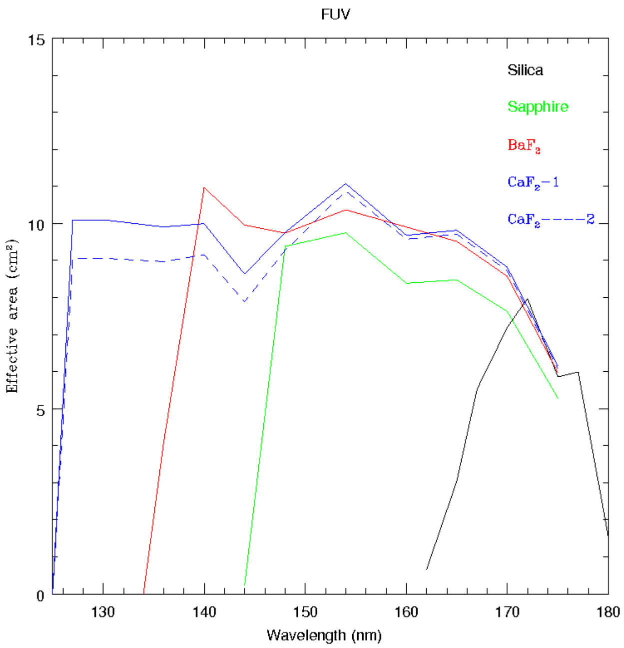
IUE spectra (archival) of Blue straggler stars

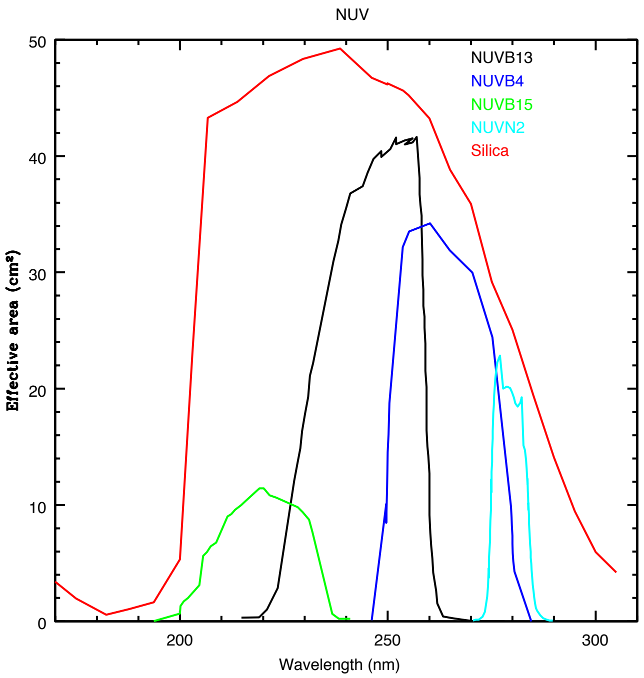


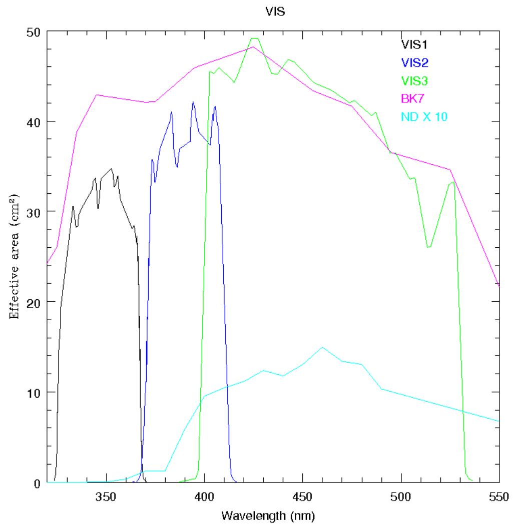



इसरो isro
PSLV-C30
ASTROSAT

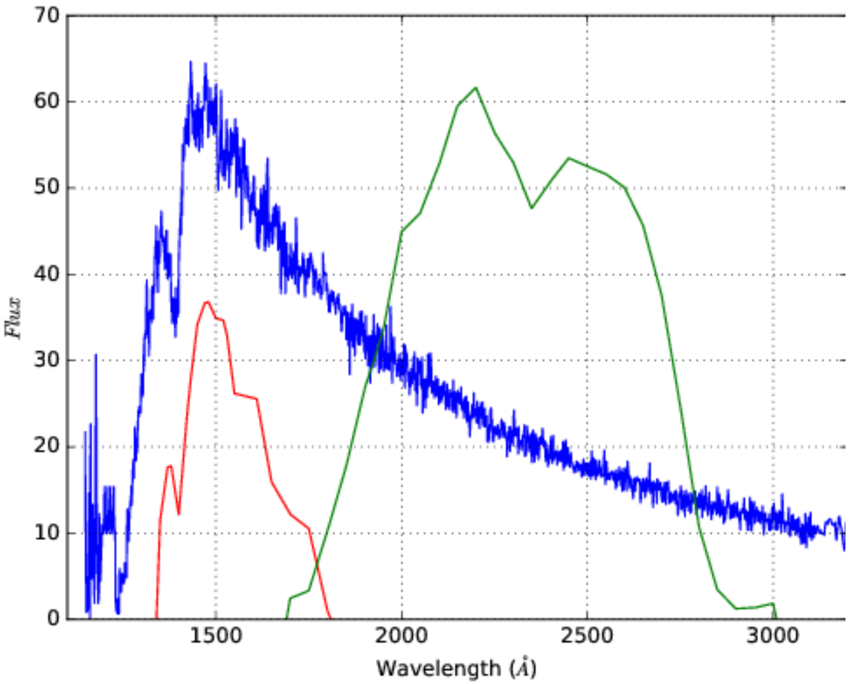
Effective areas of the UVIT filters



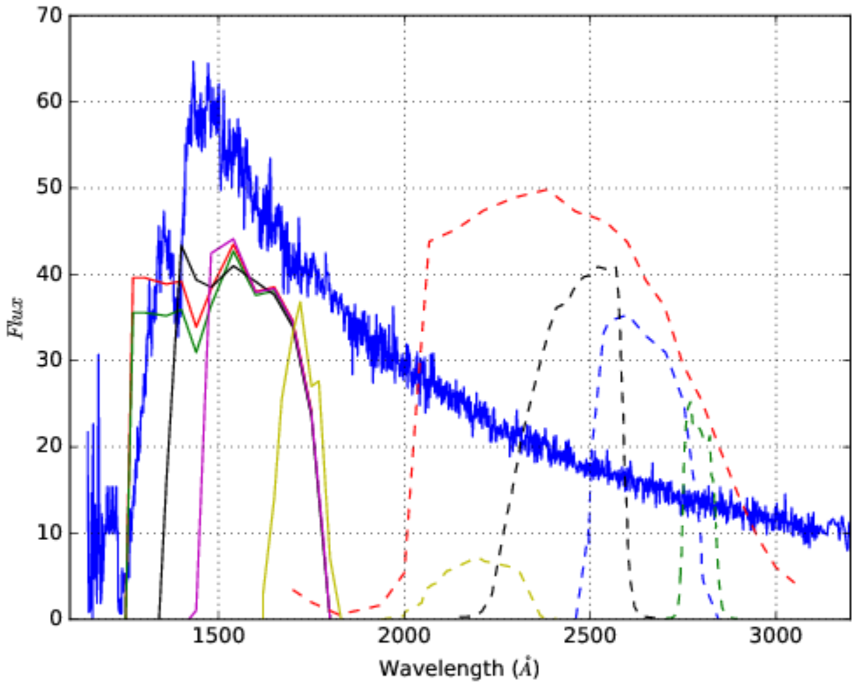




Multiple filters of UVIT



GALEX Filters



UVIT filters

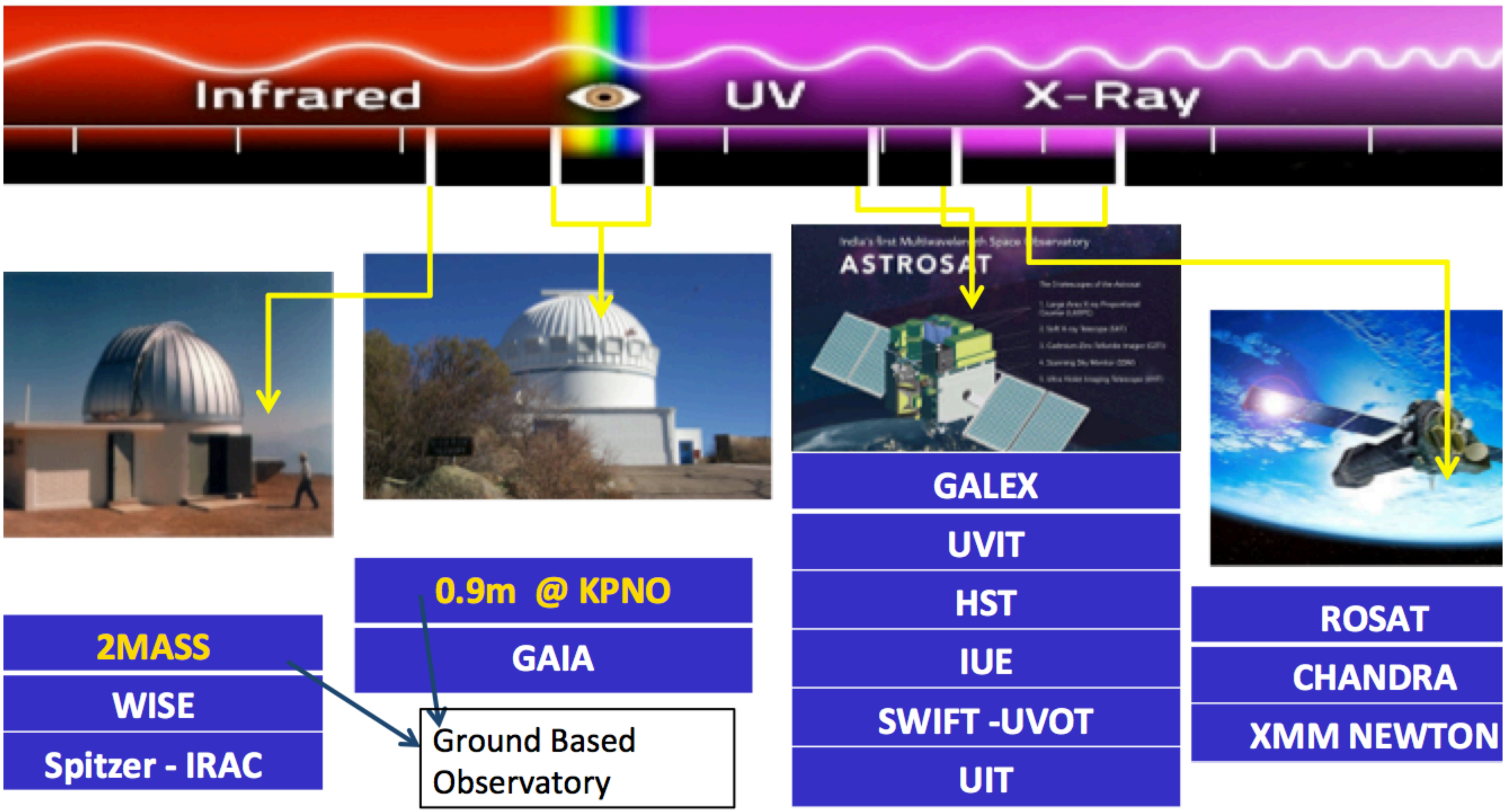
Observations - details

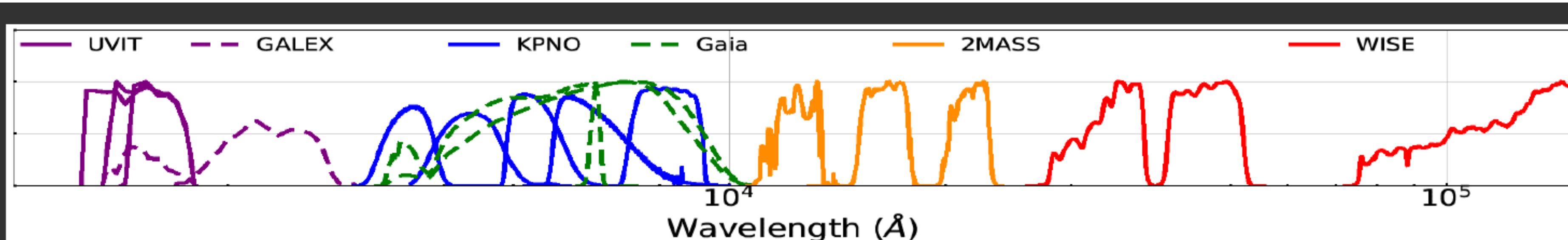
- Orbit of 90 min
- Observed only in the night part of the orbit
- Exposure time per orbit: 10 – 25min
- Minimum exposure time 120sec
- All 3 channels observe simultaneously
- FUV & NUV – PC mode, VIS – only INT mode, mainly for drift correction

Objects observed by various teams (for example):

1. Star forming galaxies
2. Active Galactic Nuclei
3. Planetary nebulae
4. Supernovae remnants
5. Exo-planets
6. Star clusters (Globular and open)
7. Cataclysmic variables, Be stars, X-ray binaries
8. Galaxy clusters
9. Chandra/HST deep fields

Multi-wavelength data





THE ASTROPHYSICAL JOURNAL LETTERS, 833:L27 (5pp), 2016 December 20 doi:10.3847/2041-8213/833/2/L27

A HOT COMPANION TO A BLUE STRAGGLER IN NGC 188 AS REVEALED BY THE ULTRA-VIOLET IMAGING TELESCOPE (UVIT) ON ASTROSAT

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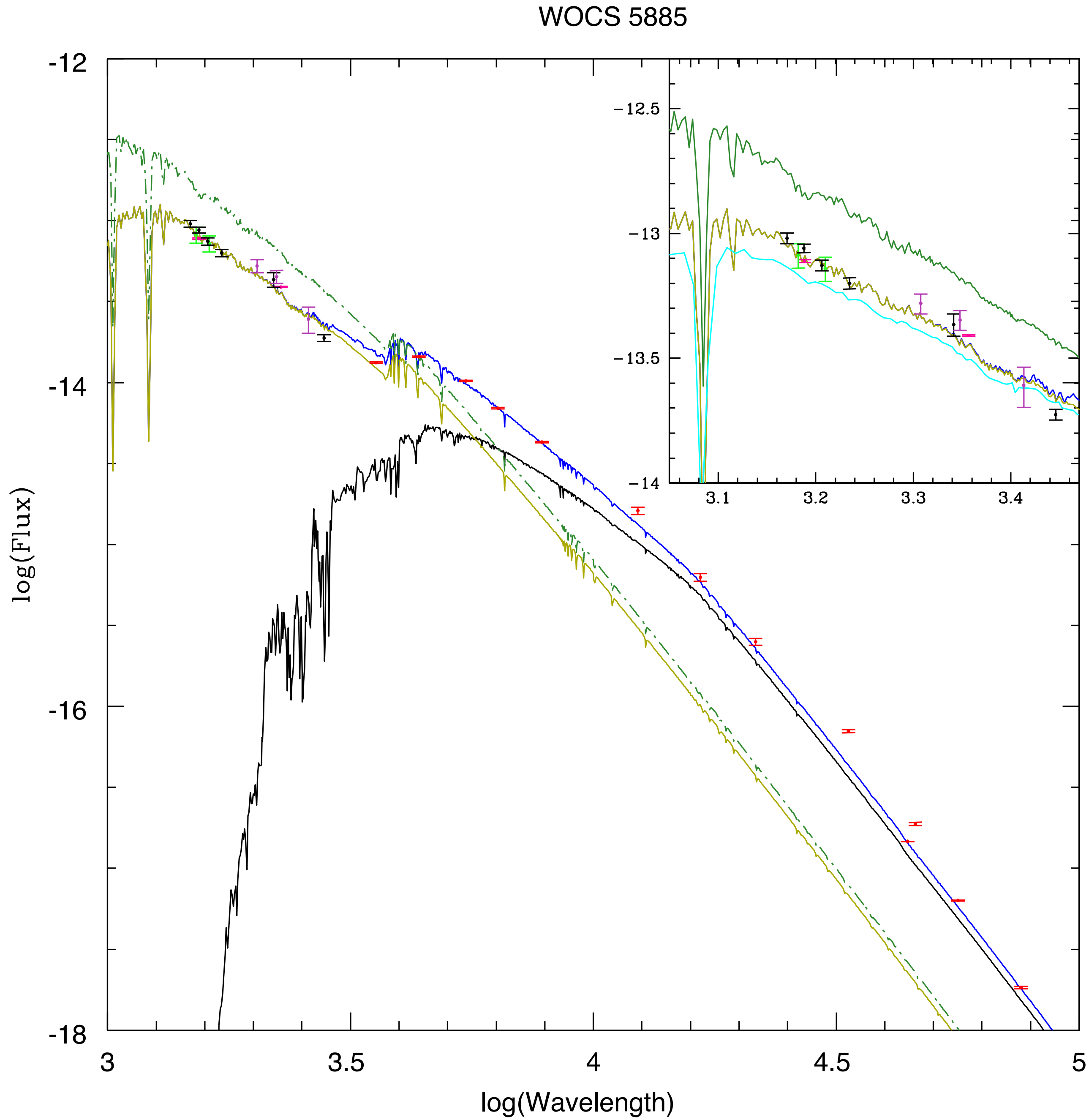
ABSTRACT

We present early results from the Ultra-Violet Imaging Telescope (UVIT) on board the ASTROSAT observatory. We report the discovery of a hot companion associated with one of the blue straggler stars (BSSs) in the old open cluster, NGC 188. Using fluxes measured in four filters in UVIT's far-UV (FUV) channel, and two filters in the near-UV (NUV) channel, we have constructed the spectral energy distribution (SED) of the star WOCS-5885, after combining with flux measurements from *GALEX*, Ultraviolet Imaging Telescope, Ultraviolet Optical Telescope, *SPITZER*, *WISE*, and several ground-based facilities. The resulting SED spans a wavelength range of 0.15 μm to 7.8 μm. This object is found to be one of the brightest FUV sources in the cluster. An analysis of the SED reveals the presence of two components. The cooler component is found to have a temperature of 6000 ± 150 K, confirming that it is a BSS. Assuming it to be a main-sequence star, we estimate its mass to be $\sim$1.1–1.2 $M_{\odot}$. The hotter component, with an estimated temperature of 17,000 ± 500 K, has a radius of $\sim$ 0.6 $R_{\odot}$ and $L \sim 30\, L_{\odot}$. Bigger and more luminous than a white dwarf, yet cooler than a sub-dwarf, we speculate that it is a post-AGB/HB star that has recently transferred its mass to the BSS, which is known to be a rapid rotator. This binary system, which is the first BSS with a post-AGB/HB companion identified in an open cluster, is an ideal laboratory to study the process of BSS formation via mass transfer.

Key words: binaries: general – blue stragglers – open clusters and associations: individual (NGC 188)



WOCS 5885
log(Flux)
log(Wavelength)
-12
-14
-16
-18
3
3.5
4
4.5
5
−12.5
−13
−13.5
−14
3.1
3.2
3.3
3.4

THE ASTRONOMICAL JOURNAL

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The Horizontal Branch Population of NGC 1851 as Revealed by the Ultraviolet Imaging Telescope (UVIT)

Annapurni Subramaniam[1], Snehalata Sahu[1], Joseph E. Postma[2], Patrick Côté[3], J. B. Hutchings[3], N. Darukhanawalla[3], Chul Chung[4], S. N. Tandon[1,5], N. Kameswara Rao[1], K. George[1], S. K. Ghosh[6,7], V. Girish[8], R. Mohan[1], J. Murthy[1], A. K. Pati[1], K. Sankarasubramanian[1,8,9], C. S. Stalin[1], and S. Choudhury[10] — Hide full author list

Published 2017 November 17 •

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+ Article information

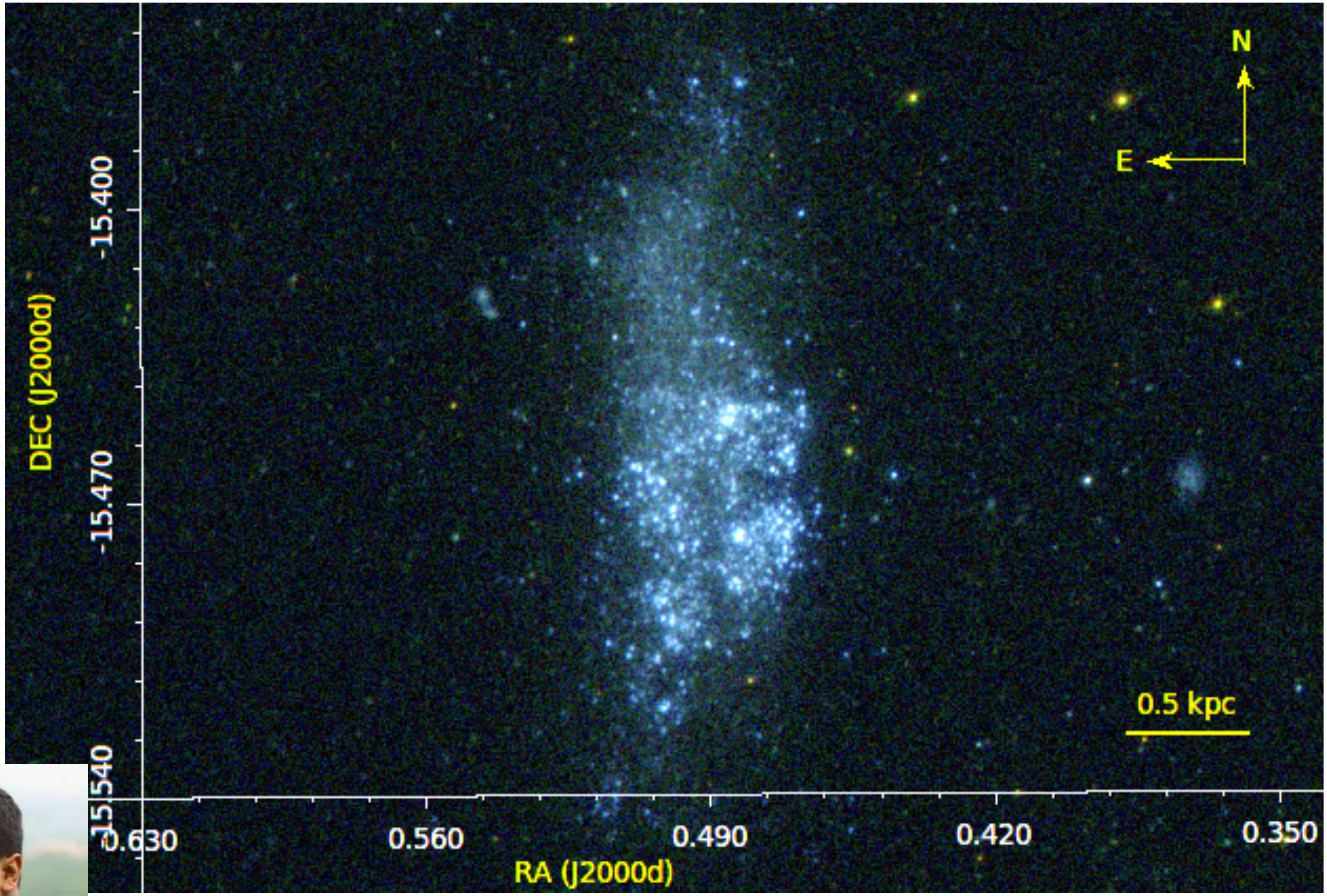
Abstract

Abstract

We present the UV photometry of the globular cluster NGC 1851 using images acquired with the Ultraviolet Imaging Telescope (UVIT) onboard the *ASTROSAT* satellite. Point-spread function fitting photometric data derived from images in two far-UV (FUV) filters and one near-UV (NUV)

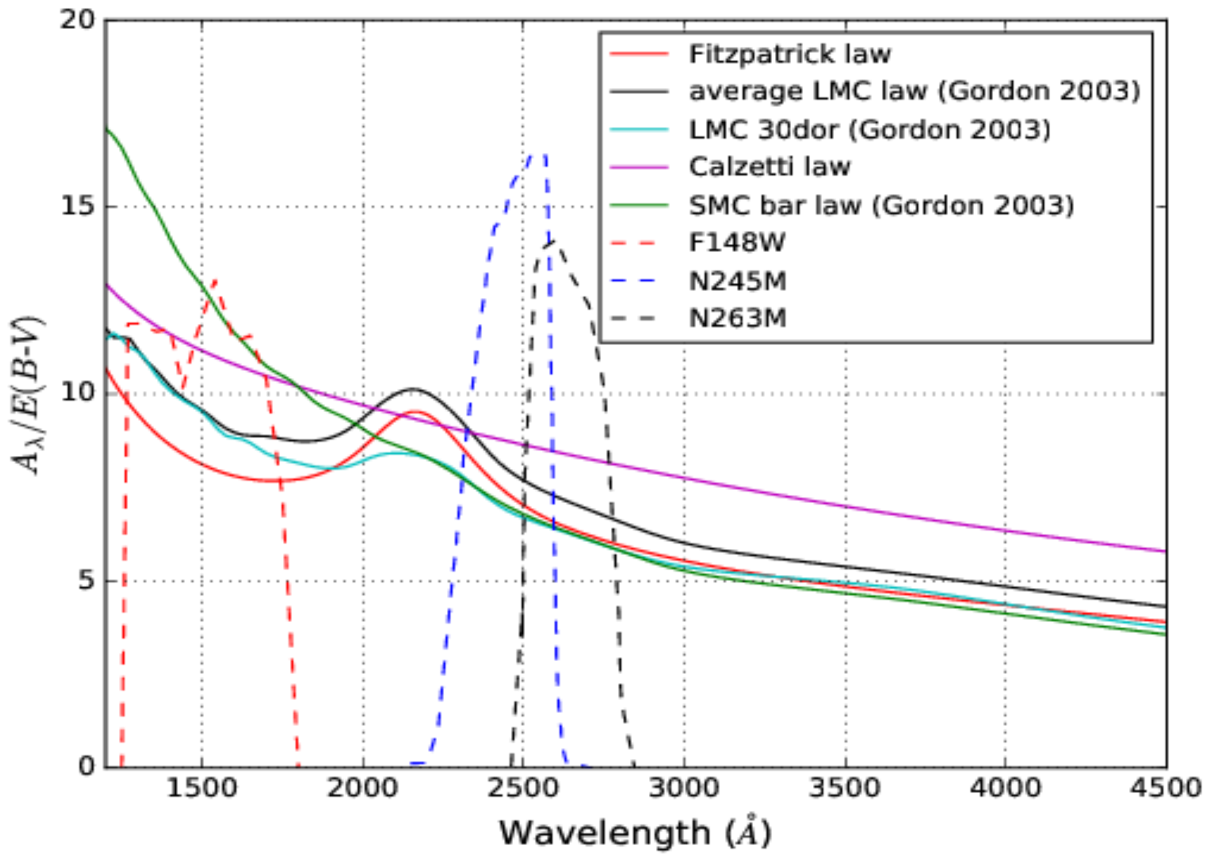
WLM – metal poor isolated dwarf irregular galaxy

Distance – 995 kpc (First APOM picture)



Mondal, Subramaniam & George (AJ, 2018) *arXiv:1807.07359*

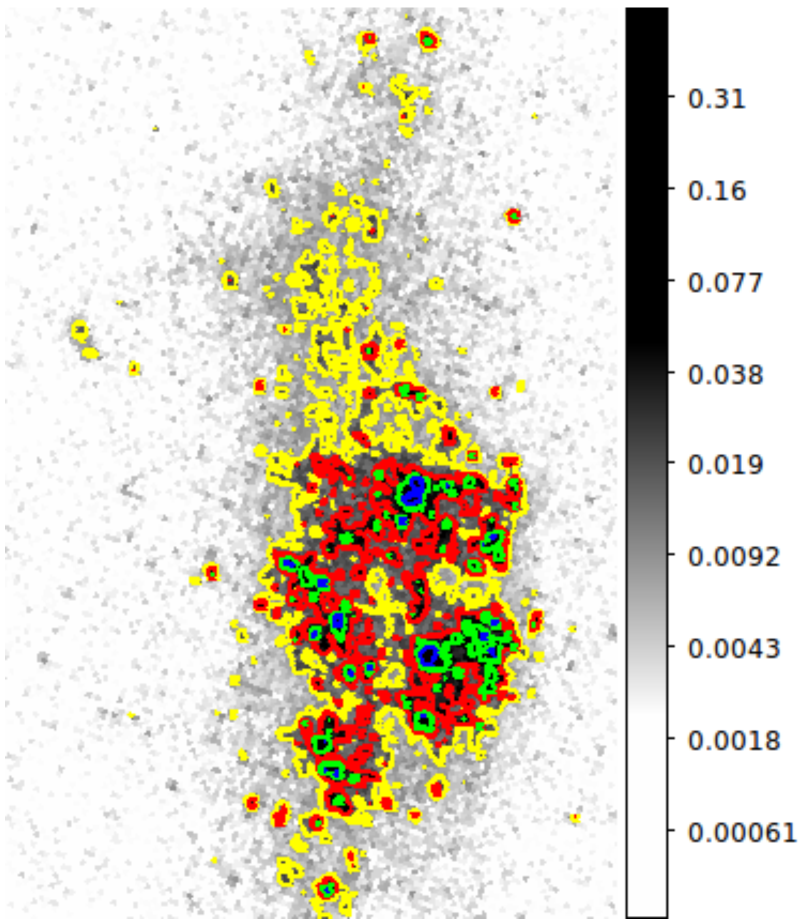
Extinction in UV

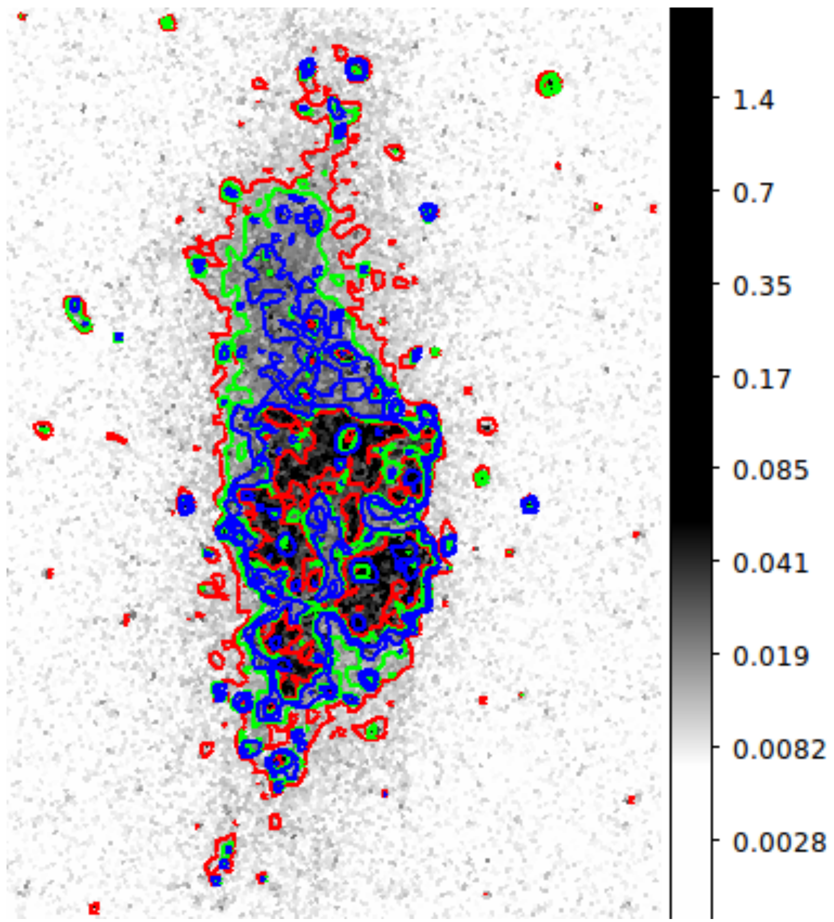


Average LMC reddening Law Is used for WLM– note the location of NUV filters

Structure of UV emission

The NUV disk is more extended than the FUV disk (1.7kpc)



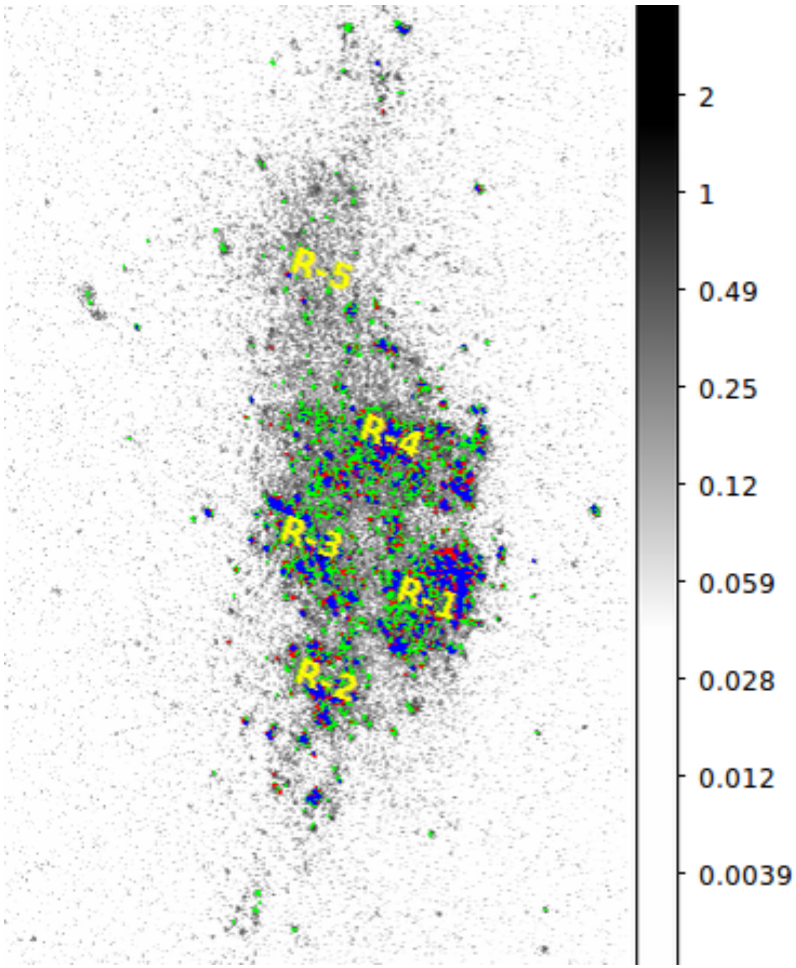


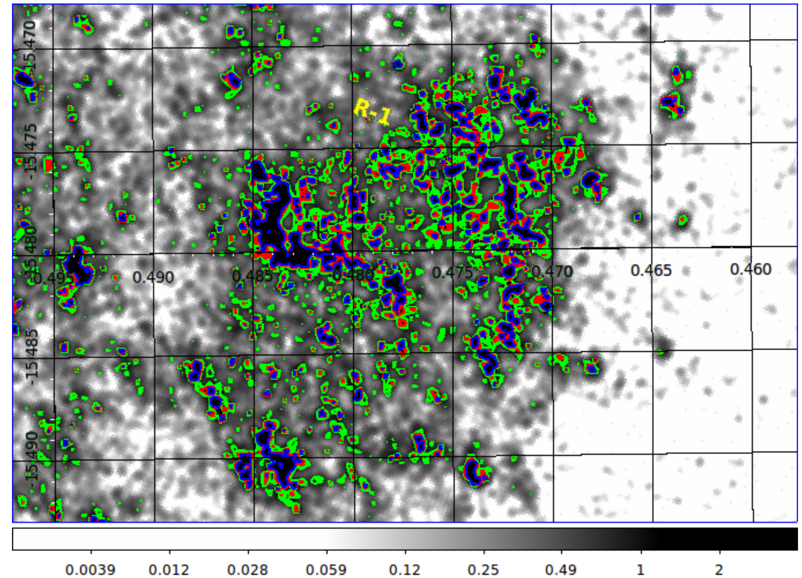
Blue < 20 mag
Green 20 – 21 mag
Red 21- 22 mag
Yellow 22 – 23 mag

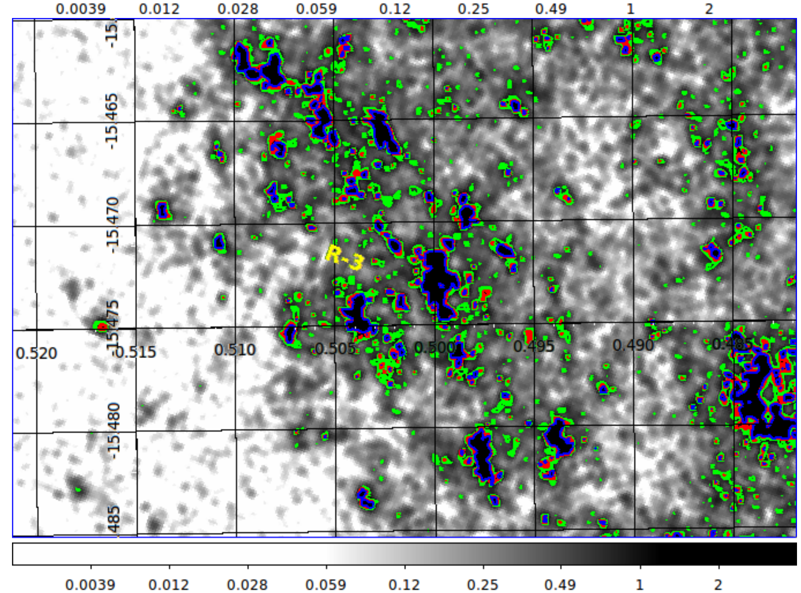
Blue - F148W
Green – N245M
Red – N263M

Color map - Temperature morphology

The SFR are highly structured and shows a hierarchical nature
Largest SFR ~50pc; A large number of regions less than 20pc



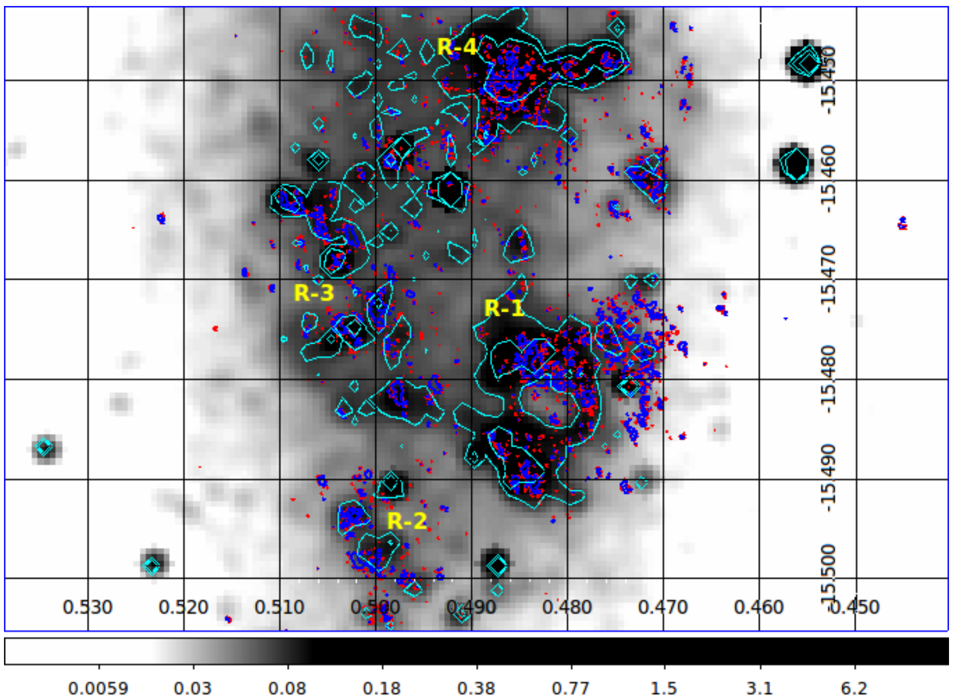




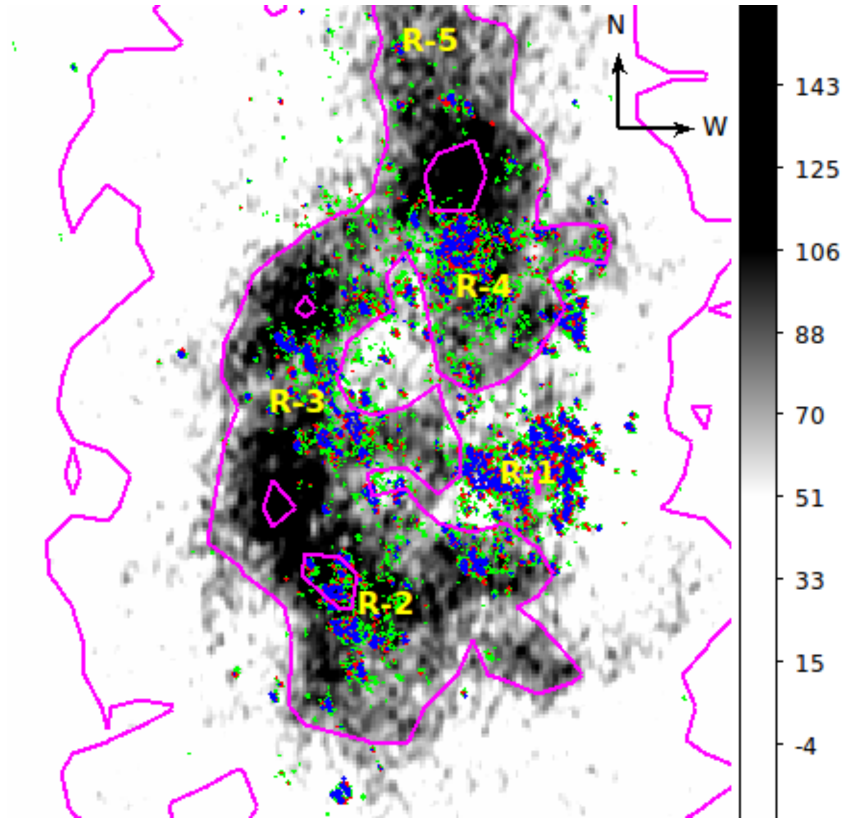
Blue : T > 35000K
Green : 25000K < T < 35000K
Red : 17500K < T < 25000K

Correlating with H alpha and H I

A hook like structure in HI; a hole in FUV and HII

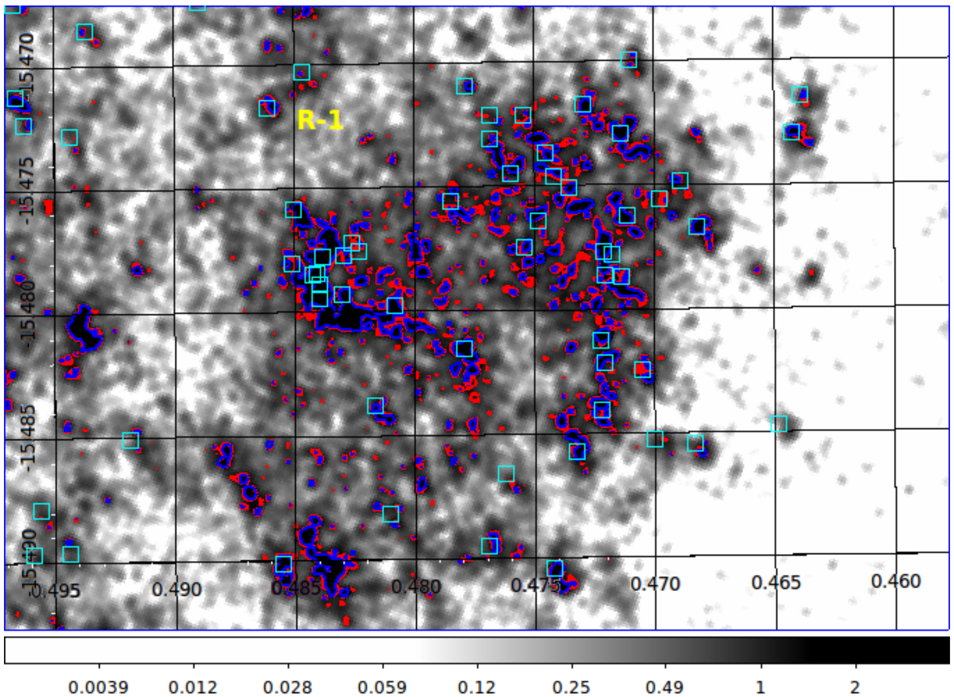


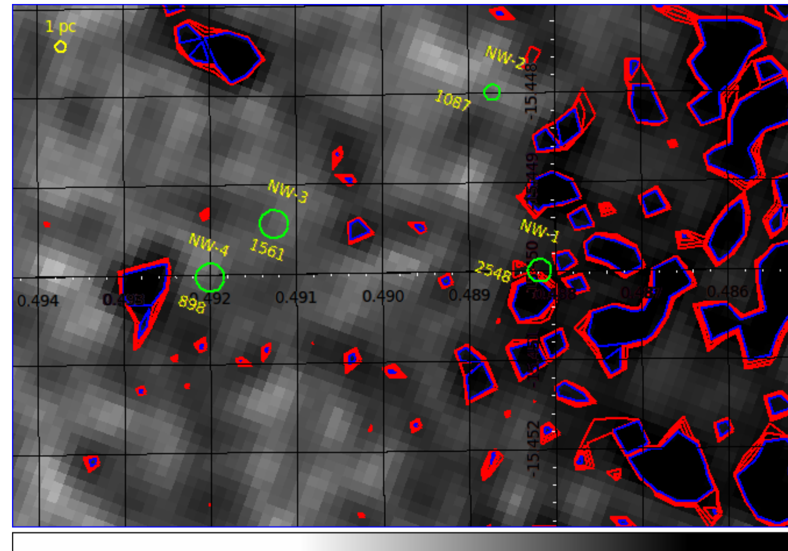
H alpha

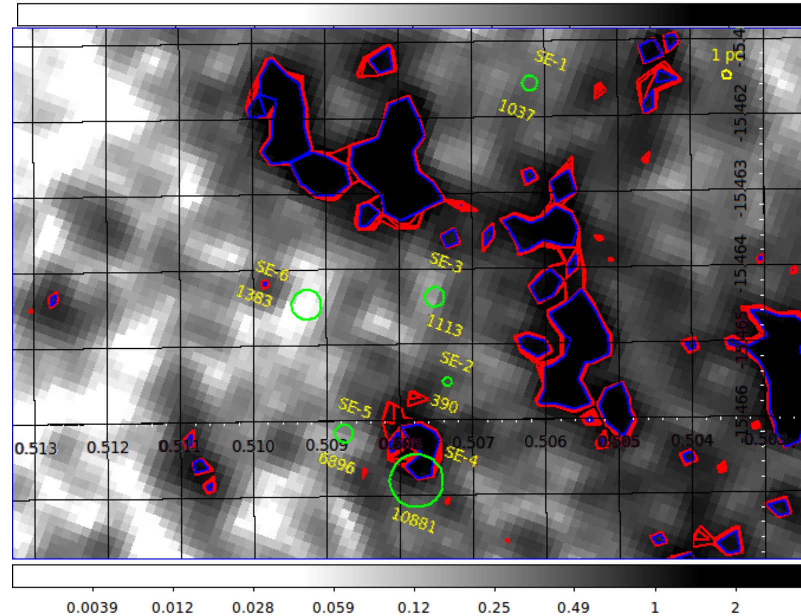


H I

Comparison with HST & ALMA

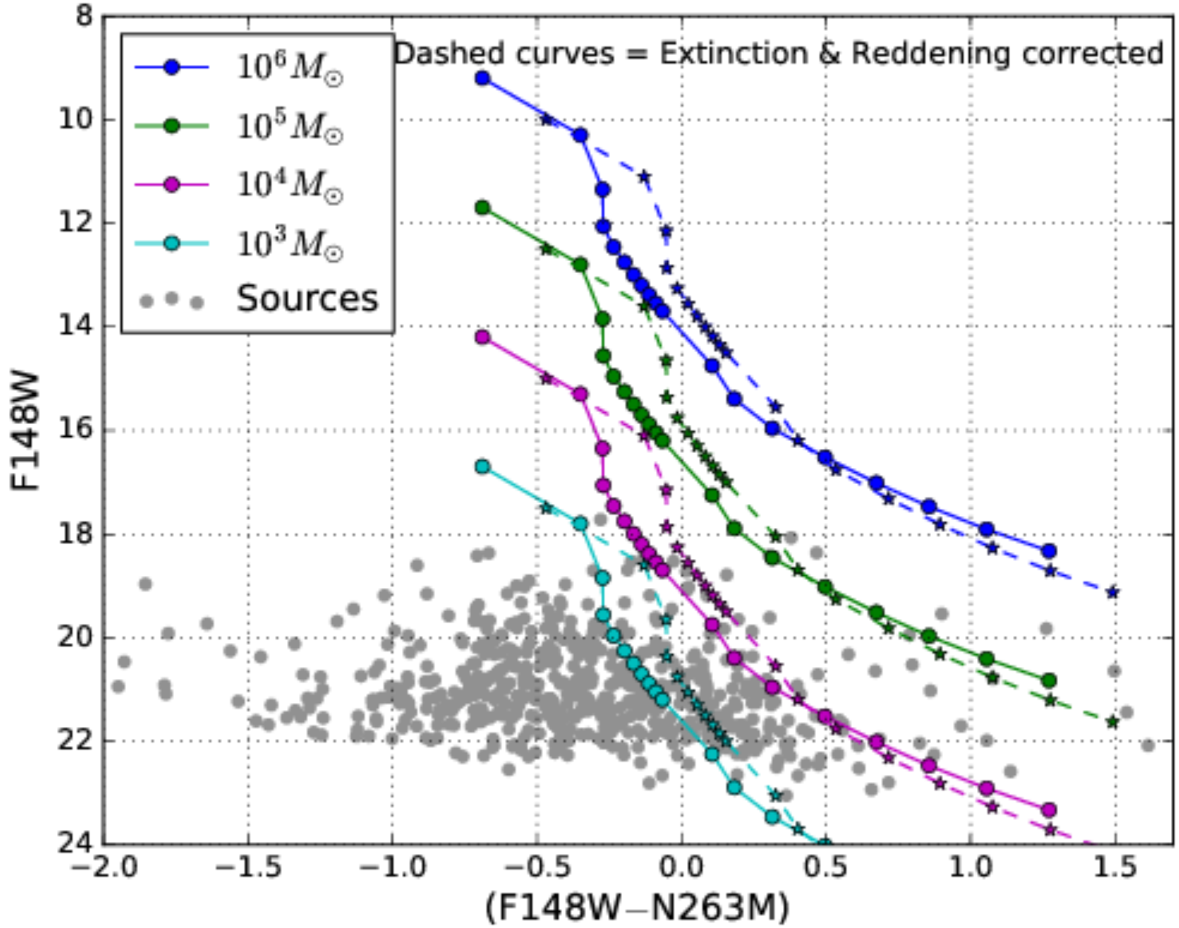






Mass of compact star forming regions:

Low mass SFRs in agreement with ALMA estimates



SFR from FUV similar to other dwarf systems

Galaxy formation and evolution
(Environment effect)

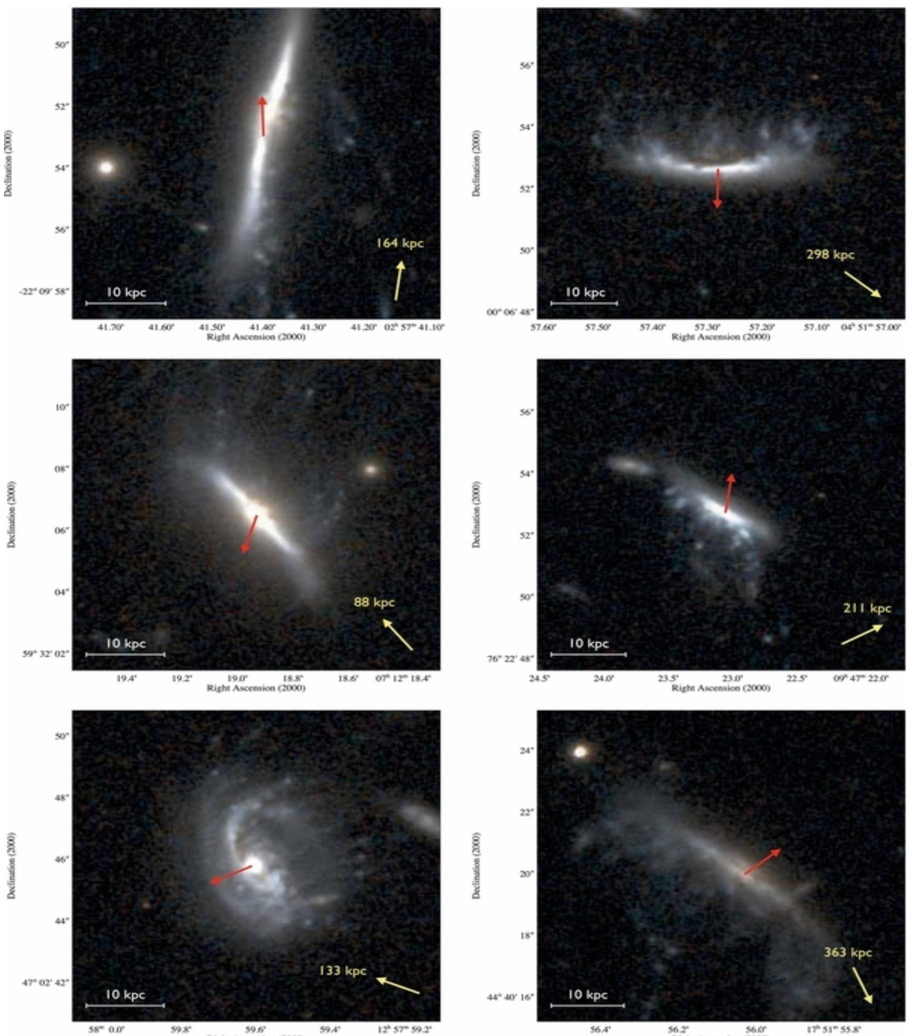
Low density: Galaxy merging is the most frequent morphological transformation process in low-density environments such as field and galaxy cluster outskirts. Merger of two gas-rich spiral galaxies can result in the formation of an elliptical galaxy .

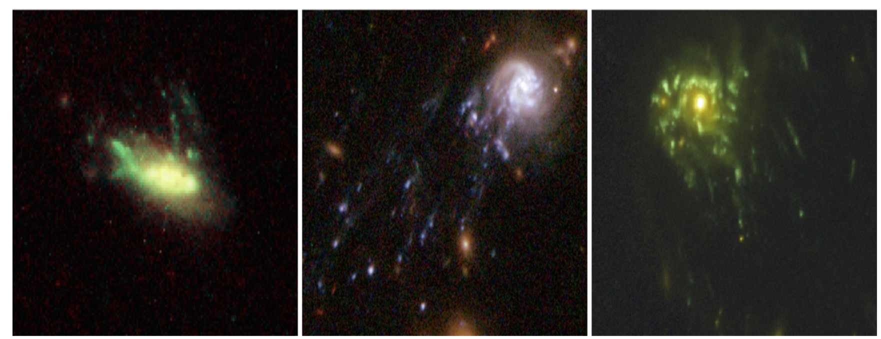
Toomre & Toomre 1972

High density: Ram-pressure stripping, Starvation, Harassment. Processes involving gas removal or gas supply cut down.

Boselli & Gavazi 2006

Ram pressure stripping





Extreme case of ram-pressure stripping in galaxy clusters at z > 0.2

Ebeling et al. 2014 ApJL 781 L40

HST images (F606W+F814W) of extreme cases of ram-pressure stripping in MACS galaxy clusters at 0.30 < z < 0.43.

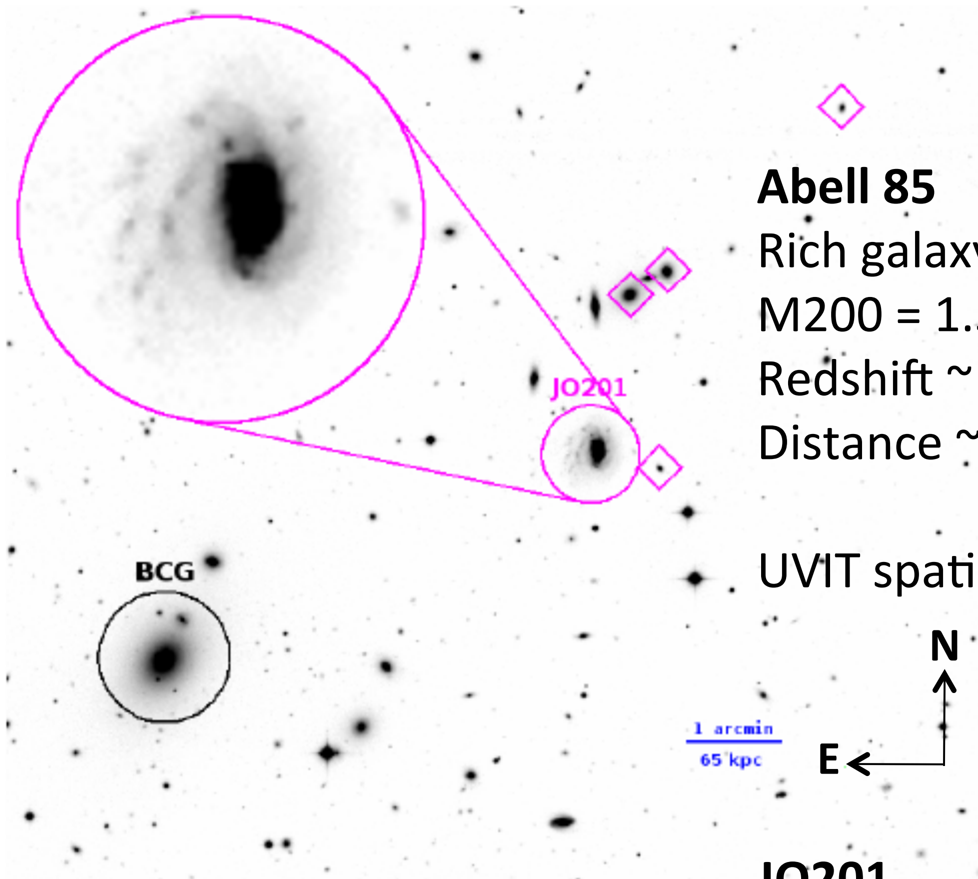
Ram pressure stripping

Galaxies undergoing strong ram pressure stripping appear with tentacles of material resembling a Jellyfish

ESO 137-001 as it moves through the heart of the galaxy cluster Abell 3627.

HST images (F606W+F814W) of extreme cases of ram-pressure stripping in MACS galaxy clusters at $0.30 < z < 0.43$.

Jellyfish galaxy JO201



Abell 85

Rich galaxy cluster

M200 = $1.58 \times 10^{15} M_{\odot}$

Redshift ~ 0.05

Distance ~ 250 Mpc

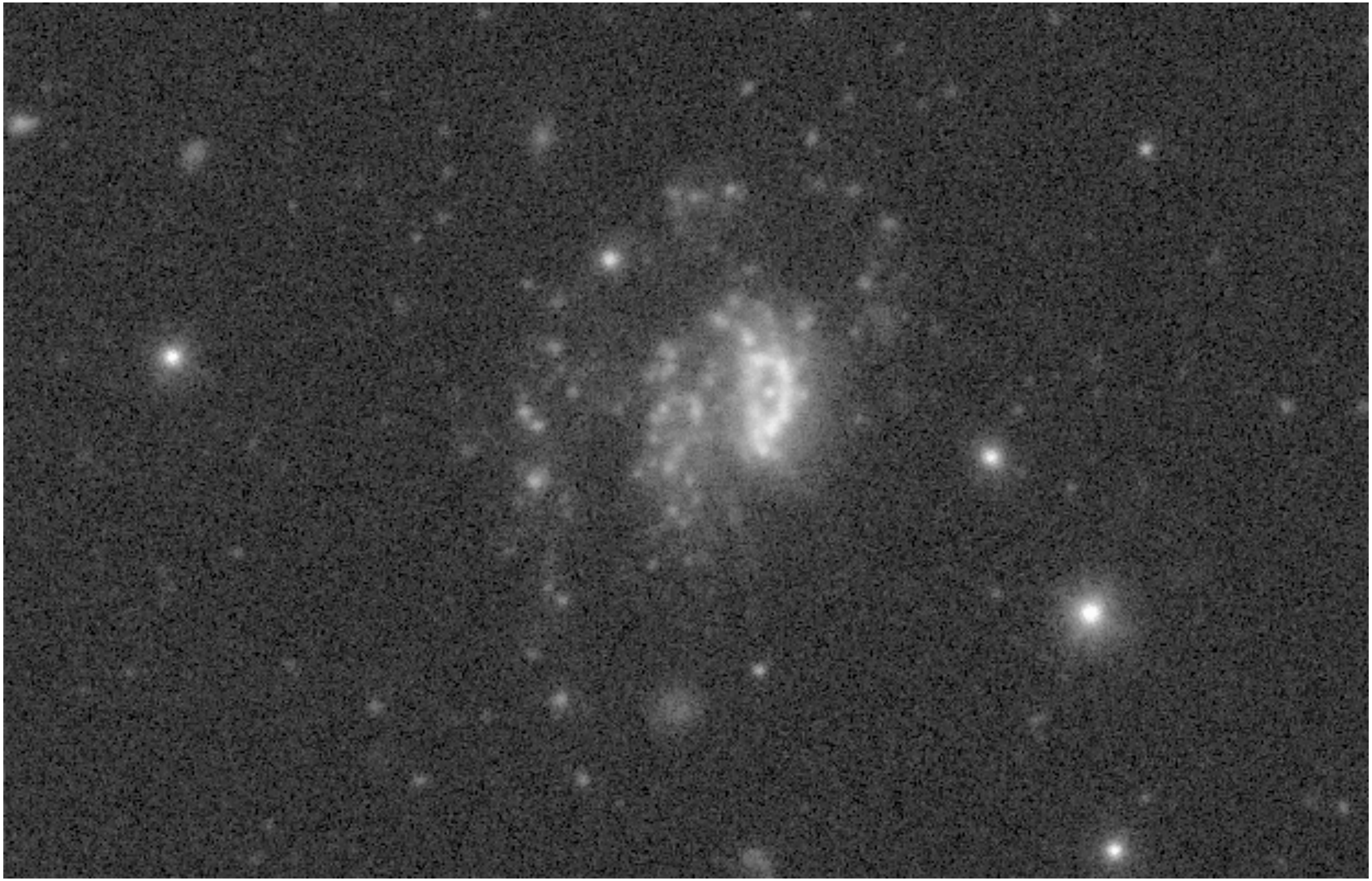
UVIT spatial resolution ~ 1.3 kpc

JO201

Spiral galaxy

$M_{stellar} = 3.55 \times 10^{10} M_{\odot}$

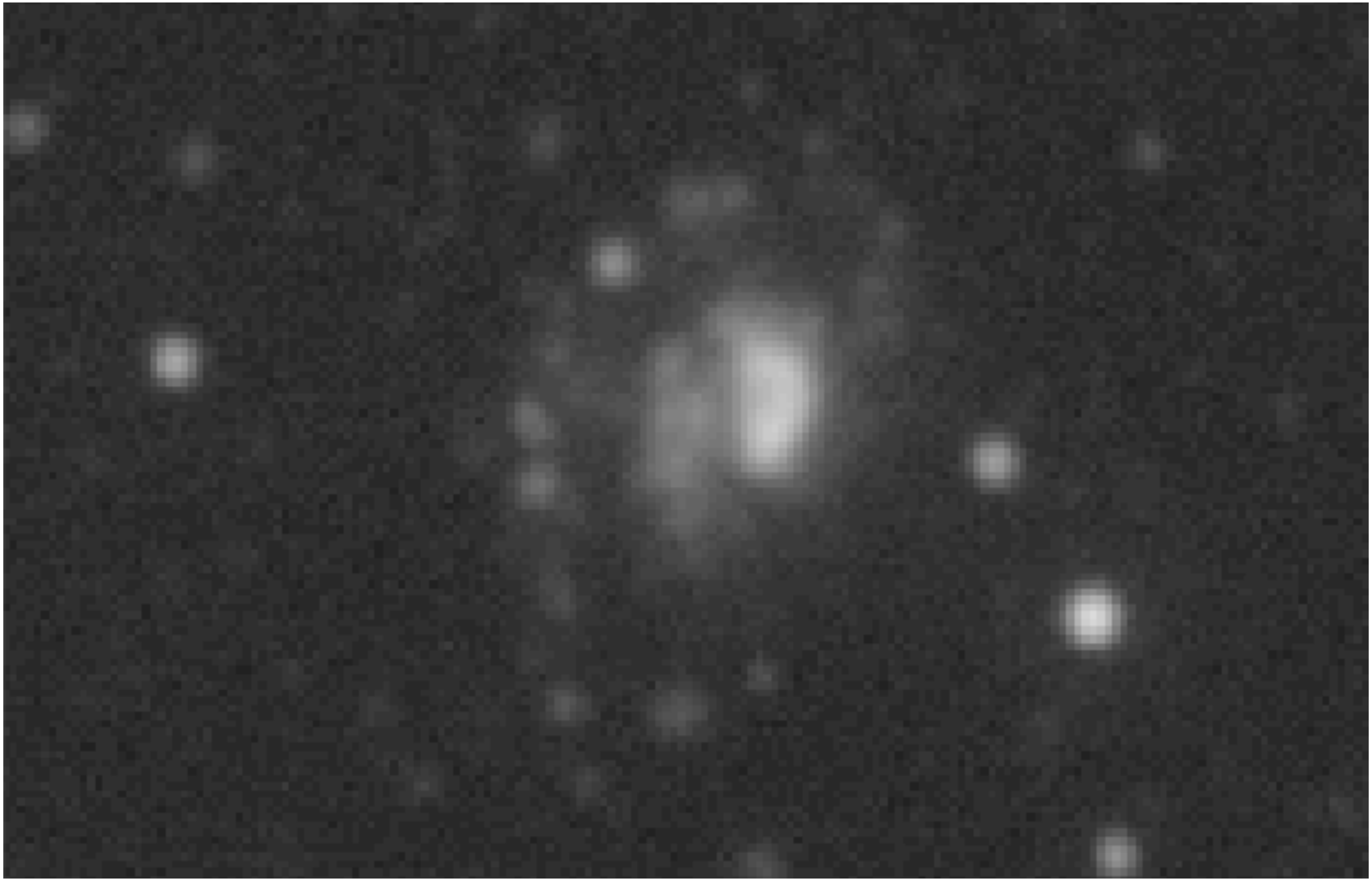
UVIT NUV image of Jellyfish galaxy JO201



UVIT NUV Exposure time ~ 18ks

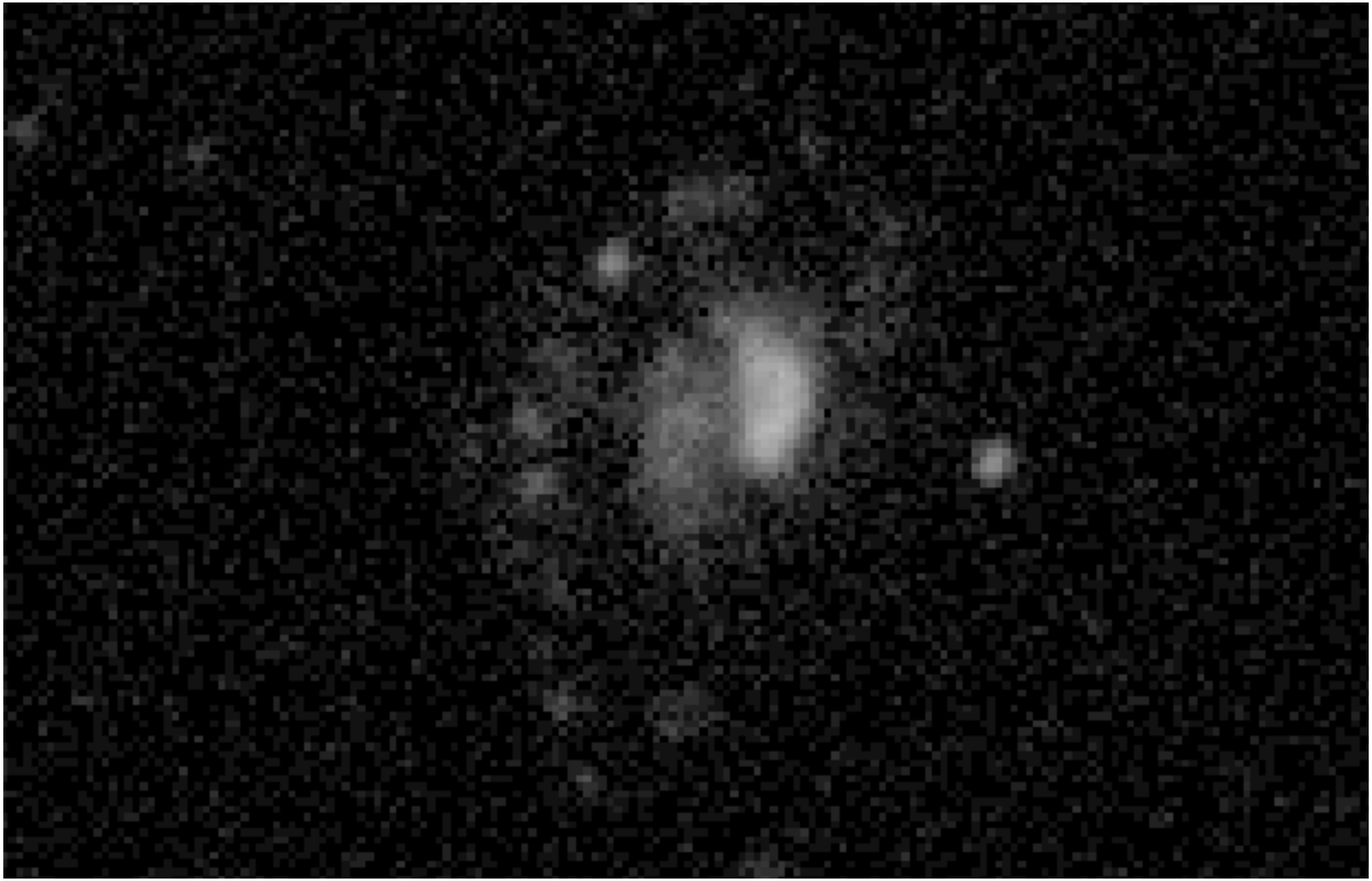
Koshy et al. 2018, MNRAS, 475, 4279

GALEX NUV image of Jellyfish galaxy JO201



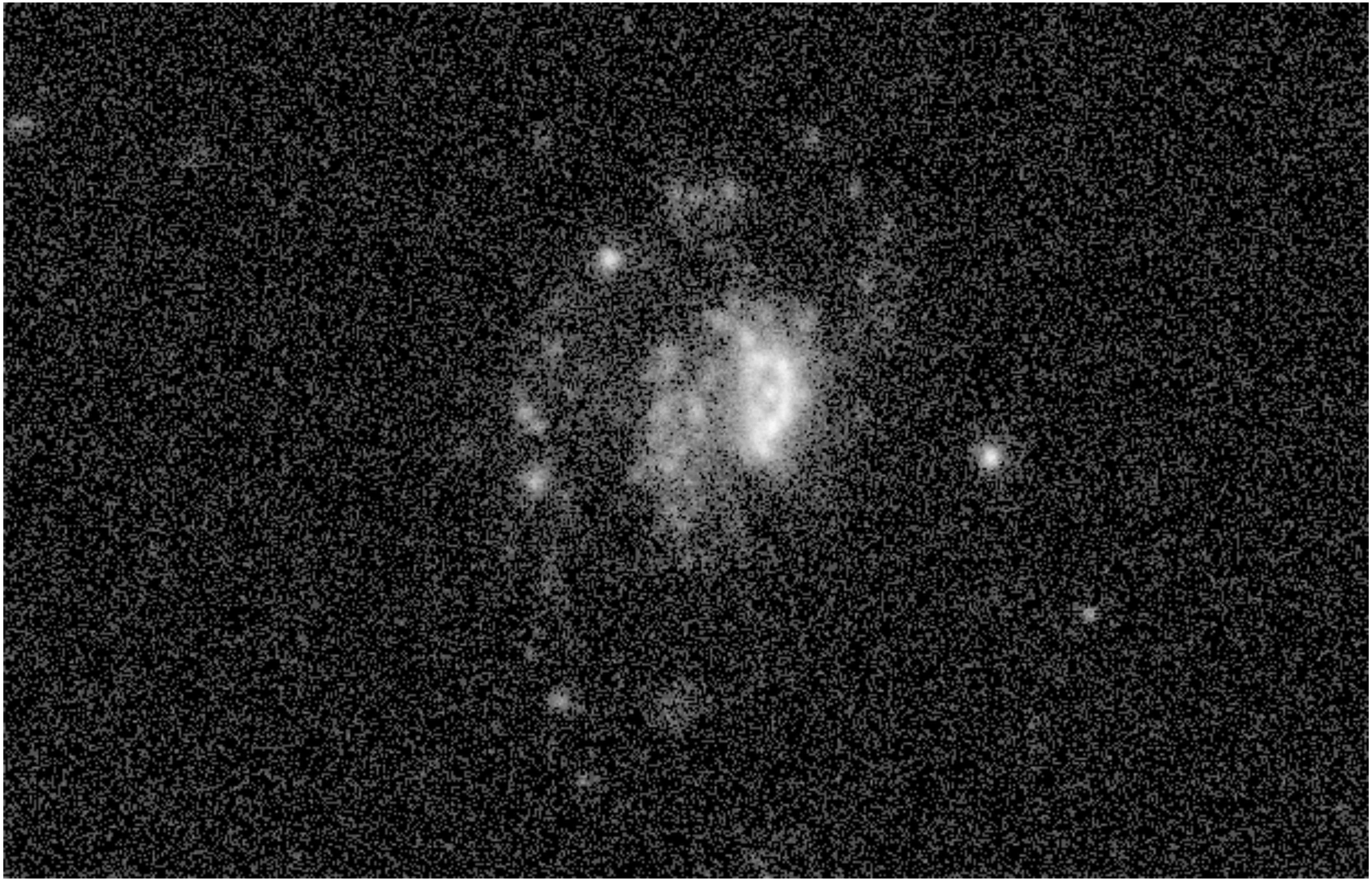
GALEX NUV Exposure time ~ 29ks

GALEX FUV image of Jellyfish galaxyJO201

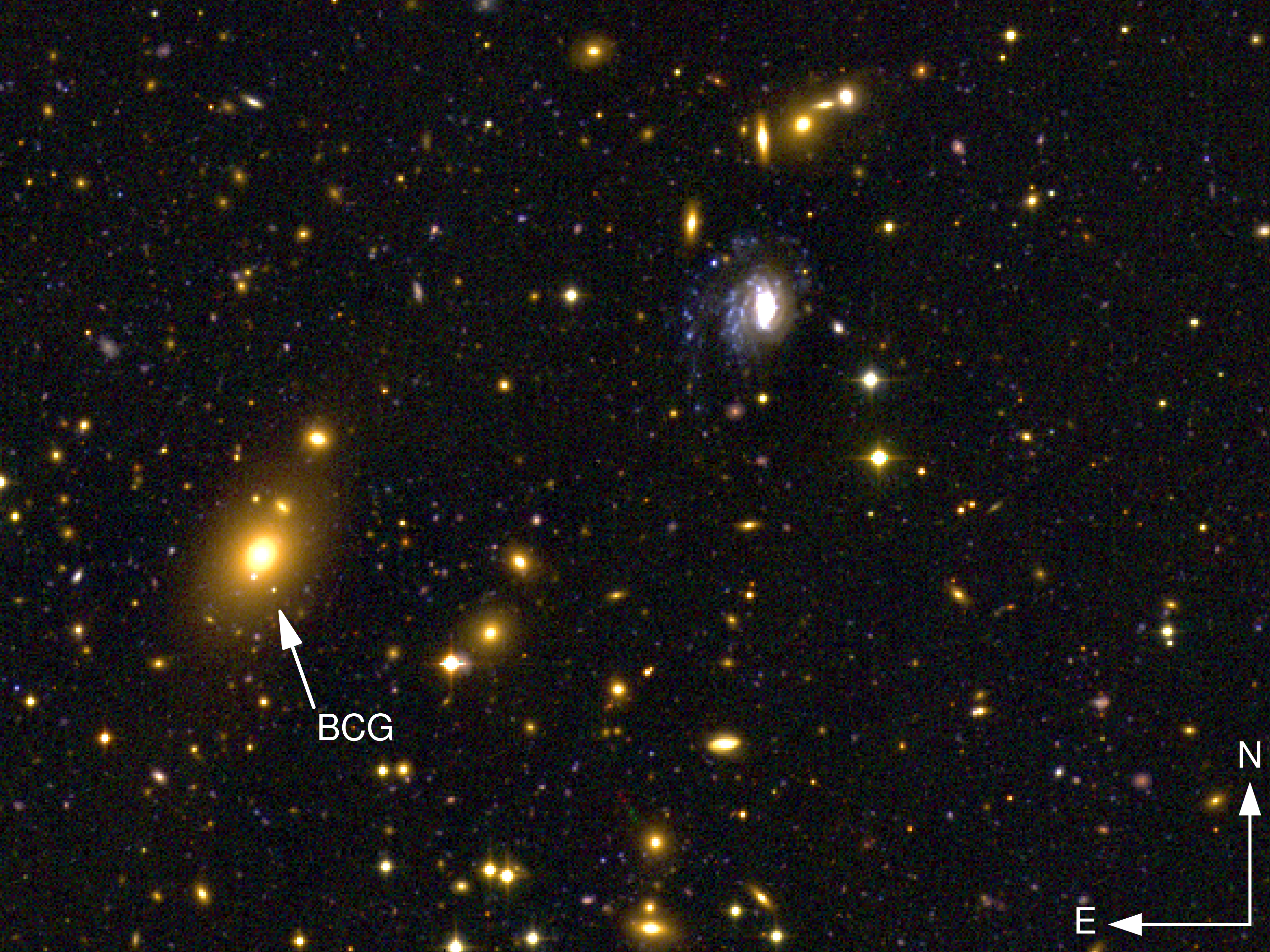


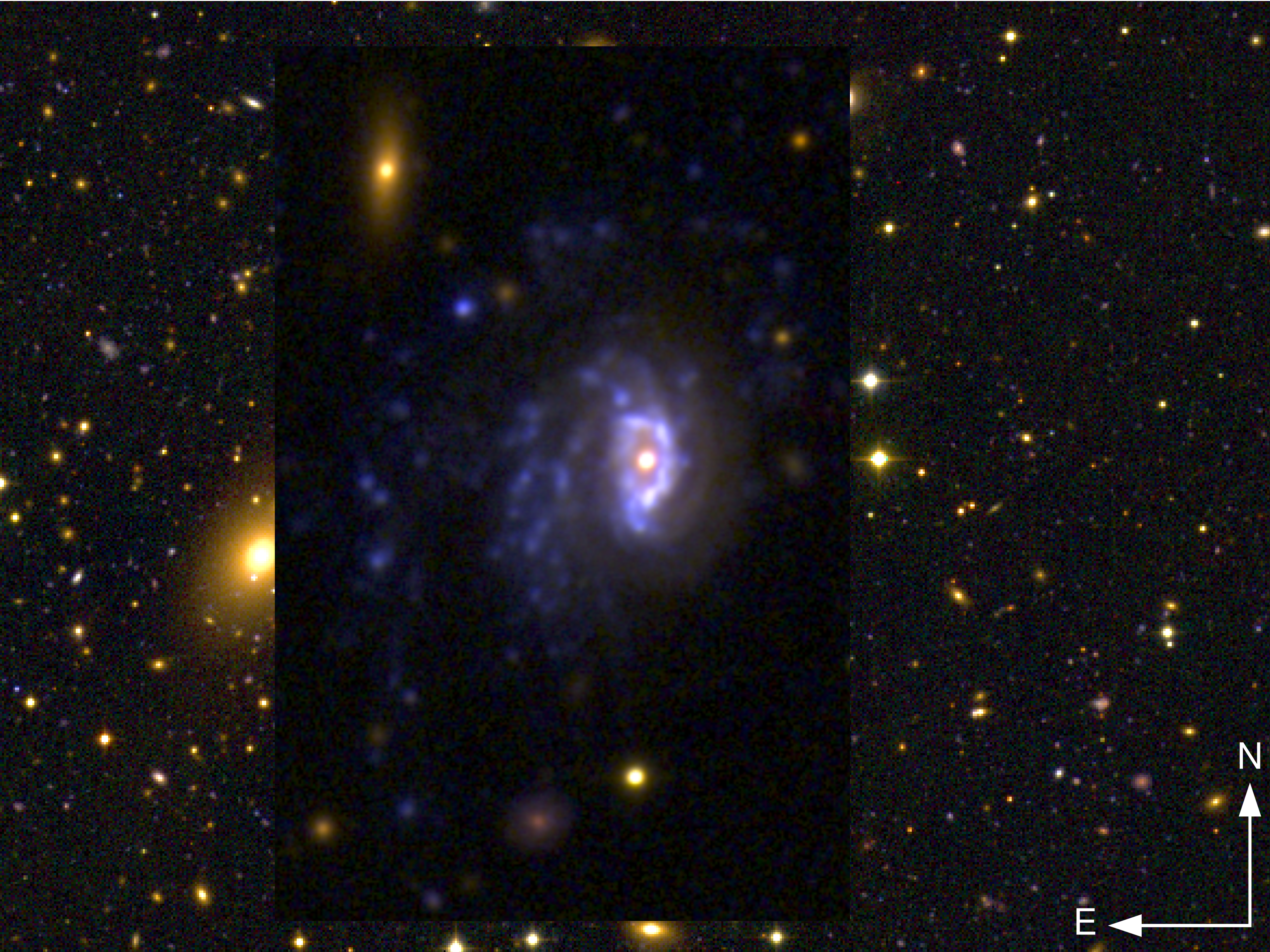
GALEX FUV Exposure time ~ 2.5ks

UVIT FUV image of Jellyfish galaxy JO201



UVIT FUV Exposure time ~ 15ks


BCG
N
E


N
E

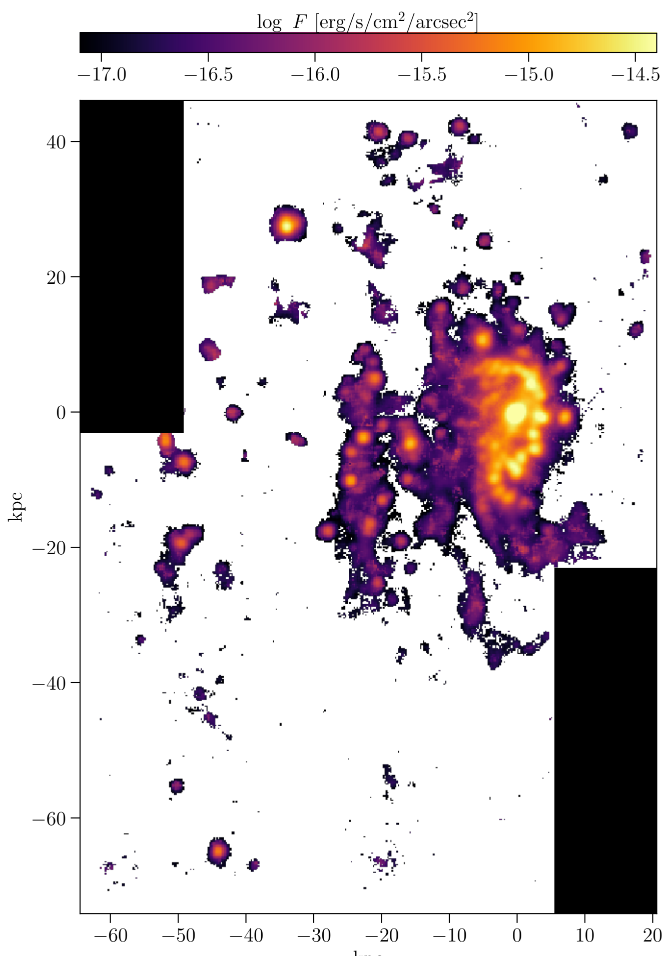
JO201: Hα & NUV imaging

GASP: Gas stripping phenomena in galaxies with MUSE on VLT

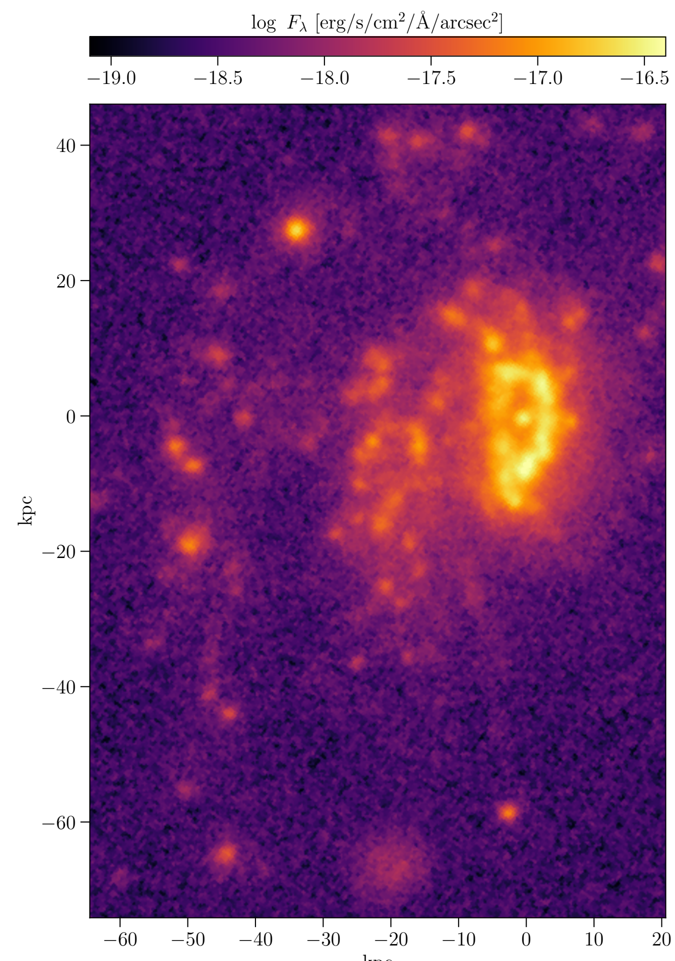
(PI:Bianca Poggianti, Padova)

Koshy et al. 2018, MNRAS

Hα image



NUV image



JO201: Hα & FUV imaging

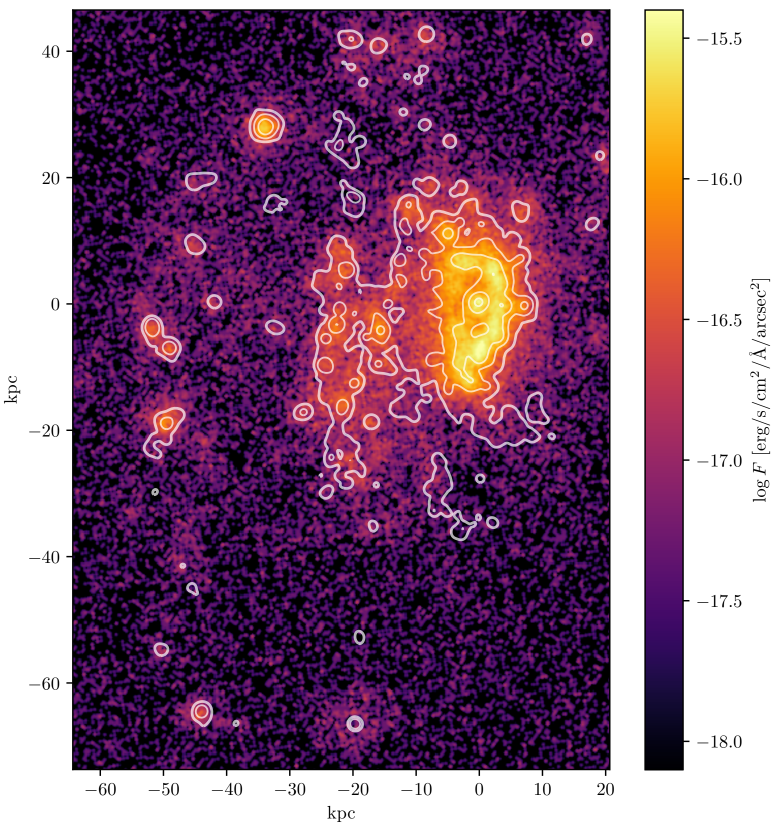
GASP: Gas stripping phenomena in galaxies with MUSE on VLT
(PI:Bianca Poggianti, Padova)

The star formation in the knots outside the disk of JO201 can be interpreted as in-situ newly born stars from the ram-pressure stripped gas.

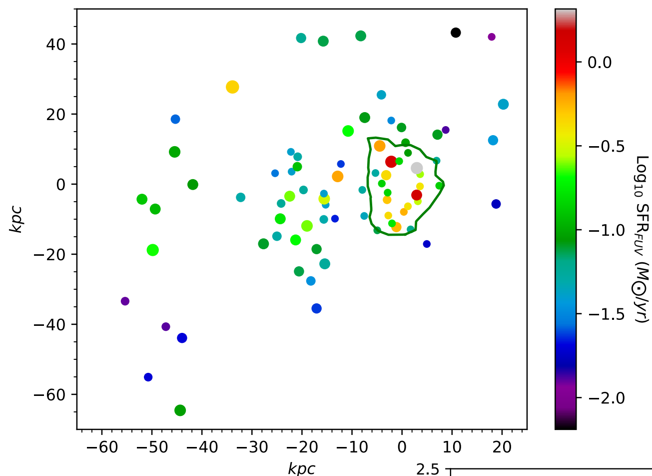
Slightly older stars could be decoupled from the natal gas cloud and hence the UV (which directly traces < 200 Myr stars) and Hα (tracing < 10 Myr stars) emission could have an offset.

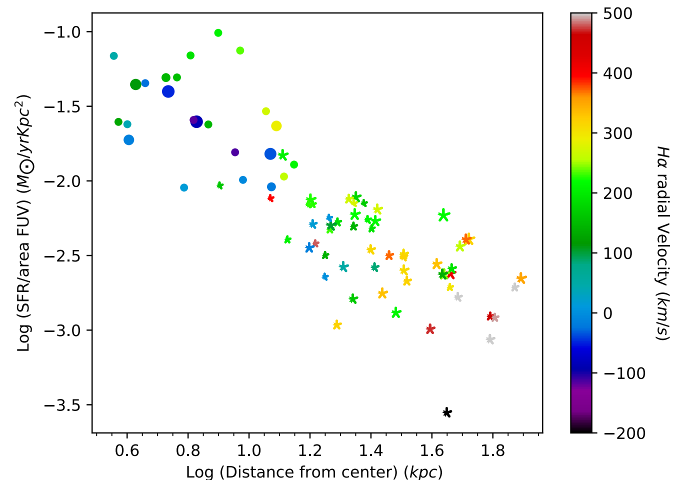
There is no offset between the UV and Hα peak emission within the knots of JO201.

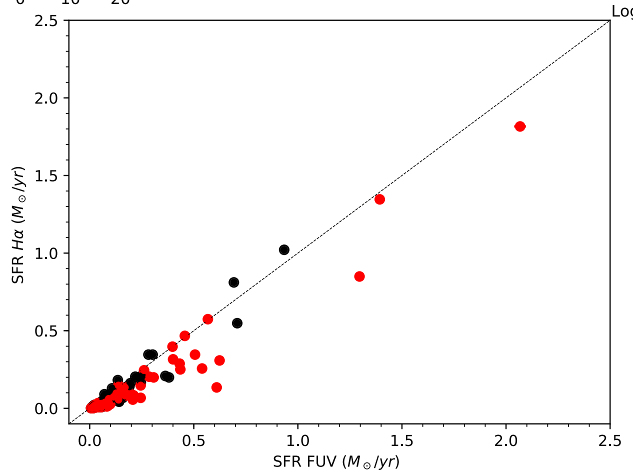
Hα & FUV image



JO201: star formation rate of blobs







Star formation rate of blobs range from 0.01 -to- 2.07 $M_\odot yr^{-1}$

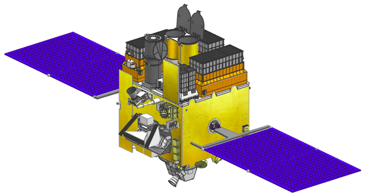
Integrated star formation rate ~ 15 $M_\odot yr^{-1}$

Koshy et al. 2018, MNRAS, 475, 4279

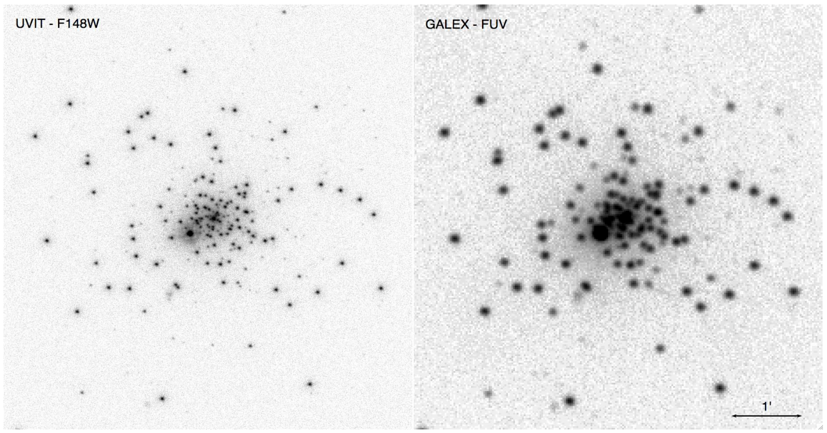
UV bright population in Globular Cluster NGC 288

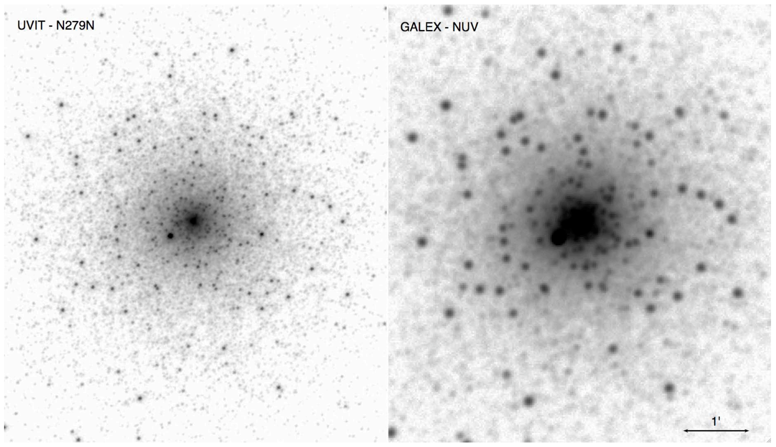
Snehalata et al. (MNRAS, 2018)

The Horizontal Branch Population of NGC 1851 as Revealed by the Ultraviolet Imaging Telescope (UVIT), Subramaniam et al. 2017, AJ, Volume 154, 233.



- Observed during 19-21 March 2016.
- Observation in three Filters: F148W (6 ksec), F169M (5 ksec) and N279N (12 ksec).
- Drift correction was done using **CCDLAB** (J.Postma et al. 2017) and the images were generated for different filters.
- PSF photomtery was performed using IRAF/DAOPHOT to obtain the magnitudes of the sources.



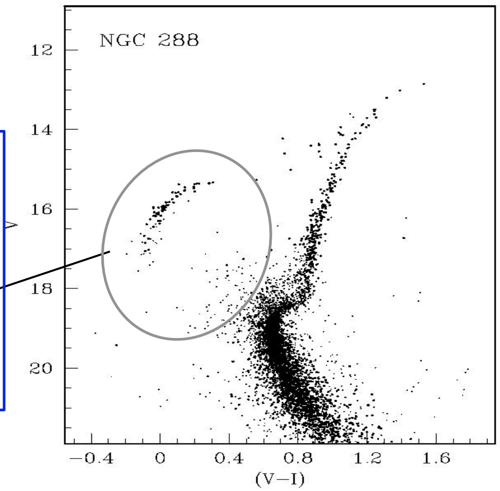


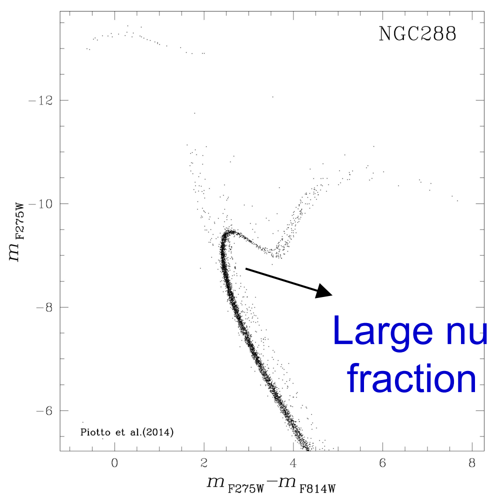
NGC 288

- A loose Galactic Globular Cluster (GGC) of intermediate metallicity ([Fe/H] =-1.3, age=13 Gyr at a distance of 8.8 Kpc.
- 

Extended Blue horizontal Branch and Large number of BSS

UV bright populations

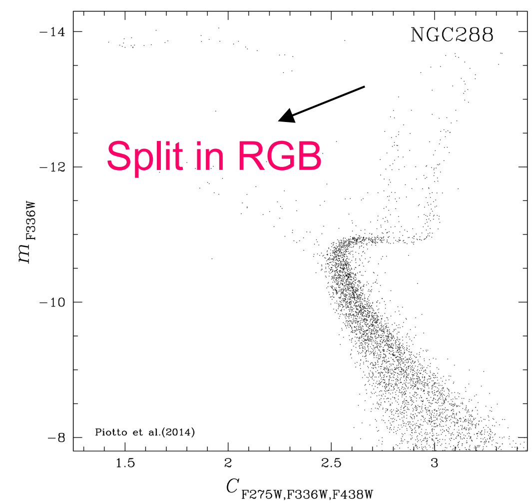




Advantage of UV CMDs

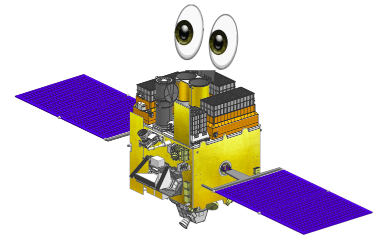
HST UV legacy Survey of GCs (Piotto et al. 2015)

Large number of binaries with binary fraction 10< f_b<25% (Bellazani et al. 2001)



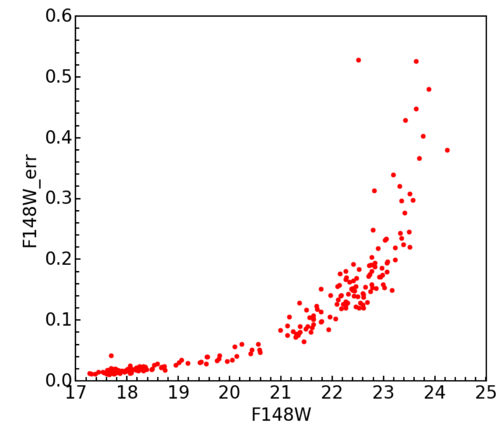
Split in RGB

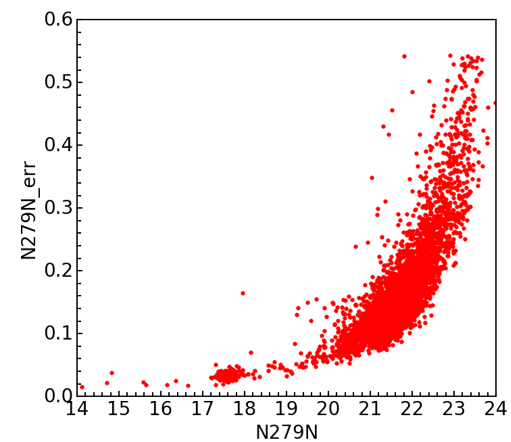
UVIT Observations



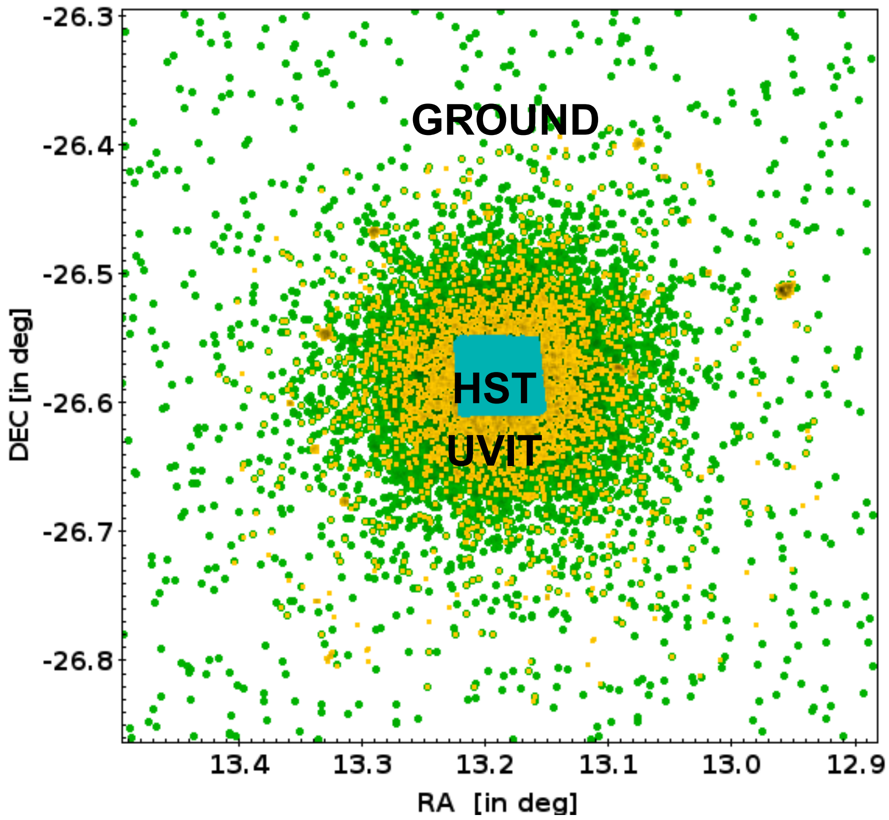
- Guaranteed Time proposal (observed on 21-22 August 2016)
- Observation in three Filters: F148W, F169M and N279N.
- Drift correction was done using **CCDLAB** (J.Postma et al. 2017, in prep.) and the images were generated for different filters.
- PSF photomtery was performed using IRAF/DAOPHOT to obtain the magnitudes of the sources.

UVIT Filter	λ_{eff} (in Å)	M_{zp}	Exposure Time (in s)
F148W	1480.8	18.00	7057.67
F169M	1607.7	17.45	4573.03
N279N	2792.3	16.46	14778.28





Comparison with HST and Ground



- Need to sample entire cluster in order to know the spatial distribution of HB and BSS

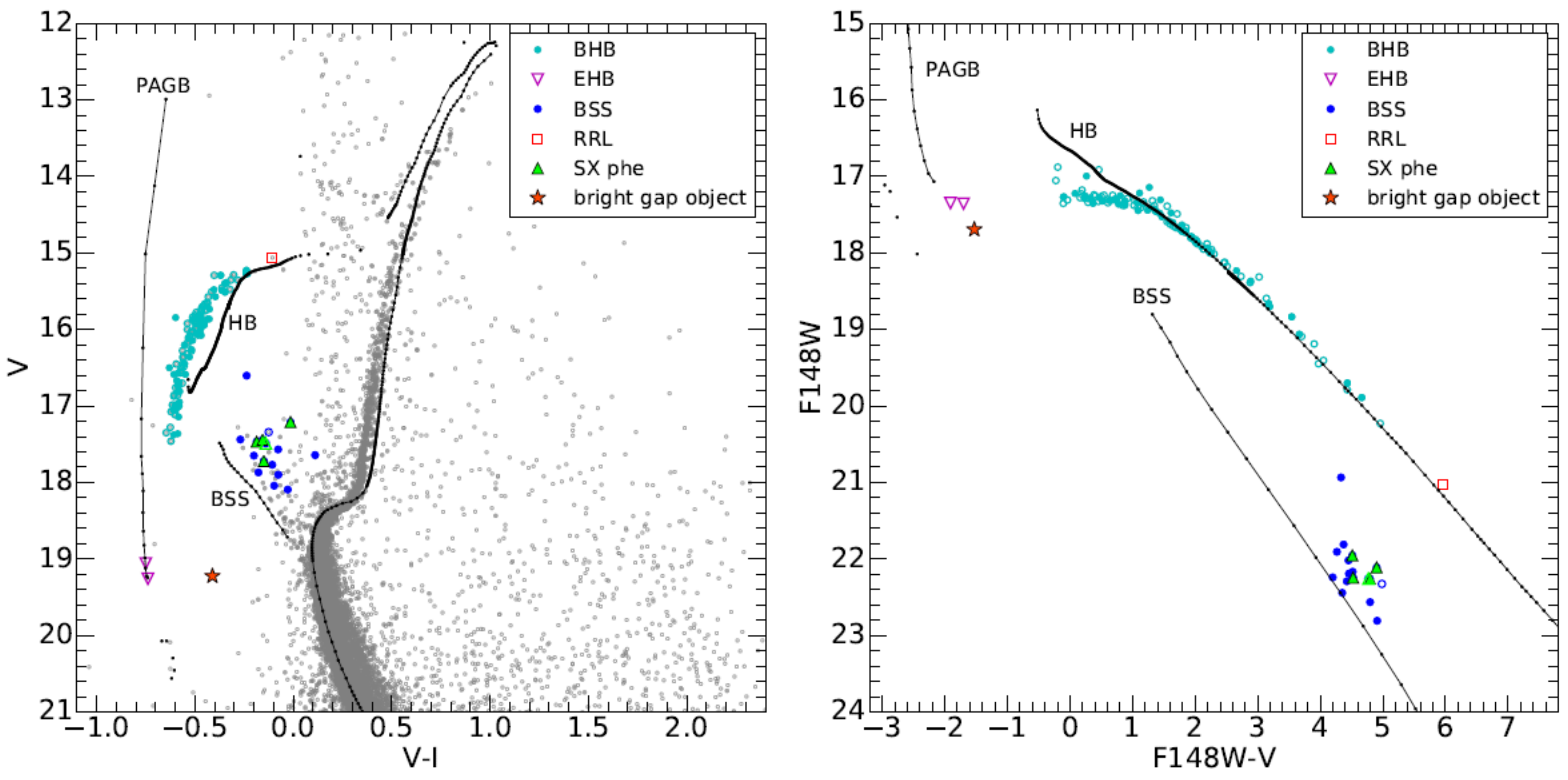
- HST data from ACS survey of GCs (Sarajedini et al. 2007)
- Ground data (Peter Stetson in private commun.)

FSPS Model

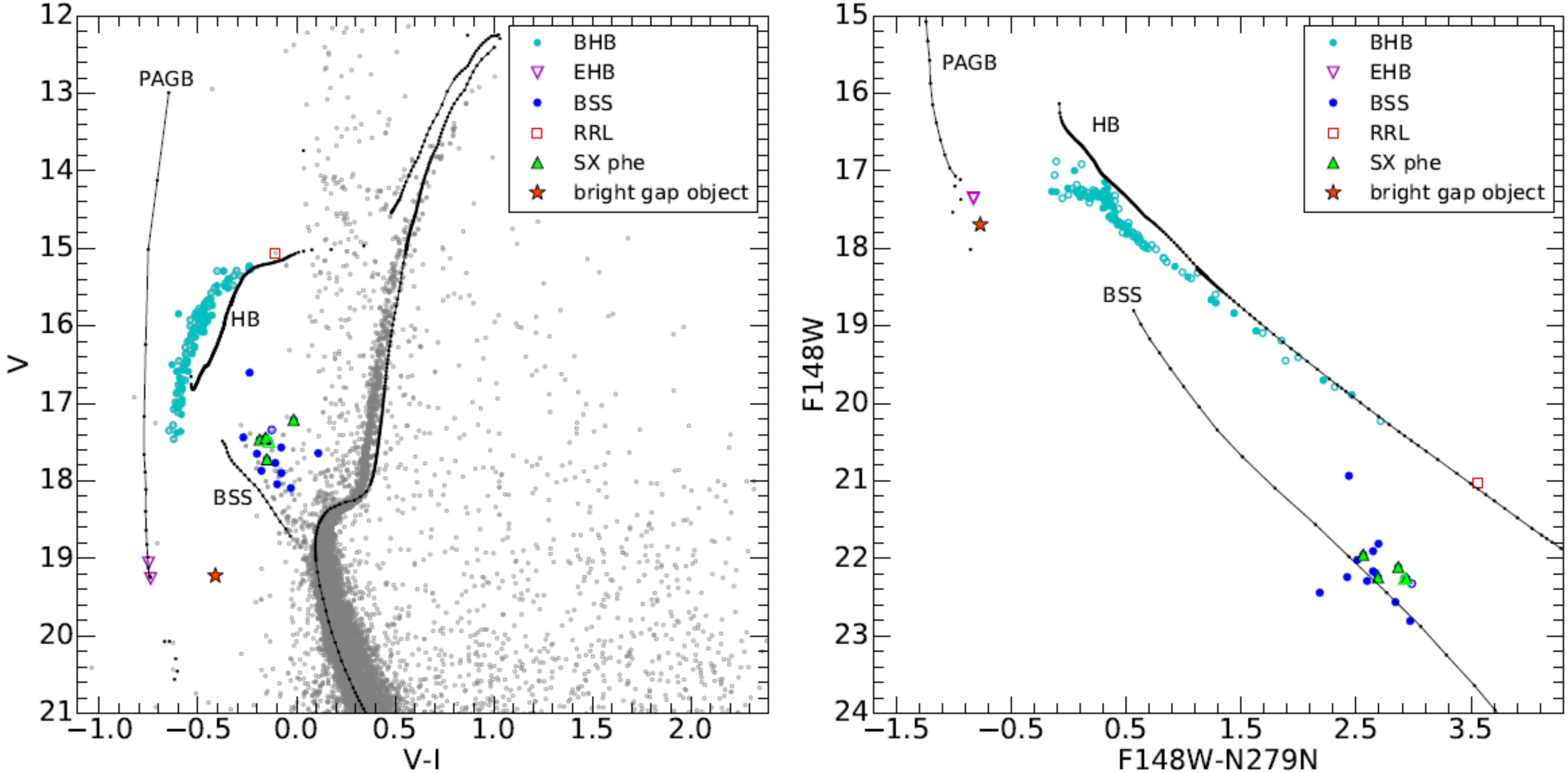
- Flexible stellar population synthesis (FSPS) is a collection of Fortran routines which computes the simple stellar population for a variety of IMFs and metallicities. (Conroy et al., 2009)

- added UVIT filters in the code and generated isochrones for fixed metallicity.
  - Parameters of NGC 288
    - Isochrone Table: BaSTI
    - Metallicity: [Fe/H]= -1.28
    - Age: 12.6 Gyr
    - Corrected for Distance Modulus and reddening:
    - DM: 14.84
    - E(B-V)=0.03

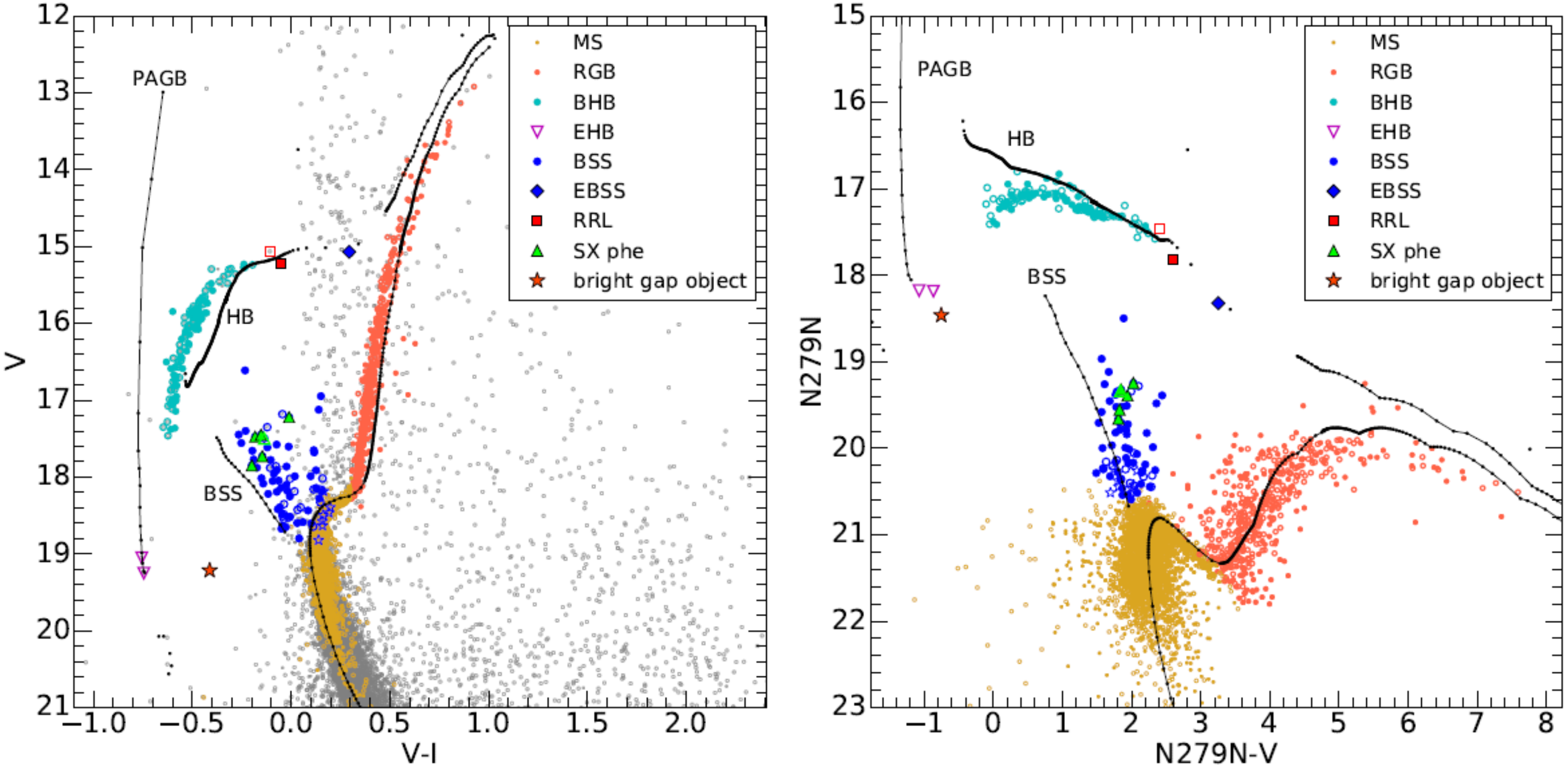
FUV and Optical CMD



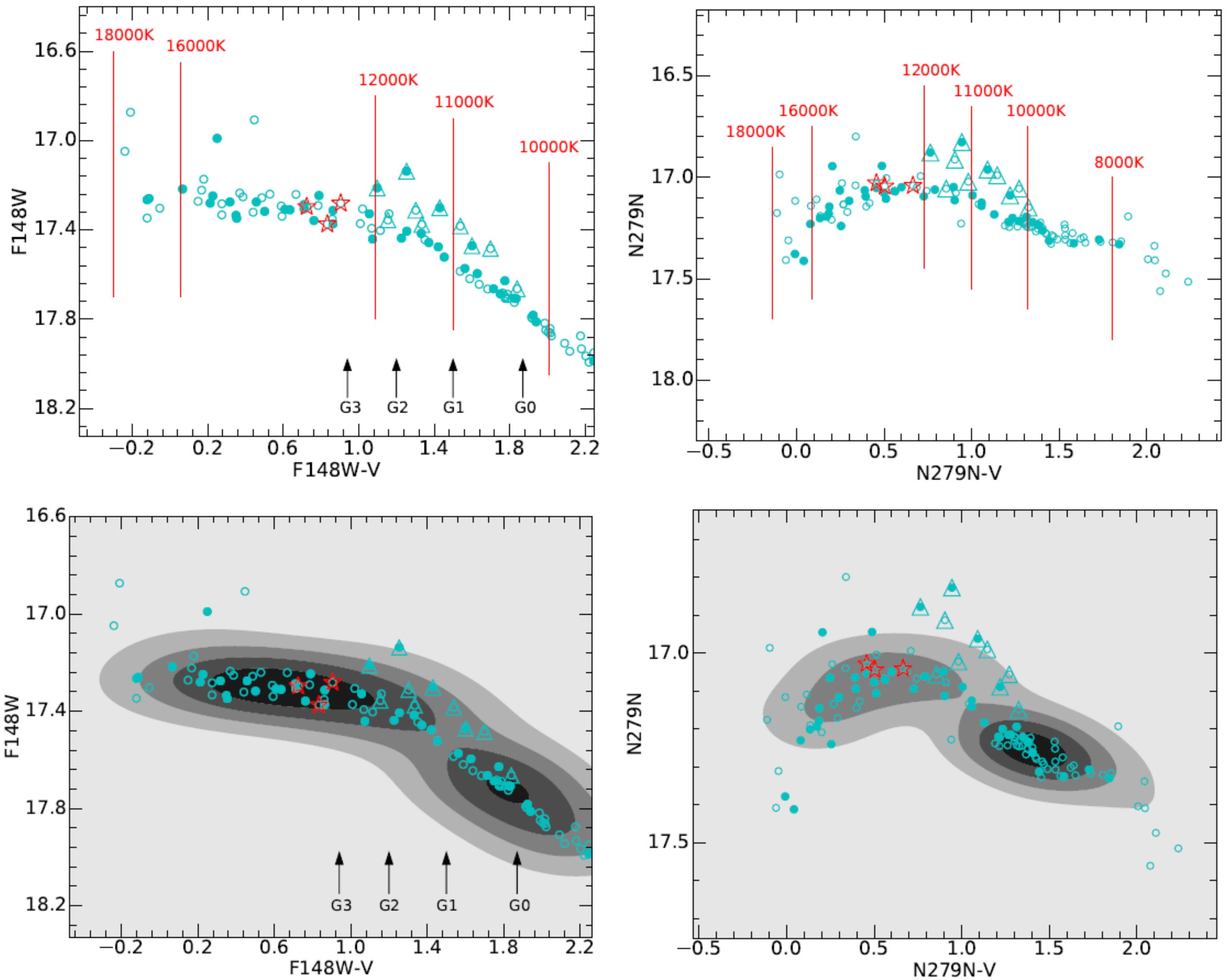
FUV and Optical CMDs



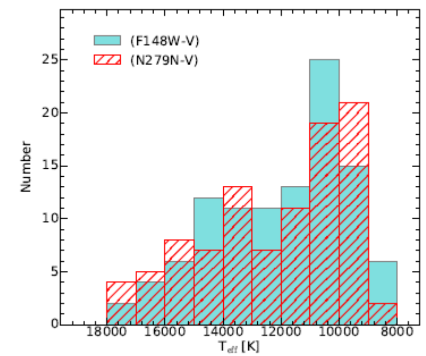
NUV and Optical CMDs



Diffusion in BHB stars – FUV plateau



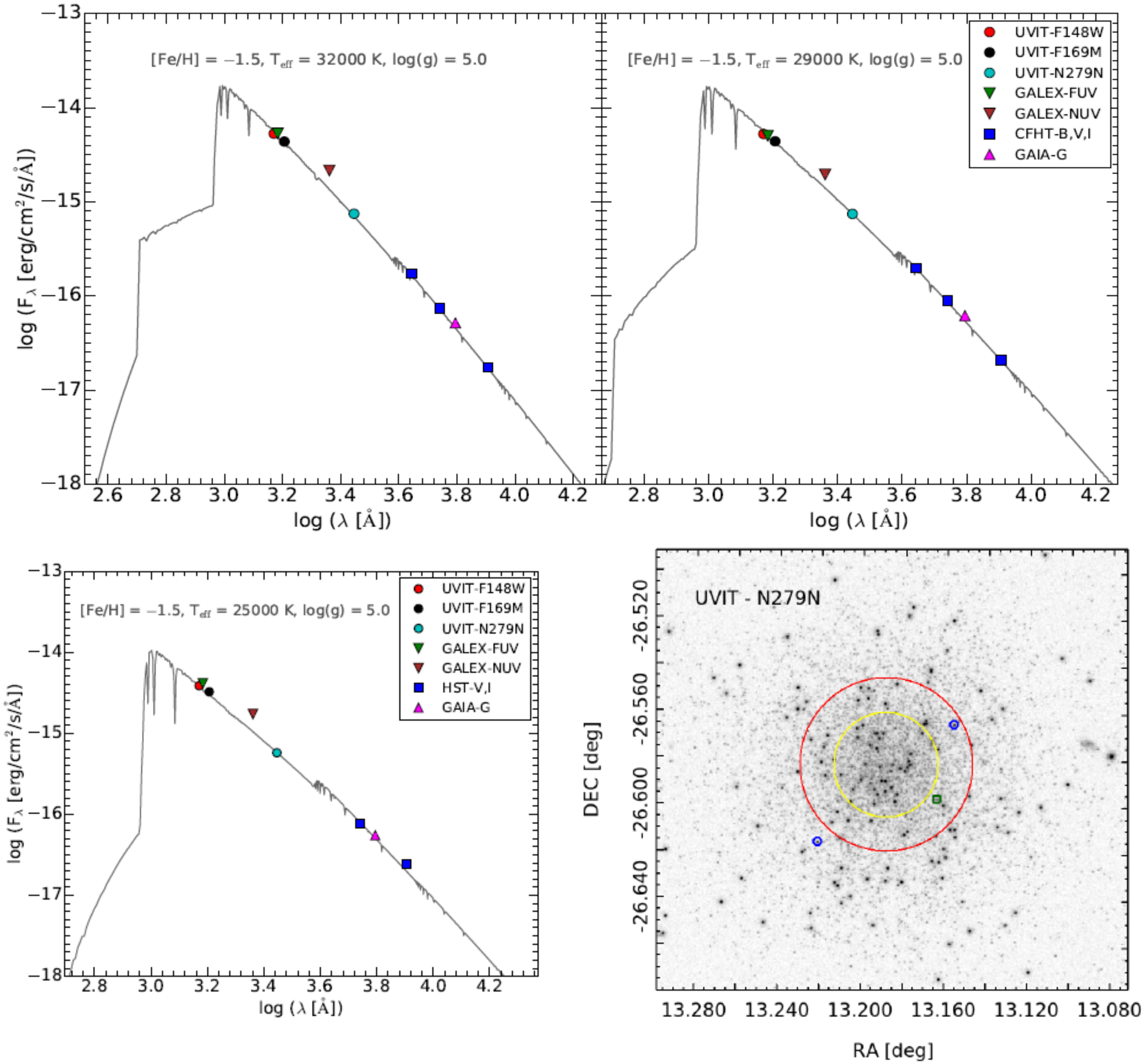
Temperature distribution derived from the color-teff relation using Kurucz models



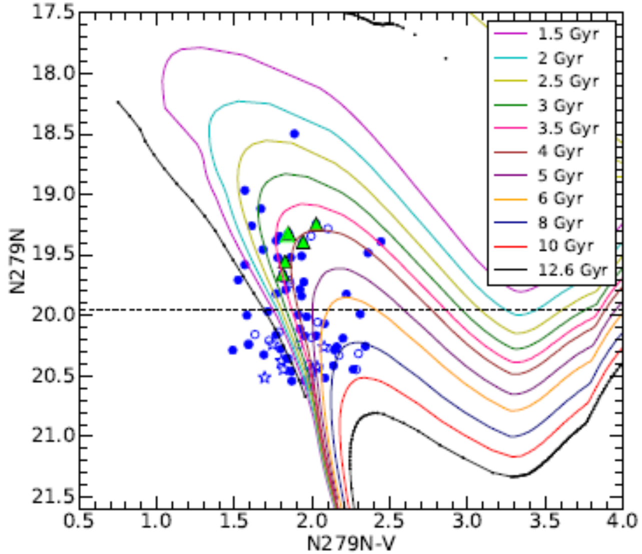
Khalack et al. 2010, Moehler et al. 2014

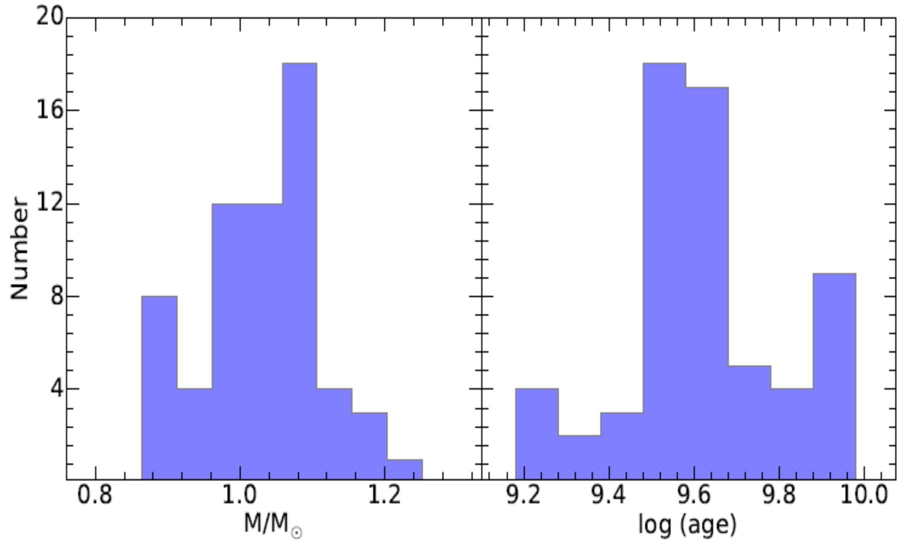
Snehalata et al. 2018 (to be submitted)

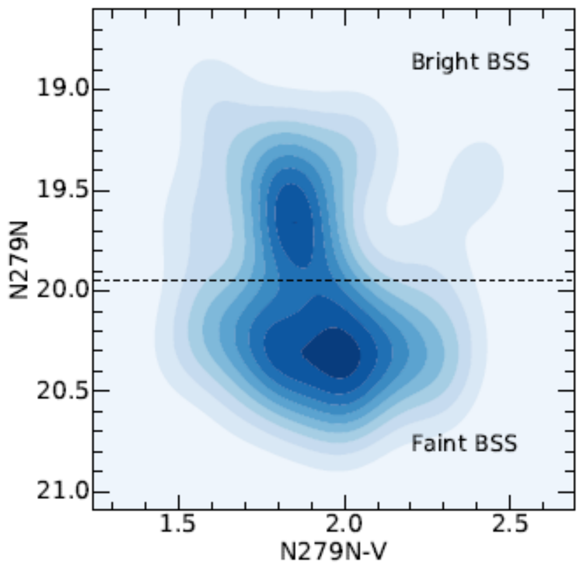
SEDs of EHB stars



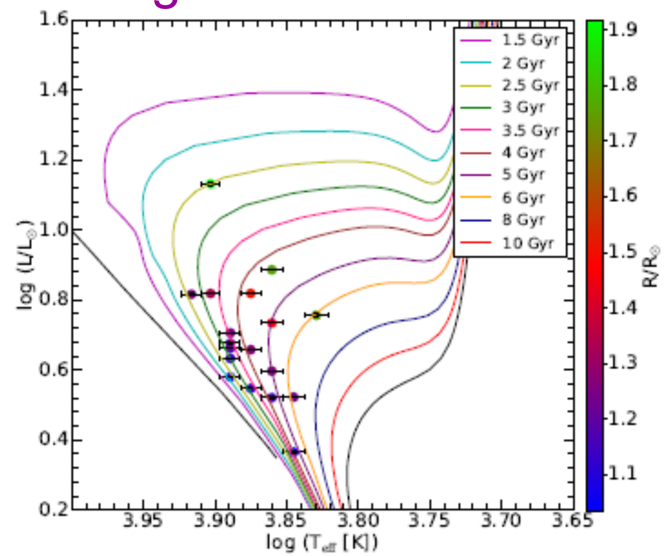
Properties of BSS



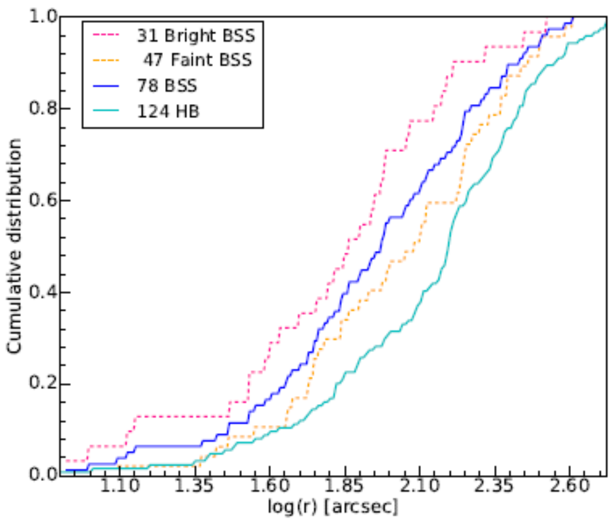


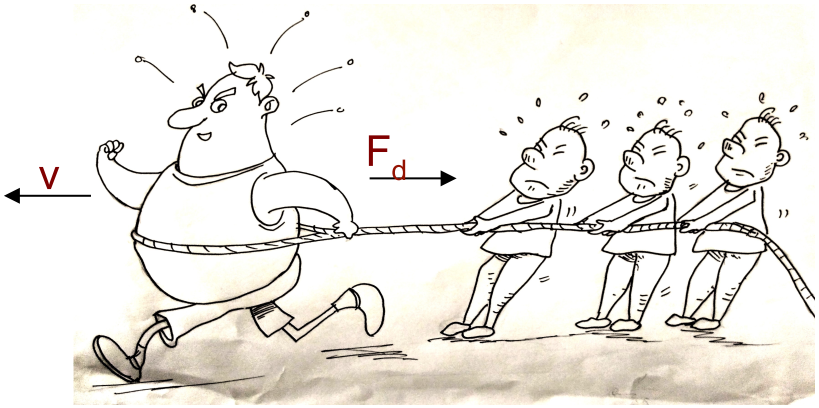


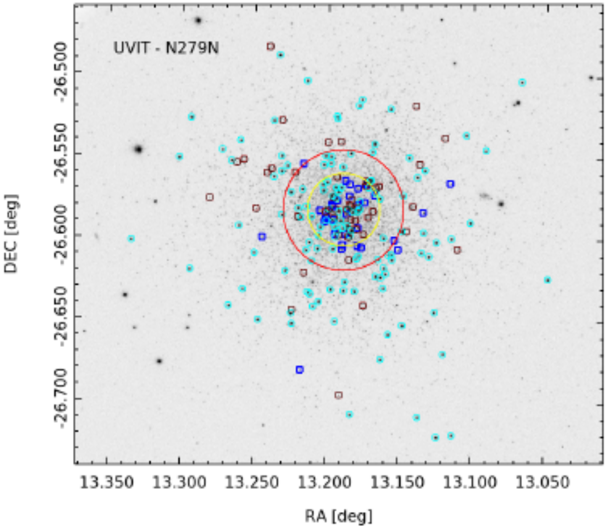
H-R diagram derived from SED



Radial Distribution of BSS

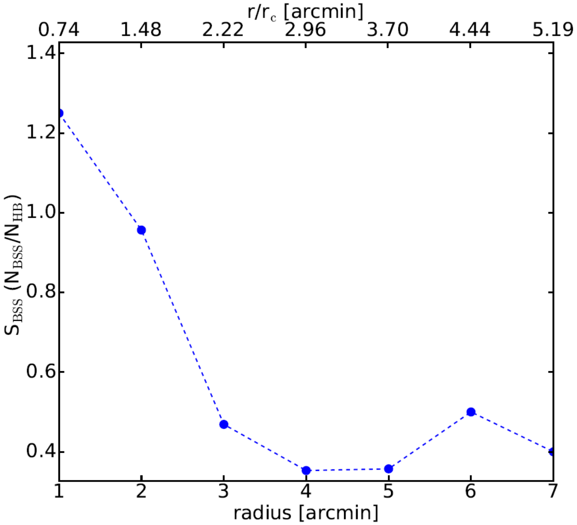






Dynamical friction has affected only the most internal BSS located at a distance of 4' from the cluster center. Specific frequency of BSS = 1.25±0.53.

Bimodal Distribution- Family II cluster as defined by Ferraro et al. 2012

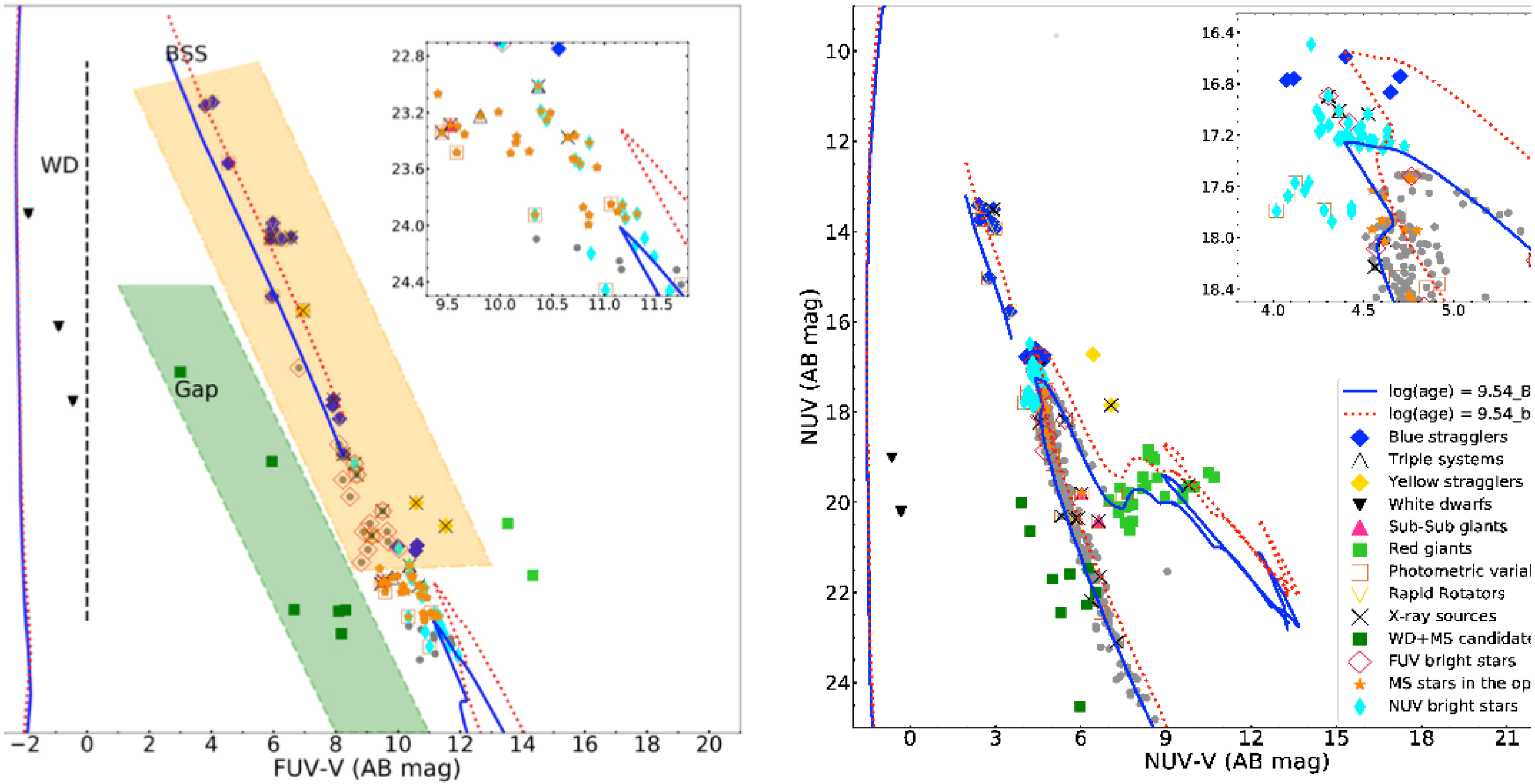


The well studied Old open cluster M67 – Detection of WD companions to 8 BSS

- Old open cluster as old as the Sun - located at ~ 800 pc
- **Significant BSS population and binaries**
- Observation with three FUV filters – F148W, F154W and F169M
- Among the 14 BSS known, 10 are detected in all three UVIT filters.
- We observe significant UV excess in 8 stars.
- We fitted multiple SEDs to these stars to detect the possible hot companion.

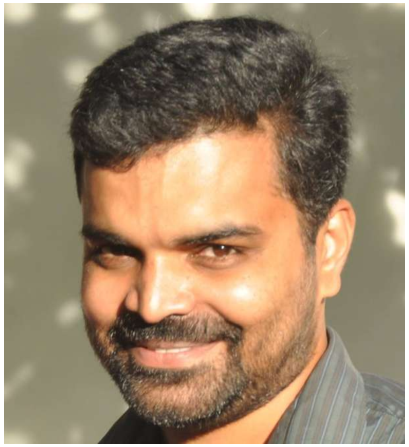
Sindhu et al 2018 (in preparation)

UV-optical Colour magnitude diagrams (GALEX)



Sindhu et al. 2018 (MNRAS)

Thank you for your attention



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Chayan Mondal

Snehalata Sahu

Sindhu N