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The E.W.O.C.S. view of super massive star clusters

E.W.O.C.S.

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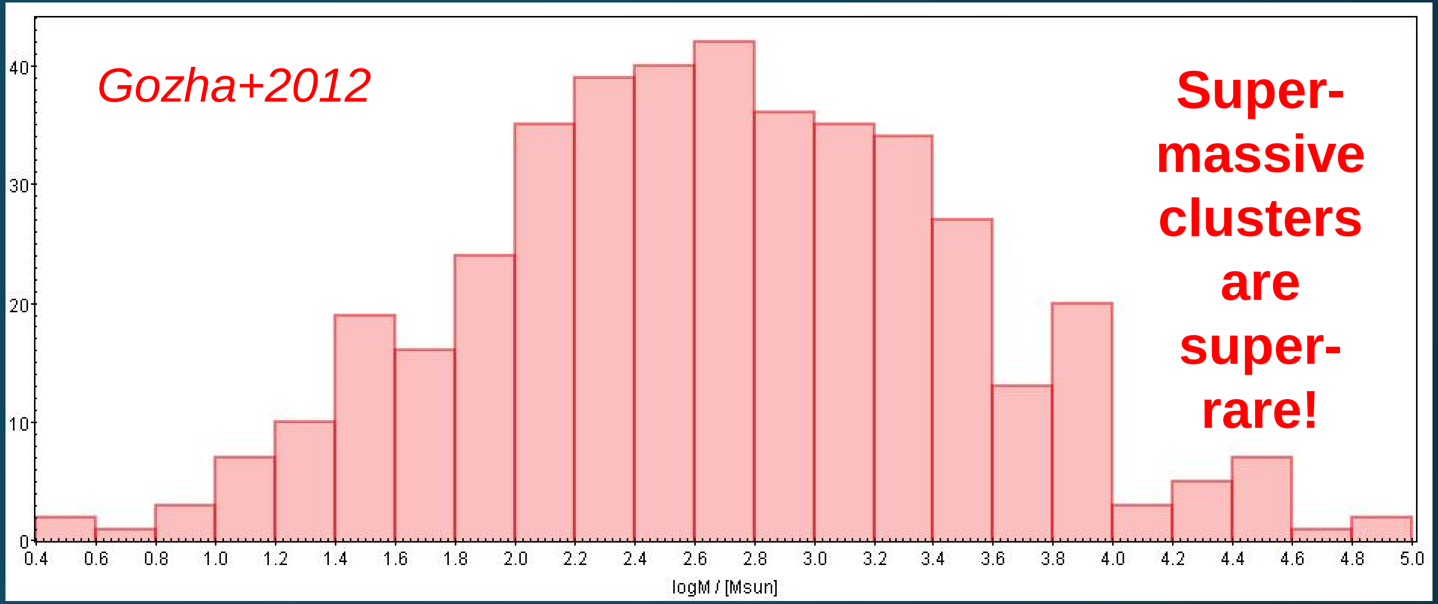
E.W.O.C.S.

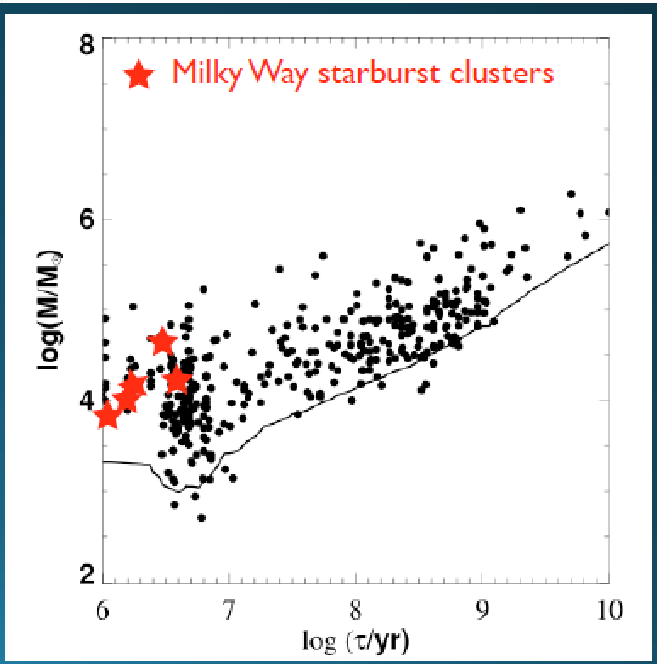
Young Supermassive Star Clusters

Mass distribution of star clusters in the Milky Way. **Clusters with mass >10^4 $M_\odot$ are very rare**.

In galaxies experiencing starbursts, star formation mainly takes place in concentrated and very massive clusters *(e.g. de Grijs+2001, 2003)*



HST image of M51



Cluster mass vs. age scatter plot in M51 compared with the most massive clusters of the Milky Way (adapted from Lee+2005)

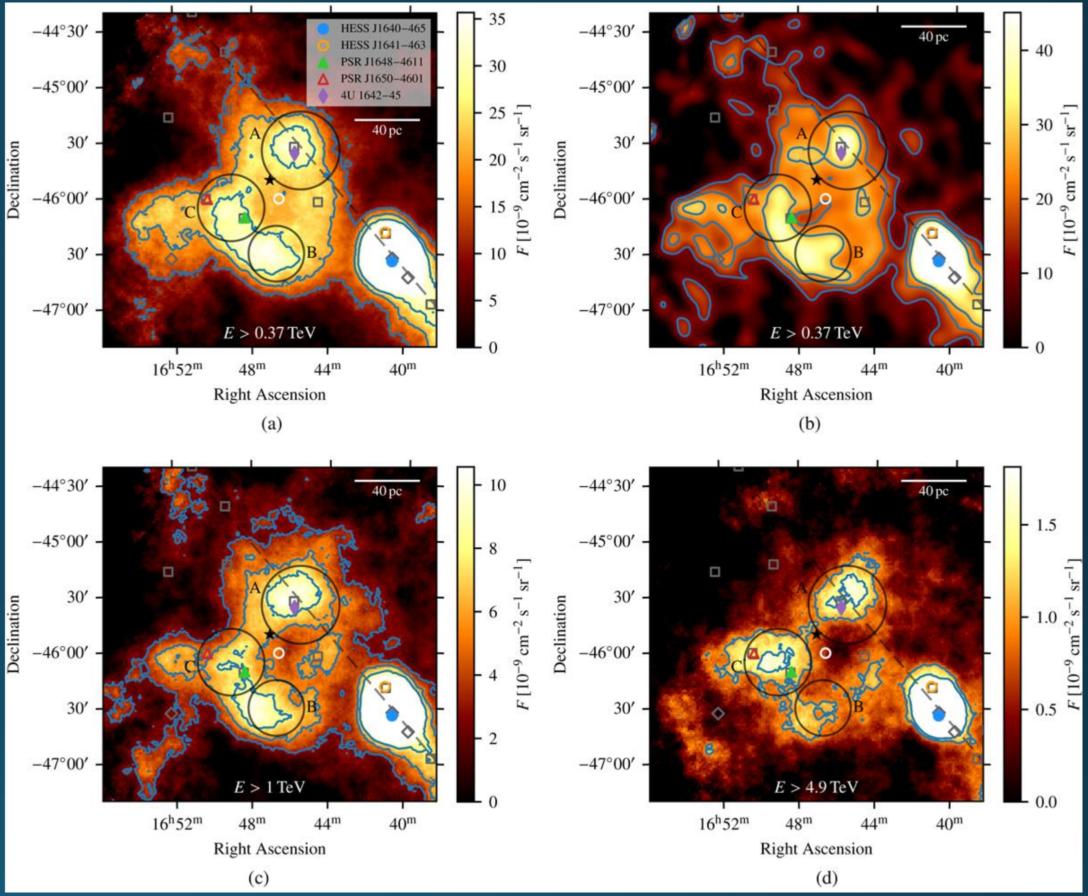
The SSCs environment

Very high stellar density

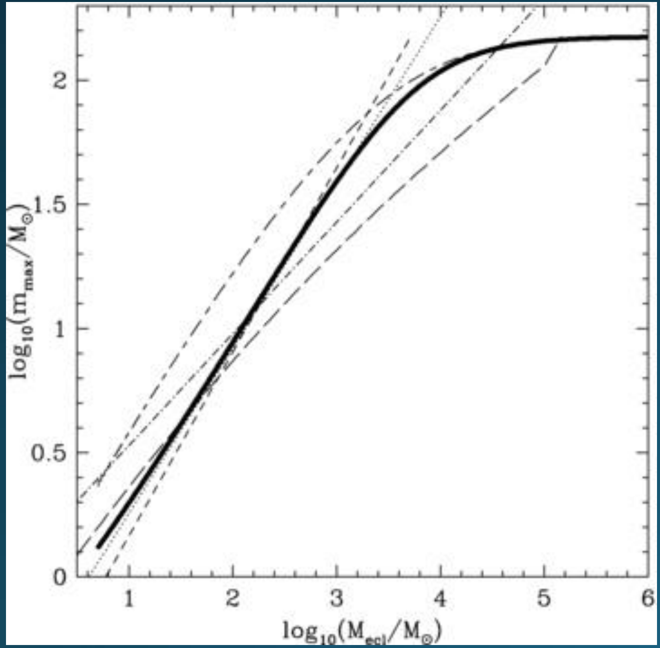
Rich, compact and variegate population of massive stars (e.g. > 8 $M_{\odot}$)

Intracluster environment dominated by energetic radiation and relativistic particles

The most massive stars produce supernovae and compact objects in a few Myrs



Map of the γ-ray flux around Westerlund1 from HESS (Aharonian+2022)



Mass of the most massive stars in clusters vs. cluster mass

Elmegreen 1983 [long dashed line], Elmegreen 2000 [short-dashed line], Bonnel+2003 [dotted line], Larson+2003 [dash-dotted line], Weidner & Kroupa 2004 [thick-solid line], Oey & Clarke 2005 [short-dashed–long-dashed line]

The impact of the starburst environment

IMF and brown dwarf formation in SSCs can be different than in low-mass environments *(Bastian+2010, Offner+2013)*.

Planets form in protoplanetary disks around young stars in a few Myrs (≤10 Myr). In SSCs, the dispersal of protoplanetary disks can be very quick (≤1 Myr). (e.g. Winter+2018)

The chemistry of protoplanetary disks, the planet formation process, and the properties of the atmosphere of new-born planets can be altered by UV, X-ray radiation and incident particles.

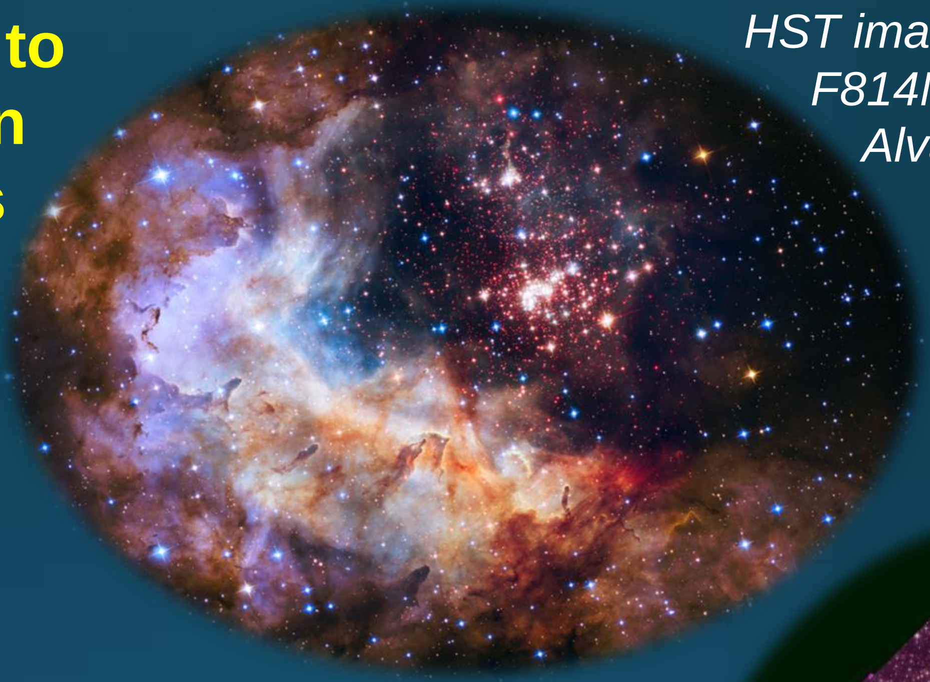
It is important to determine:

- SSCs formation: fast monolithic collapse from a dense cloud (e.g. *Bonnell, Bate & Vine 2000*) or slow assemble of smaller subclusters (*Allison+2009*)?

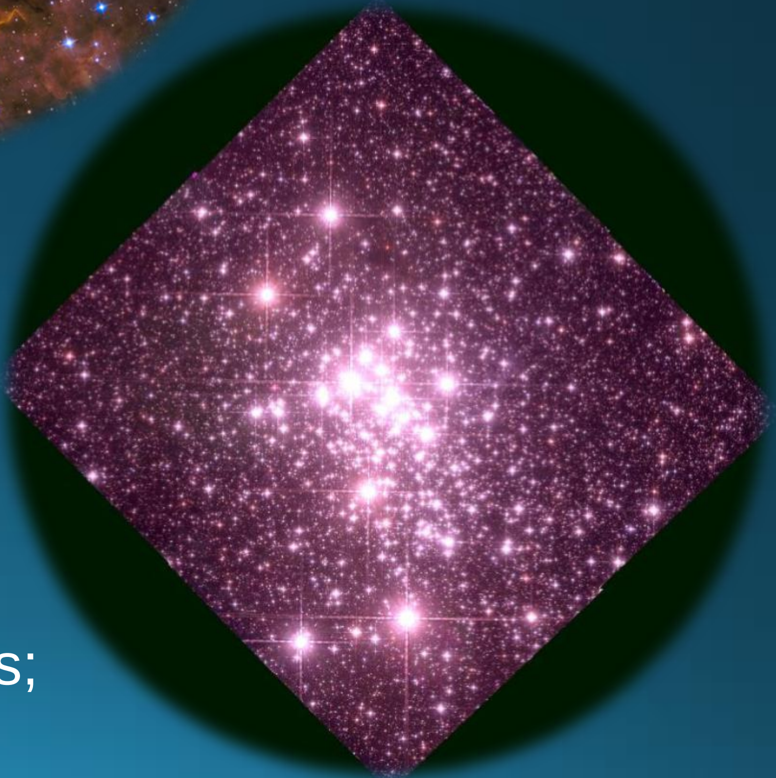
- SSCs evolution: will SSCs eventually disperse or form gravitationally bound systems? Can star formation proceed from polluted material accumulated in the cluster core?

WESTERLUND 1 and WESTERLUND 2

Wd1 and Wd2 are the best targets to study stars and planets formation and early evolution in starbursts



HST image of Wd2 (F555W, F814M, F125W, Vargas Alvarez+2013)



HST image of Wd1 (F125W, F139M, F160W, Andersen+2017)

- Relatively nearby (Wd1: 2.6-5 kpc, *Aghakhanloo+2019, Clark+2005;* Wd2: 4.2 kpc, *Vargas Alvarez+2013*)
- The most massive young clusters known in the MW (several 10^4 $M_{\odot}$; *Andersen+2017, Zedler+2017*)
- Richest population of massive stars in clusters (*many authors*)
- Wd1 hosts compact objects (at least two!; *Muno+2005, Borghese+ in prep, Israel+ in prep*)
- Young enough to host protoplanetary discs (Wd1: 3.2-10.4 Myrs; Wd2: 1-2 Myrs; *many authors*)

The EWOCS project: data and main objectives

- Study protoplanetary disk evolution and planet formation in SSCs
- Understanding the role played by binarity and mass-loss on the evolutionary path of massive stars and how the initial mass of massive stars maps into the compact objects
- Study the SSCs stellar mass distribution and determine whether it is affected by the environment
- Study how SSCs form, evolve and disperse from dynamics, age spread, binarity
- Study the compact objects, in particular IMBHs

Project mainly based on the following observations (P.I. Guarcello):

Wd1:
- **1 Msec Chandra/ACIS-I, proposal number 21200267**
- **GO-1905, 18.9 hours JWST NIRCam/MIRI**

Wd2:
- **GO-3523, 26.7 hours JWST NIRCam/MIRI**

Why X-ray data?

- **Young stars** are thousands times brighter in X-rays than old stars, offering a powerful selection criterion for the young stars of the cluster.
- **Massive stars** emit X-rays thanks to their winds (colliding and self-shocked).
- **Compact objects** emit in X-rays because of accretion, magnetic activity and the presence of hot and energetic plasma.
- A **diffuse X-ray emission** is typically observed in rich clusters with massive stars.
- The X-ray telescope returns energy, time of detection, and position of each detected photon. This allow low-resolution **spectral and temporal analysis**, shading light on the properties of the X-ray emitting plasma and the emission processes

Why JWST data?

- Warm dust in **protoplanetary discs** emits in infrared bands, providing powerful criteria to select stars with discs

- Analysis and modelling of the **Spectral Energy Distribution** potentially reveals properties of the discs and of the status of their dust grains population

- **Brown Dwarf** are cold (Teff < 3000K) and faint stars, which can be detected more easily in infrared than in other bands. JWST observations will allow us to push the selection of cluster members down to very low masses.

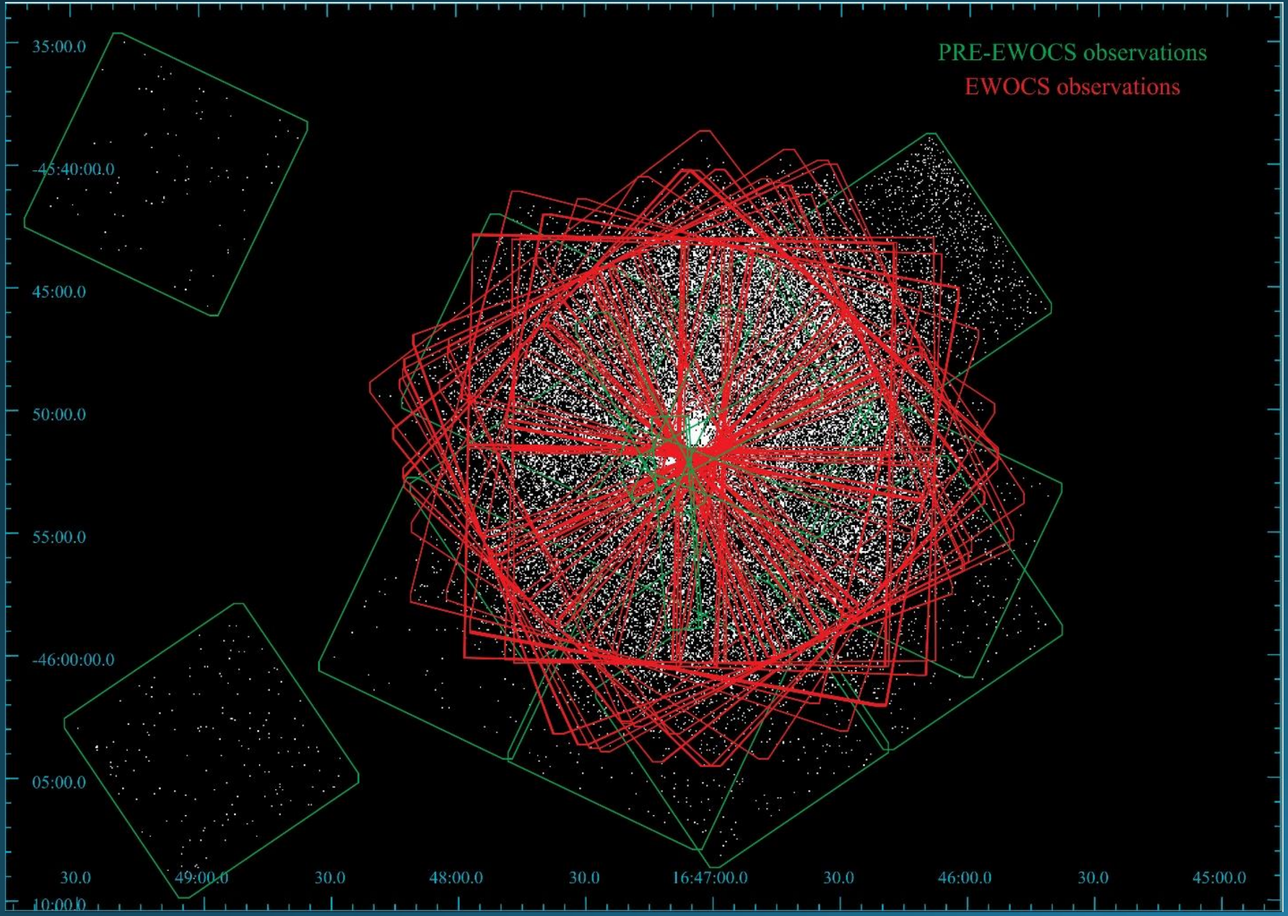
- Some **massive stars** in specific transient phases are extraordinary dust factories, and are surrounded by bright dusty envelopes.

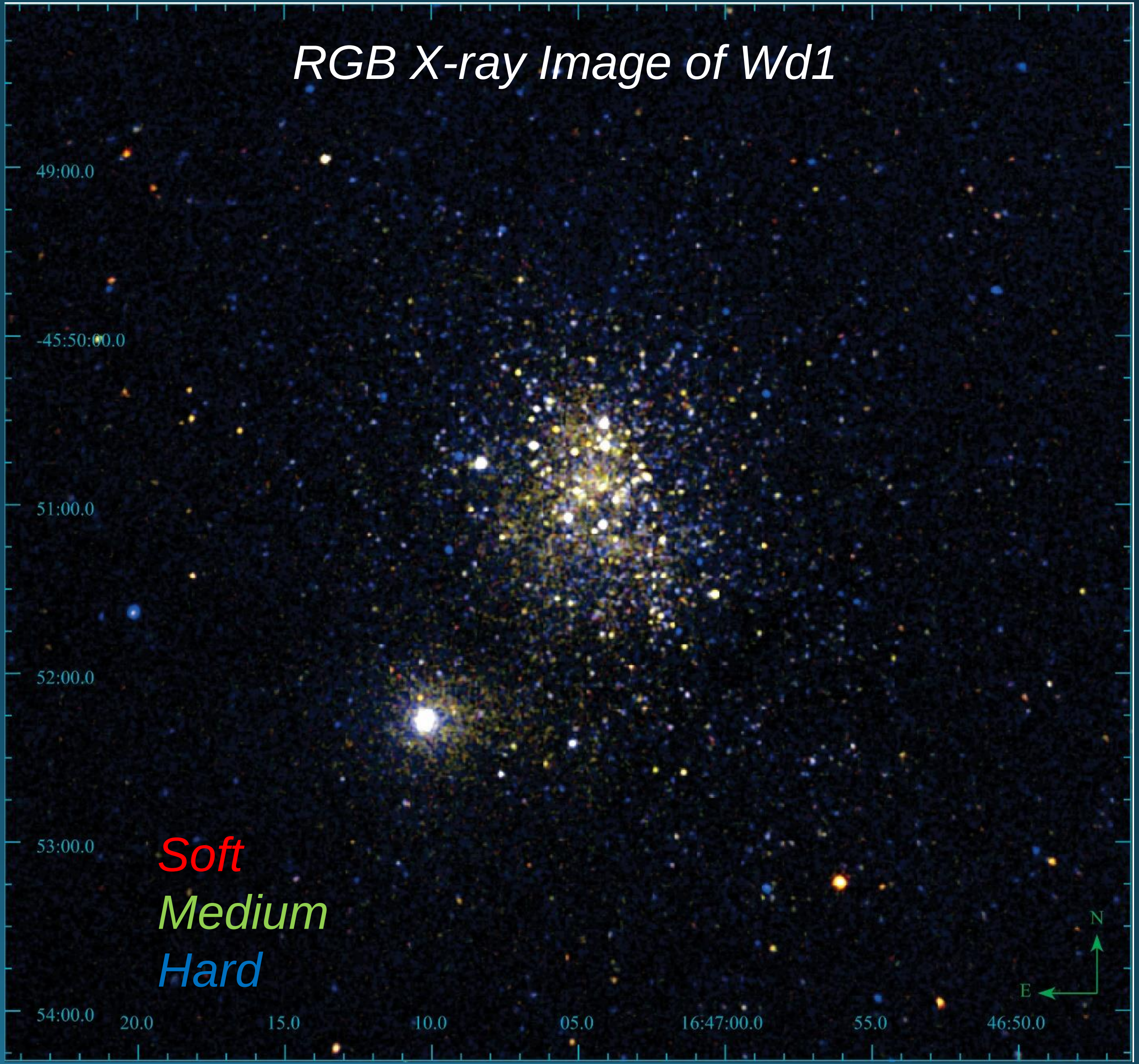
X-ray sources in Westerlund 1

Chandra/ACIS observations of Wd1

8 pre-EWOCS ACIS-S, 152 ksec,
6/2002 – 2/2018

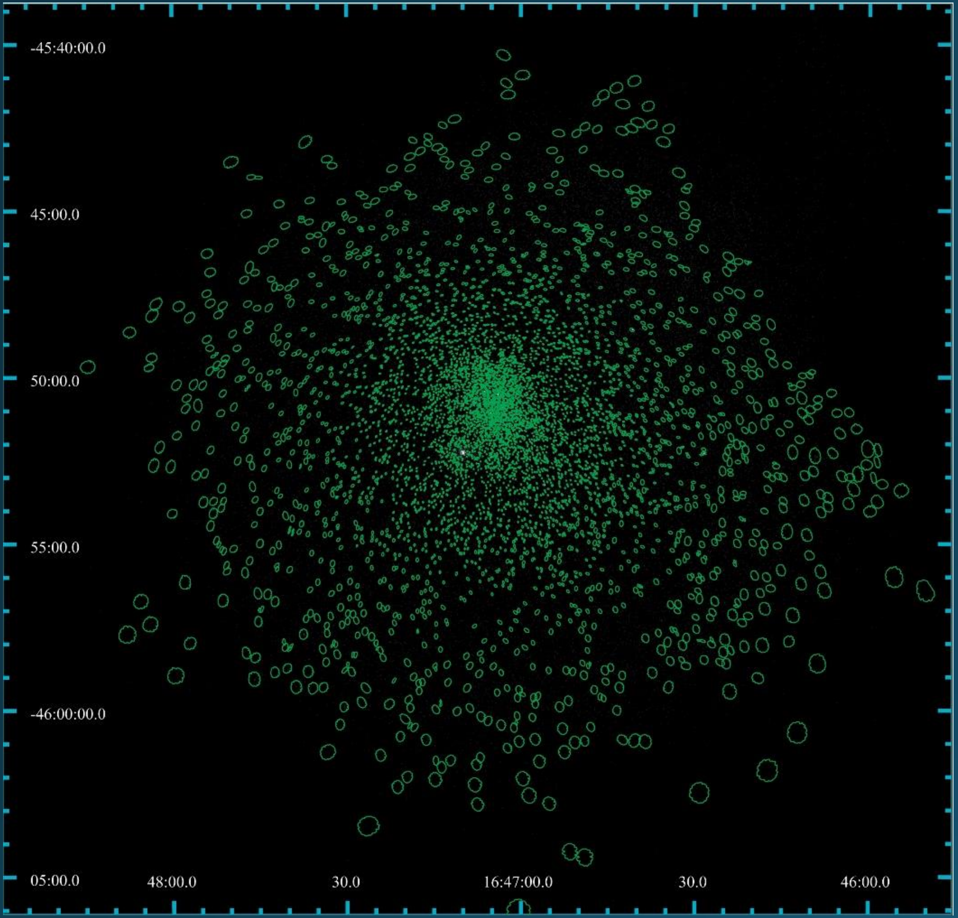
36 EWOCS ACIS-I, 967.8 ksec,
6/2020 – 8/2021





The orientation of the ACIS observations of Wd1

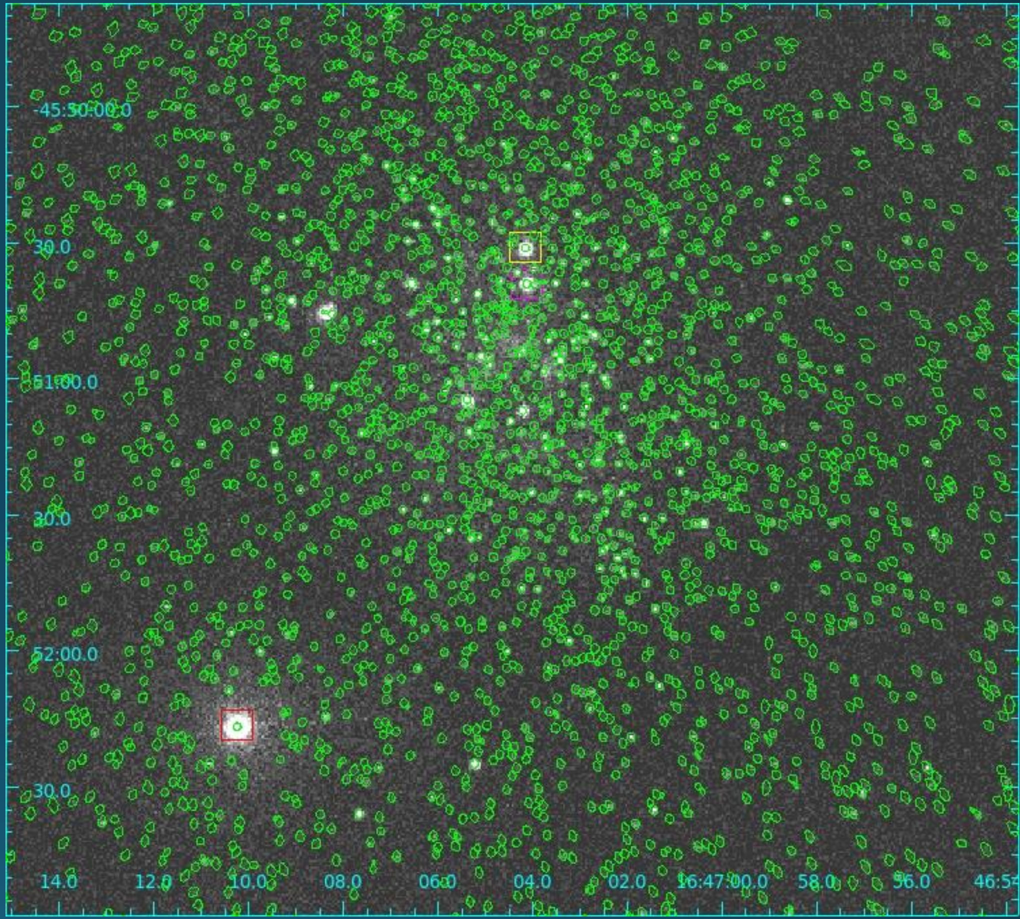
X-ray sources in Wd1 *(Guarcello, Flaccomio)*



5423 X-ray sources validated (*Guarcello+ subm.*).

Most X-ray sources populate a rich and extended cluster halo.

The magnetar CXP J164710.2-455216 is the brightest source (71600 net counts, *Borghese+ in prep*).



140 known massive stars (Clark+2020) detected in X-rays, among which 20 WR stars (*Anastasopoulou+ in prep., Ritchie+ in prep*).

X+OIR sources in Westerlund 1

The search for OIR counterparts

(Guarcello, Wright, Andersen, Pallanca)

Catalog	Nsources	Bands	Nmatched
ASAS-SN	72	Optical-IR	
BailerJones2021	19897		926
DENIS	7081	IJK	372
GAIA/DR3	24231	G BP RP	1082
ESO NTT/SofI*	6080	JHK	1323
GLIMPSE	22658	[3.6][4.5][5.8] [8.0]	105
SPICY	91	[3.6][4.5][5.8] [8.0]	
StarHorse 2022	4905		234
2MASS	13772	JHK	414
VISTA	96952	ZYJHK	1891
VPHAS	72924	ugriha	1332
WISE	2694	[3.4][4.6][12.1] [22.2]	77
HST	61583	F125W, F139M, F160W	1529

OIR catalogs crucial to assess the properties of the individual stars and Westerlund 1 (Gaia, HST, NTT/SofI, etc…)

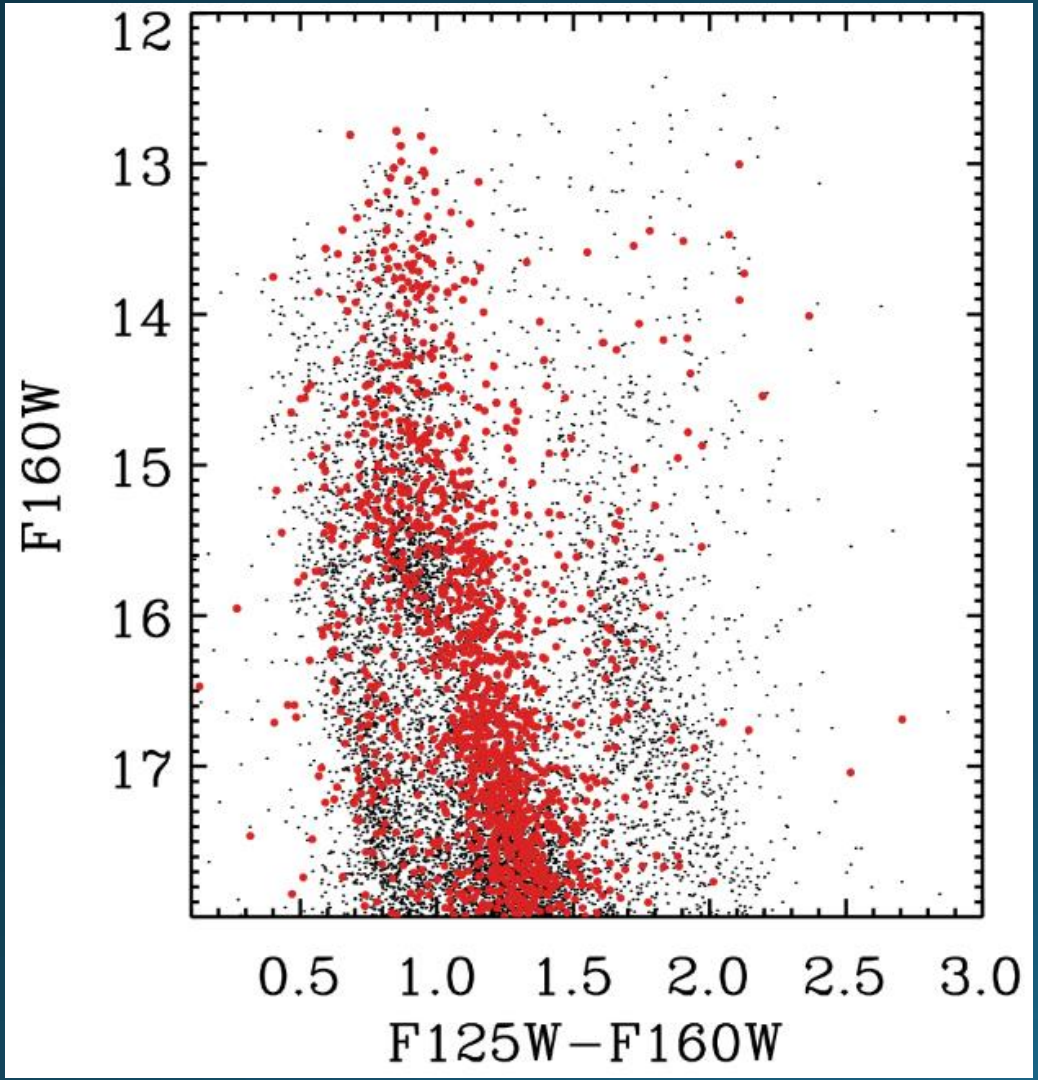
Matching procedure complicated by the:

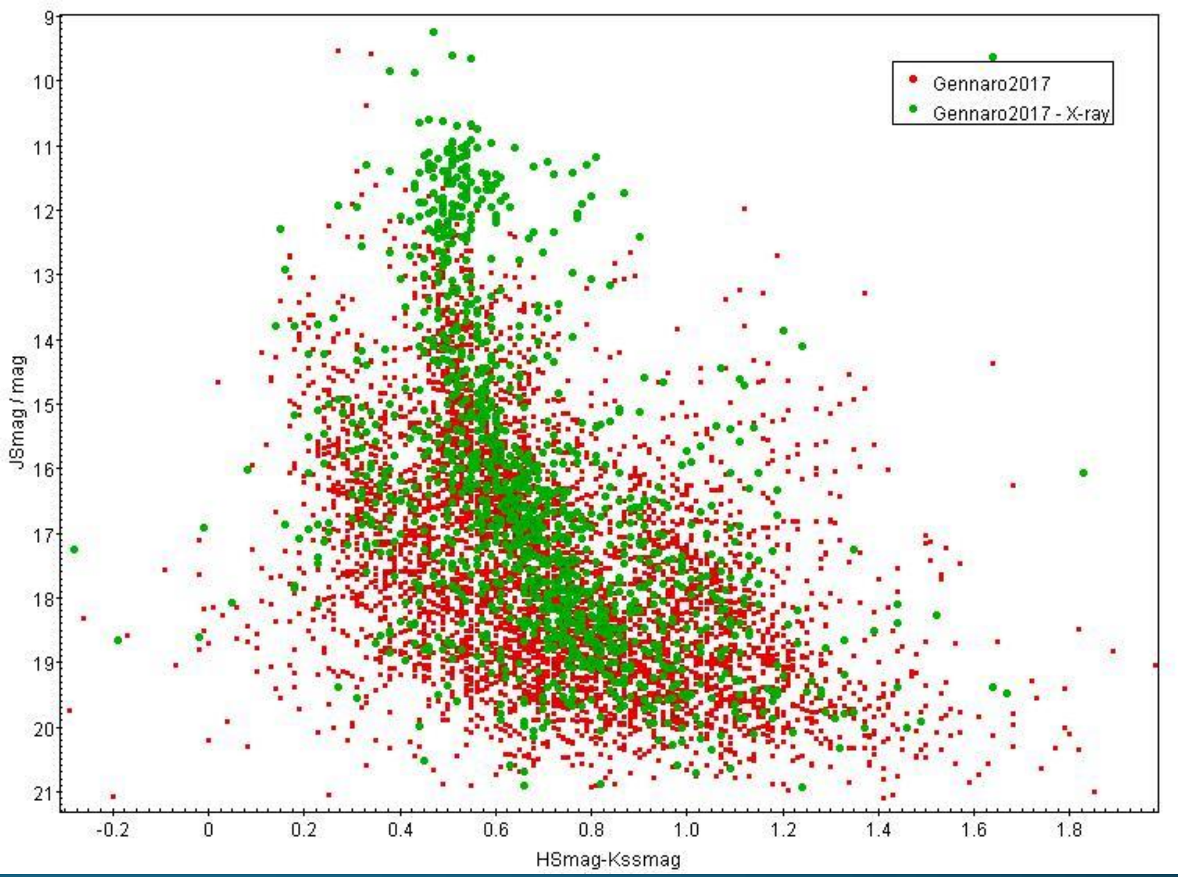
- large spatial density of sources
- Inhomogeneity between catalogs

Searching area: 11.5 from cluster core

** From Gennaro+2017*

Preliminary closest-neighborhood matches





Preliminary positional matches with HST and SOFI catalogs already show a cluster sequence in the colour-magnitude diagrams

WR stars in Westerlund 1

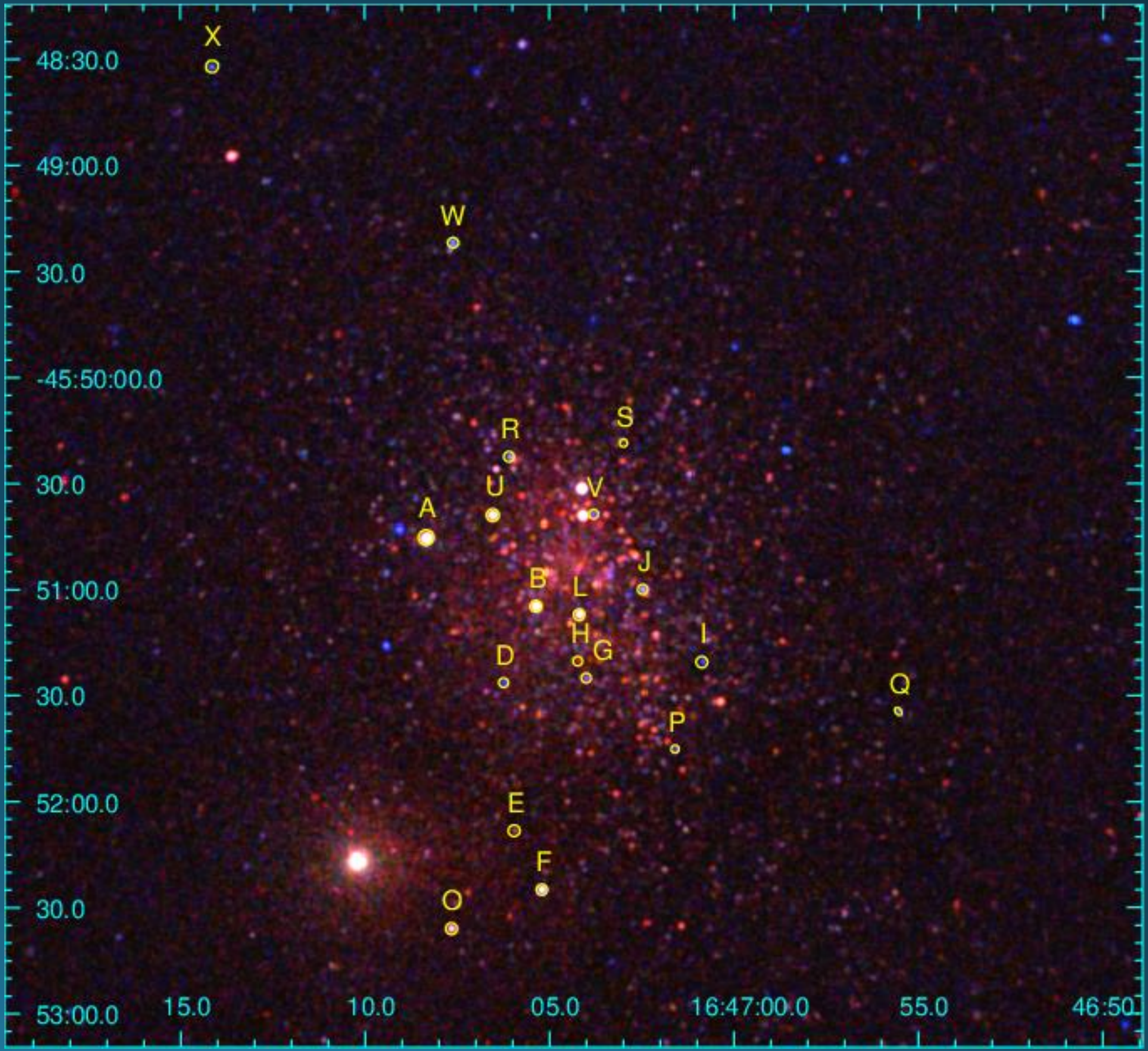
The massive stars: The WR stars *(Anastasopoulou)*

The WR stellar population of Westerlund1 is a challenge to theory.

Is binarity required to form such WR population in about 5 Myrs?

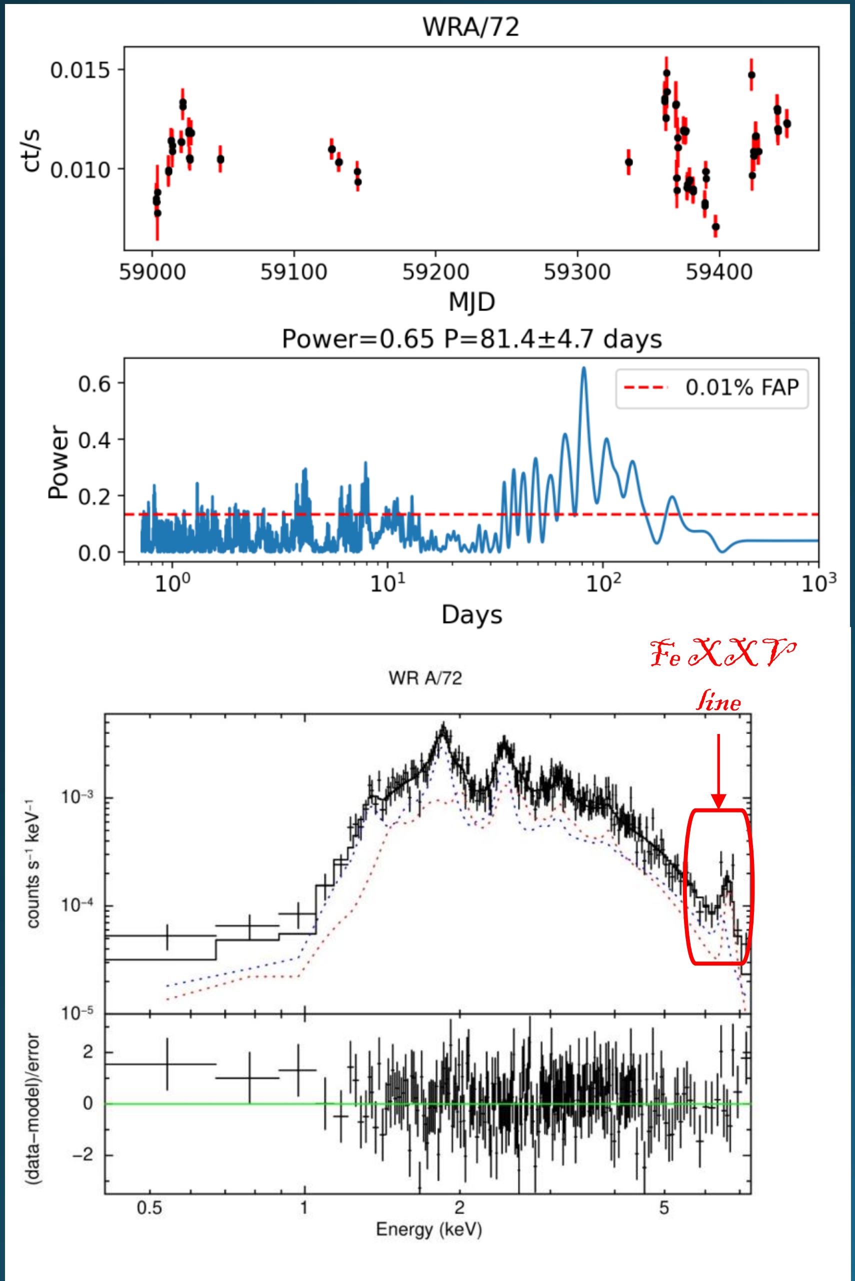
What are the high-energy processes in WR stars leading to the production of X-rays?

What EWOCS data can say about multiplicity in massive stars, and what implications on cluster formation/evolution?



Known WR stars in Westerlund 1

The binary fraction of WR stars



EWOCS data cover a long time baseline, allowing to search for periodic signals in the source photon flux.

The X-ray spectra of WR stars show evidence for the presence of >10 MK plasma, indicative of binarity and colliding winds.

Faint X-ray WR stars are dust producer carbon-type WR stars in binary systems.

Resulting binary fraction in WRs in Wd1 is about 100%.

Is this a property of all massive stars in Wd1, or binarity is required to form all these WRs in 5 Myrs?

(*Anastasopoulou+ in prep*)

Diffuse emission in Westerlund 1

DIFFUSE X-RAY EMISSION *(Albacete-Colombo)*

Not all detected X-ray photons are associated with sources.

Diffuse emission main sources should be:

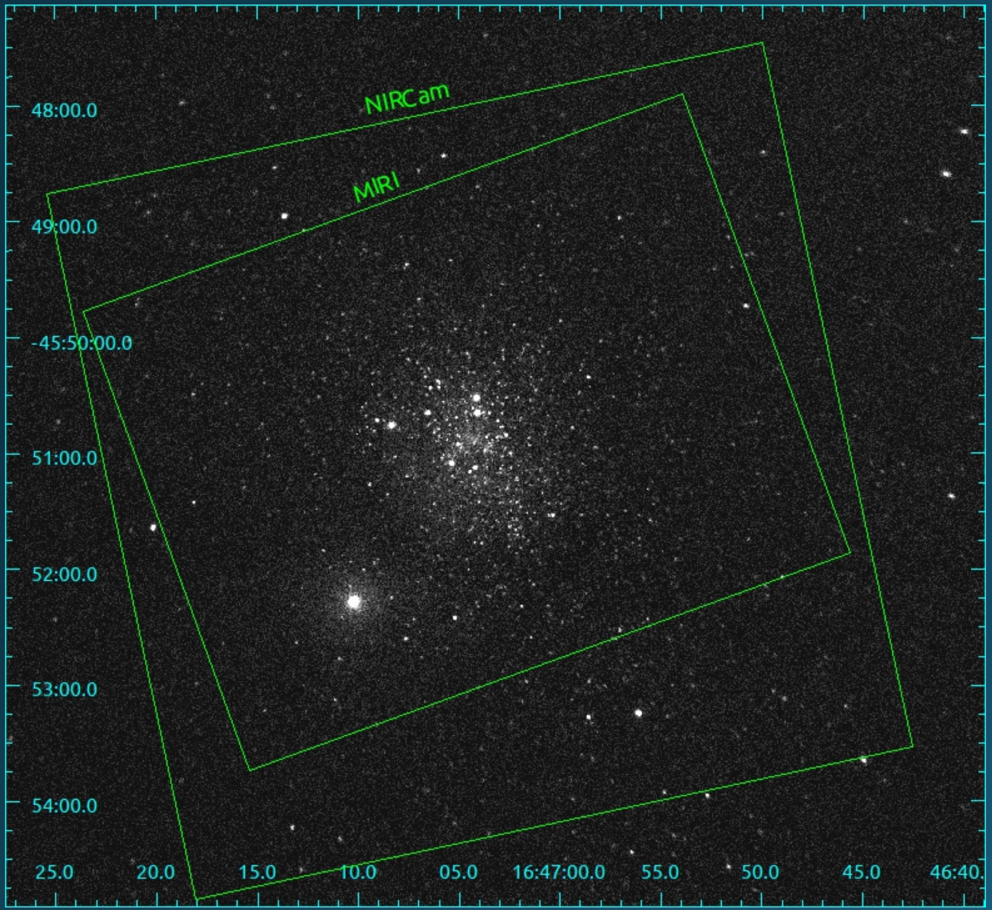
- Unresolved sources
- Winds from massive stars
- Hot intracluster gas

Very preliminary diffuse emission map in the 0.5-7 keV energy band.

Contamination from faint point sources still not completely assessed.

JWST observations of Westerlund 1

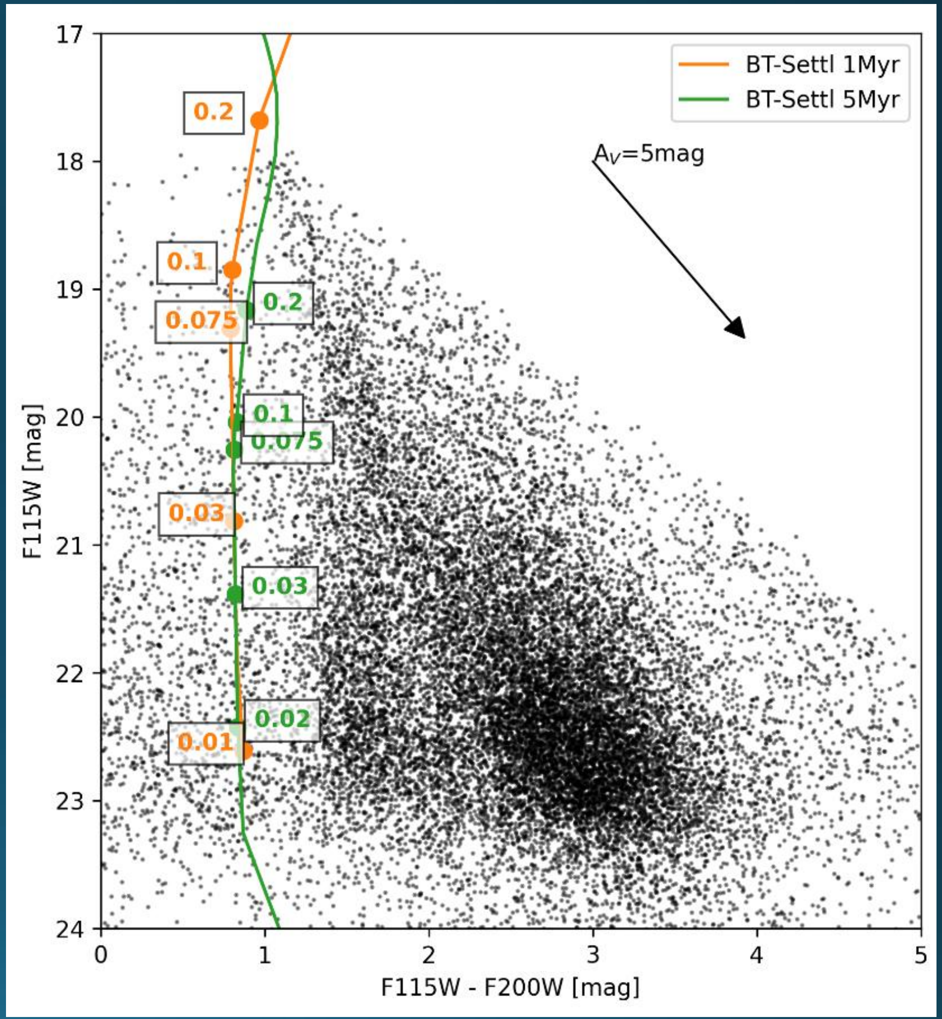
JWST/NIRCam images of Wd1 *(Almendros Abad, Muzic)*



NIRCam and MIRI field of views overplotted on the ACIS combined image

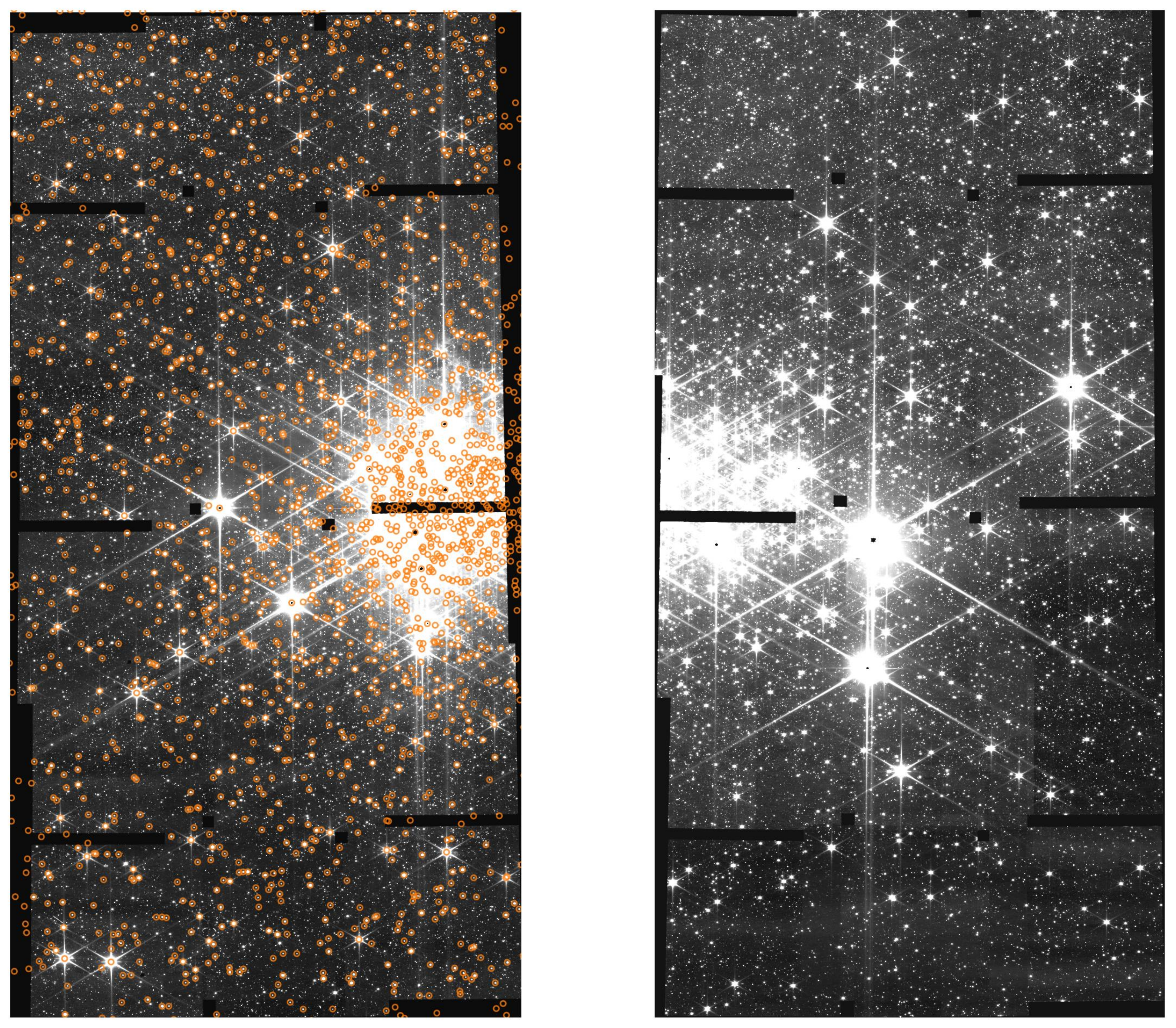
Analysis of the NIRCam and MIRI data of Wd1 still ongoing

The observations have successfully reached the brown dwarf regime of the cluster



NIRCam CMD plotted using the catalog distributed by the archive

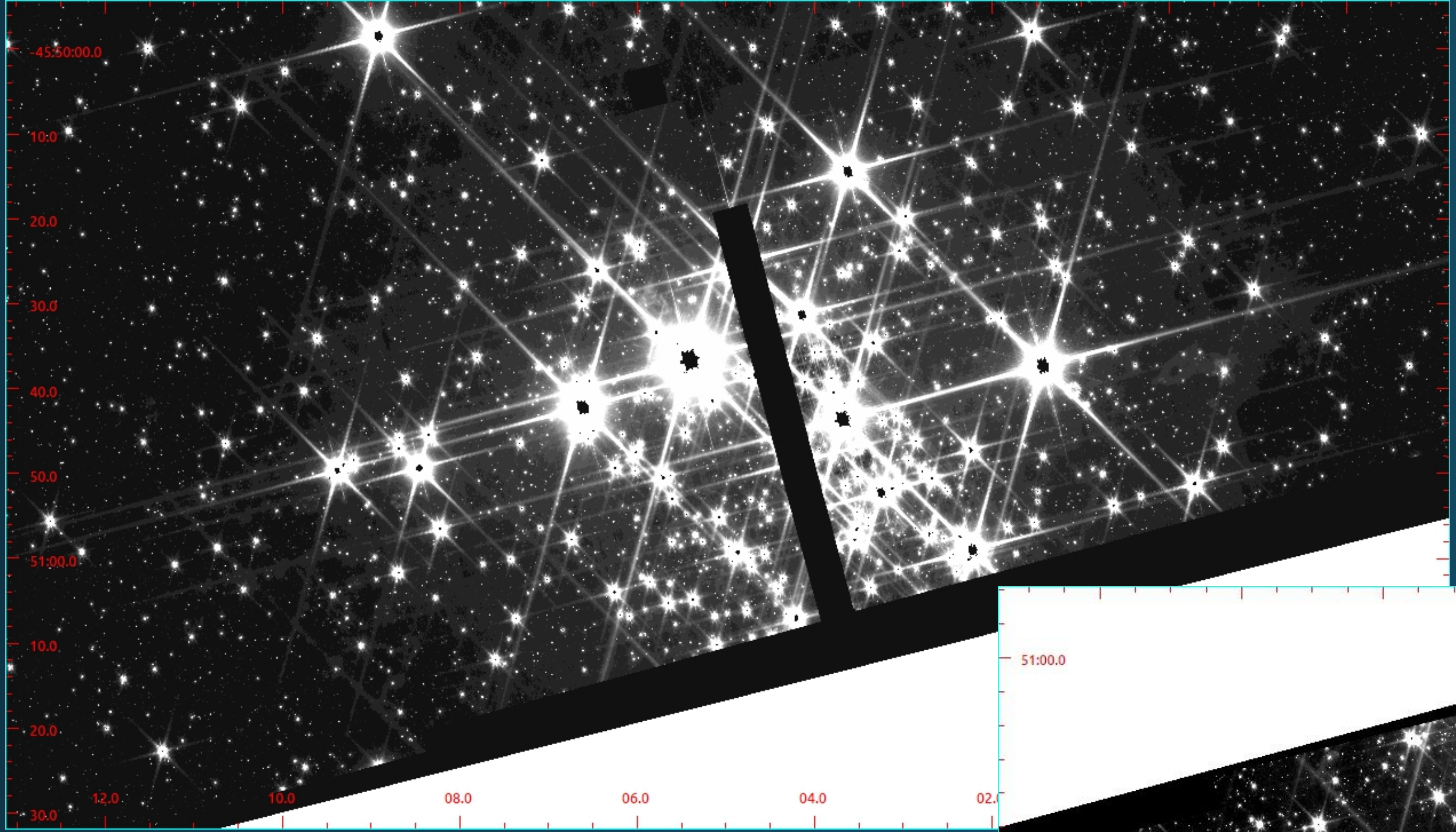
Phase 2 NIRCam mosaic



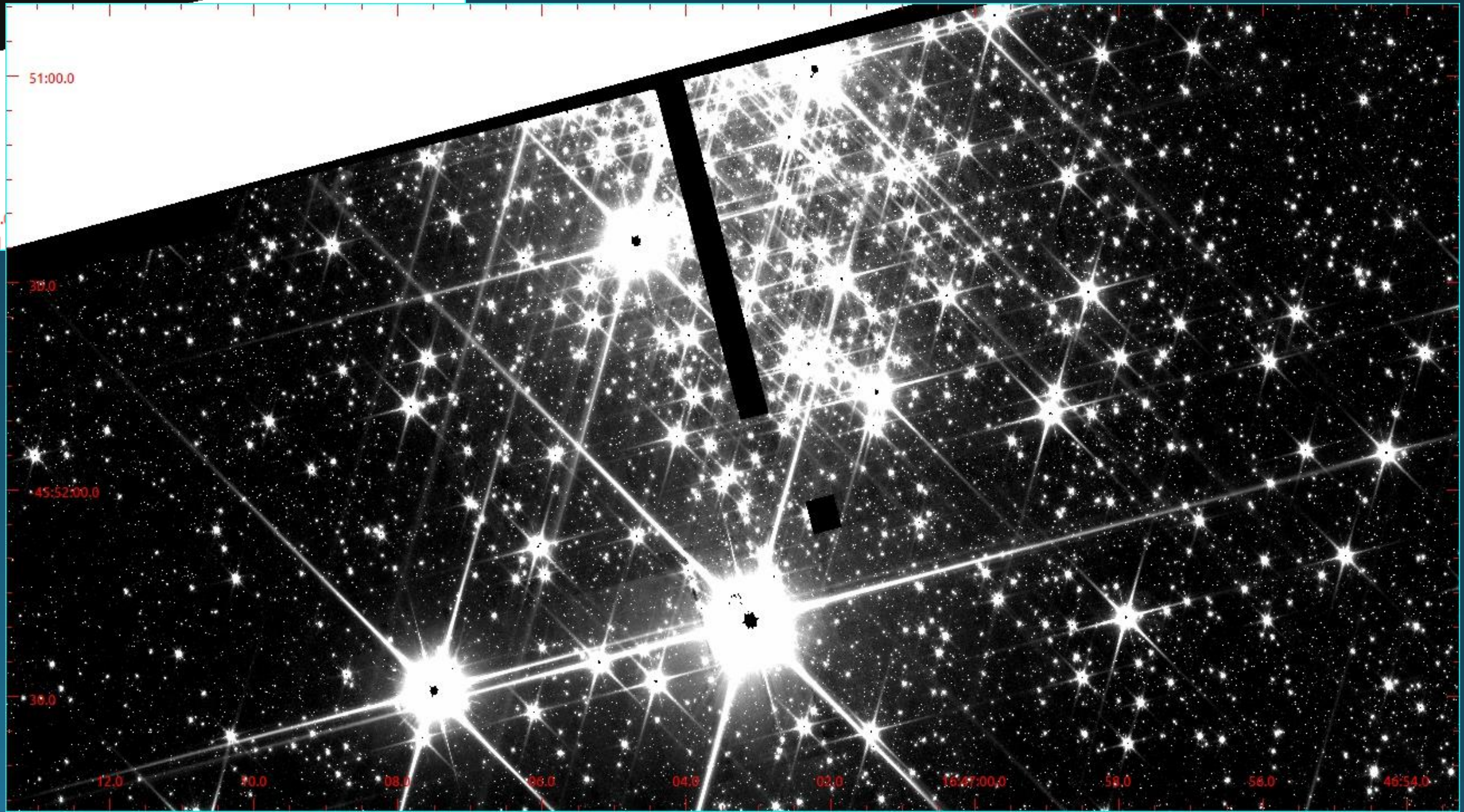
Current analysis focuses on WCS alignment, and phase 1 and 2 data reduction.

The pipeline still has several issues, some steps must be done carefully

Mosaic of NIRCam/F115W image of Westerlund 1. Orange circles: Gaia sources



Again, the central part of the F115W mosaic, with a different stretching of the image



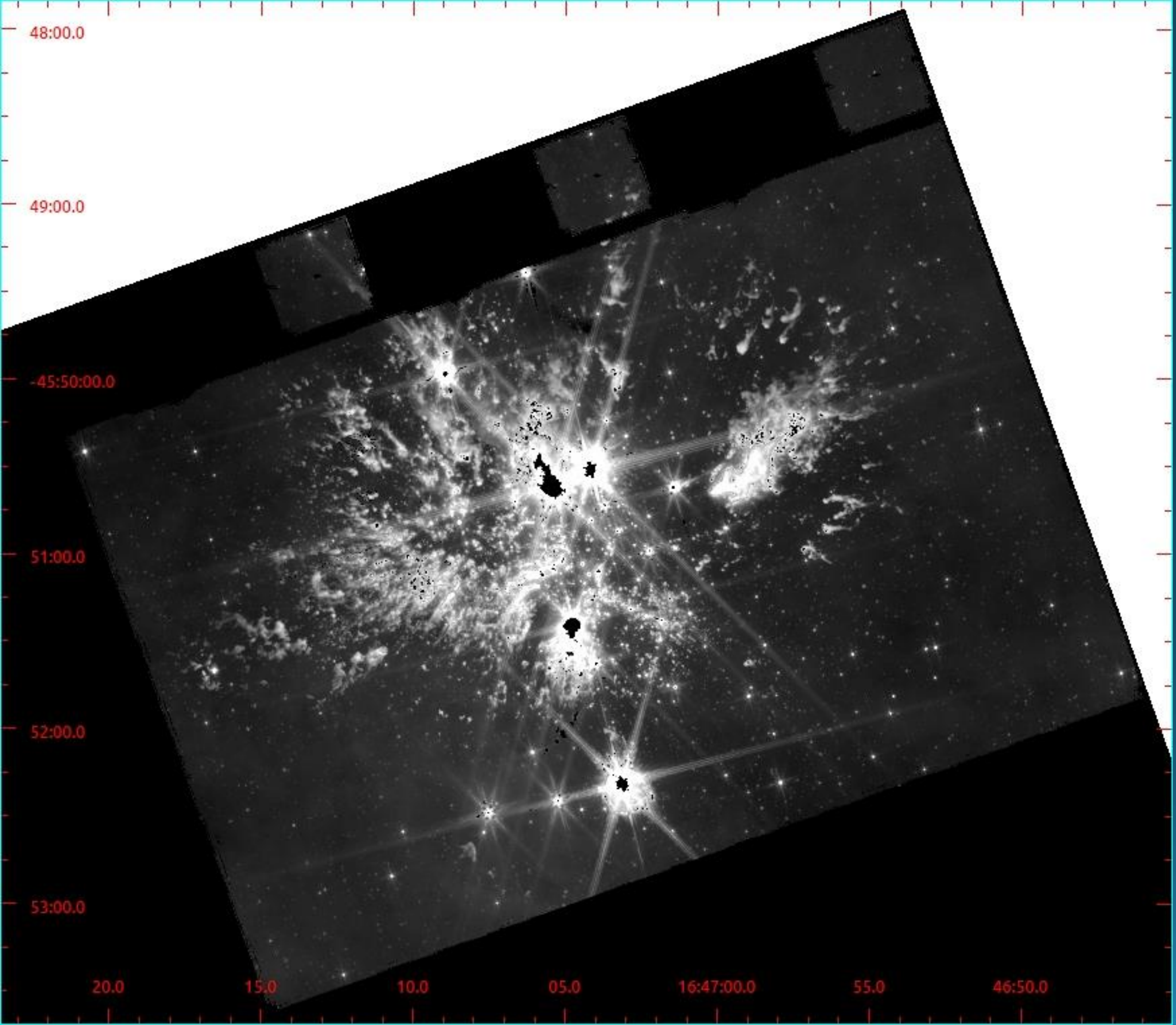
Cluster dynamics, formation and evolution *(Andersen, Wright)*

HST+JWST provides a time baseline of 12 years and an expected astrometric precision of 1 mas.

At the distance of Wd1, we will resolve stellar velocity down to 1.5 km/sec, well below the expected velocity dispersion if the cluster is virialised.

Main results:

- Cluster boundedness
- Energy equipartition (velocity dispersion vs. mass)
- Cluster expansion/contraction and rotation



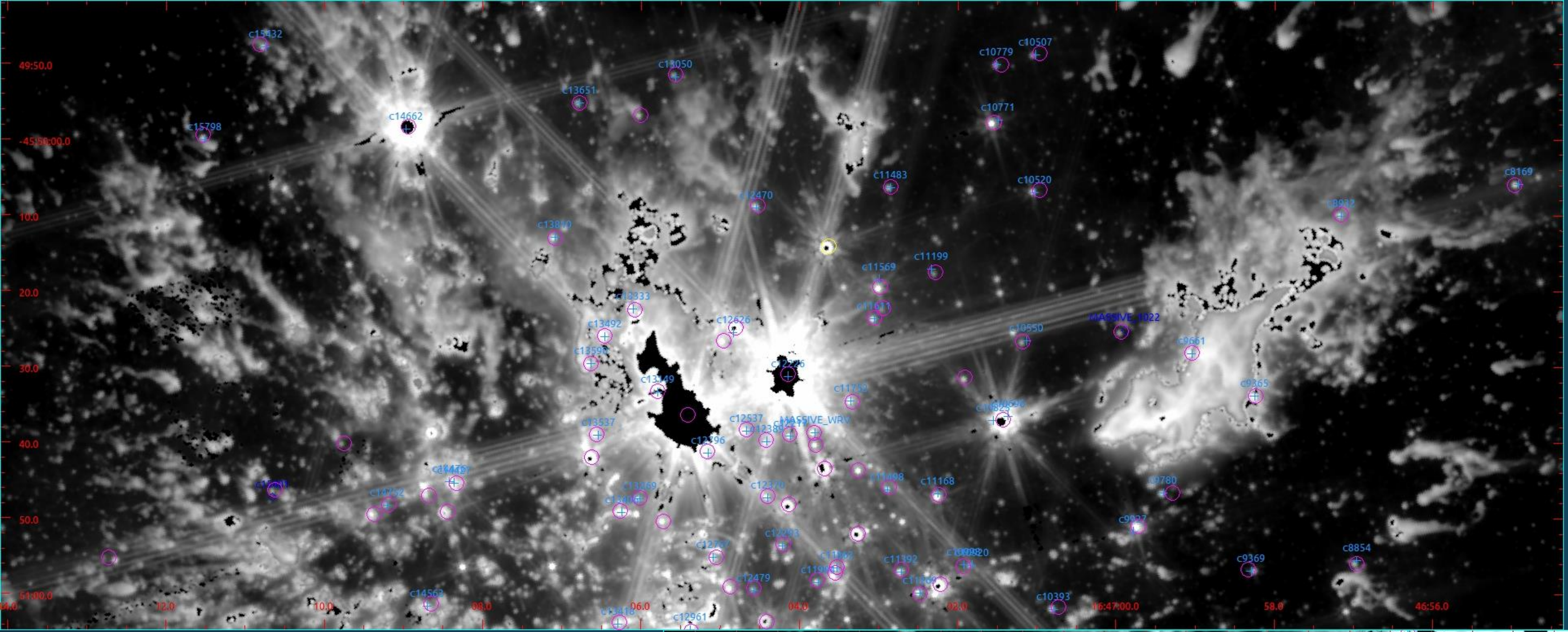
MIRI data *(Galarza-Martinez)*

MIRI image reduction still ongoing.

The images reveal an unexpected dense dusty nebulosity blown away by the central cluster.

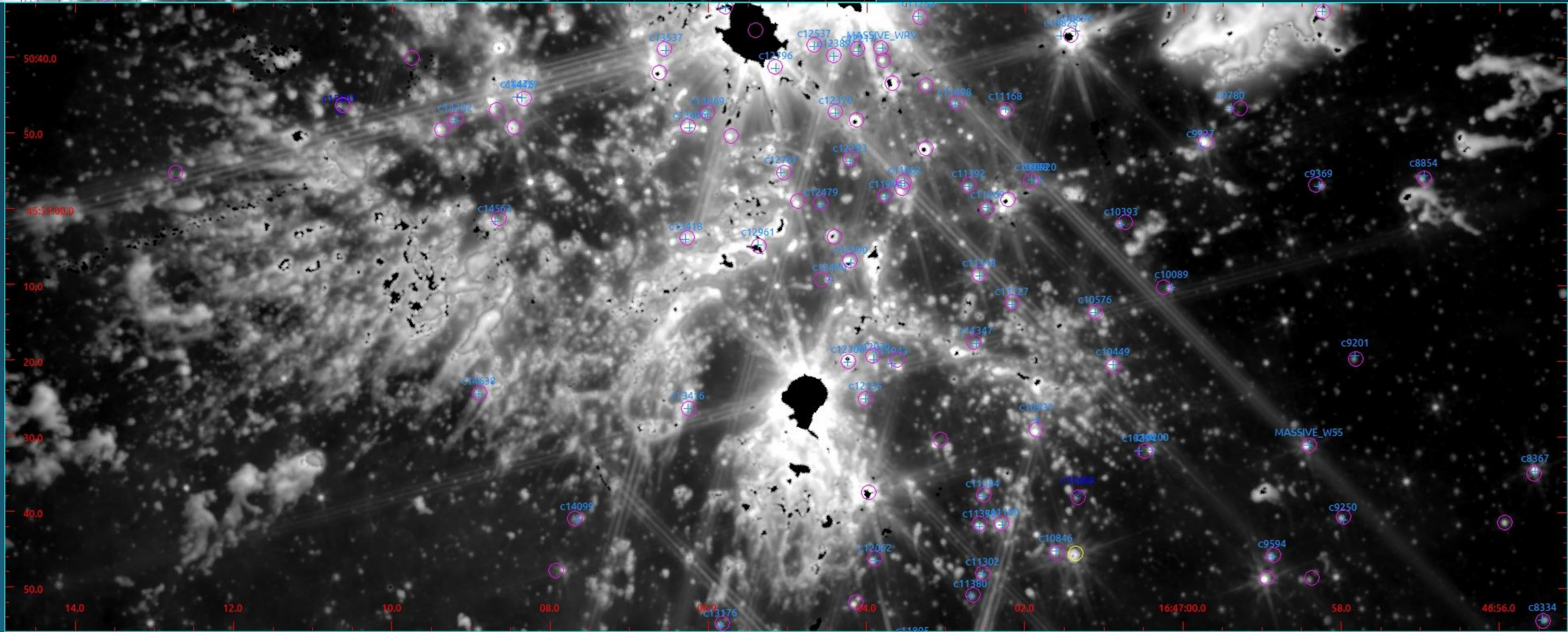
Remnant of the cloud?
Winds from the massive stars?
Second-generation of dust?

Not sure… but definitely exciting..



A zoom-in in the cluster core

Position of massive stars marked



Anything about Westerlund 2?

EWOCS:
Extended Westerlund One Chandra Survey

JWST GO program 3523 on Westerlund 2

EWOCS team
(43 astronomers from 21 Institutions)

GO 3523 Co.I. (7 US astronomers mainly from STScI)

EWOCS:
Extended Westerlund 1 and 2 Open Clusters Survey

JWST observations will be delivered in the first half of 2024.

Westerlund 2 has been observed with NIRSpec with NIRCam in parallel mode (GO: 2640, P.I. W. Best).

NIRSpec pointing in the outskirt; NIRCam image on a random position in the surrounding cloud.

Image reduction by G. Albani Lattanzi

Conclusions

The young supermassive clusters in the Milky Way allow us to study star and planet formation and early evolution in starburst conditions.

This is the objective of the EWOCS project, which is currently focused on Westerlund 1 and 2 thanks to deep Chandra/ACIS, JWST, and archival observations

In Westerlund 1, we detected a rich population of X-ray sources in the core and the halo, investigated the nature of the WR stars, and obtained great JWST data!