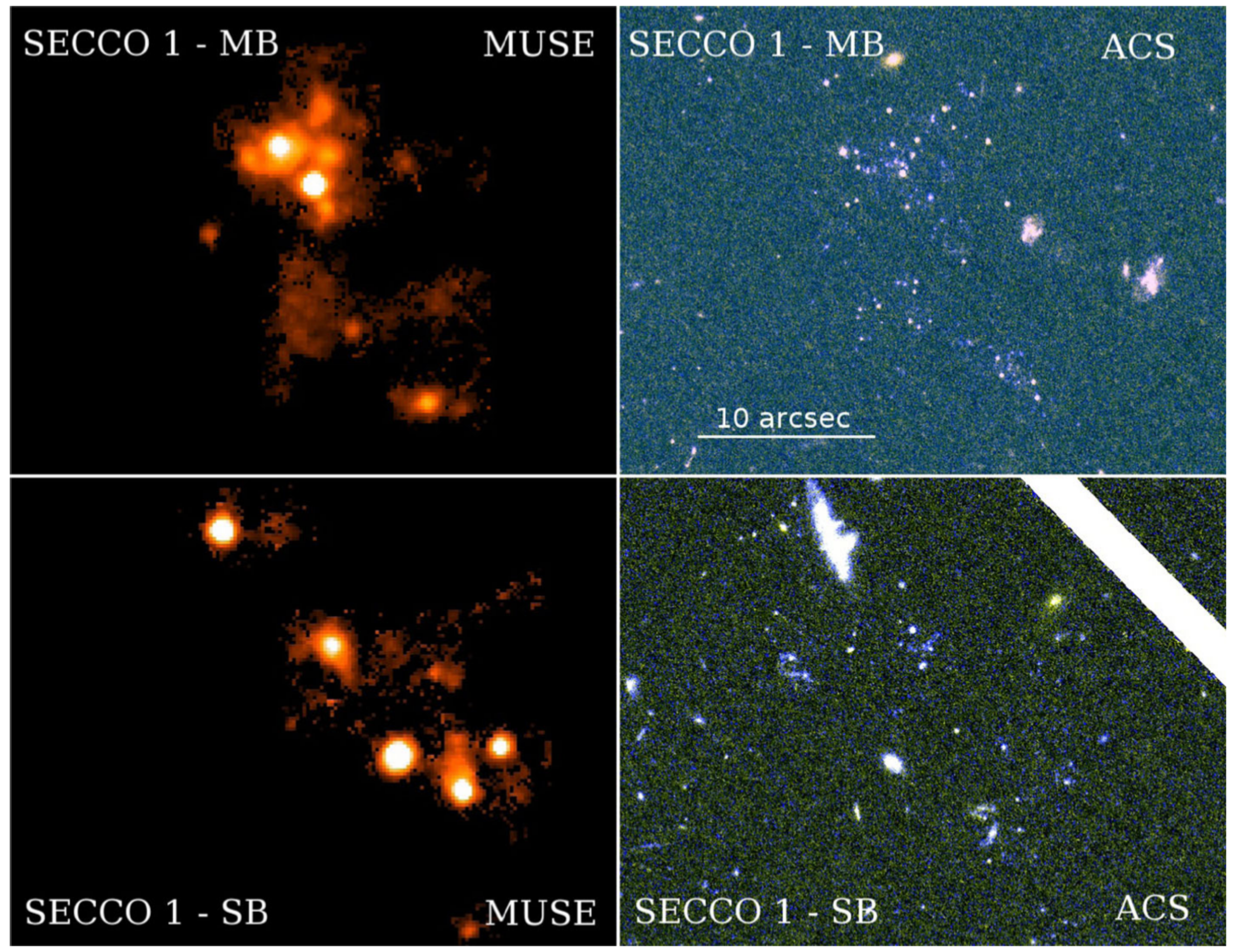
Young, Blue, and Isolated Stellar Systems in the Virgo Cluster

I. 2D Optical Spectroscopy

II. A New Class of Stellar System

Intro

- ALFALFA (compact HI sources) + GALFA (detecting their stellar counterparts) —> search new very dark local dwarf galaxies



SECCO 1 (AGC 226067):

- Low-mass($M^* \sim 10^5\ M_\odot$, $M_{HI} \sim 2 \times 10^7\ M_\odot$)
- Star-forming stellar system in Virgo cluster
- High mean metallicity ($\langle 12+\log(O/H) \rangle = 8.38 \pm 0.11$) —> stripped from: massive gas-rich galaxy (tidal interaction/ram pressure)
- Isolated (200 kpc from nearest candidate parent galaxy)

Theory/simulations:

- survive as long as ~ 1 Gyr, kept together by the pressure confinement of the ICM
- A rich population?

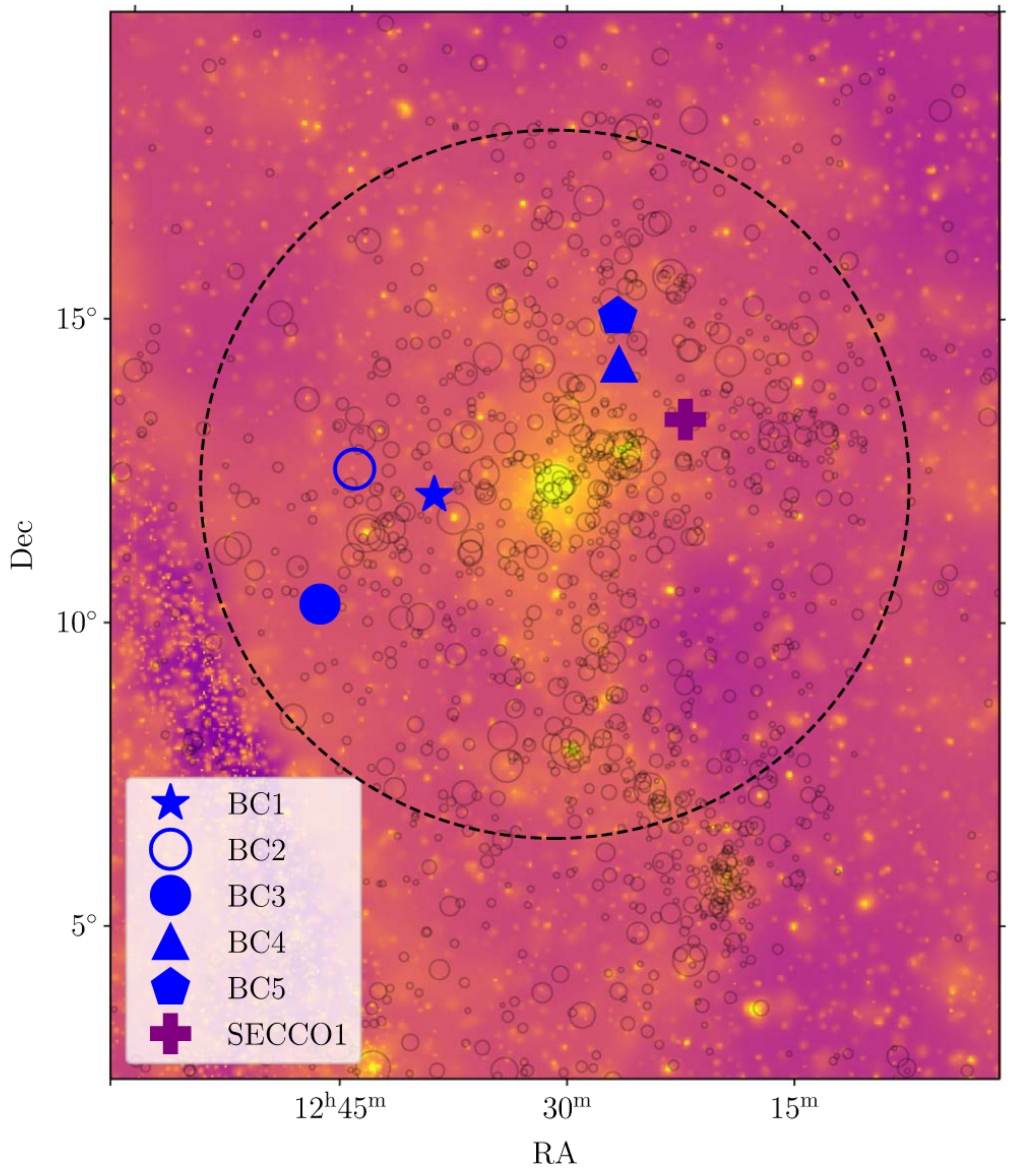
Intro

Five Blue Candidates (BCs) : selected from UV and optical images

- ~ 100 deg2 of NGVS ugi & GALEX UV images
- overdensity of compact blue sources
- strong associated UV emission
- lack a diffuse red component

Confirm their nature:

- Radial velocity (RV): their location within Virgo
- HII regions: any ongoing star formation
- Metallicity: assessing the origin



All are projected within the virial radius

Observations

MUSE — measure their redshifts and obtain metallicity measurements

- Integral field unit optical (4650-9300A) spectroscopy
- Six 1'.0 × 1'.0 fields
- Resolution: $\lambda/\Delta\lambda \simeq$ 2000-4000
- For each field, six t_{exp} = 966 s exposures
- Visually inspected in DS9 for Hα in Virgo redshift range (-500 km/s < *cz* <3000 km/s) —> easily found all sources except BC2 (a small group of background blue galaxies)

Observations

Extract their spectra

1. Split into 3801 single layers, from 4600.20 to 9350.29A (wavelength step 1.25A)
2. Stacking together the four layers where local Hα signal reached its maximum — spectral window of 5.0A, white image: stacking all 3801 layers
3. Searched for sources: intensity peaks > 3.0 σ (Sextractor)
4. Photometry through an aperture of radius 1".5 (Sextractor)
5. Recombined —> 1D spectrum for each source
6. Visually inspect

Observations

- 53 sources
- Identify emission lines: Hβ, [O III]4959, [O III]5007, [N II]6548, Hα, [N II]6583, [S II]6717, [S II]6731
- Heliocentric RV — IRAF RVIDLINES
- Line fluxes — IRAF SPLOT, 37 sources: both Hα and Hβ — estimate extinction

HII regions

- Significant reddening differences — some have higher internal extinction
- Variation in the degree of ionization: [O III] in only some of them
- Not associated with metallicity variations, but with the temperature of the ionizing stars

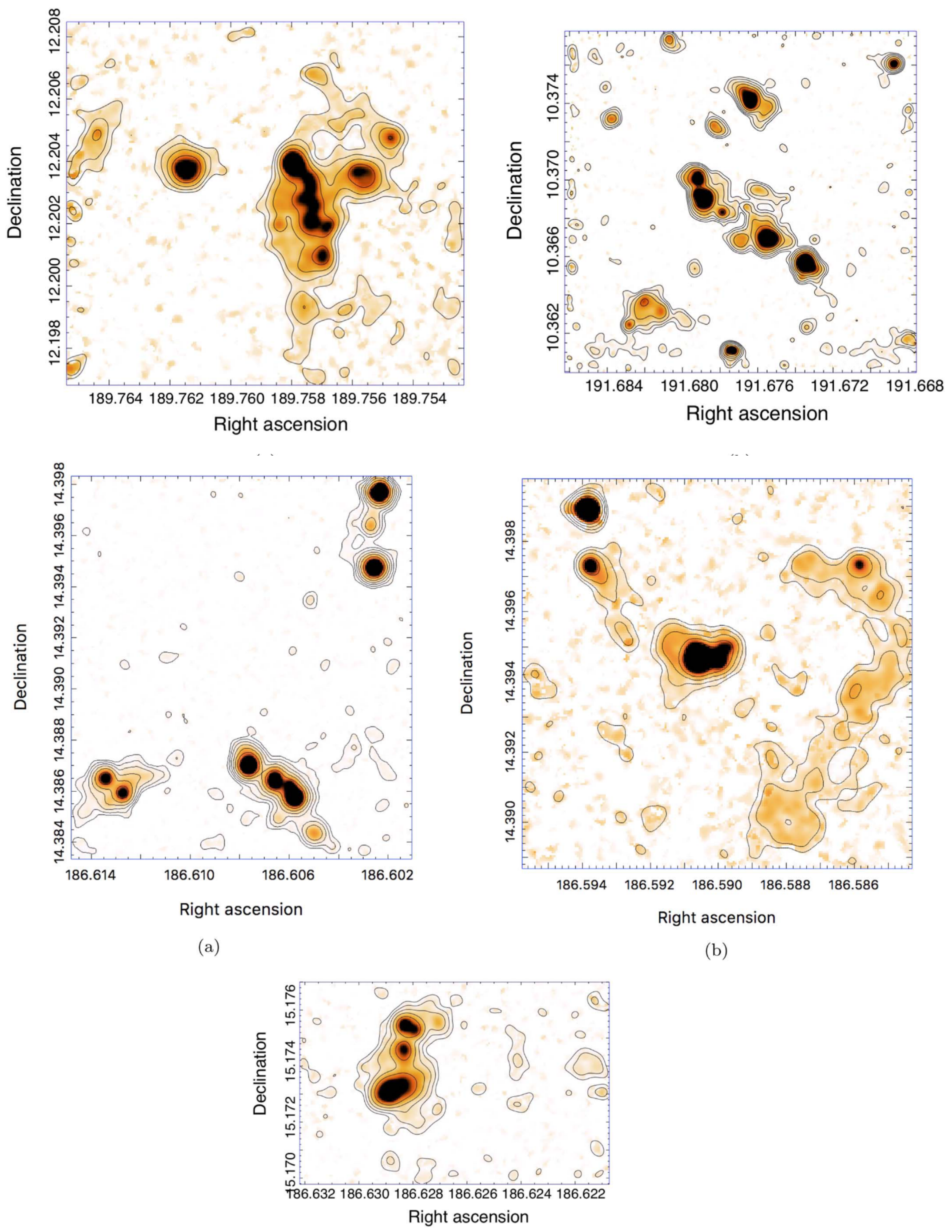
Observations

GALEX

- BC 2, 3, 4 and SECCO 1: GUViCS (no FUV available for BC 4 and SECCO 1)
- BC 1: Virgo_Epoque_MOS05, NGA_Virgo_MOS04
- BC 5: NGA_NGC4421, GI1_079012_Group5
- Aperture photometry — estimate the SFR

Morphology, Classification, and Kinematics

- continuum-subtracted Hα images (stacking four slices near the emission line)
- Elongated configuration (similar to SECCO 1)
- Separate pieces (except BC5): typical separation < 0’.5 (< 2.4 kpc in Virgo)
- Two pieces of BC4: ~ 8 kpc —> a very young collection of objects formed in a gas-rich stream, or an older object that has become gravitationally unbound



BC 1 , BC 3

BC4L, BC4R

BC5

Morphology, Classification, and Kinematics

- Position of the systems within Virgo (with EVCC catalog)
- Phase-space diagram (M87 as center): mean velocity within EVCC range
—>Virgo cluster member
—> BC 1 and BC 3 consistent with Cluster C
—> SECCO 1, BC 4, BC 5: Low Velocity Cloud/Cluster A

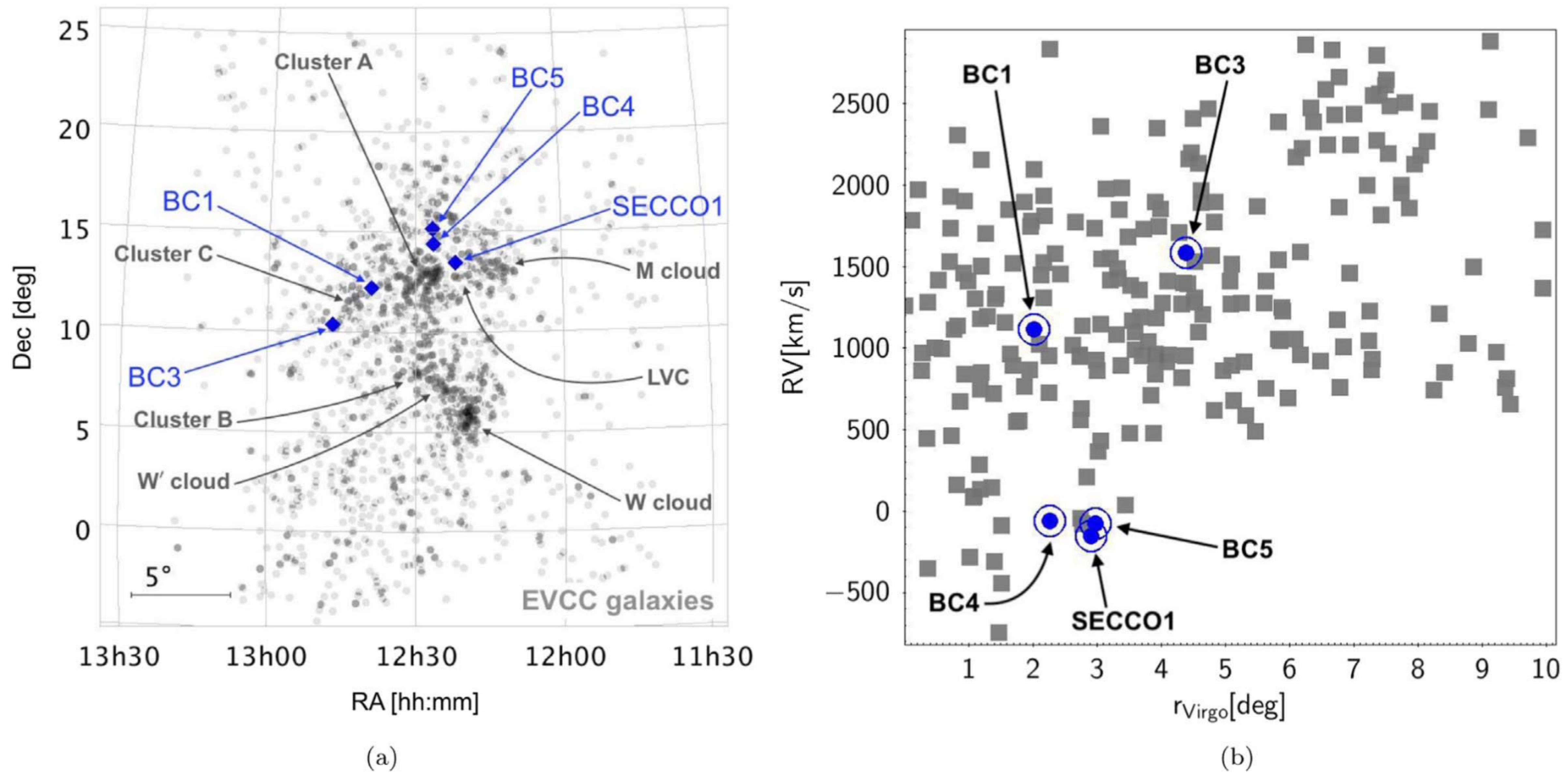


Figure 5. Locations of the BCs and SECCO 1 within the Virgo cluster. In panel (a), the positions of the systems (blue diamonds) are indicated within a wide map of the Virgo cluster, as traced by the distribution of the EVCC galaxies (small gray circles; Kim et al. 2014); the main substructures of the cluster are labeled following Boselli et al. (2014). In panel (b), the EVCC galaxies (gray squares) and BCs (encircled blue filled circles) are plotted into a phase-space diagram opposing the heliocentric line-of-sight velocity to the angular distance from M 87, taken as the center of the Virgo cluster.

Morphology, Classification, and Kinematics

- BC 4, BC 5, and SECCO 1: negative radial velocities, but in the vicinity of M 86, a region of Virgo cluster where negative velocities are common

Table 3
Metallicities of BCs

Object	$v_{\mathrm{H}\alpha}$/km s^{-1}	$N_{\mathrm{H}\alpha}$	$N_{\mathrm{O/H}}$	$\langle 12 + \log\mathrm{O/H} \rangle$
BC1	1117 ± 6	18	2	8.35 ± 0.15
BC3	1584 ± 4	15	5	8.29 ± 0.17
BC4	-60 ± 19	16	6	8.73 ± 0.15
BC5	-74 ± 5	4	2	8.70 ± 0.14
SECCO1[a]	-153.2 ± 1.4	33	9	8.38 ± 0.11

Morphology, Classification, and Kinematics

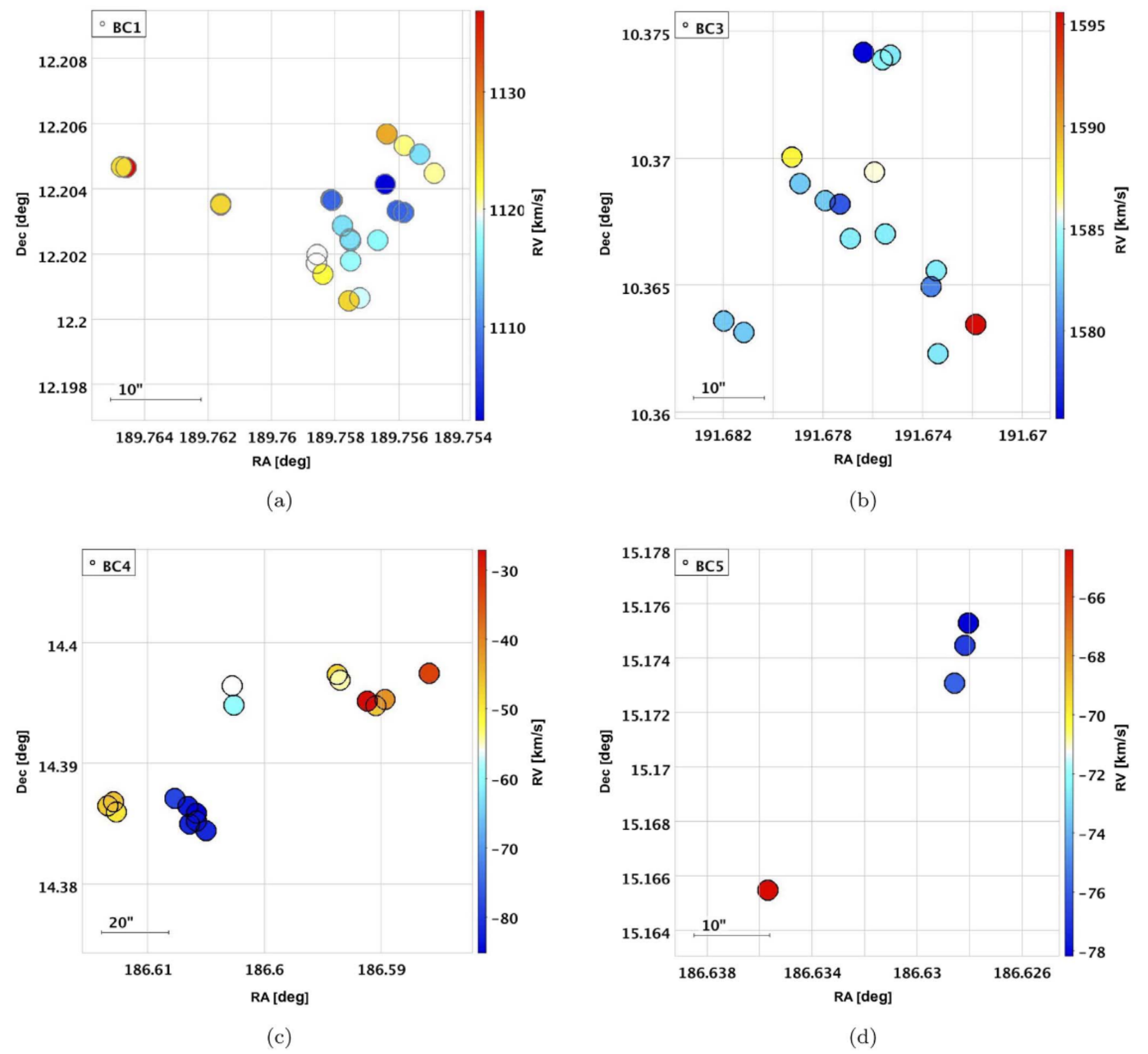
RV fields, in R.A. [deg] and decl. [deg]

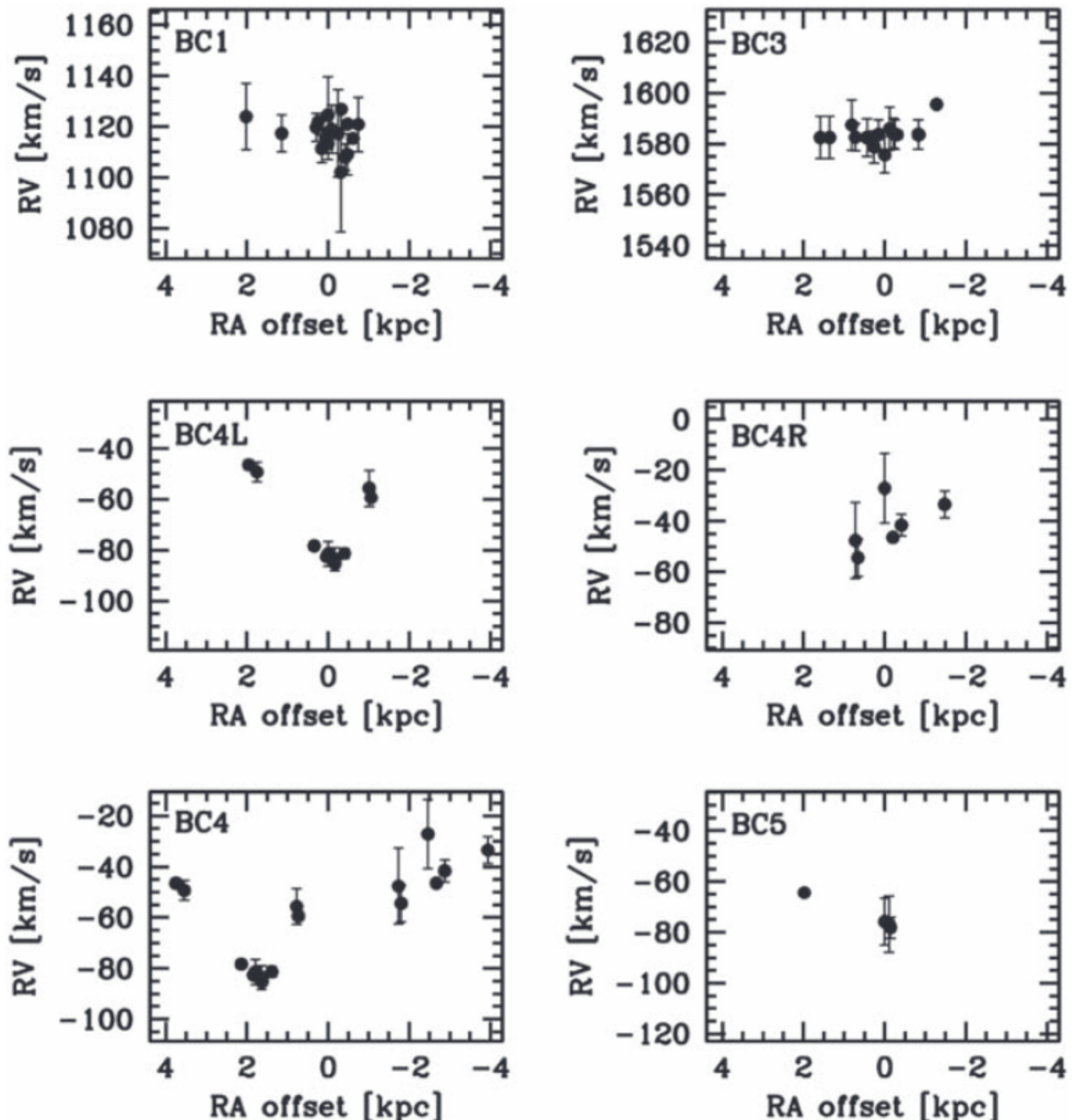
- BC 4L and BC 4R: similar RVs —> common origin
- Star-forming sources: same RVs —> part of the same system, common origin
- Systems are structured into clumps (possibly slowly flying apart from one another)

Projected distance from the center of the system

- Spatial and kinematic coherence, hints of velocity gradients
- BC 4 together diagram: a system moving toward us (led by clump around R.A. offset = 2 kpc, both sides of it are lagging behind)

—> **Simple velocity dispersion — not adequate for capturing the internal kinematics**

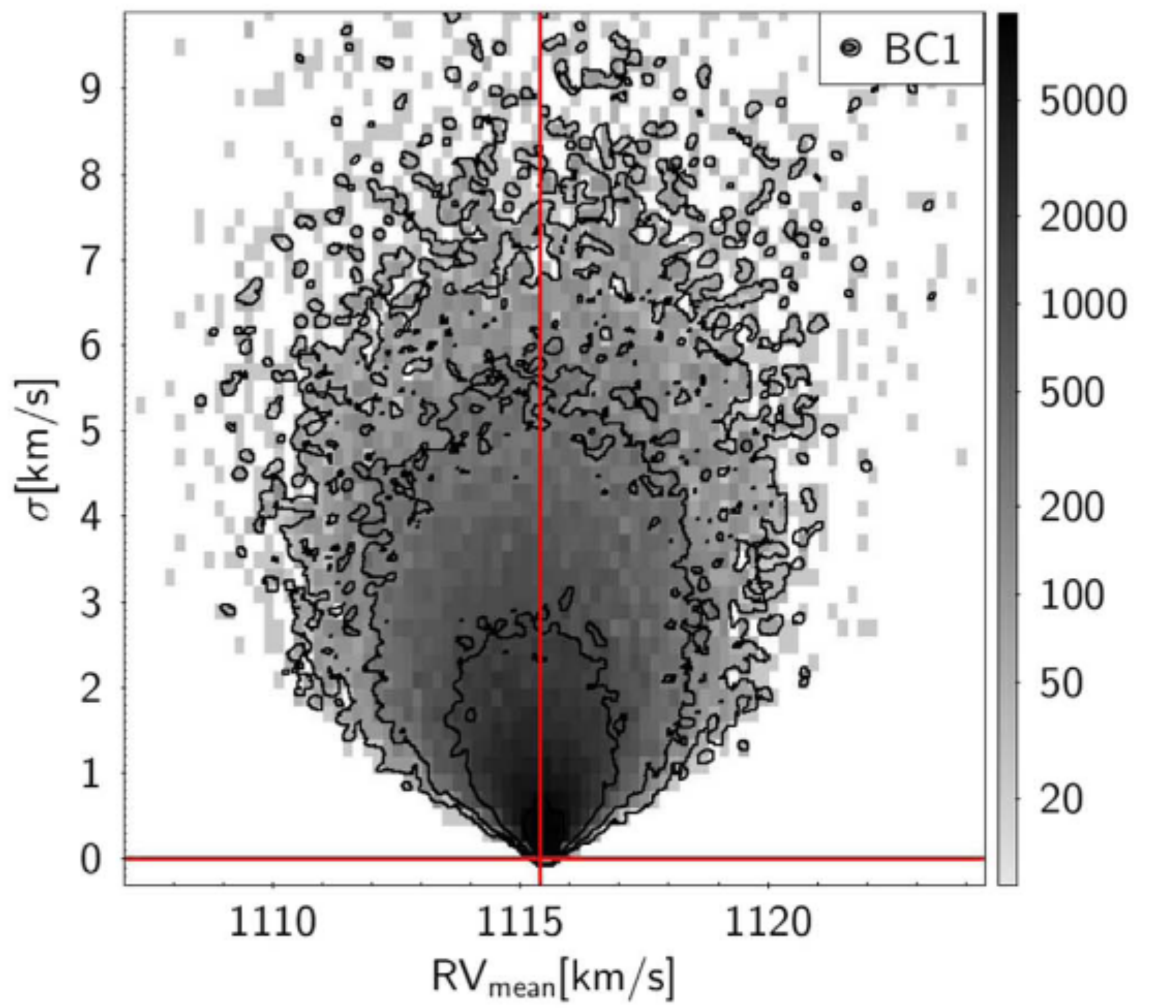


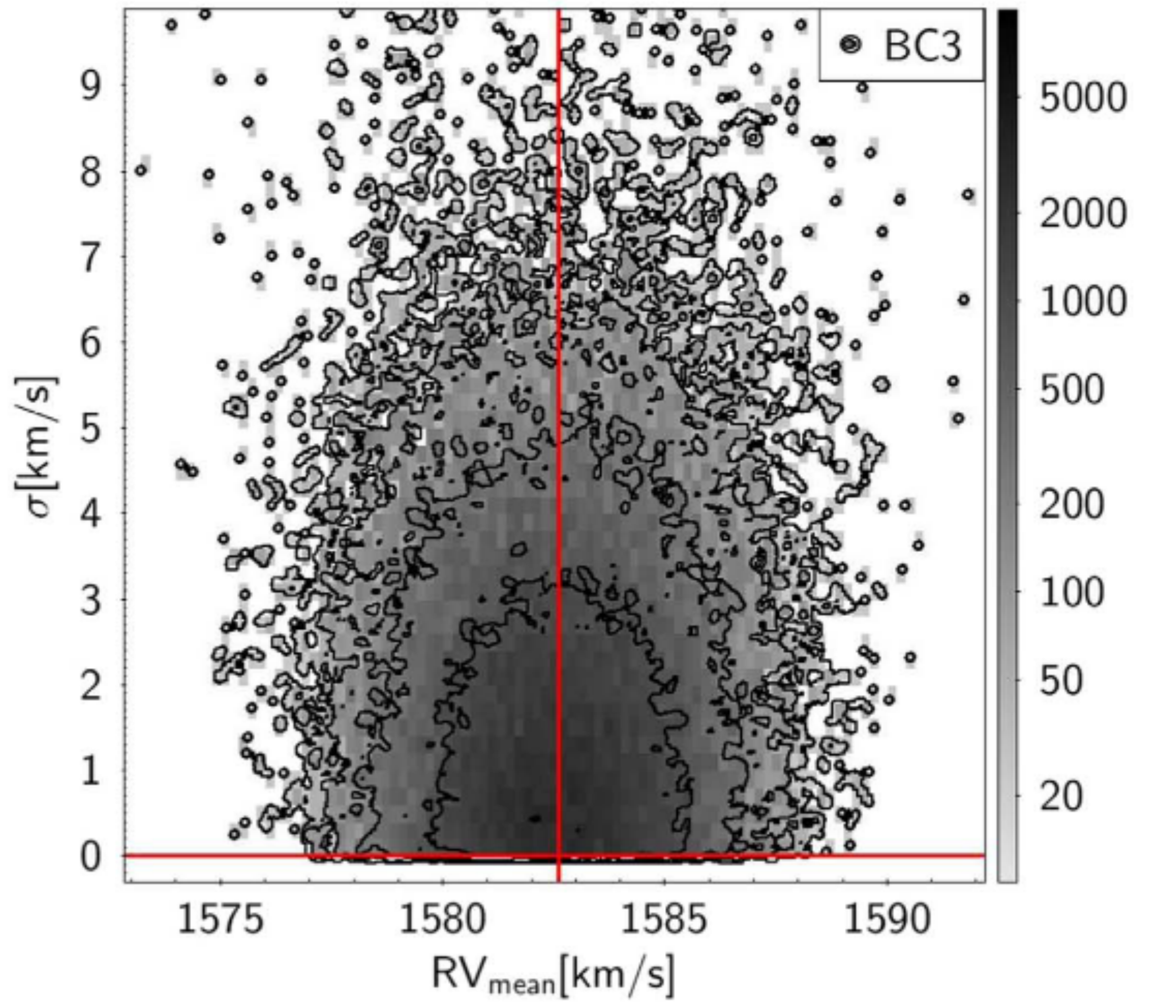


Morphology, Classification, and Kinematics

Velocity dispersions: unresolved ?

- Intrinsic dispersion: BC 1 and BC 3 (highest degree of kinematic coherence)
- Derive the probability density function(PDF) of the parameters — simple Gaussian model — Bayesian analysis — Monte Carlo Markov Chain(MCMC)
- JAGS within R environment — 4 independent MCMCs of 10000 steps each
  —> BC 1: P_{50} = 1115.4 ± 1.2 km s^{-1}, BC 3: P_{50} = 1582.6 ± 2.1 km s-1
  —> within the uncertainty
- ……





Morphology, Classification, and Kinematics

Stellar virial ratio (Calura et al. 2020)

$$\alpha_{vir} = 2.32 \times 10^5 \left(\frac{3\sigma^2 R_{hm}}{M} \right)$$

- Whether a stellar system is gravitationally bound ($\alpha_{vir} \lesssim 1$) or not ($\alpha_{vir} >> 1$)
- Assuming $M = 10^5\ M_\odot$, $\sigma_{int} = 1.0$ km/s
  —>α_{vir} = 6.9, 11.7, 7.4, 6.8, and 4.2 for BC1, BC3, BC4L, BC4R, and BC5
- $M = 10^5\ M_\odot$, $\sigma_{int} = 2.0$ km/s —> α_{vir} in range 15-50
- $M = 10^6\ M_\odot$, $\sigma_{int} = 1.0$ km/s —> $\alpha_{vir} \lesssim 1$ for all the systems
- —> most likely unbound
- Some of the subclumps would leave a bound remnant
- A small open cluster-like system floating undisturbed within Virgo, stars evolve passively

Metallicity and Star Formation

Gas-phase oxygen abundance

- N2 = [NII]/Hα and O3N2=([OIII]/Hβ)/([NII]/Hα)
- Measure N2 for 35 sources, O3N2 for 15 (compute abundance as average)
- The mean abundance: from 12+log (O/H) = 8.29 ± 0.10 to 12+log (O/H) = 8.73 ± 0.04
- Much larger than the expected values for this mass (typically 12+log(O/H) ≤ 7.5)
- —> originated from gas stripped from larger galaxies (like SECCO 1)

Metallicity dispersion also not resolved —> **collective constraints on the intrinsic dispersion**

- maximum-likelihood algorithm — mean oxygen abundance
- Most likely intrinsic dispersion: zero
- —> remarkably homogeneous from the chemical point of view
- Support: HII regions within a given BC, born from the same gas cloud — born together, lie between ~ 1 and 8 kpc —> dissolving

Metallicity and Star Formation

Current star formation rate from Hα

- Total integrated Hα flux for each BC
- BC 1, BC 5: $\simeq 0.3 \times 10^{-3}\ M_{\odot}\ yr^{-1}$
- BC 3: $\simeq 1.7 \times 10^{-3}\ M_{\odot}\ yr^{-1}$
- Same range with SECCO 1: $\simeq 0.7 \times 10^{-3}\ M_{\odot}\ yr^{-1}$

SFRs from NUV and FUV fluxes

- $-\ 3.5 < \log SFR/\ M_{\odot}\ yr{-1} < -\ 3$
- Consistent between NUV and FUV: SFRs not varied strongly over past ~100 Myr
- SFR: similar to the faintest dwarf irregular galaxies, but extremely low stellar masses
- sSFR: - $-8.2 < \log(SFR/M^*)/yr\ {-1} < -7.7$, significantly higher than average, but within low-mass, gas-rich, field galaxies

Observations

VLA observations — search for associated HI and quantify their neutral gas content

- **BC 3:** ALFALFA "Almost Dark" galaxies sample (VLA program 13A-028), D-configuration, channel width of 7.81 kHz (~1.65 km s-1), total bandwidth of 8 MHz, 1.6h on-source time —> Brigg's robust = 0.5 weighting, channels rebinned to 5 km s-1
- **The remaining four candidates:** VLA program 18A-185, D-configuration, 1.5h on-source, 3072 channels of 10.42 kHz (~2.2 km s-1) —> average over four channels: 8.8 km s-1, Brigg's robust = 2 weighting maximize detection capabilities

Observations

GBT observations — search for associated HI and quantify their neutral gas content

- Much deeper HI spectra than VLA
- (Redshifts were known from Hα) Only BC 1 suitable for single-dish follow-up
- BC 4 and BC 5 confused with Milky Way emission
- BC 3 already strongly detected with VLA
- BC 2 background galaxy group (from HST imaging)
- **21A-433**, 3h total, ON-OFF, rms noise: 0.25 mJy after smoothing to 30 km s-1

HI Mass & Limits

- VLA HI spectra: using an aperture equal to the synthesized beam size
- BC 3: only object detected in their VLA observations, VLA flux is 0.3 dex lower than ALFALFA
- Jones et al.2022: BC 3 connect to VCC 2034, 70 kpc to the SW

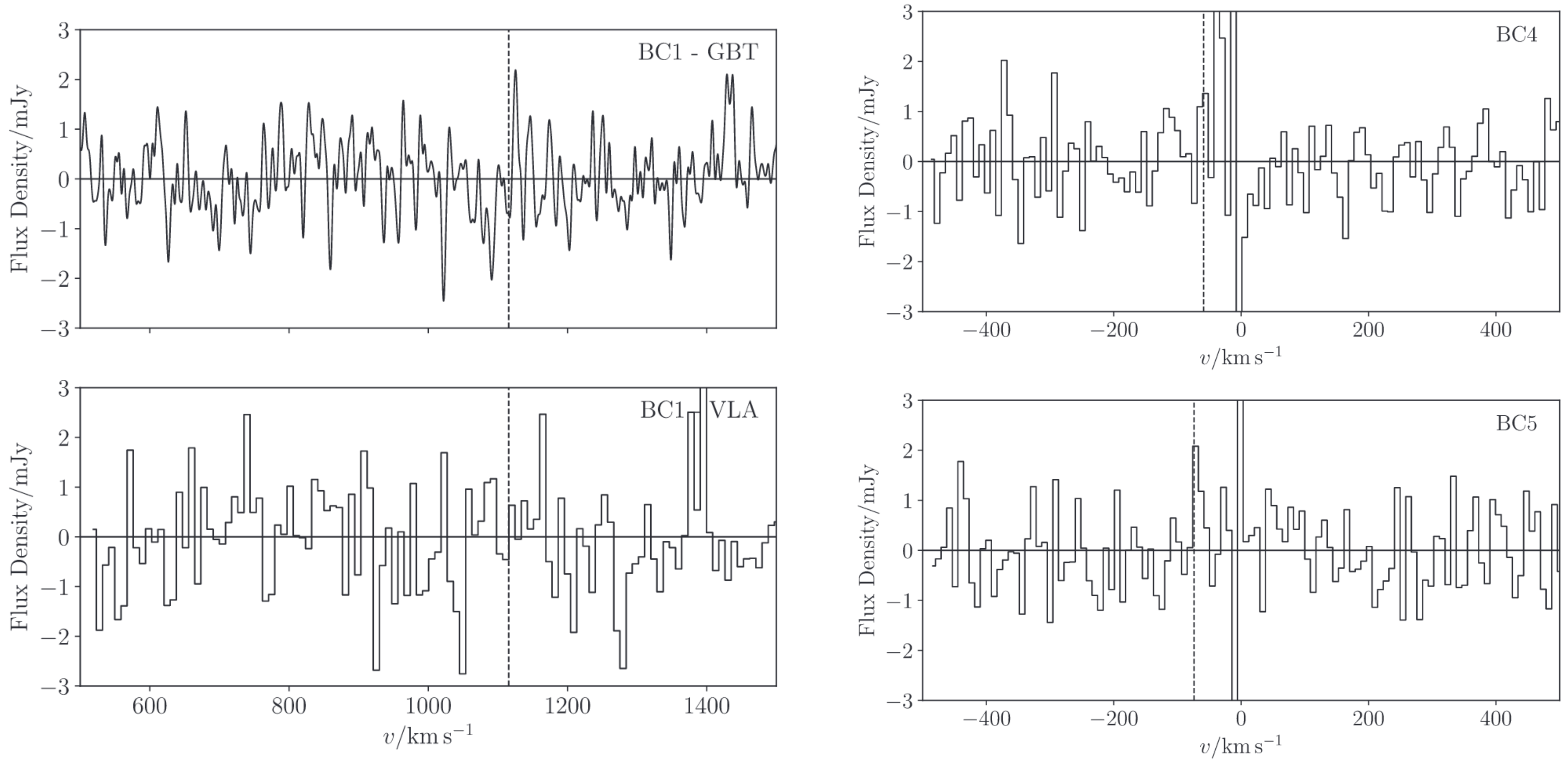
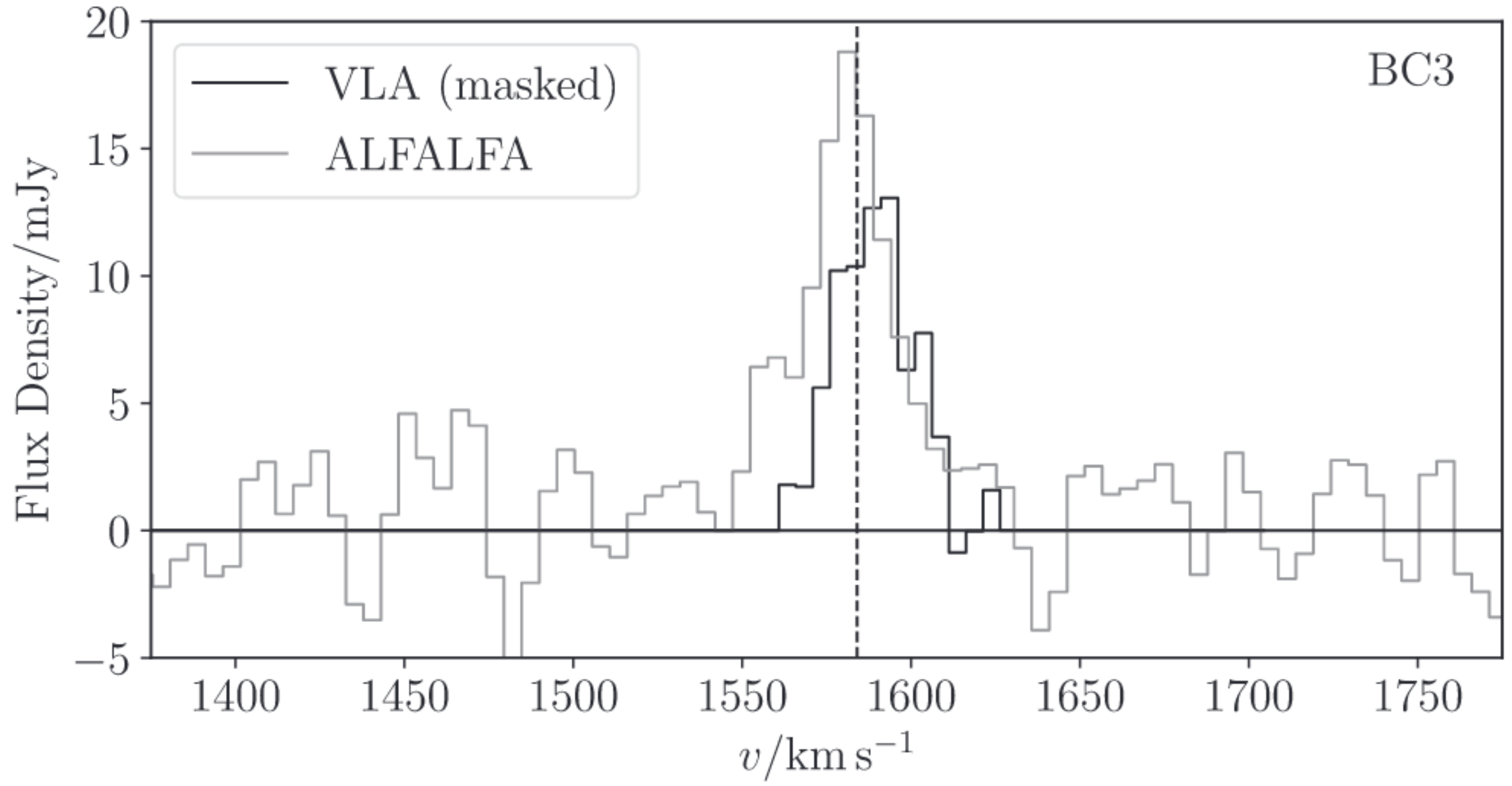


Table 4
H I Masses of BCs

Object	$M_{\rm HI}/{\rm M}_\odot$	Telescope
BC1	$< 1.6 \times 10^6$	GBT
BC3	4.0×10^7	Arecibo[a]
BC4	$< 2.9 \times 10^6$	VLA
BC5	$< 3.2 \times 10^6$	VLA
SECCO1	1.5×10^7	Arecibo[b]



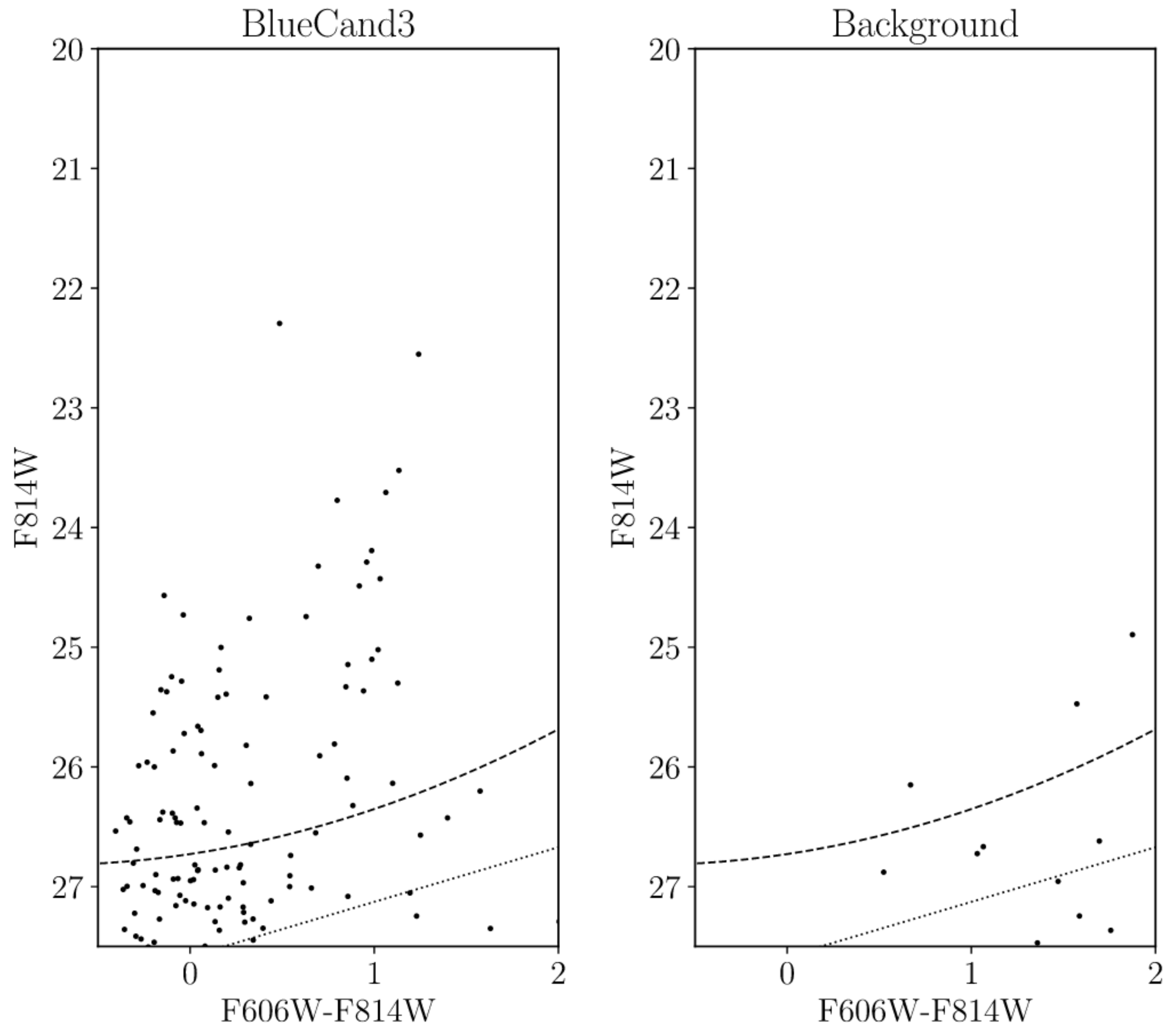
Observations

HST — better understand their detailed morphology and stellar populations

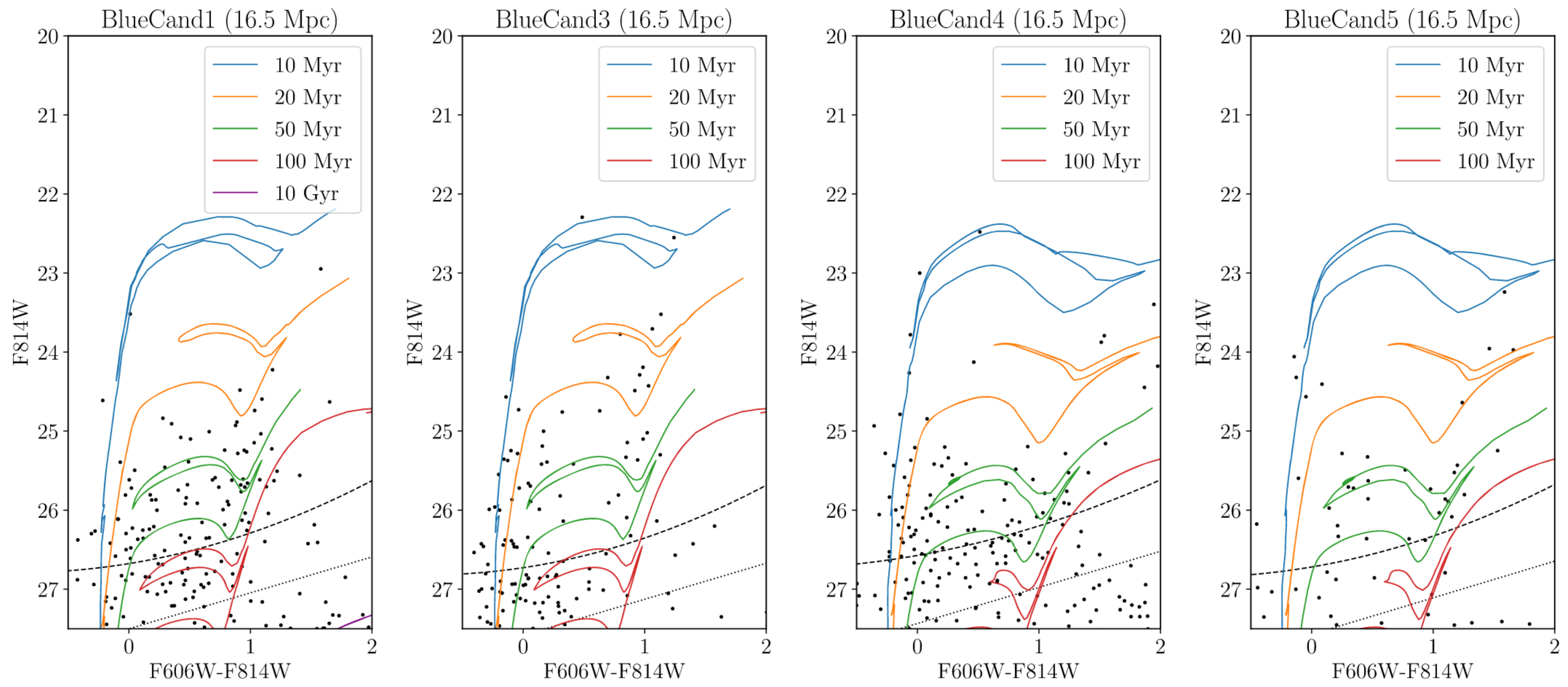
- ACS: F606W and F814W
- Total of 2120 s and 2180s (except for BC4, 2000s in each)
- DOLPHOT: point-source photometry of resolved stellar population
- Galactic extinction correction: dust map of Schlegel et al. 1998, R_{F606W} and R_{F814W} of Schlafly & Finkbeiner
- Aperture photometry (measure the integrated magnitudes and colors of the systems): Astropy package Photutils

Stellar Populations

- CMD (from HST) and UV —> have predominantly young, blue stellar populations
- Hα —> youngest stars must be ≤ 10 Myr old
- Difference with low-mass, gas-rich dwarf Leo P: no clear RGB
- At high metallicities: TRGB becomes less defined, RGB stars become redder —> impede the detectability of RGB
- Population of stars in all BCs: young blue main-sequence, (blue and red) helium-burning stars, no RGB
- Youngest BCs (BC 3 & SECCO 1) ~ 50 Myr old



BC 3 CMD — most similar to that of SECCO 1
BC 3: made up almost entirely of blue MS & helium-burning stars & RHeB stars, almost no RGB stars
—> the young age of the population



Stellar Masses

Emitted light — youngest stars

Mass — oldest, most numerous stars

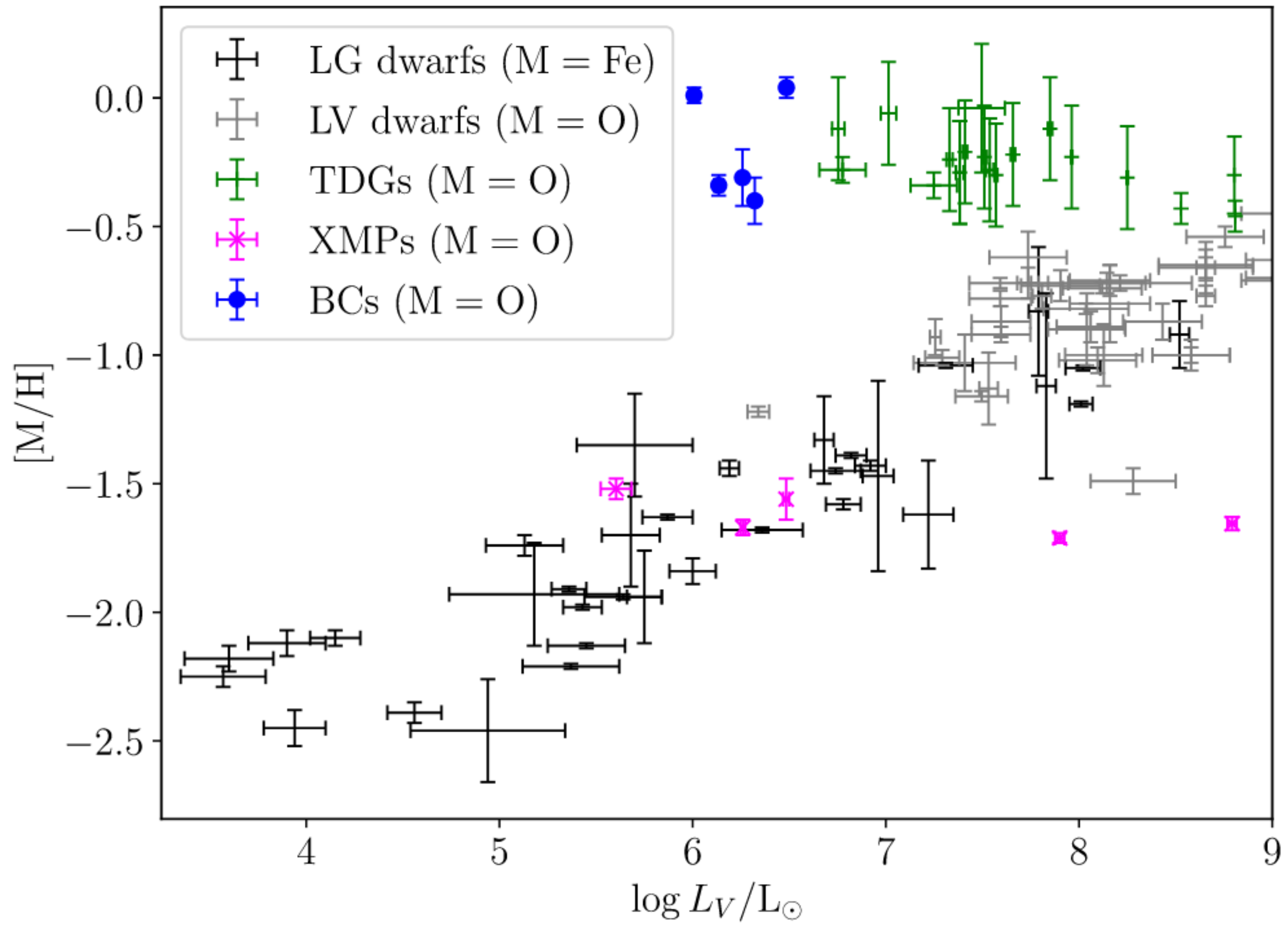
- BCs: young objects —> mass-to-light ratio highly uncertain (depend on age)
- Current SFRs can represent the SFRs over the lifetime of the BCs: —> **total stellar mass** = **age of each object** × **its SFR**
- PARSEC: obtain age (F814W magnitude)
- NUV SFR measurements
- The age estimates for BCs 1, 3, 4, 5, and SECCO 1 are 90, 50, 110, 160, and 60 Myr

Table 5
Magnitudes and Stellar Mass Estimates

Object	F814W	F606W-F814W	$M_*/M_\odot$
BC1	20.29 ± 0.38	0.08 ± 0.41	$\sim 5 \times 10^4$
BC3	20.23 ± 0.15	-0.23 ± 0.17	$\sim 5 \times 10^4$
BC4	19.86 ± 0.26	-0.26 ± 0.29	$\sim 1 \times 10^5$
BC5	20.56 ± 0.10	0.06 ± 0.12	$\sim 5 \times 10^4$
SECCO1	20.39 ± 0.41	-0.23 ± 0.46	$\sim 4 \times 10^4$

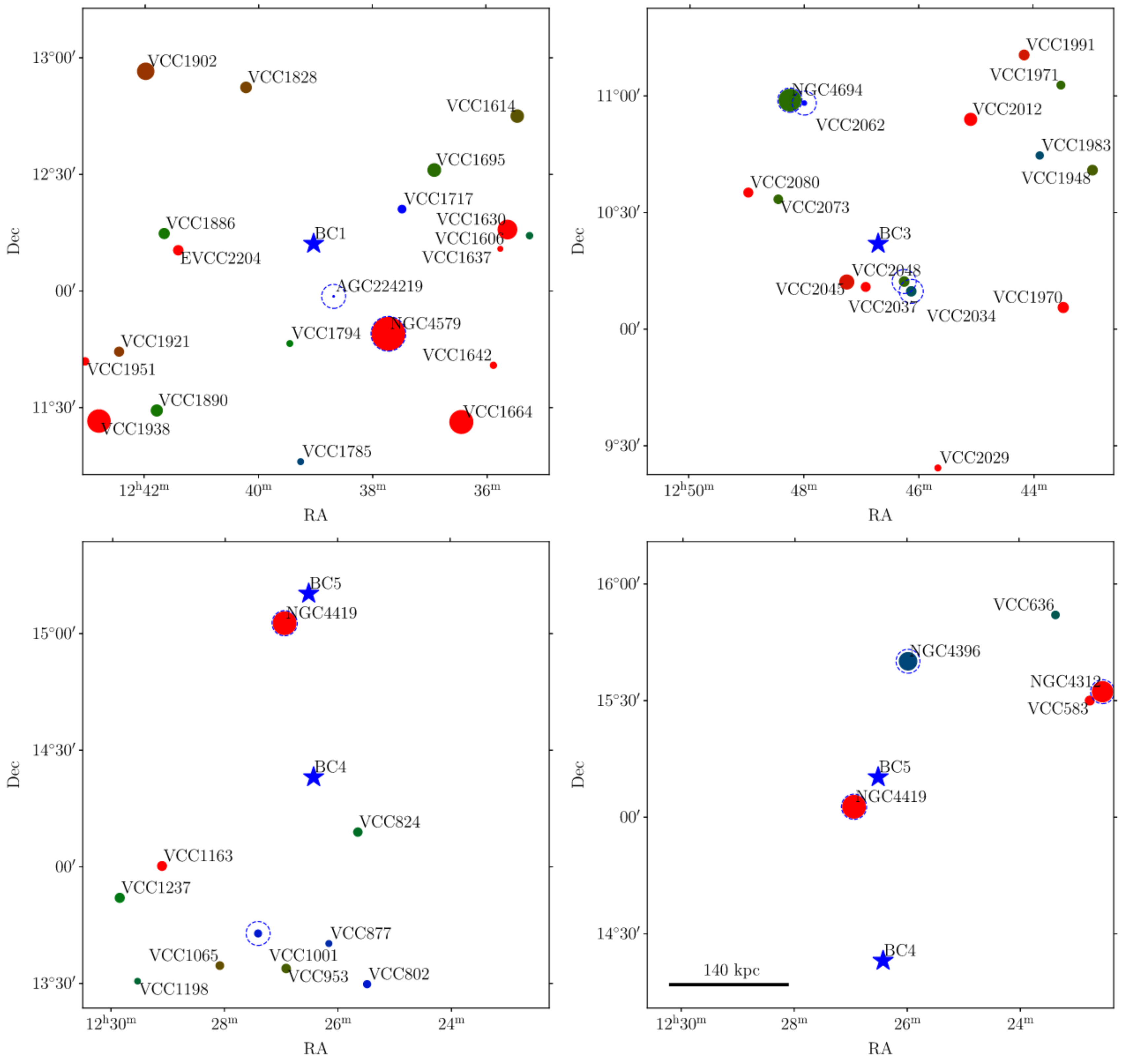
Point of Origin

- **Tidal Dwarf Galaxies:** similar metallicities, but higher luminosities
- **Extremely metal-poor galaxies:** same luminosity, metallicities different
- MZR —> stellar mass —> type of galaxies formed from
- Parent objects: $8.3 \lesssim \log M^*/M_\odot \lesssim 10.1$ —> should be included in existing catalogs, gas-bearing (or were in the recent past)



Point of Origin

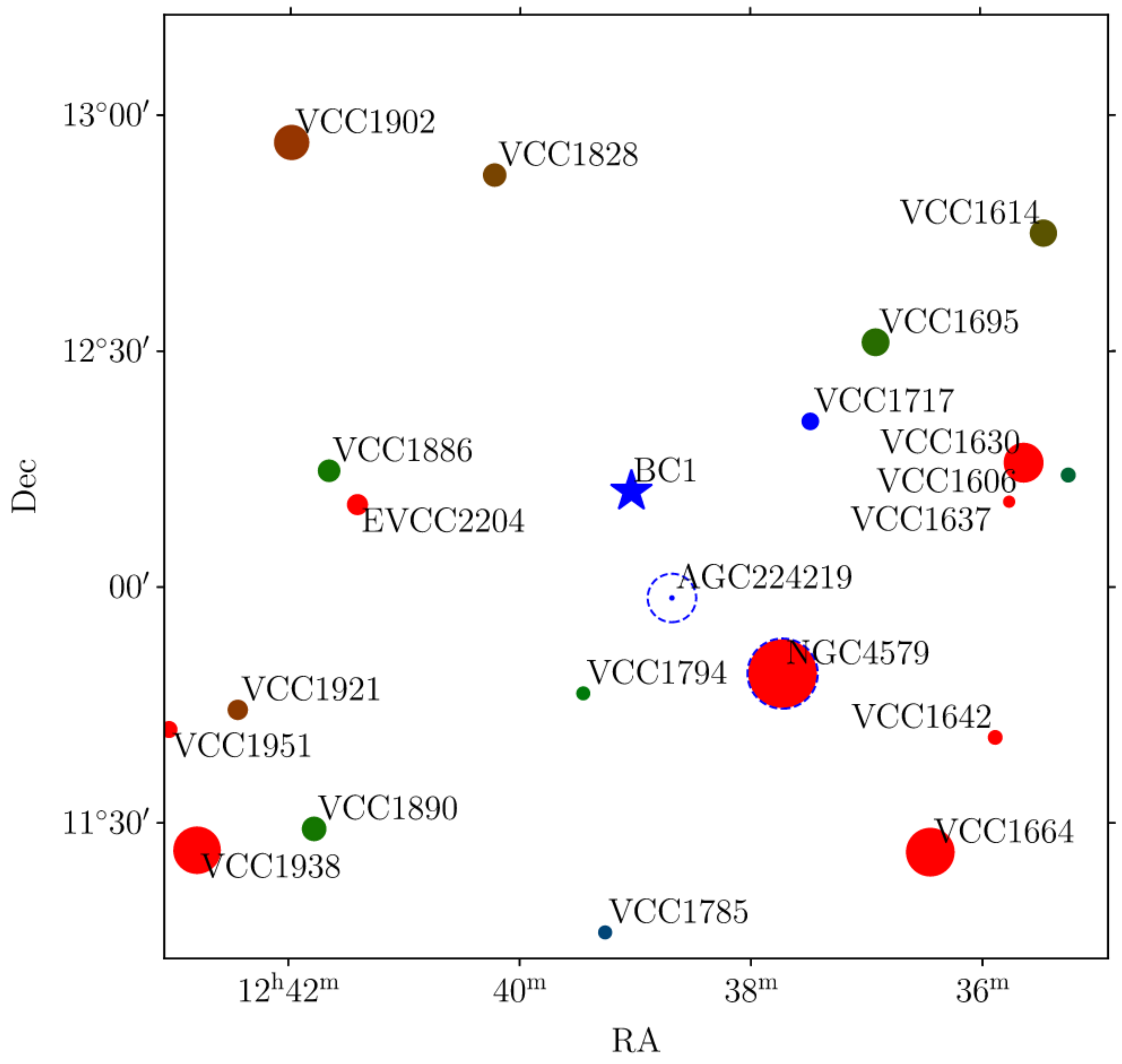
- Most BCs are undetected in HI, formed from stripped gas, must have contained gas in the recent past
- Good candidate: nearby, gas-rich galaxies



Point of Origin

BC 1

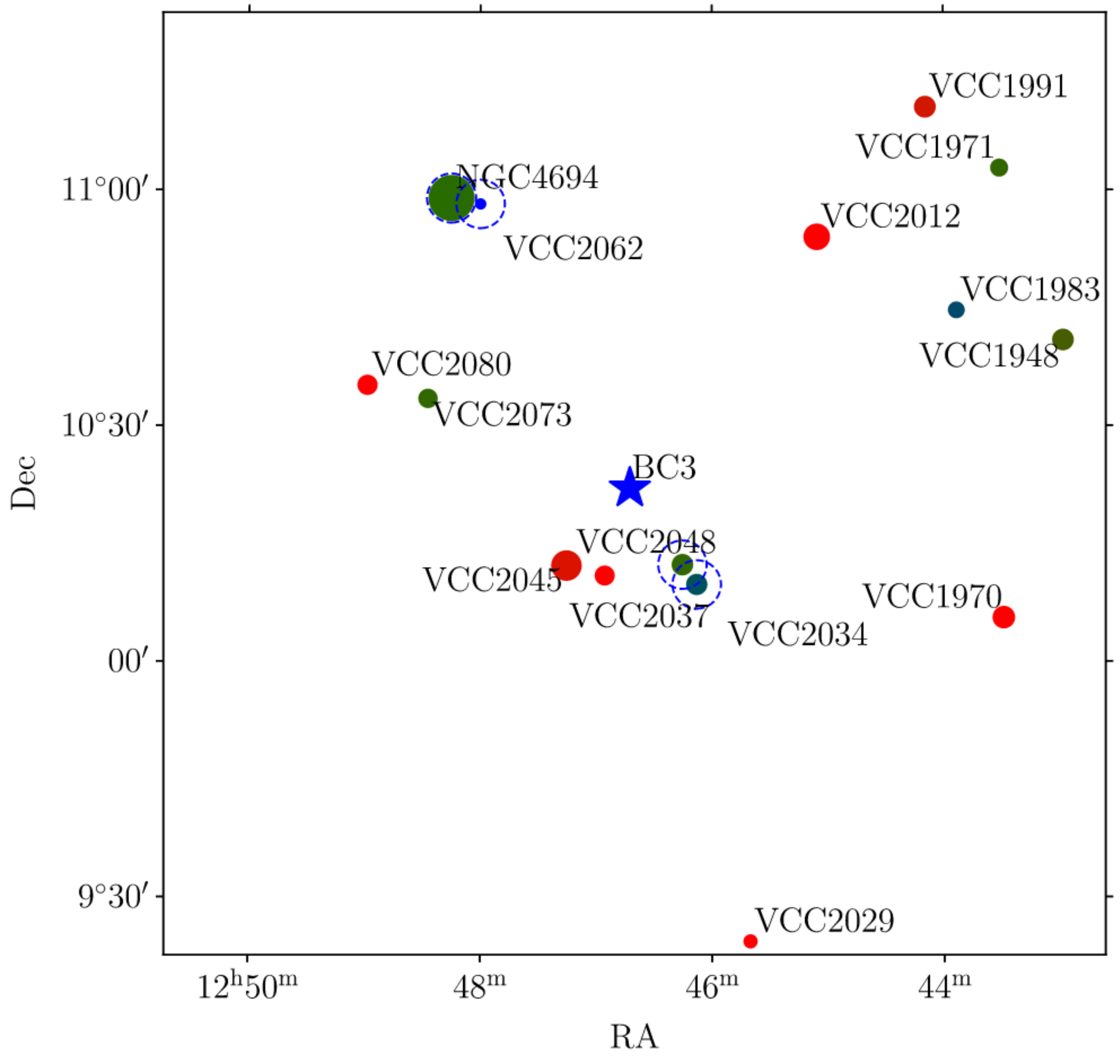
- NGC 4579: only one contains HI, sufficiently massive, 140 kpc
- Separated from BC 1 in ~ 400 km s-1
- Little recent disturbance in HI or CO
- Too metal-rich: 12 + log(O/H) = 8.87 ± 0.05 (BC 1: 12 + log(O/H) = 8.35 ± 0.15)
- —> not a viable candidate
- > 280 kpc away: unable to identify



Point of Origin

BC 3

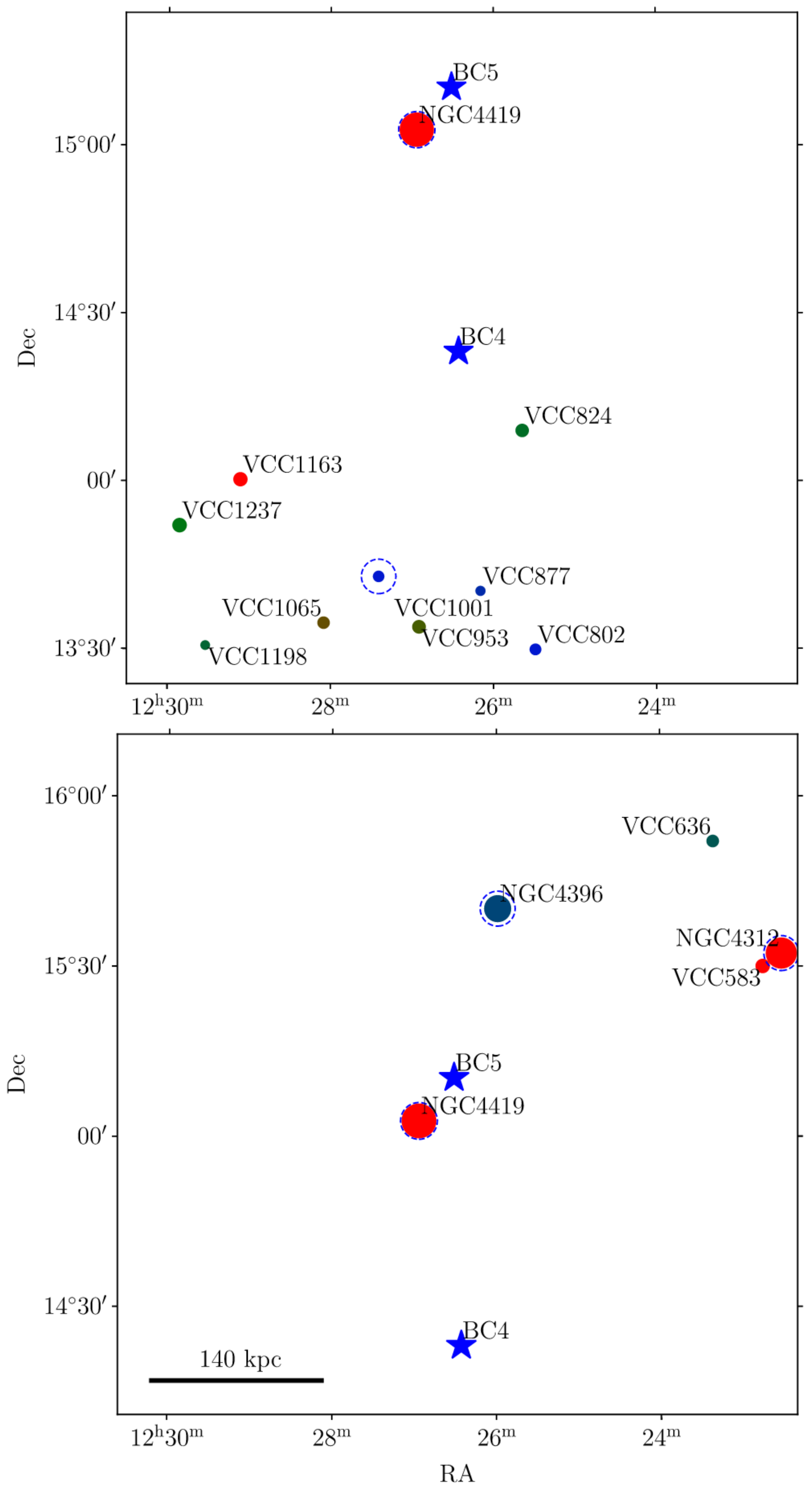
- extremely complicated field
- nearest apparent neighbor is NGVS 3543 — LSB galaxy at the same distance as BC 3 (Junais et al. 2021), foreground object at ~ 10 Mpc (Jones et al. 2022)
- HI: possible bridge between BC3 and a pair of galaxies VCC 2034 and VCC 2037, VCC 2037 another foreground object at 10 Mpc
- Unable to determine: ram pressure or tidal stripping



Point of Origin

BC 4 and BC 5

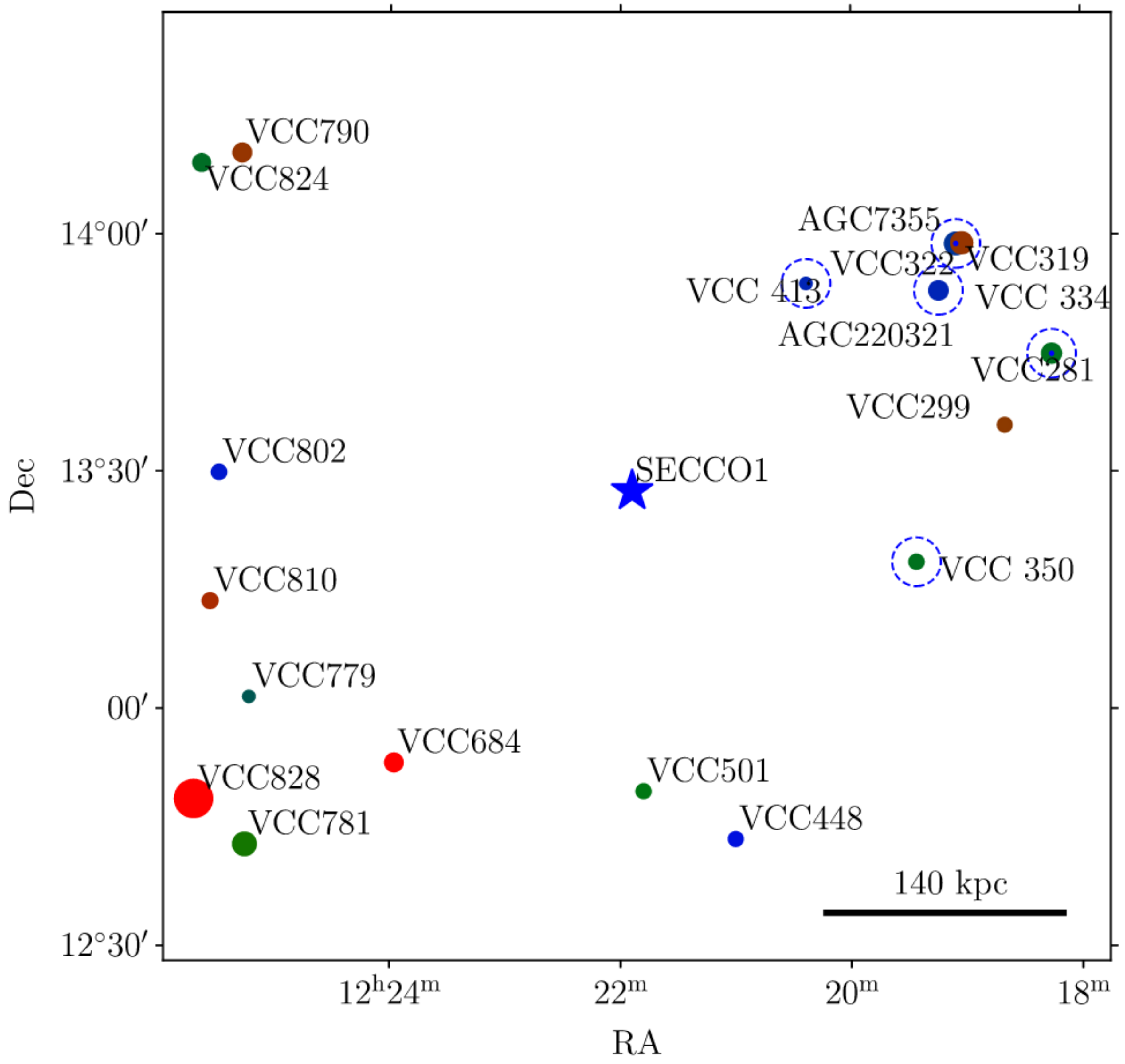
- Likely formed from same parent object (they are only separated by 45’ on the sky, almost the same velocity)
- NGC 4419: strong evidence in HI and CO of ram pressure stripped
- Ram pressure tails only in one general direction — unlikely
- Molecular gas extension: toward south (BC 4)
- If NGC 4419 simultaneously undergoes ram pressure and tidal stripping — form both BCs, no evidence of this
- UGC 7695: further candidate with a bow-shape wake extending, ~ 450 kpc in projection — require a very large eject velocity



Point of Origin

SECCO 1

- extraordinary isolation
- Previous work: M 86 subgroup of Virgo: ~350 kpc to the SE & The group of dwarf galaxies ~200 kpc to the NW
- VCC 322 and 334: metallicities match, VCC 332 a stellar tail towards SECCO 1
- NGC 4438: candidate, combination of ram pressure and tidal forces



Point of Origin

Other origin scenarios

- Gas stripped from an LSB galaxy (frequently absent from established catalogs of cluster members) — relatively close by
- Dark objects contained neutral gas for an extended period, but formed essentially no stars until very recently (highly unlikely)

Formation Mechanism

- Unable to distinguish between ram pressure or tidal forces
- Parent objects: new cluster members — all new members are stripped of their gas and quenched during their first orbit

Comparison to TDGs and the **Need for Ram Pressure Stripping**

- Typical long-lived TDGs: over 10^8 $M_\odot$ — below this mass cannot resist the tidal field of their parent galaxies — larger than any of the BCs
- TDGs: ejected at the circular velocity of the originated galaxy (~ 300 km/s)
- Take ~ 1 Gyr to traverse 300 kpc
- The isolation of BCs —> difficult to explain via a tidal formation mechanism
- Ram pressure stripping (galaxies relative to the cluster) can > 1000 km/s —> most likely pathway

Formation Mechanism

Comparison to TDGs and the Need for Ram Pressure Stripping

Kapfferer et al.2009

- Gas-rich galaxies falling 1000 km/s relative to an ICM of varying densities
- After 500 Myr, the length of the plume of stripped gas — density of the surrounding ICM
- The electron number density of ICM in Virgo
- Near M87: $> 10^{-2}$ cm^{-3} ($\sim 2 \times 10^{-26}$ g cm^{-3})
- At a distance of 230 kpc: $\sim 6 \times 10^{-4}$ cm^{-3} ($\sim 1 \times 10^{-27}$ g cm^{-3})

Rapidly achieving large separations between stripped material and parent

- Especially true — within a few hundred kilo parsecs of the cluster center
- Could be true — almost anywhere within the cluster

Formation Mechanism

Properties of Ram Pressure Stripped Gas Clumps in Simulations

- **Lee et al.2022:** molecular gas clouds (in the tail of rps galaxies) — form in situ — rapid cooling of warm ionized gas (radiative cooling)
- **Mueller et al.2021:** magnetic sheathing — protect rps gas from evaporation in cluster
- **Lee et al.2022** (radiative hydrodynamical simulations): SF clumps ~ 100 kpc from parent. (SF occurred ~ 200 Myr after rps —> underestimate their progenitor was stripped)
- Bright Hα clumps —> SF activity
- Diffuse Hα emission —> expected through-out the rps tail —> identify the points of origin of BCs —> should they exist, would be detectable in VESTIGE.
- **Kapferer et al.2009:** numerous gas clumps ~ 400 kpc (SF only in if wind speed > 500 km/s)

Formation Mechanism

Properties of Ram Pressure Stripped Gas Clumps in Simulations

- **Tonnesen & Bryan 2021:** the masses of such clumps ~ in the order of 10^5 $M_\odot$ (an order less than BC 3 and SECCO 1)

Metallicity

- Generally, same as its parent galaxy
- **Tonnesen & Bryan 2021:** rps clouds rapidly mix with the ICM —>decrease with the distance from their parent galaxy

Still challenging to explain

Fate and Production Rate

- Morphologies & stellar mass: unlikely to be gravitationally bound
- Velocity dispersions not well resolved:
  —> if dynamically cold ($\sigma_v < 1$ km s^{-1}): maybe bound
  —> $\sigma_v > 2$ km s^{-1} : certainly be unbound
- Most likely: BC as a whole is unbound, but individual component clumps or star clusters may be bound
- In the long term: BCs —> likely disperse into the intracluster light
- Without sustained SF —> quickly become undetectable —> must be continually produced in the cluster ~ 50 Myr

Future Directions

- Significant difficulty in identifying the point of origin: if RPS, **extremely faint Hα** still connect the BCs to their parent
- **X-rays**: characterizing the properties of the stripping events
- **CO observations** with ALMA (should be readily detectable)
- BCs with slightly older stellar populations: no HI detection —> SF triggers evaporation?
- To detect or rule out this older stellar population —> full SF histories of BCs: **JWST**
- Should also exist in other clusters, Fornax cluster

Conclusions

- All confirmed BCs, identified several HII regions + some diffuse hot gas
- The mean heliocentric velocity consistent with Virgo membership
- Each is composed of a few, separated, star-forming clumps. BC 4, velocity gradients suggesting ongoing disruption
- Velocity dispersion in all cases, $\sigma \lesssim 20$ km s–1, unlikely to survive as gravitationally bound stellar systems
- The mean oxygen abundance significantly larger than expected, originated from gas stripping. Internally homogeneous, born from the same gas cloud
- The instantaneous SFR: $0.3 \times 10^{-3}\ M_{\odot}\ yr^{-1} \lesssim SFR \lesssim 2.0 \times 10^{-3}\ M_{\odot}\ yr^{-1}$
- Potential formation mechanism: ram pressure stripping
- BCs: a new class of stellar system