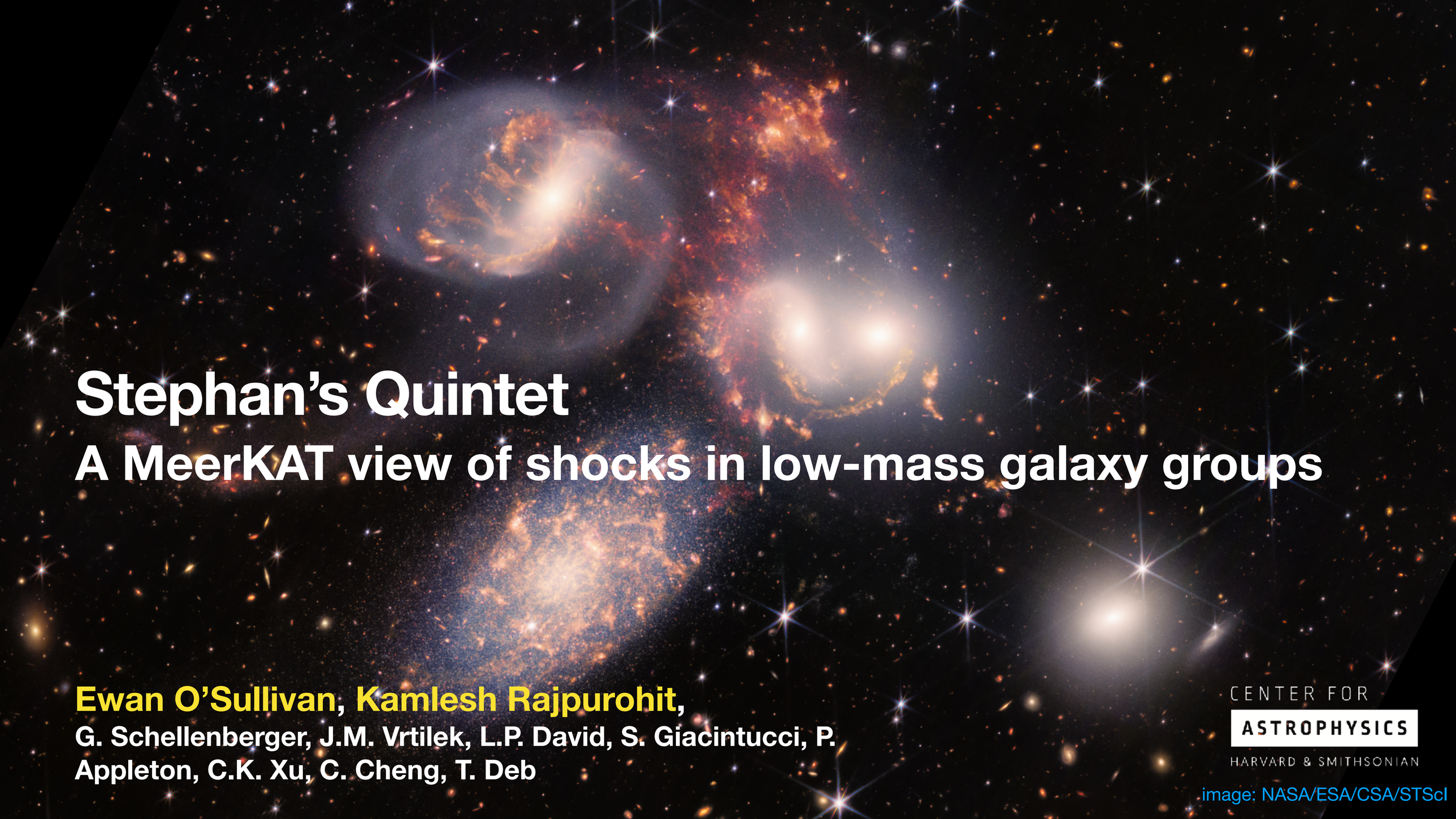


Stephan's Quintet

A MeerKAT view of shocks in low-mass galaxy groups

Ewan O'Sullivan, Kamlesh Rajpurohit,
G. Schellenberger, J.M. Vrtilek, L.P. David, S. Giacintucci, P. Appleton, C.K. Xu, C. Cheng, T. Deb

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

image: NASA/ESA/CSA/STScI

Outline

Introduction to low-mass groups

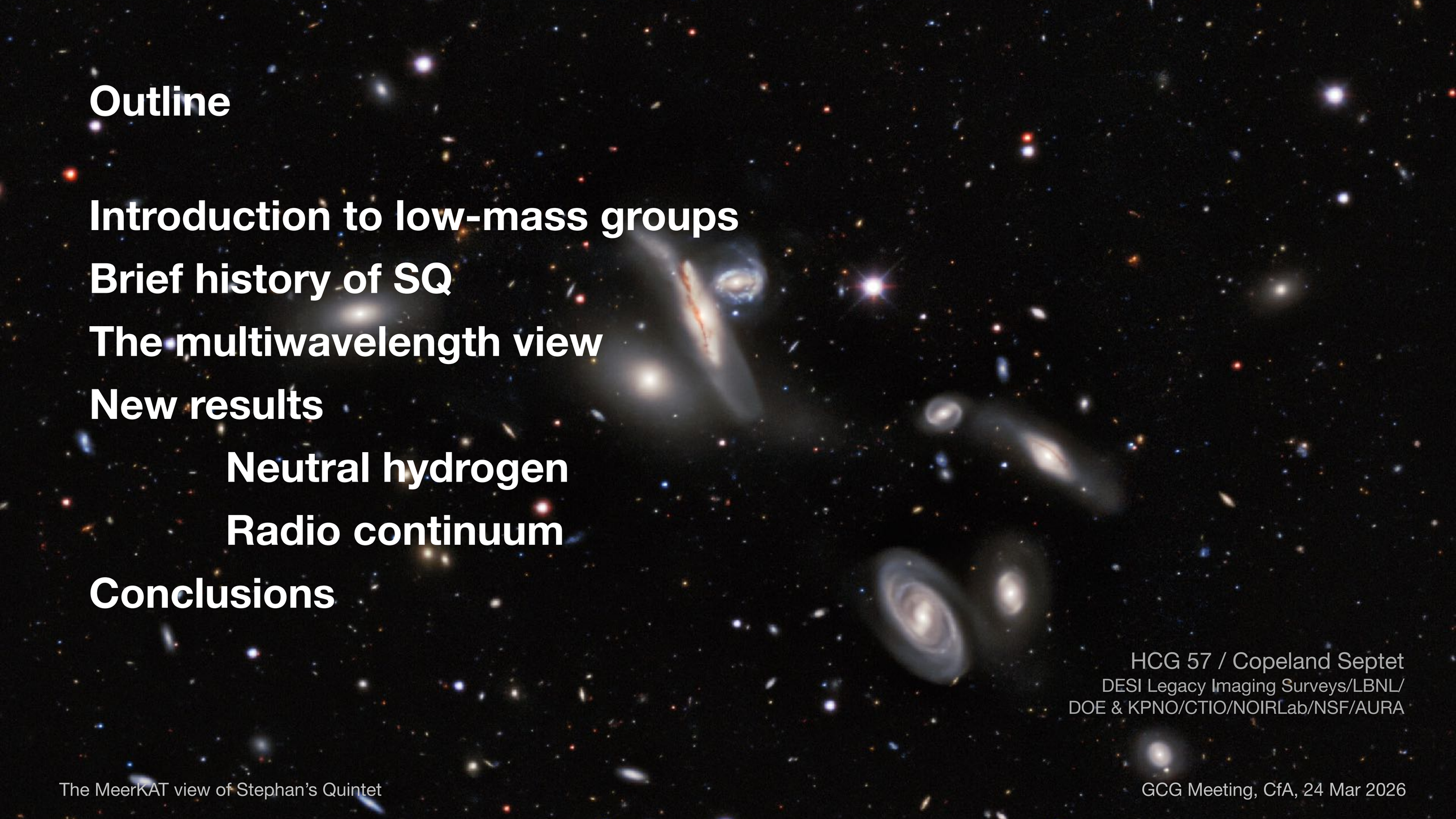
Brief history of SQ

The multiwavelength view

New results

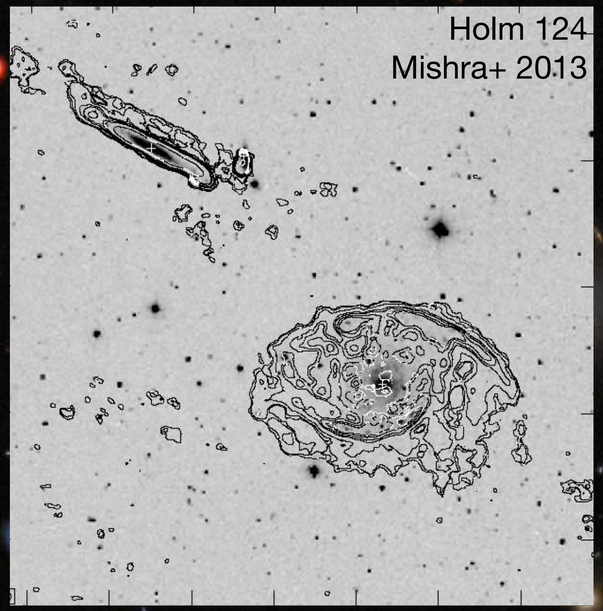
- Neutral hydrogen
- Radio continuum

Conclusions

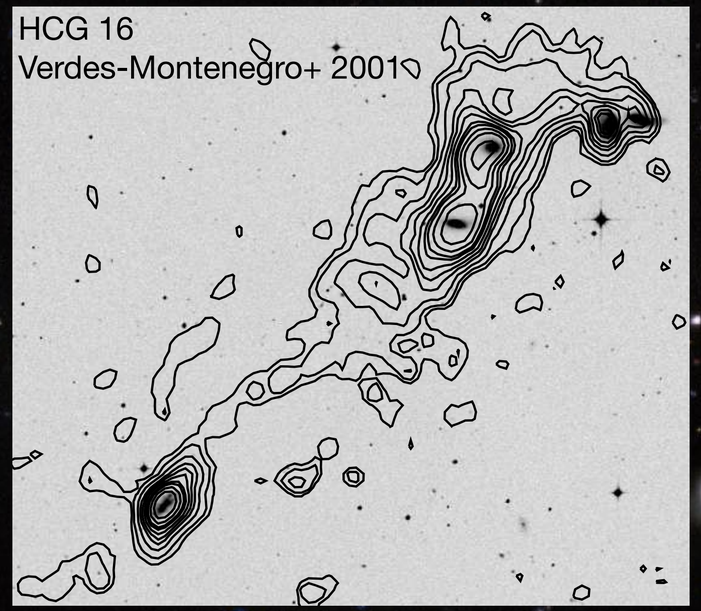


HCG 57 / Copeland Septet
DESI Legacy Imaging Surveys/LBNL/
DOE & KPNO/CTIO/NOIRLab/NSF/AURA

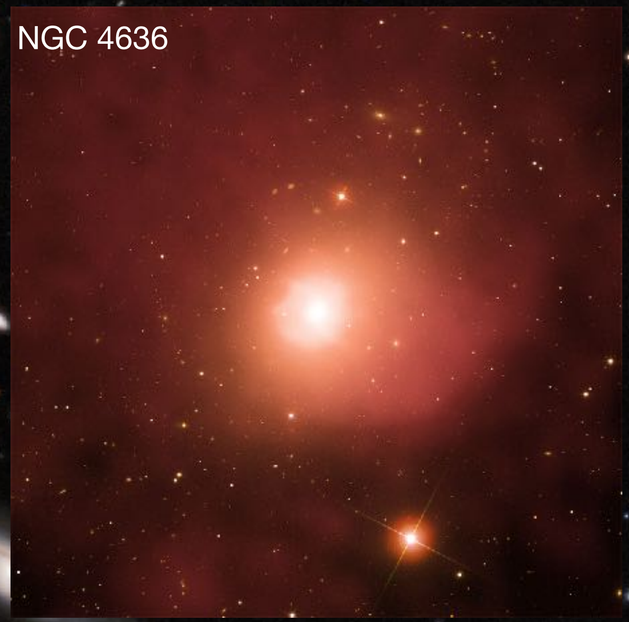
Galaxy Groups - gas content



Spiral rich
HI in galaxies
X-ray halo undetected



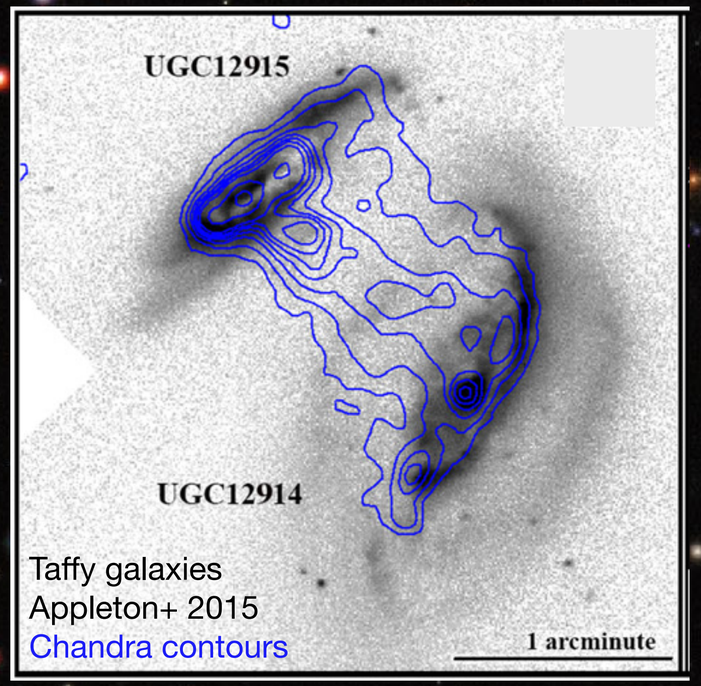
Spiral rich
HI outside galaxies
Faint X-ray halo, often disturbed

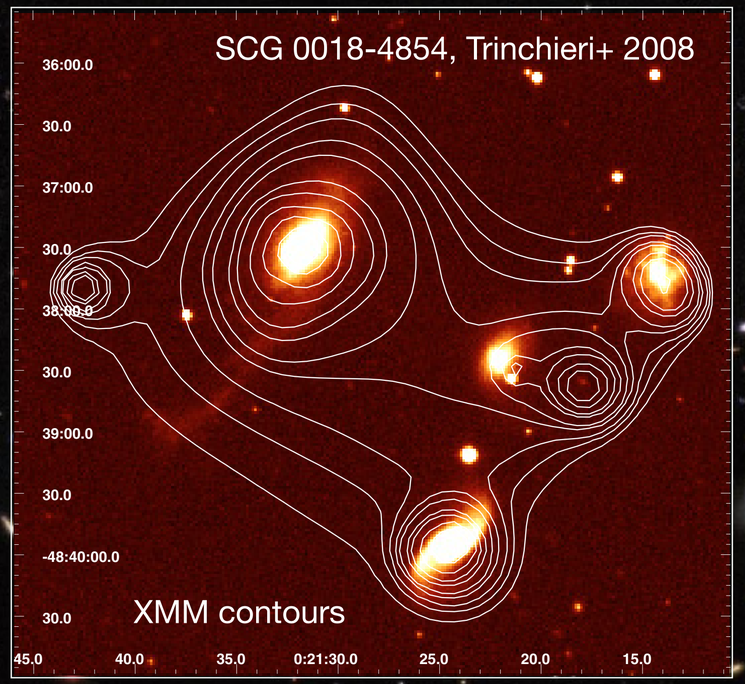


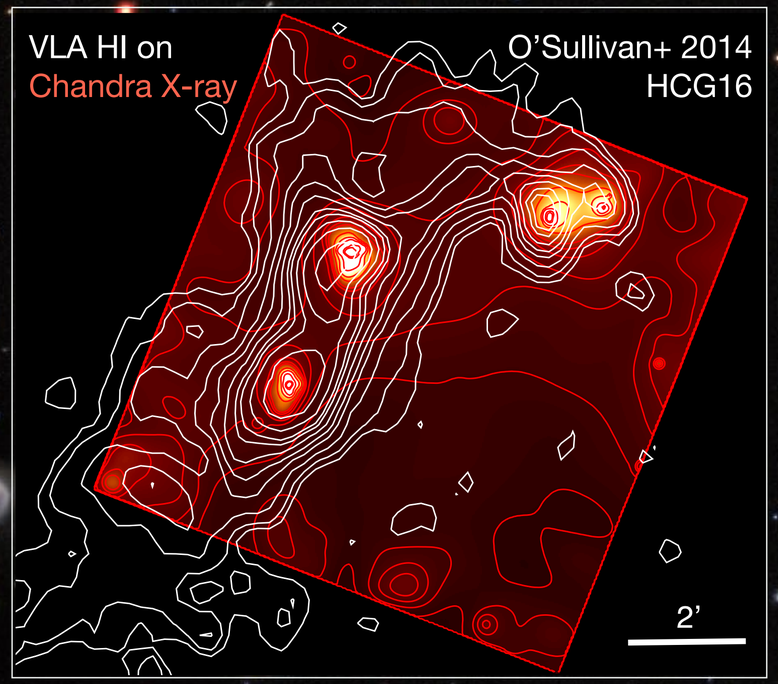
Elliptical dominated
HI relegated to group outskirts
Bright X-ray halo

Mass, dynamical evolution

Low-mass groups - galaxy interactions







Only a handful of spiral-rich groups with a X-ray detected IGrM known, Lx ≈ 10^{41} erg/s
IGrM appears strongly influenced by galaxy interactions

- Collisional shocks
- Tidal interactions and stripping
- Star formation & AGN-driven winds

Stephan’s Quintet

Édouard Jean-Marie Stephan
Reported in 1877 (MNRAS, 37, 334)

“…excessivement excessivement faibles; excessivement petites; très difficilement observables.”

PanSTARRS gri

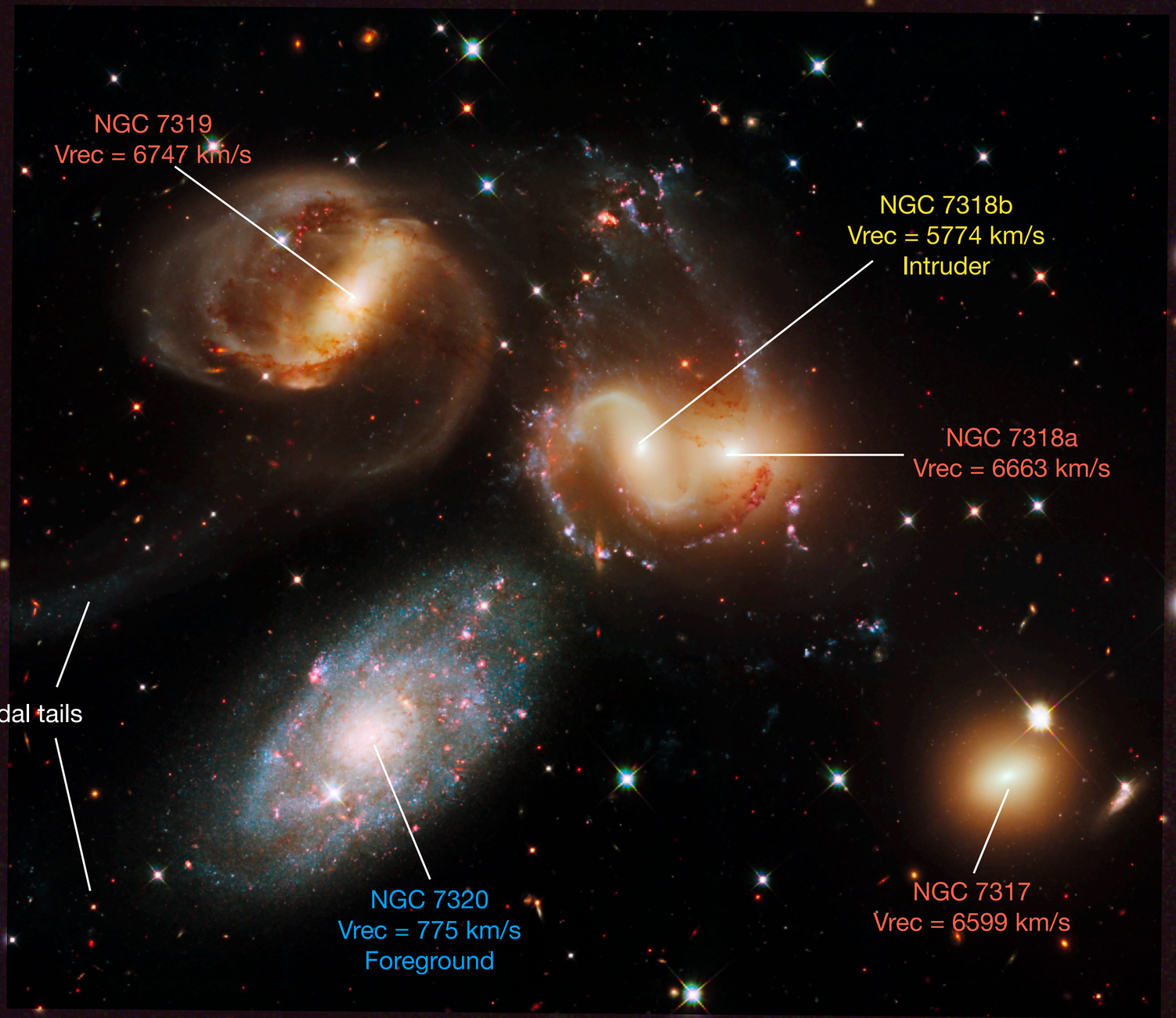
Stephan’s Quintet

Édouard Jean-Marie Stephan
Reported in 1877 (MNRAS, 37, 334)

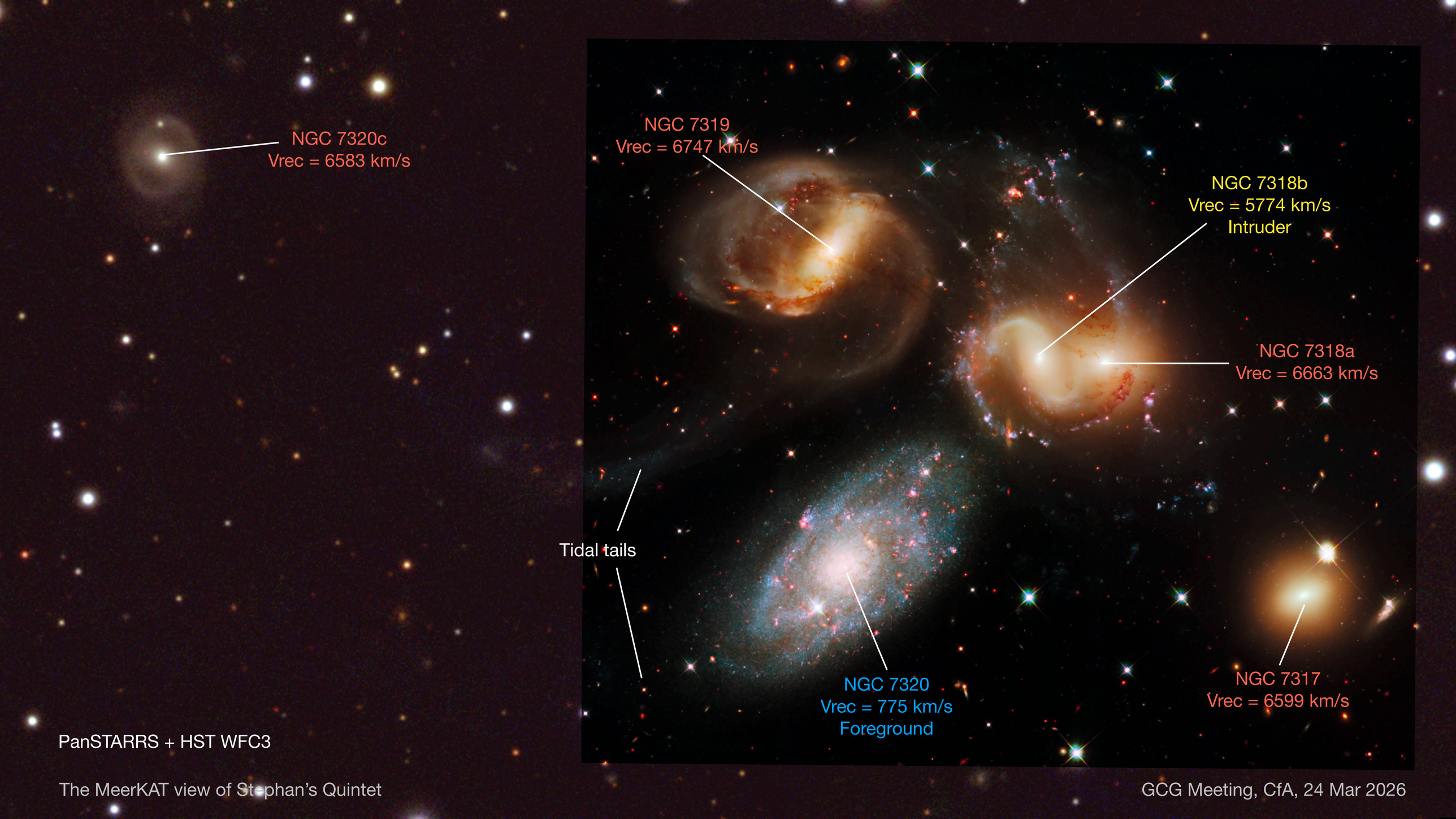
“…excessively faint; excessively small; very difficult to observe.”

Distance 94 Mpc
3’ = 82kpc

PanSTARRS gri



PanSTARRS + HST WFC3

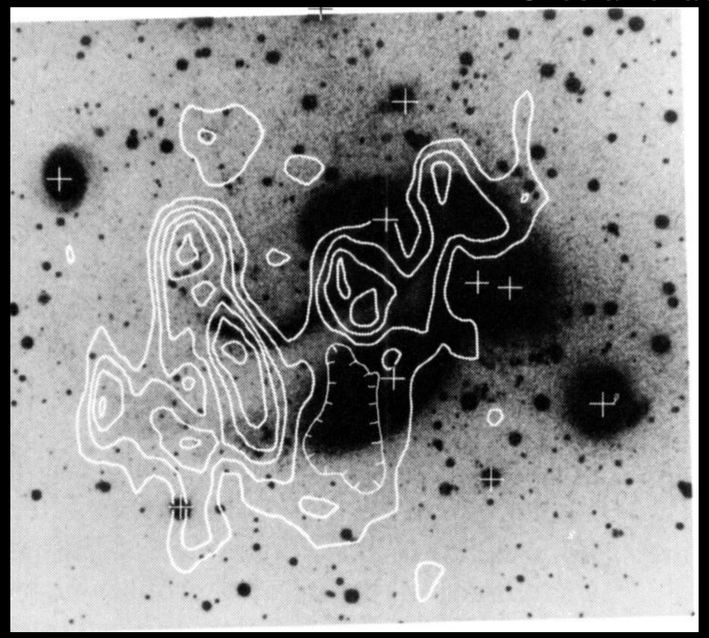


The MeerKAT view of Stephan's Quintet

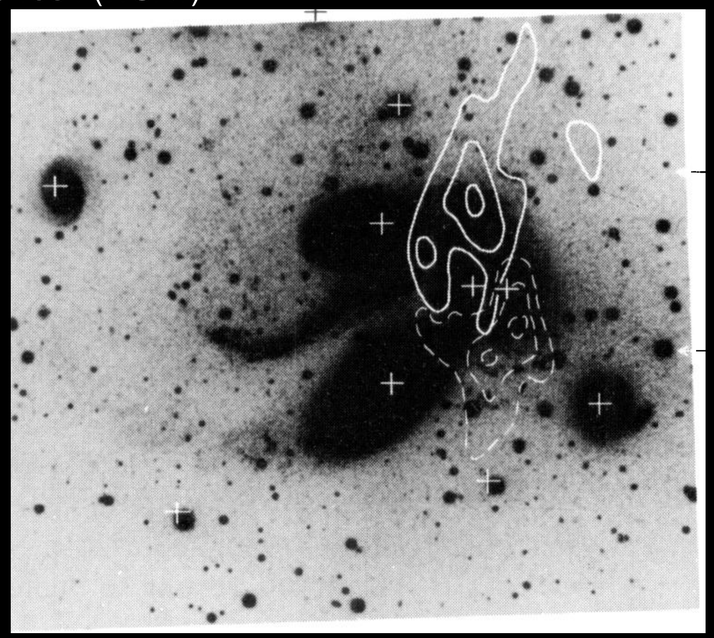
GCG Meeting, CfA, 24 Mar 2026

Stephan's Quintet: early radio observations

Shostak et al. 1984 (WSRT)

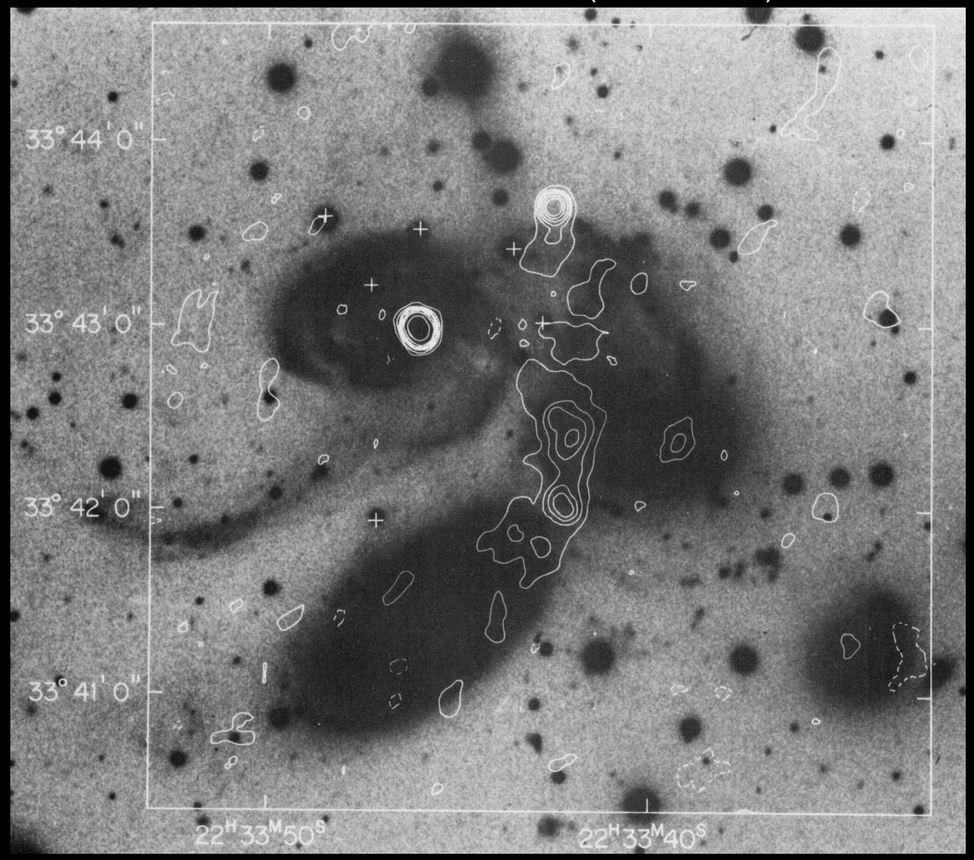


HI near 6600 km/s



HI near 5700 (dashed) and 6000 km/s (solid)

van der Hulst & Rots 1981 (VLA L-band)

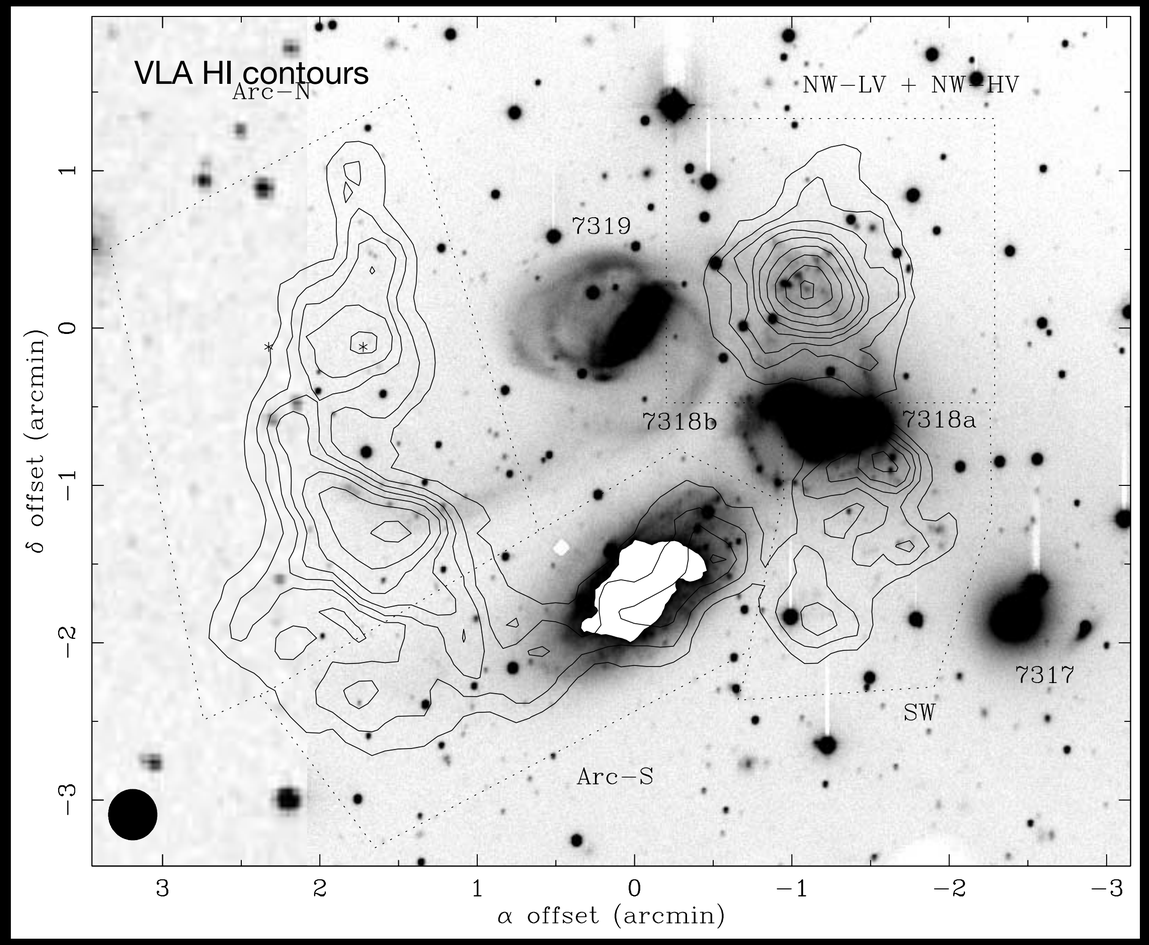


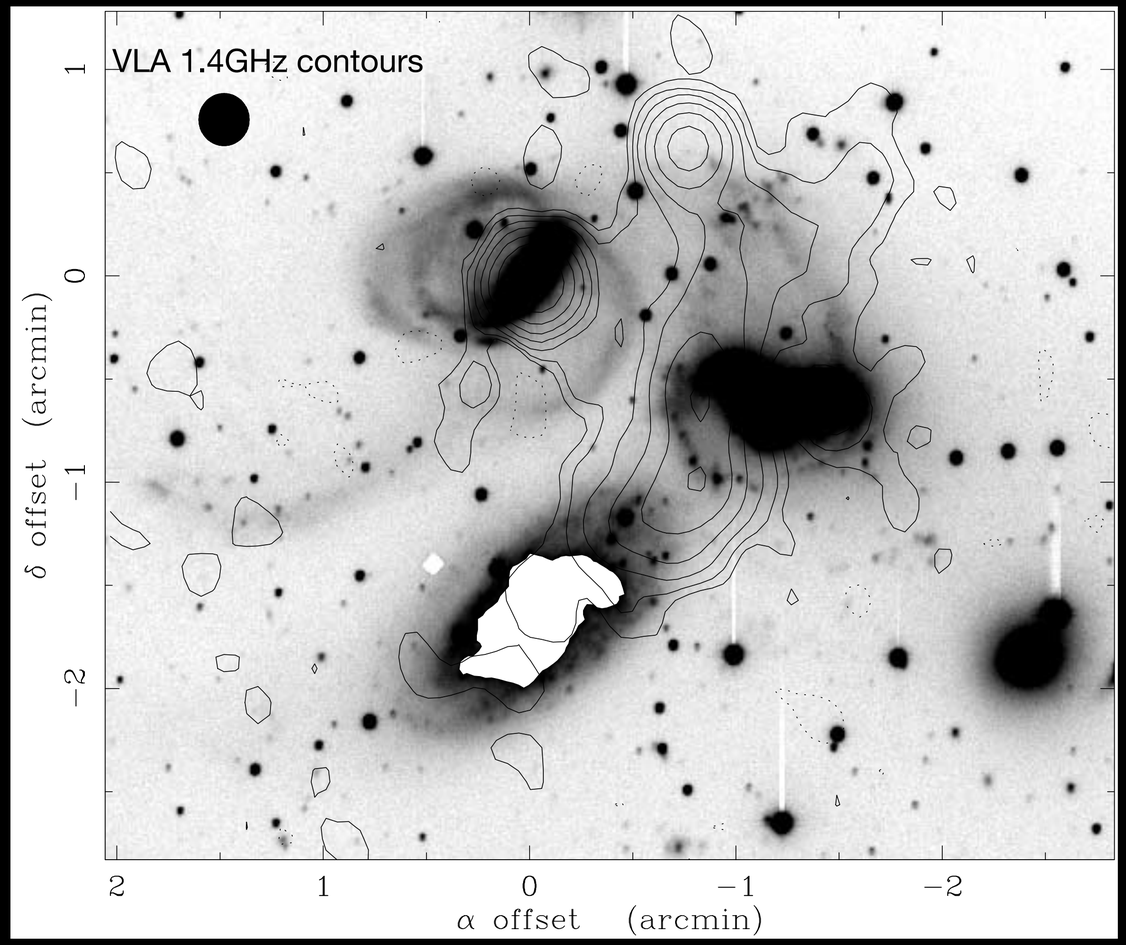
HI confirmed NGC 7320 as a foreground spiral, but also revealed

- HI structures at ~6600 km/s (group) and 5700-6000 km/s (intruder)
- A N-S ridge of continuum emission on the east side of the intruder NGC 7318b

Stephan's Quintet: the VLA view

Williams et al. 2002

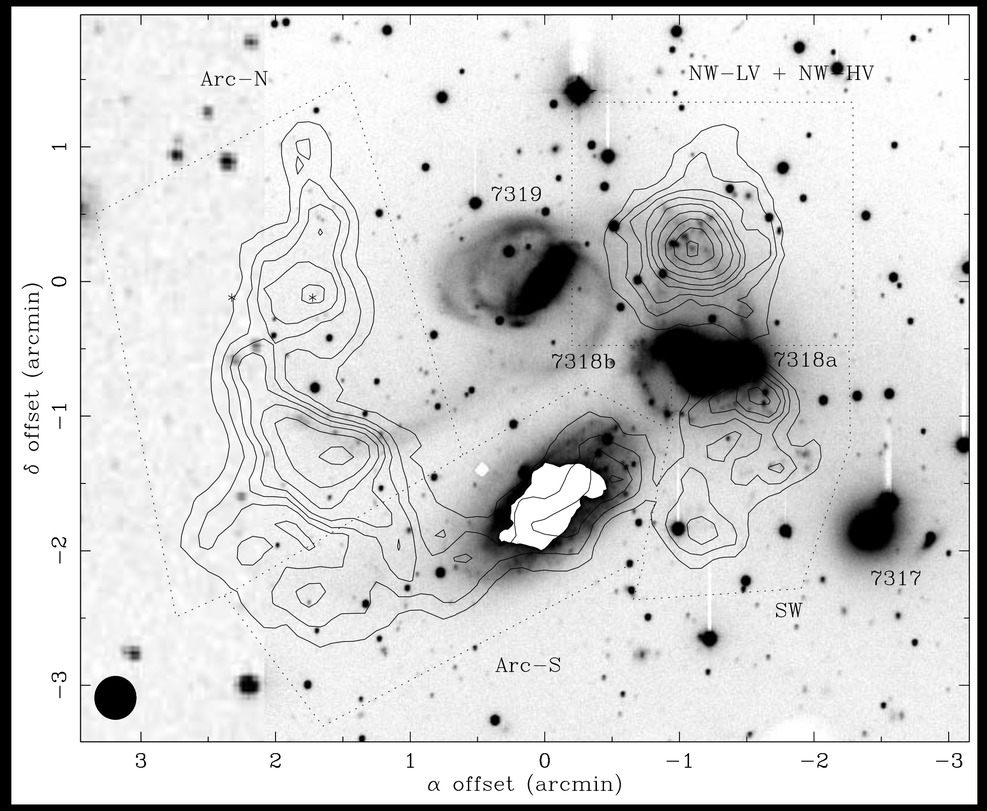




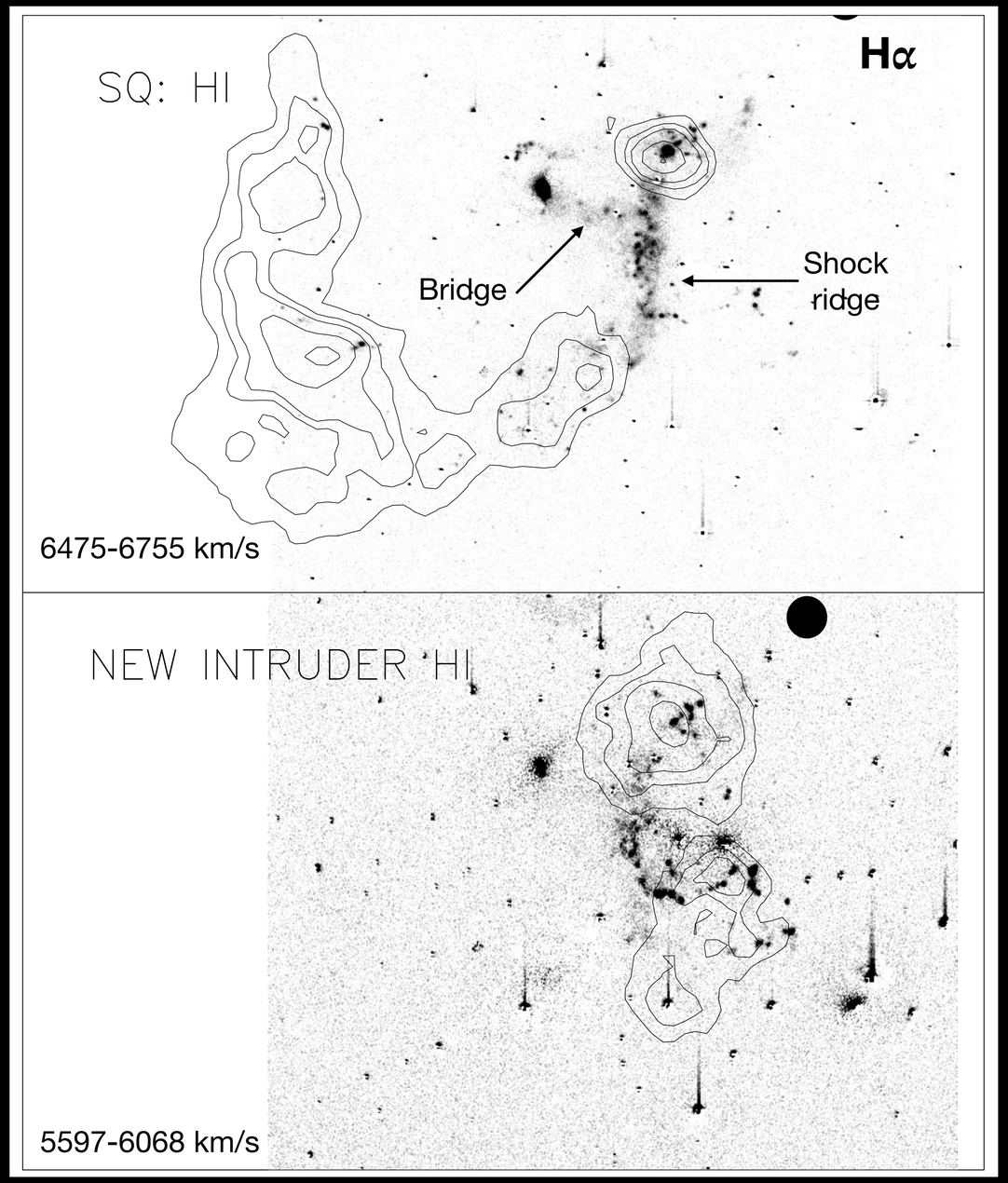
HI mainly outside the galaxies, long 6600 km/s HI tail overlapping optical tails
Continuum ridge links 6600 km/s HI components
➜ Single tidal filament whose central section has been transformed by collision shock?

Stephan's Quintet: VLA + Hα

- High velocity Hα links 6600 km/s HI
  - Note bridge to NGC 7319
- Low velocity Hα links 5700/6000 km/s HI



Sulentic et al. (2001) narrow-band Hα imaging



Observed by everyone

X-ray: XMM-Newton, Chandra, NuSTAR

UV: Galex, HST

Optical: HST, CFHT/SITELLE+MegaCam, WHT/WEAVE, APO/KOSMOS, Gemini/GMOS, etc etc

IR: Spitzer, Herschel, JWST (MIRI, NIRCam)

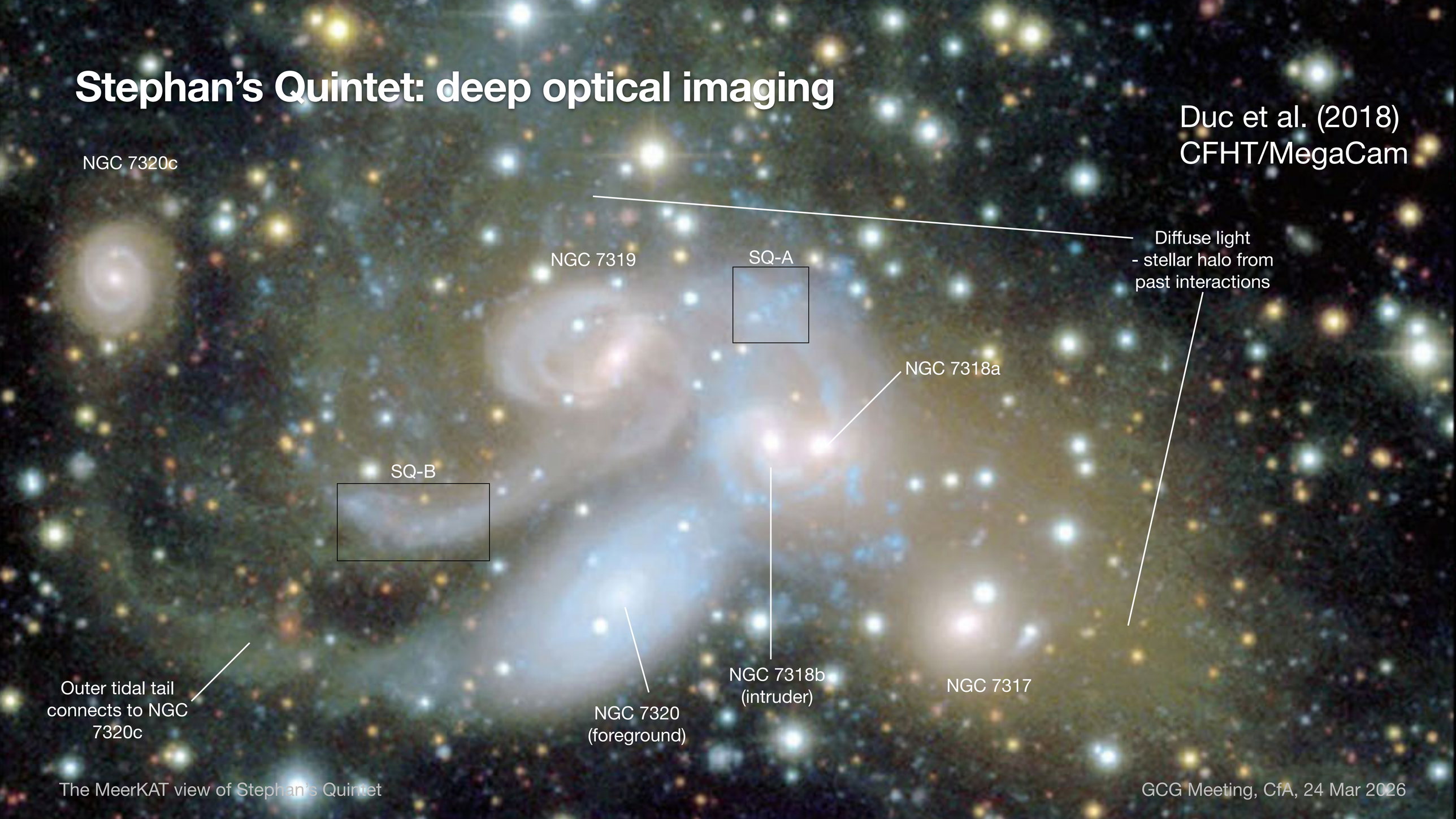
Radio continuum: WSRT, VLA, Effelsberg, Merlin, VLBA, GMRT, LOFAR

HI: WSRT, VLA, Arecibo, Green Bank, FAST

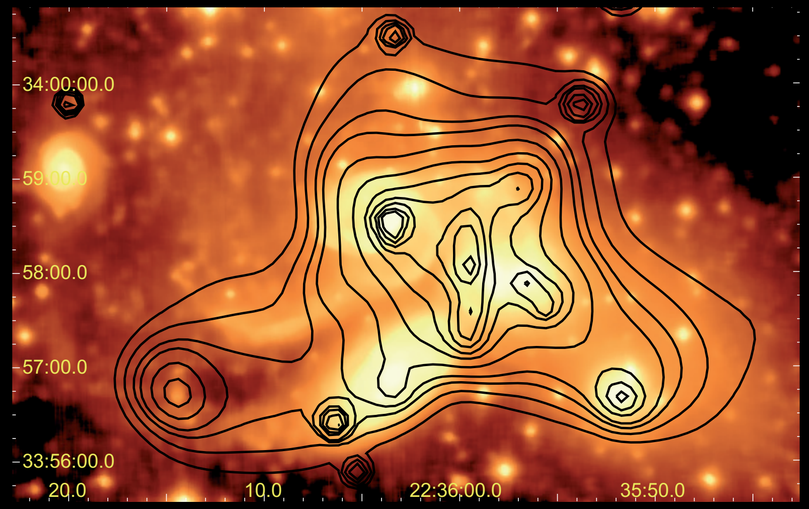
CO: IRAM 30m, PdBI, CARMA, ALMA+ACA+TP, in CO(1-0), (2-1), (3-2)

PanSTARRS + HST WFC3

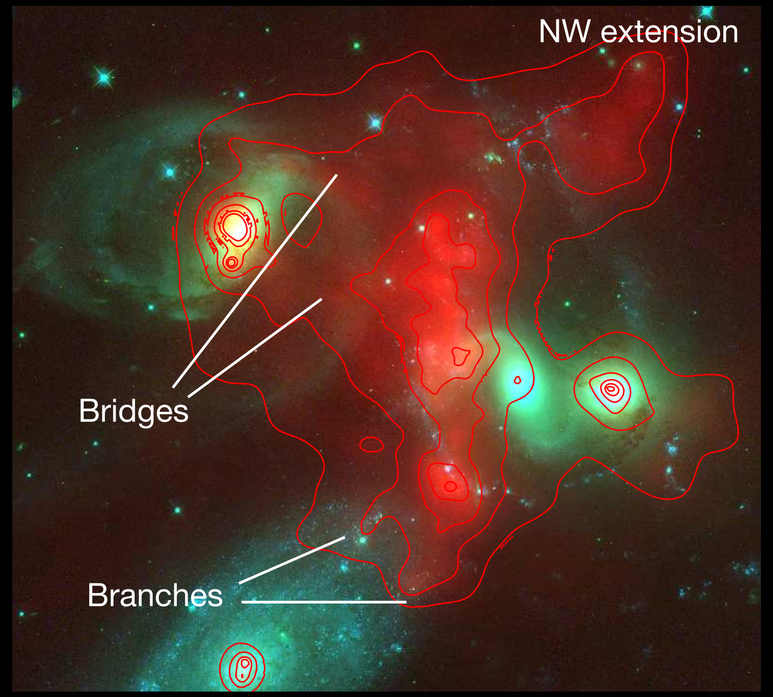
Stephan's Quintet: deep optical imaging



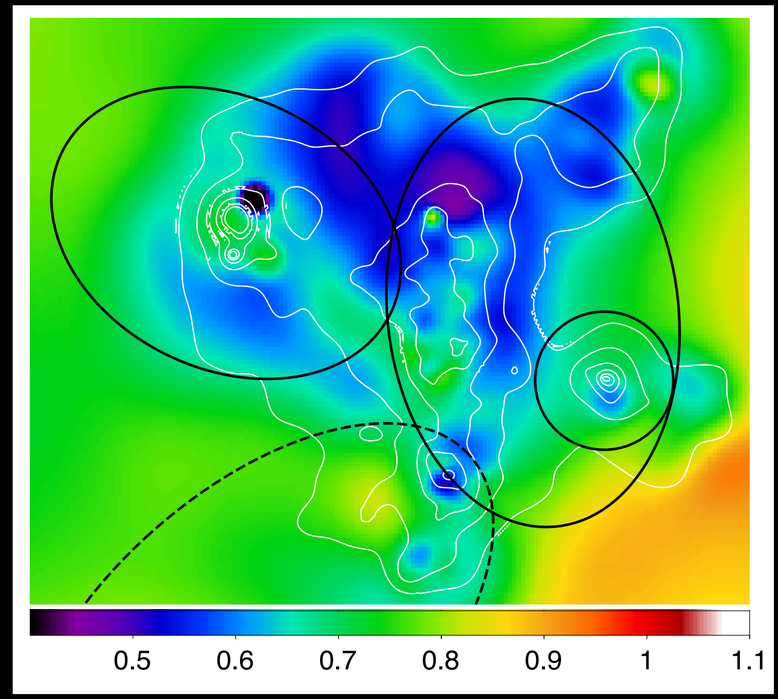
Stephan's Quintet: X-ray (Trinchieri et al. 2003, 2005, O'Sullivan et al. 2009)



XMM 0.5-3 keV contours on deep R-band optical
(Trinchieri et al. 2005)



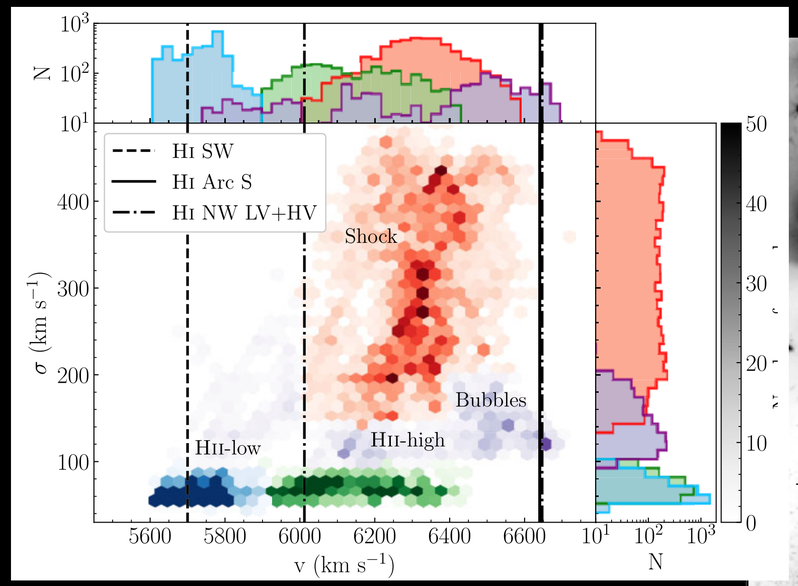
Chandra 0.3-2 keV on HST optical



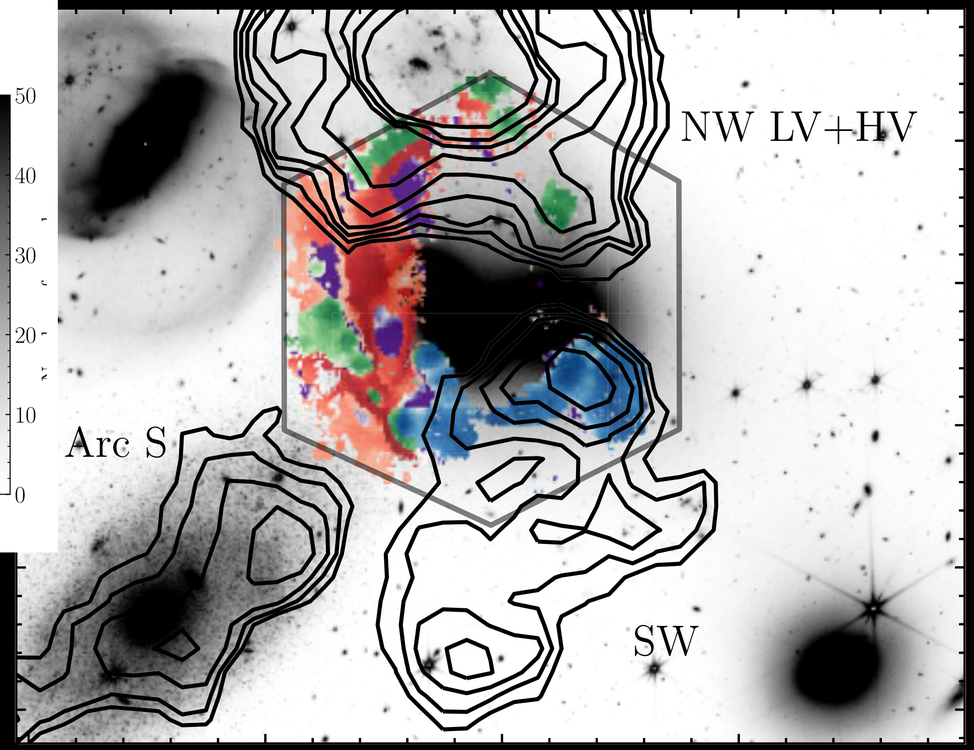
Chandra temperature (keV)

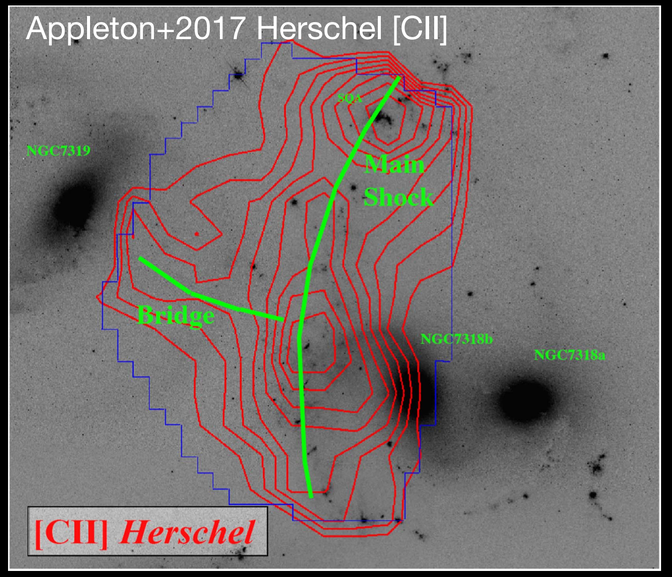
- Irregular X-ray morphology correlated with galaxies and tidal features, centered on shock ridge
- Northwest extension, branches at southern tip of ridge, bridges linking ridge to NGC 7319
- Halo kT~0.8 keV ➜ $M_{500} \approx 2 \times 10^{13}\ M_\odot$
- Shock ridge is *cooler* than surrounding gas! Expect kT=1.3-2.0 keV, observe kT=0.6 keV
  ➜ oblique shock? additional cooling mechanisms?

Stephan's Quintet: Multiphase gas in the shock ridge

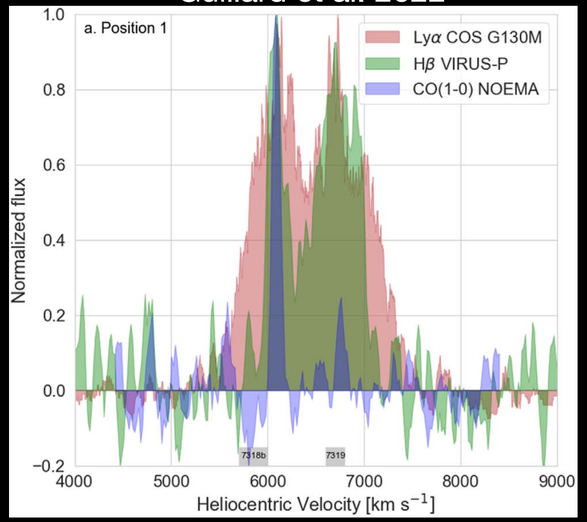


Arnaudova+ 2024 WHT/WEAVE Hα



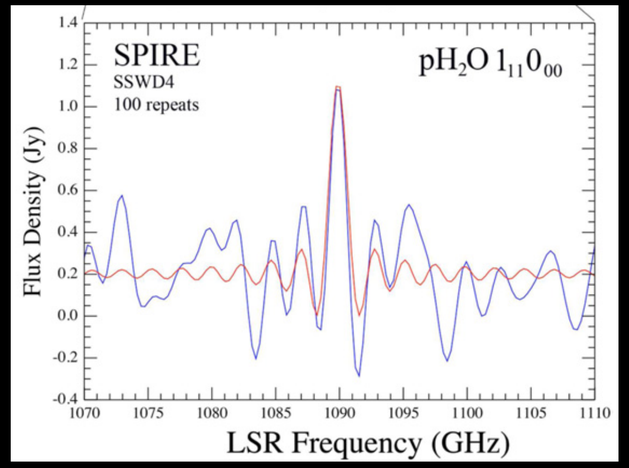


Guillard et al. 2022



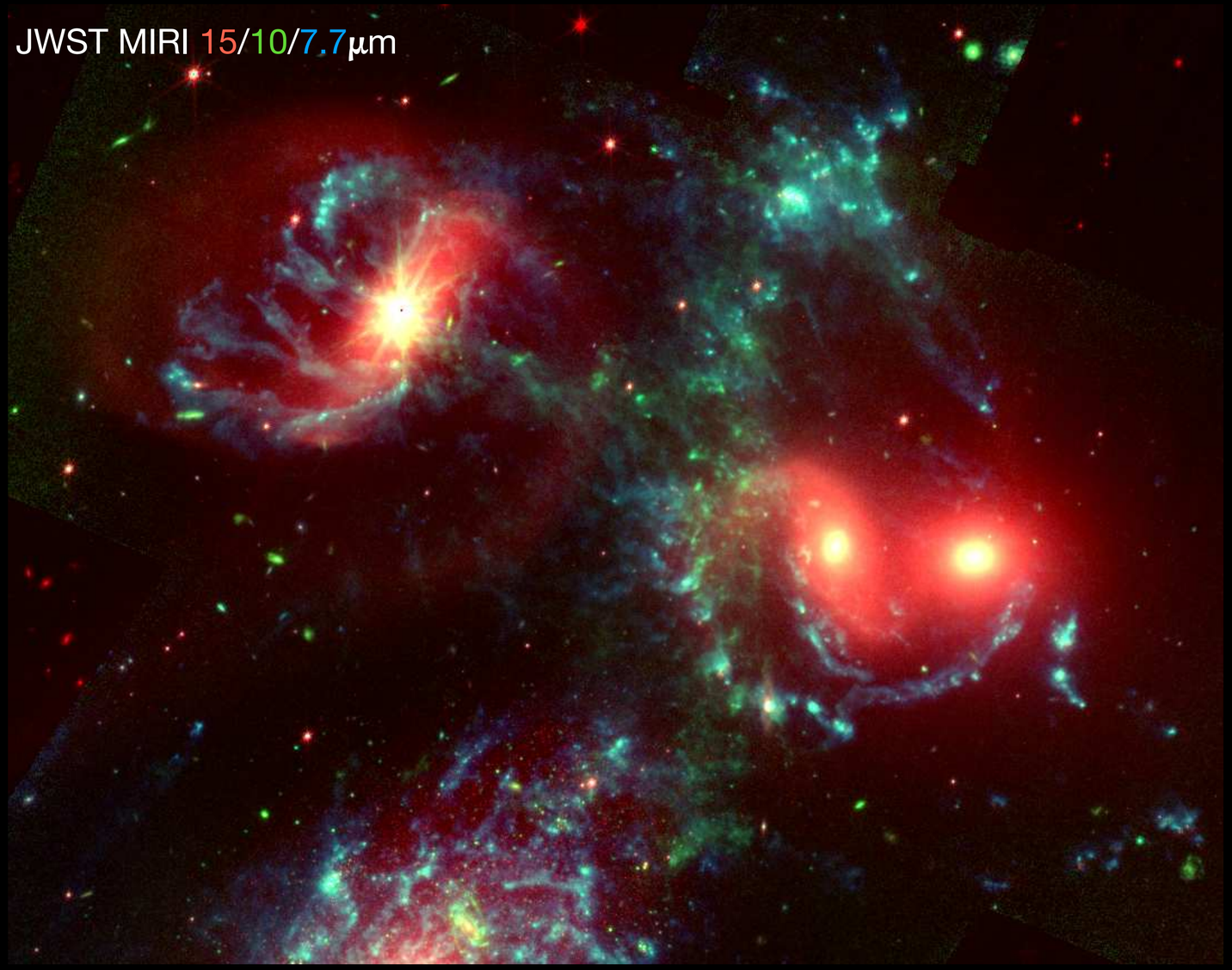
Line emission from shock includes:
Hα, Hβ, Lyα, [CII], H_2O, CO, H_2, [FeII], [SiII], [NeII]…

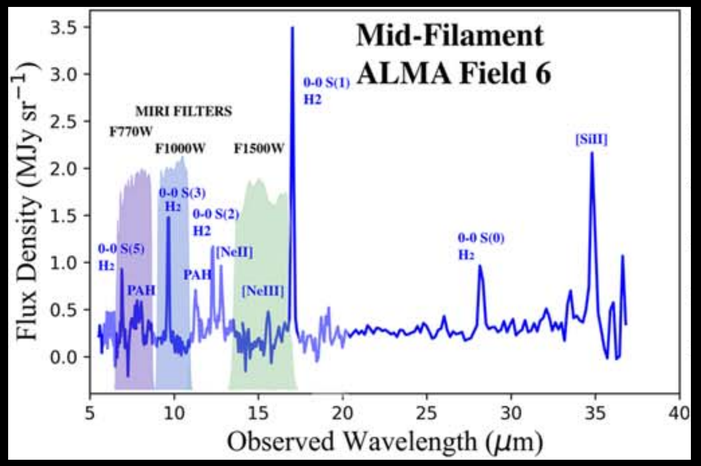
- High-σ Hα associated with shock mainly in 6200-6500 km/s range
- Ionized gas sees shocks of 100-300 km/s



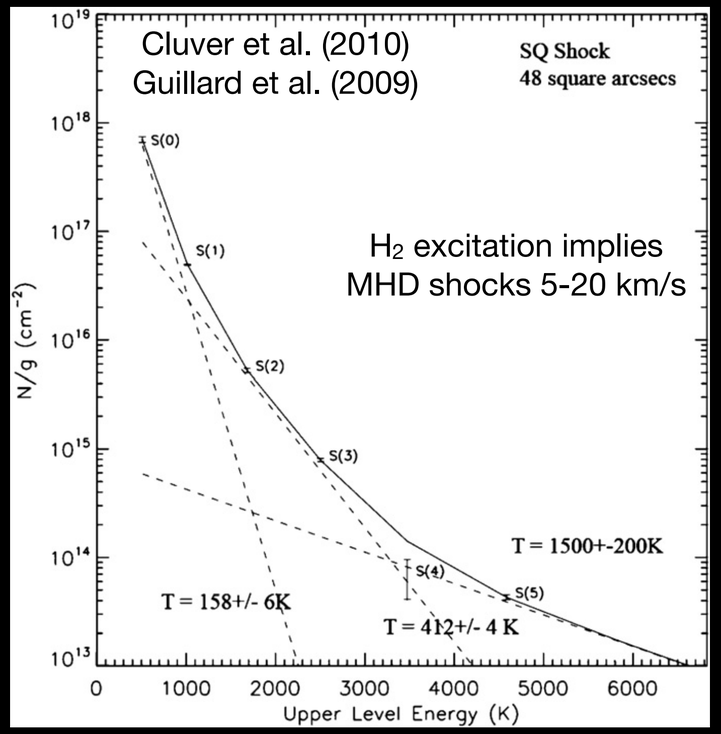
Appleton et al. 2013 Herschel H_2O

Stephan's Quintet: H_2

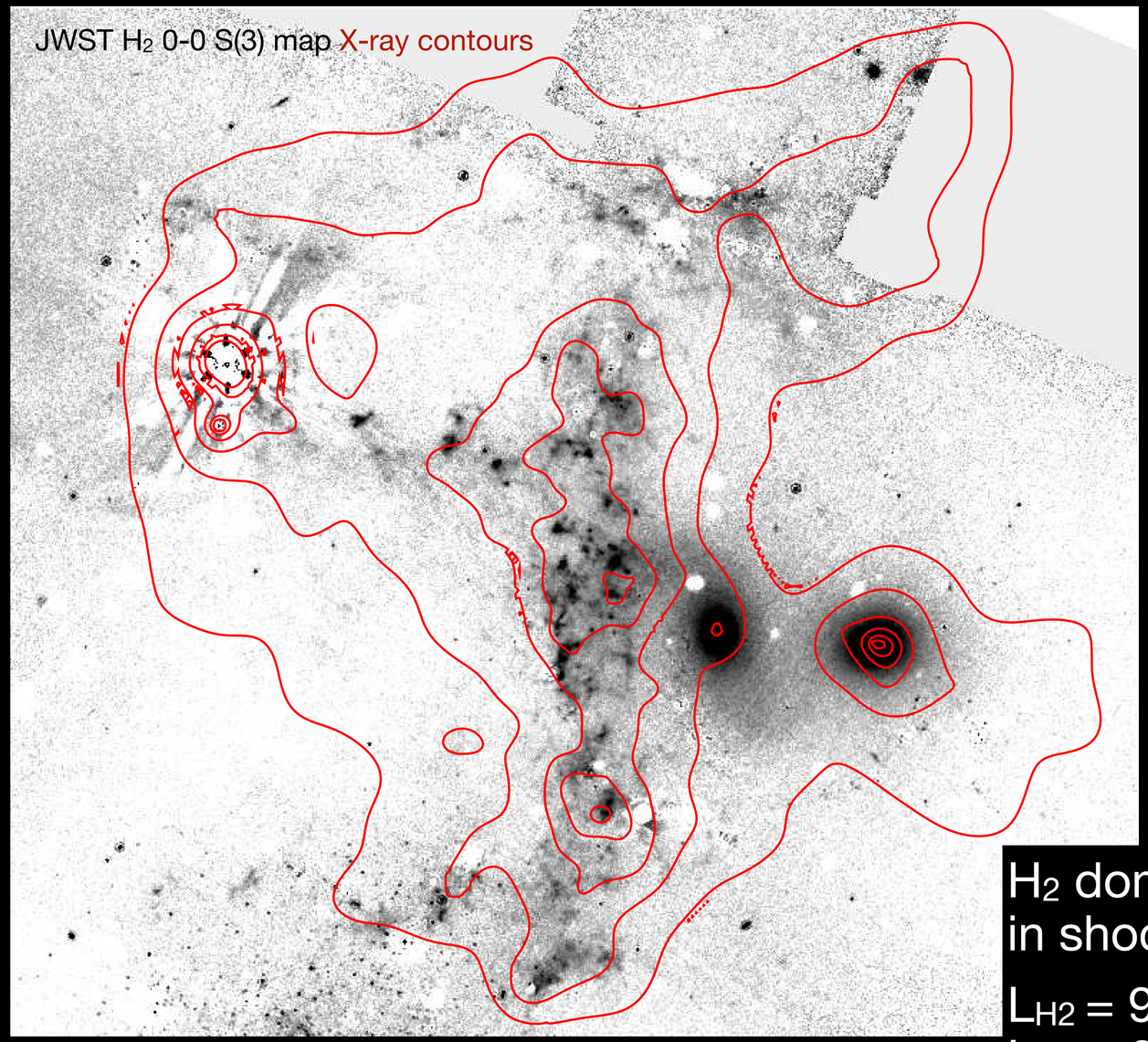


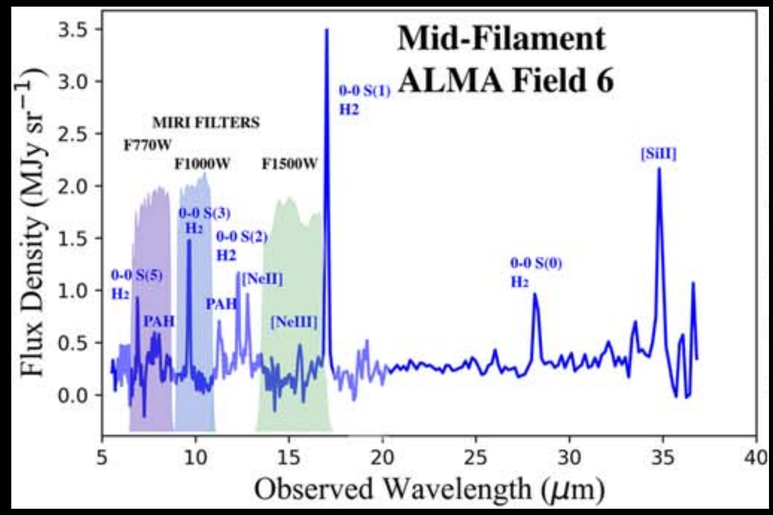


Appleton+2023
Spitzer IRS
spectrum

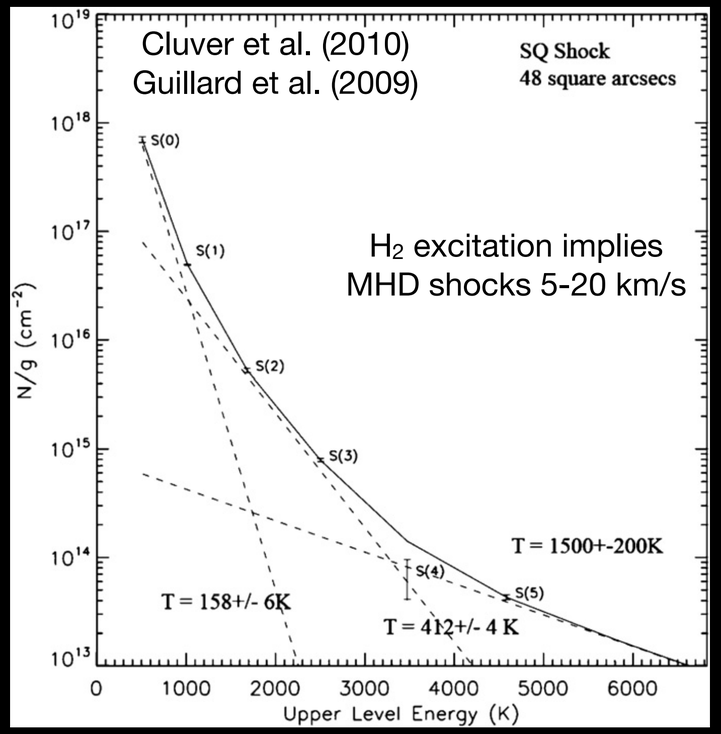


Stephan's Quintet: H_2





Appleton+2023
Spitzer IRS
spectrum

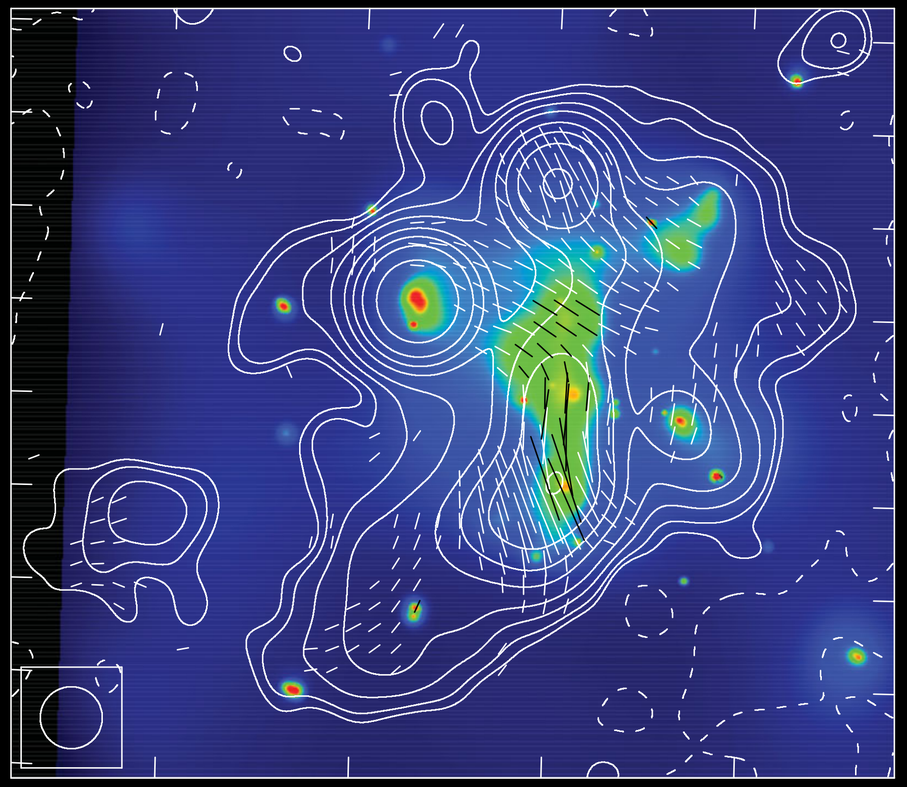


H_2 excitation implies
MHD shocks 5-20 km/s

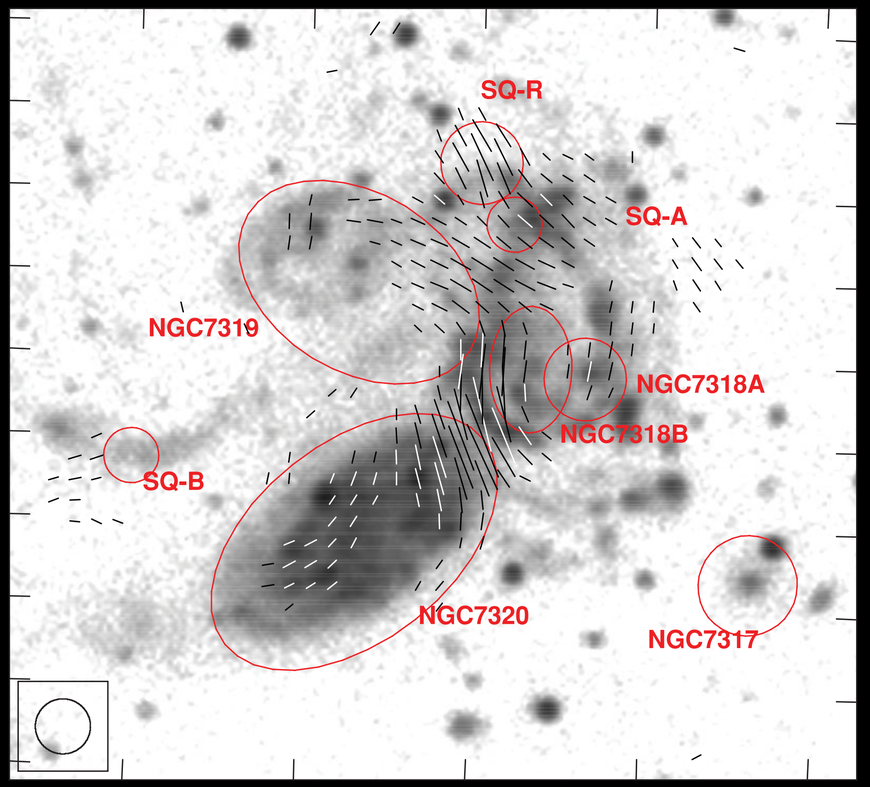
H_2 dominates cooling in shock ridge!

$L_{H2} = 9.7 \times 10^{41}$ erg/s
$L_{Xbol} = 3.0 \times 10^{41}$ erg/s

Stephan's Quintet: Polarization (Nikiel-Wroczynski et al. 2013, 2020)



VLA 8.45 GHz on Chandra soft X-ray, 20" resolution



VLA 8.45 GHz on GALEX NUV

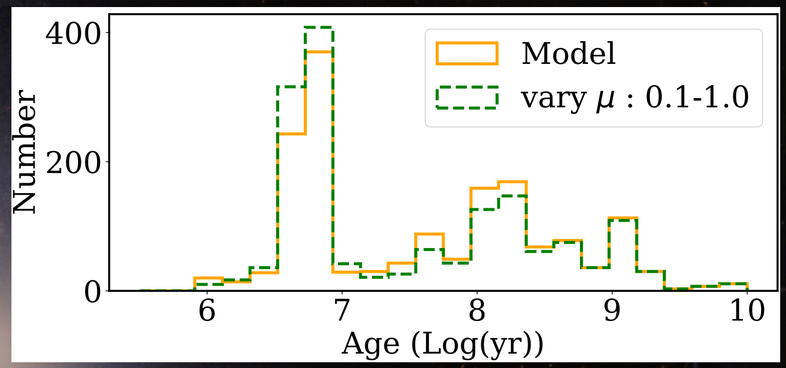
VLA 8.45 GHz polarization study: 5% polarization in the shock, 2% in surrounding diffuse emission

➜ low polarization fraction suggests we're viewing shock face-on, not edge-on.

B-field vectors not a great match to shock morphology

Stephan's Quintet: Open Questions

Star cluster age distribution, Aromal+ 2025



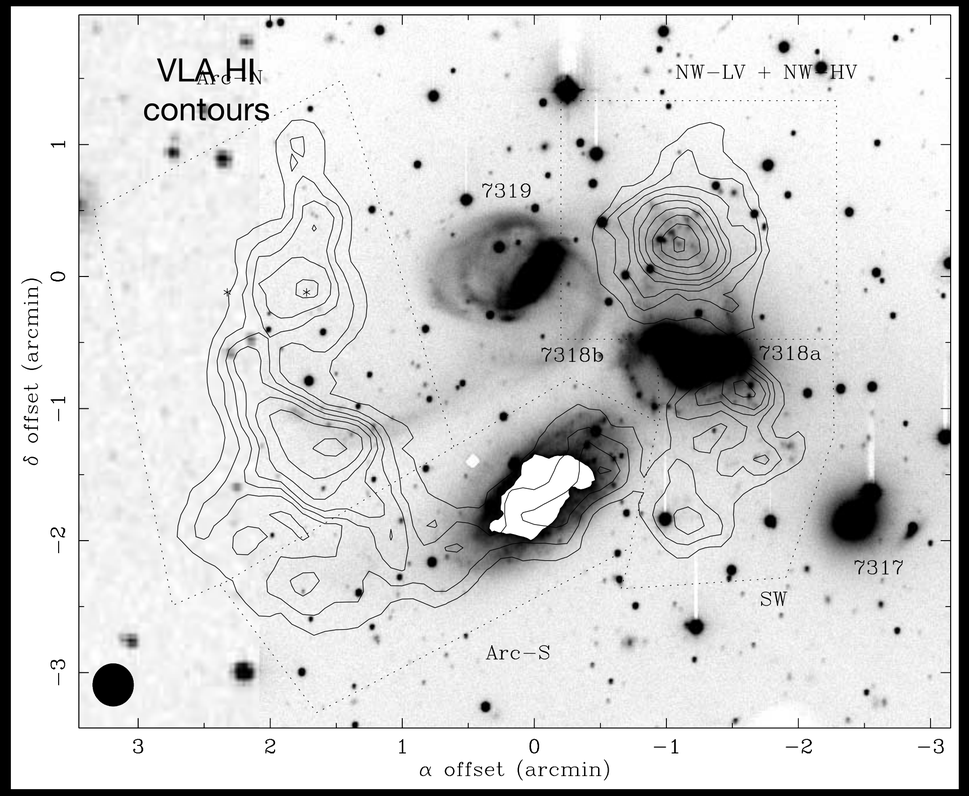
✗ What is the age of the collision?
- youngest star clusters <10 Myr

✗ What is the collision vector?
- Is there a plane-of-sky component?

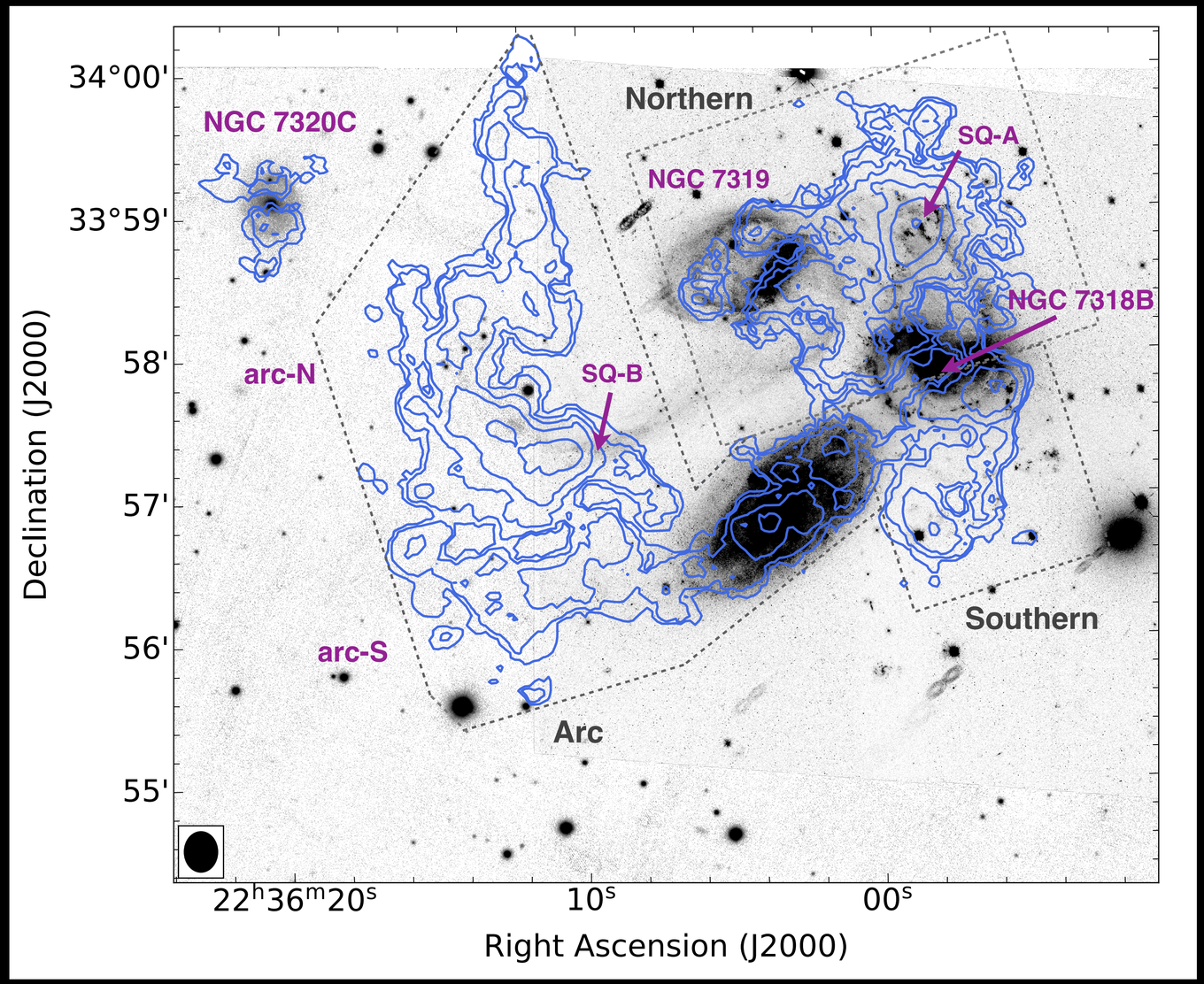
✗ How was the radio ridge formed?
- Direct collision of HI clouds? hypersonic collision, 900 km/s is Mach ~40
- Diffusive Shock Acceleration from a shock in the hot (X-ray) phase?
  - X-ray suggests Mach 2.3-2.9 oblique shock
  - Relativistic seed population required?
- Adiabatic compression? Requires Mach ~3.8 (Arnaudova+ 2024)
  - Relativistic seed population required

✓ New data: MeerKAT L-band (6 hrs), uGMRT bands 3 & 4 (7 hrs each)
✓ Archival data: LOFAR HBA (LoTSS data) , JVLA S & C band [obs'd 2020-21, unpublished]

MeerKAT: HI mapping



Williams+2002, 19.4”x18.6”, 1st contour 5.8x10^{19} atoms/cm^2



MeerKAT HI, 17”x14”, 1st contour 5.6x10^{19} atoms/cm^2

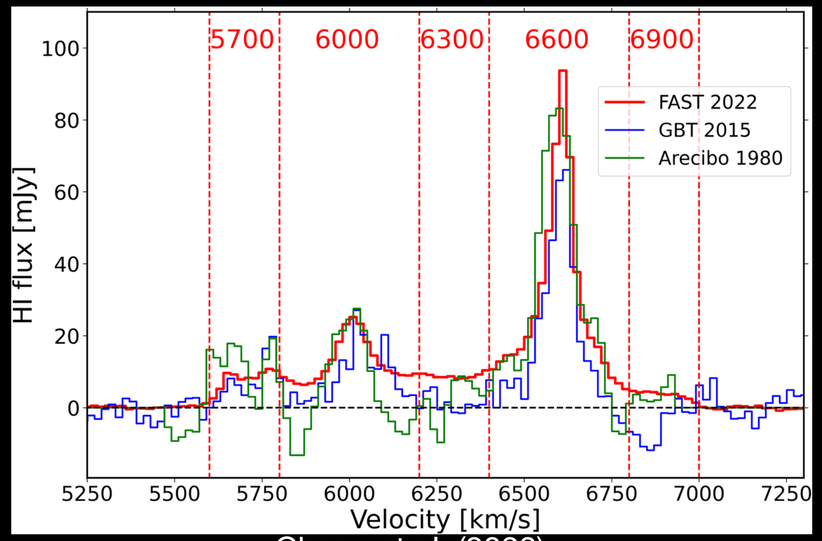
HI spectra

MeerKAT captures majority of HI seen by single dish studies

Additional components not seen by VLA:

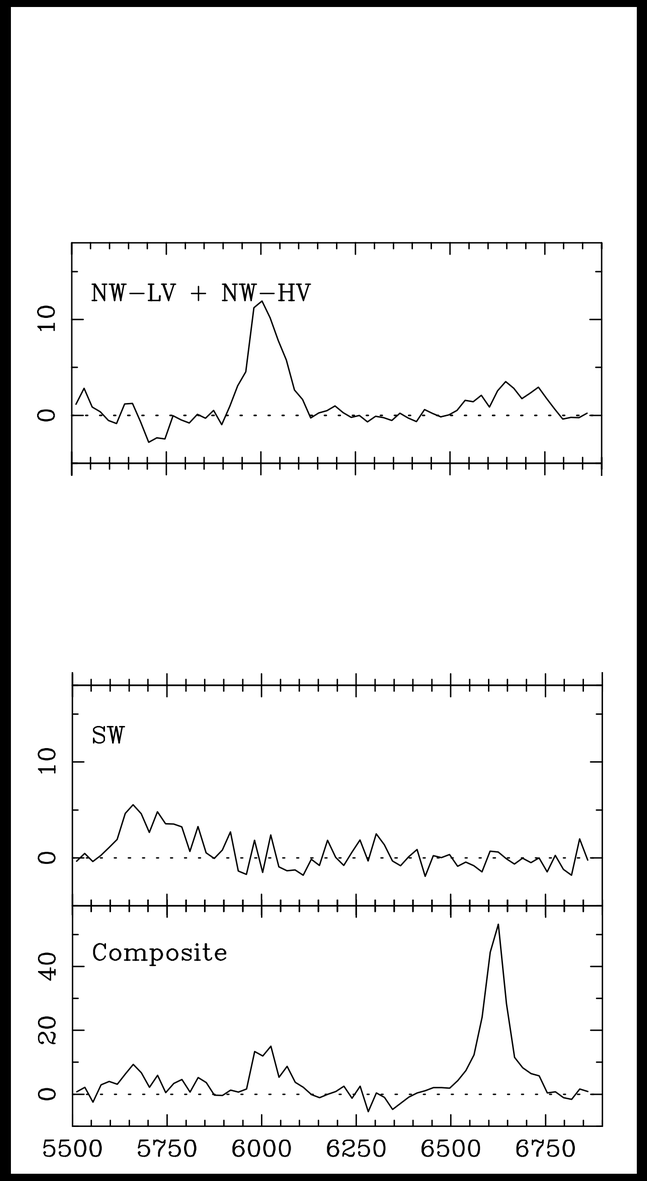
- 6900 km/s peak
- flux at intermediate velocities, ~6200-6500 km/s

Single dish



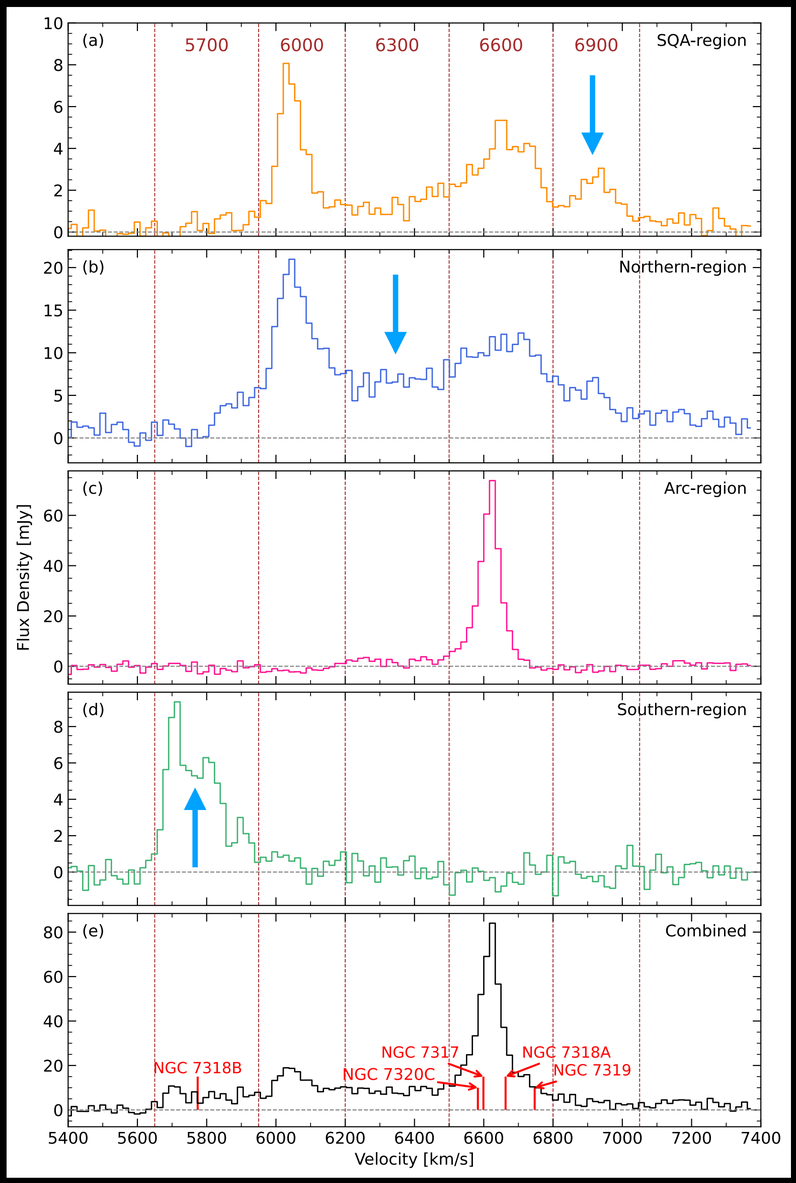
Cheng et al. (2023)

VLA

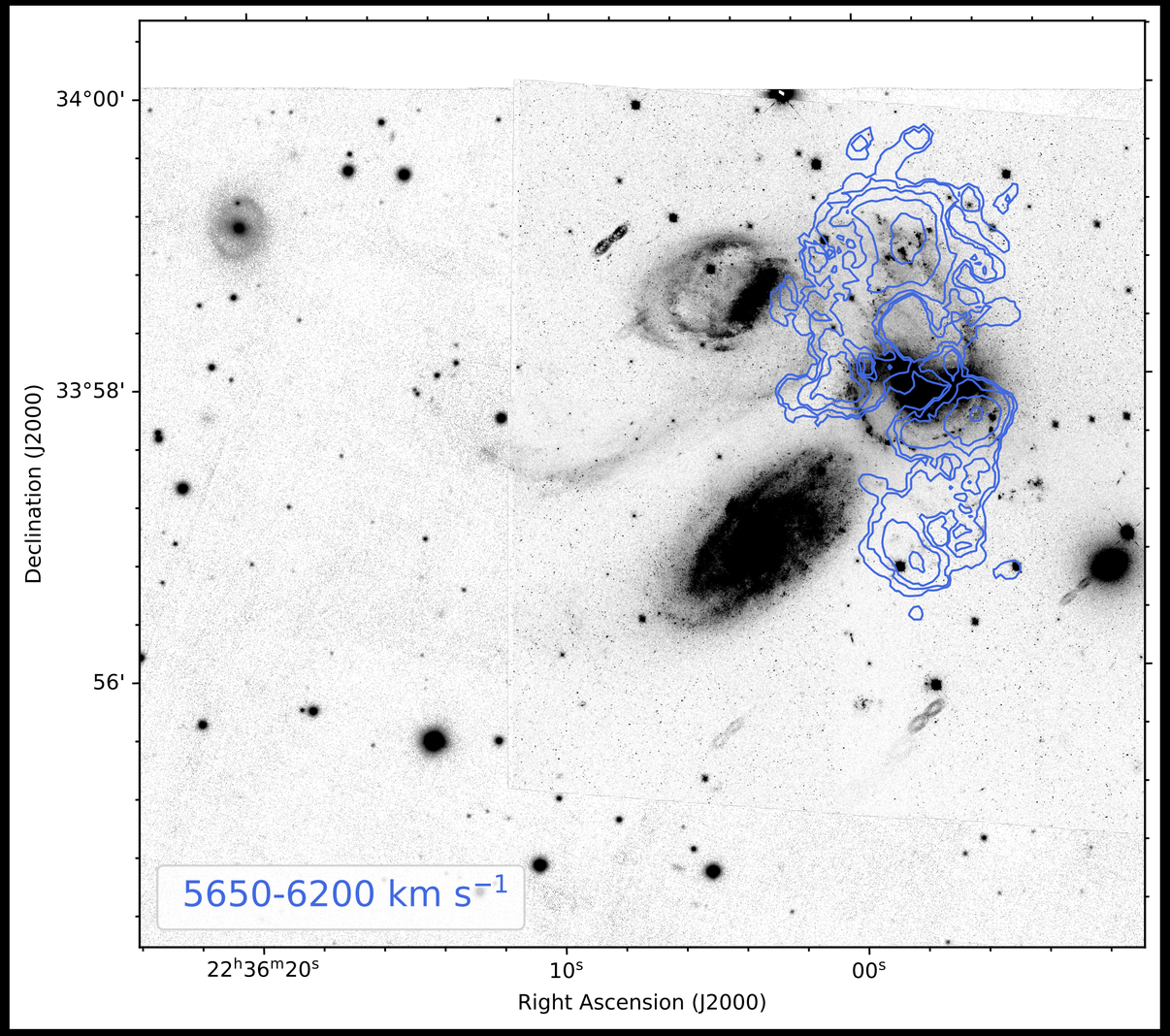


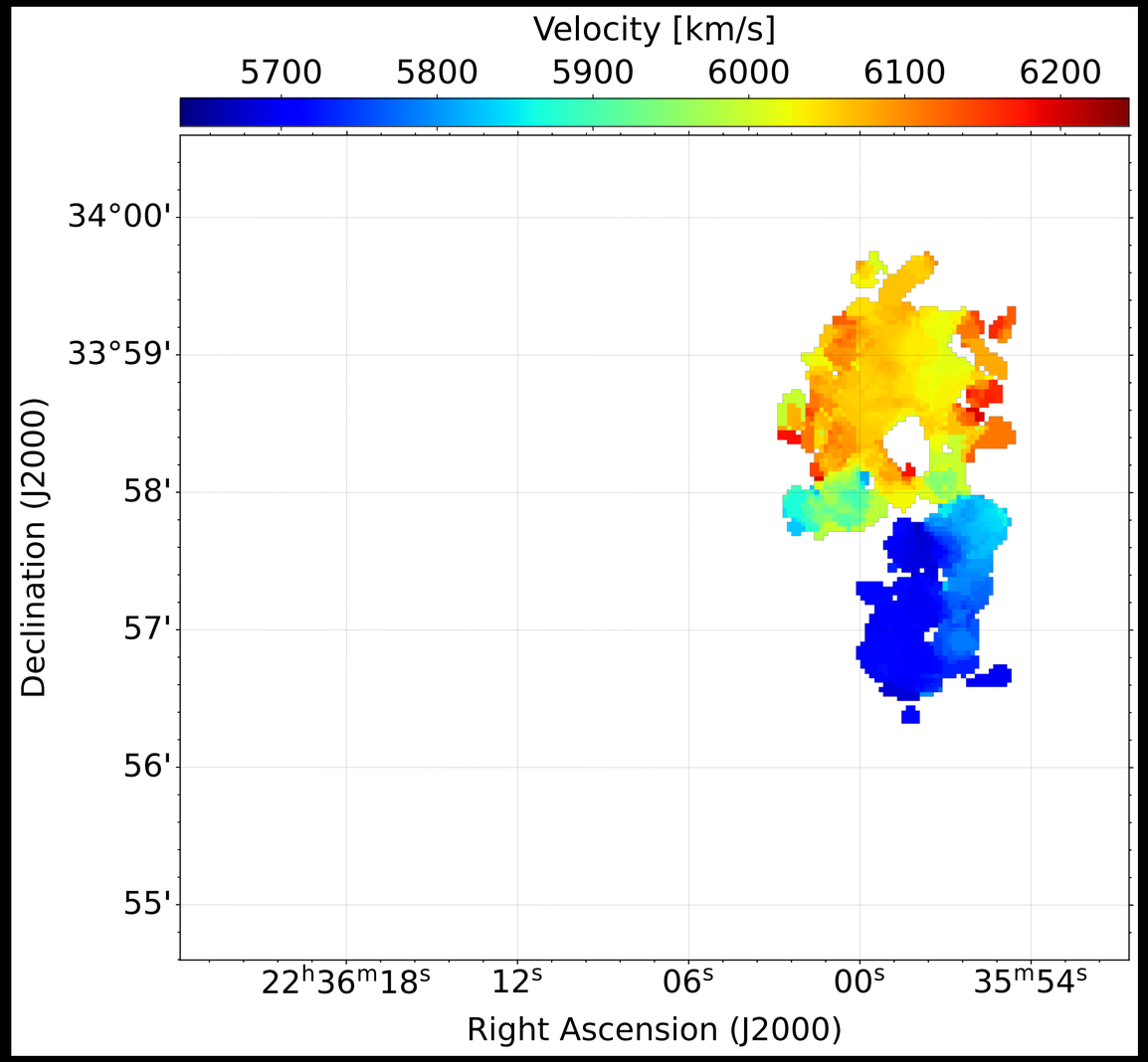
Williams et al. (2001)

MeerKAT



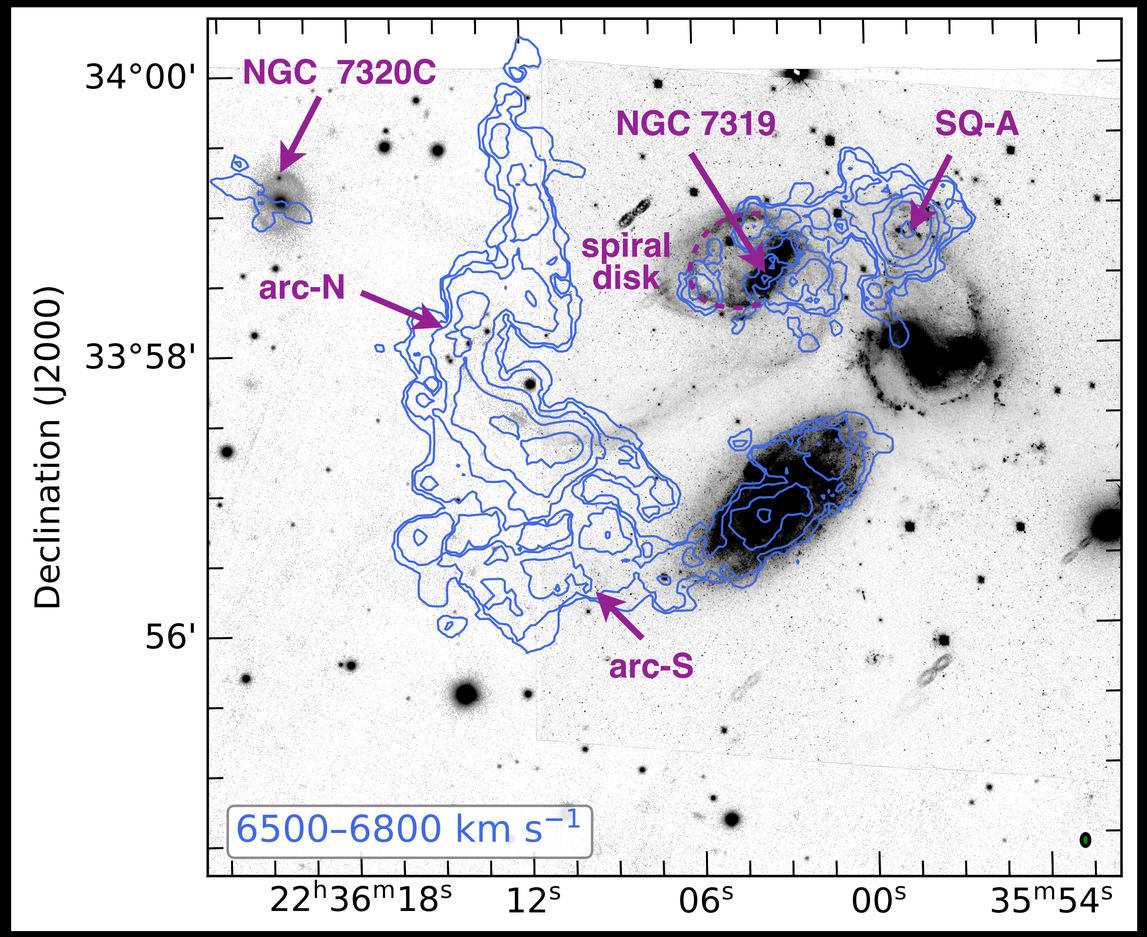
HI: low-velocity component



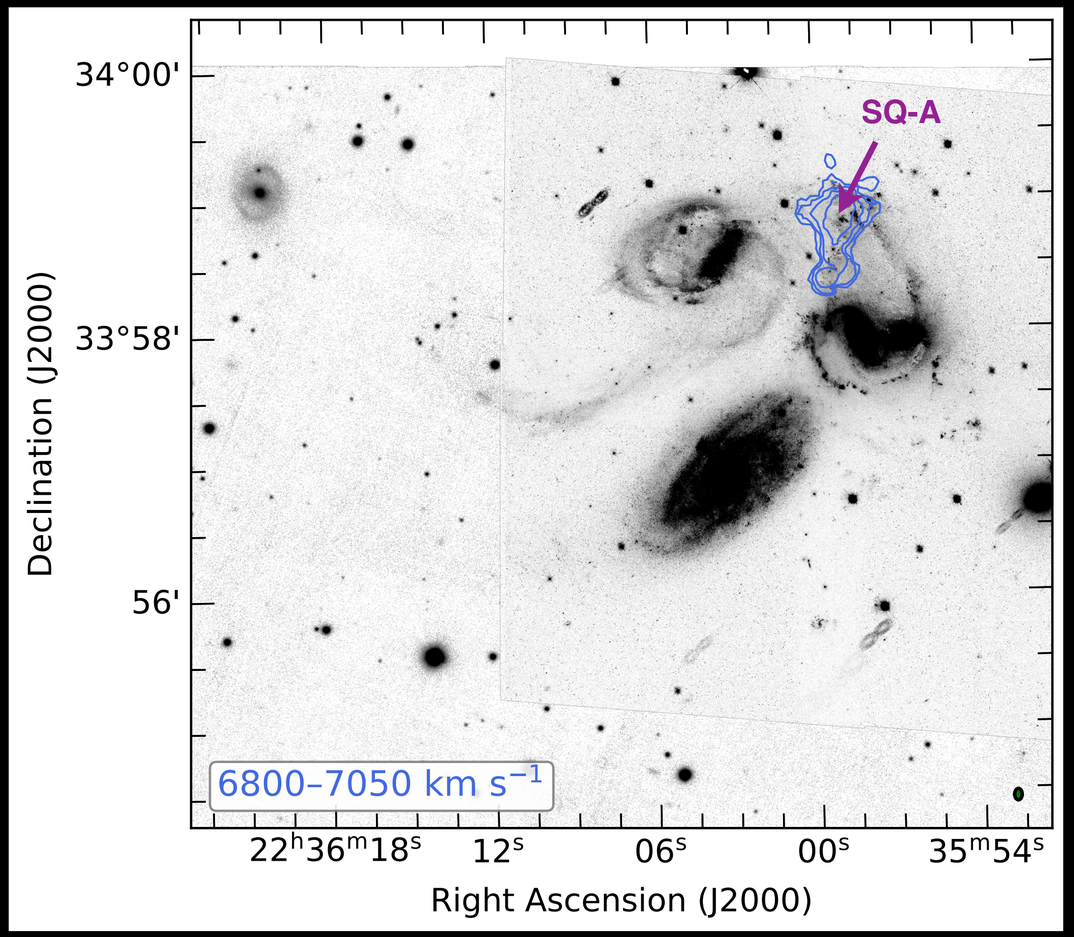


Gaps filled in ➜ Disturbed disk of intruder galaxy (NGC 7318b), clockwise rotation, V_{rot}=175 km/s

HI: high-velocity component

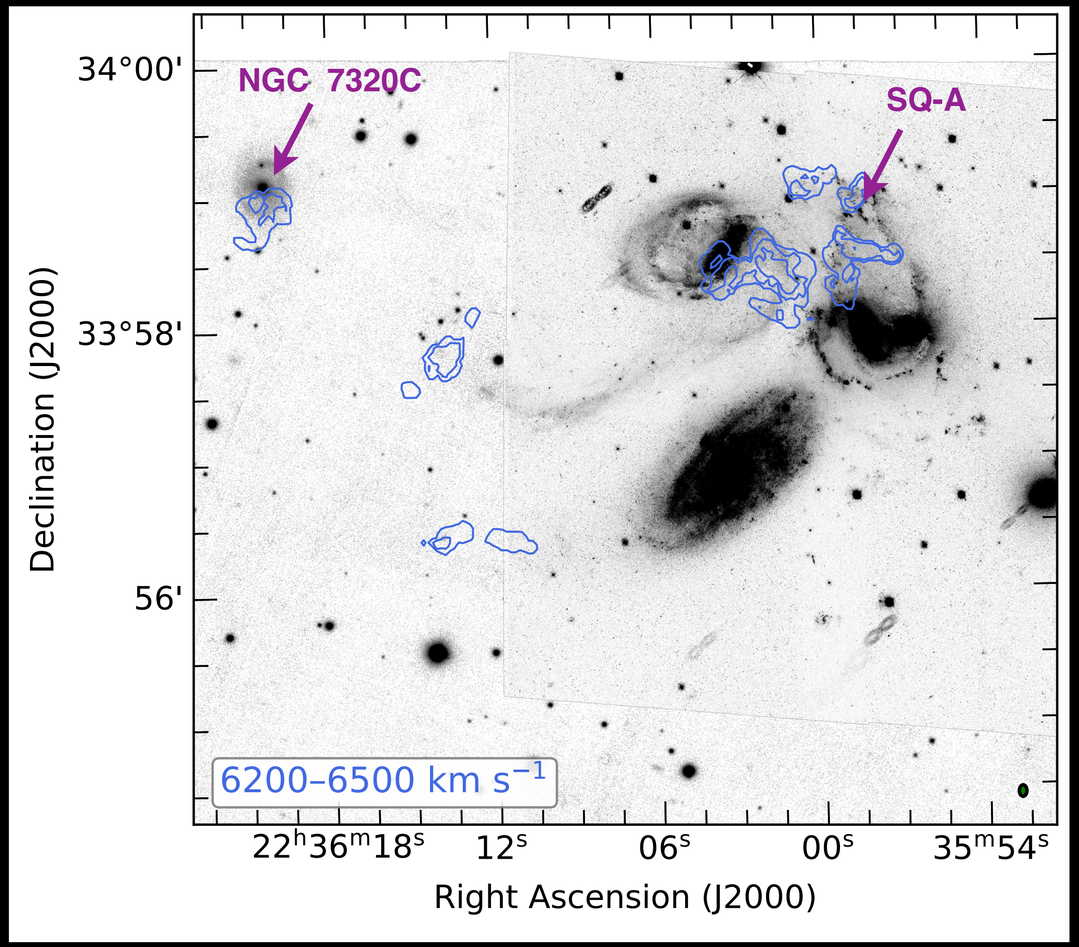


NGC 7319 linked to SQ-A by northern HI bridge at the group velocity (6500-6800 km/s)

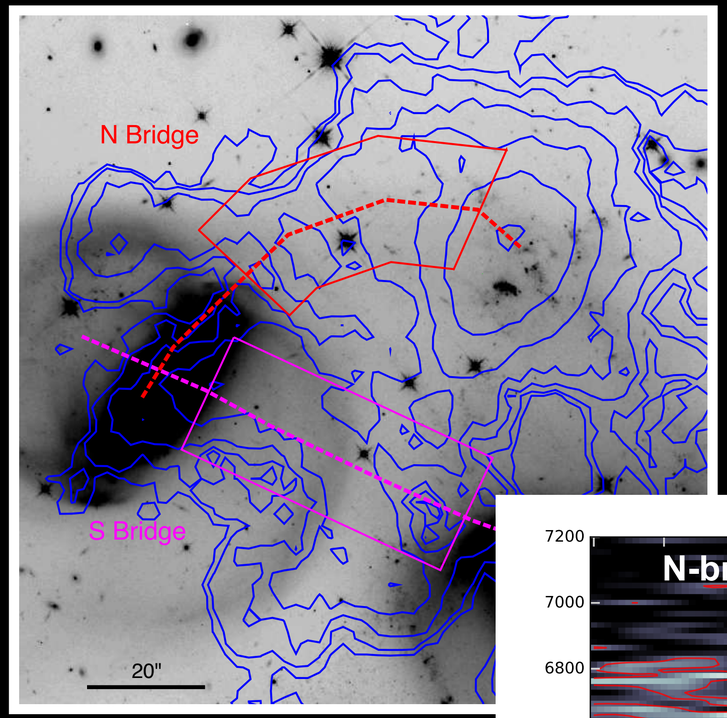


Highest velocity HI (>6800 km/s) localized to SQ-A and northeast “arm” of NGC 7138b

HI: intermediate velocities

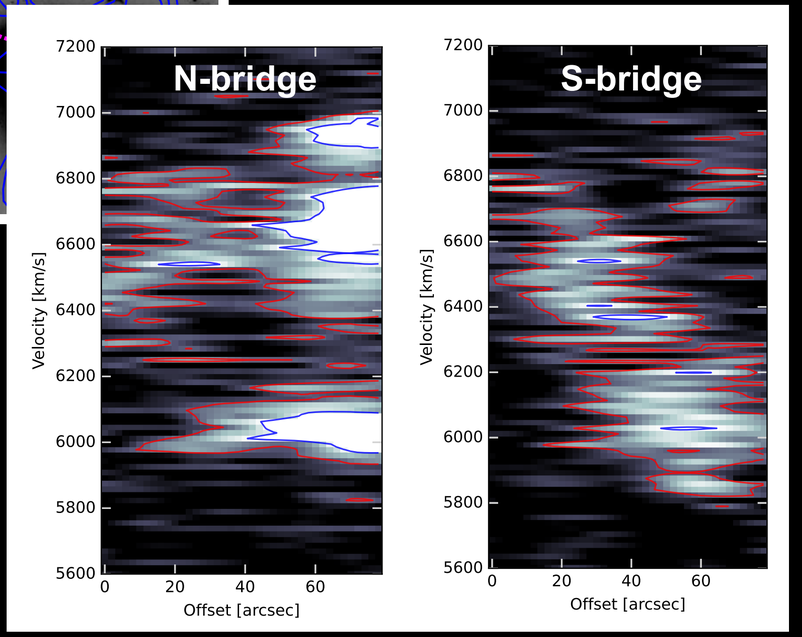


Intermediate velocity HI in bridges, SQ-A, northern disk of NGC 7318b

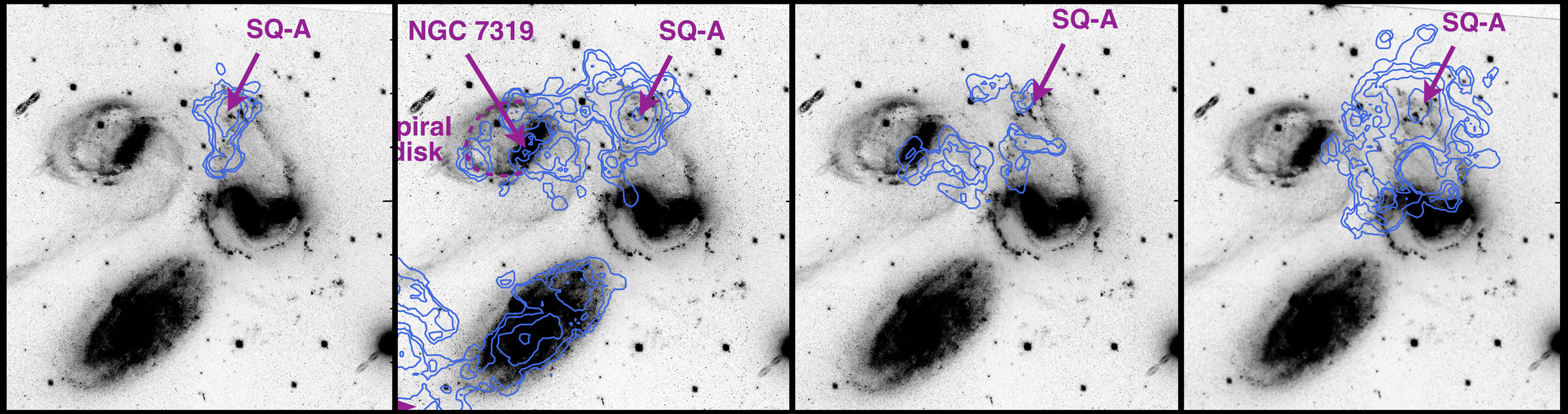


N bridge: roughly constant velocity

S bridge: 700+ km/s velocity gradient



HI: correlated structures at *very* different velocities



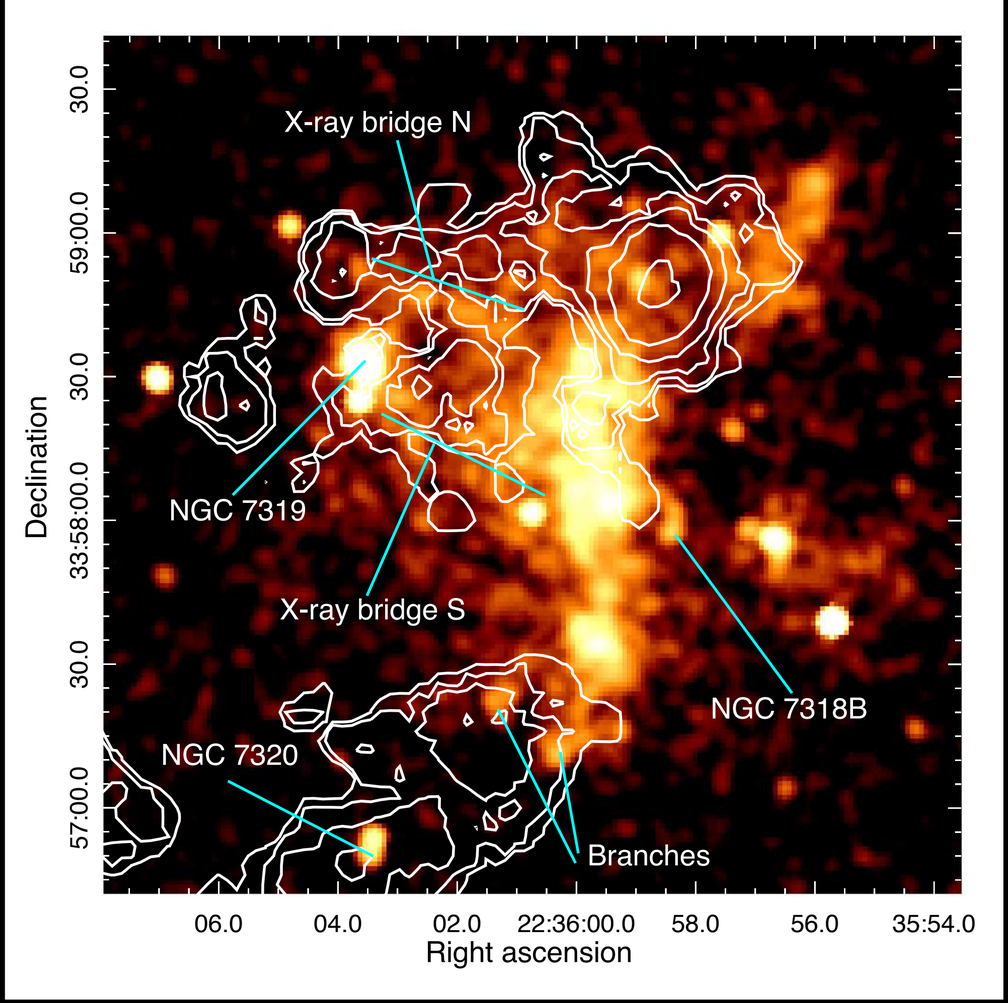
6800 - 7050 km/s | 6600 - 6800 km/s | 6200 - 6500 km/s | 5950 - 6200 km/s

Group velocity range

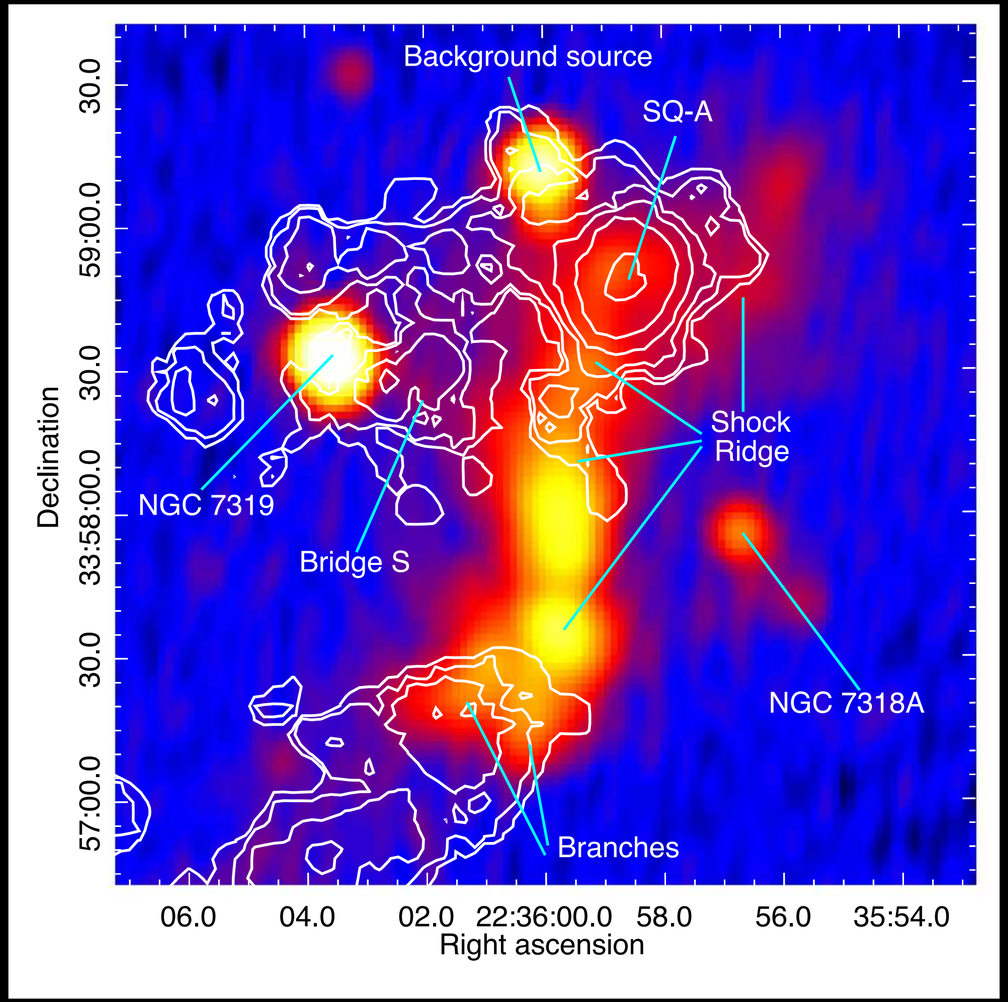
Intruder galaxy

- Gas around SQ-A and in northeast “arm” shows velocities across 1000 km/s range
- Spatial correlation ➜ limited plane-of-sky motion

Shock ridge connects high-velocity HI components

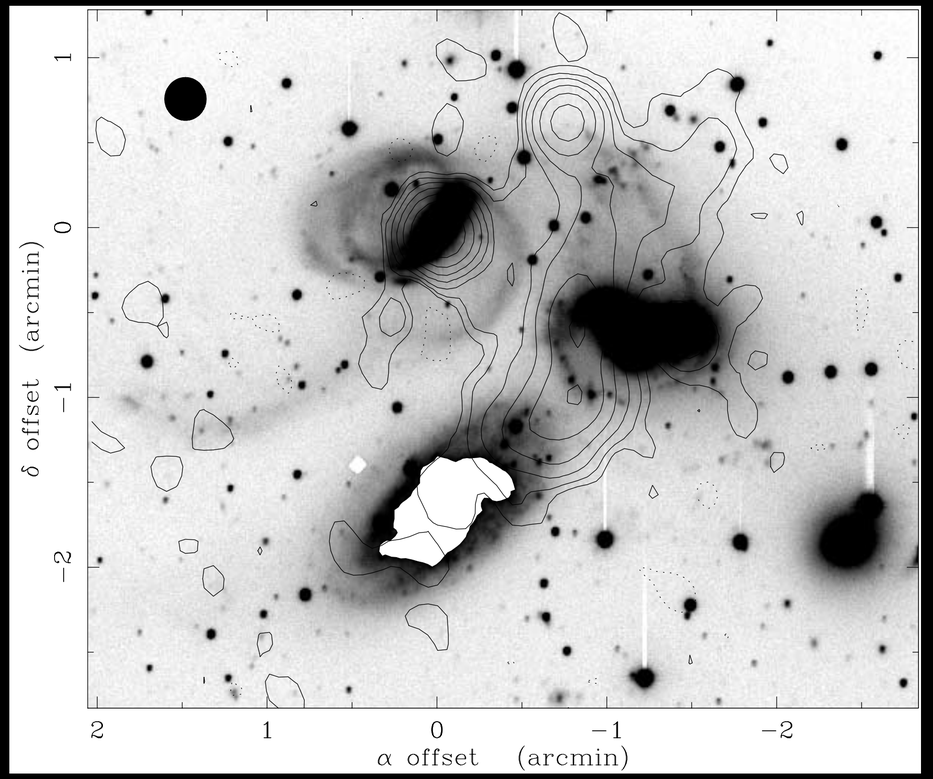


Chandra 0.3-2 keV with
6500-6800 km/s HI contours



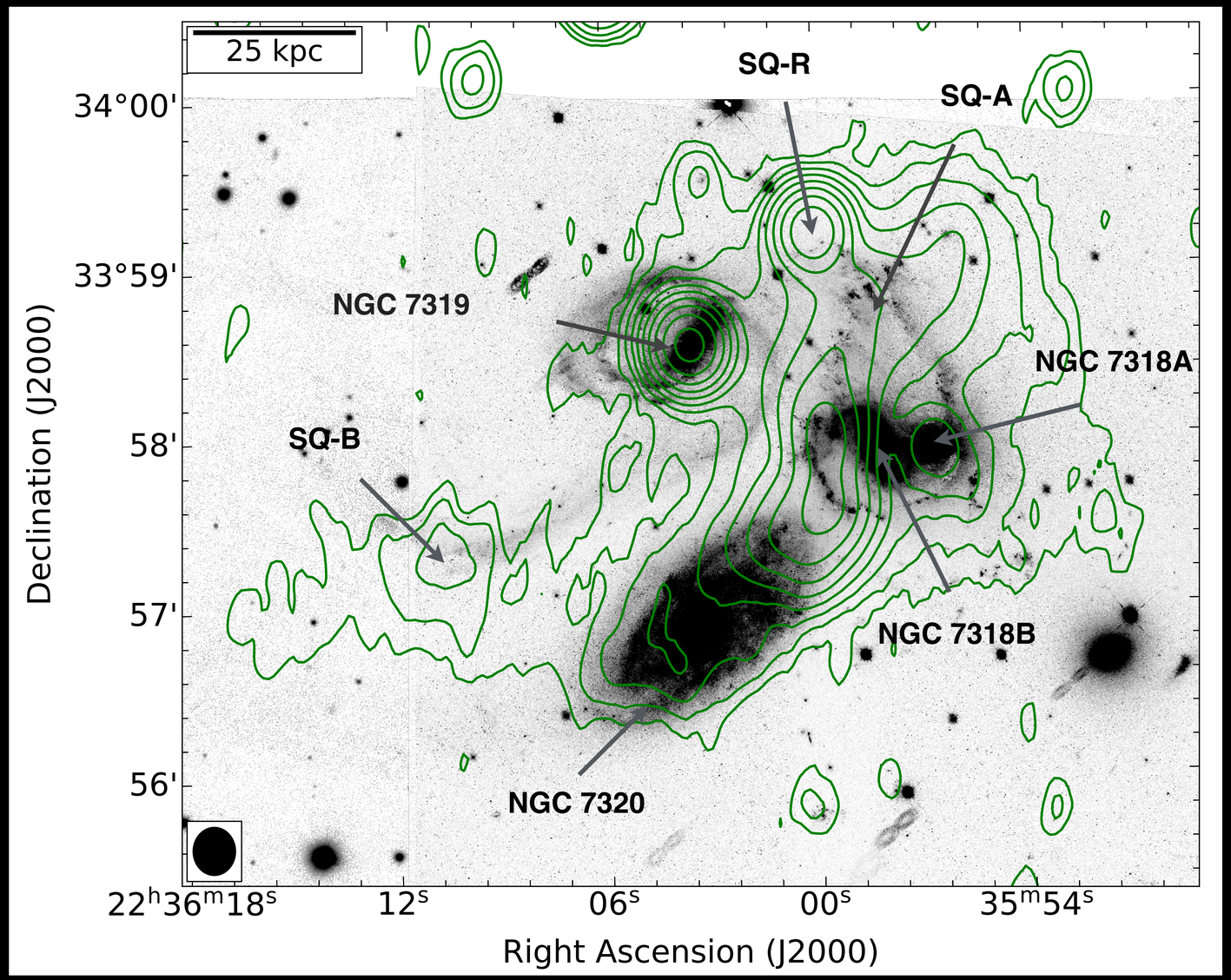
MeerKAT L-band (8” HPBW) continuum
with 6500-6800 km/s HI contours

Radio continuum morphology



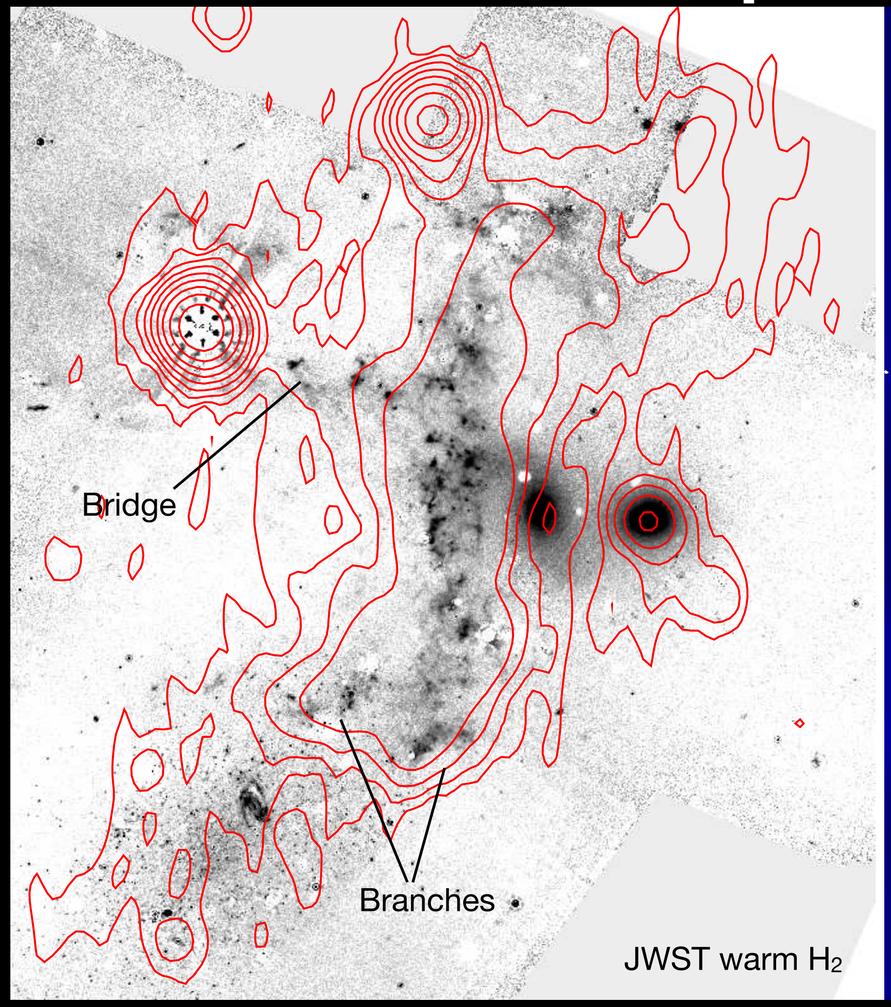
old VLA 1.4 GHz, ~15” HPBW, 100μJy/bm, Williams+ 2002

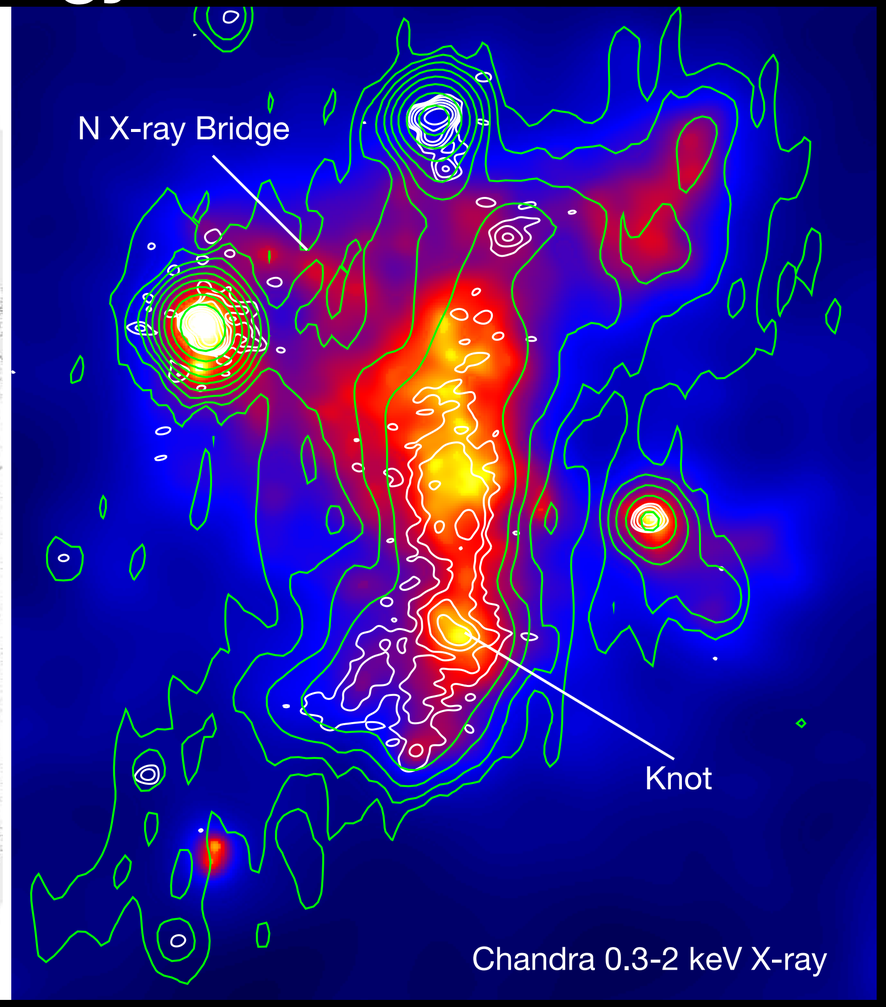
See also structures found by
Nikiel-Wroczynski+ 2013, 2020



MeerKAT L-band, 15” HPBW, 15μJy/bm, on HST+DSS

Radio continuum morphology - correlated structures



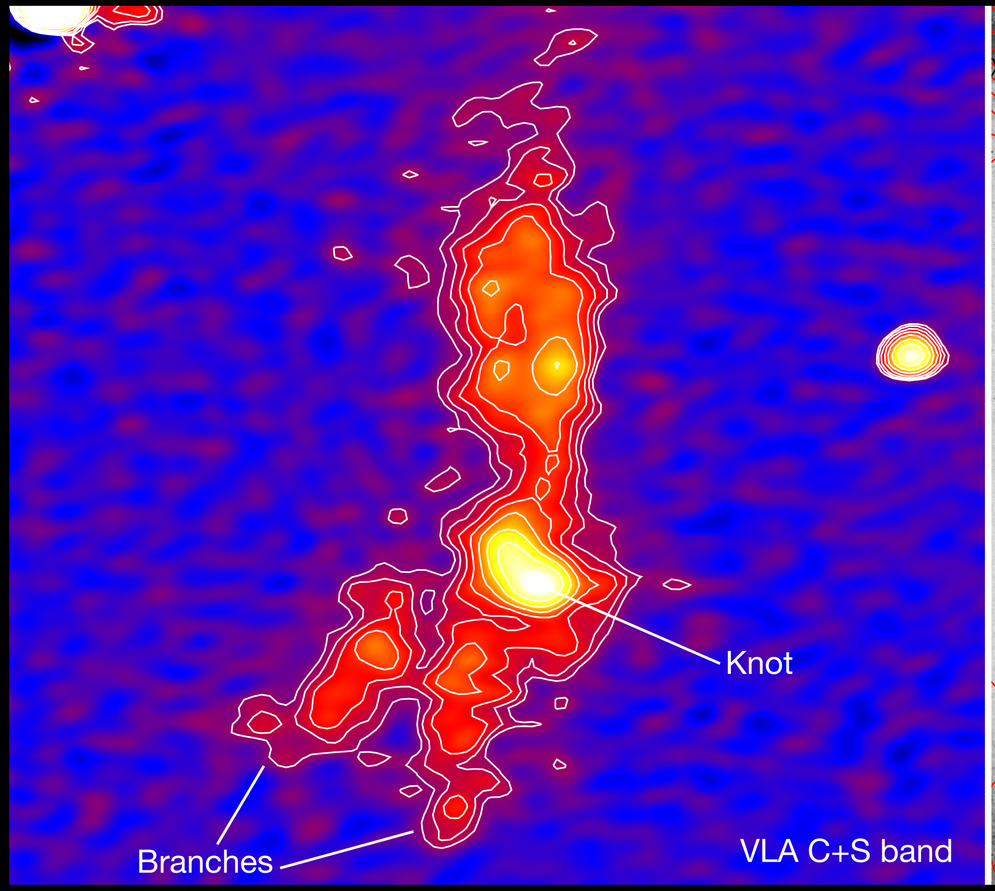


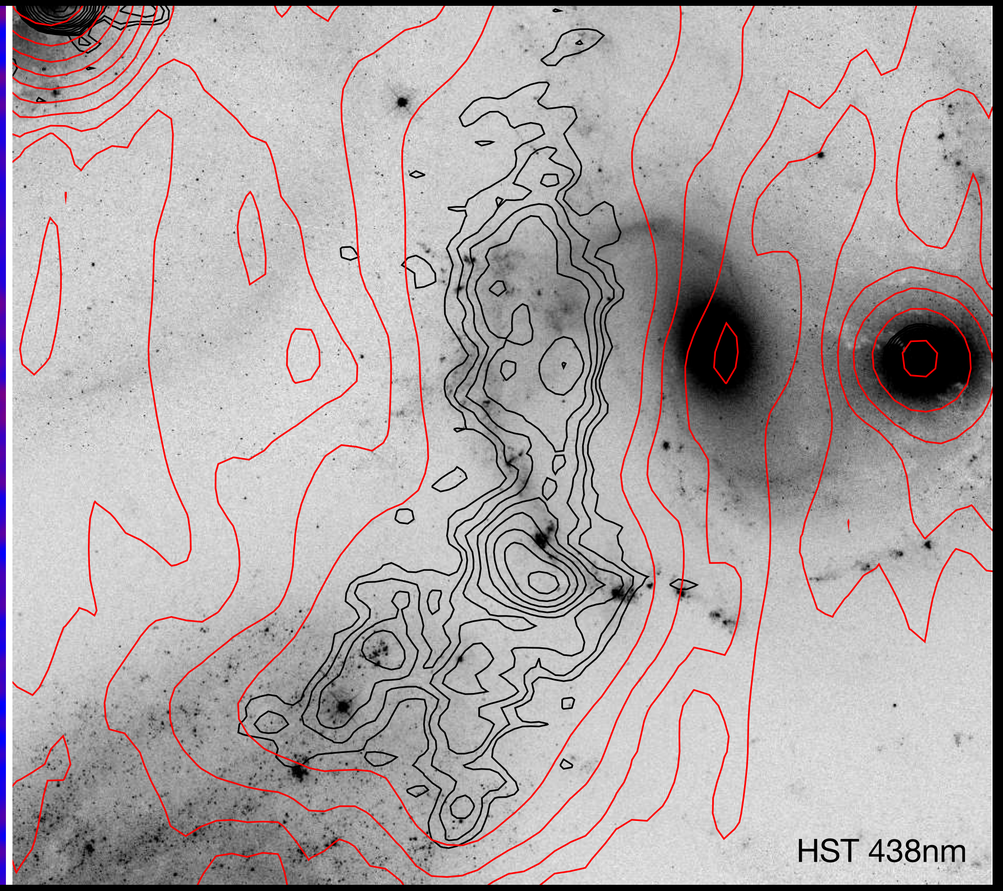
Red / Green contours = MeerKAT L-band
8” HPBW, 12μJy/bm

White contours = VLA C+S-band
3.4”x2.4” HPBW, 8μJy/bm

- On large scale radio ridge correlated with cooler gas (bridge, branches, but not N X-ray bridge)
- X-ray brighter in N ridge, radio in S ridge ➜ Age? Available gas mass? influence of SF?

Radio morphology - correlated structures



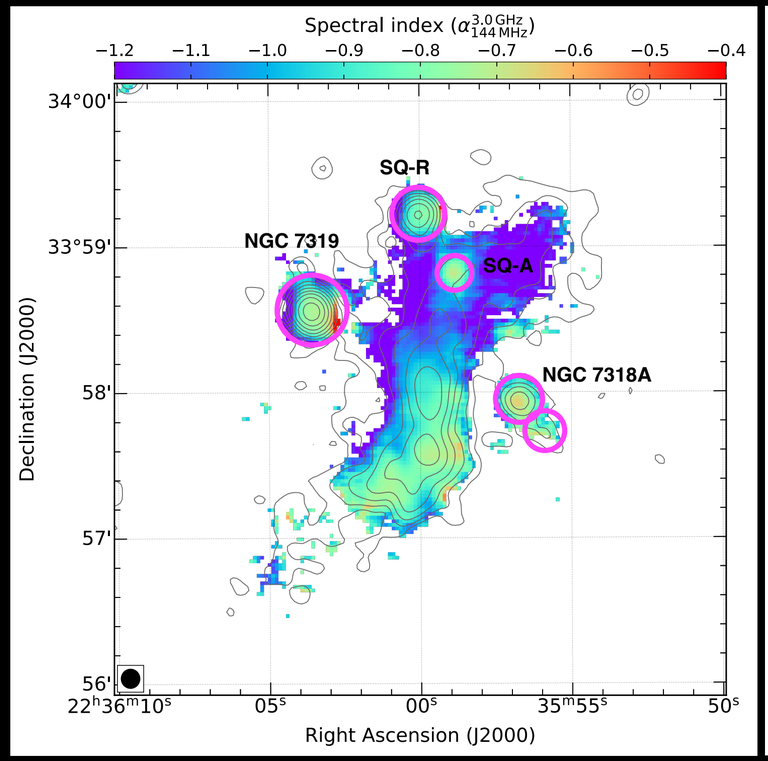


Red contours =
MeerKAT L-band
8” HPBW, 12μJy/bm

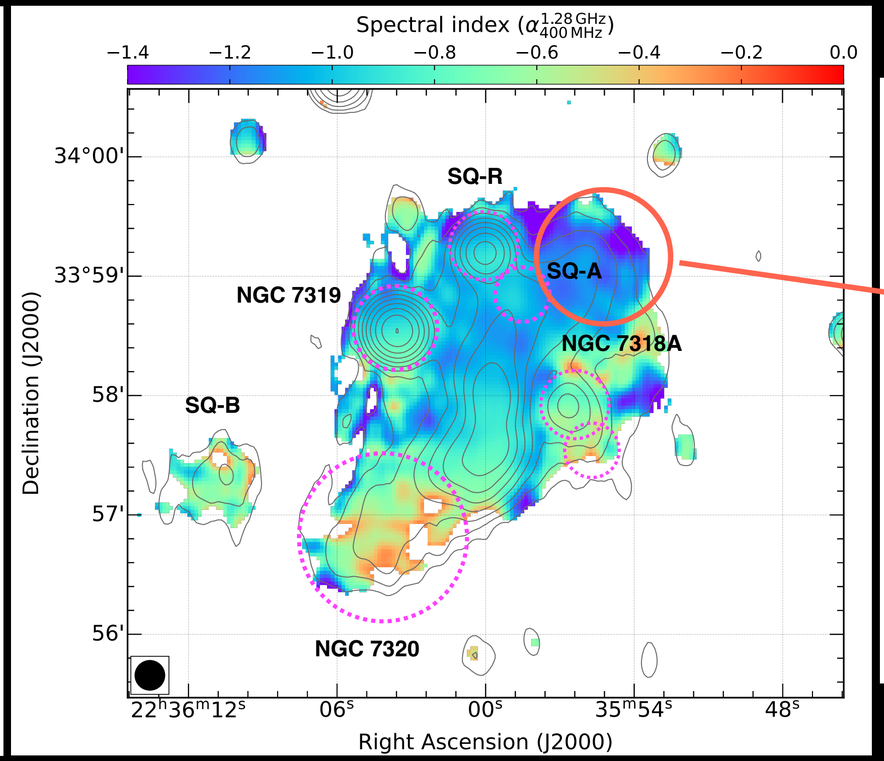
Black / White contours
= VLA C+S-band
3.4”x2.4” HPBW
8μJy/bm

- VLA C+S band traces brightest parts of southern ridge
- Bright knot near (but not on) young star clusters and CO clouds in tidal arm ➜ SF?
- Other radio-bright regions (e.g., branches) not well correlated with SF

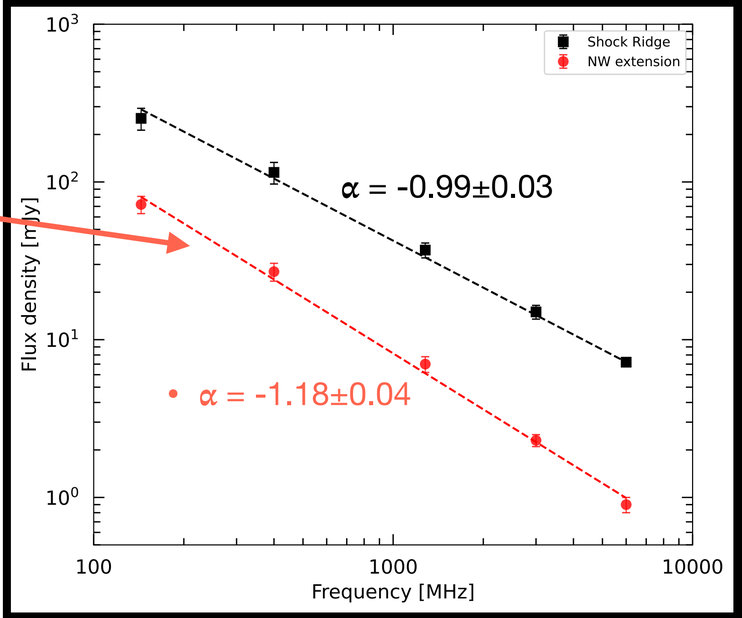
Spectral index



144 MHz - 3 GHz index, 8” HPBW

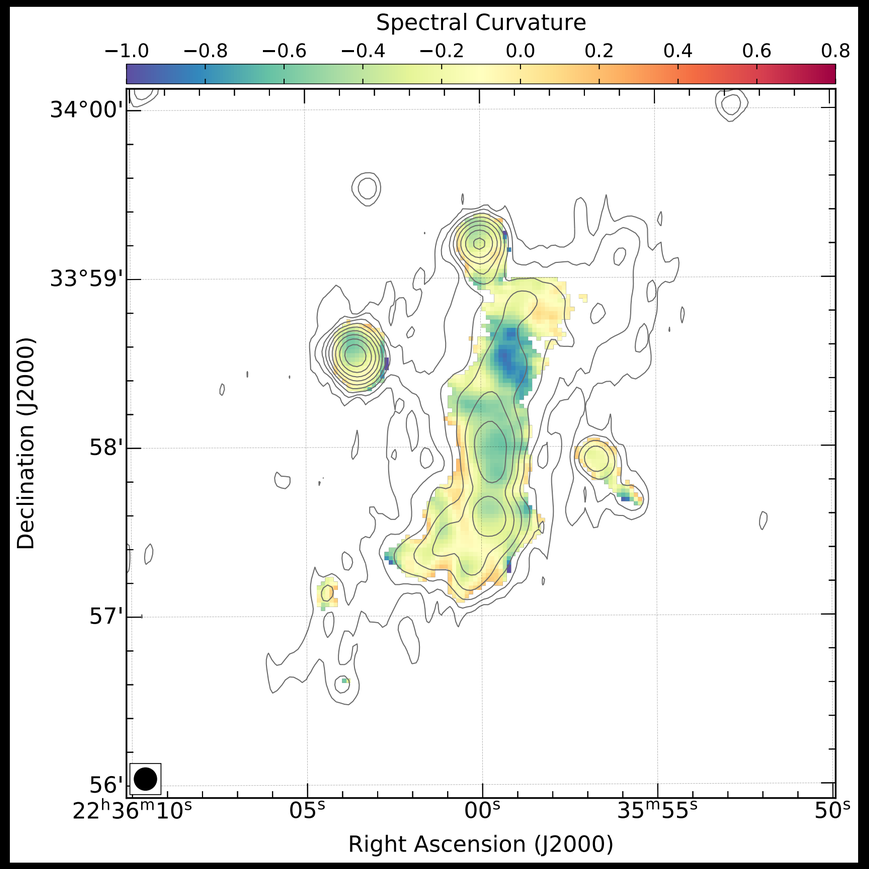


400 MHz - 1.28 GHz index, 15” HPBW

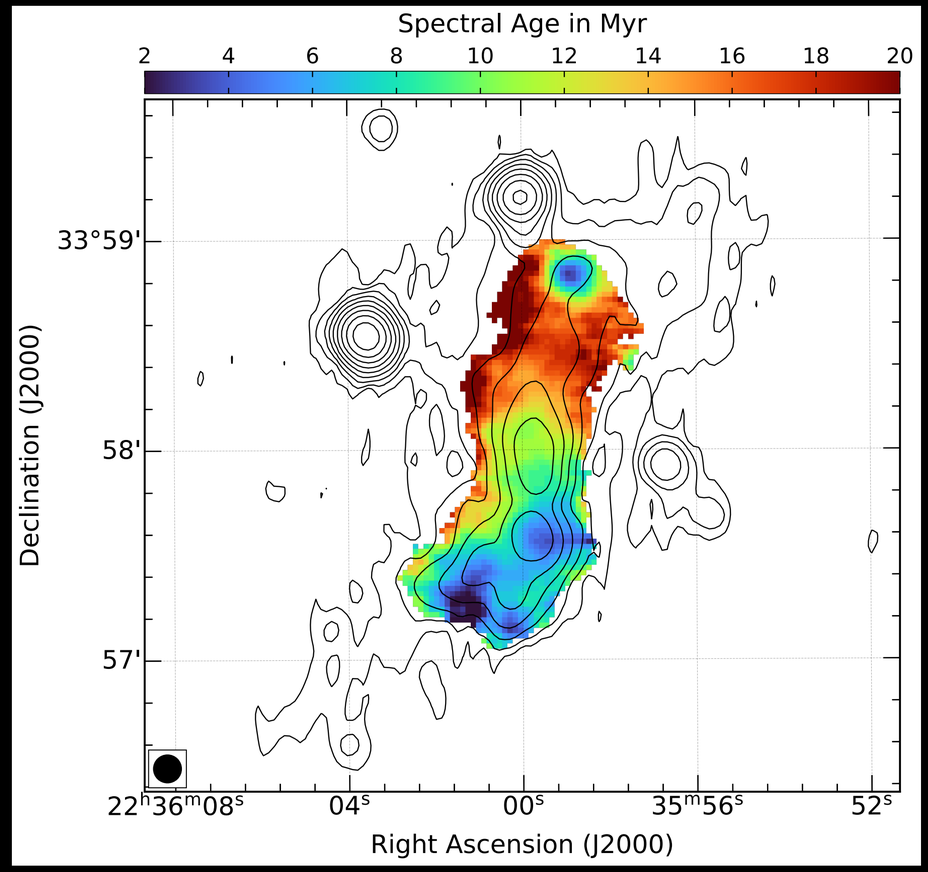


- No E-W spectral index gradient across ridge ➜ interloper vector close to line of sight
  - Bad news: we’re looking through the shock front
  - Good news: 900 km/s V_{rec} offset is a good measure of collision velocity
- Integrated spectral index of steepest emission α = -1.18

Curvature and age



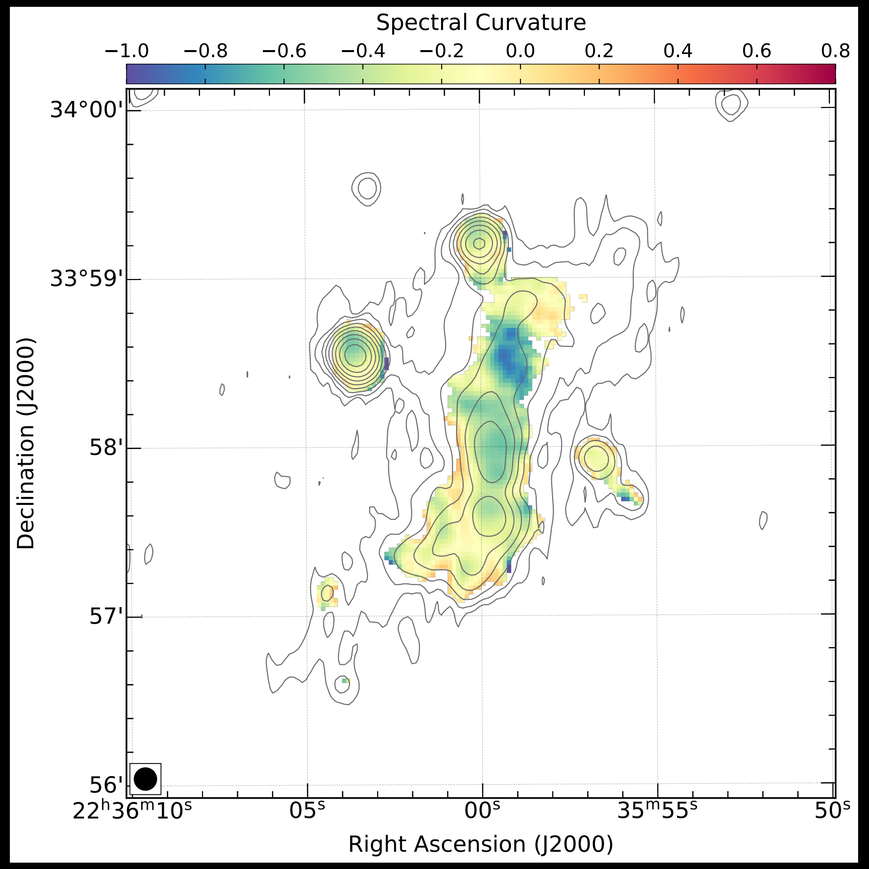
144-400 MHz vs 1.28-6 GHz, 8” HPBW



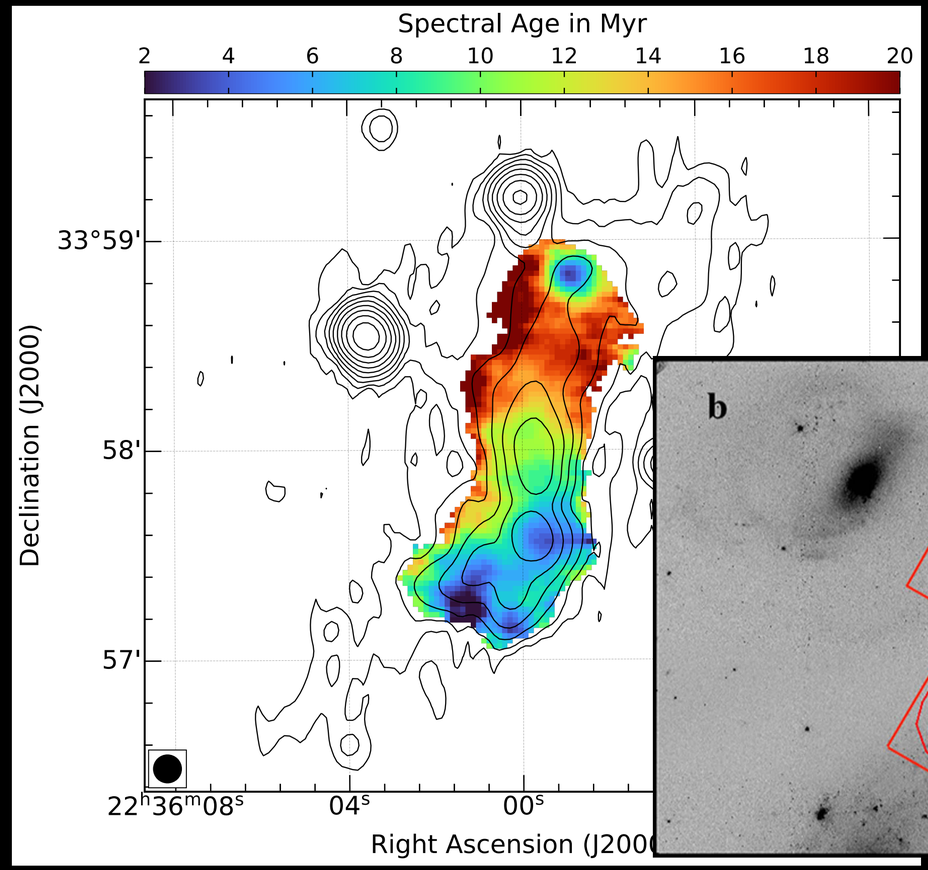
Radiative age (Myr) assuming α_{inj} = -0.7

- Strongest curvature, oldest ages in N ridge, ~15-20 Myr.
- Over 20 Myr, at 900 km/s, intruder travels ≈ 18 kpc toward us, comparable to width of ridge

Curvature and age

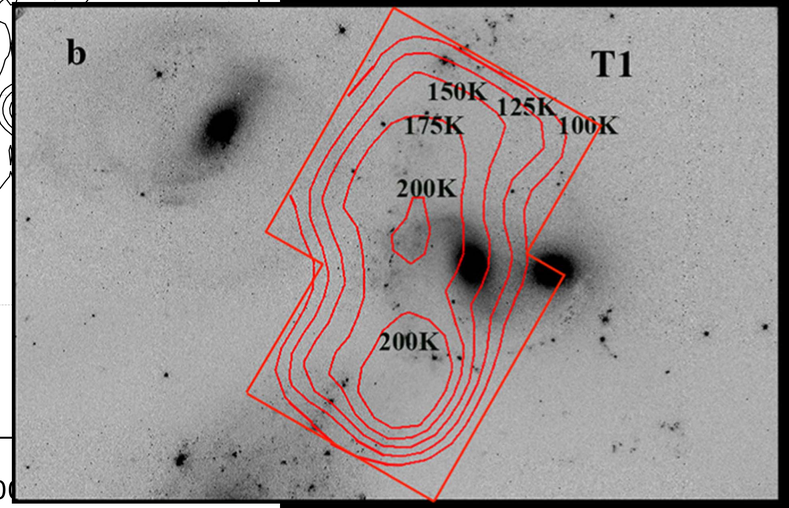


144-400 MHz vs 1.28-6 GHz, 8” HPBW



Radiative age (Myr) assuming α_{inj} = -0.7

Spitzer H2 temperature
Appleton+2017



- Strongest curvature, oldest ages in N ridge, ~15-20 Myr.
- Over 20 Myr, at 900 km/s, intruder travels ≈ 18 kpc toward us, comparable to width of ridge

What have we learned? - Shock mechanism

- Star formation - important in some regions but can only contribute 10-15% of ridge flux
- Adiabatic compression
  - Requires Mach ~3.8 shock, E-W velocity comparable to line-of-sight: inconsistent with data
  - Relativistic seed population unlikely to last 100 Myr in tidally-stripped gas
- Diffusive Shock Acceleration
  - Also implies high shock speed: integrated α = -1.18 ➜ Mach ~3.5
  - Requires star formation to produce $\alpha < 1$ in southern shock ridge
  - Factor 10^6 too luminous to be consistent with M_{500}:L_{radio} relation for radio relics
- Strong shock in HI
  - Mach ~40 will produce $\alpha \approx 0.55$ as seen in southern ridge
  - Highly (up to ~30%) efficient acceleration by strong shock
  - Radio and X-ray have same origin, shocked HI ➜ spatial correlations as expected

What have we learned? - History of the collision

- Radio ridge structures correlated with cooler gas ➜ origin in stripped ISM material

- No E-W spectral index gradient, low polarization fraction, HI structures near SQ-A correlated over 1000 km/s of velocity.

  ➜ intruder has minimal E-W velocity, collision vector close to line of sight

- Age of collision ~15-20 Myr, based on spectral curvature

  ➜ Age gradient implies collision started in north

  ➜ Suggests ~15-20° N-S tilt of tidal filament relative to intruder

  ➜ Intruder still within a few kpc of tidal filament, only passed through south end ~5 Myr ago

- HI in southern ridge destroyed, but starting to reform in northern ridge?
  ➜ Turbulent cascade, line cooling highly effective in reforming cold phases


Thank you!