

**МАТФ**

Универзитет у Београду  
Математички факултет



# Extragalactic search for supernova remnants

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# Supernova remnants

- End of life of massive stars, or explosion of near-Chandrasekar mass white dwarf in a binary system with mass transfer (SN Ia)
- Emission nebulae visible in optical, X-rays, radio, ...
- **Importance:**
  - SN Ia
  - Particle acceleration
  - Elements enrichment of ISM
  - Strong shock studies

# Galactic vs. extragalactic SNRs

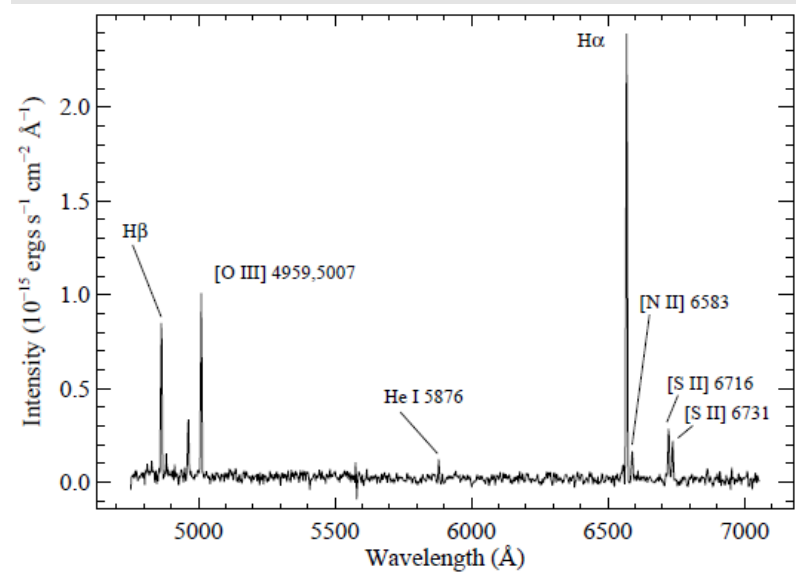
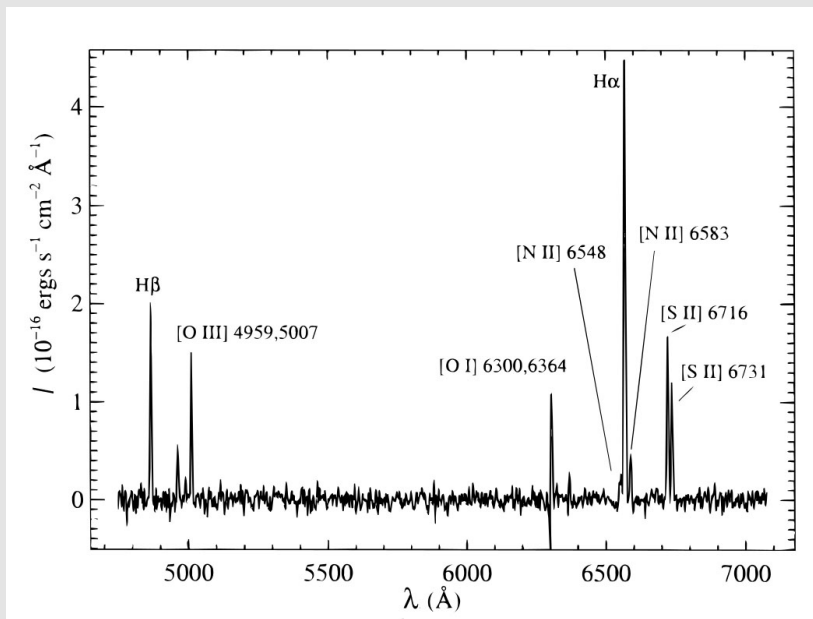
- ~ **300** Galactic SNRs known
- **Distance problem** in the Galaxy
- Galactic absorption present
- Very detailed studies possible
- Nearly **3000** extragalactic SNRs
- Samples at the same distance, but different environment for each sample
- Galactic absorption can be avoided
- Resolution limit

# Optical detection of SNRs

- Mathewson & Clarke (1973) – SNRs in LMC (combination of radio and optical observations)
- [SII]/H $\alpha$  emission line ratio
  - Shock heated SNRs > 0.4; Photoionized nebulae - HII regions < 0.4 (0.2) (D'Odorico et al. 1978; Matonick & Fesen 1997; Blair & Long 1997)
- Data reduction challenges
  - Low fluxes – long exposures – good tracking needed
  - Continuum subtraction from emission-line filters
  - Absolute calibration with non-standard narrow-band filters
- Spectroscopic or some other band confirmation needed

# SNR and HII region spectra comparison

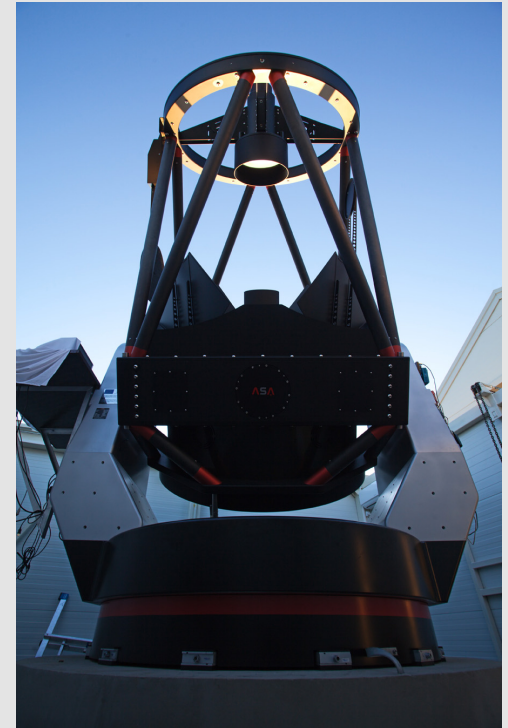
(from Matonick & Fesen 1997)



## Observations from NAO Rozhen, Bulgaria and AS Vidojevica, Serbia

- 2 m RCC telescope, FOV  $5.45' \times 5.35'$ , with FORERO  $15' \times 15'$
- Narrowband photometry through  $H\alpha$ , [SII] and continuum filters ( $\sim 30 \text{ \AA}$ )

- 1.4m ASA telescope
- FOV  $13' \times 13'$
- $H\alpha$  and [SII] filters ( $\sim 50 \text{ \AA}$ )

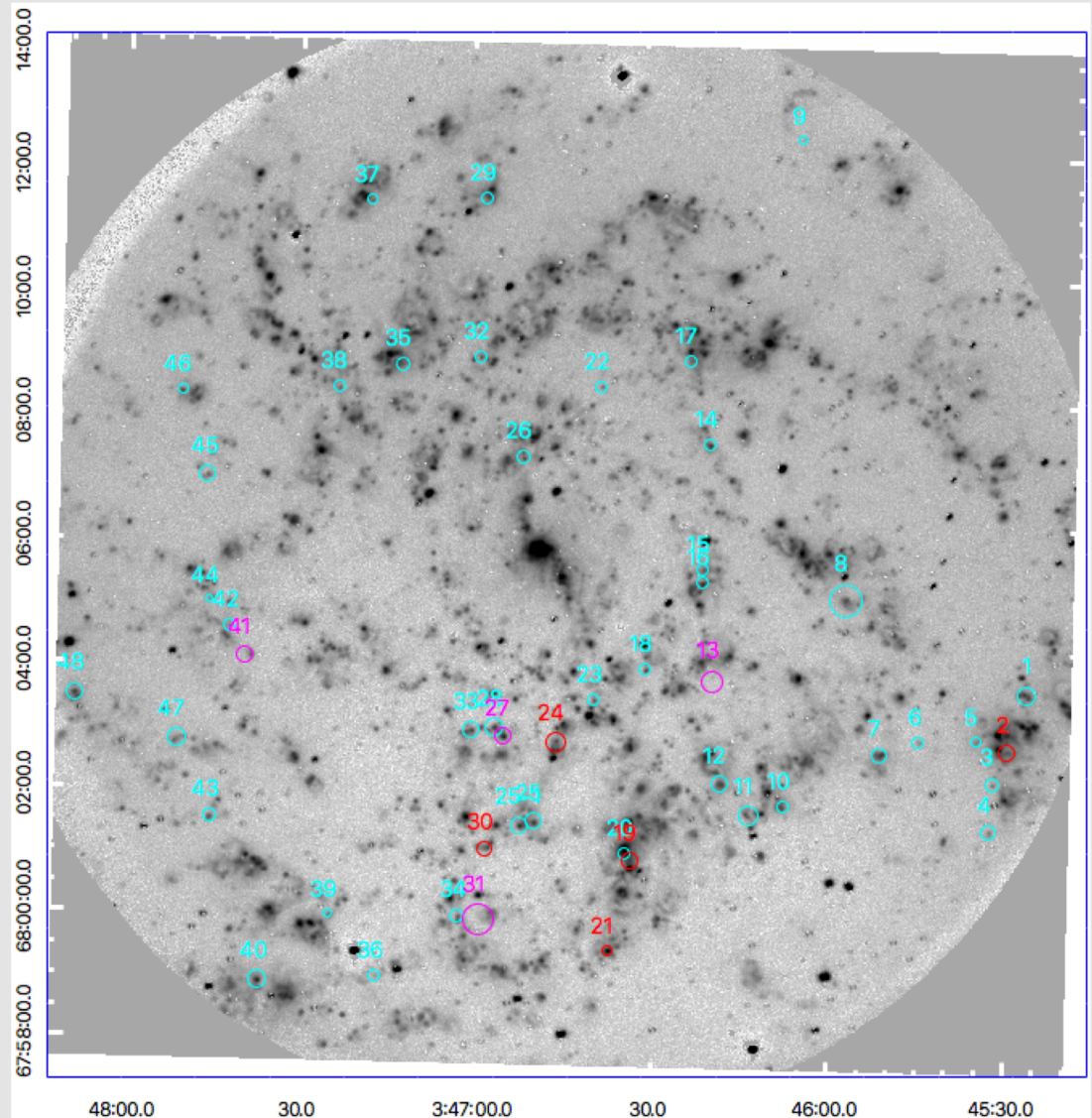


## Observed galaxies

- **Holmberg IX** – ULX source Ho IX X-1 (Arbutina et al. 2009; Andjelić 2011, SerAJ)
- **IC342** – 203 HII regions (Vučetić et al. 2013, SerAJ); 16 new SNR candidates (Vučetić et al. 2015b, SerAJ); 28 new SNR candidates and 12 probable SNRs (Andjelić et al. in prep.)
- **NGC 3077** – 12 new HII regions (Andjelić et al. 2011)
- **NGC 1156** – 59 HII regions (Vučetić et al. 2018)
- **NGC 2366** – 2 SNRs, 3 superbubbles, 64 HII regions (Vučetić et al. 2019a, SerAJ)
- **NGC 185** – 3 SNR candidates (Vučetić et al. 2019b, A&A)

# IC342 galaxy from NAO Rozhen

- **November 2021**
- **Exposure 110 mins**
- **FOV 15 arcmin**
- **28 SNR candidates**
- **12 probable SNR candidates**  
( $0.3 < [\text{SII}]/\text{H}\alpha < 0.4$ )
- **5 not SNRs** from Vučetić et al. (2015)
- **4 are SII sources**



# IC342 – archival radio and X-ray data

- X-rays

- XMM Newton: 60ks exposure, energy band 0.4-5keV
- Chandra: merged dataset has a total exposure of 149 ks

- Radio data:

VLA observations

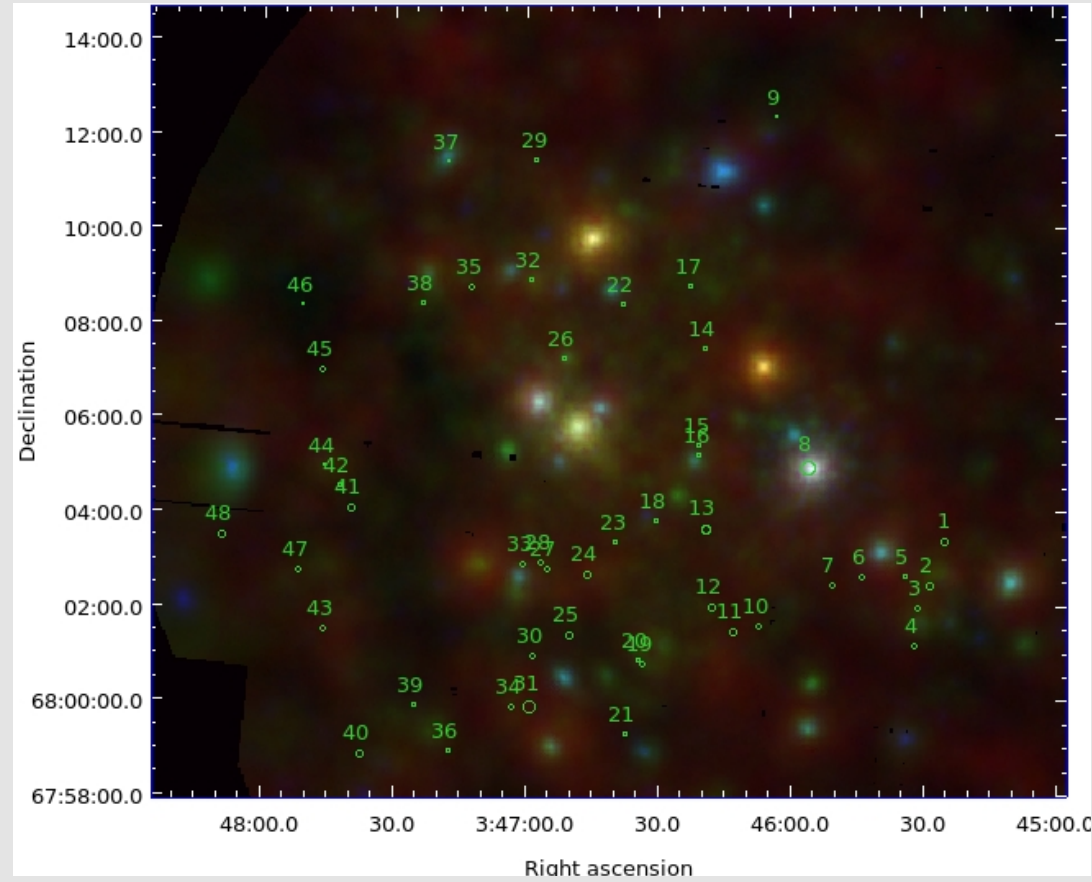
A configuration

20 cm (L band)

**6 radio+optical+X**

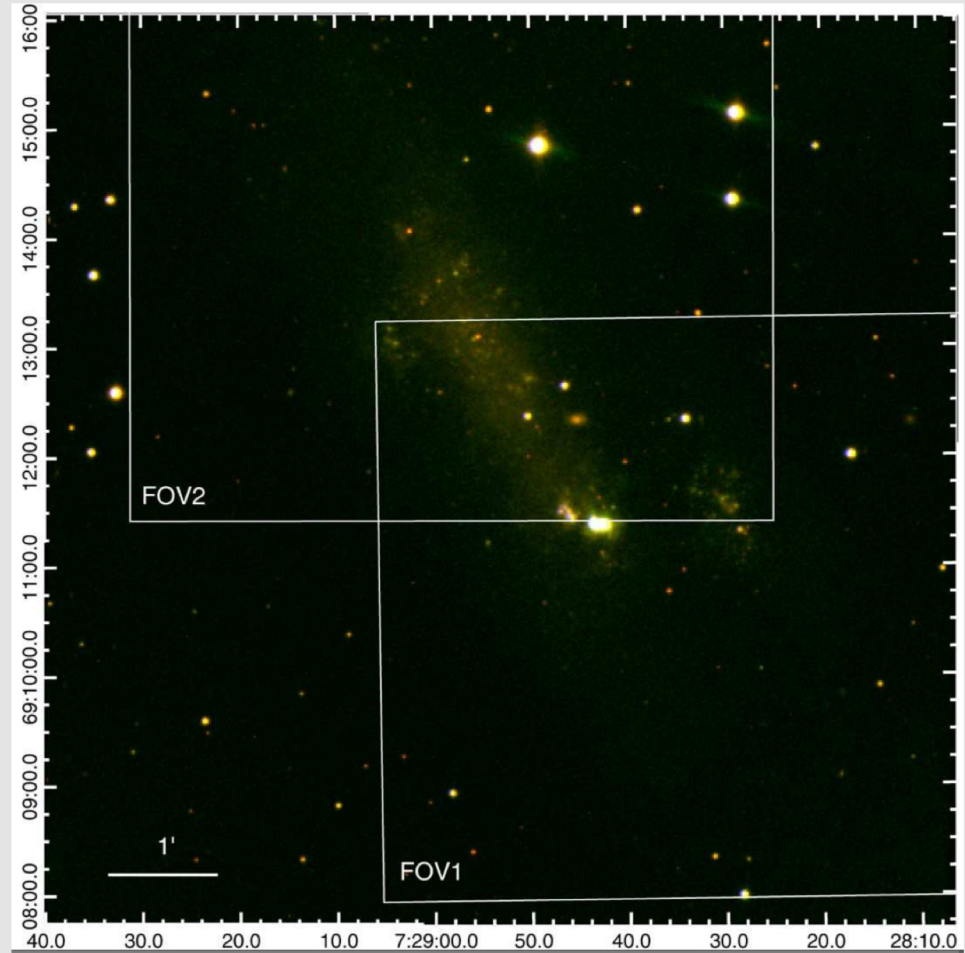
**11 radio+optical**

**4 radio+X**

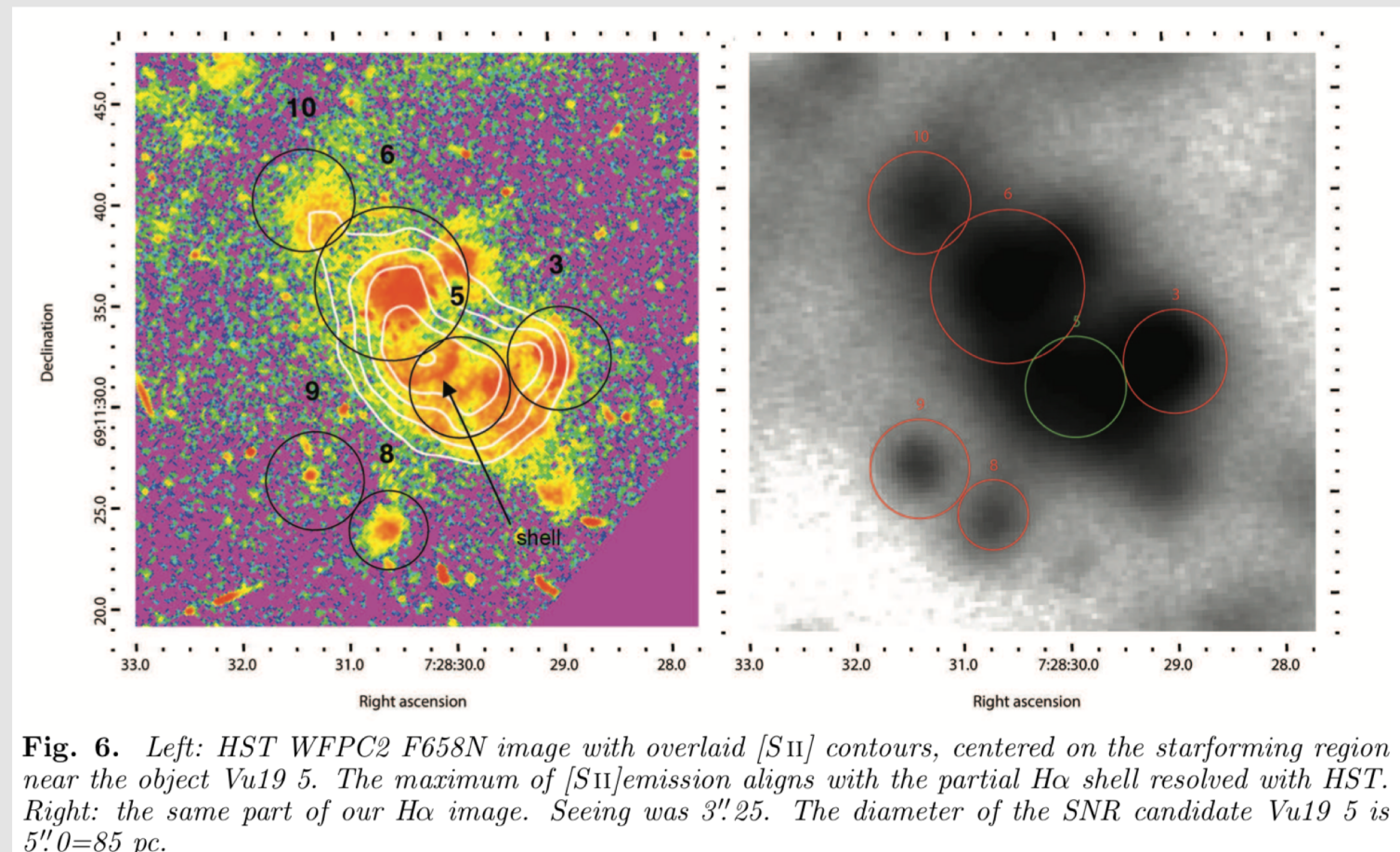


# NGC 2366 dwarf galaxy

- Dwarf galaxy,  $d=3.4$  Mpc
- Previous VLA radio and XMM observations
- Observed from NAO Rozhen in 2015 and 2016
- 2 SNRs, 3 superbubbles, 64 HII regions (Vučetić et al. 2019a, [SerAJ](#))
- 2 SNRs optical detected also in radio and X-rays
- 1 SNR in radio and X-rays



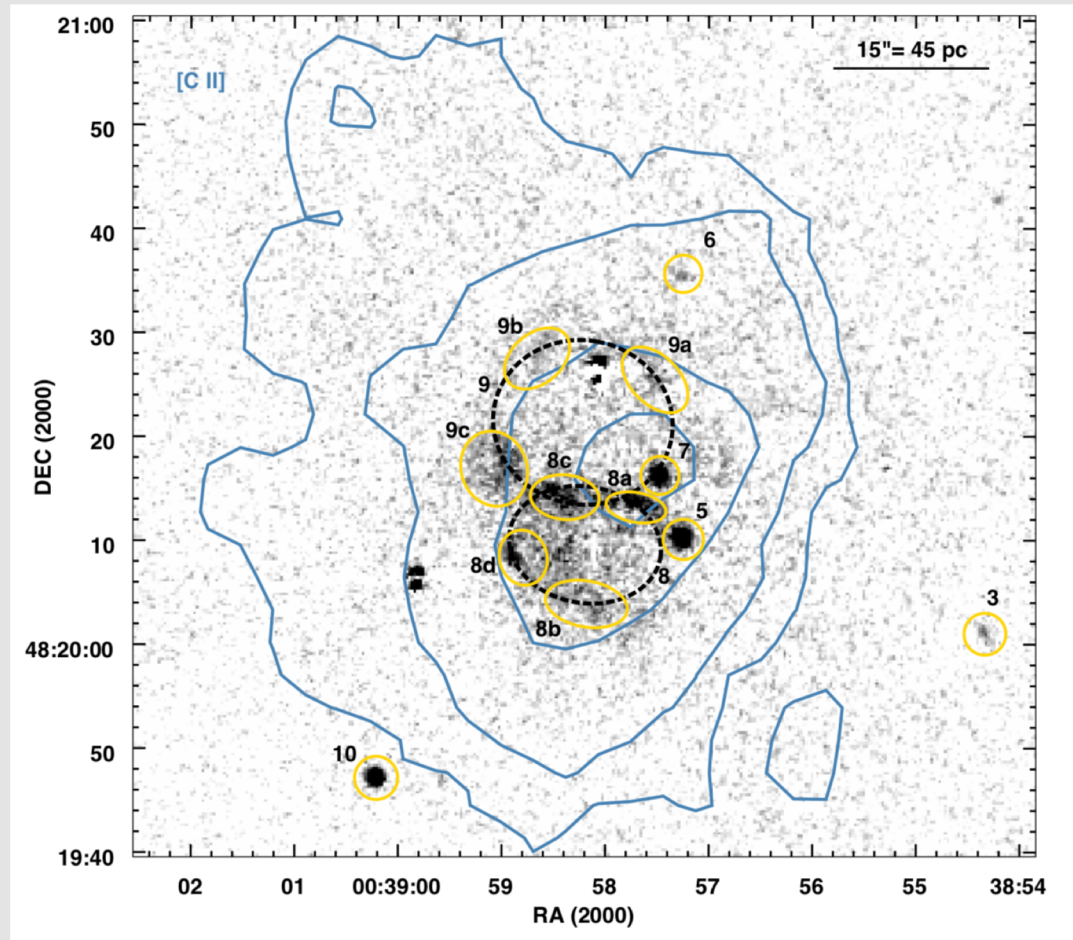
## Comparison of HST and 2m telescope at NAO Rozhen



# NGC 185 galaxy

- Dwarf elliptical,  $d=620$  kpc
- Photometry from NAO Rozhen in 2015
- 80 mins exposure
- 6 PNe, HII region candidates, 1 symbiotic star, 2 SNR candidates
- Low and high resolution spectra of central region from **BTA**

Continuum-subtracted  $H\alpha$  image of the center ( $\sim 1.5' \times 1.5'$ ) of NGC 185 with *Herschel* [CII] contours, indicating the location of dense gas (Vučetić et al. 2019b).



## Galaxies observed for optical SNRs (Vučetić et al. 2015a)

**Table 1.** Data for galaxies which have been observed for optical SNRs.

Galaxy name	R.A. (J2000) (h:m:s)	Decl. (J2000) (d:m:s)	Distance (Mpc)	Distance reference	Major axis (arcmin)	Minor axis (arcmin)	Galactic latitude (°)	Incl. <sup>a</sup> (°)	Galaxy	<i>B</i> (mag)	<i>A<sub>B</sub></i> (mag)
LMC	05:23:34.5	−69:45:22	0.05	1	645	550	−32.9	35	SB(s)m	0.9	0.272
SMC	00:52:44.8	−72:49:43	0.06	2	320	185	−44.3	58	SB(s)m pec	2.7	0.134
NGC 6822	19:44:57.7	−14:48:12	0.50	1	15.5	13.5	−18.4	33	IB(s)m	9.31	0.855
NGC 185	00:38:58.0	48:20:15	0.62	3	11.7	10.0	−14.5	–	E3 pec	10.1	0.667
IC1613	01:04:47.8	02:07:04	0.65	4	16.2	14.5	−60.6	29	IB(s)m	9.88	0.090
IC342	03:46:48.5	68:05:47	3.30	5	21.4	20.9	10.6	25	SAB(rs)cd	9.1	2.024
NGC 253	00:47:33.1	−25:17:18	3.94	6	27.5	6.8	−87.9	85	SAB(s)c	8.04	0.068
M31	00:42:44.3	41:16:09	0.79	4	190	60	−21.6	78	SA(s)b	4.36	0.225
M33	01:33:50.9	30:39:37	0.84	4	70.8	41.7	−31.3	54	SA(s)cd	6.27	0.15
NGC 300	00:54:53.5	−37:41:04	2.0	4	21.9	15.5	−79.4	45	SA(s)d	8.95	0.046
NGC 4214	12:15:39.2	36:19:37	2.92	7	8.5	6.6	78.1	39	IAB(s)m	10.24	0.079
NGC 2403	07:36:51.4	65:36:09	3.22	4	21.9	12.3	29.2	57	SAB(s)cd	8.93	0.145
M82	09:55:52.7	69:40:46	3.53	8	11.2	4.3	40.6	69	I0 edge-on	9.3	0.567
M81	09:55:33.2	69:03:55	3.63	4	26.9	14.1	40.9	62	SA(s)ab	7.89	0.291
NGC 3077	10:03:19.1	68:44:02	3.82	9	5.4	4.5	41.6	38	I0 pec	10.61	0.243
NGC 7793	23:57:49.8	−32:35:28	3.91	6	9.3	6.3	−77.2	48	SA(s)d	9.98	0.053
NGC 4449	12:28:11.1	44:05:37	4.21	9	6.2	4.4	72.4	45	IBm	9.99	0.053
M83	13:37:00.9	−29:51:56	4.47	10	12.9	11.5	31.9	28	SAB(s)c	8.2	0.241
NGC 4395	12:25:48.8	33:32:49	4.61	9	13.2	11.0	81.5	34	SA(s)m?	10.64	0.063
NGC 5204	13:29:36.5	58:25:07	4.65	9	5.0	3.0	58.0	54	SA(s)m	11.73	0.045
NGC 5585	14:19:48.2	56:43:45	5.7	11	5.8	3.7	56.6	51	SAB(s)d	11.2	0.057
NGC 6946	20:34:52.3	60:09:14	5.9	12	11.5	9.8	11.7	32	SAB(rs)cd	9.61	1.241
M101	14:03:12.5	54:20:56	6.7	4	28.8	26.9	59.8	22	SAB(rs)cd	8.31	0.031
M74	01:36:41.7	15:47:01	7.3	13	10.5	9.5	−45.7	20	SA(s)c	9.95	0.254
NGC 2903	09:32:10.1	21:30:03	8.9	14	12.6	6.0	44.5	64	SAB(rs)bc	9.68	0.113

<sup>a</sup>From Tully (1988).

## Number of detected SNRs (Vučić et al. 2015a)

Galaxy name	No. of optical SNRs	Fraction surveyed	$F_{\text{SNRs}}$ ( $\text{erg cm}^{-2} \text{s}^{-1}$ ) $\times 10^{-14}$	$\delta F_{\text{SNRs}}$ (per cent)	$L_{\text{SNRs}}$ ( $\text{erg s}^{-1}$ ) $\times 10^{38}$	$[\text{N II}]/\text{H}\alpha$ ratio	$A_B$ (mag)	$F_{\text{gal}}$ ( $\text{erg cm}^{-2} \text{s}^{-1}$ ) $\times 10^{-12}$	$L_{\text{gal}}$ ( $\text{erg s}^{-1}$ ) $\times 10^{39}$	$R$ (per cent)	$\delta R$ (per cent)	Ref.
(1)	(2)	(3)	(4)	(5)	(6)	(7) <sup>a</sup>	(8) <sup>a</sup>	(9) <sup>a</sup>	(10) <sup>a</sup>	(11)	(12)	(13)
M31	156	1	371.9	–	2.8	0.54	0.18	360.4	26.9	1.0	12	1
M33	137	1	544.6	–	4.6	0.27	0.18	383.0	32.4	1.4	12	2
NGC 300	22	1	23.1	22	1.1	0.2	0.06	31.6	15.1	0.7	34	3
NGC 4214	92	1	178.0	2	18.2	0.16	0.05	15.2	15.5	11.7	14	4
NGC 2403	150	0.88	620.7	1	77.0	0.29	0.17	48.6	60.3	12.8	13	4,5
M82	10	0.07	2.7	5	0.4	0.3	0.4	78.8	117.5	0.1	17	6
M81	41	1	18.8	–	3.0	0.51	0.24	37.3	58.9	0.5	12	7
NGC 3077	24	1	28.3	6	5.0	0.38	0.25	5.5	9.5	5.2	18	4
NGC 7793	27	1	28.8	–	5.3	0.25	0.08	20.8	38.0	1.4	12	8
NGC 4449	71	1	121.6	2	25.8	0.23	0.04	24.2	51.3	5.0	14	4
M83	296	1	653.0	–	156.0	0.53	0.21	74.4	177.8	8.8	12	9,10,11
NGC 4395	47	0.73	27.2	3	6.9	0.19	0.04	4.5	11.5	6.0	15	4
NGC 5204	36	1	23.6	4	6.1	0.13	0.03	3.1	8.1	7.5	16	4
NGC 5585	5	1	6.9	–	2.7	0.18	0.03	2.1	8.1	3.3	12	7
NGC 6946	26	0.95	12.1	–	5.0	0.54	1.54	69.2	288.4	0.2	12	7
M101	73	0.98	35.0	–	19.2	0.54	0.02	39.8	213.8	0.8	12	7,12
M74	9	0.83	9.4	–	6.0	0.4	0.21	11.6	74.1	0.8	12	13
NGC 2903	5	1	4.9	–	4.6	0.56	0.1	12.4	117.5	0.4	12	14

<sup>a</sup>From Kennicutt et al. (2008).

REFERENCES: (1) Lee & Lee (2014); (2) Long et al. (2010); (3) Millar et al. (2011); (4) Leonidaki et al. (2013); (5) Matonick et al. (1997); (6) de Grijs et al. (2000); (7) Matonick & Fesen (1997); (8) Blair & Long (1997); (9) Dopita et al. (2010); (10) Blair et al. (2013); (11) Blair et al. (2014); (12) Franchetti et al. (2012); (13) Sonbas et al. (2010); (14) Sonbas et al. (2009).

# More recent techniques

**Velocity structure** – spectroscopy with  $\sim 50 \text{ km s}^{-1}$  resolution is an effective way to separate SNRs from H II regions. Typical Gaussian velocity FWHM of the SNRs are  $\sim 130 \text{ km s}^{-1}$ , whereas the H II region lines are  $\sim 50 \text{ km s}^{-1}$  (Points et al., 2019, ApJ, 887, 66)

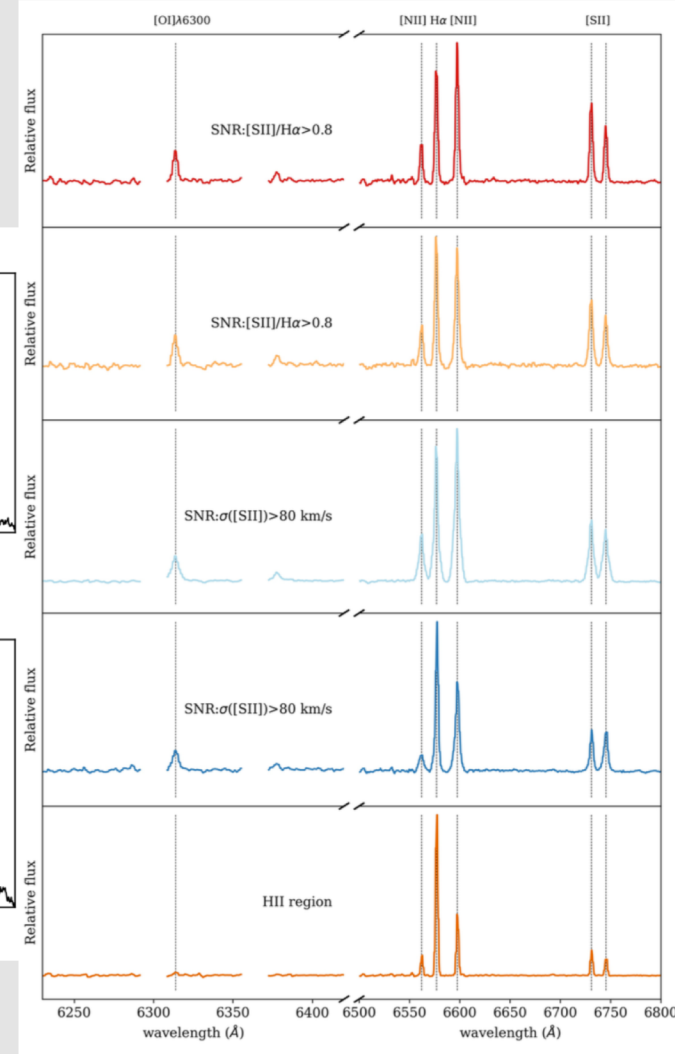
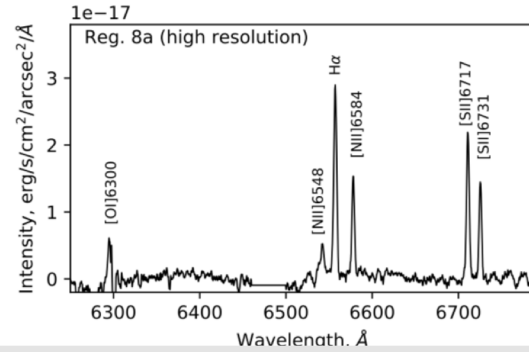
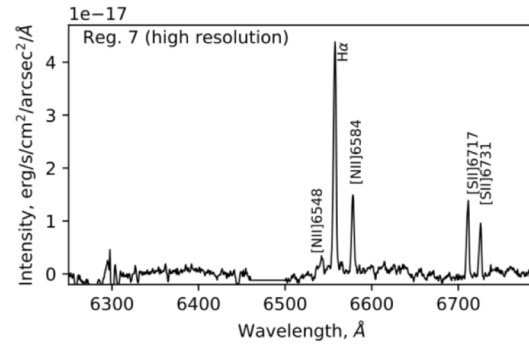
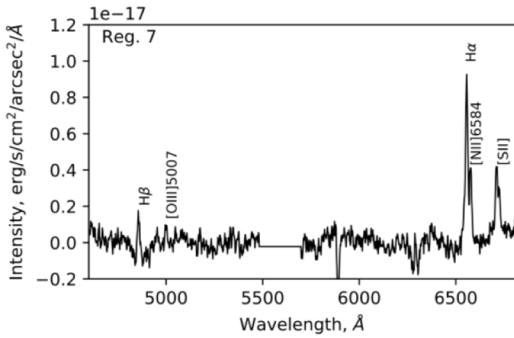
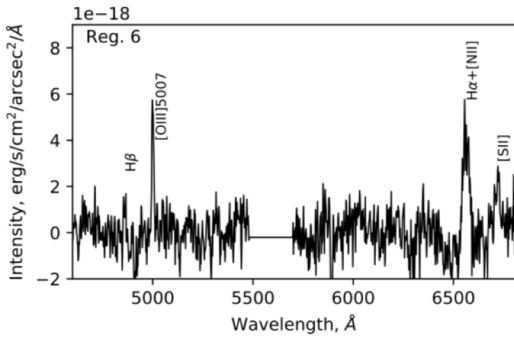
- Fabry-perot imaging (Lozynska, Moiseev & Podorvanyuk, 2003, Astron. Letters )
- **MUSE IFU** data (19 PHANGS galaxies - Jing Li et al., 2024, A&A, 690, 161; NGC7793 - Kopsacheili et al., 2024, MNRAS, 530, 1078)
- **SITELLE** imaging Fourier transform spectrometer at the Canada-France-Hawaii Telescope (NGC6822 and M33 - Duarte Puertas S. et al., 2024, MNRAS, 533, 2677; NGC4214 Vicens-Mouret S. et al., MNRAS, 2023, 524, 3623)

# PHANGS-MUSE sample (Jing Li et al., 2024)

Name	Parent number	SNRs number	Distance (Mpc)	Plate scale pc''	$\log(M_\star)$ ( $M_\odot$ )	$\log(\text{SFR})$ ( $M_\odot \text{yr}^{-1}$ )	PA (deg)	$i$ (deg)	Survey Area ( $\text{kpc}^2$ )
IC 5332	36	24	9.0	43.7	9.68	-0.39	74.4	26.9	34
NGC 628	120	79	9.8	47.7	10.34	0.24	20.7	8.9	89
NGC 1087	123	29	15.9	76.8	9.94	0.11	359.1	42.9	126
NGC 1300	23	15	19.0	92.1	10.62	0.07	278.0	31.8	356
NGC 1365	63	38	19.6	94.9	11.00	1.24	201.1	55.4	409
NGC 1385	114	63	17.2	83.5	9.98	0.32	181.3	44.0	101
NGC 1433	46	24	18.6	90.3	10.87	0.05	199.7	28.6	426
NGC 1512	25	20	18.8	91.3	10.72	0.11	261.9	42.5	266
NGC 1566	180	101	17.7	85.8	10.79	0.66	214.7	29.5	208
NGC 1672	61	28	19.4	94.1	10.73	0.88	134.3	42.6	250
NGC 2835	187	119	12.2	59.2	10.00	0.10	1.0	41.3	87
NGC 3351	46	24	10.0	48.3	10.37	0.12	193.2	45.1	73
NGC 3627	152	86	11.3	54.9	10.84	0.59	173.1	57.3	85
NGC 4254	332	154	13.1	63.5	10.42	0.49	68.1	34.4	169
NGC 4303	303	130	17.0	82.4	10.51	0.73	312.4	23.5	214
NGC 4321	132	80	15.2	73.7	10.75	0.55	156.2	38.5	191
NGC 4535	75	54	15.8	76.5	10.54	0.34	179.7	44.7	124
NGC 5068	194	92	5.2	25.2	9.41	-0.56	342.4	35.7	23
NGC 7496	21	6	18.7	90.8	10.00	0.35	193.7	35.9	92

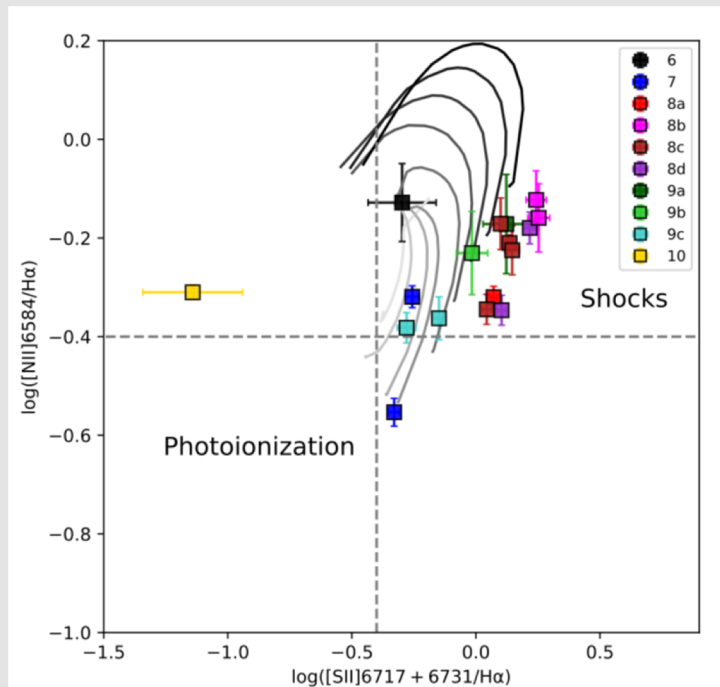
Low ( $\delta\lambda=14 \text{ \AA}$ ) and high ( $\delta\lambda=3.6 \text{ \AA}$ ) resolution spectra

NGC185 galaxy, **BTA, SCORPIO** (Vučetić et al. 2019)

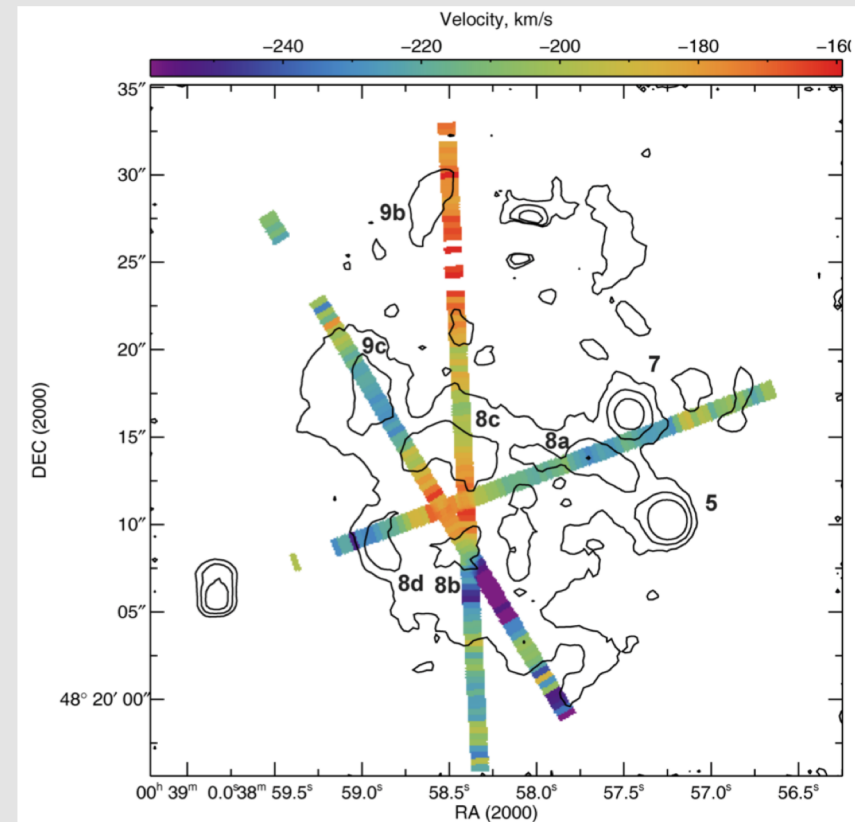


## Possibilities with high-res spectroscopy

- estimation of electron density
- estimation of shell expansion
- age of an SNR
- construction of BPT diagrams



Two-dimensional **velocity map in H $\alpha$**  line of the central 40''  $\times$  40'', constructed from three slit positions for high-resolution spectra (SCORPIO, NGC185)



**Fig. 10.** Two-dimensional velocity map in the H $\alpha$  line of the central 40''  $\times$  40'' of NGC 185, constructed from three slit positions for

# Serbian Astronomical journal

- International journal
- Free access, no pay charges
- Two issues per year
  
- Impact factor **0.80 (2023)**
- JCR SCIE position 67/84 in A&A list
  
- <https://saj.matf.bg.ac.rs/>



## Summary

- Optical photometry observations need spectral or other band observations for confirmation of SNRs
- We should obtain better samples in already observed galaxies, rather than survey new galaxies
- Improvement of statistical analysis of SNRs sample

**THANK YOU FOR YOUR ATTENTION!**



