جامعة نيويورك أبوظبي
NYU | ABU DHABI

Multi-wavelength view of large-scale galactic outflows

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Growing Black Holes: Accretion & Mergers
Kathmandu, May 19, 2022

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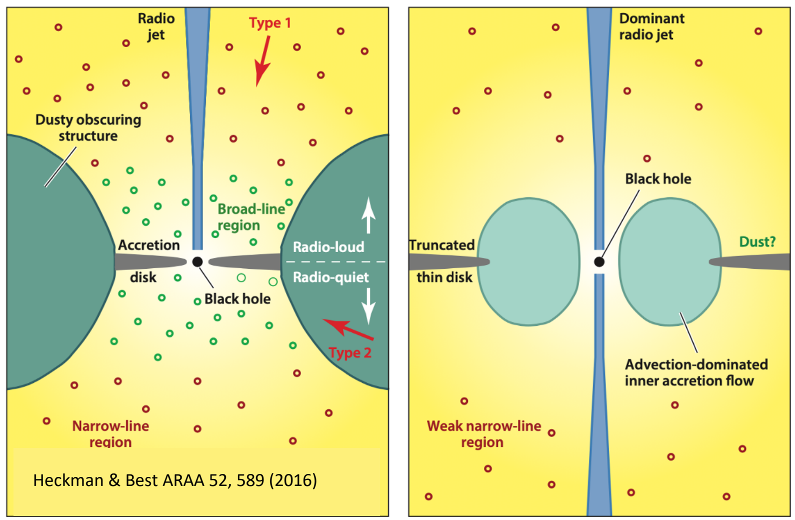
Intro

- Material accreting onto black holes release a lot of energy
- This energy (whether radiation or relativistic jets) has a significant impact on their surroundings. In the case of a SMBH, the surroundings are the entire galaxy.
- The resultant outflow driven by this energy plays an important role in galaxy evolution


Image credit: ESA/ATG medialab

Radiative-mode AGN Mechanical jet-mode AGN



Heckman & Best ARAA 52, 589 (2016)

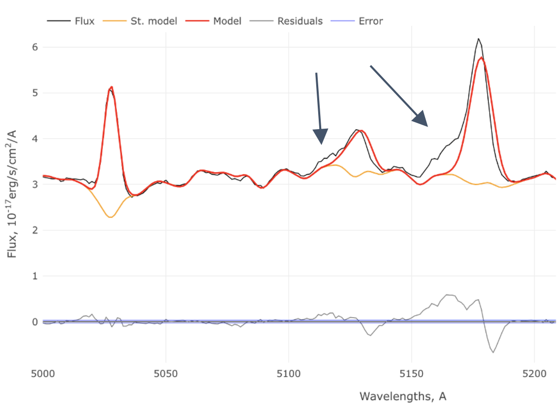
Credits: NASA and the Hubble Heritage Team

- What are the properties of these outflows?
- How are these properties related to injection of energy by the central SMBH?
- Diversity in observed "AGN feedback" among galaxies.

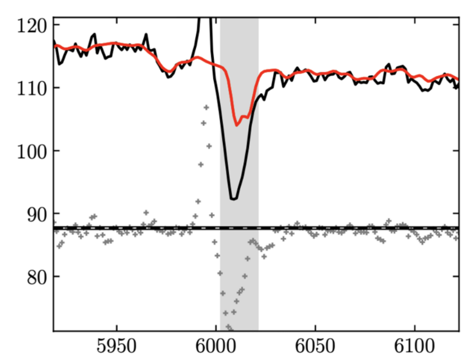
Intro: multi-phase and multi-wavelength outflow nature

Phase	Ionized warm gas	Neutral atomic gas	Molecular gas
Temperature, K	~10,000	100 - 1,000	10-100
Density, cm^{-3}	100 - 10,000	1-100	>1,000
How to measure?	- Optical emission lines	- Na I D 5900A feature in optical spectrum - HI 21cm, [CII]	- Sub-mm CO lines - Infrared H_2 lines

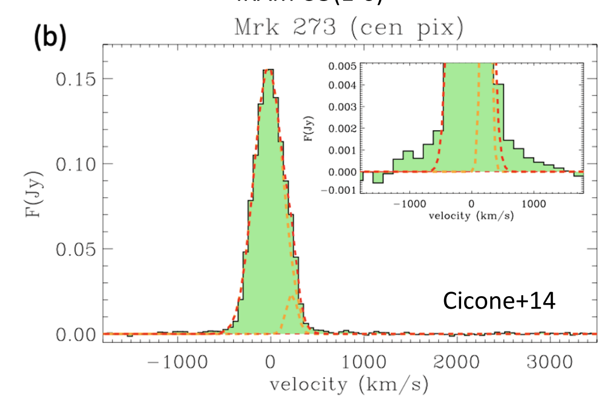
[OIII] lines



Na I D



IRAM CO(1-0)



$V_{OUTFLOW}$~100-1000 km/s

Intro: multi-phase and multi-wavelength outflow nature

V_{OF}~100-1000 km/s

Fast moving material → **Shocks**

V_{OF} >> Speed of sound

Shocks → Emission lines

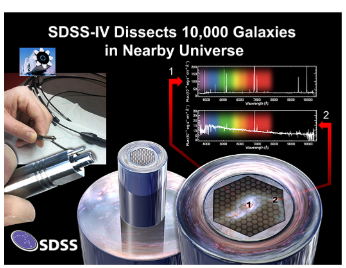
Shocks → Continuum synchrotron emission

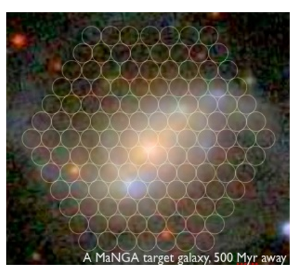
SDSS MaNGA IFU survey

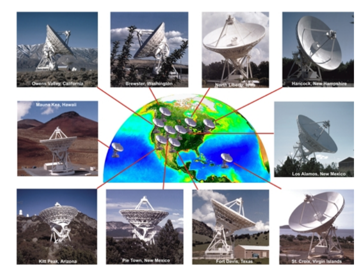
- ~10k targets
- Ionized gas state
- Host galaxy properties

Dedicated radio observations

- ***JVLA*** Jansky Very Large Array
- ***VLBA*** Very Long Baseline Array







Study a sample of AGN powered outflows

Pre-selection criteria

- MaNGA DR17, ~10k objects
- Detection in previous radio surveys (FIRST/VLASS)
- Detectable emission lines
    - Gauss. peak / err. > 5 for Hbeta and [OIII]
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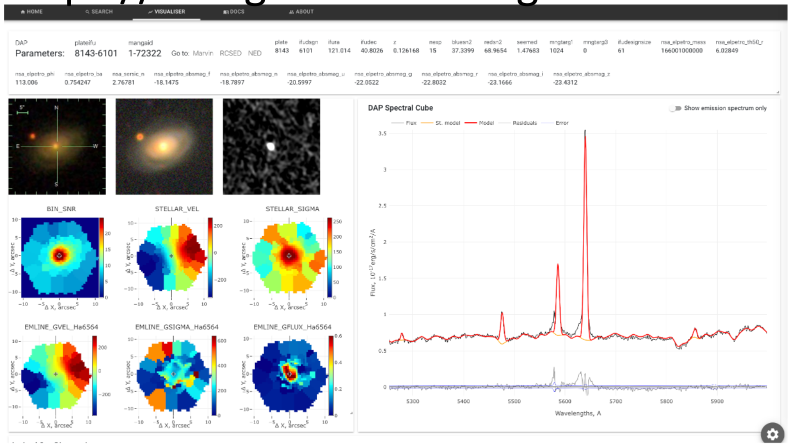
Inspection

- Visual inspection of 254 pre-selected objects and detection clear outflow cases
- Web-based interactive MaNGA Visualiser
- Avoid projected merger systems
- Parent list of 40 targets for VLBA observations

https://manga.voxastro.org



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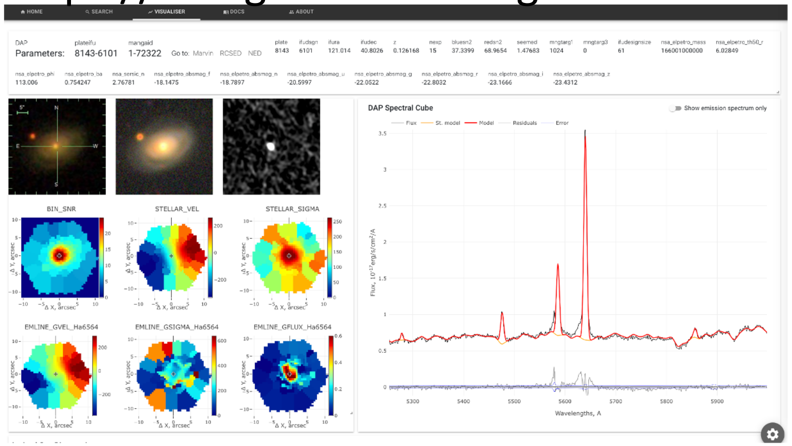
Radio follow-up observations

- JVLA – kpc properties of outflow. Angular resolution comparable to MaNGA – directly compare optical / radio morphologies.
- VLBA – radio emission from innermost pc around SMBH. Detection vs. Non-detection => different AGN modes

- Have multiple bands in each to get spectral information.

https://manga.voxastro.org



VLBA

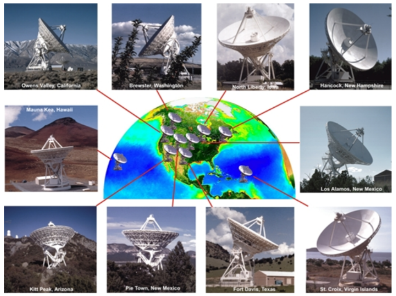
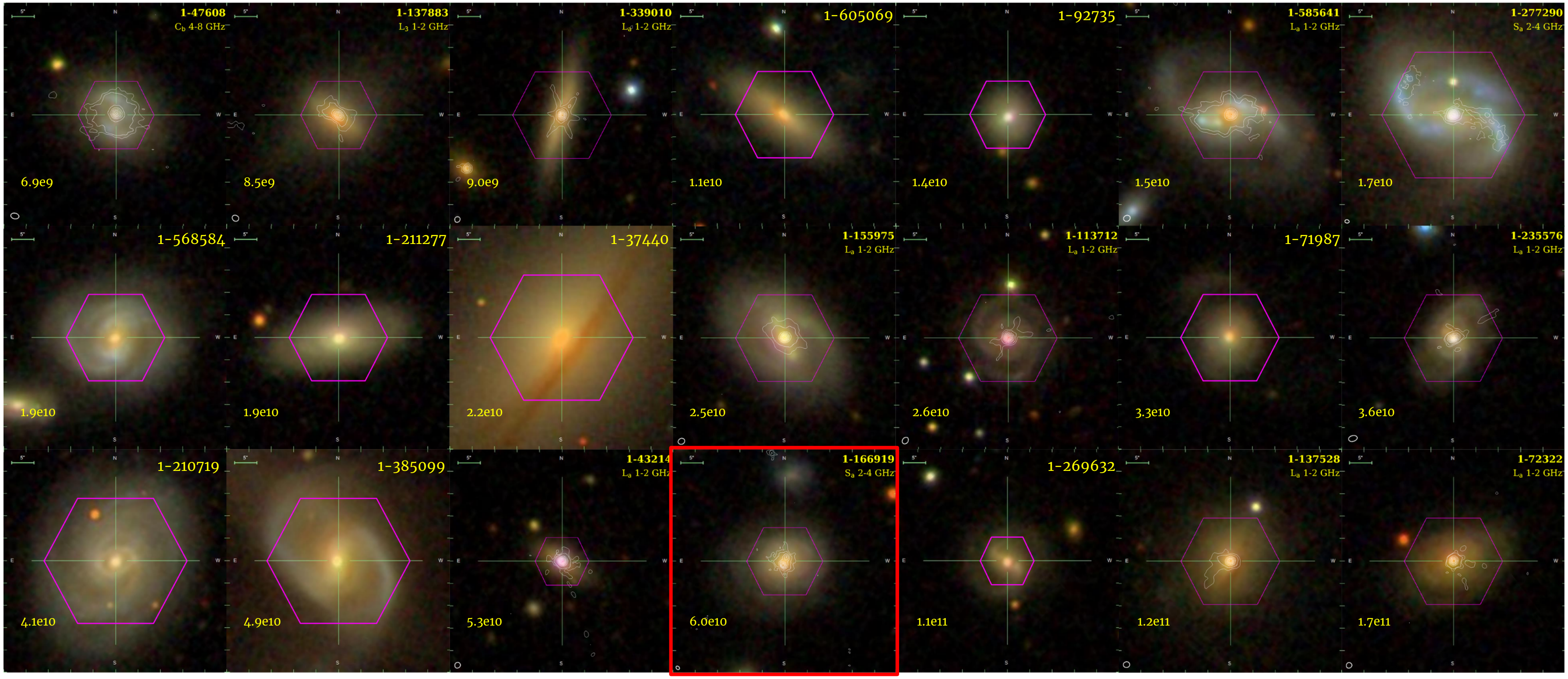


Image credit: NRAO/AUI

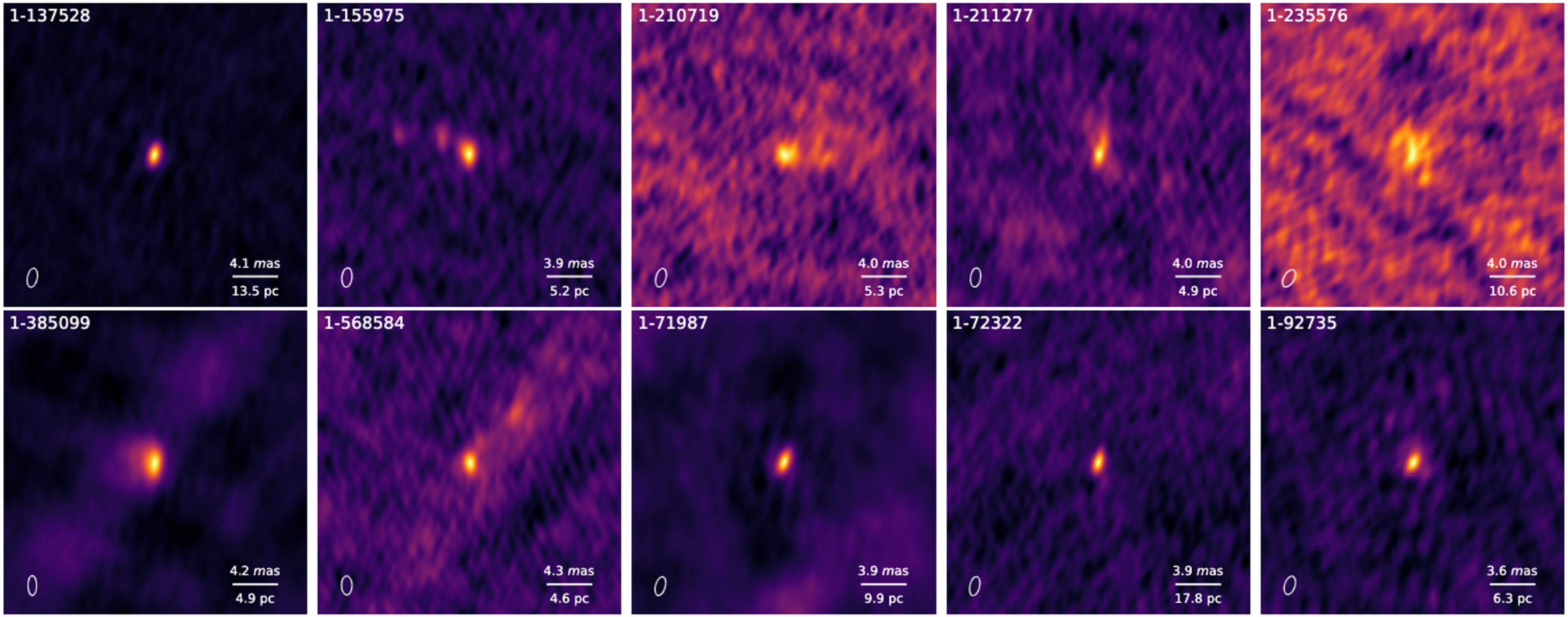
Study a sample of AGN powered outflows



M_{STAR} ~ 7e7 - 2e11 M_{SUN}

- 21 targets followed up with VLBA
  - 10 detections in C-band (4-8 GHz)
  - L-band (1-2 GHz) is still under processing…
- JVLA: 12 out 21

Study a sample of AGN powered outflows



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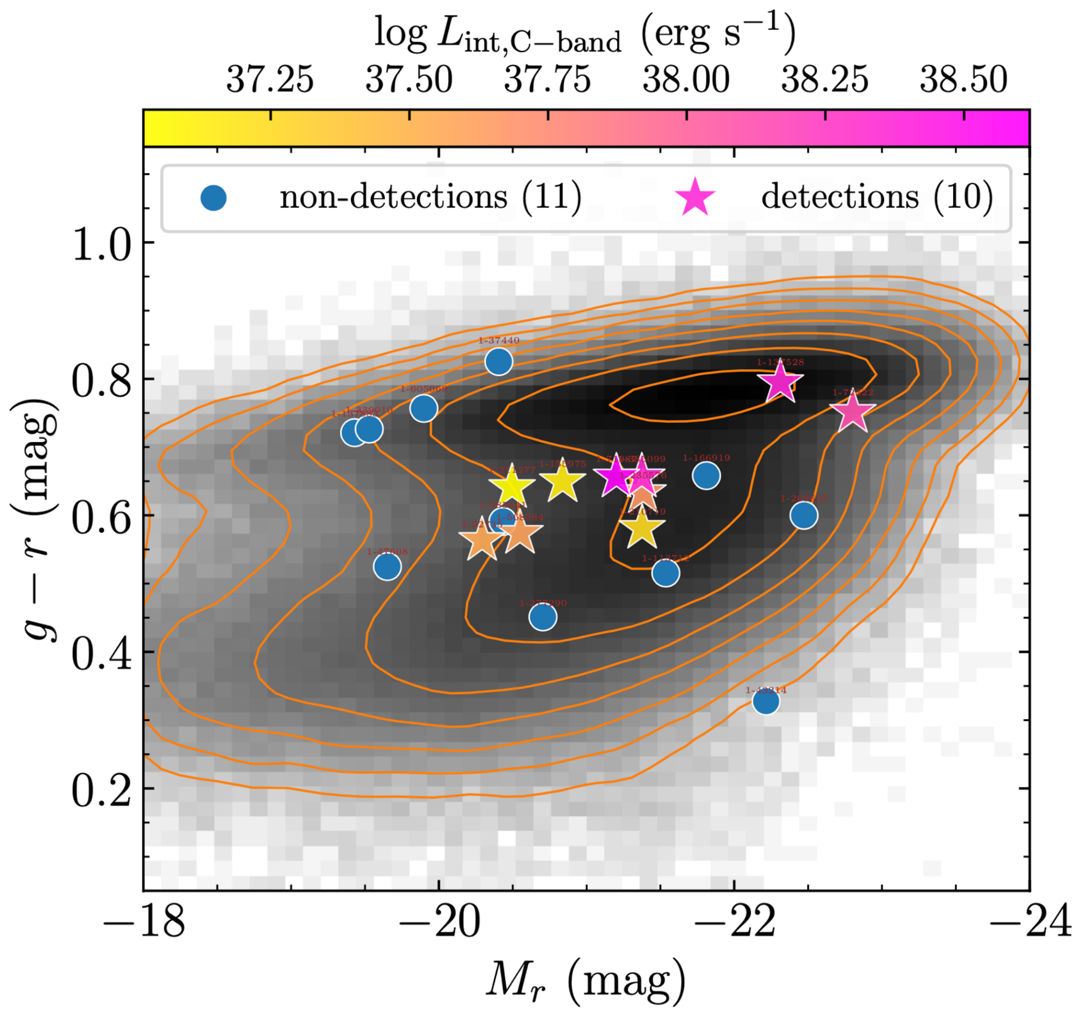
Study a sample of AGN powered outflows

- Bulk of detections in Green Valley
- Green Valley – home of HERAGN *Smolic 2016*



- *What is the origin of the VLBA detection in these – are their radio properties different / similar than red sequence detections?*
- *Are there optical outflows difference between these VLBA detections and non-detections in same part of CMD.*

Study a sample of AGN powered outflows

- Bulk of detections in Green Valley
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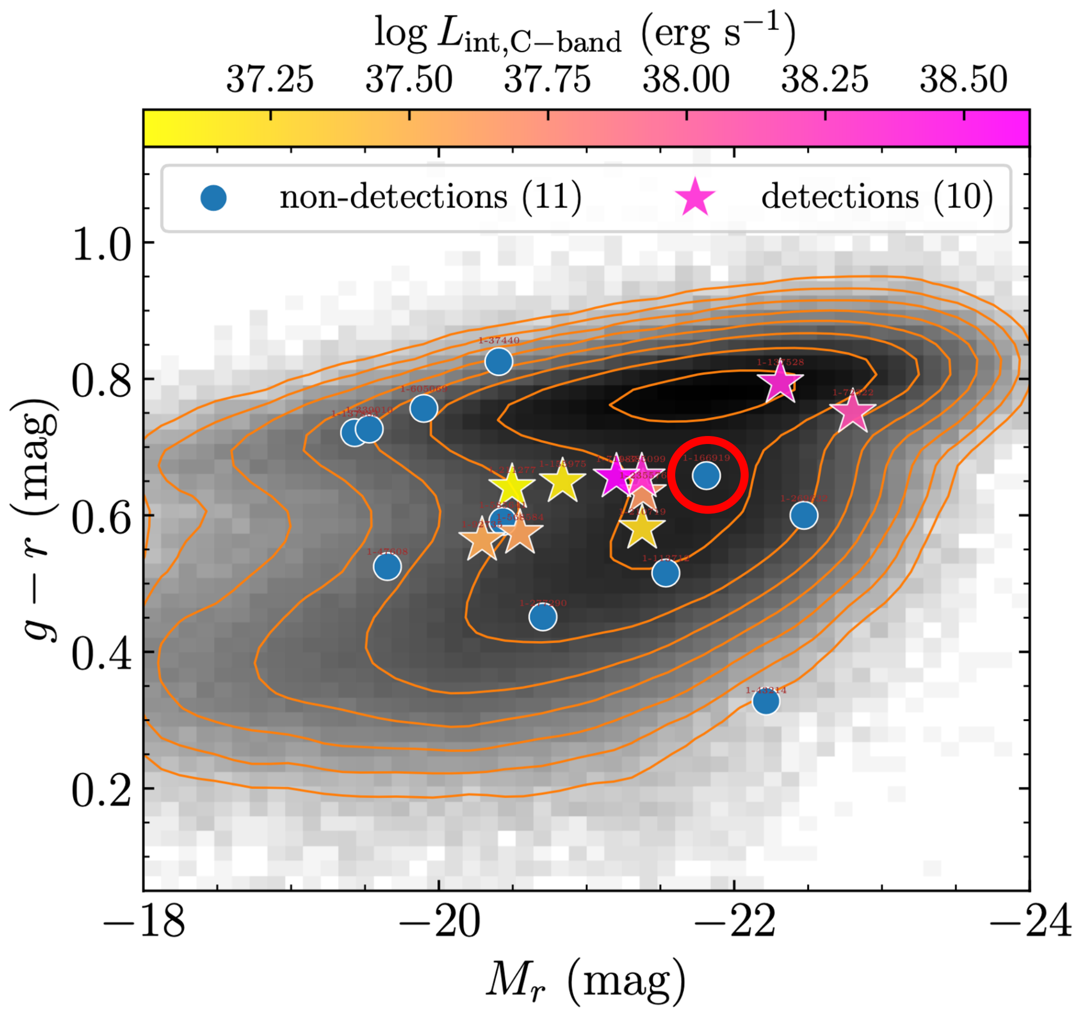
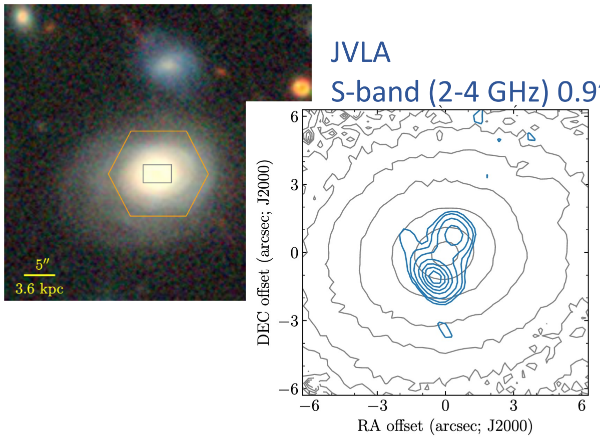
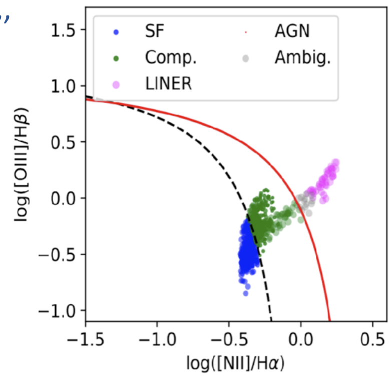


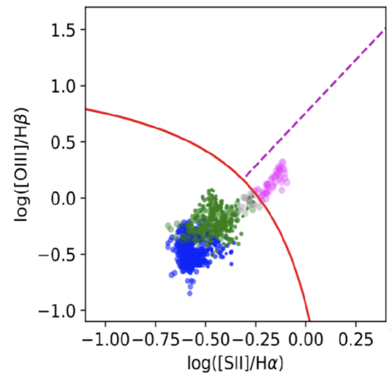
Case study: MaNGA 1-66919, “Blob” galaxy

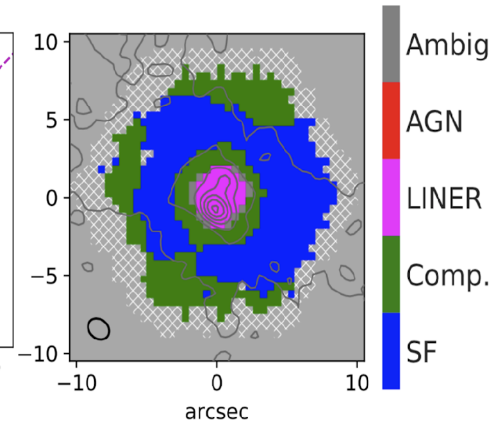
Al Yazeedi, Katkov, et al. ApJ 916, 102A (2021)

General view and stellar kinematics









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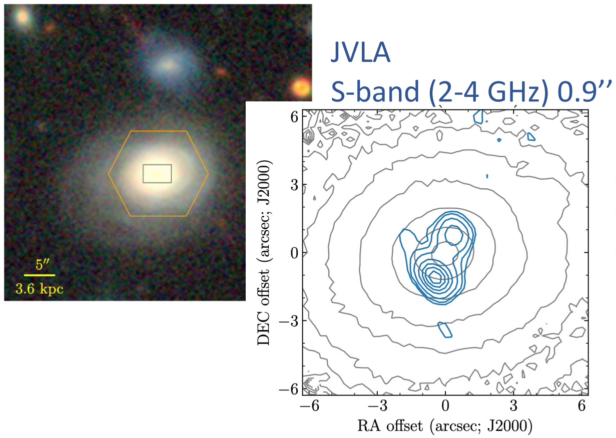

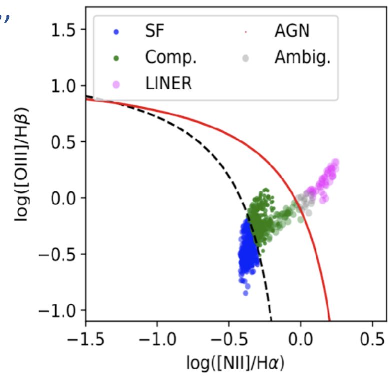

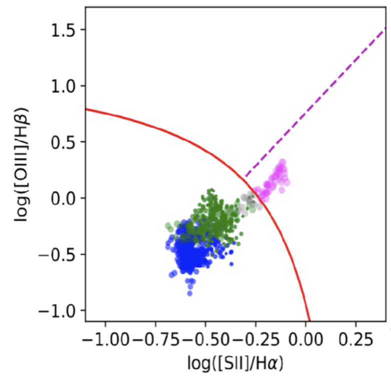

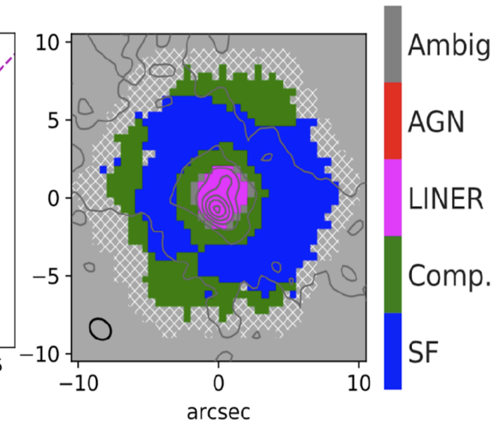

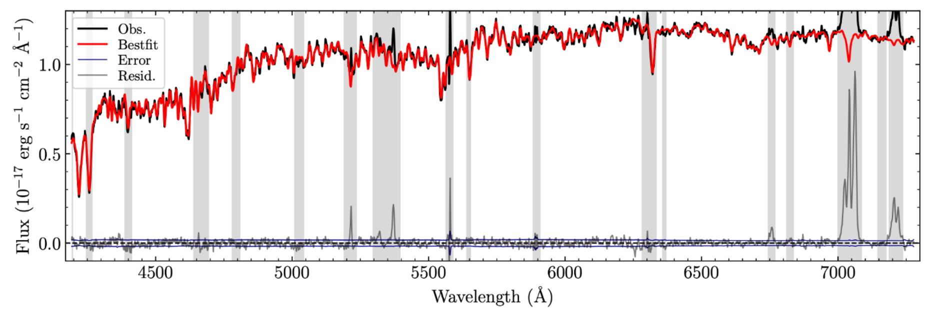

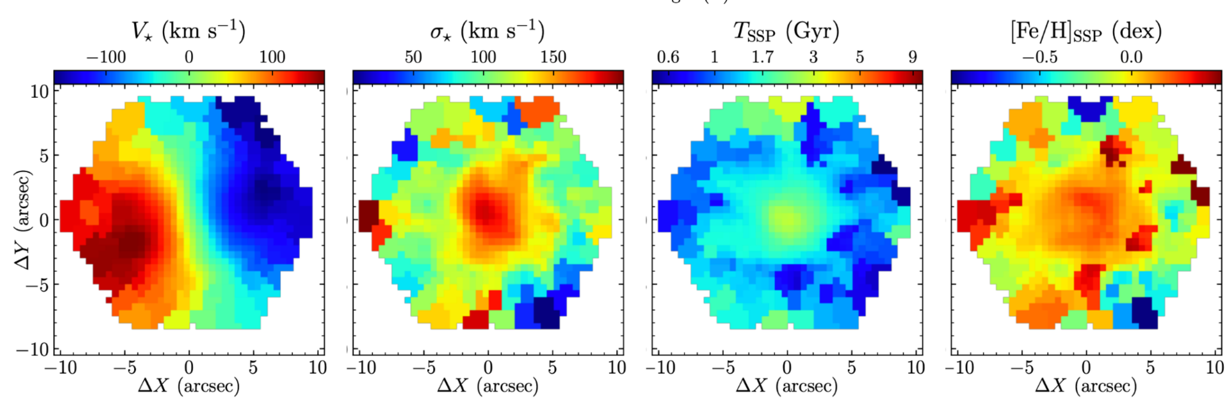

- Stellar mass ~6x10^{10} Msun
- Full spectral fitting
    - NBursts Chilingarian et al 2007
- Disk + bulge kinematics
- ~1-3 Gyr old stars
- Pure emission lines cube

Case study: MaNGA 1-66919, "Blob" galaxy

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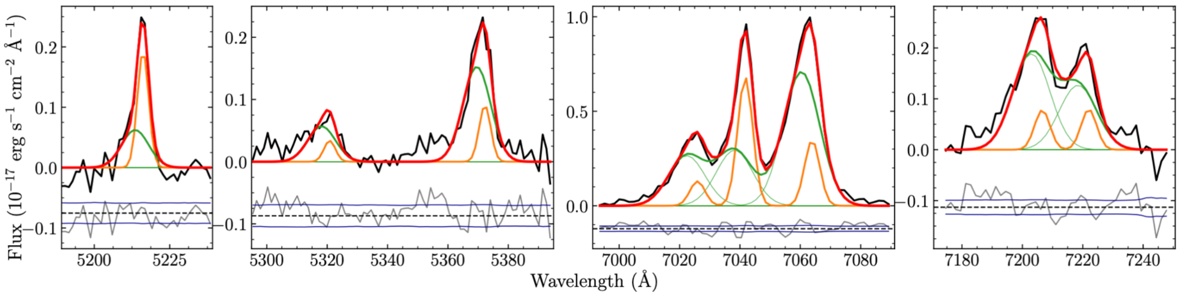
Outflow identification (MaNGA)

- Two component Gaussian model
    - Ambiguous solutions 🤔



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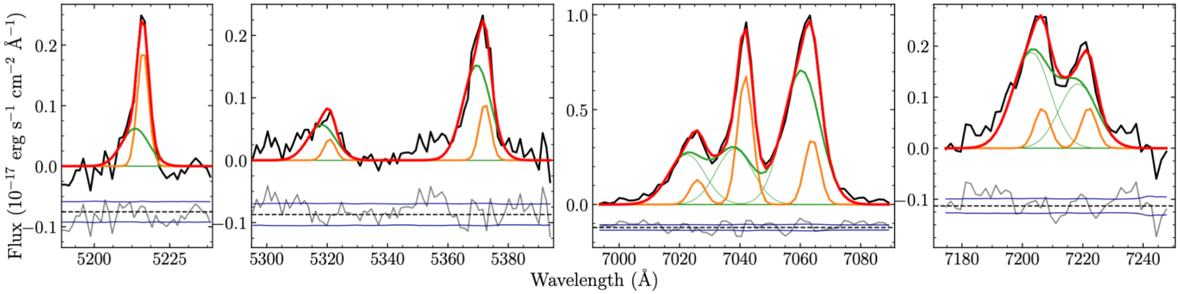
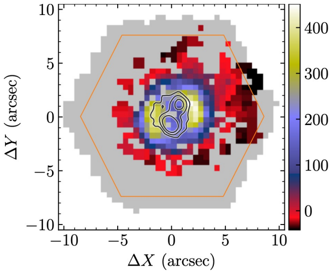


Our approach

- $BIC_{1GAUS} - BIC_{2GAUS}$ map to deintify

$$\mathrm{BIC} = N_{\mathrm{data}} \ln \frac{\chi^2}{N_{\mathrm{data}}} + N_{\mathrm{vars}} \ln N_{\mathrm{data}}$$



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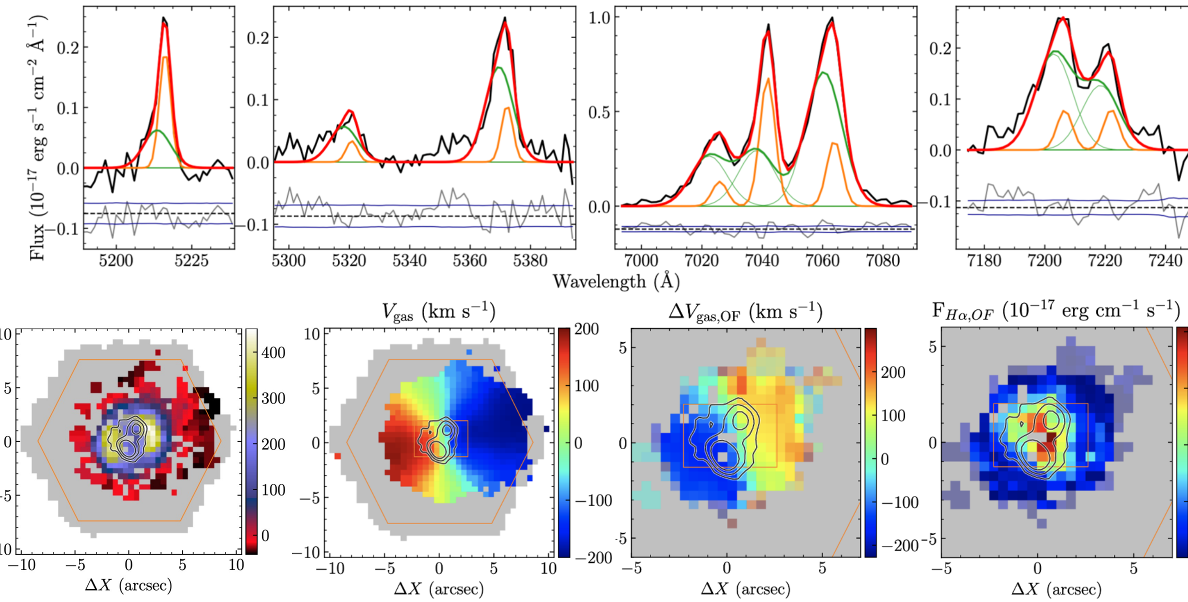

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- Simultaneous fitting all spaxels in (binned) spectral cube
- Simple model for rotation of “main” component

$$V_\phi(R) = V_0 \left(\tanh \pi \frac{R}{R_0} + c \frac{R}{R_0} \right) \quad V_{\rm LOS}(x,y) = V_{\rm sys} + V_\phi(x,y) \frac{\cos\phi \sin i}{g}.$$

- All lines are fitted simulteneousely

- Iterative approach

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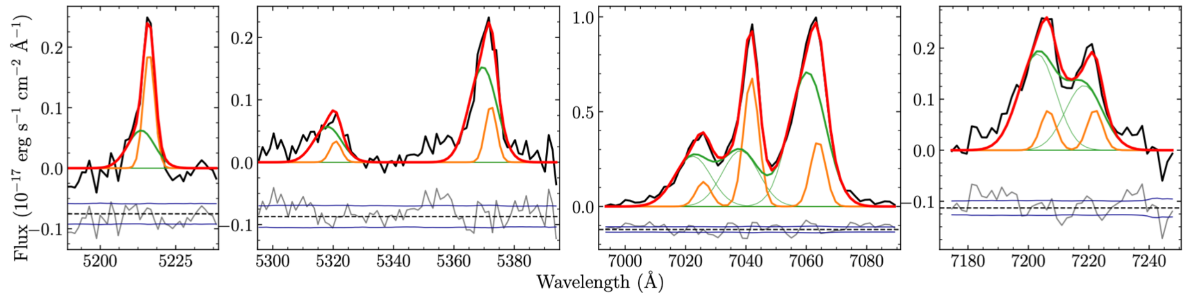

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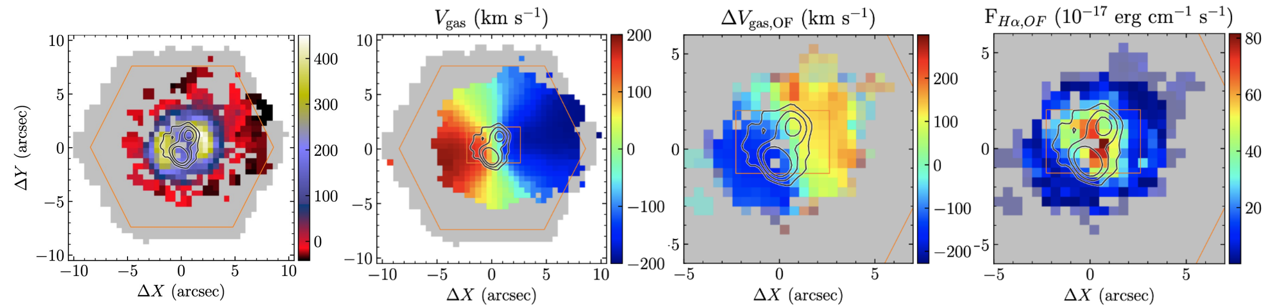

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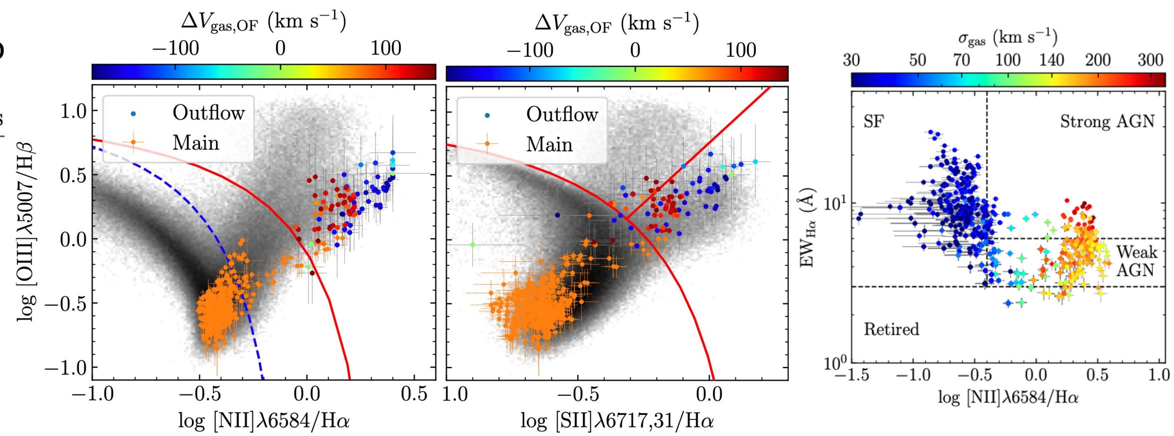

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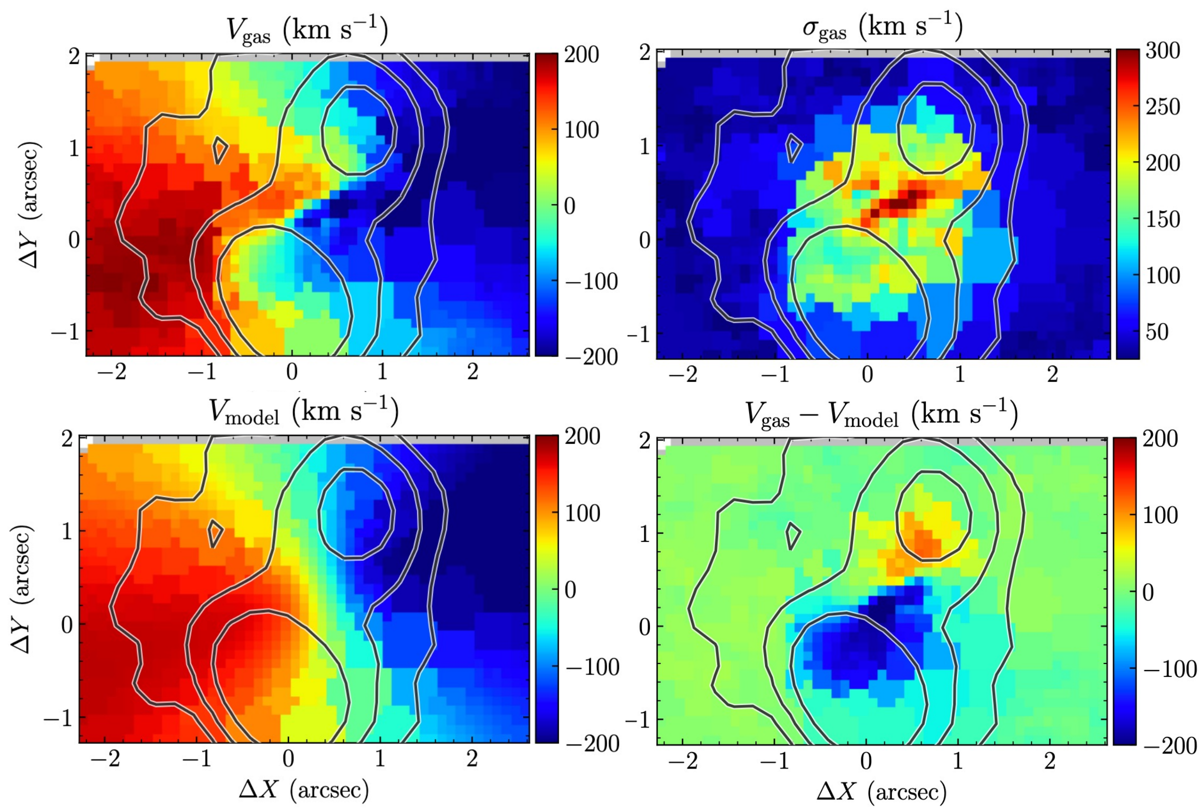
Case study: MaNGA 1-66919, “Blob” galaxy

Al Yazeedi, Katkov, et al. ApJ 916, 102A (2021)

Outflow identification (GMOS-IFU)

- Wylezalek et al. 2017
- No need to apply two-component model
- Spatial resolution 0.8-0.9 arcsec
  - 😢 MaNGA: effectively ~2.3-2.5 arcsec
  - Spatial resolution matters



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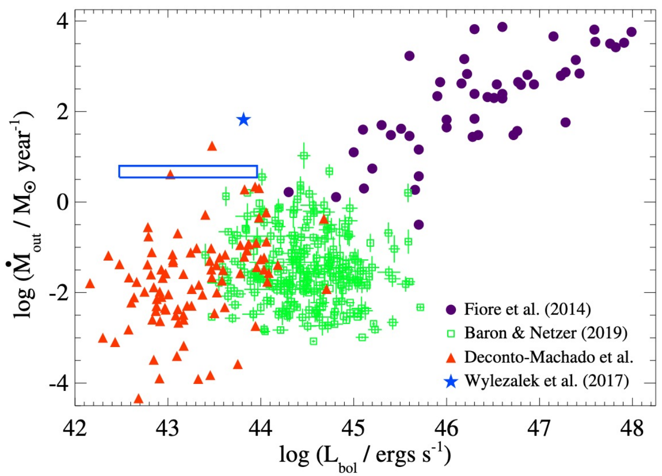
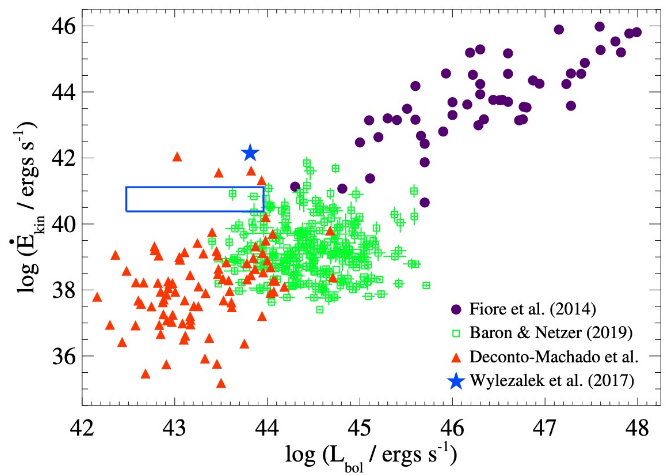
Al Yazeedi, Katkov, et al. ApJ 916, 102A (2021)

Outflow and AGN parameters

Property	This Work		Wylezalek et al. (2017)
	MaNGA	GMOS[a]	
n_e	$\approx 80\ \mathrm{cm}^{-3}$	$\approx 100\ \mathrm{cm}^{-3}$	$\equiv 100\ \mathrm{cm}^{-3}$
M_{out}	$2.4 \times 10^7\ \mathrm{M}_\odot$	$(2.2 - 3.9) \times 10^7\ \mathrm{M}_\odot$	
K_{ion}	2.4×10^{55} ergs	$(4.6 - 8) \times 10^{54}$ ergs	
t_{age}	≈ 6 Myr	6.2 Myr	$2 - 3$ Myr
$\dot{M}_{\mathrm{out}}$	$\approx 4\ \frac{\mathrm{M}_\odot}{\mathrm{year}}$	$(3.5 - 6.3)\ \frac{\mathrm{M}_\odot}{\mathrm{year}}$	$66\ \frac{\mathrm{M}_\odot}{\mathrm{year}}$
$\dot{E}_{\mathrm{kin}}$	$\approx 1.3 \times 10^{41}\ \frac{\mathrm{ergs}}{\mathrm{s}}$	$(2.4 - 4.1) \times 10^{40}\ \frac{\mathrm{ergs}}{\mathrm{s}}$	$1.4 \times 10^{42}\ \frac{\mathrm{ergs}}{\mathrm{s}}$
L_{bol}	$(0.3 - 9.1) \times 10^{43}\ \frac{\mathrm{ergs}}{\mathrm{s}}$		$(6 - 7.1) \times 10^{43}\ \frac{\mathrm{ergs}}{\mathrm{s}}$





- Eddington ratio <1%
- Low-Eddington accretion may be more efficient in producing outflows than their high-Eddington counterparts

Case study: MaNGA 1-66919, “Blob” galaxy

Al Yazeedi, Katkov, et al. ApJ 916, 102A (2021)

Outflow and AGN parameters

- LERAGN in a HERAGN host

- AGN activity in Blob is currently driving the transition of the host galaxy from HERAGN-like to LERAGN-like properties?

	HERAGN	LERAGN
Other names	HERG Cold-mode AGN Radiative-AGN Quasar-mode High SMBH accretors Thin-disk	LERG Hot-mode AGN Jet-mode AGN Radio-mode Low SMBH accretors Thick-disk, ADAF
Radio luminosity	High ($L_{20cm} \geq 10^{26}$W/Hz)	Lower ($L_{20cm} \leq 10^{26}$W/Hz)
Source of radio emission	SF+AGN	AGN
Optical color	Green	Red
Stellar mass	Lower than LERAGN	Highest ($\geq 5\times10^{10} M_{\odot}$)
Gas mass	Higher ($3\times10^{8} M_{\odot}$)	Low ($<4.3\times10^{7} M_{\odot}$)
BH mass	Lower than LERAGN	Highest ($\sim10^{9} M_{\odot}$)
BH accretion rate	~Eddington	sub-Eddington
BH accretion mode	Radiatively efficient	Radiatively inefficient

Smolcic 2016

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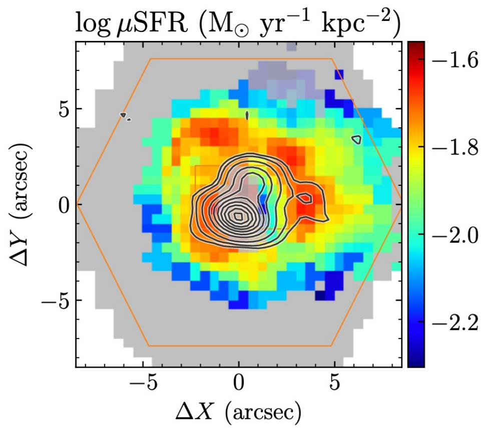
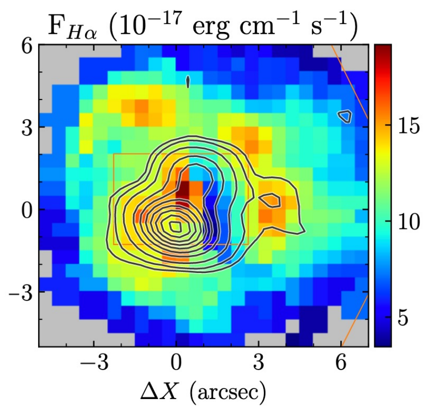
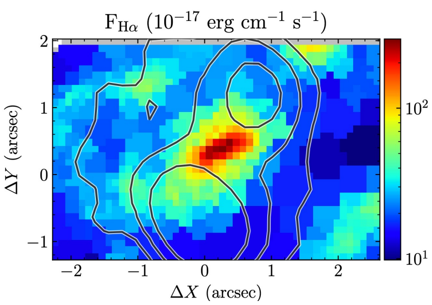
Outflow / Host galaxy interaction

MaNGA

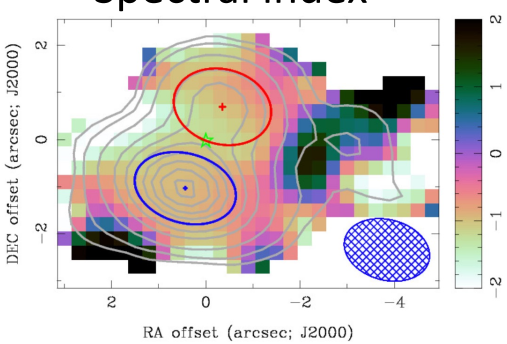




GMOS



Spectral index



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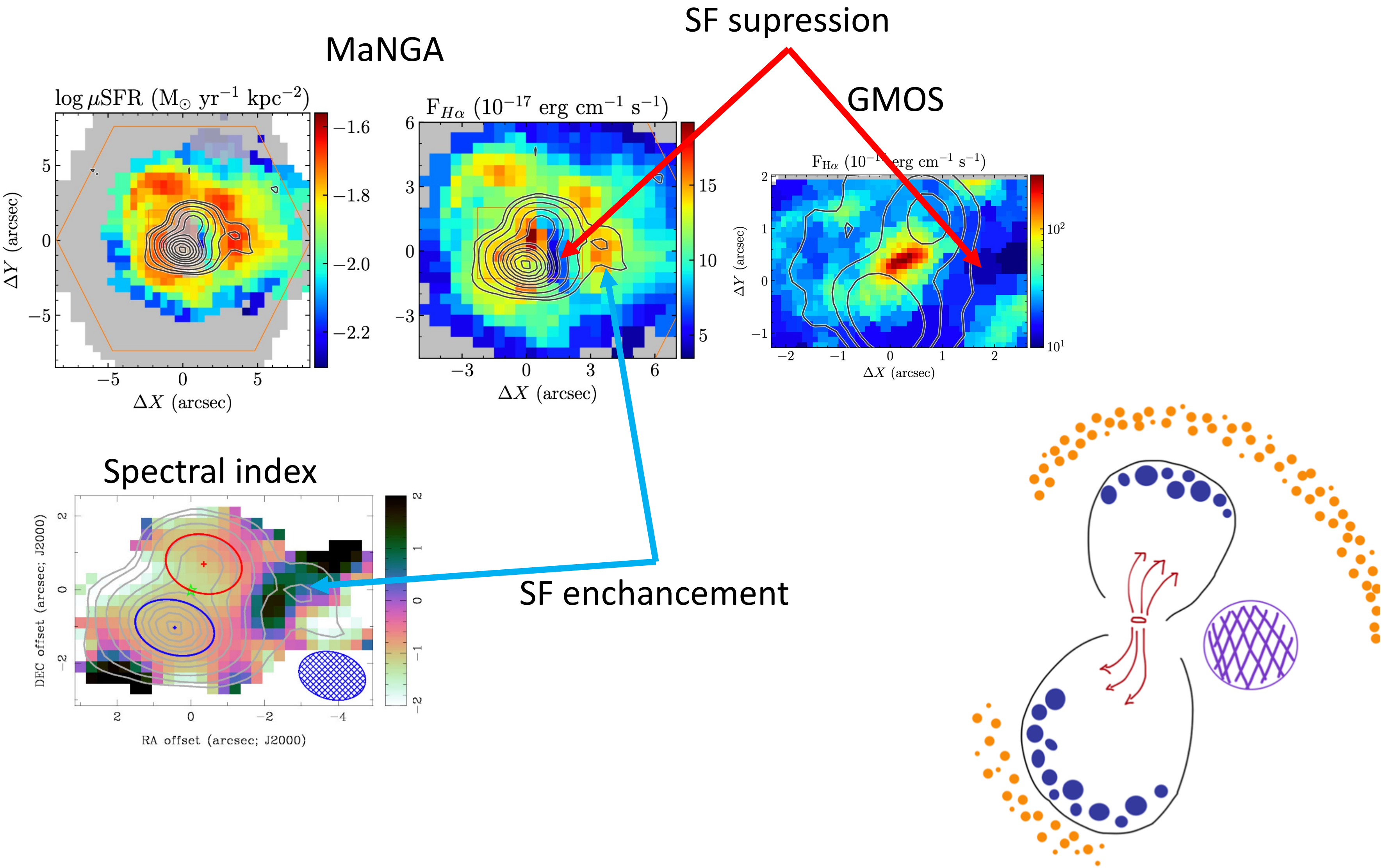
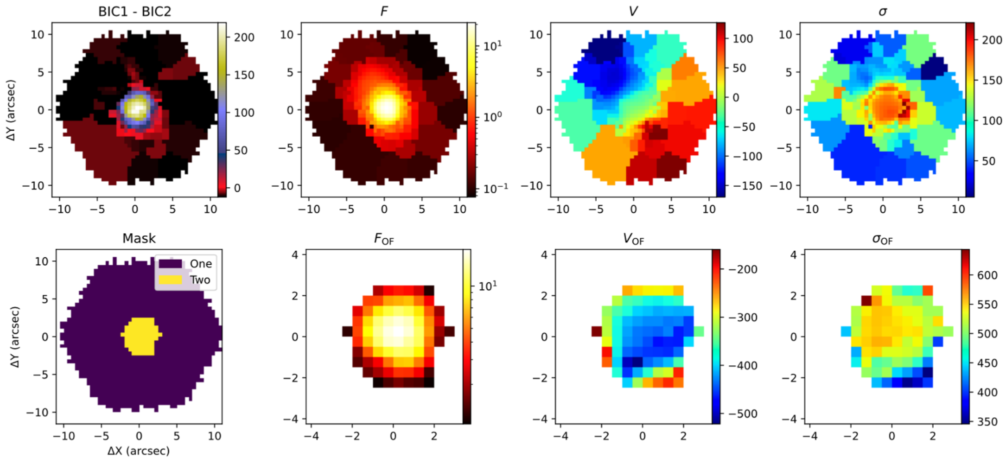
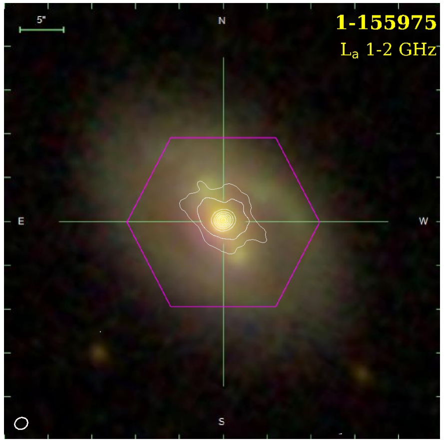
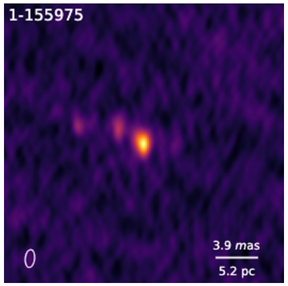


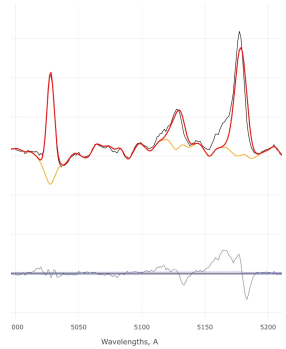
Future (ongoing) steps

- Need coherent sample and metrics
- Two component kinematical deconvolution
  - Simplified physically motivated based on [OIII] line only
- Outflow demographics





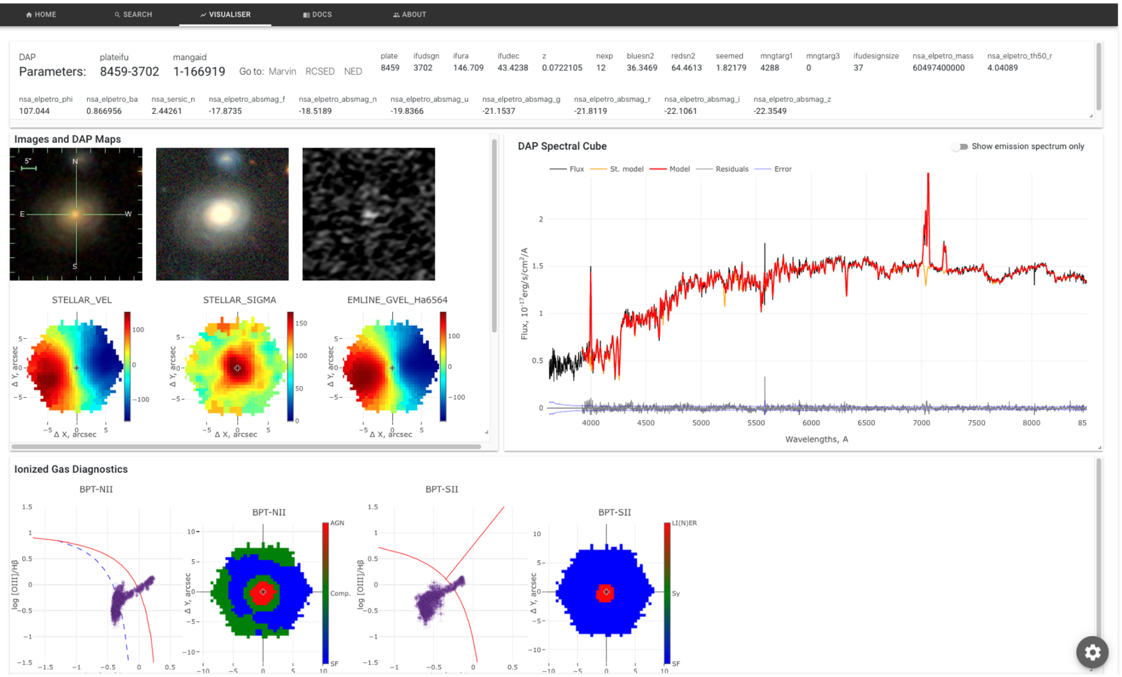




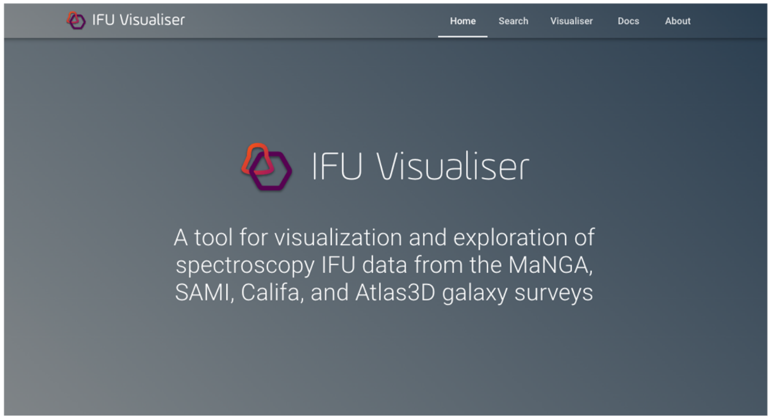
Visualization tools

- MaNGA Visualiser (https://manga.voxastro.org)
    - First prototype
    - Only MaNGA DR17
- IFU Visualiser
    - Early development stage
    - MaNGA, SAMI, Califa, Atlas3D
    - Advanced tables functionality
        - Value Added catalogs as a linked tables
        - SQL-like query syntax
        - Cone Search Query and CDS Name resolver Sesame

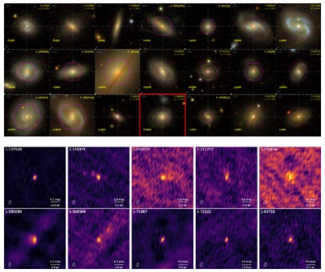
https://manga.voxastro.org



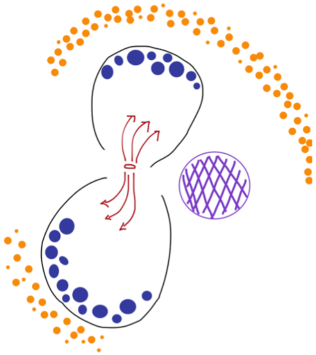
https://ifu.voxastro.org



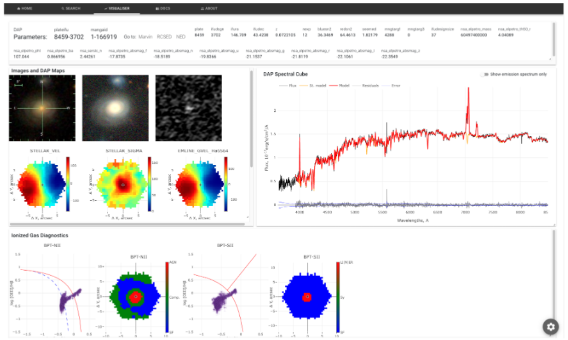
Summary



- Studying large scale outflows using combination of radio (VLA + VLBA) and optical IFU spectroscopy



- "Blob" galaxy (MaNGA 1-66919) is a nice example of detailed investigation galaxies hosting kpc-scale outflows
  - Low-Eddington <1%
  - Bi-conical outflow > 100-200 km/s
  - Relativistic electrons and ionized gas have comparable energy budget ($10^{54} – 10^{55}$ erg)
  - Positive and negative feedback in the host



- Fast interactive online IFU visualization is helpful
  - https://manga.voxastro.org
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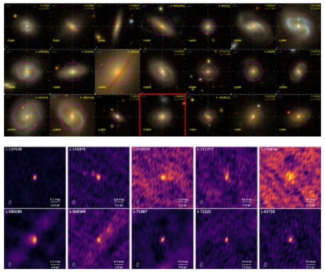
Summary

Thank you for attention!



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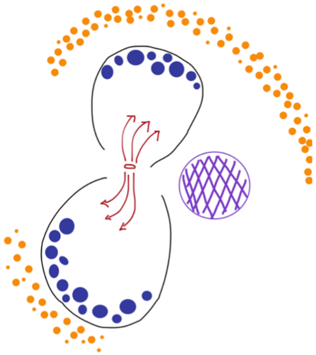

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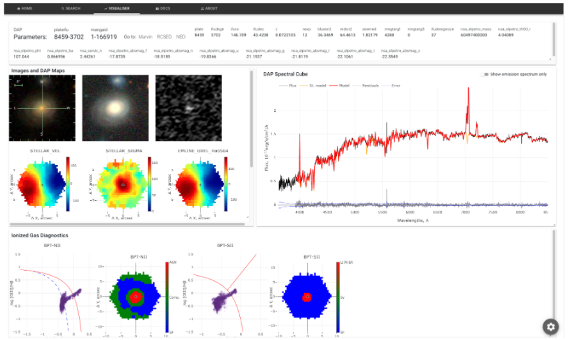

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