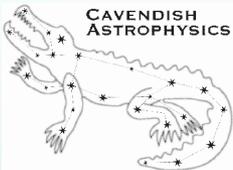


METALLICITY GRADIENTS AND RESOLVED CHEMICAL ABUNDANCES IN HIGH- z LENSED GALAXIES



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Cavendish Astrophysics
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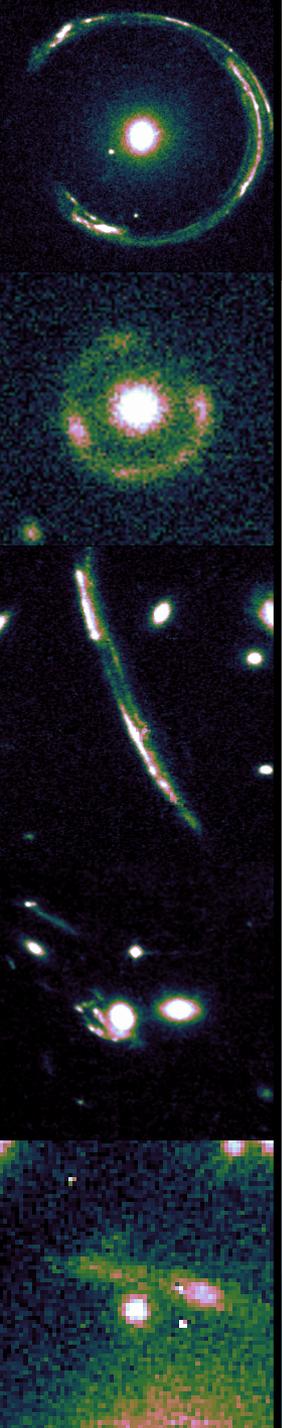
Collaborators:
Roberto Maiolino,
Matt Auger,
Bethan James

Motivation

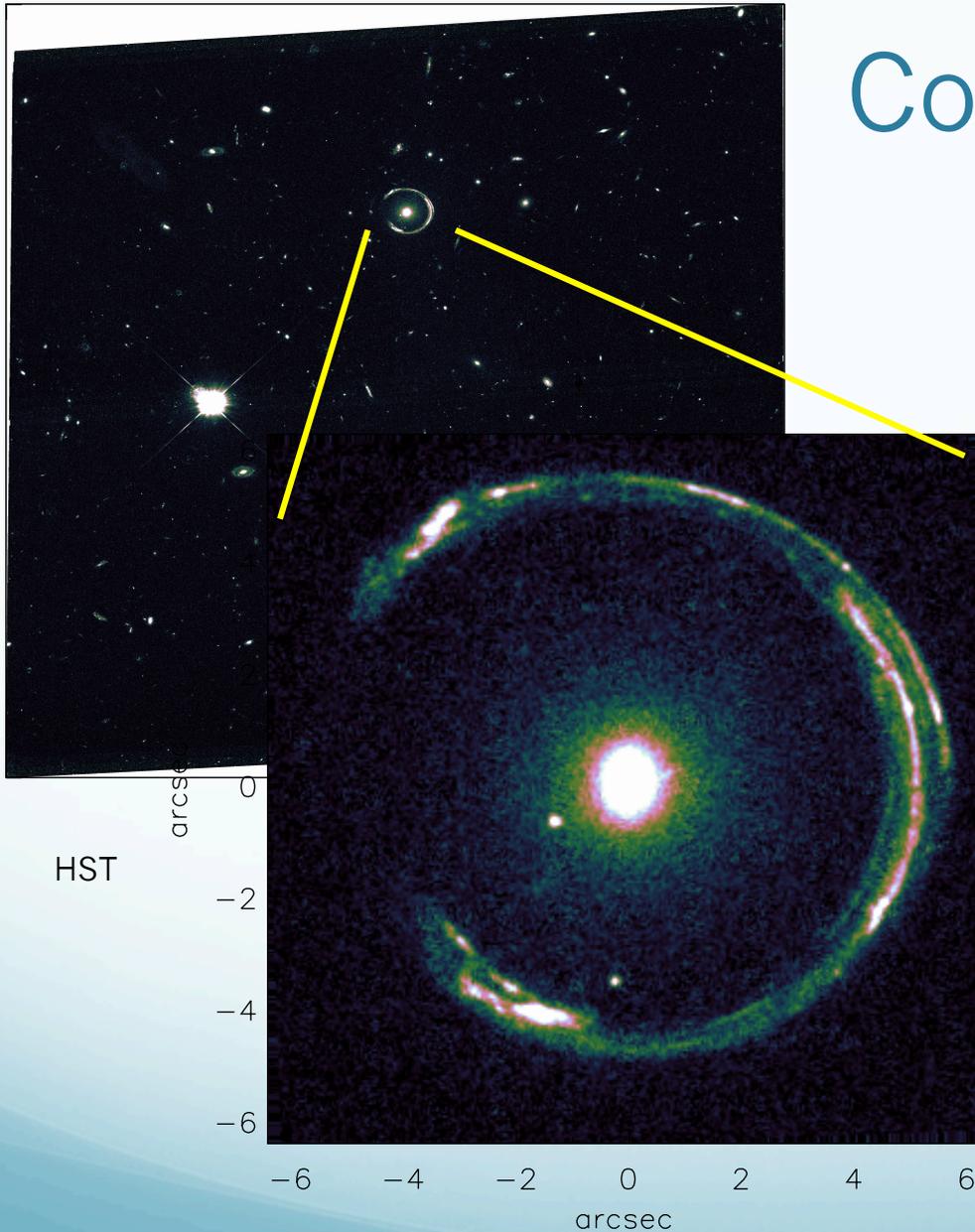
1. Strongly lensed galaxies benefit from magnification and so can be studied at a **high physical resolution** in their source plane
2. Near-IR multiband observations:
 - > BPT diagnostic
 - > Multiple metallicity tracers
 - > Break degeneracy between N/O & O/H
(most metallicity calibrators implicitly assume N/O proportional to O/H)

Sample

- Sample of highly magnified lensed galaxies at $z \sim 2$ with: $\mu = 8 - 15$
- SINFONI : 5 galaxies
- KMOS: 11 galaxies in pilot program (being observed)
- Observed in 2-3 bands
 - $H\alpha + [NII] + [SII]$
 - $H\beta + [OIII]$
 - $[OII]$ (only for a few galaxies)



Cosmic Horseshoe



- Almost complete Einstein ring discovered in SDSS data (Belokurov+07)
- Lens $z = 0.44$
- Source $z = 2.38$
- $\mu \sim 13$

Lens Modelling

- Singular Isothermal Ellipsoid (SIE) with external shear,

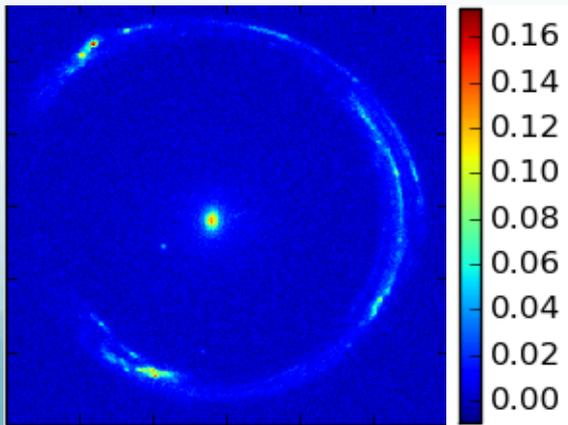
i.e.
$$\rho(R) \propto \frac{1}{R^2}$$

- Dark matter NFW profile

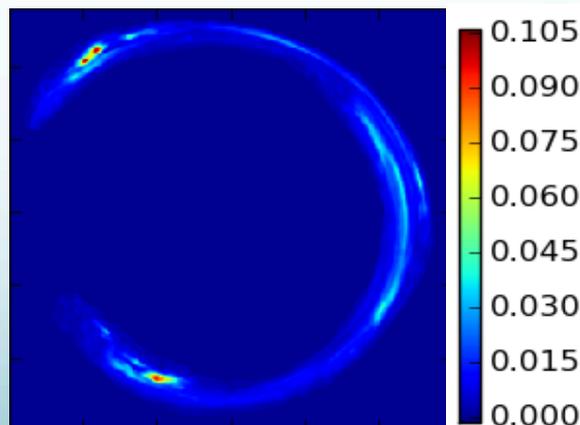
E.g. Horseshoe model:

Courtesy of Matt Auger

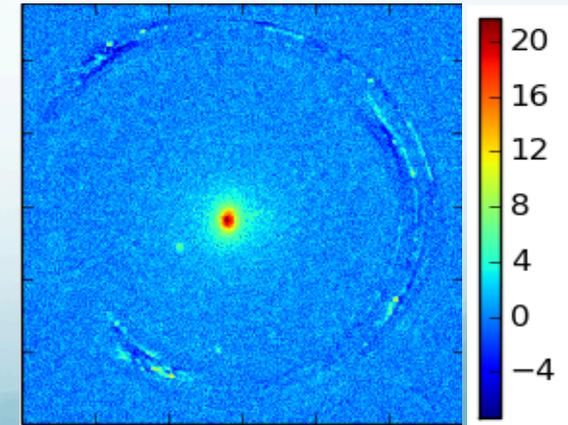
HST Bband



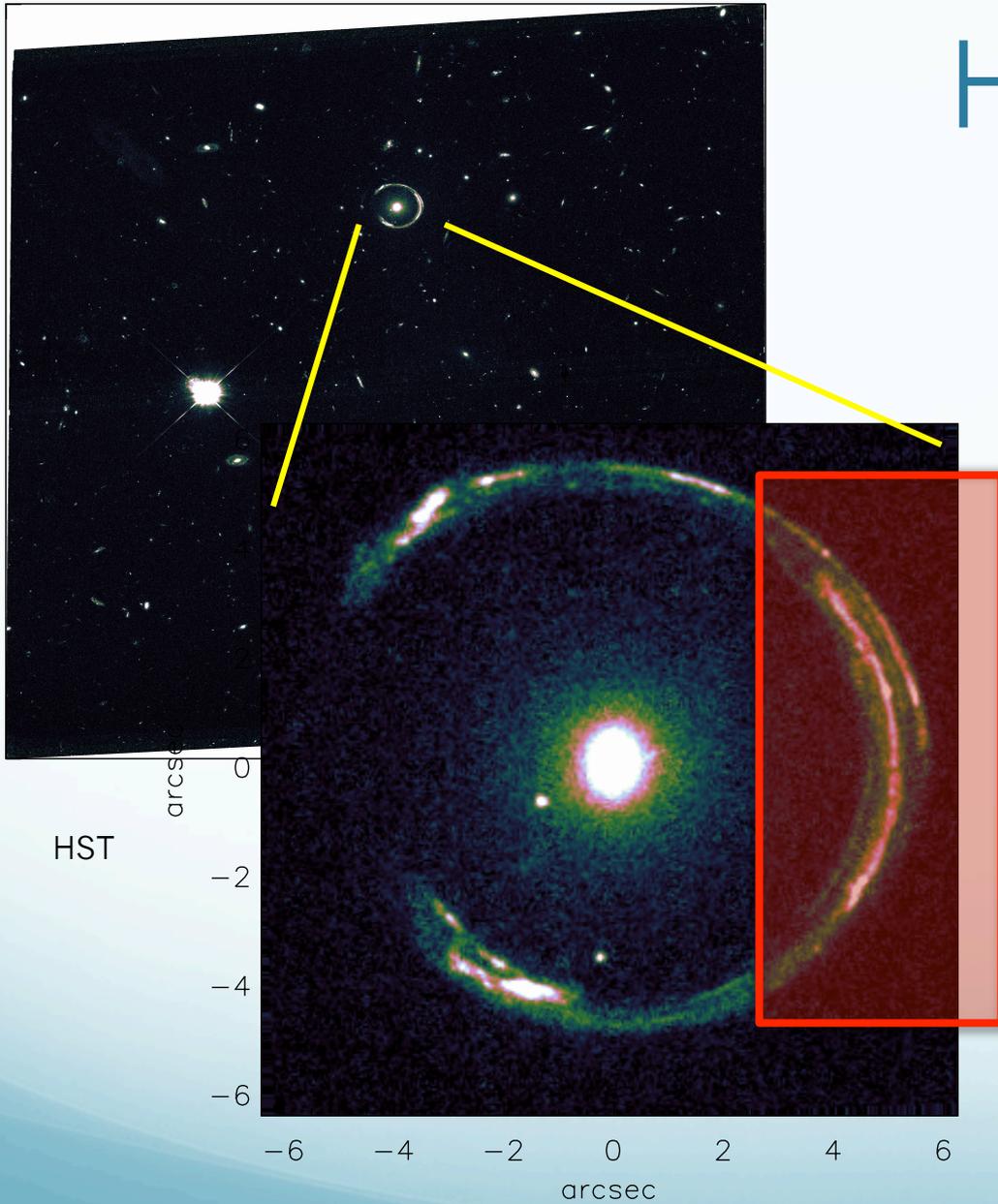
Model



Residuals



Horseshoe



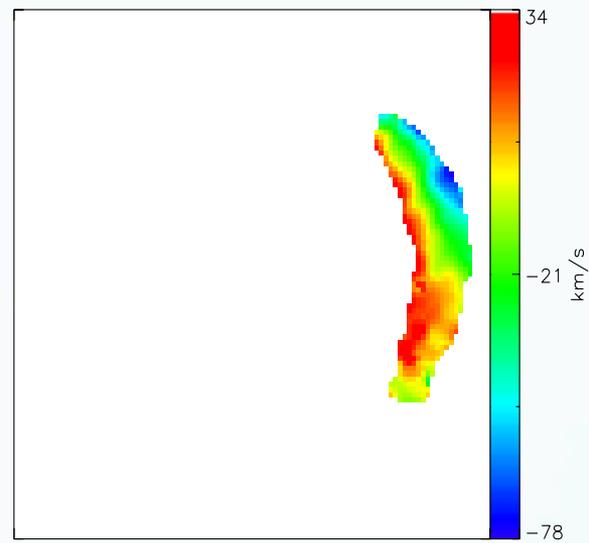
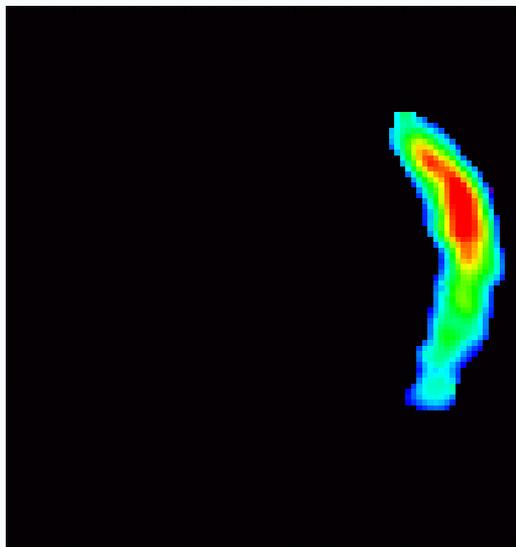
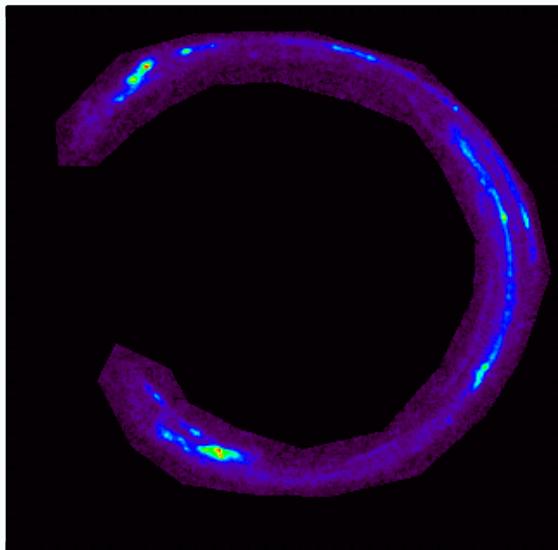
Full diagnostics
in this region

HST

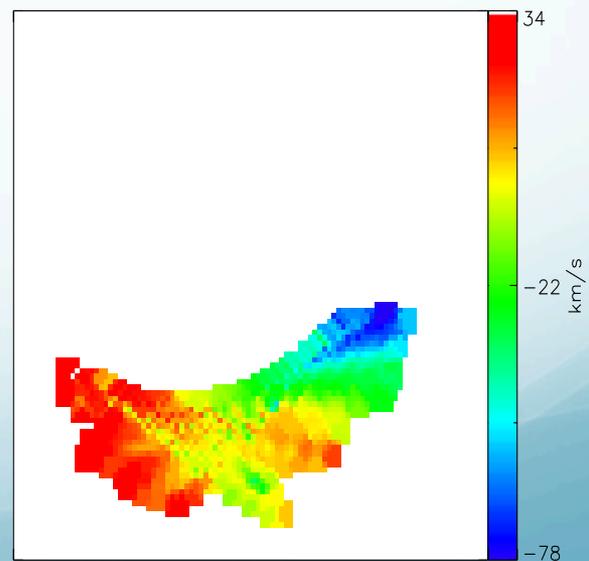
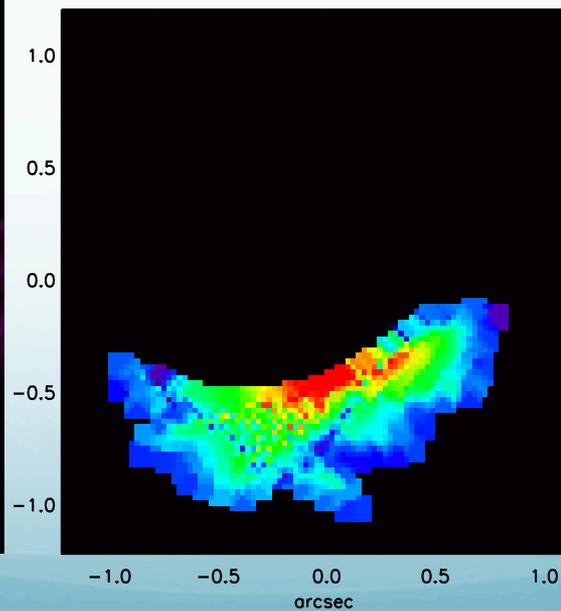
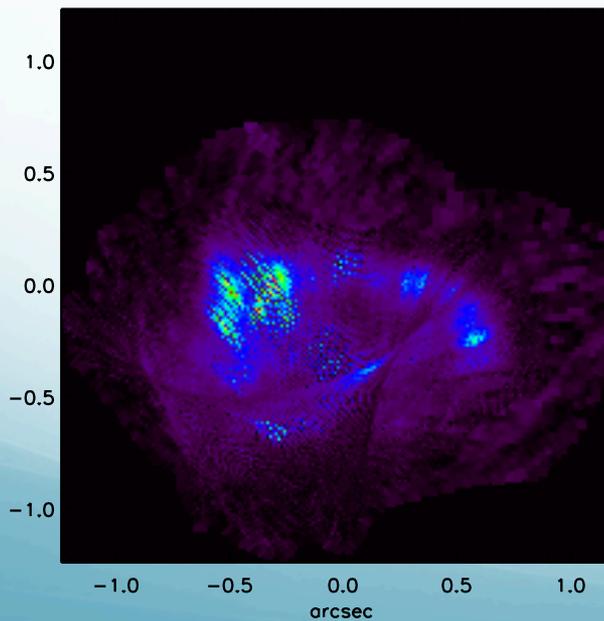
HALPHA

VELOCITY

IMAGE PLANE

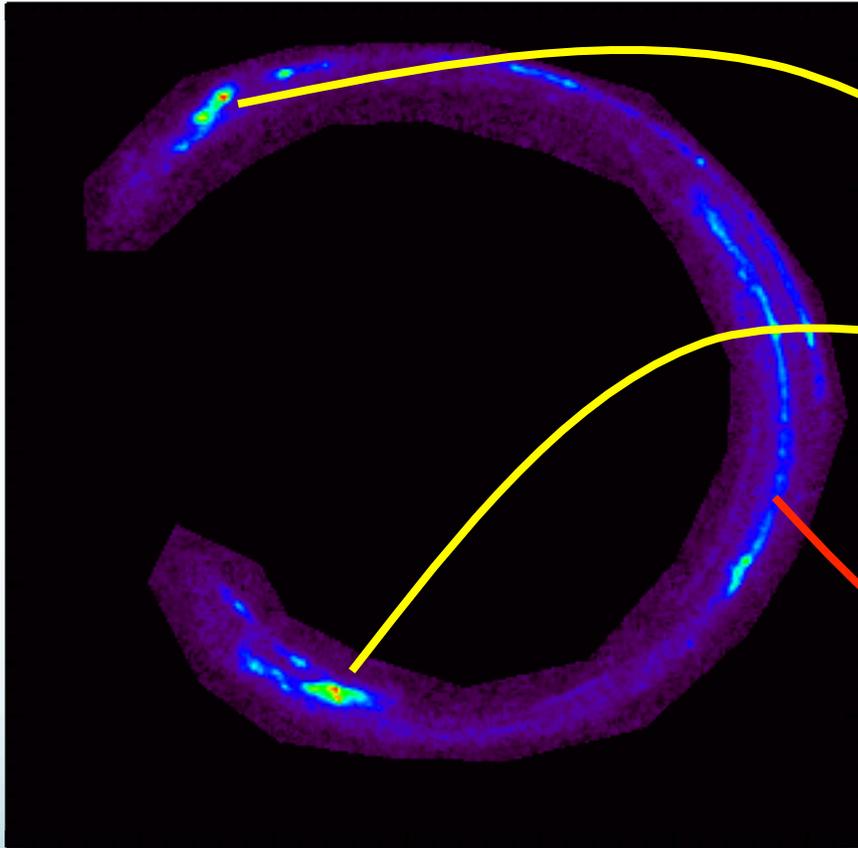


SOURCE PLANE

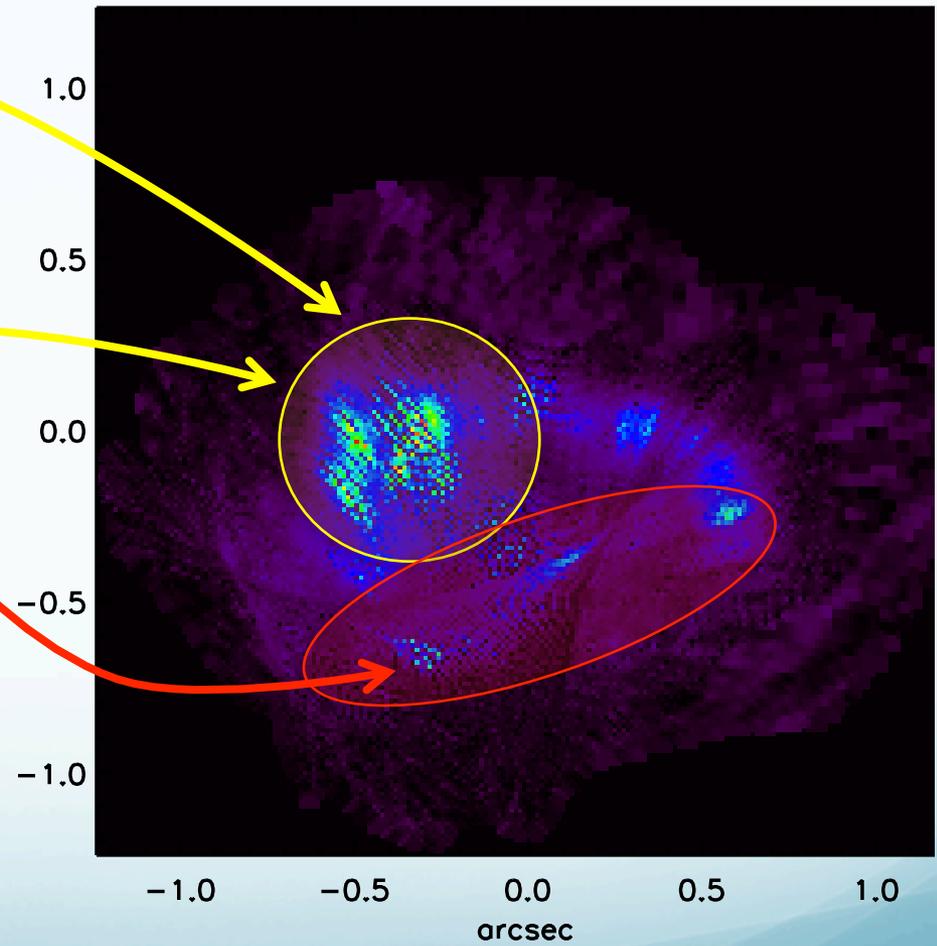


HST

IMAGE PLANE



SOURCE PLANE

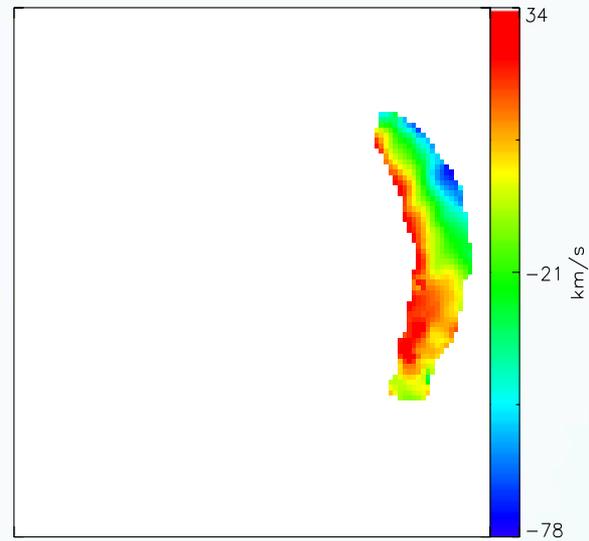
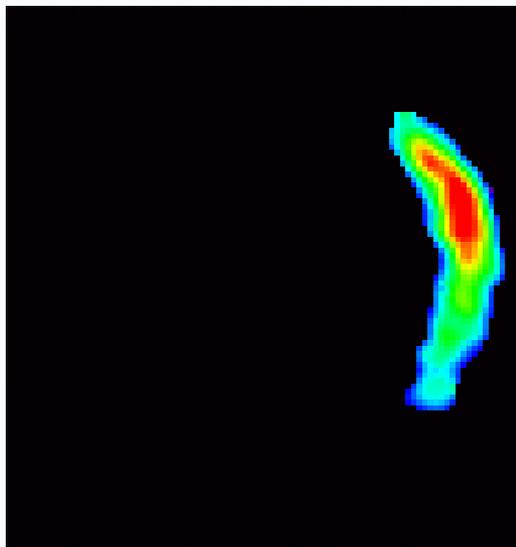
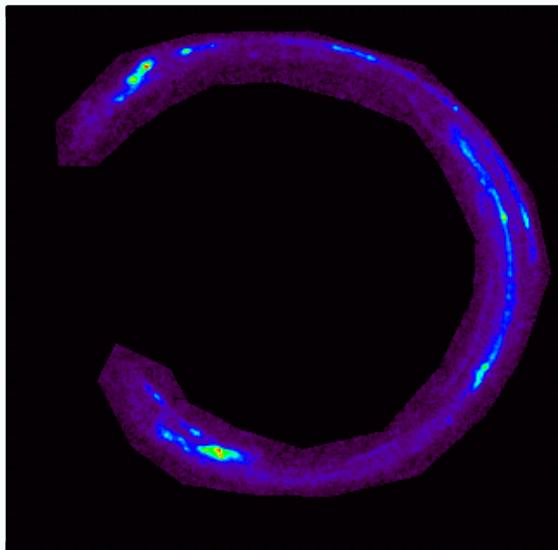


HST

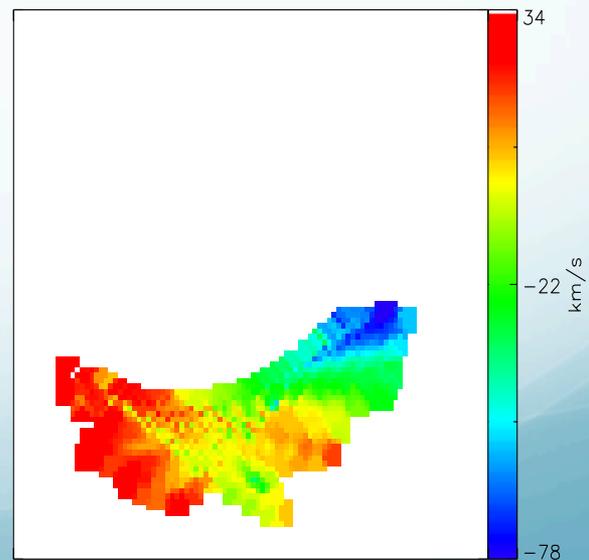
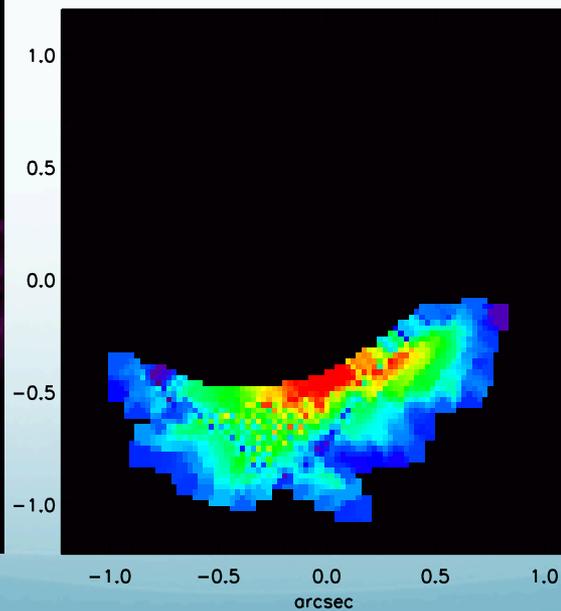
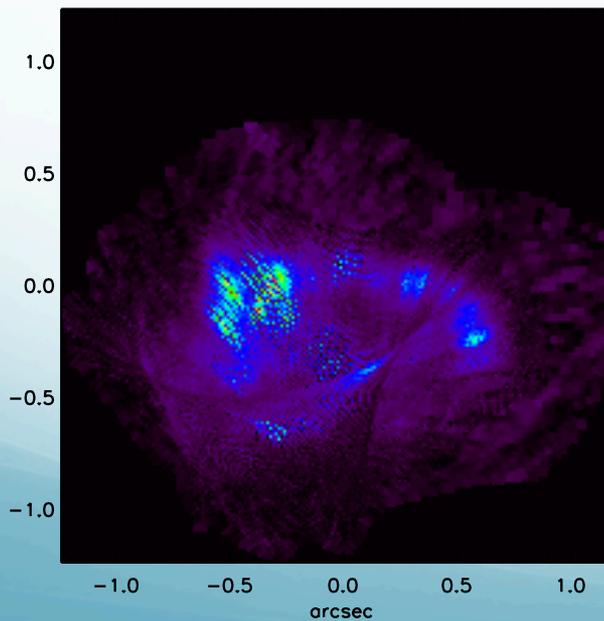
HALPHA

VELOCITY

IMAGE PLANE



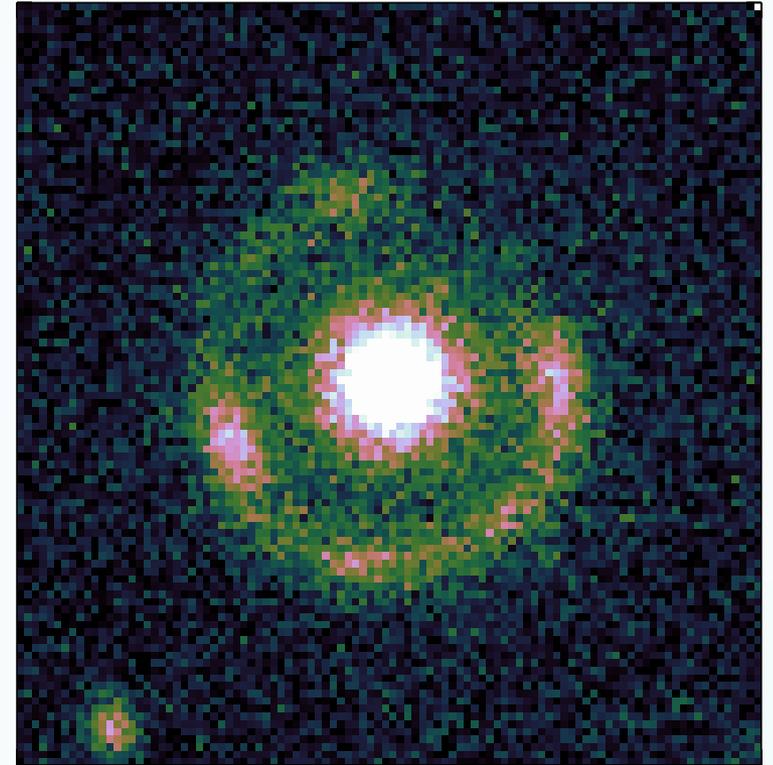
SOURCE PLANE



CSWA 64

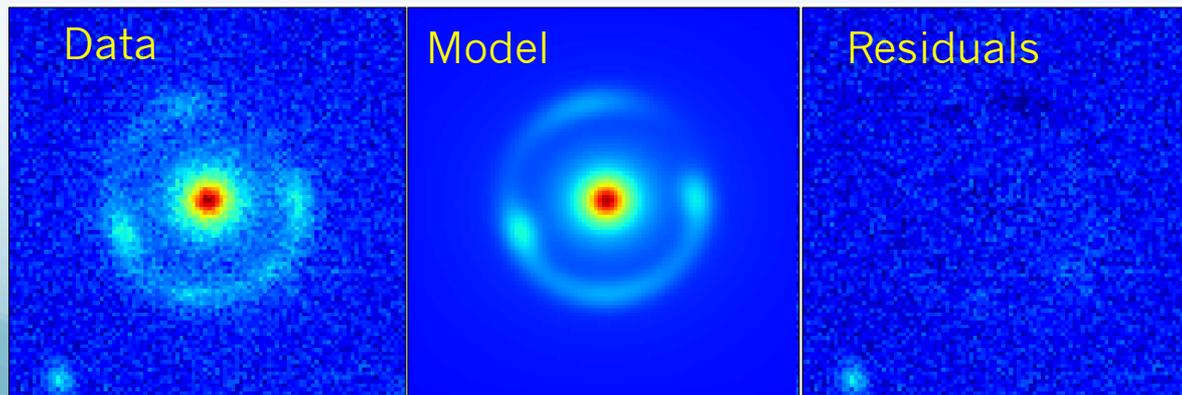
(SDSS J0232-0323)

- Selected from CASSOWARY survey of bright strongly lensed arcs discovered in SDSS images (Belokurov+09)
- Source $z = 2.52$
- $\mu \sim 14$



SINFONI data Courtesy of B. James

WORK IN PROGRESS

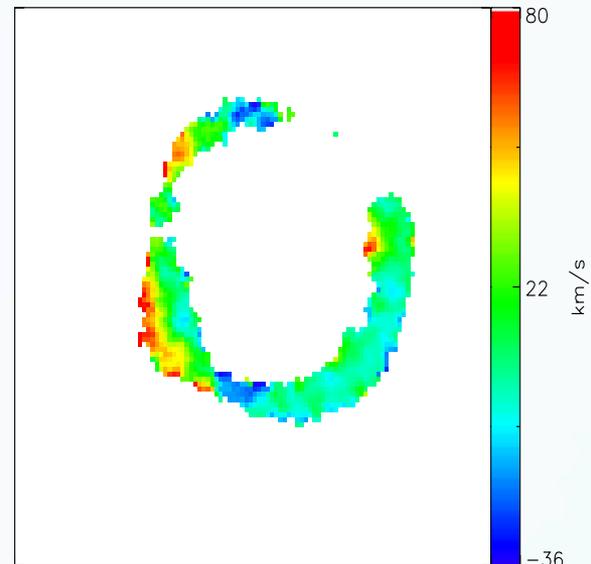
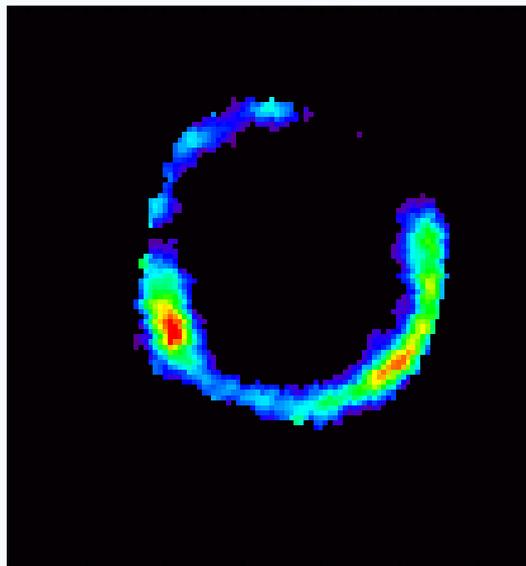
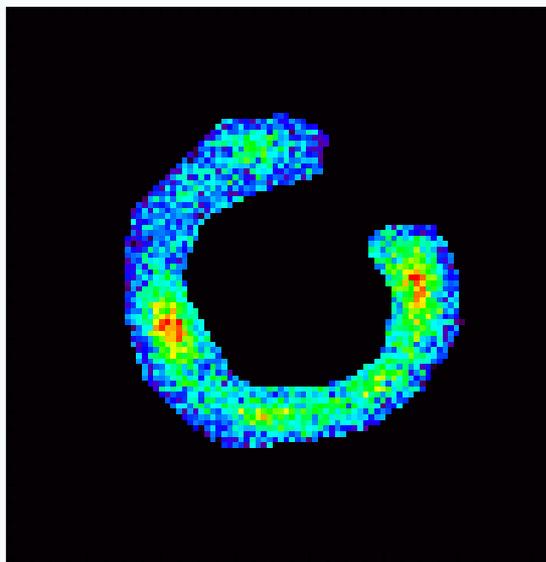


Rband

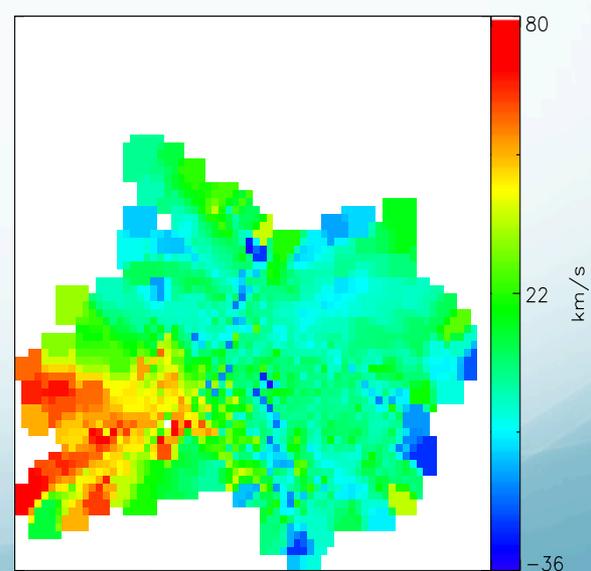
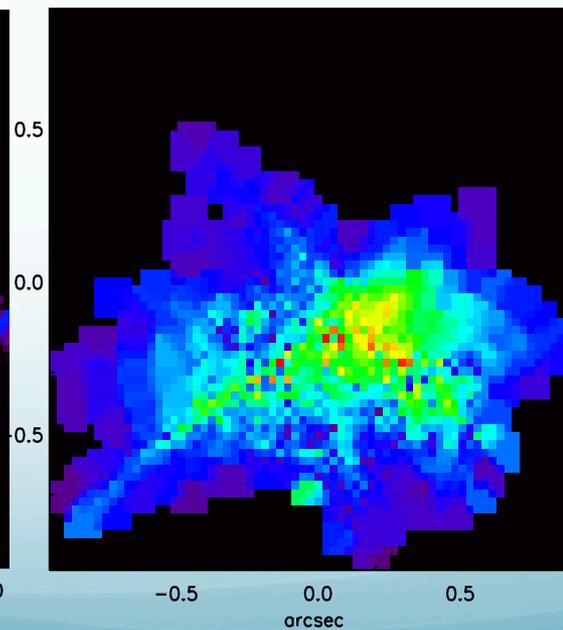
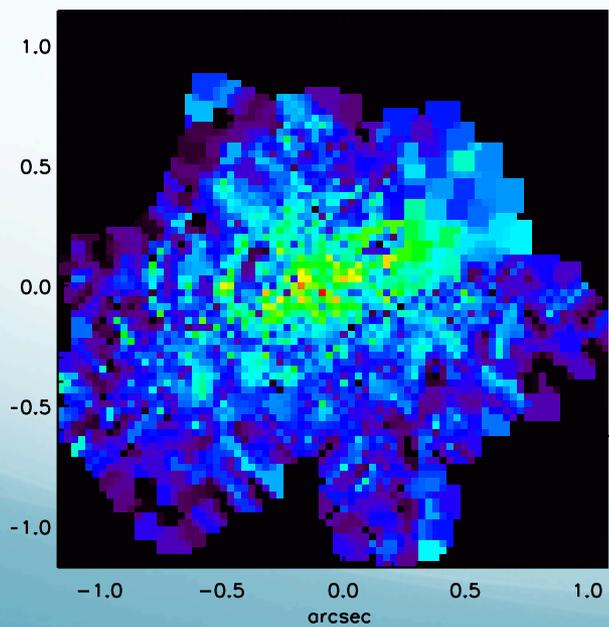
HALPHA

VELOCITY

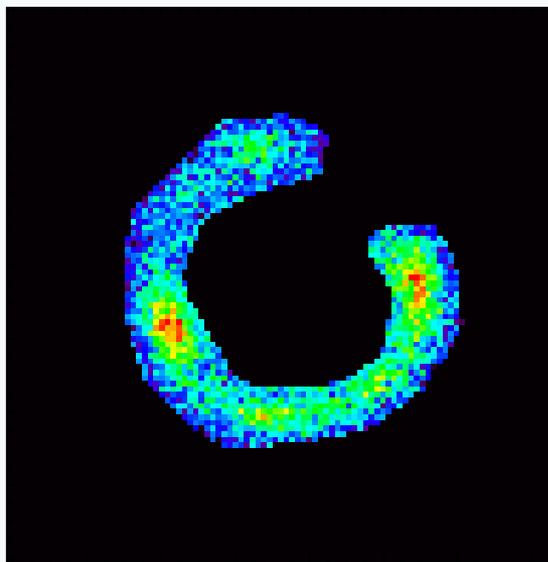
IMAGE PLANE



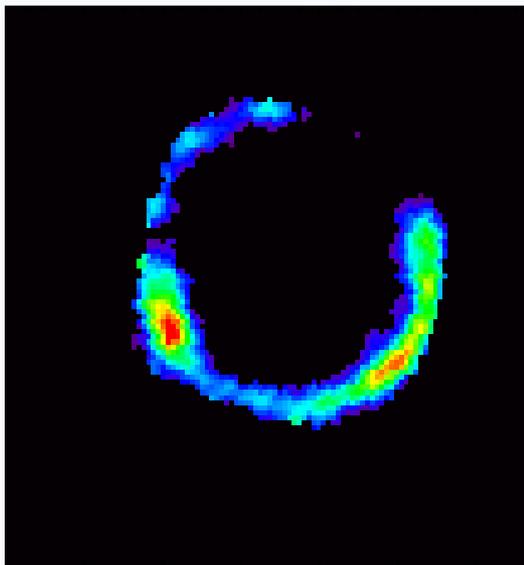
SOURCE PLANE



Rband



HALPHA



VELOCITY

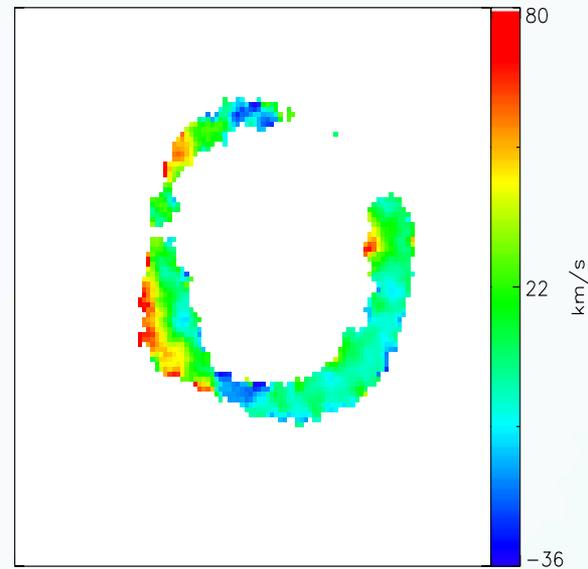
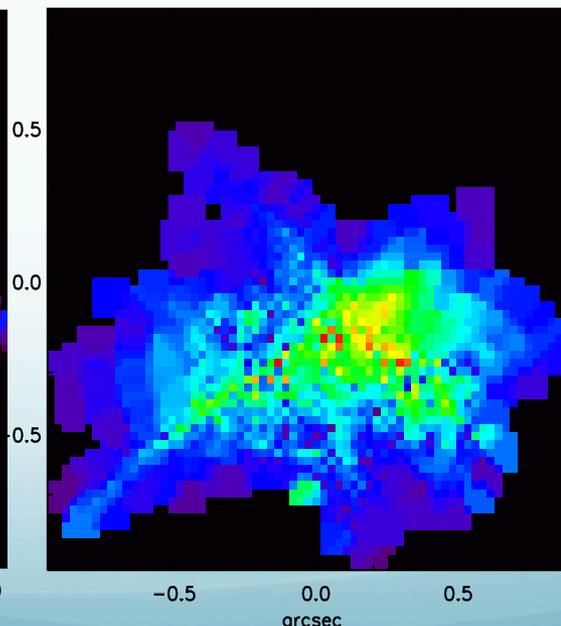
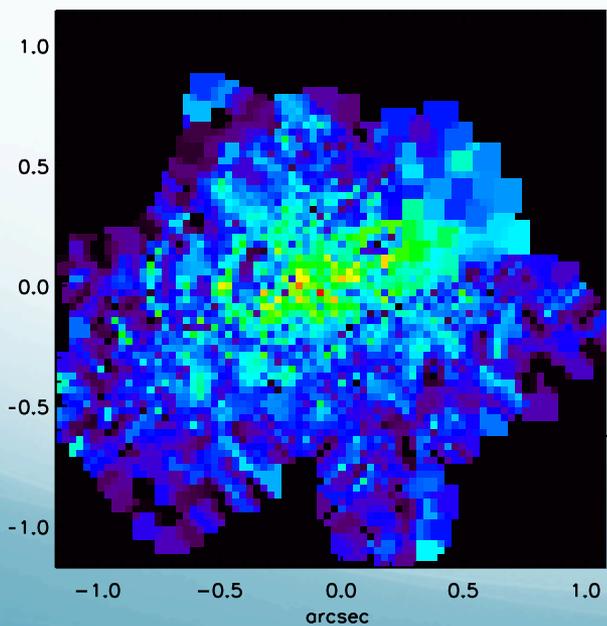
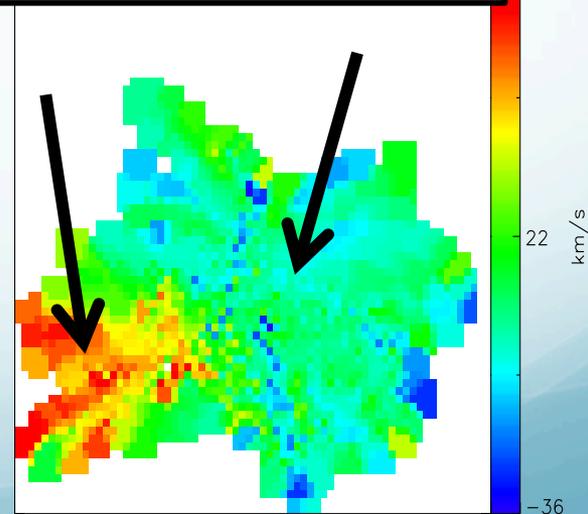


IMAGE PLANE



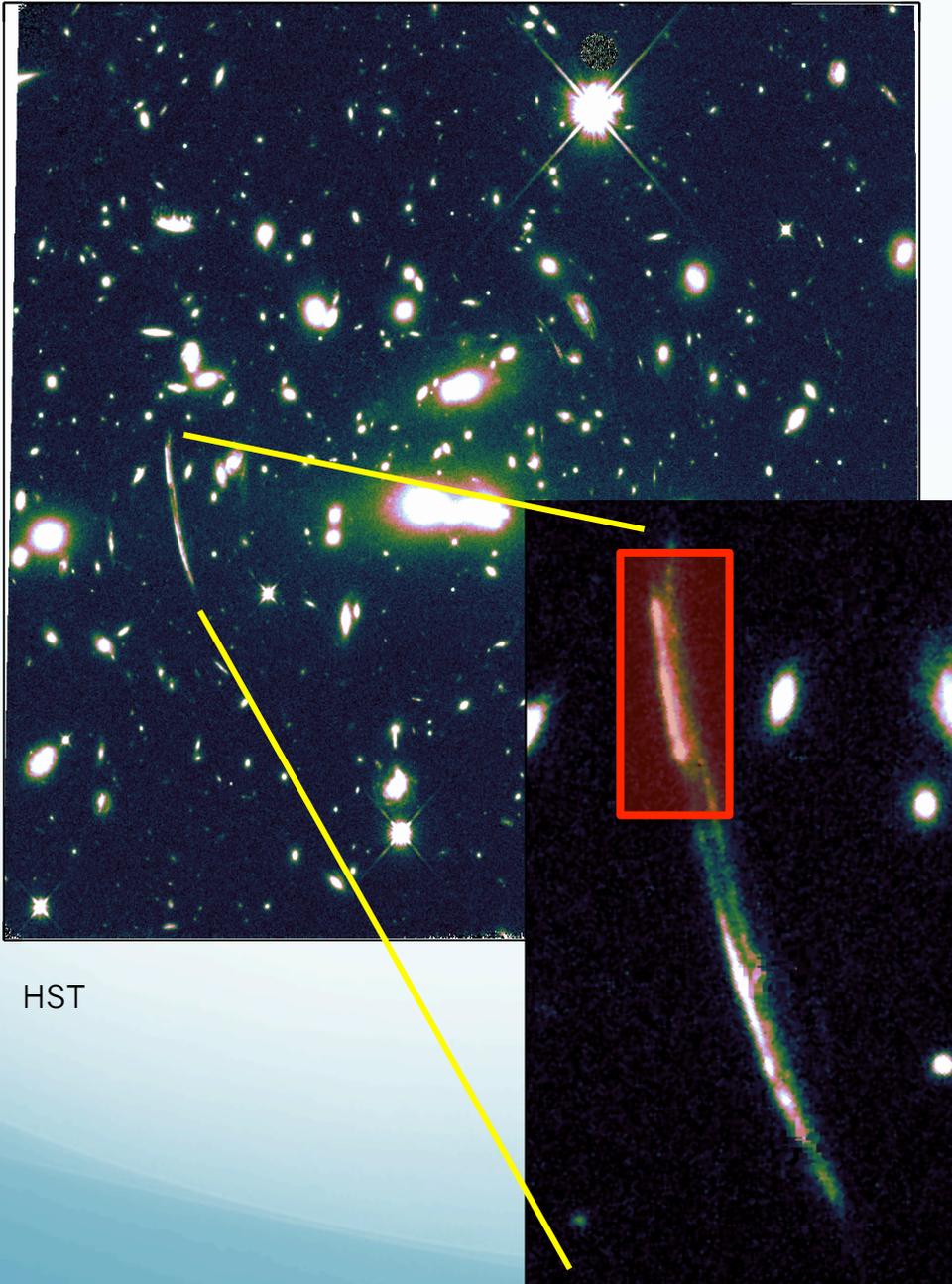
Two galaxies?



SOURCE PLANE

MACS 0451

- Galaxy cluster from MAAssive Cluster Survey
- Lens $z = 0.43$
- Source $z = 2.01$
- $\mu \sim 12$



Cluster Lens Modelling

Focus images back to source plane using:

Mass: Singular Isothermal Sphere (SIS)

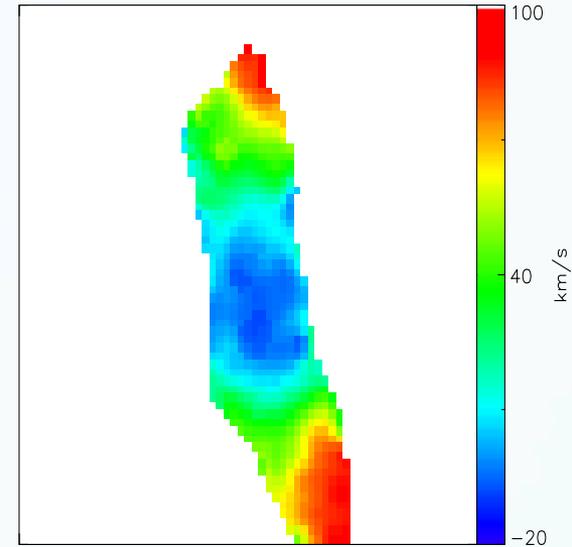
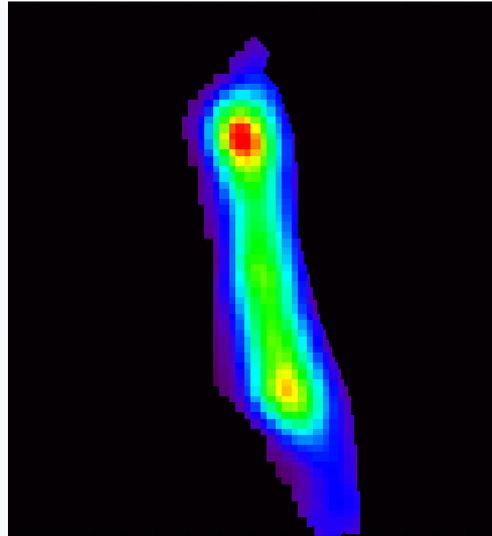
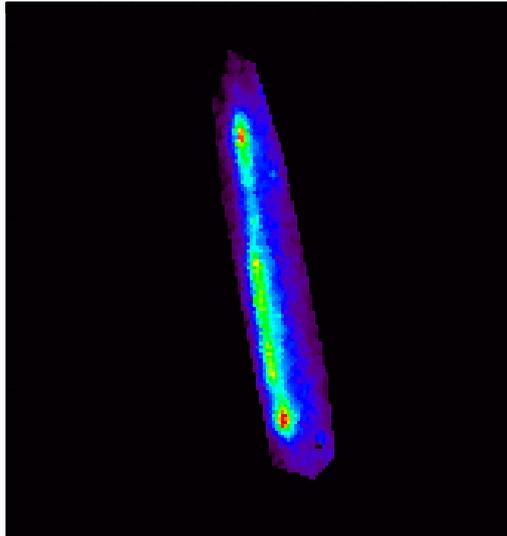
Cluster: SIE dark matter halo

HST

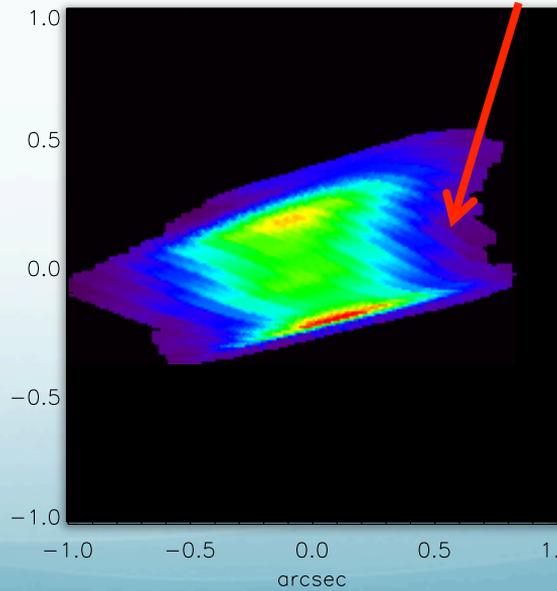
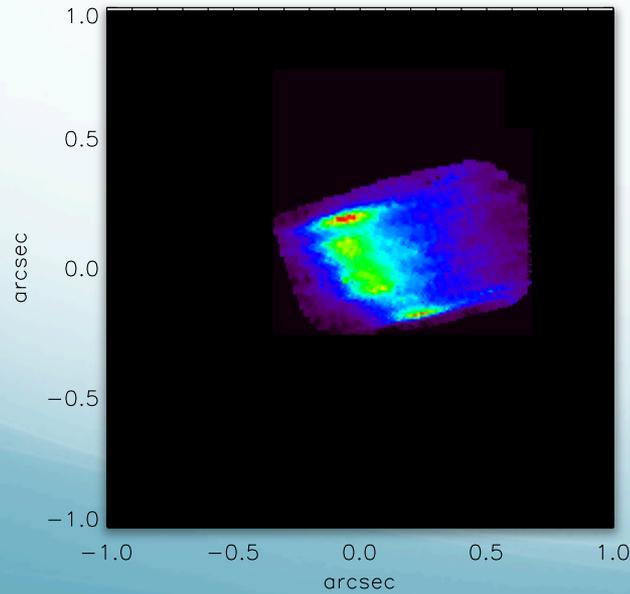
HALPHA

VELOCITY

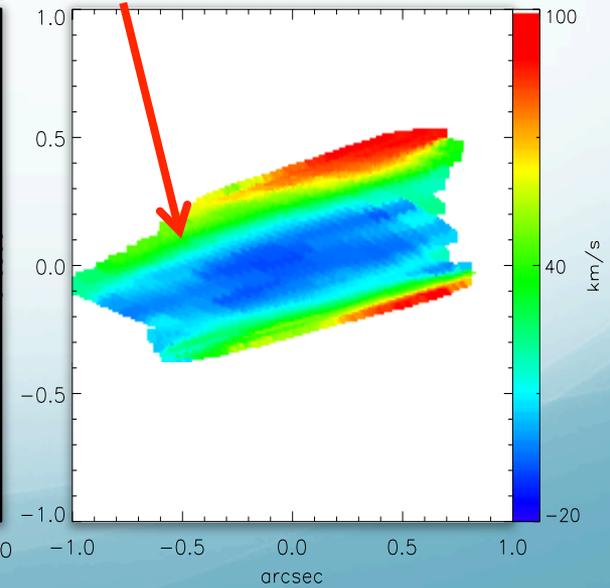
IMAGE PLANE



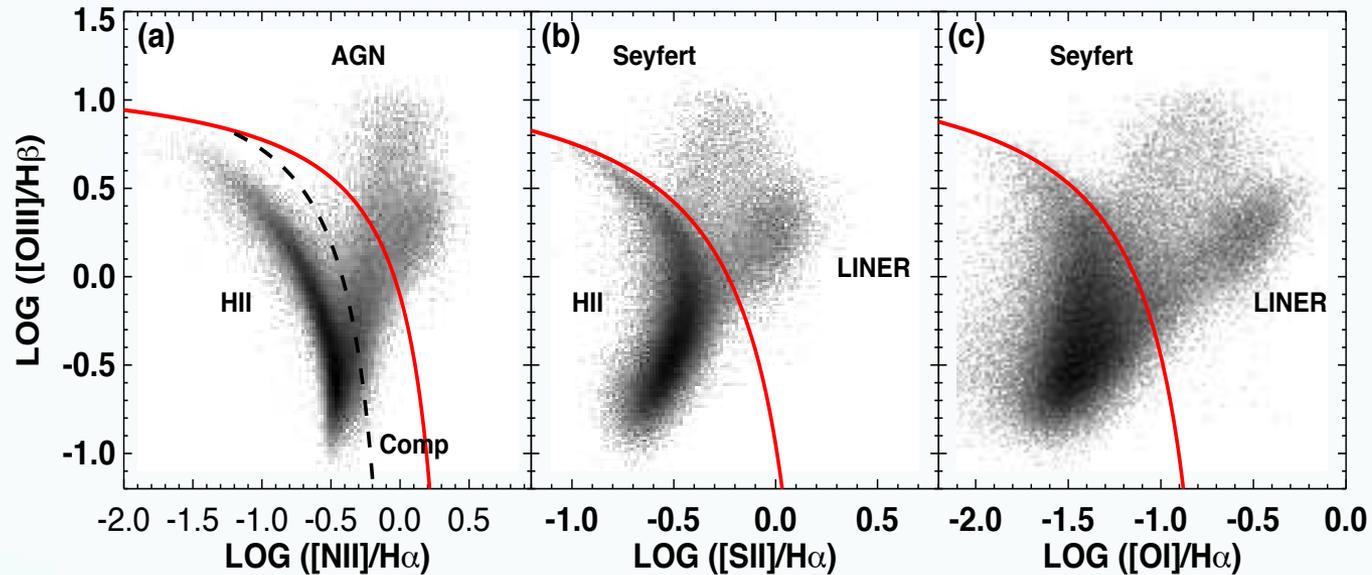
SOURCE PLANE



A warning on resolution!



BPT Diagnostic Diagram

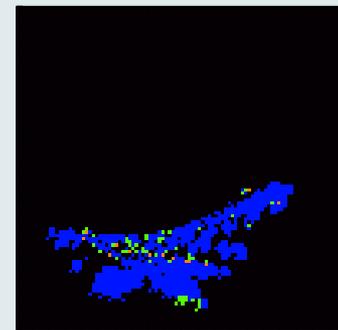
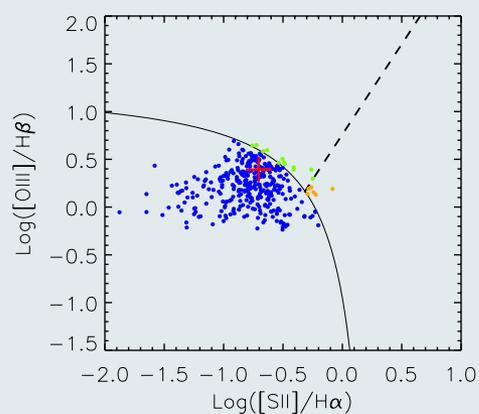
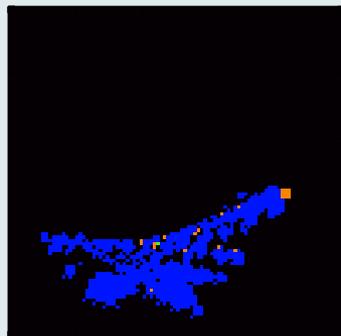
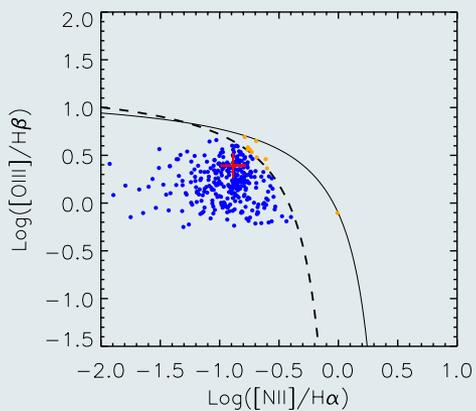


Kewley et al. (2006)

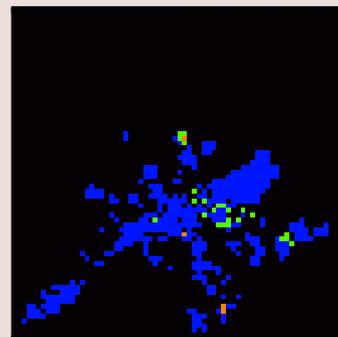
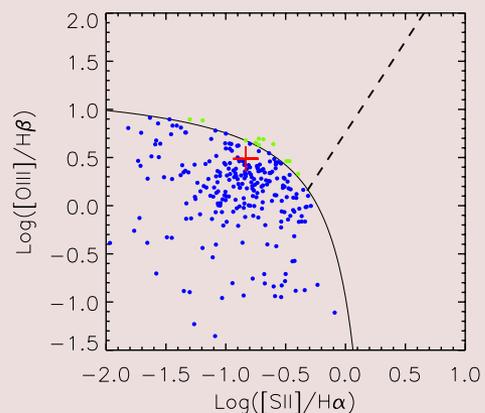
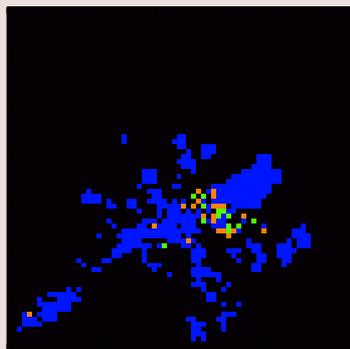
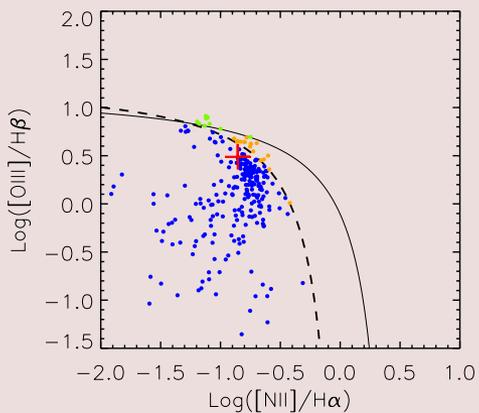
- Use emission line ratios to classify galaxies

$[OIII]/H\beta$ Vs $[NII]/H\alpha$ $[OIII]/H\beta$ Vs $[SII]/H\alpha$

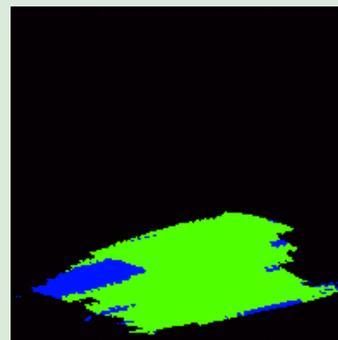
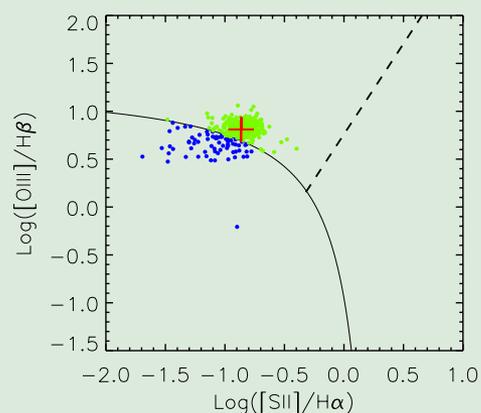
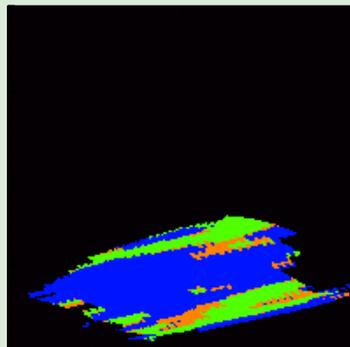
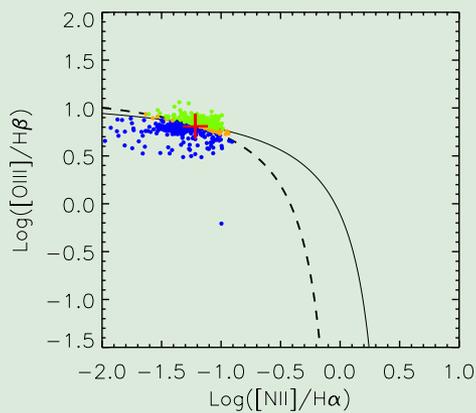
Horseshoe



CSWA

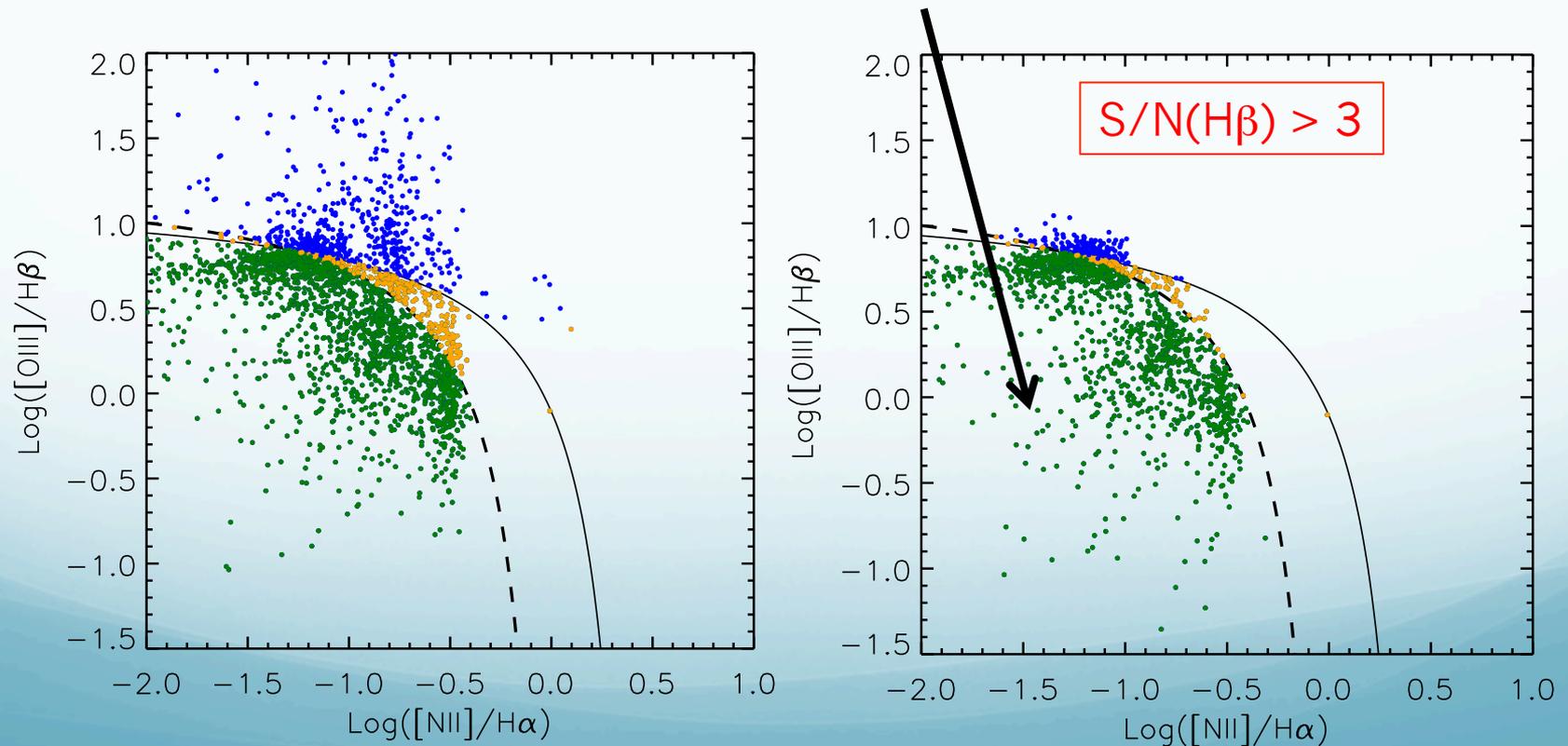


MACS 0451



Full Sample

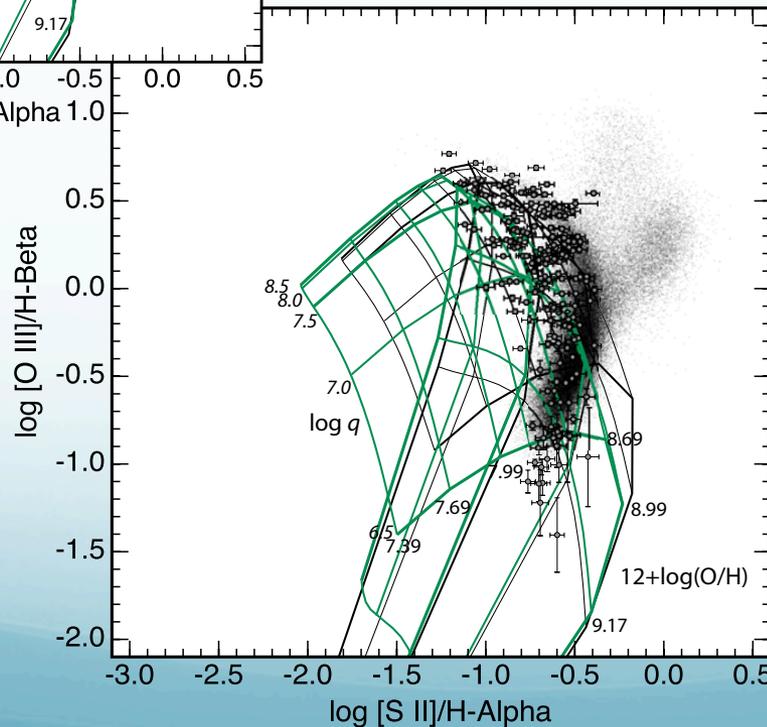
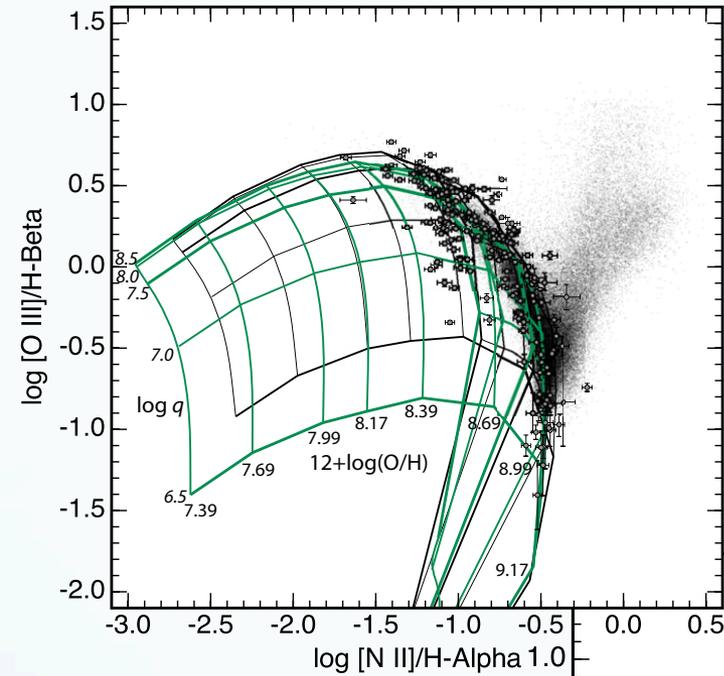
- There have been previous claims of high- z galaxies being above the local discrimination \rightarrow probably partly due to low **S/N on $H\beta$**
- Possible selection effects from previous studies \rightarrow do not observe the diffuse gas in the outskirts, which we do detect with lensing as it is non-preferential.



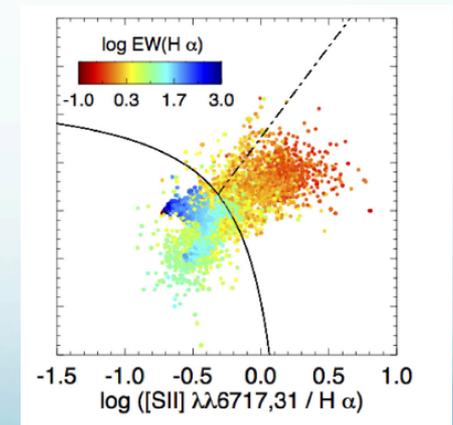
Dopita +13 Models

-> Low ionisation region

Possibly now also seen in local IFU data from MANGA

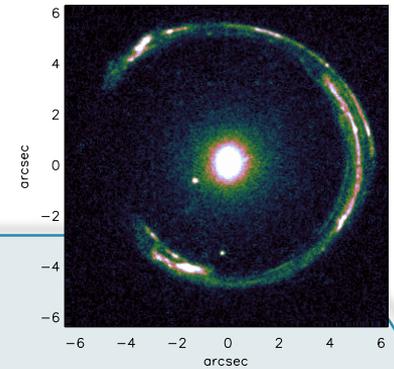


Dopita et al, 2013



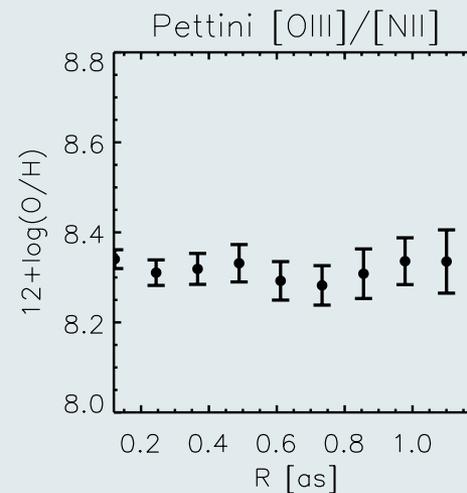
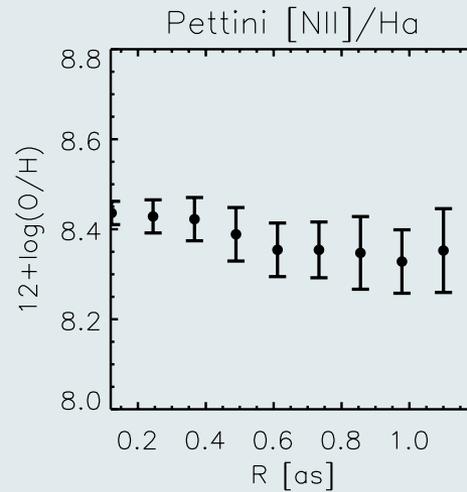
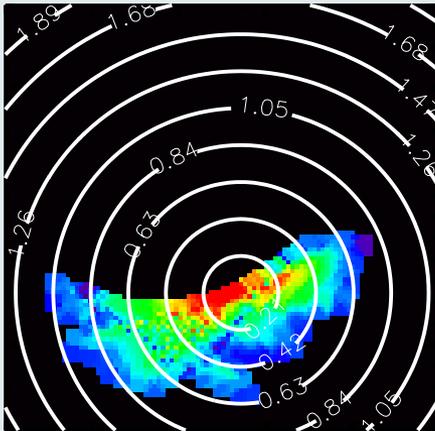
Belfiore et al., 2015

Metallicity Gradients

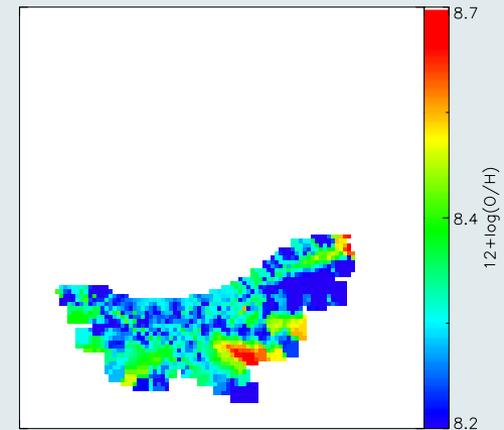


Horseshoe

H α



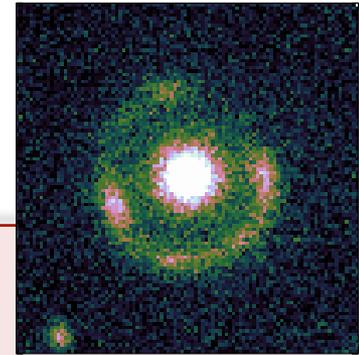
$12+\log(O/H)$



➤ Flat gradient

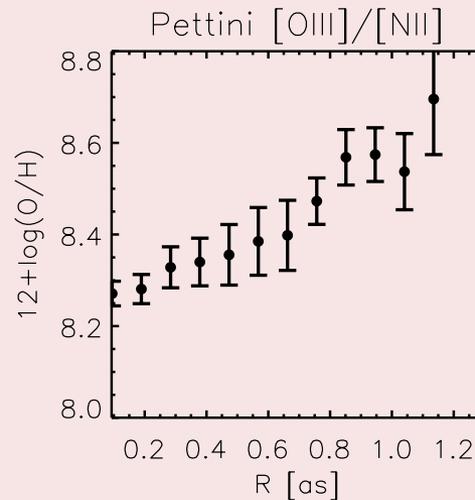
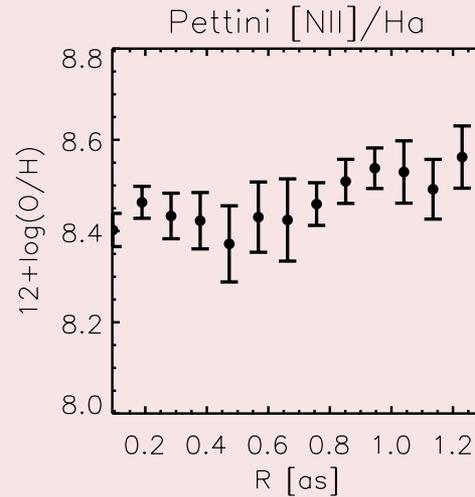
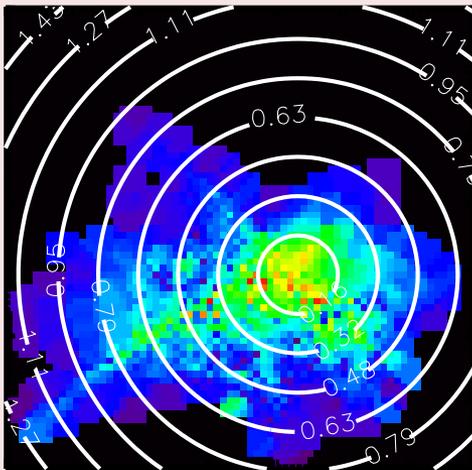
1'' ~ 8.3 kpc

Metallicity Gradients

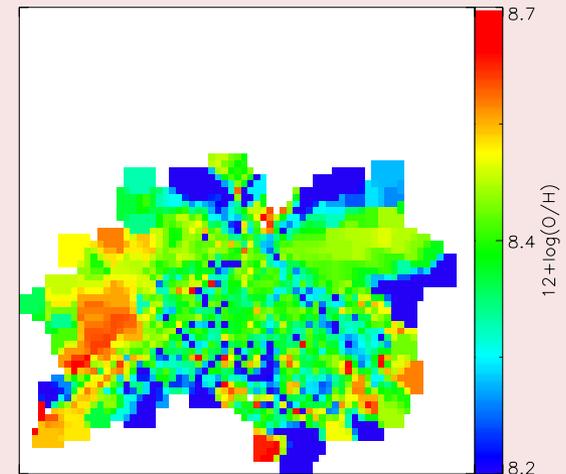


CSWA

Halpha



12+log(O/H)



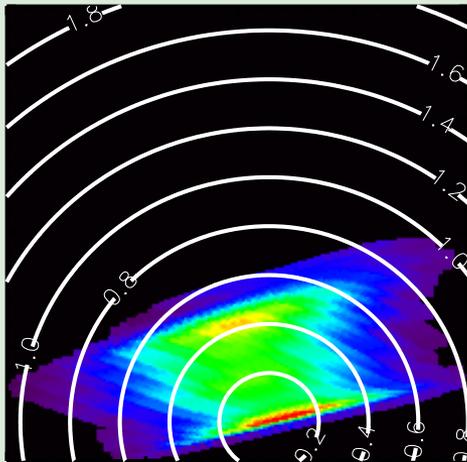
➤ Looks like an **inverted gradient**, **BUT** actually due to the **companion galaxy**

1" ~ 8.2 kpc

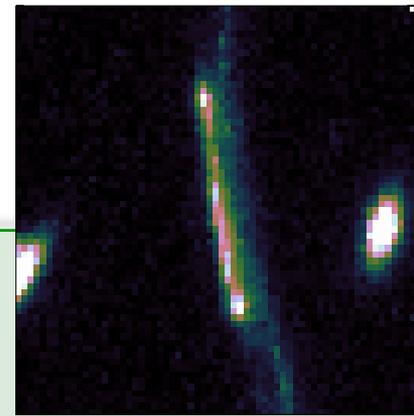
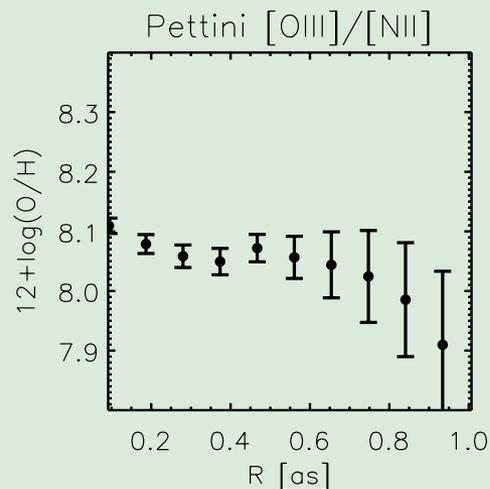
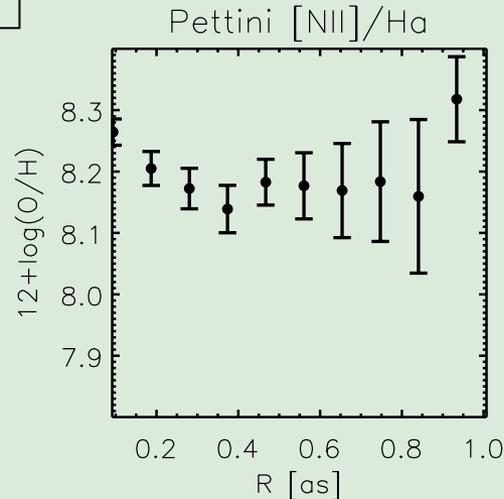
Metallicity Gradients

MACS 0451

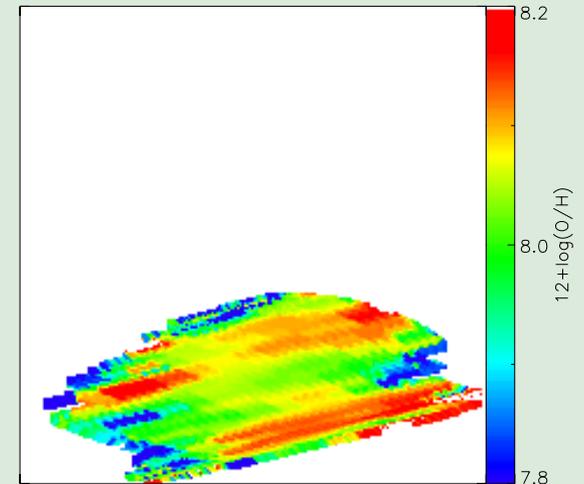
Ha α



$1'' \sim 8.5$ kpc



$12+\log(O/H)$

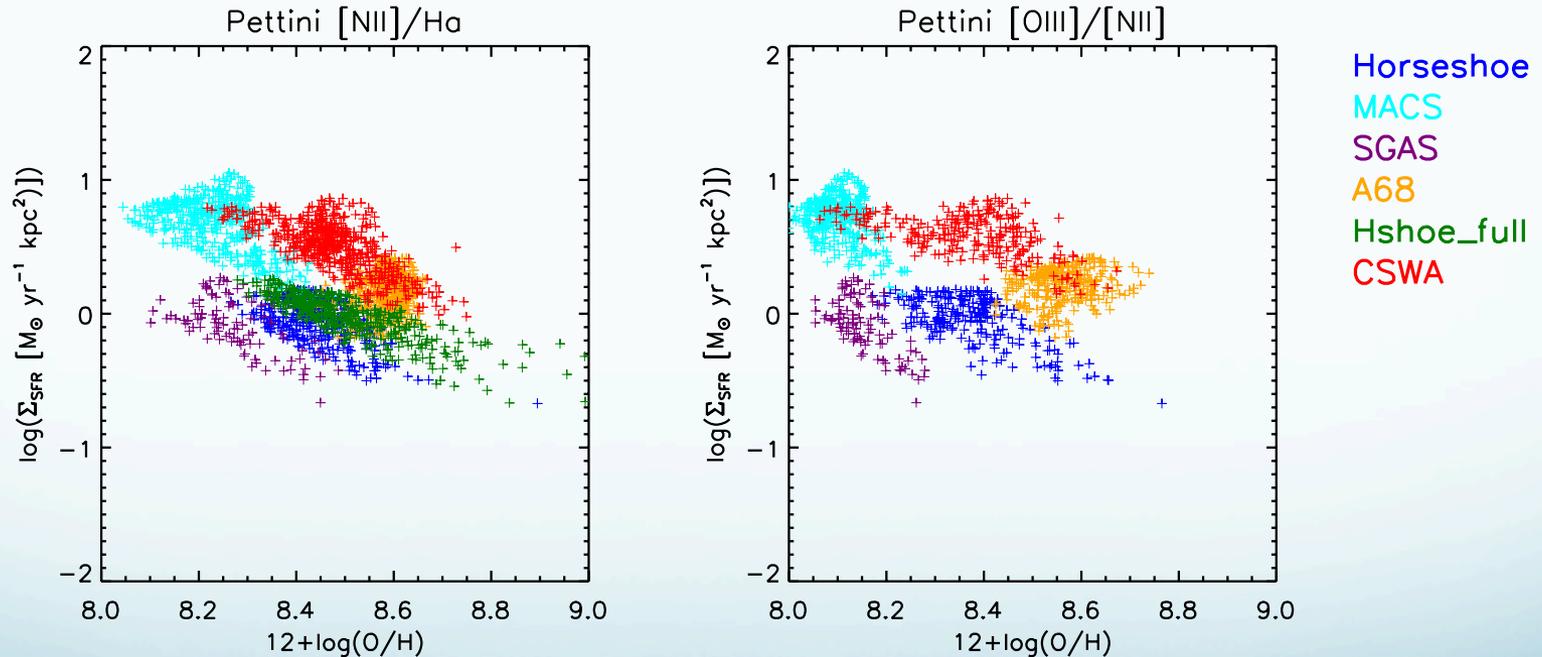


➤ Messy gradients due to interacting galaxy

FULL ANALYSIS TO COME ...

Σ_{SFR} Vs. Metallicity

- Previous works at high-z have found an inverse correlation between Σ_{SFR} and metallicity (e.g. Cresci+10, Troncoso+14) interpreted as evidence of metal poor inflows.



- Some galaxies show this trend individually but not always the case

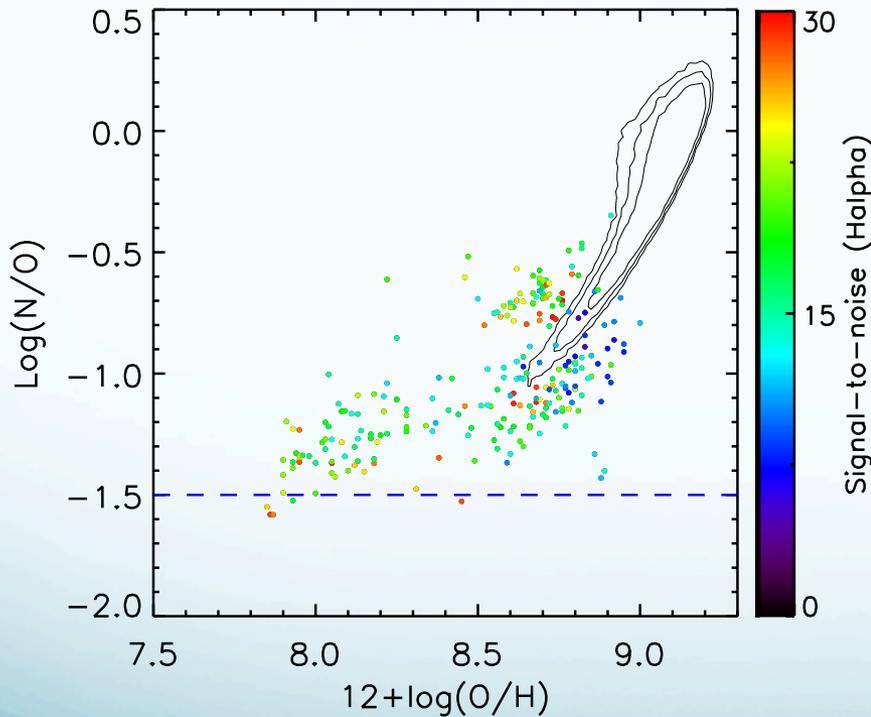
Nitrogen Vs. Oxygen

- Nitrogen is sensitive to chemical evolution in galaxies:
 - Low Z: primary origin independent of metallicity
 - Higher Z: becomes secondary product & directly proportional to the metallicity
- Try to break degeneracy between nitrogen abundance and metallicity
 - Measure N/O using calibration from Perez-Montero +09

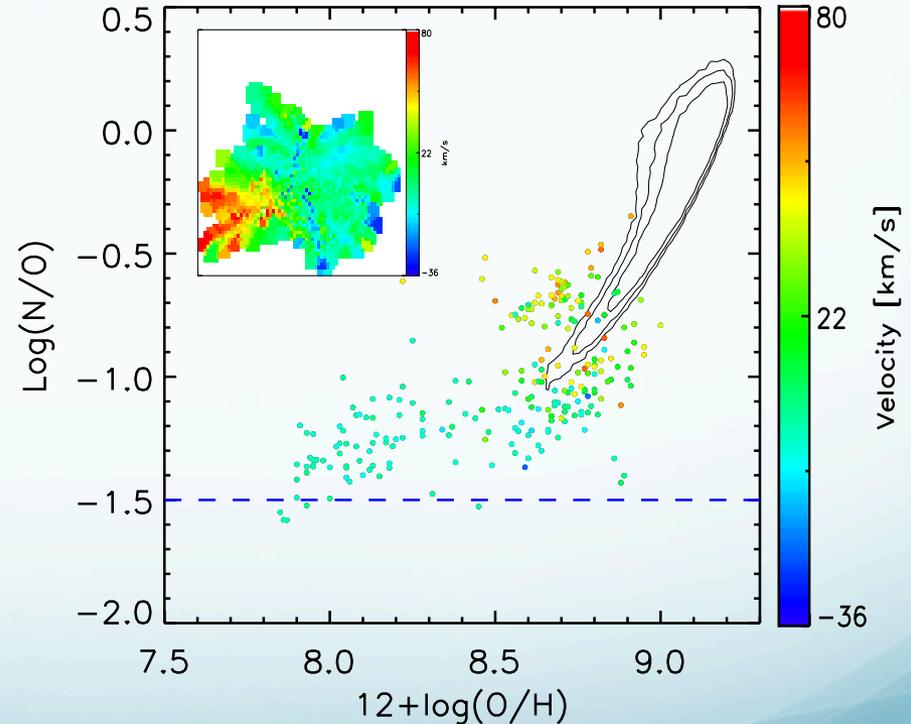
Nitrogen Vs. Oxygen

CSWA

Colour-code by S/N($H\alpha$)



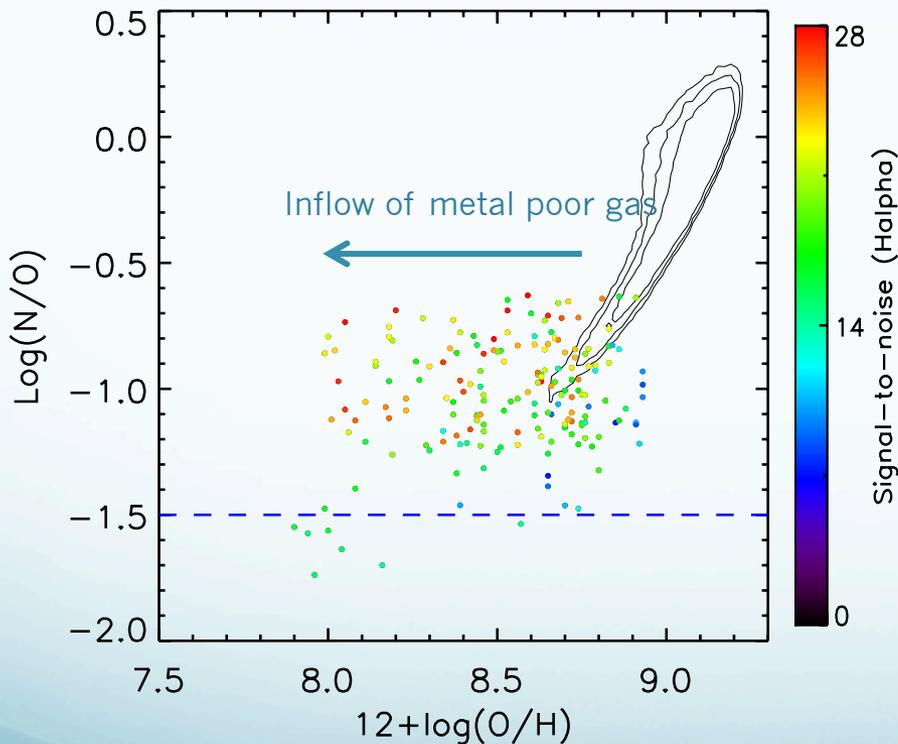
Colour-code by velocity



- Further evidence for 2 galaxies with different nitrogen enrichment (i.e. different star formation histories, evolved vs. young)

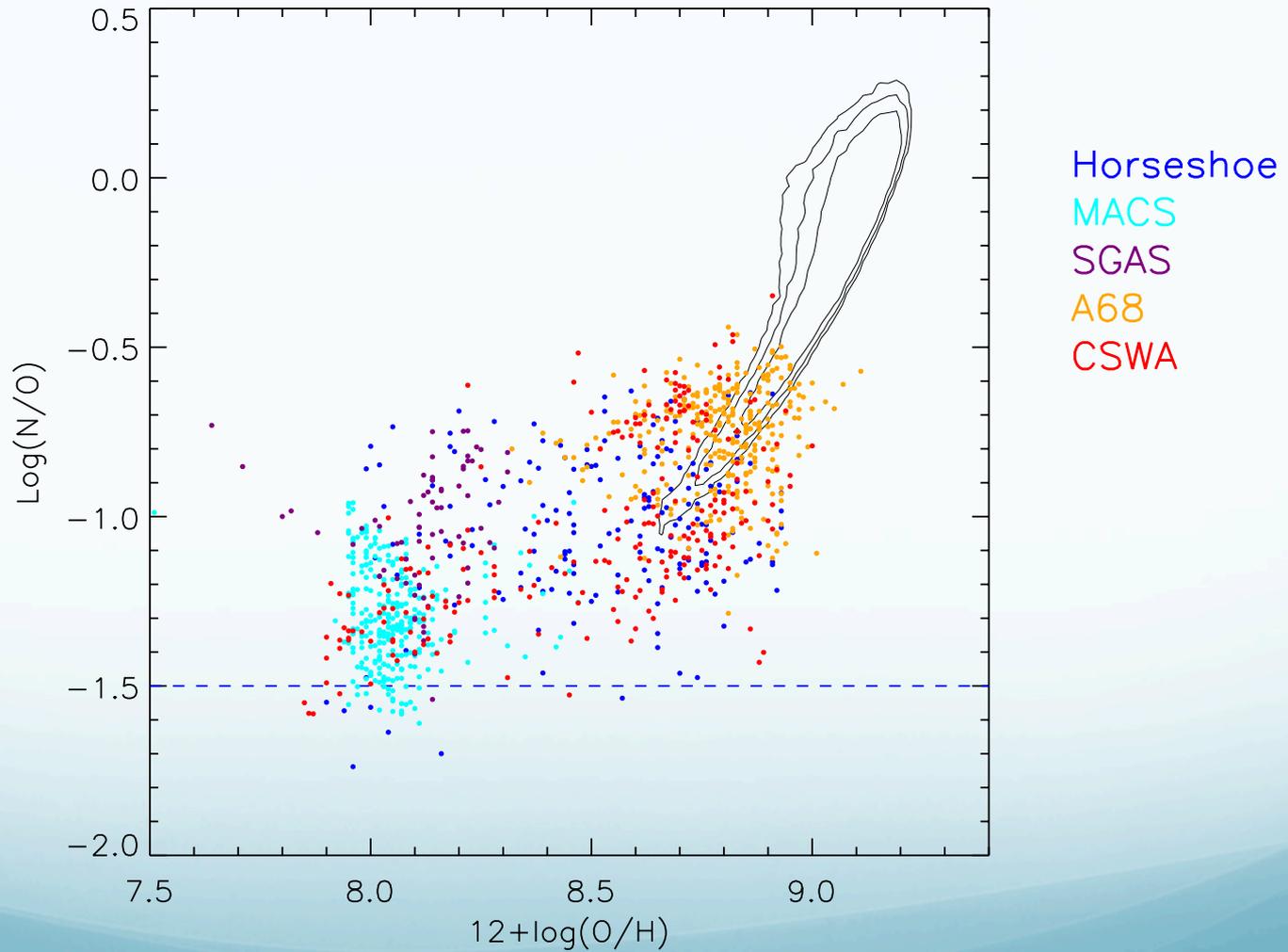
Nitrogen Vs. Oxygen

Horseshoe



- Horizontal distribution has also been seen in MANGA (Belfiore +15).
- Interpreted as **dilution** :
 - Inflows of metal poor gas dilute the metallicity while only have a small effect on N/O
- OR **fountain effects**:
 - central high N/O gas ejected, mixing with metal poor gas in outskirts

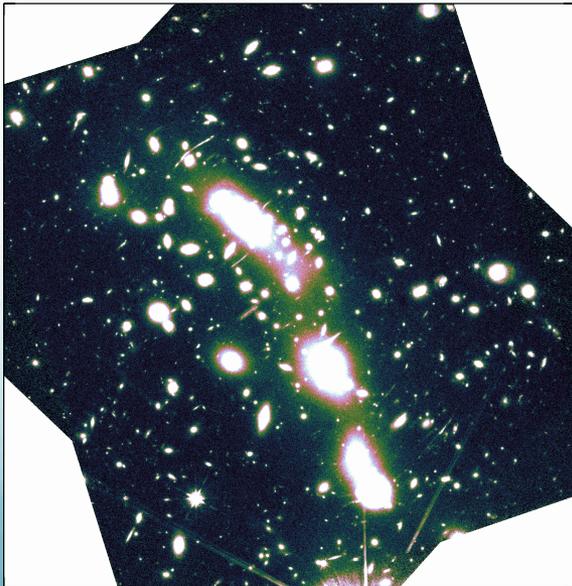
Full Sample



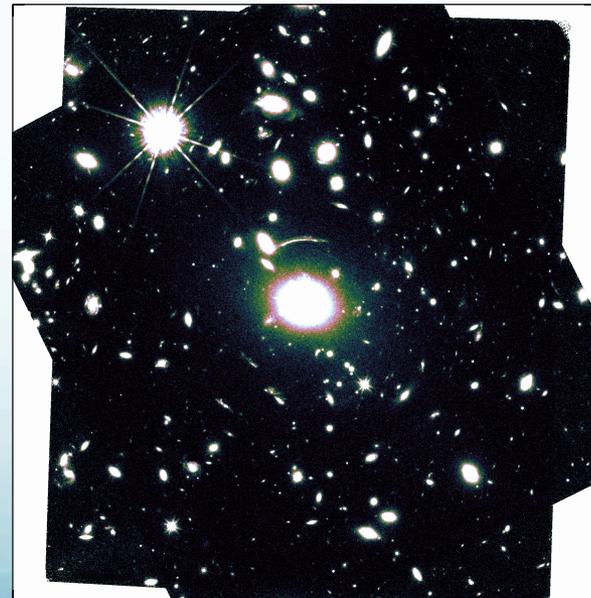
More to come – KMOS !

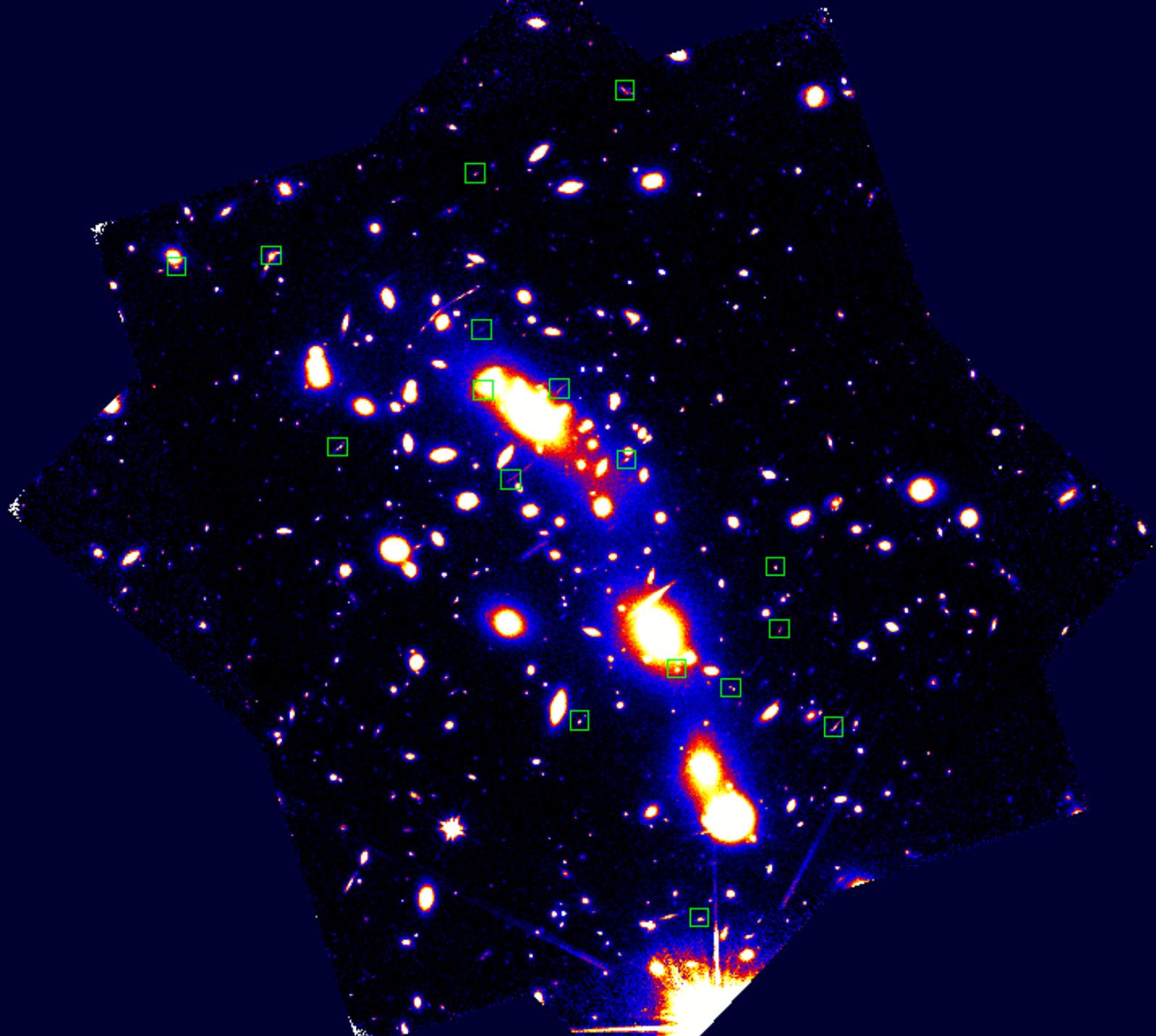
- KMOS: IFU with 24 arms each with FoV: $2.8 \times 2.8''$ in H,J,K band
- Pilot program to study lensed galaxies at $z=1.5-2$ in 2 CLASH clusters:

MACS 0416-2403



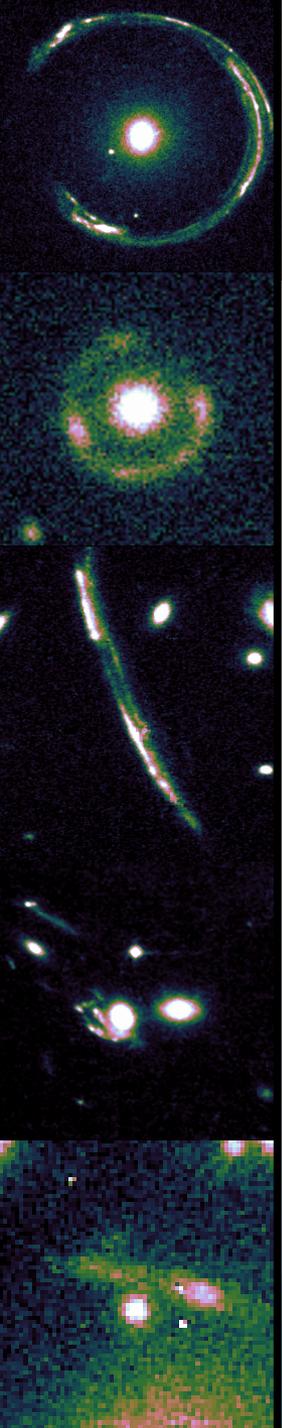
MS2137-2325 (being observed)





Conclusion

- Studying lensed galaxies at $z \sim 2$ with multiband SINFONI detections for 5 galaxies
- Can obtain metallicity gradients in the source plane using multiple diagnostics.
- Disentangle nitrogen abundance & metallicity to study the chemical evolution.
- More galaxies to come from KMOS pilot program of lensed galaxies in 2 galaxy clusters.



Fountain & Dilution Effects

