Planetary Nebulae with MUSE and BlueMUSE

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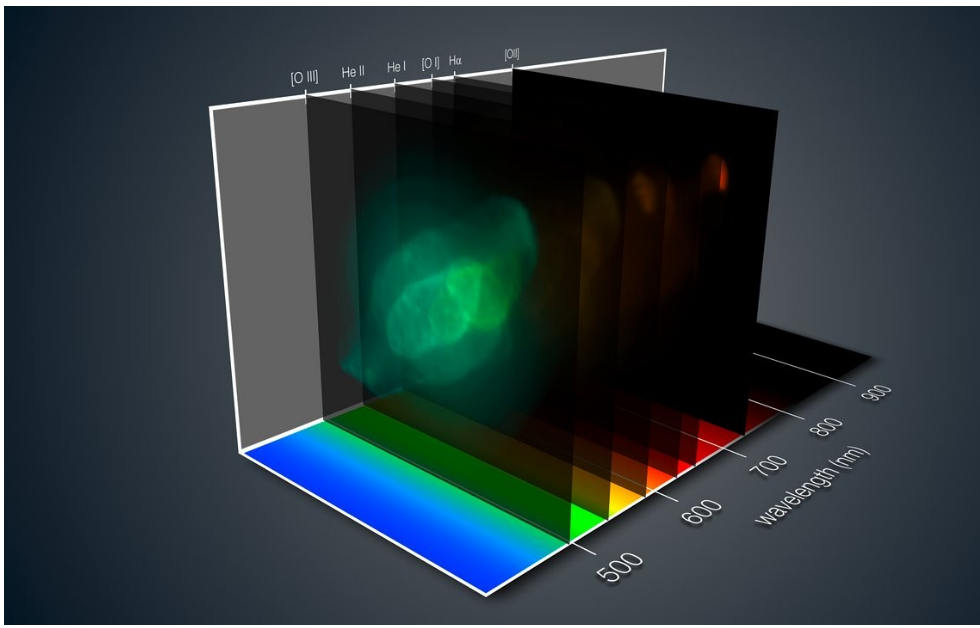


NGC 7009 with MUSE

PN with MUSE + BlueMUSE

Diagnostic emission line spectroscopy has been strongly based on planetary nebulae, with a rich history dating back to Nebulium (Huggins, 1864)

Outline:

- Match of MUSE capabilities to planetary nebulae (PNe)
- Mapping of NGC 3132 and NGC 7009 as examples: diagnostic lines, N_e, T_e , abundances
- Extra-galactic PNe role for MUSE
- BlueMUSE advantages: blue λ's, increased field & spectral resolution over MUSE; tackling the ADF problem

Why study PNe?

Tool to understand low masss stellar evolution (AGB phase)

Tracers for ISM chemical content

Some elements unchanged since formation; some enriched (s-process)

Laboratories to study ISM with a range of physical properties:
+ high to low ionization
+ compact high density knots *vs.* extended low density haloes
+ wide range in T (from cool neutral to 10^6 K)

Distance indicators

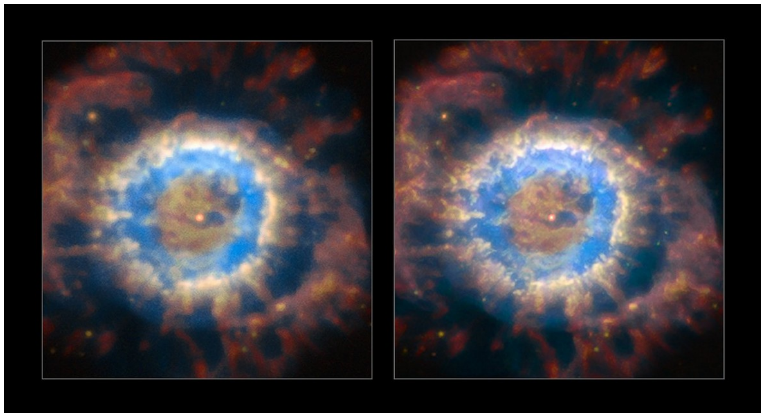
Probes of stellar populations

Tracers of galactic dynamics

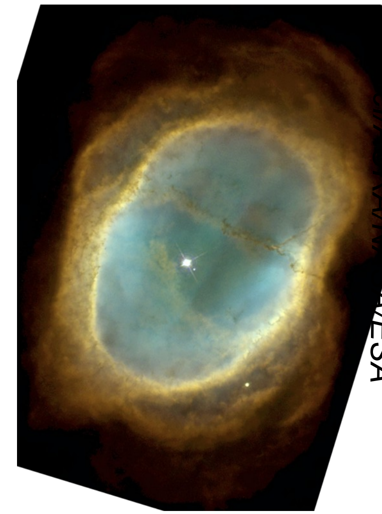
MUSE: Spatial match to PN images

- ✓ FoV ideally suited to size of Galactic PNe
- ✓ Tiling for larger nebulae
- ✓ Construct region spectra aimed at specific (e.g., morphological) features (shells, knots, ionization domains) or slit/apertures for comparison to complemetary spectroscopy in optical and other wavelengths (e.g., IR)

15 PNe observed during Commissioning of WFM, WFM+AO and NFM modes

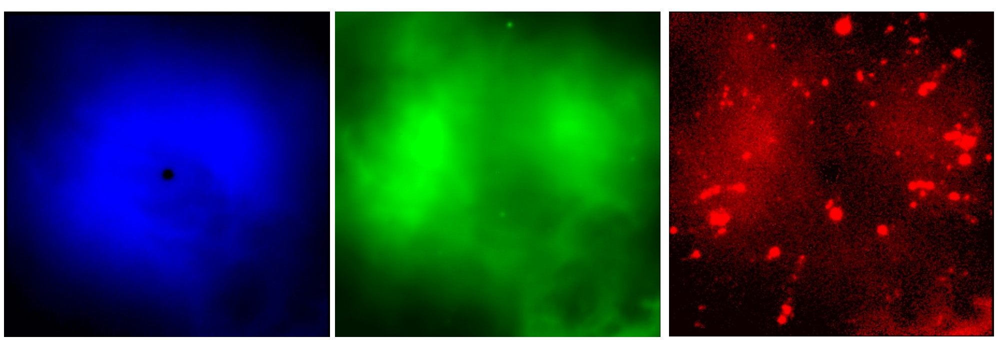


NGC 6369 without (left) and with (right) AO

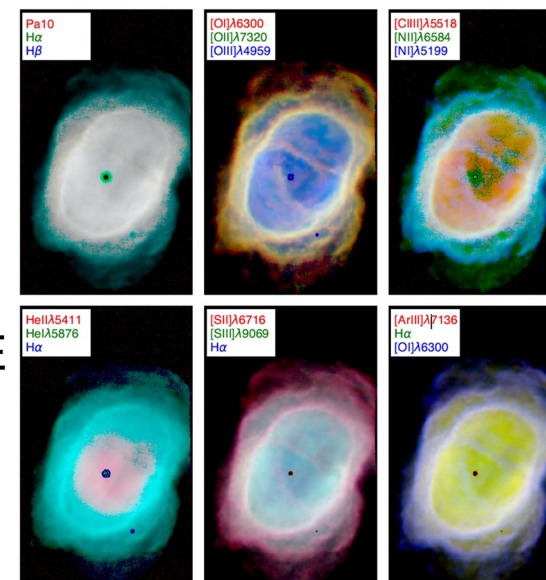


Credit:

NGC 3132 with HST



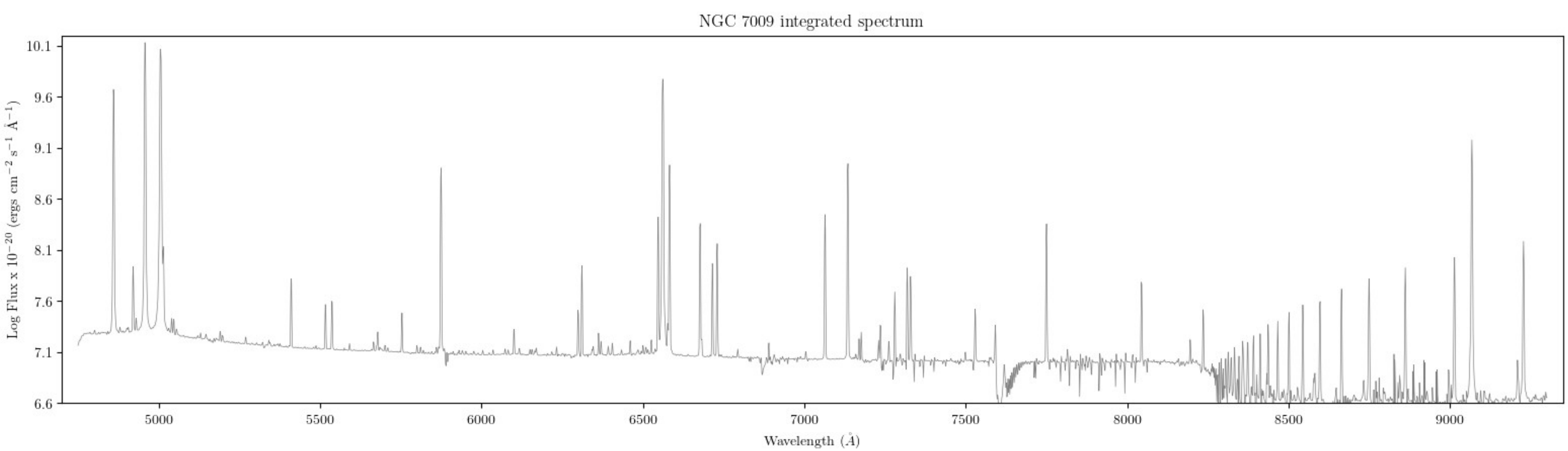
NGC 4361 He II 5411Å (left), [O III] 5007Å (centre), [N II] 6583Å (right) with WFM (Comm. 2A)



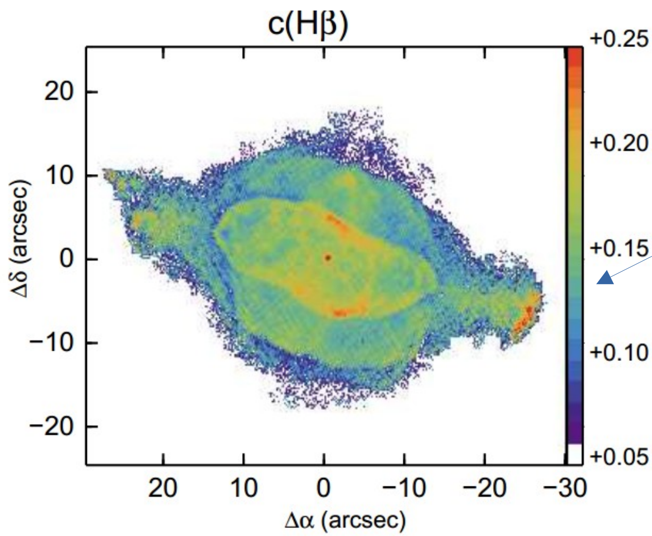
NGC 3132 with MUSE

MUSE: Spectral match for PN

- ✓ Potentially hundreds of emission lines in single shot at S/N > 100
- ✓ Spectral resolution R~2500, line blends for <3Å sepn. - deconvolve or synthesize spectra, but some limited velocity work possible
- ✓ T_e from [O I] 6302/5577Å, [N II] 6583/5755Å, [S III] 9069/6311Å and [Ar III] 7135/5192Å
- ✓ For N_e use [S II] 6716/6731Å, [Cl III] 5517/5537Å and [Ar IV] 4711/4740Å
- ✓ Wavelength coverage lacks [O III]4363Å (essential for [O III] T_e) and [O II]3727Å but much weaker [O II] 7319,7320,7330,7331Å blend available for O^+
- ✗ He II 4686Å only in Extended range, but 5411Å available (x10 fainter) in standard range
- ◆ Extended range covers some O recombination lines; standard range covers N II and some (v. faint) C II lines
- ◆ Capability for classical (UV-blue-red) ionization level coverage: He^+, He^{++}, N^+, O^0, O^+, O^{++}, S^+, S^{++}, Ar^{++}, Ar^{+++}, Ne^{+++}, but not Ne^{++}



NGC 3132 and 7009 with MUSE



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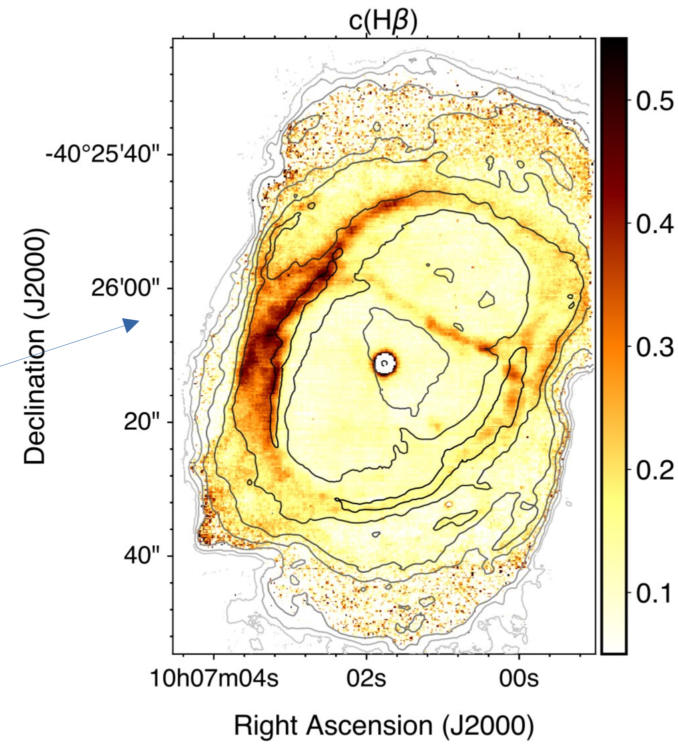
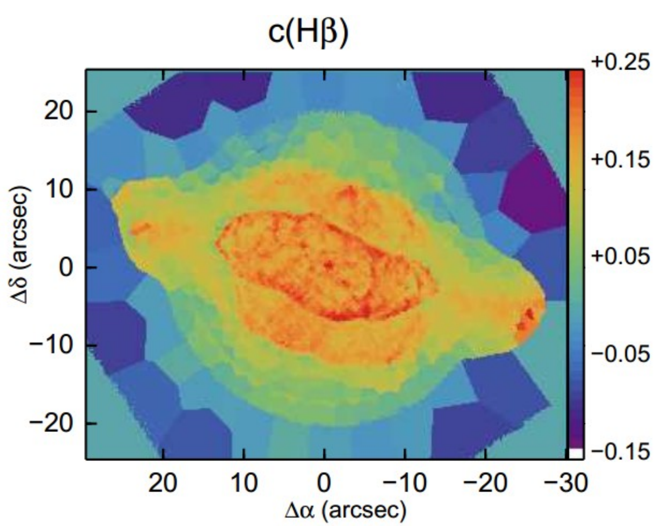


NGC 3132 c map from Hα/Hβ
(Monreal-Ibero & Walsh, 2020)

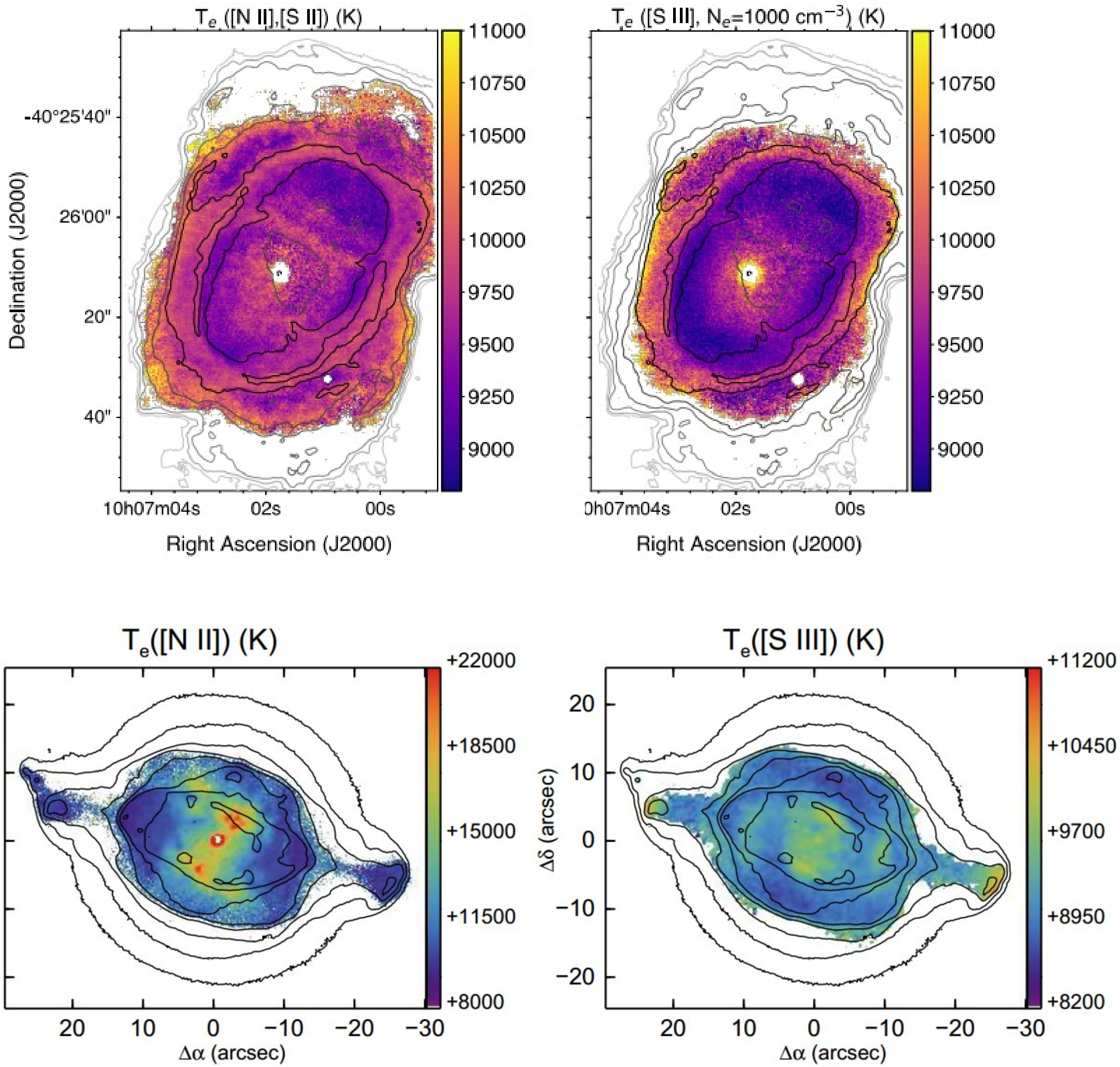


NGC 7009 c maps – per spaxel (upper), Voronoi tesselated to Hβ S/N (lower). (Walsh et al. 2016,2018)

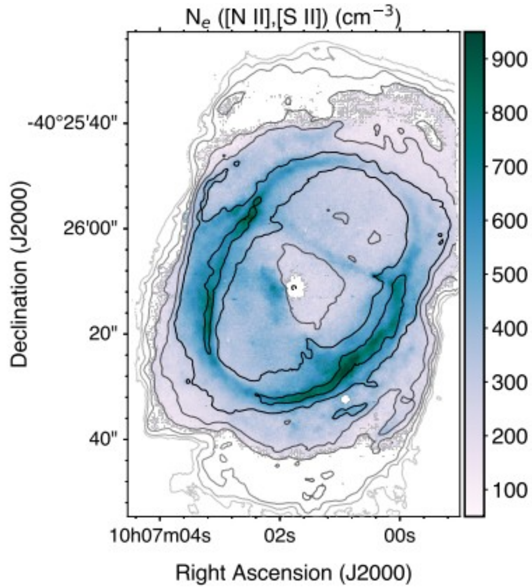
Both PNe show direct presence of small- and large-scale dust within ionized volumes

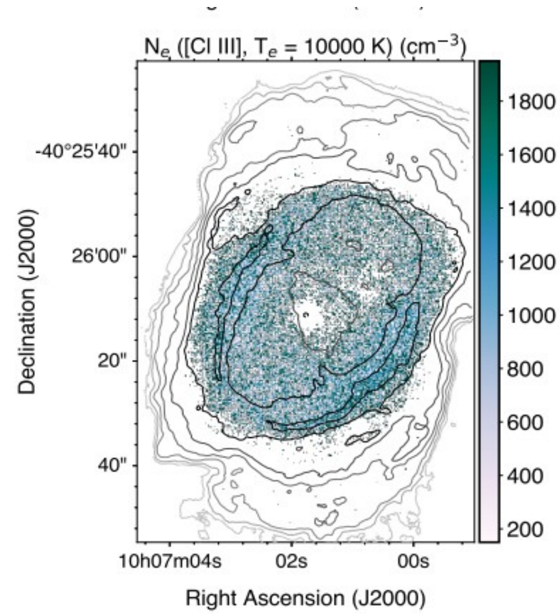
Determine extinction from both Balmer (Hα/Hβ) and Paschen (P9 - >P20) lines – investigate λ dependence of differing reddening laws

T_e maps of NGC 3132 and NGC 7009

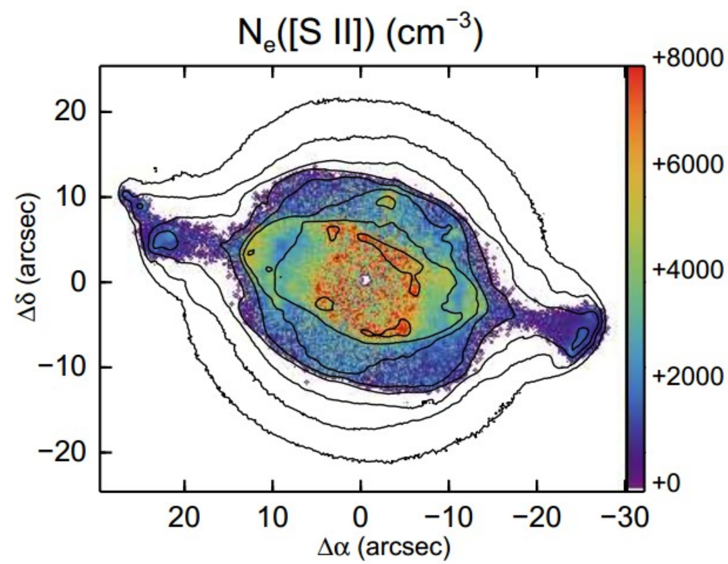


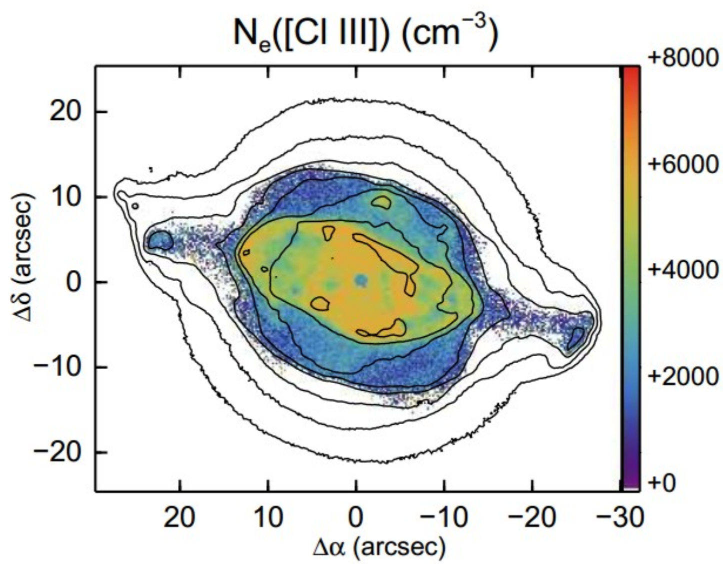
N_e maps of NGC 3132 and NGC 7009



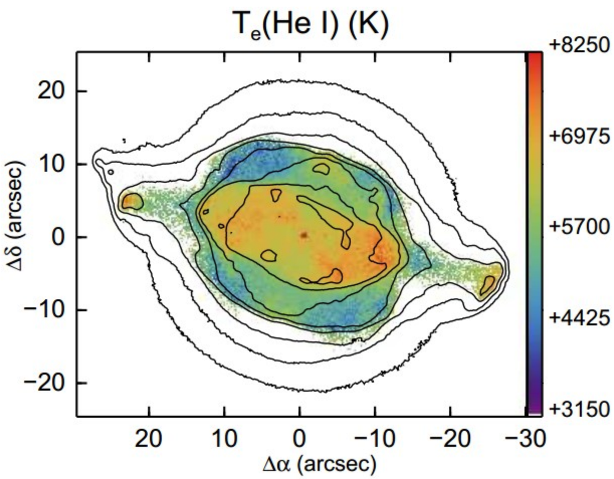


[Cl III]5517/5537Å S/N too low for full single spaxel determination!

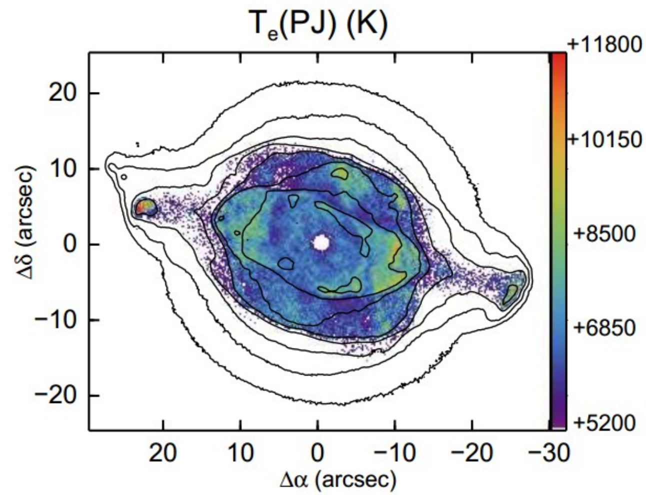




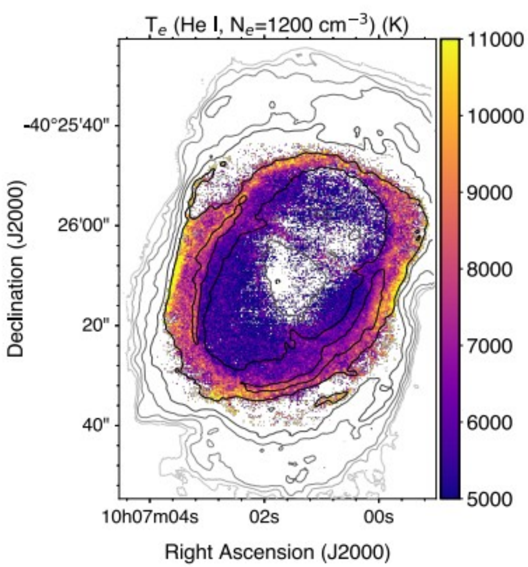
Other T_e maps of NGC 7009 and NGC 3132

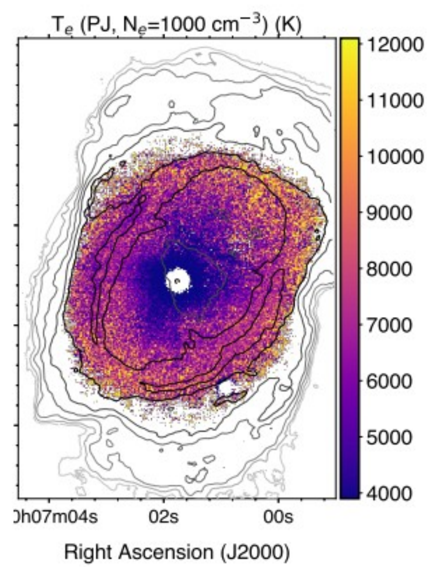


T_e from He I 6678/7281Å (Fang&Liu2011)



T_e from Paschen Jump (8200Å)/P11 (8863Å)

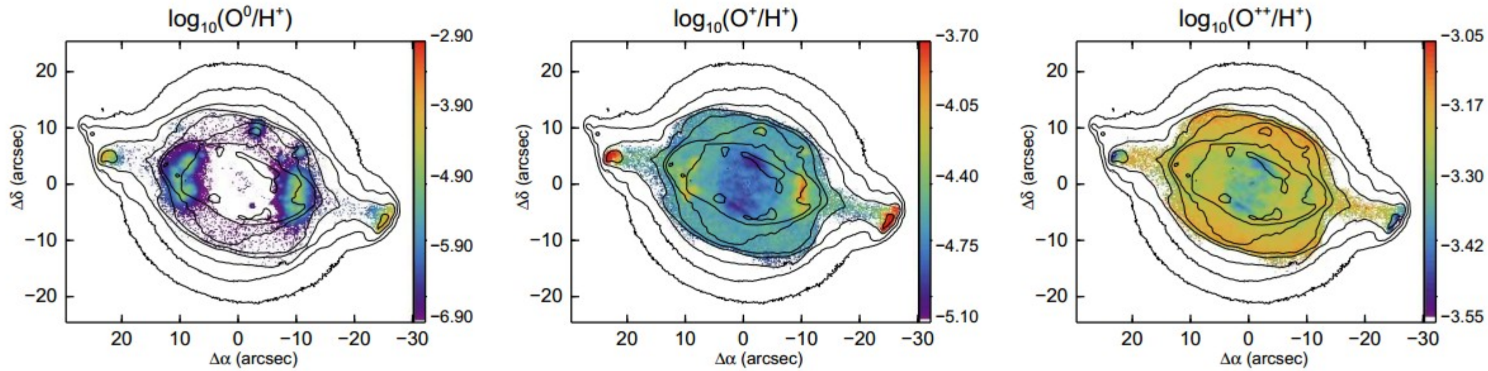




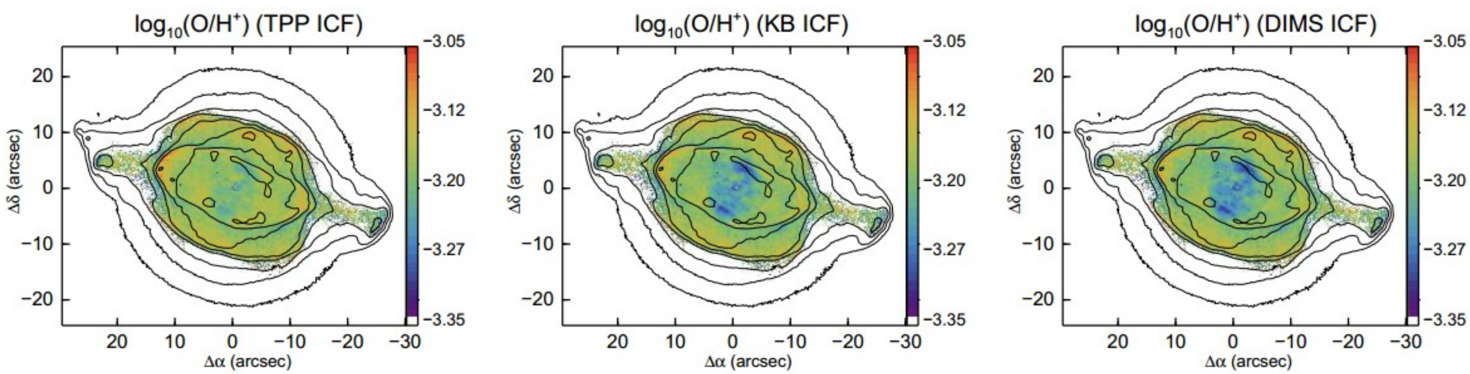
Other collisionally excited line T_e, N_e indicators:
[O I] T_e from 6302/5577Å
[Ar III] T_e from 7135/5192Å
[Ar IV] N_e from 4711/4740Å

Other recombination line T_e, N_e indicators:
T_e from N II 5667/5680Å
N_e from high Paschen line ratios
(Fang&Liu2011)

Mapping O/H abundance – NGC 7009



Maps of O^0/H, O^+/H and O^{++}/H for NGC 7009



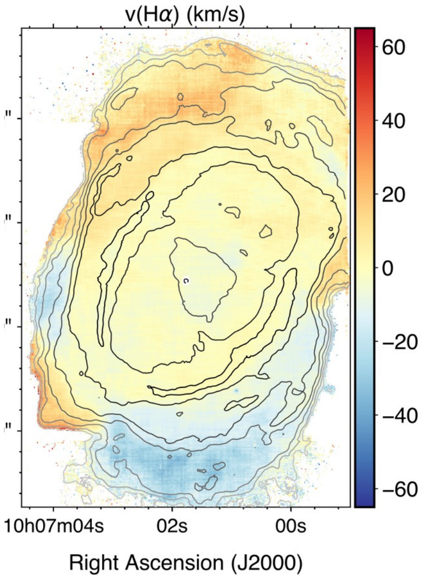
Experiments applying different O Ionization Correction Factors (ICFs) to correct for presence of O^{+++}:

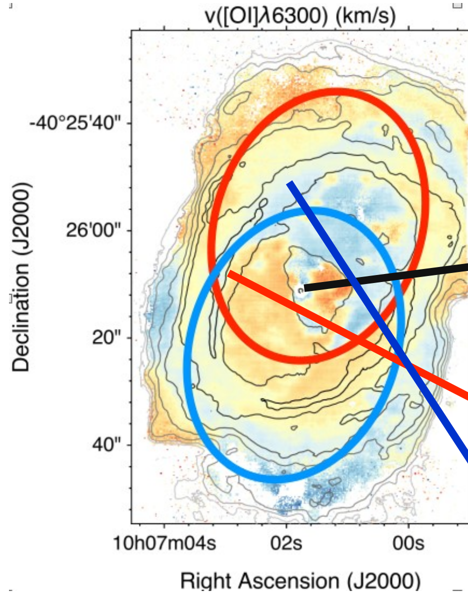
Left: ‘Classical’ (Torres-Peimbert & Peimbert, 1977);

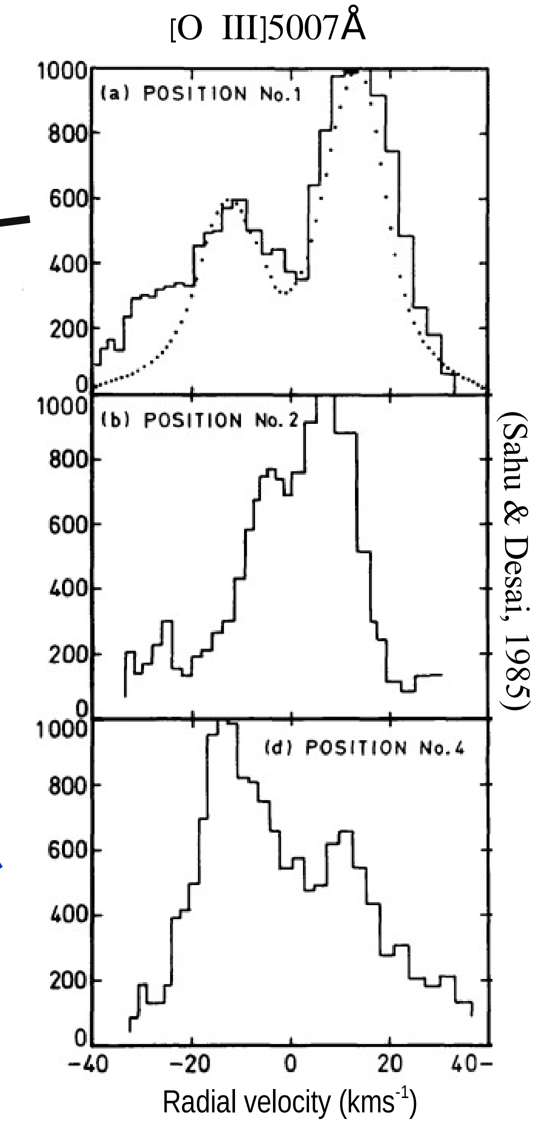
Middle: Amended ‘classical’ (Kingsburgh & Barlow, 1994);

Right: Model based (Delgado-Inglada et al. 2014).

NGC 3132 kinematical analysis







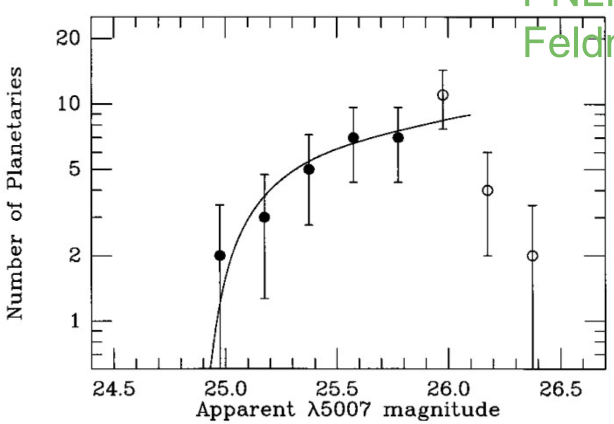
- Some velocity work possible
- PN typically have expansion velocities 15-50 kms^{-1}
- At MUSE 1800<R~3000, cannot resolve expansion but for changing -ve to +ve velocity component line ratio, shift of blended line detectable
- Depending on emission zone (higher ionization more concentrated; lower IP more distant and in shells) detect evidence of expanding velocity field – e.g., diabolo model for NGC 3132 (M-I&W, 2020)
- In cases of (rare) high velocity features (<~500 kms^{-1}), MUSE can resolve individual components

MUSE suitability for extra-Galactic PNe

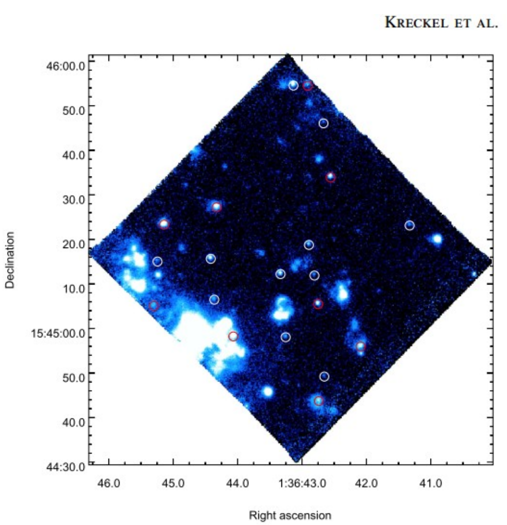
Extra-Galactic PNe (unresolved at > 1Mpc) observed in nearby (<~30Mpc) galaxies from their strong emission ([O III]5007Å). Important for distance determination through the [O III] PN luminosity function (PNLF), which is almost constant with galaxy morphological type

- With its large field, MUSE can locate PNe in nearby galaxies and clusters (e.g. Fornax (D=20 Mpc), Sarzi et al. 2018) and measure radial velocities
- NGC 300 (D=1.9 Mpc) resolved stellar pops and PNe of nearby galaxy (Roth et al. 2018)
- NGC 628 (D=9 Mpc) detection of multiple emission lines (e.g. [O III], Hα, [N II]) to distinguish PN from HII Regions, emission line stars (e.g., WR stars) and SNRs (Kreckel et al. 2017; presentation)
- NGC 1052-DF2 (D=19 Mpc) – 3 PNe discovered (Emsellem et al. 2019; Fensch et al. 2019)

PNLF in M101 (D=8 Mpc)
Feldmeier et al. 1996

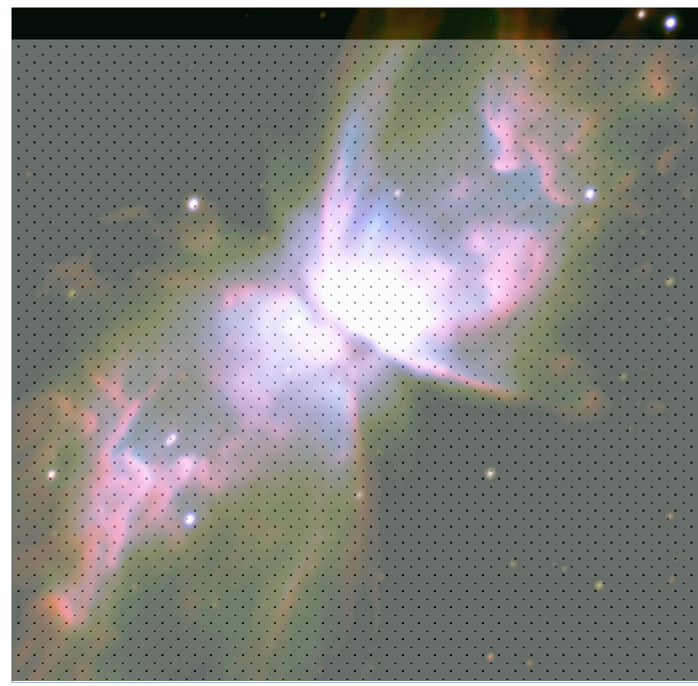


MUSE field in NGC 628
with PNe (white circles)



BlueMUSE role for study of PNe

- The blue region (3500 – 4700Å) brings a powerful set of diagnostics for PN studies
- [O III] 4363Å for determination of [O III] T_e (by ratio to 5007Å) and hence O^{++} abundance (dominant contribution for O)
- [Ar IV] 4711/4740Å for N_e of higher ionization plasma (spectral resolution an issue since He I 4713Å blends the 4711Å line)
- [Ne III] 3869Å for Ne^{++} determination (entirely missing from MUSE range)
- Balmer jump (3646Å) as a powerful estimator of T_e for the H^+ zone
- [O II] 3726,3729Å for N_e and O^+
- **Opens up study of the faint metal recombination lines which are numerous in this wavelength range**
- Field and spectral resolution promotes deeper and more extensive extragal PN surveys and studies



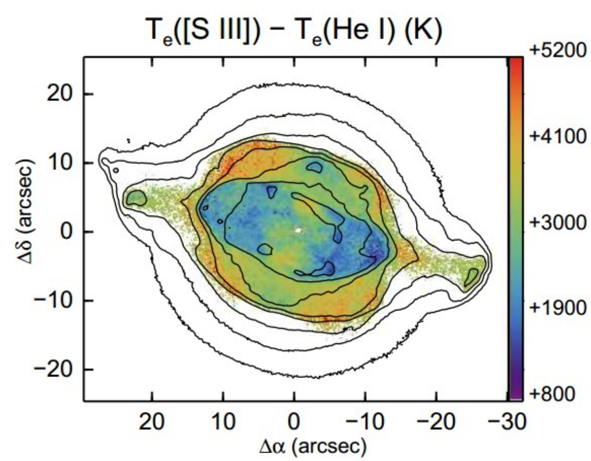
NGC 6302 VLT Comm camera *BVR* image + BlueMUSE FoV

The Abundance Discrepancy Problem

- Comparison of abundances (e.g., O, N, Ne) from collisionally excited (forbidden) lines and the >100x weaker recombination lines, shows systematic difference – the Abundance Discrepancy Factor (ADF)
- Optical recombination line (ORL) abundances always higher than for collisionally excited lines (CELs). In HII regions factor a few; in some PNe up to 100x
- So far no consistent observational solution. Suggestions:
  - Temperature fluctuations (ORLs less affected than CELs at high T_e)
  - High density intrusions
  - Metal rich (and/or H poor) intrusions
- Some evolved PNe with evidence of a late thermal stellar pulse show high He regions close to star; a trend for higher ORL/CEL abundance closer to star; also possible correlation with close binary central stars (Wesson et al. 2018)

Serious discrepancy:
Are all nebular abundances too low from CEL line ratios?
Could affect ALL ionized gas abundance estimates to highest *z* !!

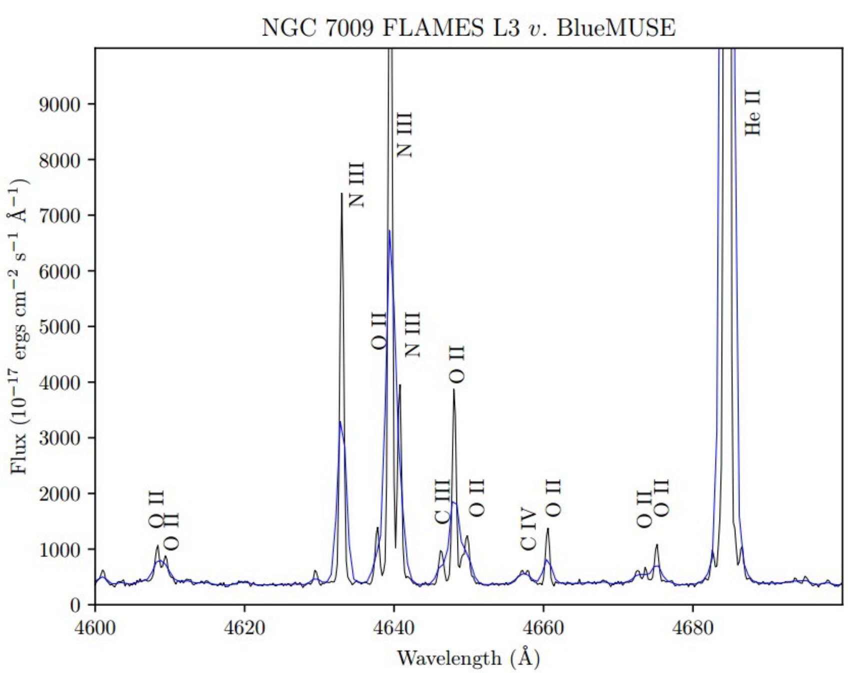
NGC 7009
higher CEL - ORL
T_e outer region



Towards BlueMUSE ...

- BlueMUSE well suited to ORL O II and O III lines (4300-4700Å) crucial for ADF problem (spatial O+ and O++ ORL v. CEL ratios), also C II, C III, C IV and Ne II ORLs
- MUSE+BlueMUSE opens up high fidelity imaging UV-Blue-Red PN spectroscopy – spatial correlations of internal extinction, physical diagnostics (N_e, T_e) from CELs and ORLs, ionization, ICFs, abundances and ADF's both internal to single PN and between PNe
- **Powerful opportunity** to strengthen and expand the role of PNe as ISM diagnostic laboratories

FLAMES LR3
R=7500
BlueMUSE
R=3500



A wealth of ORL diagnostic lines opens up with BlueMUSE