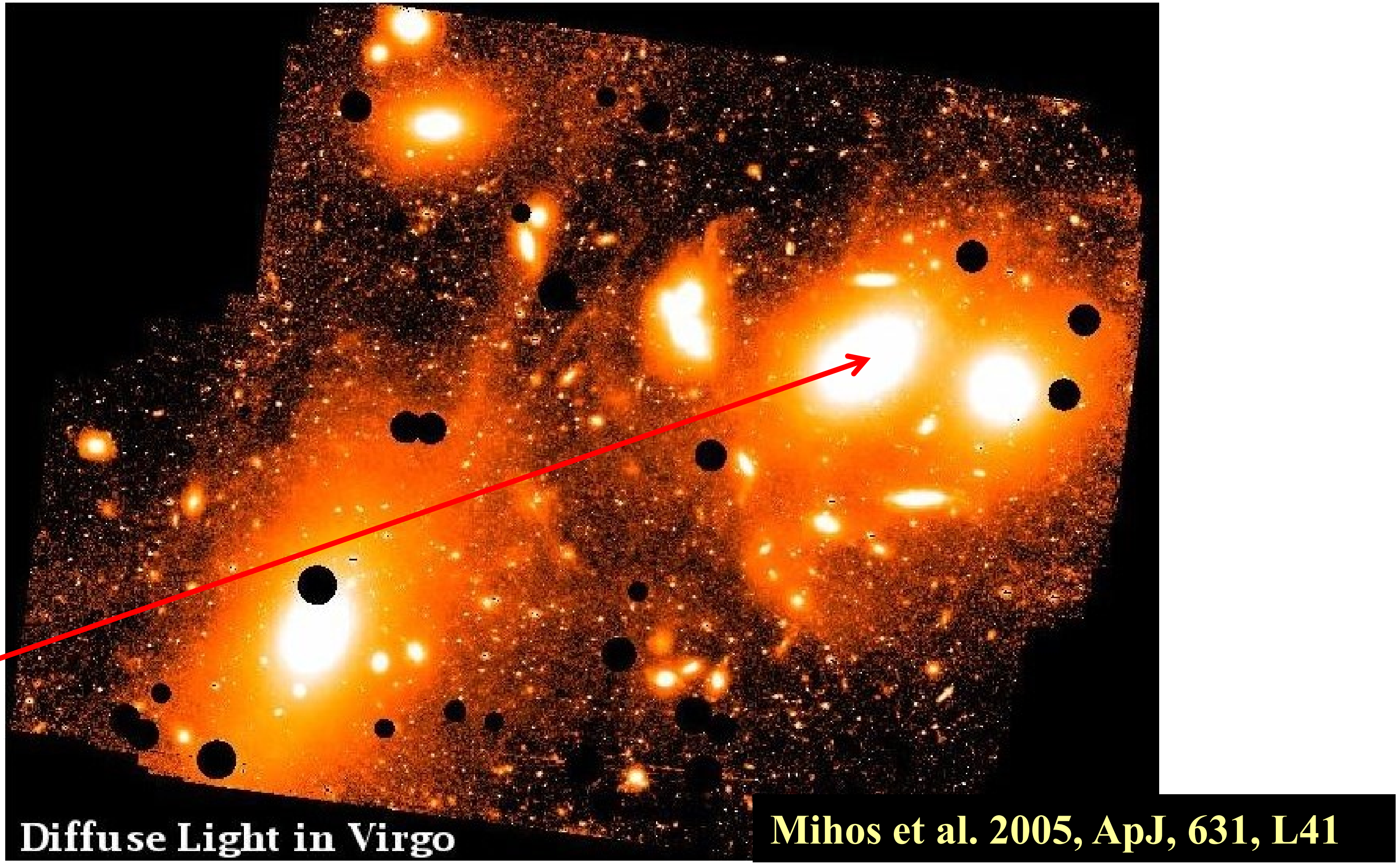
My connection with Ken Freeman

- Postdoc position at Mt. Stromlo observatory in 1993, after my Ph.D at SISSA, Trieste, Italy
- Started working with Ken on Polar Ring galaxies but then we stumble on intracluster planetary nebulae which marked the beginning of a new scientific adventure.

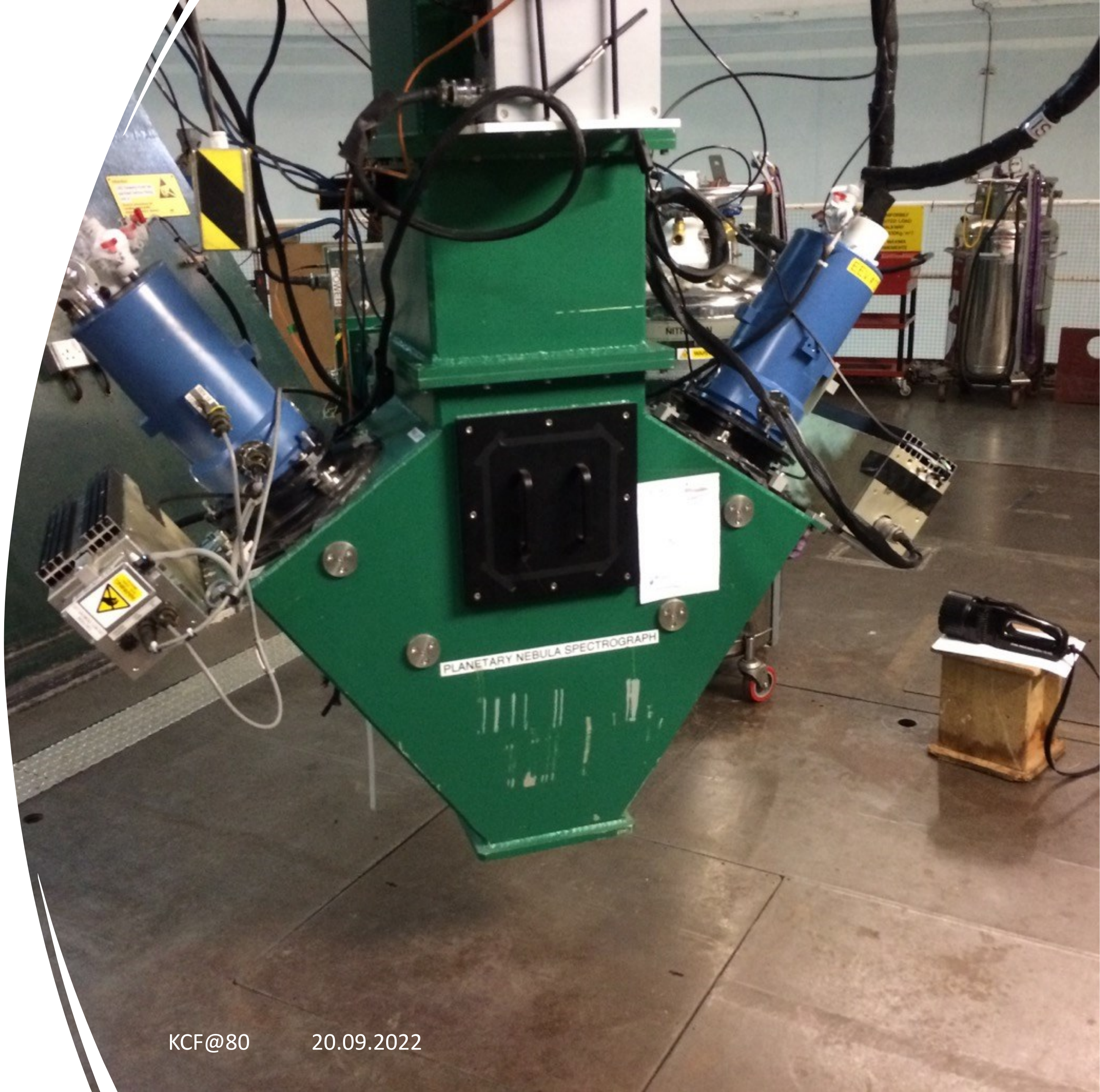
First steps in mapping ICL kinematics….



Discovery of 3 PNs at v_{mean} ~ 1400 kms^{-1} along the LOS to NGC 4406 (v_{sys} = - 240 kms^{-1})
Arnaboldi, Freeman, et al. 1996, ApJ, 472, 145

My connection with Ken Freeman

- Post doc at Mt. Stromlo observatory in 1993
- Started working with Ken on Polar ring galaxies & intracluster planetary nebulae from 1996
- Build the Planetary Nebulae Spectrograph! Commissioned at the WHT in 2001…
- Started the Early-type galaxy survey with the PN.S ..
- Project still on going with the study of discs, including M31, nearly 30 years later



Chemically distinct thin and thicker discs of Andromeda from Oxygen and Argon abundances of Planetary Nebulae

Presented by Magda Arnaboldi (ESO, Garching)

In collaboration with Souradeep Bhattacharya, Ortwin Gerhard, Chiaki Kobayashi, Nelson Caldwell, Kenneth C. Freeman, Johanna Hartke, Alan W. McConnachie, and Puragra Guhathakurta

Based on the work started during S. Bhattacharya's ESO/IMPRS PhD Thesis, now INSPIRE fellow at IUCAA

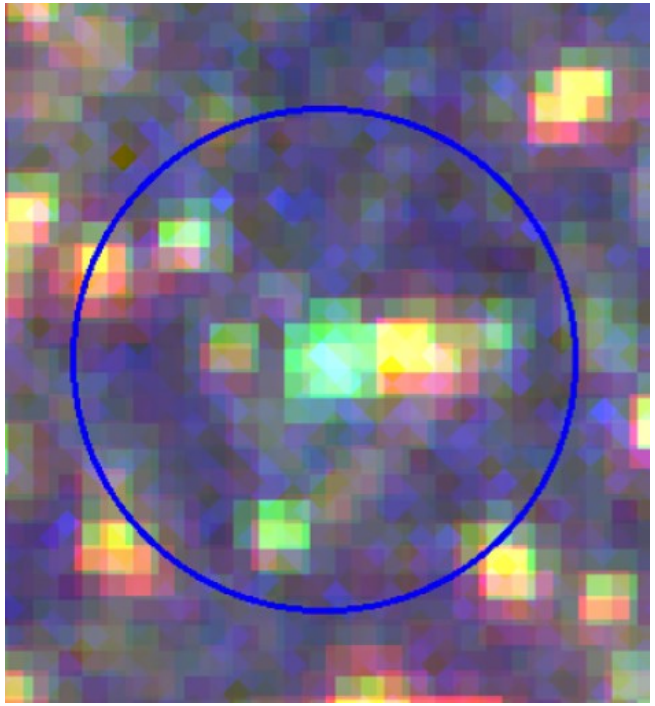
Bhattarcharya+2022, MNRAS in press, arXiv220306428 & Arnaboldi+2022, A&A in press, arxiv2208.02328

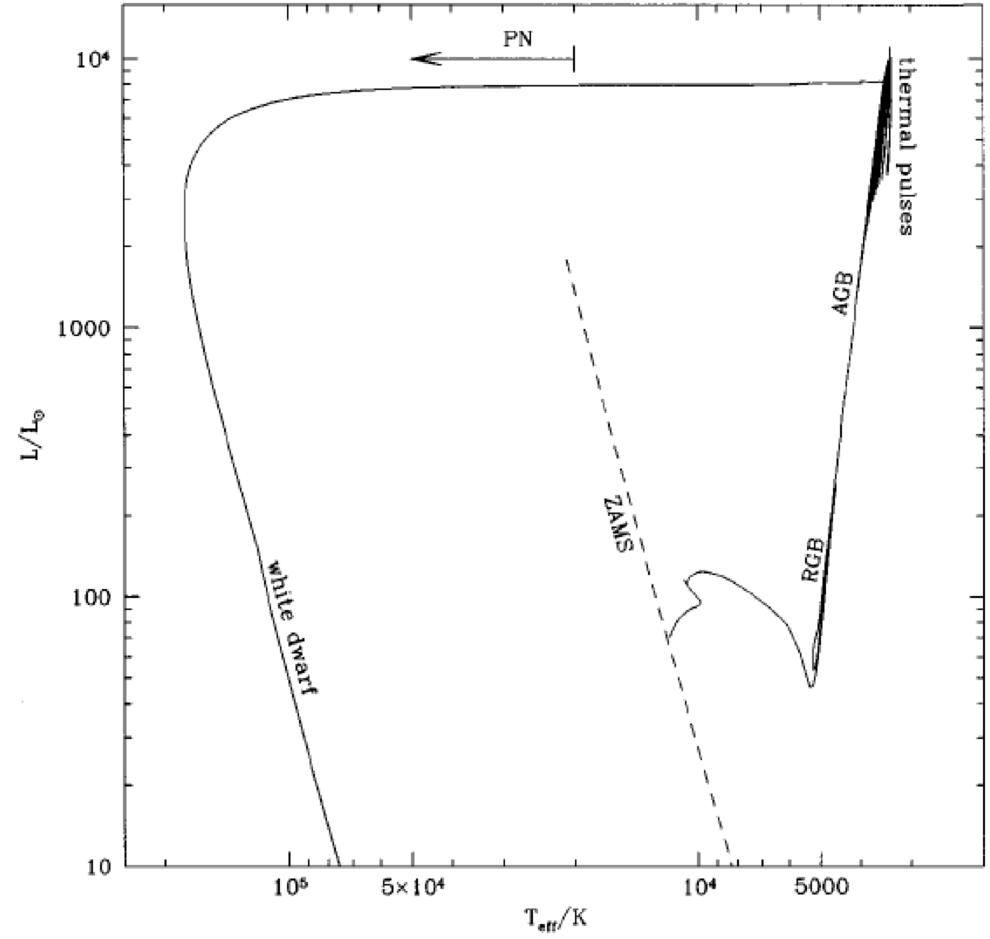
Outline

- **Why PNe?**
- **Why M31? The extended M31 PNe survey**
- **M31 disc kinematics from PNe & Age-Velocity dispersion relation**
- **Oxygen and Argon distributions for thin and thicker disc in M31 and their abundance gradient**
- **O/Ar gradients and the chemical evolution & timescales for star formation in M31 discs**
- **Conclusions**

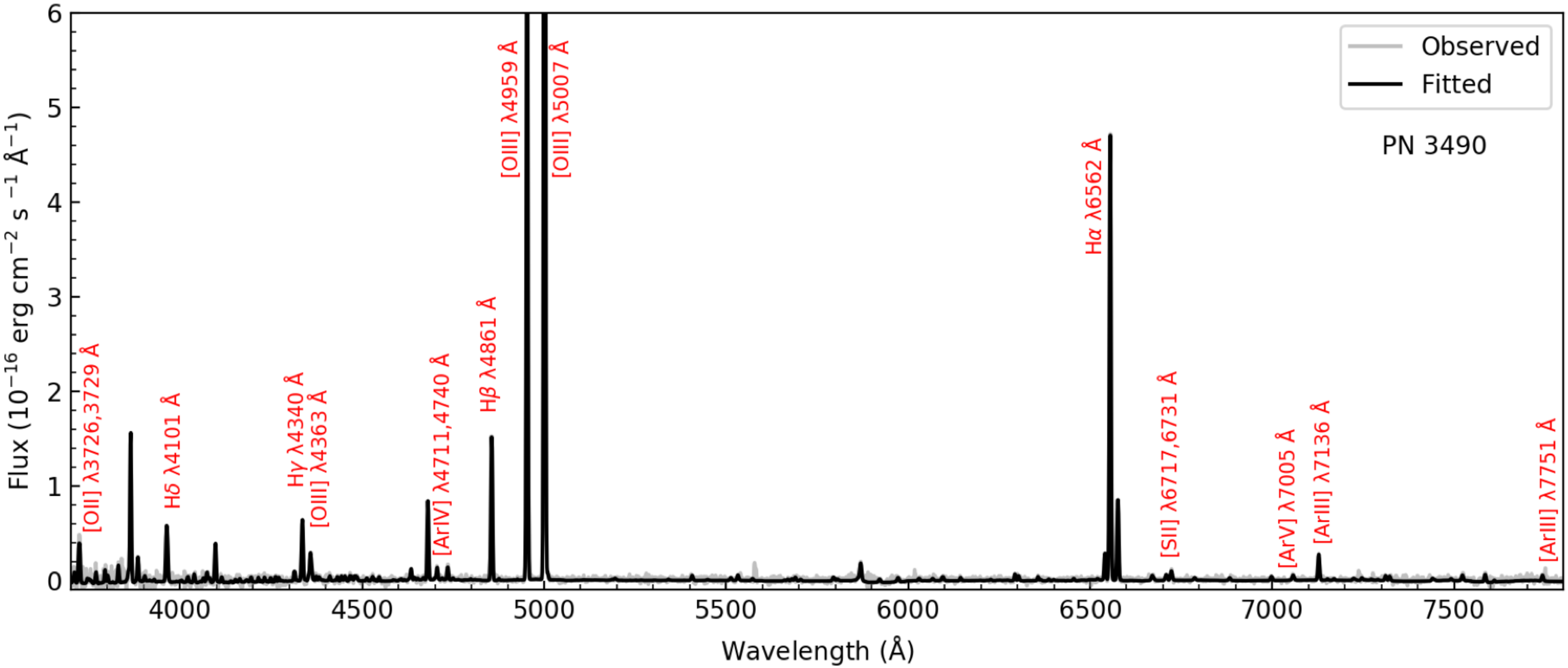
Why Pne?

- Post-AGB phase of stellar evolution
  - Stars in the mass range ~0.8-8 $M_\odot$ traditionally thought to go through the PN phase, 95% of all stars
- Extragalactic PNe appear as point-sources,
  - detect individual stars in high density regions in external discs





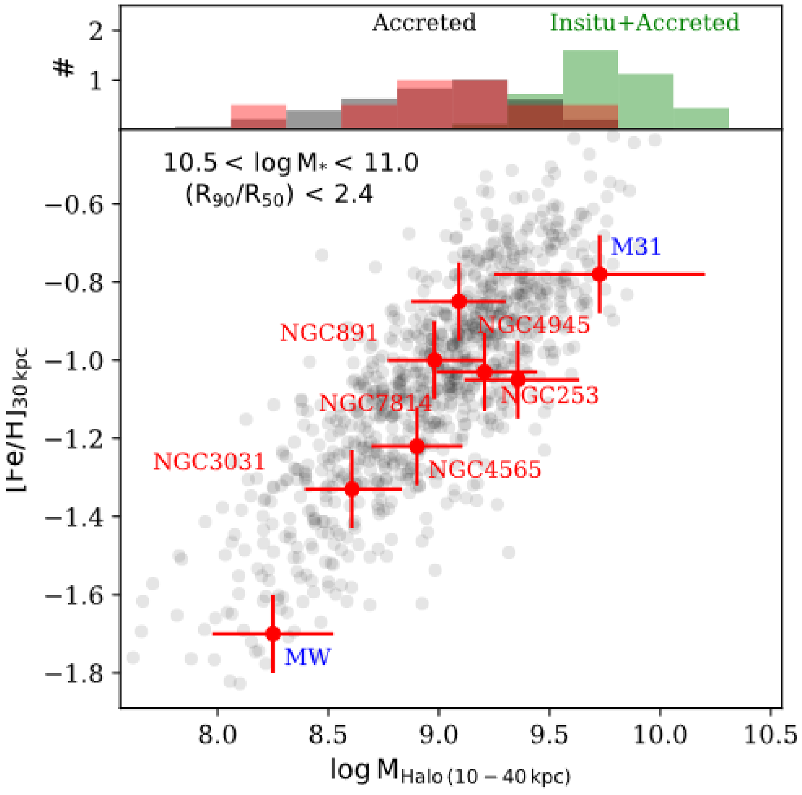
Observed PN spectra



- Several emission lines in the optical wavelength range, with no continuum

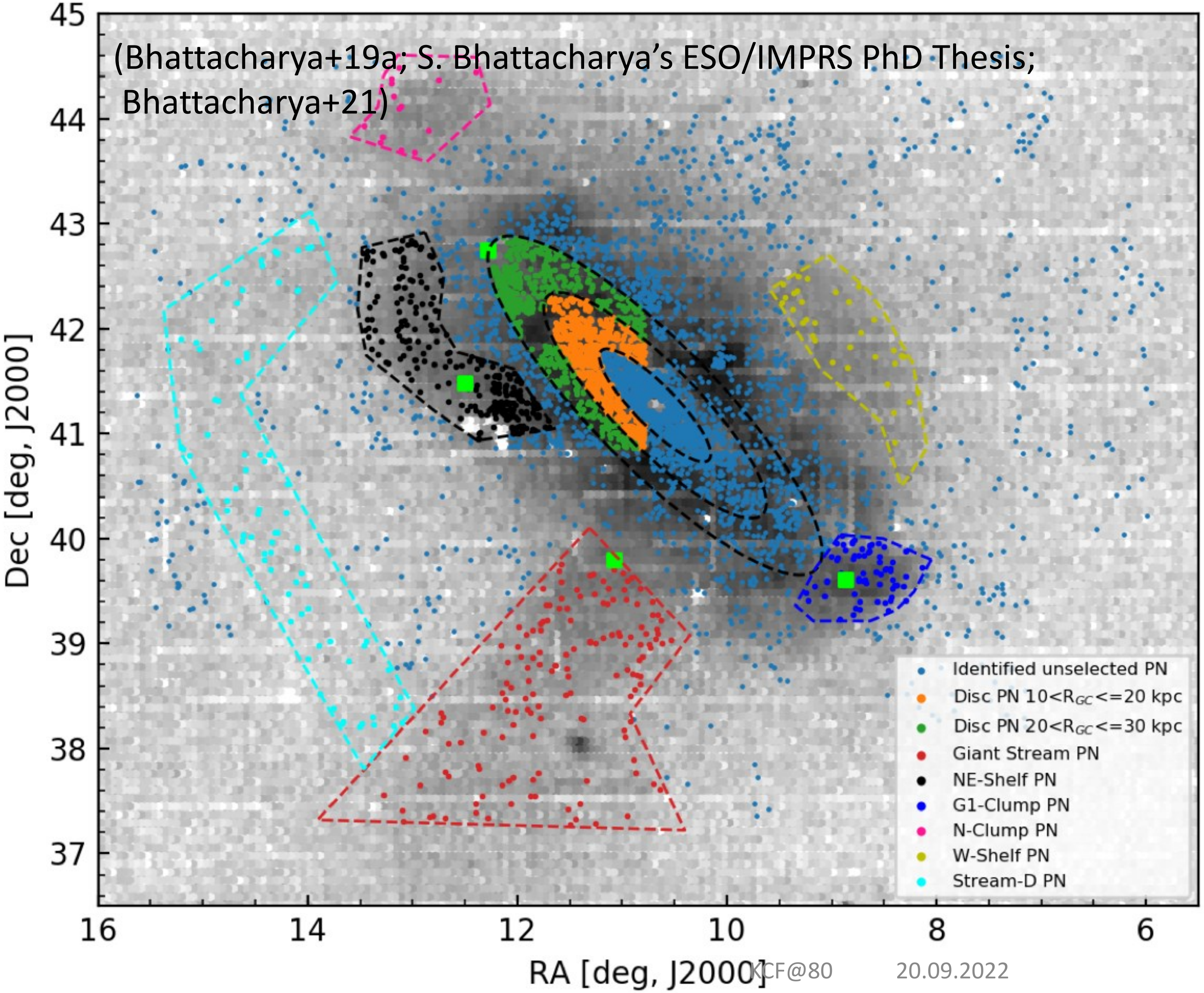
Why M31?

- Late-type galaxies can contain multi-layered populations that are kinematically distinct, for example the “cold" thin disc and the “hot" thick disc, found in the Milky Way (MW).
- Thick discs may form from accreted gas during a chaotic period of hierarchical clustering at high redshift (Brook et al. 2004) or from dynamical heating of thinner discs by secular processes (Sellwood 2014). Mergers with satellites can also heat disc (Quinn & Goodman 1986)
- The M 31 halo evolution is driven by mergers: see observational evidence of substructures in its inner halo (PAndAS – McConnachie et al. 2009).
- MW and M31 are at the two edges of the halo metallicity relation from GHOST survey
- Goal: establish links with the M31 disc, with its element abundances & gradients



Monachesi+15, Deason+16, Bell+18, d’Souza & Bell 2018

The M31 PN survey

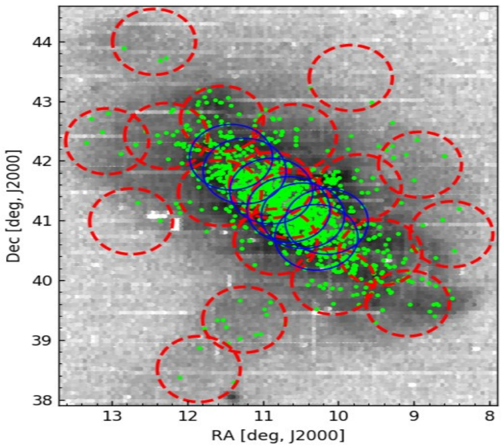


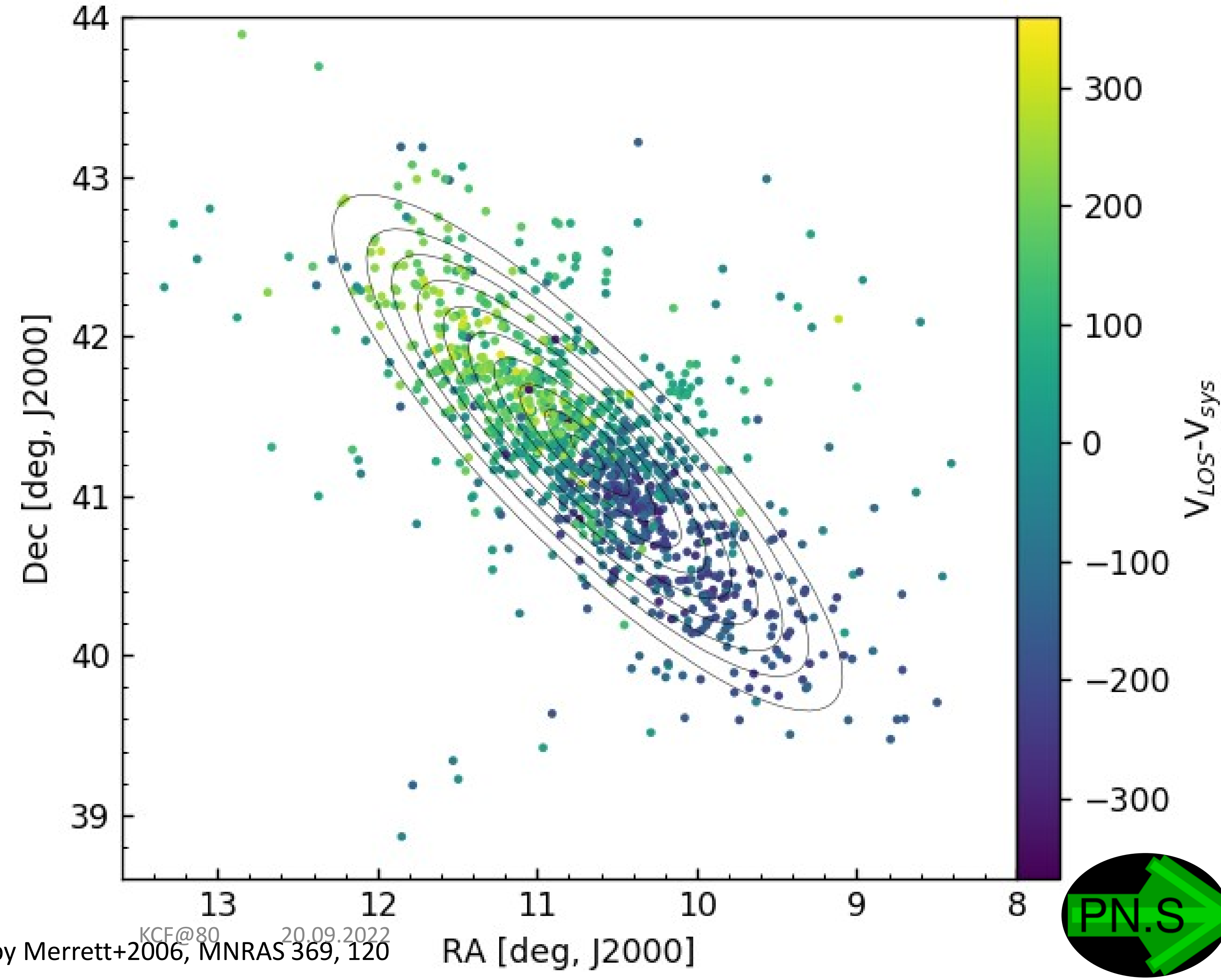
- 54 Sq. deg. survey of PNe in M31 with MegaCam@CFHT
- **5265 PN candidates in M 31 (D=773 kpc) , the largest PN sample in any galaxy**
- PAndAS N_{RGB} map from McConnachie+18 with the six substructure regions marked in colours.
- No contamination from MW halo PNe
- PNLFs of substructures revealed Giant Stream, NE and W Shelf as satellite debris with their stellar population distinct from the disc.
- G1 Clump is likely disc debris.
- Stream D is distinct from both and a separate disrupted dwarf

Bhattachaya+2021A&A...647A.130B

M31 PN 2D V_{LOS} MAP

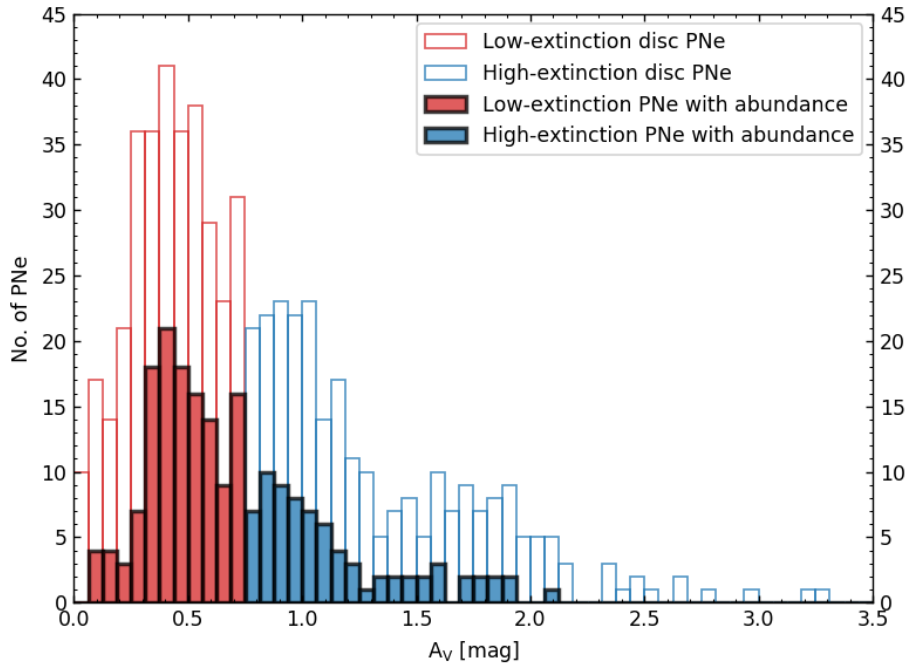
- Spectroscopic follow-up of new 2222 distinct PNe candidates with fibres in 26 separate fields with Hectospec at MMT
- 866 have confirmed detection of the [O III] 4959/5007 Å and Hα emission lines + add. 449 PNe studied by Sanders+12
- **1251 unique PNe with V_{LOS} measurements** (using ALFA) in M31
- Determine Vϕ and σϕ in annuli





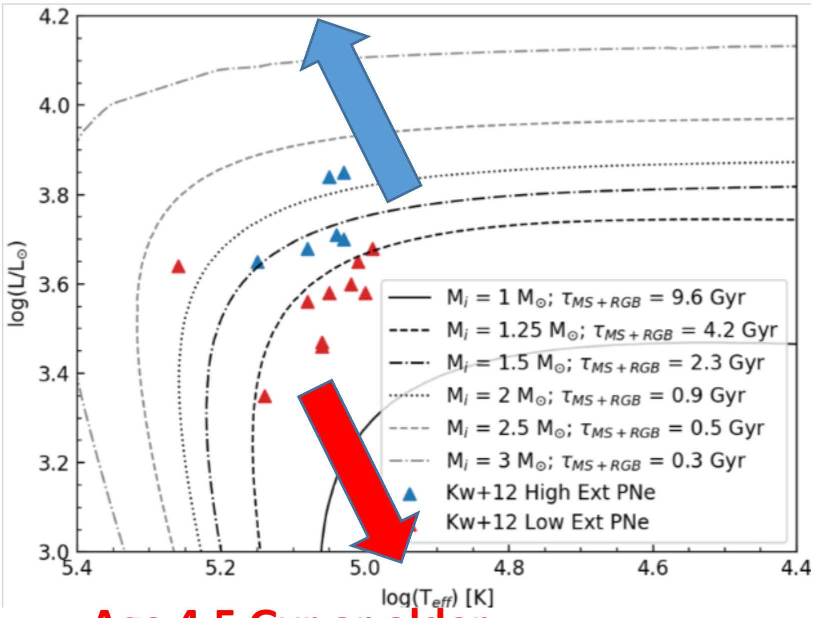
See also previous kinematical map of M31 disk and stream by Merrett+2006, MNRAS 369, 120

M31 disc PN: extinction & ages



Cloudy models for M31 Pne (Kw+12) Theoretical evol. Tracks from M.Bertolami16 See more in Bhattac.+19b

Age 2.5 Gyr or younger

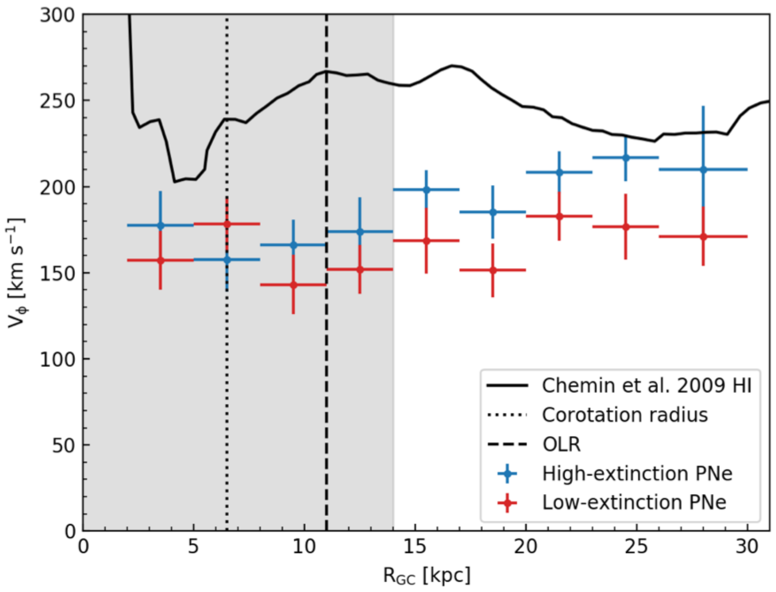


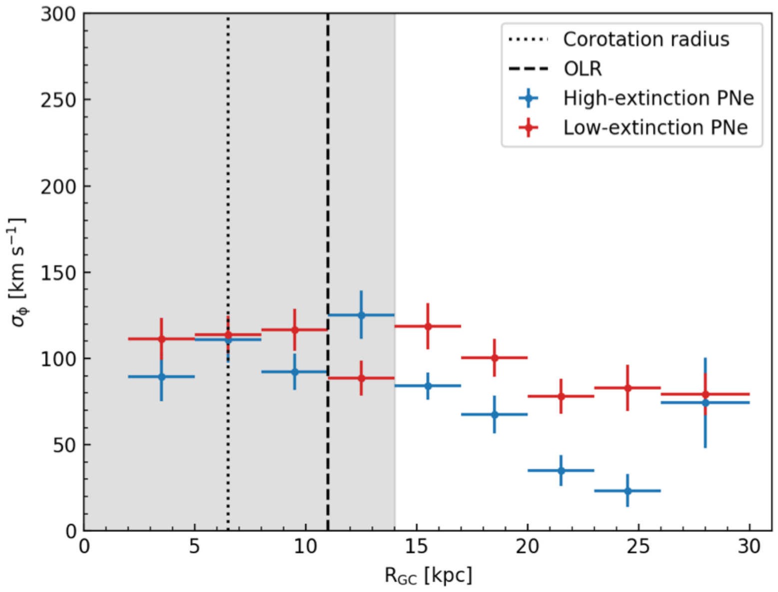
Age 4.5 Gyr or older

Correlation between PN circumstellar extinction and the mass of their central star (Ciardullo & Jacoby 1999). Dust production of stars in the AGB phase scales exponentially with their initial progenitor masses for the 1-2.5 $M_\odot$ range after which it remains roughly constant (Ventura+14).

<u>Determination of direct abundance distribution for single PN</u>: Emission line fluxes determined using ALFA (Wesson16): return VLOS and fluxes via Gaussian fits. Extinction measurements using NEAT (Wesson12); c(H_β) using Cardelli+89

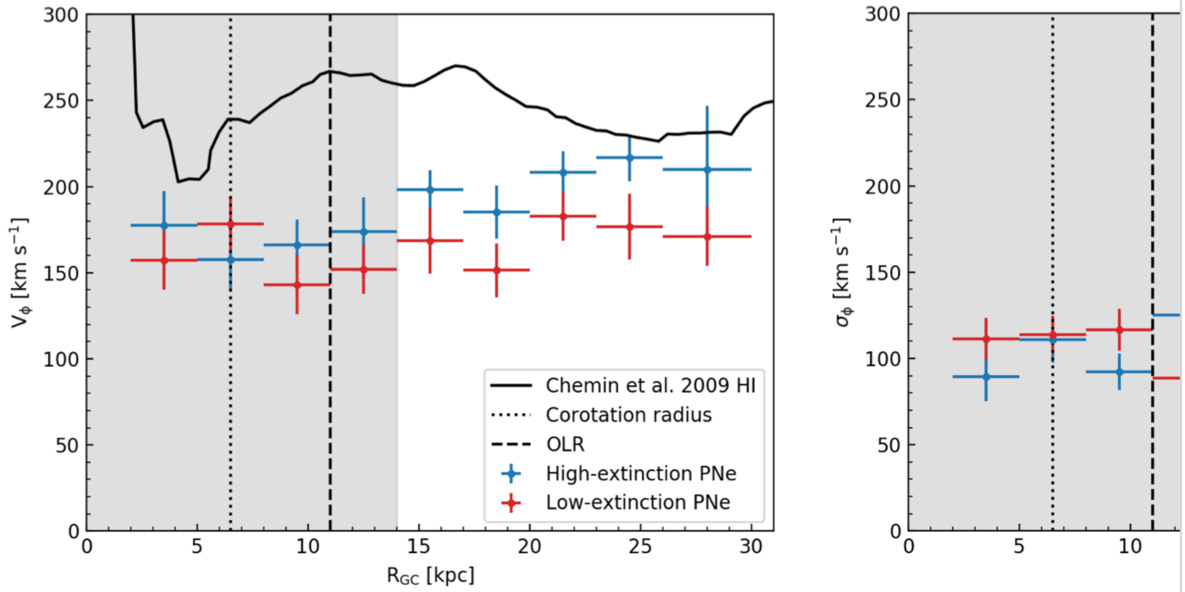
M31 disc kinematics from PNe



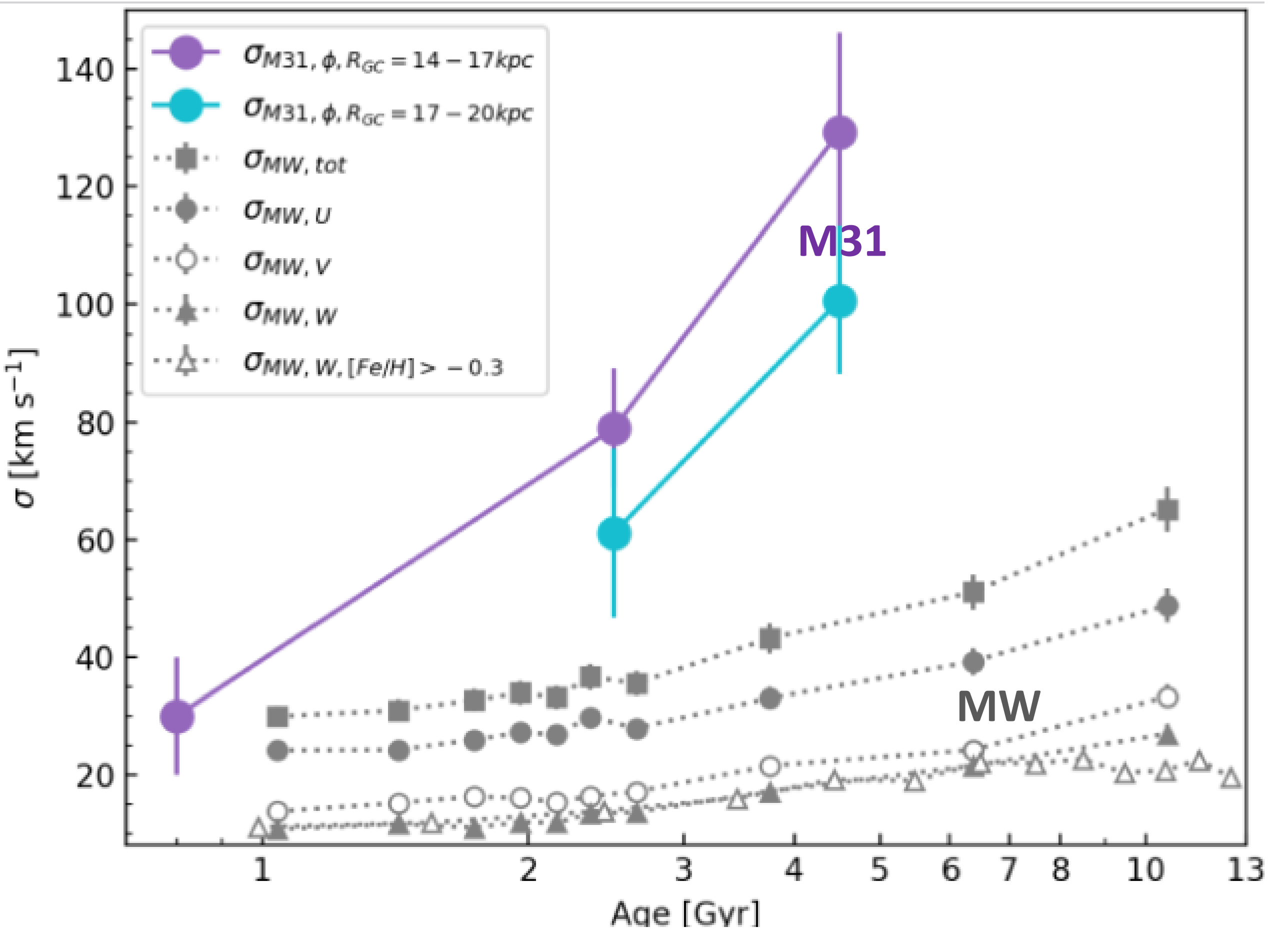


Bhattacharya+19b, A&A 631, 56

M31 disc kinematics from PNe



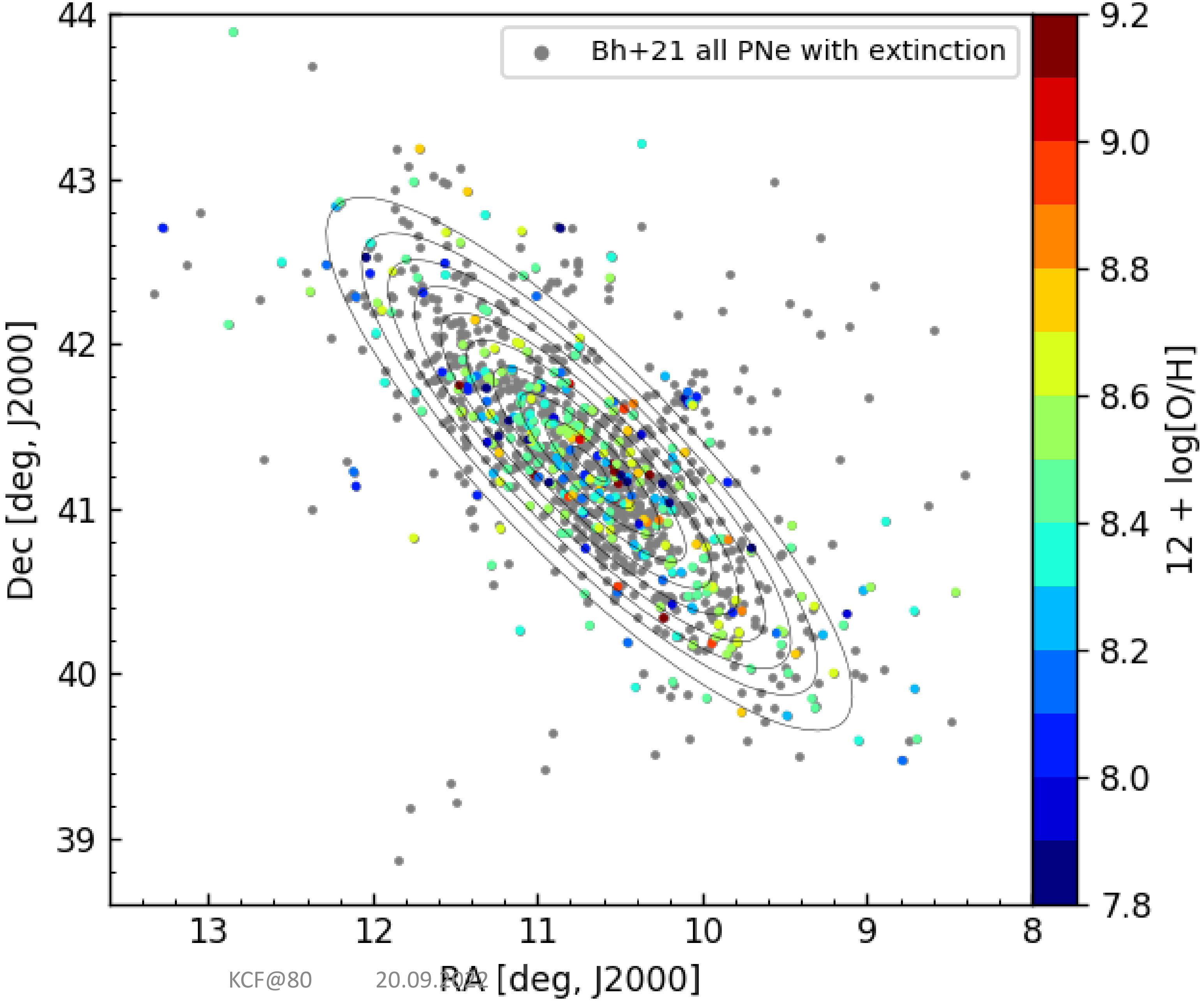
- Age velocity dispersion (AVD) relation for M31 Pne in radial interval 14-17kpc and 17-20 kpc.
- M31: MS value 30 Myr from Dorman+15, older age points from Pne (Bhattacharya+19b).
- MW: data from Nordstrom+04 and Aniyan+18
- **AVD relation determined for M31 disc requires a merger with mass ratio 1:5** (Hopkins 2008 & 2009). The baryonic mass in the merged satellite is thus $M_{sat} = 1.4 \times 10^{10} M_\odot$.



Bhattacharya+19b, A&A 631, 56

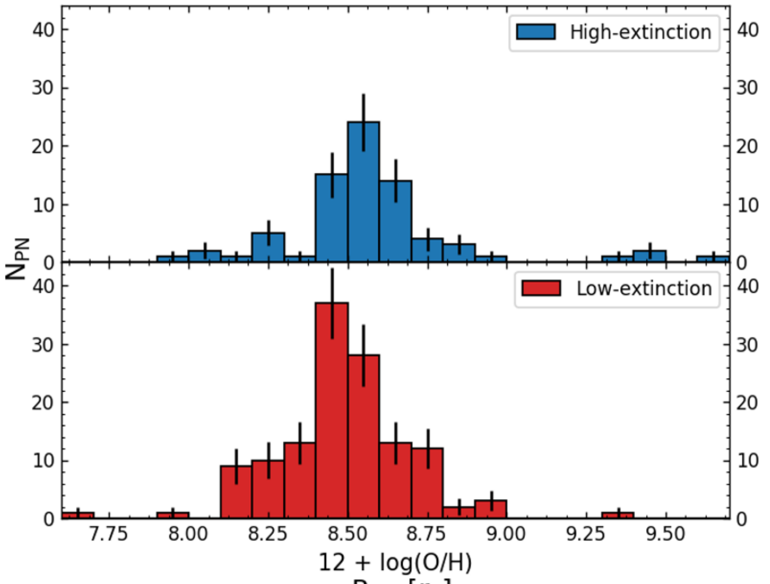
M31 PN oxygen abundance map

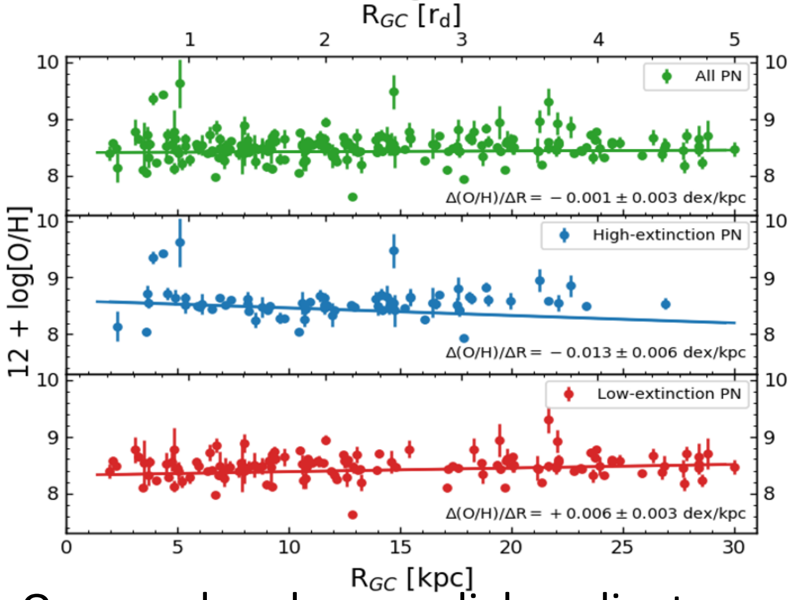
- Analysis of abundance distributions and gradients for M31 disc only.
- Use PNe where the detection fraction of [OIII] 4363 Å is higher than 75%, i.e, m_{5007} < 21.9mag (avoid bias towards metal-poorer PNe).
- Direct abundance det. for single PN using temperature sensitive [OIII] 4363 Å and density sensitive [OII] and [SII].
- **Final sample of 205 and 200 PNe with Oxygen and Argon abundance measurements, respectively [using ICF from Delgado-Inglada+14]**



M31 disc O/Ar distribution & rad abundance gradients from PNe

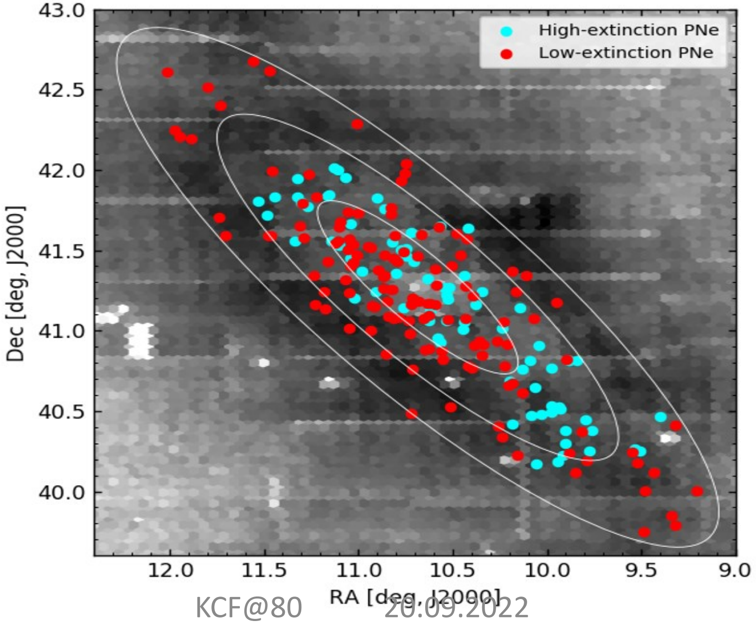
Oxygen abundance distributions



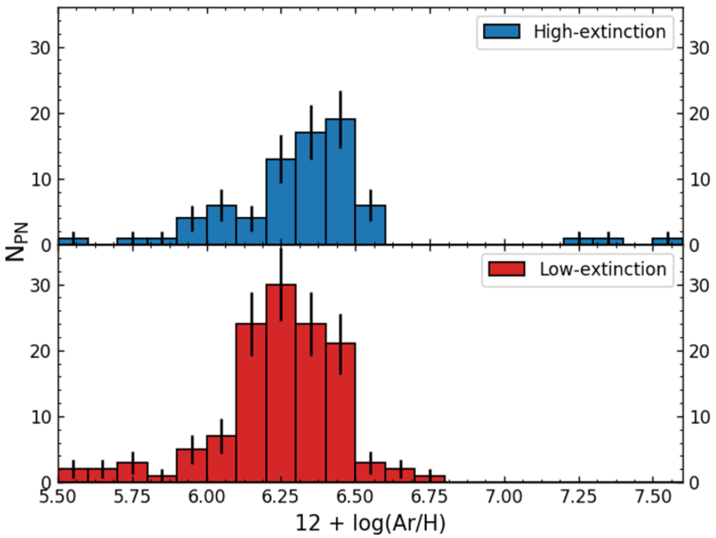


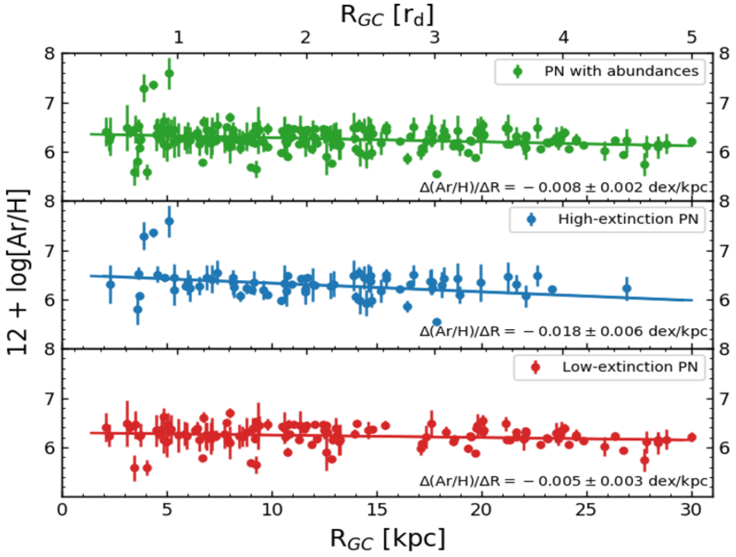
Oxygen abundance radial gradients

Oxygen/ Argon distributions for young/old discs (based on high/low ext. PNe) **are distinct,** based on AD tests: prob. 2.3% and 3.3% respect. Bhattarcharya+2022, MNRAS in press. 2022arXiv220306428B



Argon abundance distributions





Argon abundance radial gradients

PN sample	X	X0	ΔX/ΔR	
All	12+log(O/H)	8.4± 0.04	0.001± 0.003	0.006±0.018
High ext.	"	8.61±0.08	-0.013±0.006	-0.079±0.036
Low ext.	"	8.31±0.05	0.006±0.003	0.036±0.018
All	12+log(Ar/H)	6.37±0.04	-0.008±0.002	-0.049±0.012
High ext.	"	6.51±0.08	-0.018±0.006	-0.109±0.036
Low ext.	"	6.3±0.05	-0.005±0.003	-0.03±0.018

O/H gradients in units of disc scale length for 1) early/late disc types (Sanchez-Menguiano+16) , 2) MW from PNe (Stan&Hayw+18) , 3) M31 Pne

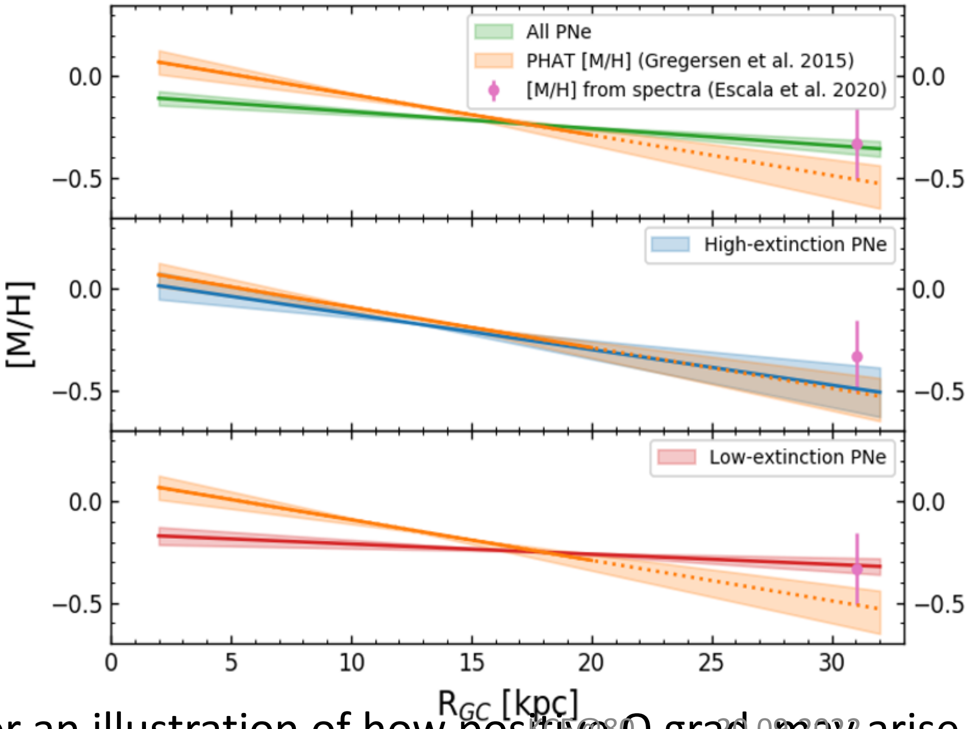
- O rad. grad. for young Pne consistent with O grad of HII regions (Zurita&Bresolin12)
- O rad. grad. for old Pne is positive *!

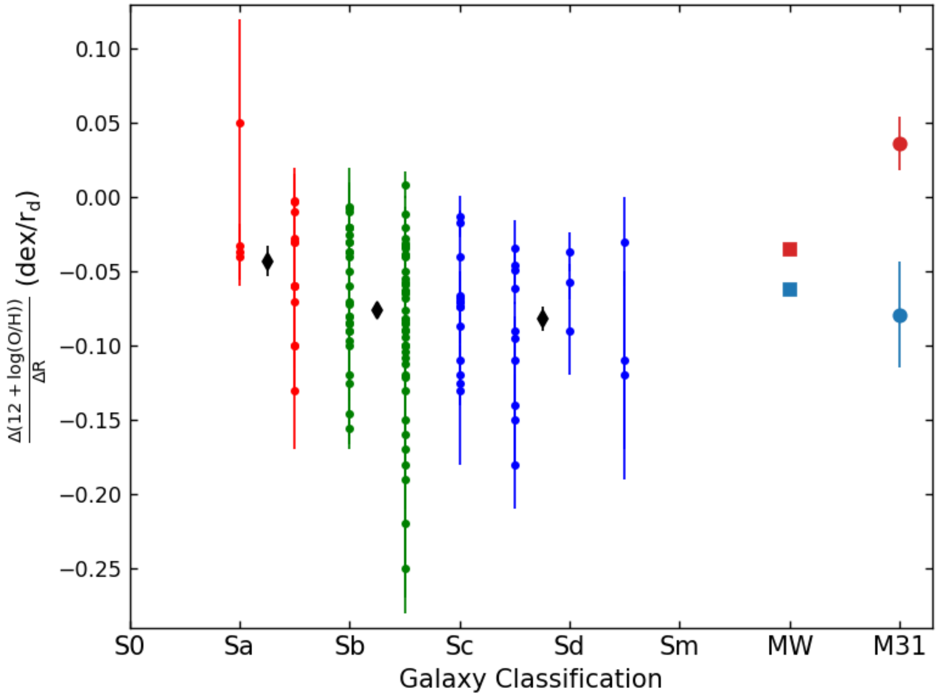
Bhattarcharya+2022, MNRAS in press 2022arXiv220306428B

Argon rad. grad. for M31 thin/thicker discs compared with PHAT phot. metallicity gradient (out to 20 kpc Gregersen+15)

- Escala+20 [M/H] estimate for RGBs

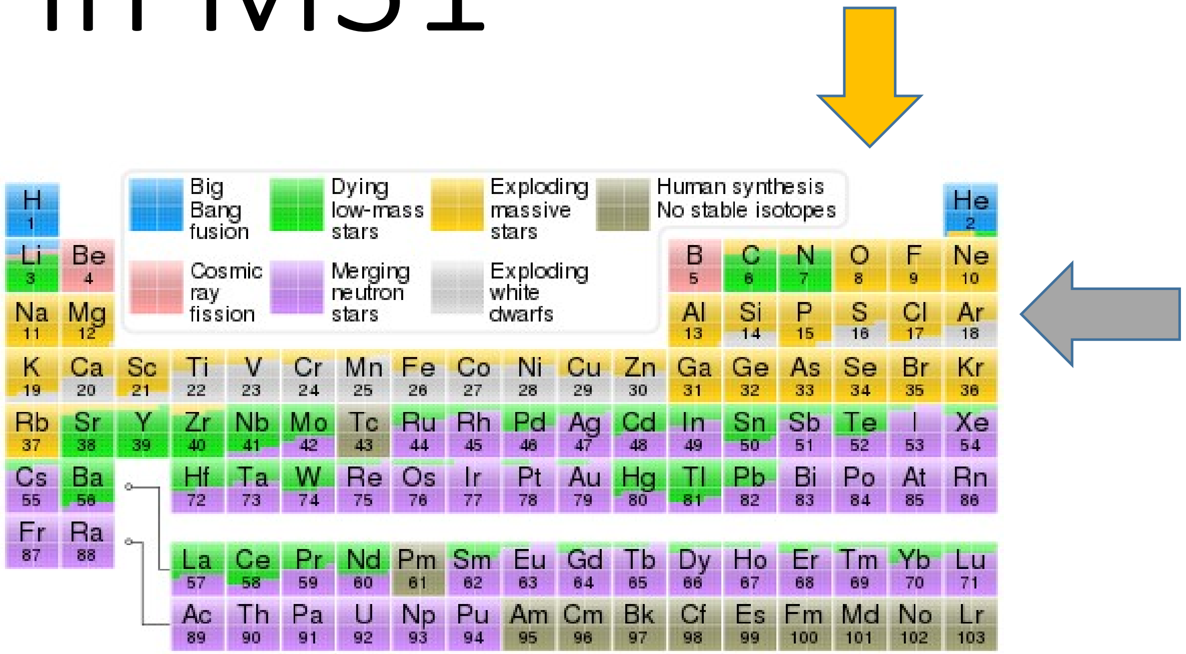
Radial gradients values consistent with those of SPLASH RGB stars in disc (p_{disc}> 0.75) and inner halo (p_{disc}< 0.25) in Escala+2022 (arxiv:2209.07962)



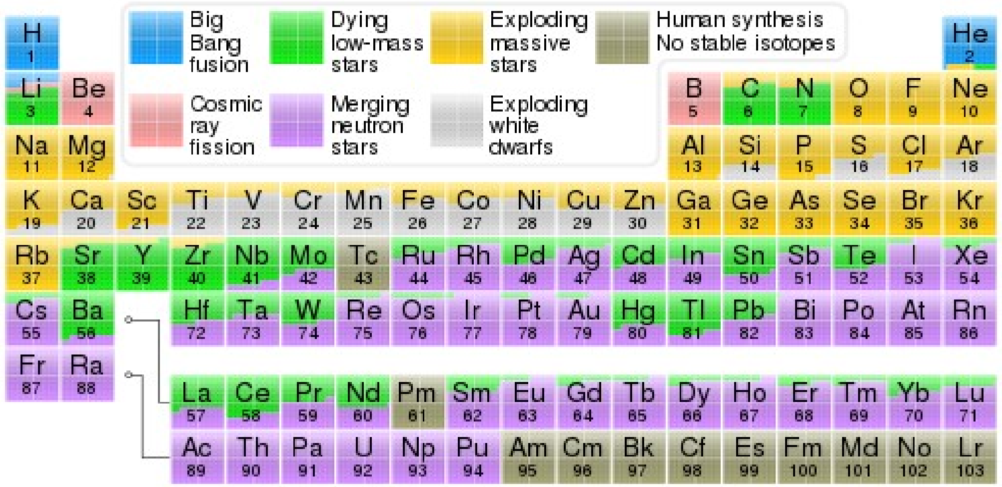


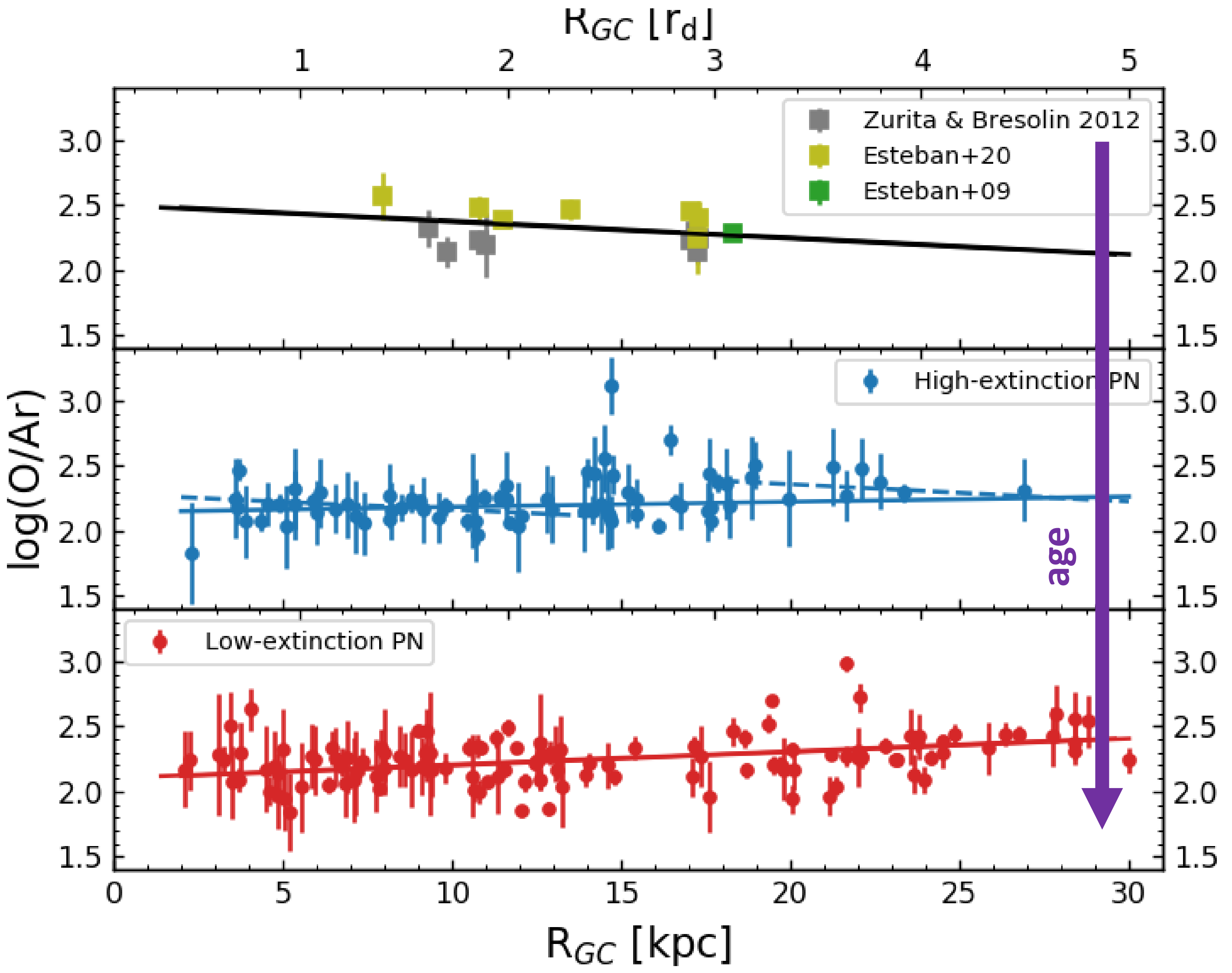
*See Minchev+2014 for an illustration of how positive O grad. may arise (Simpson's paradox)

O/Ar gradients in M31



O/Ar gradients in M31

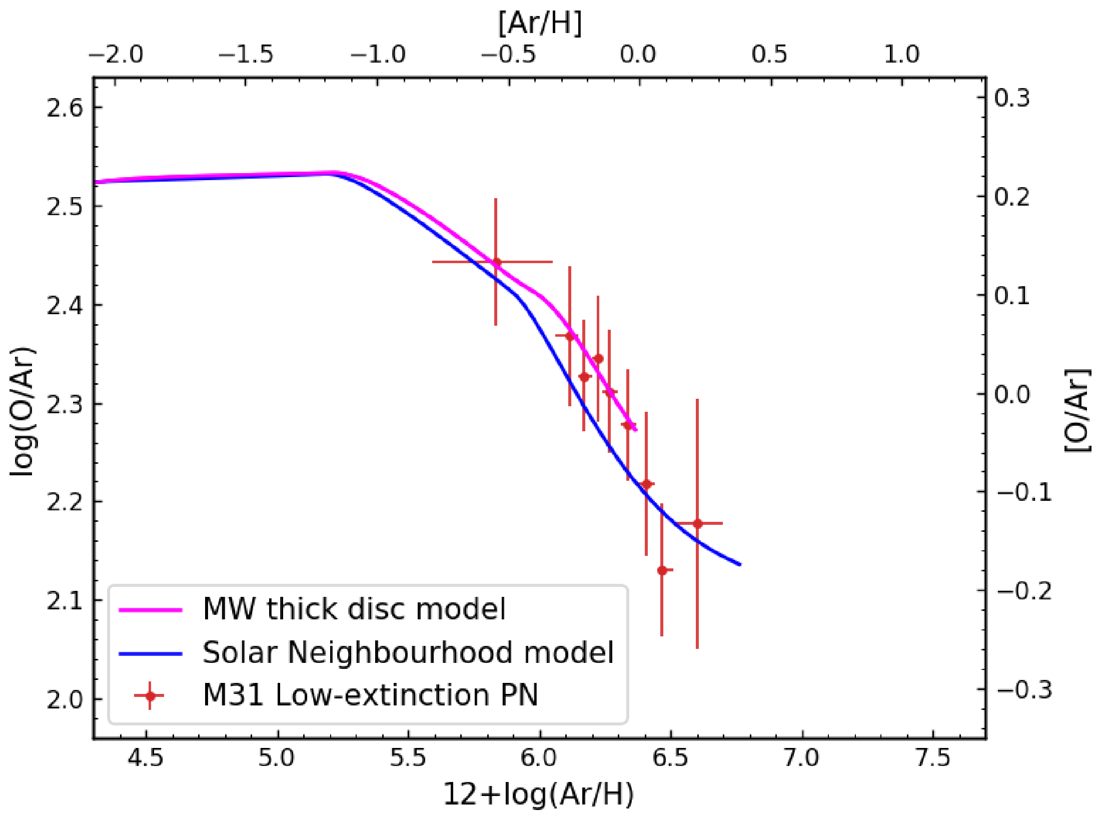




- HII reg have neg. grad, but large errors
- Pne with <2.5 Gyr have distinct behavior in 3 rad range < 14 kpc, 14-18 kpc, and > 18 kpc.
- Pne with > 4.5 Gyr have flat log (O/Ar) gradient over the entire disc (30 kpc)

Arnaboldi, Bhattacharya, Gerhard et al. 2022, A&A in press, arxiv:2208.02328

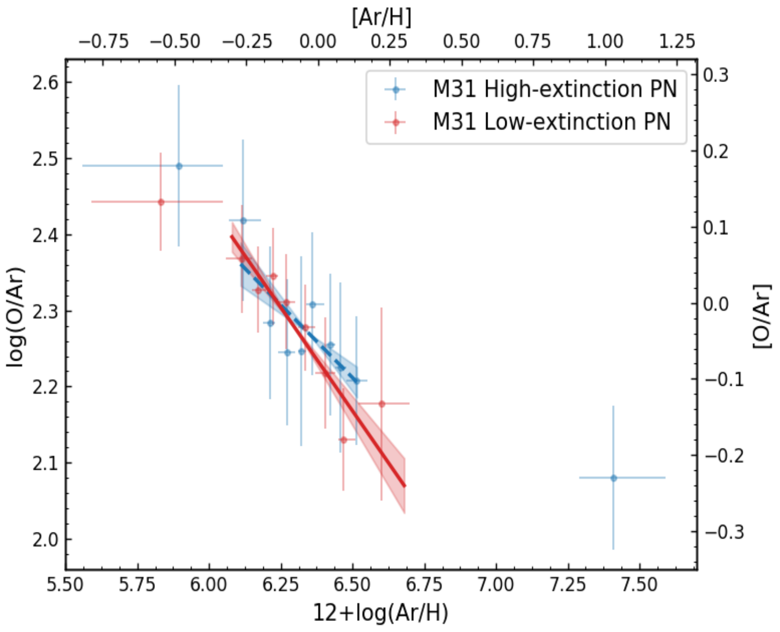
Tracing chemical enrichment with PN abundances

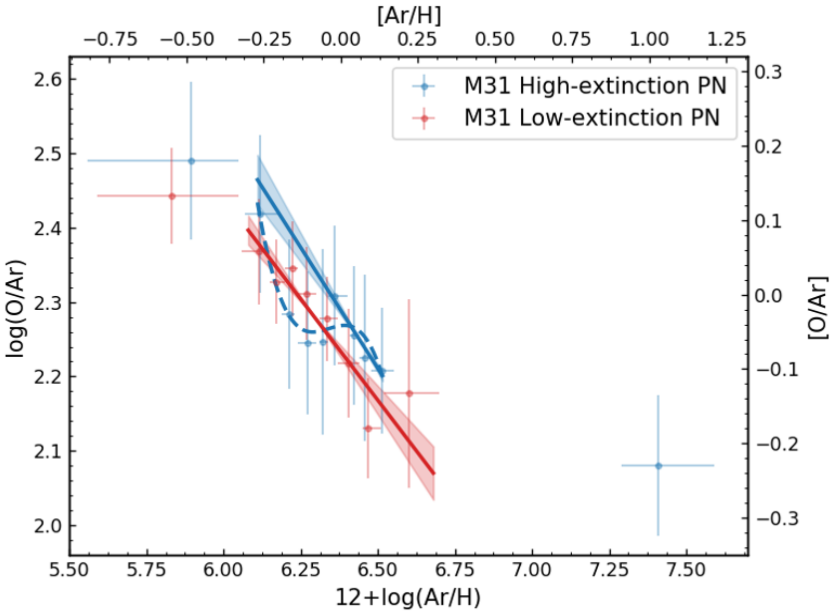


- Low ext. are ≥4.5 Gyr older PNe compared with MW chemical evolution models for O/Ar (Kobayashi et al. 2020).
- Linear decrease caused by SN type Ia which increase production of Ar, and thus decrease log(O/Ar) in ISM with chemical evolution.
- Low extinction PNe have ~ flat O and Ar abundance gradients with radii over the entire disc, and also flat log (O/Ar) gradient over the entire disc (-30 kpc).
- **Log(O/Ar) vs 12+log(Ar/H) for emission nebulae is analog to the alpha/Fe vs [Fe/H] of stars.** We can use it for the different phases of the stellar evolution, Hii regions but also for later phases, i.e. PNe.

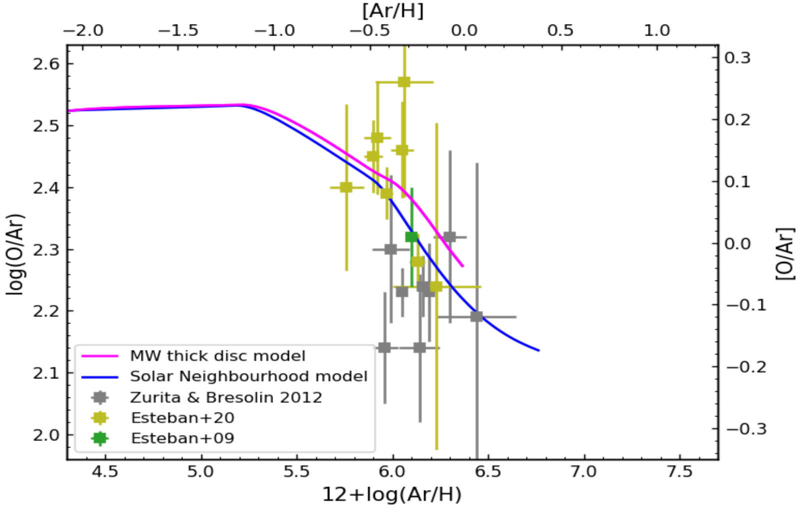
Low ext. PNe also free from possible PAGB evolution effects which could change O, either TDU which increases O, or HBB which decreases O, while Ar is known to be invariant.
Distribution in this plane represents chemical properties of the ISM at the time when the stellar progenitors of low ext. PNe formed

Different behaviour of high extinction PNe



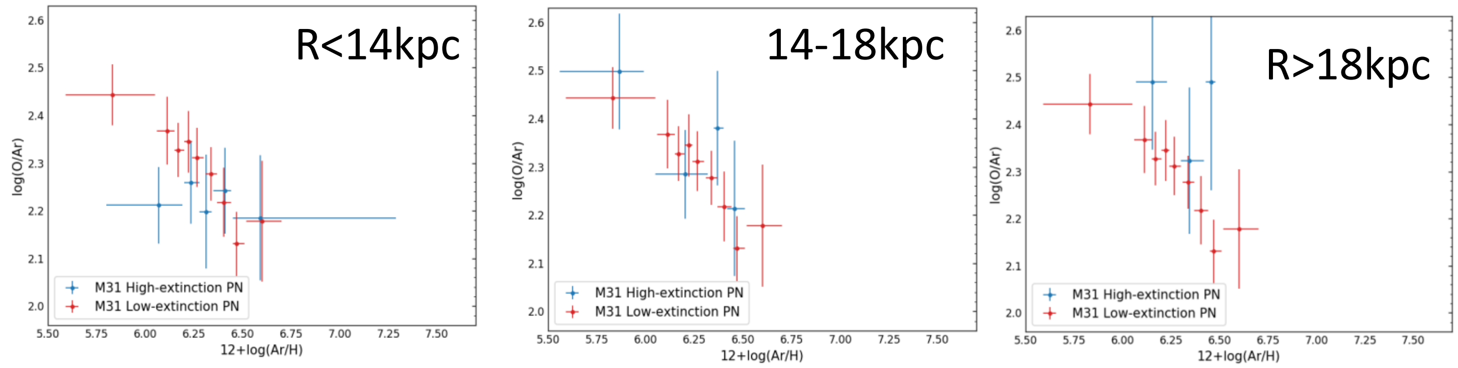


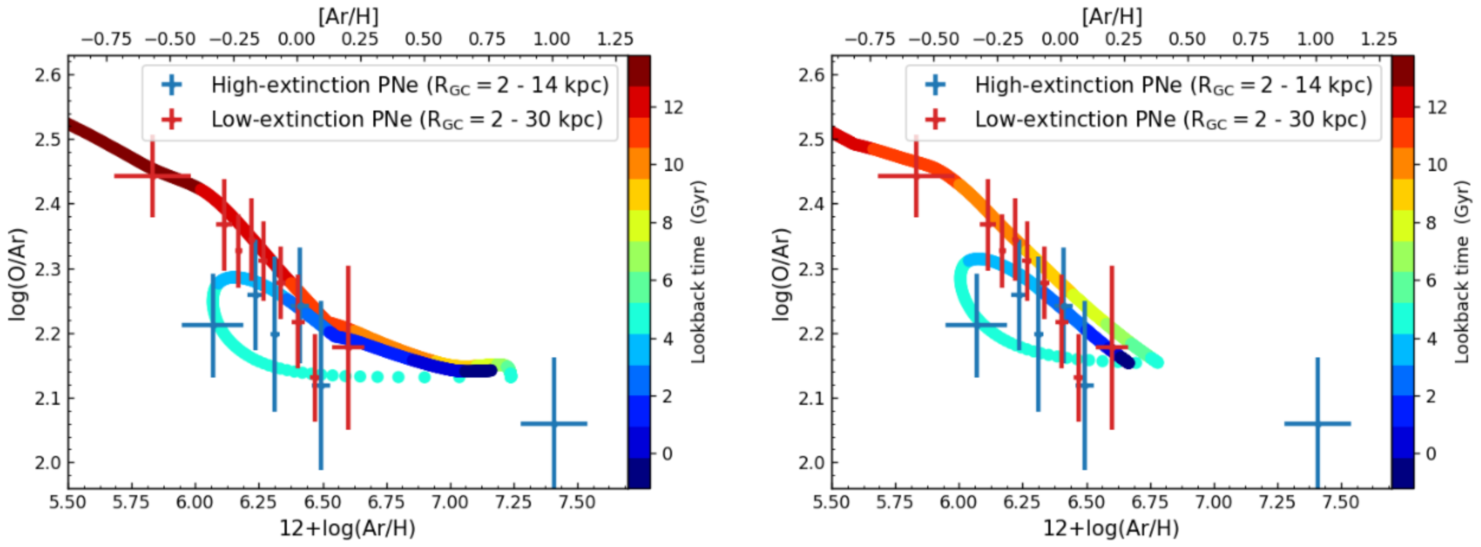
Fresh infall of gas: the log (O/Ar) vs 12+log(Ar/H) distribution for HII regions in the M31 thin disc



Chemical evolution history of the M31 disc

- High extinction Pne in three regions R< 14 kpc, 14≤R≤18, R> 18 kpc.
- **R<14kpc: high ext. PNe (2.5 gyr pop) are clustered at the end and below the low ext. PNe distrib.**
- **Consistent with chem evolution including dilution of ISM by secondary infall of metal poorer gas.**
- R> 18 kpc: young PNe are at the knee of the distribution, with high log(O/Ar) values and lower Ar abundances, to the right of the low ext. PNe. These younger Pne are consistent with being formed in a starburst from metal poorer gas during wet merger (mostly from the satellite gas).
- In 14-18 kpc range: strong starburst + abundance variation, cospatial with starforming regions in M31 (Kanak+2009)





Arnaboldi+2022, A&A in press, arxiv:2208.02328

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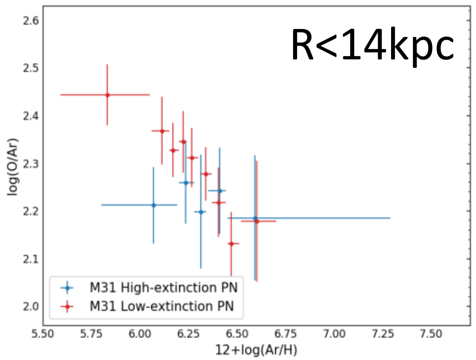
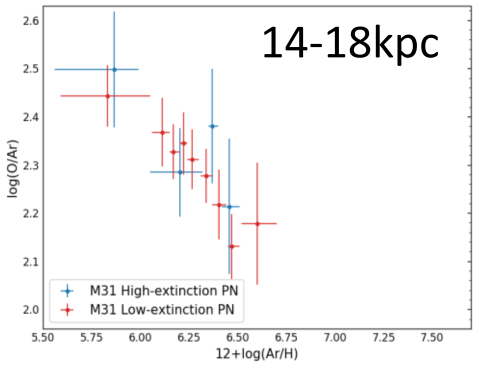
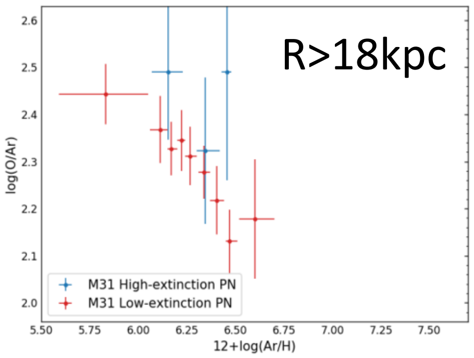
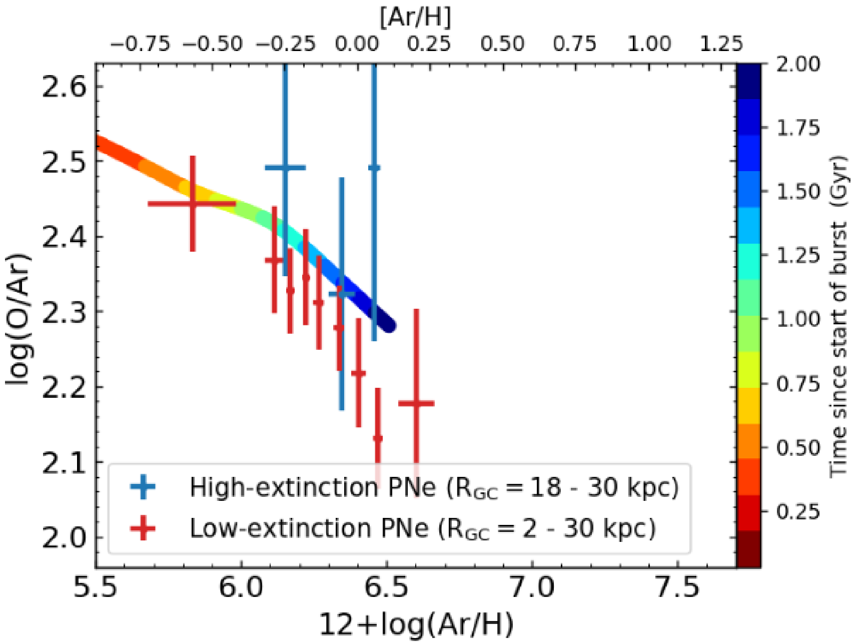


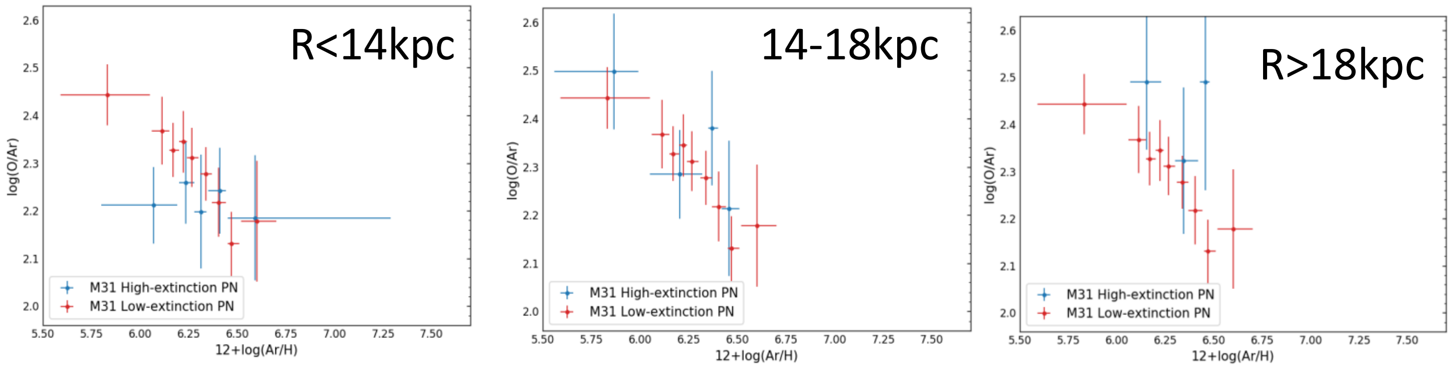






Arnaboldi+2022, A&A in press, arxiv:2208.02328

Chemical evolution history of the M31 disc



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- **In 14-18 kpc range: strong starburst + abundance variation, cospatial with star forming regions in M31 (Kanak+2009)**

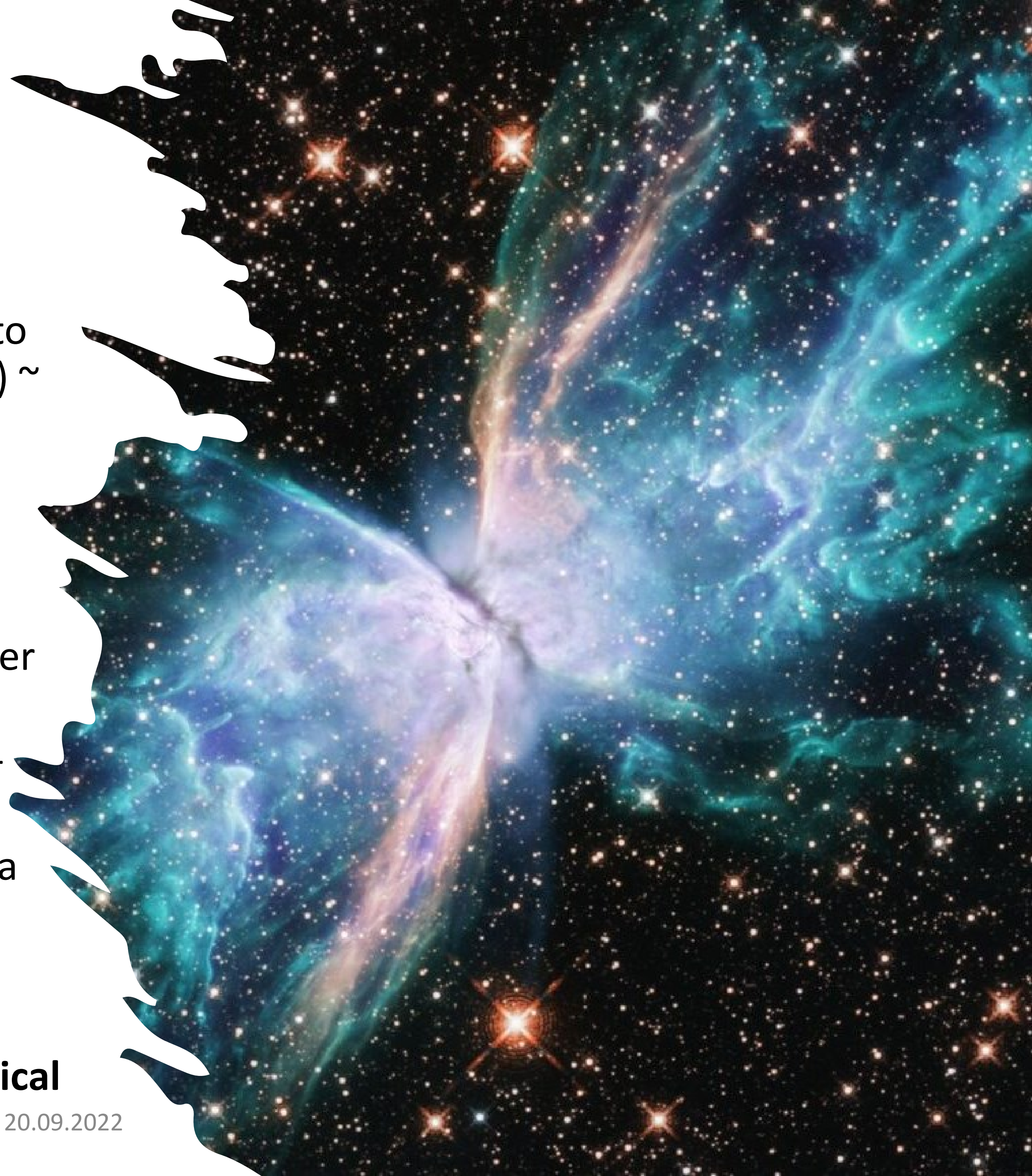
Wet merger with mass ratios 1:4-1:5 in M31 disc

Constraints on gas content and metallicity of the merging satellite

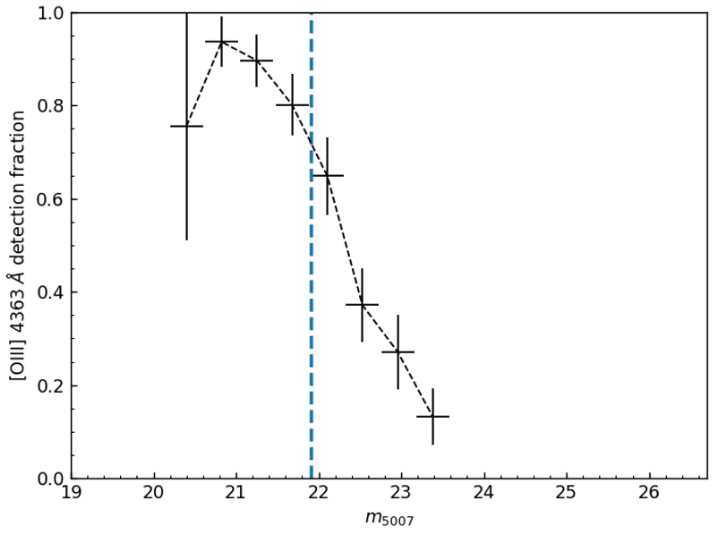
- From the AVD for PNe in M31, we constrain the baryonic mass of the satellite that merged with the M31 disc. The merger mass ratio from the AVD relation is 1:5 (Hopkins 2008 & 2009) => $M_{sat} = 1.4 \times 10^{10} M_{\odot}$.
- Assuming a gas fraction f = 20% (DiazGarcia&Knapen20), the amount of gas brought in by the wet merger is then $2.8 \times 10^{9} M_{\odot}$
- Current gas in M31 plus stellar mass formed in the last 2 Gyrs amount to 9×10^{9} $M_{\odot}$, much more than that brought in by the merger. Remaining gas had to be present still in the M31 disc which was then diluted by Δ[M/H] ~ -0.5 dex as observed in argon abundance.
- High ext. PNe were formed out of this diluted ISM at R<14 kpc; and mostly from satellite gas at R>18kpc
- Consistent with i) independent constraints on the metallicity of the gas brought in by the merger from the stellar mass metallicity relation from Zahid+2017; see also Curti+2020. Agreement also ii) with the metallicity measurements of the stars in the Giant Stream (Conn+16, Cohen+18).

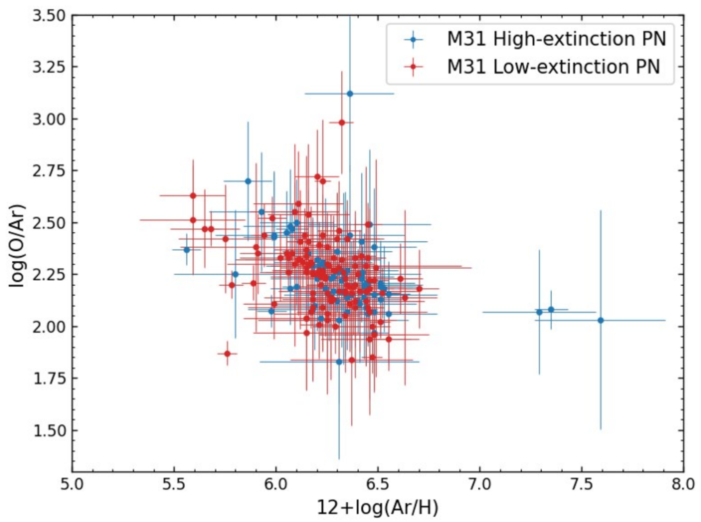
Conclusions

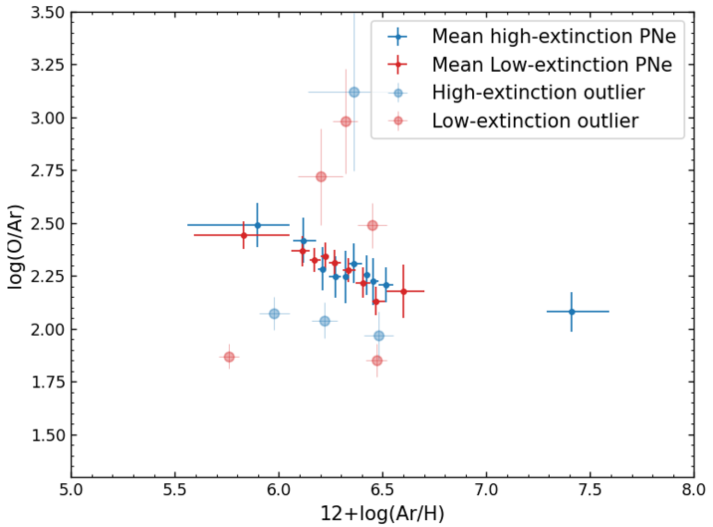
- PNe in M31 => Provide first vivid example that GCE is imprinted in the log(O/Ar) vs. [Ar/H] plane
- M31 thicker disc reaches high argon abundance similar to that of the Solar neighborhood in the MW (12+log(Ar/H) ~ 6.7)
- Three regions are identified in the M31 thin disc: inner ($R \leq 14$ kpc), starburst region (14-18 kpc) and outer disc ($R \geq 18$ kpc)
- In the inner thin disc, 2.5 Gyr and younger stars form after a secondary event, with infall of metal poor gas which mixed with the pre-enriched ISM in the pre-merger M31 disc
- In the outer thin disc, 2.5 Gyr and younger stars form in a starburst mostly from satellite’s gas
- **Differently from the MW, the thin disc in M 31 is less radially extended, formed stars more recently and at a higher star-formation efficiency, and had a faster chemical enrichment timescale than the thicker disc in M31**



End!

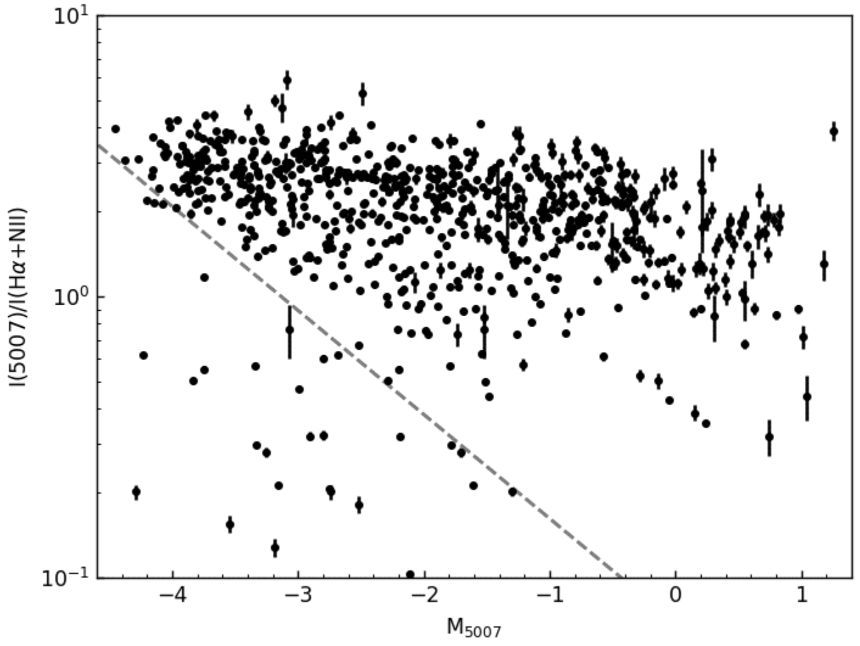




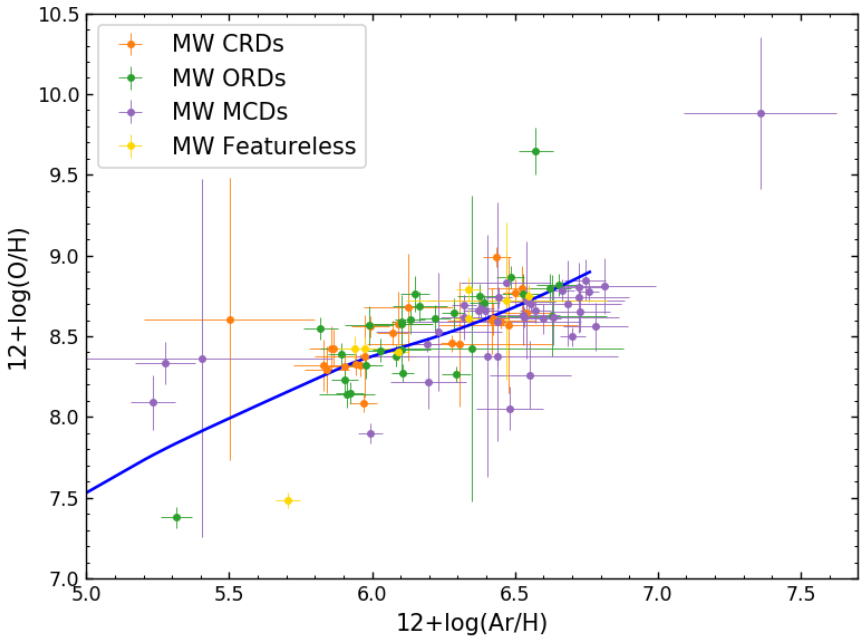


Outliers selection

Properties PNe sample in M31



Removal HII regions



No bias in Oxygen abundance in either CR dust or Ord dust PNe

PN Luminosity-specific frequency (**α**-parameter)

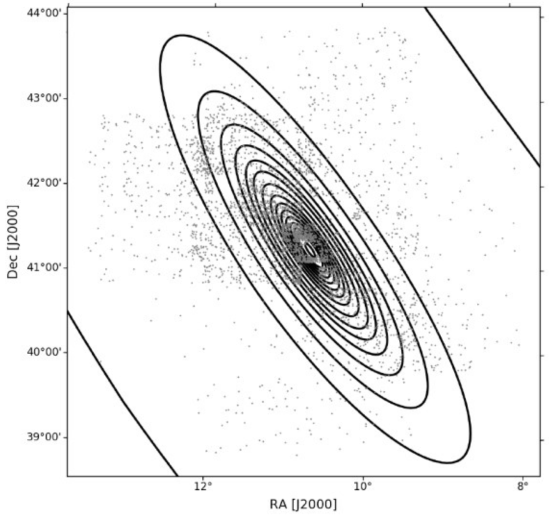
PN yield varies from galaxy to galaxy

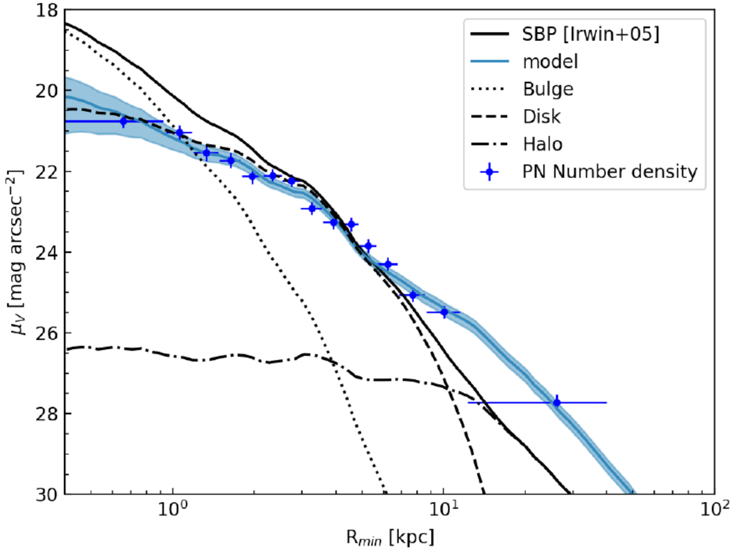
$$\alpha = \frac{N_{\rm PN}}{L_{\rm bol}}$$

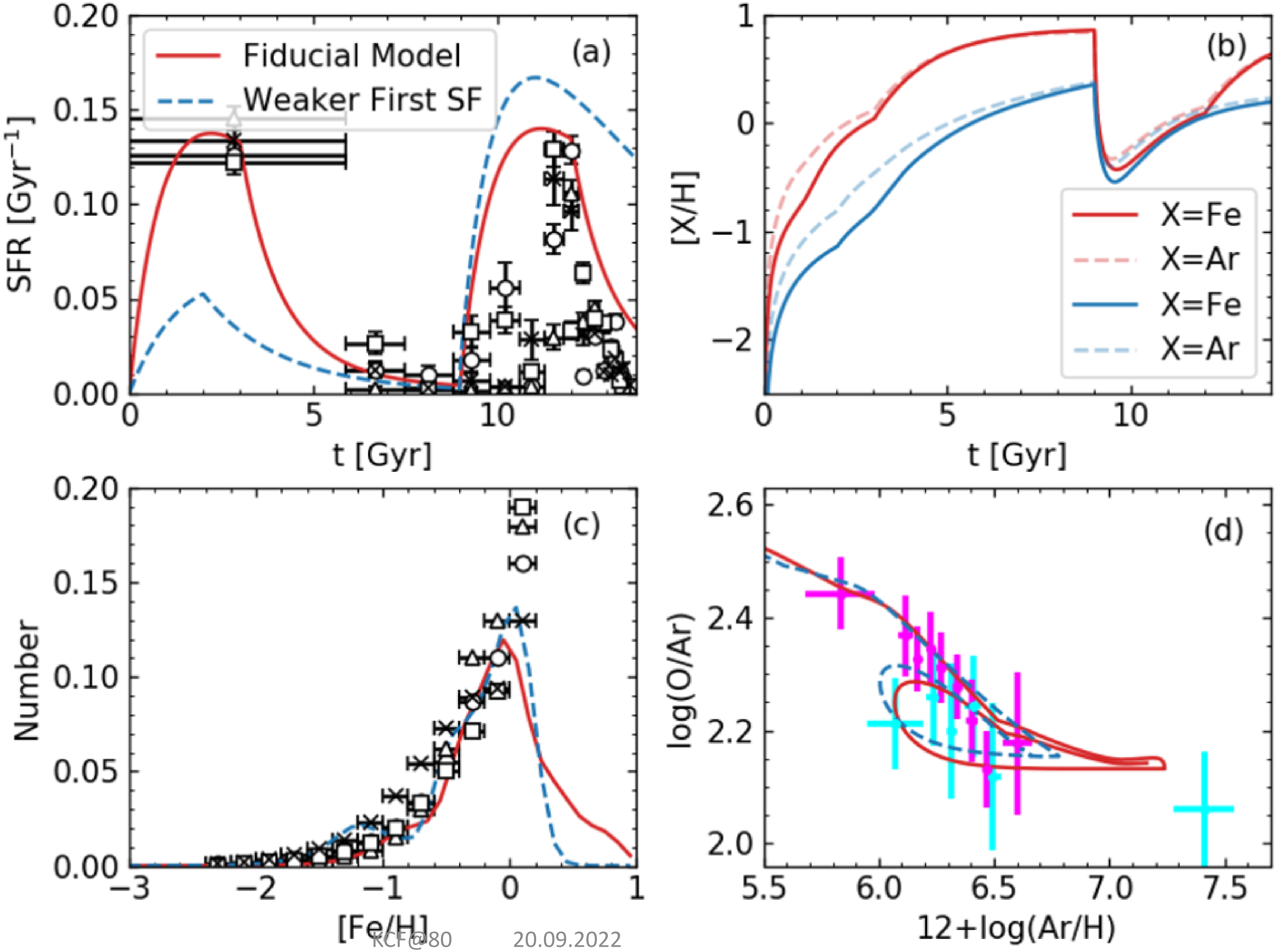
- PN density (within brightest 2.5 magnitudes) in each bin
- Compared to V-band surface brightness profile with bulge-disc-halo decomposition by Corteau et al. (2011)
- Found **α**-parameter values for the bulge, disc and halo components as:

$$\alpha_{2.5,\rm bulge} = (5.28 \pm 6.25) \times 10^{-9}\ \mathrm{PN}\ L^{-1}_{\odot,\rm bol}$$
$$\alpha_{2.5,\rm disk} = (39.16 \pm 3.33) \times 10^{-9}\ \mathrm{PN}\ L^{-1}_{\odot,\rm bol}$$
$$\alpha_{2.5,\rm halo} = (273.89 \pm 41.31) \times 10^{-9}\ \mathrm{PN}\ L^{-1}_{\odot,\rm bol}$$

- Halo PN number density may be higher due to substructure PN present.
- PN density may also be compared to PAndAS RGB star density (to-do-list)







Arnaboldi+22;
models from
C. Kobayashi

- Circumstellar extinction in Pne