The Orion nebula:

a reference for ionized gas phase abundance determinations

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M. Peimbert
S. Torres-Peimbert
Y. Tsamis

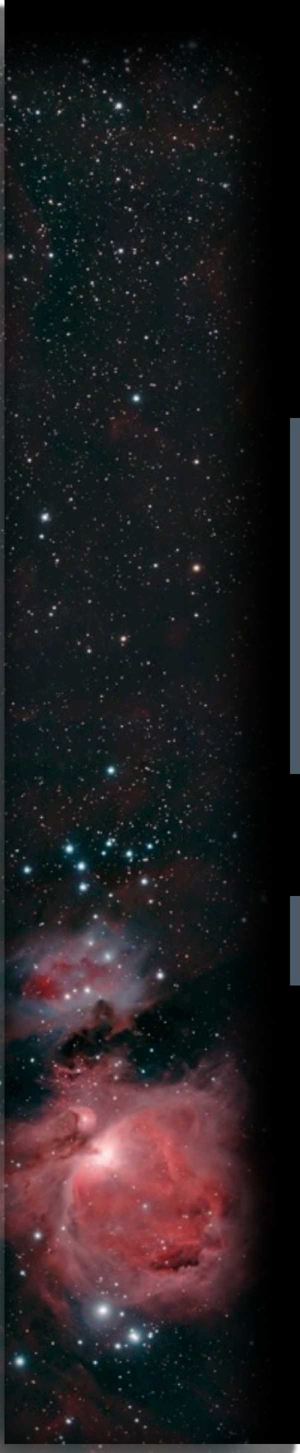
Orion Nebula: Why is it important?

The nearest and brightest HII region

- A benchmark for the determination of the ionized gas-phase present-day abundances of the Solar Neighbourhood

- Its closeness permits to attain the highest spatial resolution

- A laboratory to undestand physical and chemical processes in other Galactic and extragalactic HII regions



Abundance determinations. Optical

Optical low-intermediate resolution spectroscopy:

- Aller & Liller (1959) - First abundance determination
- Peimbert & Costero (1969)
- Simpson (1973)
- Dopita (1973), Dopita et al. (1974)
- Peimbert & Torres-Peimbert (1977)
- Osterbrock et al. (1992)
- Peimbert et al. (1993) – first determination of O^{++} from ORL

Photoelectric scanner

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CCD detector

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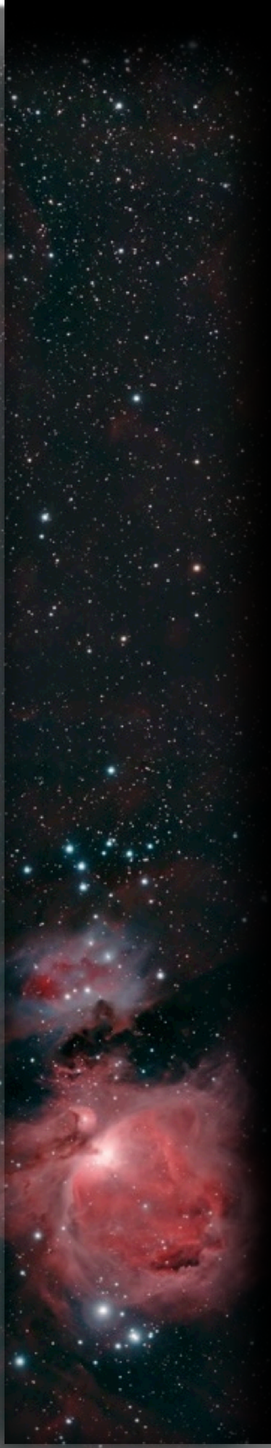


Abundance determinations. Optical

From nebular spectra we can derive abundances of:

He, C, N

α-elements: O, Ne, S, Cl, Ar, (Mg)

Iron-peak elements: Fe, Ni

Usual notation: 12 + log (X/H)

Abundance determinations. Optical

Ionization correction factors, ICFs :

$$\mathrm{ICF} = \frac{\sum_{\mathrm{total}} (X^{i+}/H^{+})}{\sum_{\mathrm{obs}} (X^{i+}/H^{+})}$$

$$X/H = \sum_{\mathrm{obs}} (X^{i+}/H^{+}) \times \mathrm{ICF}$$

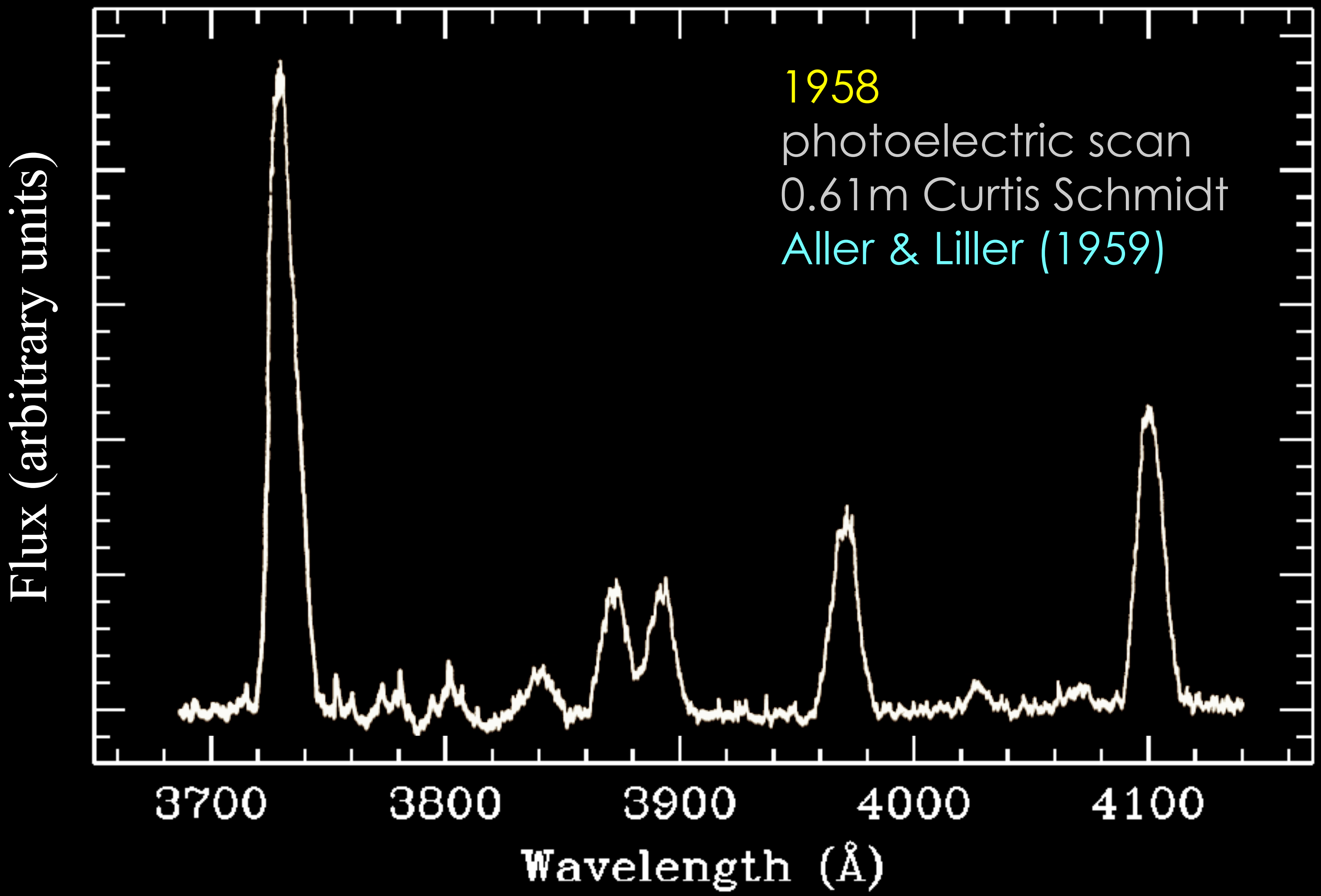
Optical-NIR spectroscopy:

O – O^{+}, O^{++}
He – He^{0}, He^{+} ICF
C – C^{+}, C^{++} ICF
N – N^{+}, N^{++} ICF
Ne – Ne^{+}, Ne^{++} ICF
S – S^{+}, S^{++}, S^{3+} ICF
Cl – Cl^{+}, Cl^{++}, Cl^{3+} problems, ICF?
Ar – Ar^{+}, Ar^{++}, Ar^{3+} ICF
Fe – Fe^{+}, Fe^{++}, Fe^{3+} problems, ICF?

ICFs based on:

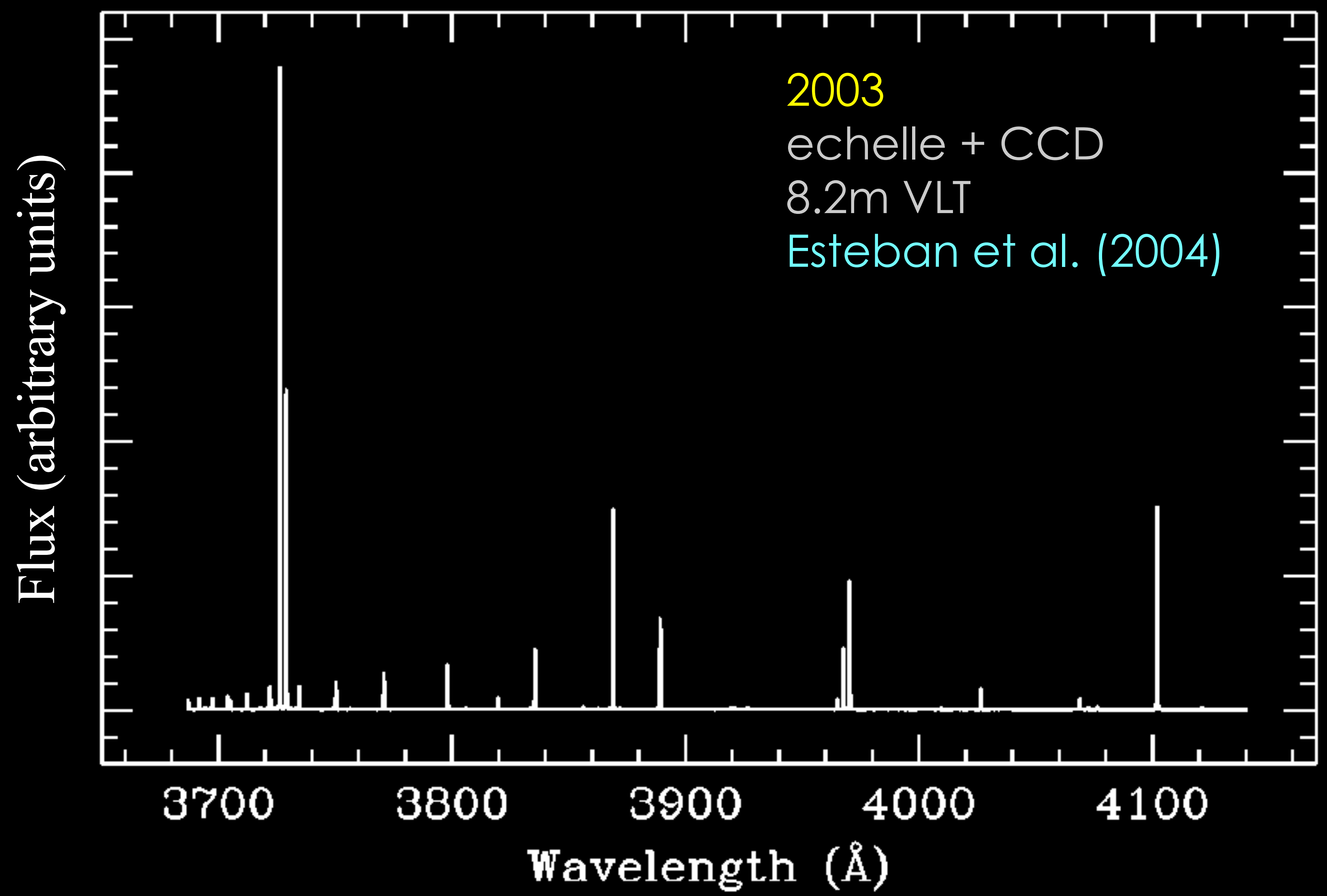
- similarity of ionization potentials of different species
- photoionization models

Problem highlighted by Simon-Díaz & Stasińska (2011)



1958
photoelectric scan
0.61m Curtis Schmidt
Aller & Liller (1959)

Same spectral range almost 50 ys after

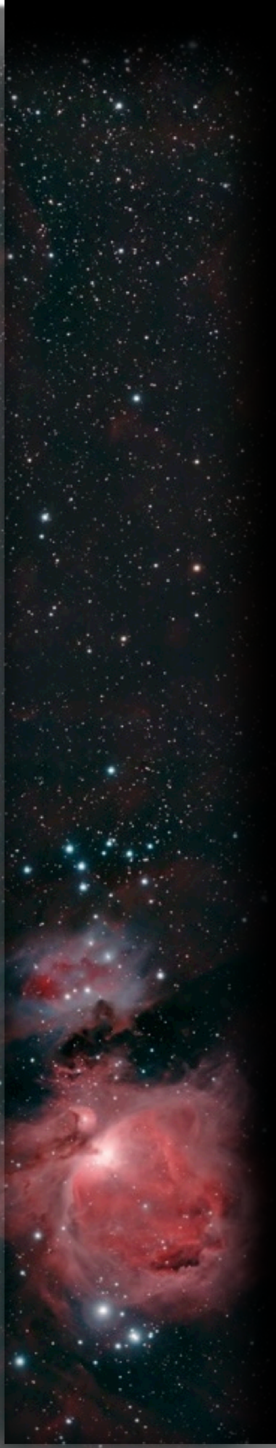


2003

echelle + CCD

8.2m VLT

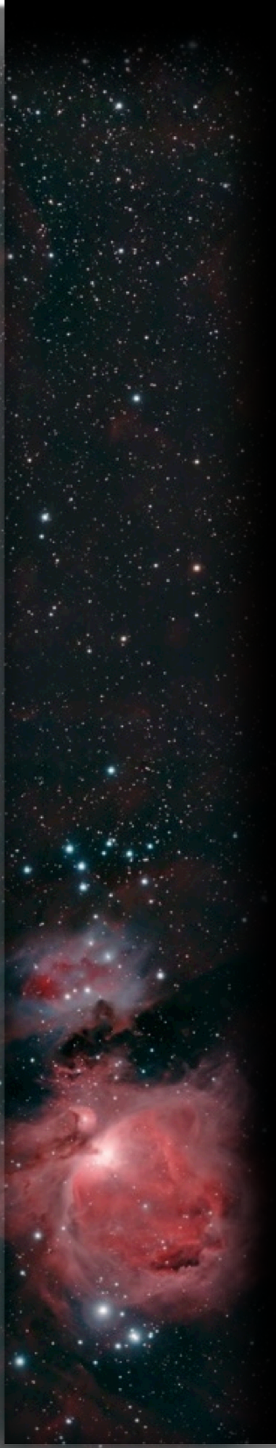
Esteban et al. (2004)



Abundance determinations. Optical

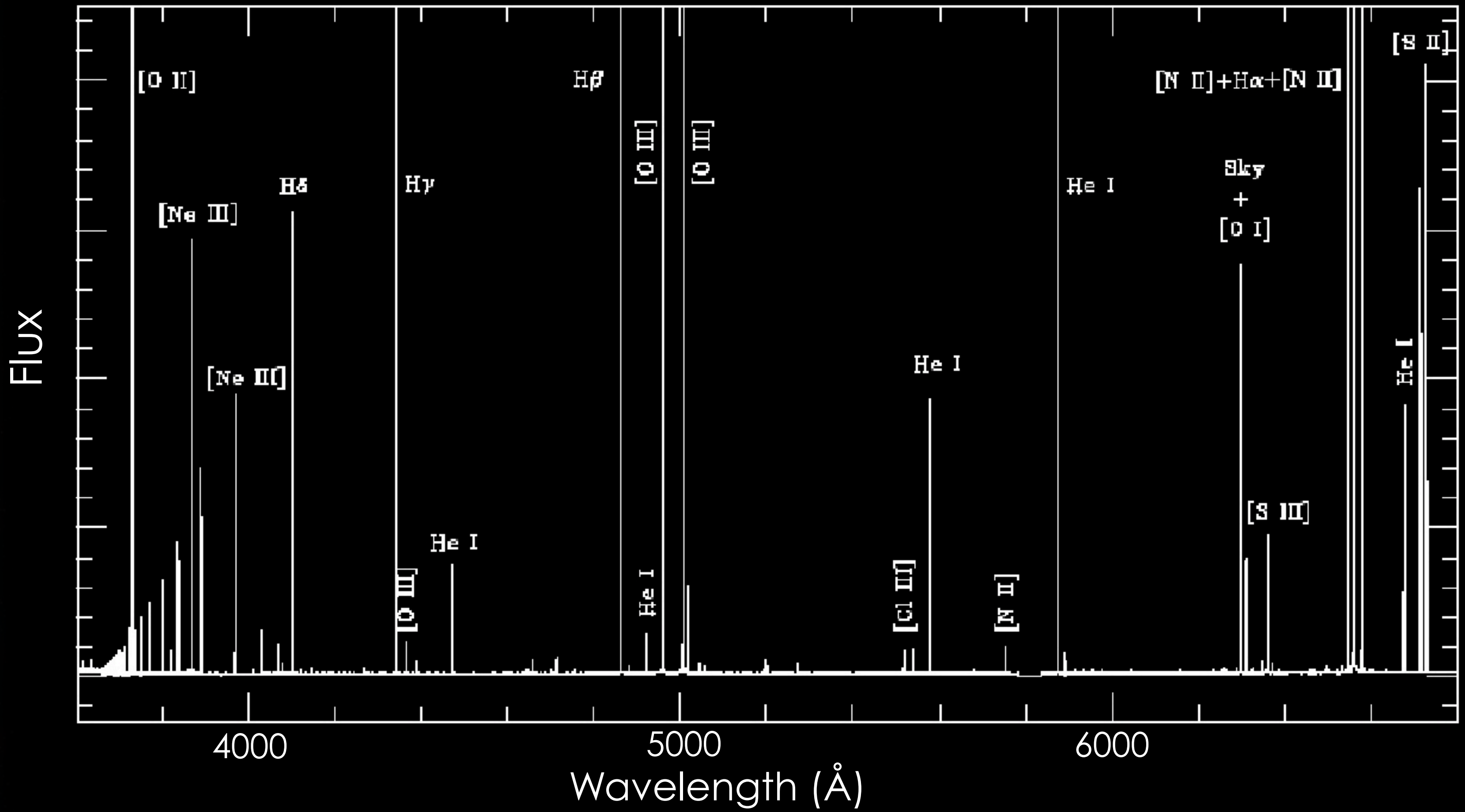
Optical echelle spectroscopy:

- Esteban et al. (1998) – 2.1m SPM data, O^{++}, C^{++} from ORLs
- Esteban et al. (2004) – VLT data, O^{+}, O^{++}, C^{++}, Ne^{++} from ORLs
- Blagrave et al. (2006) – 4m CTIO data of HH 529
- Mesa-Delgado et al. (2009) – VLT data of HH 204



Abundance determinations. Optical

VLT spectrum from 3600 to 10000 Å (Esteban et al. 2004)



- collisionally excited lines (CELs) : [OII], [OIII], [NII], [SII], [SIII] ...
- optical recombination lines (ORLs) : HI, HeI, CII, OI, OII, NeII
- other permitted lines (excited by fluorescence)

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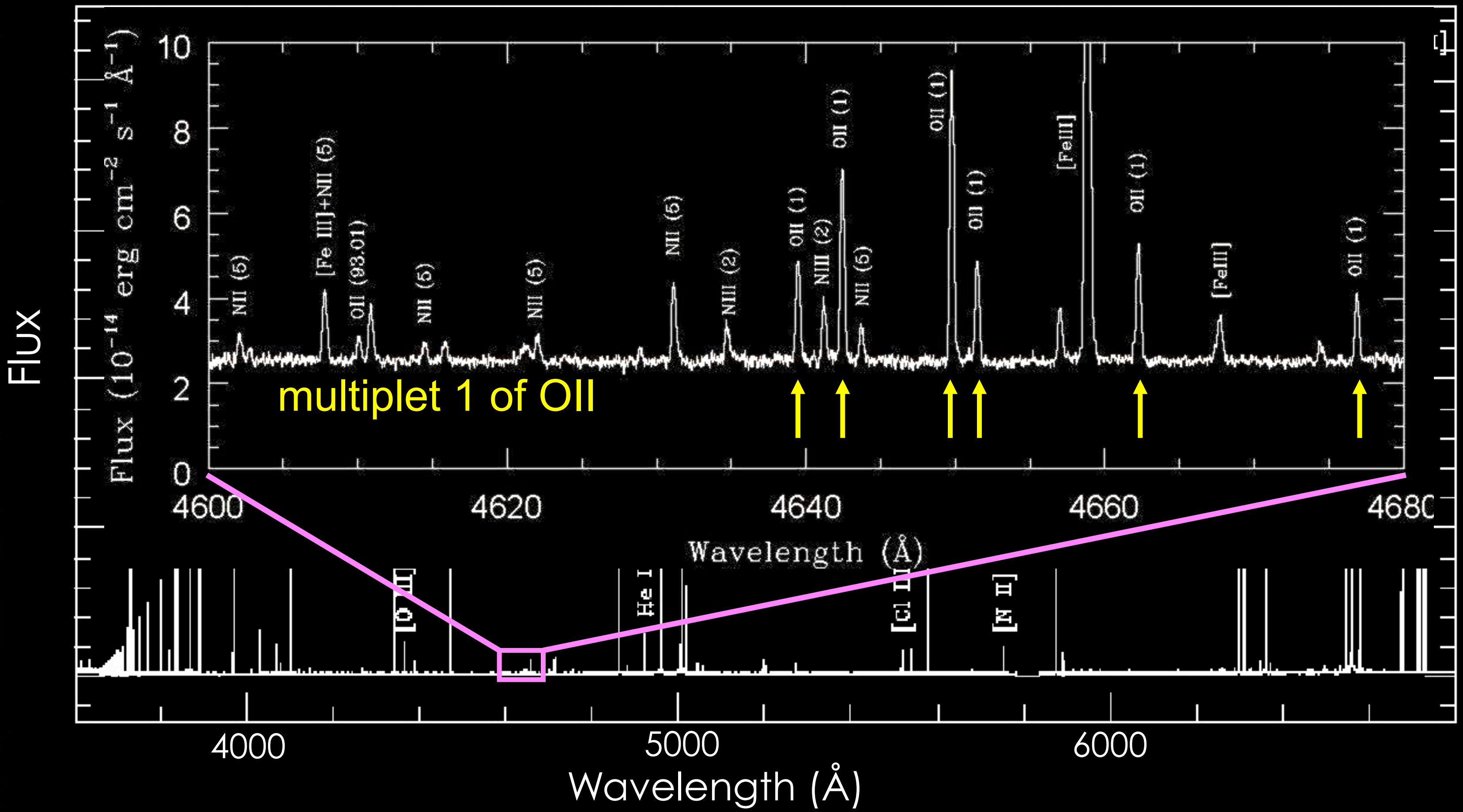

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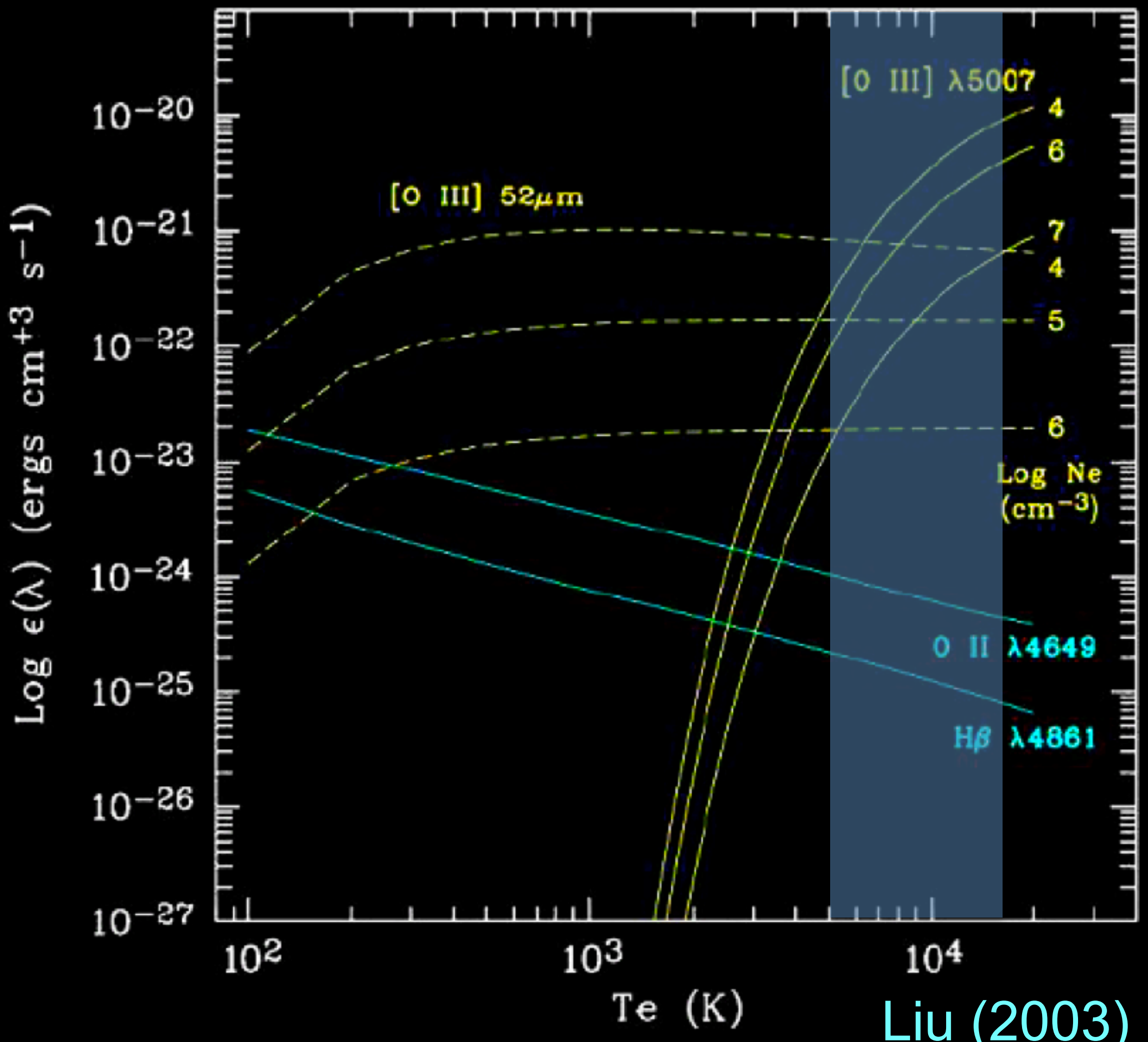
Abundance determinations

Optical CELs
IR CELs
and
ORLs

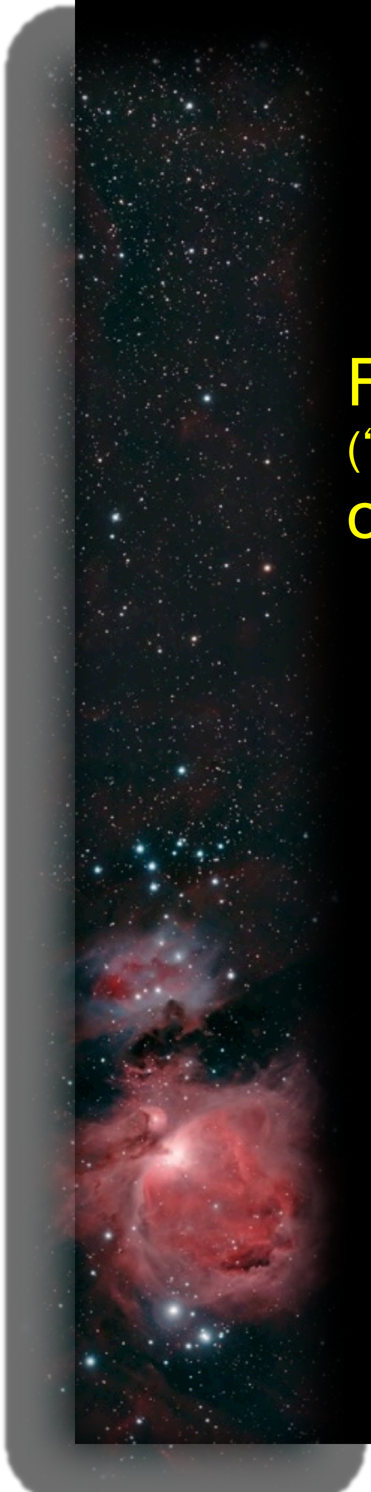
Very different dependence on electron temperature, T_e

T_e dependence of emissivities of O^{++} lines

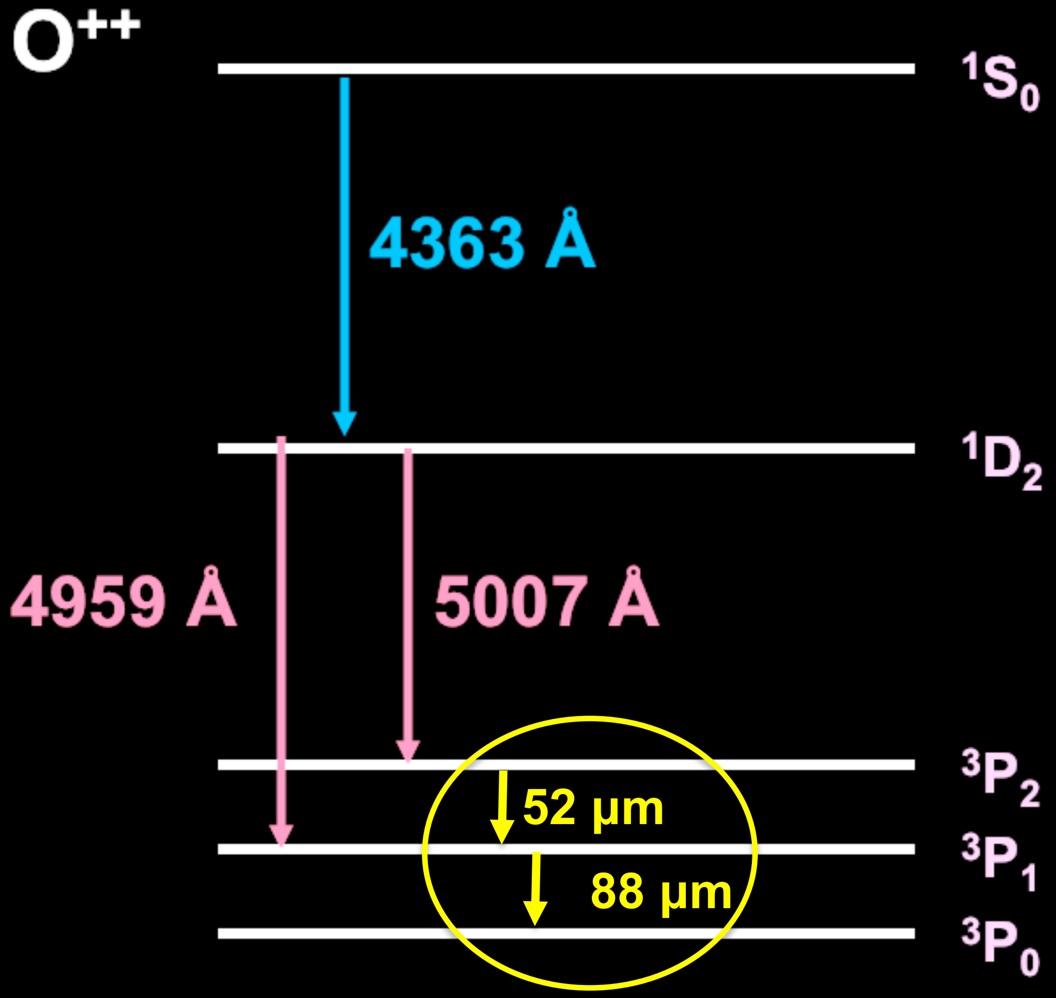


Liu (2003)

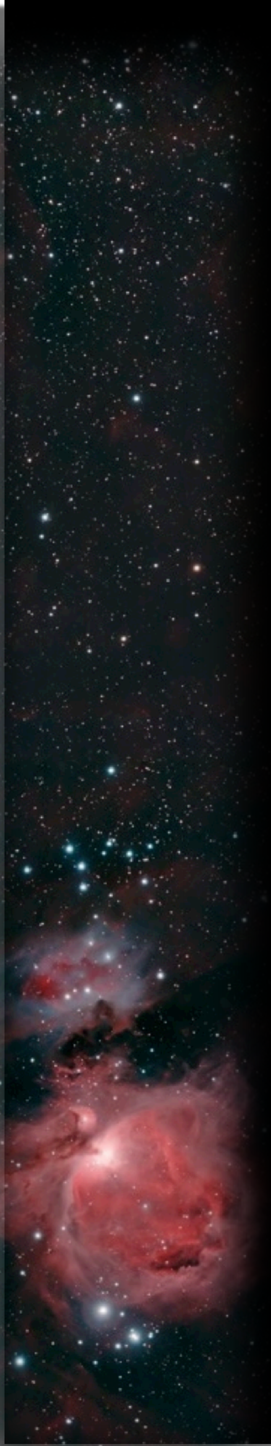
Abundance determinations. FIR



FIR CELs
("fine-structure" lines)
of [OIIII]



Energy levels
not at scale!



Abundance determinations. FIR

Simpson et al. (1983)

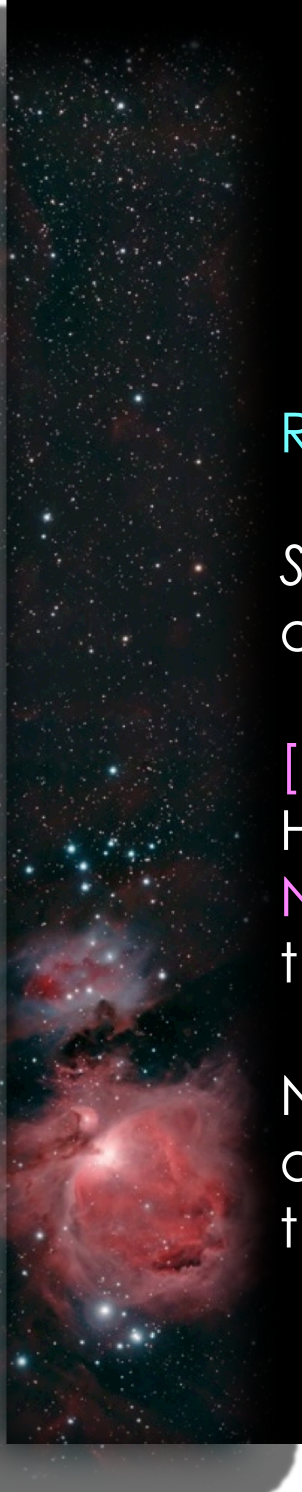
0.91m telescope at Kuiper Airborne Observatory (KAO)

[OIII] 52 and 88 μm, [NIII] 57 μm, [NeIII] 36 μm

No HI lines, abundances estimated from photoionization models

$N^{++}/O^{++} \approx 2 \times N^{+}/O^{+}$

Abundance determinations. FIR

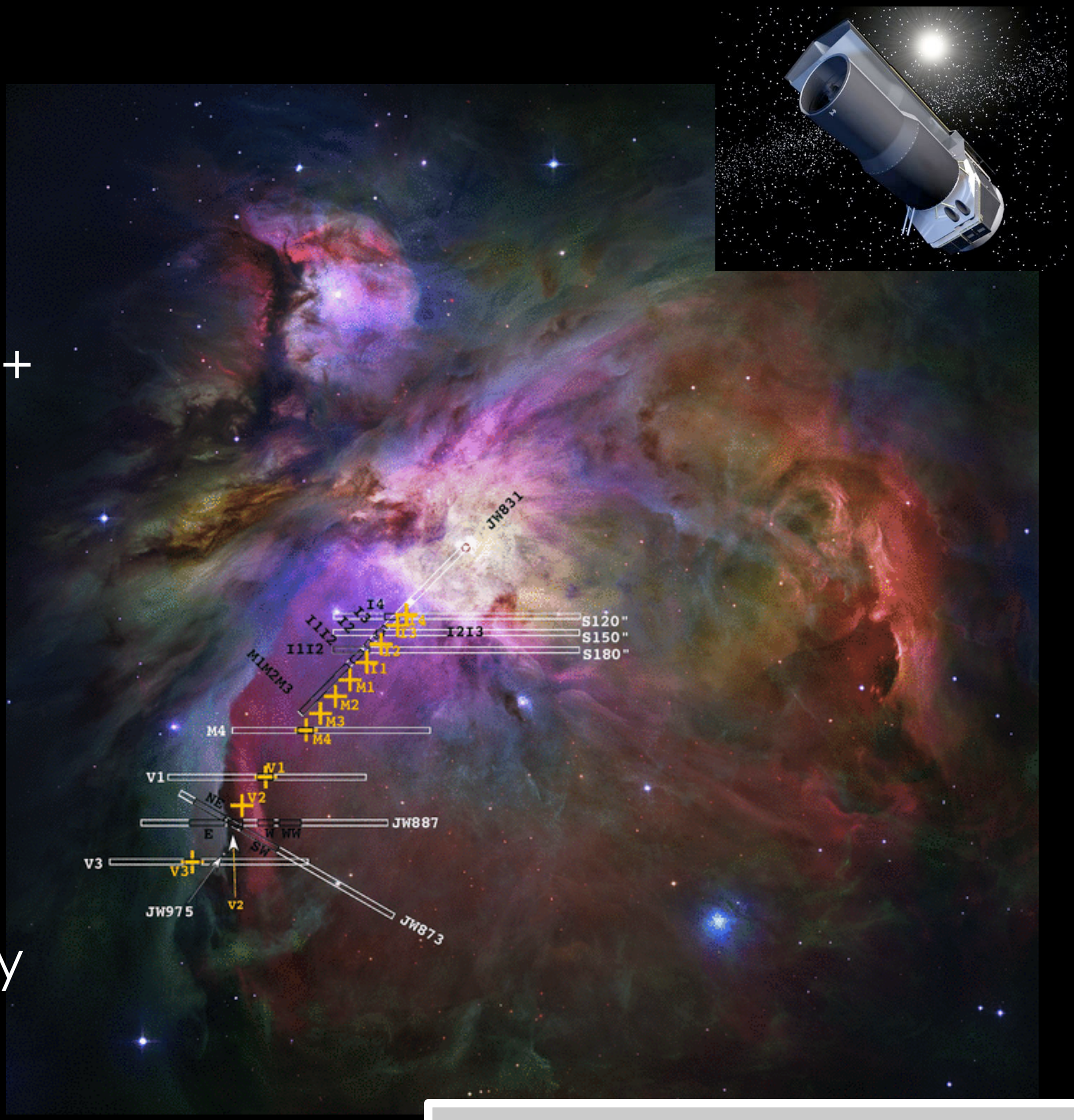


Rubin et al. (2011)

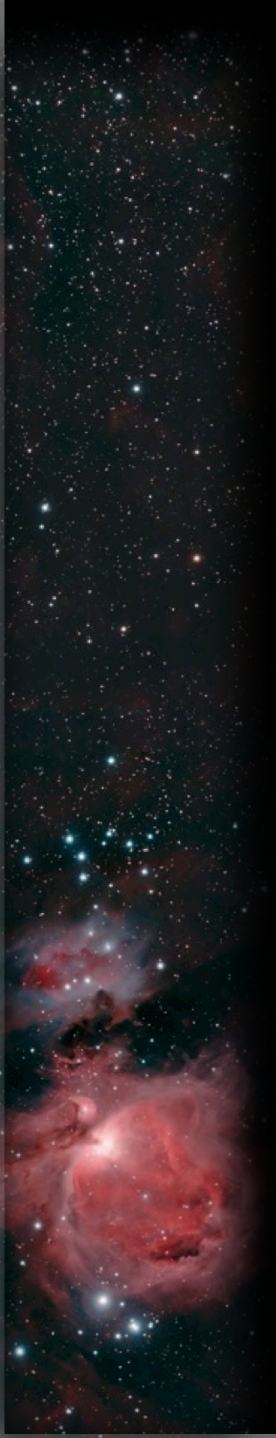
Spitzer data 10-37 µm +
optical spectra

[NeII] and [NeIII]
HI lines observed
Ne/H without ICF
the "*gold standard*"

Ne^{++} emission is
detected farther away
the Bright Bar



See Bob Rubin's talk



Abundance determinations. UV

Ultraviolet (UV) spectroscopy:

Walter et al. (1992)

IUE + optical spectra of in 99 zones of Orion Nebula

CIII] 1909 Å and CII] 2326 Å

HI lines from optical spectra

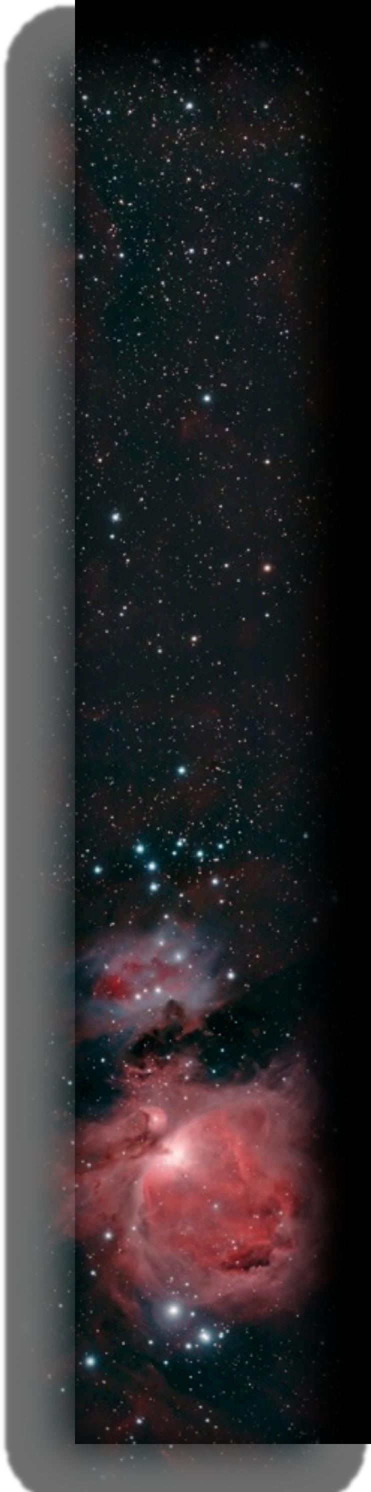
Rubin et al. (1998)

HST FOS and GHRS spectra

NII] 2142 Å, [OII] 2471 Å

$(N^+/O^+)_{UV} \approx (N^+/O^+)_{optical}$

Abundance determinations. UV

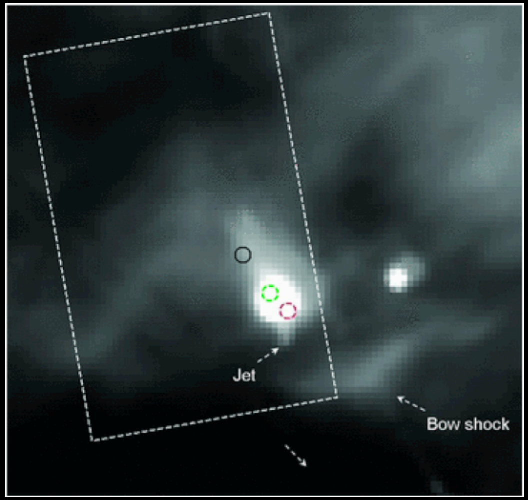


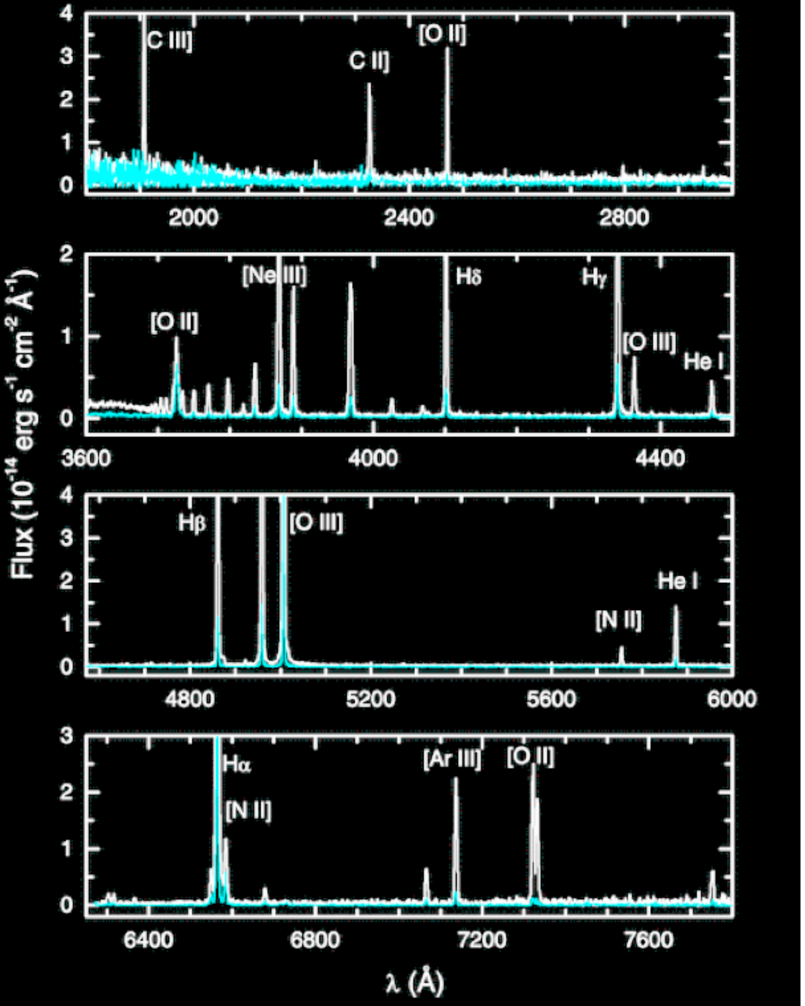
Ultraviolet (UV) spectroscopy:

Tsamis et al. (2011)

HST FOS + optical IFU FLAMES VLT spectra of proplyd LV2

CIII] 1909 Å, CII] 2326 Å and [OII] 2470 Å



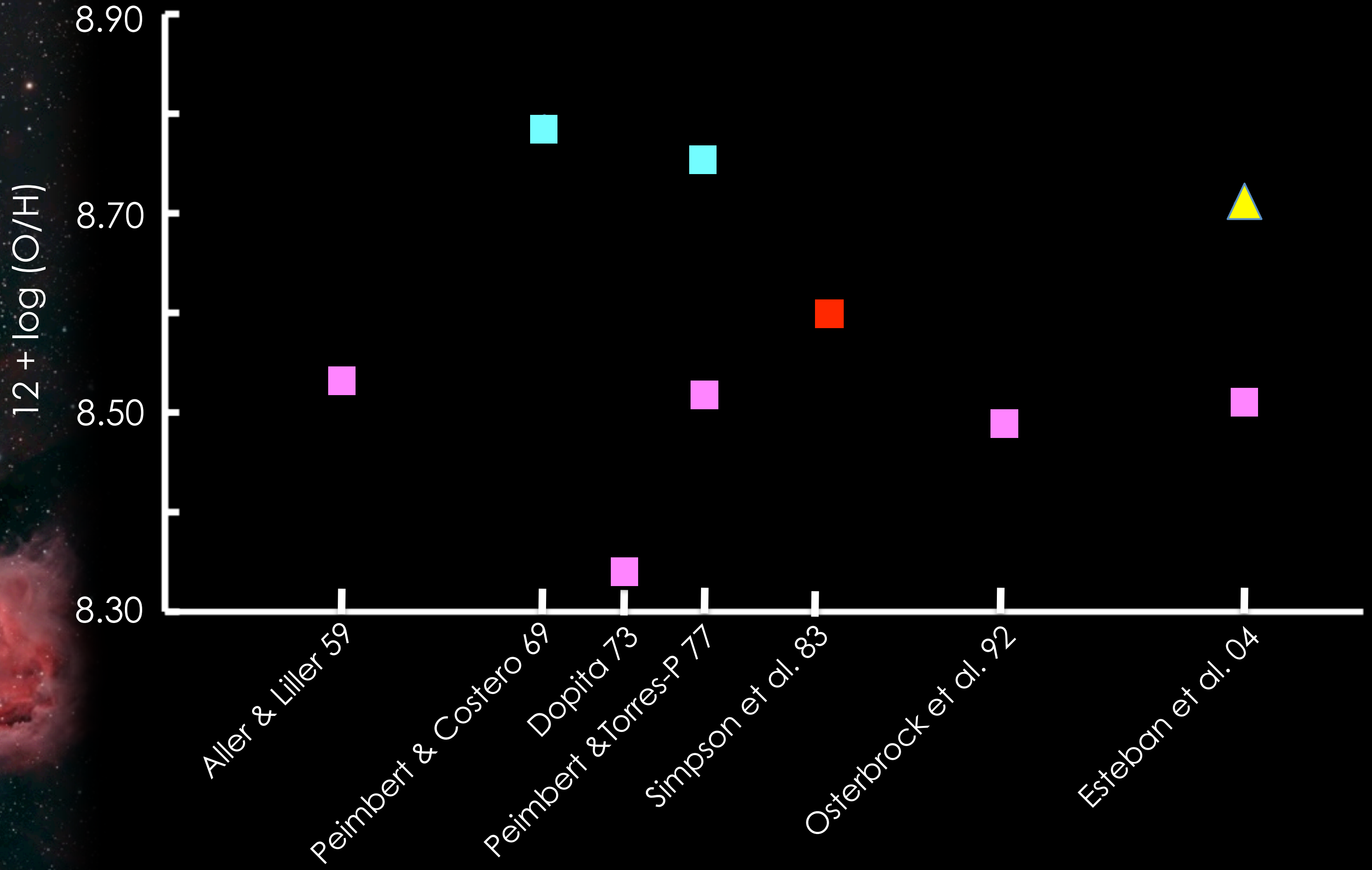


Abundance determinations

Determinations of O/H ratio:

12 + log (O/H)

$O/H = O^+/H^+ + O^{++}/H^+$



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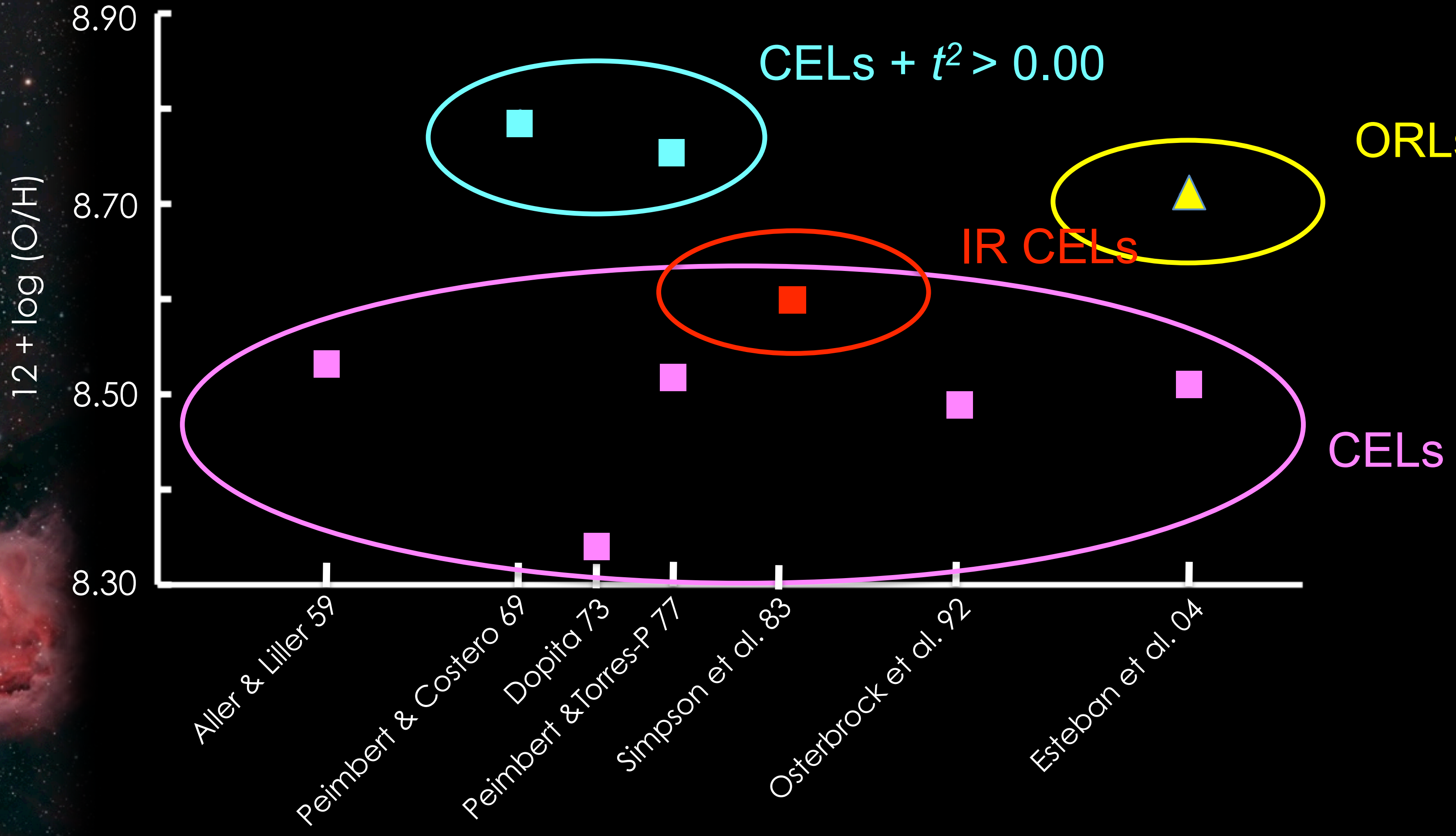

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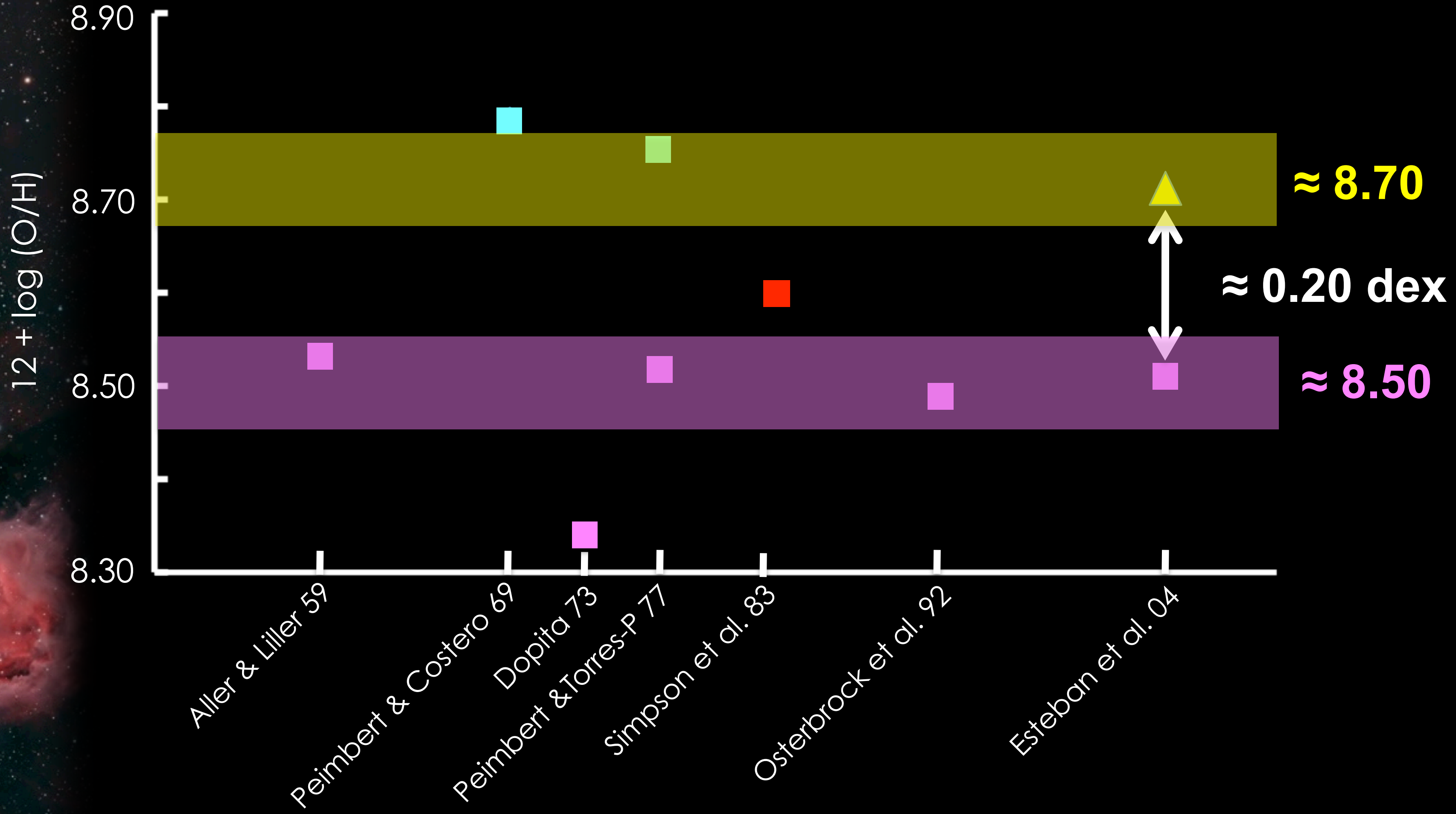


Abundance discrepancy

Ionic abundances from ORLs are systematically higher than those from CELs in photoionized nebulae

The *Abundance Discrepancy Factor* (ADF):

$$\mathrm{ADF}(X^{i+}) = \log\,(X^{i+}/H^{+})_{\mathrm{ORLs}} - \log(X^{i+}/H^{+})_{\mathrm{CELs}}$$

Abundance discrepancy

ADF in several HII regions (dex)

Ion	Orion Neb.	30 Dor	M8	NGC3576
O^{+}	+0.39	+0.26	+0.14	...
O^{++}	+0.14	+0.25	+0.37	+0.24
C^{++}	+0.40	+0.21	+0.35	+0.28
Ne^{++}	+0.26	...	...	...
	Esteban *et al.* (2004)	Peimbert (2003)	García-Rojas *et al.* (2007)	García-Rojas *et al.* (2004)

ADFs are always positive and similar for the different ions and objects

Abundance discrepancy

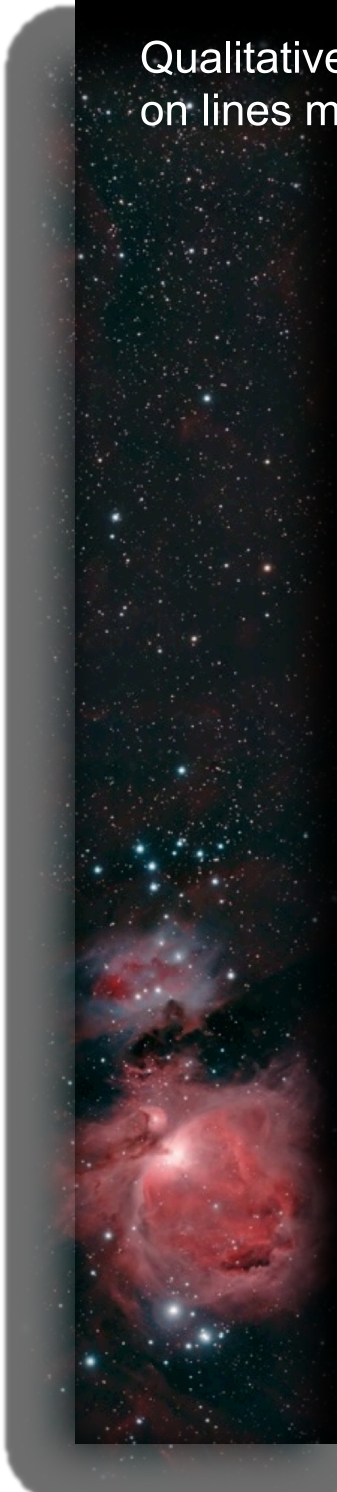
Possible explanations:

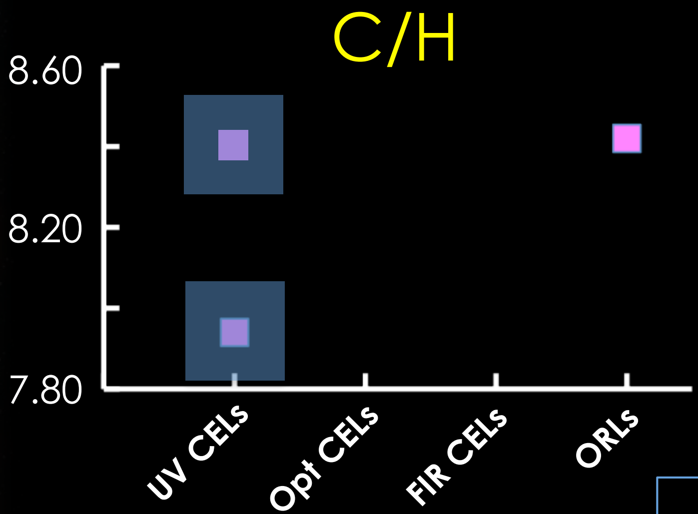
- Temperature fluctuations, t^2 (Peimbert et al. 1980)
- Chemical inhomogeneities (Pequignot et al. 2002, Stasińska et al. 2007)
- Errors in atomic data, specially in dielectronic recombination (Rodríguez & García-Rojas 2010)
- κ-distribution of electrons (Nicholls et al. 2012)

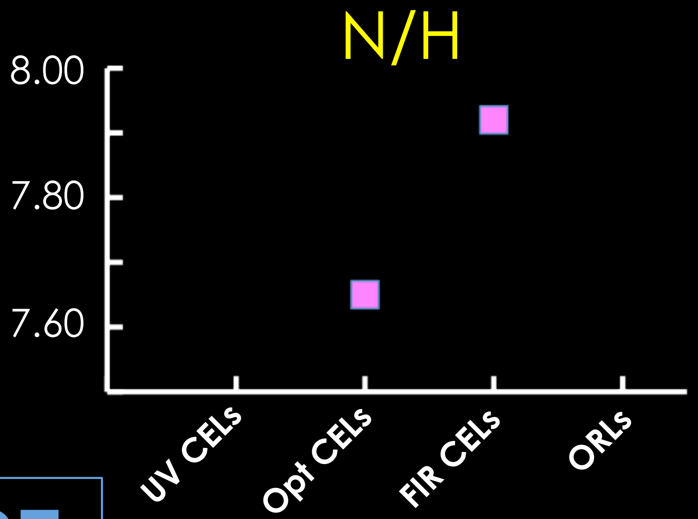
And others: density variations, X-rays….

Abundance discrepancy

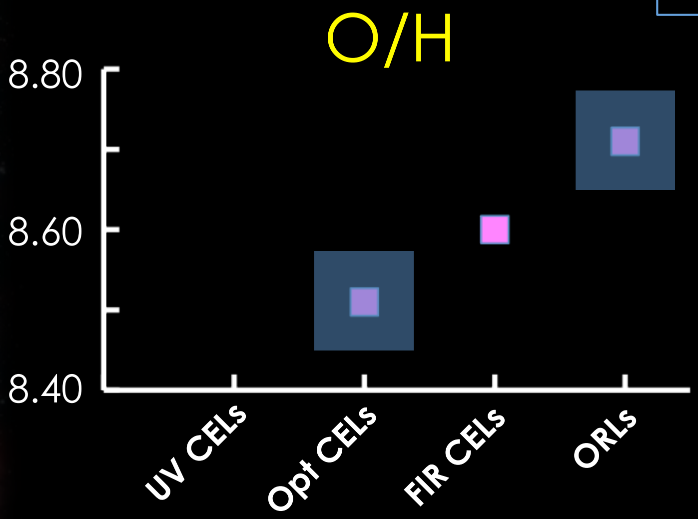
Qualitative behaviour: abundance determinations based on lines more dependent on T_e show lower values

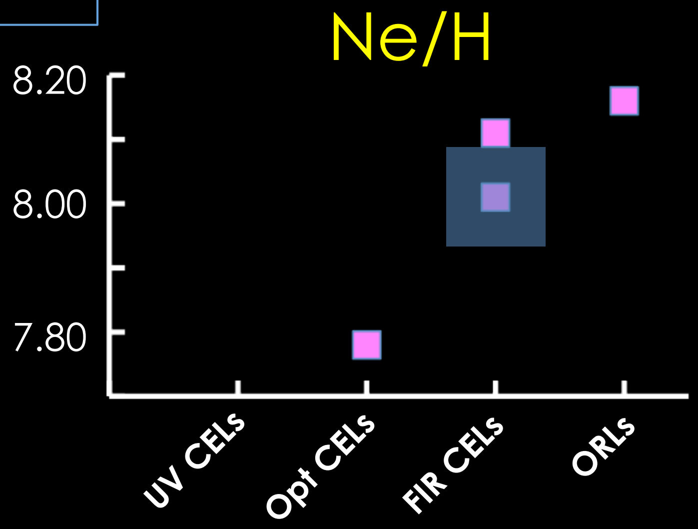




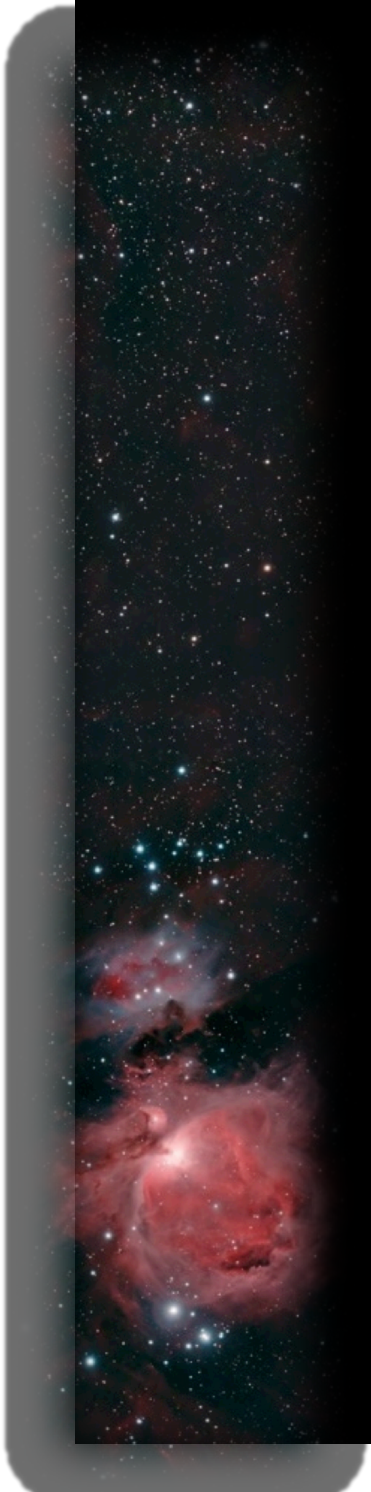


No ICF



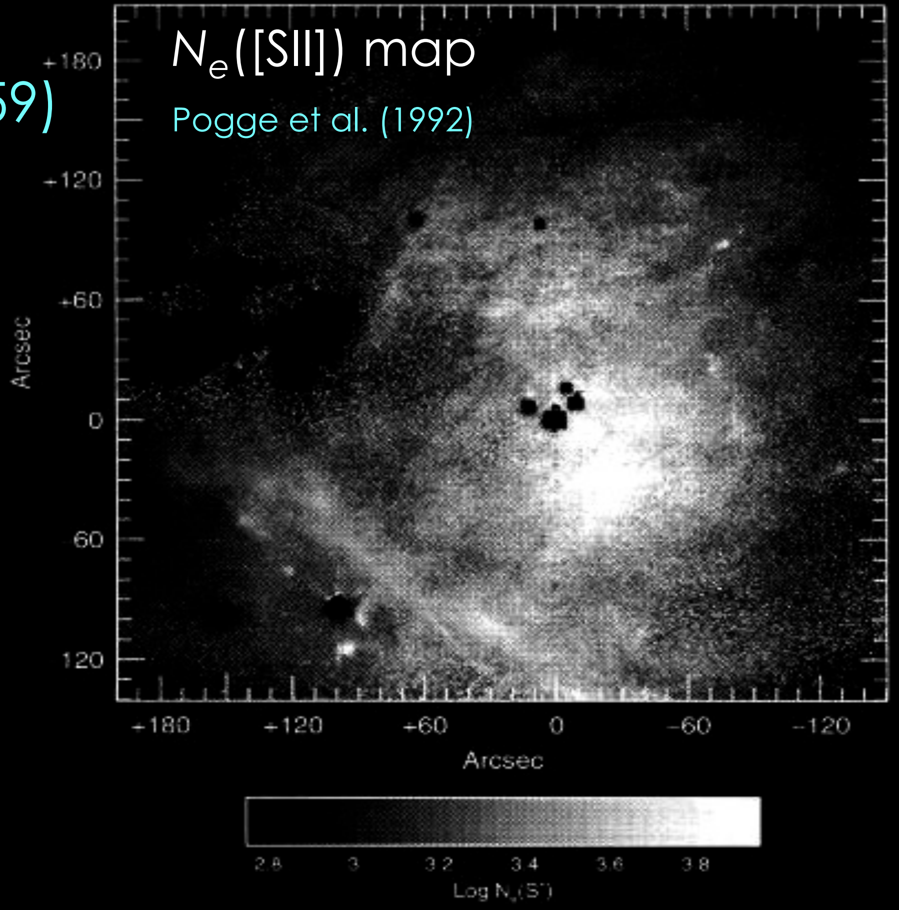


UV CELs: Walter et al. 92; Tsamis et al. 11 Opt CELs, ORLs: Esteban et al. 04
FIR CELs: Simpson et al. 83; Rubin et al. 11



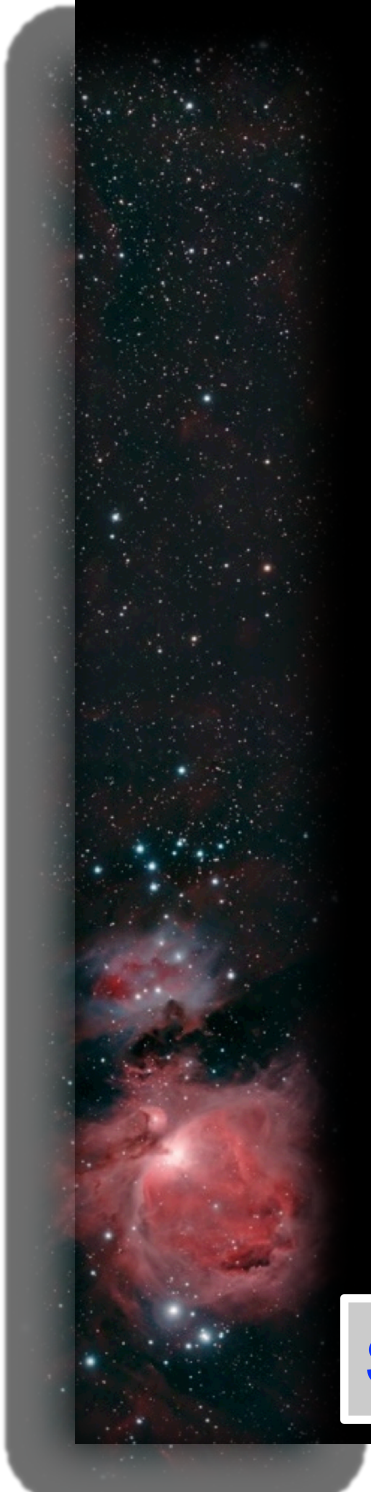
Evidence of small spatial scale variations of the physical conditions (n_e , T_e) in the Orion Nebula

- Osterbrock & Flather (1959)
- Pogge et al. (1992)



N_e([SII]) map

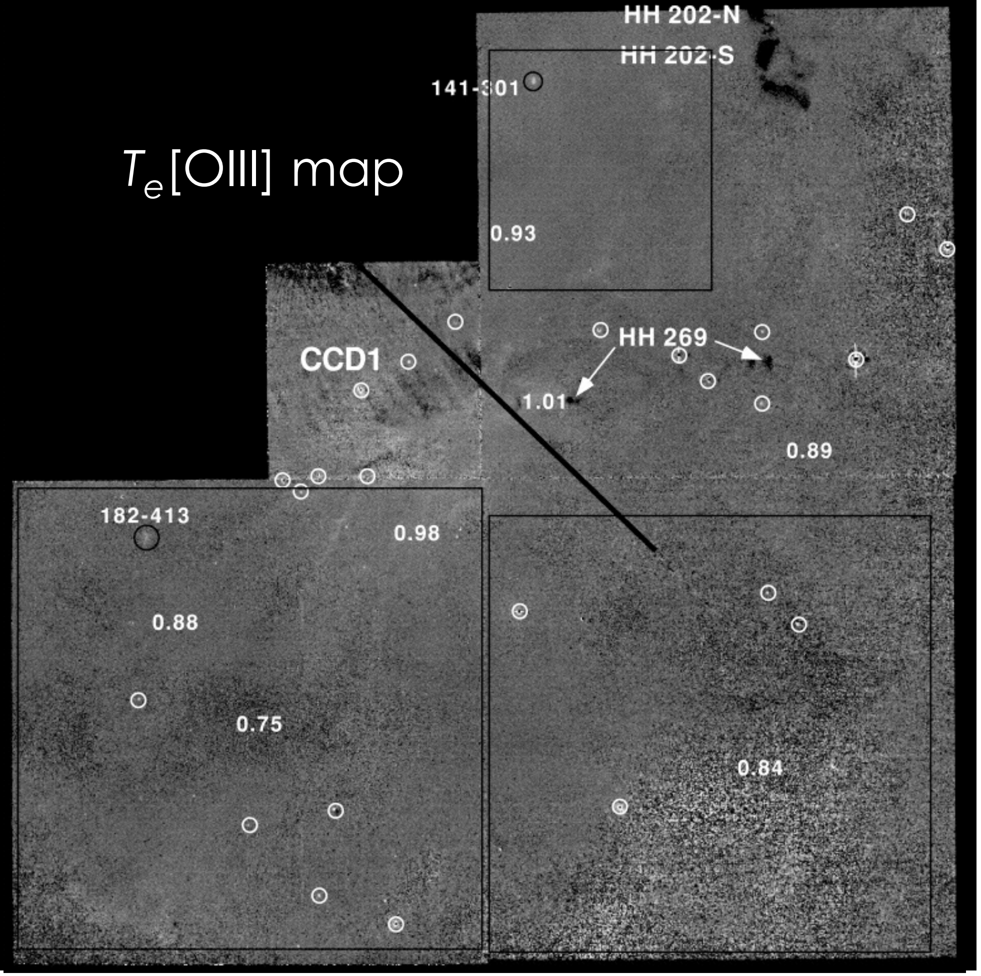
Pogge et al. (1992)



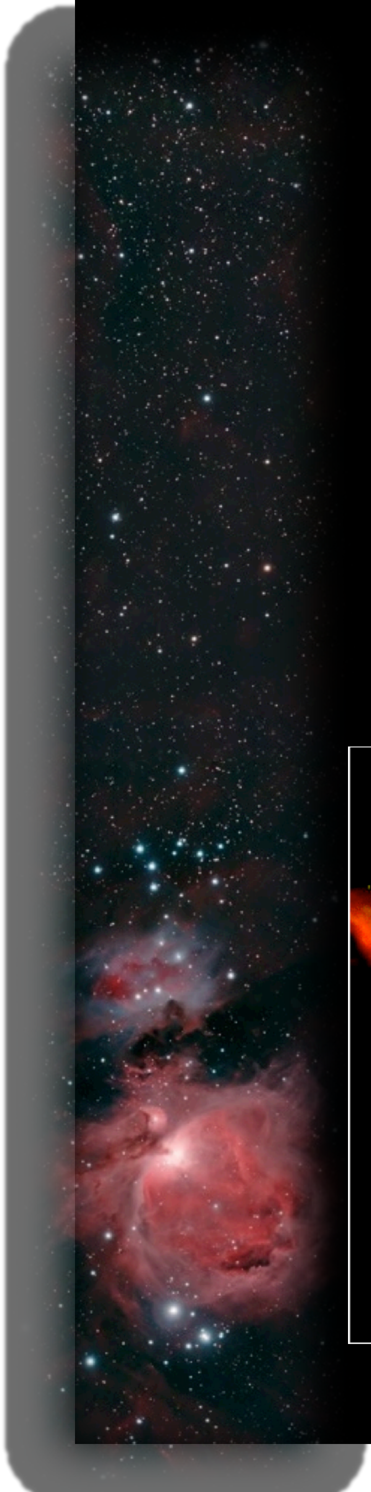
Evidence of small spatial scale variations of the physical conditions (n_e , T_e) in the Orion Nebula

- O'Dell et al. (2003)

T_e[OIII] map



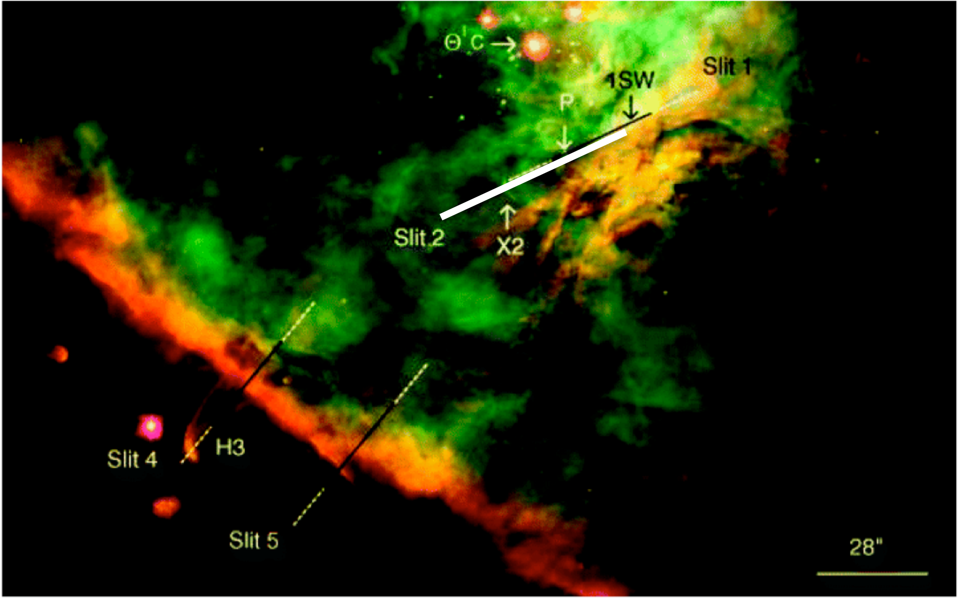
See M. Peimbert's talk

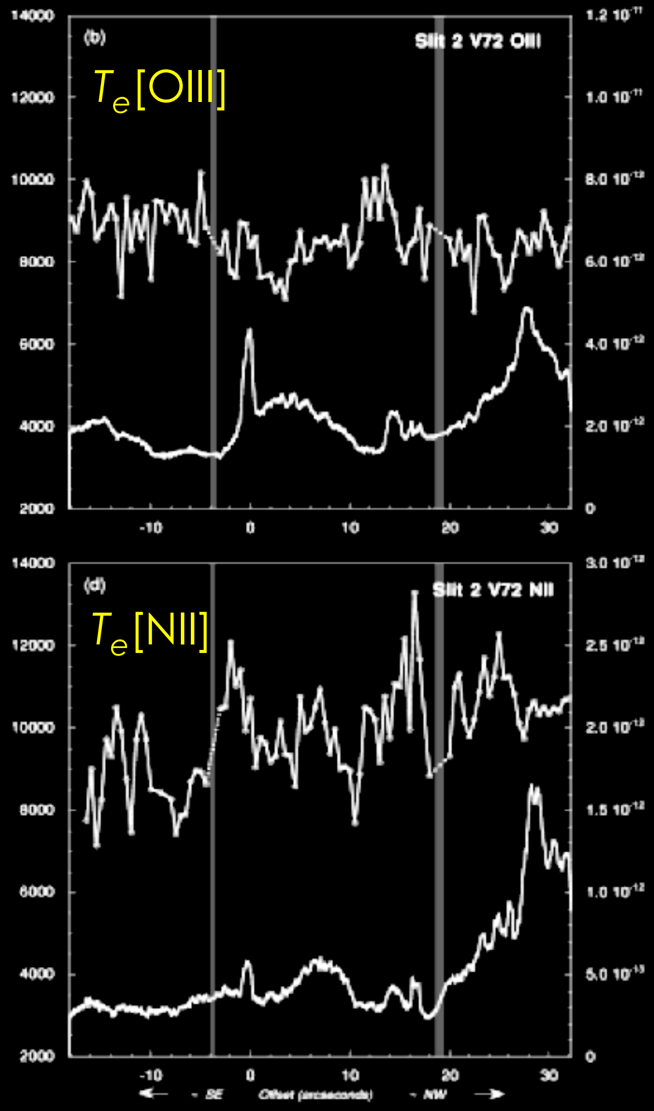


Nebular structures and abundances

- Rubin et al. (2003)

HST long-slit spectroscopy at several positions with 0.5 arcsec spatial resolution T_e[OIII] and T_e[NII] spatial distributions

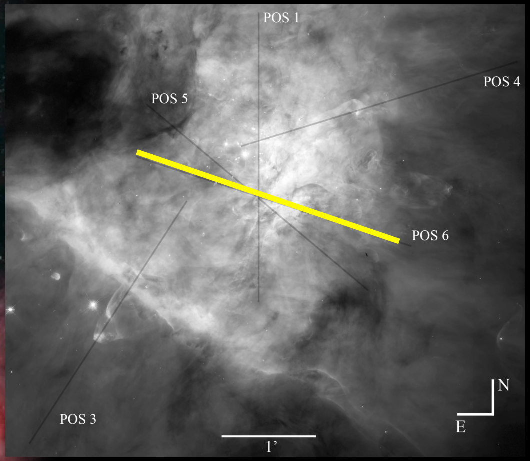


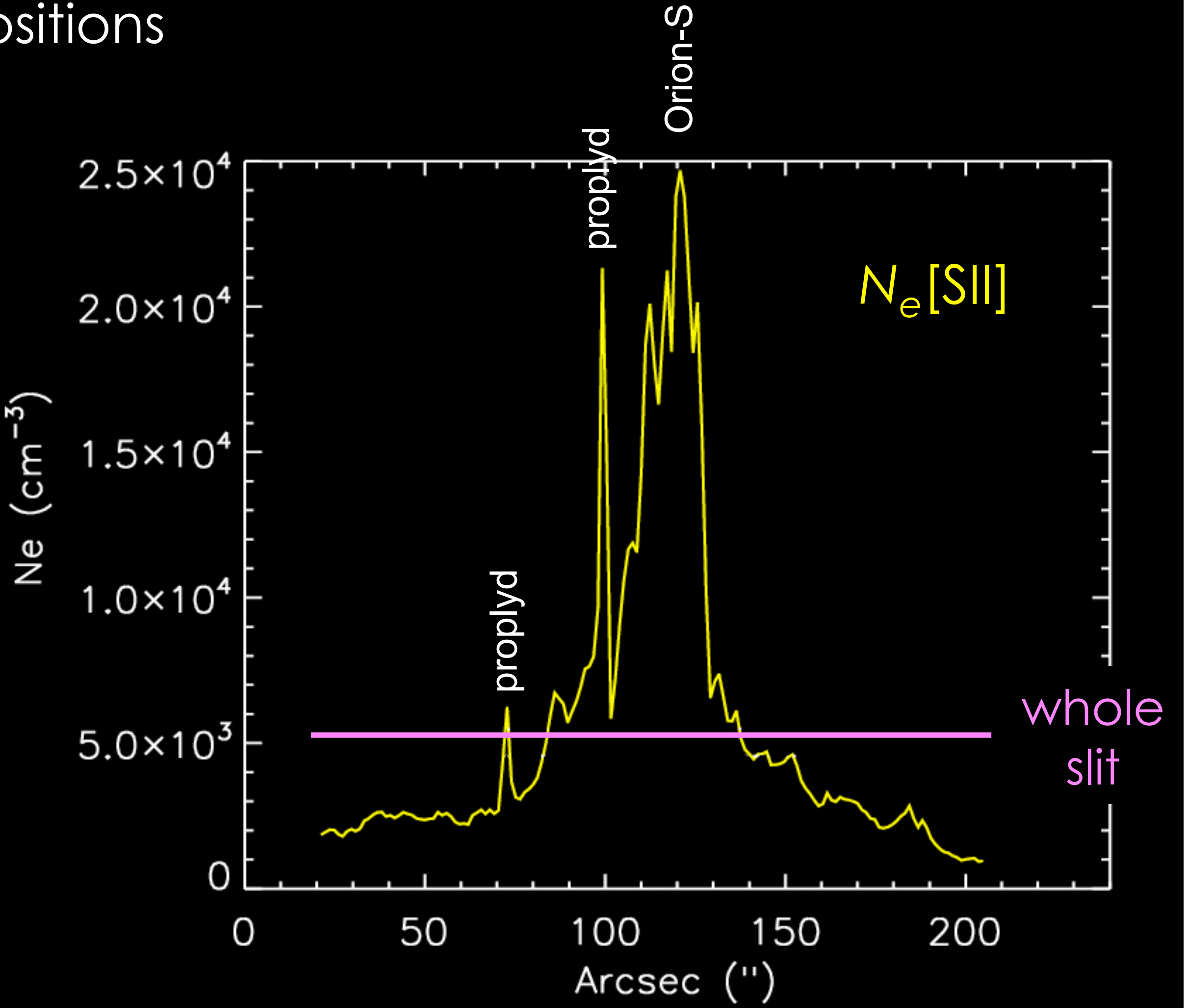


Nebular structures and abundances

- Mesa-Delgado et al. (2008)

longslit at several positions
4.2m WHT
4100 – 8700 Å,
1-4 Å FWHM
1 arcsec pixel





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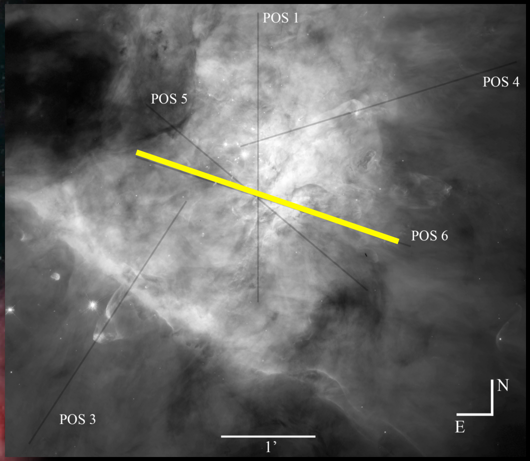

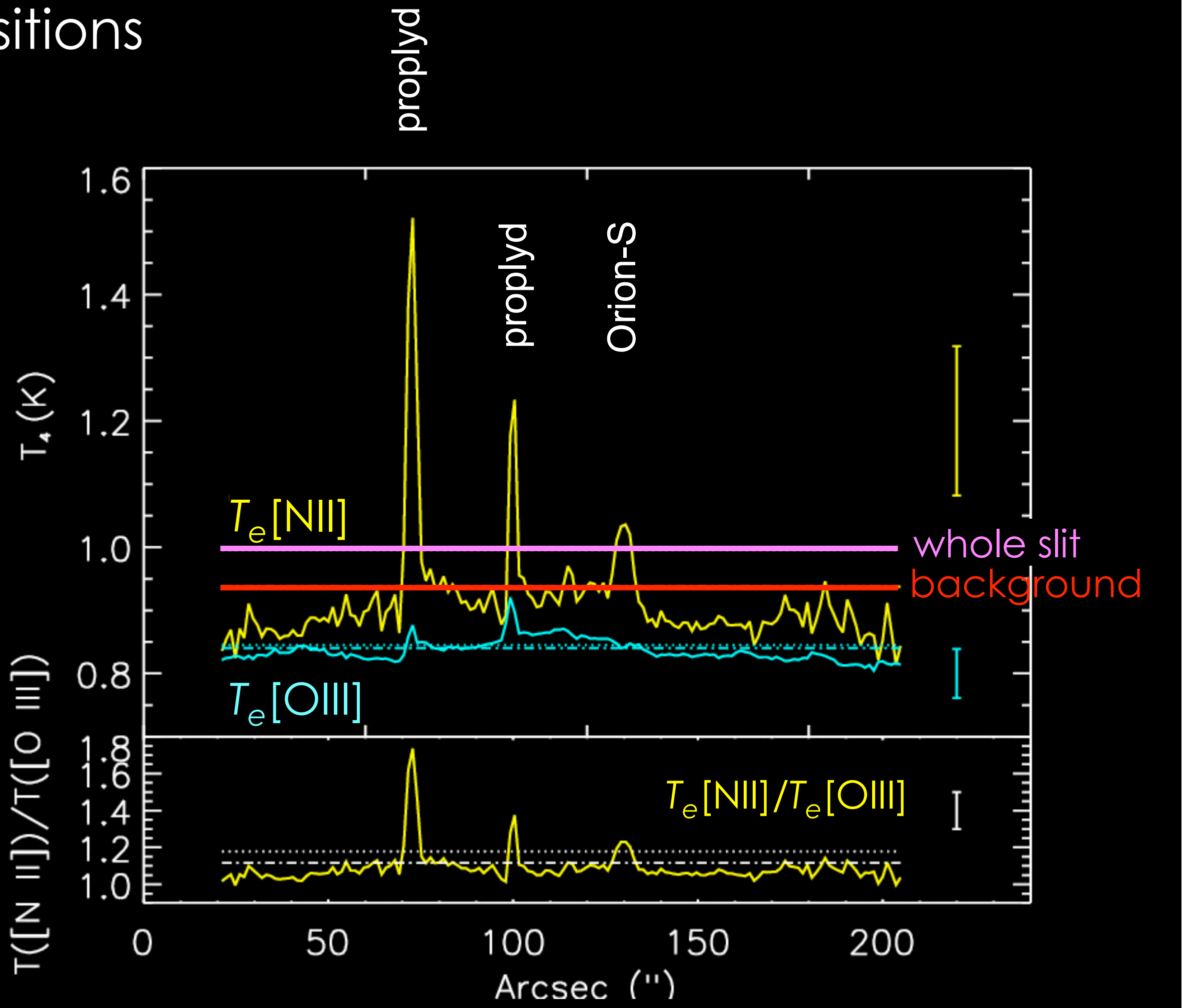

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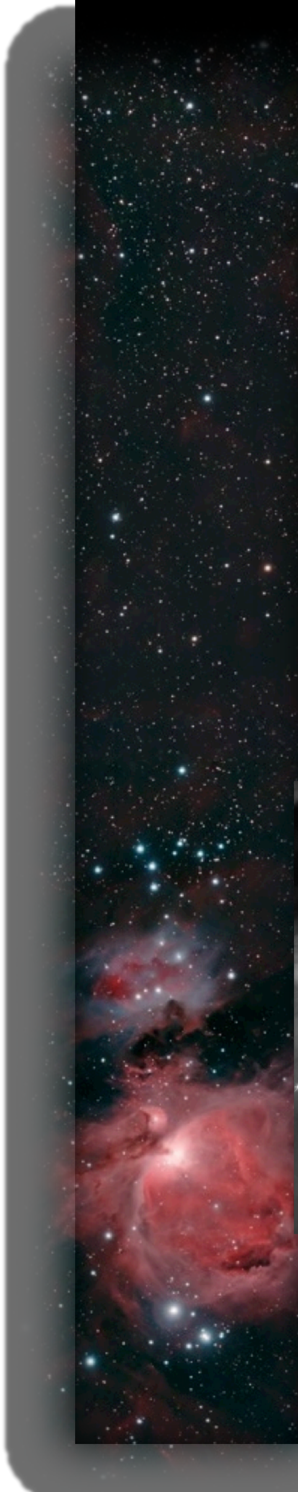

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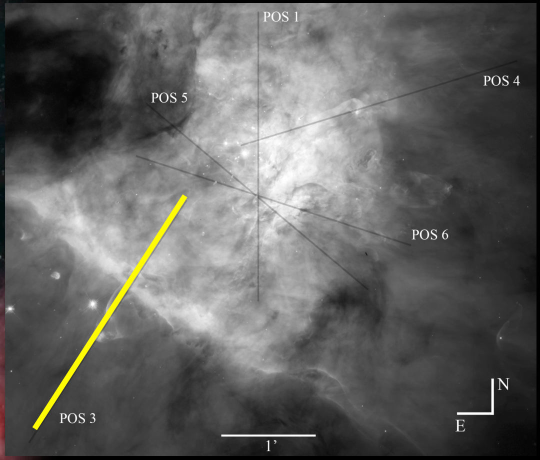
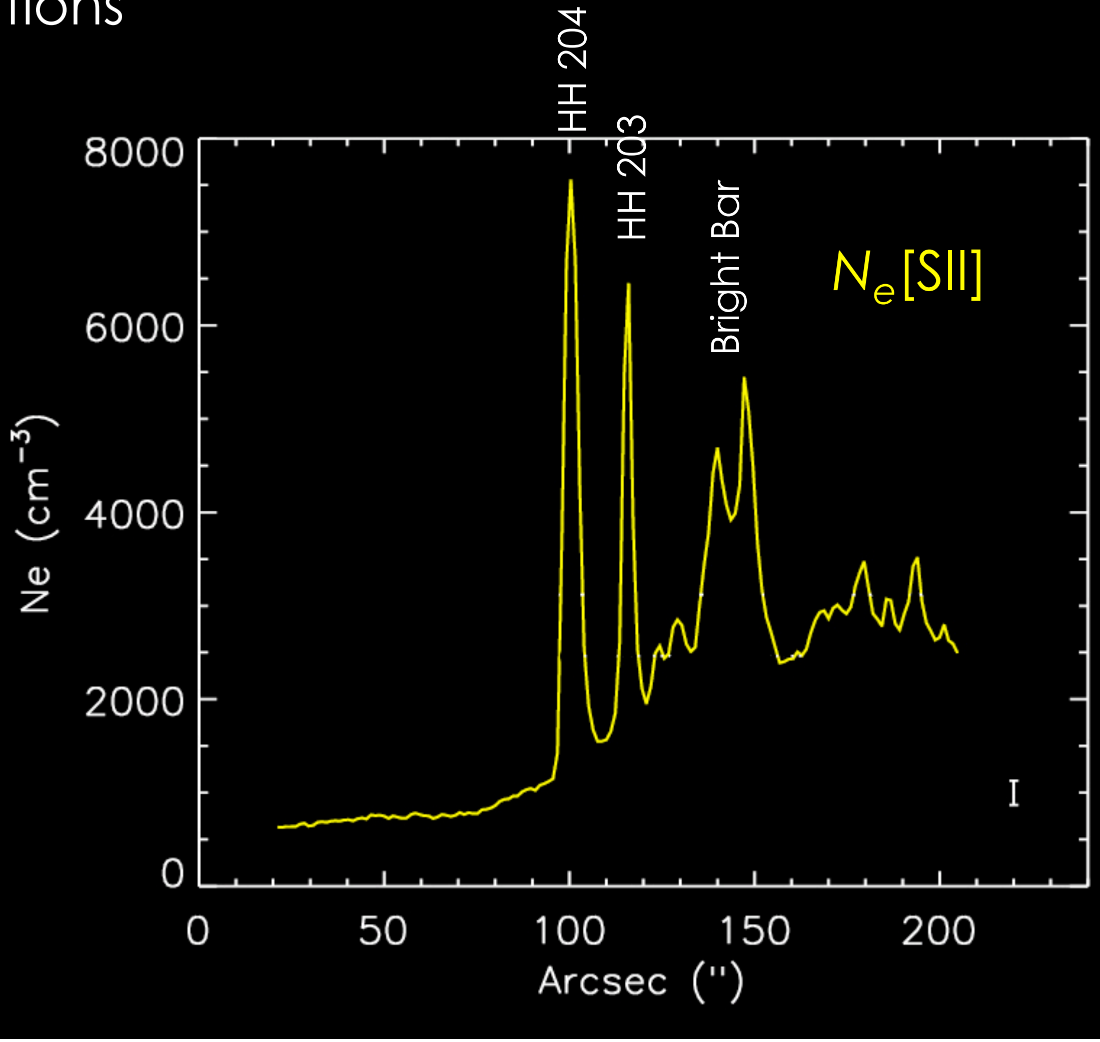
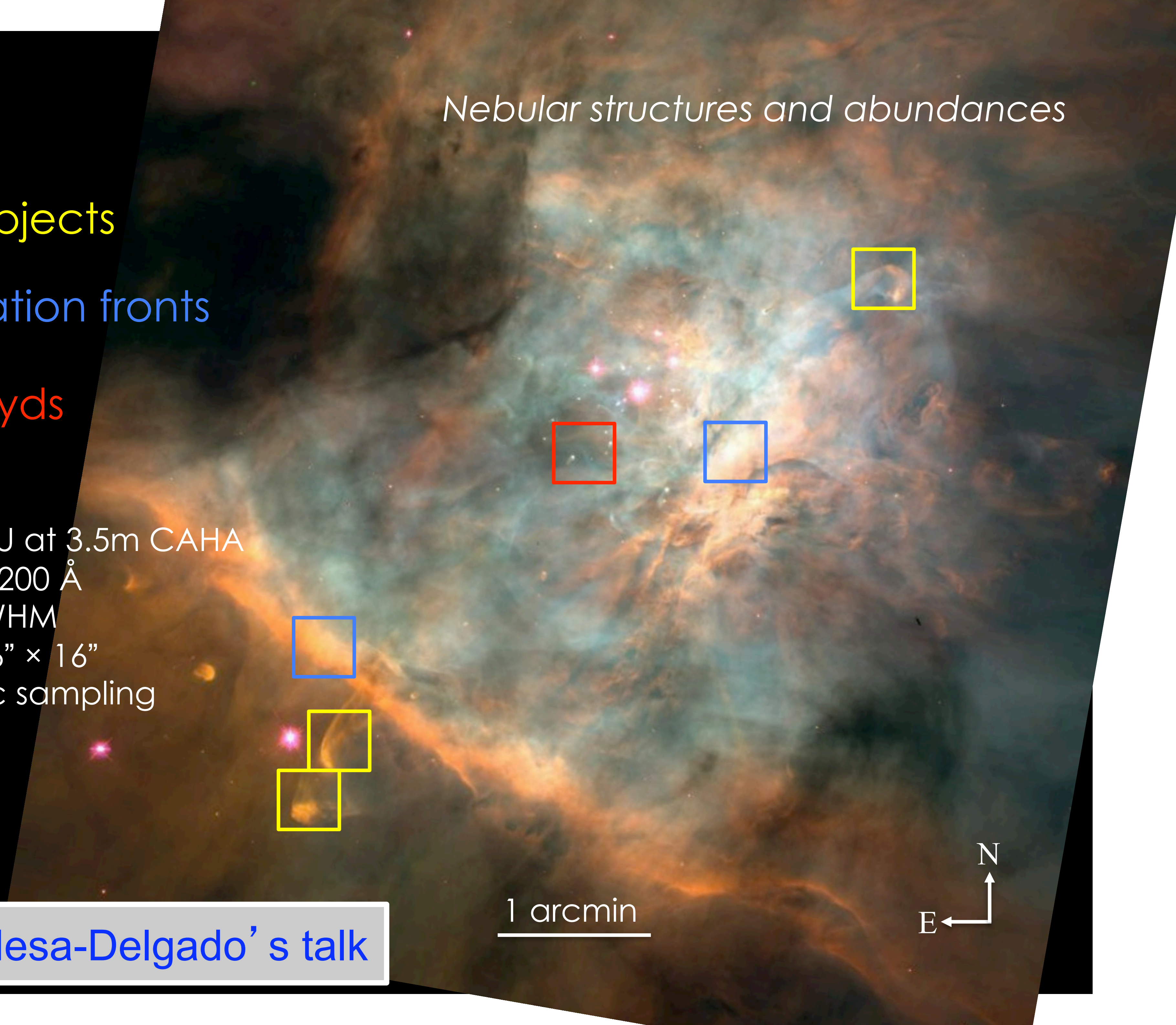




Nebular structures and abundances



- HH objects
- Ionization fronts
- Proplyds

PMAS IFU at 3.5m CAHA
3500 – 7200 Å
3.6 Å FWHM
FoV: 16” × 16”
1 arcsec sampling

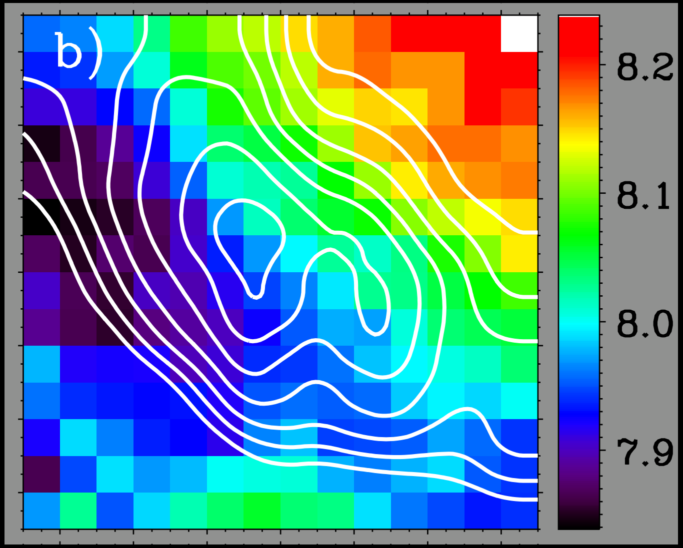
See A. Mesa-Delgado’s talk

Nebular structures and abundances

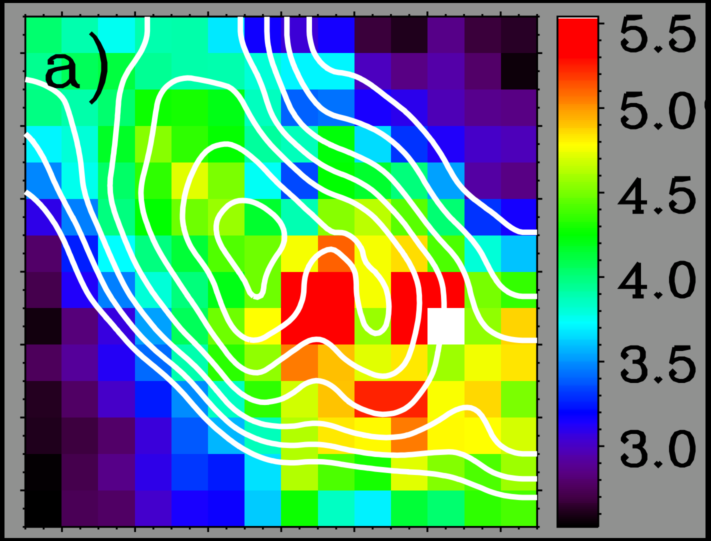
Bright Bar

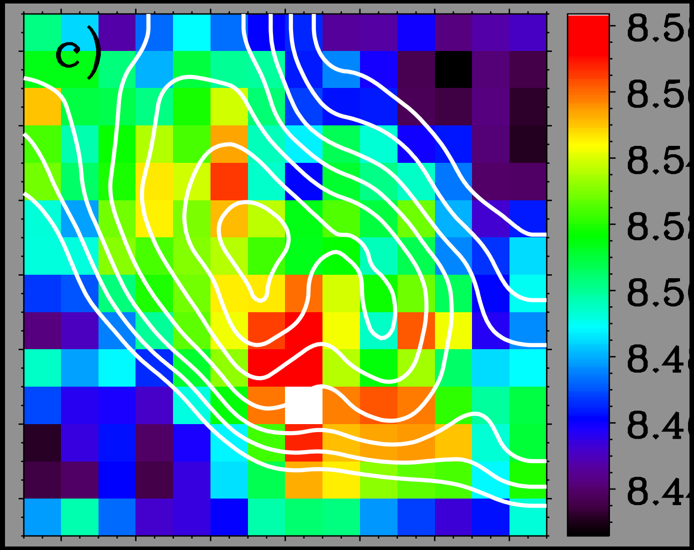
Mesa-Delgado et al. (2011)

$12+\log(O^{2+}/H^{+})$



n_e ([SII]) × 10^3 cm^{-3}





$12+\log(O/H)$

Nebular structures and abundances

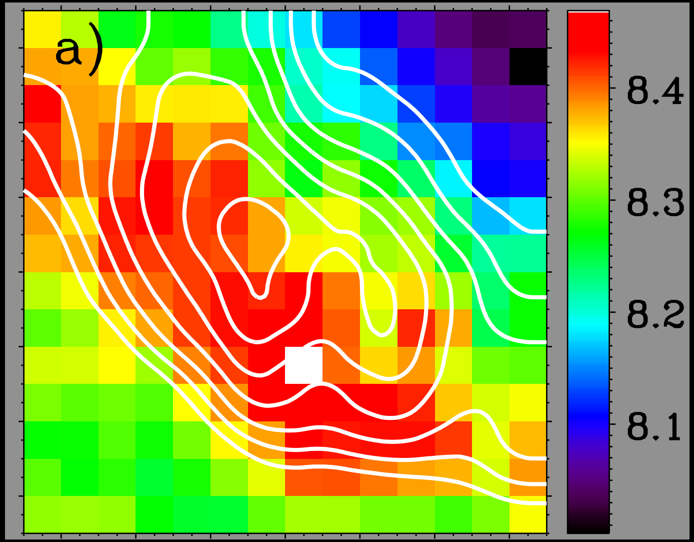
Bright Bar

Mesa-Delgado et al. (2011)

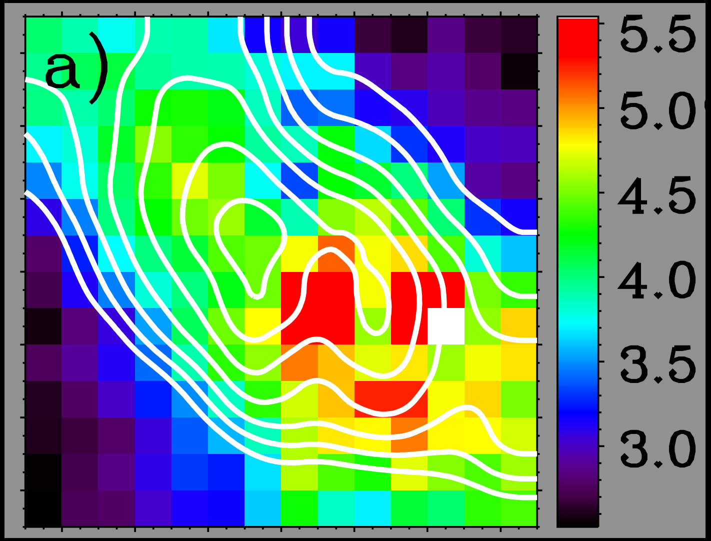
Bad density assumption produces wrong O^+/H^+

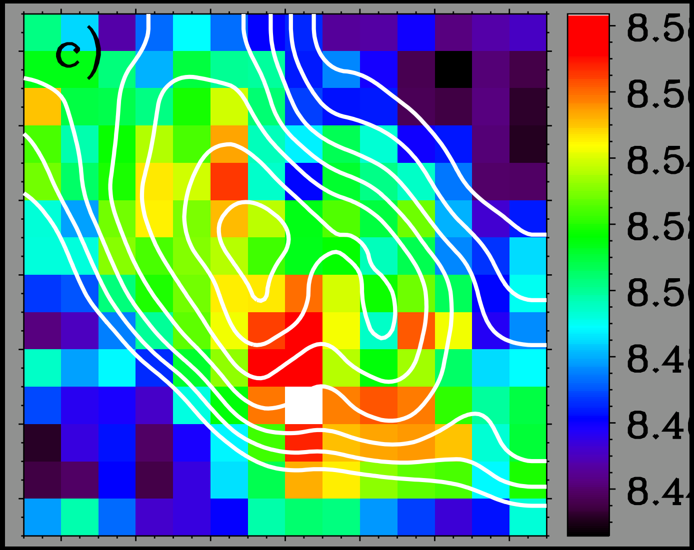
[OII] 3726, 29 Å lines have critical density ~10^3 cm^{-3}

$12+\log(O^+/H^+)$



n_e ([SII]) × 10^3 cm^{-3}





$12+\log(O/H)$

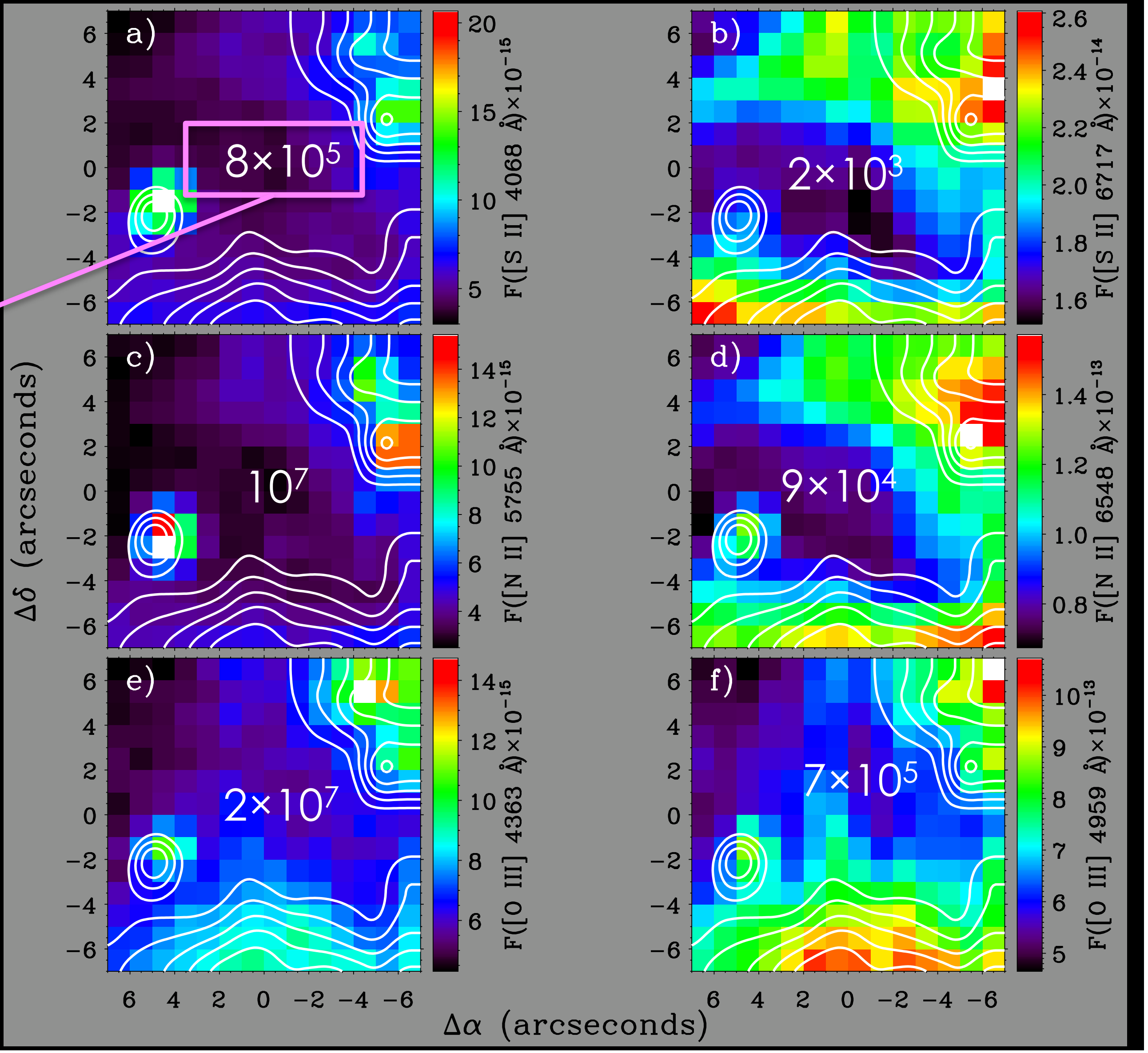
Nebular structures and abundances

Compare fluxes of auroral and nebular lines of the same ion as a function of critical density

Proplyds

auroral

nebular

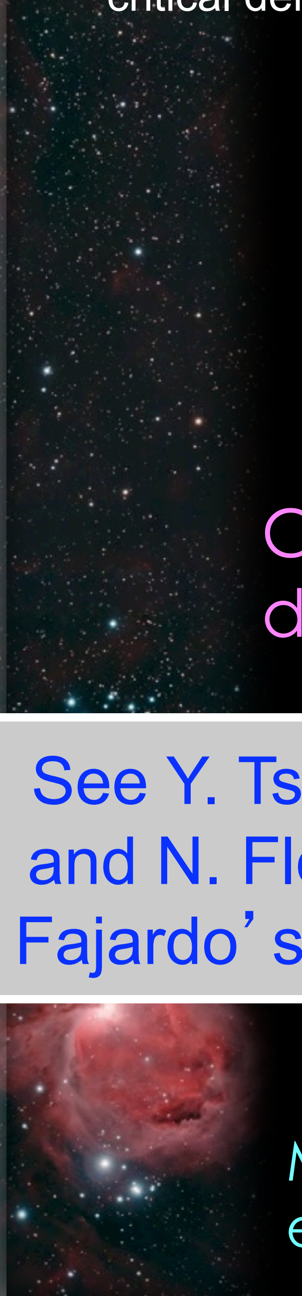


[SII]

[NII]

[OIII]

Critical density



See Y. Tsamis and N. Flores-Fajardo's talks

Mesa-Delgado et al. (2012)

Proplyds

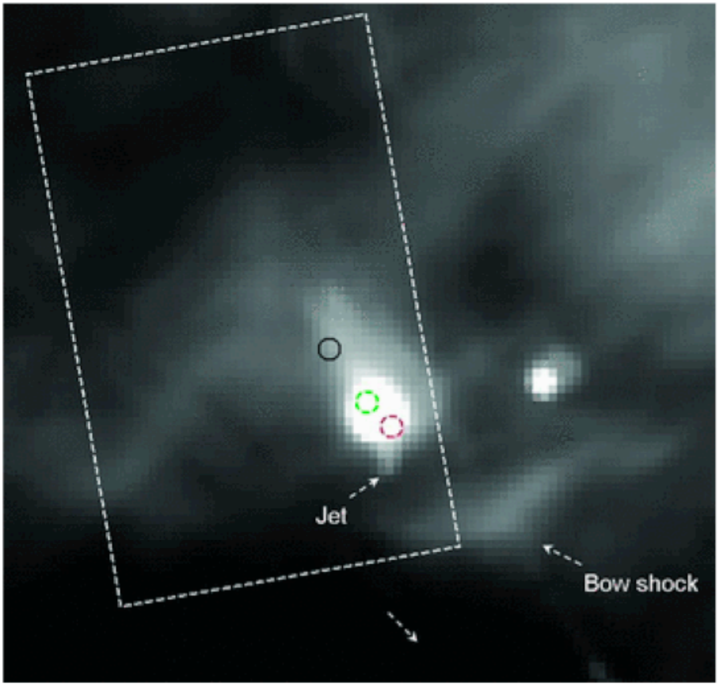
Tsamis et al. (2011)

FLAMES/Argus IFU at 8m VLT
Of LV2

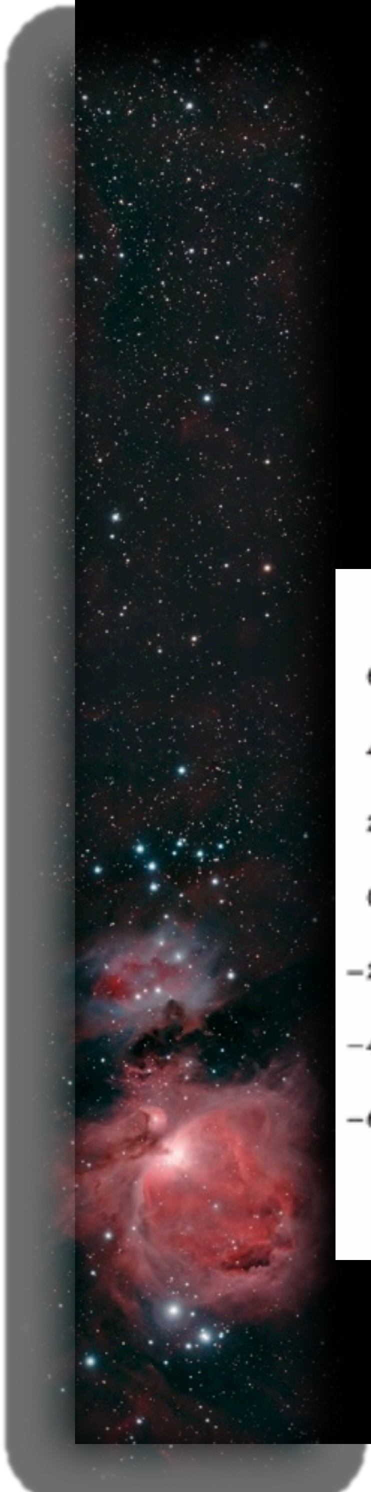
Background–subtracted
proplyd emission

C, O and Ne abundances at the proplyd 1.5 , 2 and 2.5 times higher than in the background gas.

ADF goes to 0 at the proplyd!



Density inhomogeneities are playing a role in the ADF problem

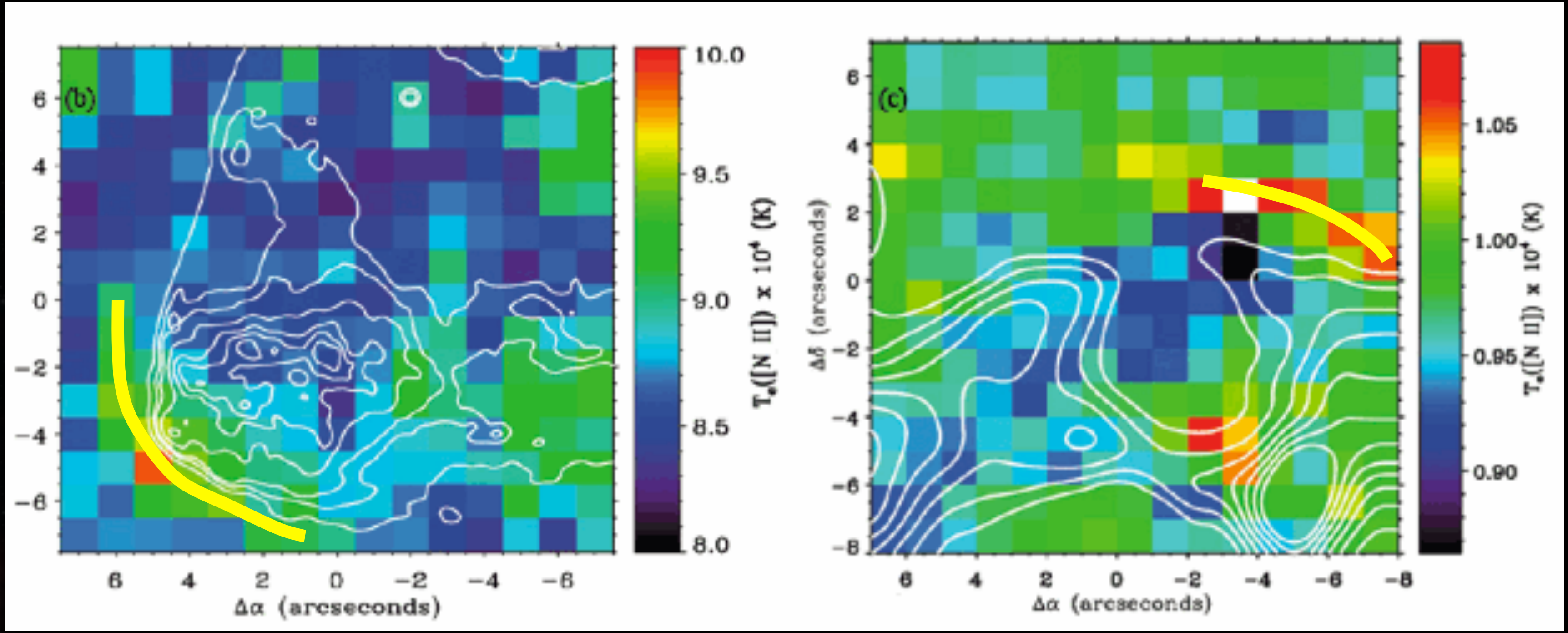


High-T_e arcs in HH objects

Núñez-Díaz et al. (2012), Mesa-Delgado et al. (2012)

T_e ([NII]) (10^4 K)

HH 204 HH 202

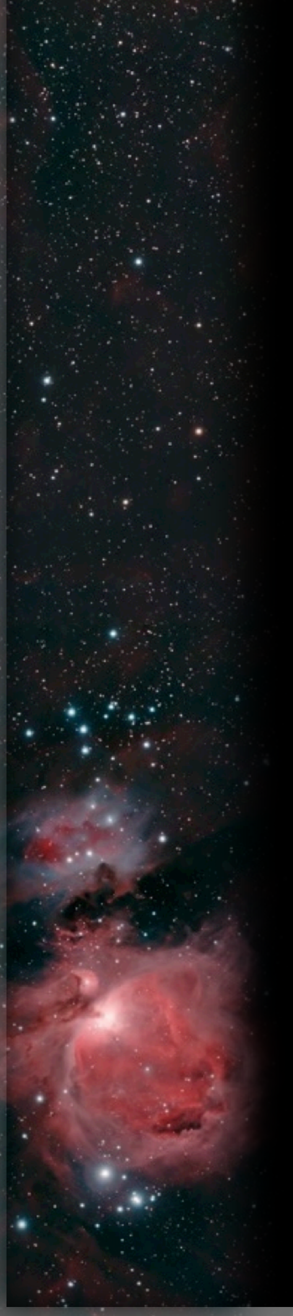


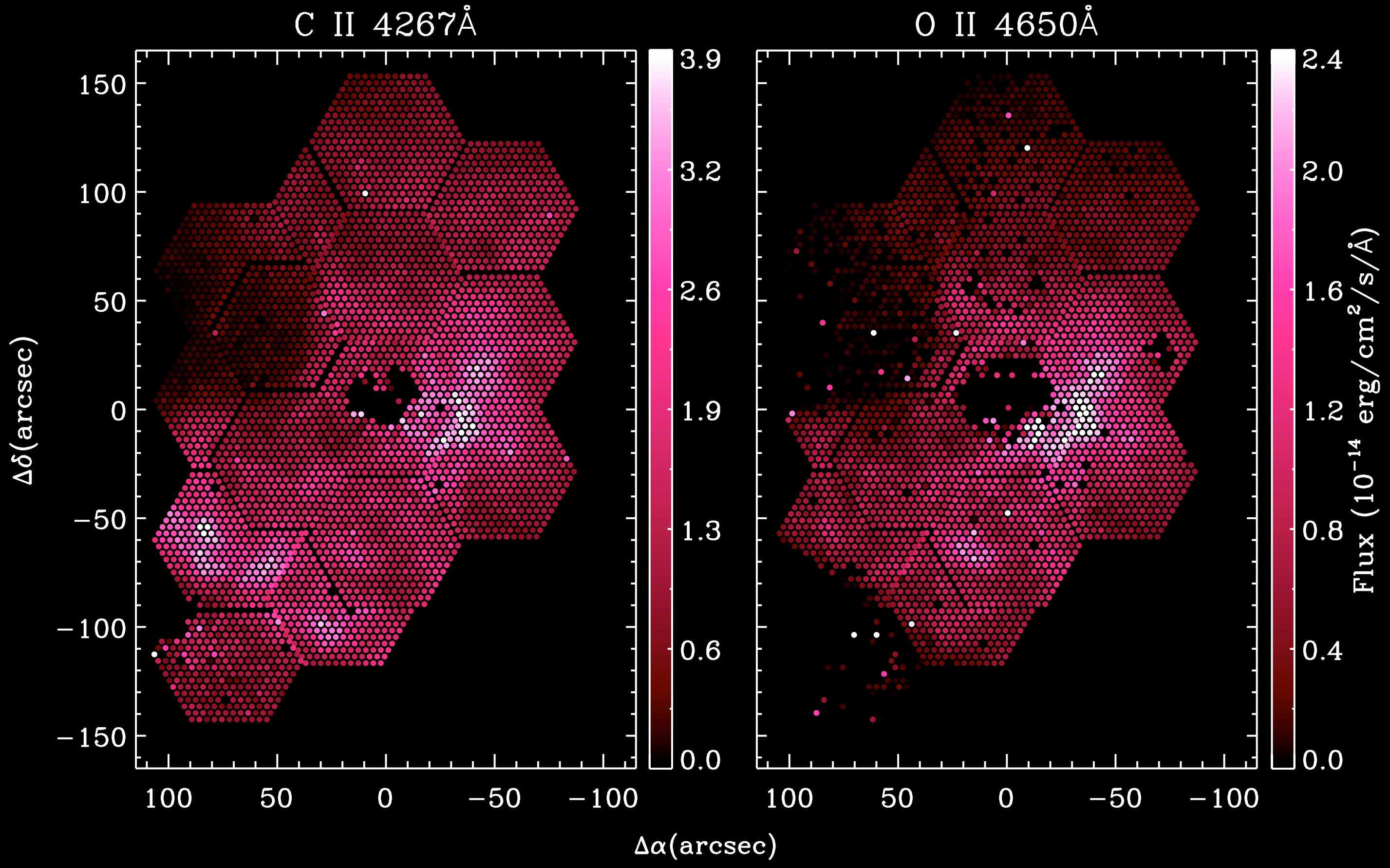
$\Delta T_e \sim 1{,}000$ K

See M. Núñez-Díaz’s talk

Deep spectrophotometric mosaic

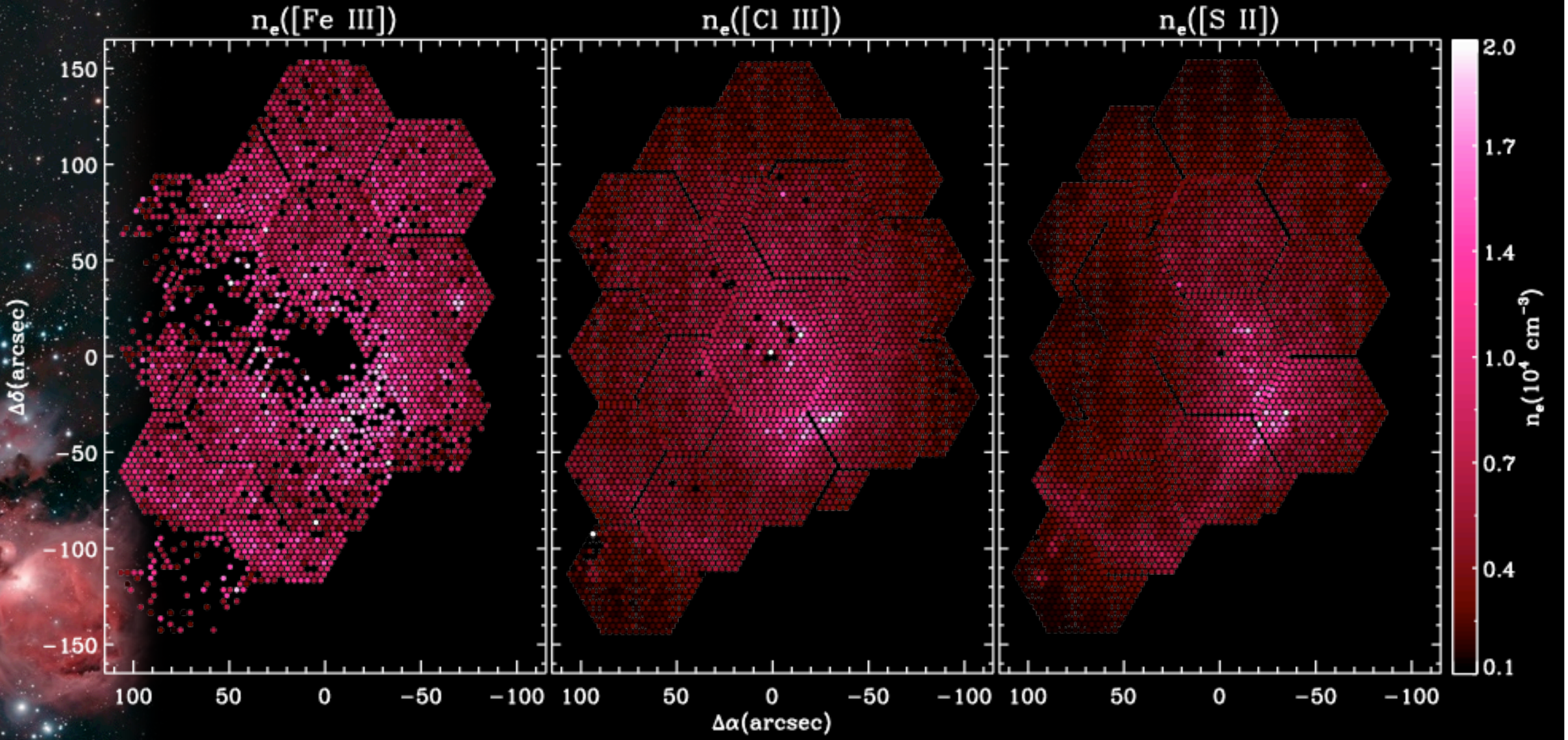
PPak@CAHA, 3550 – 6750 Å, 2 Å FWHM, fiber 2.7 arcsec
Flux-calibrated mosaic of the central 4 arcmin





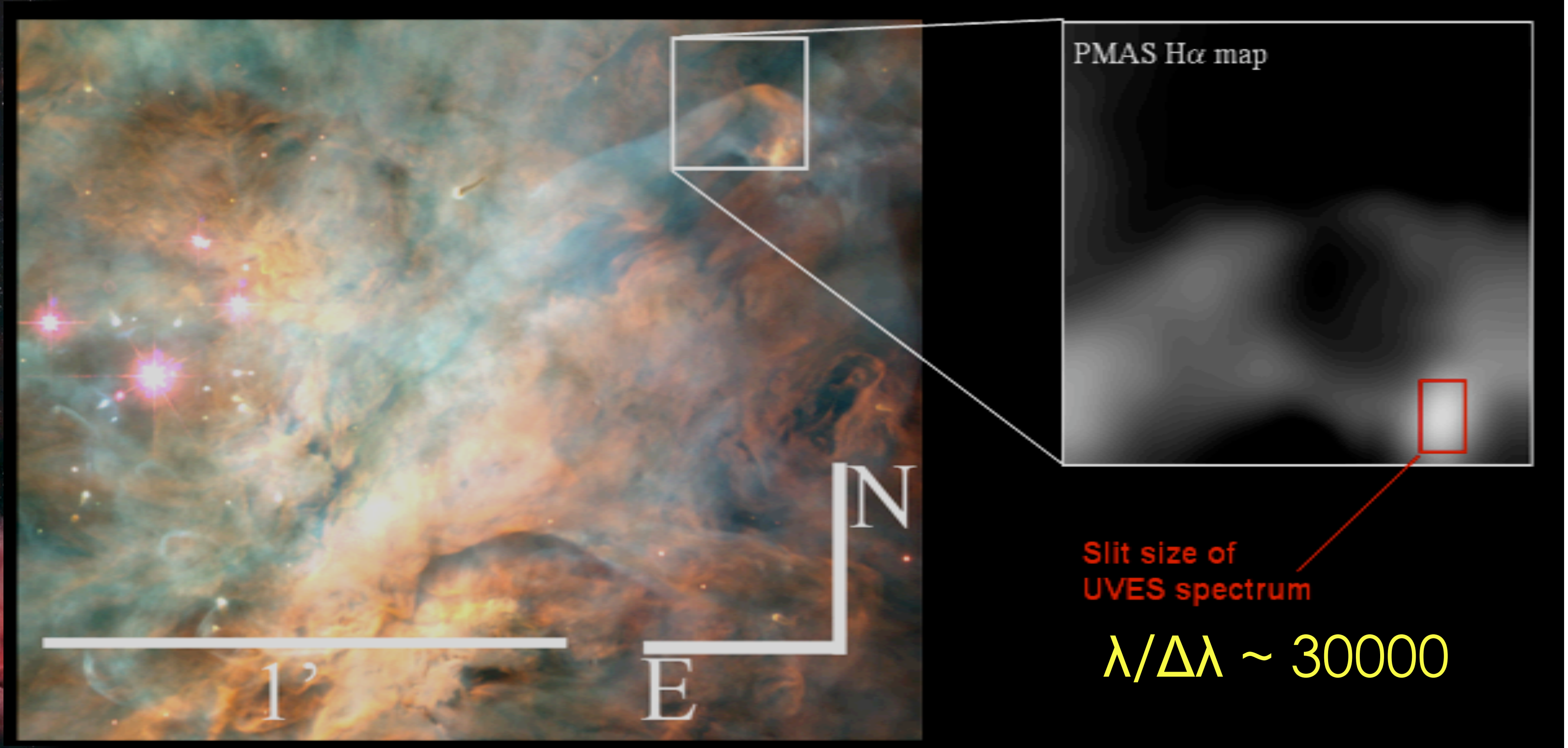
See M. Núñez-Díaz and C. Morisset’s talks

Deep spectrophotometric mosaic



Echelle spectroscopy of HH202

Mesa-Delgado et al. (2009)

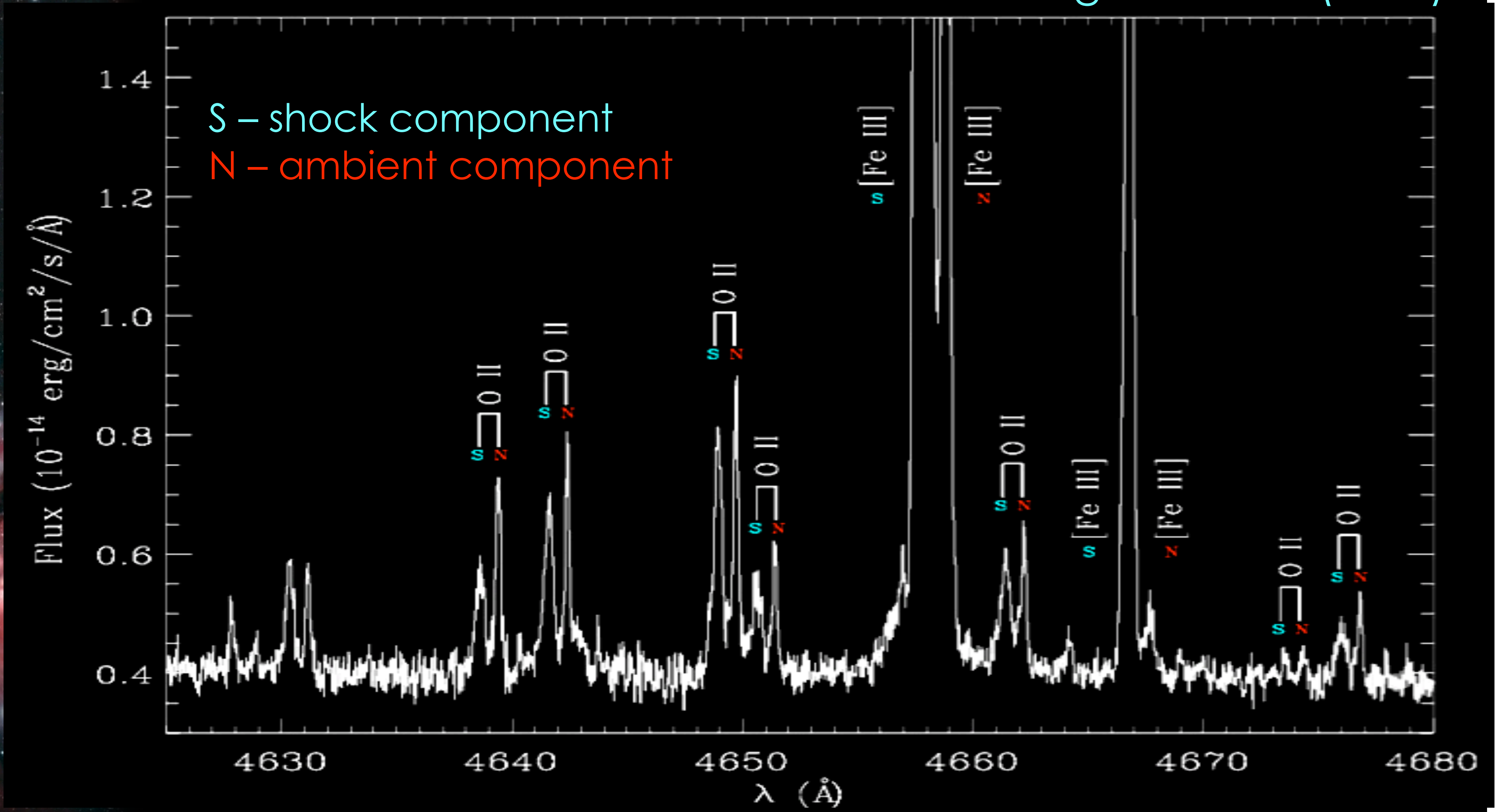


Slit size of UVES spectrum

$\lambda/\Delta\lambda \sim 30000$

Echelle spectroscopy of HH202

Mesa-Delgado et al. (2009)


S – shock component

N – ambient component

Echelle spectroscopy of HH202

Mesa-Delgado et al. (2009)

Physical conditions

	Ambient comp.	Shock comp.
n_e (cm^{-3})	2990 ± 500	17400 ± 2400
T_e([N II]) (K)	9600 ± 400	9200 ± 300
T_e([O III]) (K)	8200 ± 200	8800 ± 200

- Higher density in the shock component
- Similar temperature

Echelle spectroscopy of HH202

Mesa-Delgado et al. (2009)

ADF(O^{++})

	Ambient comp.	Shock comp.
O^{++}	0.11 ± 0.04	0.35 ± 0.05

- Higher ADF(O^{++}) in the shock comp.

Echelle spectroscopy of HH202

Mesa-Delgado et al. (2009)

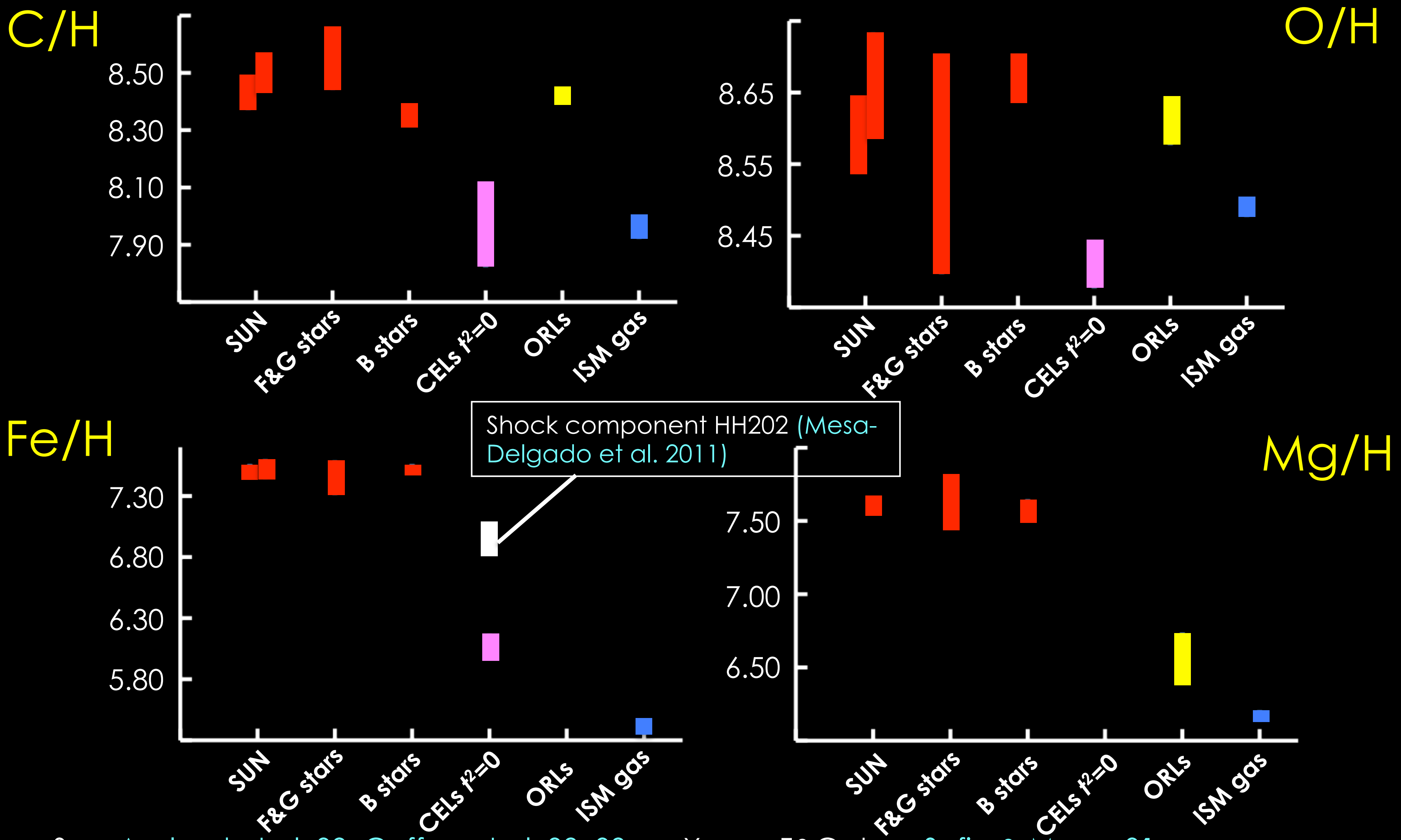
Dust destruction in HH 202

	Solar	Ambient comp.	Shock comp.	Shock—ambient
Fe/H	7.45 ± 0.05	6.10 ± 0.15	6.95 ± 0.12	0.85 ± 0.13
Ni/H	6.23 ± 0.04	5.03 ± 0.14	5.87 ± 0.11	0.84 ± 0.12
Fe/Ni	1.22 ± 0.06	1.07 ± 0.23	1.08 ± 0.17	...

- Partial destruction of dust particles (≈40% Fe & Ni)

Tsamis & Walsh (2011) also find some dust destruction in the microjet of proplyd LV2

Comparison of stellar, ON (CELs, ORLs) and neutral ISM abundances for elements that show some degree of depletion onto dust grains

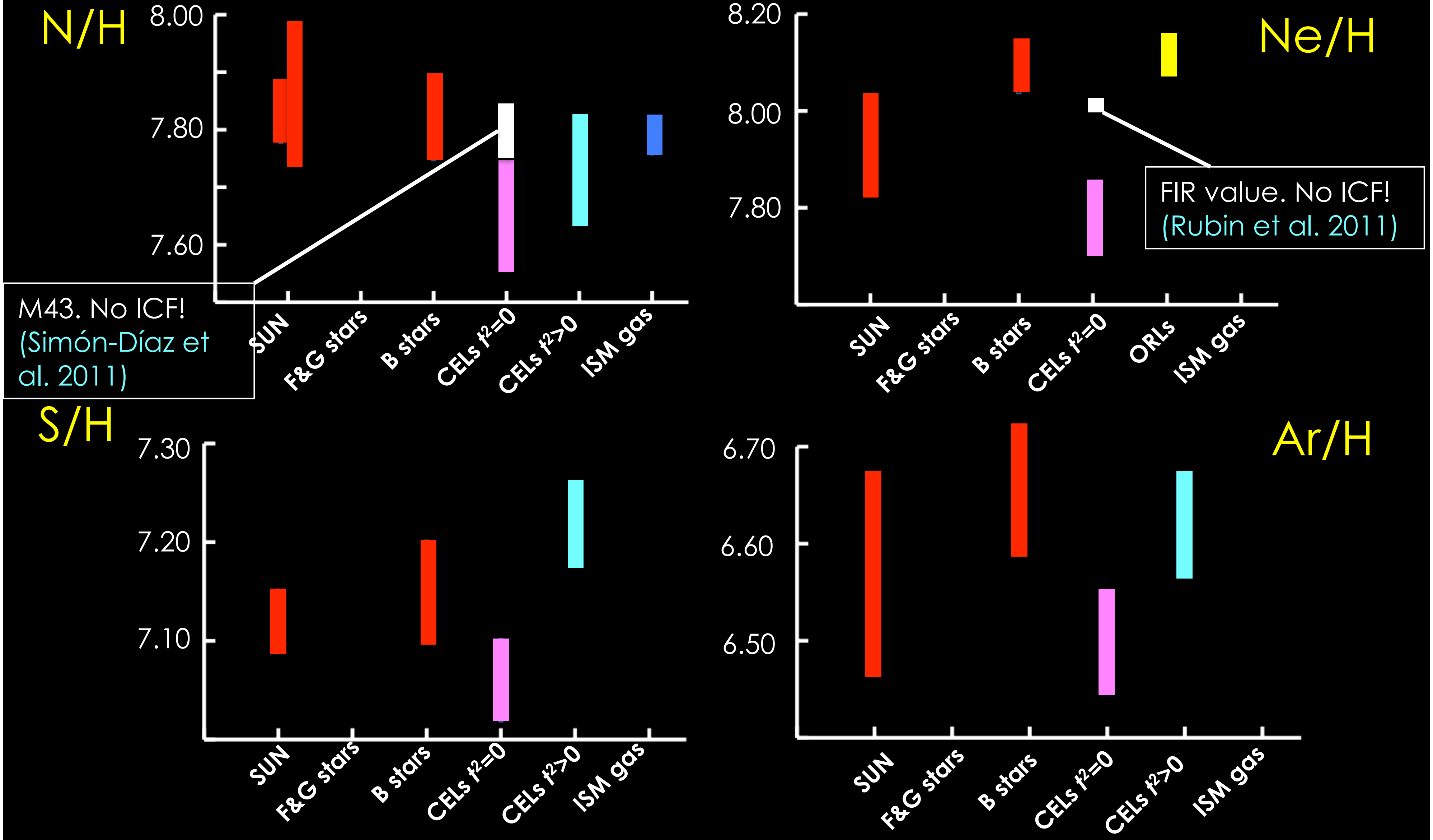


Shock component HH202 (Mesa-Delgado et al. 2011)

Sun: Asplund et al. 09, Caffau et al. 08, 09 - Young F&G stars: Sofia & Meyer 01
B stars: Nieva & Simón-Díaz 11 - ISM: Nieva & Przybilla 12
CELs t^2=0, CELs t^2>0, ORLs: Esteban et al. 04, Peimbert et al. 2010

See S. Simón-Díaz's talk

Comparison of stellar, ON (CELs, CELs+ t^2>0, ORLs) and neutral ISM abundances for elements not (or not subtantially) depleted onto dust grains



M43. No ICF! (Simón-Díaz et al. 2011)

FIR value. No ICF! (Rubin et al. 2011)

Sun: Asplund et al. 09; Caffau et al. 08, 09; Lodders 08 - Young F&G stars: Sofia & Meyer 01
B stars: Nieva & Simón-Díaz 11; Lanz et al. 08; Daflon et al. 09 - FIR CELs: Rubin et al. 11
CELs t^2=0, CELs t^2>0, ORLs: Esteban et al. 04 - ISM: Nieva & Przybilla 12

CONCLUSIONS

- ON is the best target to study the effect of small-spatial scale variations of physical conditions onto abundance determinations

- ON ionized-gas phase abundances derived from ORLs seem to be more consistent with those of other kinds of objects

- Localized dust destruction occurs in ON