ESO workshop on "Planetary nebulae beyond the Milky Way", Garching bei München 19-21 May 2004

Plasma diagnostics and abundance determinations for planetary nebulae – current status

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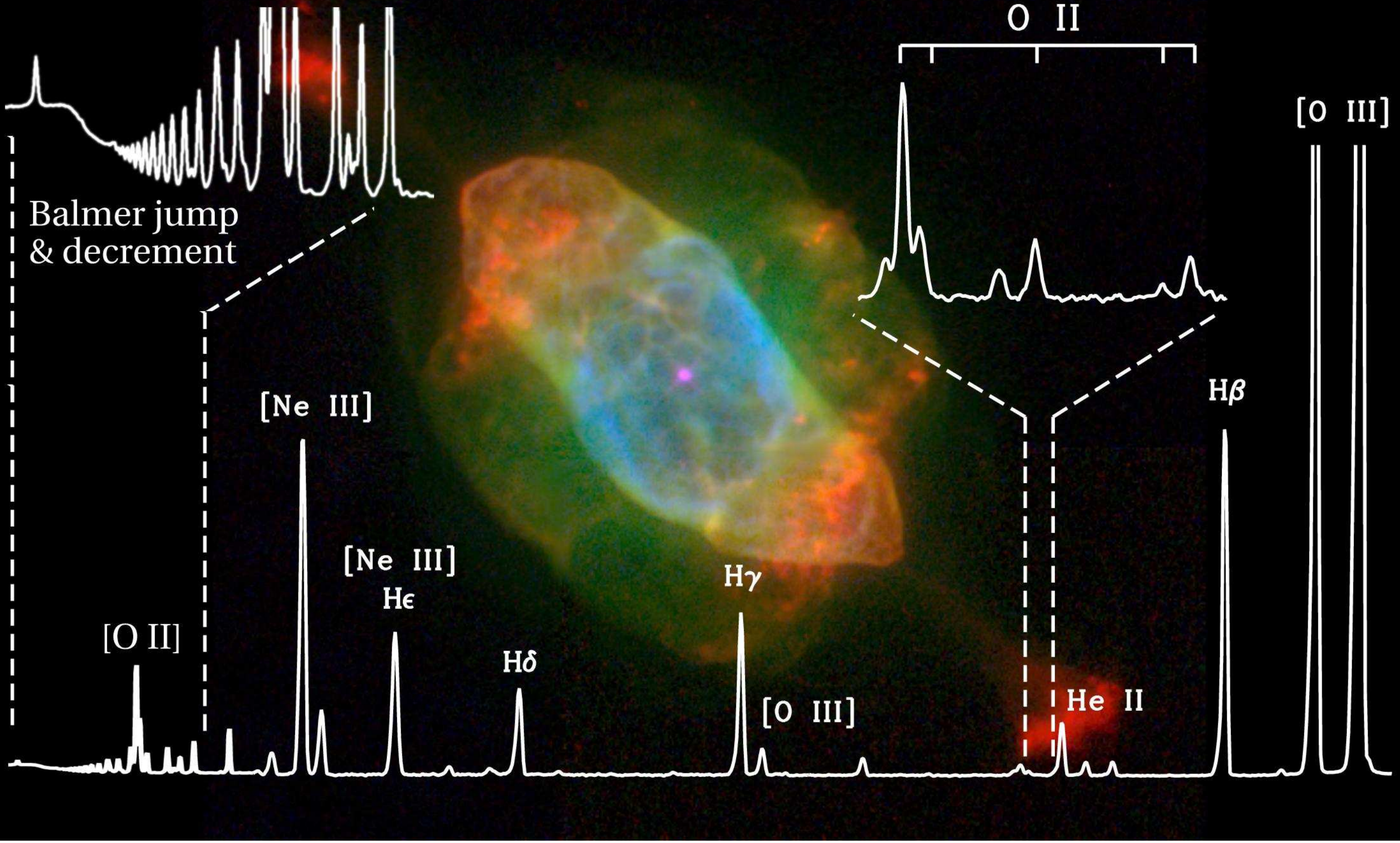


The problem

Recombination versus collision excitation

$$1)\ T_{\mathrm{e}}(\mathrm{ORLs/Continua}) < T_{\mathrm{e}}(\mathrm{CELs})$$

$$2)\ \frac{\mathrm{X}^{i+}}{\mathrm{H}^{+}}(\mathrm{ORLs\ for\ C,N,O,Ne}) > \frac{\mathrm{X}^{i+}}{\mathrm{H}^{+}}(\mathrm{CELs\ for\ C,N,O,Ne})$$

Both disparities are legitimate and of astrophysical origins, rather than caused by observational errors, uncertainties in atomic data or contaminations of (weak) ORLs by excitation mechanisms other than recombination (e.g. fluorescence)

Layout

- **Observations**
- **Interpretation and evidence for a new component of H-deficient ultra-cold plasma**
- **Failure of the paradigm of temperature/density fluctuations**
- **Conclusions and what next?**

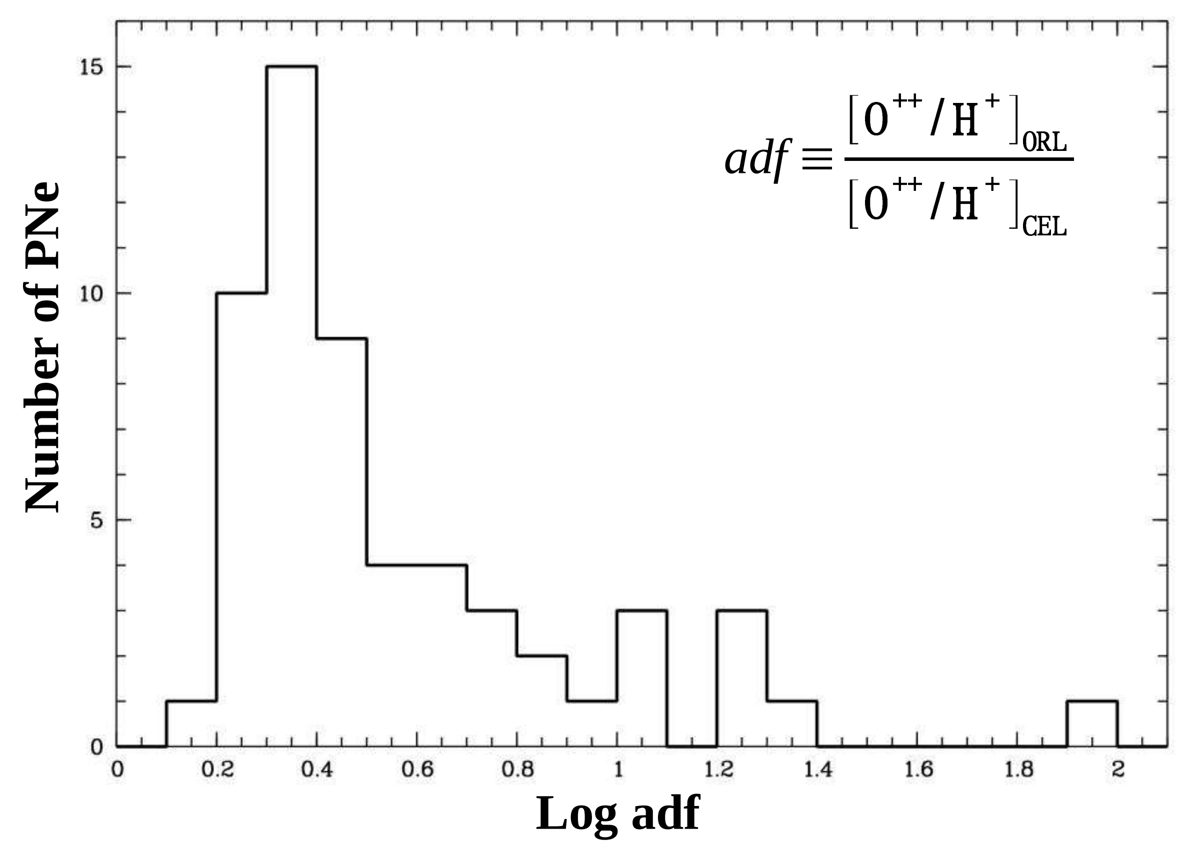
- **Tsamis et al., 2003, MN, 345, 186; 2004, MN, submitted (12 Galactic, 3 Magellanic)**
- **Liu Y., 2004ab, MN, submitted (12 Galactic)**
- **Wesson R., et al., 2004, MN, in preparation (23 Galactic)**

- **X.-W. Liu, in *Planetary Nebulae: Their evolution and role in the Universe*, IAU Symp. 209, eds. S. Kwok, M. Dopita and R. Sutherland, pp.339-346 (2003)**

Observations

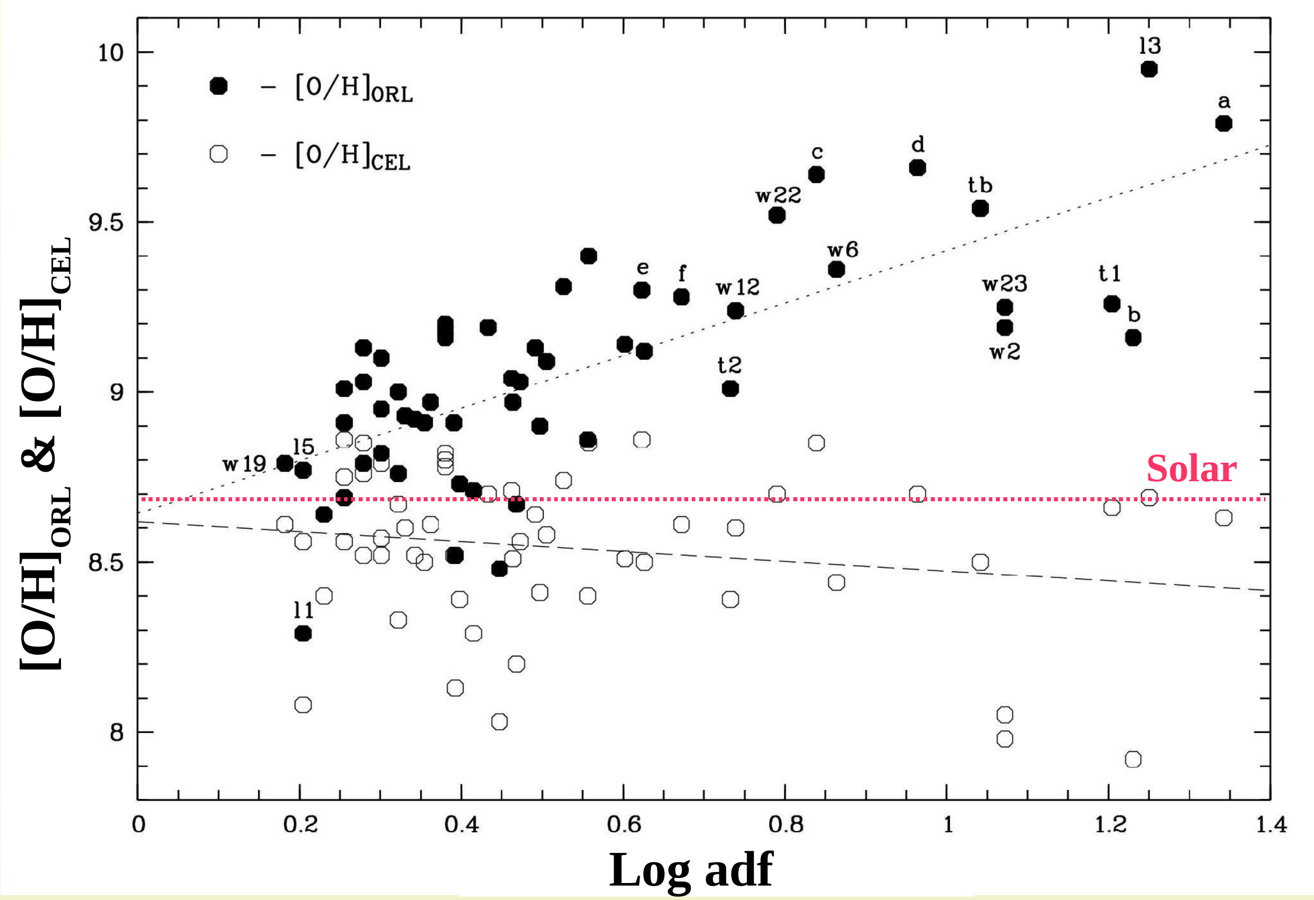
Distribution of ORL/CEL abundance discrepancy factor (adf)

53 PNe



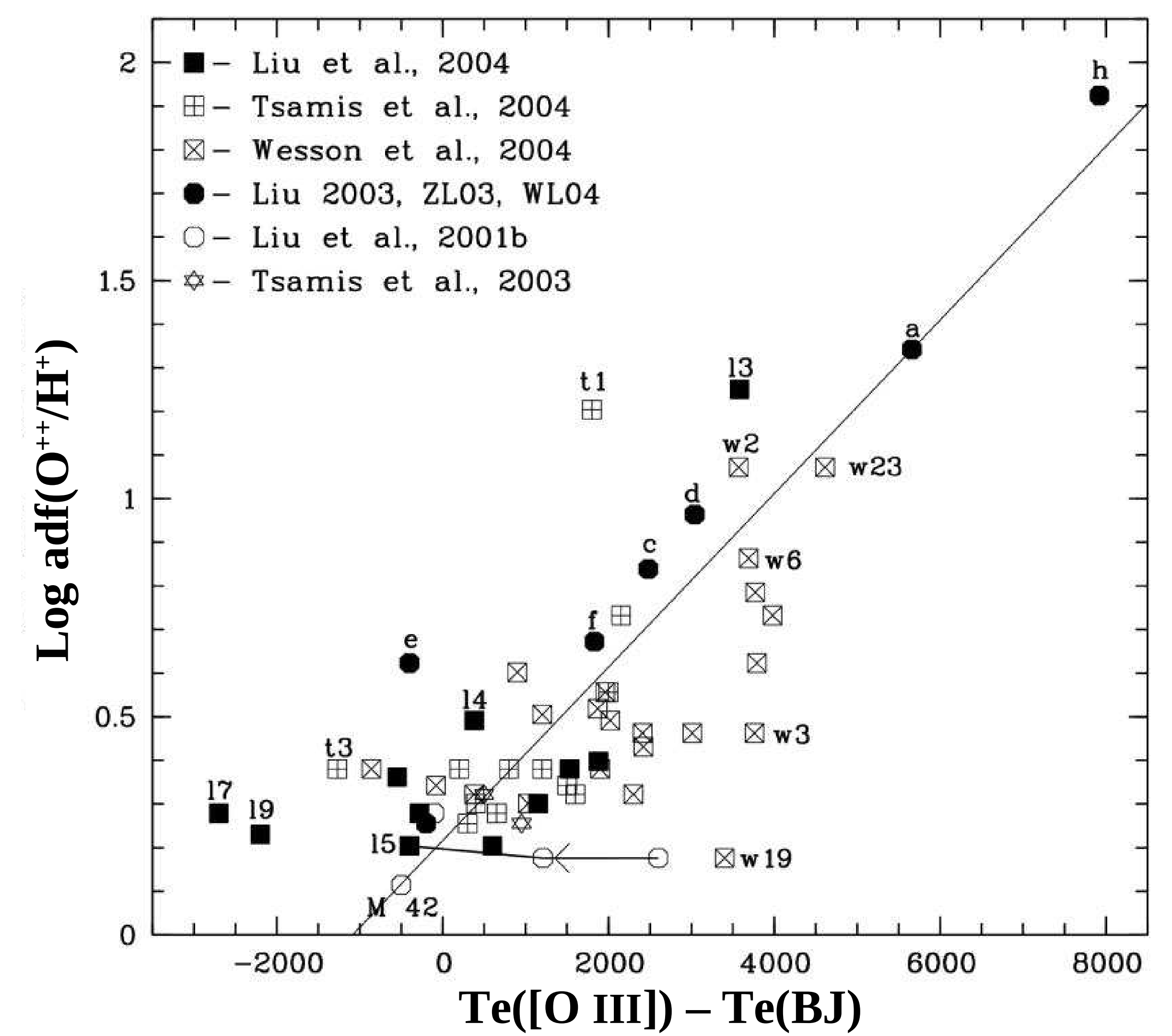
- **Log adf > 0, i.e. ORL abundance always higher than CEL values**
- **Log adf ≈ 0.35 dex, i.e. about a factor of two**
- **Largest adf found so far, log adf ≈ 1.9, i.e. about two order of magnitude**

Comparison of O/H derived from CELs and from ORLs



- $[O/H]_{CEL} \approx 8.5$, close to the solar value of 8.69
- $[O/H]_{ORL}$ varies from 8.5 to 10
- The wide range of adf is entirely caused by variations in $[O/H]_{ORL}$

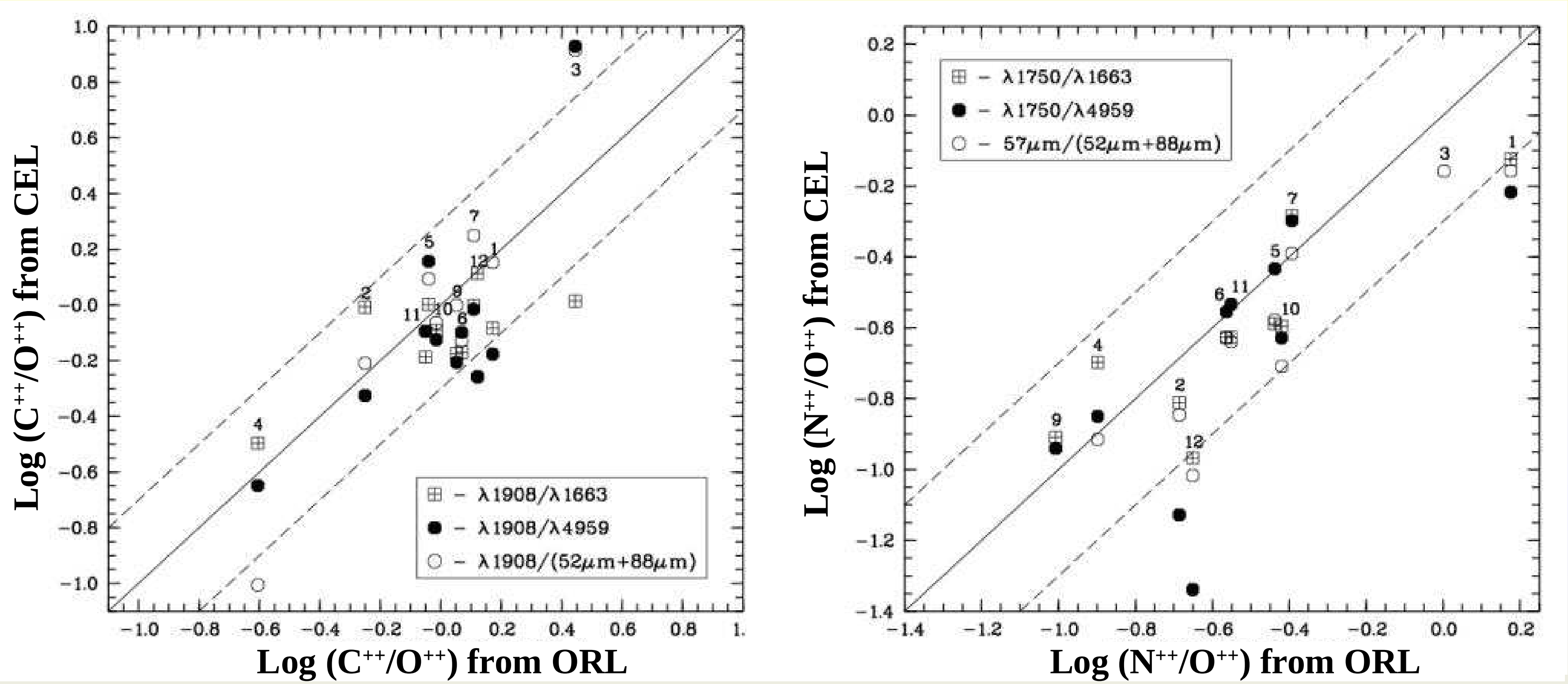
Correlation between temperature and abundance discrepancy factors



Hf 2-2
T_e = 8820 K ([O III])
= 900 K (BJ)
O^{++}/H^{+} = 1.1 10^{-4} ([O III])
= 90. 10^{-4} (O II)

Liu et al., 2001, MNRAS, 327, 141-168

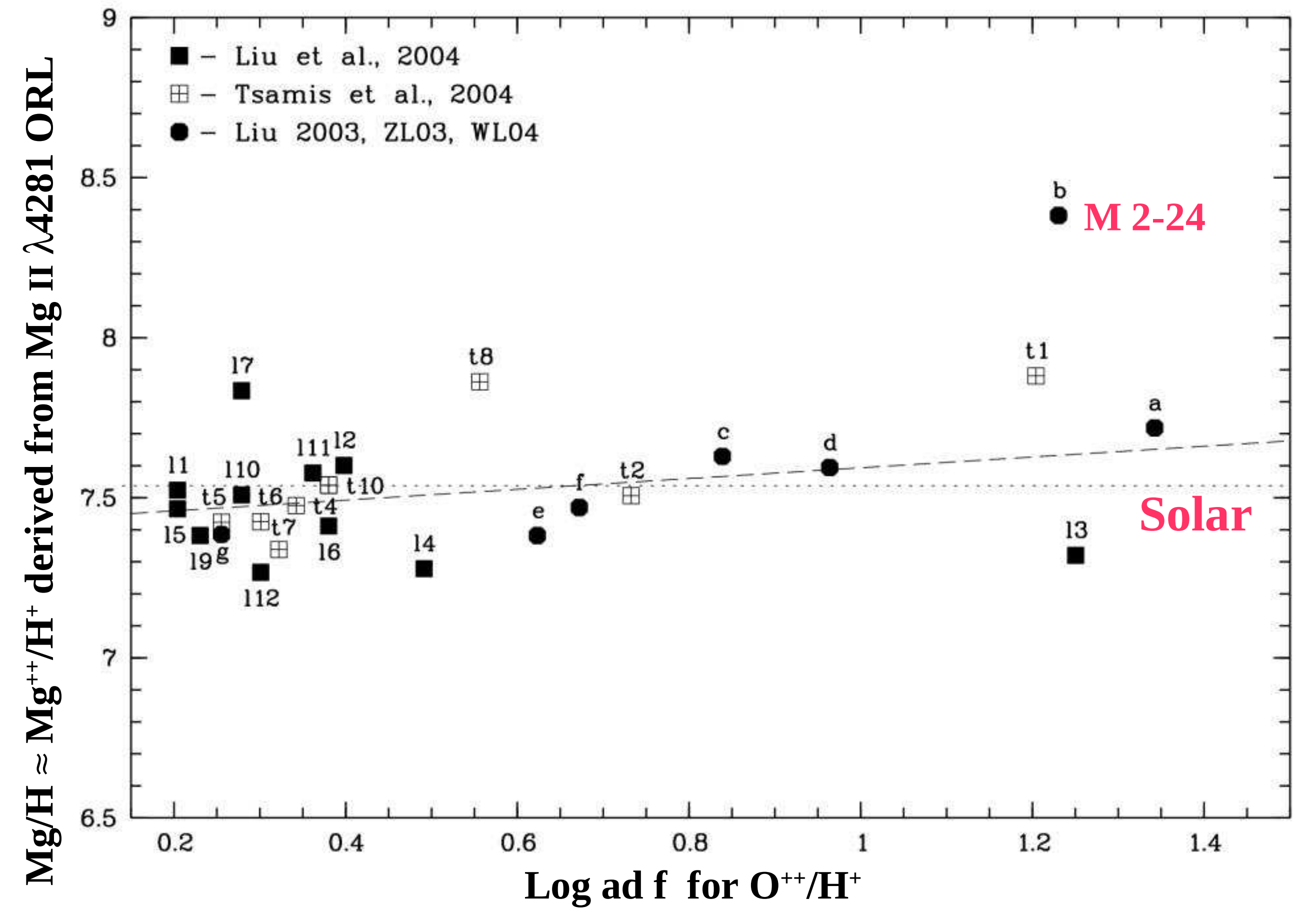
Second row elements -- C, N, O and Ne



- **Large values of adf's are found for all abundant second row elements, C, N, O and Ne**
- **For a given nebula, adf's for C, N, O and Ne are of similar magnitude, in other words, both CELs and ORLs yield**

Comparable C/O, N/O and Ne/O abundance ratios

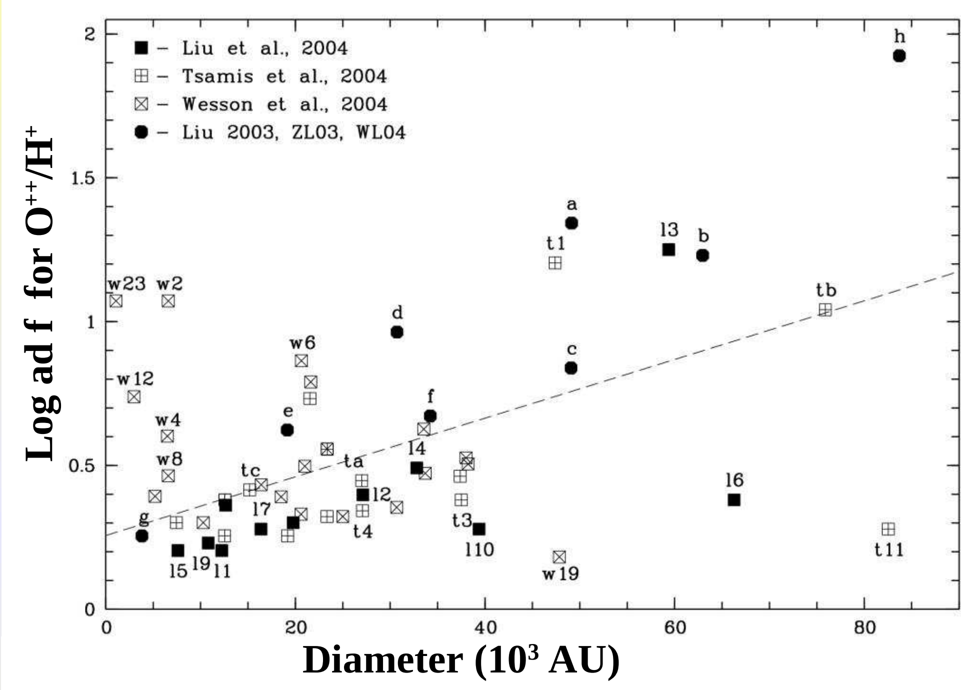
Third row element – magnesium

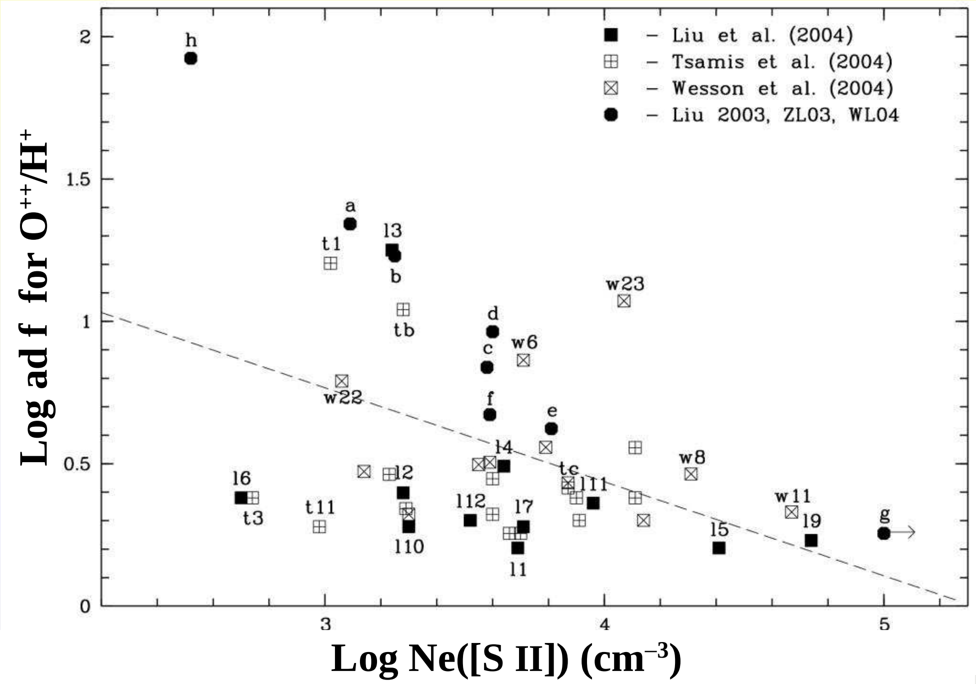


The large ORL abundance enhancement observed for second row elements is not present for the third row element magnesium.

- **Depletion onto dust grains unlikely to be significant**
- **Evidence for nuclear processed material?**

Nebular diameter and density

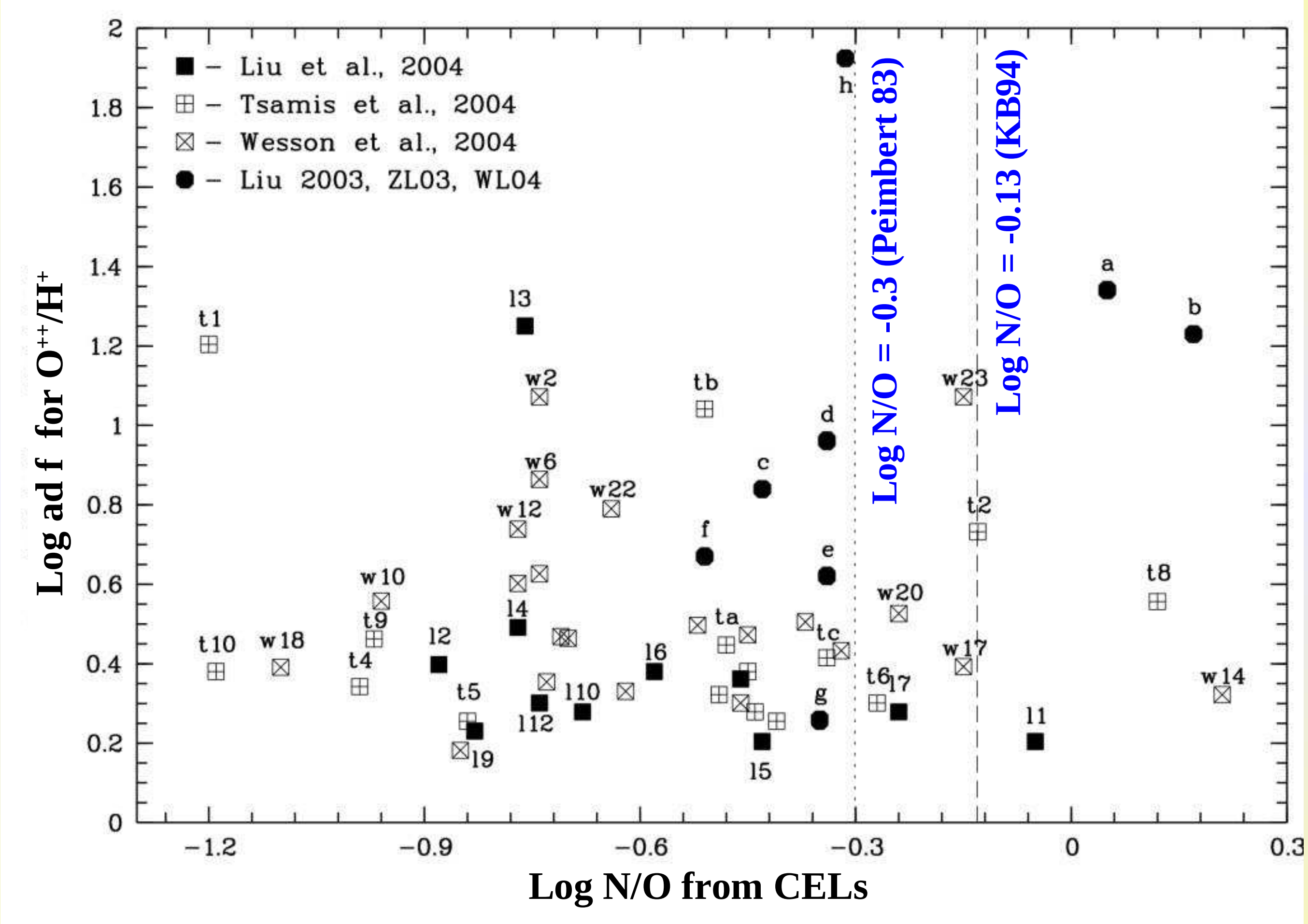




- **Negative correlation between adf and S(Hβ), N_e and E.C.**
- **Positive correlation between adf and nebular diameter**

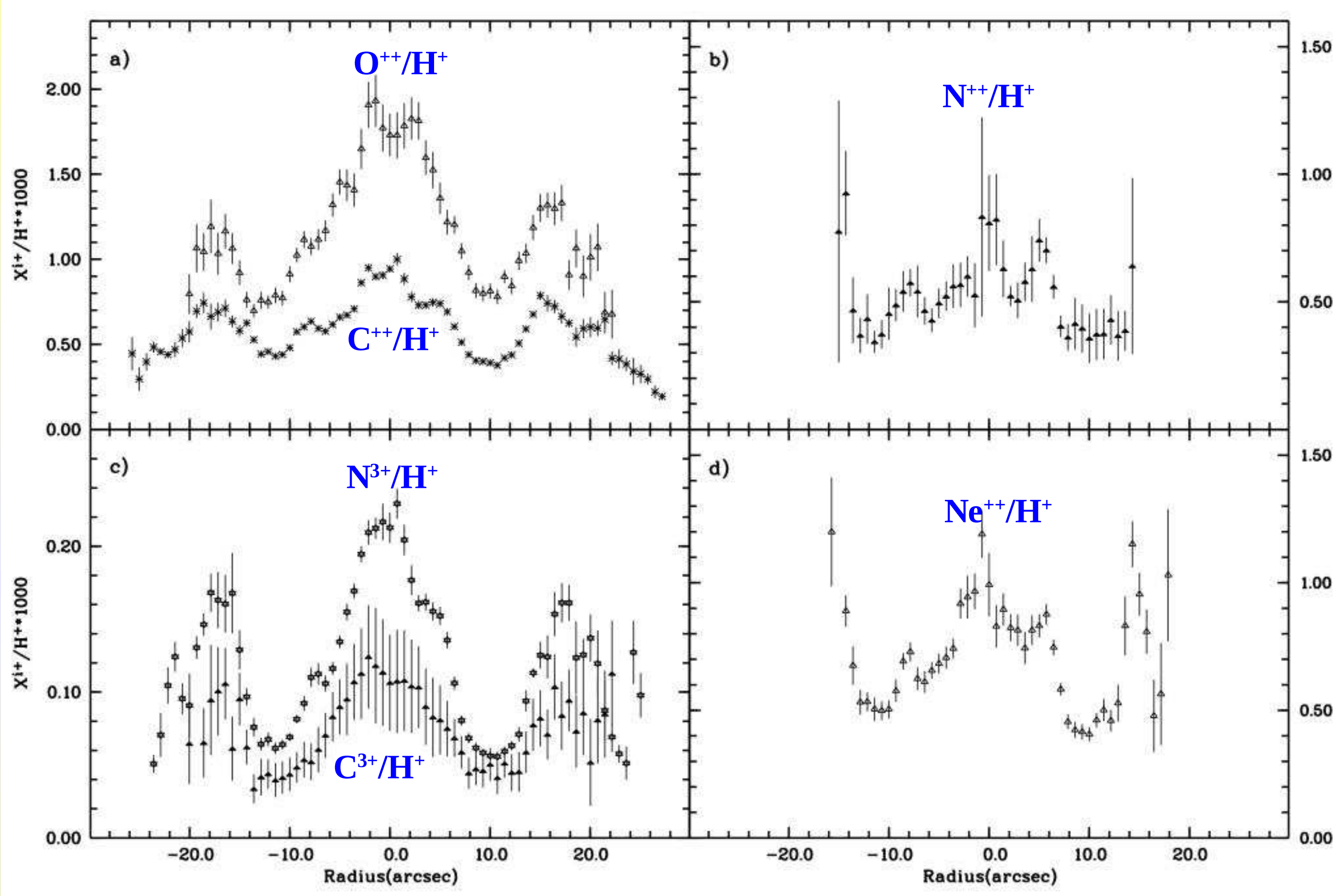
Large, low-density (therefore old) PNe have higher adf's (and ΔTe's) than young, compact ones

N/O ratio – Type-I and non-Type-I PNe



Type-I and non-Type-I PNe have comparable adf's

ORL abundance distributions along the major-axis of NGC7009



Luo et al., 2003, in Planetary Nebulae: Their Evolution and Role in the Universe, eds. S. Kwok et al., pp377

Strong central peaking of ORL abundances are also found in

- **NGC 6153** (Liu et al., 2000, MN, 312, 585)
- **NGC 6720** (Garnett & Dinerstein, 2001, ApJ, 558, 145)

Galactic and extragalactic H II regions

adf for O^{++}/H^{+}

- **Galactic**

M 42	1.3
M 17	2.1
NGC 3576	1.8
M 8	2.0

- **Magellanic Clouds**

30 Doradus	2.4
LMC N 11B	6
SMC N66	2.3

- **Extragalactic**

NGC 604 (M33)	1.6
NGC 5461 (M101)	2.0
NGC 5471 (M101)	1.6
NGC 2363	2.2

Esteban et al., 1998, MN, 295, 401
- M 42

Esteban et al., 1999, APJS, 120, 113
- M 8

Esteban et al., 1999, RmxAA, 35, 65
- M 17 (two positions; adf = 1.8, 2.2)

Tsamis et al., 2003, MN, 338, 687
- M 42, M 17, NGC 3576, 30 Doradus, LMC N11B, SMC N66

Esteban et al., 2002, ApJ, 581, 241
- NGC 604, NGC 5461, NGC 5471, NGC 2363

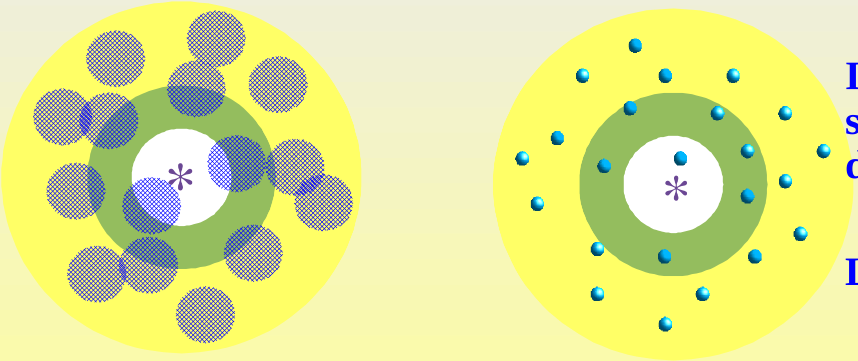
Interpretation and evidence for a new component of H-deficient ultra-cold plasma

Interpretations – a bi-abundance nebular model

- A 'normal' component (0.3 solar masses):
  - “ Normal” electron temperature ($T_e \sim 10^4$ K)
  - “ Normal” (solar) abundances where
  - Emits strongly in CELs
- A 'H-deficient' component (1×10^{-3} solar masses)
  - Very low temperature ($T_e \leq 10^3$ K)
  - Very high heavy elemental abundances (100 times solar)
  - Emits strongly in heavy element ORLs but essentially no CELs

ORLs and CELs disagree because they trace distinct ionized regions.

Two empirical models envisaged for NGC 6153 (Liu et al. 2000)



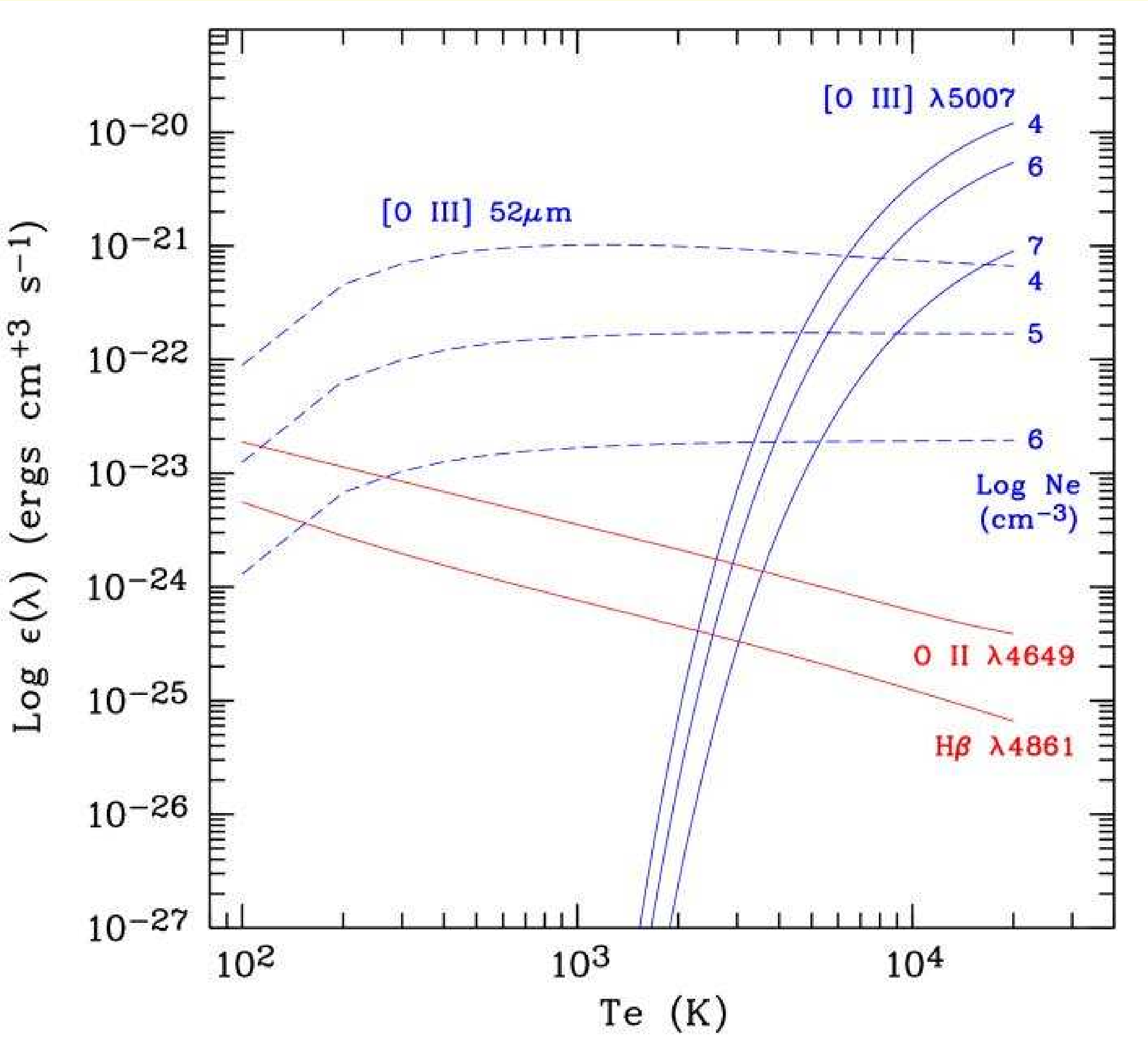
IR fine-structure lines suppressed by very low Te

Survival of the inclusions?

IR fine-structure lines suppressed by collisional de-excitation

Low Te(BJ) problematic

Emissivities of ORLs and CELs as functions of T_e and N_e



- **Collisionally excited lines**

  $j_\nu \propto T^{1/2}\exp(-E/kT)$;

  $j_\nu \propto N(X^{+i})N_e$ **for** $N_e << N_c$

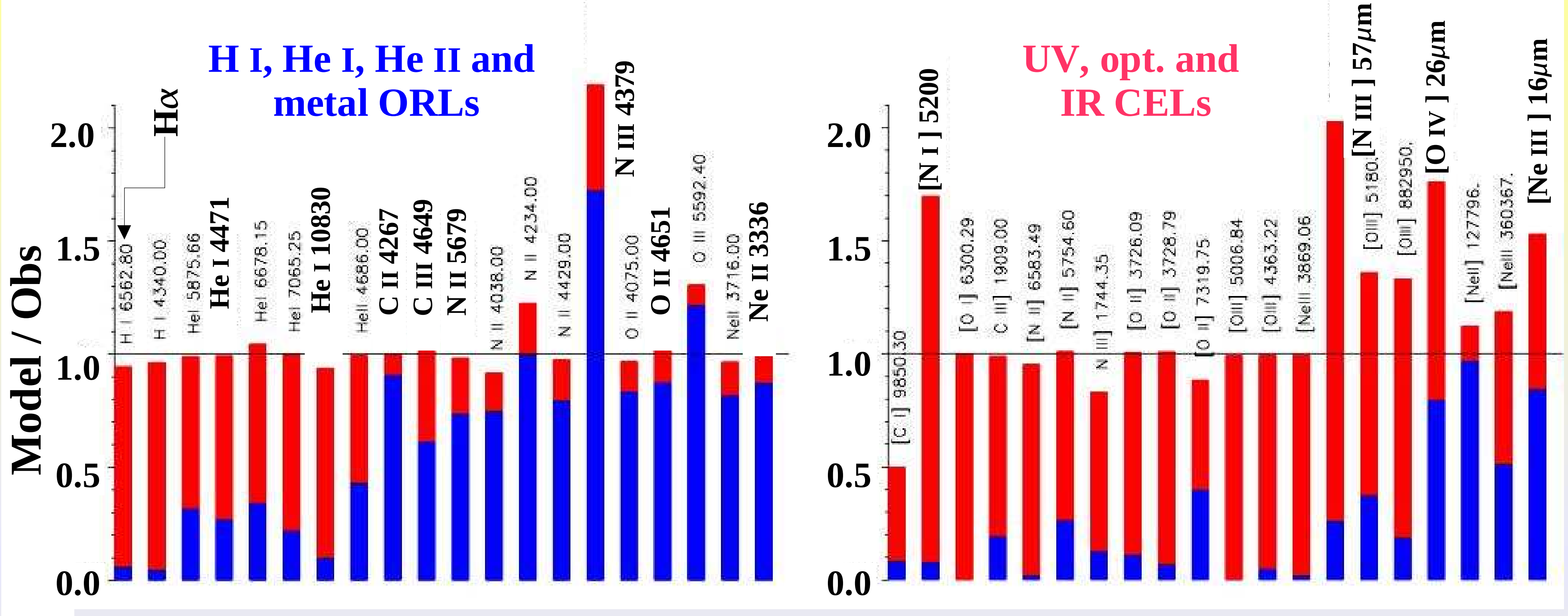
  $\propto N(X^{+i})$ **for** $N_e >> N_c$

- **Recombination lines**

  $j_\nu \propto T^{-\alpha}$ **where** $\alpha \sim 1$

  $j_\nu \propto N(X^{+i+1})N_e$

A bi-abundance model for NGC 6153



Component 1 ('metal-rich')

H: 10000 **He:** 6300 **C:** 310 **N:** 220 **O:** 600
Ne: 180 **Mg-Ar:** Solar by mass
N(H): 4410 cm^{-3} **Filling factor:** 0.005
T_e: 1390 K **Mass:** 0.0031 $M_\odot$

Component 2 ('normal')

H: 10000 **He:** 1000 **C:** 2.9 **N:** 4.2 **O:** 5.6
Ne: 1.8 **Mg - Ar:** Solar by mass
N(H): 1170 cm^{-3} **Filling factor:** 0.995
T_e: 9040 K **Mass:** 0.38 $M_\odot$

Averaged over the whole nebula

H: 10000 He: 1010 (em. ana: 1360) **O: 6.9** (≃solar; em. ana: CEL = 5, ORL = 41)

T_e([O III]): 9090 K T_e(H I BJ): 7080 K T_e(He I J3421): 3550 K T_e(C II, O II): 1400 K

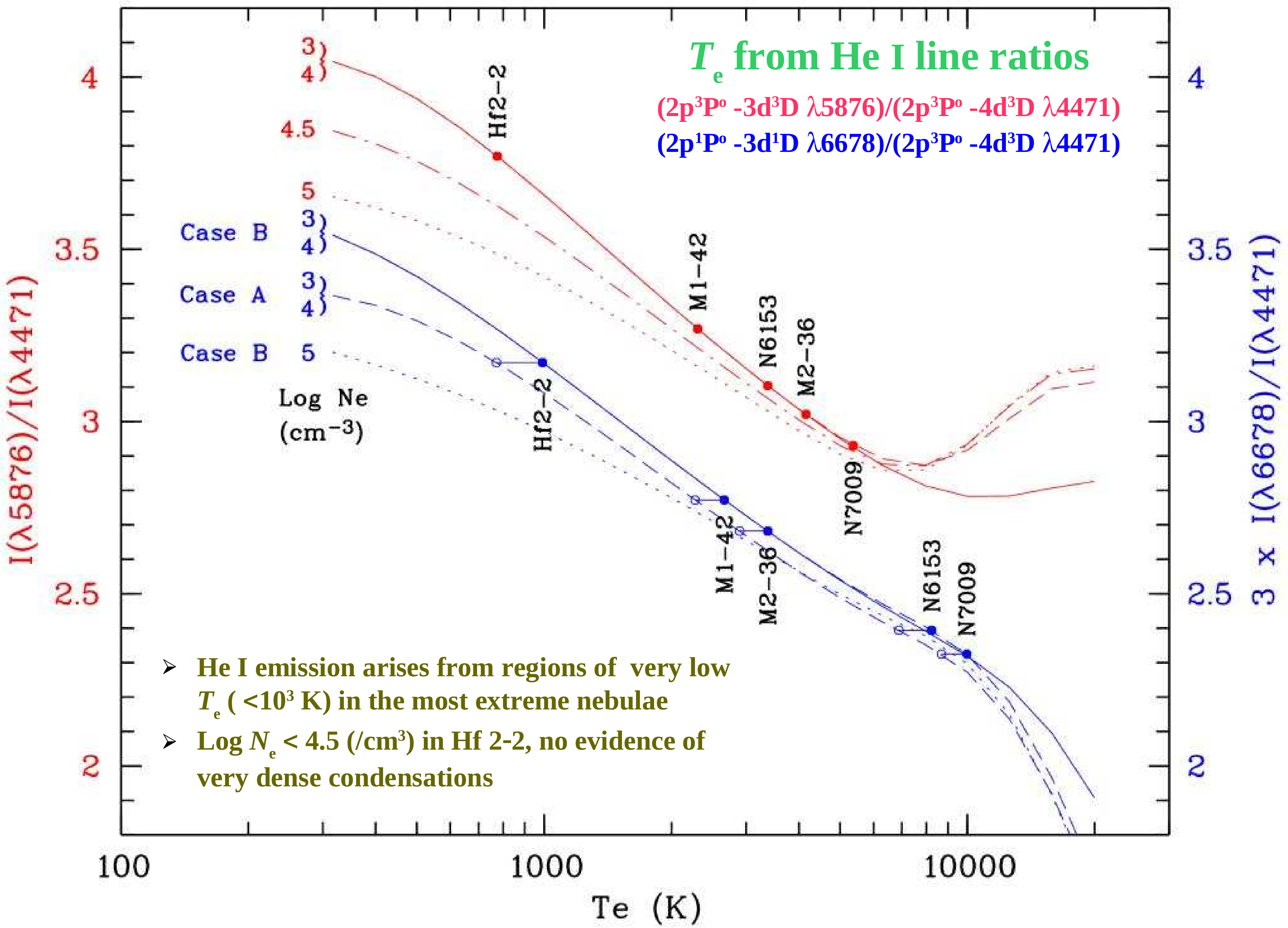
The model predicts

T_e(CNONe ORLs) $\ll$ T_e(He I) $\ll$ T_e(H I BJ) $\ll$ T_e([O III])

T_e from He I line ratios

$(2p\,^3P^o - 3d\,^3D\ \lambda5876)/(2p\,^3P^o - 4d\,^3D\ \lambda4471)$

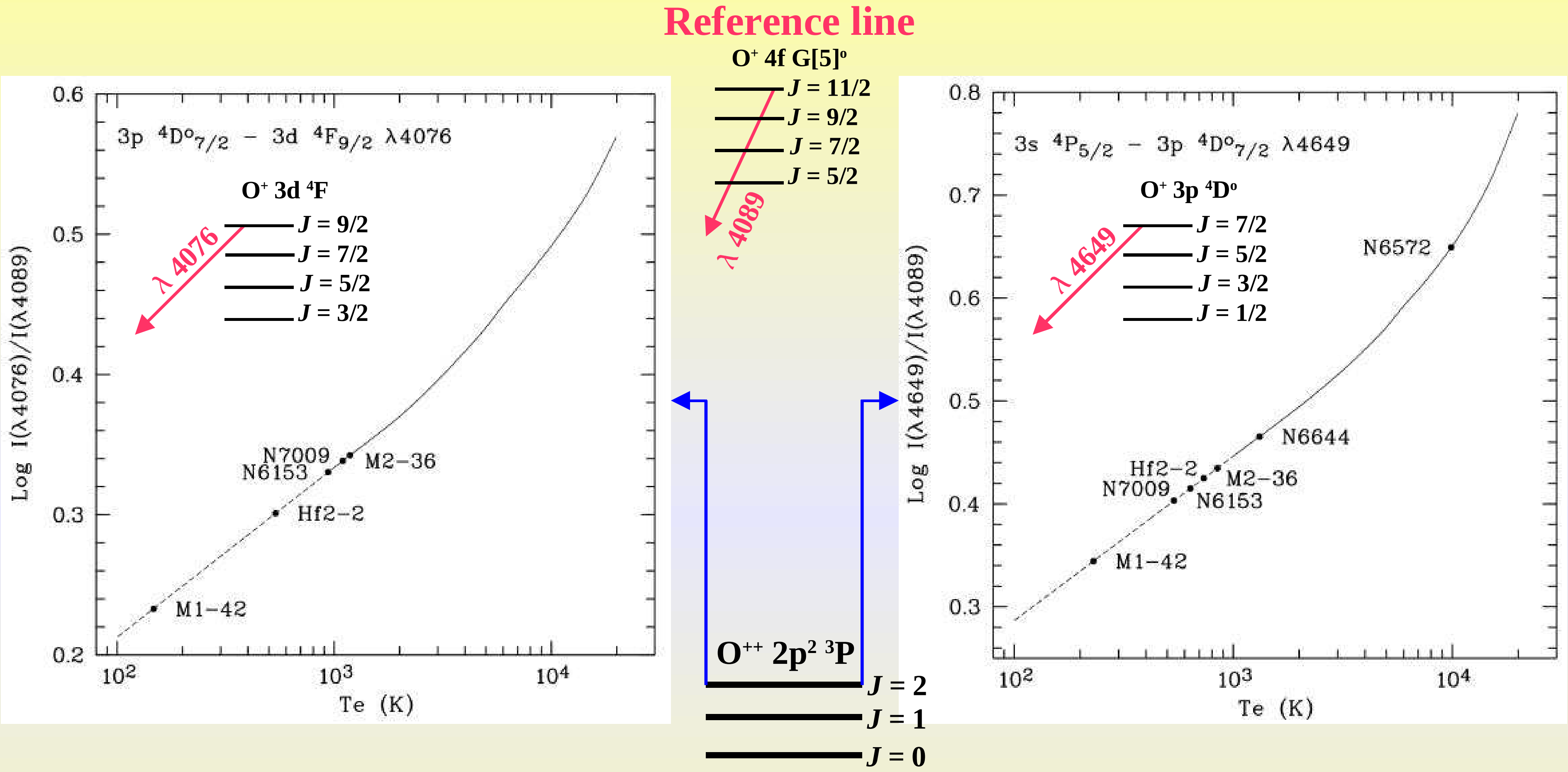
$(2p\,^1P^o - 3d\,^1D\ \lambda6678)/(2p\,^3P^o - 4d\,^3D\ \lambda4471)$



- He I emission arises from regions of very low T_e ($<10^3$ K) in the most extreme nebulae
- Log N_e < 4.5 (/cm^3) in Hf 2-2, no evidence of very dense condensations

Smits D. P., 1996, MNRAS, 278, 683;
Sawey P., Berrington K. A., 1993, Atomic Data Nucl. Data Tables, 55, 81

Average T_e's of O II ORL emitting regions



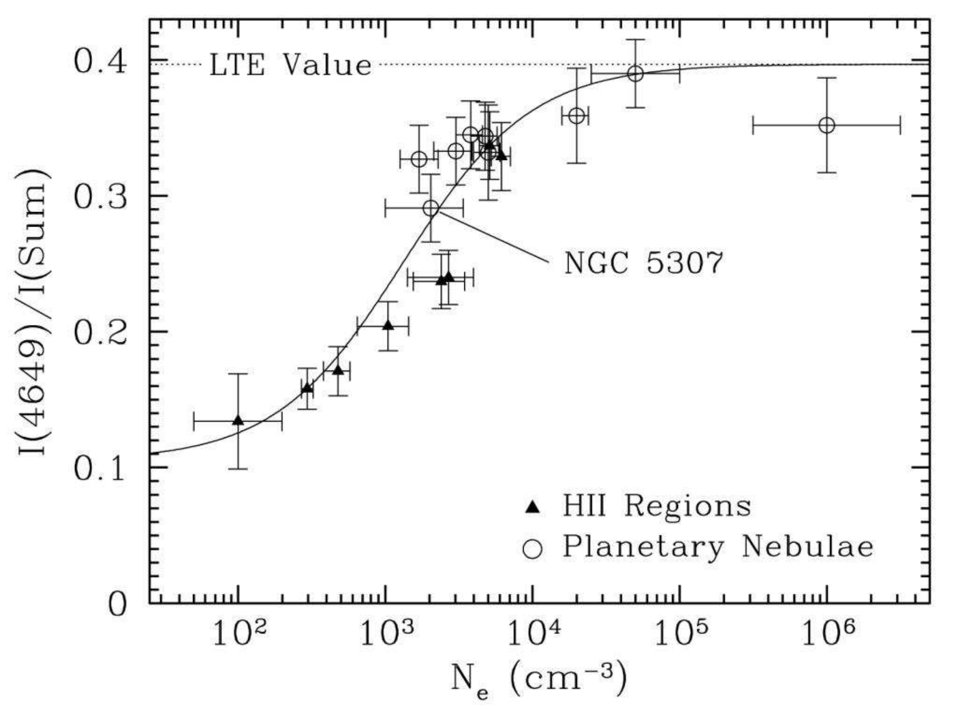
Direct recombination to the upper levels of λ4089, λ4076 and λ4649, levels of the highest *J* value of the given spectral term, are only possible from the *J* = 2 level of the ground ³P term of recombining O⁺⁺ ions. (Liu 2003, in Planetary Nebulae: Their Evolution and Role in the Universe, eds. S. Kwok, M. Dopita and R. Sutherland, pp.339-346 (2003))

O^{++} level population at $T_e = 10^3$ K and $N_e = 3000$ cm^{-3}

J	Pop	Therm
2	0.30	0.56
1	0.43	0.33
0	0.40	0.11

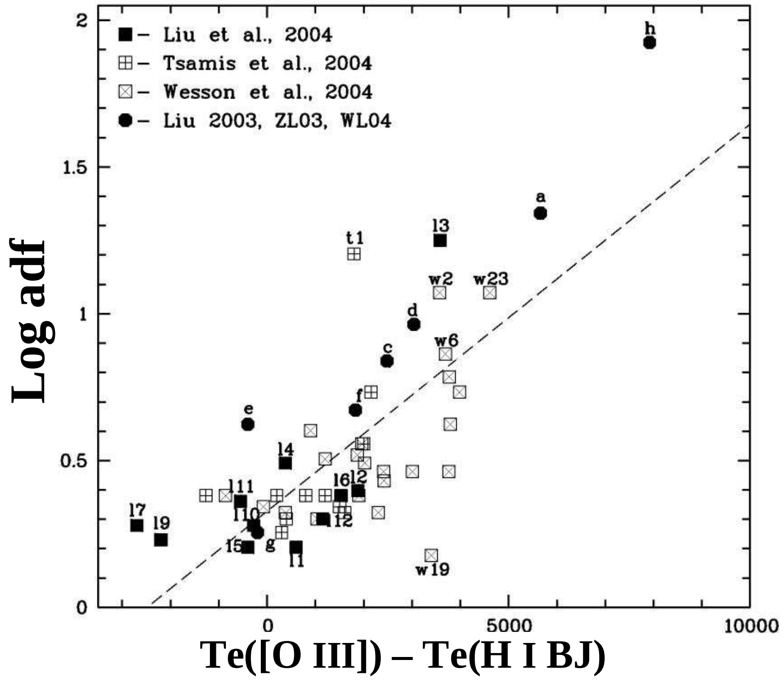
- Liu 2003, in IAU Symp. 209 Planetary Nebulae: Their Evolution and Role in the Universe, eds. S. Kwok, M. Dopita and R. Sutherland, pp.339-346 (2003)

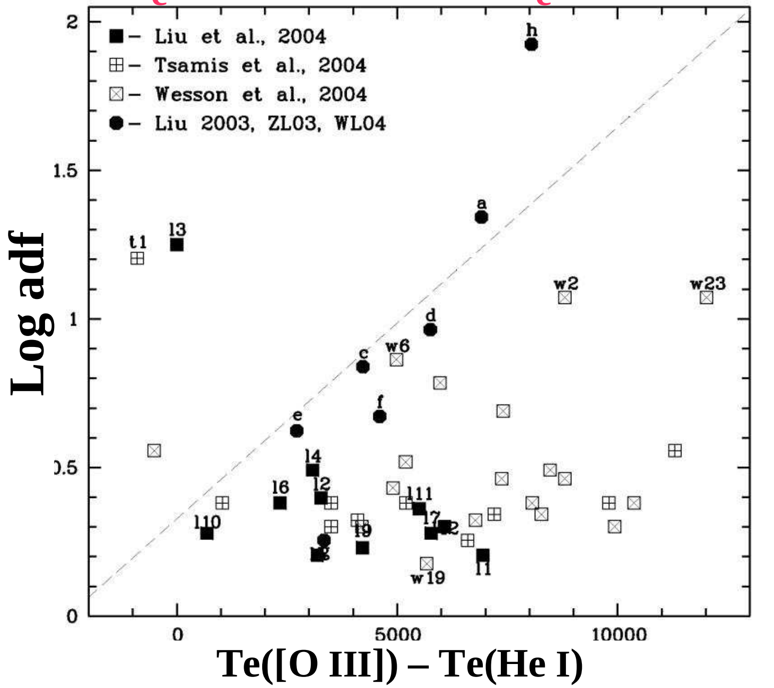
- Tsamis et al., 2003, MN, 338, 687

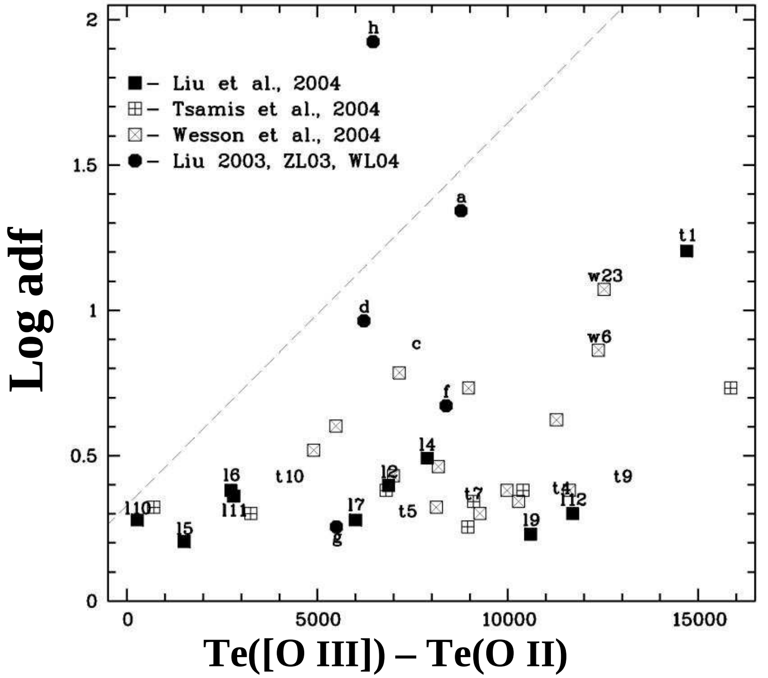


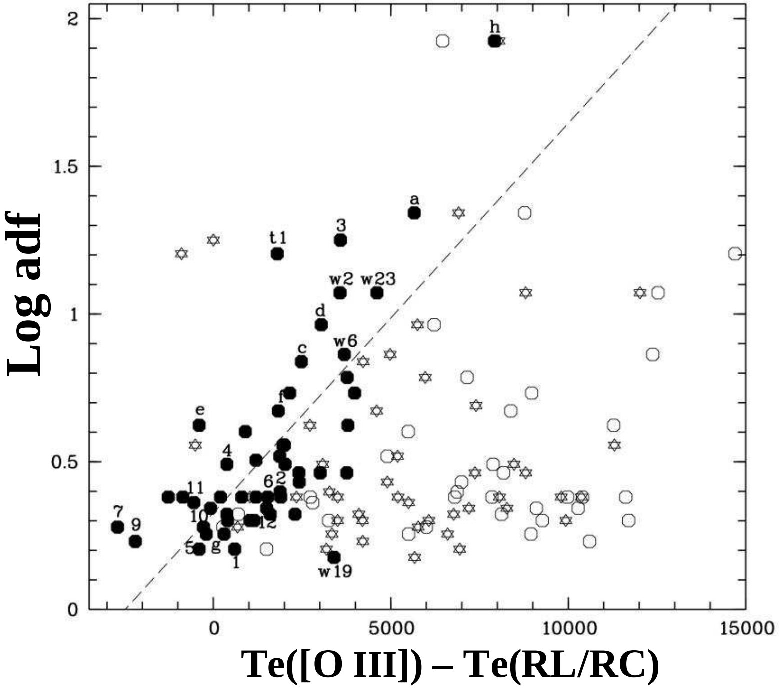
Ruiz et al., 2003, ApJ, 595, 247

T_e(CNONe ORLs) ≪ T_e(He I) ≪ T_e(H I BJ) ≪ T_e([O III])







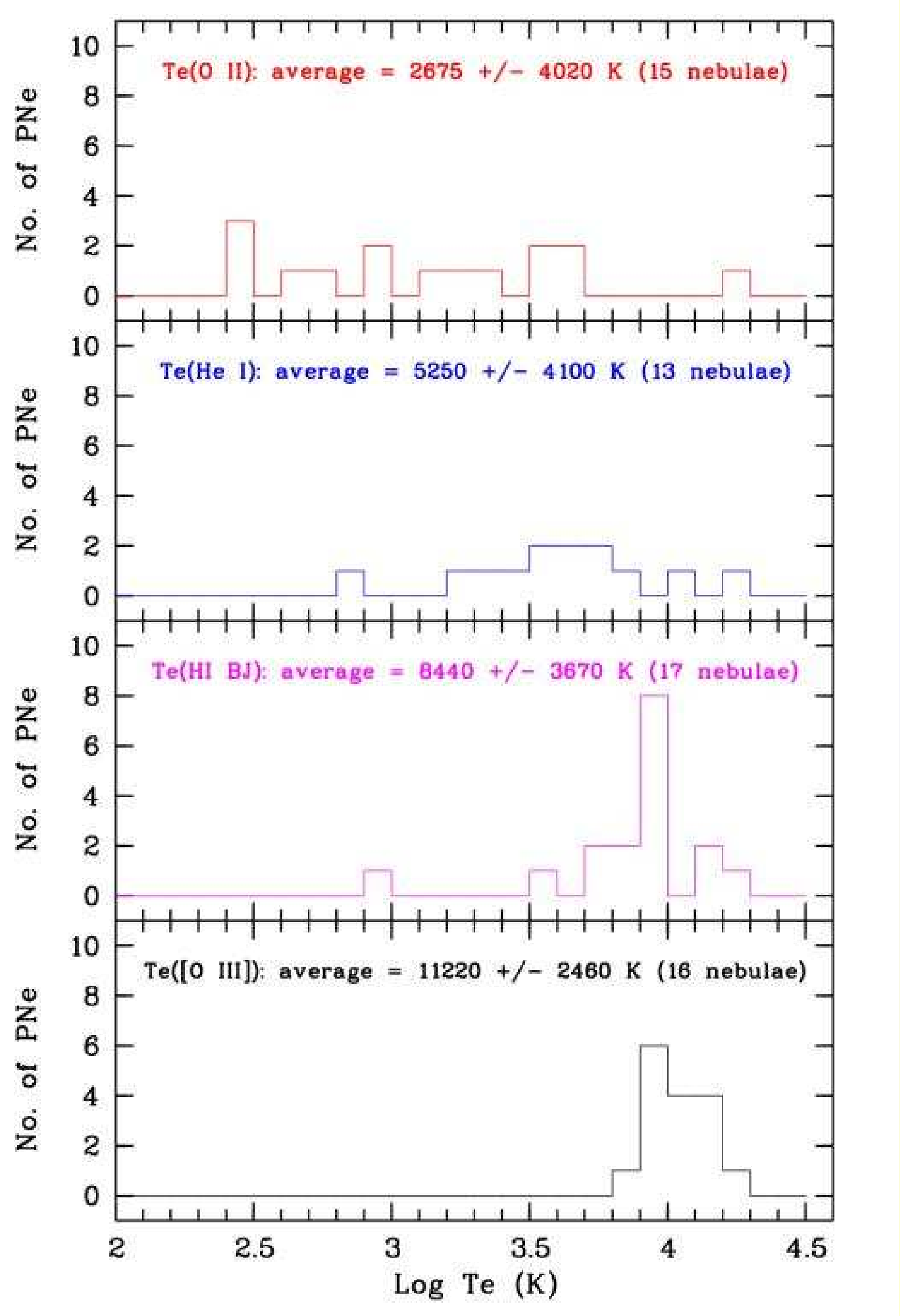


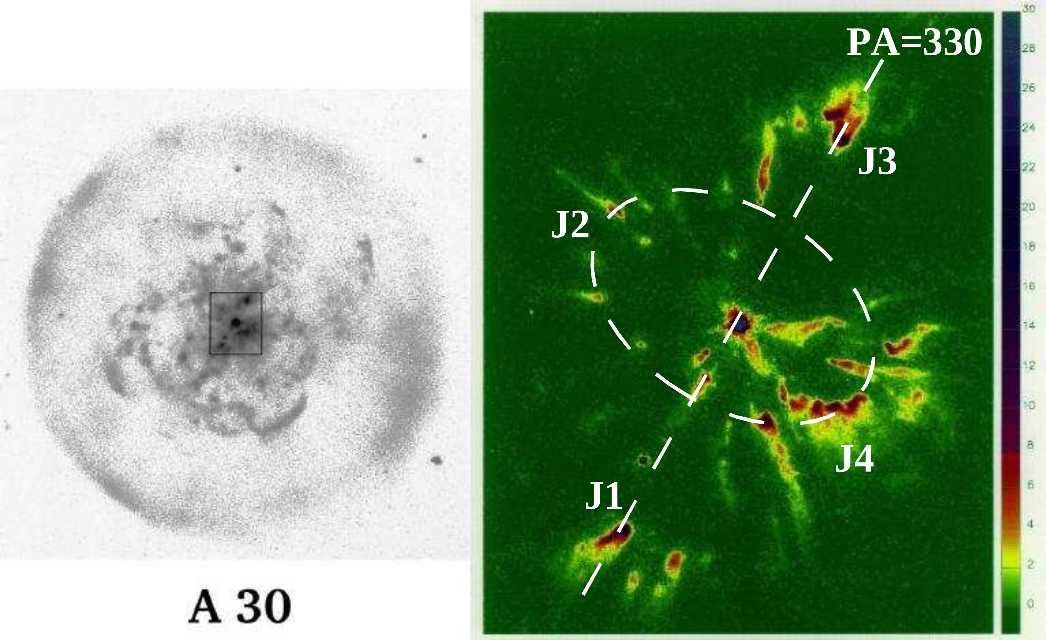
Comparison of T_e(O II), T_e(He I), T_e(H I BJ) and T_e([O III])

	T_e(O II)	T_e(He I)	T_e(BJ)	T_e([O III])	adf	N_e (cm^{-3})
Hf 2-2	2360	775	900	8820	84	300
M 1-42	450	2310	3560	9220	22	1200
NGC 40		10600	7020	10600	18	1700
M 2-24	570	3000	16300		17	1800
Vy 2-2	1380	1890	9300	13910	12	11700
DdDm 1		3500	8730	12300	12	4000
NGC 2022	< 300	15900	13200	15000	16	1050
NGC 6153	3200	3370	6080	9120	9.2	4000
IC 2003	270	7670	8960	12650	7.3	5200
M 2-36	800	4160	5900	8380	6.9	3800
Vy 1-2	3250	4430	6630	10400	6.2	1160
M 3-27	4030		9020	13000	5.5	3200
NGC 2440	< 300		14000	16150	5.4	4000
NGC 7009	1600	5380	8150	9980	4.7	3900
M 3-34	950		8440	12230	4.2	4000
NGC 6543	16300	5220	8340	7940	4.2	6400
Hu 2-1	4370		8960	9860	4.0	7900

Liu X.-W., 2003, in IAU Symp. 209 Planetary Nebulae: Their Evolution and Role in the Universe, eds. S. Kwok, M. Dopita and R. Sutherland, pp.339-346 (2003); Tsamis Y. et al., 2004, MN, submitted; Liu Y. et al., 2004, MN, submitted; Wesson R. et al., 2004, MN, in preparation

T_{e}(CNONe ORLs) $\ll$ T_{e}(He I) $\ll$ T_{e}(H I BJ) $\ll$ T_{e}([O III])





H-deficient knots in A 30

- **O II ORLs arise from 500 K plasma!**
- **H contributes < 1% in these knots, Much more extreme than the hypothesised H-deficient clumps in e.g. NGC 6153**
- **The knots are O-rich, rather than C-rich as reported previously**

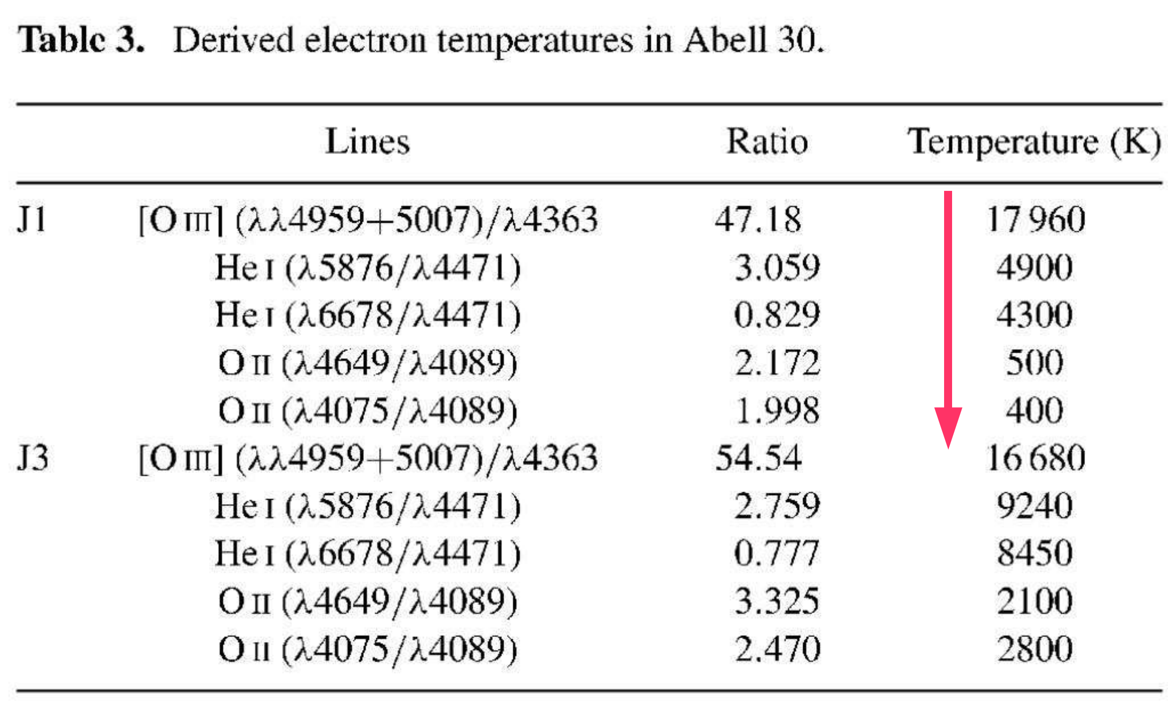


Table 3. Derived electron temperatures in Abell 30.

	Lines	Ratio	Temperature (K)
J1	[O III] (λλ4959+5007)/λ4363	47.18	17 960
	He I (λ5876/λ4471)	3.059	4900
	He I (λ6678/λ4471)	0.829	4300
	O II (λ4649/λ4089)	2.172	500
	O II (λ4075/λ4089)	1.998	400
J3	[O III] (λλ4959+5007)/λ4363	54.54	16 680
	He I (λ5876/λ4471)	2.759	9240
	He I (λ6678/λ4471)	0.777	8450
	O II (λ4649/λ4089)	3.325	2100
	O II (λ4075/λ4089)	2.470	2800

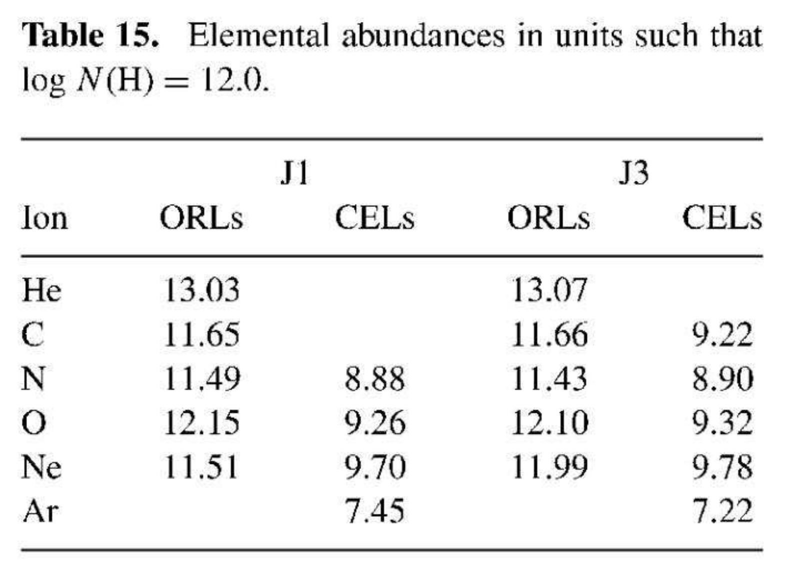
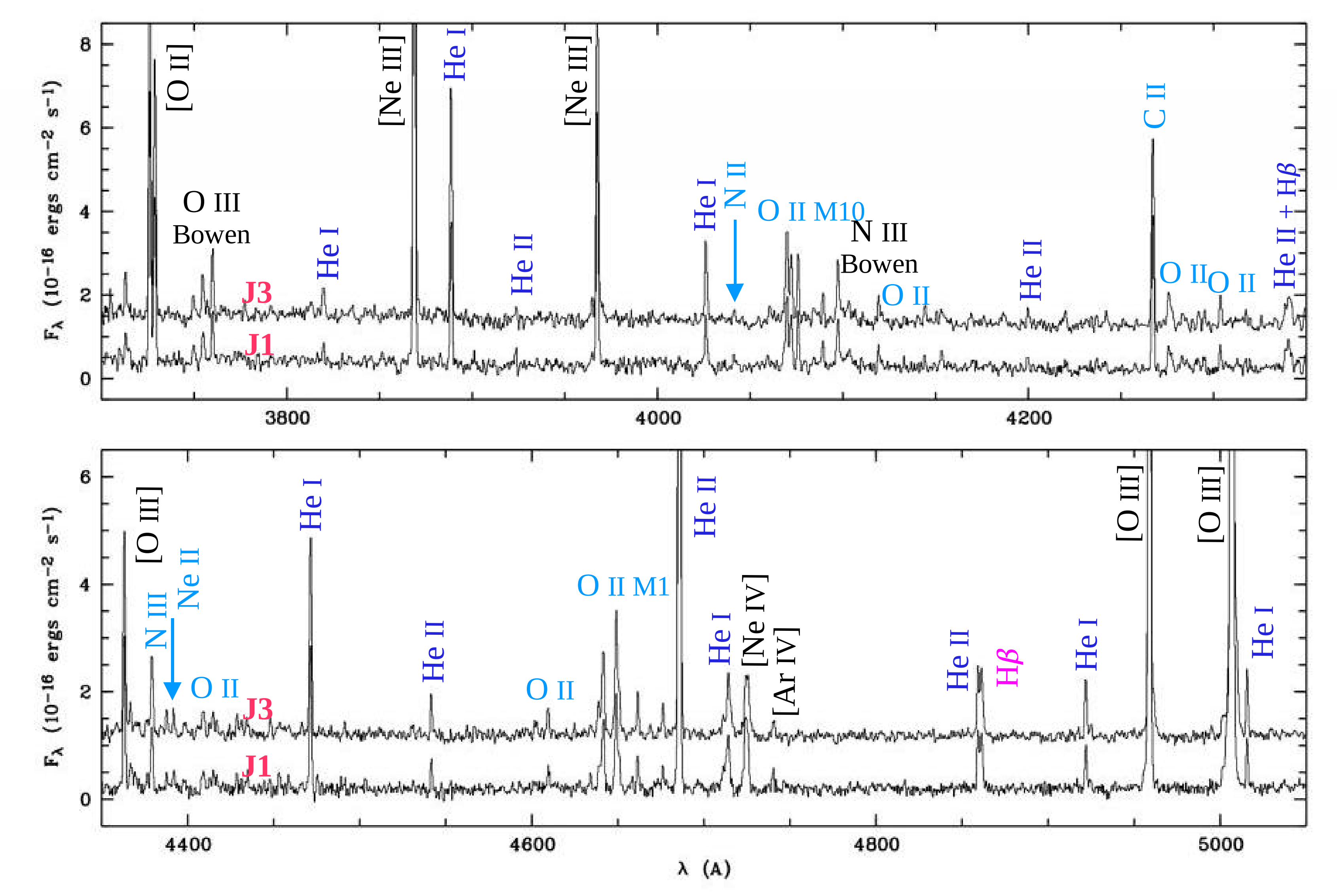


Table 15. Elemental abundances in units such that log $N(\mathrm{H}) = 12.0$.

	J1		J3	
Ion	ORLs	CELs	ORLs	CELs
He	13.03		13.07	
C	11.65		11.66	9.22
N	11.49	8.88	11.43	8.90
O	12.15	9.26	12.10	9.32
Ne	11.51	9.70	11.99	9.78
Ar		7.45		7.22

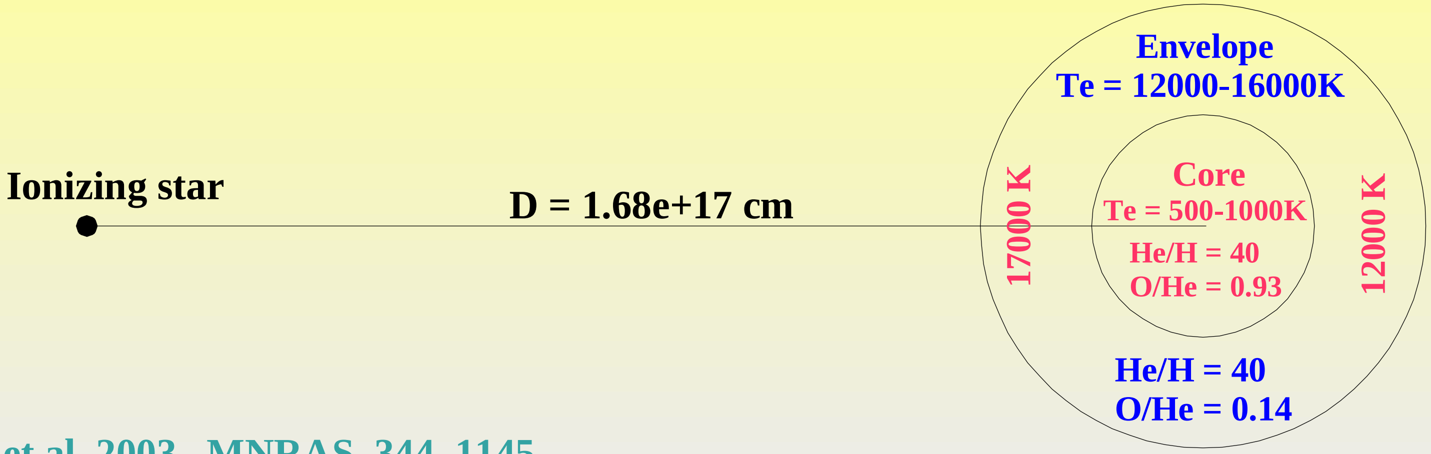
(Wesson et al. 2003, MN, 340, 253)

WHT/ISIS spectra of knots J3 and J1 in Abell 30



The observed ORLs from C, N, O & Ne ions and their relative strengths are remarkably similar to those observed in other Pne such as Hf 2-2, M 1-42 and N6153

A 3-D photoionization model for a H-deficient knot in Abell 30



Ionizing star

D = 1.68e+17 cm

Envelope
Te = 12000-16000K

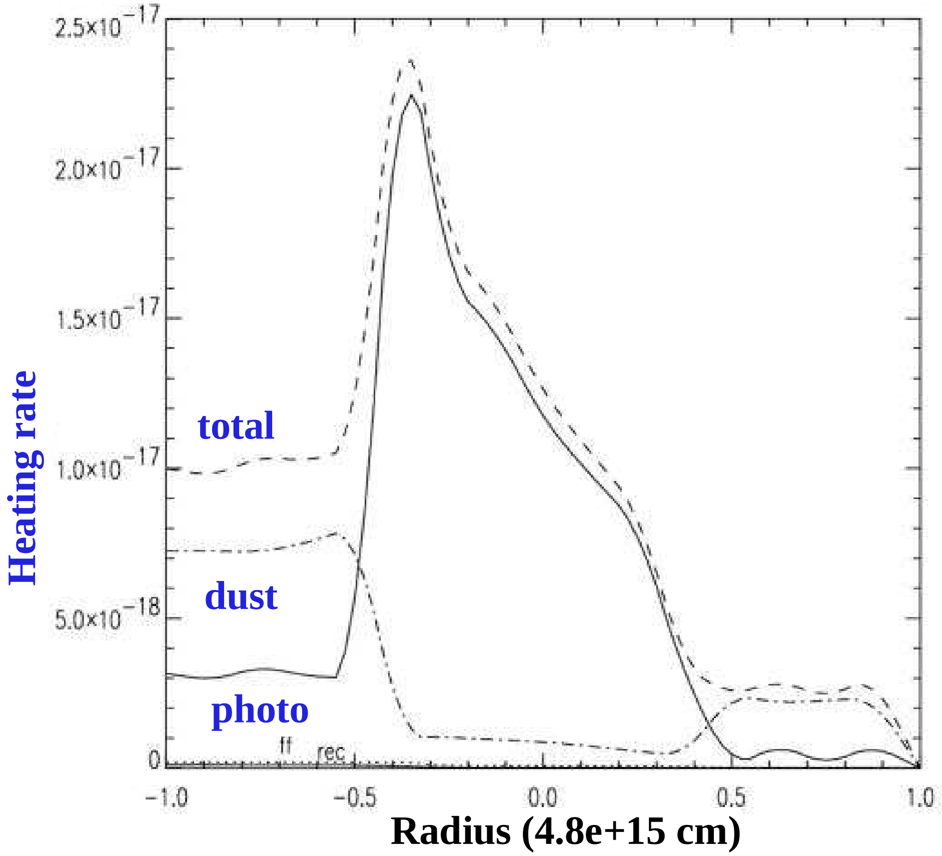
Core
Te = 500-1000K
He/H = 40
O/He = 0.93

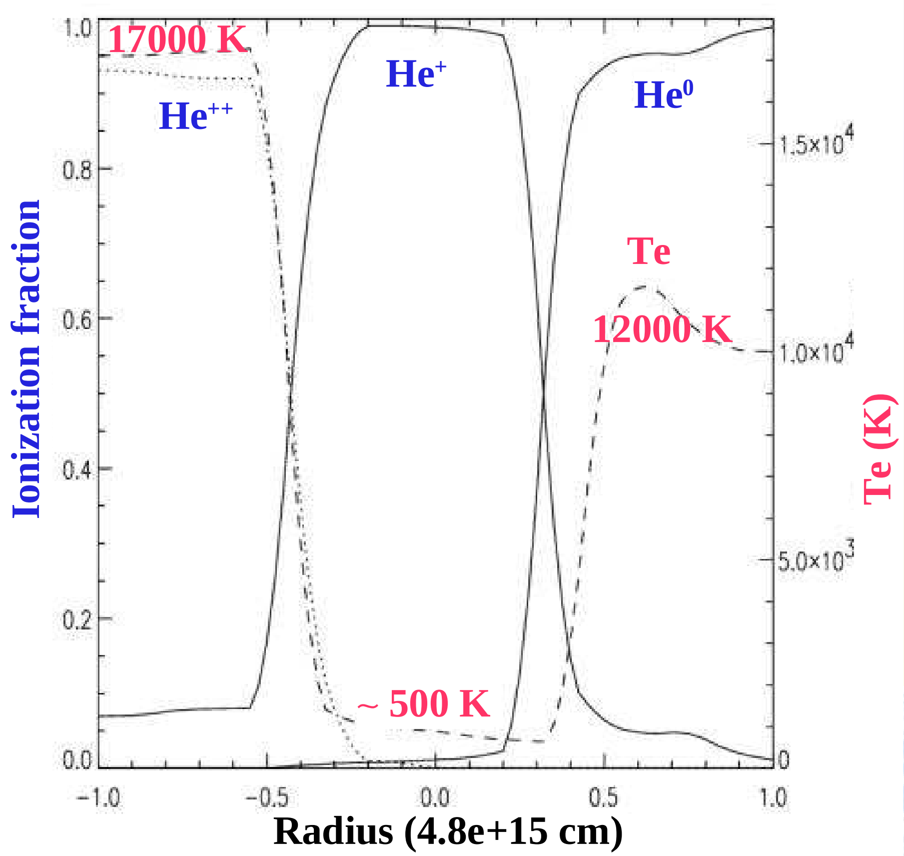
17000 K

12000 K

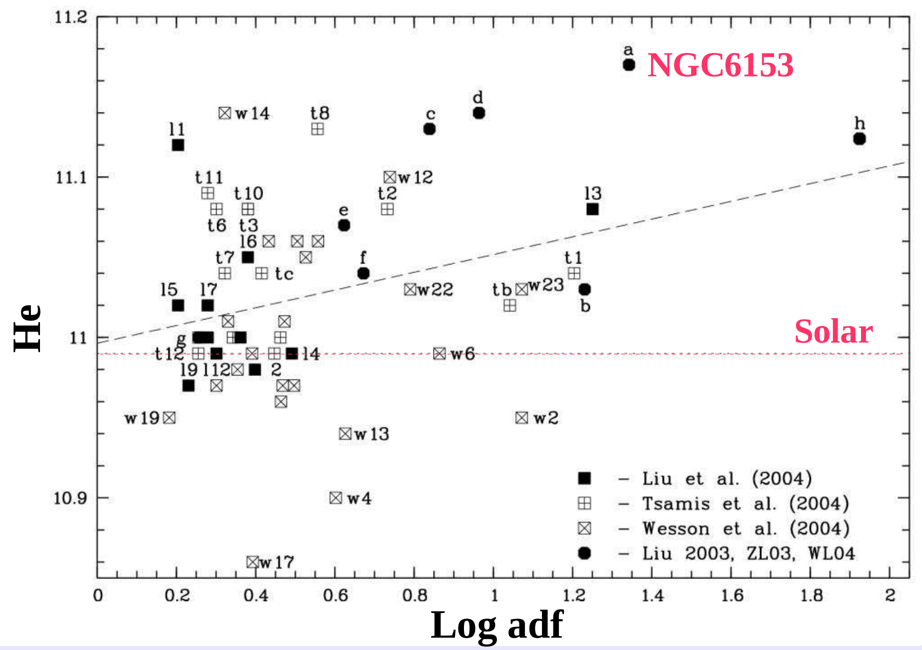
He/H = 40
O/He = 0.14

Ercolano et al. 2003, MNRAS, 344, 1145





Implications for He abundances of ionized gaseous nebulae



He/H is well correlated with adf and with Te([O III]) – Te(BJ)

→ He/H overestimated?

(Zhang et al., 2004, MN, in press; Liu et al., 2004, MNRAS, submitted)

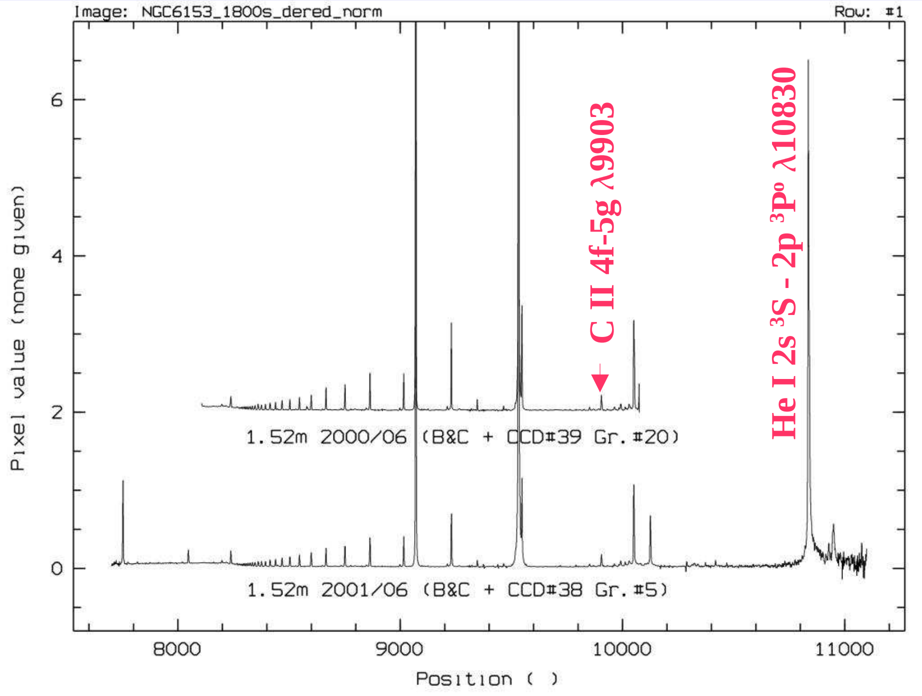
NGC6153

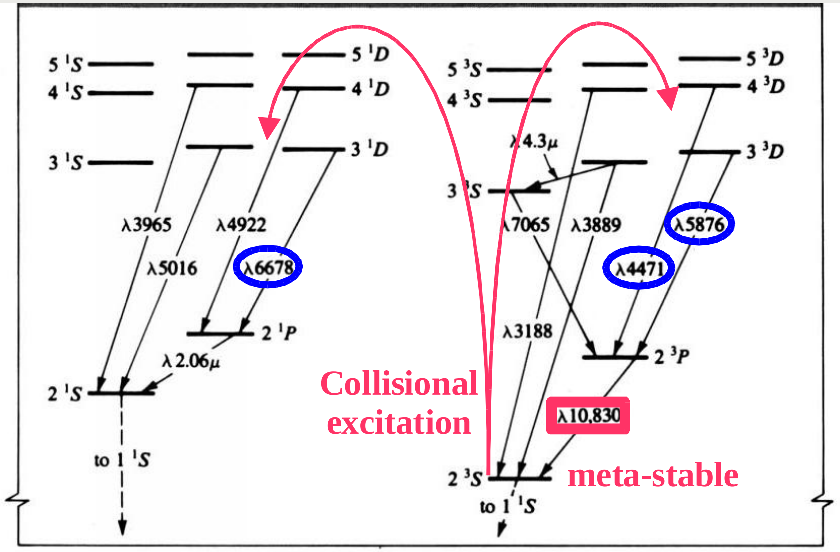
Component 1	Component 2
He/H=0.100	He/H = 0.63
Te = 9000 K	Te = 1400 K
M = 0.38 M_{sun}	M = 0.0031 M_{sun}

Average for the whole nebula

He/H = 0.101

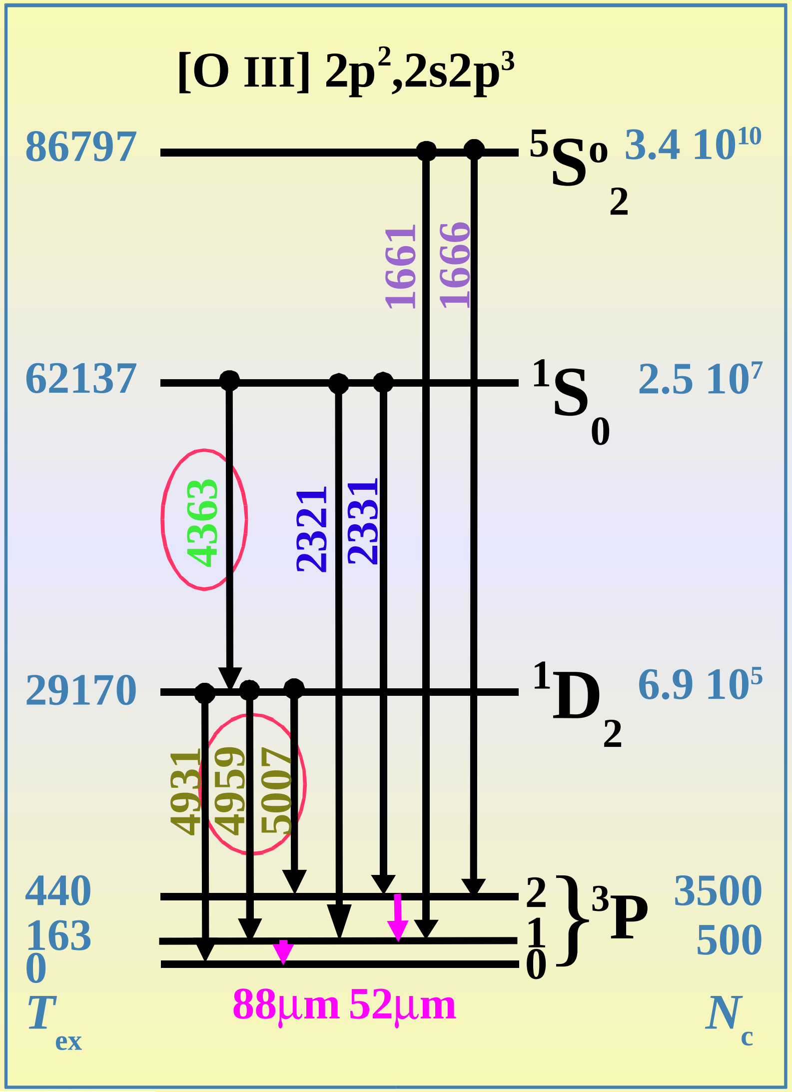
(empirical analysis: 0.136)





Failure of the paradigm of temperature fluctuations and density inhomogeneities

Effects of temperature/density fluctuations

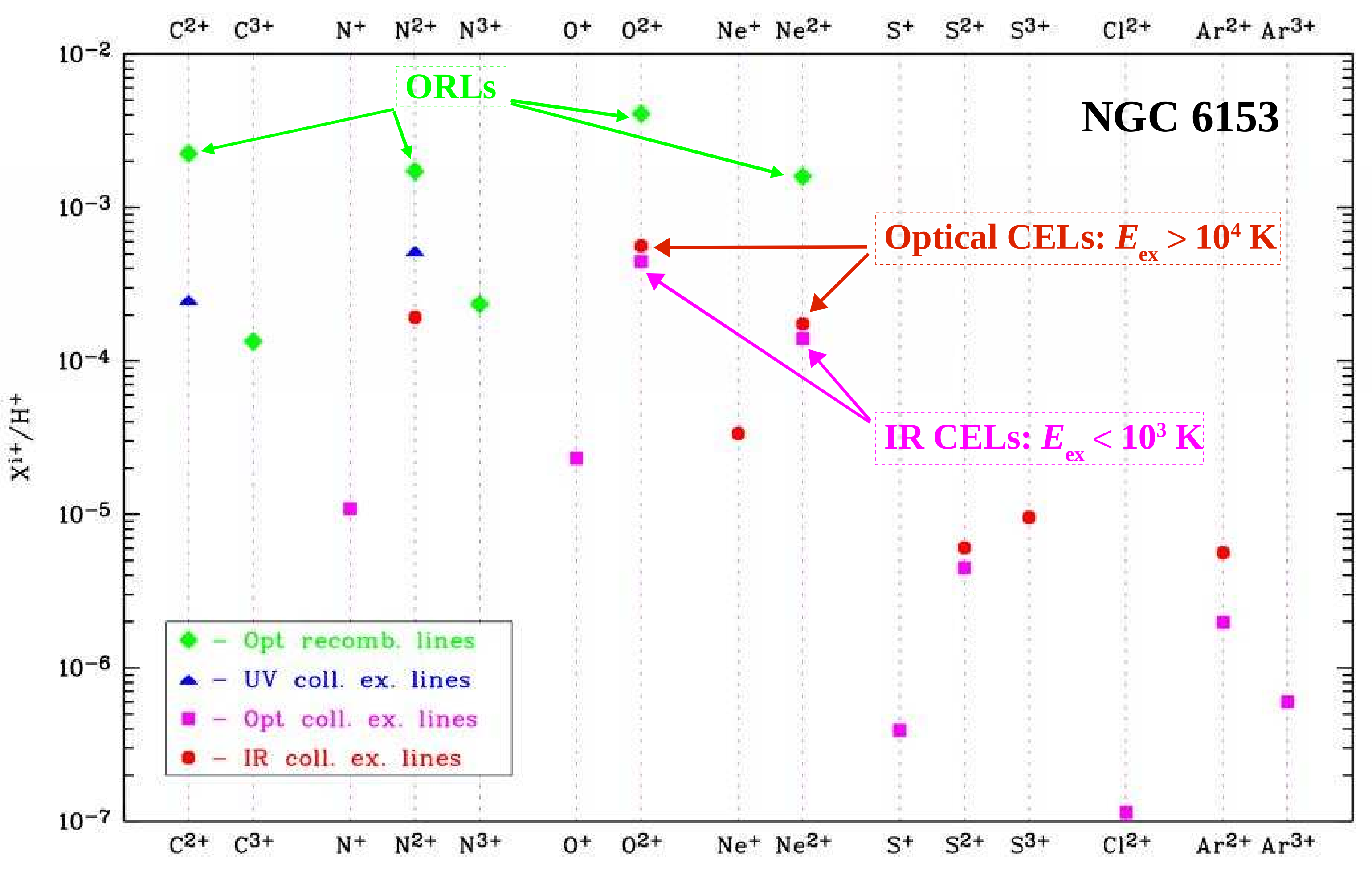


- **Temperature fluctuations**
  - **Opposite effects on CELs and ORLs**
  - **T_e derived from the [O III]na ratio will be overestimated, causing the O^{++}/H^{+} derived from the [O III]/Hβ ratio being underestimated (Peimbert 1967; 1971)**

- **Density inhomogeneities**
  - **CELs suppressed in high density regions**
  - **For condensations with $10^6 < N_e < 10^7$ cm^{-3}, the λλ4959, 5007 lines are suppressed relative to the λ4363 auroral line, causing T_e derived from the [O III]na ratio being overestimated (Rubin 1988; Viegas & Clegg 1994)**

Both scenarios predict that:
adf should correlate with E_{ex} and/or N_c

CEL versus ORL abundances – evidence against temperature fluctuations and density inhomogeneities

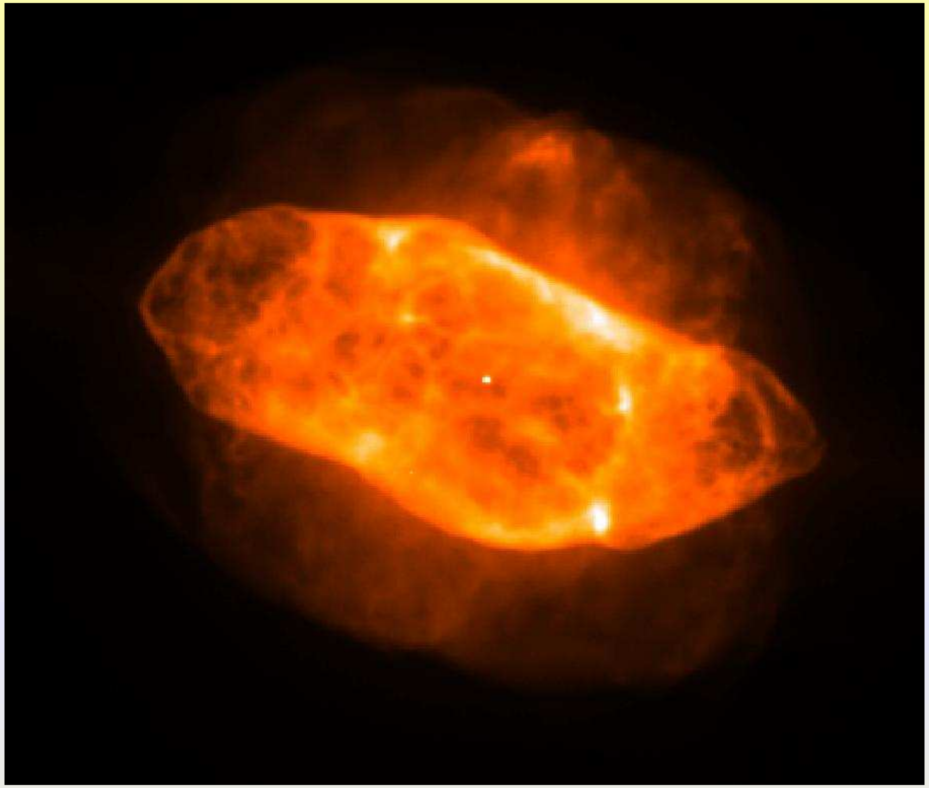


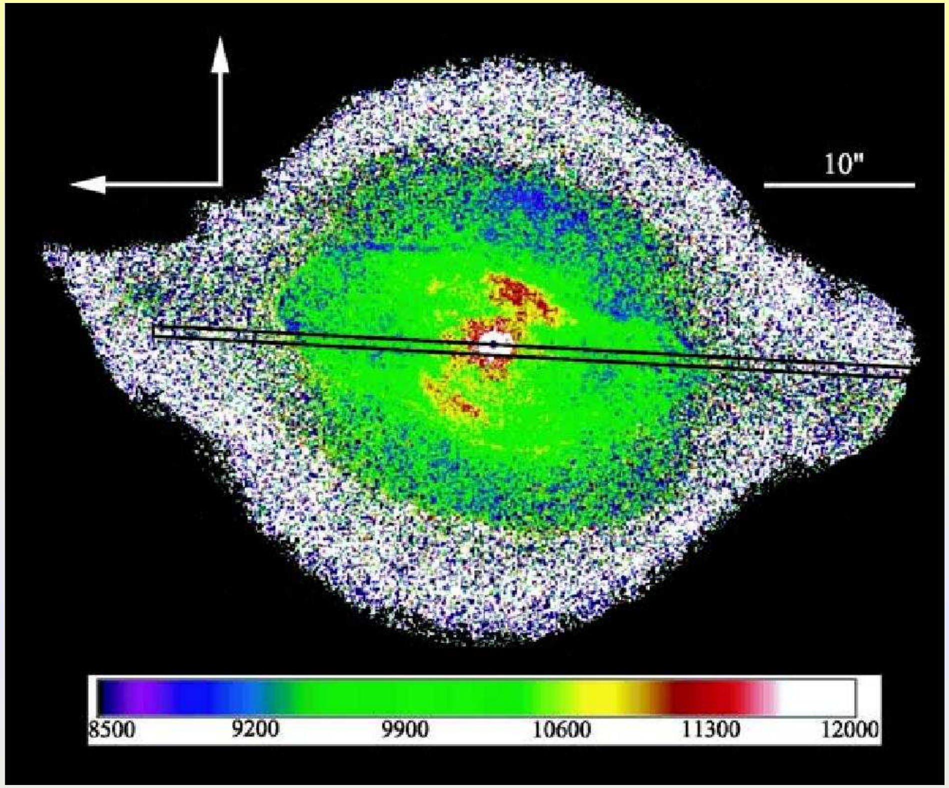
For essentially all nebulae analysed:

- **Abundances derived from various CELs -- UV, Opt. or IR, agree with each other**
- **ORL abundances consistently higher than CEL values**

Large <u>low-density</u> PNe have higher adf's and ΔTe's

Temperature fluctuations in NGC7009 from HST/STIS spectroscopy





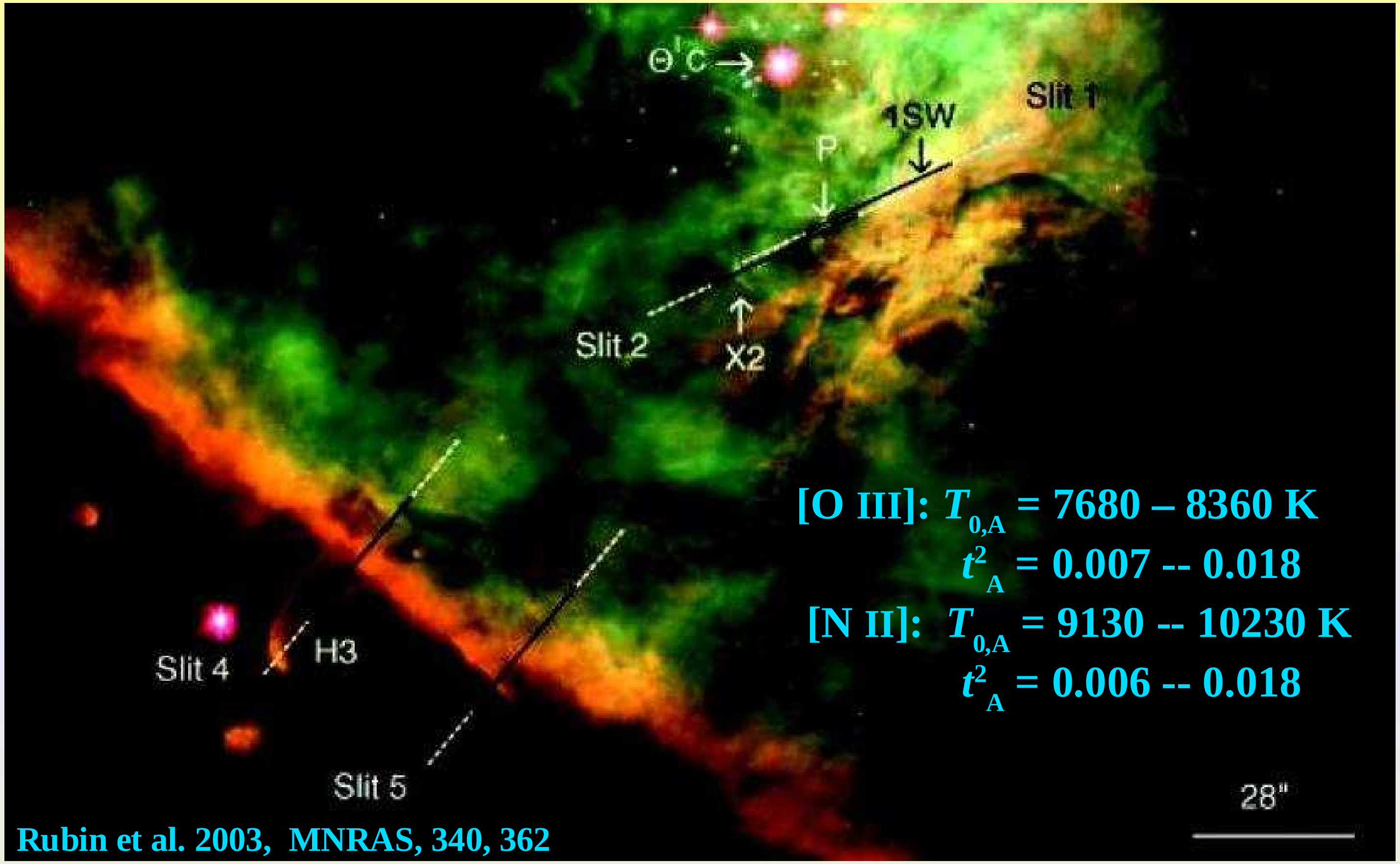
Rubin et al., 2002, MNRAS, 334, 777

$$T_{0,A} = \frac{\int\int T_e N_e N_i \, dl \, dA}{\int\int N_e N_i \, dl \, dA}, \quad t_A^2 = \frac{\int\int (T_e - T_{0,A})^2 N_e N_i \, dl \, dA}{T_{0,A}^2 \int\int N_e N_i \, dl \, dA}$$

[O III]: $T_{0,A}$ = 9000 – 11000 K, $t^2_A < 0.01$

Similar conclusion for NGC 6543 (Wesson & Liu 2004, MN, in press)

Temperature fluctuations in M 42 from HST/STIS spectroscopy



[O III]: $T_{0,A}$ = 7680 – 8360 K

t^2_A = 0.007 -- 0.018

[N II]: $T_{0,A}$ = 9130 -- 10230 K

t^2_A = 0.006 -- 0.018

Rubin et al. 2003, MNRAS, 340, 362

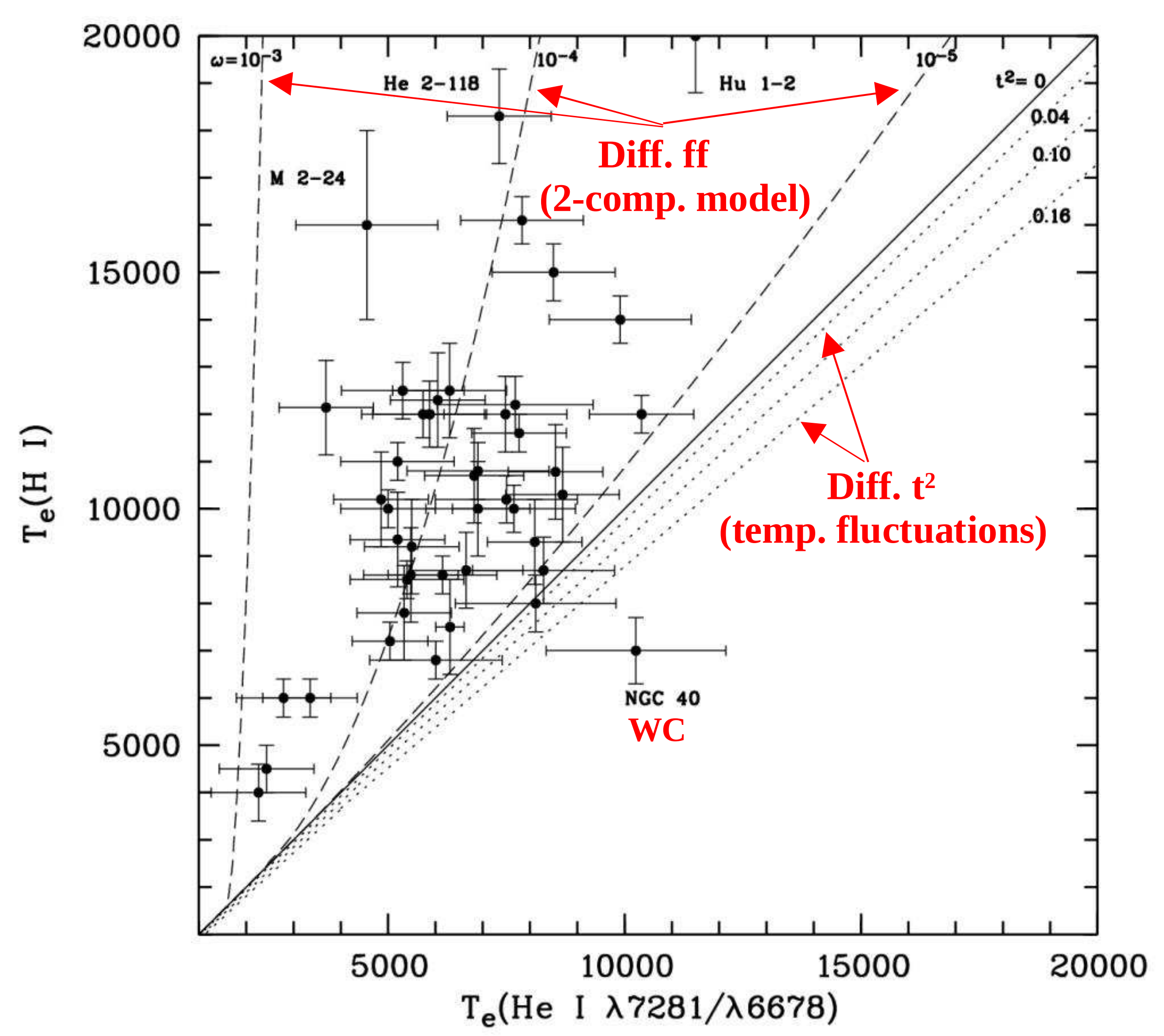
WFPC2 imaging (O'Dell, Peimbert, Peimbert, 2003, AJ, 125, 2590)

[O III]: $T_{0,A}$ = 9240 – 9390 K, t^2_A = 0.005 – 0.016

Ground-based Long-slit spectroscopy (Liu et al., 1995, ApJ, 450, L59)

Te([O III]) ≈ Te(BJ) ≈ constant across the nebula

Consistent with ORL/CEL ~ 1



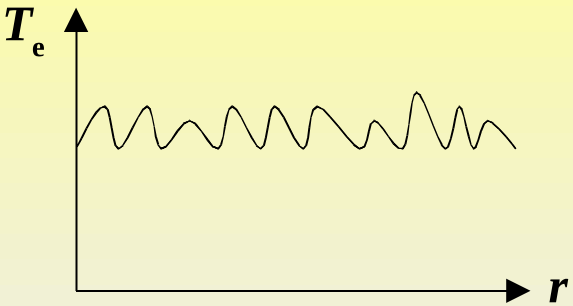
Diff. ff
(2-comp. model)

Diff. t^2
(temp. fluctuations)

WC

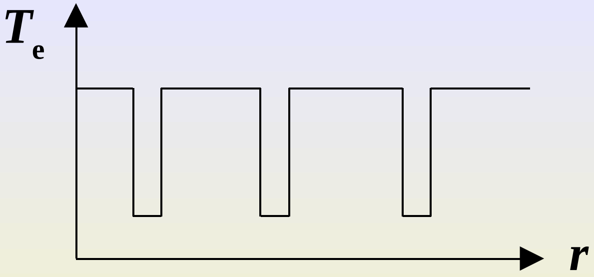
Zhang, Liu & Liu, 2004, in preparation

Temperature fluctuations



Te(H I) < Te(He I) < Te([O III])

Two-component model



Te(He I) < Te(H I) < Te([O III])

A small amount of H-deficient gas (ω ~10^{-5} to 10^{-3}) can account for the observations

Comparison of ORL and CEL widths

- **IC 418 (adf ~ 1)** (Williams et al., 2004, in preparation)
  - **Line widths**

    {O II = 16.8±0.8 km/s} ~ {[O III] = 15.7±0.2 km/s} < {[O II] = 42.6±0.6 km/s}
- **NGC 5307 (adf = 1.9)** (Ruiz et al., 2003, ApJ, 595, 247)
  - **Line widths**

    {O II = 44±7 km/s} ~ {[O III] = 48.4±0.7 km/s}
  - **Radial velocities**

    {O II = 33±4 km/s} ~ {[O III] = 30.1±0.5 km/s}
  - **Similar results for NGC 5315 (adf = 1.7)** (Peimbert et al. 2004, APJS, 150, 431)

    → "No evidence in favour of high velocity O-rich clumps" in NGC 5307 and NGC 5315 (as in Abell 30 and Abell 58)

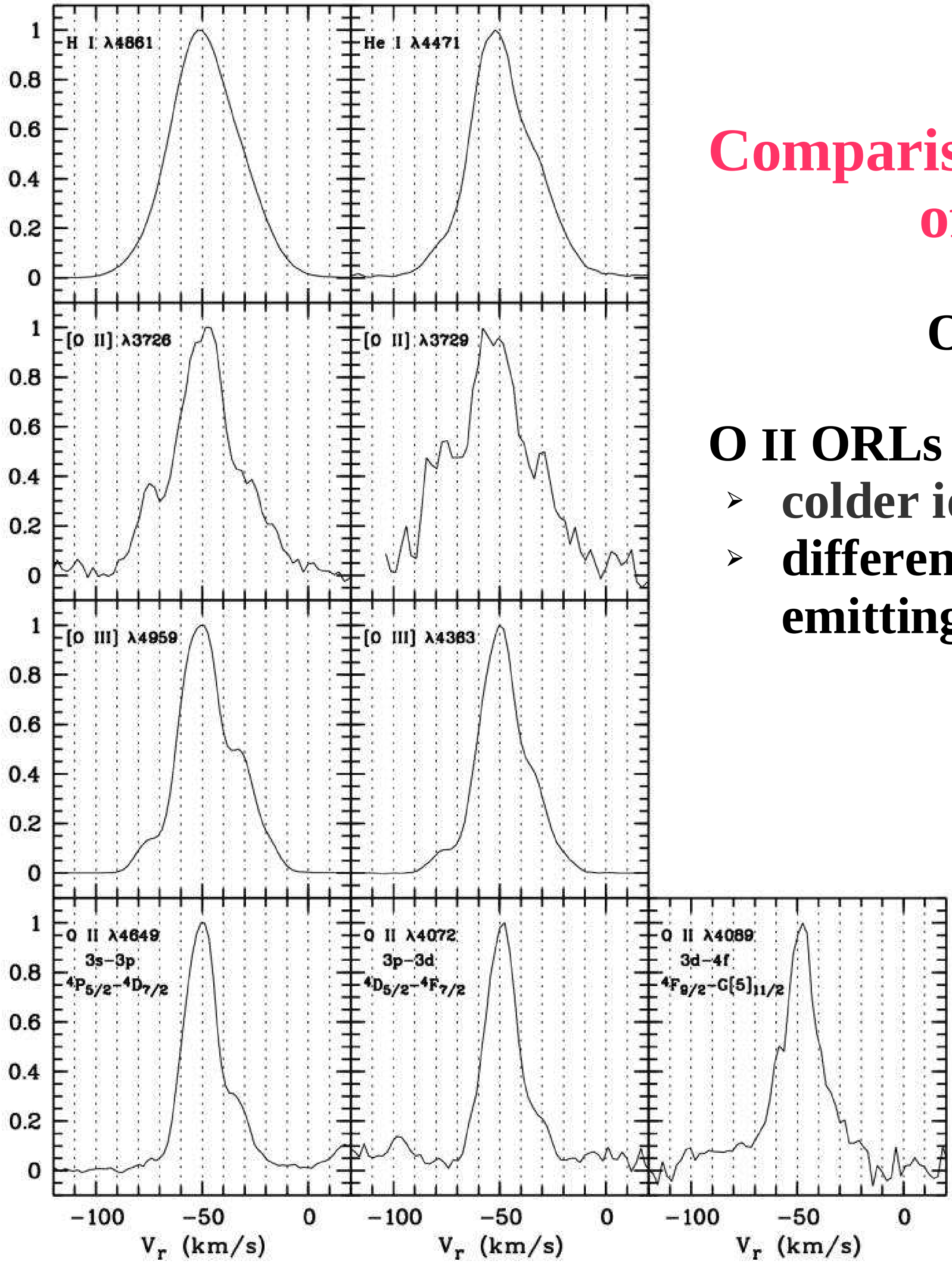
Our H-deficient knot model doesn't require that the posited knots be high-velocity

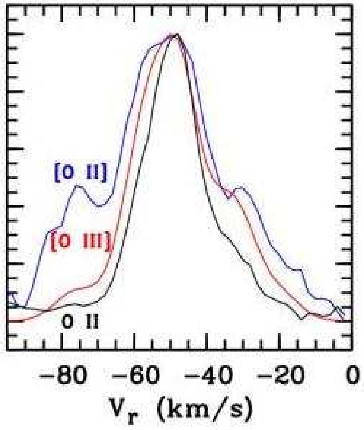
Comparison of emission line widths of ORLs and CELs

O II < [O III] < [O II]

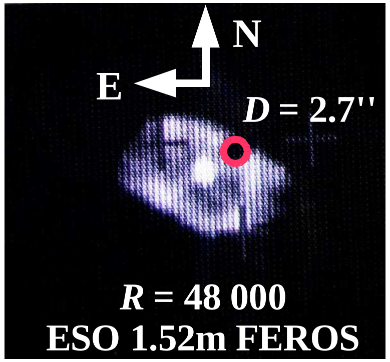
O II ORLs arise from either

- **colder ionized regions or**
- **different spatial regions than those emitting [O III] and [O II] CELs**





NGC 7009
adf ~ 5



***R* = 48 000**
ESO 1.52m FEROS

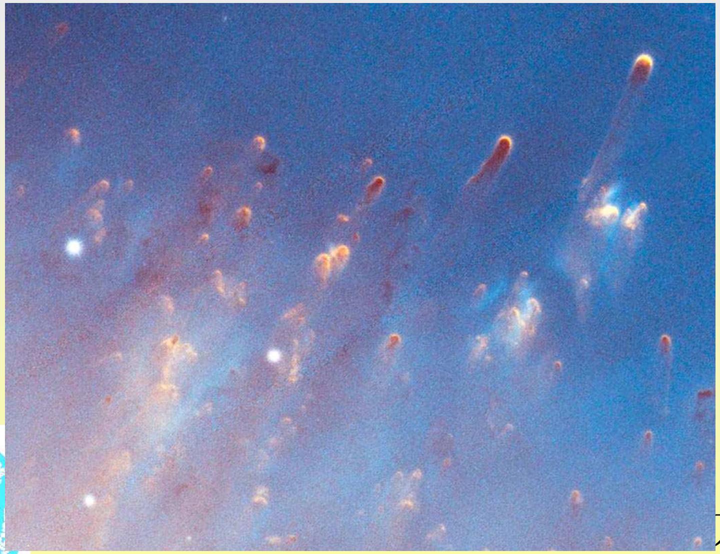
Conclusions and what next?

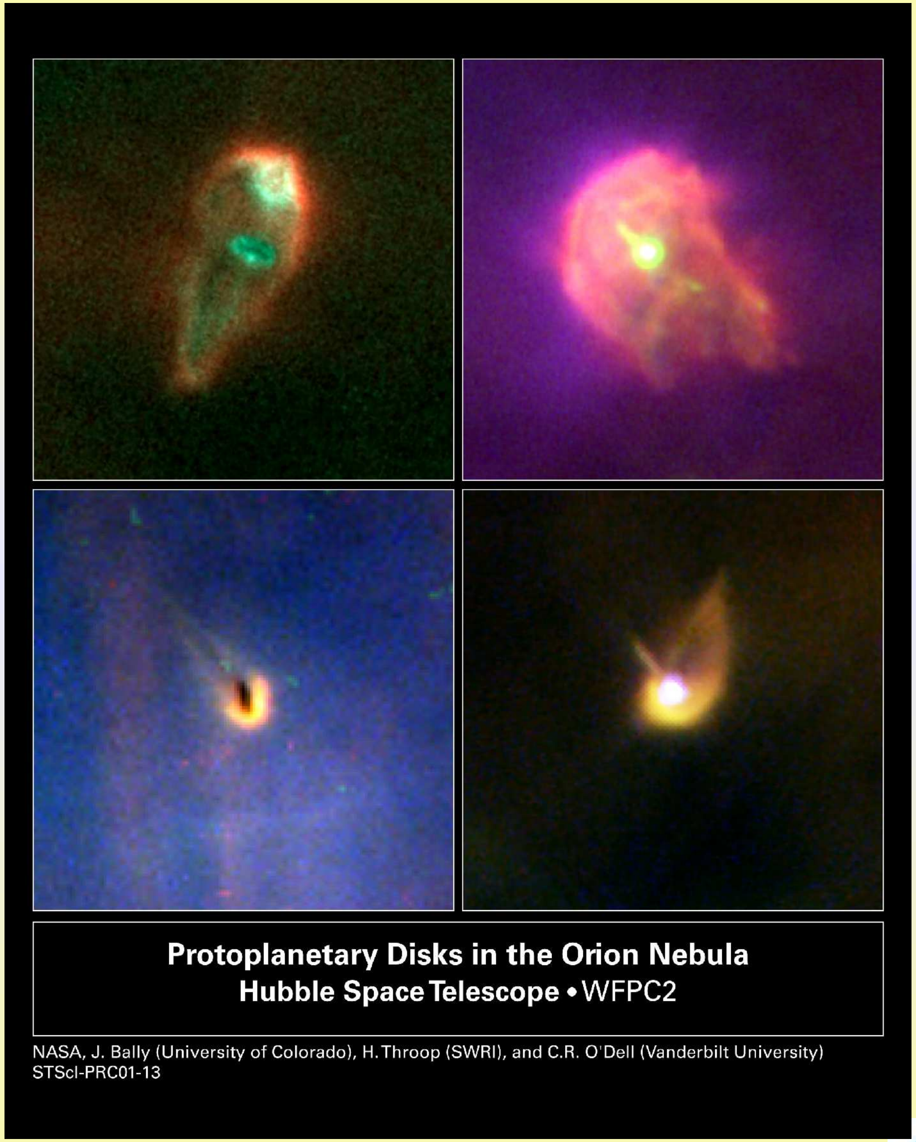
- **Conclusions**
    - **ORLs good abundance tracers?**
    - **CELs poor abundance tracers?**
    - **Temperature/density fluctuations present? Full story?**
    - **H-deficient ultra-cold plasma?**

- **Nature and origins of H-deficient inclusions**
    - **Nuclear processed and then ejected material?**
    - **Evaporating planetary disks?**

- **Future progress will rely on an intimate interplay between:**
    - **Observations: deep, quantitative spectroscopy of faint emission lines**
        - ★ **Temperature, density, mass, composition (CNONe versus Mg)**
    - **Atomic and plasma physics**

Origins of cold, metal-rich plasmas – evaporating planetesimals?





Protoplanetary Disks in the Orion Nebula
Hubble Space Telescope • WFPC2

NASA, J. Bally (University of Colorado), H. Throop (SWRI), and C.R. O'Dell (Vanderbilt University)
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