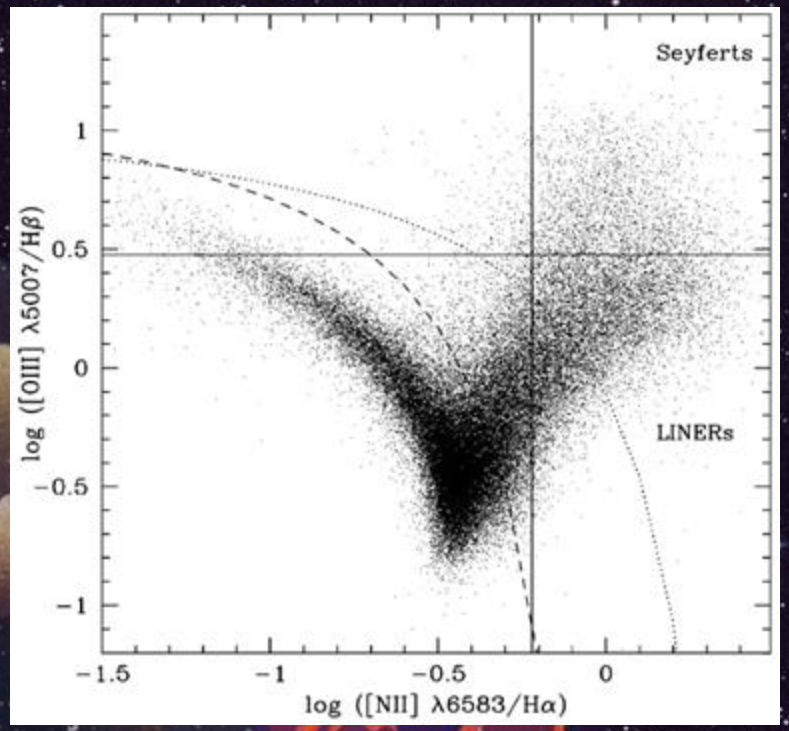
https://arxiv.org/abs/2508.01102

BPT Diagnostic Diagrams



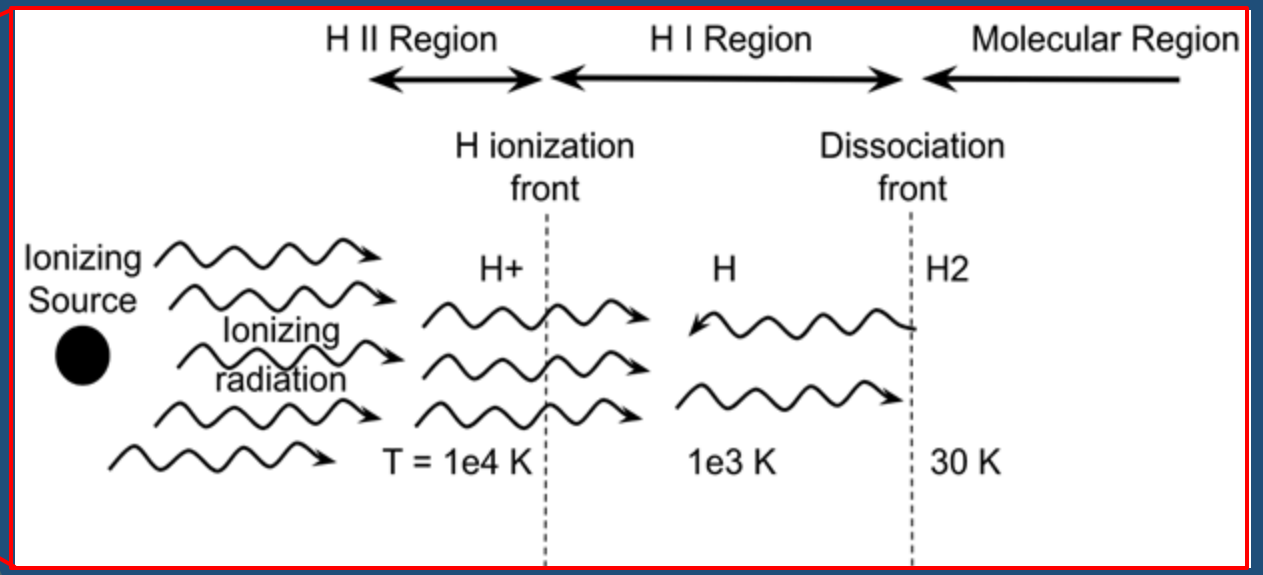
Chamani Gunasekera

Collaborators: Xihan Ji, Renbin Yan, Marios Chatzikos, Gary Ferland

The Interstellar Medium = Gas + Dust

Stellar nursery N159 H II region

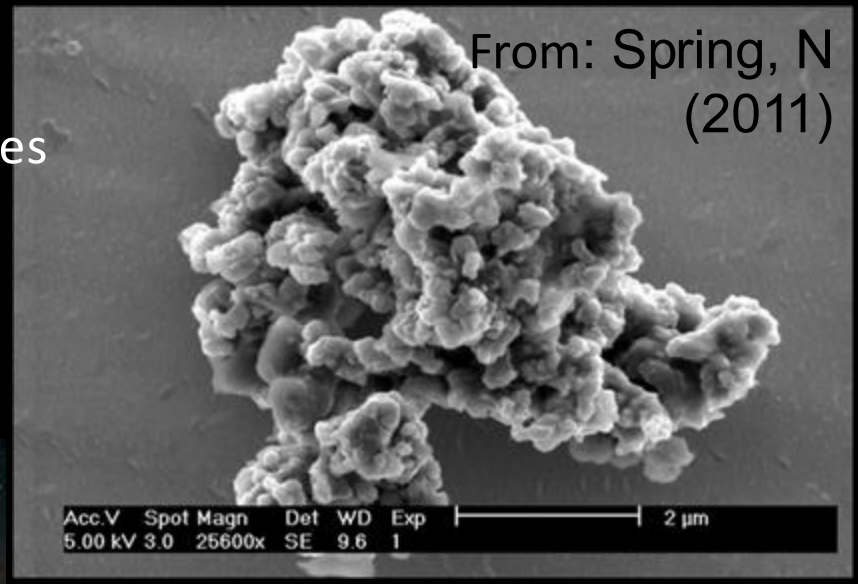
Starlight propagating through ionized H II region



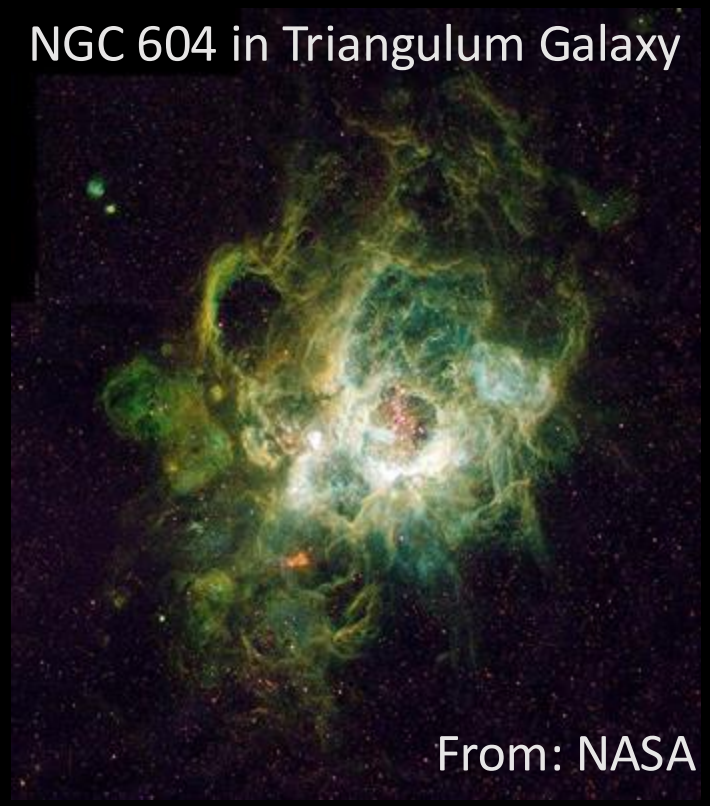
- Star forming (SF) ionized regions found near O & B stars
- H II regions – interstellar region with mainly H^+
- H II region elements come in two forms: gas & dust
- Most notable & useful emission lines: O III, O II, S II, N II

Grain Depletions in H II Regions

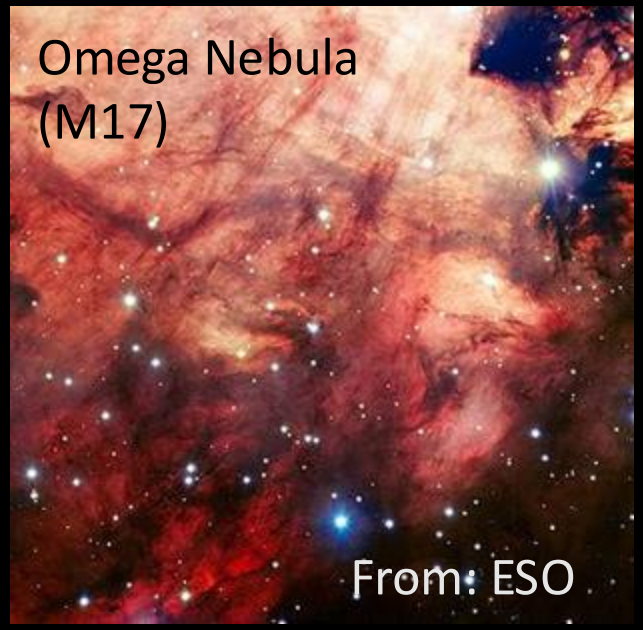
- Heavy element abundances are lower in the ISM than in solar abundances
- The degree of depletion varies between different elements.
- The collective depletion strengths of many heavy elements varied significantly across different sightlines



NGC 604 in Triangulum Galaxy



Orion Nebula (M42)



Heating & Cooling in the ISM

Electron temperature T_e = kinetic temperature of charged particles

- for H II regions $T_e \sim 10{,}000$ K

Dominant Heating: Hydrogen Photoionization

$$H_l + h\nu \rightleftharpoons H_u^+ + e^-$$

- dust also contributes through photoelectric heating

Dominant Cooling: Inelastic electron-ion collisional excitation

$$e^- + X_u \rightleftharpoons X_l + e^-$$

Calculating depleted abundances

Depletion

$$[X_{gas}/H] \equiv log\{N(X)/N(H)\} - log(X/H)_{\odot}$$

Jenkins (2009)
Depletion Model

$$[X_{\rm gas}/{\rm H}]_{F_*} = B_X + A_X(F_* - z_X)$$

Gas-phase Abundance

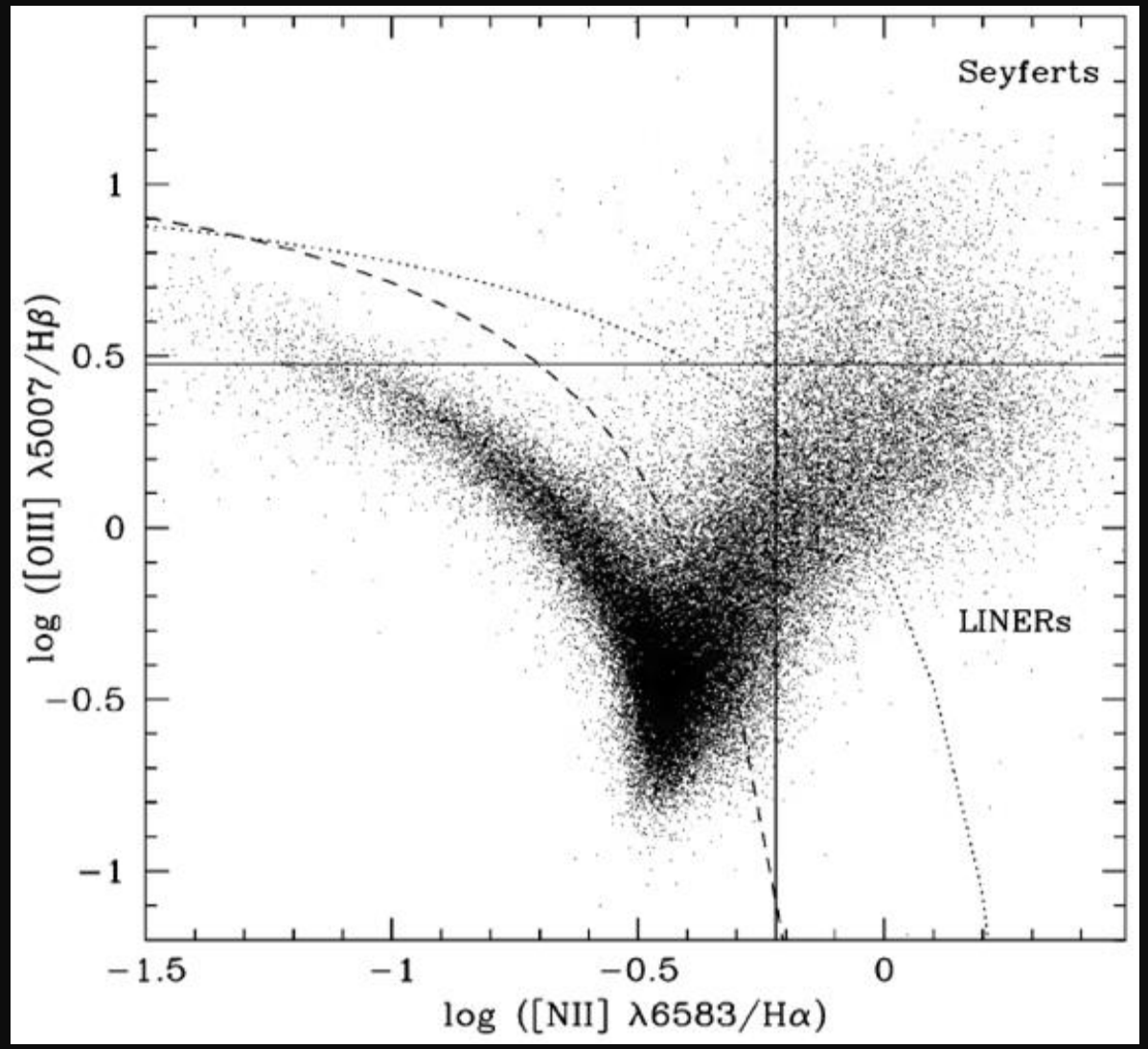
$$D_X = 10^{B_X + A_X(F_* - z_X)}$$

$$(X_{gas}/H)_{F_*} = (X/H)_{\odot} D_X$$

Depletion Strength

$$0 \leq F_* \leq 1$$

Baldwin, Philips, & Terlevich



Credit: Kauffmann (2003)

The Classic BPT diagrams:

[O III] 5007/Hβ vs. [N II] 6583/Hα

[O III] 5007/Hβ vs. [S II] 6716,6731/Hα

[O III] 5007/Hβ vs. [O I] 6300/Hα

Cloudy Model

- SED: starburst99 model with continuous star formation history
- Age: 4 million years
- Background radiation: cosmic ray background, with local universe at redshift z=0
- Hydrogen density: 14 cm^{-3}
- Equation of state using constant gas pressure
- Ionization parameter grid: $-4 \leq \log U \leq -2$
- Gas chemical composition:
  - Reference abundance: GASS
  - Metallicity scale factor: $Z = 0.05, 1.0, 3.16$
  - Depletion strength grid: $0 \leq F_* \leq 1$

```
table star "con_sf0" age=4.0e6 years
ionization parameter -4 vary
grid range from -4.0 to -2.0 with 0.5 dex
Background, z=0
Cosmic rays background
hden 1.15 log
constant gas pressure
abundances GASS
element helium scale 0.88000
element nitrogen scale 0.07070
element carbon scale 0.19028
#metals deplete
metals deplete jenkins 2009 fstar 1e-10 print
#grid list "fstar_grid_list.dat"
grains ISM 0.430
metals and grains 0.05000
iterate to convergence
stop temperature 100K
stop efrac -2
print line sort wavelength range 1500A to 10000A
save grid ".grd"
save overview ".ovr" last #separate
save continuum ".con" units microns last #separate
save cooling last ".col" last
save line list ".line" "LineList.dat" column last #separate
#save grain abundances ".grain" last #separate
#print last iteration
```

Cloudy Model

- SED: starburst99 model with continuous star formation history
- Age: 4 million years
- B
- H
- E
- Ion
- Gas chemical composition:
  - Reference abundance: GASS
  - Metallicity scale factor: Z = 0.05, 1.0, 3.16
  - Depletion strength grid: $0 \leq F_* \leq 1$

New Lodders+25 abundances in cloudy/docs/abundances/ !!!

```
table star "con_sf0" age=4.0e6 years
ionization parameter -4 vary
grid range from -4.0 to -2.0 with 0.5 dex
Background, z=0
Cosmic rays background
hden 1.15 log
constant gas pressure
abundances GASS
stop
print line sort wavelength range 1500A to 10000A
save grid ".grd"
save overview ".ovr" last #separate
save continuum ".con" units microns last #separate
save cooling last ".col" last
save line list ".line" "LineList.dat" column last #separate
#save grain abundances ".grain" last #separate
#print last iteration
```

Cloudy output files

```
                                Cloudy (master, d1f6531, modified)
                                        www.nublado.org

                                     PRNG seed: 0xda3a31a80da0bba4

                  ************************************13Jun01*****************************************
                  *                                                                                  *
                  * table star "con_sf3.mod" age=4.0e6 years                                         *
                  * #<< con_sf3      model    3 read.       Age =    4000000.00                >>> *
                  * #<< FINAL:     Age =    4000000.00                                            >>> *
                  * ionization parameter -4 vary                                                     *
                  * grid range from -4.0 to -2.0 with 0.5 dex                                        *
                  * Background, z=0                                                                  *
                  * Cosmic rays background                                                           *
                  * hden 1.15 log                                                                    *
                  * constant gas pressure                                                            *
                  * #abundances "ISM-HD20.abn"                                                       *
                  * abundances GASS                                                                  *
                  * element helium scale 1.14787                                                     *
                  * element nitrogen scale 0.35927                                                   *
                  * element carbon scale 0.96698                                                     *
                  * #metals deplete                                                                  *
                  * metals deplete jenkins 2009 fstar 0.5 print                                      *

 Jenkins 2009, print set, found Fstar = 5.000e-01 limit = 1.000e+38

 GetJenkins09: report of range of depletion scale factors follows:
 Fstar  HYDR        HELI        LITH        BERY        BORO        CARB        NITR        OXYG        FLUO        NEON        SODI        MAGN
0.000   1.000e+00   1.000e+00   5.675e-01   1.000e+00   4.989e+00   7.729e-01   7.780e-01   9.762e-01   1.000e+00   1.000e+00   8.730e-04   5.363e-01
0.100   1.000e+00   1.000e+00   4.369e-01   1.000e+00   4.103e+00   7.551e-01   7.780e-01   9.269e-01   1.000e+00   1.000e+00   1.406e-03   4.263e-01
0.200   1.000e+00   1.000e+00   3.364e-01   1.000e+00   3.374e+00   7.377e-01   7.780e-01   8.801e-01   1.000e+00   1.000e+00   2.266e-03   3.388e-01
0.300   1.000e+00   1.000e+00   2.589e-01   1.000e+00   2.775e+00   7.208e-01   7.780e-01   8.357e-01   1.000e+00   1.000e+00   3.650e-03   2.693e-01
0.400   1.000e+00   1.000e+00   1.993e-01   1.000e+00   2.282e+00   7.042e-01   7.780e-01   7.935e-01   1.000e+00   1.000e+00   5.880e-03   2.141e-01
0.500   1.000e+00   1.000e+00   1.535e-01   1.000e+00   1.877e+00   6.880e-01   7.780e-01   7.534e-01   1.000e+00   1.000e+00   9.473e-03   1.702e-01
0.600   1.000e+00   1.000e+00   1.181e-01   1.000e+00   1.544e+00   6.722e-01   7.780e-01   7.154e-01   1.000e+00   1.000e+00   1.526e-02   1.353e-01
0.700   1.000e+00   1.000e+00   9.095e-02   1.000e+00   1.270e+00   6.568e-01   7.780e-01   6.793e-01   1.000e+00   1.000e+00   2.459e-02   1.075e-01
0.800   1.000e+00   1.000e+00   7.002e-02   1.000e+00   1.044e+00   6.417e-01   7.780e-01   6.450e-01   1.000e+00   1.000e+00   3.961e-02   8.547e-02
0.900   1.000e+00   1.000e+00   5.390e-02   1.000e+00   8.588e-01   6.269e-01   7.780e-01   6.124e-01   1.000e+00   1.000e+00   6.381e-02   6.794e-02
1.000   1.000e+00   1.000e+00   4.150e-02   1.000e+00   7.063e-01   6.125e-01   7.780e-01   5.815e-01   1.000e+00   1.000e+00   1.028e-01   5.400e-02
```

.ovr

#depth	Te	Htot	hden	eden	2H_2/H	HI	HII	HeI	HeII	HeIII	CO/C	C1	C2	C3	C4	O1	O2	O3	O4	O5	O6	H2O/O	AV(point)	AV(extend)	Tau912
1.73025e+14	8.6691e+03	5.362e-22	1.4100e+01	1.4598e+01	1.6163e-10	4.8114e-02	9.5189e-01	1.6622e-01	8.3373e-01	4.9161e-05	1.5569e-13	8.2043e-03	7.8500e-01
1.03815e+15	8.6642e+03	5.366e-22	1.4132e+01	1.4606e+01	1.6207e-10	4.8099e-02	9.5190e-01	1.6641e-01	8.3354e-01	4.9074e-05	1.5554e-13	8.1946e-03	7.8525e-01
4.49865e+15	8.6496e+03	5.354e-22	1.4156e+01	1.4632e+01	1.6390e-10	4.8215e-02	9.5179e-01	1.6730e-01	8.3266e-01	4.8680e-05	1.5685e-13	8.2332e-03	7.8629e-01
1.83406e+16	8.6154e+03	5.315e-22	1.4218e+01	1.4677e+01	1.7112e-10	4.8970e-02	9.5103e-01	1.7070e-01	8.2925e-01	4.7239e-05	1.6376e-13	8.3713e-03	7.9018e-01
4.38099e+16	8.4821e+03	5.230e-22	1.4462e+01	1.4914e+01	1.8445e-10	4.9177e-02	9.5082e-01	1.7621e-01	8.2375e-01	4.4945e-05	1.6872e-13	8.6044e-03	7.9648e-01
7.69200e+16	8.3805e+03	5.151e-22	1.4649e+01	1.5077e+01	2.0411e-10	5.0650e-02	9.4935e-01	1.8392e-01	8.1604e-01	4.2111e-05	1.8384e-13	8.9066e-03	8.0456e-01
1.19963e+17	8.3082e+03	5.070e-22	1.4790e+01	1.5154e+01	2.3373e-10	5.3693e-02	9.4631e-01	1.9487e-01	8.0509e-01	3.8699e-05	2.1373e-13	9.2999e-03	8.1497e-01
1.74062e+17	8.2727e+03	5.009e-22	1.4903e+01	1.5169e+01	2.8043e-10	5.9148e-02	9.4085e-01	2.1083e-01	7.8914e-01	3.4672e-05	2.7167e-13	9.8338e-03	8.2841e-01
2.30652e+17	8.2777e+03	4.964e-22	1.4972e+01	1.5097e+01	3.4384e-10	6.6701e-02	9.3330e-01	2.2966e-01	7.7030e-01	3.1023e-05	3.6356e-13	1.0401e-02	8.4223e-01
2.81144e+17	8.3258e+03	4.934e-22	1.4957e+01	1.4928e+01	4.2283e-10	7.6184e-02	9.2382e-01	2.4997e-01	7.5000e-01	2.7976e-05	4.9894e-13	1.0917e-02	8.5504e-01

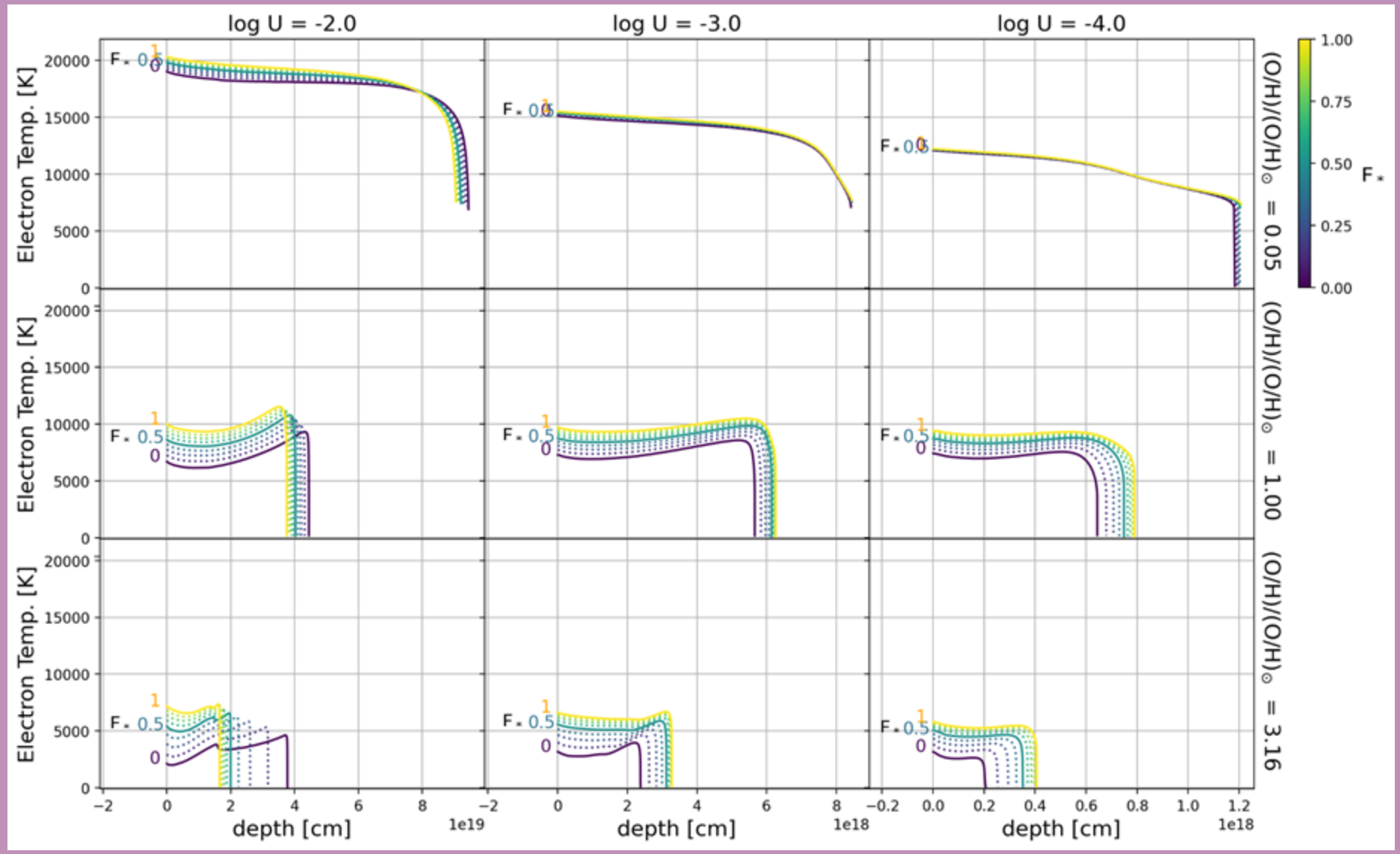
.con

#Cont	nu	incident	trans	DiffOut	net trans	reflc	total	reflin	outlin	lineID	cont	nLine
2.99293e+07	1.057e-14	8.203e-15	3.641e-12	3.649e-12	2.827e-12	6.476e-12	0.000e+00	0.000e+00	0.00
2.98297e+07	1.068e-14	8.299e-15	3.656e-12	3.664e-12	2.841e-12	6.505e-12	0.000e+00	0.000e+00	0.00
2.97304e+07	1.079e-14	8.397e-15	3.670e-12	3.679e-12	2.856e-12	6.534e-12	0.000e+00	0.000e+00	0.00
2.96315e+07	1.089e-14	8.496e-15	3.685e-12	3.693e-12	2.870e-12	6.563e-12	0.000e+00	0.000e+00	0.00
2.95329e+07	1.100e-14	8.596e-15	3.699e-12	3.708e-12	2.884e-12	6.592e-12	0.000e+00	0.000e+00	0.00
2.94347e+07	1.111e-14	8.698e-15	3.714e-12	3.723e-12	2.899e-12	6.621e-12	0.000e+00	0.000e+00	0.00
2.93367e+07	1.123e-14	8.800e-15	3.729e-12	3.737e-12	2.913e-12	6.651e-12	0.000e+00	0.000e+00	0.00
2.92391e+07	1.134e-14	8.903e-15	3.743e-12	3.752e-12	2.928e-12	6.680e-12	0.000e+00	0.000e+00	0.00

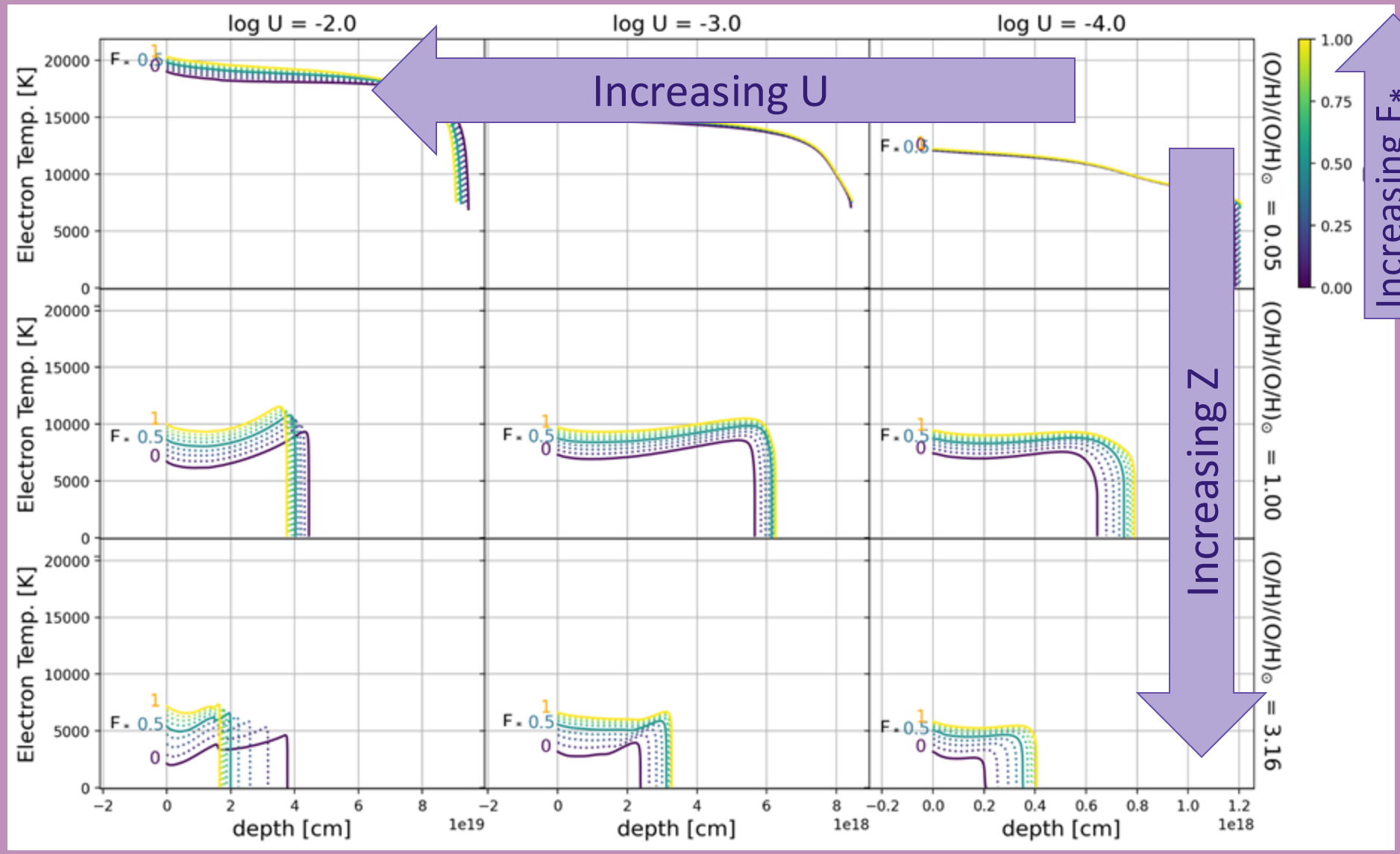
.col

#depth cm	Temp K	Htot erg/cm3/s	Ctot erg/cm3/s	Adve Ctot erg/cm3/s	cool fracs																	
1.73025e+14	8.6691e+03	5.3619e-22	5.3616e-22	0.0000e+00	O	1	0.0	0.2736005	ISrcolH	H	0.0	0.1594395	S	1	0.0	0.1403324	S	2	0.0	0.0812160	FF	c	0.0
1.03815e+15	8.6642e+03	5.3655e-22	5.3660e-22	0.0000e+00	O	1	0.0	0.2735254	ISrcolH	H	0.0	0.1589860	S	1	0.0	0.1404775	S	2	0.0	0.0813064	FF	c	0.0
4.49865e+15	8.6496e+03	5.3542e-22	5.3540e-22	0.0000e+00	O	1	0.0	0.2732207	ISrcolH	H	0.0	0.1576951	S	1	0.0	0.1410141	S	2	0.0	0.0814414	FF	c	0.0
1.83406e+16	8.6154e+03	5.3153e-22	5.3149e-22	0.0000e+00	O	1	0.0	0.2726785	ISrcolH	H	0.0	0.1536768	S	1	0.0	0.1427816	S	2	0.0	0.0814329	FF	c	0.0

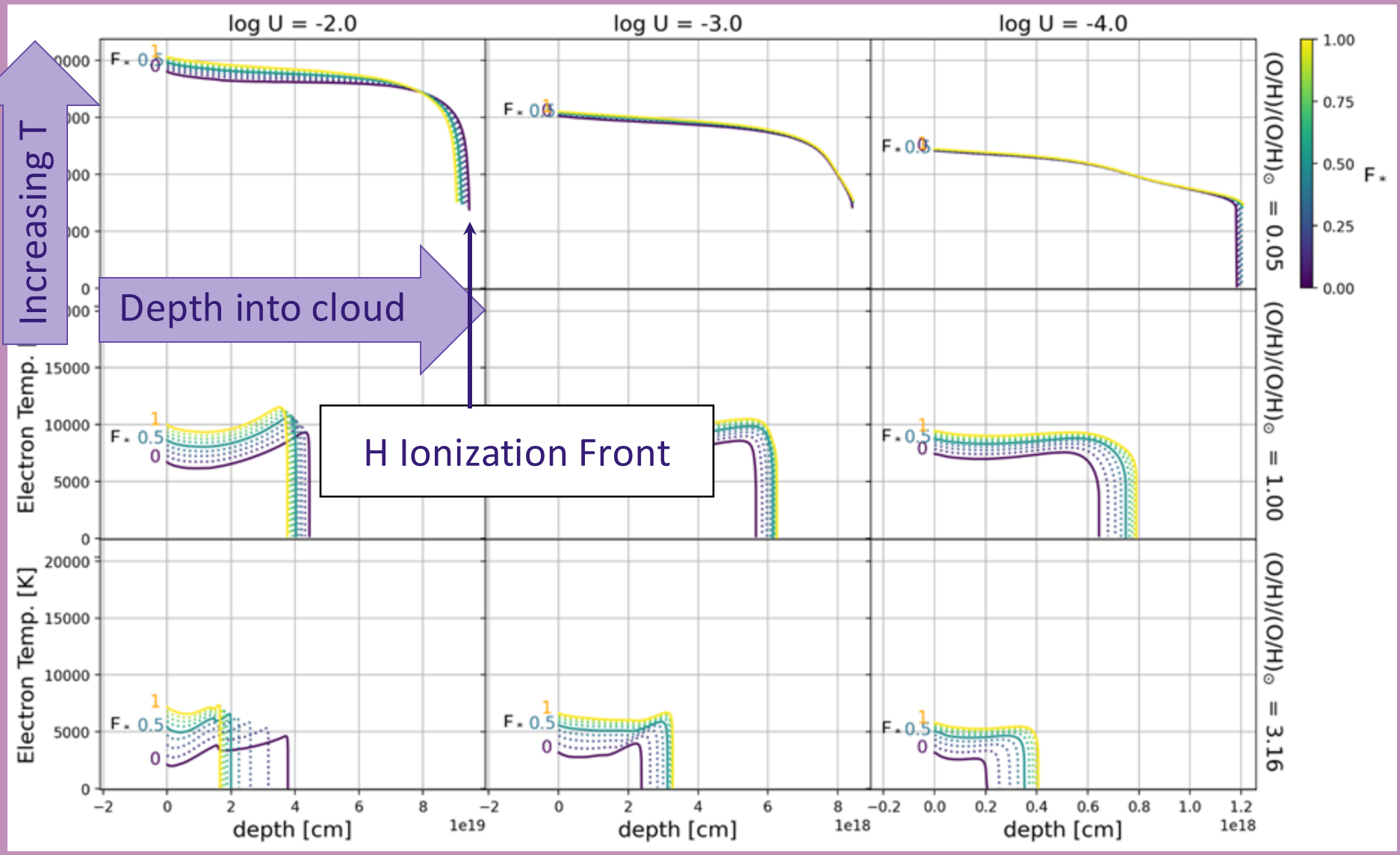
Temperature vs. F_*



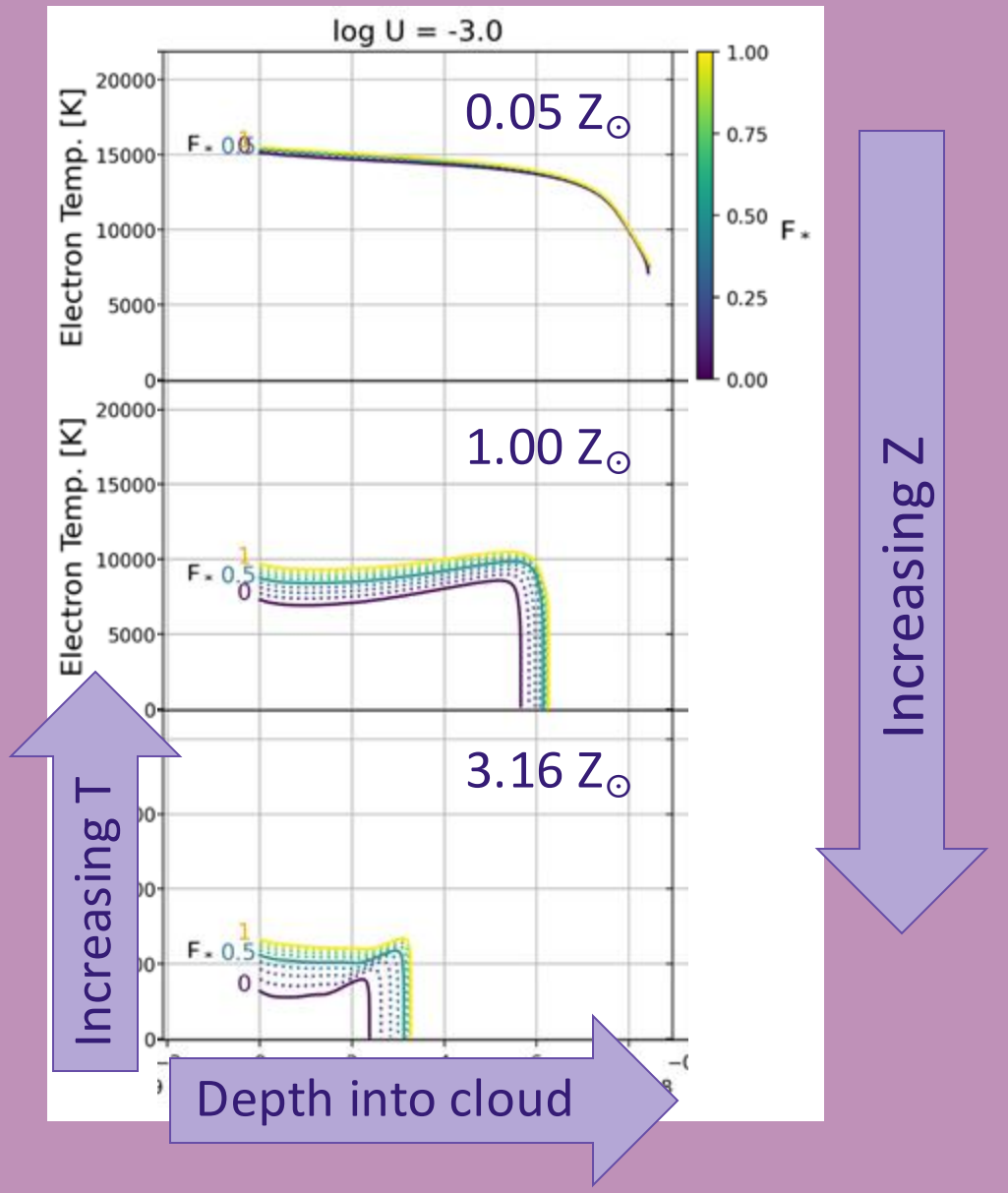
Temperature vs. F_*



Temperature vs. F_*



Temperature vs. F_*

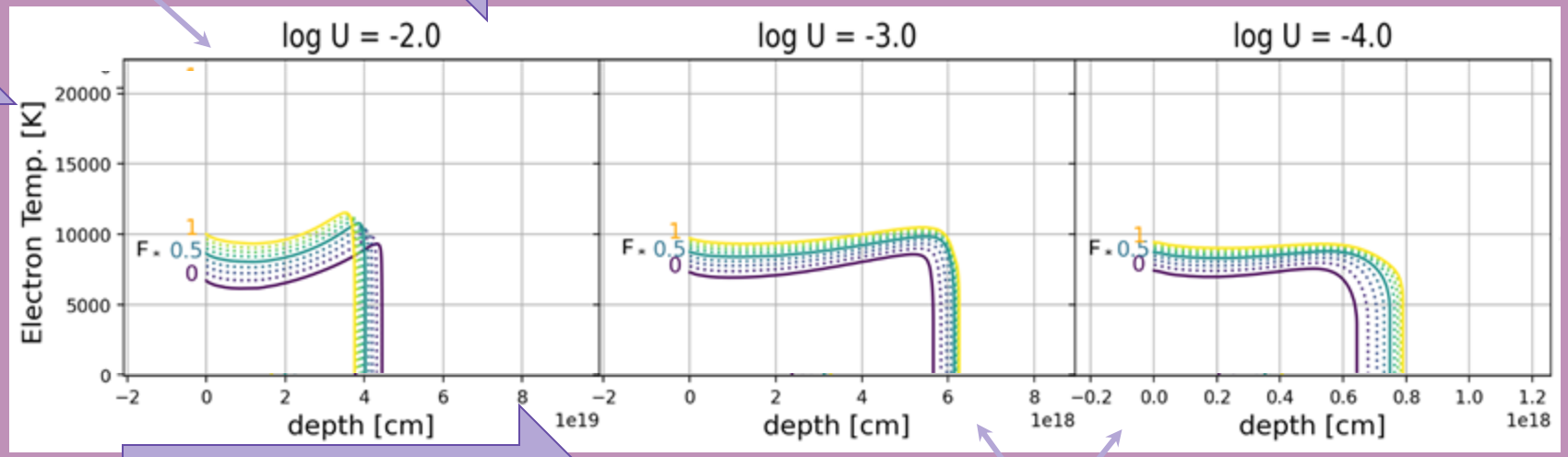


Temperature vs. F_*

Log $U \geq -2$:
Grains dominantly absorb ionizing photons

Increasing U

Increasing T



1.00 $Z_\odot$

Depth into cloud

Log $U < -2$: $L \propto \frac{U}{2.9 \times 10^{-10} T_e^{-0.77}}, \qquad T_e \leq 2.6 \times 10^4\ K$

Temperature vs. F_*

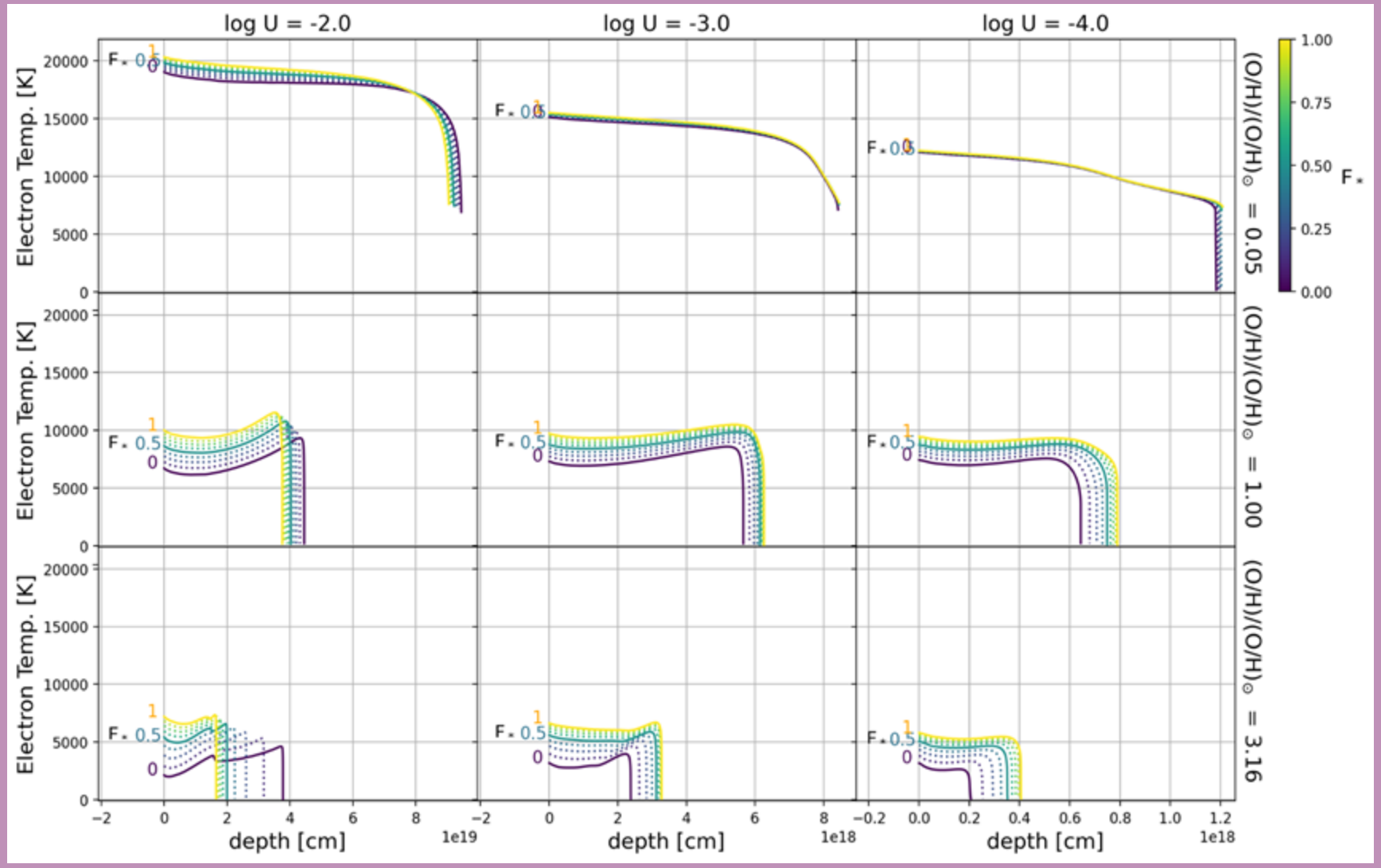
- Te increases with F*

- Log U >= -2:

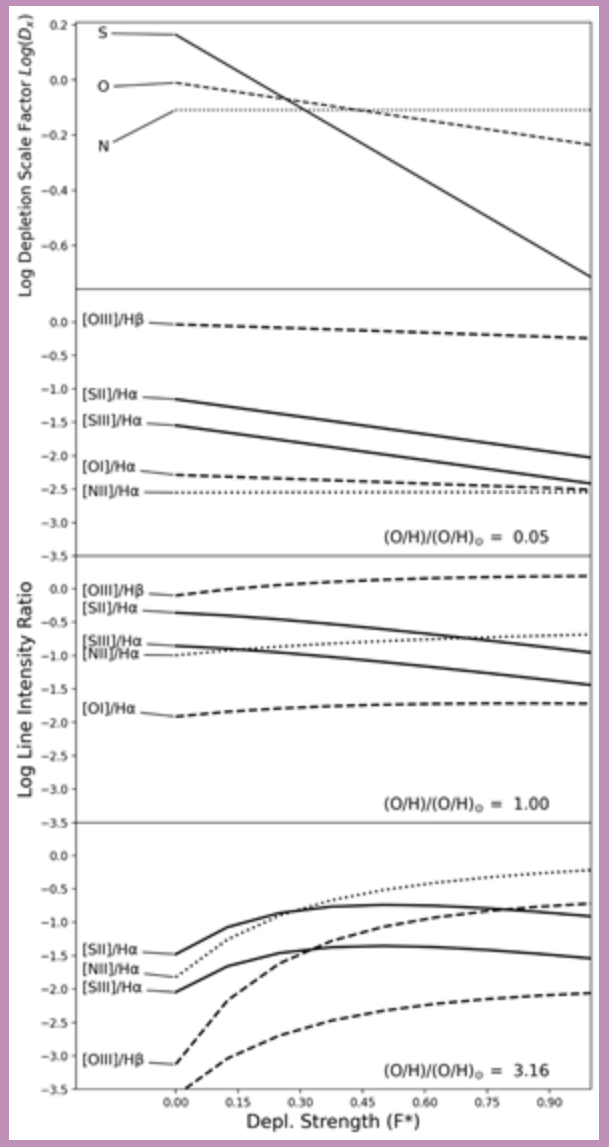
Ionized layer shrinks with increasing F*

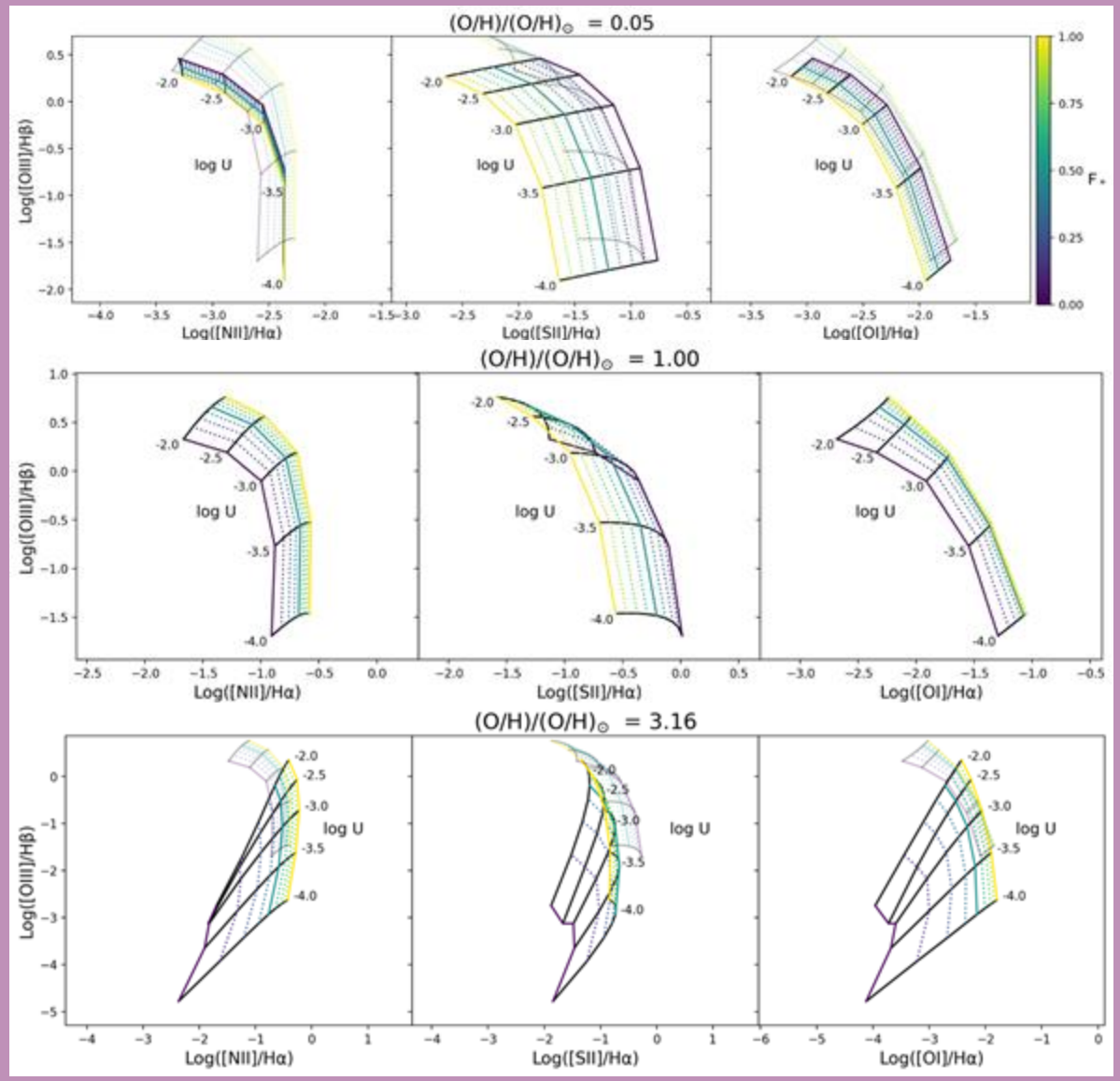
- Log U <-2:

Ionized layer expands with increasing F*



BPT Diagrams: emission line-ratio vs. F_*





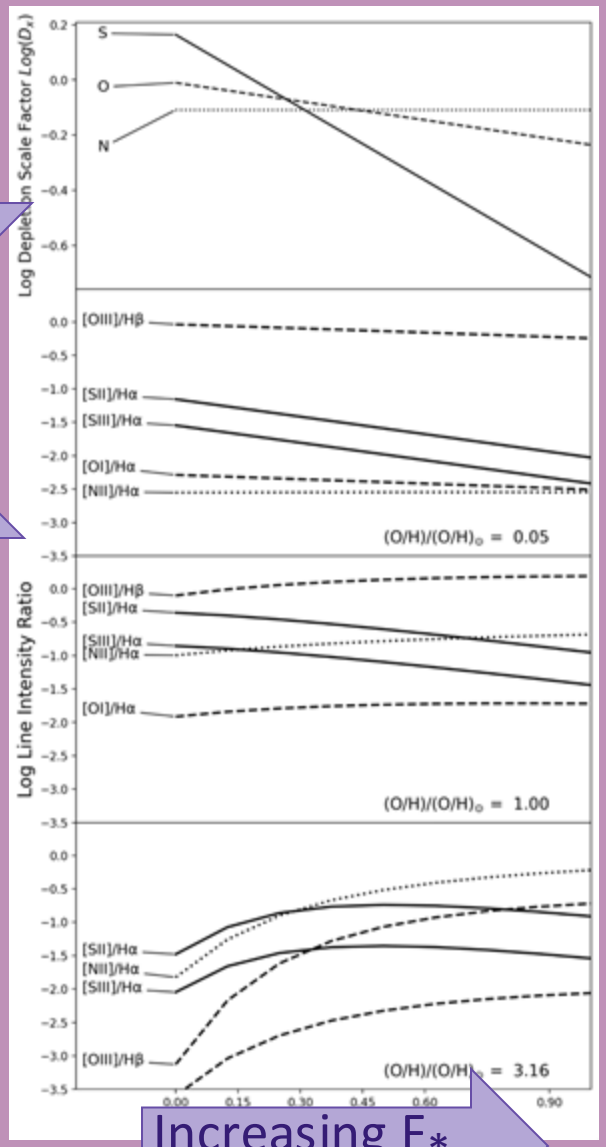
BPT Diagrams: emission line-ratio vs. F_*

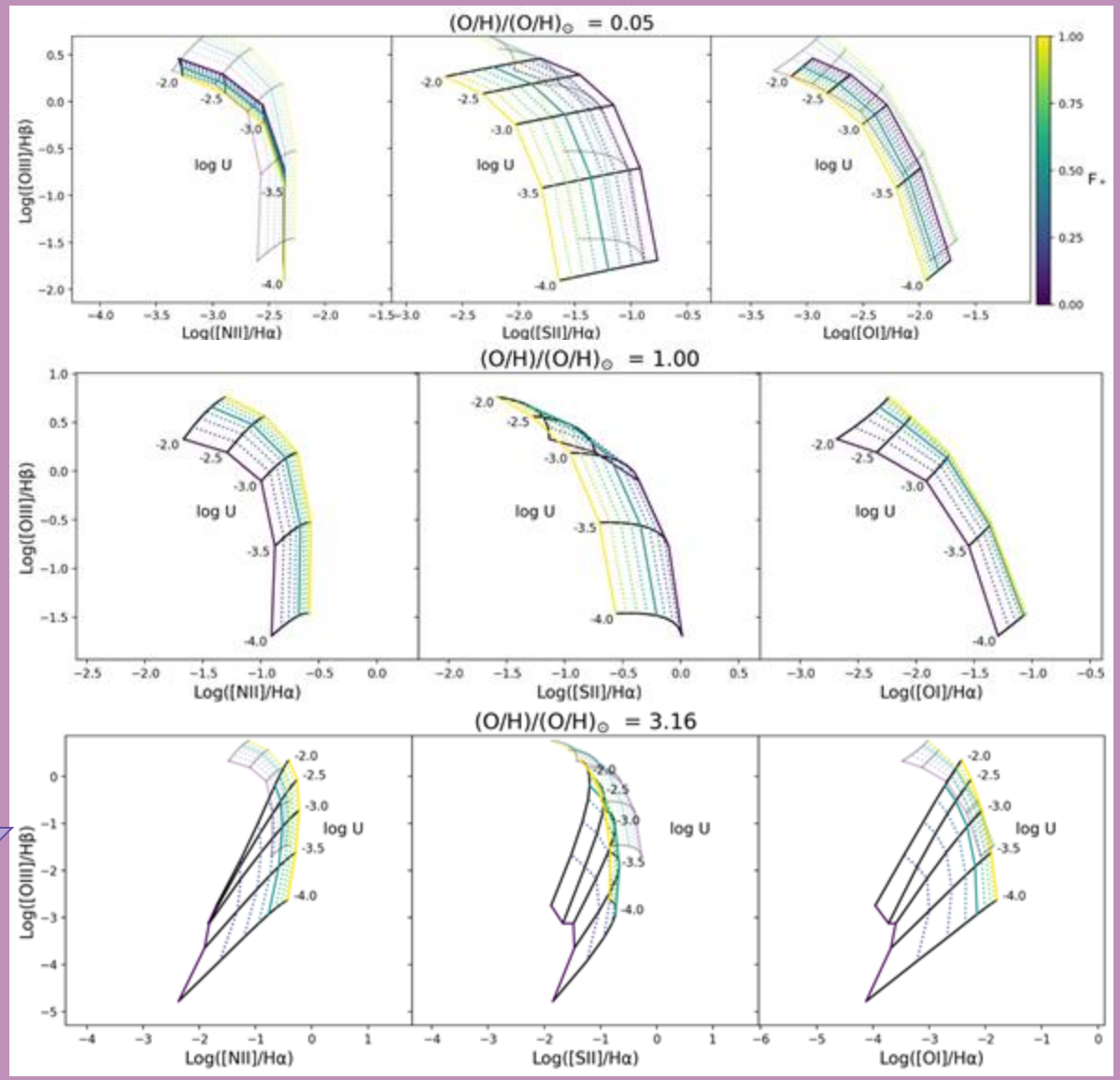
Amount Depleted

Line Intensity

Increasing Z

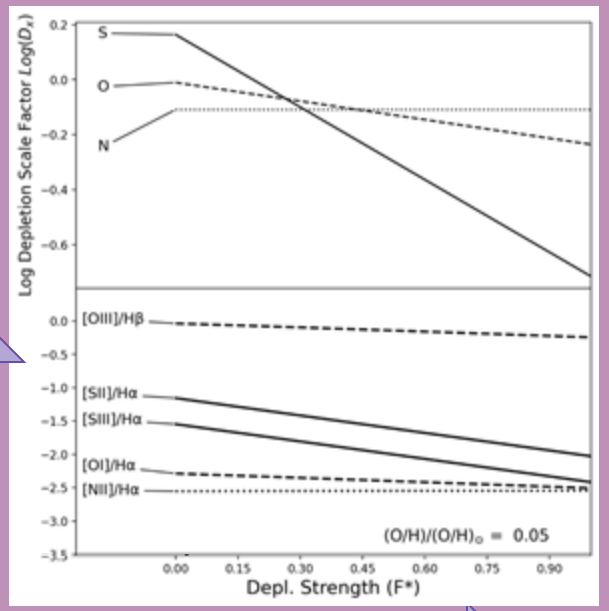
Increasing F_*



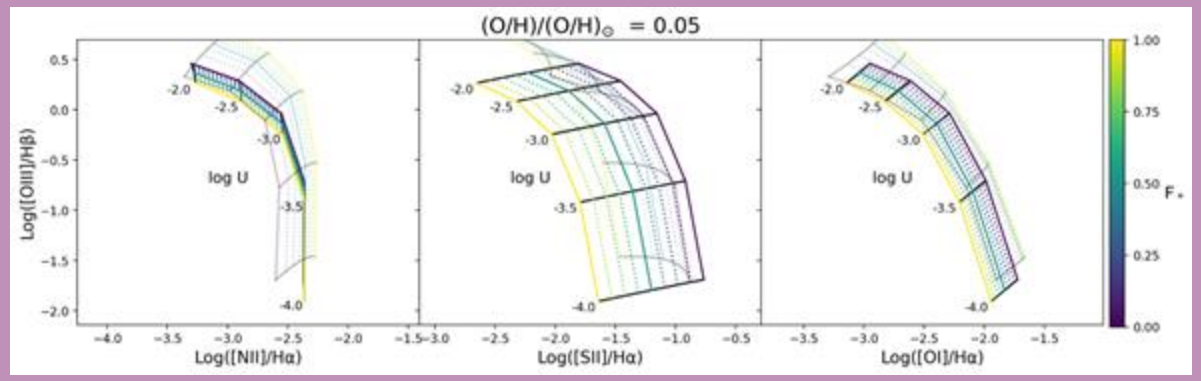


BPT Diagrams: emission line-ratio vs. F_*

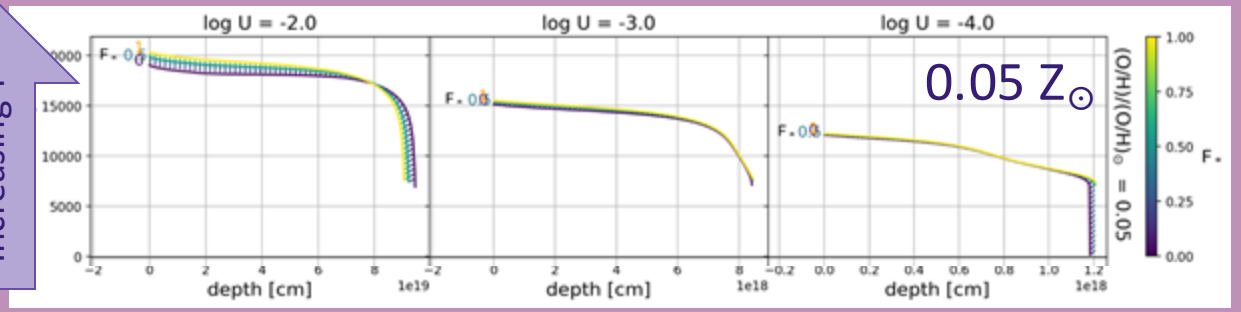
Line Intensity



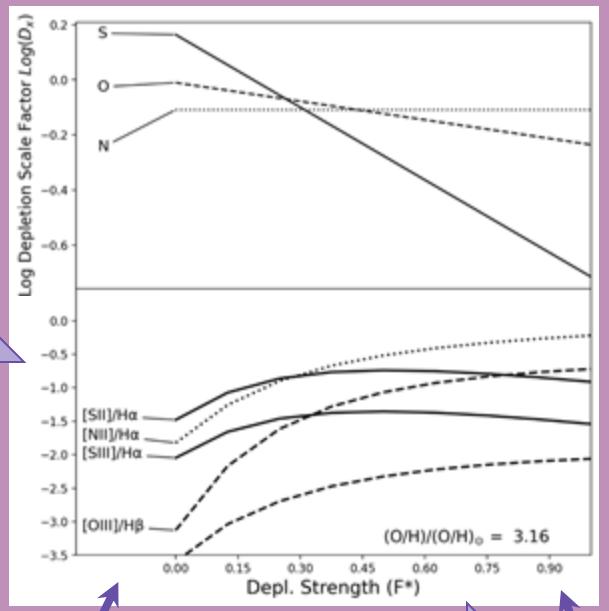
Increasing F_*



Increasing T

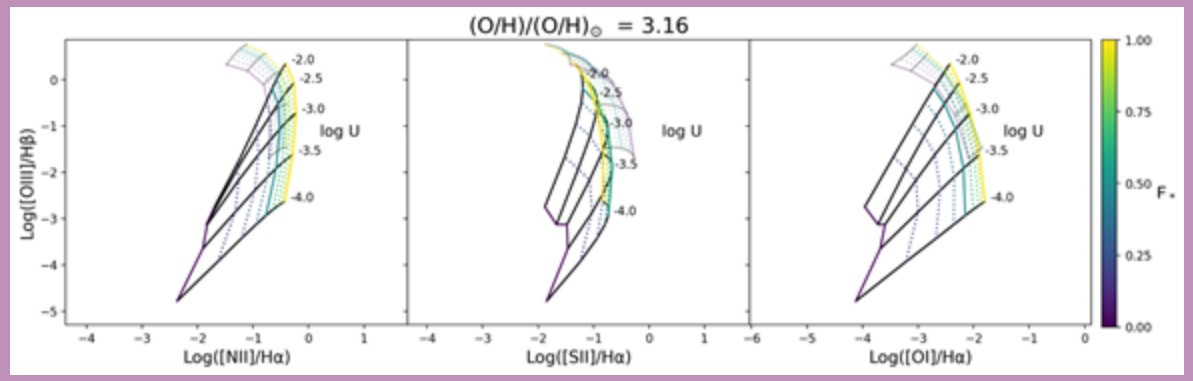


BPT Diagrams: emission line-ratio vs. F_*

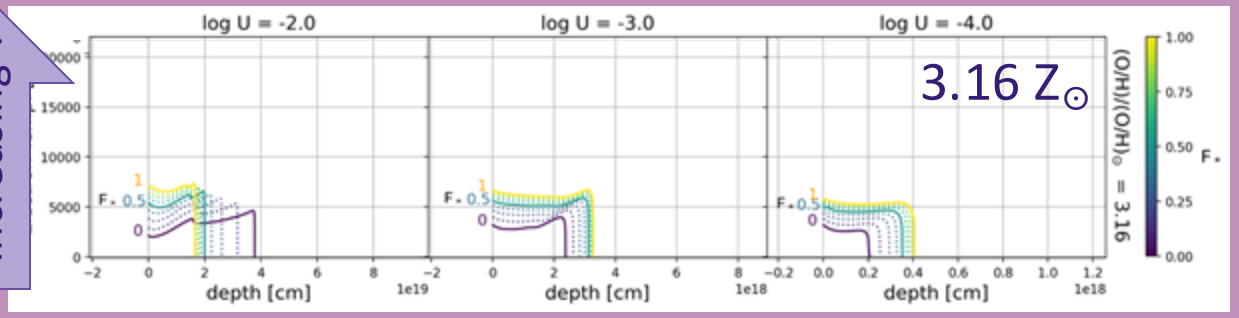


Line Intensity

Increasing F_*



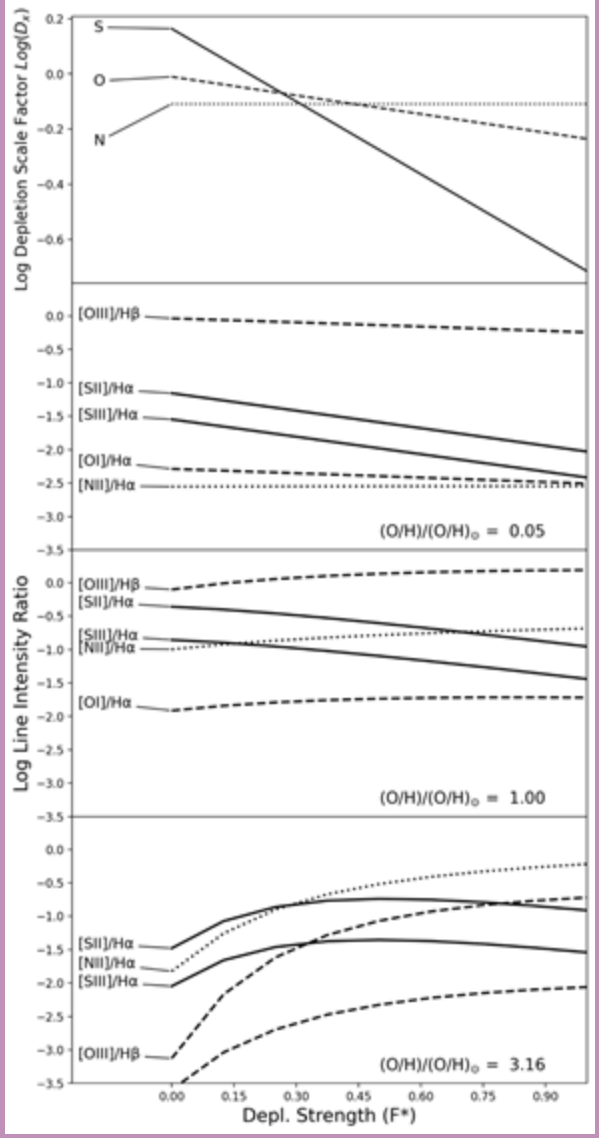
Increasing T



S cooling: 12%
O,N cooling: 1%

S cooling: 5%
O,N cooling: 17%

BPT Diagrams: emission line-ratio vs. F_*



Low Z:

- Line ratios dominated by changes in abundance
- Only Z needs to be constrained to constrain F_*.

High Z:

- Line ratios dominated by changes in temperature
- Z & U needs to be constrained to constrain F_*.
- Increasing F_* shifts dominant coolant.