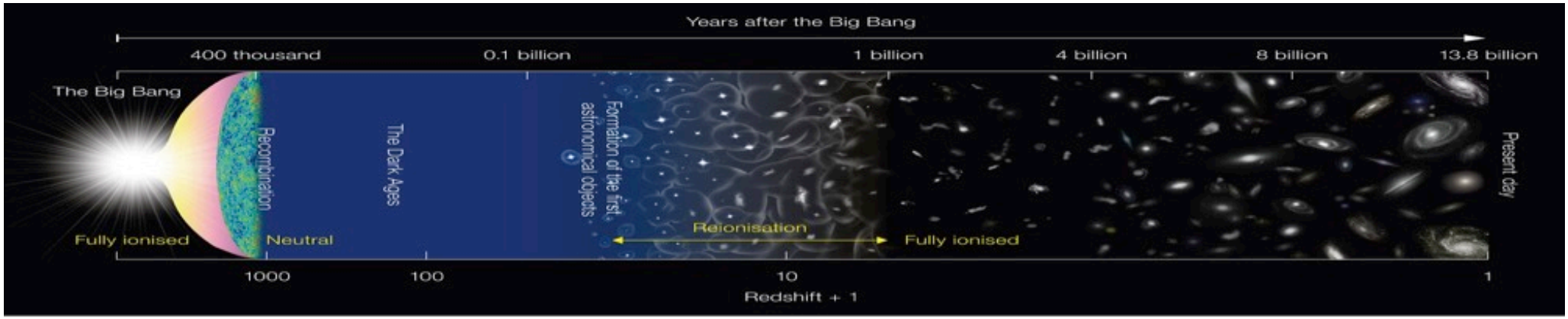
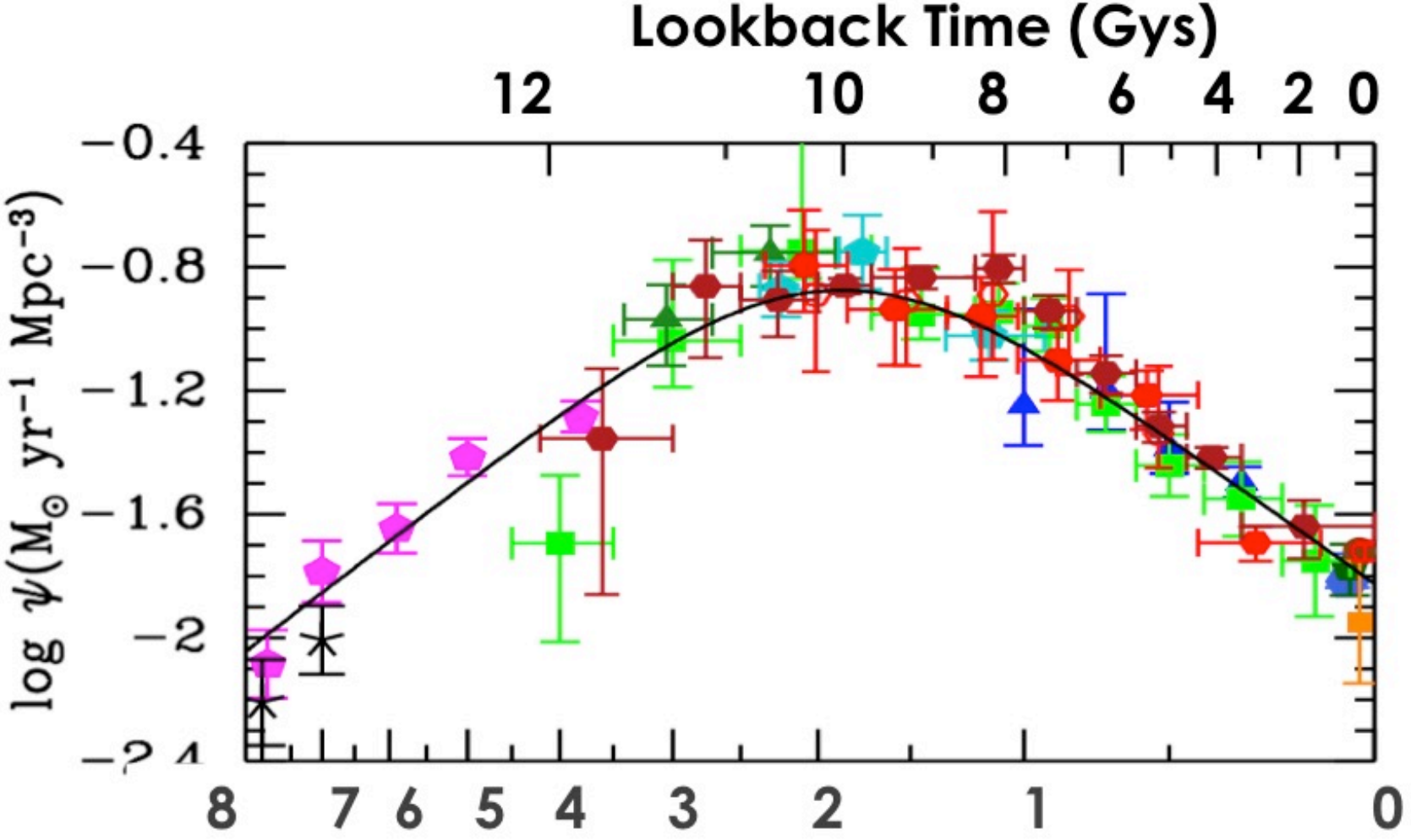
Turbulence in the Circumgalactic Medium

Evan Scannapieco (Arizona State)
Edward Buie (ASU), William Gray (U Mich.)

ES et al.



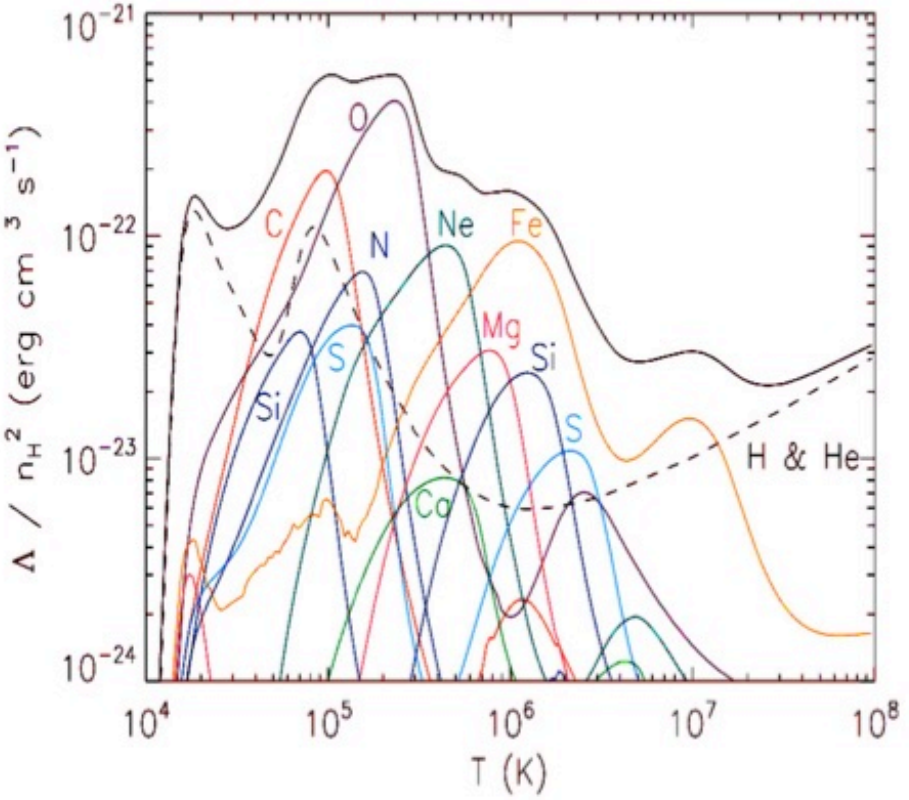


Madau & Dickenson (2014)

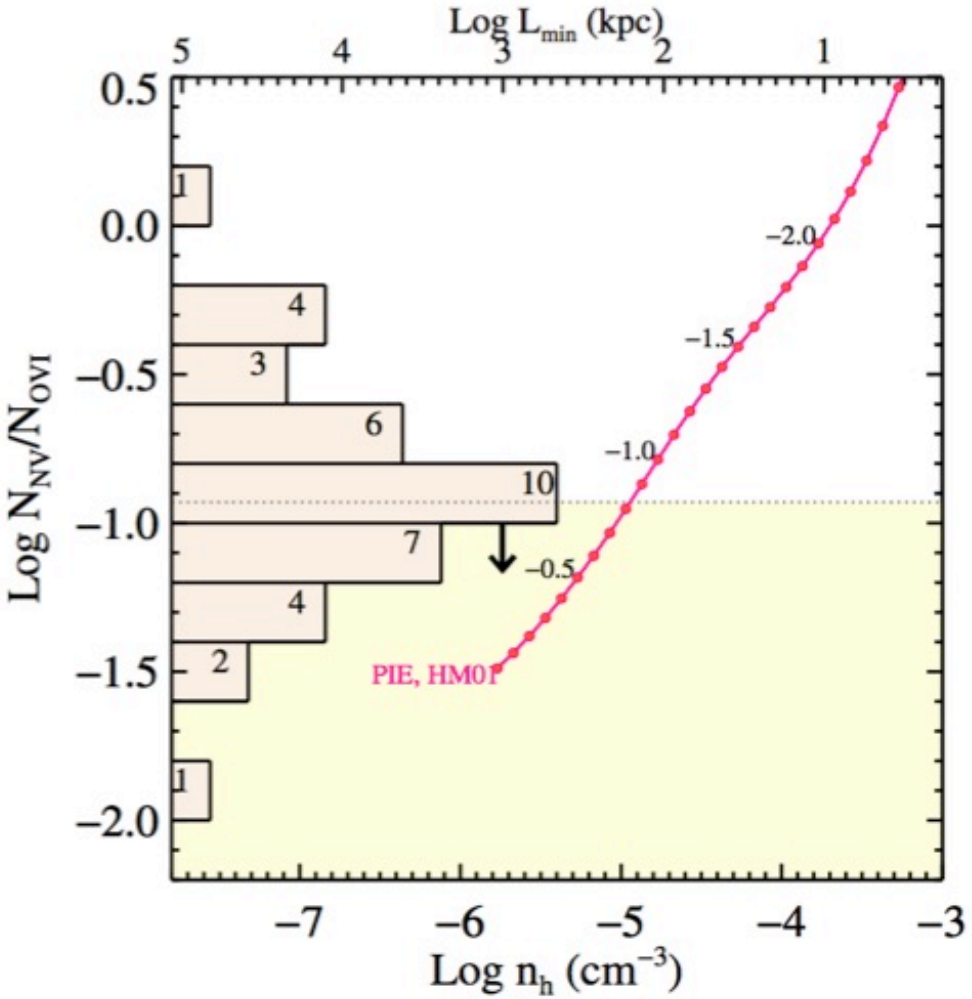
OVI & NV

NV 1242.80 77eV 98 eV

OVI 1030.91 77eV 138 eV



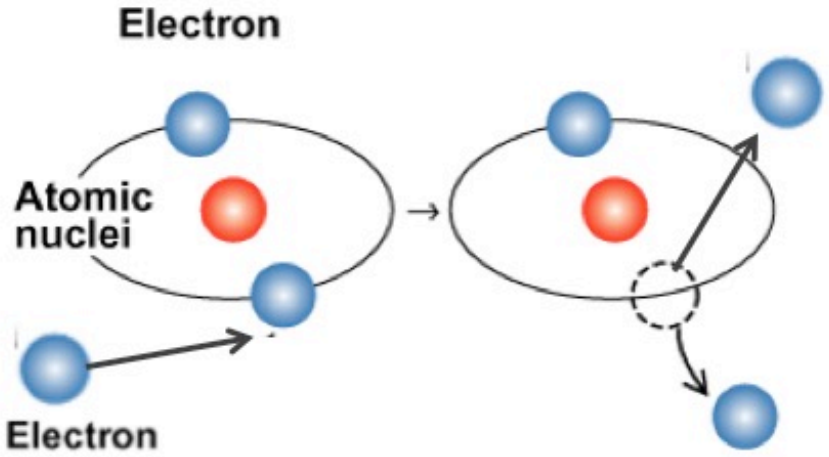
Wiersma, Schaye, & Smith (2009)



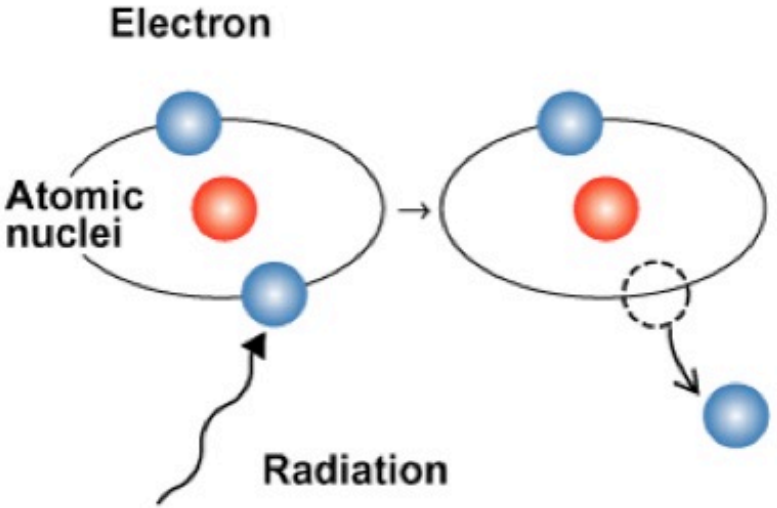
Werk et al (2017)

Ionization Balance

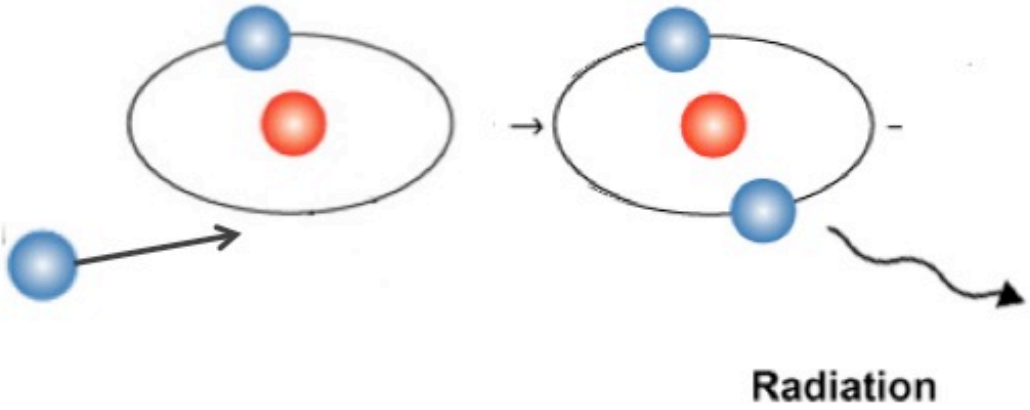
Collisional Ionization



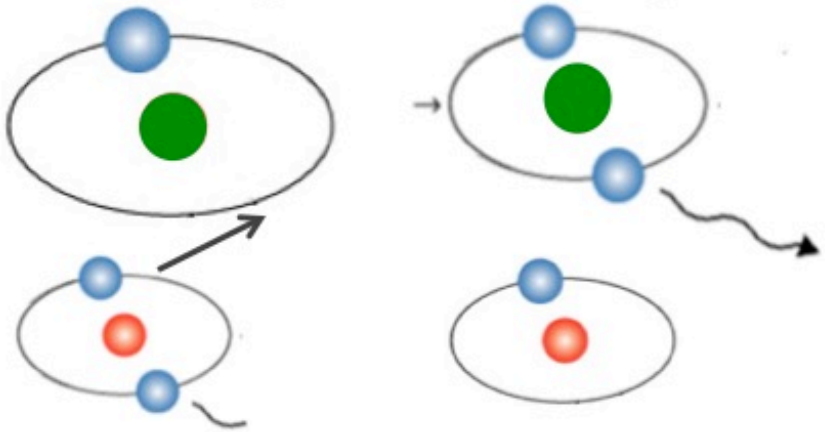
Photoionization



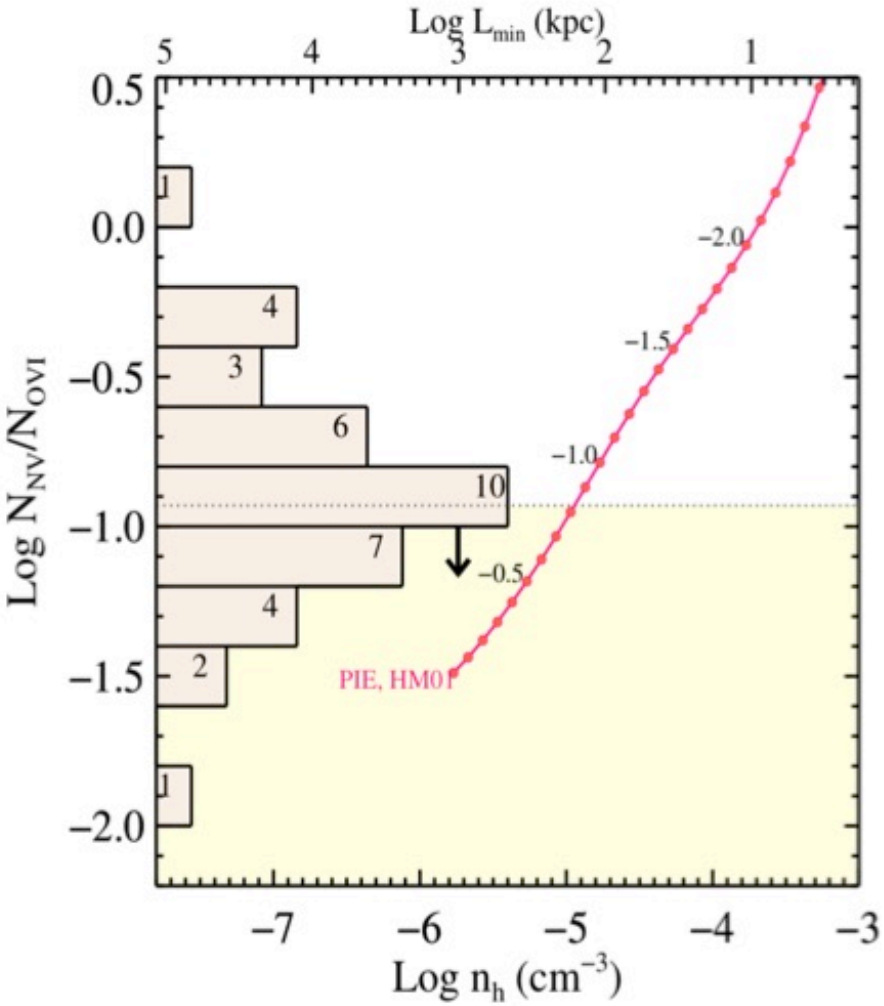
Recombination



Charge Exchange

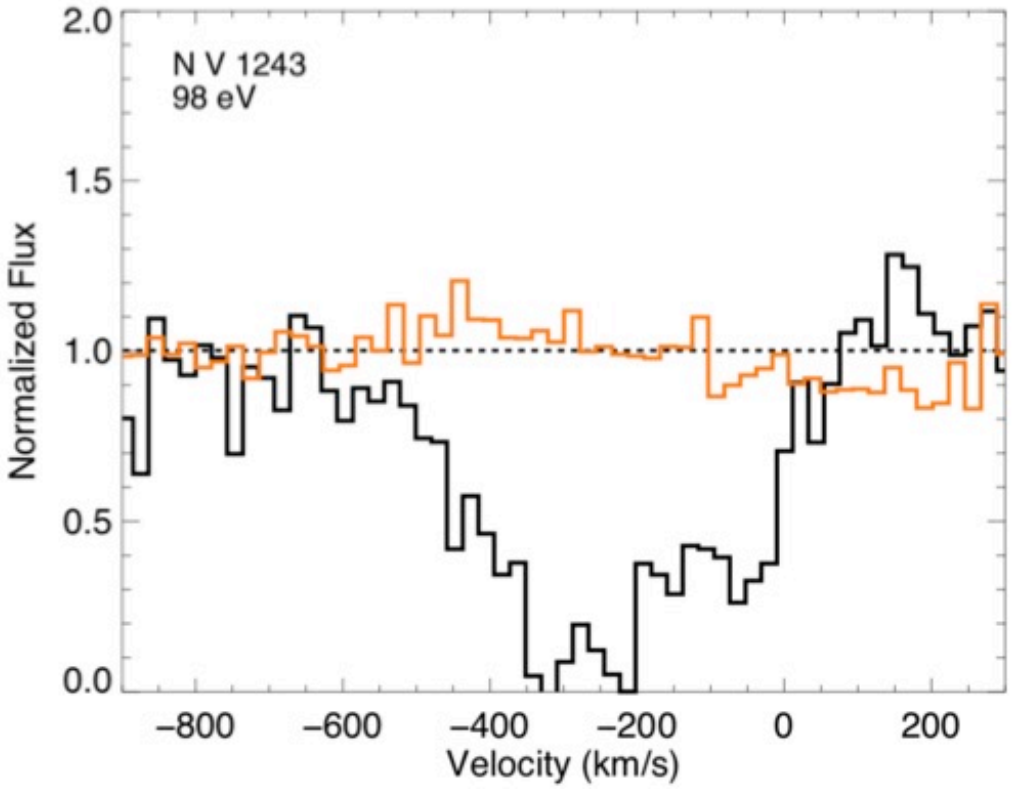


NV 1242.80 77eV 98 eV
OVI 1030.91 77eV 138 eV



$\log(N_{NV}/cm^2) < 14.25$

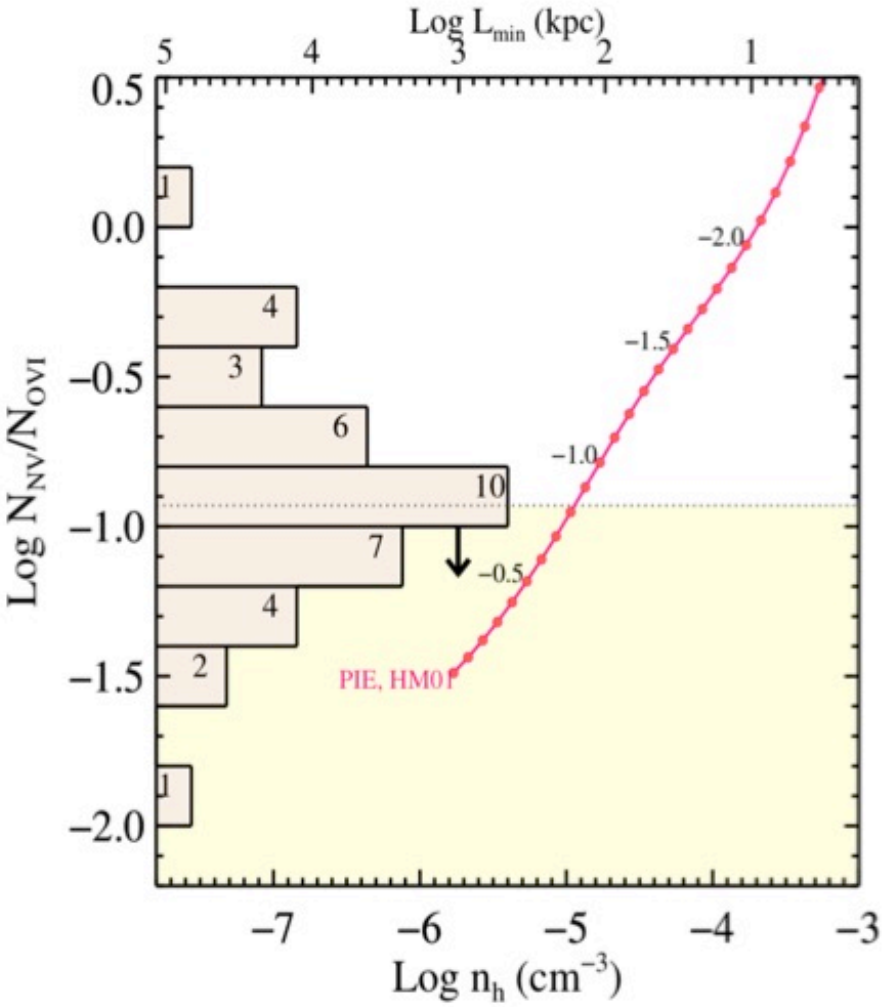
$\log(N_{OVI}/cm^2) = 15.35 \pm 0.05$



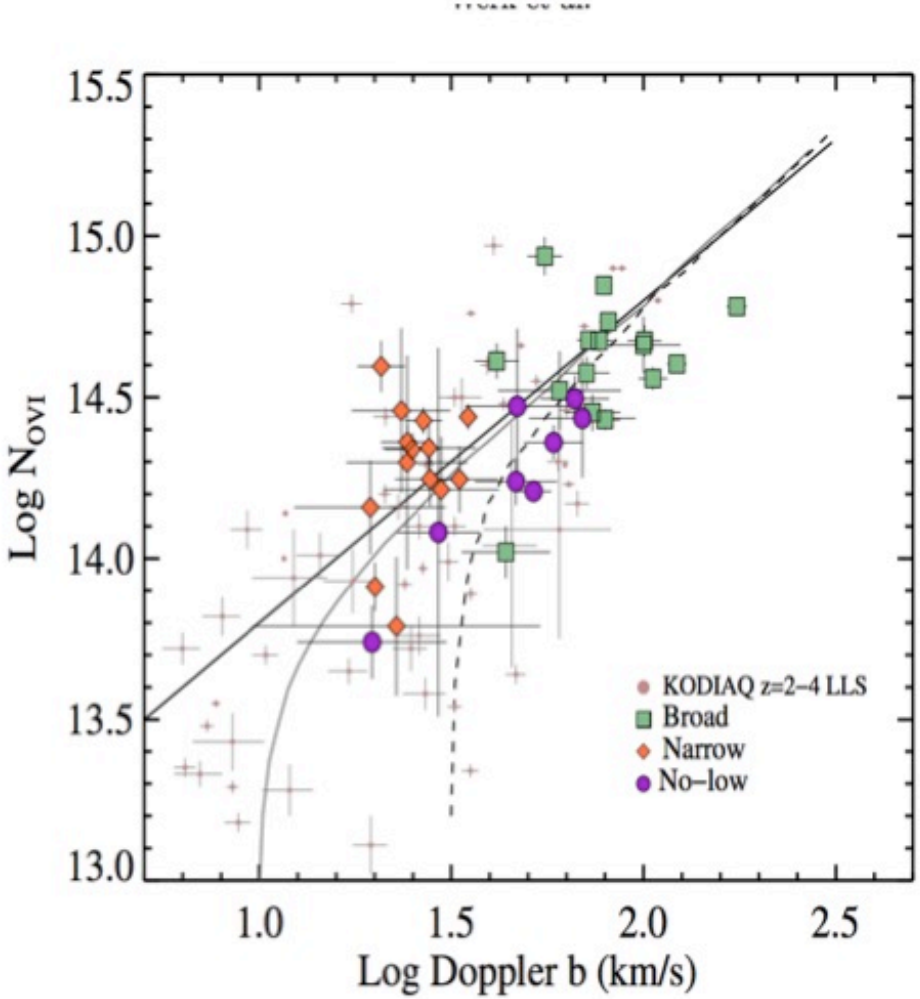
Werk et al. (2017)

Chisholm, Rigby, Bordoloi, & Bayliss (2017)

b-parameters Suggest Turbulence



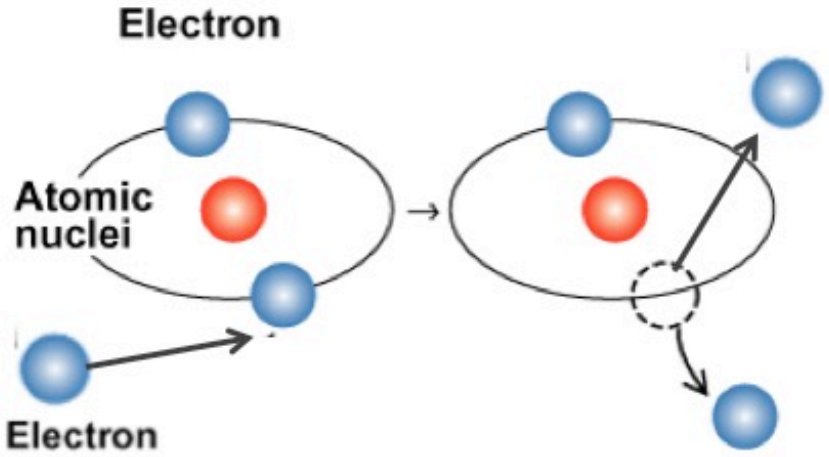
Large Doppler Parameters



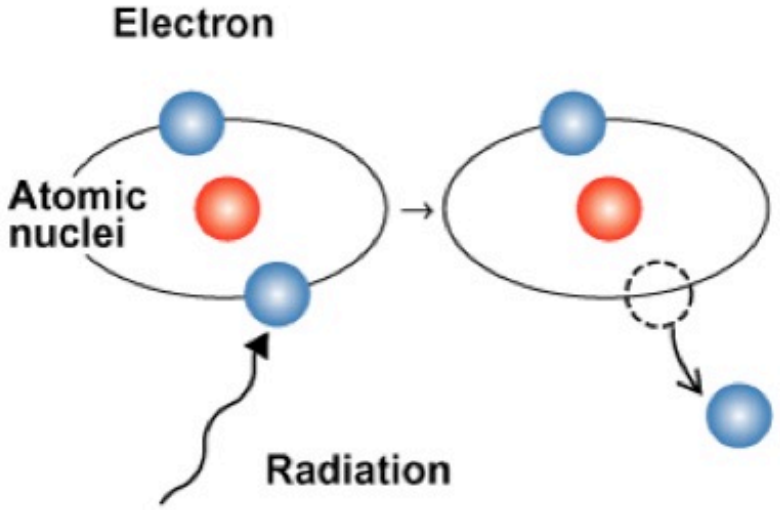
Werk et al. (2017)

Reaction Timescales

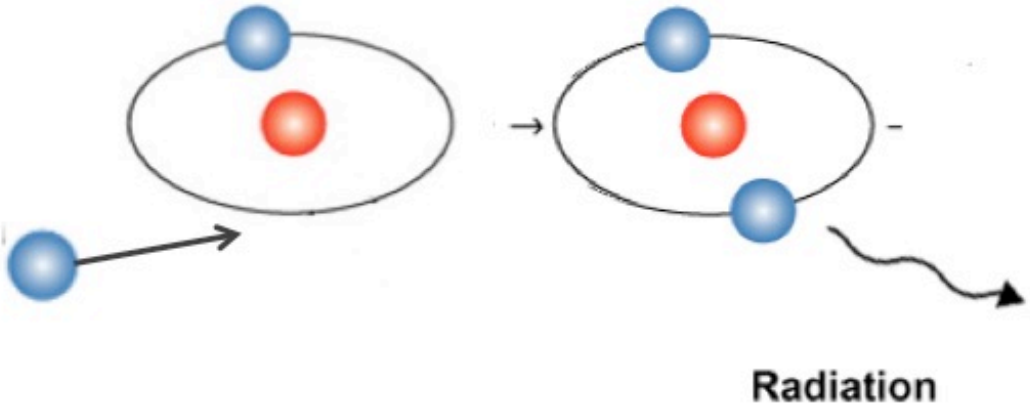
Collisional Ionization



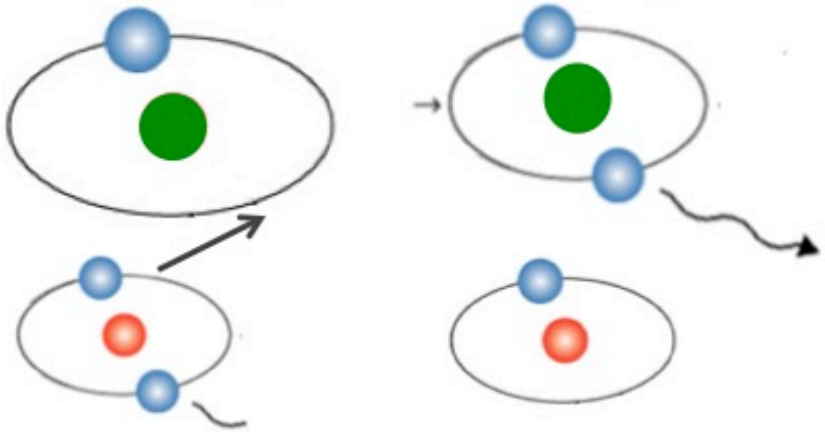
Photoionization



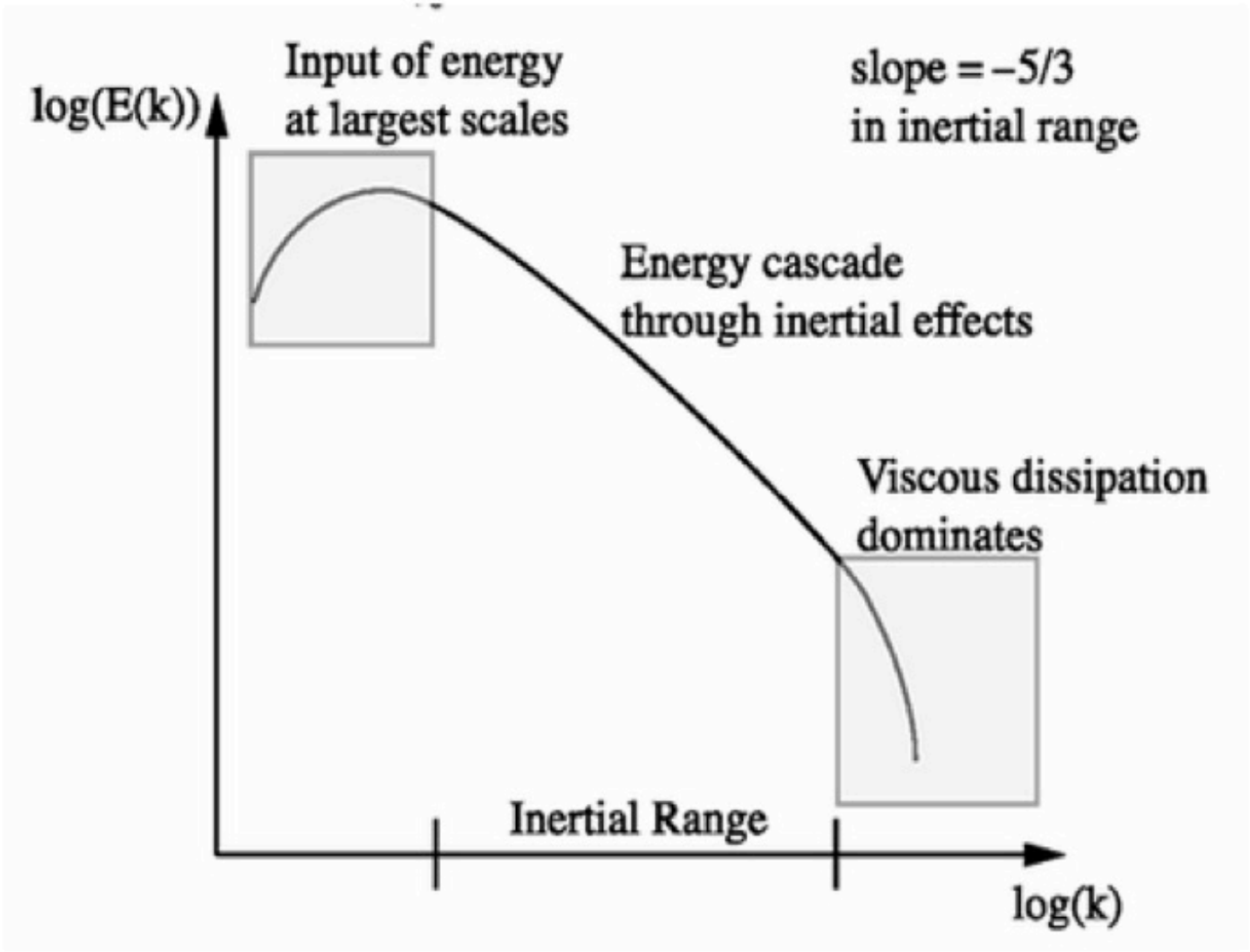
Recombination



Charge Exchange

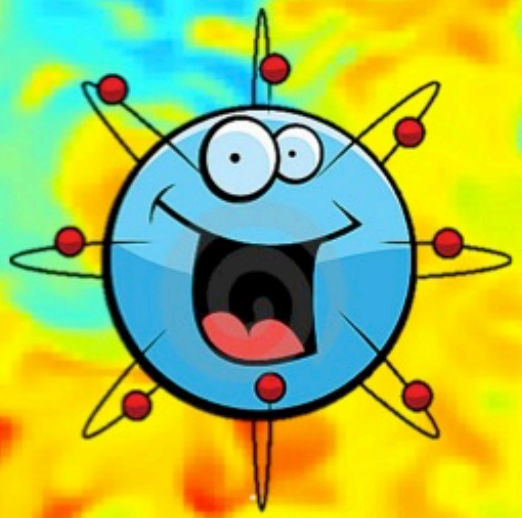


Mixing is Driven by (Unresolved) Turbulence



Eddy turnover time $t_{Eddy} = L/V_t$

Turbulent Ionization



MAIHEM

Models of Agitated and Illuminated Hindering and Emitting Media

12 Elements (65 Species, 240 reactions)

H through H^{+}
He through He^{2+}
C through C^{5+}
N through N^{6+}
O through O^{7+}
Ne through Ne^{9+}
Na through Na^{2+}
Mg through Mg^{3+}
Si through Si^{5+}
S through S^{4+}
Ca through Ca^{4+}
Fe through Fe^{3+}

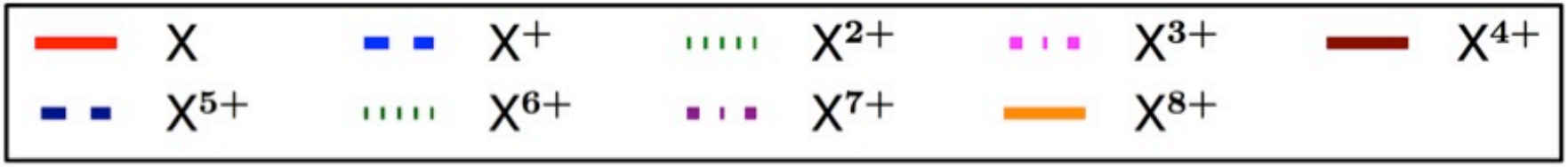
Built on the FLASH CODE

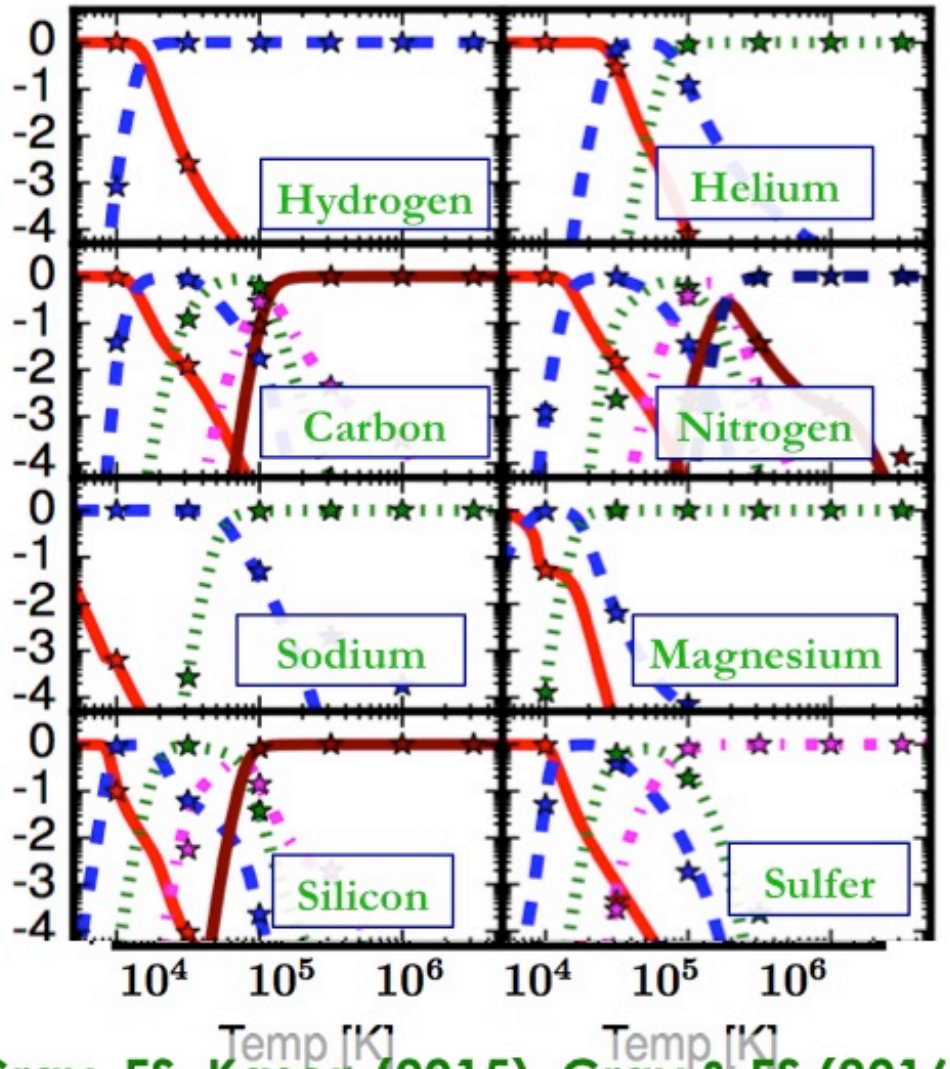
An implicit Runge-Kutta Method (4^{th} order) evolves the species, with subcyling as needed

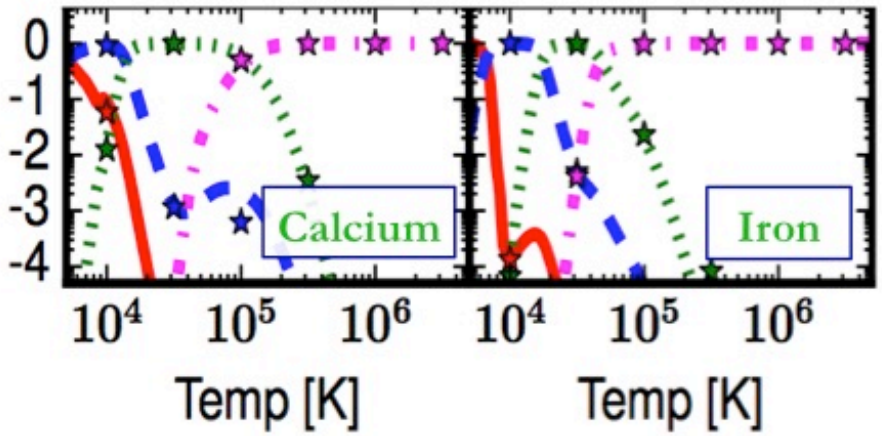
Collisional ionization,
radiative and dielectronic recombinations,
charge transfer reactions,
photoionizations.

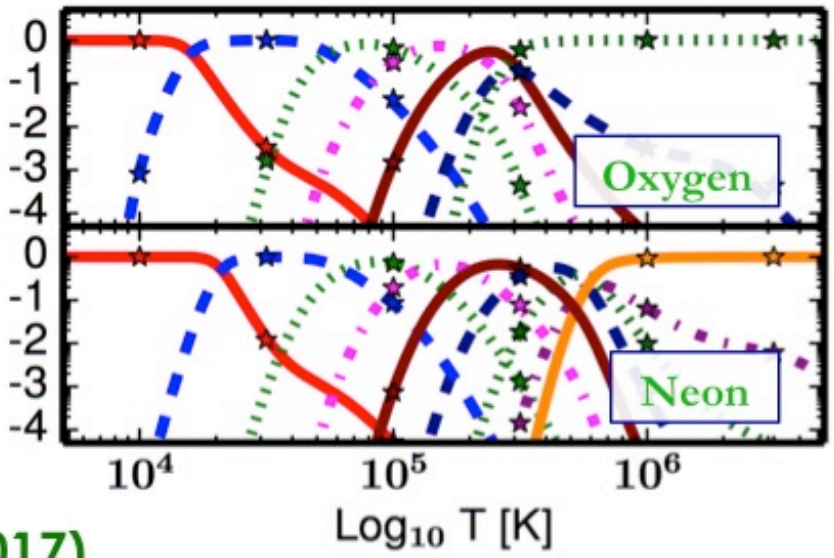
Gray, ES, Kasen (2015), Gray & ES (2016,2017)

No Ionizing Background



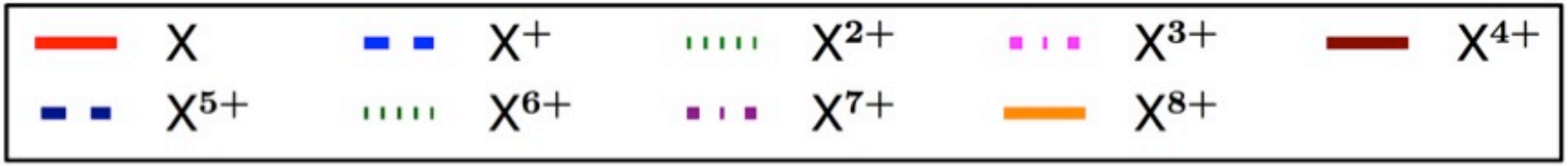


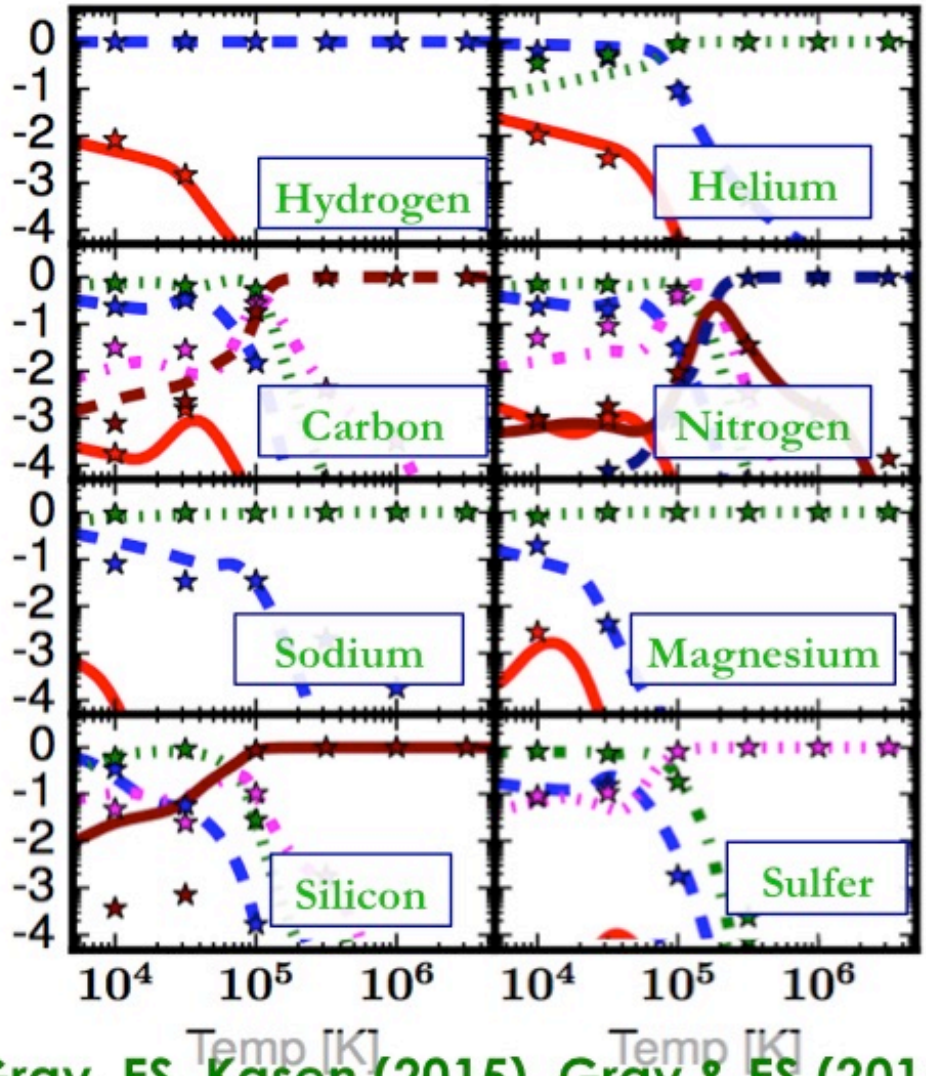


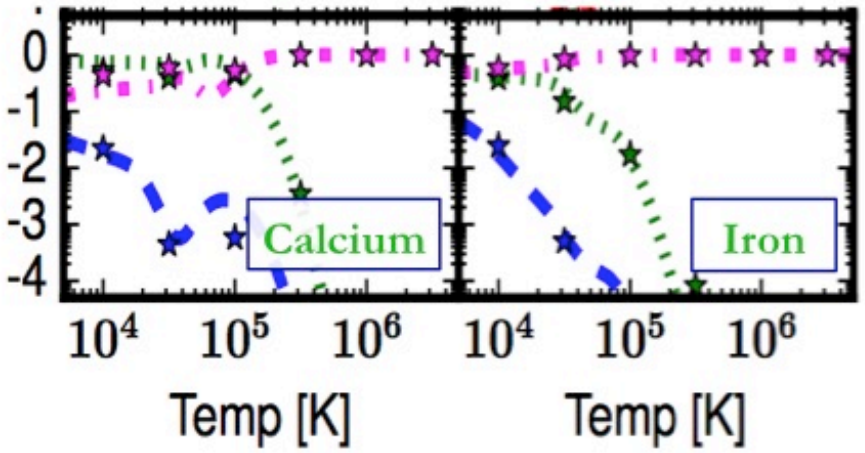


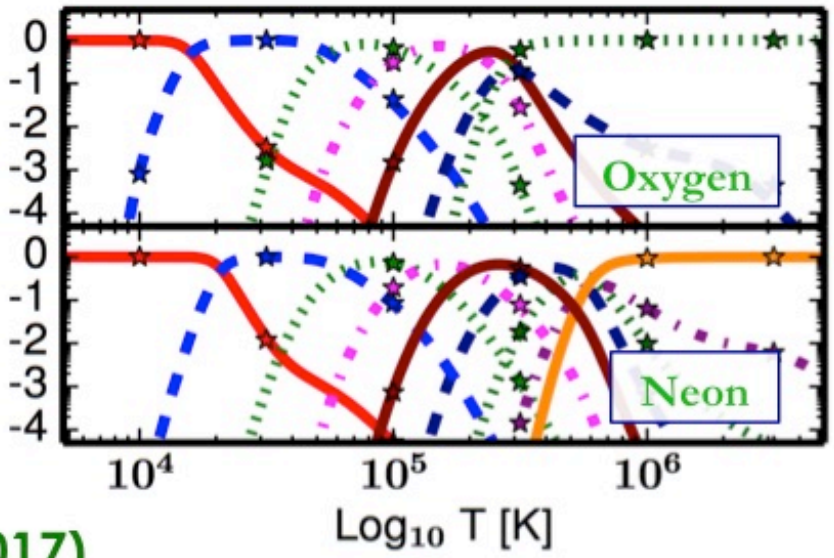
Gray, ES, Kasen (2015), Gray & ES (2016,2017)

$U=10^{-3}$



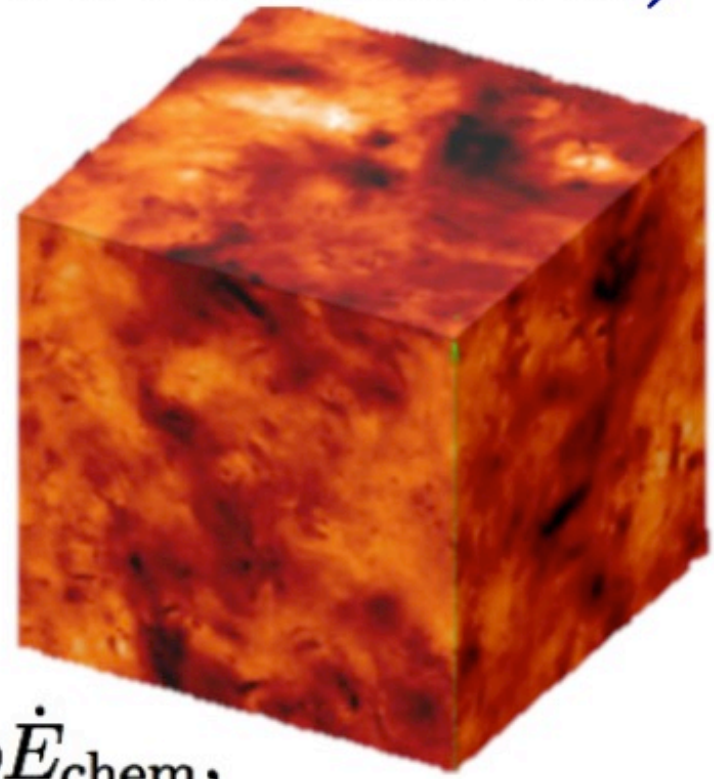






Gray, ES, Kasen (2015), Gray & ES (2016,2017)

Turbulent Media
(Cooling, & Ionizations/Recombinations)



$$\frac{D\rho}{Dt} = 0,$$

$$\frac{D\rho u_i}{Dt} + \frac{\partial P}{\partial x_i} = \rho f_i$$

$$\frac{D\rho E}{Dt} + \frac{\partial P u_j}{\partial x_j} = \rho \dot{E}_{\rm cool} + \rho \dot{E}_{\rm chem},$$

$$\frac{D\rho X_s}{Dt} = \rho A_s \dot{R}_s.$$

Gray, ES, Kasen (2015), Gray & ES (2016,2017)

What sets the parameter space?

Metallicity,

Spectral Shape

Ionization parameter ($U=n_g/n_H$),

Turbulent velocity (V_T) ,

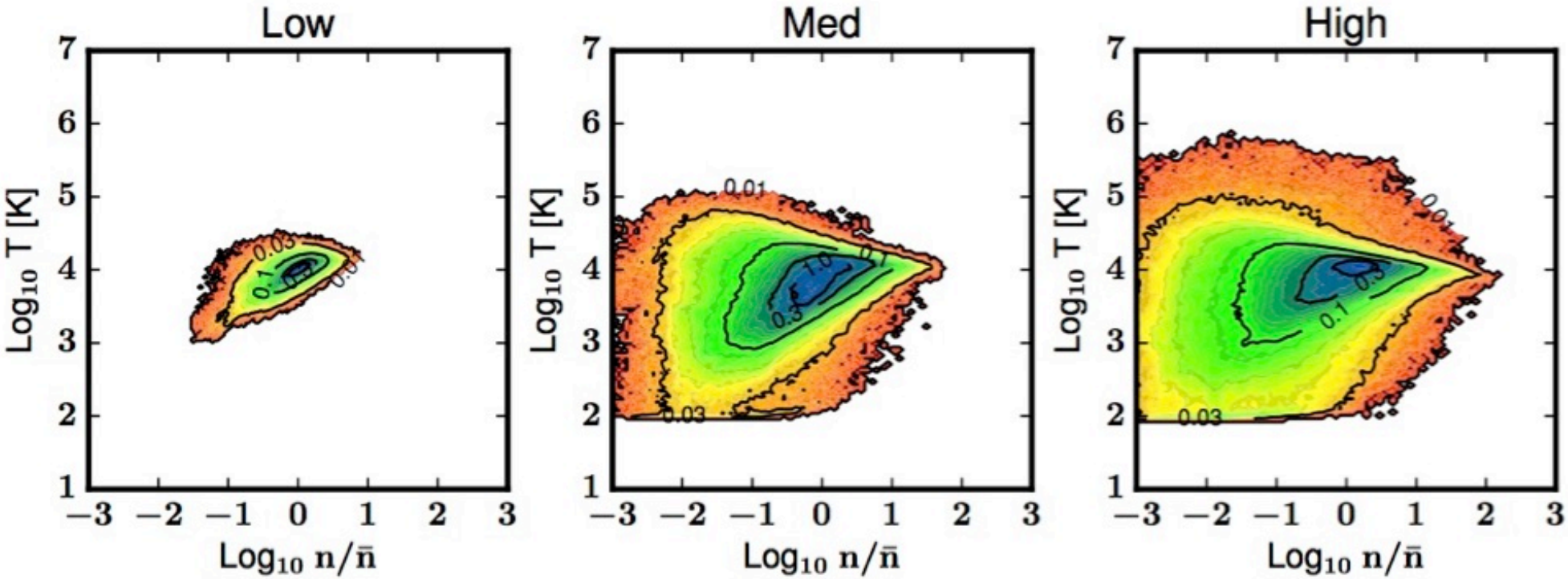
$n \times L_T$:

Energy input per unit mass: $\propto V_T^3/L_T$

Cooling rate per mass: $\propto n$

Gray, ES, Kasen (2015), Gray & ES (2016,2017)

Impact of Turbulence on Phase Diagrams (U=0)



$\sigma_{1D} = 11$ km/s
$T_{MW} = 1.1 \times 10^4$K
$M_{MW} = 1.4$

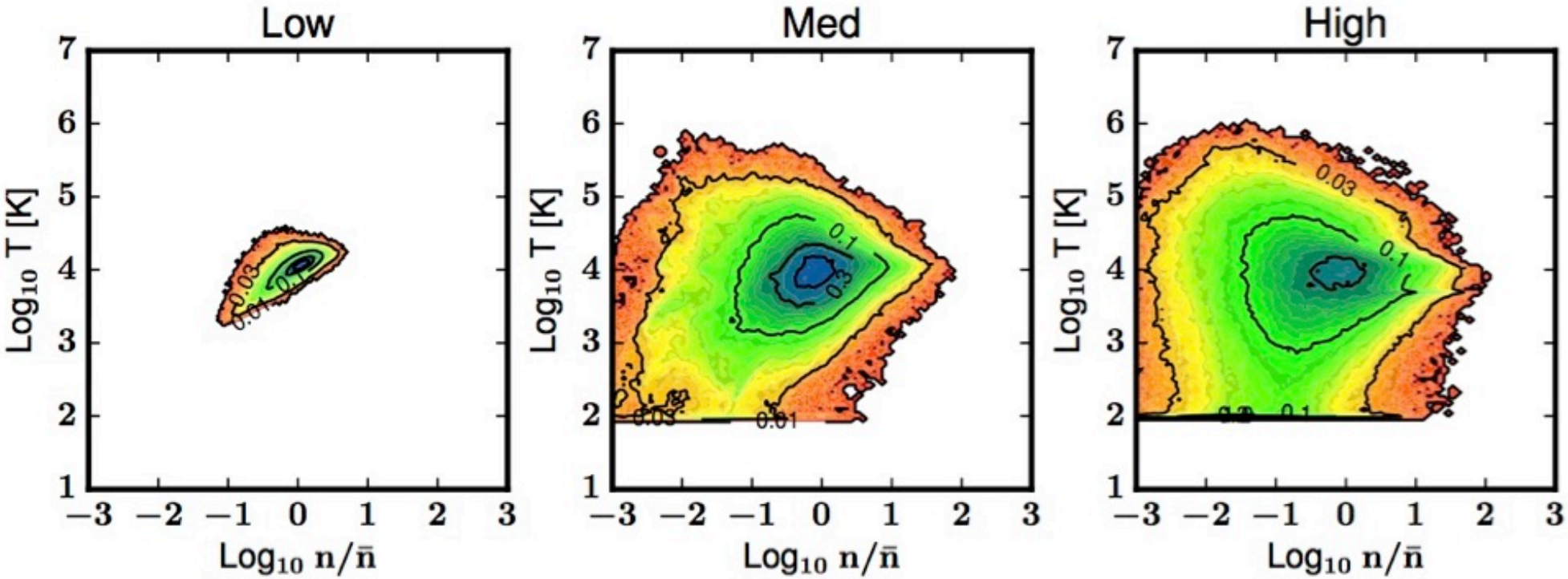
$\sigma_{1D} = 35$ km/s
$T_{MW} = 1.0 \times 10^4$K
$M_{MW} = 5.4$

$\sigma_{1D} = 58$ km/s
$T_{MW} = 0.9 \times 10^4$K
$M_{MW} = 10.6$

$nL = 10^{20}$

Gray, ES, Kasen (2015), Gray & ES (2016,2017)

Impact of Turbulence on Phase Diagrams (U=-4)



$\sigma_{1D} = 11$ km/s
$T_{MW} = 1.3\times10^4$K
$M_{MW} = 1.1$

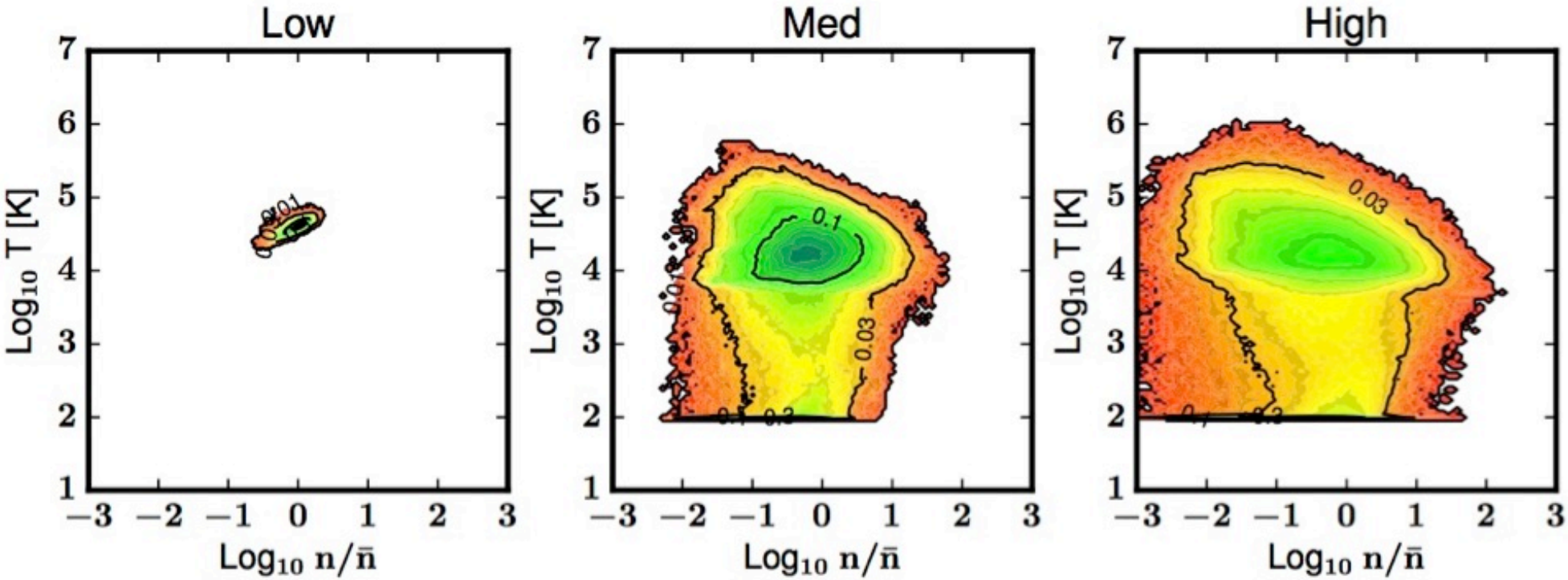
$\sigma_{1D} = 35$ km/s
$T_{MW} = 1.3\times10^4$K
$M_{MW} = 4.2$

$\sigma_{1D} = 58$ km/s
$T_{MW} = 1.1\times10^4$K
$M_{MW} = 9.3$

Gray, ES, Kasen (2015), Gray & ES (2016,2017)

$nL = 10^{20}$

Impact of Turbulence on Phase Diagrams (U=-2)



$\sigma_{1D} = 11$ km/s
$T_{MW} = 4.3\times10^4$K
$M_{MW}=0.7$

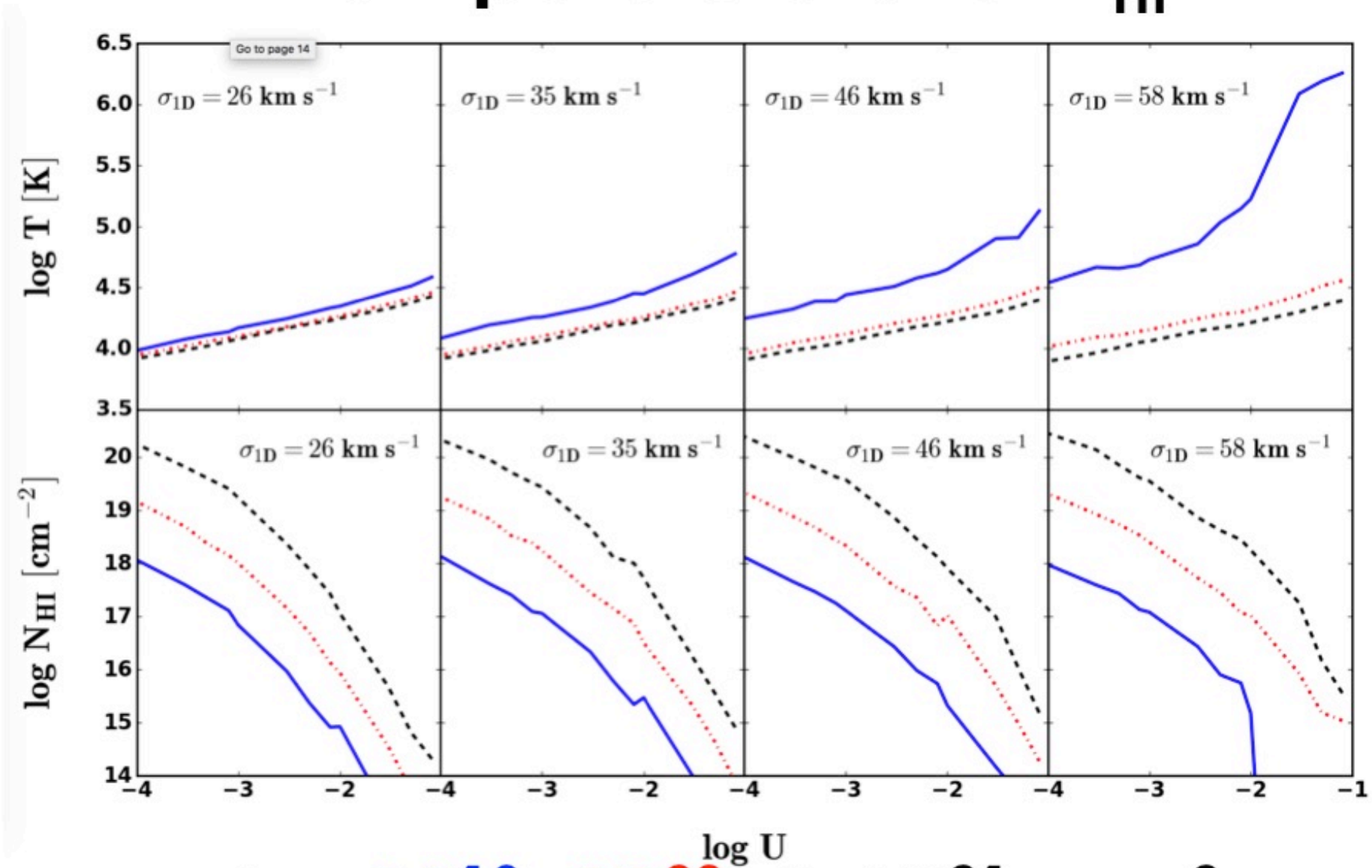
$\sigma_{1D} = 35$ km/s
$T_{MW} = 2.2\times10^4$K
$M_{MW}=4.6$

$\sigma_{1D} = 58$ km/s
$T_{MW} = 1.6\times10^4$K
$M_{MW}=12.4$

$nL = 10^{20}$

Gray, ES, Kasen (2015), Gray & ES (2016,2017)

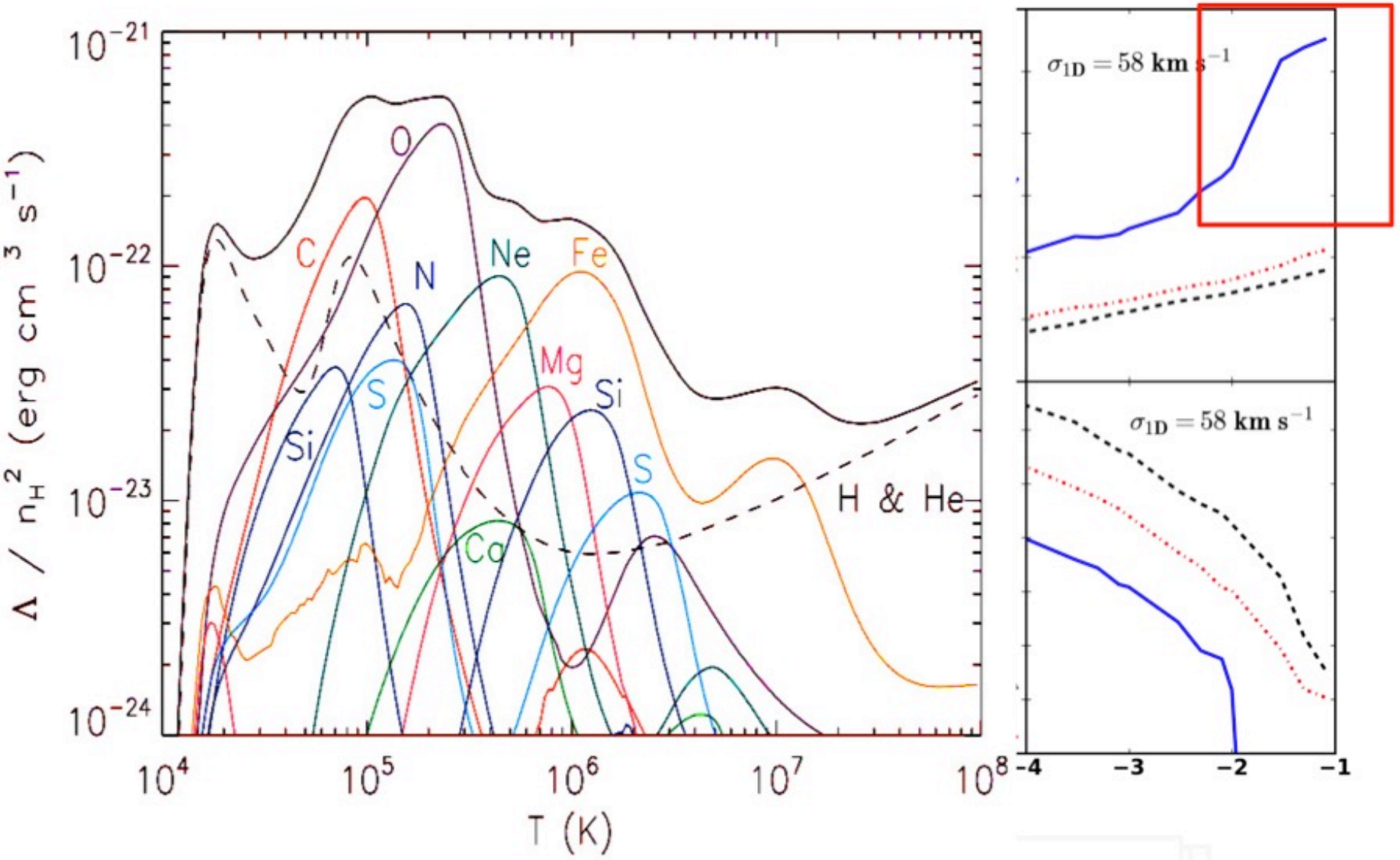
Temperature and N_{HI}



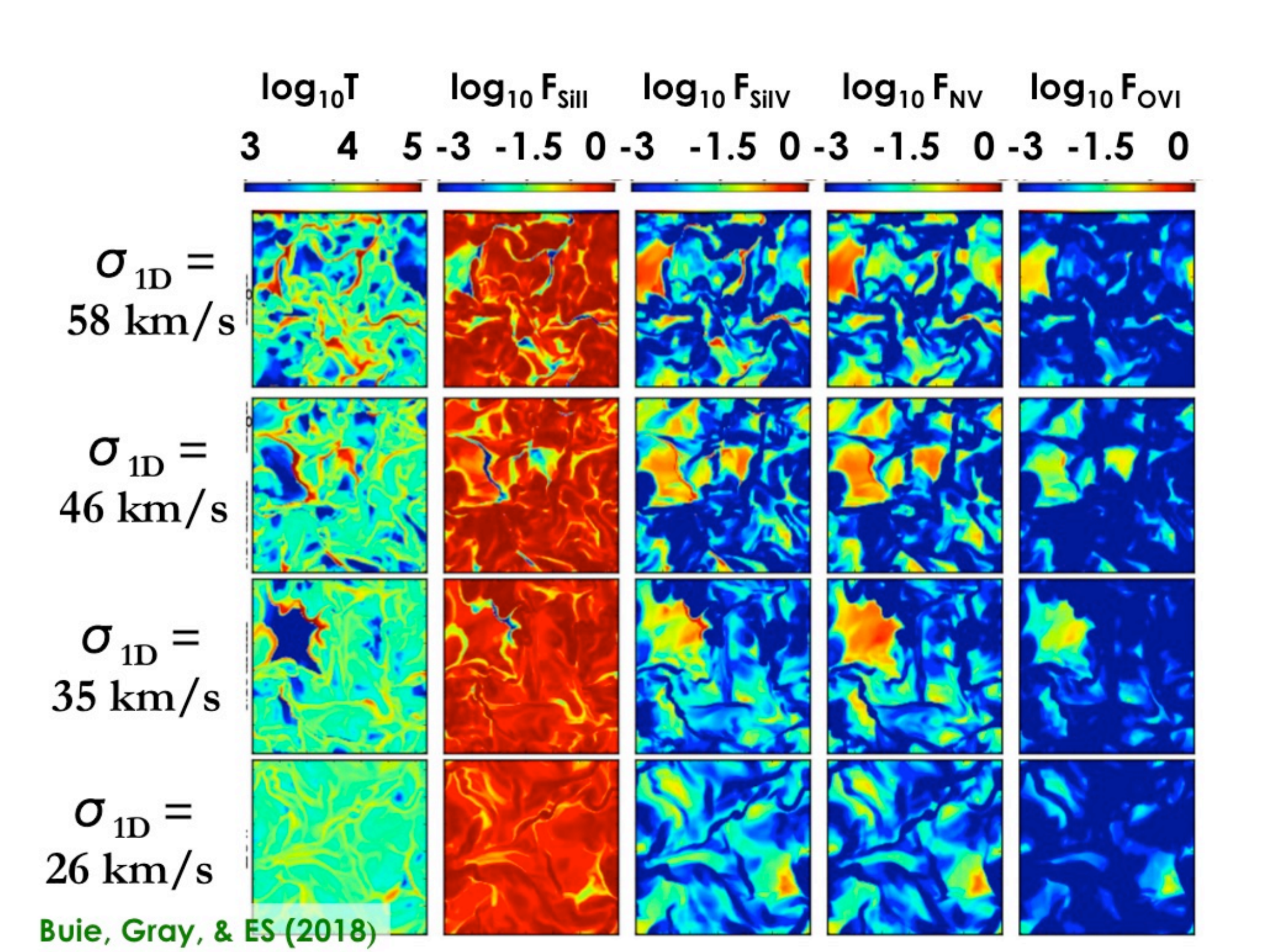
nL = 10^{19}, 10^{20}, & 10^{21} cm^{-2}

Buie, Gray, & ES (2018)

Runaway!

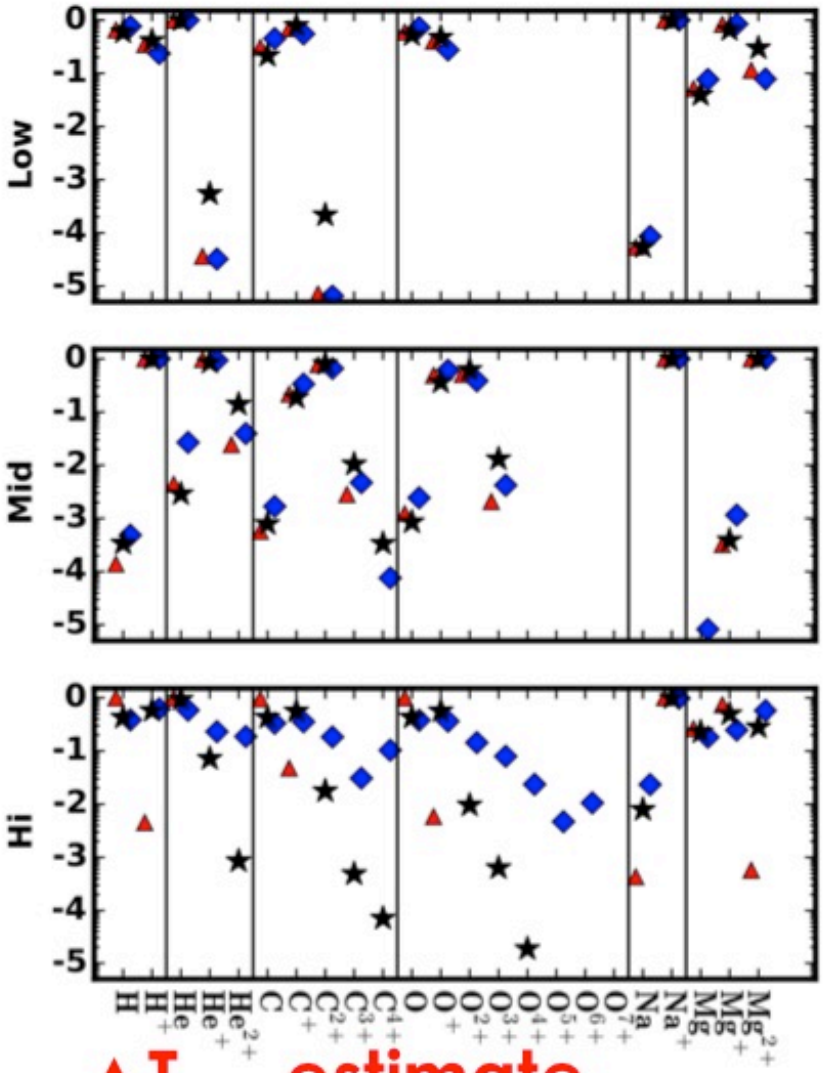


Buie, Gray, & ES (2018)



Buie, Gray, & ES (2018)

Species Fractions

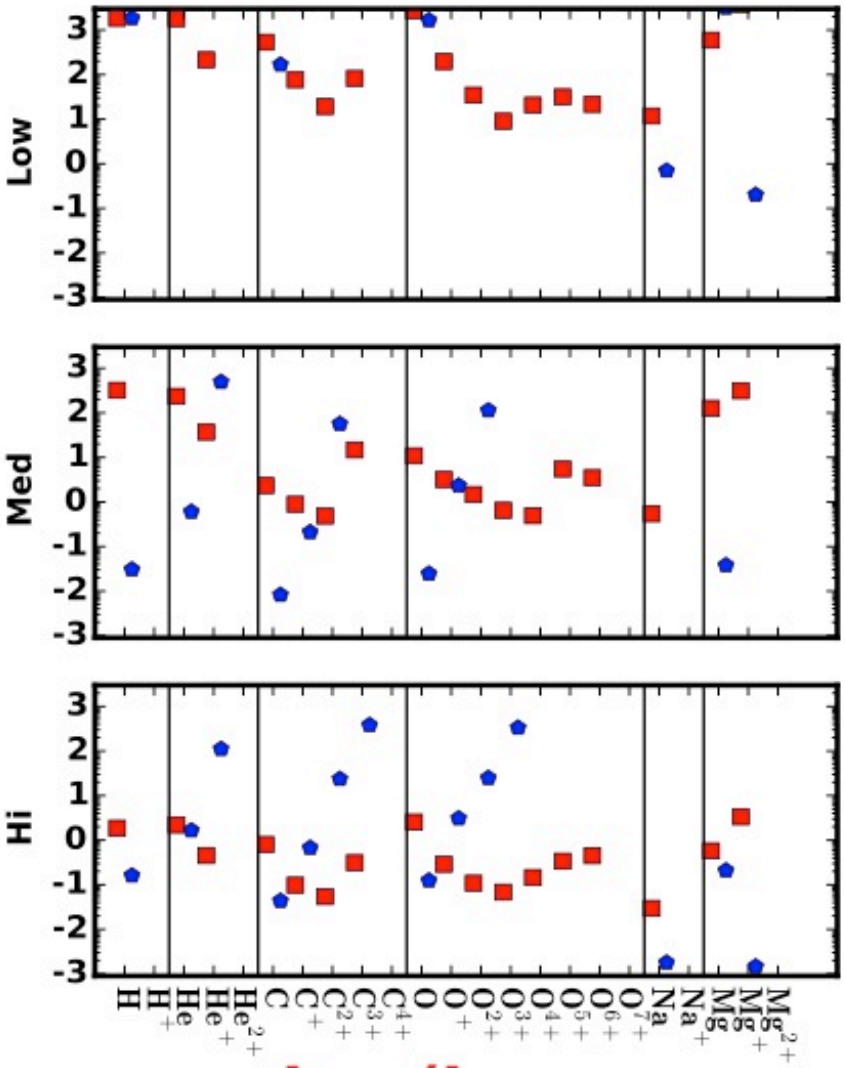


▲ T_{MW} estimate

◆ PDF estimate

★ True Value

Timescales



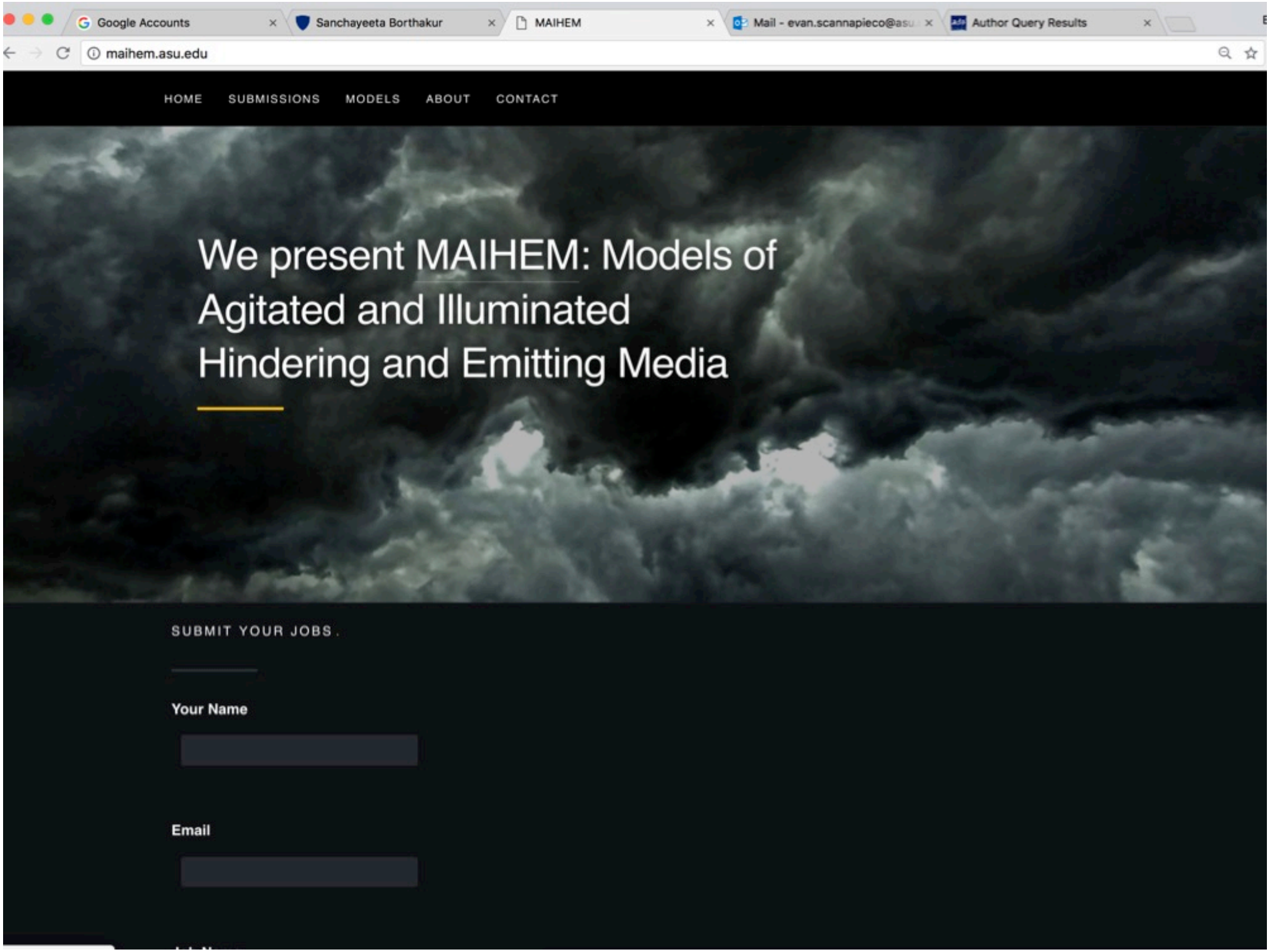
■ t_{rec}/t_{eddy}

⬟ $t_{collisional}/t_{eddy}$

Table 5: Results for U∼1.0×10^{-4}.

Col. (cm^{-2})	1.0E16	1.0E17	2.9E17	1.0E18	7.1E17	1.4E18	7.1E18	1.4E19	1.4E18	4.3E18	1.4E19	4.3E19	5.7E18	1.4E19	5.7E19	1.0E19	2.9E19	1.0E20	2.9E20
σ_{1D} (km s^{-1})	5.8	11.5	11.5	11.5	20.2	20.2	20.2	20.2	34.6	34.6	34.6	34.6	46.2	46.2	46.2	57.7	57.7	57.7	57.7
T$_{DW}$ (10^4 K)	1.5	4.9	1.3	0.9	3.2	1.1	0.6	0.5	5.8	1.3	0.4	0.6	1.6	1.2	1.2	2.2	1.1	0.4	0.5
M$_{DW}$	0.4	0.7	1.1	1.3	1.4	2.6	3.7	3.6	1.9	4.2	8.8	7.4	6.0	7.0	7.5	7.1	9.3	14.3	14.9
H	-1.0	-3.6	-1.0	-1.2	-2.5	-1.1	-0.9	-0.8	-3.0	-0.9	-0.6	-0.7	-0.9	-0.7	-0.7	-1.0	-0.7	-0.6	-0.6
H$^+$	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.1	-0.1	-0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
He	-0.1	-2.1	-0.5	-0.9	-1.6	-0.8	-0.7	-0.6	-2.5	-0.7	-0.5	-0.5	-0.6	-0.5	-0.5	-0.7	-0.5	-0.4	-0.5
He$^+$	-0.5	-0.0	-0.2	-0.1	-0.0	-0.1	-0.1	-0.1	-0.4	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
He^{2+}	-2.7	-1.7	-1.7	-1.3	-1.2	-1.5	-1.4	-1.5	-0.2	-1.4	-1.7	-1.6	-1.4	-1.5	-1.4	-1.0	-1.5	-1.7	-1.6
C	-2.2	-2.9	-2.3	-2.4	-2.3	-2.1	-1.9	-1.9	-2.7	-1.8	-1.6	-1.7	-1.8	-1.6	-1.7	-1.7	-1.6	-1.6	-1.6
C$^+$	-0.1	-0.5	-0.2	-0.2	-0.3	-0.1	-0.1	-0.1	-0.7	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.1	-0.1	-0.1
C^{2+}	-0.7	-0.2	-0.5	-0.5	-0.3	-0.6	-0.6	-0.7	-0.2	-0.6	-0.8	-0.7	-0.6	-0.7	-0.7	-0.6	-0.7	-0.8	-0.8
C^{3+}	-3.8	-2.3	-3.4	-3.2	-2.4	-3.2	-3.0	-3.0	-1.0	-2.6	-3.2	-2.8	-2.1	-2.4	-2.3	-1.8	-2.5	-3.0	-2.8
C^{4+}	-7.3	-5.0	-6.7	-6.1	-4.3	-5.7	-5.0	-4.9	-1.1	-3.8	-5.3	-4.5	-2.7	-2.8	-2.2	-2.0	-3.2	-4.7	-3.8
C^{5+}	-11.0	-8.9	-10.1	-9.2	-7.4	-8.7	-7.6	-7.4	-4.1	-6.9	-8.1	-6.9	-5.7	-5.5	-4.2	-5.0	-6.0	-7.1	-6.2
N	-1.3	-2.6	-1.4	-1.2	-2.0	-1.1	-0.8	-0.7	-2.5	-0.9	-0.5	-0.6	-0.9	-0.7	-0.6	-0.9	-0.6	-0.5	-0.5
N$^+$	-0.0	-0.2	-0.0	-0.1	-0.2	-0.1	-0.1	-0.1	-0.5	-0.1	-0.2	-0.2	-0.1	-0.1	-0.2	-0.1	-0.2	-0.2	-0.2
N^{2+}	-1.4	-0.4	-1.3	-1.1	-0.5	-1.2	-1.1	-1.1	-0.3	-1.1	-1.4	-1.2	-1.1	-1.2	-1.1	-0.9	-1.2	-1.3	-1.3
N^{3+}	-4.3	-2.2	-4.0	-3.4	-2.2	-3.3	-2.8	-2.7	-0.9	-2.5	-2.9	-2.6	-2.0	-2.3	-2.1	-1.7	-2.4	-2.6	-2.5
N^{4+}	-7.8	-5.0	-7.2	-6.1	-4.7	-5.8	-4.7	-4.5	-2.1	-4.0	-4.7	-4.1	-3.1	-3.3	-2.8	-2.6	-3.5	-4.1	-3.8
N^{5+}	-10.8	-8.2	-9.9	-8.5	-7.1	-8.1	-6.6	-6.3	-2.5	-5.1	-6.8	-5.9	-3.7	-3.6	-2.6	-2.6	-3.9	-5.9	-4.7
O	-1.0	-3.1	-1.0	-1.2	-2.5	-1.1	-0.8	-0.8	-3.1	-0.9	-0.6	-0.6	-0.8	-0.7	-0.7	-0.9	-0.7	-0.6	-0.5
O$^+$	-0.1	-0.2	-0.1	-0.1	-0.2	-0.1	-0.1	-0.1	-0.6	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2
O^{2+}	-1.7	-0.5	-1.5	-1.3	-0.5	-1.3	-1.3	-1.4	-0.2	-1.2	-1.6	-1.4	-1.1	-1.3	-1.3	-0.9	-1.3	-1.6	-1.5
O^{3+}	-4.5	-2.1	-4.1	-3.5	-2.0	-3.3	-2.9	-2.9	-0.8	-2.5	-3.2	-2.6	-2.0	-2.2	-2.1	-1.7	-2.4	-2.8	-2.5
O^{4+}	-7.1	-4.6	-6.7	-5.8	-4.2	-5.4	-4.6	-4.4	-2.1	-4.0	-4.9	-4.0	-3.1	-3.2	-2.8	-2.6	-3.5	-4.3	-3.7
O^{5+}	-10.0	-7.8	-9.3	-8.1	-6.9	-7.7	-6.5	-6.2	-3.5	-5.4	-6.7	-5.6	-4.3	-4.3	-3.4	-3.4	-4.4	-5.8	-5.0
O^{6+}	-13.4	-11.5	-12.4	-11.0	-9.8	-10.4	-8.7	-8.3	-4.4	-6.9	-9.0	-7.7	-5.1	-4.7	-3.0	-3.6	-4.7	-7.8	-6.0
O^{7+}	-17.9	-16.1	-16.4	-14.9	-13.7	-14.1	-11.9	-11.4	-7.9	-11.1	-12.0	-10.8	-8.6	-7.8	-5.5	-7.2	-8.3	-10.8	-9.0
Ne	-0.5	-3.0	-1.6	-2.0	-2.8	-1.7	-1.4	-1.4	-3.4	-1.5	-1.1	-1.1	-1.3	-1.2	-1.2	-1.4	-1.2	-1.0	-1.0
Ne$^+$	-0.2	-0.1	-0.2	-0.4	-0.4	-0.3	-0.2	-0.2	-0.7	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
Ne^{2+}	-1.0	-0.6	-0.4	-0.3	-0.3	-0.3	-0.4	-0.4	-0.2	-0.4	-0.6	-0.5	-0.5	-0.5	-0.5	-0.4	-0.5	-0.6	-0.6
Ne^{3+}	-3.9	-2.2	-3.0	-2.6	-1.7	-2.6	-2.5	-2.5	-0.8	-2.3	-2.7	-2.4	-2.0	-2.1	-2.0	-1.7	-2.2	-2.6	-2.3
Ne^{4+}	-7.2	-4.4	-6.1	-5.3	-3.7	-5.0	-4.2	-4.1	-1.9	-3.9	-4.5	-3.7	-3.1	-3.2	-2.7	-2.5	-3.4	-4.0	-3.4
Ne^{5+}	-10.5	-7.7	-9.1	-8.2	-6.5	-7.6	-6.4	-6.2	-3.6	-5.4	-6.7	-5.5	-4.3	-4.3	-3.3	-3.5	-4.4	-5.8	-5.0
Ne^{6+}	-14.4	-11.6	-13.0	-12.0	-10.1	-11.0	-9.2	-8.8	-5.8	-7.3	-9.6	-8.0	-5.8	-5.7	-3.9	-4.7	-5.4	-8.2	-6.8
Ne^{7+}	-14.8	-13.5	-14.4	-13.6	-13.0	-13.7	-11.9	-11.5	-8.4	-9.9	-10.3	-10.7	-7.5	-7.2	-4.2	-6.0	-6.6	-10.6	-8.6
Ne^{8+}	-14.8	-12.7	-14.3	-13.5	-12.5	-13.6	-12.3	-12.3	-10.4	-12.6	-10.7	-13.2	-9.7	-8.8	-5.0	-7.1	-8.0	-12.1	-10.5
Ne^{9+}	-15.3	-13.5	-14.9	-14.4	-13.0	-14.4	-13.0	-13.0	-10.5	-12.9	-10.4	-13.9	-10.0	-8.4	-4.0	-7.2	-8.2	-12.5	-10.4
Na	-4.3	-5.9	-3.5	-2.7	-5.0	-2.5	-1.7	-1.6	-5.3	-2.2	-1.3	-1.4	-2.2	-1.8	-1.6	-2.3	-1.6	-1.2	-1.2
Na$^+$	-0.0	0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0	-0.0
Mg	-2.0	-6.2	-1.7	-1.7	-4.0	-1.8	-1.8	-1.9	-4.5	-1.9	-1.9	-1.8	-1.9	-1.7	-1.7	-1.9	-1.7	-1.9	-1.8
Mg$^+$	-0.5	-3.2	-0.2	-0.1	-2.0	-0.2	-0.1	-0.1	-2.6	-0.3	-0.1	-0.1	-0.3	-0.2	-0.1	-0.4	-0.2	-0.1	-0.1
Mg^{2+}	-0.2	-0.0	-0.5	-0.6	-0.0	-0.4	-0.7	-0.7	-0.0	-0.3	-1.0	-0.8	-0.3	-0.5	-0.6	-0.2	-0.5	-0.9	-0.9
Si	-3.4	-4.7	-3.5	-3.5	-4.2	-3.3	-3.0	-2.9	-4.6	-3.0	-2.6	-2.7	-3.0	-2.7	-2.7	-2.9	-2.7	-2.5	-2.5
Si$^+$	-0.1	-1.6	-0.1	-0.1	-1.1	-0.1	-0.0	-0.0	-1.6	-0.1	-0.0	-0.0	-0.2	-0.1	-0.1	-0.2	-0.1	-0.0	-0.0
Si^{2+}	-0.5	-0.1	-0.6	-0.7	-0.1	-0.7	-1.1	-1.3	-0.3	-0.6	-2.1	-1.3	-0.6	-0.8	-0.8	-0.5	-0.8	-2.0	-1.3
Si^{3+}	-3.1	-1.1	-3.2	-3.1	-1.4	-2.8	-3.1	-3.2	-0.8	-2.1	-3.9	-2.9	-1.7	-2.0	-2.1	-1.5	-2.1	-3.5	-2.8
Si^{4+}	-7.2	-3.5	-7.2	-6.6	-3.2	-5.1	-5.4	-5.4	-0.5	-2.9	-6.3	-4.4	-2.0	-2.3	-2.1	-1.6	-2.6	-5.4	-3.5
Si^{5+}	-9.5	-5.8	-9.3	-8.4	-4.7	-7.1	-6.6	-6.4	-2.1	-4.5	-7.6	-5.5	-3.6	-3.6	-2.8	-3.0	-3.9	-6.4	-4.5
Fe	-3.9	-6.6	-4.0	-4.3	-5.4	-4.1	-4.1	-4.1	-6.0	-4.1	-4.0	-4.0	-4.1	-4.0	-4.0	-4.1	-4.0	-4.0	-3.8
Fe$^+$	-0.5	-3.0	-0.4	-0.3	-2.1	-0.3	-0.1	-0.1	-2.7	-0.3	-0.0	-0.1	-0.3	-0.2	-0.2	-0.4	-0.1	-0.0	-0.0
Fe^{2+}	-0.2	-0.4	-0.2	-0.3	-0.2	-0.3	-0.7	-0.9	-0.7	-0.4	-1.7	-1.0	-0.4	-0.6	-0.6	-0.4	-0.6	-1.7	-1.1
Fe^{3+}	-2.1	-0.2	-2.0	-1.8	-0.5	-1.7	-1.9	-2.1	-0.3	-1.4	-3.2	-2.0	-1.2	-1.4	-1.5	-1.0	-1.5	-2.8	-1.9
Fe^{4+}	-4.8	-1.6	-4.5	-3.8	-1.7	-3.4	-3.0	-3.0	-0.5	-2.4	-4.4	-2.7	-1.9	-2.1	-1.9	-1.5	-2.2	-3.7	-2.5

Notes: Abundances values are given as $\log_{10}(F_i/F_i)$.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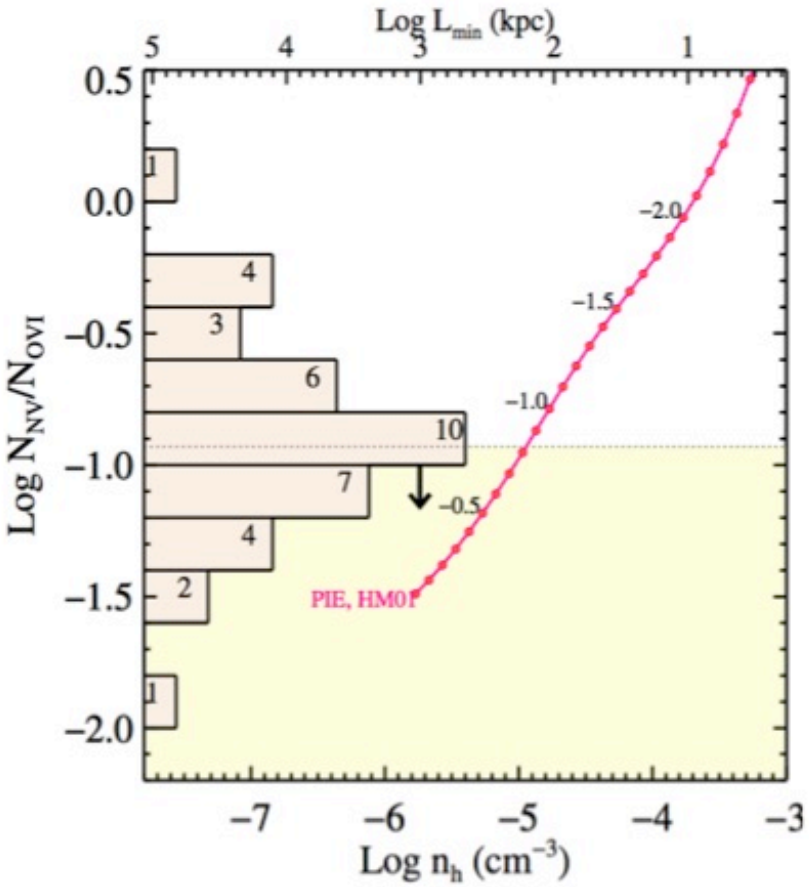
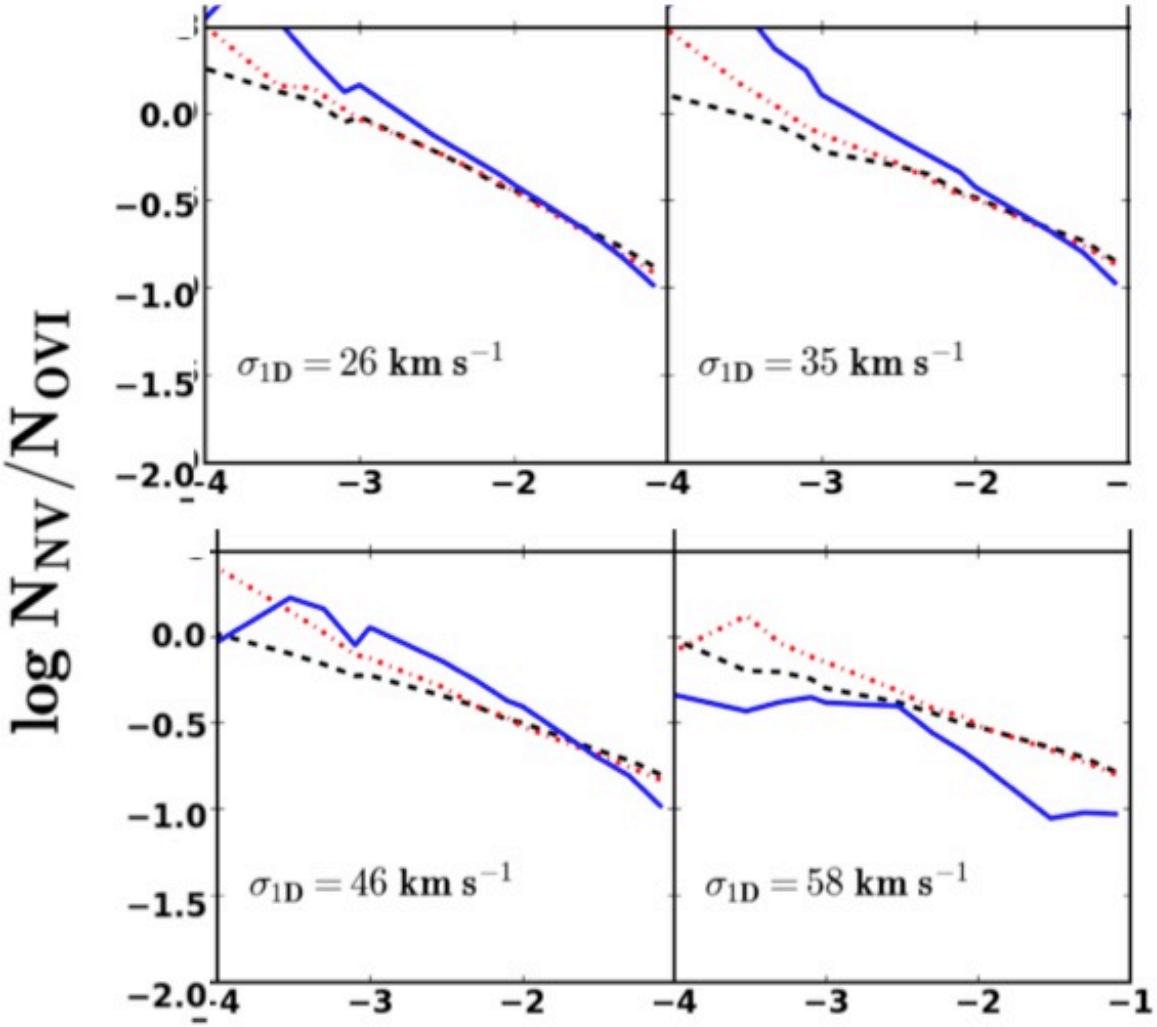
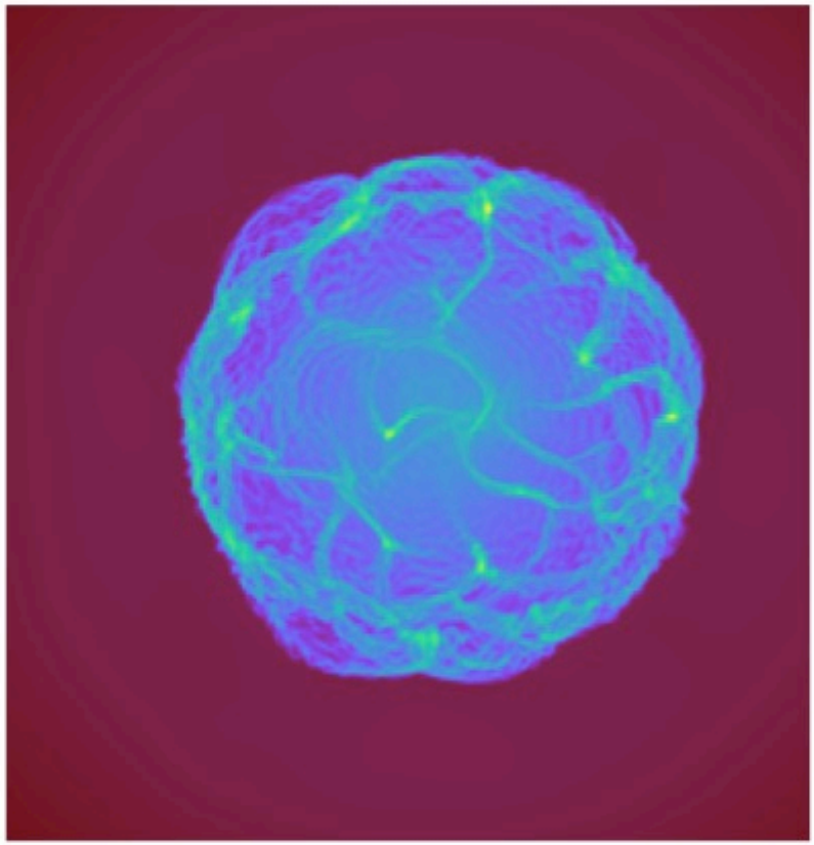
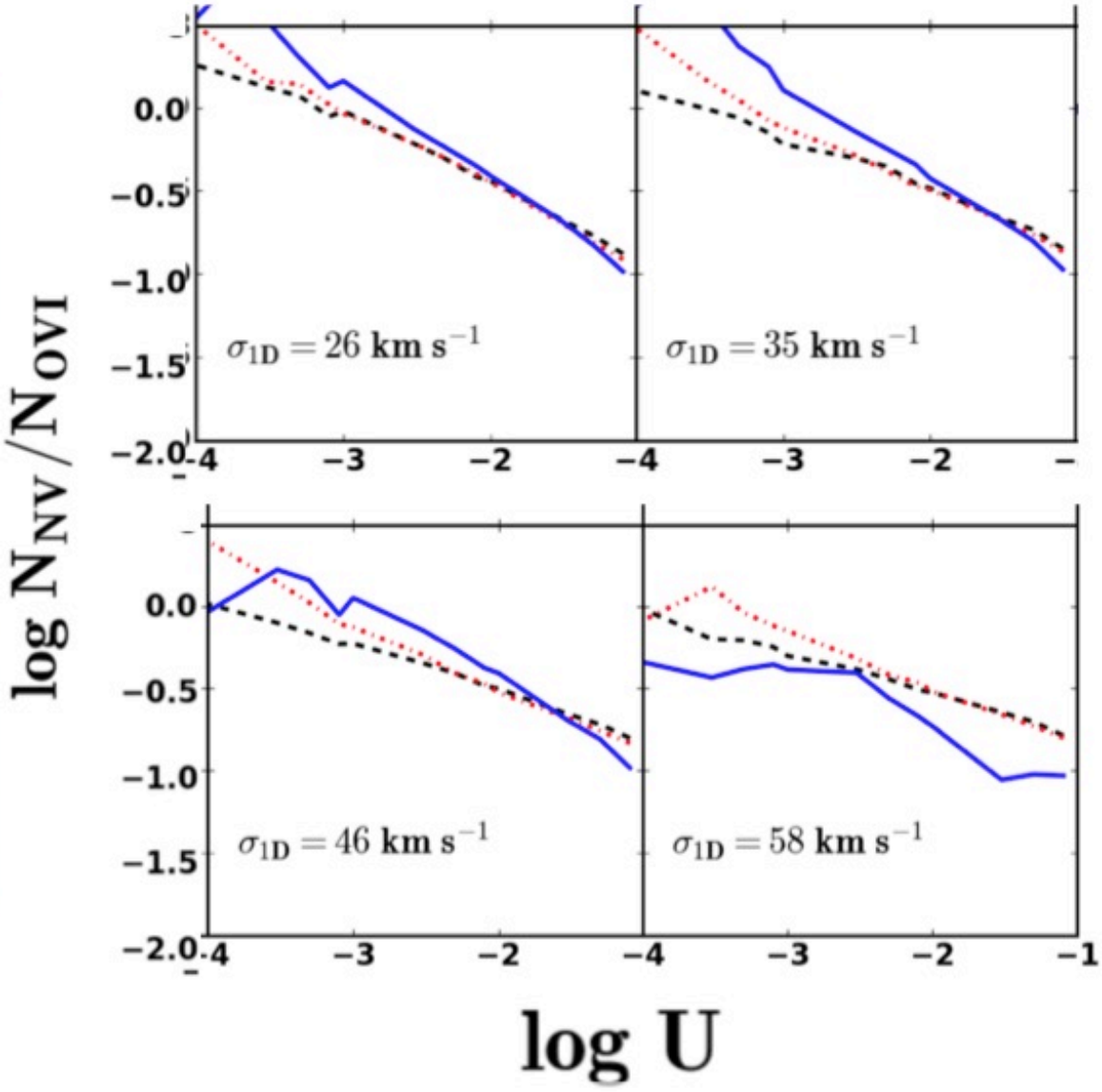




Buie, Gray, & ES (2018)

OVI & NV

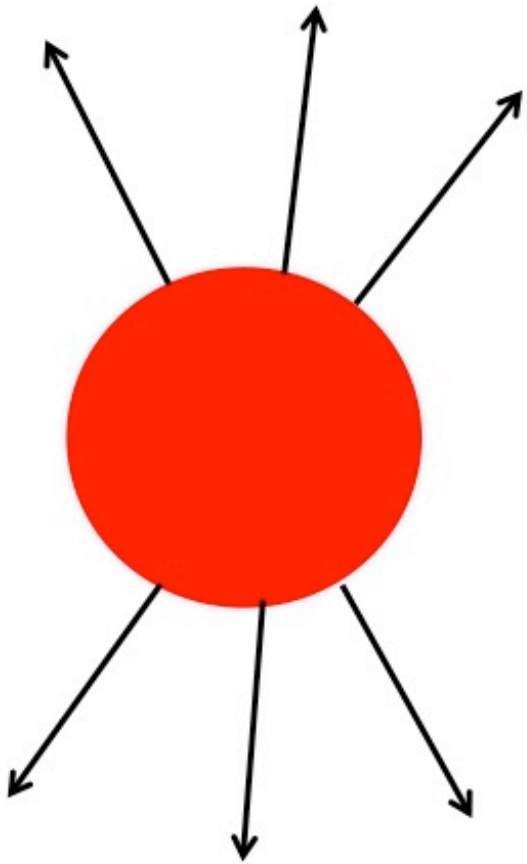


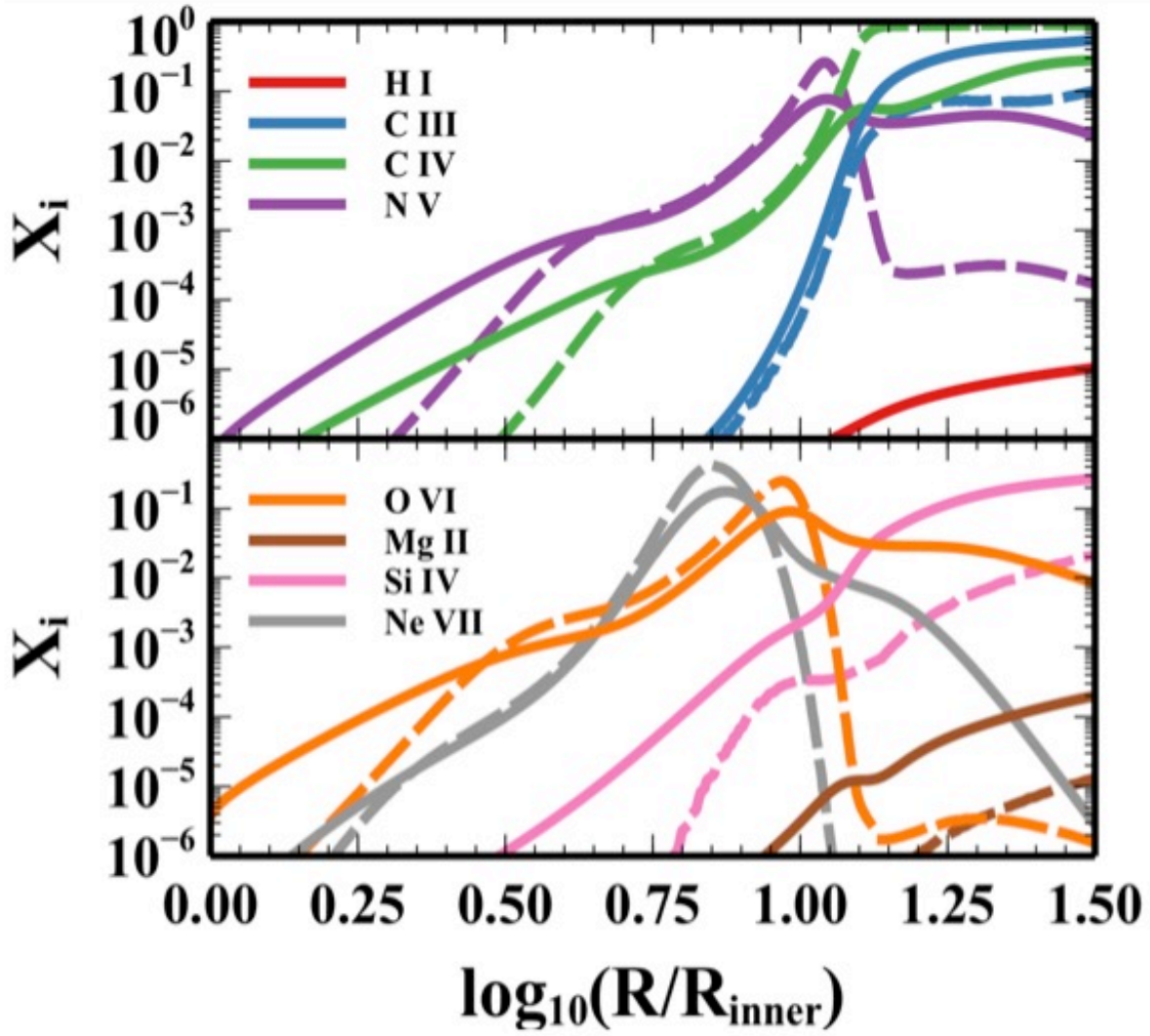


Buie, Gray, & ES (in prep)

Buie, Gray, & ES (2018)

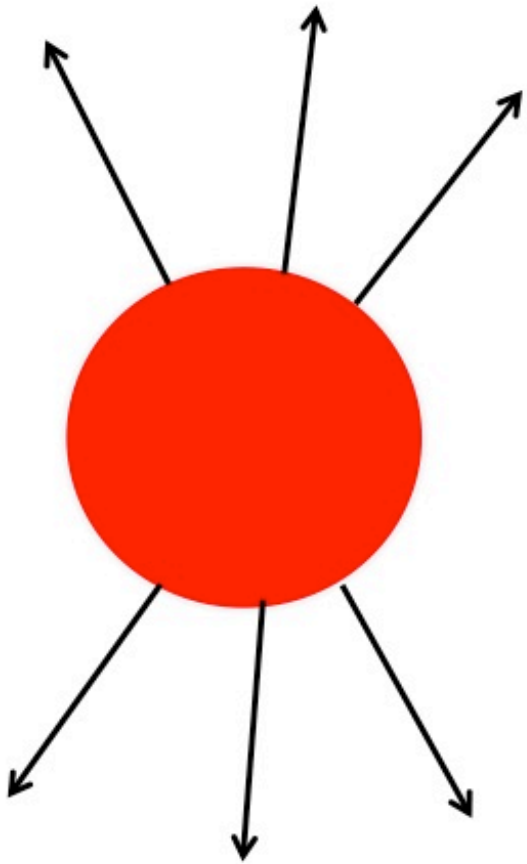
Chevalier & Clegg Wind

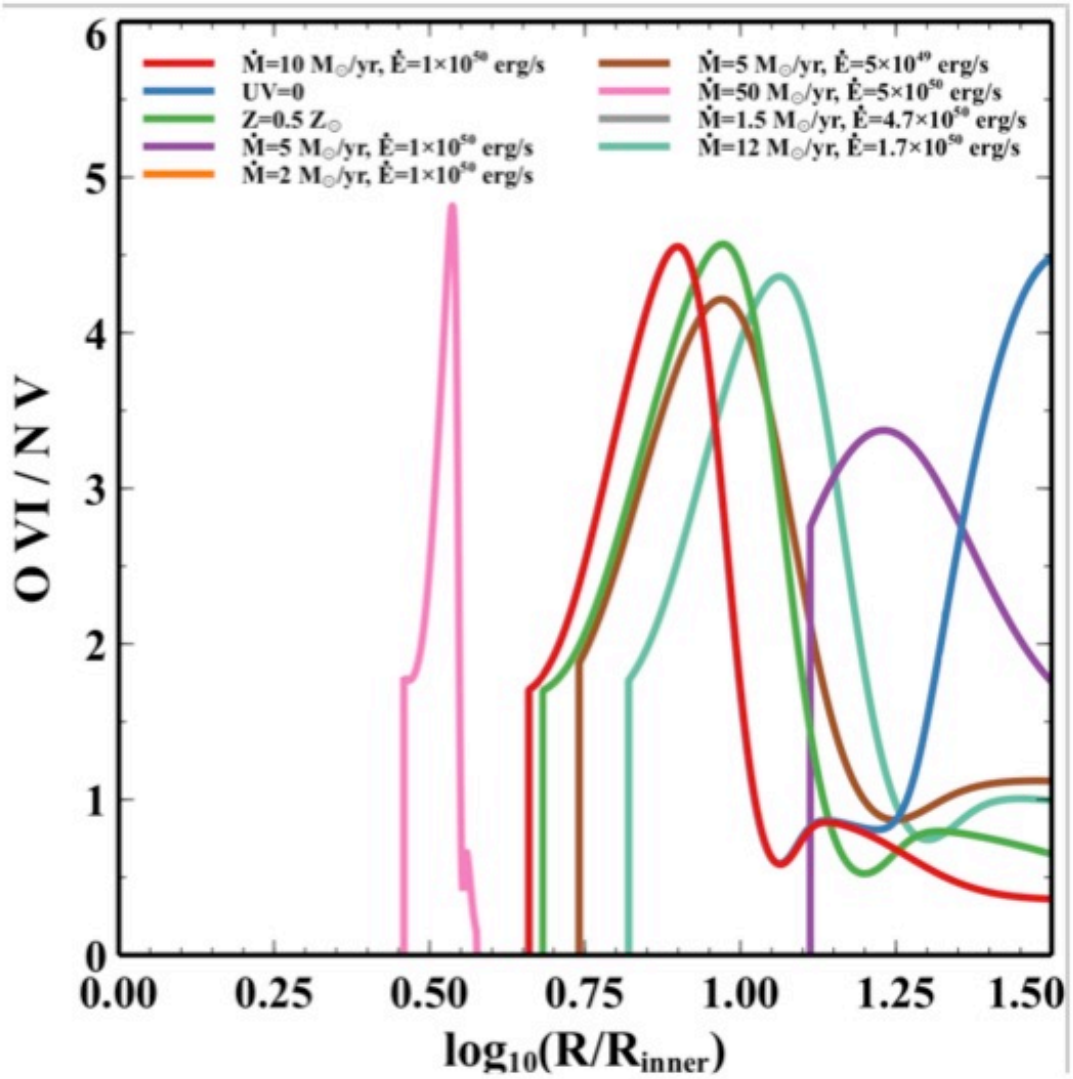




Gray, ES (in prep)

Chevalier & Clegg Wind





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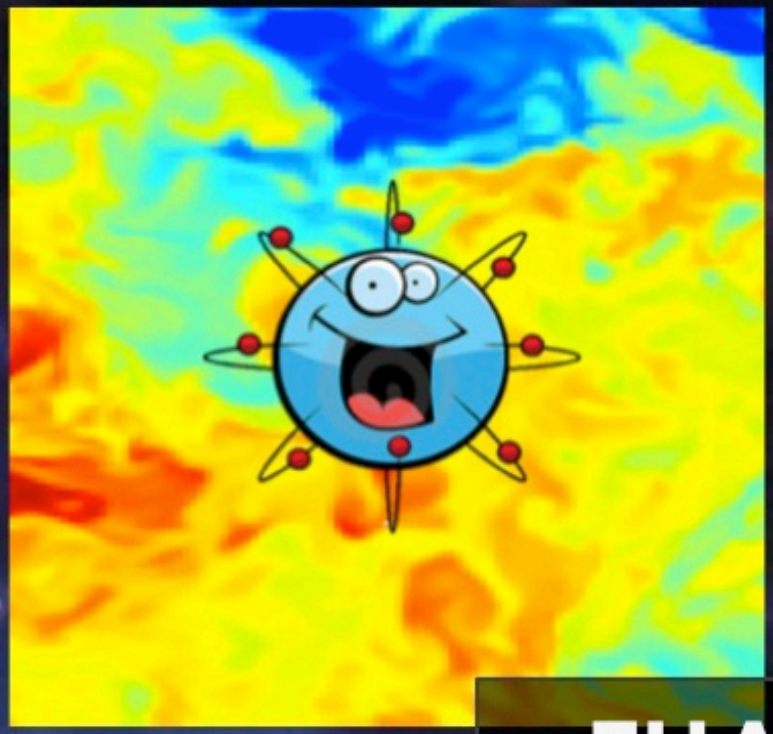
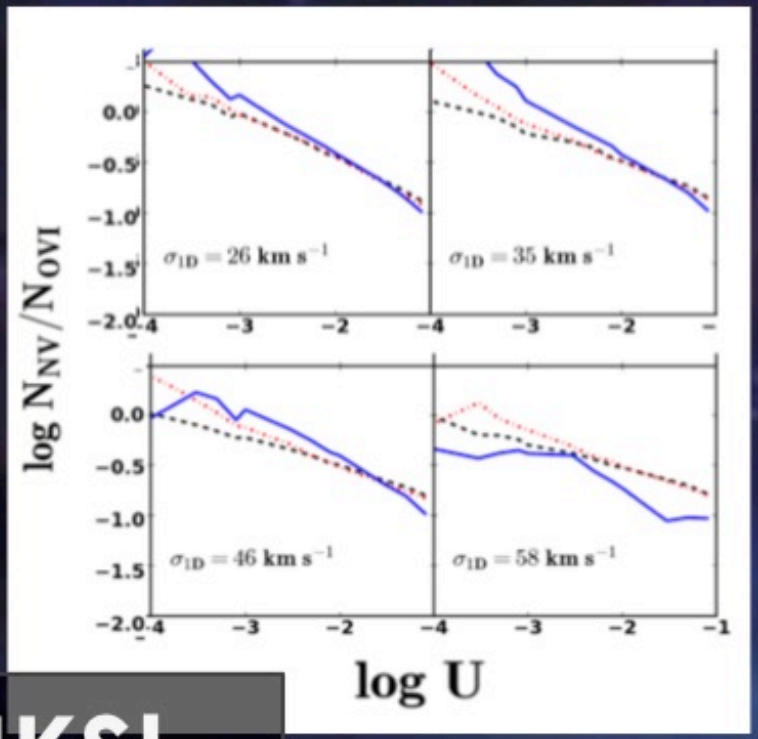
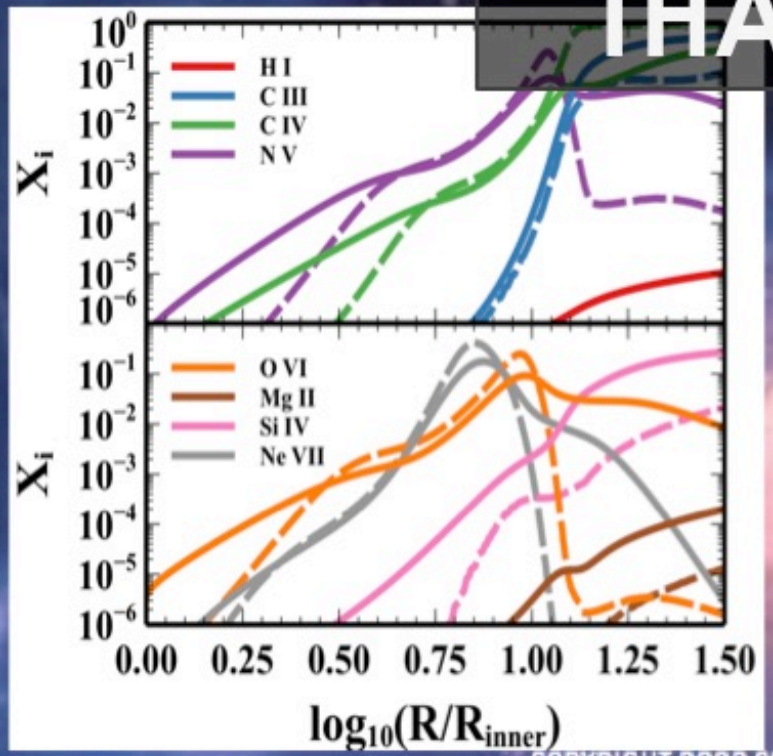


II



THANKS!

III



IV