Modeling the irradiated ISM in starburst galaxies and AGN

Rowin Meijerink
Leiden Observatory, Leiden University, The Netherlands

Credits

- Mher Kazandjian (Leiden Observatory)
- Marissa Rosenberg (Leiden Observatory)
- Paul van der Werf (Leiden Observatory)
- The HerCULES team

Outline

- Background: FUV versus X-ray irradiation
- Complicating matters: Cosmic rays and mechanical heating
- Application to Arp 299
- Conclusions

Photon Dominated Regions

- Regions where photons dominate the thermal and chemical balance of the gas
- Examples:
  - AGN environments
  - OB stars environments
  - T Tauri stars and their surrounding proto-planetary disks
  - Red giant outflow (AGB stars)
  - Planetary nebulae

PDRs and XDRs

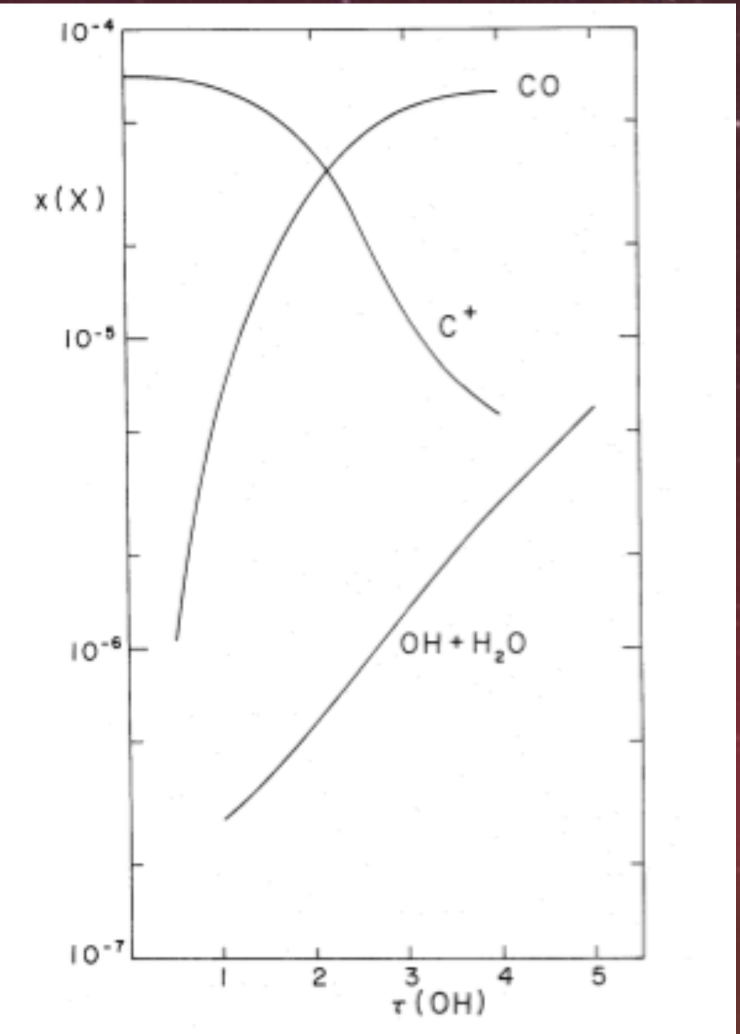
Energetics:

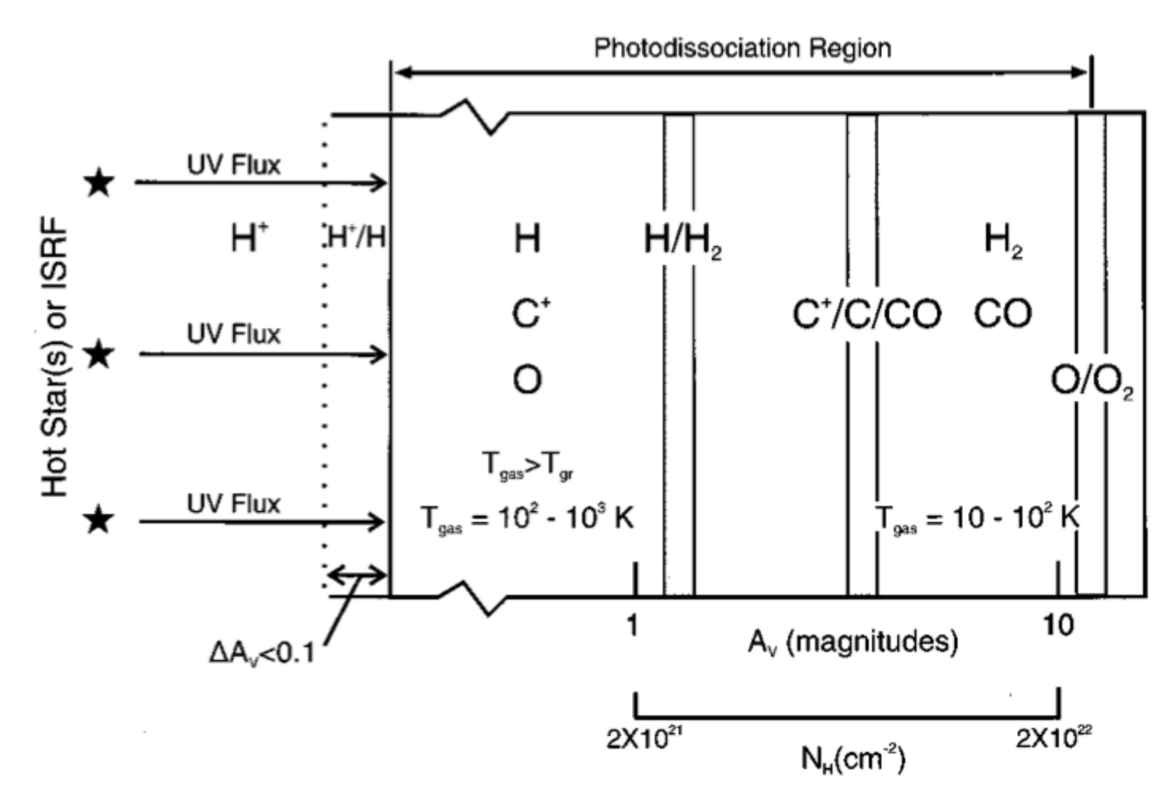
- $G_0 = 1.6 \times 10^{-3}$ erg cm^{-2} s^{-1}
- Habing flux: 6-13.6 eV
- $F_x = 84\, L_{44} r_2^{-2}$ erg cm^{-2} s^{-1}
- X-ray flux: 1-100 keV
  - Seyfert nucleus at 100 pc (can influence the chemistry up to 500 pc distance)
  - T Tauri star with 10^{32} erg/s at 20 AU

PDRs: 6.0 < E < 13.6 eV

- Heating:
  - Photo-electric heating
  - Cosmic rays
- Cooling:
  - Fine-structure lines [OI] 63, 145; [CII] 158 μm
  - H_2, CO and H_2O rotational-vibrational lines
- FUV photon penetration limited by dust absorption
- Chemical transitions:
  - Chemistry driven by FUV ionization
  - $H \rightarrow H_2$; $C^+ \rightarrow C \rightarrow CO$

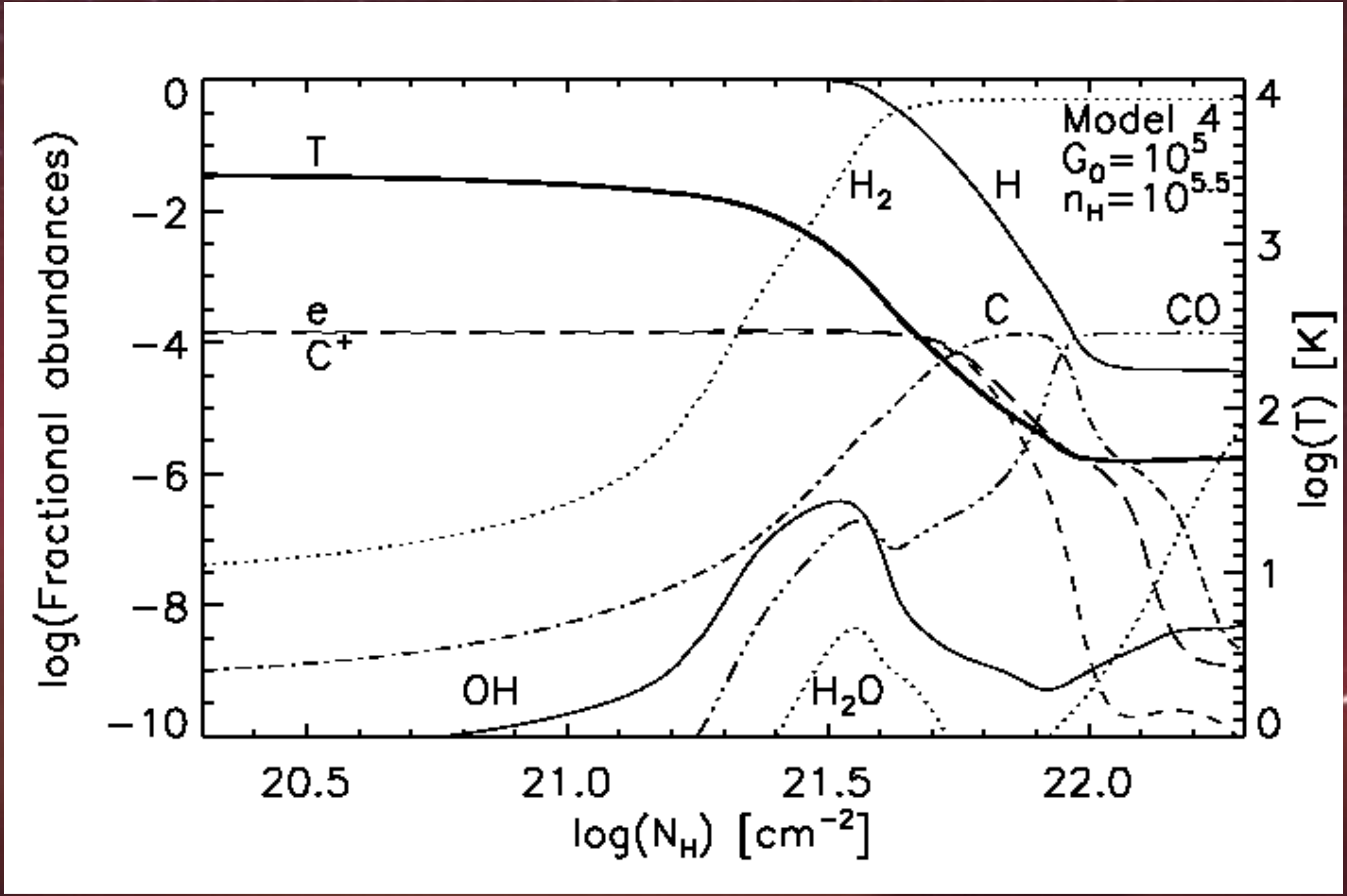
PDR structure





Glassgold & Langer 1975 Tielens & Hollenbach 1985

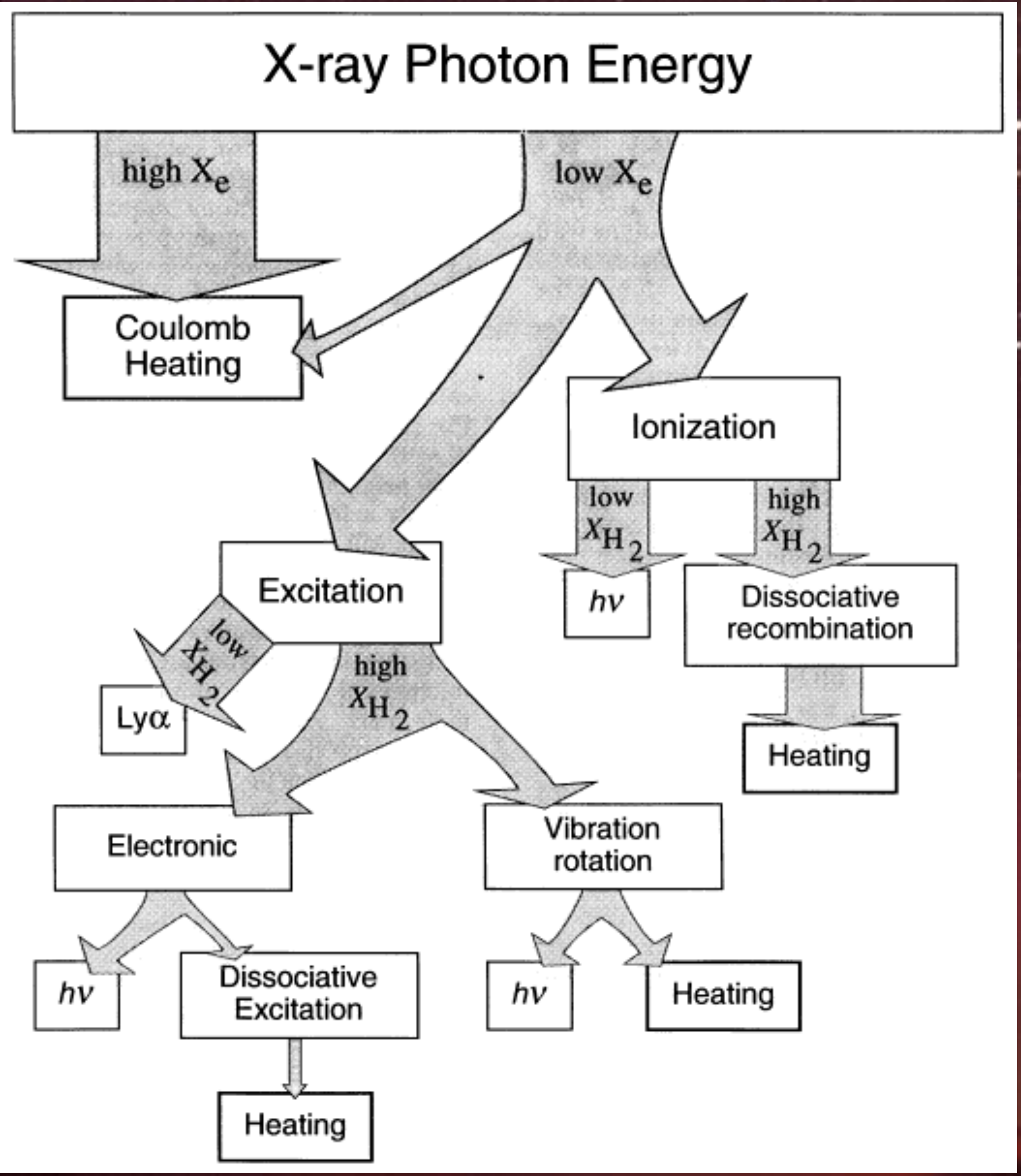
PDR structure



Meijerink & Spaans (2005)

XDRs: E > 1 keV

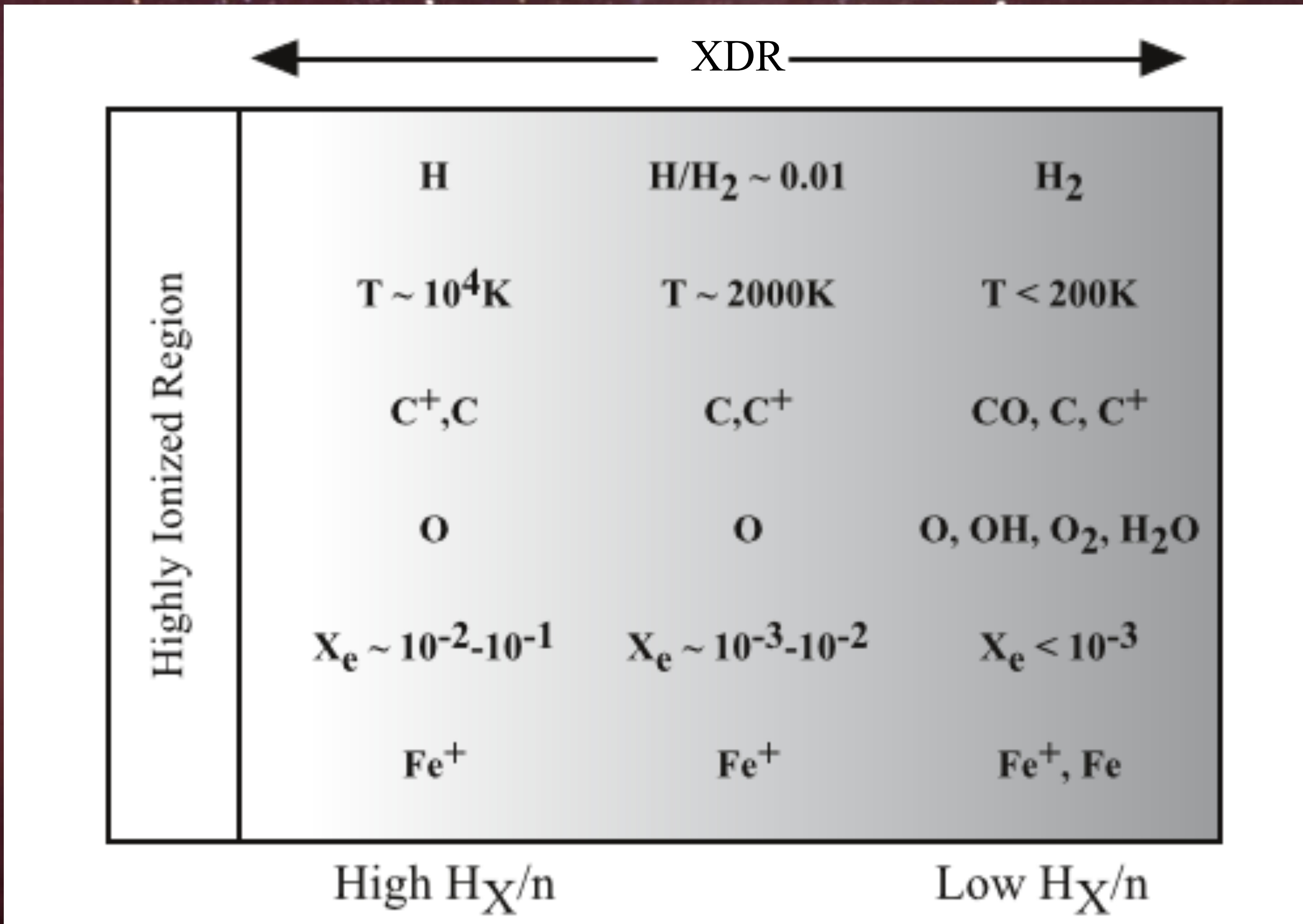
- Heating: X-ray photo-ionization, followed by:
  - fast electrons
  - H and H_2 excitation
  - UV emission: Ly α, Lyman-Werner
- Cooling:
  - [FeII] 1.26, 1.64 μm
  - [OI] 63; [CII] 158; [SiII] 35 μm
  - thermal H_2 v=1-0 S(1)
- Chemistry driven by X-ray ionization:
  - Fast ion-molecule chemistry



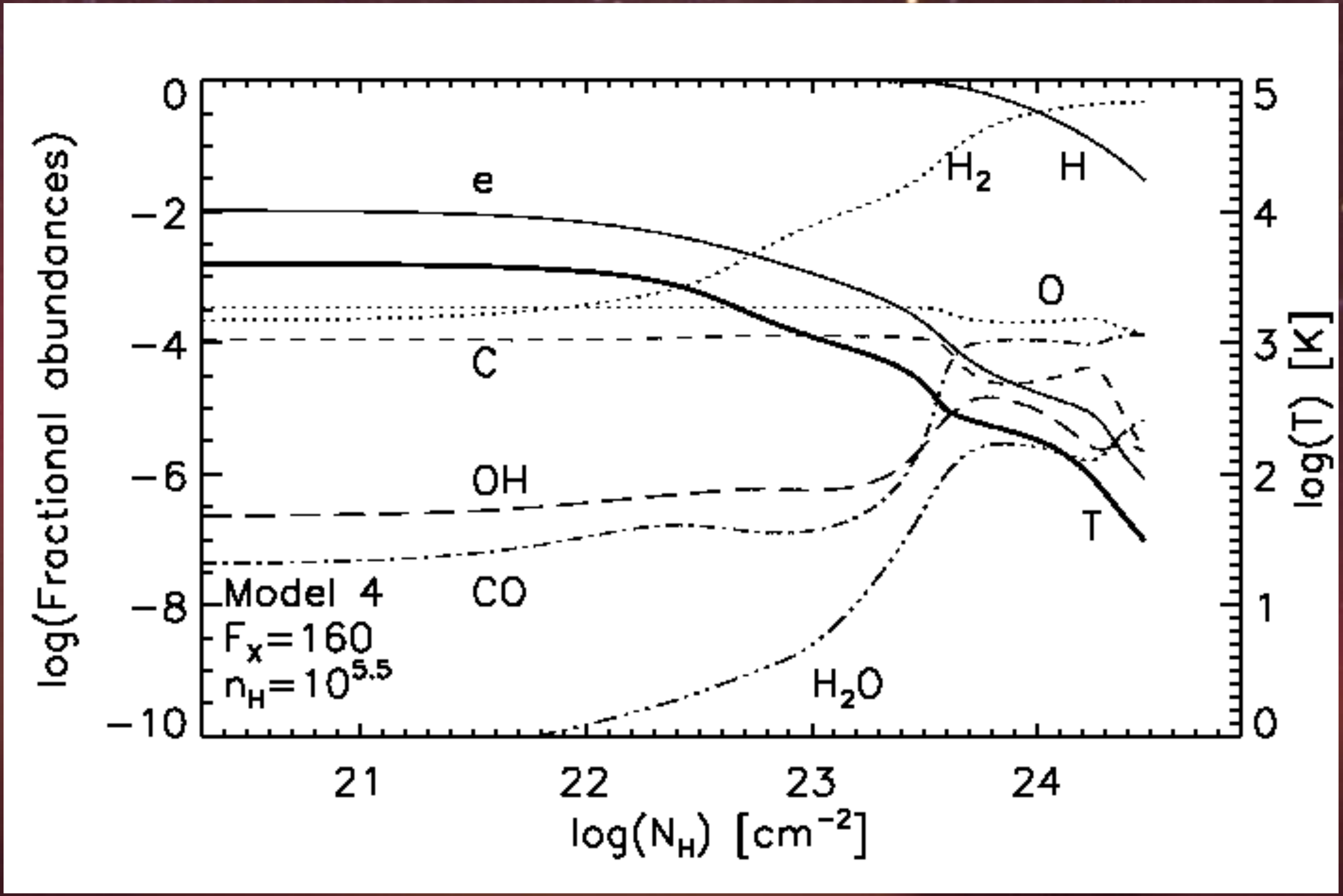
XDR energy deposition

Maloney et al. 1996

XDRs: structure

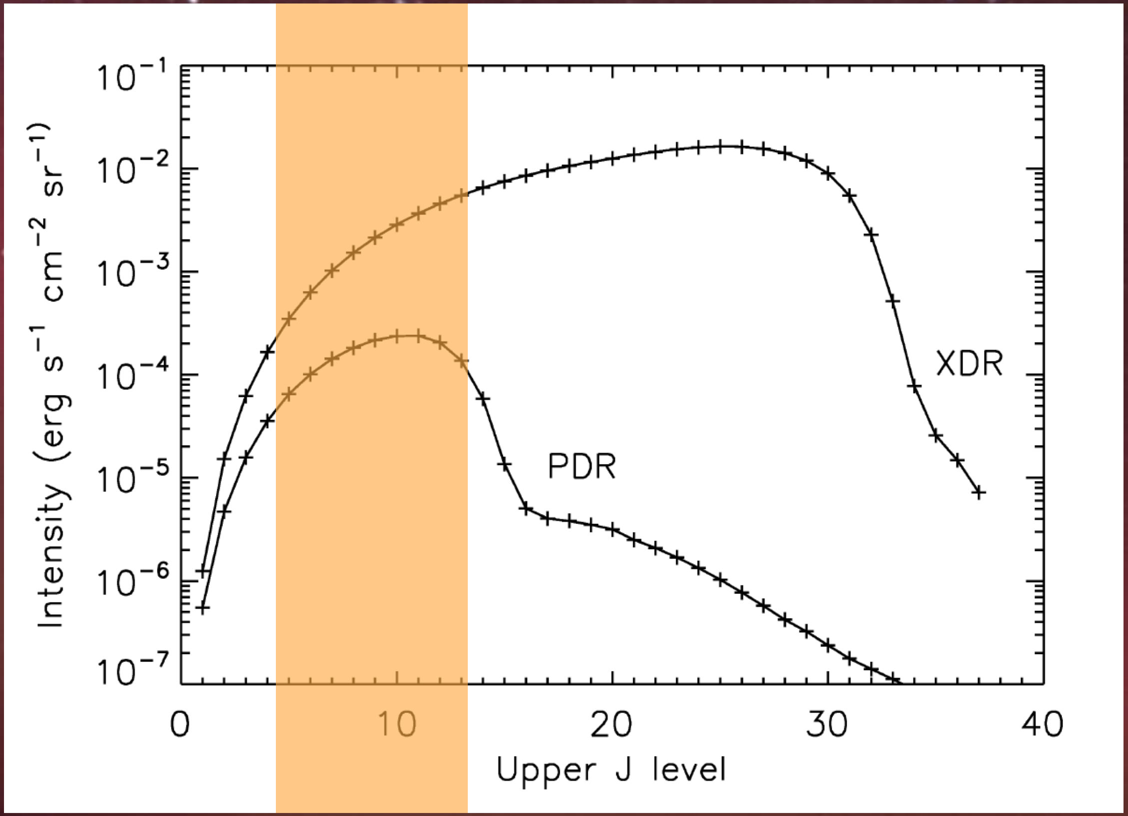


XDR structure



Meijerink & Spaans (2005)

UV vs. X-rays: CO lines



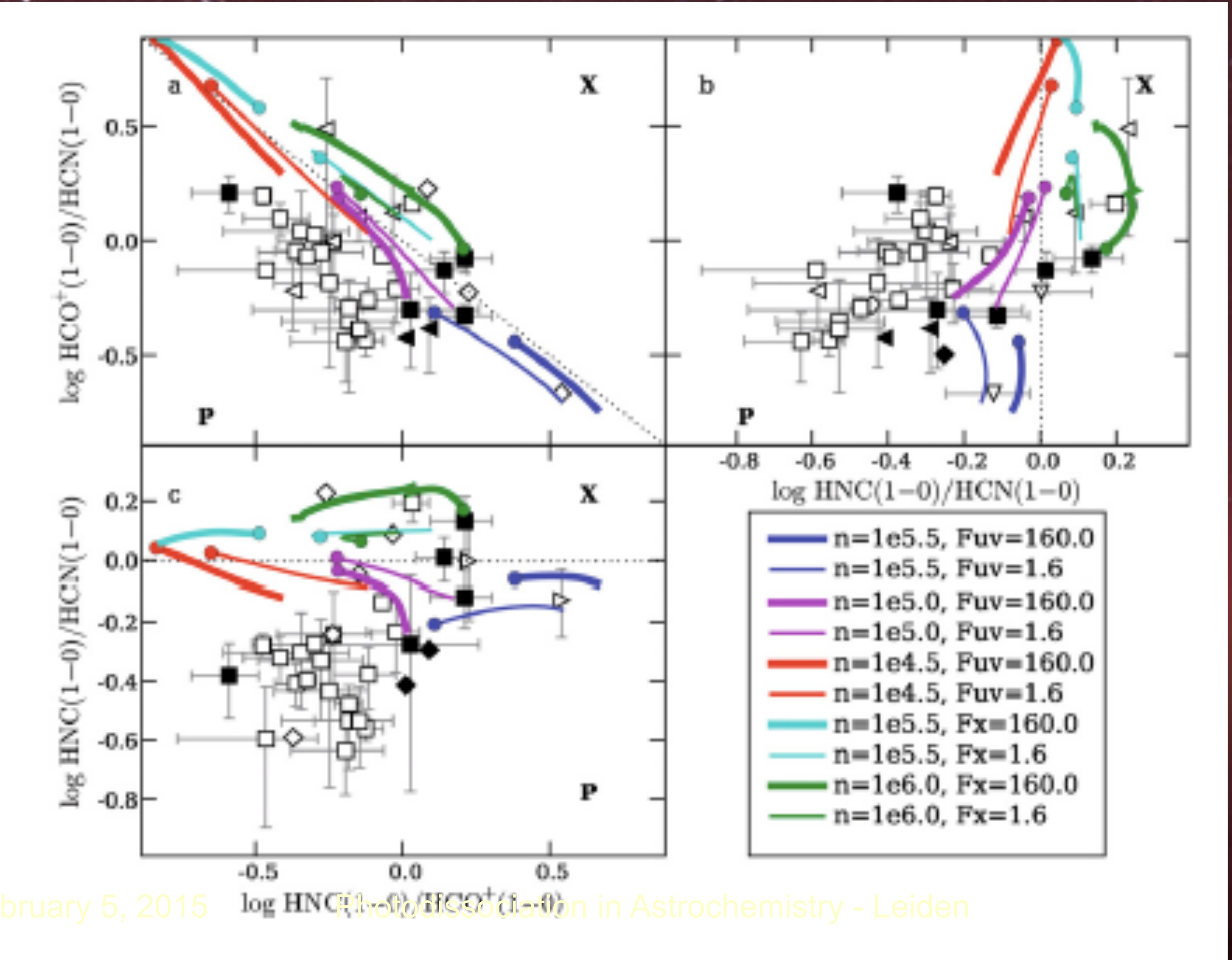
- XDRs produce larger column densities of warmer gas
- Identical incident energy densities give very different CO spectra
- Very high J CO lines are excellent XDR tracers
- Need good coverage of CO ladder

Meijerink (PhD 2006); Spaans & Meijerink (2008)

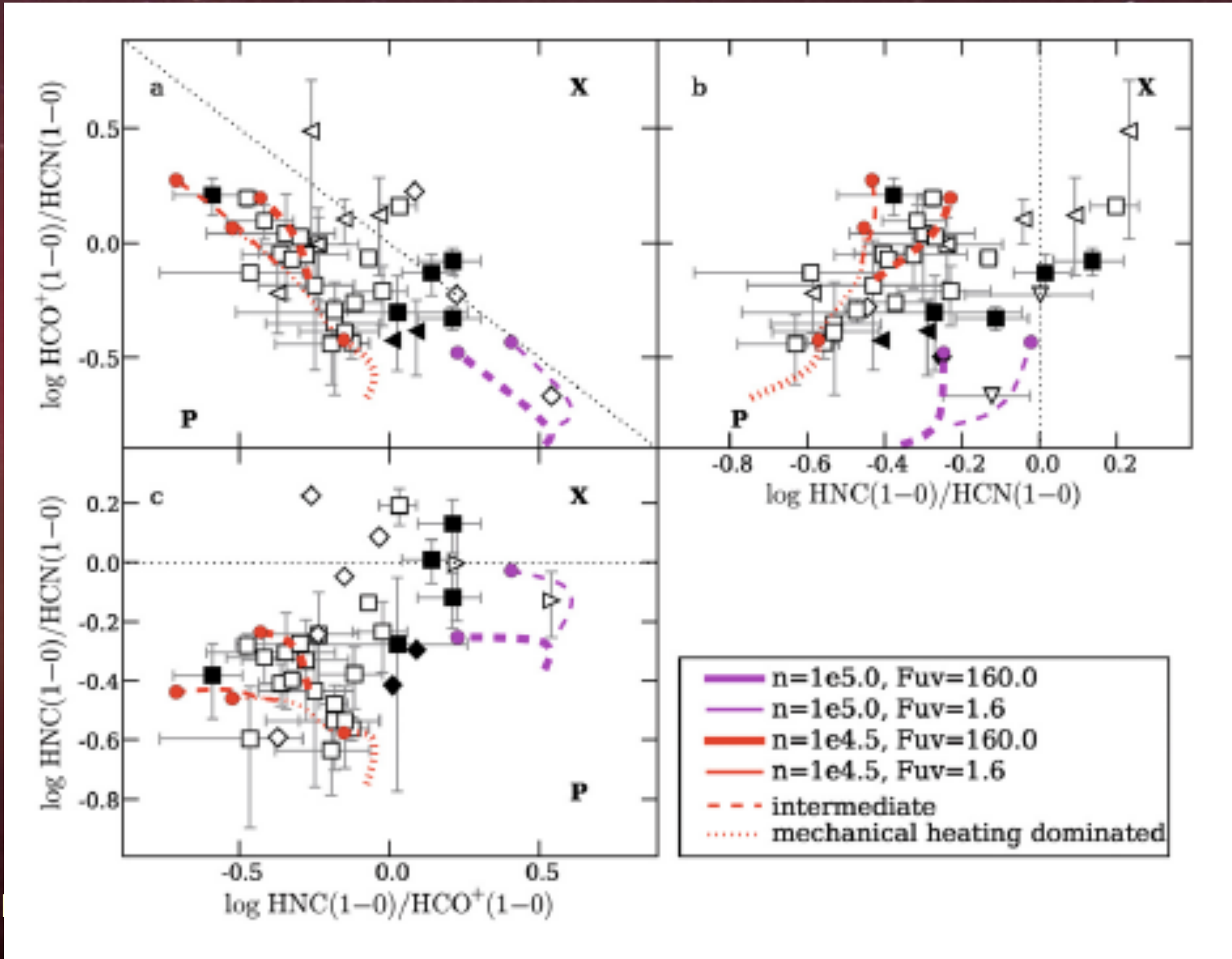
Warning: the ISM may contain...

- Quiescent molecular (and atomic) gas
- Star-forming molecular gas (PDRs)
- AGN (X-ray) excited gas (XDRs)
- Cosmic ray heated gas
- Shocks
- Mechanically (dissipation of turbulence) heated gas
- Warm very obcured gas (hot cores)

HCN, HNC and HCO^+ emission in ULIRGs (Loenen et al. 2008)



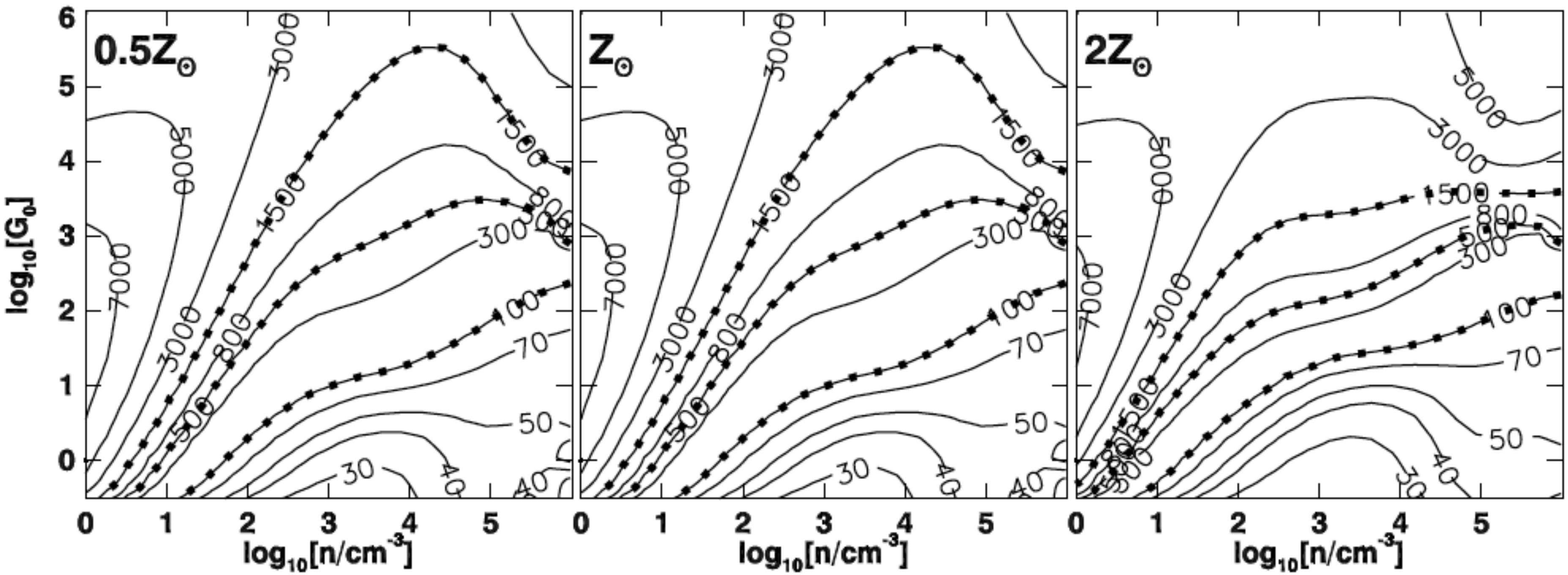
Mechanical heating is an important heating source!



Fe

A PDR model grid with mechanical heating

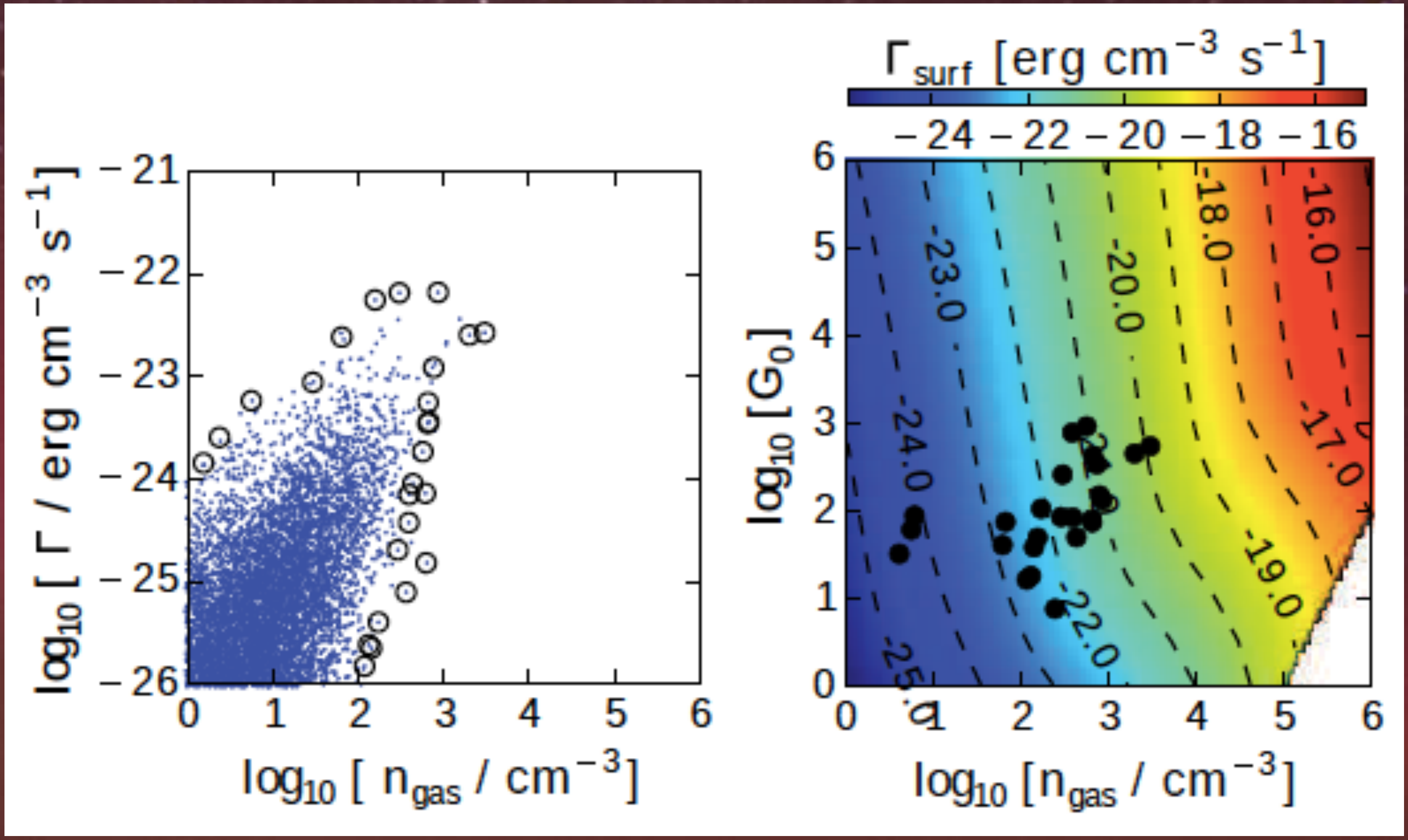
Kazandjian, RM et al. 2012, A&A, 542, A65



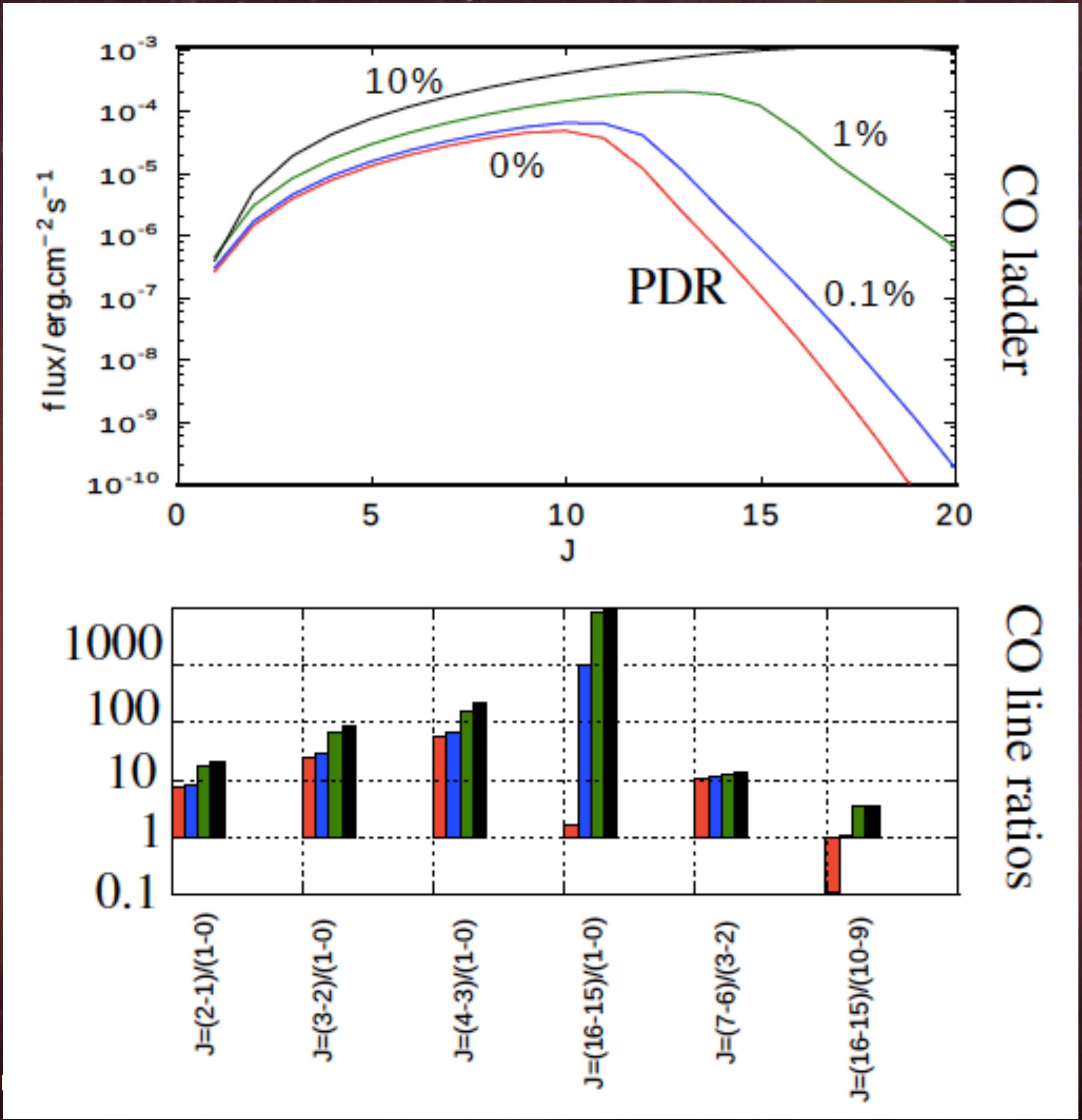
- Parameters: G_0, n, Z, Av, Γ_{mech}, cosmic ray rate

Parameterization of Γ_{mech}

Kazandjian, RM et al. 2015, A&A , 574, A127

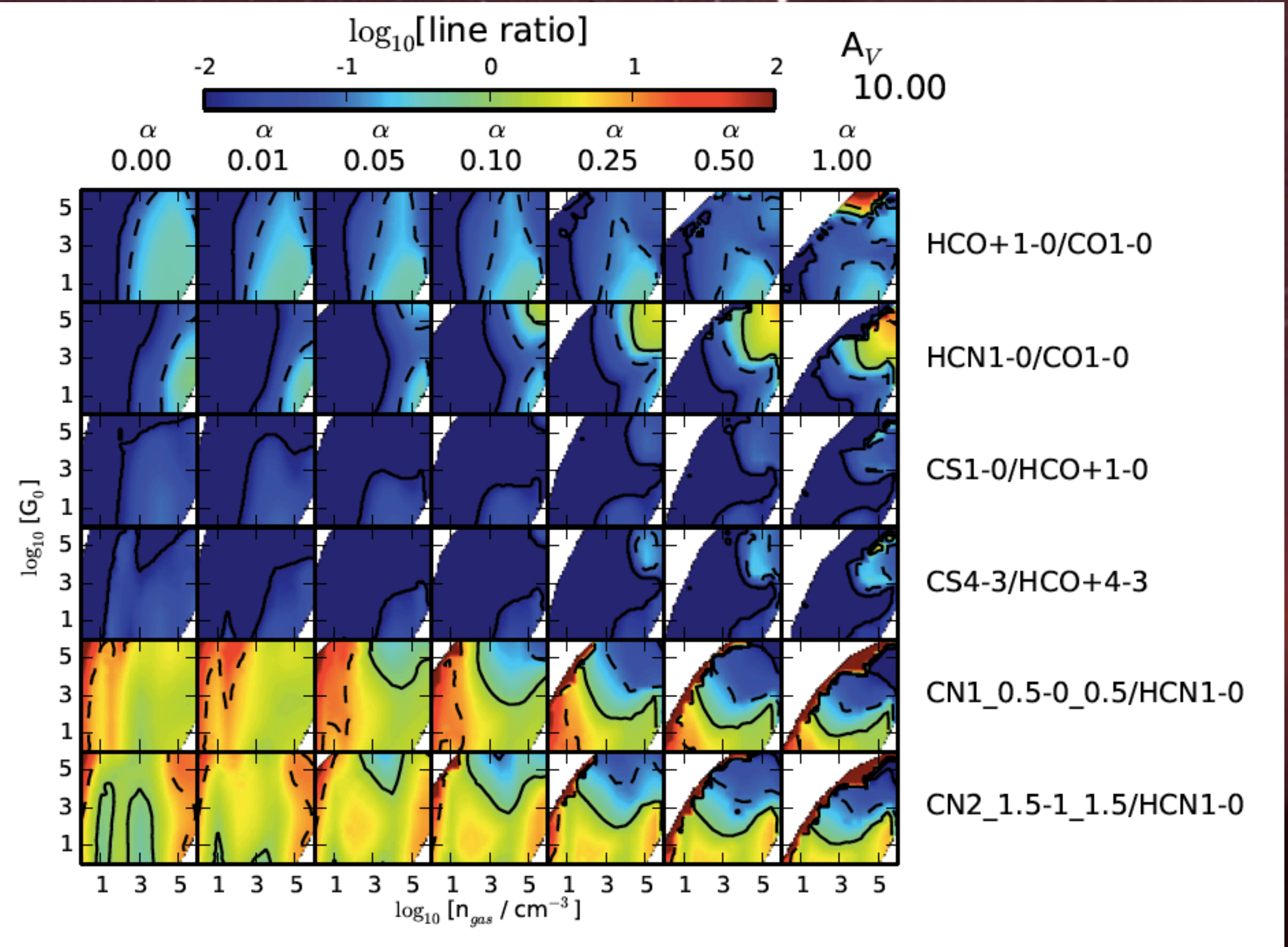


- Based on SPH simulations (Pelupessy 2005; Pelupessy & Papadopoulos): $\Gamma_{mech} = \alpha \, \Gamma_{phot}$

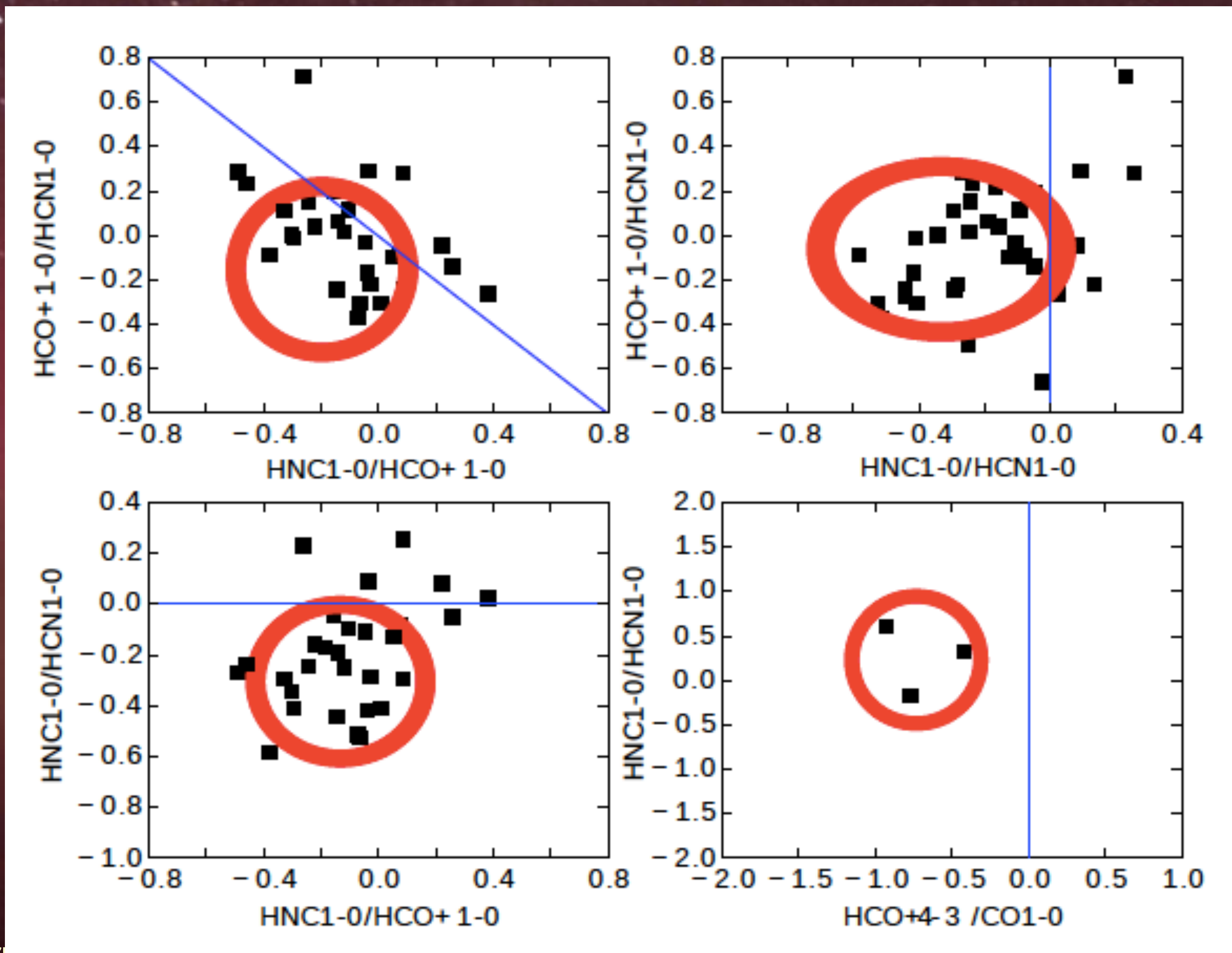


10%
1%
0%
PDR
0.1%
CO ladder
flux / erg.cm^{-2}s^{-1}
J
CO line ratios
J=(2-1)/(1-0)
J=(3-2)/(1-0)
J=(4-3)/(1-0)
J=(16-15)/(1-0)
J=(7-6)/(3-2)
J=(16-15)/(10-9)

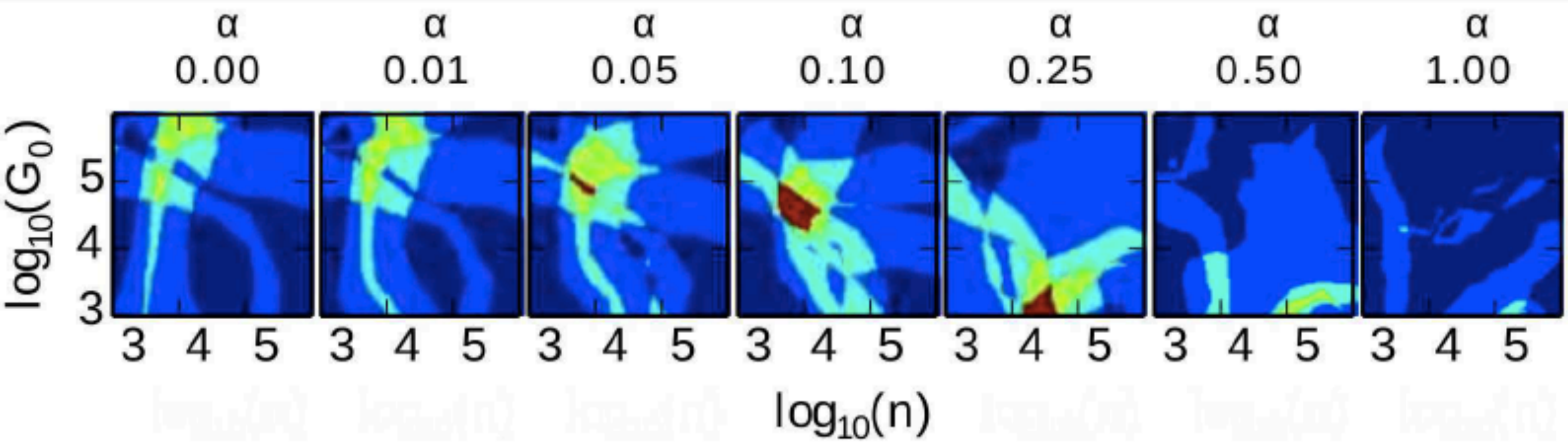
Summary of important line ratios



Returning to the ULIRGs in HCN, HNC and HCO+

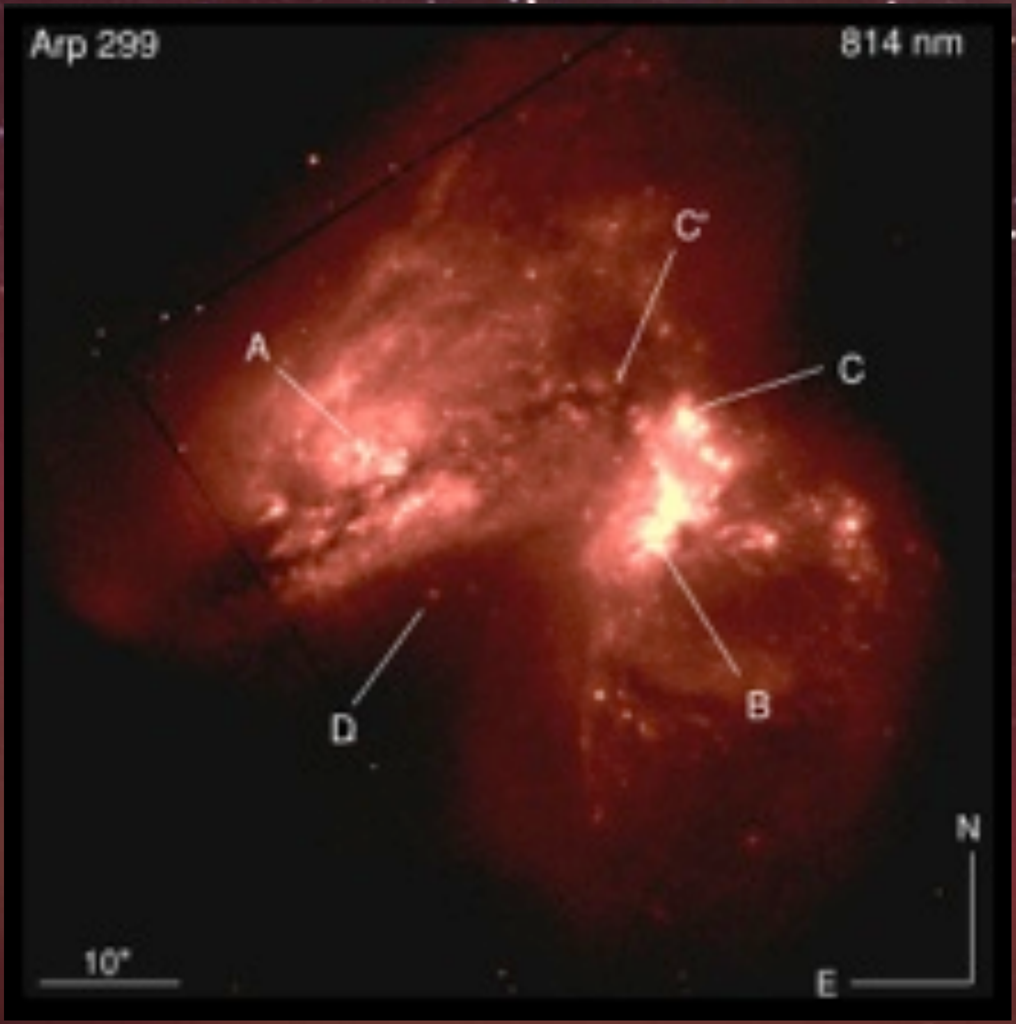


Determining the physical parameters



1.5 < HCN1-0/HNC1-0 < 4.0 , 0.6 < HCN1-0/HCO+1-0 < 3.2
0.3 < HNC1-0/HCO+1-0 < 1.0, 0.1 < HCO+4-3/CO1-0 < 0.5

Arp 299

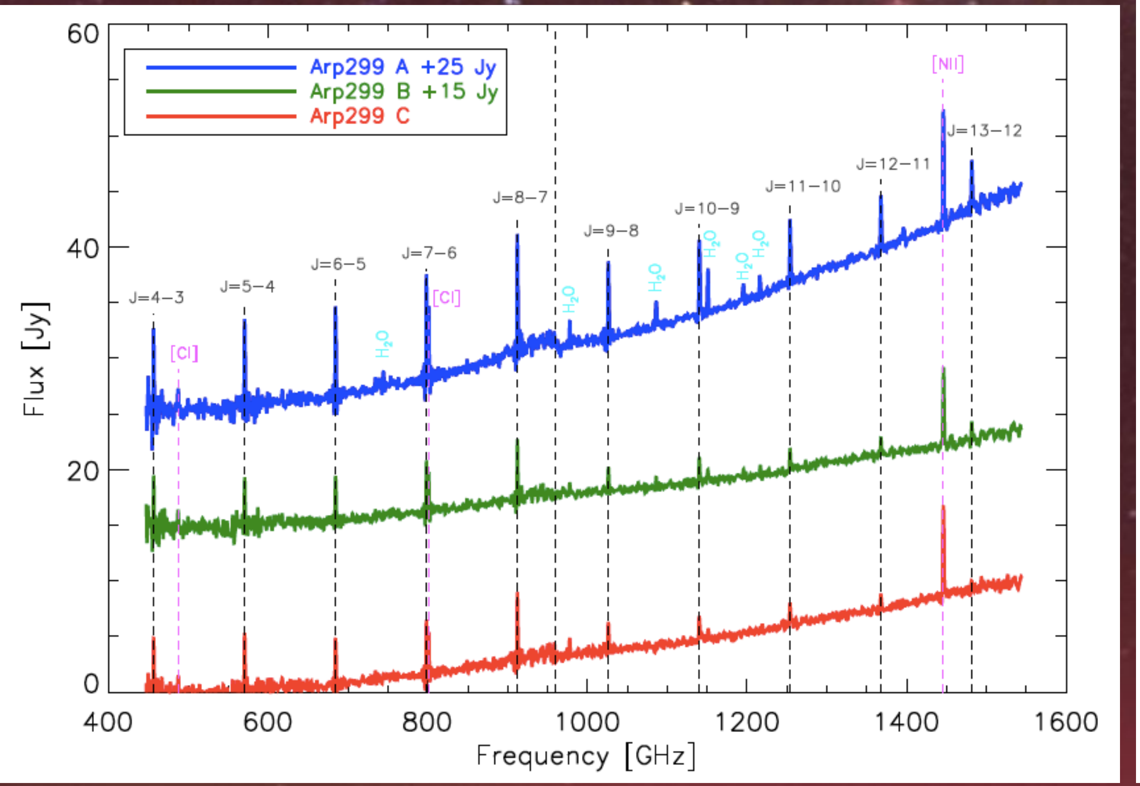


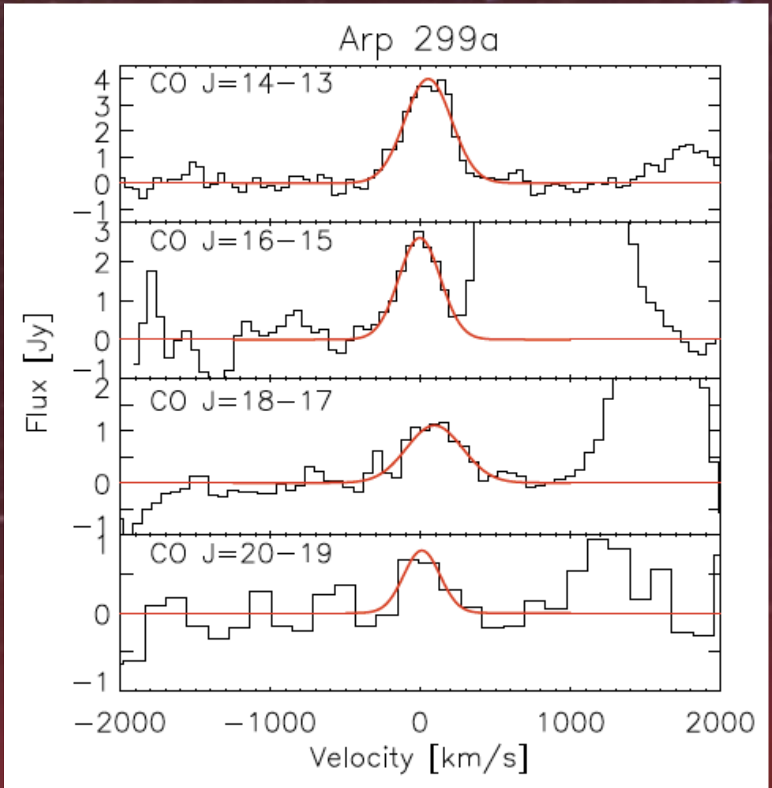
814 nm image, Neff et al. (2004)

- D_L = 50.7 Mpc
- $\text{Log}(L_{IR})$ = 11.88 L_{sun}
- Merger
- Starburst
- AGN

SPIRE + PACS Herschel observations

Rosenberg, RM et al. 2014, A&A, 568, A90



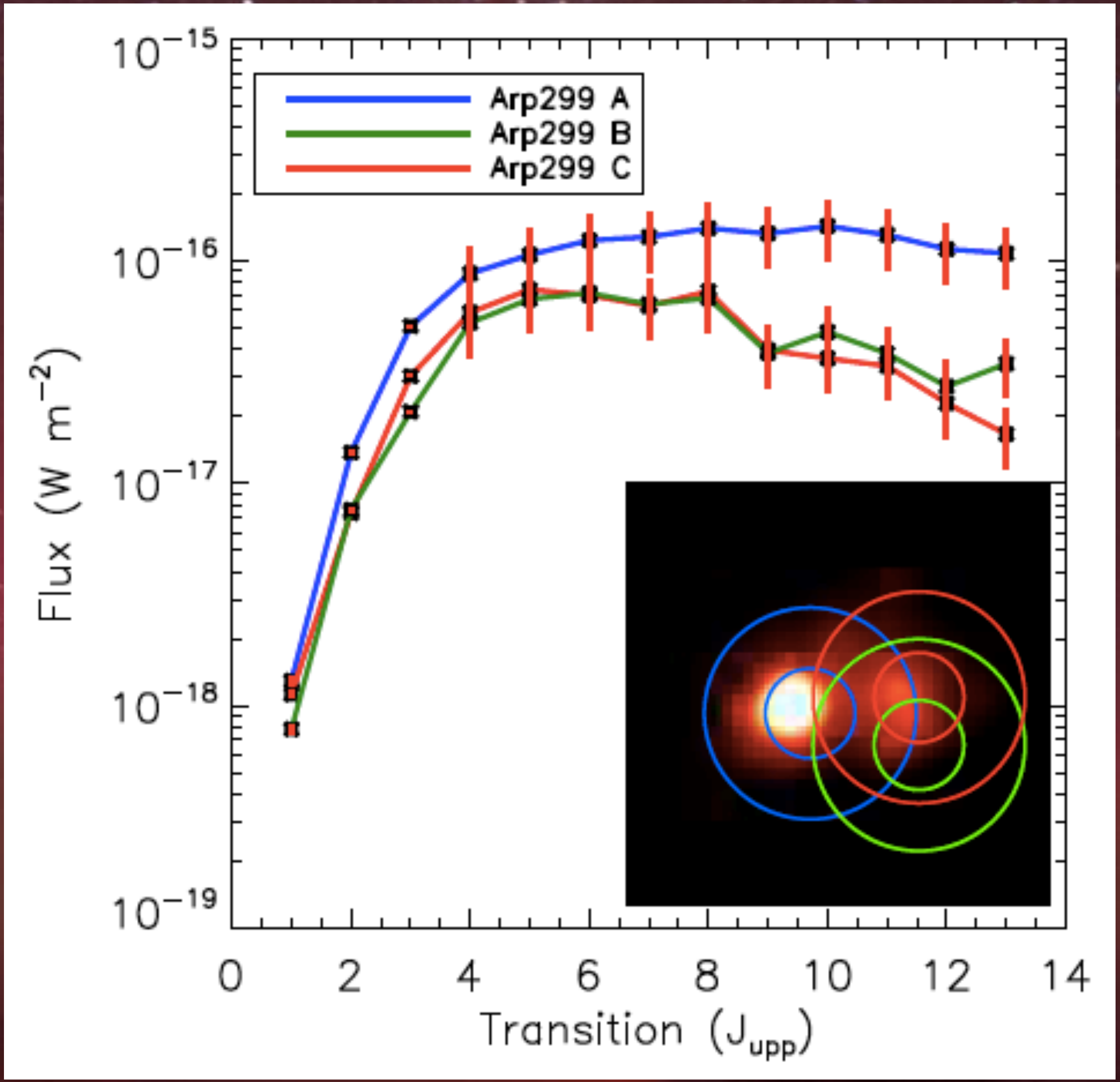


HerCULES

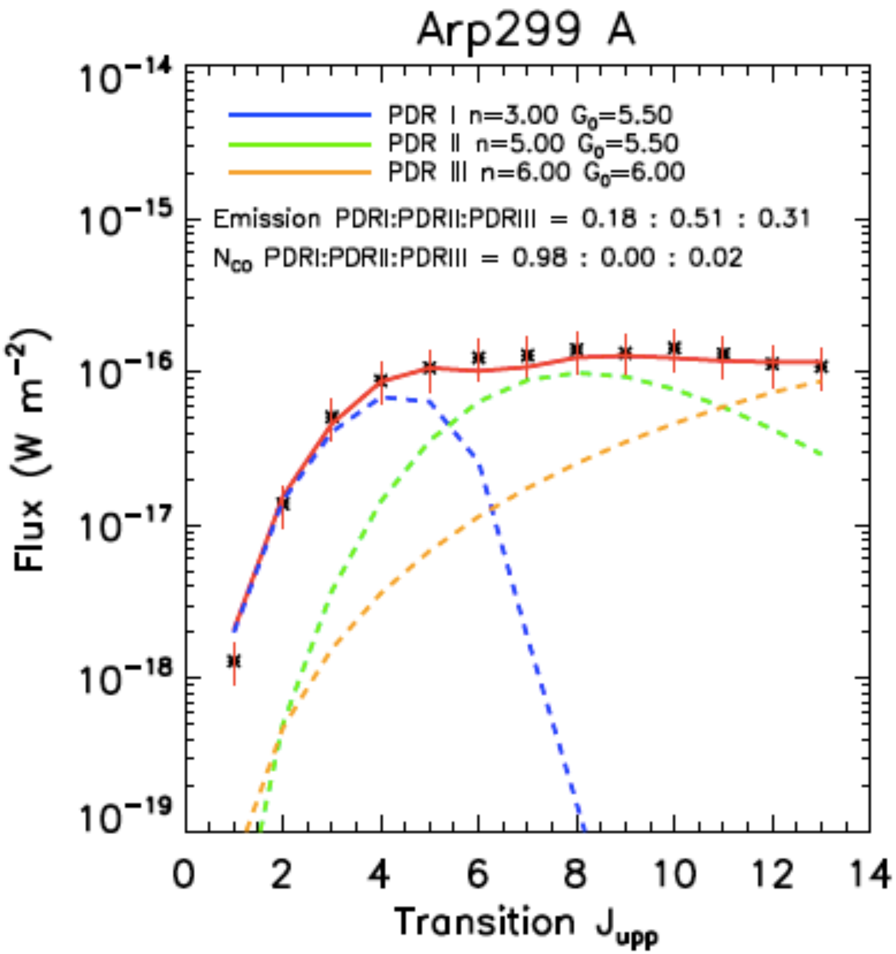
OT1 Meijerink + Hailey-Dunsheath

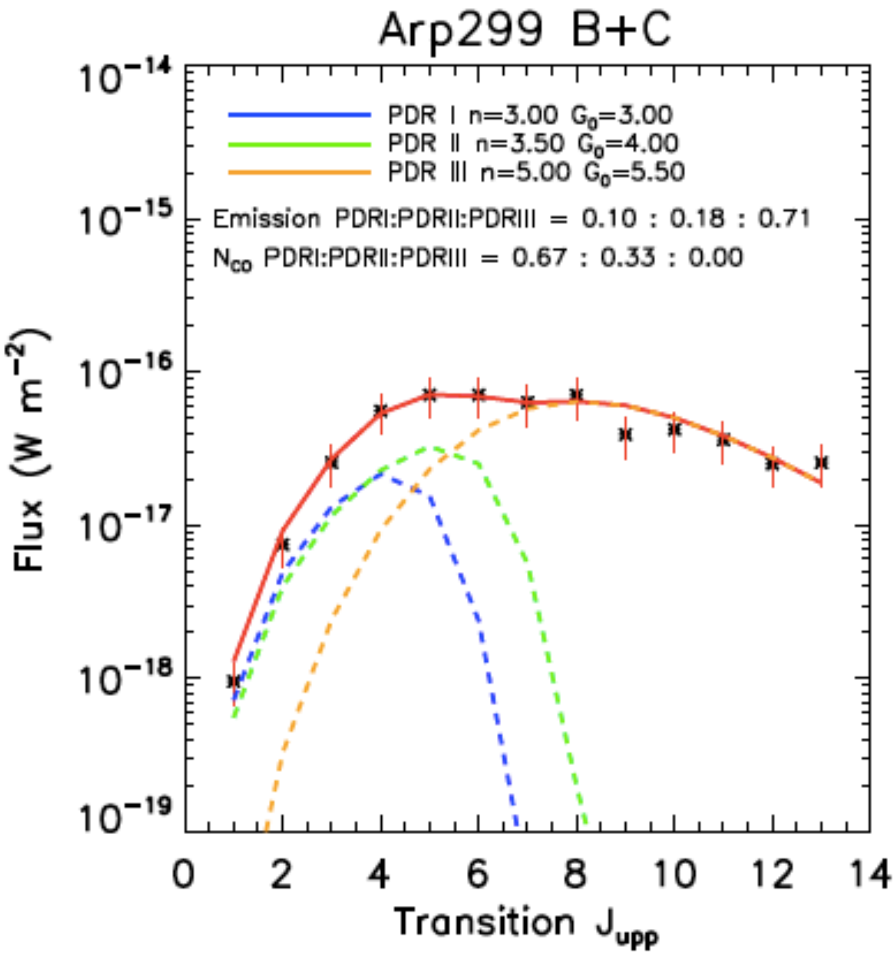
Complemented with ground based CO, ^{13}CO, HCN data from IRAM + JCMT + Sliwa et al. (2012), Imanishi & Nakanishi (2006)

CO ladders from SPIRE FTS

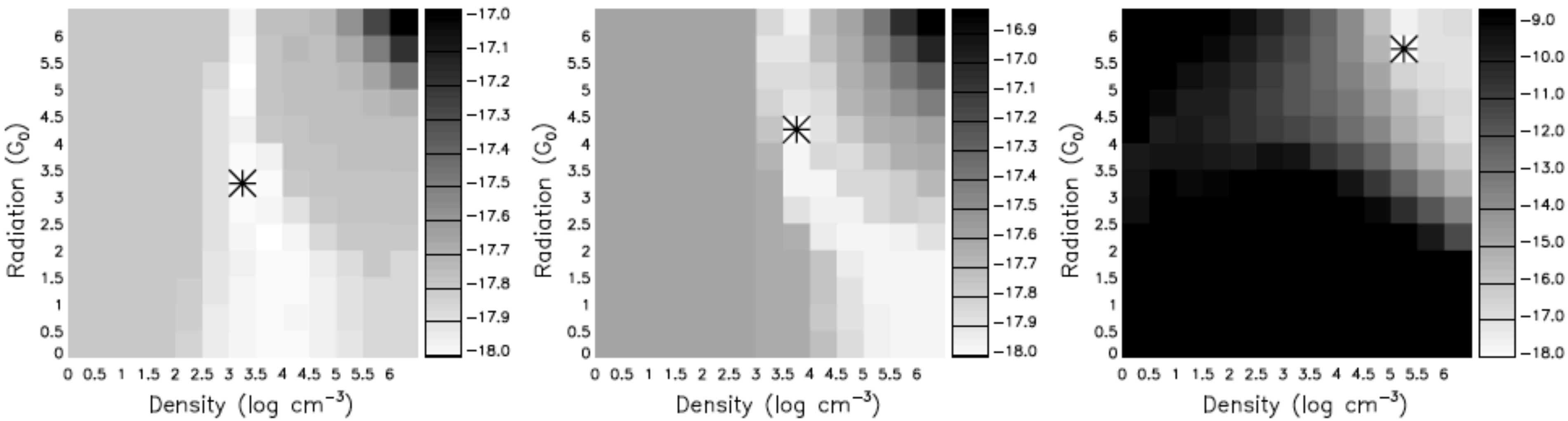


Fits with regular PDRs

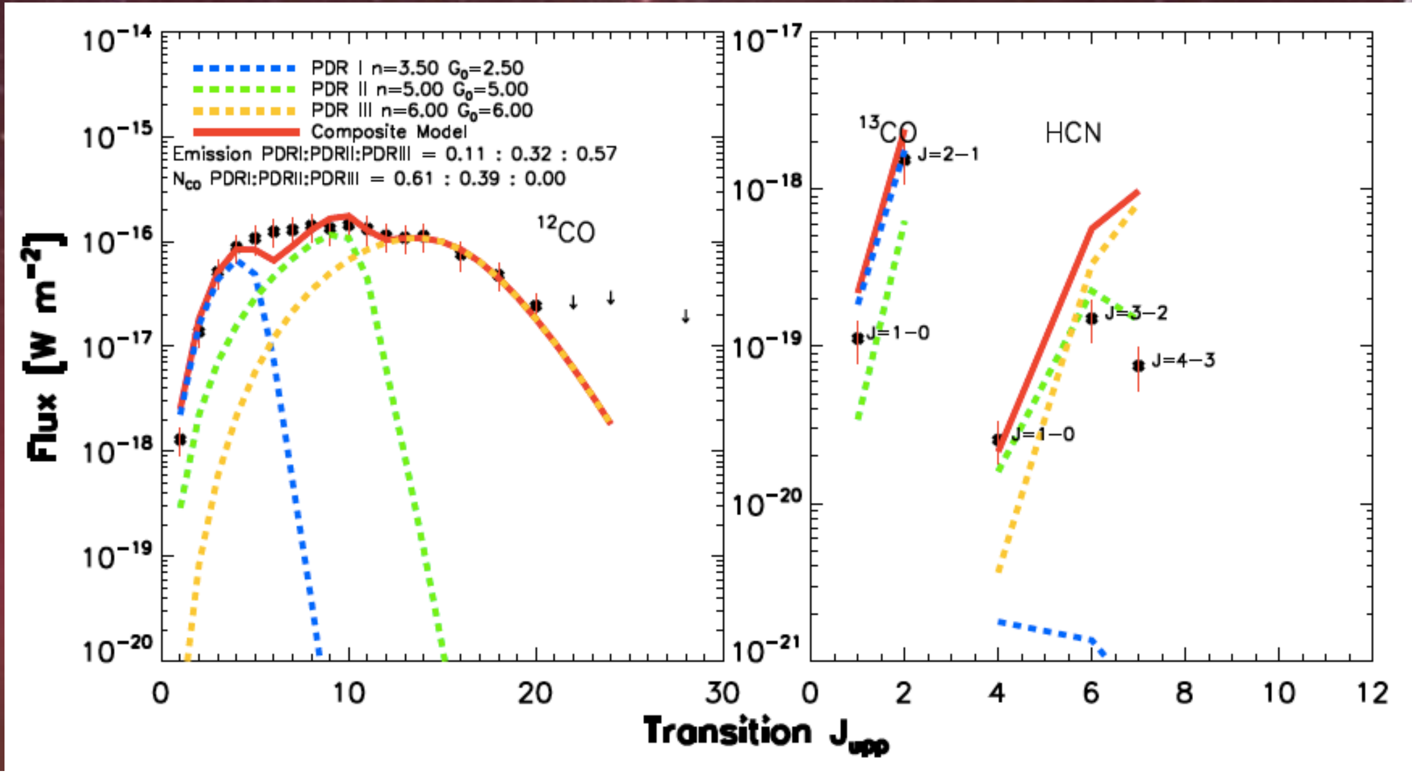




Degeneracy plots of PDR fit

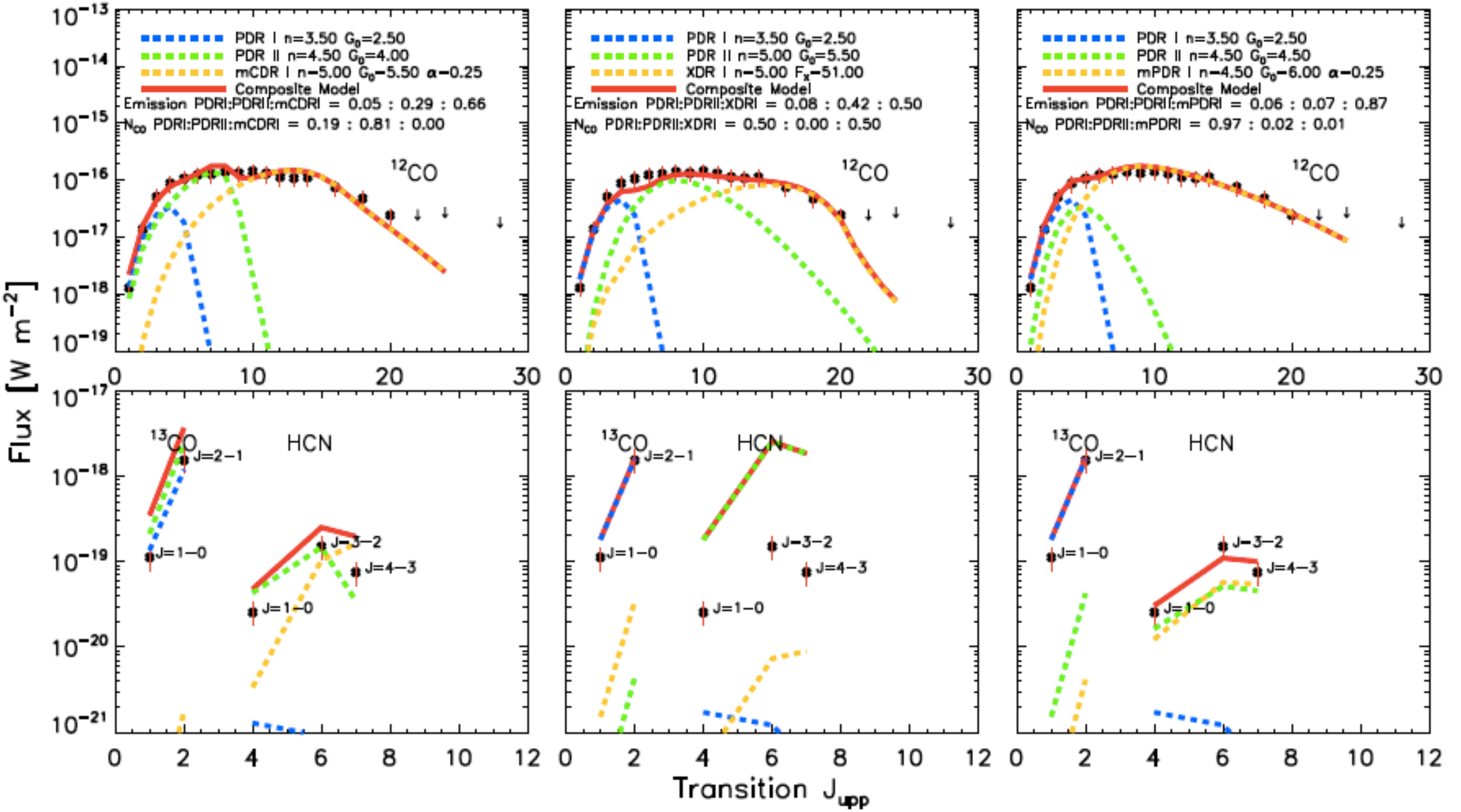


PDR fits with additional constraints from ^{13}CO and HCN



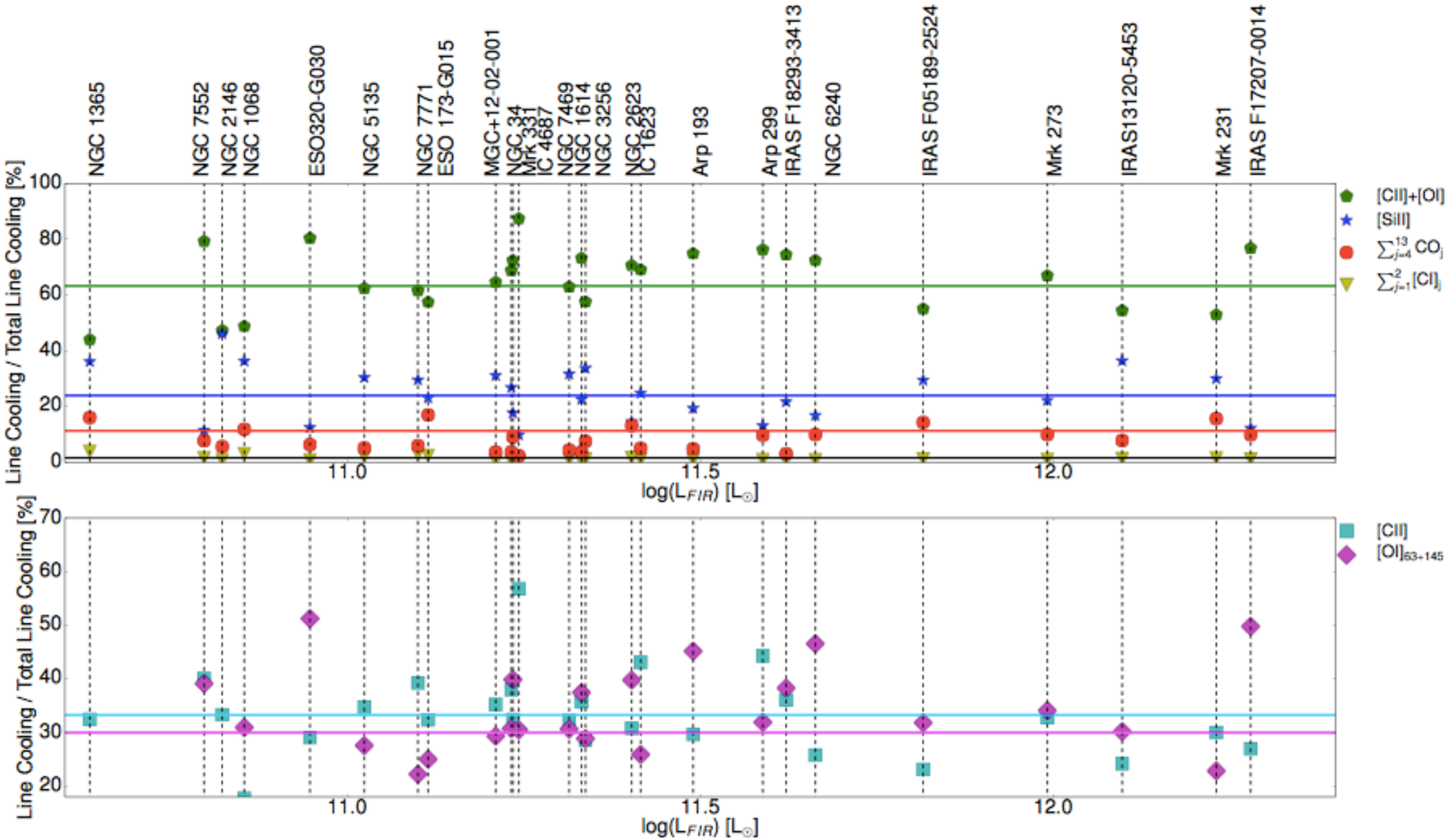
Component	Density $\log(n_H)$ $\log[cm^{-3}]$	$\log(G)$ G_0	$\log(N_{CO})$ $\log[cm^{-2}]$	$\log(N_{H2})$ $\log[cm^{-2}]$	Ω^a	$C_{em}{}^b$	$C_{N_{CO}}{}^c$	$Mass_{N_{H2}}{}^d$ $M_\odot$
M_{tot}: 2×10^9 $M_\odot$								
PDR I	3.5	2.5	17.1	21.5	1.2	0.11	0.61	2×10^9
PDR II	5.0	5.0	18.2	21.9	0.06	0.32	0.39	3×10^8
PDR III	6.0	6.0	16.7	21.2	0.006	0.57	< 0.01	6×10^6

Alternative fitting with mCDR, XDR, and mPDR



HerCULES data summary

Rosenberg et al. 2014, ApJ, accepted, arXiv:1501.02985

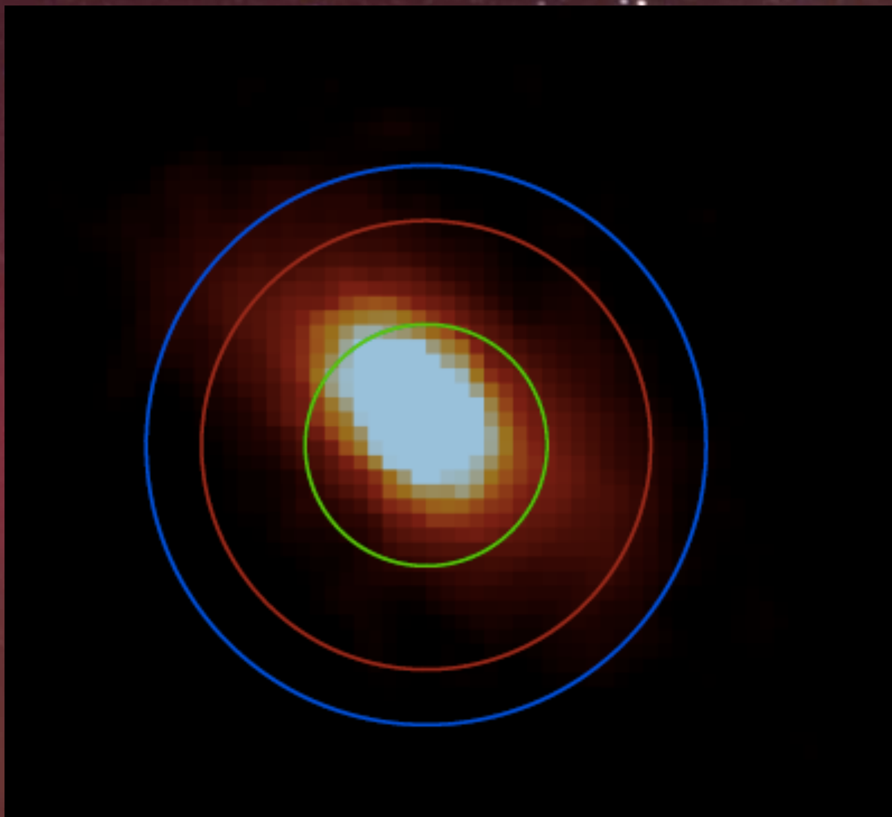


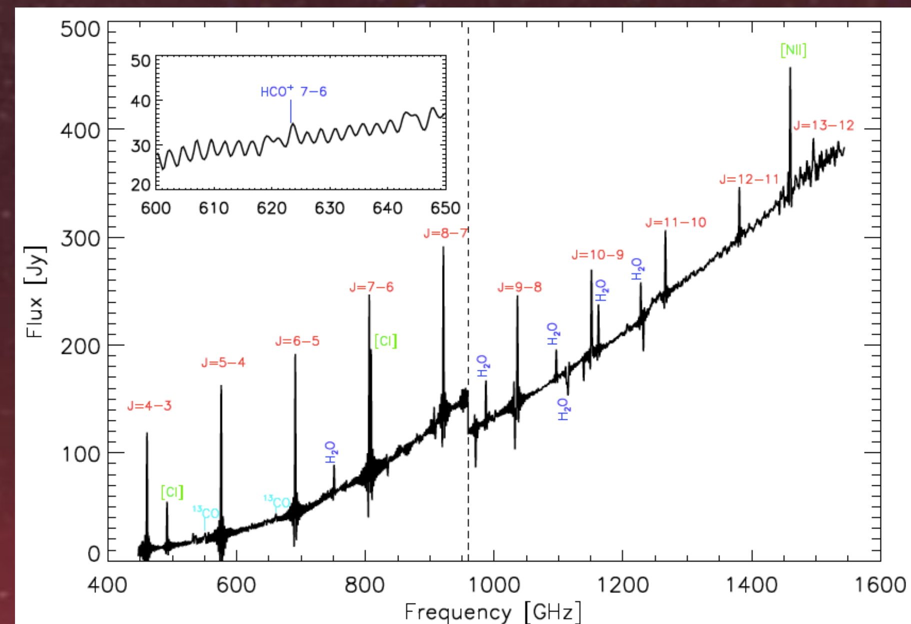
Conclusions

- Mechanical heating and cosmic rays affect the chemical and thermal balance of the ISM in ULIRGs
- High density tracers such as HCN, HNC, and HCO^+ are essential in constraining parameter space
- **NOTE:** Revisited nitrogen chemistry and high temperature chemistry need to be implemented, and may alter results.
- Next steps: It is needed to combine high resolution ALMA observations with
  - Maps from post-processed hydro-simulations or SLEDs obtained from density PDFs.
  - Simulations that allow the mutual feedback of chemistry and dynamics.

NGC 253

(Rosenberg et al. 2014)

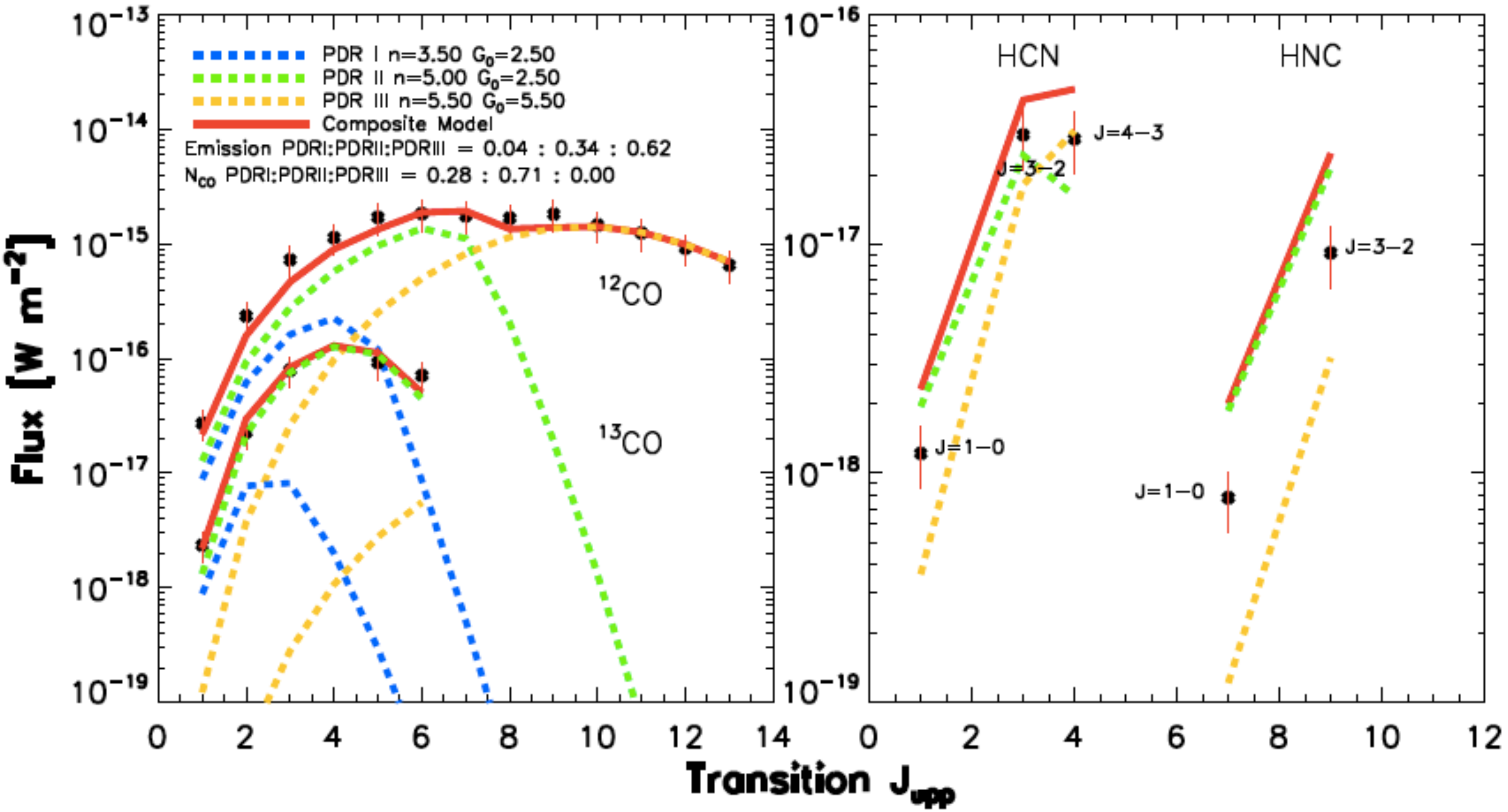




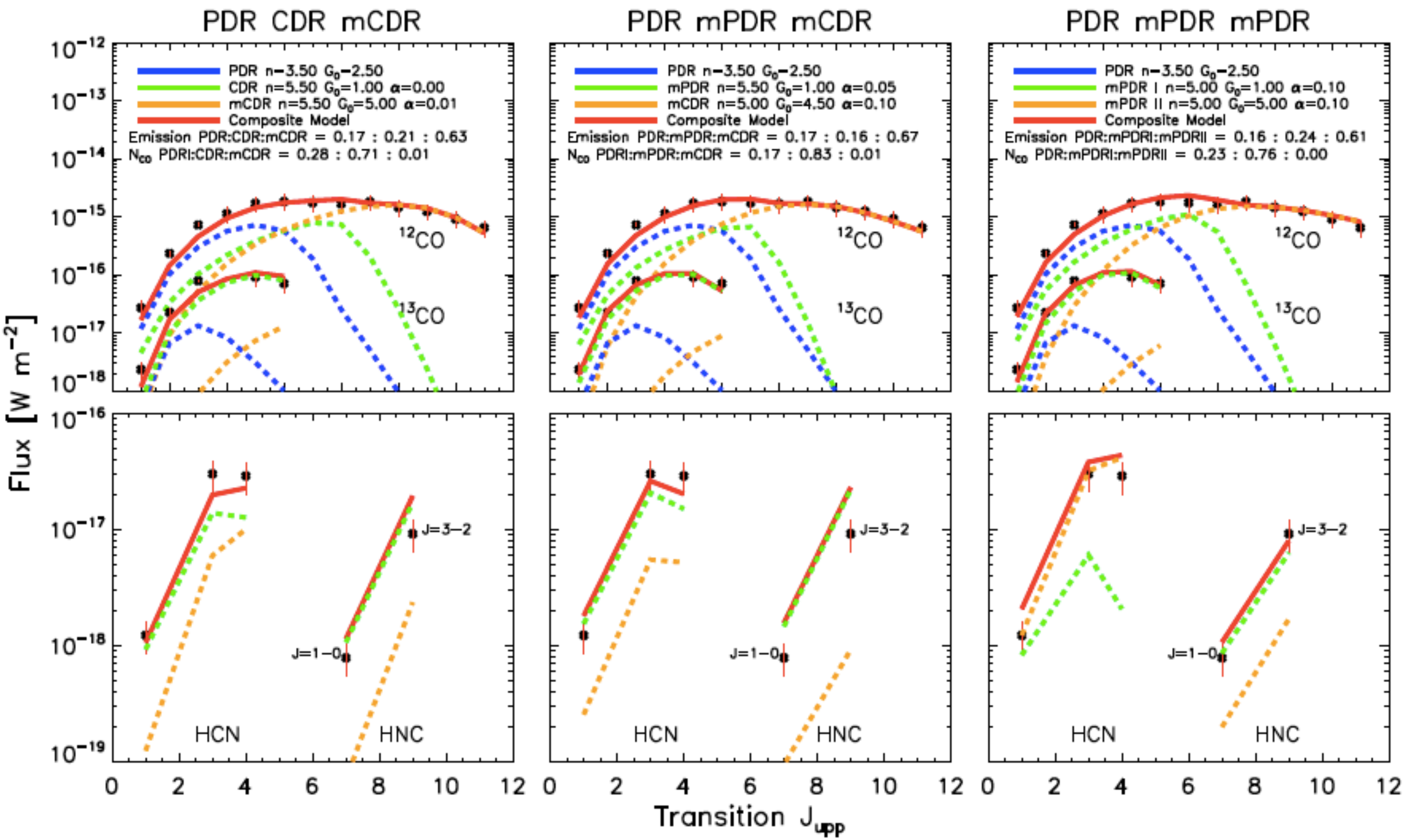
- D_L = 2.5 Mpc
- Log(L_{IR}) = 10.3 L_{sun}
- Starburst

Complemented with ground based CO, ^{13}CO, and HCN data + Israel et al. (1995) + Knudsen et al. (2007)

Fit with regular PDR models



CO ladder fits with various PDR models



Models parameters of the three fits

Component	Density $\log(n_H)$ $\log[cm^{-3}]$	$\log(G)$ G_0	$\log(N_{CO})$ $\log[cm^{-2}]$	$\log(N_{H_2})$ $\log[cm^{-2}]$	α %	Ω^a	$C_{em}{}^b$	$C_{N_{CO}}{}^c$	$Mass_{N_{H_2}}{}^d$ $M_\odot$
Case 1 M_{tot}: 8.4×10^7 $M_\odot$									
mPDR	3.5	2.5	17.1	21.5	1	6.0	0.17	0.28	5.7×10^7
CDR	5.5	1.0	17.8	21.4	0	3.0	0.21	0.71	2.3×10^7
mCDR	5.5	5.0	16.8	21.4	1	0.5	0.63	0.01	3.8×10^6
Case 2 M_{tot}: 1.1×10^8 $M_\odot$									
mPDR I	3.5	2.5	17.1	21.5	1	6.0	0.17	0.17	5.7×10^7
mPDR II	5.5	1.0	17.8	21.4	5	5.0	0.16	0.83	4.5×10^7
mCDR	5.0	4.5	16.2	21.2	10	1.5	0.67	< 0.01	7.1×10^6
Case 3 M_{tot}: 1.1×10^8 $M_\odot$									
mPDR I	3.5	2.5	17.1	21.5	1	6.0	0.16	0.23	5.7×10^7
mPDR II	5.0	1.0	17.7	21.4	10	5.0	0.24	0.76	3.8×10^7
mPDR III	5.0	5.0	15.5	21.0	10	5.0	0.61	< 0.01	1.5×10^7