The Excited and Exciting ISM in Galaxies: PDRs, XDRs and Shocks as Probes and Triggers

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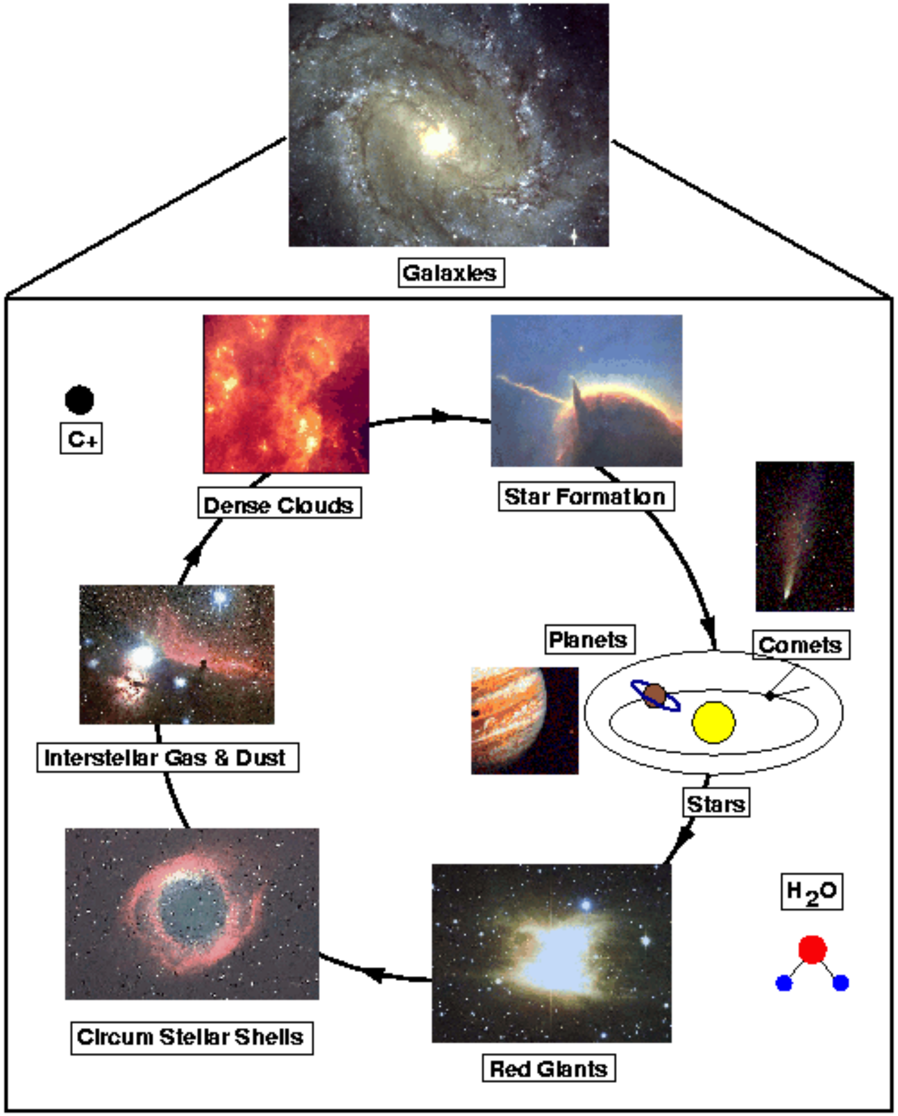


- Concentrate on irradiated turbulent gas in star-forming regions and close to AGN ↔ **feedback**

- PDRs (UV/SB)
- XDRs (X-ray/AGN)
- CDRs (SNe)
- Shocks

PDRs: 6 < E < 13.6 eV

- Heating: Photo-electric emission from grains and cosmic rays
- Cooling: Fine-structure lines like [OI] 63, 145; [CII] 158 μm and emission by H_2, CO, H_2O
- 10 eV photon penetrates 0.5 mag of dust
- Heating efficiency ~ 0.1 – 1.0 %

XDRs: E > 1 keV

- Heating: X-ray photo-ionization -->
  fast electrons - Coulomb heating
  H and H_2vib excitation - UV
- Cooling: [FeII] 1.26, 1.64; [OI] 63;
  [CII] 158; [SiII] 35 µm; thermal H_2vib; gas-dust
- 1 keV photon penetrates 10^{22} cm^{-2} of N_H
- Heating efficiency ~ 10 – 50 %

Energetics

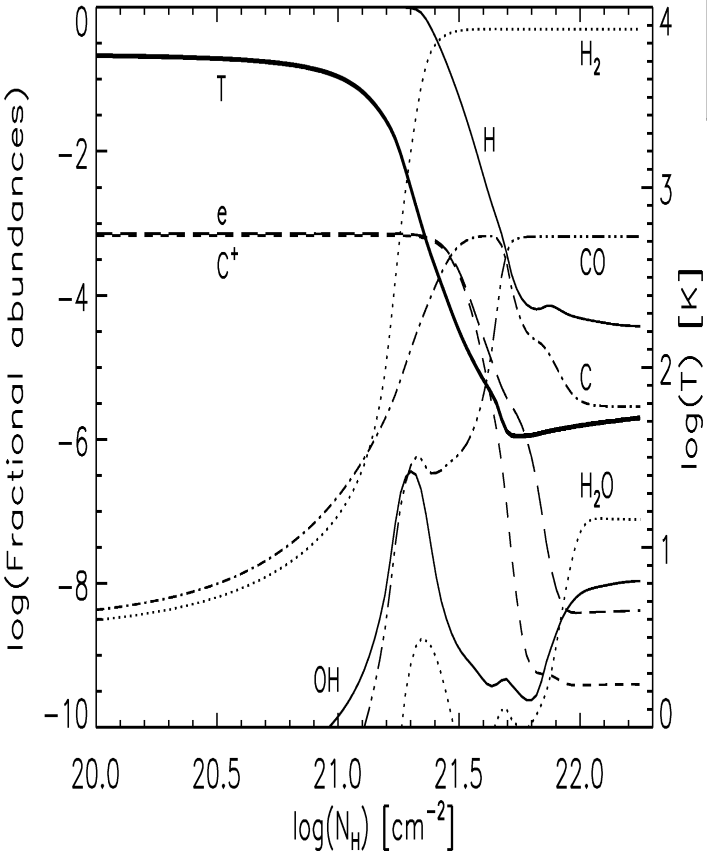
$G_0 = 1.6\times10^{-3}$ erg cm^{-2} s^{-1} Habing flux over 6-13.6 eV

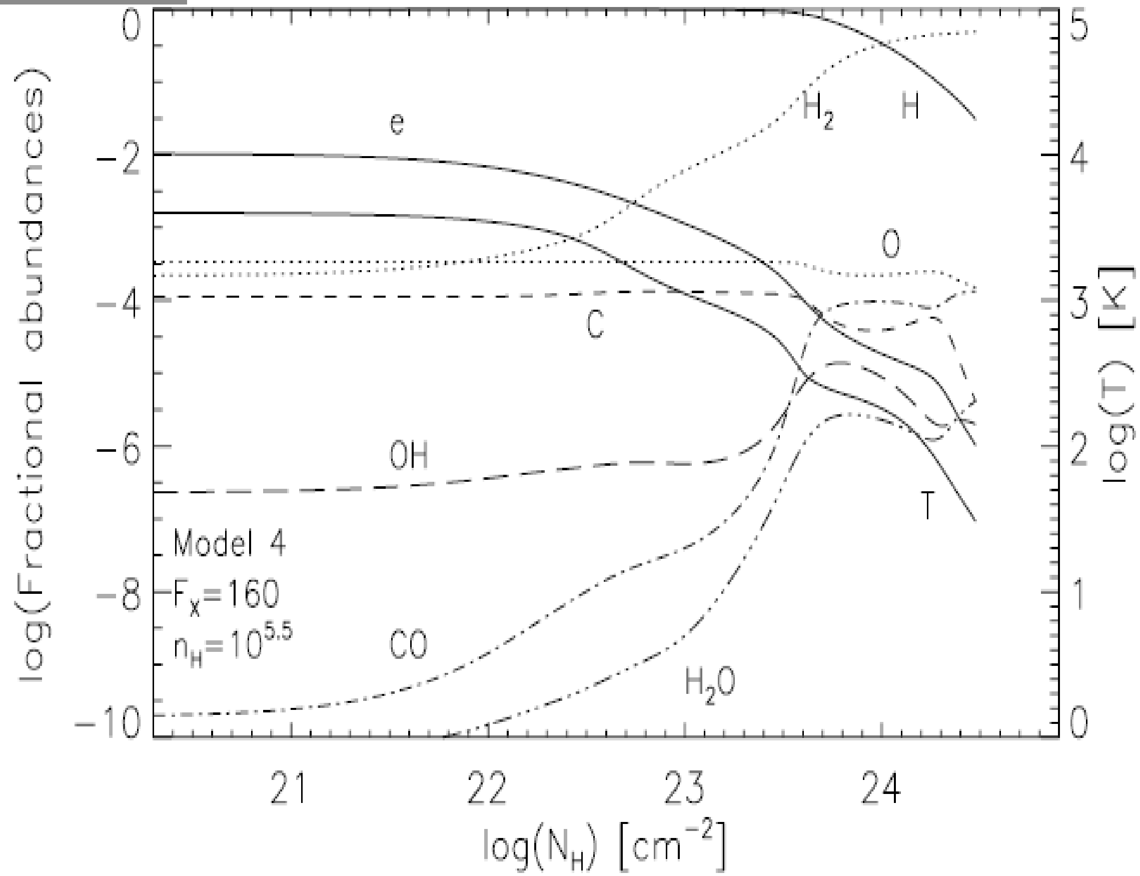
Orion Bar has 10^5 G_0

$F_X = 84\ L_{44}\ r_2^{-2}$ erg cm^{-2} s^{-1}

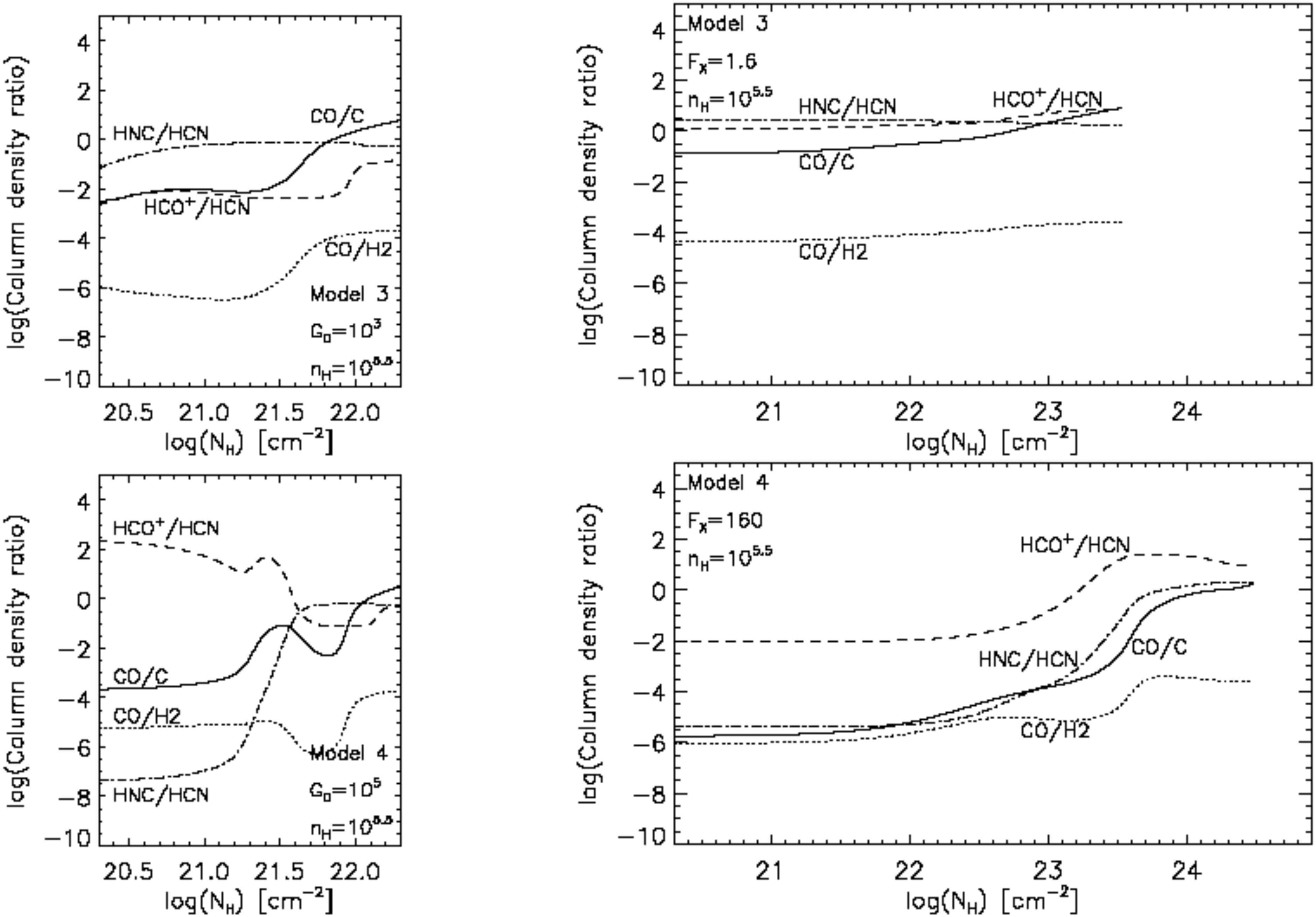
X-ray flux over 1-100 keV with a power law $E^{-0.9}$

Think of Seyfert nucleus at 100 pc



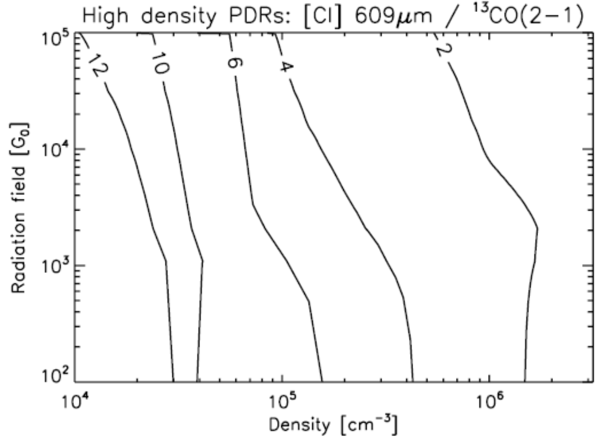


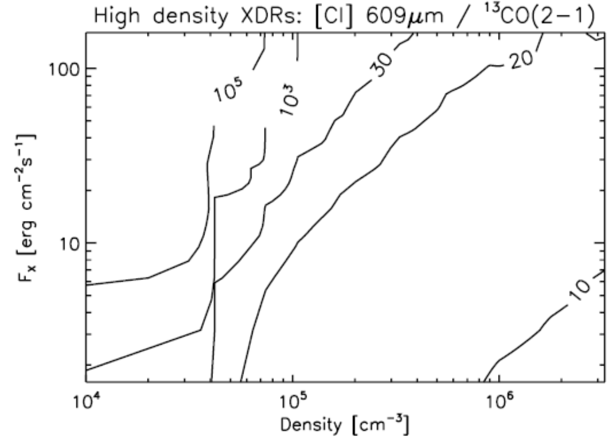
- PDR (left) with $n=10^{5.5}$ cm^{-3}, $G_0=10^5$
- XDR with $n=10^{5.5}$ cm^{-3}, $F_X=160$ erg s^{-1} cm^{-2}
- Note N_H dependence H_2, C^+, C, CO, OH, etc.

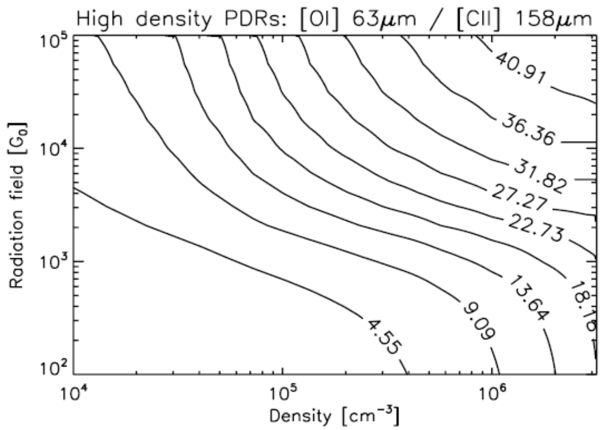

log(Column density ratio)
log(N_H) [cm^-2]
CO/C
HNC/HCN
HCO+/HCN
CO/H2
Model 3
G0=10^3
n_H=10^6.5
Model 3
Fx=1.6
n_H=10^5.5
HNC/HCN
HCO+/HCN
CO/C
CO/H2
HCO+/HCN
CO/C
CO/H2
Model 4
G0=10^5
n_H=10^6.5
HNC/HCN
Model 4
Fx=160
n_H=10^5.5
HCO+/HCN
HNC/HCN
CO/C
CO/H2

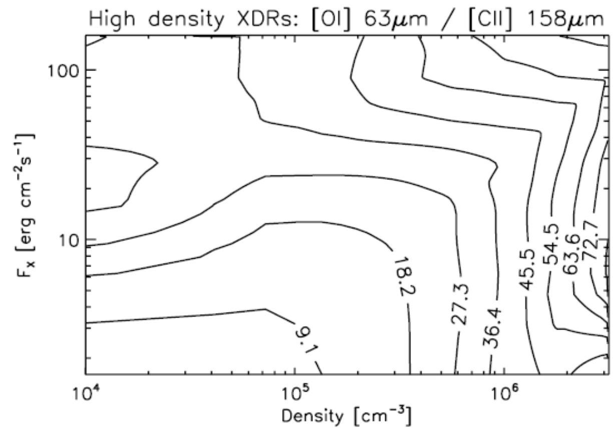
Fine-structure lines

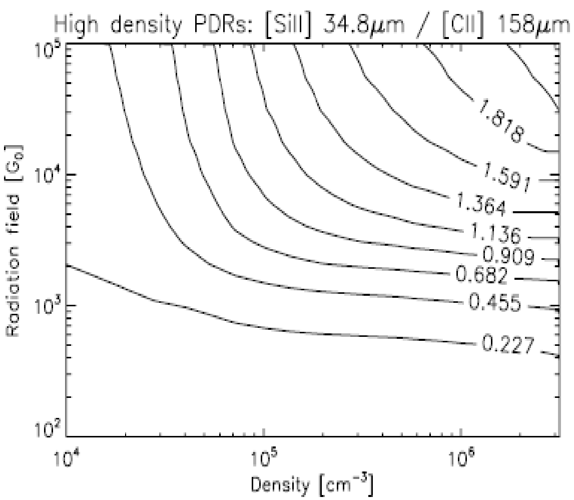
(Kaufman et al. 1999; Meijerink et al. 2007)

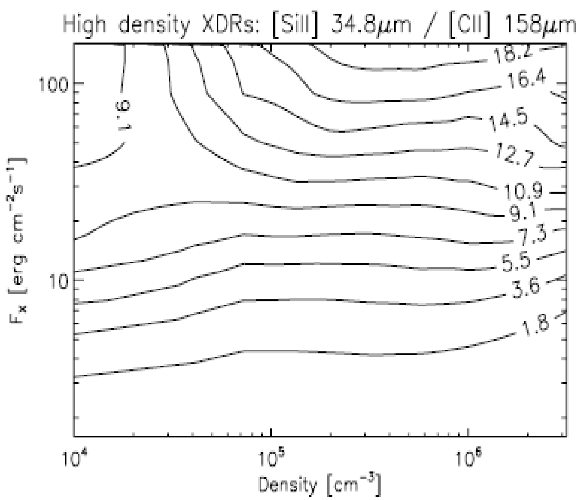






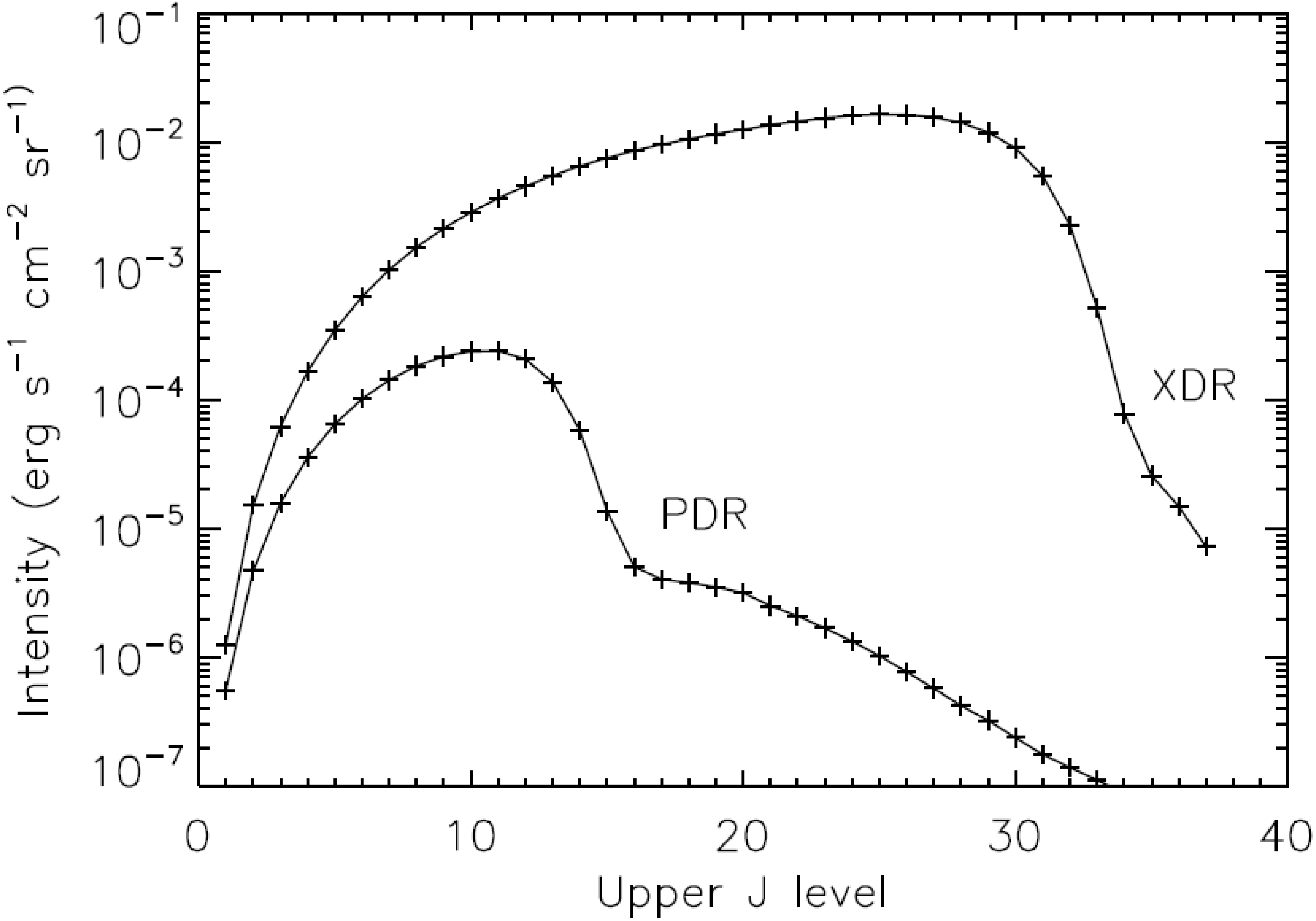




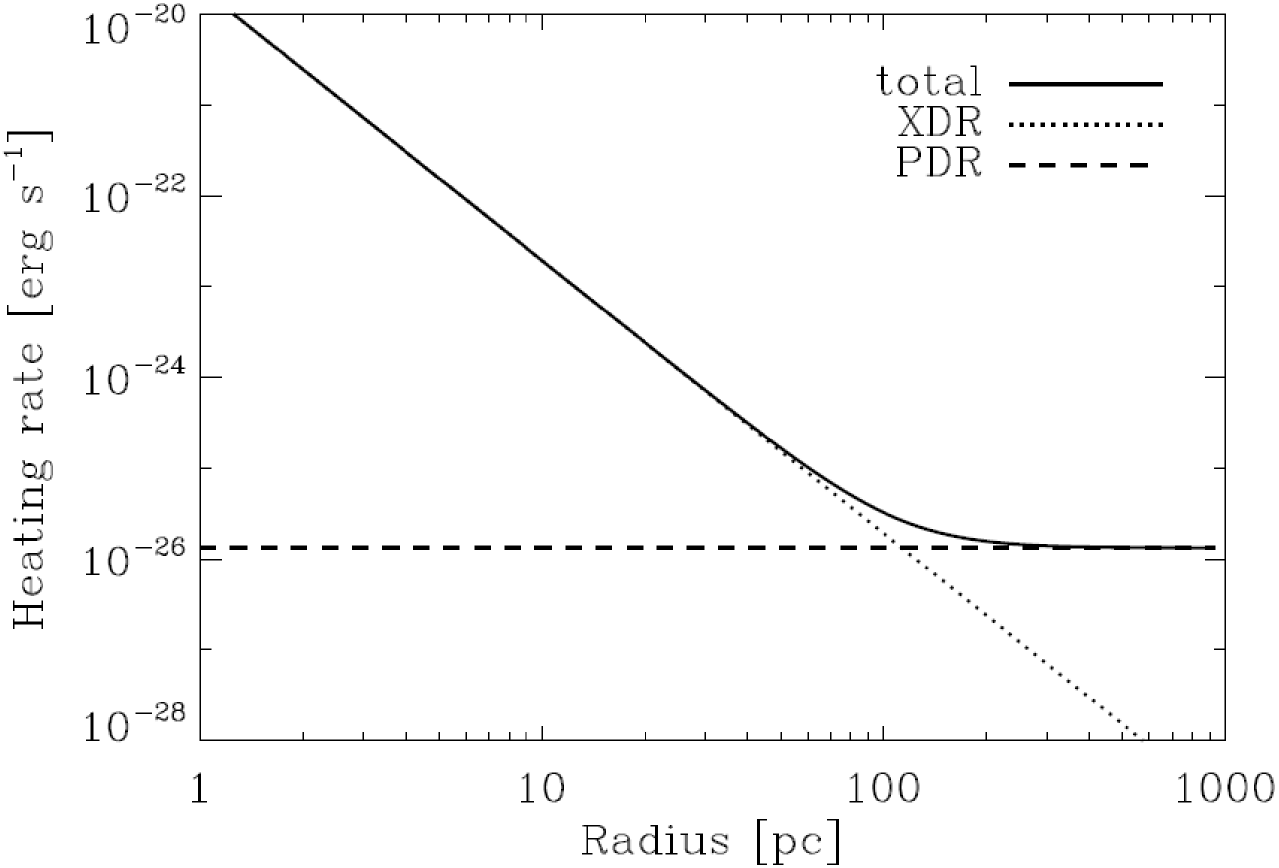


J=16-15 at 1841 GHz (0.16 mm)

(Spaans & Meijerink 2008)



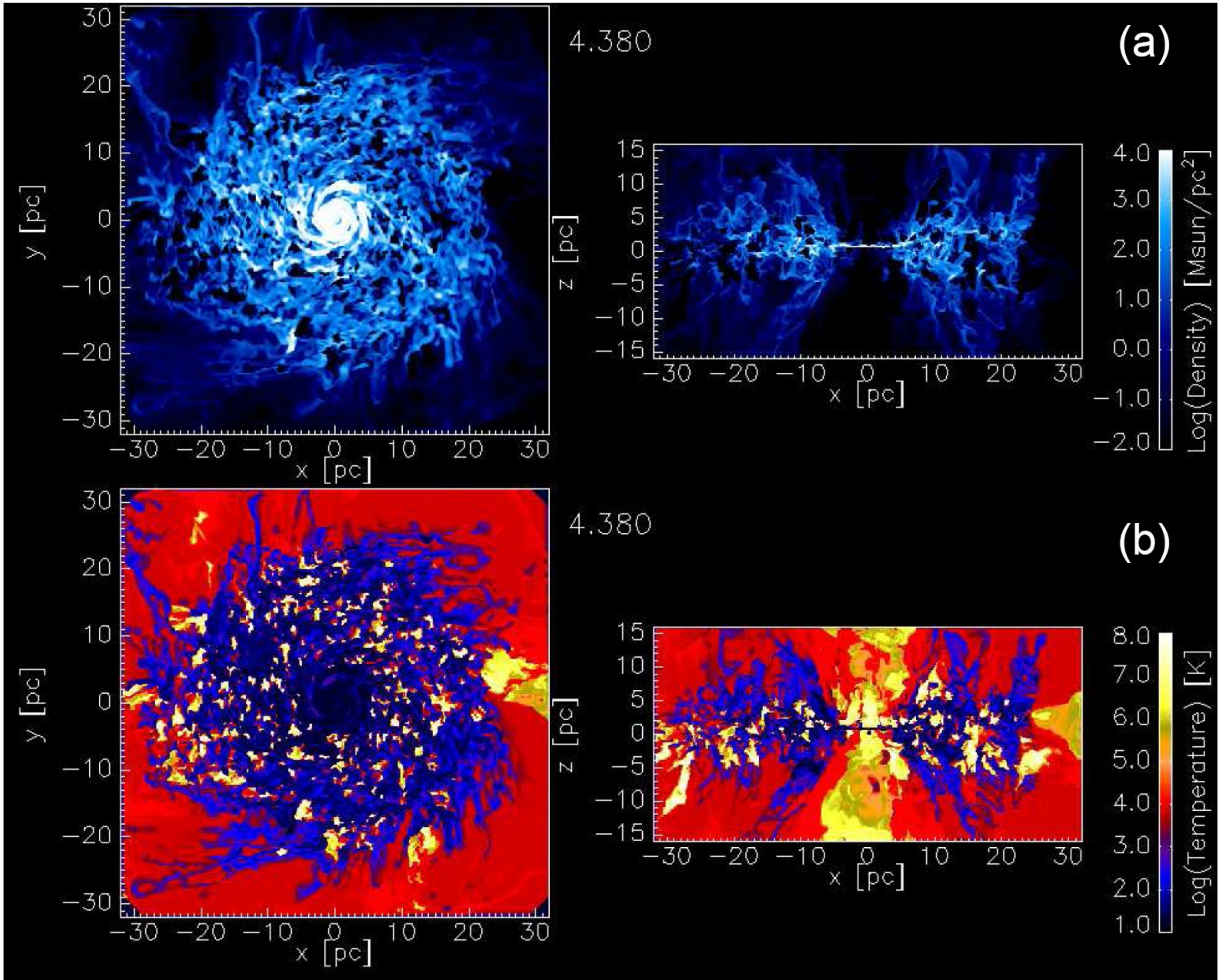
Comment on AGN: Relative Size PDR/XDR

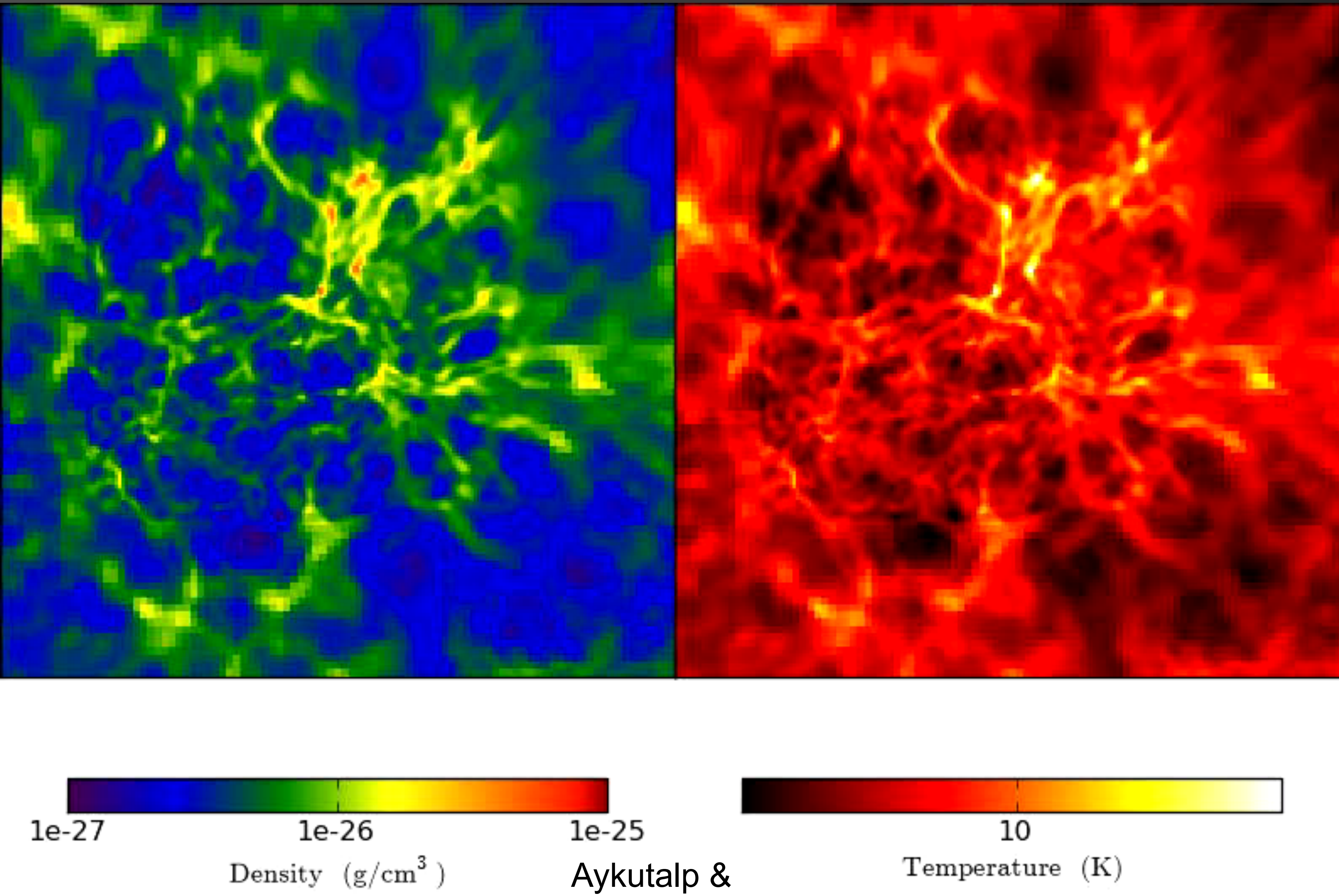


- 10^7 M☉ BH at 3% Eddington for G_0=100 and 1-100 keV powerlaw of slope -1 (with 10% L_{bol}; Schleicher ea 10)

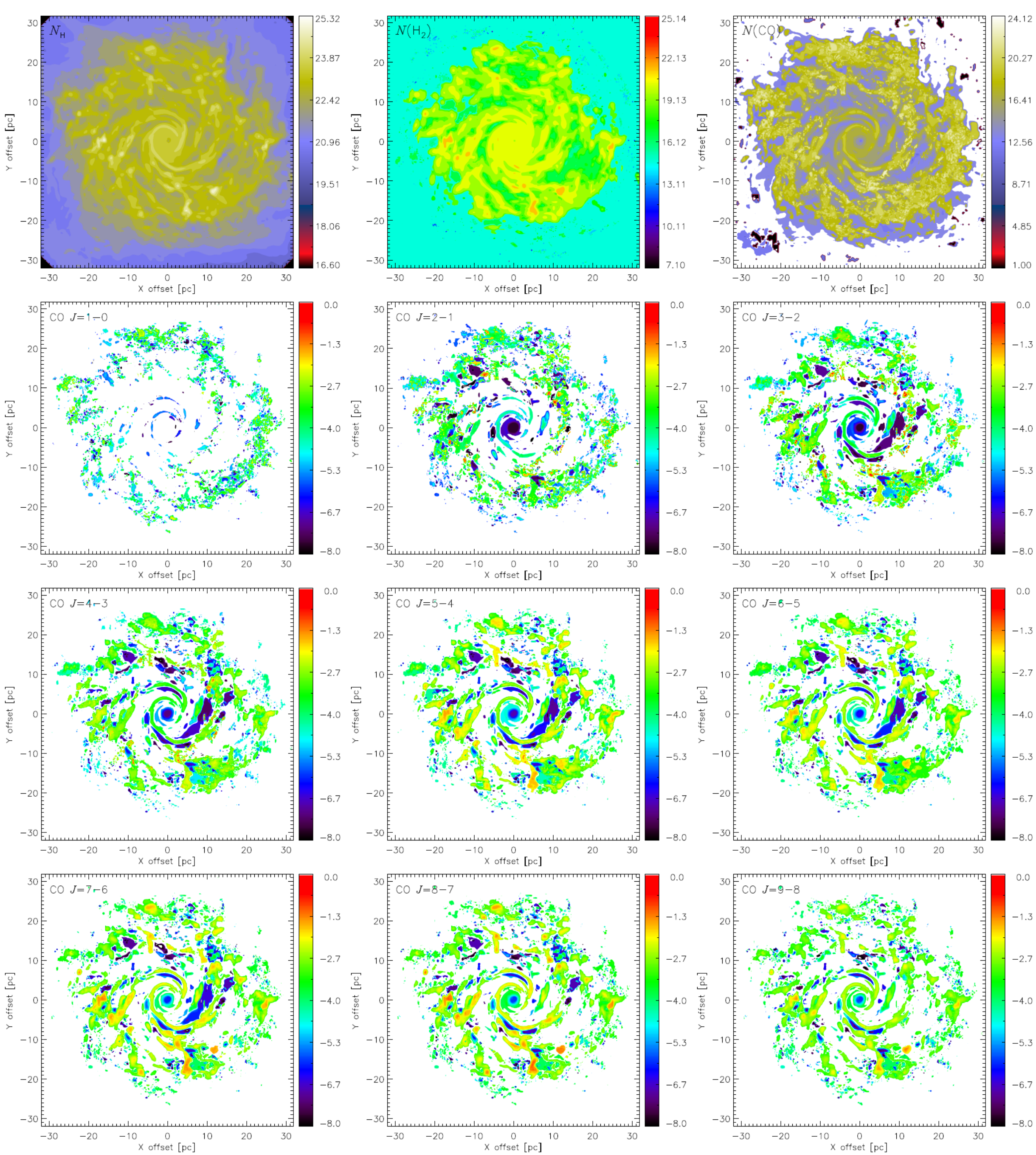
E.g., circumnuclear torus with SN feedback and a supermassive black hole, note the warm gas

(Wada ea 09)

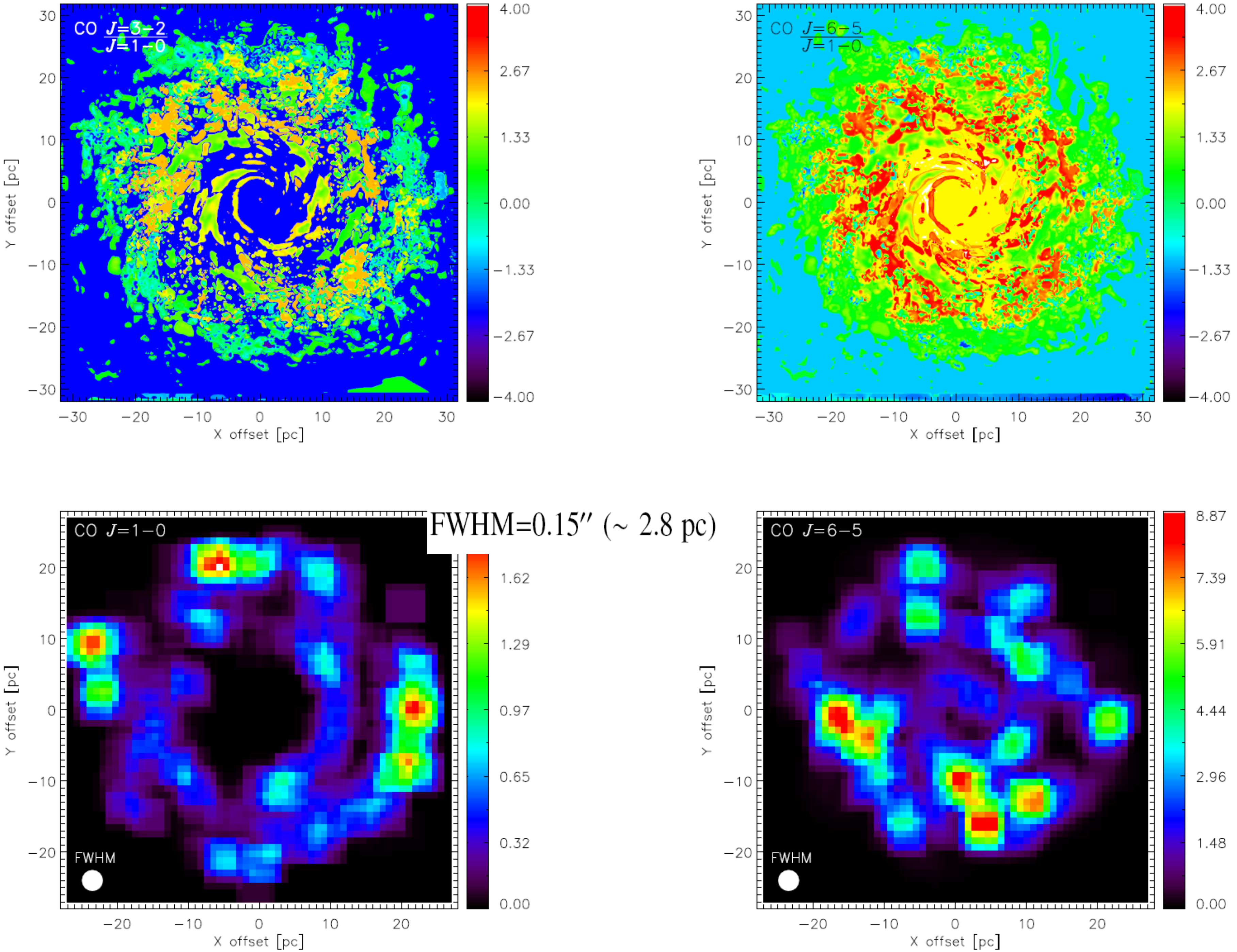




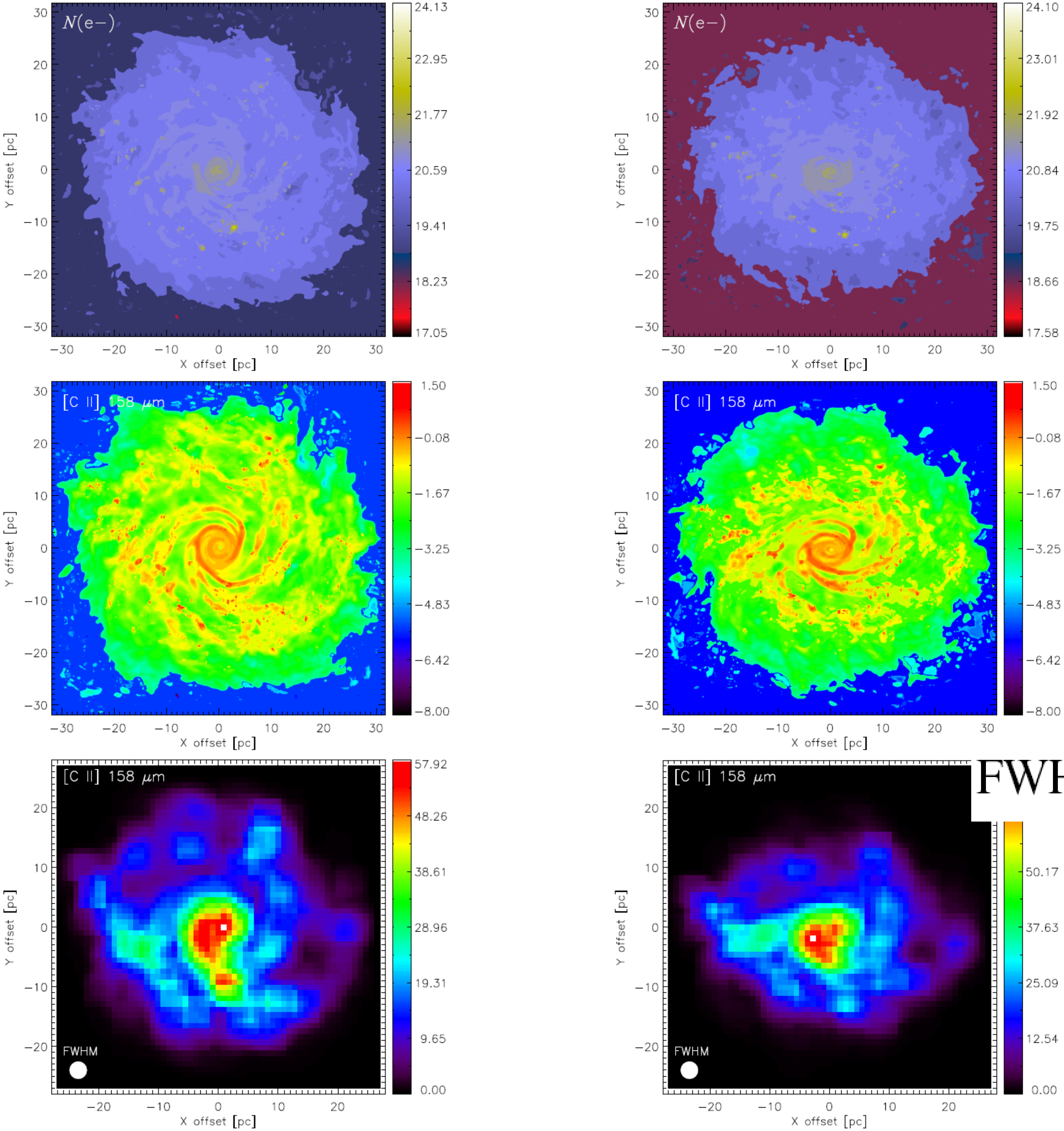
Aykutalp & Spaans 2011



This allows one to generate atomic and molecular line maps at ALMA resolution (Pérez-Beaupuits ea 01).

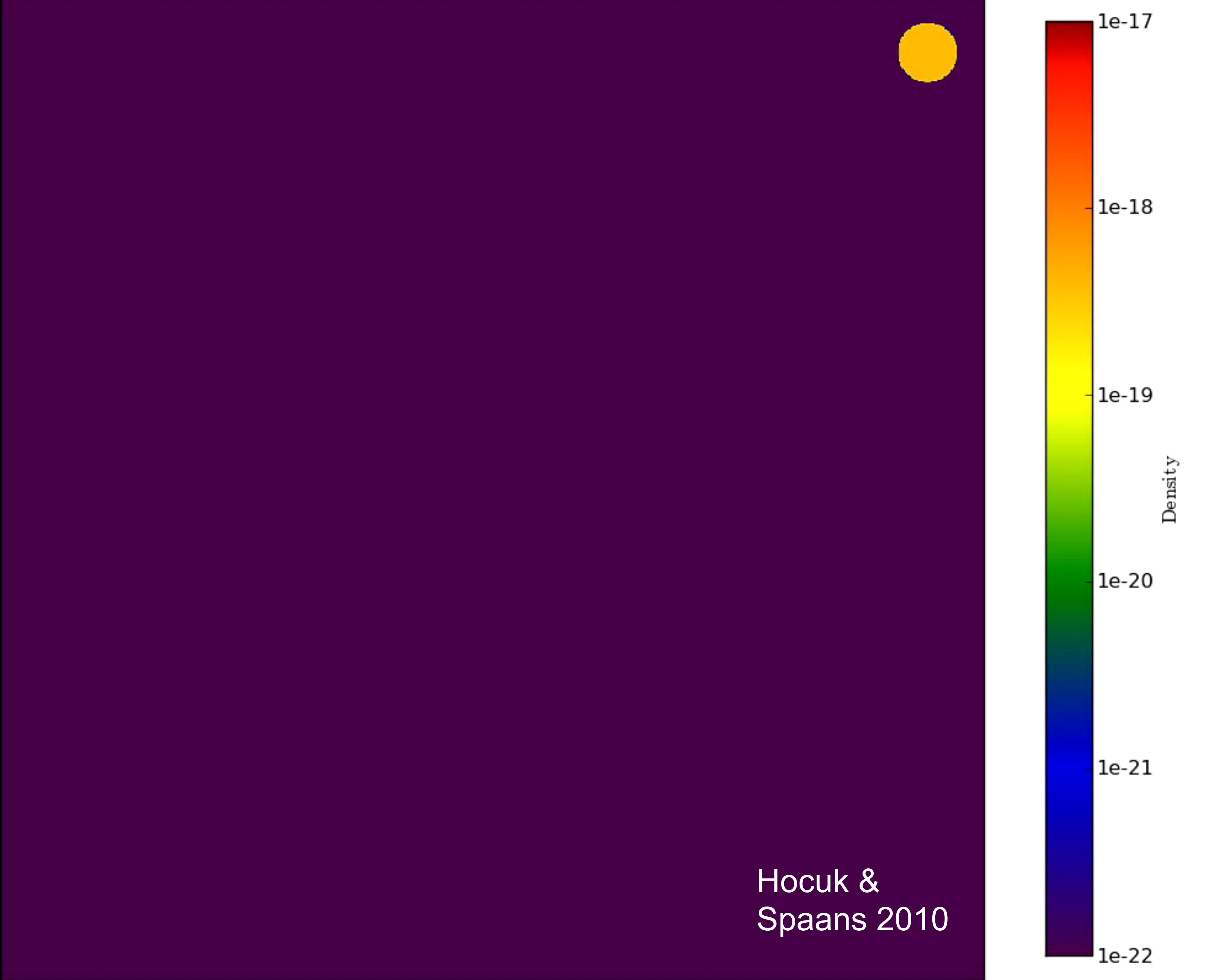


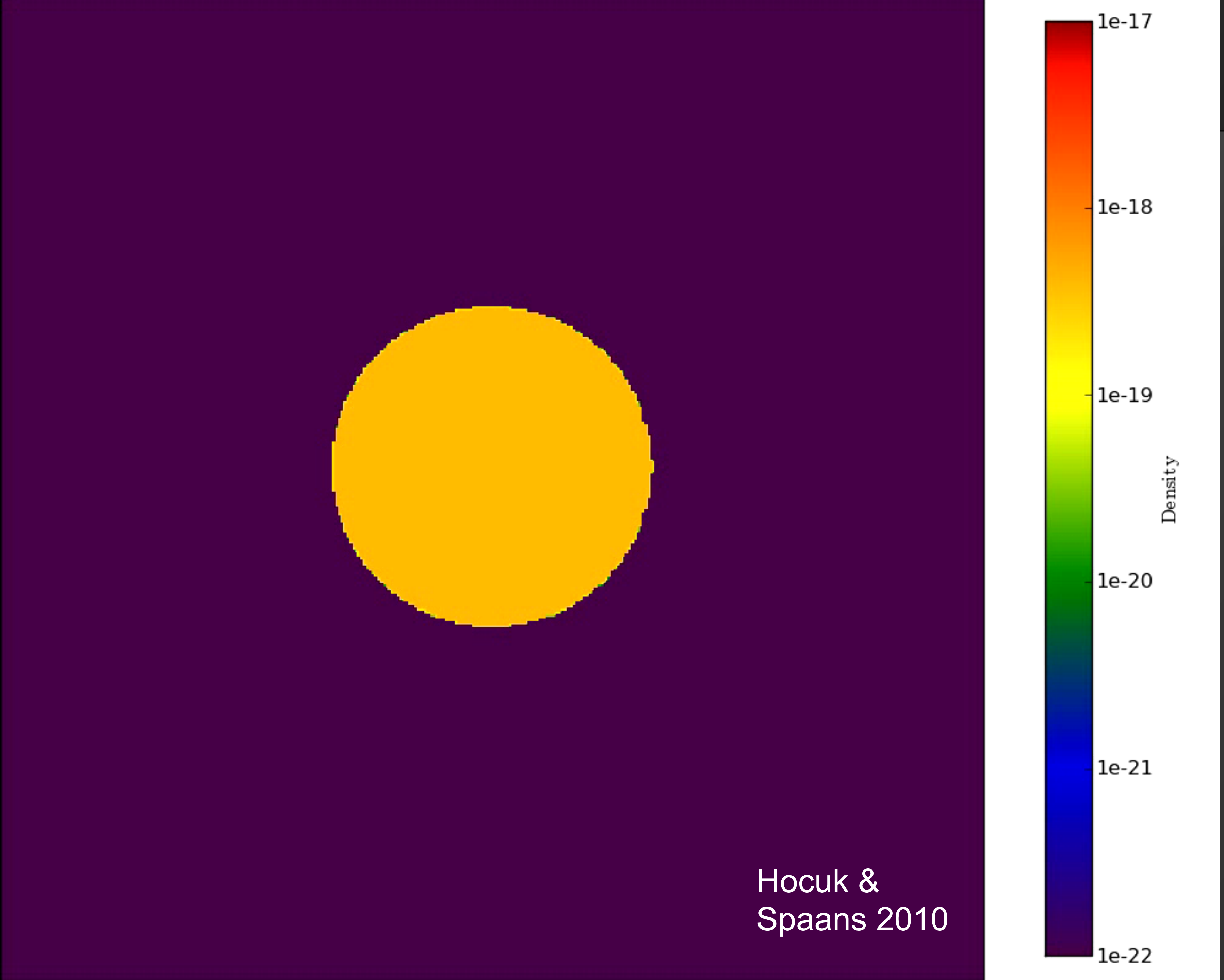
CO J=3−2 / J=1−0
CO J=6−5 / J=1−0
CO J=1−0
CO J=6−5
FWHM=0.15″ (~ 2.8 pc)
FWHM
X offset [pc]
Y offset [pc]
4.00
2.67
1.33
0.00
−1.33
−2.67
−4.00
1.62
1.29
0.97
0.65
0.32
8.87
7.39
5.91
4.44
2.96
1.48



FWHM=0.15″ (~ 2.8 pc)

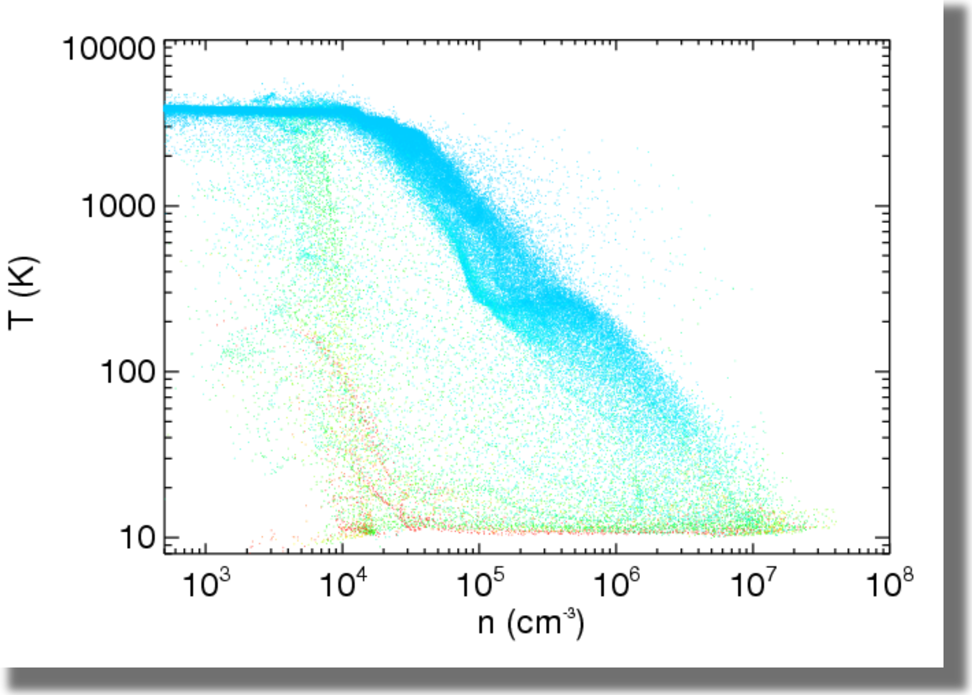
[CII] 158 μm
only for z>1
of course


1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
Density
Hocuk & Spaans 2010



Hocuk &
Spaans 2010

The T-n phase diagram

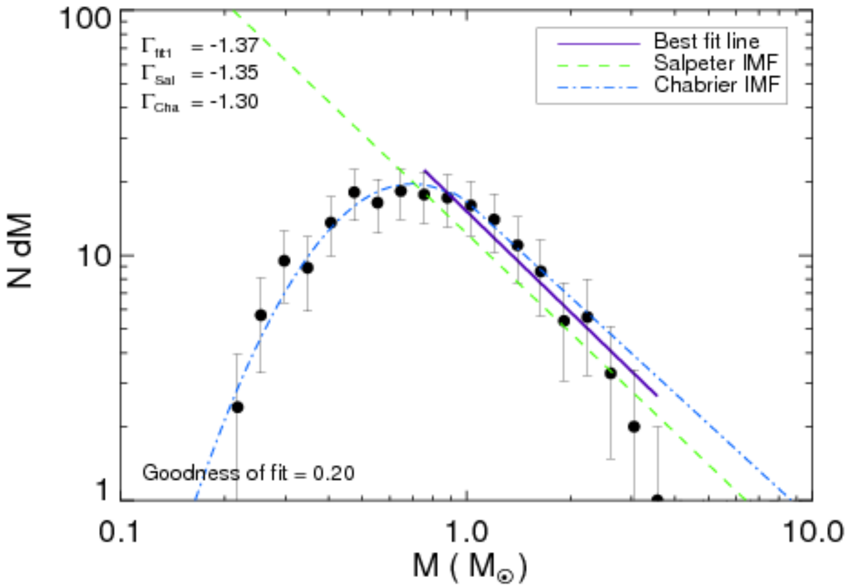


color represents column density

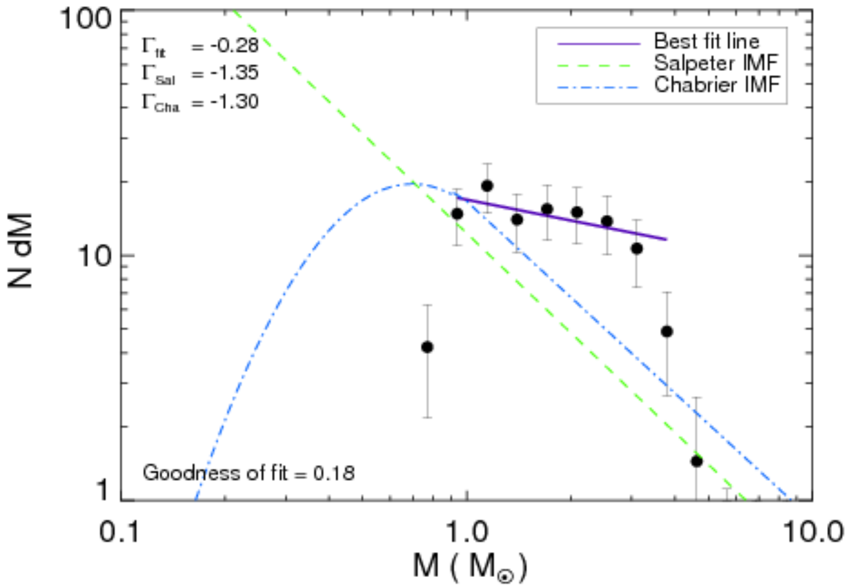
Gas that is lying behind the high densities is shielded and cold (but >10 K)

The Initial Mass Function

Without X-rays

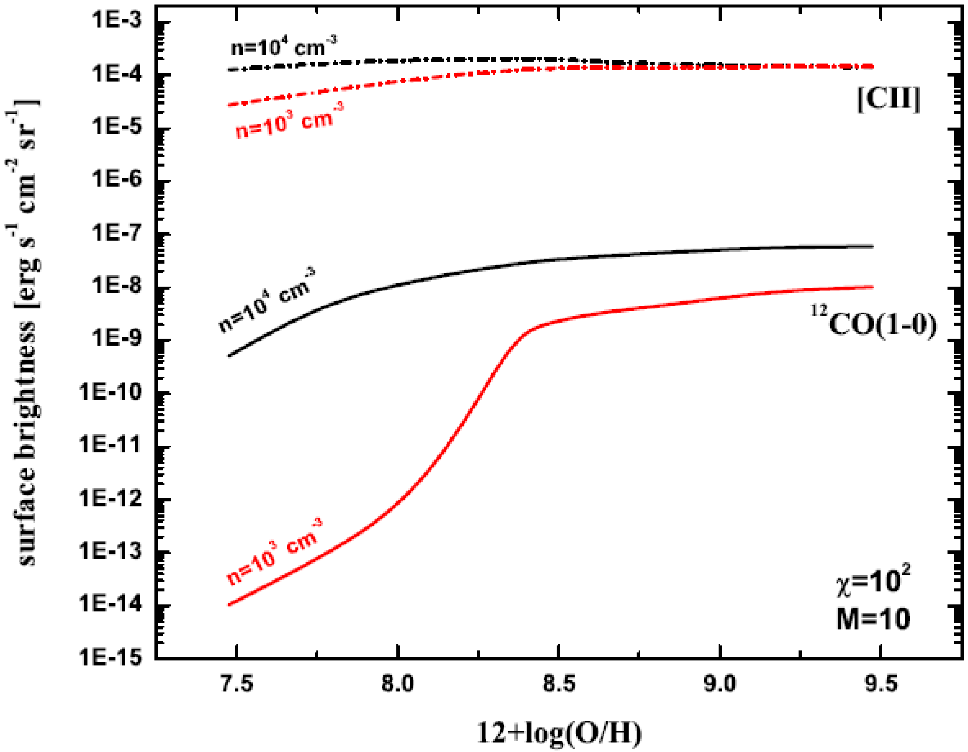


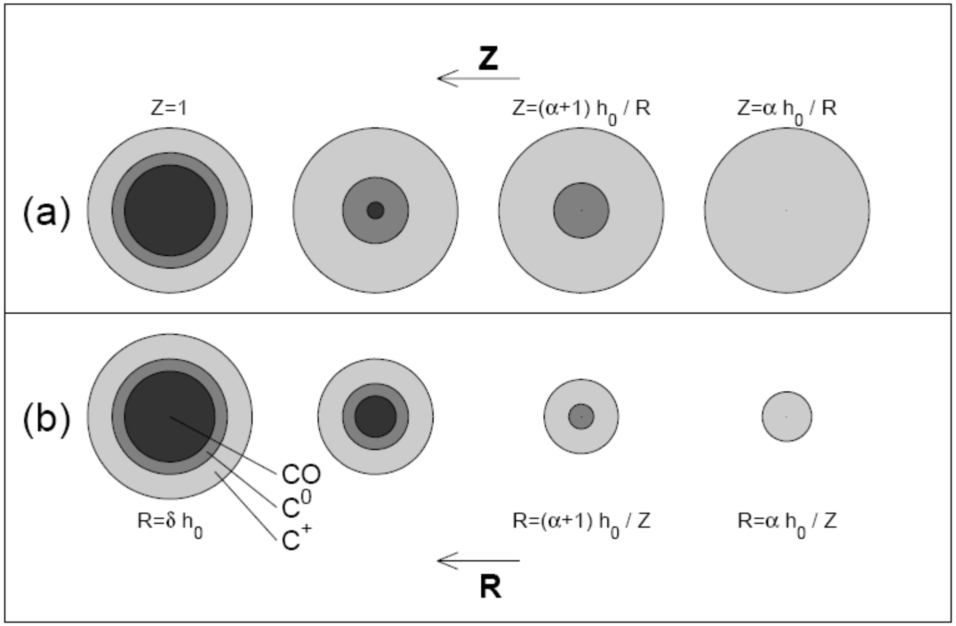
With X-rays



- Very good fit to Chabrier

- Much flatter slope
- Higher (characteristic) masses





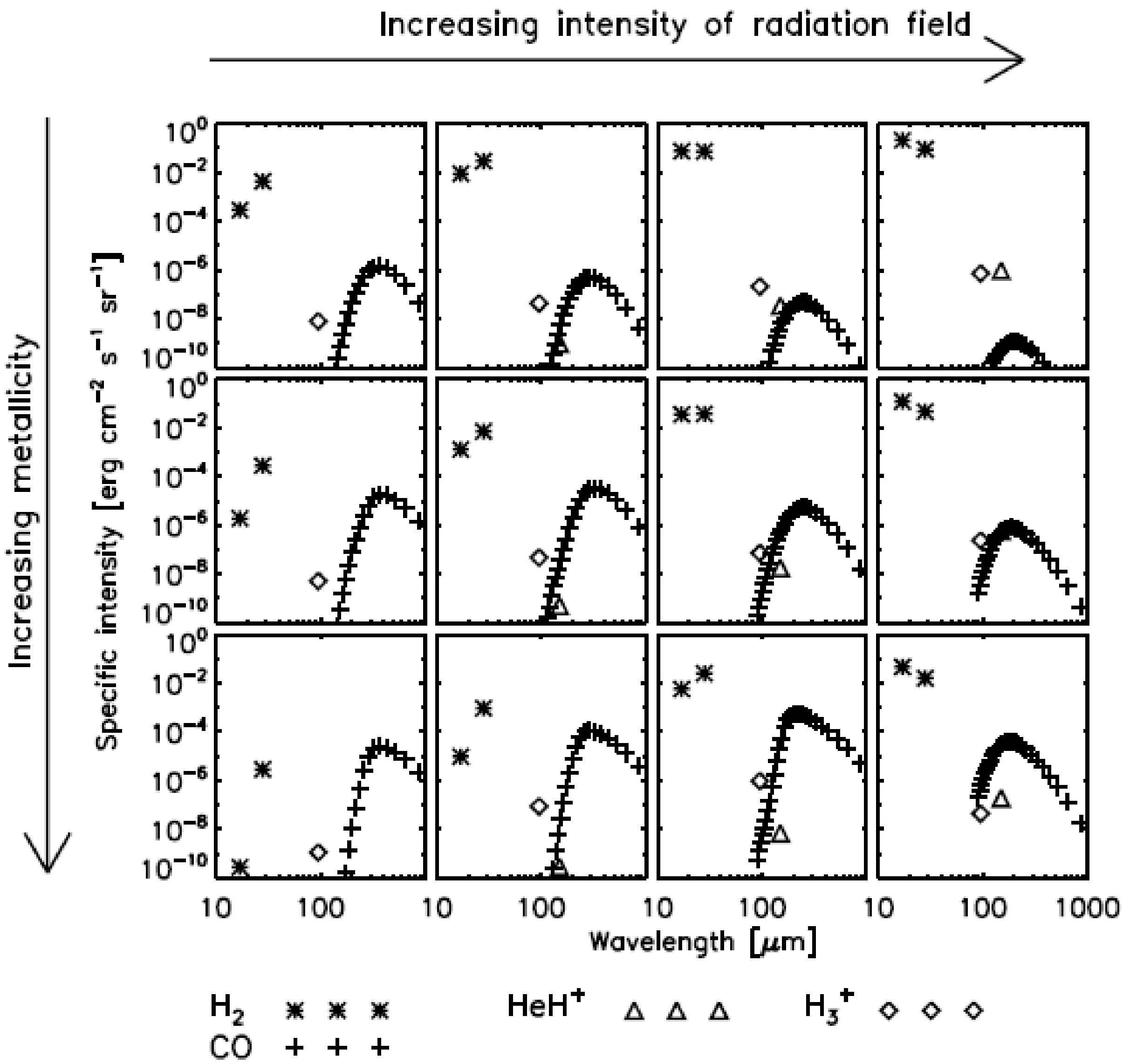
Metallicity & Multi-Phase ISM:

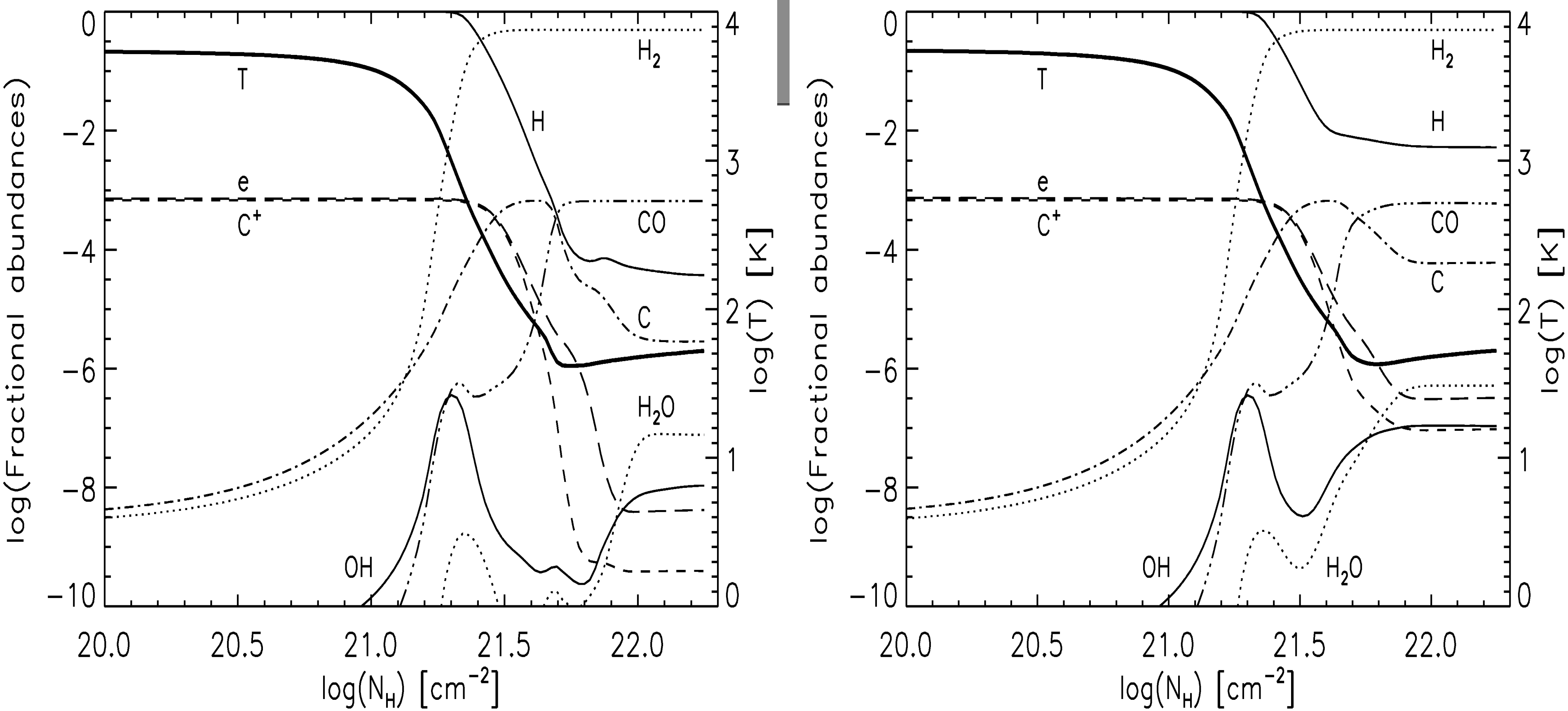
- Lower metallicity yields smaller molecular clouds
- X-factor: CO/H_2

Mihos et al. (1999), Bolatto et al. (1999), Roellig et al. (2006)

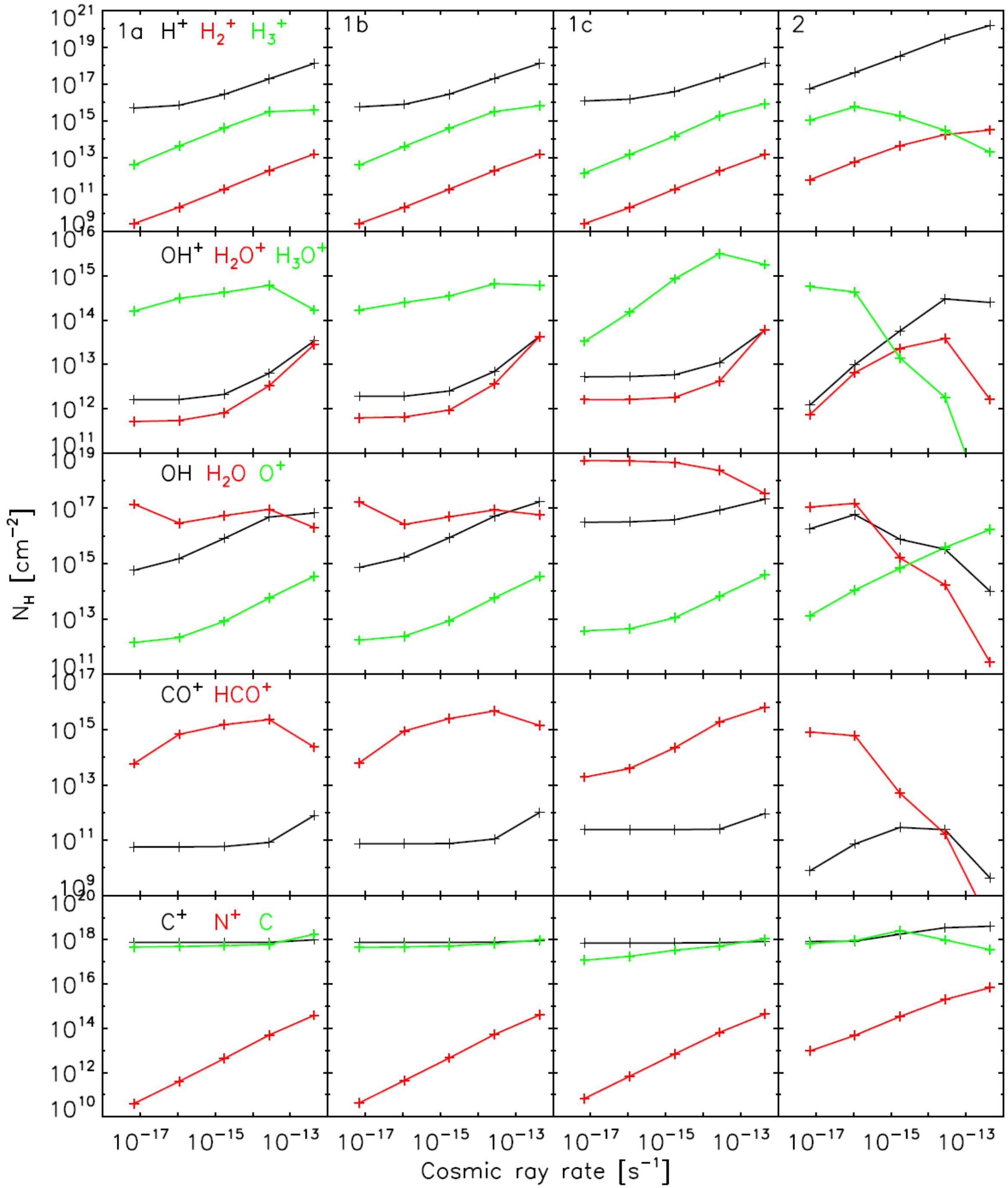
H_2 dominates for $Z<10^{-2}\,Z_{\odot}$

(Spaans & Meijerink 2008)

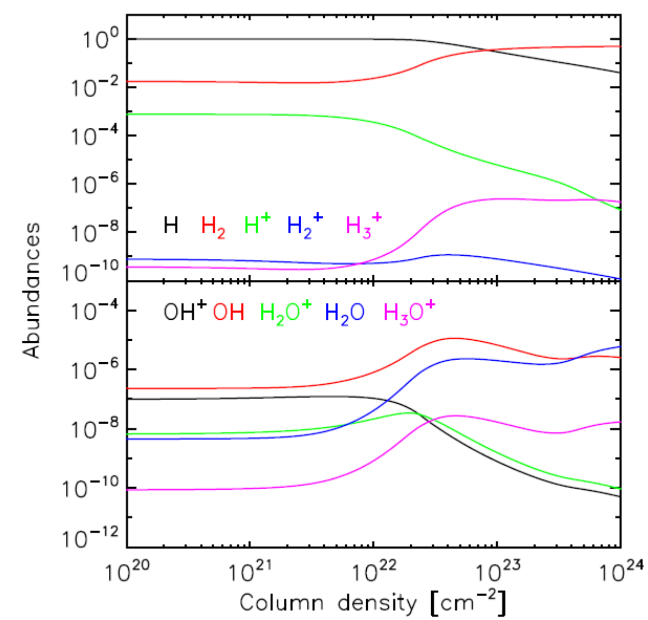




- **Effects of CRs?**
- One often has a UV irradiated cloud edge
- PDR model with CR rate = $5x10^{-15}$ s^{-1}; so SN rate for ~100 M_0/yr
- Note changes in C, OH and H_2O



BUT: CRs ≠ X-rays; only very high CR rates boost OH^+ and H_2O^+ (fine-structure lines little affected by CRs)



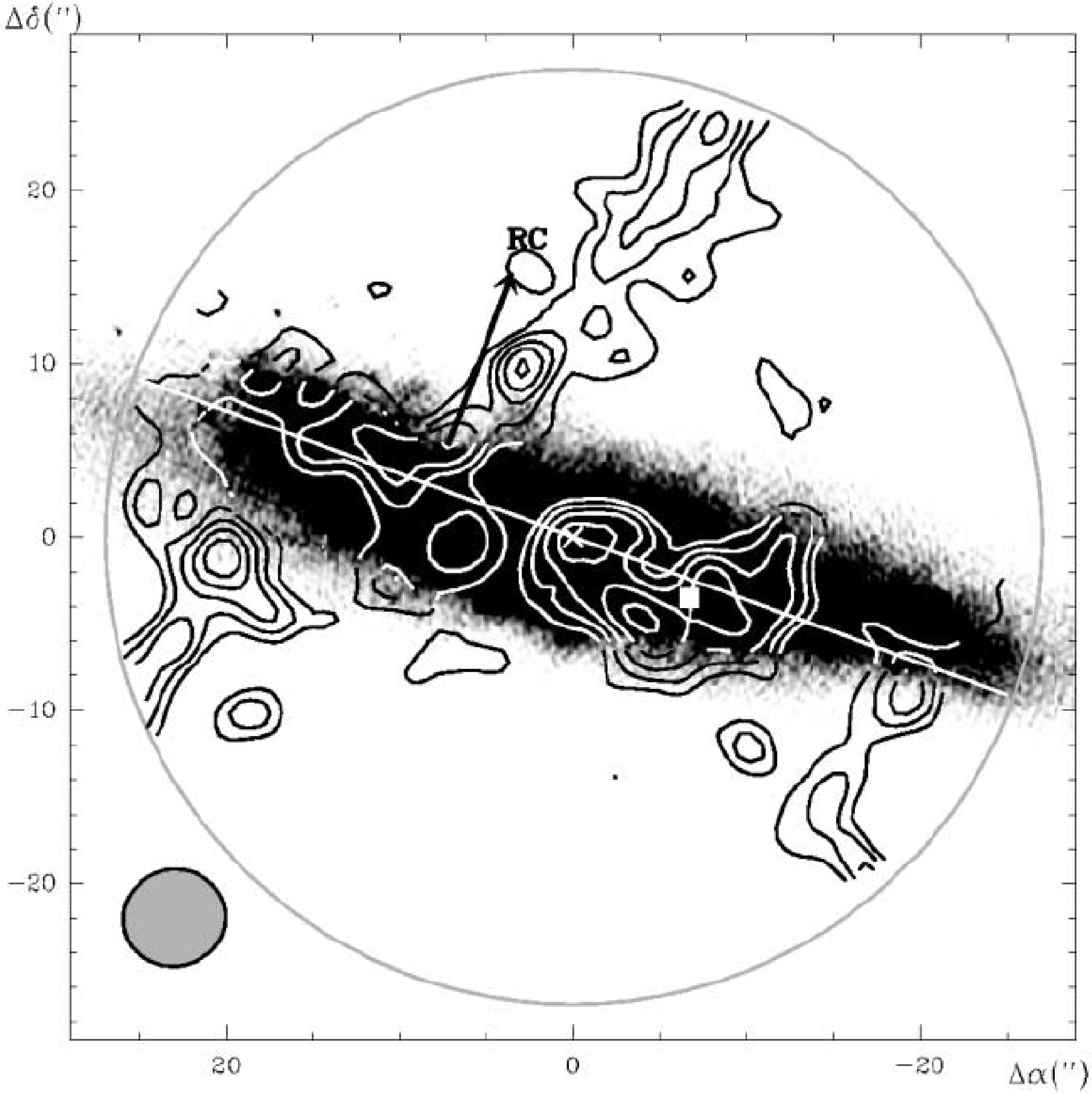
CR protons upto 100 MeV: H_2 ionization, while 1-20 GeV CRs responsible for bulk of π^0 mesons → 2γ and, e.g., pp→pnπ^+

E (MeV) (1)	Total Ionization Ratio (2)	$f(H_2^+)$ (3)	$f(H^+)$ (4)	N (H) (5)	T (eV) (6)	h (eV) (7)
1.....	1.44	0.970	0.030	2.06	4.2	6.3
2.....	1.50	0.971	0.029	2.12	4.4	6.6
10....	1.61	0.970	0.030	2.25	4.7	7.0
20....	1.65	0.970	0.030	2.30	4.8	7.2
50....	1.71	0.969	0.031	2.36	5.0	7.5
100...	1.74	0.969	0.031	2.40	5.1	7.6

NOTE.—Column (2) gives the ratio of the total and primary ionization rates in H_2; columns (3) and (4), the fractions f of H_2^+ and H^+ ions; column (5), the number N(H) of hydrogen atoms; column (6), the kinetic energy T (eV) of the neutral hydrogen atoms; column (7), the heat h (eV) deposited into a gas of low fractional ionization per primary ionization event.

PROTON IMPACT IONIZATION CROSS SECTIONS $\sigma_i(E)$ IN cm^2 AND MEAN ENERGIES $\bar{w}_i$ IN eV OF THE SECONDARY ELECTRONS

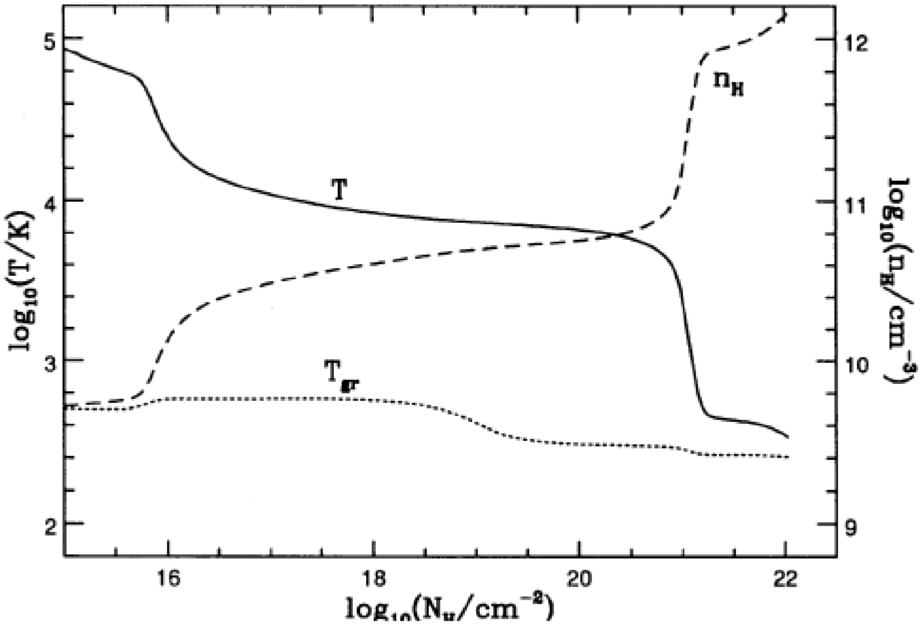
E (MeV)	σ_i (cm^2)	$\bar{w}_i$ (eV)
1........	4.0×10^{-17}	24.3
2........	2.3×10^{-17}	26.0
10.......	5.7×10^{-18}	30.4
20.......	3.1×10^{-18}	32.1
50.......	1.4×10^{-18}	34.1
100......	7.2×10^{-19}	35.6

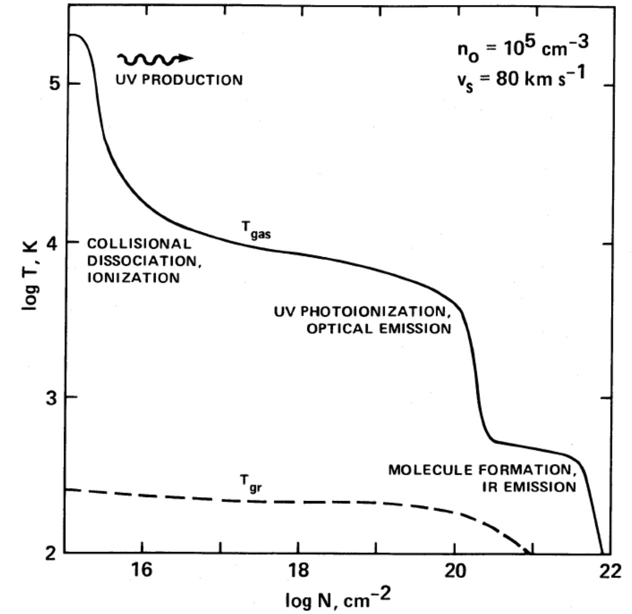


How about shocks?

M82, shock tracer SiO 2-1 + 4.8 GHz radio (García-Burillo et al. 2001, IRAM PdB)

J-Shocks of > 50 km/s lead to high compression, molecule dissociation and reformation in the shock wake; C-shocks are more gentle





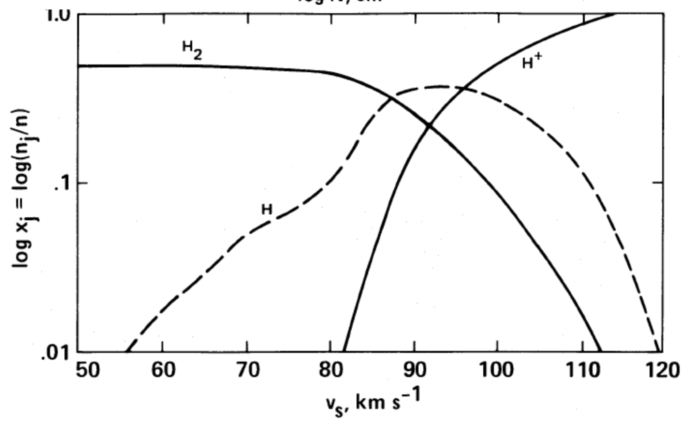
$$[\rho v_{\parallel}] = 0$$

$$[\rho v_{\parallel}^2 + p + B_{\perp}^2/8\pi] = 0$$

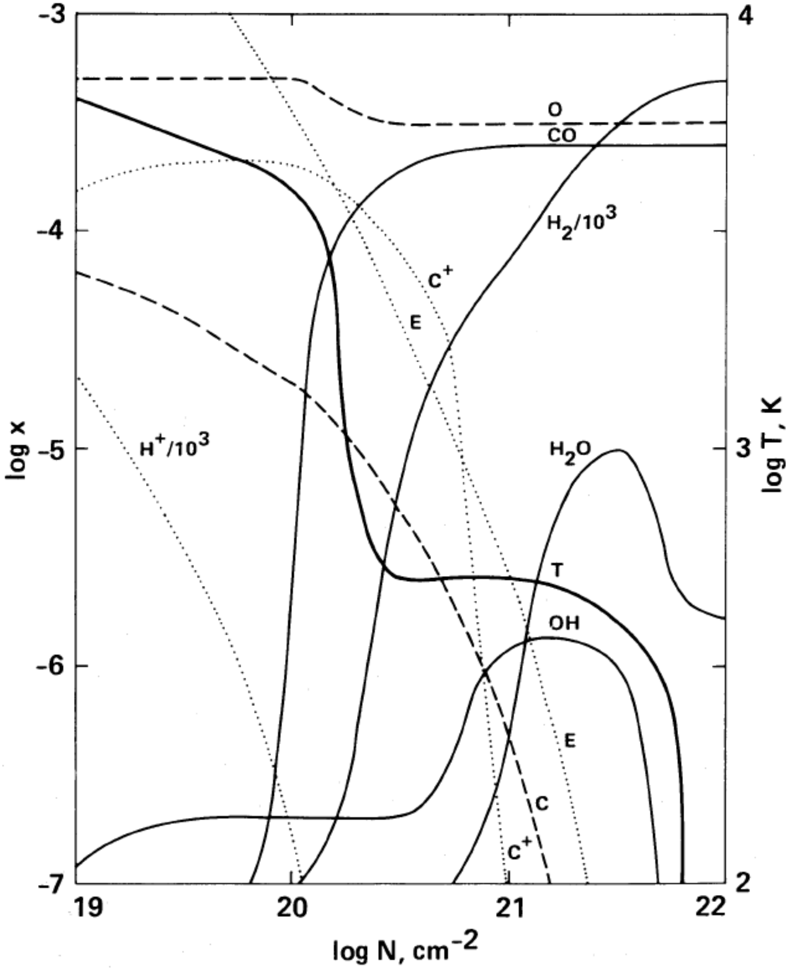
$$[\rho v_{\parallel} v_{\perp} - B_{\parallel} B_{\perp}/4\pi] = 0$$

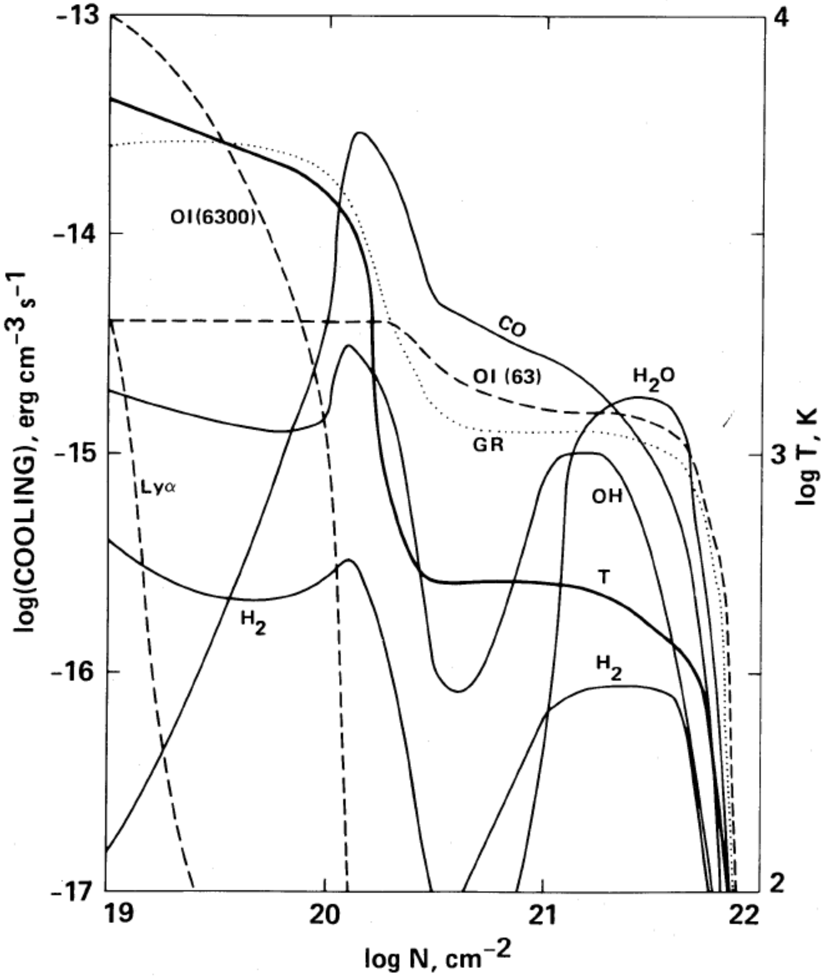
$$[v_{\parallel}(\tfrac{1}{2}\rho v^2 + u + p) + (v_{\parallel} B_{\perp}^2 - v_{\perp} B_{\perp} B_{\parallel})/4\pi + F] = 0$$

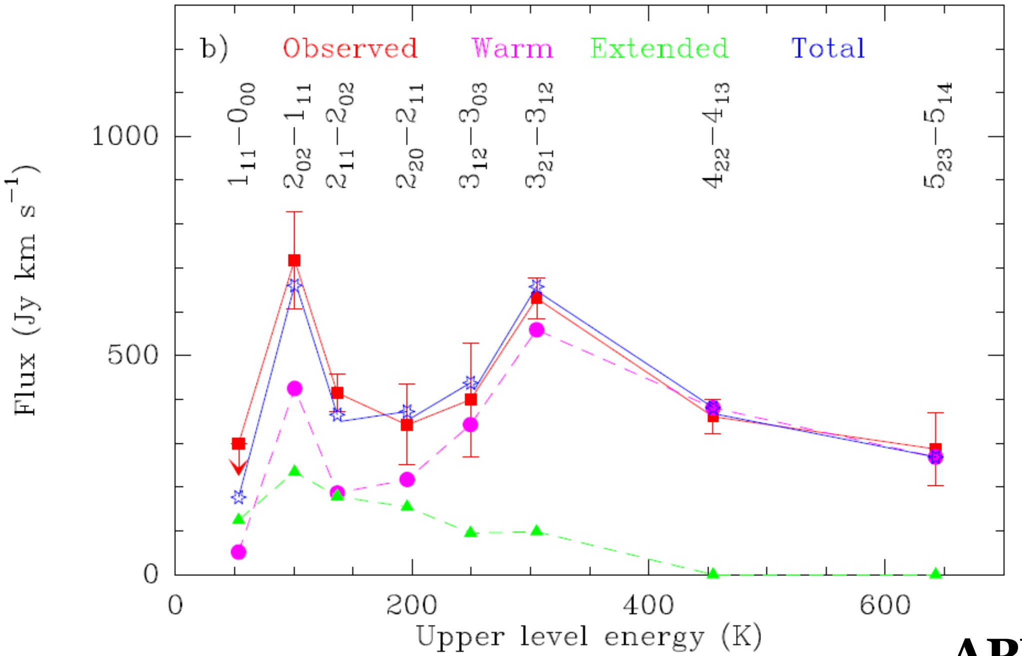
$$[B_{\parallel}] = 0 \qquad [v_{\parallel} B_{\perp} - v_{\perp} B_{\parallel}] = 0$$



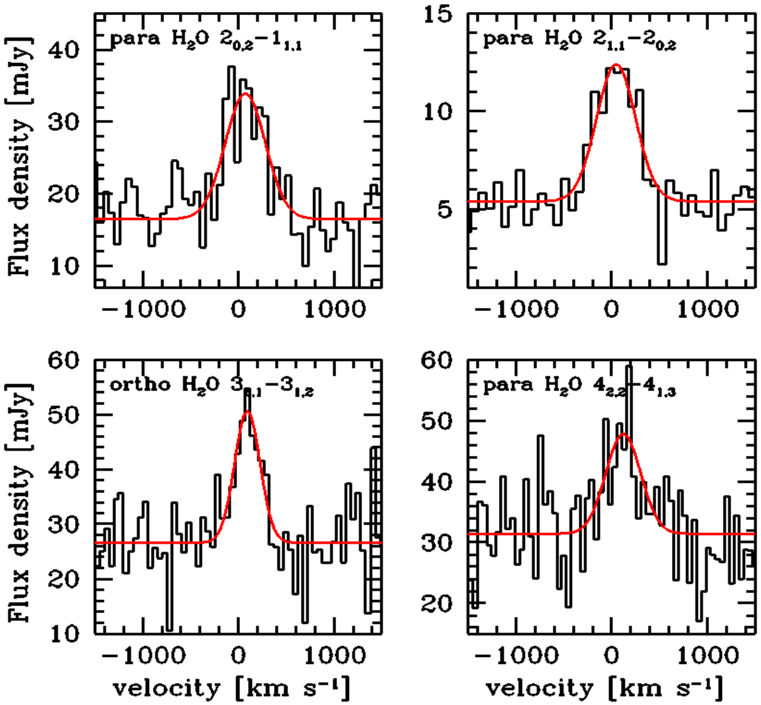
J-shock chemistry







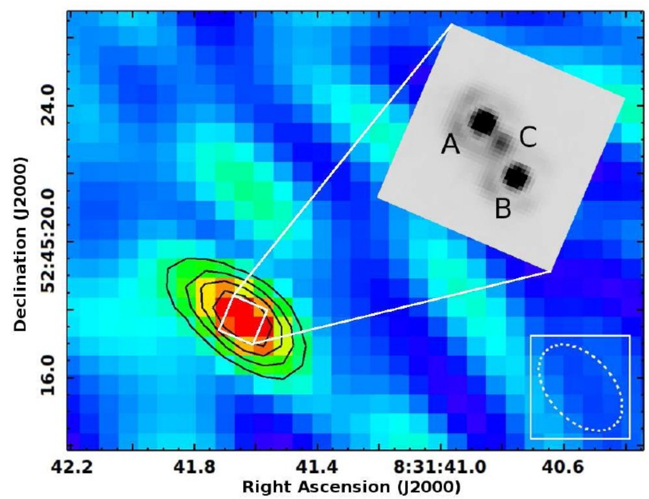
Mrk 231; SPIRE, **IR pumping** of water lines by dust emission (González-Alfonso ea 10)



APM 08279+5255

- **Lensed QSO (3 images); SMBH $10^{9.5}$ $M_\odot$**
- **z=3.9; water ~ dust ~ 220 K**
- **Lensing magnification μ = 4**

(van der Werf ea 11)



HerCULES

- **Her**schel **C**omprehensive **UL**IRG **E**mission **S**urvey (PI: van der Werf)
- Measure gas cooling lines in a flux-limited sample of 29 (U)LIRGs; high-z template

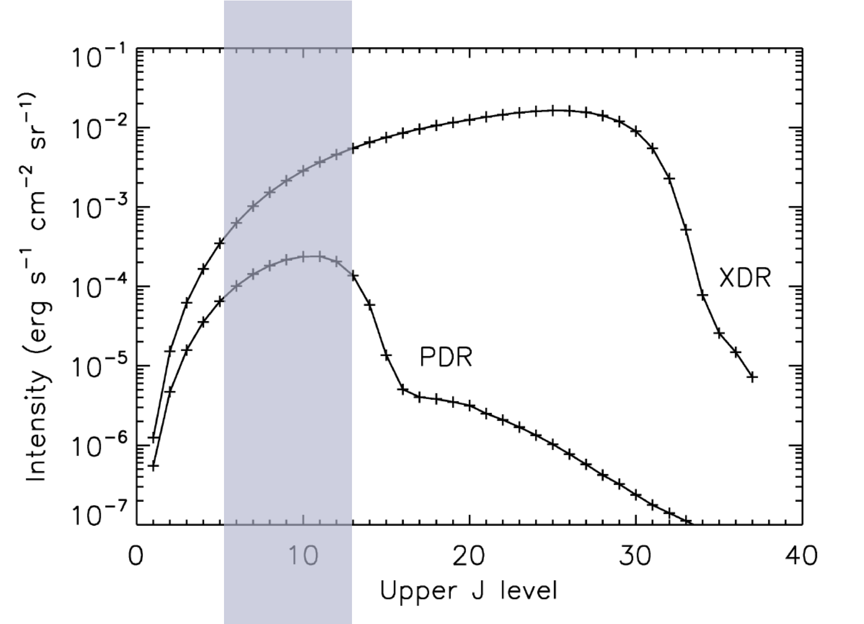
- Observations:
  - High resolution SPIRE FTS: **CO**, [CI], [NII], etc.
  - PACS: [CII] 158μm, [OI] 63 and 146 μm
  - All targets observed to same (expected) S/N
  - Extended sources observed at several positions

Markarian 231 (van der Werf ea 13)

- Perfect test case:
  - Most luminous ULIRG in sample ($L_{IR} = 4 \times 10^{12}\ L_{\odot}$)
  - Optically visible AGN/XDR [Boksenberg et al., 1977]
  - $L_X = 6 \times 10^{43}$ erg/s (2-10 keV)
  - ~500-1000 pc CO & star formation/PDR disk

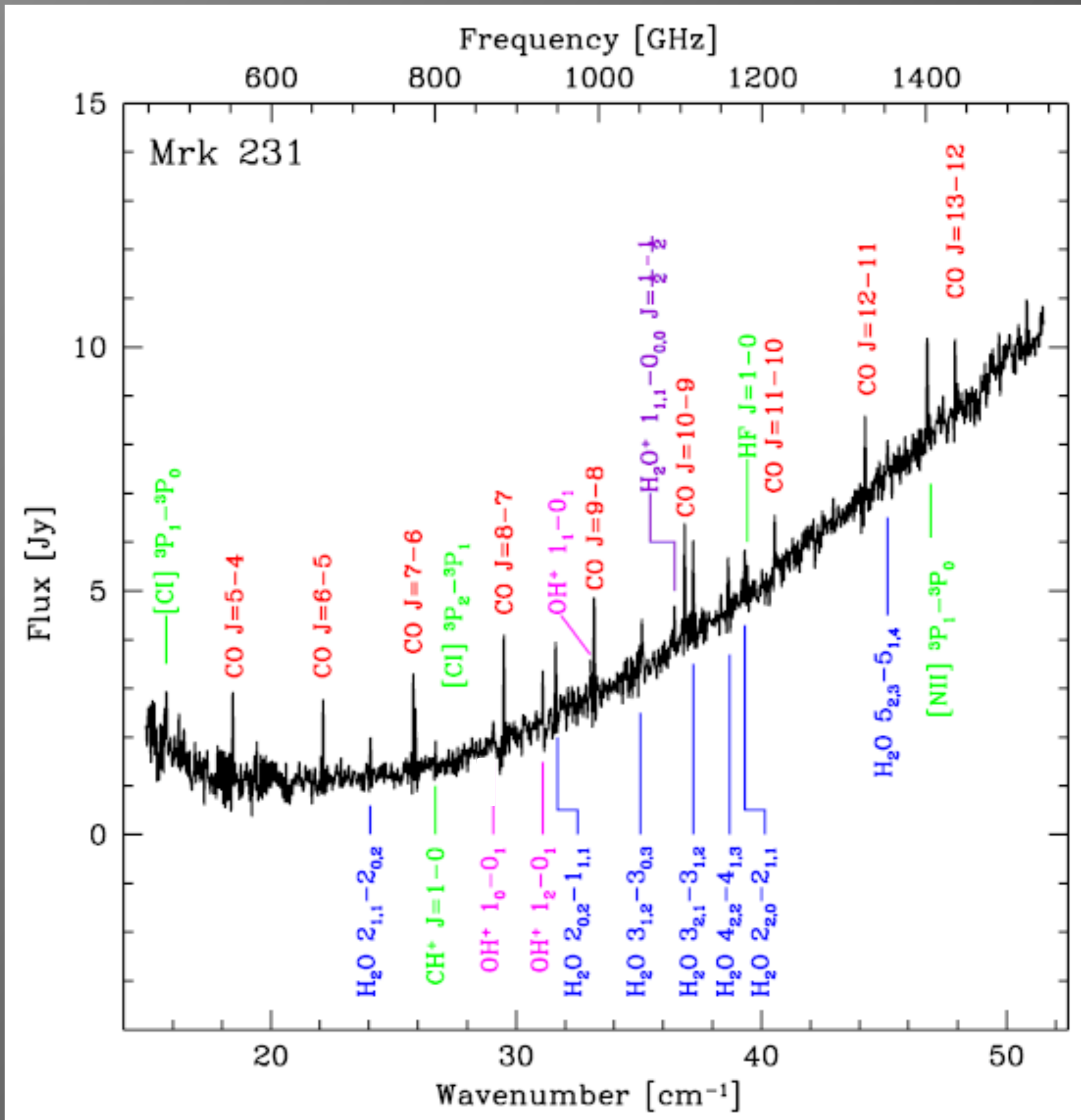
[Downes & Solomon 1998, Taylor et al., 1999]

- Observed during SDP:
  - SPIRE high resolution in both bands
  - Total on source time: ~2 hrs



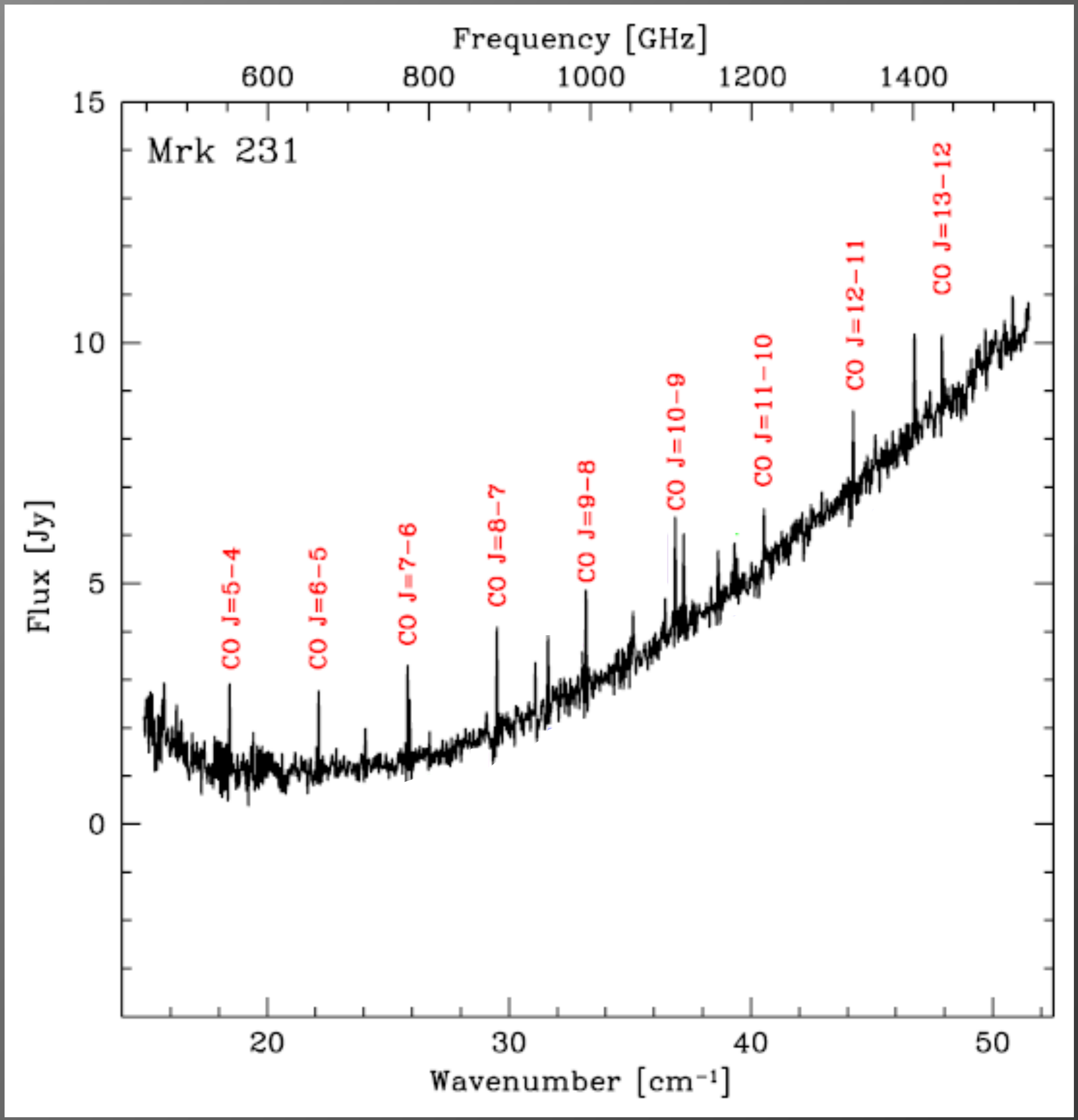
[Spaans & Meijerink, 2008]

Markarian 231



- 25 lines:
  - 9x CO (5-4 to 13-12)
  - 2x [CI]
  - [NII]
  - 7x H_2O
  - 3x OH^+
  - H_2O^+
  - CH^+
  - HF

Markarian 231



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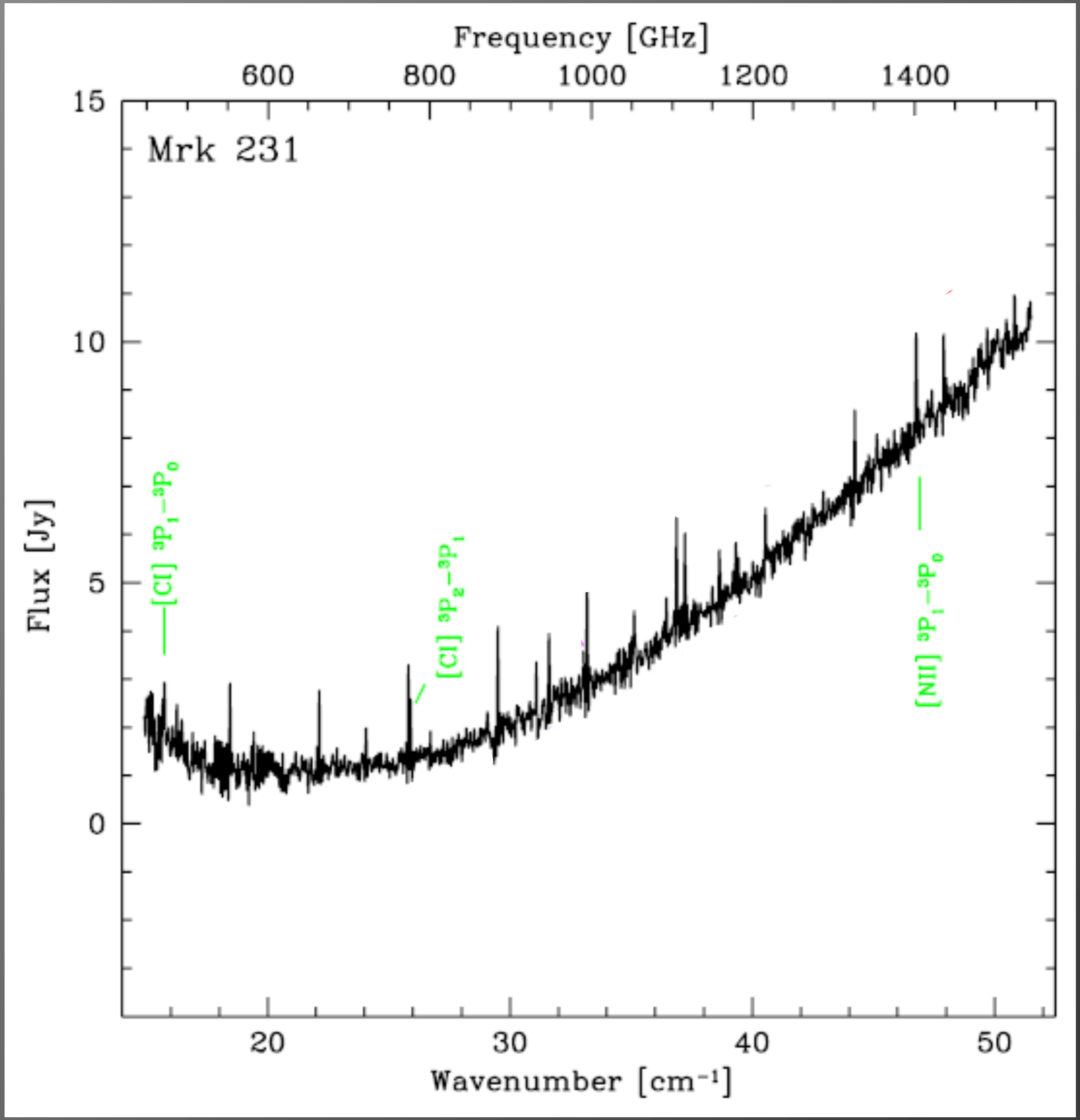
Markarian 231



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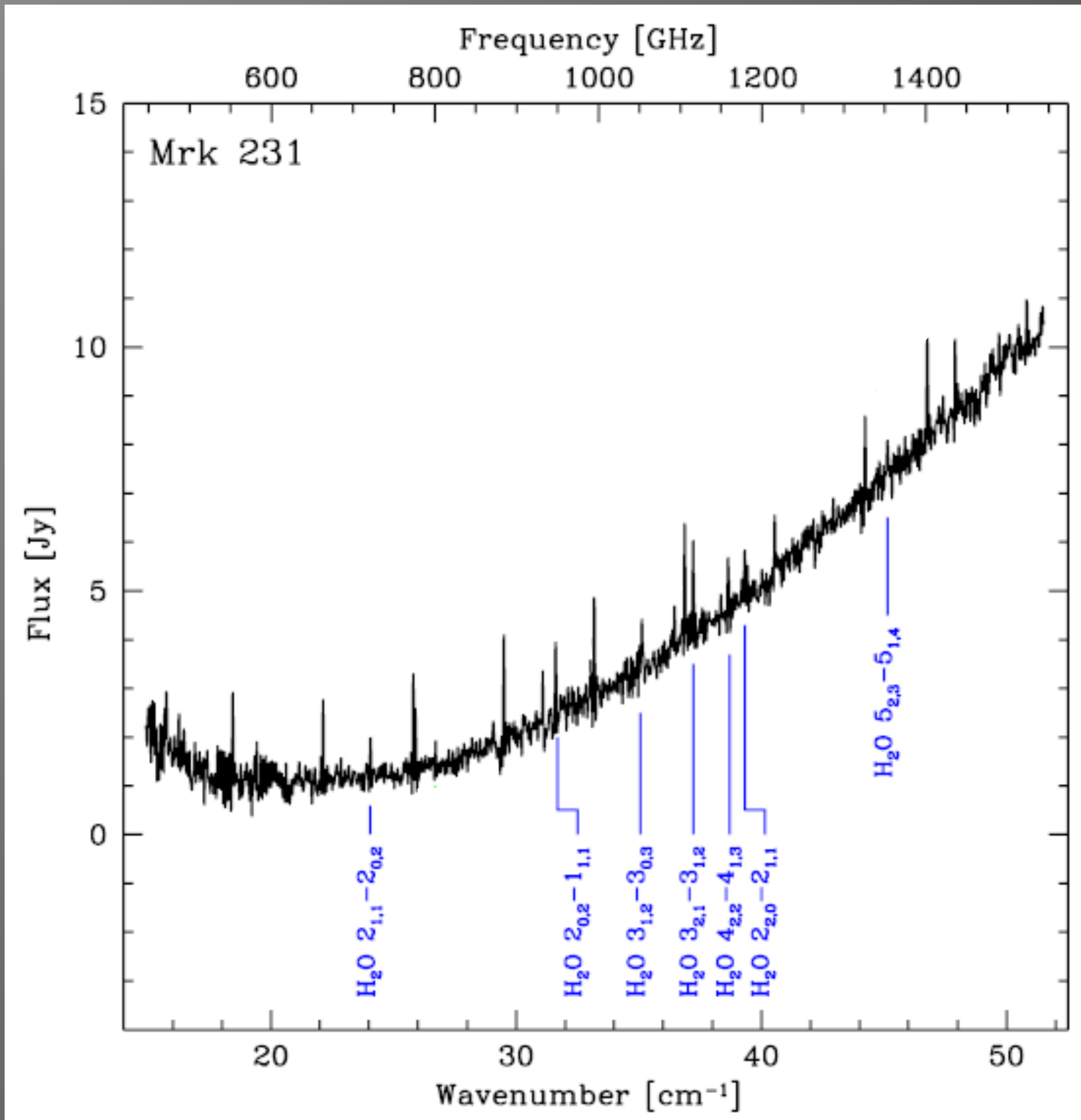
Markarian 231



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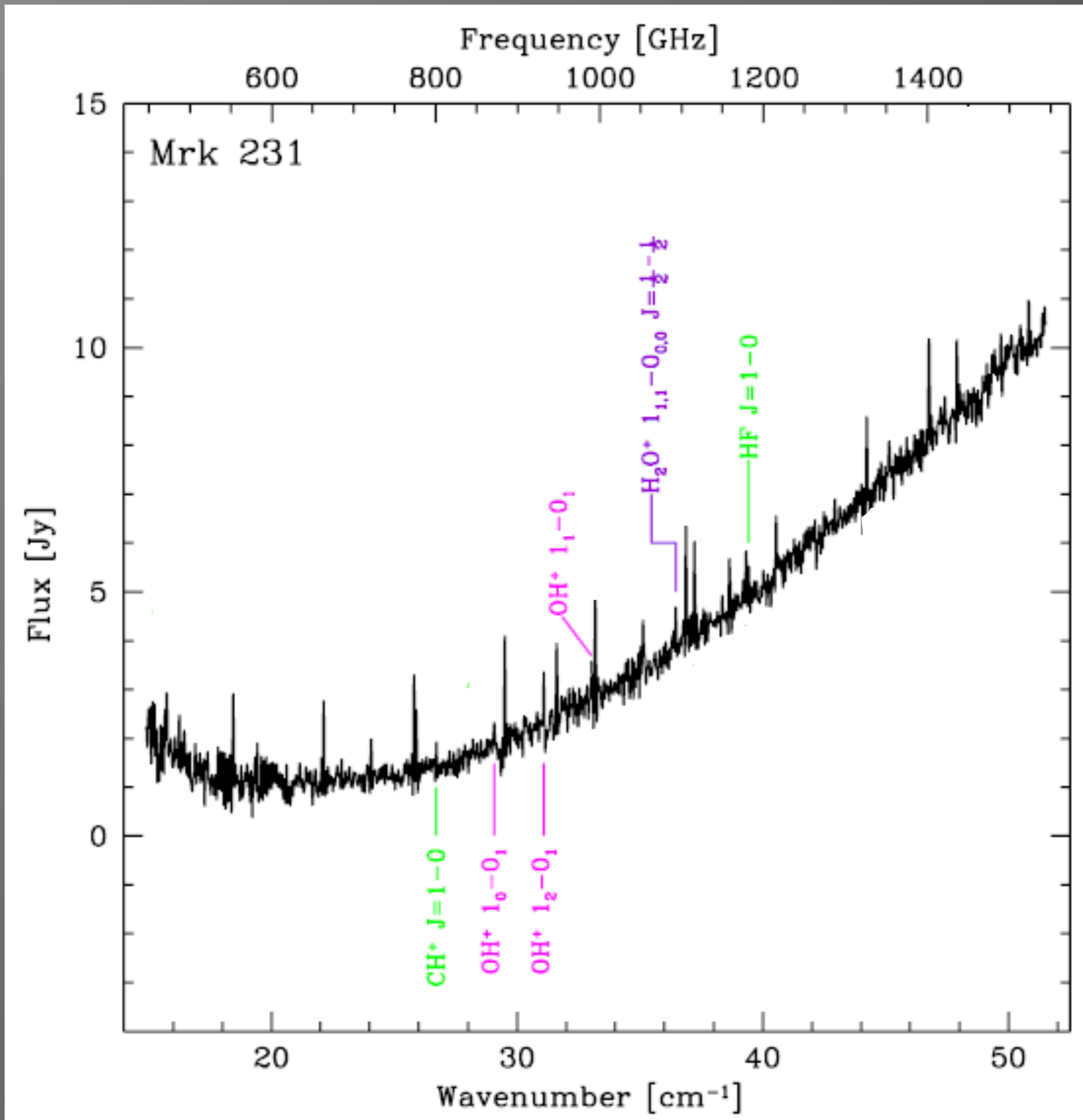
Markarian 231

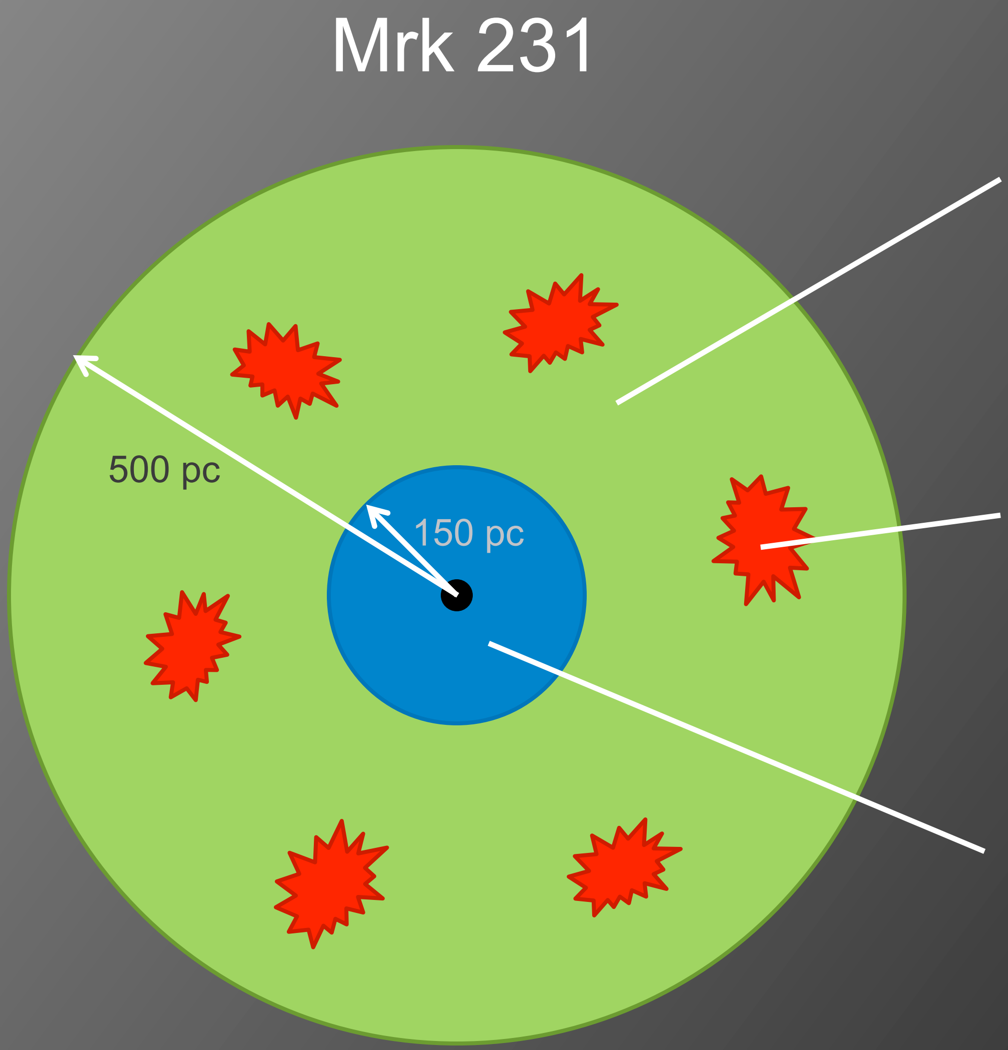


- 25 lines:
  - 9x CO (5-4 to 13-12)
  - 2x [CI]
  - [NII]
  - 7x H_2O
  - 3x OH^+ (**not in**
  - H_2O^+ Orion Bar!)
  - CH^+
  - HF

1400 km/s OH bulk outflow (Fischer ea 10)

~1% of L_{IR} (~10^8 M☉)

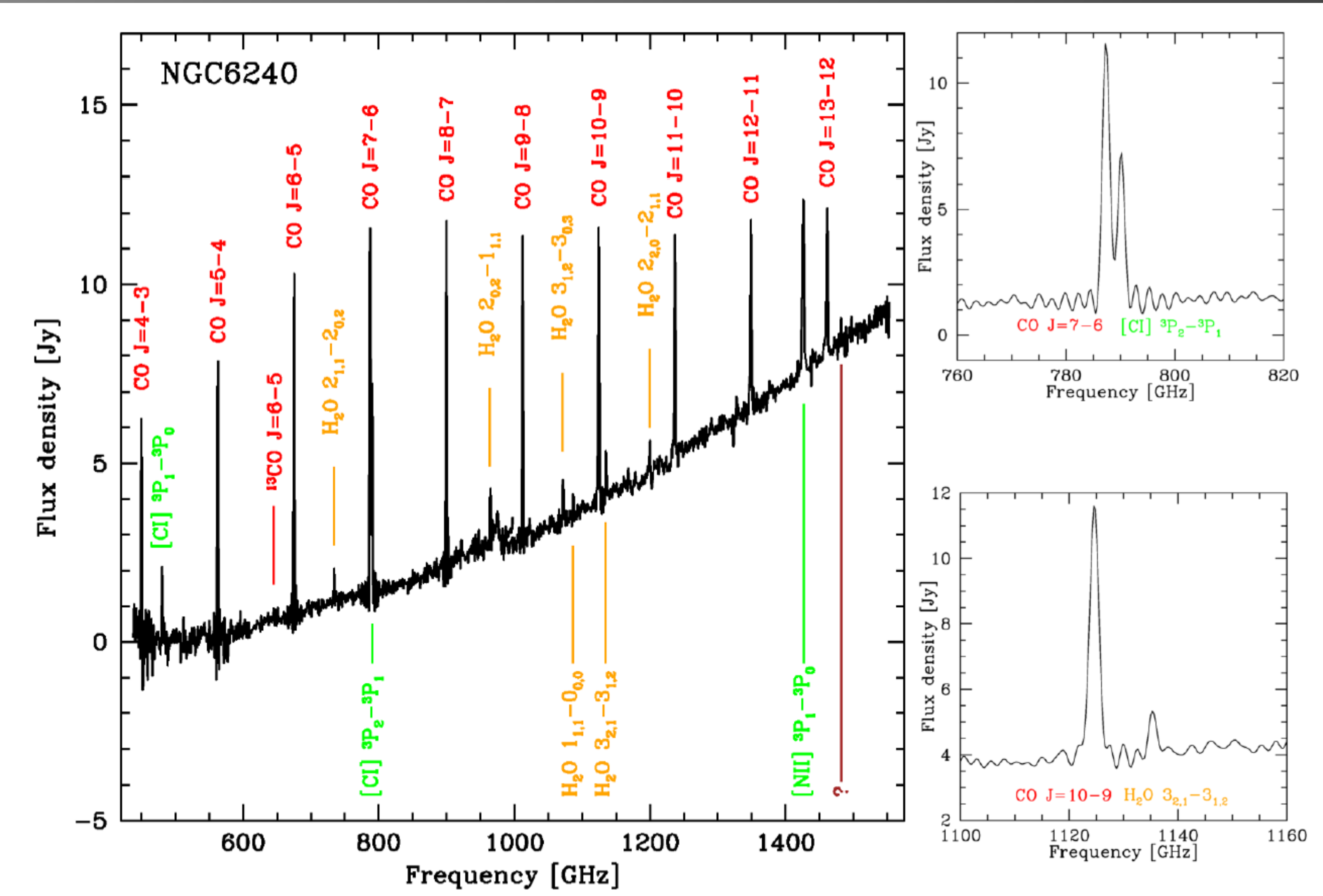
Model feedback zone



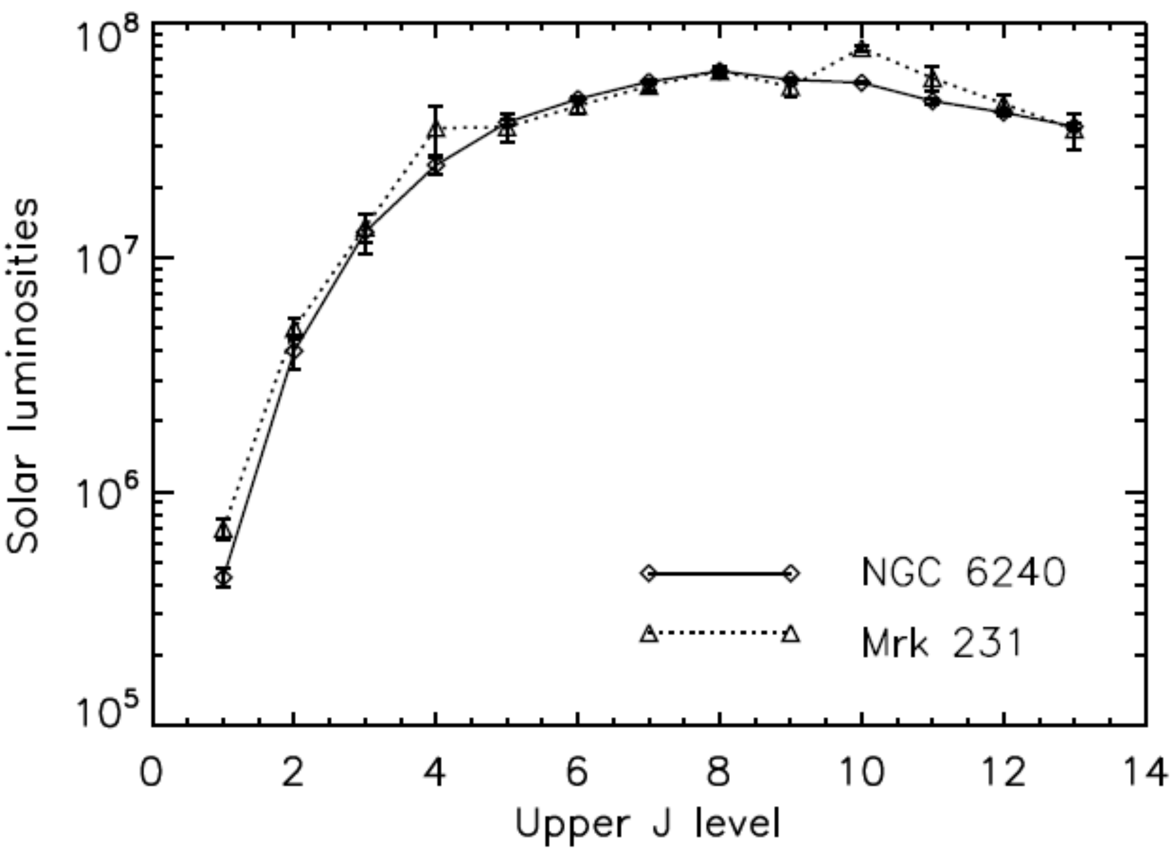
3 main components:

- PDR 1:
  - $n=10^{3.5}$, $G_0=10^2$, r~500pc
  - Large scale molecular gas
  - → Low-J CO lines
- PDR 2:
  - $n=10^5$, $G_0=10^{3.5}$
  - Small, dense SF clumps
  - → mid-J CO lines
- XDR:
  - $n=10^{4.2}$, $F_X=28$ cgs, r~150pc
  - Circum-nuclear disk
  - → High-J CO, OH^+, $H2O^+$

NGC 6240 (Meijerink ea 13)



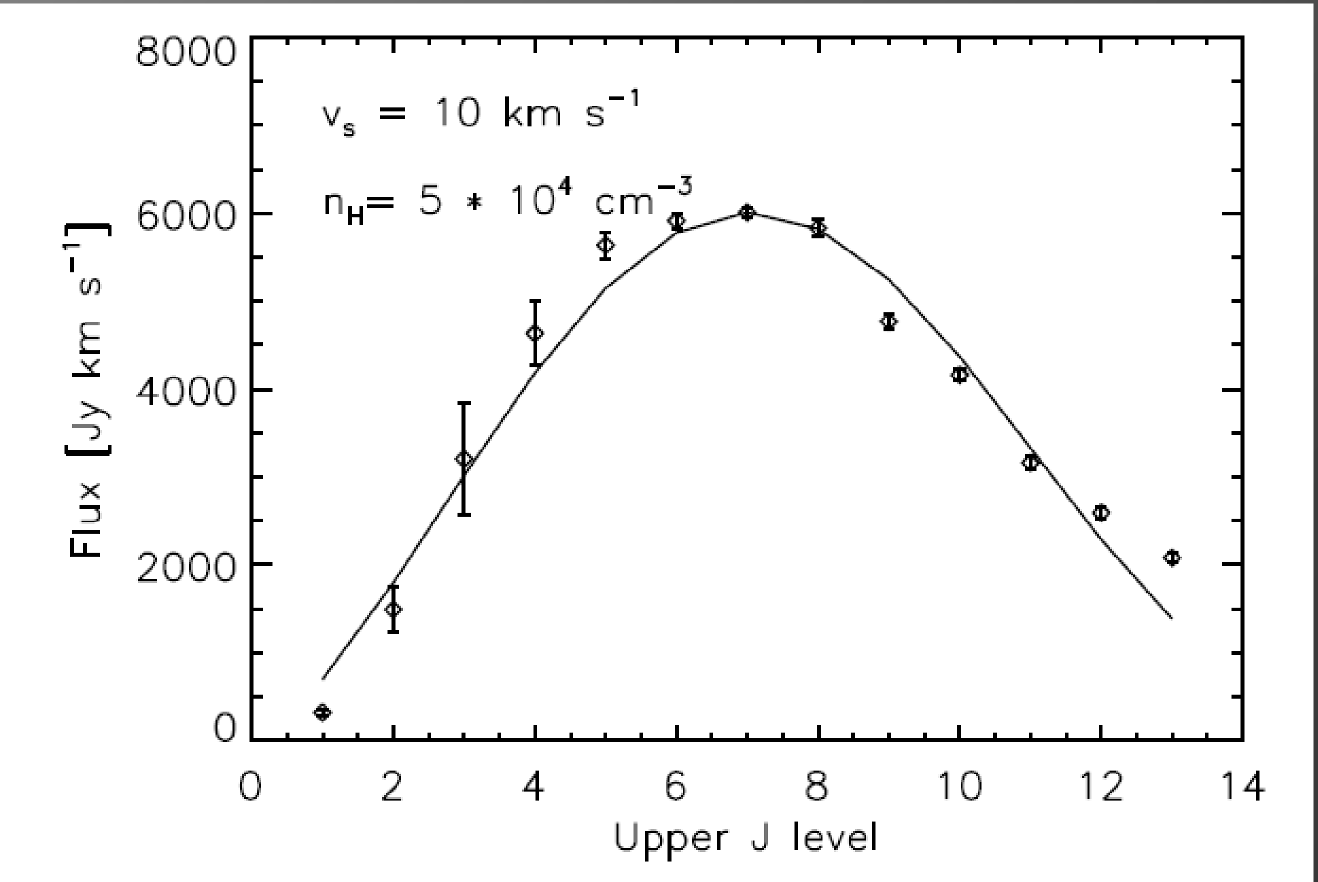
Line SEDs similar, but…



AGNs NGC6240 contribute 10-15% to total power, when looking at geometry of the two nuclei: CO in the middle

Shocks drive high-J CO excitation

High line-to-continuum diagnostic for presence of shocks (H_2O, H_2O^+, OH^+ help as well in this)



C-type, transverse magnetic field = $bn^{1/2}$ μG (b=1-5)

H_2 v=1-0 S(1) and v=2-1 S(1) require v_s ~ 50 km s^{-1}, but for ~1% of the gas

Conclusions

- Future of HerCULES is very exciting
- Can distinguish PDRs, XDRs, CDRs, shocks

With ALMA one can further get:

- Dynamical masses in NLR and BLR
- Accretion rates
- Eddington and star formation efficiencies
- Quantitative measures of local feedback