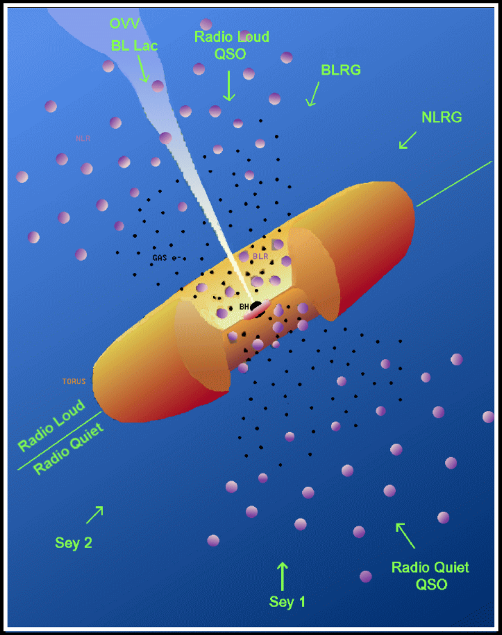
Extragalactic CO Observations and their Interpretation

E. Sturm

MPE

- High-J CO in local galaxies (Herschel)
- High redshift applications (ALMA, IRAM/NOEMA, …)
  - CO SLEDs
  - Modes of star formation
- low-J CO in local galaxies: Outflows

- NOT: general low-J CO in local galaxies



Extragalactic High-J CO: „Historical“ context

Krolik & Lepp (1989):

If the AGN torus exists, it should emit not only in thermal continuum (mid-IR), but also in molecular cooling lines (e.g. FIR)

→ detectable fraction of L_bol in IR molecular lines (mid-IR H2, far-IR CO)

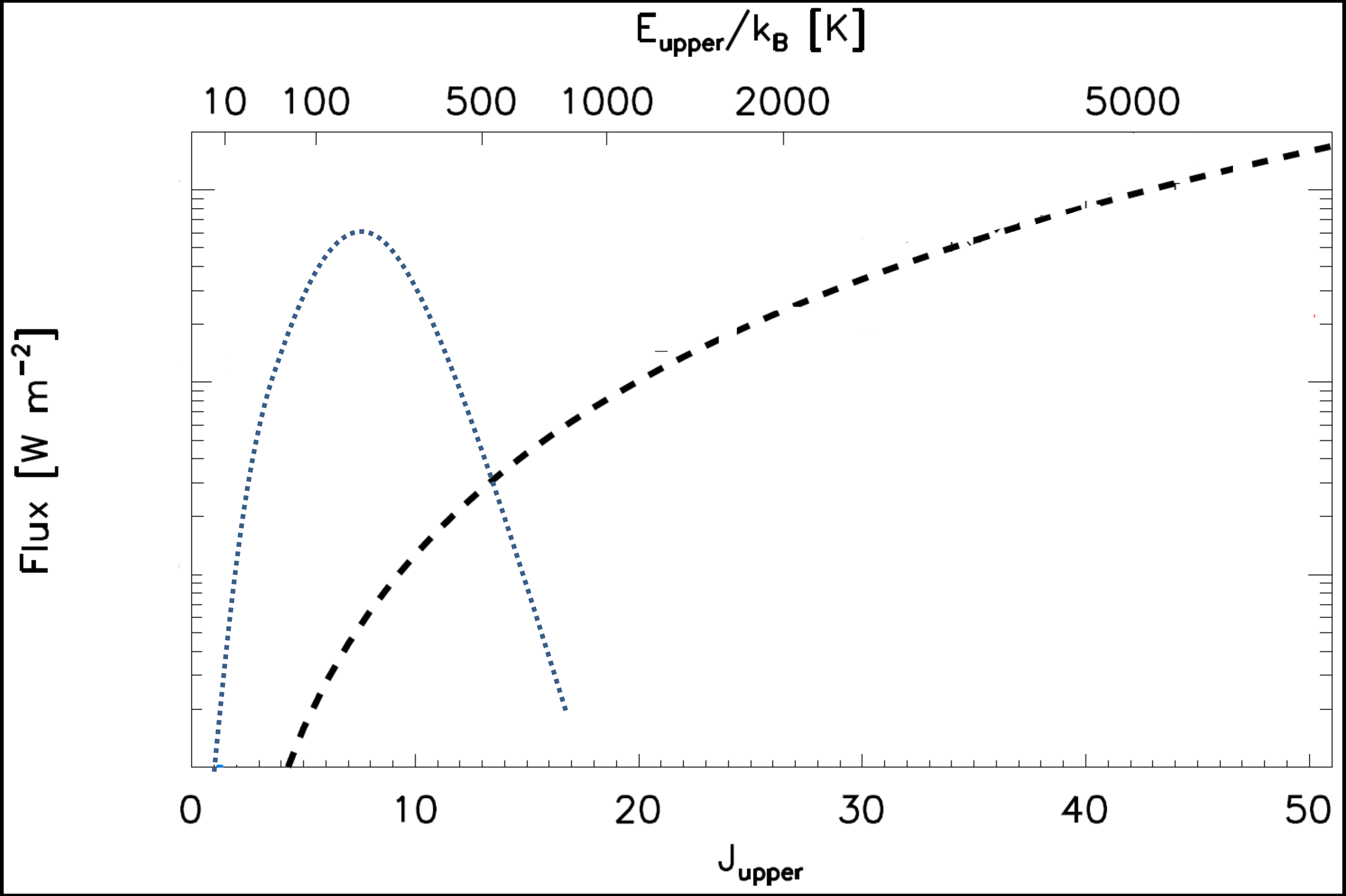
Promise of high-J CO lines: strong enough, little extinction, not or only weakly produced in normal star formation regions (i.e. direct tracer of torus)

Krolik & Lepp 1989 – FIR CO lines from the Torus

- $L_{57} = 7x10^{40} f_{abs} L_{x44}$ ergs^{-1} (J = 58 → 57, 46 μm)

E.g. NGC1068: Molecular gas ~ 1 pc from L_x ~ 10^{44} erg/s source, f_{abs}*$L_{x,44}$ = 0.05

→ L_{CO} ~ (f_{abs}*$L_{x,44}$)*J^3 :



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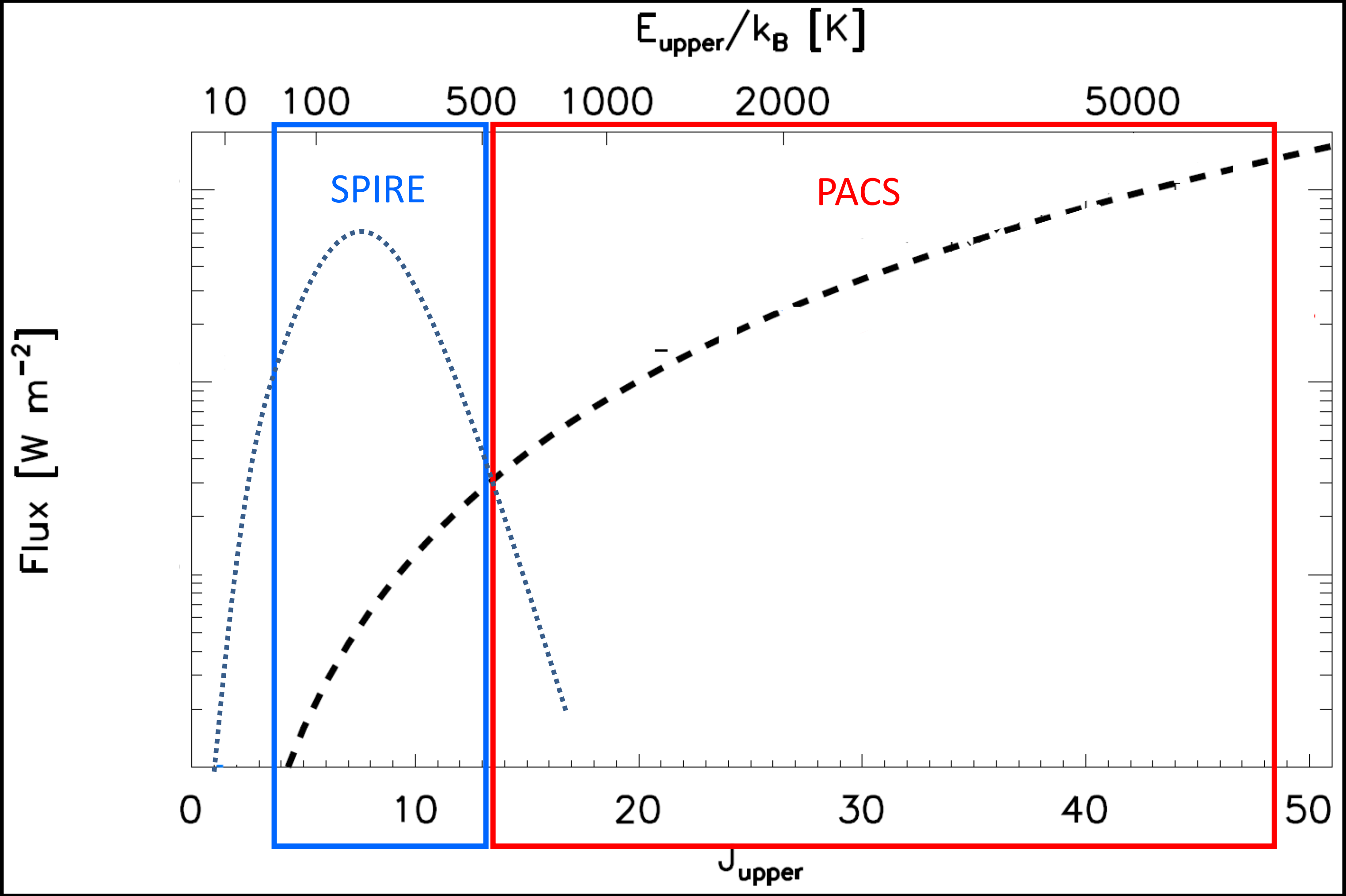
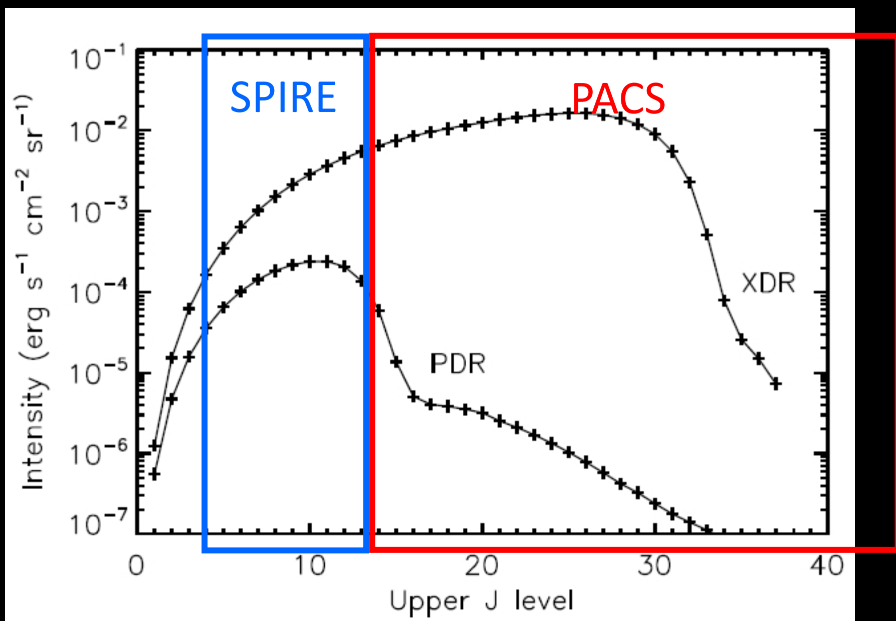
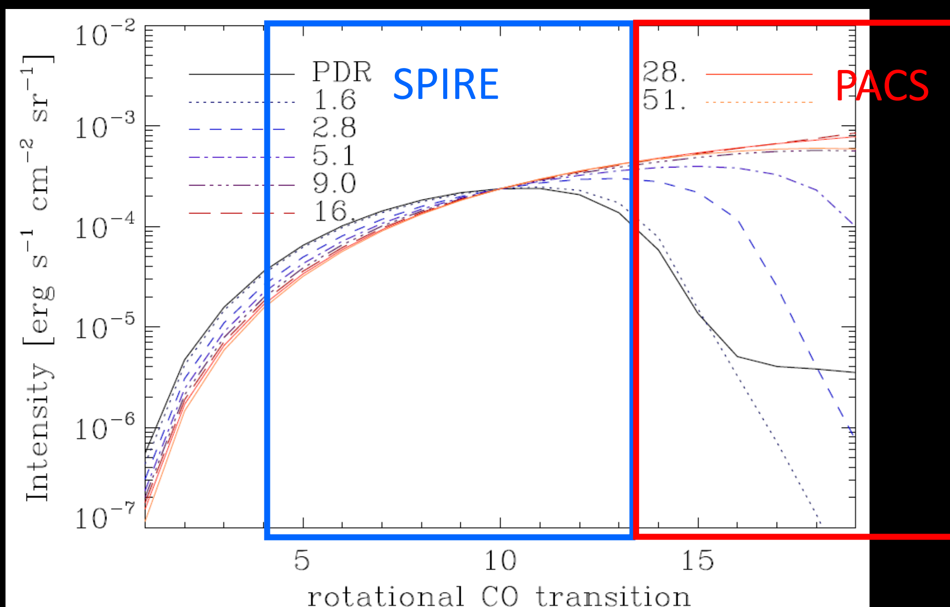
$\rightarrow L_{CO} \sim (f_{abs} * L_{x,44}) * J^3$:



Extragalactic High-J CO: „modern“ context

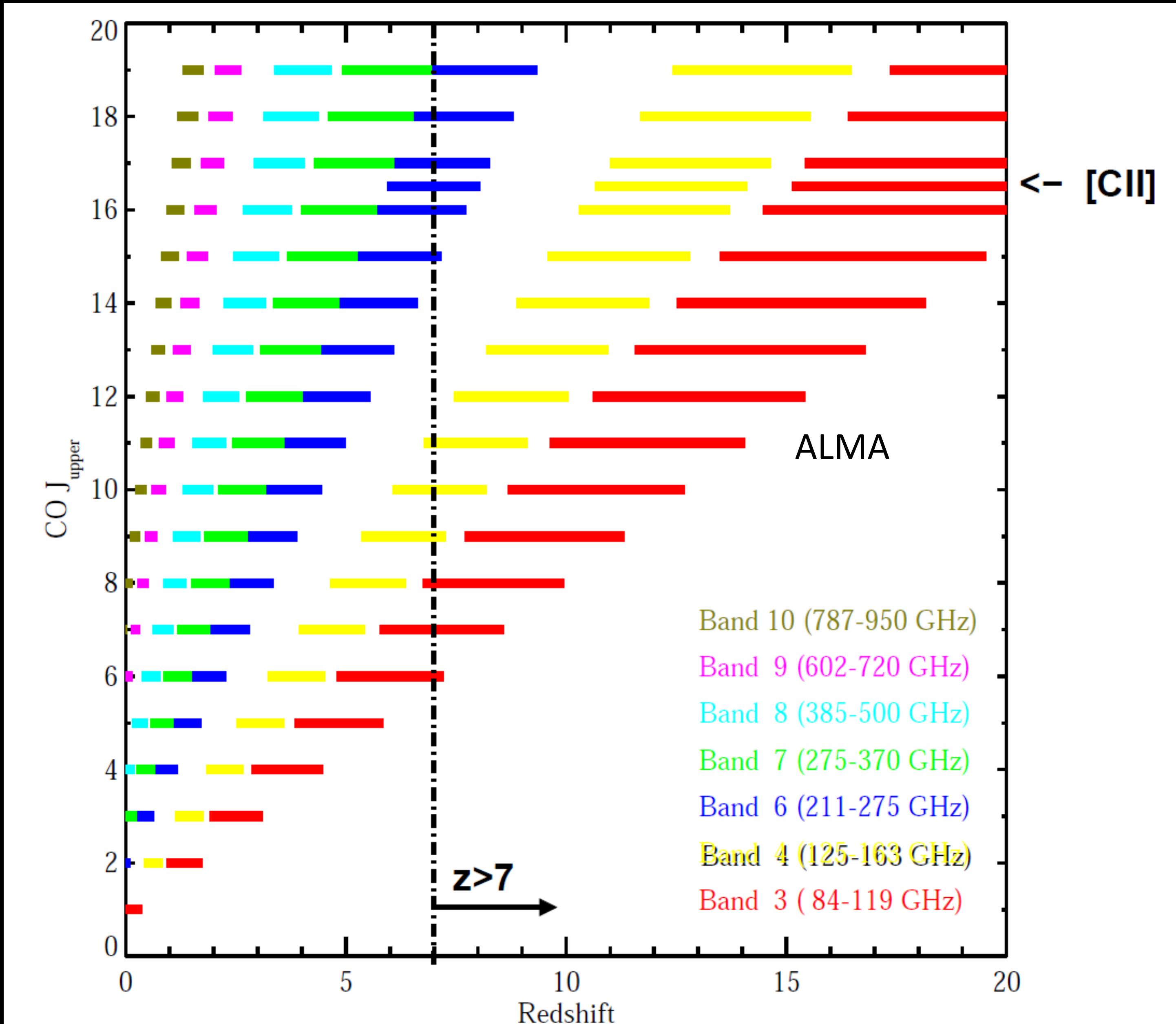


Spaans & Meijerink 2008



Schleicher+ 2010

High-J is all you get at high z



Walter & Carilli 2008

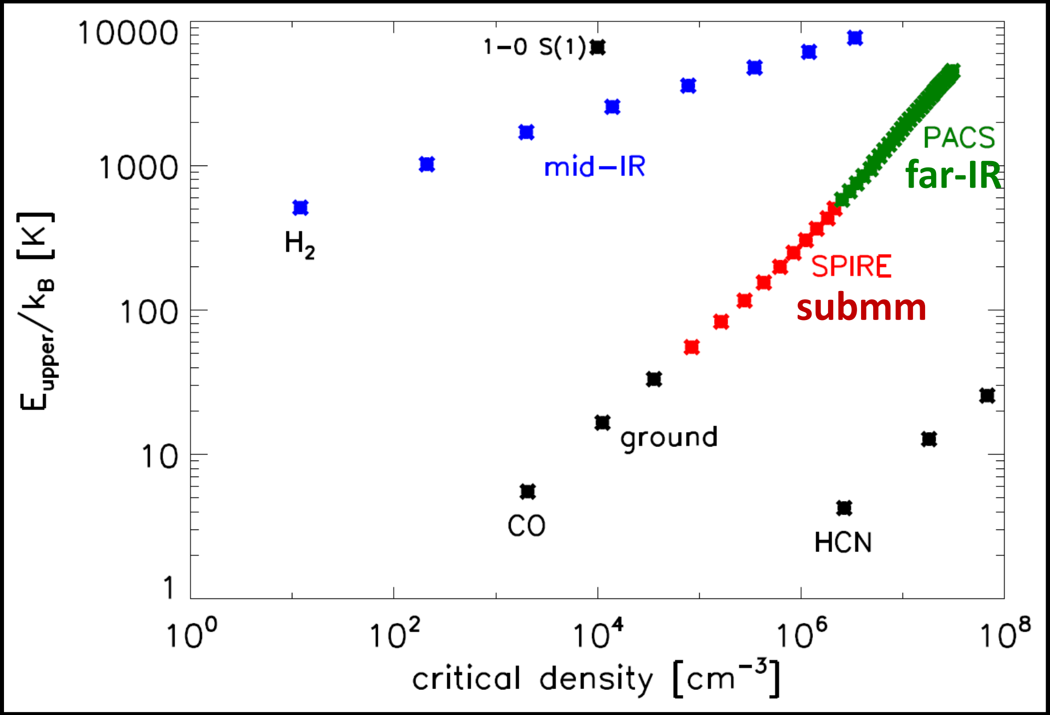
What can we learn from high-J CO line observations ?

- Excitation source (PDR, XDR, shocks, CRs, others)?
- CO (high J) / CO (1-0) ?

High-J CO --> A new probe of warm and dense molecular gas

- SB, AGN, feedback, galaxy evolution
  - UV/X-ray (AGN torus)
  - Cosmic rays
  - Jets
  - turbulence
  - Mergers vs. cold accretion
  - galaxy dynamics
  - outflows

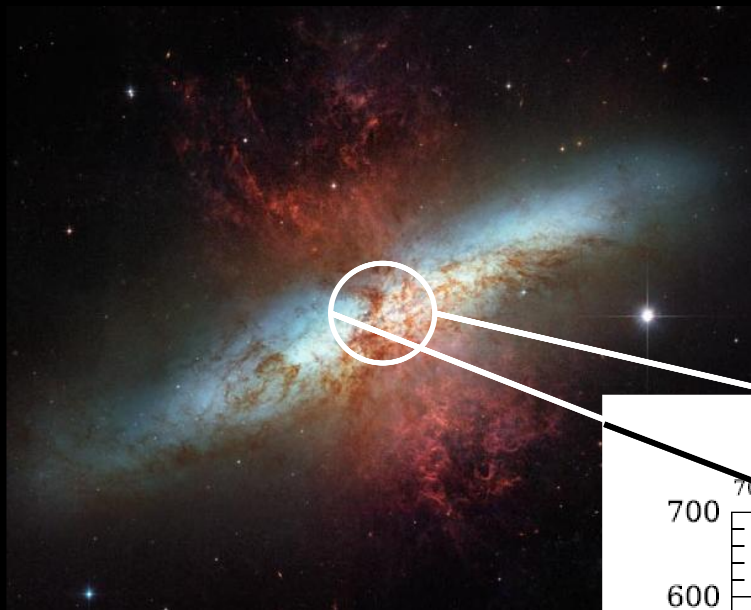
- Methods
  - Galactic templates
  - Non-LTE radiative transfer
  - PDR/XDR/shock models
  - High resolution spectral imaging

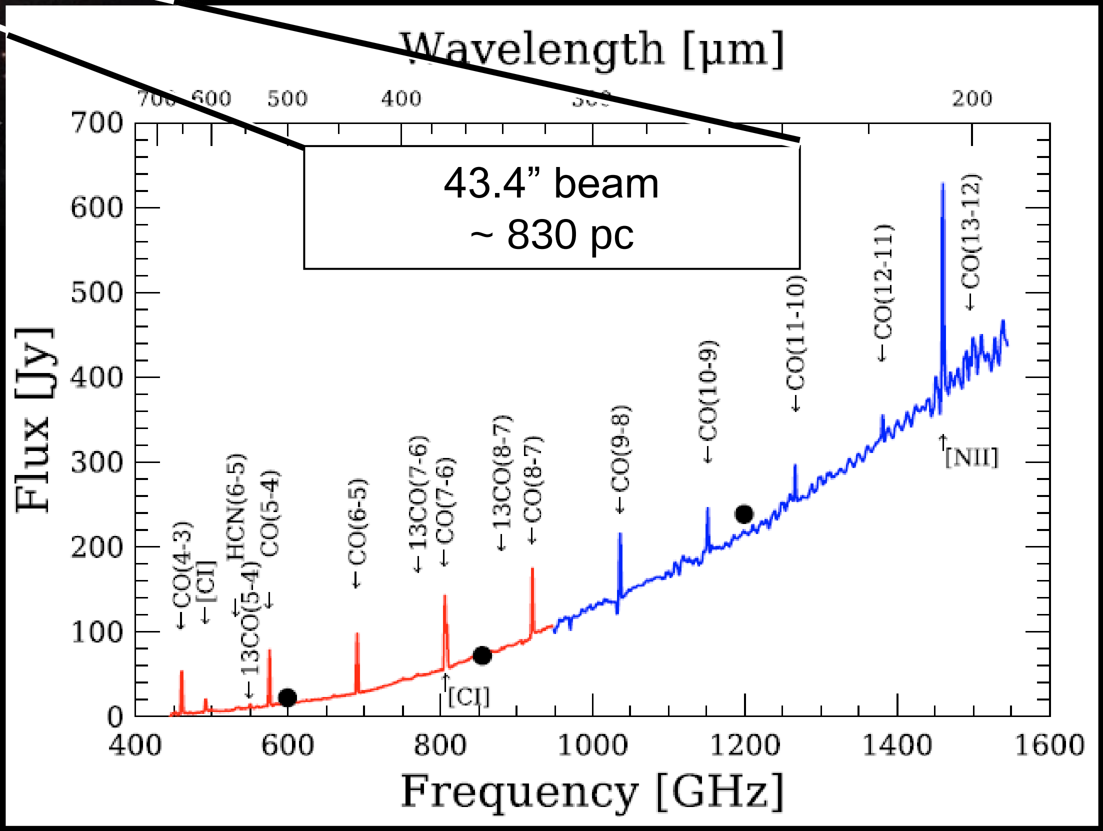


Nearby templates

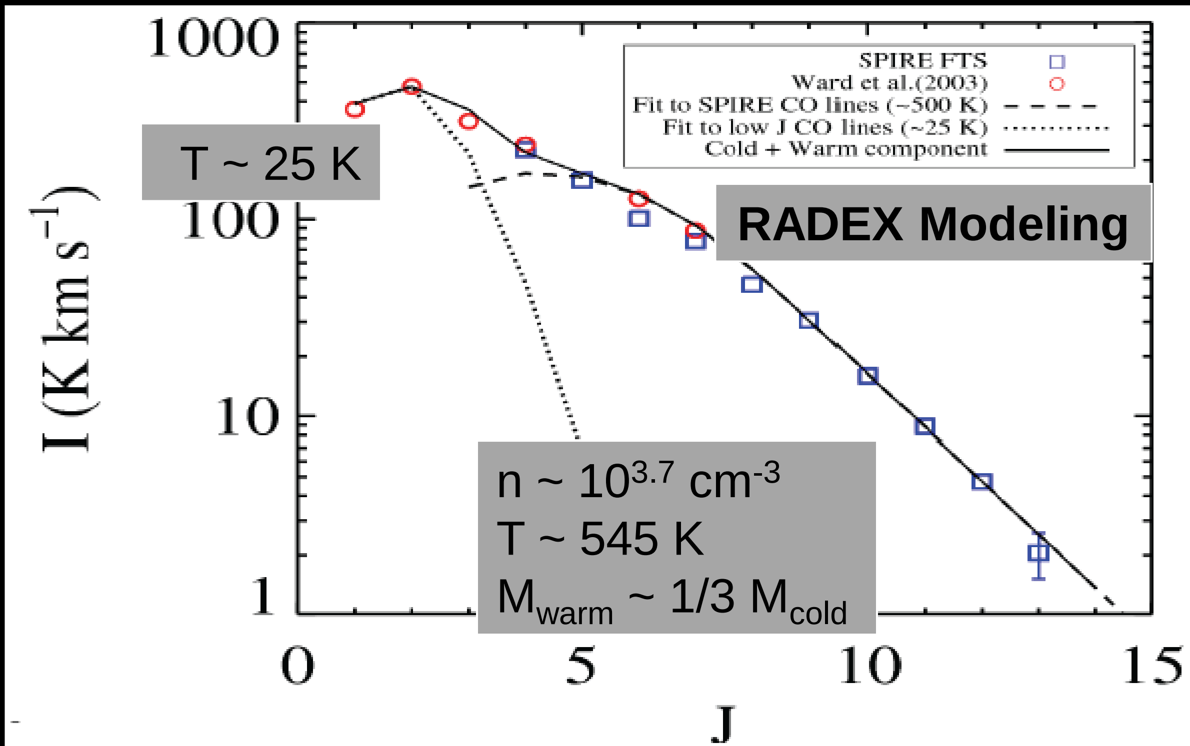
- M82(SB)
- NGC1068 (Sy)

M82 (Panuzzo+2010, SPIRE)





M82 (Panuzzo+2010, SPIRE)



CO(6-5) and CO(7-6) brighter than PDR predictions
⇒ not tracing UV-heated gas

- T ~ 545 K consistent with H_2 S(0)/S(1) ratio --> **L/M ~ 2.6 L_{sun}/M_{sun}**
- Cosmic ray density too low
- Dissipation of turbulence

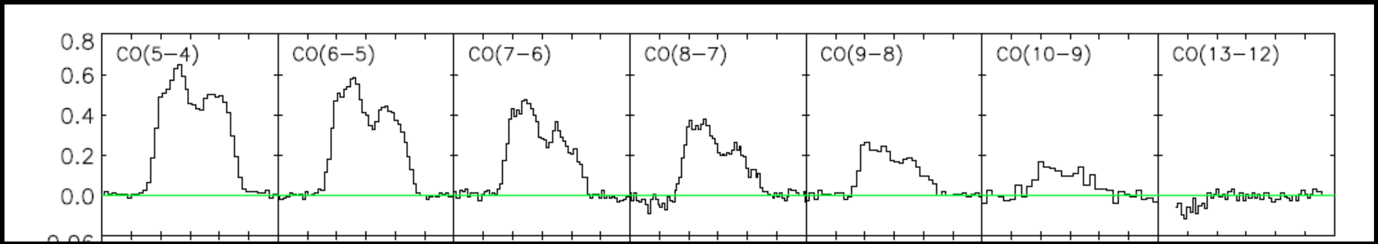
  ⇒ stellar wind and supernovae

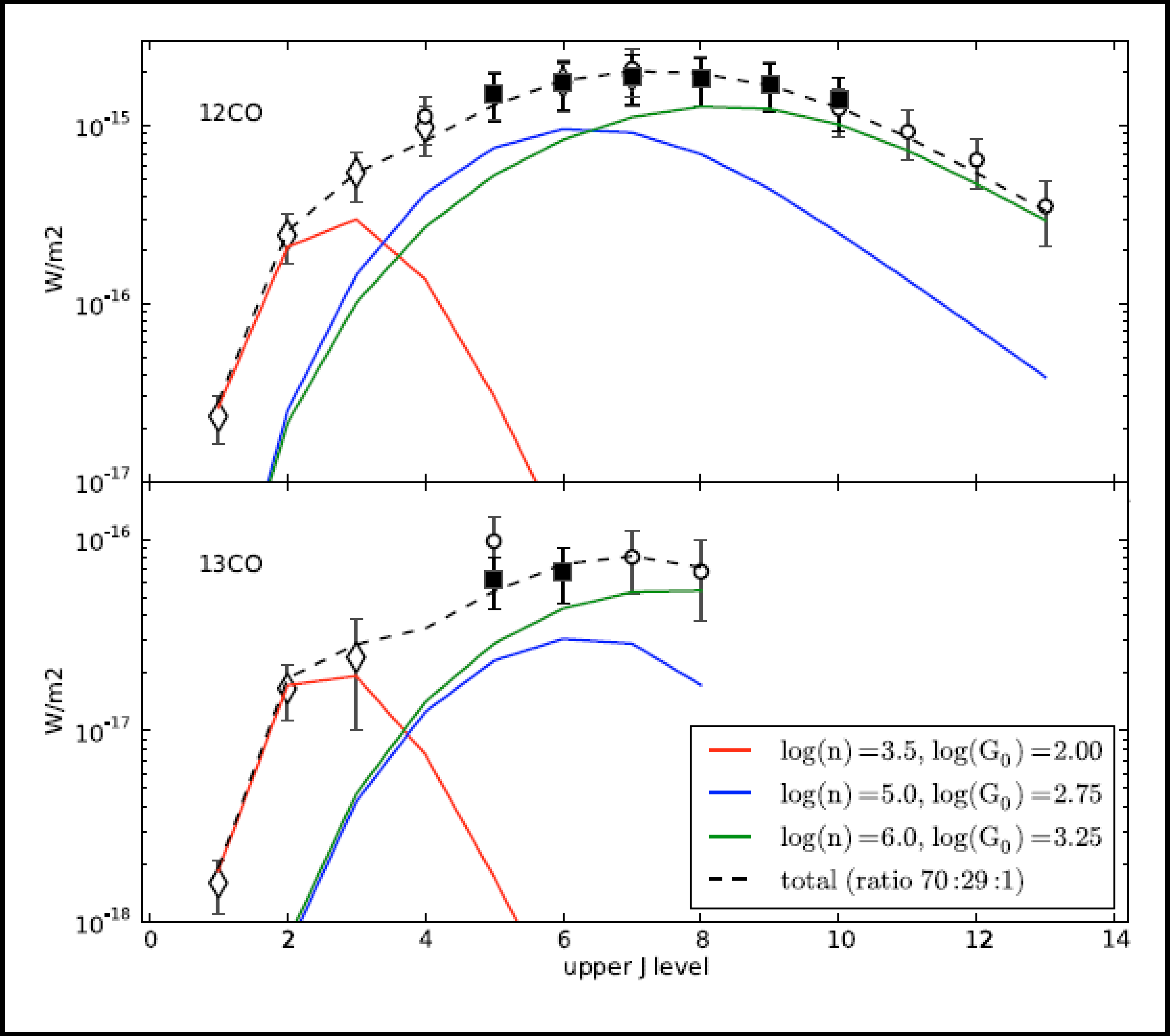
Mac Low 99, Pan & Padoan 09

$$\frac{L}{M} = 0.42\frac{v_{\rm rms}^3}{\Lambda_d} = 1.10\left(\frac{v_{\rm rms}}{25\,km\,s^{-1}}\right)^3\left(\frac{1\,{\rm pc}}{\Lambda_d}\right)\frac{{\rm L}_\odot}{{\rm M}_\odot},$$

HIFI

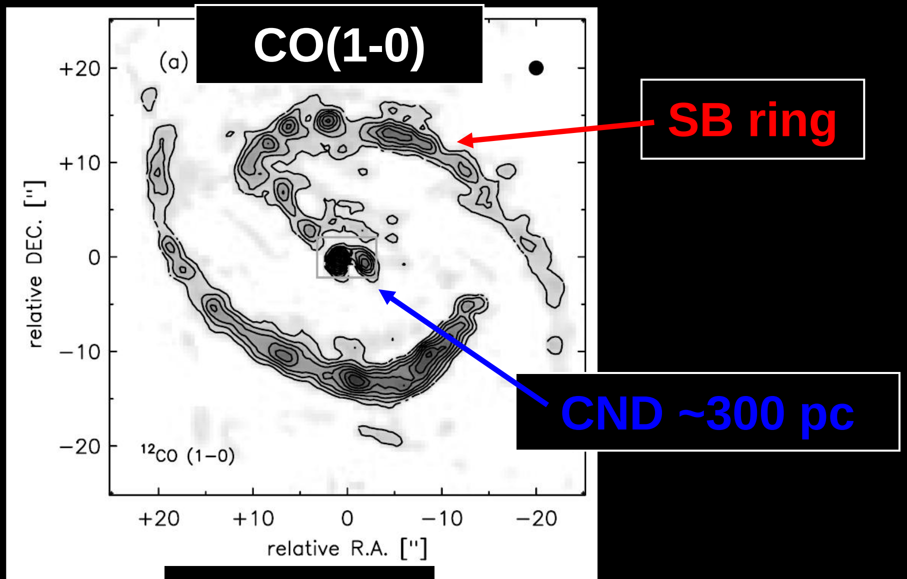
Loenen+ 2010



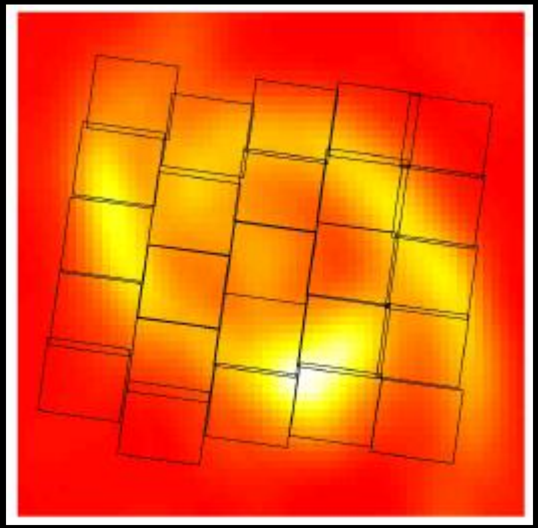


NGC 1068 (Hailey-Dunsheath+2012, PACS)

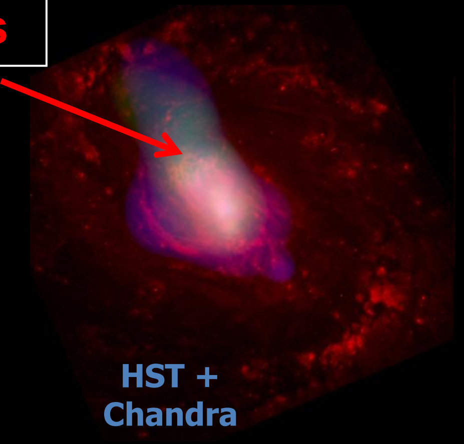
2 kpc

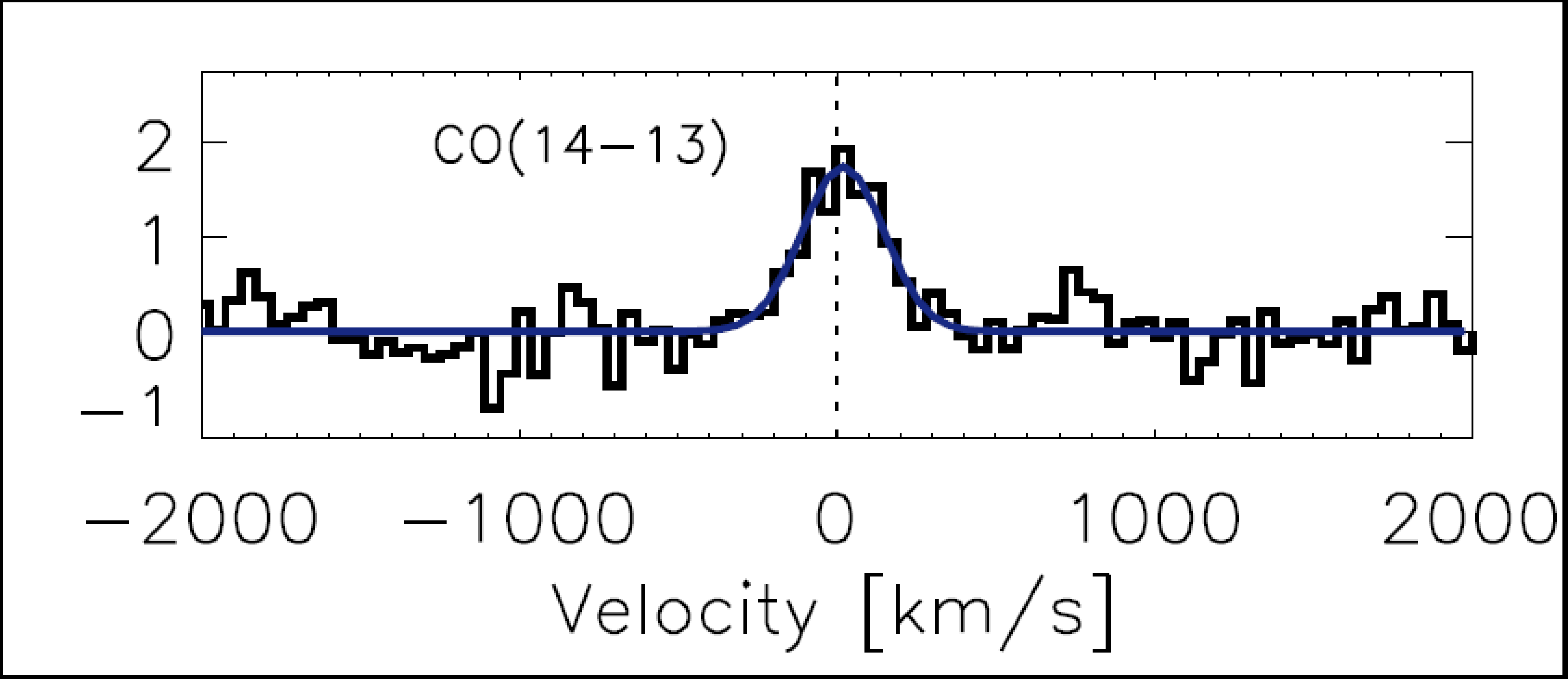


Schinnerer+00

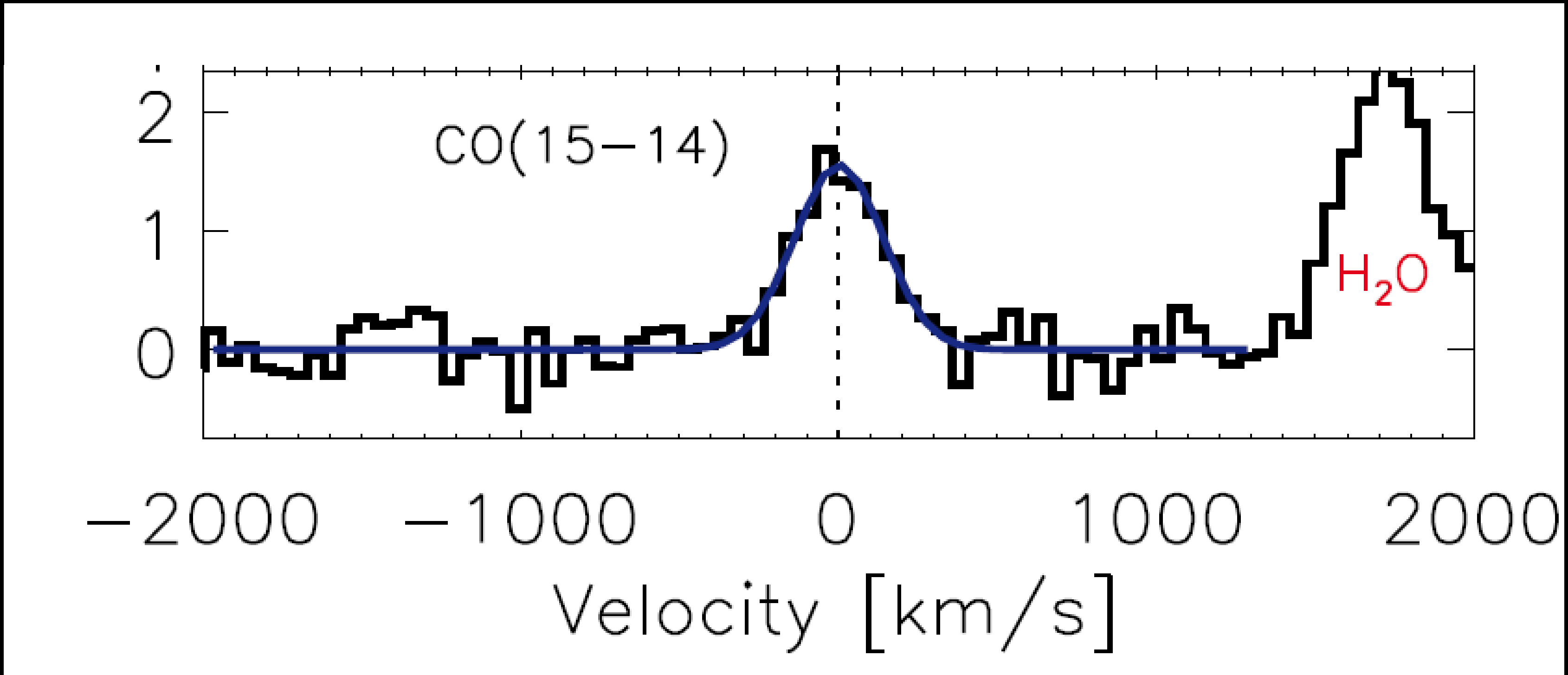


X-rays

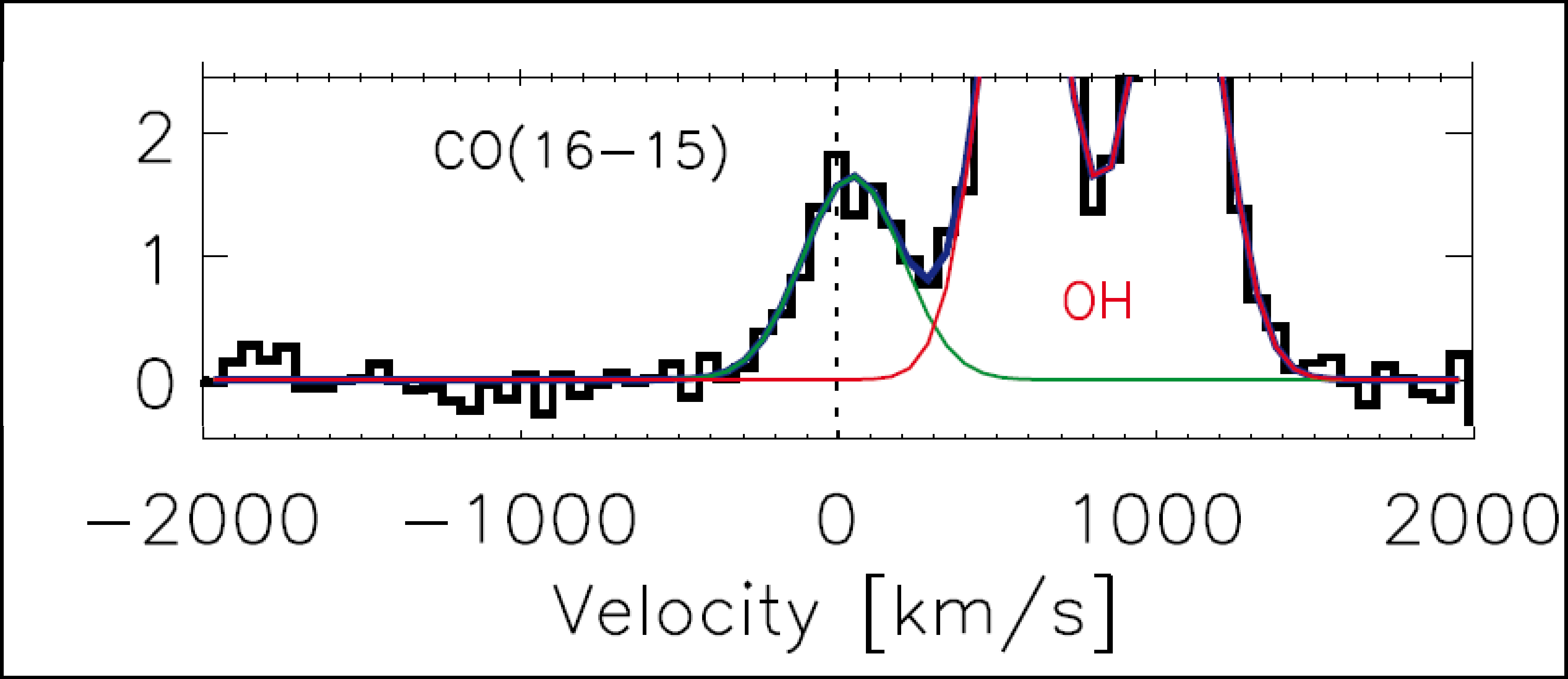




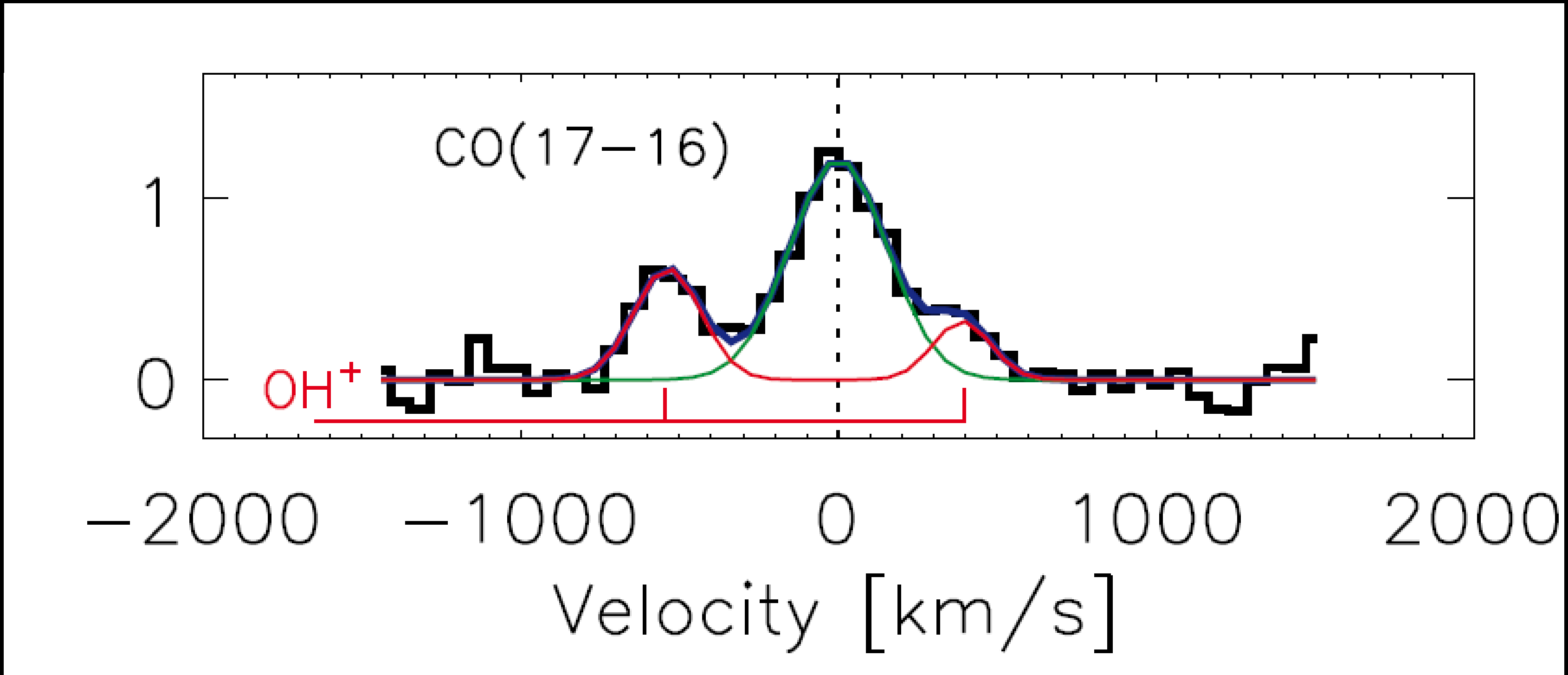
CO(14−13)
2
1
0
−1
−2000
−1000
0
1000
2000
Velocity [km/s]

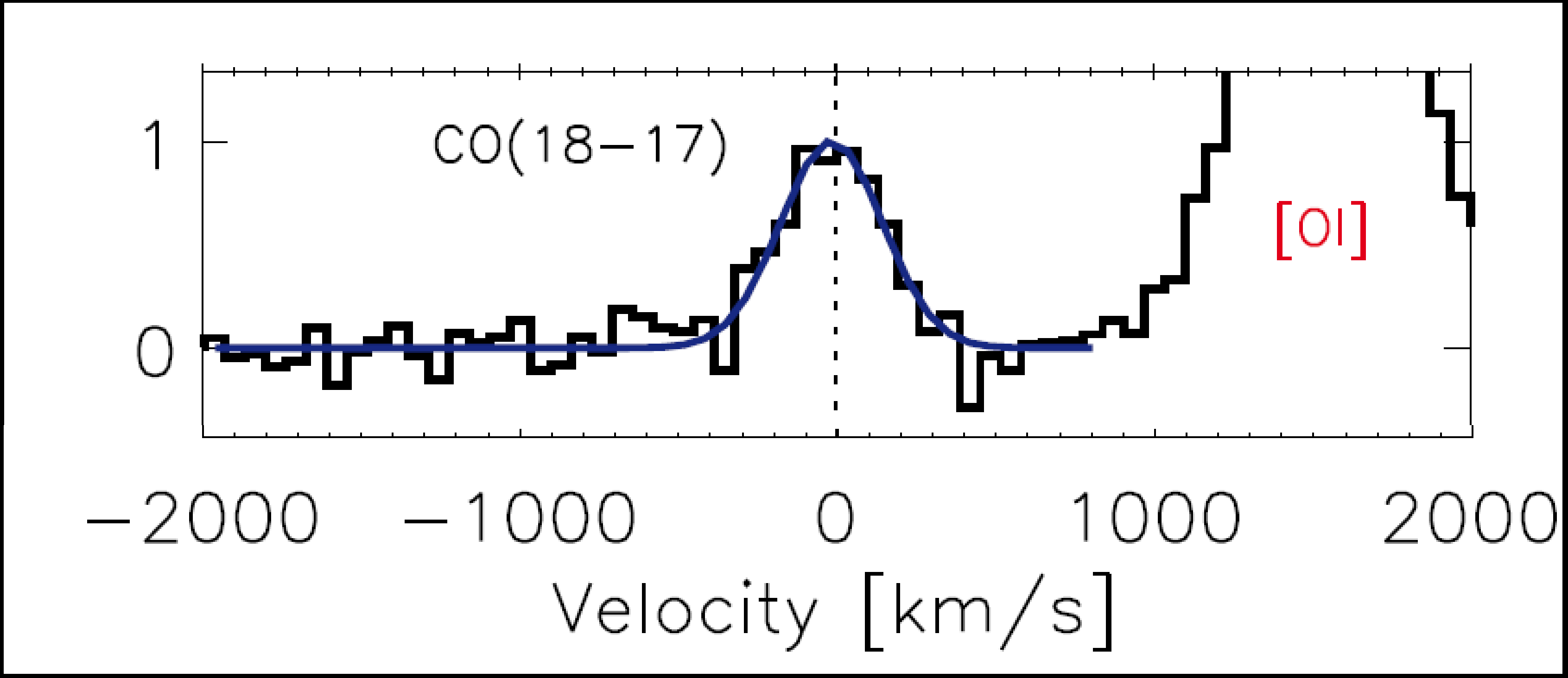


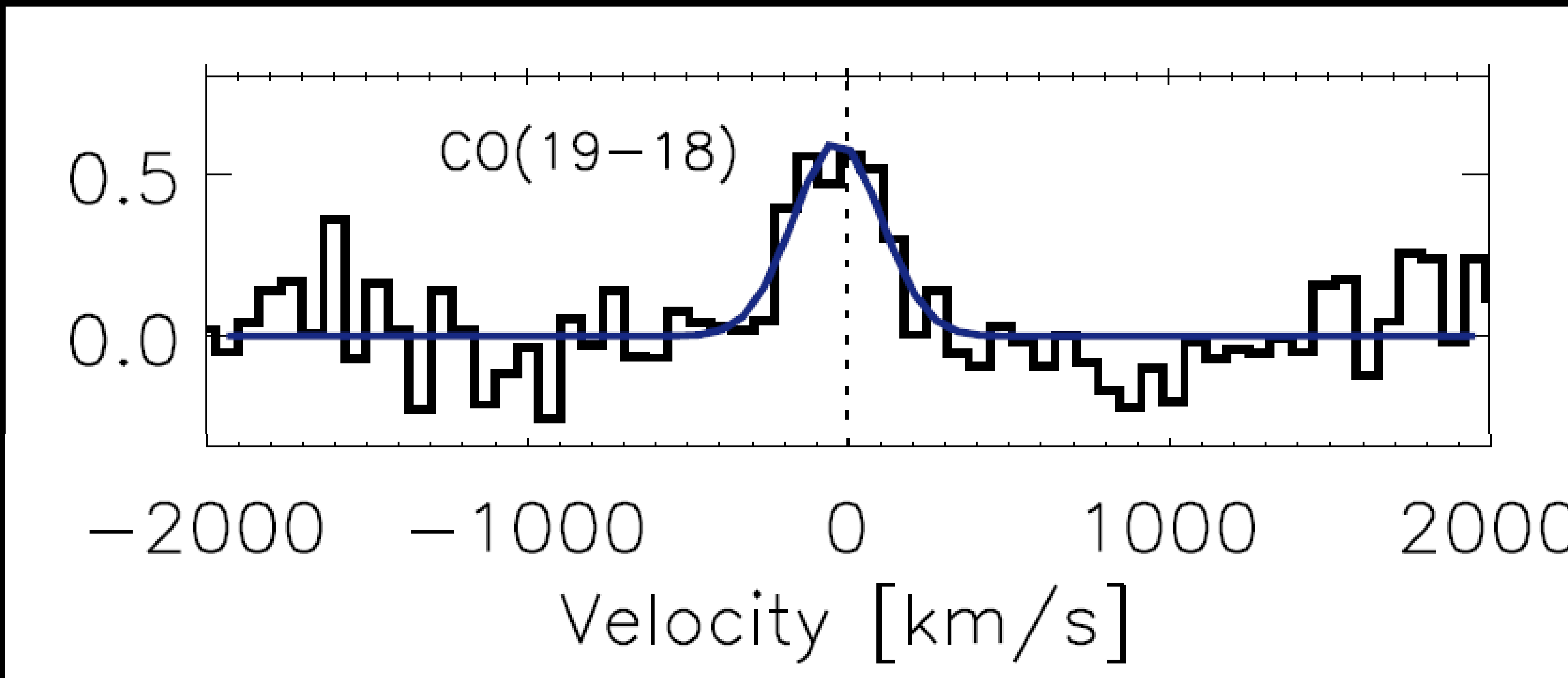
CO(15−14)
H_2O
2
1
0
−2000
−1000
0
1000
2000
Velocity [km/s]



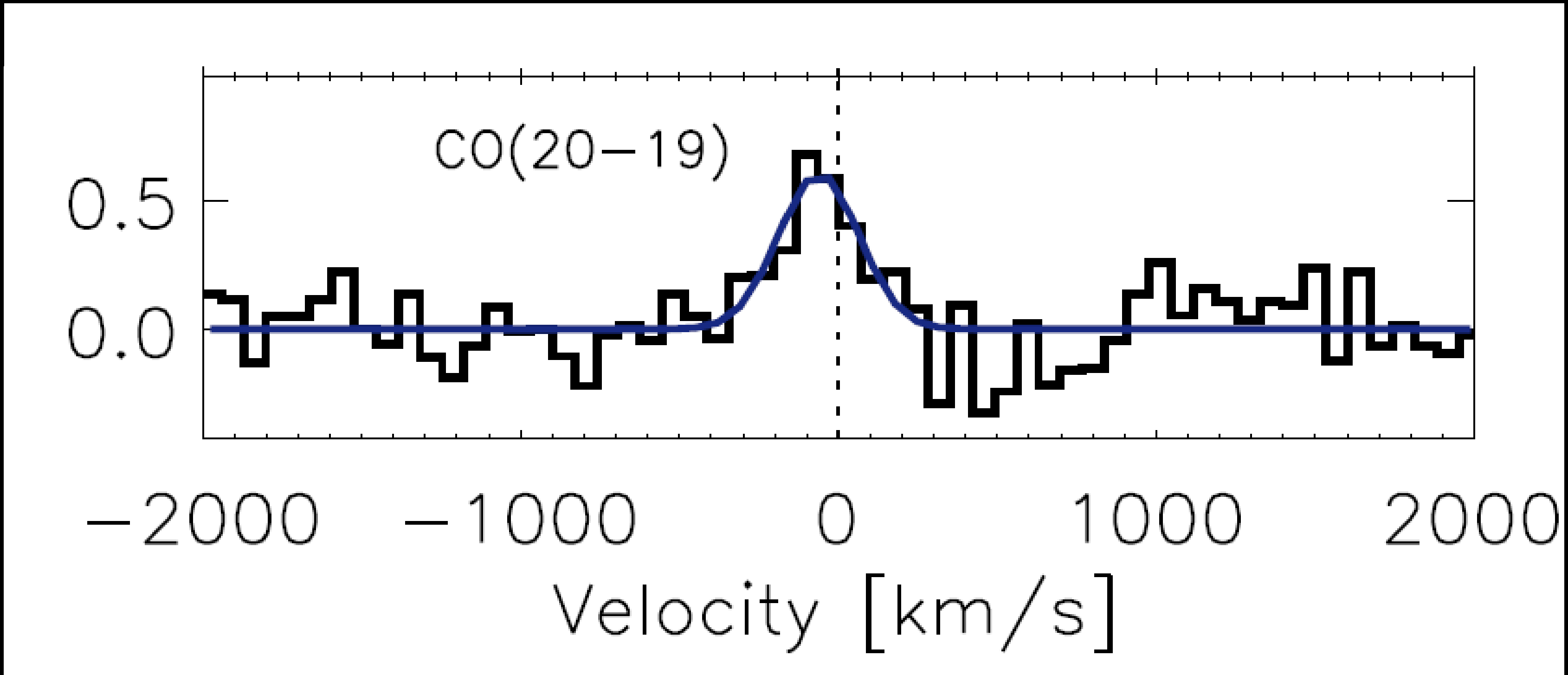
CO(16−15)
OH
2
1
0
−2000
−1000
0
1000
2000
Velocity [km/s]

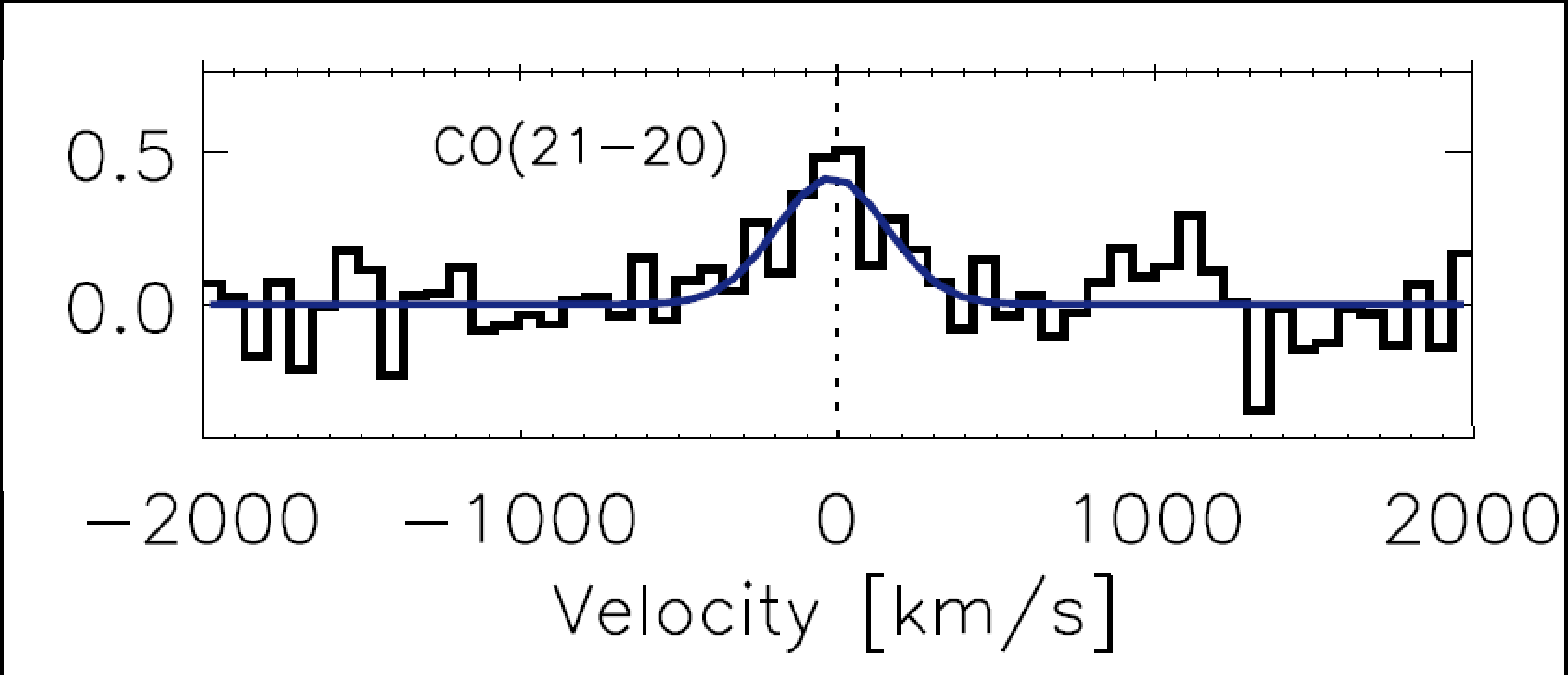

CO(17−16)
OH+
1
0
−2000
−1000
0
1000
2000
Velocity [km/s]


CO(18−17)
[OI]
1
0
−2000
−1000
0
1000
2000
Velocity [km/s]

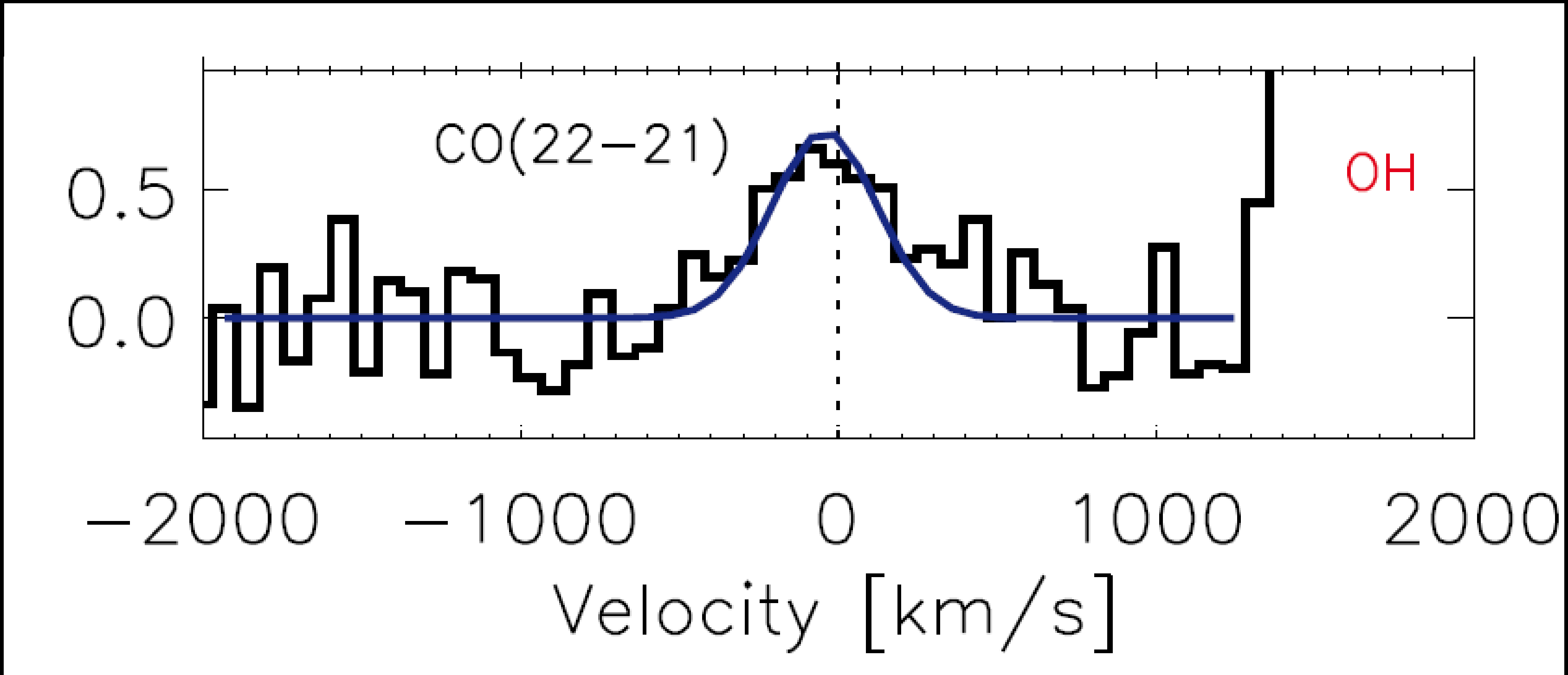


CO(19−18)
0.5
0.0
−2000
−1000
0
1000
2000
Velocity [km/s]

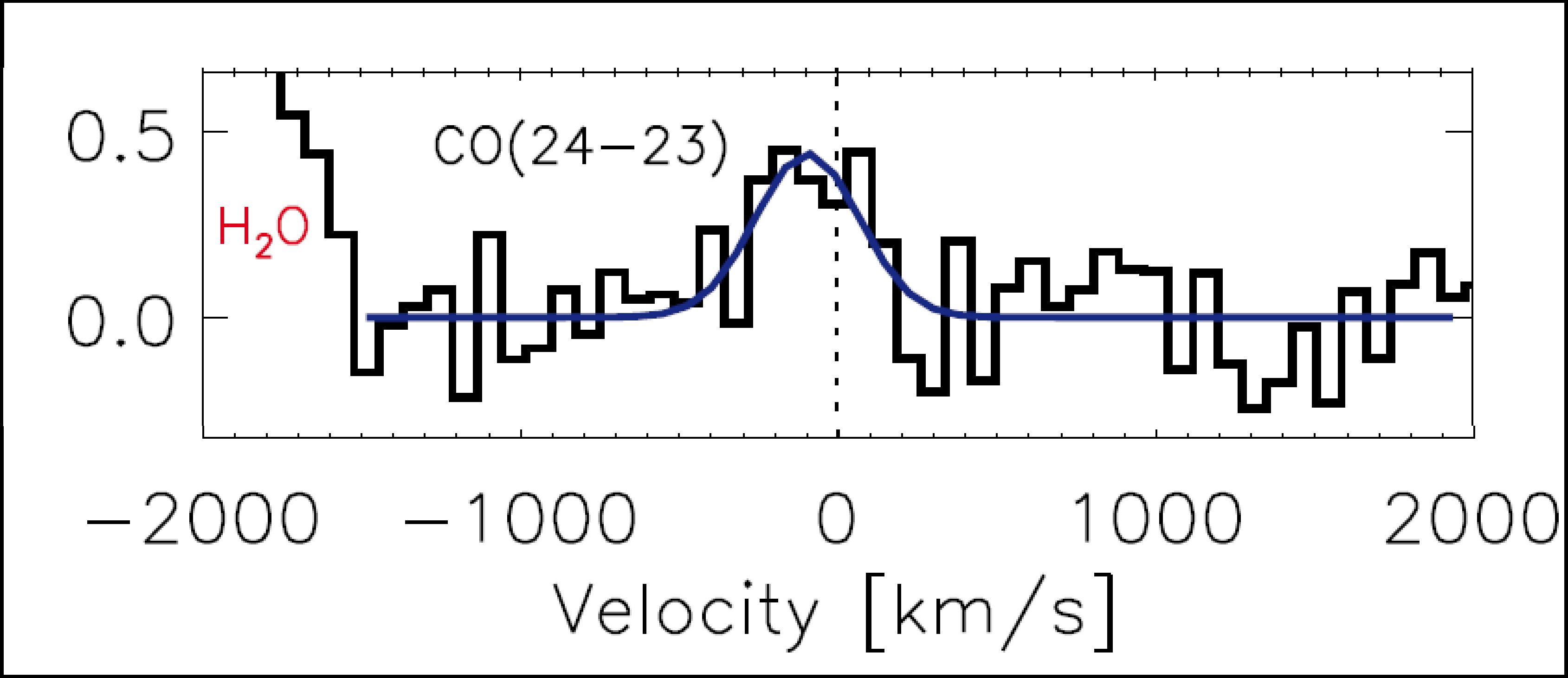

CO(20−19)
0.5
0.0
−2000
−1000
0
1000
2000
Velocity [km/s]



CO(21−20)
0.5
0.0
−2000
−1000
0
1000
2000
Velocity [km/s]

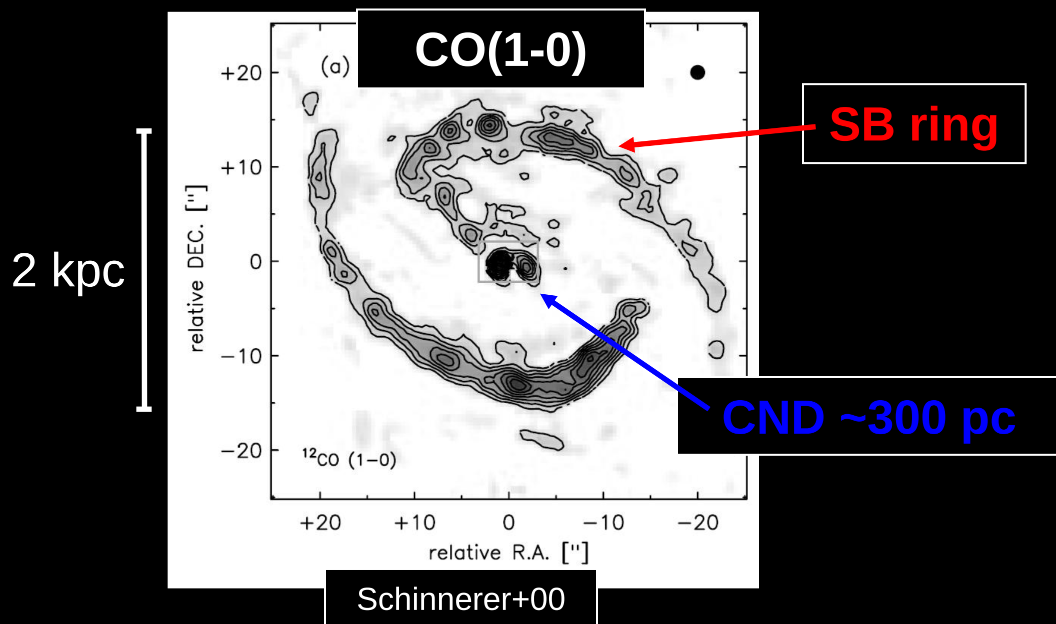


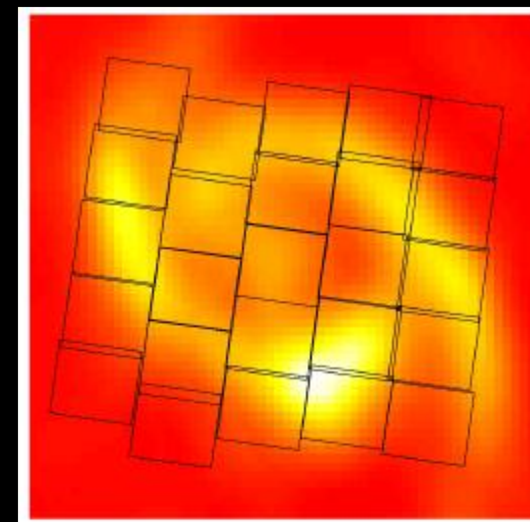
CO(22−21)
OH
0.5
0.0
−2000
−1000
0
1000
2000
Velocity [km/s]



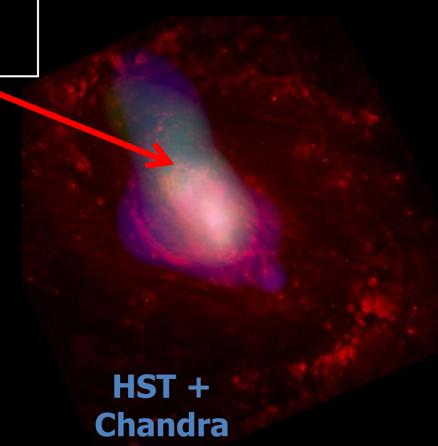
0.5
0.0
CO(24−23)
H_2O
−2000
−1000
0
1000
2000
Velocity [km/s]

NGC 1068 (Hailey-Dunsheath+2012, PACS)





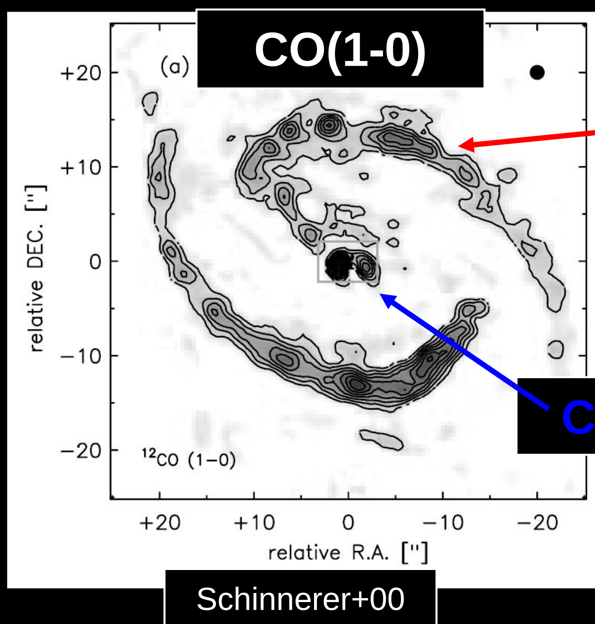
X-rays

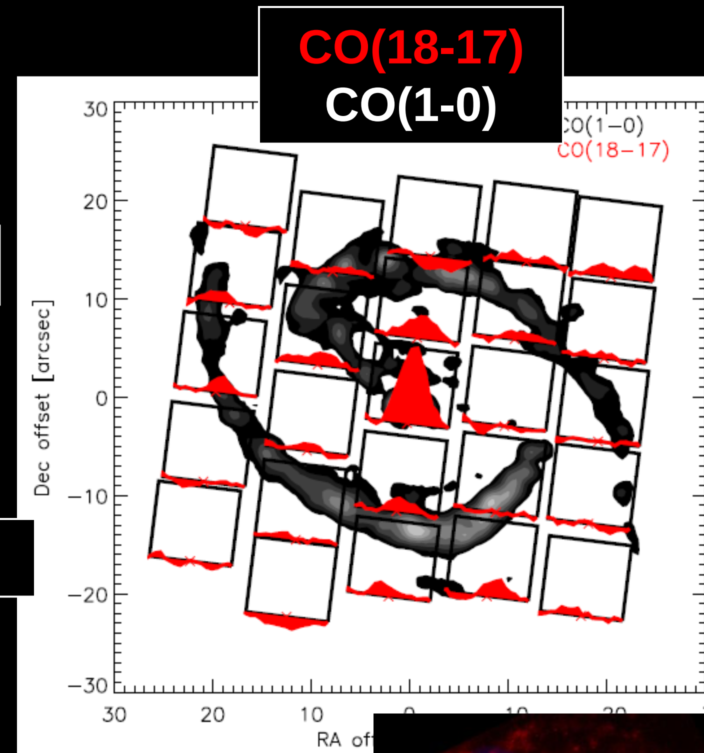


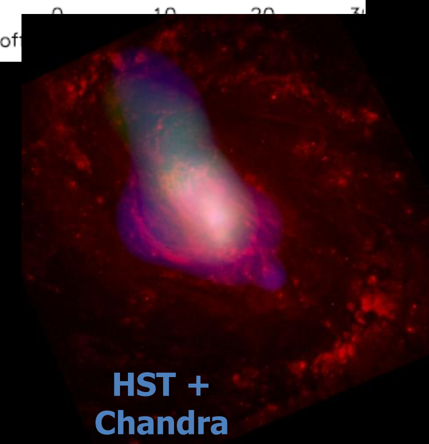
- x11 CO lines --> **First extragalactic far-IR CO**
- Atomic fine-structure lines ([CII], [OI], [NII], [OIII], [NIII])
- OH, H_2O, **OH^+, H_2O^+,** …
- Molecular emission concentrated in central spaxel

NGC 1068 (Hailey-Dunsheath+2012, PACS)

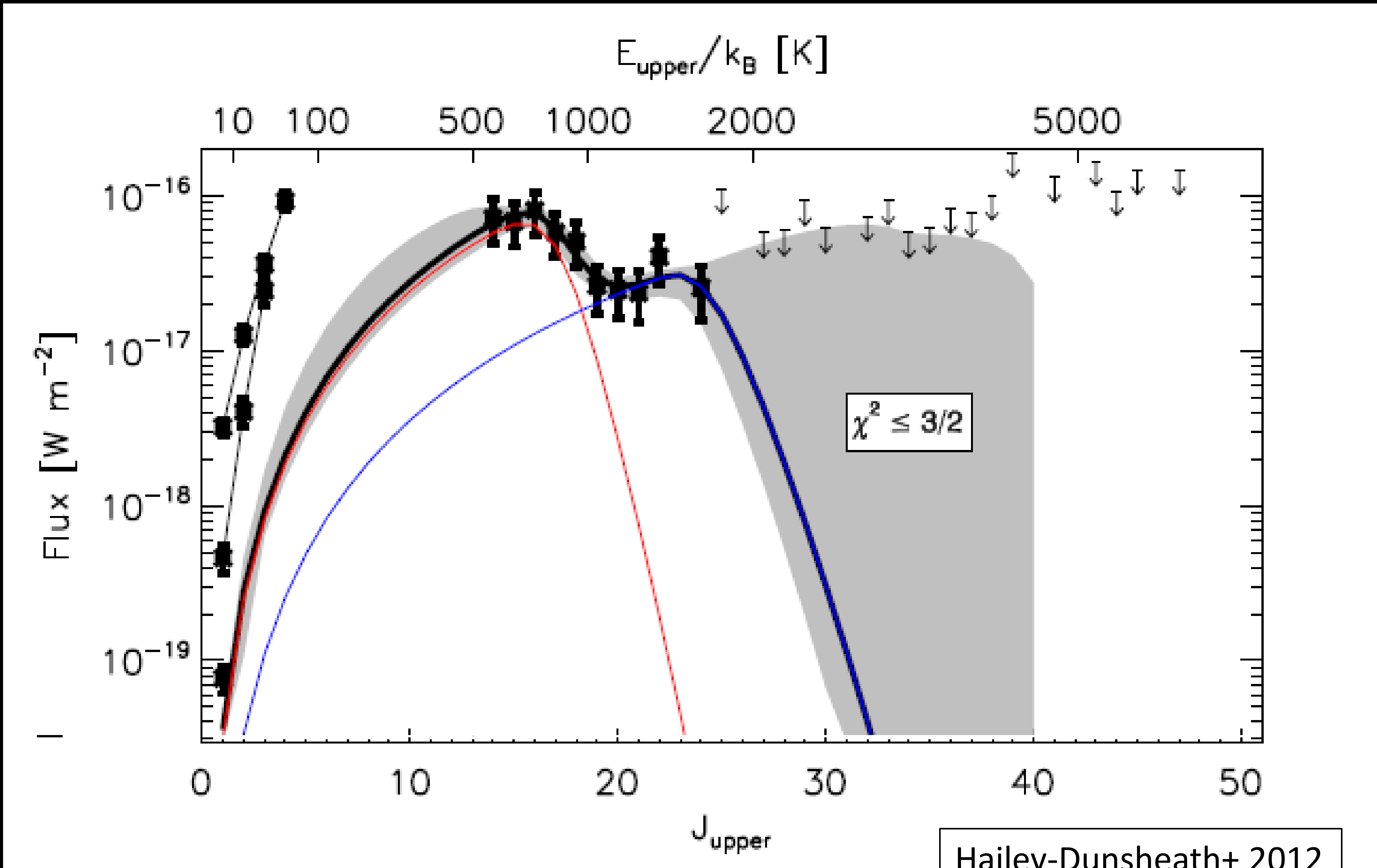
2 kpc



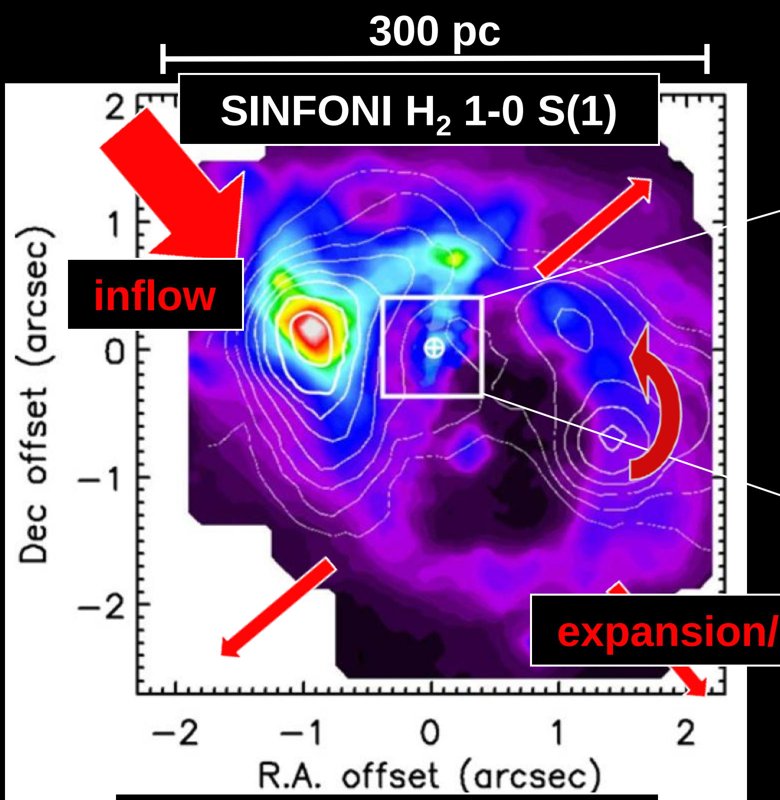


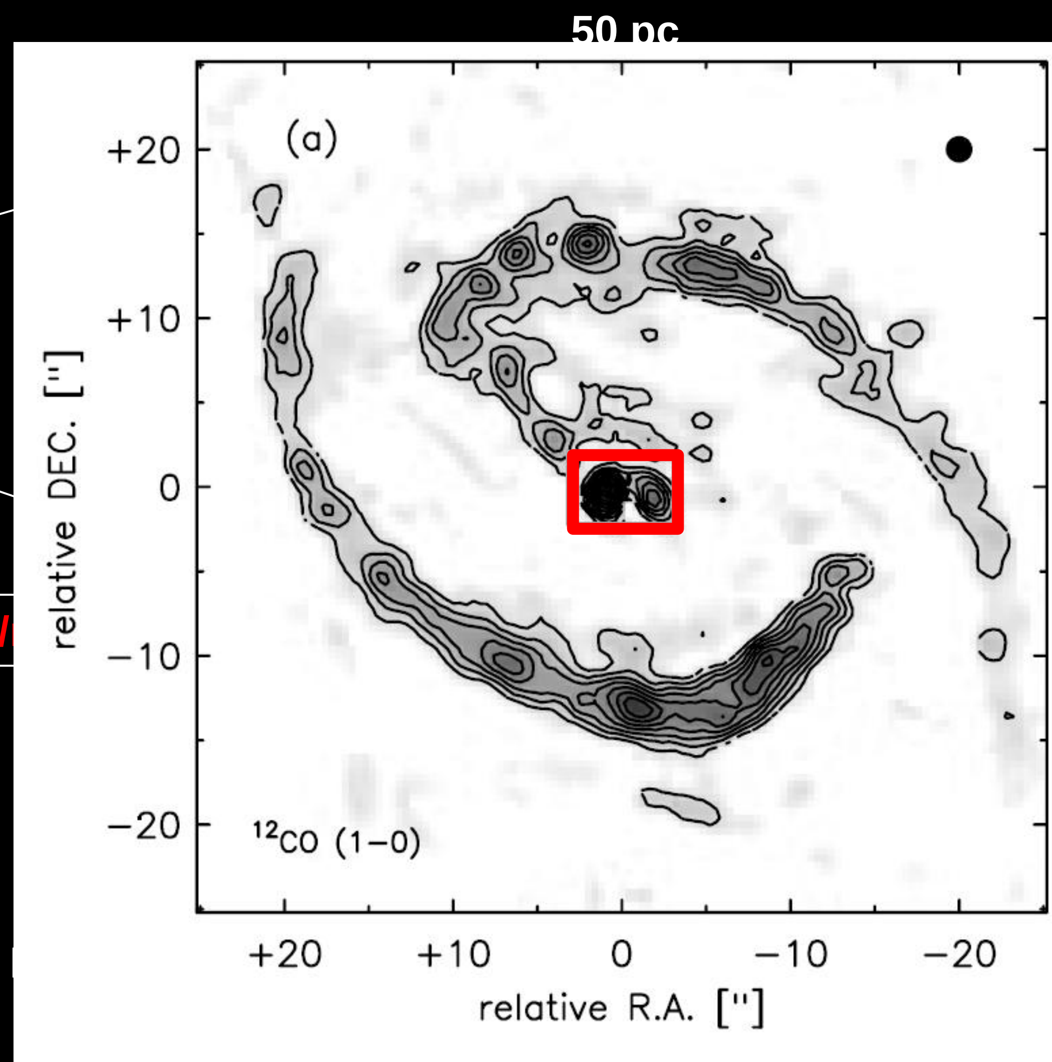


- x10 CO lines --> **First extragalactic far-IR CO**
- Atomic fine-structure lines ([CII], [OI], [NII], [OIII], [NIII])
- OH, H_2O, **OH^+, H_2O^+,** …
- Molecular emission concentrated in central spaxel

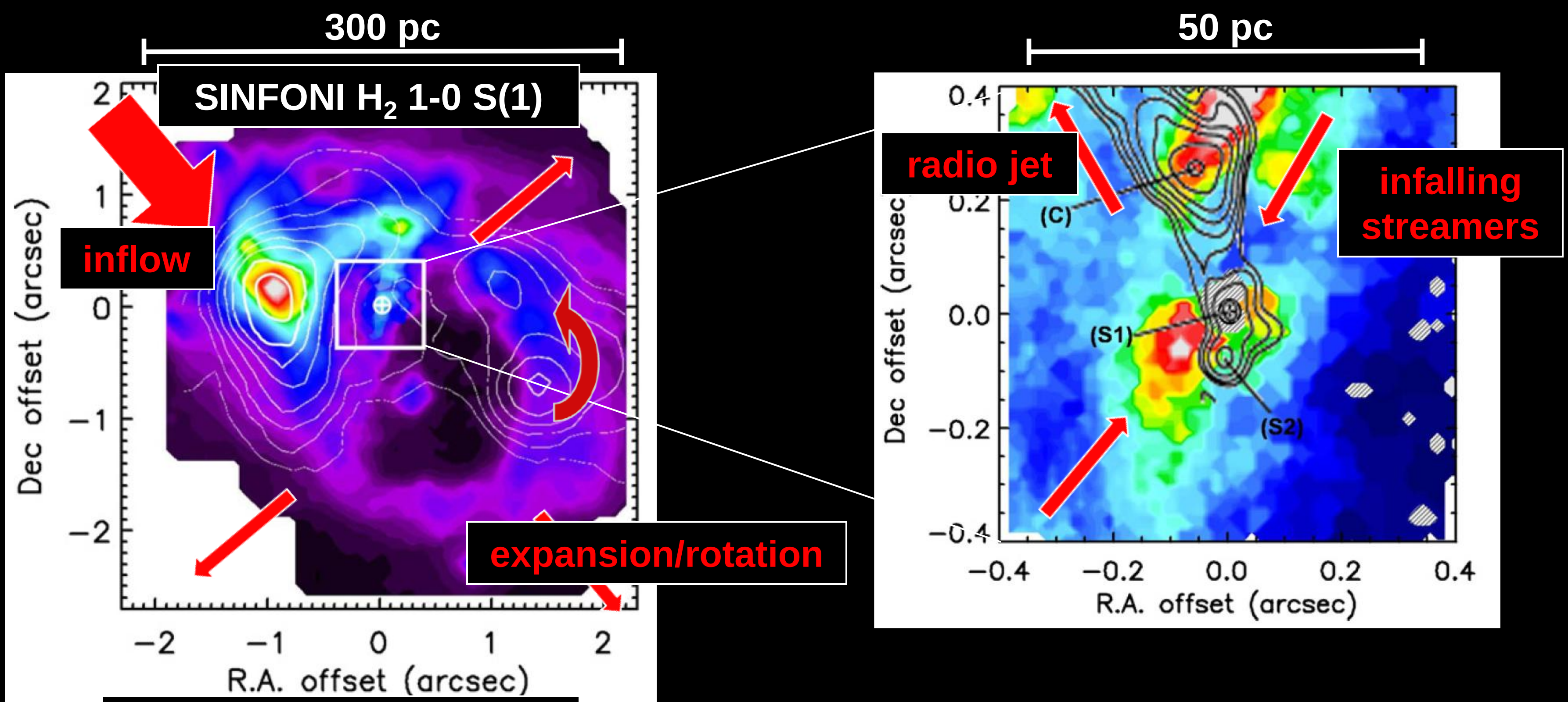


Hailey-Dunsheath+ 2012

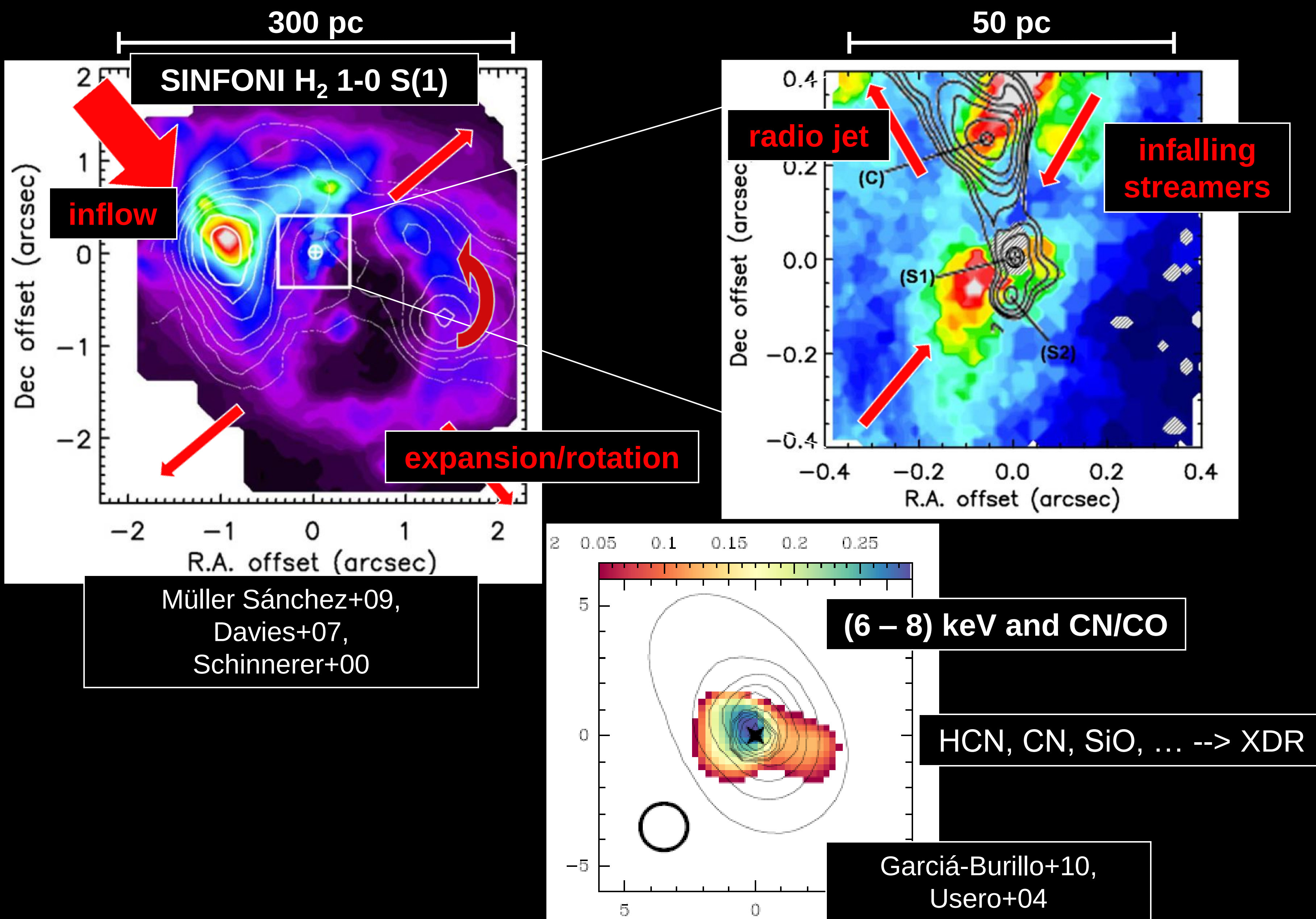




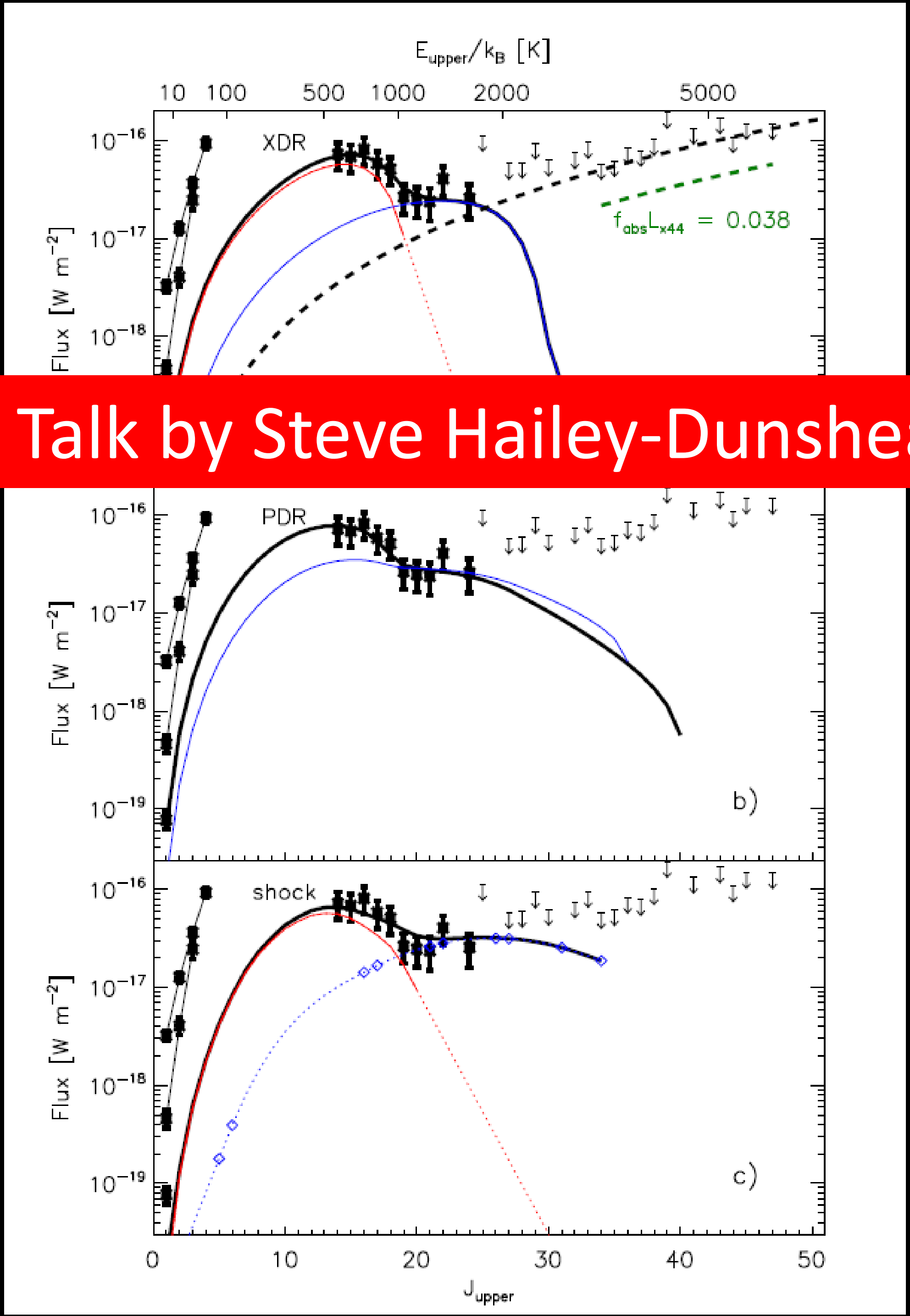
Müller Sánchez+09,
Davies+07,
Schinnerer+00



Müller Sánchez+09,
Davies+07,
Schinnerer+00



300 pc
SINFONI H2 1-0 S(1)
inflow
expansion/rotation
Dec offset (arcsec)
R.A. offset (arcsec)
Müller Sánchez+09,
Davies+07,
Schinnerer+00
50 pc
radio jet
infalling
streamers
(C)
(S1)
(S2)
(6 – 8) keV and CN/CO
HCN, CN, SiO, … --> XDR
Garciá-Burillo+10,
Usero+04



→ Talk by Steve Hailey-Dunsheath

XDR

PDR

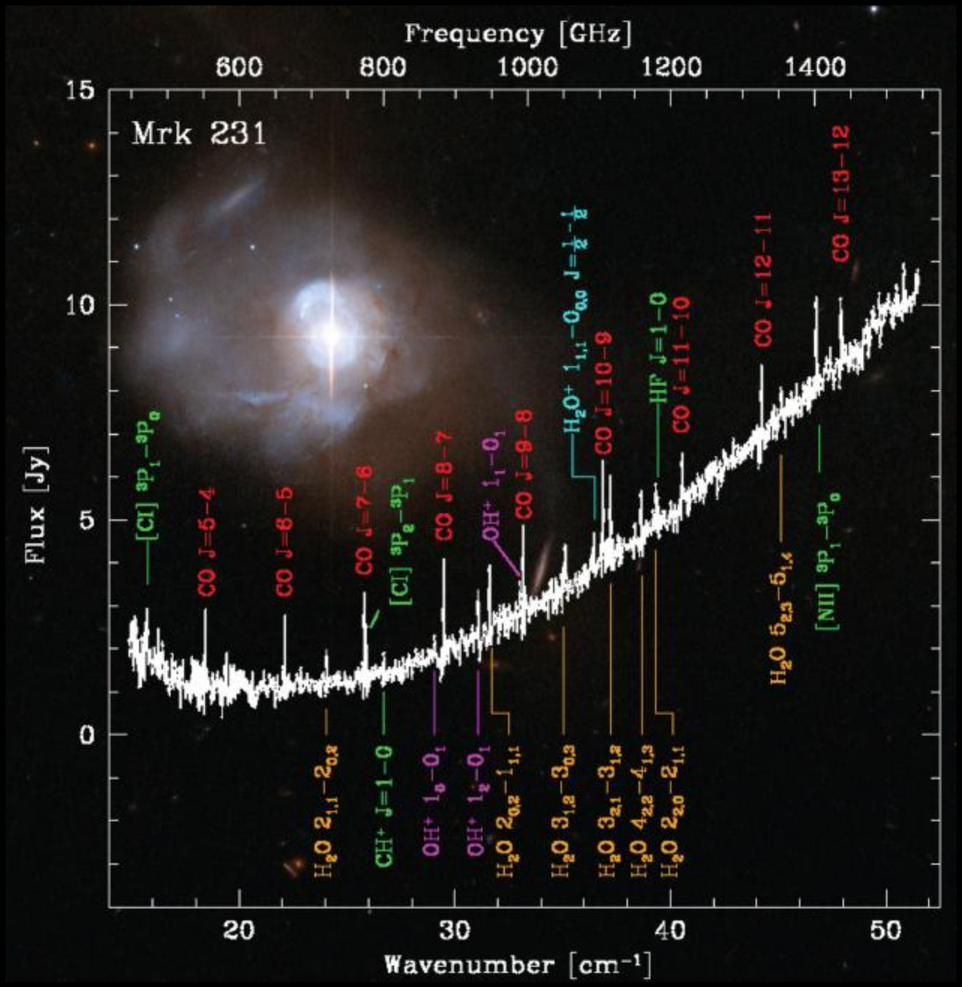
Shock

SPIRE (GTO):

→ Sacchi, Spinoglio, Wilson et al. in prep

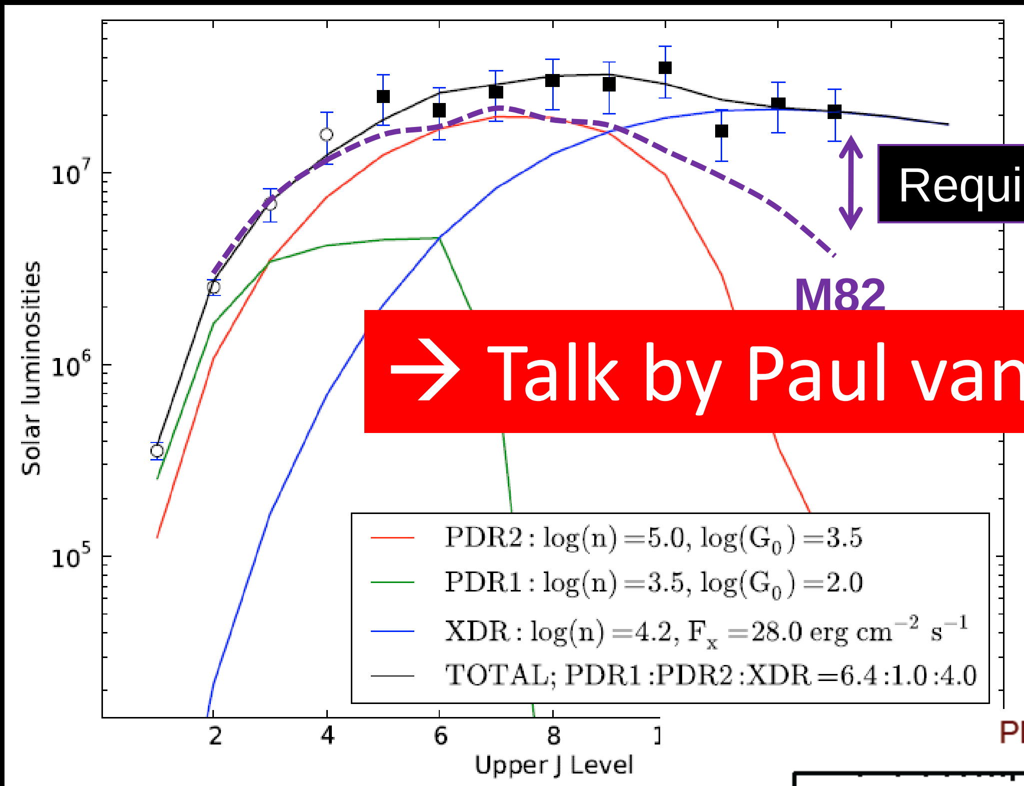
Application to ULIRGs

Mrk 231 (van der Werf+2010, SPIRE)



- Most luminous ULIRG in RBGS: $L_{IR} = 4 \times 10^{12}\ L_{sun}$
- Optical BAL QSO
- AGN accounts for ~ 70% of L_{bol}
- Molecular outflows: V ~ 1000 km/s

- All 9 CO lines, [CI], [NII]
- 7 lines of H_2O
- OH^+, H_2O^+, CH^+, HF

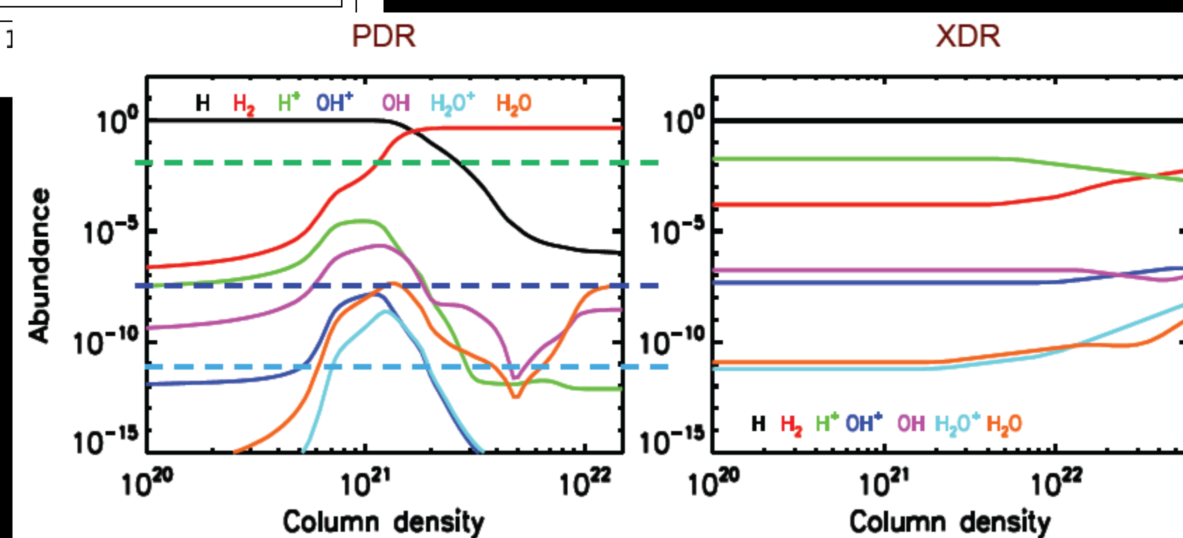


- PDR/XDR models (Meijerink+05,+07)

Require a 3rd component for highest-J

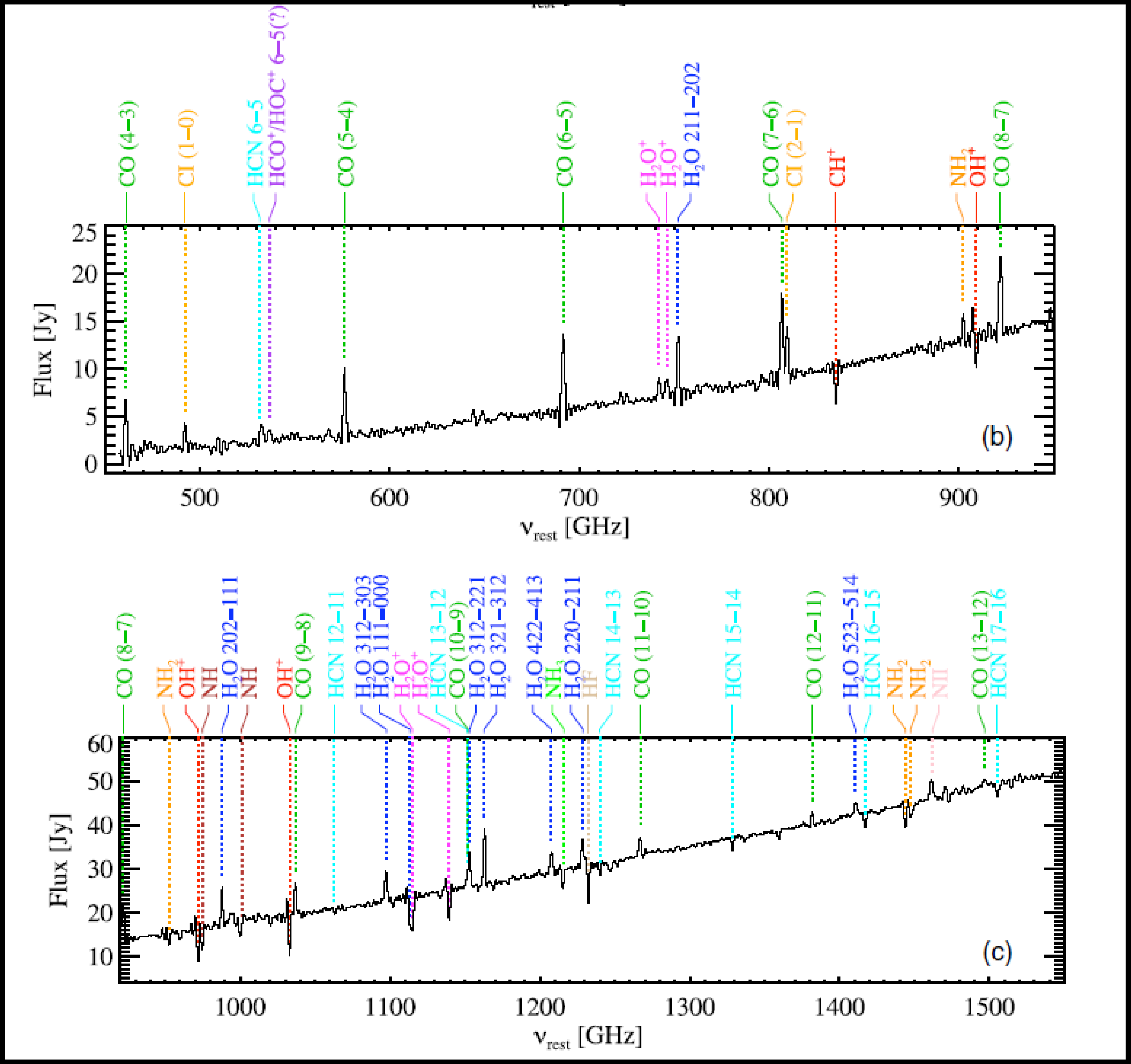
- High-G_0, high-n PDR
  - ecular gas in the vicinity of O5 or earlier stars (~0.7% of disk volume)
  - Half the dust would be ~ 170 K
  - Not account for OH^+, H_2O^+ abundances > 2 x 10^{-10}

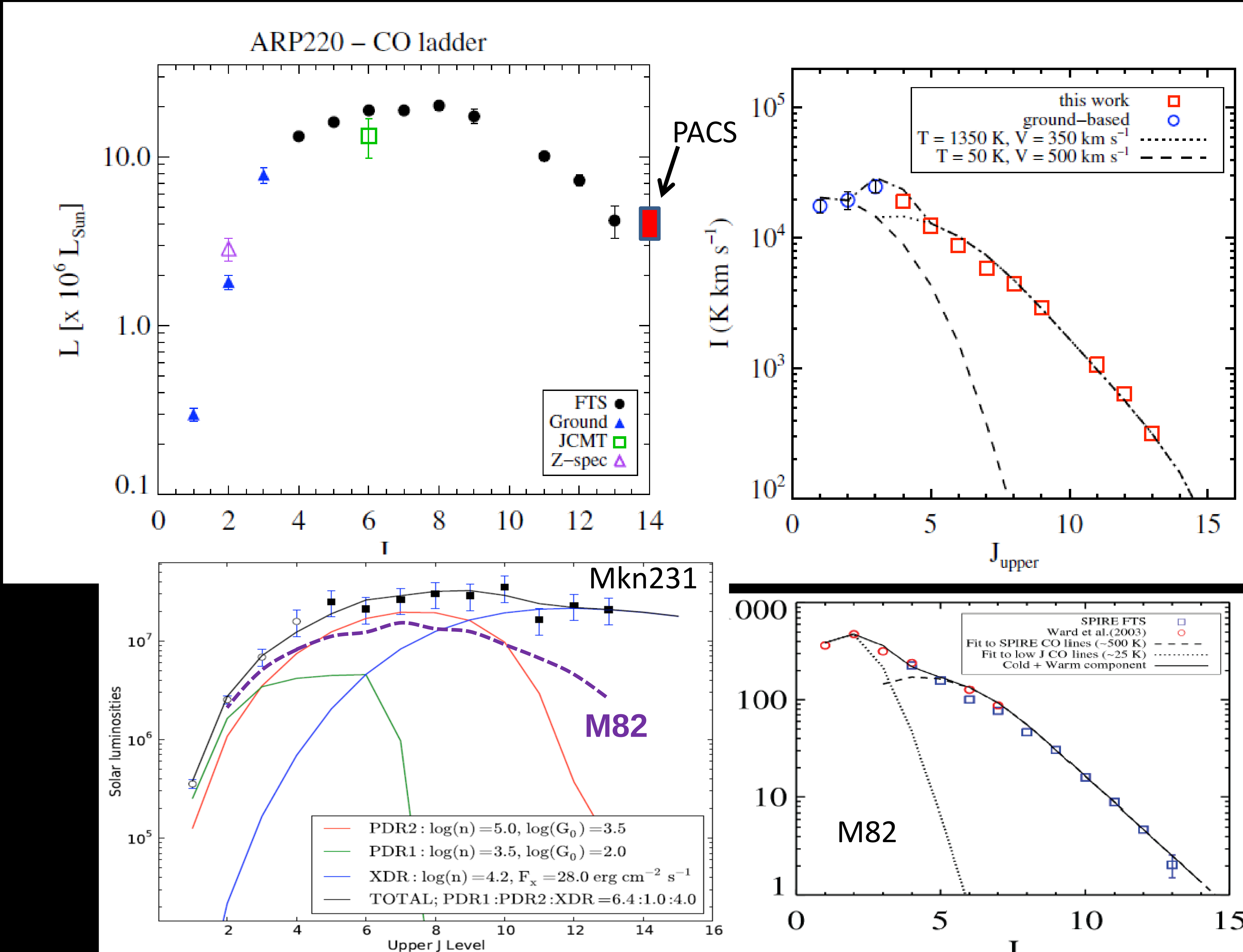
→ Talk by Paul van der Werf



⇒ X-ray heated gas over central ~ 300 pc

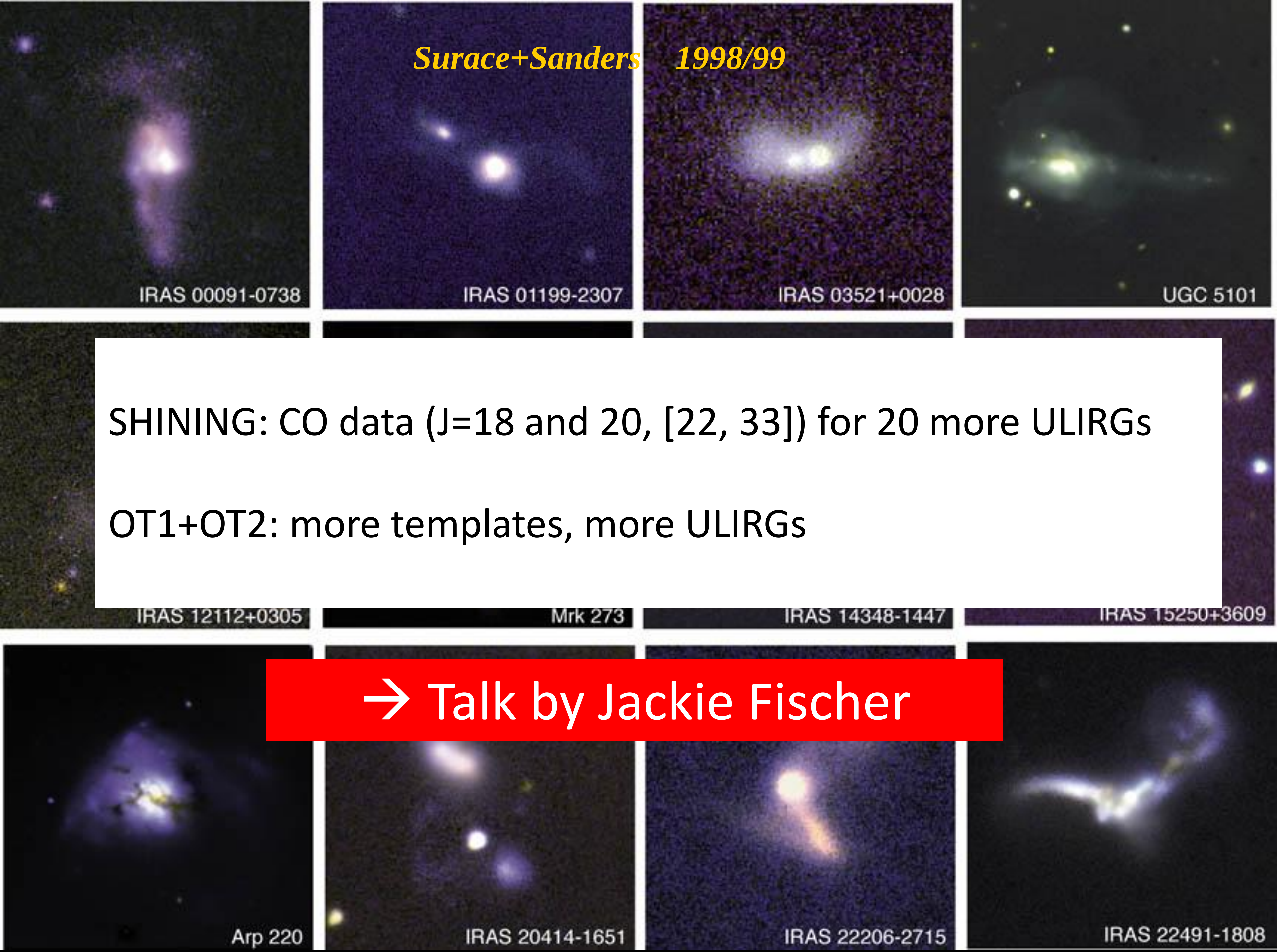
Arp220 (Rangwala+2011, SPIRE)





ARP220 – CO ladder
PACS
L [x 10^6 L_Sun]
FTS
Ground
JCMT
Z–spec
J
this work
ground–based
T = 1350 K, V = 350 km s^-1
T = 50 K, V = 500 km s^-1
I (K km s^-1)
J_upper
Mkn231
M82
Solar luminosities
PDR2 : log(n) = 5.0, log(G_0) = 3.5
PDR1 : log(n) = 3.5, log(G_0) = 2.0
XDR : log(n) = 4.2, F_x = 28.0 erg cm^-2 s^-1
TOTAL; PDR1 : PDR2 : XDR = 6.4 : 1.0 : 4.0
Upper J Level
SPIRE FTS
Ward et al.(2003)
Fit to SPIRE CO lines (~500 K)
Fit to low J CO lines (~25 K)
Cold + Warm component
M82
J

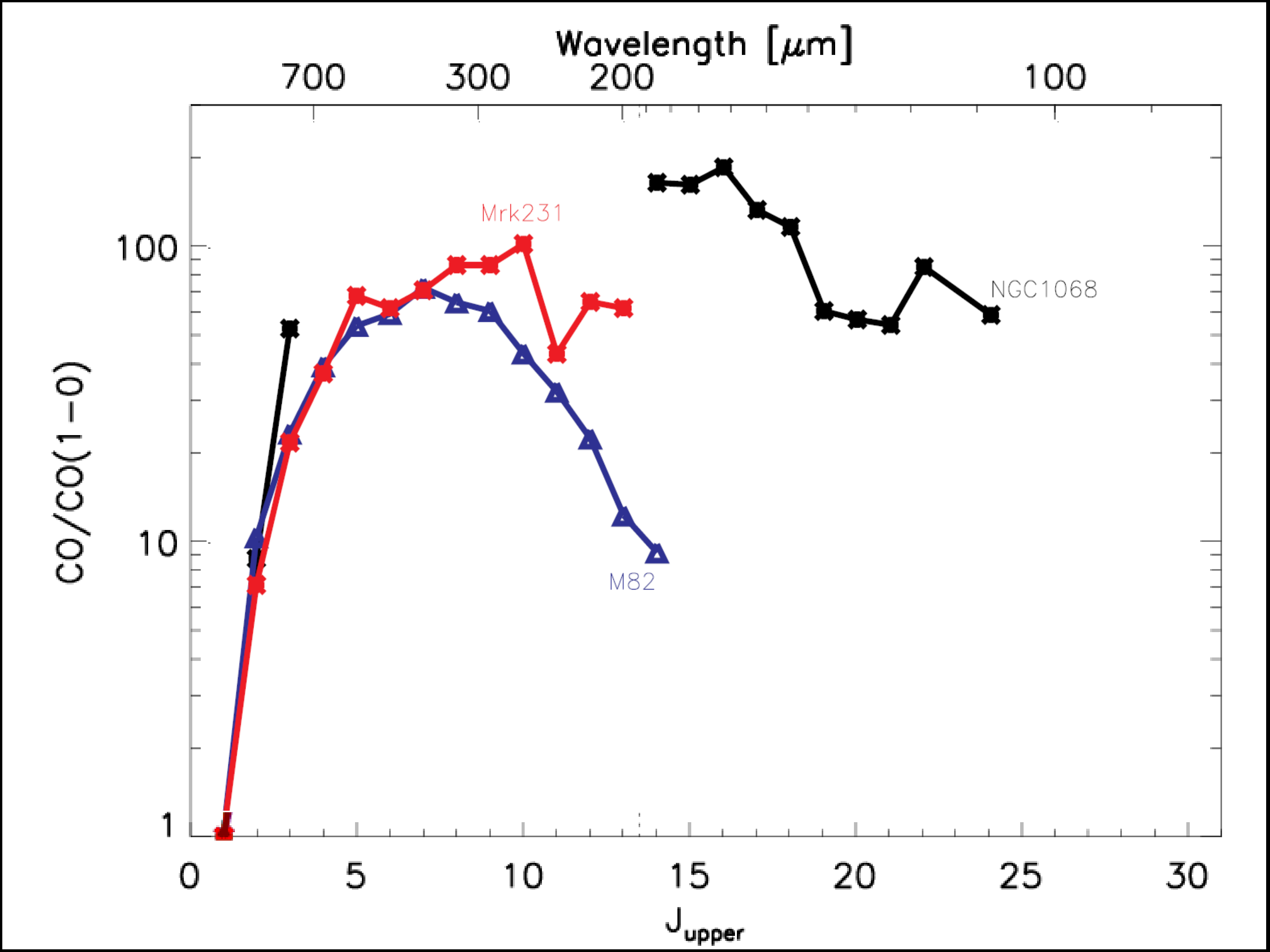
Surace+Sanders 1998/99



SHINING: CO data (J=18 and 20, [22, 33]) for 20 more ULIRGs

OT1+OT2: more templates, more ULIRGs

→ Talk by Jackie Fischer

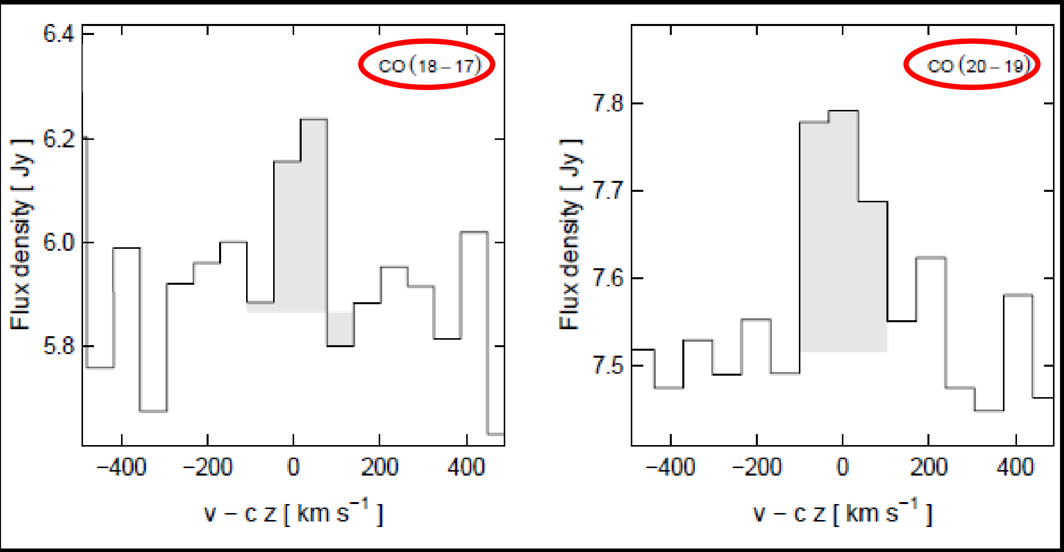


Wavelength [μm]
700
300
200
100
Mrk231
NGC1068
M82
100
10
1
CO/CO(1−0)
0
5
10
15
20
25
30
J_upper

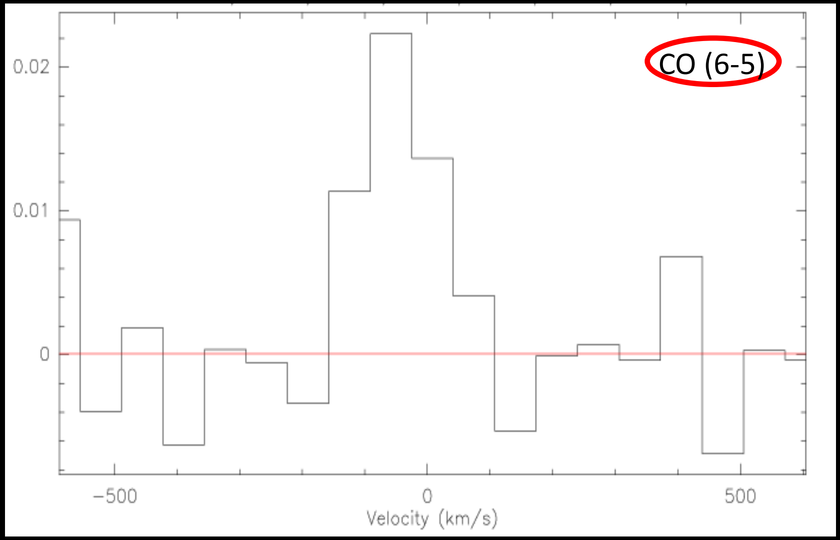
CO Line Ratios in local ULIRGs

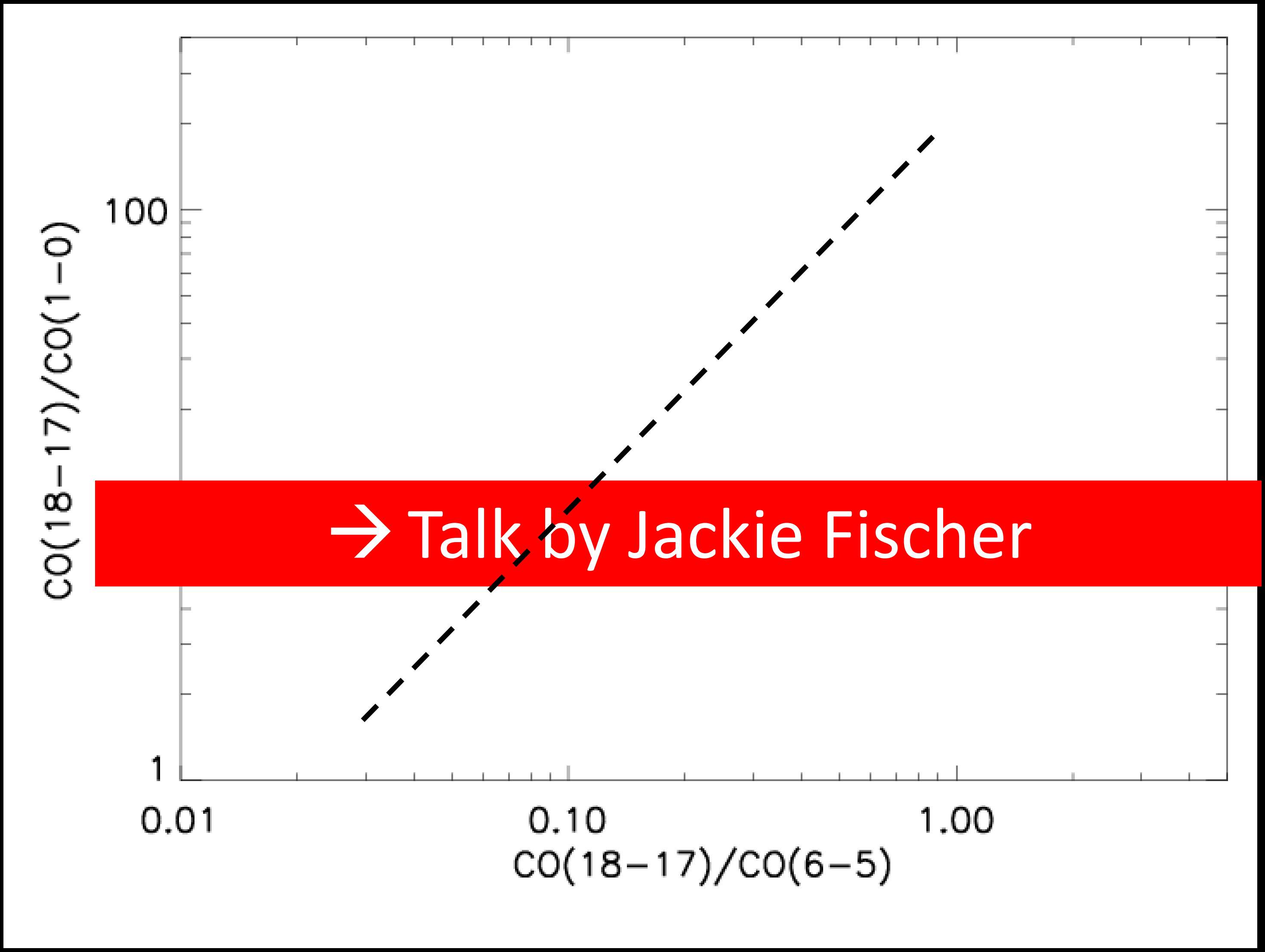
Characterizing the excitation of the molecular gas and the nature of the energy source

PACS spectra
(SHINING)

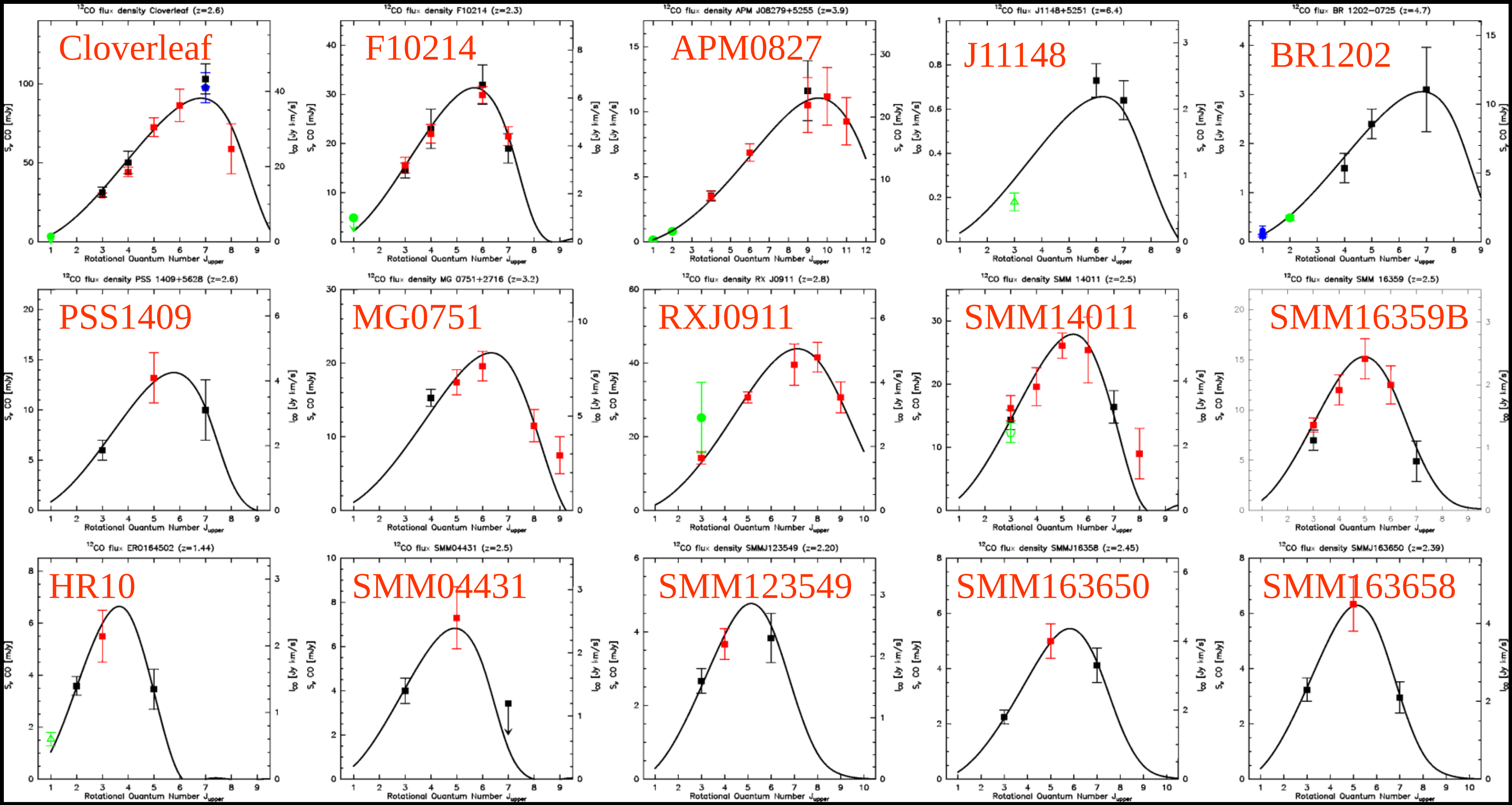


APEX spectrum



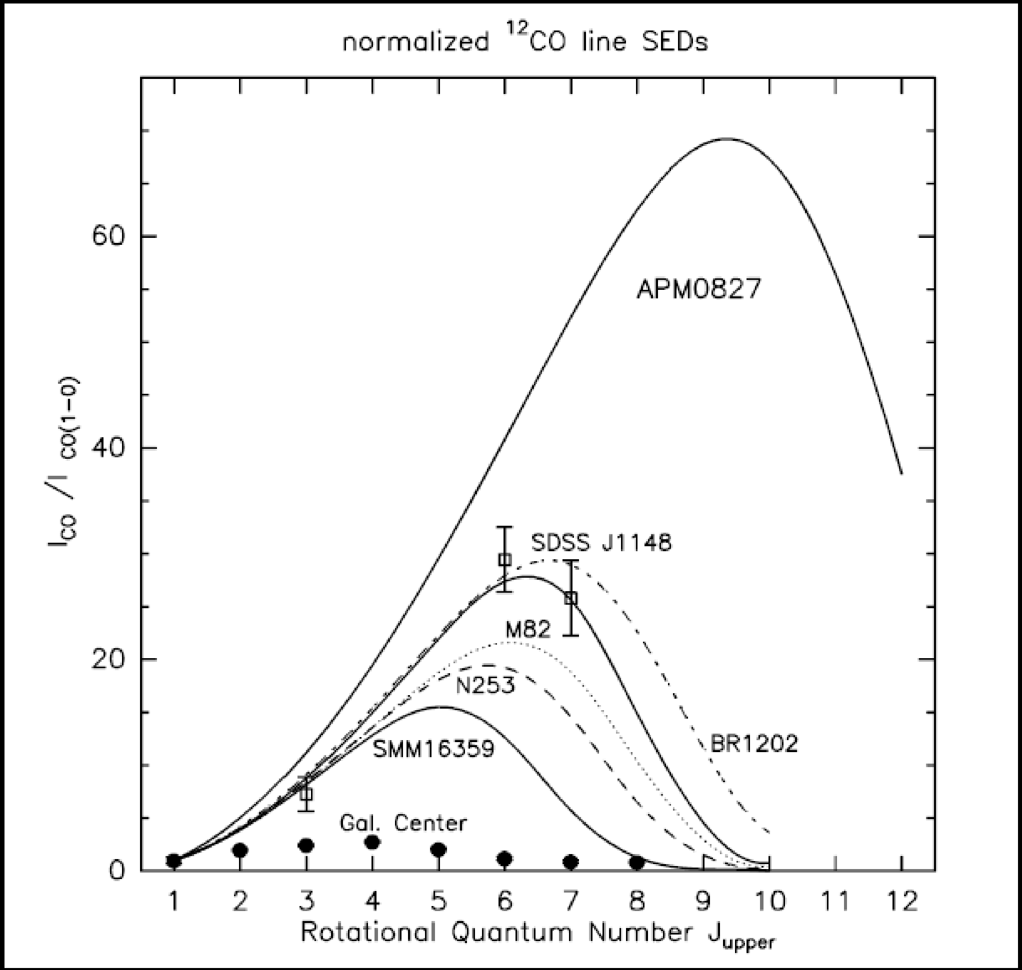

100
1
0.01
0.10
1.00
CO(18−17)/CO(1−0)
CO(18−17)/CO(6−5)
→ Talk by Jackie Fischer

CO at high redshifts

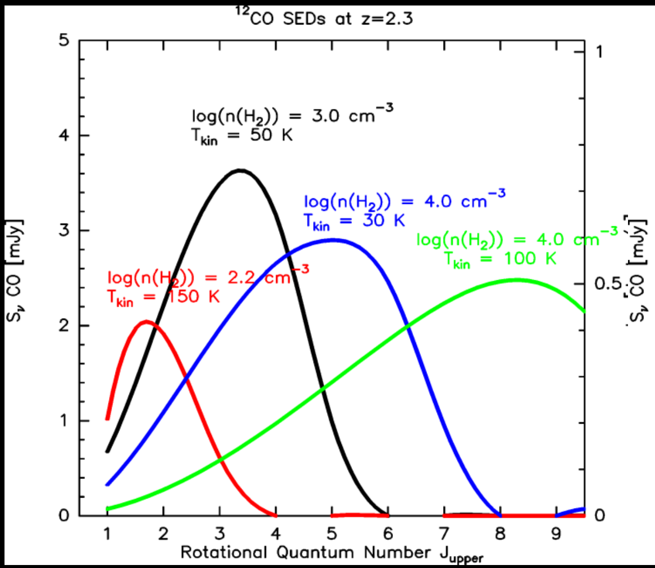


Alloin etal 1997, Ao etal. 2007, Barvainis etal 2002, Beelen etal 2004, Bertoldi etal 2003, Downes etal 2003, Greve etal 2003, Greve etal 2005, Hainline etal 2004, Riecherts etal 2006, Tacconi etal 2006/08, Papadopoulos etal 2002, Walter etal 2003, Weiss etal. 2005, Weiss etal. 2007

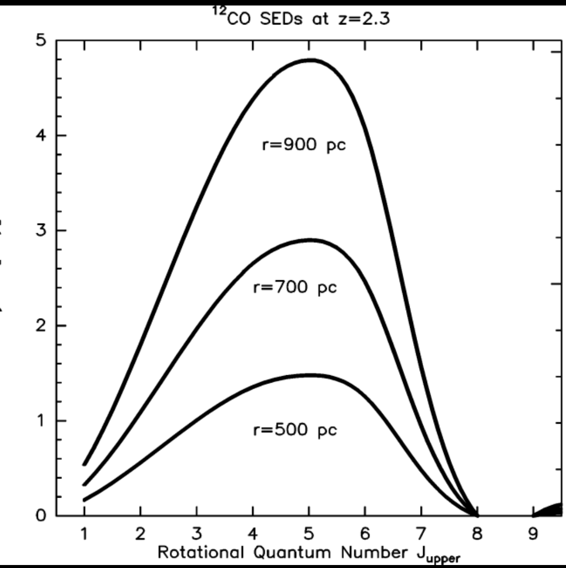
APM08279+5255 at z =3.9
Weiß+2007



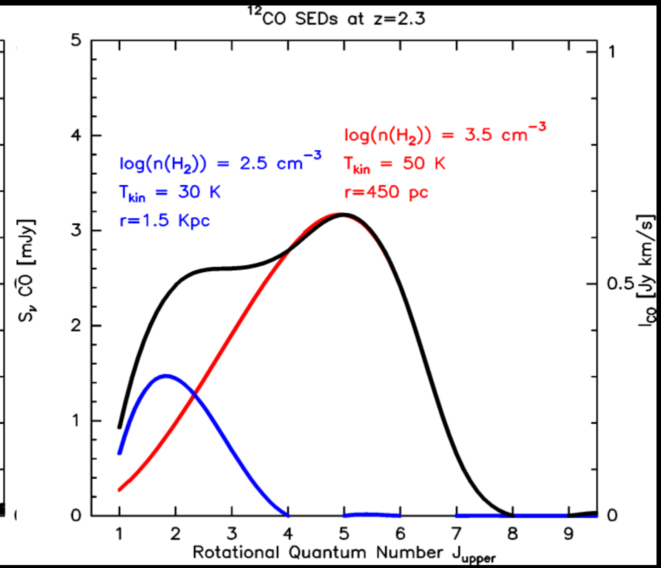
CO excitation



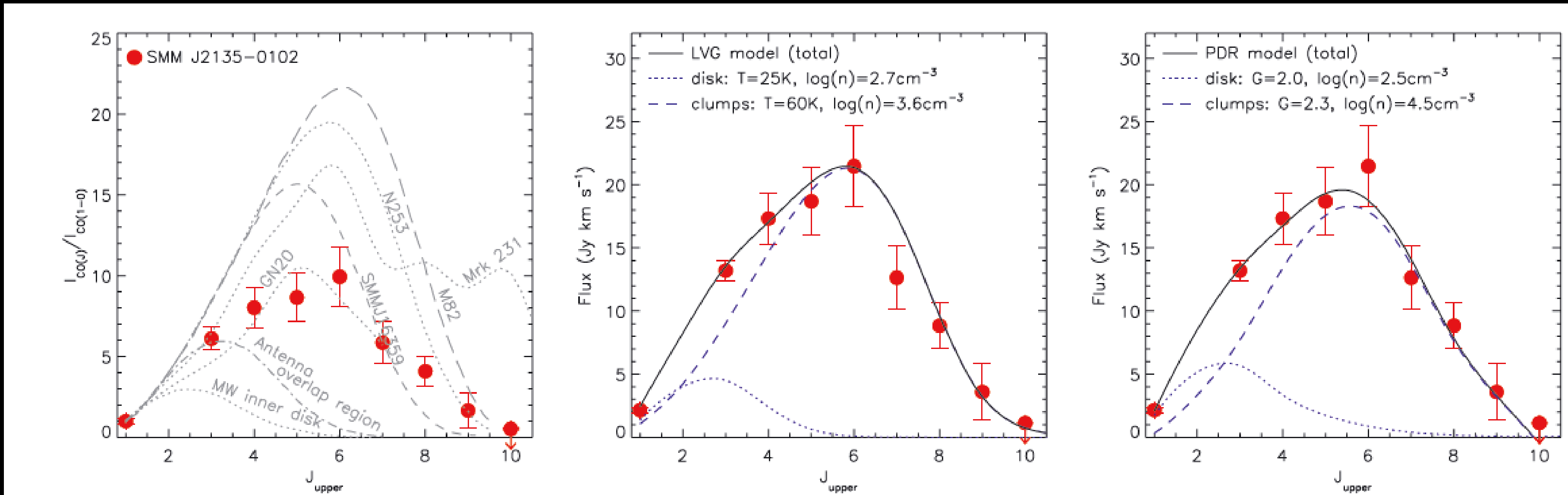
size determination



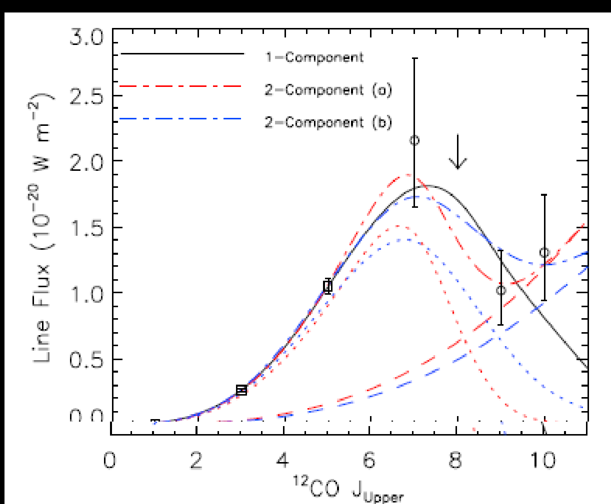
ISM structure



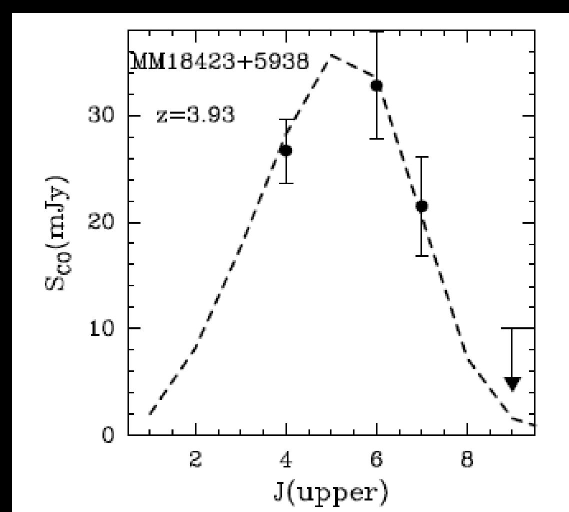
the lensed z=2.3 submillimetre galaxySMMJ2135−0102, Danielson+2011



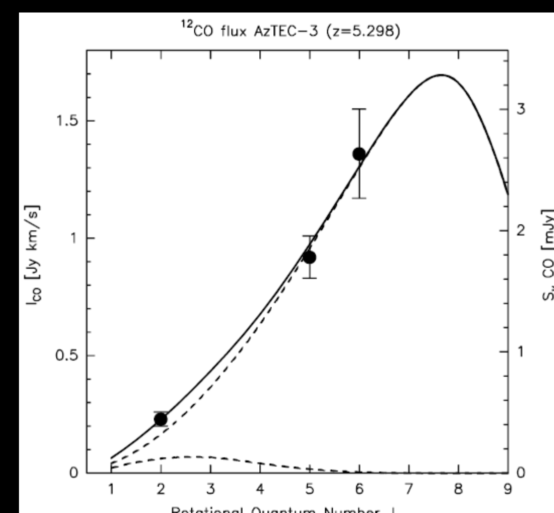
K.S. Scott+ 2011
Lensed Galaxy HLSW-01, z=2.96



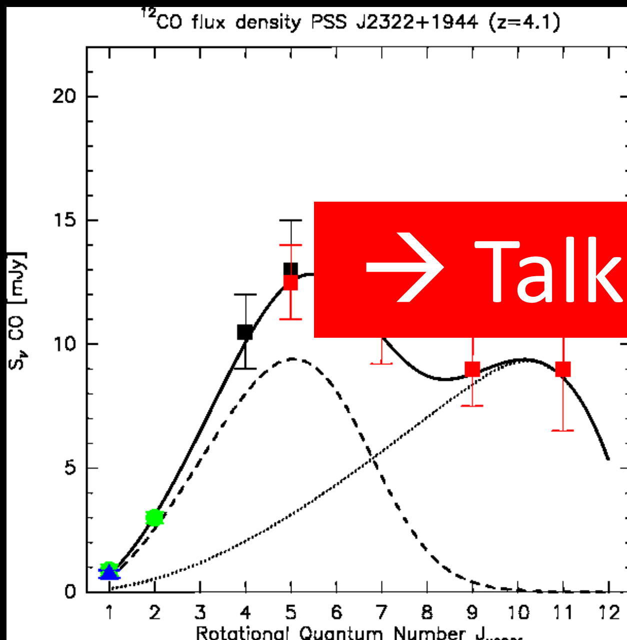
Lestrade+ 2010
SMG MM18423+5938, z = 3.93



Riechers+ 2010
SMG AzTEC-3, z = 5.3

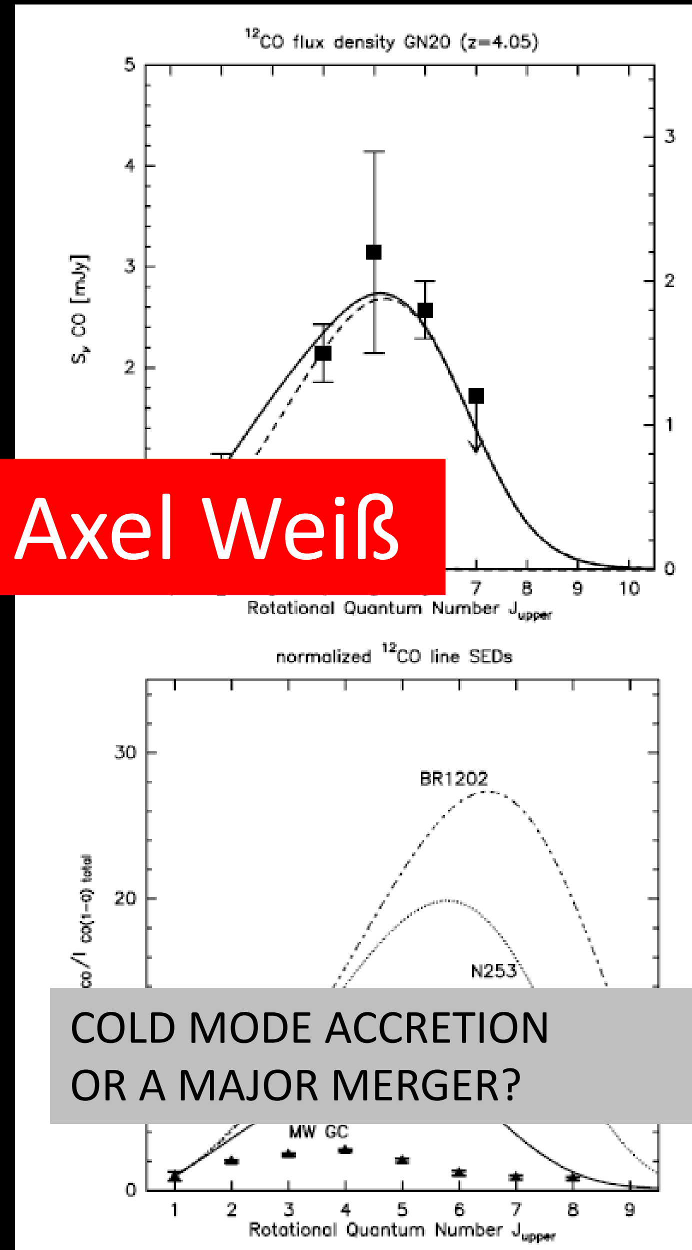


Weiß+ 2011
PSSJ2322+1944 z=4.1



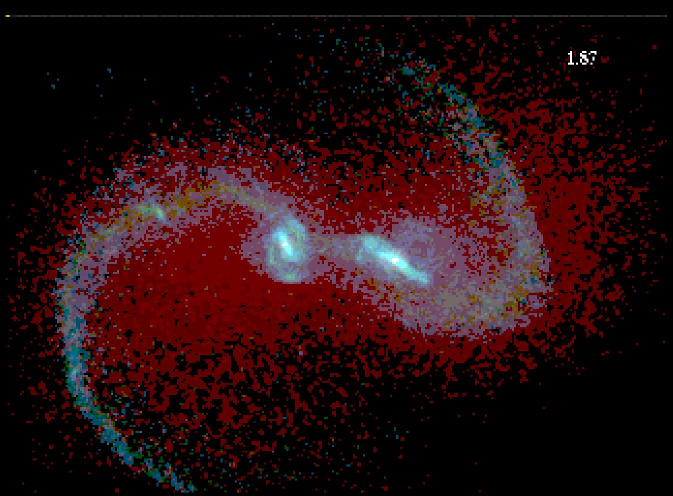
→ Talk by Axel Weiß

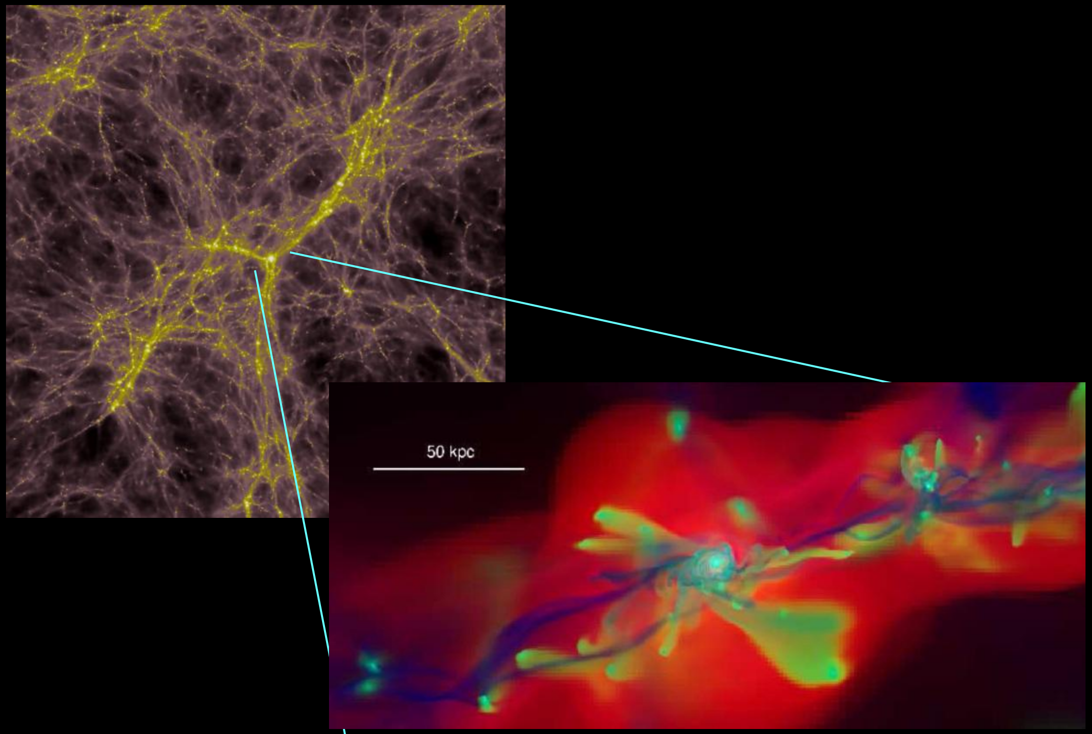
Carilli+ 2010
SMG GN20 at *z* = 4.05



COLD MODE ACCRETION
OR A MAJOR MERGER?

The roles of Major Mergers vs. Steady Accretion, and the SFE



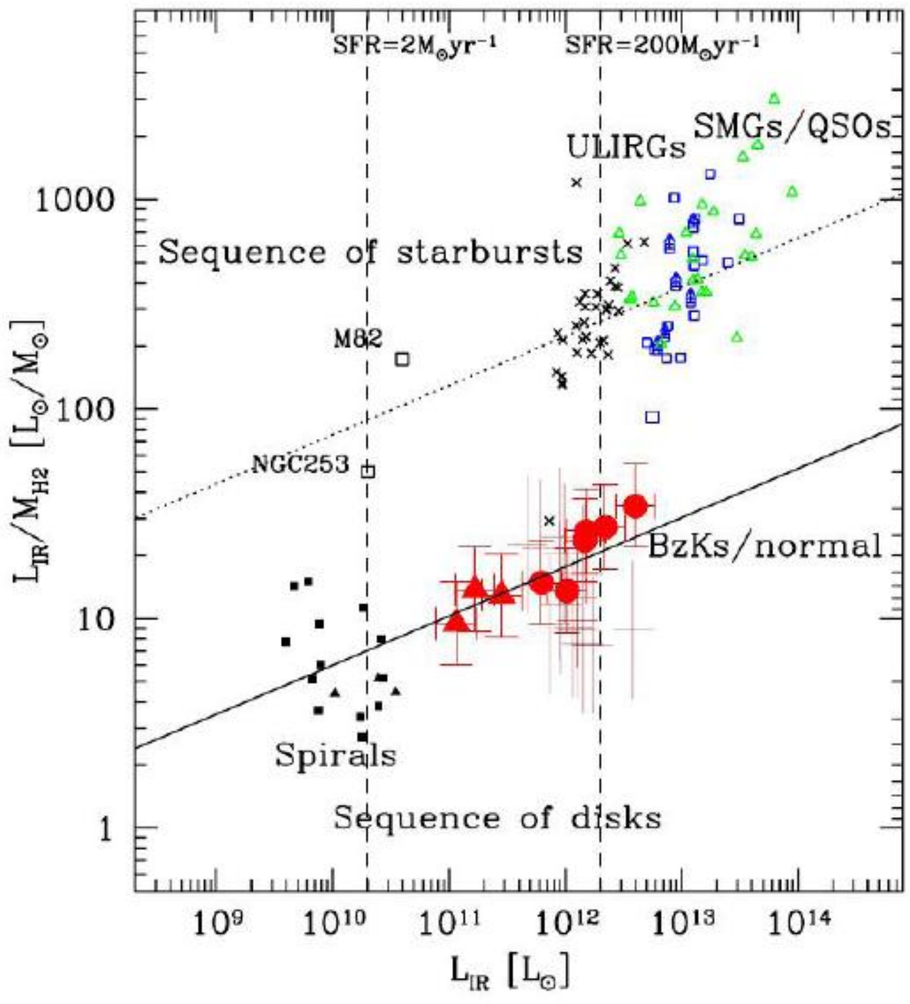


Major mergers

Kauffmann et al. 1993, Steinmetz & Navarro 2003, Hernquist, Springel, di Matteo, Hopkins et al. 2003-2006, Robertson & Bullock 2008

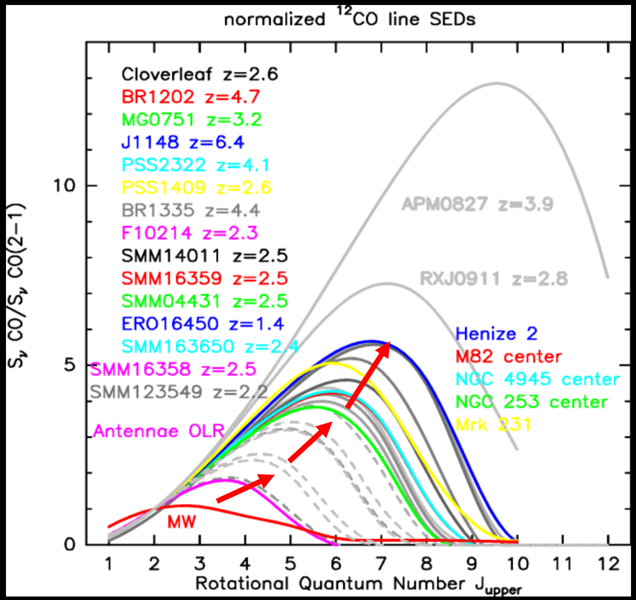
Minor mergers and steady accretion:

Dekel & Birnboim 2003,2006, Keres et al. 2005, Nagamine et al. 2005, Davé 2007, Kitzbichler & White 2007, Naab et al. 2007, Governato et al. 2008, Ocvirk et al. 2008, Dekel et al. 2009, Agertz et al. 2009



[Genzel et al. 2010, MNRAS 407: 2091]

[Daddi et al. 2010, ApJ 714: L118]

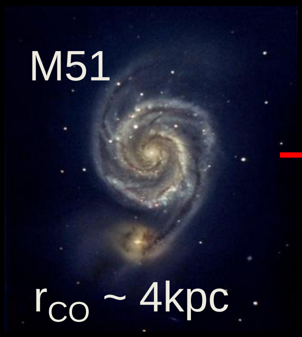


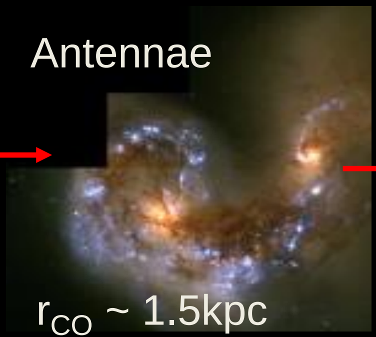
AGN heating

Advanced mergers & starbursts

Early mergers
quiet disk galaxies

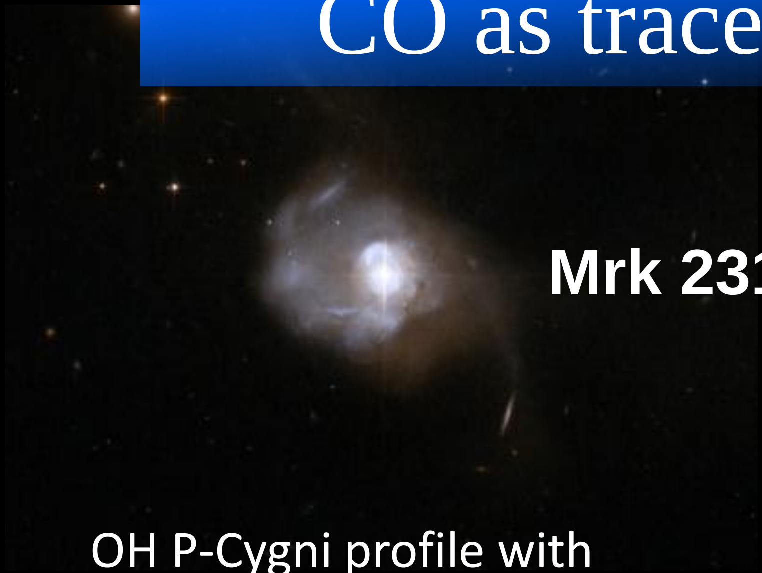
L_{FIR}, SFR, $n(H_2)$





CO as tracer of galactic outflows

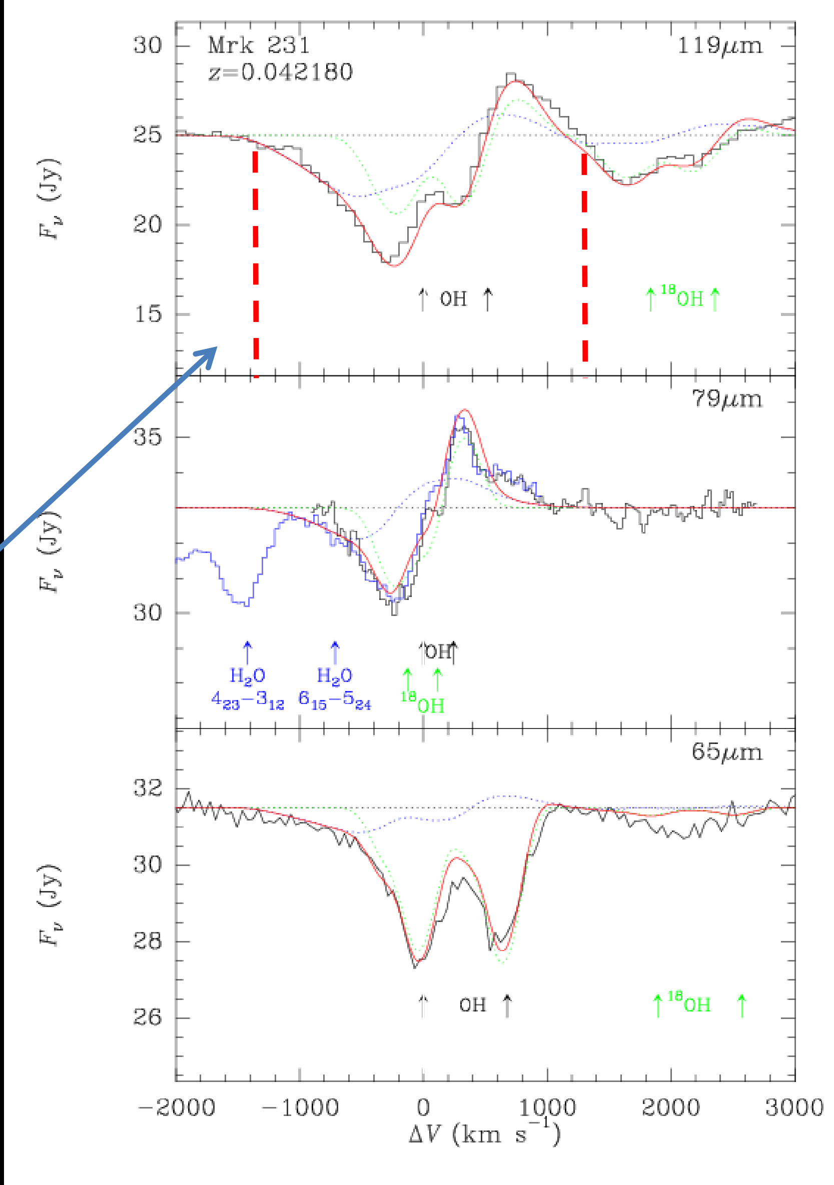
CO as tracer of galactic outflows



Mrk 231

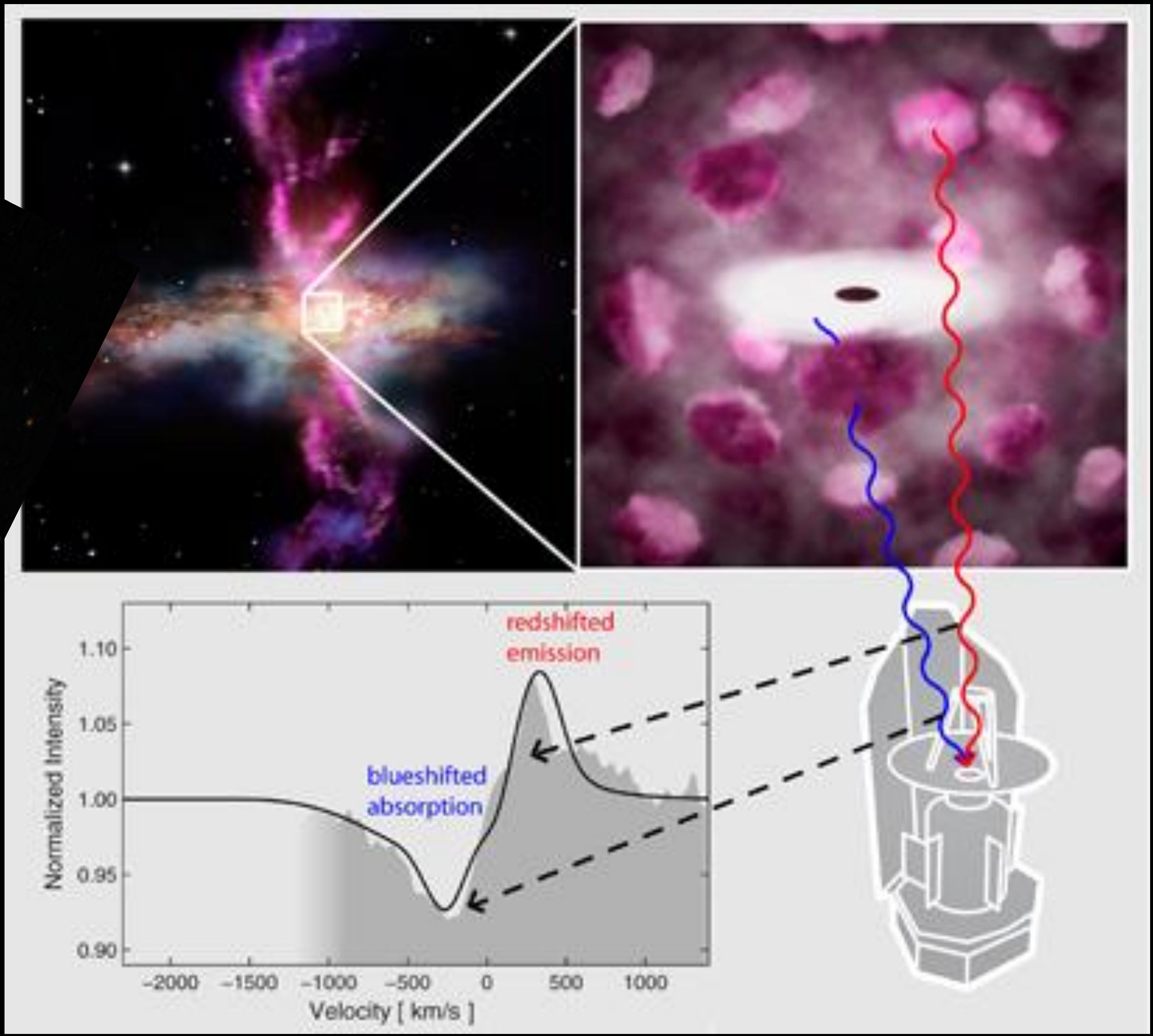
OH P-Cygni profile with
blue-shifted absorption
and red-shifted emission

Δv ~ 1,170 km/s



Fischer + 2010
Sturm + 2011

Mrk 231



Artists conception
©ESA

Mrk 231 – OH Outflow

terminal velocity (obs): ~1.100 km/s

R_{out} (model) ~1.0 kpc

outflow rate (dM/dt): ~1.200 $M_\odot$/yr

SFR: ~100 $M_\odot$/yr

gas mass (from CO): 4.2 x 10^9 $M_\odot$

depletion time scale ($M_{gas}/\dot{M}$): ~4 x 10^6 yr

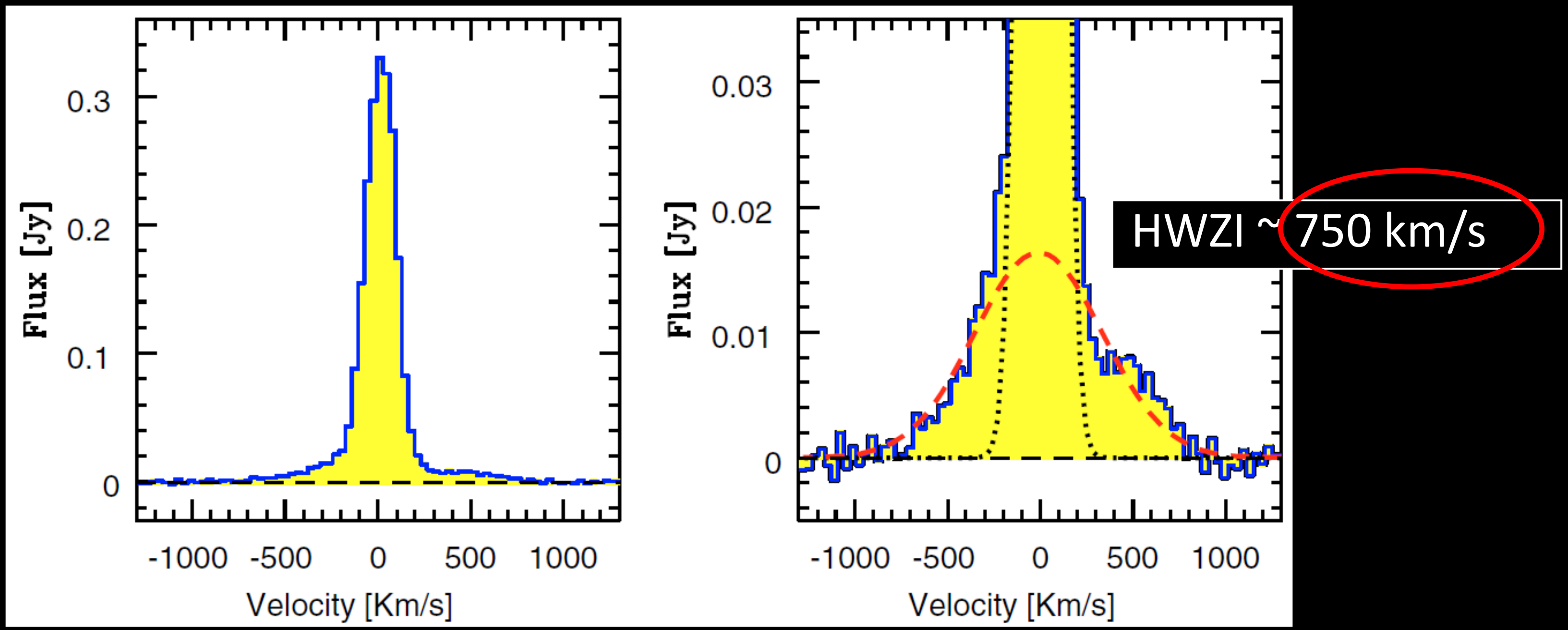
mechanical energy: ≥ 10^{56} ergs

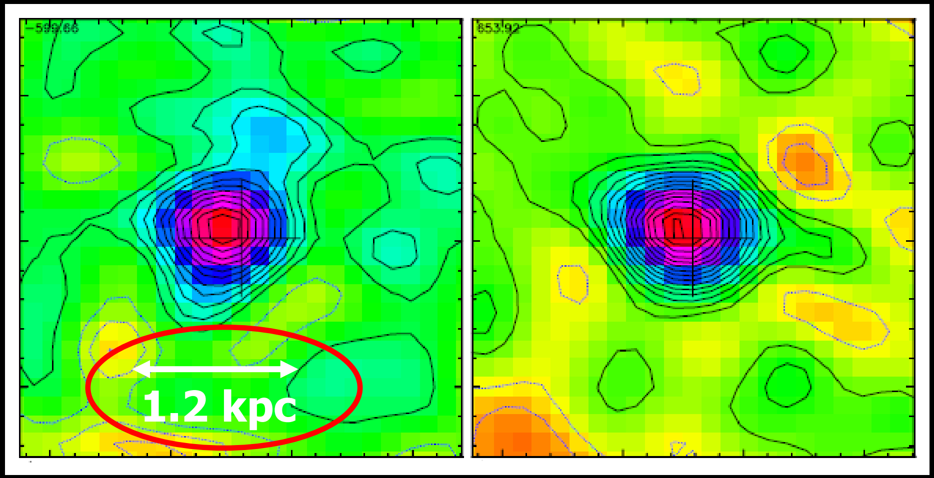
$$T = \frac{1}{2} M_{\mathrm{gas}} v^2$$

mechanical luminosity: ≥ 1% L_{IR}

$$P = \frac{T}{t_{\mathrm{dyn}}}$$

Mrk 231 – CO Outflow

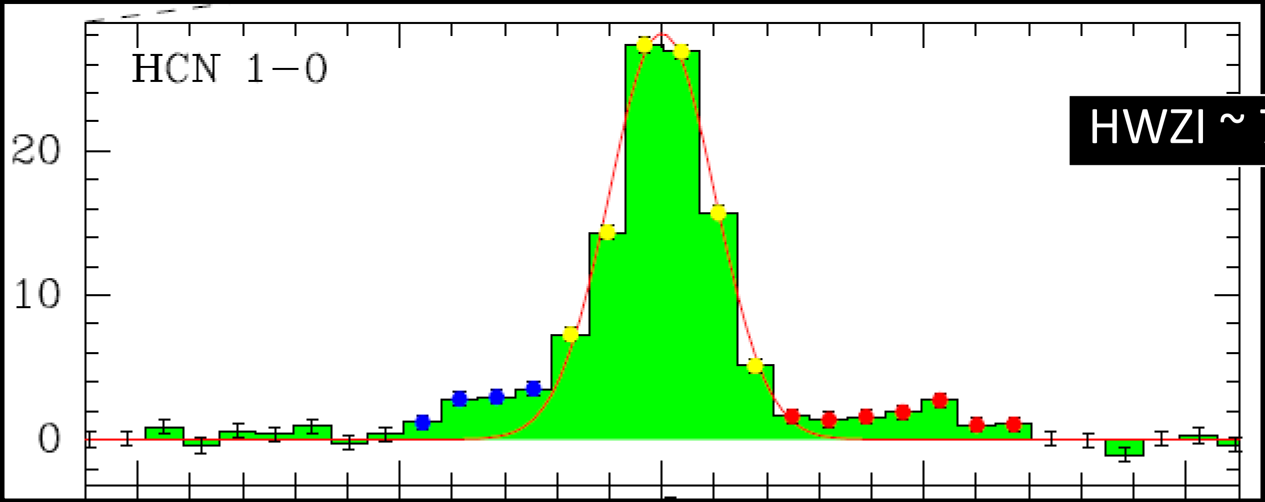




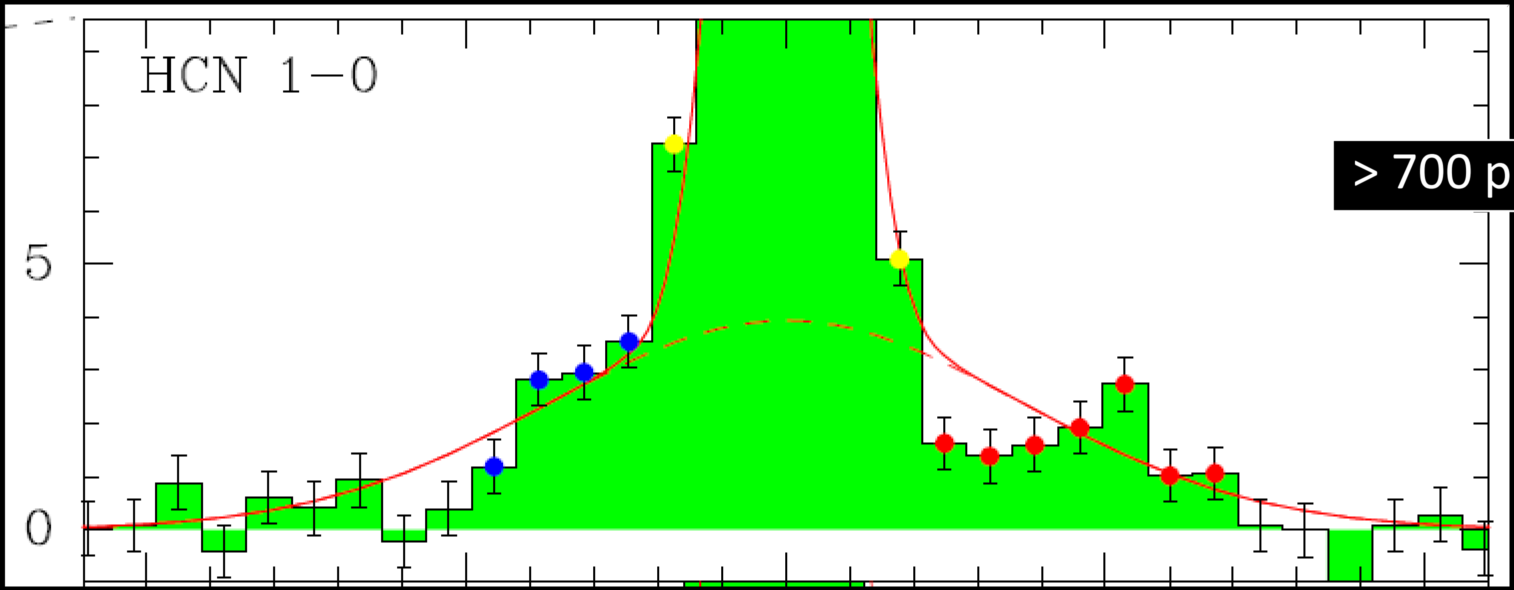
outflow mass of 5.8 x 10^8 $M_\odot$

outflow rate of ≳ 700 $M_\odot$/yr

Aalto+2011



HWZI ~ 750 km/s



> 700 pc

[C II] as substitute for CO ?

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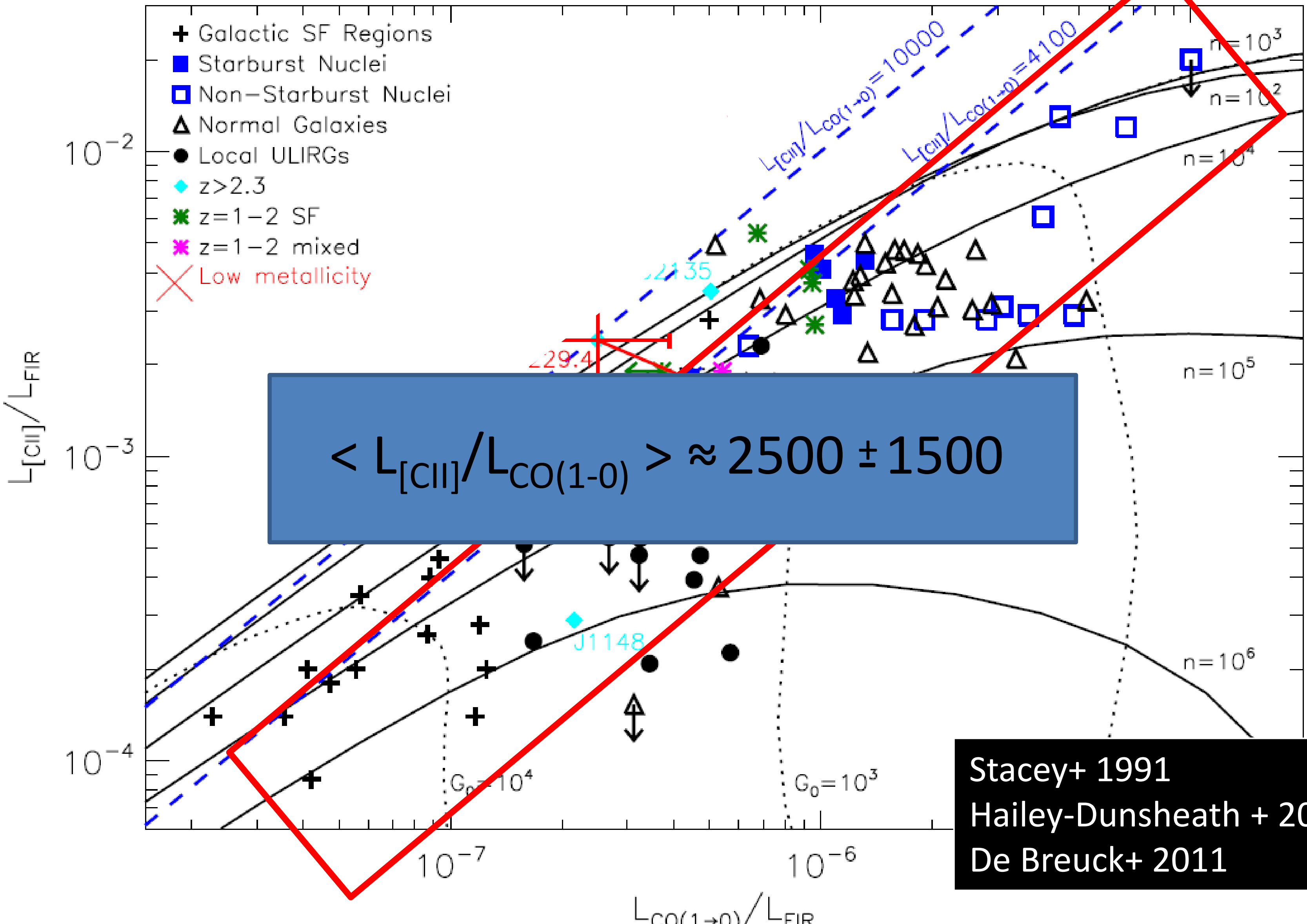
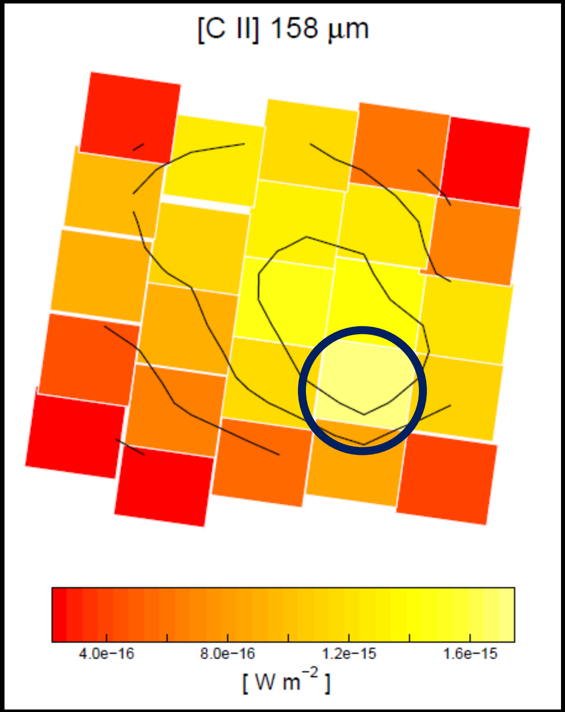
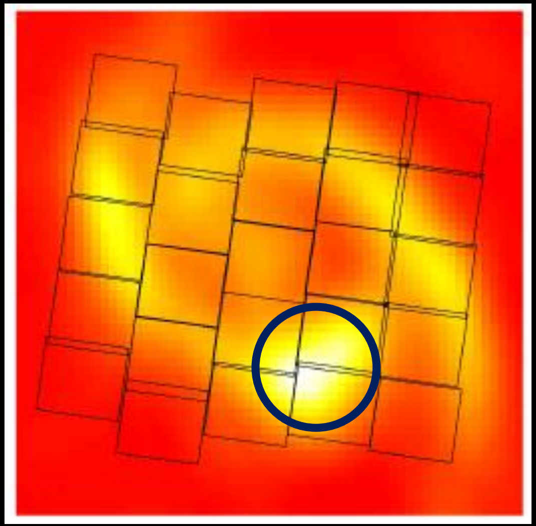


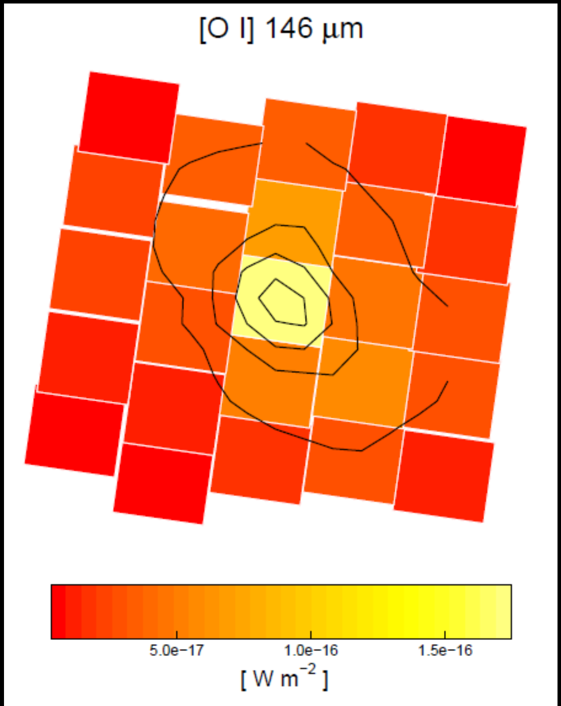
$$< L_{[CII]}/L_{CO(1\text{-}0)} > \approx 2500 \pm 1500$$

Stacey+ 1991
Hailey-Dunsheath + 2010
De Breuck+ 2011

[C II] as substitute for CO ?







Summary

To be written

- High-J CO, local (Herschel)
- High redshift applications (ALMA, IRAM/NOEMA, …)
- Modes of star formation
- Outflows, local (low-J CO)