HIFI Spectroscopy of H_2O sub-millimeter Lines in Nuclei of Actively Star Forming Galaxies

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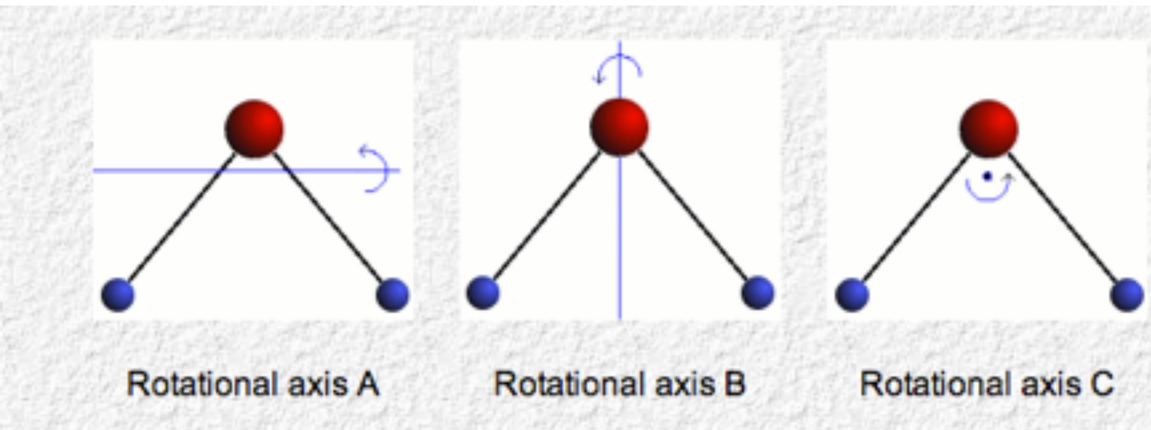
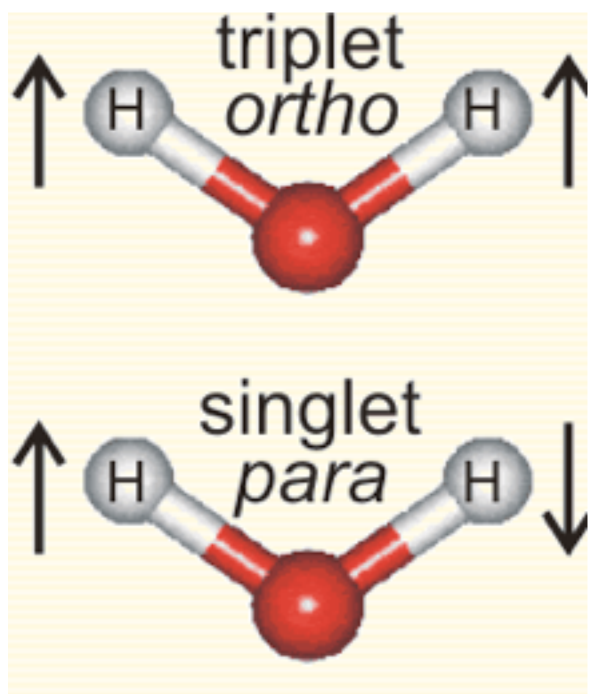
Liu et al. 2017 submitted

The H_2O molecule

Angular momentum: $J_{Ka,kc}$

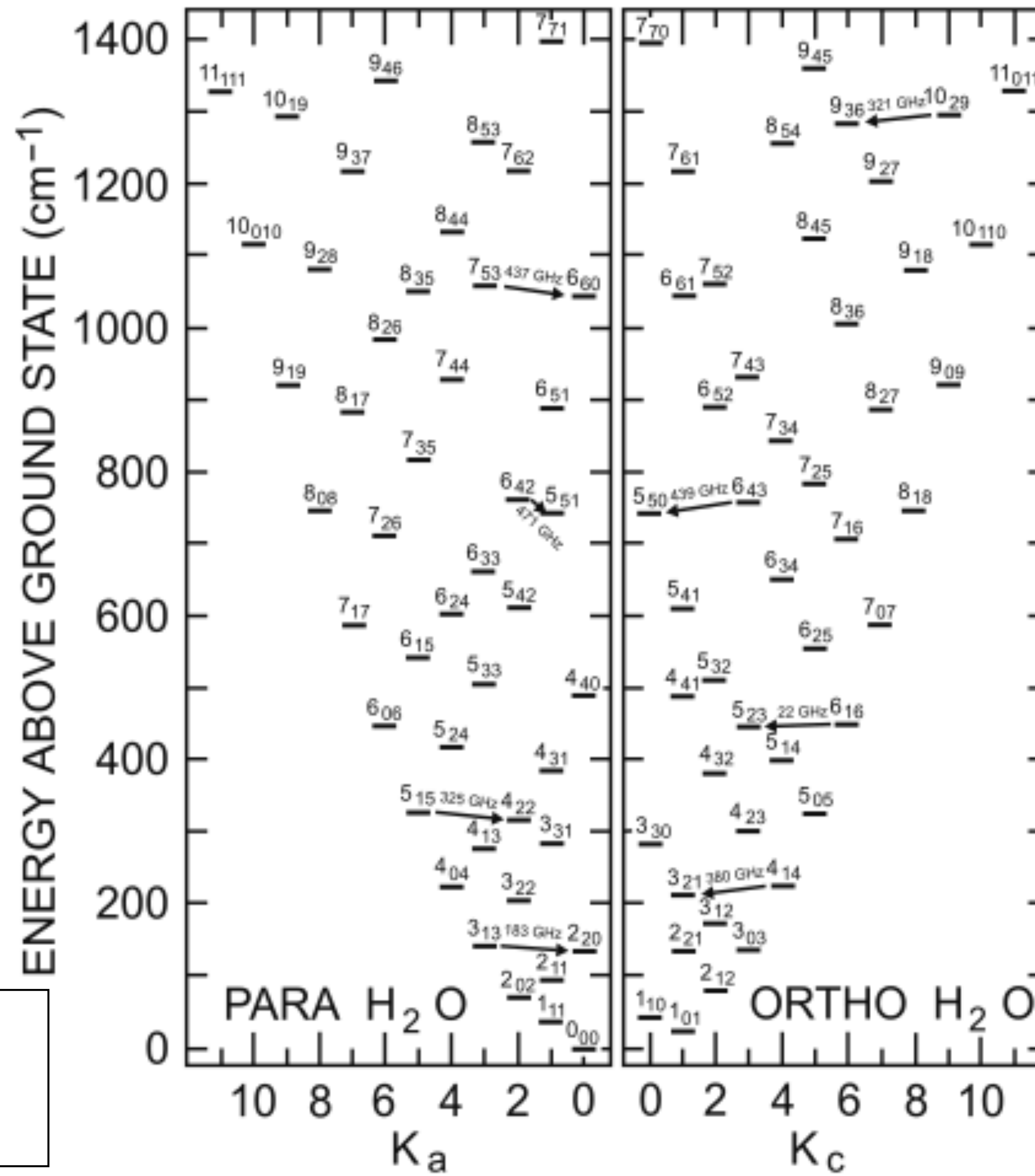


ortho-H_2O
para-H_2O



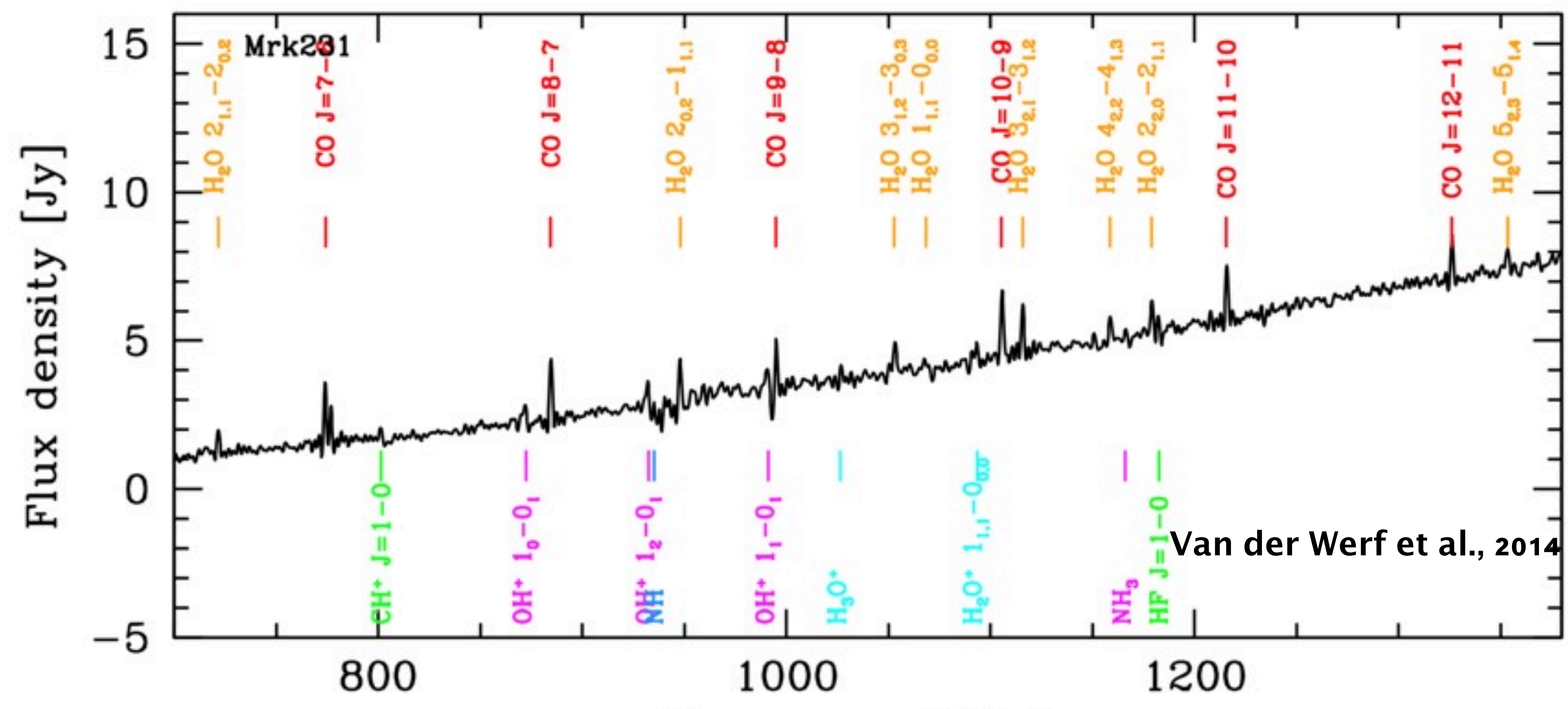
Selection rules:
- ΔJ=0,+/-1

Energy diagram



Why do we care about H_2O in galaxies?

- H_2O is one of the most abundant gas in molecular clouds (the 3rd most abundant species ~10^{-5}-10^{-4} in warm regions).
- H_2O possesses a large number of sub-mm and FIR transitions. It can be an important coolant in dense molecular clouds.
- H_2O can be effectively excited by collision and IR pumping. The relative strengths of H_2O lines give us information of the ISM physical structure and FIR radiation density.



Observations of Extragalactic Water So Far

Table 1. Important Telescopes for Water Observations

telescope	wavelength/frequency	spectral resolving power R	spatial resolution[a]
SWAS	557 GHz	10^6	3.2′ × 4.0′
Odin	557 GHz	10^6	2′
ground cm	22 GHz	10^6	0.001″ to a few arcsec
ground mm	many, e.g., 183, 380 GHz	10^7	0.2−20″
	203[b], 391[b], 692[b] GHz	10^7	0.2−20″
Herschel-HIFI[c]	480−1250 GHz	10^7	44″−17″
	1410−1910 GHz	10^7	15″−9″
Herschel-PACS[d]	55−210 μm	$(1-5)\times 10^3$	9.4″
Herschel-SPIRE[e]	200−670 μm	$\sim 10^3$	17−42″
Spitzer	10−38 μm	600	10″
ISO-SWS[f]	2.5−45 μm	2000, 20000	14″ × 20″ to 17 × 40″
ISO-LWS[g]	45−197 μm	200, 10000	~80″
ground 4−10 m optical	2.8−3.3 μm	$\leq 10^5$	≤1″
ground 4−10 m infrared	11−14 μm	10^4	1″

SWAS & ODIN, not sensitive enough
ISO & Spitzer, only high excitation lines
Herschel-PACS/SPIRE, coarse spectra/velocity resolution

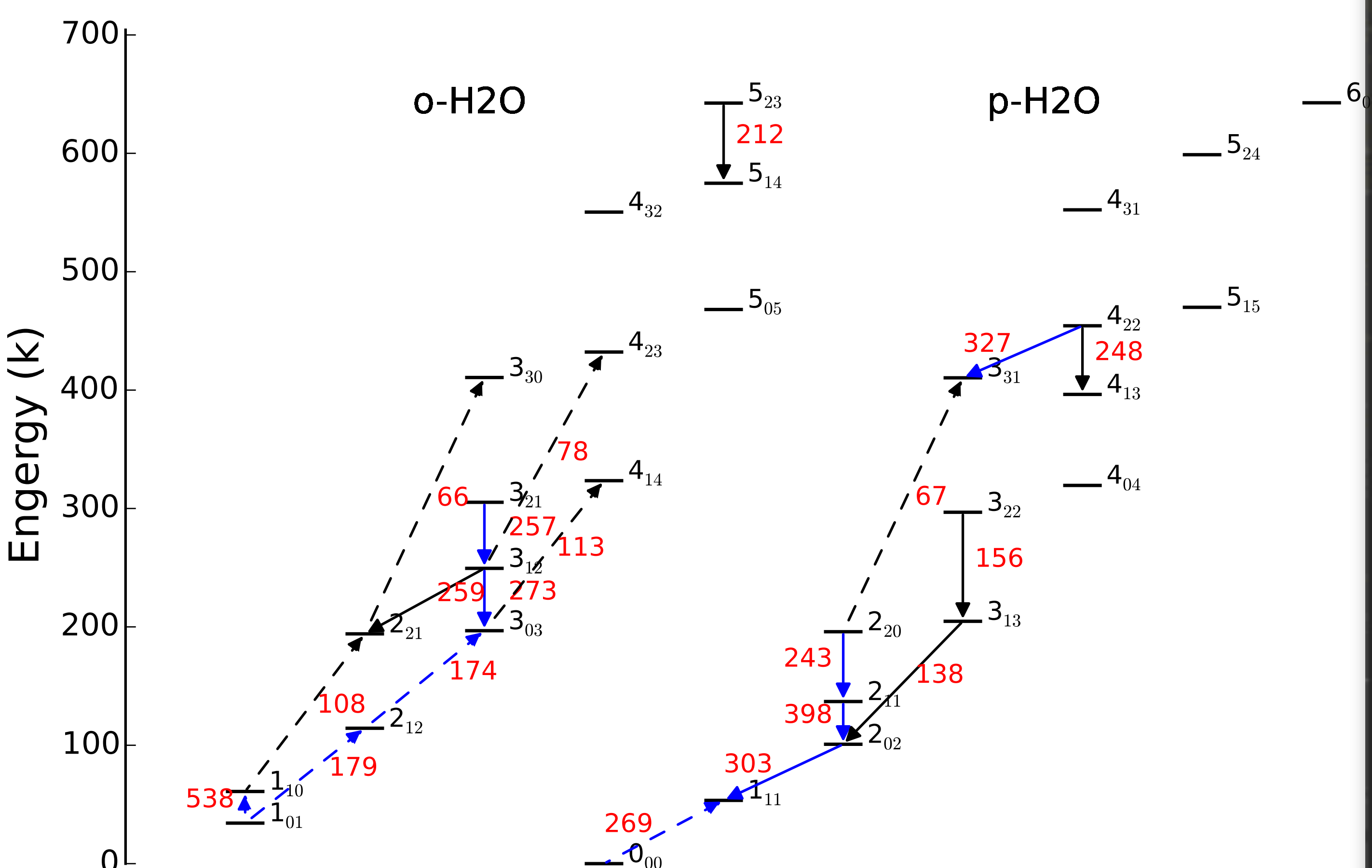
Herschel-HIFI: allowed for the first systematic and comprehensive studies of multiple H_2O lines in galaxies

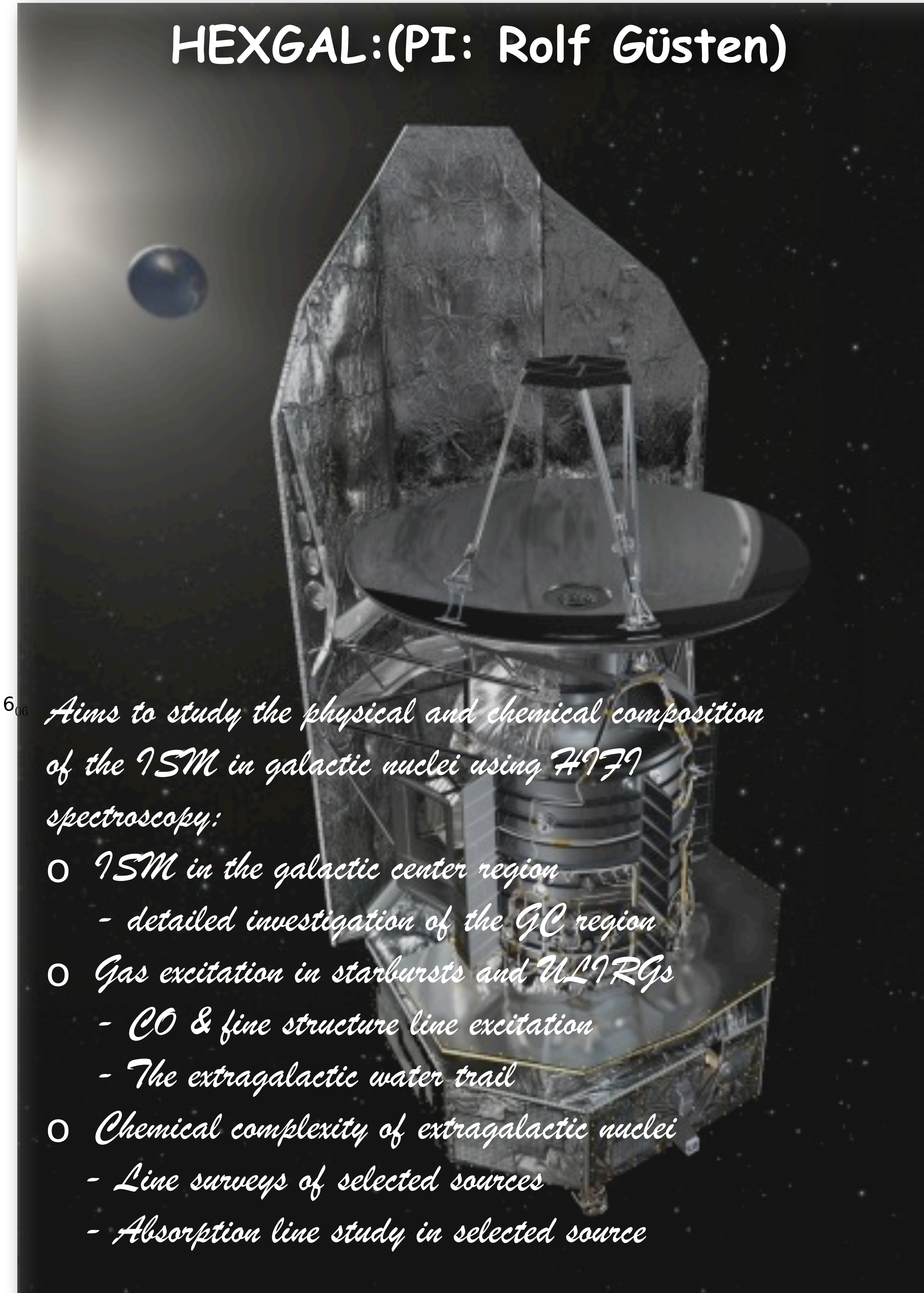
The Herschel/HIFI EXtraGALactic (HEXGAL) Key Project

Sample: nine nearby galaxies:

M82	nuclear SB	LIRG	extended
NGC 253	nuclear SB	LIRG	extended
NGC 4945	nuclear SB/AGN	LIRG	extended
Centaurus A	nuclear SB/AGN	LIRG	extended
Arp220	SB/AGN Major Merger	ULIRG	compact
NGC 4038/39	SB Major Merger	LIRG	extended
NGC1068	AGN/SB	LIRG	extended
Mrk 231	AGN/SB	ULIRG	compact
NGC6240	AGN/SB	LIR	compact

Selected H2O transitions:



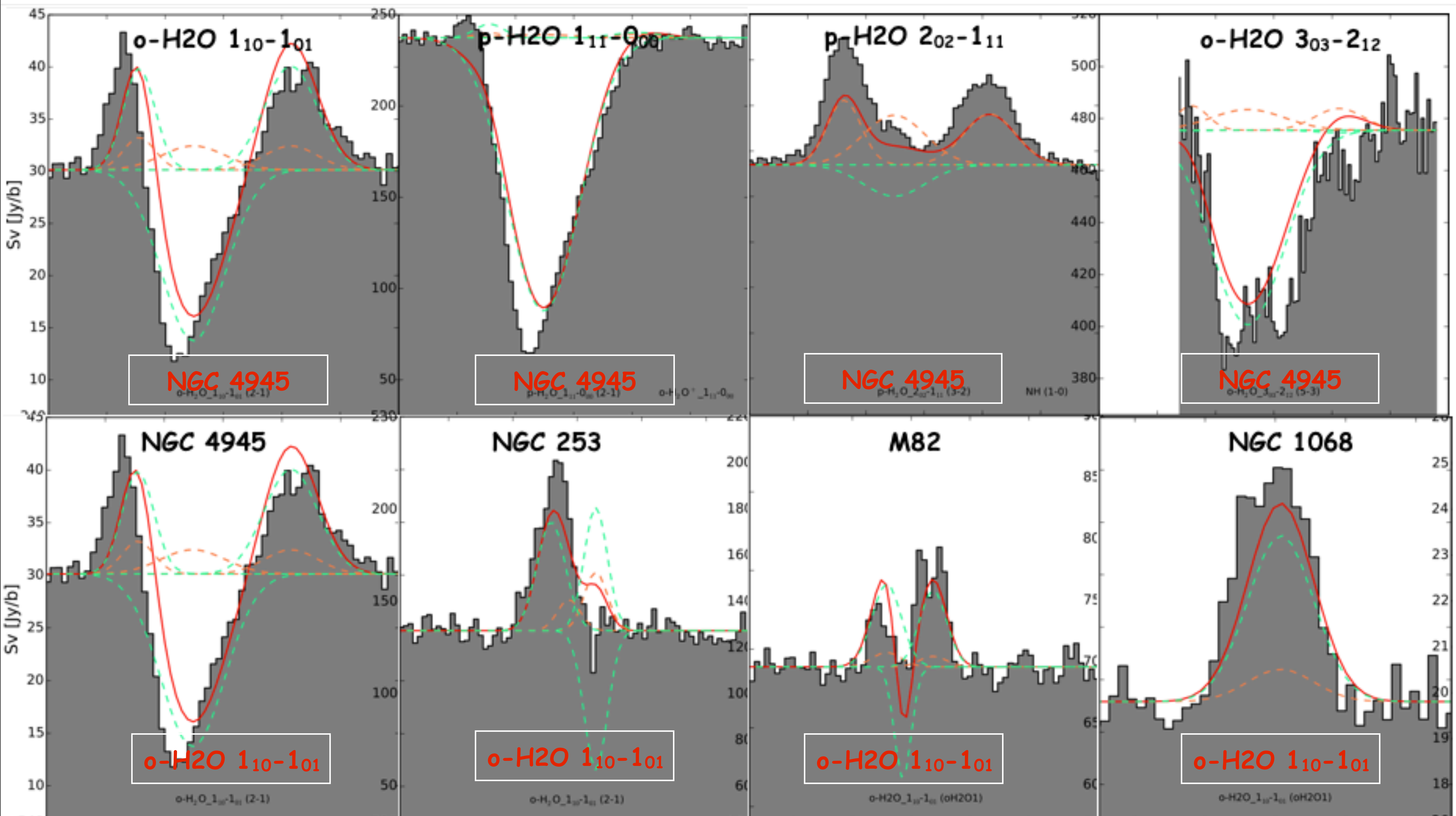


HEXGAL:(PI: Rolf Güsten)

Aims to study the physical and chemical composition of the ISM in galactic nuclei using HIFI spectroscopy:

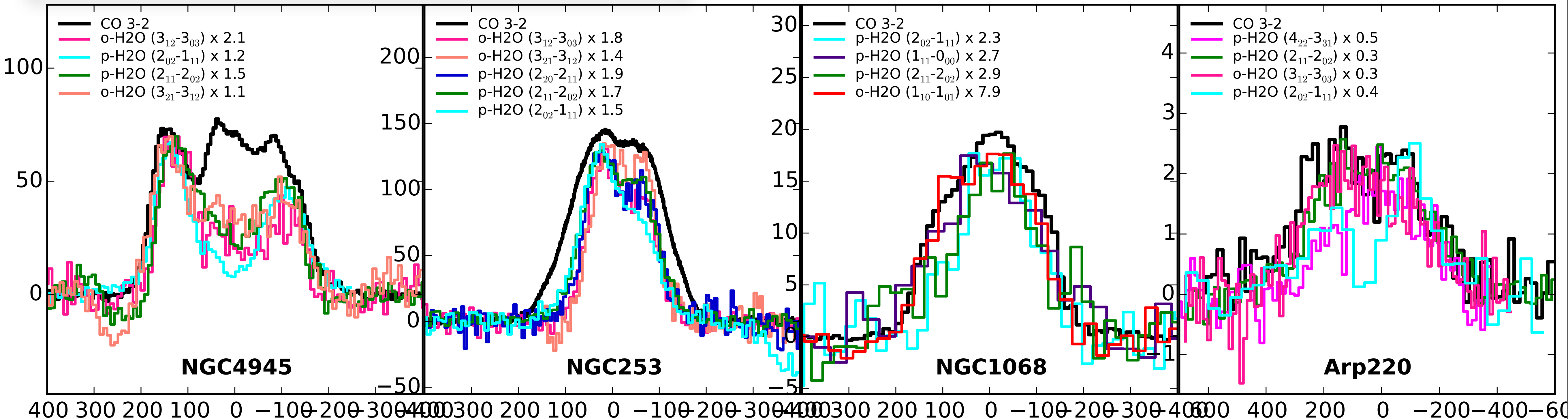
- *ISM in the galactic center region*
  - *detailed investigation of the GC region*
- *Gas excitation in starbursts and ULIRGs*
  - *CO & fine structure line excitation*
  - *The extragalactic water trail*
- *Chemical complexity of extragalactic nuclei*
  - *Line surveys of selected sources*
  - *Absorption line study in selected source*

HIFI H_2O Spectra

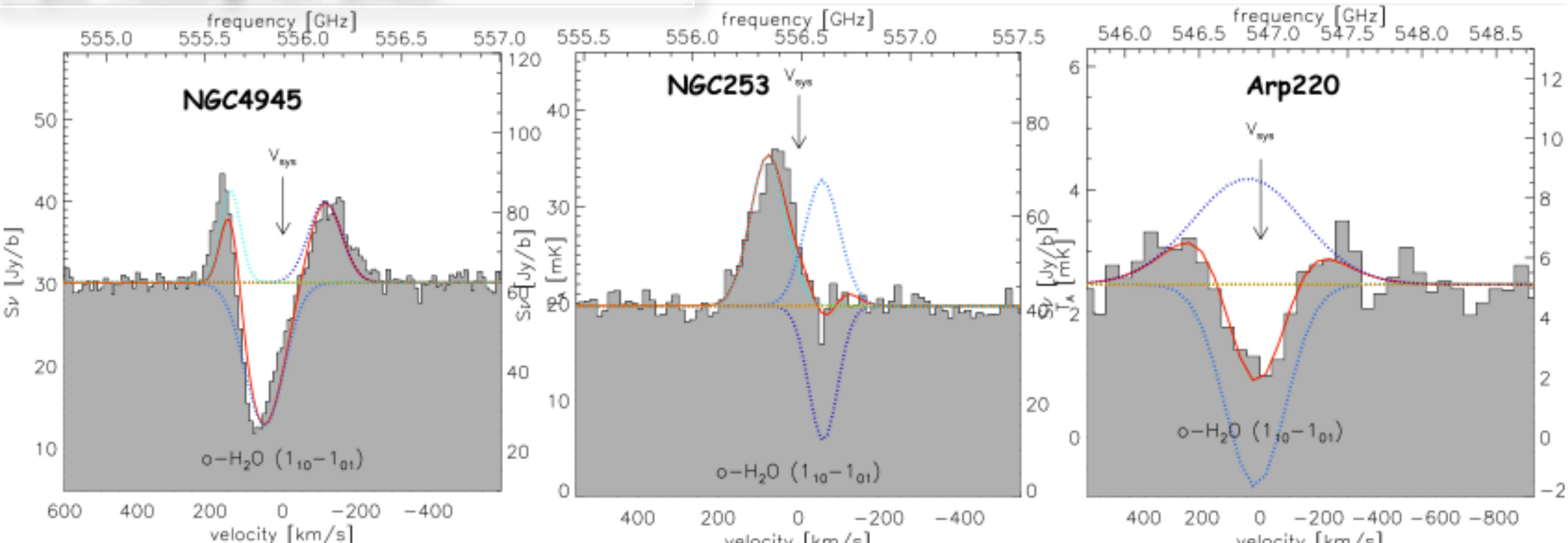


HIFI H_2O Line Shape

H_2O Emission Lines & CO Line



H_2O Absorption Lines



H_2O Line Modelling

- **Step 1: Spectra Gaussian Decomposition**

Method: fit full water spectra into several gaussian components with almost fixed velocity centers ($\Delta\upsilon \leq 5\ \mathrm{km\ s^{-1}}$) and line width ($\Delta$FWHM $\leq$ 10%FWHM).

- **Step 2: IR and (sub)mm Photometry & Dust SED Fitting**

IR maps: Spitzer, WISE, IRAS, Herschel PACS/SPIRE and ISO
(sub)mm maps: APEX SABOCA/LABOCA
Method: measure the fluxes within apertures of various HIFI beams, and use the derived fluxes to fit dust SED and perform aperture corrections required by resolved sources.

- **Step 3: CO SLED (1 <= Jup <=14)**

CO fluxes: SPIRE, HIFI, ground telescopes

- **Step 4: Radiative Transfer Calculation**

Method: β3D

H_2O Line Modelling - β3D

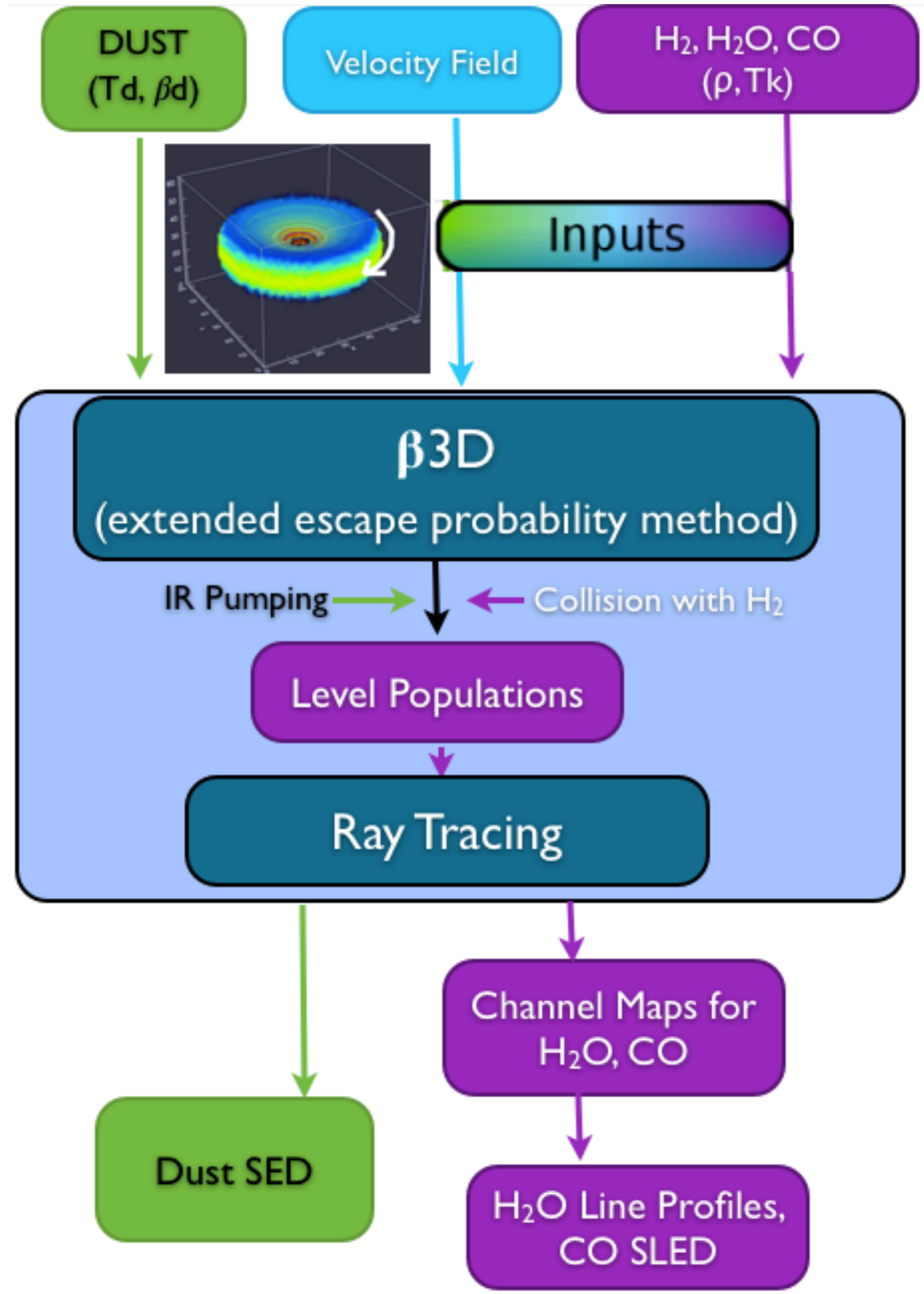
Advantages of β3D:

(1) its dimensionality: a unique temperature, density, abundance value and, more importantly, 3D velocity vector can be attributed to every position in the model

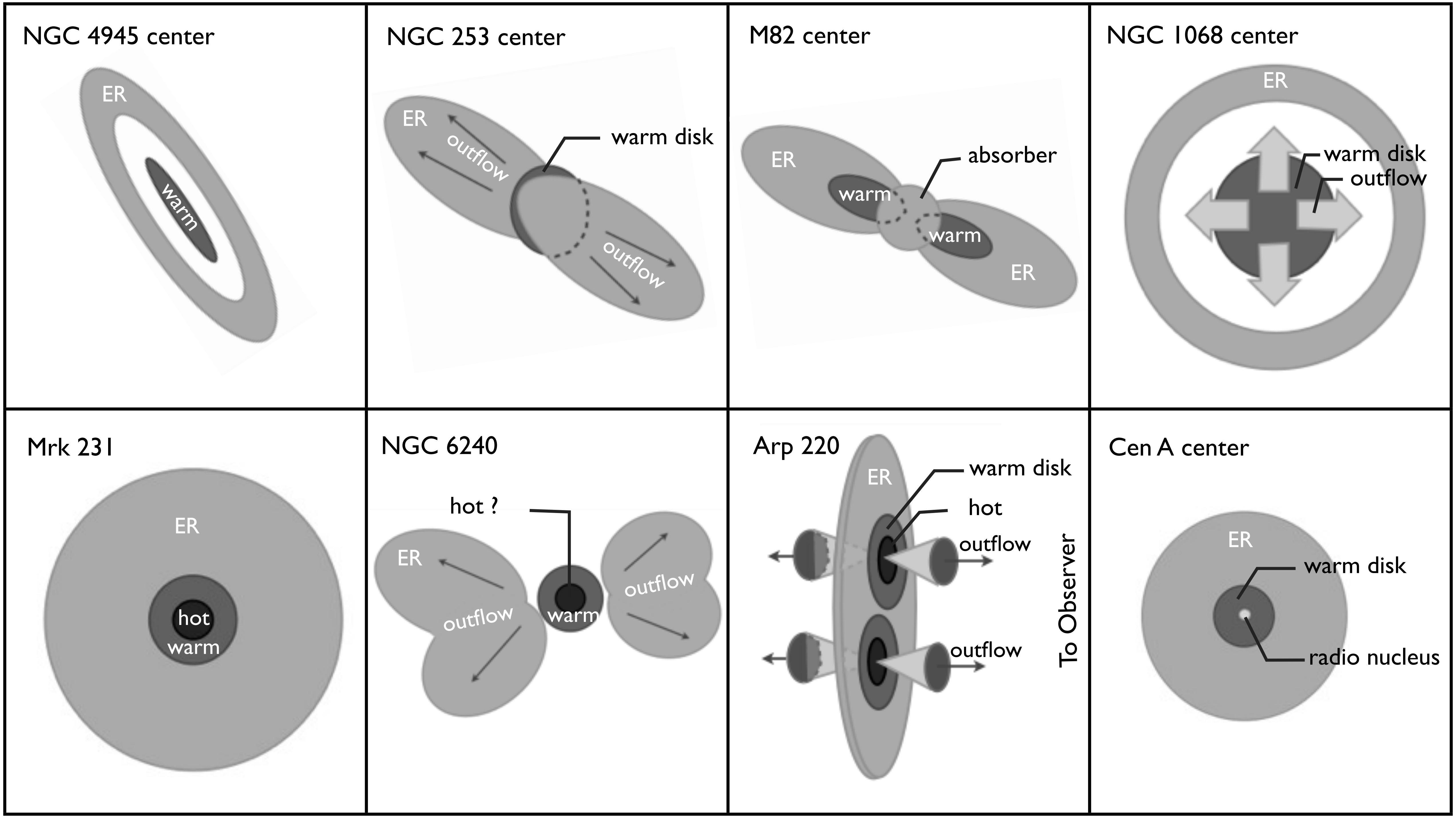
(2) its high speed of convergence: due to the extended escape probability method implemented

(3) its ability to account for the effects of dust: the effect of dust emission and absorption (i.e., IR-pumping) on the excitation of molecules was also considered

(4) its output of channel maps: a new line tracing approach where both line and continuum emission are calculated across the full velocity range (i.e., line profile) over a projected surface along an arbitrary viewing angle



Models for Individual Galaxies

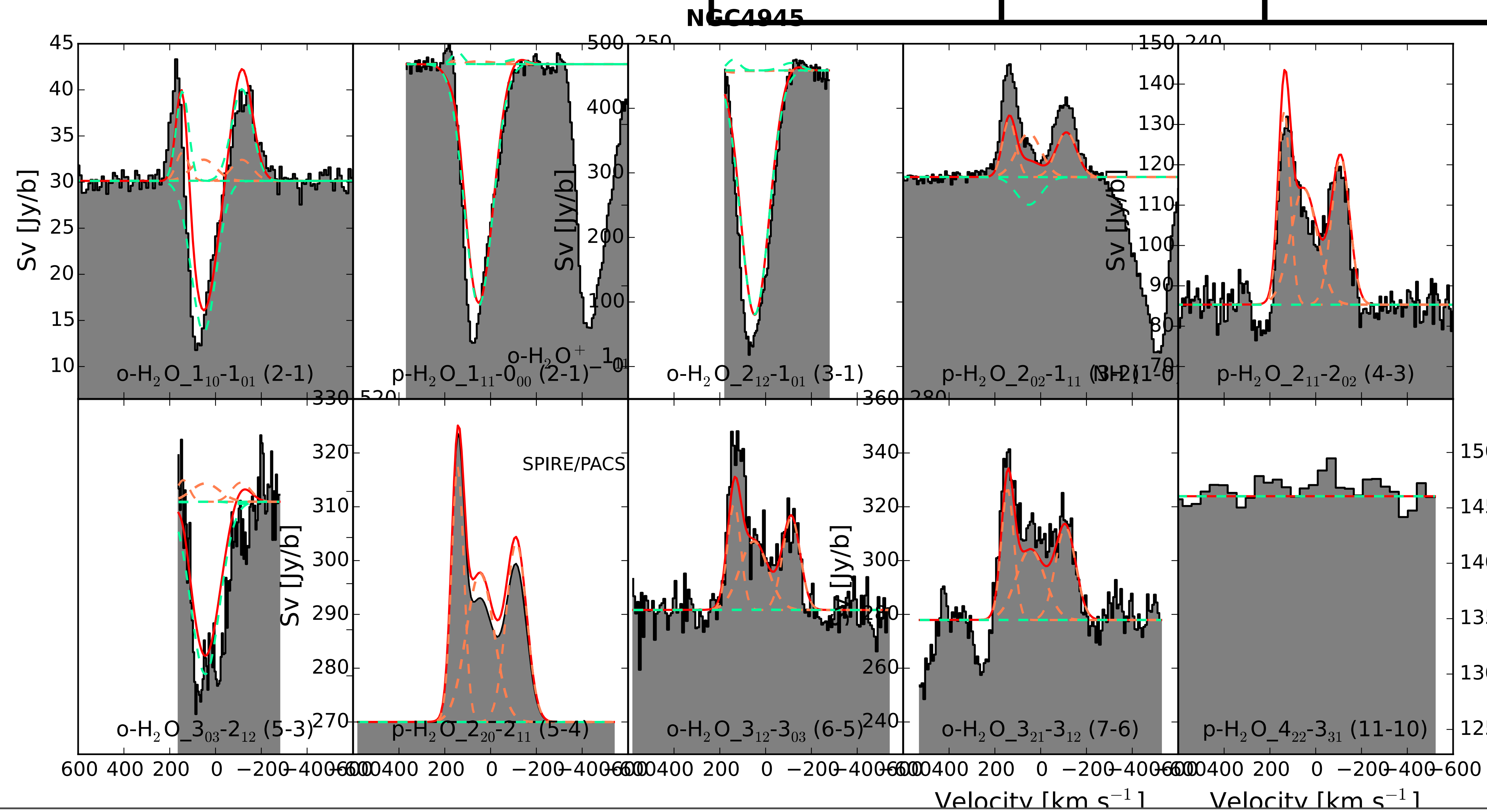


General Modelling Results: warm + cold ER

Two Typical Components

Typical Parameter Values

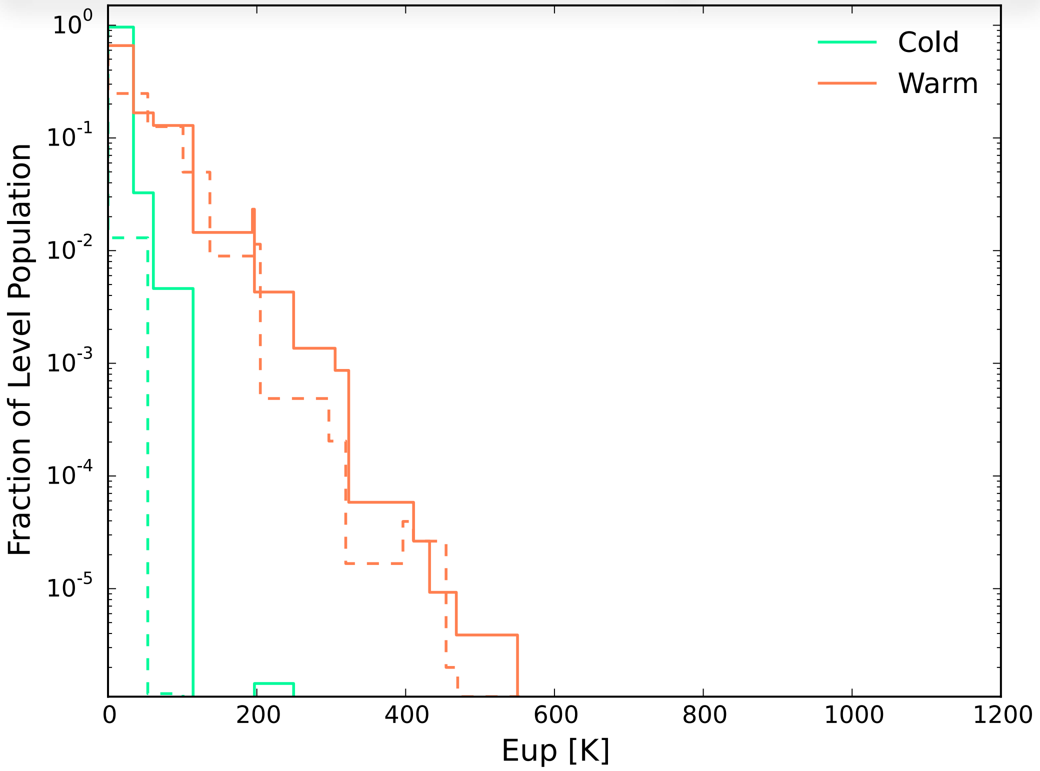
Component	WARM	COLD ER
ρ [H/cm^{-3}]	10^5 - 10^6	10^3 - 10^4
Tk [K]	40 - 70	20 - 30
x(H_2O)	10^{-8} - 10^{-7}	10^{-9} - 10^{-8}
Tdust [k]	40 - 70	20-30
N_H [H/cm^{-2}]	1 - 4 x 10^{24}	1 - 6 x 10^{23}



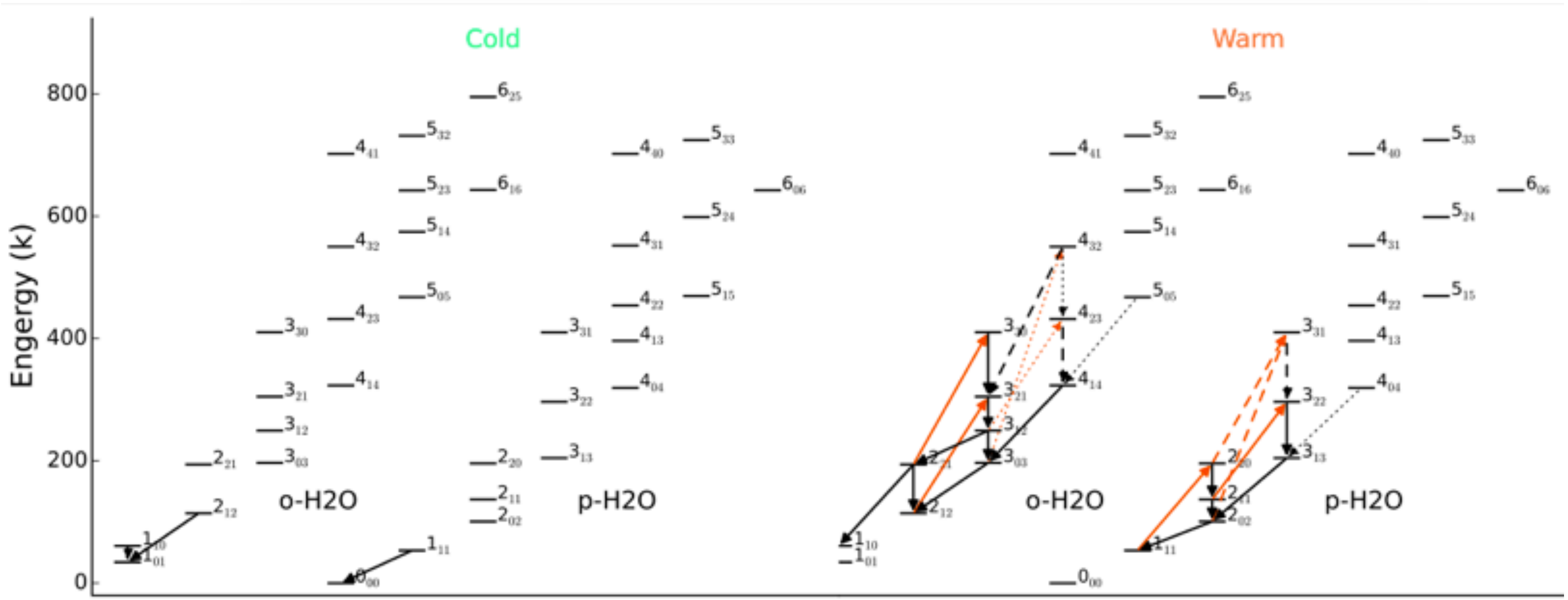
General Modelling Results: warm + cold ER

Two Typical Components

Fraction of Level Populations

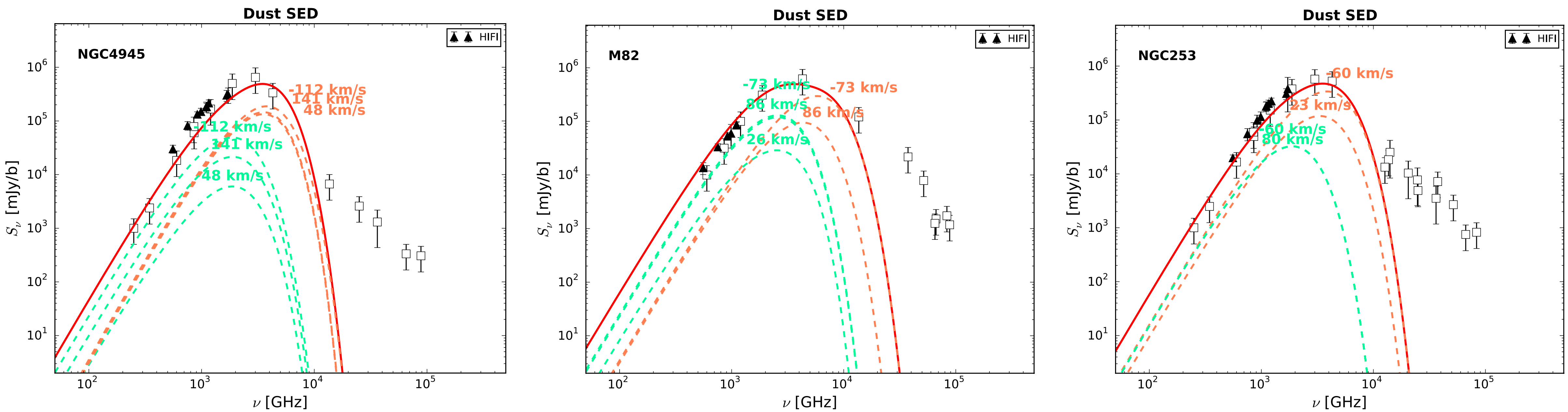


Line Features from Cold and Warm Components

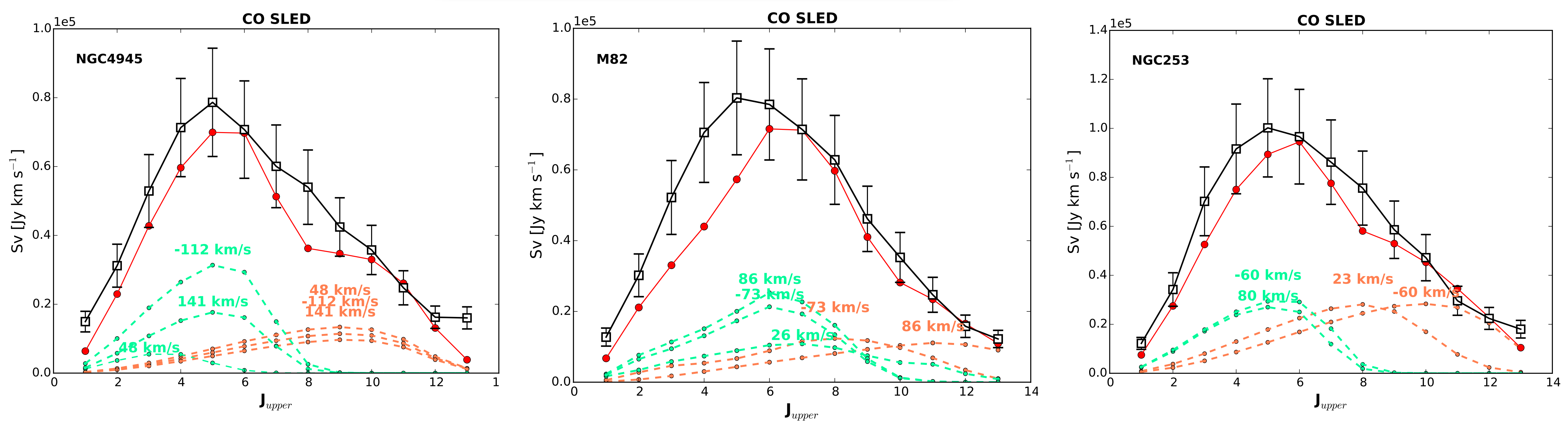


General Modelling Results: warm + cold ER

Dust SED

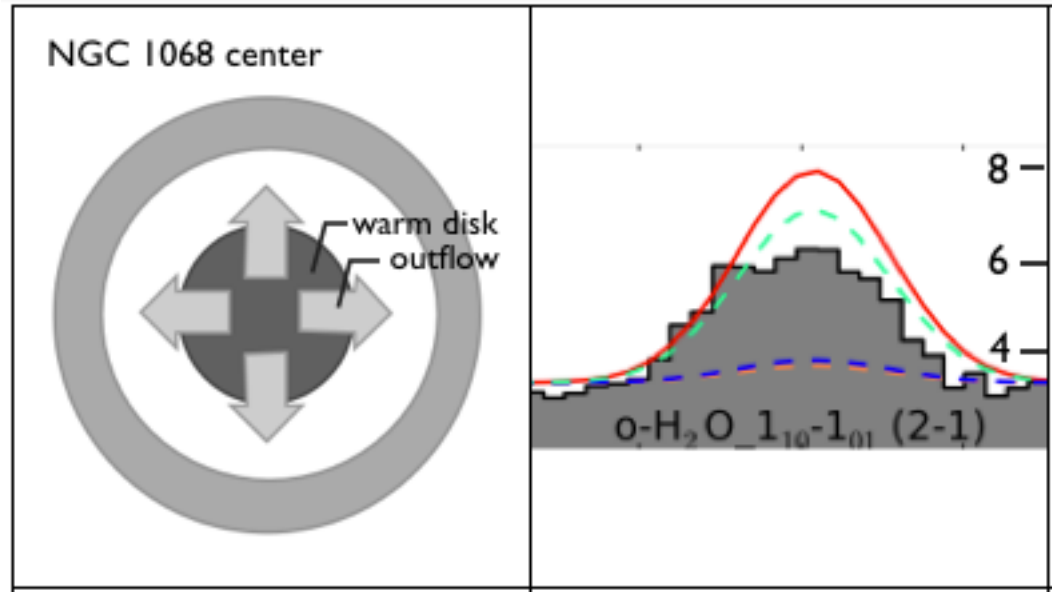


CO SLED

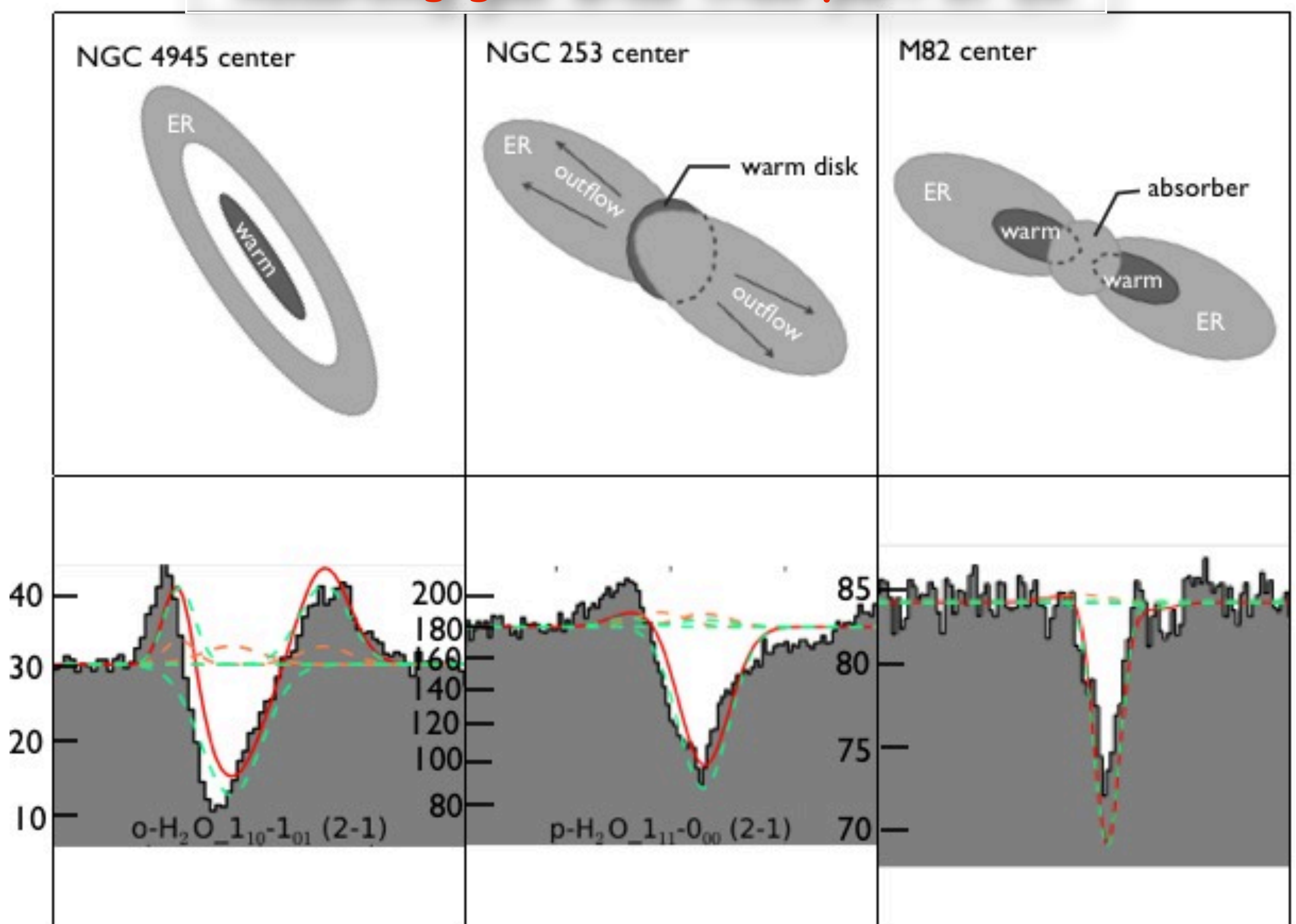


General Modelling Results: absorbing gas

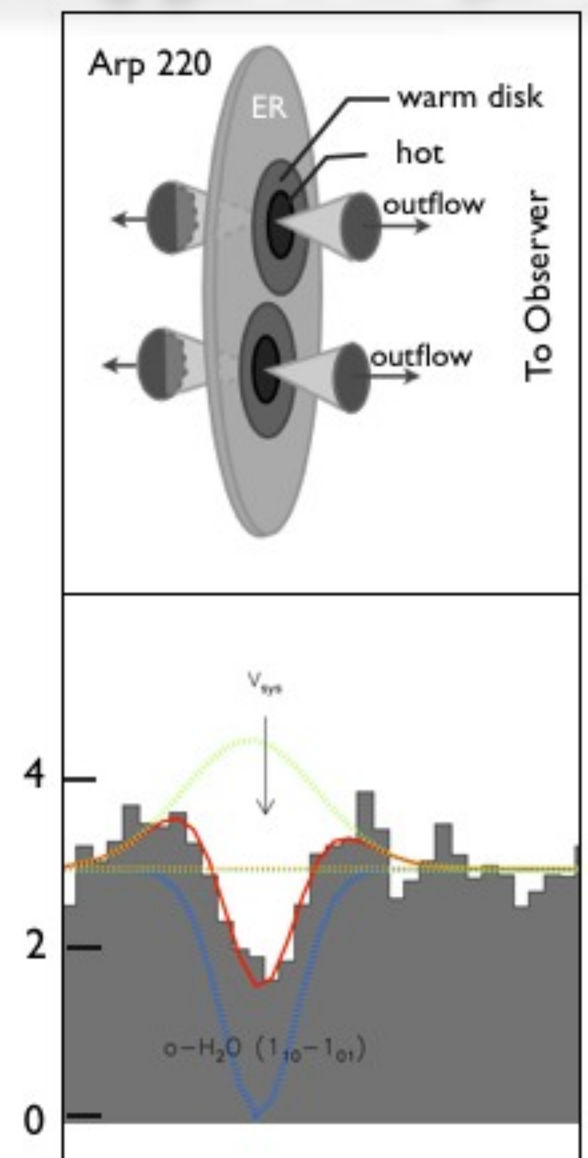
No absorbing gas in NGC 1068: i < 40 deg



Absorbing gas arise from part of ER



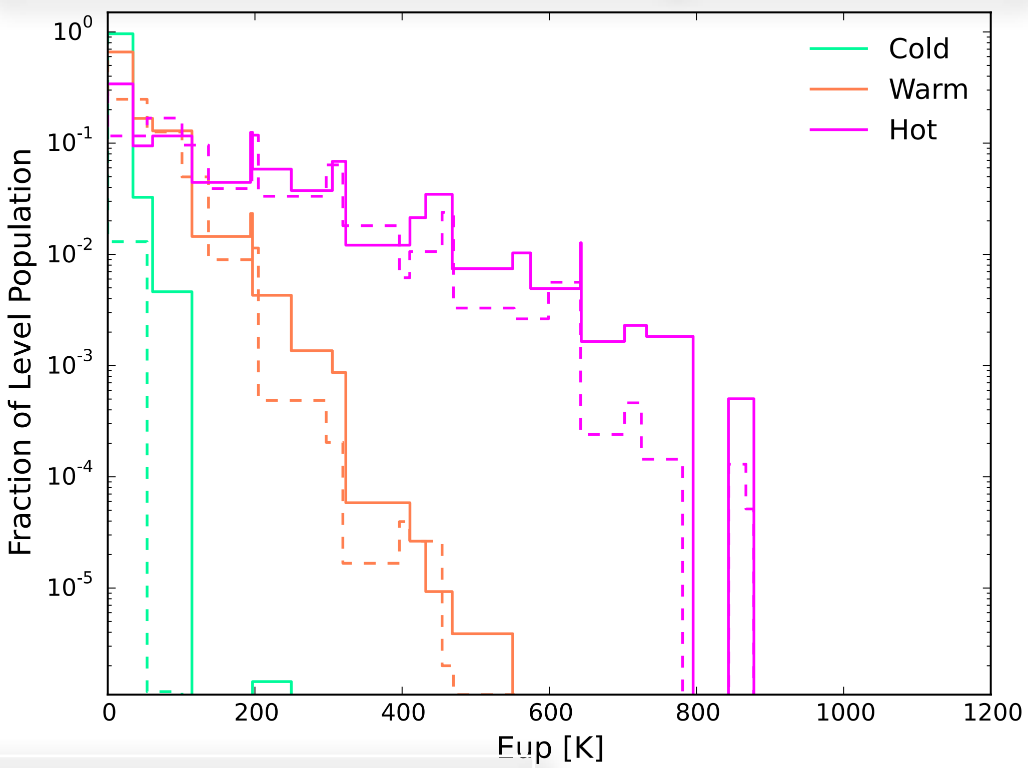
Absorbing gas is not part of ER



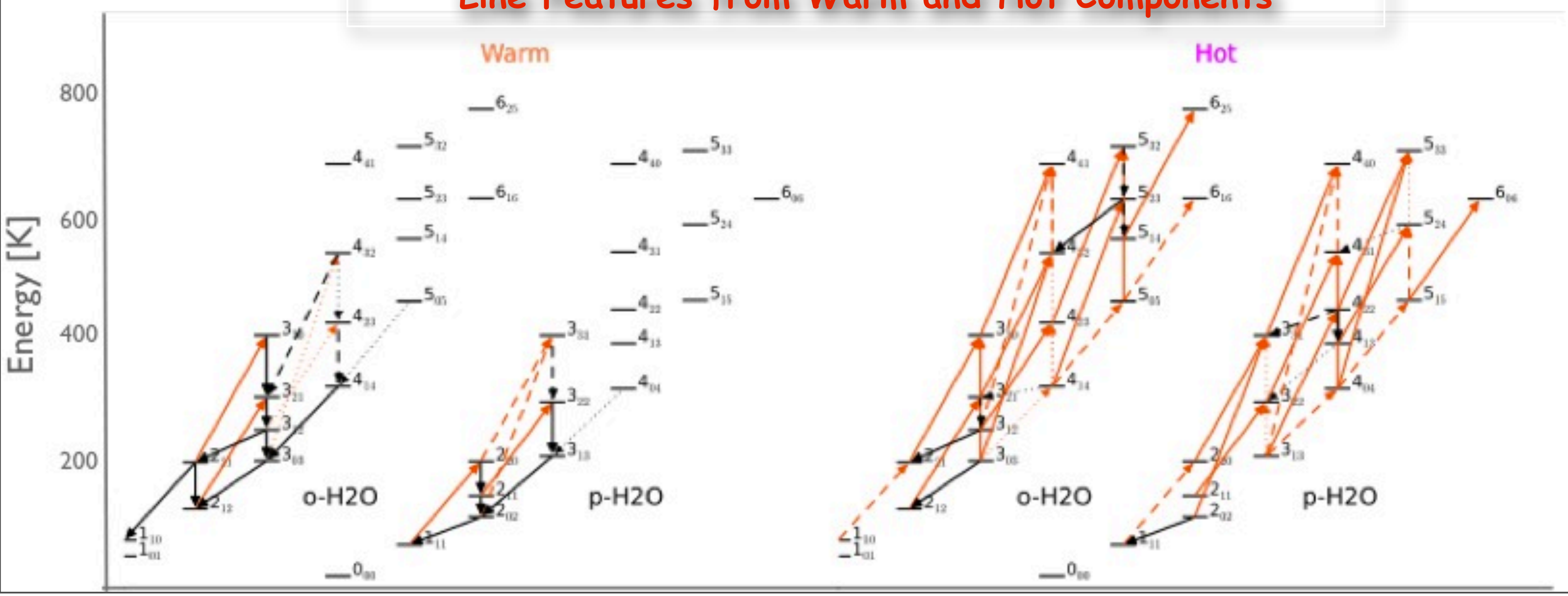
General Modelling Results: hot component

Component	Hot
ρ [H/cm^{-3}]	~ 10^6
Tk [K]	100 - 200
x(H_2O)	10^{-6} - 10^{-5}
Tdust [k]	100 - 200
N_H [H/cm^{-2}]	10^{24} - 10^{25}

Fraction of Level Populations

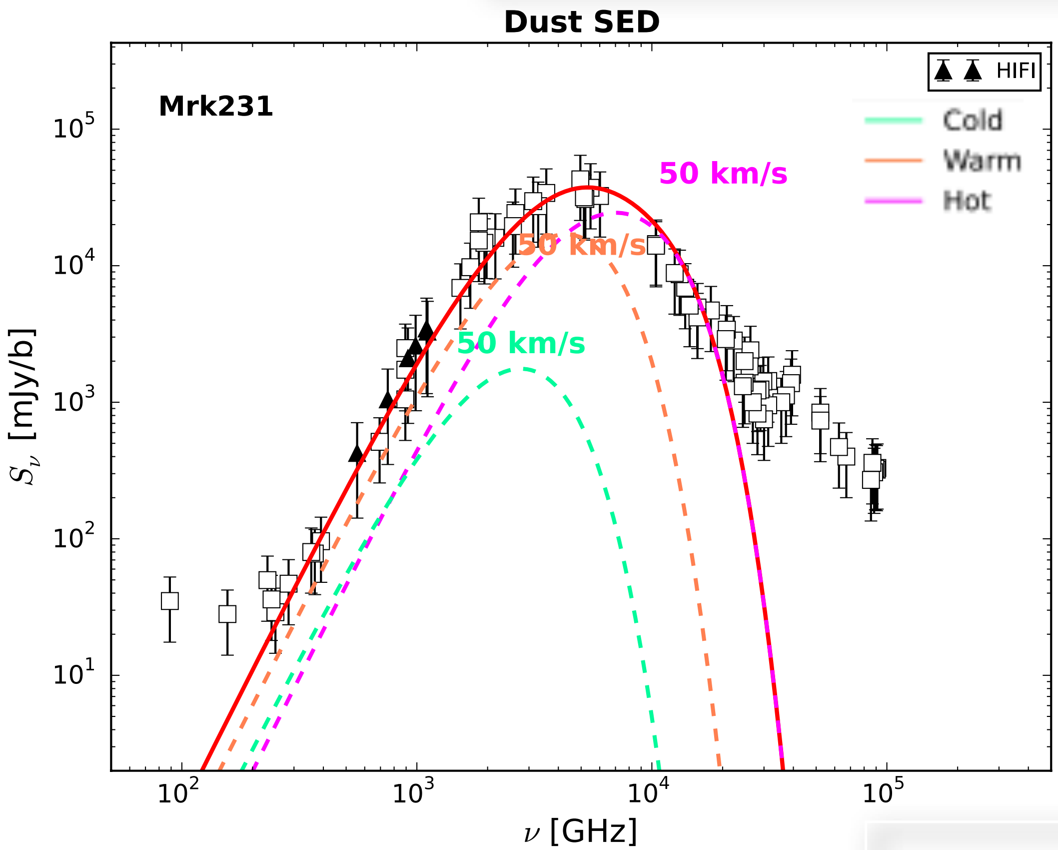


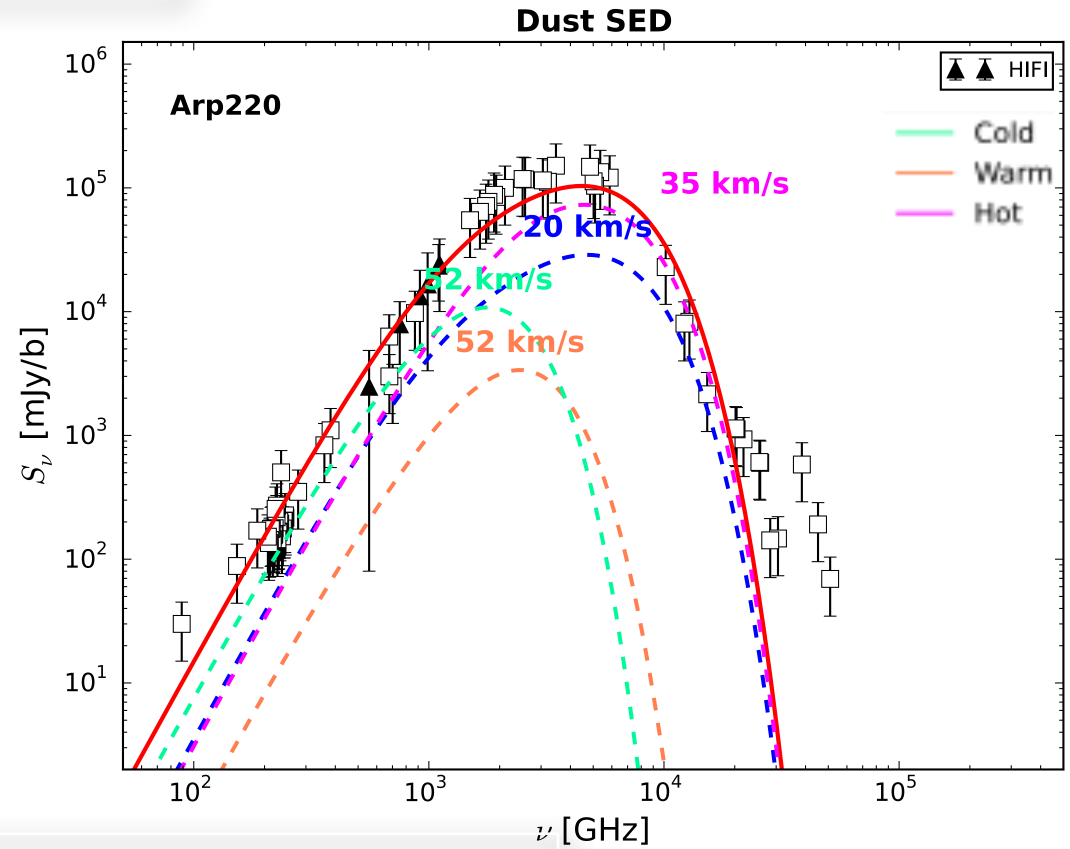
Line Features from Warm and Hot Components



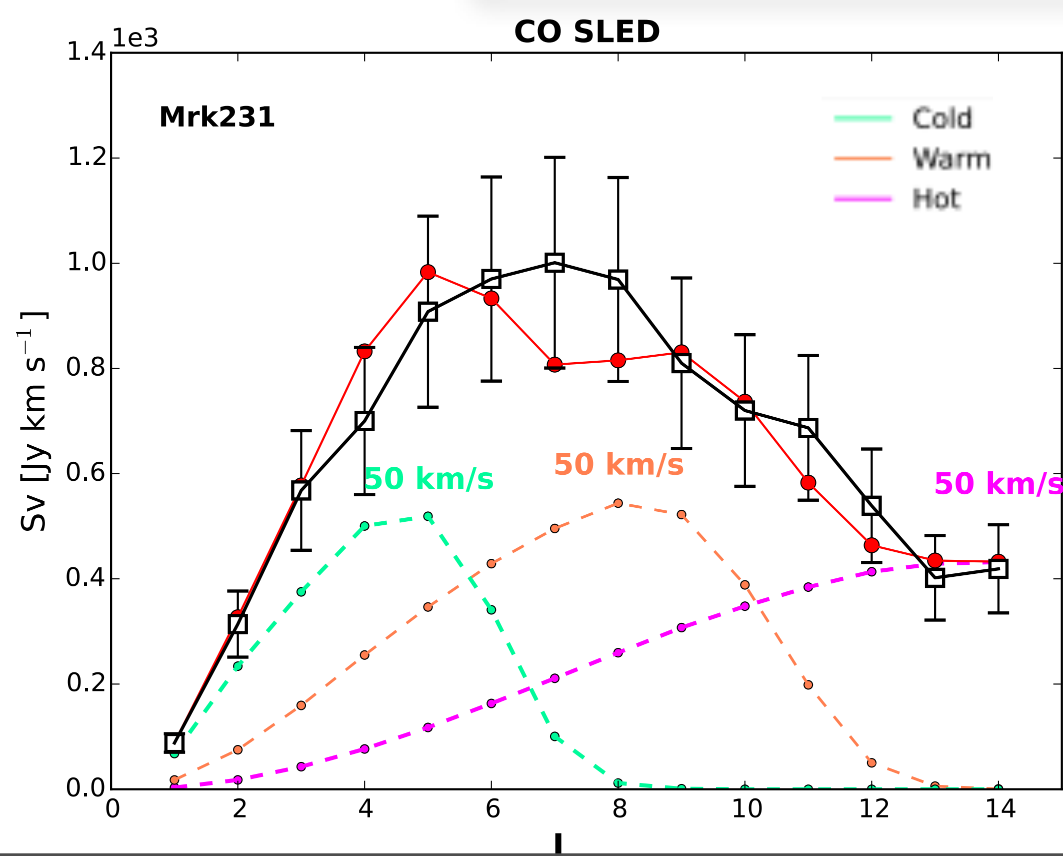
General Modelling Results: hot component

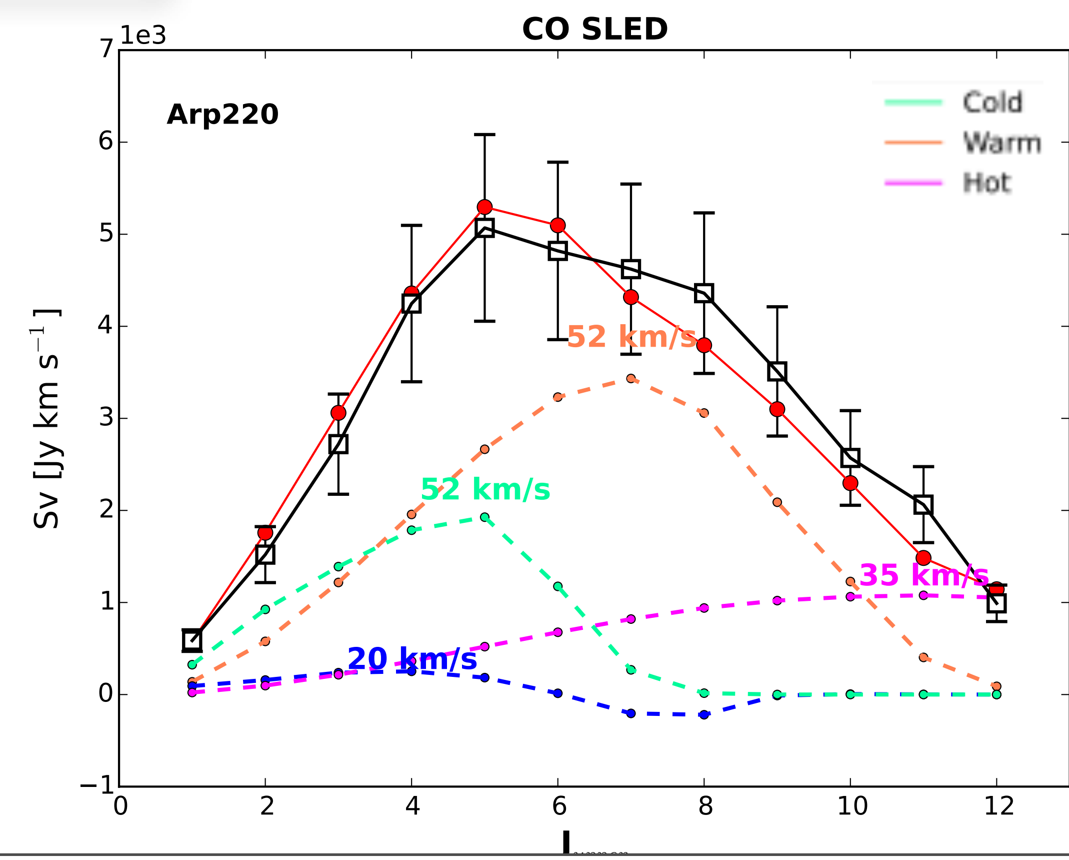
Dust SED





CO SLED





Water Excitation: collision vs. IR-pumping

- **Cold ER:** water gas is mainly collisionally excited
- **Warm Component:**

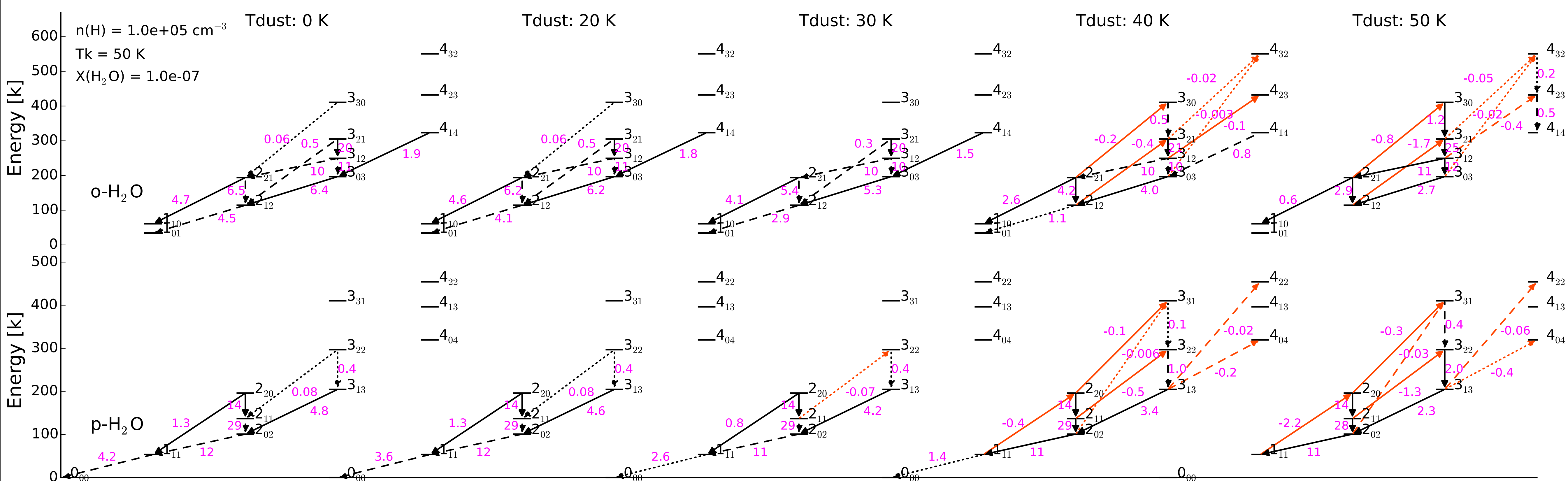
levels with Eup <= 300 - 400: collisionally exited

levels with Eup >= 300 - 400: IR-pumping exited

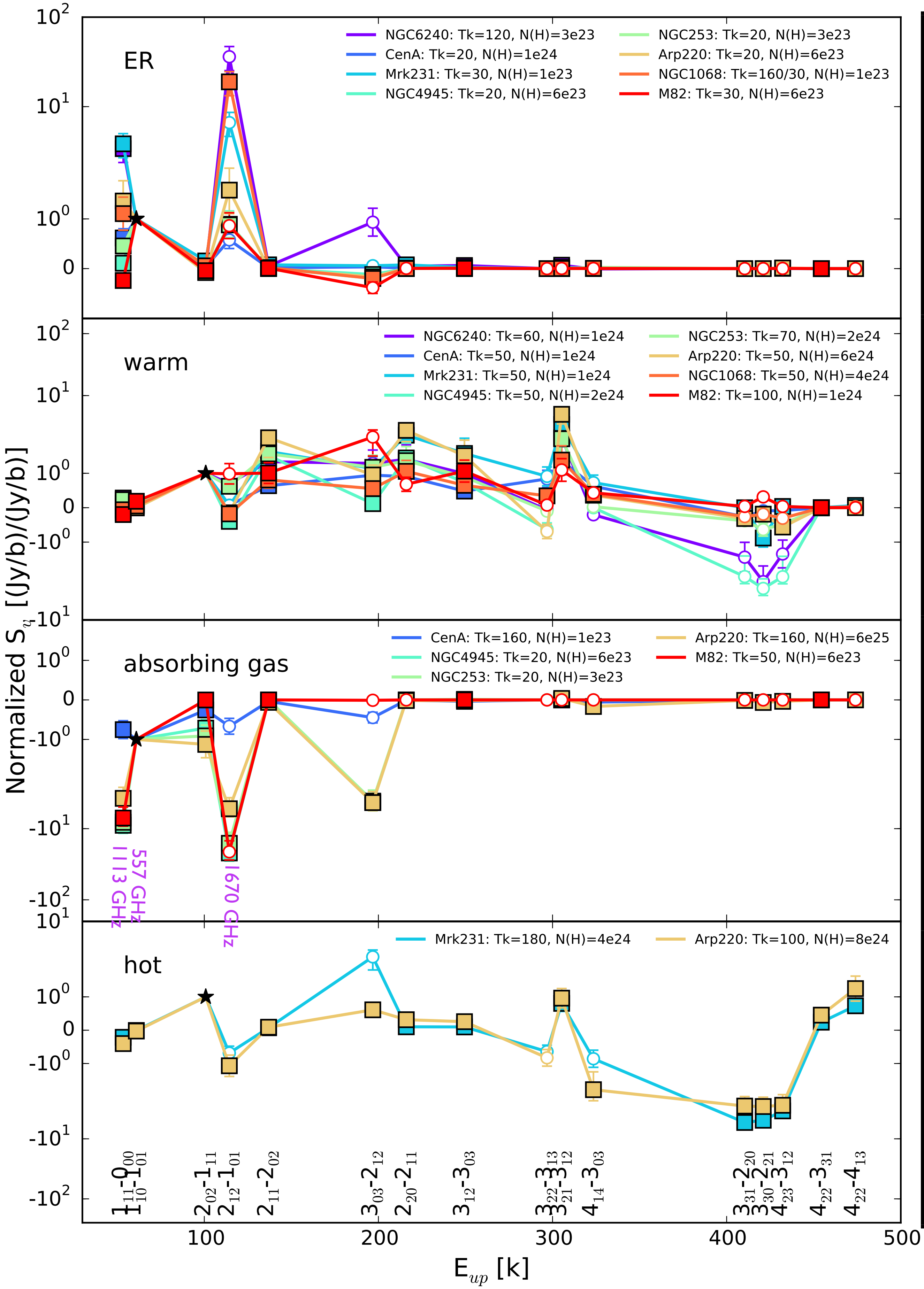
- **Hot Component:**

levels with Eup <= 800 - 1000: collisionally exited

levels with Eup >= 800 - 1000: IR-pumping exited



H_2O SLED



Cold ER:

- 2_{12}-1_{01}/1_{10}-1_{01} line ratios is a good indicator of "shock condition"

Warm Component:

- H2O SLED seen in middle-lying lines (2_{12}-2_{02} to 3_{22}-3_{13}) are nearly flat;
- The 3_{21}-3_{12} line has higher T_{ex} and stronger line intensity

Absorbing gas:

- The absorption line ratio depends on mainly the dust optical depth of absorbing gas;
- The 1_{11}-0_{00}/1_{10}-1_{01} (1113/557 GHz) and 2_{12}-1_{01}/1_{10}-1_{01} (1670/557 GHz) absorption line ratio > 1, if background is dust continuum; and < 1, if background is radio source

Hot component:

- Strong detections in high-lying lines (including both emission and absorption)

Summary

- **Our work has led to the first complete view of a number of water lines including ground transitions in a variety of active nuclear environments with spectral resolution**

- **The water spectra show a diversity of line shapes. The middle-lying lines are always seen in emission, while the low-lying lines tend to appear in absorption**

- **Line modelling with 3D radiative transfer code** β3D **suggests that water line profiles provide a powerful diagnostic tool, by:**

(1) revealing the geometry and dynamics structure of ISM (gas and dust) through the various line shapes
(2) revealing the physical and chemical conditions of ISM
(3) constraining dust continuum model and local conditions of infrared-opaque sources (even without spatially resolving them), since IR-pumping is found to play an important role in warm regions

- **The luminous IR galaxies (nuclei) contain three typical components:**

(1) a widespread cold component, where only the lowest few energy levels of H2O are excited mainly by collision
(2) a warm region, a main contributor to the middle-lying H2O lines, dust SED and middle/high-J CO emissions
(3) a hot core (usually appears in ULIRGs), where high-lying water, mid-IR and high-J CO lines arise from