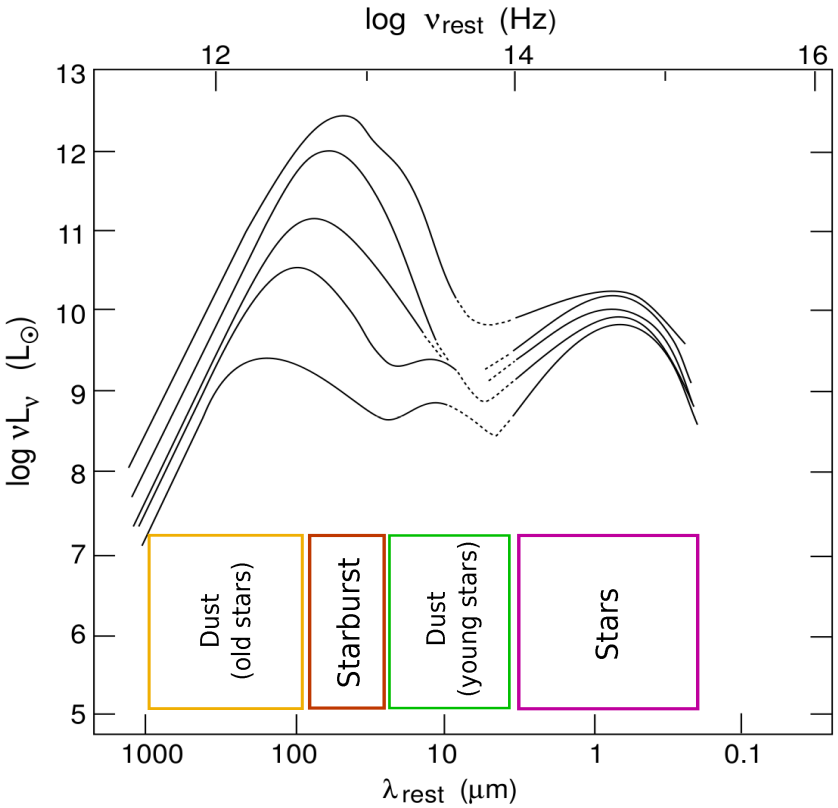
Observations of Molecules in Luminous Infrared Galaxies

Francesco Costagliola

Outline

- Luminous Infrared Galaxies
- Molecular emission as a diagnostic tool
- *Examples:*
  - *Vibrationally excited HC_3N in NGC 4418*
  - *Molecular tracers of galactic evolution*
- Current projects & Future work

Luminous IR Galaxies



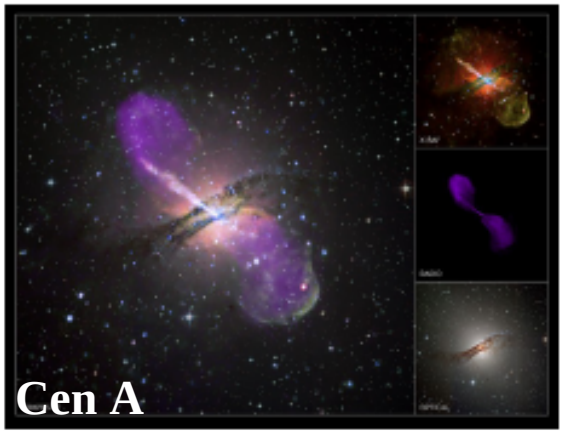
Sanders & Mirabel (1996)

- IR- Galaxies discovered by IRAS satellite (1980's)
- Emit most of their energy in the IR (8-1000 μm)
- Most galaxies with $L_{Bol} > 10^{11} L_\odot$ are IRG
- LIRG: $L_{IR} > 10^{11} L_\odot$

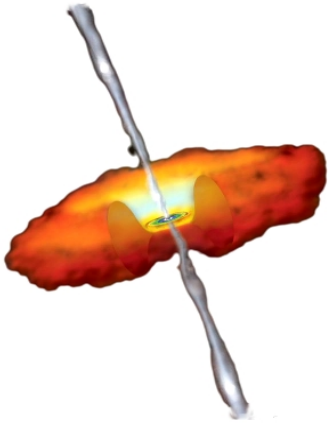
Starburst or AGN?

- Observed IR luminosities require large amounts of dust heated by AGN or Starburst
- Deep mid-IR silicate absorption
- Dense ($n>10^5$ cm^{-3}), warm ($T>100$ K) molecular gas in the nuclear regions
- Highly obscured by dust

  ⇒ direct investigation of central regions precluded at IR and optical wavelengths
- Nature of the energy source often unclear



Molecules as Tools



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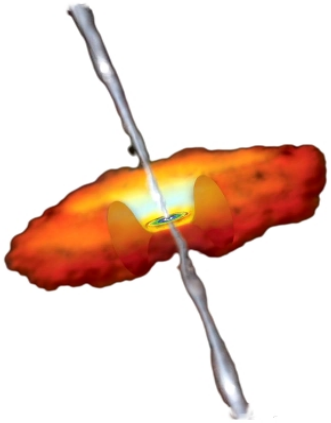
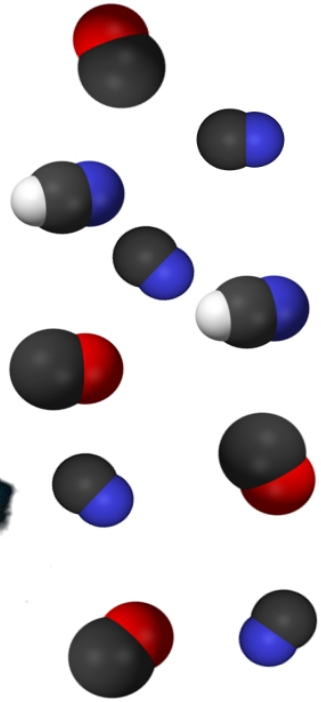
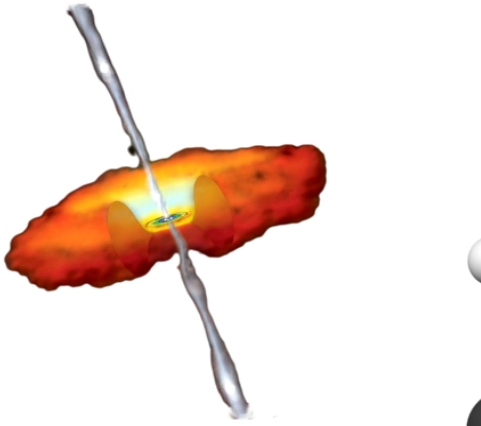


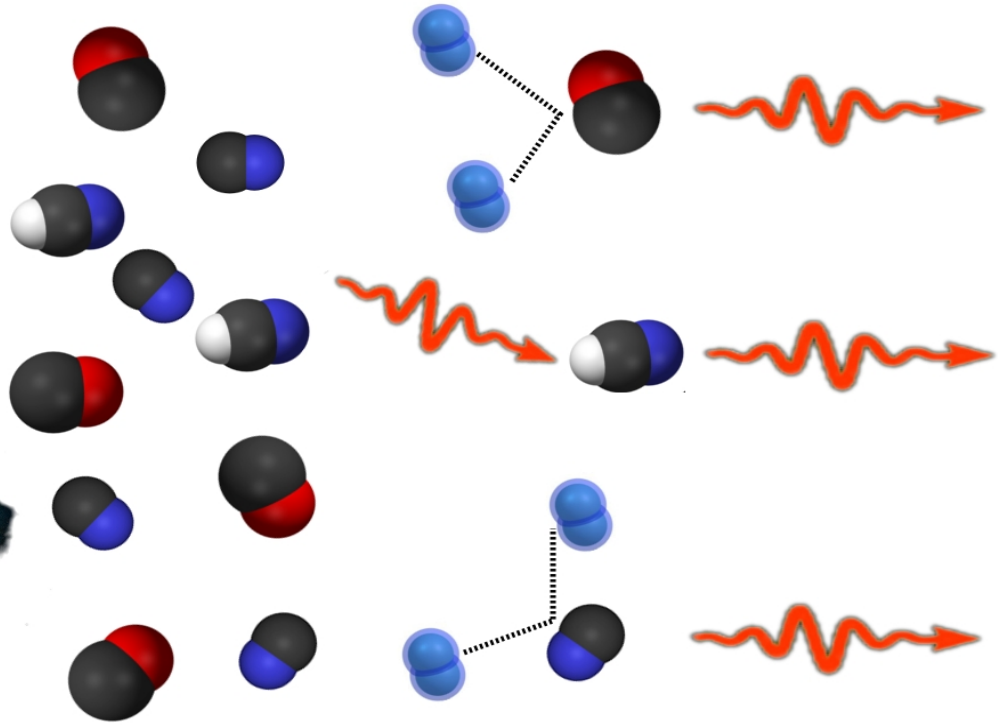


Environment
density, radiation

Chemistry
abundances

Molecules as Tools



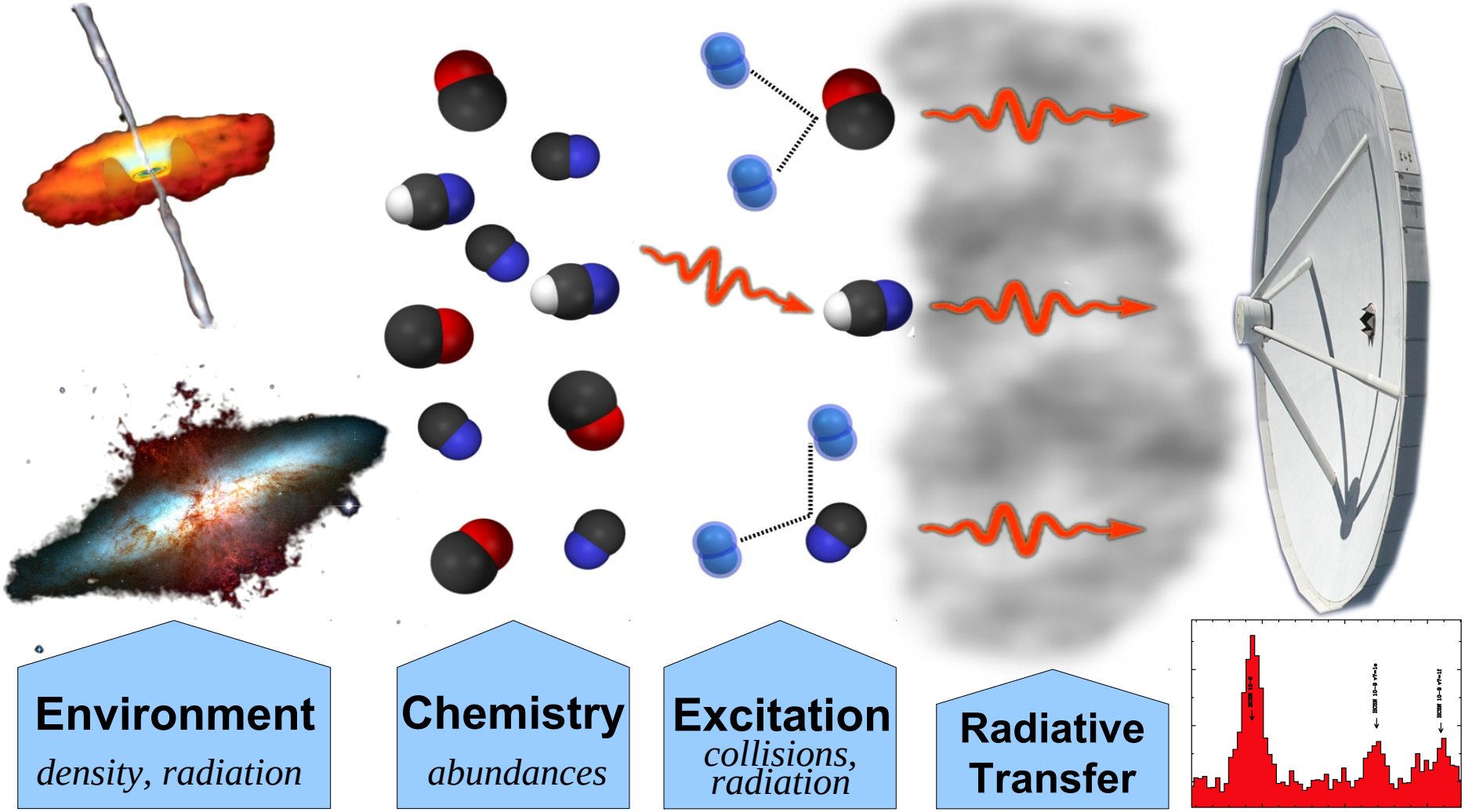


Environment
density, radiation

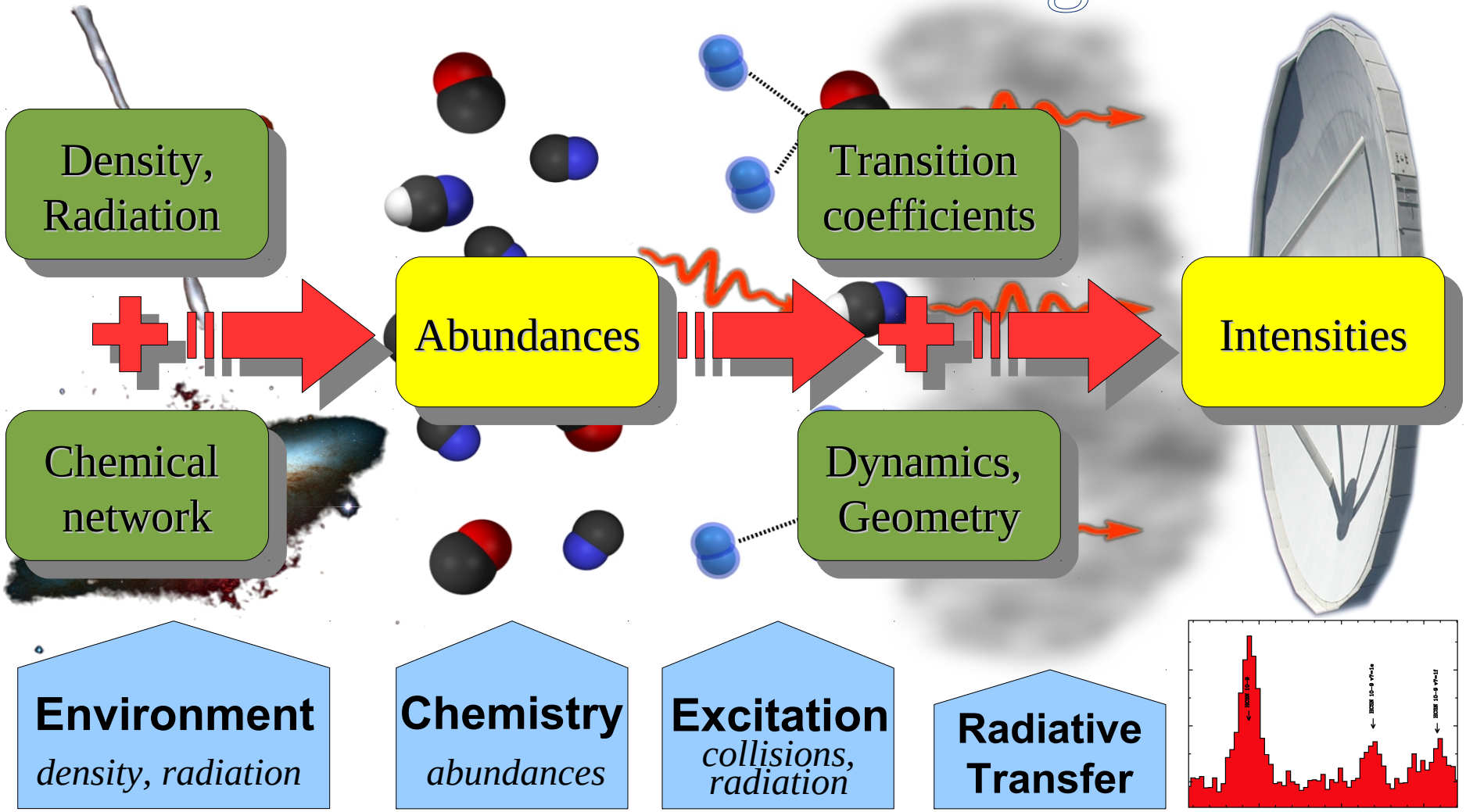
Chemistry
abundances

Excitation
collisions, radiation

Molecules as Tools



Chemical Modeling



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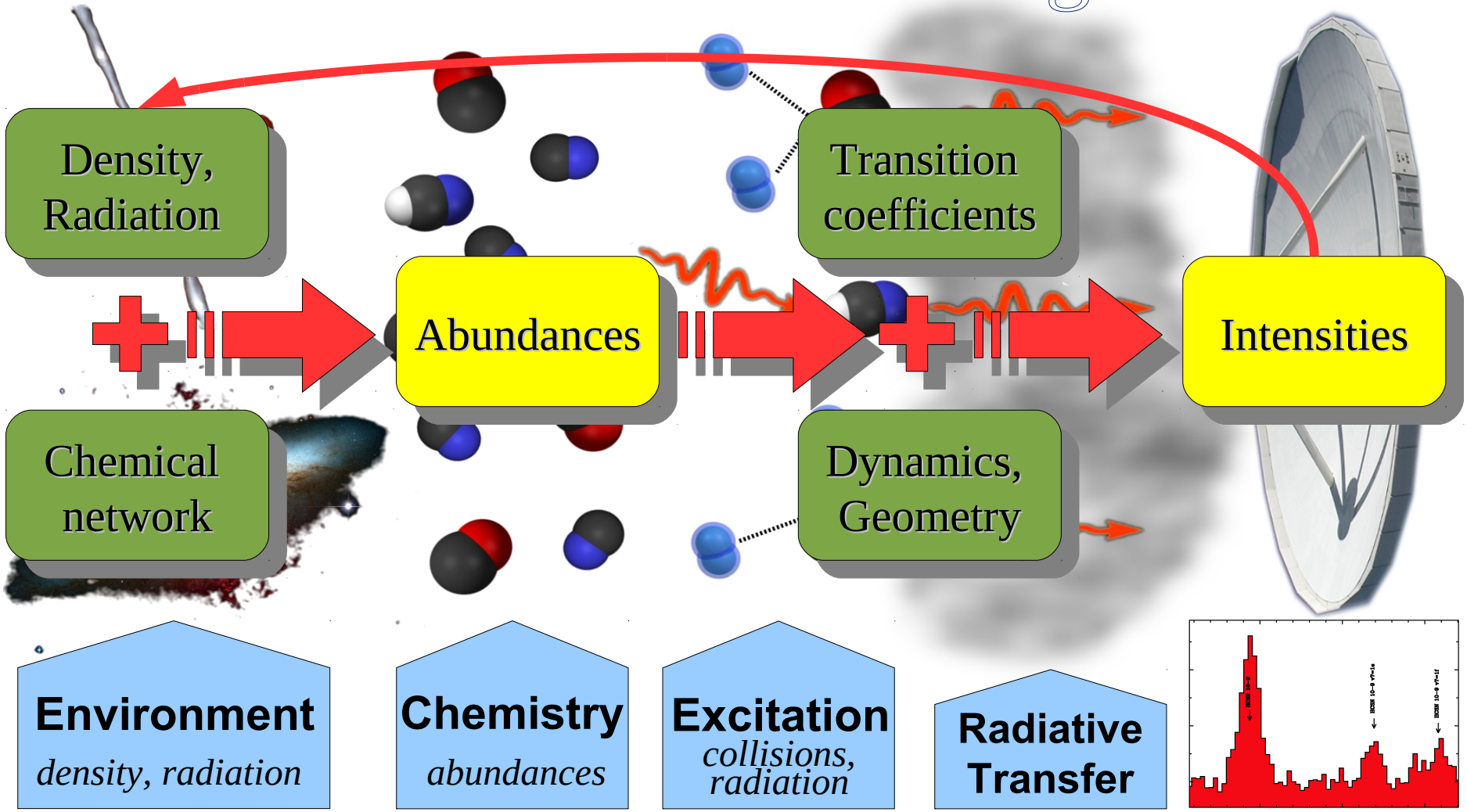
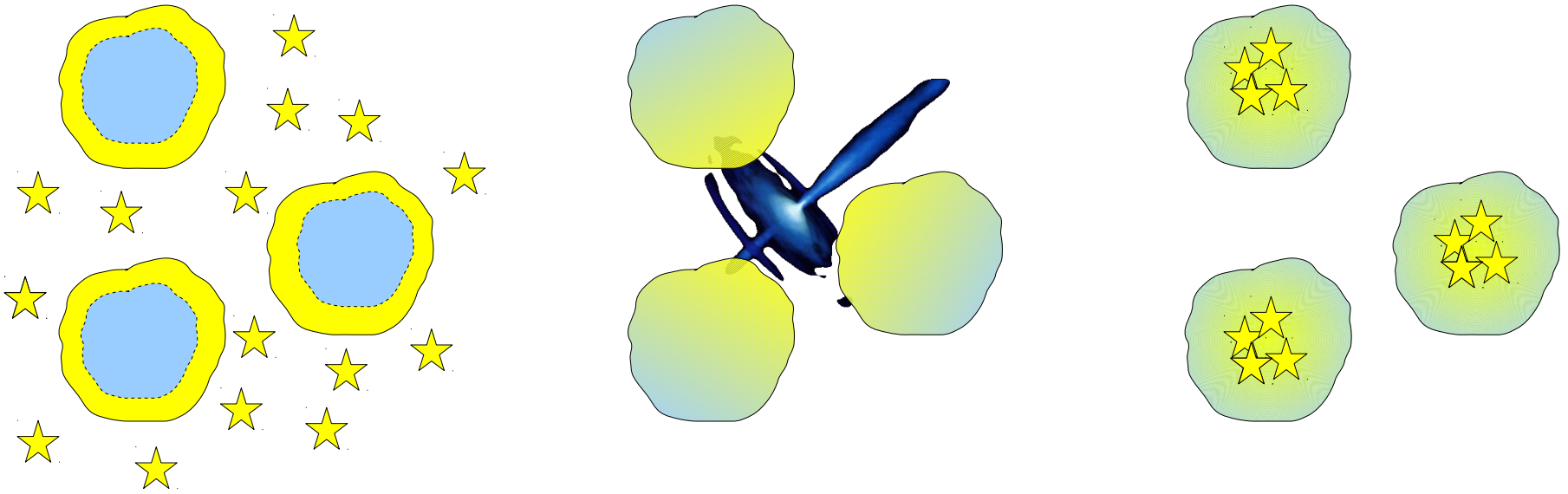


PDRs, XDRs and Hot cores



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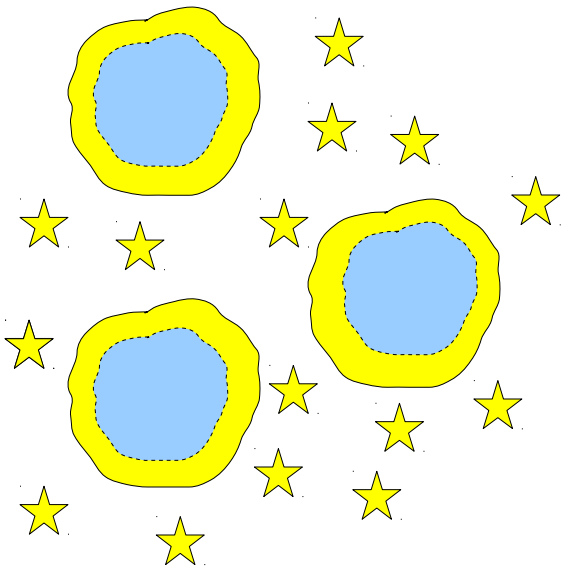
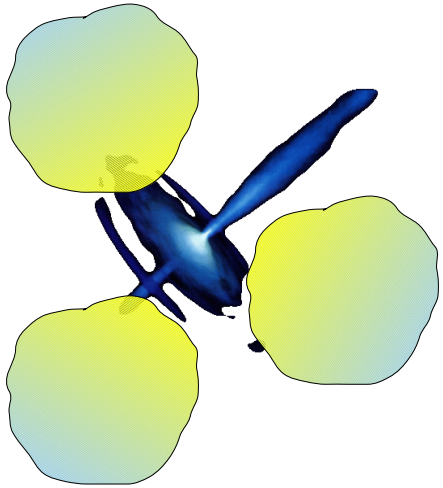


- Dominated by FUV from massive stars
- Layered Structure:
  $C^+ \rightarrow C \rightarrow CO$
  $H \rightarrow H_2$
- Mainly on cloud surfaces
- Photoelectric heating
- $T \sim 1000$ K , $n \sim 10^5$ cm^{-3}
- Ion-molecule reactions

Tielens & Hollenbach (1985), Meijerink & Spaans (2005)

PDRs, **XDR**s and Hot cores

- Dominated by X-rays from accreting BH
- High ionization C, CO and C^+ coexist
- X-rays penetrate deep in the cloud volume ($N<10^{24}$ cm^{-2})

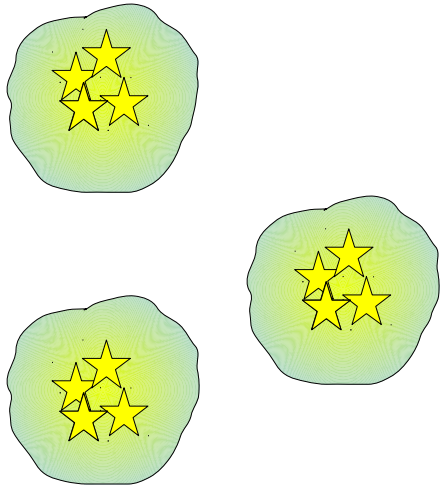


- Photoionization heating
- $T\sim500$ K , $n\sim10^5$ cm^{-3}
- Ion-molecule reactions

Maloney et al. (1996), Meijerink & Spaans (2005)

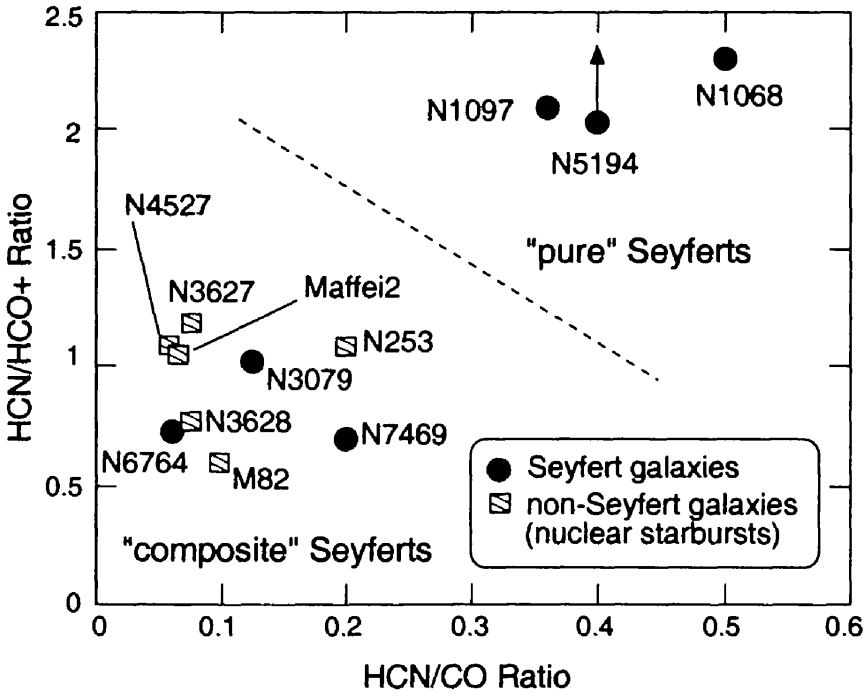
PDRs, XDRs and **Hot cores**

- Dense, warm regions around young stars
- T~300 K, n>10^6 cm^{-3}
- Evaporation of molecules from grain surfaces
- Shielded from UV radiation (A_v>100 mag)
- Formation of large organic molecules



Blake et al. (1987), Bayet et al. (2008)

The HCO^+/HCN ratio



- Kohno et al. (2001):
  HCO^+/HCN ↑ in Starburst
  ↓ in AGN
- Lepp & Dalgarno (1996):
  HCN ↑ in XDRs
- Meijerink et al. (2007)
  HCO^+ ↑ in XDRs

⇒ HCO^+/HCN is an XDR tracer at $n>10^5$ cm^{-3}

The HNC/HCN ratio

- Main formation: $\mathrm{HCNH^+} + e^- \rightarrow \begin{cases} \mathrm{HCN + H} & 50\ \% \\ \mathrm{HNC + H} & 50\ \% \end{cases}$

- HNC destroyed by neutral-neutral reactions

  $\mathrm{HNC + H \rightarrow HCN + H}$, T > 30 K (Hirota et al. , 1998)

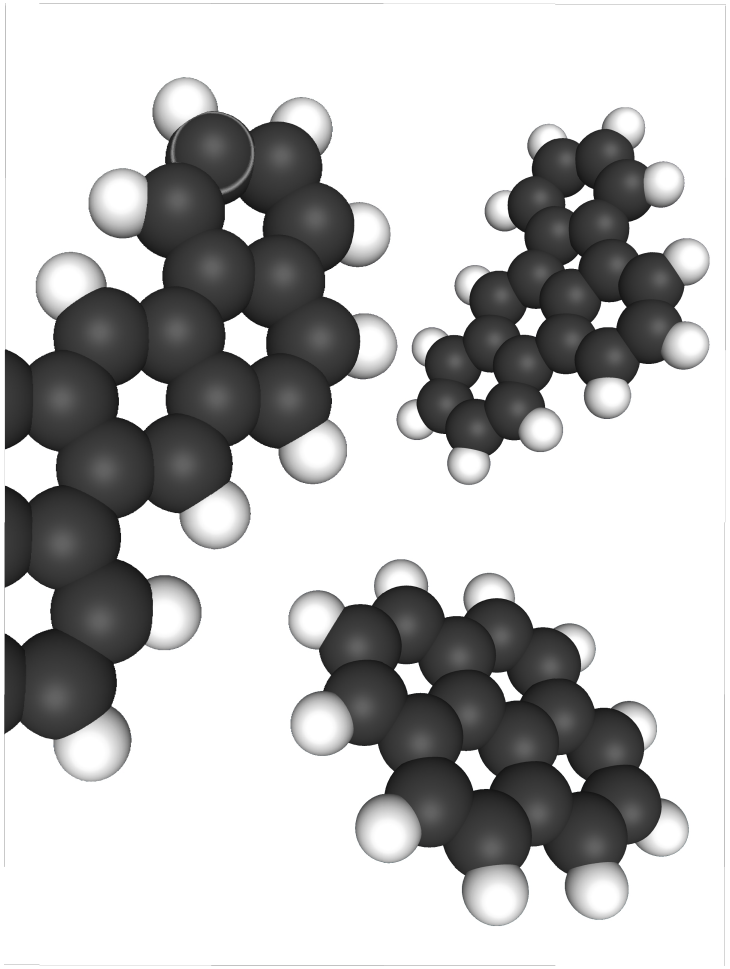
- In the Galaxy: HNC/HCN ↓ as T ↑
- In many extragalactic objects HNC/HCN~1
- Meijerink & Spaans (2005): HNC/HCN>1 in XDRs

  HNC=HCN in PDRs

HC_3N

- Usually observed in Galactic hot cores (e.g. , Rodriguez-Franco, 1998)
- Easily destroyed by UV radiation and reactions with C^+ and He^+ (e.g. , Turner et al. 1998)
- Important formation routes:
  - Evaporation from grain mantles
  - $C_2H_2 + CN \rightarrow HC_3N + H$ for T>100 K
- Strongly connected with IR field via vibrations (Wyrowski et al., 1999, Paper I)

Polycyclic Aromatic Hydrocarbons (PAH)



- First observed as unidentified emission bands (3.3-11.2 μm)
- Planar molecules containing ~50 carbon atoms
- Excited by UV radiation
- Destroyed by X-rays and hard UV (cannot survive at <1 kpc from AGN)
- Interpreted as tracers of star formation (e.g. , Genzel et al. , 1998)

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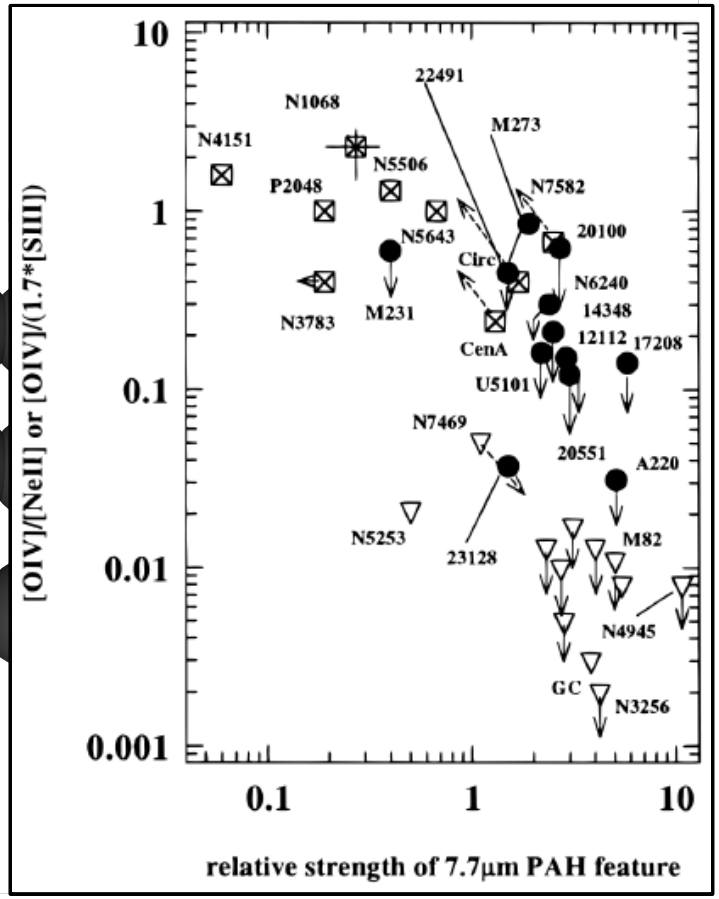

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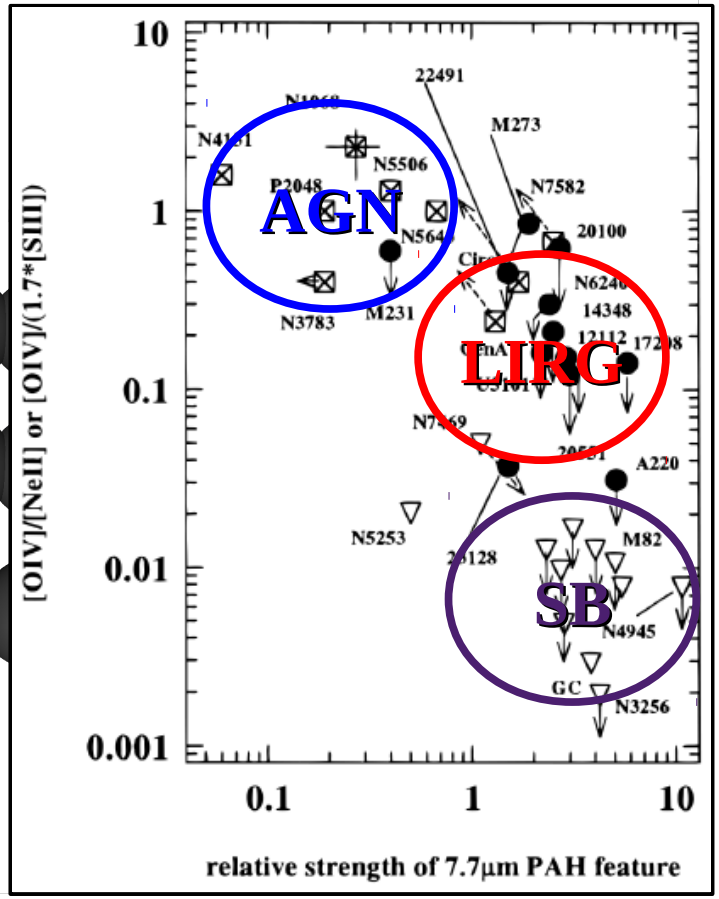

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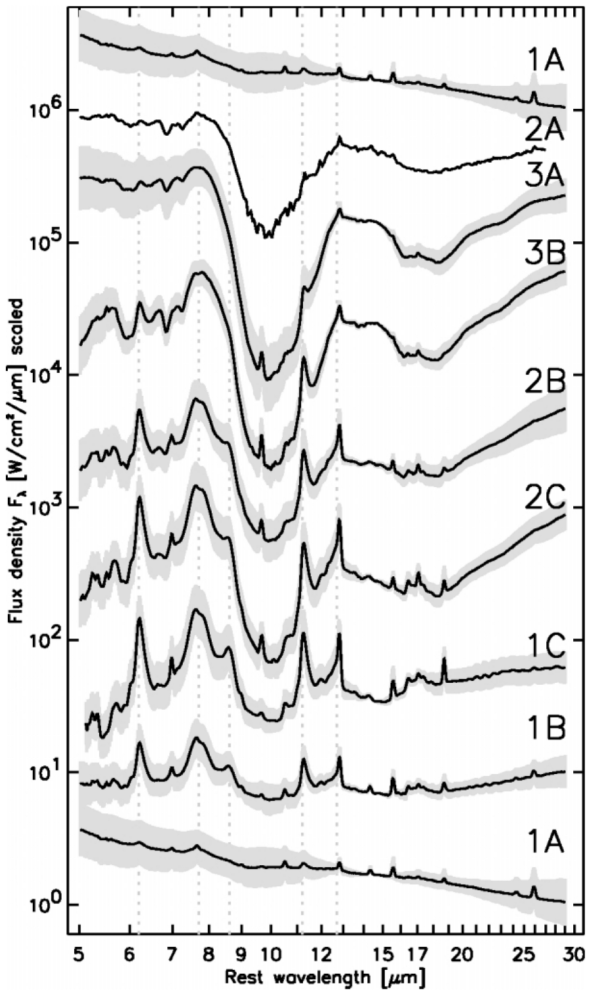
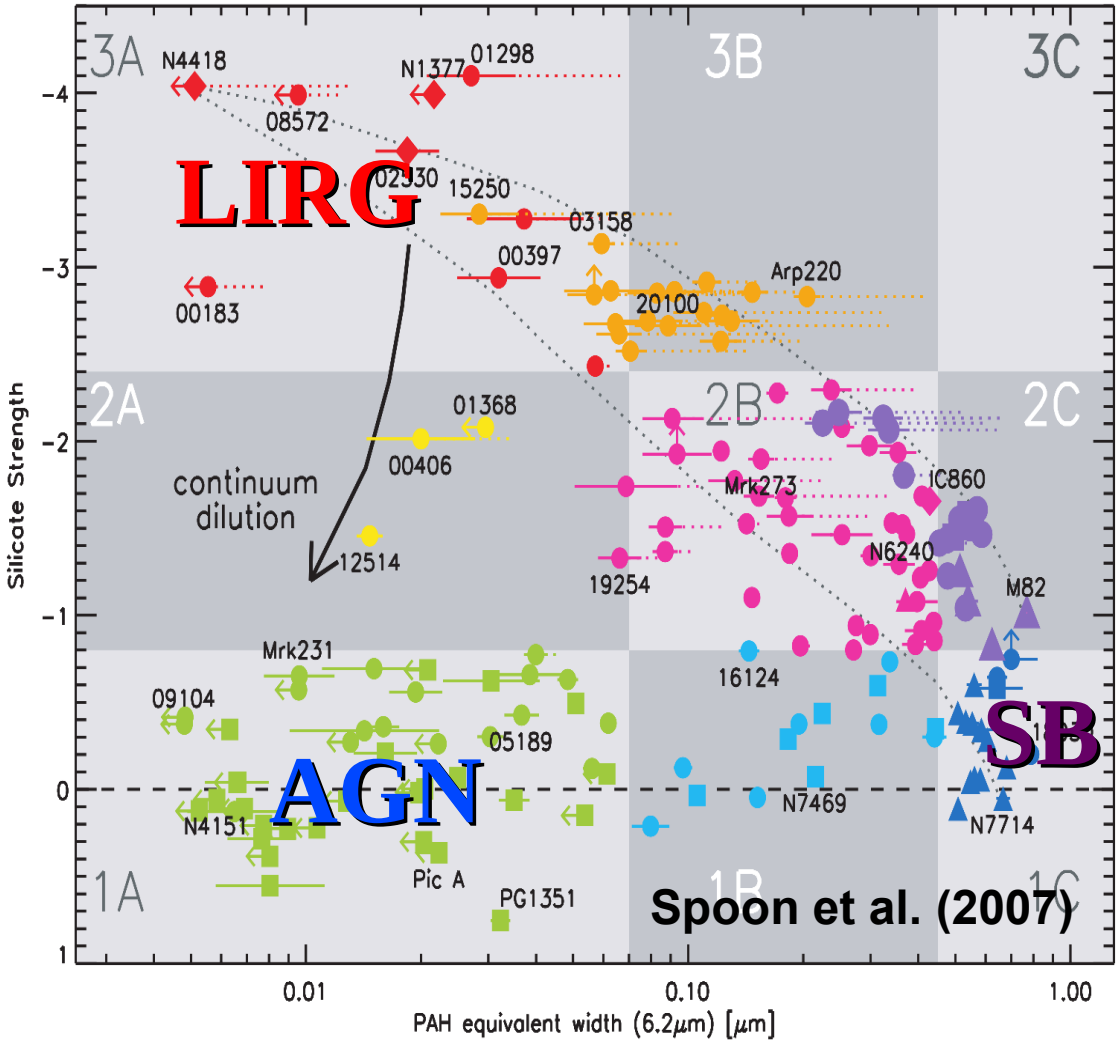
PAH vs Silicate Diagnostics





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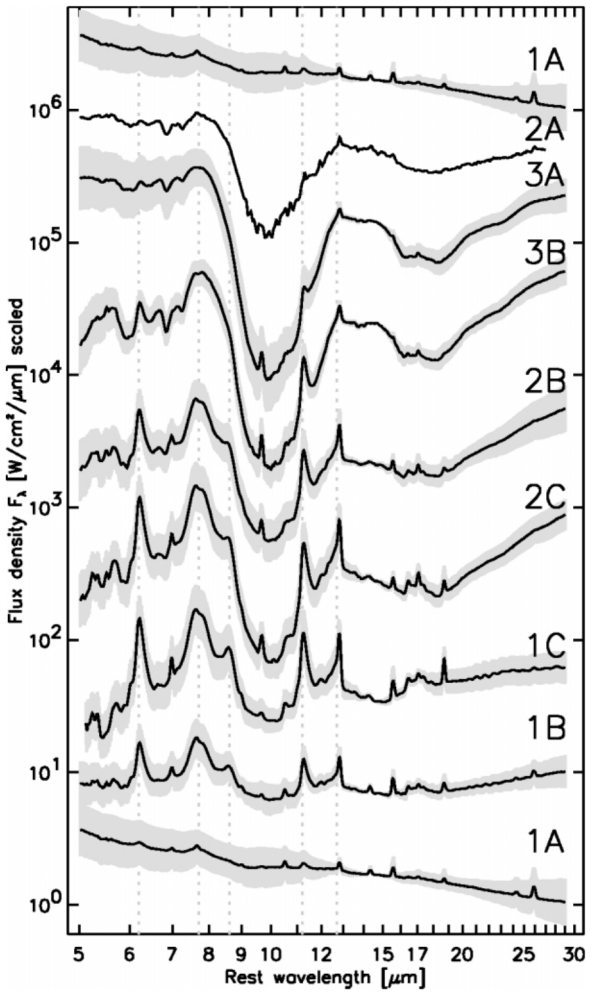
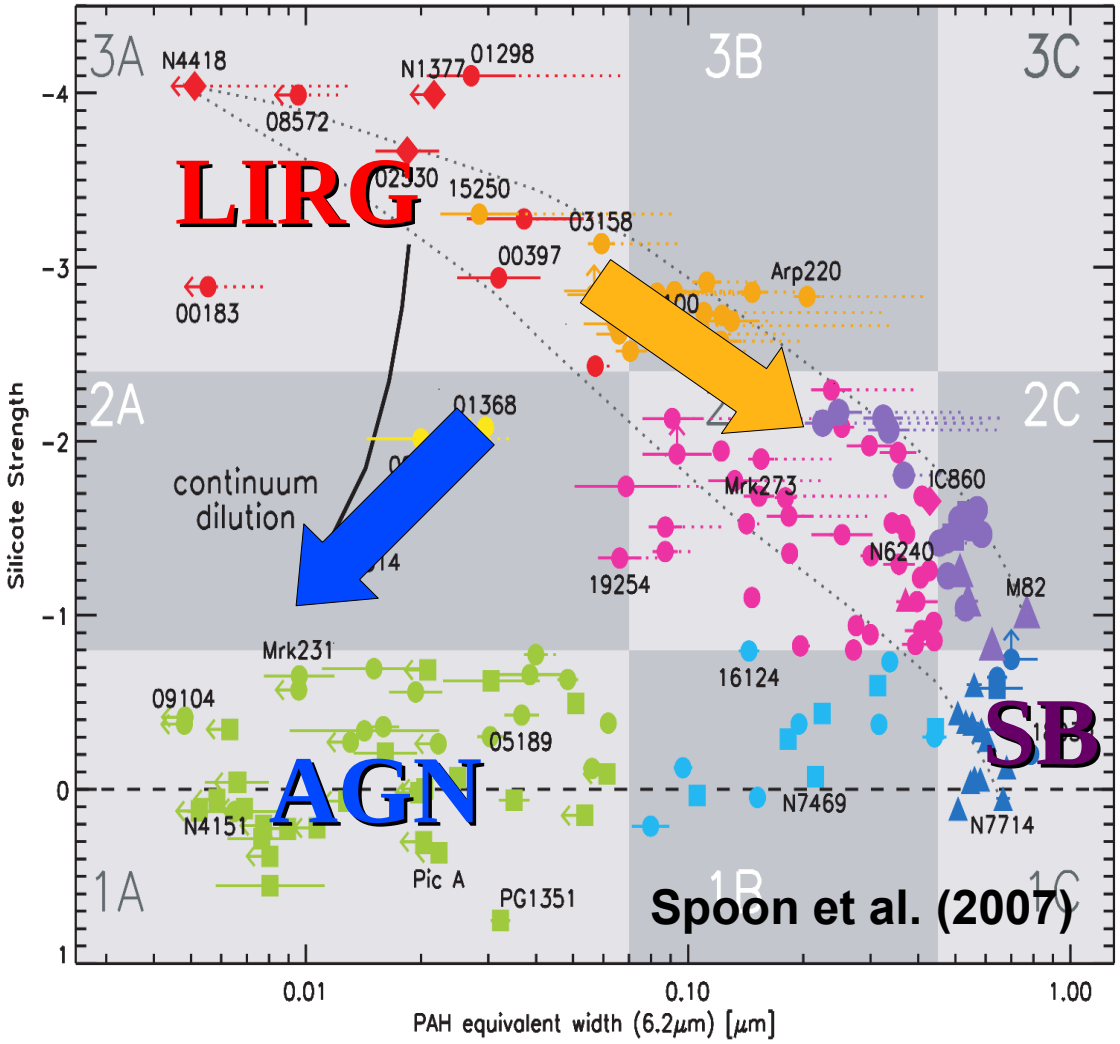




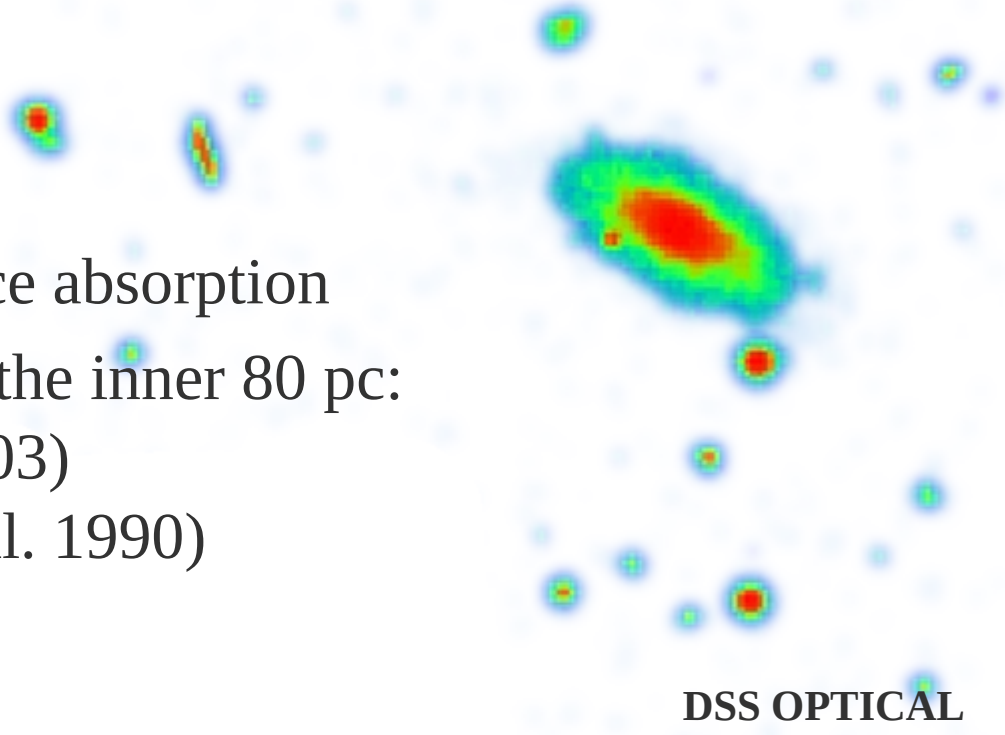
Example I

“Vibrationally excited HC_3N in NGC 4418”

F. Costagliola, S. Aalto, *A&A*, *2010*

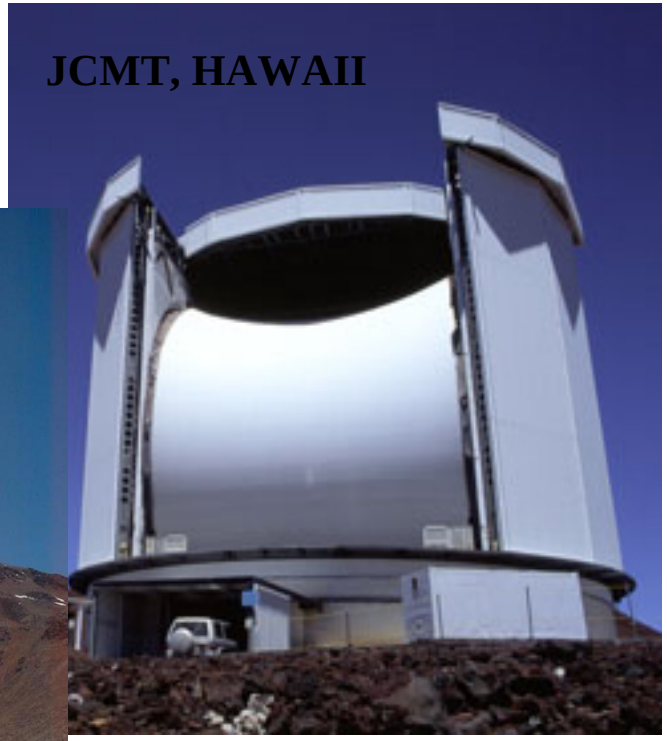
The LIRG NGC4418

- Edge-on, Sa-type
- $L_{IR} = 10^{11} L_{\odot}$
- Deep mid-IR silicate and ice absorption
- Energy source confined in the inner 80 pc:
  85 K dust (Evans et al., 2003)
  6 cm continuum (Eales et al. 1990)
- Synchrotron-deficient
  (Nascent Starburst?)
- No 6.2 μm PAH emission
- Bright HC_3N 10-9 (Aalto et al., 2007)

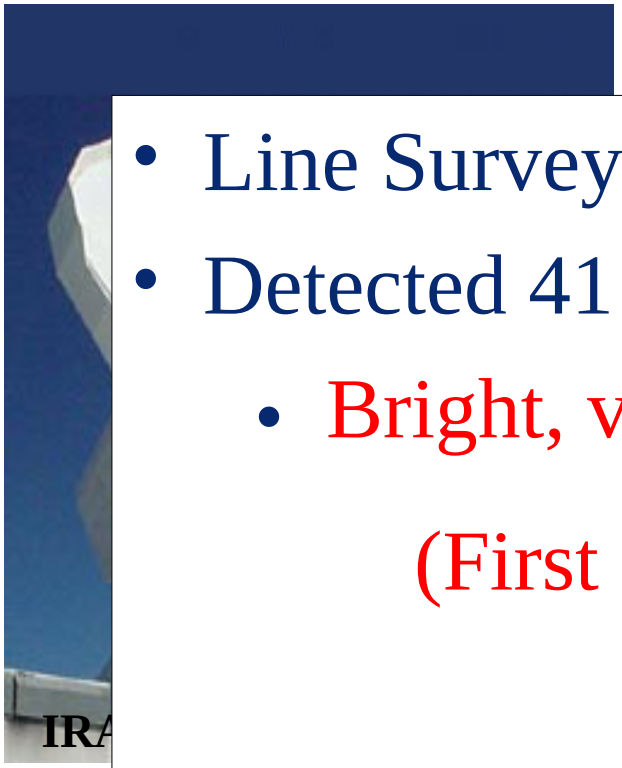


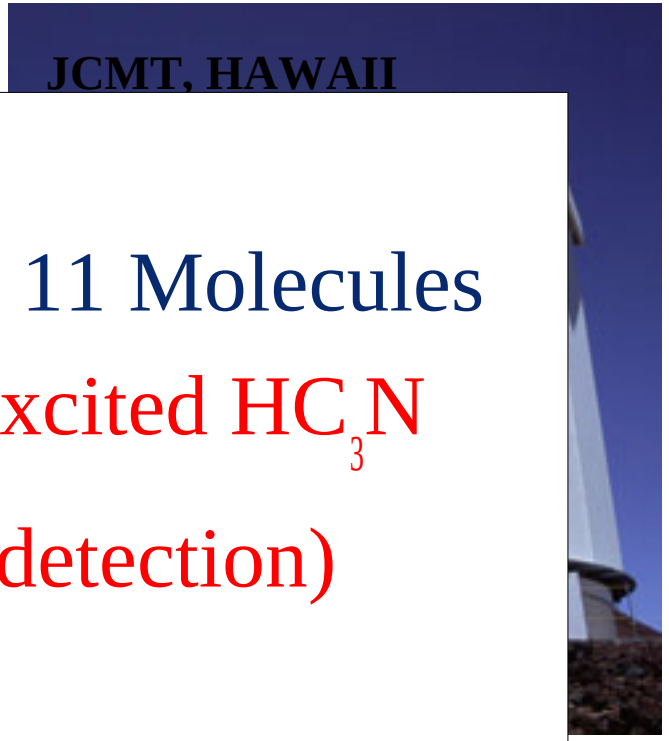
DSS OPTICAL

Observations: 2007-2009



Observations: 2007-2009

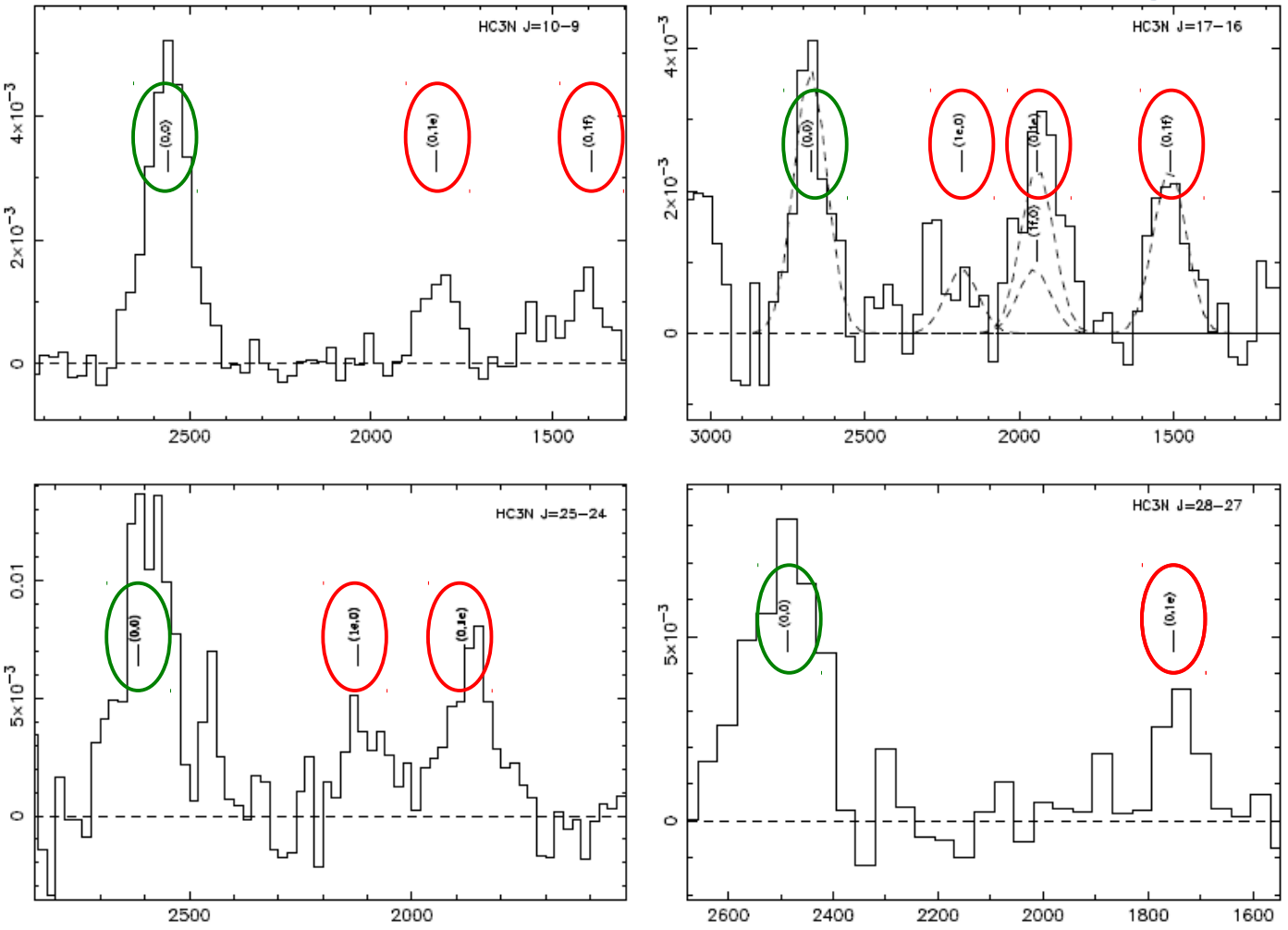




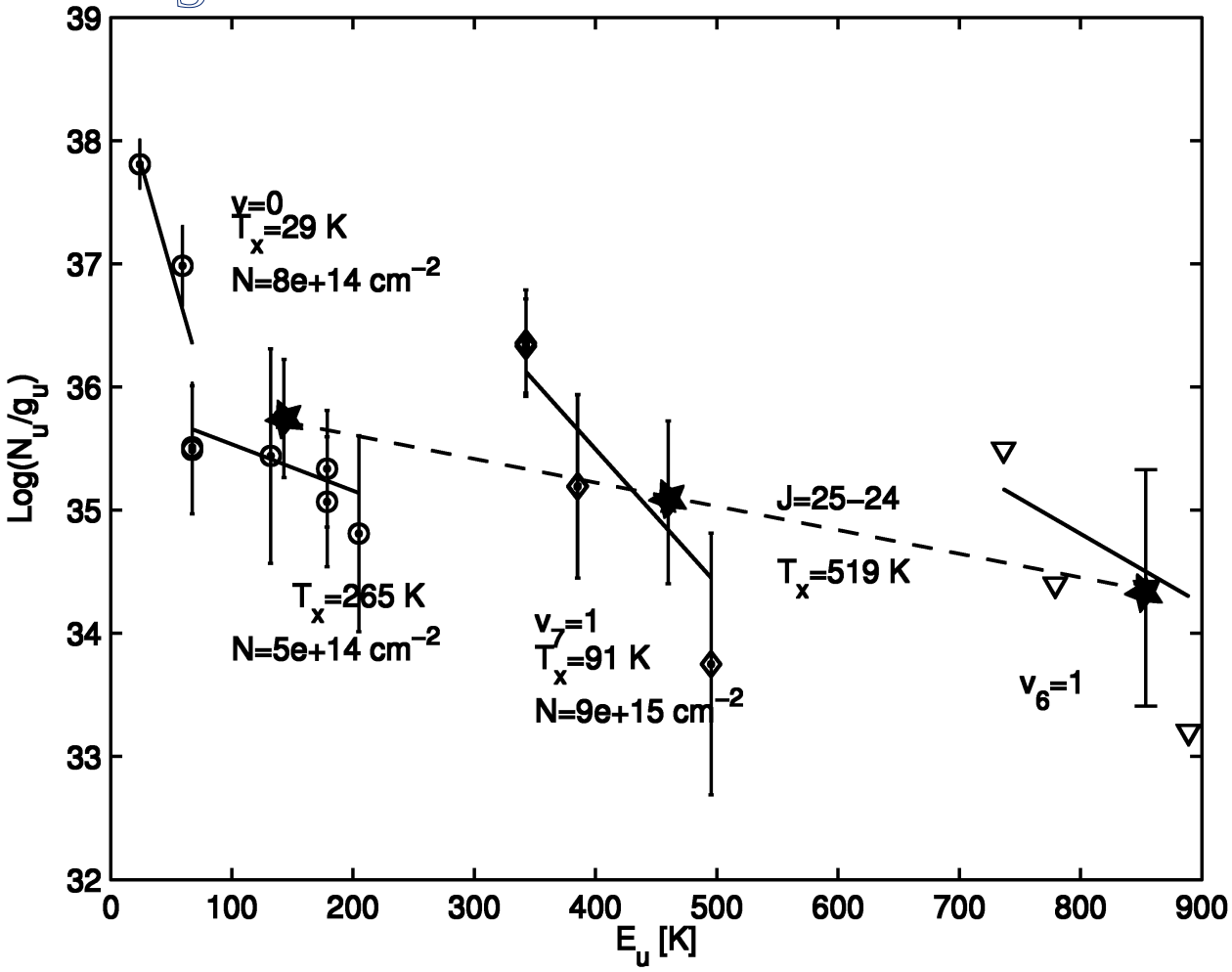
- Line Survey 90-360 GHz
- Detected 41 transitions of 11 Molecules
  - Bright, vibrationally excited HC_3N

(First extragalactic detection)

Vibrationally Excited HC_3N



HC_3N Population Diagram



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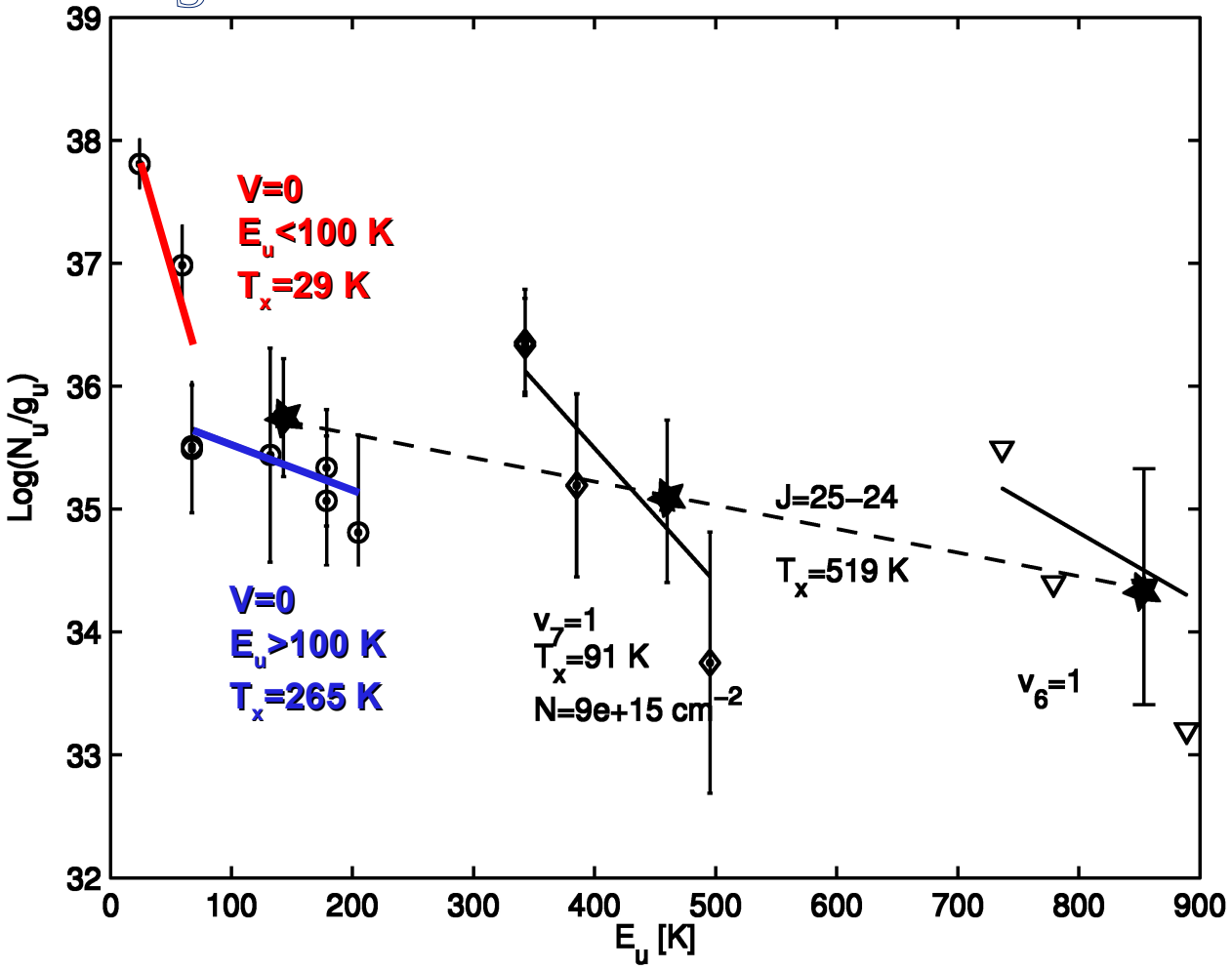

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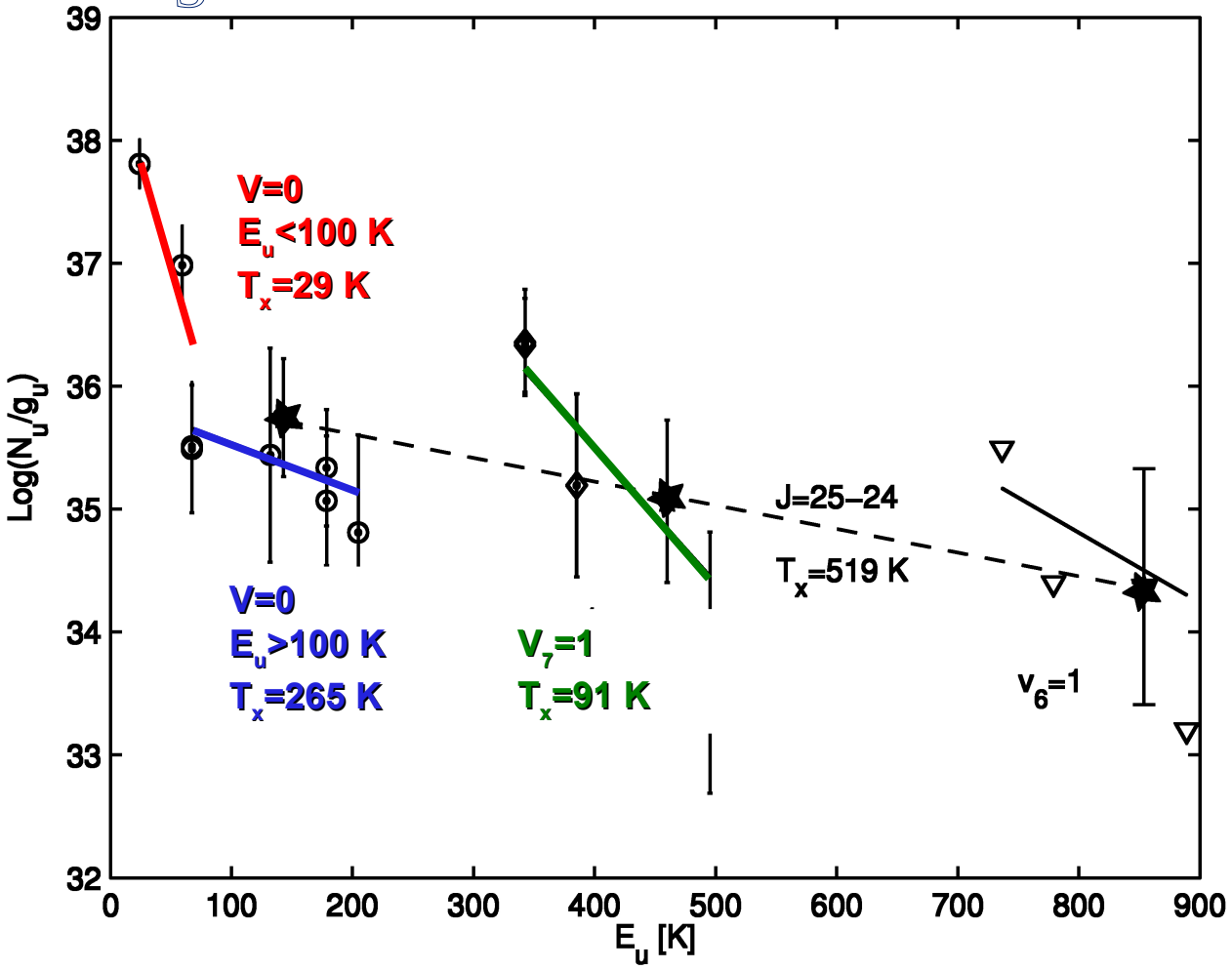

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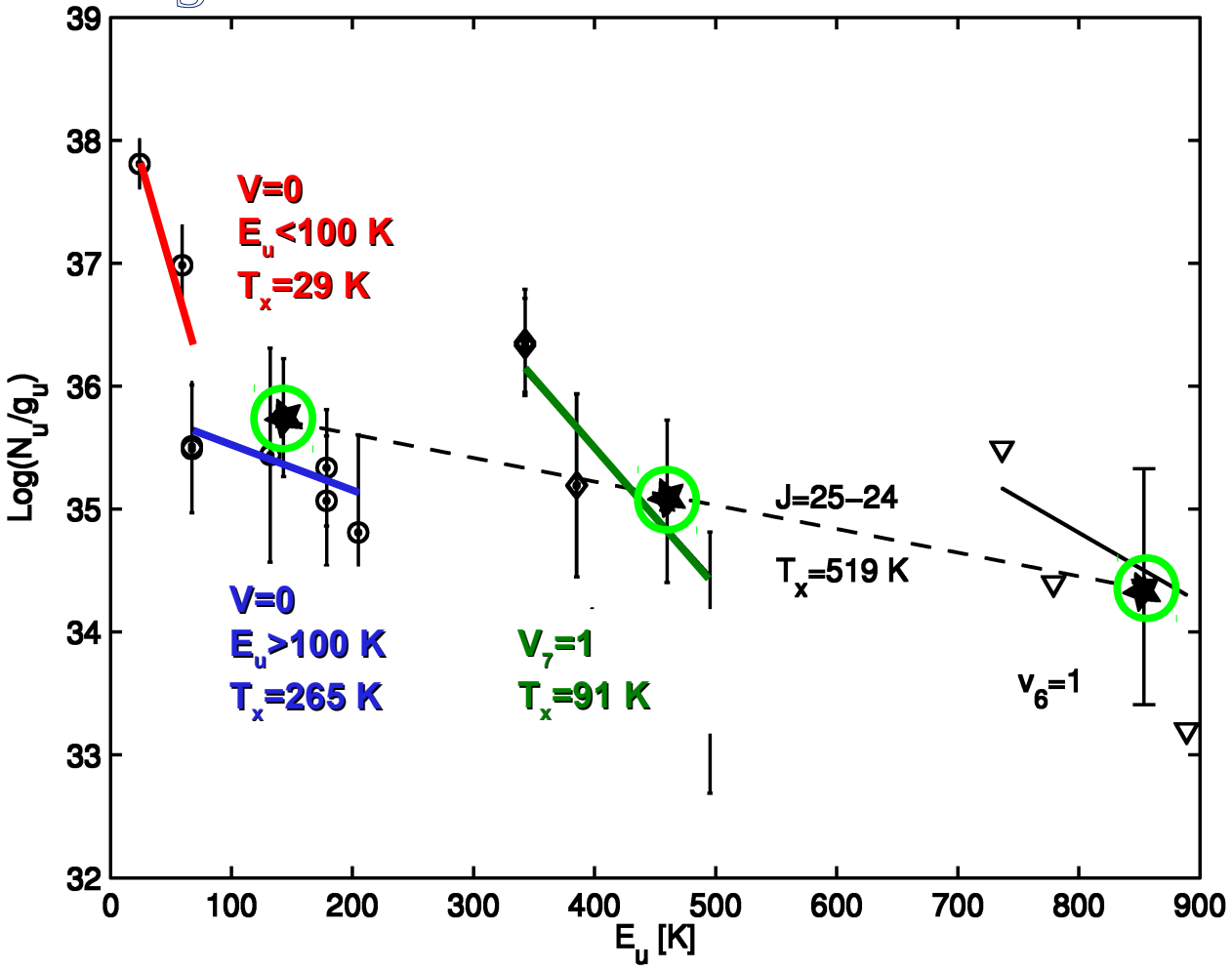

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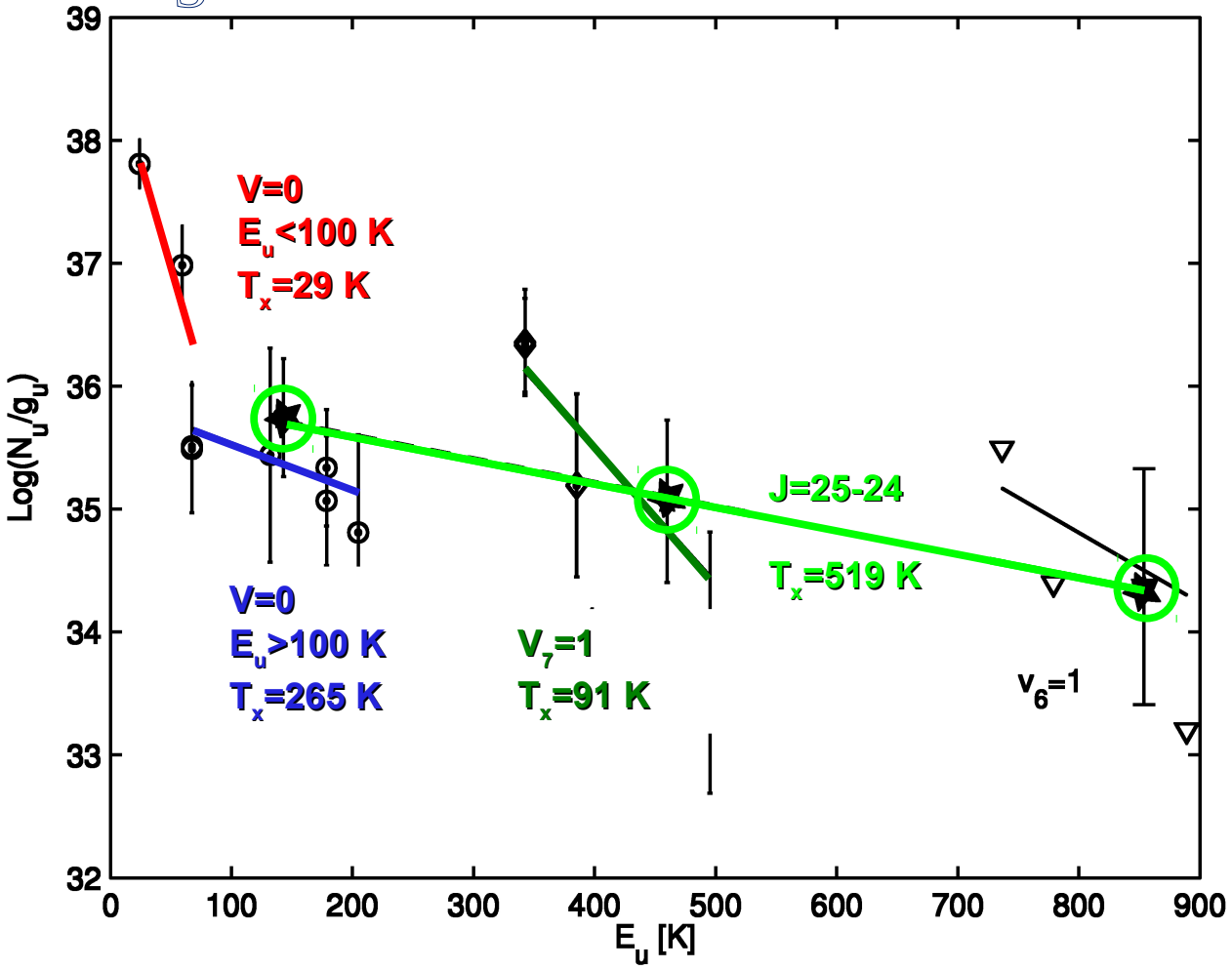


Excitation of HC_3N

Four different temperatures:

- 29 K for the low-J levels (E_u<100 K).

  ⇒ collisions, extended gas ?
- 265 K for the high-J levels (E_u>100 K).

  ⇒ radiation, collisions in a dense phase ?
- 91 K for the rotational transitions between v_7=1 vibrationally excited levels .

  ⇒ dense gas and dust at 85K in inner 0.5" (Evans, 2003)
- 519 K for vibrational transitions of the J=25-24 level.

  ⇒ radiation from embedded source ?

Example II

”Molecules as Tracers of Galactic Evolution: an EMIR Survey ”

F. Costagliola, S. Aalto, M. Rodriguez

and the EVOLUTION team

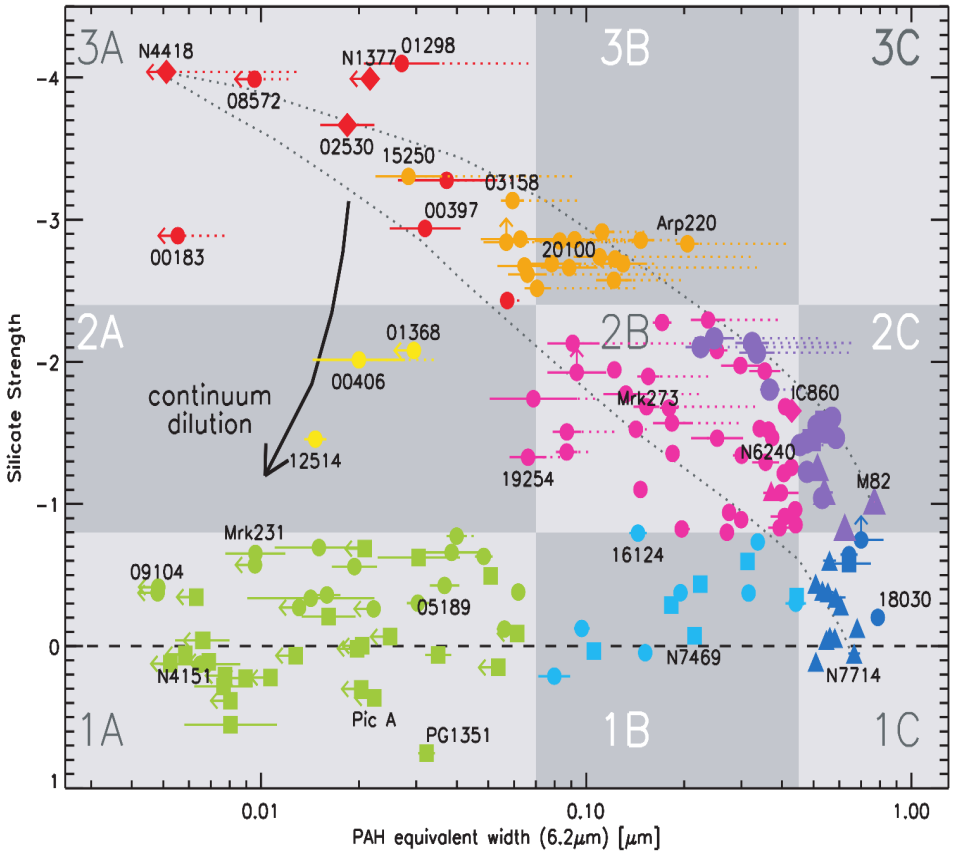
...to be submitted to A&A (soon!)

Motivation of the Study

- Can molecular observations trace galactic evolution?
- Can molecular observations distinguish between Starburst and AGN-dominated objects ?
- How are molecular abundances related to other tracers at different wavelengths?

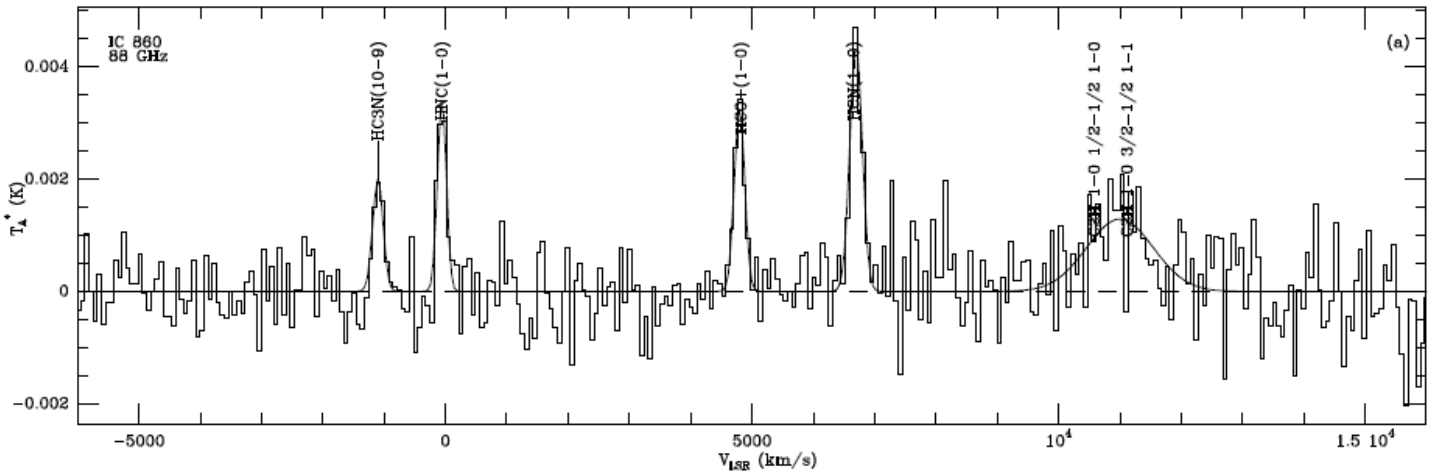
The Sample

- Observed 23 galaxies
- Source selection criteria:
  - Uniform coverage of the classes from Spoon (2007)
  - Uniform representation of different galaxy types
- Observed bands:
  88 and 112 GHz

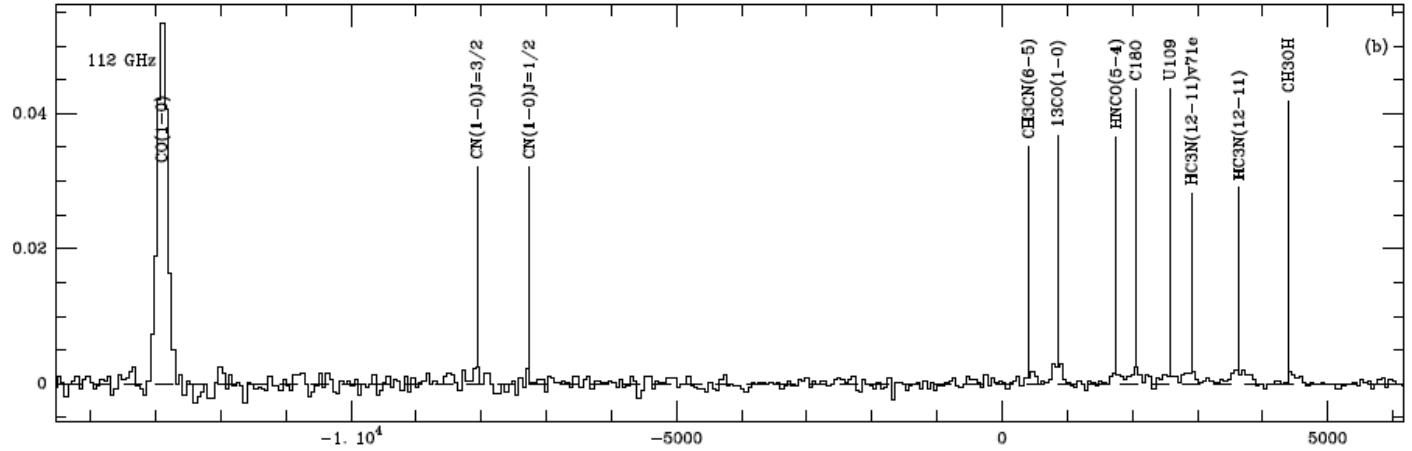


Observed Bands

88 GHz



112 GHz



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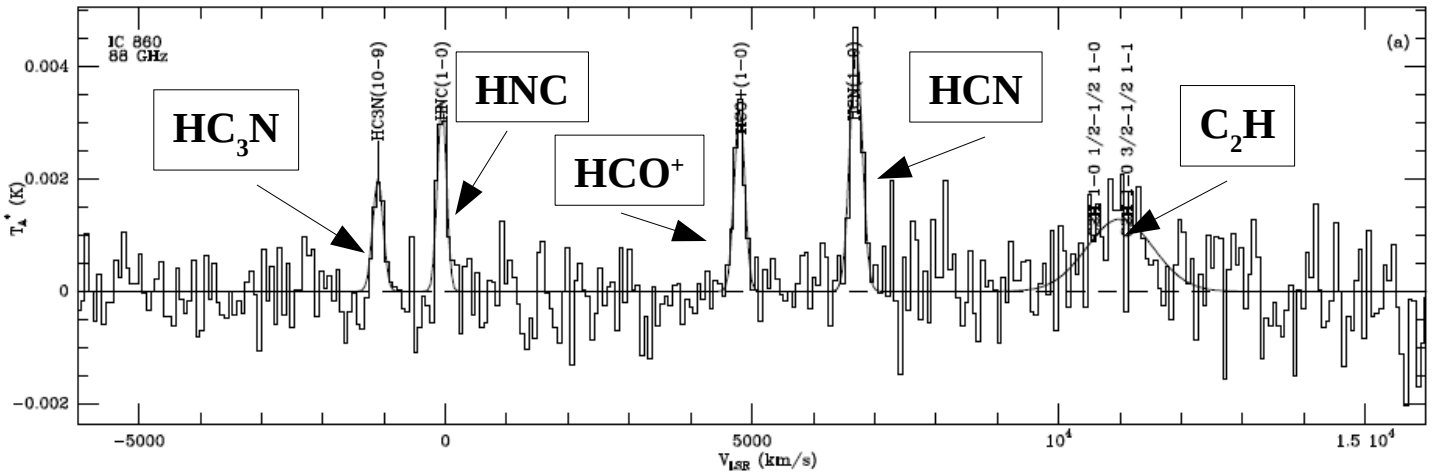

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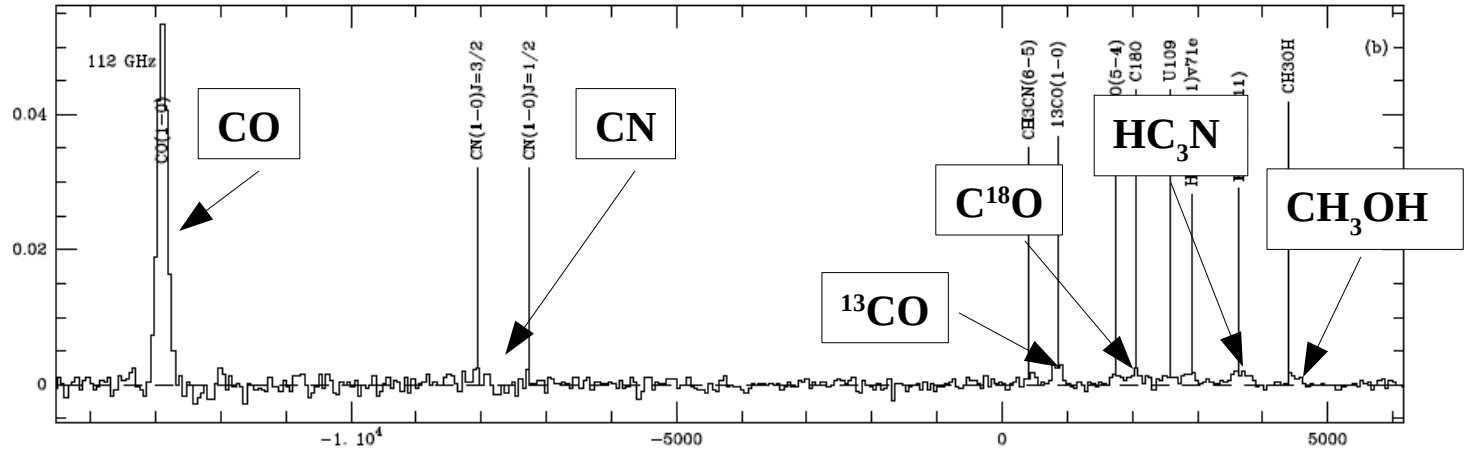
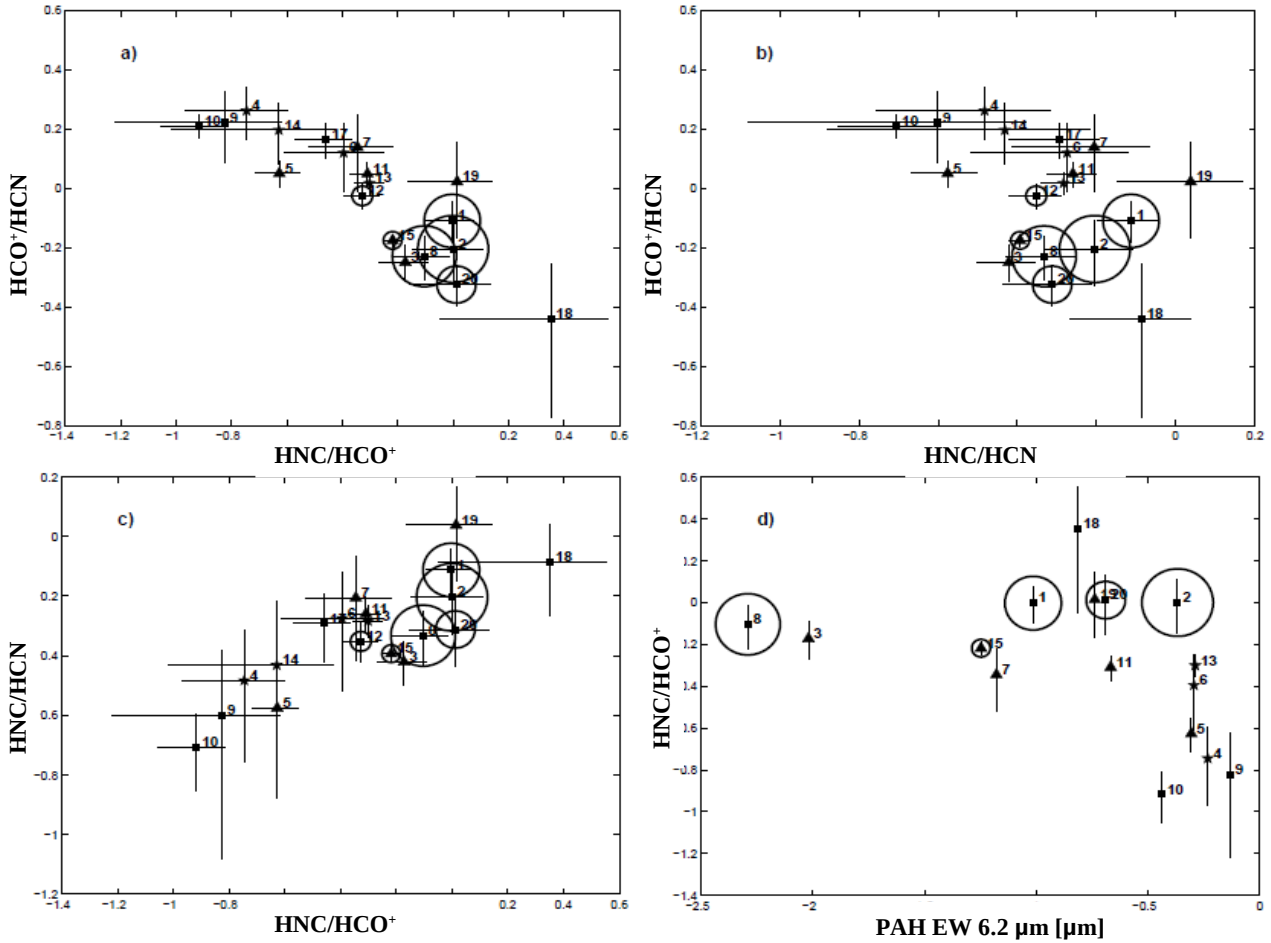
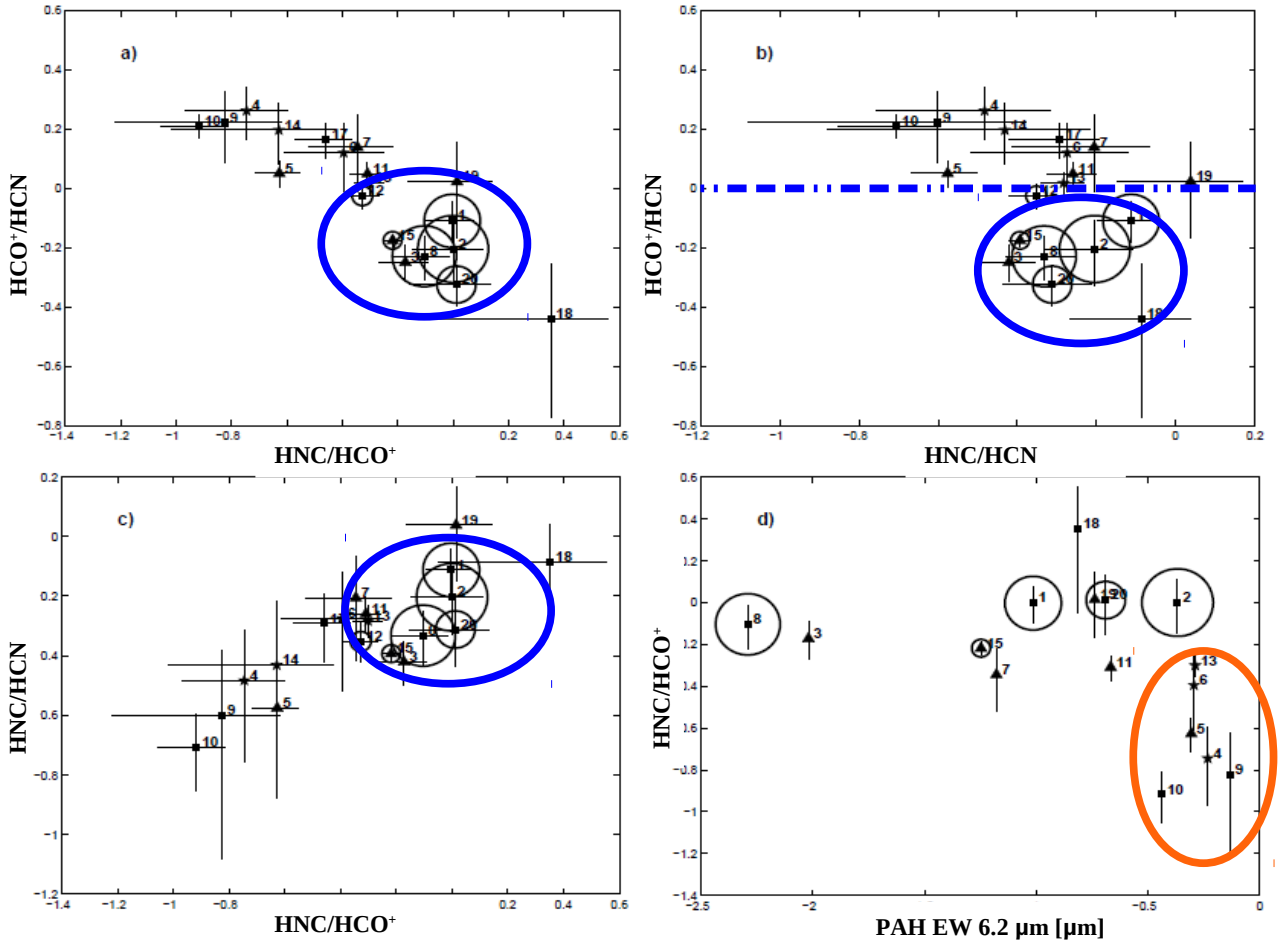


Diagnostic Diagrams



Stars: Starburst; *Triangles:* AGN; *Squares:* LIRG; *Circles:* HC_3N

Diagnostic Diagrams



Starbursts : faint HNC and bright HCO^+

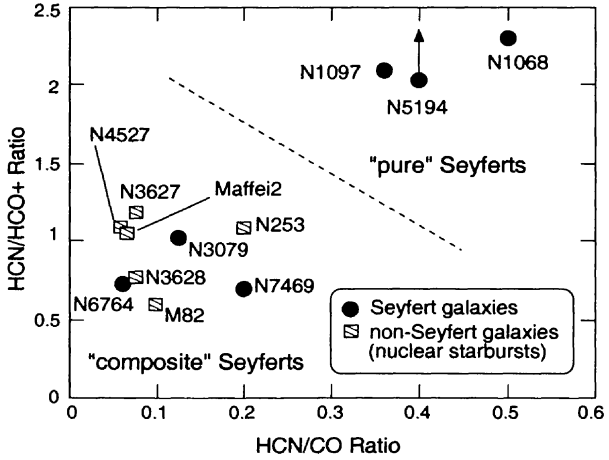
LIRG/AGN: bright HNC faint HCO^+

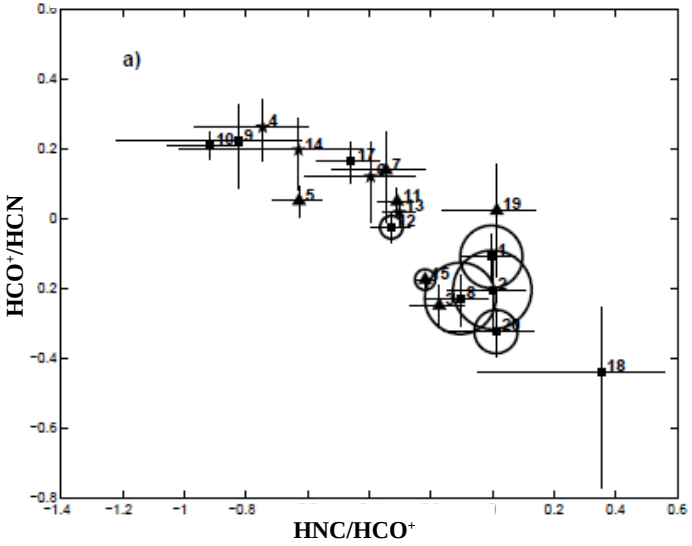
HC_3N detected where $HCO^+/HCN<1$

Low HNC/HCO^+ in Starbursts with large PAH EW

Stars: Starburst; *Triangles:* AGN; *Squares:* LIRG; *Circles:* HC_3N

Is HCO^+/HCN driven by XDR chemistry ?





- Consistent with obs. by Kohno et al. (2001): HCO^+/HCN ↓ in AGN
- Models by Meijerink et al. (2007): HCO^+/HCN ↓ in dense PDRs
- HC_3N detected in galaxies with AGN- like HCO^+/HCN

  ⇒ ***how can HC_3N survive ?***
- Blake et al. (1987) in Orion: HCO^+/HCN ↓ in hot cores
- A density effect ? HCO^+ can be excited at $n<10^5$ cm^{-3}

  ⇒ ***different volume filling ?***

Current Projects

- The rich chemistry of NGC 4418:

  Chemical and NLTE modeling of molecular emission observed in the LIRG NGC 4418

- Extragalactic H_3O^+

  NLTE modeling of JCMT observations of H_3O^+ in different galaxy types

Future Directions

- Interferometric observations to resolve spatial distribution of chemical tracers (e.g. HC_3N in AGN) ⇒ ALMA
- Sub-mm observations of high-J transitions of CO (XDR tracers) ⇒ Herschel
- More sensitive instruments to detect less abundant chemical tracers (e.g. , CH_3OH) ⇒ ALMA
- Chemical modeling of HC_3N in extreme environments
- Multi-transition studies, to constrain molecular excitation ⇒ 1 mm EMIR observations in the Evolution sample


That's all Folks!

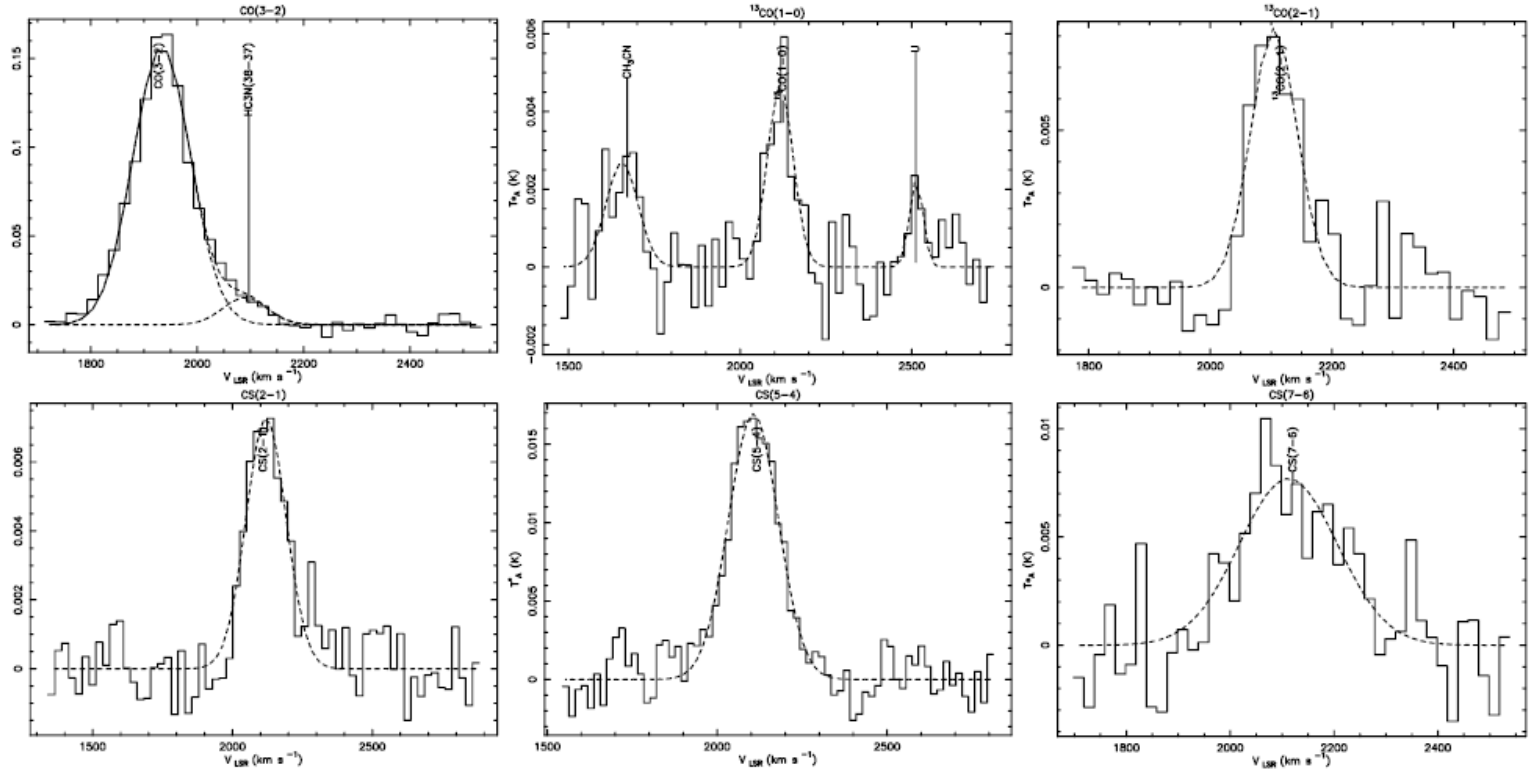
Summary

- LIRGs important to understand star formation history of the Universe, but often power source is unclear (Starburst or AGN?)
- Molecular observations can help to constrain properties of central regions in LIRGs
- Example I: Vibrationally excited HC_3N in NGC 4418
  - High abundance and excitation (~ Galactic hot cores)
  - Possible evidence of a compact source
- Example II: Molecular tracers of galactic evolution
  - HC_3N detections challenge standard interpretation of HCO^+/HCN
  - HNC/HCN<0.5 not reproduced by PDR models (mech. heating??)
- More observations and modeling needed (new facilities, chem. models)

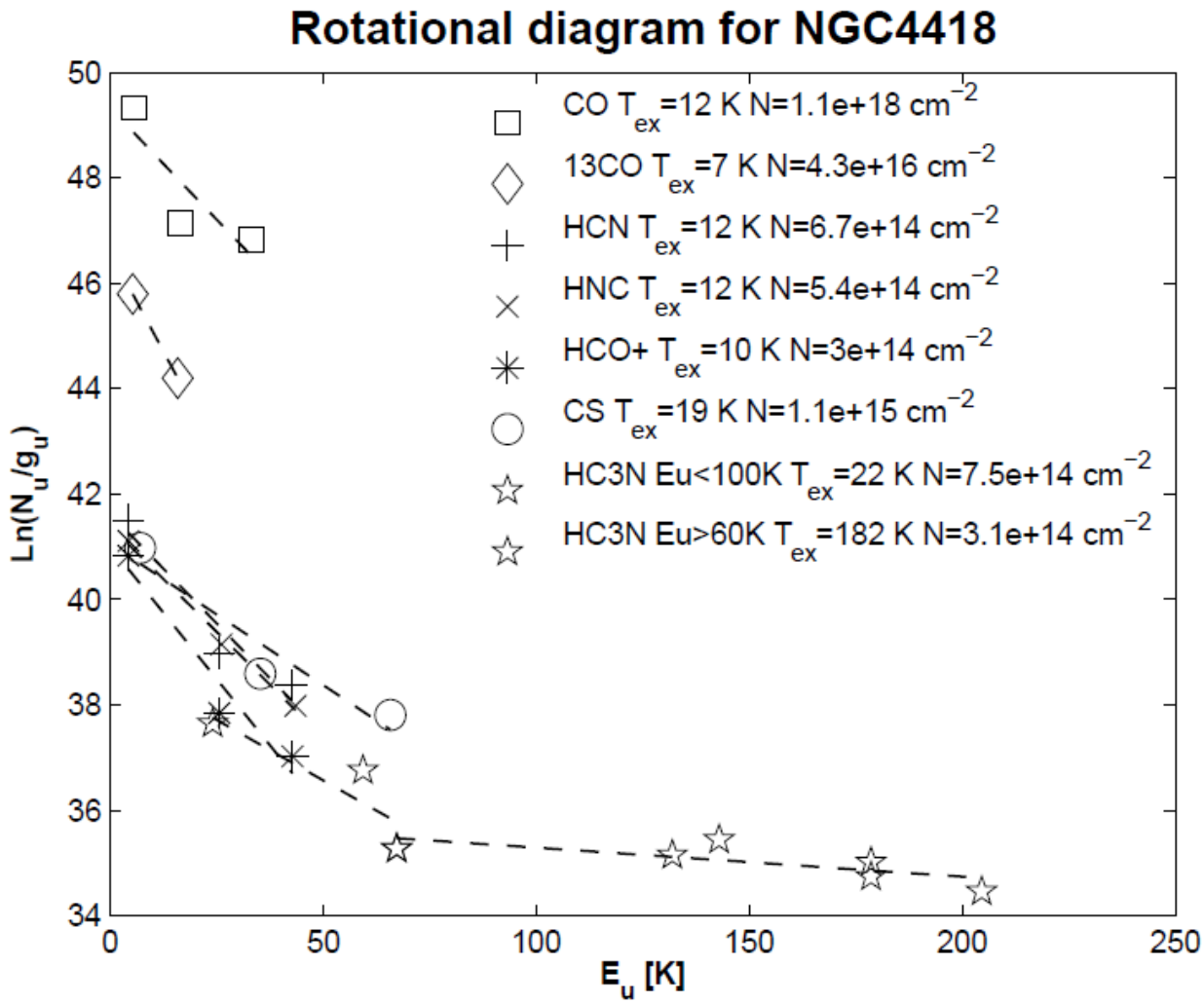
Current Projects

Rich Chemistry in NGC 4418

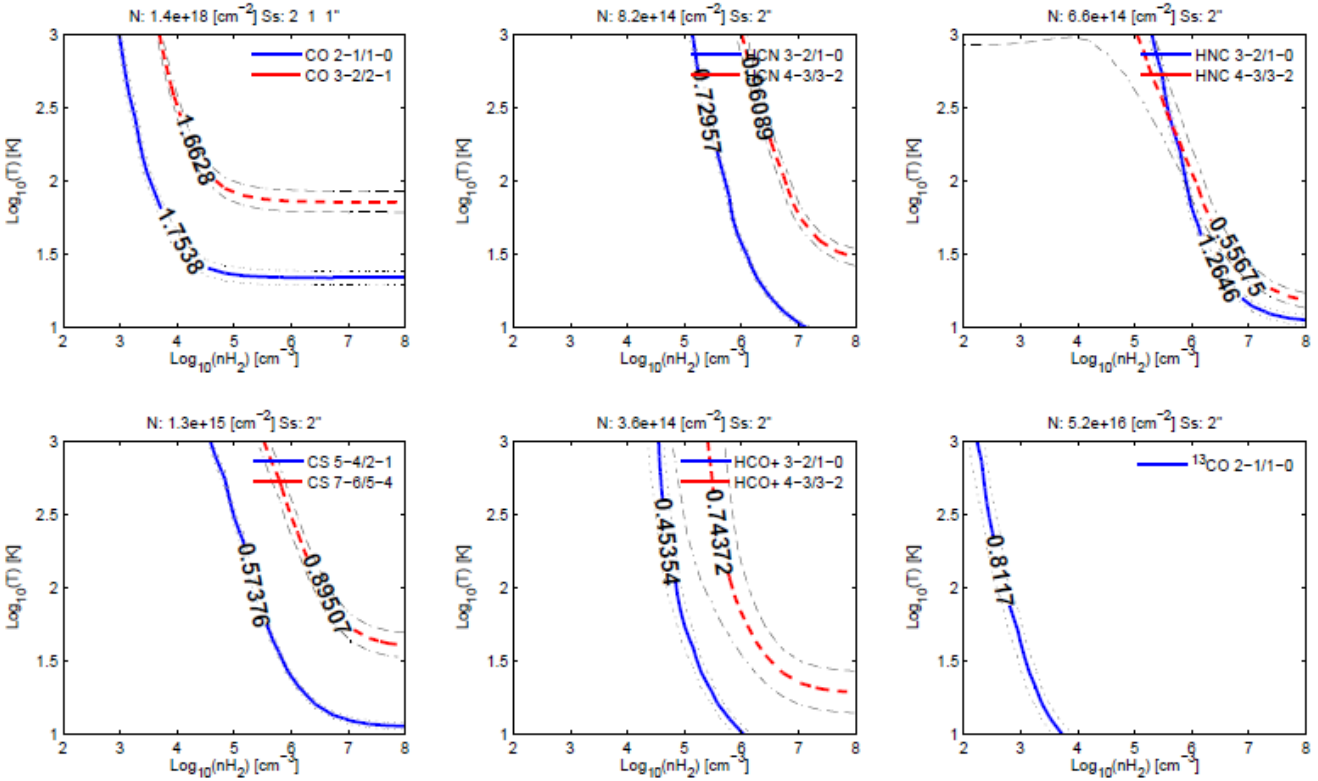
Observed 1 mm, 2 mm and 3 mm transitions of
CO, 13CO, CS, HCN, HNC, HCO+, SiO, H2CO and HC_3N



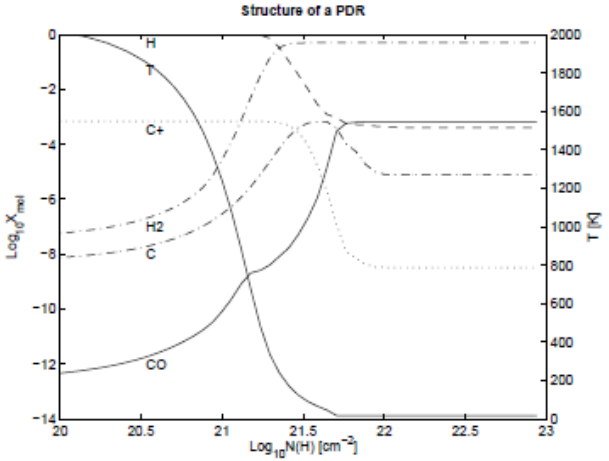
Population diagrams

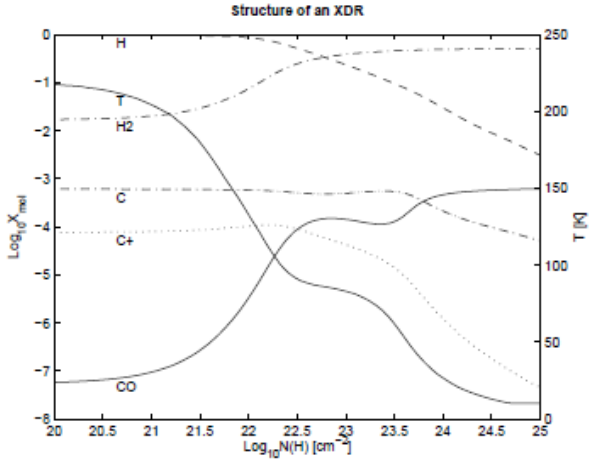


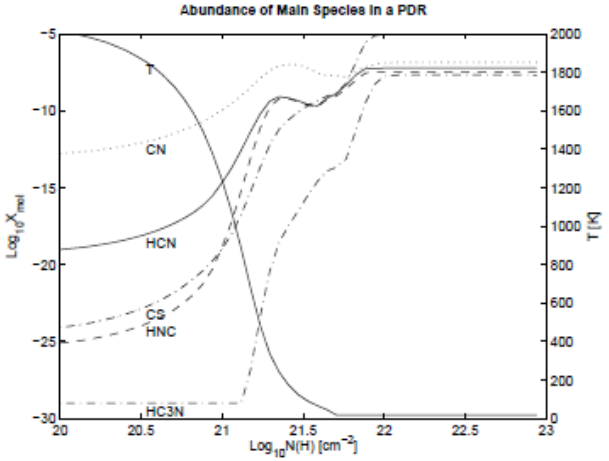
Radiative transfer modeling

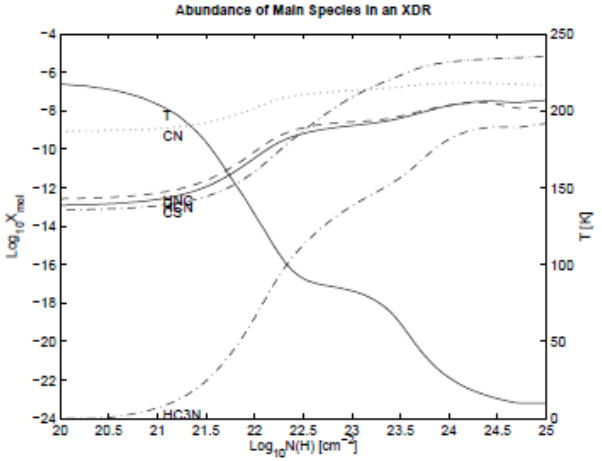


Chemical Modeling



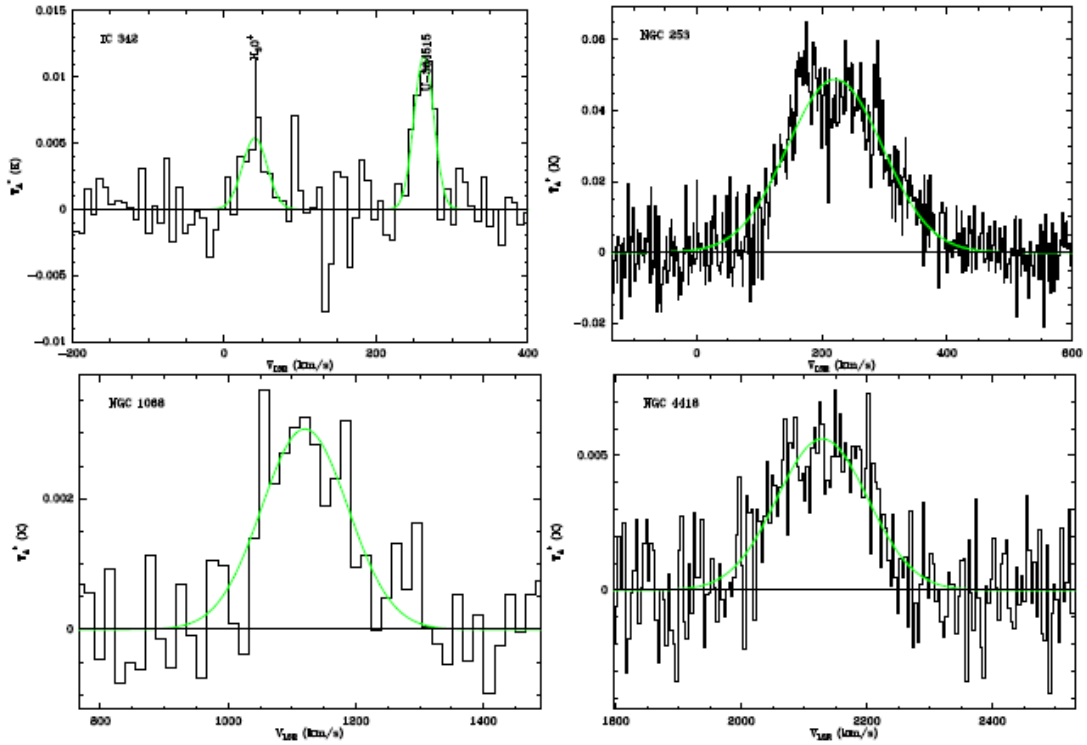


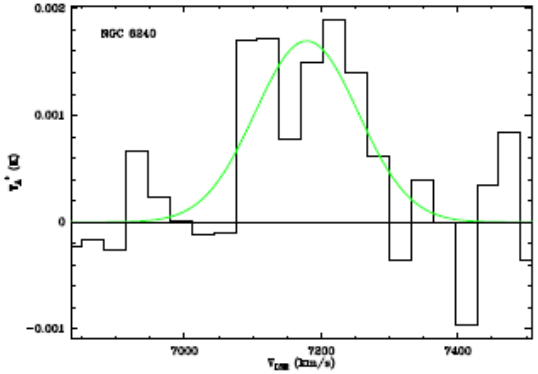




Extragalactic H_3O^+

In February 2008 we detected the $3^+_2 - 2^-_2$ line of H3O+ at 364.797 GHz in IC 342, NGC 1068, NGC 253, NGC 4418, and NGC 6240 with the JCMT telescope.





Radex modeling