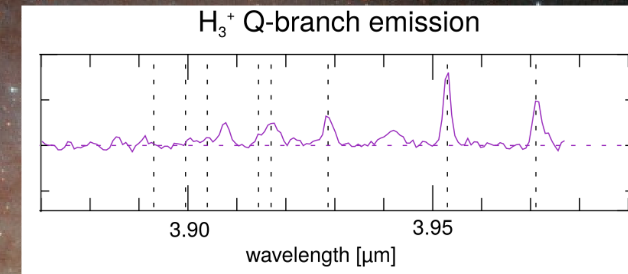
Ionization rate in extreme infrared galaxies using JWST

Miguel Pereira Santaella (IFF)



Cosmic Rays 3
Florence, Oct 2024

PS+24a, A&A 689, L12
PS+24b, A&A 681, A117

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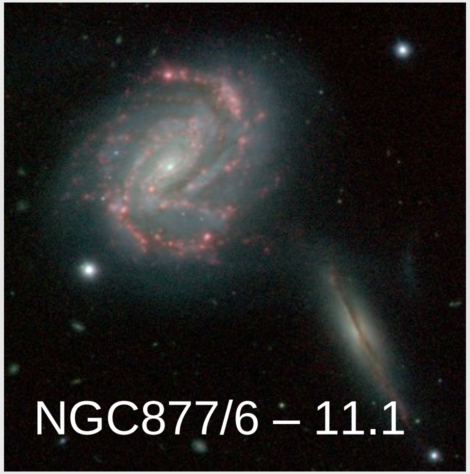
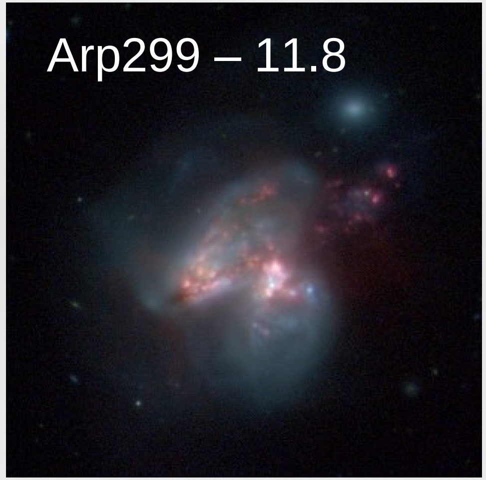
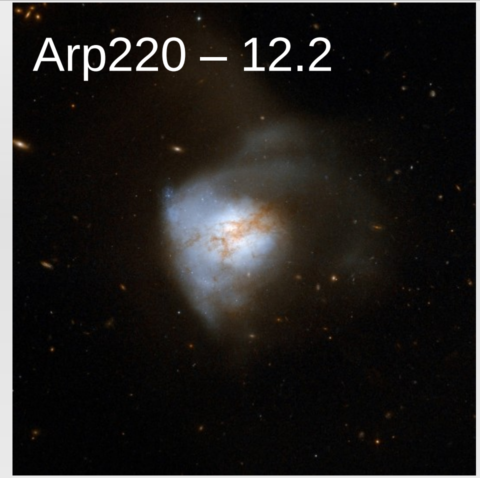
Local dusty galaxies: U/LIRGs







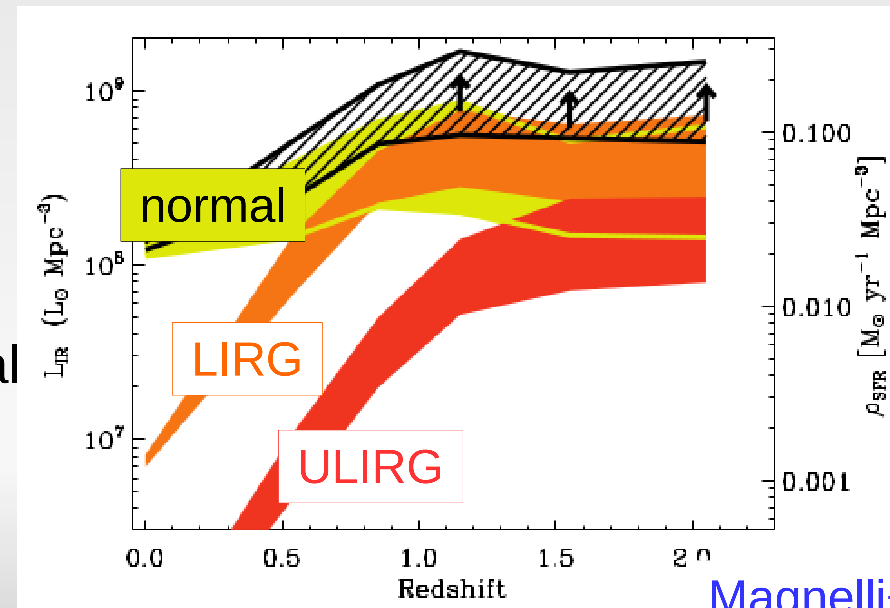
LIRGs: $10^{11}L_{Sun} < L_{IR(8\text{-}1000\mu m)} < 10^{12}L_{Sun}$

ULIRGs: $10^{12}L_{Sun} < L_{IR(8\text{-}1000\mu m)} < 10^{13}L_{Sun}$

(Sanders & Mirabel 96, Pérez-Torres+21)

>10-100 times more luminous than normal spirals

Not common locally, but important at z > 1

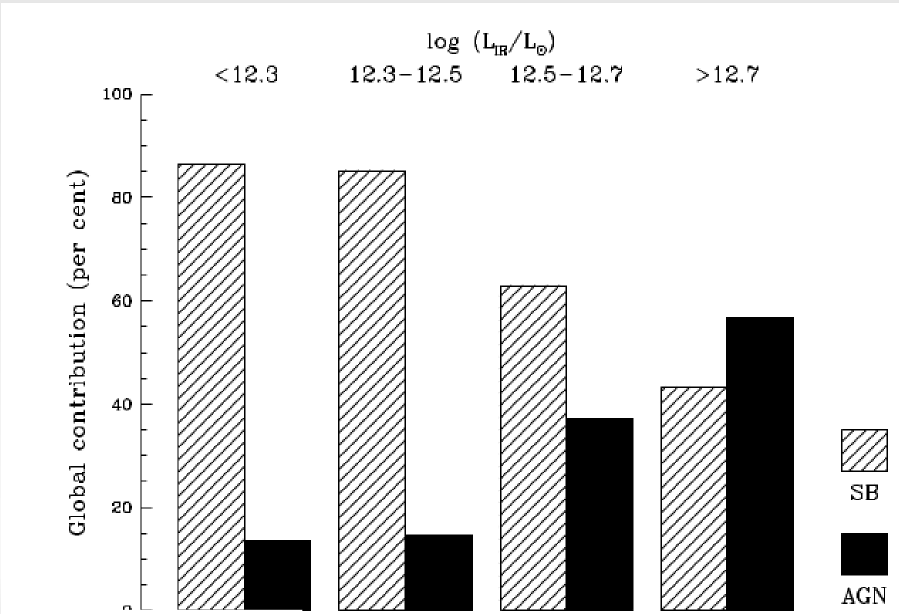


Magnelli+13

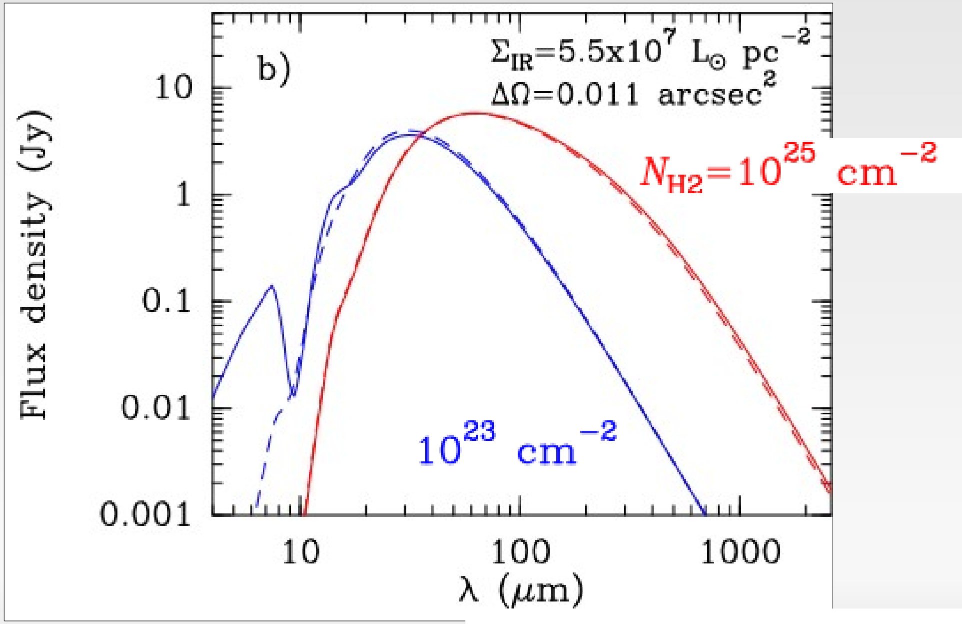
What powers U/LIRGs?

- Extremely obscured systems (average Av > 50-100 mag)
- Mid-IR ISO & Spitzer (Genzel+98, Veilleux+09, Nardini+10, Alonso-Herrero+12) :

Star formation dominates, but (*detected*) AGN increases with L(IR)



Nardini+10

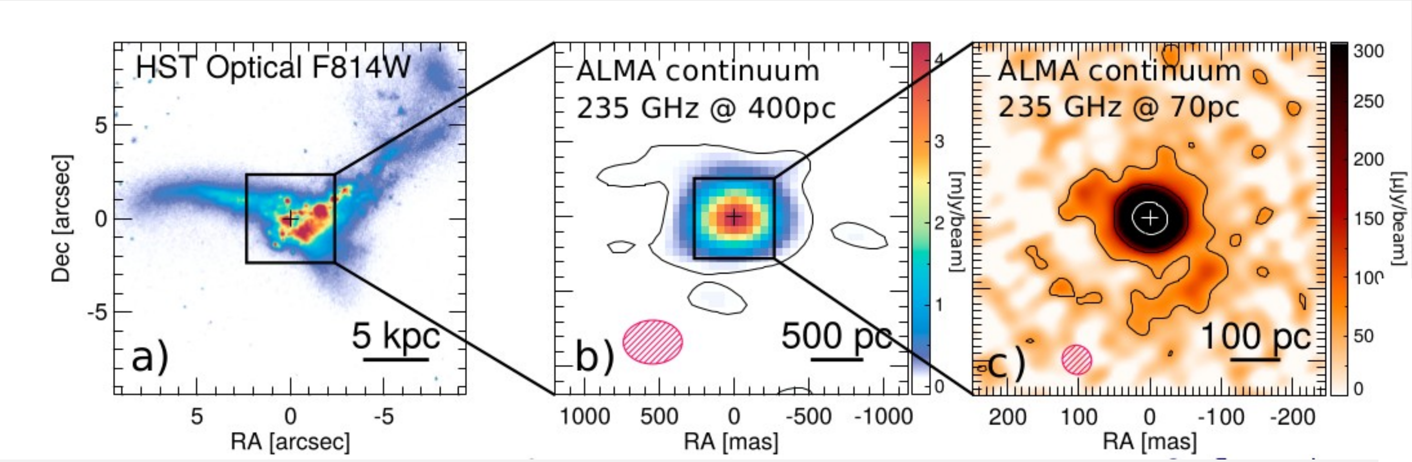


Gonzalez-Alfonso+20

Compact infrared sources

- Majority have compact nuclei in radio and sub-mm with VLA and ALMA (Barcos-Muñoz+17, Pereira-Santaella+21, Hayashi+21)

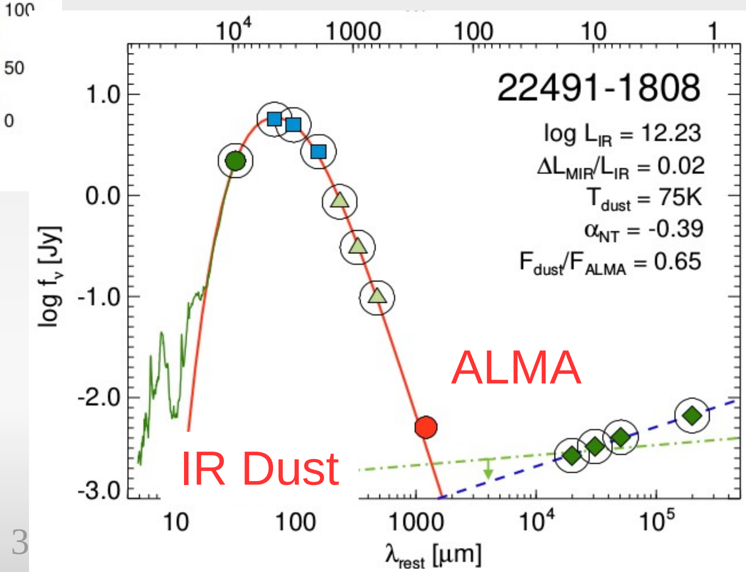
  - r = < 10 - 80 pc   ~240 GHz continuum 0.05”-0.2” ALMA



- Σ (LIR) > 10 [8] Lsun/pc

Higher than expected for starburst

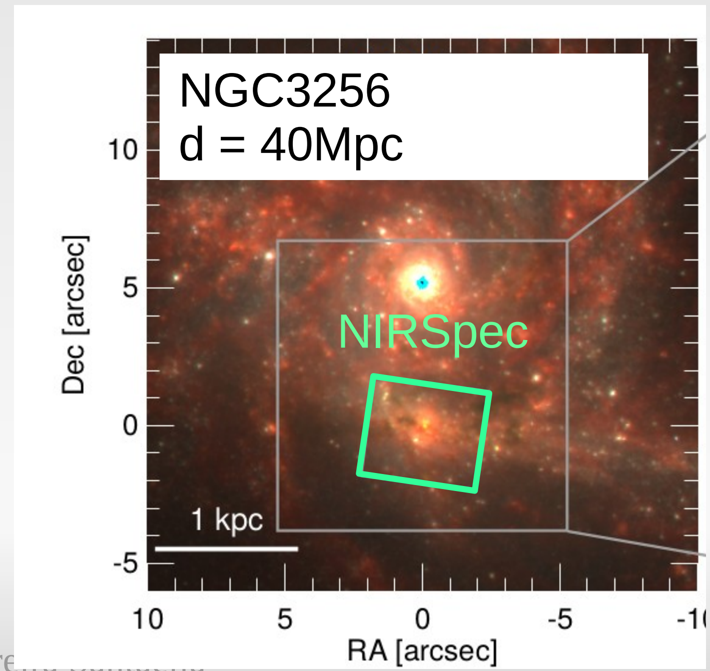
→ extremely obscured AGN



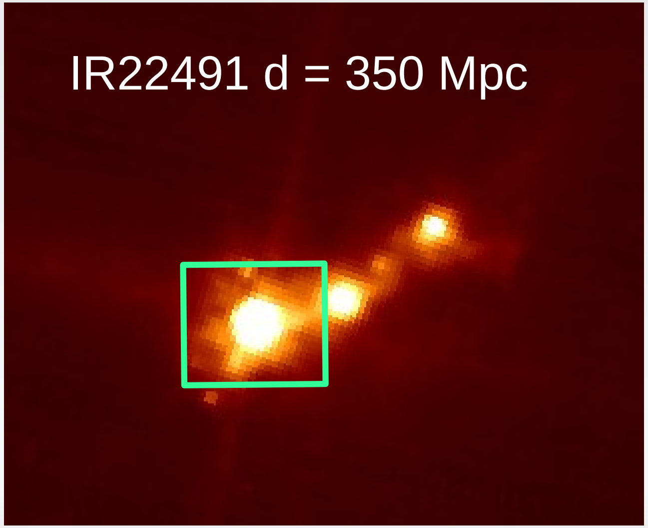
JWST NIRSpec archive data

- ~25 U/LIRGs with JWST IFU spectroscopy as part of ERS, GTO, GO and GOALS Large Program
- NIRSpec (3–5μm) ~0.2” resolution

LIRGs d < 100 Mpc
Spatially resolved



ULIRGs d > 200 Mpc
Unresolved nuclei



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H_3^+ and Cosmic Rays

- H_3^+ production:

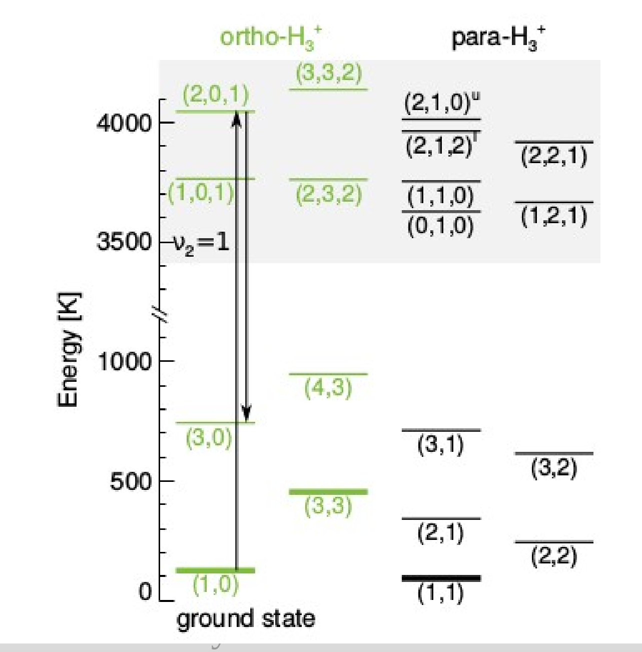
Key molecule for the ISM chemistry

$$H_2 + \text{CR (or X-ray)} \rightarrow H_2^+ \rightarrow H_3^+$$

- and destruction:

$H_3^+ + e^-$ or $H_3^+ + X \rightarrow HX^+$ (X are abundant molecules, eg CO)

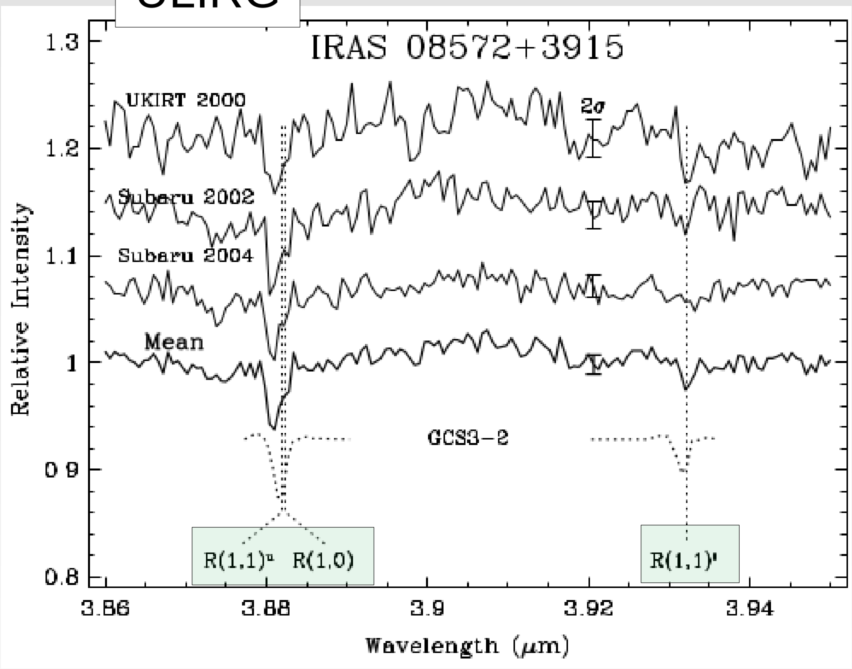
H_3^+ can be observed through IR ro-vibrational bands in the JWST range



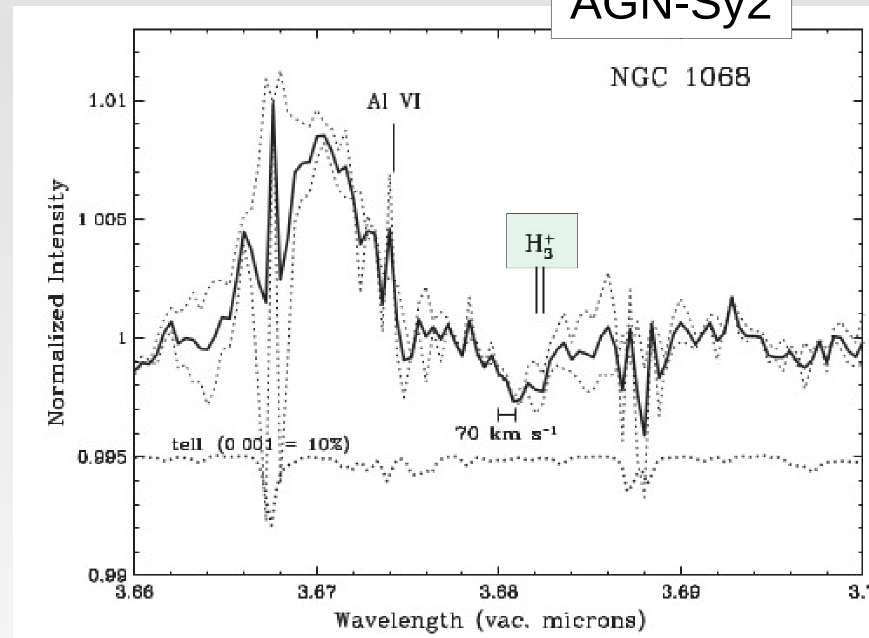
Extragalactic H_3^+ before JWST

- 2 detections (Geballe+06 and +15) from the ground: R-branch

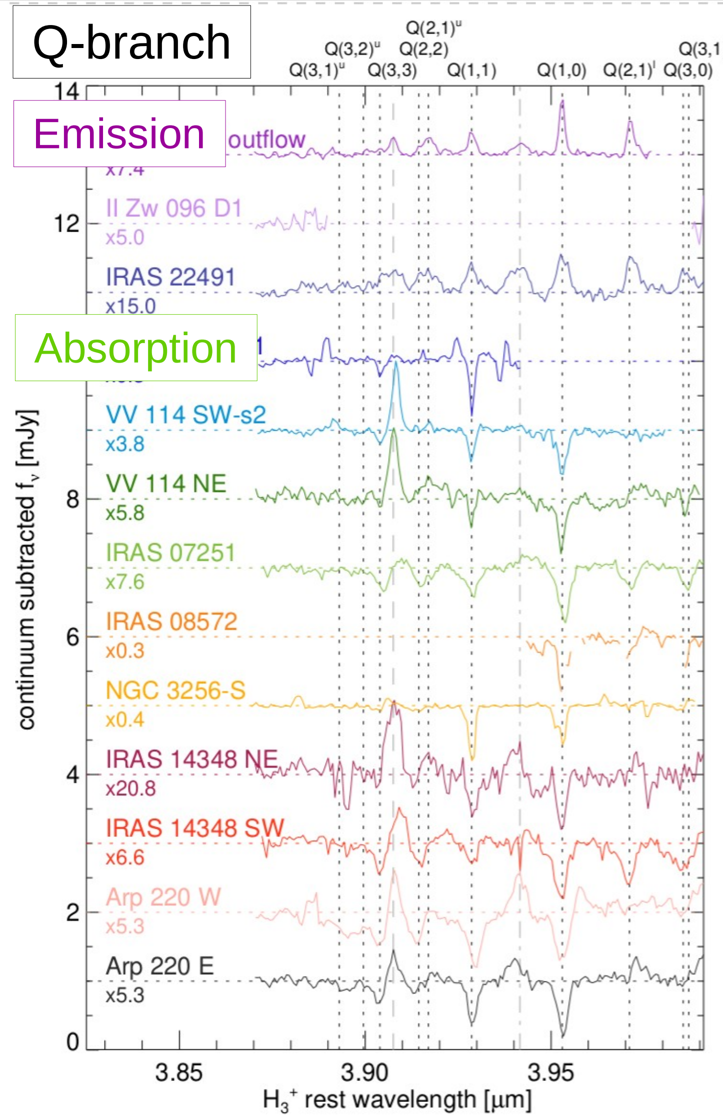
ULIRG



AGN-Sy2

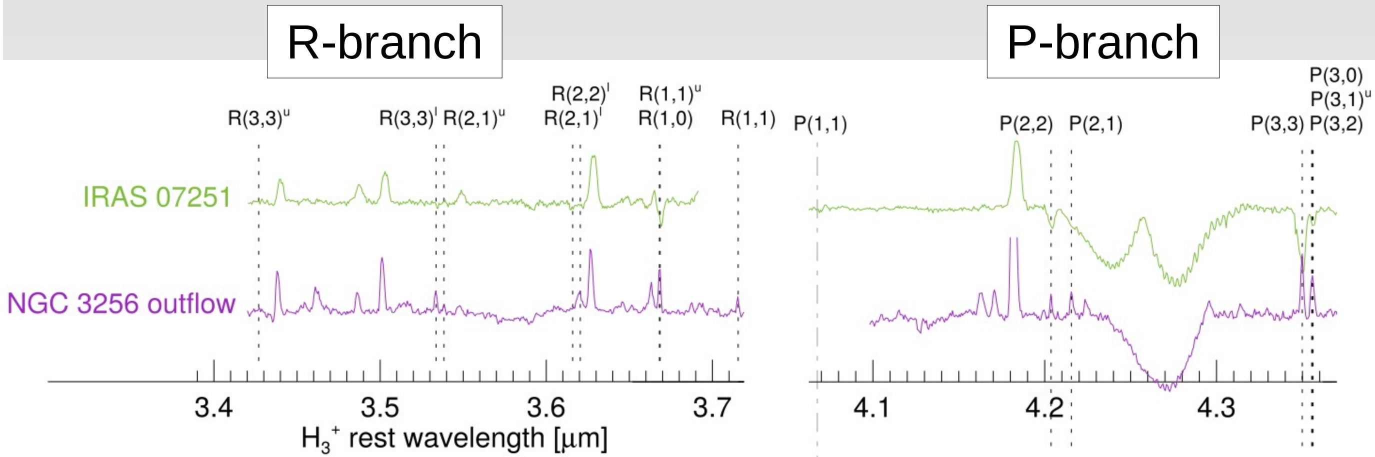


Extragalactic H_3^+ with JWST/NIRSpec



- 13 out of 20 nuclei detected with JWST.

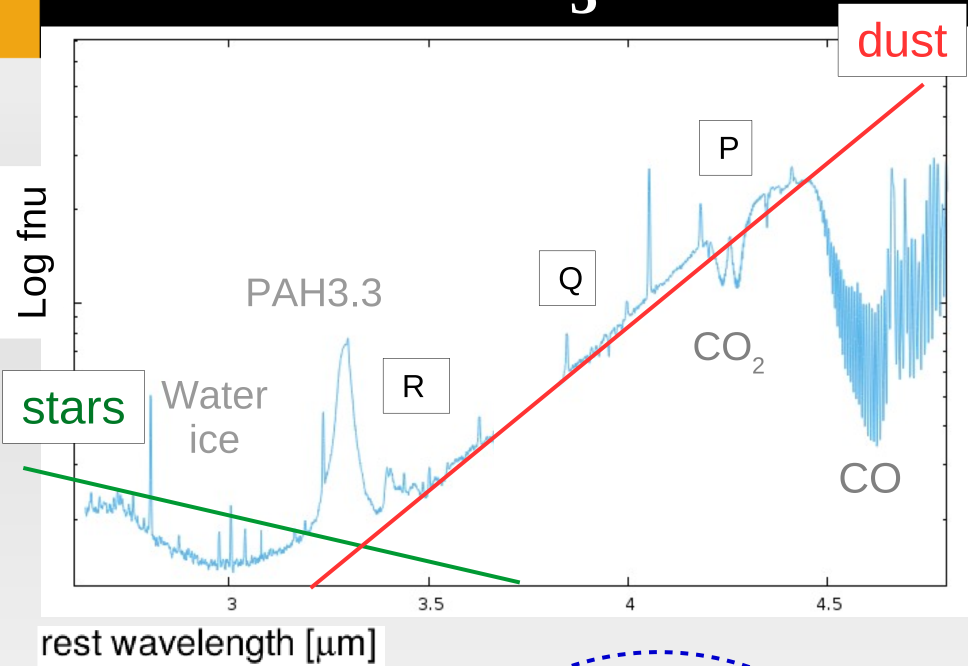
  R, **Q** and **P** branches



Pereira-Santaella+24b

- 10 nuclei absorption
- **First detections of H_3^+ emission from the ISM in 3 objects**

Where is H_3^+ located in these objects?

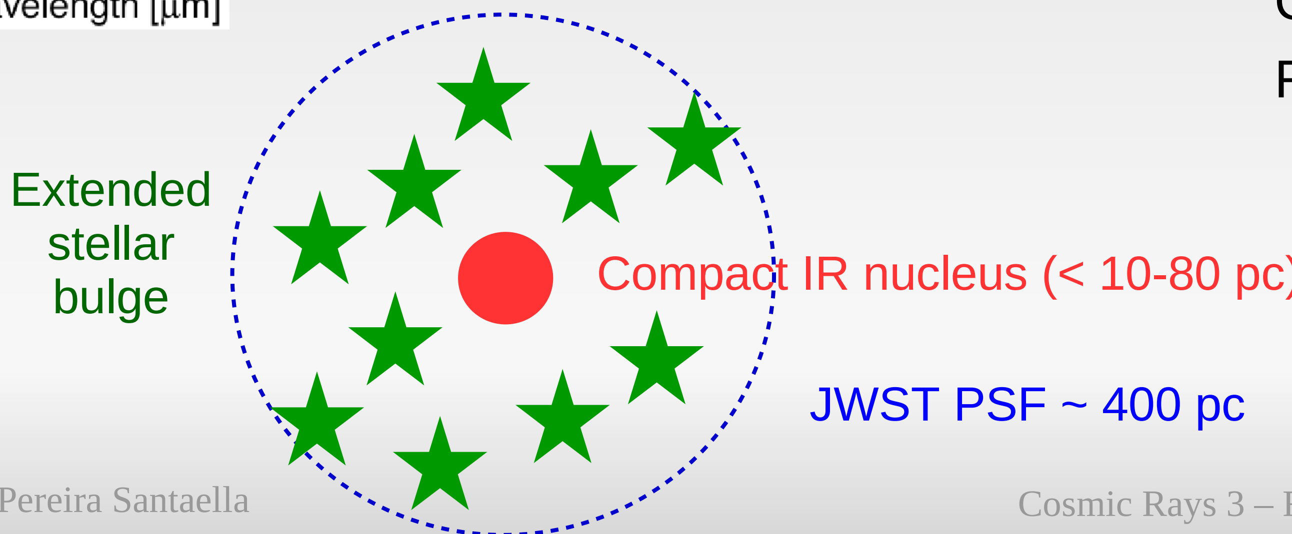


- In MW H_3^+ absorption toward continuum of individual stars
- In U/LIRGs H_3^+ are toward dust continuum
  - Dust dominates at > 3.5 µm
  - Lines with same lower level (3,3)

P(3,3) 4.35µm. highest EW

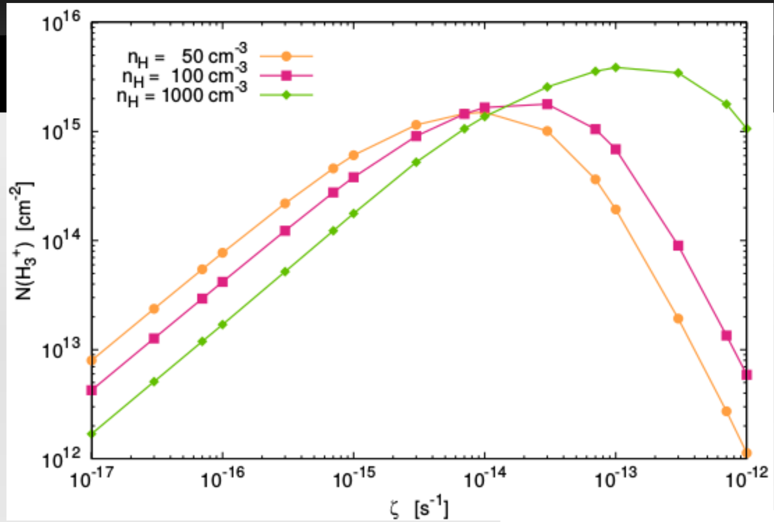
Q(3,3) 3.90µm

R(3,3) 3.43µm. Not detected

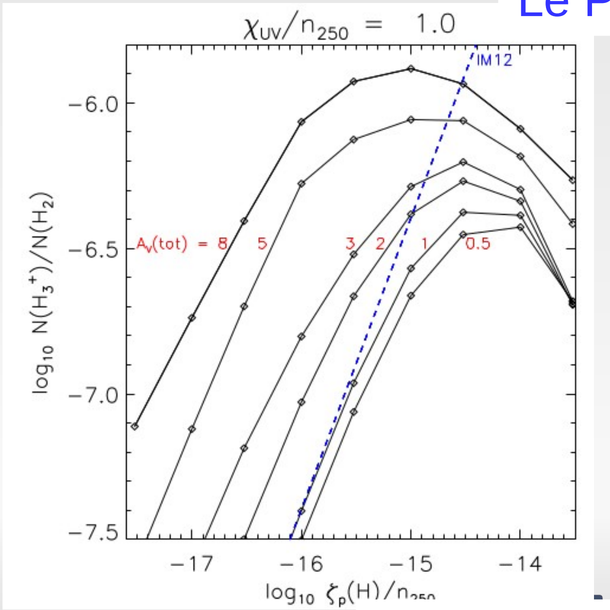


H_2 ionization rate

- For low ζ → H_3^+ abundance proportional to ζ
- For high ζ → H_3^+ abundance decreases
  - Molecular fraction decreases
  - Free electron abundance increases → enhanced recombination of H_3^+



Le Petit +16



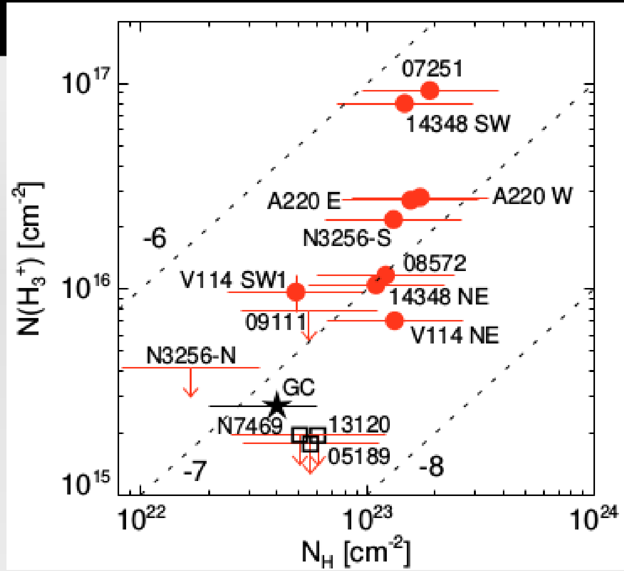
Neufeld & Wolfire 17

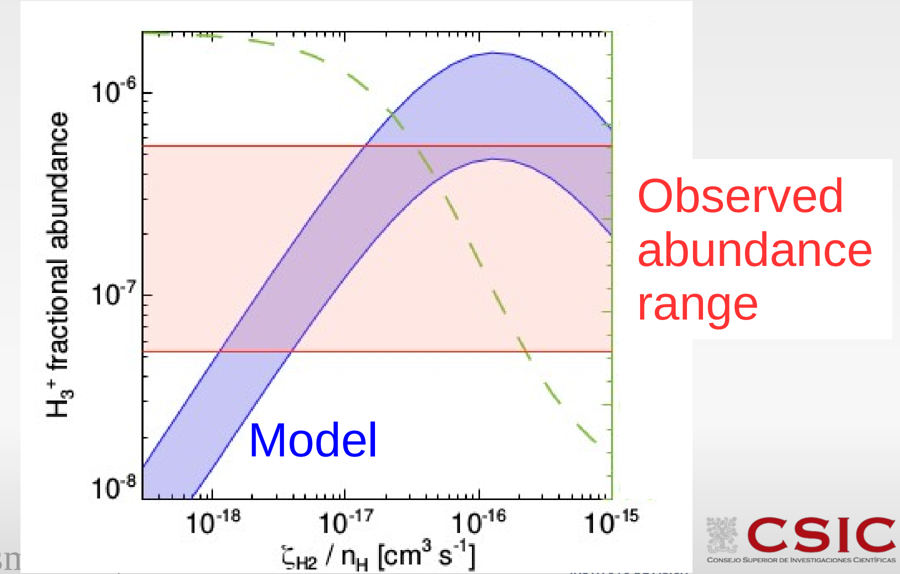
H_2 ionization rate

- $N(H_3^+)$ from absorption lines
- N_H based on the dust optical depth

- H_3^+ abundance 2×10^{-7} (>= GC)

  $\rightarrow \zeta \sim 3\times10^{-16}$ - > $4\times10^{-15}\ s^{-1}$





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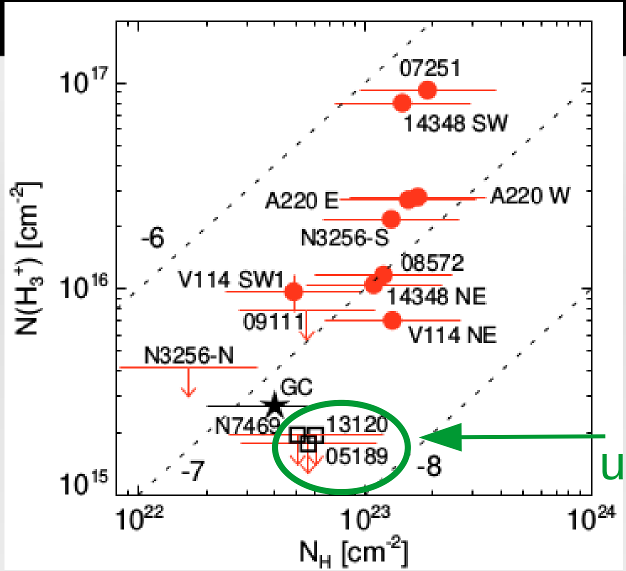
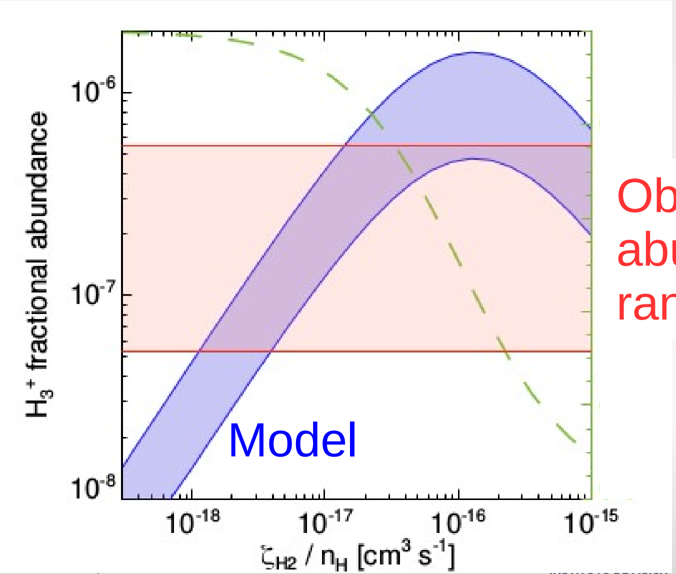
- The 3 "less obscured" AGN ($N_H \sim 5\times10^{23}$ cm^{-2}) have H_3^+ upper limits.

  High X-ray flux imply $\zeta > 10^{-13}$ s^{-1} $\rightarrow$ low H_3^+ abundance



AGN with upper limits !



Observed abundance range

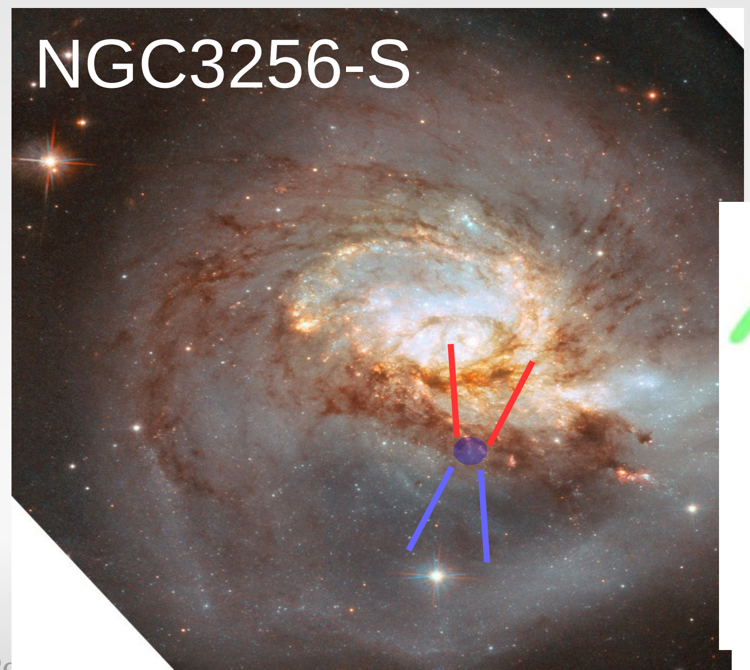
H_3^+ emission in NGC3256

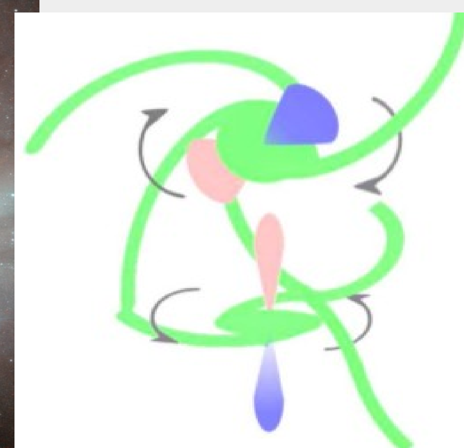
Emission detected for the first time in ISM in 3 objects :

NGC3256-S most nearby (40 Mpc)

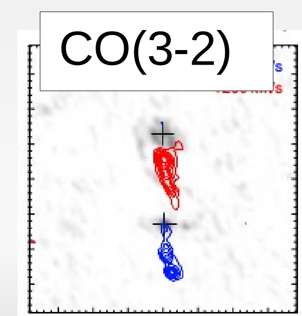
Spatially resolved emission

- N: face-on nuclear starburst
- S: edge-on **extremely obscured AGN + radio jet + collimated molecular outflow (v~100-1000 km/s)**

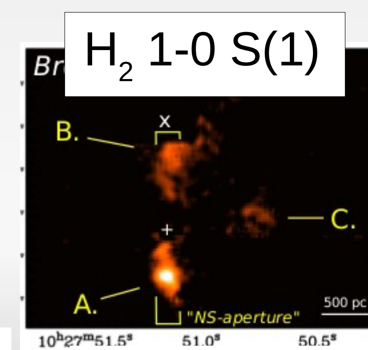




Harada+20

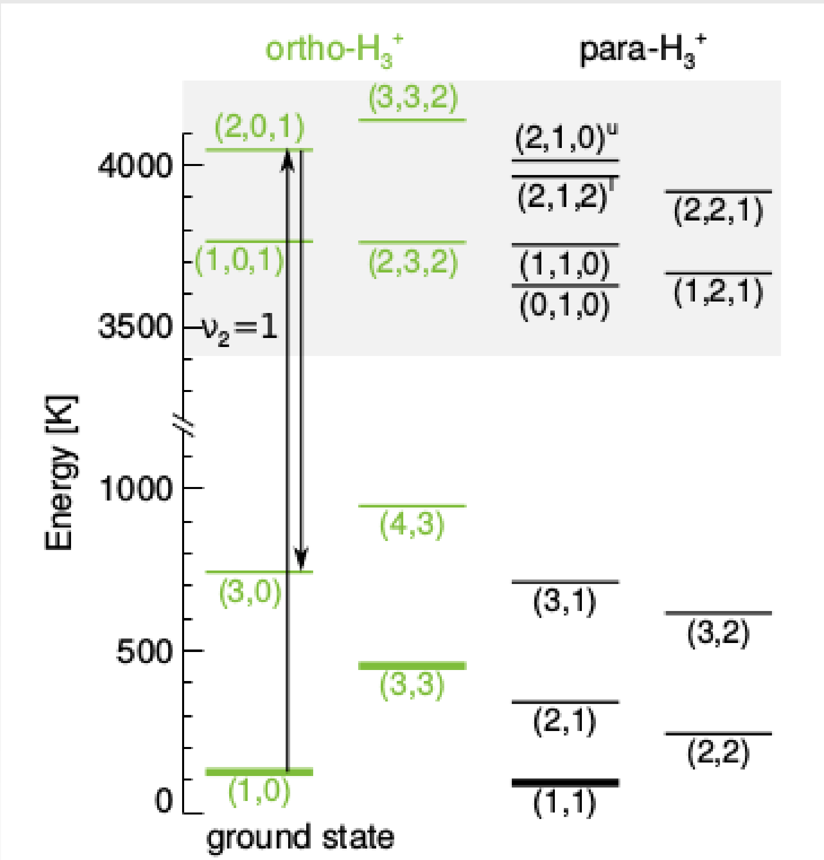


Sakamoto+14



Emonts+14

H_3^+ v2=1 excitation



- Collisions with H_2 ?

  X Low density in the outflow

- Formation pumping.

  $H_2^+ + H_2 \rightarrow H_3^+ + H$

  highly exothermic (E~20000 K)

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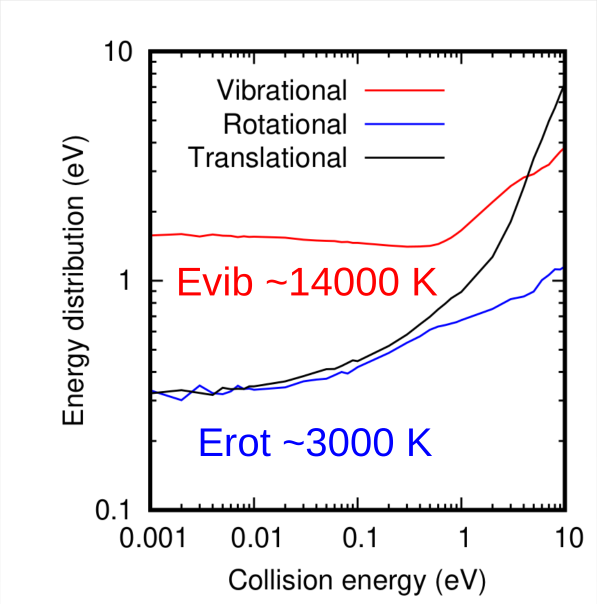
Formation pumping

Simulations

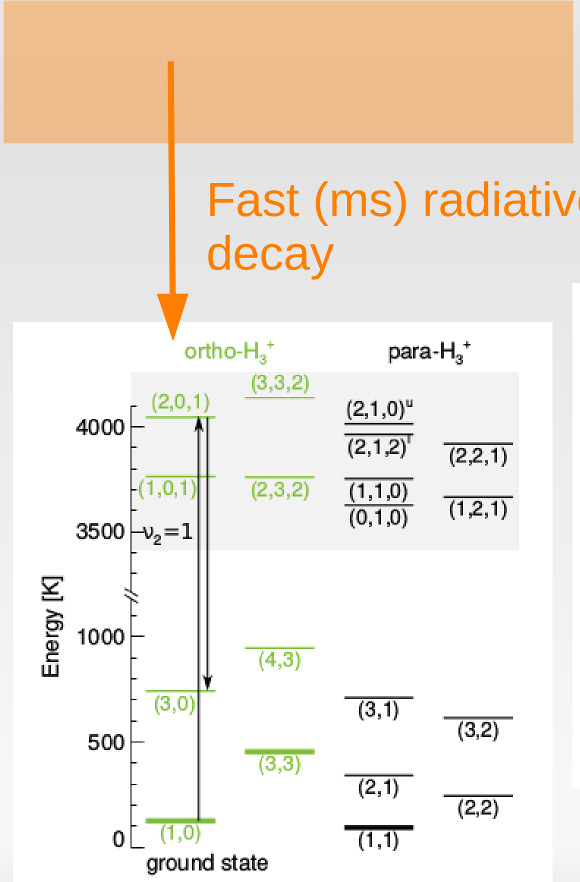
$H_2^+ + H_2 \rightarrow H_3^+ + H$



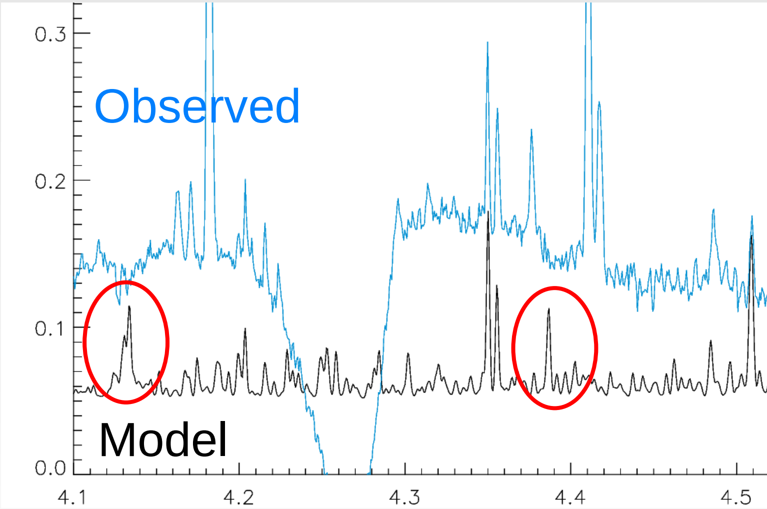
del Mazo-Sevillano+24
O. Roncero group

Highly excited vib levels

Fast (ms) radiative decay

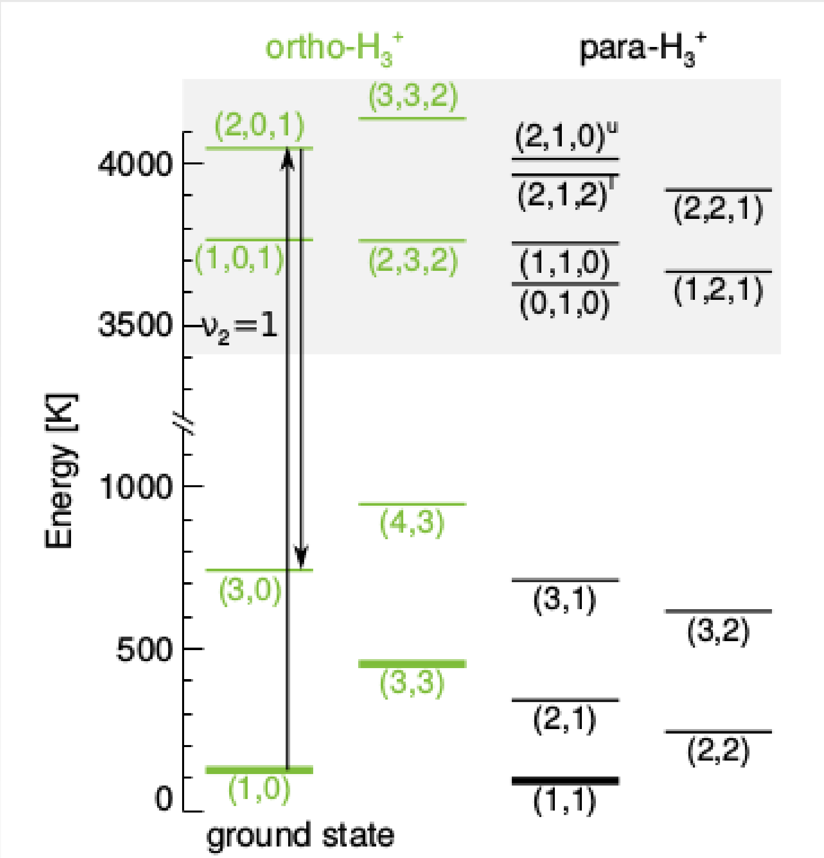


Simulated formation spectrum



Some transitions are not observed

H_3^+ v2=1 excitation



- X Collisions with H_2 ?

  Low density in the outflow

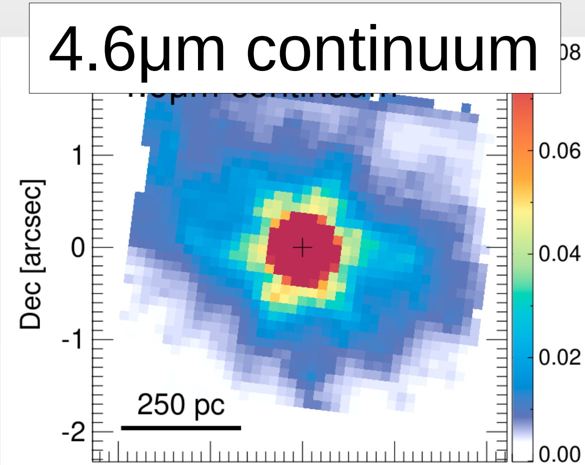
- X Formation pumping.

  $H_2^+ + H_2 \rightarrow H_3^+ + H$

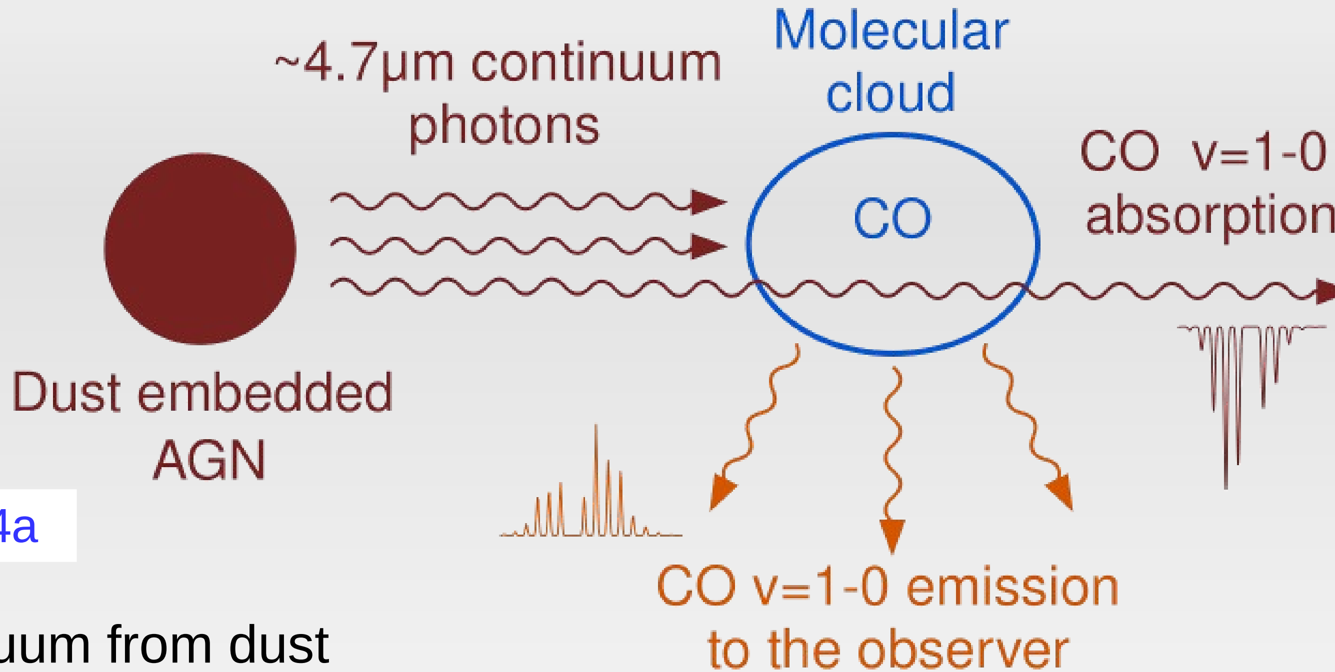
  highly exothermic (E~20000 K)

- IR radiation

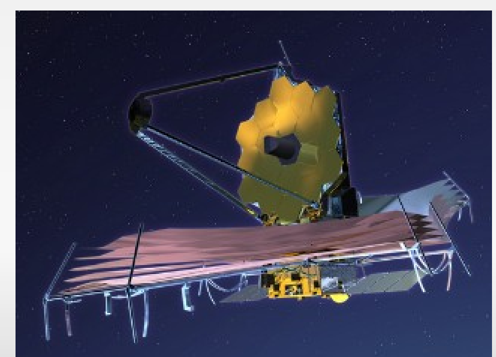
CO v=1-0 4.7μm emission from the outflow



Pereira-Santaella+24a



- Bright mid-IR continuum from dust around AGN
- Illuminates cold molecular cloud – CO absorbs photons
- Re-emitted in all directions



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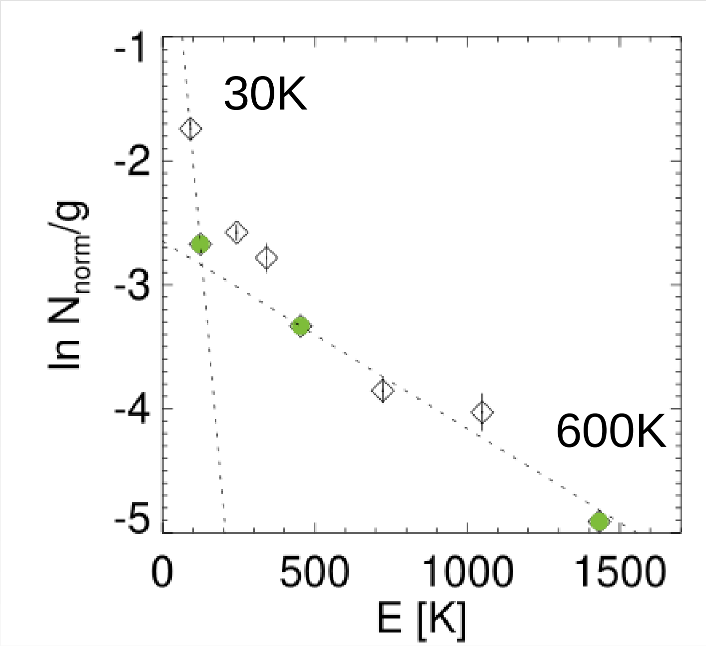
IR radiation

- From the emission line ratios
  - Relative population of the v=0 levels



- IR radiation excites v=1 levels → emission

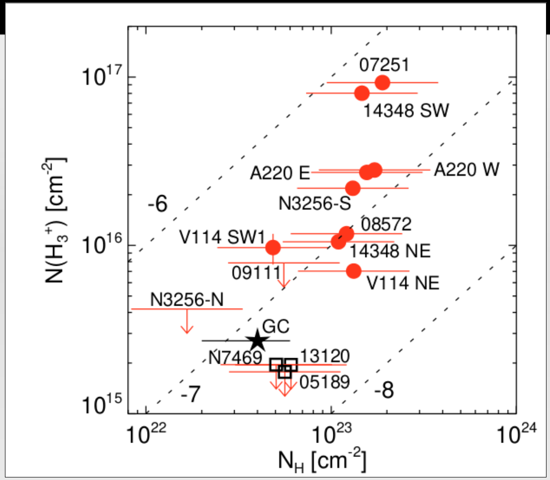
- Collisions with H_2 thermalize lower levels

- Formation pumping populate “metastable” levels

- Estimated H_3^+ fraction in metastable levels (>50%)
- Will allow measurements of ζ in the molecular outflow → Quantify molecular gas destruction and Energy and momentum transfer

Summary

- H_3^+ absorption. Pereira-Santaella+24a
    - Associated to dust continuum in the nucleus
    - H_3^+ possible destroyed in less obscured AGN
    - High $\zeta \sim 3\times10^{-16}$ - > 4×10^{-15} s^{-1}



- H_3^+ emission. Preliminary results
    - Excited by IR radiation
    - Level population dominated by collisions with H_2 (low-J) and formation pumping (high-J)
    - >50% in metastable levels