New Sub-millimeter HCN Lasers in C-rich AGB stars

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Homepage: http://wjyang7.github.io/

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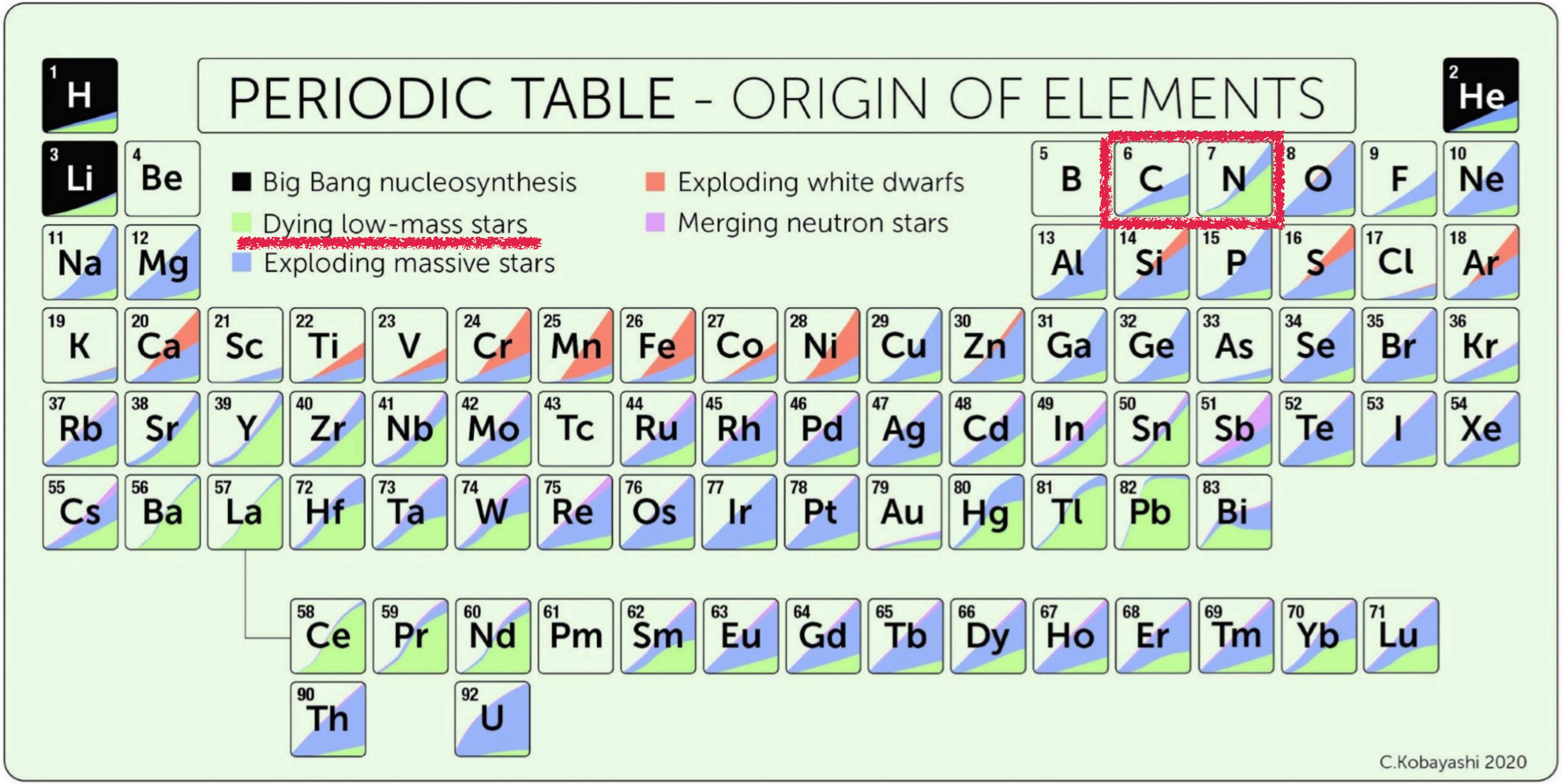
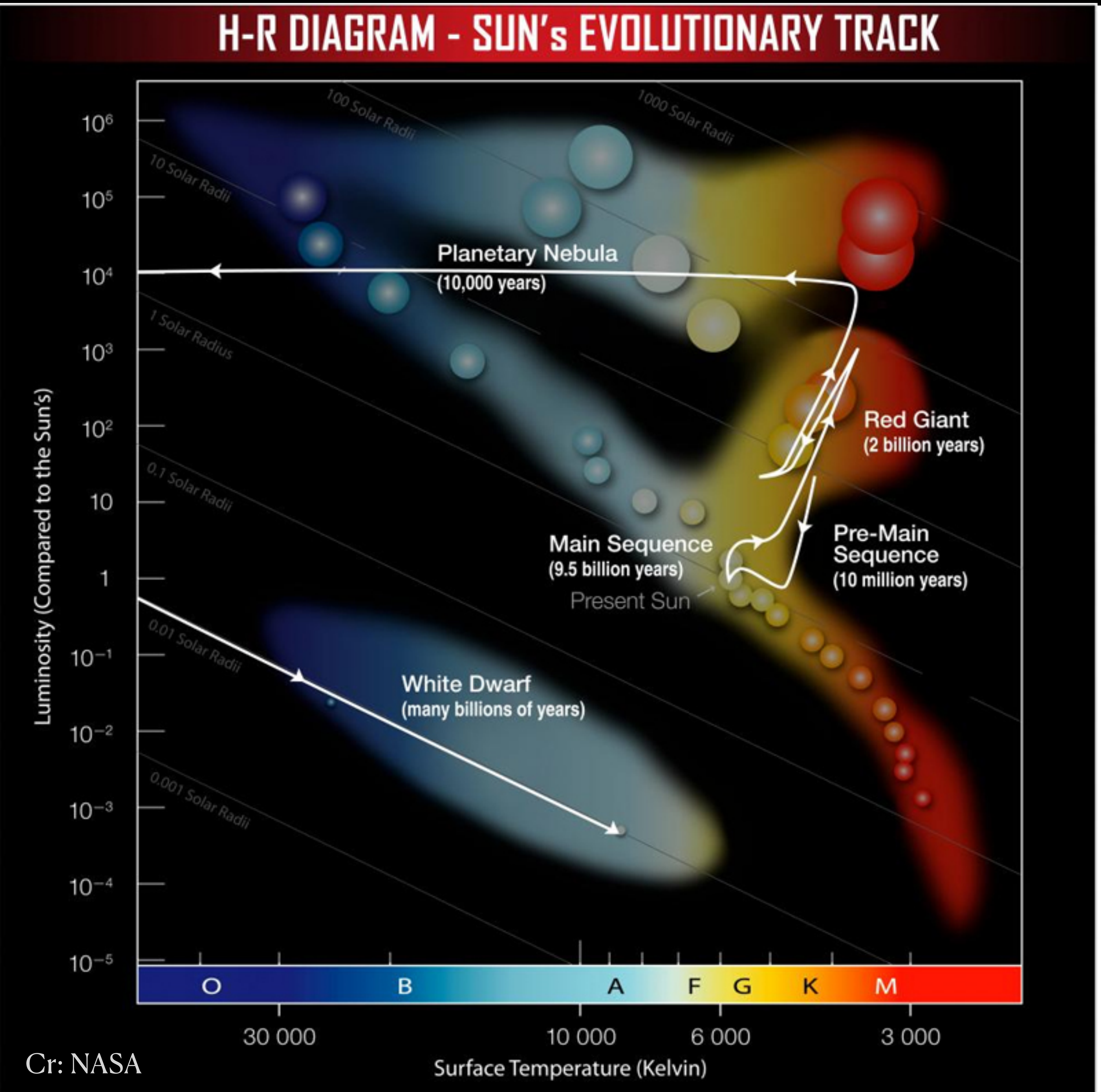
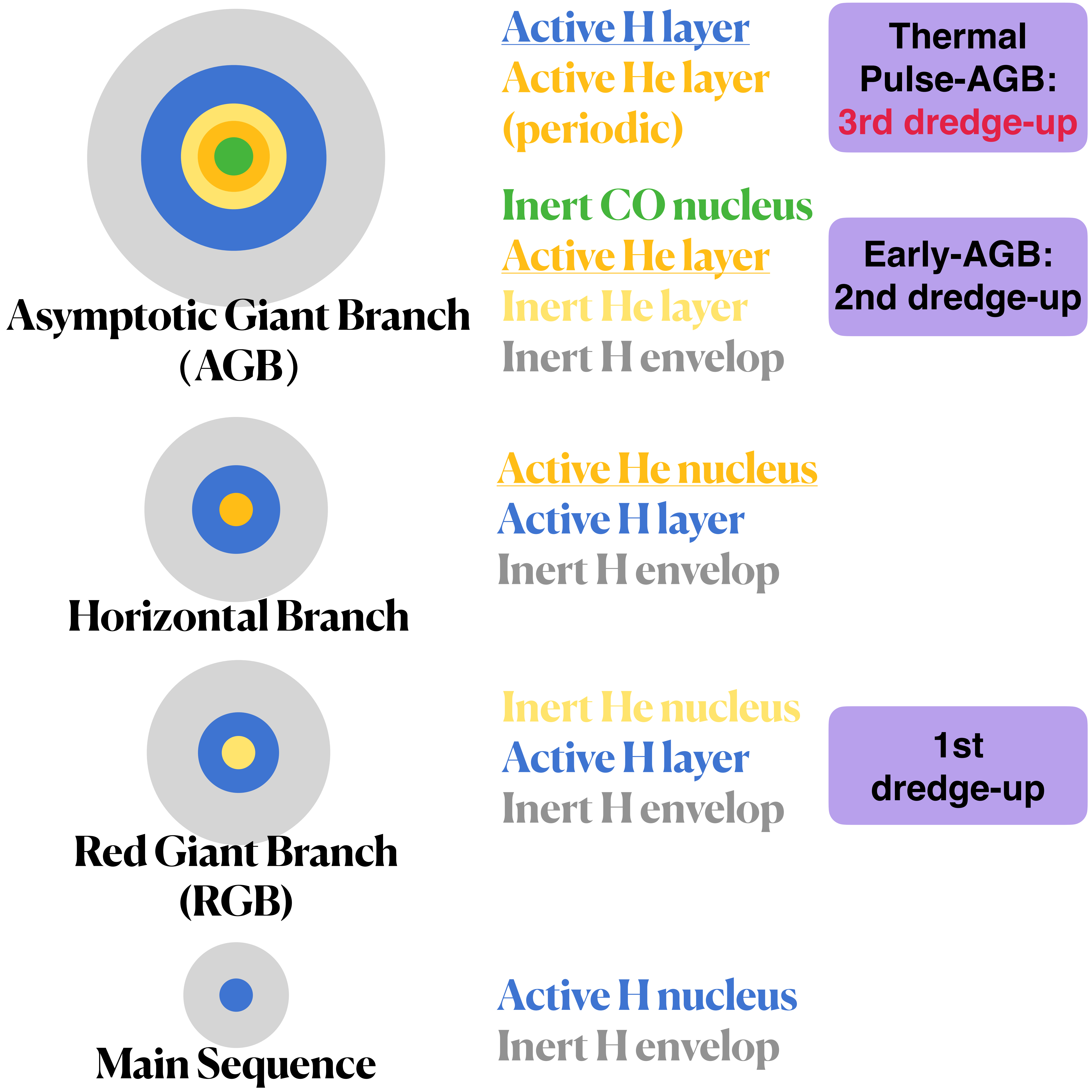
Stellar yields



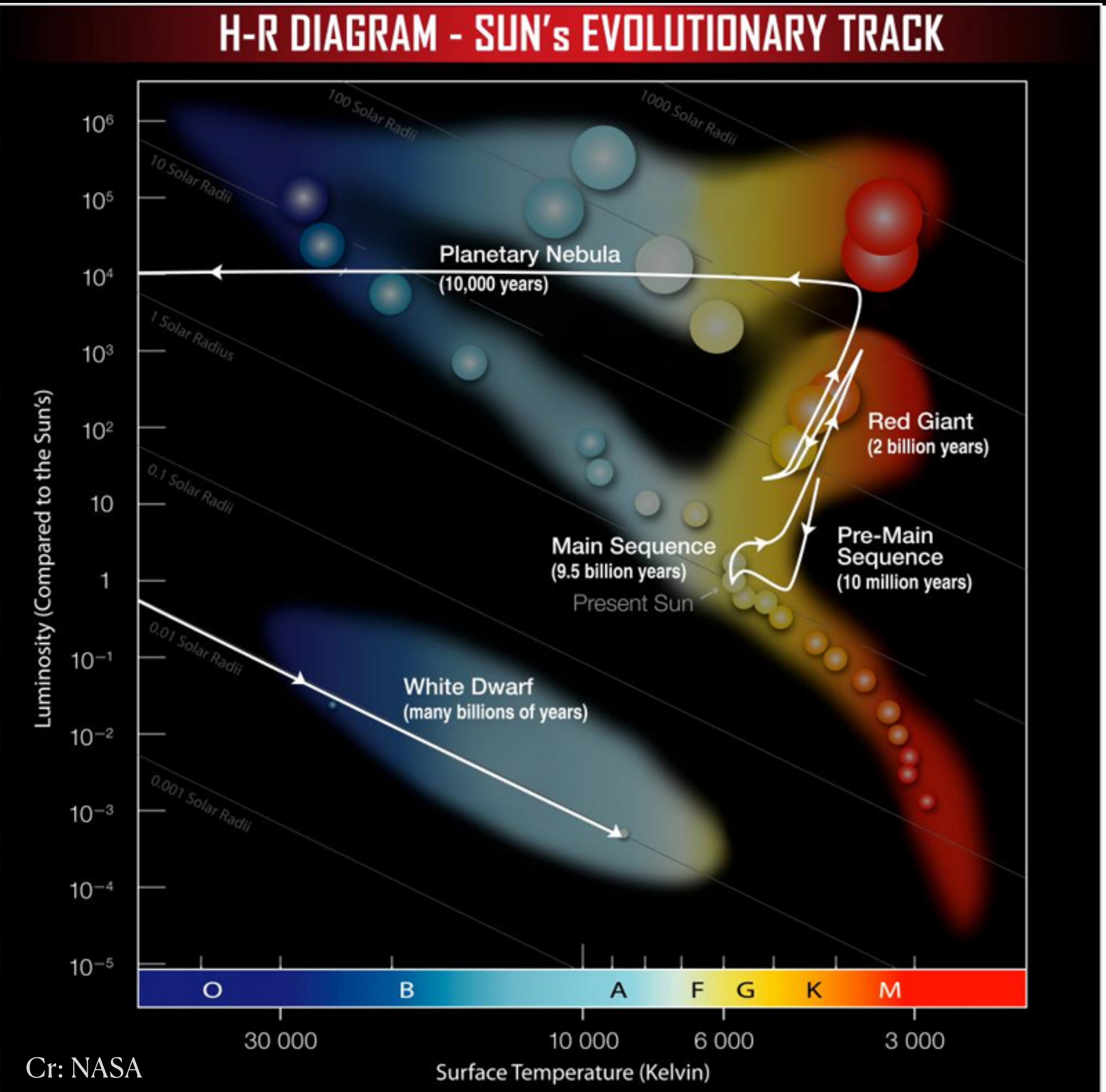
Stellar evolution



Cr: NASA



Stellar evolution



Cr: NASA

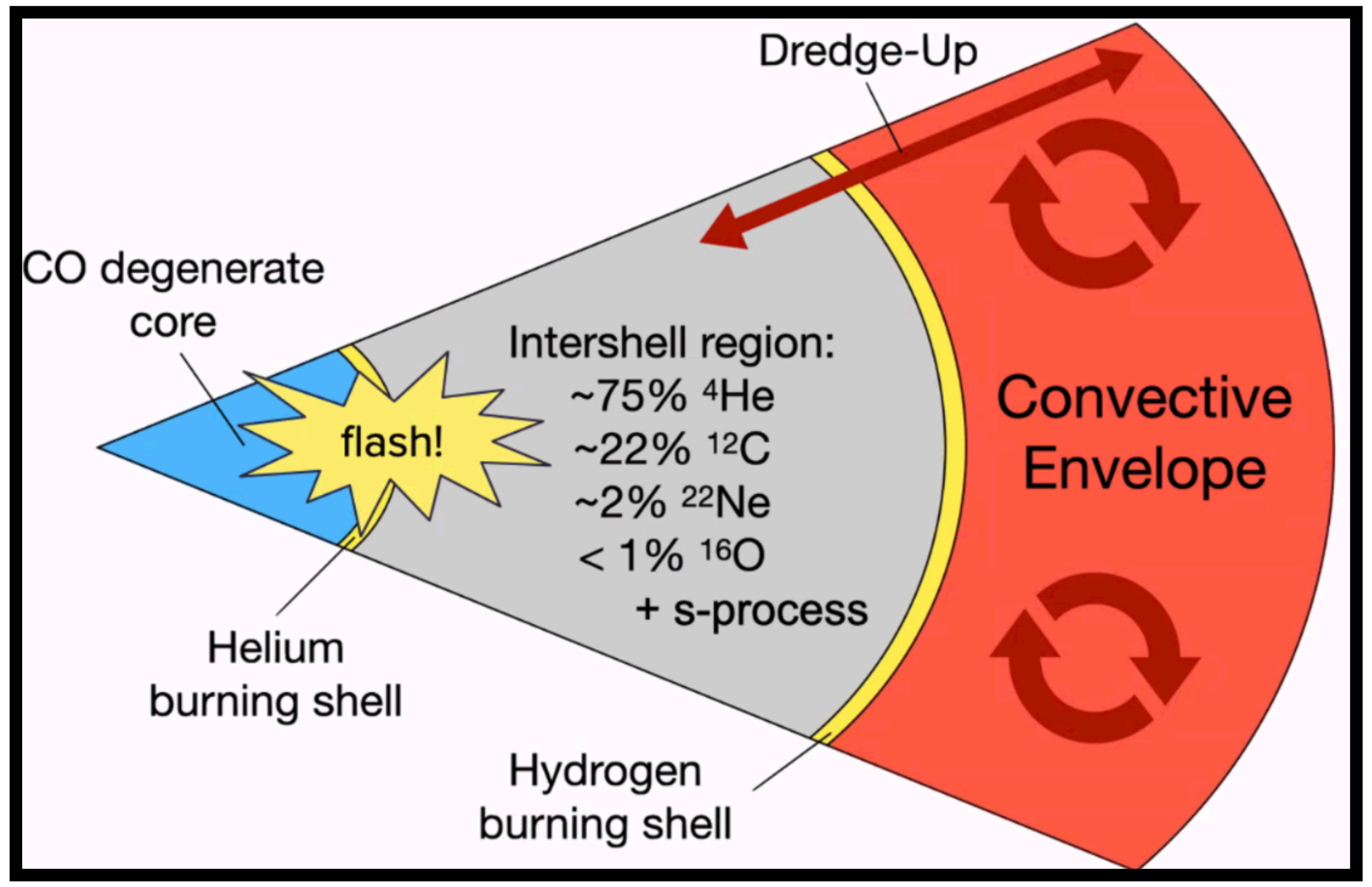
Asymptotic Giant Branch (AGB)

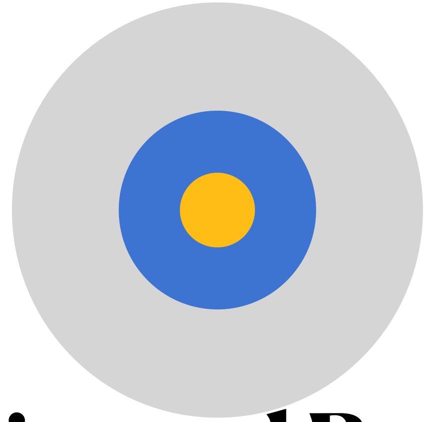
Active H layer
Active He layer (periodic)

Thermal Pulse-AGB: 3rd dredge-up

Inert CO nucleus
Active He layer
Inert He layer
Inert H envelop

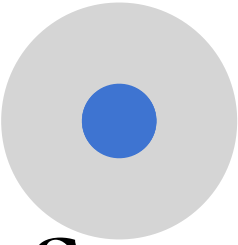
Early-AGB: 2nd dredge-up





Horizontal Branch

Red Giant Branch (RGB)

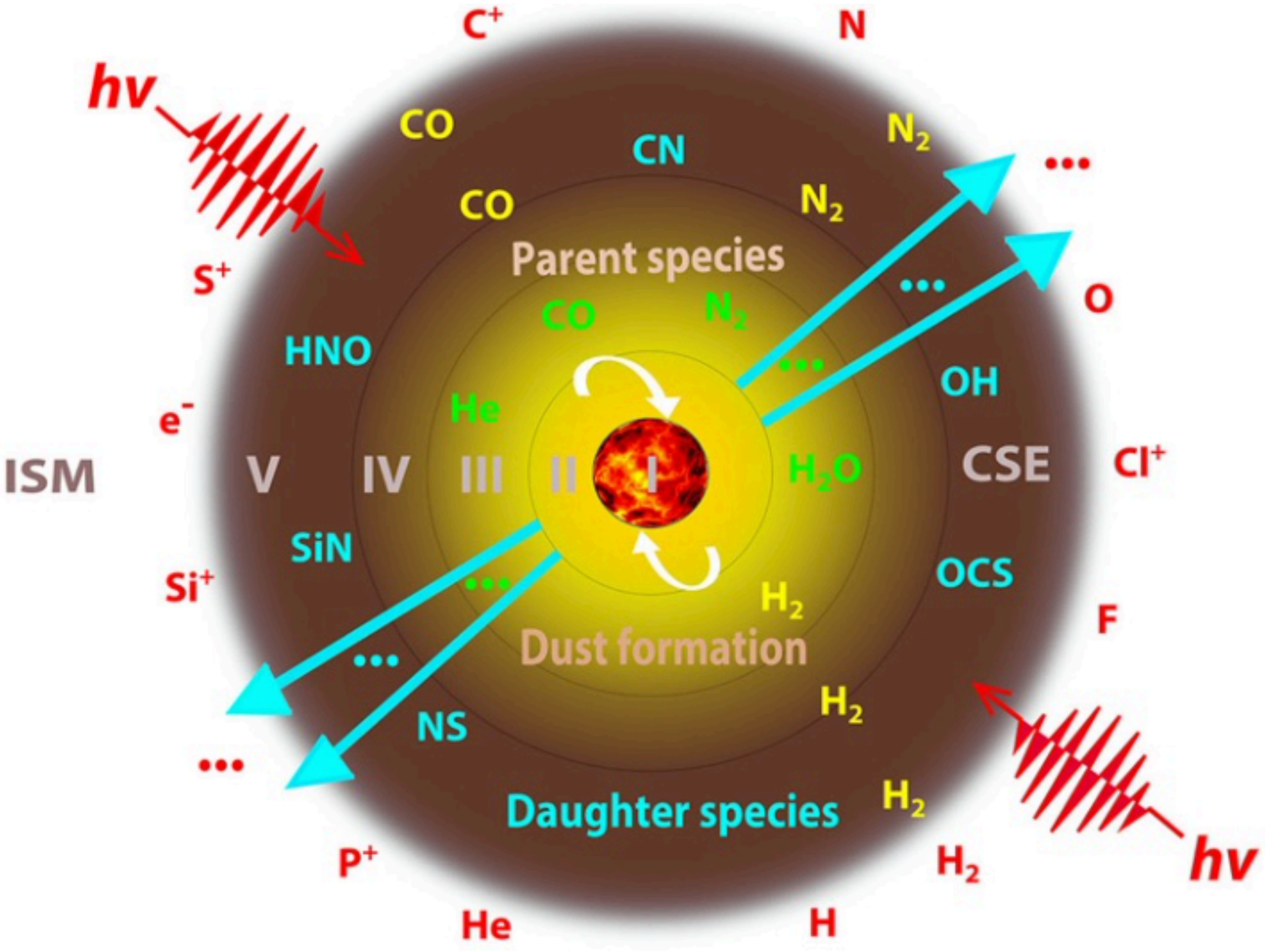


Main Sequence

Active H nucleus
Inert H envelop

AGB star (O- / C- rich)

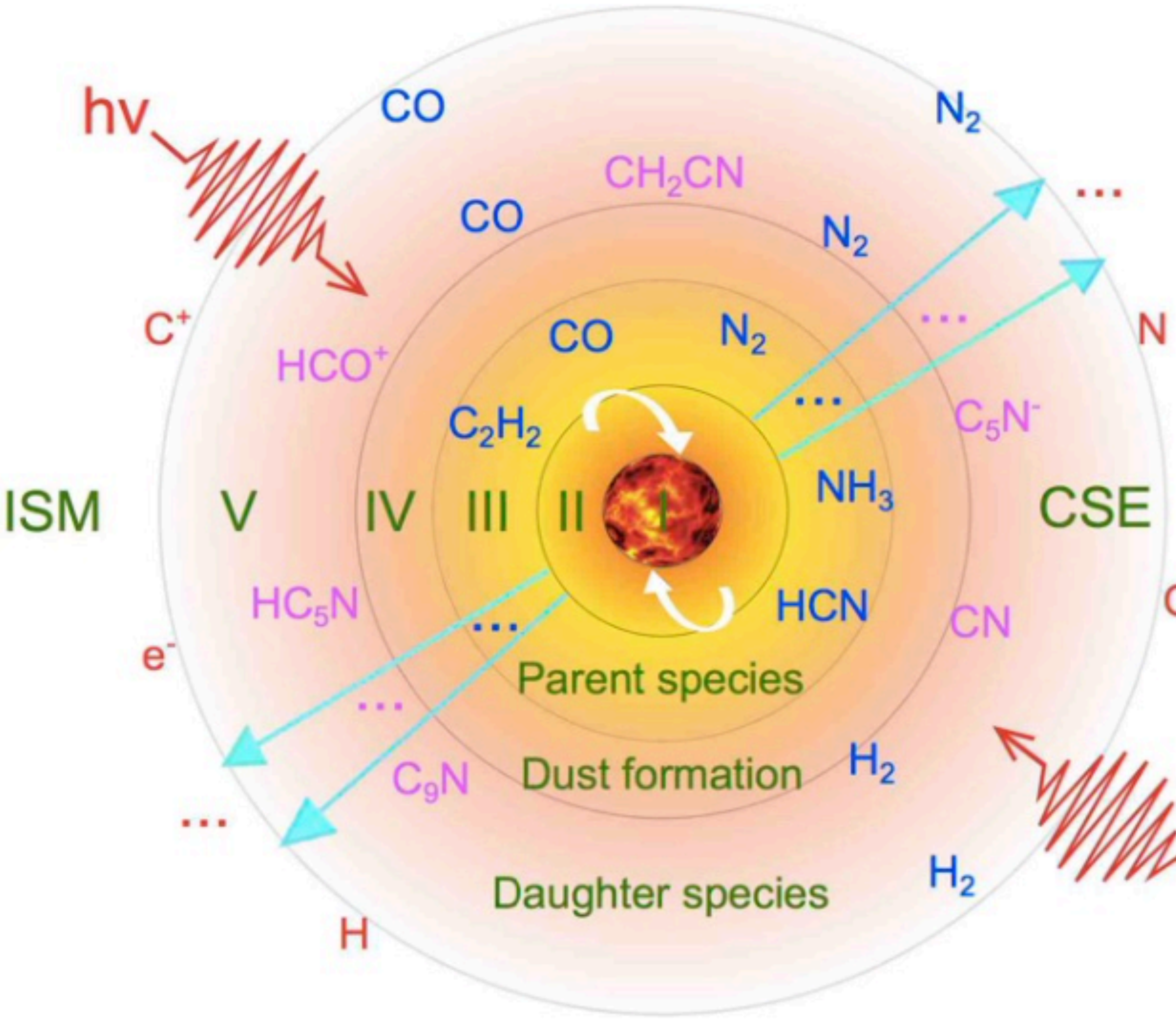
[C/O] < 1 Oxygen-rich



Li et al. (2016) A&A 588, A4

CO, SiO, H_2O, OH, etc.

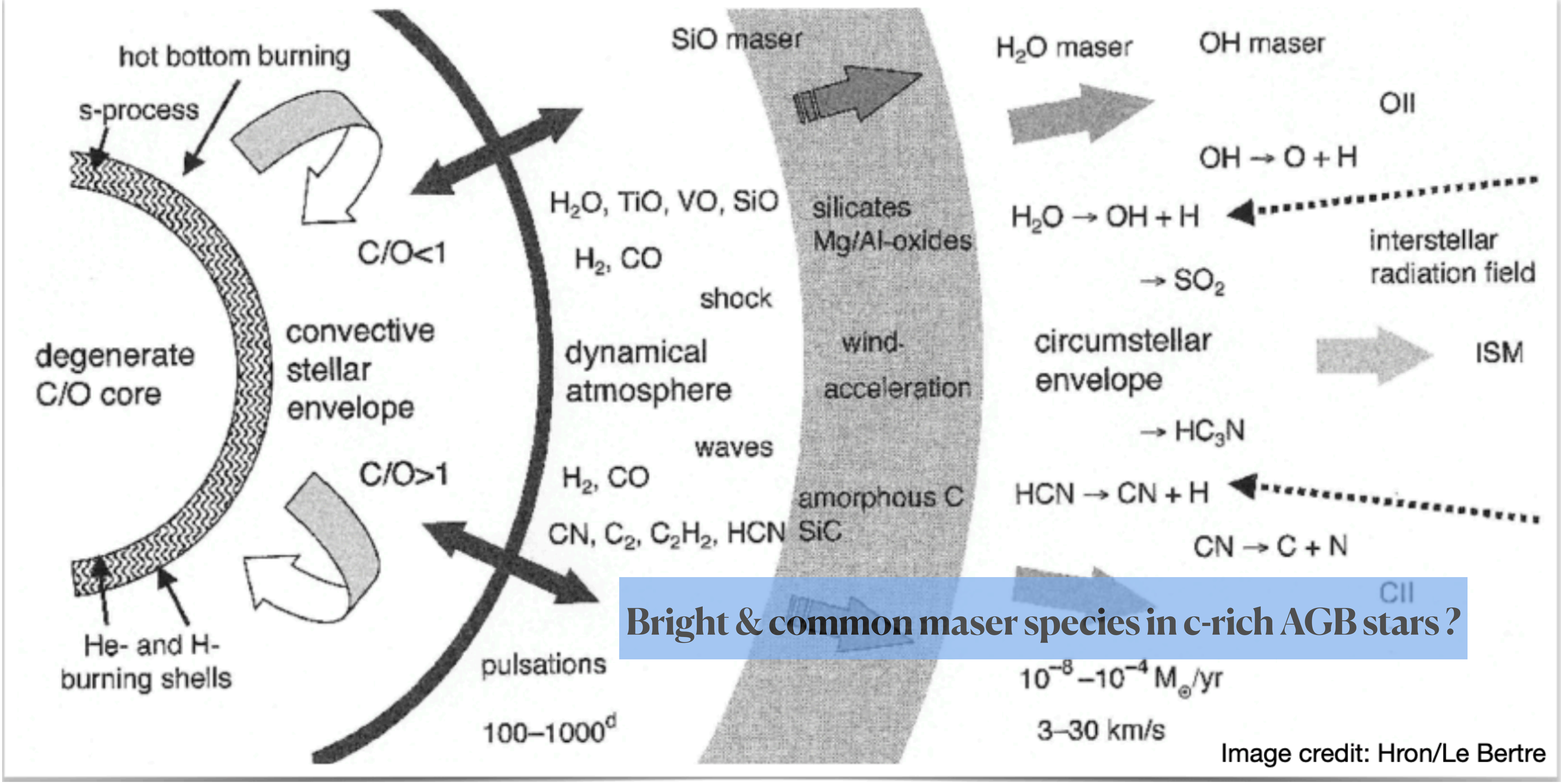
Carbon-rich [C/O] > 1



Li et al. (2014) A&A 568, A111

CO, HCN, CN, C_2H_2, etc.

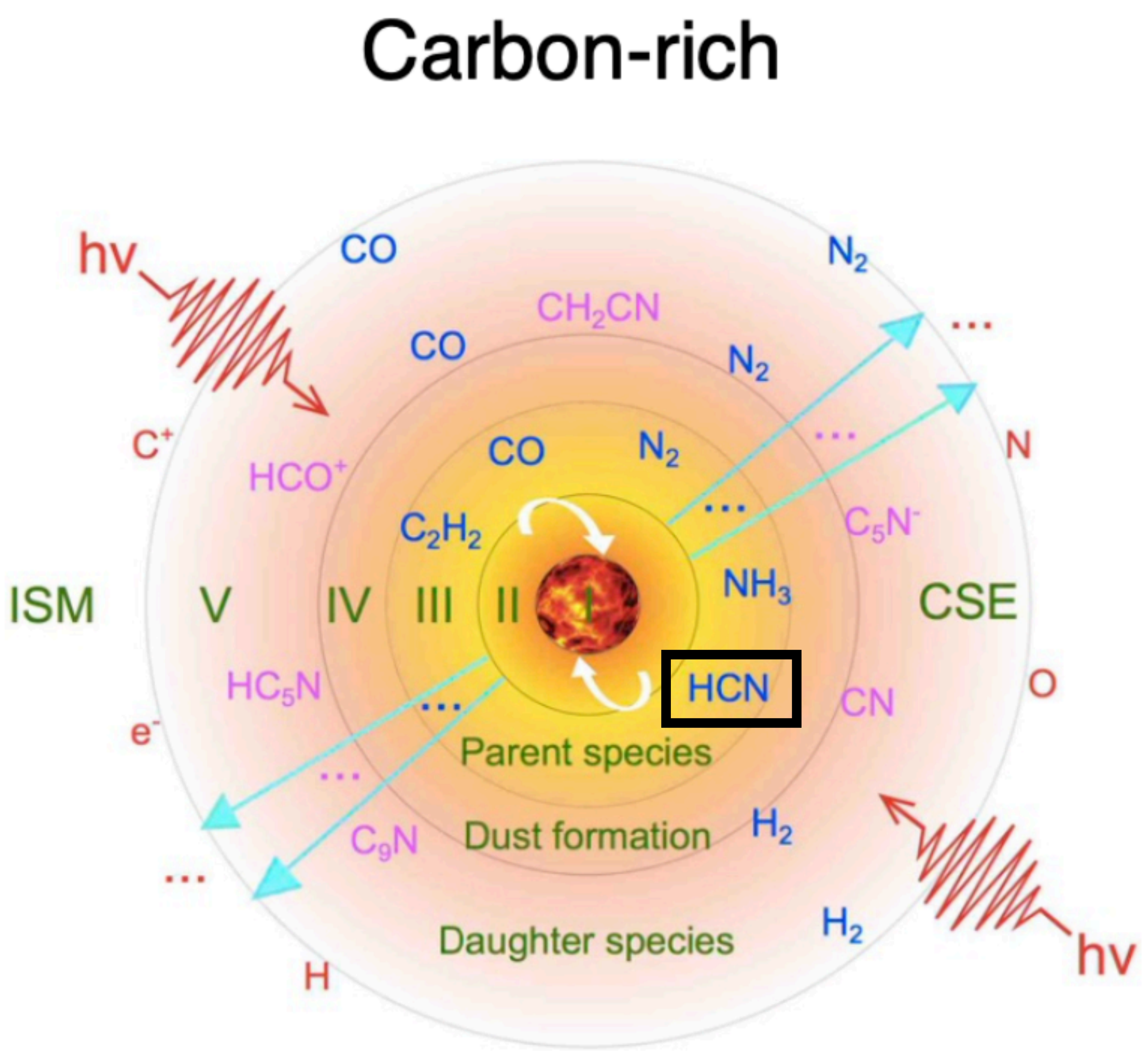
Maser emission in circumstellar envelop



Bright & common maser species in c-rich AGB stars ?

Image credit: Hron/Le Bertre

HCN in C-rich AGB stars



Li et al. (2014) A&A 568, A111

CO, HCN, CN, C_2H_2, etc.

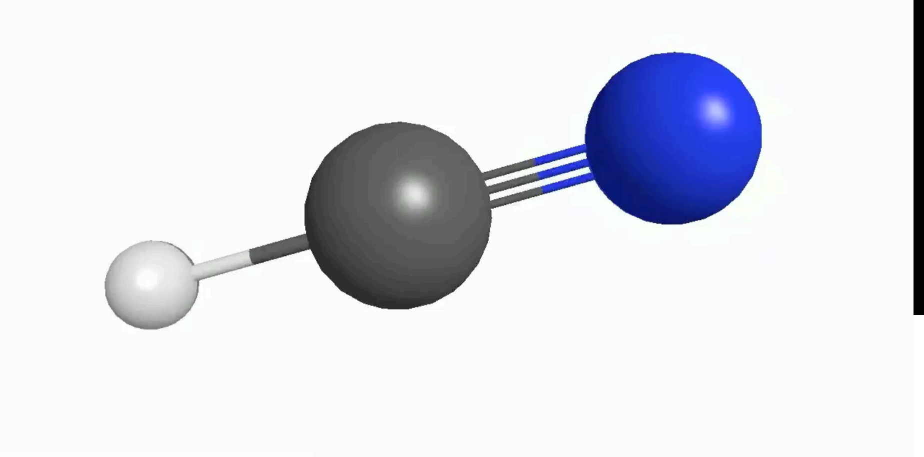
- **HCN is abundant in C-rich AGBs**
  $[HCN/H_2] \sim 10^{-5}$
  (Schöier et al. 2013)

- **Form close to the star** (e.g. Cherchneff 2006)

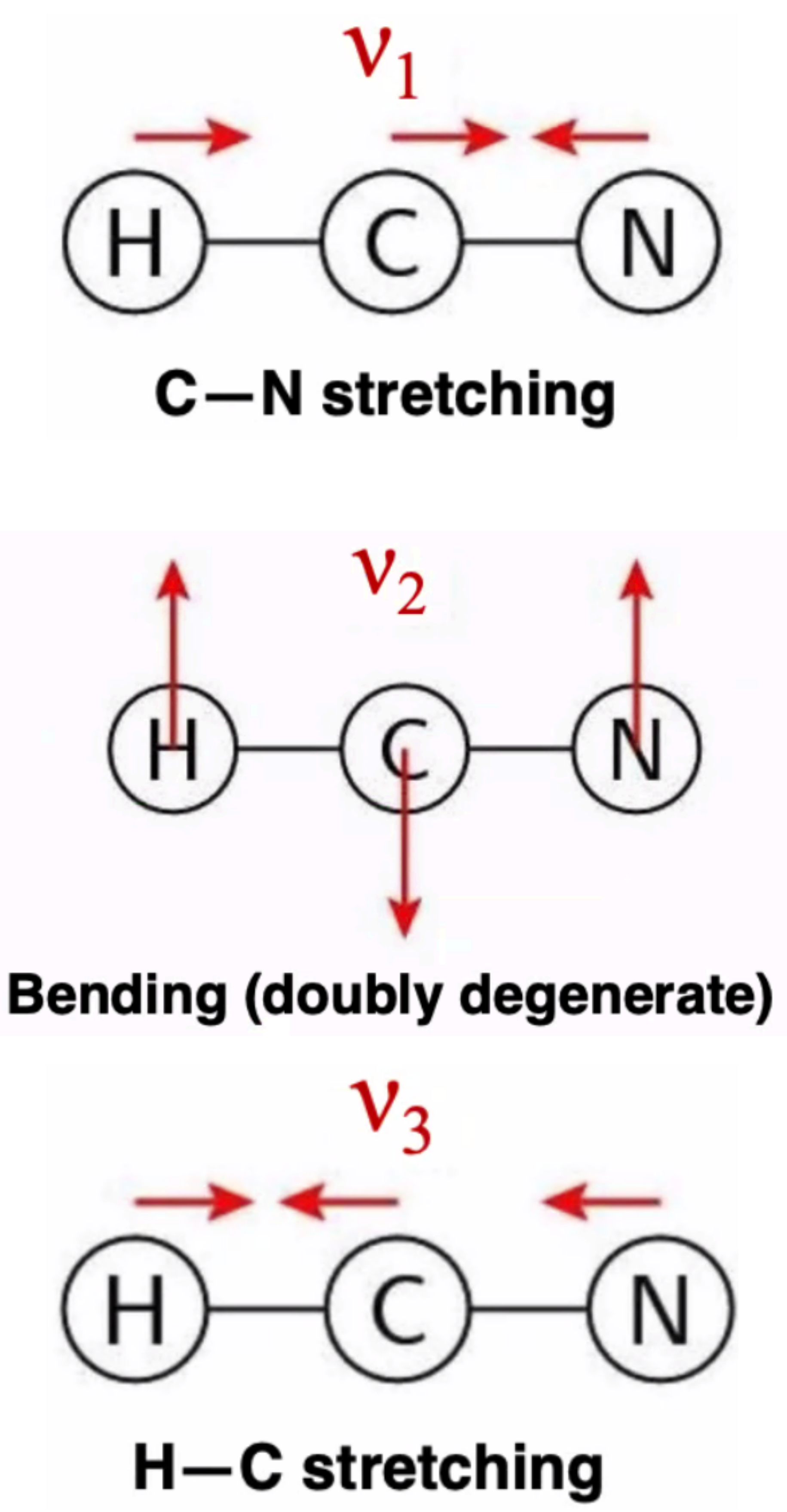
  $CN + H_2 \rightarrow HCN + H$

- **HCN masers exist in > 30 carbon stars**
  (e.g. Menten et al. 2018, Jeste et al. 2022)

- **Strong HCN masers in ground and excited vibrational states)**
  e.g. (0, 2, 0), J = 1–0 (Guilloteau et al. 1987, 1988)
  (0, 0, 0), J = 1–0 (Izumiura et al. 1995)
  (0, 1^1e, 0), J = 2–1 (Jeste et al. 2022)
  ~ a few hundred Jy

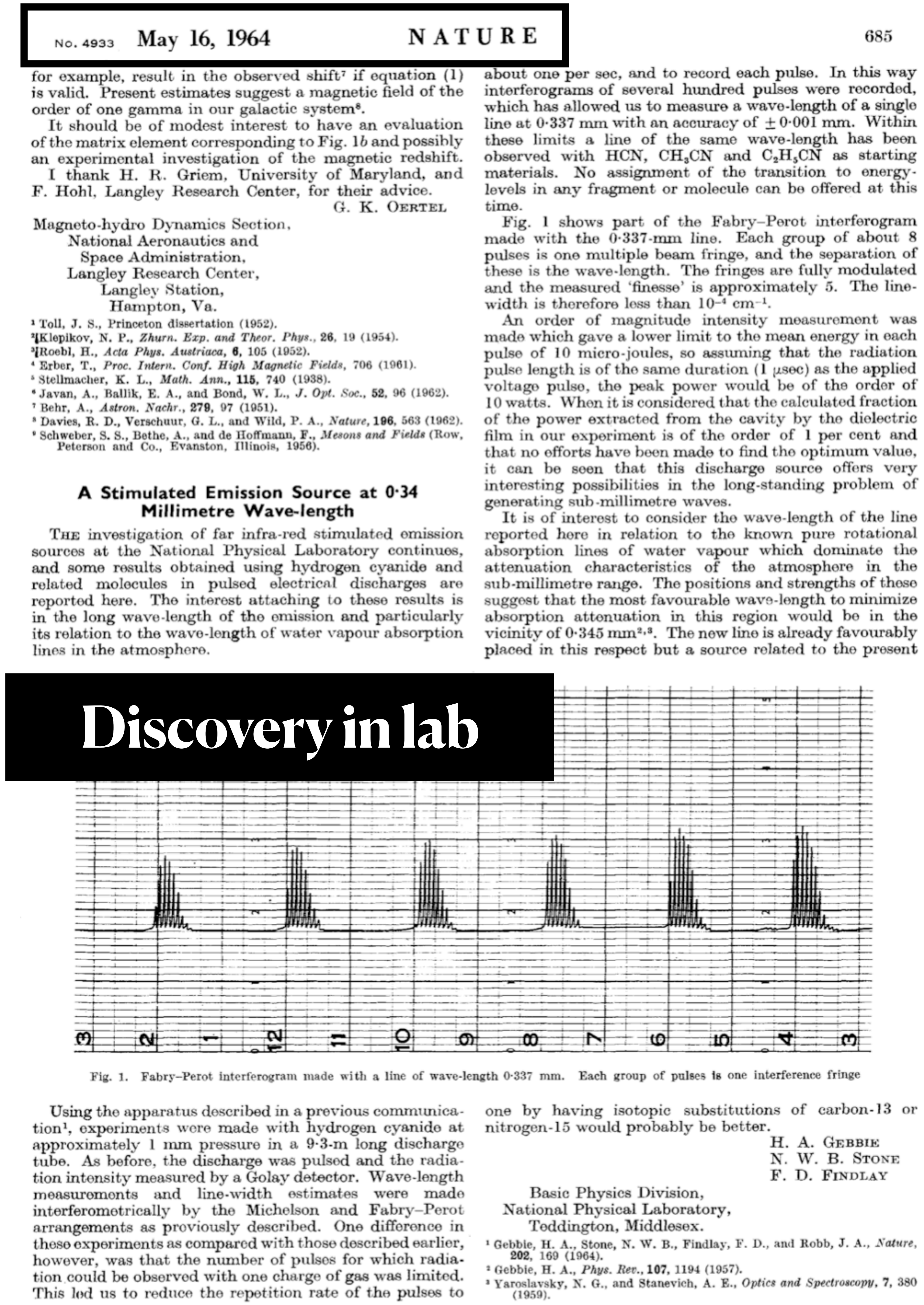


(ν_1, ν_2, ν_3)



Bright HCN laser lines found in Lab

- **First 'HCN' laser was found in lab** (Gebbie et al. 1964)
- **Strong HCN laser confirmation & wavelength measurements** (Lide & Maki 1967, Hocker & Javan 1967)
- **Rotation-vibration interactions of (1, 1^1e, 0) and (0, 4^0, 0) states**



No. 4933 May 16, 1964 NATURE 685

for example, result in the observed shift[7] if equation (1) is valid. Present estimates suggest a magnetic field of the order of one gamma in our galactic system[8].

It should be of modest interest to have an evaluation of the matrix element corresponding to Fig. 1b and possibly an experimental investigation of the magnetic redshift.

I thank H. R. Griem, University of Maryland, and F. Hohl, Langley Research Center, for their advice.

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A Stimulated Emission Source at 0·34 Millimetre Wave-length

THE investigation of far infra-red stimulated emission sources at the National Physical Laboratory continues, and some results obtained using hydrogen cyanide and related molecules in pulsed electrical discharges are reported here. The interest attaching to these results is in the long wave-length of the emission and particularly its relation to the wave-length of water vapour absorption lines in the atmosphere.

Using the apparatus described in a previous communication[1], experiments were made with hydrogen cyanide at approximately 1 mm pressure in a 9·3-m long discharge tube. As before, the discharge was pulsed and the radiation intensity measured by a Golay detector. Wave-length measurements and line-width estimates were made interferometrically by the Michelson and Fabry–Perot arrangements as previously described. One difference in these experiments as compared with those described earlier, however, was that the number of pulses for which radiation could be observed with one charge of gas was limited. This led us to reduce the repetition rate of the pulses to about one per sec, and to record each pulse. In this way interferograms of several hundred pulses were recorded, which has allowed us to measure a wave-length of a single line at 0·337 mm with an accuracy of ±0·001 mm. Within these limits a line of the same wave-length has been observed with HCN, CH_3CN and C_2H_5CN as starting materials. No assignment of the transition to energy-levels in any fragment or molecule can be offered at this time.

Fig. 1 shows part of the Fabry–Perot interferogram made with the 0·337-mm line. Each group of about 8 pulses is one multiple beam fringe, and the separation of these is the wave-length. The fringes are fully modulated and the measured 'finesse' is approximately 5. The line-width is therefore less than 10^{-4} cm^{-1}.

An order of magnitude intensity measurement was made which gave a lower limit to the mean energy in each pulse of 10 micro-joules, so assuming that the radiation pulse length is of the same duration (1 μsec) as the applied voltage pulse, the peak power would be of the order of 10 watts. When it is considered that the calculated fraction of the power extracted from the cavity by the dielectric film in our experiment is of the order of 1 per cent and that no efforts have been made to find the optimum value, it can be seen that this discharge source offers very interesting possibilities in the long-standing problem of generating sub-millimetre waves.

It is of interest to consider the wave-length of the line reported here in relation to the known pure rotational absorption lines of water vapour which dominate the attenuation characteristics of the atmosphere in the sub-millimetre range. The positions and strengths of these suggest that the most favourable wave-length to minimize absorption attenuation in this region would be in the vicinity of 0·345 mm[2,3]. The new line is already favourably placed in this respect but a source related to the present one by having isotopic substitutions of carbon-13 or nitrogen-15 would probably be better.

Fig. 1. Fabry–Perot interferogram made with a line of wave-length 0·337 mm. Each group of pulses is one interference fringe

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[1] Gebbie, H. A., Stone, N. W. B., Findlay, F. D., and Robb, J. A., *Nature*, **202**, 169 (1964).
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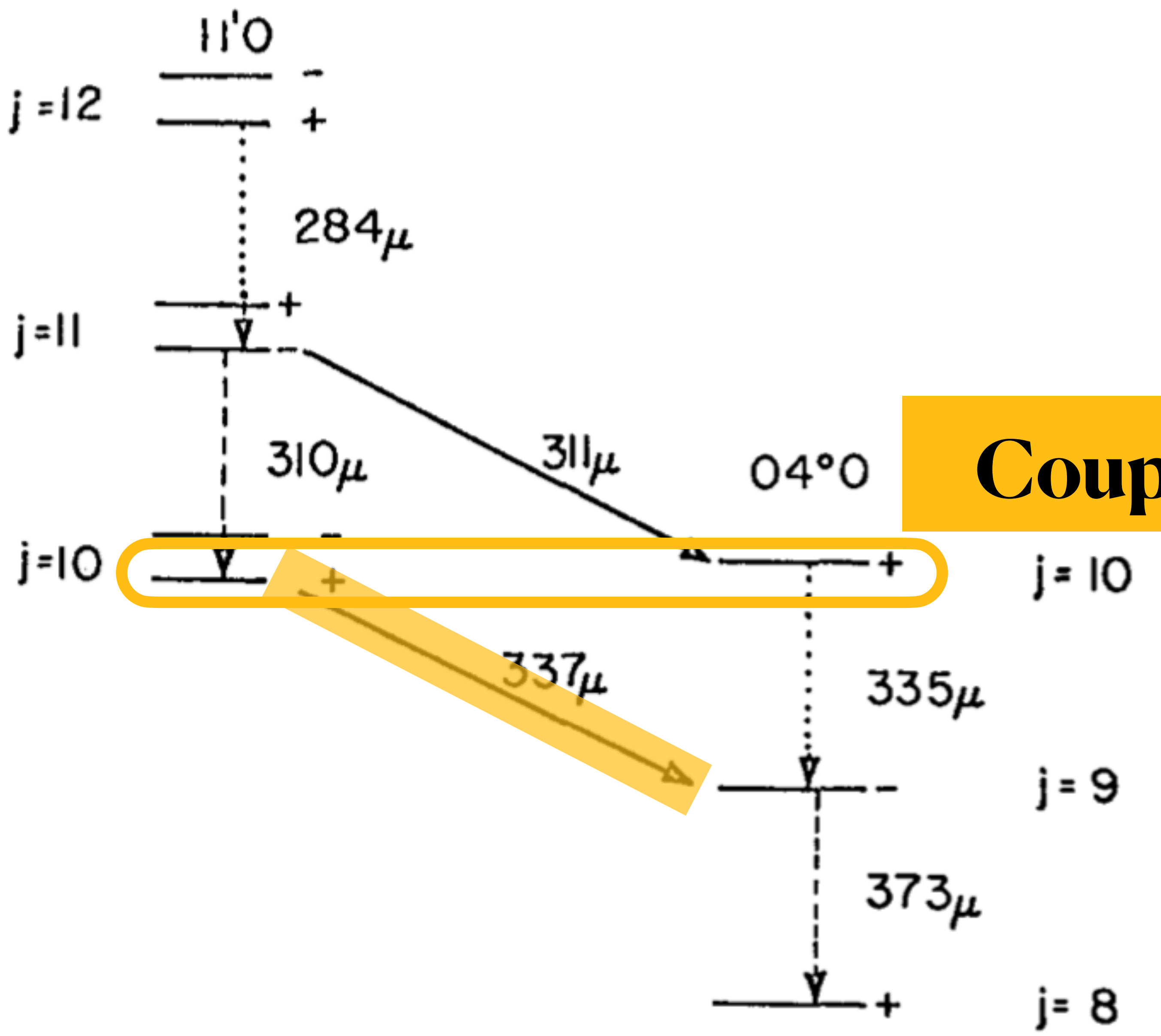
Discovery in lab

Confirmation of HCN laser

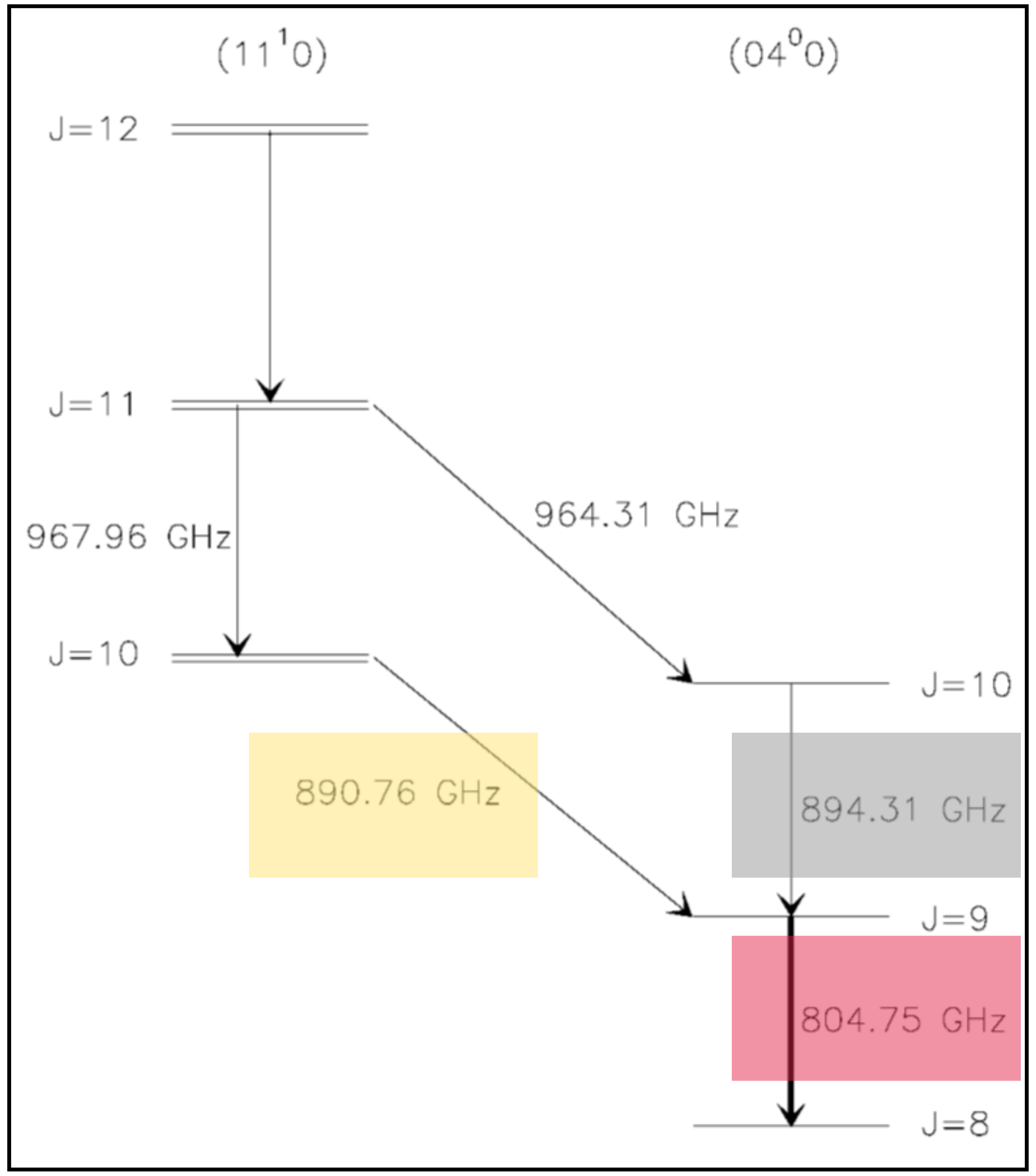


Coupling

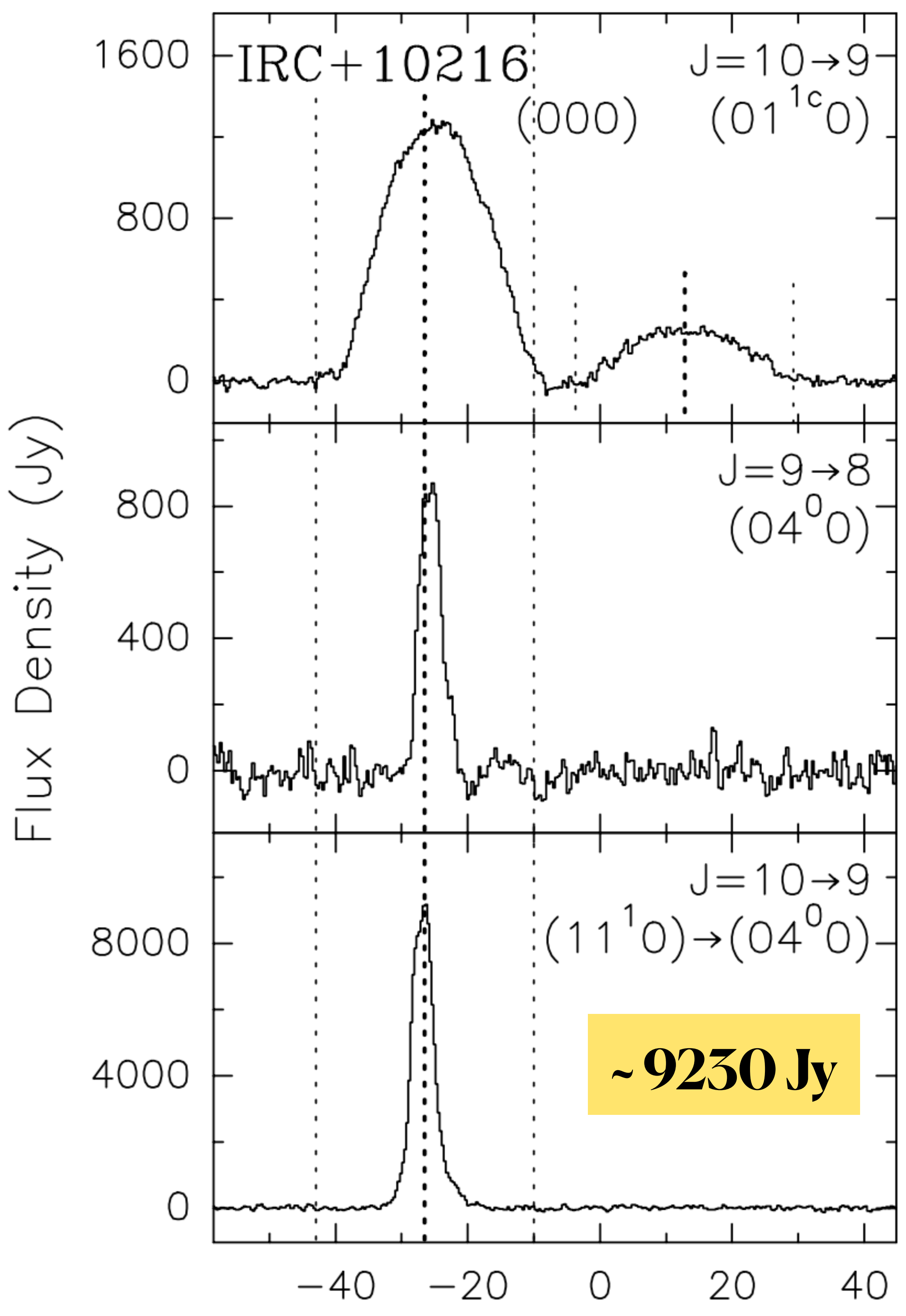
Coriolis-coupled system

HCN Laser in astronomy

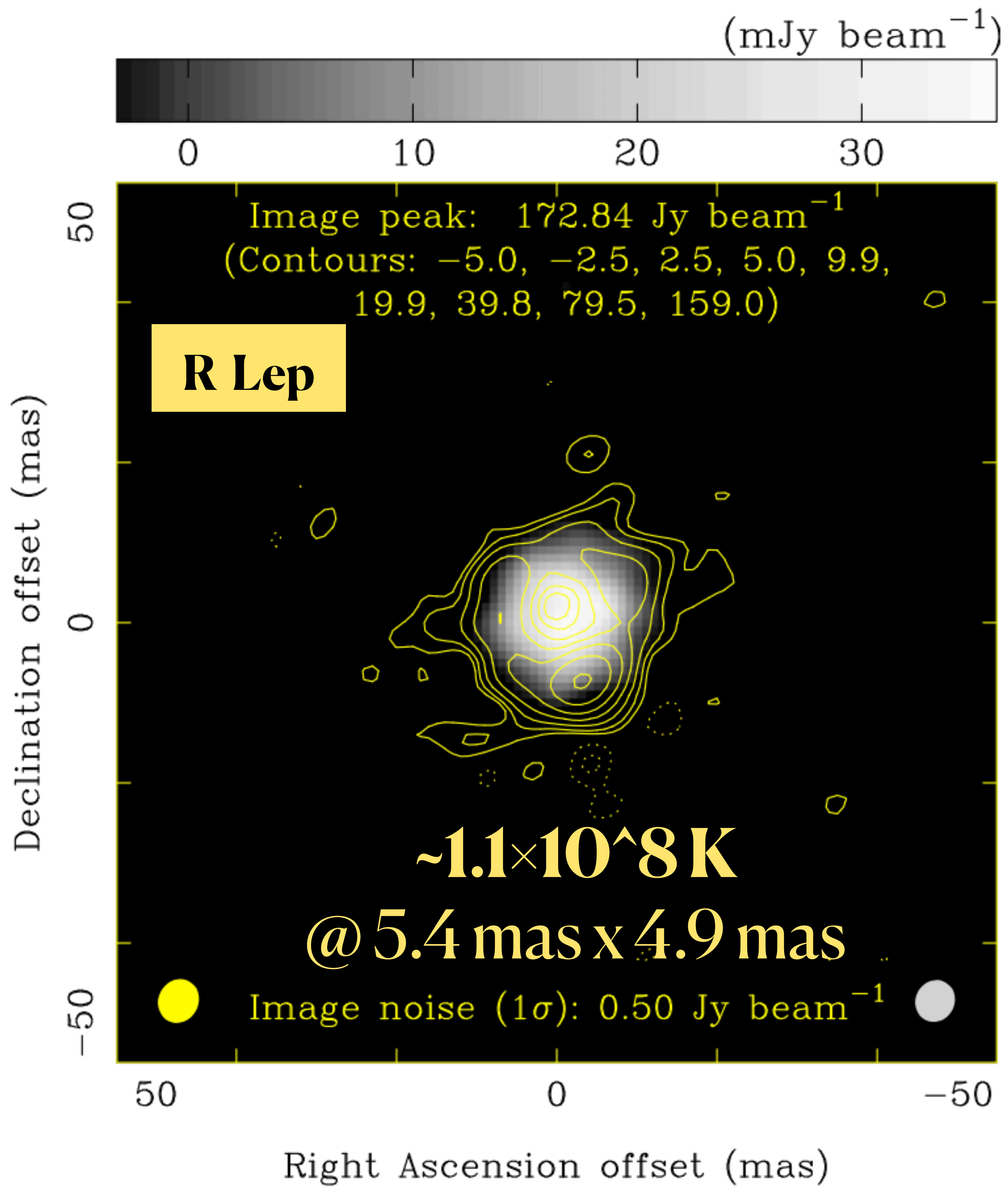
- **(0, 4^0, 0), J= 9–8** (Schilke et al. 2000): **805 GHz**
- **(1, 1^1e, 0)–(0, 4^0, 0) , J= 10–9** (Schilke & Menten 2003): **891 GHz**



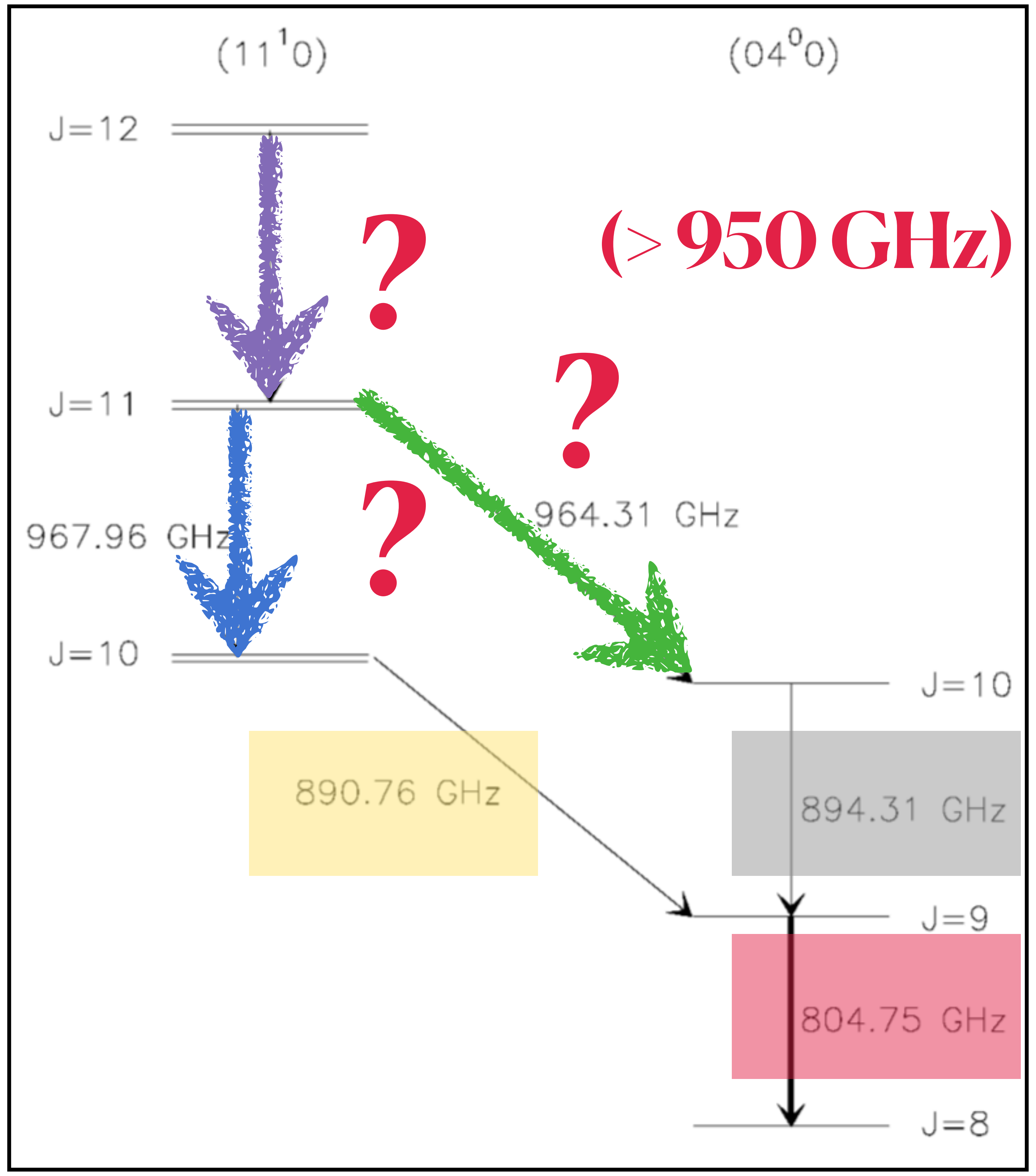
CSO spectra (Schilke & Menten 2003)



ALMA image (Asaki et al. 2023)

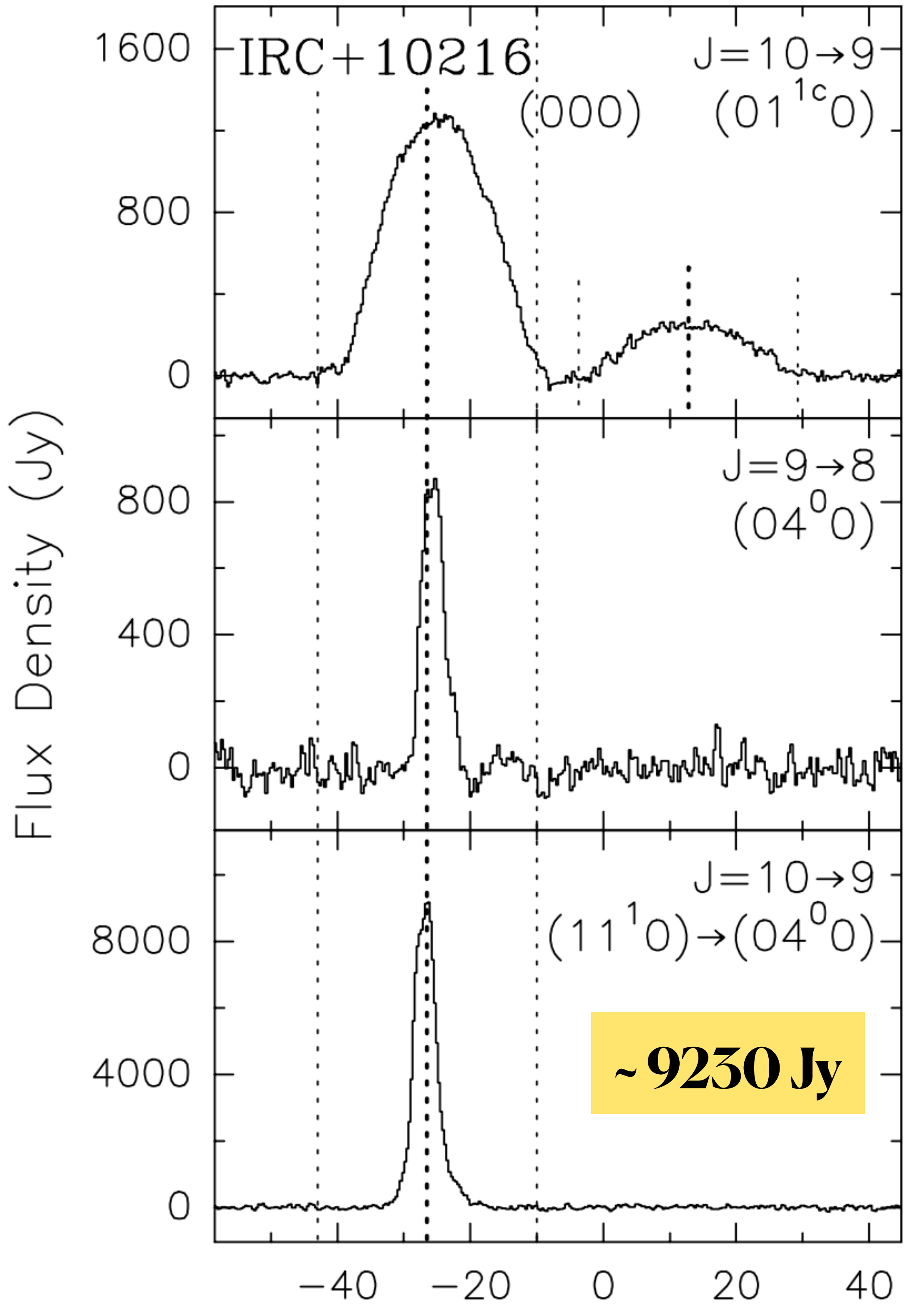


HCN Laser in astronomy

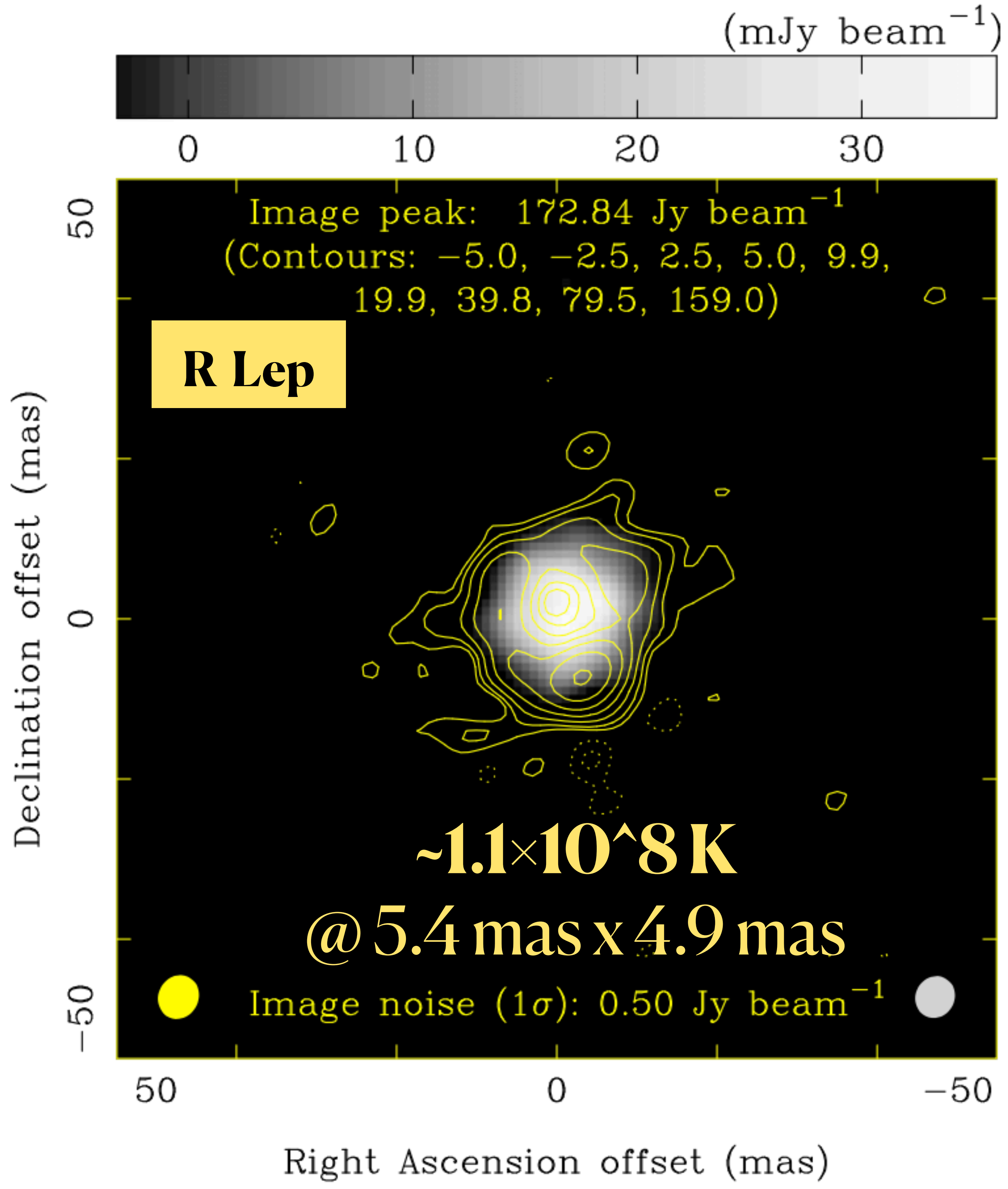


- (0, 4^0, 0), J= 9–8 (Schilke et al. 2000): 805 GHz
- (1, 1^1e, 0)–(0, 4^0, 0) , J= 10–9 (Schilke & Menten 2003): 891 GHz

CSO spectra (Schilke & Menten 2003)



ALMA image (Asaki et al. 2023)



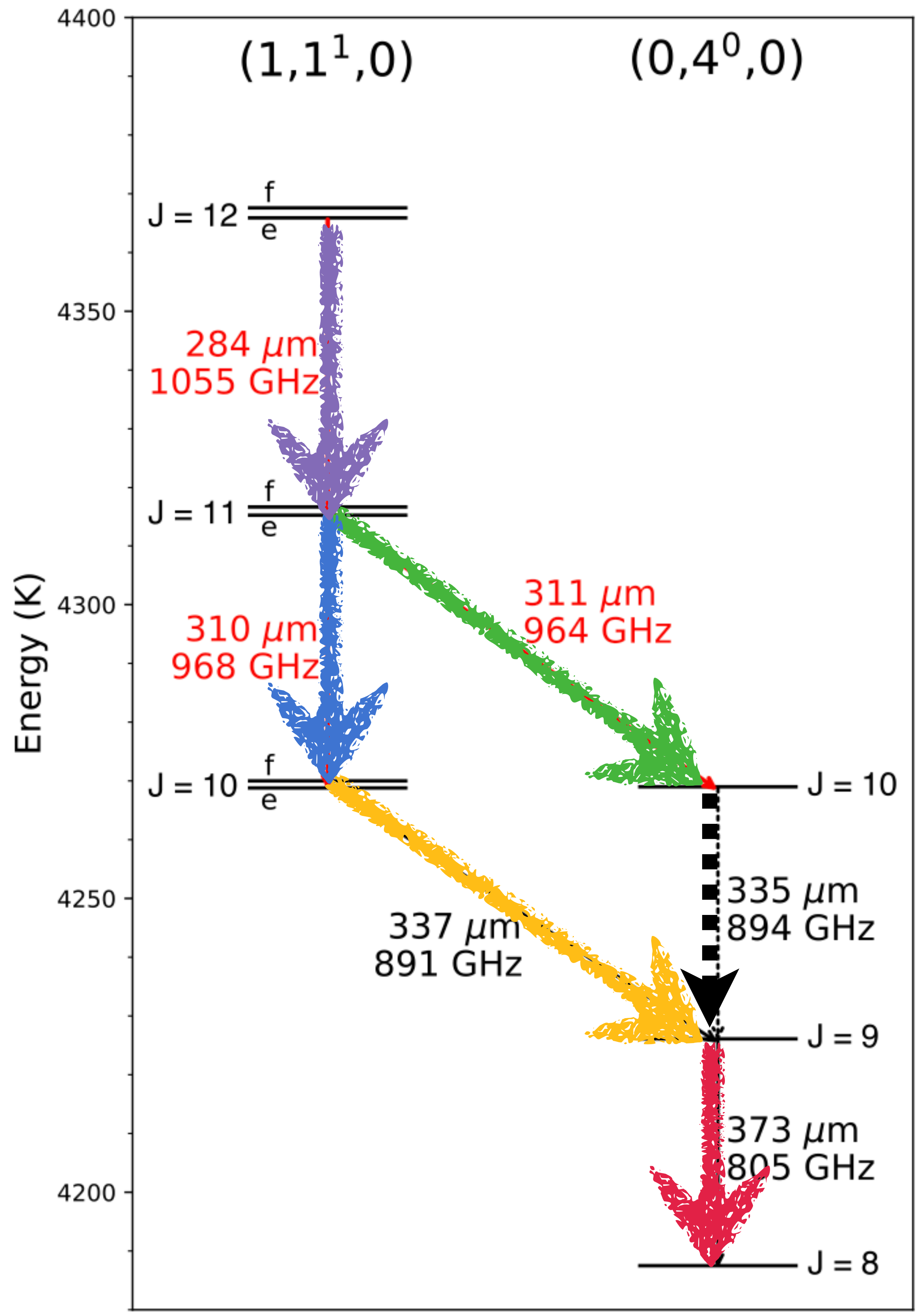
Impossible ground-based observations (> 950 GHz)

- **SOFIA** (Stratospheric Observatory For Infrared Astronomy)
  2010 – 2022 Sep. / 2.5 m
  4GREAT (German REceiver for Astronomy at Terahertz Frequencies)
- **Herschel**
  2009 May — 2013 Jun. / 3.5 m
  HIFI (Heterodyne Instrument for the Far- Infrared)

SOFIA

Herschel

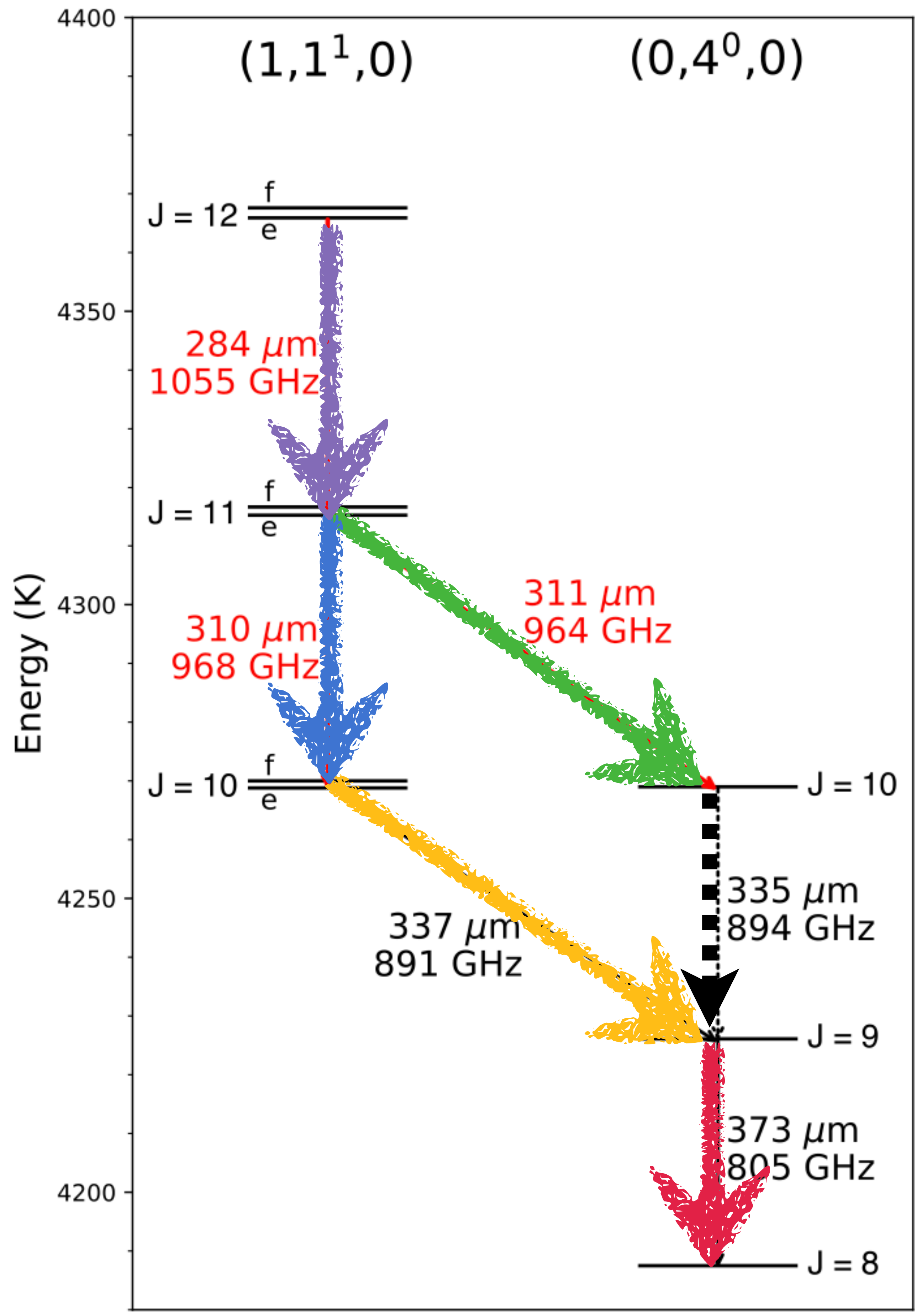
SOFIA observations & Herschel Archives



- **Archival Herschel / HIFI data** (PIs: J. Cernicharo, E. De Beck; 6 projects)
  - > observations that cover all 6 lines: 805, 891, 894, 964, 968, 1055 GHz
  - > **8 stars**: IRC+10216, CIT 6, Y CVn, S Cep, IRC+50096, V Cyg, II Lup, CRL 3068
  - > **IRC+10216**: observed in 6 epochs from 2010 May — 2013 Apr.
  - > beam size: 20" — 26", channel spacing: ~0.15 km/s

- **SOFIA / 4GREAT observations** (PI: K. M. Menten; Project id: 83_0625)
  - > IRC+10216 : 891, 964, 968, 1055 GHz
  - > CIT 6, Y CVn, S Cep: 964, 968 GHz
  - > One flight observations on 2018 Dec. 17, beam size: 26" — 31", channel spacing: ~0.15 km/s

SOFIA observations & Herschel Archives



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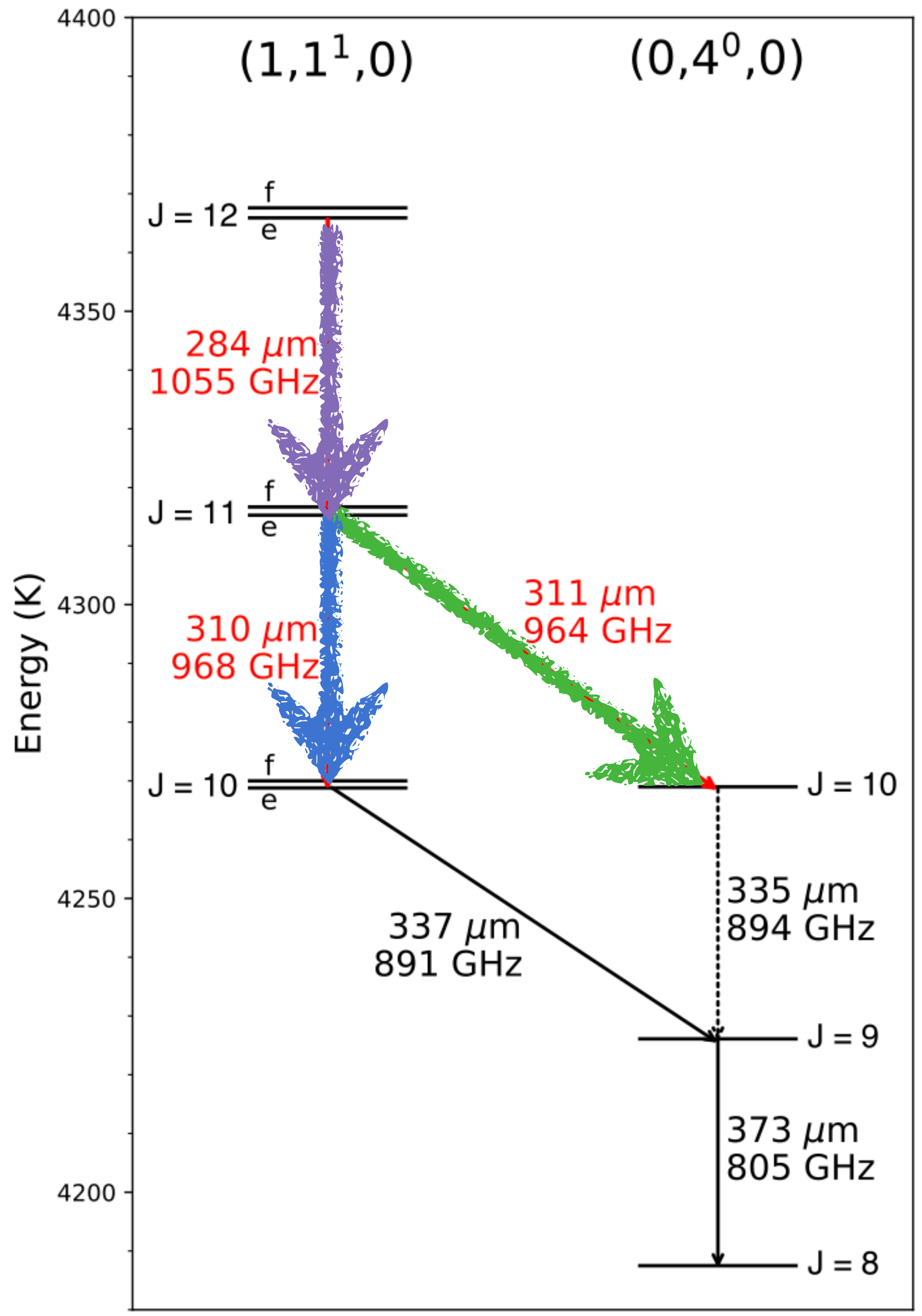
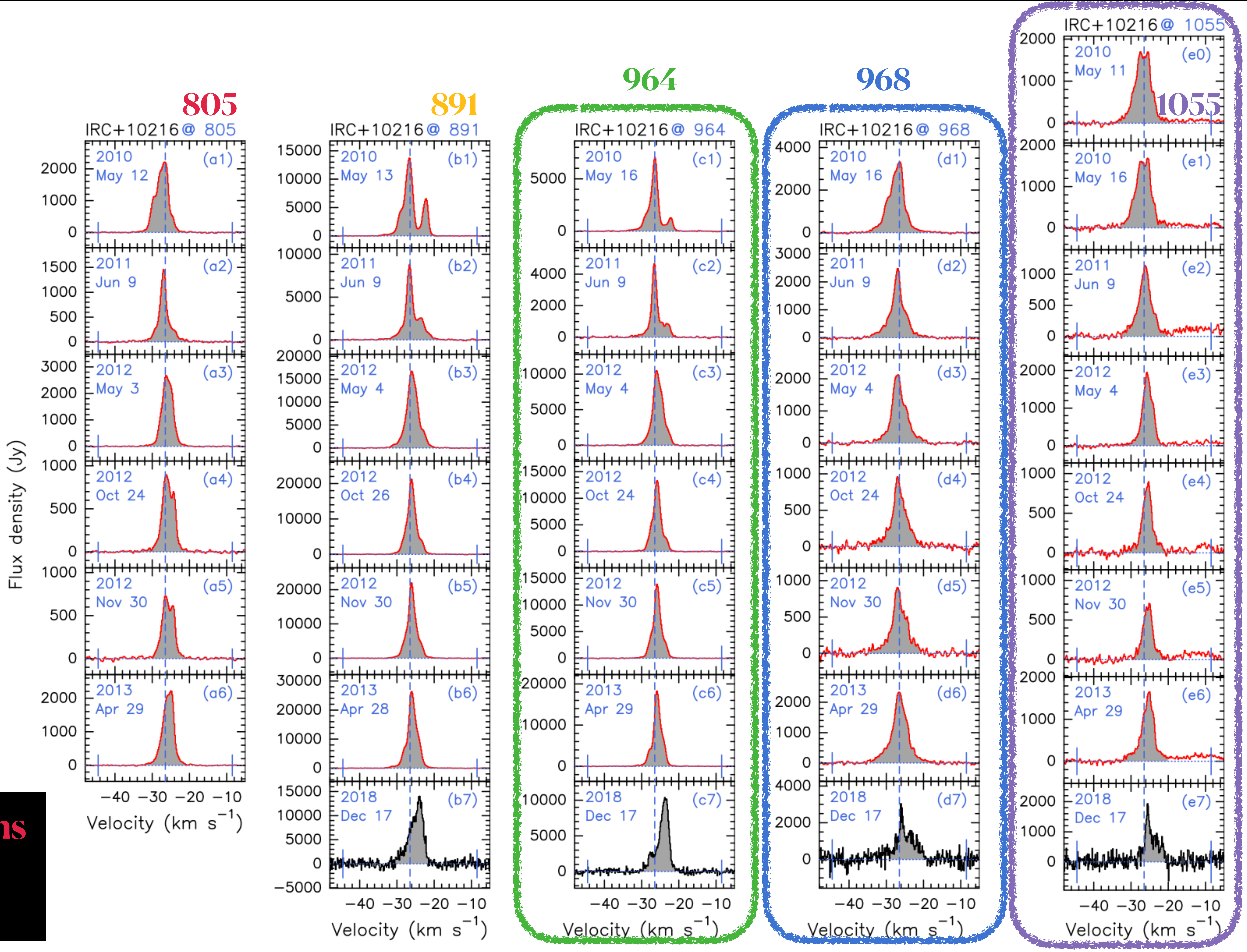
- **Detection overview**
  > 805, 891, **964** GHz: detected in **7** / 8 stars
  > **968** GHz: detected in **6** / 8 stars
  > **1055** GHz: detected in **5** / 8 stars
  > **894 GHz: 0 star**
  > CRL 3068: no HCN laser lines detected

Widespread !

[Yang et al. 2025, A&A, 696, A60]

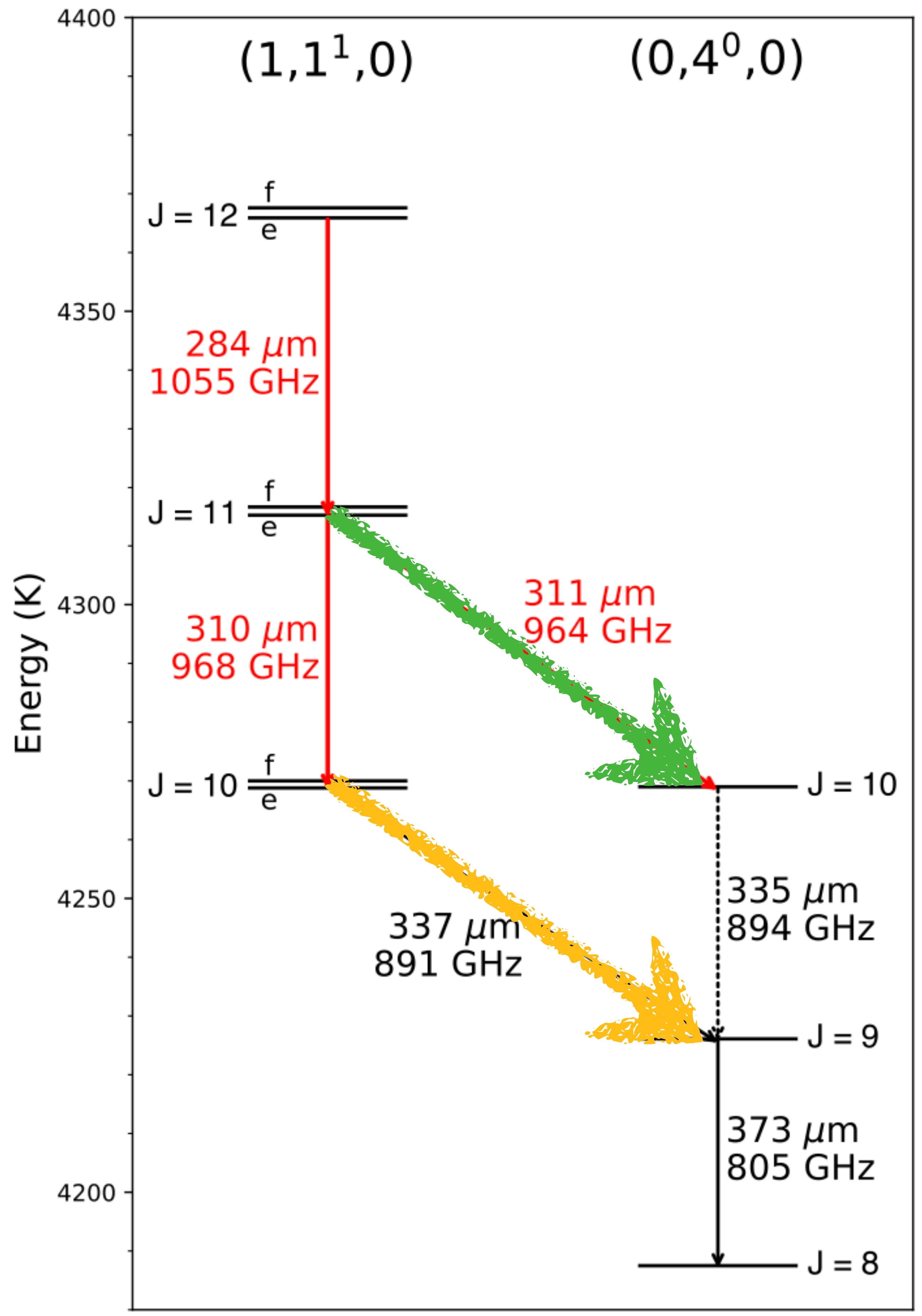
IRC+10216: HCN Laser detections

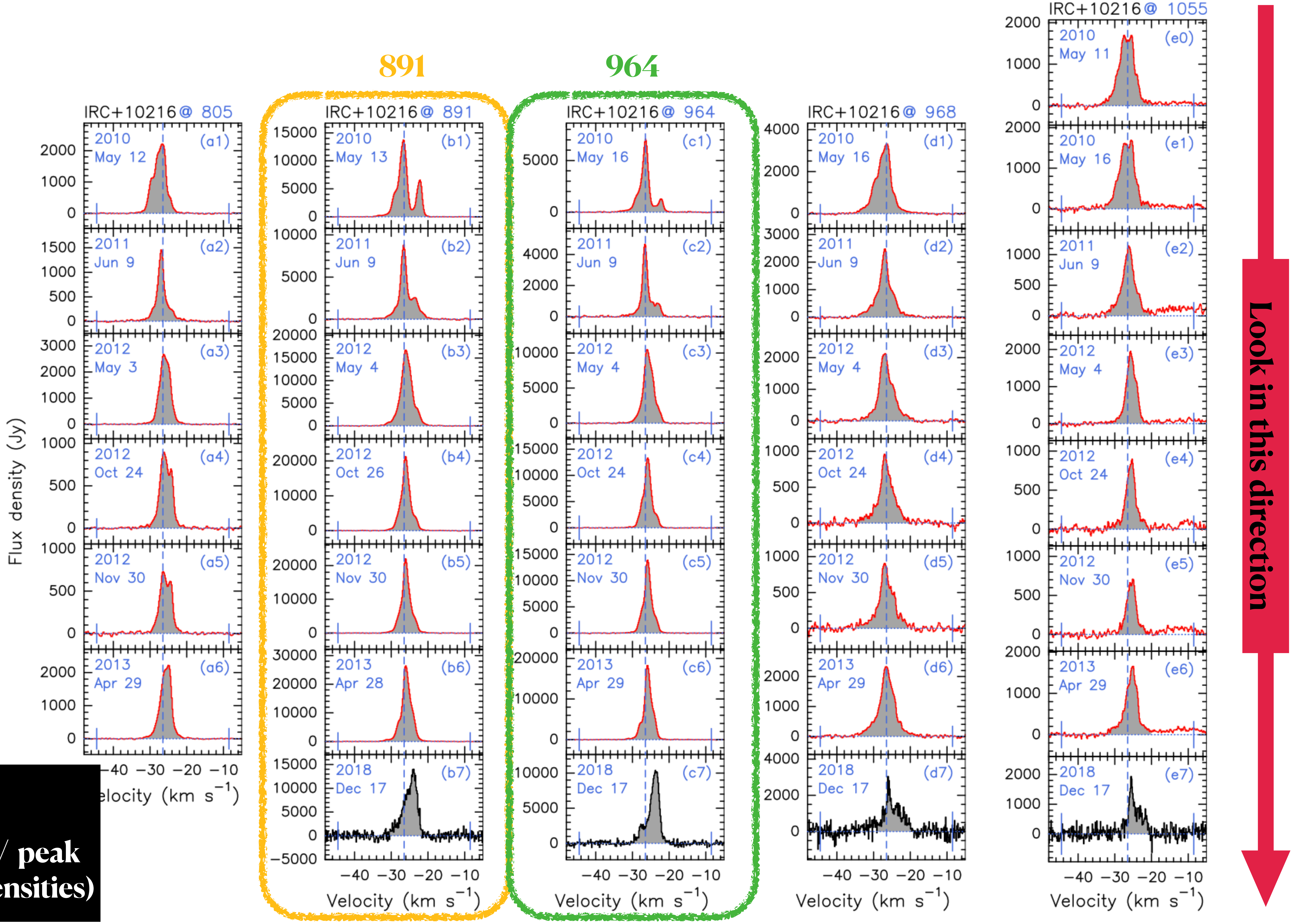




Discovery of HCN laser transitions at 964, 968 & 1055 GHz in space

Laser variability (line profile)

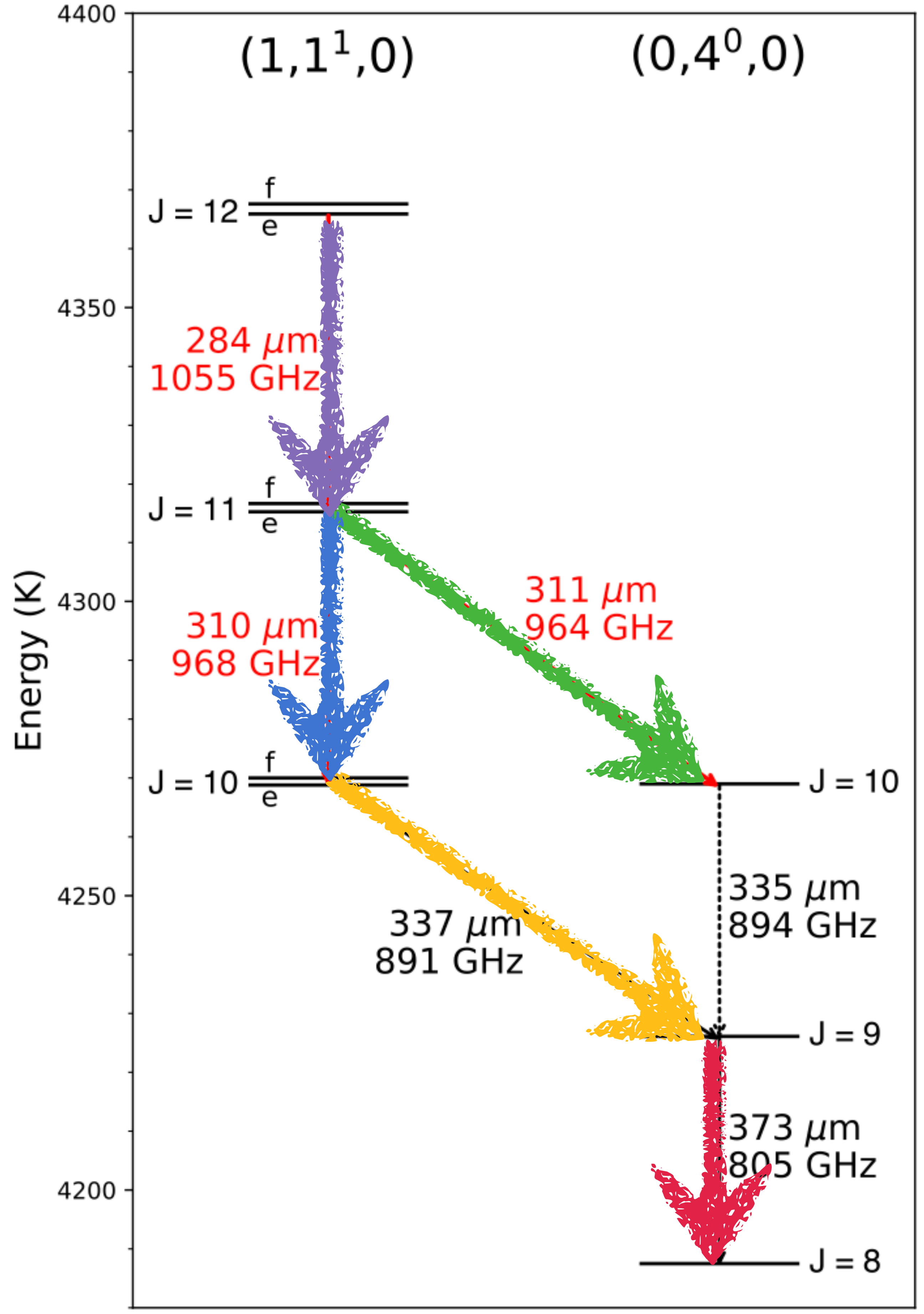




Dramatically changed

(number of laser features / feature widths / peak velocities / peak intensities / integrated intensities)

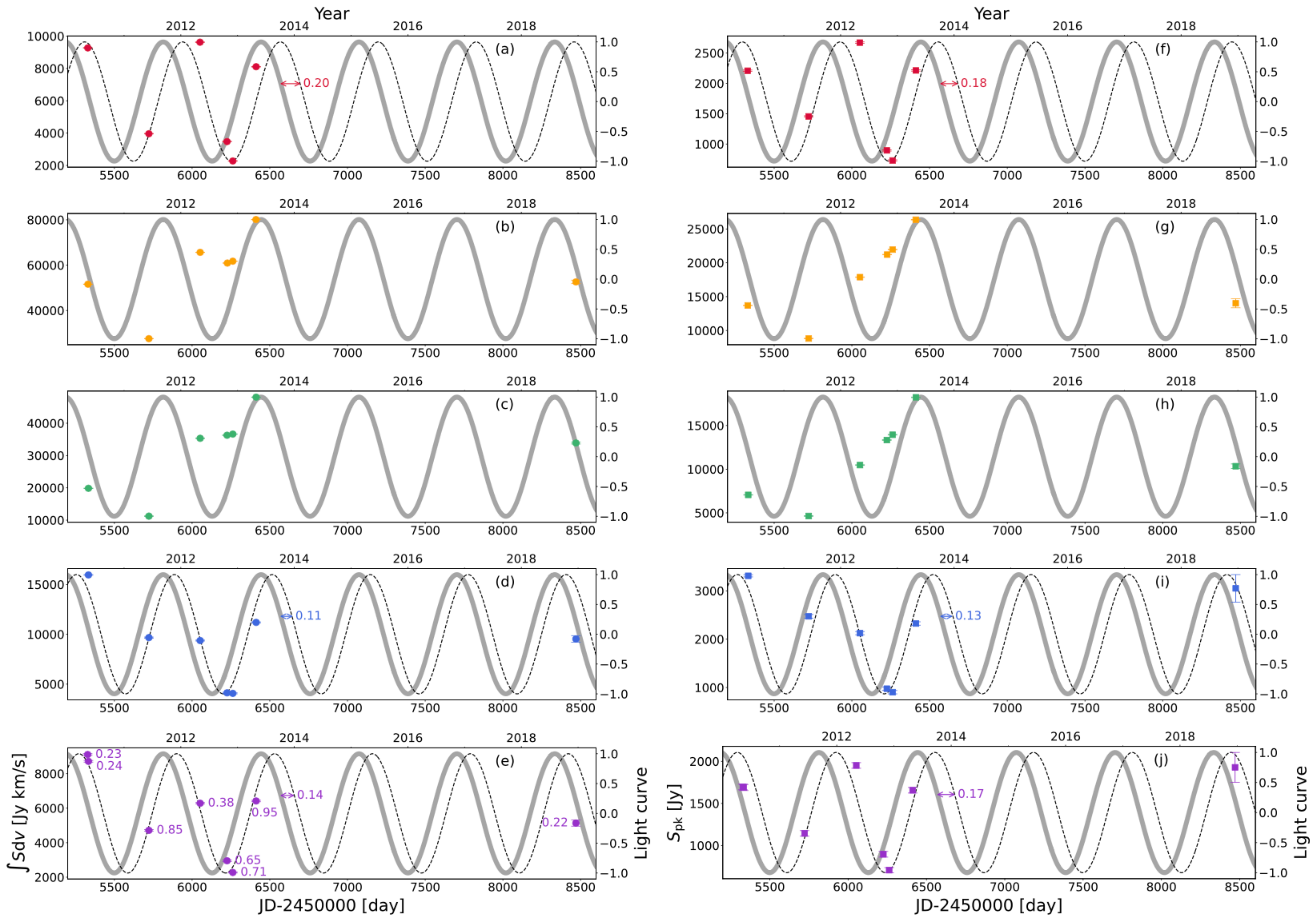
Laser Variability (intensity vs. NIR light curve)



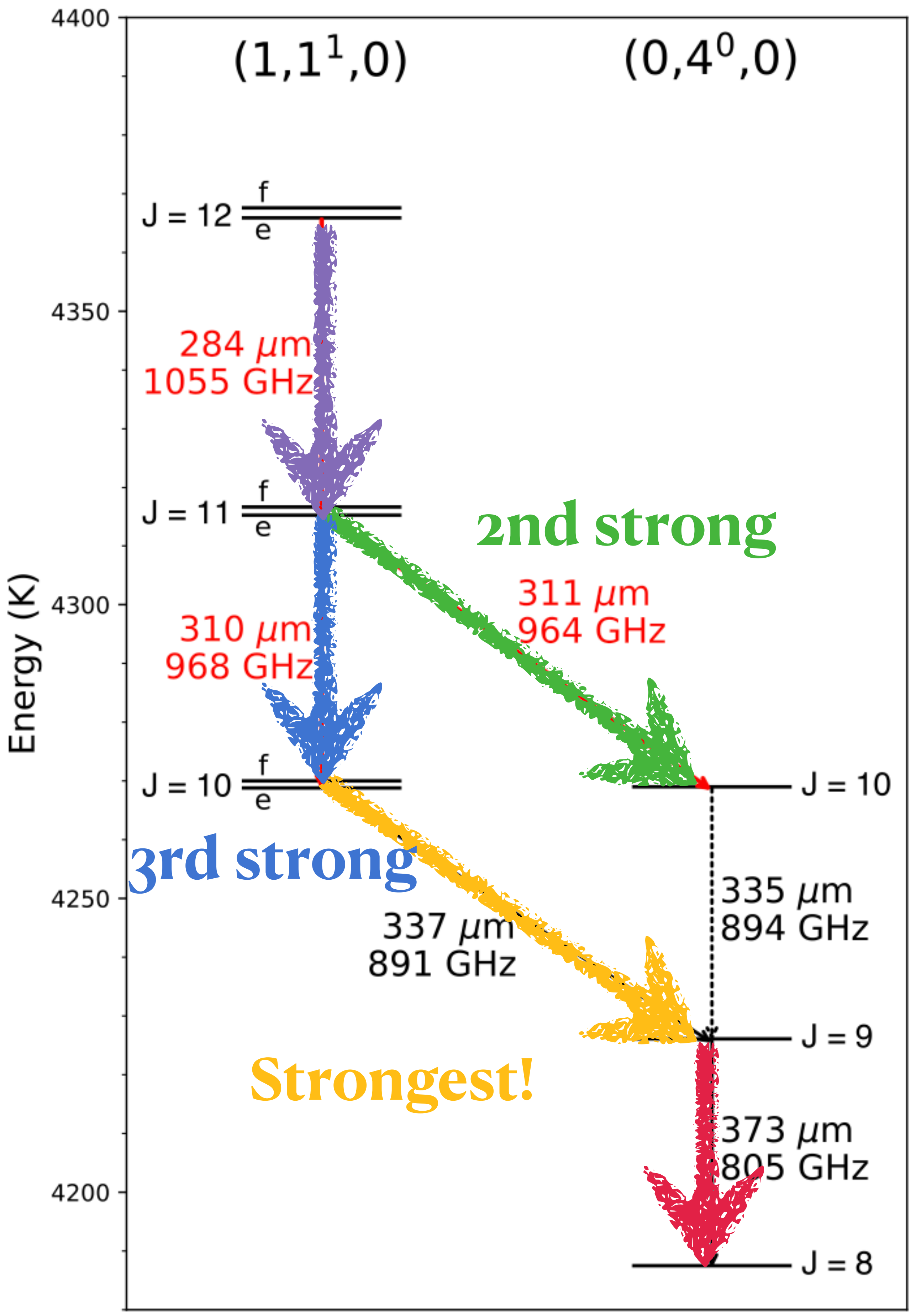
Two variation patterns
Cross-ladder lines (891 & 964 GHz)
Rotational lines (804, 968 & 1055 GHz)

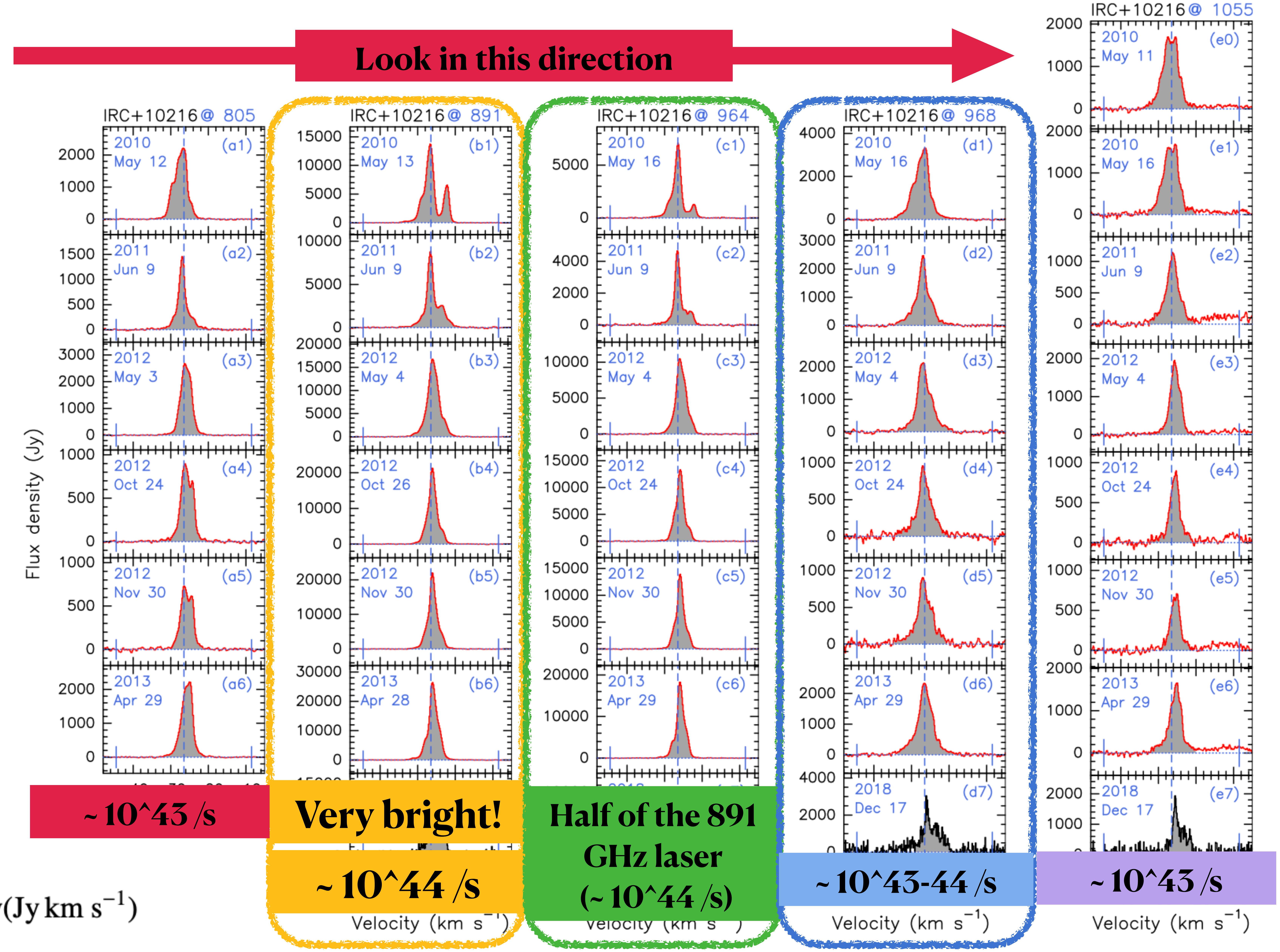
Integrated intensity

Peak intensity



Laser comparison

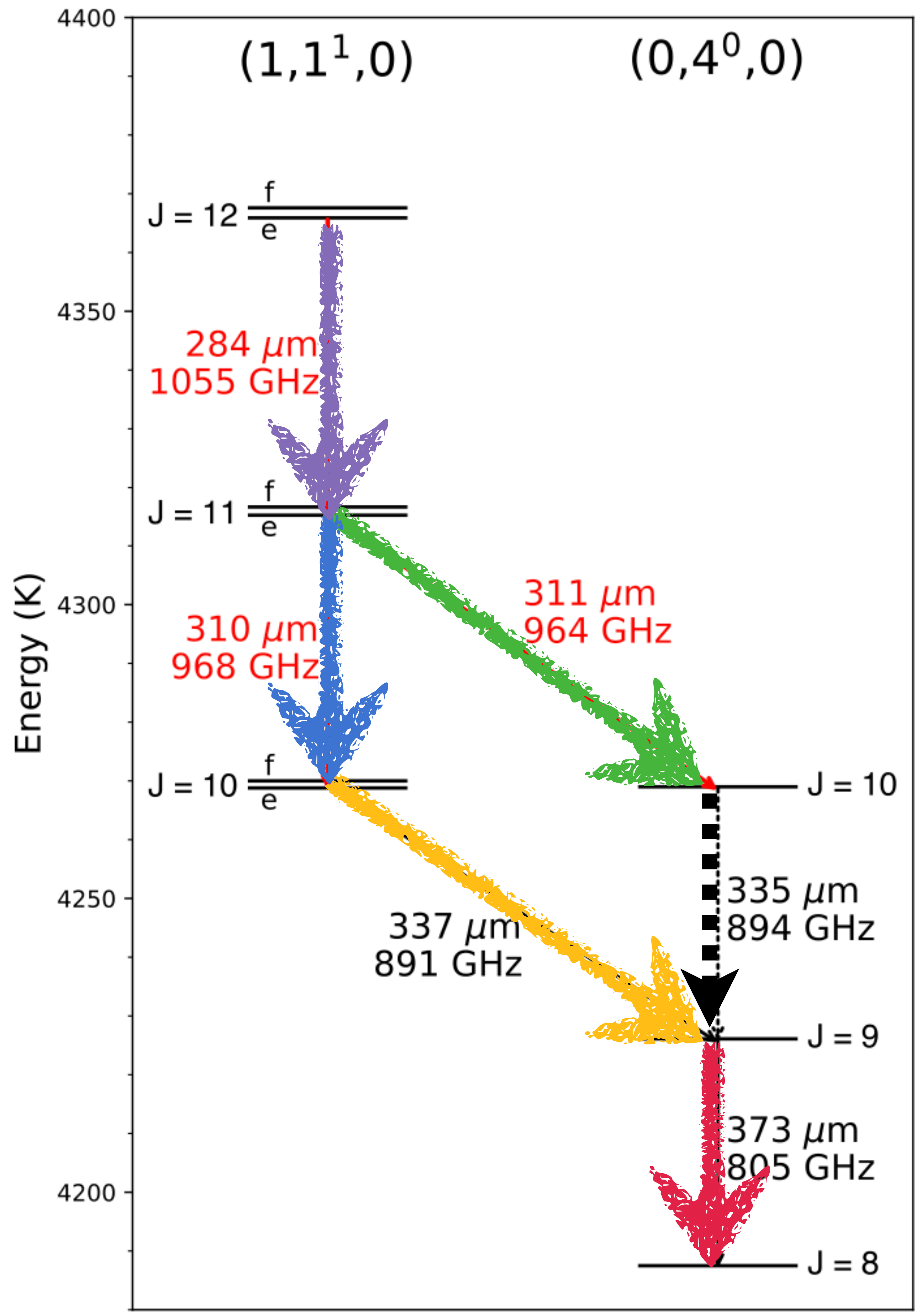




Isotropic luminosity (**photon rate**)

$$L_{\mathrm{HCN}}(\mathrm{photons\ s^{-1}}) = 6.04\times10^{41}\ D^2(\mathrm{kpc}) \int S\,\mathrm{d}v(\mathrm{Jy\ km\ s^{-1}})$$

HCN Laser excitation



[Yang et al. 2025, A&A, 696, A60]

Observation Findings:

1. 891 GHz laser always strongest
2. 964 GHz laser is similar to 891 GHz laser, 2nd strong
3. 968 GHz laser stronger than 1055 GHz laser
4. 804 GHz laser co-exists with 891 GHz laser
5. 894 GHz line was not detected in any observed targets

Match the scenario revealed in early laboratory studies (Maki & Blaine 1964; Lide & Maki 1967)

Cross-ladder lines (891 & 964) dominate the population

Chemical pumping

Possible

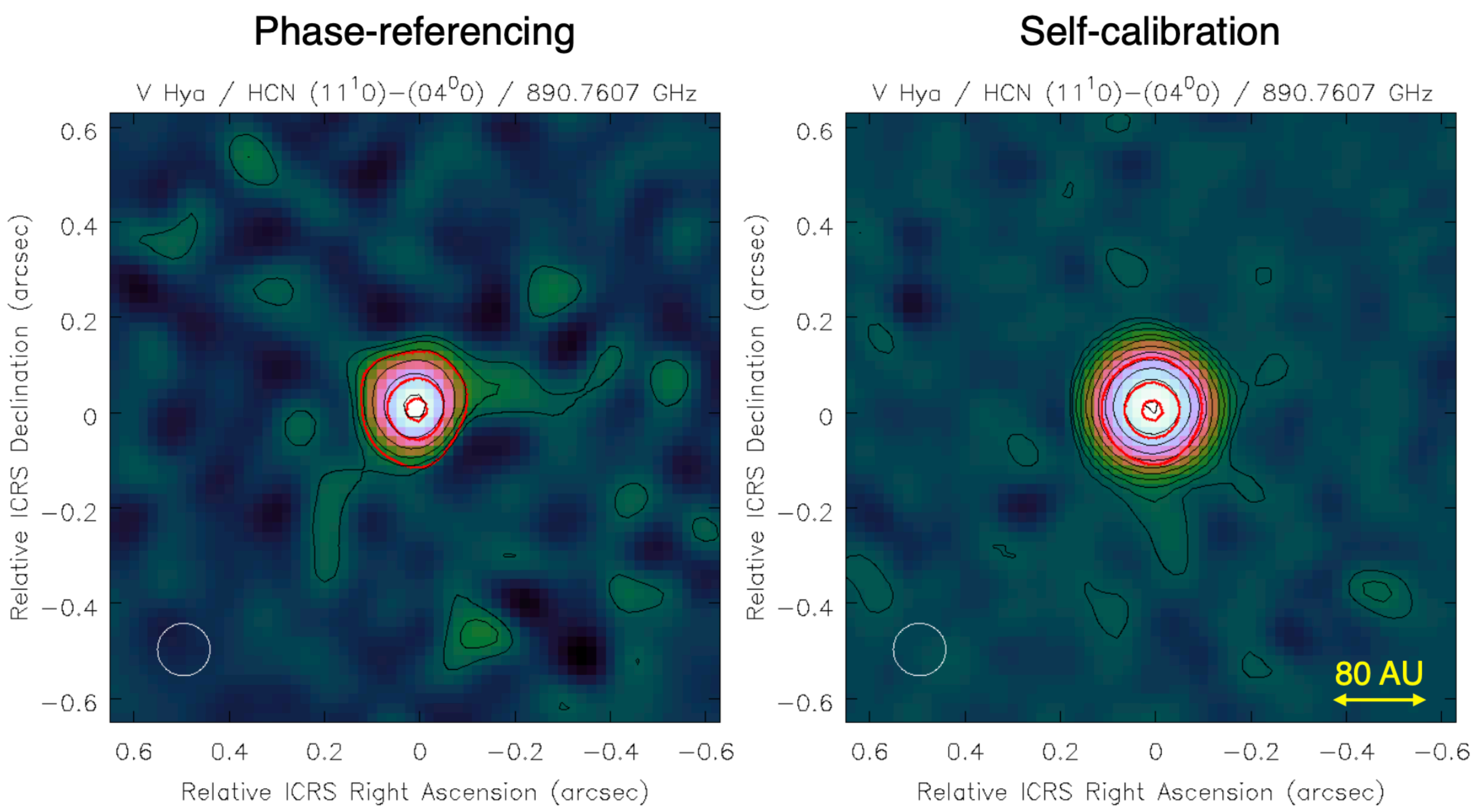
Direct formation of HCN molecules in vibrationally excited states

Outlook

ALMA Cycle 6 (main 12 m array)
> 805 GHz: R For, R Lep, CQ PyX, V Hya
> 891 GHz: R For, R Lep, CQ PyX, **V Hya**, IRC+10216, X Vel

ALMA Cycle 10 (ACA array)
> 805, 891 & 894 GHz
> 36 stars to be observed

PI: Ka Tat Wong



Contours: 3, 6, 12, 24, 48, 96 × 4.0 Jy/beam
Dynamic range ~ 107

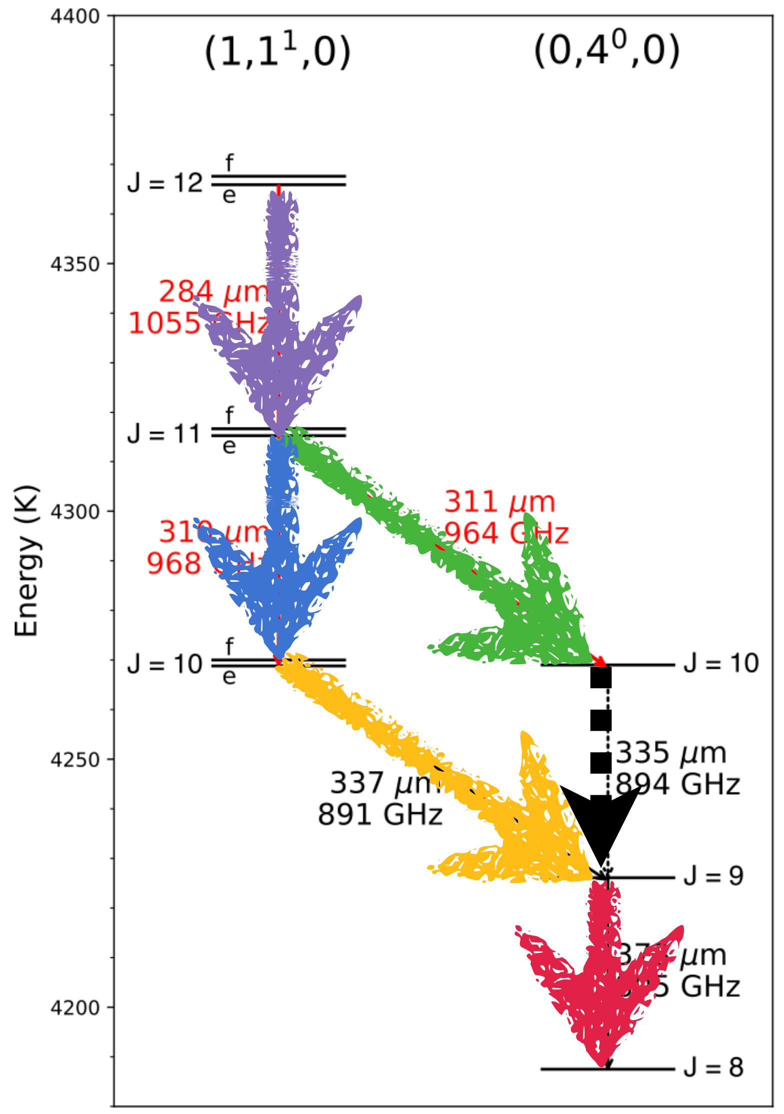
Contours: 3, 6, 12, …, 3072 × 0.18 Jy/beam
Dynamic range ~ 3100 (29× improvement)

Challenging phase calibration
Lack of nearby, bright-enough quasars

Self-calibration with HCN laser lines

Achieving angular resolution of <10 mas with ALMA
→ stellar surface tomography, hydrodynamics

Summary



- **Discovery of three HCN Laser lines in space :**
  964 , 968 & 1055 GHz

- **Systematically study the HCN Lasers in the Coriolis-coupled system:**
  variability, excitation & possible pumping mechanisms

[Yang et al. 2025, A&A, 696, A60]

For memory of Prof. Karl Menten

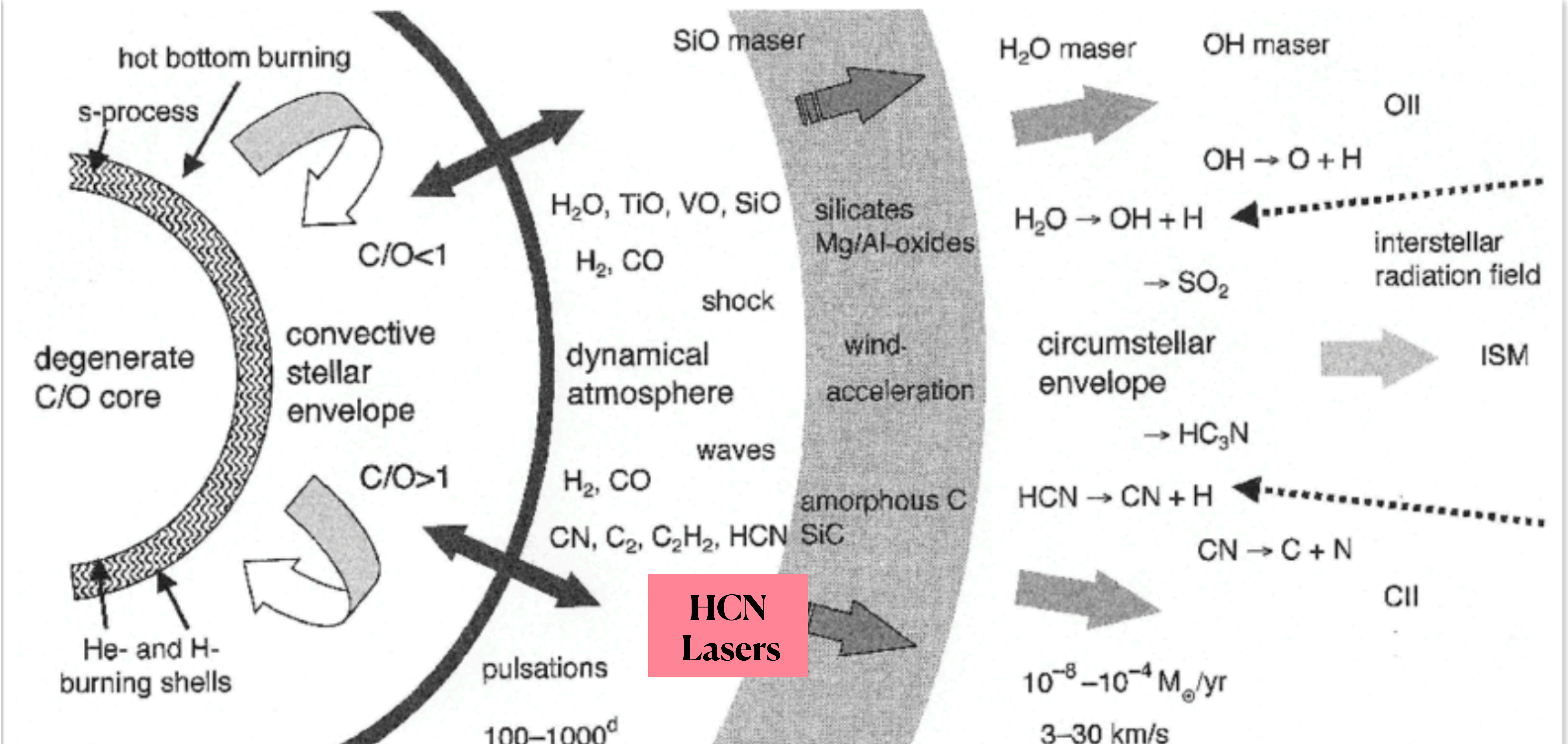


Image credit: Hron/Le Bertre

Thanks!