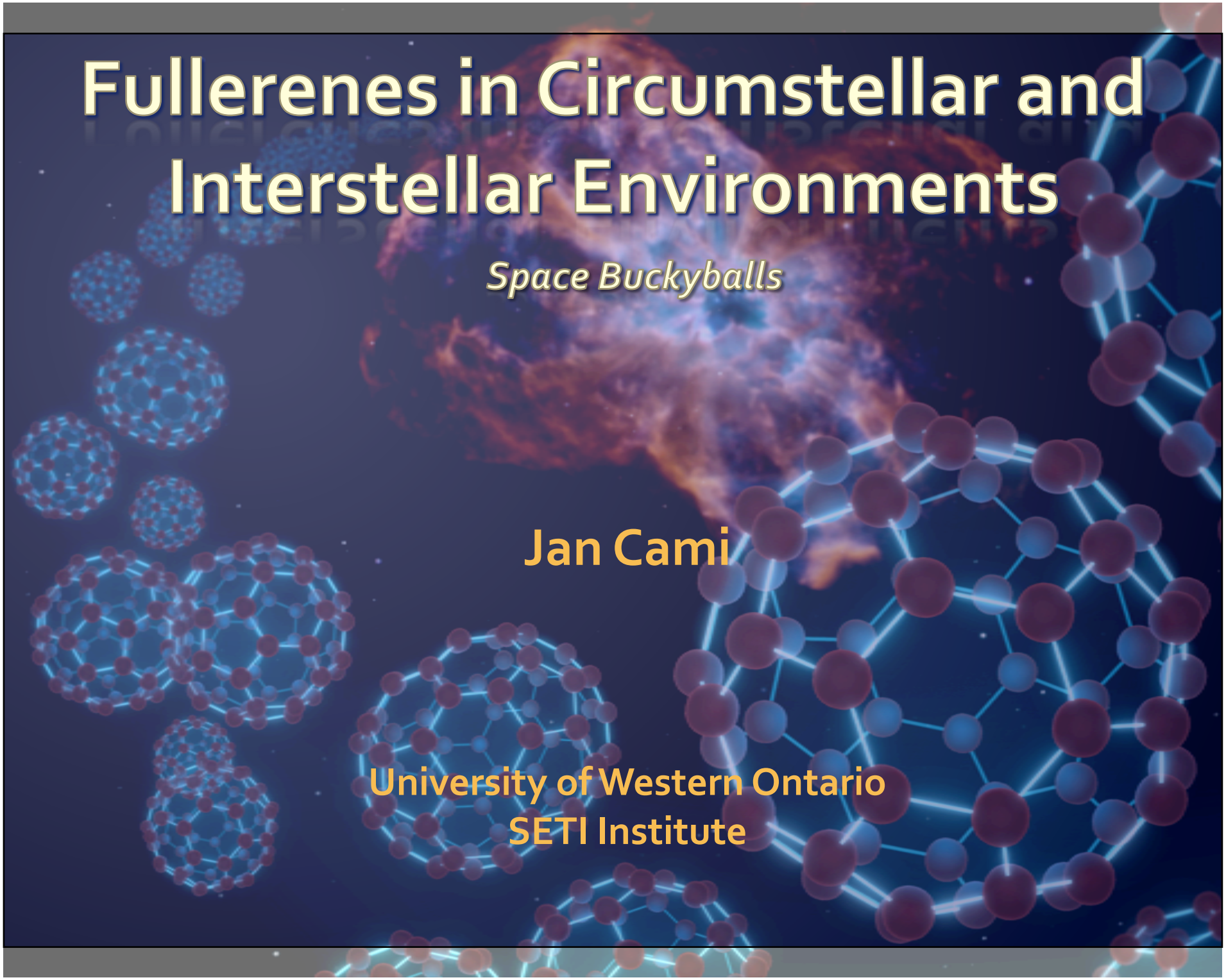

Fullerenes in Circumstellar and Interstellar Environments
Space Buckyballs
Jan Cami
University of Western Ontario
SETI Institute

Outline & Key Points

- Intro: Meet the Fullerenes.
- Astronomical Detections

Lifecycle of fullerenes
Formation?

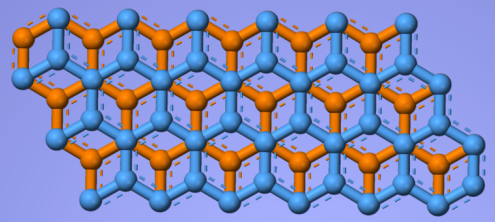
- Surprises: neutral and cool.

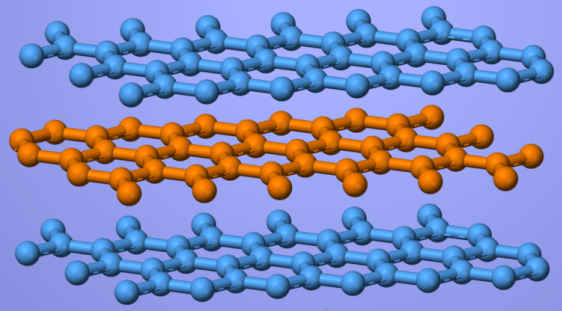
Excitation mechanism?
State (solid/gas)

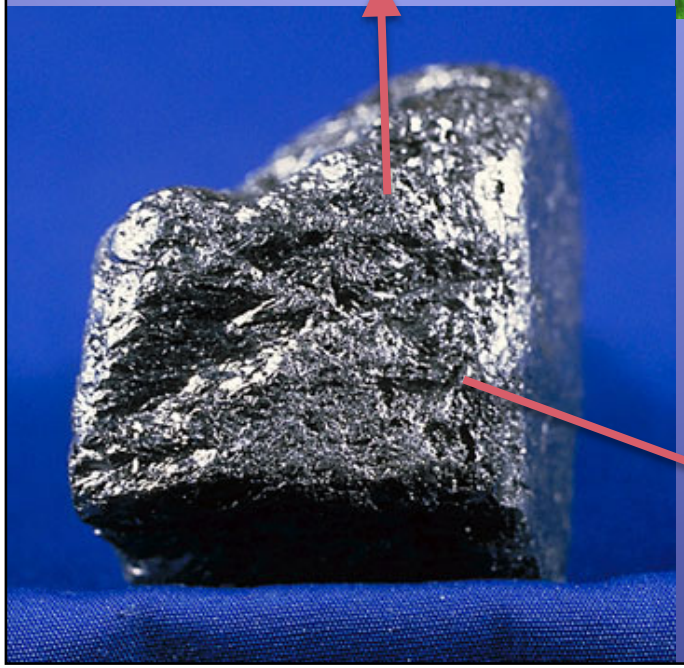
- Recent & ongoing work

Presence of C_{60} and C_{70} in space firmly established

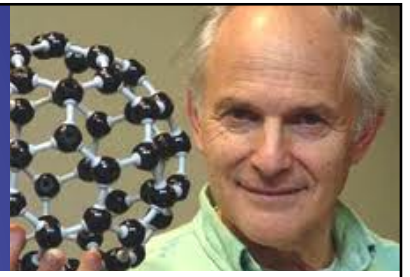
The discovery of C_{60} and C_{70}







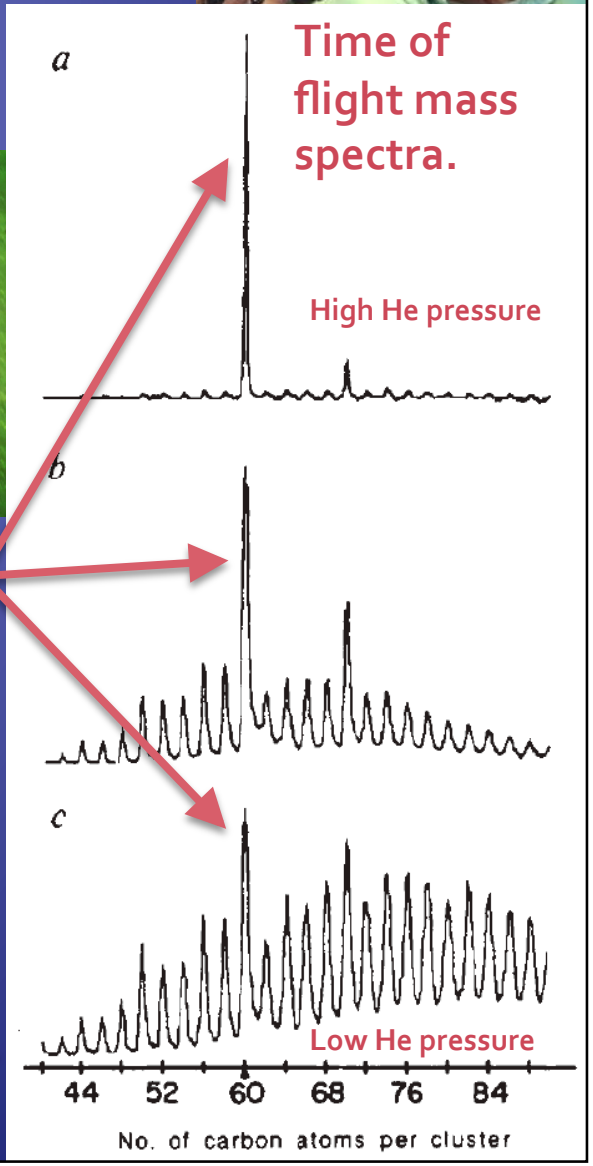
Kroto et al. 1985



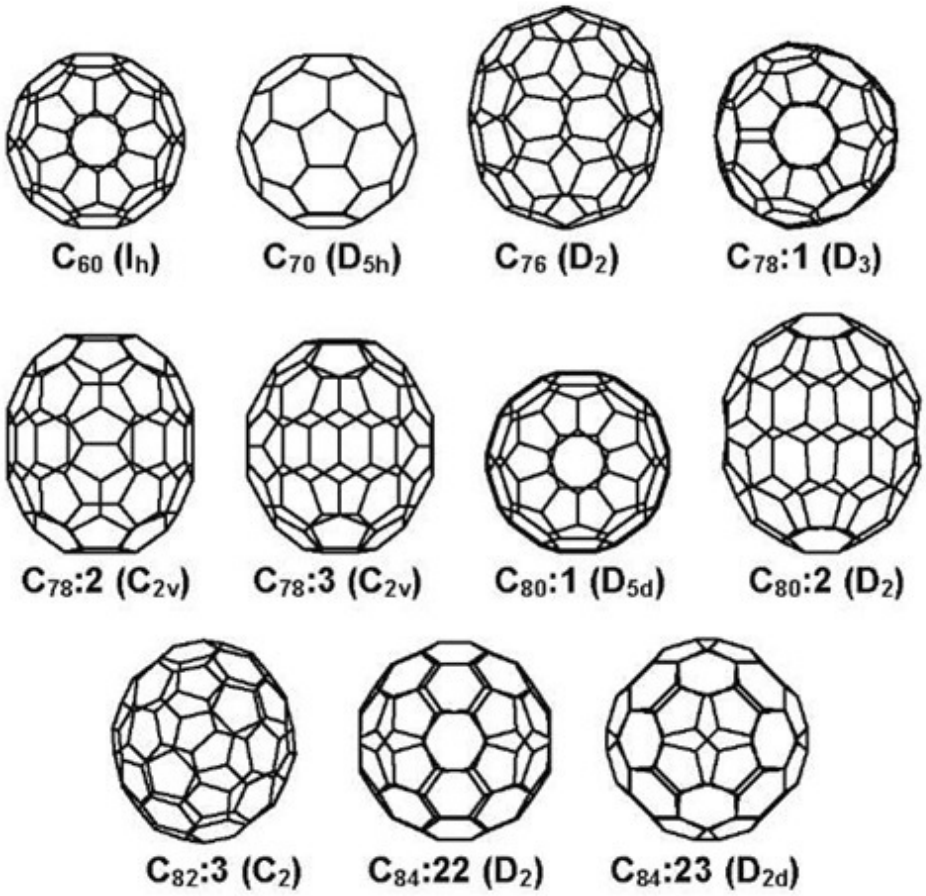
Survival of the fittest: discovery of C_{60} and C_{70}.

Widespread and abundant in space?

Graphite vaporization.

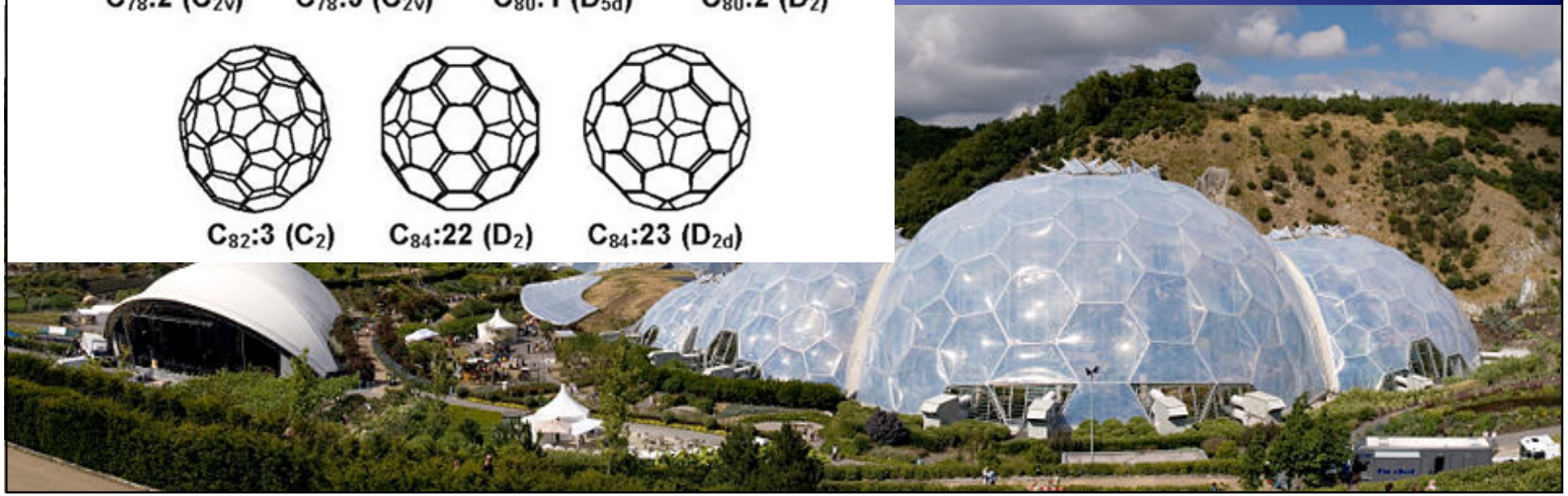


Meet the Fullerenes

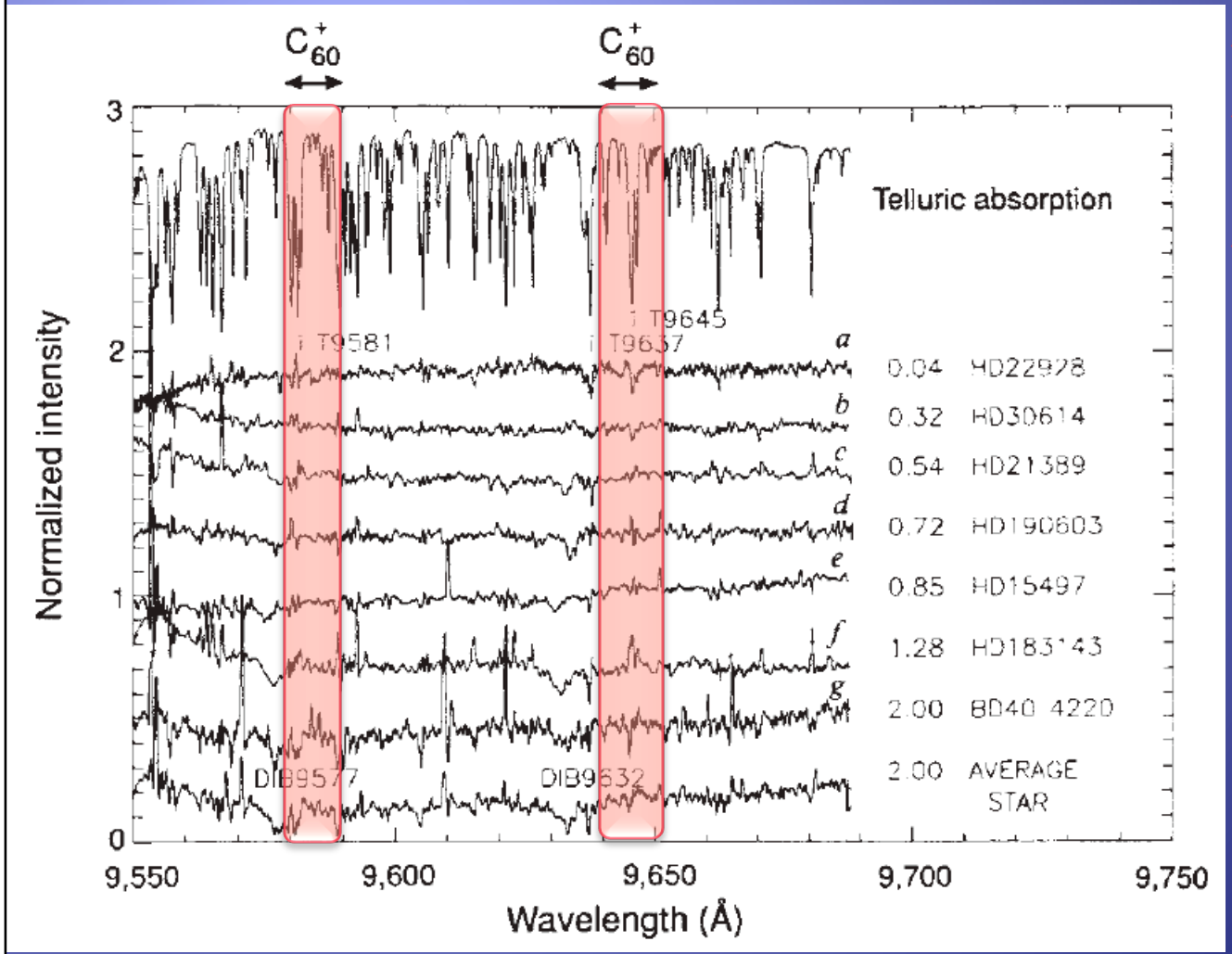


Fullerenes:

large cage-like molecules made of carbon.

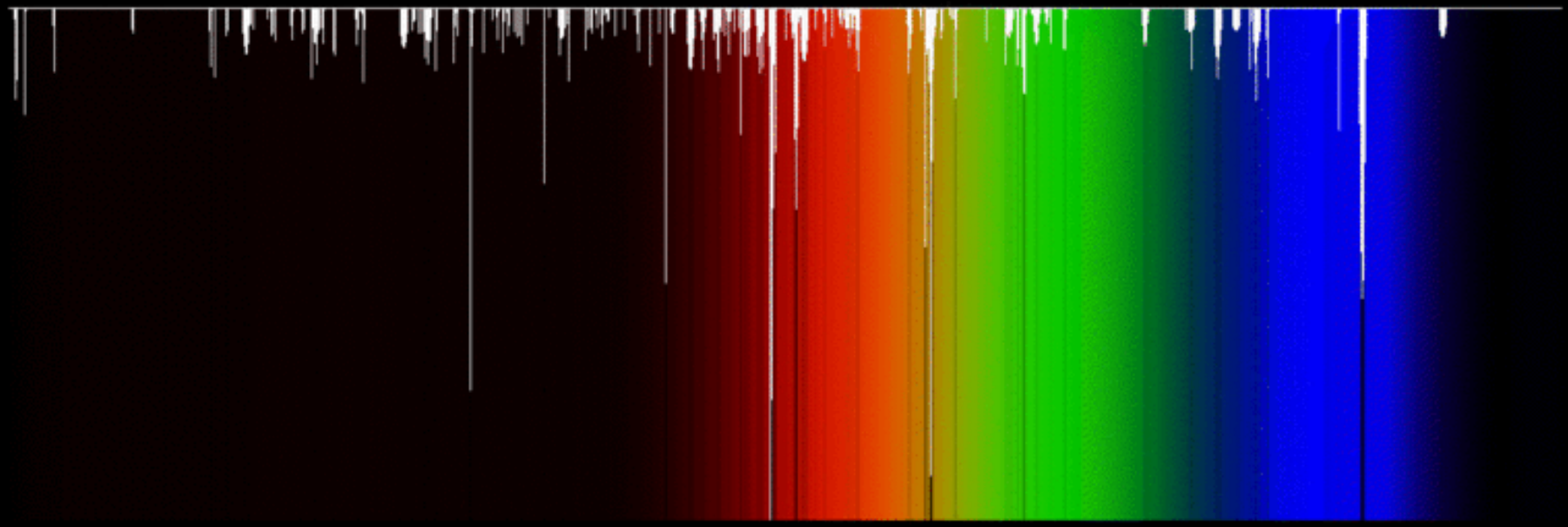


Astro Searches



- Electronic transitions.
- ***neutral*** C_{60} in ISM: not found (Herbig, 2000).
- C_{60}^+: Two DIBs found close to lab position; promising case, awaiting further laboratory confirmation (Foing & Ehrenfreund, 1994).

The Diffuse Interstellar Bands



Latest DIB surveys: ≈ 600 DIBs!

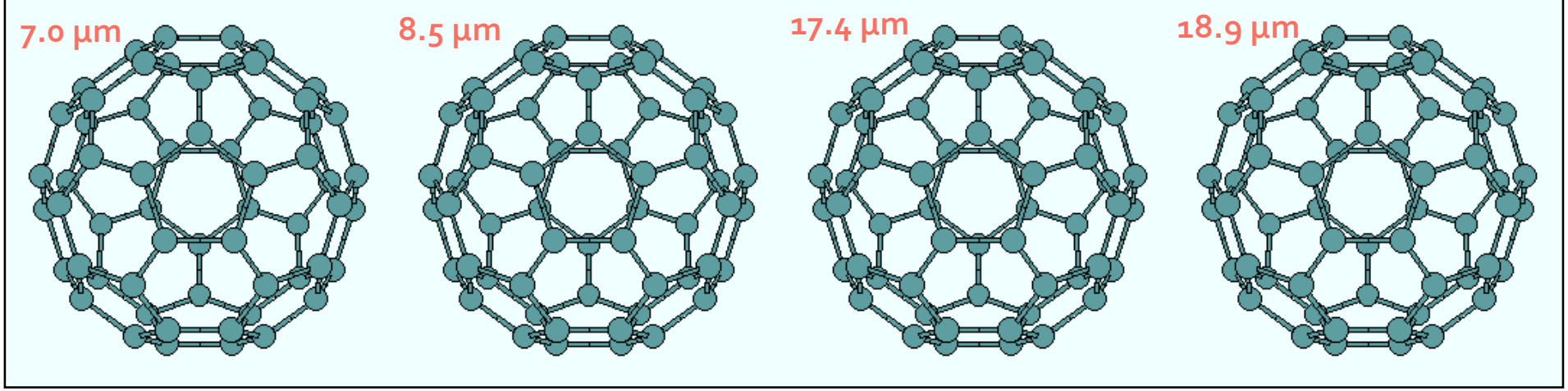
Courtesy: P. Jenniskens, F.-X. Desert

May 20—24, 2013 (tentative): DIB conference, the Netherlands

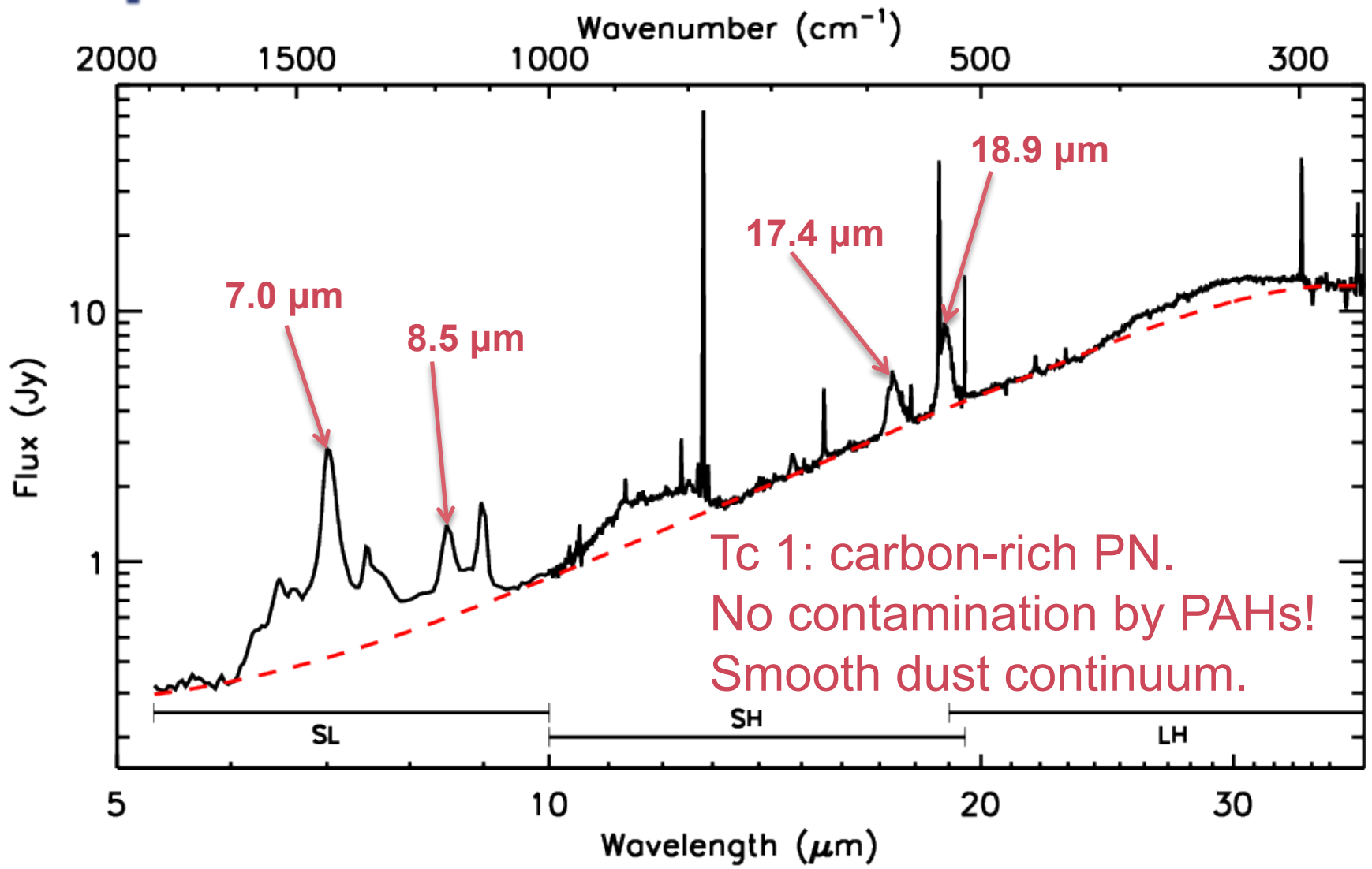
C_{60} & C_{70} vibrational modes

- Neutral C_{60}: 174 fundamental vibrational modes, but only 4 are IR active: 7.0, 8.5, 17.4, 18.9 μm.
- Neutral C_{70}: 204 fundamental vibrational modes; 32 are IR active.
- Note: cation spectra quite different.

Menéndez & Page (2000)



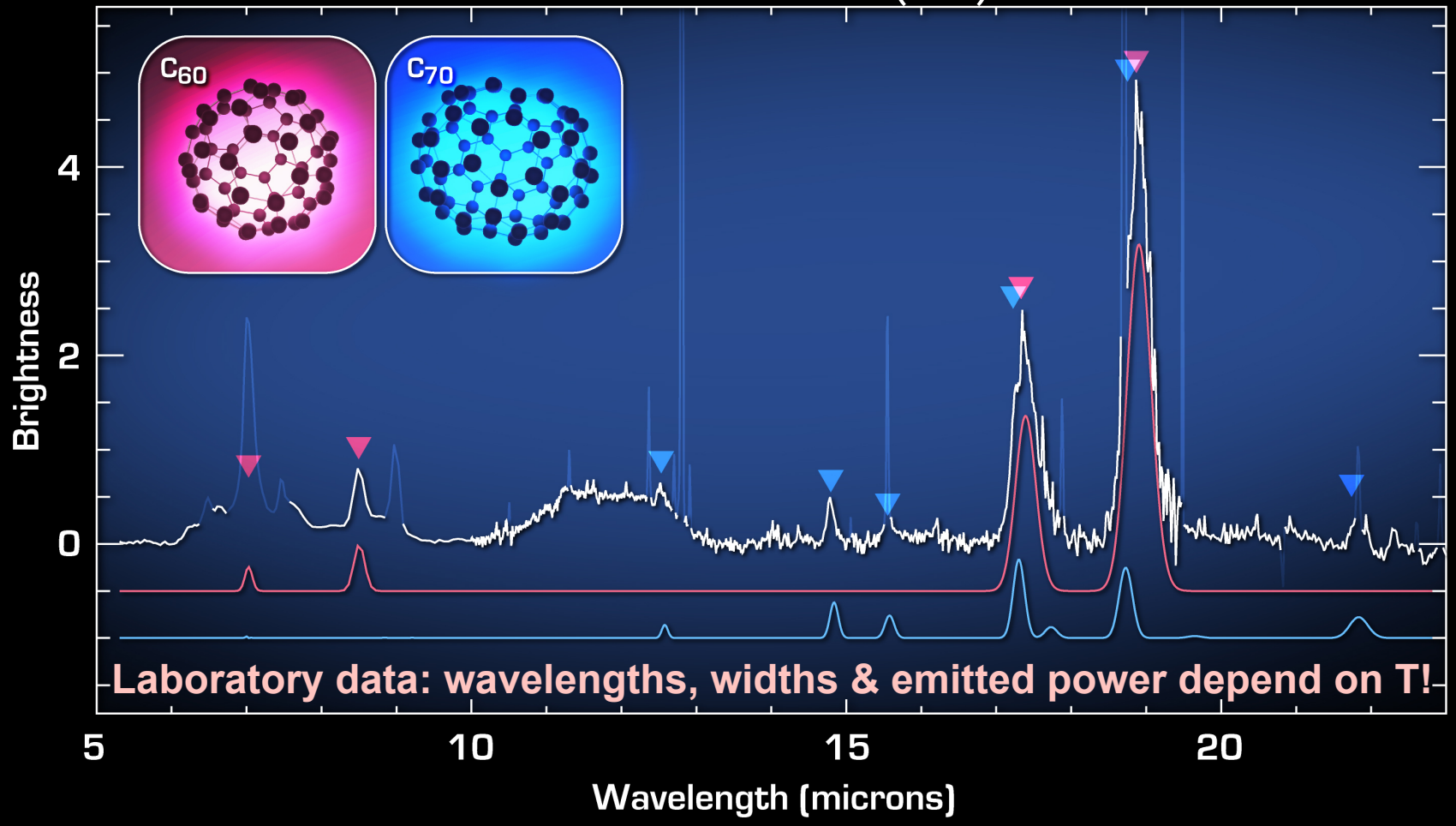
Spitzer-IRS observations of Tc 1



Observed Mar 21, 2005 with IRS in both Low-Resolution and High-Resolution modules.

Cami et al. (2010; Science 329, 1180)

For identification: wavelengths, widths & relative strengths
need to match measured (lab) values.



Buckyballs In A Young Planetary Nebula

NASA / JPL-Caltech / J. Cami (Univ. of Western Ontario/SETI Institute)

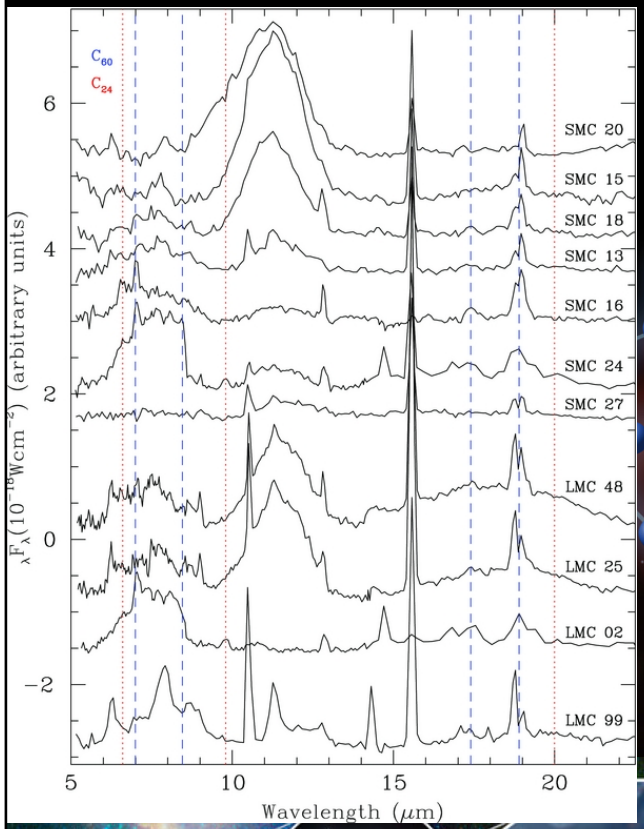
Spitzer Space Telescope • IRS

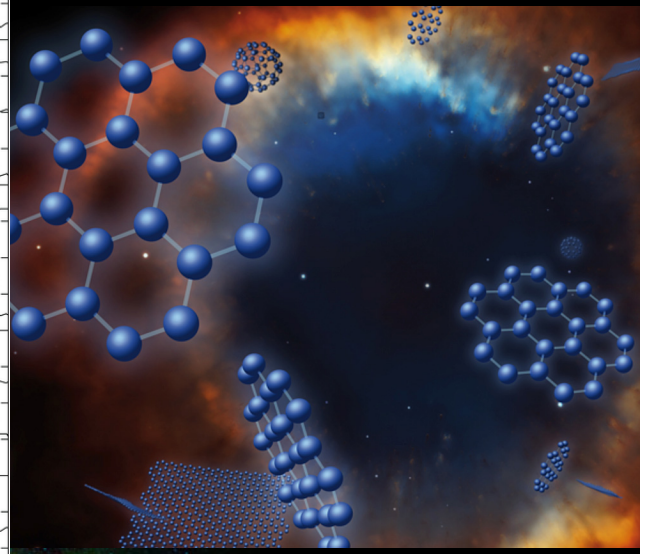
ssc2010-06a

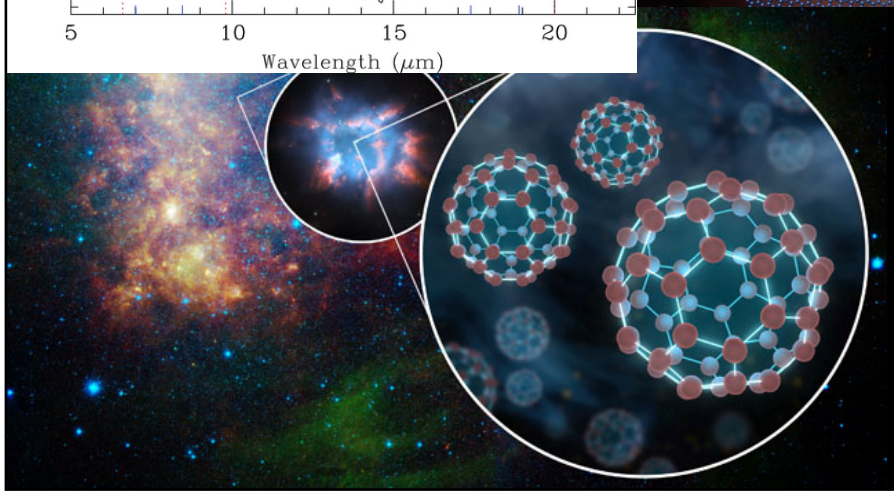
All measurable quantities are consistent with laboratory experiments carried out at temperatures comparable to what we derive.

More fullerene-rich (proto)PNe

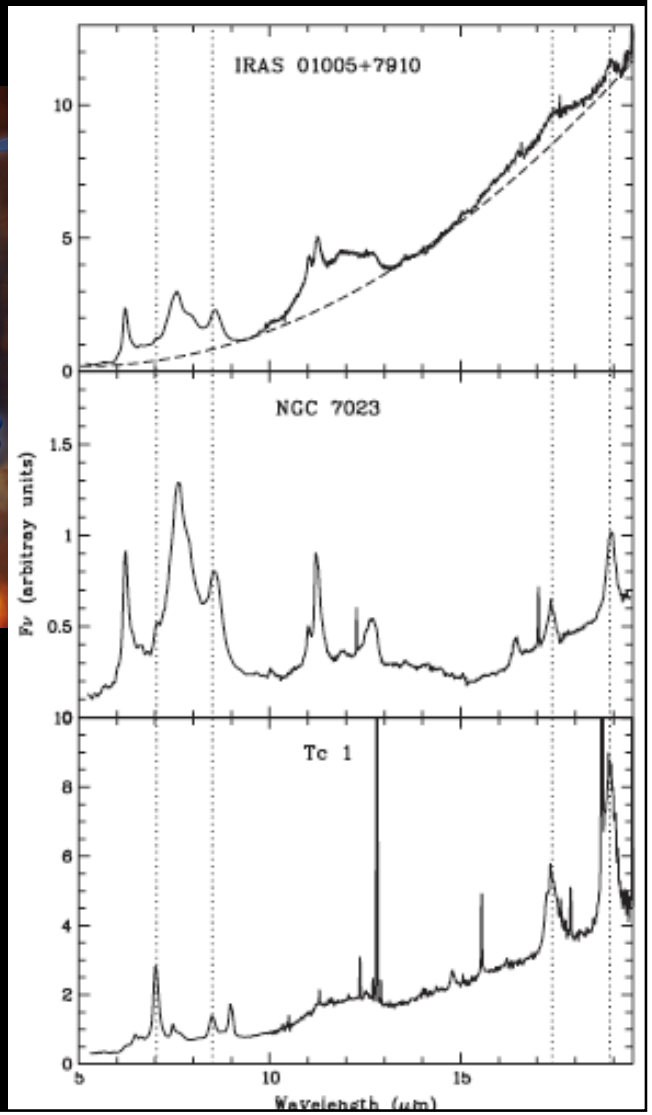
Garcia-Hernandez et al. (2010, 2011)



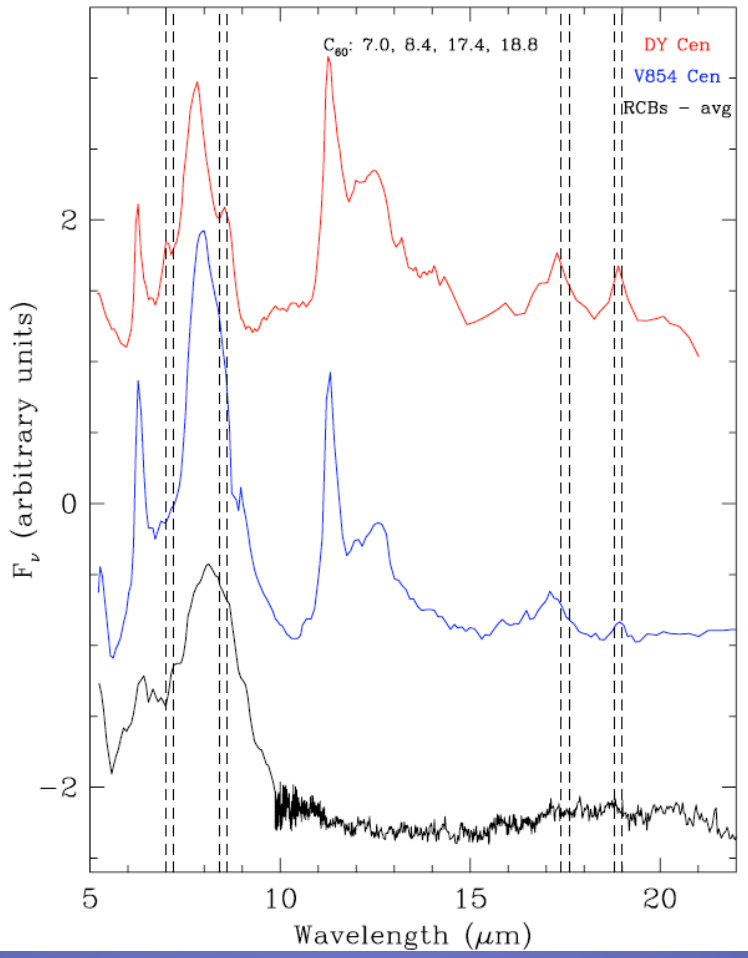




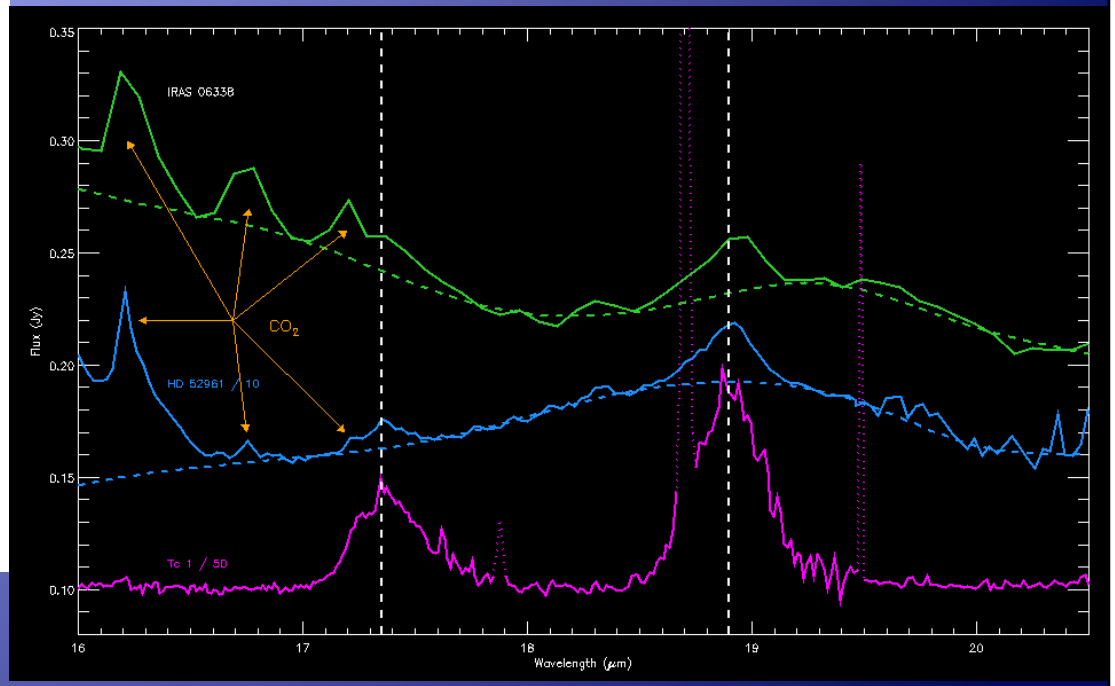
Proto-PN: Zhang & Kwok, 2011



Detections: More evolved stars

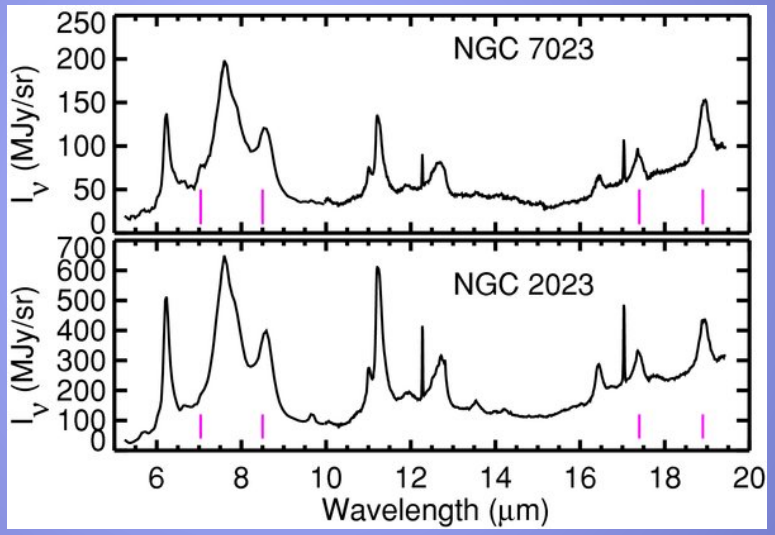


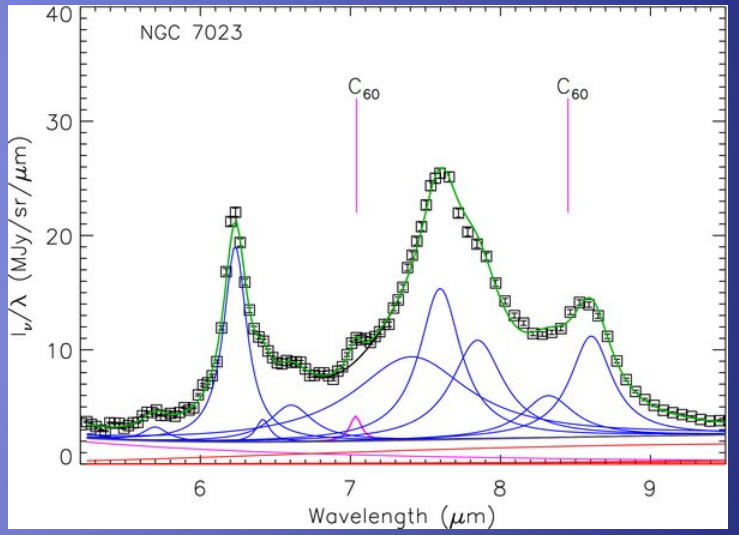
R Cor Bor stars
(Garcia-Hernandez et al., 2011)



O-rich binary post-AGB stars
(Gielen et al., 2011).

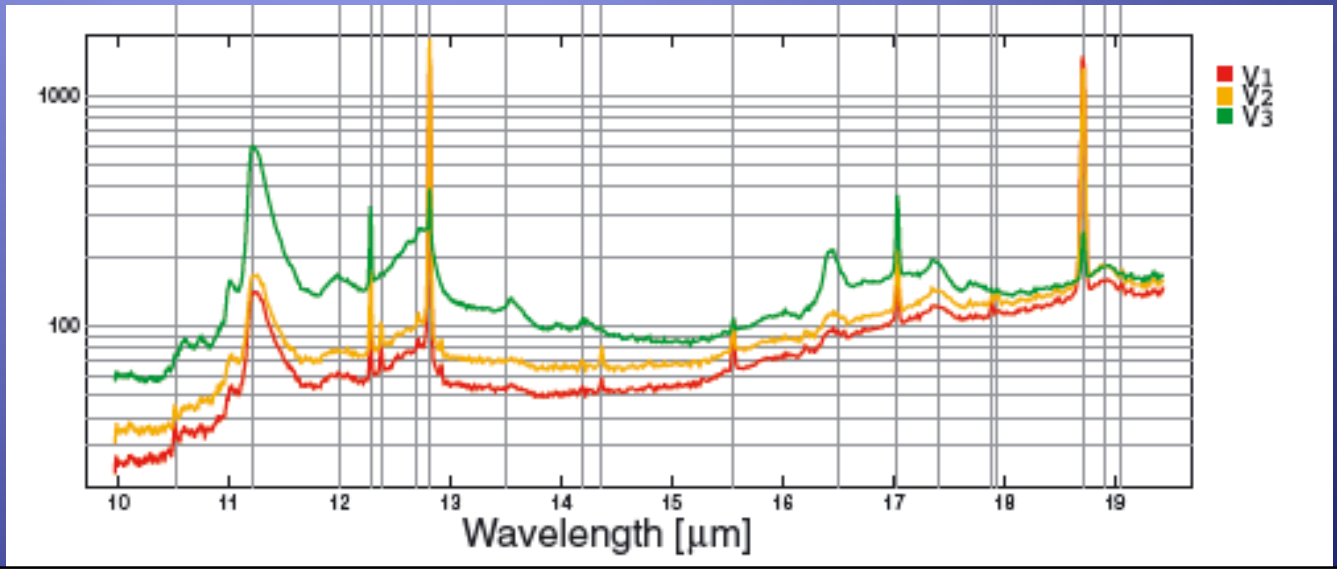
C_{60} in ISM





RNe

(Sellgren et al., 2010)



Orion Nebula

(Rubin et al., 2011)

(Boersma et al., 2012)

C60 in Young Stellar Objects

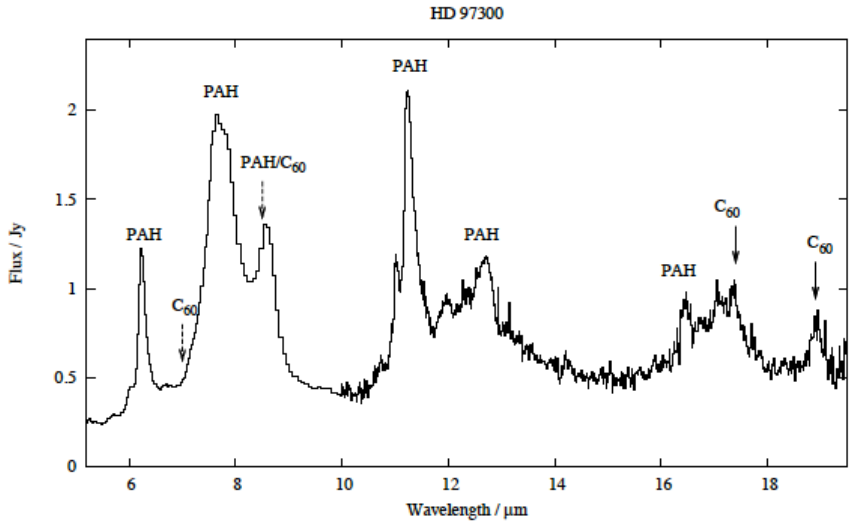
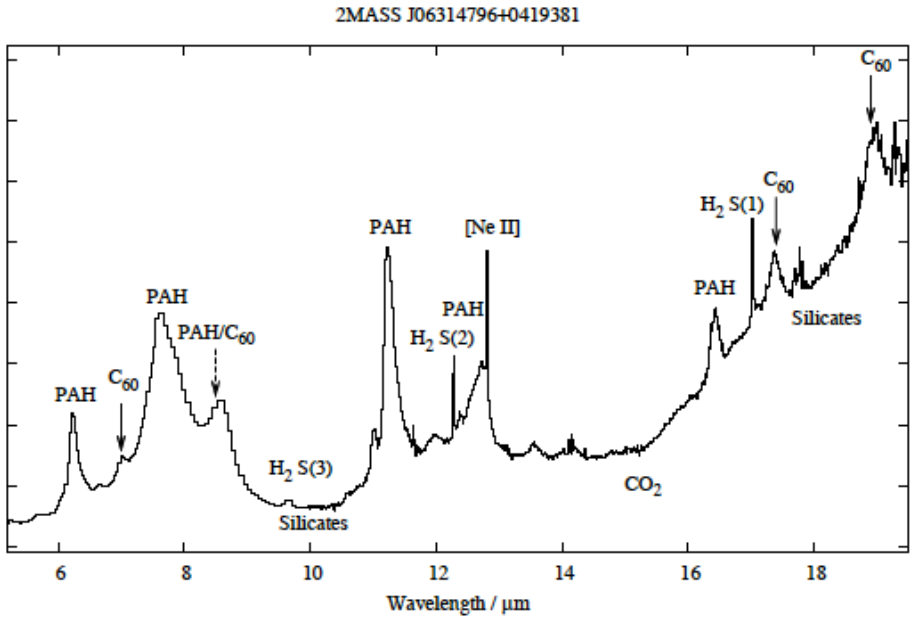
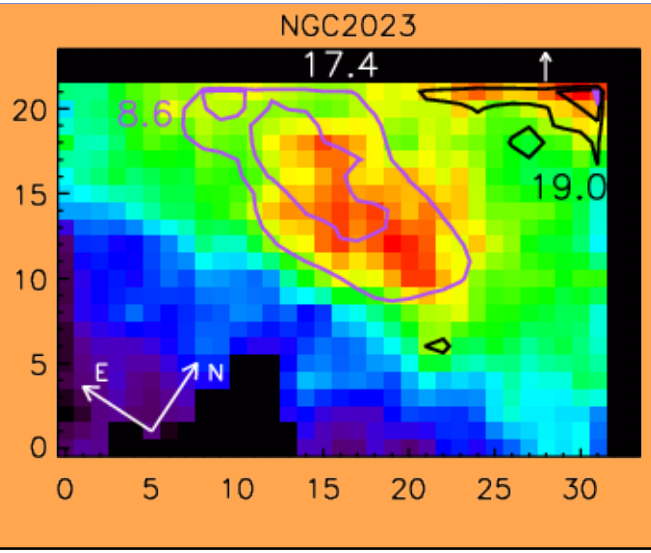


Figure 7. *Spitzer* IRS spectrum of the Herbig Ae/Be star HD 97300 covering the region of the C_{60} bands. Annotations are as in earler figures.

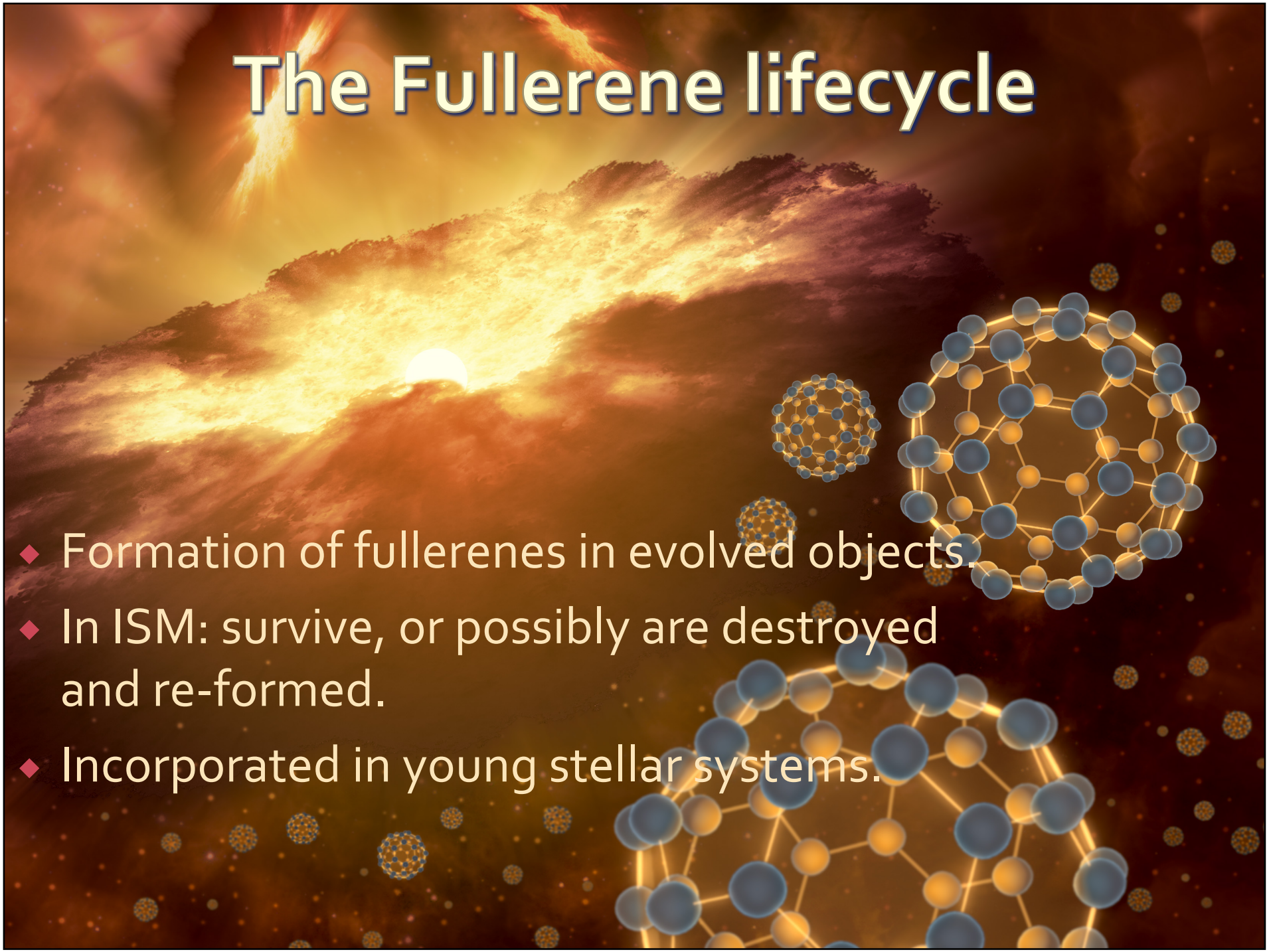




Roberts, Smith & Sarre (2012)

Peeters et al. (2011): 17.4 often blended with PAH feature at same wavelength!

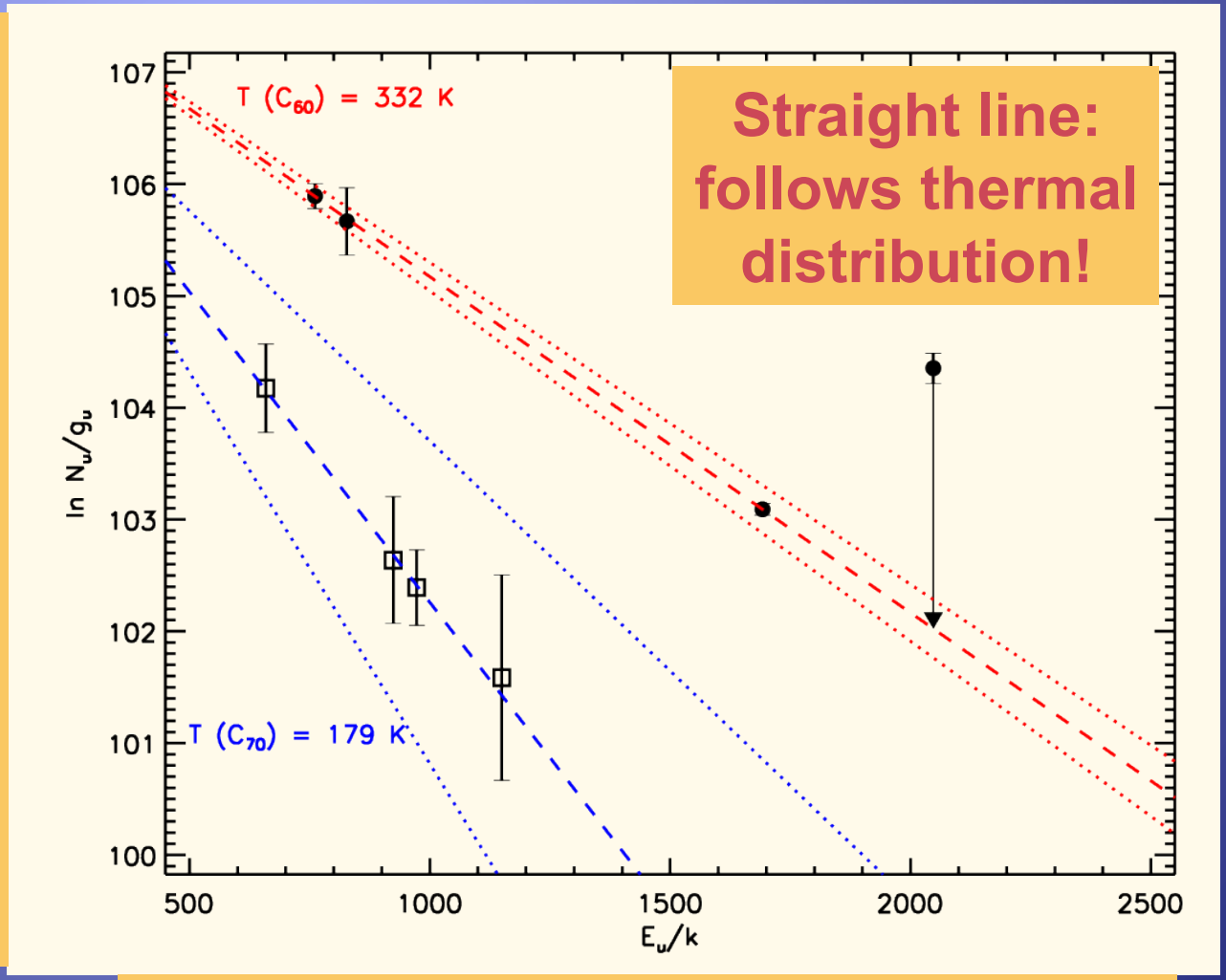
The Fullerene lifecycle



- Formation of fullerenes in evolved objects.
- In ISM: survive, or possibly are destroyed and re-formed.
- Incorporated in young stellar systems.

Excitation diagram

Population from emitted power



Straight line: follows thermal distribution!

Energy of excited vibrational levels

Emitted power yields number of molecules in excited states.

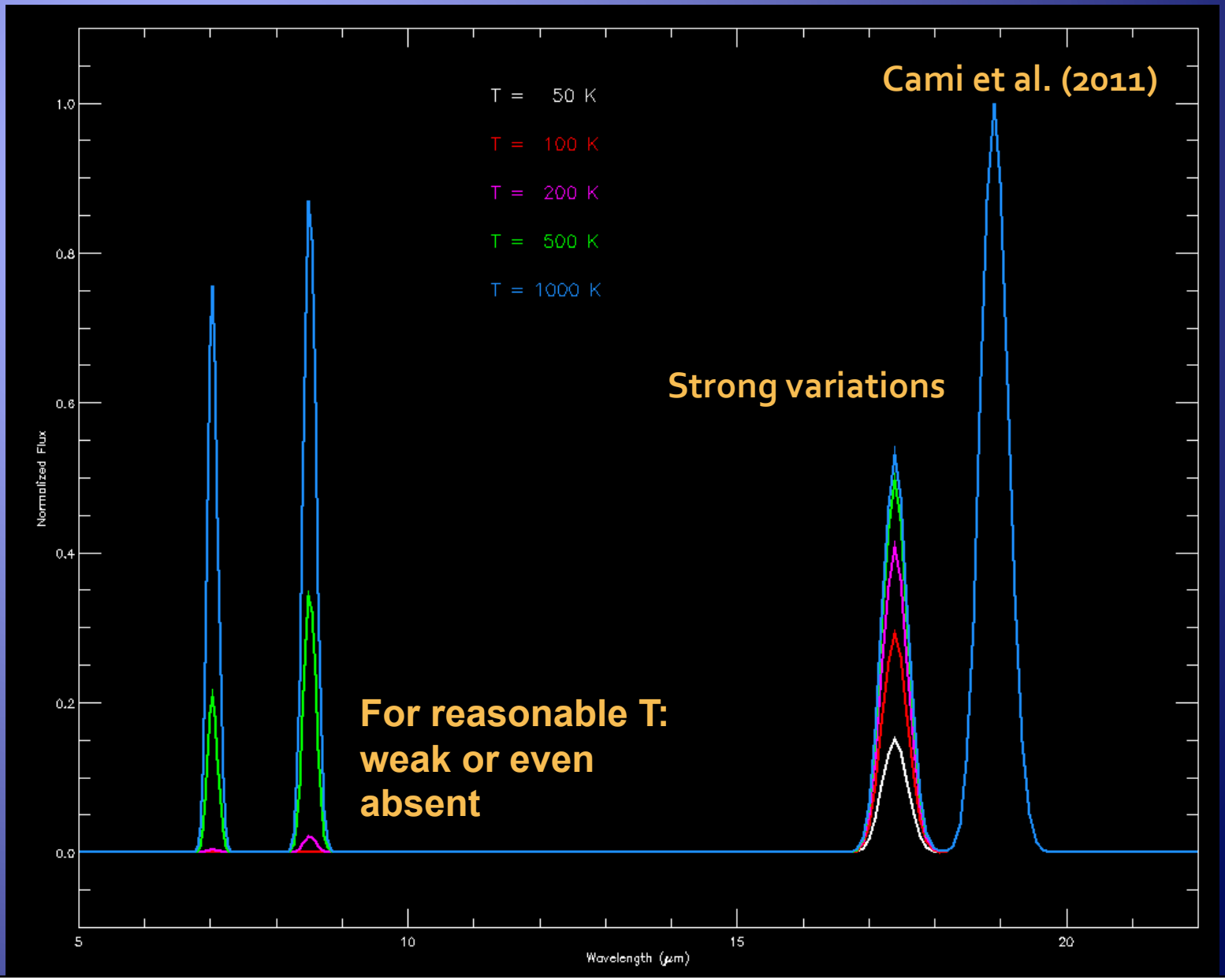
Thermal distribution not expected for free gas phase species!

Slope → T

Intercept → N_{tot}

Cami et al. (2010)

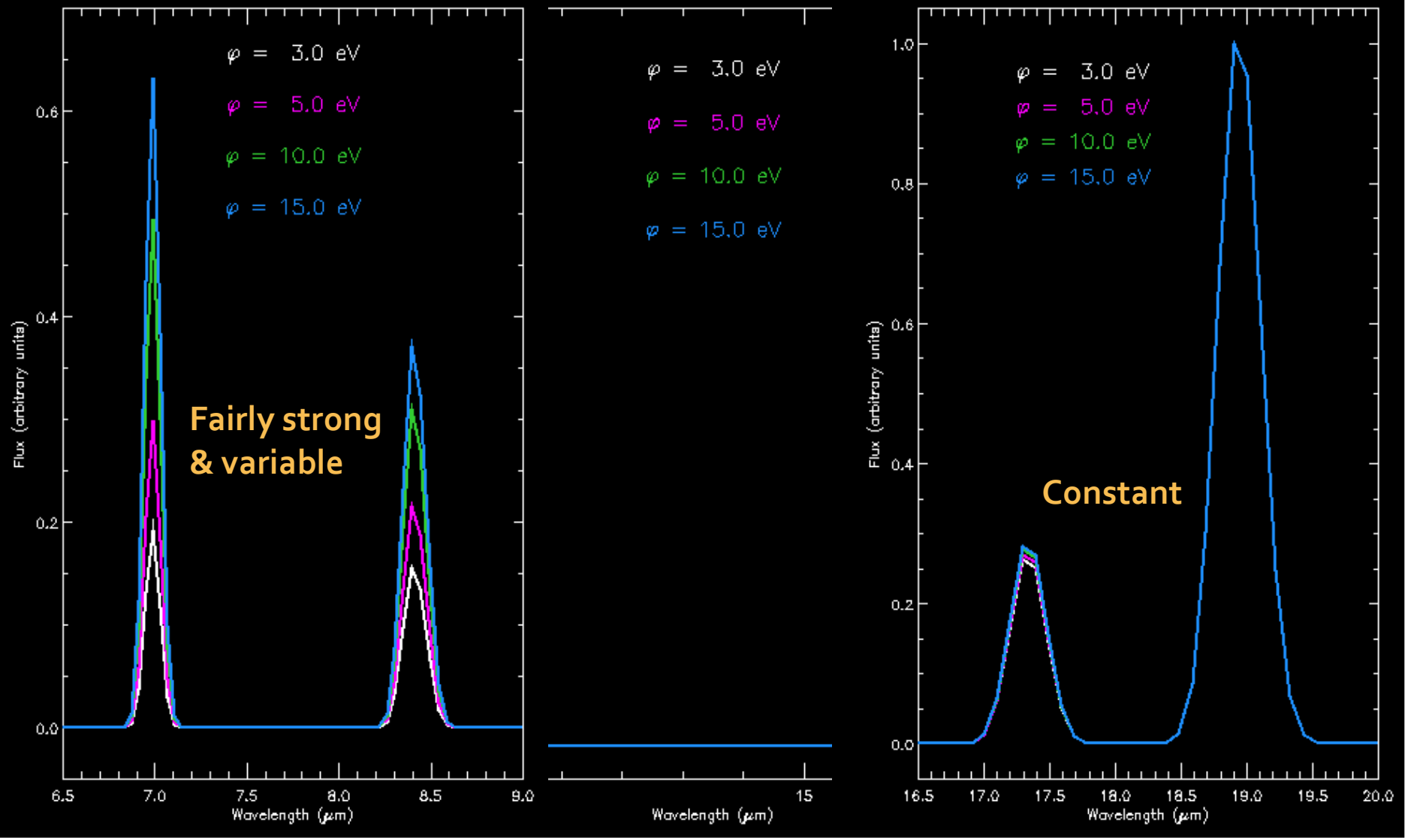
Thermal Excitation



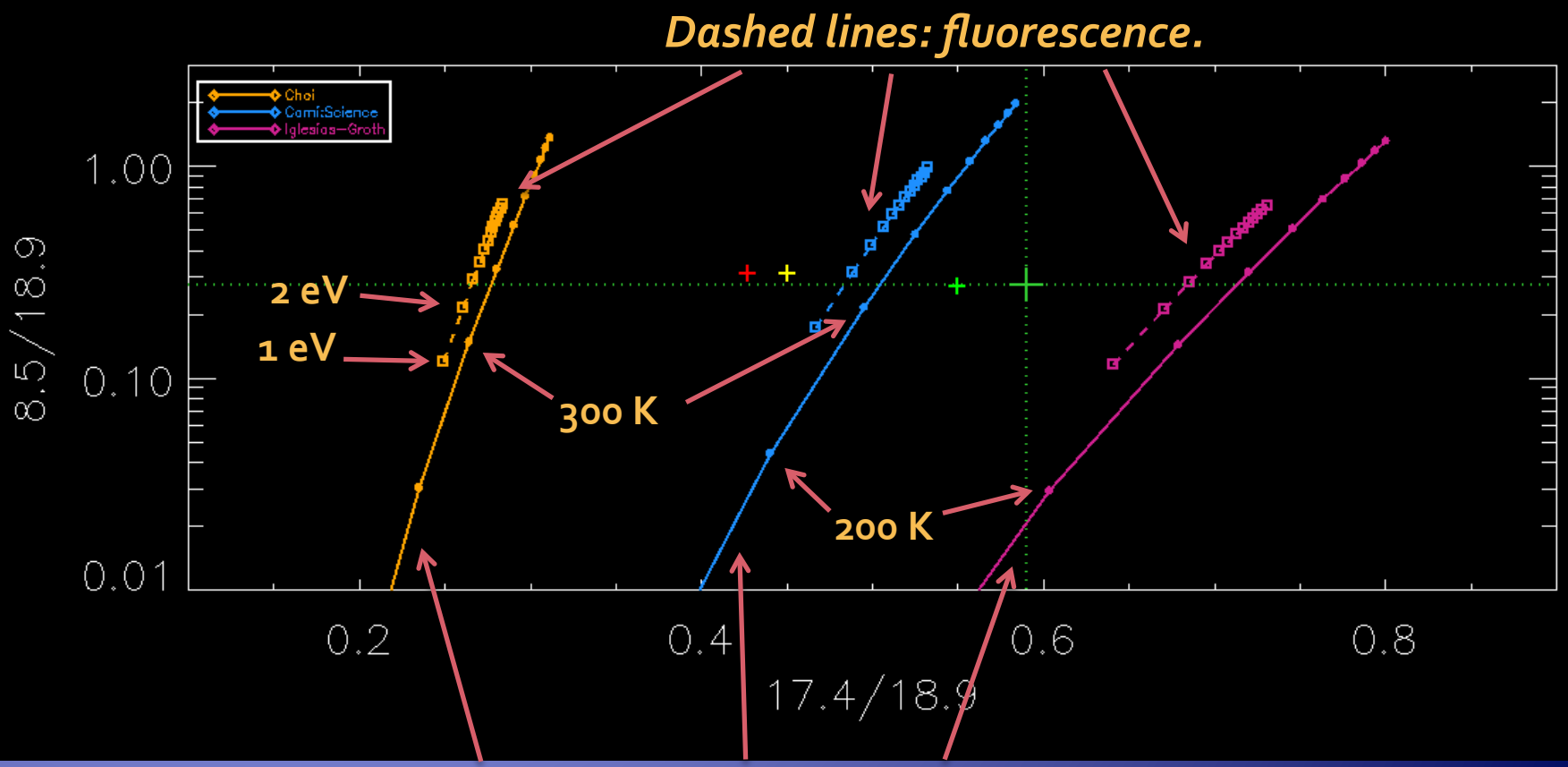
Fluorescence Cooling Cascade

Holds for free gas-phase species!

Cami et al. (2010)



Excitation diagnostic



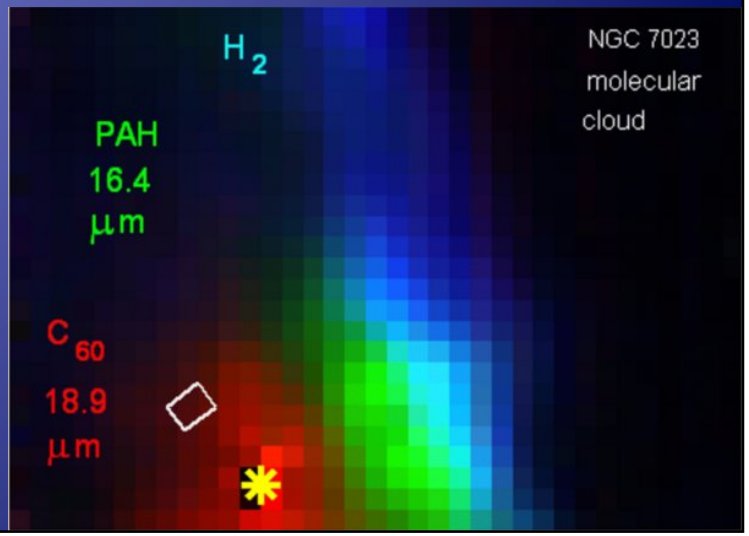
Solid lines: thermal models.

If thermal: all precisely at same T ?!
If fluorescence: only absorb low energy photons ?!

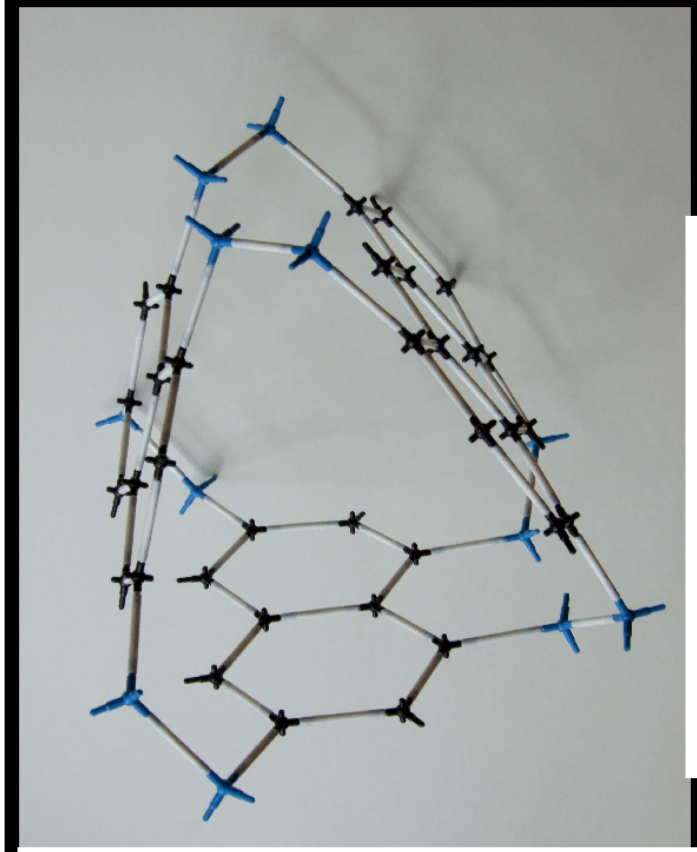
Bernard-Salas et al., 2012

Formation of fullerenes in space

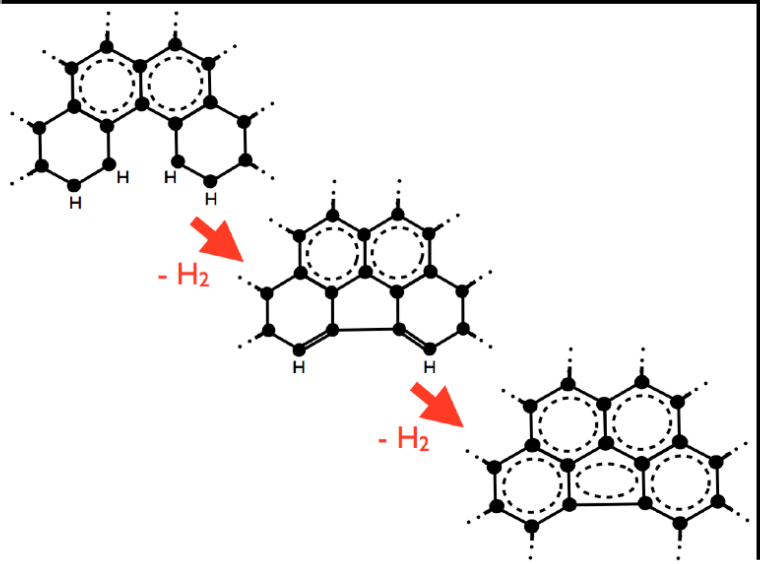
- Routes to form fullerenes:
  - Hydrogen-poor, moderate temperature
  - High-temperature (>3,500 K; H no problem)
  - Photo-processing of HACs
  - Fullerenes from destruction of PAHs (e.g. Berné & Tielens, 2011).
- Problem: none of the formation routes seem to work in space.

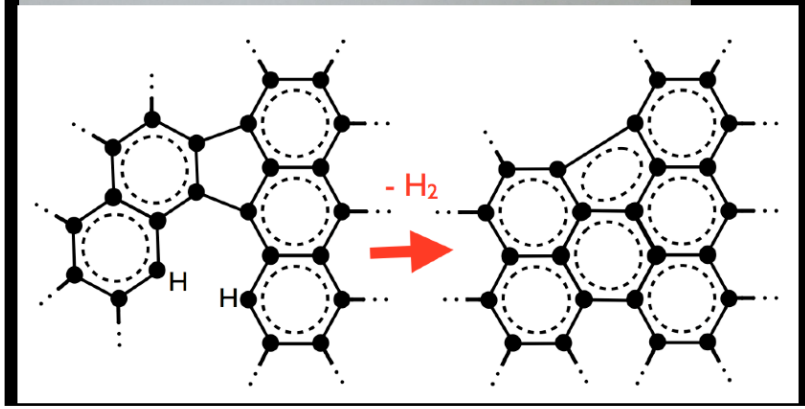


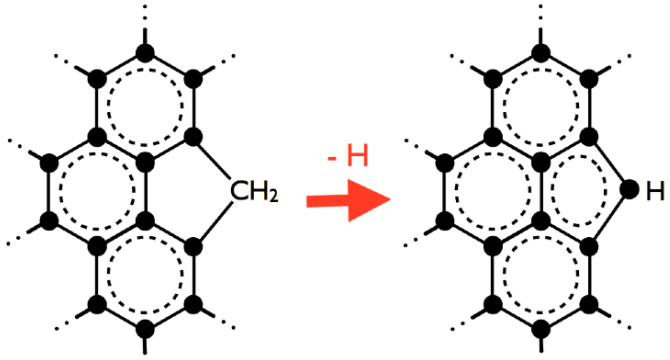
Formation of fullerenes



Large "Arophatic Structures": HAC-like material. Dehydrogentation; formation of pentagon causes curling up; C_2 ejection shrinks to C_{60} size.







Micelotta et al. (2012)

Conclusions

Presence of C_{60} and C_{70} in space firmly established

Diverse objects: lifecycle of fullerenes

Excitation mechanism: unclear; problematic

State (solid/gas): Unclear

Formation: most promising seems top-down formation from arophatic clusters

The Cast

Collaborators: Jeronimo Bernard-Salas, Els Peeters, Sarah Malek, Elisabetta Micelotta, Anthony P. Jones, Giovanni Fanchini

Graphics, animation, media: Gordon Squires, Whitney Clavin, Robert Hurt, Tim Pyle, Gay Lee Hill, Jeff Renaud, Heather Travis, Henry Leparskas

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