Jan Cami

J. Bernard-Salas, E. Peeters, I. Aleman, M. Leal-Ferreira, B. Ochsendorf, R. Wesson, D. Stock, S. Akras, A.G.G.M. Tielens, N. Cox, M. Otsuka, F. Kemper, G. Doppmann, J. de Buizer, G. Sloan, A. Candian, H. MacIsaac, G. Pagomenos, V. Staroverov

Cosmic Fullerenes

NSERC CRSNG

NASA

Western UNIVERSITY · CANADA

SPITZER SPACE TELESCOPE

SETI INSTITUTE

Key Points

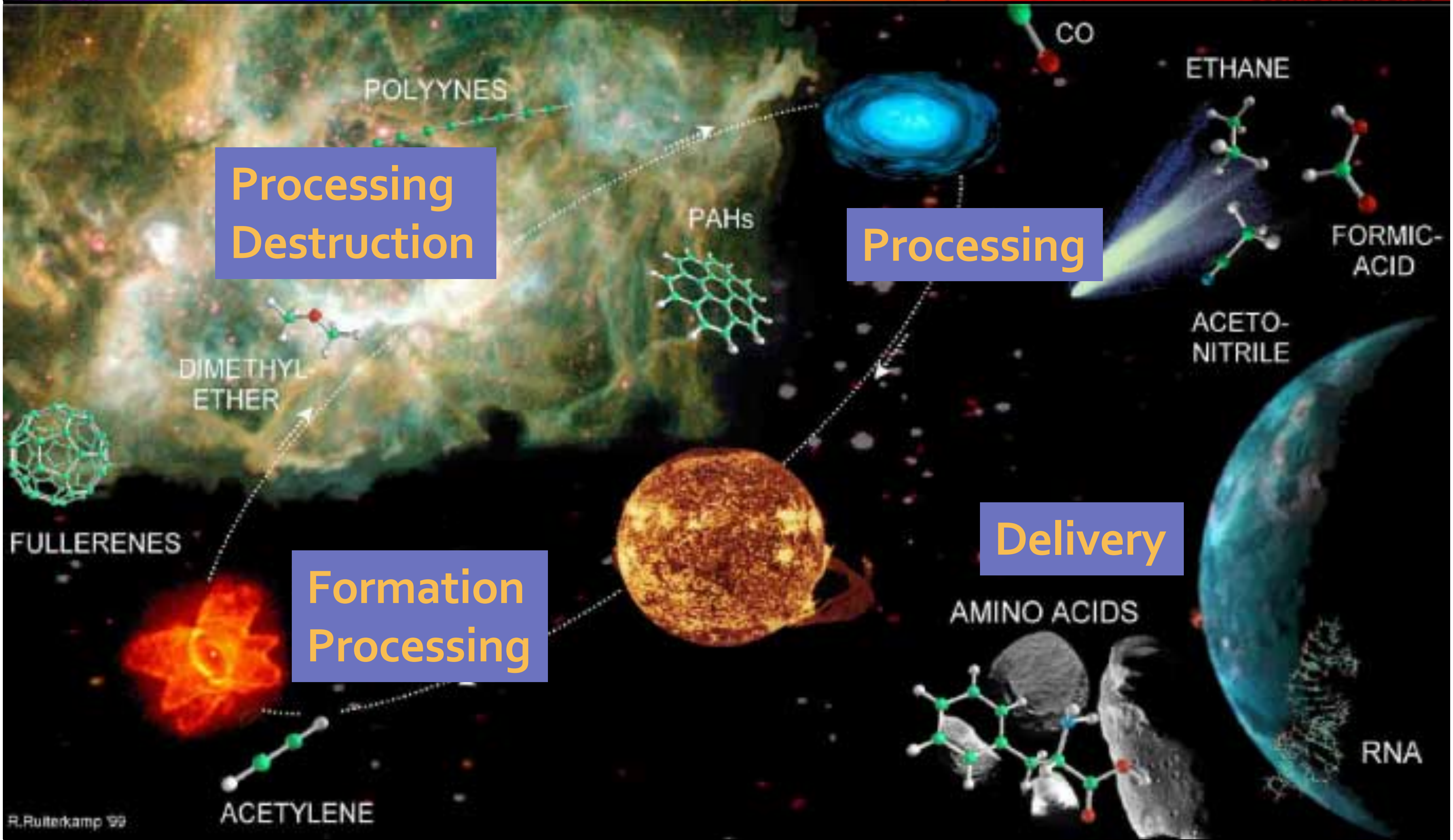
Fullerenes are abundant and widespread

C_{60} can form in the ISM from UV photo-processing of large PAHs

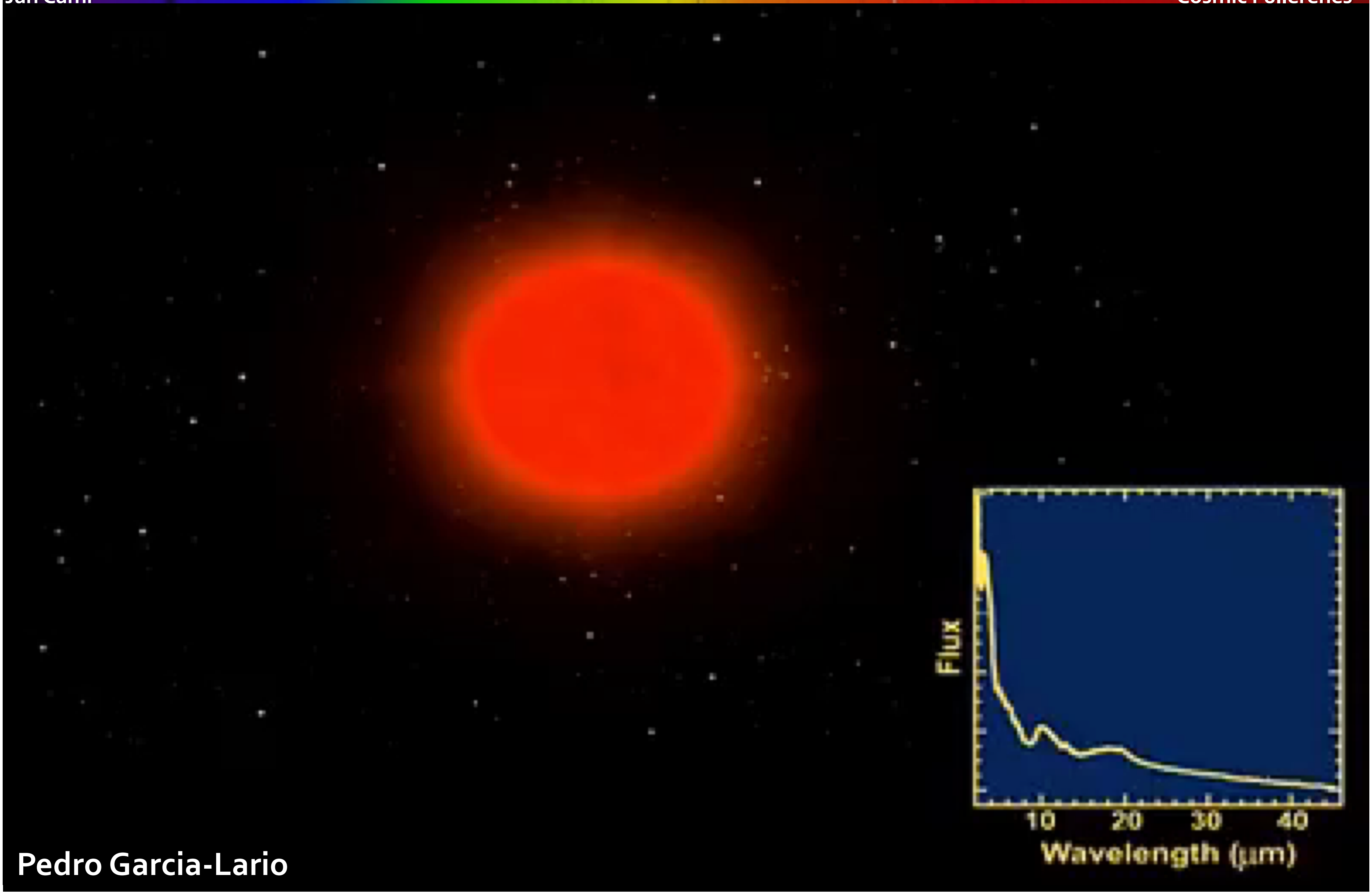
In PNe, condensation at high T (C-rich and/or H-poor) followed by dust destruction yields C_{60} (?)

Fullerene chemistry important to consider!

Carbon (re)cycling in space



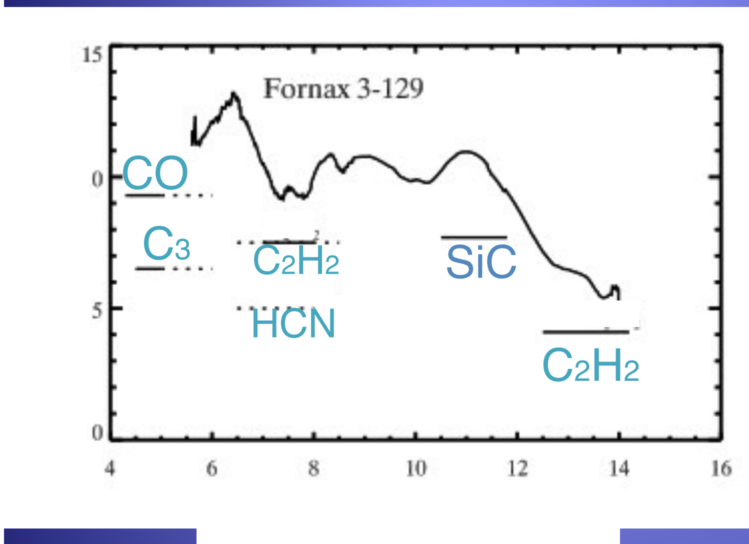
The (IR) end of a low-mass star.



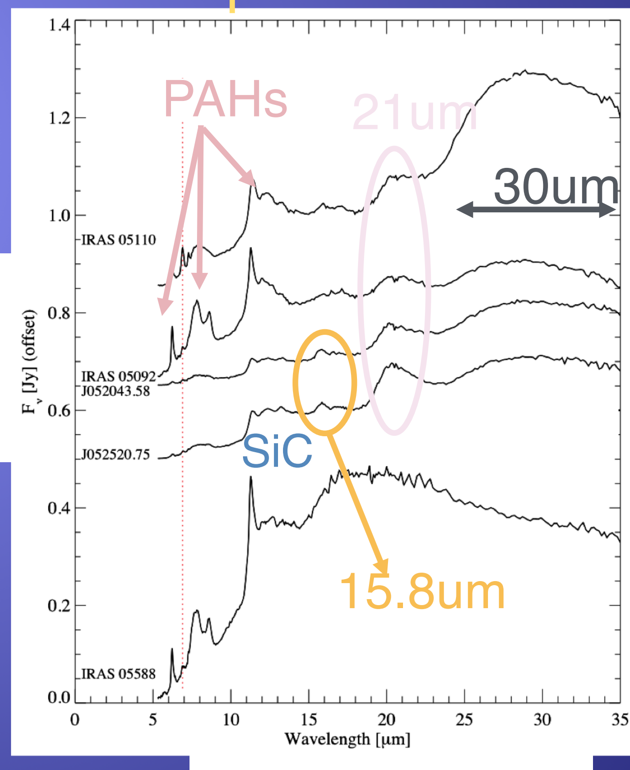
Pedro Garcia-Lario

C-rich dust: Diversity

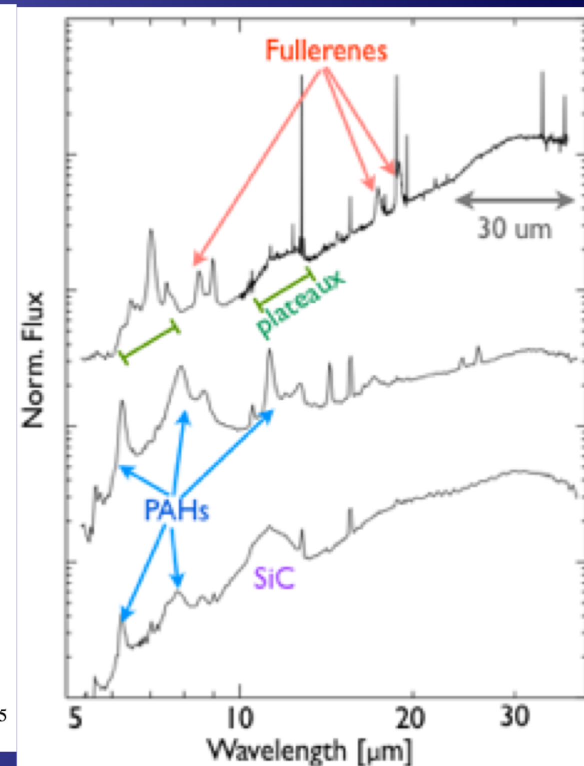
AGBs



post-AGBs



PNe



Matsuura et al. (2007; 2014),
Sloan et al. (2014),
Bernard-Salas et al. (2012)

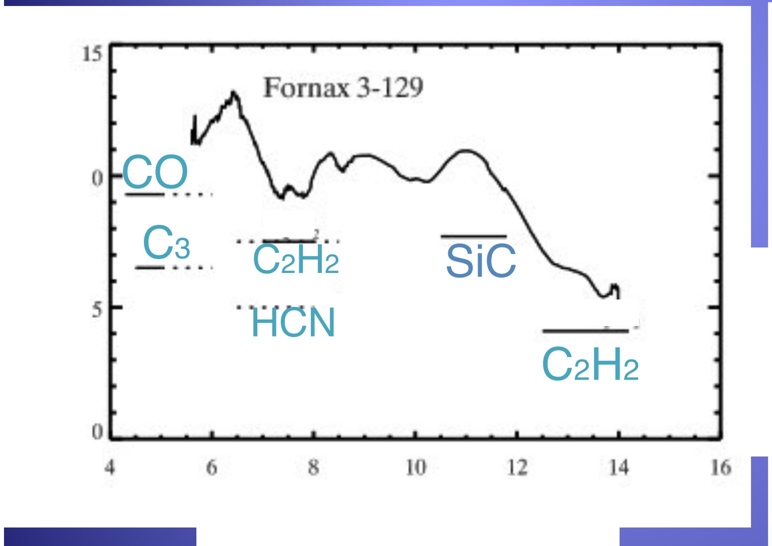
What is the origin of this diversity?
How do the species form & evolve, are they linked?
What's their dust composition and production over cosmic time?

Jan Cami

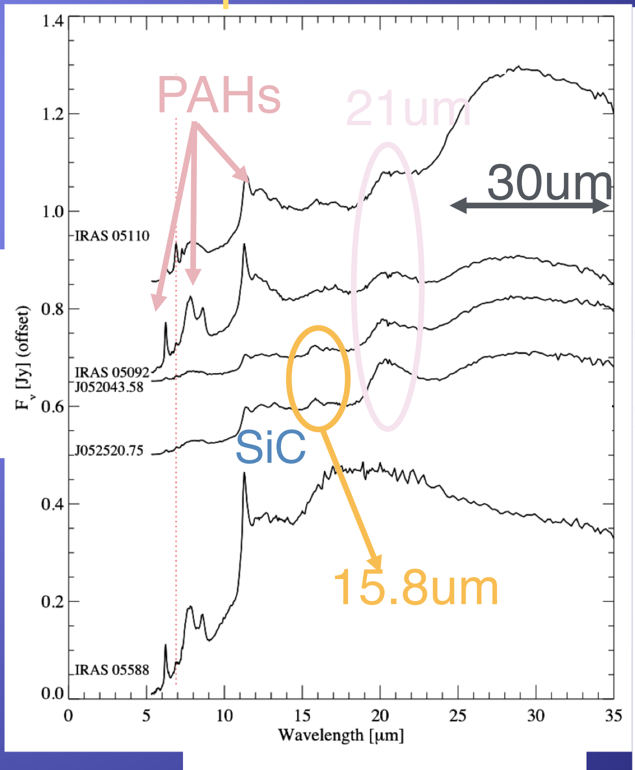
C-rich dust: Diversity

Cosmic Fullerenes

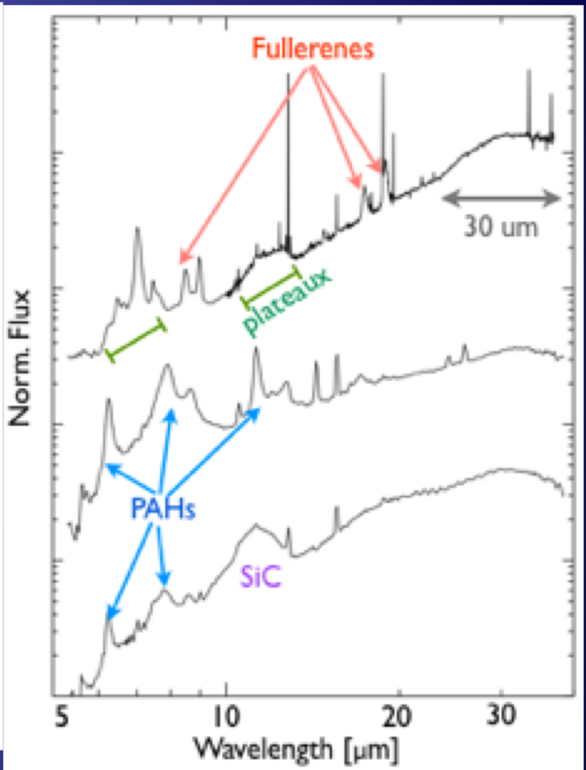
AGBs



post-AGBs



PNe

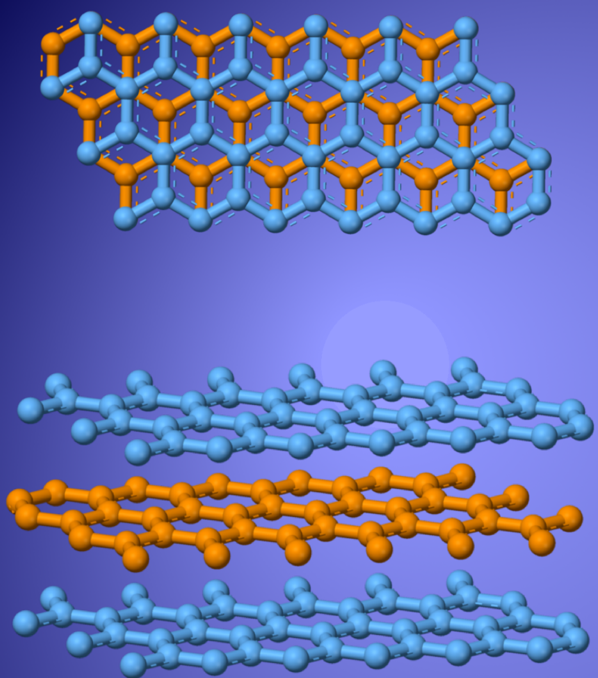


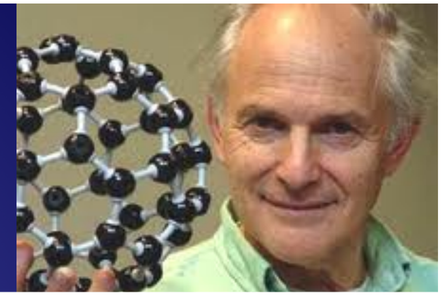
Matsuura et al. (2007; 2014),
Sloan et al. (2014),
Bernard-Salas et al. (2012)

We don't really understand the carbon chemistry leading to large aromatics and carbonaceous dust in evolved star environments.

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

Kroto et al. 1985

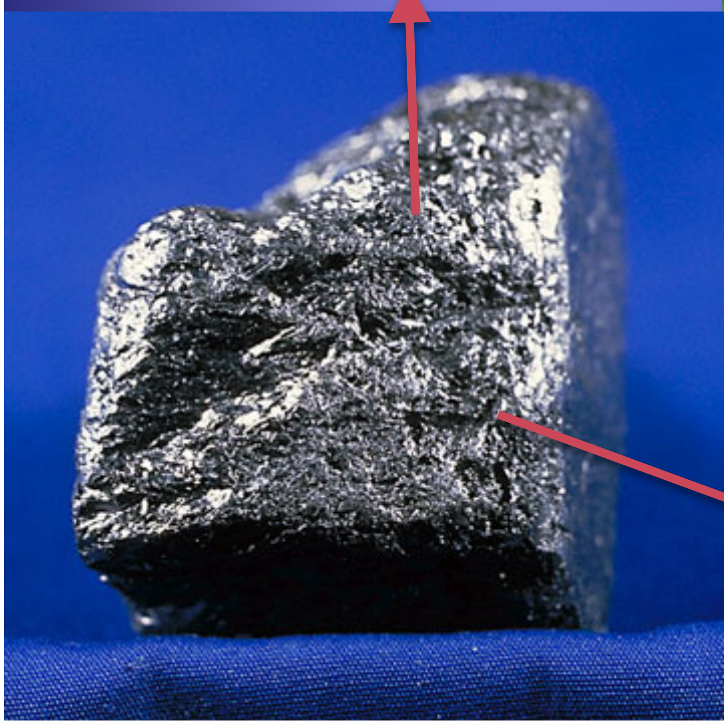


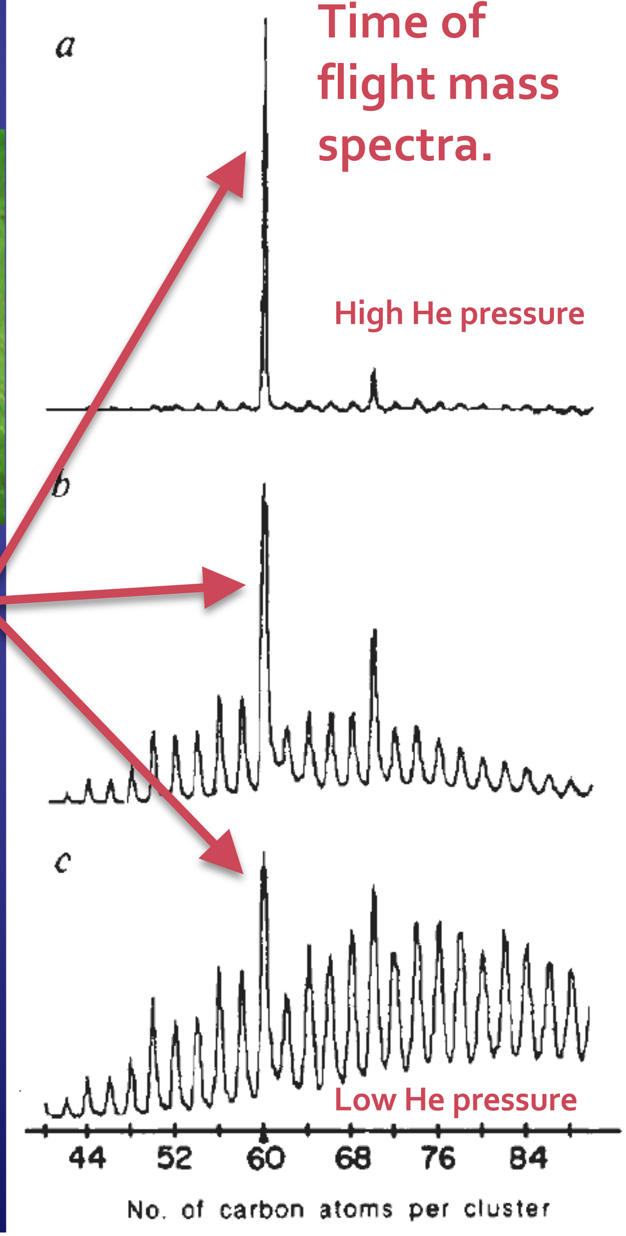


Survival of the fittest: discovery of C_{60} and C_{70}.

Widespread and abundant in space?

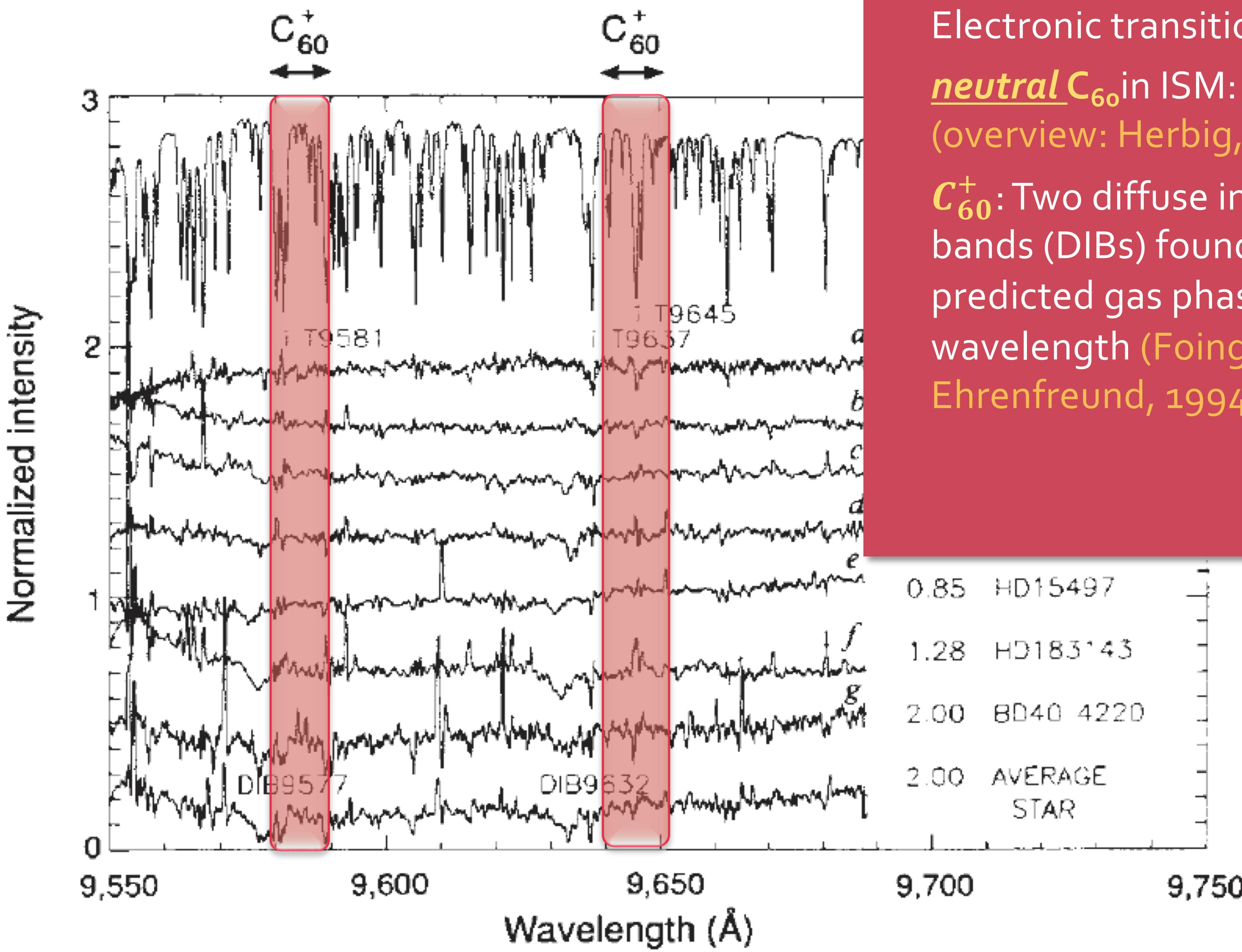
Graphite vaporization.





Time of flight mass spectra.

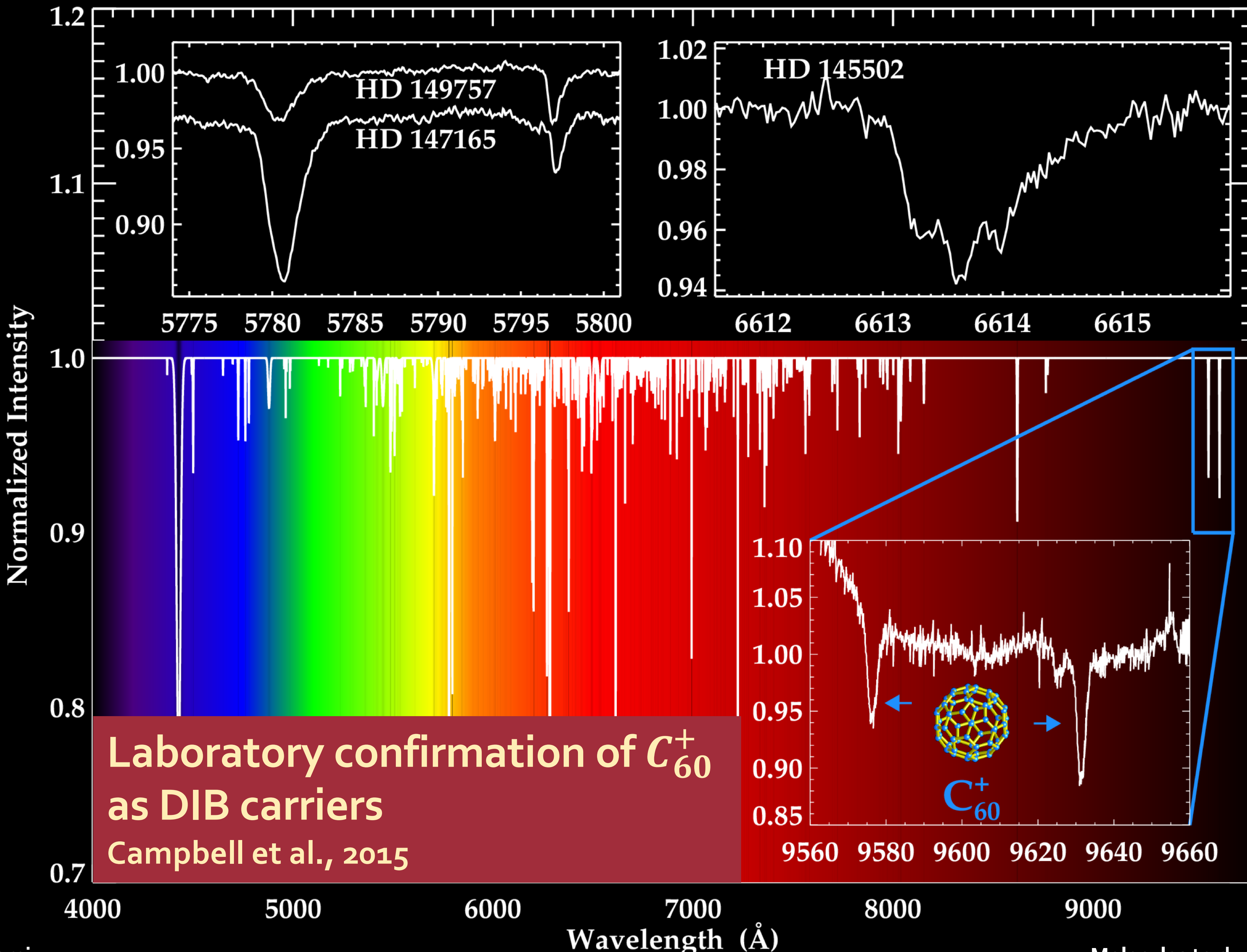
Early Searches



Electronic transitions.

neutral C_{60} in ISM: not found (overview: Herbig, 2000).

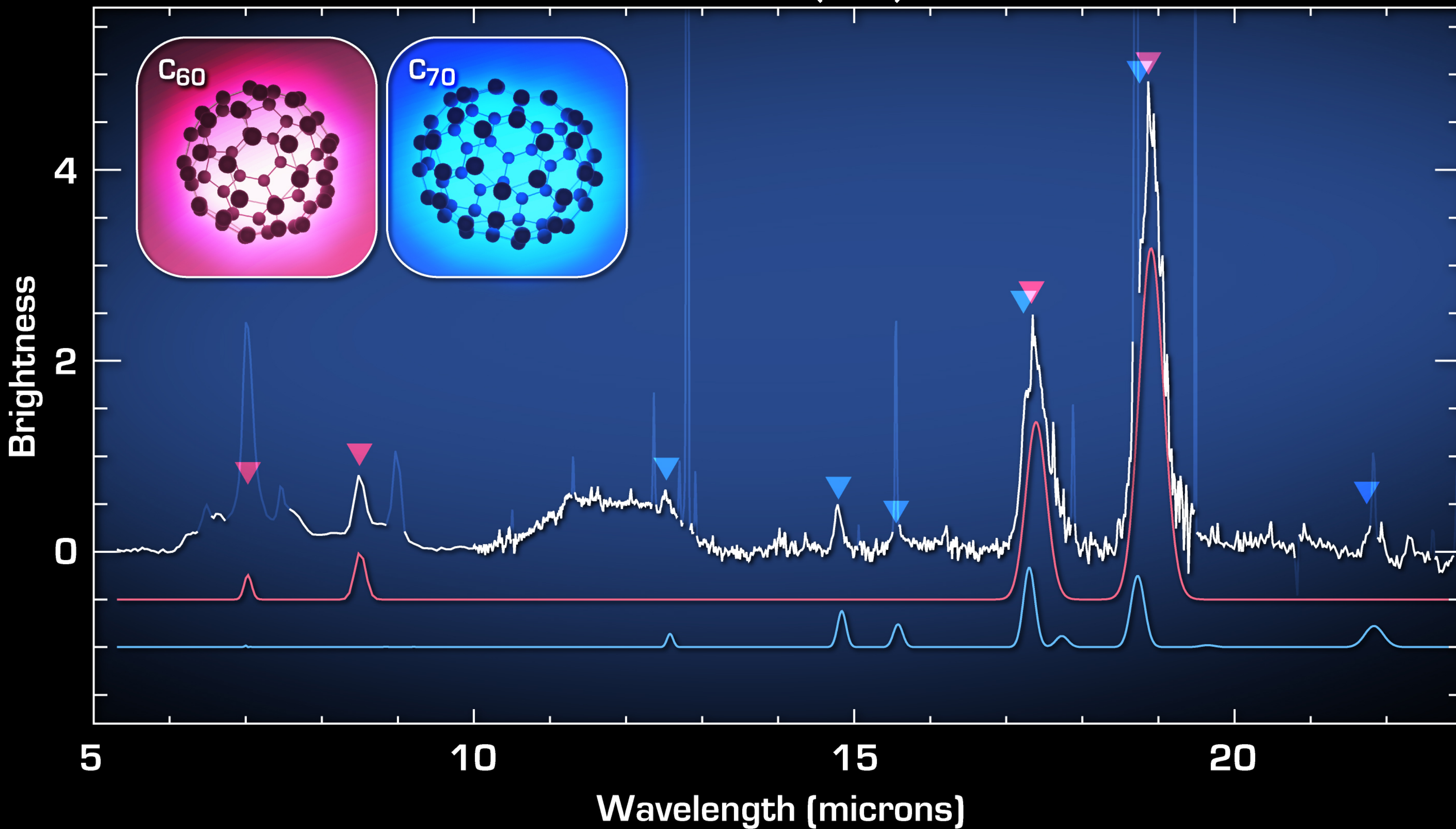
C_{60}^{+}: Two diffuse interstellar bands (DIBs) found close to predicted gas phase wavelength (Foing & Ehrenfreund, 1994).



Laboratory confirmation of C_{60}^{+} as DIB carriers

Campbell et al., 2015

Wavelengths, widths & relative strengths
match measured (lab) values.

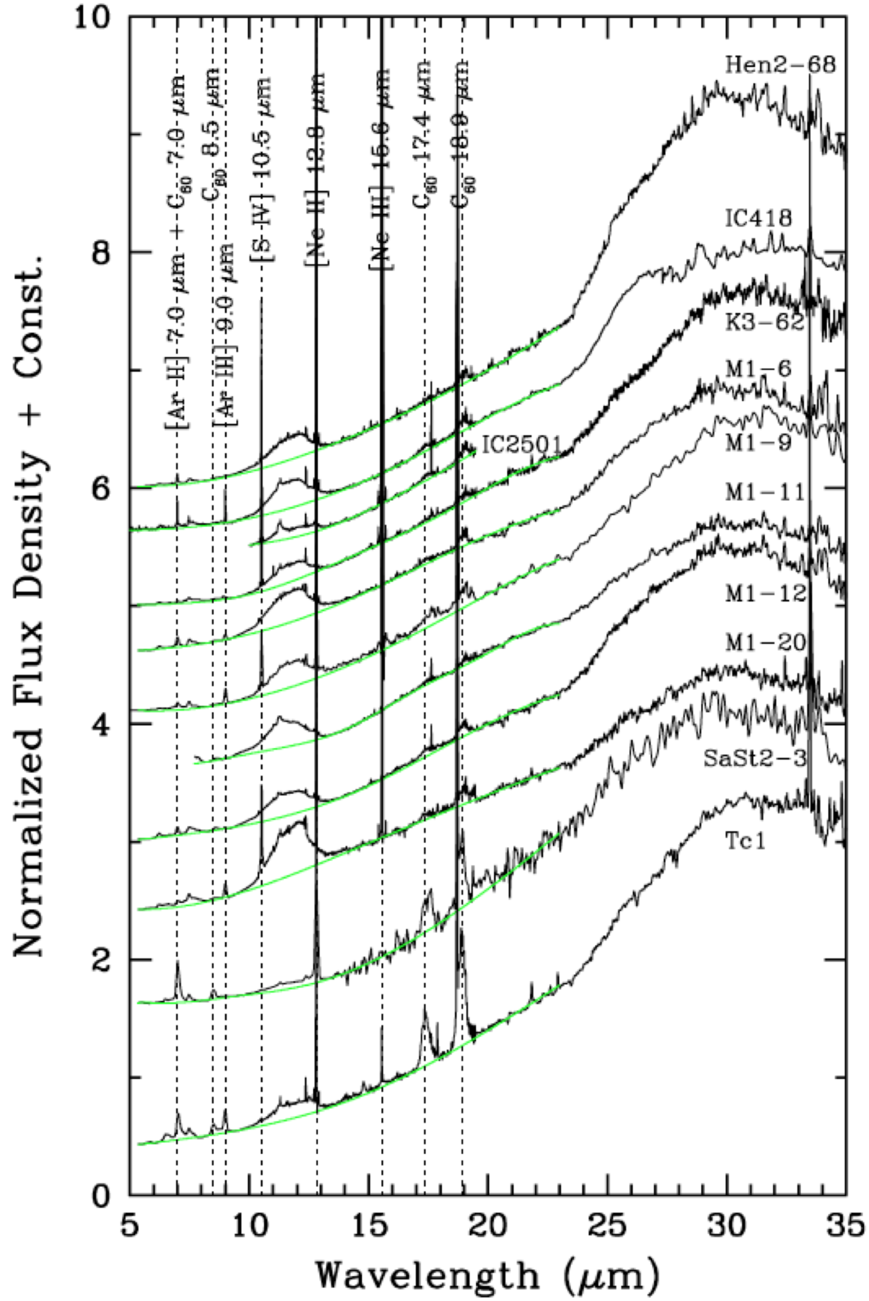


Buckyballs In A Young Planetary Nebula
NASA / JPL-Caltech / J. Cami (Univ. of Western Ontario/SETI Institute)

Spitzer Space Telescope • IRS
ssc2010-06a

Cami et al. (2010)

C_{60}-PNe spectra



- 11 Galactic C_{60}-PNe:
  - No (or very weak) PAHs.
  - 6—9 μm plateau.
  - 11—13 μm plateau. SiC?
  - Strong 30 μm feature.
- Strength of C_{60} bands relative to continuum is variable.

Conditions that favor fullerene formation or survival also result in other dust components!

Otsuka et al., 2014

Conditions & formation

Kinetic, bottom-up, C-rich (Jäger et al., 2009)

$T \lesssim 1,700\ K$ → **PAHs**

$T \gtrsim 3,000\ K$ → C_{60}

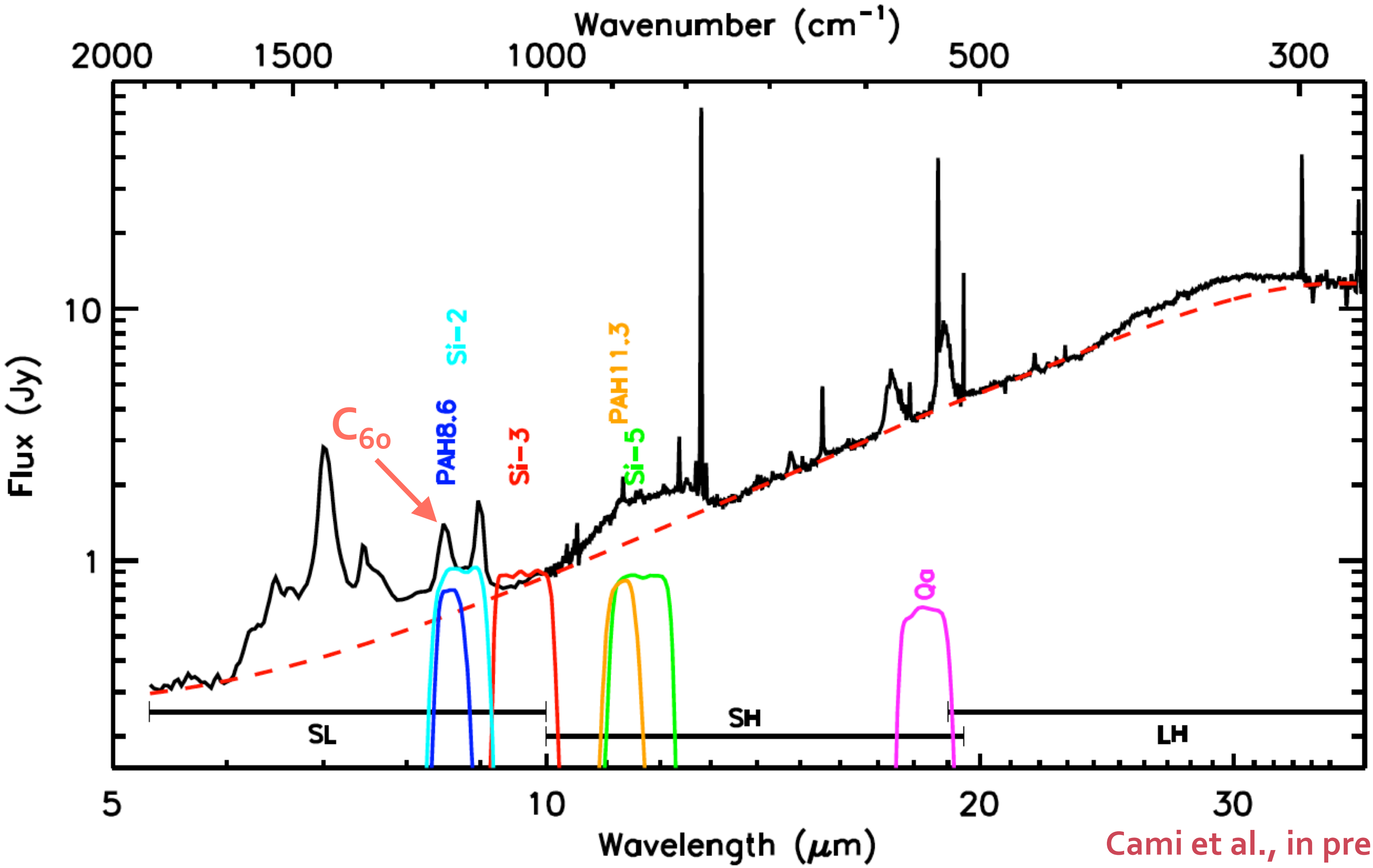
Closed Network Growth
(CNG)
(Dunk et al. 2012, 2013)

Very H-poor
(Wang et al., 1995)

Gemini T-ReCS observations

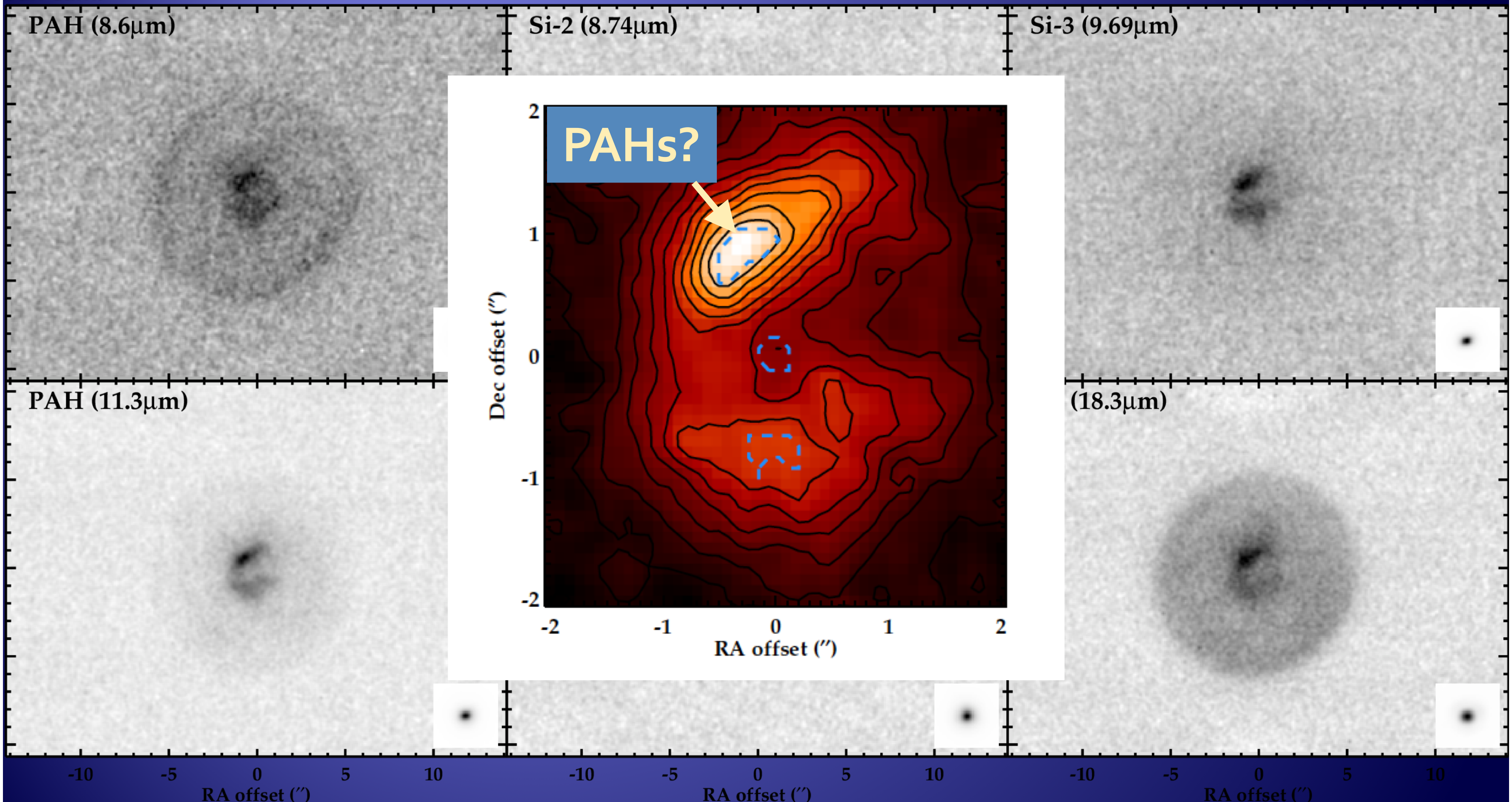
Jan Cami

Cosmic Fullerenes



Cami et al., in prep

Tc1: Lord of the Fullering

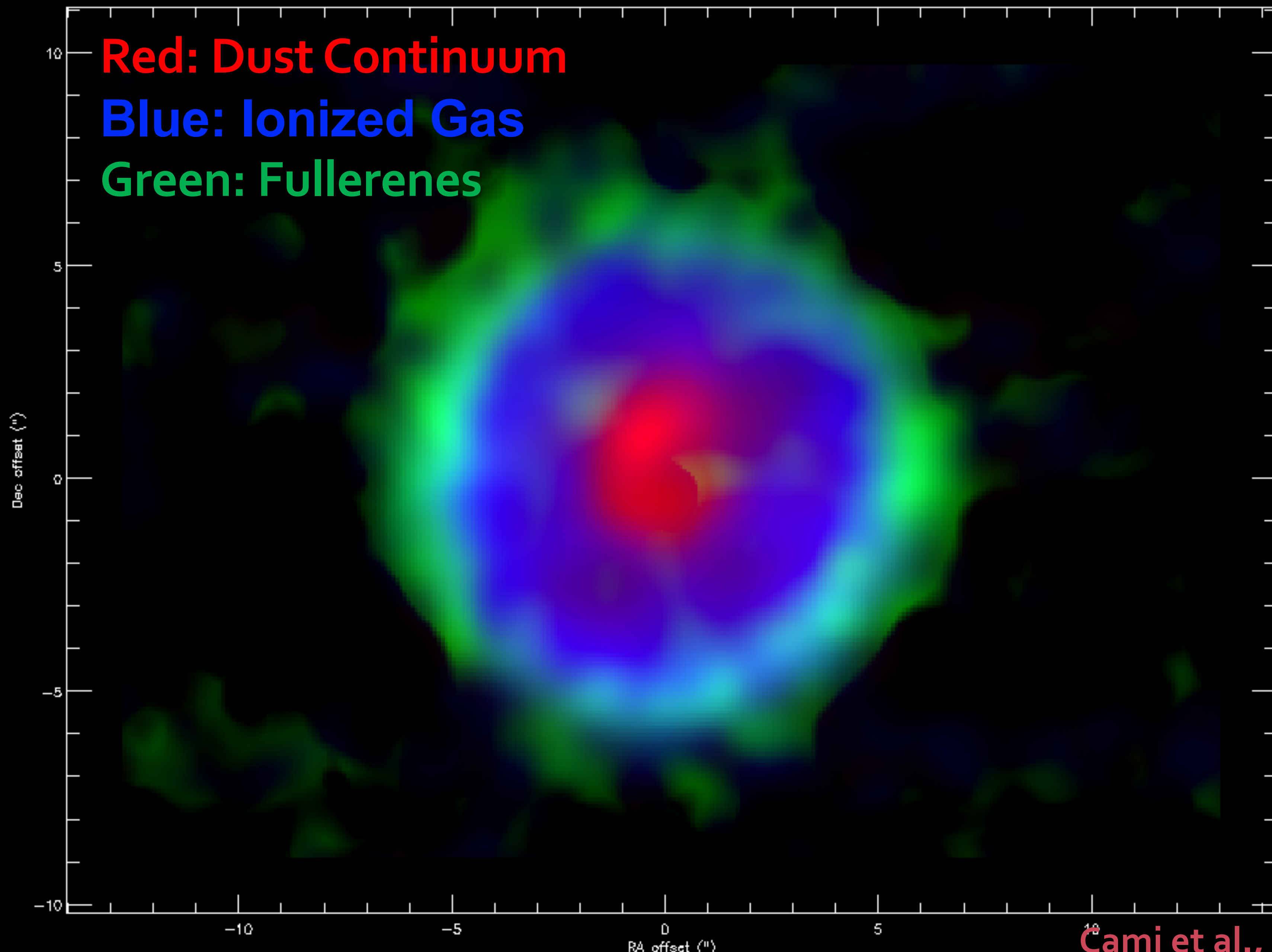


Cami et al., in prep

Tc1 Decomposed

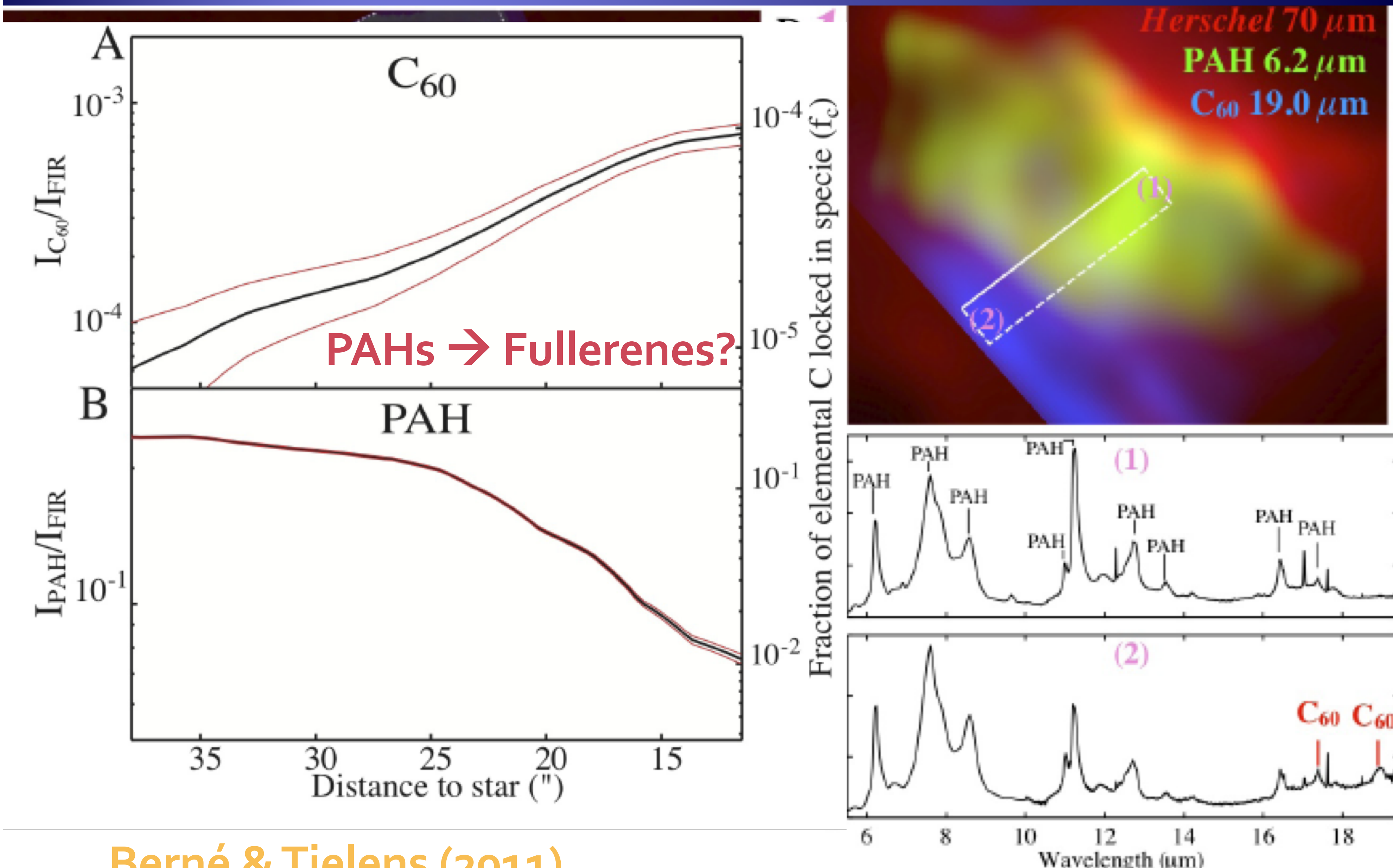
Jan Cami

Cosmic Fullerenes



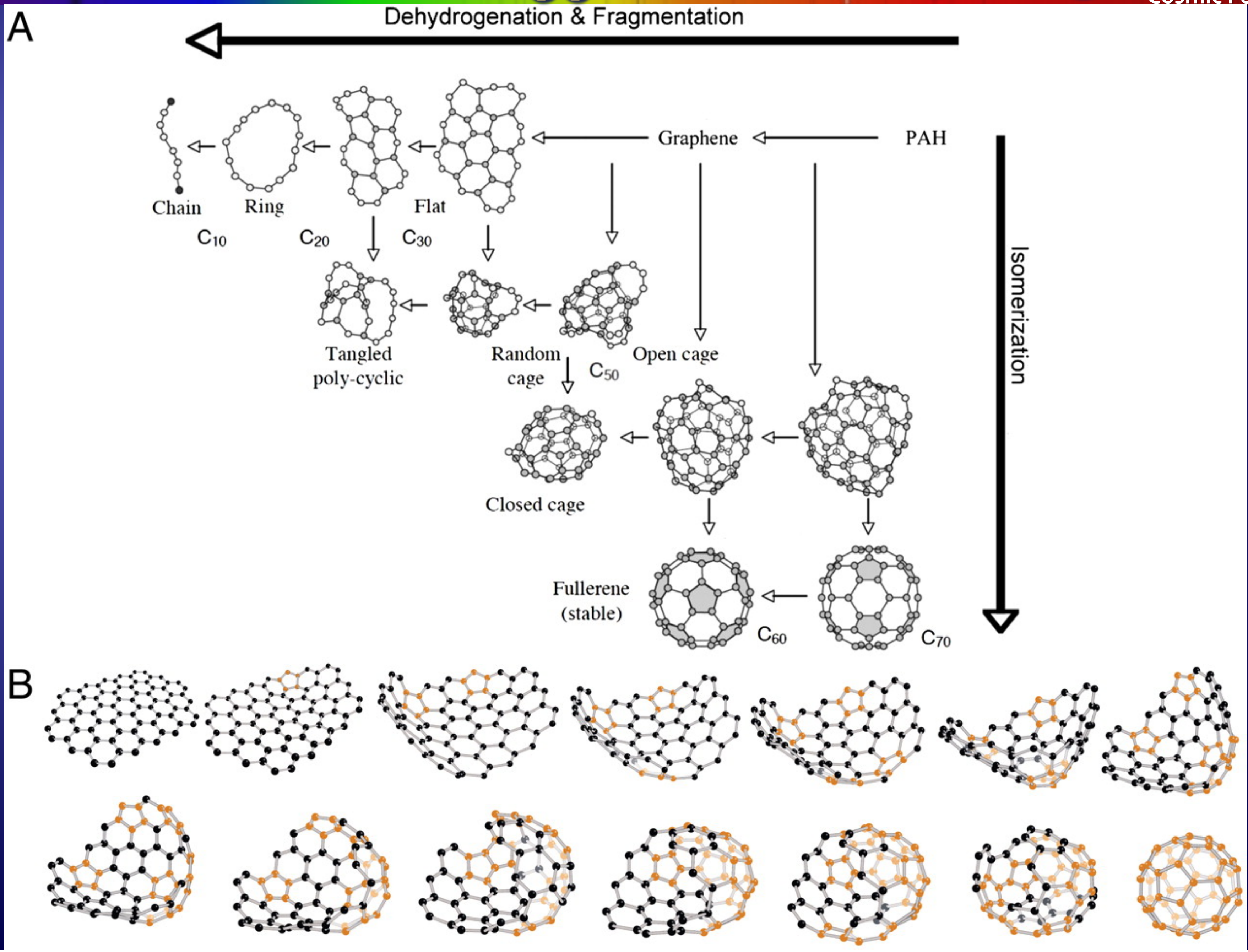
Cami et al., in prep

PAHs & C_{60} in NGC 7023



Berné & Tielens (2011)

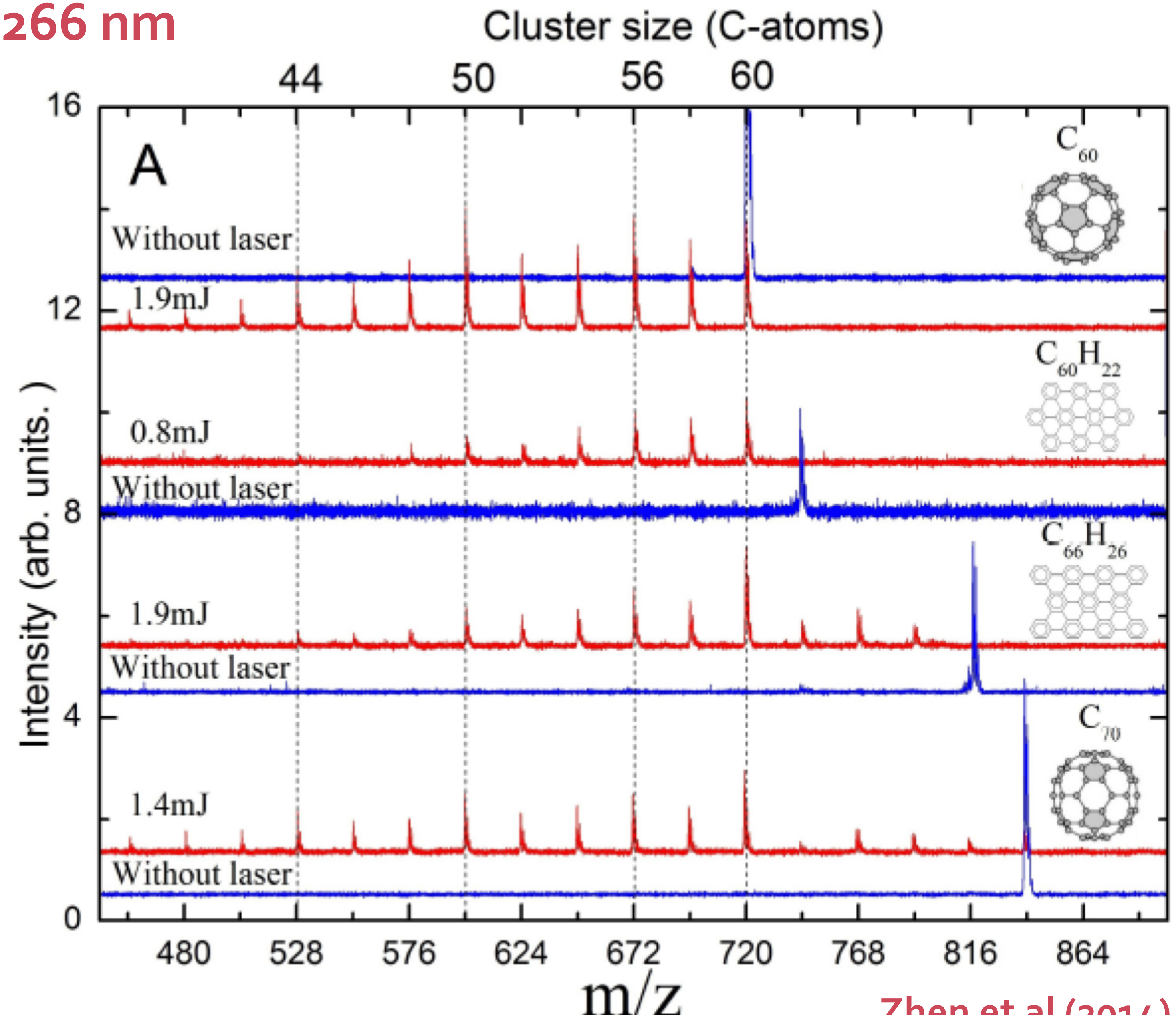
PAHs & C_{60} in NGC 7023



Berné & Tielens (2011)

Meanwhile at the lab (II)

266 nm



Zhen et al (2014)

Conditions & formation

Kinetic, bottom-up, C-rich (Jäger et al., 2009)

$T \lesssim 1,700\ K$

$T \gtrsim 3,000\ K$

Closed Network Growth (CNG)
(Dunk et al. 2012, 2013)

Very H-poor
(Wang et al., 1995)

PAHs

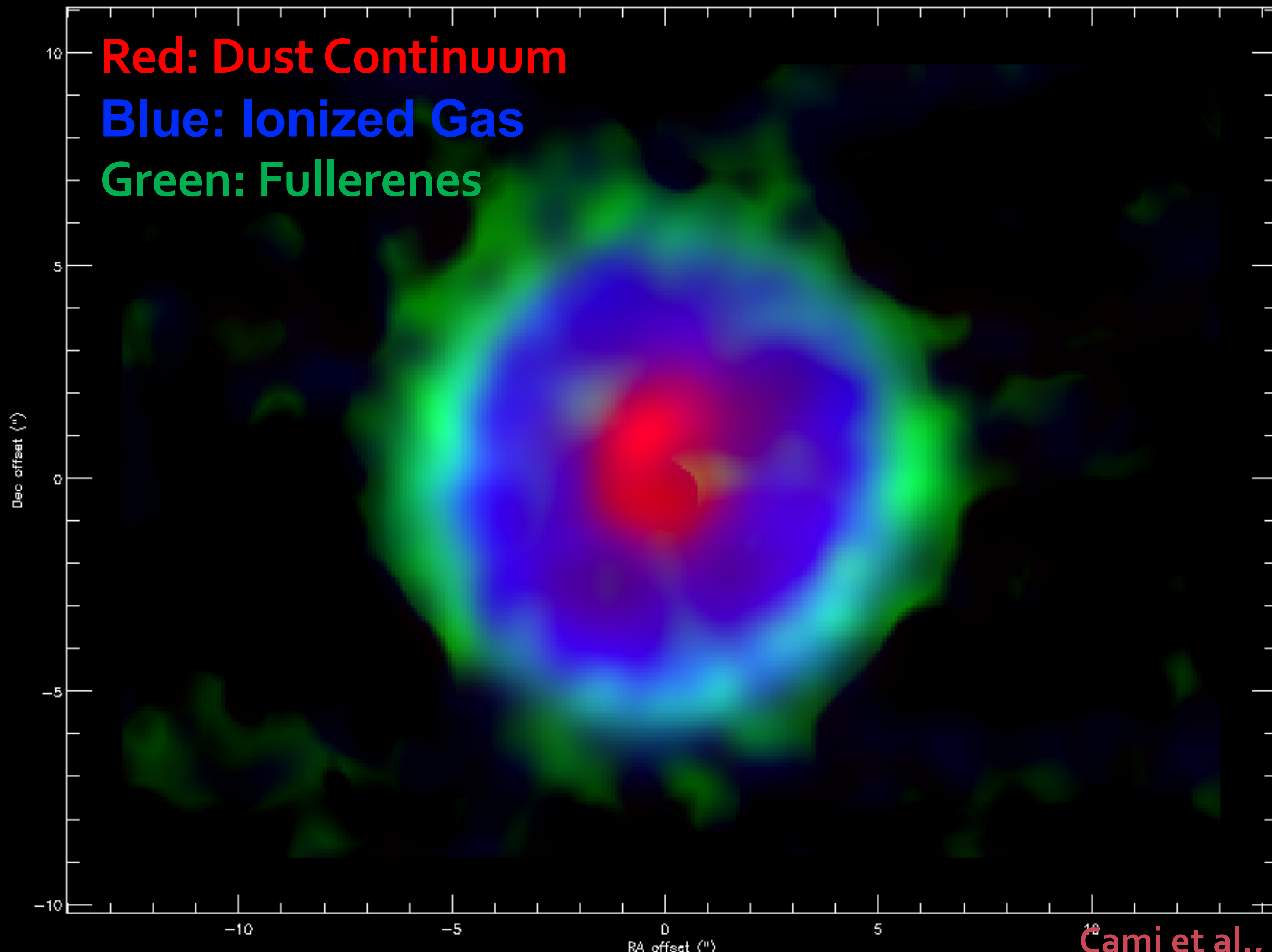
C_{60}

Photochemistry, top-down (Zhen et al., 2015)

PAHs

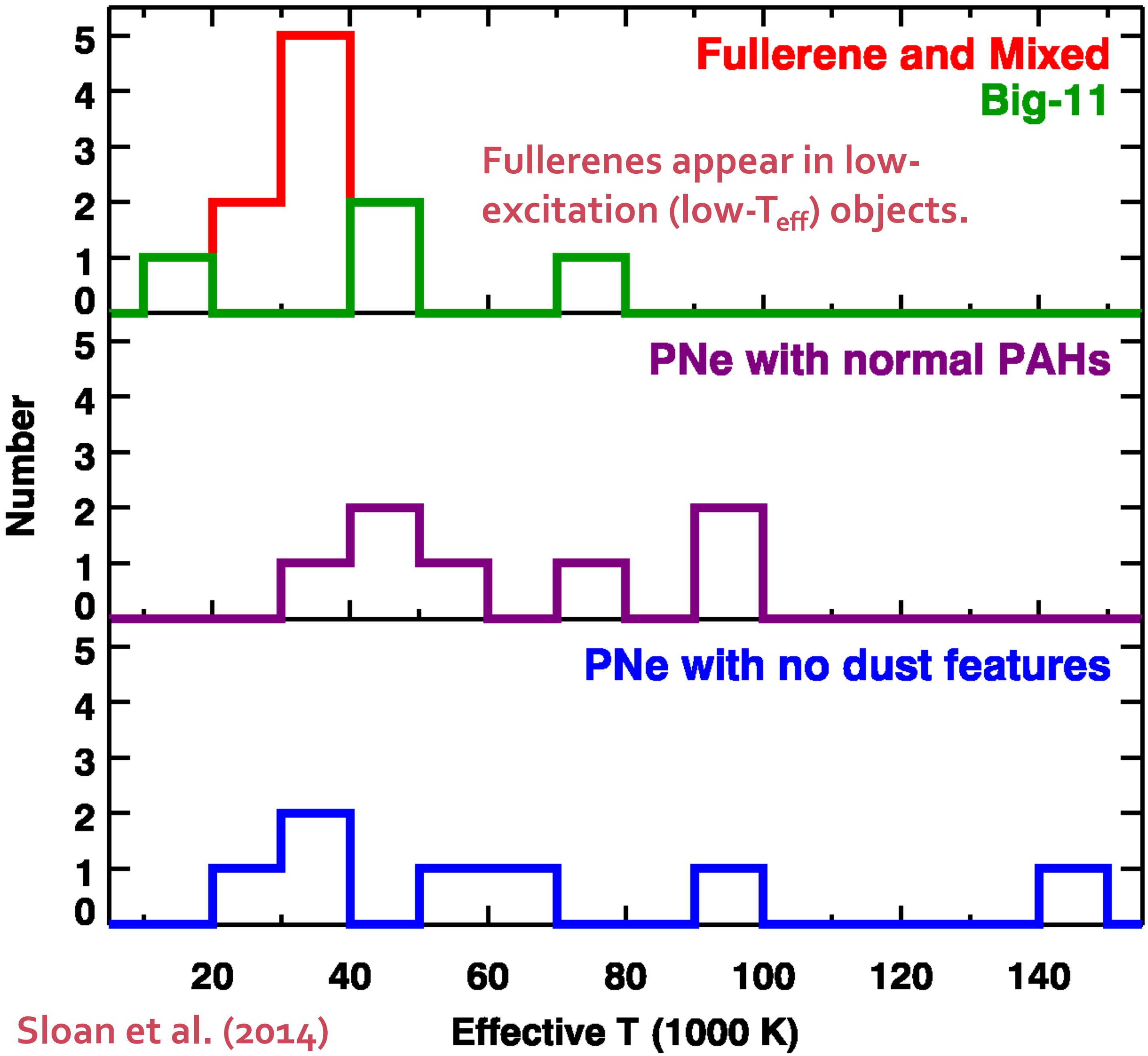
C_{60}

Tc1 Decomposed



Cami et al., in prep

Fullerenes and T_{eff}

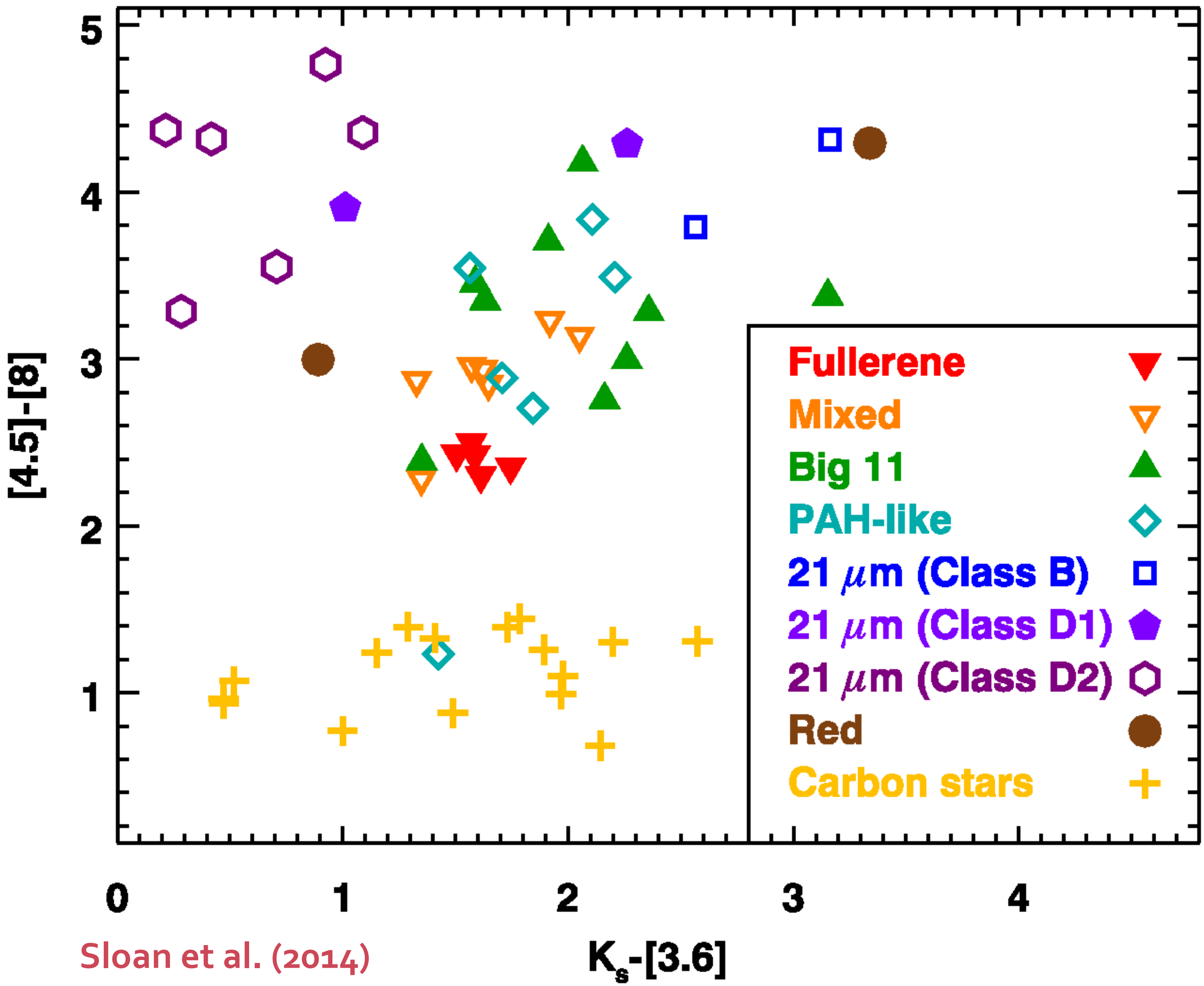


Sloan et al. (2014)

Fullerenes' true colors

Jan Cami

Cosmic Fullerenes



Sloan et al. (2014)

Fullerenes in evolved stars

To figure out the formation of fullerenes in evolved stars, we should consider that:

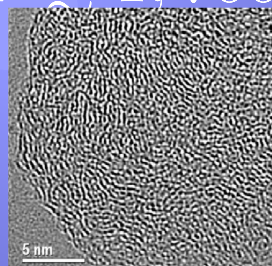
- ★ Fullerenes are ***not*** common in evolved stars: only 3% of a sample of galactic PNe show 17.4/18.9 micron bands (Otsuka et al. 2014).
- ★ Fullerenes do ***not*** require the strongest or hardest UV fields; in fact fullerenes are generally seen in the somewhat more mild environments (Sloan et al., 2014). Note: in Tc 1, fullerenes much further from star than PAHs, and in different geometry!
- ★ Fullerenes are seen in the least reddened sources.

Do the C60-PNe represent "special" sources, or a short-lived evolutionary phase?

Conditions & formation

Kinetic, bottom-up, C-rich (Jäger et al., 2009)

$T \lesssim 1,700\ K$

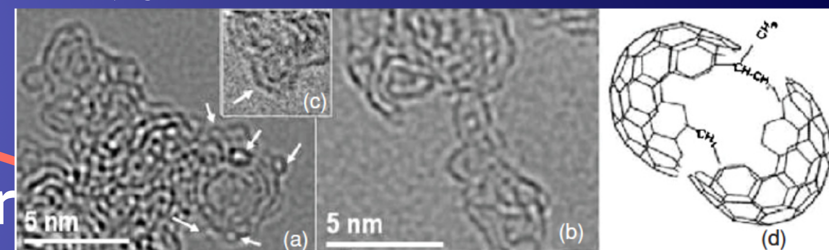


PAHs

Very H-poor

(Wang et al., 1995)

$T \gtrsim 3,000\ K$



C_{60}

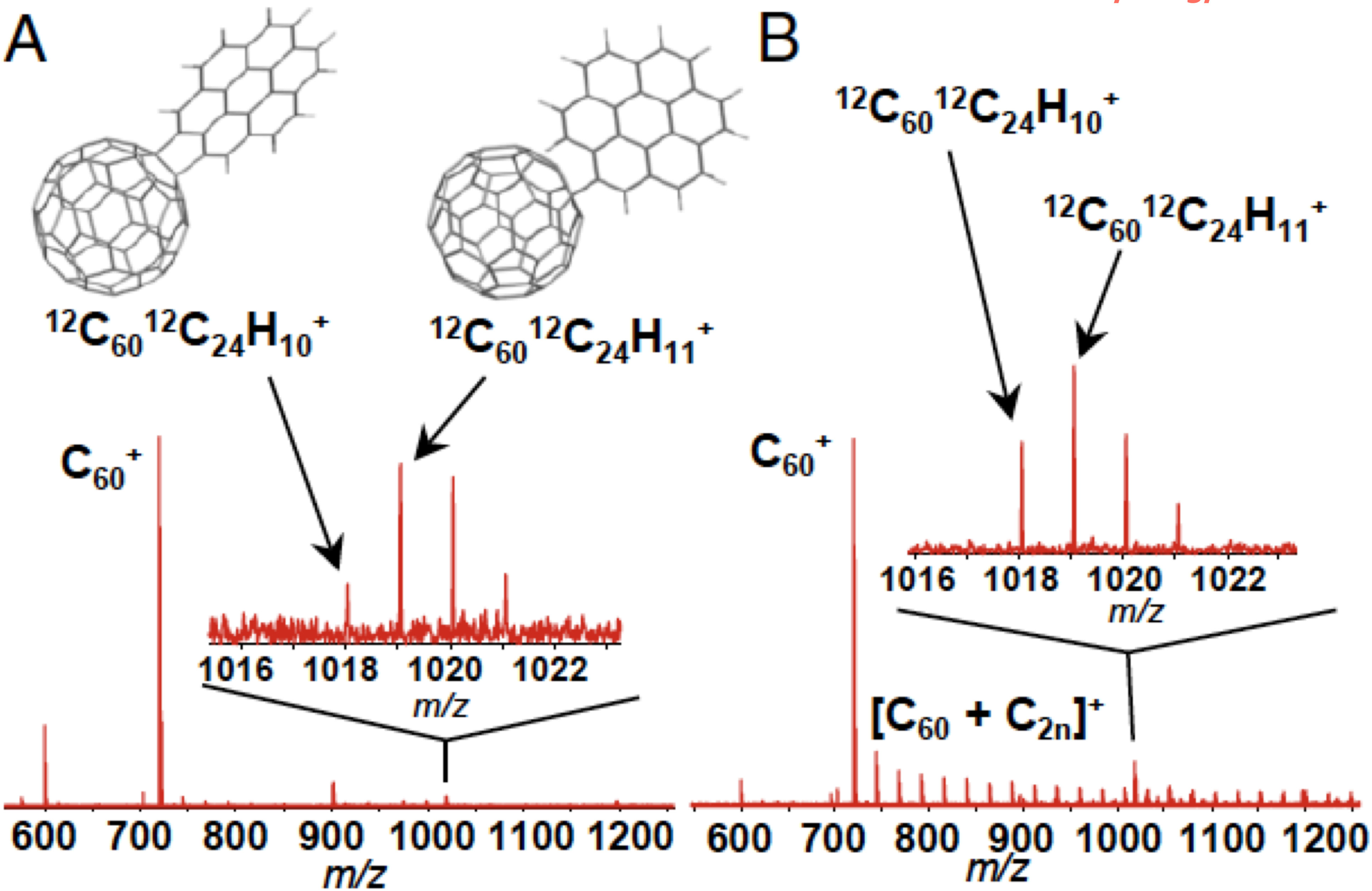
Photochemistry, top-down (Zhen et al., 2015)

Carbon Dust or PAHs, XL

C_{60}

C_{60} to carbon dust.

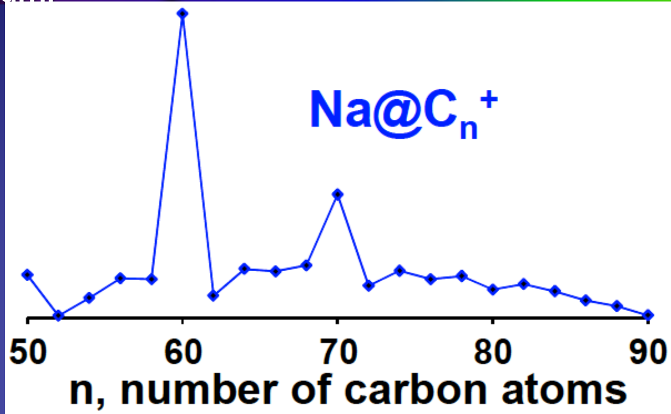
Dunk et al., 2013, PNAS.

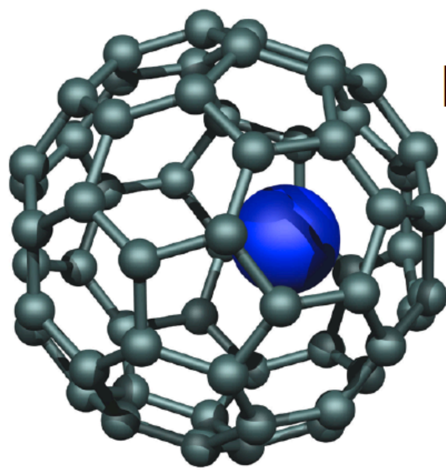


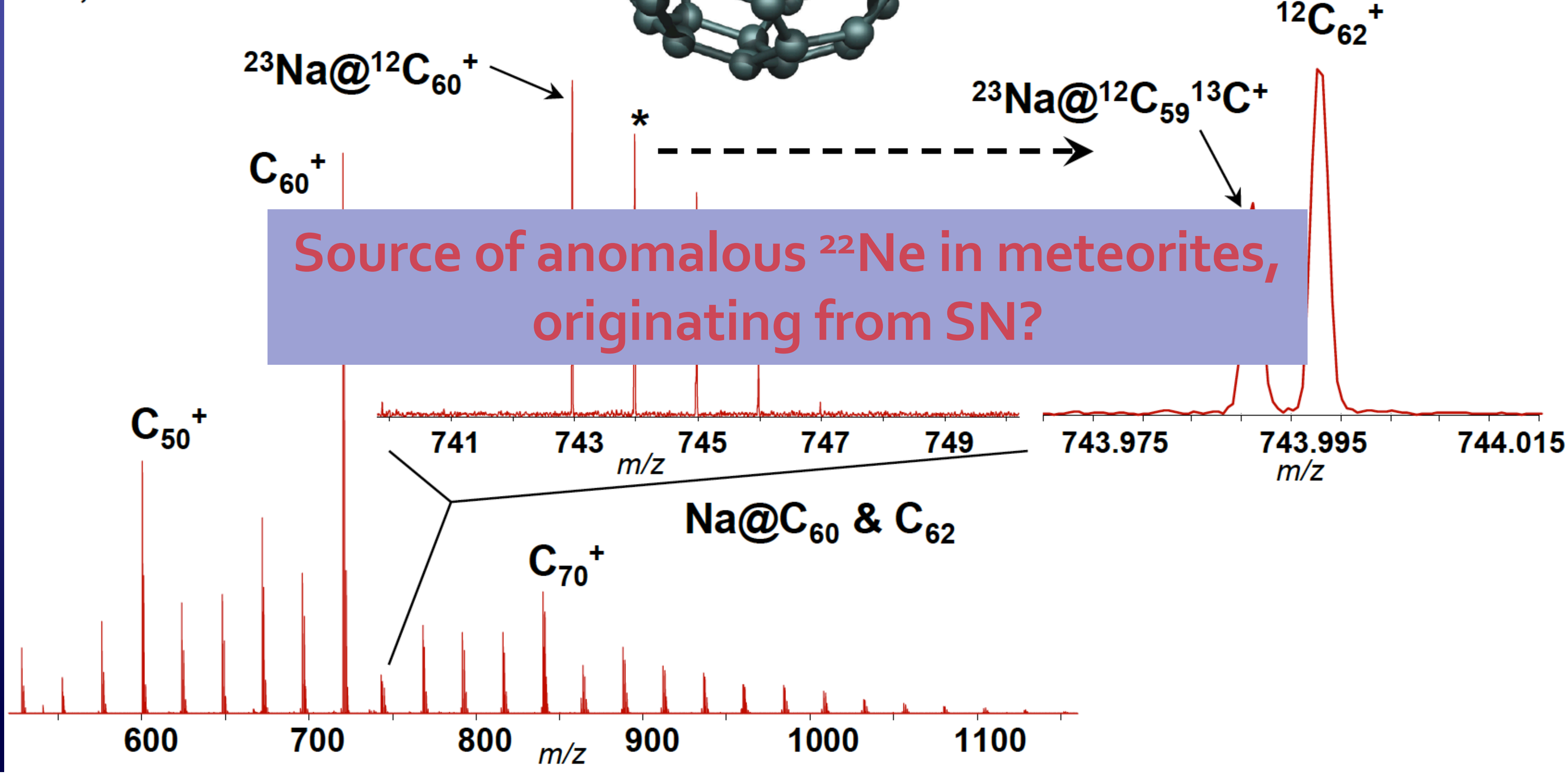
SN-fullerenes-meteorites

Dunk et al., 2013, PNAS.

Metallofullerenes: form as easily as fullerenes in "dirty" atmospheres.







Source of anomalous ^{22}Ne in meteorites, originating from SN?

C_{60} from dust in PNe?

- Start with material that is C-rich and either H-poor, or hotter than usual for some reason (unusual evolutionary status?)
- Condensation: fullerenic dust.
- Onset of PN phase: much of the dust is destroyed (Radiation? Shocks?), but fullerenes survive – before they turn into something else.
- Special geometry: does the torus play a role?

If dust destruction is key, this is relevant to ISM as well (DIBs anybody?)

Key Points

Fullerenes are abundant and widespread

C_{60} can form in the ISM from UV photo-processing of large PAHs

In PNe, condensation at high T (C-rich and/or H-poor) followed by dust destruction yields C_{60} (?)

Fullerene chemistry important to consider!