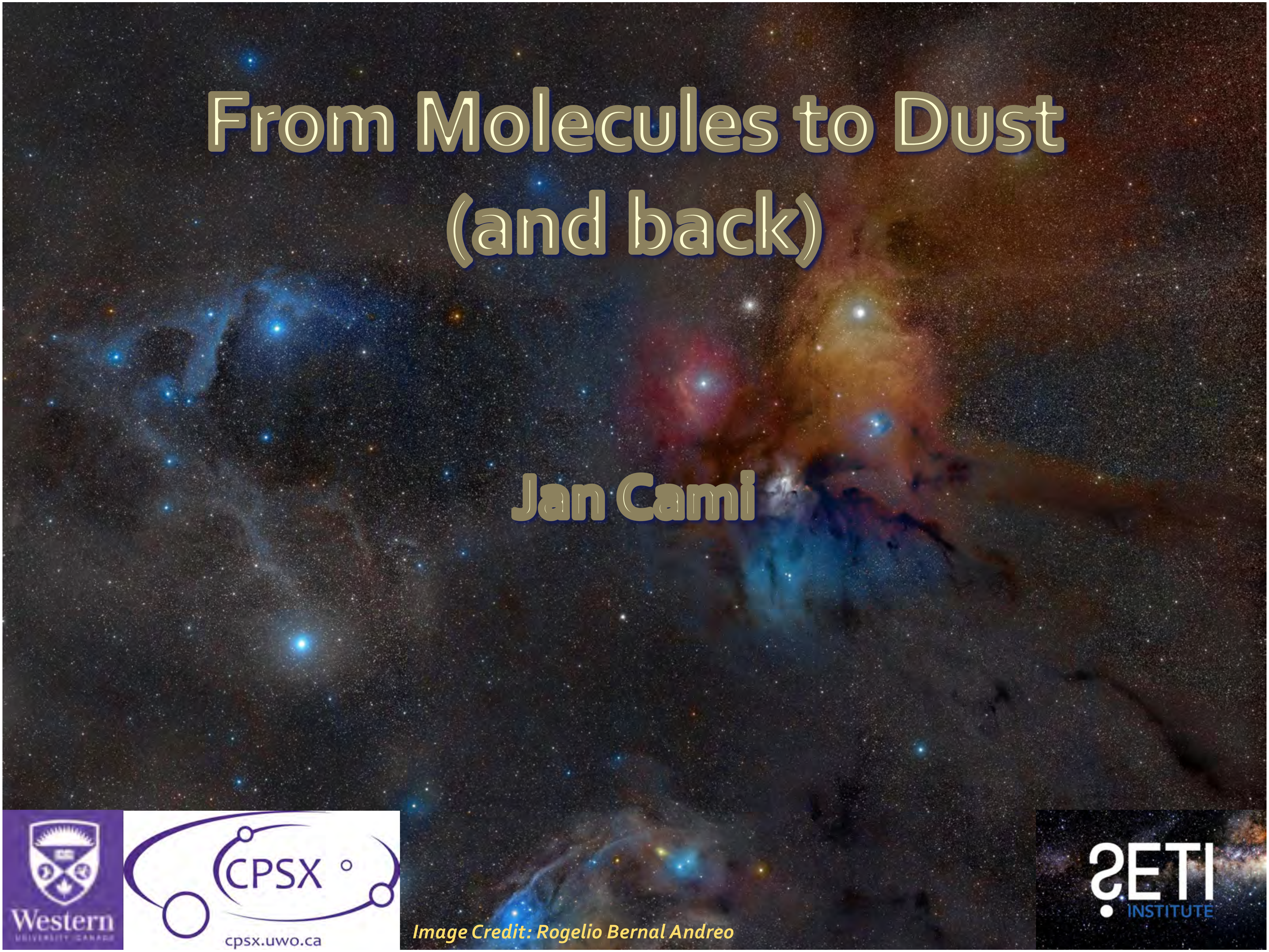
From Molecules to Dust (and back)

Jan Cami



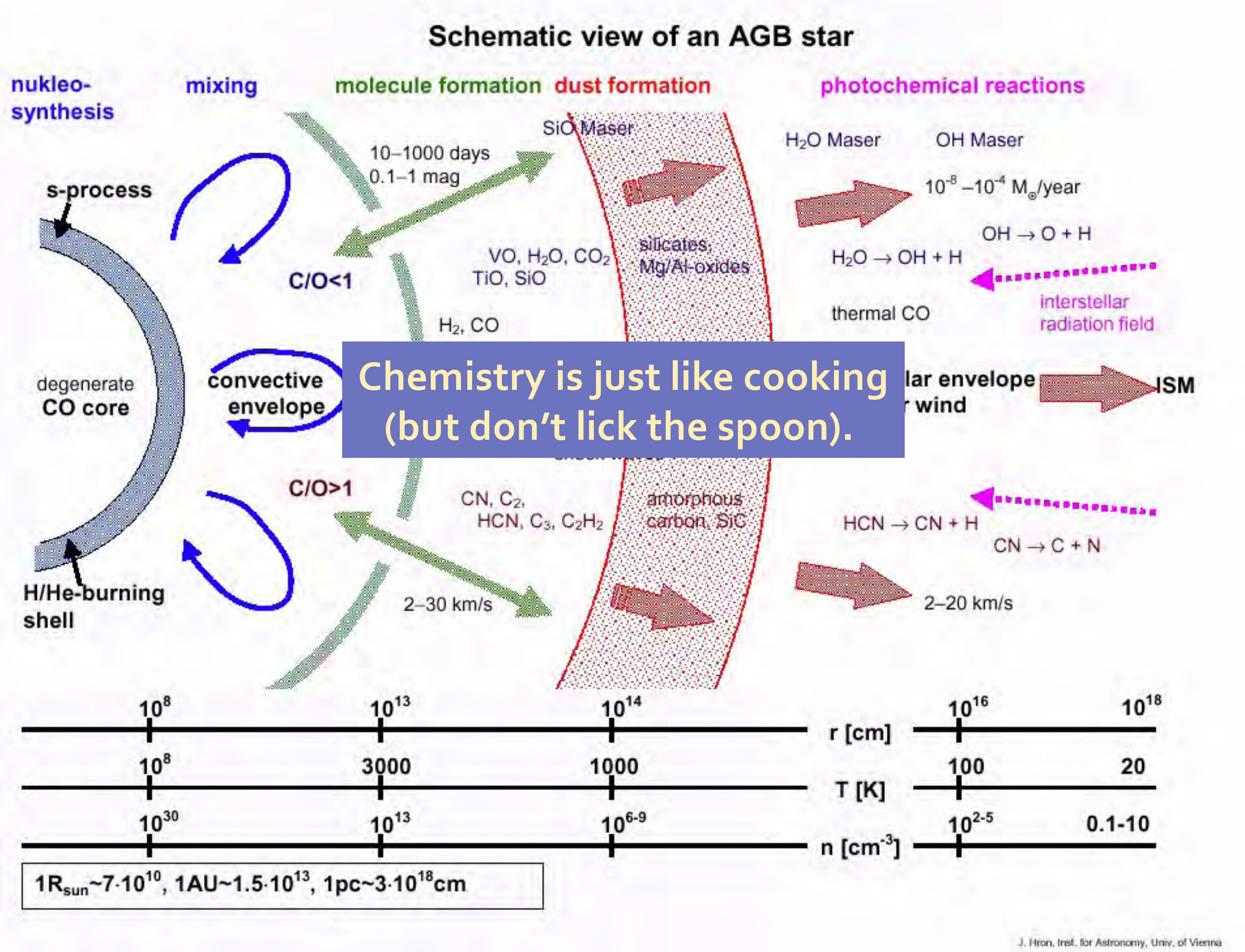
cpsx.uwo.ca

Image Credit: Rogelio Bernal Andreo

Molecules in Dusty Environments

- Important chemically (molecules ⇌ dust).
- Tremendous potential diagnostic value (figure out the physical conditions).
- Pathways to dust often go through molecules.
- Like dust, complicated interplay between physics and chemistry.

→ Better understanding of life cycle of molecular gas will lead to improved understanding of life cycle of dust.

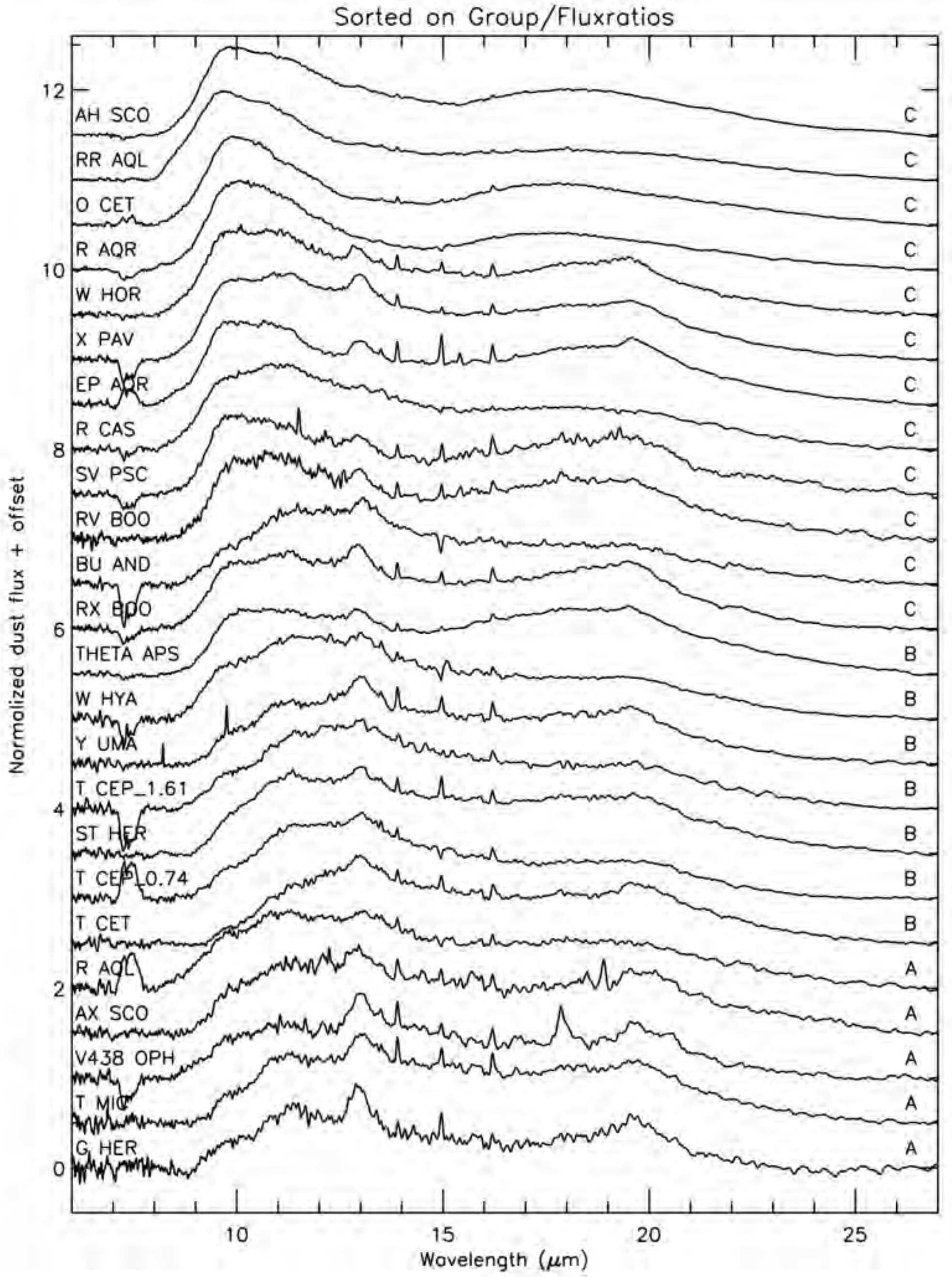


Chemistry is just like cooking
(but don't lick the spoon).

O-rich dust: diversity

Jan Cami

Molecules to dust



High mass loss rates: Silicates

Dust Diversity: → physical conditions and/or chemical inventory must be sufficiently different to change the outcome of the dust formation process (but molecular inventory very similar).

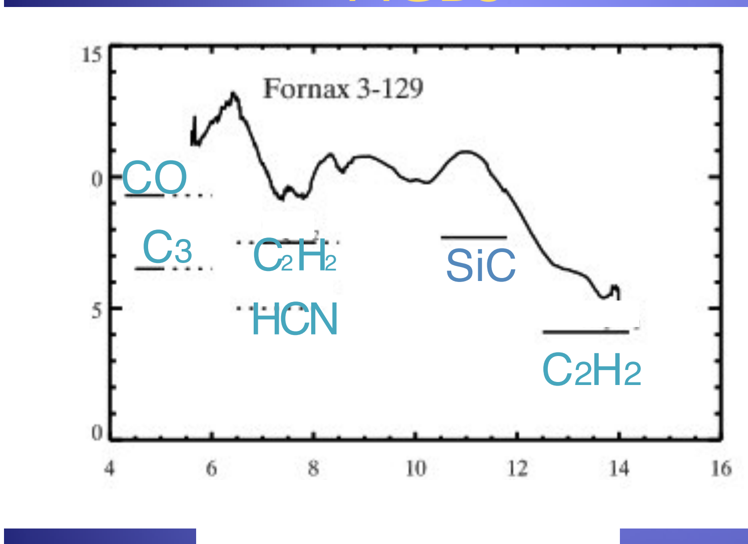
Low mass-loss rates: Oxides

C-rich dust: Diversity

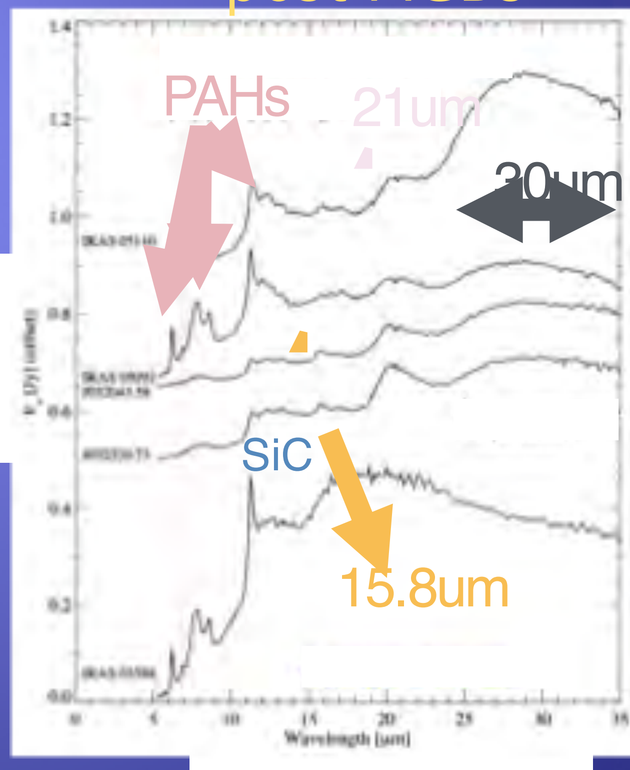
Jan Cami

Molecules to dust

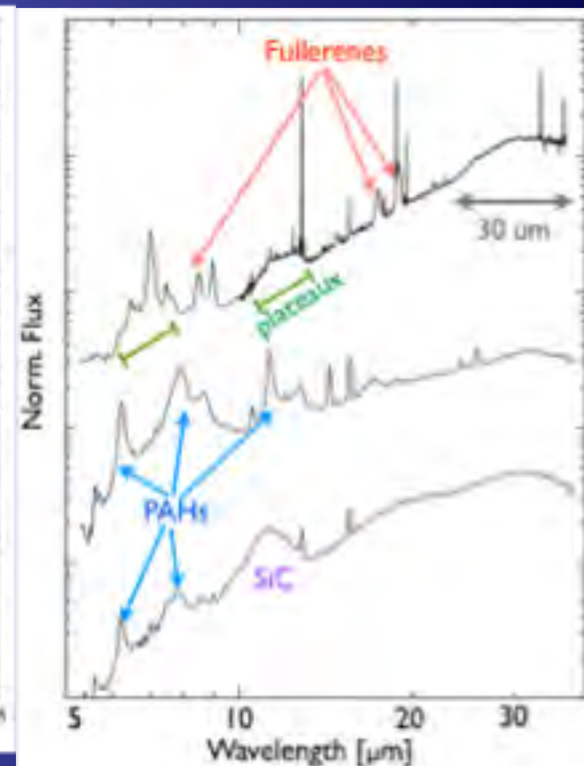
AGBs



post-AGBs



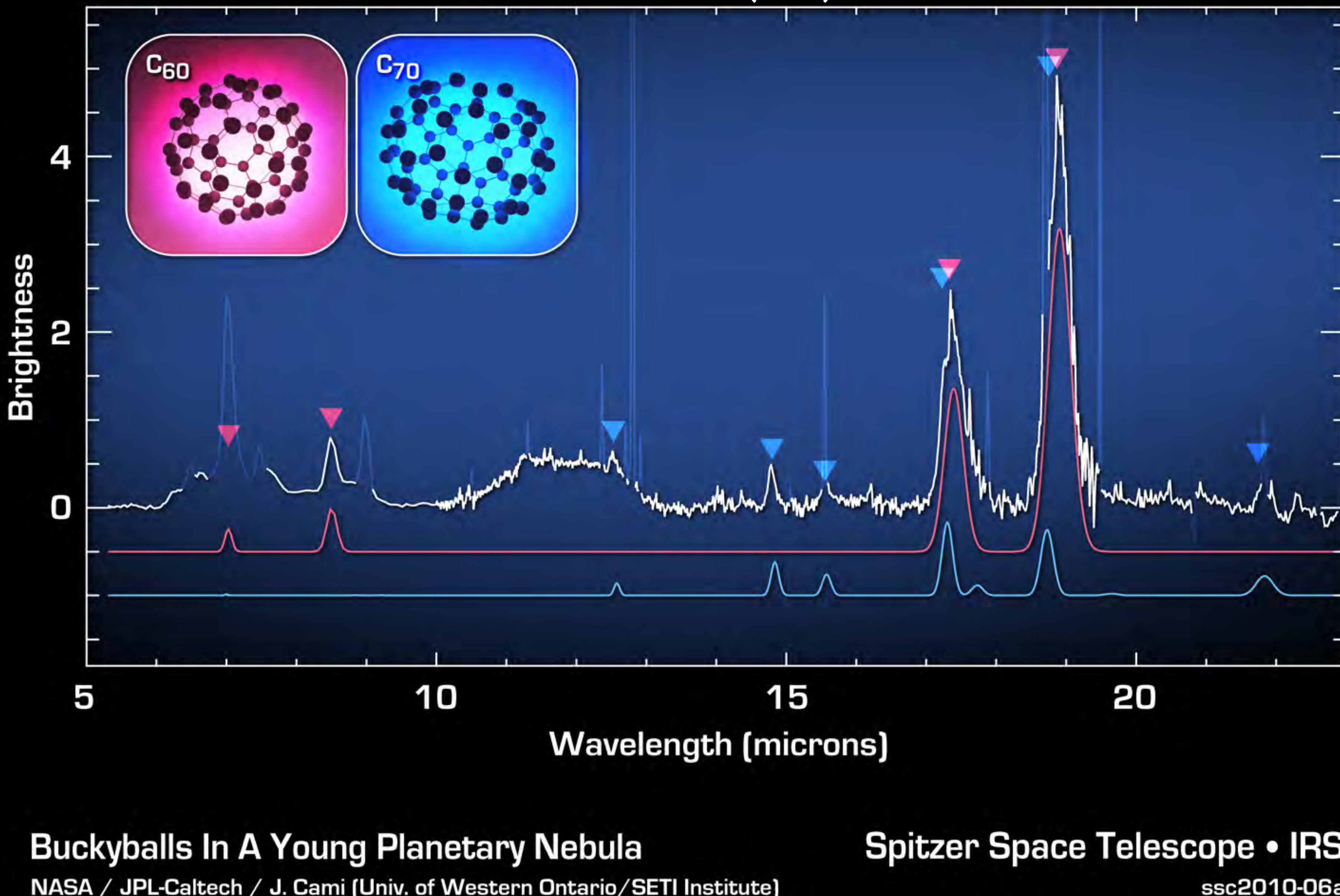
PNe



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.

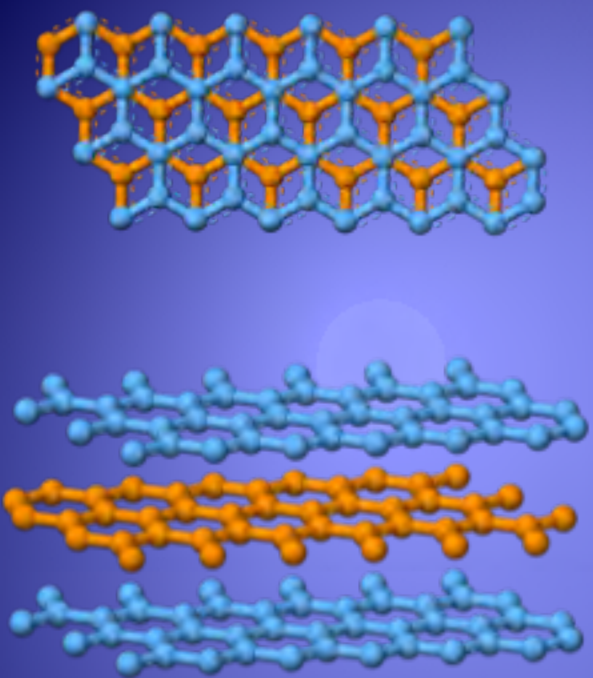
Wavelengths, widths & relative strengths
match measured (lab) values.

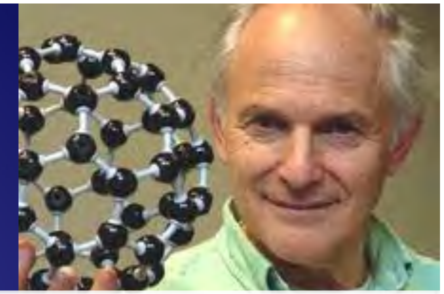


Cami et al. (2010)

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

Kroto et al. 1985

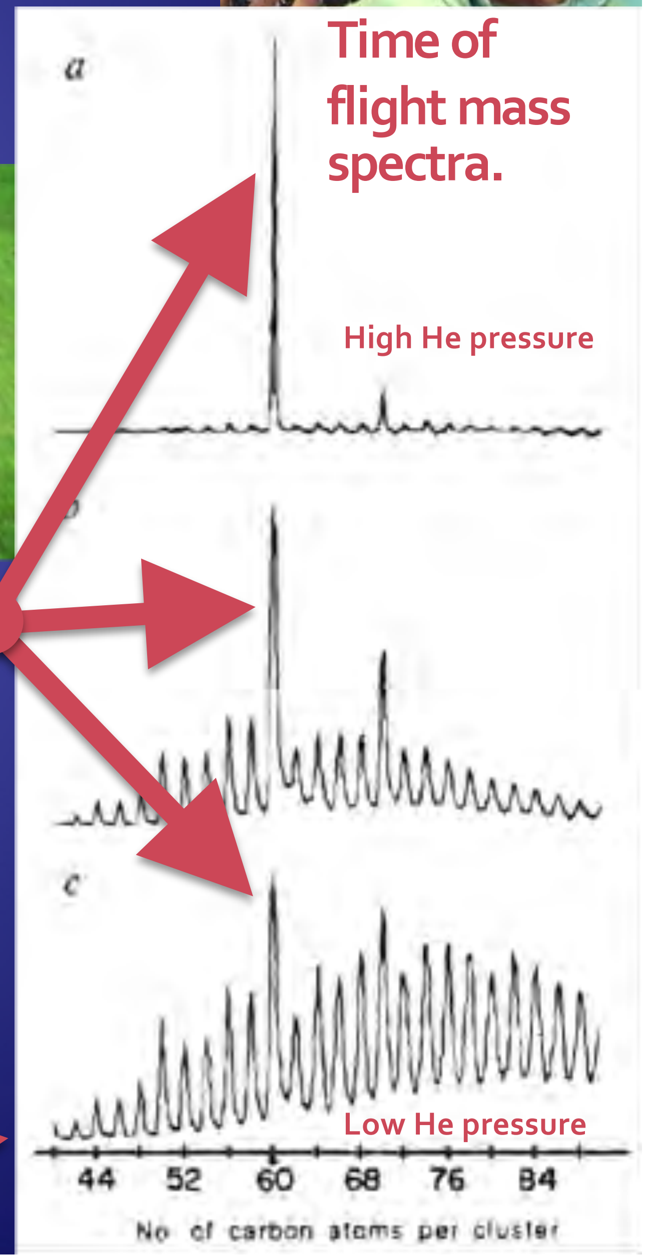




Survival of the fittest discovery of C_{60} and C_{70}.

Widespread and abundant in space?

Graphite vaporization.



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)

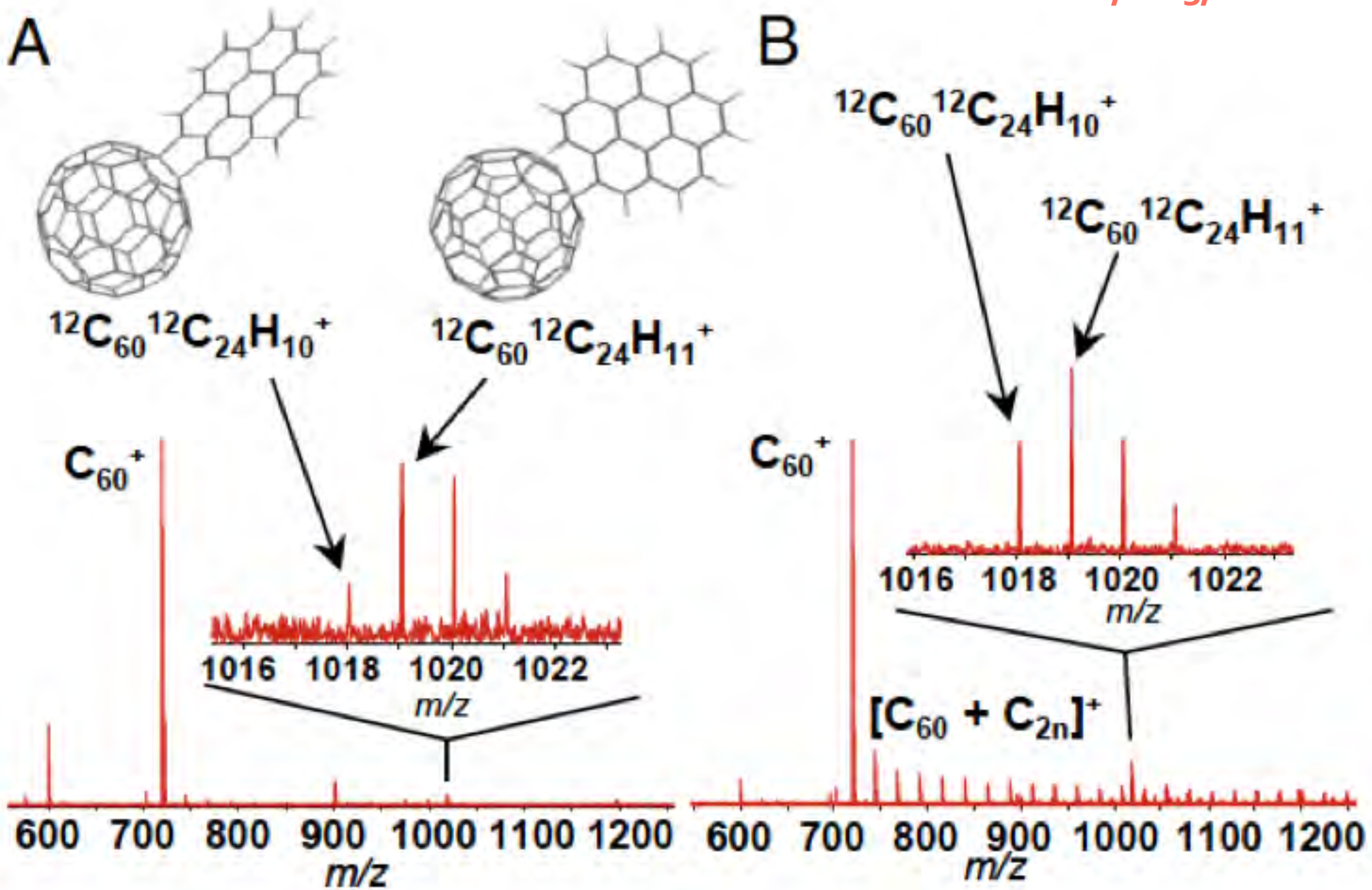
Very H-poor
(Wang et al., 1995)

PAHs

C_{60}

C_{60} to carbon dust.

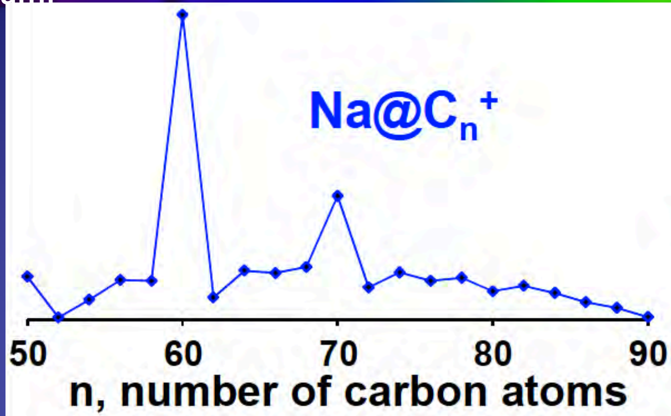
Dunk et al., 2013, PNAS.

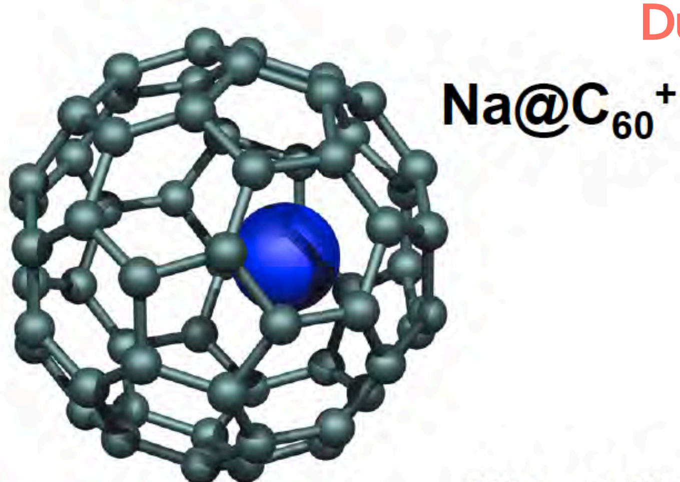


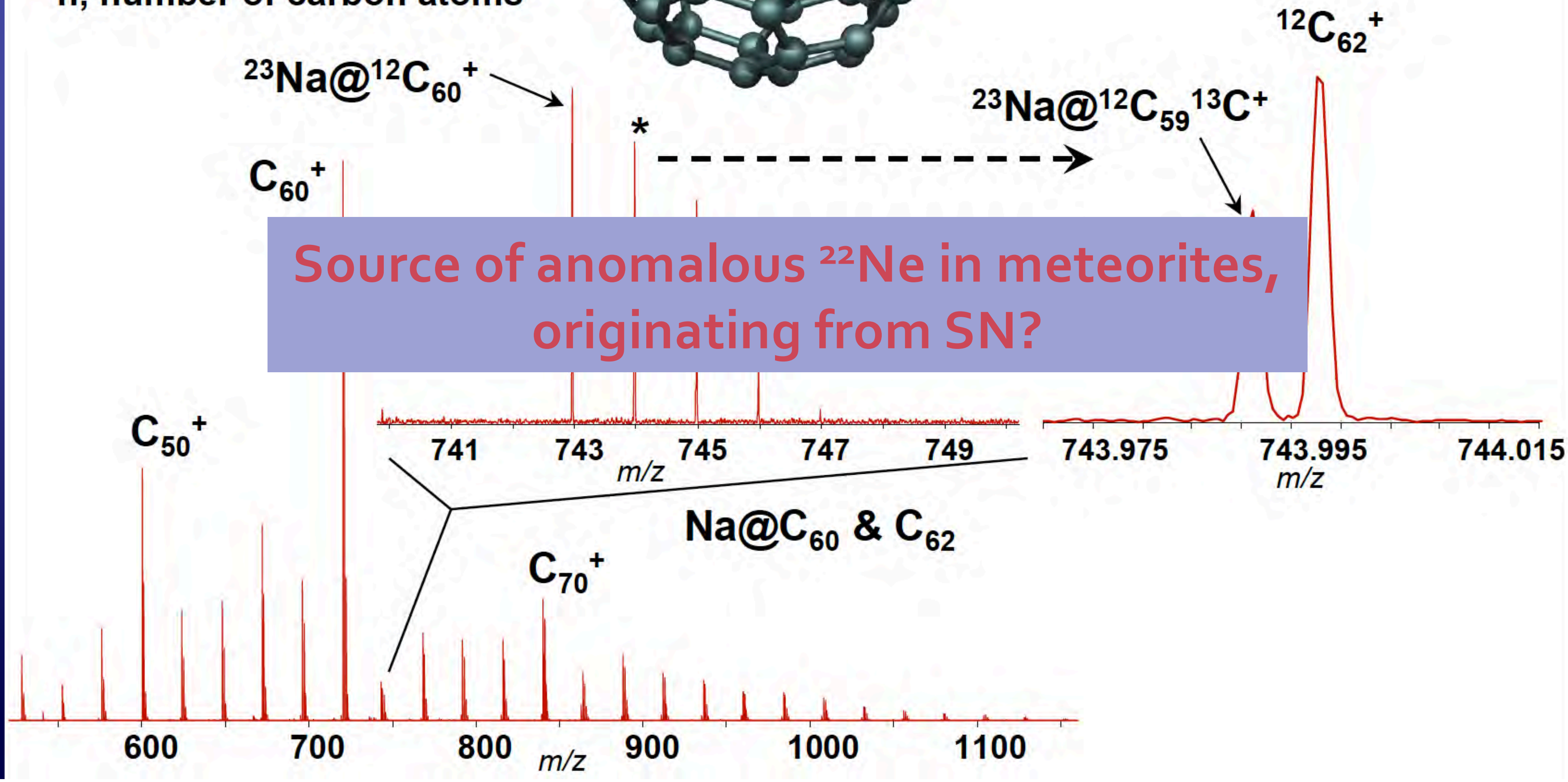
SN-fullerenes-meteorites

Dunk et al., 2013, PNAS.

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

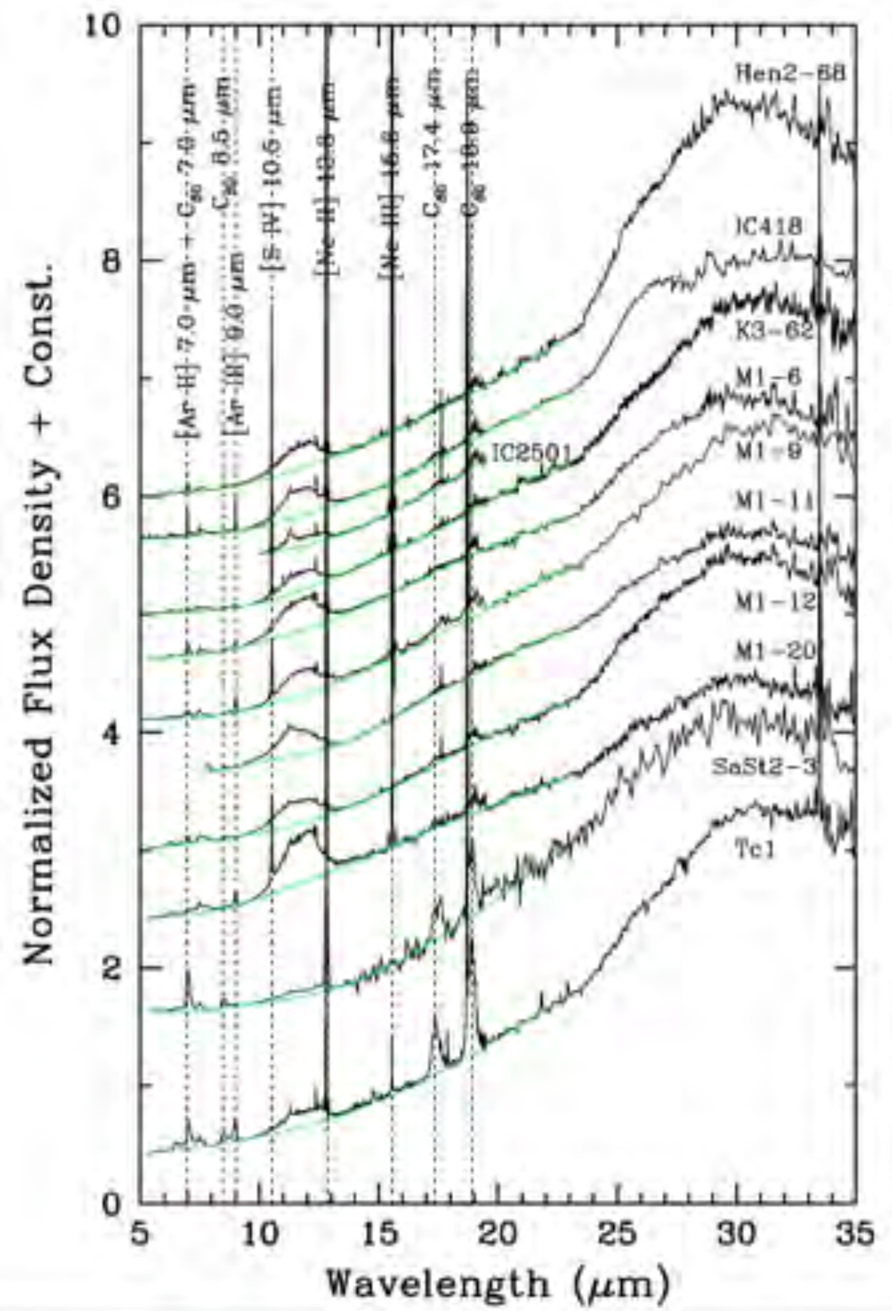






Source of anomalous ^{22}Ne in meteorites, originating from SN?

C_{60}-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.

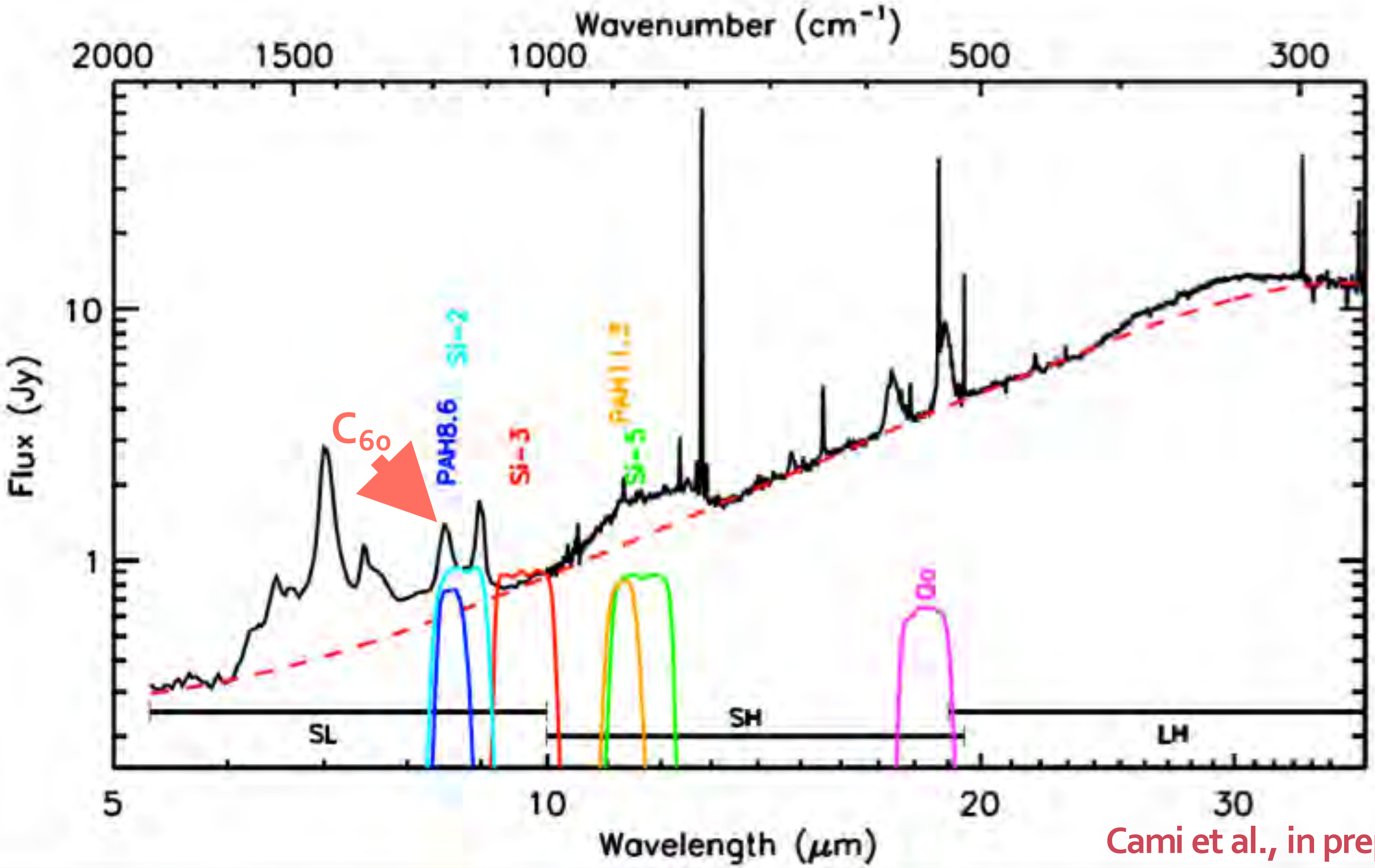
Conditions that favor fullerene formation or survival also result in other dust components!

Otsuka et al., 2014

Gemini T-ReCS observations

Jan Cami

Molecules to dust

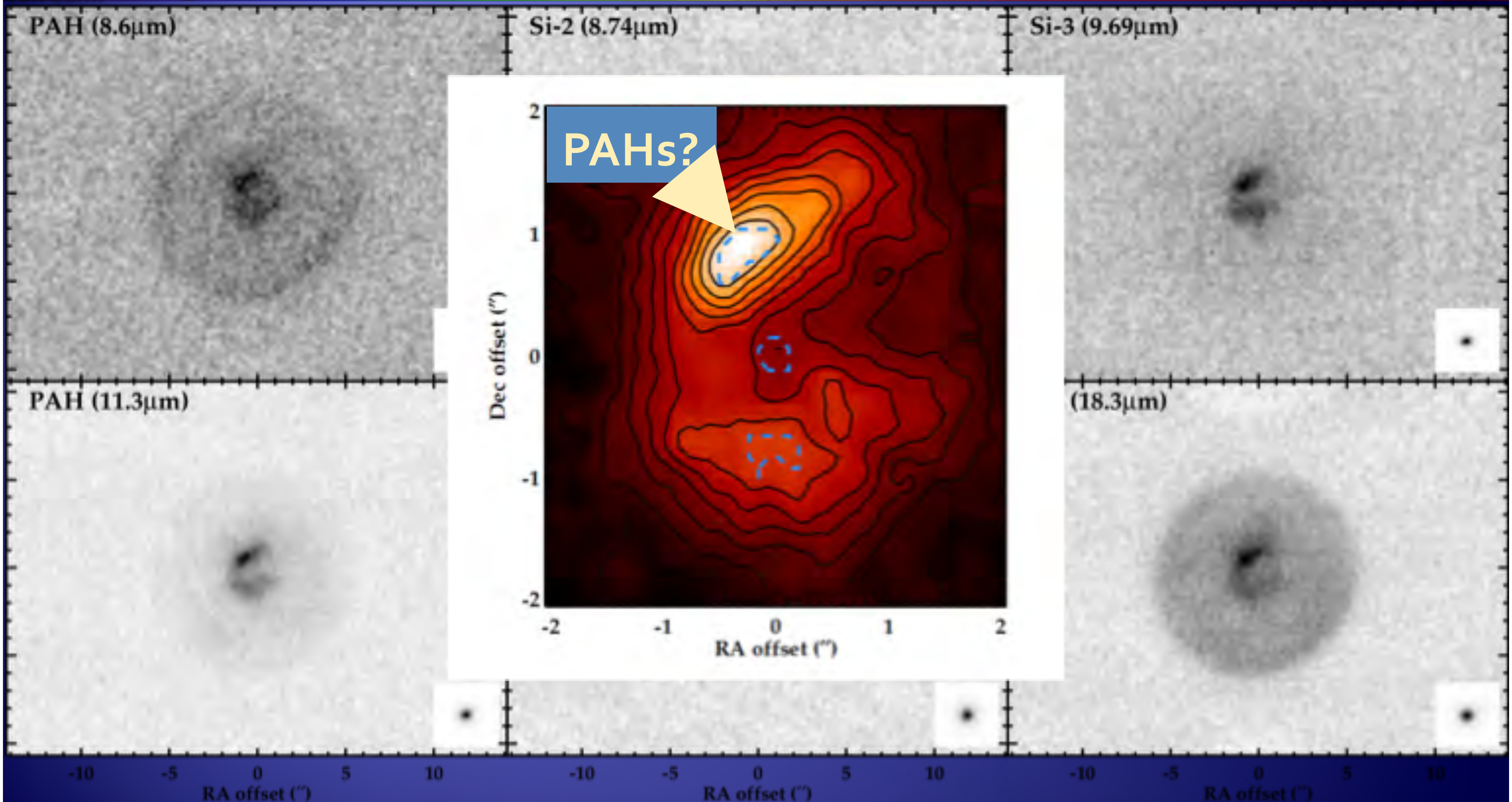


Cami et al., in prep

Tc1: Lord of the Fullering

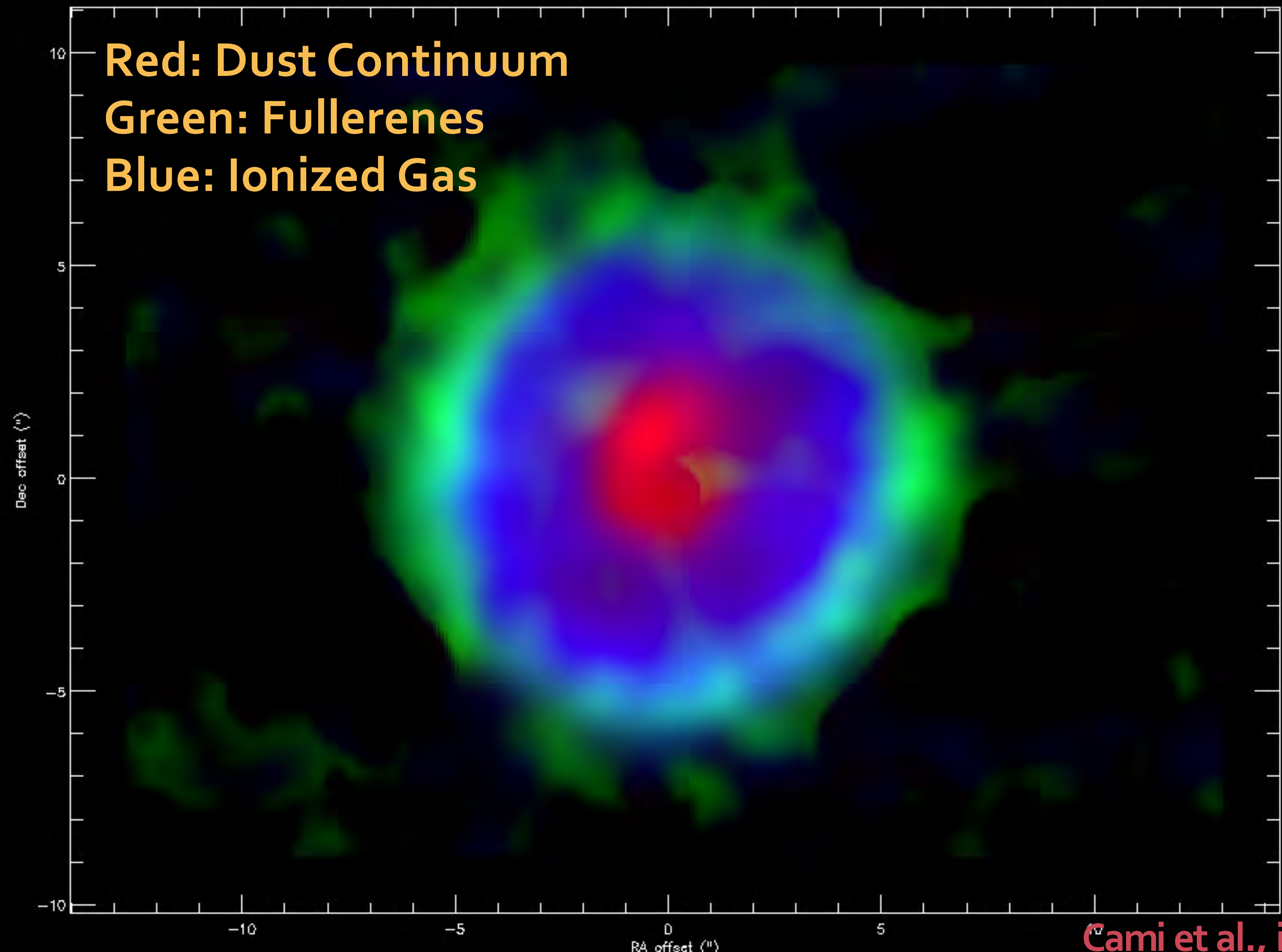
Jan Cami

Molecules to dust



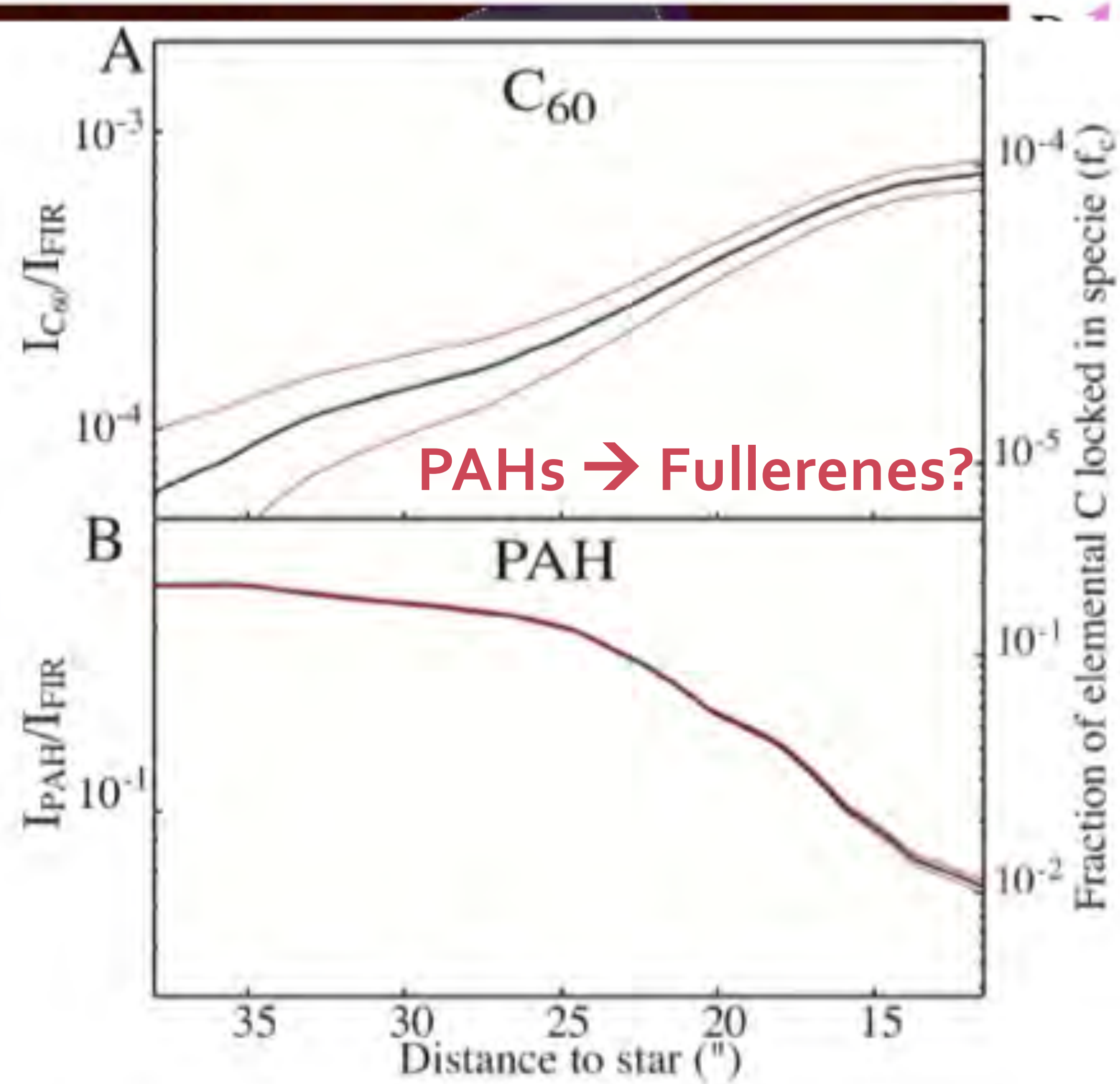
Cami et al., in prep

Tc1 Decomposed

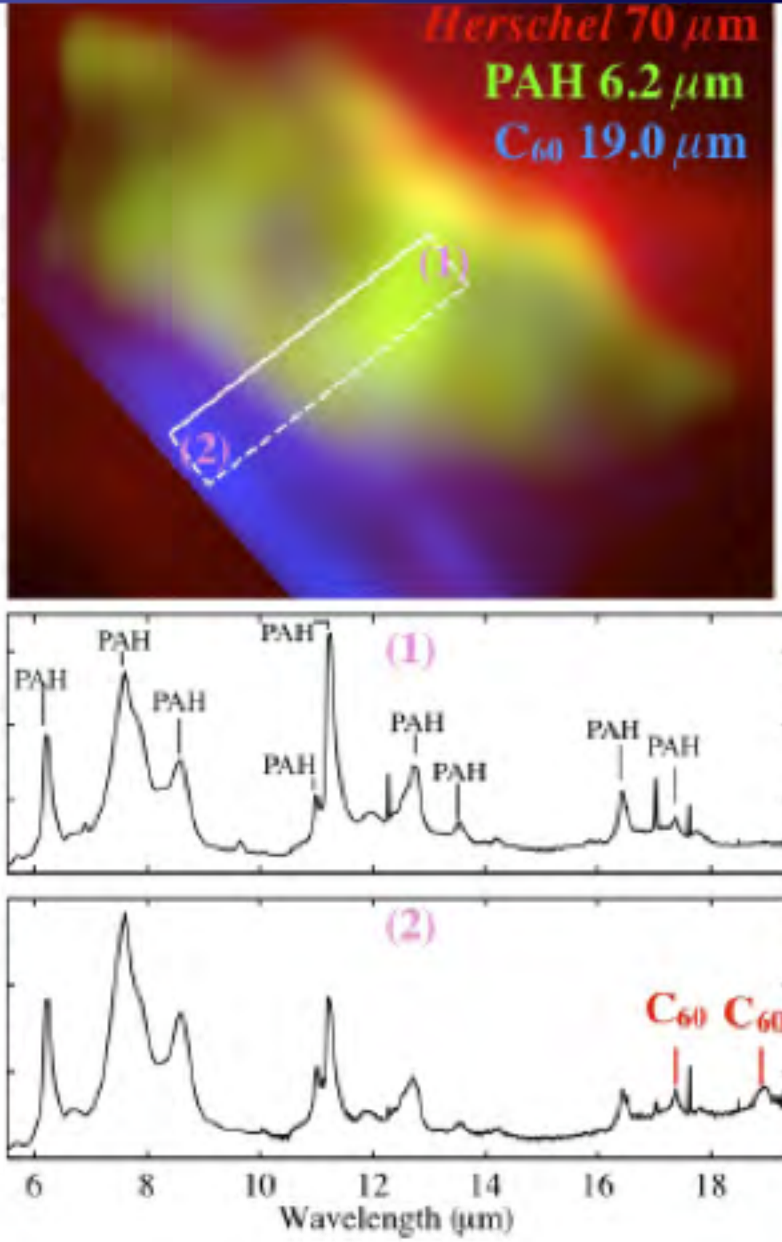


Cami et al., in prep

PAHs & C_{60} in NGC 7023

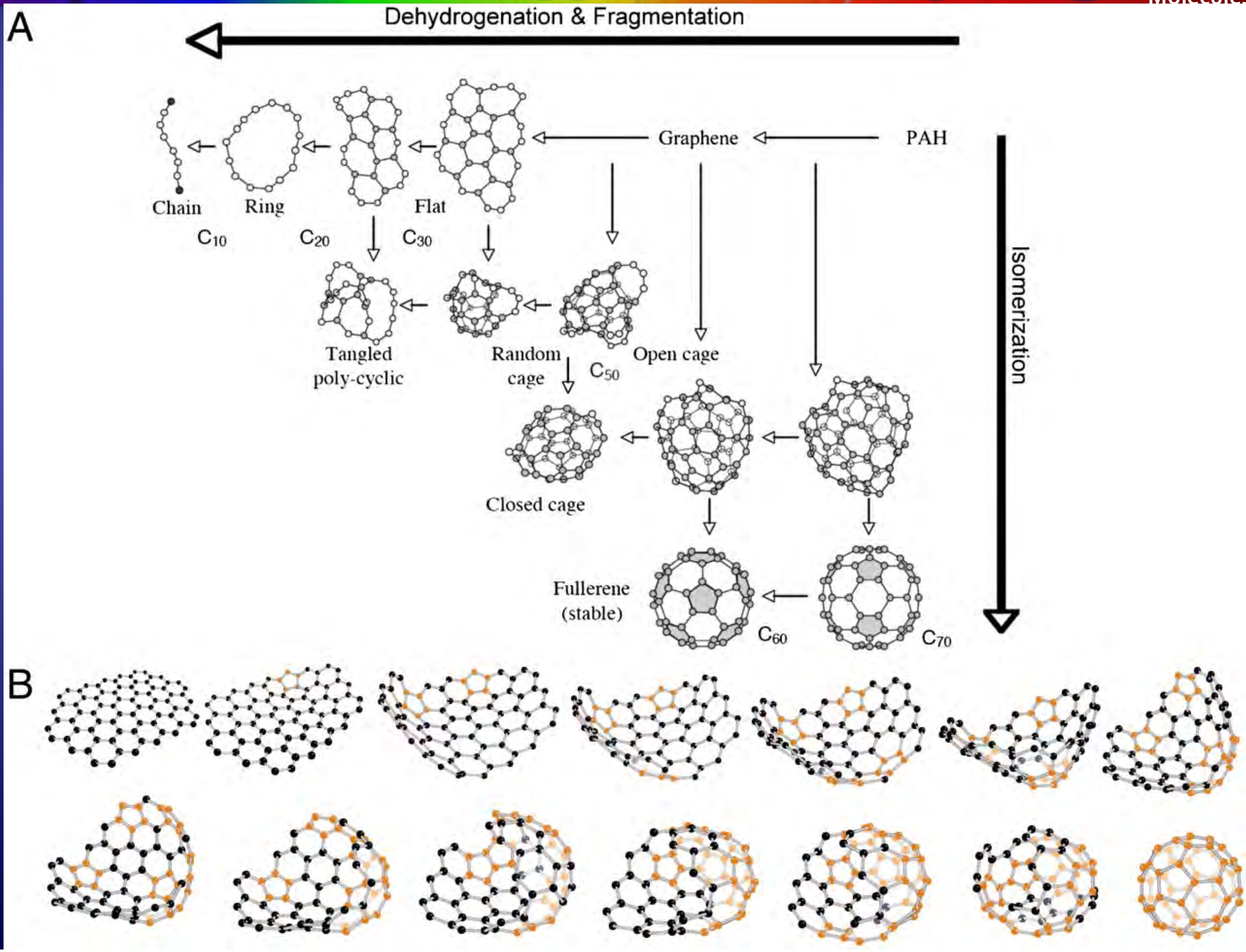


PAHs → Fullerenes?



Berné & Tielens (2011)

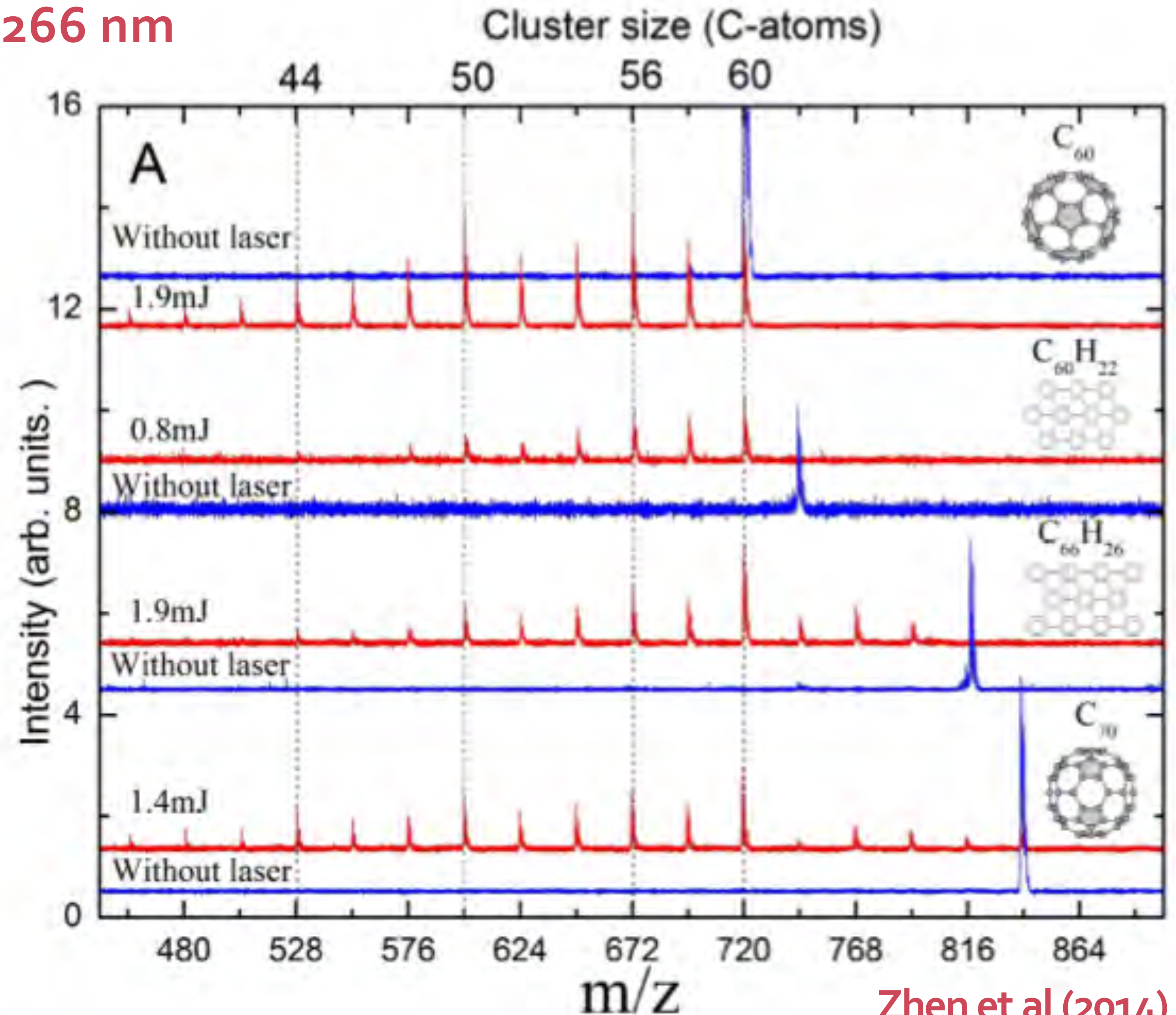
PAHs & C_{60} in NGC 7023



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)

$T \lesssim 1,700\ K$ → **PAHs**

$T \gtrsim 3,000\ K$ → **C_{60}**

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

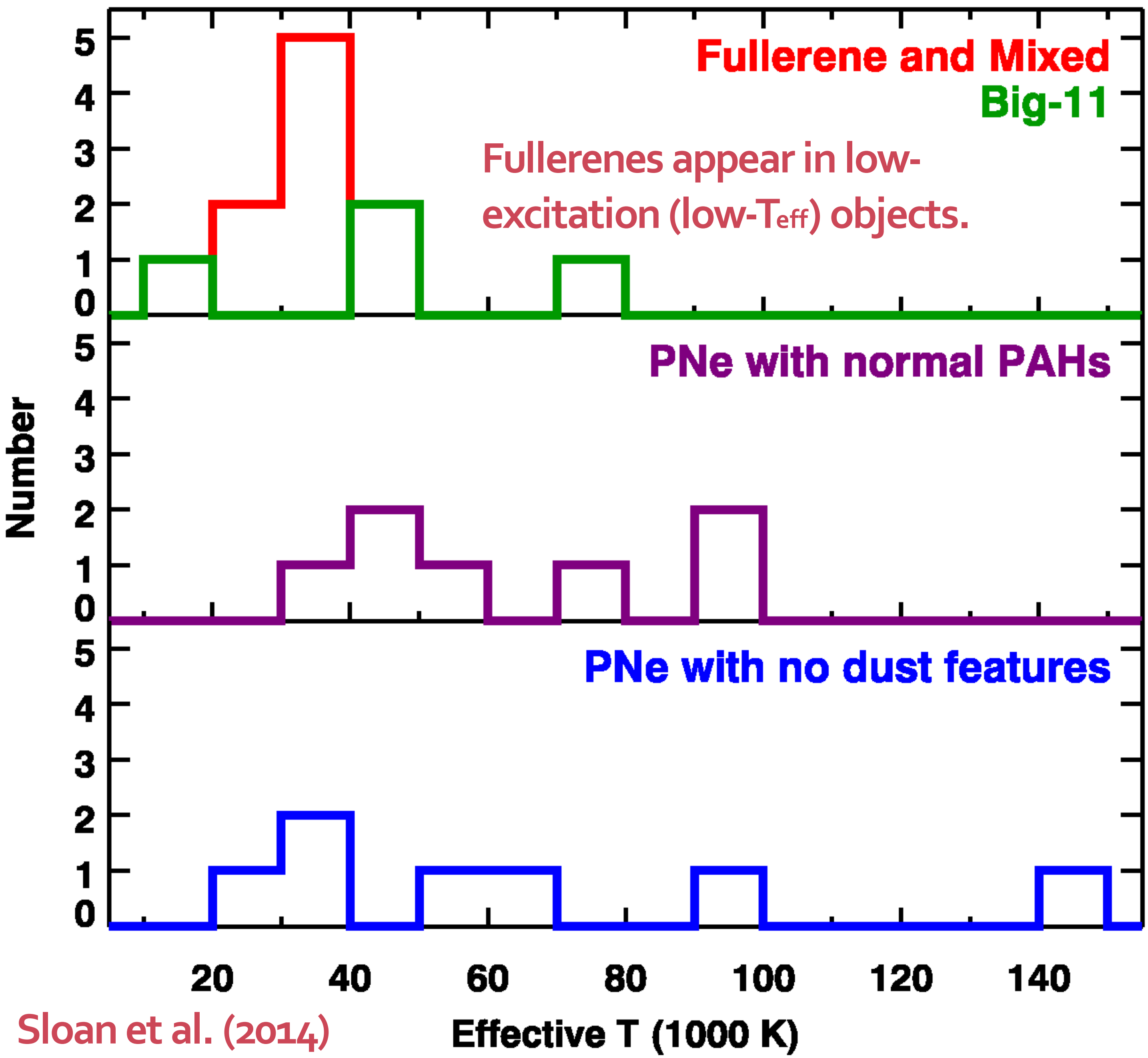
Very H-poor (PAHs → C_{60})
(Wang et al., 1995)

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

PAHs

C_{60}

Fullerenes and T_{eff}

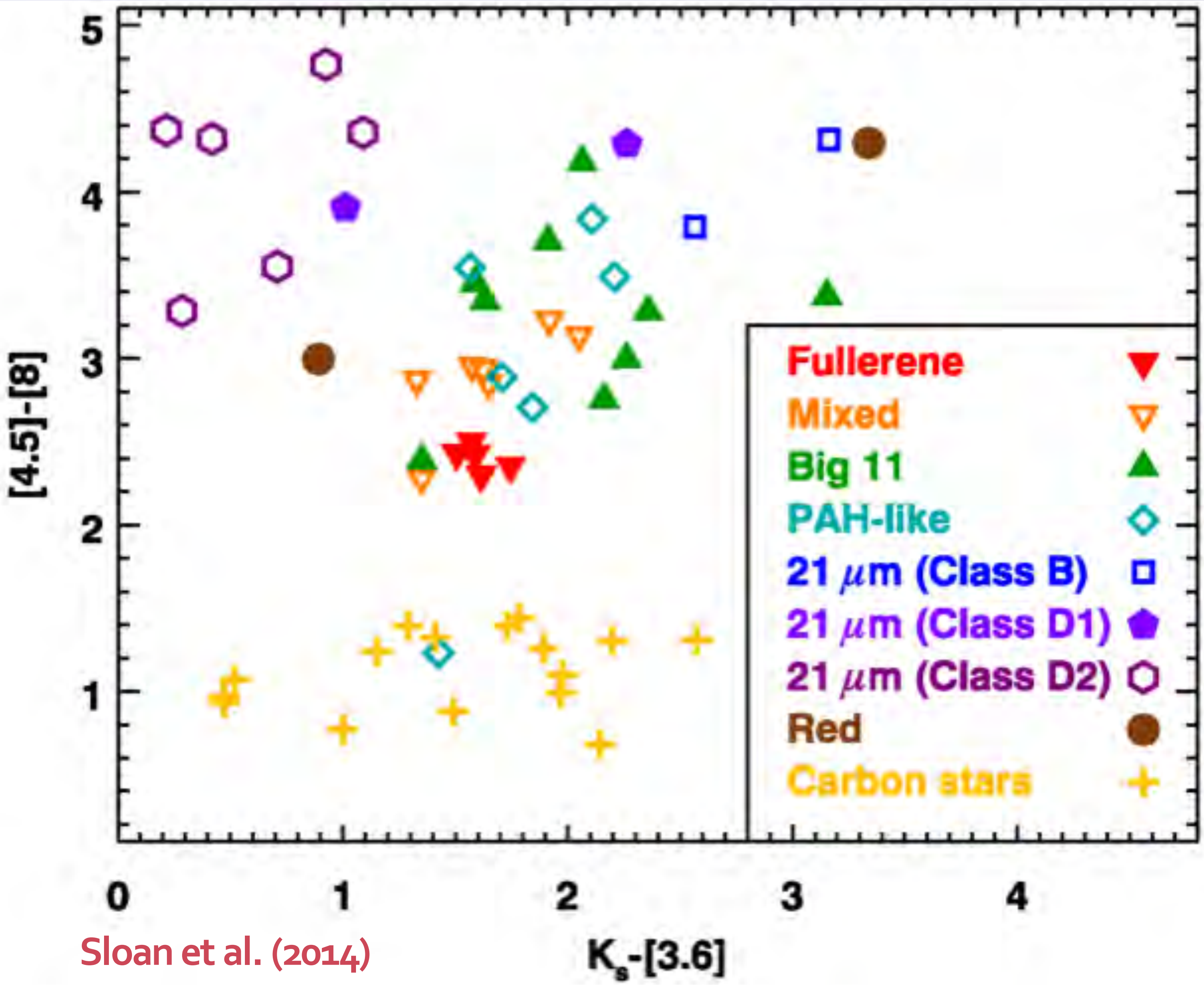


Sloan et al. (2014)

Fullerenes' true colors

Jan Cami

Molecules to dust

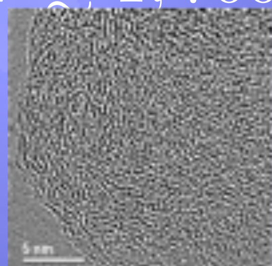


Sloan et al. (2014)

Conditions & formation

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

$T \lesssim 1,700\ K$

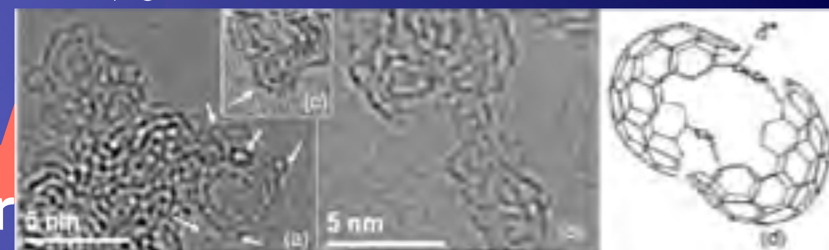


PAHs

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

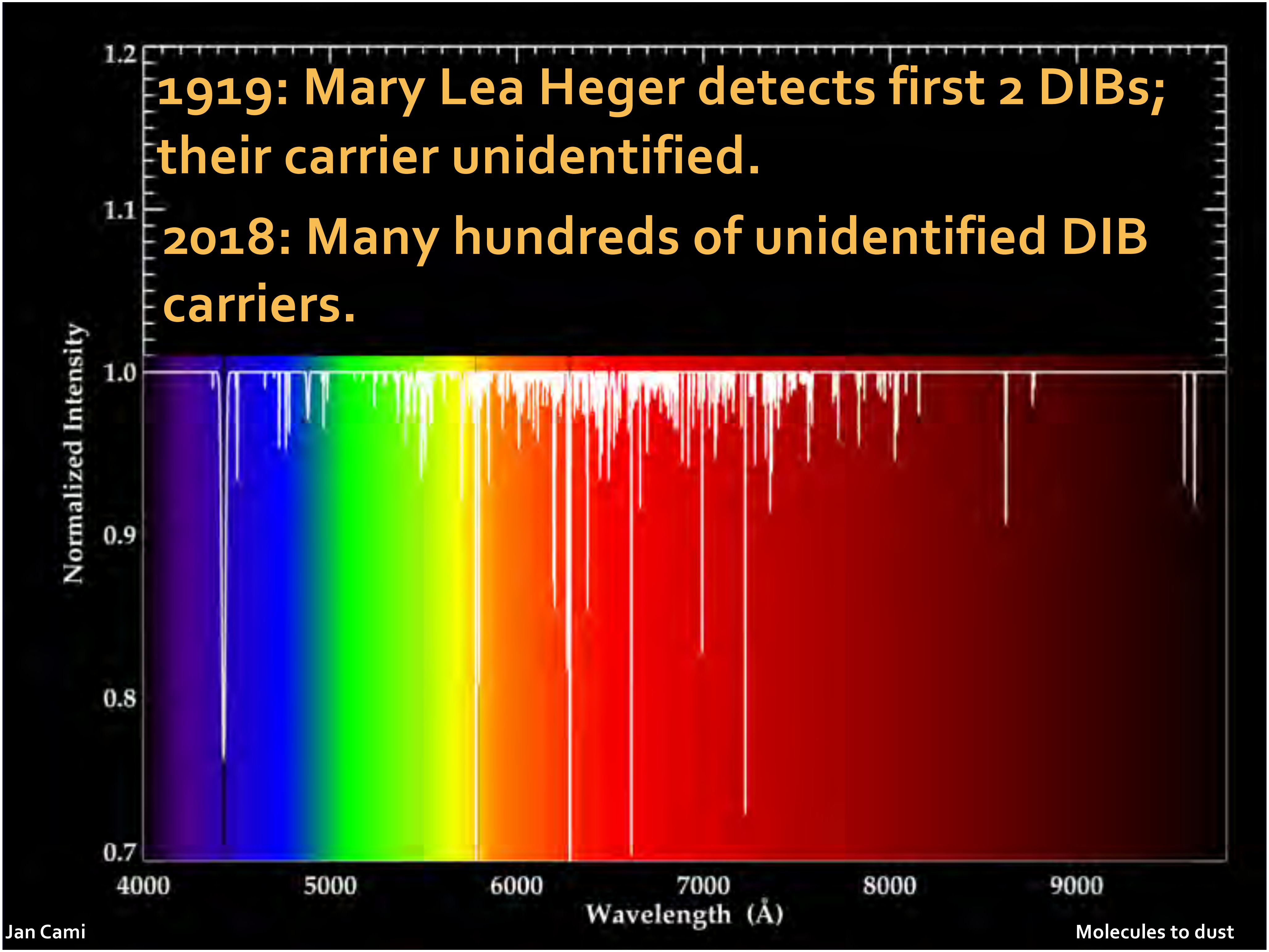
C_{60}

C_{60} 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.
- Special geometry: does the torus play a role?

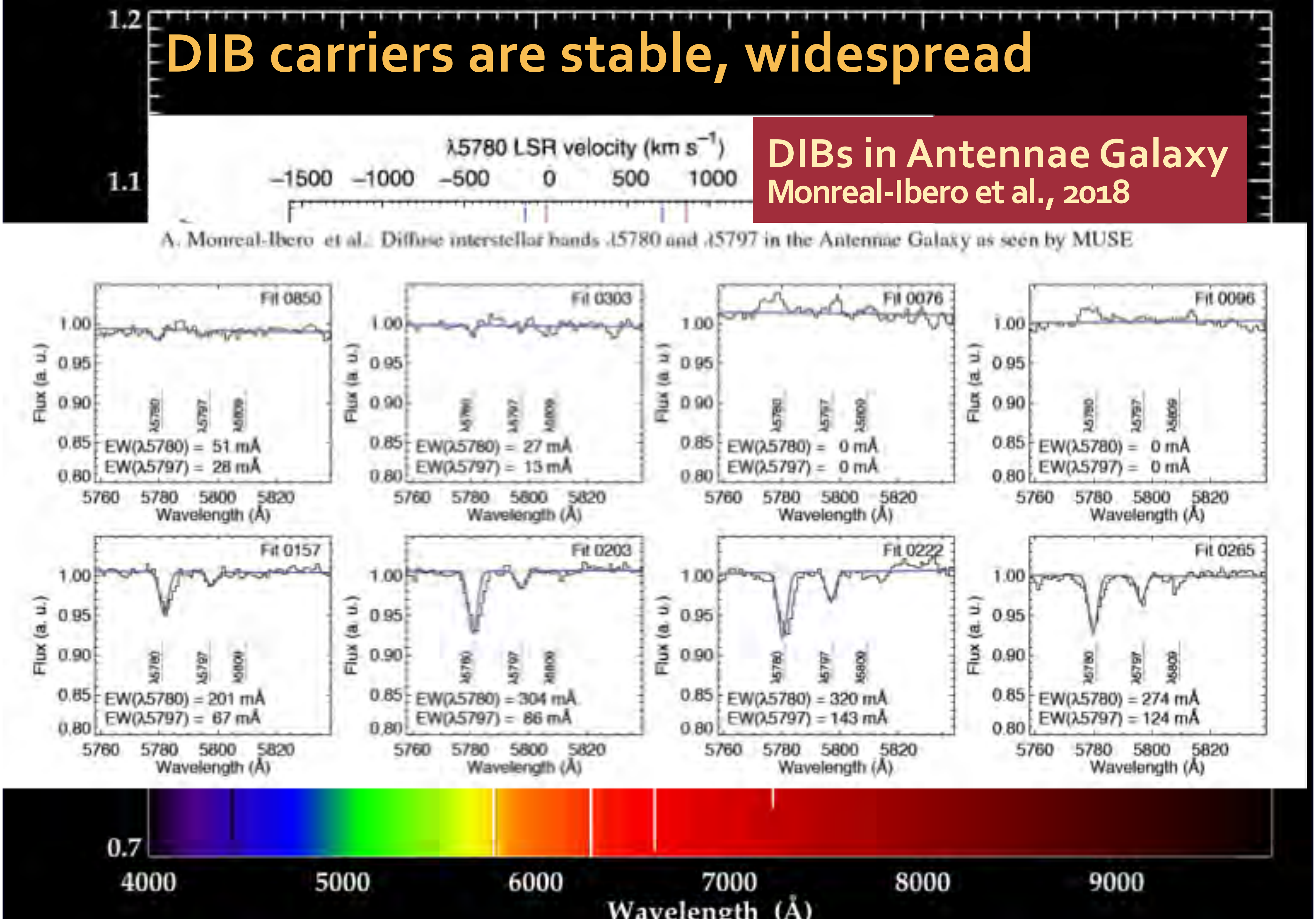
If dust destruction is key, this is relevant to ISM as well!


Normalized Intensity
1.2
1.1
1.0
0.9
0.8
0.7
HOUSTON, WE HAVE DIBS
Diffuse Interstellar Bands

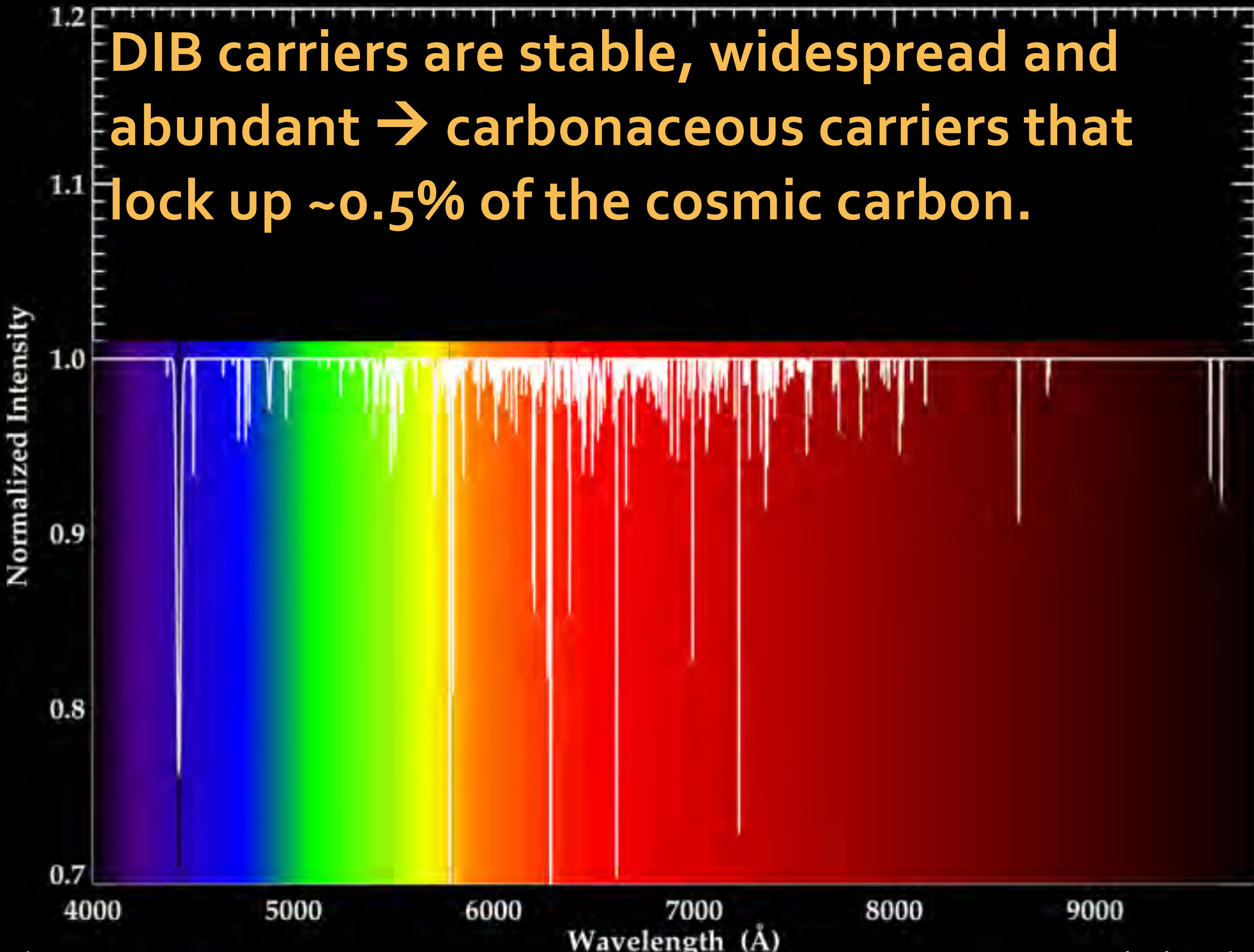

1919: Mary Lea Heger detects first 2 DIBs; their carrier unidentified.
2018: Many hundreds of unidentified DIB carriers.
1.2
1.1
1.0
0.9
0.8
0.7
Normalized Intensity
4000
5000
6000
7000
8000
9000
Wavelength (Å)
Jan Cami
Molecules to dust

DIB carriers are stable, widespread

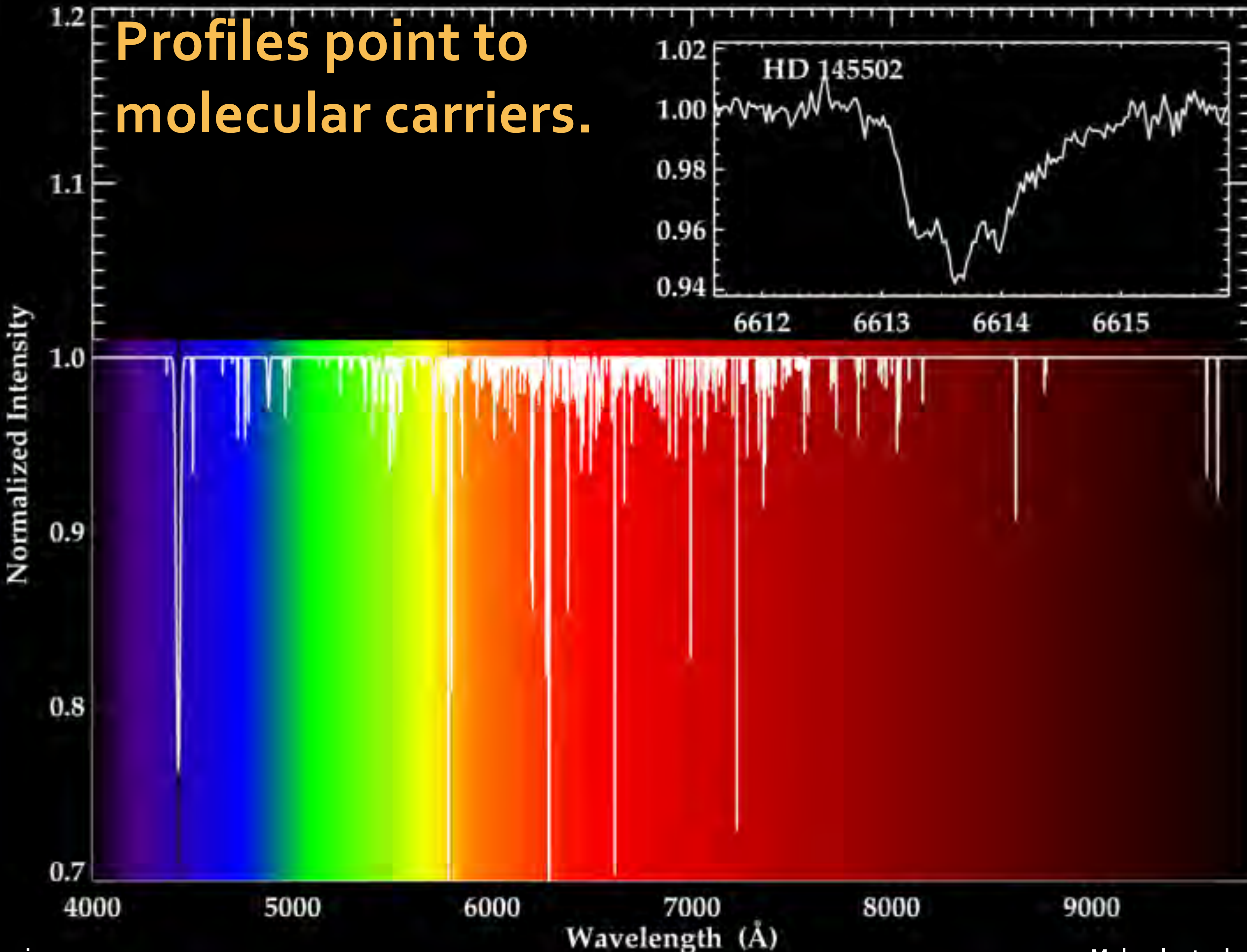
DIBs in Antennae Galaxy
Monreal-Ibero et al., 2018



DIB carriers are stable, widespread and abundant → carbonaceous carriers that lock up ~0.5% of the cosmic carbon.



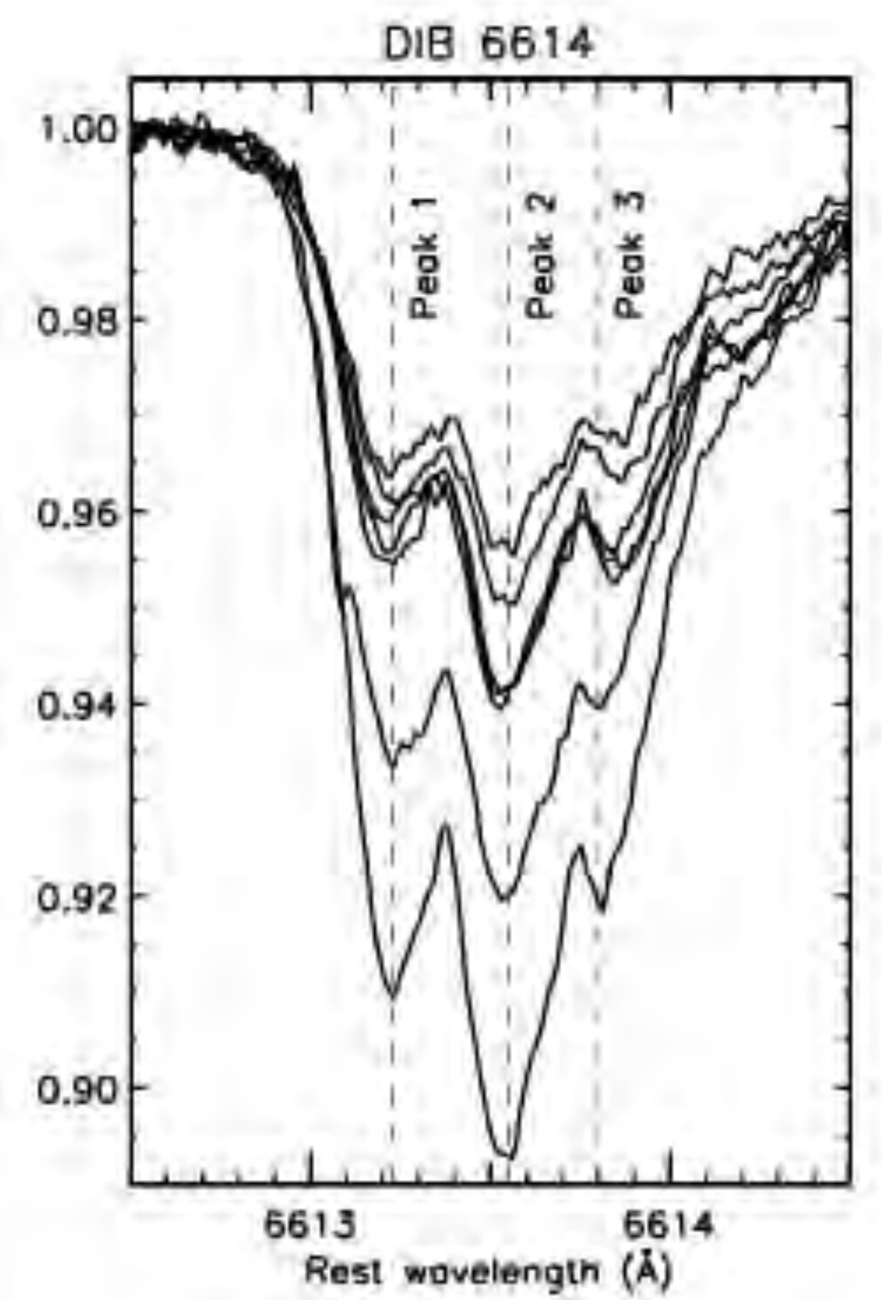
Profiles point to molecular carriers.



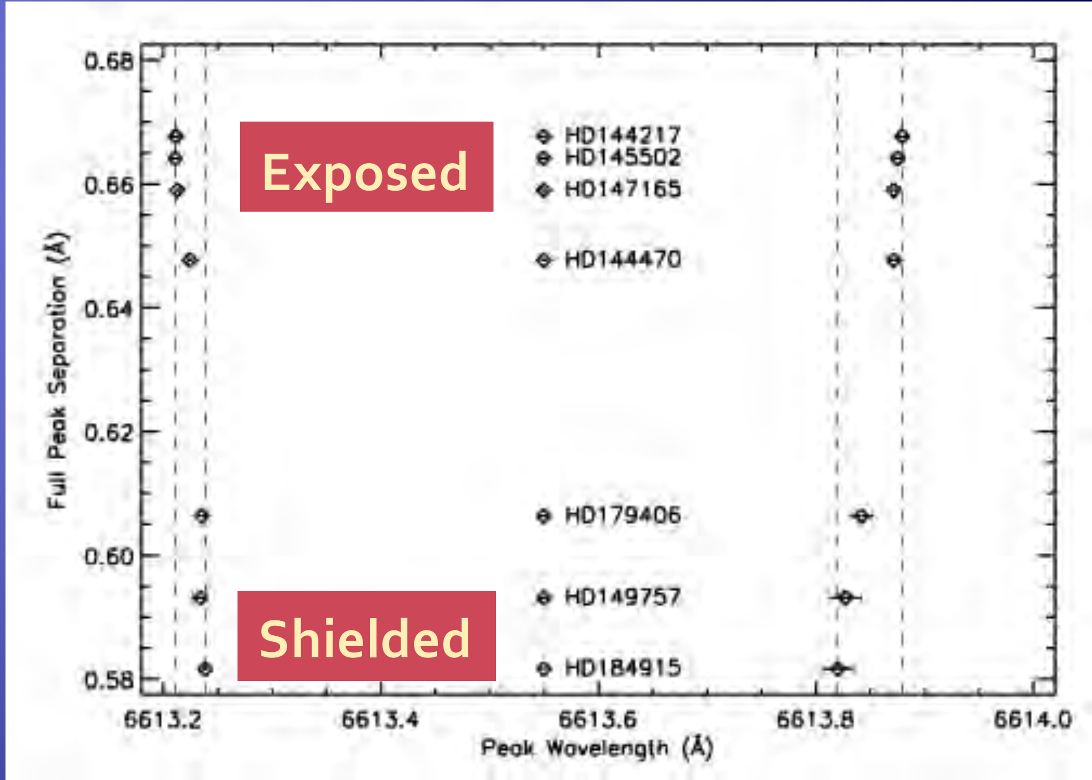
The power of DIB line profiles

Jan Cami

Molecules to dust



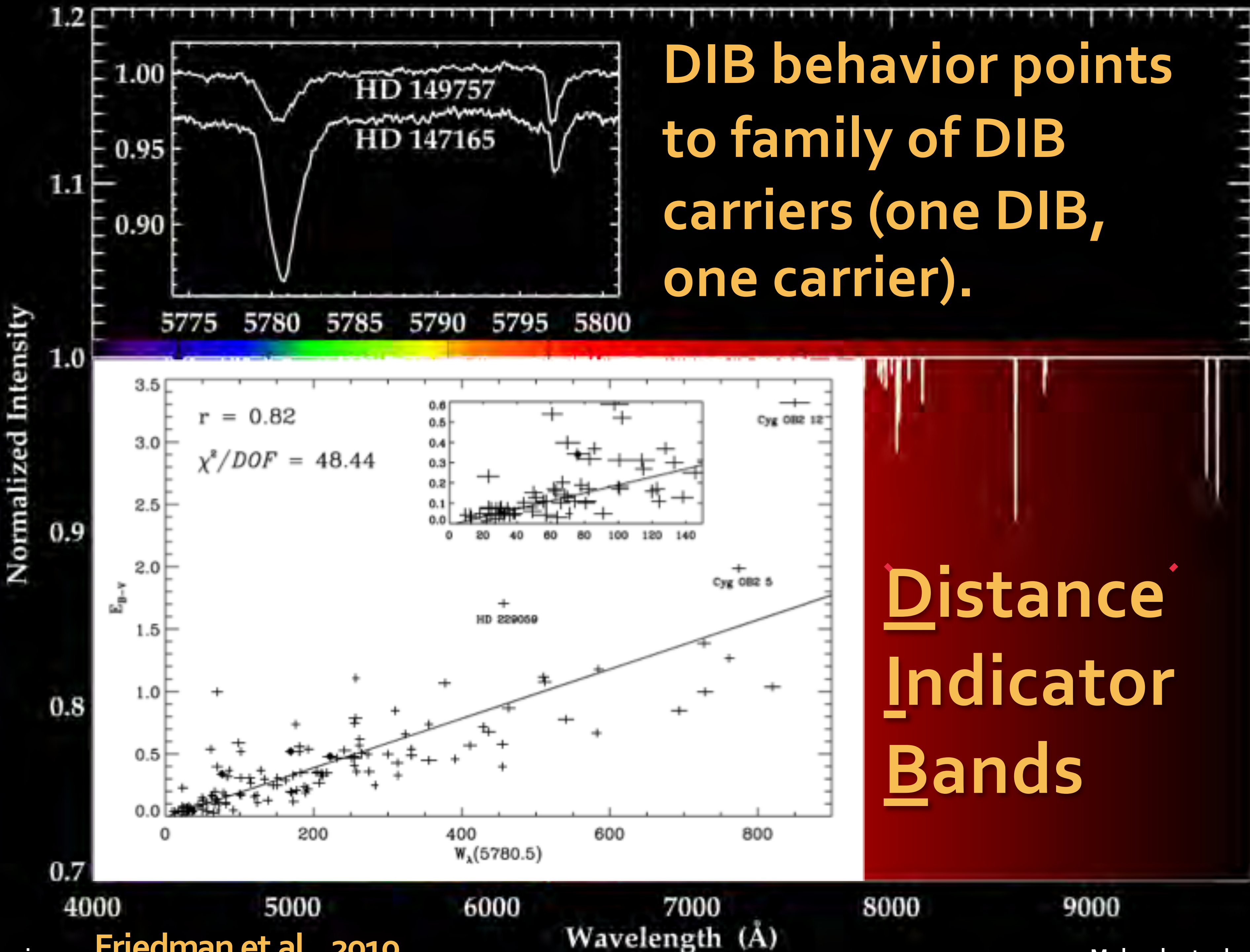
Ro-vibrational lines:
Peak separation scales with BT



→ 8—15 C atom molecule.

Line Profile Variations of 6614 DIB
Cami et al., 2004

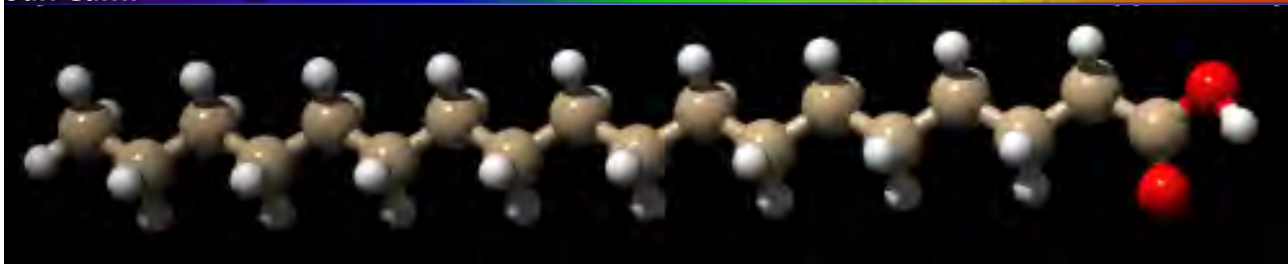
DIB behavior points to family of DIB carriers (one DIB, one carrier).



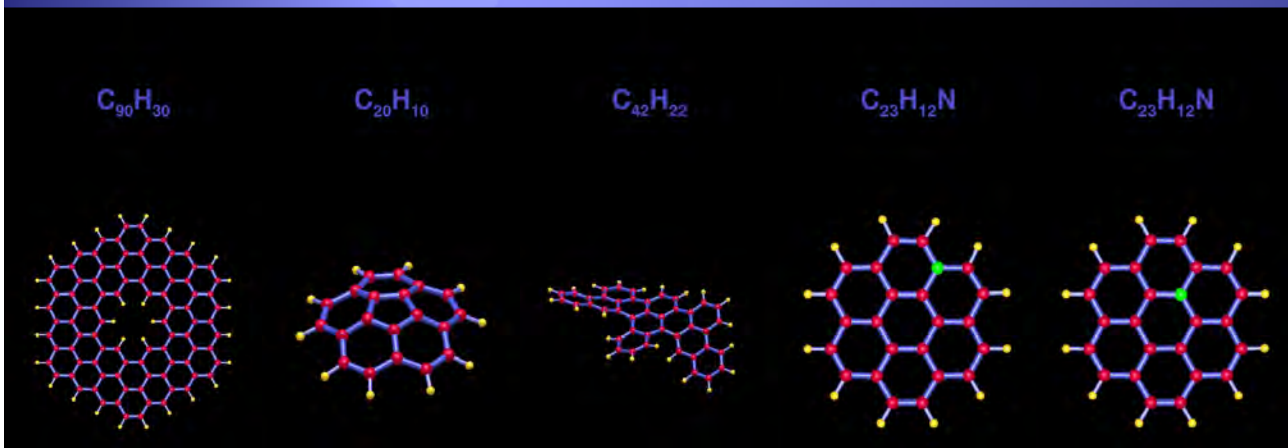
Distance Indicator Bands

Friedman et al., 2010

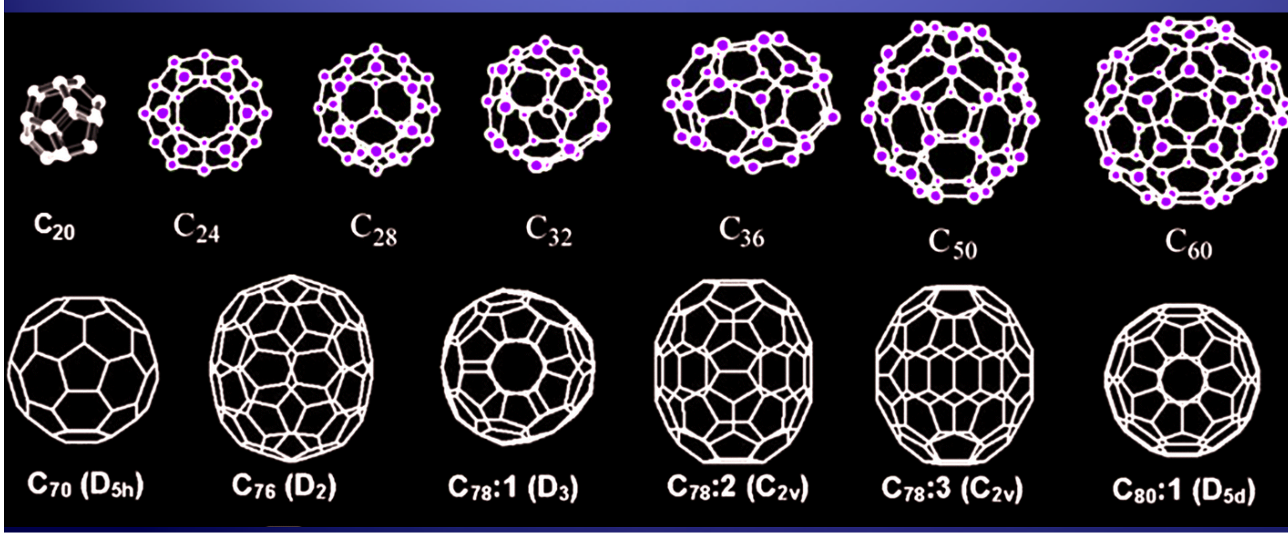
DIB carrier candidates



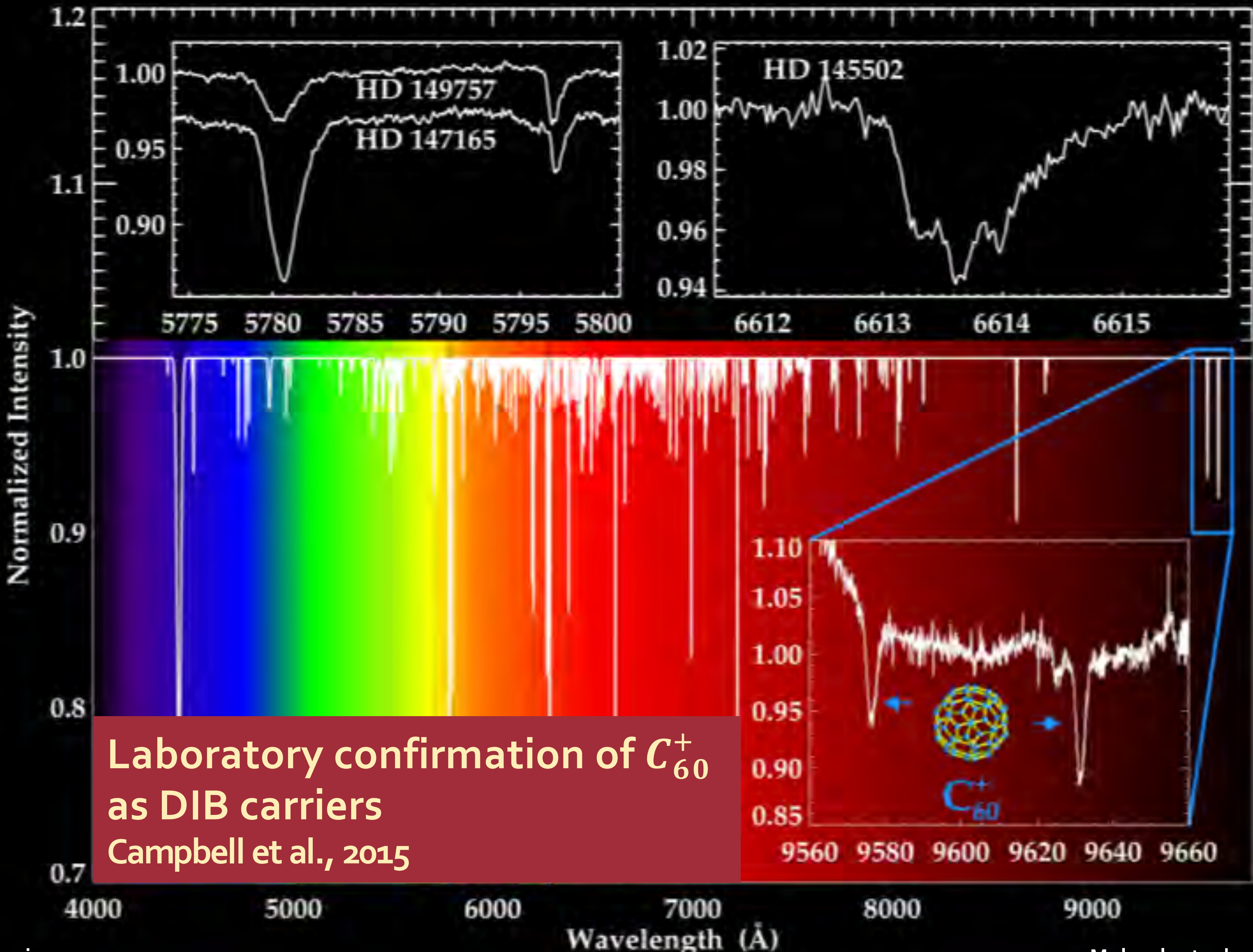
Carbon Chains
…and their cousins



PAHs
…and their cousins



Fullerenes
…and their cousins



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

Campbell et al., 2015

The Key DIB Questions

The DIBs point to a voluminous chapter of interstellar physics and chemistry that we have yet to discover and understand.

- What are the DIB carriers?
- How are these species formed, excited, destroyed?
- What can these features tell us about the physical conditions of the environments in which they reside, and what about the chemical evolution of the ISM?

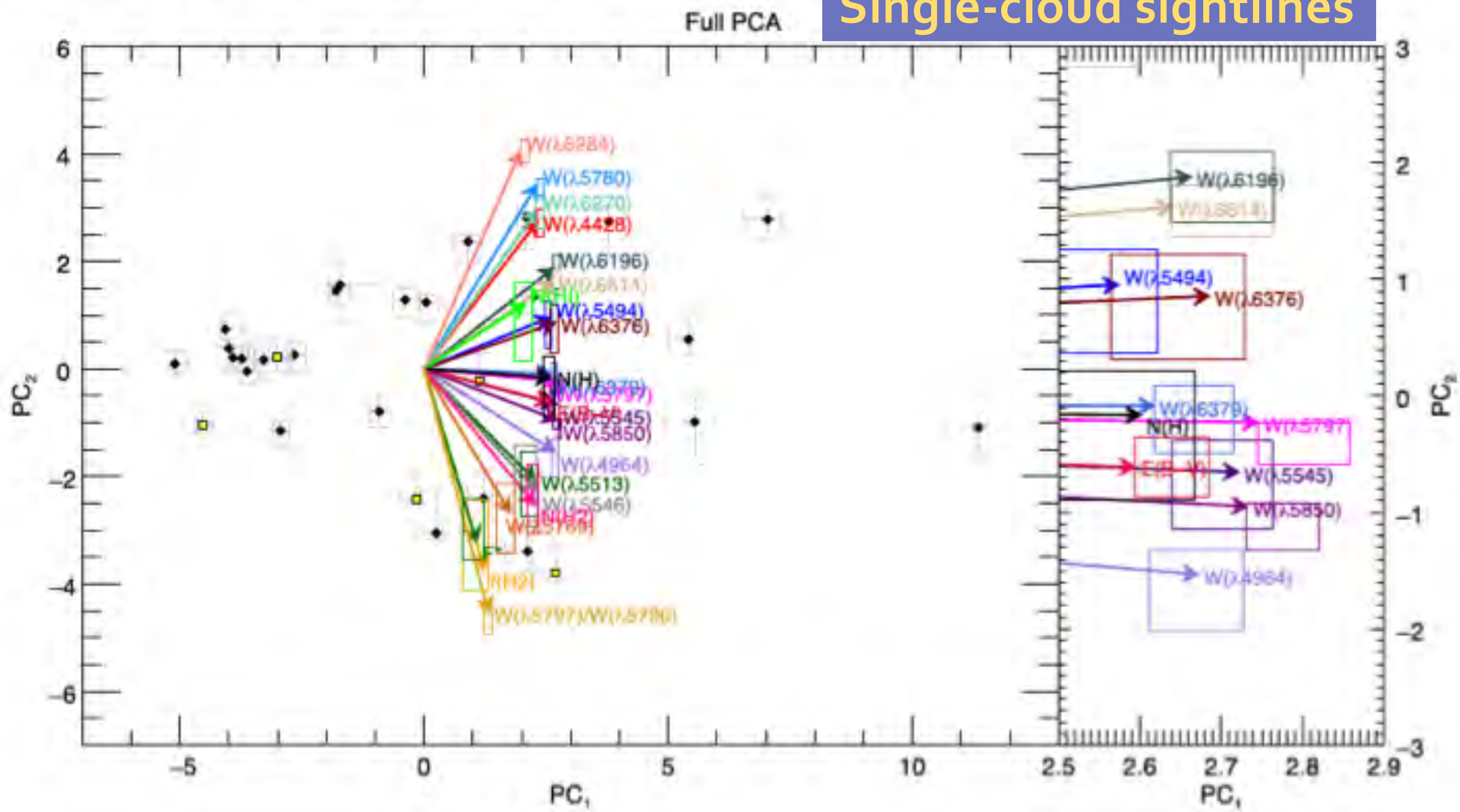
DIBs and their tool potential

Jan Cami

Molecules to dust

THE ASTROPHYSICAL JOURNAL, 836:162 (24pp), 2017 February 20 Ensor et al.

Single-cloud sightlines



A Principal Component Analysis of the DIBs

Ensor et al., 2017

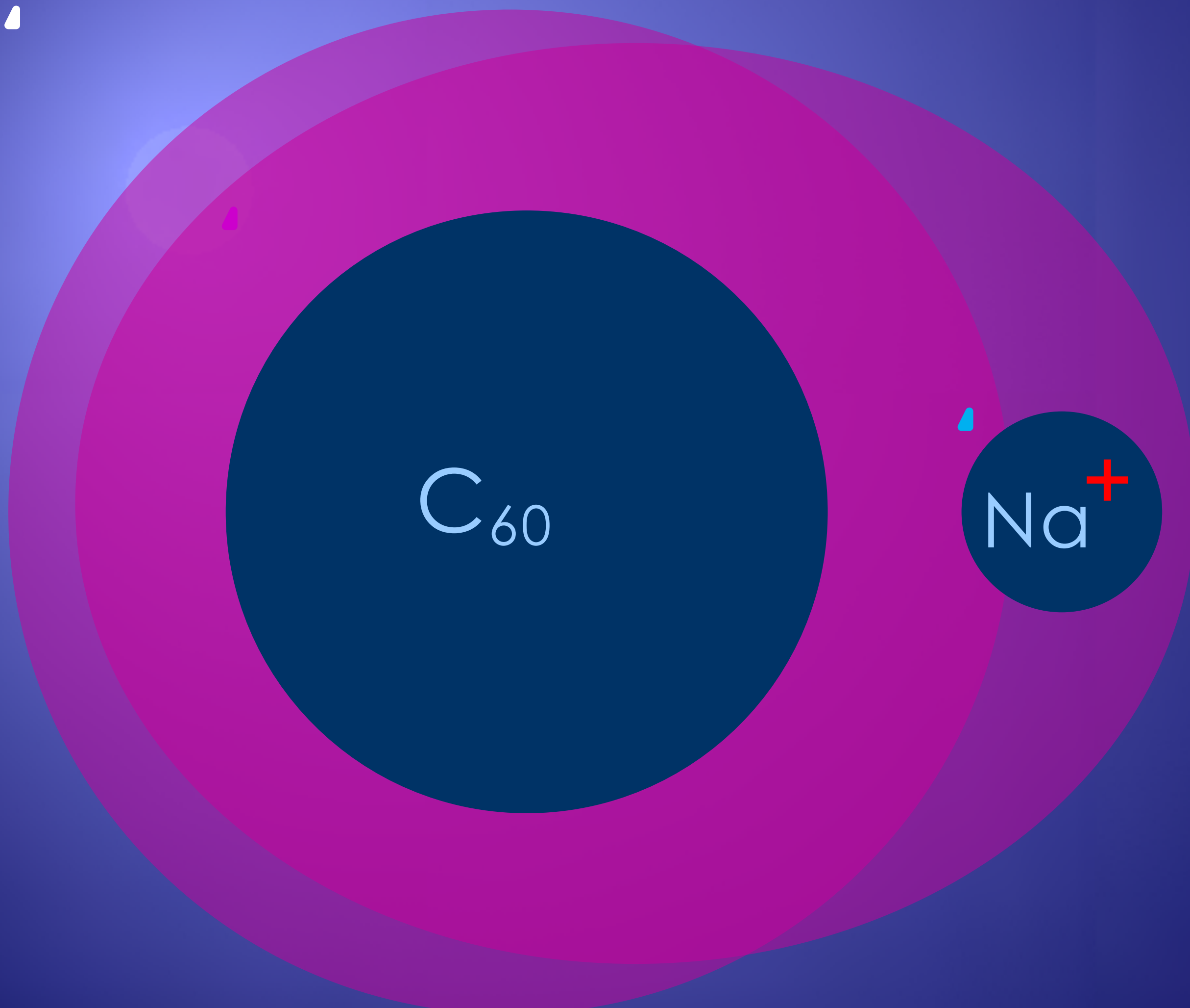
Abundances / Strengths

$$\frac{W}{E_{B-V}} = 3\ [\mathrm{m}\mathring{A}] \left(\frac{\chi_{DIB}}{10^{-4}}\right) \left(\frac{60}{N_C}\right) \left(\frac{\lambda}{5000\,\mathring{A}}\right)^2 \left(\frac{f}{10^{-2}}\right)$$

χ_{DIB} **Fraction of C in DIB carrier**

- Medium / strong DIBs require:
  - **High Abundance** and/or
  - **Small**(er) **size** and/or
  - **Large** Oscillator **strength**: can we find species (or mechanisms) with much stronger transitions?

M-C_{60} complexes



Charge Transfer Bands

C_{60} Na^{+}

$C_{60}^{+} \cdot Na$

$C_{60} \cdot Na^{+}$

DIBs …due to charge transfer bands of $C_{60} \cdot M^{+}$?

(Kroto and Jura 1992)

The Way Forward

We can turn the DIBs into powerful probes of physical conditions in the Universe near and far even without knowing the identity of their carriers!

- Carry out a **sensitive** and **systematic** study of the DIBs in order to:
  - Characterize the observational properties of a large number of DIBs in great detail.
  - Establish **quantitative** relationships between the DIB properties and other line of sight parameters.
  - Map in detail how the DIBs depend on environmental parameters – both physical and chemical.

The ESO Diffuse Interstellar Band Large Exploration Survey (EDIBLES)

Jan Cami, N.L.J. Cox, A. Farhang, J. Smoker, M. Elyajouri, R. Lallement, X. Bacalla, N.H. Bhatt, E. Bron, M.A. Cordiner, A. de Koter, P. Ehrenfreund, C.J. Evans, B.H. Foing, A. Javadi, C. Joblin, L. Kaper, H.G. Khosroshahi, M. Laverick, F. Le Petit, H. Linnartz, C.C.M. Marshall, A. Monreal-Ibero, G. Mulas, E. Roueff, P. Royer, F. Salama, P.J. Sarre, K.T. Smith, M. Spaans, J.Th. van Loon, G. Wade

Image Credit: Miguel Claro

The EDIBLES Survey

- EDIBLES is a Large Program on VLT/UVES (P.I. N.L.J. Cox; Acting P.I. J. Cami)
  - 286 h; ~80% complete to date
  - 114 targets (mostly O and B stars) with wide range in interstellar parameters (dust & gas).
  - Large spectral range: 304.2 nm – 1042.0 nm; allows to include many known atomic and molecular lines.
  - Sensitive: S/N ~1000 per target in the red.
  - Detailed: Resolving power R~80,000 across range.

The EDIBLES Survey
Cox et al., 2017; Cami et al. 2018

EDIBLES target distribution

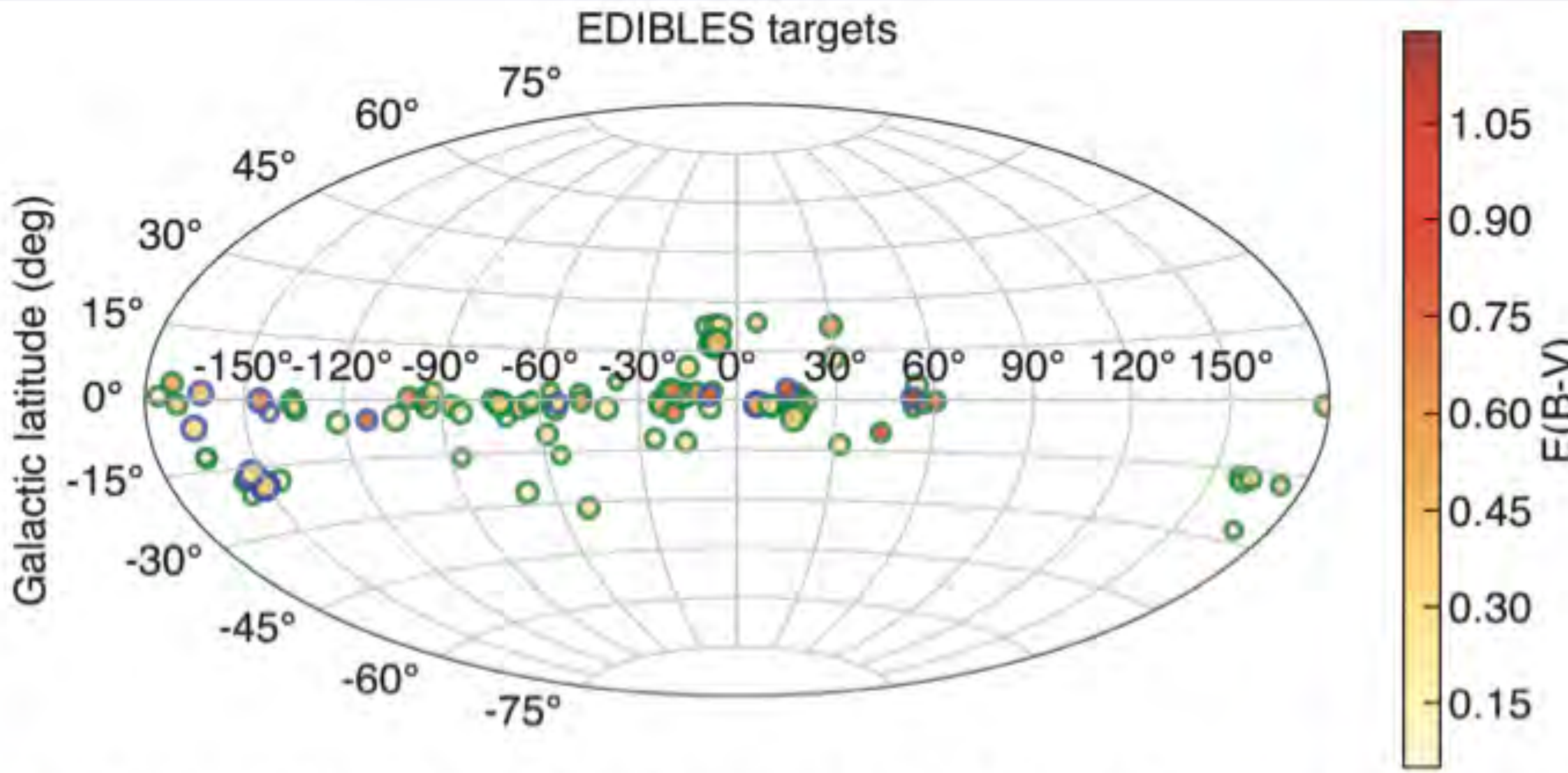


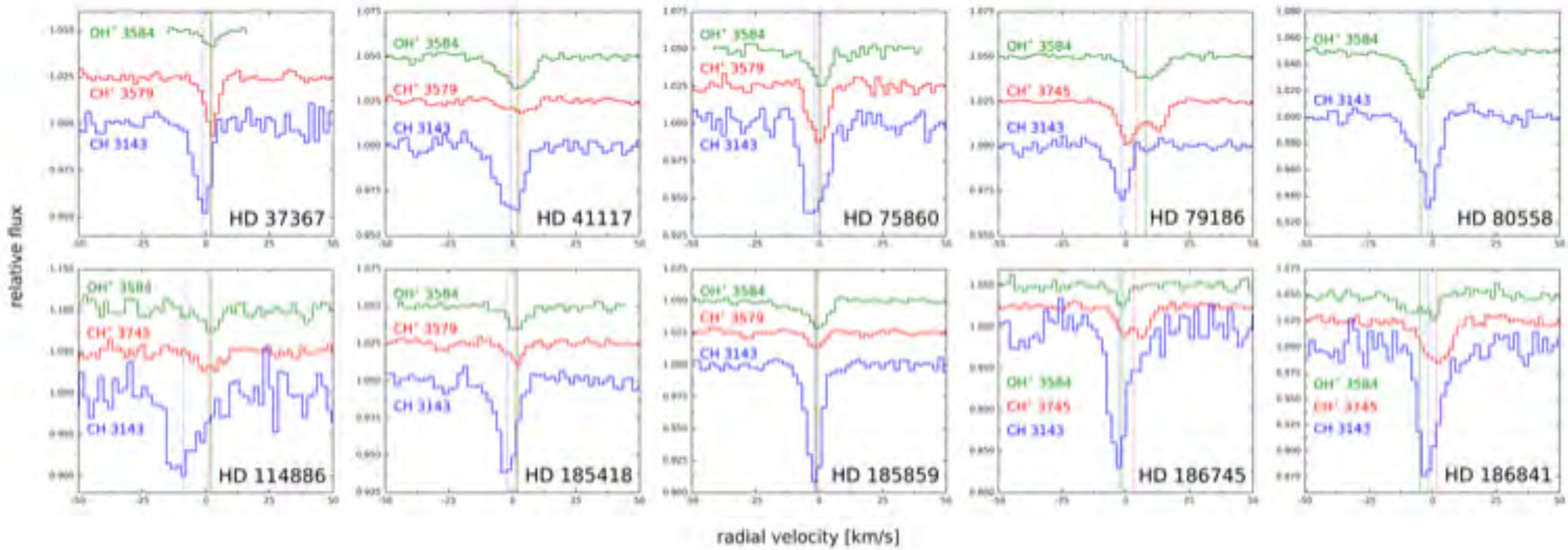
Fig. 1. Galactic distribution of EDIBLES targets. The symbol size reflects the value of R_V, while the interior colour represents the line-of-sight reddening, $E(B-V)$. Symbols with green edges represent the observed targets, while blue edges correspond to the targets to be observed by the end of the programme.

Range in E(B-V), A_V, R_V, N(H), f_{H_2}, elemental depletion

Results: sensitivity & range

Jan Cami

Molecules to dust



Access to diagnostic lines that could yield important clues. Example: OH^+ → cosmic ray ionization rate from ground-based observations!

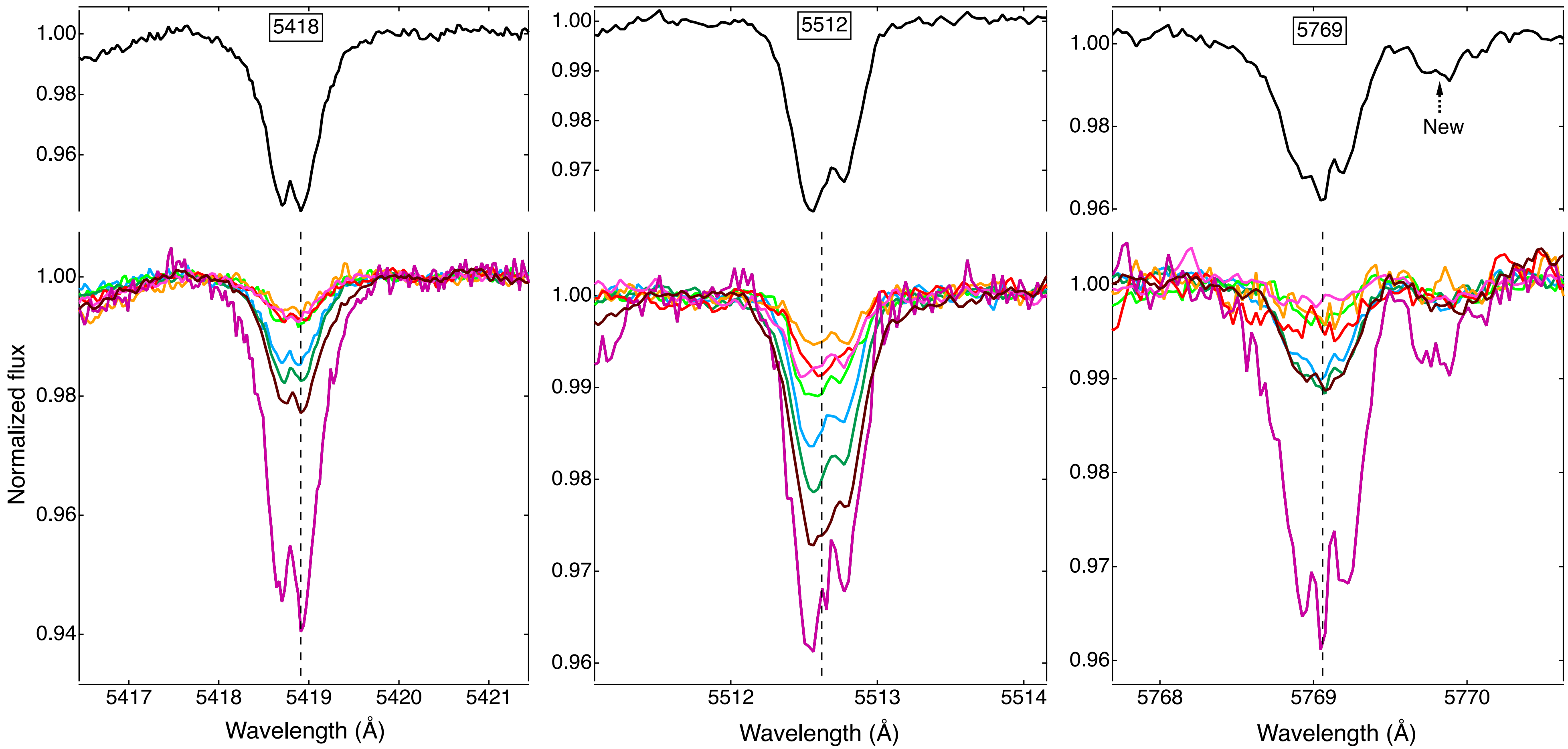
Cosmic ray ionization rate from OH^+
Bacalla et al., under review.

Results: sensitivity & resolution

Jan Cami

Molecules to dust

All (weak) C_2-DIBs show substructure in their profiles!



→ Size distribution of DIB carriers.

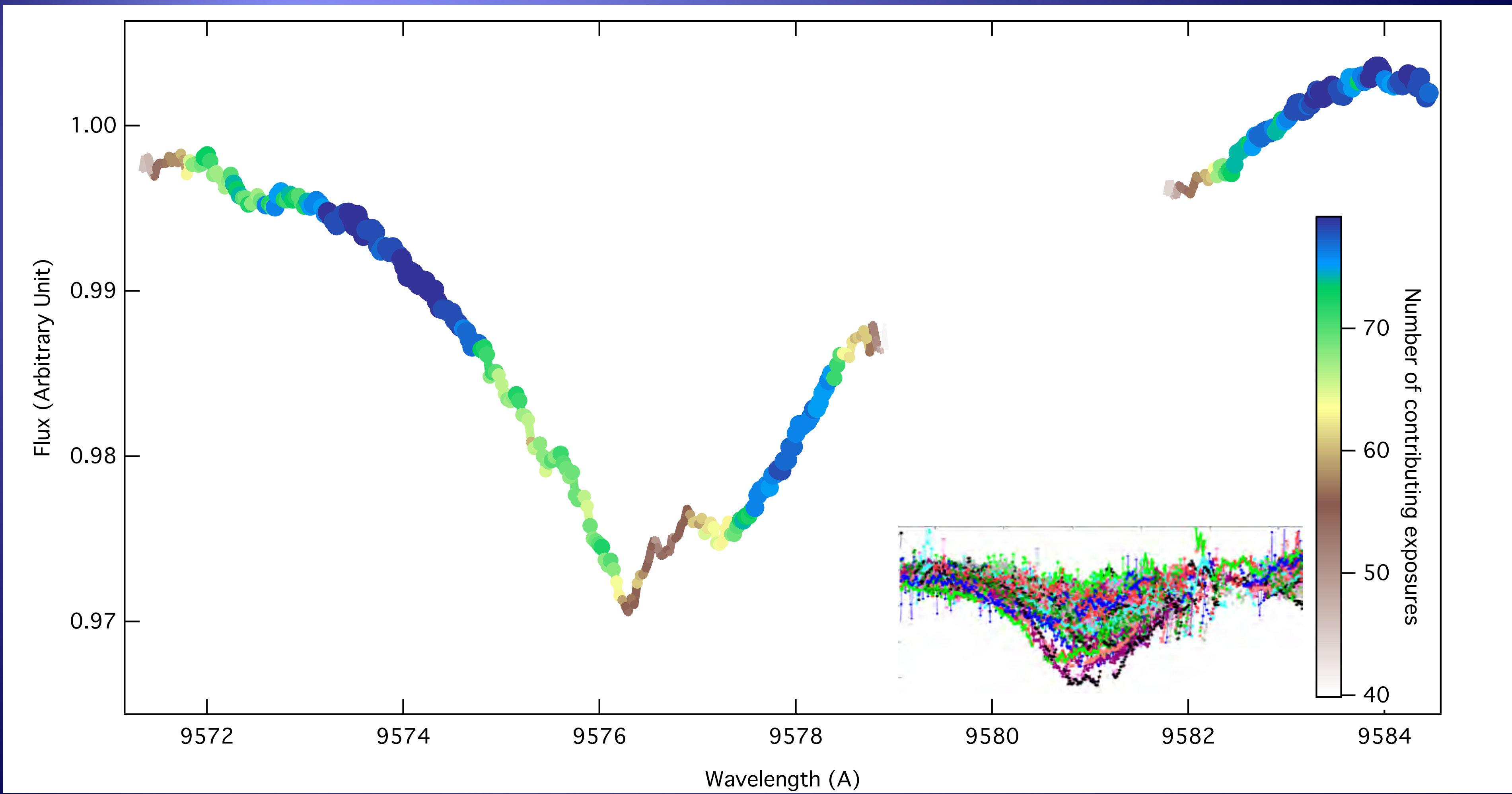
C_2-DIBs and their profiles
Elyajouri et al., in press

Results: sensitivity & resolution

Jan Cami

Molecules to dust

Supporting the identification of the C_{60}^{+} DIBs



The profiles of the C_{60}^{+} -DIBs.

Lallement et al., in prep.

Summary

- Cosmic Fullerenes may form from bottom-up dust formation followed by dust destruction – but the fullerenes survive.
- Top-down processes are important to include in astrochemistry.
- DIBs can reveal much about interplay between atomic gas, (large) molecules and dust in the ISM. Identification not required – stay tuned!