Observations of hydrodynamical instabilities in interstellar space

Orion nebula (near infrared with ESO-VISTA)

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and
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C. Joblin (CNRS/Univ. Toulouse, France)
A. G. G. M. Tielens (Leiden observatory)

Outline

- The infrared interstellar medium

- Evolution of carbonaceous nano-grains in the interstellar medium

- Using mid-IR emission of carbonaceous nanograins to probe astrophysical environments

- Discovery of Kelvin-Helmholtz instability in the interstellar medium

- If there is time: the story of the Football/Soccerball molecule in space

- Acknowledgements

My «career»

x (Born)

x (2000-2003)

x (2004-2008)

& now

x (2008-2009)

Research interests

- I am an observer

- Mostly infrared observations, especially spectroscopy in the infrared

- Galactic nebulae, starforming regions, protoplanetary disks

- Astrochemistry

- Signal processing (especially blind signal separation)

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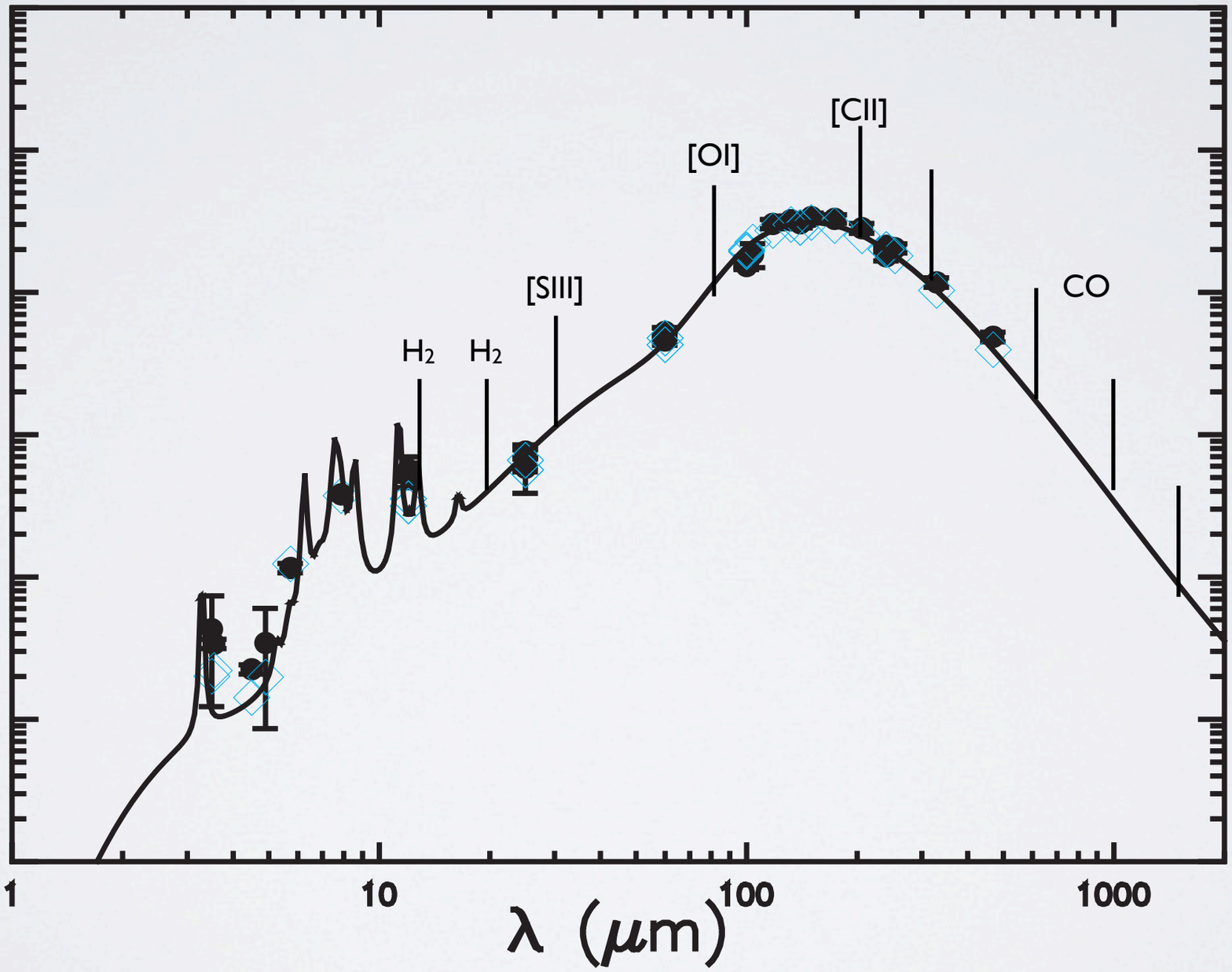
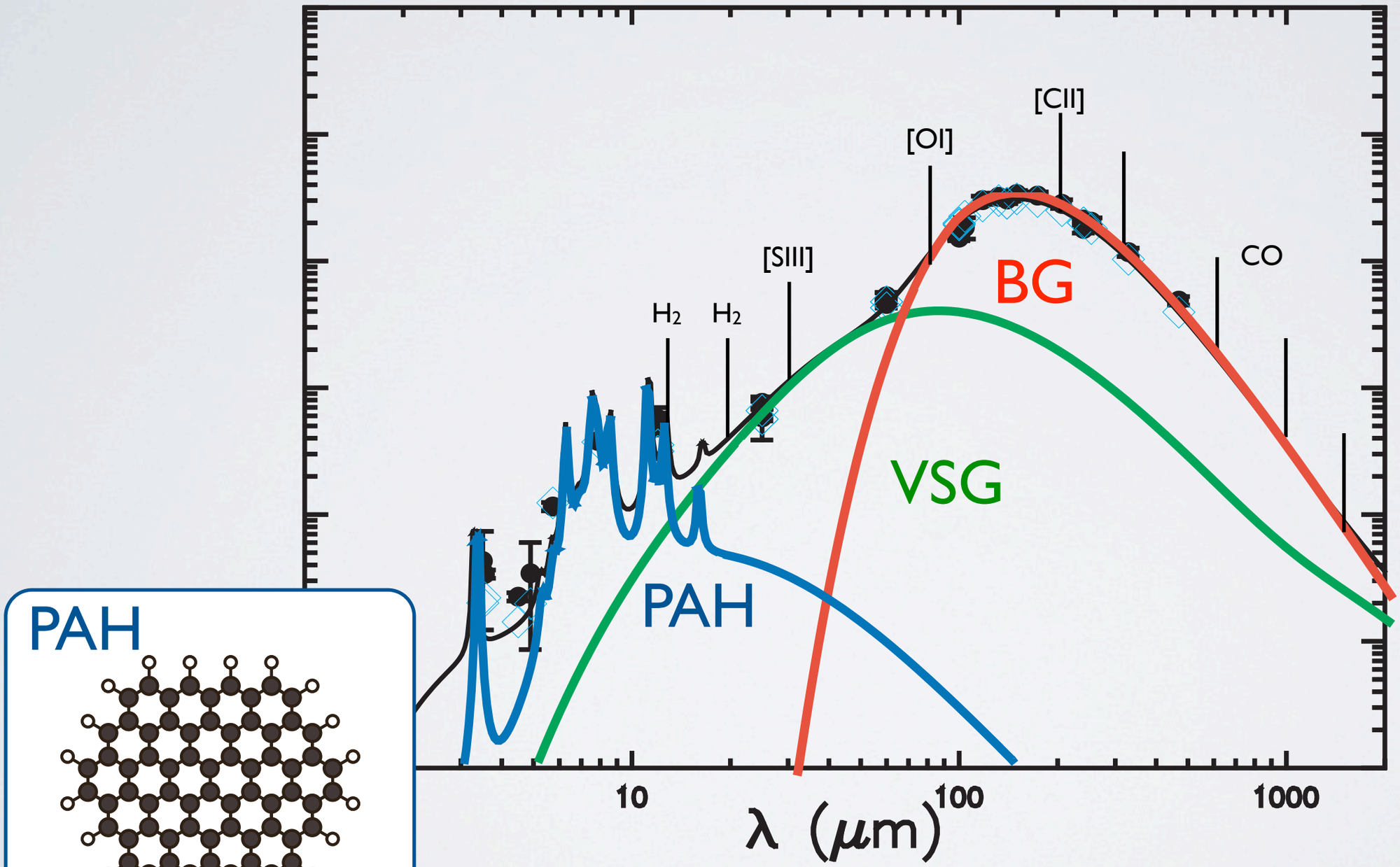
- **Acknowledgements**

Infrared spectroscopy



Infrared spectroscopy



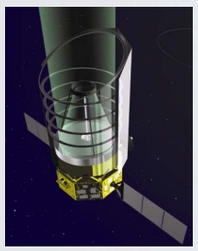
PAH

Infrared spectroscopy

Spitzer
2003-2009

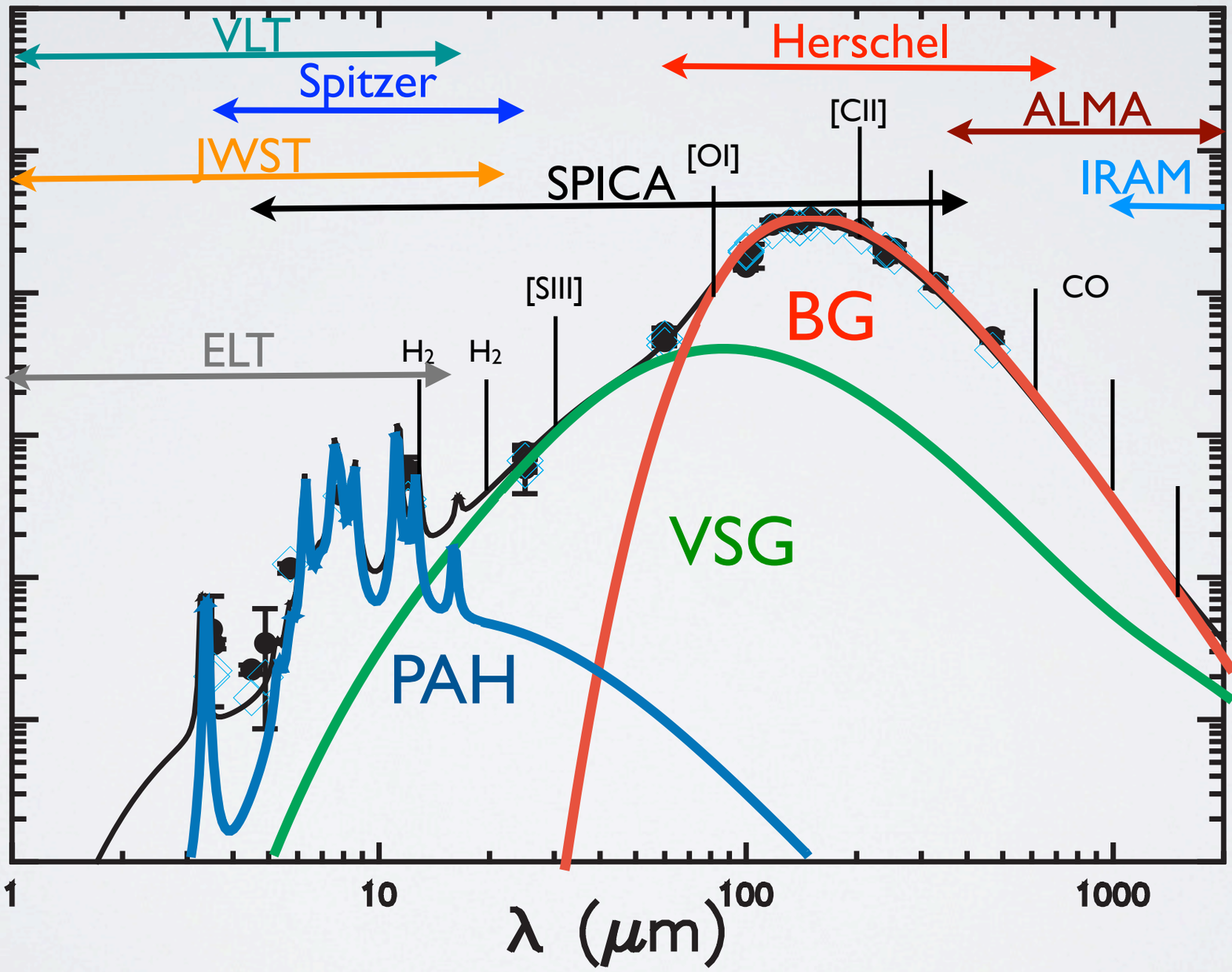
Herschel
2009-2013

JWST
2017-2022



SPICA
2018-2023

SOFIA
2011-20..



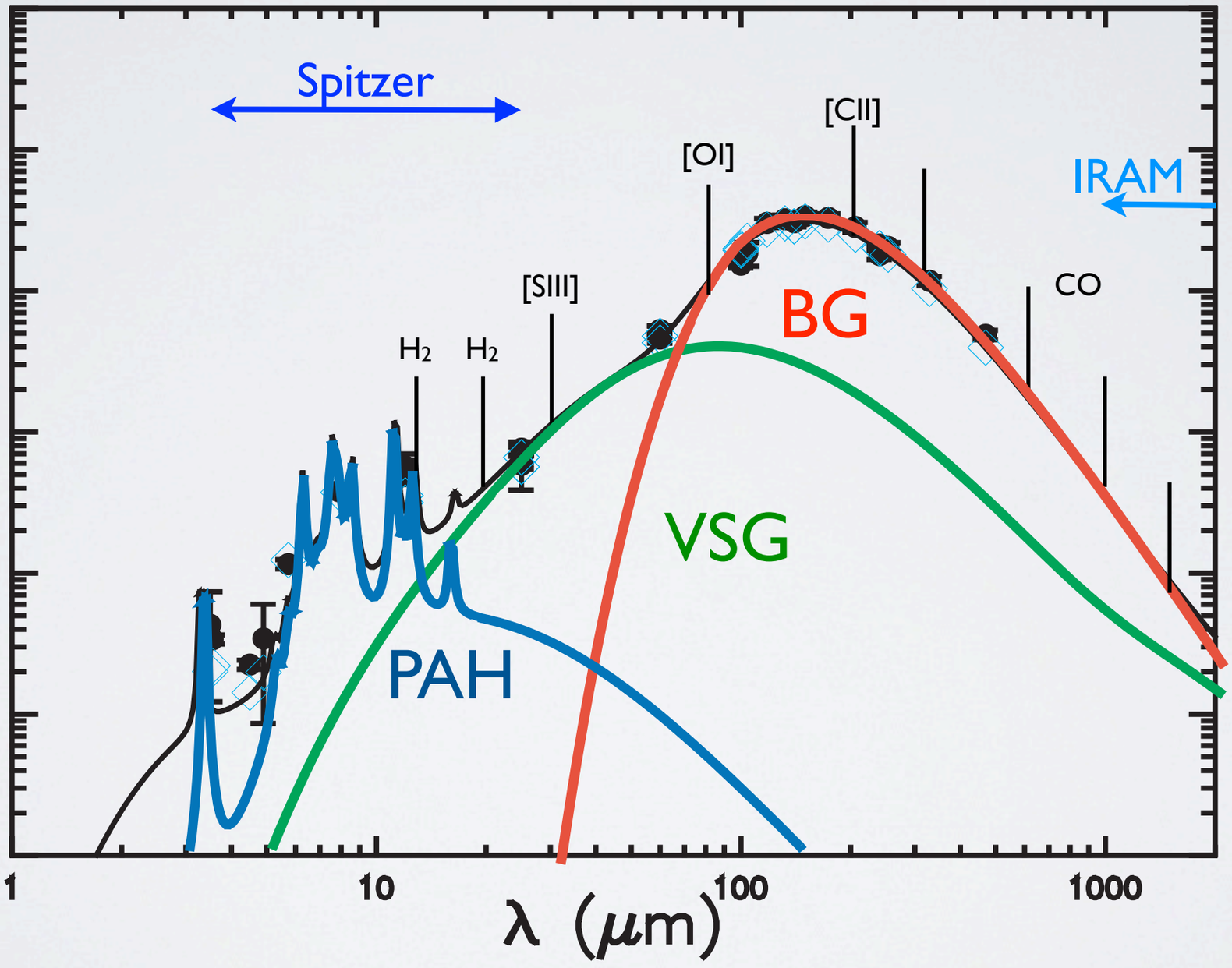
VLT
In function

IRAM 30m
In function

ALMA
Starting operations

Infrared spectroscopy

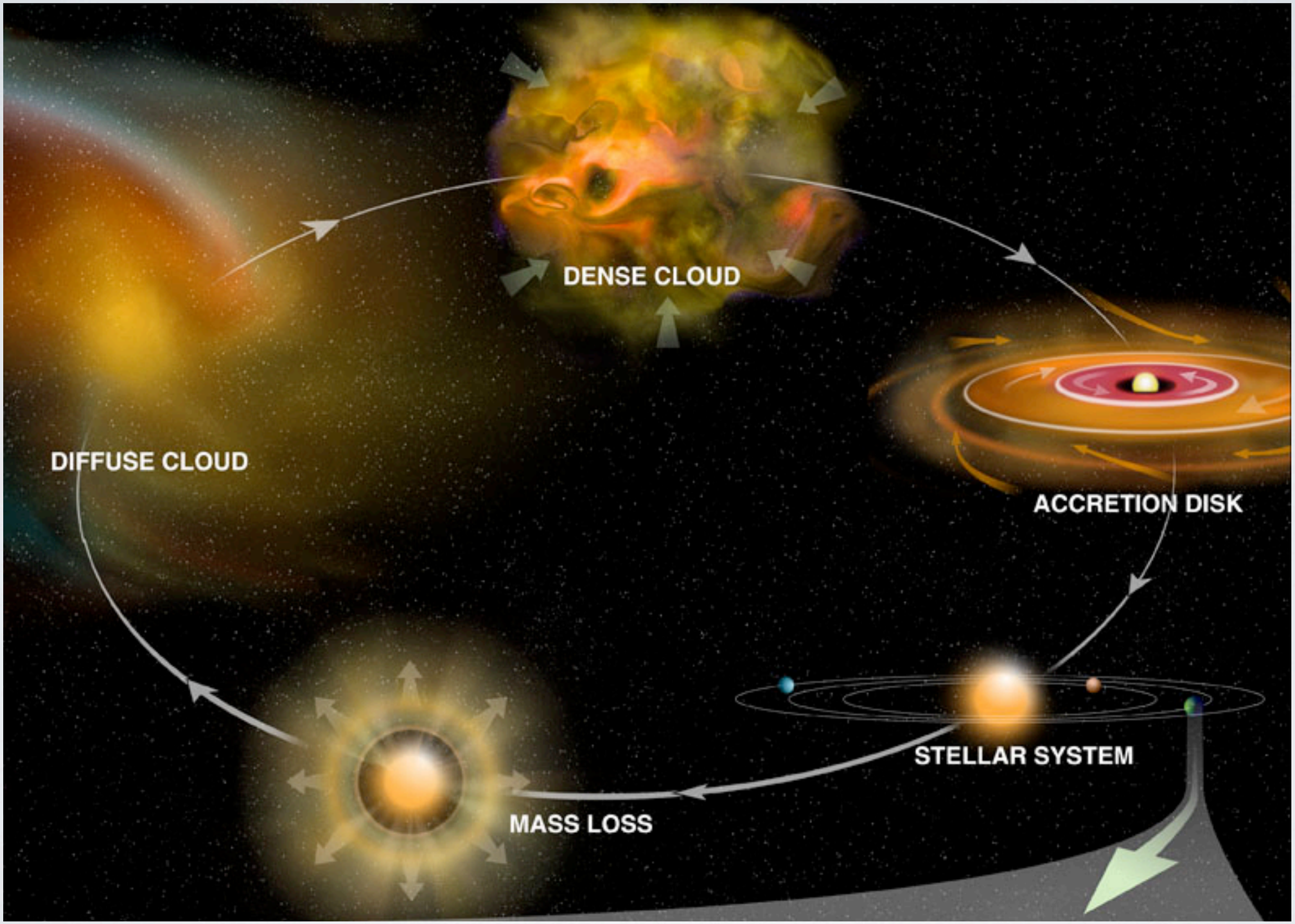
Spitzer
2003-2009



IRAM 30m
In function

Lifecycle of low mass stars

M<8Msun



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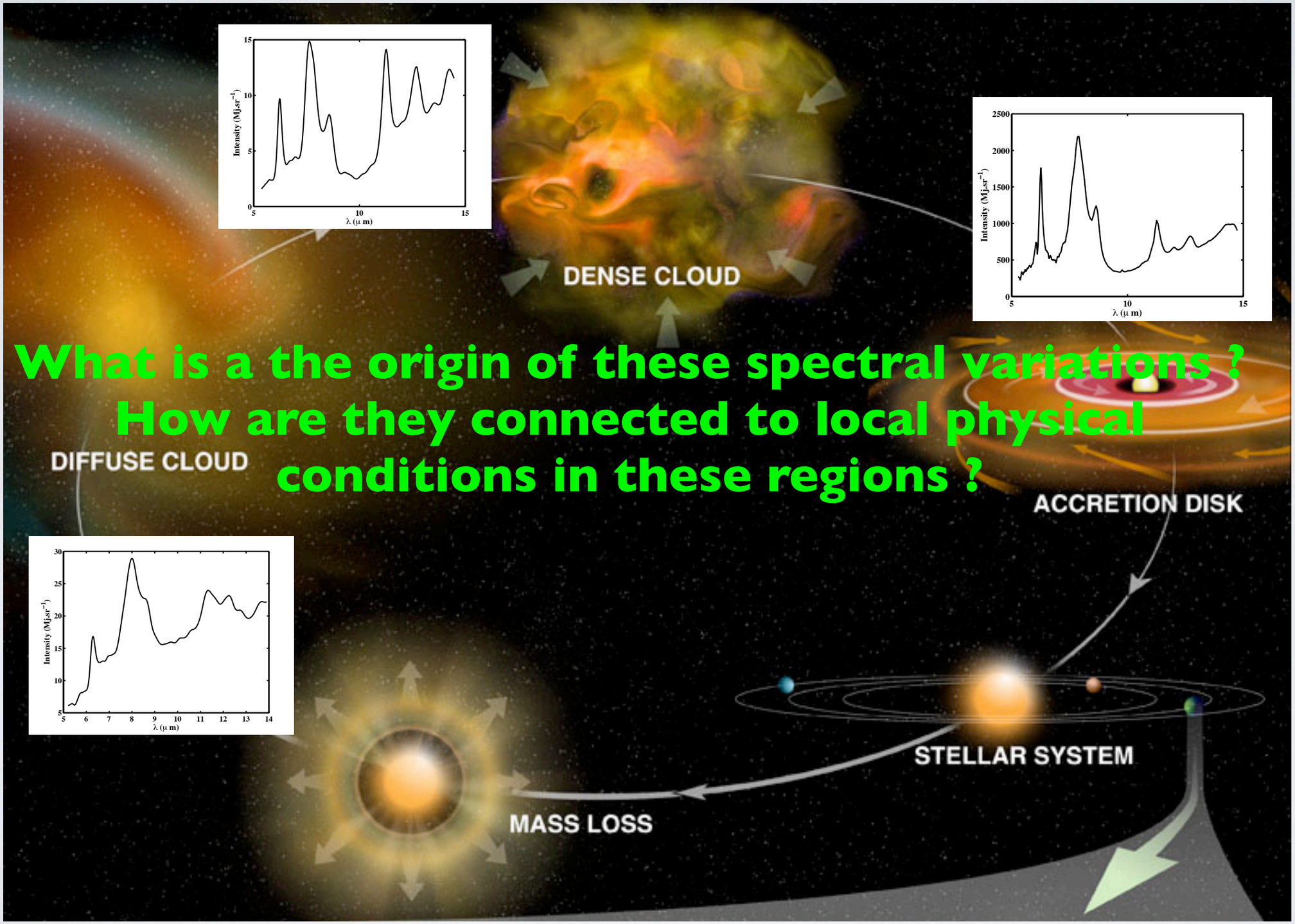

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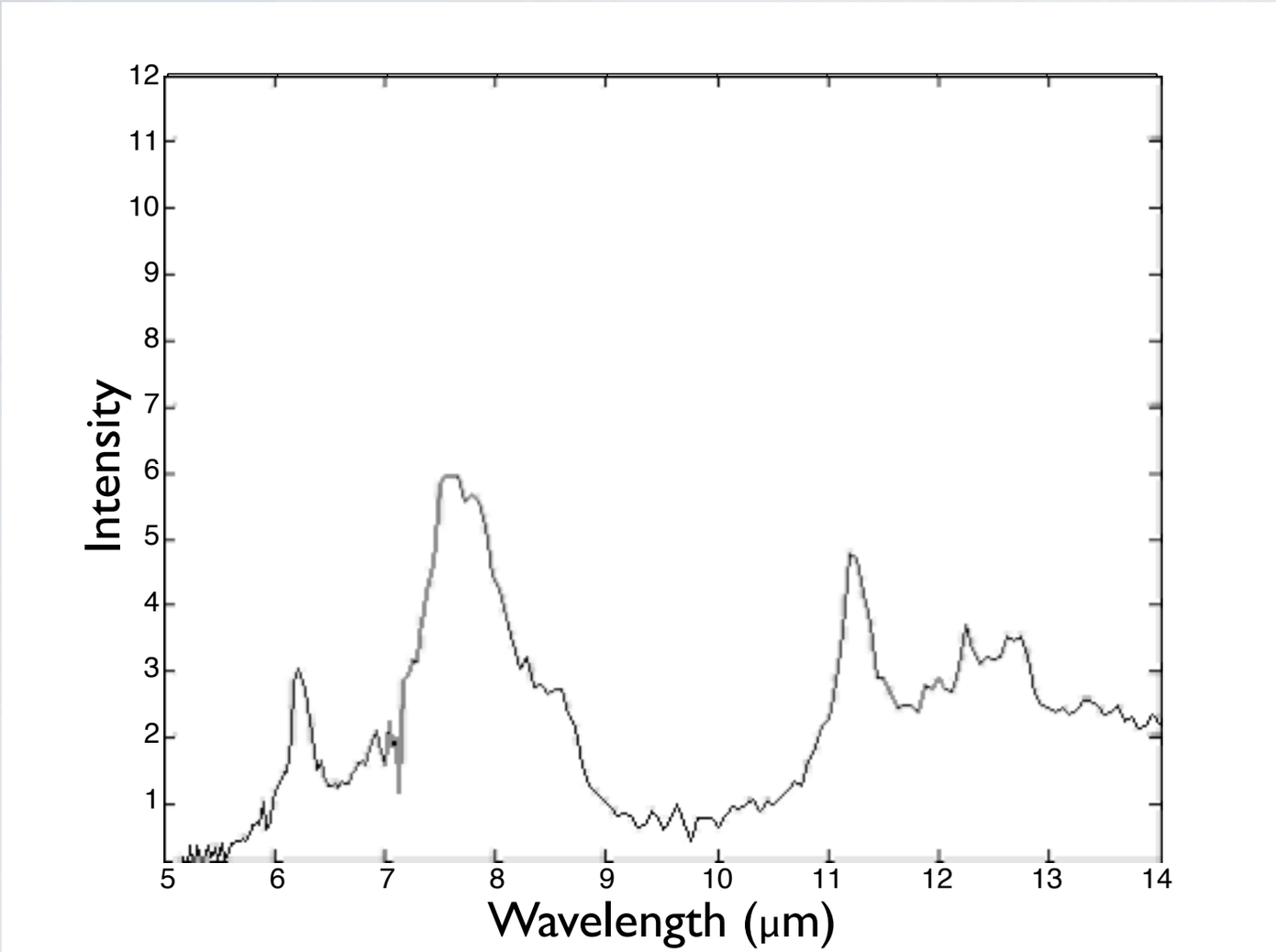
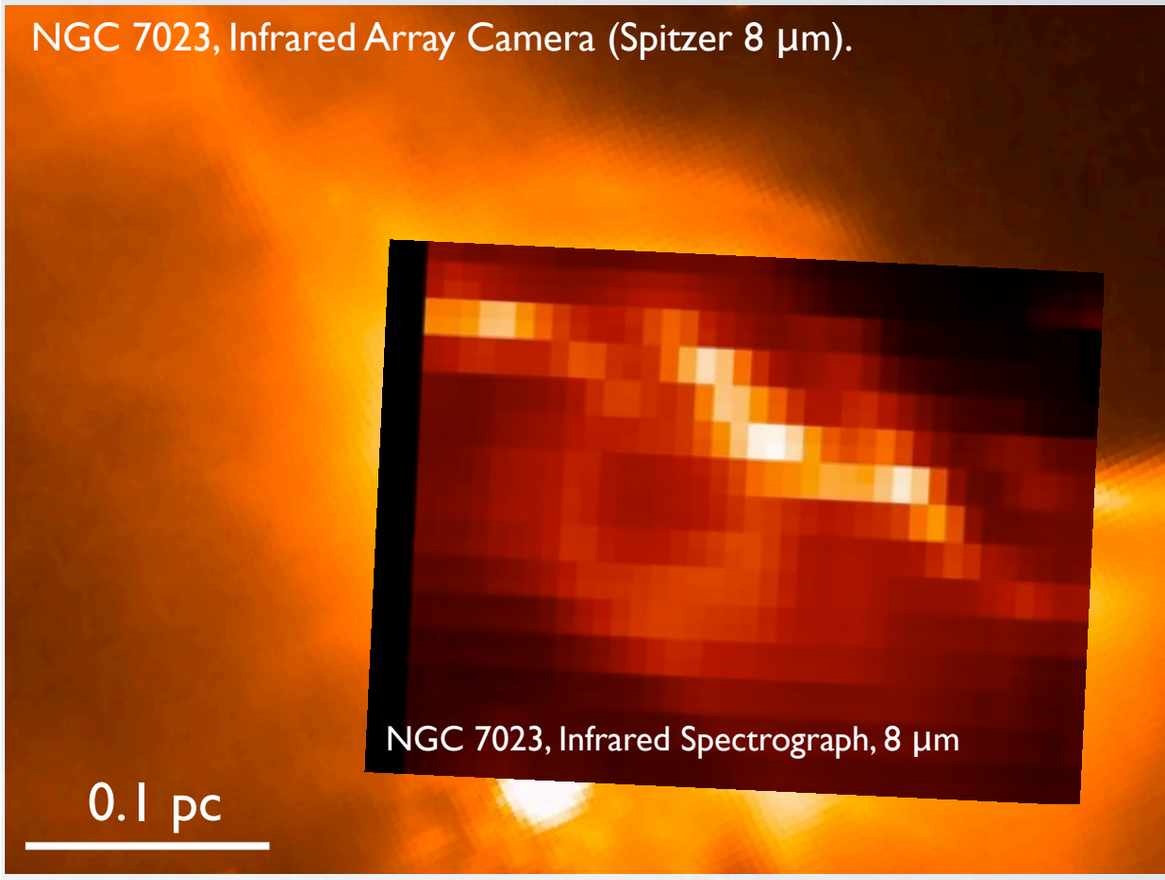
Evidence for PAH evolution in the ISM





- Each observed spectrum is a linear combination of elementary spectra
  - We observe different mixtures of the same elementary spectra

Mathematical model for evolution of PAHs

Linear instantaneous model

$$x_i(\lambda) = a_{i1} \times S_1(\lambda) + a_{i2} \times S_2(\lambda) + a_{i3} \times S_3(\lambda) \dots$$

$$\begin{pmatrix} x_i(\lambda) \\ \vdots \\ x_m(\lambda) \end{pmatrix} = \begin{pmatrix} a_{1,1} & \dots & a_{1,r} \\ \vdots & & \vdots \\ a_{m,1} & \dots & a_{m,r} \end{pmatrix} \times \begin{pmatrix} S_1(\lambda) \\ \vdots \\ S_r(\lambda) \end{pmatrix} \quad \text{with } r \ll m$$

Observation matrix

Mixing matrix

Matrix of «source» spectra

$$X = A \times S$$

Goal identifying A *and* S, from X

Solving the problem using Non-negative matrix factorization (NMF)

The problem

$$X = A \times S$$

Approach:

$$X \approx W \times H$$

The criteria, Euclidian distance / Kullback's divergence :

$$\|X - WH\|^2 = \sum_{ij} (X_{ij} - (WH)_{ij})^2$$

$$D(X|WH) = \sum_{ij} (X_{ij} \log \frac{X_{ij}}{(WH)_{ij}} - X_{ij} + (WH)_{ij})$$

The algorithm

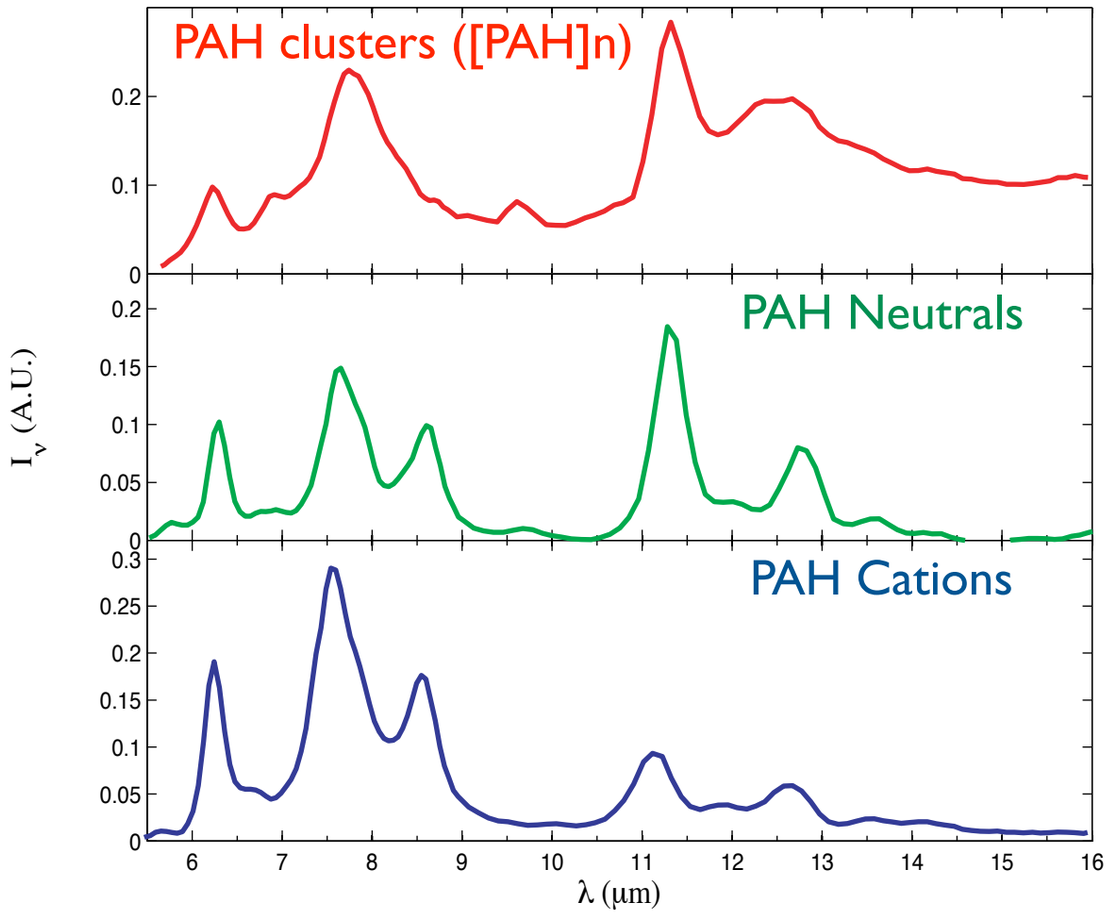
$$H_{a\mu} \leftarrow H_{a\mu} \frac{\sum_i W_{ia} X_{i\mu} / (WH)_{i\mu}}{\sum_k W_{ka}}, W_{ia} \leftarrow W_{ia} \frac{\sum_\mu H_{a\mu} X_{i\mu} / (WH)_{i\mu}}{\sum_\nu H_{a\nu}}$$

- We set the numbers or rows of **H**
- **W** and **H** must be positive
- We start iteration with random **W** and **H**
- Results do not depend on initialization

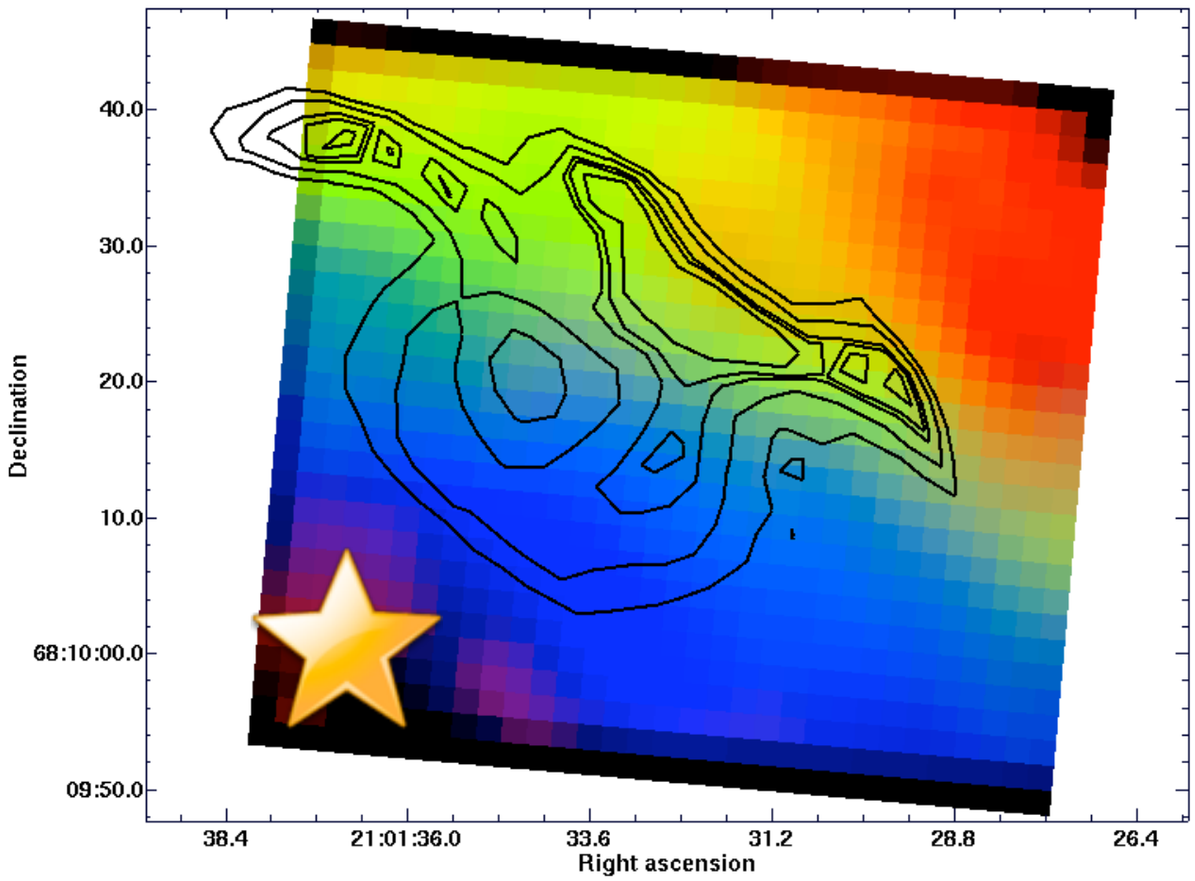
[Lee and Seung, Nature, 2001]

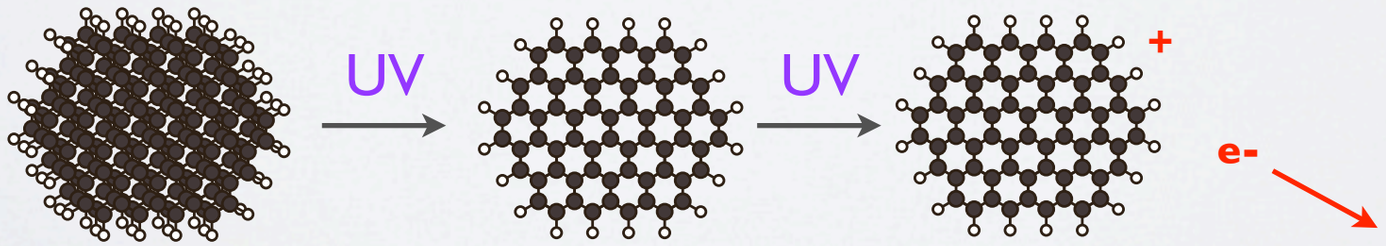
Photochemical evolution of PAHs

Extracted spectra



Spatial distribution





[Rapacioli et al. *Astron. Astrophys.* 2005, Berné et al. *Astron. Astrophys.* 2007]

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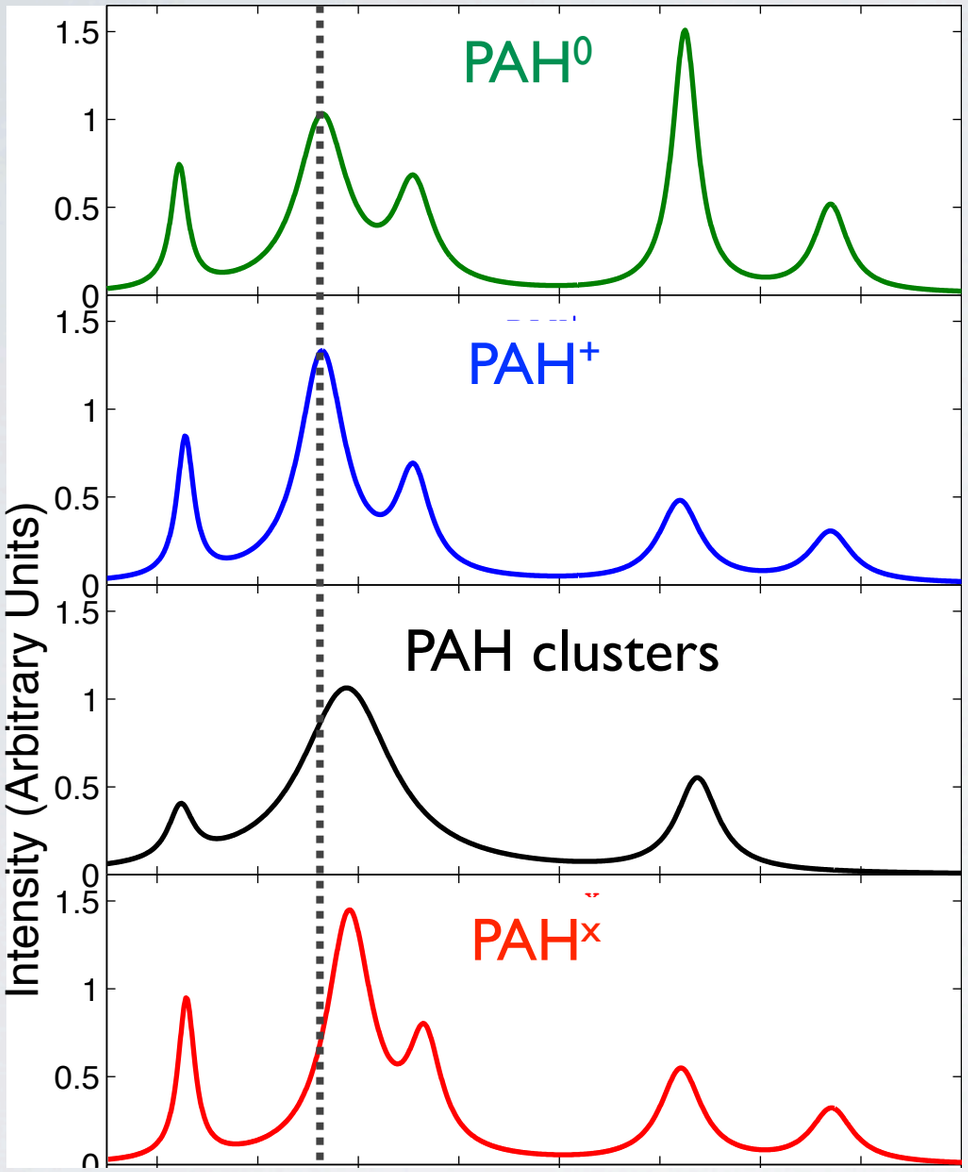
Constructing a model



Spectra adapted from decomposition

Spectra of large (>100 carbon atoms) ionized PAHs inspired from Quantum Chemistry results

[Joblin et al 2008, Bauschlischer 2008, P. by C. Boersema, J. Cami]

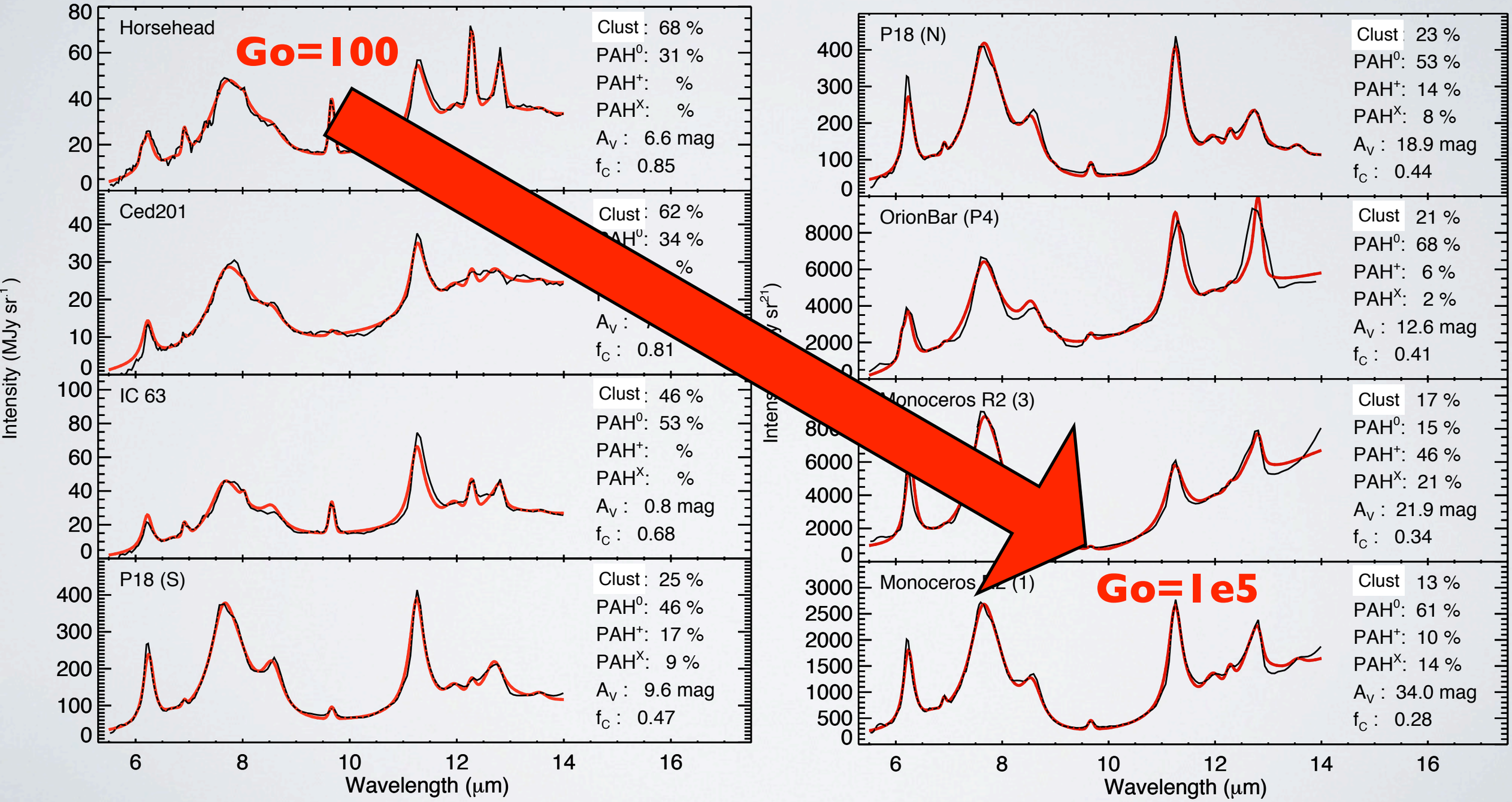
Model benchmarking in galactic nebulae

[Pilleri et al. **A&A** 2012 accepted]

Observations

Model

Go: intensity of UV radiation field emitted by stars into the ISM



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Model

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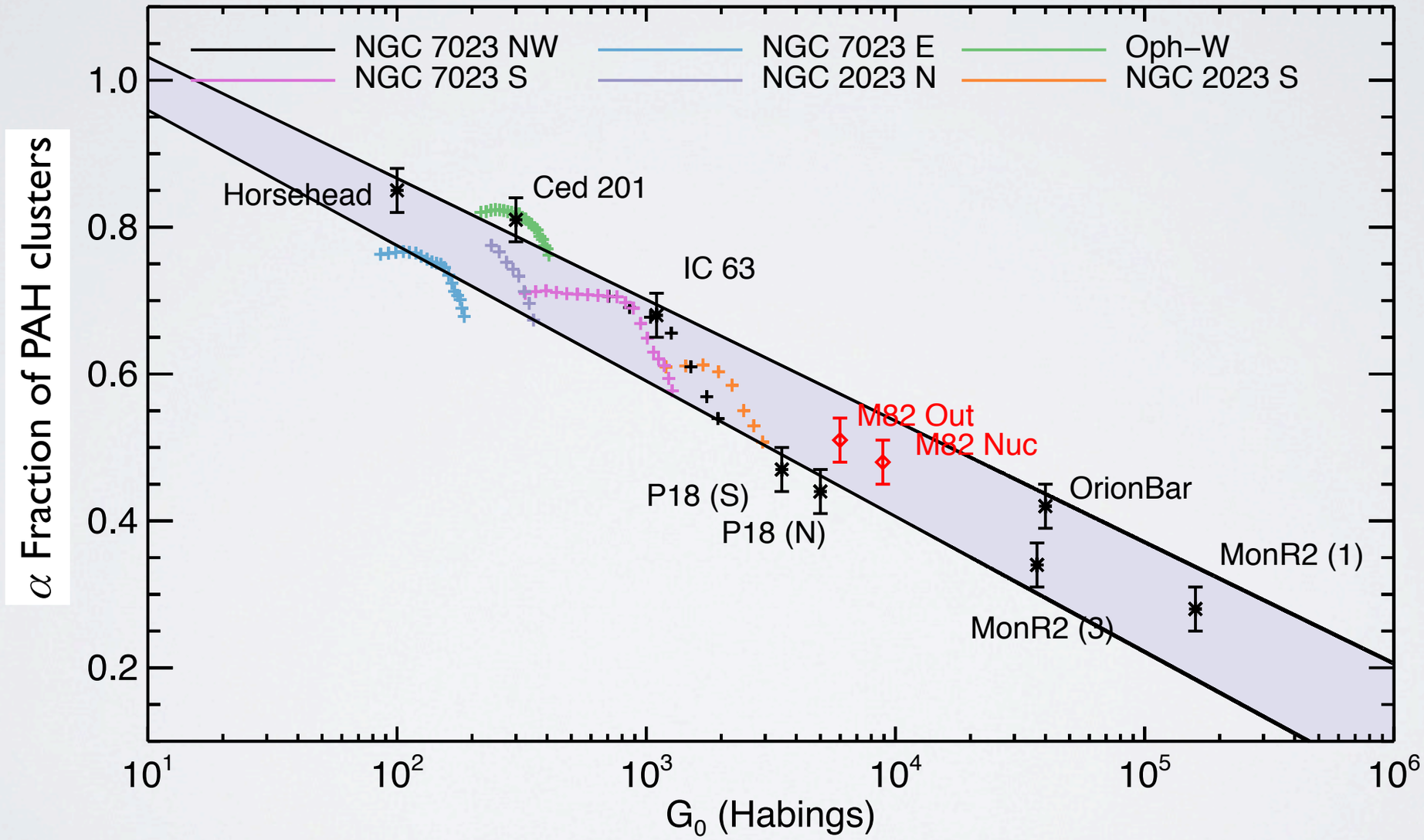
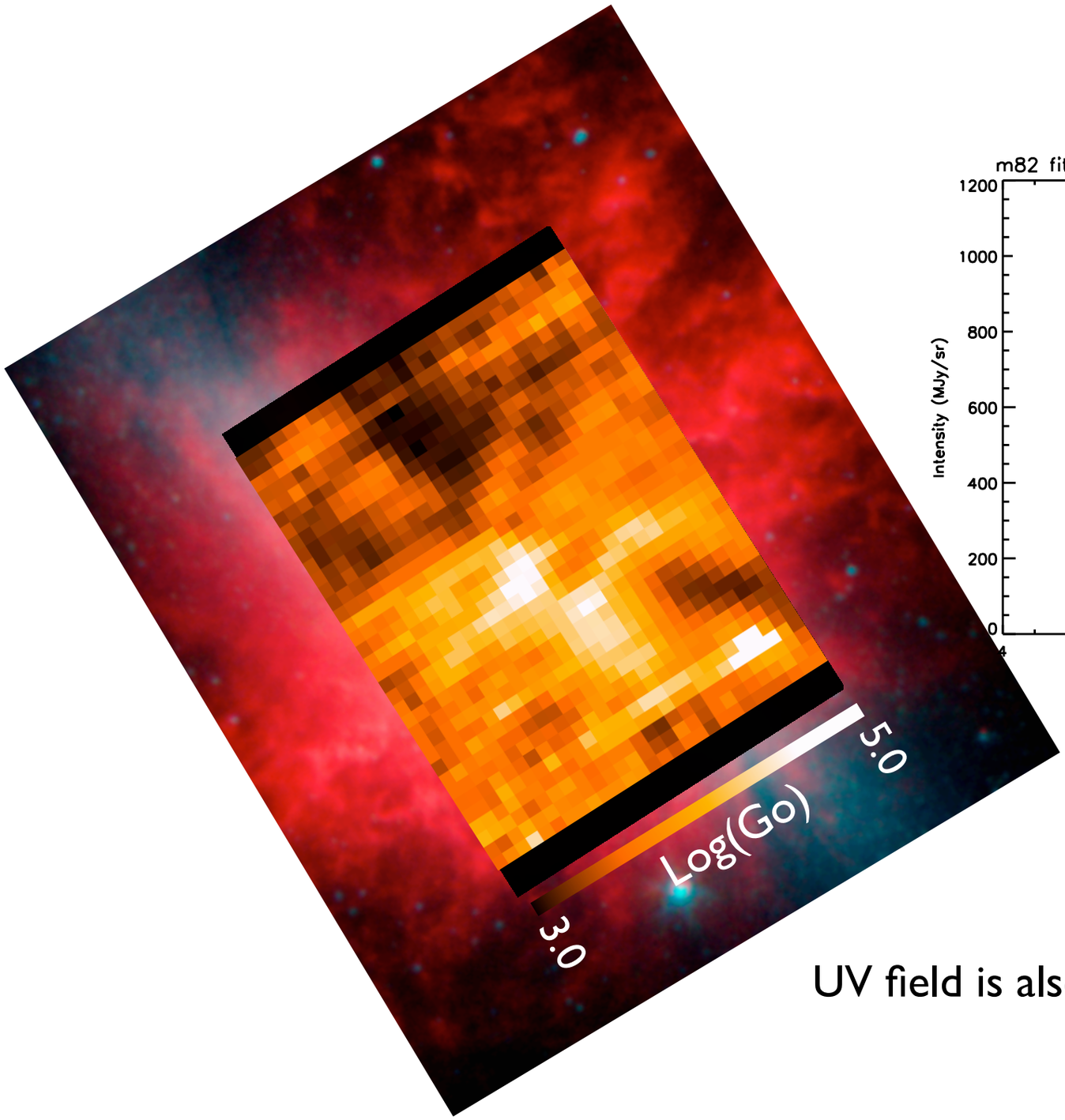
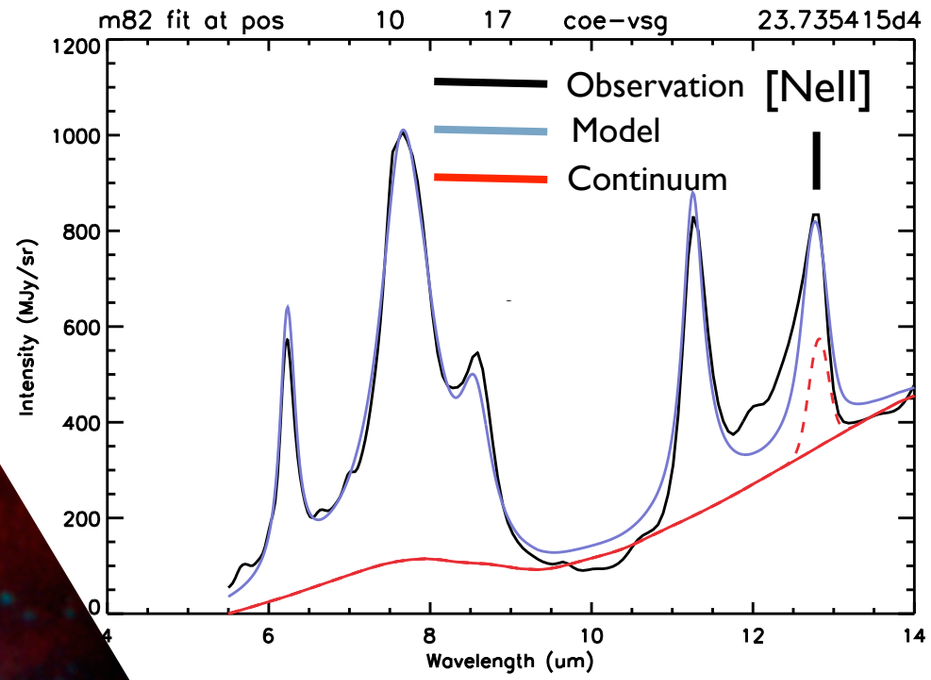


Application to nearby galaxy M82



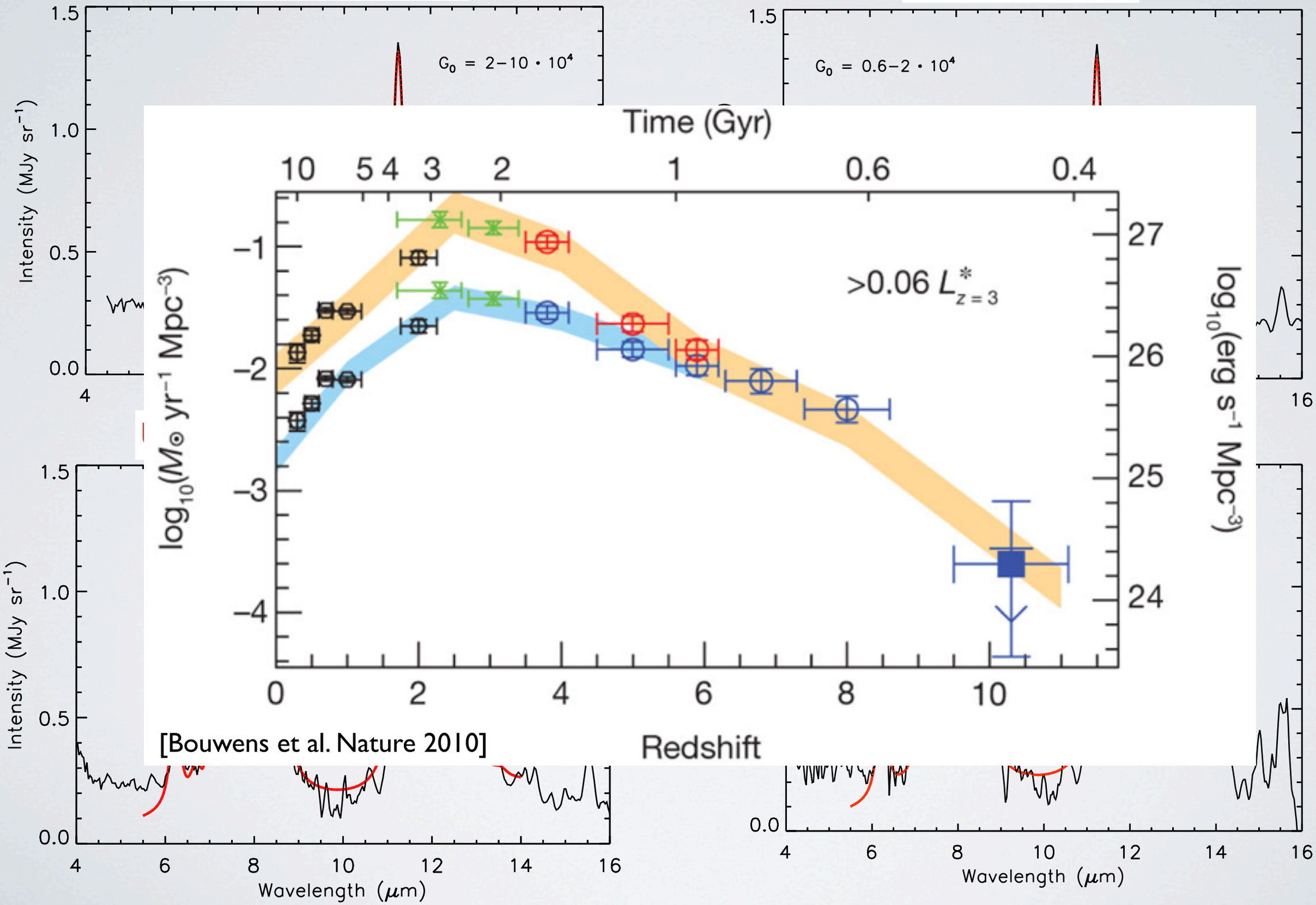


UV field is also a tracer of star-formation

Application to remote galaxies
(data from K. Dasyra)

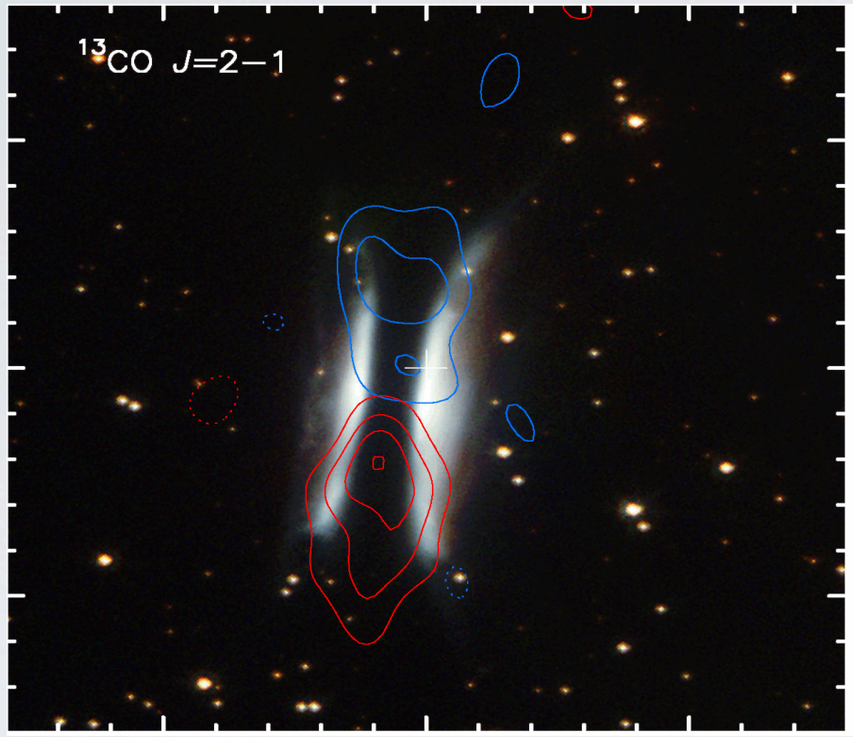
Luminous IR Galaxy

Galaxies at z <1

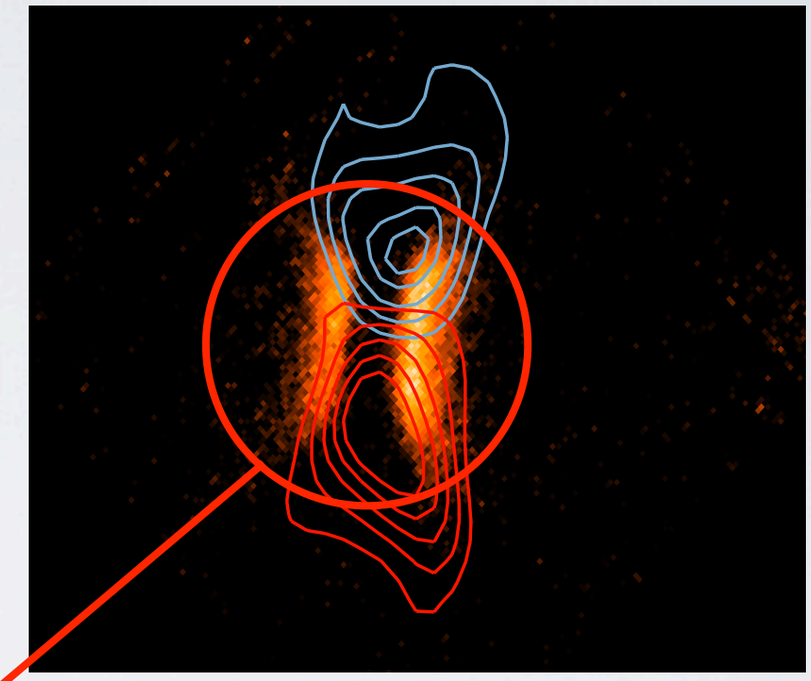


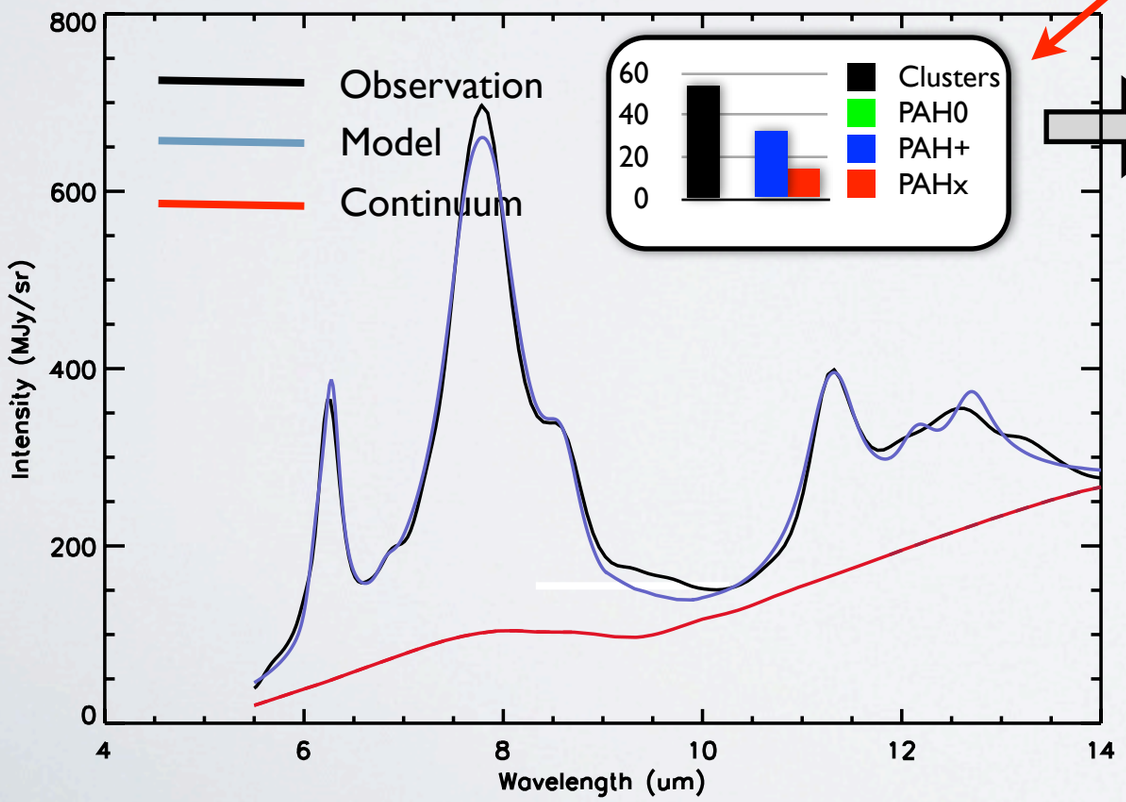
Application to the «Gomez hamburger» protoplanetary disk

Scattered light (visible)
13 CO (millimeter)



PAH (mid-IR)
12 CO millimeter





Abundance of PAH clusters

Radiation field

Star luminosity

For the following:

Mid-IR PAH emission is a high angular resolution, optically thin tracer of of UV illuminated couds in star forming regions

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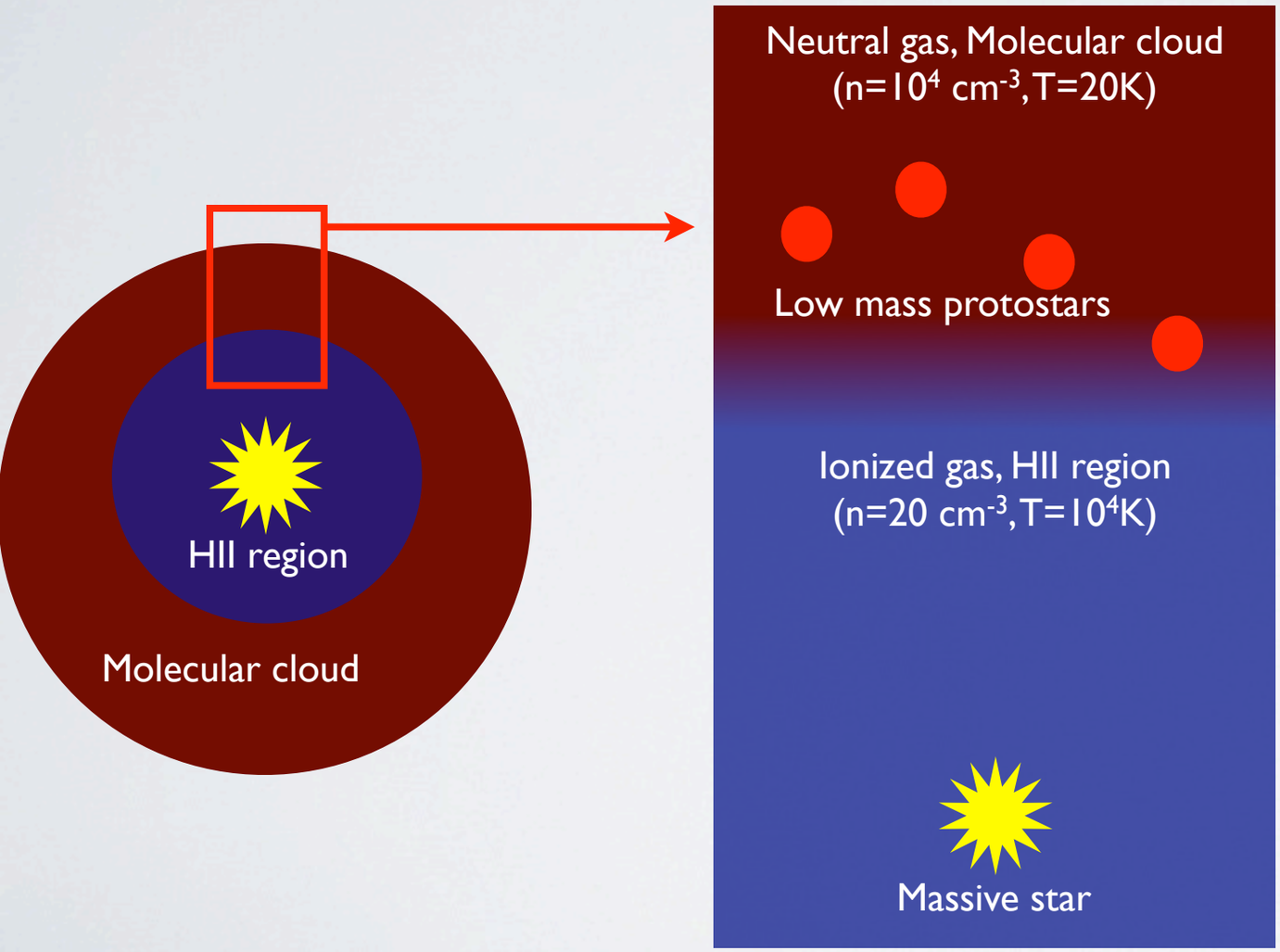
Background

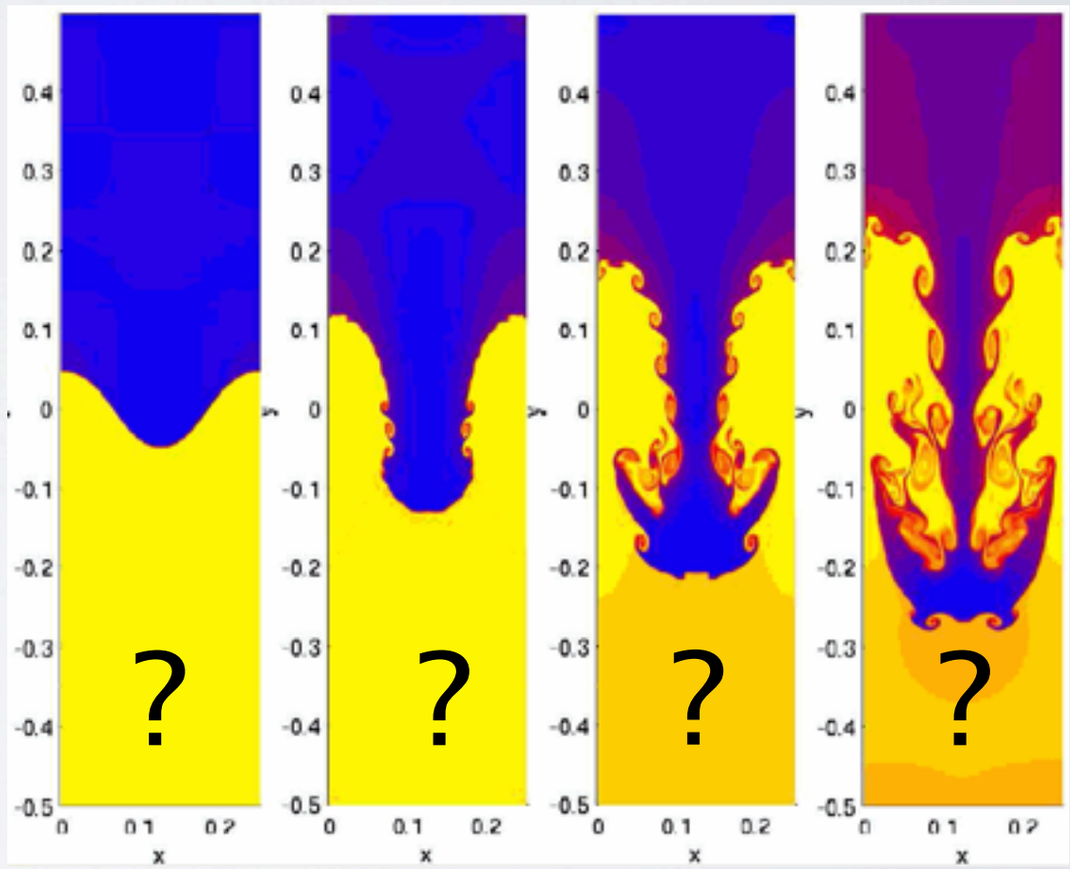
- Since the seminal work of Lyman Spitzer 1954 (ApJ 120) it was proposed that hydrodynamic instabilities can happen in star-forming regions

- This is important because it will determine the structure of the ISM, induce turbulence, and chemical mixing of heavy elements injected by massive stars

Schematic morphology of star-forming region

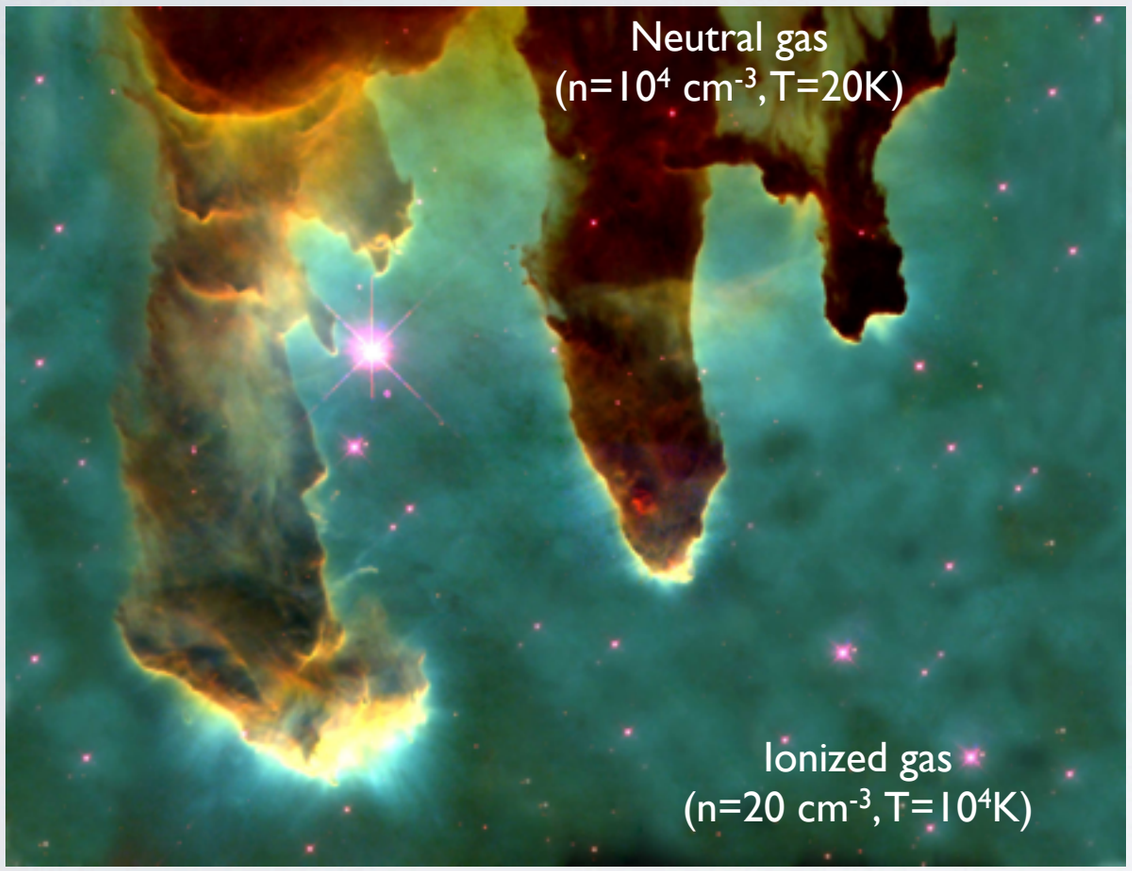


Rayleigh Taylor instability

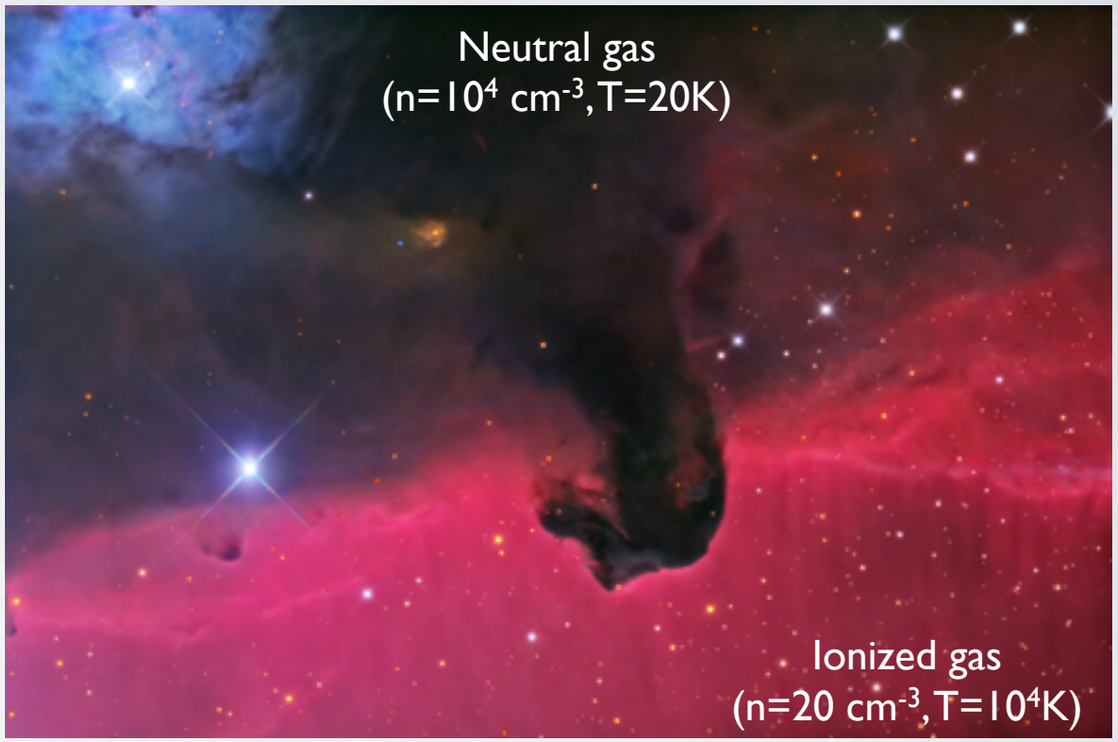


The Rayleigh Taylor instability ?

Pillars of creation



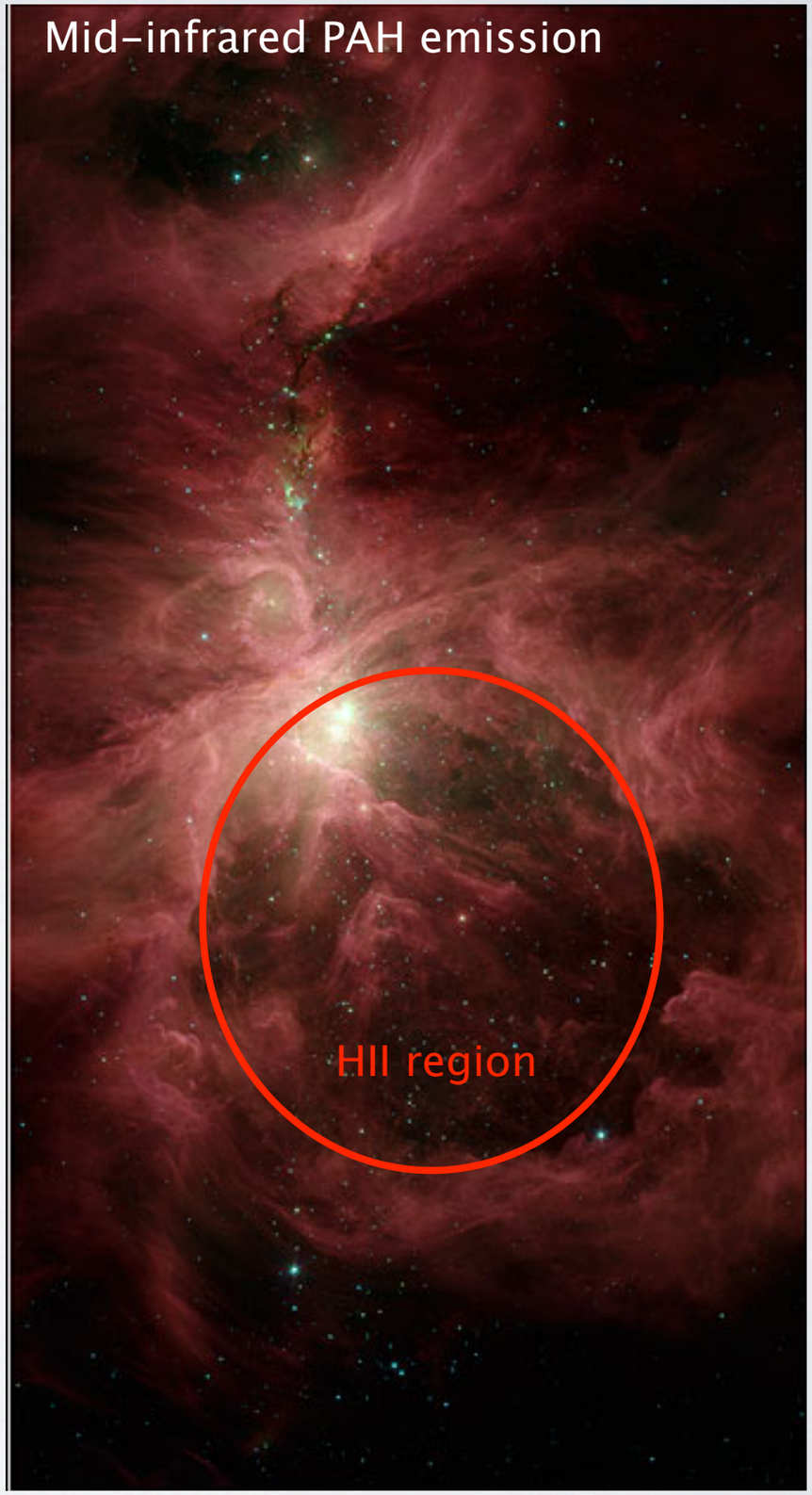
Horsehead nebula



Studies with radio-telescopes show that velocity fields do not match models of RT instability
[M. Pound **ApJ** 1998, **ApJ** 2003]

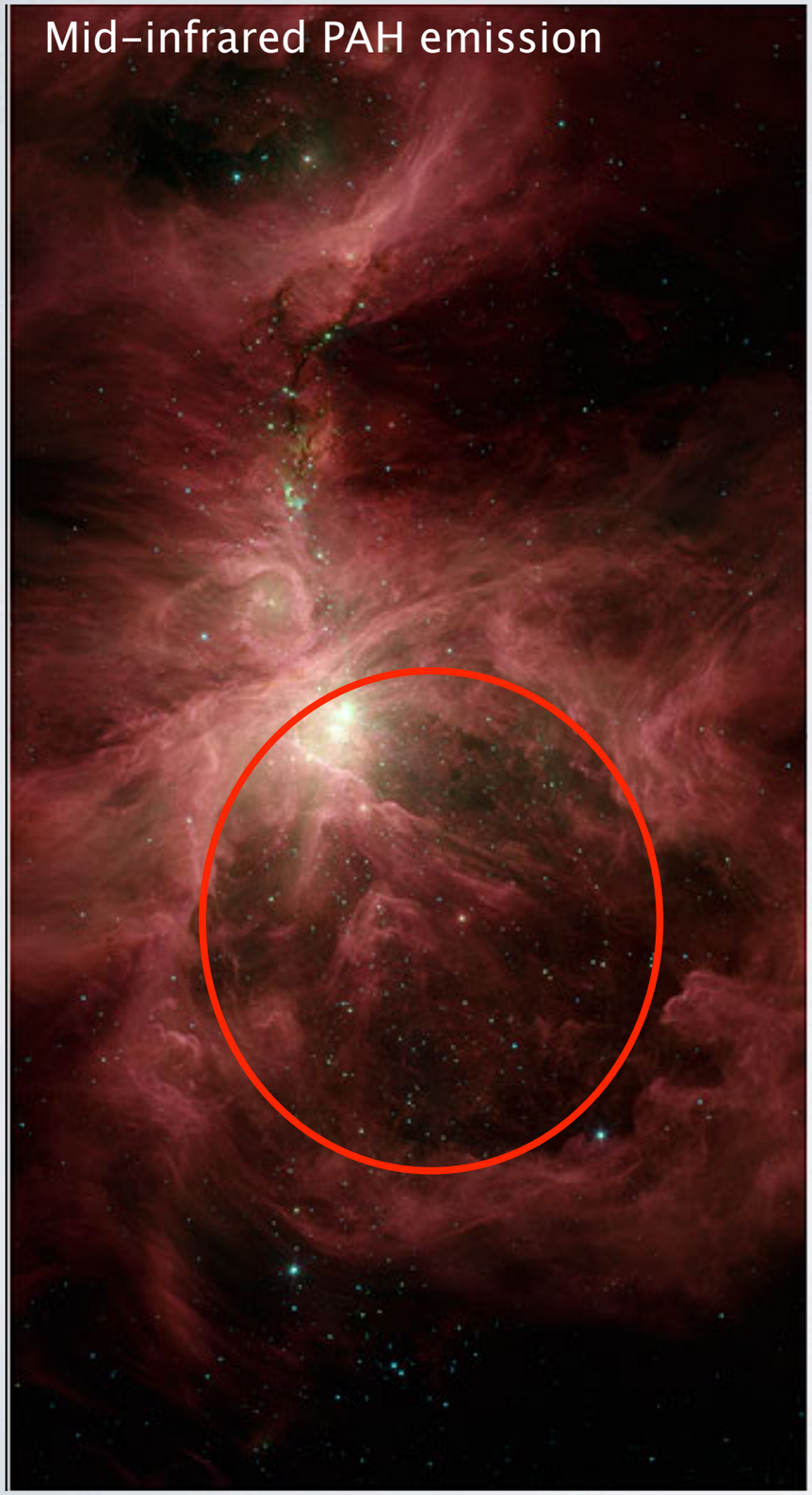
Study of Orion visible vs infrared

[Berné, Marcelino & Cernicharo, **Nature** 2012]



Study of Orion infrared vs millimeter

[Berné, Marcelino & Cernicharo, **Nature** 2012]



IRAM 30m radio-telescope, ^{12}CO (2-1) spatial resolution of 11”,
spectral resolution of 2km.s^{-1}

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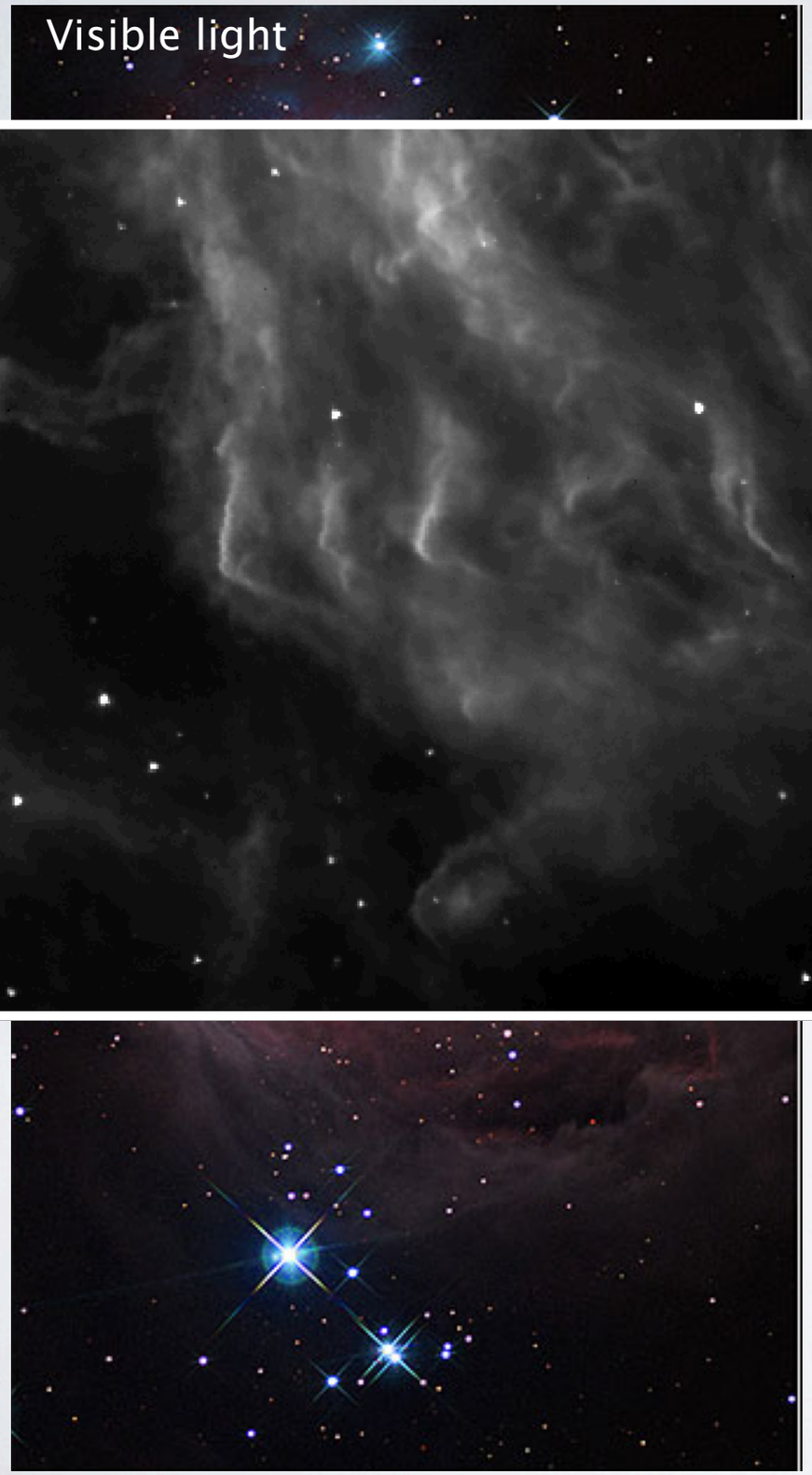
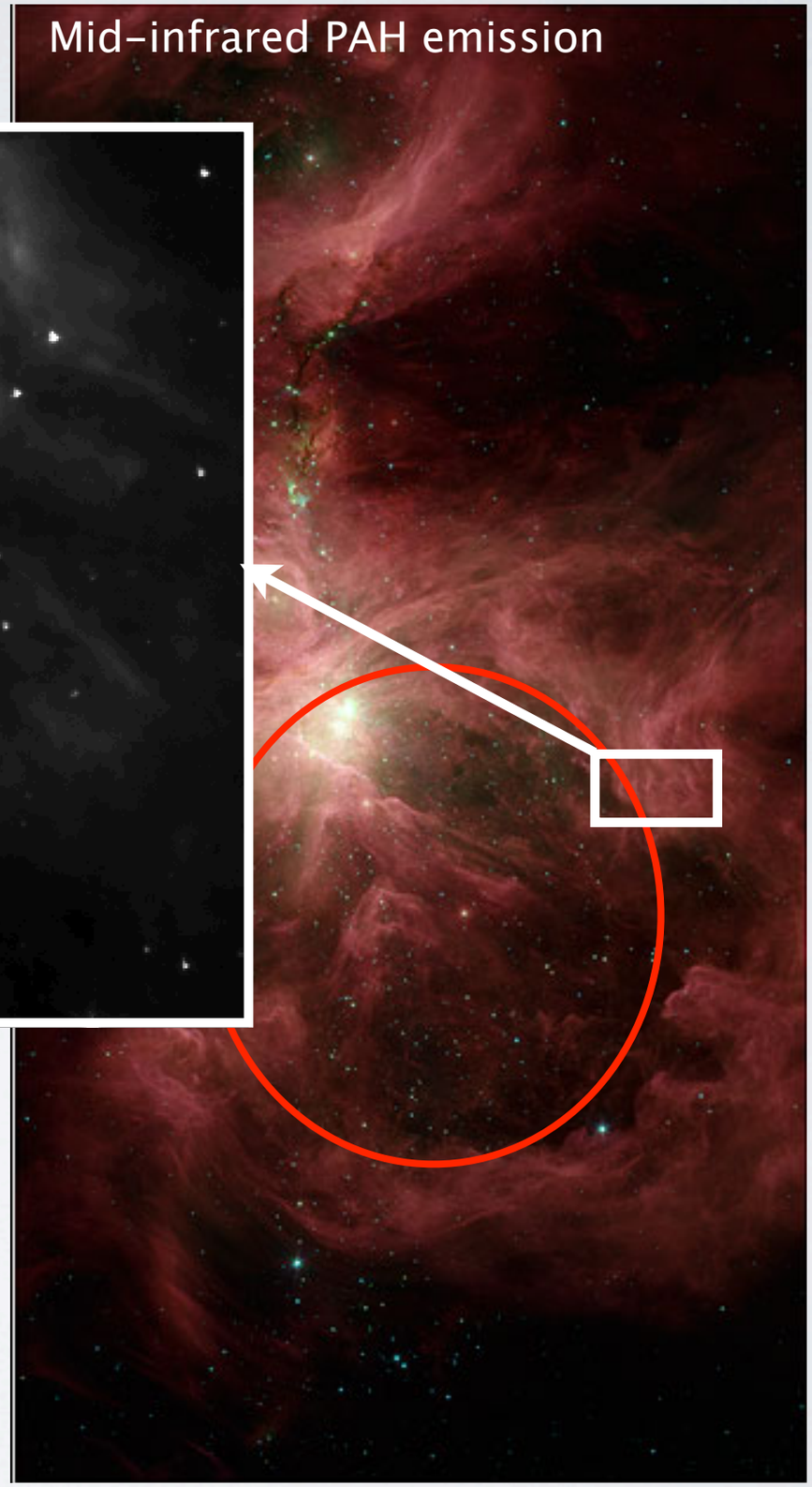
[Berné, Marcelino & Cernicharo, **Nature** 2012]

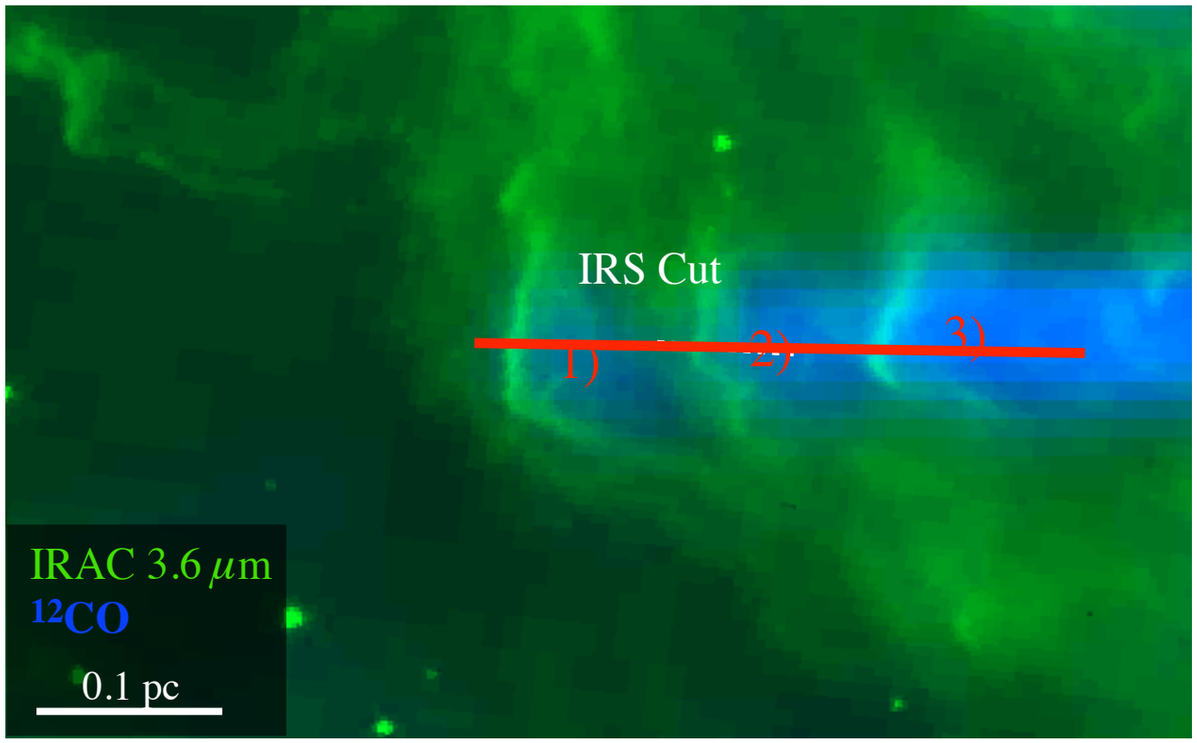


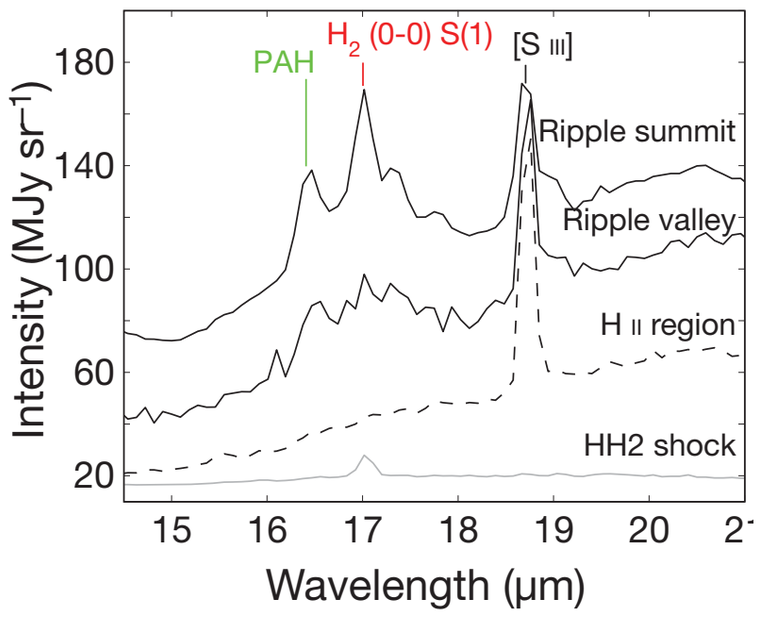


The Orion «Ripples», geometry

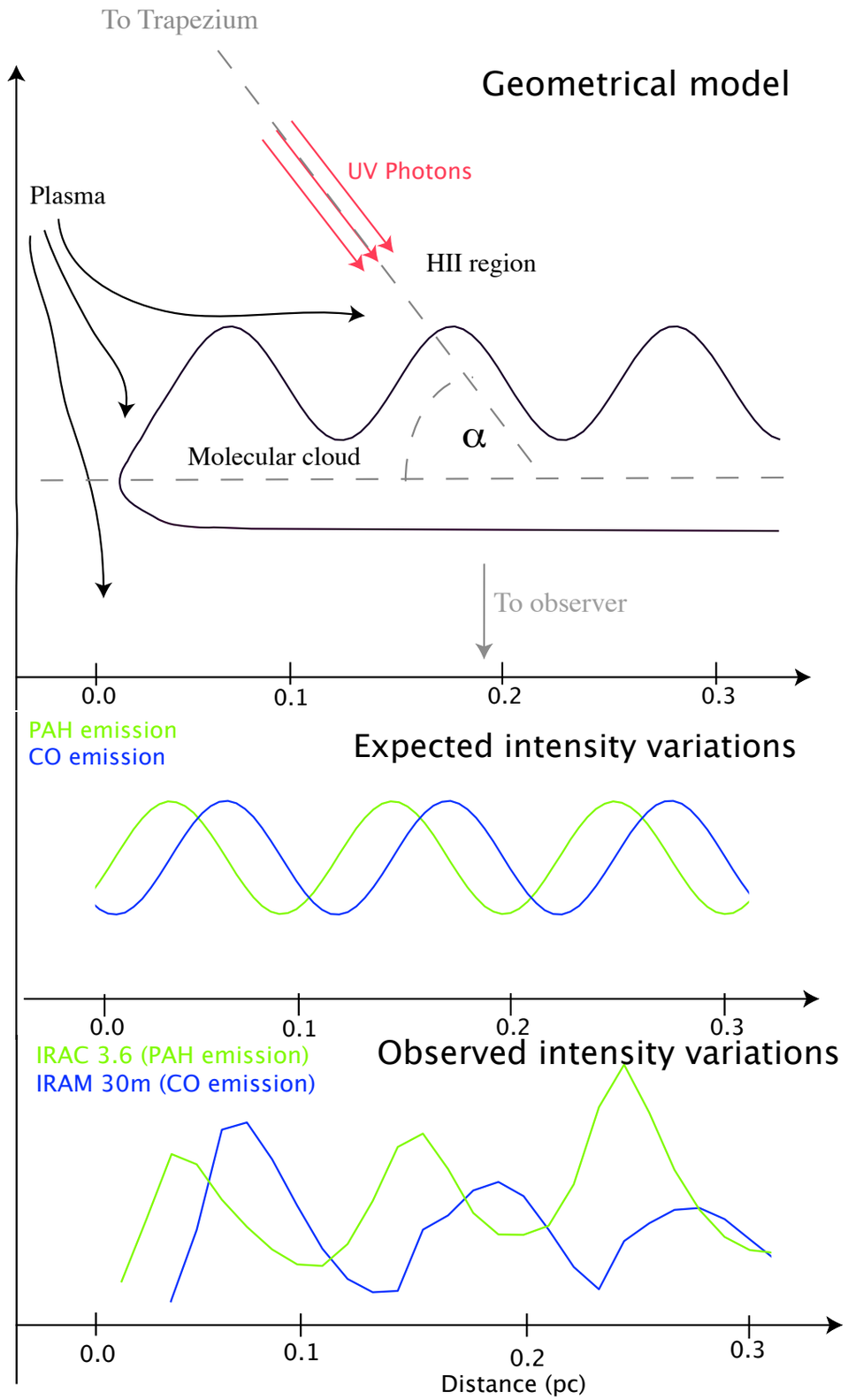
[Berné, Marcelino & Cernicharo, **Nature** 2012]

✦ Morpholgy: PAH emission + integrated CO map





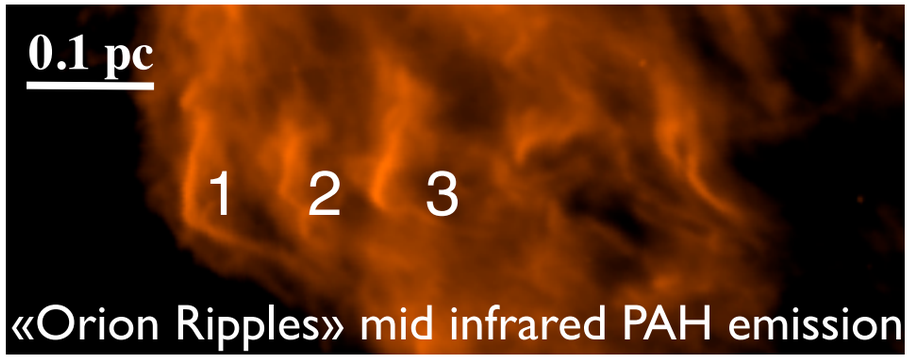
No shocks !

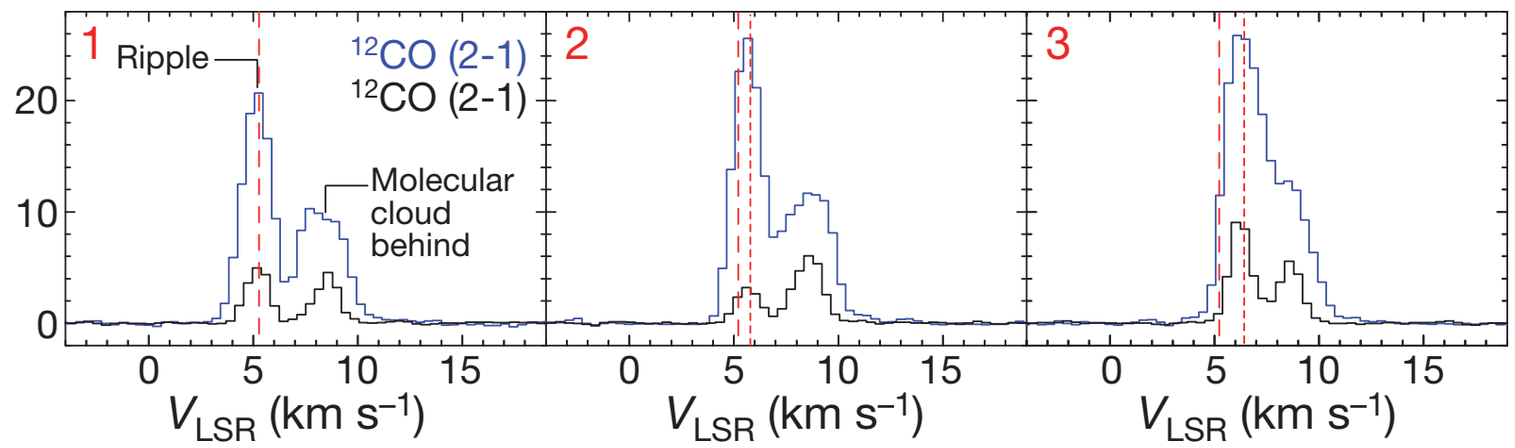


The Orion «Ripples», kinematics

[Berné, Marcelino & Cernicharo, **Nature** 2012]

✦ Kinematics with the CO line Doppler shift

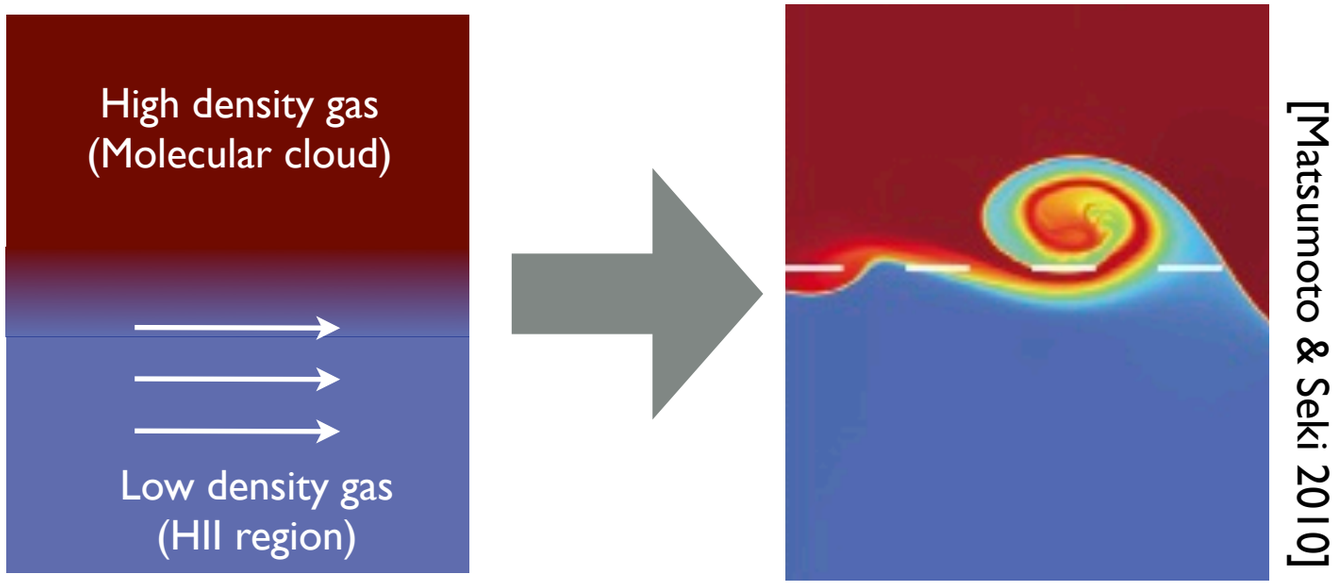




➙ Wavelike periodic structure (no high velocity shock)

➙ Evidence for a strong velocity gradient

Kelvin-Helmholtz instability [Chandrasekhar 1961]



The Orion «Ripples», first level analysis

[Berné, Marcelino & Cernicharo, **Nature** 2012]

Kelvin Helmholtz wavelength

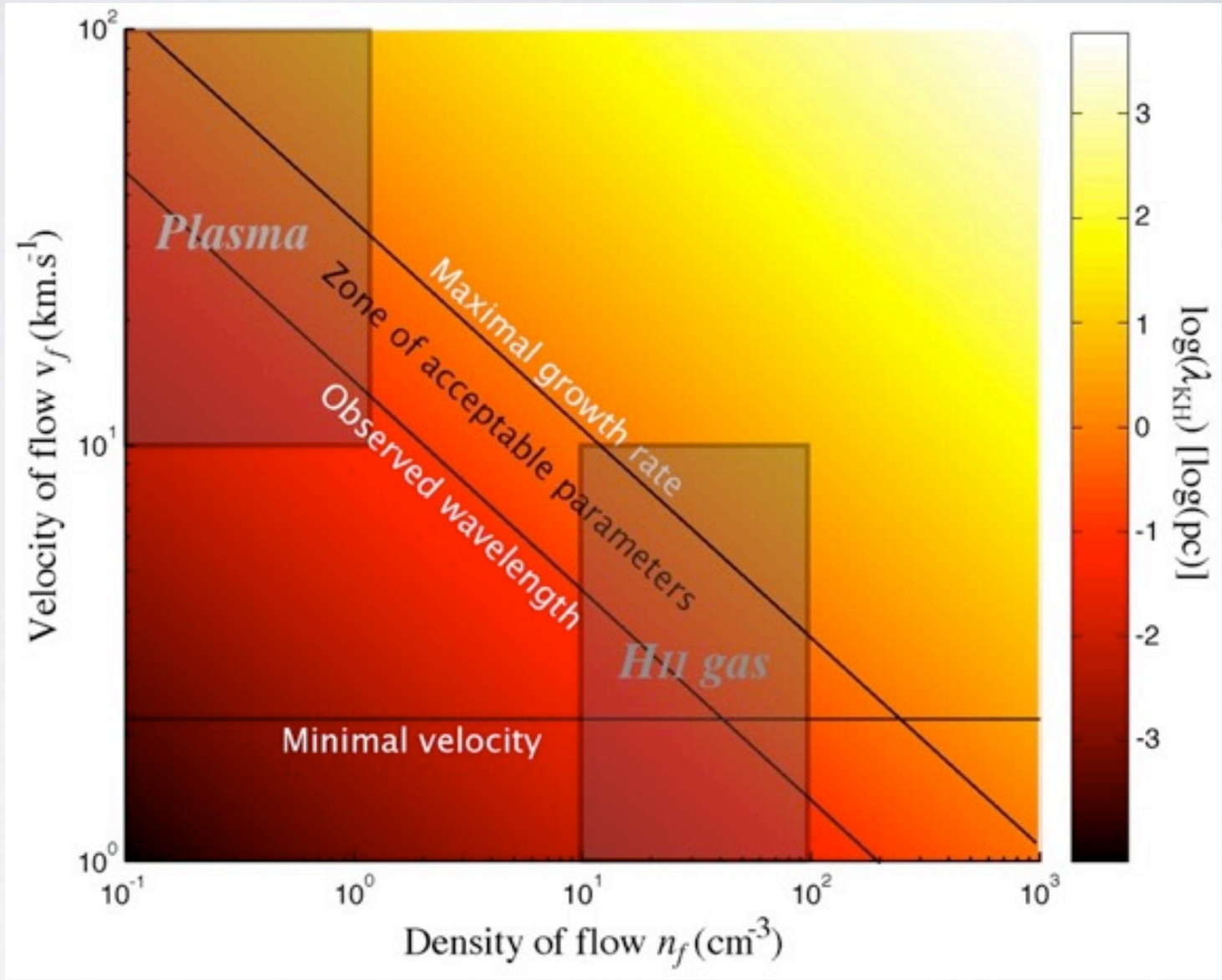
$$\lambda < \lambda_{kh} = 2\pi \times v_f^2(\rho_f/\rho_c)/g_c.$$

$$\lambda = 0.1\mathrm{pc}$$

Kelvin Helmholtz growth rate

$$\omega_{kh}^2 = \frac{k^2 \rho_f \rho_c v_f^2}{(\rho_f + \rho_c)^2}$$

$$\frac{1}{\omega_{kh}} < 3\mathrm{Myrs}$$



The observed structure is compatible with a KH instability for velocities and densities of the HII region

New images

Near IR images of Orion Ripples from European Southern Observatory in Chile

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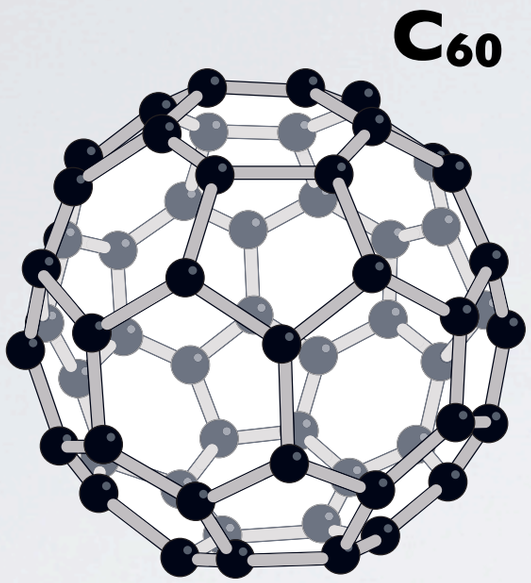
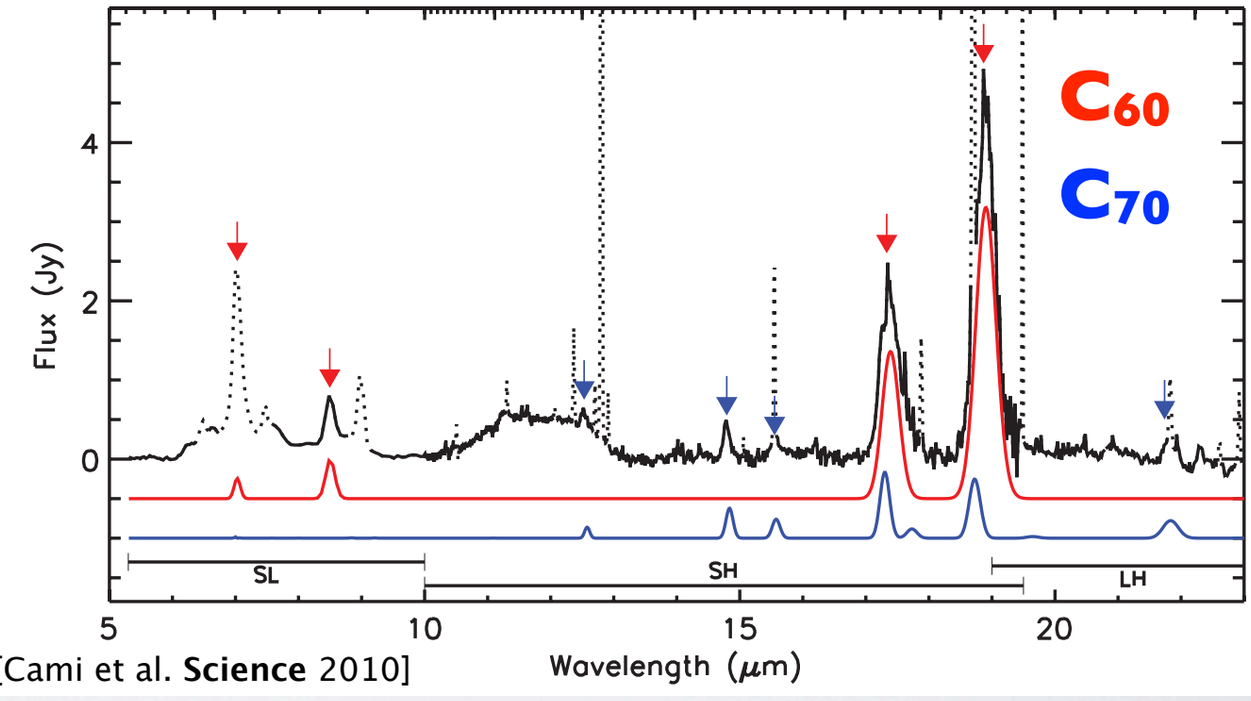
Soccerball molecule in space

Fullerenes (buckyballs) in space !



Tc1 planetary nebula (evolved star)



[Cami et al. **Science** 2010]

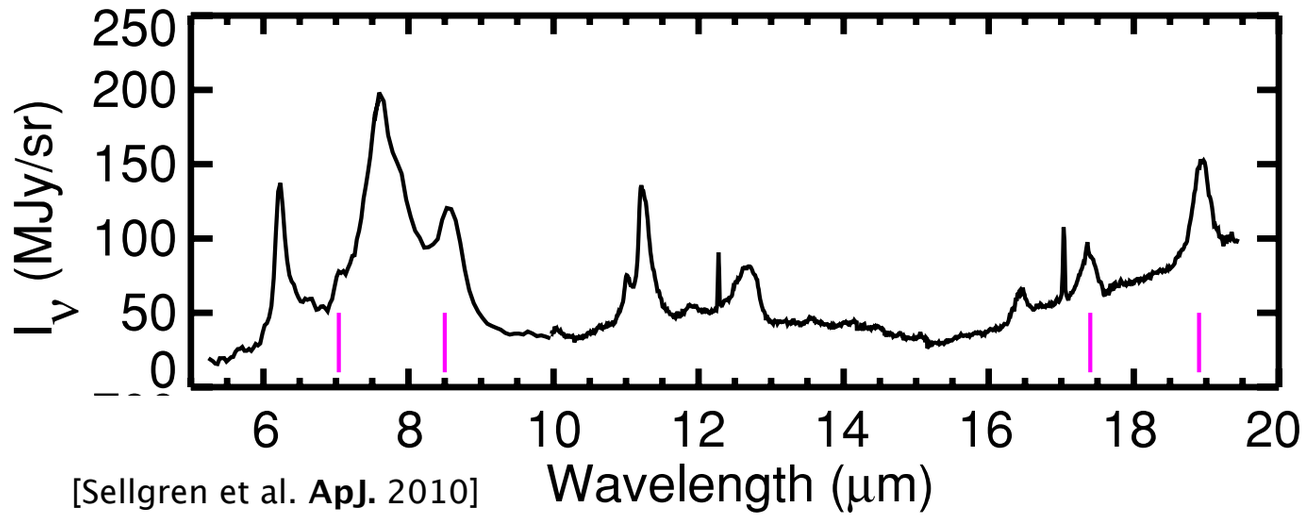
- Discovered in the lab in 1985
[Kroto et al. **Nature** 1985]

- Discovered in space through IR spectroscopy with Spitzer in 2010

- Present in evolved stars and in the ISM

- Formation process ?

NGC 7023 reflection nebula (interstellar medium)



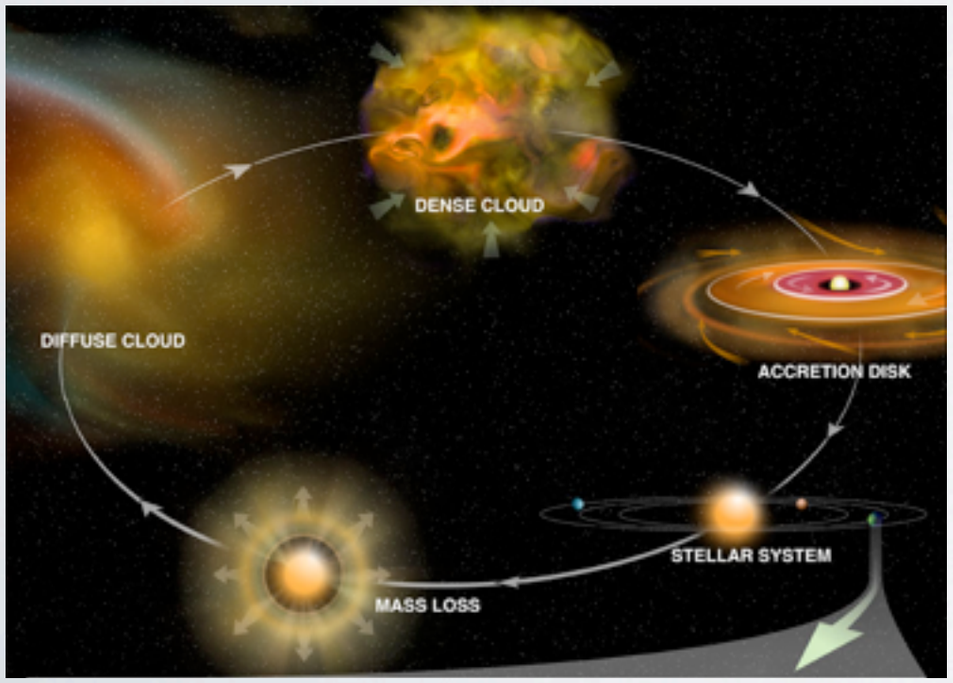
[Sellgren et al. **ApJ.** 2010]

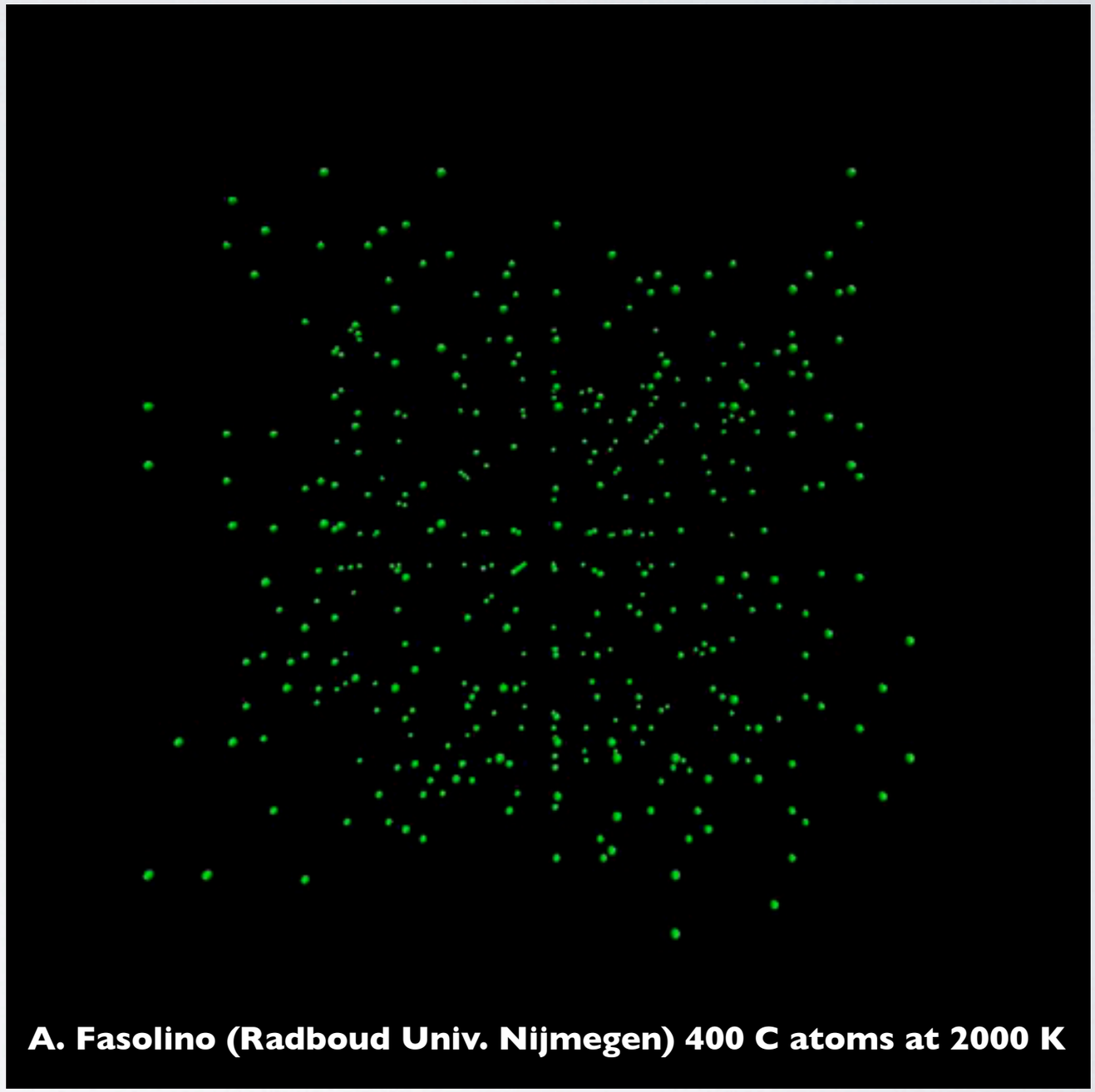
Standard formation process (bottom-up)

- Aggregation of C atoms, through rings, chains...

- In the dense and hot and H poor envelopes of evolved stars: $n_H > 10^{11}$ cm^{-3},T=1500K

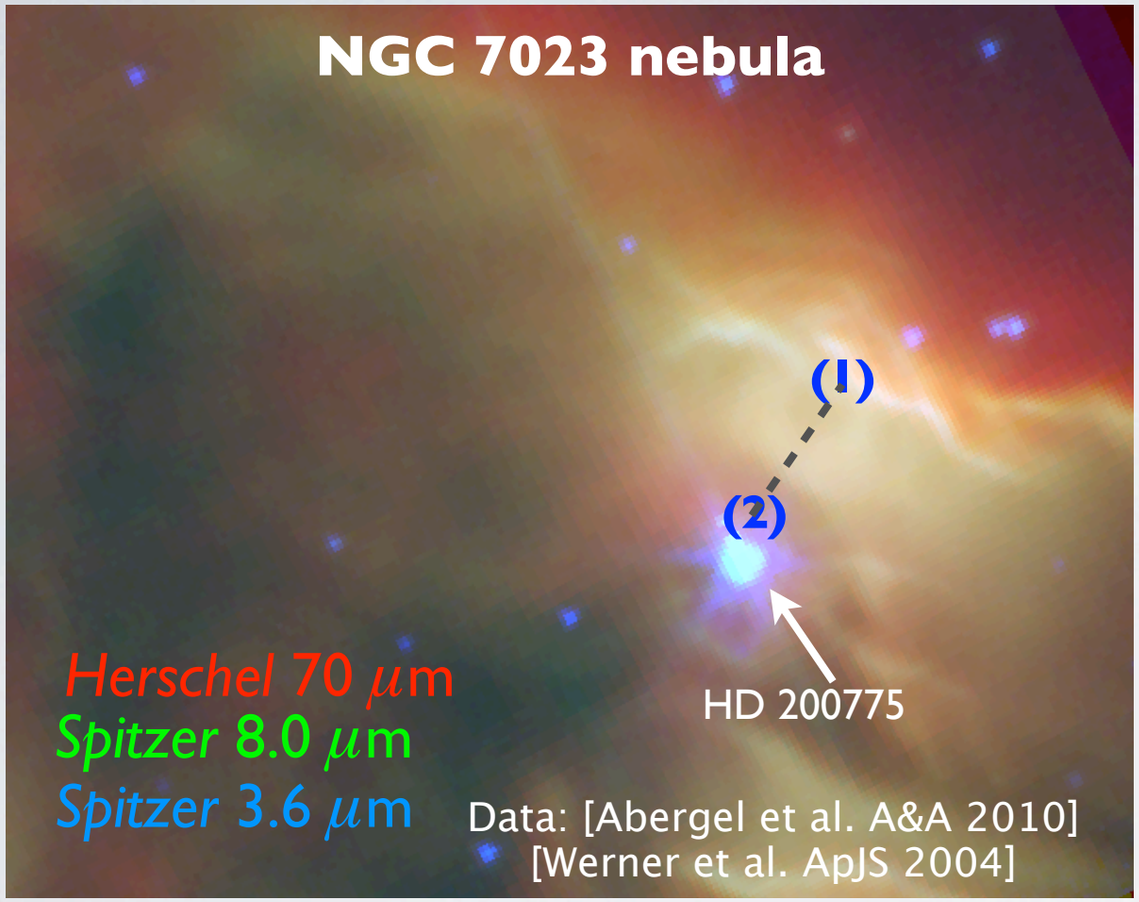
[Cherchneff et al. **A&A** 2000]

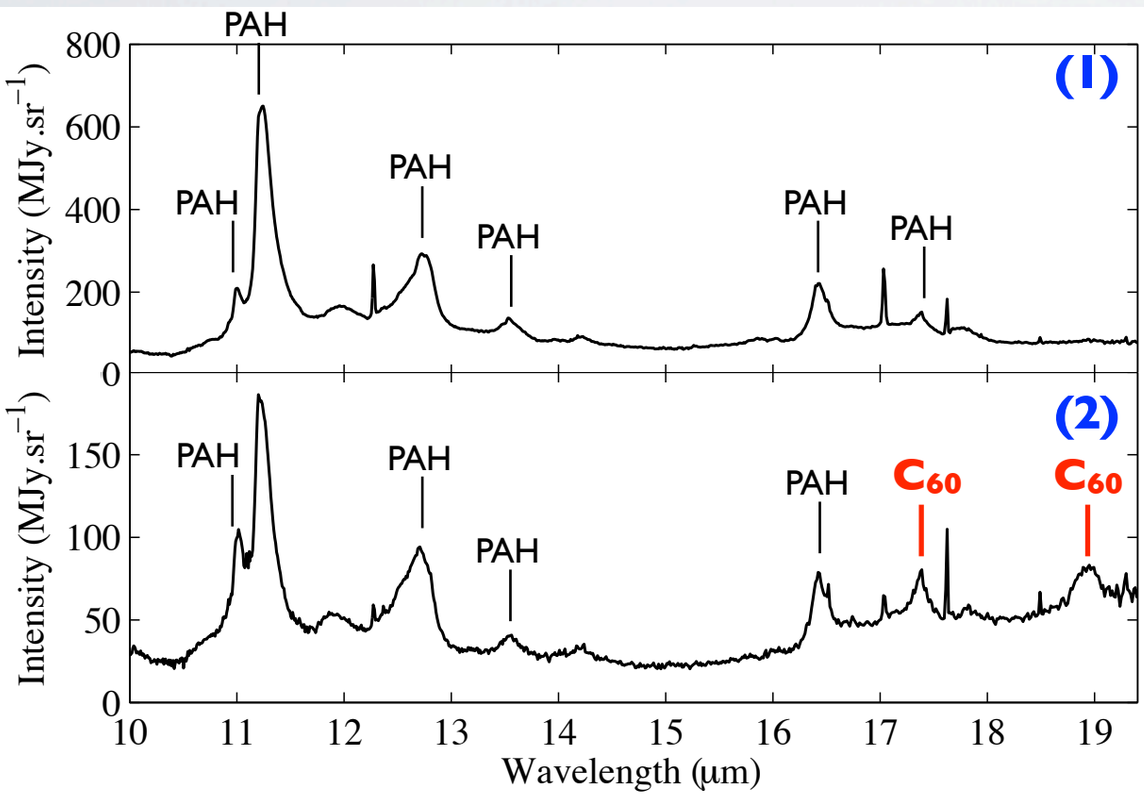


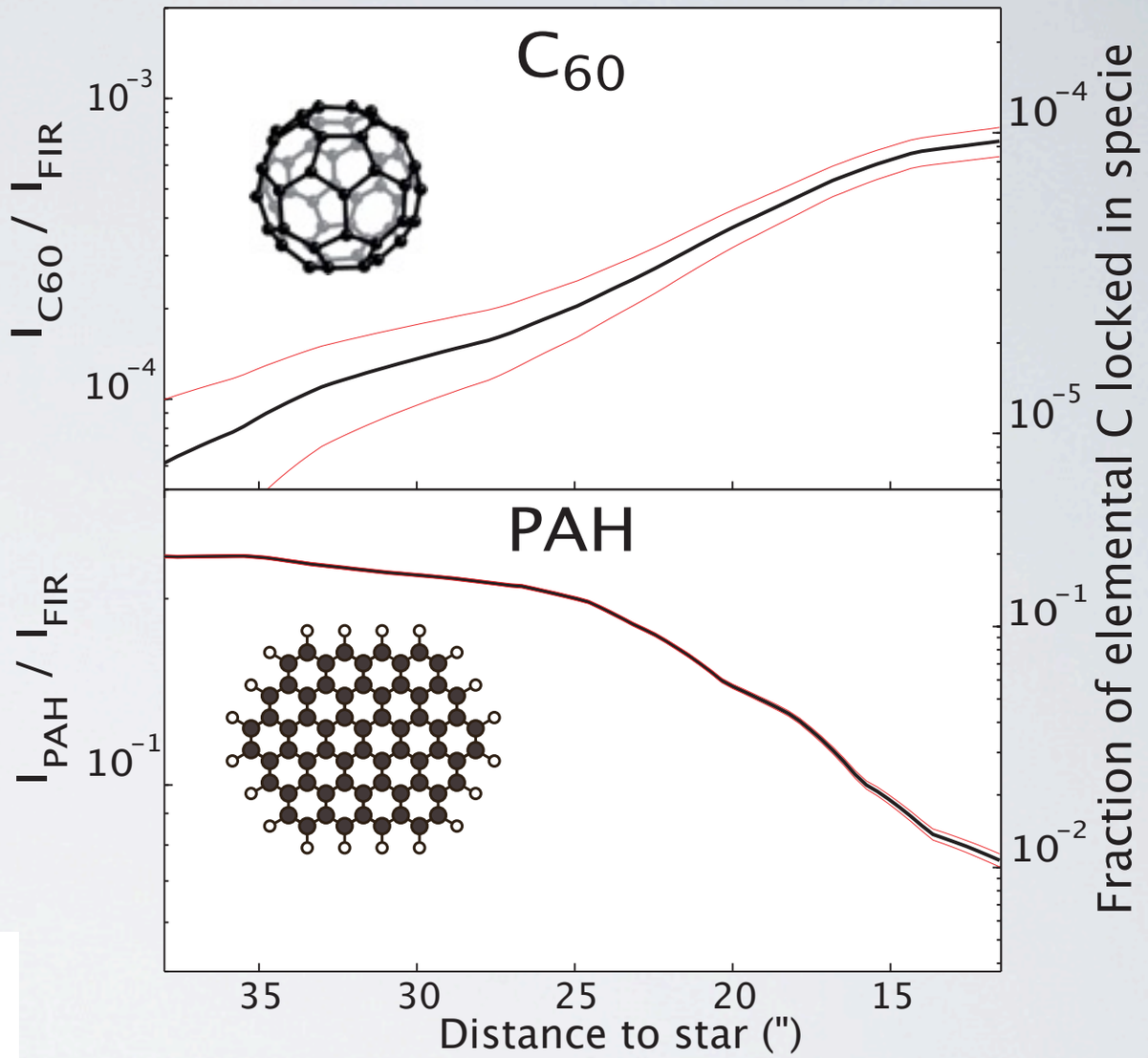


A. Fasolino (Radboud Univ. Nijmegen) 400 C atoms at 2000 K

An unexpected discovery using Spitzer and Herschel







C_{60} is formed in the interstellar medium, at low density (n_H=100 cm^{-3}) !

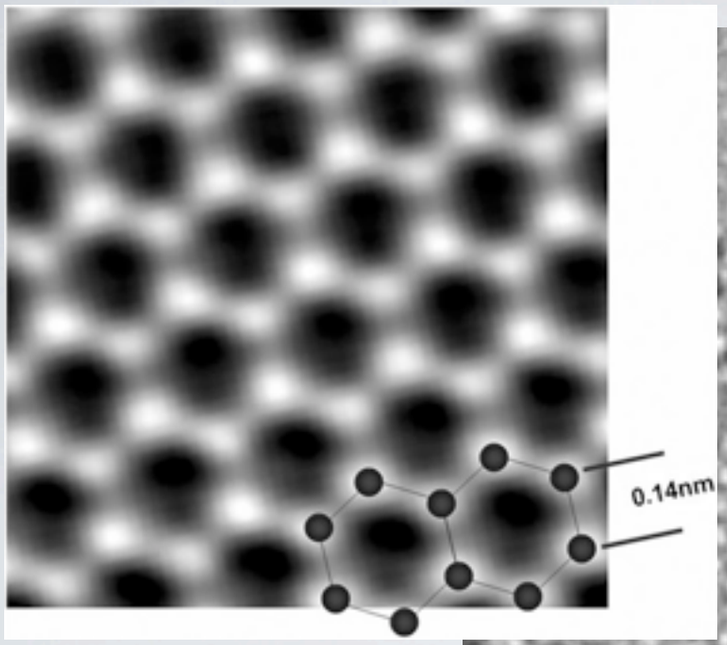
Aggregation process not possible !

UV photons control C_{60} formation and PAH destruction and evolution ?

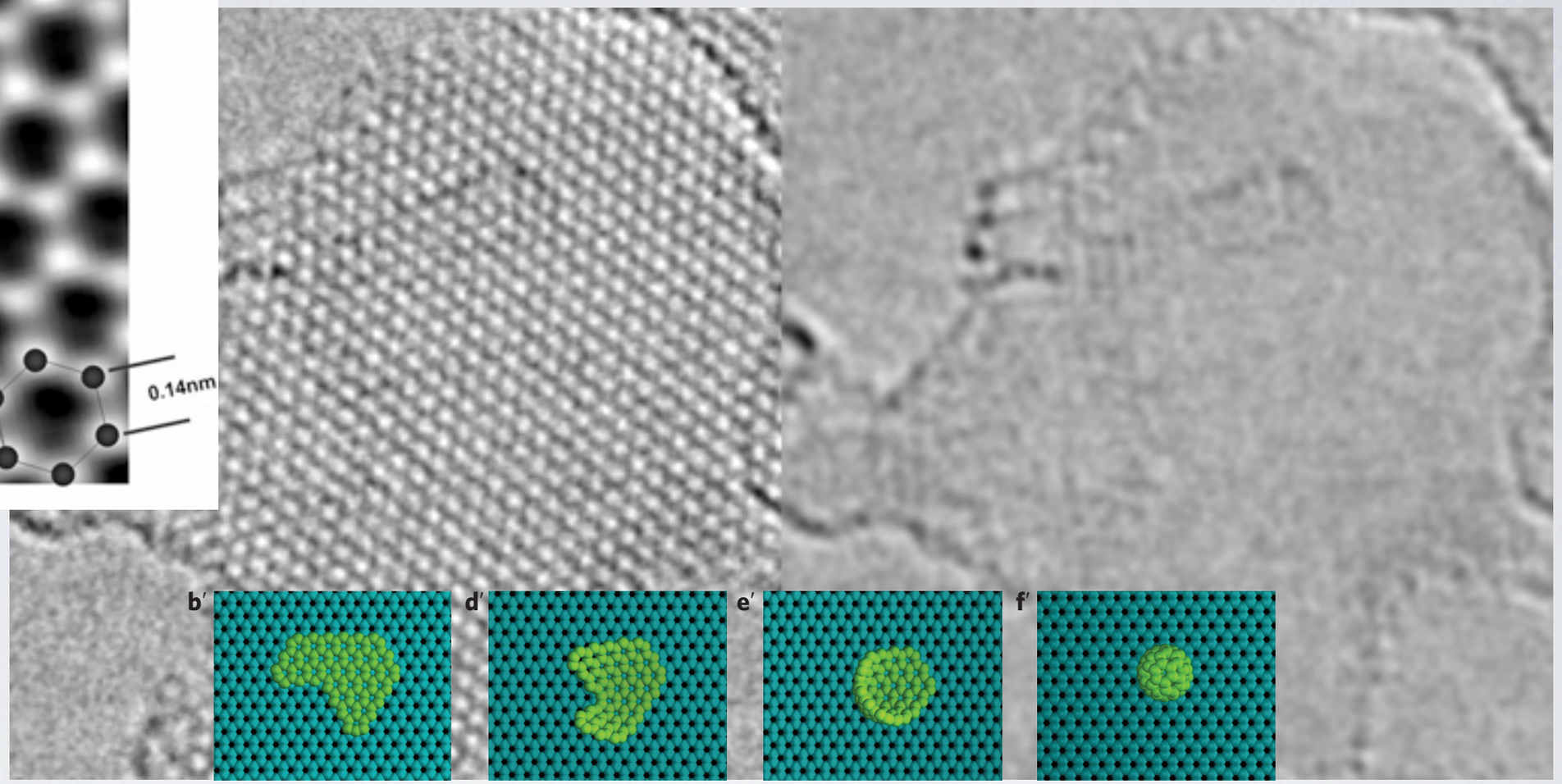
[Berné & Tielens **PNAS** 2012]

The roll up route

[National Center for electron microscopy]



[Chuvilin et al. Nature Chem. 2010]



- Graphene is a sheet of C atoms in hexagonal network, Graphene is an infinite PAH with no H
- Direct transformation of a graphene flake into C_{60} observed under electron irradiation

Proposed formation route in the ISM

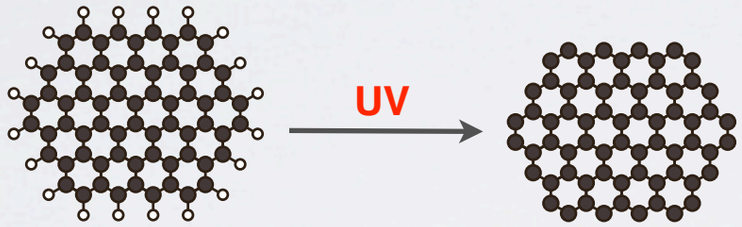
[Berné & Tielens **PNAS** 2012]

- UV induced **dehydrogenation**

- UV induced **removal of single atoms** at the edge of the flake make **pentagons** in the hexagonal network which curls the molecule till zipping of open edges

- DFT calculations show that only C loss requires energy, pentagon migration & **roll up is barrier-less**

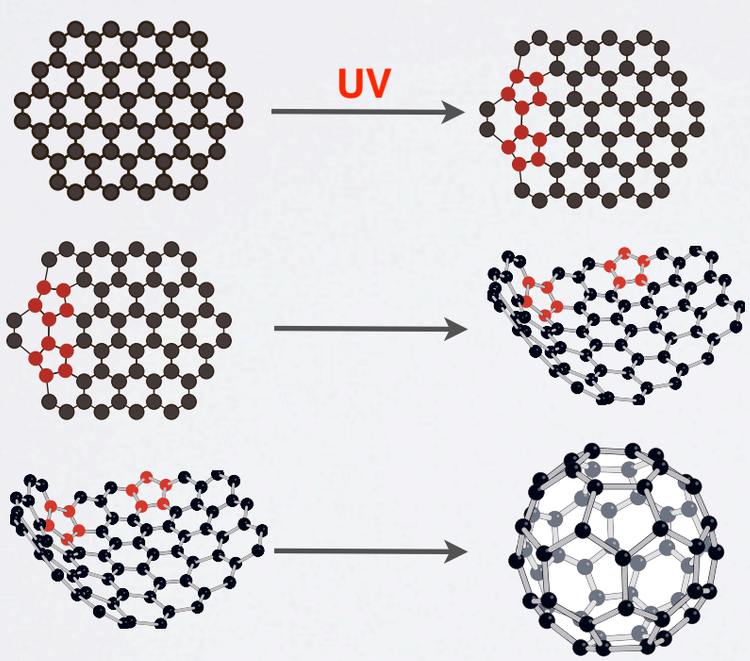
A) Dehydrogenation



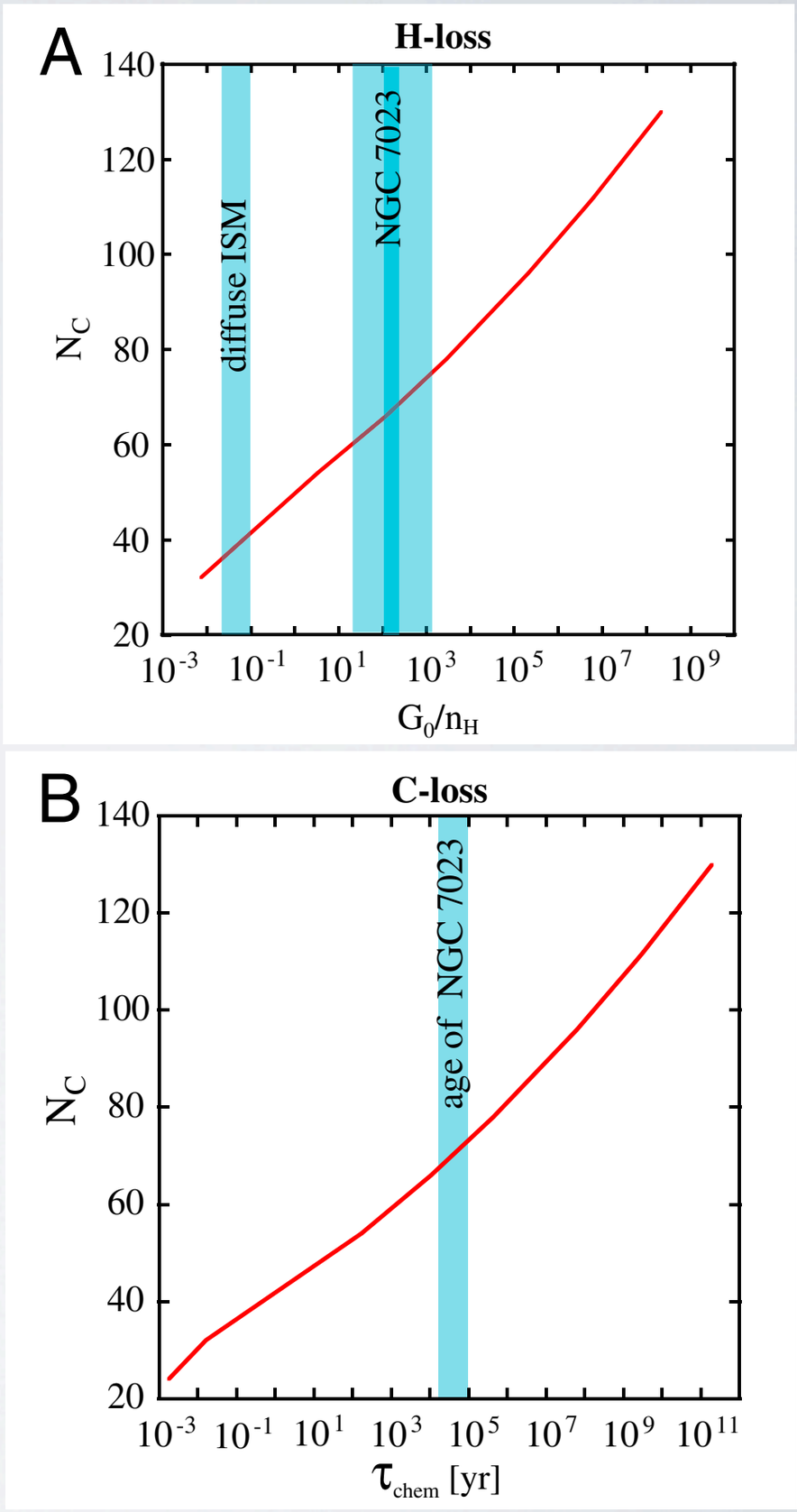
B) C loss and Pentagon formation

C) Curling

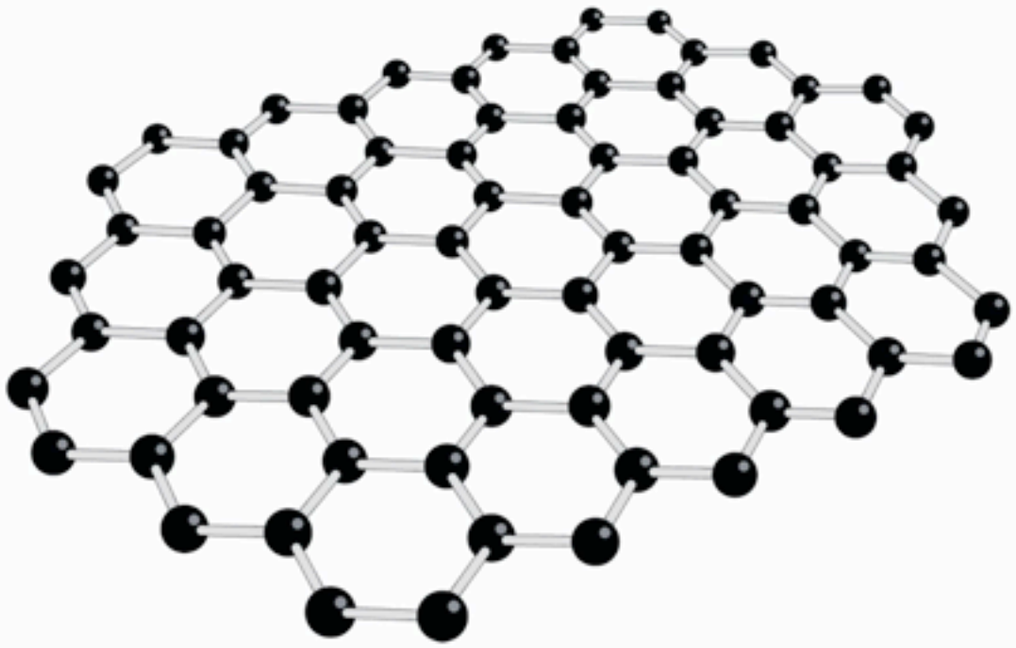
D) Zipping



- Evaluation with photochemical model based on Le Page et al. 2003 and lab data, for UV photons of 10 eV



Proposed formation route in the ISM



C atoms in a hexagon only
C atoms in a pentagon

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