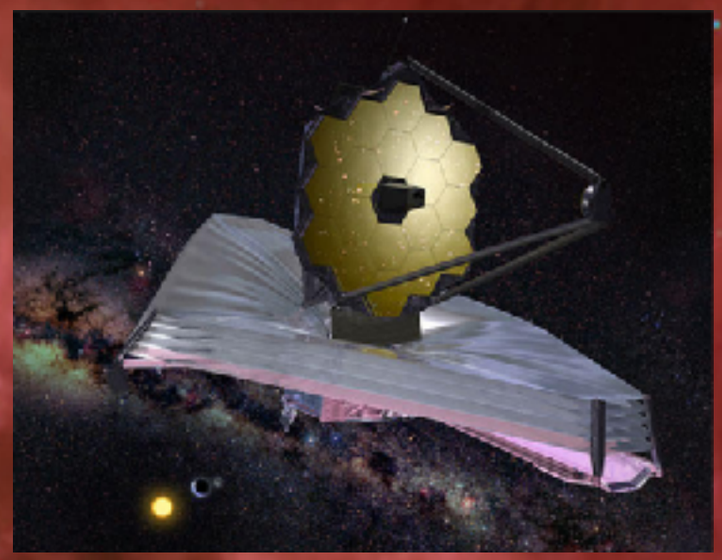
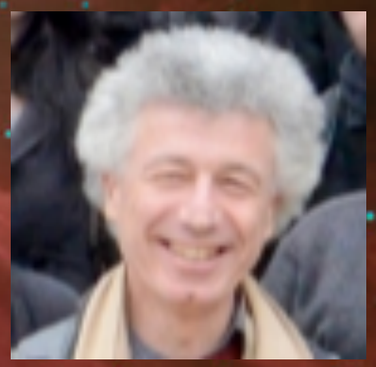
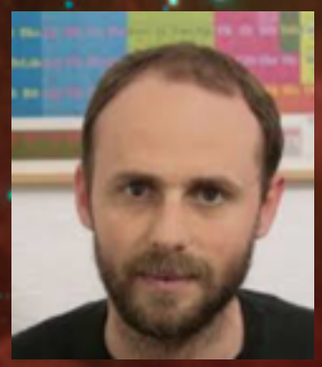
Photodissociation fronts in star-forming regions as revealed by high angular resolution observations



E. Habart

A. Abergel and O. Berné





Institut d'Astrophysique Spatiale (IAS), CNRS, Université Paris-Sud, France
Institut de Recherche en Astrophysique et en Planétologie (IRAP), CNRS, Université de Toulouse, France

Outline

1) Observational context for galactic PDRs

Spitzer, Herschel, ALMA, JWST

2) Highly structured medium and importance of the dynamics

challenge the traditional view of PDRs

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UV heating & photo-evaporation

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that are strongly contrasted

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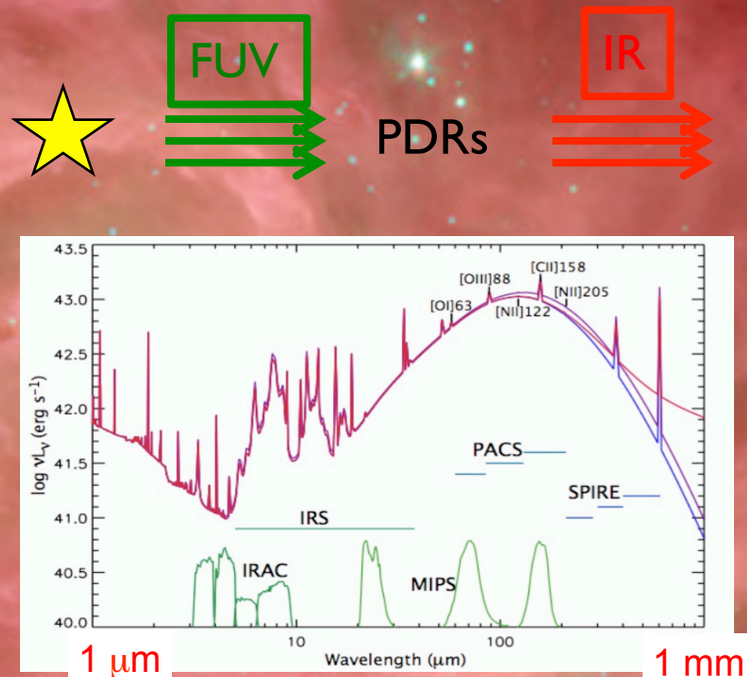
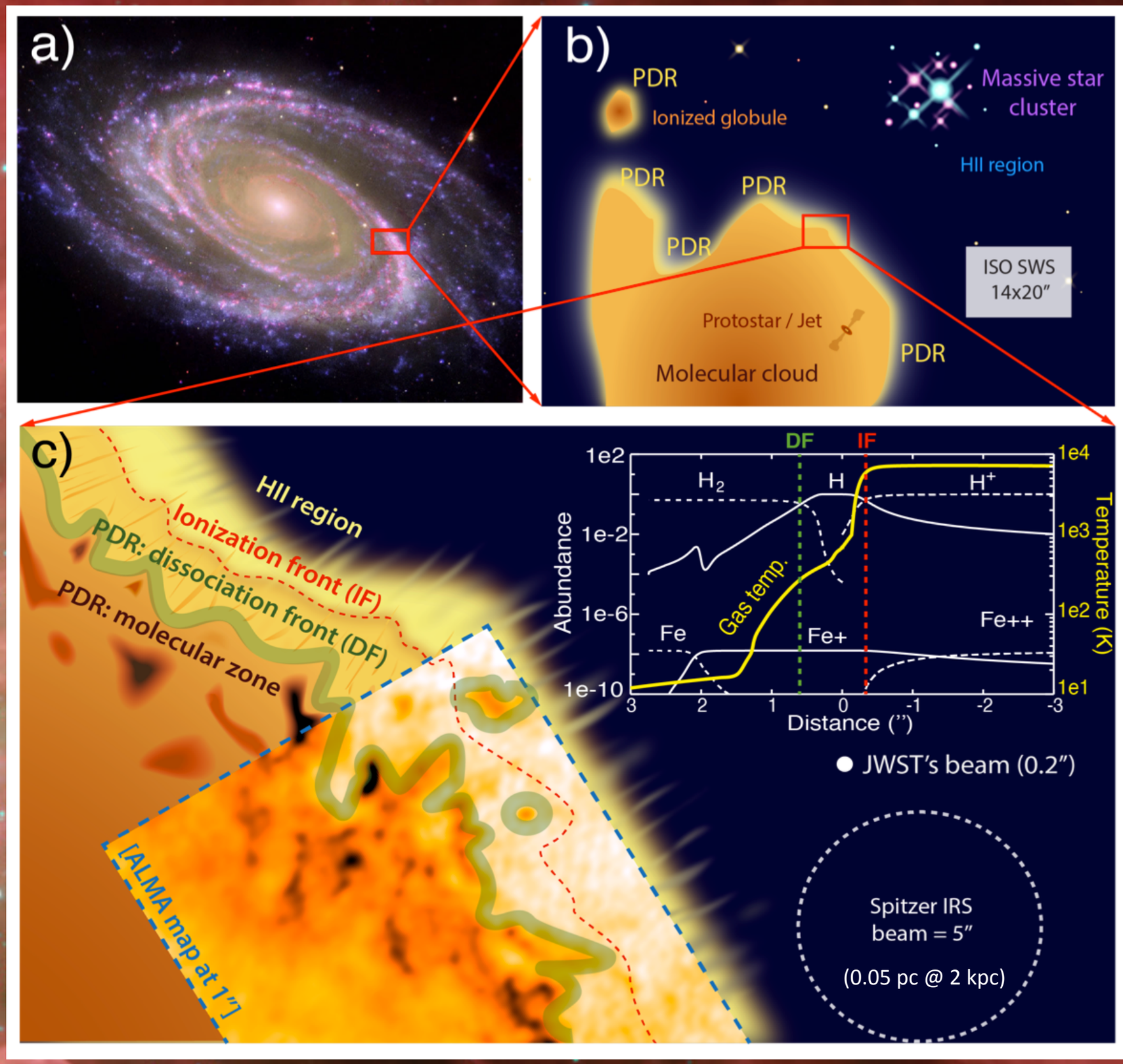
Photo-Dissociation Regions or PDRs

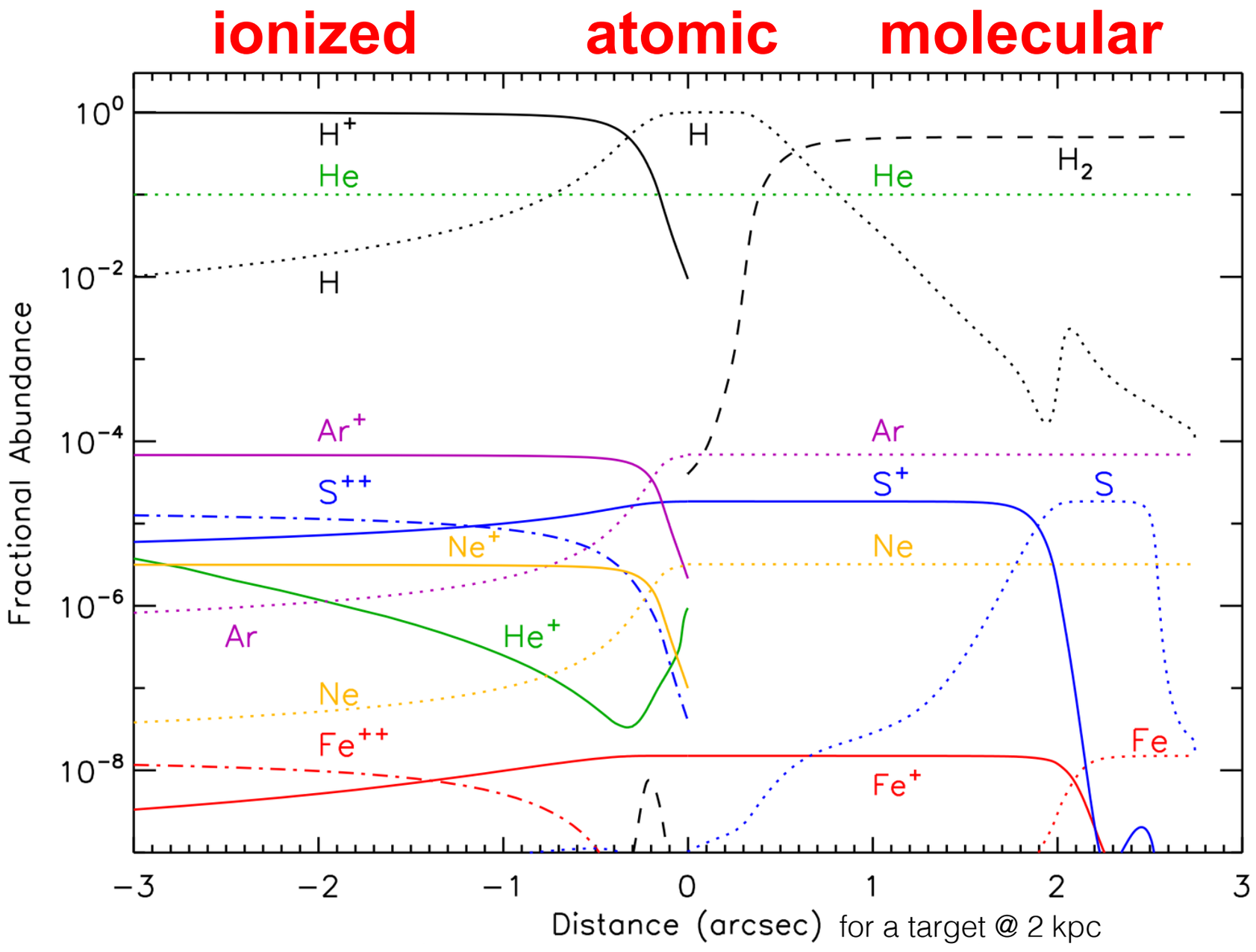


- **FUV photon penetration scale length ~ a few arcsec**
- **Highly structured at small scales**



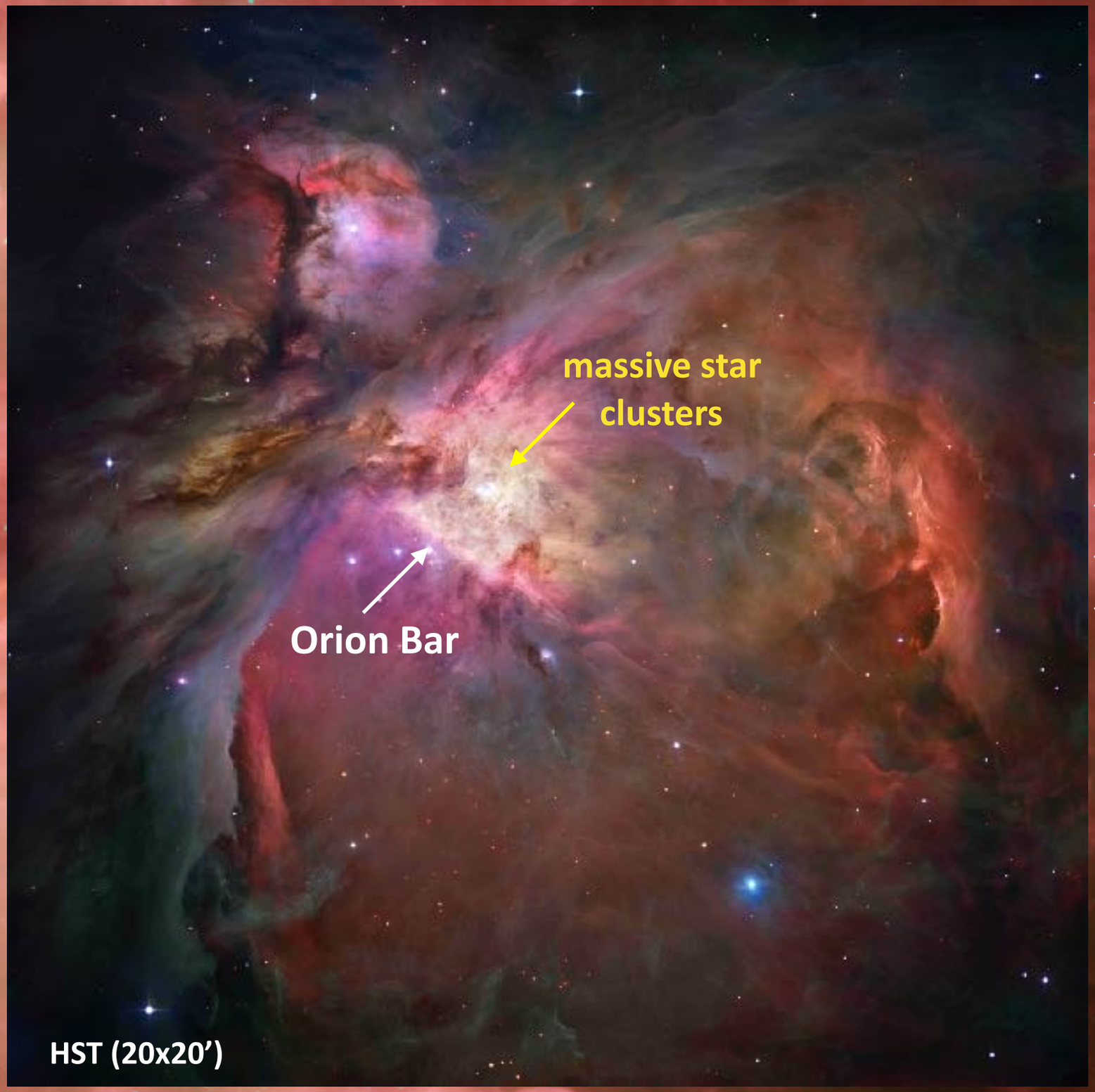
Critical physical frontiers

EUV
FUV



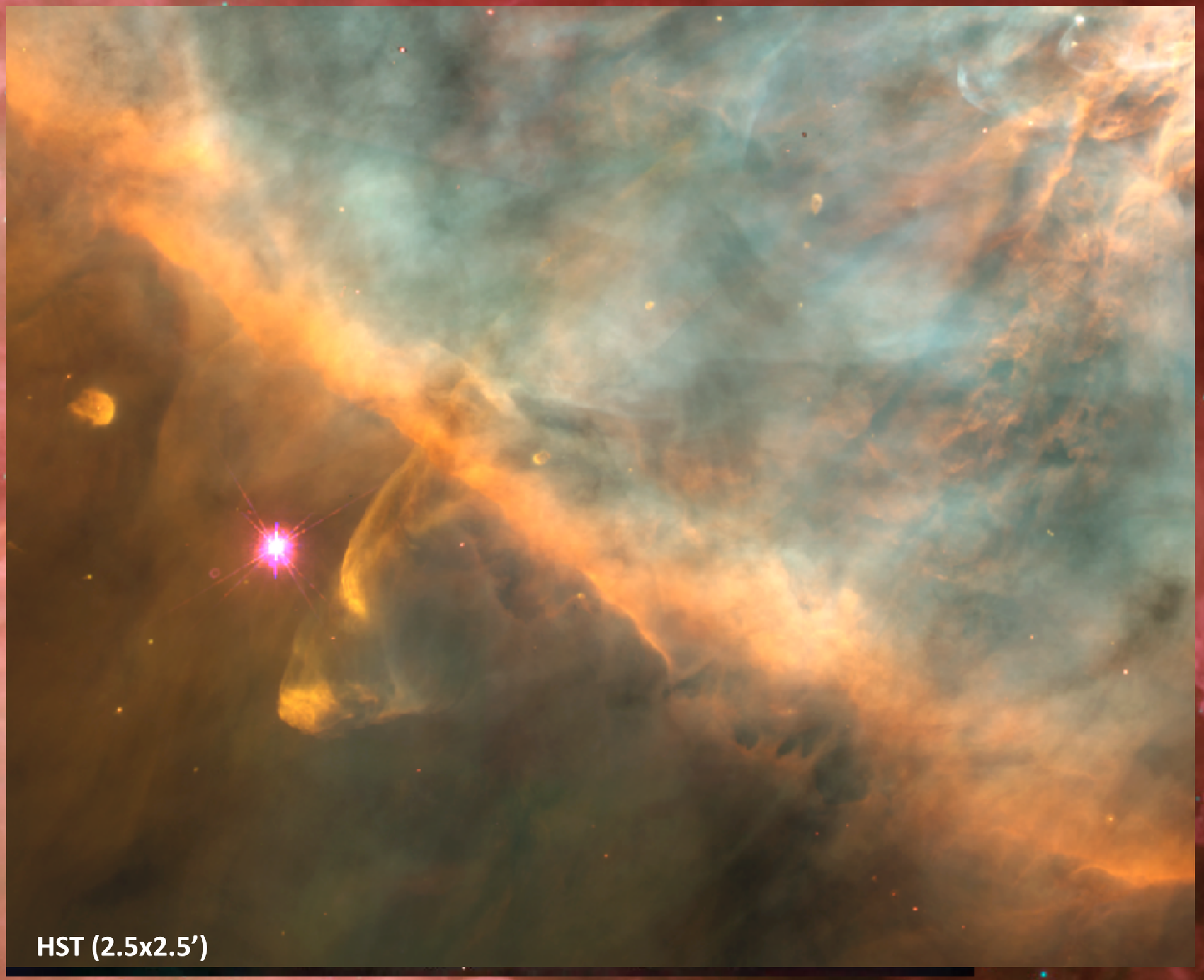
Occur on a few arcsec

Target: Orion Bar



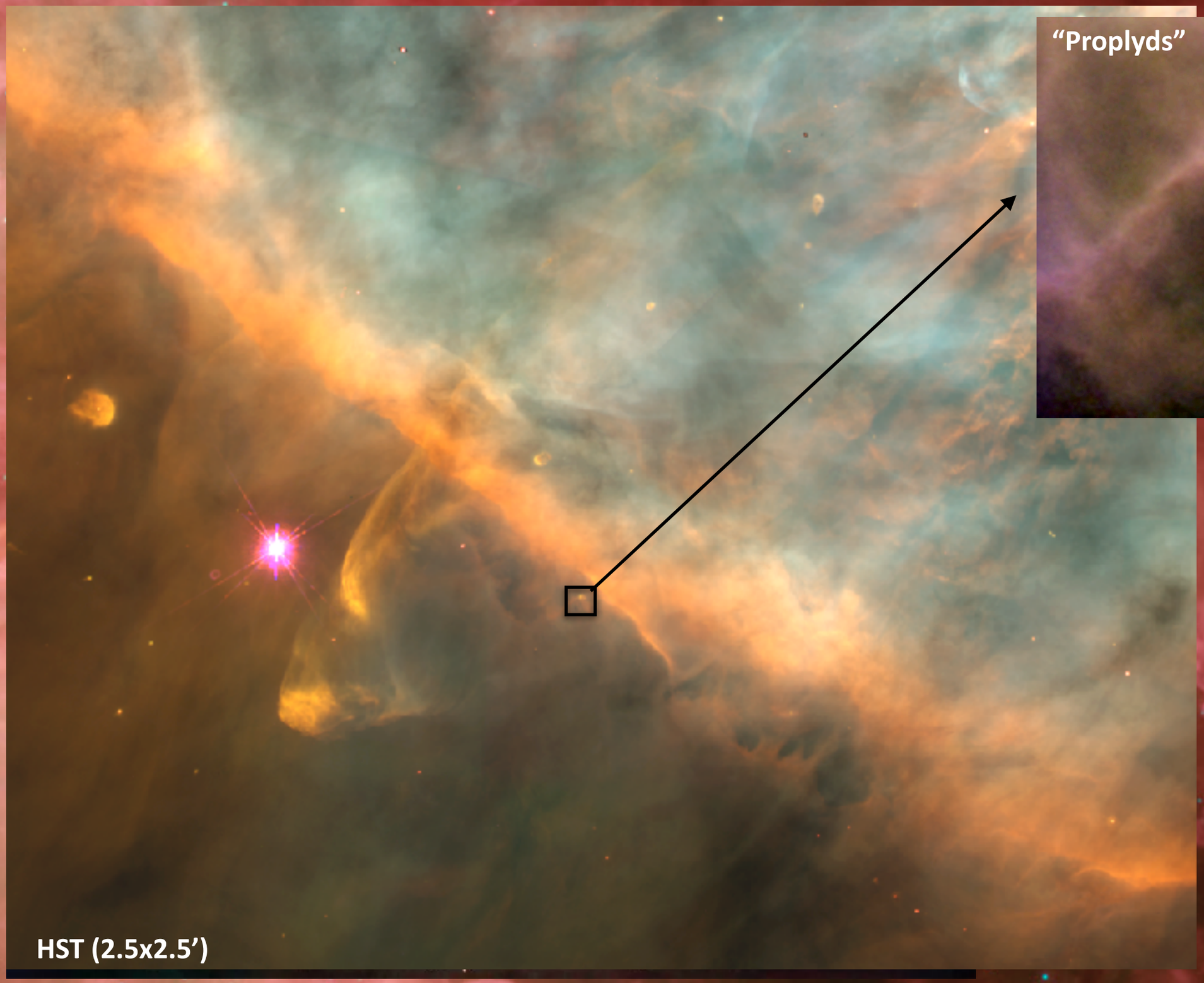
- Archetypical PDR
- Nearby (414 pc)
- G_0=20,000
- Well studied
- Observed with Spitzer, Herschel, ALMA and in the futur with JWST

Target: Orion Bar

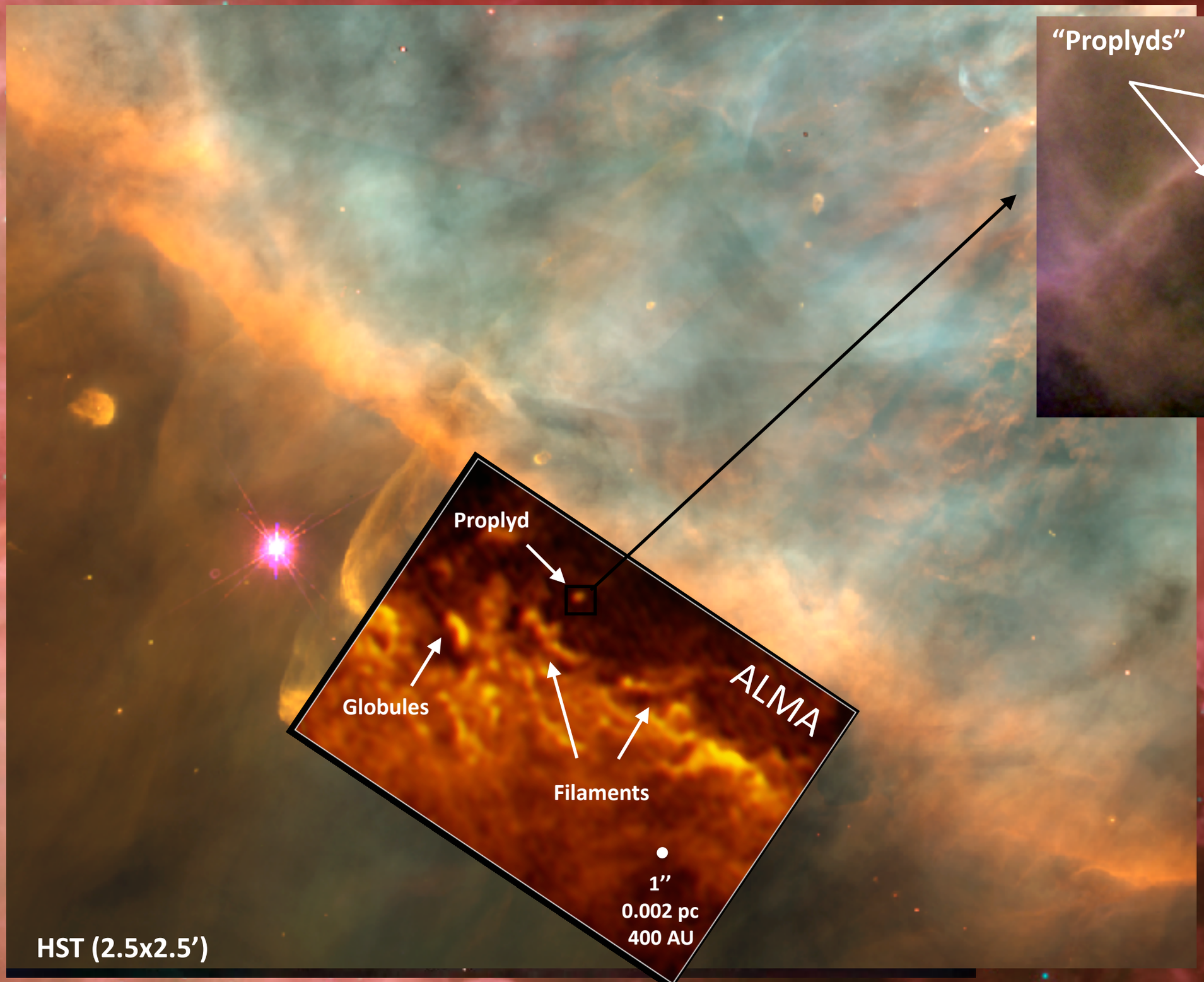


HST (2.5x2.5’)

Target: Orion Bar



Target: Orion Bar

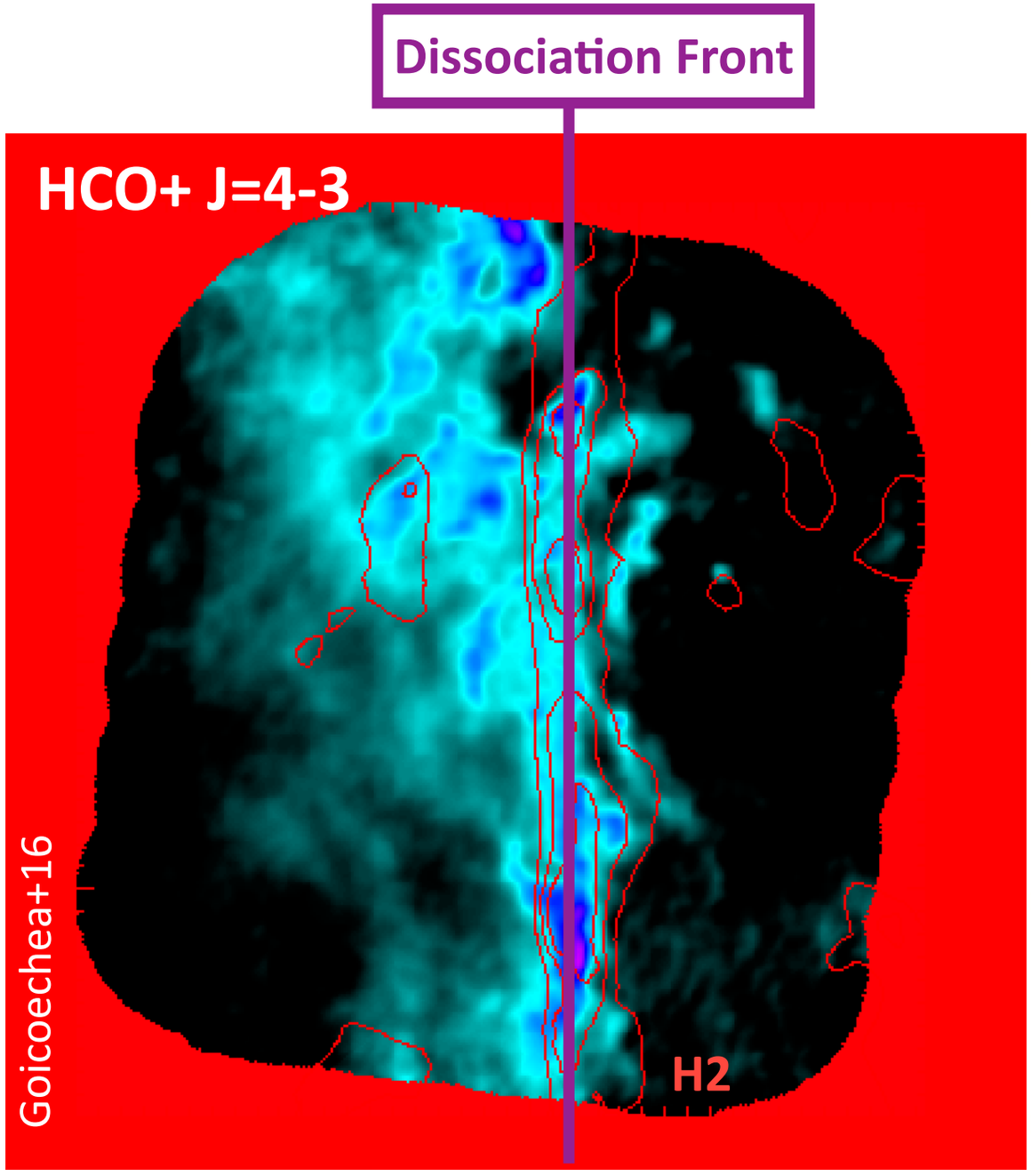


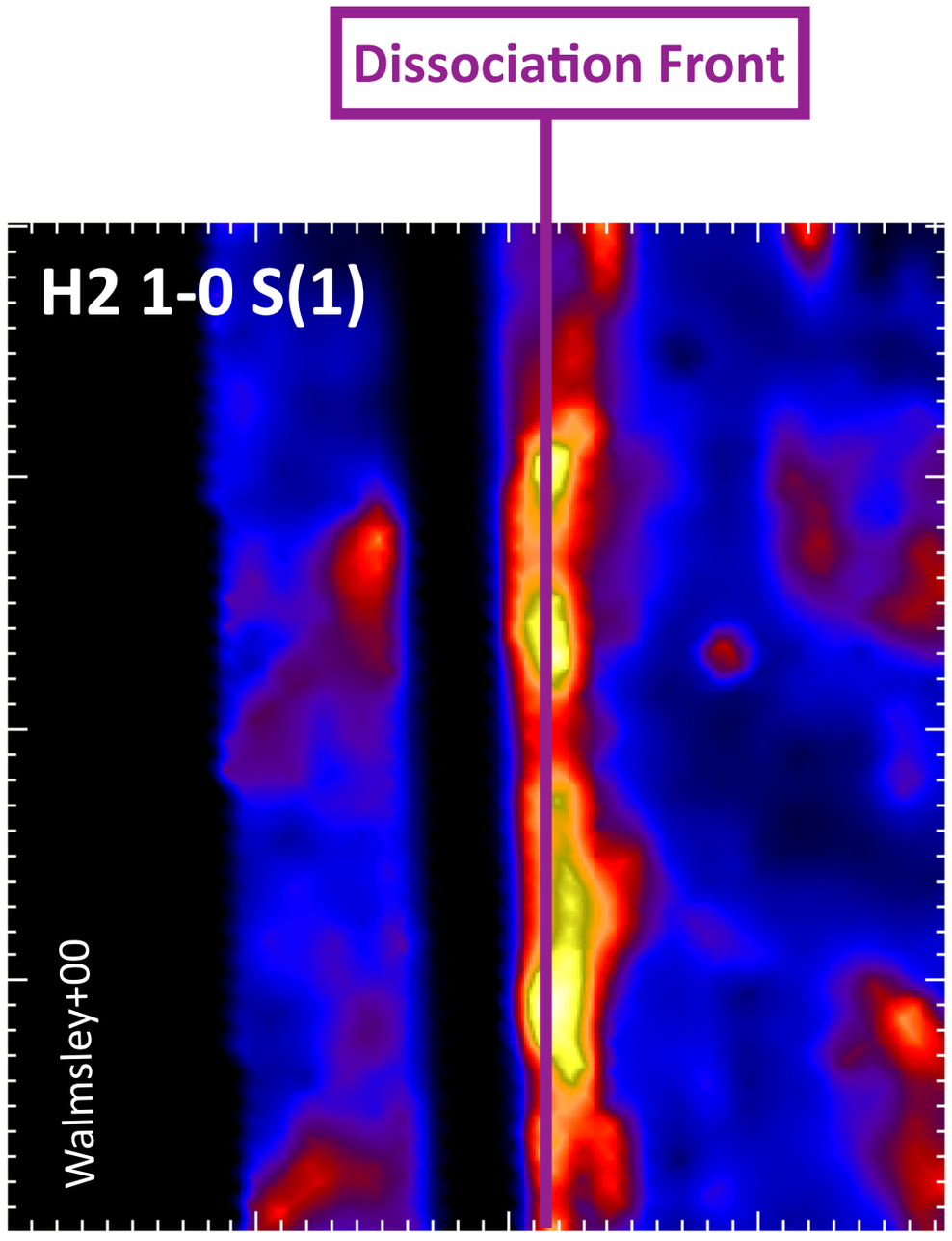
Highly structured medium

A fragmented ridge of high-density, with filamentary substructures (some akin to globules, size<0.002 pc)

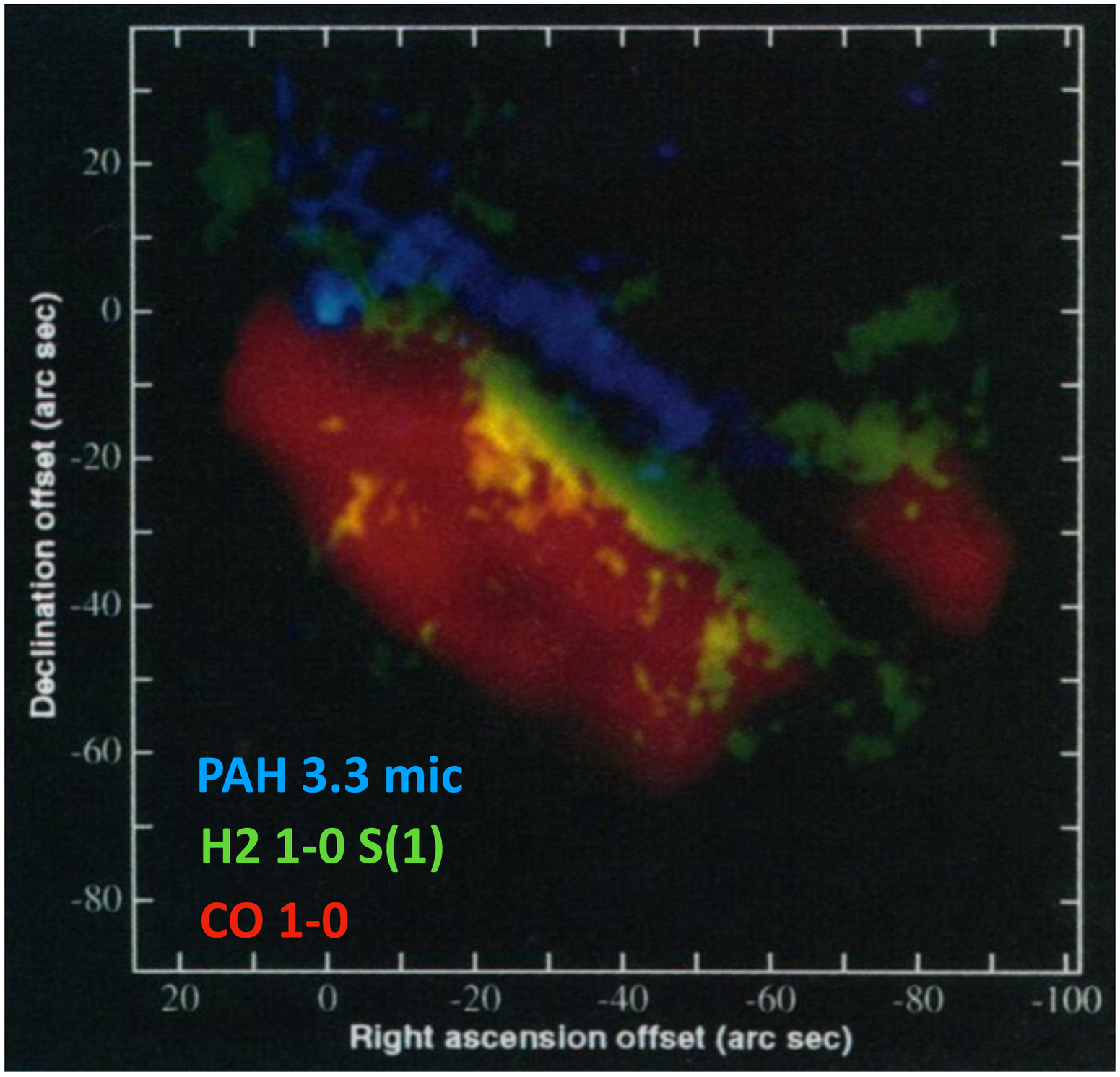
Goicoechea+16

Rotated images: HCO+ and H2





- Main substructures observed with ALMA observed in the H2 vibrational emission
- No appreciable offset between the edge of the observed CO J=3-2 and HCO^+ J=4-3 lines and the H2 vibrational
- C^+/C/CO transition may occur very near the H/H2 transition (not expected by model)



Orion Bar PDRs mostly homogeneous with nH ~1e5 cm-3

Tielens 1993

Steeply interface between the molecular clouds and the ionized gas

Goicoechea+16

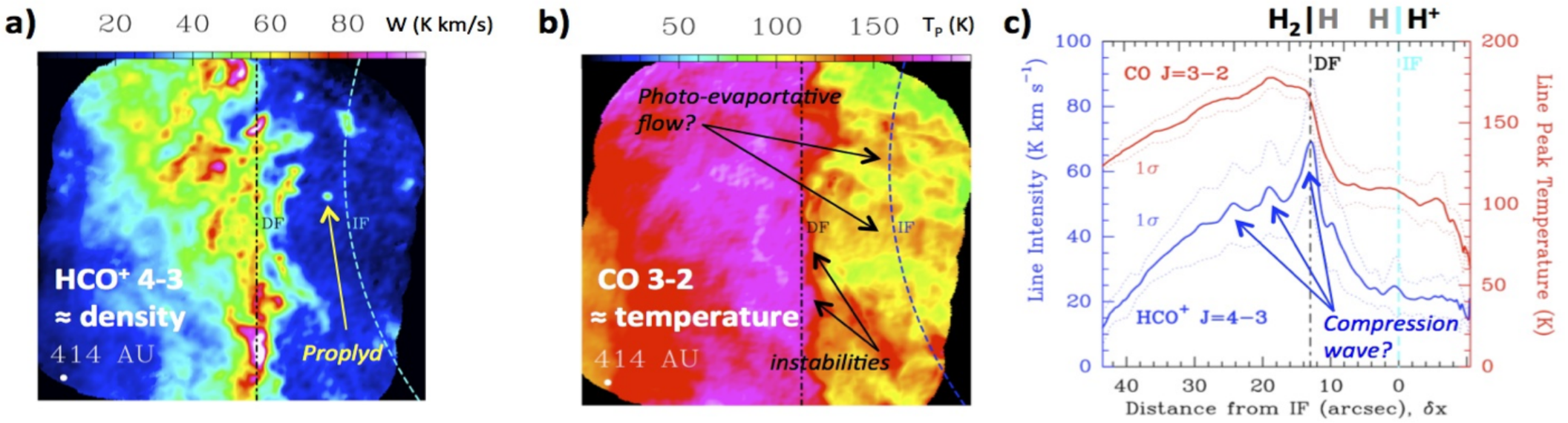


Figure 3. ALMA view of a small field of the Orion Bar in two tracers of the molecular gas: a) HCO^+ J=4-3 and b) CO J=3-2. c) Vertically averaged intensity cuts perpendicular to the Orion Bar. The flux of FUV photons decreases from right to left in these rotated images.

- Dynamic effects: compression waves ?
- Photo-evaporative gas flows and instabilities at the molecular cloud surface ?

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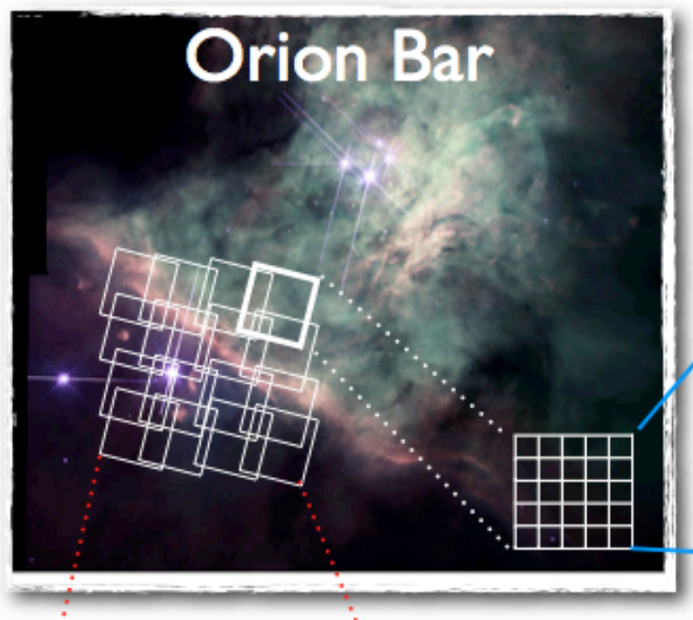
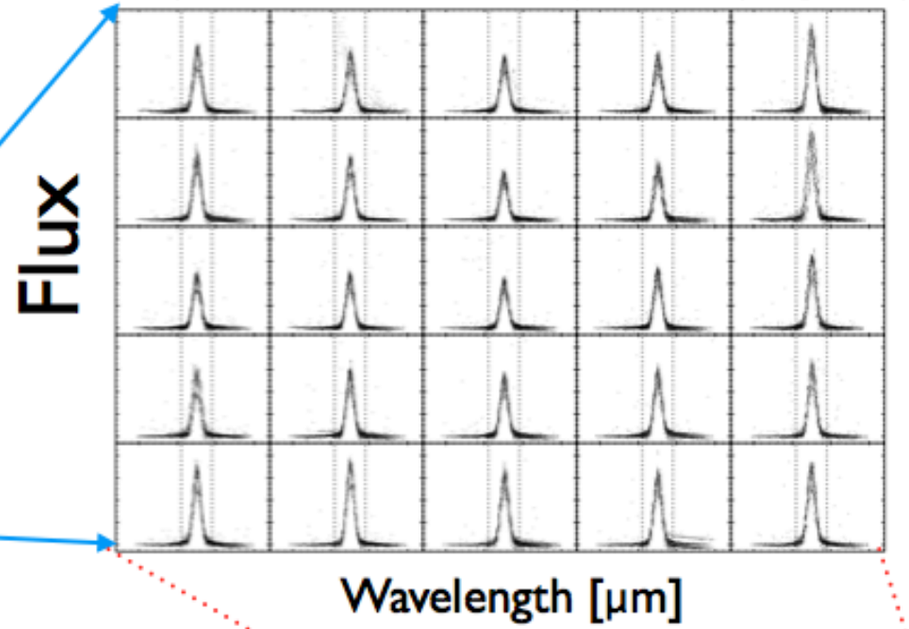
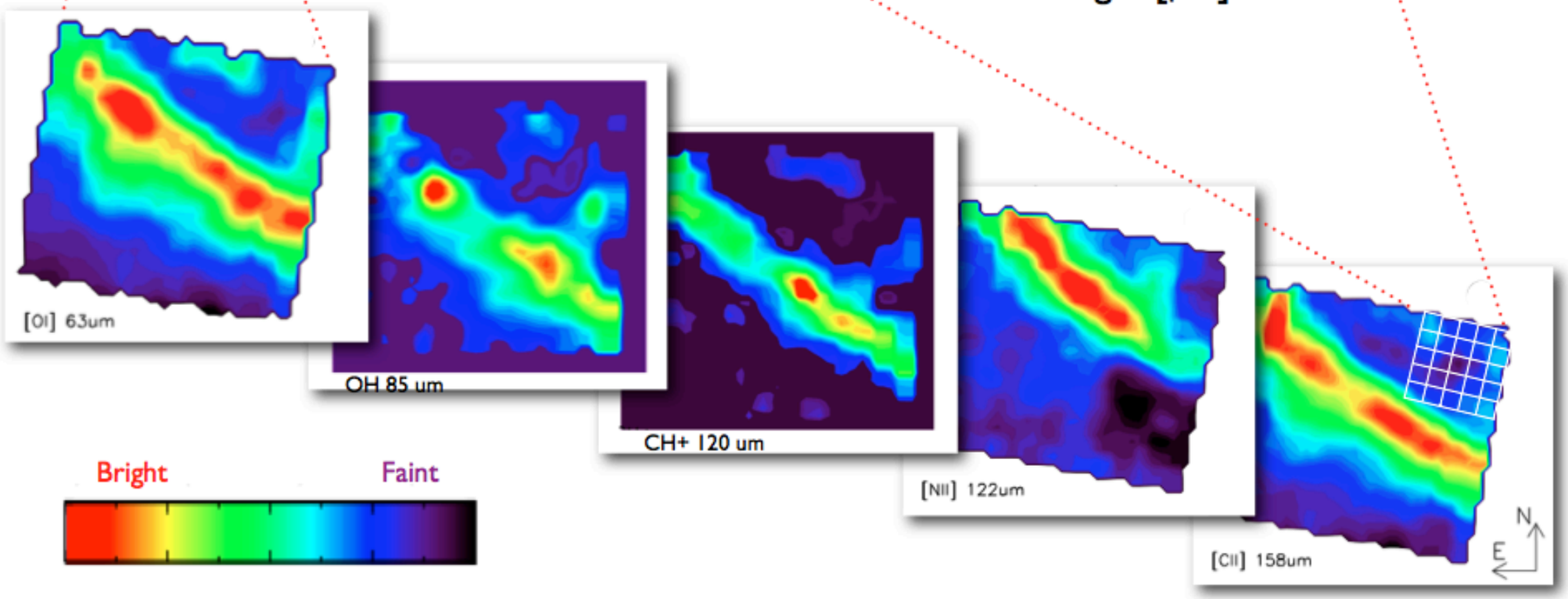
Herschel spectral mapping

Fully-sampled maps
Total area : 100''x100''
Spatial resolution : 6''-10'' (0.01-0.02 pc @ 400 pc)







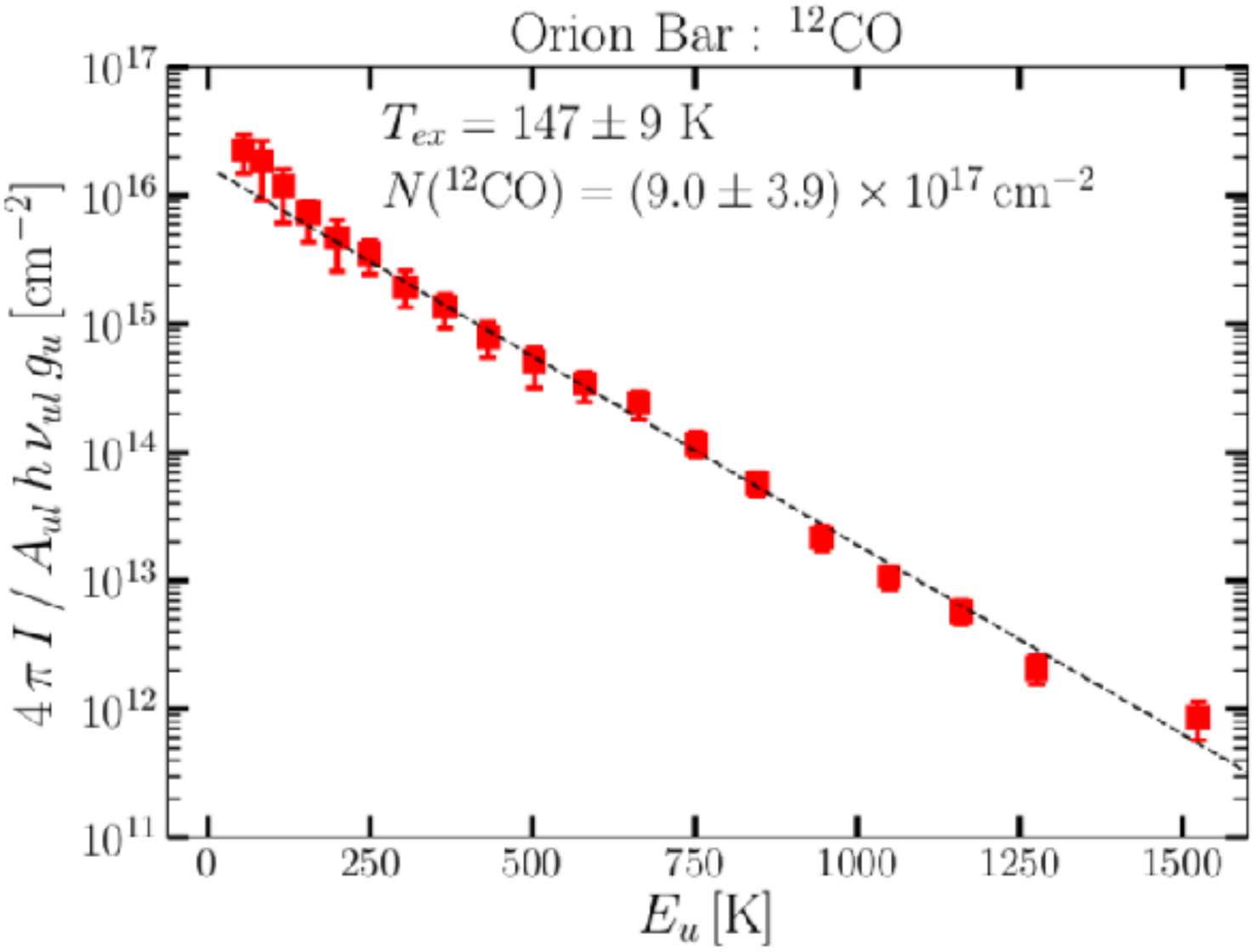
Bernard-Salas et al. 2012, 2015
Parikka et al. 2017, 2018

Resolve the gas cooling lines in the Bar
Each species shows a specific morphology very dependent on the local conditions and processes
Opportunity to study the link between the energetics and structure

CO energetics (1)

- Herschel opened the possibility to observe systematically the warm molecular gas in galactic and extragalactic sources by covering all CO excitation lines from Jup = 4 to Jup = 50

- Nevertheless, up to recently, it was unclear if, in star forming regions, the CO high-J excitation probes heating by UV photons or if additional energy sources are required

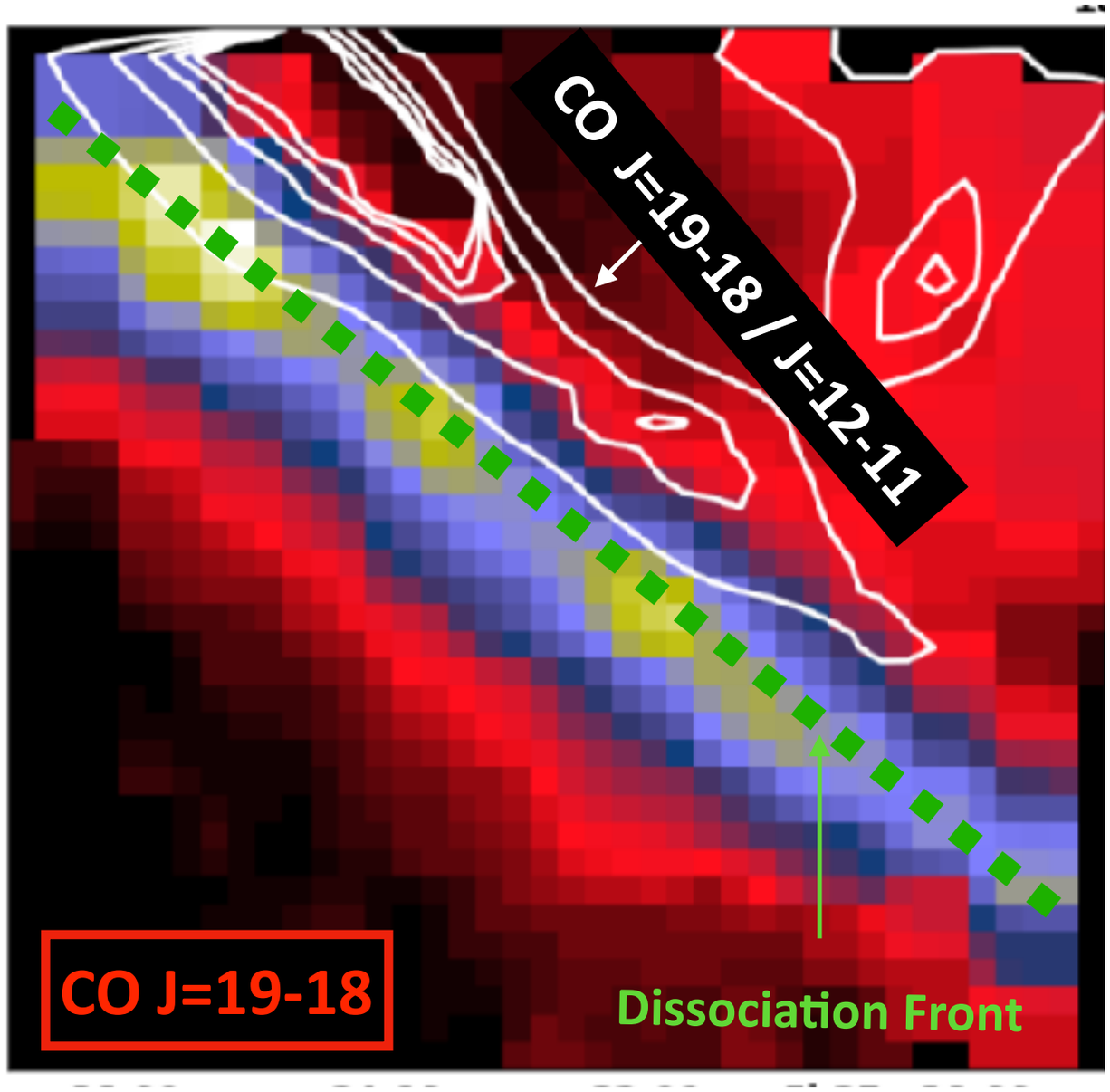


Joblin et al. 2018

CO energetics (2)

1st high spatial resolution images of the highly rotationally excited CO

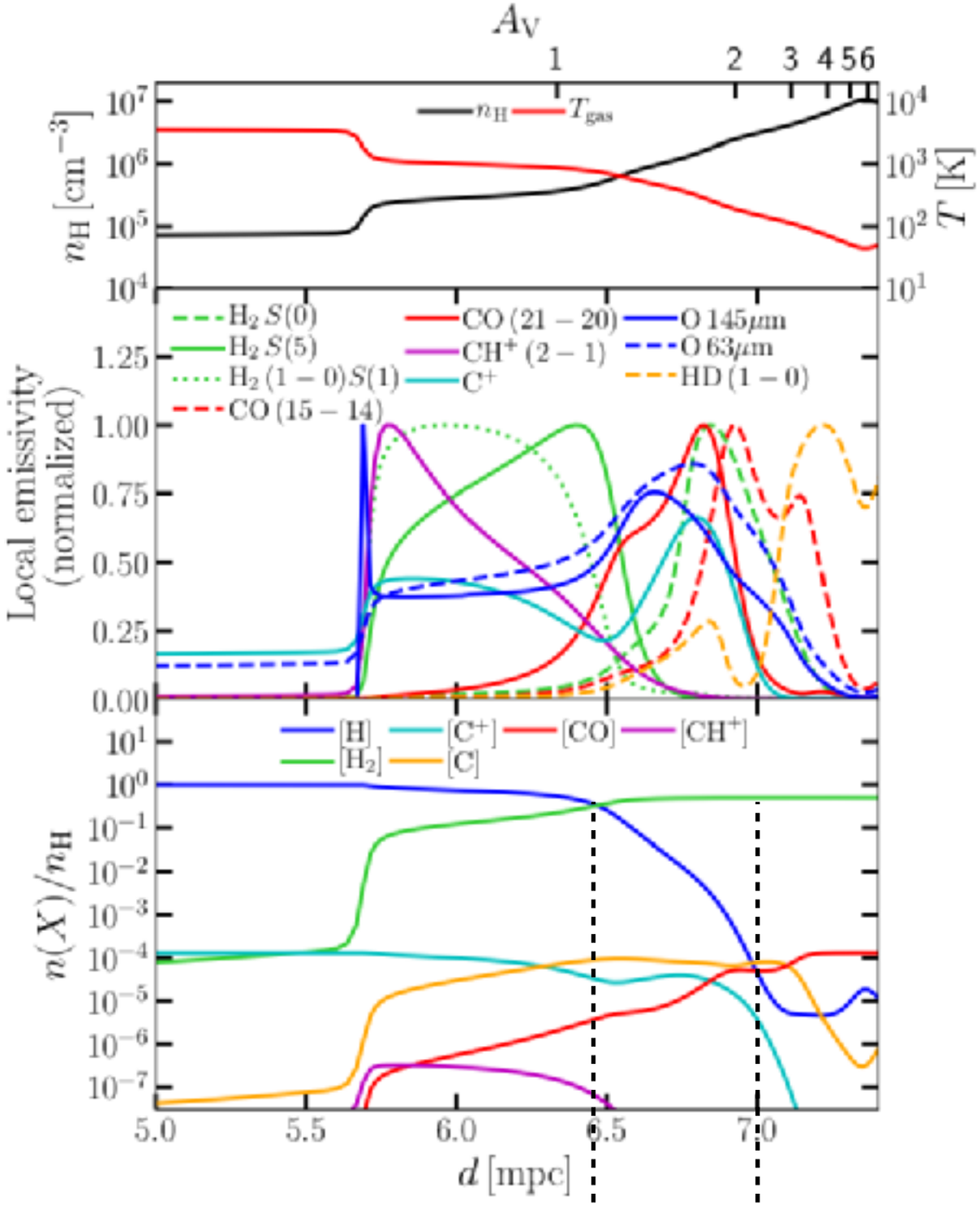
- High-J CO emission peaks very closed to the DF => can be explained by UV heating (via PE effect)
- CO J=19-18/J=12-11 peaks in front of the CO J=19-18 between the DF and IF
- A warm/hot molecular gas is present in the atomic region. In agreement with recent ALMA detections of photo-evaporative gas flows
- RADEX modeling for beam-averaged physical conditions :
  $P/k = nH \times T \sim 1\text{-}2\times10^{8}$ K cm^{-3}

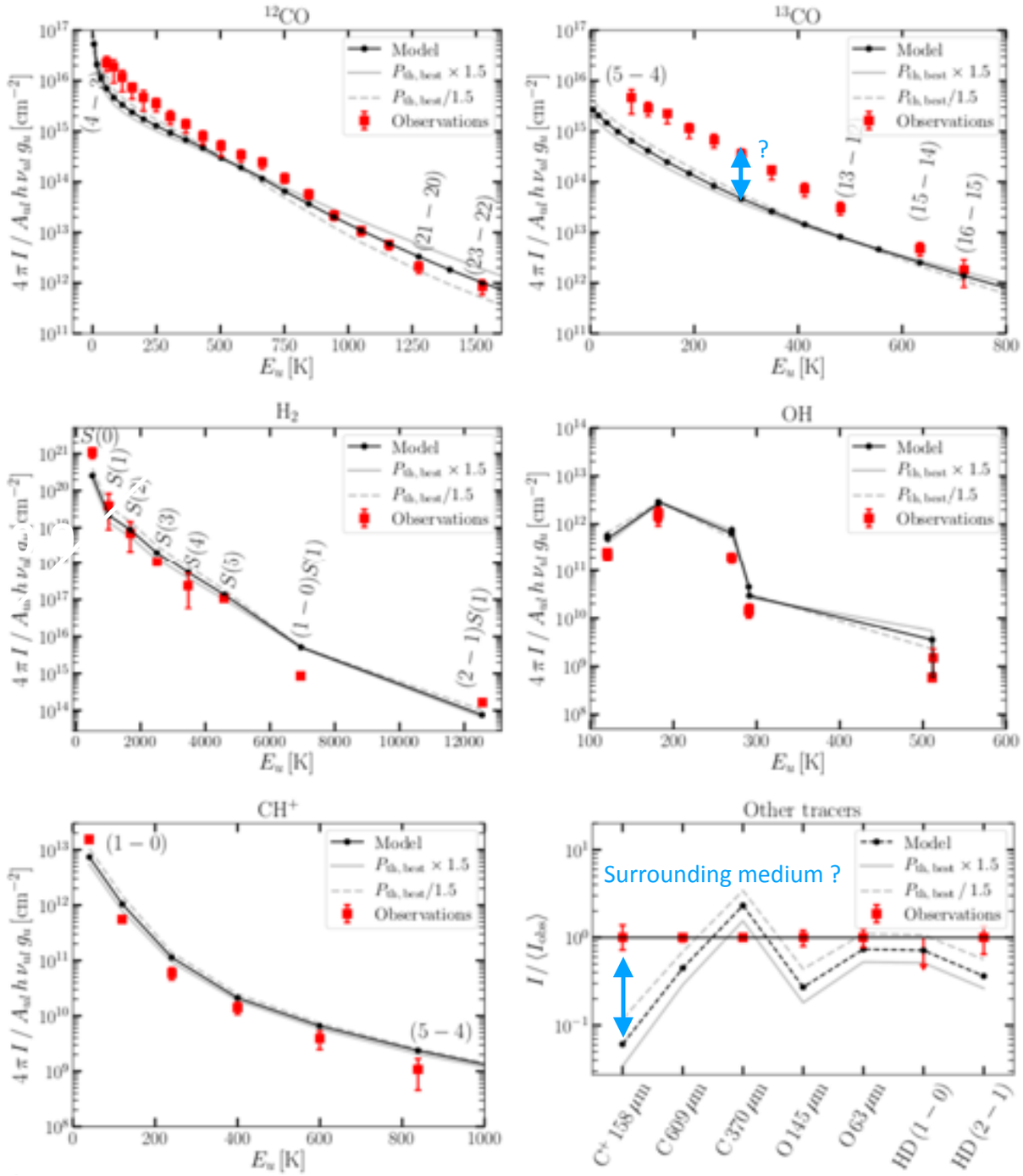


Parikka et al. 2018

PDR meudon model: high Pth

PDRs are characterised by a high pressure zone (few 10^8 K cm^{-3}) where a hot chemistry takes place

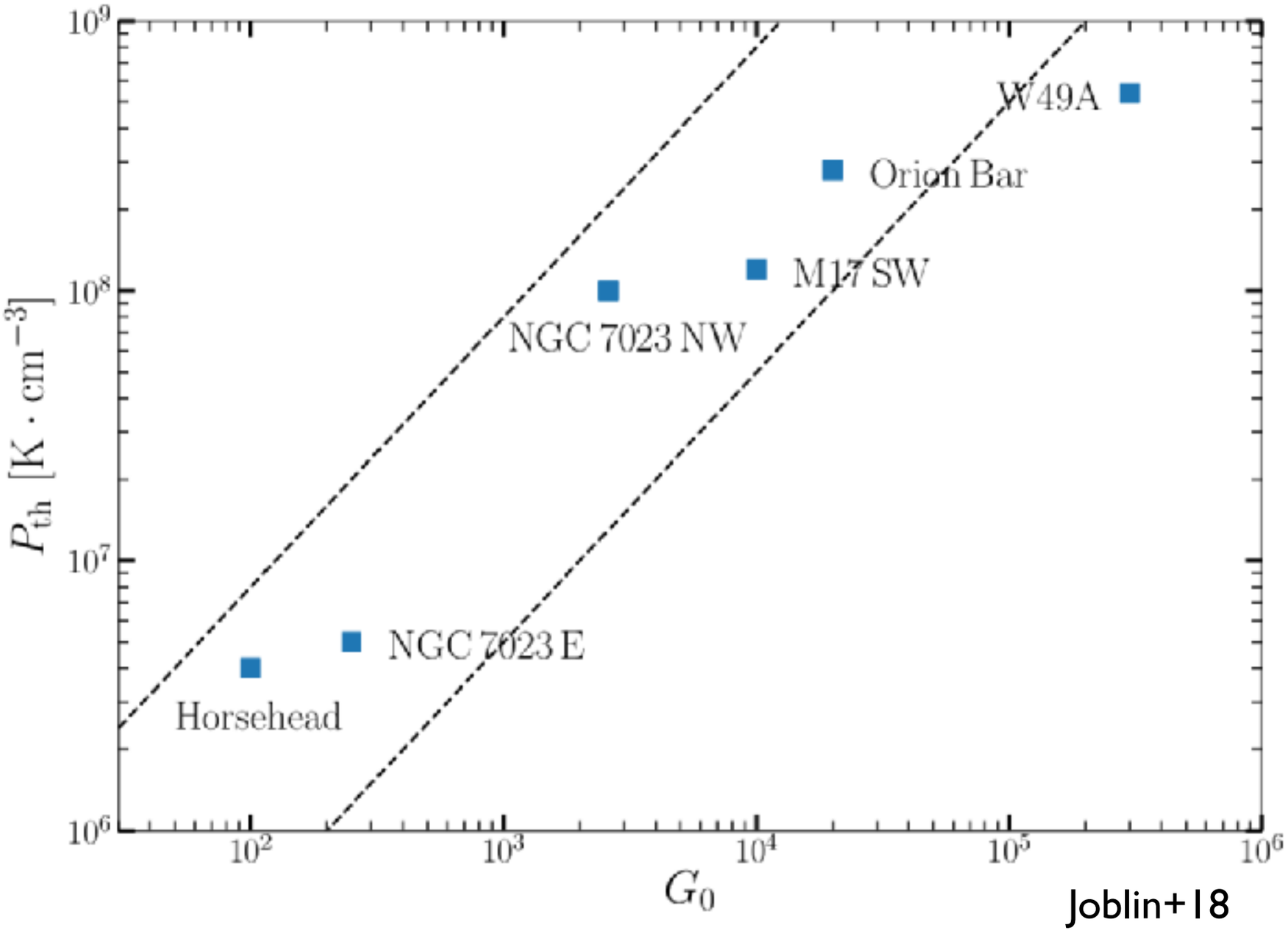




Joblin et al. 2018

Linear relation between Pth and the UV intensity

High pressure zone created by the photo-evaporation of the gas ?



Joblin+18

Observations (Habart+04, Perez-Beaupuits+10, Nagy+12, Koehler+14)

Hydrodynamical simulation of photoevaporating PDR (Bron+18)

- Photoevaporation @ IF and DF generates high P
- Pre-existing inhomogeneities might be present, but the observed density contrasts do not imply small-scale clumpiness

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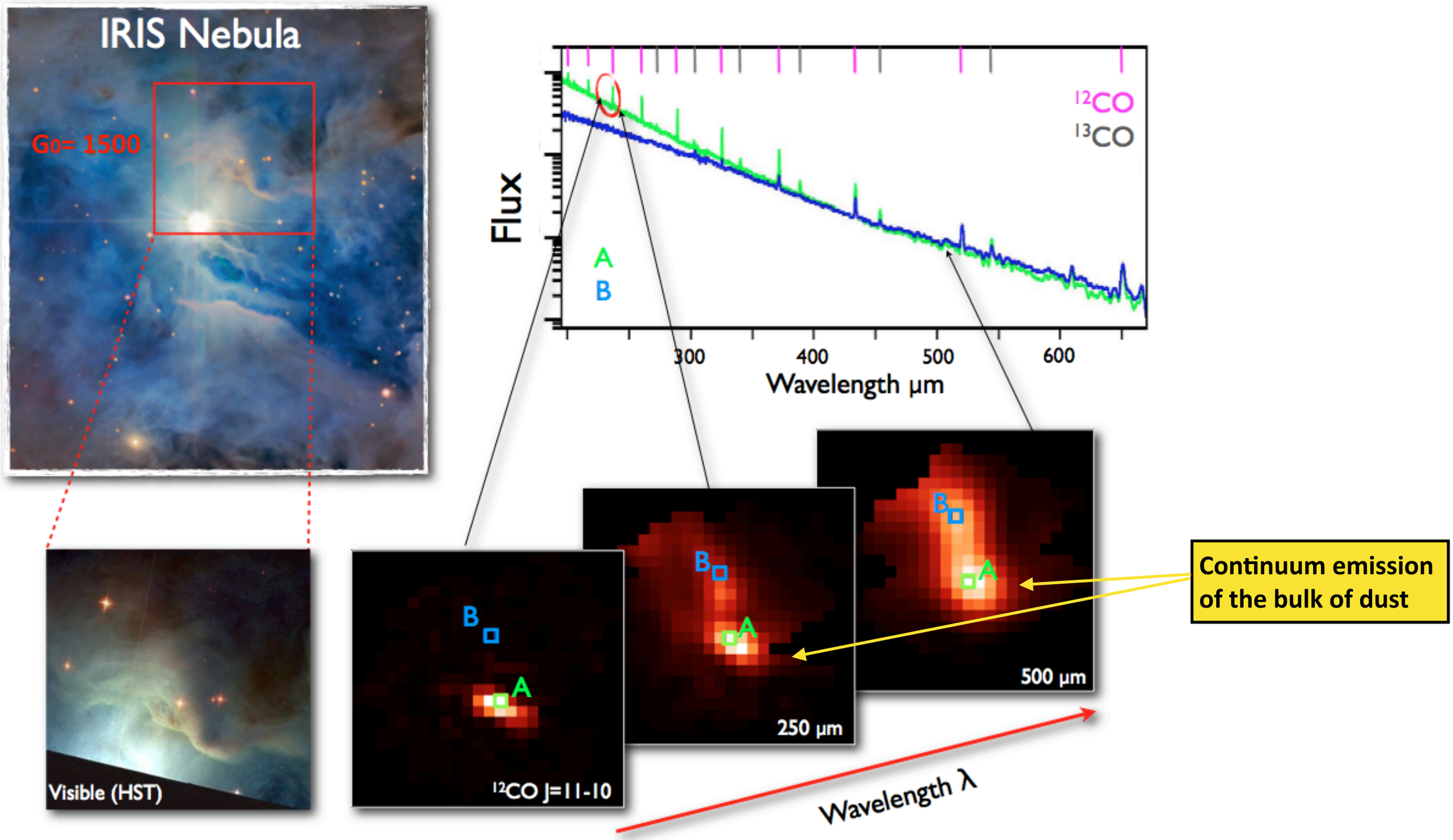
Combined analysis of dust and warm/cool gas in NGC 7023 NW

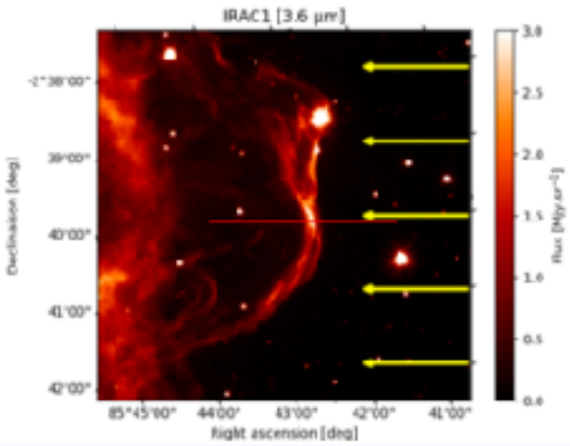
Köhler+2014



- Inhomogenity with irradiated dense structures producing the high-J
- Warm/Cool dust and gas in agreement in the local and column density of the irradiated dense structures

How evolve the dust with the local physical conditions

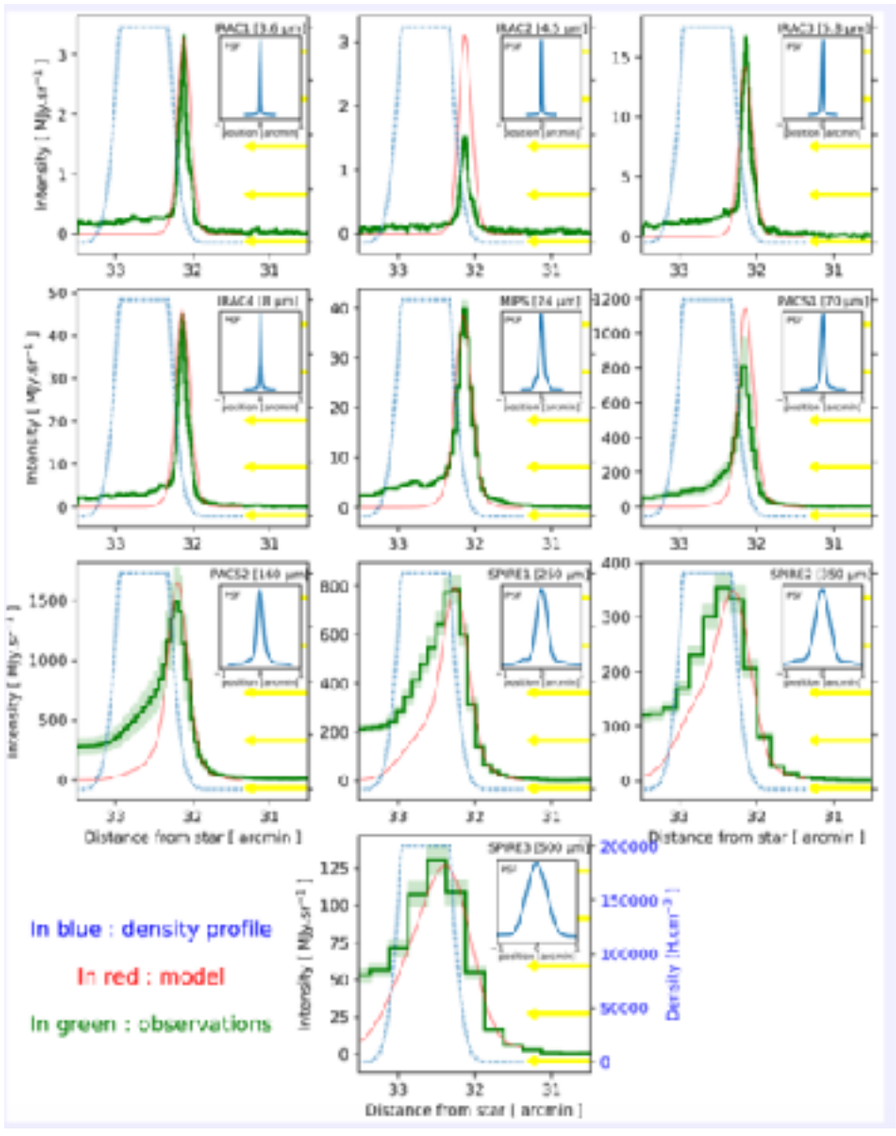
Schirmer in prep.

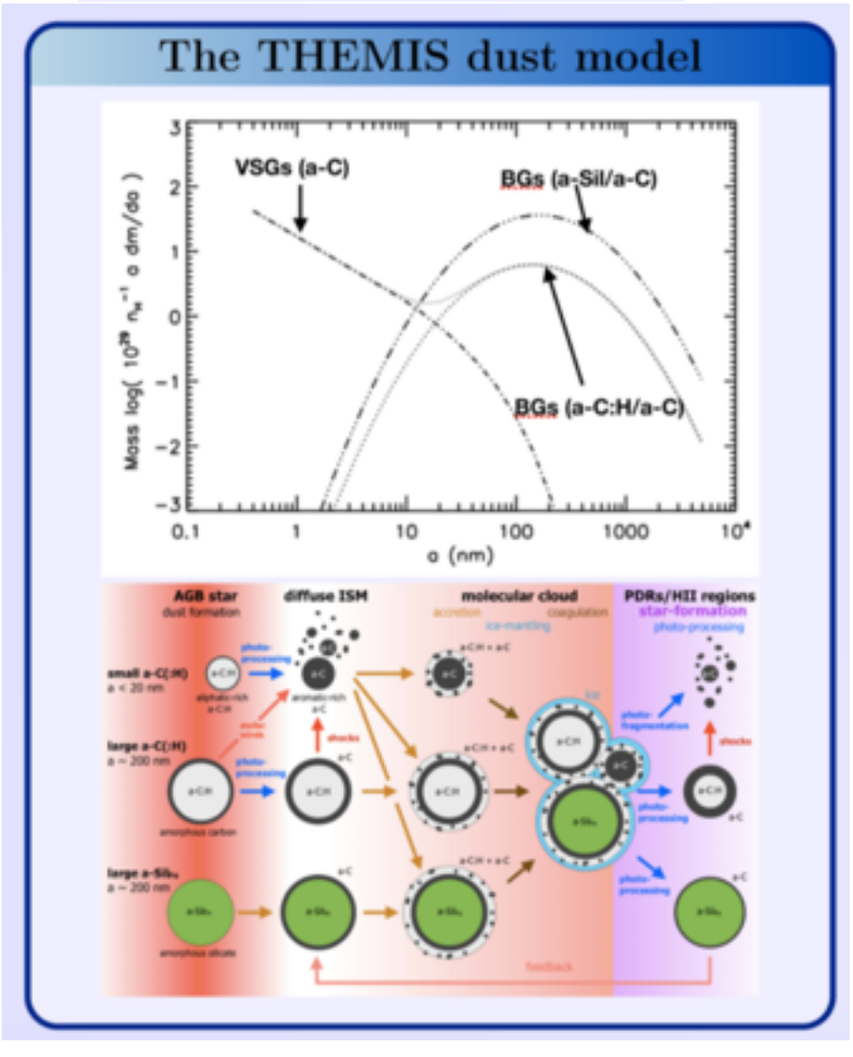


G_0= 100

density profile from PDR isobaric model

Best model with 3 times less very small grains in PDRs than in the diffuse ISM and an increase of the minimum size from 0.4 to 0.6 nm





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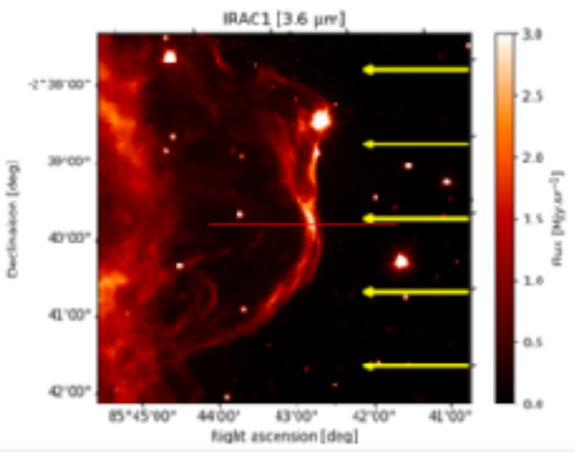

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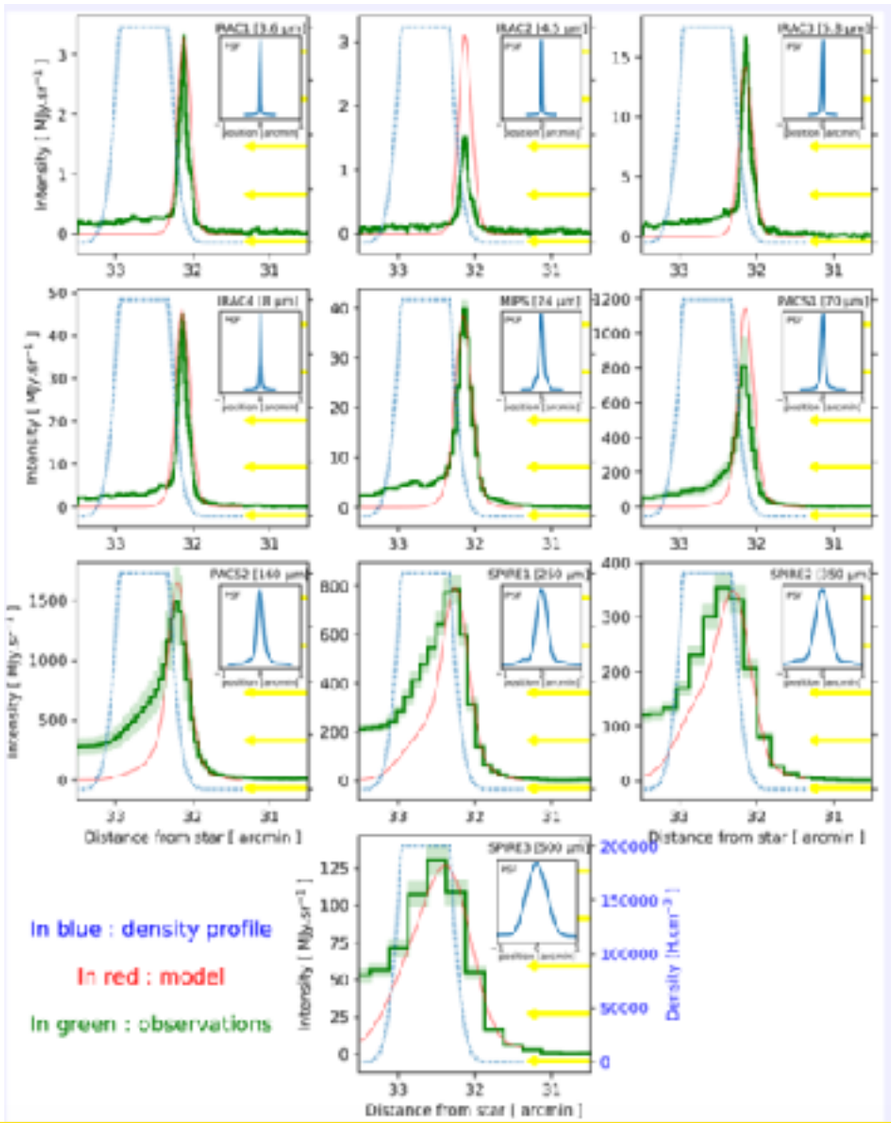

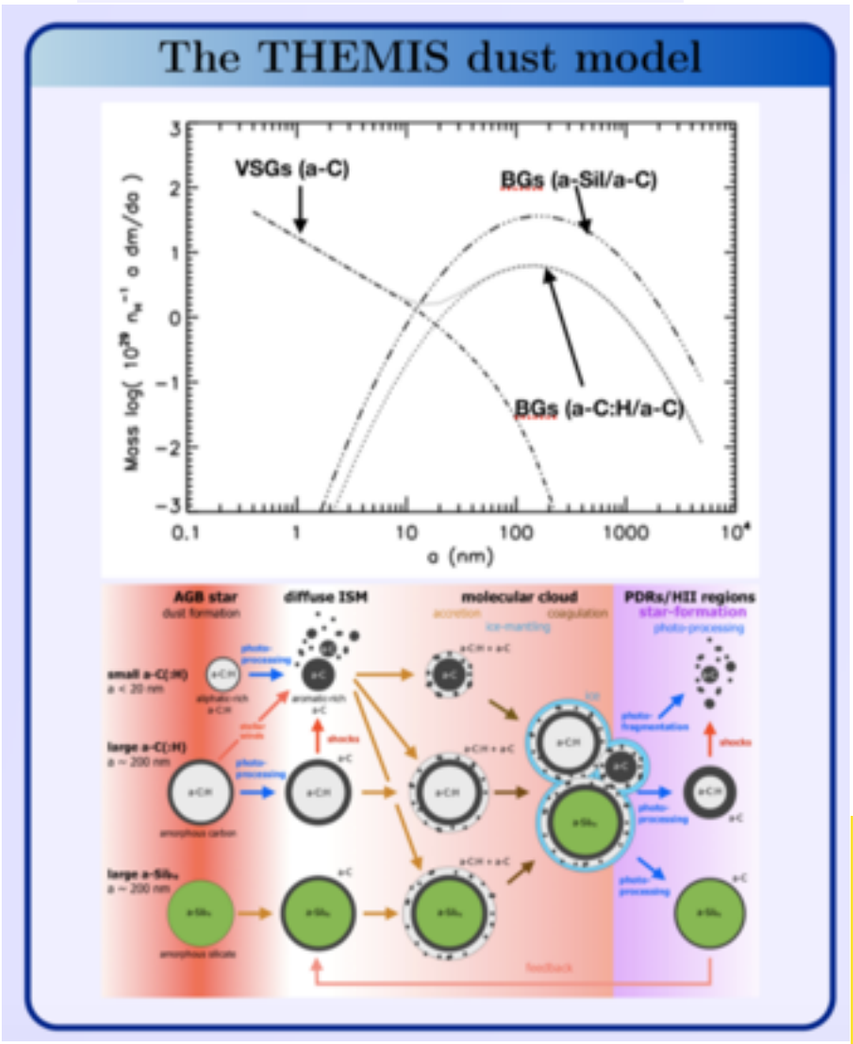

- **Photo-destruction ?**
- **Coagulation ? Necessity to get more emissive grains inside**
- **Higher angular resolution => help to characterize the evolutionary processes**

On-going work :

- **model the scattering that will influence the short wave bands and probe the dust growth at the edge**
- **investigate the impact on the gas (thermal budget, chemistry) ? Coupling THEMIS with PDR Meudon**
- **ALMA CO (3-2) and HCO+ (4-3) (PI:Guzman): density, photo-evaporative flows, efficiency at eroding/compressing cloud**

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JWST

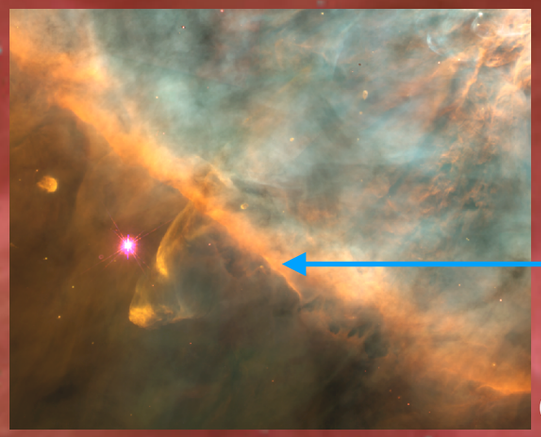
The largest ever launched space telescope (mirror diameter of 6.5 m,) will observe in the infrared with a sensitivity and a spatial resolution better than one to two orders of magnitude than its predecessors.

JWST will profoundly change our current understanding of the evolution of matter as it passes from the most diffuse regions of the interstellar medium of our Galaxy to star formation sites.

New launch date March 31, 2021

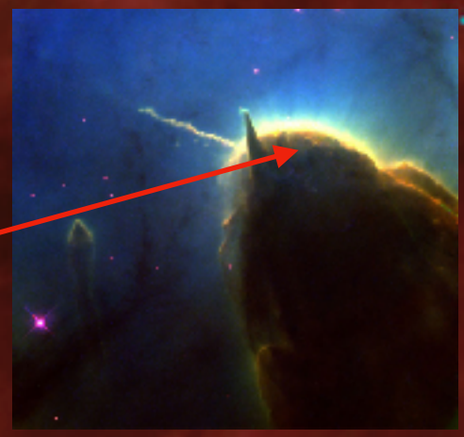
JWST

- *Early Release Science program ID1288: Radiative feedback from massive stars as traced by multiband imaging and spectroscopic mosaics (~30h, PIs: O. berne, E. Habart, E. Peeters)*

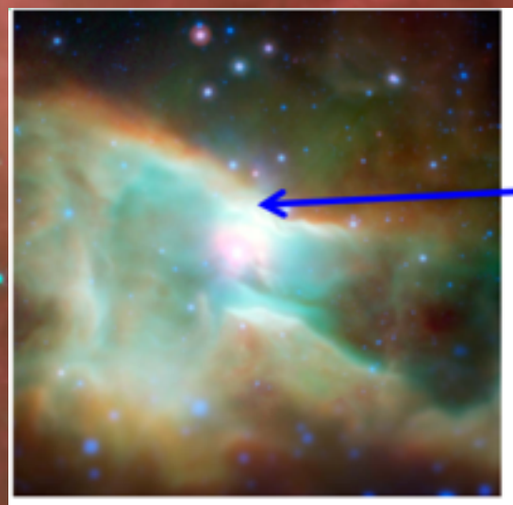


Orion Bar or **Trifid**
G_0=10,000 or **1000**

depending on the launch date



- *GTO program (~60h, PI: K. Misselt; Is: K. Gordon, A. Abergel)*



Multi-wavelength study of two canonical Photo-Dissociation-Regions (PDR):
NGC 7023 and **The Horsehead**

- Excitation conditions: G_0=100 to 1500.
- Nearly edge on geometry minimizing projection degeneracies in modeling.
- Part of on-going observational and theoretical programs designed to characterize & understand physical and chemical states of PDRs.

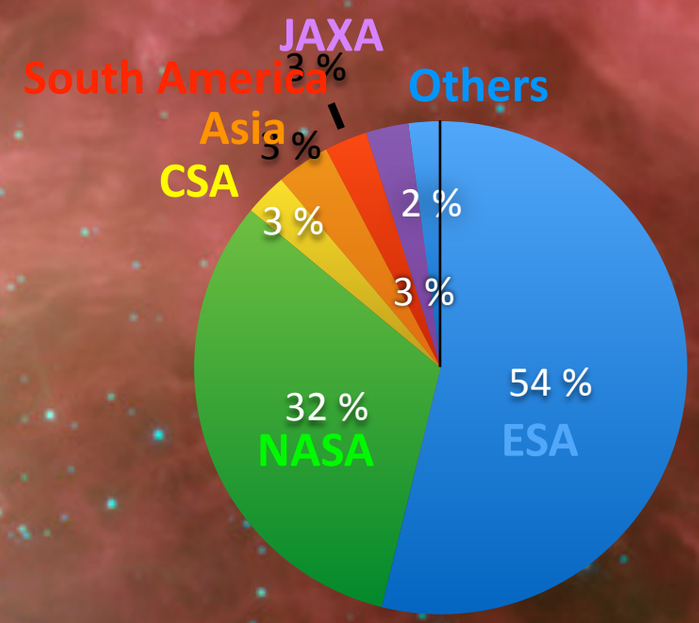
ERS Team

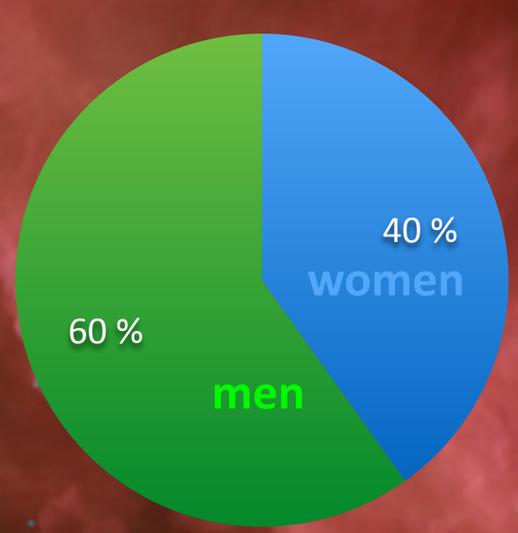
PI team: Olivier Berné (France), Emilie Habart (France), Els Peeters (Canada)

CoIs (17): Abergel A. (FR), Bergin E. (US), Bernard-Salas J. (UK), Bron E. (ES), Cami J. (CA), Cazaux S. (NL), Dartois E. (FR), Fuente A. (ES), Goicoechea J. (ES), Gordon K. (US), Okada Y. (DE), Onaka T. (JP), Robertto M. (US), Röllig M. (DE), Tielens A. (NL), Vicente S. (PT), Wolfire M. (US)

122 Science collaborators from 18 countries.

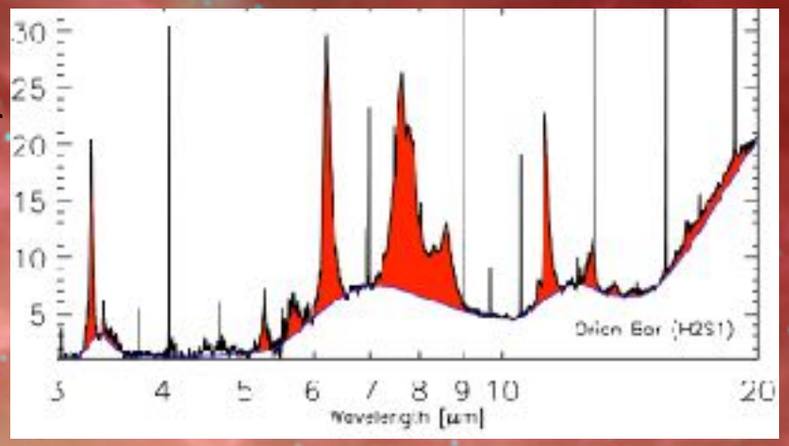
Team demographics:





Community oriented program

www.jwst-ism.org



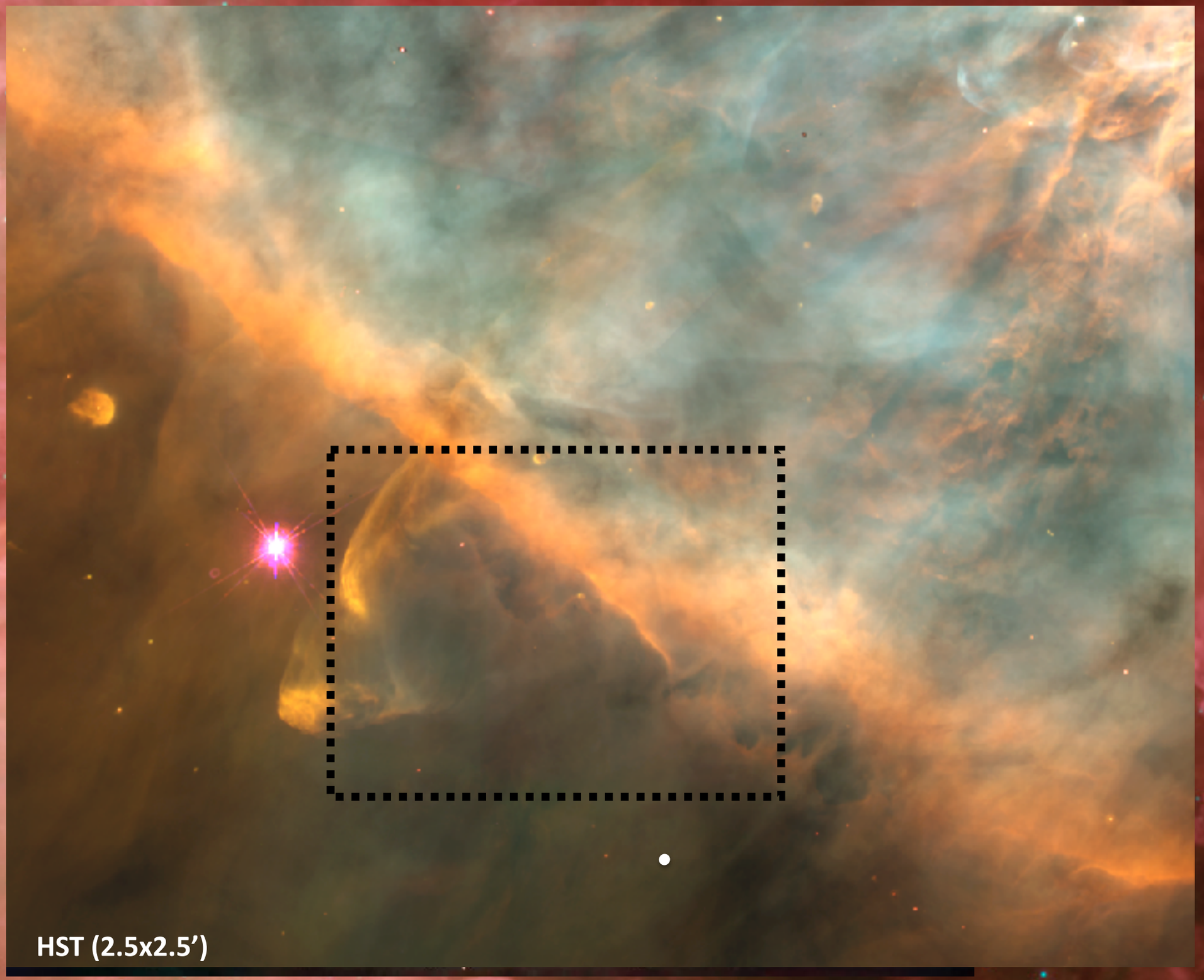
Synopsis

- A **large fraction of the IR emission in galaxies** to be observed with JWST **originates from PDRs** (i.e. a largely neutral, but warm region of gas and dust FUV-irradiated)

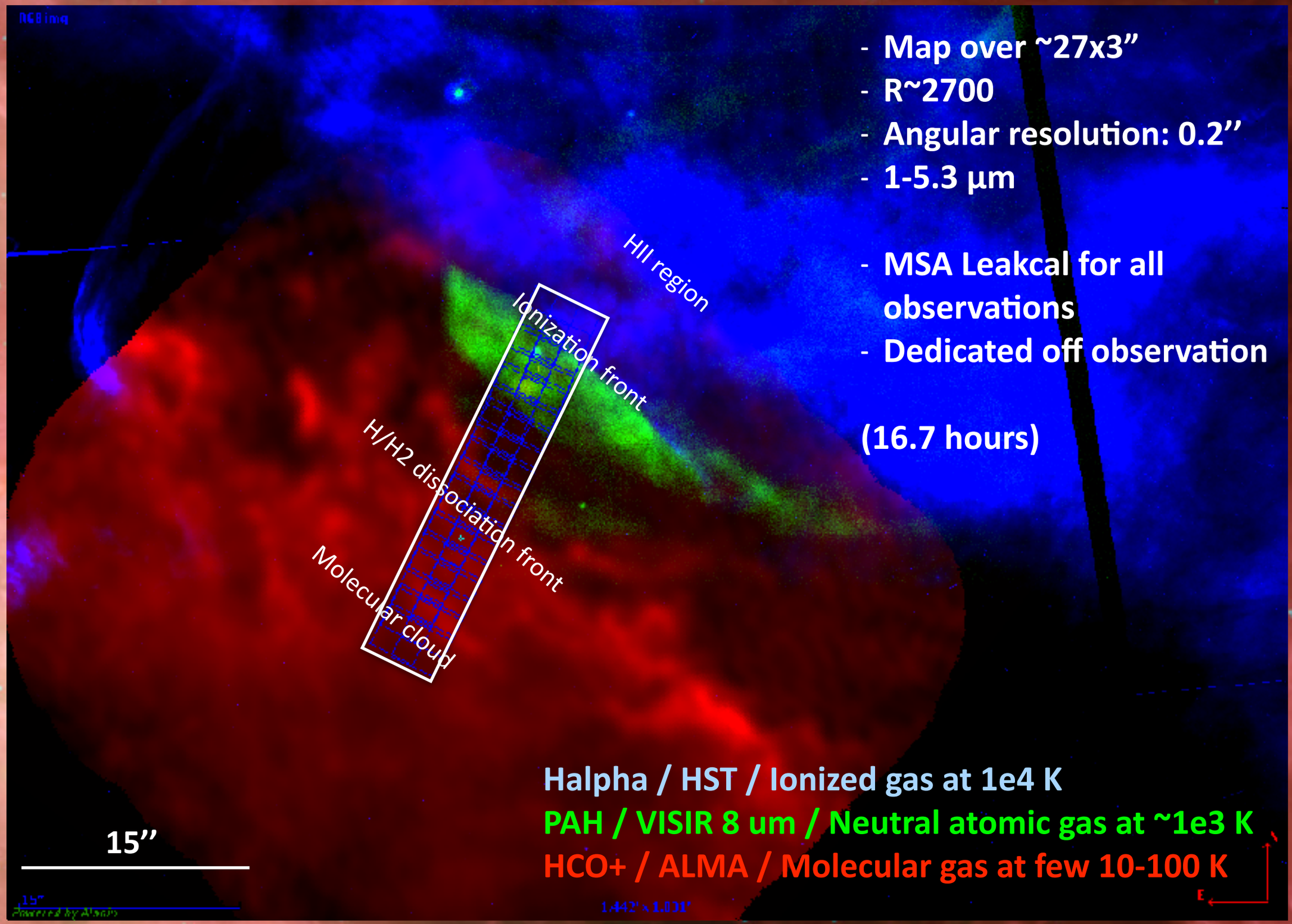
- Key objective for JWST: Understanding the **physical-chemical processes in PDRs**

- Program's goal:
  - **obtain the first spatially resolved, high spectral resolution observations of a PDR** with well-defined UV illumination in a typical massive star-forming region using NIRCam, NIRSpec and MIRI
  - JWST will resolve for the 1st time the key zone, the IF and DF, where the main radiative heating and photochemical feedback processes occur
  - Provide **"template data"** and **science-enabling products for PDRs**
  - Guide the preparation of **Cycle 2 proposals on star-forming regions in our Galaxy and beyond**

Target: Orion Bar

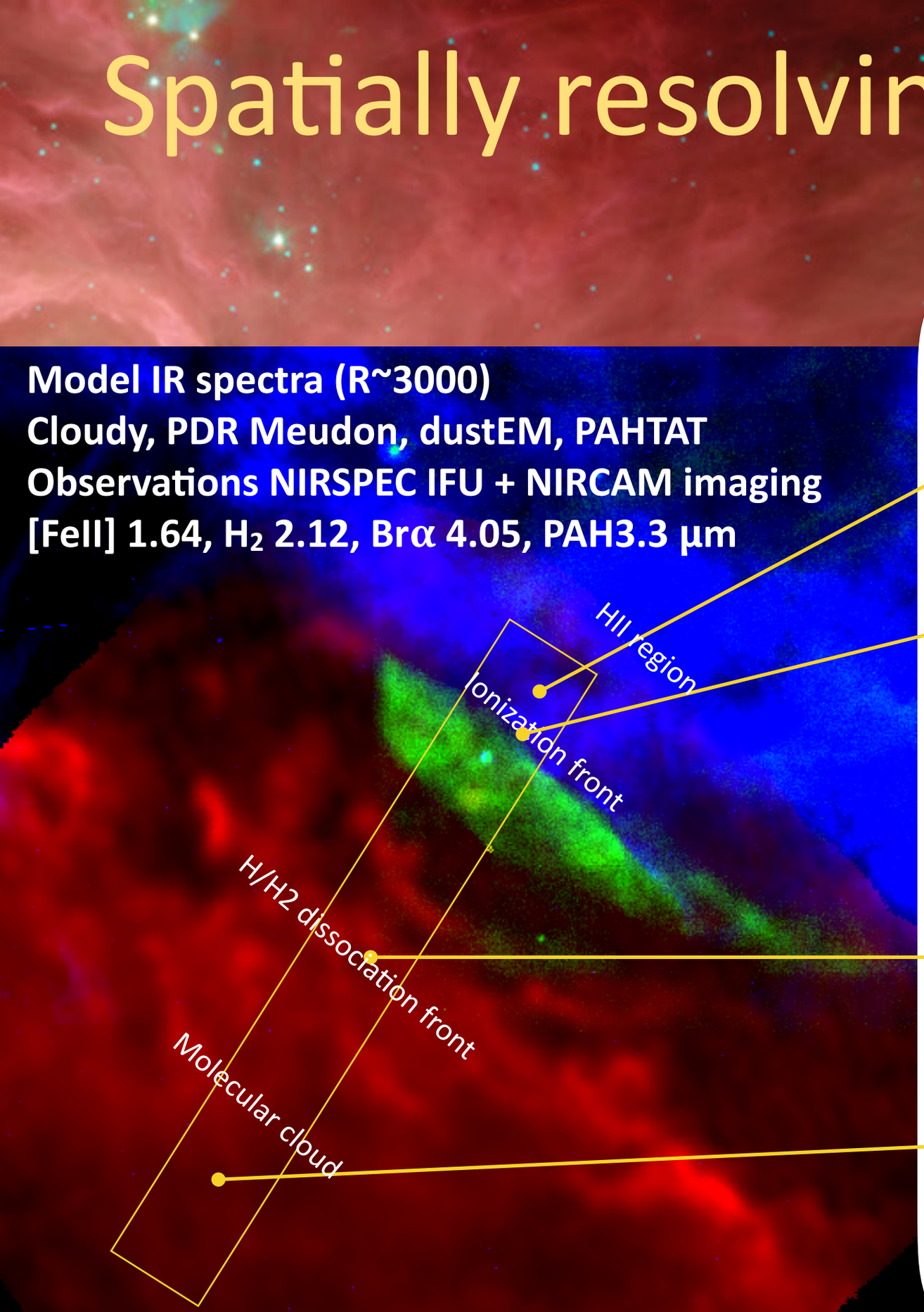


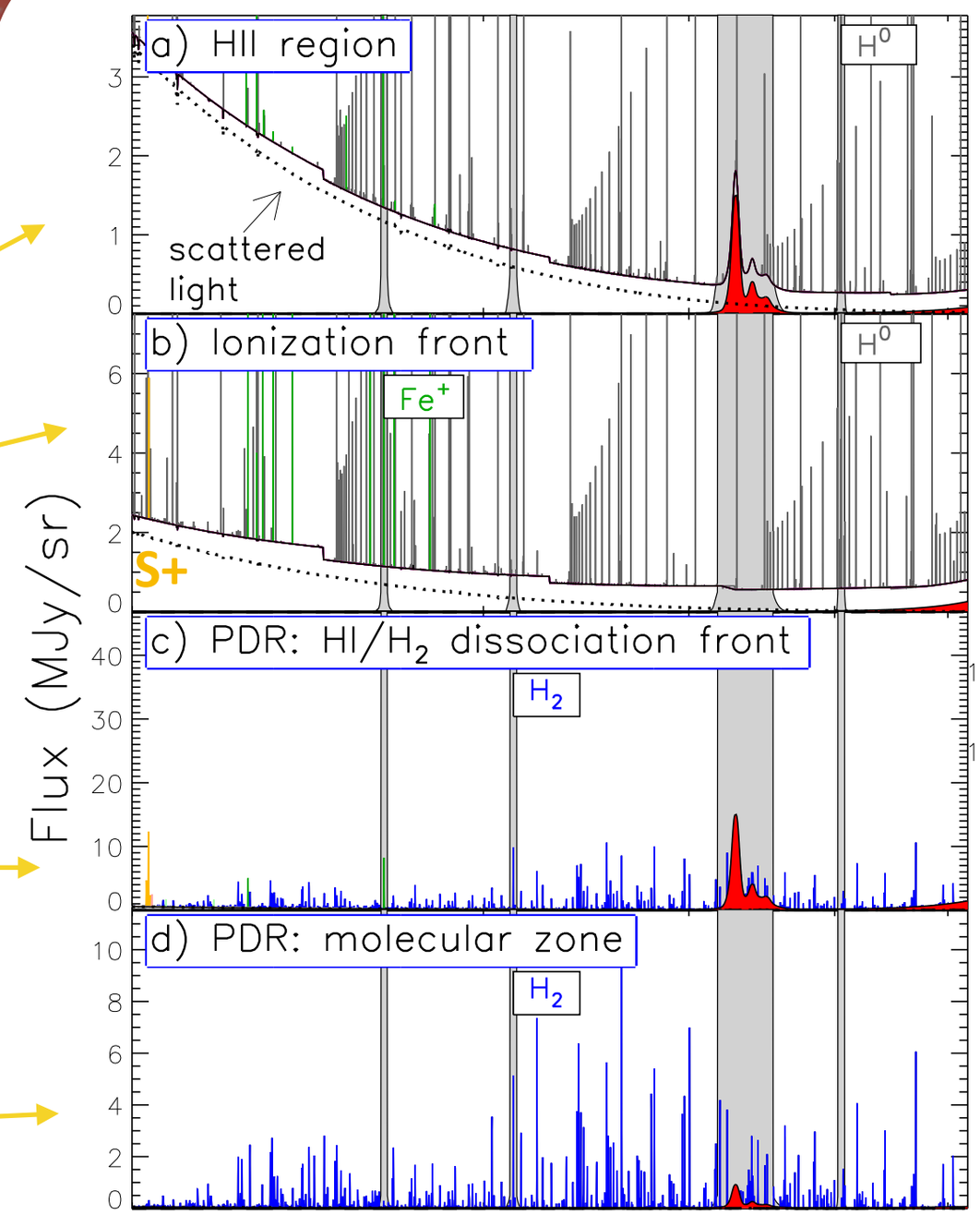
Observations: NIRSPEC IFU mosaics



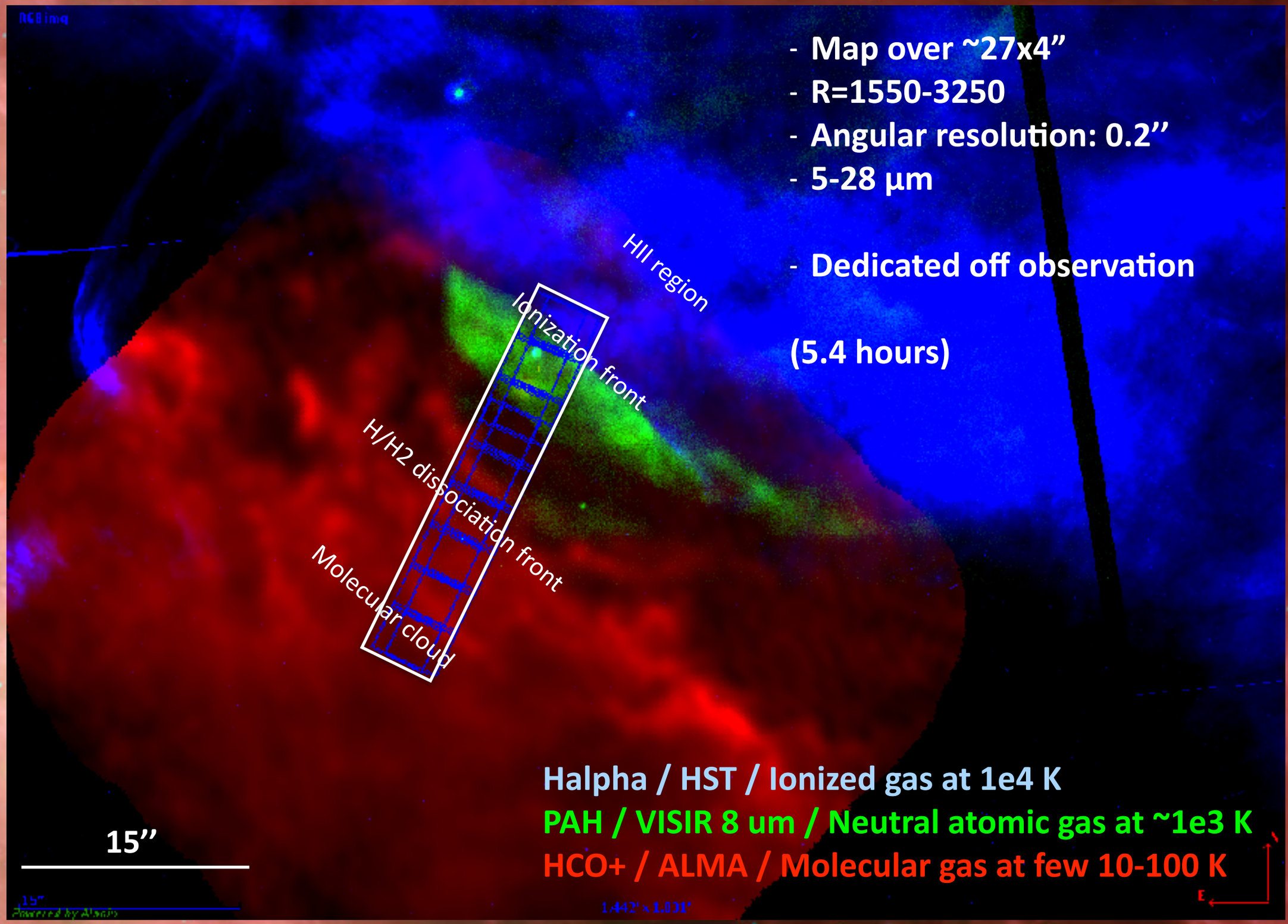
Spatially resolving the key zones

Model IR spectra (R~3000)
Cloudy, PDR Meudon, dustEM, PAHTAT
Observations NIRSPEC IFU + NIRCAM imaging
[FeII] 1.64, H_2 2.12, Brα 4.05, PAH3.3 µm





Observations: MIRI IFU mosaics



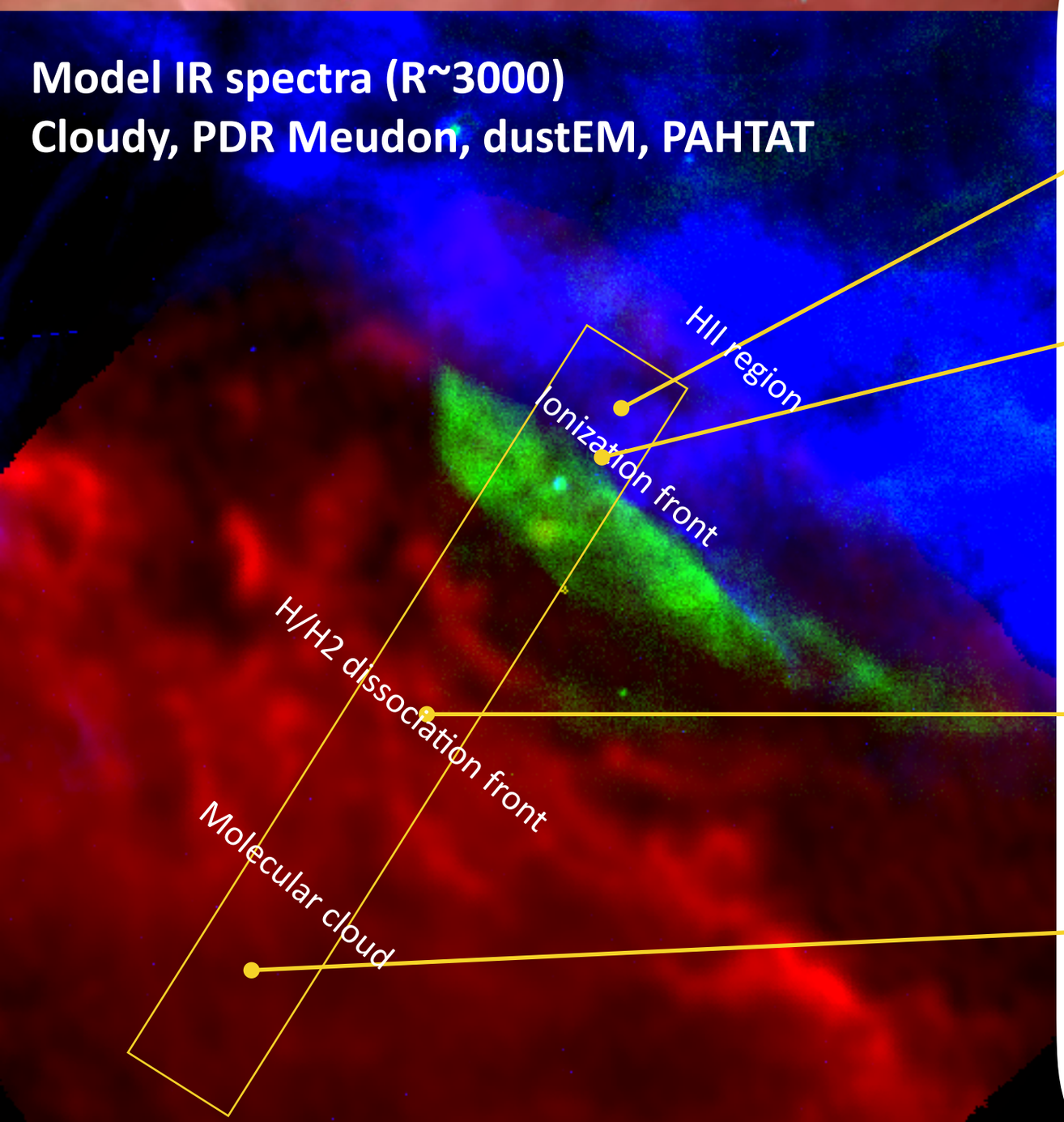
- Map over ~27x4”
- R=1550-3250
- Angular resolution: 0.2’’
- 5-28 µm

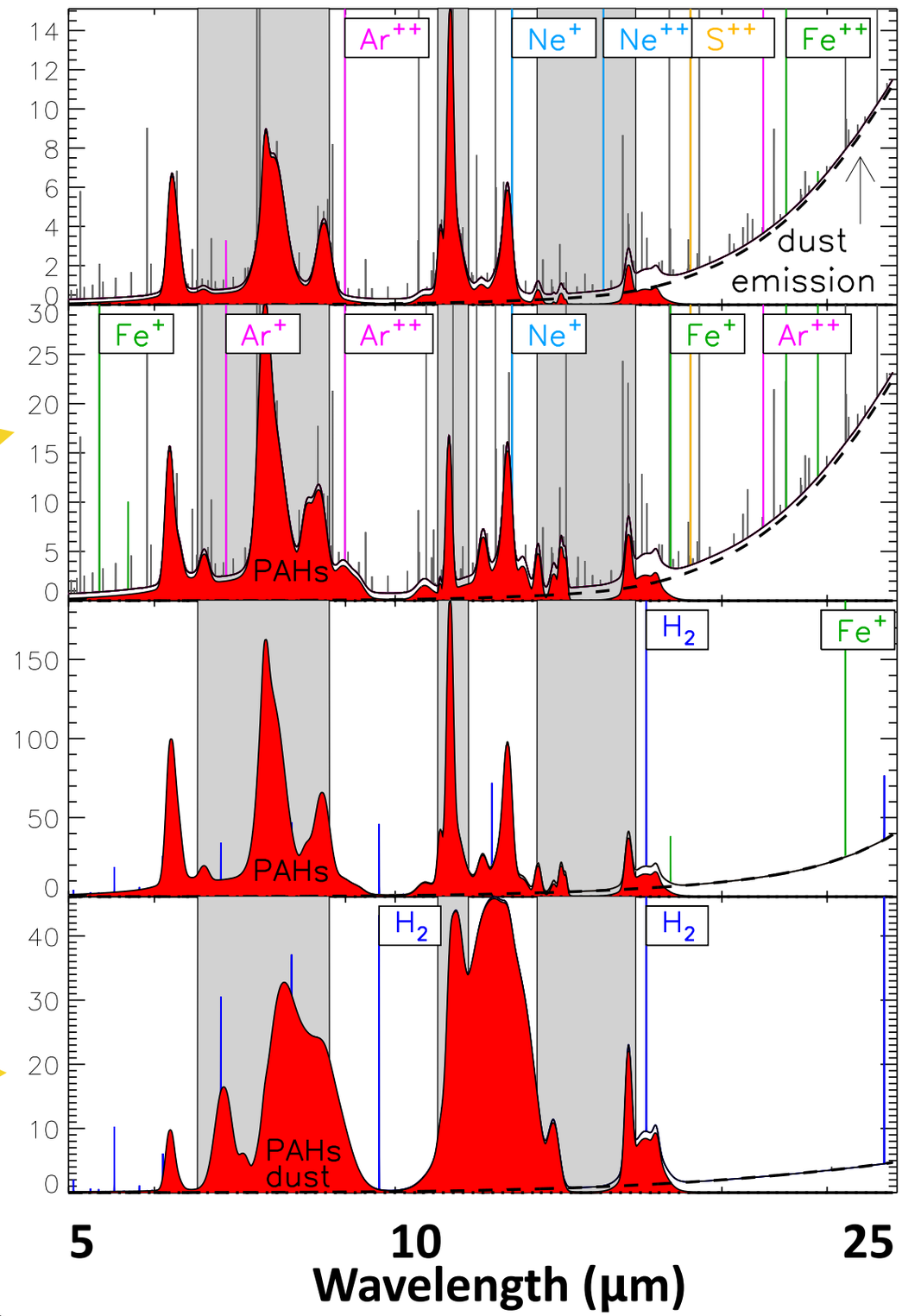
- Dedicated off observation

(5.4 hours)

Spatially resolving the key zones

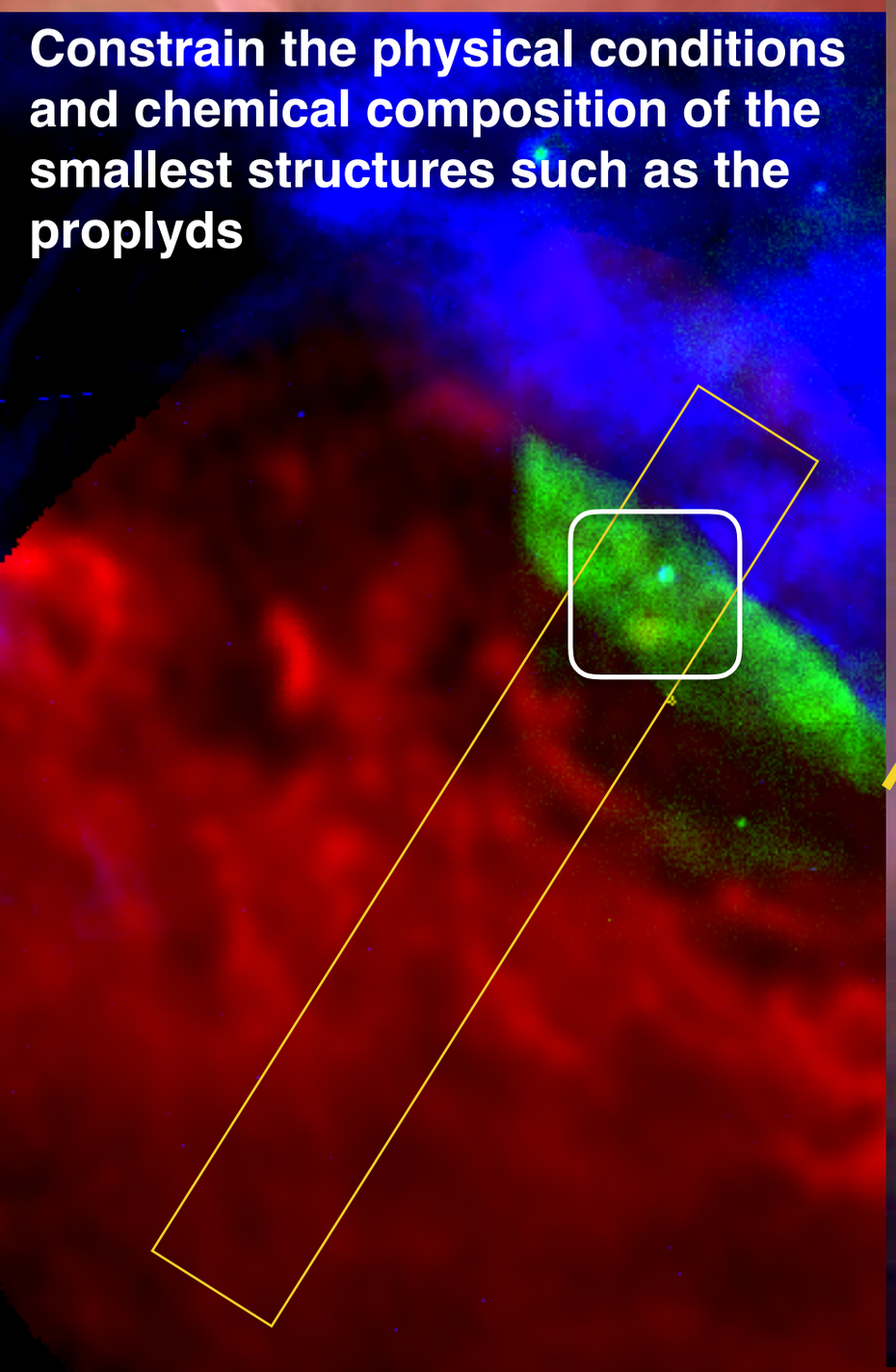
Model IR spectra (R~3000)
Cloudy, PDR Meudon, dustEM, PAHTAT

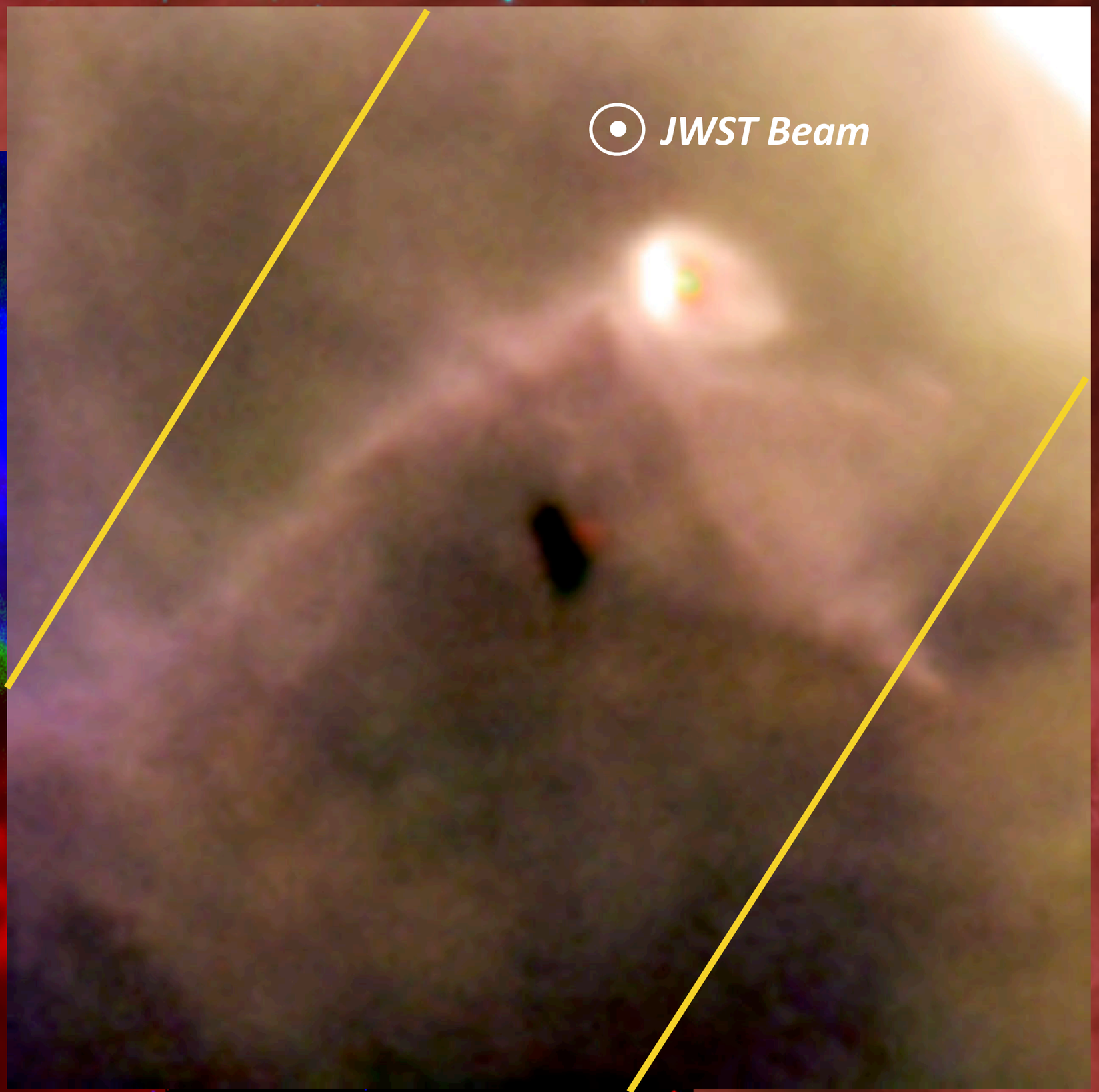




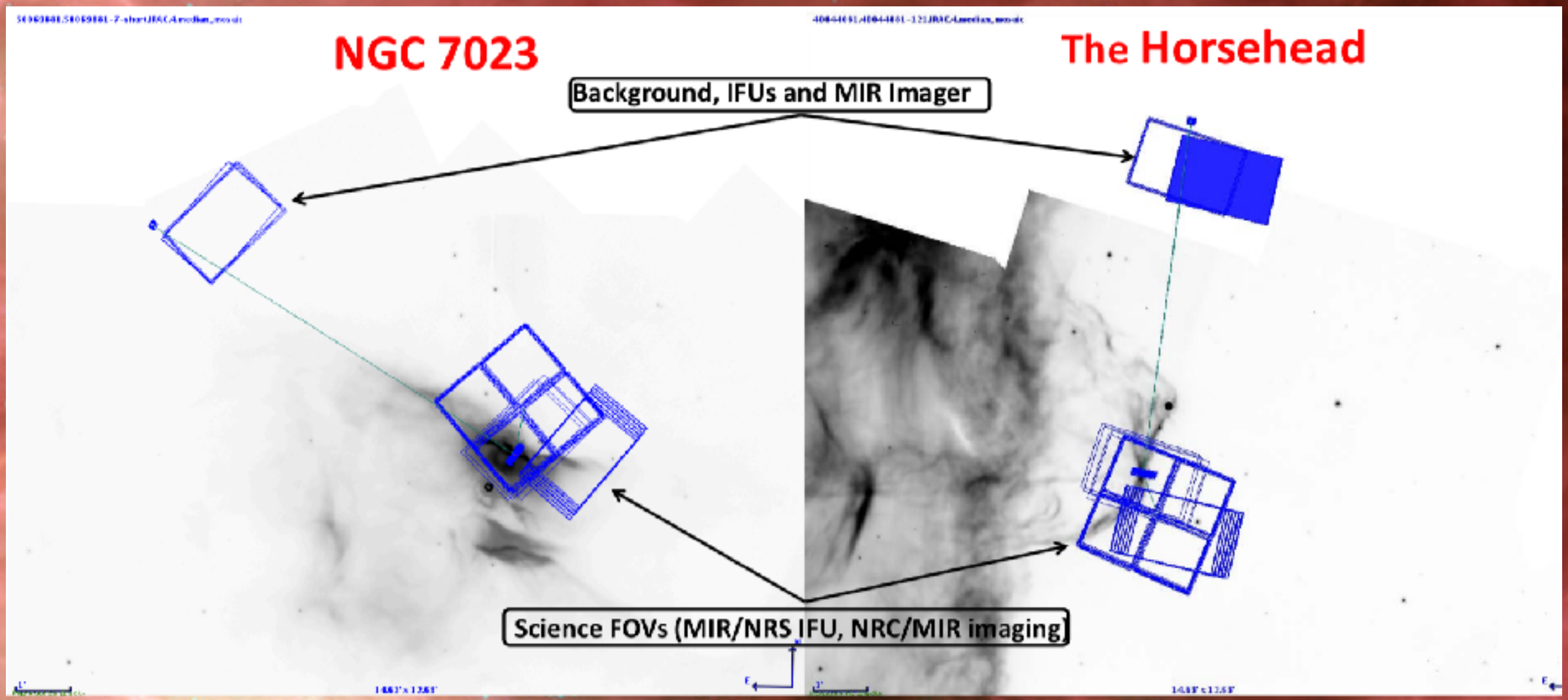
Observations: NIRSPEC/MIRI IFU

Constrain the physical conditions and chemical composition of the smallest structures such as the proplyds





GTO programs



powerfull NIR/MIR spectroscopic diagnostics

- **fine-structure lines of ions and atoms (IP<13.6 eV: [FeII], [FeI], [SII], [SI], [NiII] …, IP>13.6 eV: [FeIII], [ArIII], [ArII], [SIV], [SIII], [PIII], [NeIII], [NeII] …**

[ionized gas before IF, IF-DF, inside PDRs; impinging EUV-FUV radiation field, cooling, T, ne, pressure gradients —> elemental abundances, metallicities (extragalactic need)]

- **fluorescent lines (O, N …)**

[excellent tracer of the IF front, intensity & wavelength dependence of the UV field]

- **recombination lines (H, He, C …)**

[C+ layer at high resolution, physical conditions in the neutral layer beyond the IF]

- **pure rotational and rovibrational lines of H2 and possibly HD (both collisional & fluorescent)**

[major cooling, great thermometer for the bulk of the warm gas, pressure gradients inside the PDRs, H2 formation processes]

- **possibly high excited rotational & rovibrational lines of CO, H2O (HDO), OH, CH+**

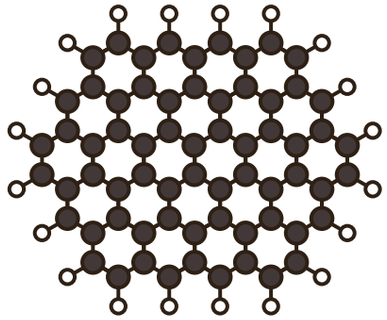
[hot gas / non-thermal processes, radiative & chemical formation pumping]

- **rovibrational lines of non-polar molecules (CH4, C2H2, HCN …)**

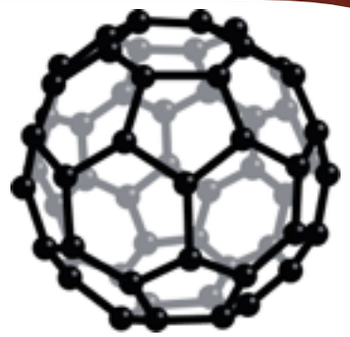
[complete inventory of hydrocarbon species, connection with grain processing]

- **bands of carbonaceous dust in its multiform (aromatic, aliphatic, fullerenes)**
- **continuum emission, dust scattering, extinction**

Radiative feedback from massive stars
as traced by multiband imaging and spectroscopic mosaics



Sub-features
from aromatic/PAHs, aliphatics, fullerenes ..



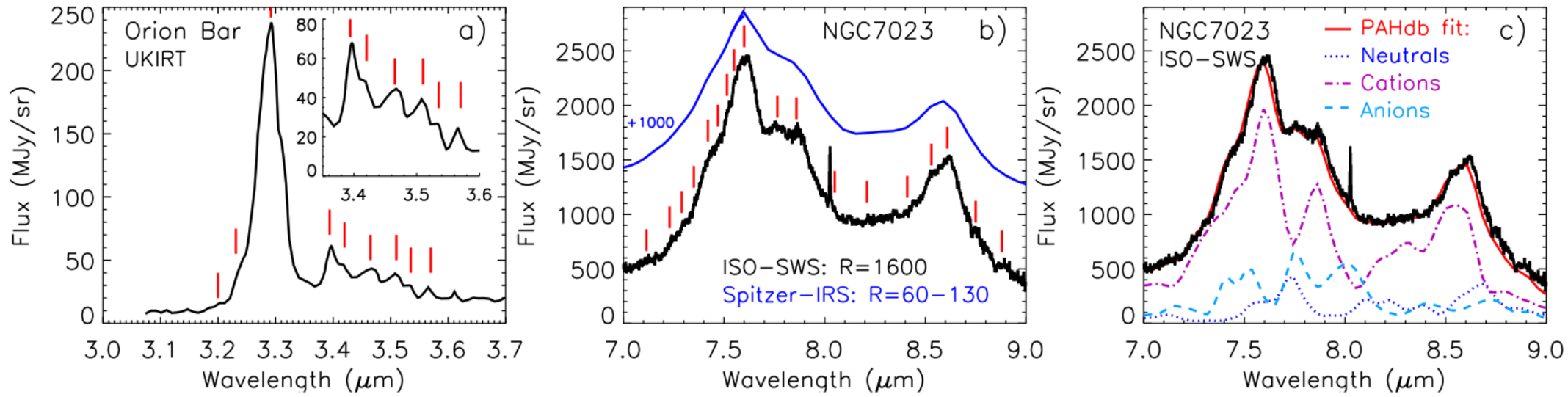


Figure 3: The spectral richness of the PAH emission toward two prototypical PDRs shown for **a)** the 3 μm and **b)** the 8 μm region (11; 12). Vertical bars indicate sub-structure (reflecting sub components). These are not detectable at low spectral resolution (panel **b**, blue line, offset=1000). **c)** PAHdb fitting shown for the 8 μm region with its breakdown in charge states (13; 14).

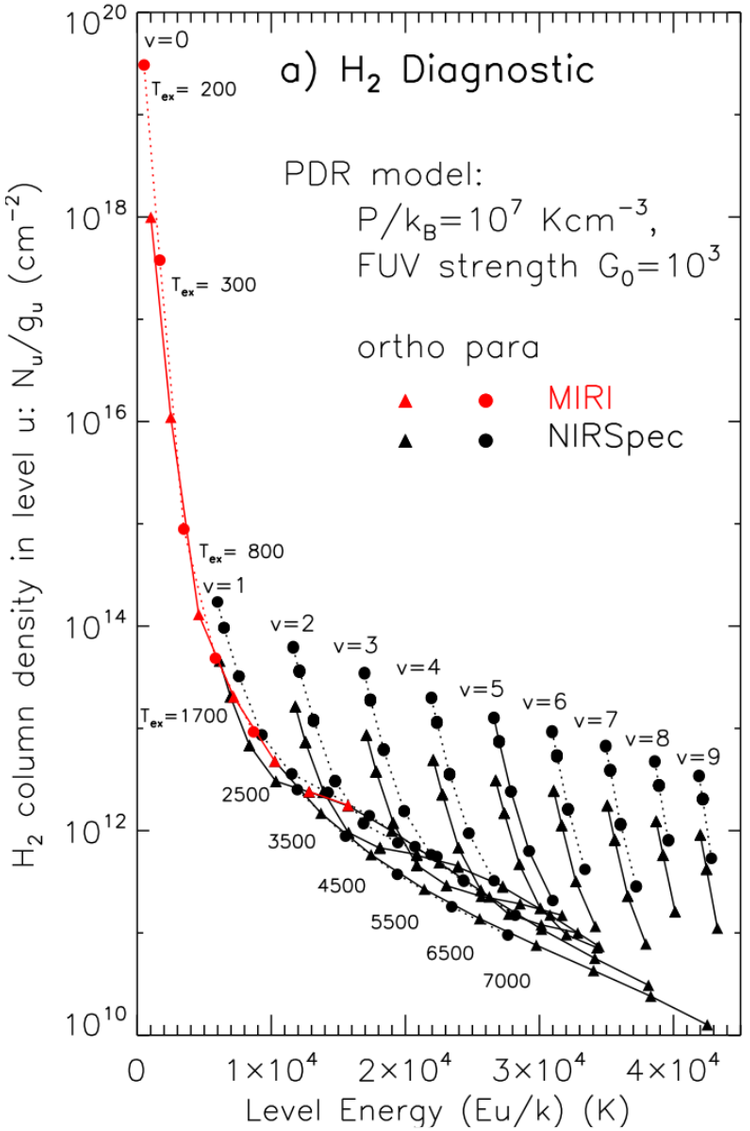
Radiative feedback from massive stars
as traced by multiband imaging and spectroscopic mosaics

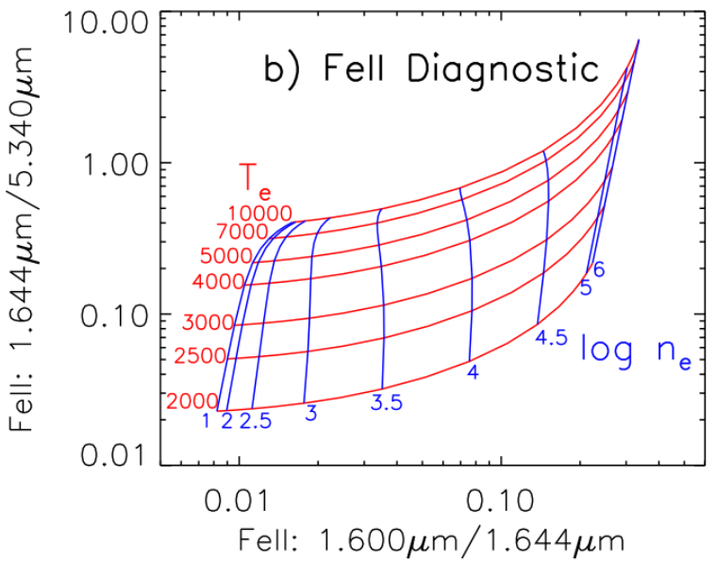
Example of IR PDR diagnostics

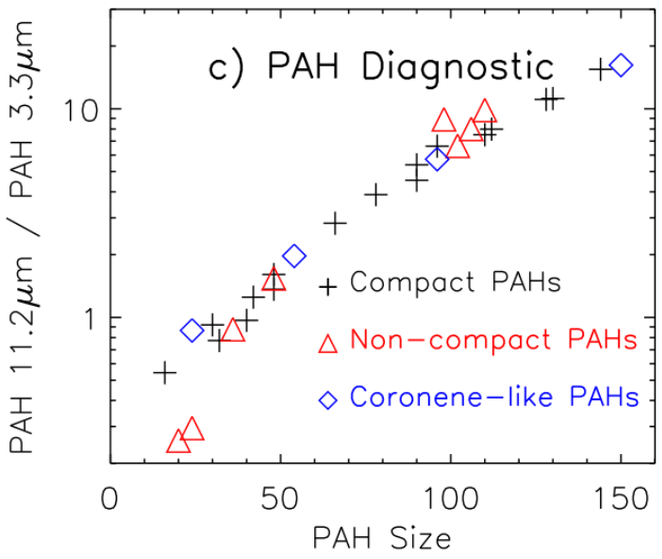
Excitation diagrams from H_2 lines observable by MIRI and NIRSpec as tracer of the warm and hot (UV pumped) excitation temperatures (excitation temperatures derived from the level populations by a local Boltzmann fit are indicated)

FeII lines as a tracer of the temperature and density distribution from the ionized gas to the PDR

The 11.2/3.3 PAH ratio as a tracer of PAH size



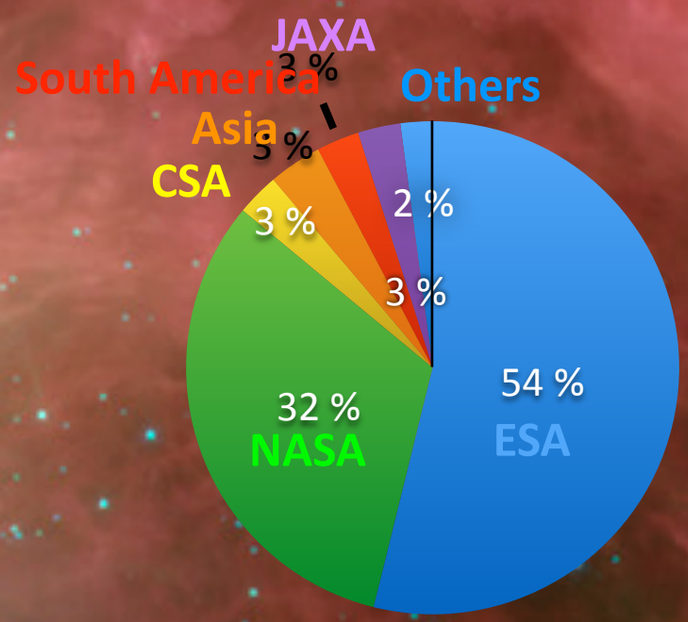


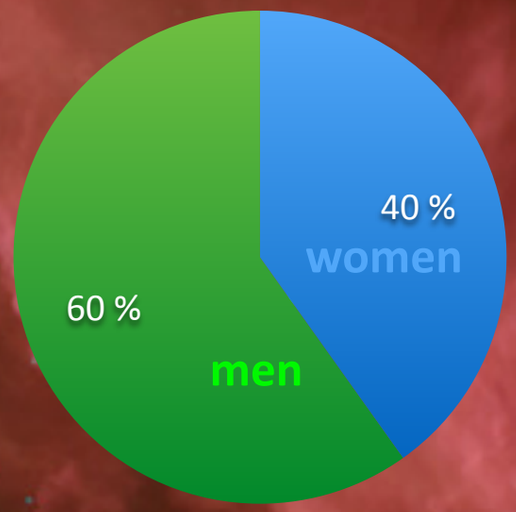


ERS Community oriented program

- Telecons open to the community will be organized on a regular basis
- Community workshop
- People interested are welcome to register on our website to keep posted and participate

Team demographics:





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