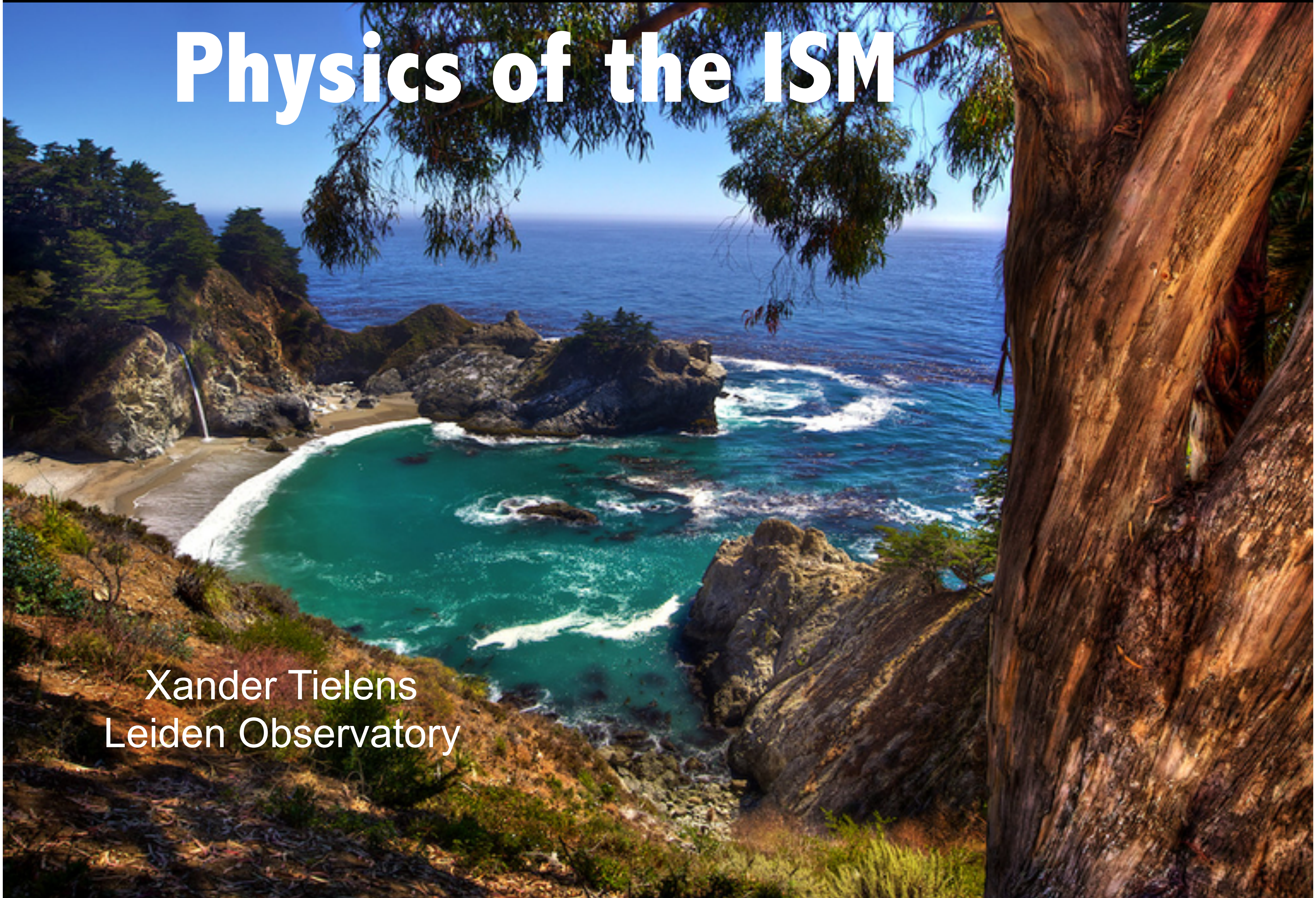
Physics of the ISM



Xander Tielens
Leiden Observatory

Where are all those butterflies coming from ?
What sets them moving ?
How did this system evolve and where is it going to ?

Grand Questions in ISM Ecology

- What is the mass budget of the ISM ?
- What is driving the evolution of the ISM ?
- What does that tell us about the ecology ?

Grand Questions in ISM Ecology

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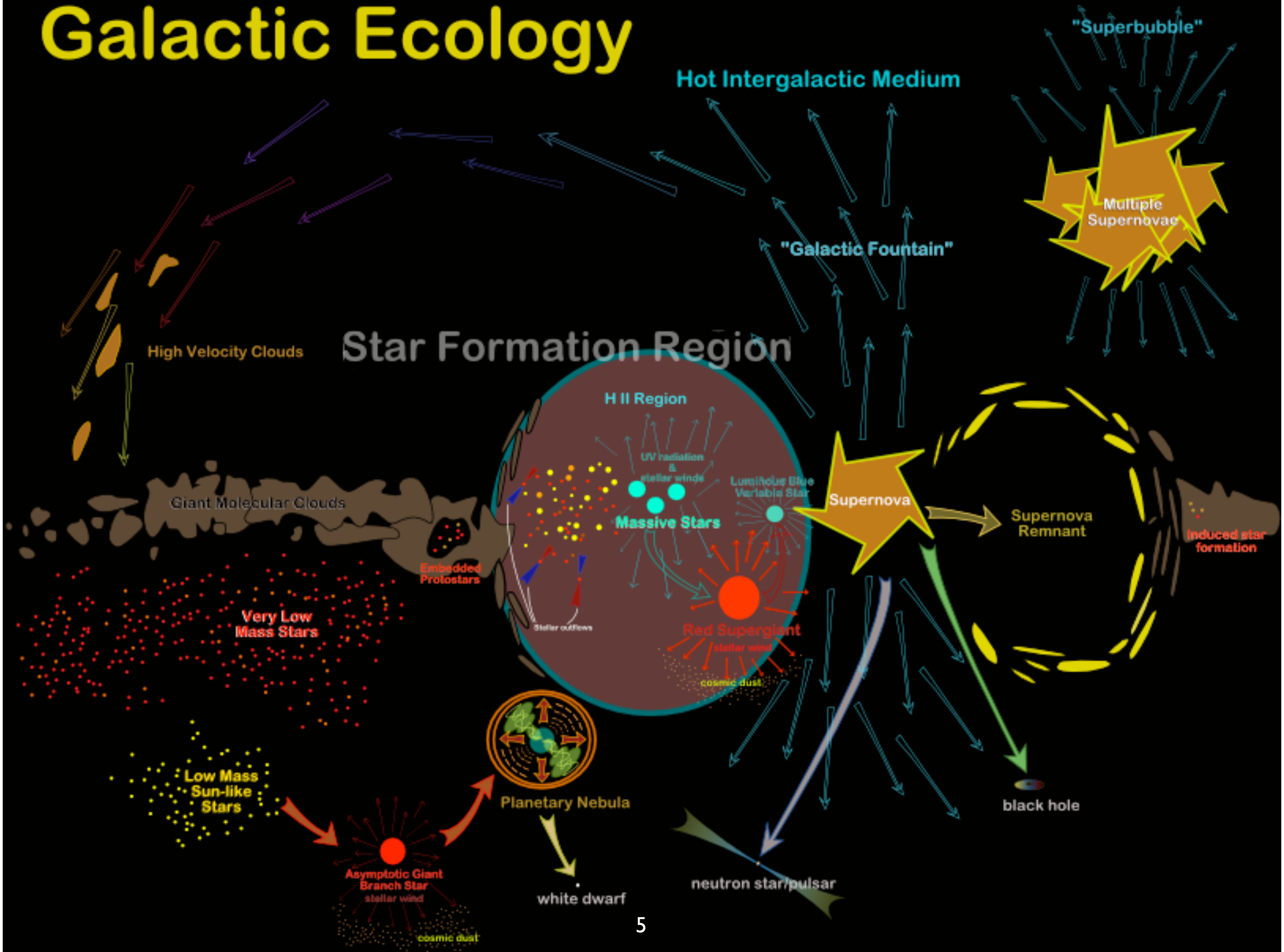
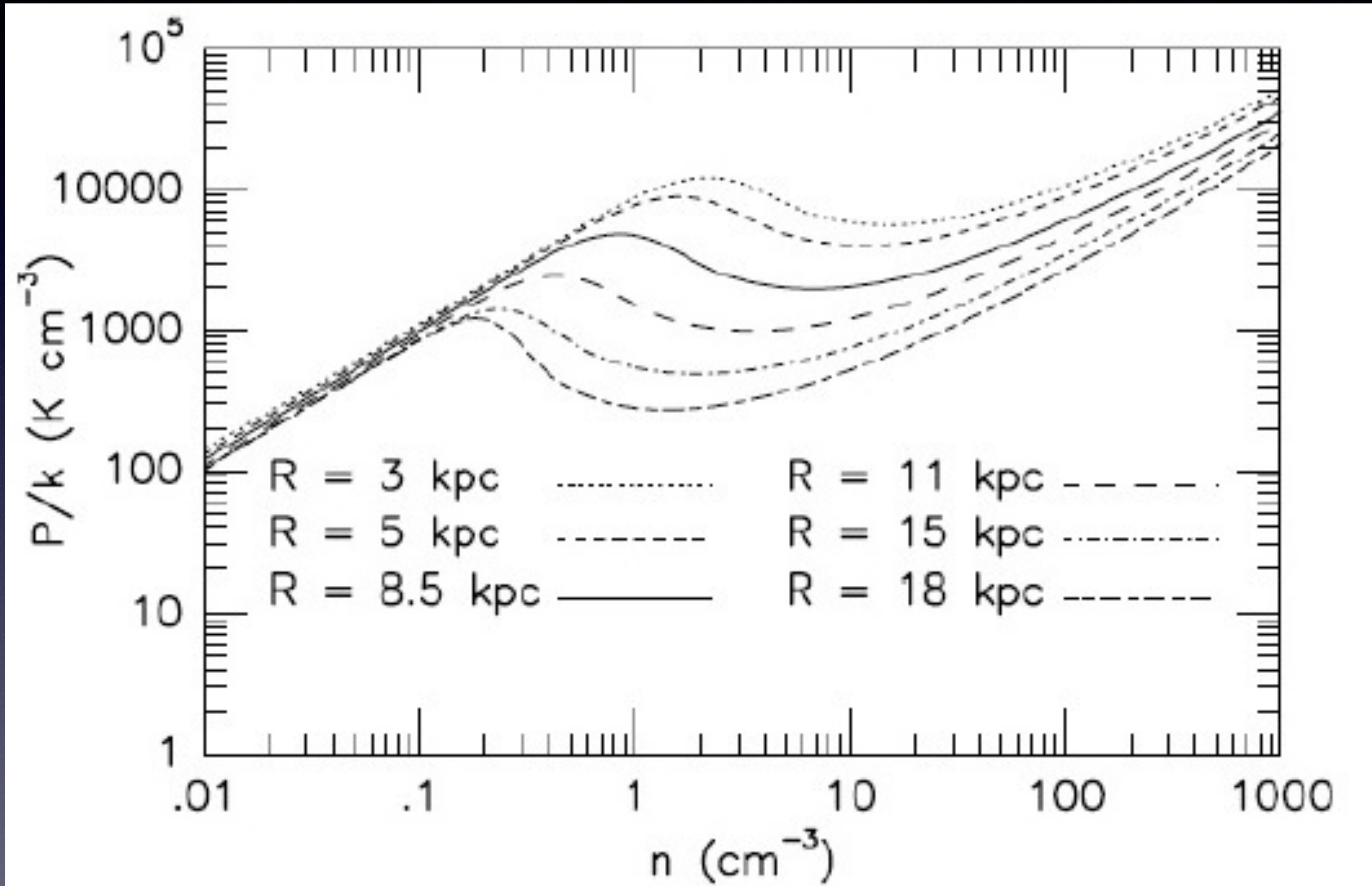
Galactic Ecology



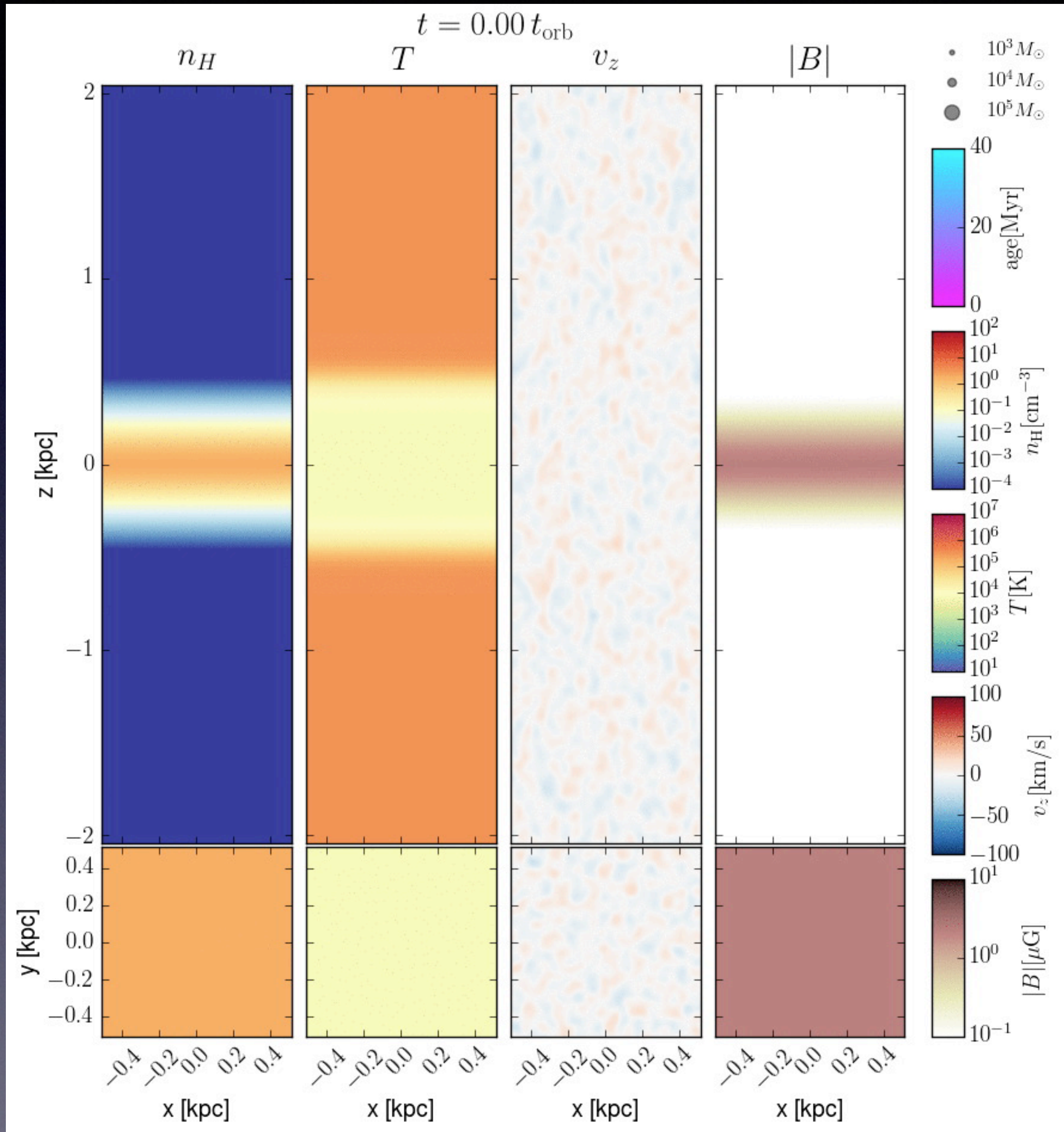
Thermodynamics & the Two Phase ISM

Wolfire et al 1995, 2003



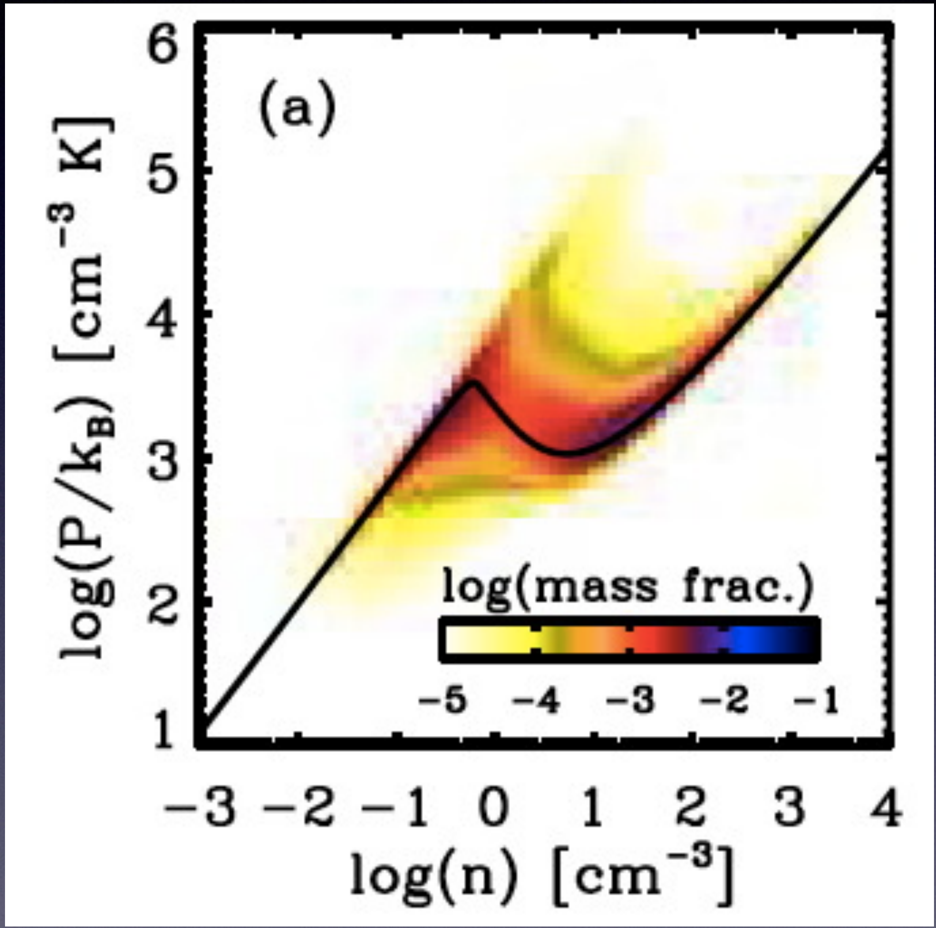
Essentially, the cooling/heating functions of atomic gas

Feedback in the Turbulent ISM



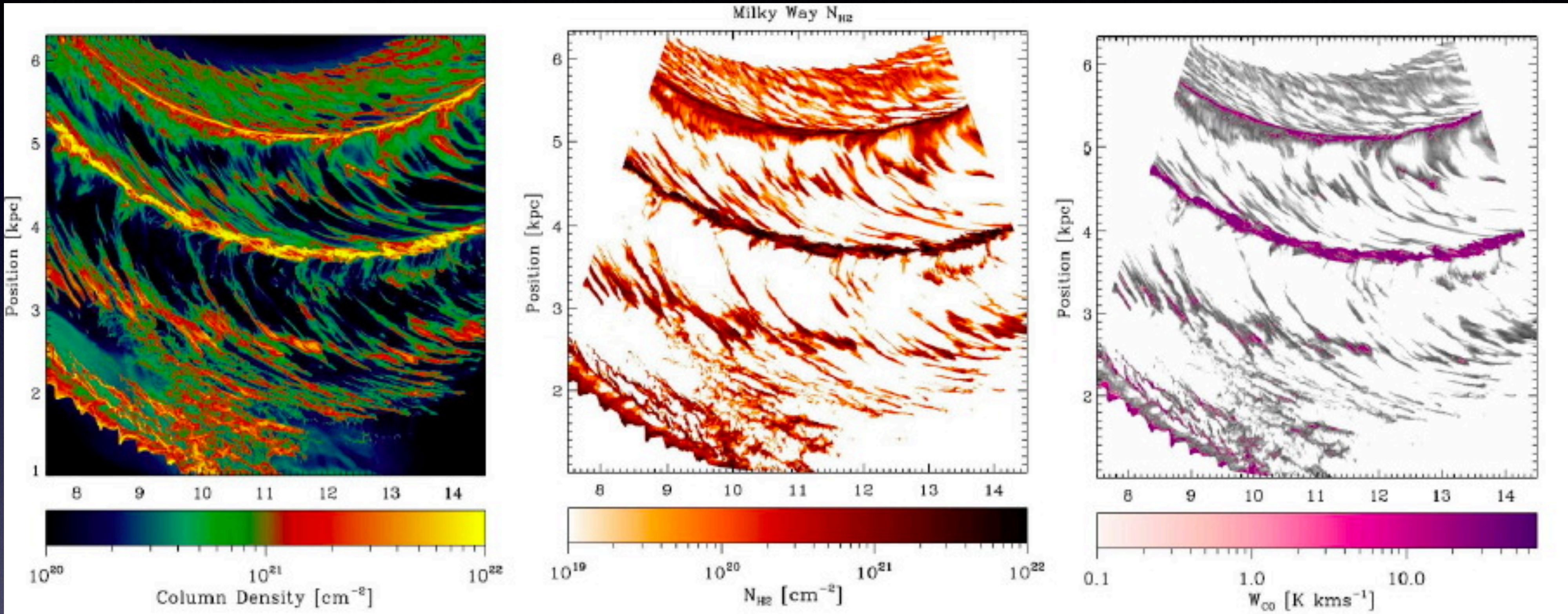
Kim & Ostriker, 2016, in prep

Phases in a Turbulent Medium



Kim et al., 2013, ApJ, 776,1
Kim & Ostriker, 2016, in prep

CO-Dark Molecular Gas



molecular clouds | H_2 clouds | CO clouds

Galactic shear produces long, filamentary clouds where CO is readily dissociated. The CO-dark fraction is ~0.4.

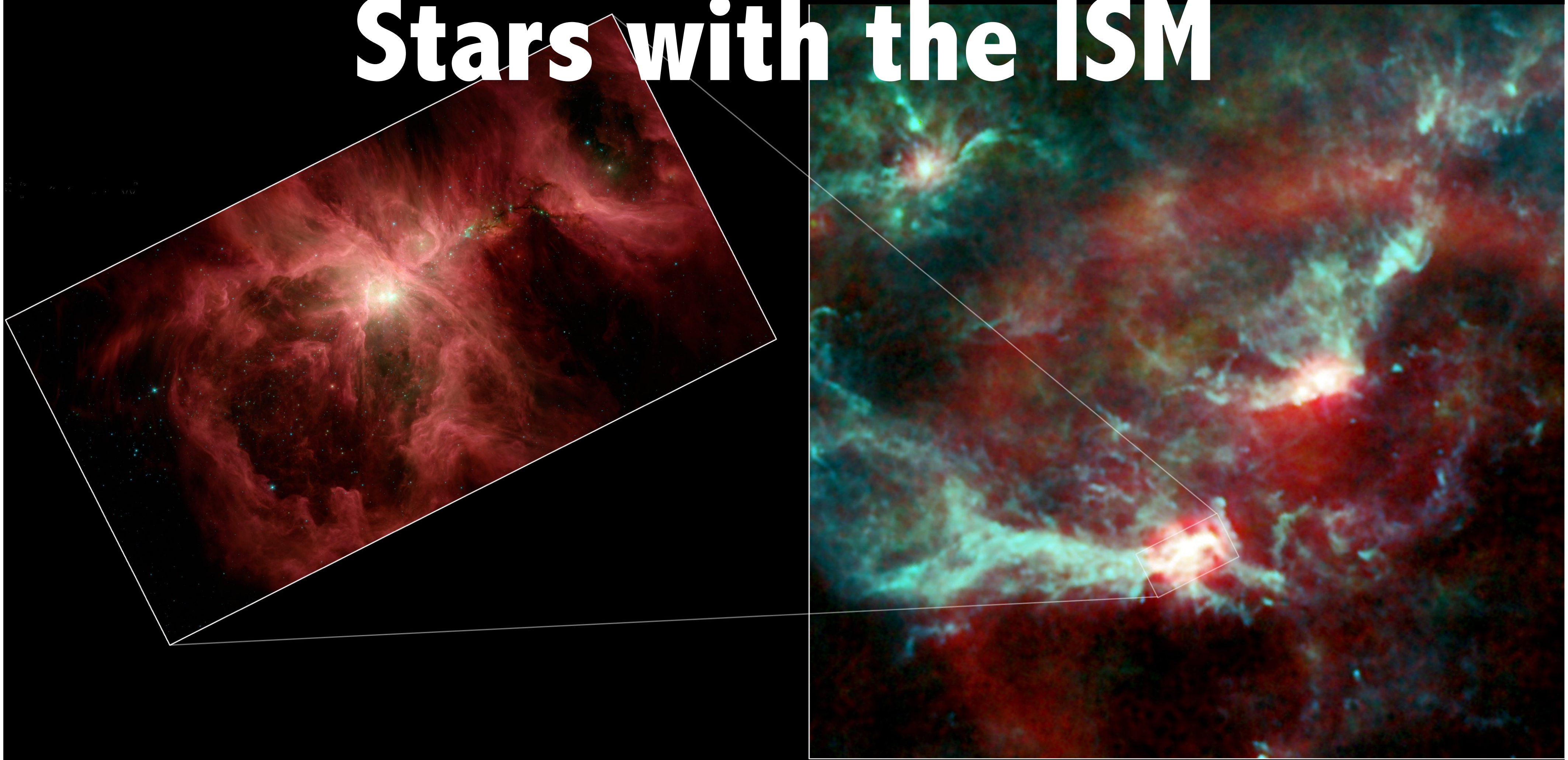
Smith et al, 2014,MNRA, 441, 1628

Probing the Phases of the ISM

Theoretically, phases are largely controlled by equation of state, but

- Pressure variations
- “Unstable” temperatures
- CO-dark molecular gas

Radiative Interaction of Stars with the ISM



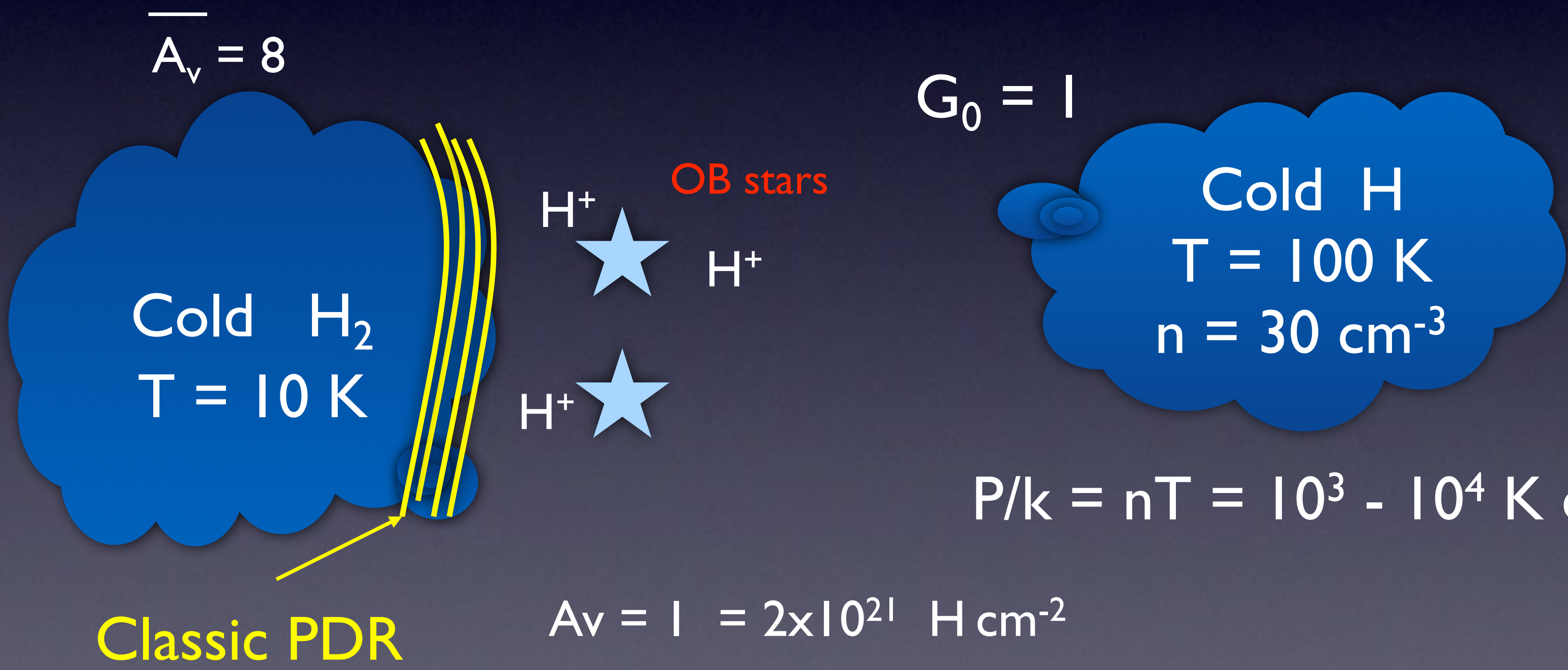
PDR: Gas phase in which FUV radiation plays a role in the heating and/or chemistry

FUV: 6 eV – 13.6 eV

$G_0 = 1$ Interstellar field

G_0: Habing χ:Draine ~1.7 G_0

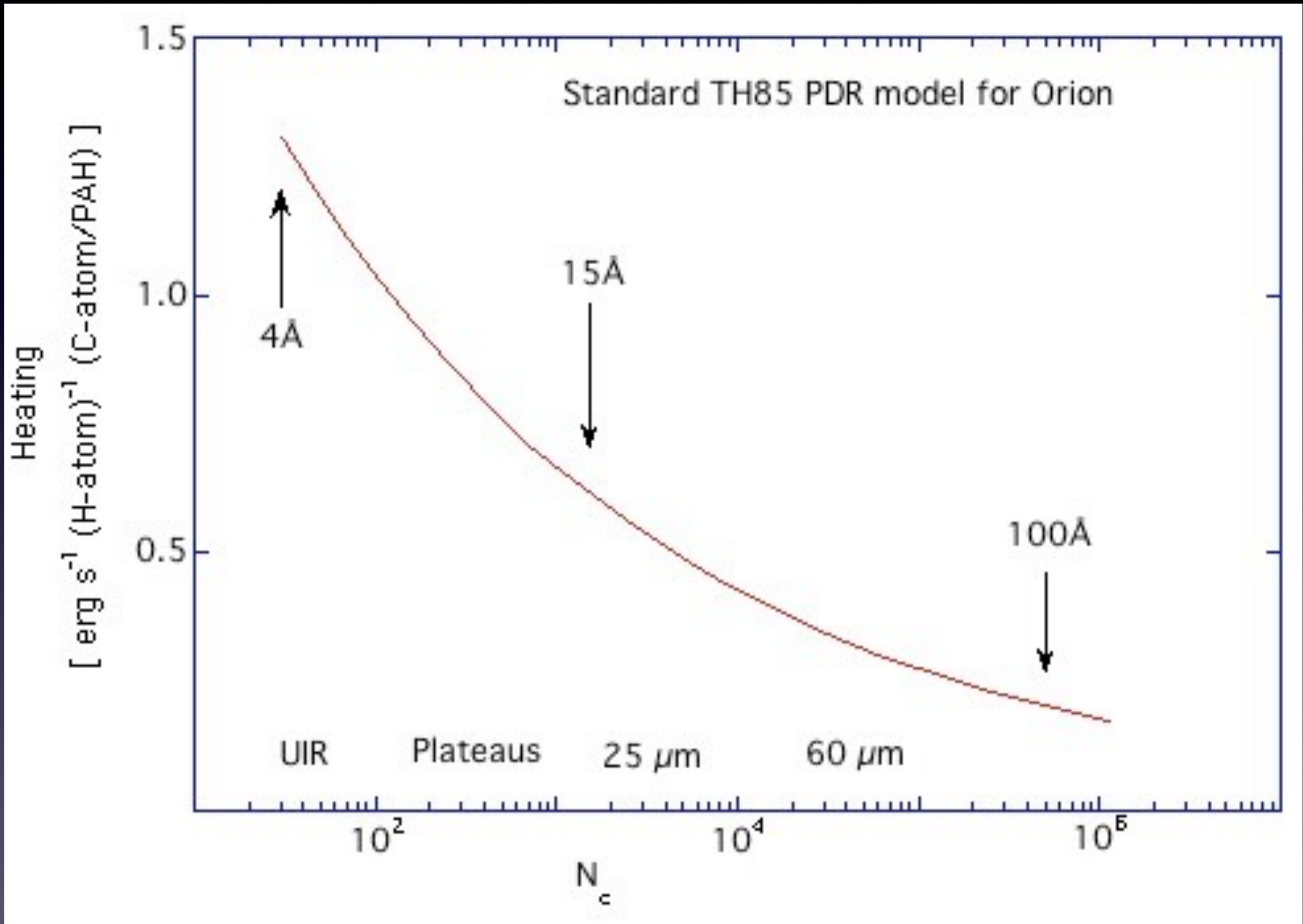
$G_0 = 10^5$ Orion trapezium



$P/k = nT = 10^3 - 10^4$ K cm^{-3}

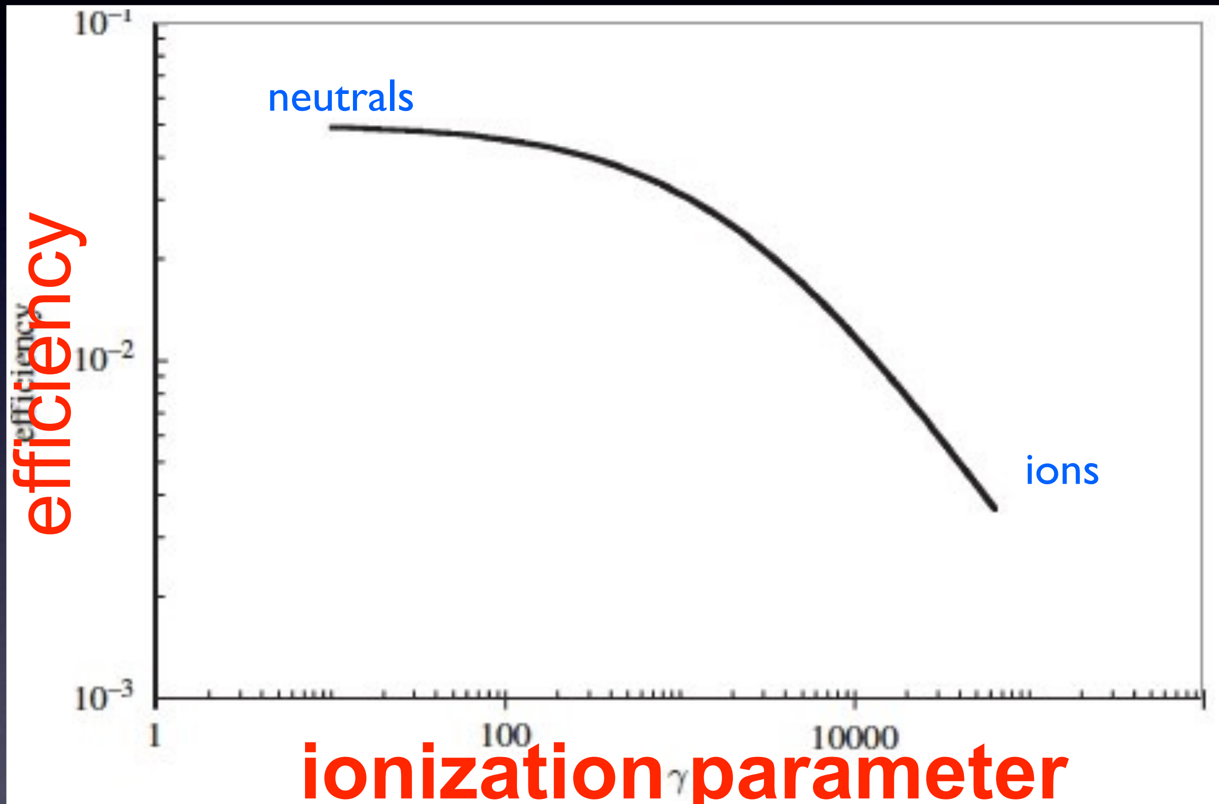
Av = 1 = 2×10^{21} H cm^{-2}

Photo Electric Heating Rate



Bakes & Tielens, 1994, ApJ, 427, 822

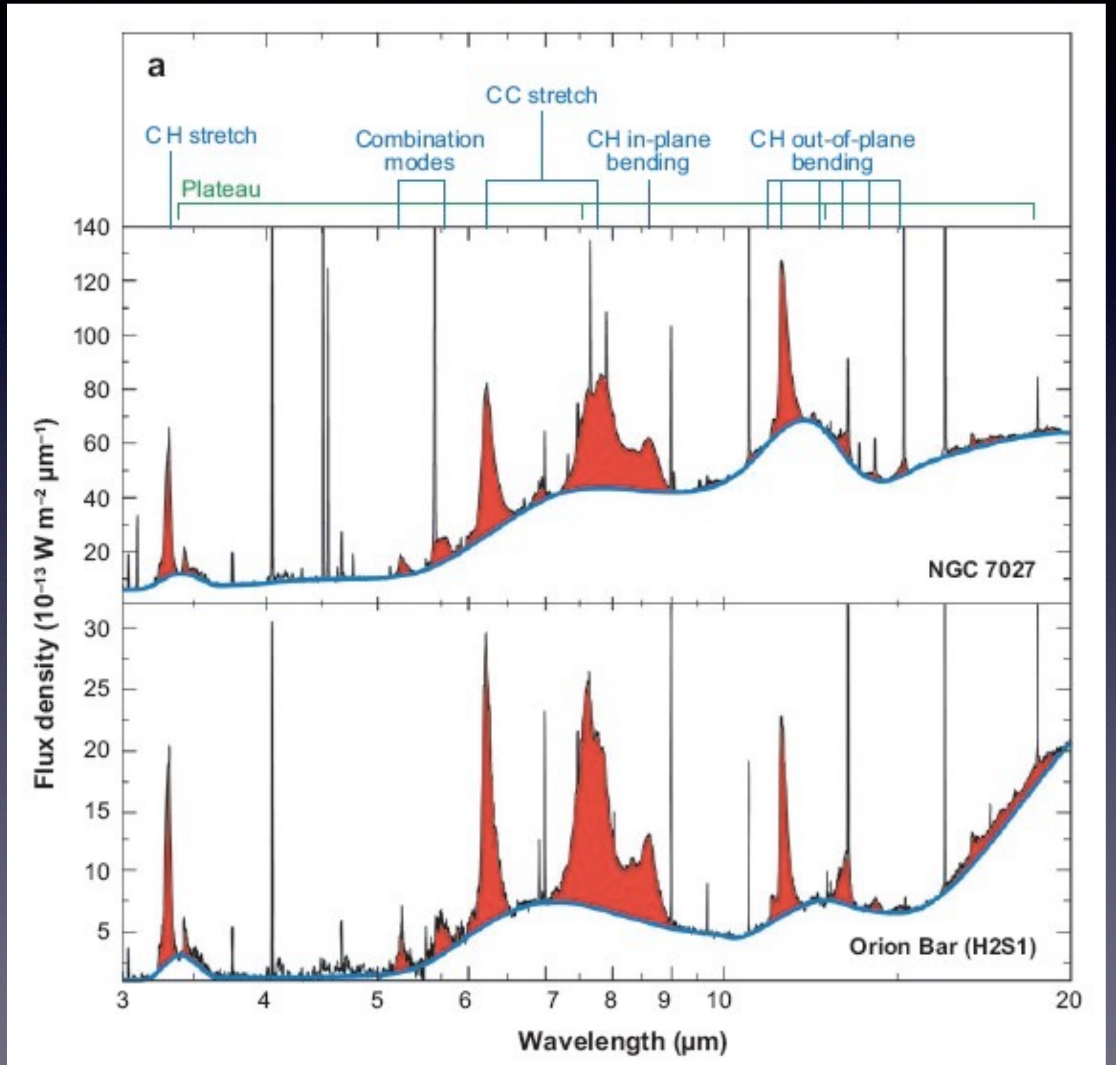
Photo-electric Heating Efficiency



$$\epsilon = \frac{4.87 \times 10^{-2}}{1 + 4 \times 10^{-3} \gamma^{0.73}} + \frac{3.65 \times 10^{-2} (T/10^4)^{0.7}}{1 + 2 \times 10^{-4} \gamma}.$$

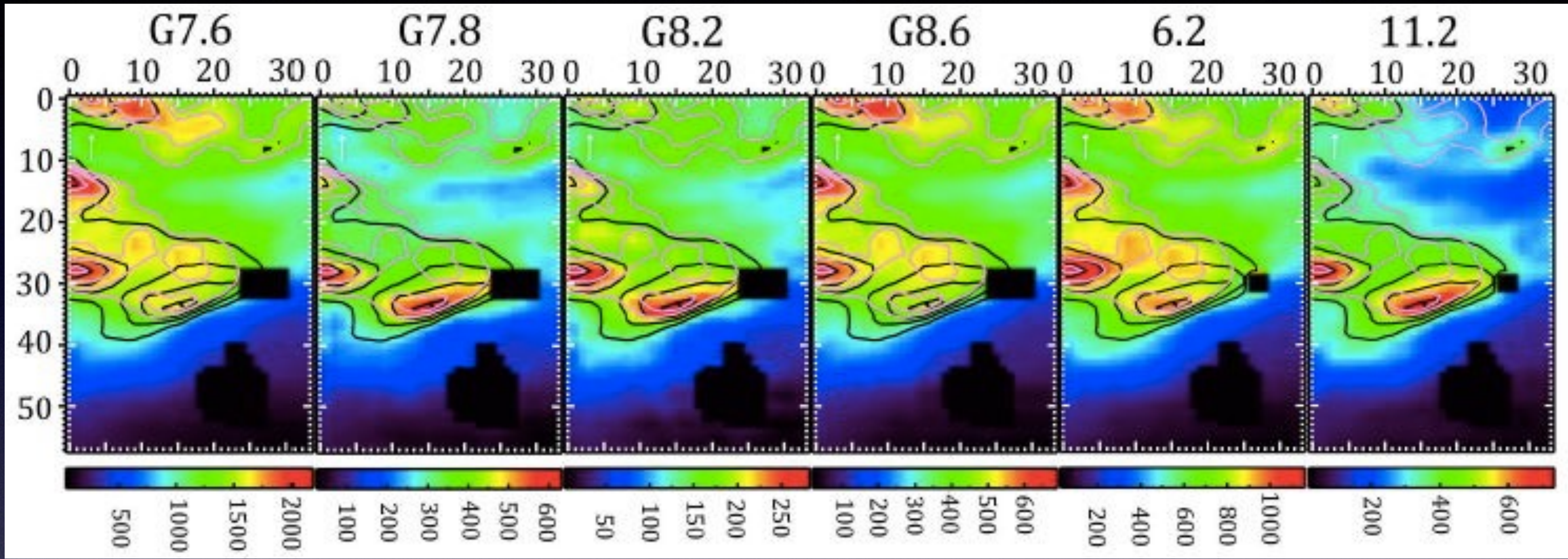
Bakes & Tielens, 1994, ApJ, 427, 822

The incredibly rich spectrum of interstellar PAHs



Peeters et al, 2002, A&A,390, 1089

Chemical Variations

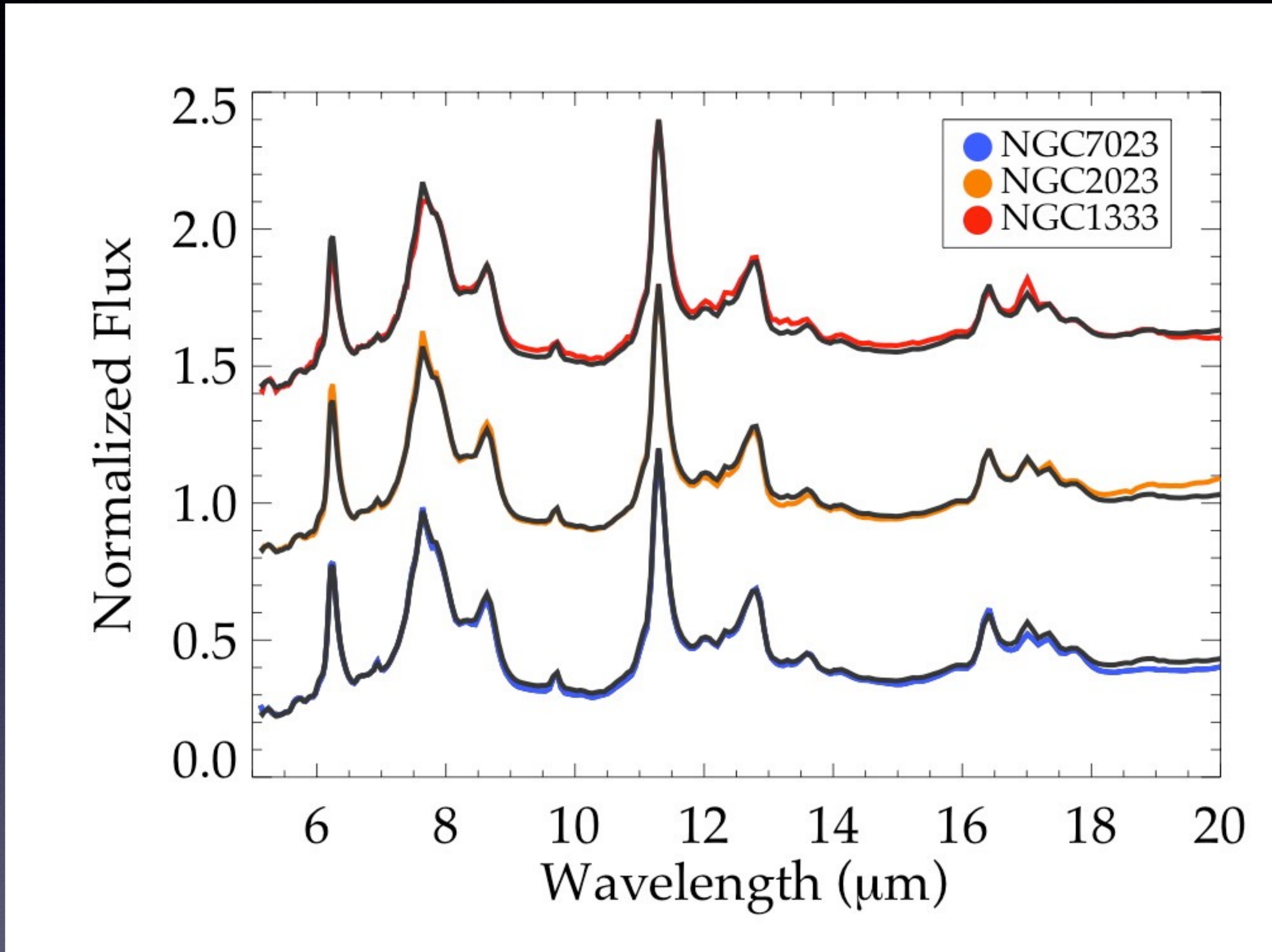


Spatial distribution of PAH emission components in NGC 2023 reveals presence of multiple carriers & chemical variations

Yet, extreme positions in different nebulae have similar spectra

Peeters et al, 2016, submitted

‘GrandPAH’



In “hot spots”, the interstellar PAH family seems to be dominated by a few, large, very stable, compact PAHs

Andrews et al, 2015, ApJ, 807, 99
Werner et al, 2009, AAS, 213, 412.15

GrandPAHs cont.

Under extreme conditions, IR emission spectra are very similar

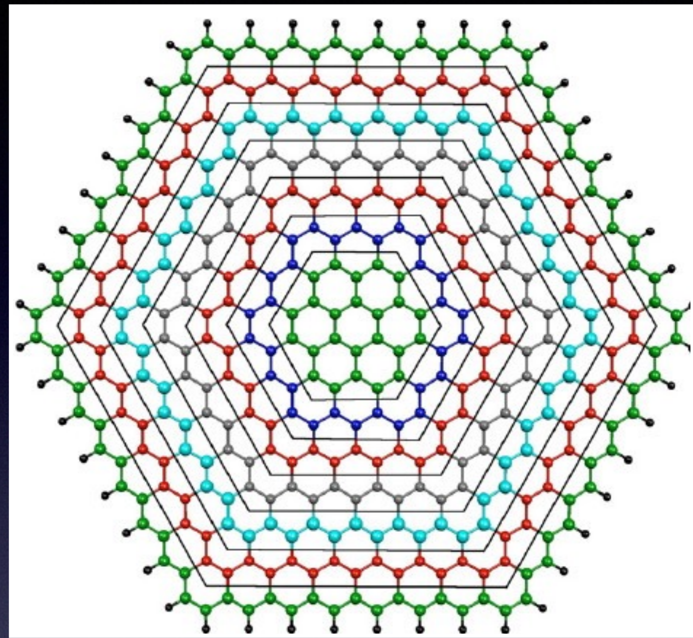
Database analysis:

- Limited number of species can contribute
- Subtle spectral variations among intrinsic PAH spectra imply very limited differences between PAH populations
- Abundance variations are less than 30%

15-20 μm region dominated by a few bands (16.4/17.4/17.8 μm)

- A few, large, compact PAHs dominate the population

C_{60} as the (photo-processed) grandson

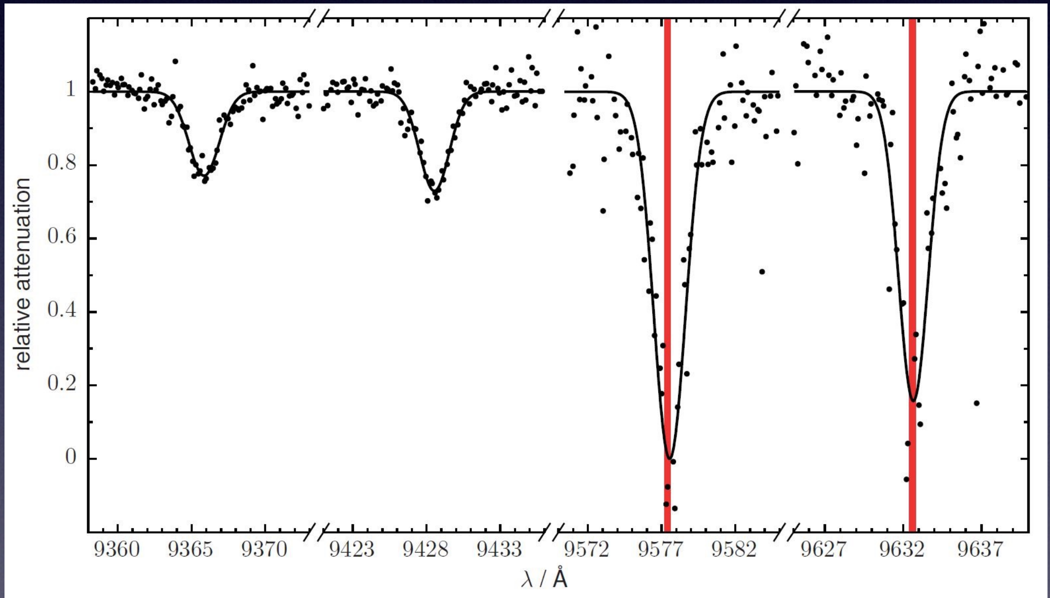


circumcoronene family

Andrews et al, 2015, ApJ, 807, 99

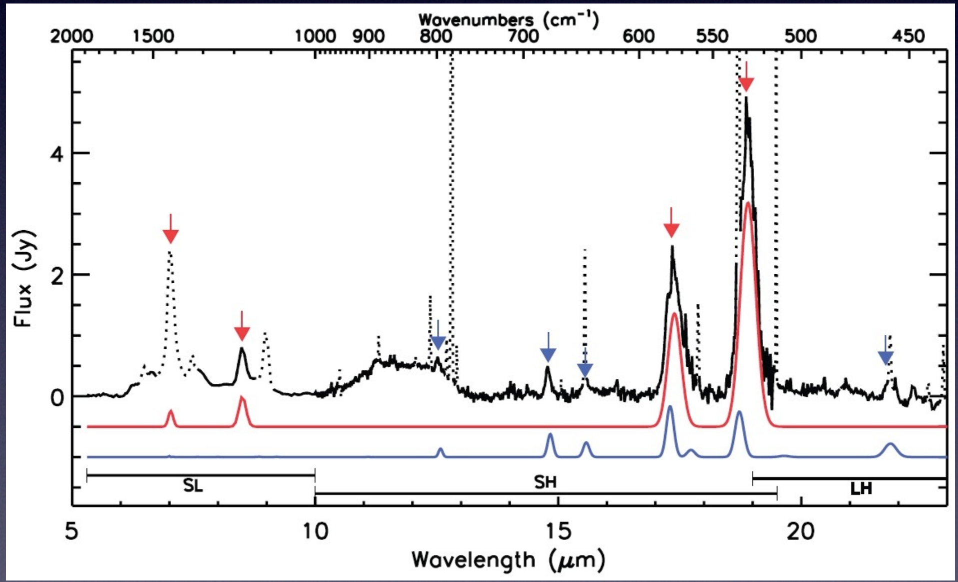
The Largest Molecule in Space: C_{60}

C_{60}^+ & the DIBs

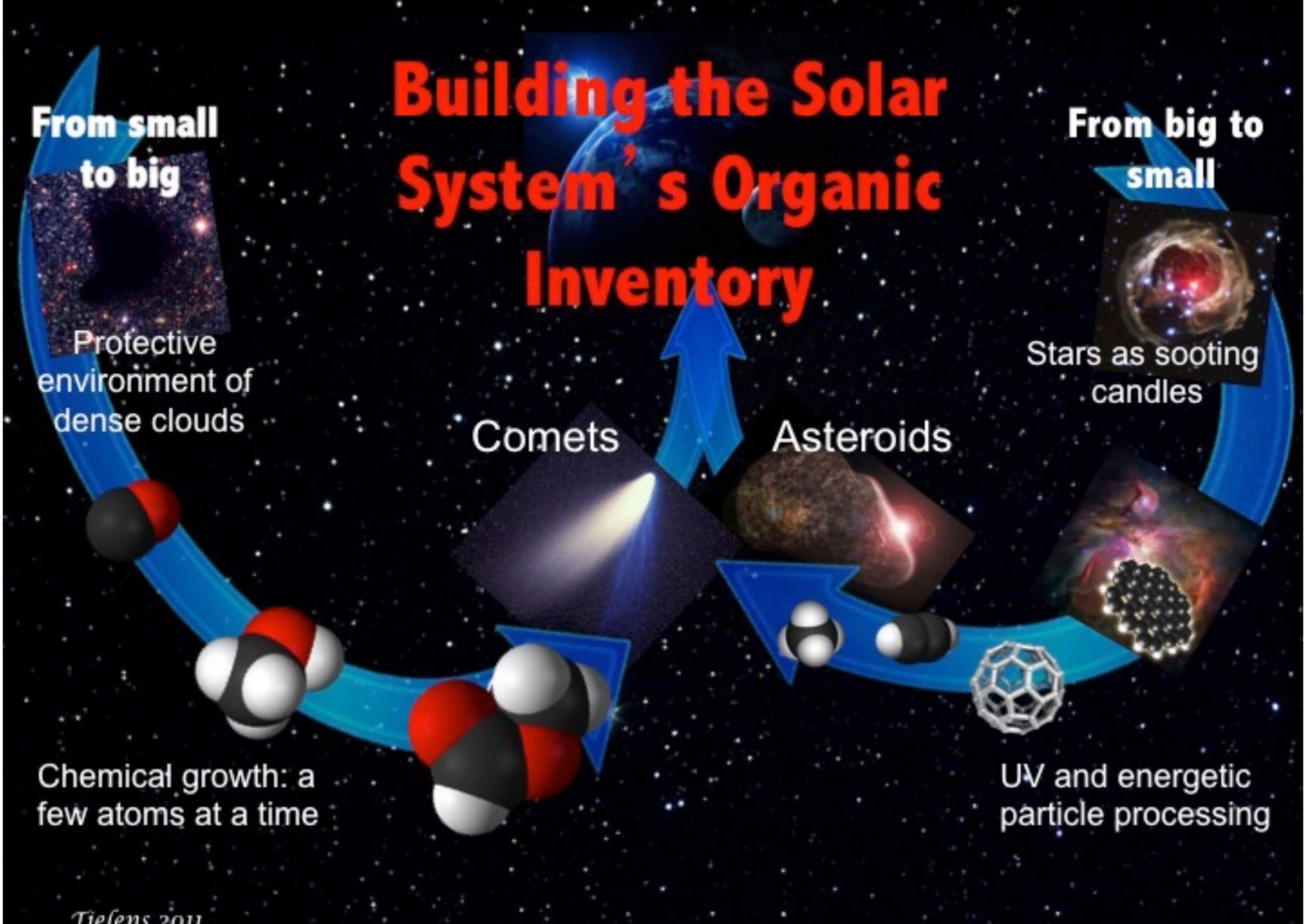


Campbell et al, 2015, Nature, 523, 322

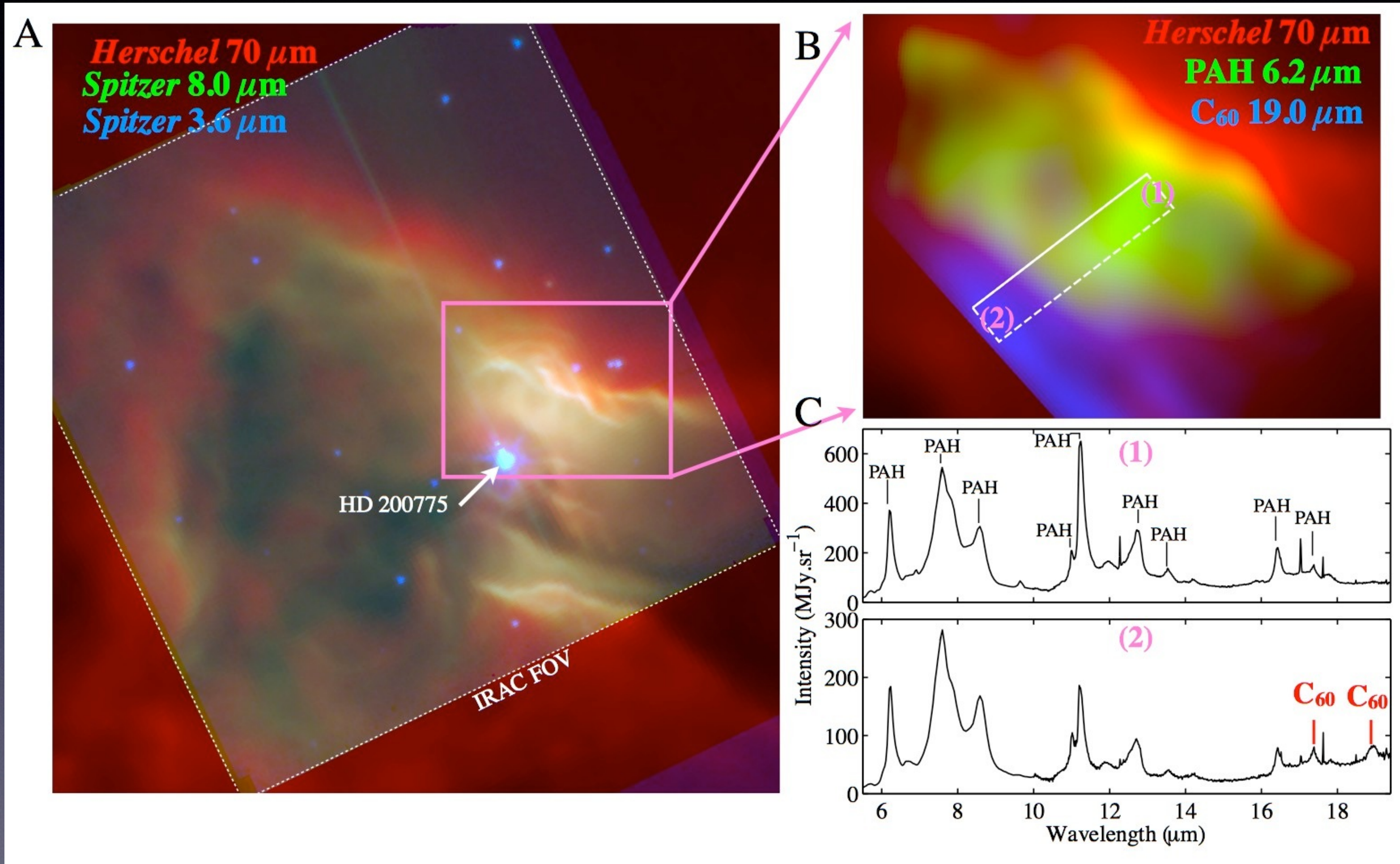
C_{60} in the PNe, TC1



Cami et al, 2010, Science, 329, 1180

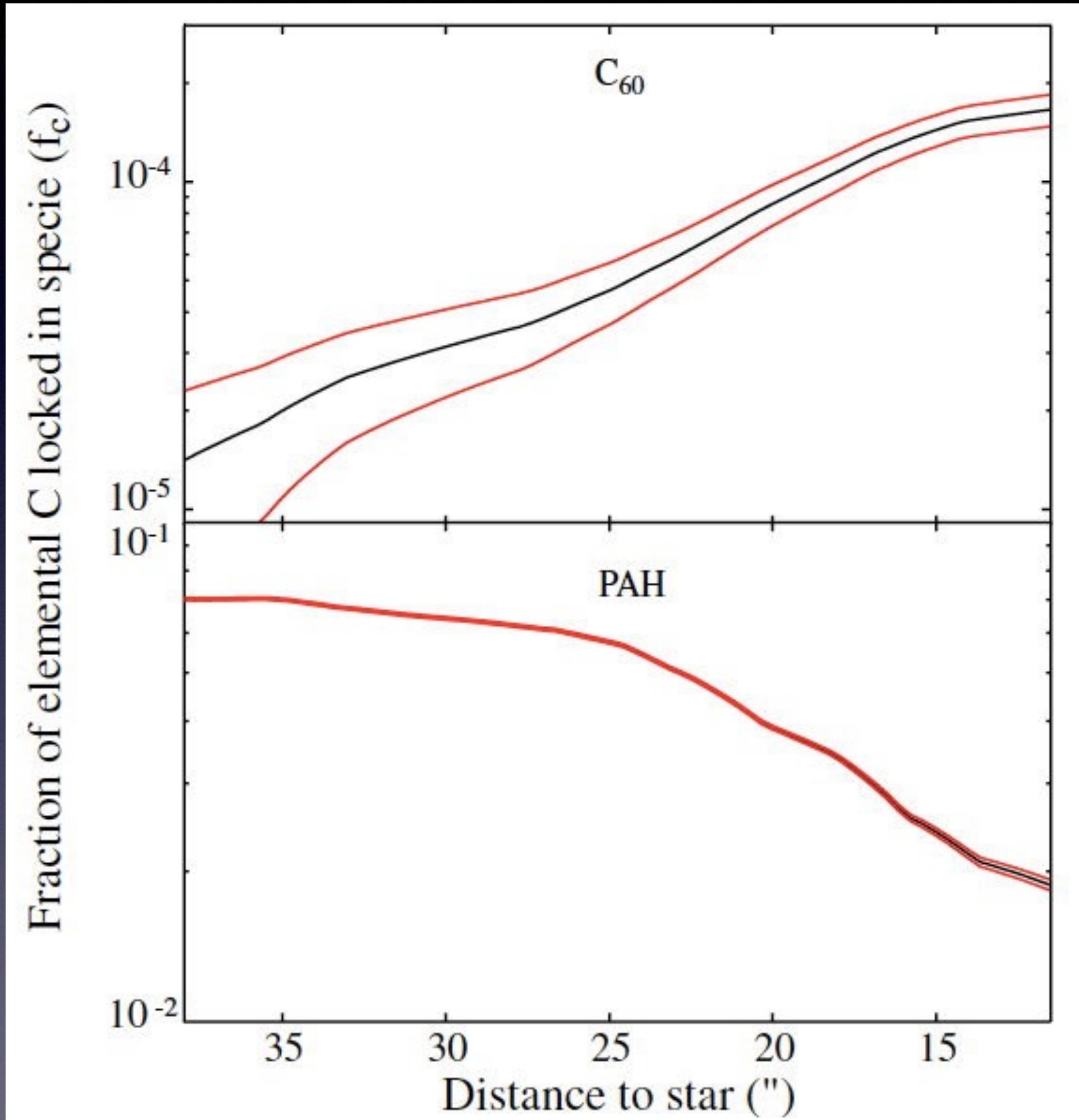

Building the Solar System's Organic Inventory
From small to big
Protective environment of dense clouds
From big to small
Stars as sooting candles
Comets
Asteroids
Chemical growth: a few atoms at a time
UV and energetic particle processing
Tielens 2011

PAHs & C_{60} in NGC 7023



Berne & Tielens, 2012, PNAS, 109, 401

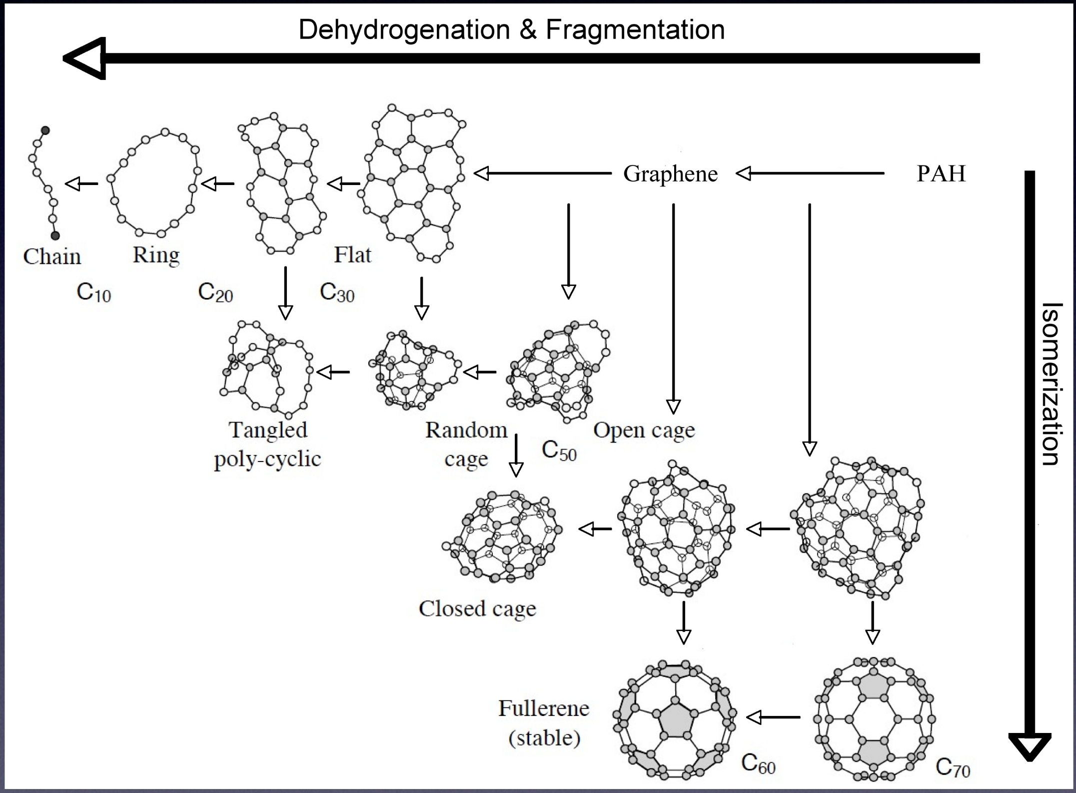
PAHs & C_{60} abundance



Berne & Tielens, 2012, PNAS, 109, 401

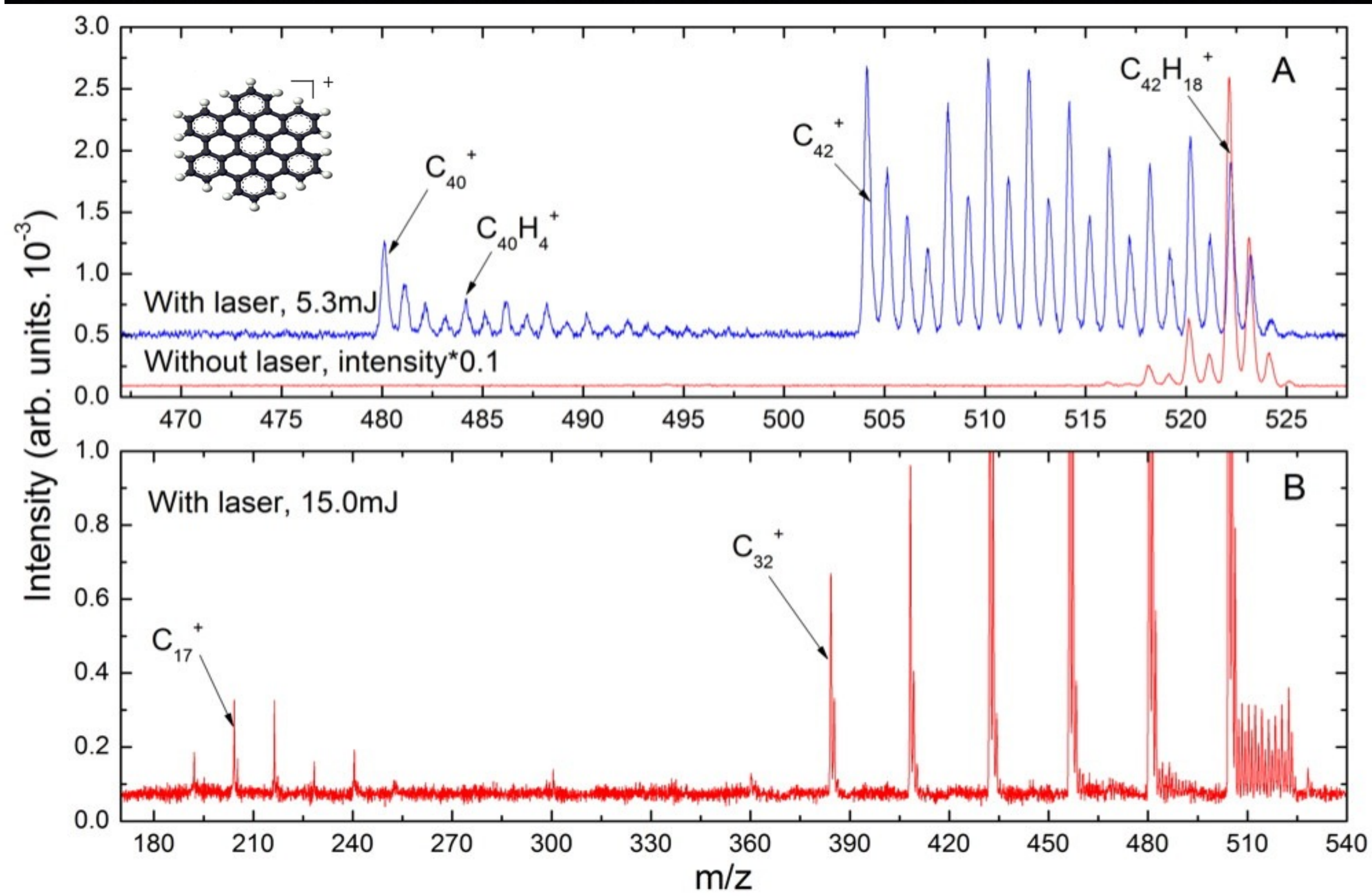
PAH photolysis

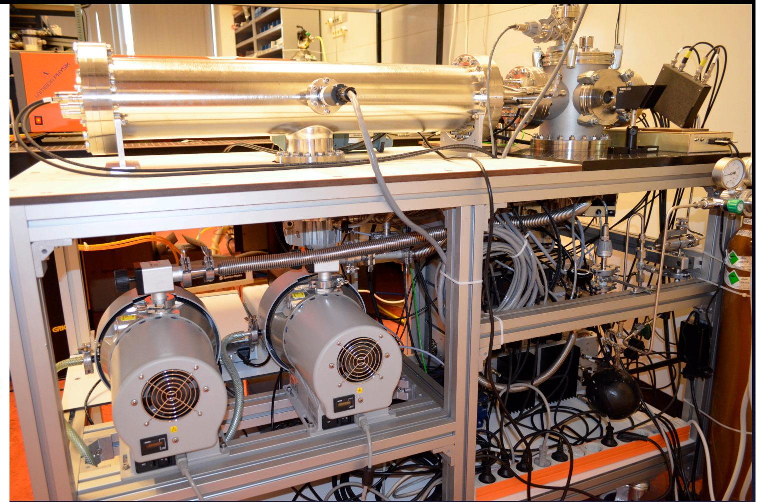
- Dehydrogenation & isomerization
- Stable intermediaries: cages & fullerenes
- Fragmentation products: hydrocarbon chains & radicals



Berne & Tielens, 2012, PNAS, 109, 401
Pety et al, 2005, A&A, 435, 885
Wehres et al, 2010, A&A, 518, 36

PAHs Photolysis



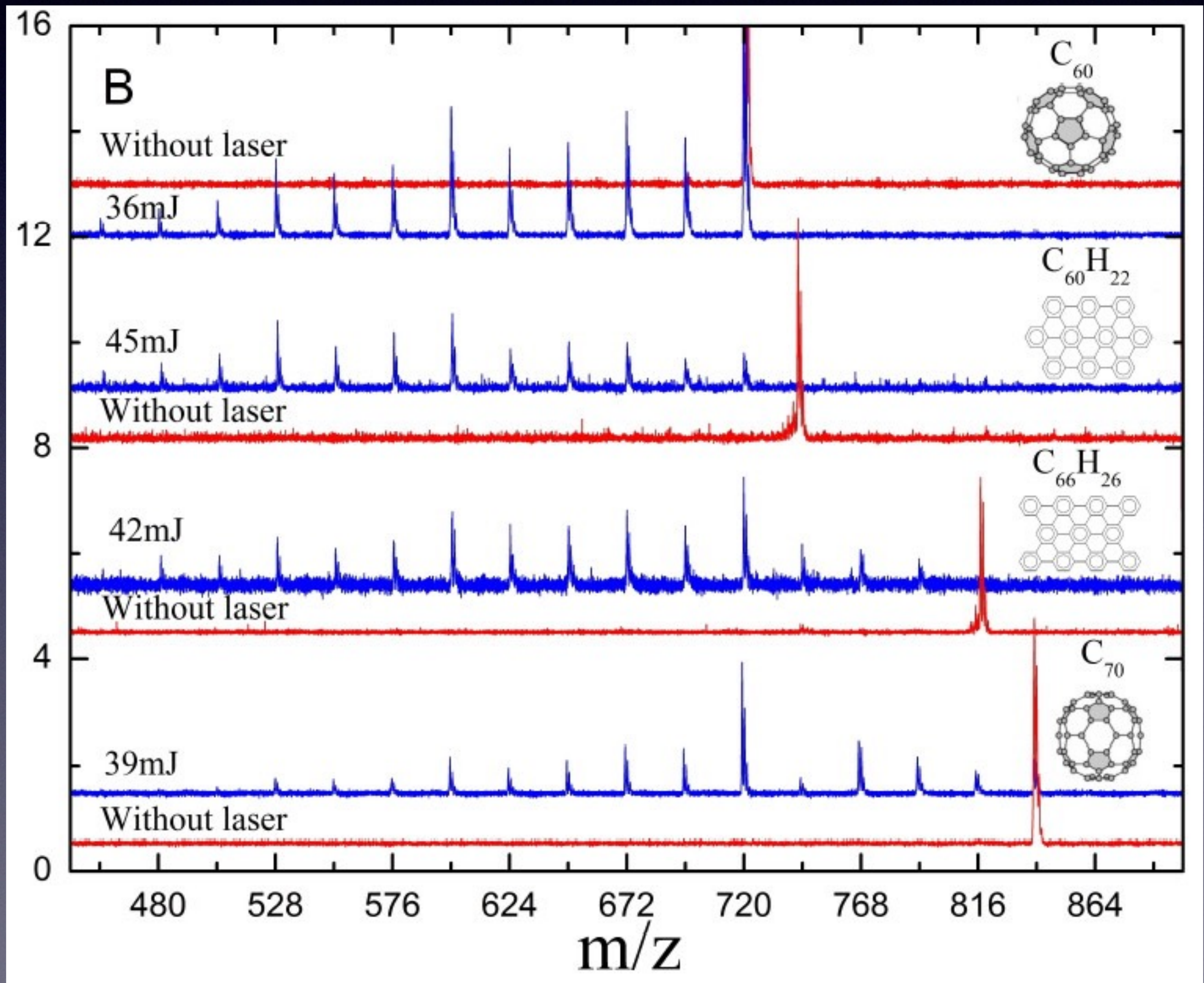


Ekern et al, 1997, ApJ, 488 L39
Joblin et al, 2003, Edp. Sci. Conf. Ser. 175
Zhen et al, 2014, Chem Phys Lett, 592, 211

- Multiphoton absorption leads to fragmentation in a laser pulse
- Many pulses strip the molecule down
- Loss of all H followed by loss of C_2 and C units (magic numbers)

From PAHs to C_{60}

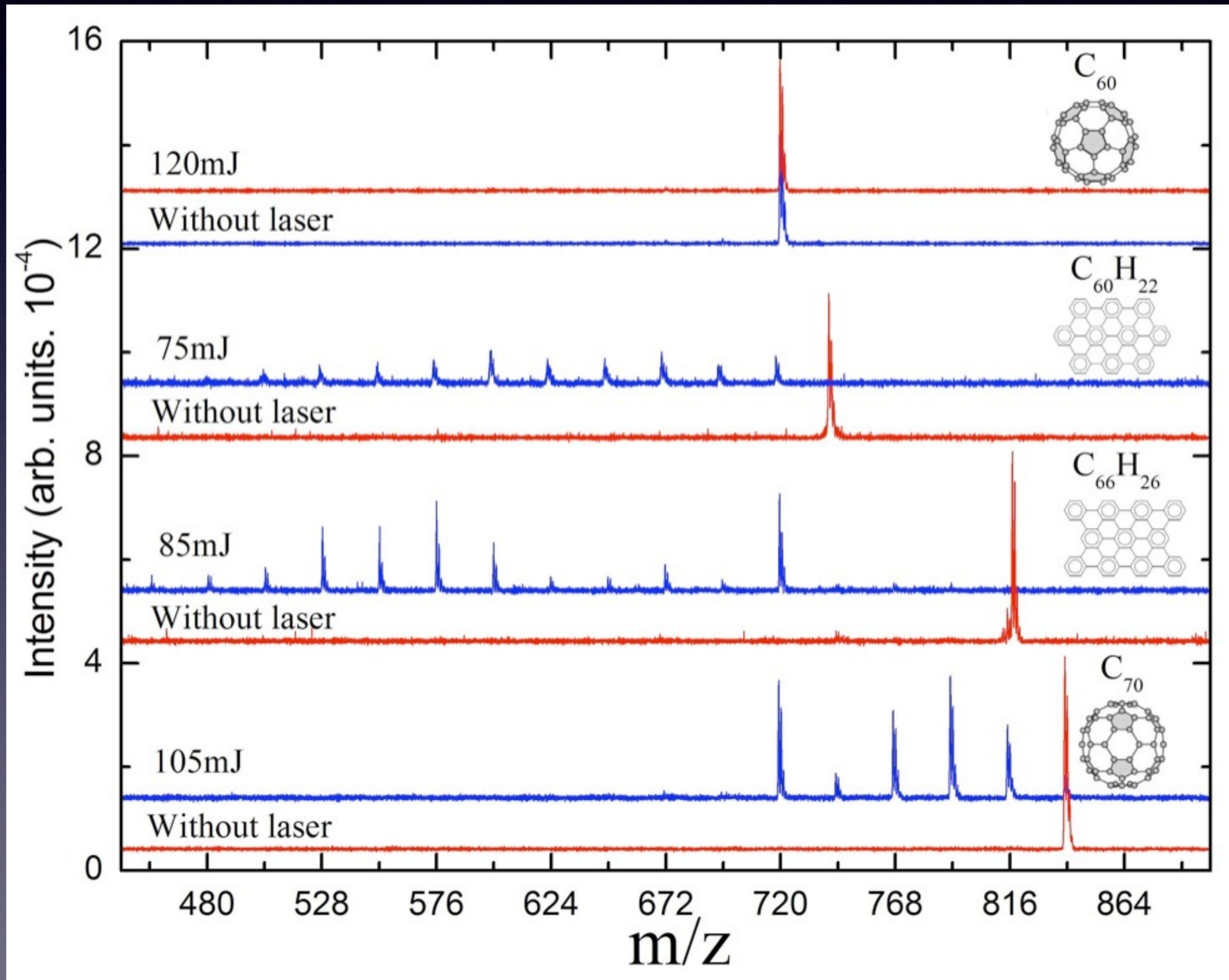
UV photolysis at 355 nm



Zhen et al, 2014, ApJ, 797, L30

From PAHs to C_{60}

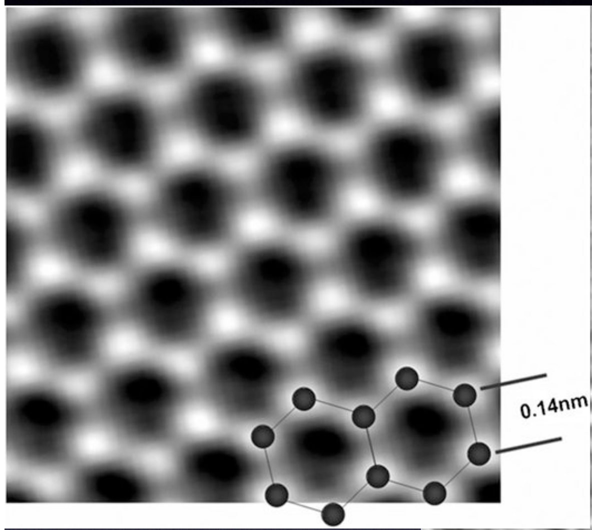
UV photolysis at 532 nm

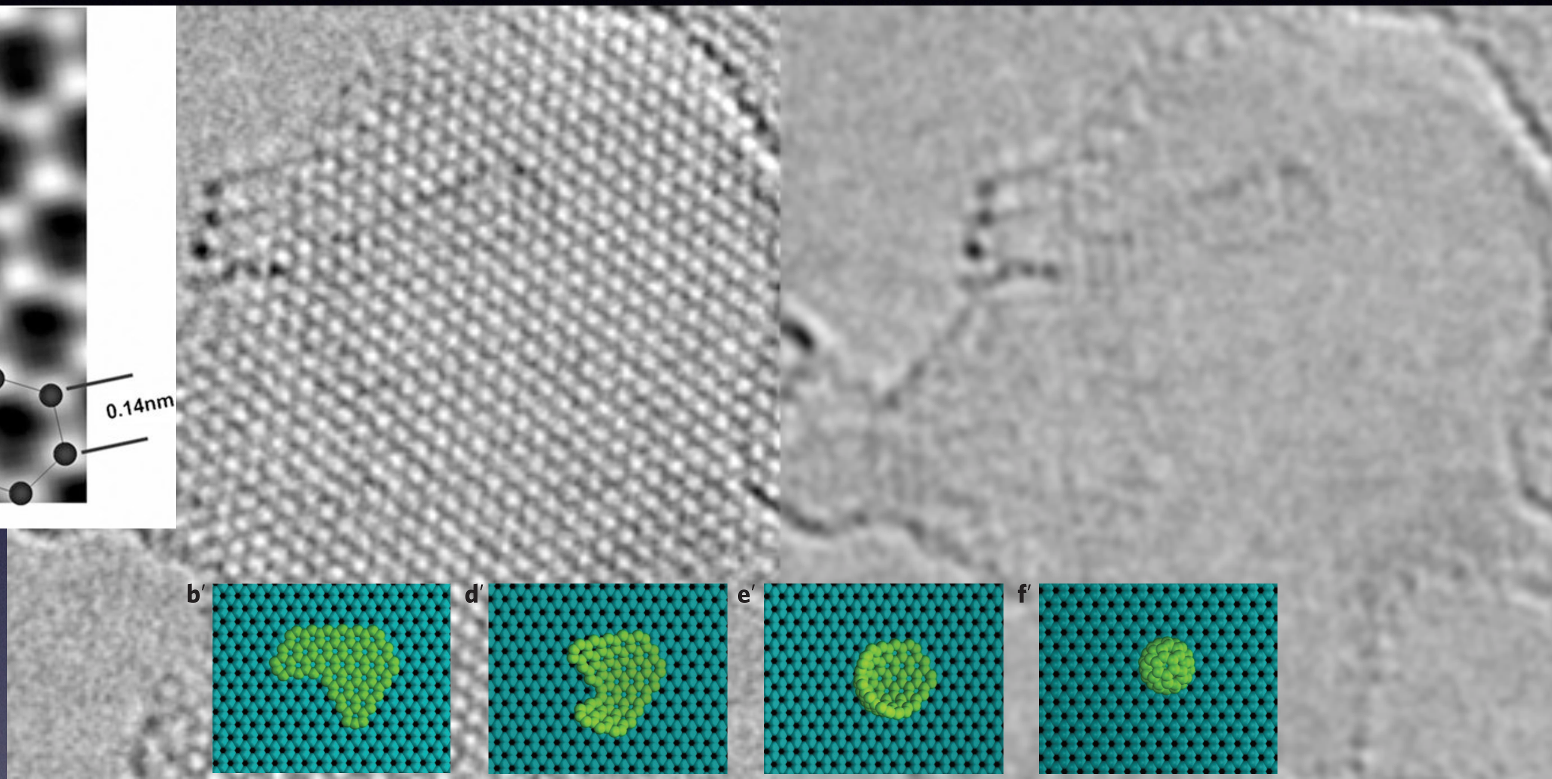


Zhen et al, 2014, ApJ, 797, L30

From Graphene to C_{60}

[National Center for electron microscopy]

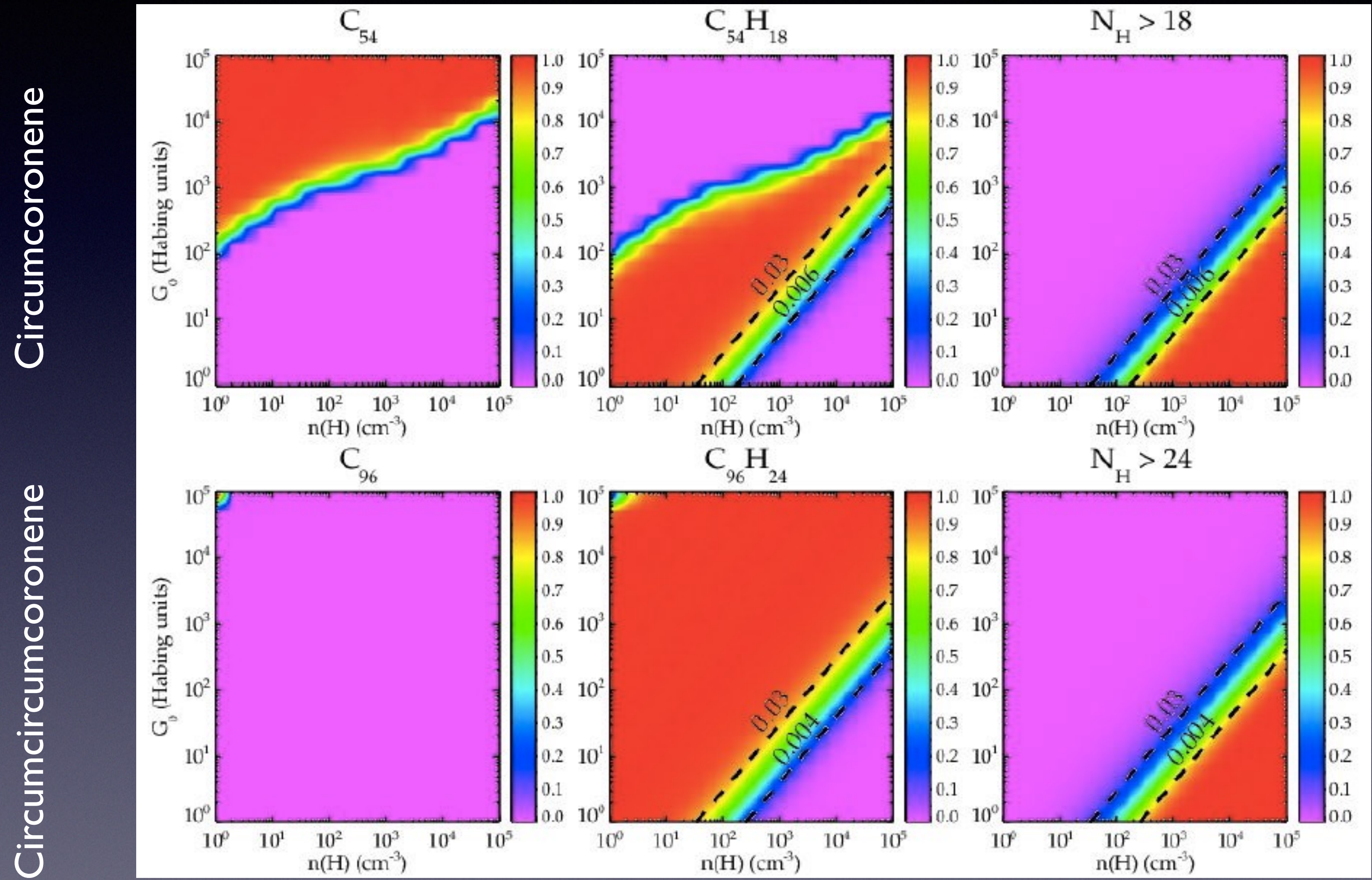




[Chuvilin et al. Nature Chem. 2010]

Transformation of graphene to C_{60}, driven by electron irradiation

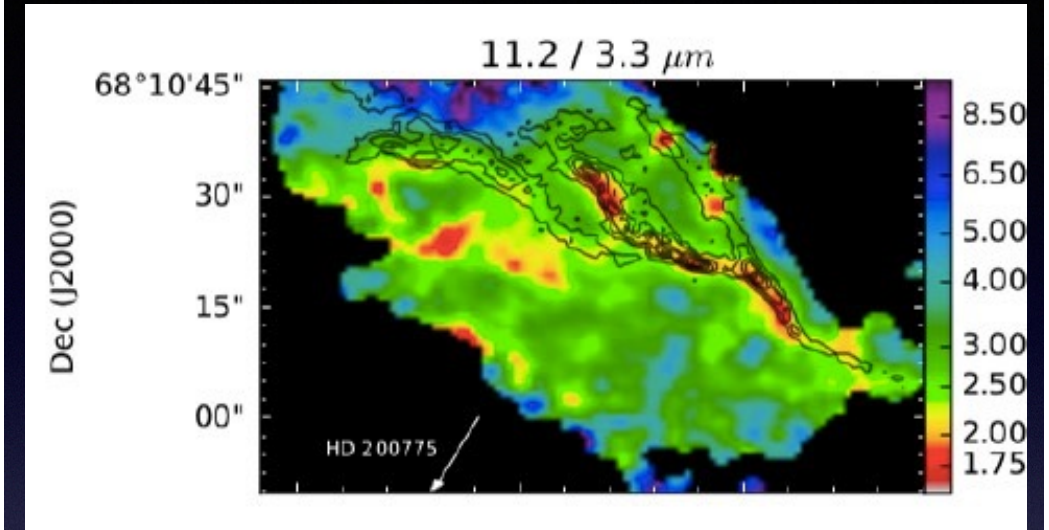
UV Processing in Space

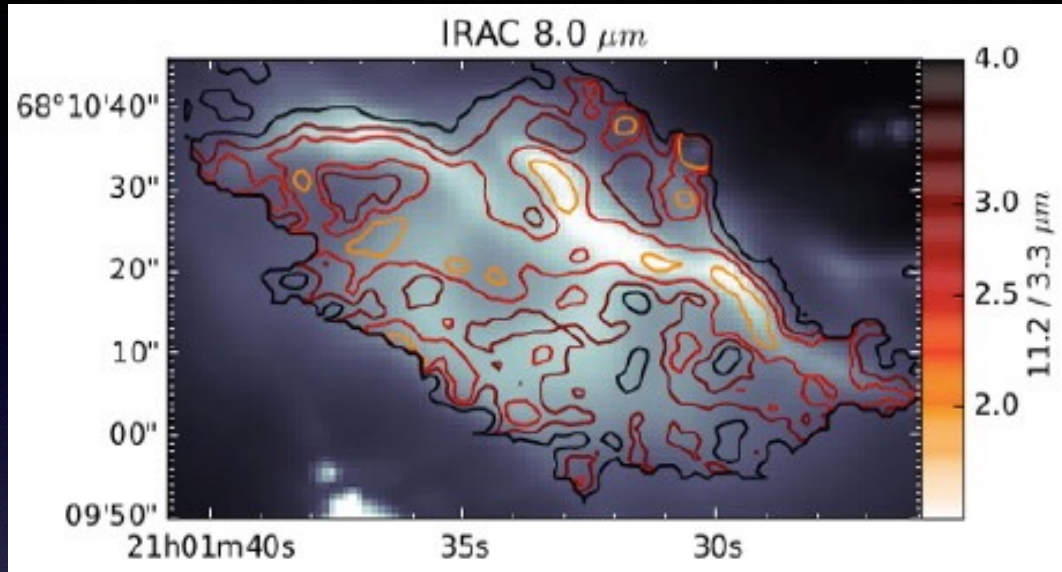


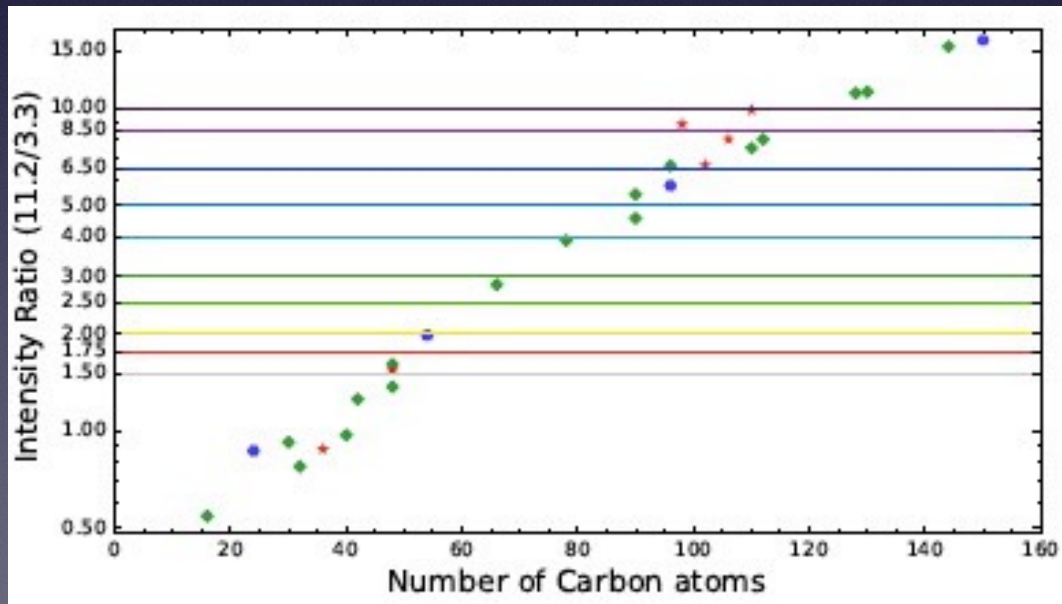
Bare clusters fully hydrogenated Superhydrogenated

Andrews et al, 2016, in prep
Montillaud et al, 2013, A&A, 552, A15

SOFIA & the Interstellar PAHs size





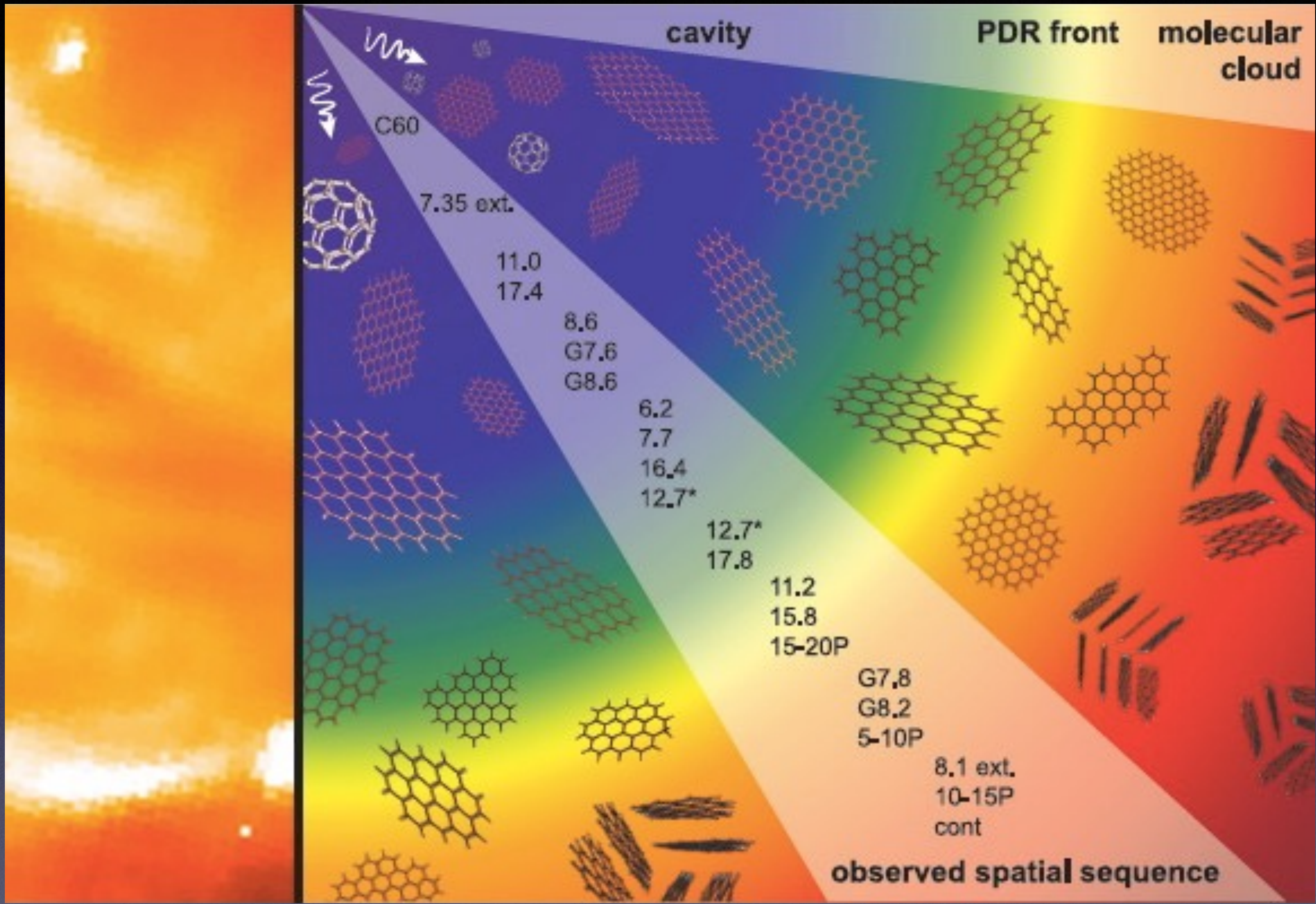


The 11.2/3.3 μm ratio measures PAH size

Factor ~2 variations in PAH size over the PDR

Croiset et al, 2016, A&A, 590, A26

PAH evolution in PDRs



Andrews et al, 2015, ApJ, 807, 99
Peeters et l, ApJ, submitted

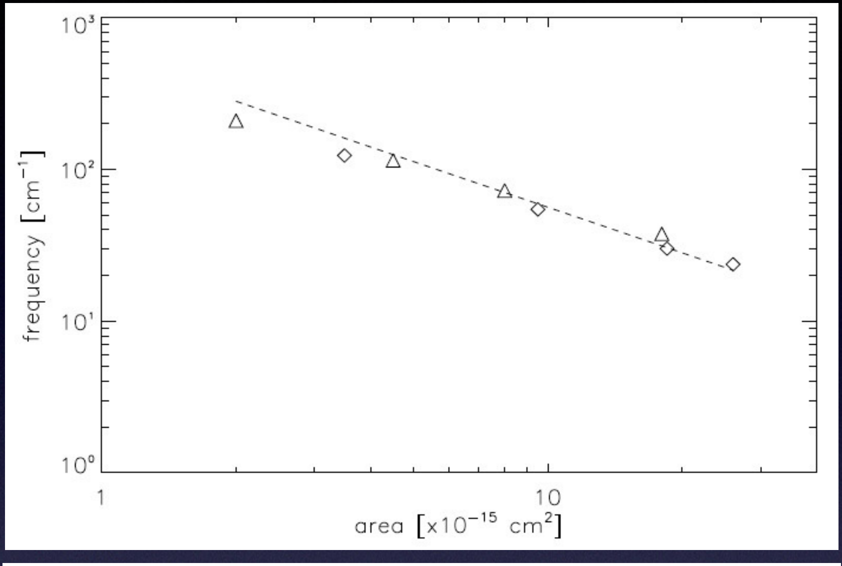
As the gas flows through the PDR and into the cavity, PAH clusters fall apart, the PAHs get converted into the most stable ones (GrandPAHs), and then destroyed or converted into C_{60} and other cages

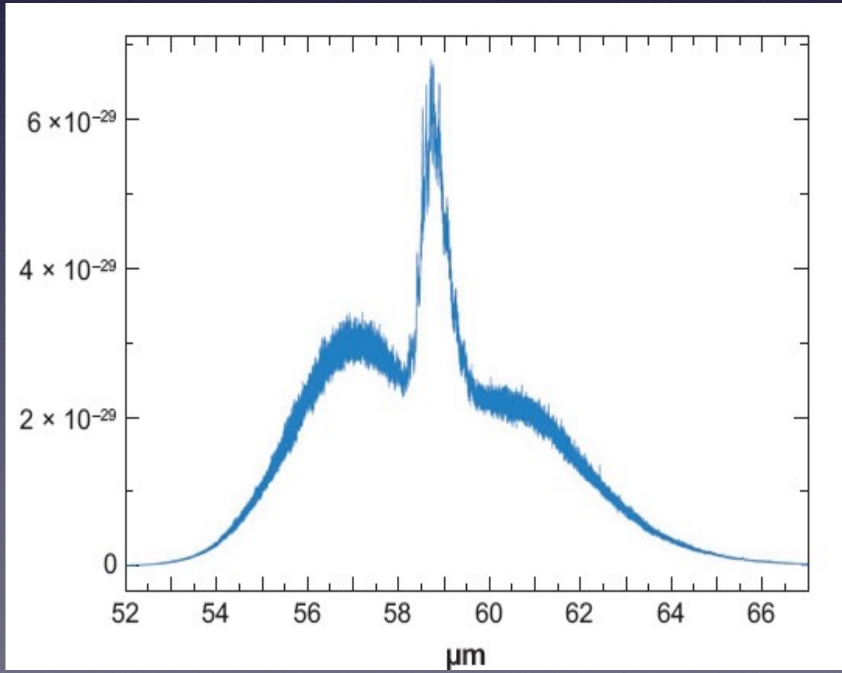
Looking for mr 'GrandPAH'

The interstellar PAH family seems to be dominated by a few, large, very stable, compact PAHs

Identification of specific PAHs

- Drumhead or jumping jack modes: Lowest-lying vibrational state will emit when the modes have decoupled and will show rotational substructure
- Pure rotational spectra: Anomalous microwave emission

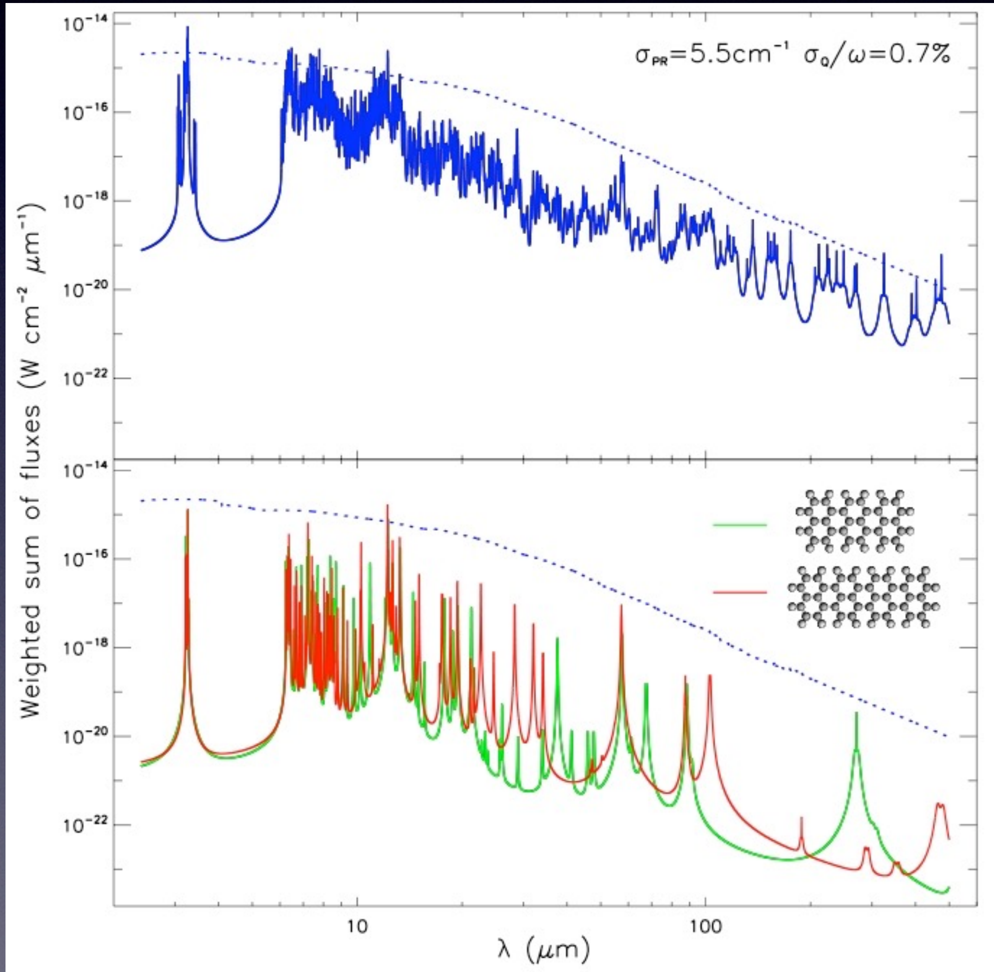




Mulas et al, 2006, A & A, 456, 161, Boersma et al, 2010, A&A, 511, A32, Ricca et al, 2012, ApJ, 754, 75

Looking for mr ‘grandPAH’

- A spectroscopists approach: The far-IR ‘drum head’ or Jumping Jack modes are highly molecule specific
- “Blind” approach: Spectral-spatial survey of many sources. Can identify GrandPAH modes if X>0.15



Calculated spectrum for the Red Rectangle

Mulas et al, 2006, A & A, 456, 161

Photo-electric efficiency & the GrandPAH

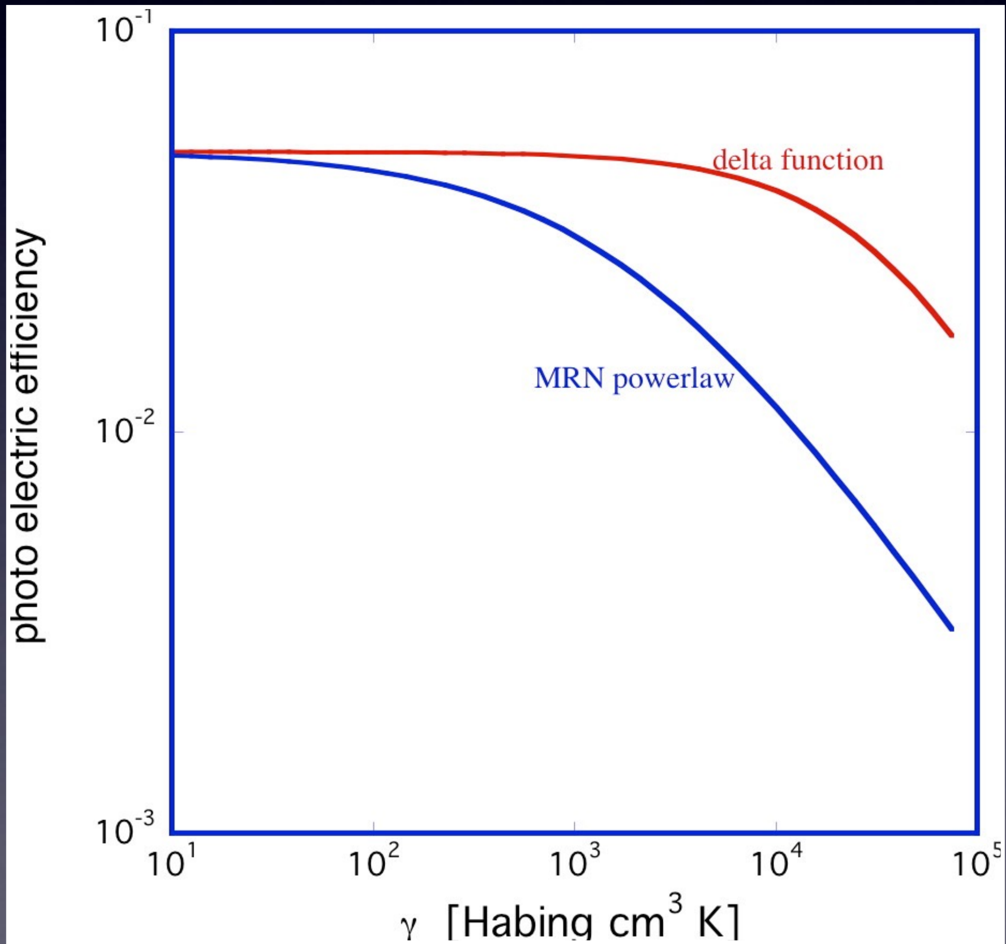
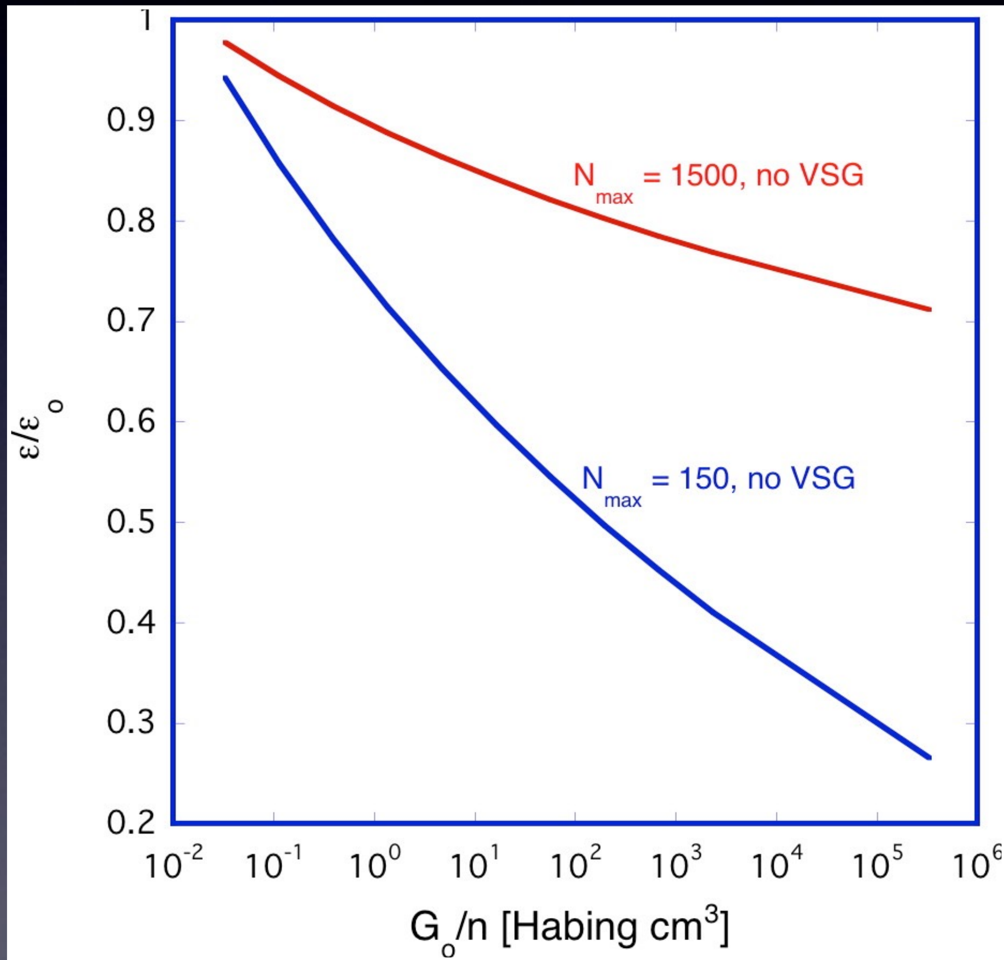


Photo-electric efficiency & size distribution

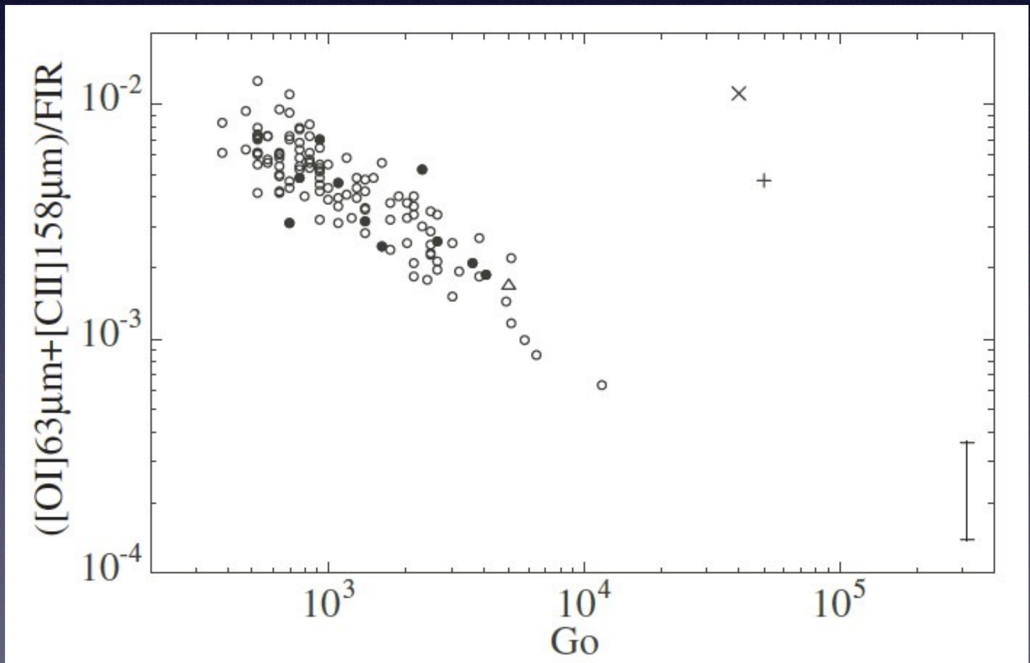
- Starting from an MRN distribution ranging from N_{min} (G_0/n) to N_{max}
- VSGs = PAH clusters, evaporate far from star (50” for NGC 7023)
- Small PAH destruction depends on G_0/n



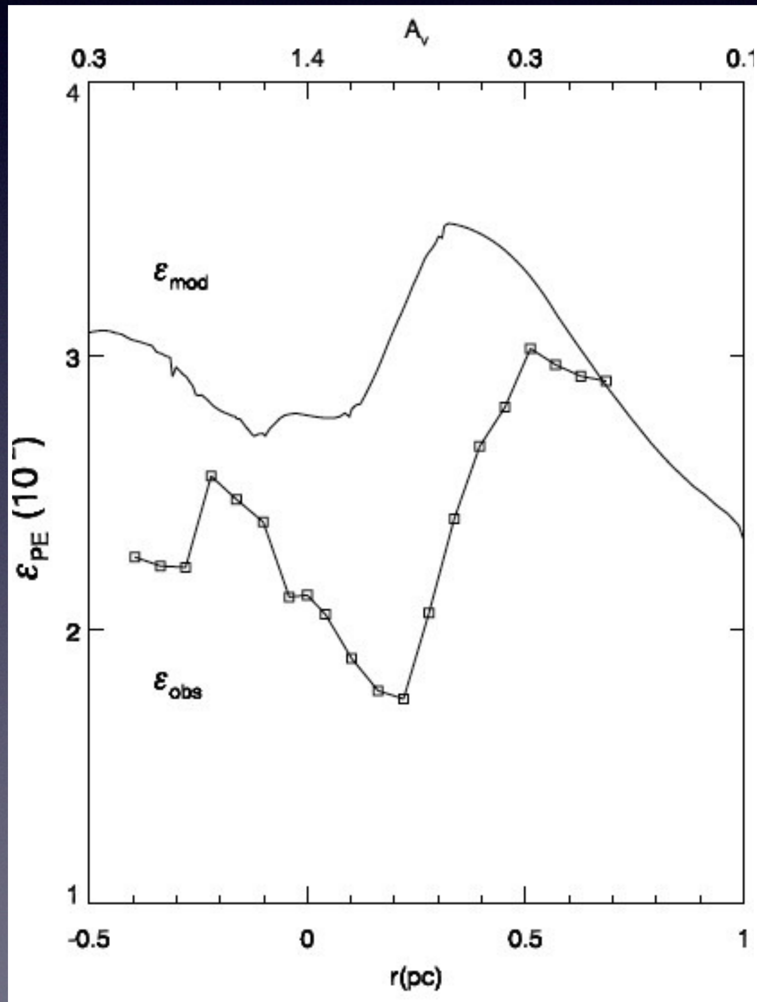
Berne & Tielens, 2012, PNAS, 109, 401
Rapacioli et al, A&A, 429, 193

PDRs as Laboratories

Carina Nebula

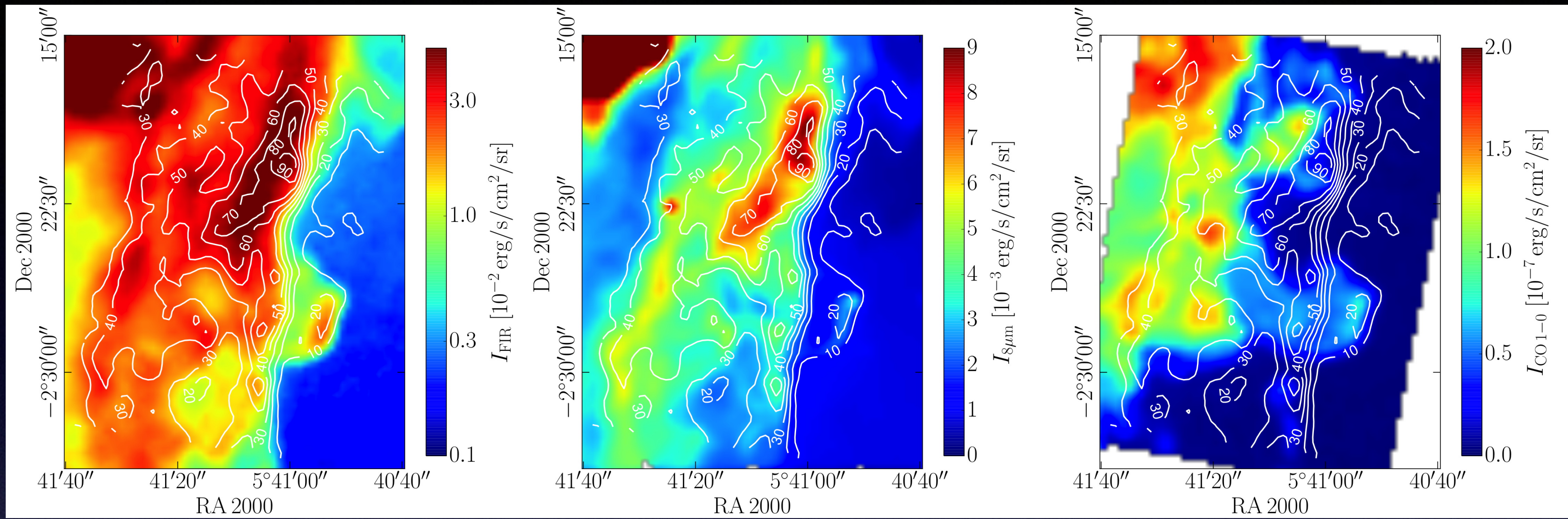


across the ρ Oph cloud



Habart et al, 2001, A&A, 373, 702
Mizutani et al, A&A, 2004, 423, 579

SOFIA Study of [CII] 158 µm in L1630

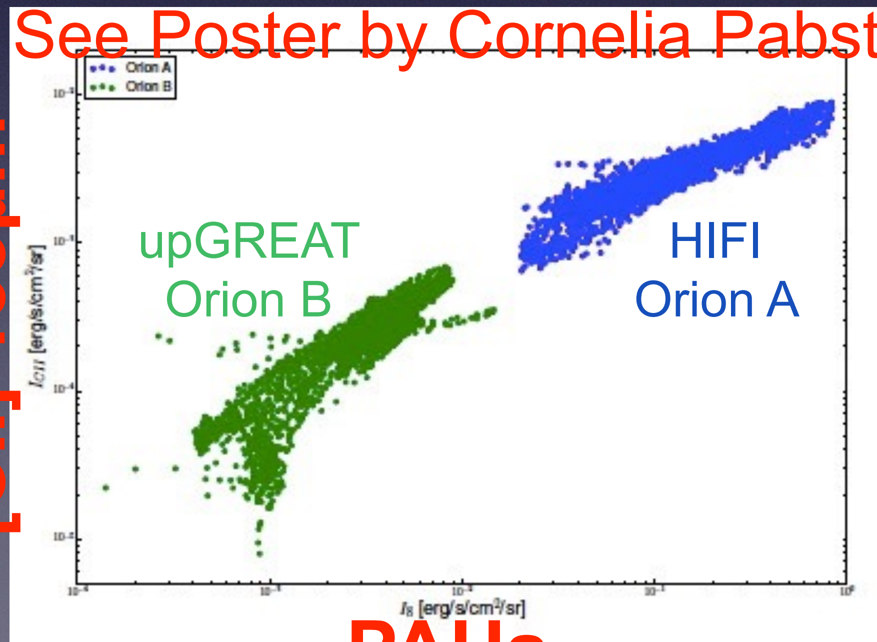


FIR PAHs CO

Note: CO-dark gas

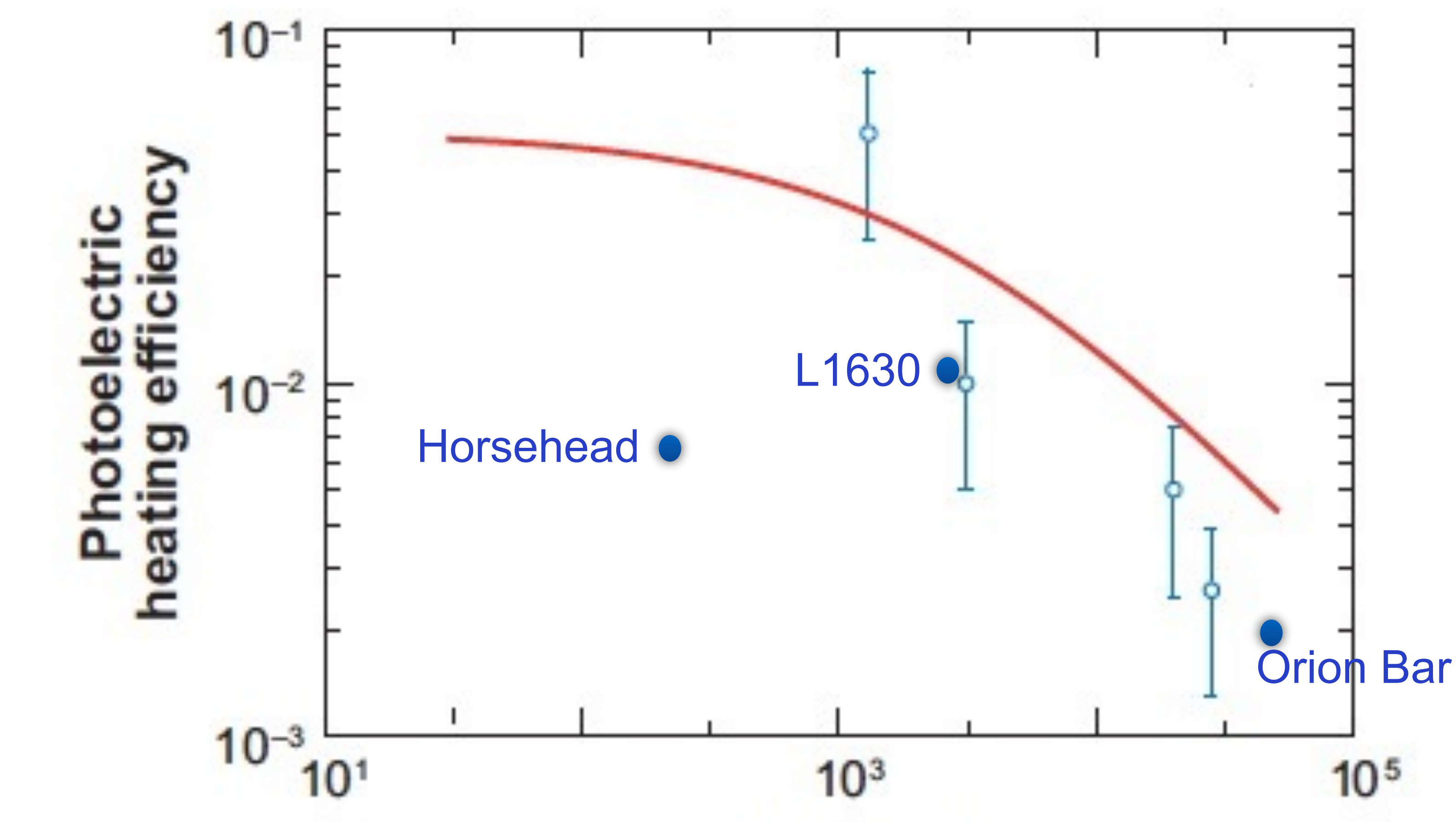
PDR Energy Balance:

CII as the cooling agent
PAHs as the heating agent



Pabst et al 2016, in preparation

SOFIA & Photo-Electric Effect

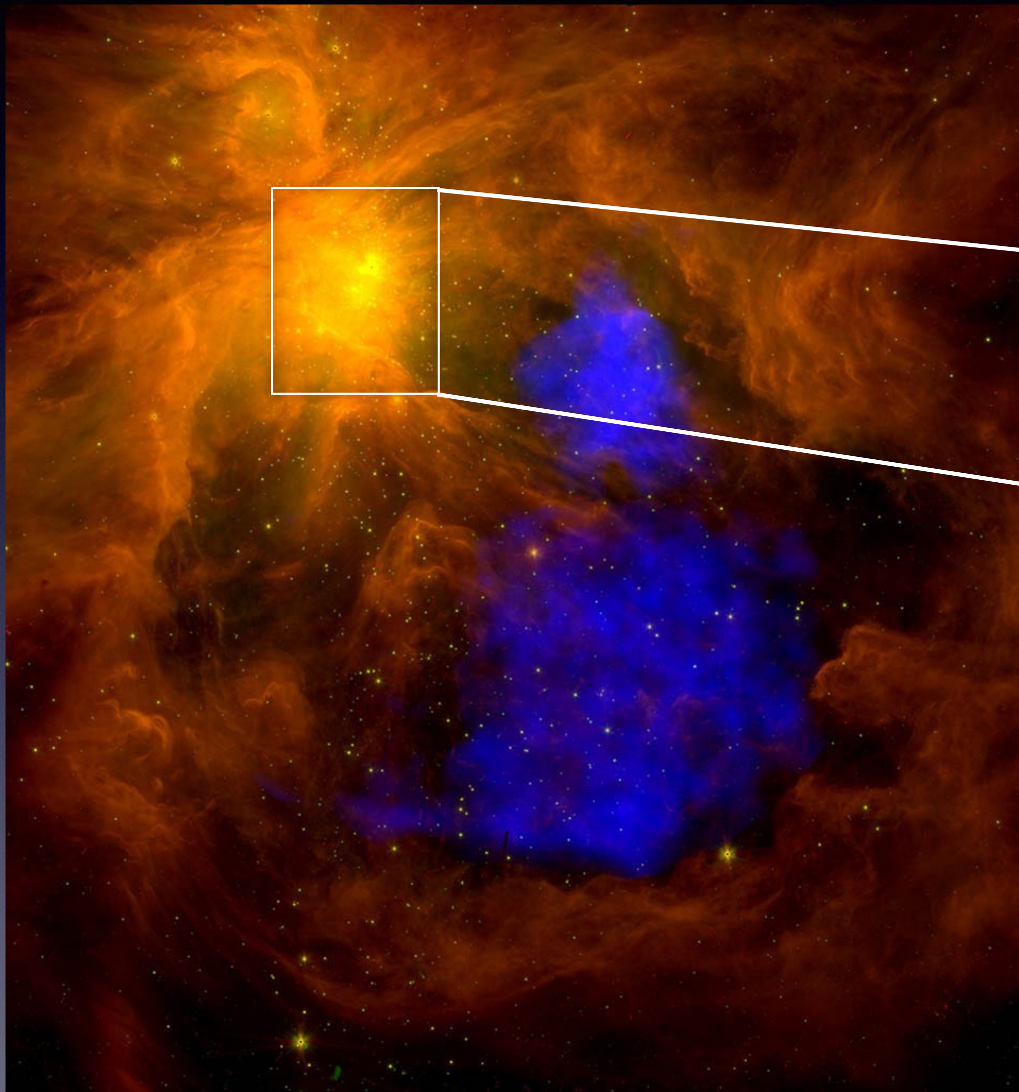


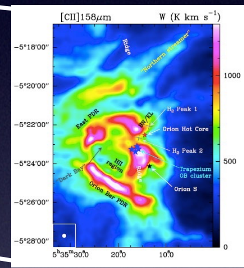
$G_0T^{1/2}/n_e$

SOFIA & the photo-electric effect

Salgado et al, 2016, ApJ, in press
Pabst et al 2016, in preparation

SOFIA & the Radiative and Kinetic Interaction of the Trapezium Stars with the ISM





HIFI/Herschel
100 sq arc min in ~20 hrs

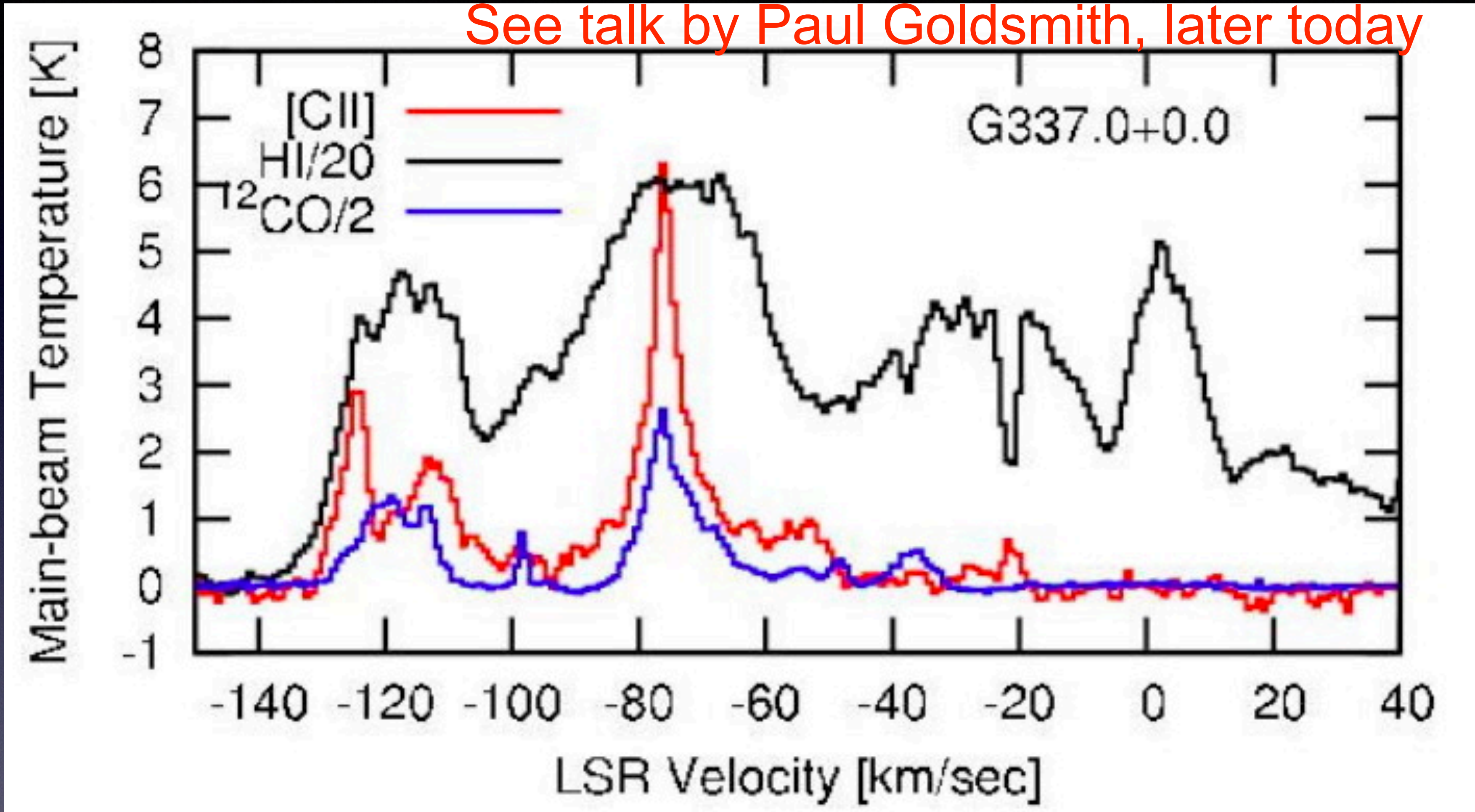
upGREAT/SOFIA
~1 sq degree in ~40 hrs

Structure of the ISM

Probing the Phases of the ISM

- Observationally, the phases of the ISM are not well characterized
- This is changing with [CII] 158μm and Carbon Radio Recombination Line surveys:
  - GOTC+
  - upGREAT/SOFIA
  - STO2
  - and hopefully: GUSTO & FIRSPEX
  - LOFAR
  - SKA

GOTC+ Survey



Origin of [CII] 158μm emission:
warm, dense PDRs: 0.30; cold HI: 0.25; CO-dark: 0.25; HII: 0.20

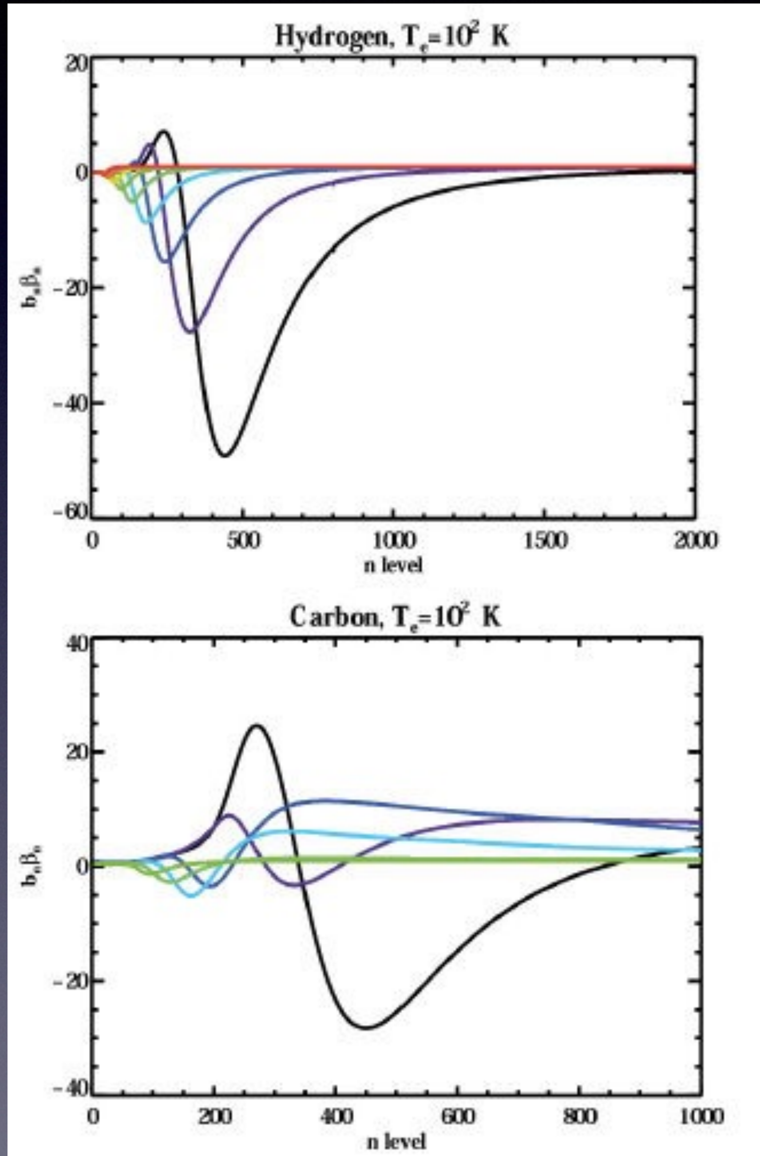
Pineda et al, 2013, A&A, 554, 103

Carbon Radio Recombination Lines

- High n states are hydrogenic
- Populated by recombination
- Dielectronic capture:

$$T_e = 50\ \mathrm{K} \Rightarrow n \approx 60$$

- *n,l* changing collisions
- Hundreds of CRRLs (n~200-1000) at 10-100MHz
- Measure physical conditions (n_e, *T*, *P*) in HI clouds
- Measure ionization rate, carbon abundance



LOFAR

Power of LOFAR

Spectral coverage

Spectral resolution

Sensitivity

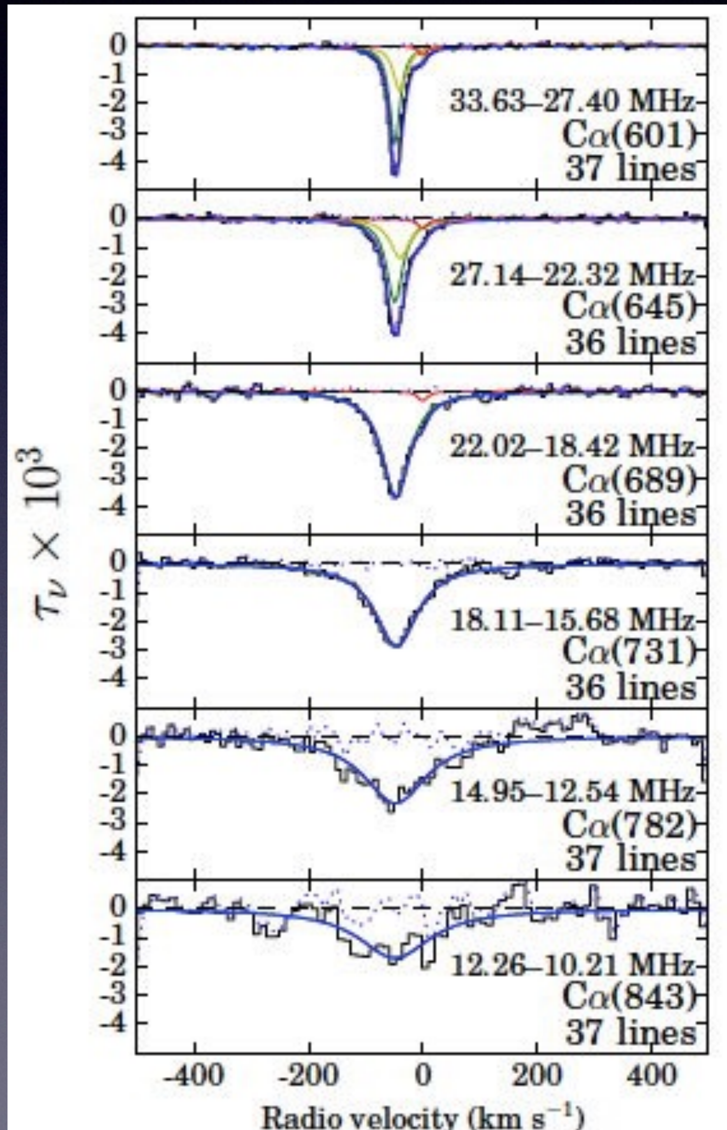
Field of view

LOFAR & CRRL

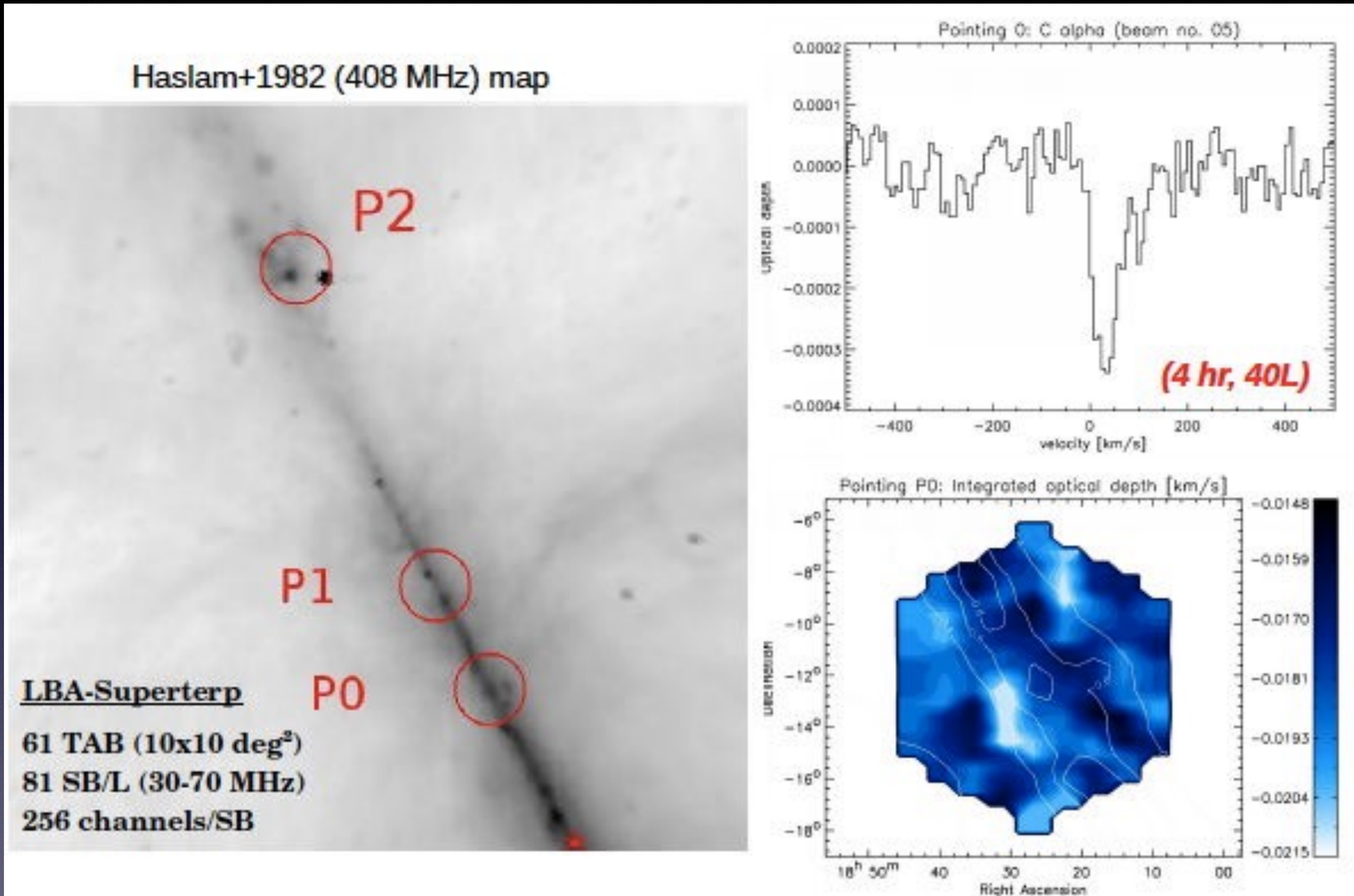
See Pedro Salas' talk on Tuesday

- Cas A
- absorption lines 10-35 MHz

  $\tau \sim 3 \times 10^{-3}$; power of stacking
- Radiation/pressure broadening



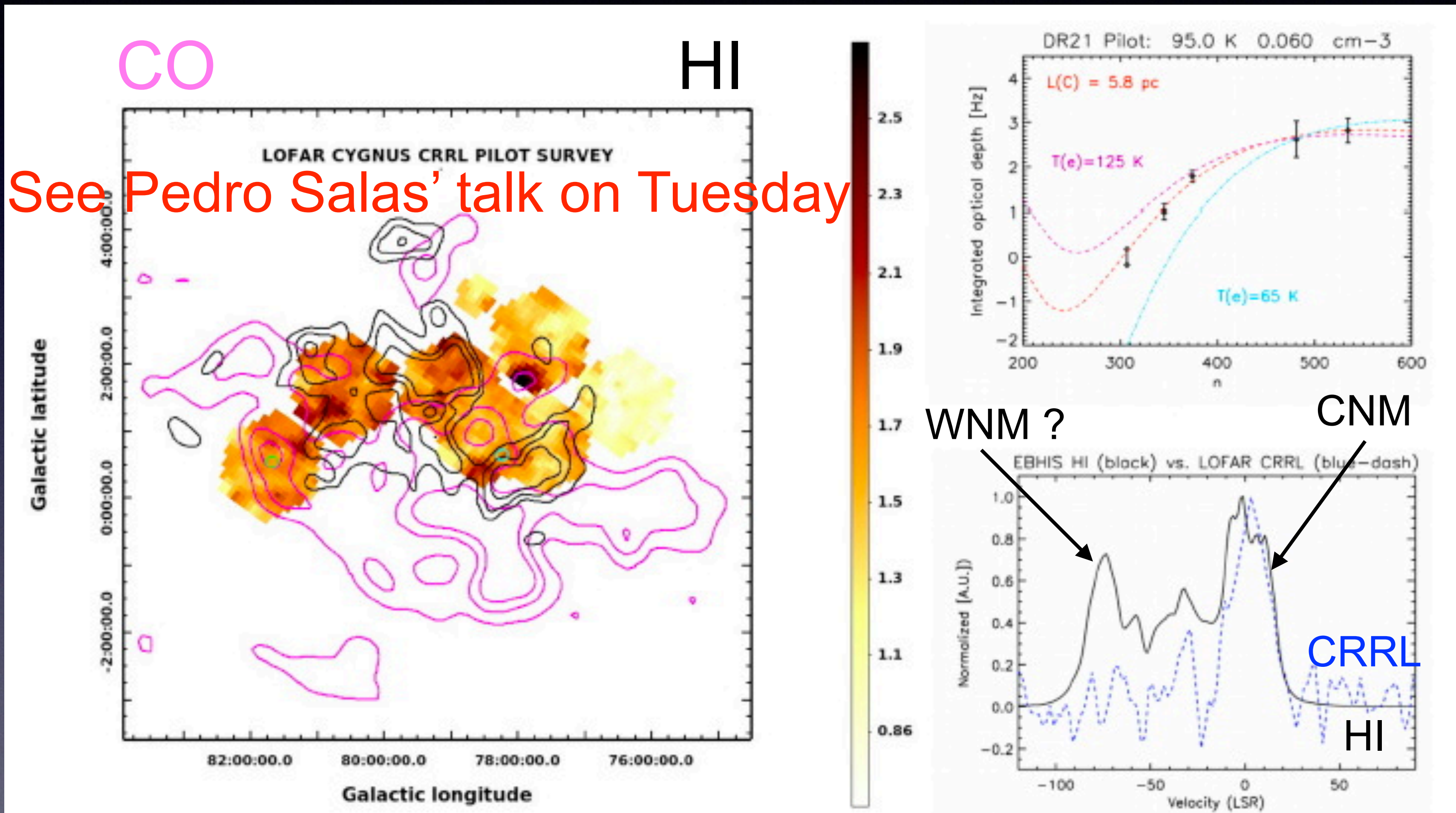
Salas et al, 2016, A&A, submitted



Galactic Plane Survey: 1 degree pilot

Galactic Plane Survey: 10’ pilot

Oonk et al, 2016, in prep



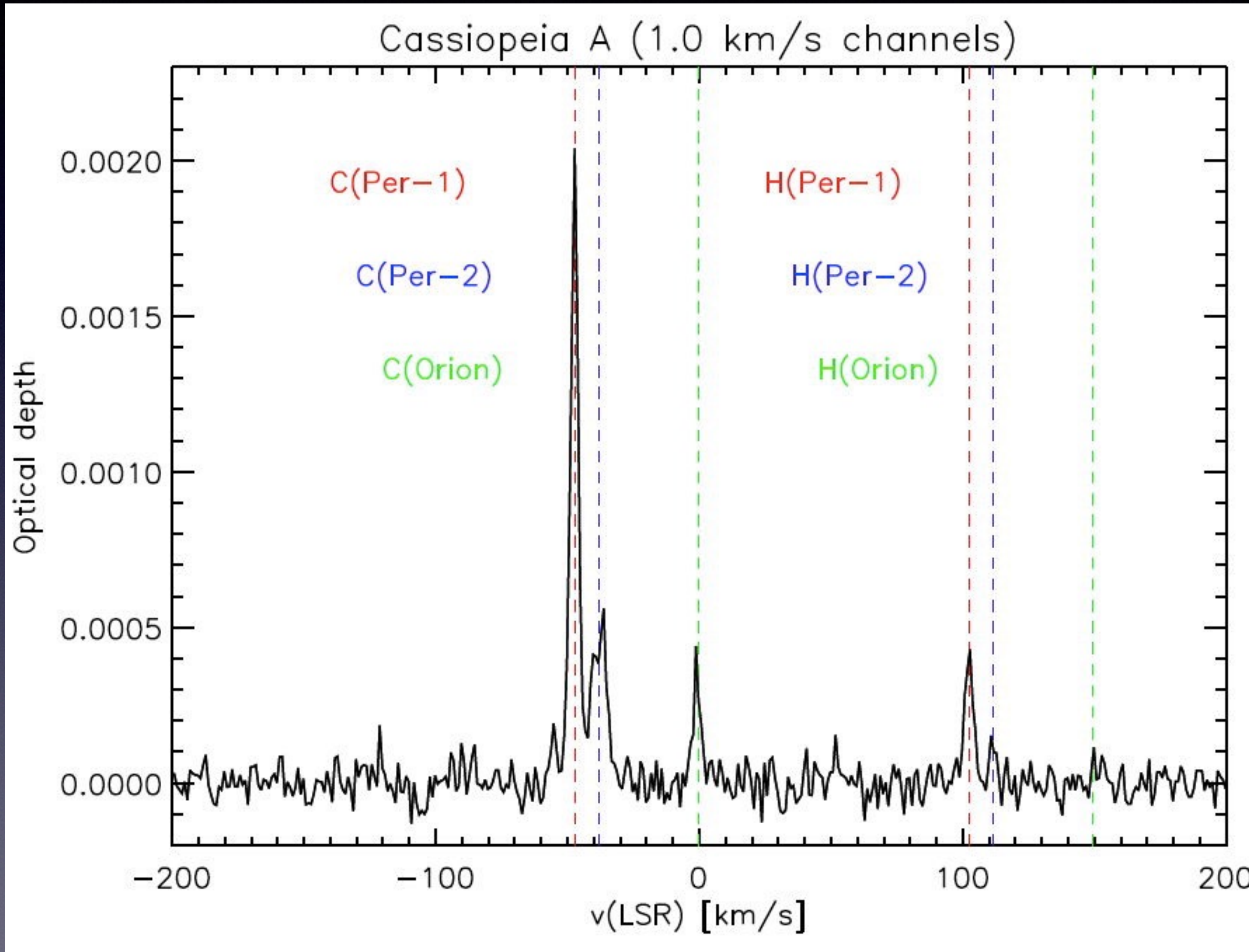
CRRL:dark is higher optical depth

10’ beam, 1.5 degree FoV

LOFAR: great barometer

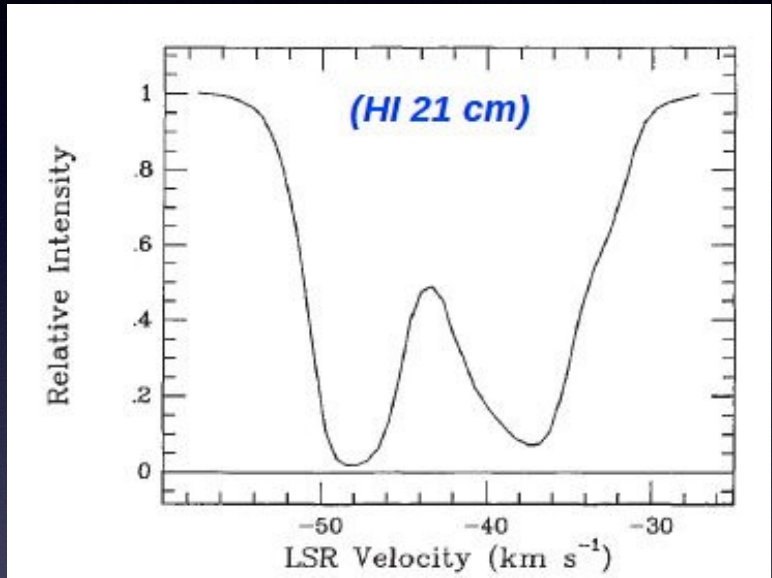
[CII] 158μm or higher frequency CRRL yields accurate *n* and *T*

Cosmic Ray Ionization Rate



$$\varsigma_H = 7 \times 10^{-17}\ \mathrm{s}^{-1}$$

Carbon Abundance

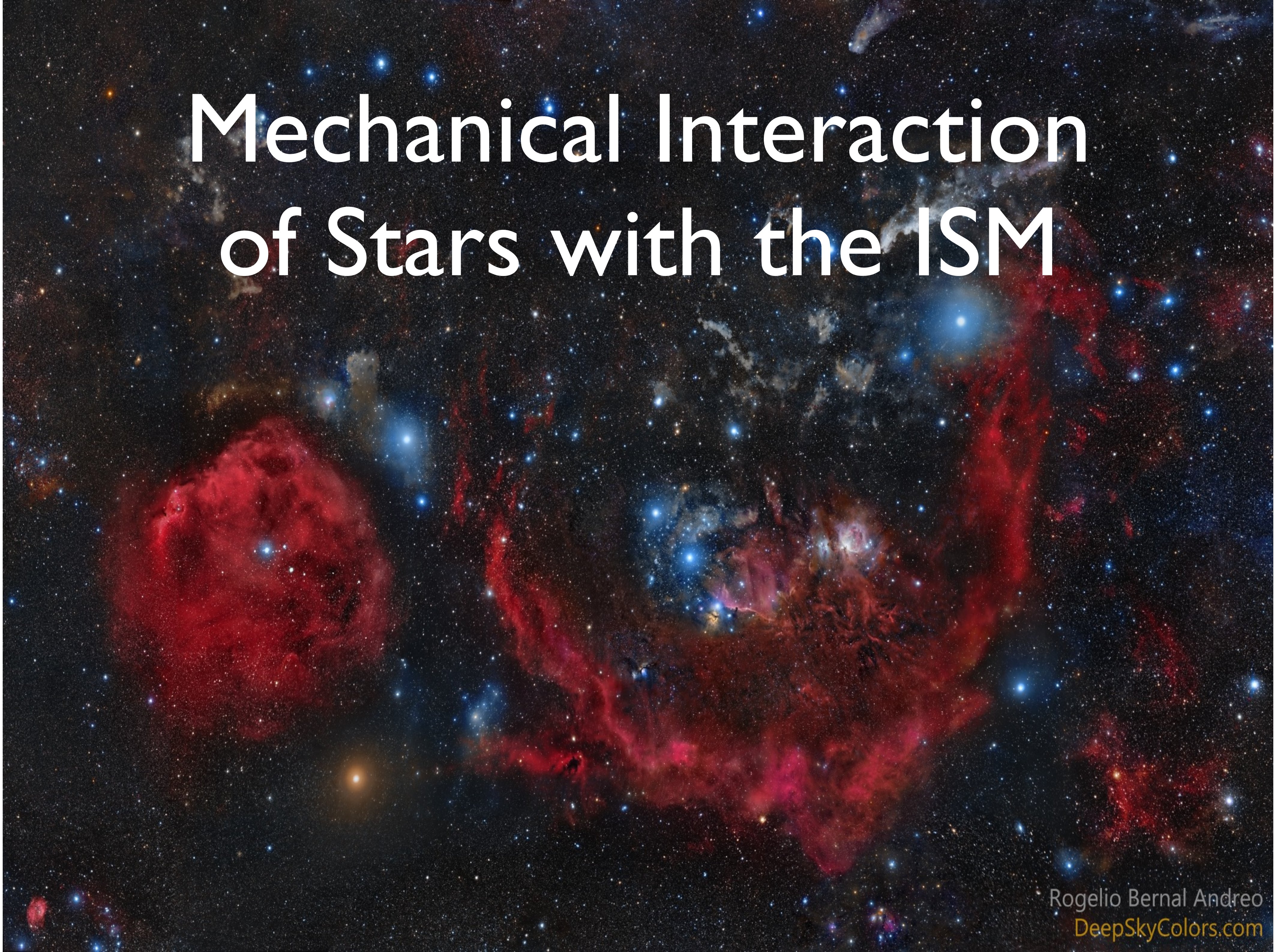


HI 21 cm: $N_H > 4 \times 10^{21}\ \text{cm}^{-2}$

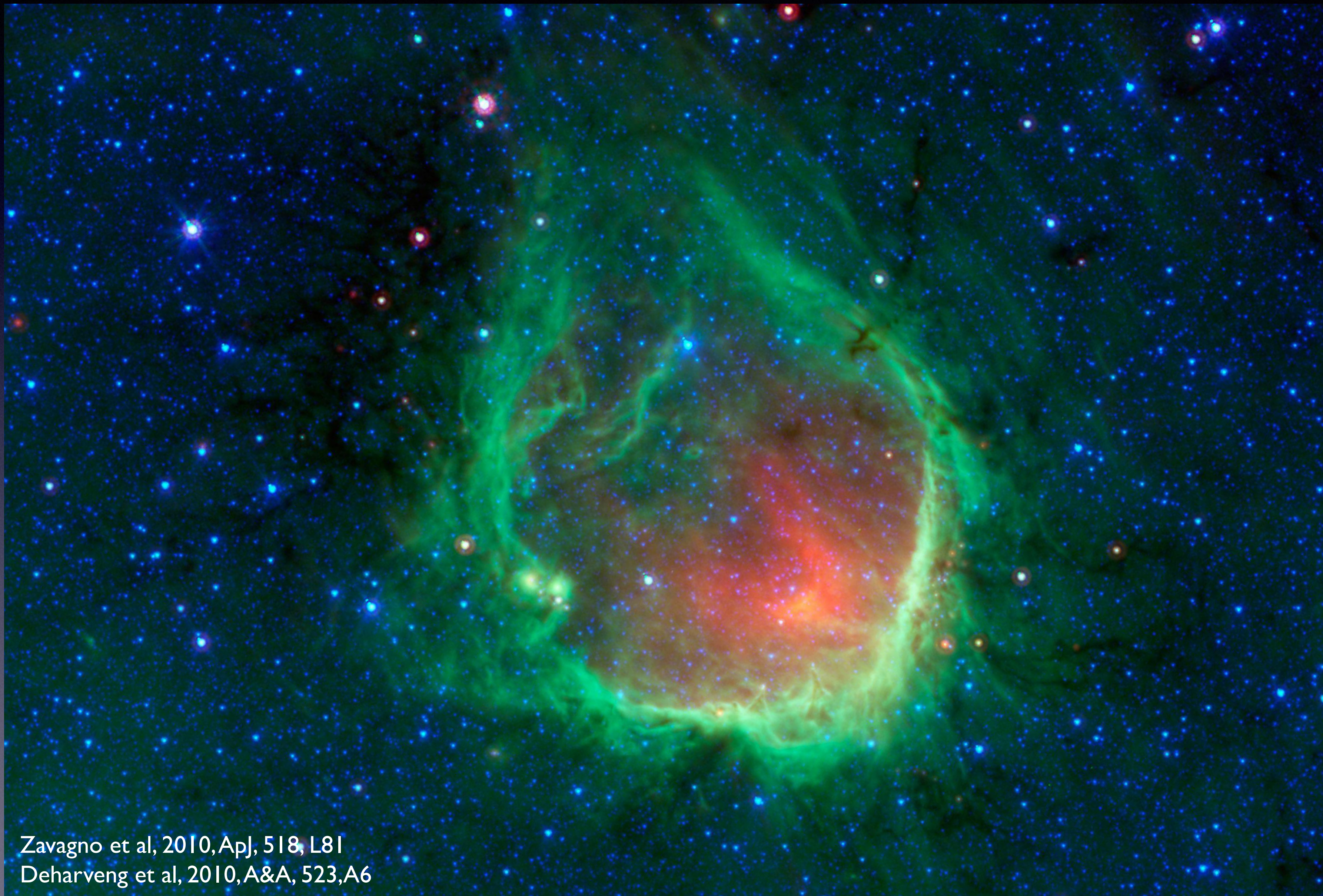
X-ray: $N_H < 3.5 \times 10^{22}\ \text{cm}^{-2}$

$X(C) \approx 1.3 - 11 \times 10^{-4}$

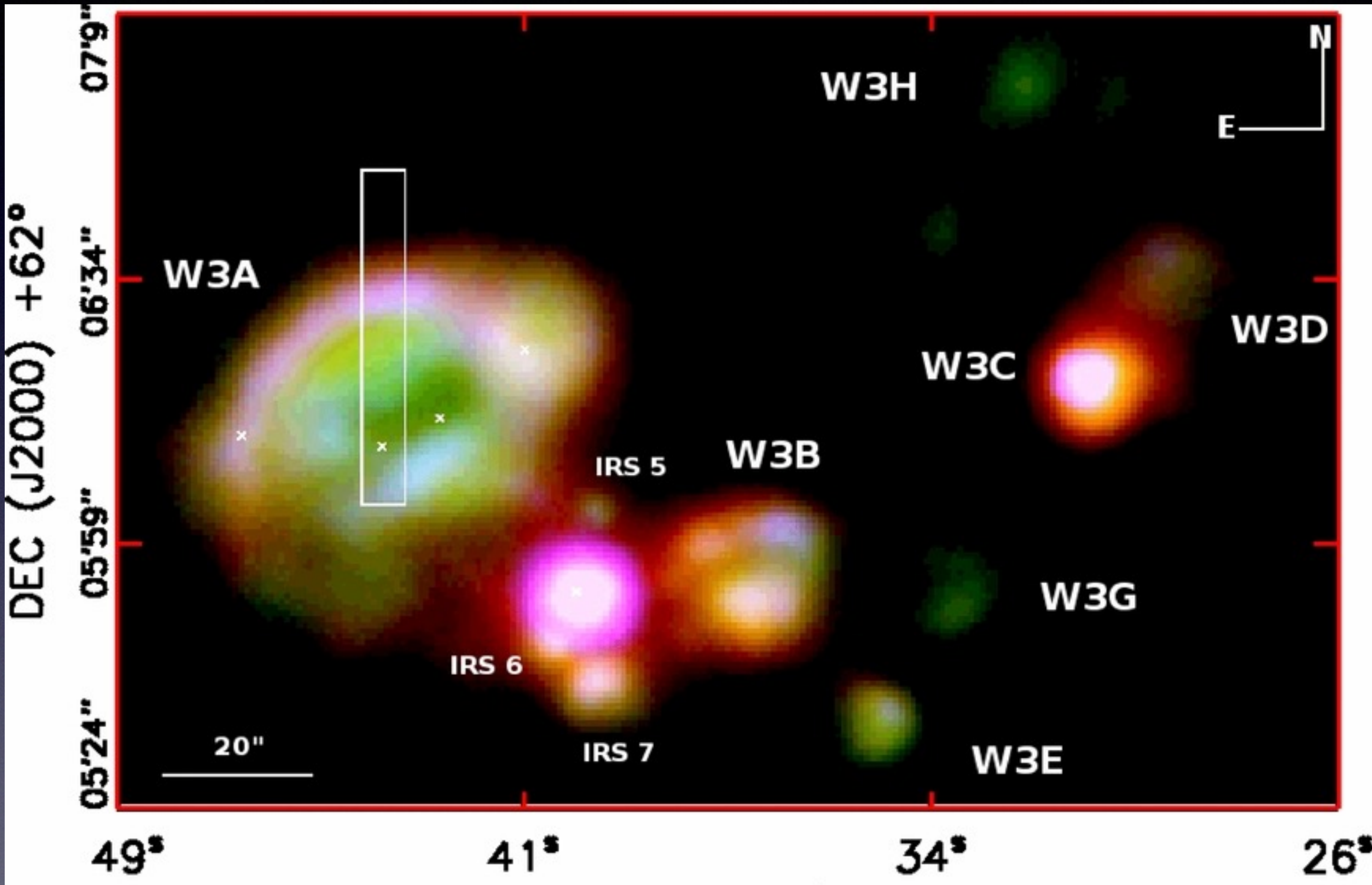
Mechanical Interaction of Stars with the ISM



RCW 120

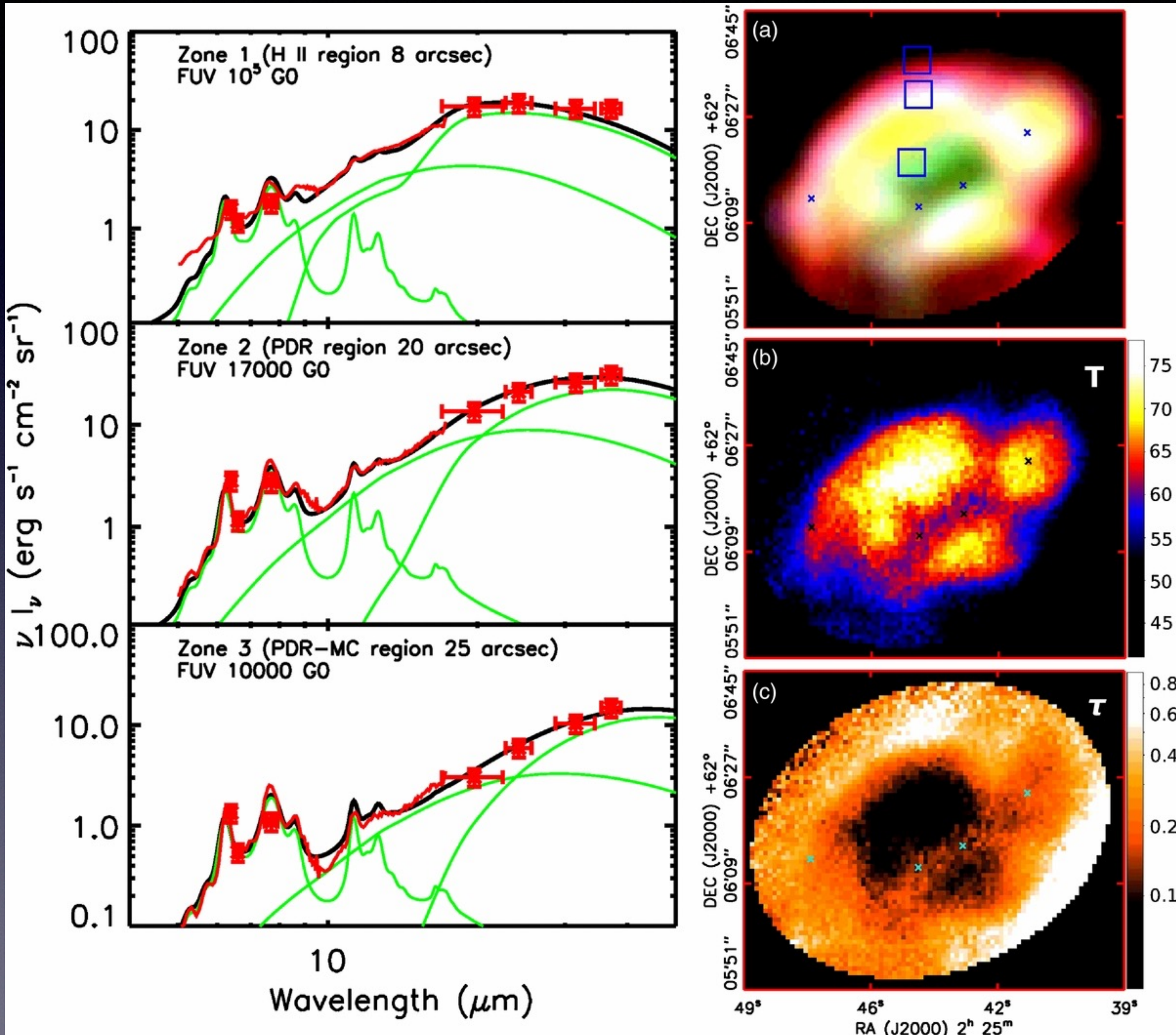


W3A & SOFIA's View of Bubbles



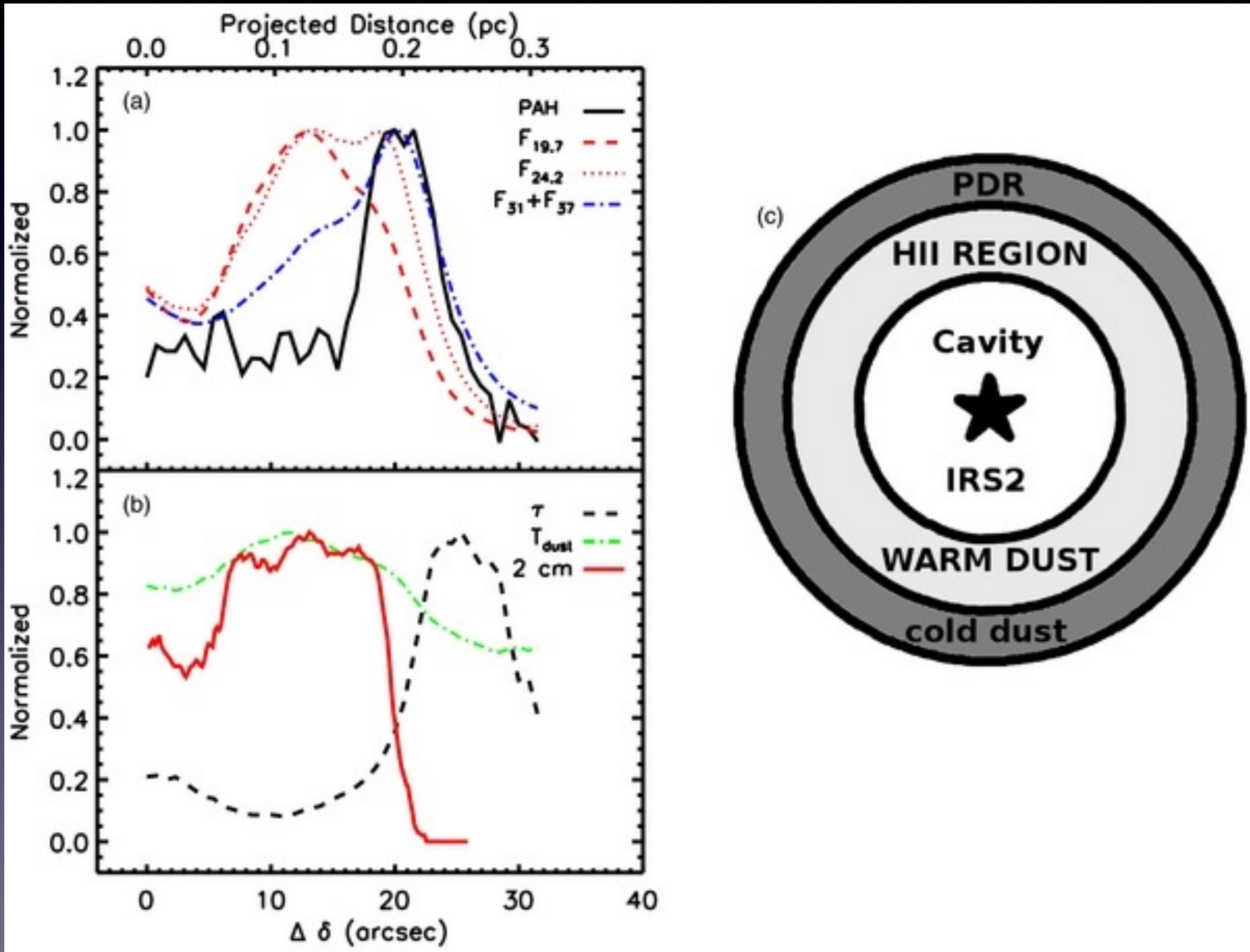
Salgado, et al, 2012, ApJ, 749, L24

W3A

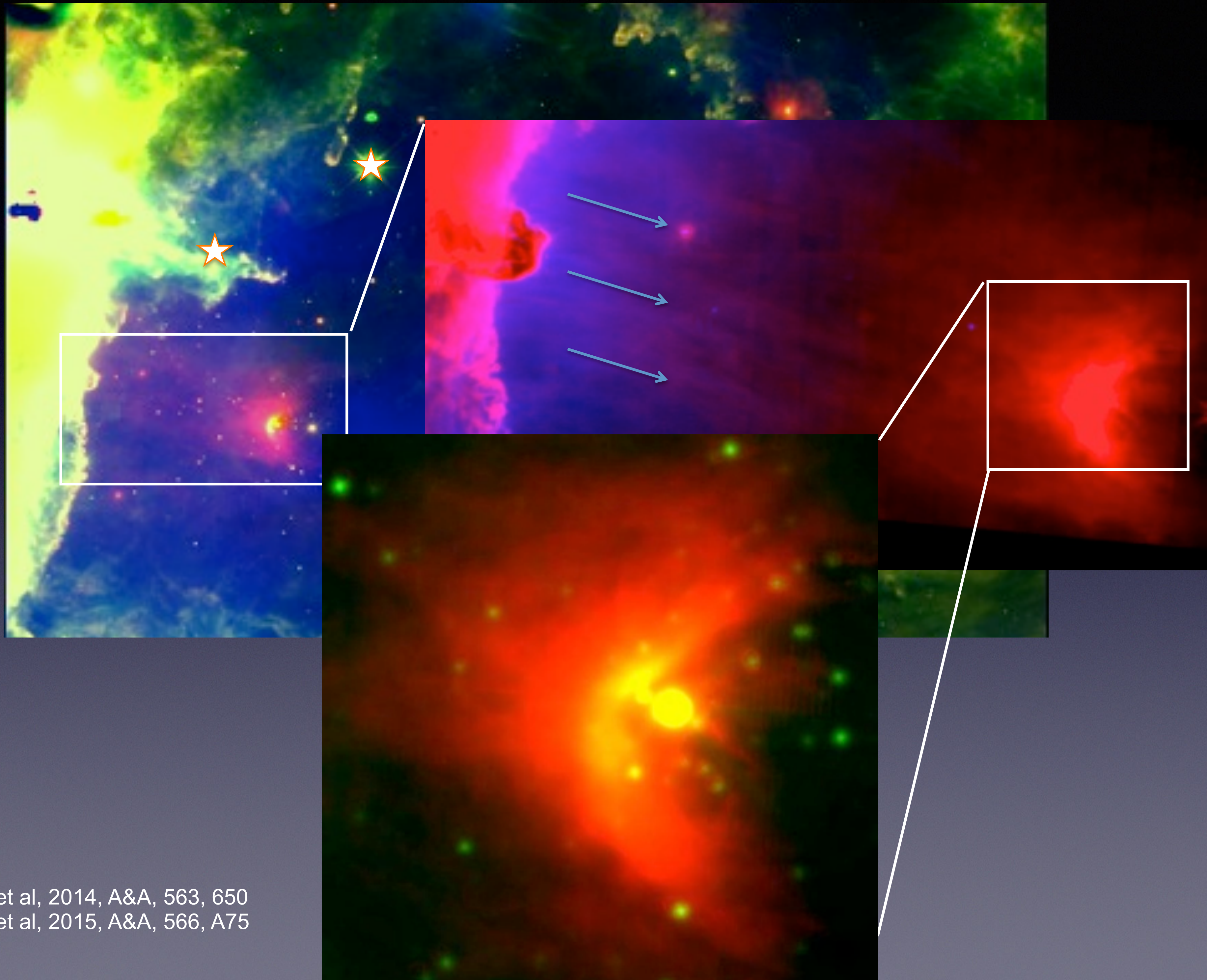


Salgado, et al, 2012, ApJ, 749, L24

W3A

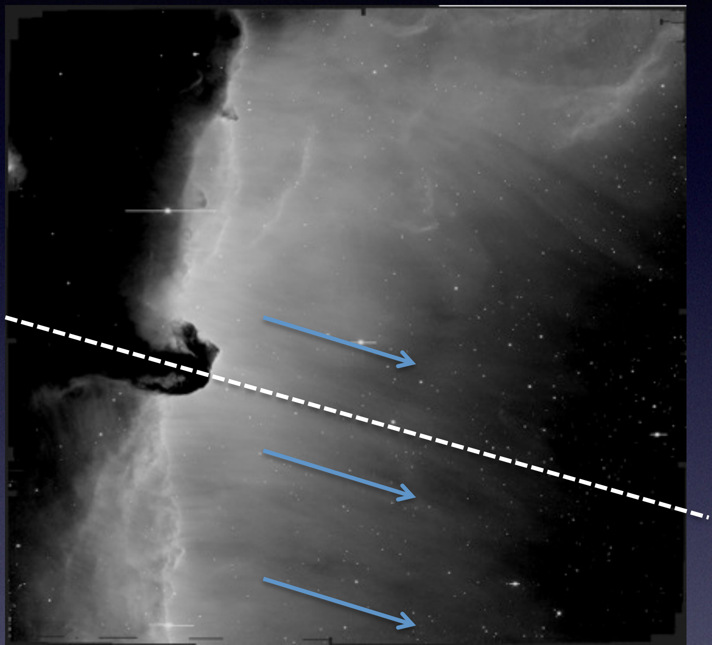


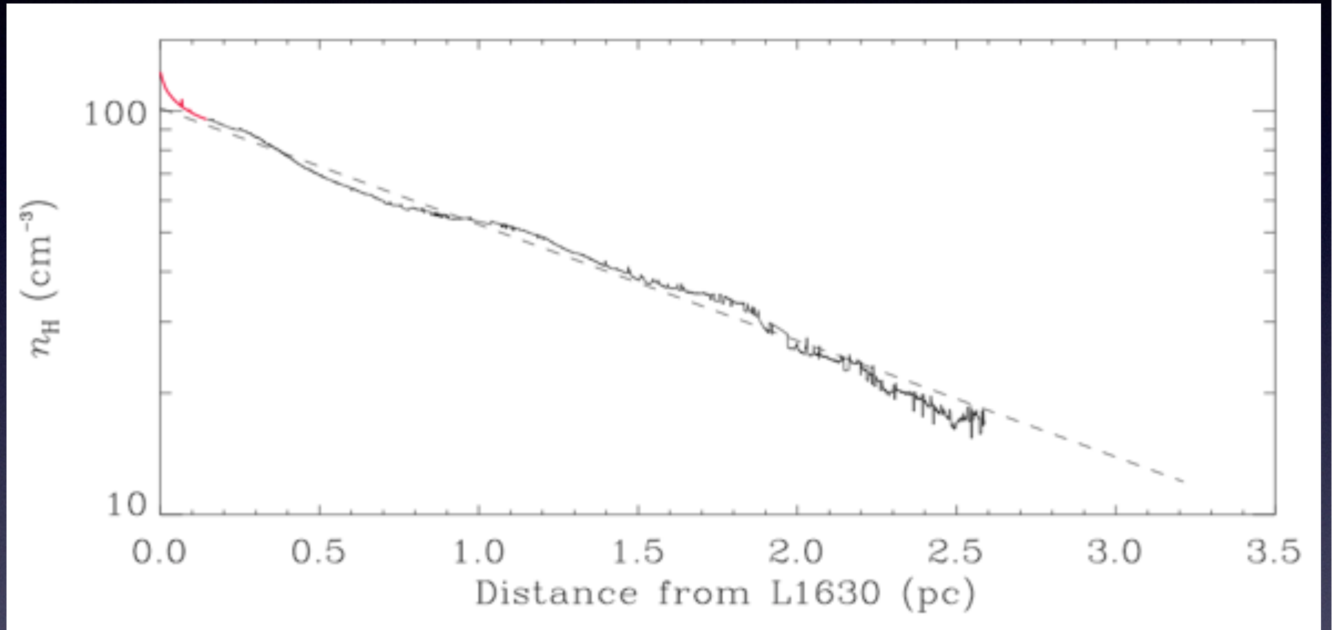
Salgado, et al, 2012, ApJ, 749, L24



Ochsendorf et al, 2014, A&A, 563, 650
Ochsendorf et al, 2015, A&A, 566, A75

Champagne Flow

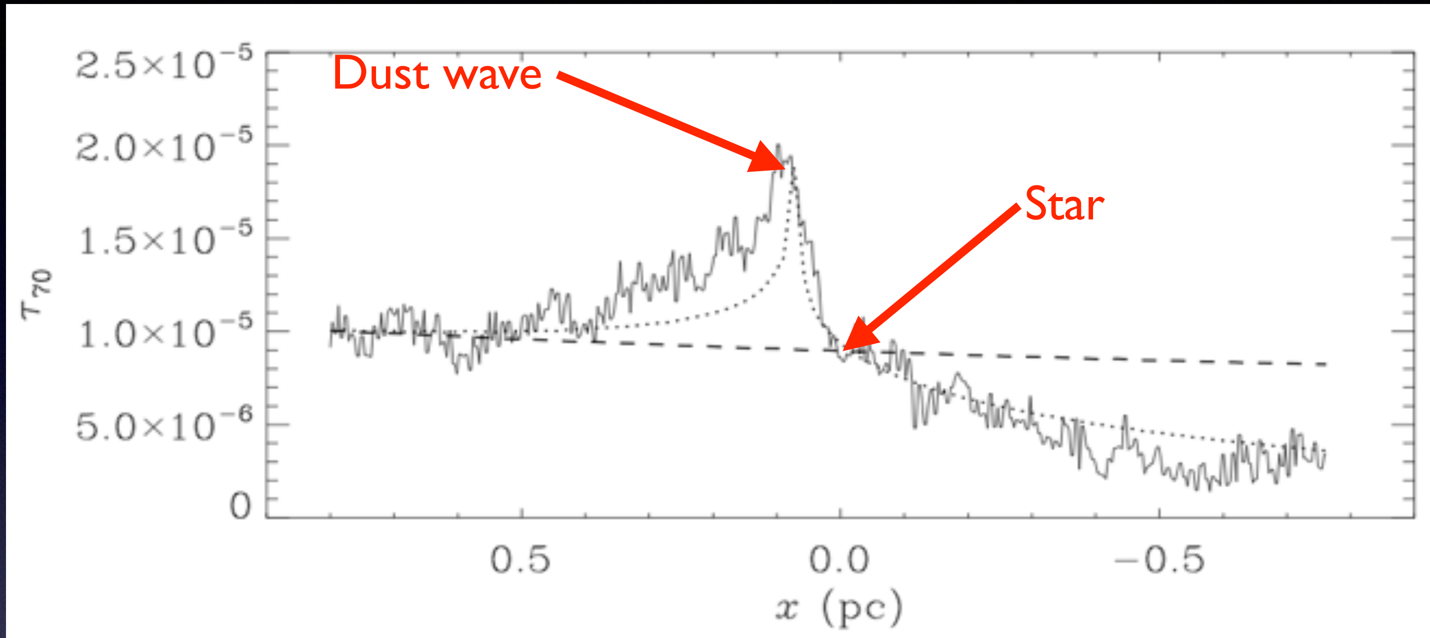


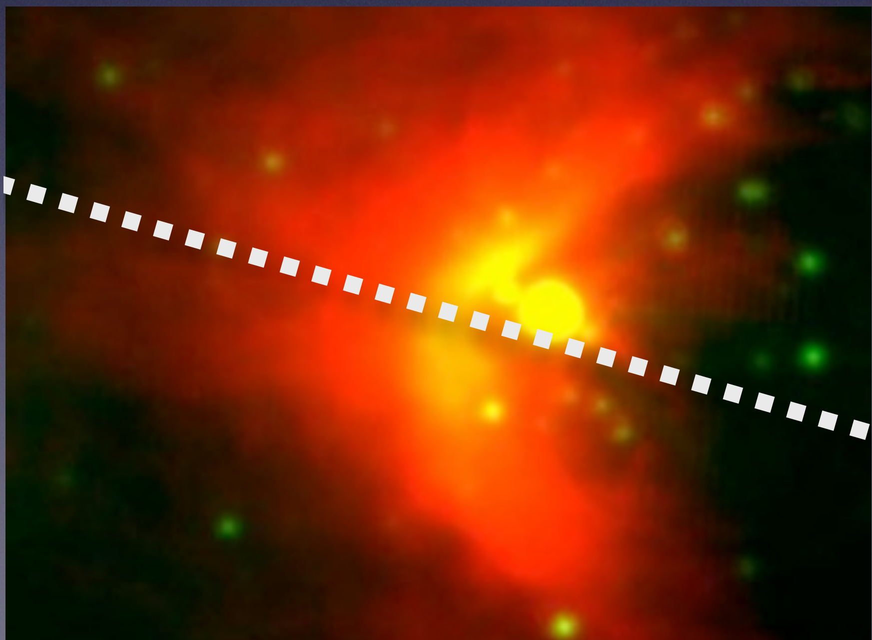


A 'champagne flow' of ionized gas described by an exponential density gradient *(Tenorio-Tagle 1979)*

Ochsendorf et al, 2014, A&A, 563, 650
Ochsendorf et al, 2015, A&A, i576, A2

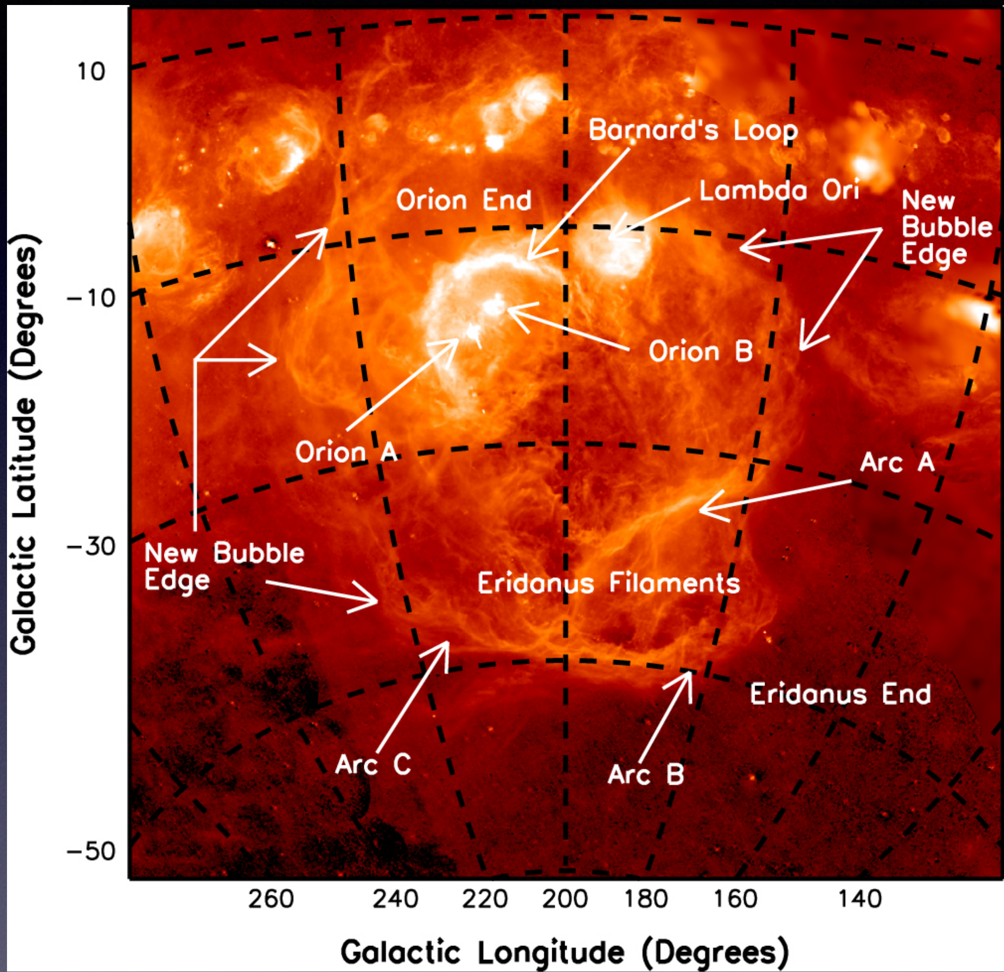
Dust Wave in IC 434





Ochsendorf et al, 2014, A&A, 563, 650
Ochsendorf et al, 2015, A&A,576, A2

Orion-Eridanus Bubble



Cycle: SN clean out/rejuvenates the superbubble, new generation of (massive) stars reload the interior with photo-ionized/evaporated gas at a rate of 10^4 M_{sun}/Myr

Grand Questions in ISM Ecology

- What processes drive the evolution of the ISM ?
- What does that tell us about the ecology of the ISM ?

SOFIA & Galactic Ecology

- The interaction of massive stars with their environment
- Evolution of PAHs and the thermal characteristics of the ISM
- Searching for the GrandPAH: HIRMES
- [CII] 158μm emission from regions of massive star formation: radiative and kinetic interaction: SuperGREAT
- CRRL: LOFAR & SKA

The people who approve this message