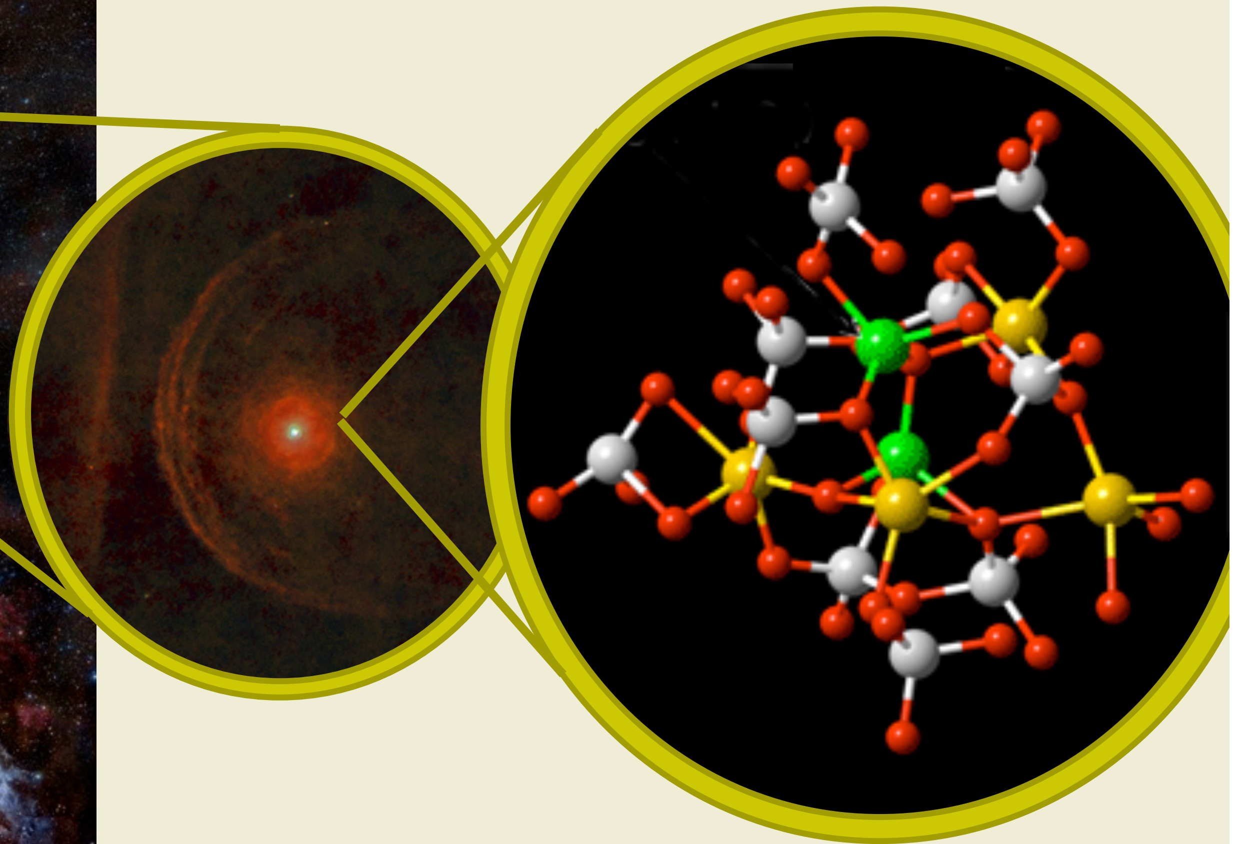
Unraveling the morpho-kinematical and chemical structure in the winds of evolved stars



Leen Decin

University of Leuven
Belgium

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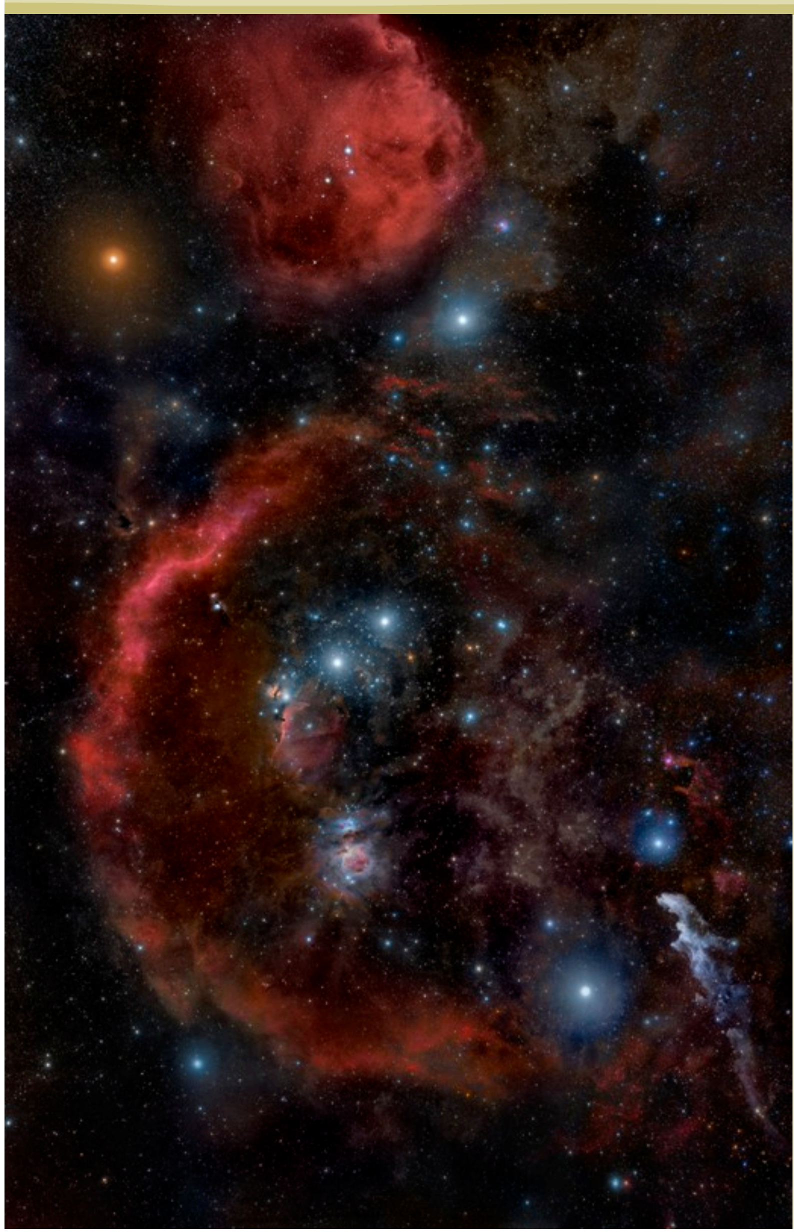
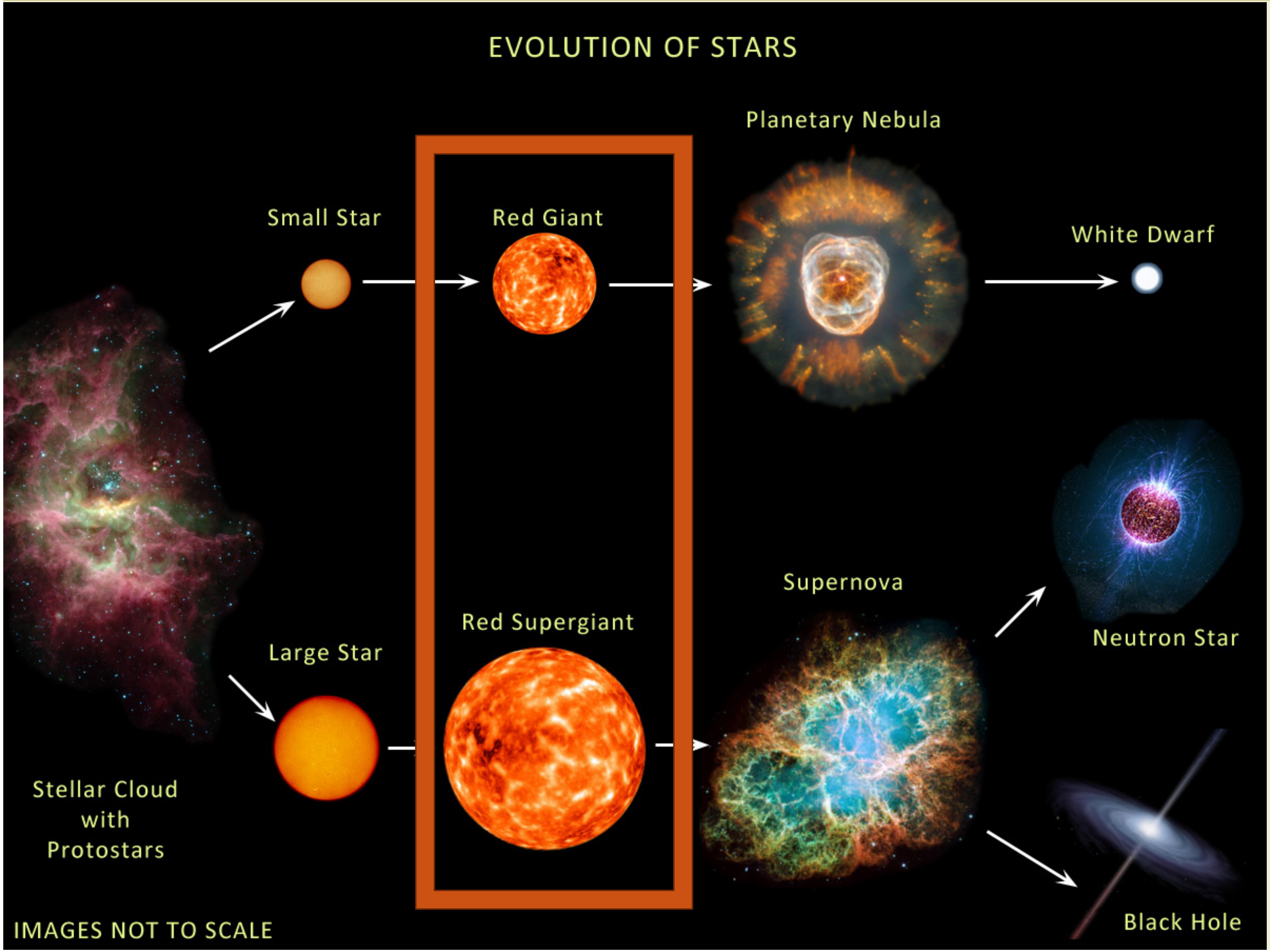
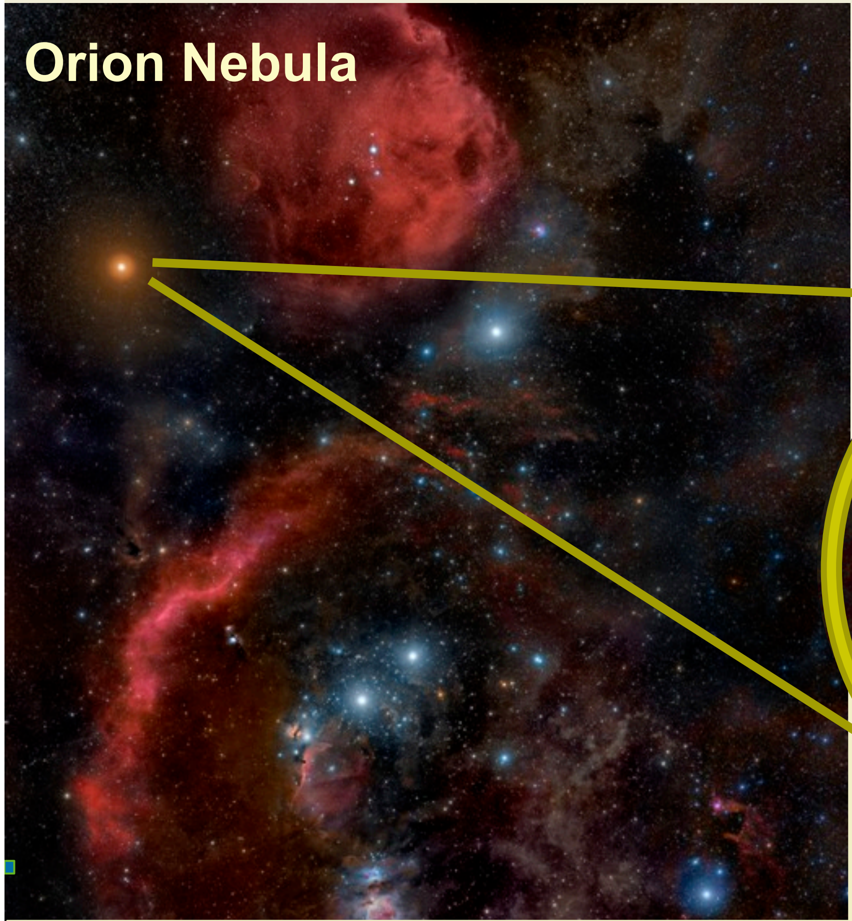


1. Introduction
2. Ingredients
3. Some Herschel results
4. Future - ALMA

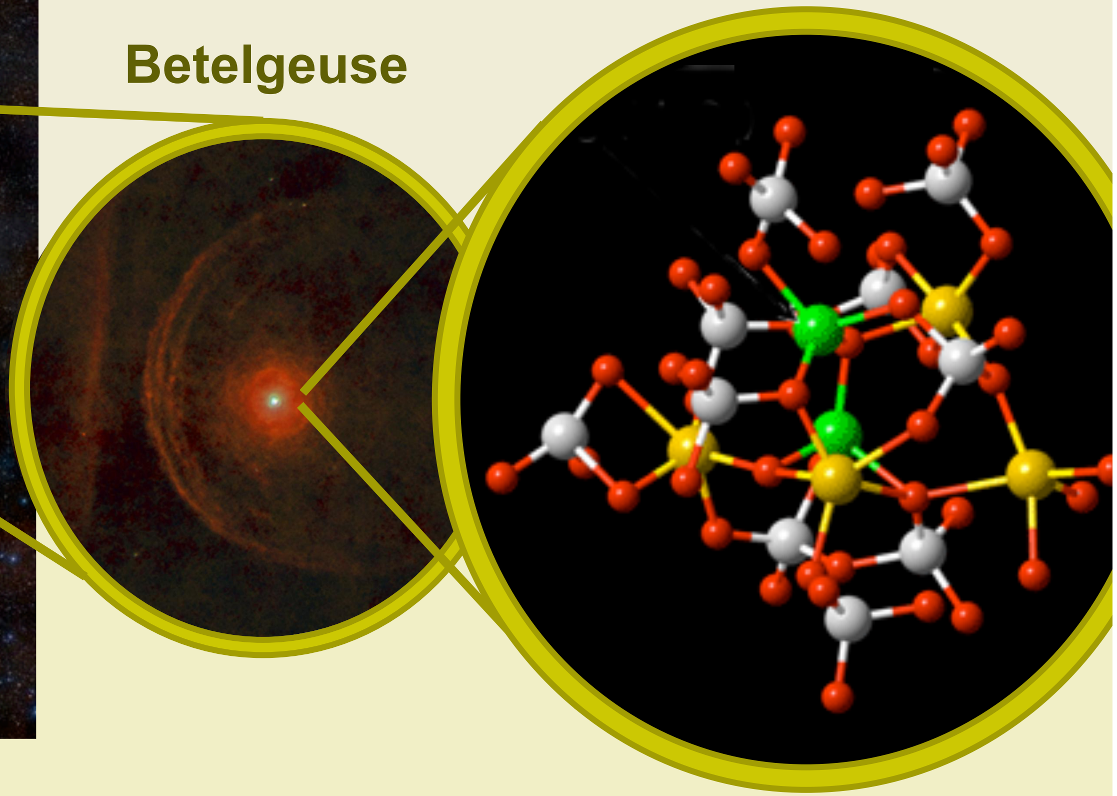
1. Introduction



1. Introduction



* 97% of all stars evolve through (super)giant phase

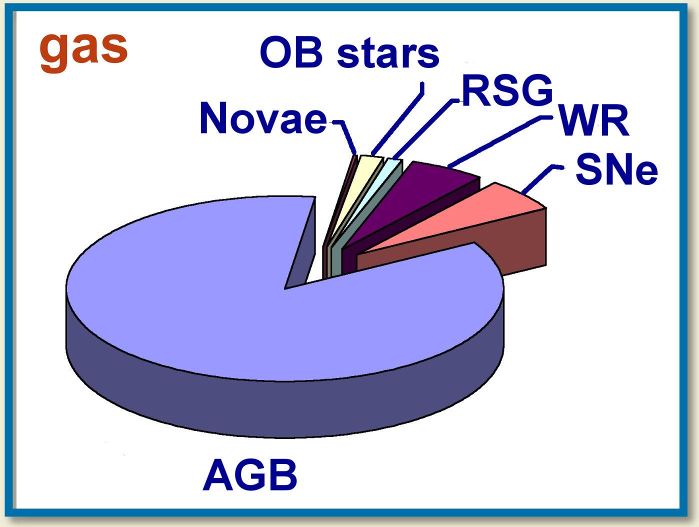


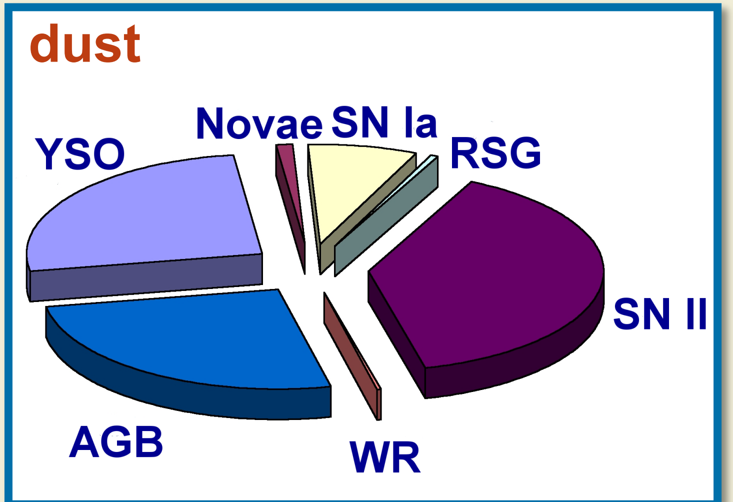
* old giant stars: lose mass via stellar wind

* wind: molecules (>70) + dust (>15)
  → unique chemical laboratories

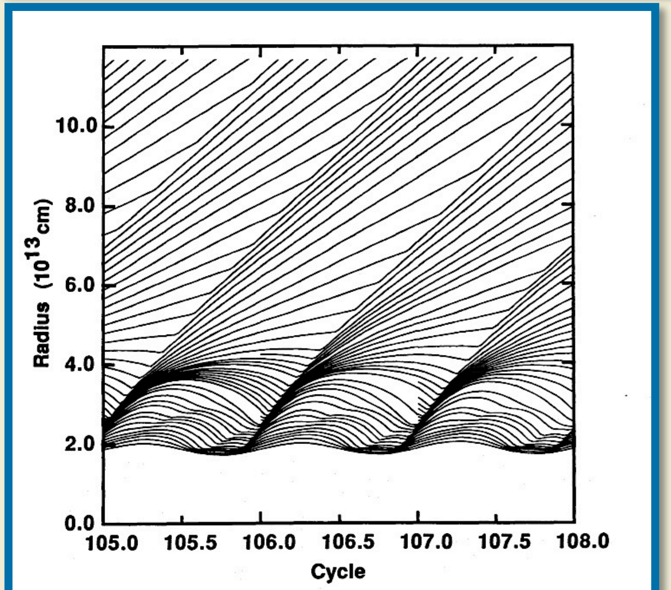
1. Importance (super)giant stars

✓most important sources for **enrichment ISM**



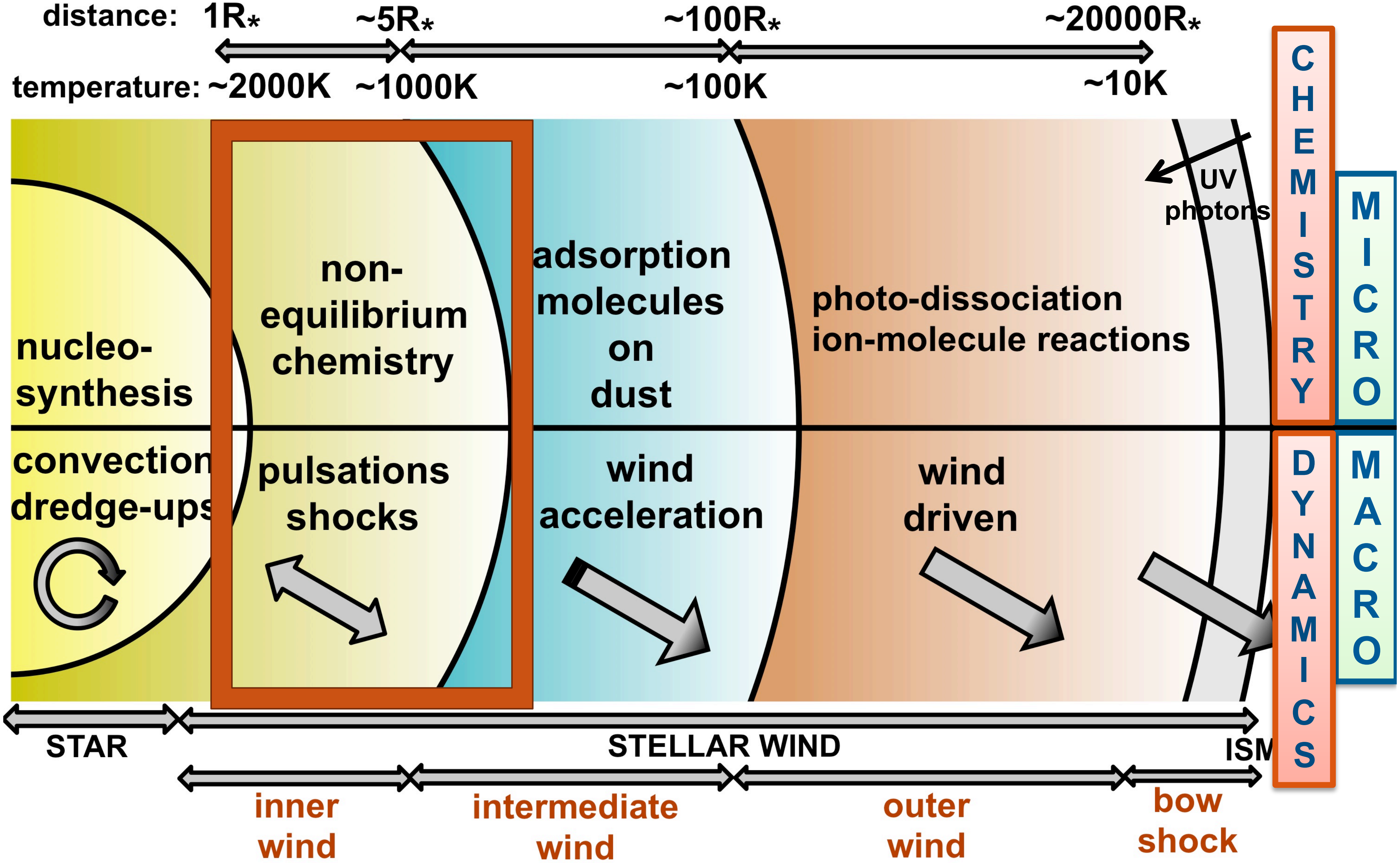


✓**dynamically quite `simple'** molecules + dust



astrochemistry in giant winds → more complex systems

1. Stellar wind: from micro-scale chemistry to macro-scale dynamics



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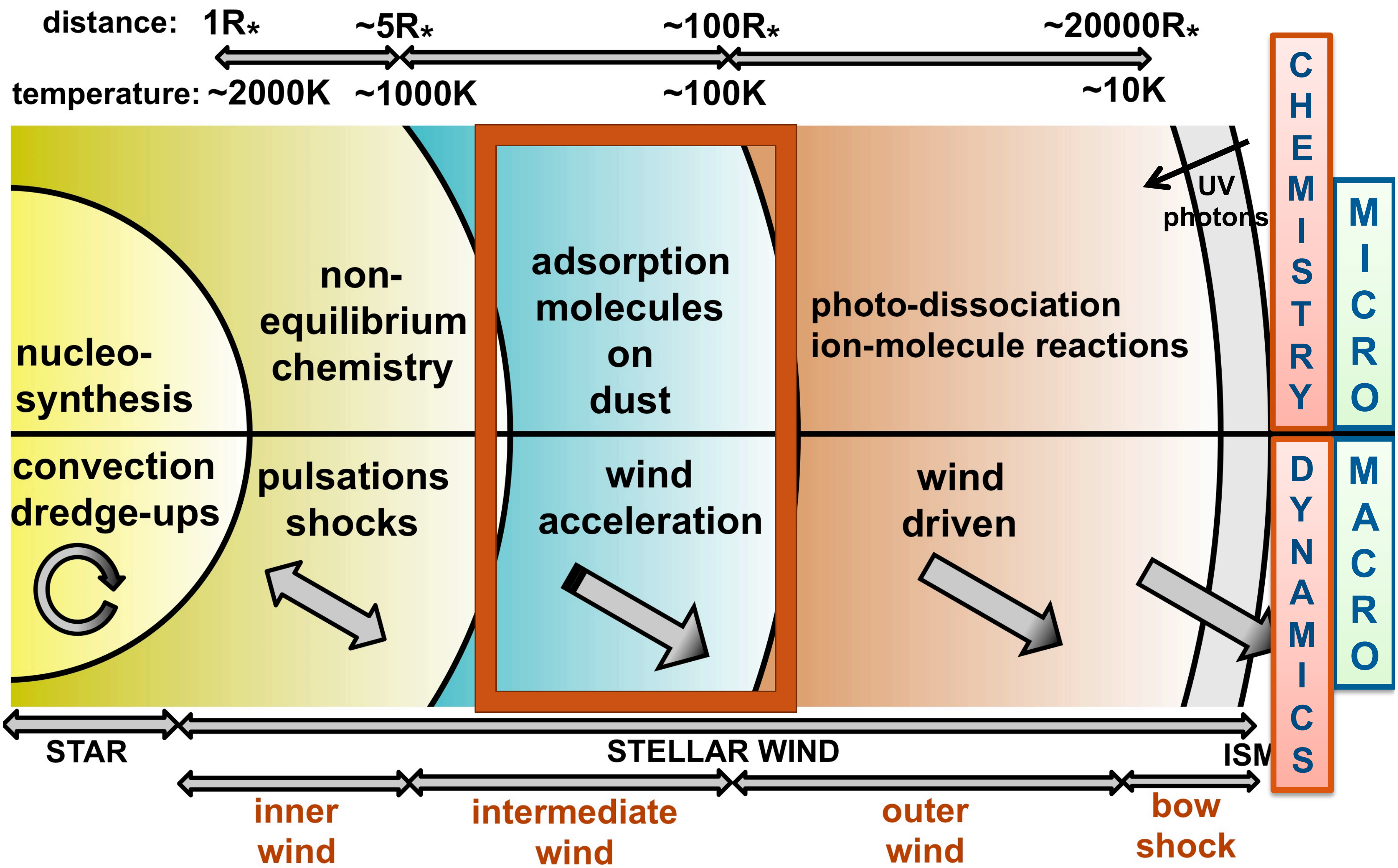

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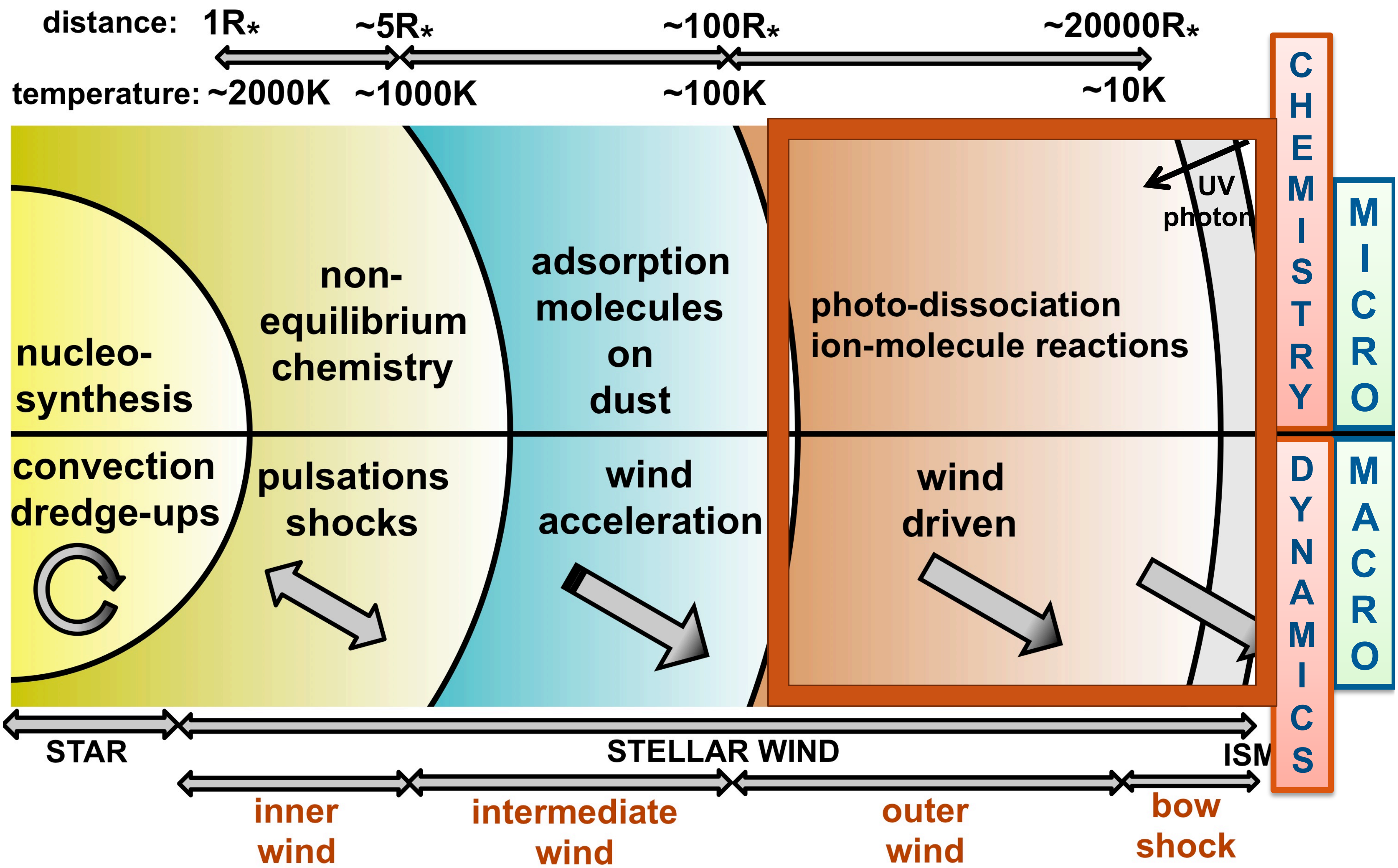
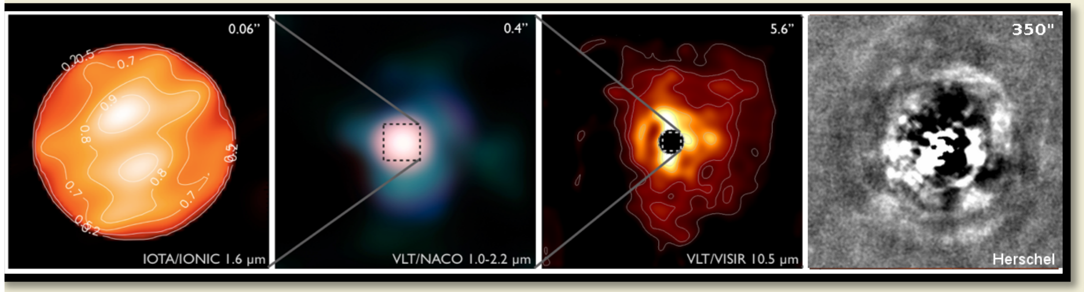
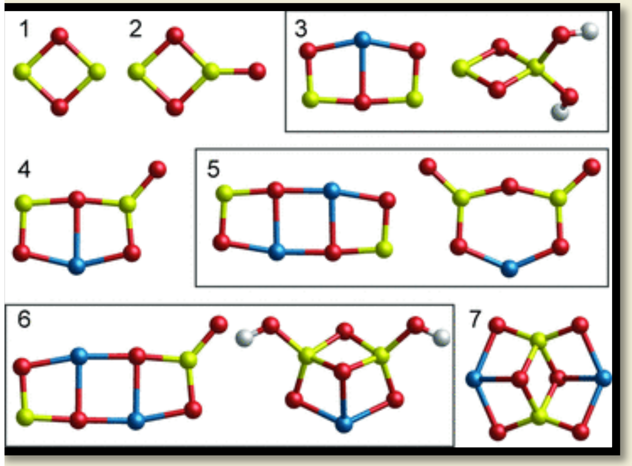


2. Ingredients

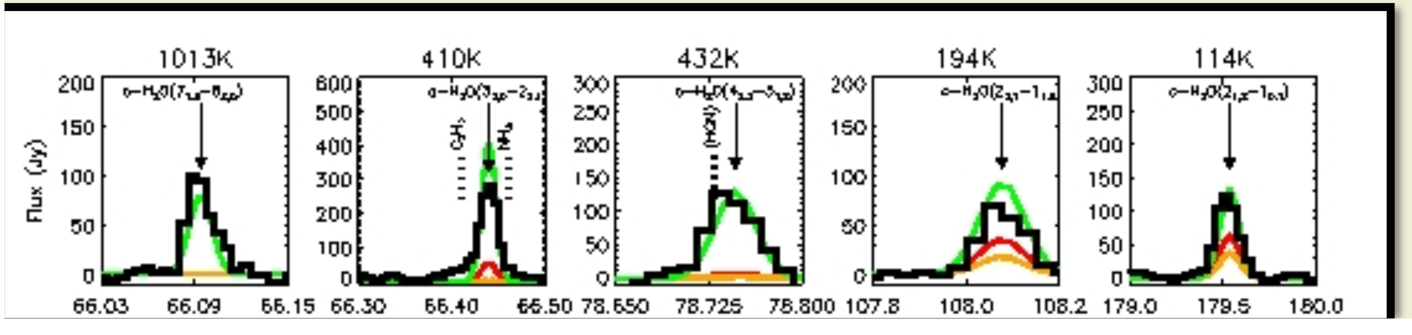
A. Observations



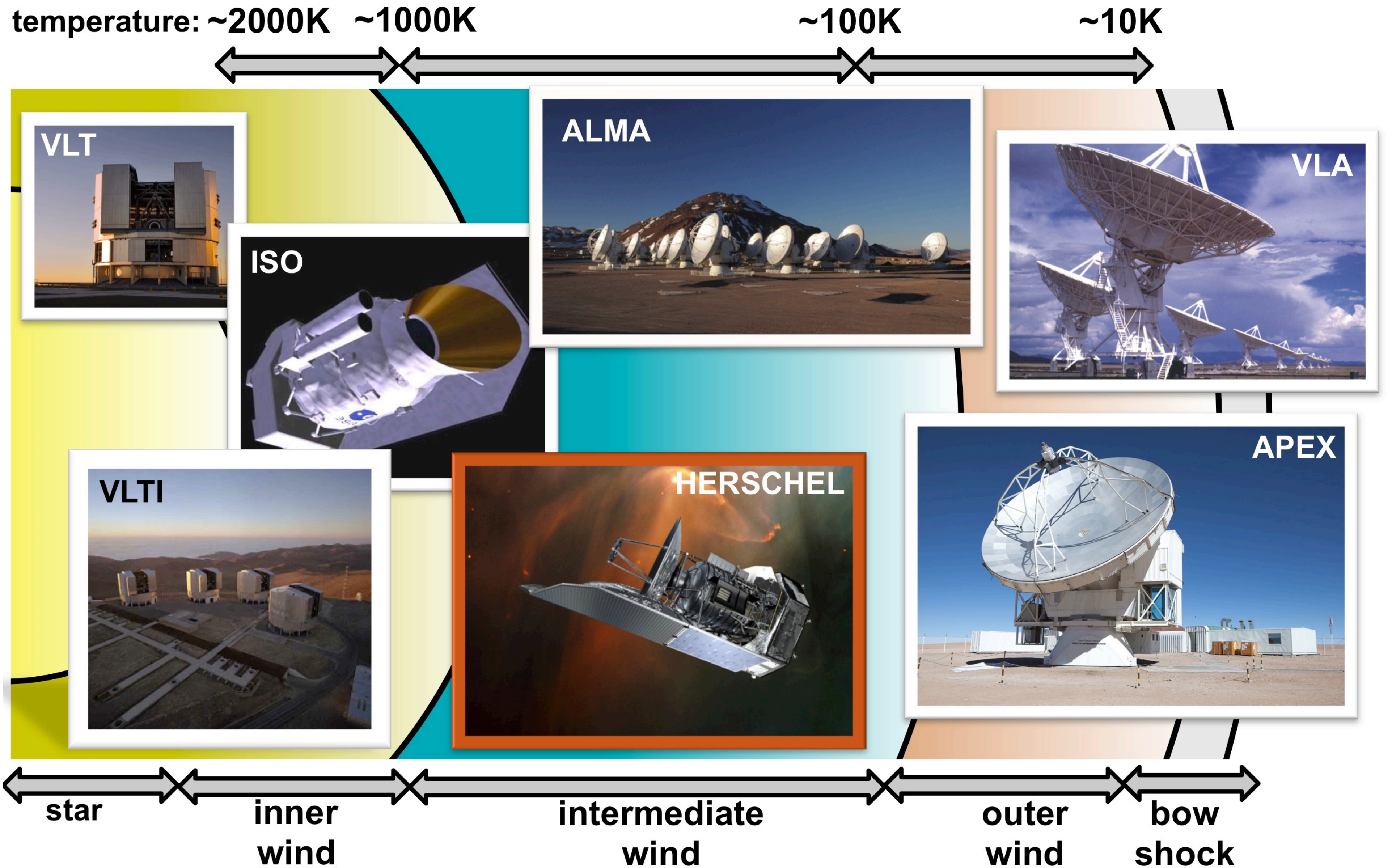
B. Chemistry



C. Theoretical models



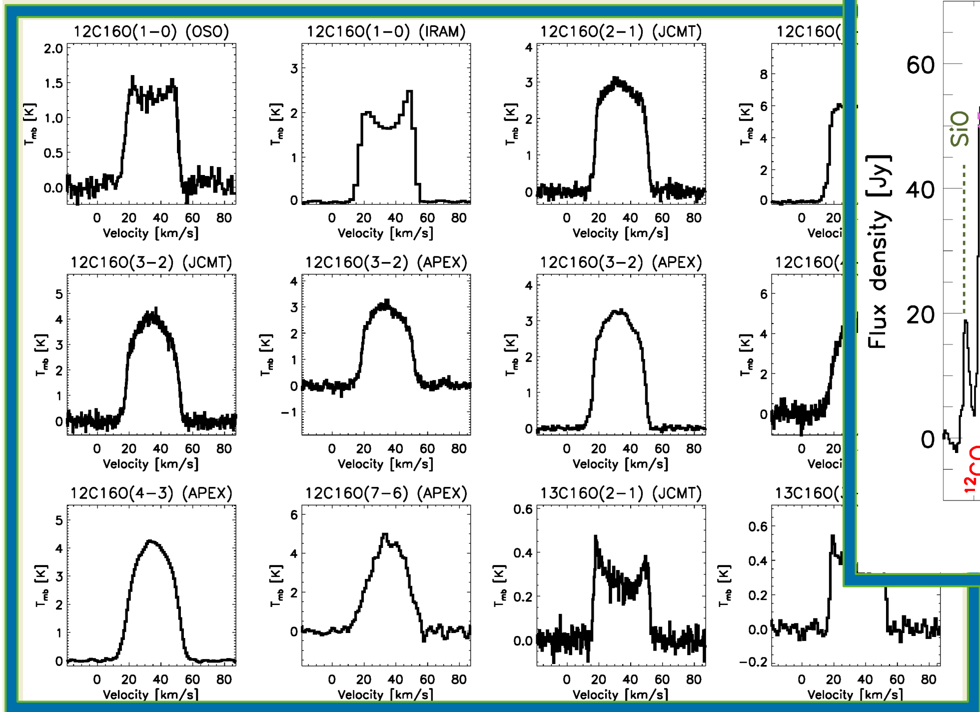
2. Ingredients: Observations

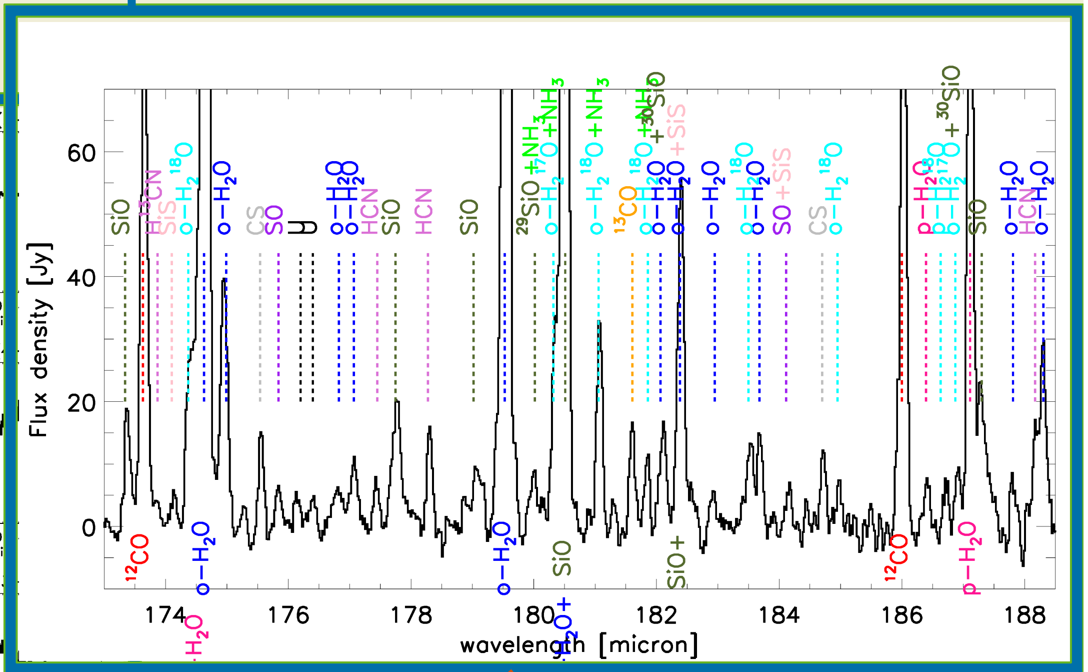


2. Ingredients: Role of Herschel

→ 12 molecular line transitions: ~40hr

→ 930 molecular line transitions: 2hr





Royer,Decin et al. 2010

Decin et al. 2010

>50 targets

2. Ingredients: Chemistry: from atoms to molecules and grains

atoms ⟹ molecules ⟹ clusters ⟹ dust grains

? nucleation

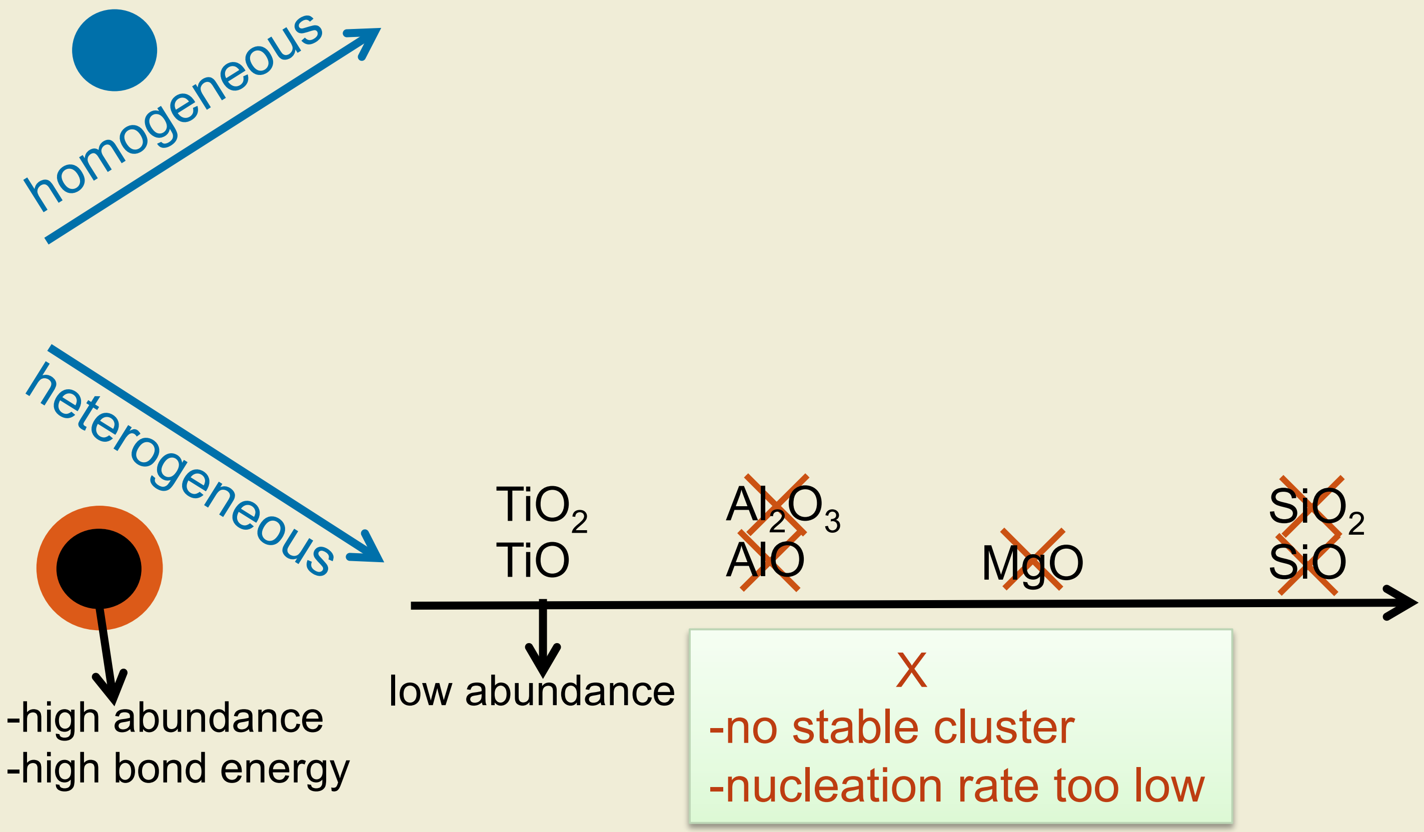
? condensation

O-rich giants

silicates: $MgSiO_3$, Mg_2SiO_4

alumina: Al_2O_3

silica: SiO_2



2. Ingredients: Chemistry: from molecules to grains

? ?

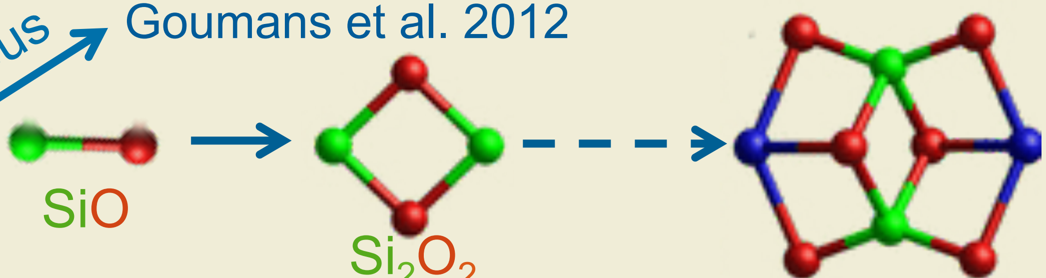
atoms ⟹ molecules ⟹ clusters ⟹ dust grains

nucleation — condensation

O-rich giants
silicates: $MgSiO_3$, Mg_2SiO_4
alumina: Al_2O_3
silica: SiO_2

homogeneous

Goumans et al. 2012



SiO

Si_2O_2

$(MgSiO_3)_2$

bottleneck

heterogeneous

TiO_2 / TiO | $\cancel{Al_2O_3}$ / $\cancel{AlO}$ | $\cancel{MgO}$ | SiO_2 / SiO

low abundance

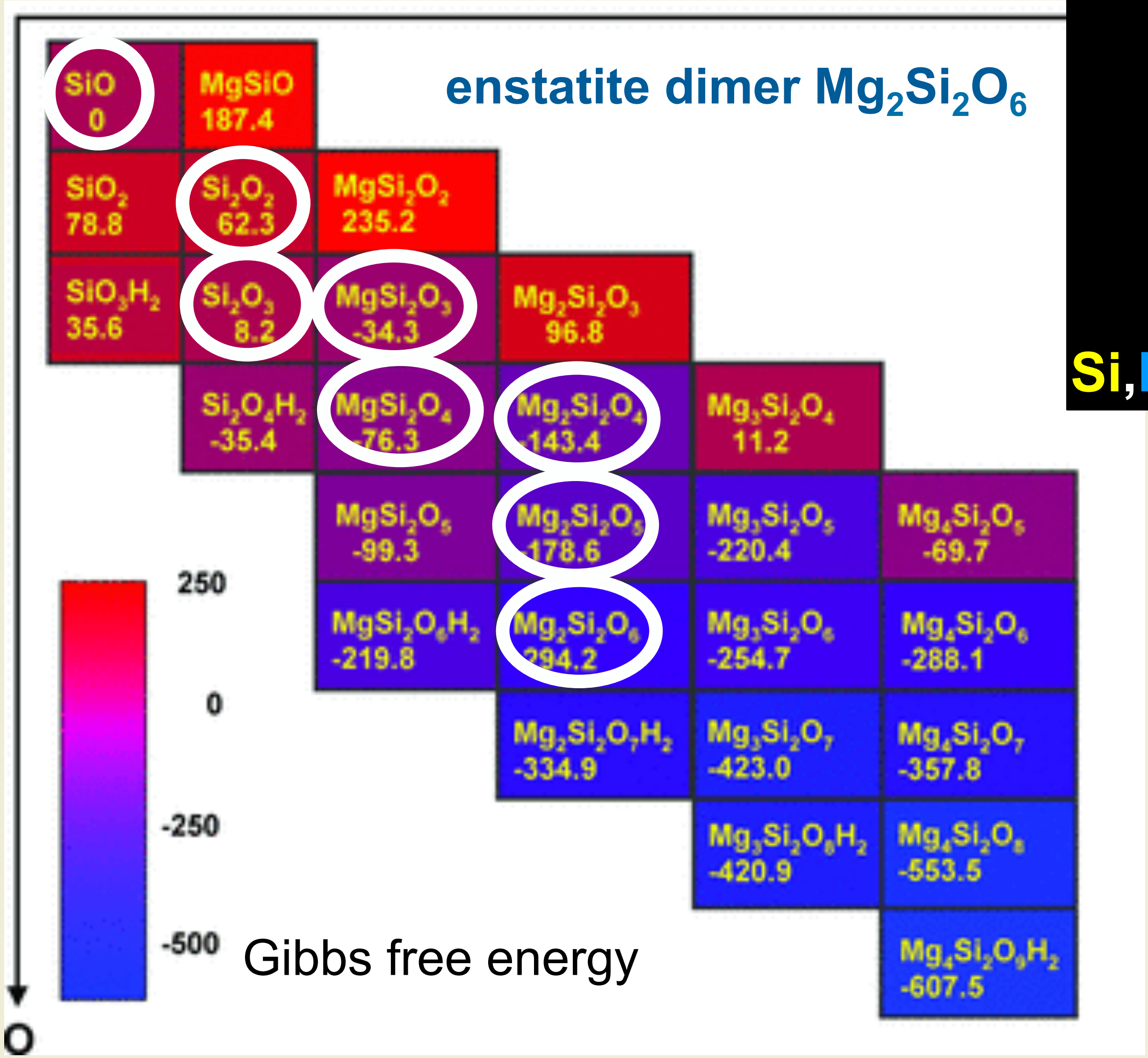
-high abundance
-high bond energy

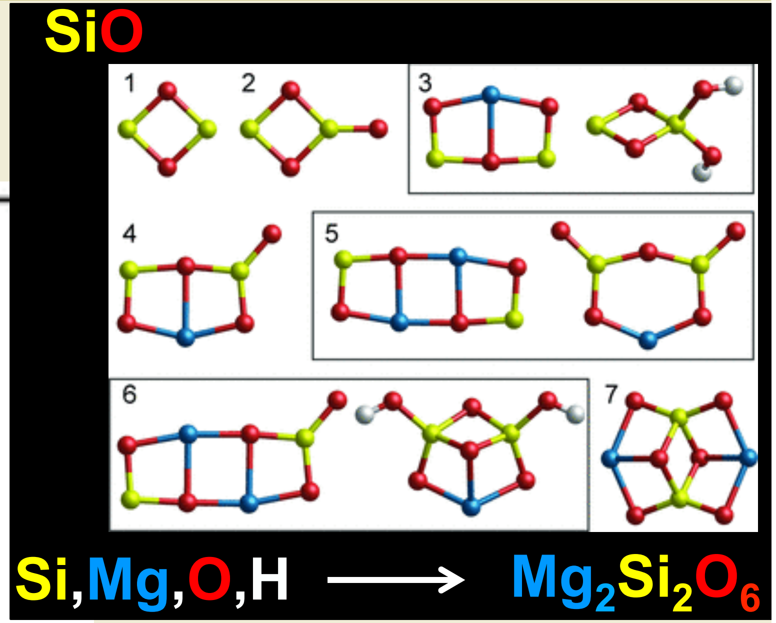
X
-no stable cluster
-nucleation rate too low

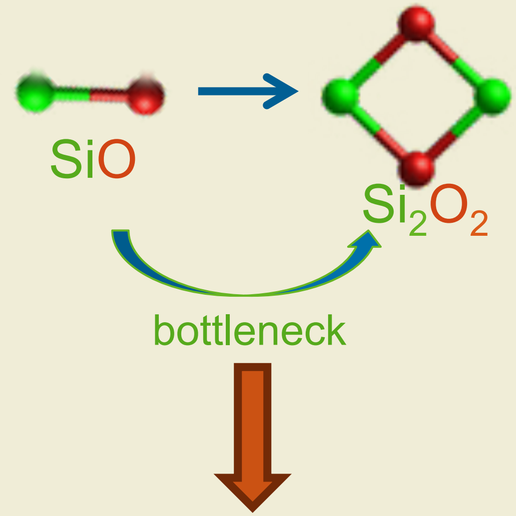
BUT:
- new SiO vapour pressure measurements (2006,2013)
- **details nucleation not yet understood**

2. Ingredients: Chemistry: from molecules to grains

Goumans et al. 2012







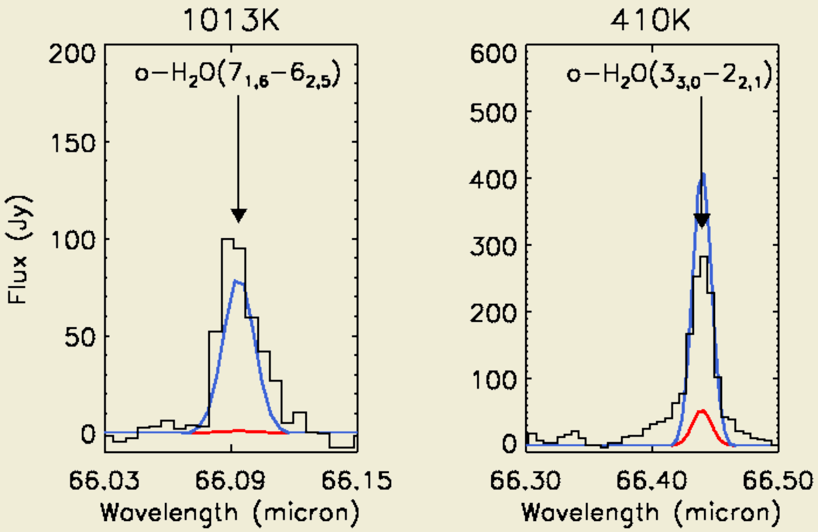
crucial role of H_2O

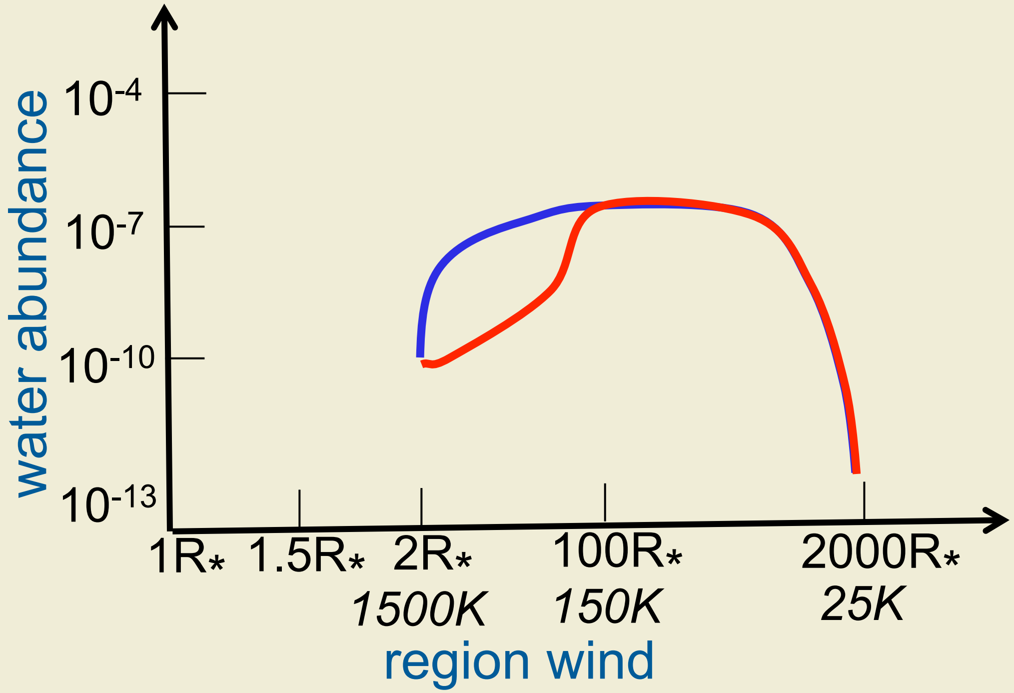
2. Ingredients: Theoretical models

I. Radiative transfer models

$$\boxed{dI_\nu/d\tau_\nu = S_\nu - I_\nu}$$

→ need collisional rates, Einstein coefficients, temperature, density, …





2. Ingredients: Theoretical models

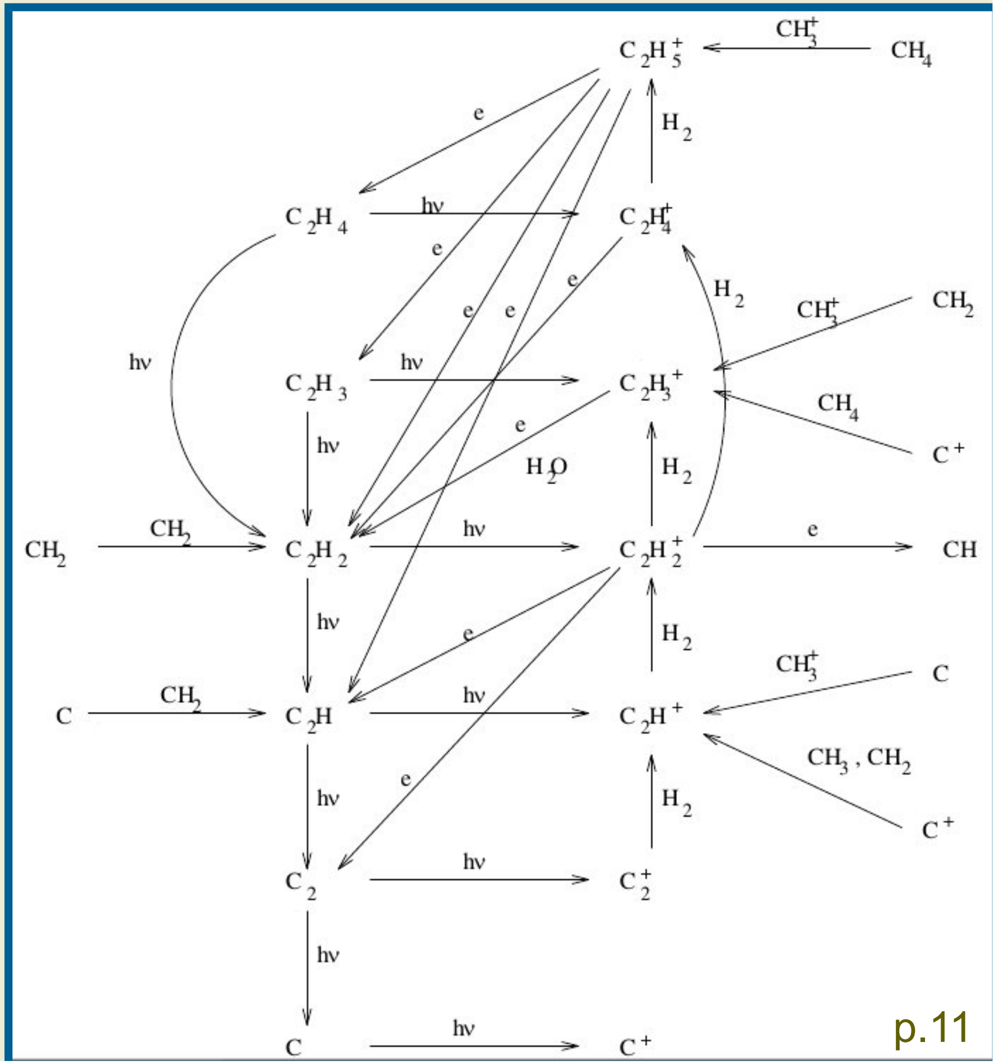
I. Radiative transfer models

$$dI_\nu/d\tau_\nu = S_\nu - I_\nu$$

II. Chemical network

$$A + B \xrightarrow{k(T)} C + D$$

→ Dominant chemical pathways



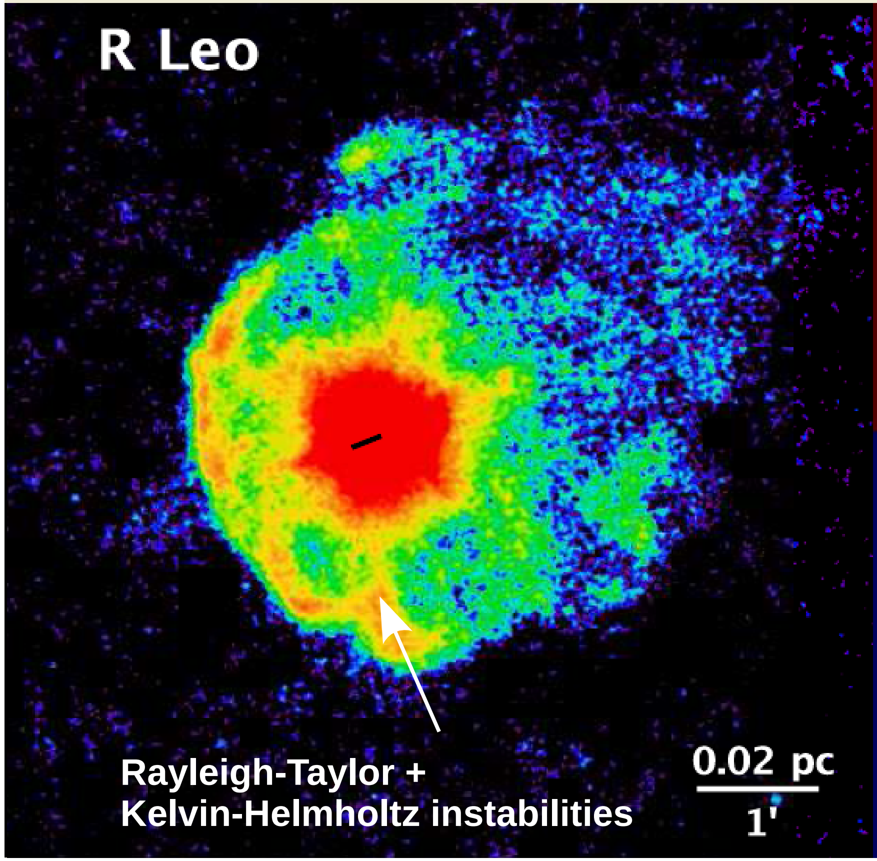
2. Ingredients: Theoretical models

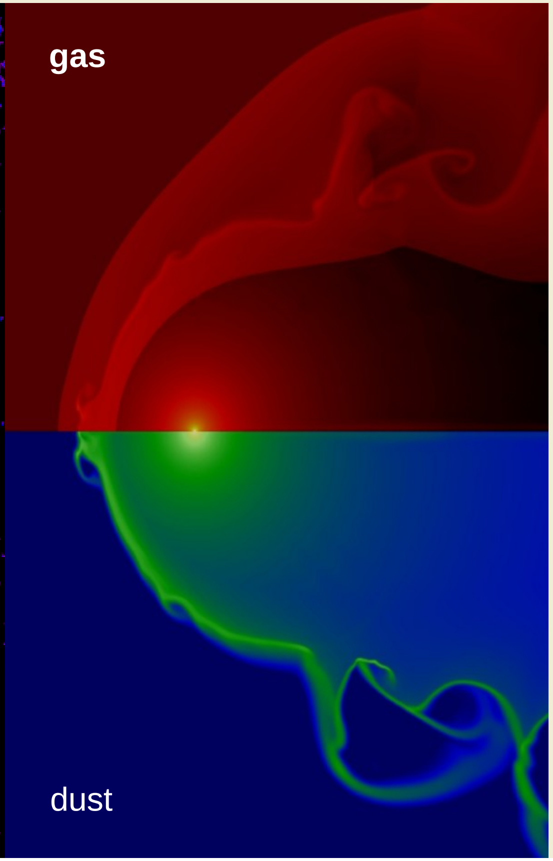
I. Radiative transfer models $dI_\nu/d\tau_\nu = S_\nu - I_\nu$

II. Chemical network

III. (Magneto-)hydrodynamical models

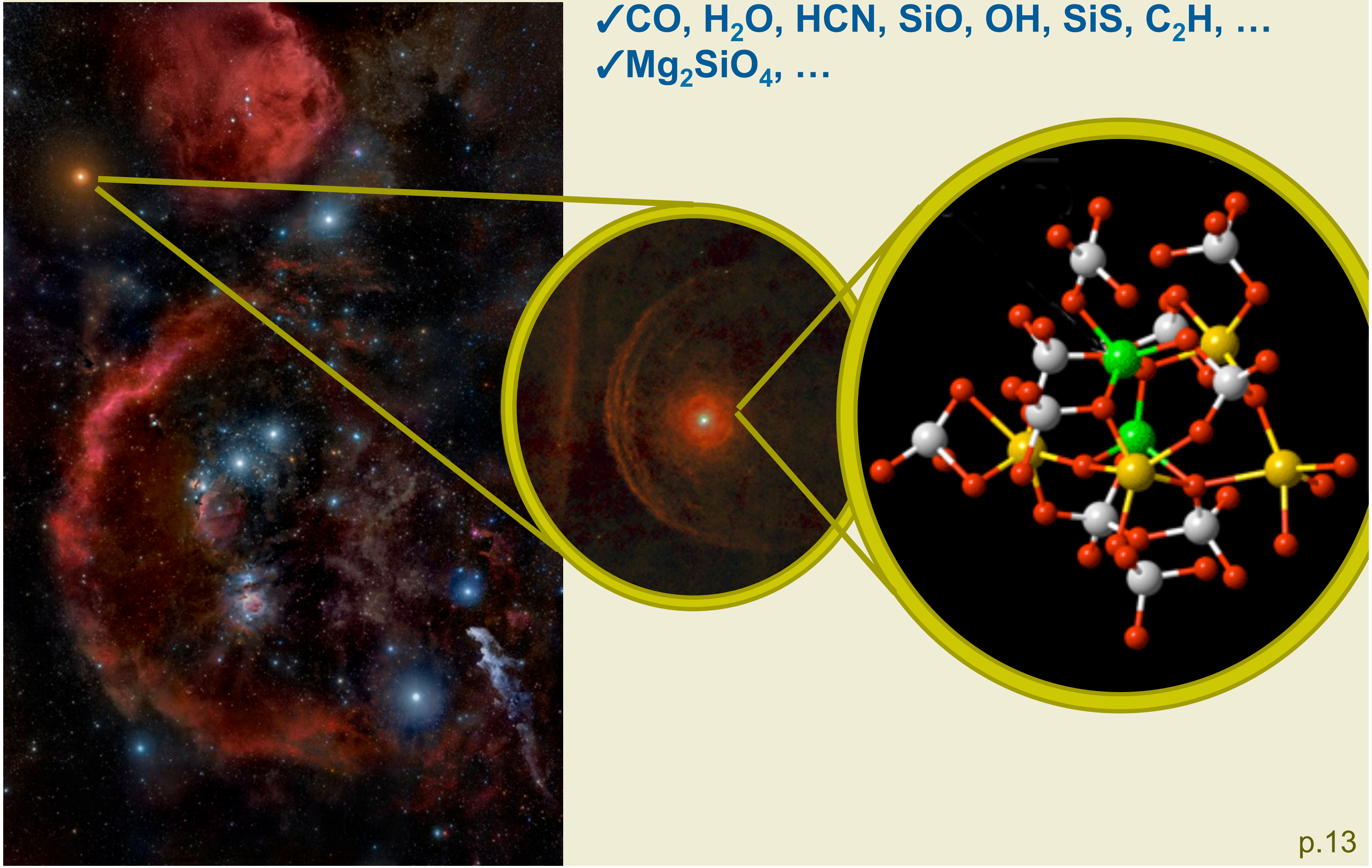
conservation of mass, momentum, energy → temperature, velocity, density





3. Some Herschel results

✓CO, H_2O, HCN, SiO, OH, SiS, C_2H, …
✓Mg_2SiO_4, …



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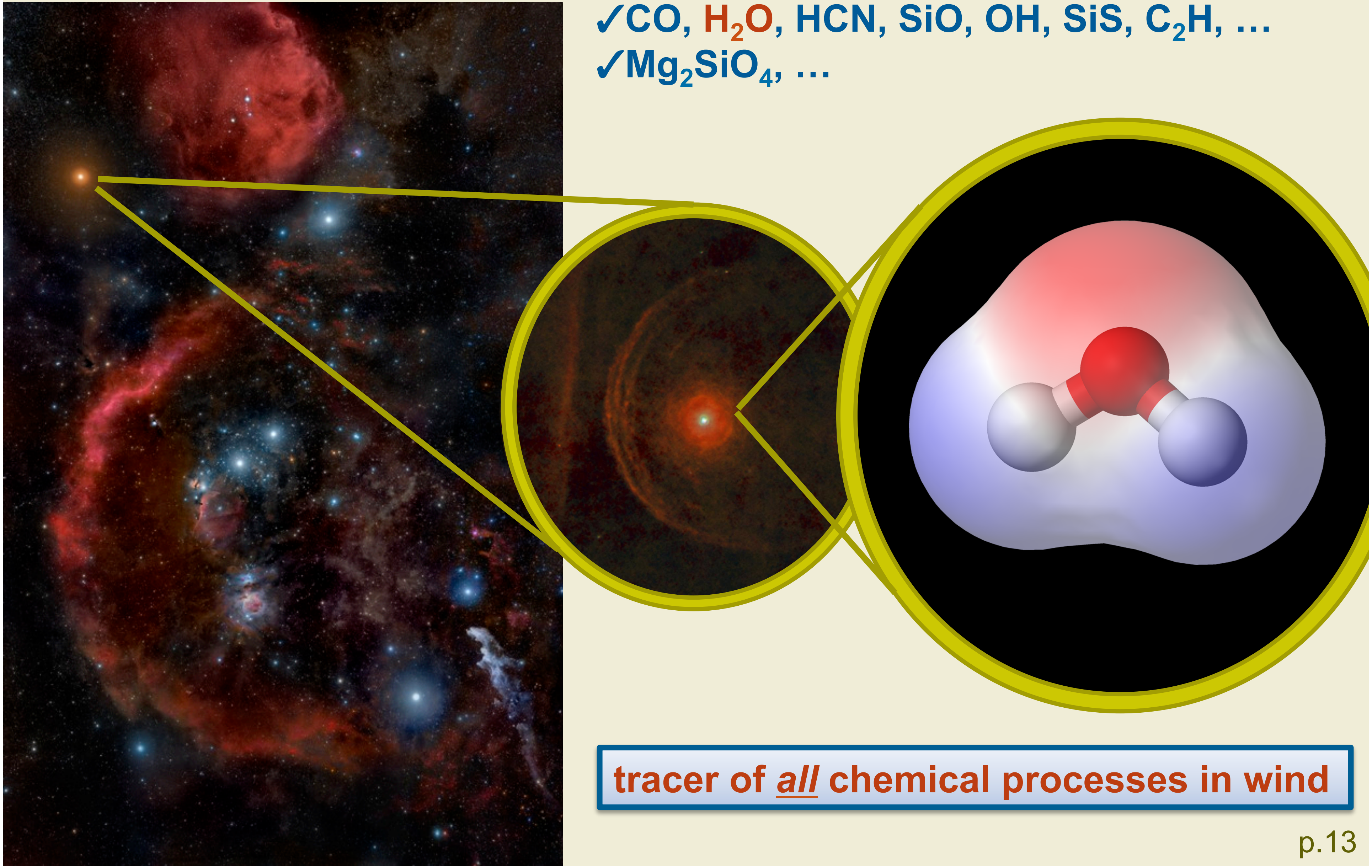


tracer of *<u>all</u>* chemical processes in wind

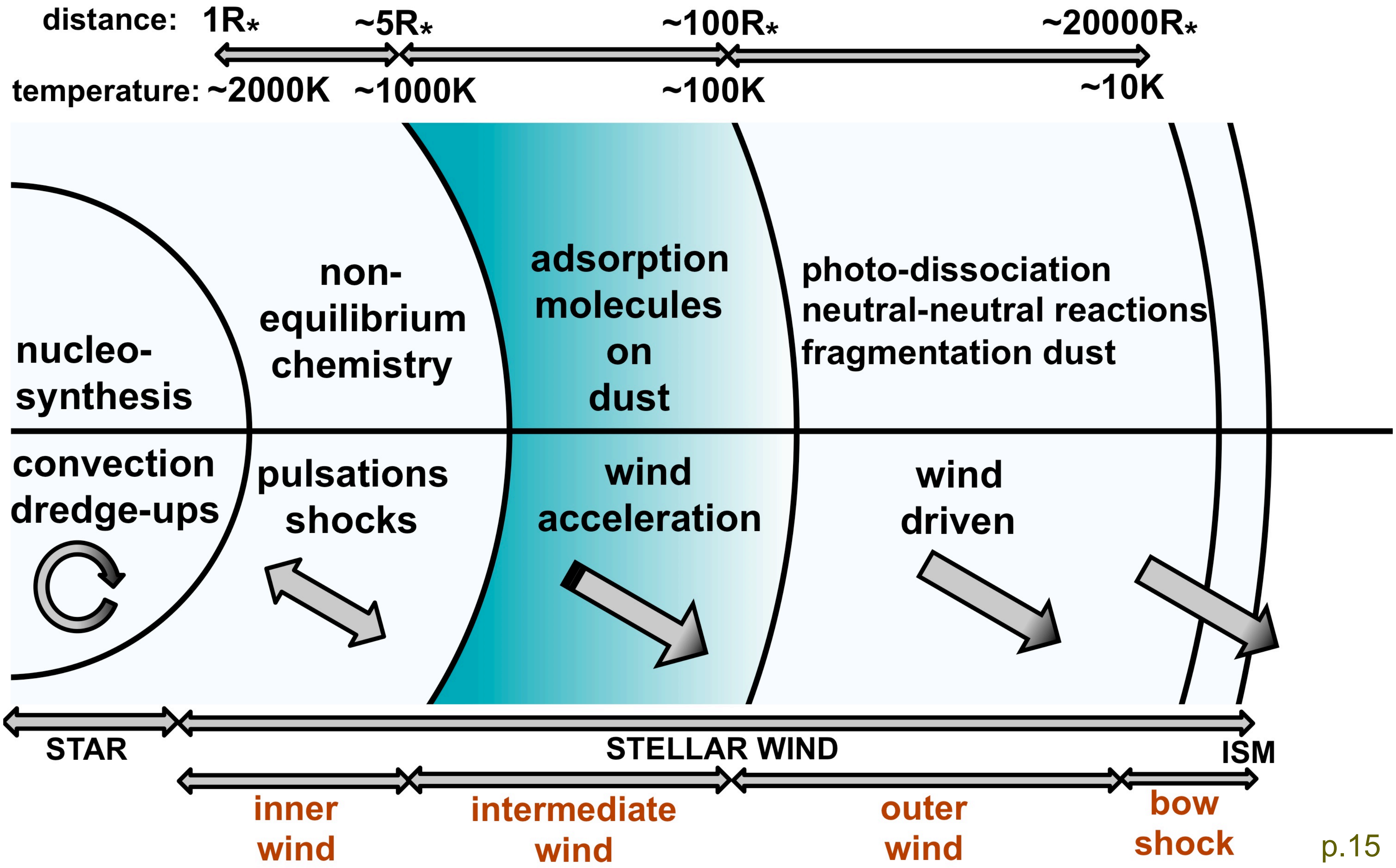
3. Some Herschel results: H_2O

H_2O in oxygen-rich winds (C/O<1)

H_2O in carbon-rich winds (C/O>1)

3.1. H_2O in oxygen-rich winds

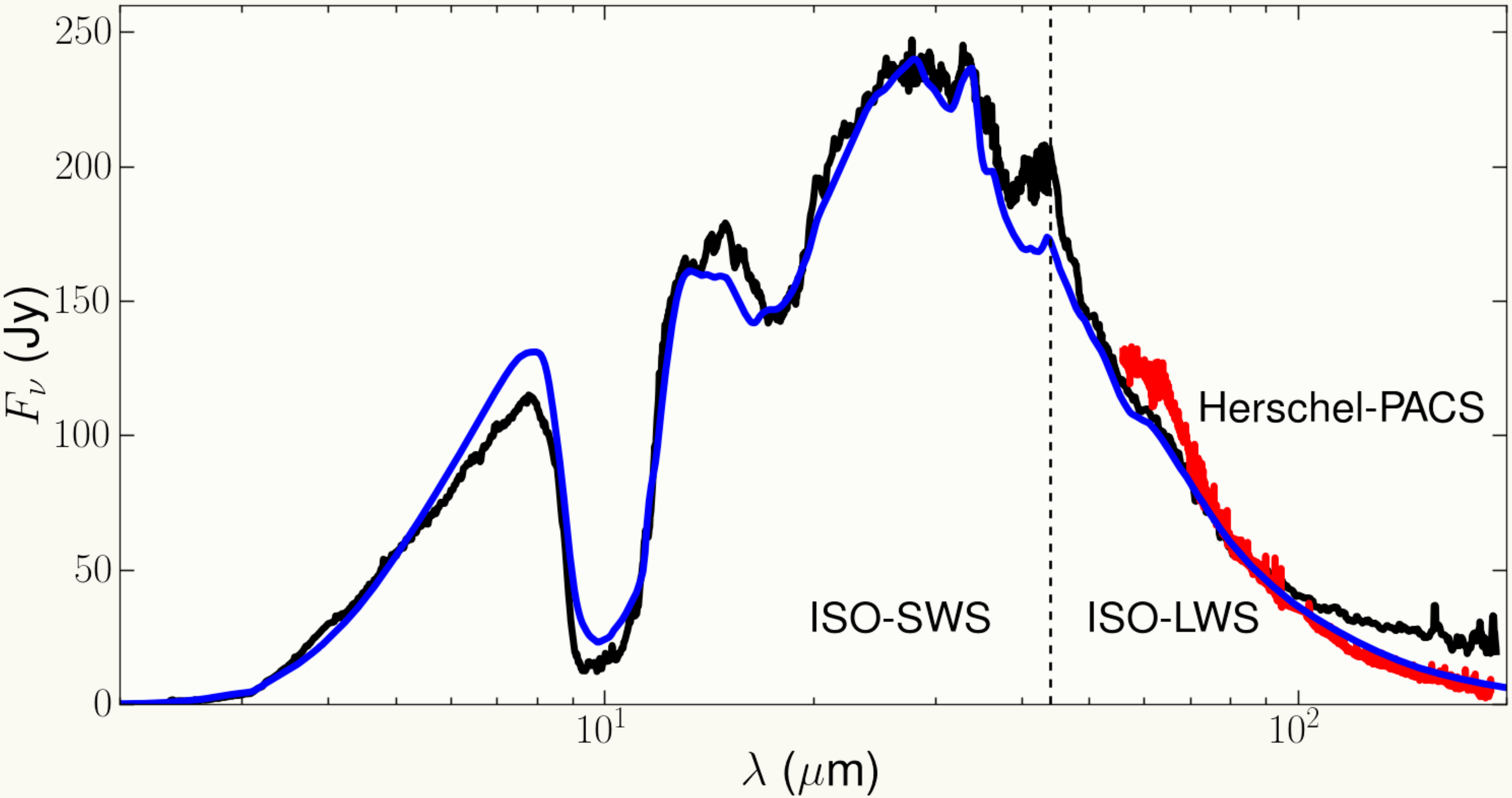
→ Gas-dust interaction



3.1. H_2O in oxygen-rich winds

Example 1

high mass-loss rate: OH/IR 127.8+0.0



Lombaert et al. 2013

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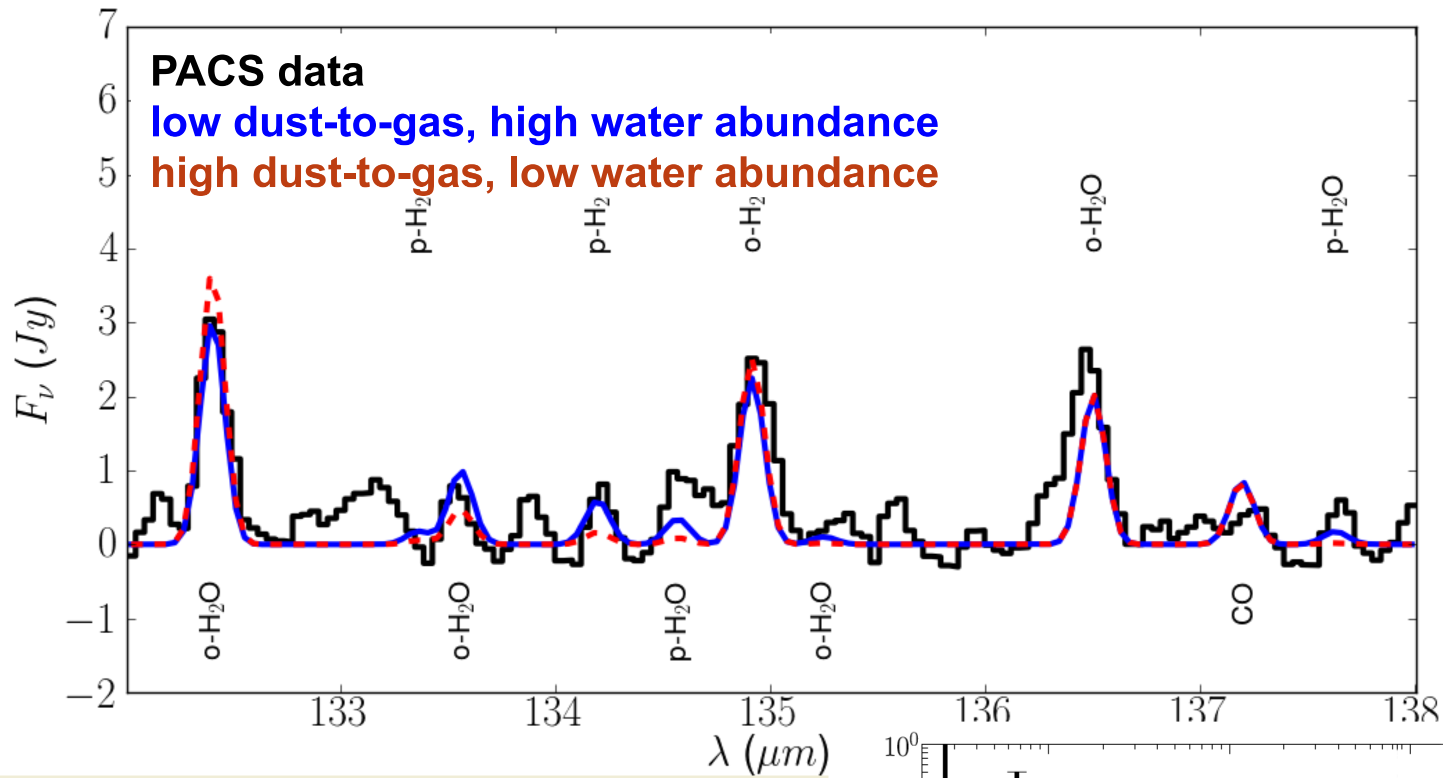

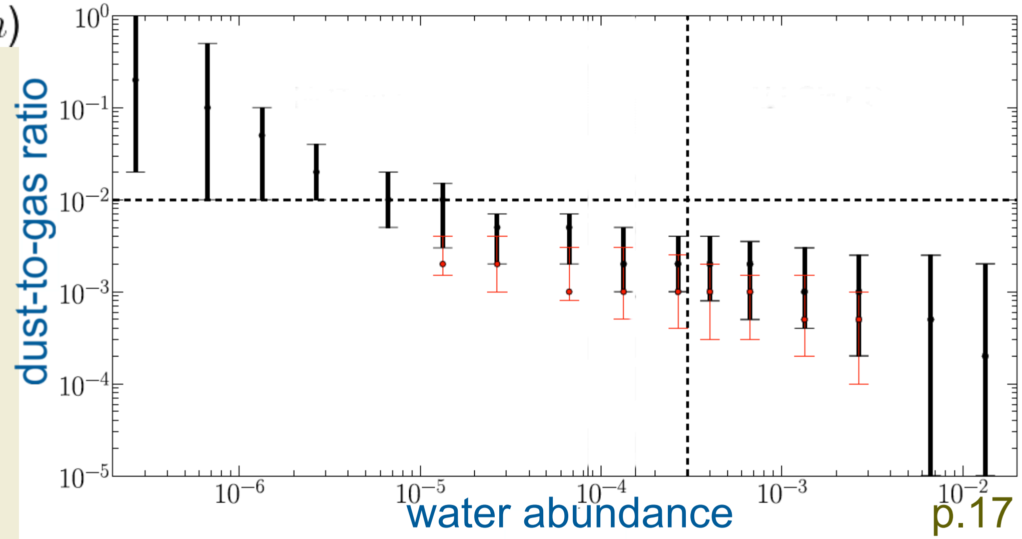

Lombaert et al. 2013

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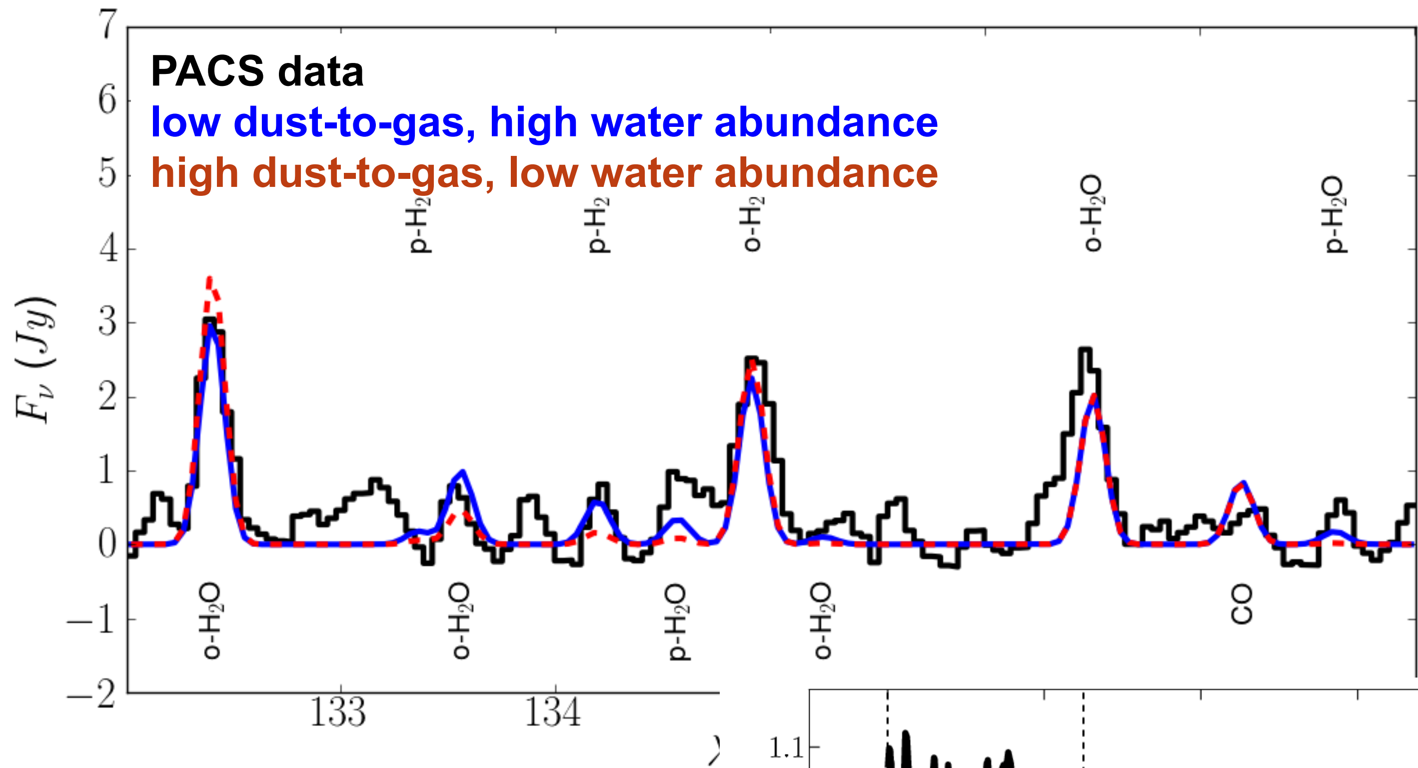
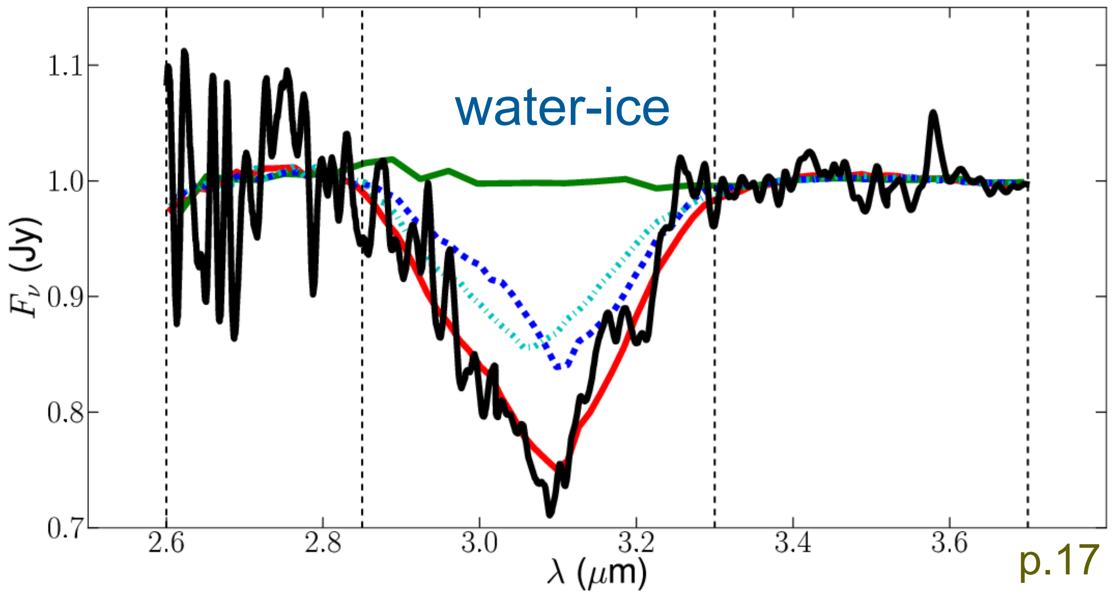


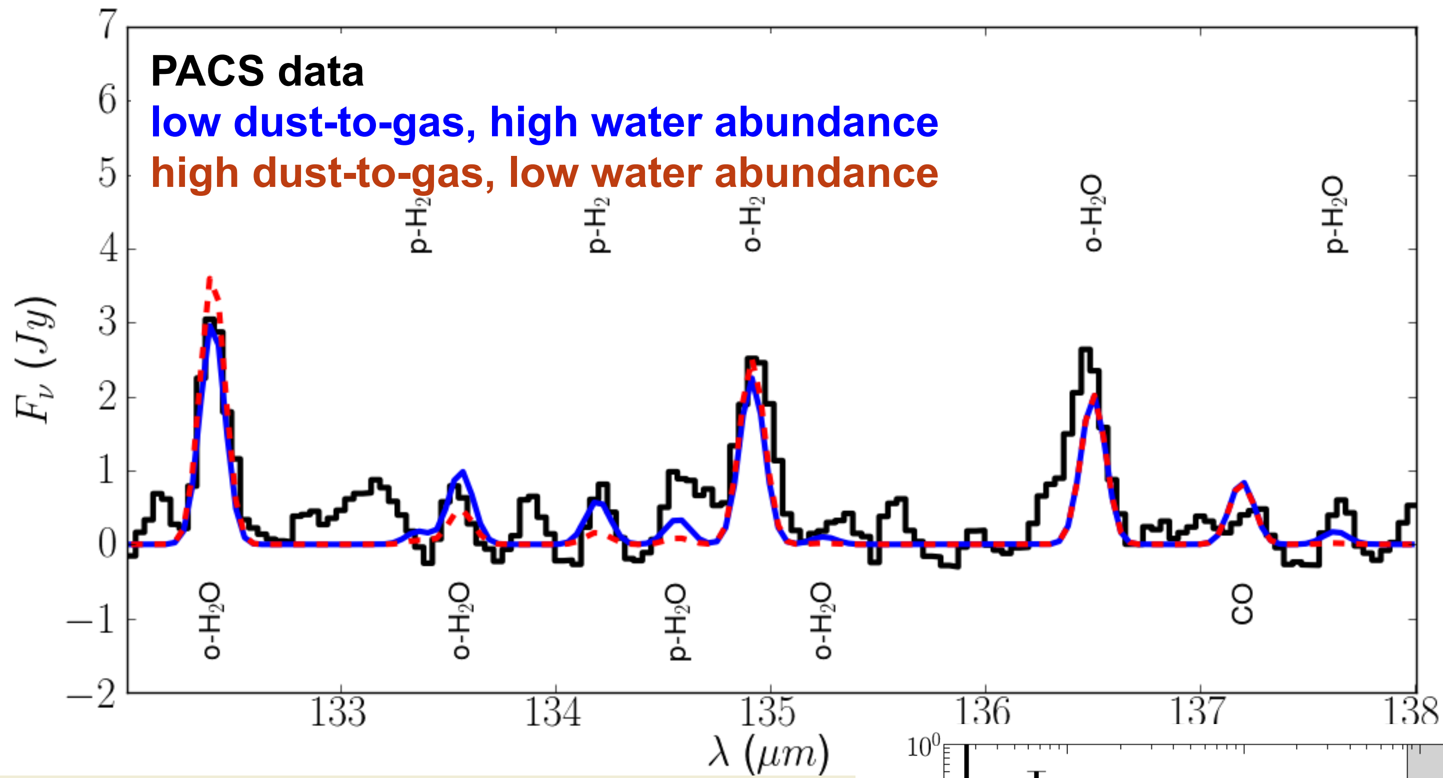
ISO



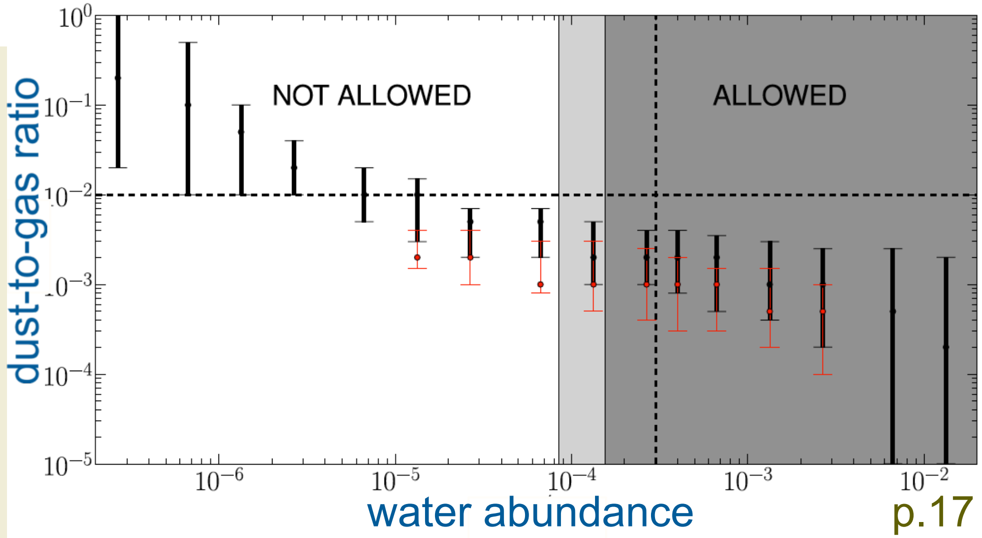
n(H_2O-ice) → n^{min}(H_2O-gas)

Lombaert et al. 2013

3.1. H_2O in oxygen-rich winds

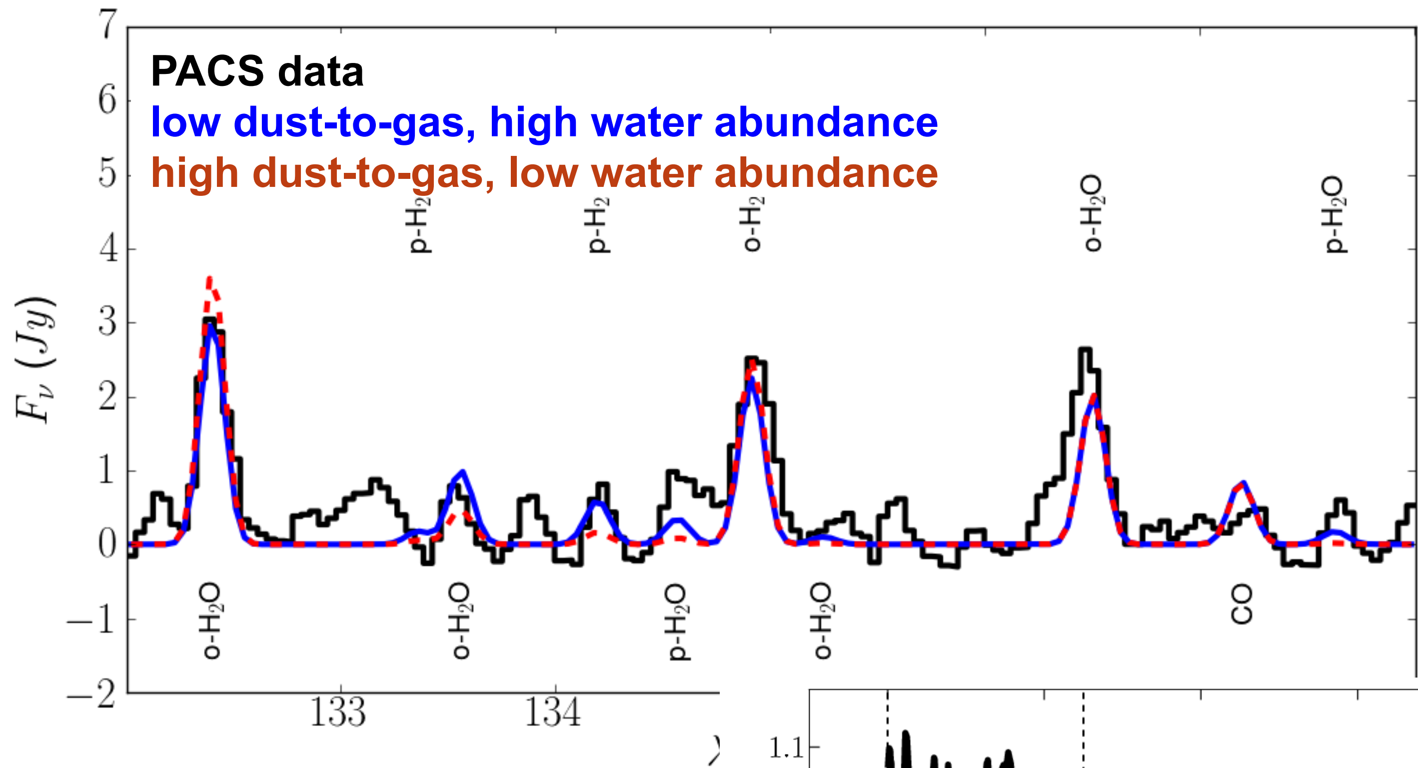


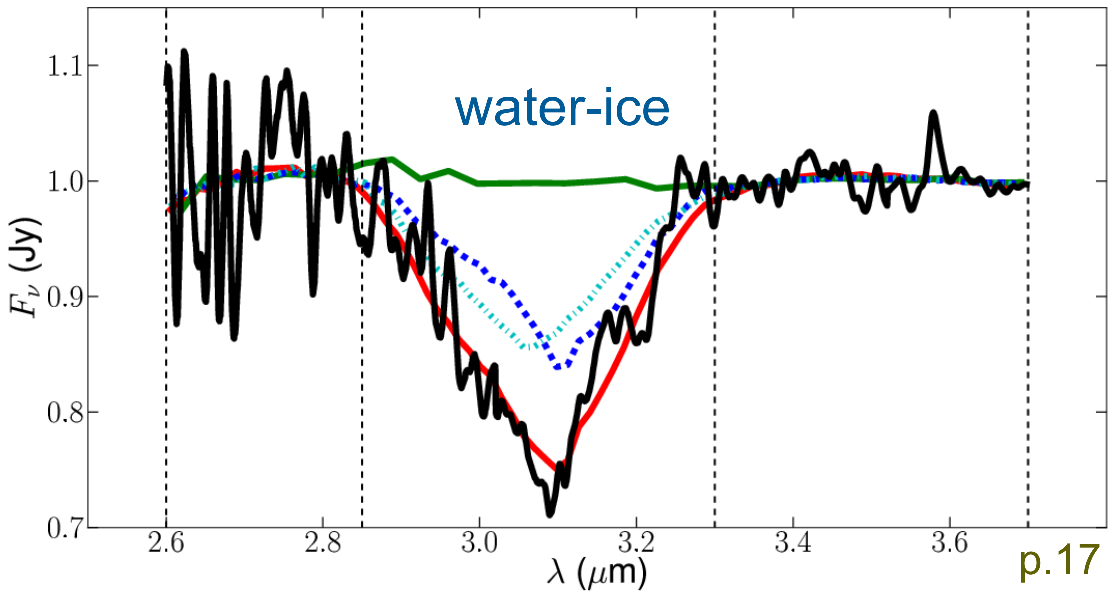
$n(H_2O\text{-ice}) \rightarrow n^{min}(H_2O\text{-gas})$



Lombaert et al. 2013

3.1. H_2O in oxygen-rich winds





n(H_2O-ice) → n^{min}(H_2O-gas)

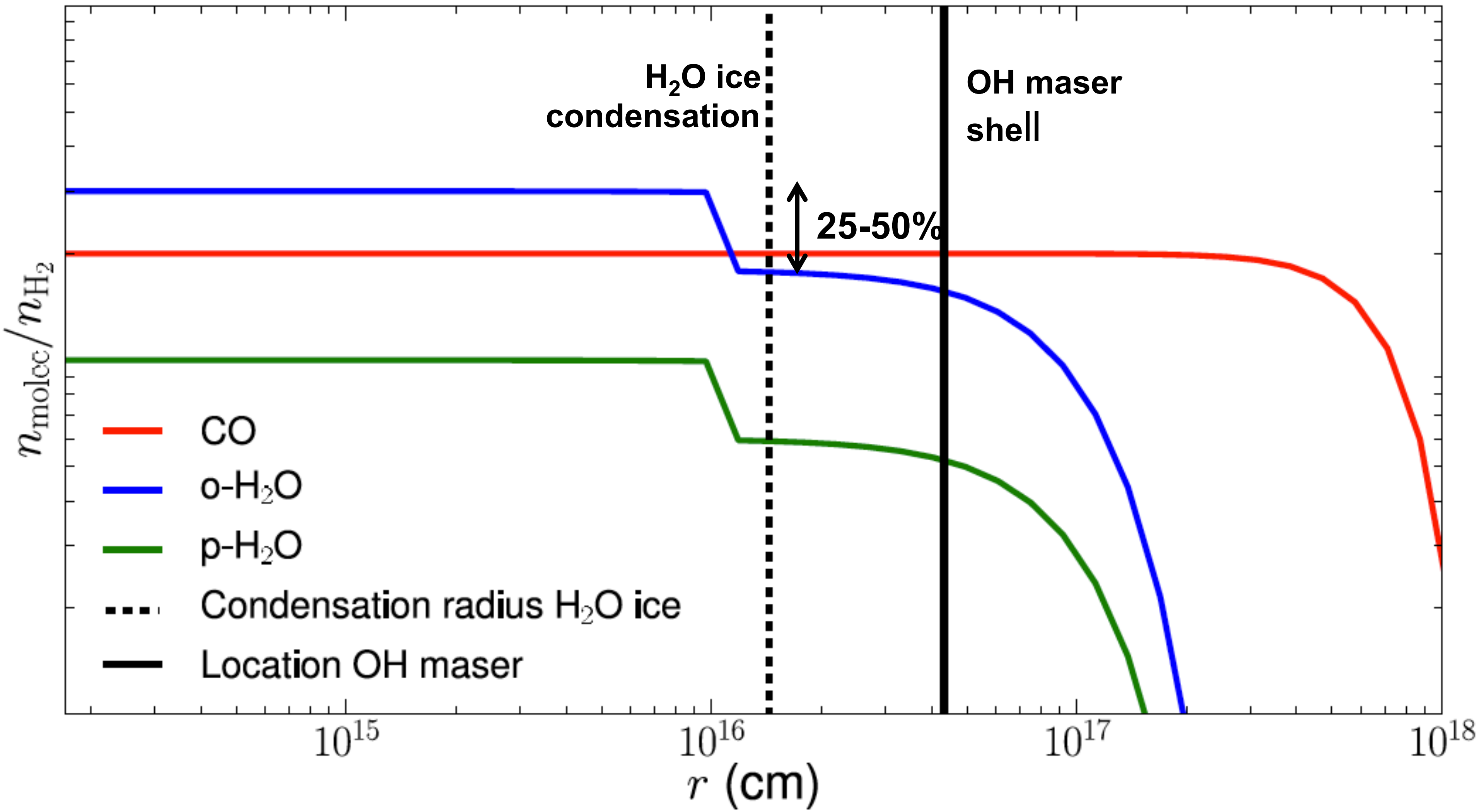
efficiency ice formation?

Lombaert et al. 2013

3.1. H_2O in oxygen-rich winds

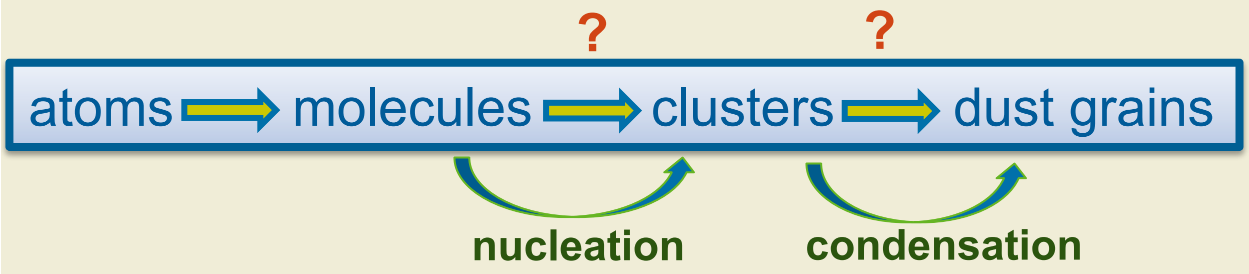
efficiency ice formation? → from OH maser

$H_2O \rightarrow OH + H$

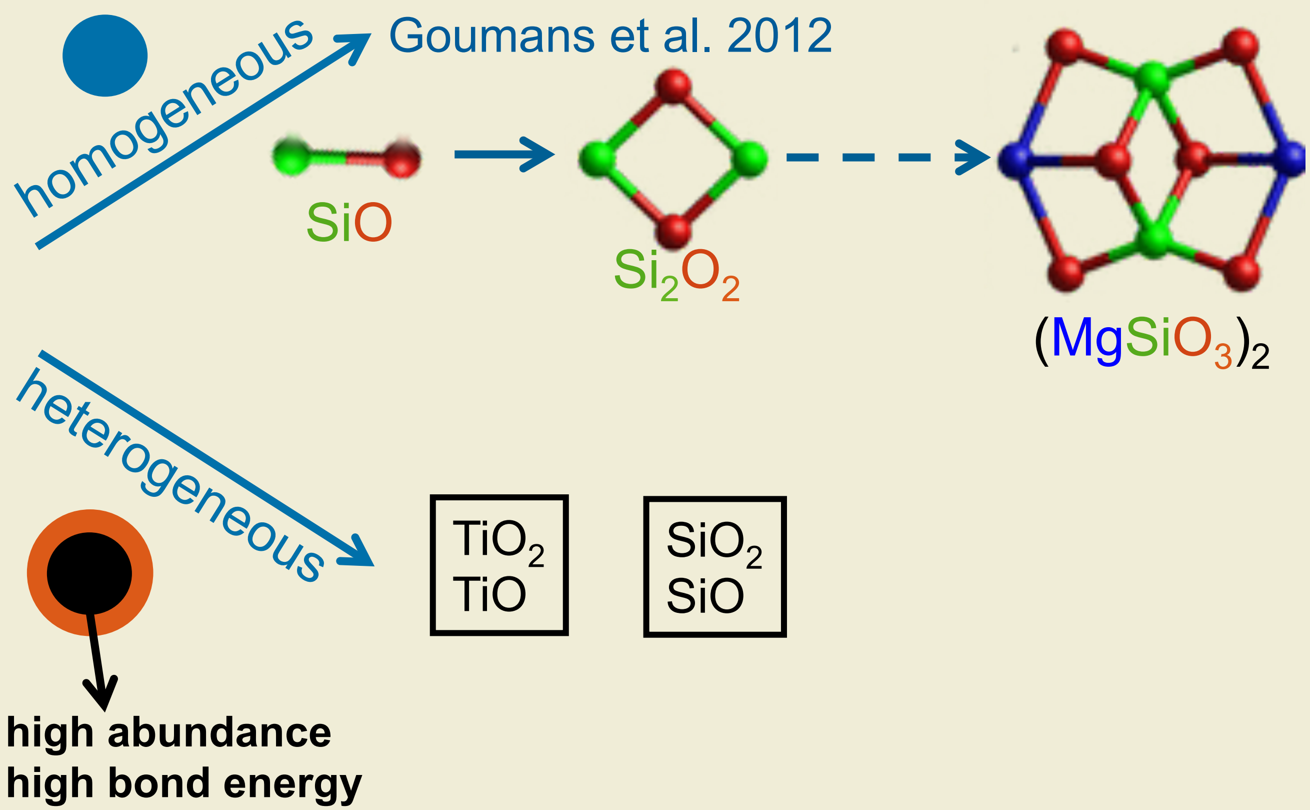


3.2. H_2O in oxygen-rich winds

Example 2

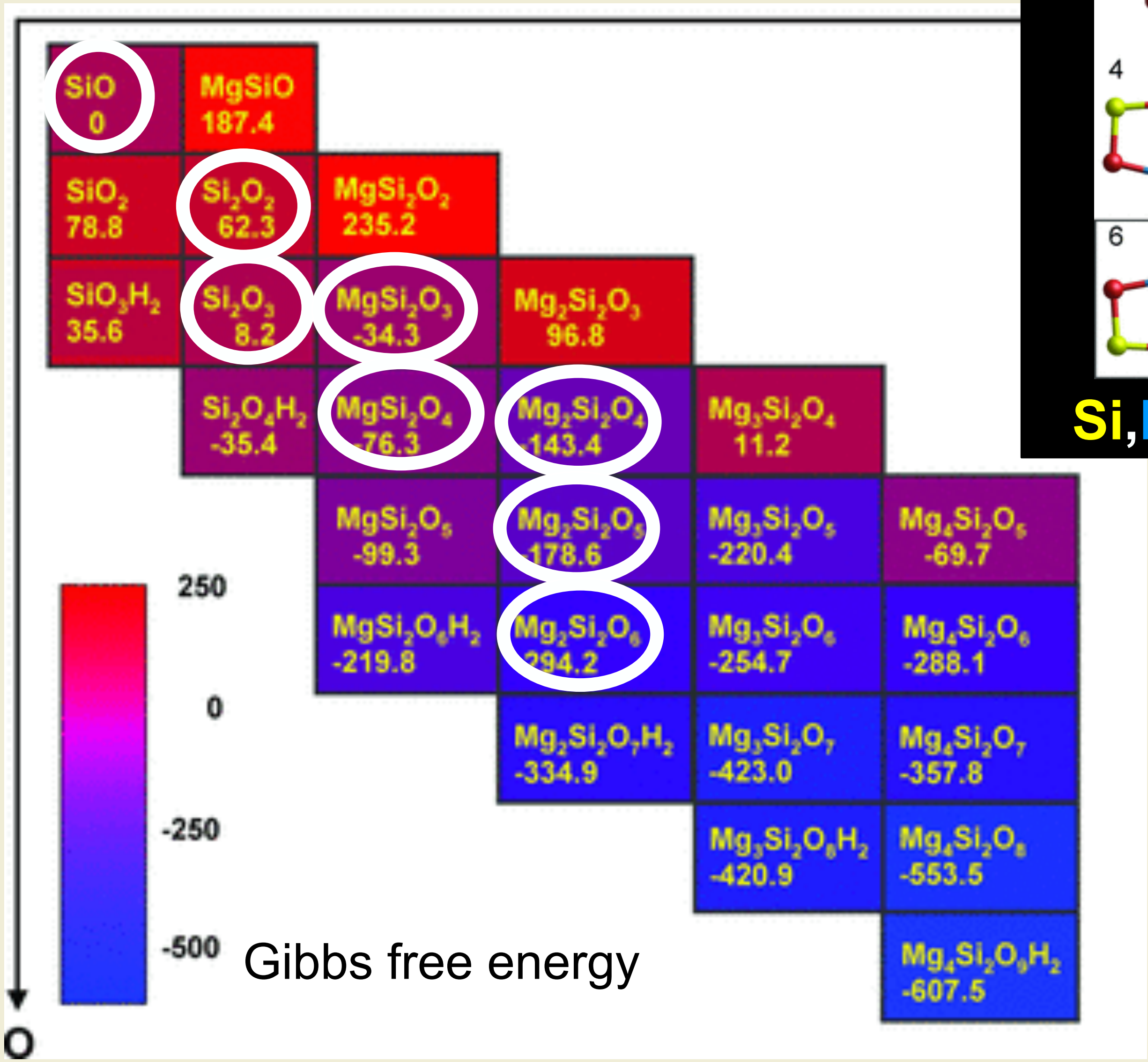


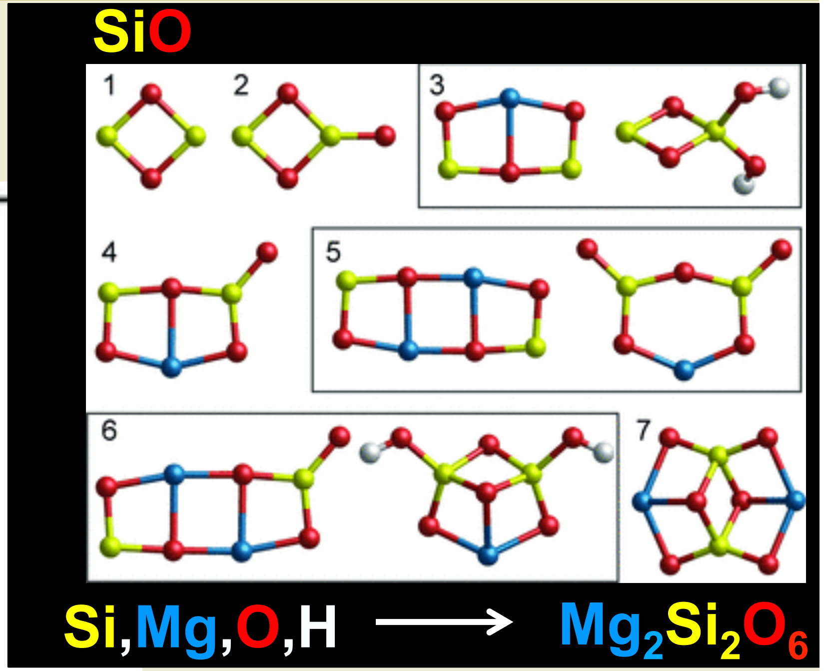
O-rich giants
silicates: $MgSiO_3$, Mg_2SiO_4
alumina: Al_2O_3
silica: SiO_2



3.2. H_2O in oxygen-rich winds

Goumans et al. 2012





enstatite dimer $Mg_2Si_2O_6$

crucial role of H_2O

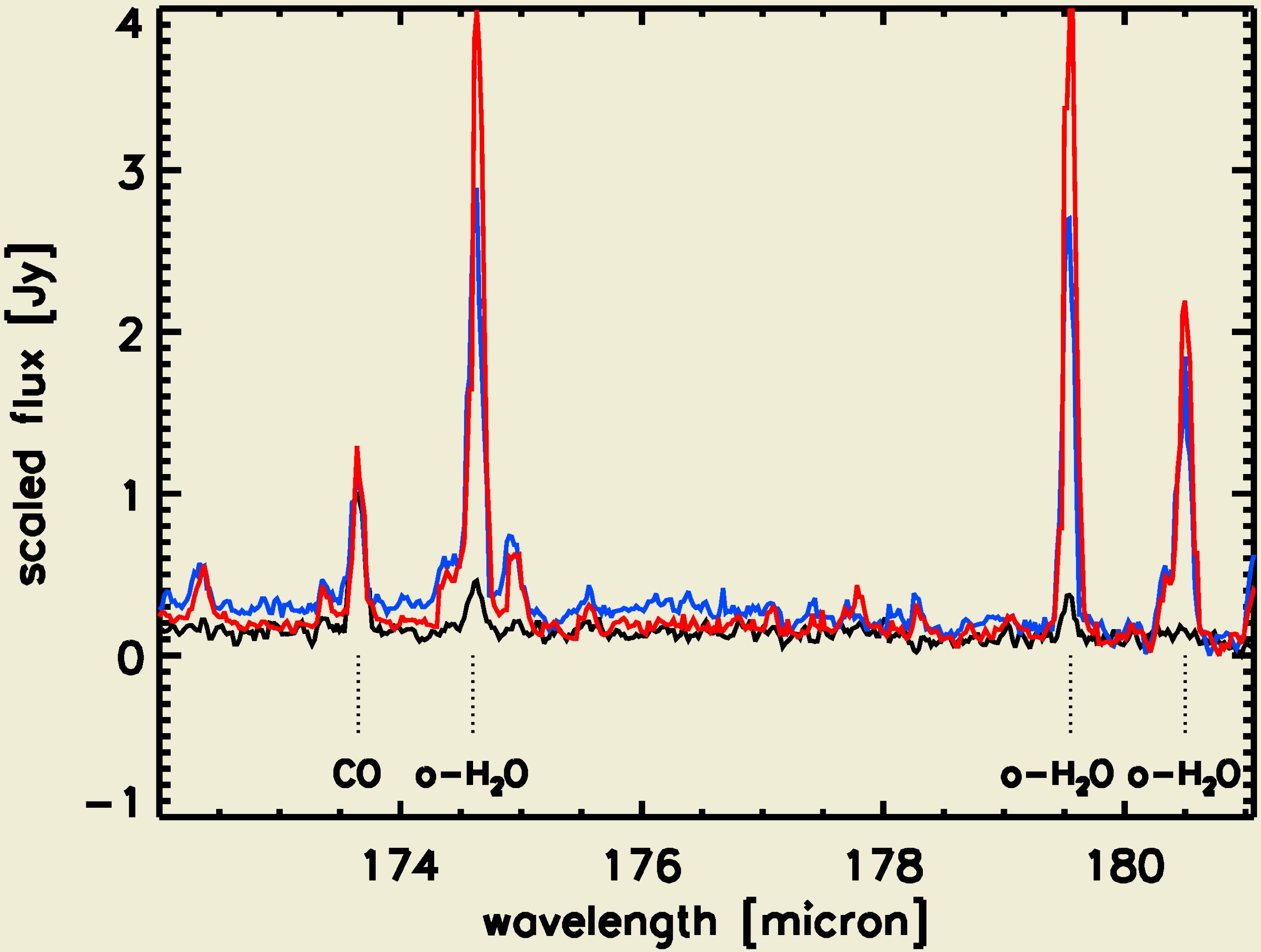
3.2. H_2O in oxygen-rich winds

Betelgeuse: Mdot ~ 2×10^{-6} Msun/yr

NML Cyg: Mdot ~ 1×10^{-4} Msun/yr

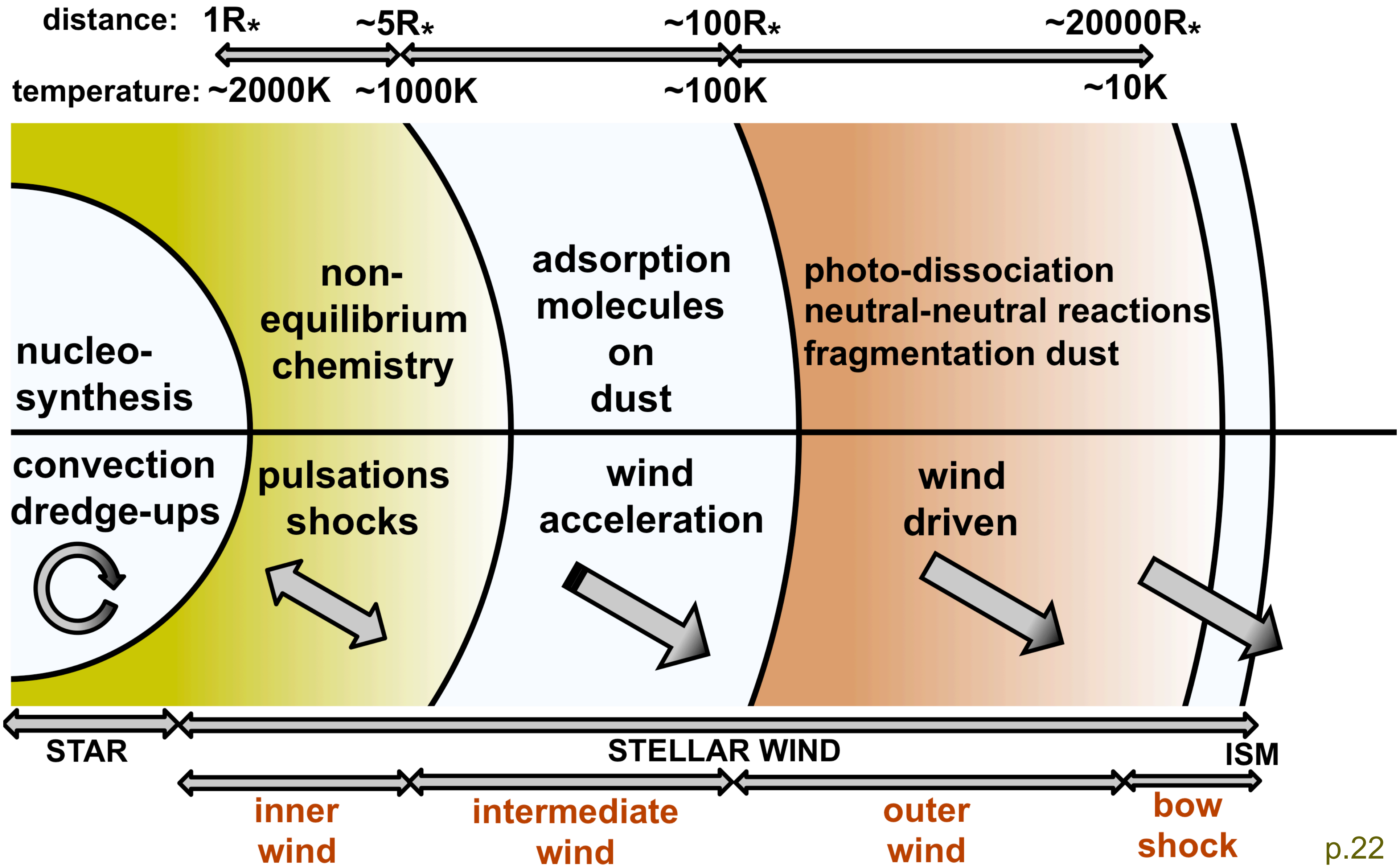
VY CMa: Mdot ~ 3×10^{-4} Msun/yr

Role of H_2O



3.3. H_2O in carbon-rich winds

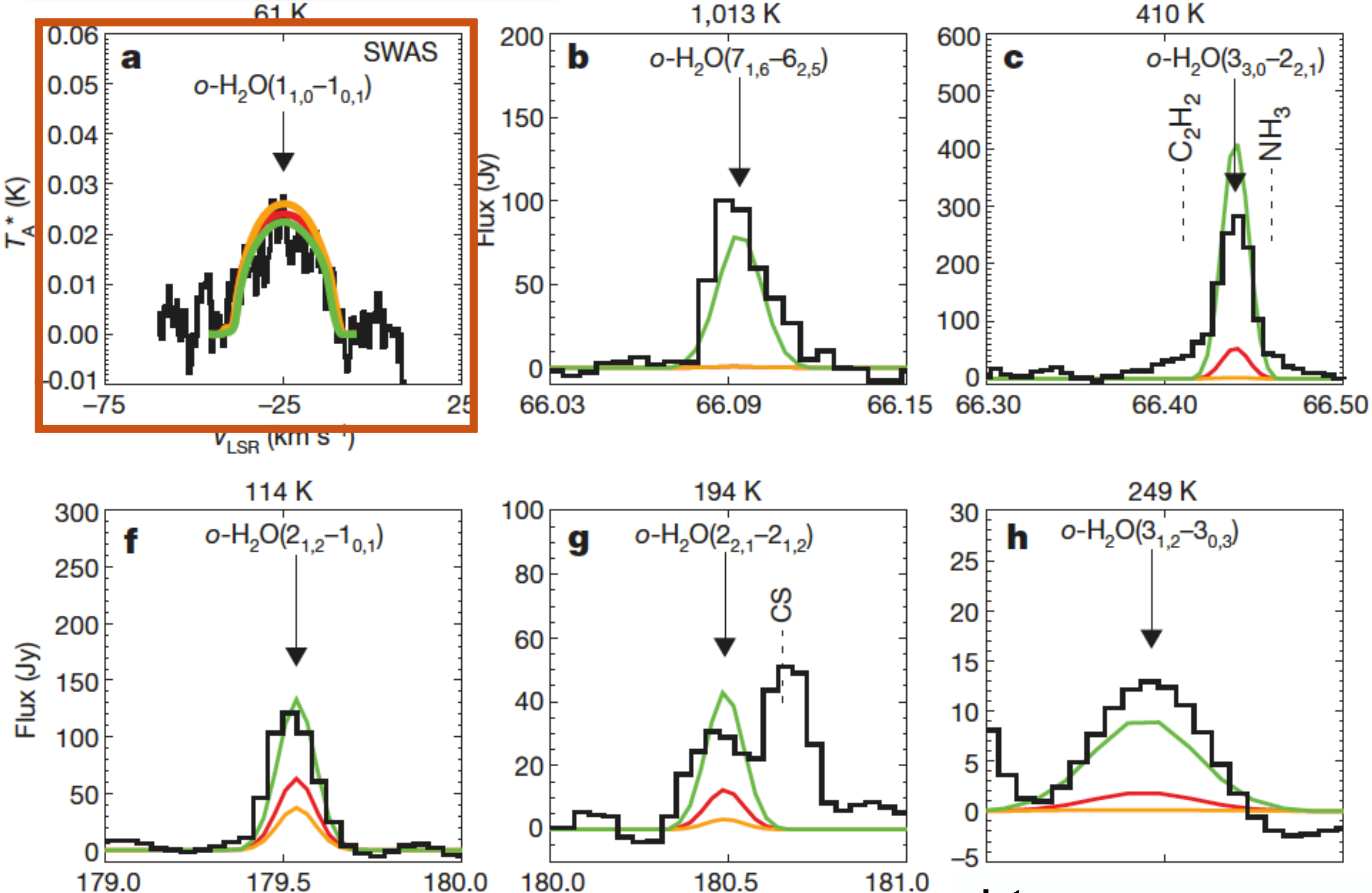
→ Formation of warm H_2O-vapour in the sooty outflow of giant stars



3.3. H_2O in carbon-rich winds

Melnick et al. 2001, Nature

Decin et al. 2010, Nature; Neufeld et al. 2011

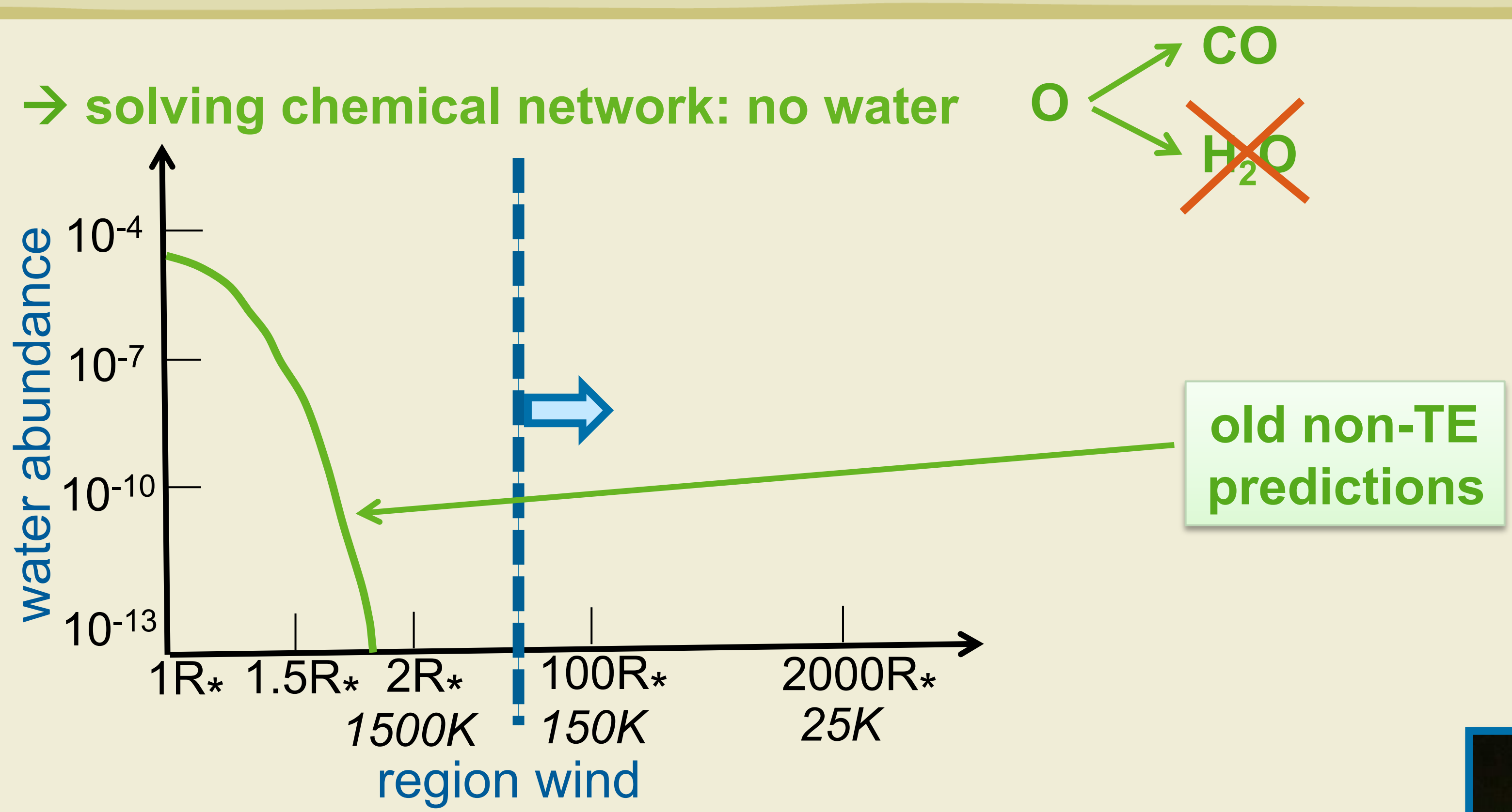


data
inner wind origin (T<1500K)
intermediate wind origin (T<150K)
outer wind origin (T<40K)

CW Leo – most nearby C-rich AGB

3.3. H_2O in carbon-rich winds: Origin?

→ solving chemical network: no water



Before Herschel: origin (cool) water vapour

(1) ***R>15 R*:*** sublimation of icy bodies (Melnick et al. 2001)

(2) ***R>15 R*:*** grain surface reactions (Fischer-Tropsch catalysis, Willacy 2004)

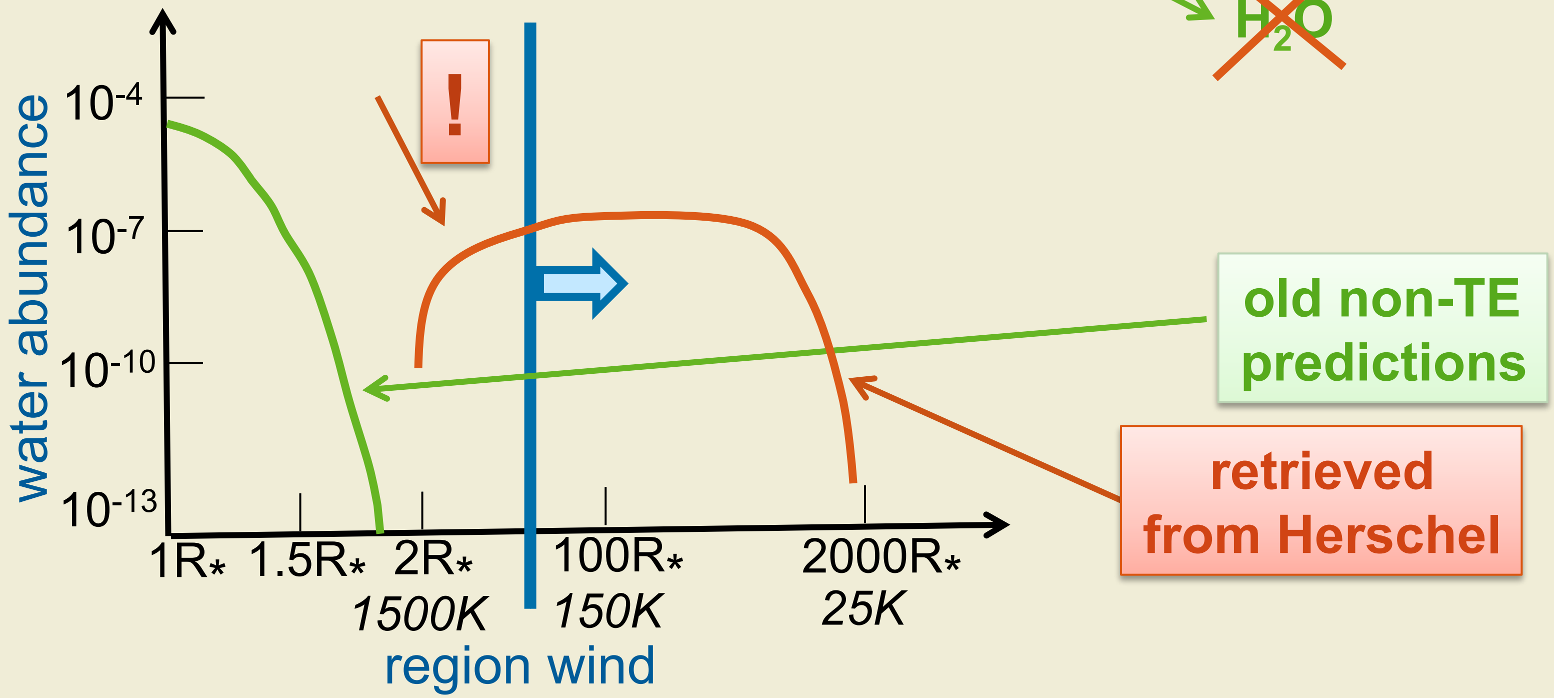
(3) ***R>150 R*:*** radiative association O+H_2 (Agúndez et al. 2006)

3.3. H_2O in carbon-rich winds: Origin?

→ solving chemical network: no water

$O \rightarrow CO$

$O \rightarrow \cancel{H_2O}$



After Herschel: origin *warm* water vapour

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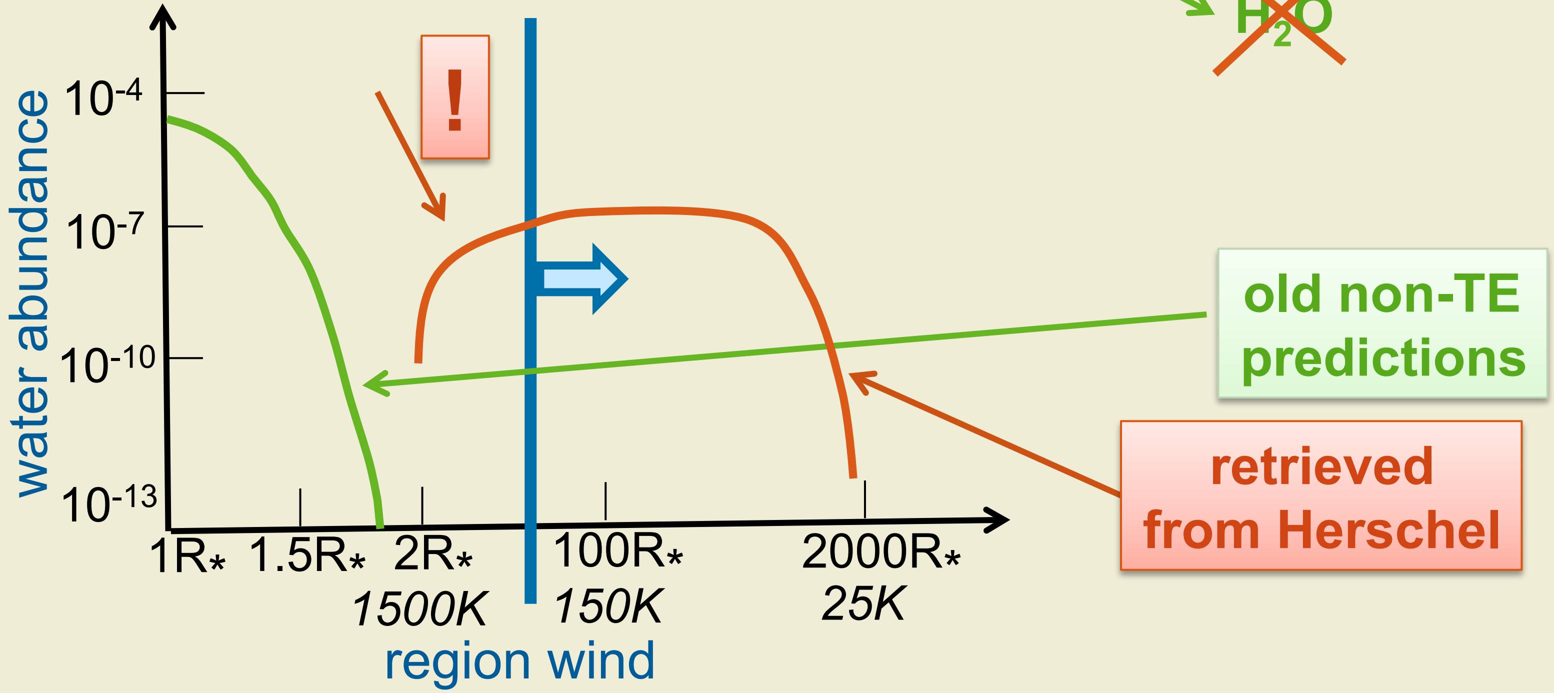


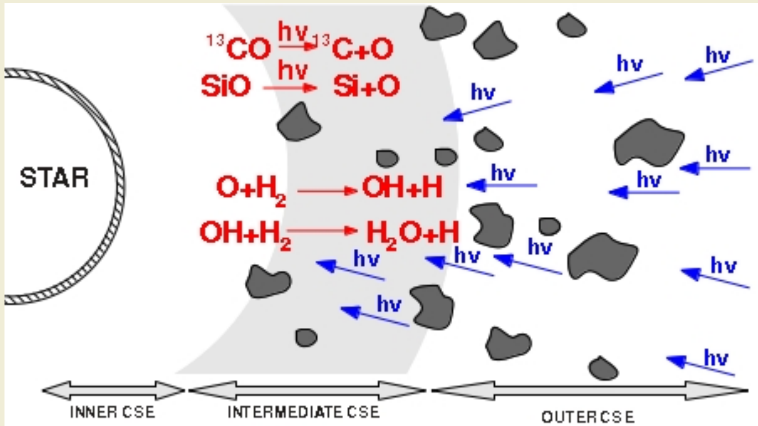
After Herschel: origin *warm* water vapour

(1) penetration of UV photons in clumpy wind

→***photo-dissociation* of CO, SiO: free O**

→***reaction with H_2*: creation OH and H_2O**

(Decin et al. 2010, Agúndez et al. 2010)

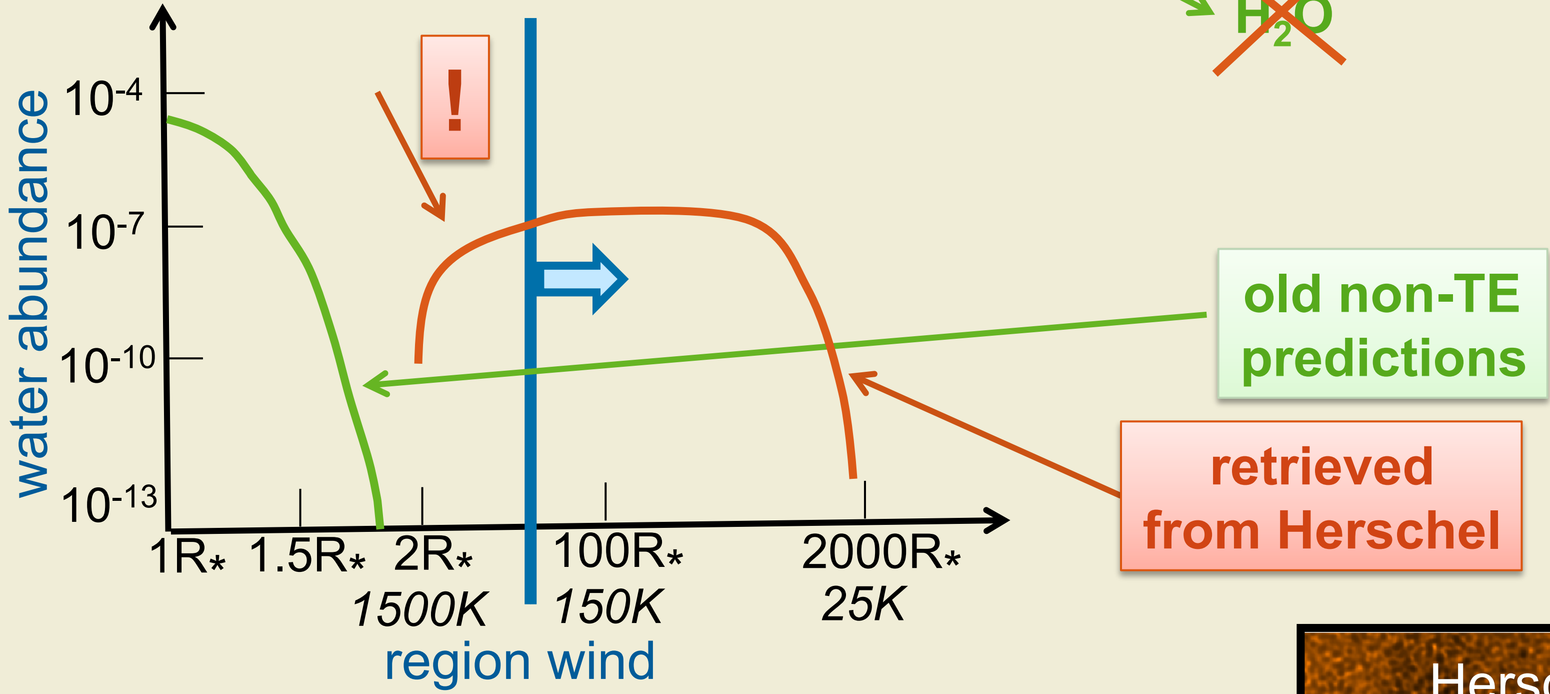


3.3. H_2O in carbon-rich winds: Origin?

→ solving chemical network: no water

O → CO

O → ~~H_2O~~



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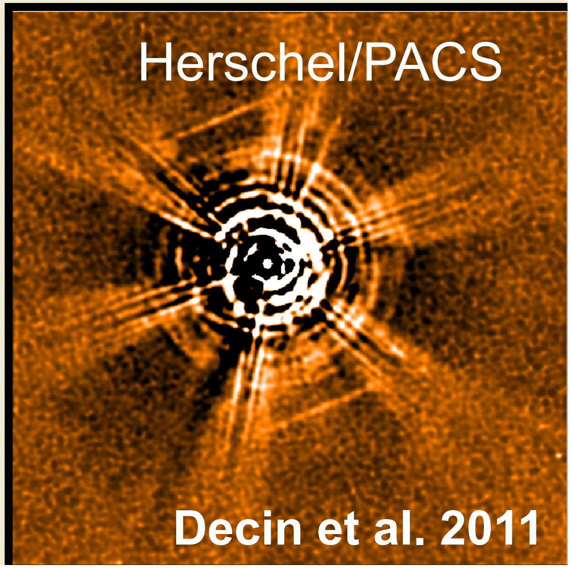

3.3. H_2O in carbon-rich winds: Origin?

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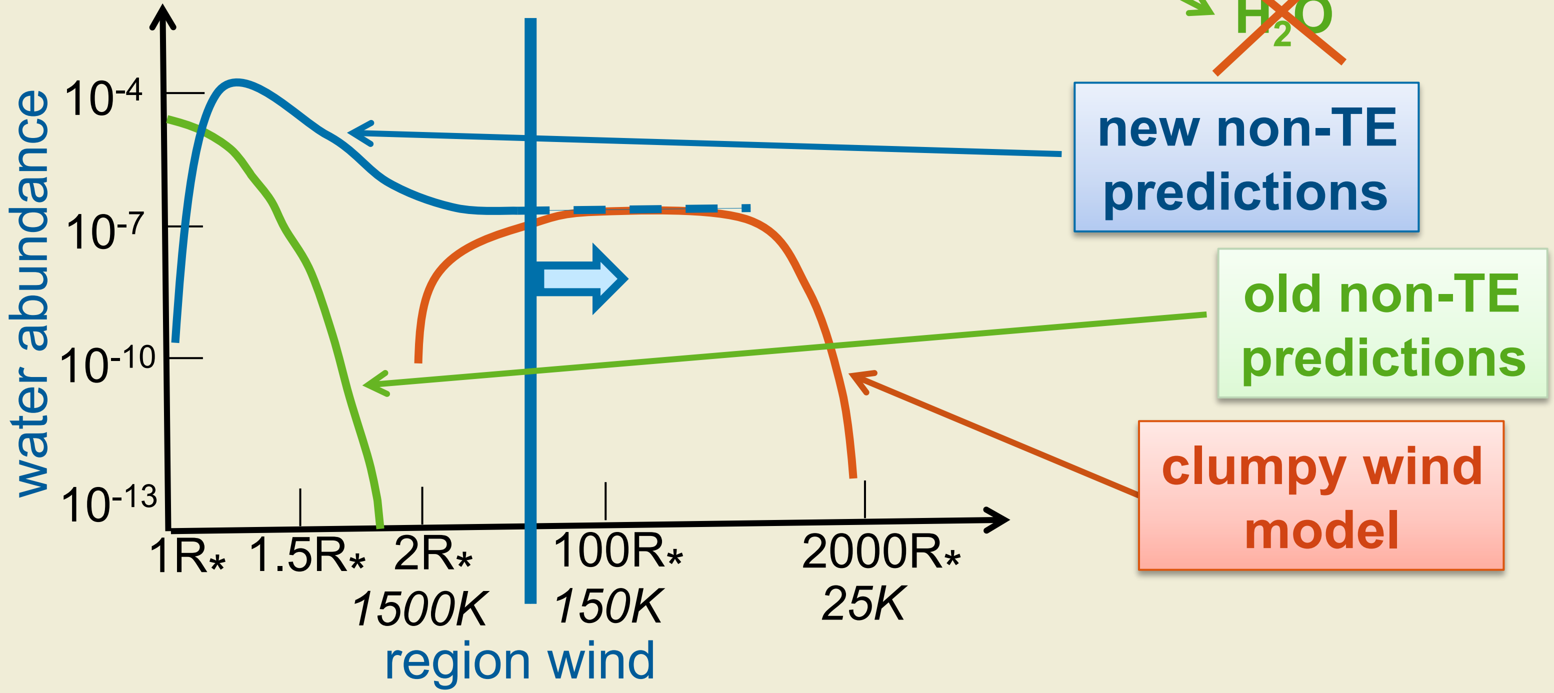


After Herschel: origin *warm* water vapour

(1) penetration of UV photons in clumpy wind

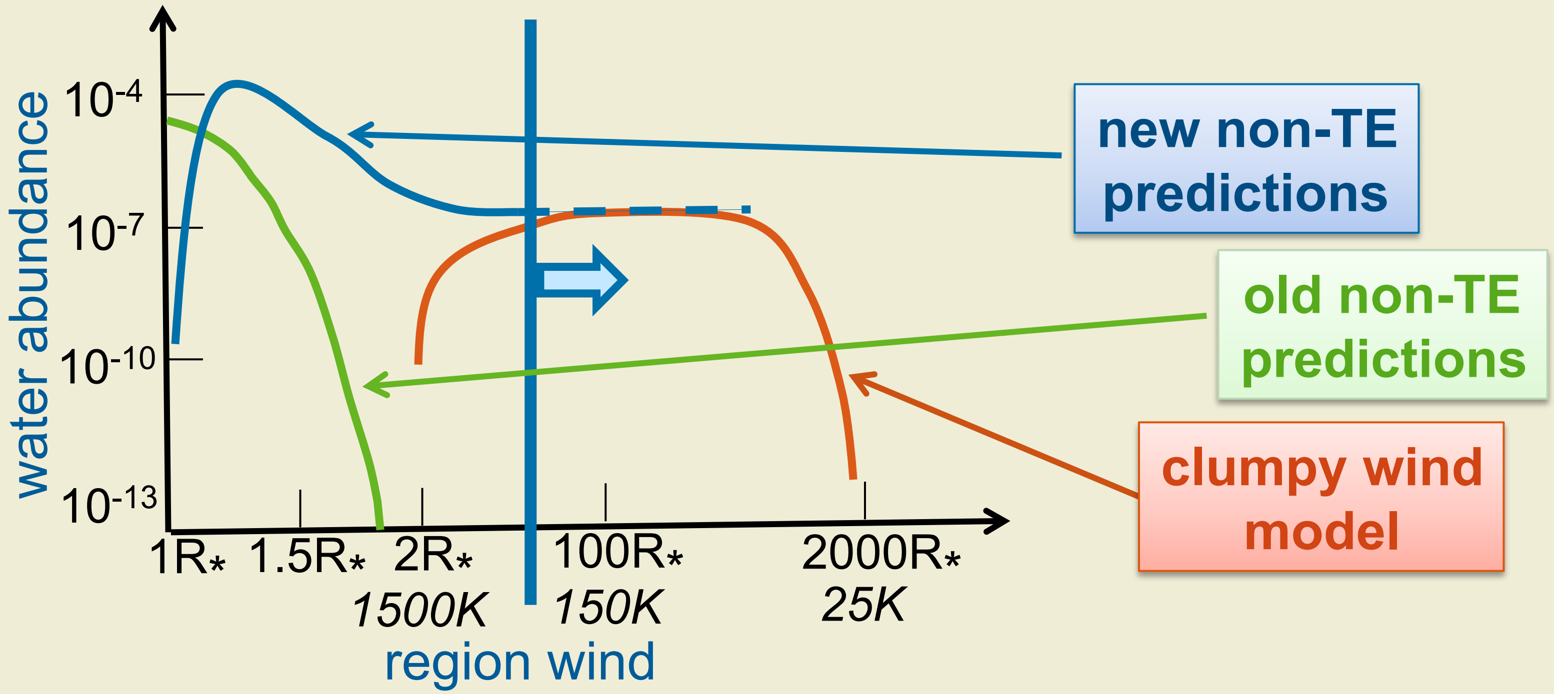
(2) shock-induced non-equilibrium chemistry

→ manually adapt Si + OH → SiO + H

(Cherchneff 2011, 2012)

HOW TO DISTINGUISH?

3.4. H_2O in carbon-rich winds: Origin?

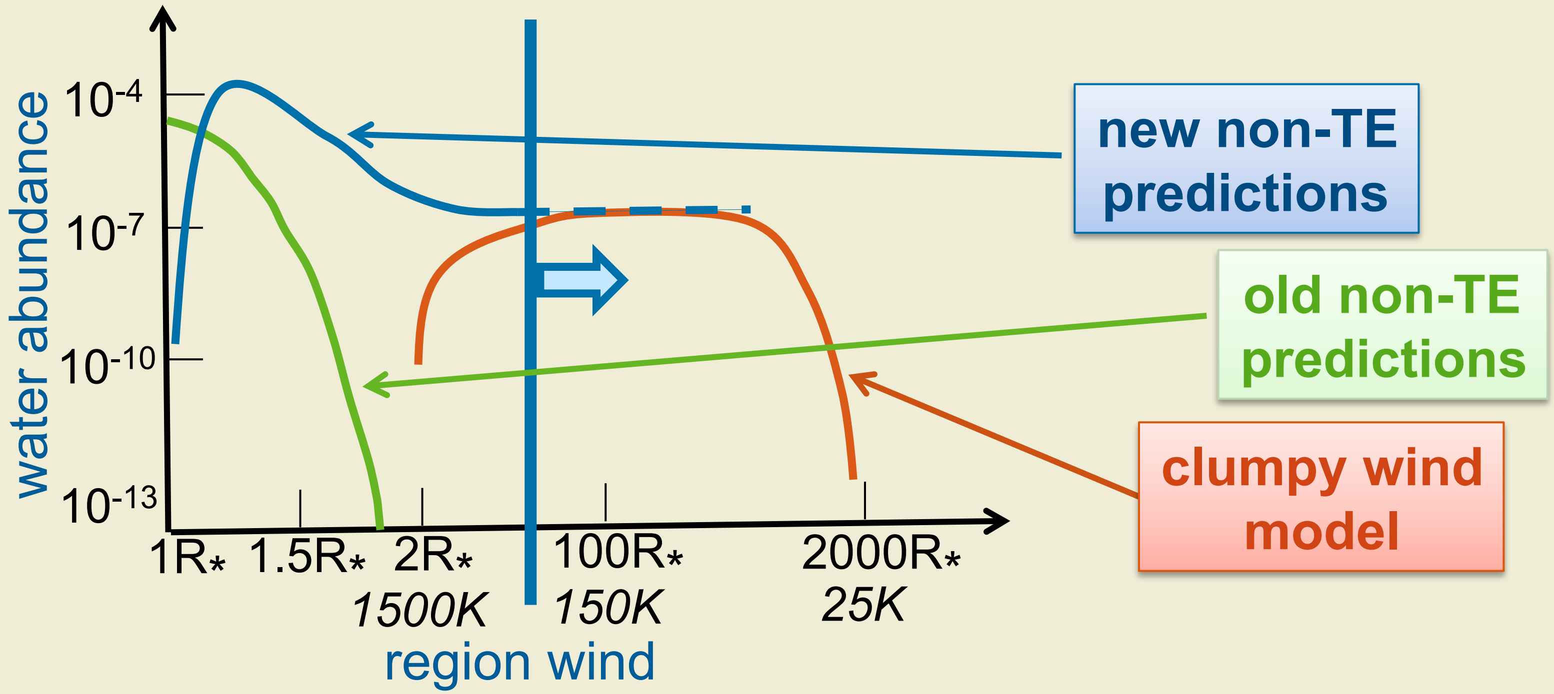


After Herschel: origin *warm* water vapour

- ✓ALMA
- ✓isotopic ratios
- ✓sample analysis

HOW TO DISTINGUISH?

3.4. H_2O in carbon-rich winds: Origin?



After Herschel: origin *warm* water vapour

- ✓**ALMA**
- ✓**isotopic ratios**
- ✓**sample analysis (Lombaert et al. 2015)**

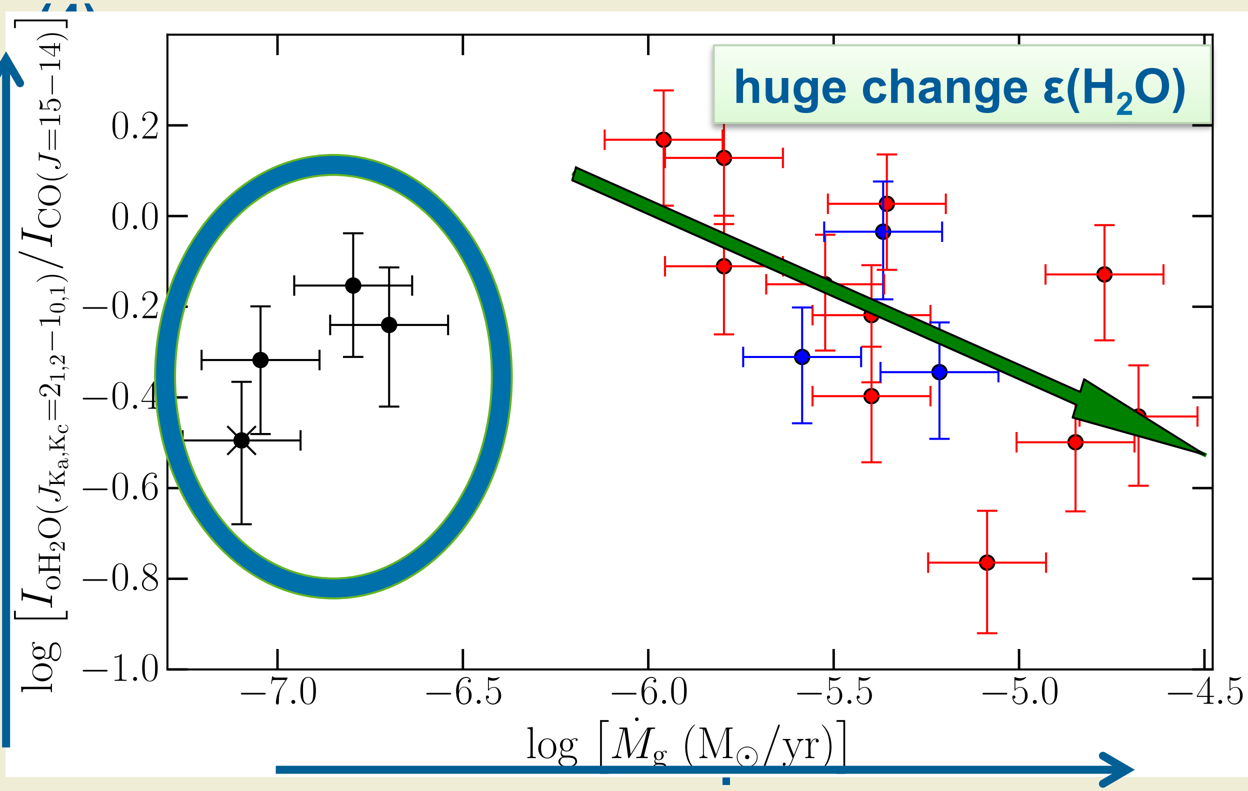
HOW TO DISTINGUISH?

3.4. H_2O in carbon-rich winds: sample analysis (Lombaert et al. 2014)

Method: * observe 18 carbon stars with PACS (MESS GTKP + OT2)
* different mass-loss rate, variability type, expansion velocity, …
* select 7 unblended H_2O lines and 6 CO lines

Result: (1) H_2O (up to E_{up} = 200K) detected in *all* carbon stars
(2) H_2O (E_{up} > 200K) detected for all *low mass-loss rate* stars
(3) opposite trend H_2O strength with mass-loss rate, except SRb

$n(H_2O)/n(H_2)$
$I(H_2O)/I(CO)$



$\dot{M}$

high $\dot{M}$, high P,
high shock velocity

Miras
SRa
SRb

low $\dot{M}$,
low (multiple) P,
low shock velocity

3.4. H_2O in carbon-rich winds: sample analysis (Lombaert et al. 2014)

Method: * observe 18 carbon stars with PACS (MESS GTKP + OT2)
* different variability type, mass-loss rate, expansion velocity, …
* select 7 unblended H_2O lines and 6 CO lines

Result: (1) H_2O (up to E_{up} = 200K) detected in *all* carbon stars
(2) H_2O (E_{up} > 200K) detected for all *low mass-loss rate* stars
(3) opposite trend H_2O strength with mass-loss rate, except SRb
→ change H_2O abundance with 3 orders of magnitude
(4) increase H_2O abundance ($r<50R_*$) – outside acceleration zone from line excitation analysis

3.4. H_2O in carbon-rich winds: sample analysis (Lombaert et al. 2014)

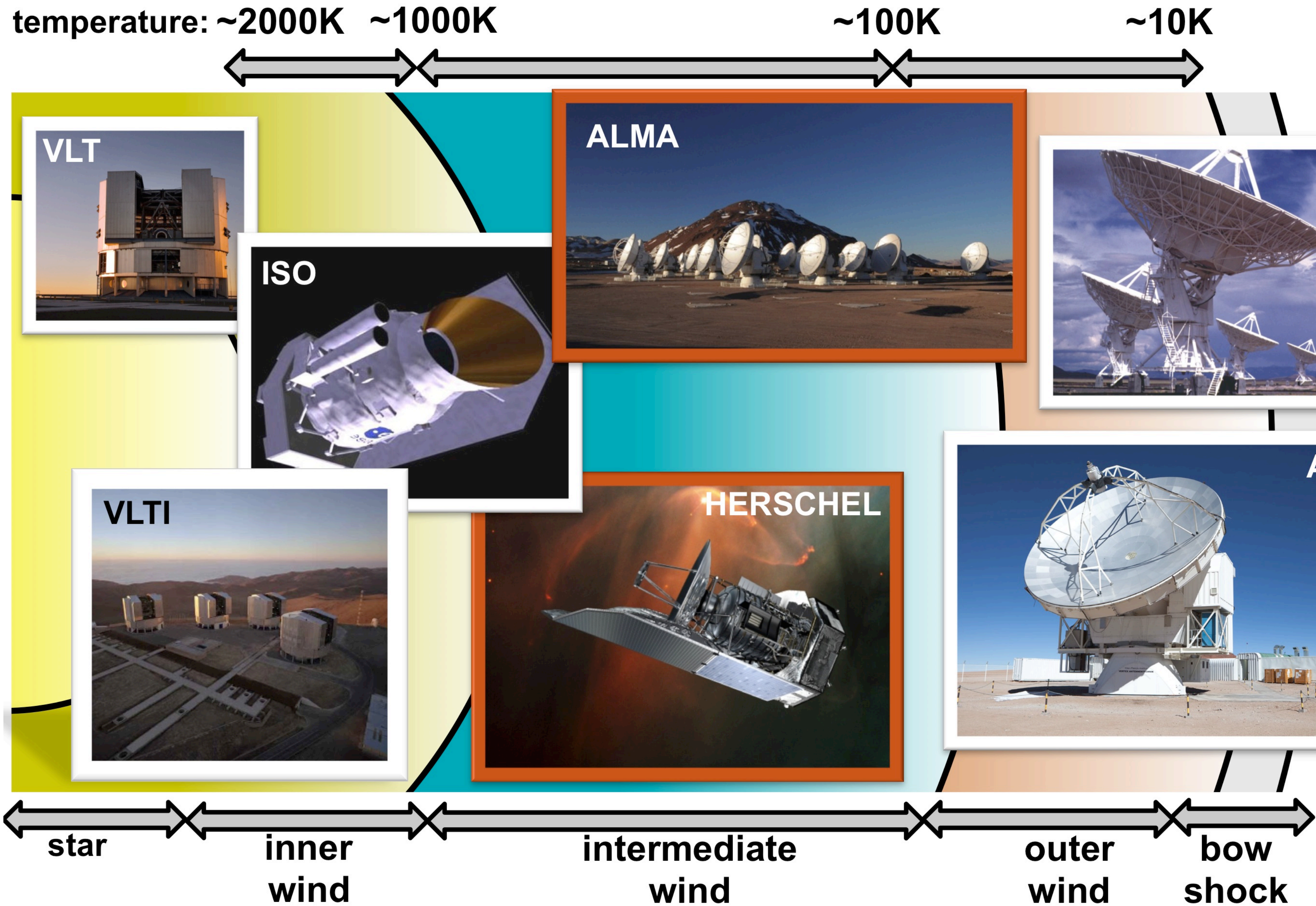
4 constraints:

Model 1: UV photons penetrate in clumpy wind	Constraint	Model 2: shock-induced non-equilibrium chemistry
✓	in *all* carbon stars	✓
✓	ε(H_2O)↓ when $\dot{M}$↑	✓
✗	except SRb	✗
		✗ no models difficult to predict
✓	ε(H_2O)↑ up to ~50 R_* outside acceleration region	✗
		✗ + Fischer-Tropsch catalysis on grains

+ isotopic constraint on selective photo-dissociation (Neufeld et al. 2012)

Note: SRb: solar-like oscillations (Mosser et al. 2013)

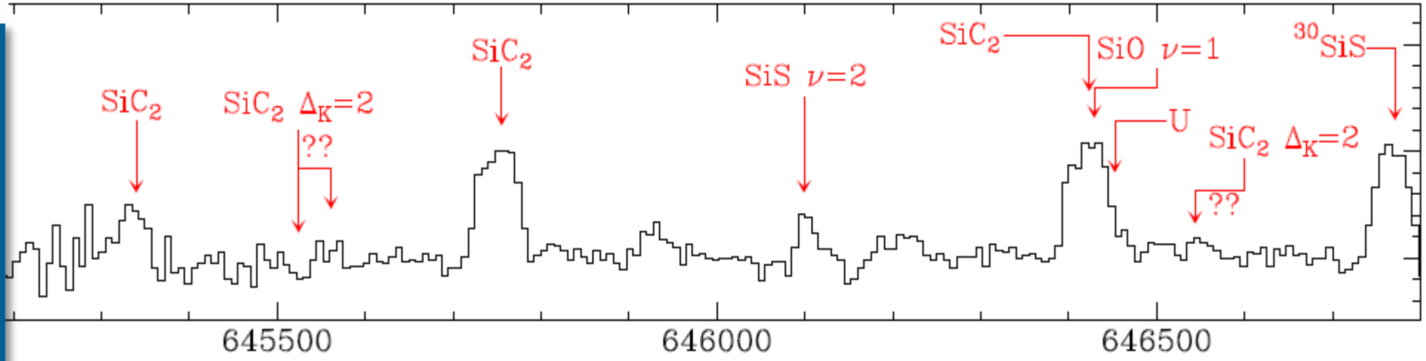
4. The future - ALMA



From observations to chemical abundance pattern

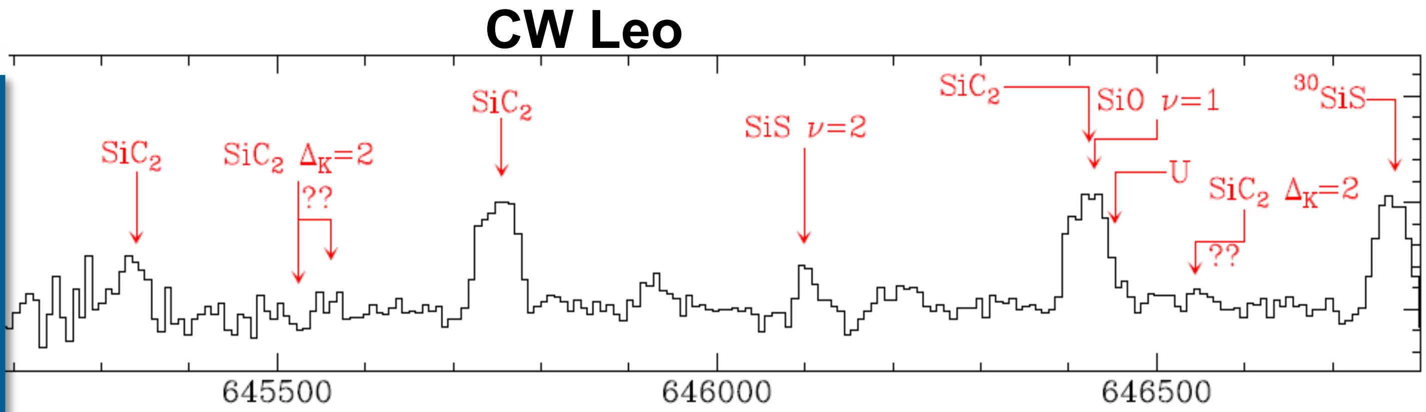
beam: 30”

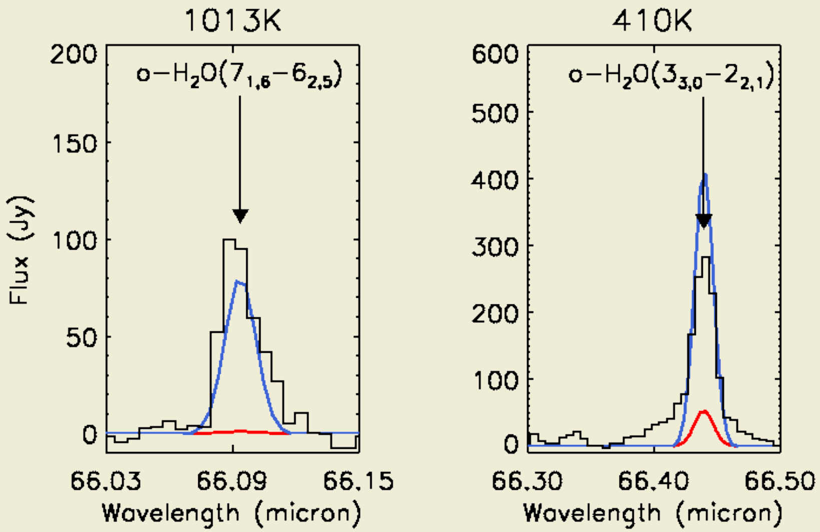
CW Leo

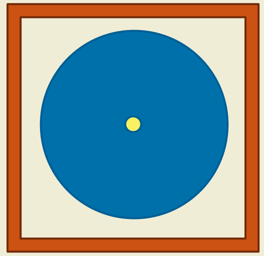


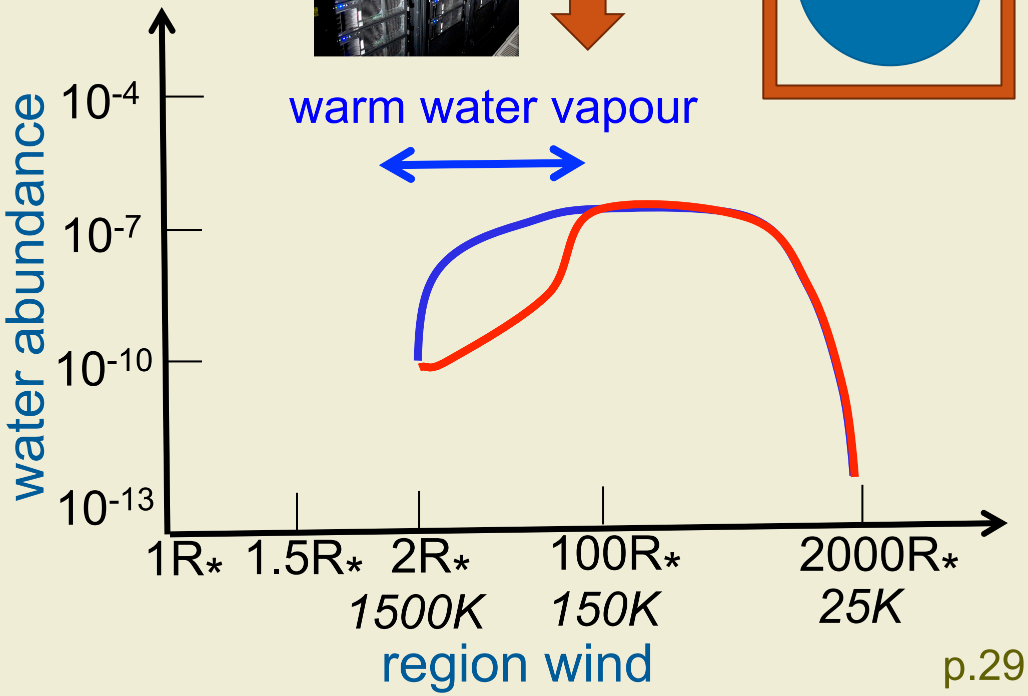
From observations to chemical abundance pattern

beam: 30”





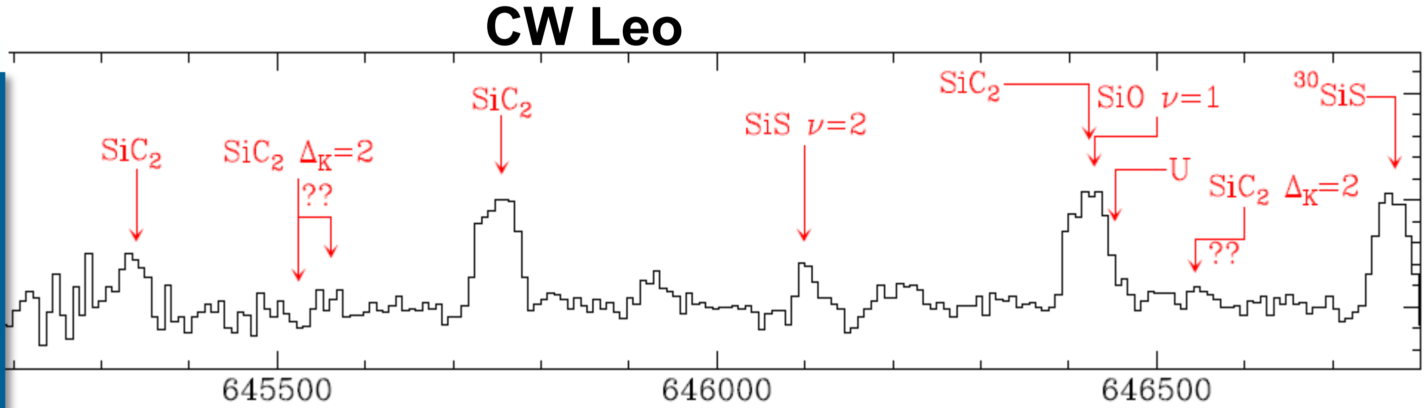


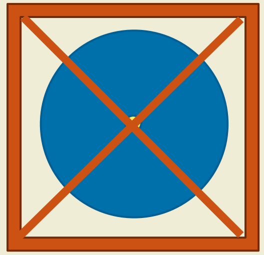


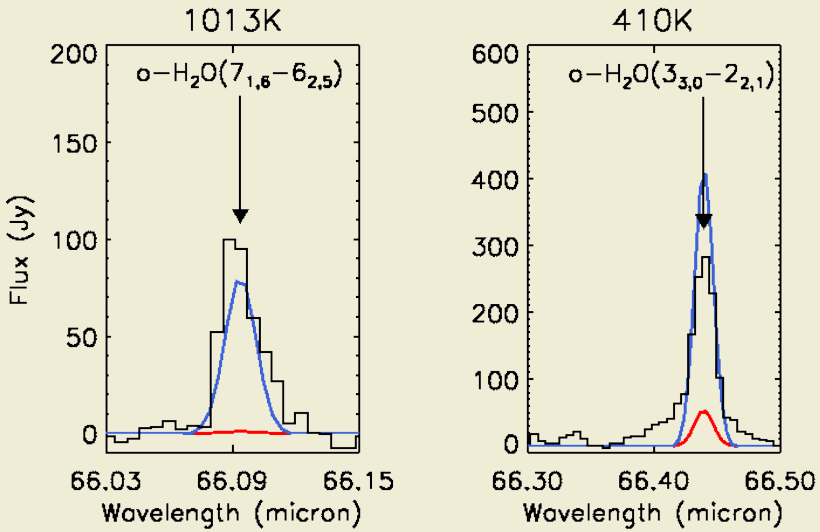
Decin et al. 2010

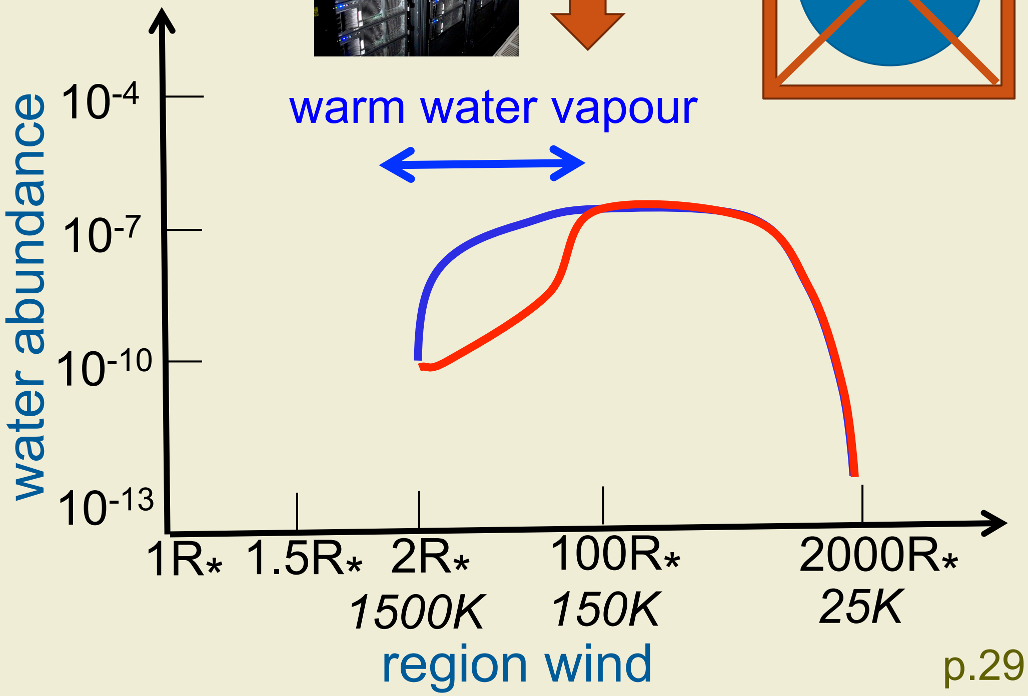
From observations to chemical abundance pattern

beam: 30”



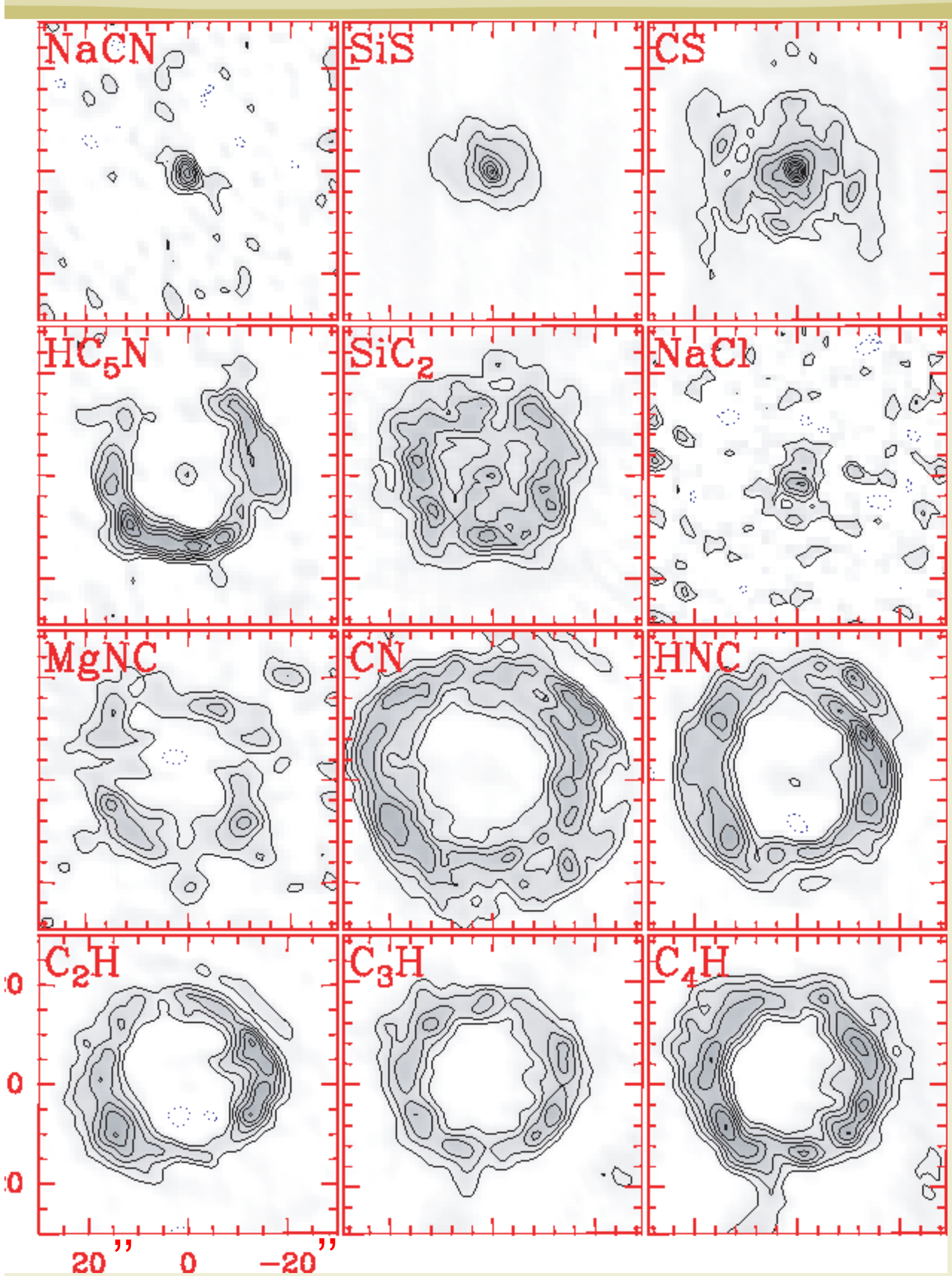






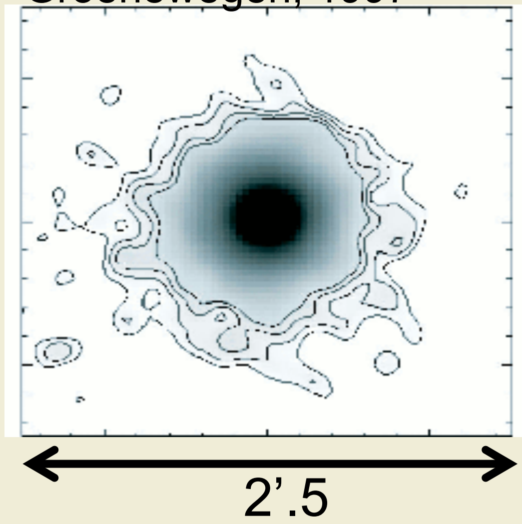
Decin et al. 2010

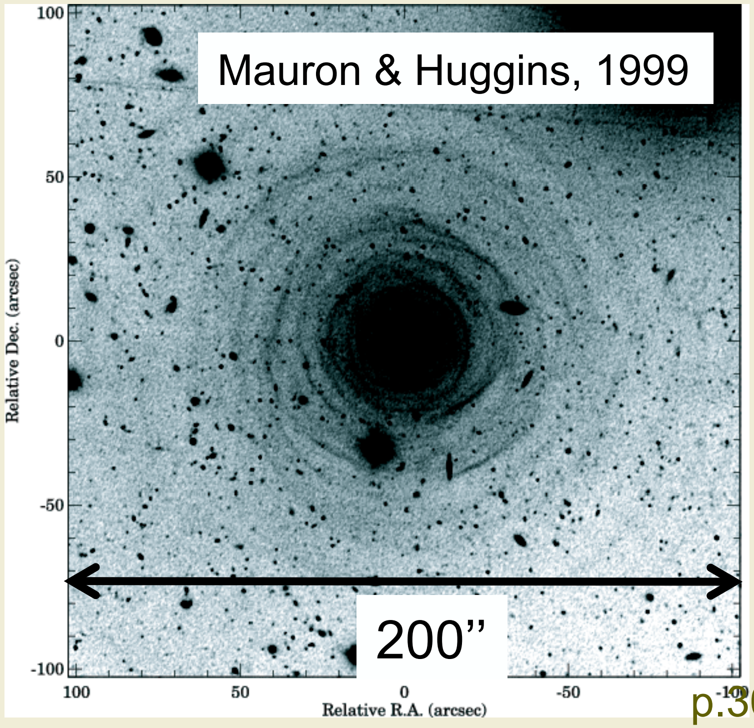
CW Leo as seen through different 'eyes'… [199x]



Guélin et al. 1993

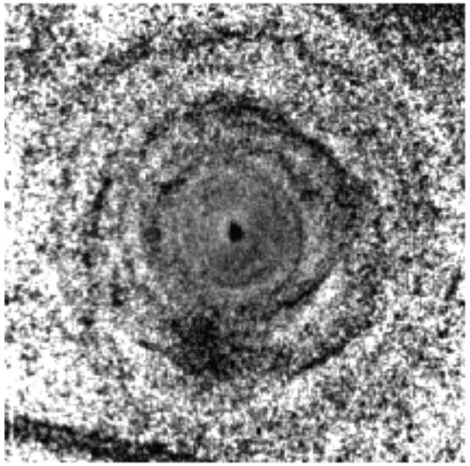
Groenewegen, 1997

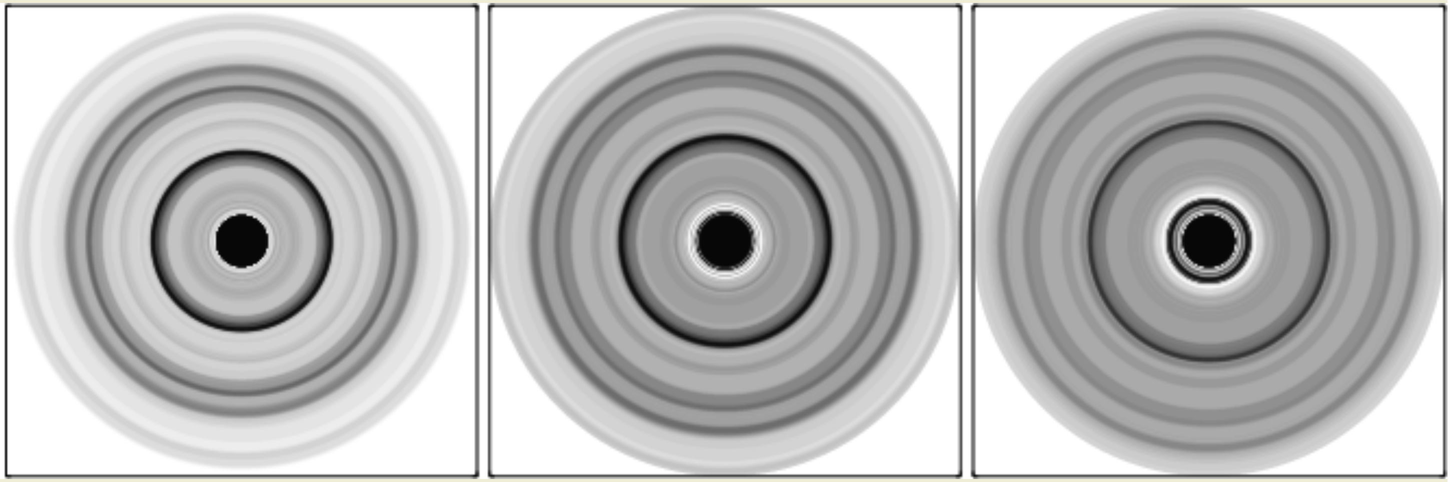




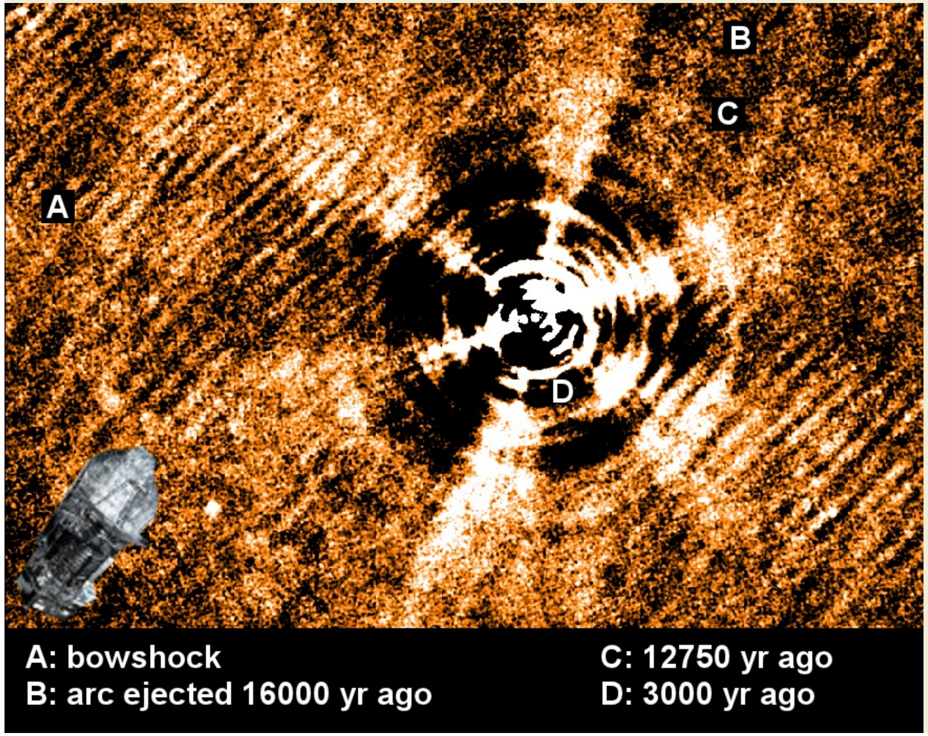
CW Leo as seen through different 'eyes'… [199x]

hydrodynamical models: complex dust formation process



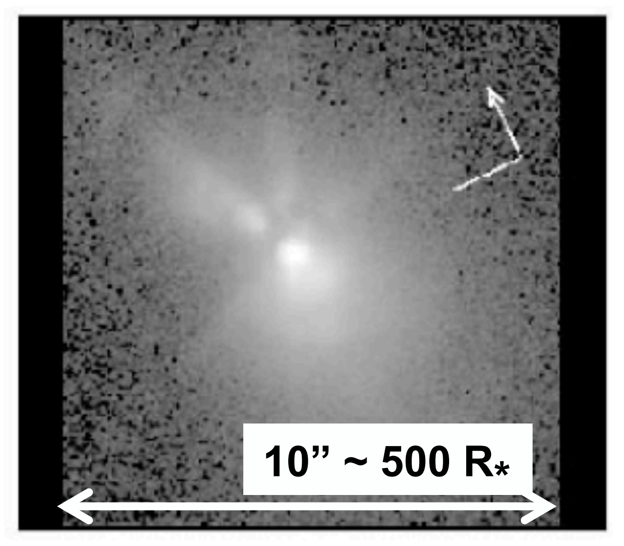


Simis et al. 2003

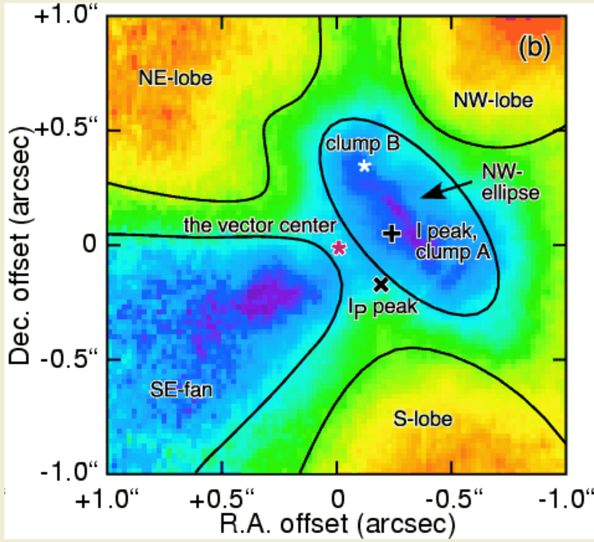


Decin et al. 2011

CW Leo as seen through different ‘eyes’… [1998 - …]



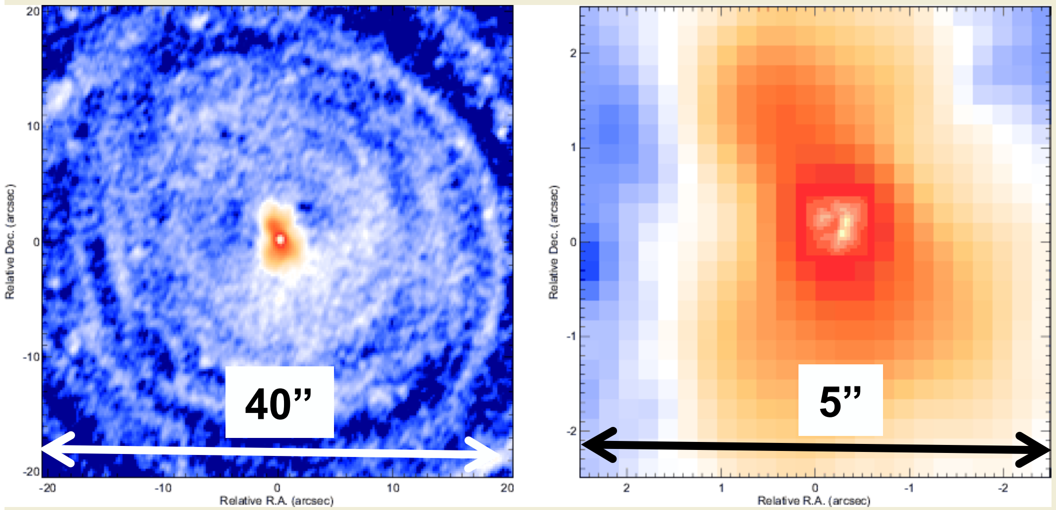
Skinner et al. 1998



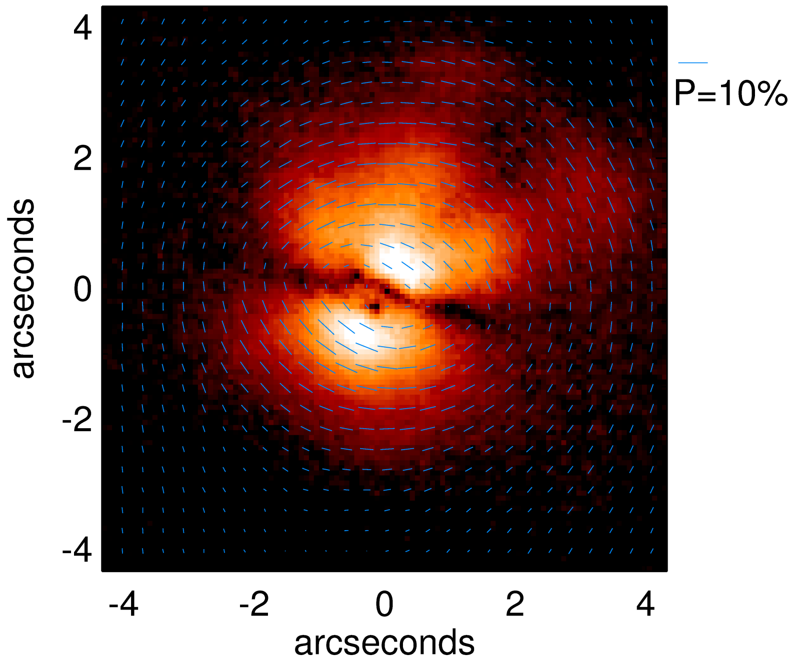
Murakawa et al. 2005

bipolar morphology

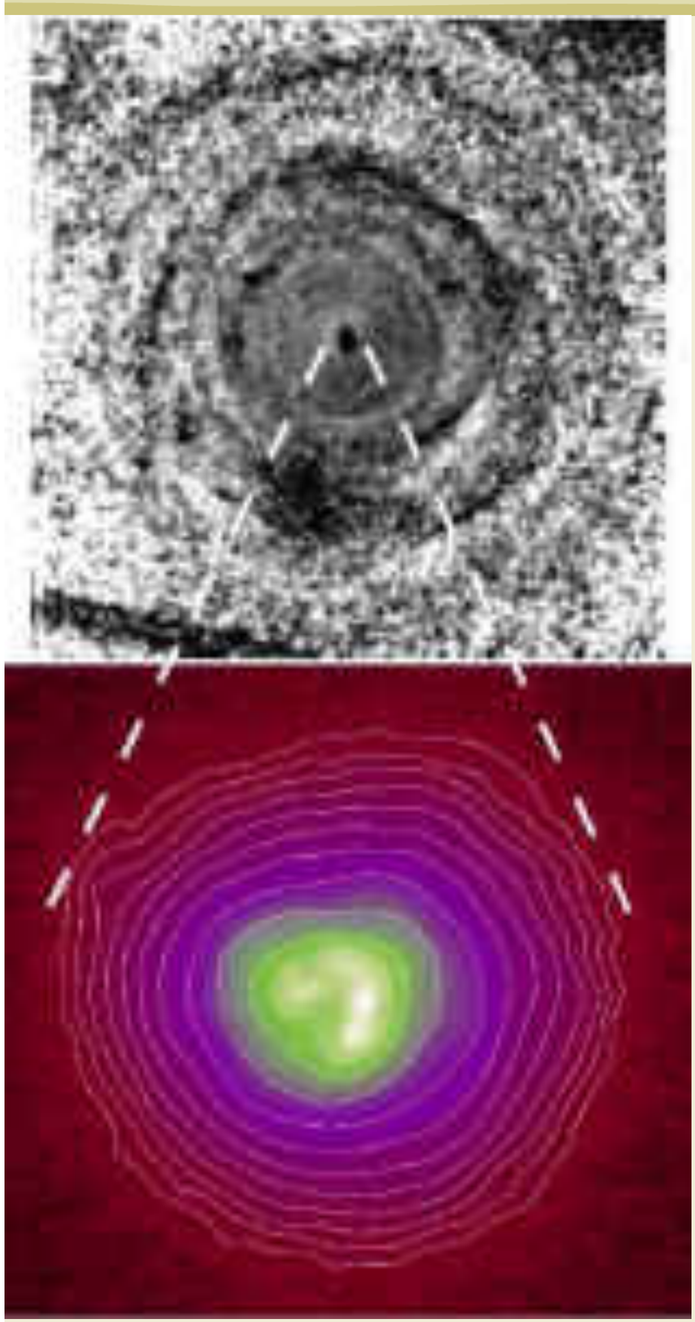
Jeffers et al. 2014

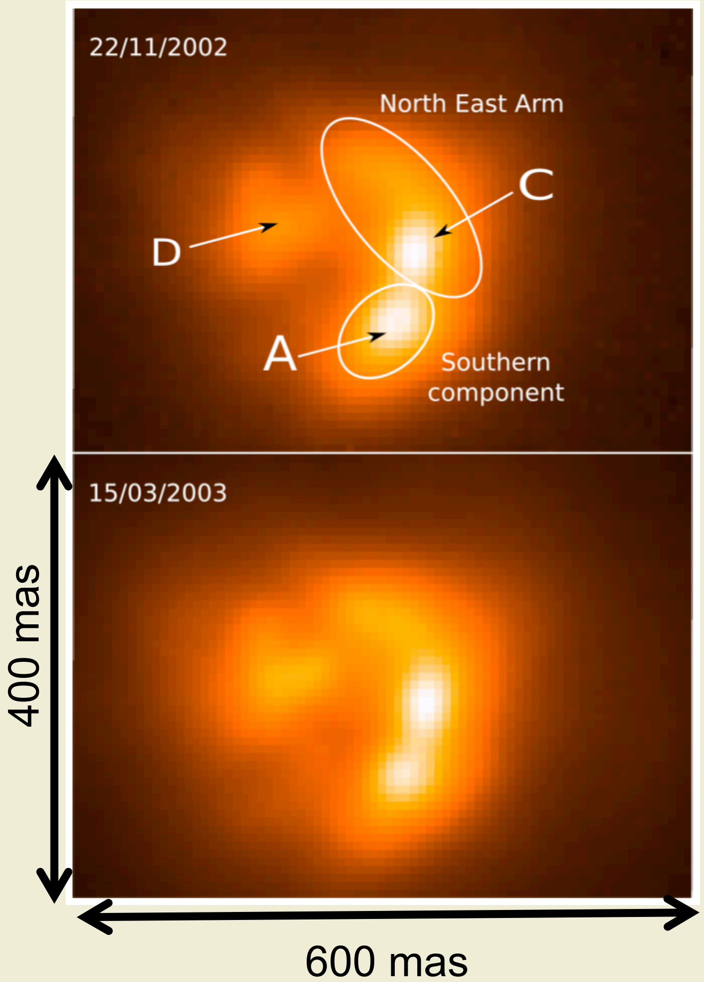


Mauron et al. 2000



CW Leo as seen through different 'eyes'… [2000 - …]





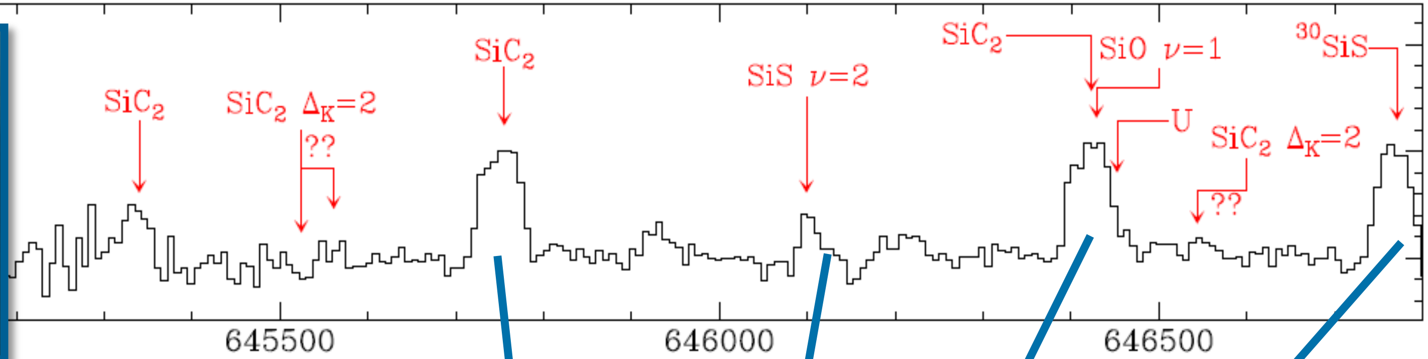
clumps

Tuthill et al. 2000, Weigelt et al. 2002, Menut et al. 2007

CW Leo as seen through ‘ALMA’… [2012 - …]

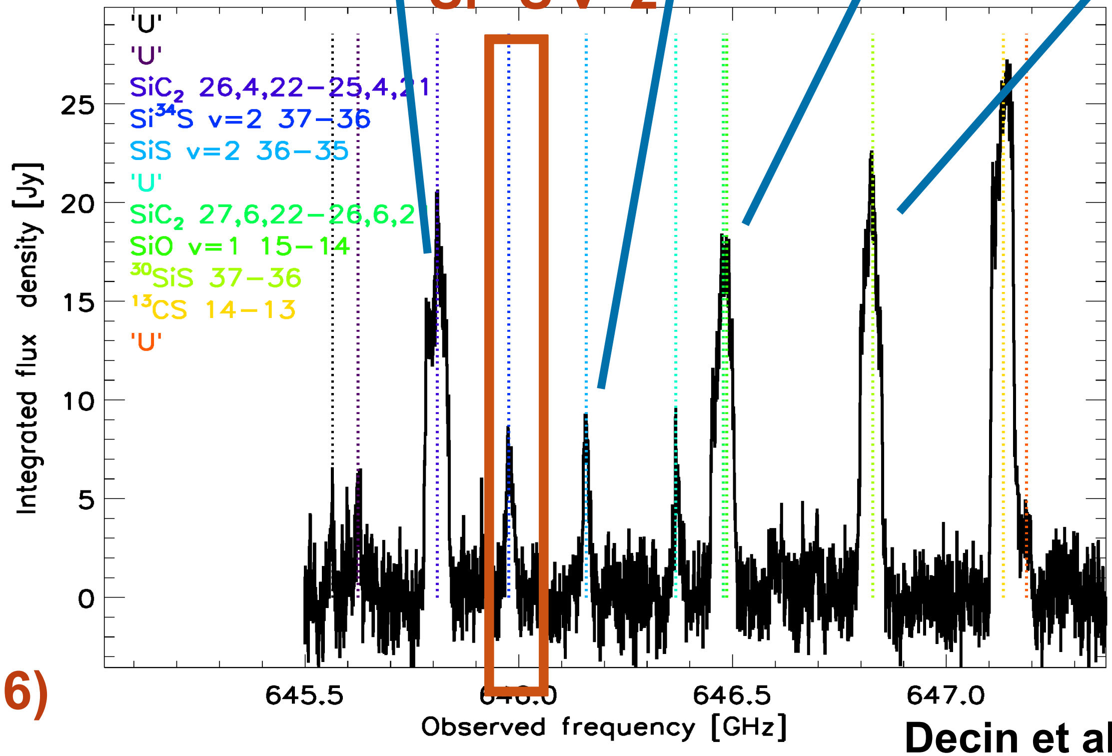
beam: 30”

Cernicharo et al. 2010



beam: 0.24”x0.43”

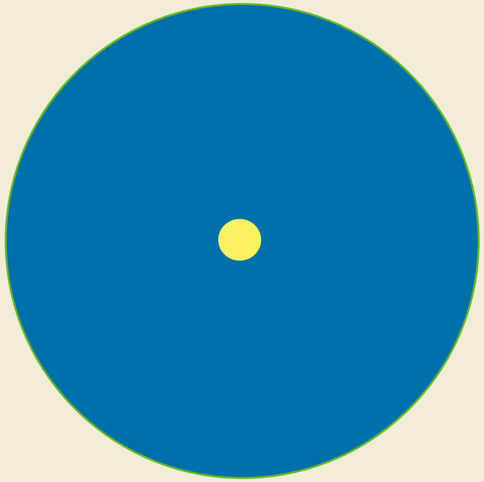
$Si^{34}S$ v=2

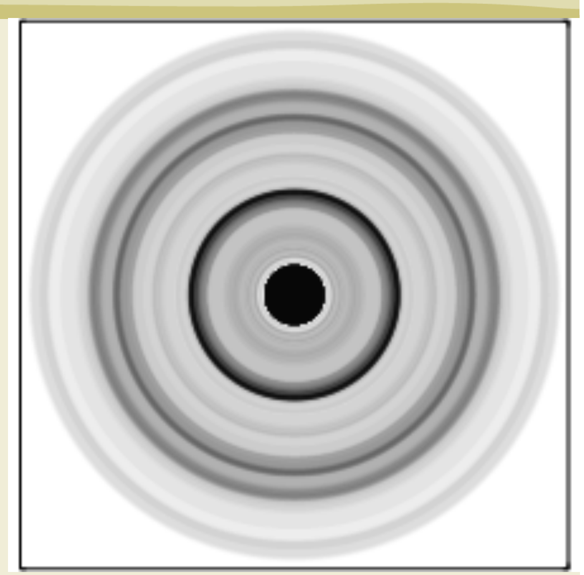


CW Leo
(IRC+10216)

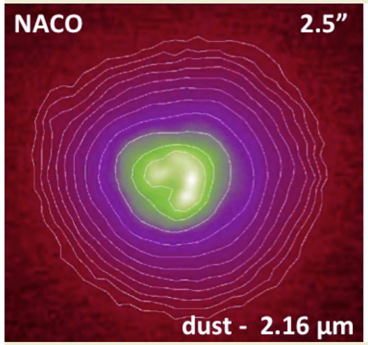
Decin et al. 2014

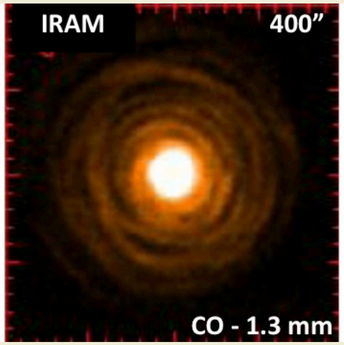
CW Leo as seen through ‘ALMA’… [2012 - …]

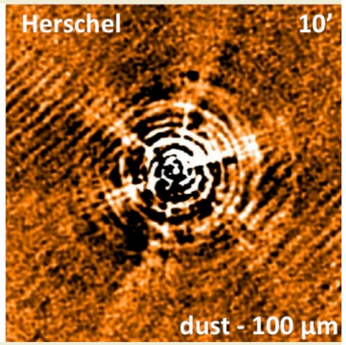




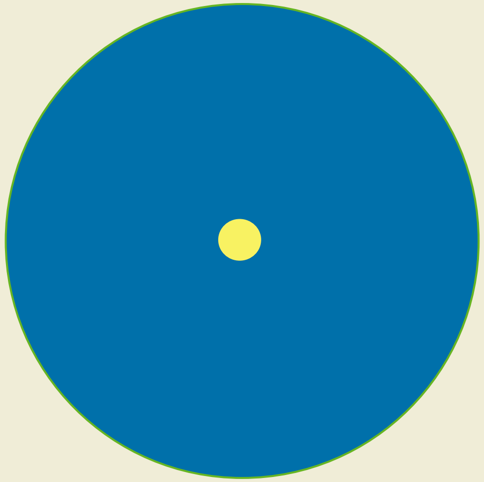
CW Leo

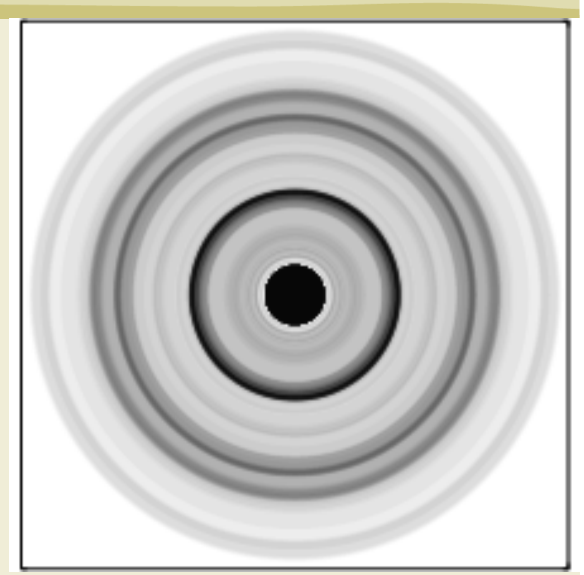






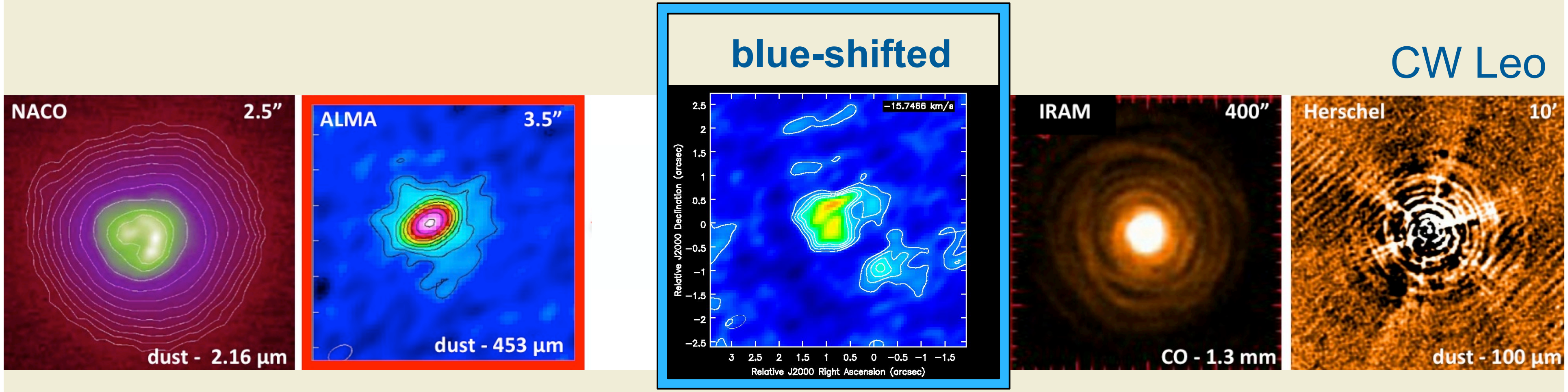
CW Leo as seen through 'ALMA'… [2012 - …]





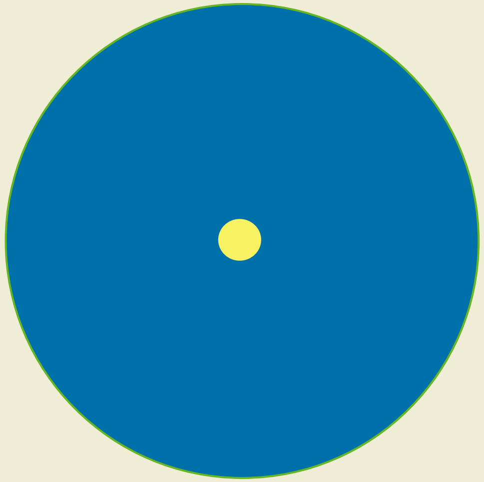
^{13}CO J=6-5

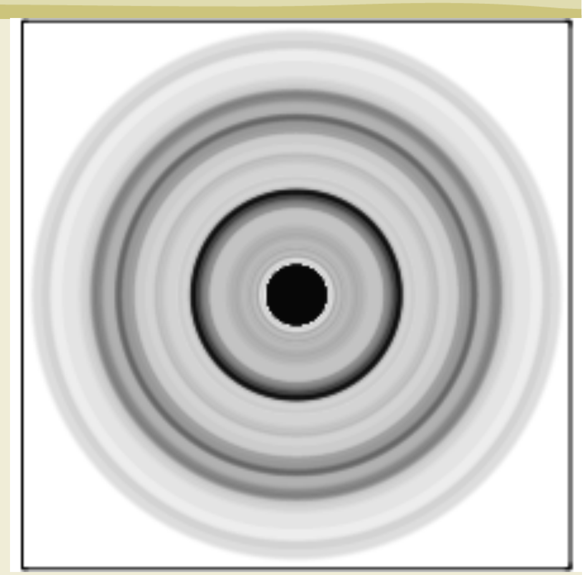
CW Leo



ALMA (Decin et al. 2014)

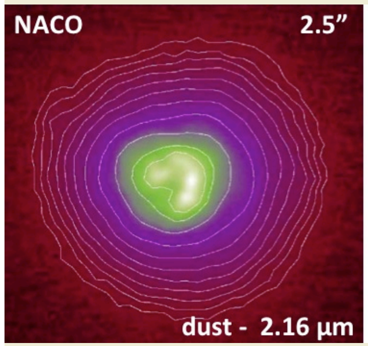
CW Leo as seen through ‘ALMA’… [2012 - …]

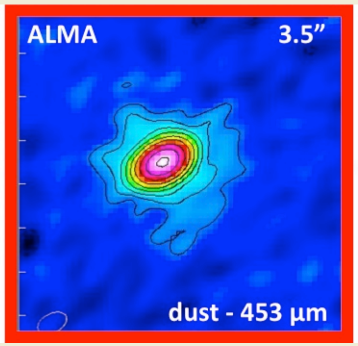


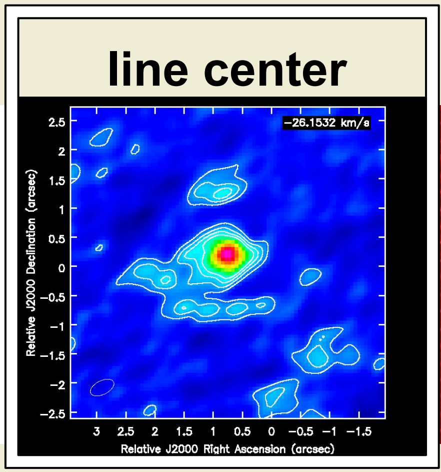


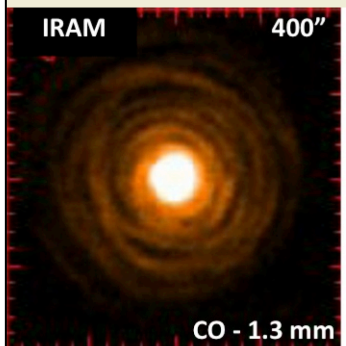
^{13}CO J=6-5

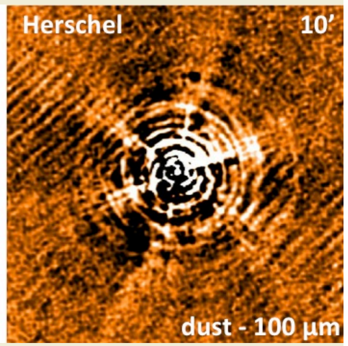
CW Leo





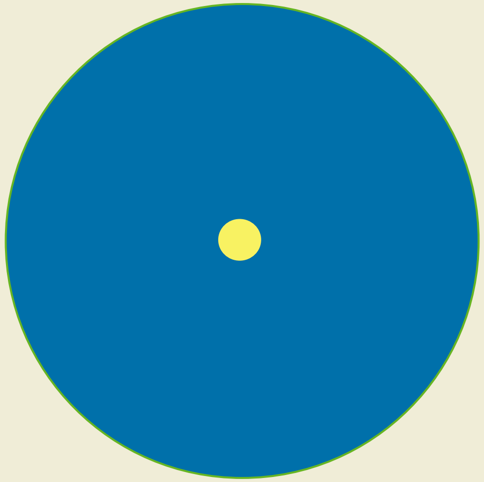


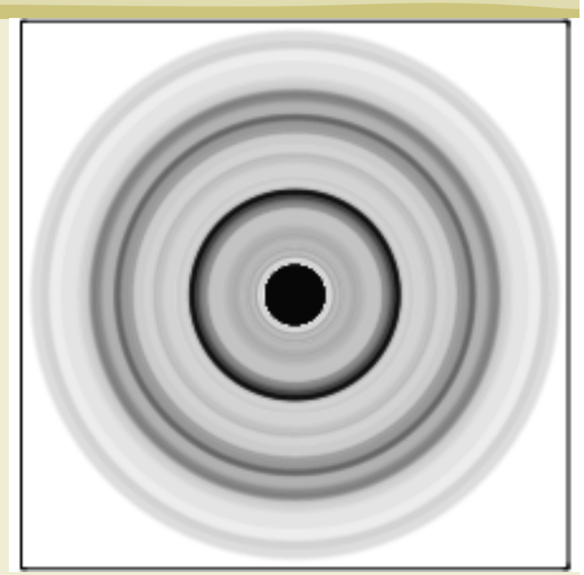




ALMA (Decin et al. 2014)

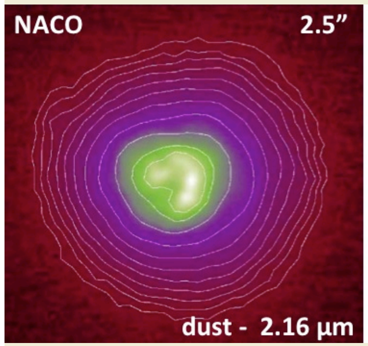
CW Leo as seen through ‘ALMA’… [2012 - …]

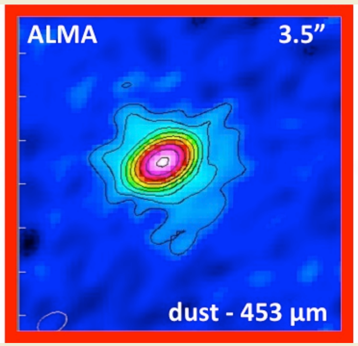


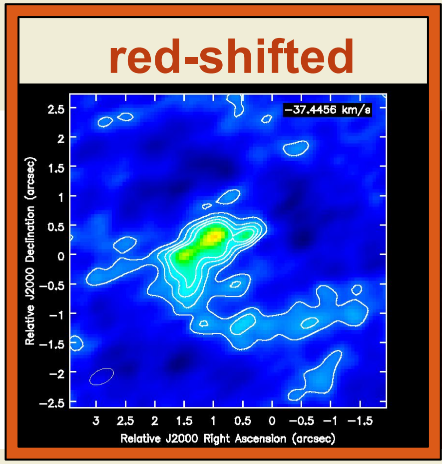


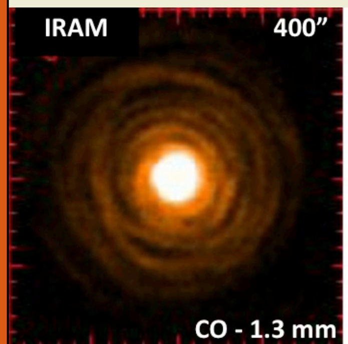
^{13}CO J=6-5

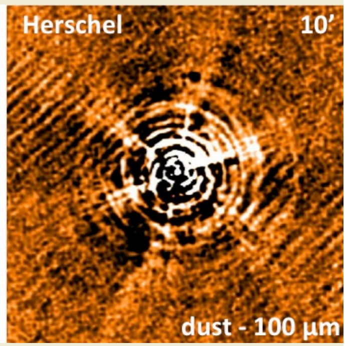
CW Leo





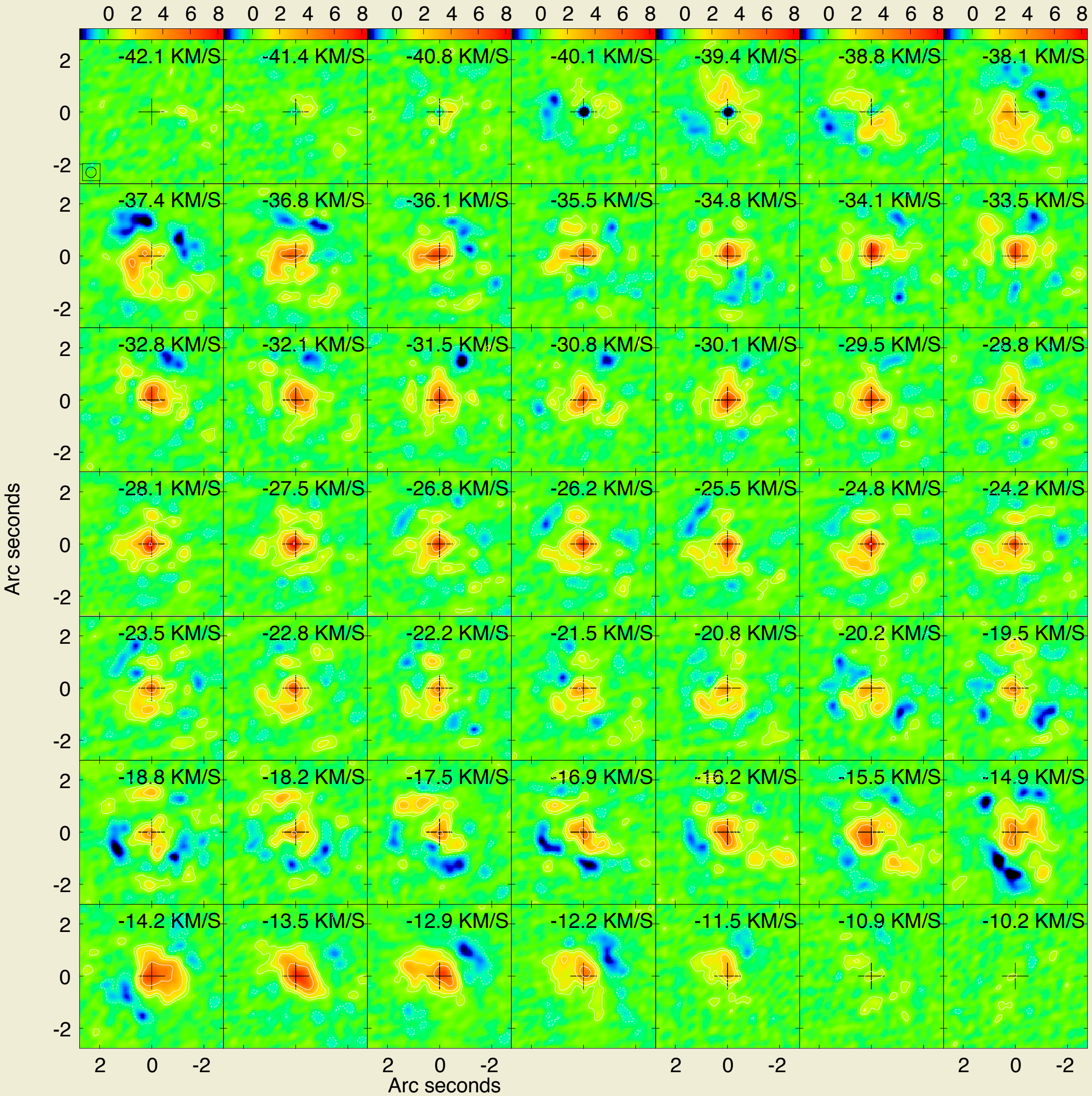




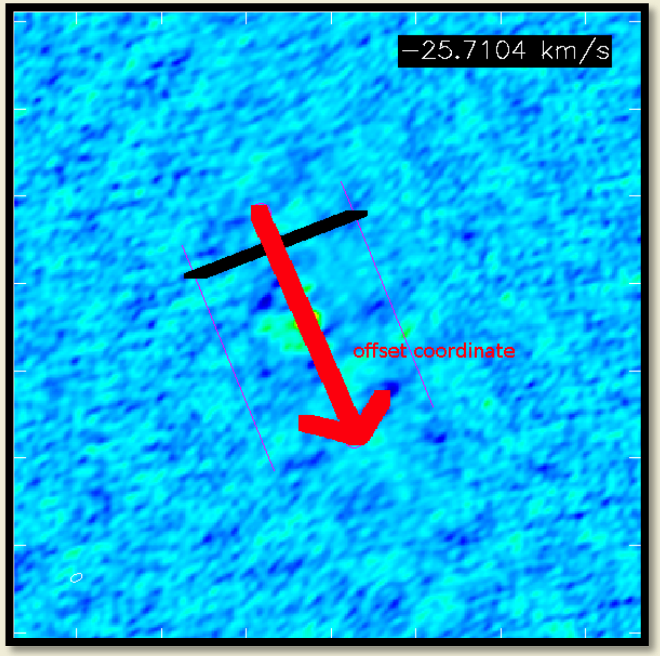


ALMA (Decin et al. 2014)

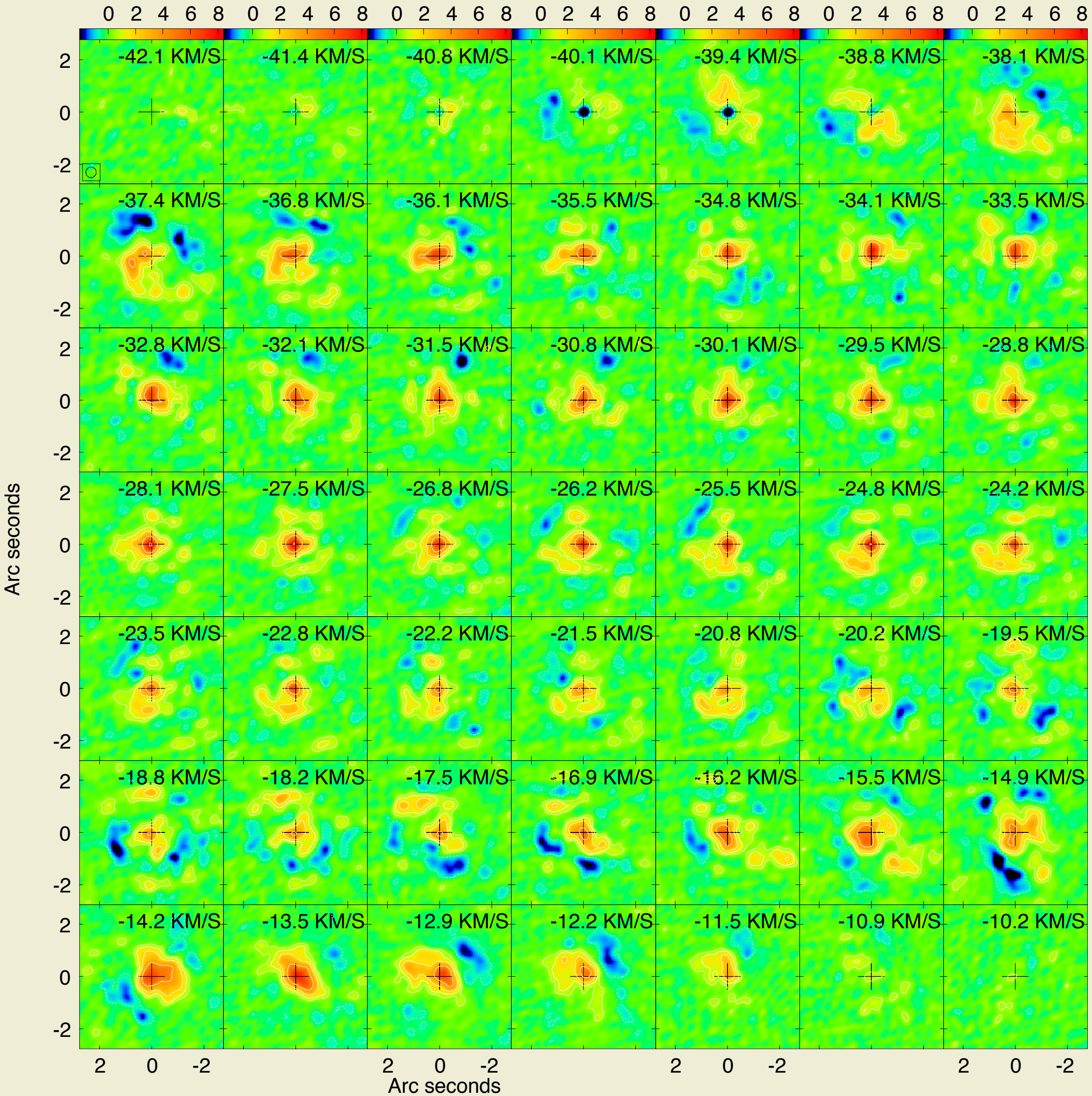
CW Leo as seen through ‘ALMA’… [2012 - …]



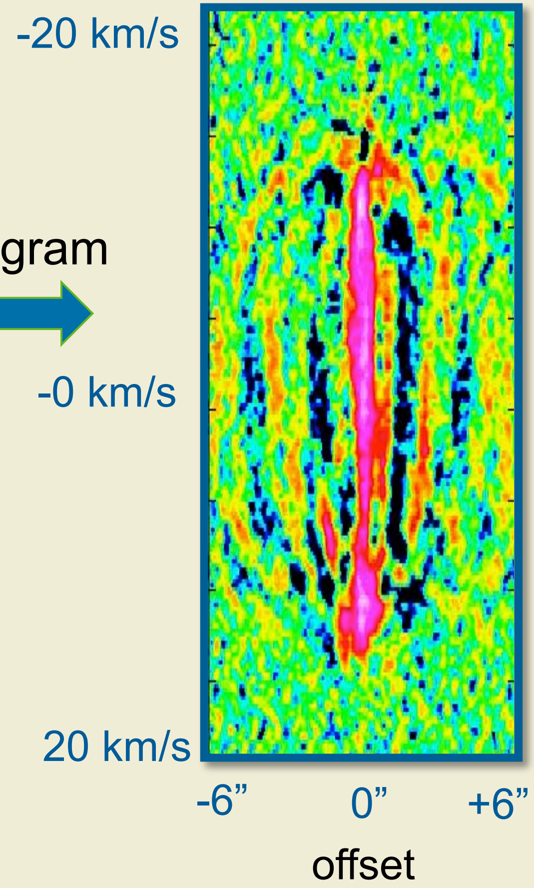
PV-diagram



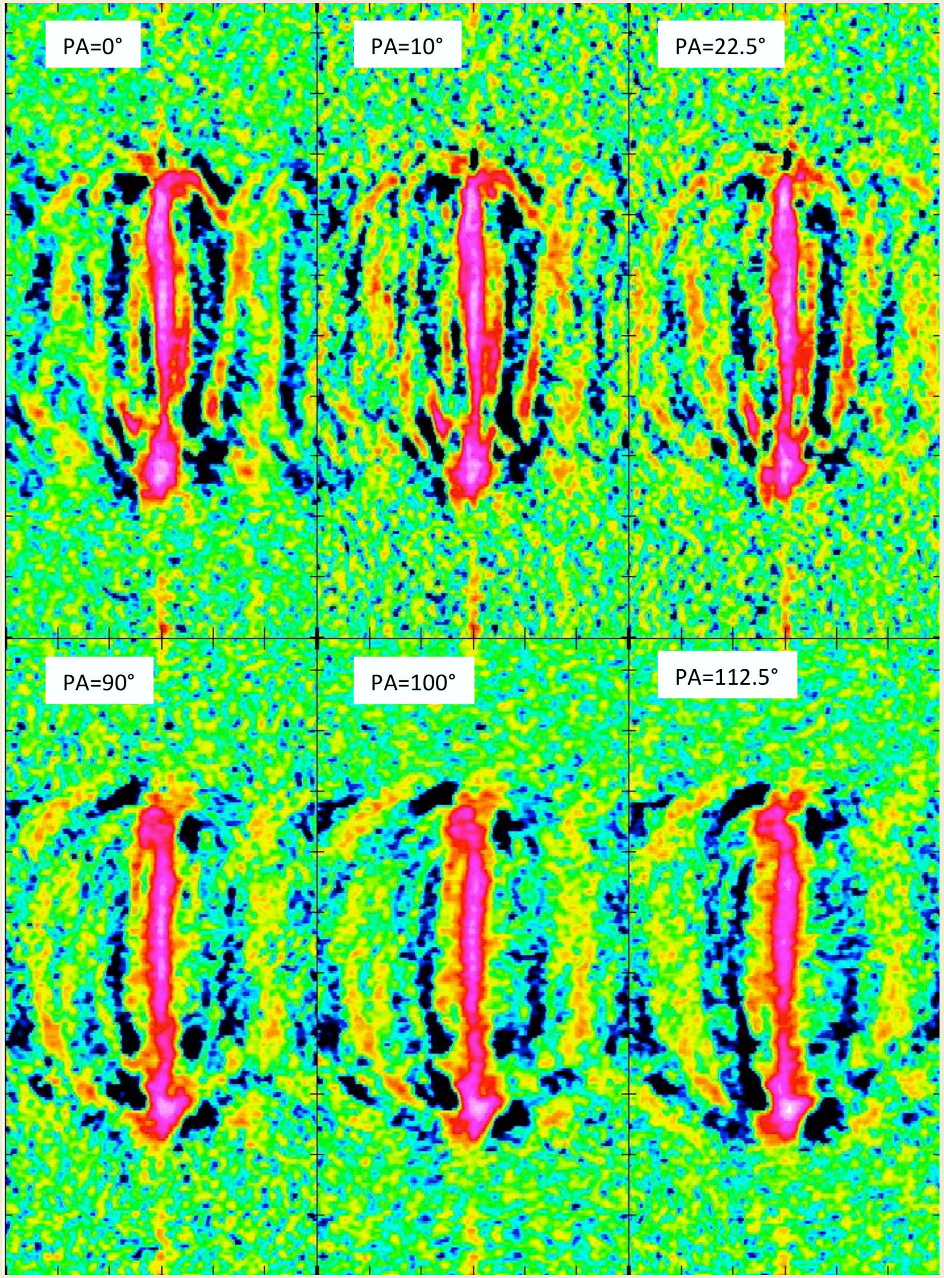
CW Leo as seen through 'ALMA'… [2012 - …]

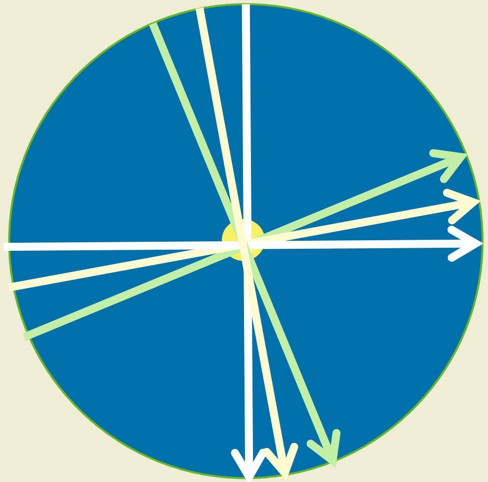


PV-diagram



CW Leo as seen through 'ALMA'… [2012 - …]





Decin et al. 2015

Qualitative interpretation: binary-induced spiral structure

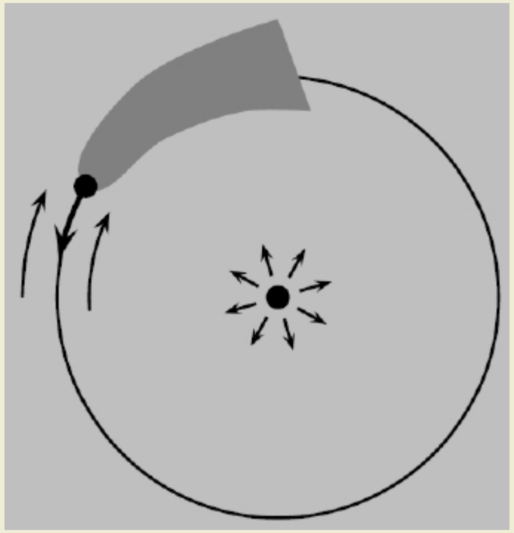
www.eso.org

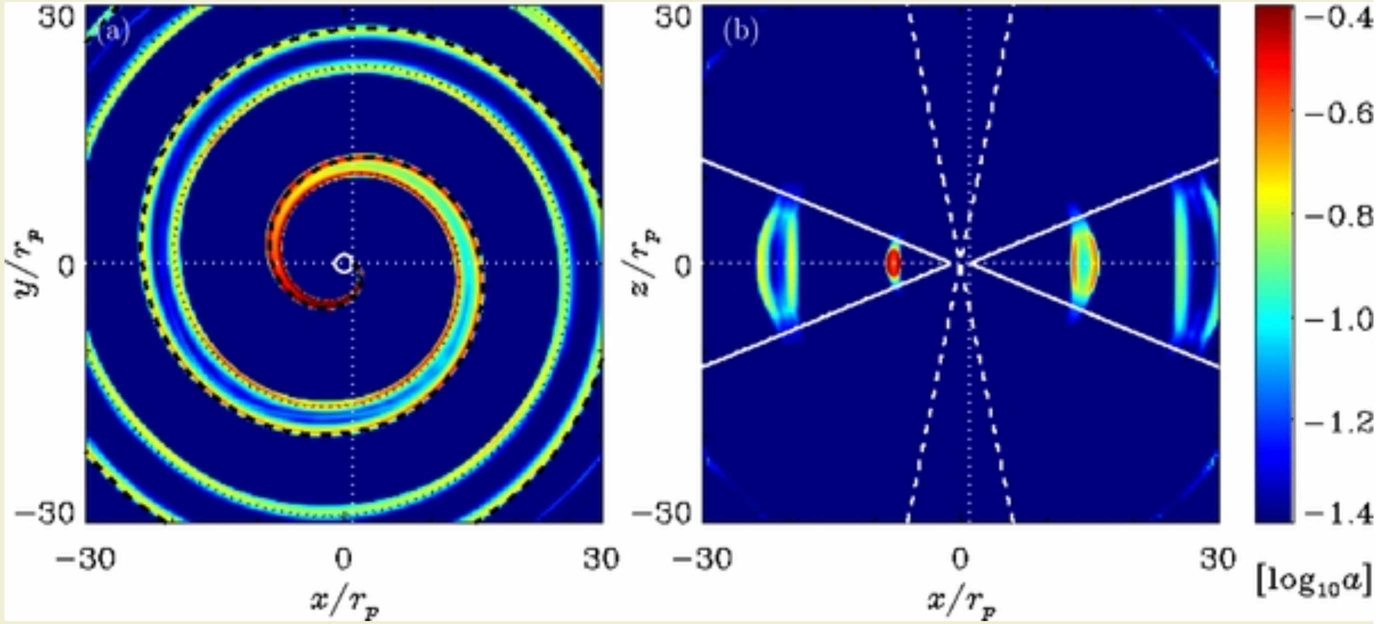
Qualitative interpretation: binary-induced spiral structure

→ 2 'types' of spiral structure

1. **Gravitational wake of the companion**
   → focus of material toward orbital plane

Kim et al. 2012





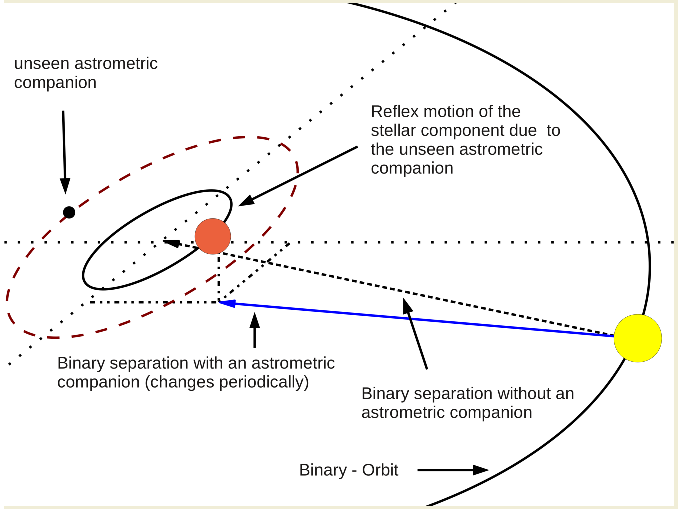
Binary-induced spiral structure

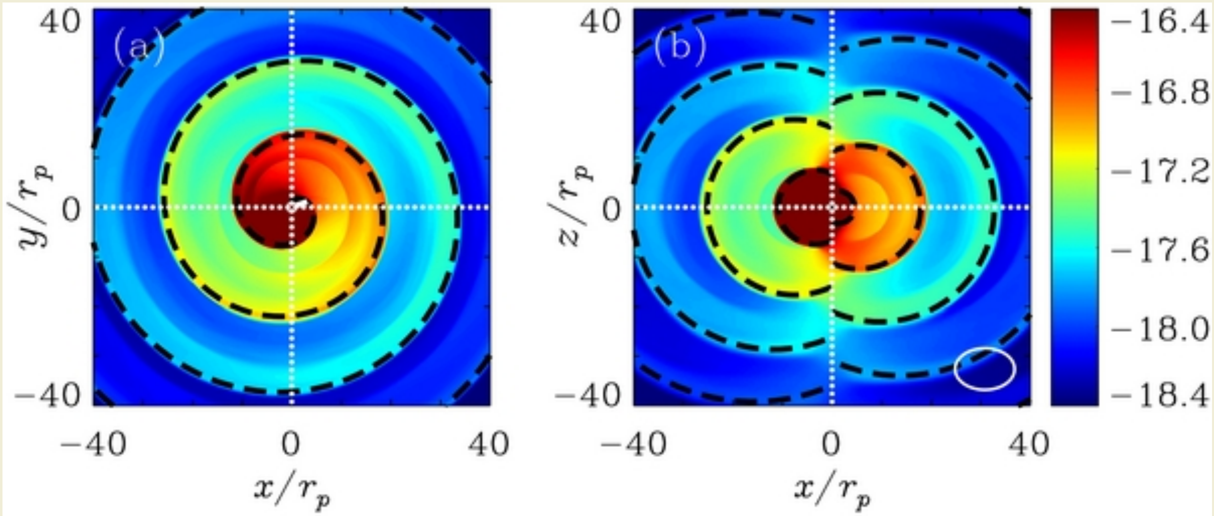
→ 2 'types' of spiral structure

2. Orbital motion of mass-losing AGB star around center of gravity

→spiral structure reaching almost orbital axis

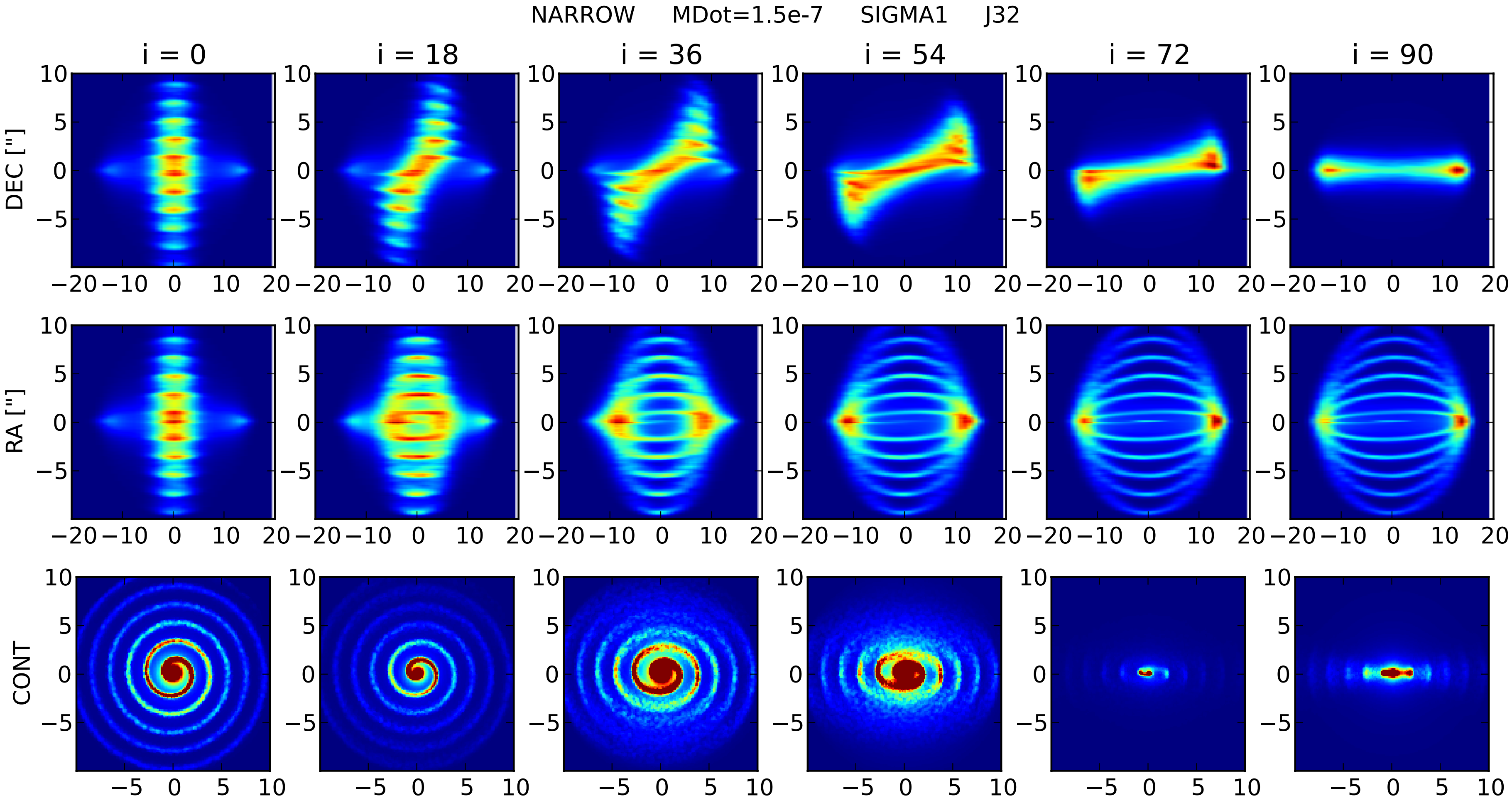
Kim et al. 2012





Binary-induced spiral structure: impact inclination

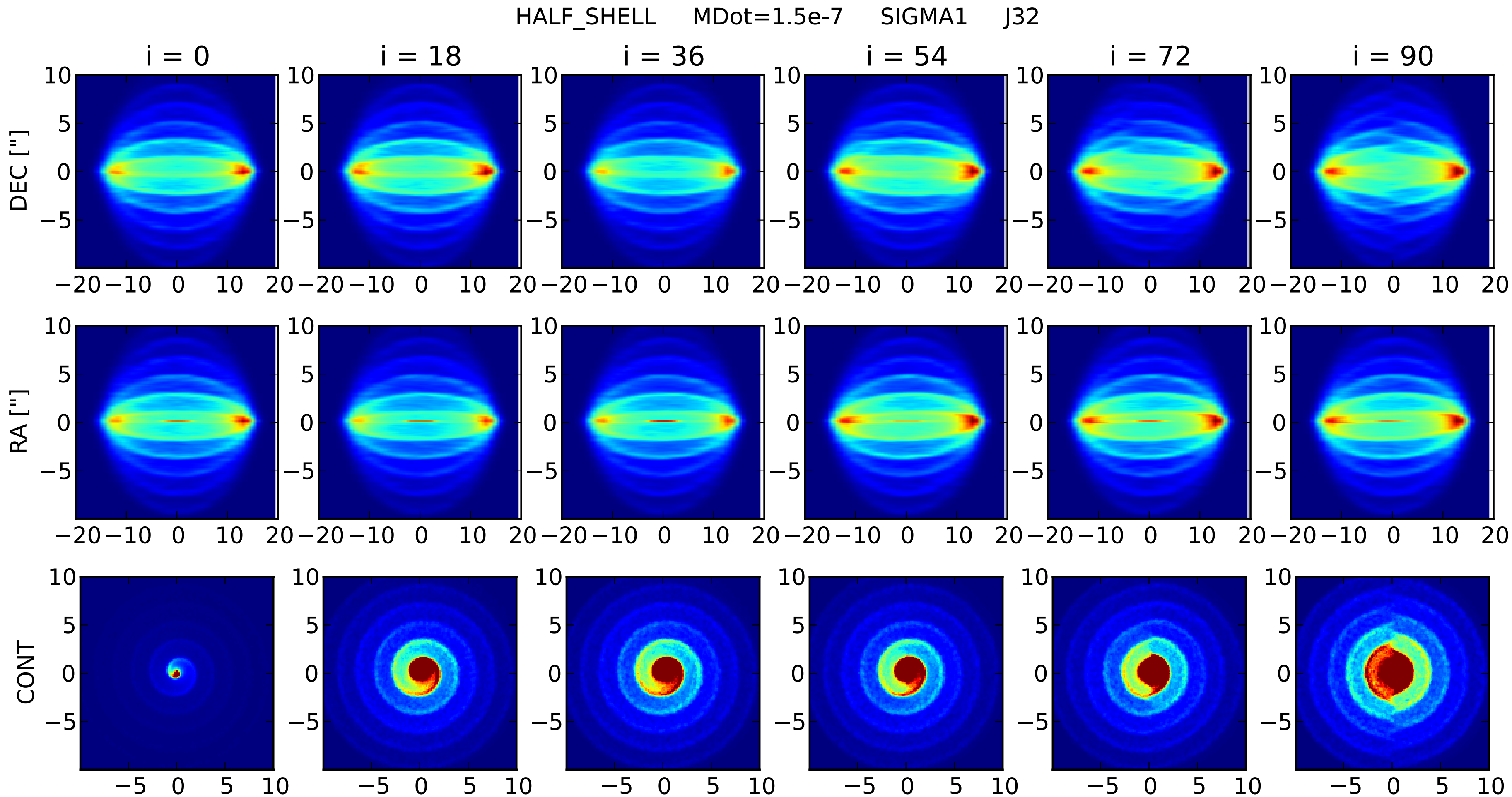
'Narrow spiral' due to gravitational wake



Homan et al. (2015)

Binary-induced spiral structure: impact inclination

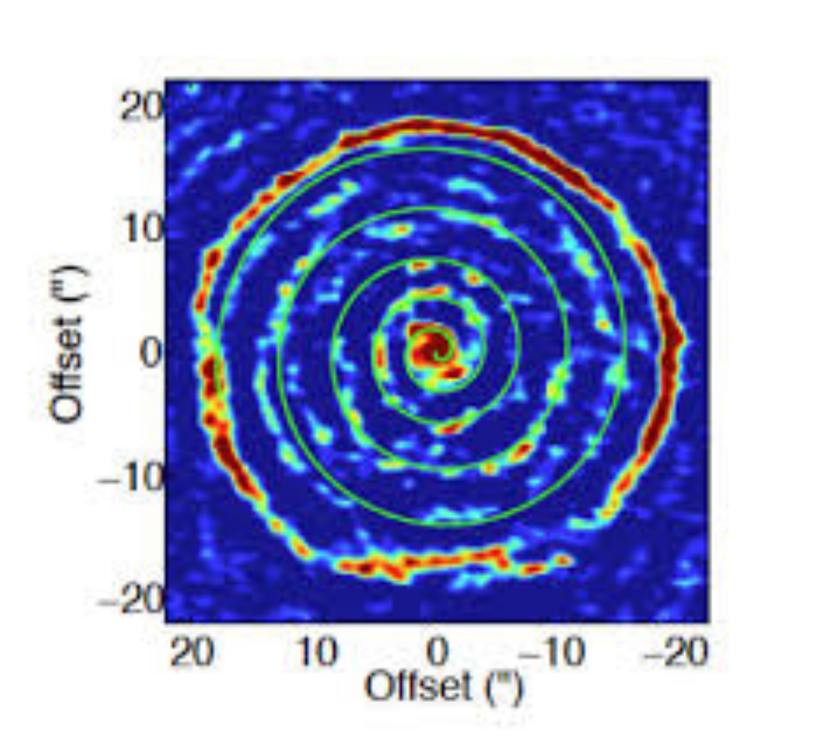
‘Shell spiral’ due to reflex motion AGB star



Homan et al. (2015)

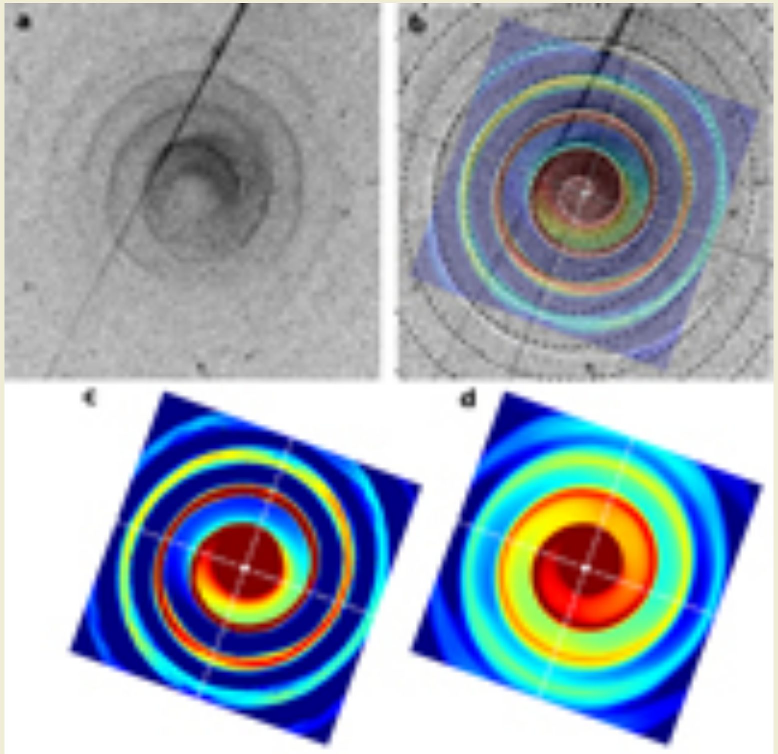
Binary-induced spiral structures in AGB winds

R Scl



Maercker et al. 2012

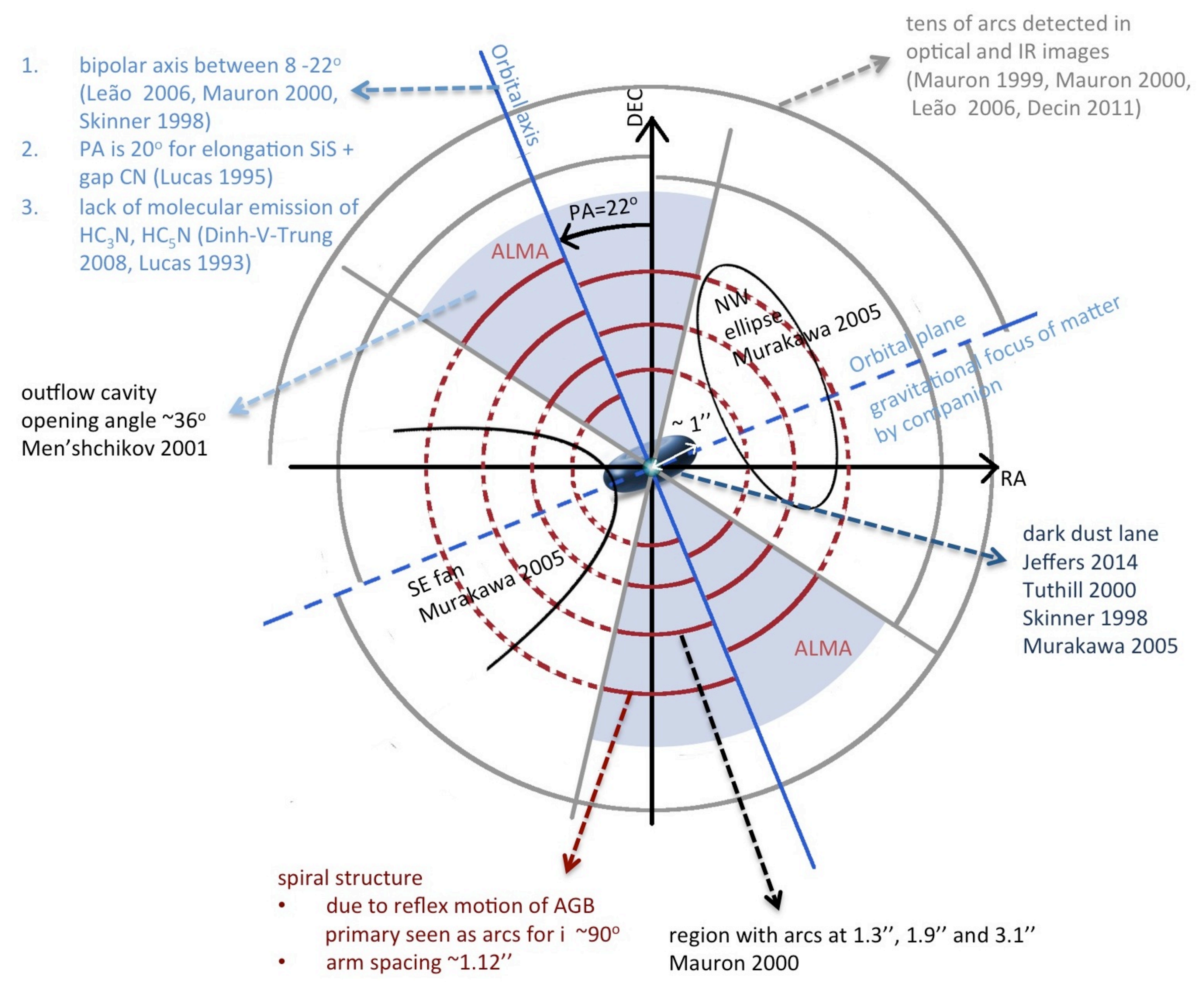
AFGL 3068



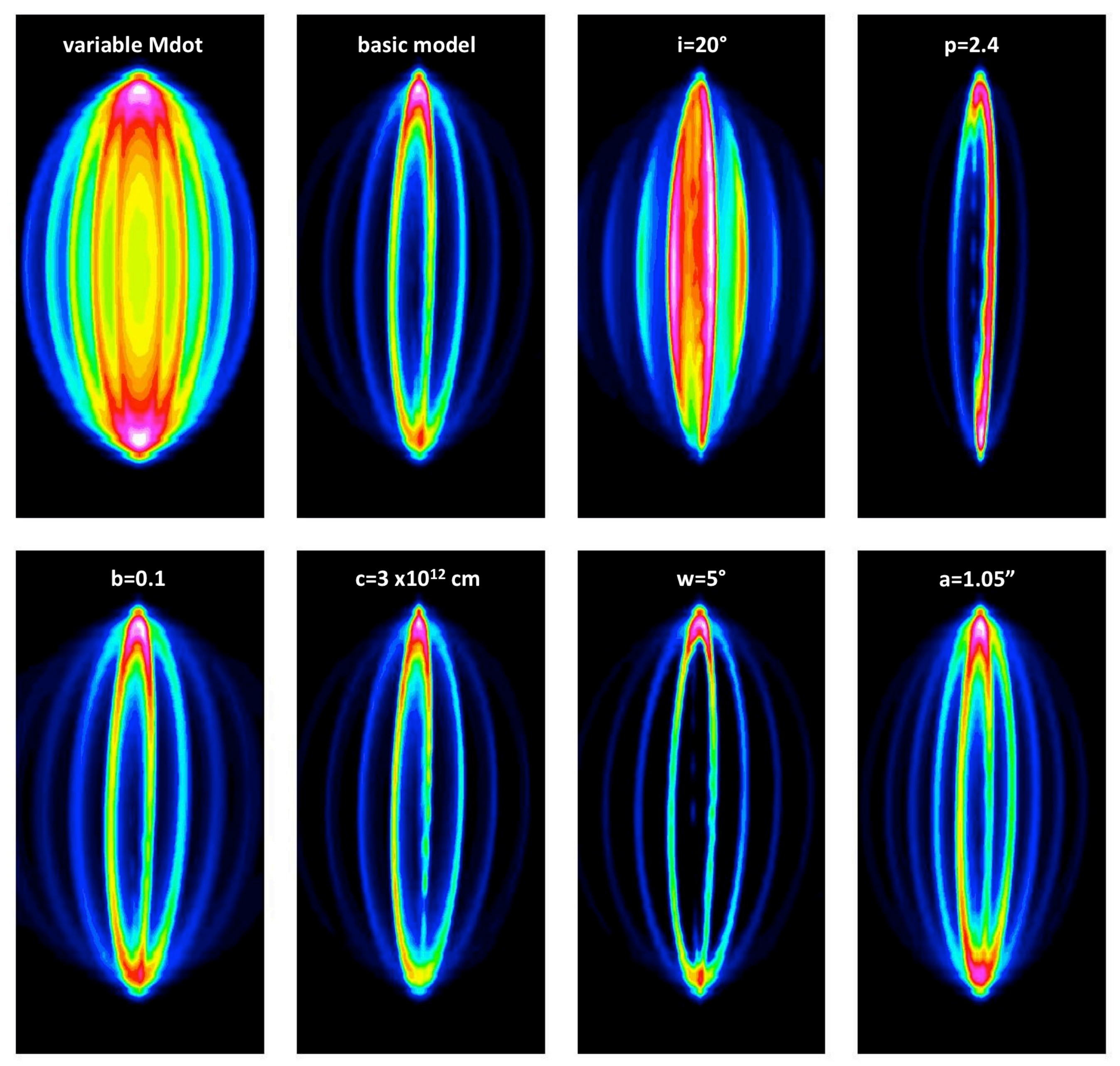
Mauron et al. 2006

→ spiral structures seen (almost) **face-on**

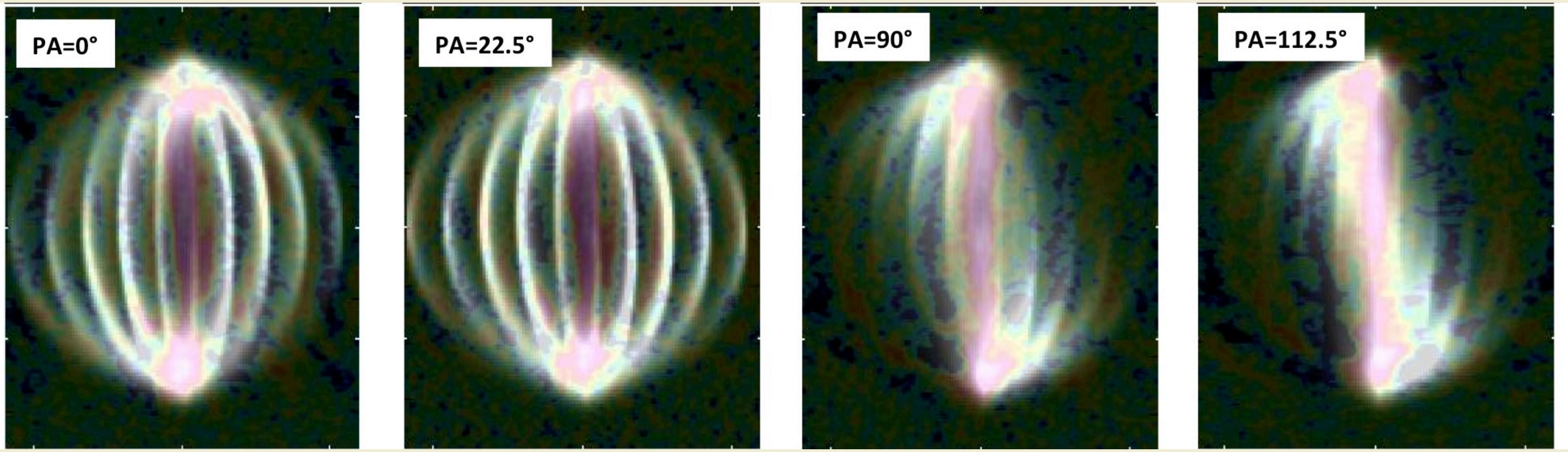
CW Leo: binary-induced spiral structure seen almost edge-on



Archimedean spiral with 3D non-LTE radiative transfer **(Shape, Steffen et al)**



Binary-induced spiral structure in ALMA data of CW Leo

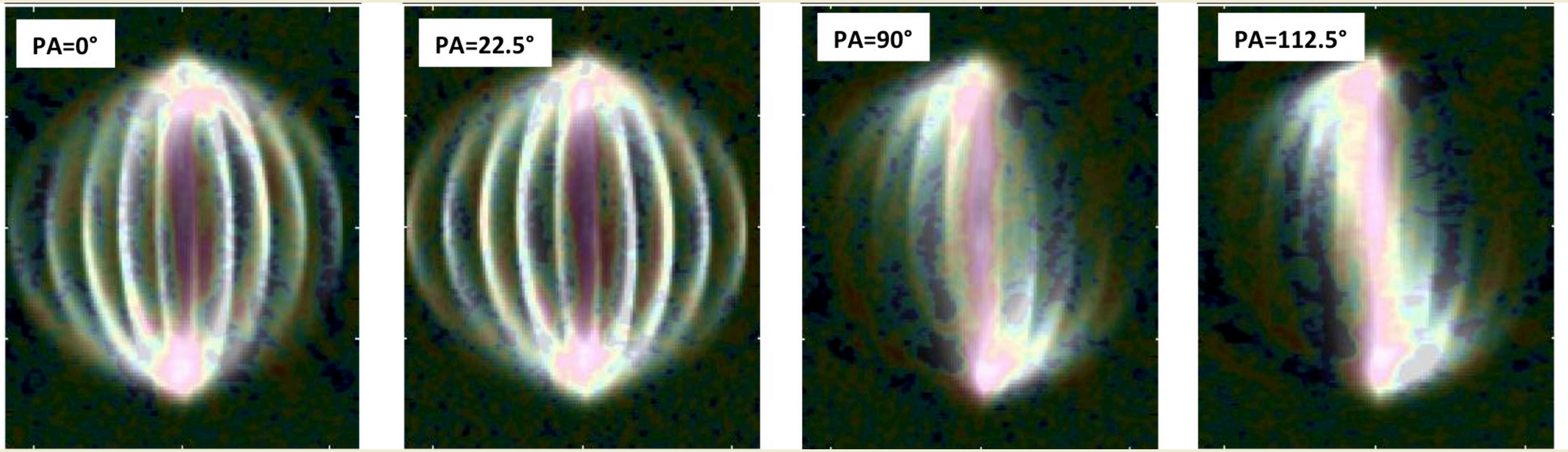


i=60-80°
a=1.12” (spiral arm spacing)

$$\Delta r_{\rm arm} = \left(\langle V_w \rangle + \cancel{\frac{2}{3} V_p} \right) \times \frac{2\pi r_p}{V_p}$$

orbital period: P=55 yr

Binary-induced spiral structure in ALMA data of CW Leo



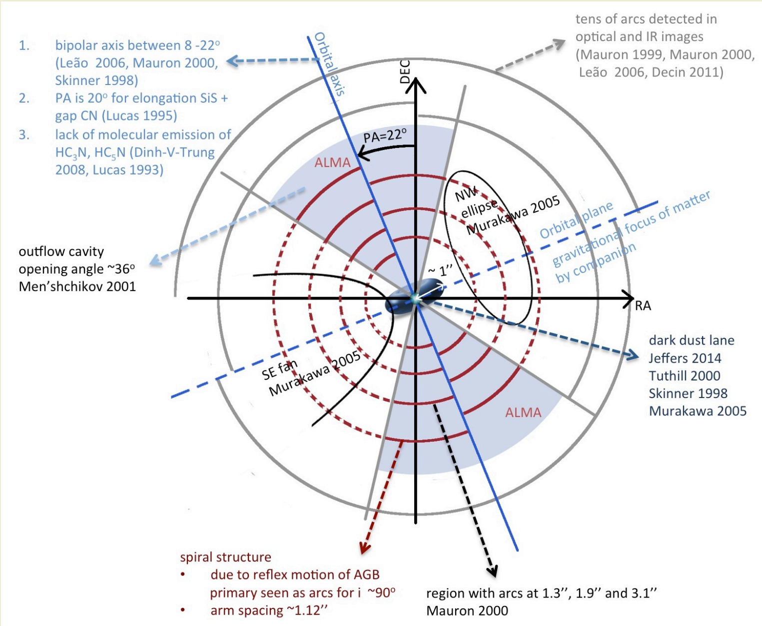
i=60-80°
a=1.12” (spiral arm spacing)

$$\Delta r_{\mathrm{arm}} = \left(\langle V_w \rangle + \cancel{\frac{2}{3} V_p} \right) \times \frac{2\pi r_p}{V_p}$$

orbital period: P=55 yr

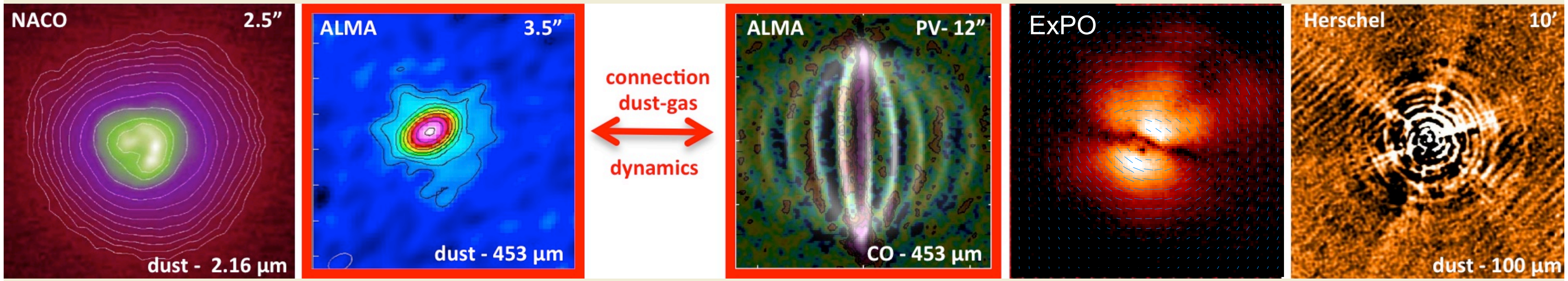
mean orbital separation: d~25±2 au (~8.2R⋆=0.17”)

(M_s ~0.6-1M_{sun} → unevolved M-dwarf)



1. bipolar axis between 8 -22° (Leão 2006, Mauron 2000, Skinner 1998)
2. PA is 20° for elongation SiS + gap CN (Lucas 1995)
3. lack of molecular emission of HC3N, HC5N (Dinh-V-Trung 2008, Lucas 1993)
tens of arcs detected in optical and IR images (Mauron 1999, Mauron 2000, Leão 2006, Decin 2011)
Orbital axis
DEC
PA=22°
ALMA
NW ellipse Murakawa 2005
Orbital plane
gravitational focus of matter by companion
~ 1''
RA
outflow cavity opening angle ~36° Men'shchikov 2001
SE fan Murakawa 2005
ALMA
dark dust lane Jeffers 2014 Tuthill 2000 Skinner 1998 Murakawa 2005
spiral structure
• due to reflex motion of AGB primary seen as arcs for i ~90°
• arm spacing ~1.12''
region with arcs at 1.3'', 1.9'' and 3.1'' Mauron 2000

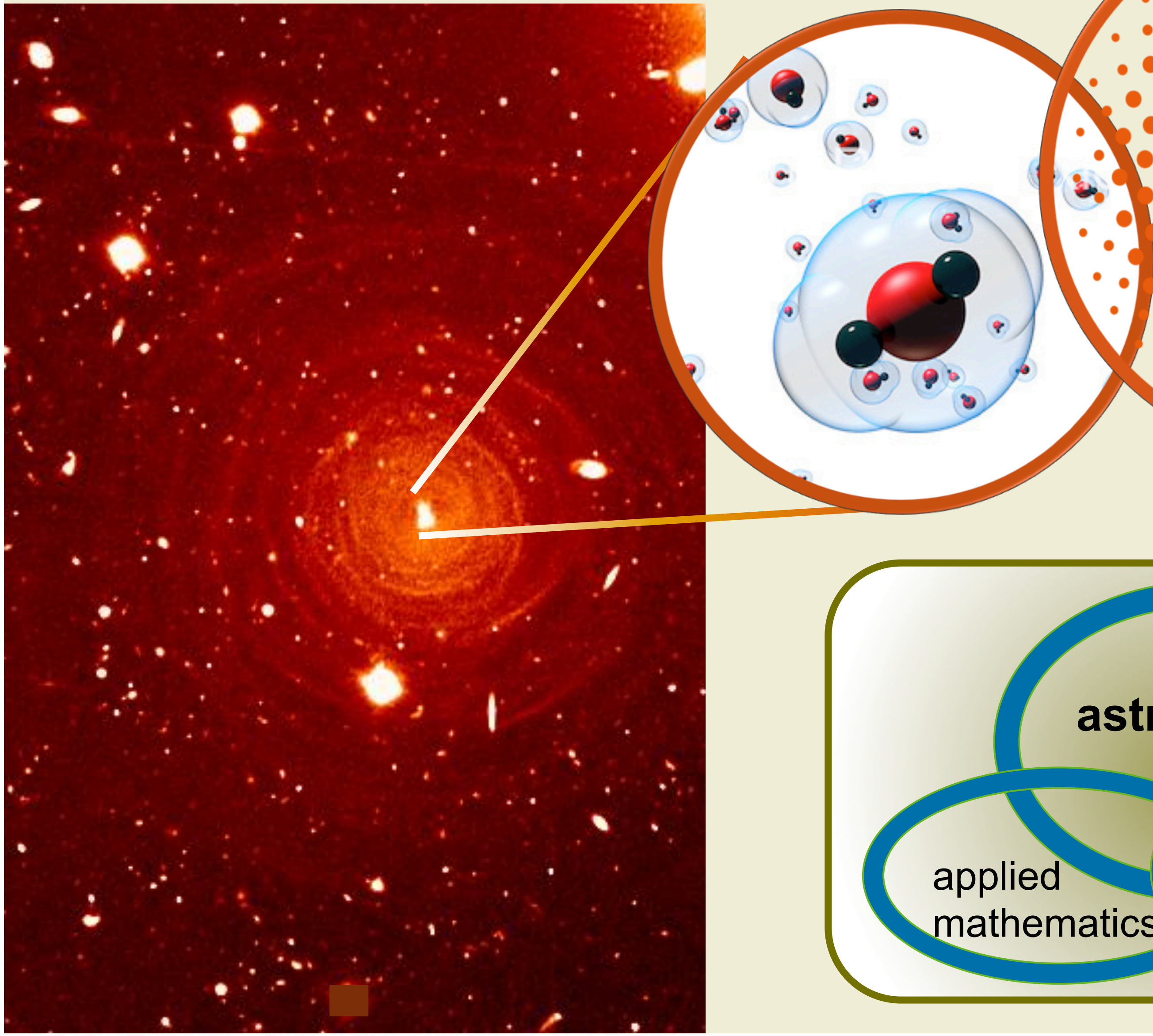
Thank you

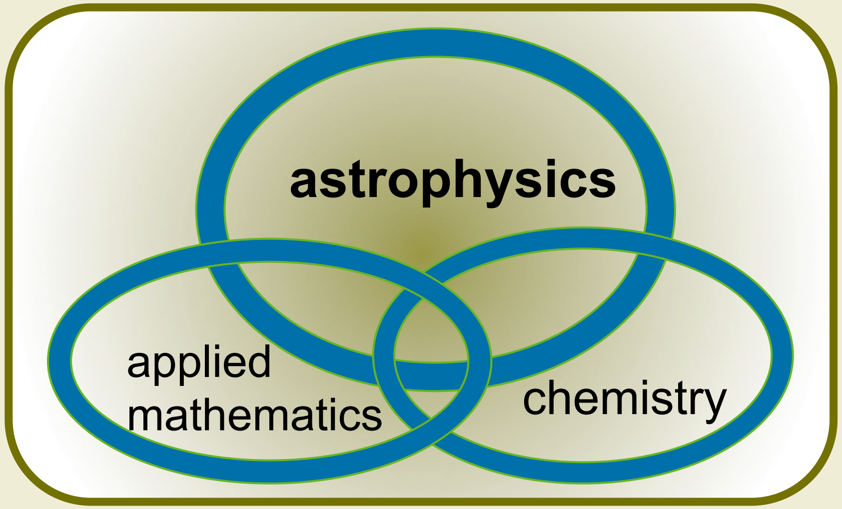


NACO
2.5''
dust - 2.16 μm
ALMA
3.5''
dust - 453 μm
connection dust-gas
dynamics
ALMA
PV- 12''
CO - 453 μm
ExPO
Herschel
10'
dust - 100 μm

ERC-CoG: AEROSOL

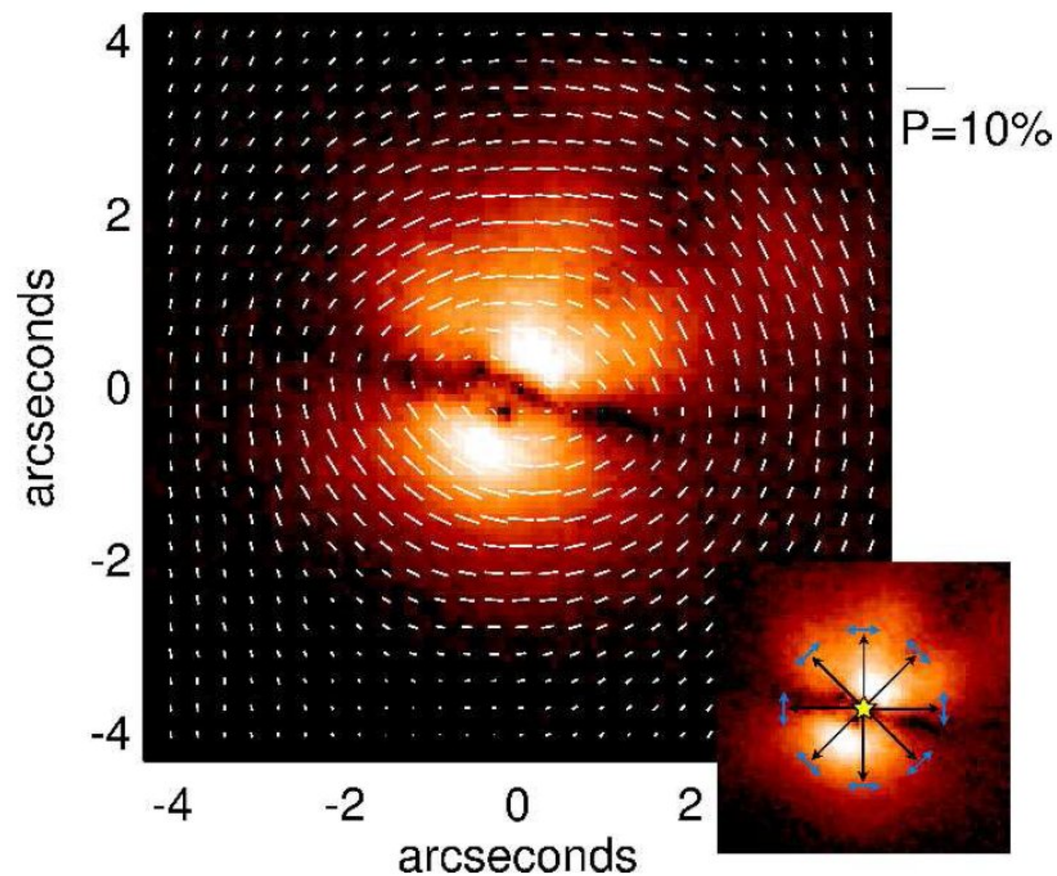
AEROSOL

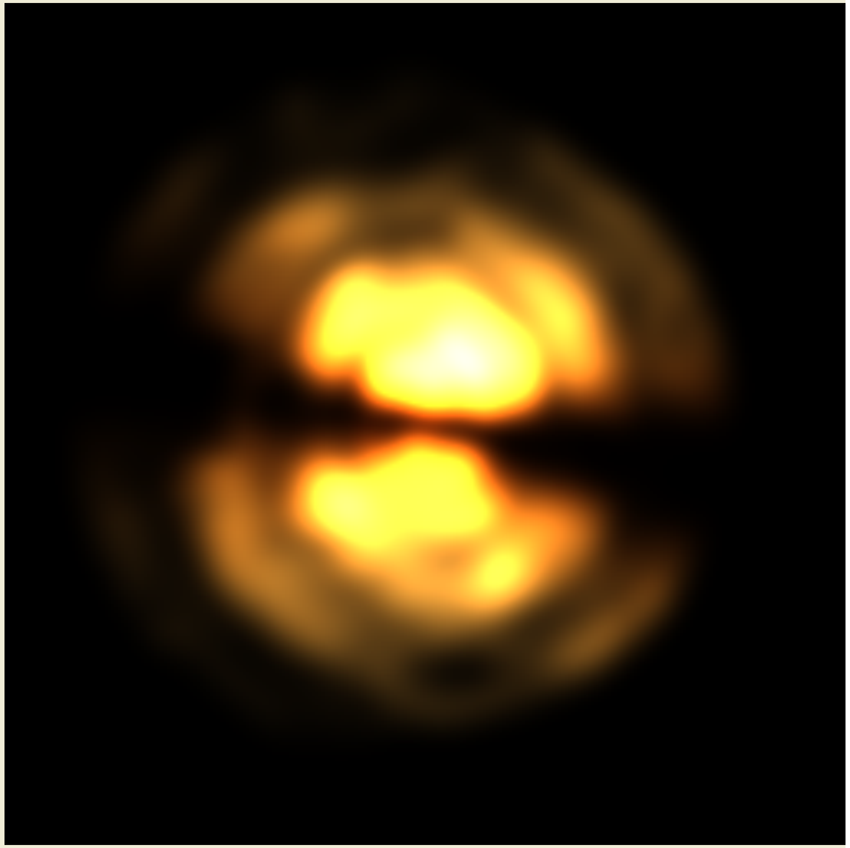




ExPO data: scattered light at optical wavelengths

binary-induced 2 spirals at i=85 deg

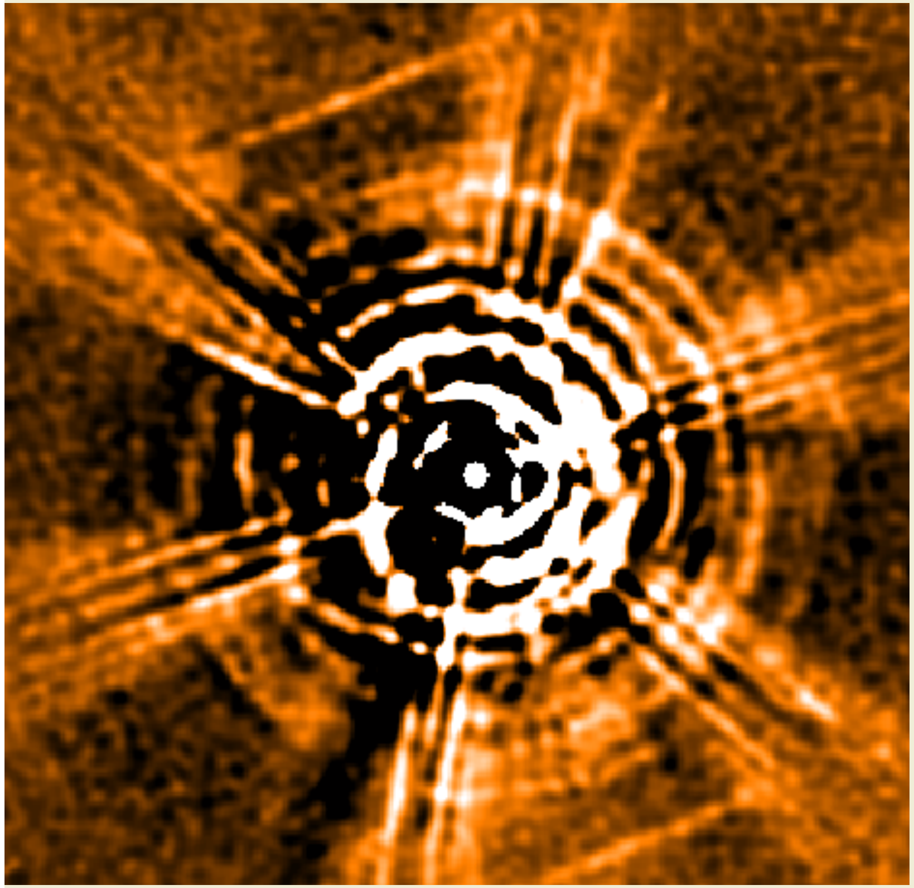


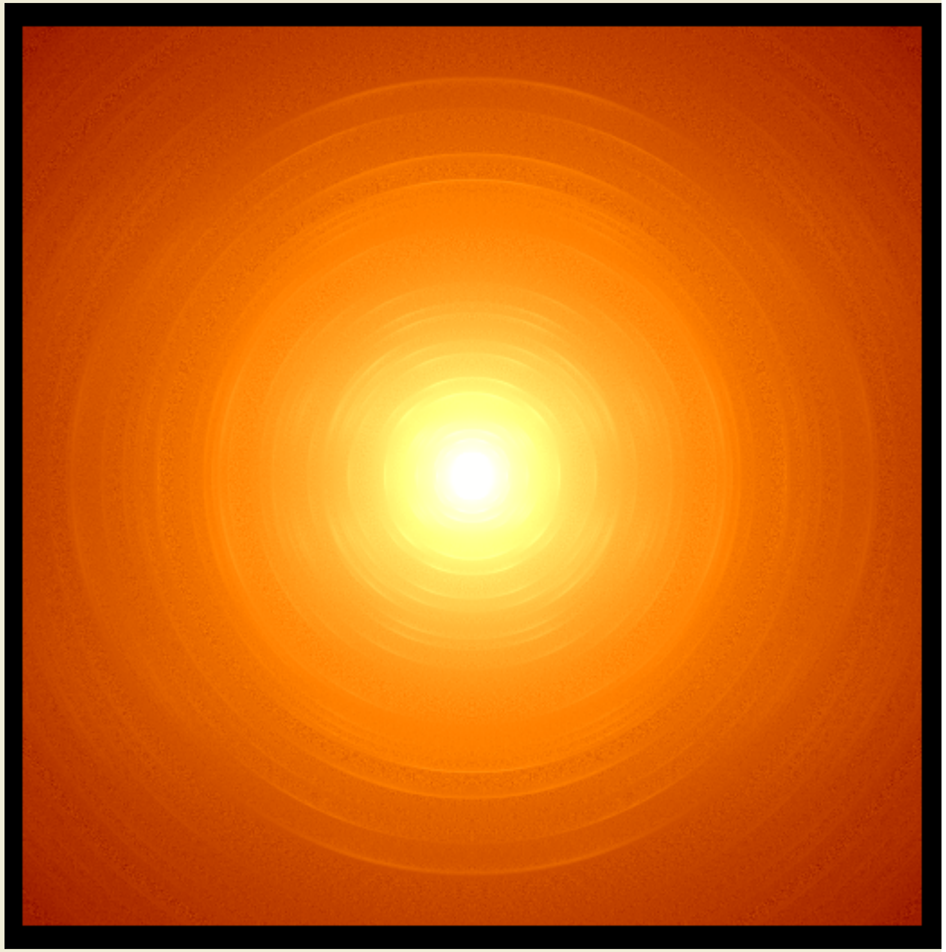


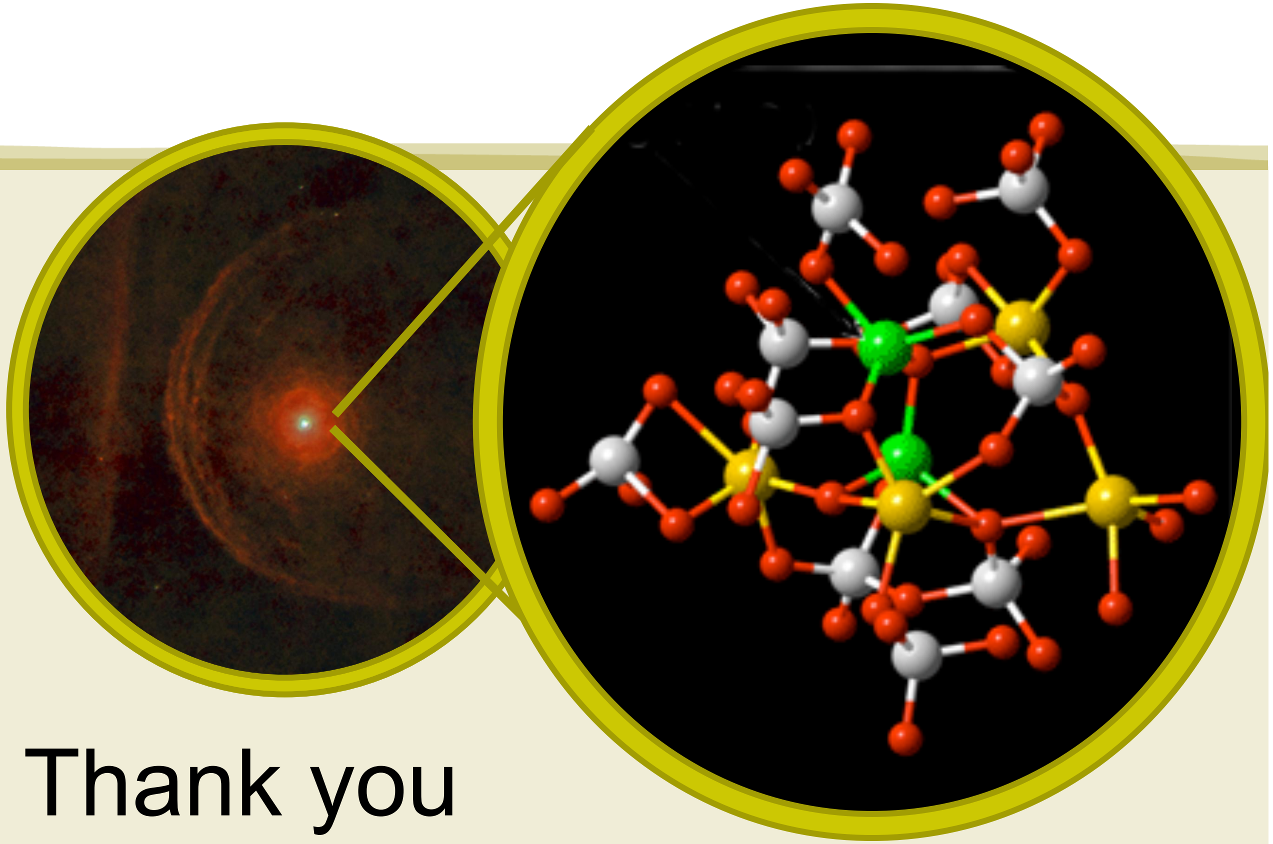
PACS data: limb-brightened (latitudinal) bands

binary-induced 2 spirals at i=85 deg

Herschel/PACS







Thank you