Berlin

April 2018

I. Mass loss in evolved stars

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Berlin

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II. Exoplanets around evolved stars

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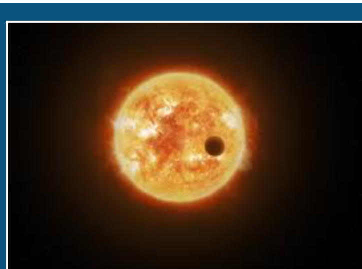
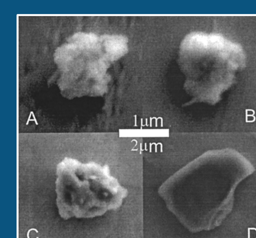
Alien visitors rule cosmic makeup





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KU LEUVEN
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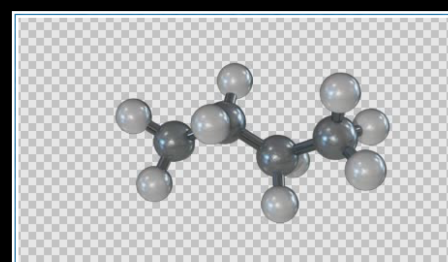
The mud …

thermodynamics

+

chemistry

pc

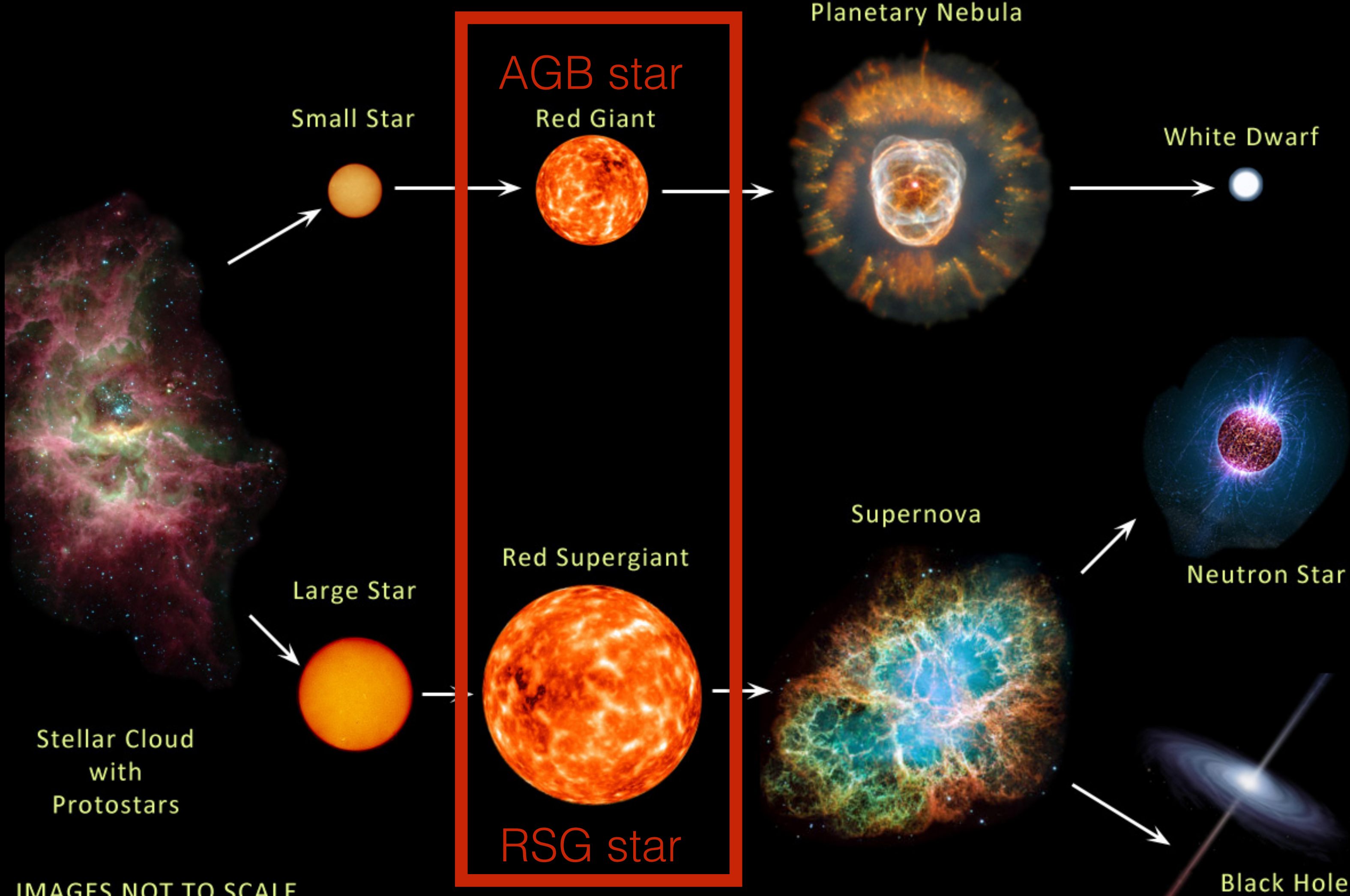


nm

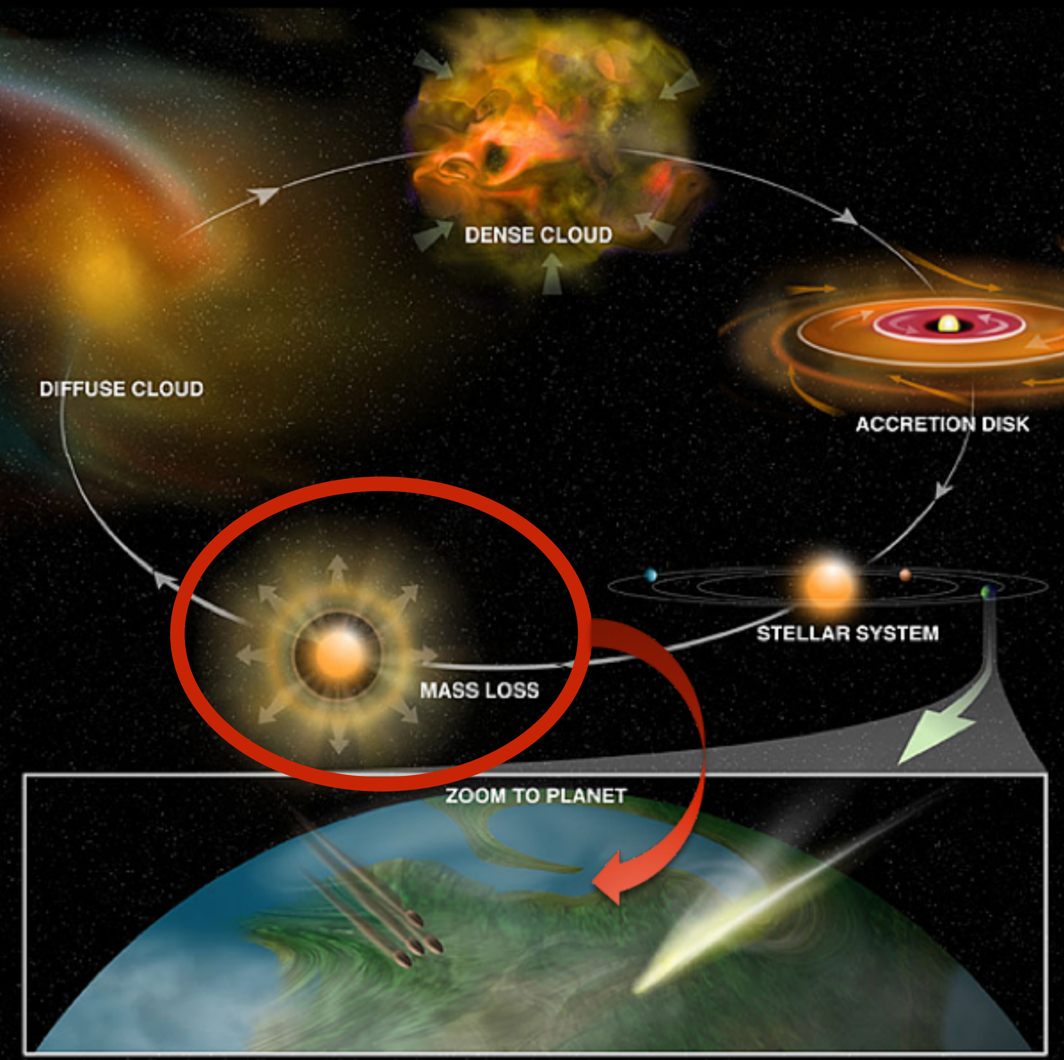
1. Introduction
2. Microscopes for telescopes
3. Corundum: conundrum
4. What about exoplanets

I. Introduction

Stellar evolution



Our life: thanks to old stars



STELLAR WIND

- ✓water (H, O)
- ✓muscles (C)
- ✓sand (Si)
- ✓atmosphere (N,O)

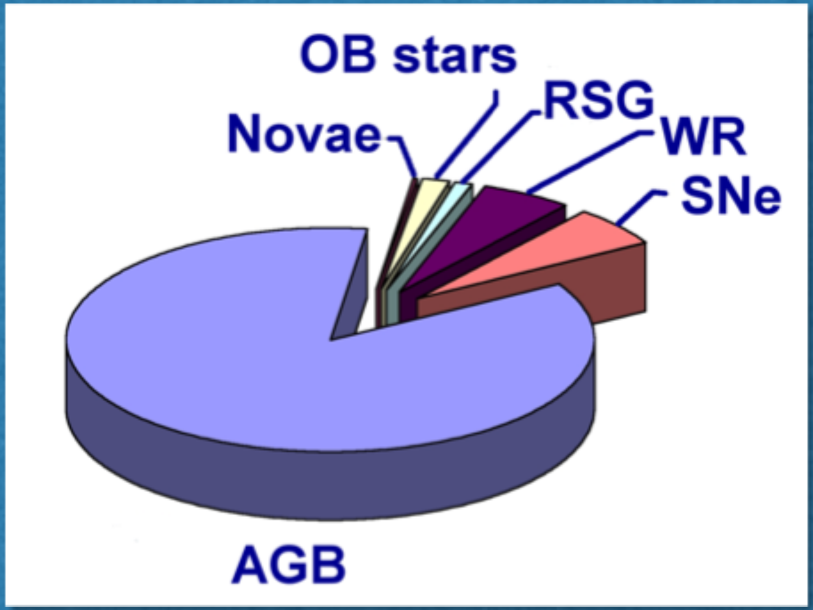
- ✓molecules (>90)
- ✓dust (>15)

→ unique E.T. chemical labs

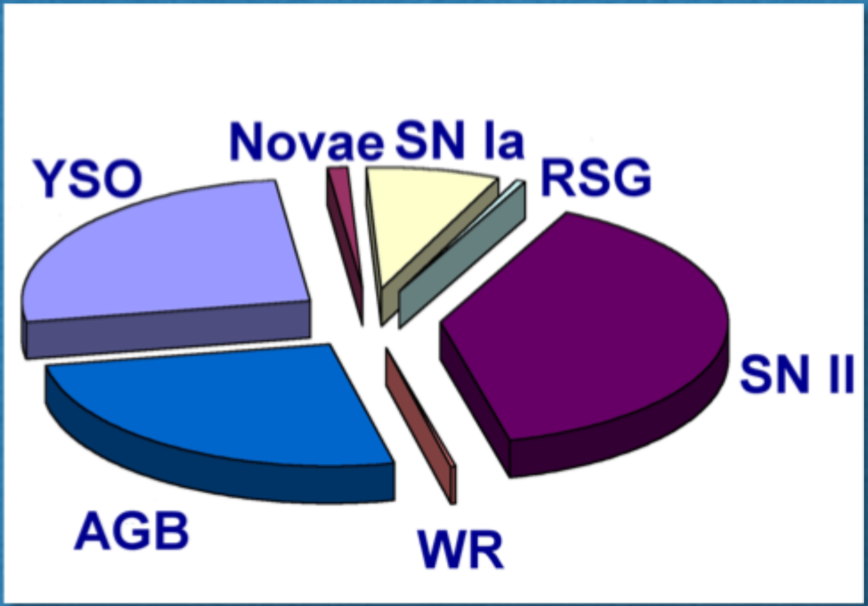
Our life: thanks to old stars

interstellar

gas



dust



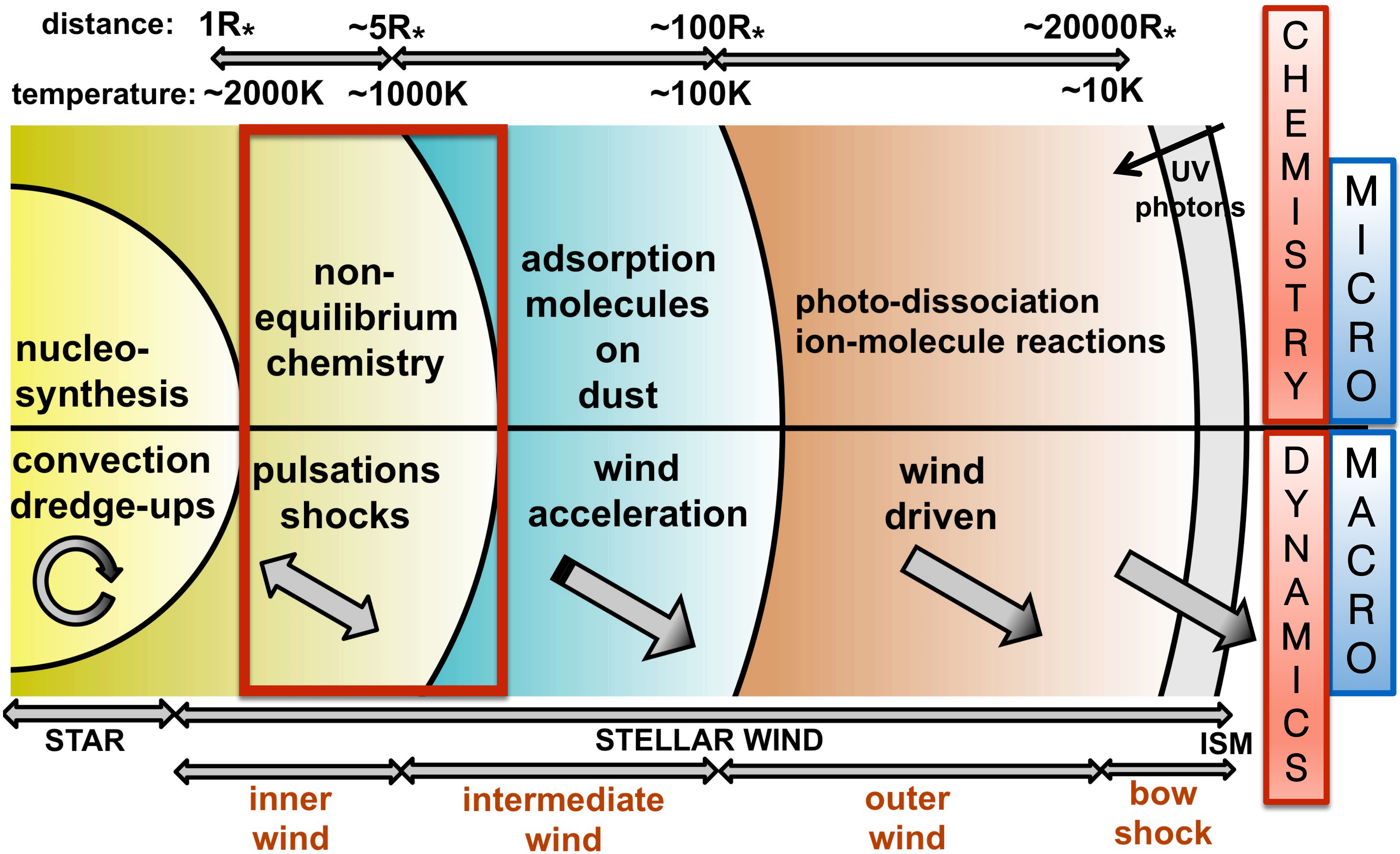
The beauty of being old

rich
(chemicals)

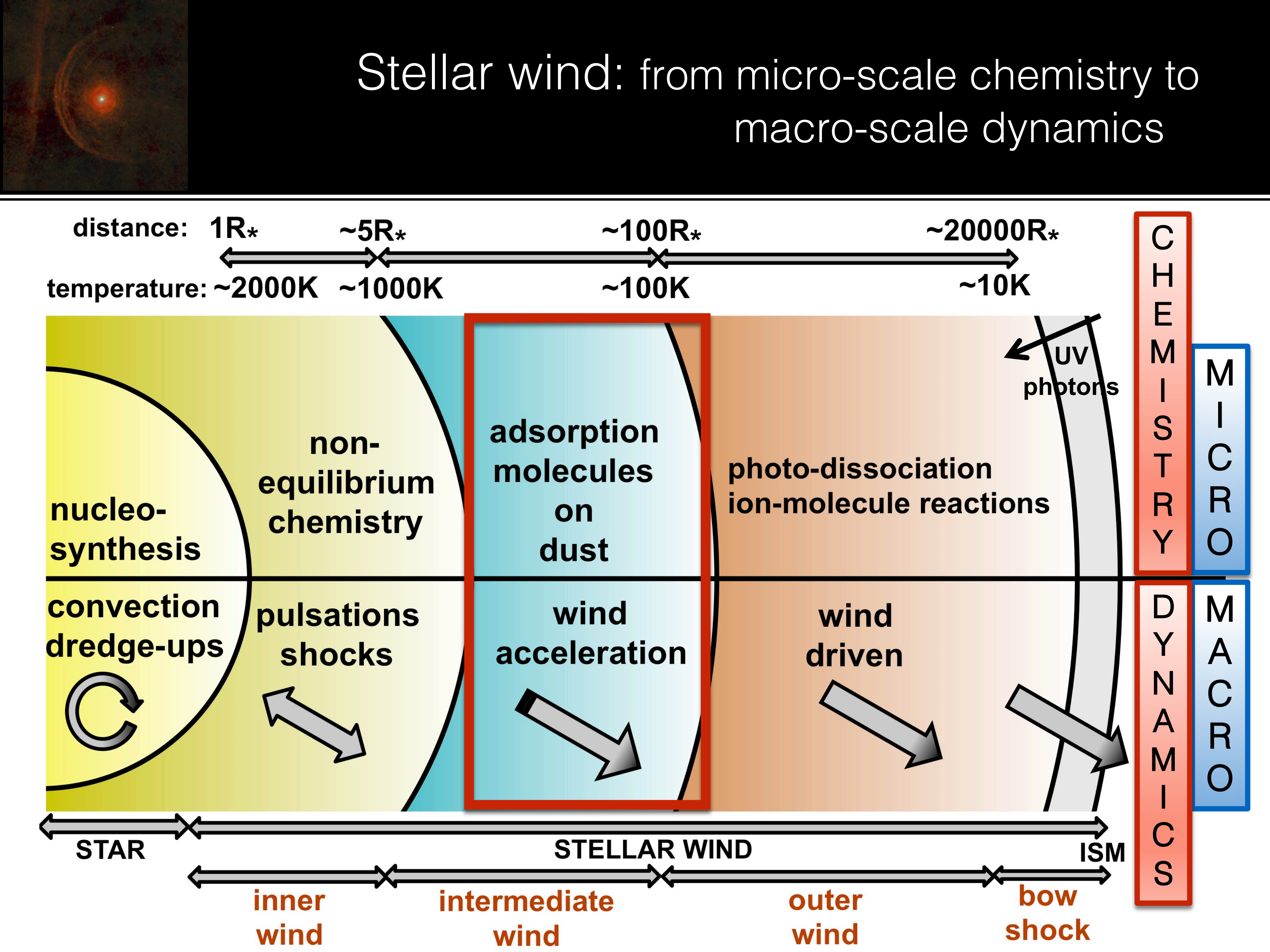
extraterrestrial laboratory
gas → dust

testbed exoplanets, YSOs, ISM, (extra)galactic media

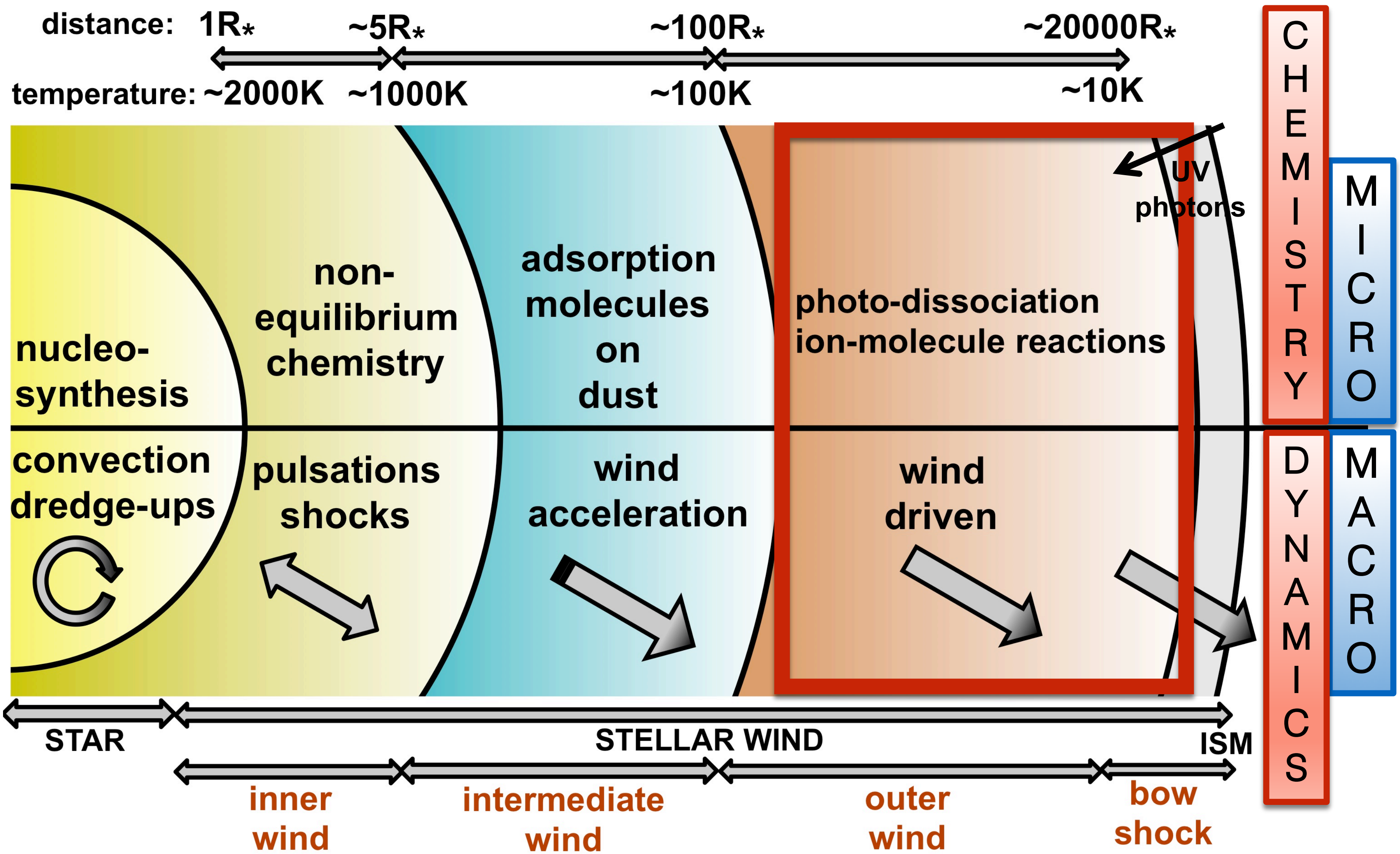
Stellar wind: from micro-scale chemistry to macro-scale dynamics



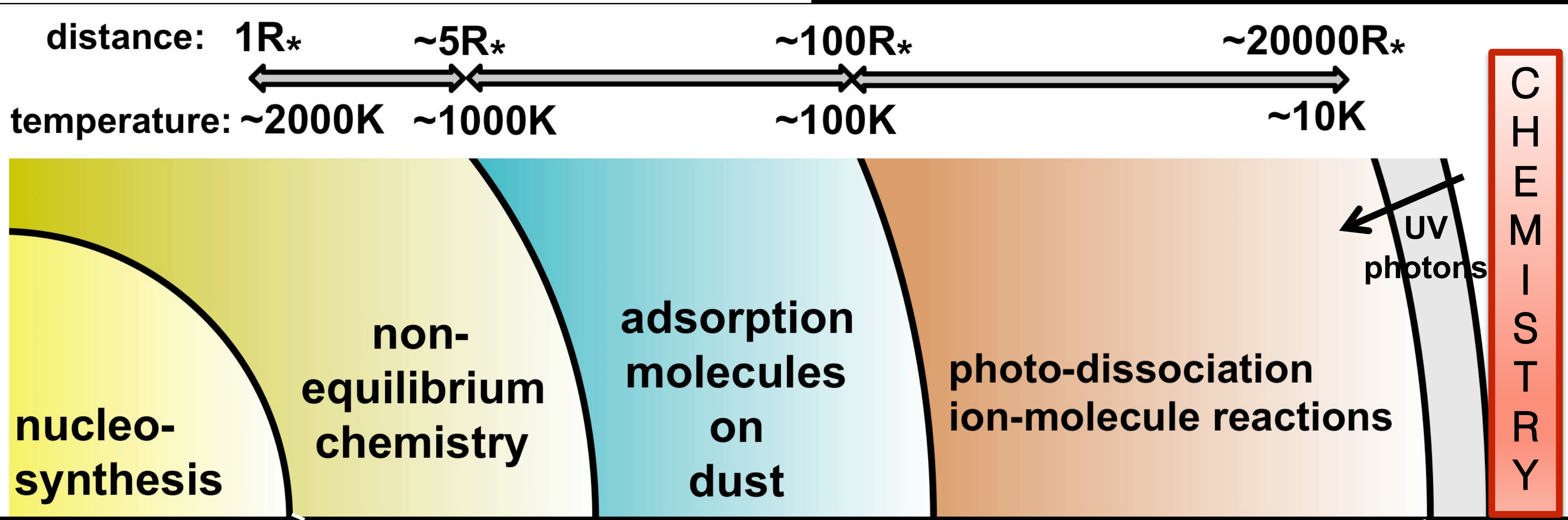
Stellar wind: from micro-scale chemistry to macro-scale dynamics



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



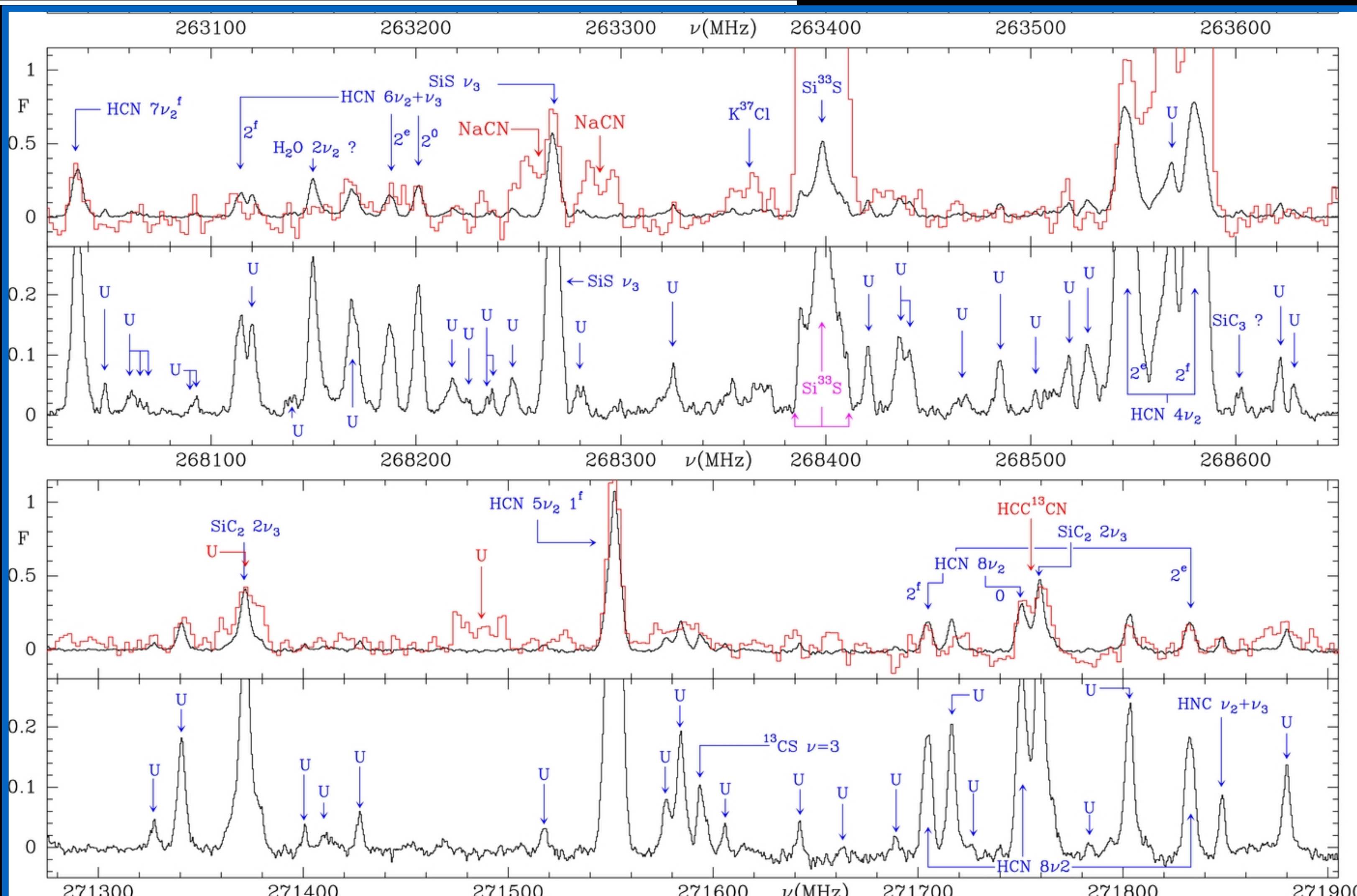
Chemical roadmap



1. Molecules
2. Dust
3. From molecules to dust
4. Grain – molecule reactions

II. Microscopes for telescopes

Stellar wind: molecules



Cernicharo 2013

Stellar wind: molecules

2-atoms:	AlCl	CP	NaCl	SiO
	AlF	CS	OH	SiS
	C_2	ClH	PN	SO
	CO	FH	SiC	
	CN	KCl	SiN	
3-atoms:	AlNC	FeCN	HNC	SiC_2
	C_3	HCN	KCN	SiCN
	C_2H	HCP	MgCN	SiCSi
	C_2S	H_2O	MgNC	SiNC
	CO_2	H_2S	NaCN	SO_2
4-atoms:	ℓ-C_3H	C_2H_2	HMgNC	PH_3
	C_3N	HC_2N	MgC_2H (?)	SiC_3
	C_3O	H_2CO	NC_2P (?)	
	C_3S	H_2CS	NH_3	
5-atoms:	C_5	c-C_3H_2	CH_2NH	H_2C_3
	C_4H	CH_2CN	HC_3N	HNC_3
	C_4Si	CH_4	HC_2NC	SiH_4
6-atoms:	C_5H	C_5S	CH_3CN	H_2C_4
	C_5N	C_2H_4	HC_4N	SiH_3CN (?)
$\geq$7-atoms:	C_6H	CH_2CHCN	HC_7N	
	C_7H	CH_3CCH	HC_9N	
	C_8H	HC_5N	H_2C_6	
Ions:	C_4H^-	C_6H^-	C_8H^-	HCO^+
	CN^-	C_3N^-	C_5N^-	

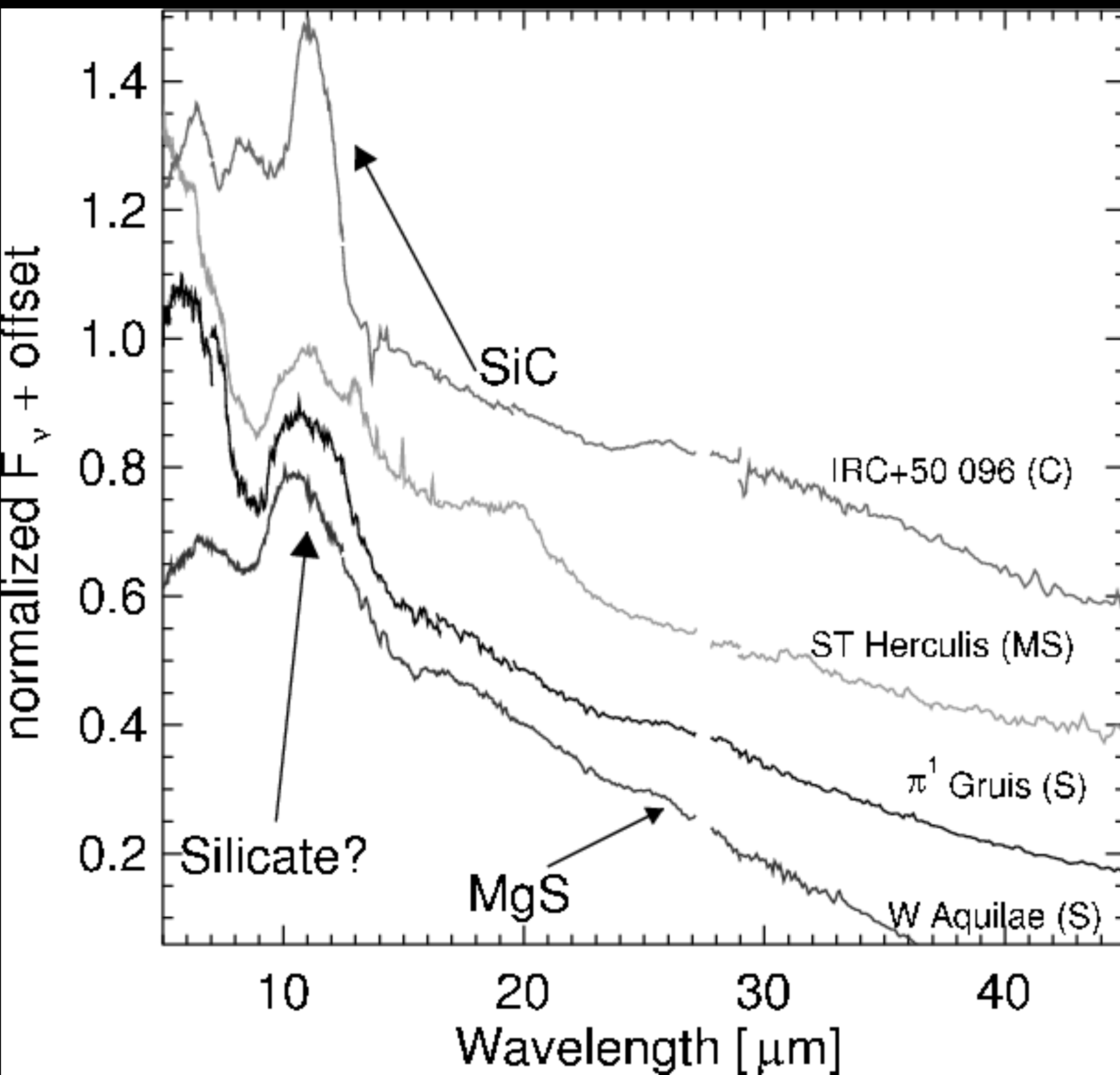
88 molecules

$\downarrow$

70 –C–

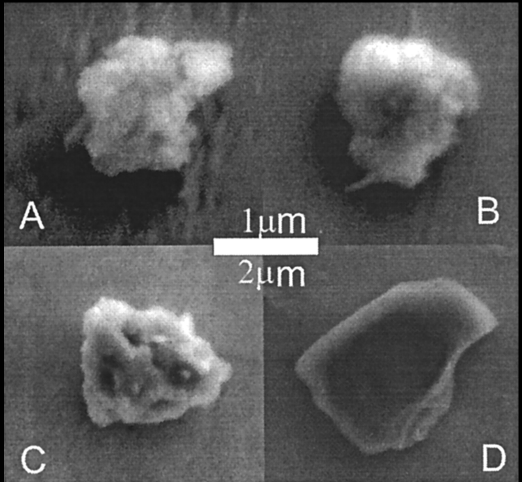
Olofsson

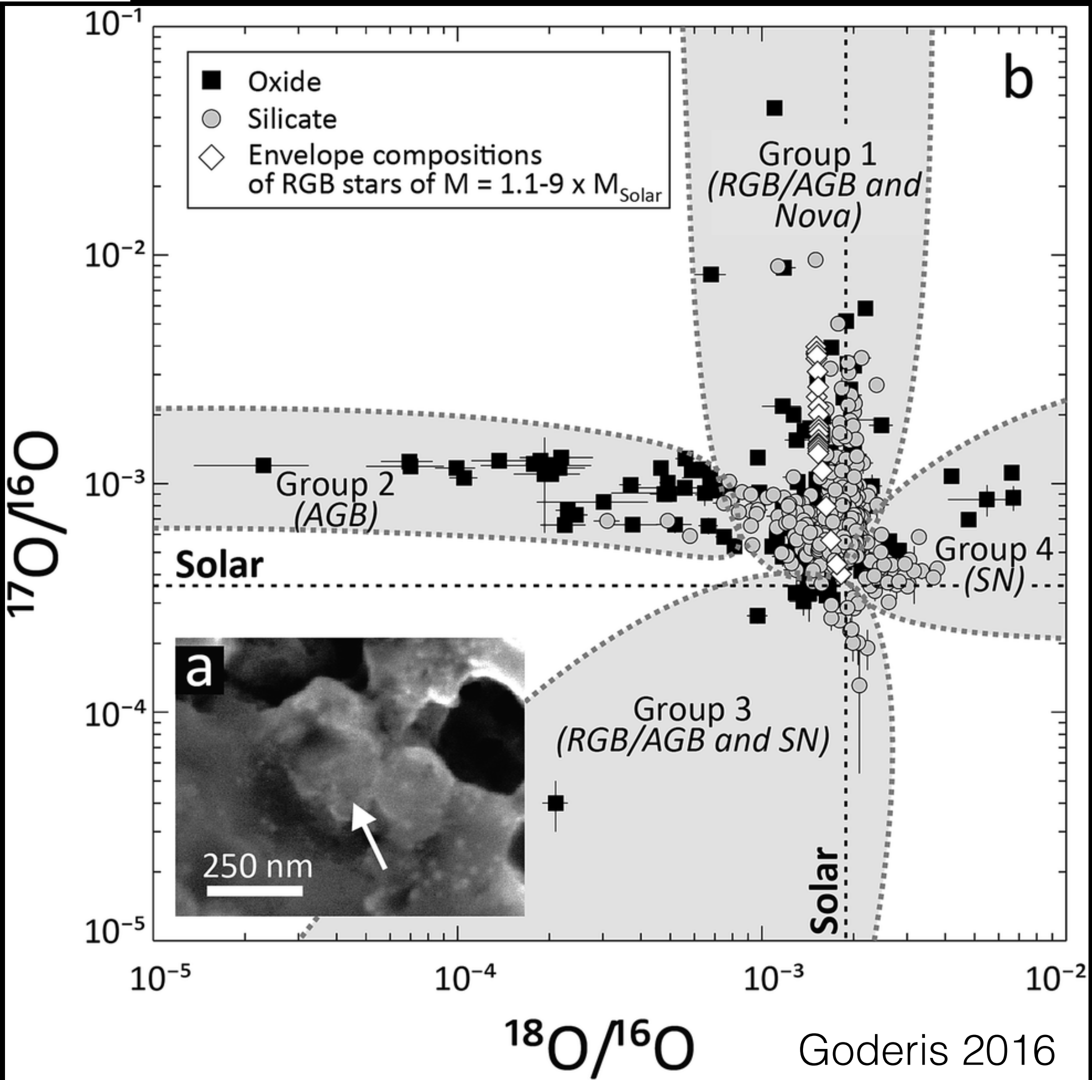
Stellar wind: dust



Hony 2009

Isotopes - cosmochemistry





Goderis 2016

Isotopes – Cosmochemistry

C/O

Table 1 Types, sizes, abundances, and stellar source(s) of presolar grains

Mineral/species[a]	Typical size	Typical abundance[b]	Parent stars
Carbonaceous grains			
Diamond	Few nm	?	SNe[d], ?
Graphite	Few µm	<10 ppm	AGB stars (~50%), novae (≪1%), SNe (~30%)
SiC (moissanite)	0.1–3 µm	10–100 ppm	AGB stars (~95%), J-type carbon stars (few %), novae (≪1%), SNe (1.3%)
Refractory carbides (*e.g.*, TiC)	20–100 nm	≪1 ppm (incl)[c]	AGB stars, SNe
O-rich grains			
Silicates	0.2–0.3 µm	200–300 ppm	RGB and AGB stars (85–90%), novae (≪1%), SNe (10–15%)
Spinel	0.1–1 µm	Together: 5–30 ppm	RGB and AGB stars (~90%), novae (≤1%), SNe (<10%)
Al_2O_3 (corundum and amorphous)	0.1–1 µm		RGB and AGB stars (~90%), novae (≤1%), SNe (<10%)
Hibonite	0.1–1 µm		RGB and/or AGB stars (~90%), SNe (~10%)
SiO_2	0.2–0.3 µm	Together: 1–1.5 ppm	AGB stars (~75%), SNe (~25%)
TiO_2	0.2–0.3 µm		RGB and/or AGB stars (~80%), SNe (~20%)
MgO	0.2–0.3 µm		
FeO	0.2–0.3 µm		
Other grain types			
Si_3N_4	0.2–1 µm	≪1 ppm	SNe
TiN	Tens of nm	≪1 ppm (incl)	SNe
AlN	Tens of nm	≪1 ppm (incl)	AGB stars?, SNe
Fe, Ni metal (kamacite) and Fe, Ni silicides	Tens of nm	≪1 ppm (incl)	AGB stars?, SNe
Refractory metal nuggets	Tens of nm	≪1 ppm (incl)	AGB stars, SNe

Goderis 2016

Isotopes – Cosmochemistry

C/O

Table 1 Types, sizes, abundances, and stellar source(s) of presolar grains

Mineral/species[a]	Typical size	Typical abundance[b]	Parent stars
Carbonaceous grains			
Diamond			
Graphite			
SiC (moissanite)			
Refractory carbides (*e.g.*, TiC)			
O-rich grains			
Silicates			15%)
Spinel			)
Al_2O_3 (corundum and amorphous)			)
Hibonite			
SiO_2			
TiO_2			
MgO			
FeO			
Other grain types			
Si_3N_4			
TiN			
AlN			
Fe, Ni metal (kamacite) and Fe, Ni silicides	Tens of nm	≪1 ppm (incl)	AGB stars?, SNe
Refractory metal nuggets	Tens of nm	≪1 ppm (incl)	AGB stars, SNe

Silicates (Mg_2SiO_4, $MgFeSiO_4$, …)

Al_2O_3 (corundum & amorphous)

SiO_2

TiO_2

Goderis 2016

O-rich grains: 2 condensation sequences

Al-oxides

[1760-1300K]
Al_2O_3, Alumina

↓

[1625-1400K]
$Ca_2Al_2SiO_7$, Gehlinite

↓

[1450-1100K]
$CaMgSi_2O_6$, Diopside

↓

[1360-1000K]
$CaAl_2Si_2O_8$, Anorthite

silicates

[1440-1050K]
Mg_2SiO_4, Forsterite

↓

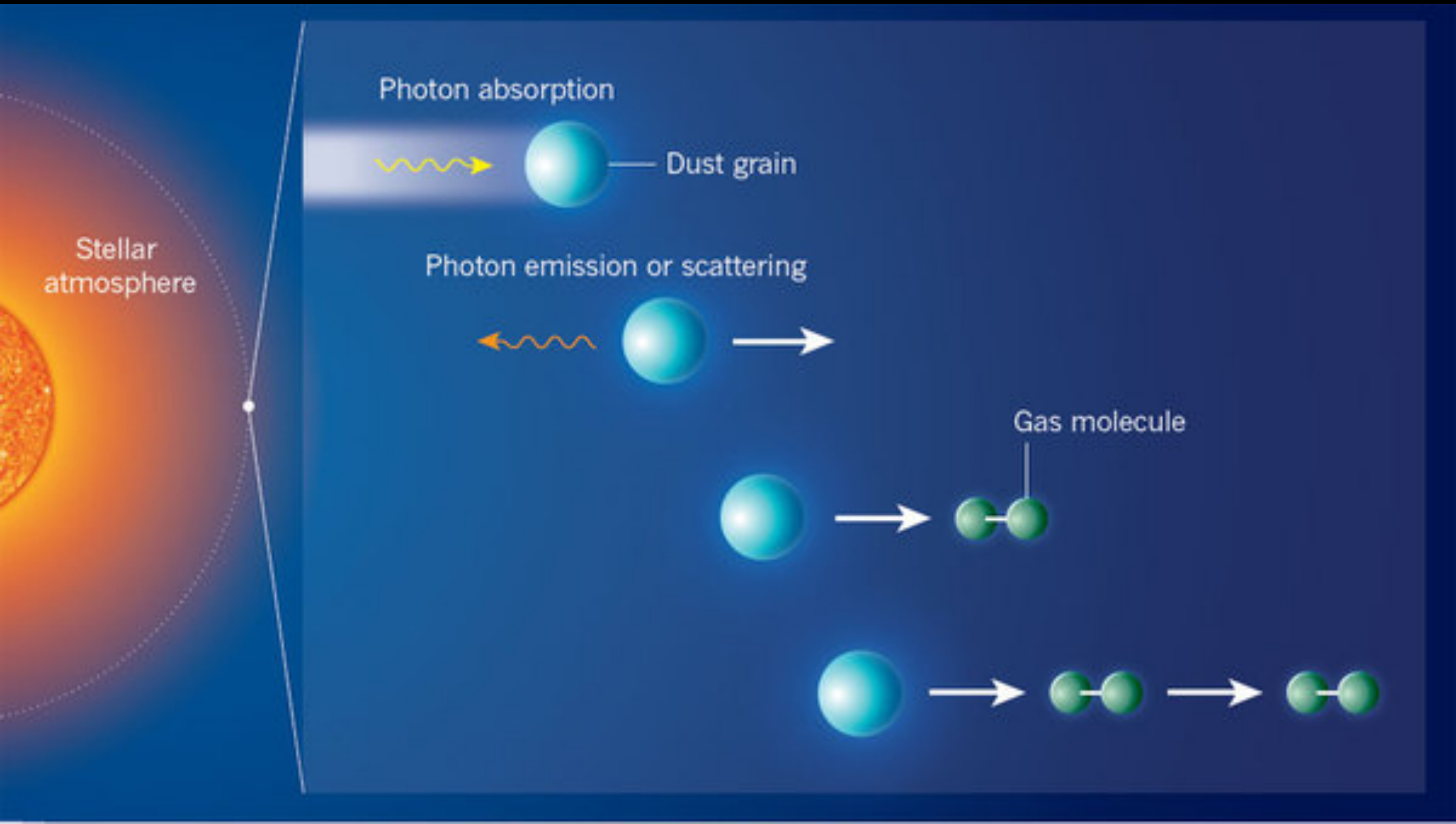
[1350-1040K]
$MgSiO_3$, Enstatite

↓

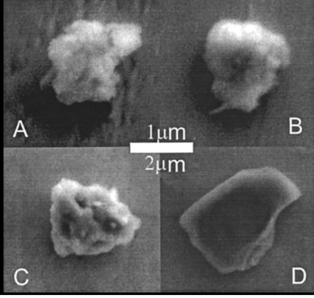
[1100-950K]
$[Mg,Fe]_2SiO_4$, Olivine

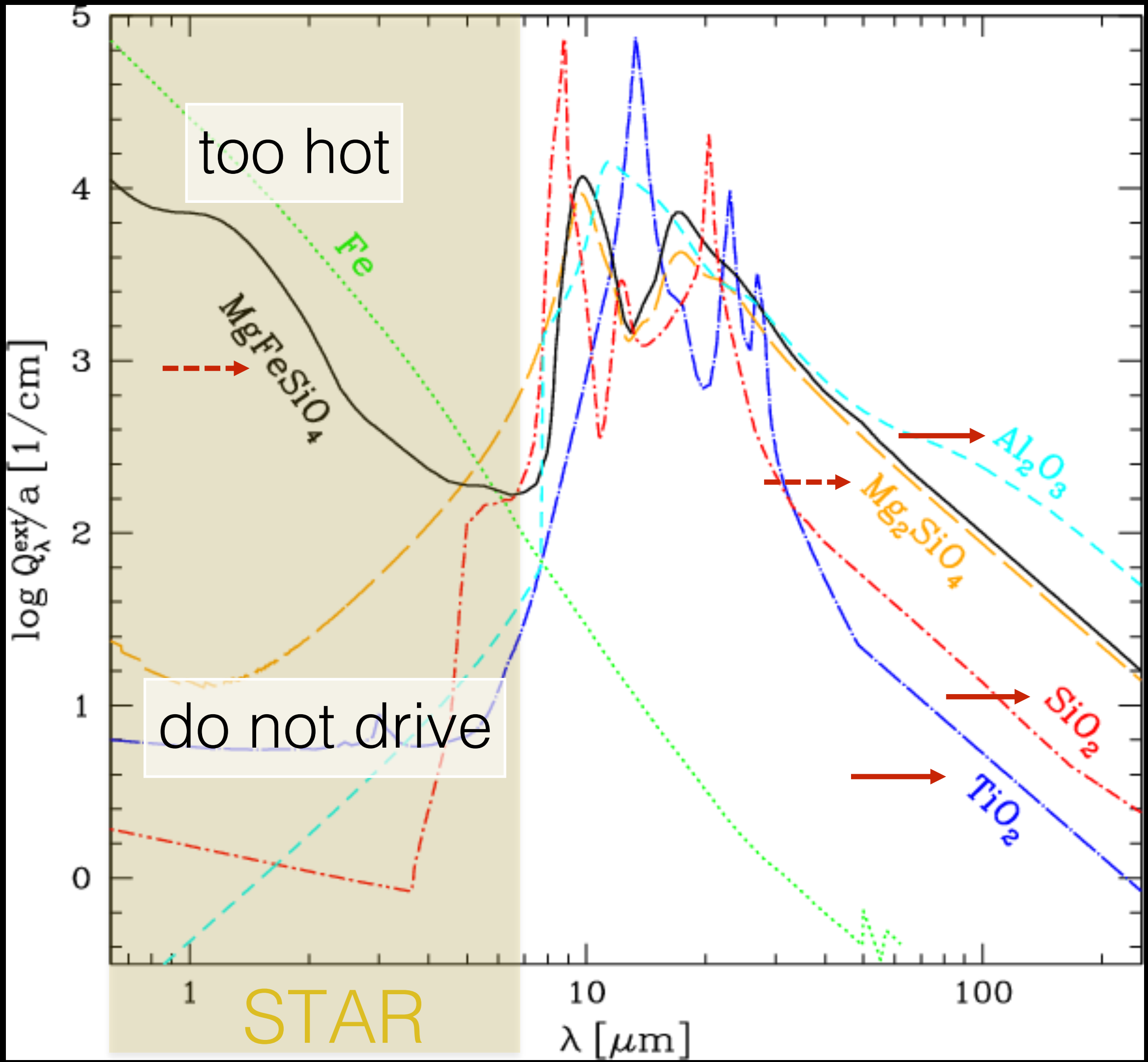
Tielens 1998

Driving a wind...



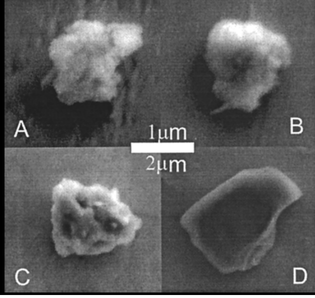
O-rich winds!?

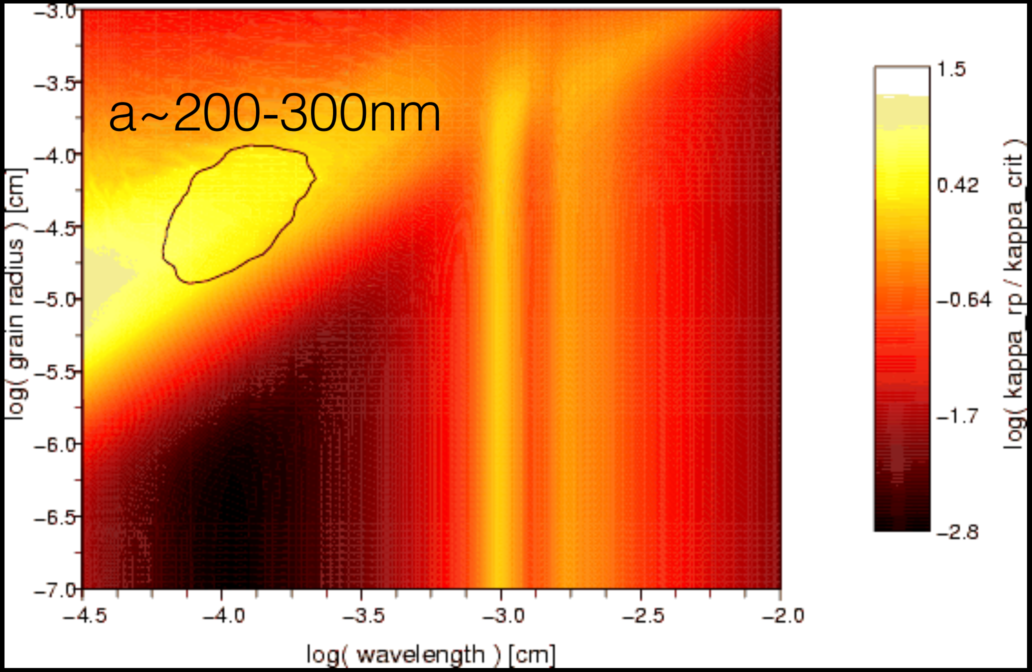




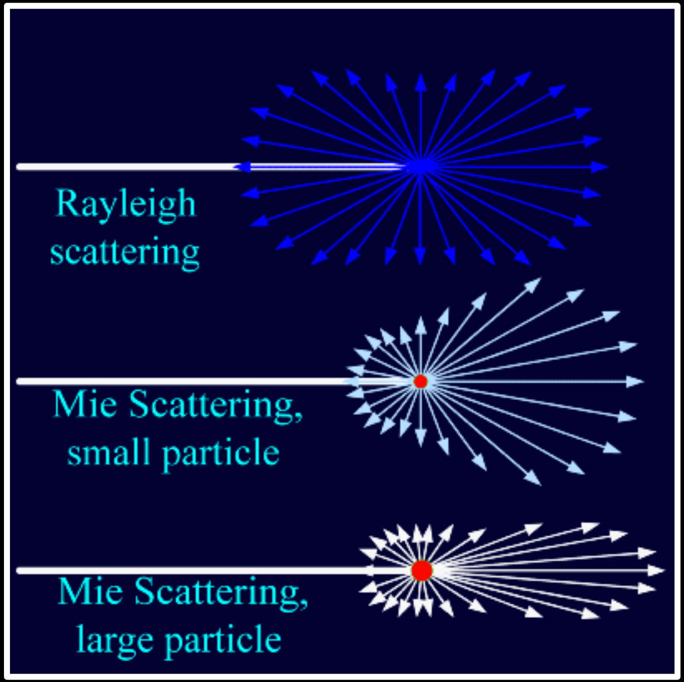
Woitke 2006

Size matters





Höfner 2008



From molecules to grains

atoms ⇒ molecules $\xrightarrow{?}$ clusters $\xrightarrow{?}$ dust grains

nucleation (molecules → clusters)

condensation (clusters → dust grains)

homogeneous

heterogeneous

TiO_2	~~Al_2O_3~~	~~MgO~~	~~SiO_2~~
TiO	~~AlO~~		~~SiO~~

high abundance
high bond energy

low abundance

X
-no stable cluster
-nucleation rate too low

From molecules to grains

atoms → molecules → clusters → dust grains

? ?

nucleation

condensation

homogeneous

heterogeneous

high abundance
high bond energy

TiO_2
TiO

$\cancel{Al_2O_3}$
$\cancel{AlO}$

$\cancel{MgO}$

SiO_2
SiO

low abundance

X
-no stable cluster
-nucleation rate too low

BUT:
- 2006, 2013: new SiO vapour pressure measurements

→ details nucleation not yet understood

From molecules to grains

? ?

atoms ⟹ molecules ⟹ clusters ⟹ dust grains

nucleation

condensation

homogeneous

heterogeneous

high abundance
high bond energy

TiO_2
TiO

low abundance

$\cancel{Al_2O_3}$
$\cancel{AlO}$

$\cancel{MgO}$

$\cancel{SiO_2}$
$\cancel{SiO}$

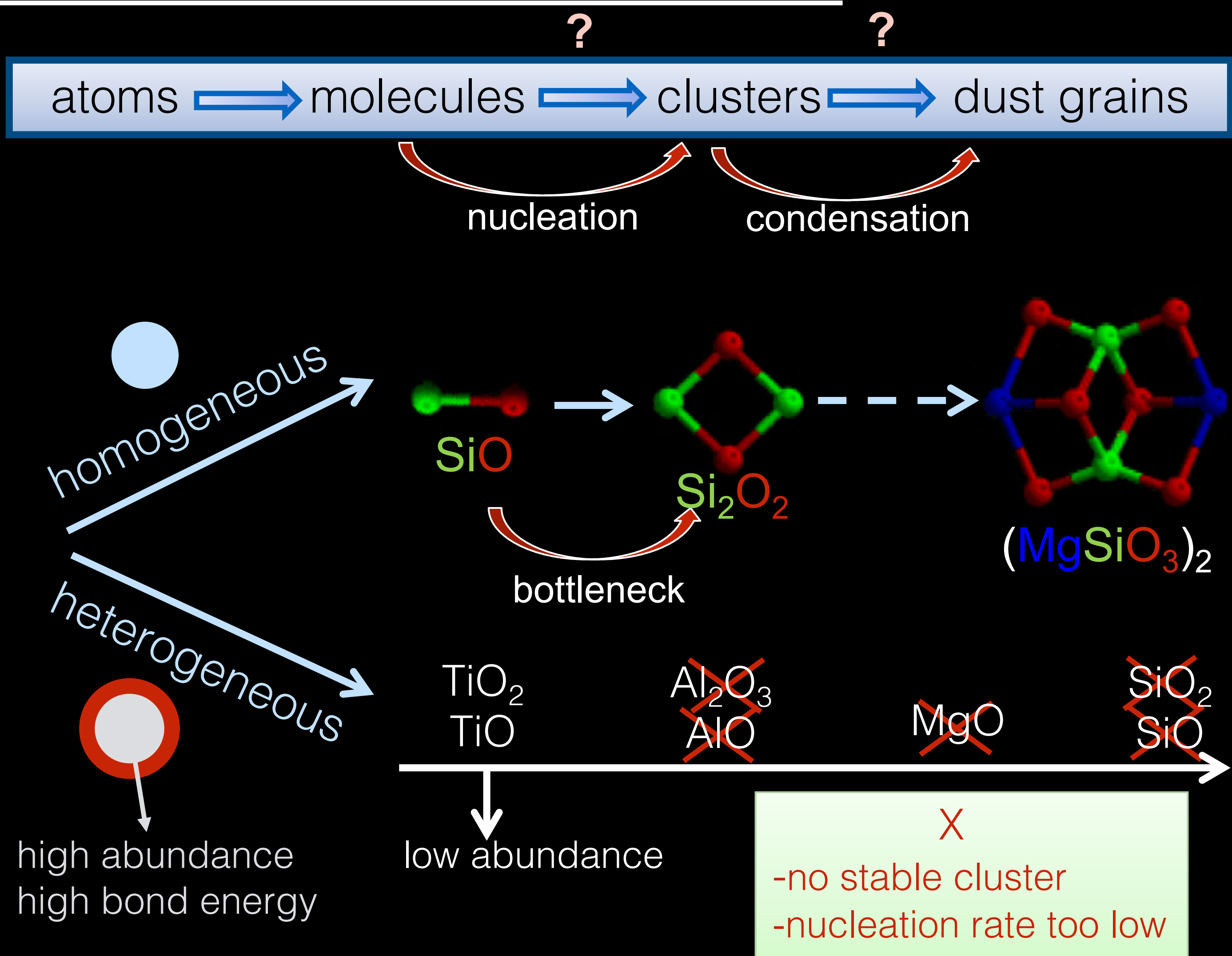
X
-no stable cluster
-nucleation rate too low

<u>BUT:</u>

- 2006, 2013: new SiO vapour pressure measurements
- 2016: $(SiO)_n$ studies

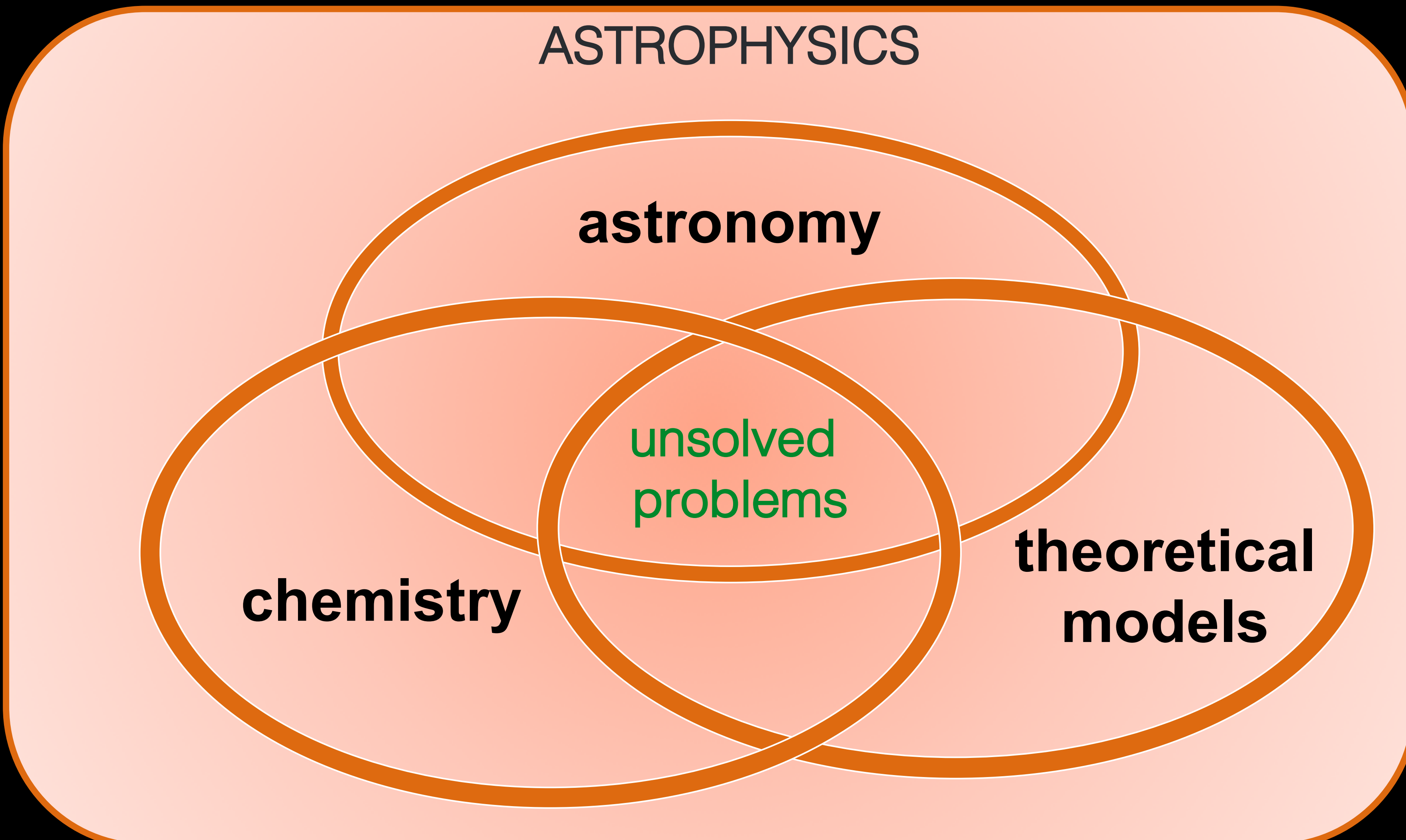
→ **details nucleation not yet understood**

From molecules to grains



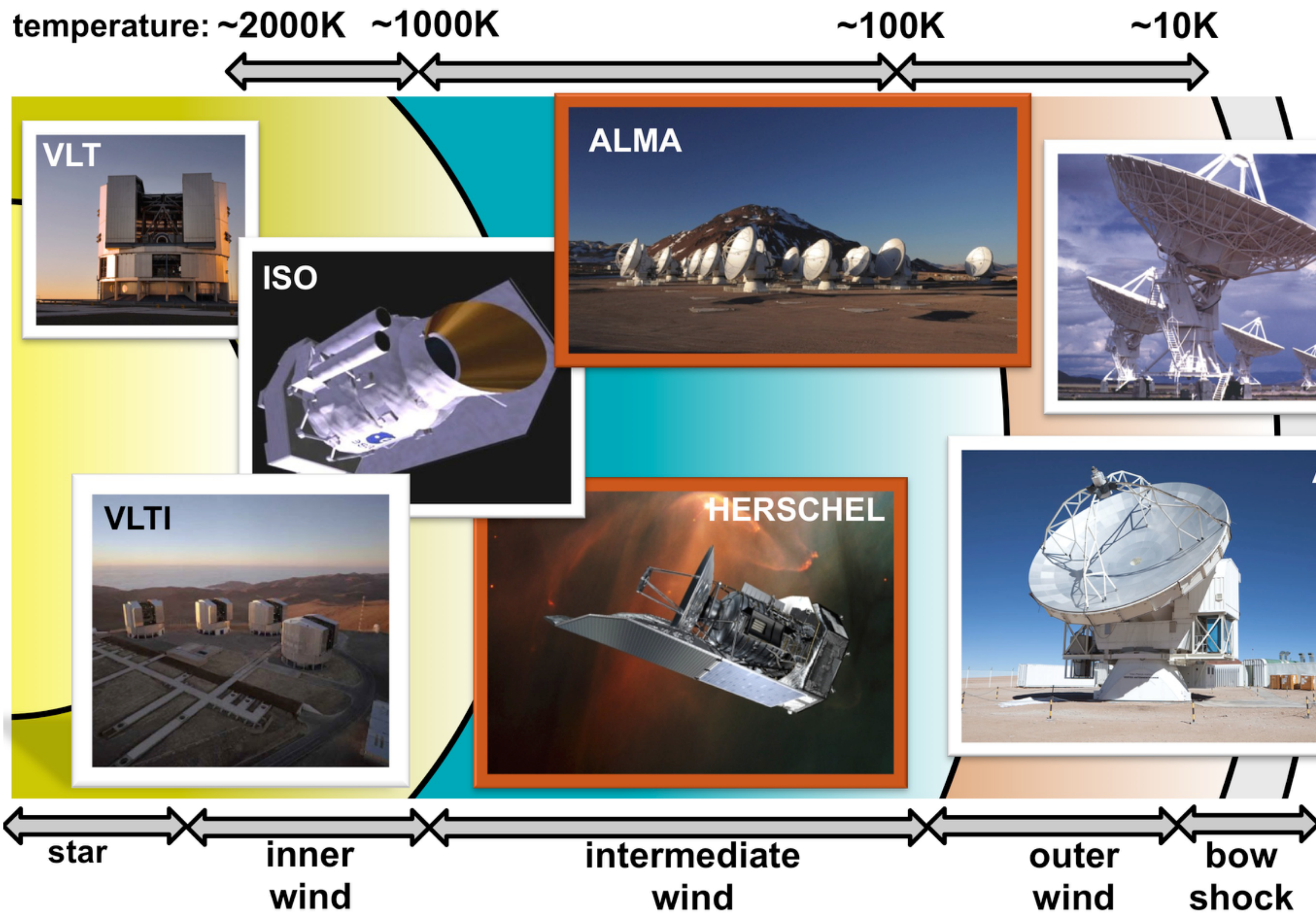
Goumans 2012, 2013

Cross-section



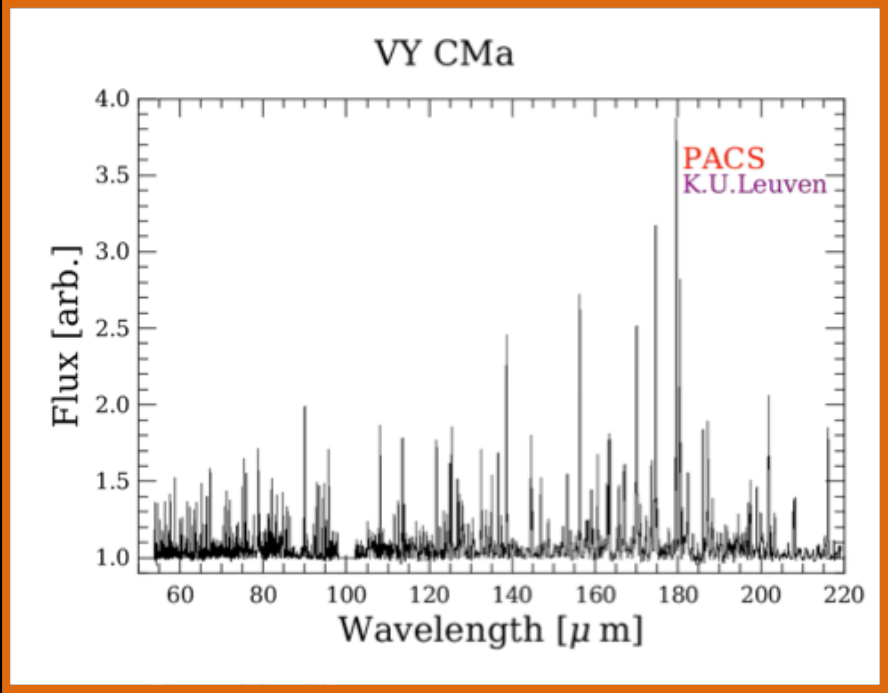
III. Corundum: conundrum

Crucial role of spectral information



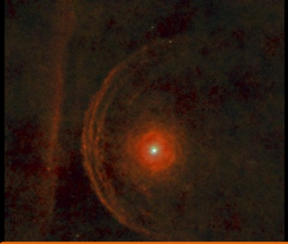
Crucial role of ALMA

→ 930 molecular line transitions: 2hr



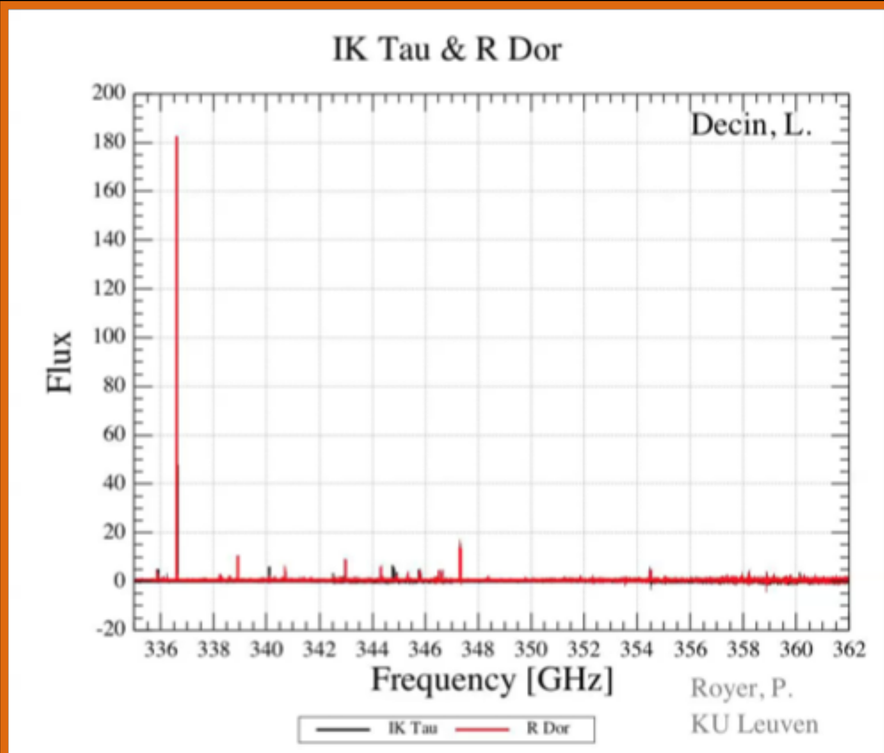
Royer 2010

>50 targets



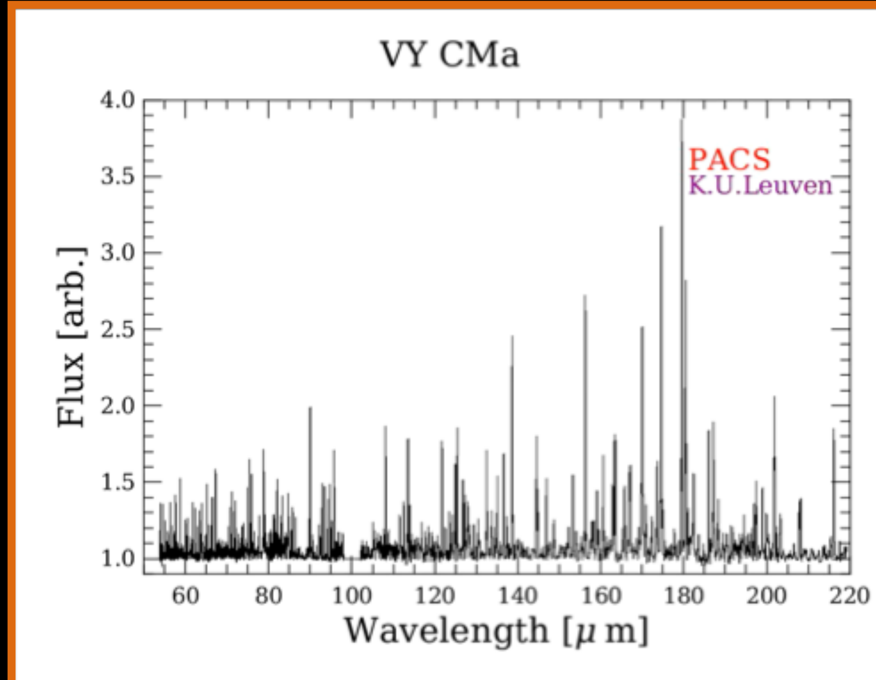
Crucial role of ALMA

→ 100s molecular line transitions: 2Tb
spectrally resolved + channel maps



27 GHz

→ 930 molecular line transitions: 2hr



Royer 2010

>50 targets

Crucial role of ALMA

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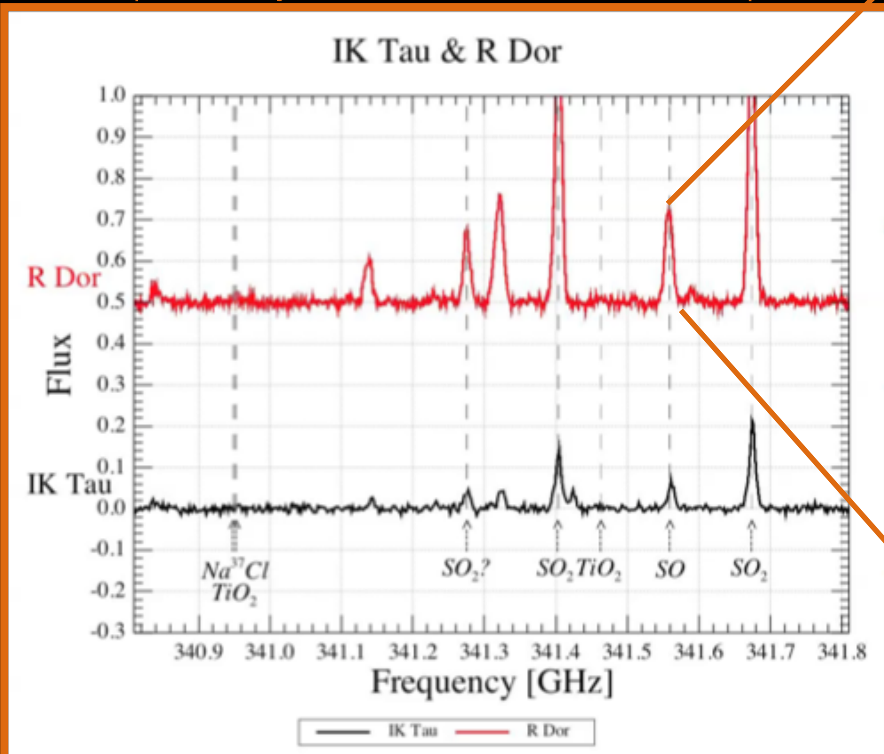
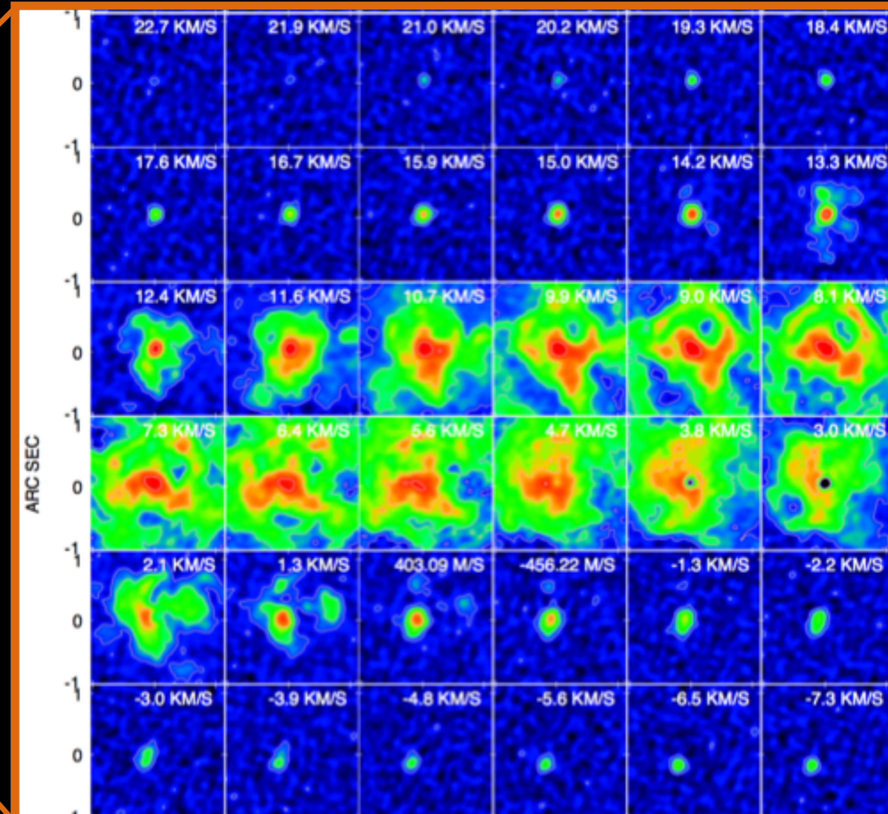


120 x 150 mas



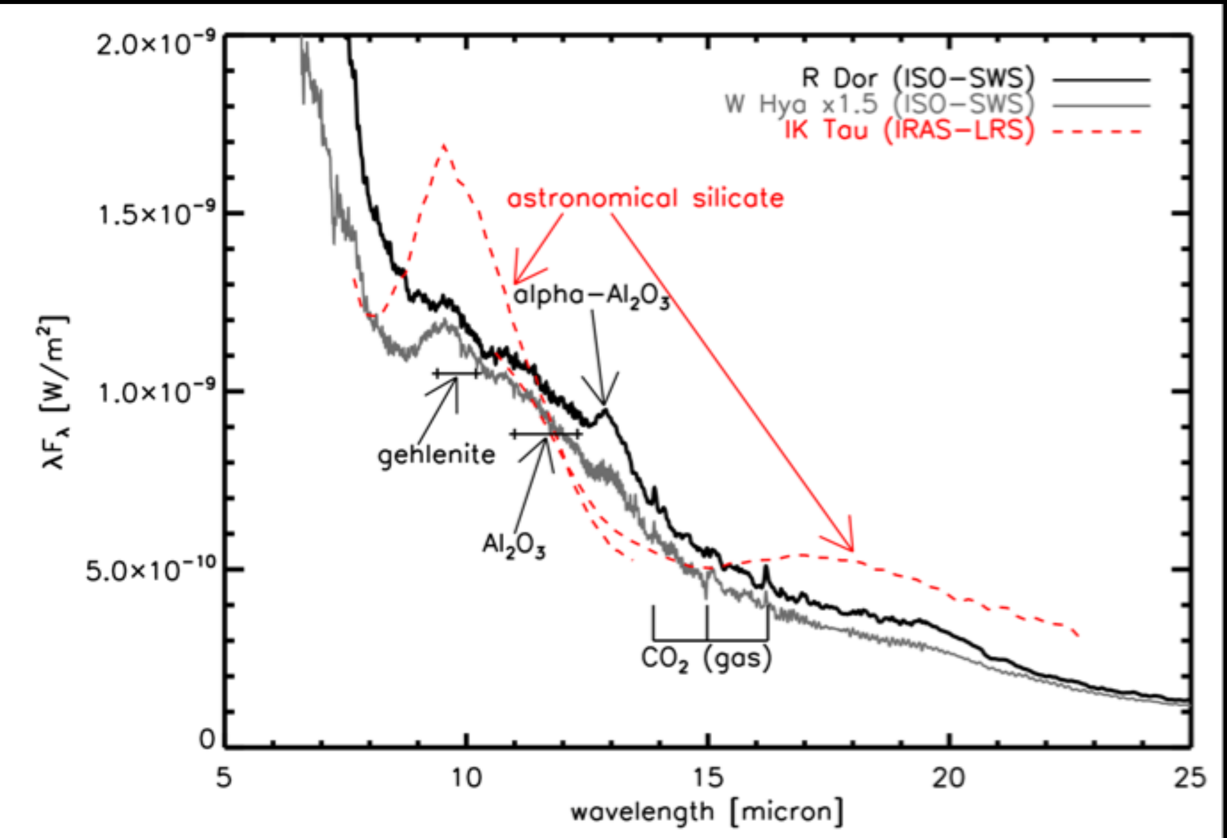
27 GHz

Decin 2017, 2018

Dust species

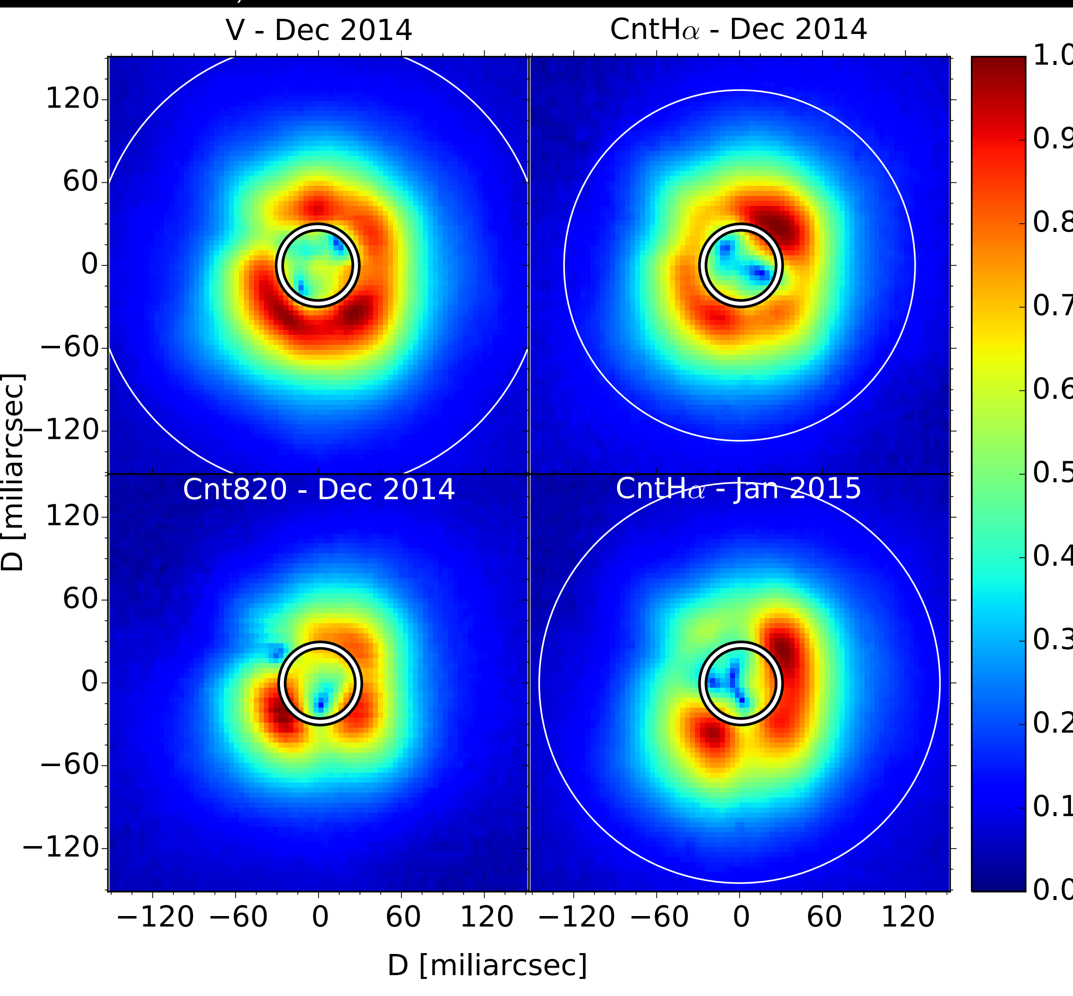
R Dor: $\dot{M}$ = 1 x 10^{-7} M_{sun}/yr → low $\dot{M}$ – corundum + amorphous Al_2O_3

IK Tau: $\dot{M}$ = 4.5 x 10^{-6} M_{sun}/yr → high $\dot{M}$ - silicates



Dust in R Dor

Norris 2012, Khouri 2016

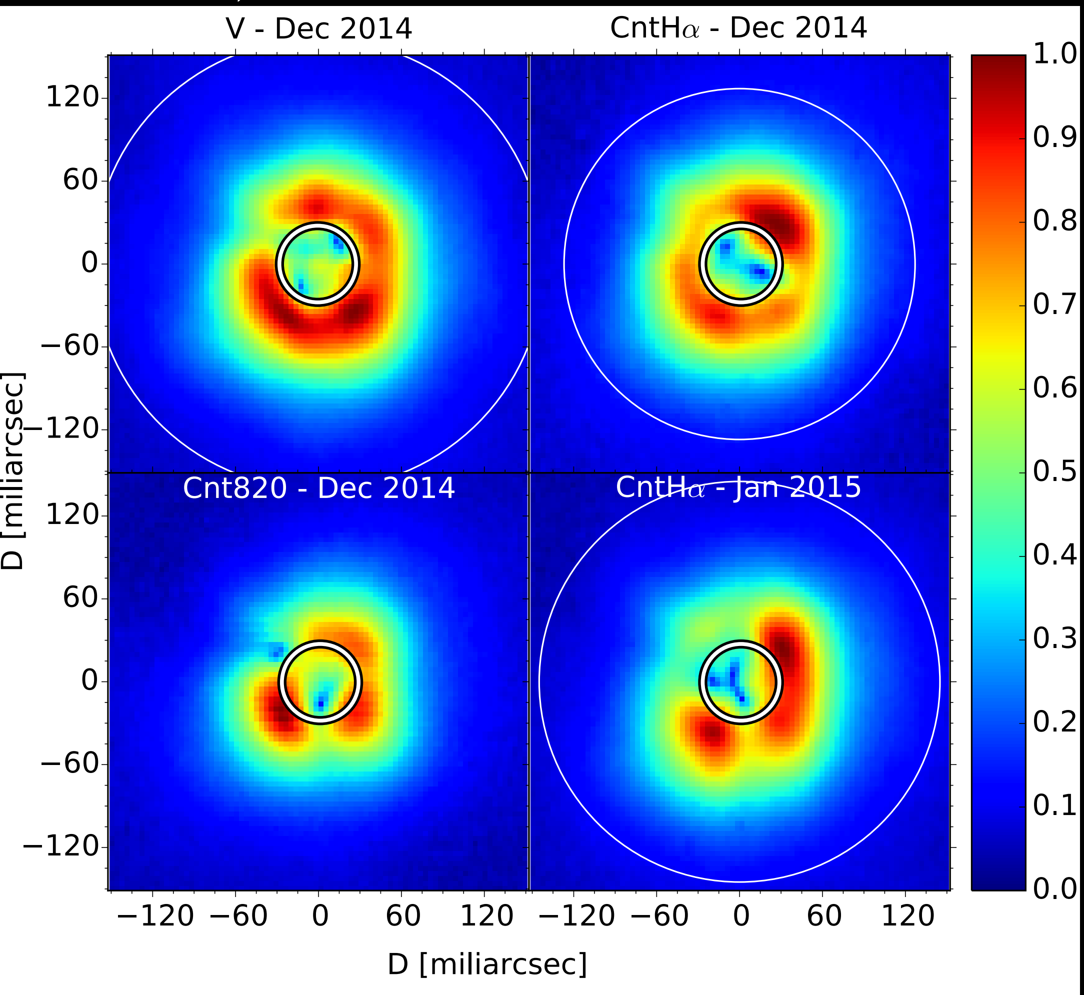


= stellar surface

→ Large (300 nm) grains at 0.5 R_*
→ Composition?:
Fe-free silicates or Al_2O_3

Dust in R Dor

Norris 2012, Khouri 2016



= stellar surface

→ Large (300 nm) grains at 0.5 R_*
→ Composition?:
Fe-free silicates or Al_2O_3

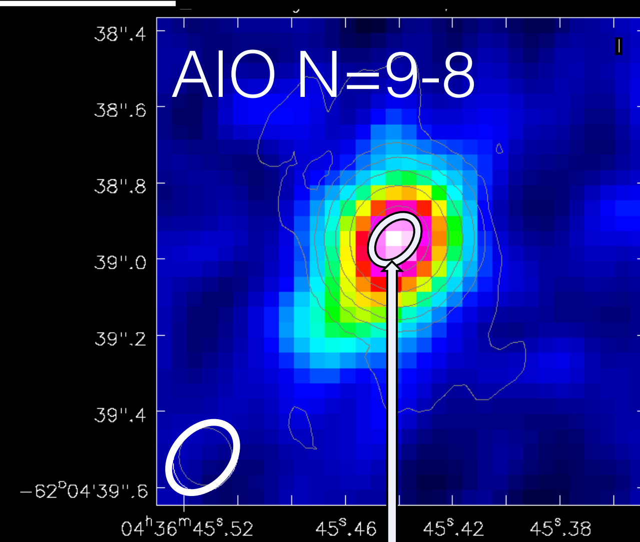
Al-bearing species

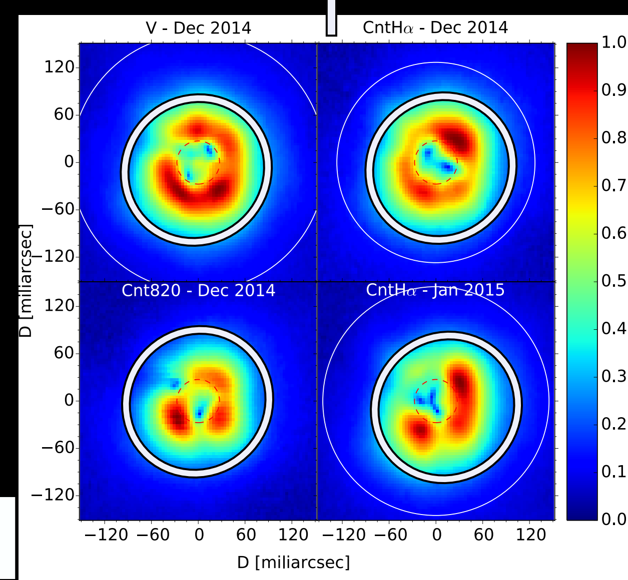
R Dor: $\dot{M} = 1 \times 10^{-7}\ M_{sun}/yr$

→ AlO, (AlOH), AlCl

IK Tau: $\dot{M} = 4.5 \times 10^{-6}\ M_{sun}/yr$

→ (AlO), AlOH, AlCl





dust grains

Fit model to data

NLTE radiative transfer

SE rate equations

$$\frac{\mathrm{d}n_i(\vec{r})}{\mathrm{d}t} = \sum_{j\neq i}^{N} n_j(\vec{r})P_{ji}(\vec{r}) - n_i(\vec{r})\sum_{j\neq i}^{N} P_{ij}(\vec{r}) = 0,$$

Rates per particle

$$P_{ij} = R_{ij} + C_{ij}.$$

Bound-bound radiative

$$R_{ij} = A_{ij} + B_{ij}\overline{J}_{\nu_0}.$$

Radiative transfer

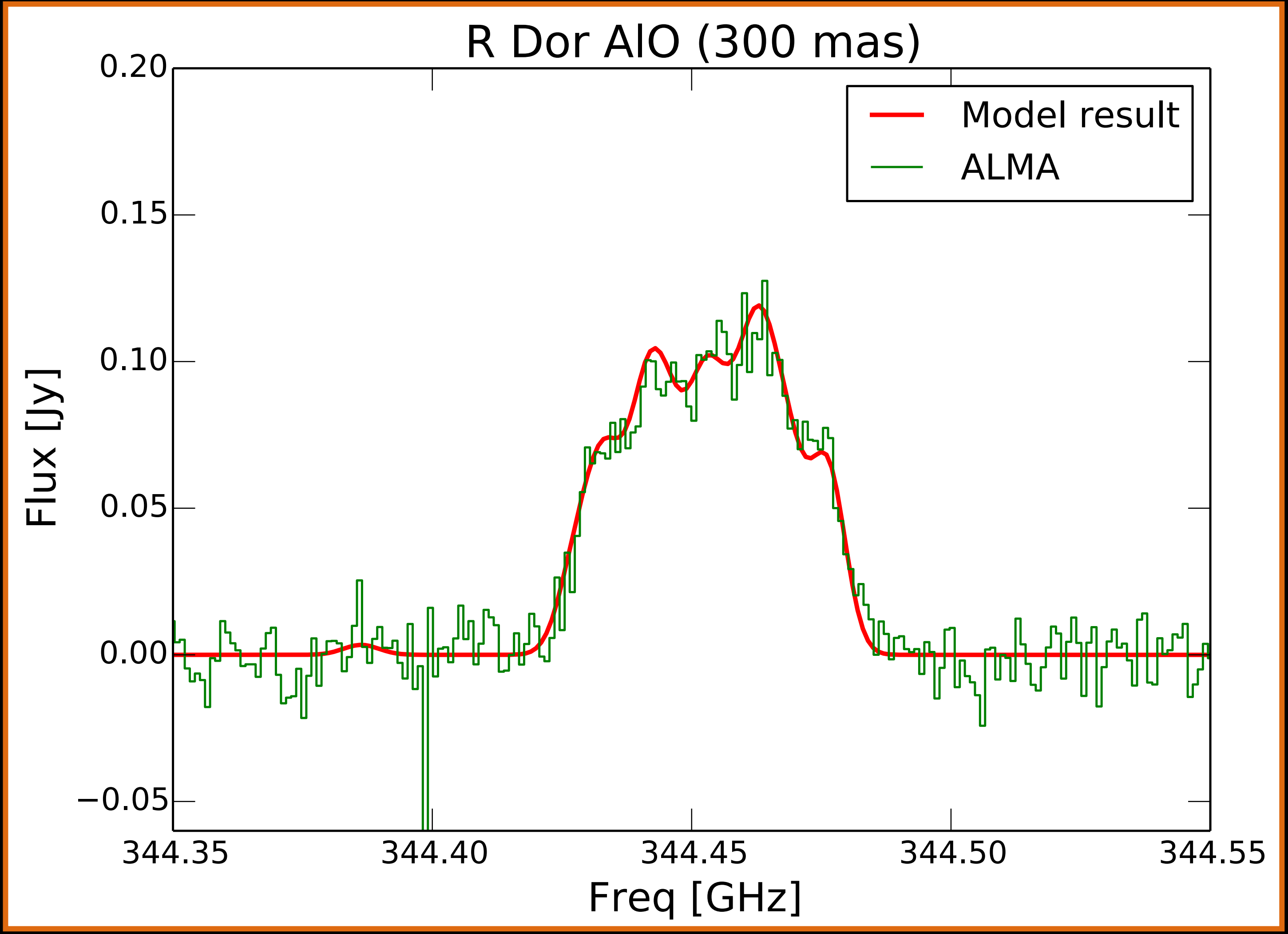
$$\mu\,\frac{\mathrm{d}I_\nu(\vec{r},\mu)}{\mathrm{d}\tau_\nu(\vec{r})} = -S_\nu(\vec{r}) + I_\nu(\vec{r},\mu)$$

+

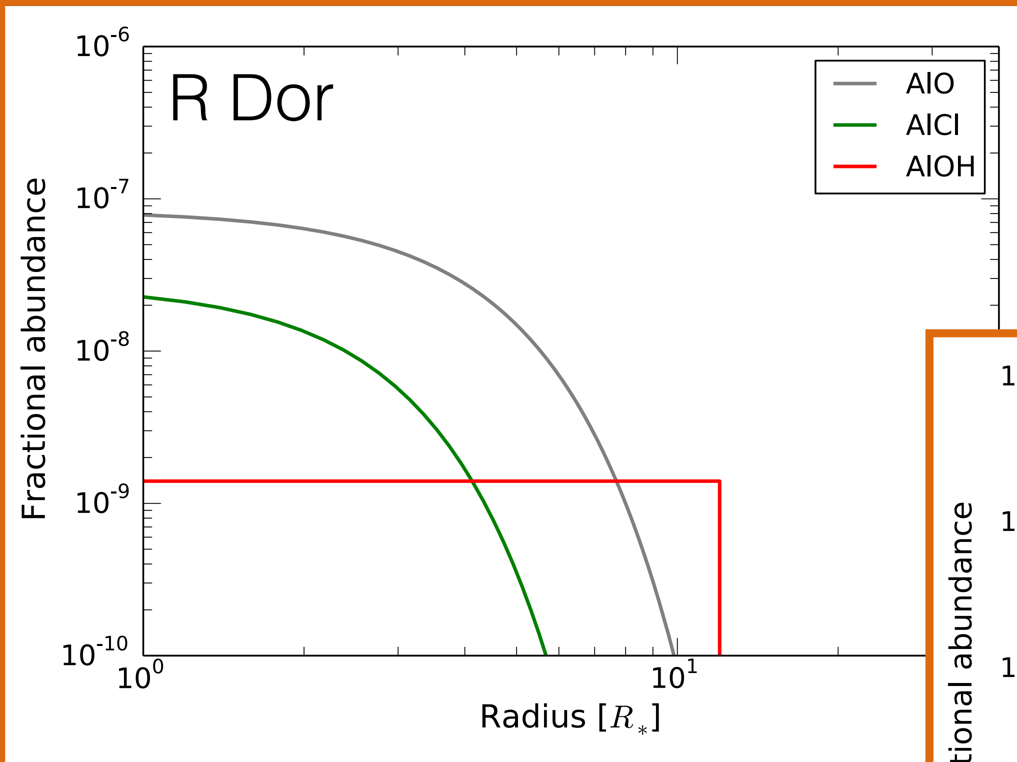
conservation of

- mass
- energy
- momentum

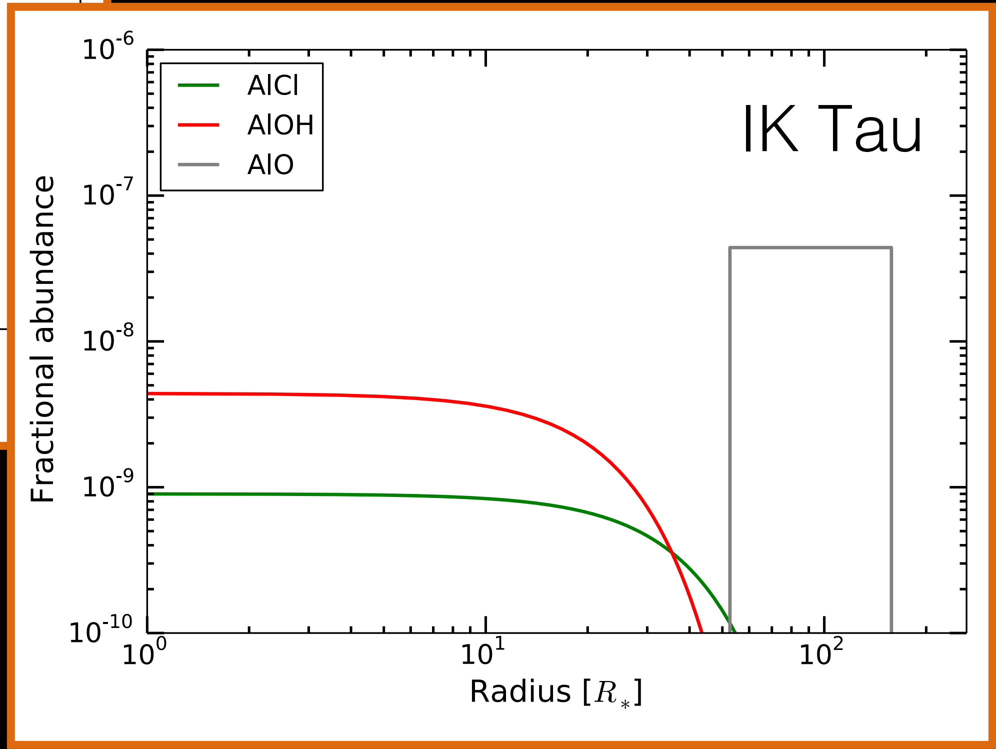
Fit model to ALMA data



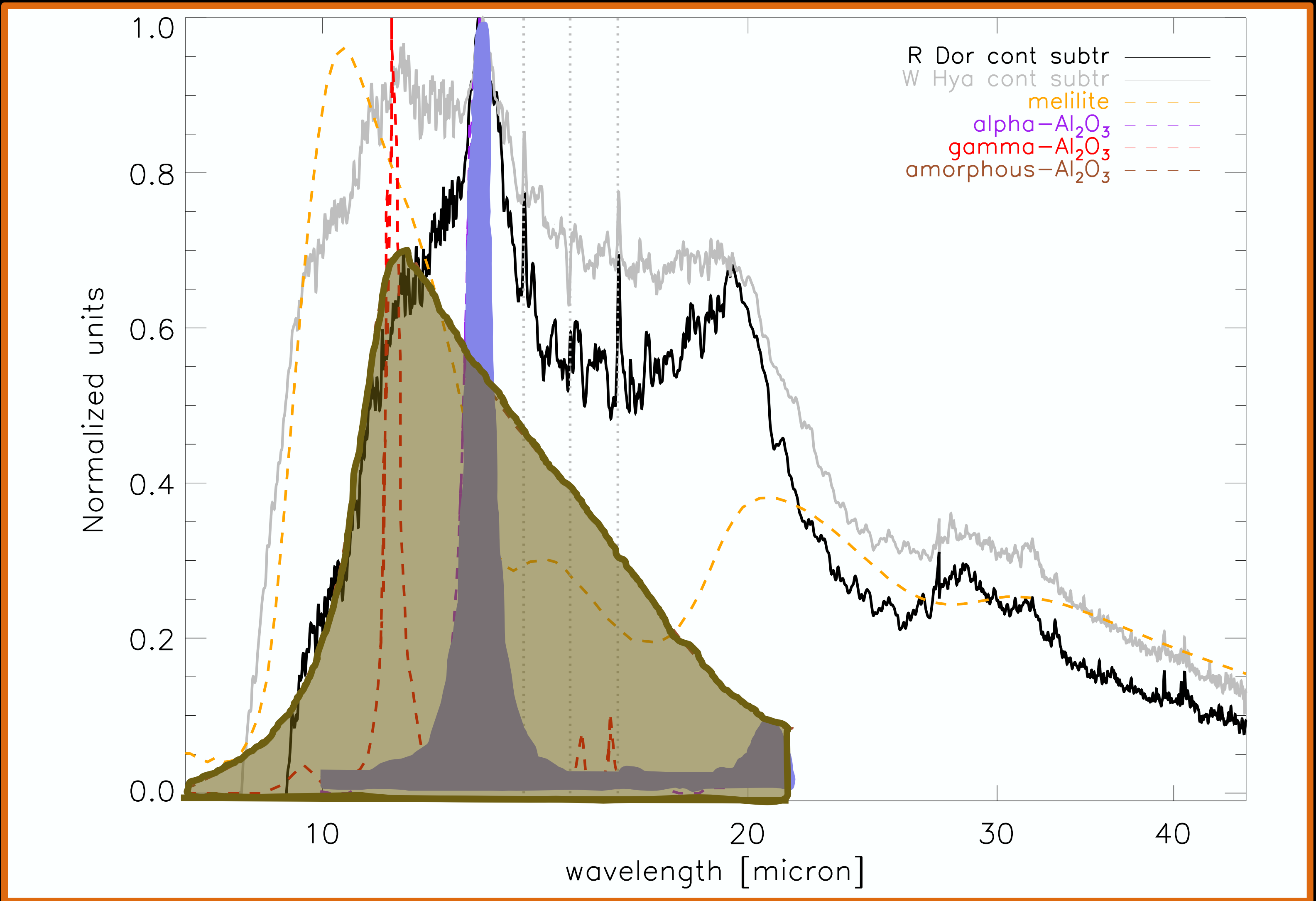
Al-bearing molecules



$\lesssim$2% Al

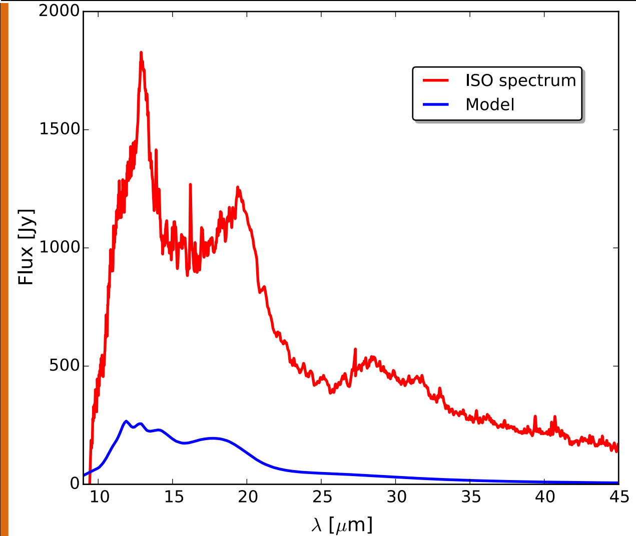


Al_2O_3 dust in R Dor

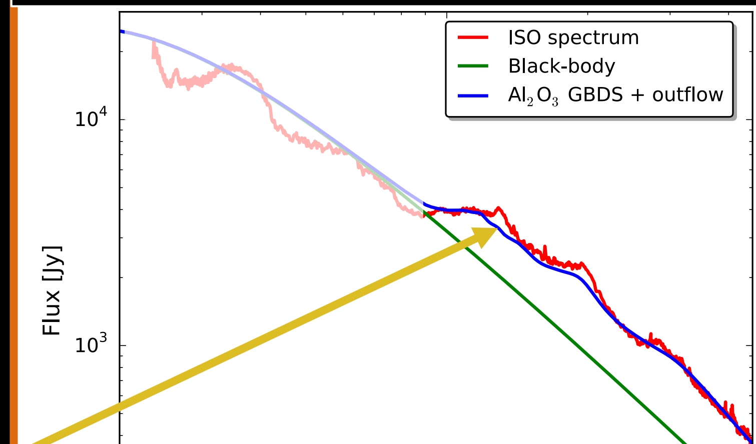


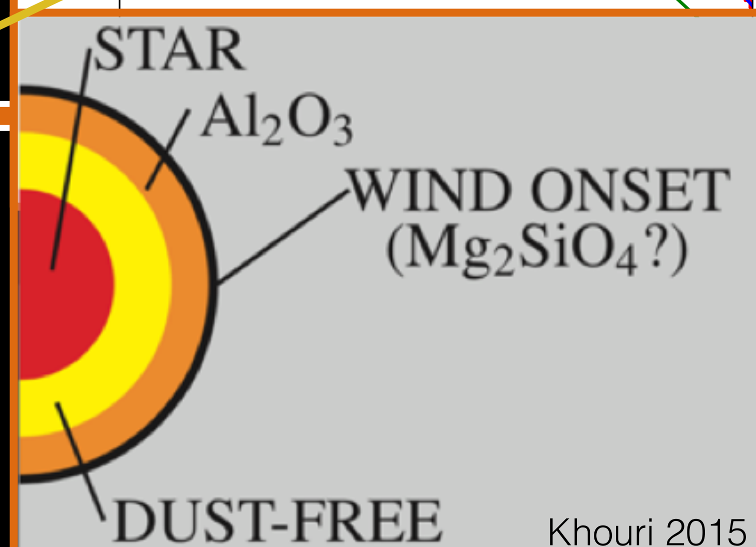
Al_2O_3 dust in R Dor

Al_2O_3 emission from outflow



Al_2O_3 emission from GBDS+outflow



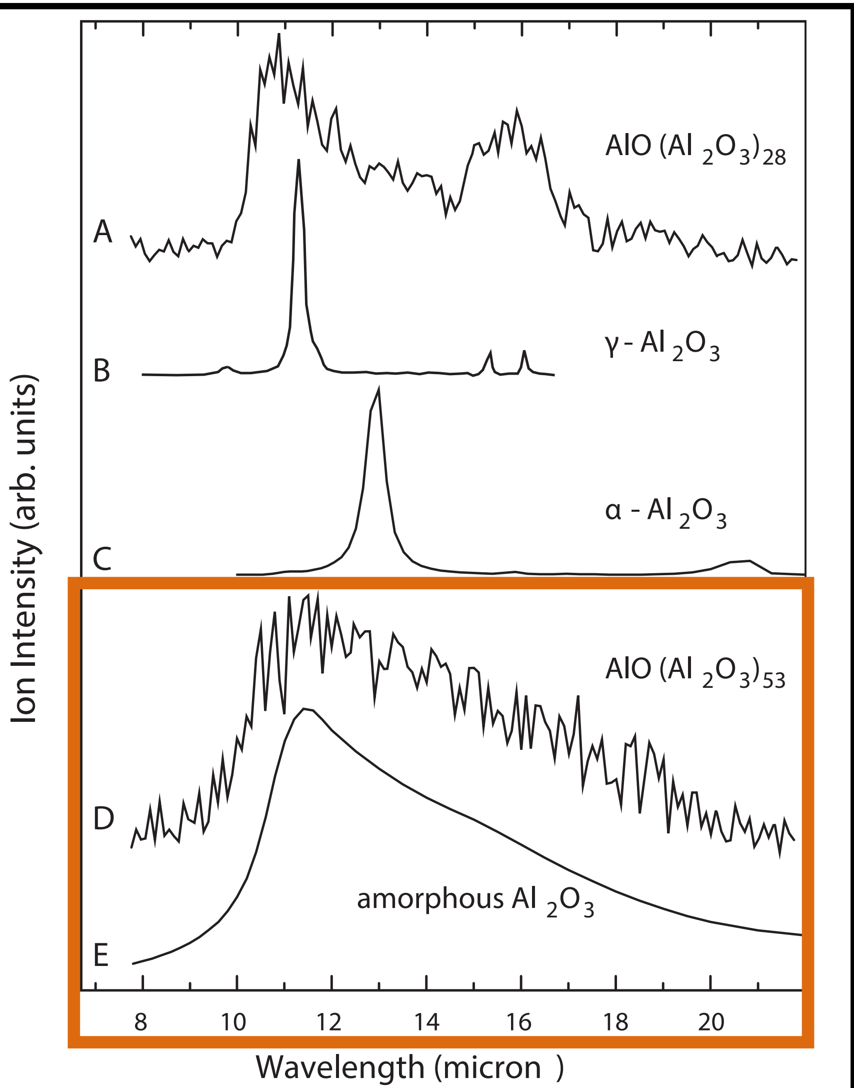


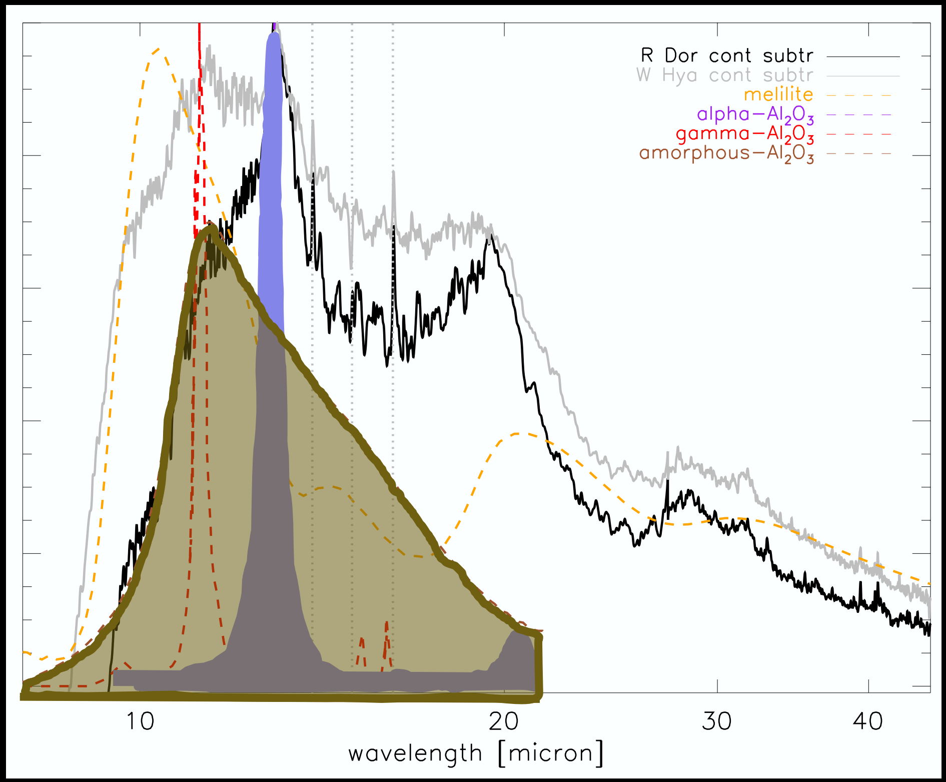
$T(Al_2O_3)$ ~1200 – 1600K

crystalline!

11 micron feature?

Postulate: Large aluminium clusters: $(Al_2O_3)_n$ ($n \geq 34$)





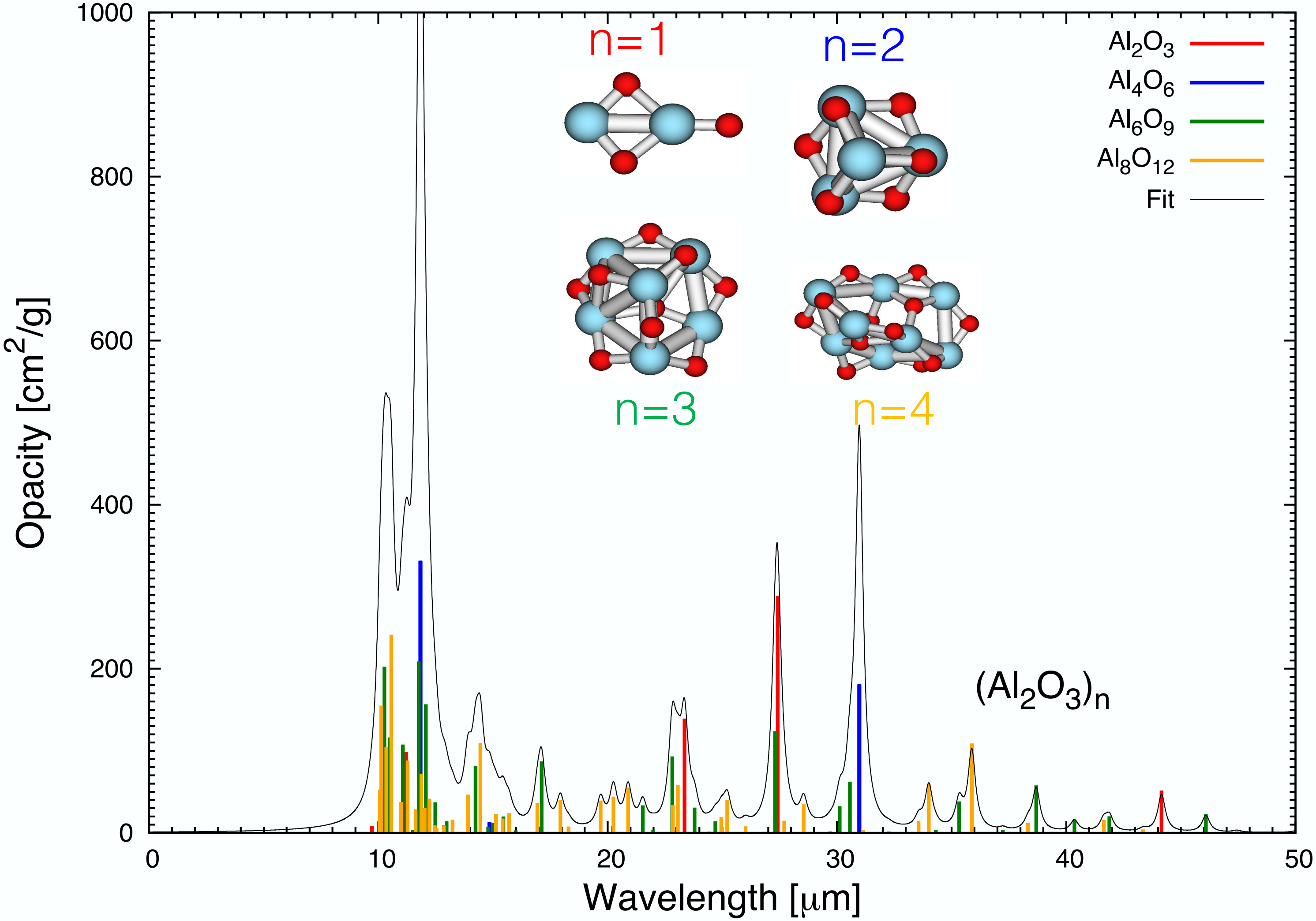
van Heijnsbergen 2003, Demyk 2004

Very small $(Al_2O_3)_n$ ($n \leq 4$) clusters?

DFT - Gaussian09

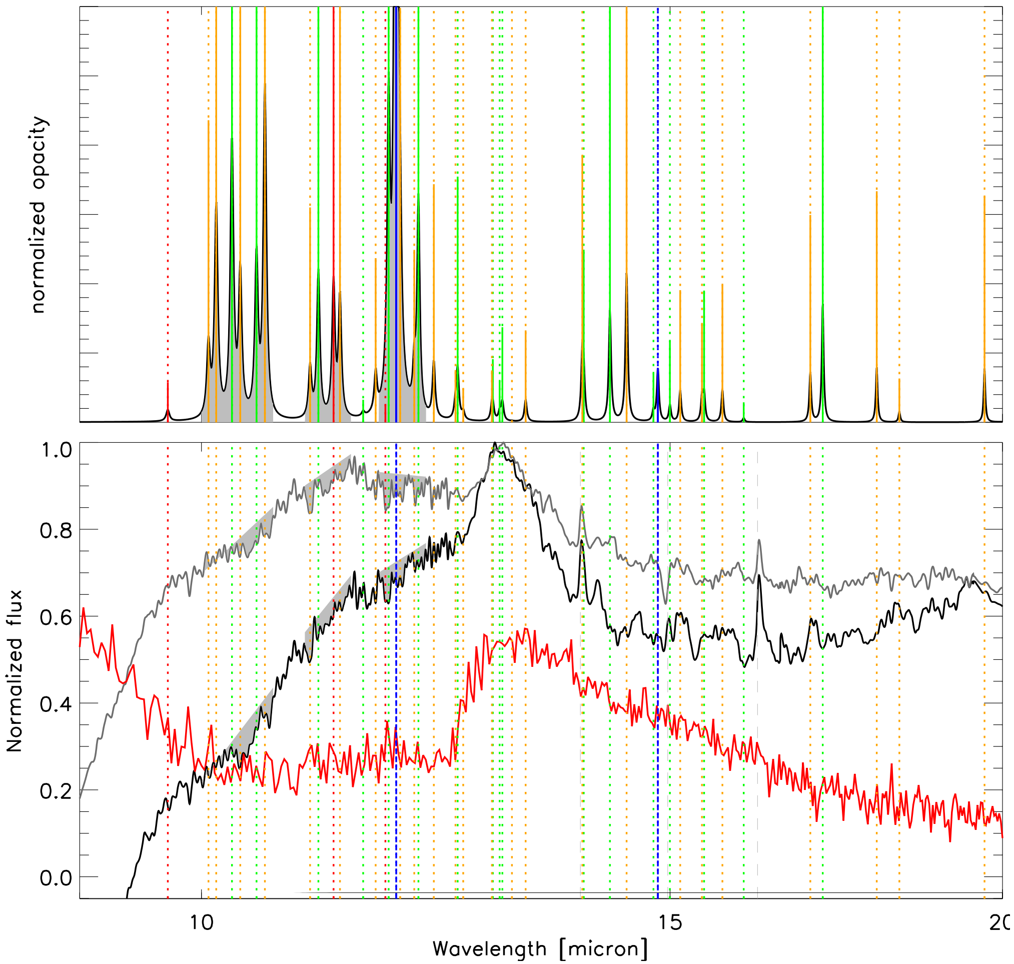
most stable clusters

p=0.001-50 Pa
T=500-3000K



Gobrecht

Very small $(Al_2O_3)_n$ ($n \leq 4$) clusters?

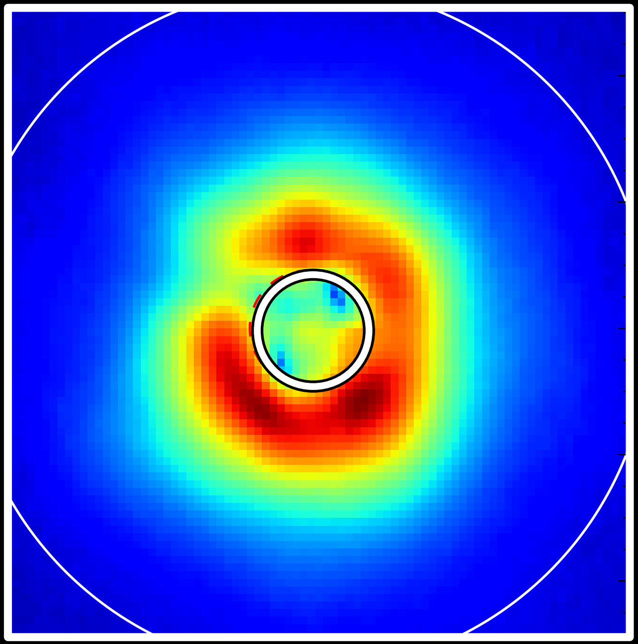


correlation, but !?

need ELT/METIS!

Conundrum …

Norris 2012, Khouri 2016



○ = stellar surface

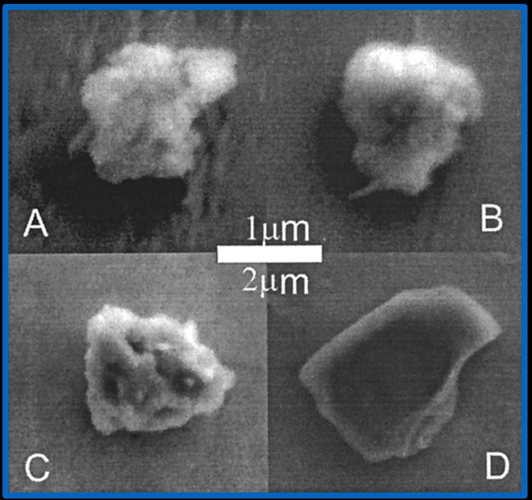
?

- → Large (300 nm) grains at 0.5 R_*
- → Composition: Fe-free silicates or $\boldsymbol{\alpha}$-Al_2O_3?
- → First condensation seed?

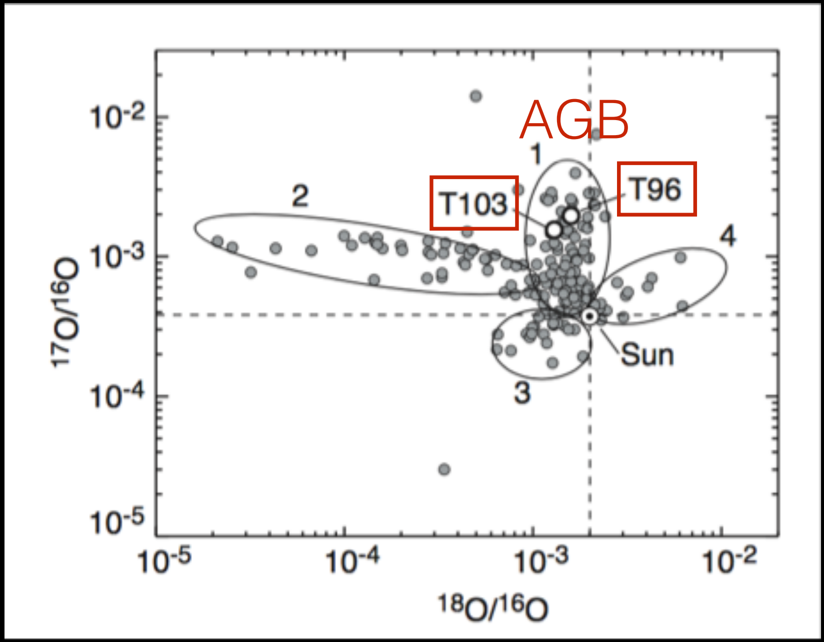
Conundrum …

Back on
Planet Earth

Back on Planet Earth



Stroud 2004



Grain T103

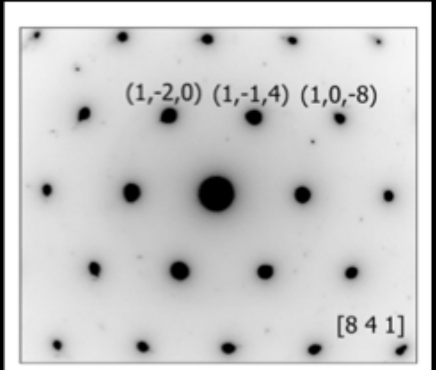


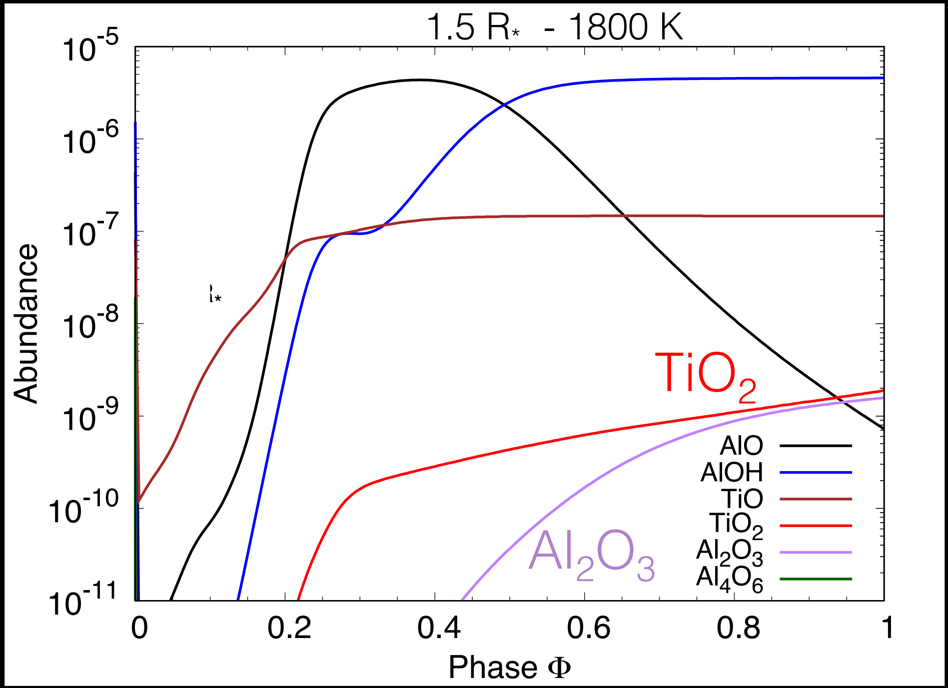
Fig. 2. Electron diffraction pattern from T103 indexed to the corundum structure.

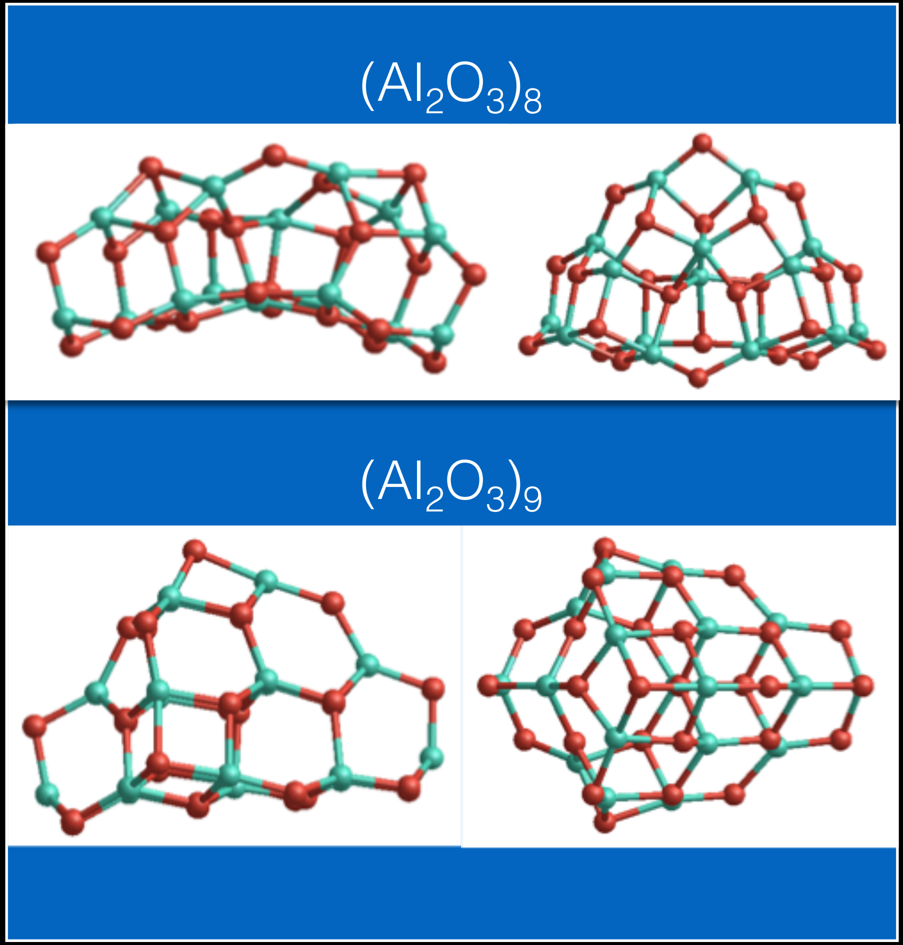
Grain T96: amorphous - no (<0.05 weight %) Ti
Grain T103: corundum (α-Al_2O_3) + 0.1 weight % Ti

+ lack of subgrains in T103 & T96 → Al_2O_3 is first solid to condense (not TiO_2!)
(1wt% Ti → 60 nm TiO2 → not detected; Ti to stabilize corundum)

Al_2O_3- conundrum

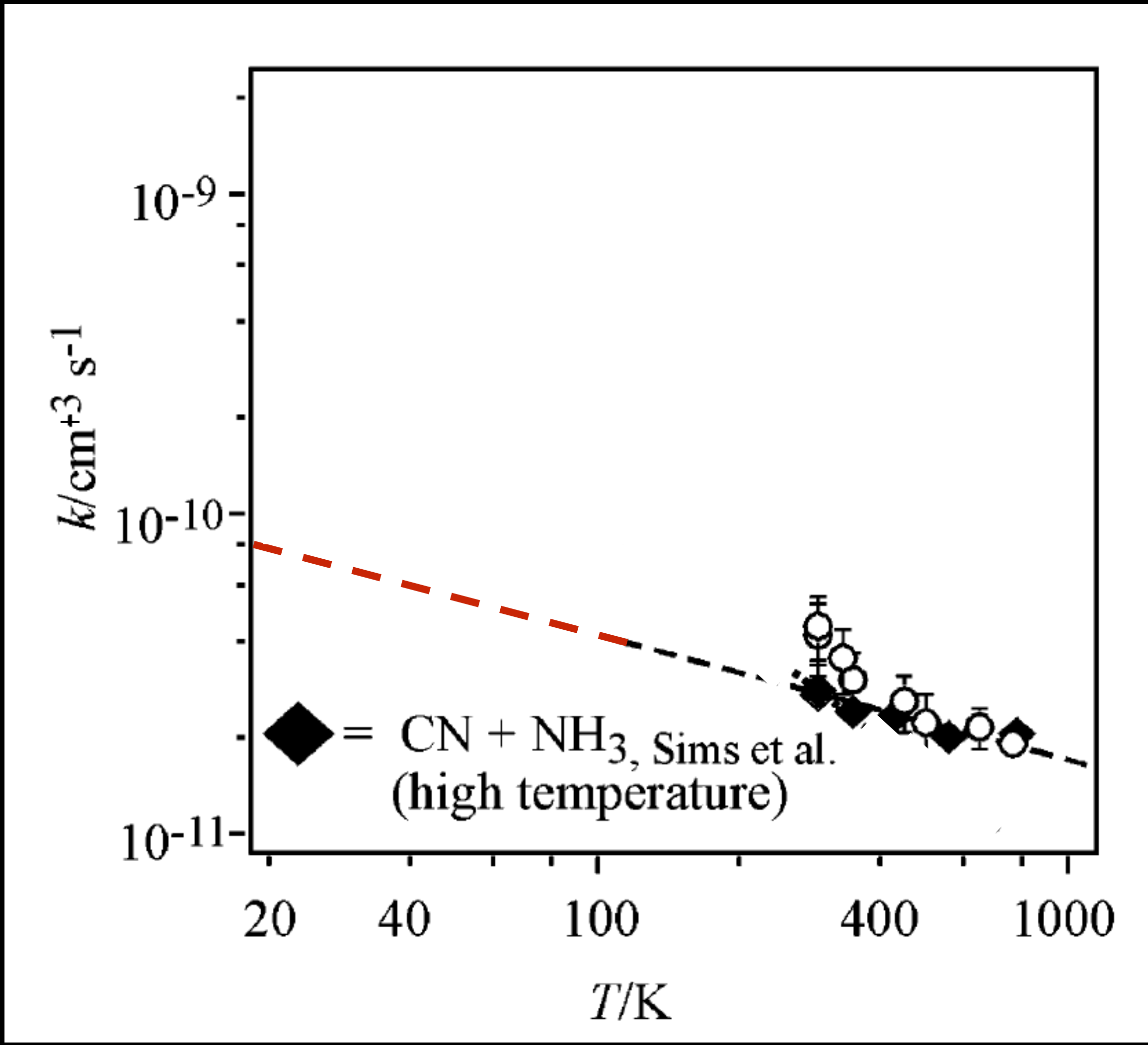
Pulsation-induced shock
non-equilibrium chemistry





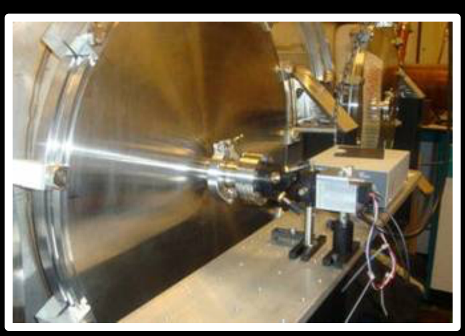
Gobrecht, in prep.

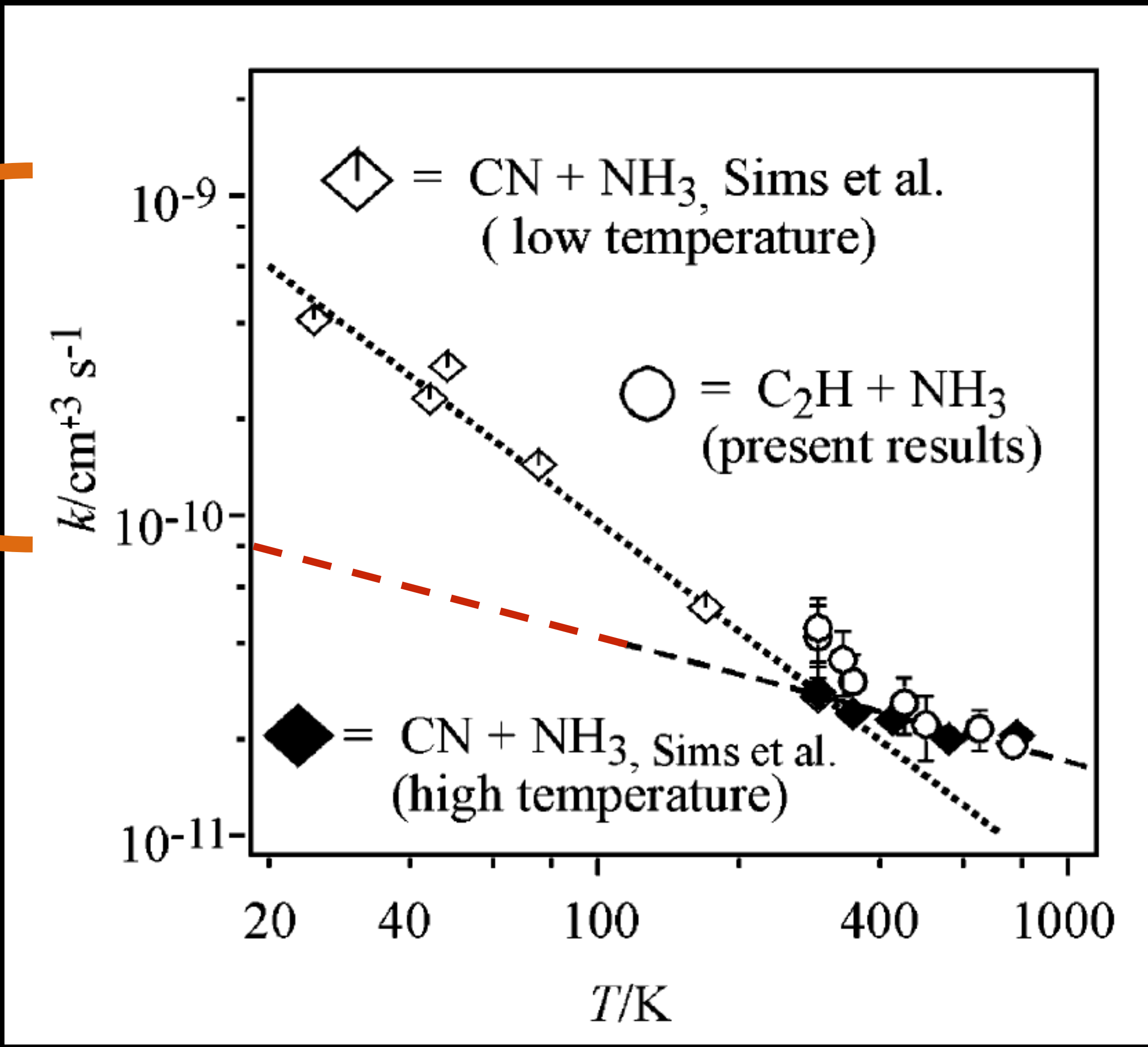
Laboratory experiments



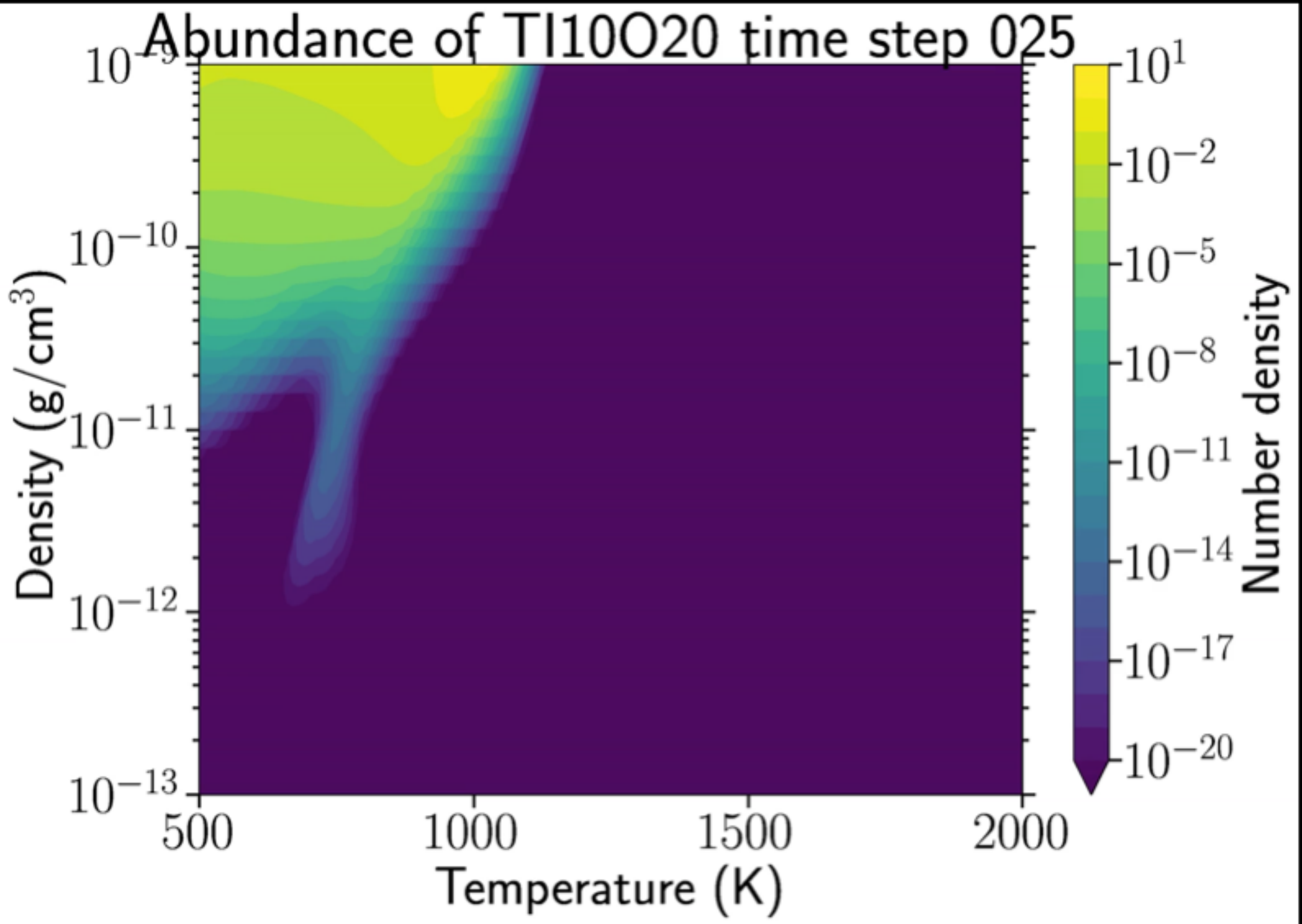
Laboratory experiments

factor ~10 difference





Soon to come…

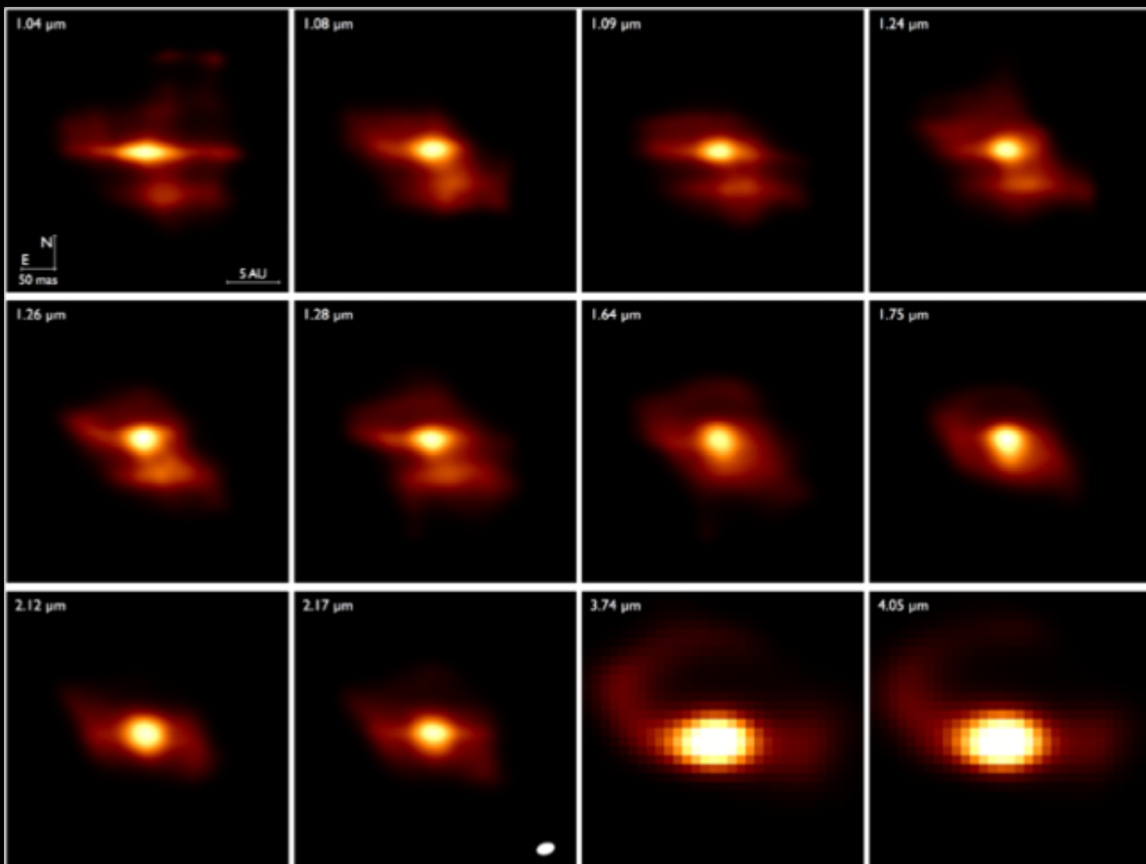


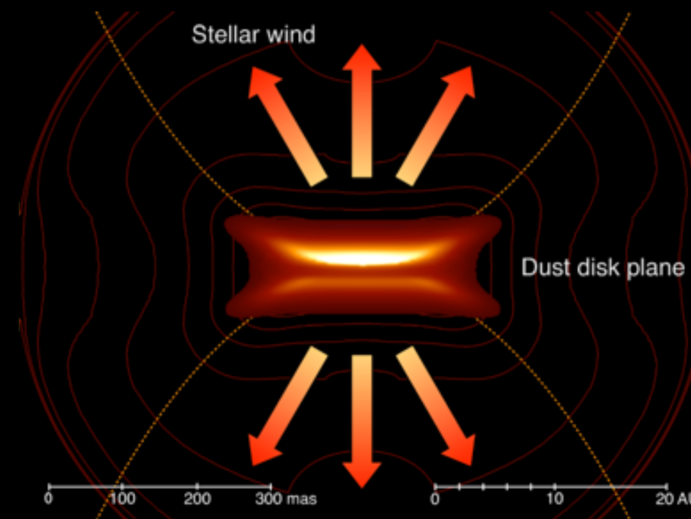
Boulangier et al.
in prep.

IV. What about exoplanets

L_2 Pup

VLT/NACO: 1 – 4 µm: edge-on dust disk, at i~84°

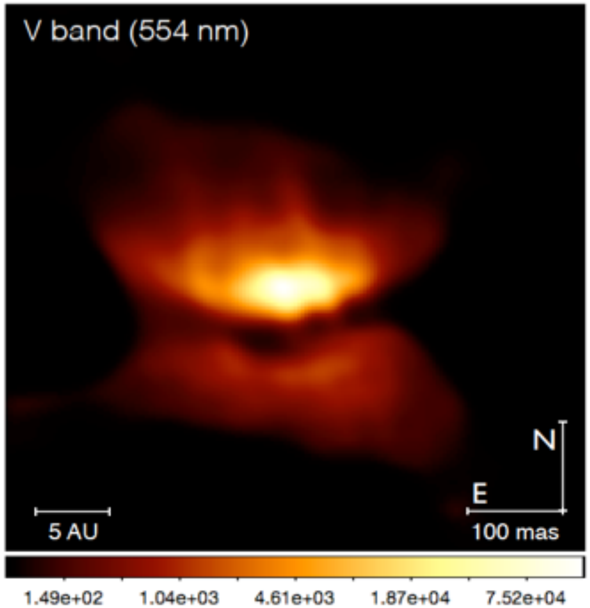


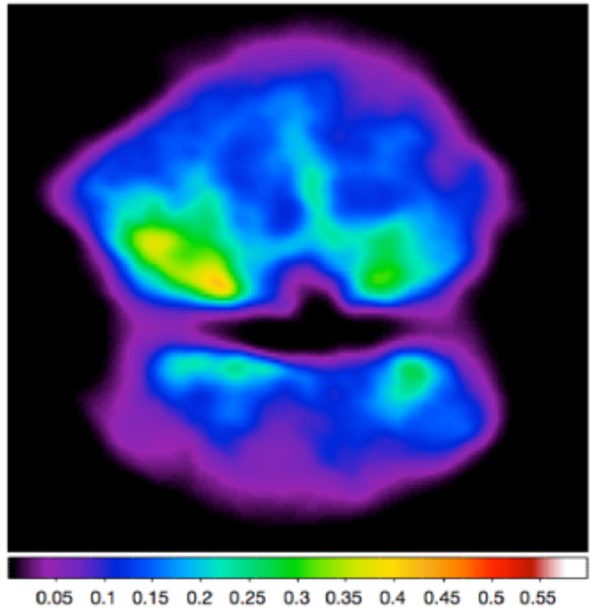


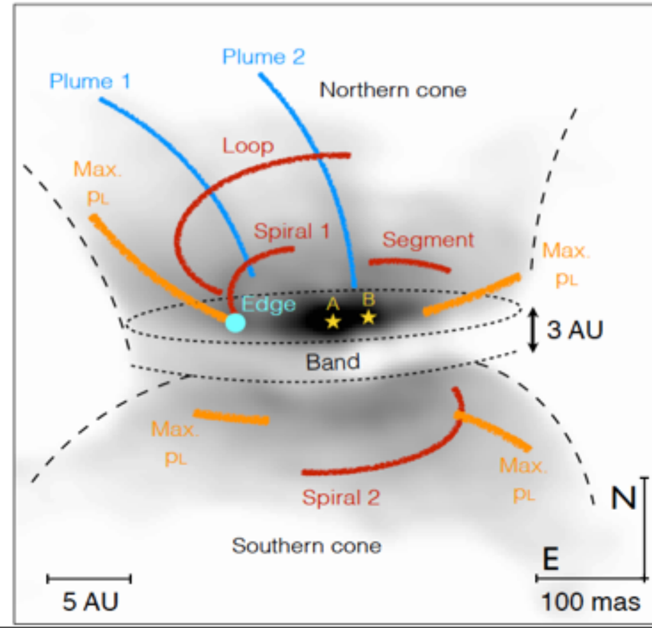
Kervella et al. 2014

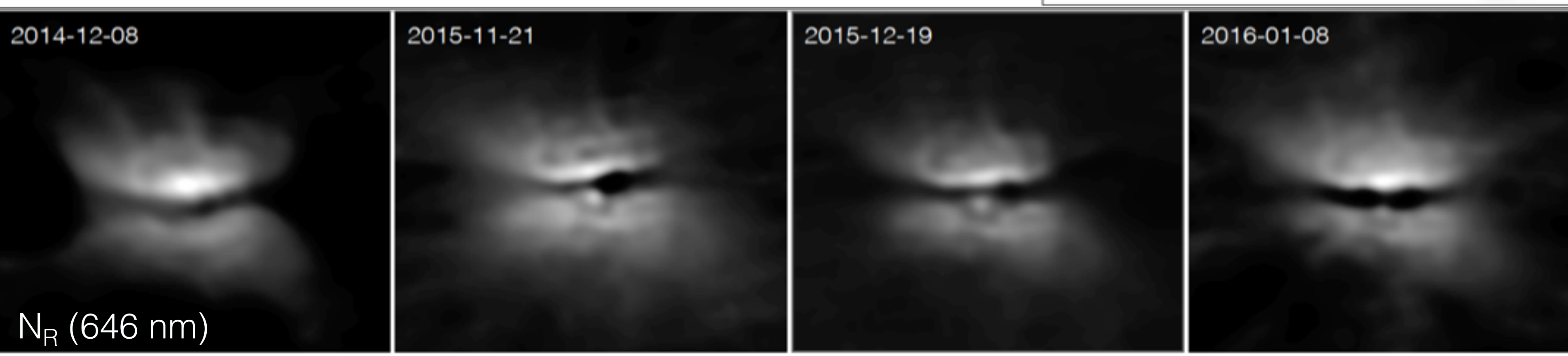
L_2 Pup

Kervella et al. 2015: SPHERE

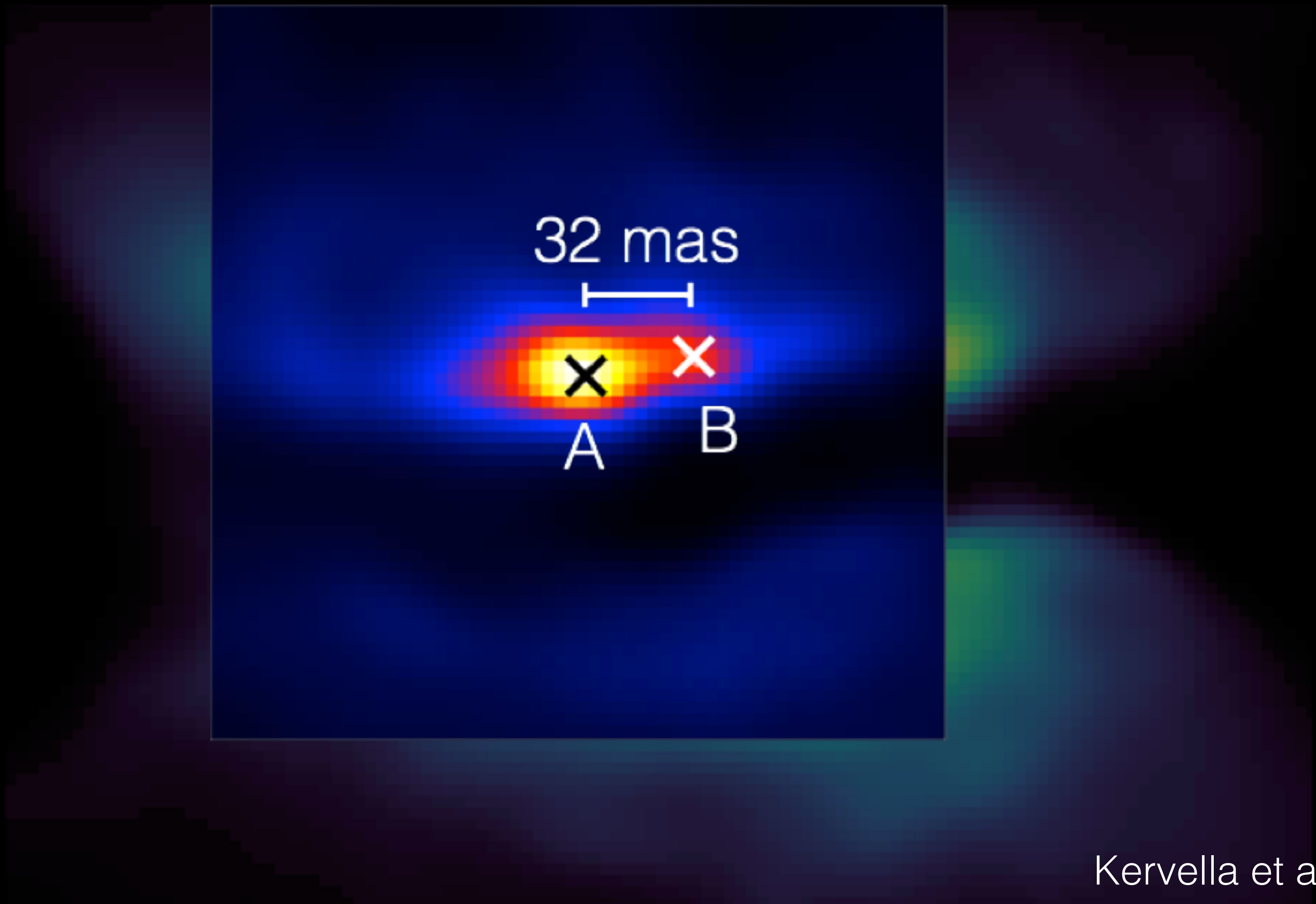








L_2 Pup

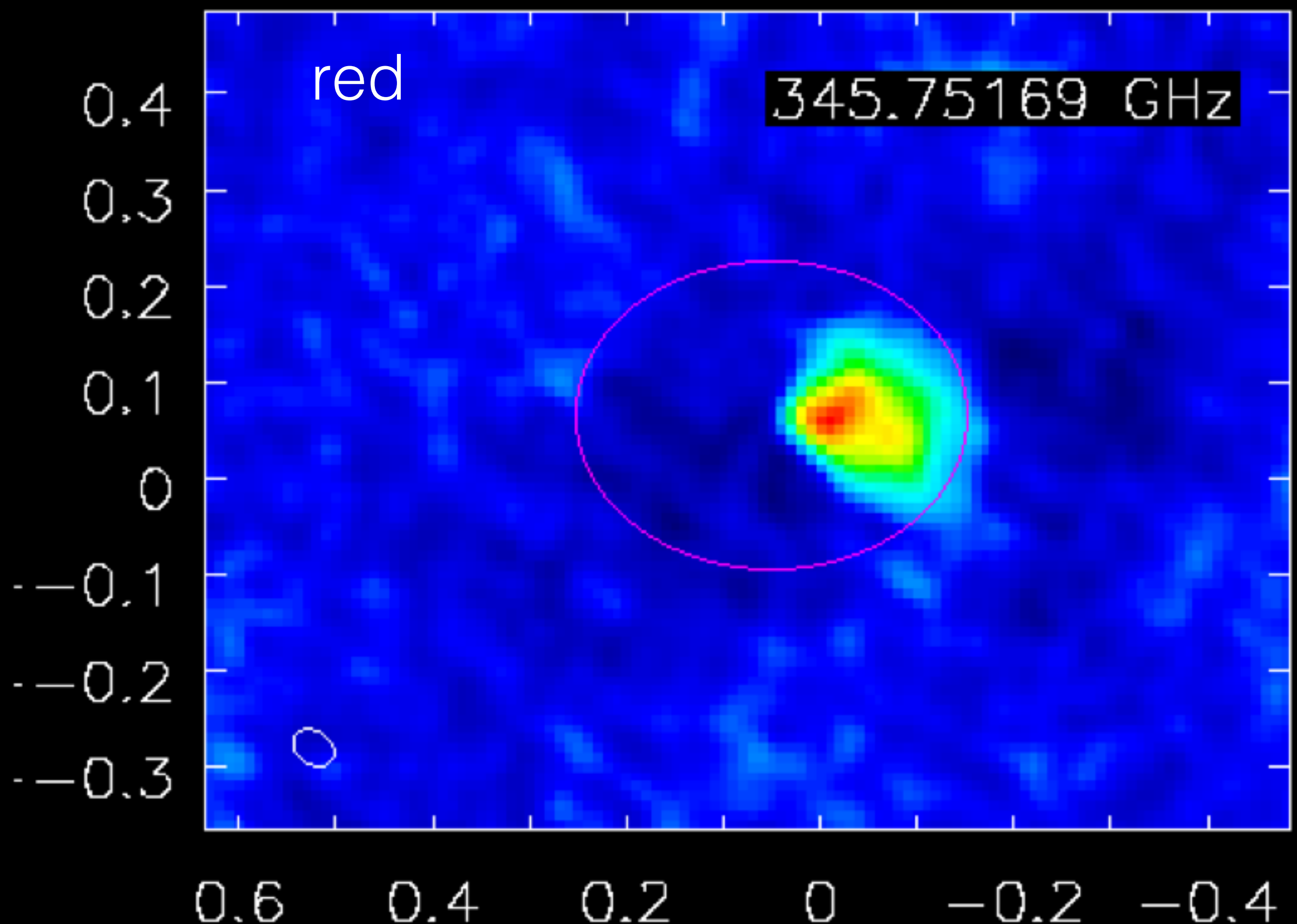


Kervella et al. 2015

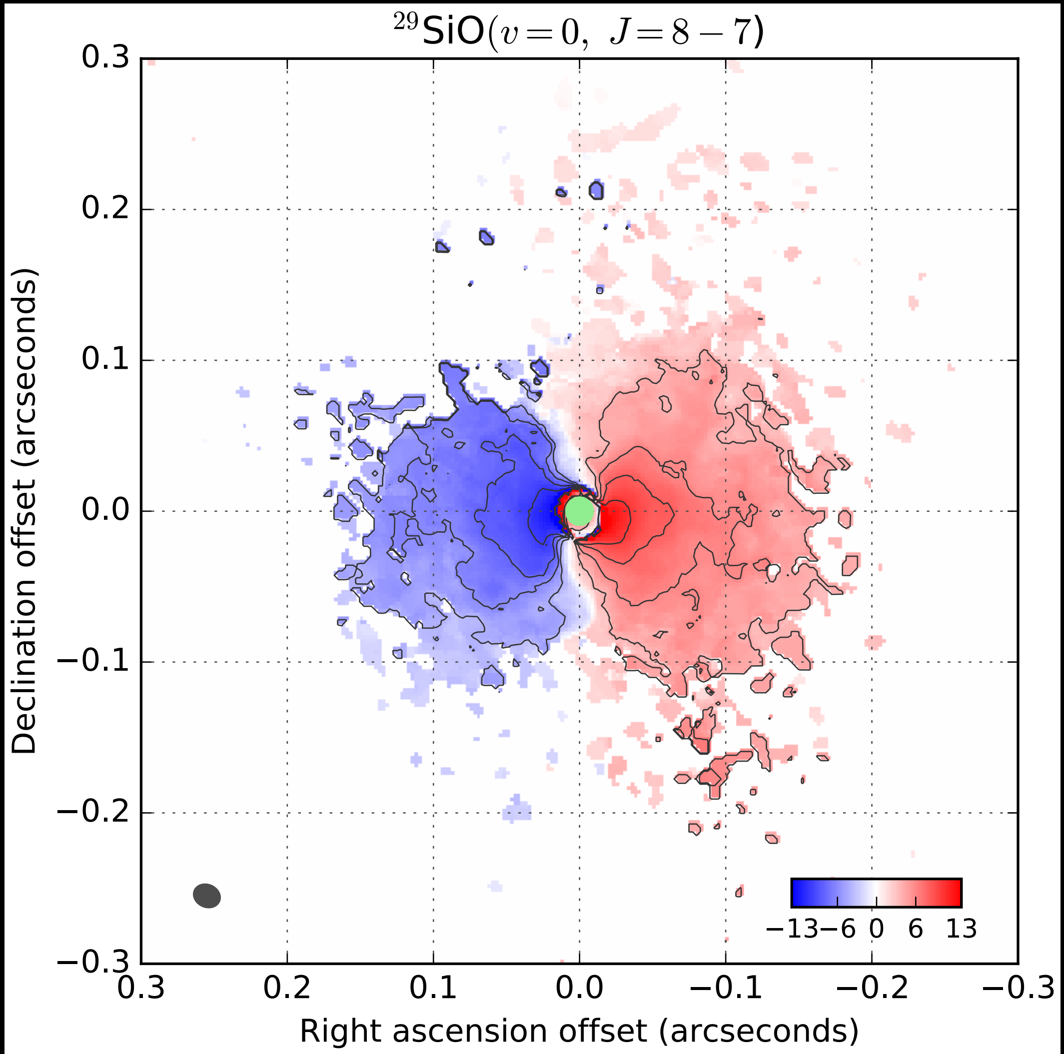
L_2 Pup

- Cycle 3, extended configuration (16 km)
- Band 7, CO J=3-2 emission (345.8 GHz)
- Maximum angular resolution 0.015”

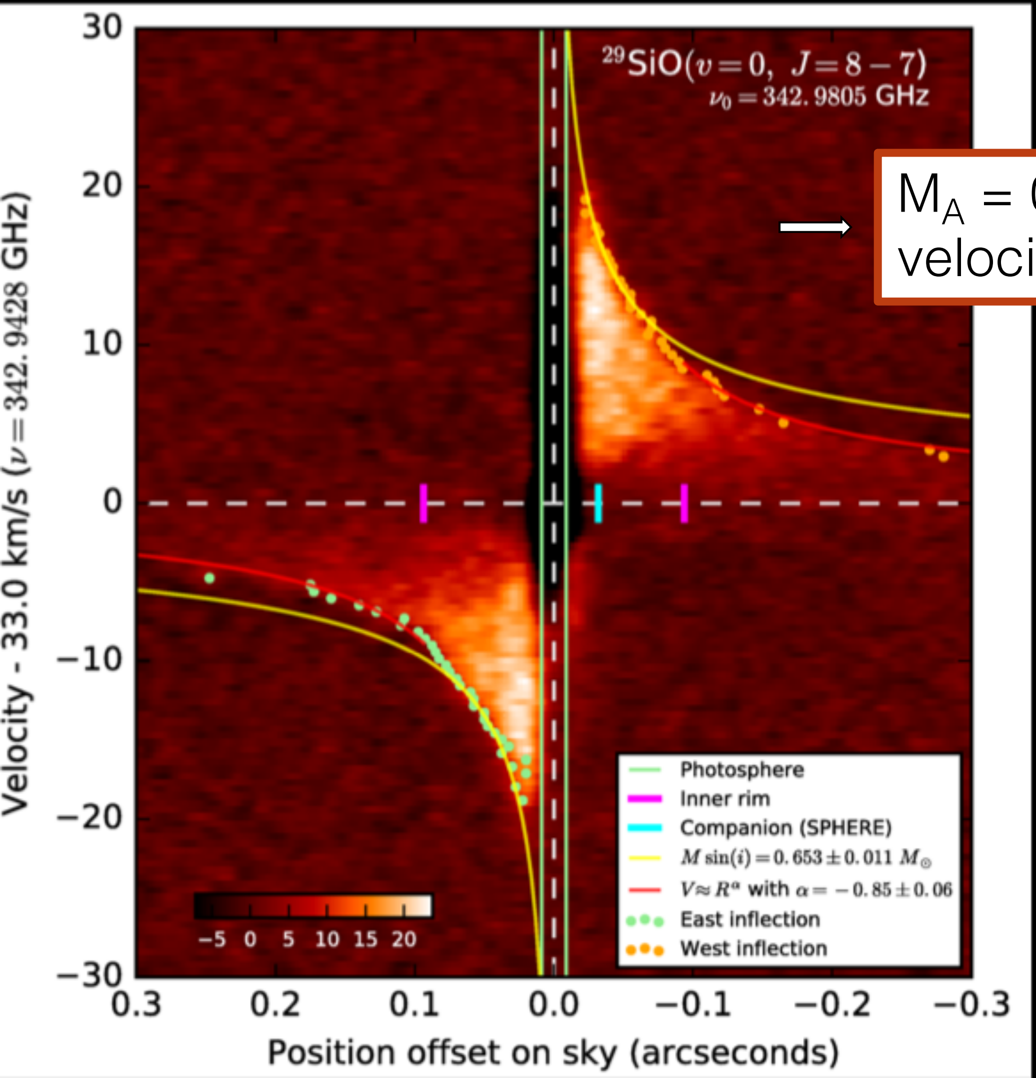
L_2 Pup



L_2 Pup


^{29}SiO$(v=0,\ J=8-7)$
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
Declination offset (arcseconds)
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
Right ascension offset (arcseconds)
−13
−6
0
6
13

L_2 Pup



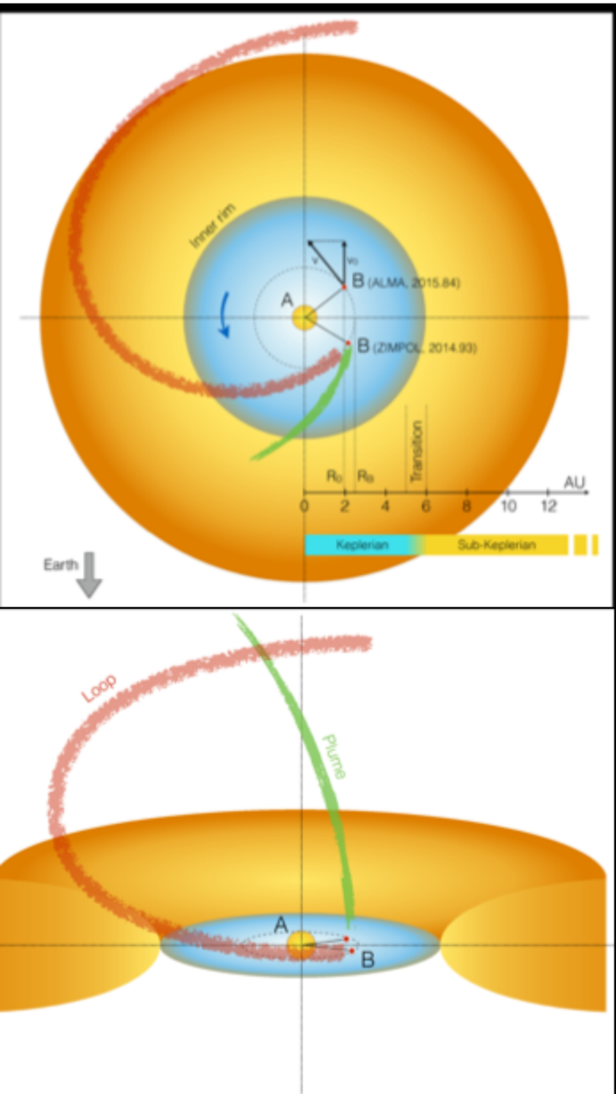
M_A = 0.659± 0.011± 0.041 $M_\odot$
velocity: Keplerian → sub-Keplerian

M_B=12 ± 16 M_{Jup}

M_{disc}~0.01 M_{sun}

Kervella et al. 2016
Homan et al. 2017

L_2 Pup



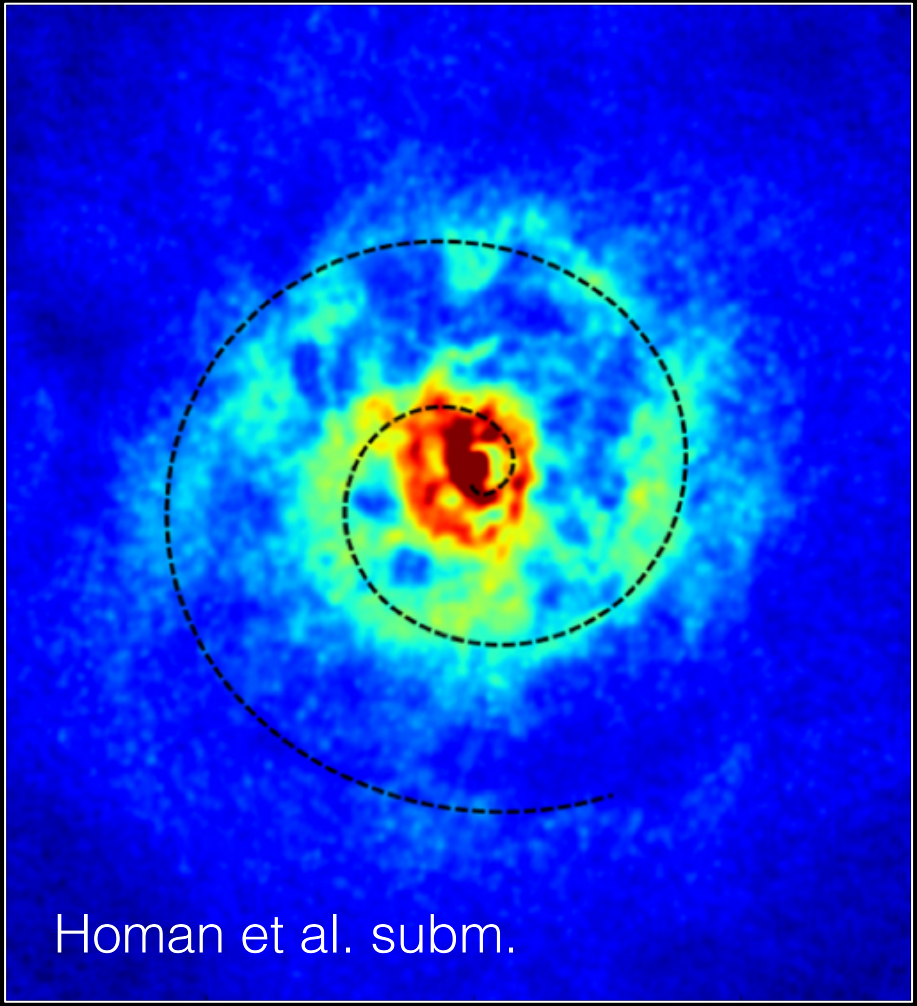
- Isotopes: disc ~ AGB composition
- Timescales: planet not formed in disc
- Roche lobe B: 0.3 AU
- Plume/loop: related to potential accretion disc around B

↓

Future of our Sun

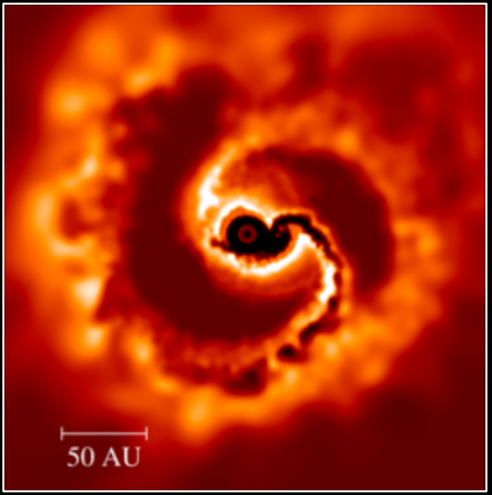
Kervella et al. 2016
Homan et al. 2017

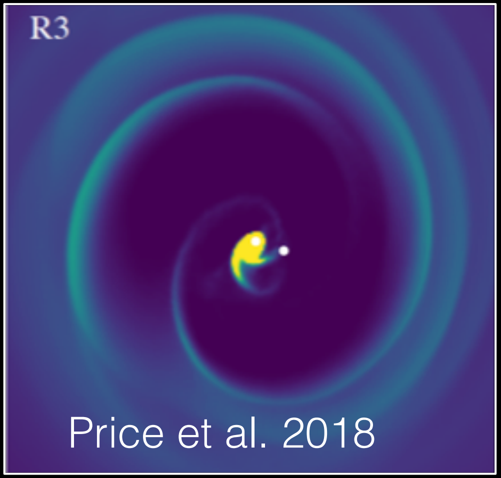
EP Aqr



Homan et al. subm.

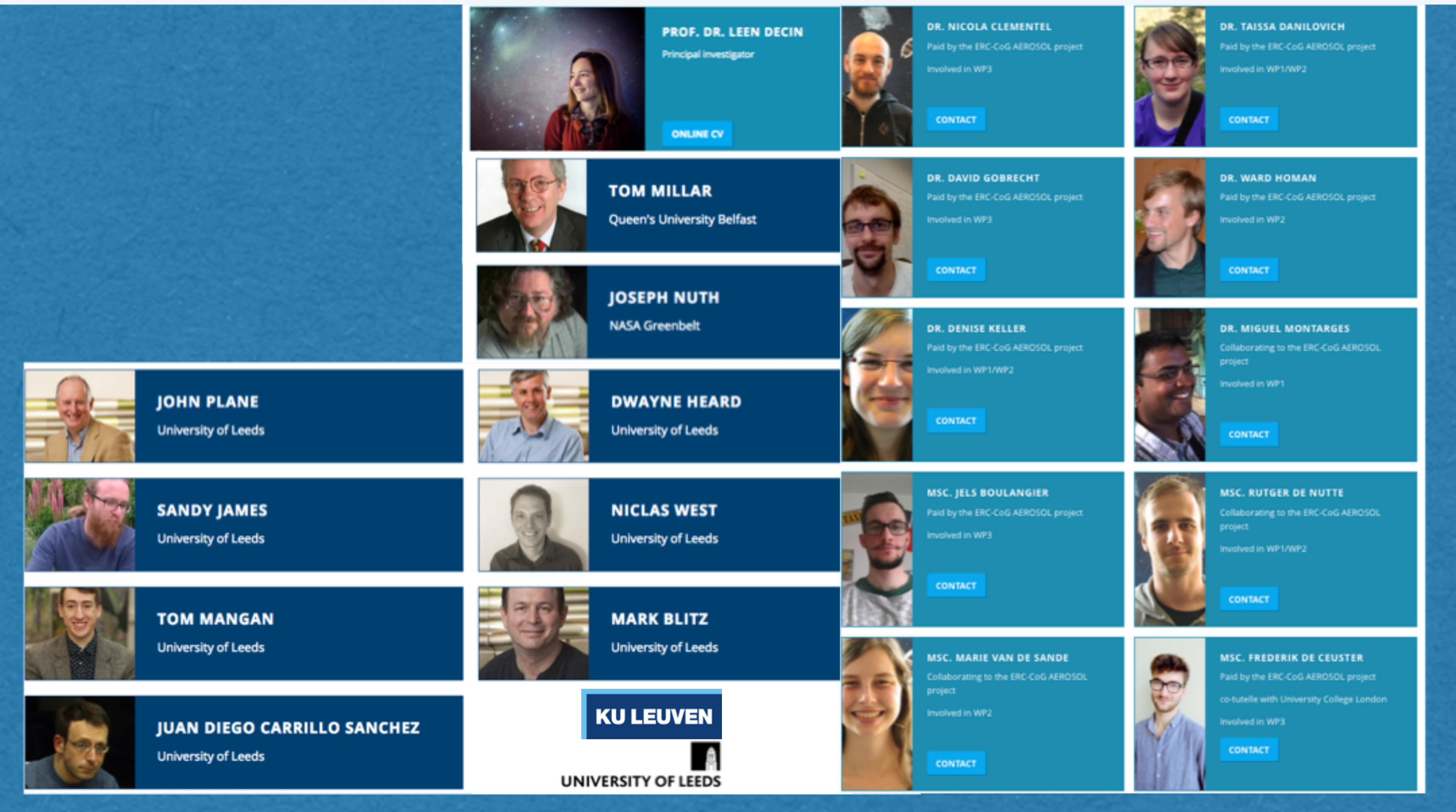
Mohamed et al. 2012





Price et al. 2018

THANKS!



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