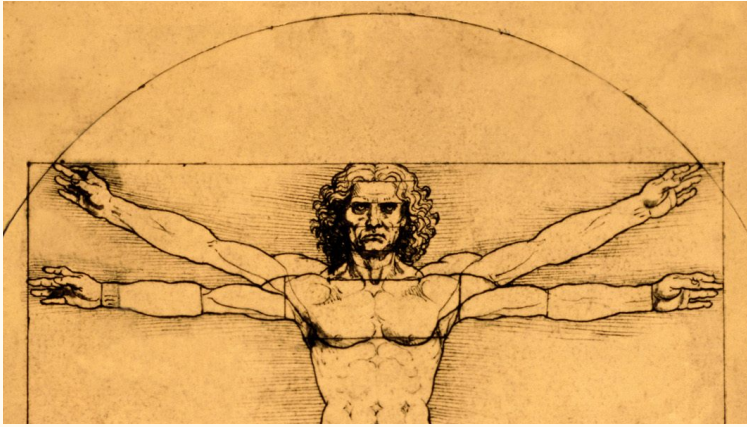
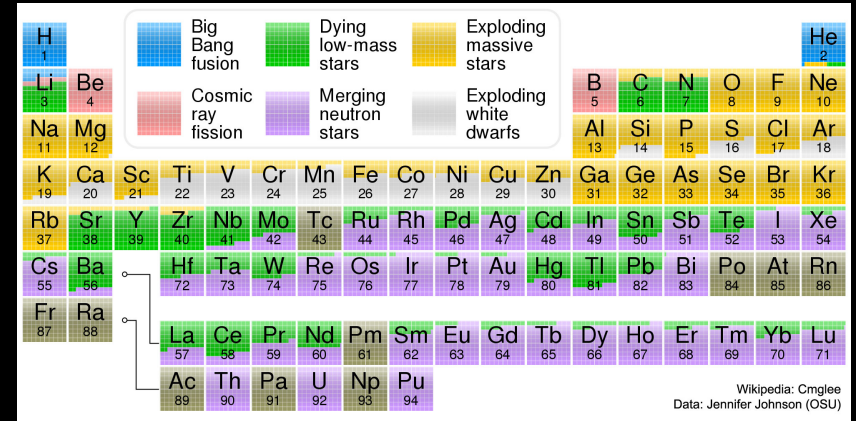




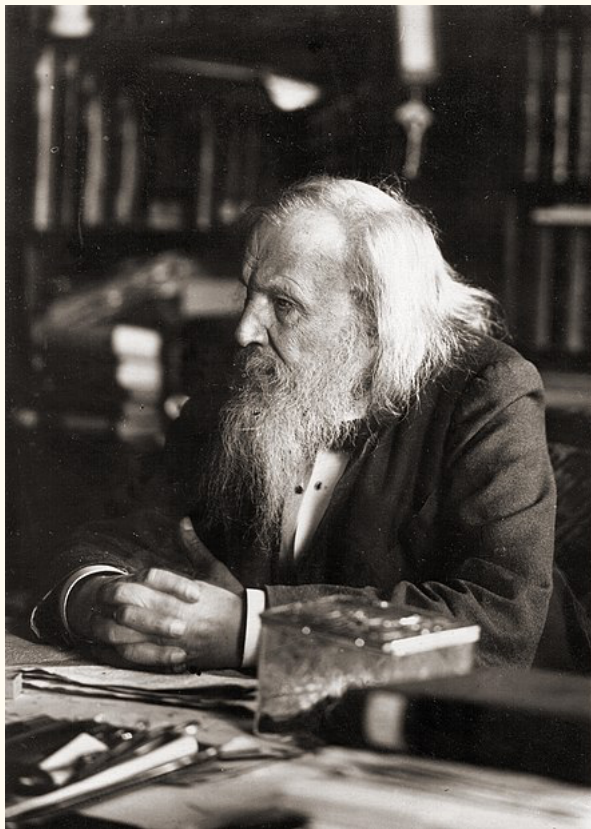
We are made of stardust



Evolved stars govern the periodic table of Mendeleeev

Leen Decin – KU Leuven – Belgium
– University of Leeds – UK

Dmitri Ivanovich Mendeleev



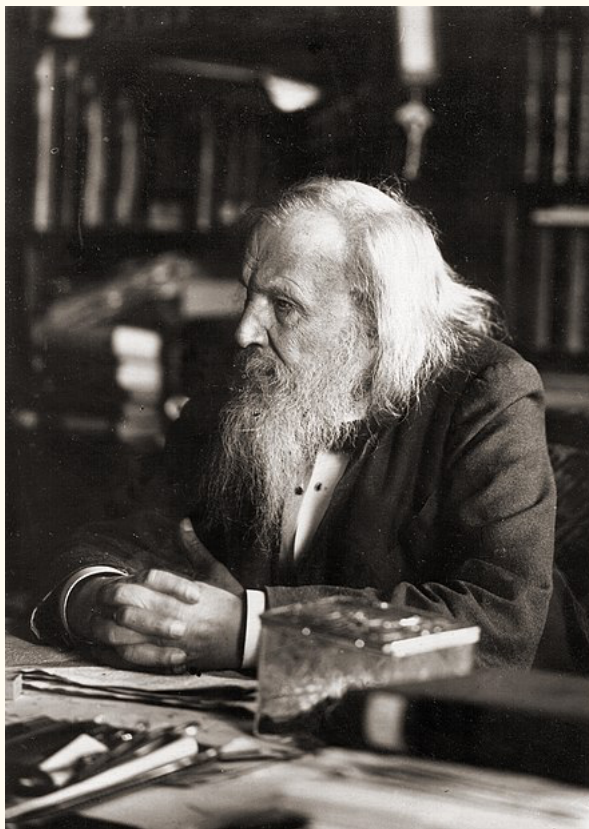
1834 - 1907

1869

Менделѣевъ
таблица

H=1.	?=8	?=32	Cu=63.4	La=138.4	H=187.4
Li=7	Li=7	Be=9.4	Zn=65.4	Pi=202	?
B=11	Al=27.4	?=68	?=70	Br=118	As=175?
Ca=40	Sr=87.6	I=127	S=32	Se=78.4	Te=128?
N=14	P=31	As=75	K=39	Rb=85.4	Ag=108
O=16	F=19	K=39	Li=7	Na=23	Ac=227
Na=23	Mg=24.3	Co=58.9	Fe=55.8	Mn=54.9	Cr=52.0
		Ti=47.9	Sc=44.9	Y=88.9	La=138.9
		U=238	Th=232	Pa=231	Ac=227

Dmitri Ivanovich Mendeleev



1834 - 1907

2019

1 H hydrogen [1.008, 1.009]																	18 Ar argon [39.948, 39.961]
2 He helium [4.0026, 4.0026]																	19 K potassium [39.098, 39.101]
3 Li lithium [6.941, 6.955]	4 Be beryllium [9.0122, 9.0122]															20 Ca calcium [40.078, 40.078]	21 Sc scandium [44.956, 44.956]
5 B boron [10.811, 10.811]	6 C carbon [12.011, 12.011]	7 N nitrogen [14.006, 14.006]	8 O oxygen [15.999, 15.999]	9 F fluorine [18.998, 18.998]	10 Ne neon [20.180, 20.180]	11 Na sodium [22.990, 22.990]	12 Mg magnesium [24.304, 24.304]	13 Al aluminum [26.982, 26.982]	14 Si silicon [28.086, 28.086]	15 P phosphorus [30.974, 30.974]	16 S sulfur [32.06, 32.06]	17 Cl chlorine [35.45, 35.45]	18 Ar argon [39.948, 39.961]	19 K potassium [39.098, 39.101]	20 Ca calcium [40.078, 40.078]	21 Sc scandium [44.956, 44.956]	22 Ti titanium [47.88, 47.88]
23 V vanadium [50.942, 50.942]	24 Cr chromium [51.996, 51.996]	25 Mn manganese [54.938, 54.938]	26 Fe iron [55.845, 55.845]	27 Co cobalt [58.933, 58.933]	28 Ni nickel [58.69, 58.69]	29 Cu copper [63.546, 63.546]	30 Zn zinc [65.38, 65.38]	31 Ga gallium [69.723, 69.723]	32 Ge germanium [72.63, 72.63]	33 As arsenic [74.922, 74.922]	34 Se selenium [78.96, 78.96]	35 Br bromine [79.904, 79.904]	36 Kr krypton [83.80, 83.80]	37 Rb rubidium [85.468, 85.468]	38 Sr strontium [87.62, 87.62]	39 Y yttrium [88.906, 88.906]	40 Zr zirconium [91.224, 91.224]
41 Nb niobium [92.906, 92.906]	42 Mo molybdenum [95.94, 95.94]	43 Tc technetium [98.906, 98.906]	44 Ru ruthenium [101.07, 101.07]	45 Rh rhodium [102.91, 102.91]	46 Pd palladium [106.42, 106.42]	47 Ag silver [107.87, 107.87]	48 Cd cadmium [112.41, 112.41]	49 In indium [114.82, 114.82]	50 Sn tin [118.71, 118.71]	51 Sb antimony [121.76, 121.76]	52 Te tellurium [127.60, 127.60]	53 I iodine [126.905, 126.905]	54 Xe xenon [131.29, 131.29]	55 Cs cesium [132.91, 132.91]	56 Ba barium [137.33, 137.33]	57-71 La-Lu lanthanides	72 Hf hafnium [178.49, 178.49]
73 Ta tantalum [180.948, 180.948]	74 W tungsten [183.84, 183.84]	75 Re rhenium [186.21, 186.21]	76 Os osmium [190.23, 190.23]	77 Ir iridium [192.22, 192.22]	78 Pt platinum [195.08, 195.08]	79 Au gold [196.967, 196.967]	80 Hg mercury [200.59, 200.59]	81 Tl thallium [204.38, 204.38]	82 Pb lead [207.2, 207.2]	83 Bi bismuth [208.98, 208.98]	84 Po polonium [209, 209]	85 At astatine [210, 210]	86 Rn radon [222, 222]	87 Fr francium [223, 223]	88 Ra radium [226, 226]	89-103 Ac-Lr actinides	104 Rf rutherfordium [261, 261]
105 Db dubnium [262, 262]	106 Sg seaborgium [266, 266]	107 Bh bohrium [264, 264]	108 Hs hassium [277, 277]	109 Mt meitnerium [268, 268]	110 Ds darmstadtium [271, 271]	111 Rg roentgenium [272, 272]	112 Cn copernicium [285, 285]	113 Nh nihonium [284, 284]	114 Fl flerovium [289, 289]	115 Mc moscovium [288, 288]	116 Lv livermorium [293, 293]	117 Ts tennessine [289, 289]	118 Og oganeson [294, 294]				

Key

Atomic number

Symbol

name

relative atomic mass

standard atomic weight

87 Fr francium [223, 223]	88 Ra radium [226, 226]	89-103 Ac-Lr actinides	104 Rf rutherfordium [261, 261]	105 Db dubnium [262, 262]	106 Sg seaborgium [266, 266]	107 Bh bohrium [264, 264]	108 Hs hassium [277, 277]	109 Mt meitnerium [268, 268]	110 Ds darmstadtium [271, 271]	111 Rg roentgenium [272, 272]	112 Cn copernicium [285, 285]	113 Nh nihonium [284, 284]	114 Fl flerovium [289, 289]	115 Mc moscovium [288, 288]	116 Lv livermorium [293, 293]	117 Ts tennessine [289, 289]	118 Og oganeson [294, 294]
119 Uu unbinilium [295, 295]	120 Uu unbinilium [296, 296]	121 Uu unbinilium [297, 297]	122 Uu unbinilium [298, 298]	123 Uu unbinilium [299, 299]	124 Uu unbinilium [300, 300]	125 Uu unbinilium [301, 301]	126 Uu unbinilium [302, 302]	127 Uu unbinilium [303, 303]	128 Uu unbinilium [304, 304]	129 Uu unbinilium [305, 305]	130 Uu unbinilium [306, 306]	131 Uu unbinilium [307, 307]	132 Uu unbinilium [308, 308]	133 Uu unbinilium [309, 309]	134 Uu unbinilium [310, 310]	135 Uu unbinilium [311, 311]	136 Uu unbinilium [312, 312]
137 Uu unbinilium [313, 313]	138 Uu unbinilium [314, 314]	139 Uu unbinilium [315, 315]	140 Uu unbinilium [316, 316]	141 Uu unbinilium [317, 317]	142 Uu unbinilium [318, 318]	143 Uu unbinilium [319, 319]	144 Uu unbinilium [320, 320]	145 Uu unbinilium [321, 321]	146 Uu unbinilium [322, 322]	147 Uu unbinilium [323, 323]	148 Uu unbinilium [324, 324]	149 Uu unbinilium [325, 325]	150 Uu unbinilium [326, 326]	151 Uu unbinilium [327, 327]	152 Uu unbinilium [328, 328]	153 Uu unbinilium [329, 329]	154 Uu unbinilium [330, 330]
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173 Uu unbinilium [349, 349]	174 Uu unbinilium [350, 350]	175 Uu unbinilium [351, 351]	176 Uu unbinilium [352, 352]	177 Uu unbinilium [353, 353]	178 Uu unbinilium [354, 354]	179 Uu unbinilium [355, 355]	180 Uu unbinilium [356, 356]	181 Uu unbinilium [357, 357]	182 Uu unbinilium [358, 358]	183 Uu unbinilium [359, 359]	184 Uu unbinilium [360, 360]	185 Uu unbinilium [361, 361]	186 Uu unbinilium [362, 362]	187 Uu unbinilium [363, 363]	188 Uu unbinilium [364, 364]	189 Uu unbinilium [365, 365]	190 Uu unbinilium [366, 366]
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227 Uu unbinilium [403, 403]	228 Uu unbinilium [404, 404]	229 Uu unbinilium [405, 405]	230 Uu unbinilium [406, 406]	231 Uu unbinilium [407, 407]	232 Uu unbinilium [408, 408]	233 Uu unbinilium [409, 409]	234 Uu unbinilium [410, 410]	235 Uu unbinilium [411, 411]	236 Uu unbinilium [412, 412]	237 Uu unbinilium [413, 413]	238 Uu unbinilium [414, 414]	239 Uu unbinilium [415, 415]	240 Uu unbinilium [416, 416]	241 Uu unbinilium [417, 417]	242 Uu unbinilium [418, 418]	243 Uu unbinilium [419, 419]	244 Uu unbinilium [420, 420]
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445 Uu																	

Part 1 – The origin of the periodic elements

→ atomic mixture

➤ role nuclear reactions in evolved stars

Part 2 – From atoms to dust

→ atomic, molecular, dust composition

➤ role of stellar winds

Part 3 – Enrichment of the interstellar medium

→ atoms, (exited) molecules,
(large) grains

➤ role of bow shocks

Part 4 – The quest for dust nucleation

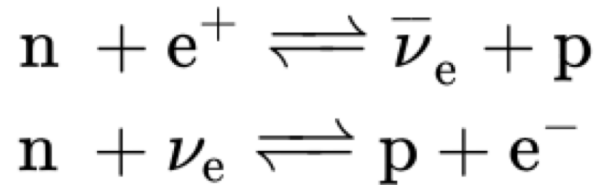
➤ Why wonder about astrochemistry
in old stars' winds?

Part I -

The cosmic origin of the
periodic elements

Initial conditions - Standard Model physics

$T < 1 \text{ sec}$



Freeze-out: $n/p \sim 1/6$

Big Bang nucleosynthesis

Freeze-out: $n/p \sim 1/6$



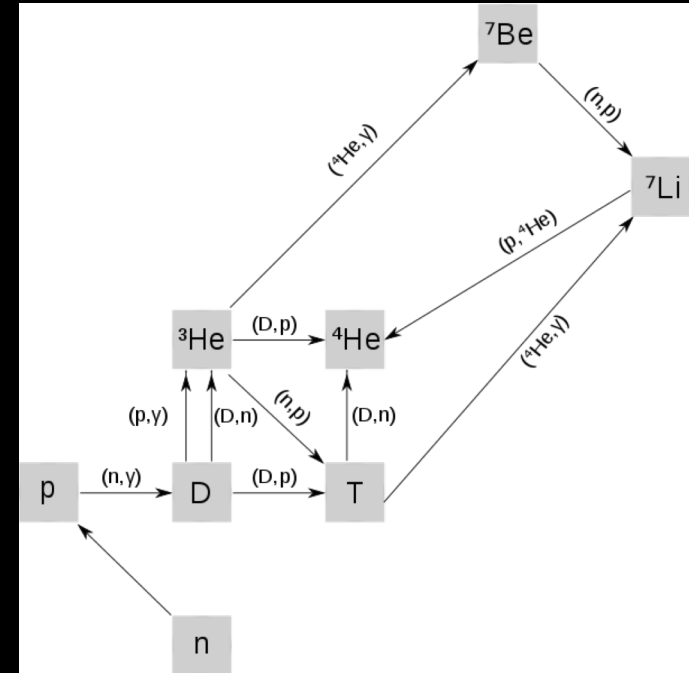
n decay: $n/p \sim 1/7$

n fused $\rightarrow$ ^4He



$\sim 8\%$ He ($\sim 25\%$ in mass)

10 sec $< T < 20$ min



Big Bang nucleosynthesis

Freeze-out: $n/p \sim 1/6$



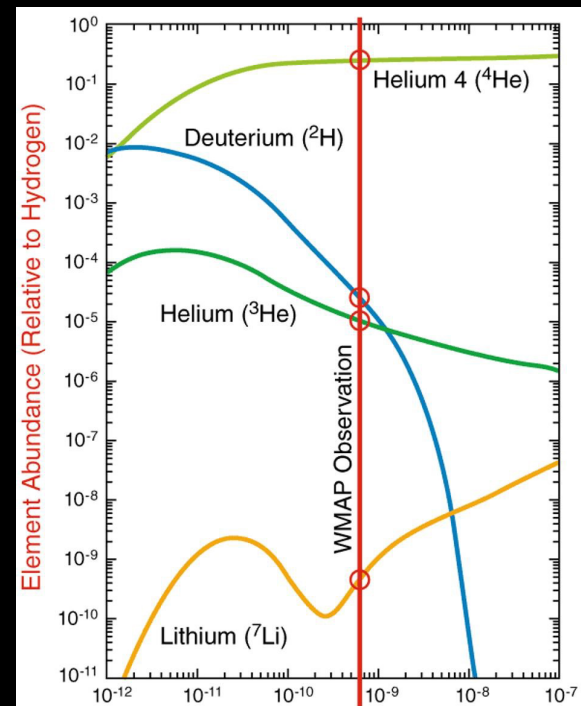
n decay: $n/p \sim 1/7$

n fused $\rightarrow$ ${}^4\text{He}$



$\sim 8\%$ He ($\sim 25\%$ in mass)

$10 \text{ sec} < T < 20 \text{ min}$



Density of Ordinary Matter (Relative to Photons)

The periodic table through time

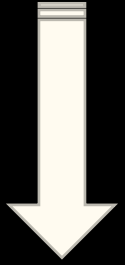
Universe at ~15 minutes old

1
H
3
Li

big bang fusion

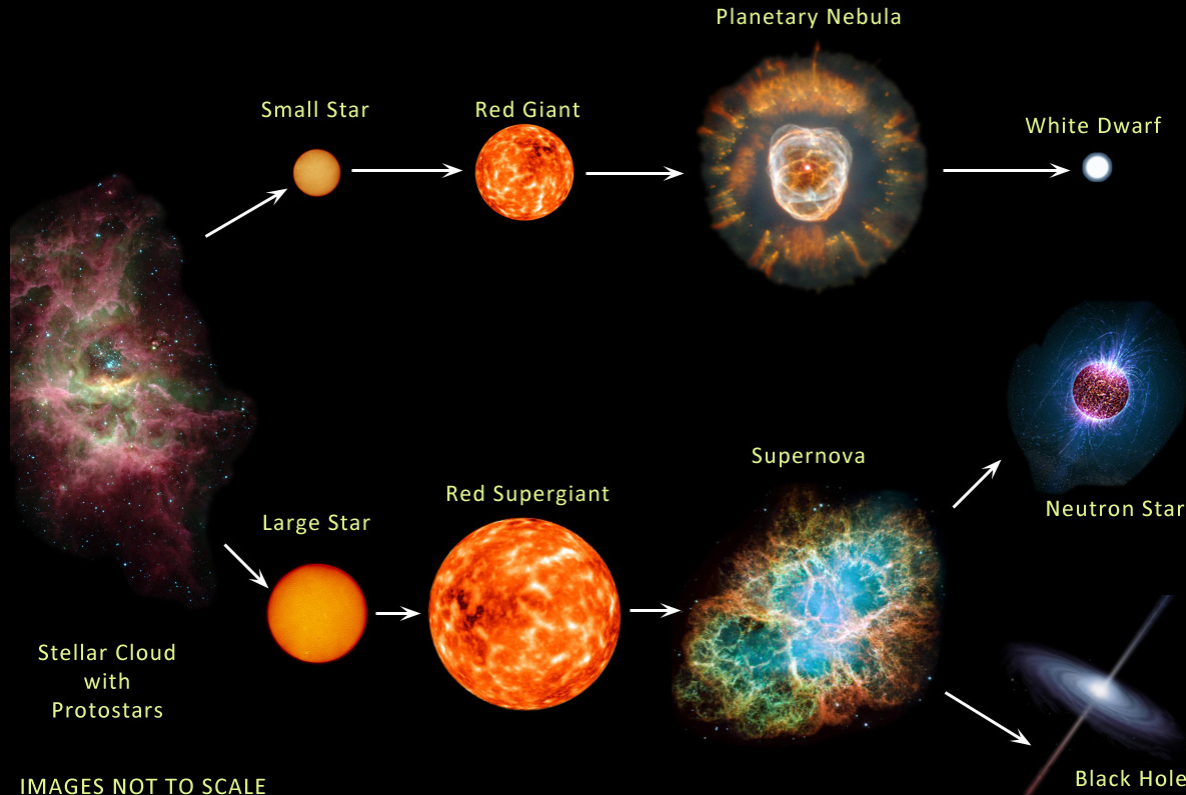
2
He
4He

T ~ 15 min



Stellar
nucleosynthesis

Stellar evolution



Stellar nucleosynthesis

Hydrogen fusion

- Deuterium fusion
- Proton-proton chain
- CNO cycle

Helium fusion

- Triple α -process
- α -process

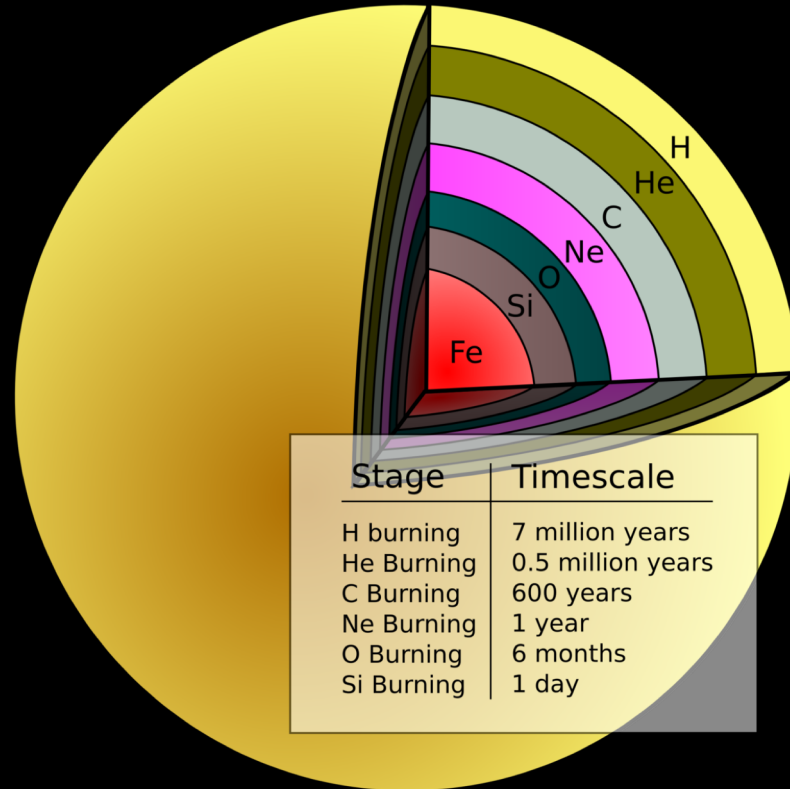
Fusion of heavier elements

- Li, C, Ne, O, Si-burning

Production of elements $> \text{Fe}$

- Neutron capture
 - r-process
 - s-process
- Proton capture
 - Rp-process
 - P-process
- Photo-disintegration

Stellar nucleosynthesis: massive stars



The periodic table through time

Universe at ~100 Million Years

1 H	big bang fusion										cosmic ray fission										2 He
3 Li	4 Be	exploding massive stars										5 B	6 C	7 N	8 O	9 F	10 Ne				
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar				
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr				
37 Rb																					

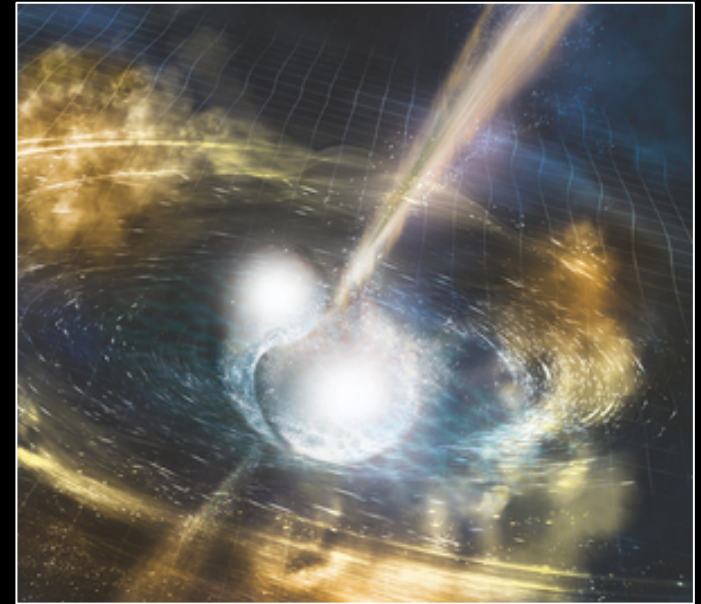
The periodic table through time

Universe at ~200 Million Years

1 H	big bang fusion										cosmic ray fission										2 He							
3 Li	4 Be	merging neutron stars										exploding massive stars										5 B	6 C	7 N	8 O	9 F	10 Ne	
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar											
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr											
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe											
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn										
87 Fr	88 Ra																											
				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu										
				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu																			

GW170817

FIRST COSMIC EVENT OBSERVED IN
GRAVITATIONAL WAVES AND LIGHT



r-process: gold, platinum

The periodic table through time

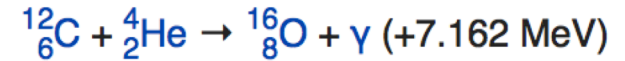
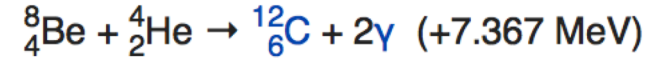
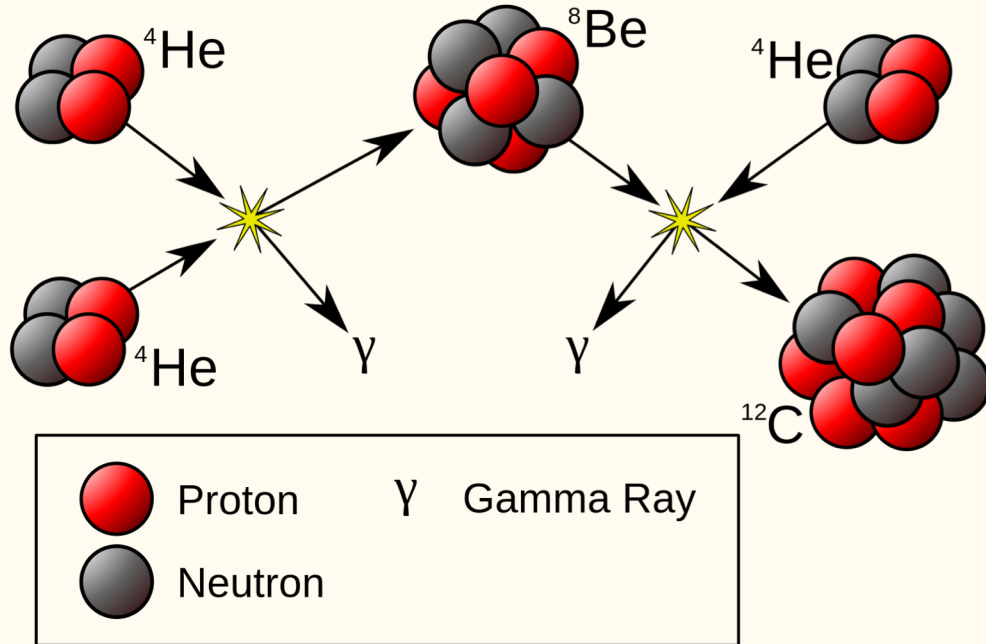
The Universe at ~8 Billion Years

1 H	big bang fusion					cosmic ray fission					2 He						
3 Li	4 Be	merging neutron stars					exploding massive stars					5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	dying low mass stars					exploding white dwarfs					13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	Very radioactive isotopes; nothing left from stars								

Hoyle (1954): triple- α process
B²FH (1957): s-process

Triple- α process

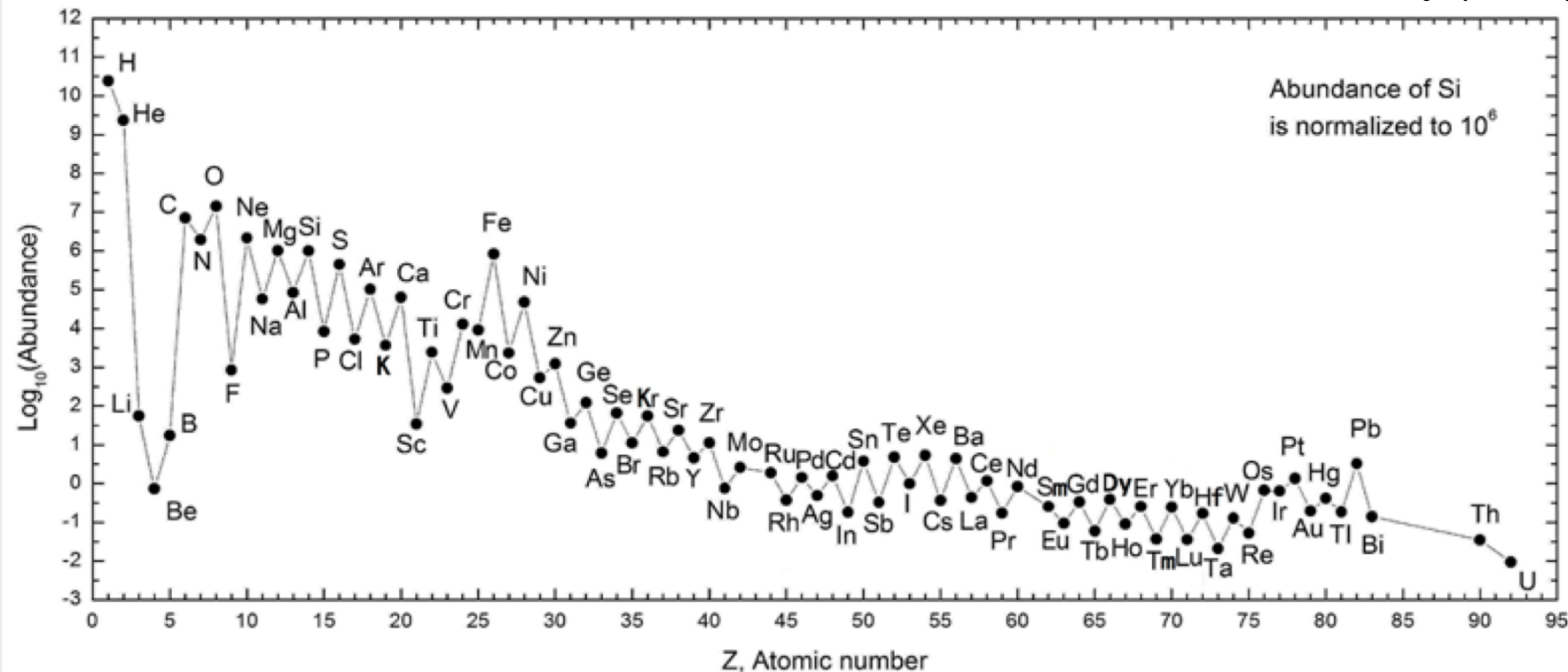


We exist ...

hence there must be a
7.68 MeV ${}^{12}\text{C}$ resonance

The cosmic chemical budget

Suess & Urey (1956)

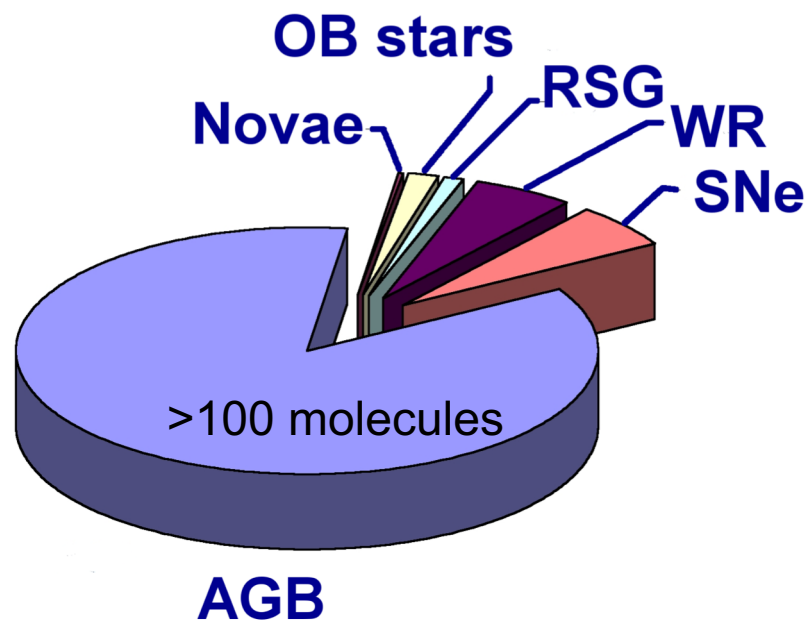


Part II -

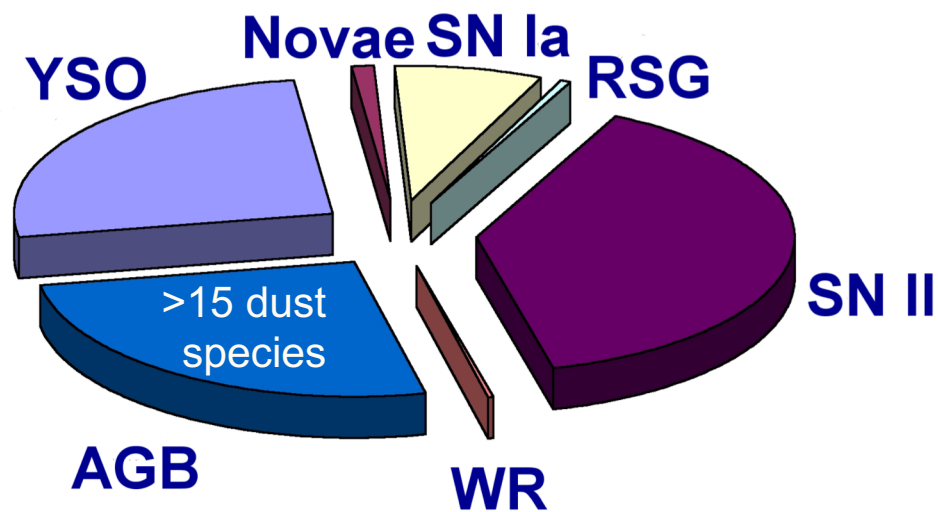
From atoms to dust

Interstellar budget

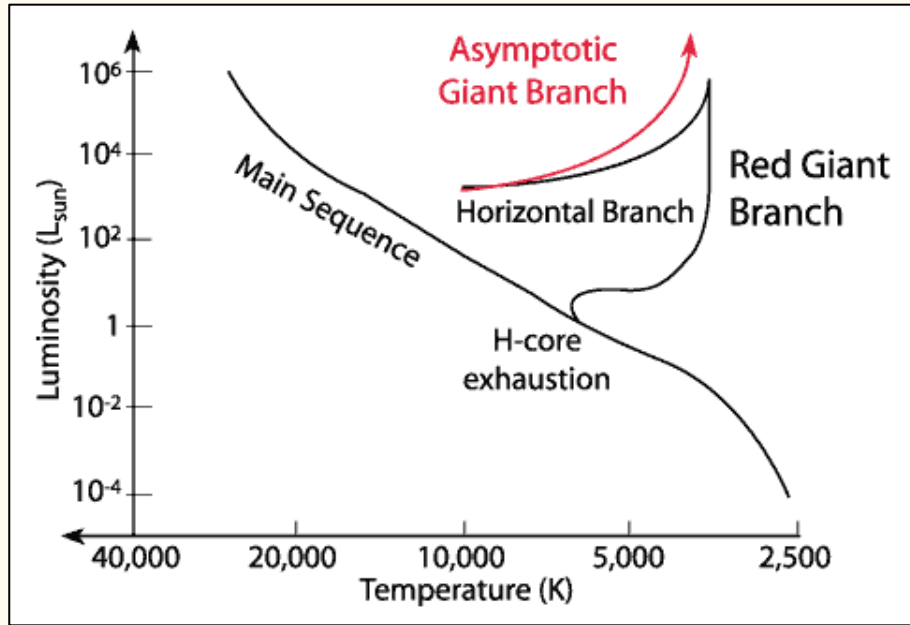
gas



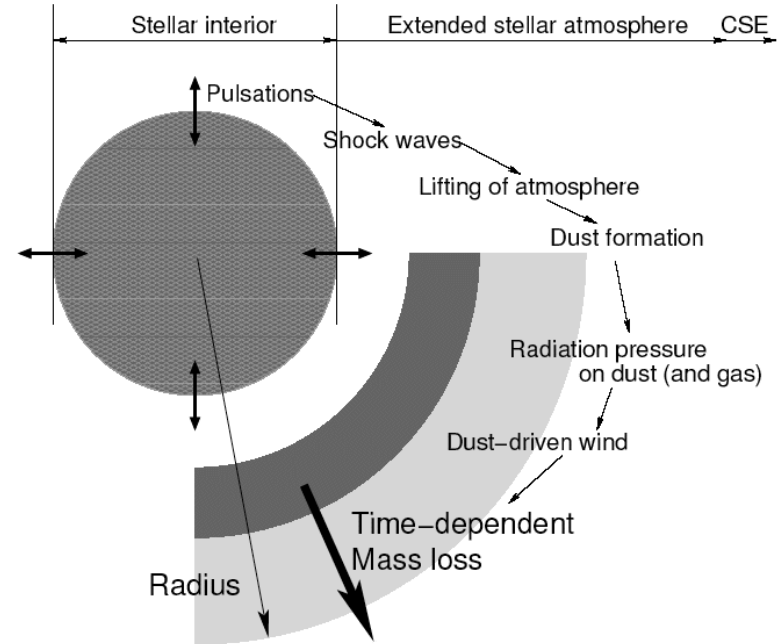
dust

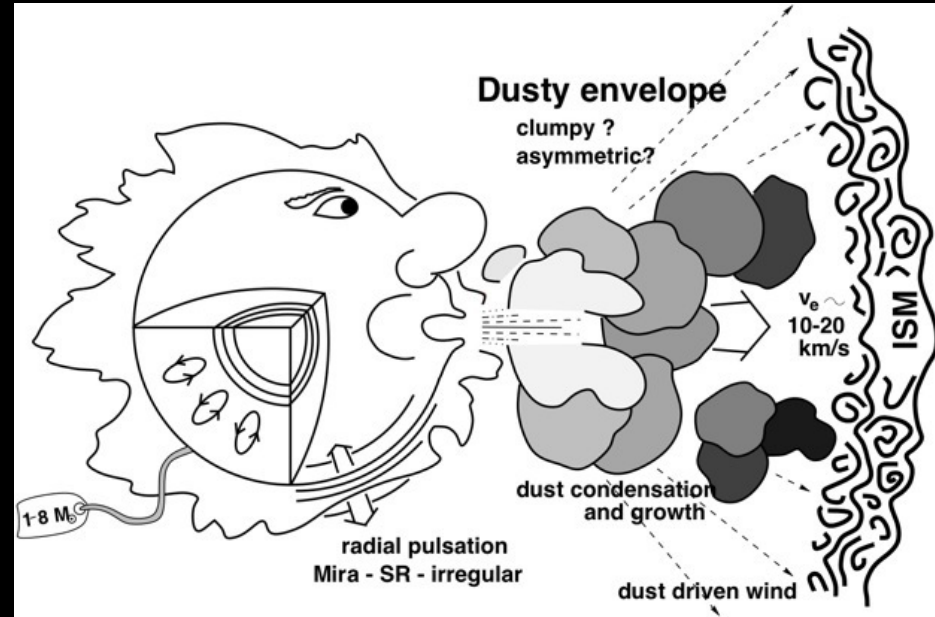
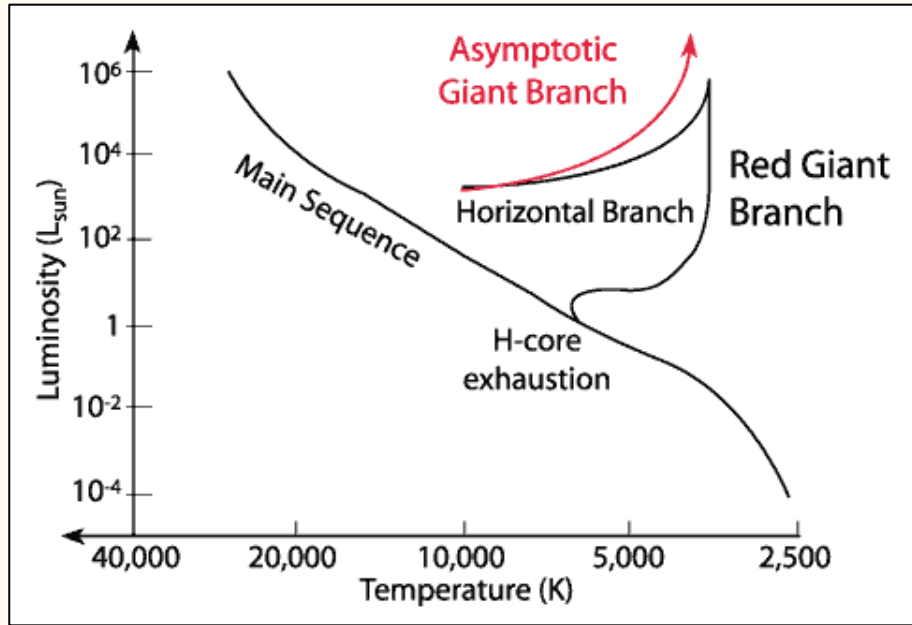


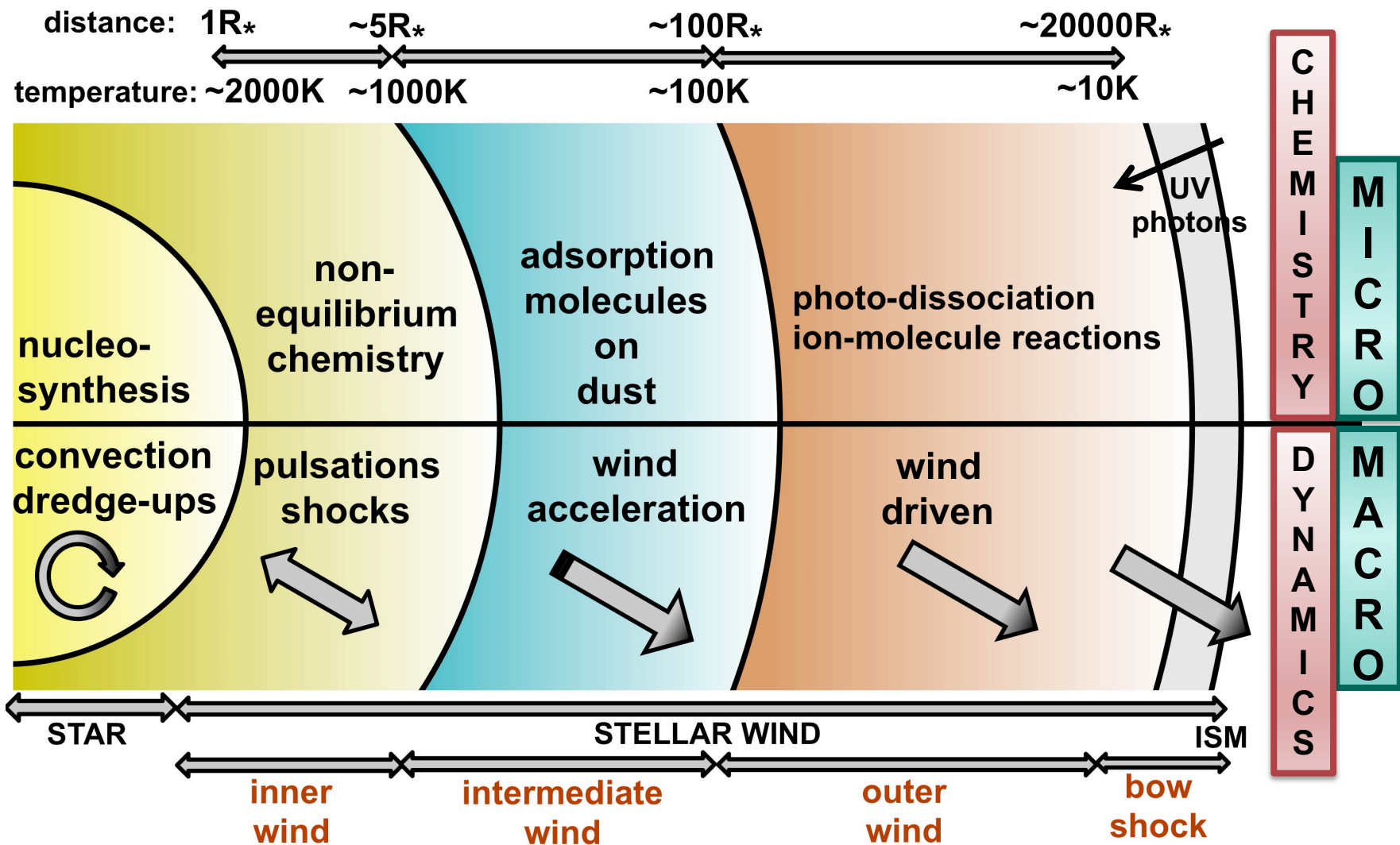
What is an AGB star?



The outer parts of the AGB star





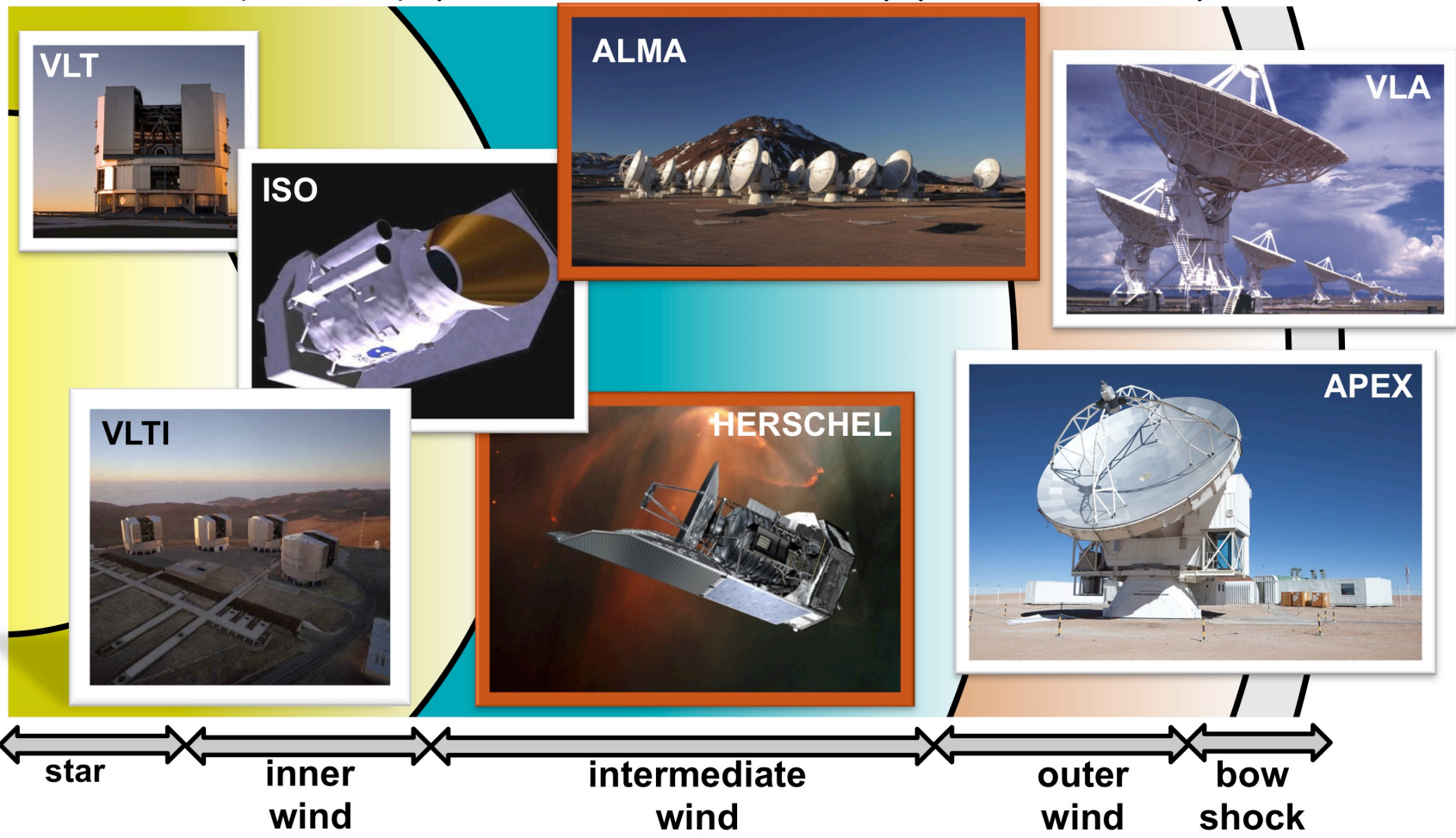


Observing stellar winds

temperature: $\sim 2000\text{K}$ $\sim 1000\text{K}$

$\sim 100\text{K}$

$\sim 10\text{K}$

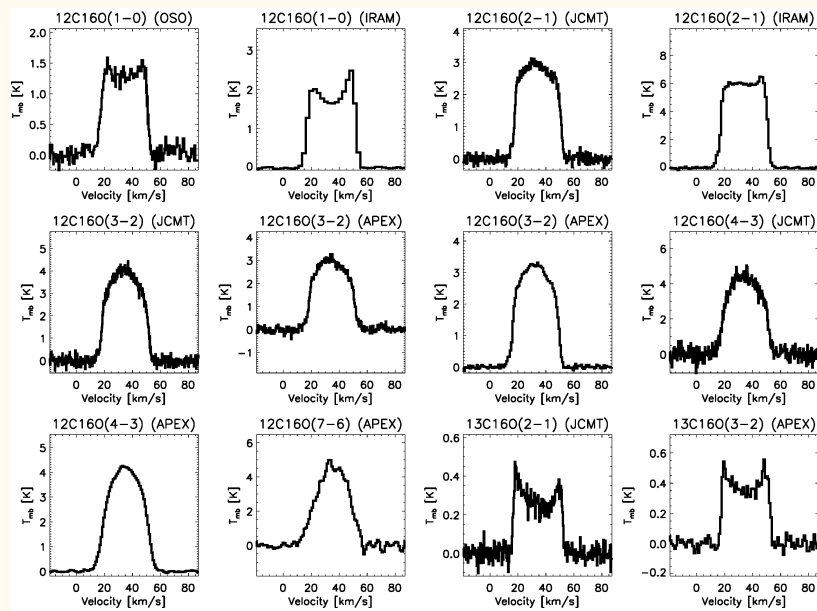


Crucial role of Herschel

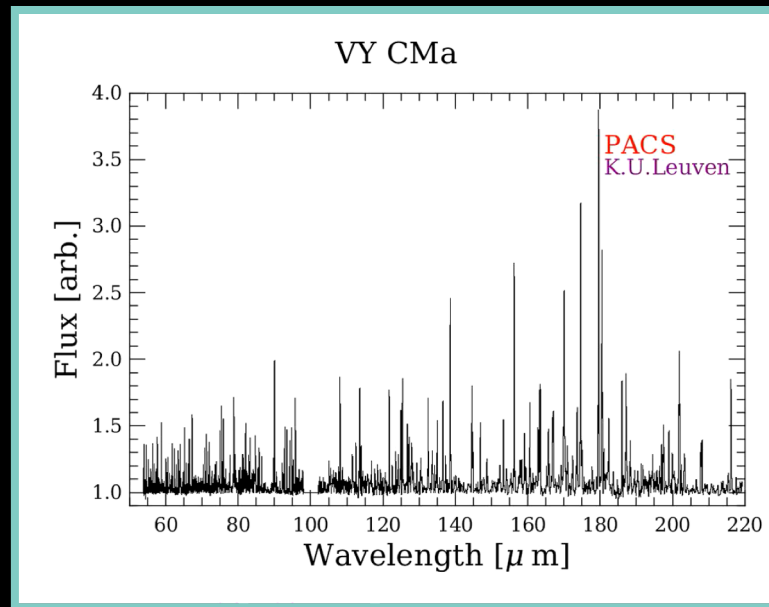


2009-2013

→ 12 molecular line transitions: ~40hr



→ 930 molecular line transitions: 2hr



>50 targets

Royer 2010

Decin 2010

Crucial role of ALMA

ALMA

HERSCHEL

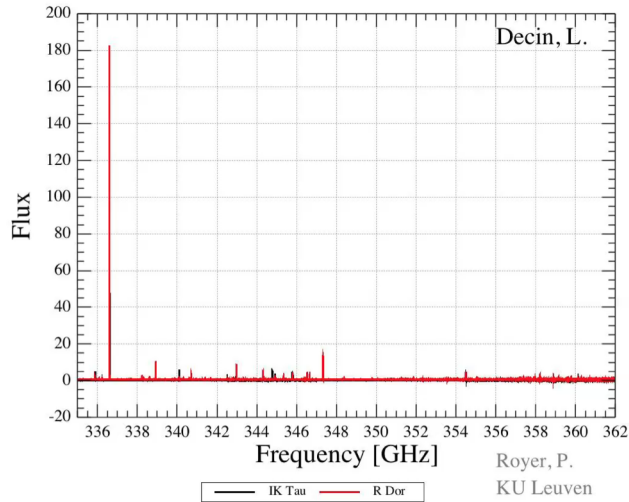


2009-2013

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

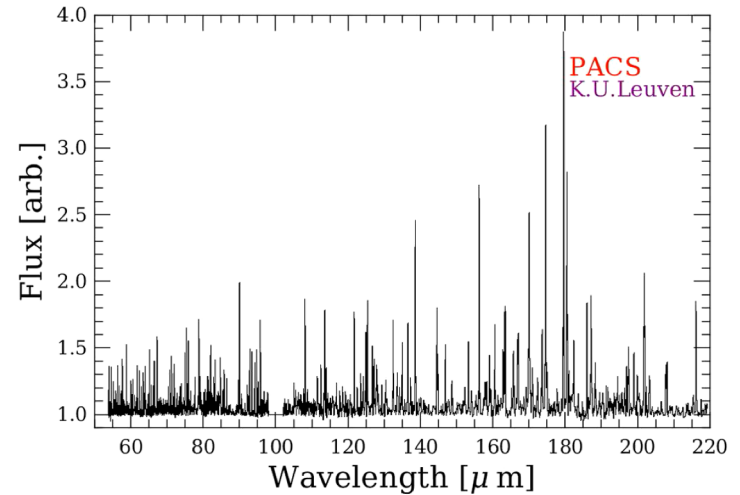
→ 930 molecular line transitions: 2hr

IK Tau & R Dor



27 GHz

VY CMa



Royer 2010

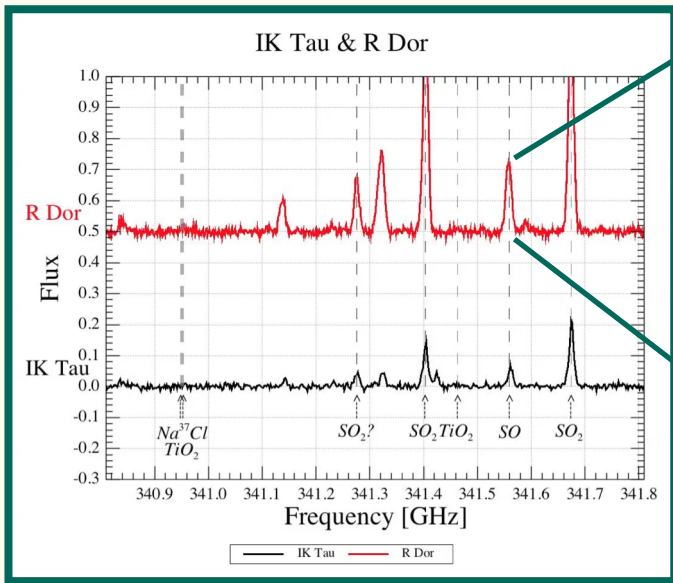
>50 targets

Crucial role of ALMA

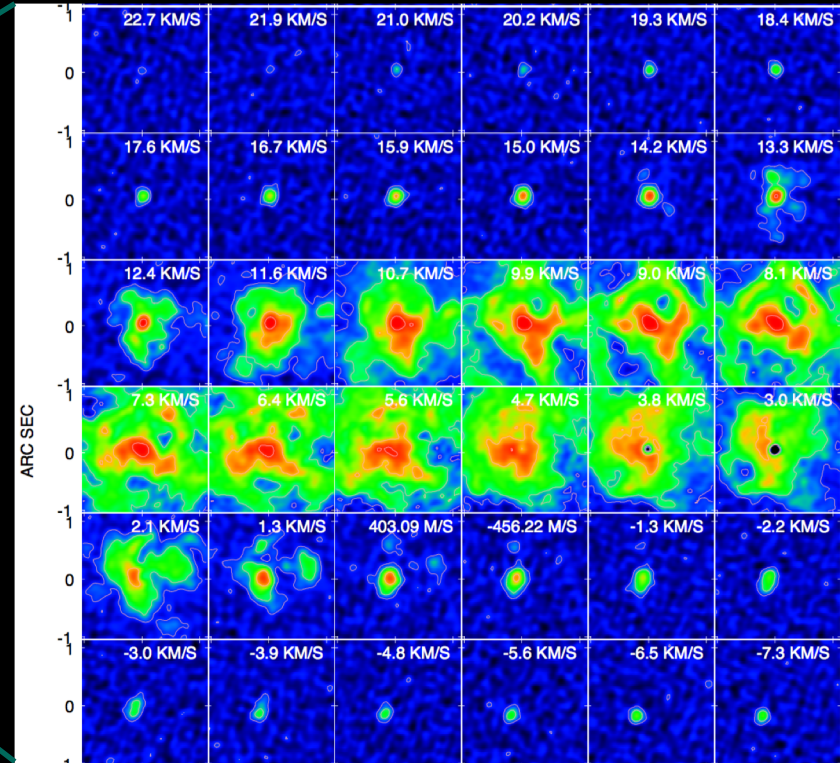
ALMA



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



120 x 150 mas



Decin 2017, 2018

Stellar wind: molecules

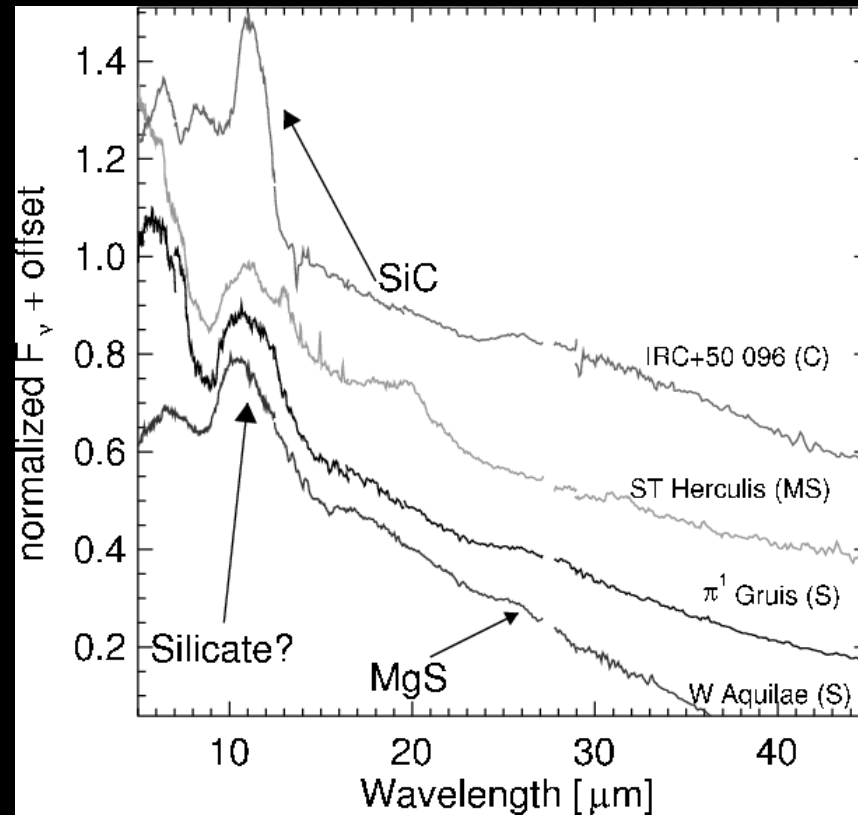
<i>2-atoms:</i>	AlCl	CP	NaCl	SiO
	AlF	CS	OH	SiS
	C ₂	ClH	PN	SO
	CO	FH	SiC	
	CN	KCl	SiN	
<i>3-atoms:</i>	AlNC	FeCN	HNC	SiC ₂
	C ₃	HCN	KCN	SiCN
	C ₂ H	HCP	MgCN	SiCSi
	C ₂ S	H ₂ O	MgNC	SiNC
	CO ₂	H ₂ S	NaCN	SO ₂
<i>4-atoms:</i>	<i>ℓ</i> -C ₃ H	C ₂ H ₂	HMgNC	PH ₃
	C ₃ N	HC ₂ N	MgC ₂ H (?)	SiC ₃
	C ₃ O	H ₂ CO	NC ₂ P (?)	
	C ₃ S	H ₂ CS	NH ₃	
<i>5-atoms:</i>	C ₅	<i>c</i> -C ₃ H ₂	CH ₂ NH	H ₂ C ₃
	C ₄ H	CH ₂ CN	HC ₃ N	HNC ₃
	C ₄ Si	CH ₄	HC ₂ NC	SiH ₄
<i>6-atoms:</i>	C ₅ H	C ₅ S	CH ₃ CN	H ₂ C ₄
	C ₅ N	C ₂ H ₄	HC ₄ N	SiH ₃ CN (?)
<i>≥ 7-atoms:</i>	C ₆ H	CH ₂ CHCN	HC ₇ N	
	C ₇ H	CH ₃ CCH	HC ₉ N	
	C ₈ H	HC ₅ N	H ₂ C ₆	
<i>Ions:</i>	C ₄ H ⁻	C ₆ H ⁻	C ₈ H ⁻	HCO ⁺
	CN ⁻	C ₃ N ⁻	C ₅ N ⁻	

88 (>100) molecules



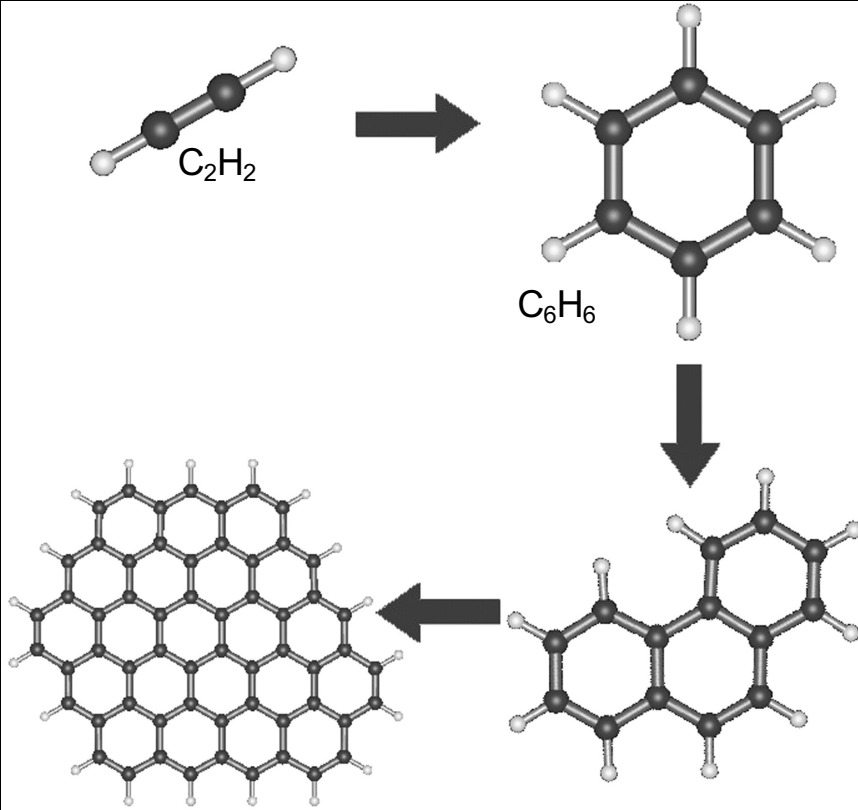
70 -C-

Stellar wind: dust



Carbon-rich grains

$C/O > 1$



Cherchneff 2010
Ehrenfreund 2011

O-rich grains: 2 condensation sequences

Al-oxides

silicates

C/O < 1

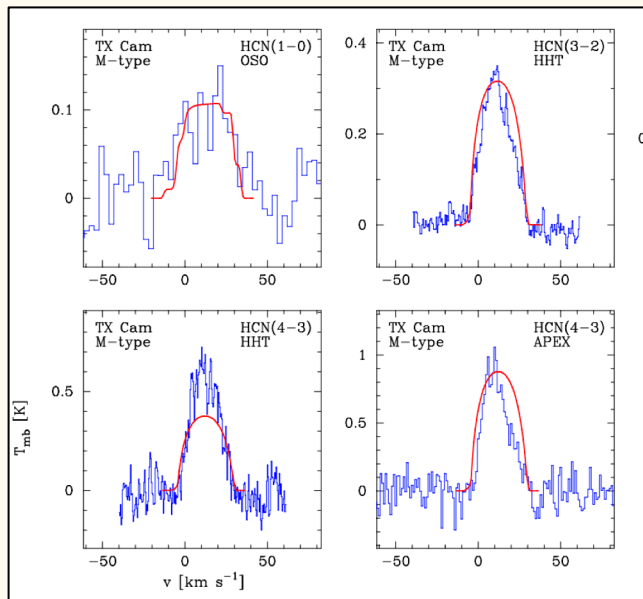
Tielens 1998

[1760-1300K]
 Al_2O_3 , Alumina
↓
[1625-1400K]
 $\text{Ca}_2\text{Al}_2\text{SiO}_7$, Gehlinites
↓
[1450-1100K]
 $\text{CaMgSi}_2\text{O}_6$, Diopside
↓
[1360-1000K]
 $\text{CaAl}_2\text{Si}_2\text{O}_8$, Anorthite

[1440-1050K]
 Mg_2SiO_4 , Forsterite
↓
[1350-1040K]
 MgSiO_3 , Enstatite
↓
[1100-950K]
 $[\text{Mg},\text{Fe}]_2\text{SiO}_4$, Olivine

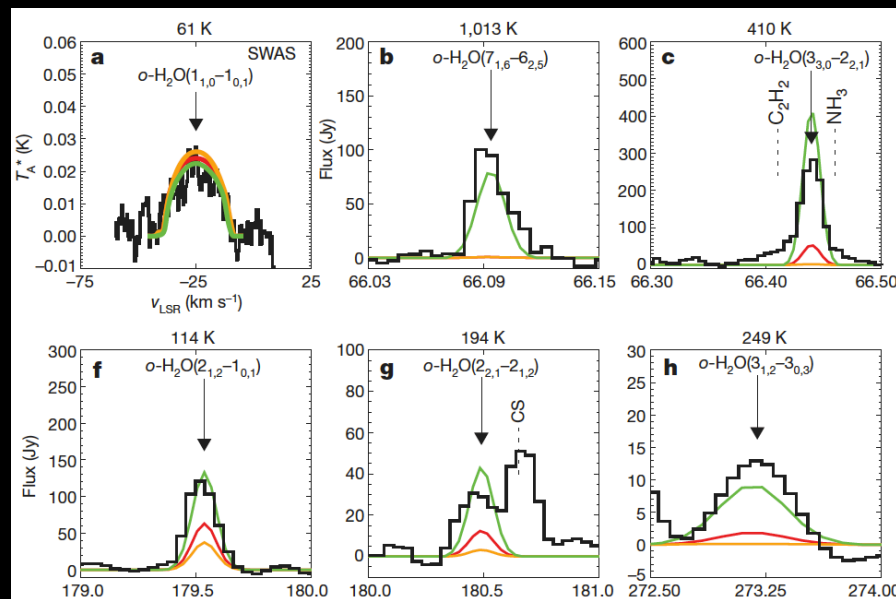
Chemical surprises

HCN@O-rich



Schöier 2013

H₂O@C-rich

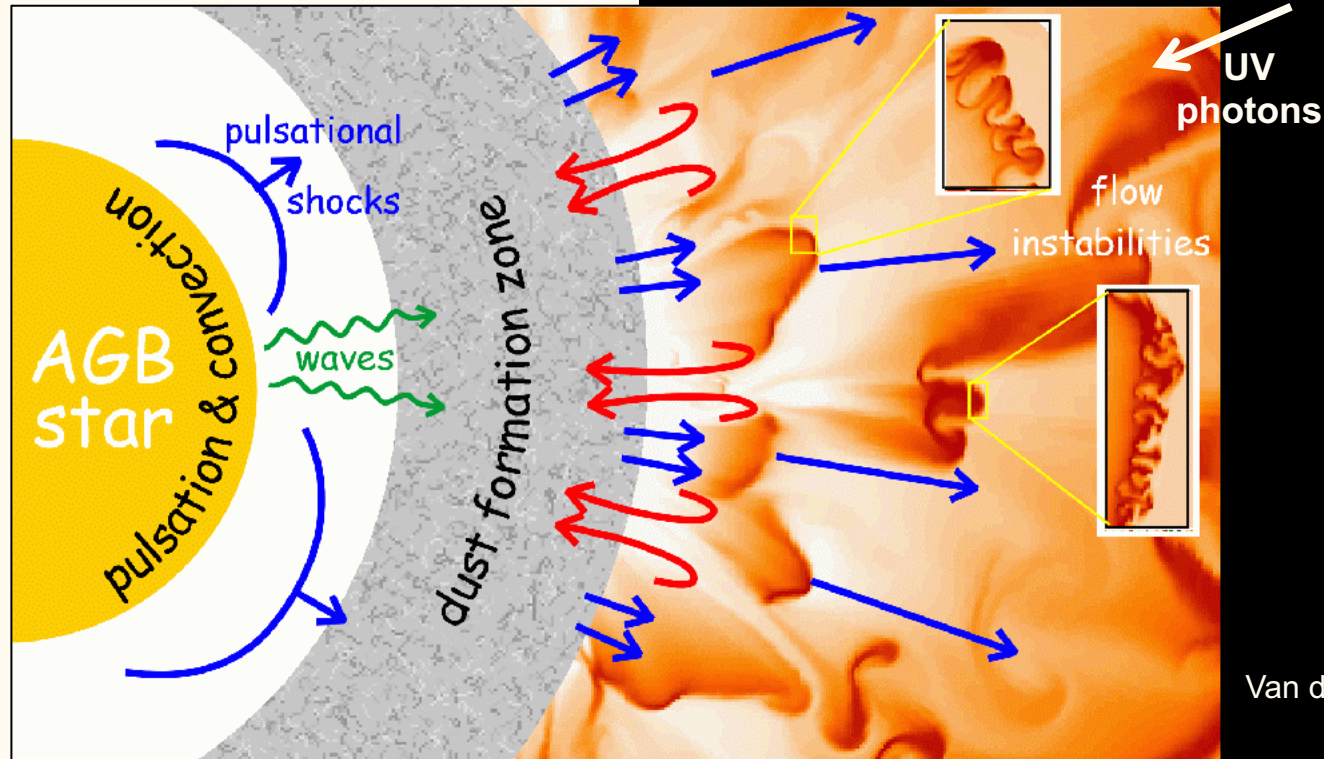


Decin 2010

Chemical surprises

Non-equilibrium chemistry due to pulsation-induced shocks

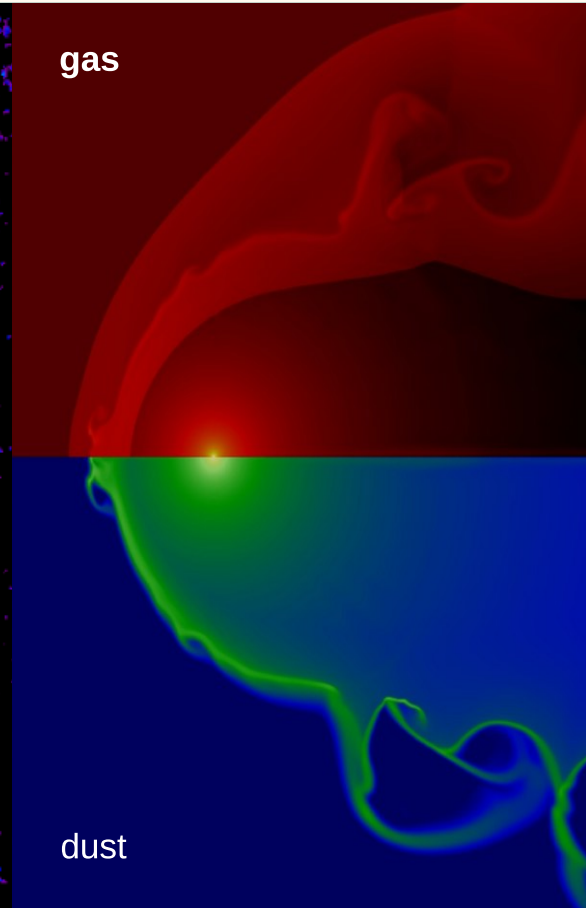
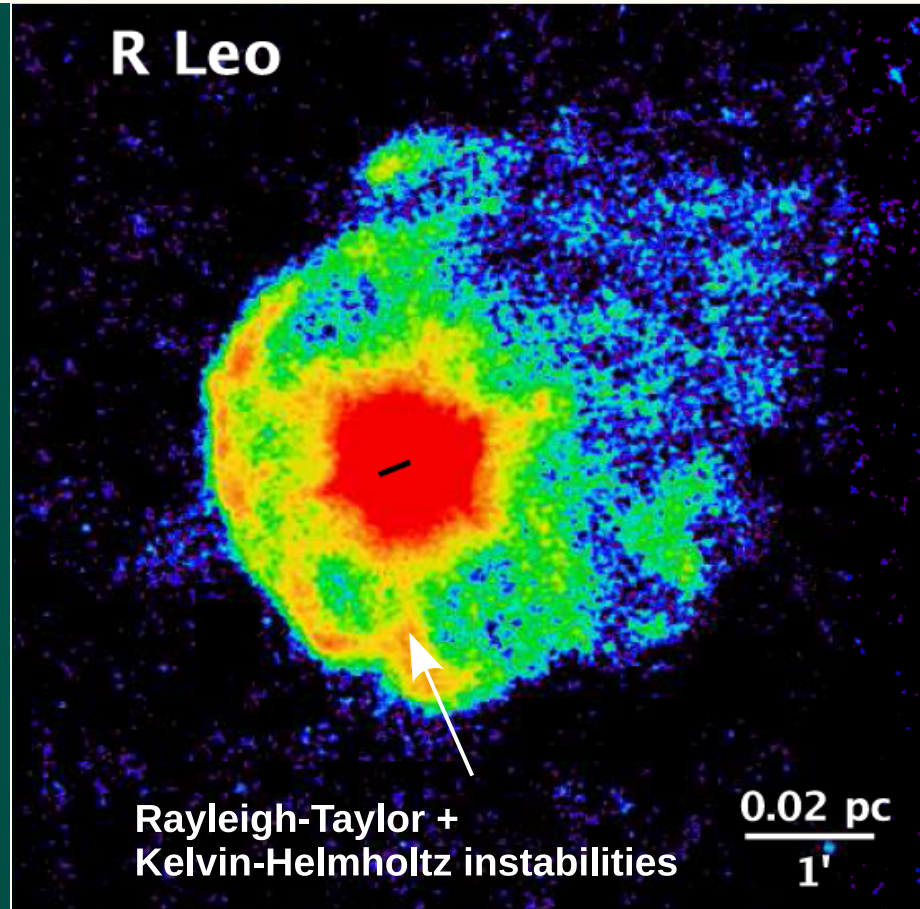
Photochemistry in a clumpy medium



Part III - Enrichment of the interstellar medium

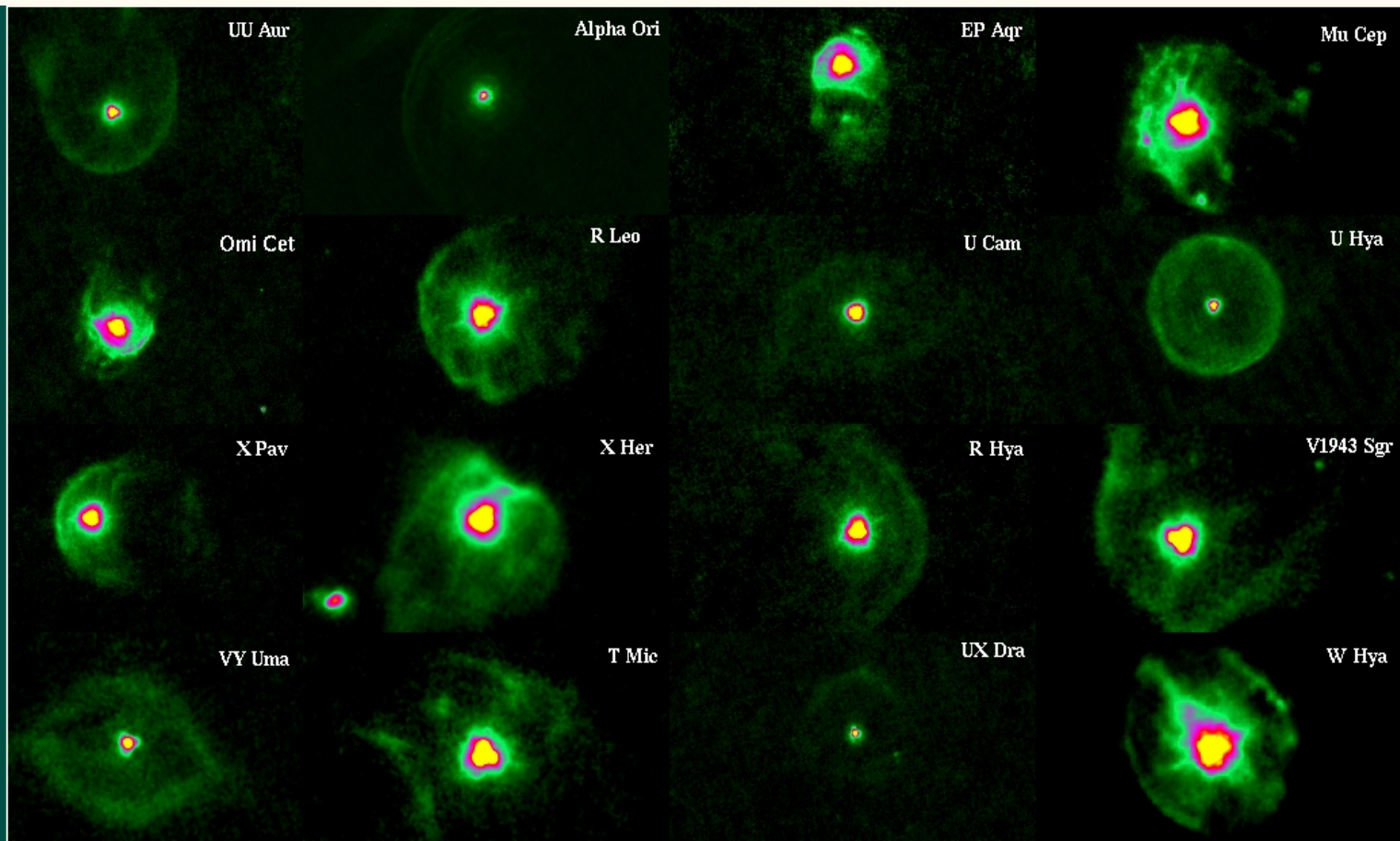
Bow shocks

Bow shocks: interaction wind - ISM



Cox 2012

Bow shocks: interaction wind - ISM

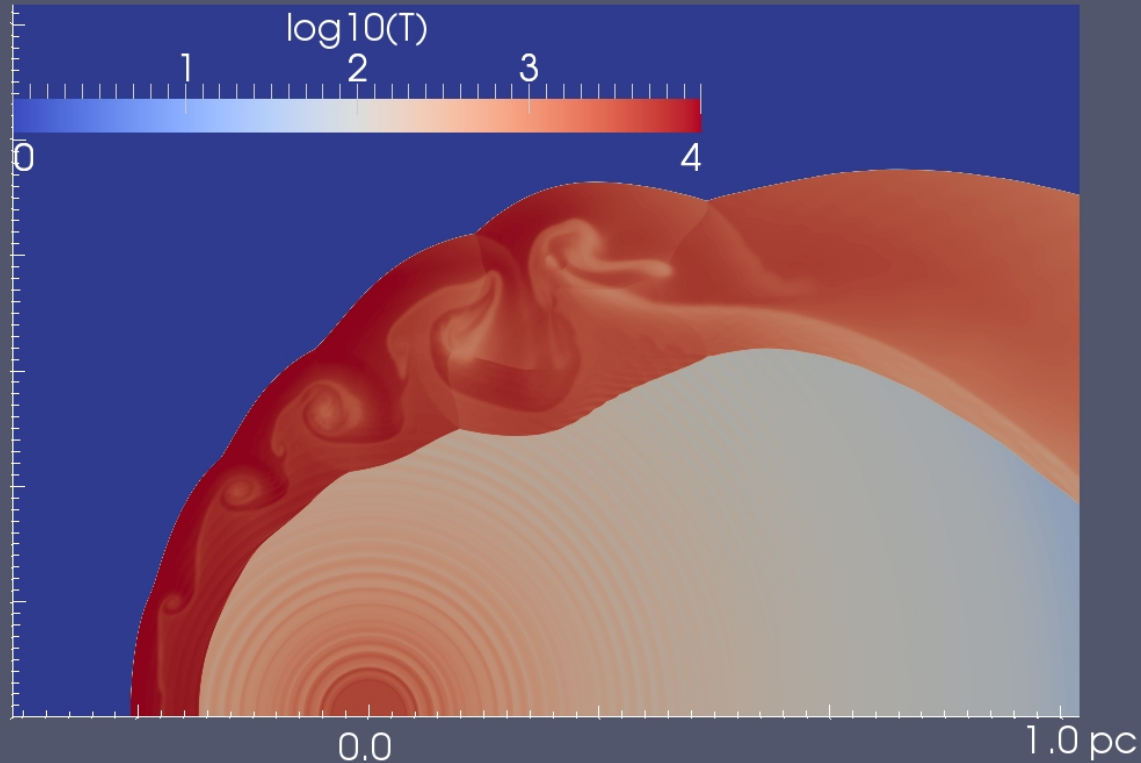


Cox 2012

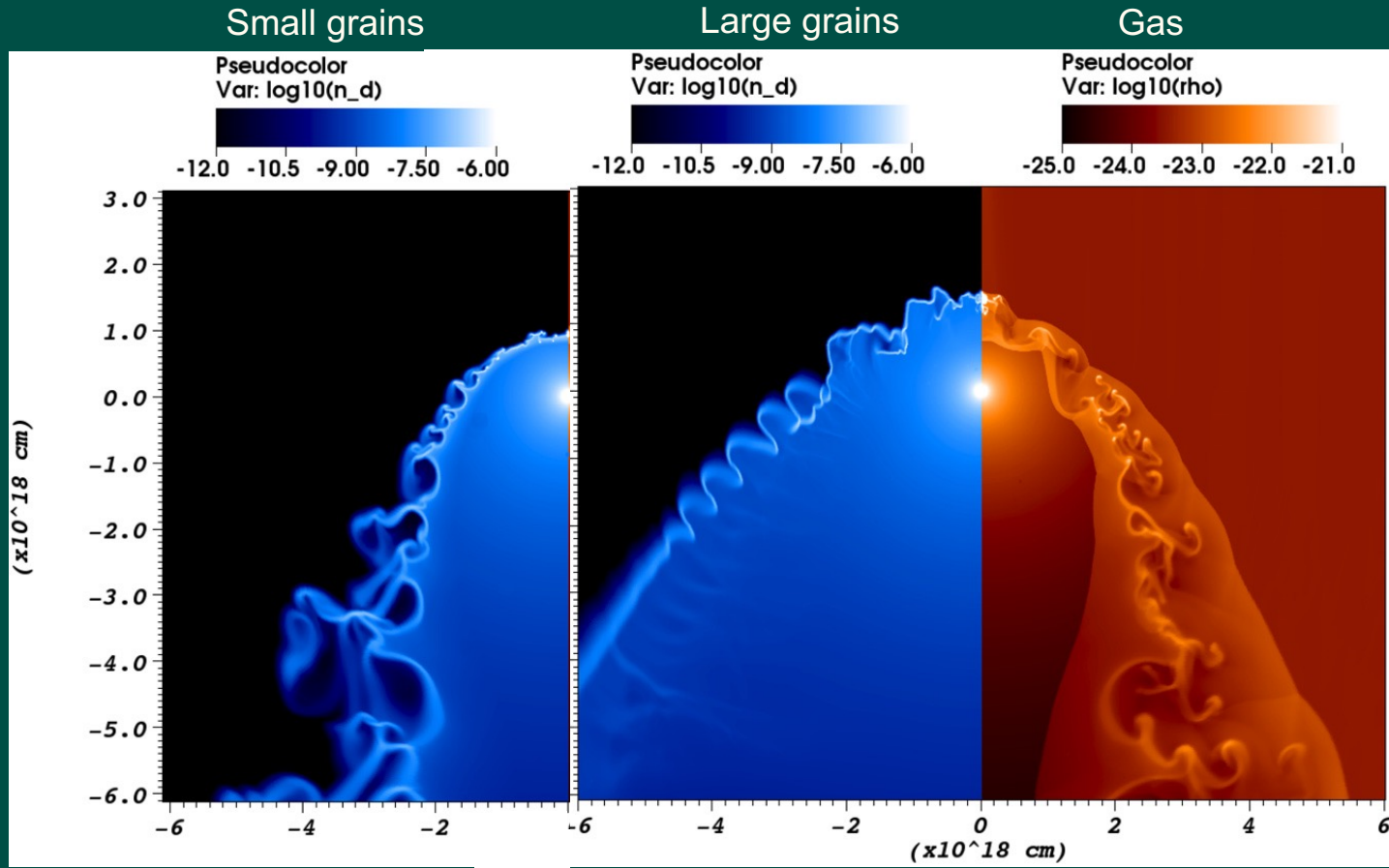
Bow shocks: interaction wind - ISM

gas temperature

Van Marle, 2012



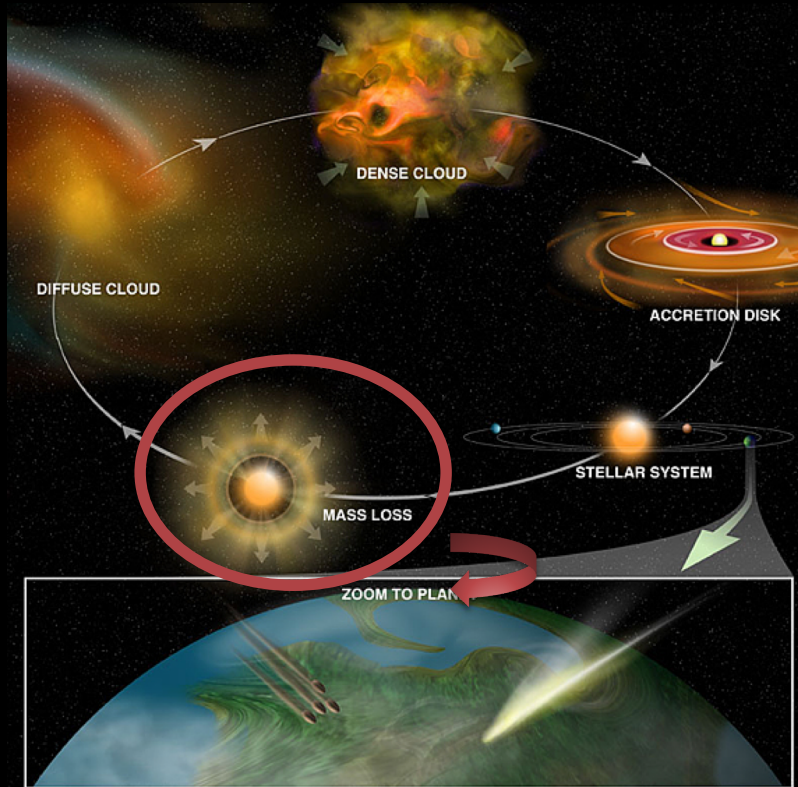
Bow shocks: interaction wind - ISM



Van Marle, 2012

Interstellar budget

Our life: thanks to old stars



STELLAR WIND

✓ water (H, O)

✓ muscles (C)

✓ sand (Si)

✓ atmosphere (N,O)

✓ molecules

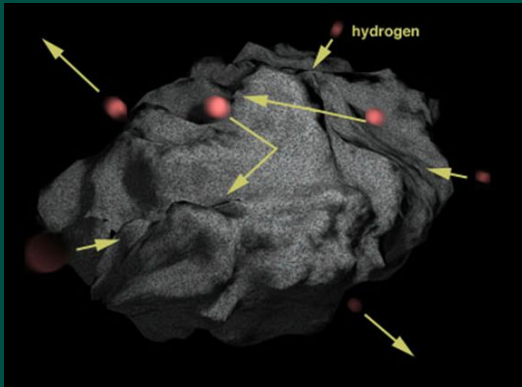
✓ dust

→ unique E.T. chemical labs

Interstellar budget: H₂



surface of dust grains



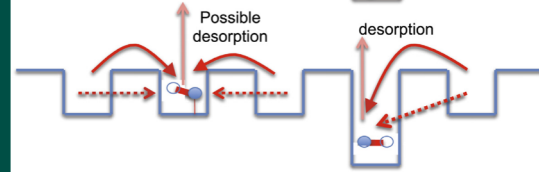
sticking



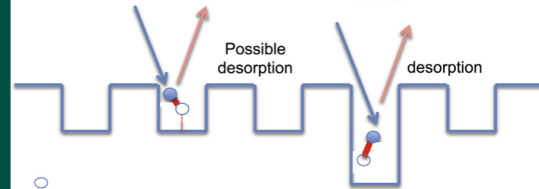
diffusion



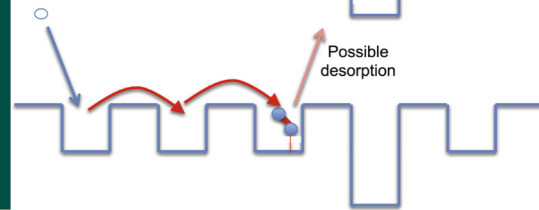
Langmuir-Hinshelwood mechanism



Eley-Rideal mechanism



'hot atom' mechanism



Part IV - The quest of dust nucleation

Oxygen-rich winds

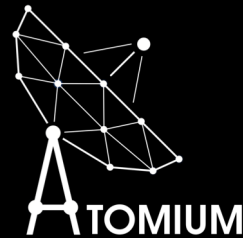
Why?

→ Other astrophysical media

➤ Novae, supernovae, protoplanetary
nebulae, interstellar shocks, exoplanets, ...

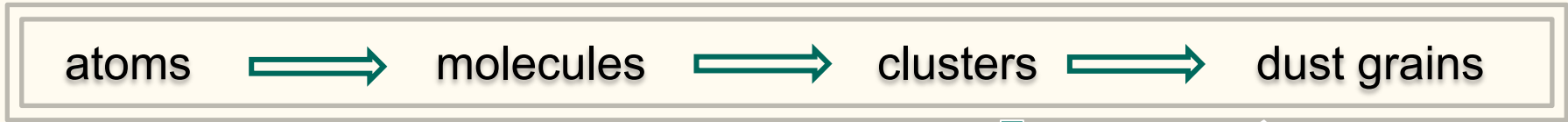
→ ALMA

➤ oxides & hydroxides as dust precursors



Corundum – Conundrum

Setting the stage



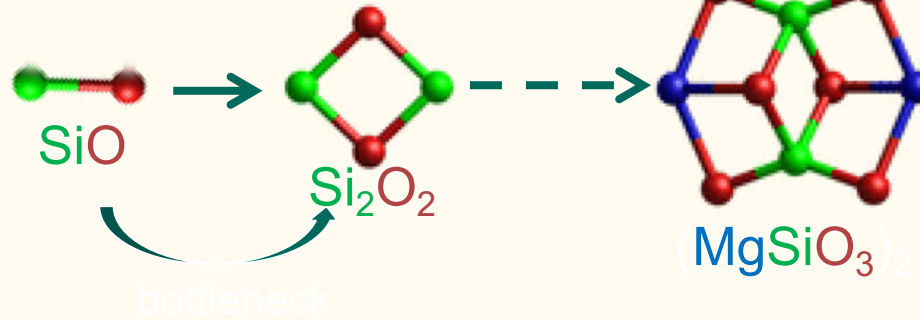
nucleation



condensation

homogeneous

heterogeneous



Goumans 2012, 2013

TiO_2
 TiO

~~Al_2O_3~~
 ~~AlO~~

~~MgO~~

~~SiO_2~~
 ~~SiO~~

high abundance
high bond energy

low abundance

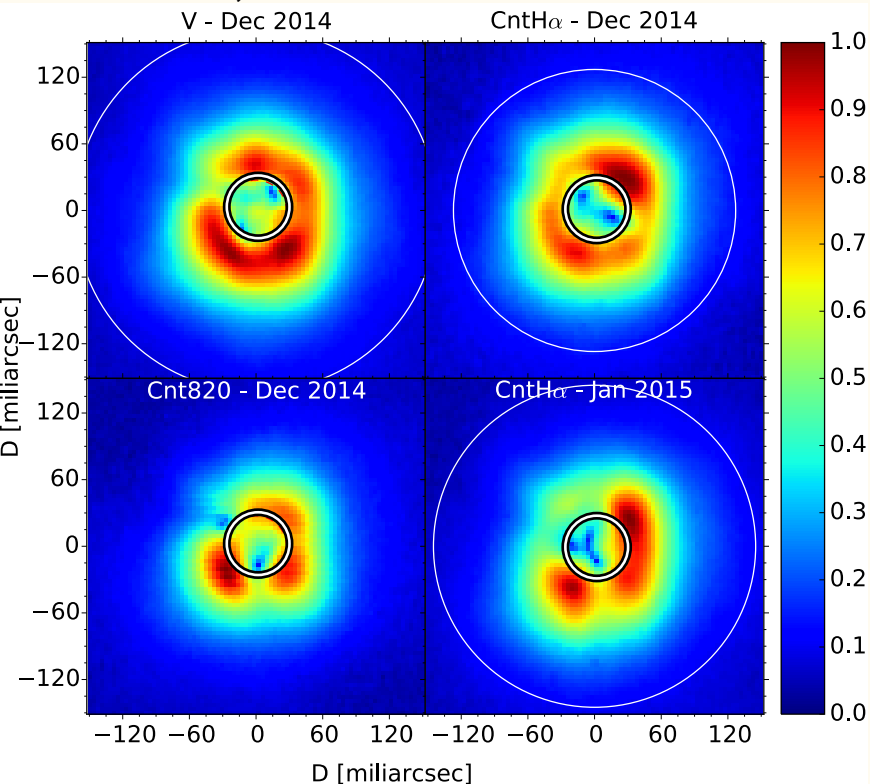
X
no stable cluster
nucleation rate too low

Corundum – Conundrum Observations

—

Dust grains in R Dor

Norris 2012, Khouri 2016



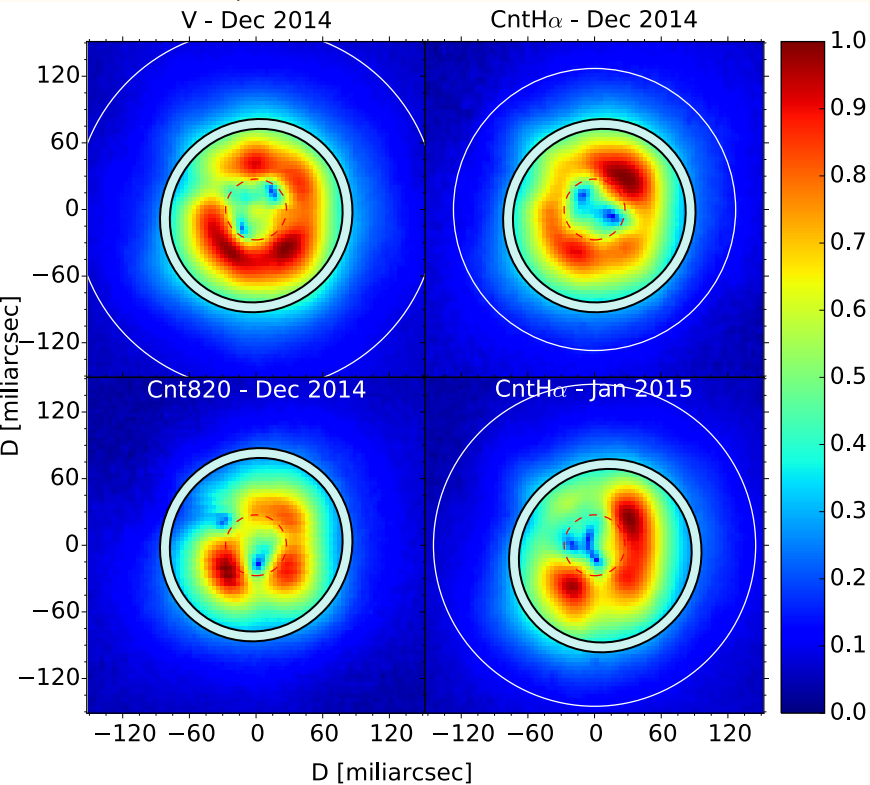
→ Large (300 nm) grains at 0.5 R_*

➤ Composition?
Fe-free silicates or Al_2O_3

○ = stellar surface

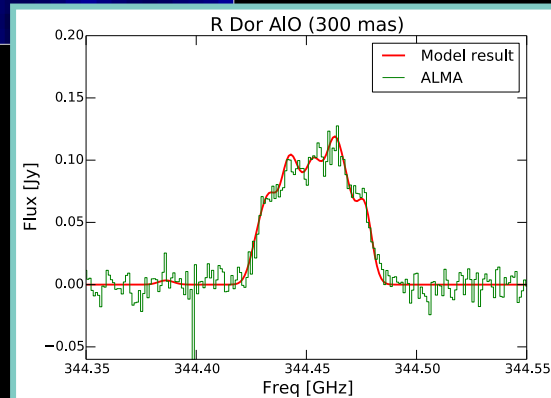
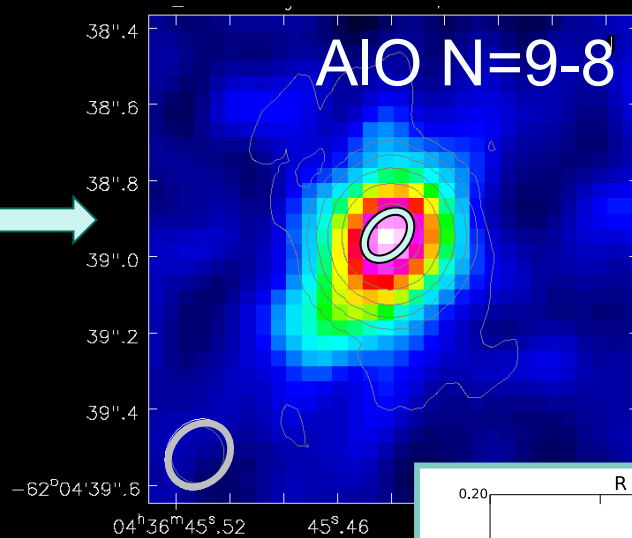
Dust grains

Norris 2012, Khouri 2016

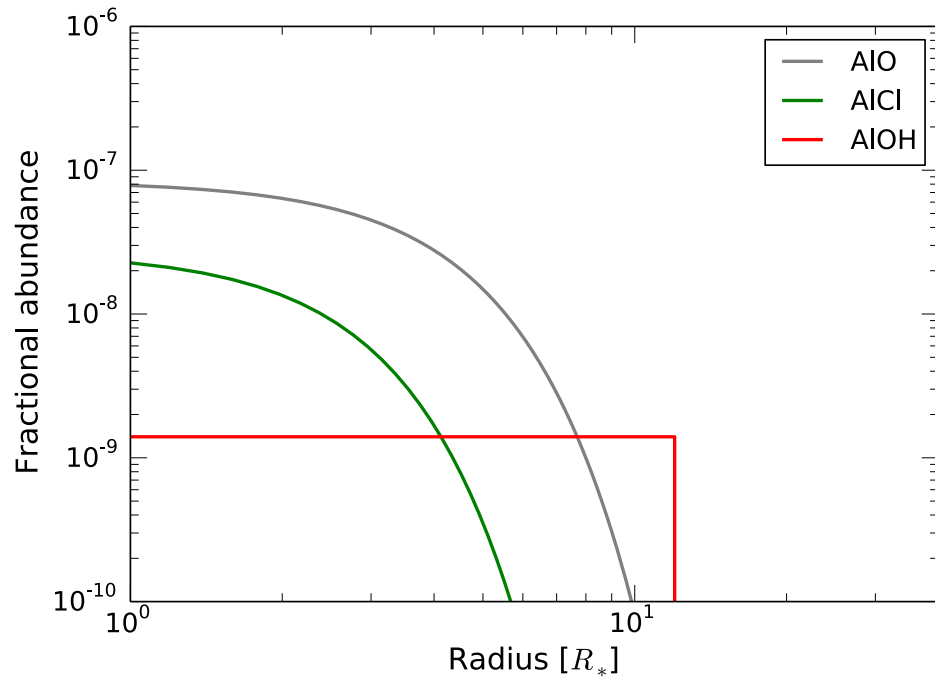


Al-bearing molecules

AIO, (AIOH), AlCl



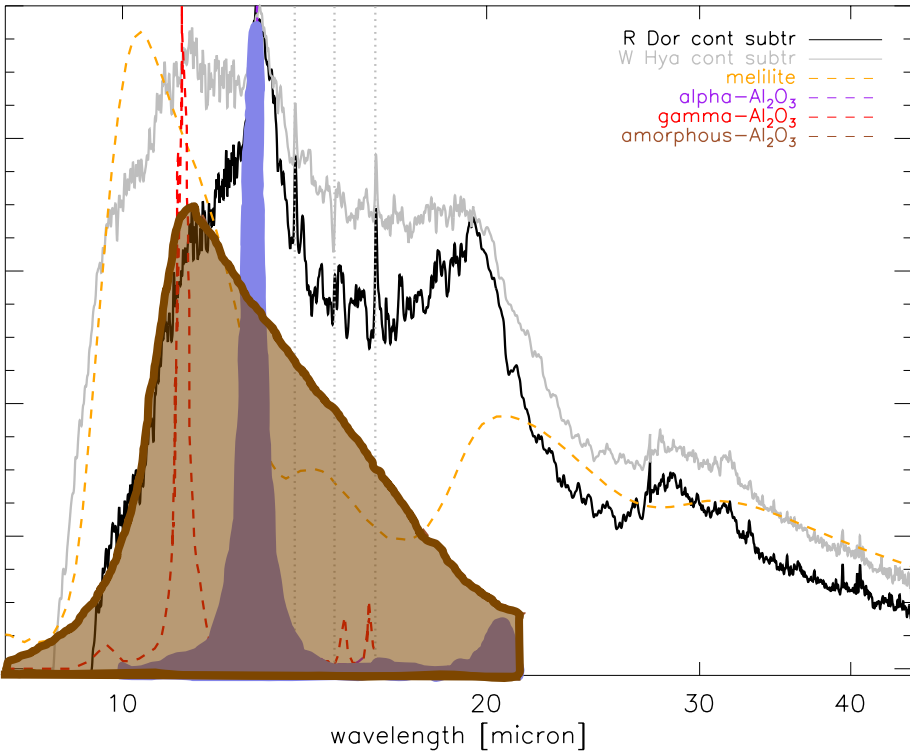
Al-bearing molecules



→ $\lesssim 2\%$ Al

➤ Room for Al-bearing grains

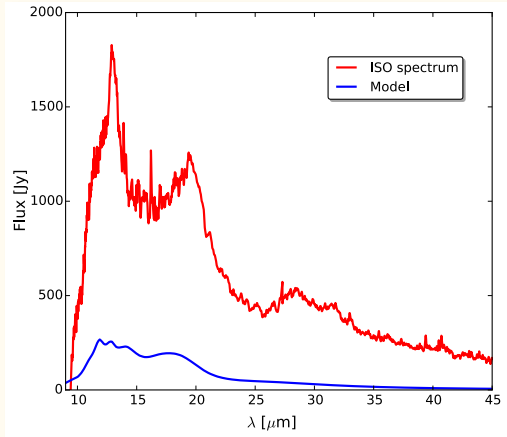
Spectral energy distribution



→ Al₂O₃ grains
➤ crystalline (α -Al₂O₃) + amorphous

Al_2O_3 dust grains in R Dor

Al_2O_3 emission from outflow

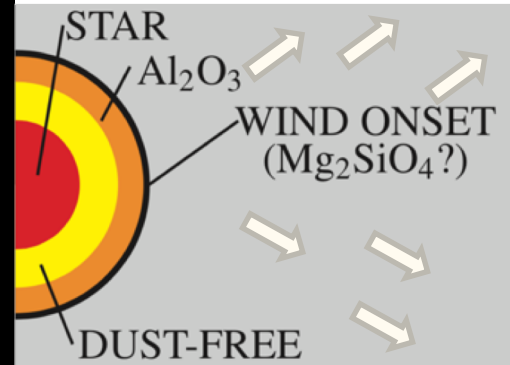
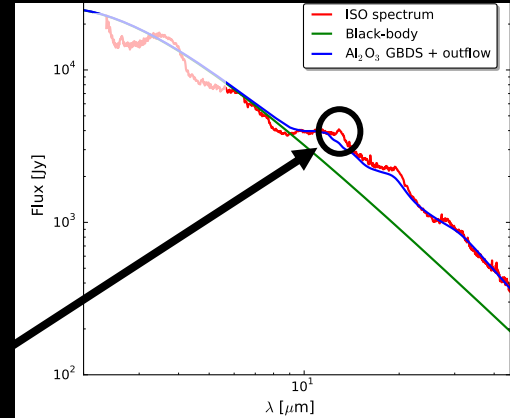


$(\text{Al}_2\text{O}_3) \sim 1200 - 1600\text{K}$

crystalline!

11 micron feature?

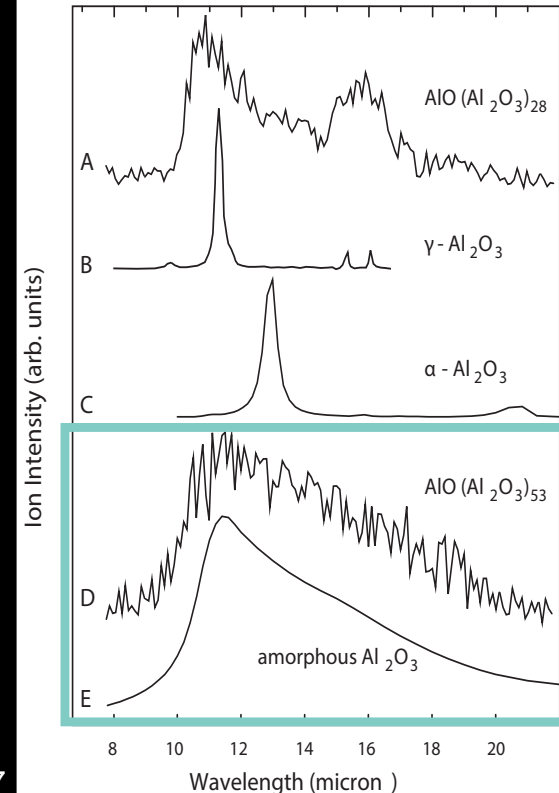
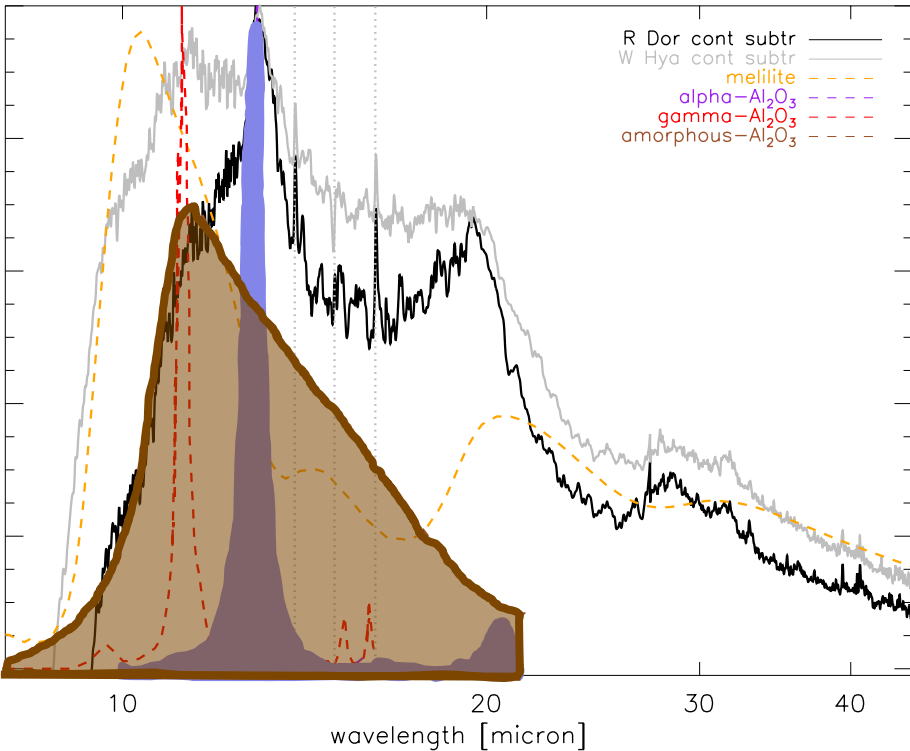
Al_2O_3 emission from GBDS+outflow



Khouri 2015

Conjecture

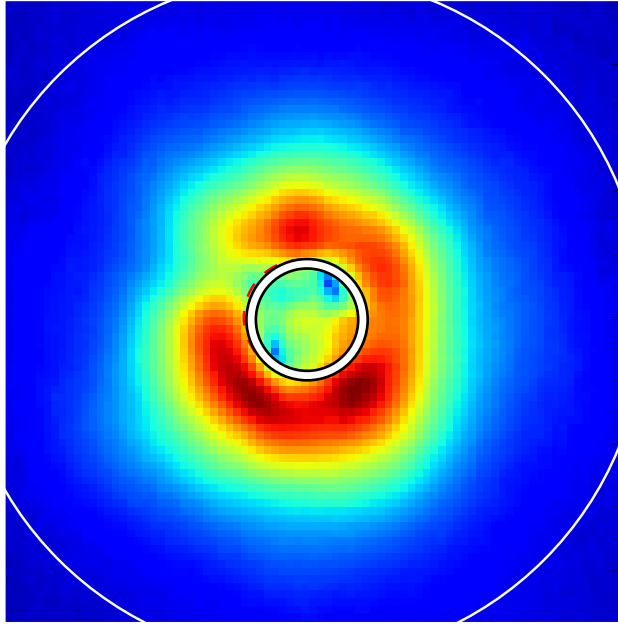
large clusters $(\text{Al}_2\text{O}_3)_n$ ($n \geq 34$)



van Heijnsbergen 2003,
Demyk 2004, Decin 2017

Conundrum...

Norris 2012, Khouri 2016



○ = stellar surface

?

- Large (300 nm) grains at 0.5 R_*
- Composition: Fe-free silicates or $\alpha\text{-Al}_2\text{O}_3$?
- First condensation seeds?

Corundum – Conundrum: Theory



Self-consistent AGB wind

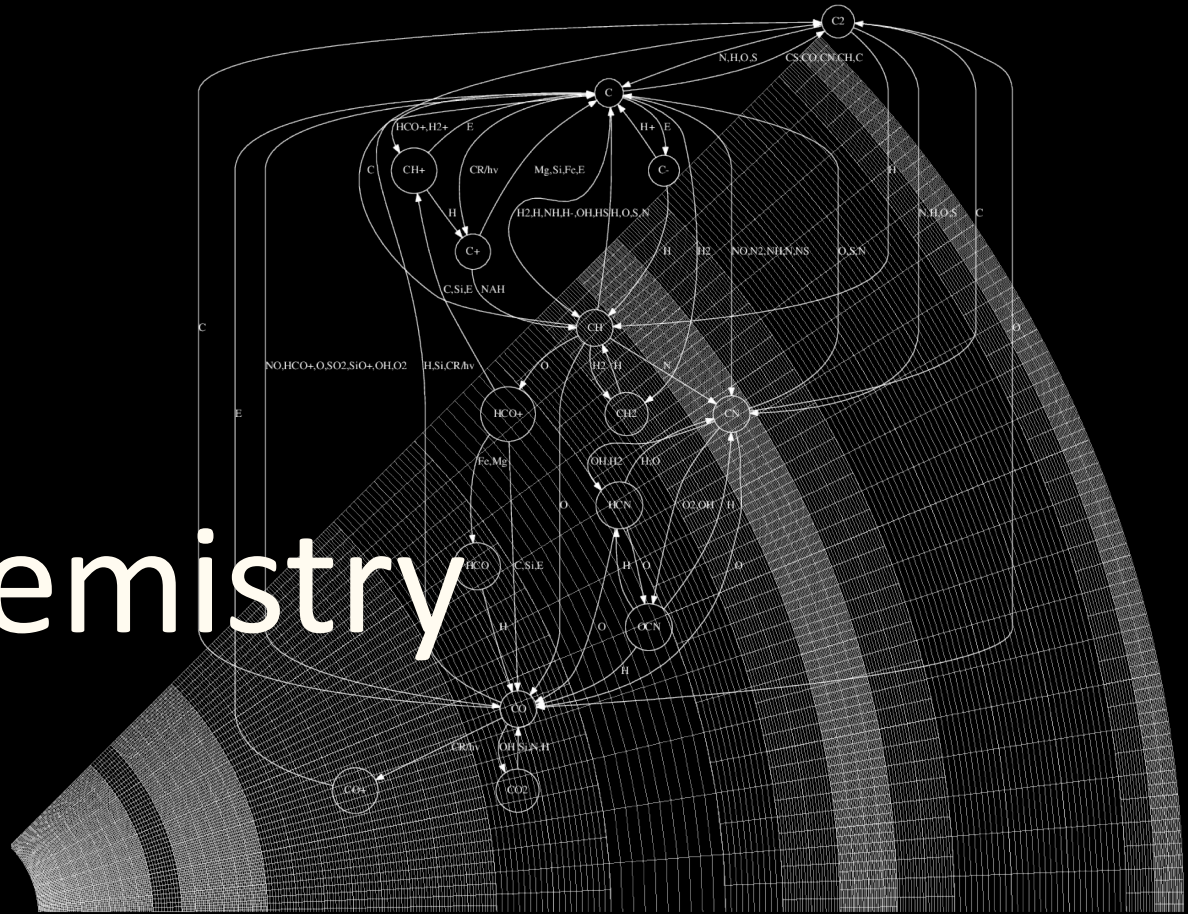
Hydrochemistry



Nucleation theory

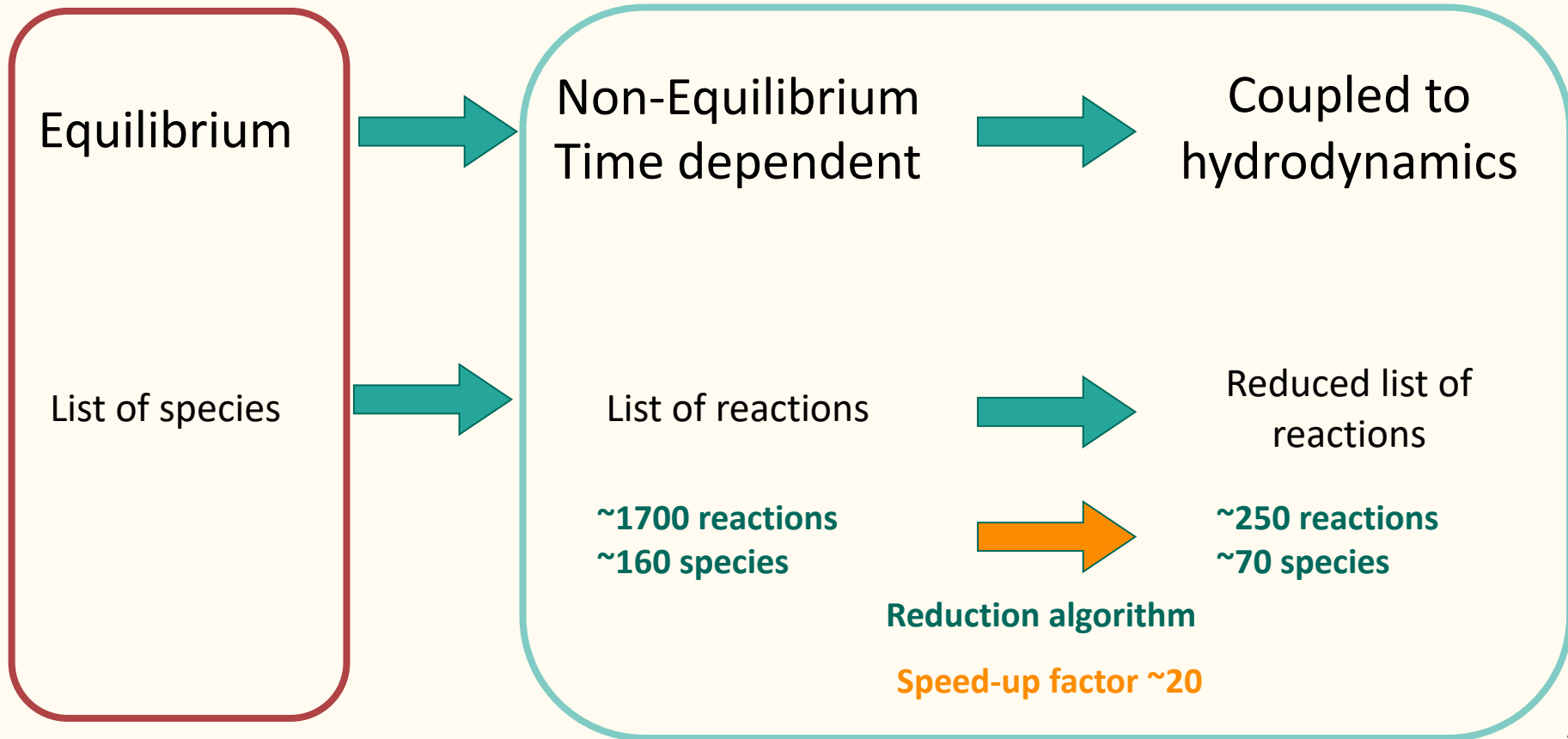


Dust evolution with
radiation field

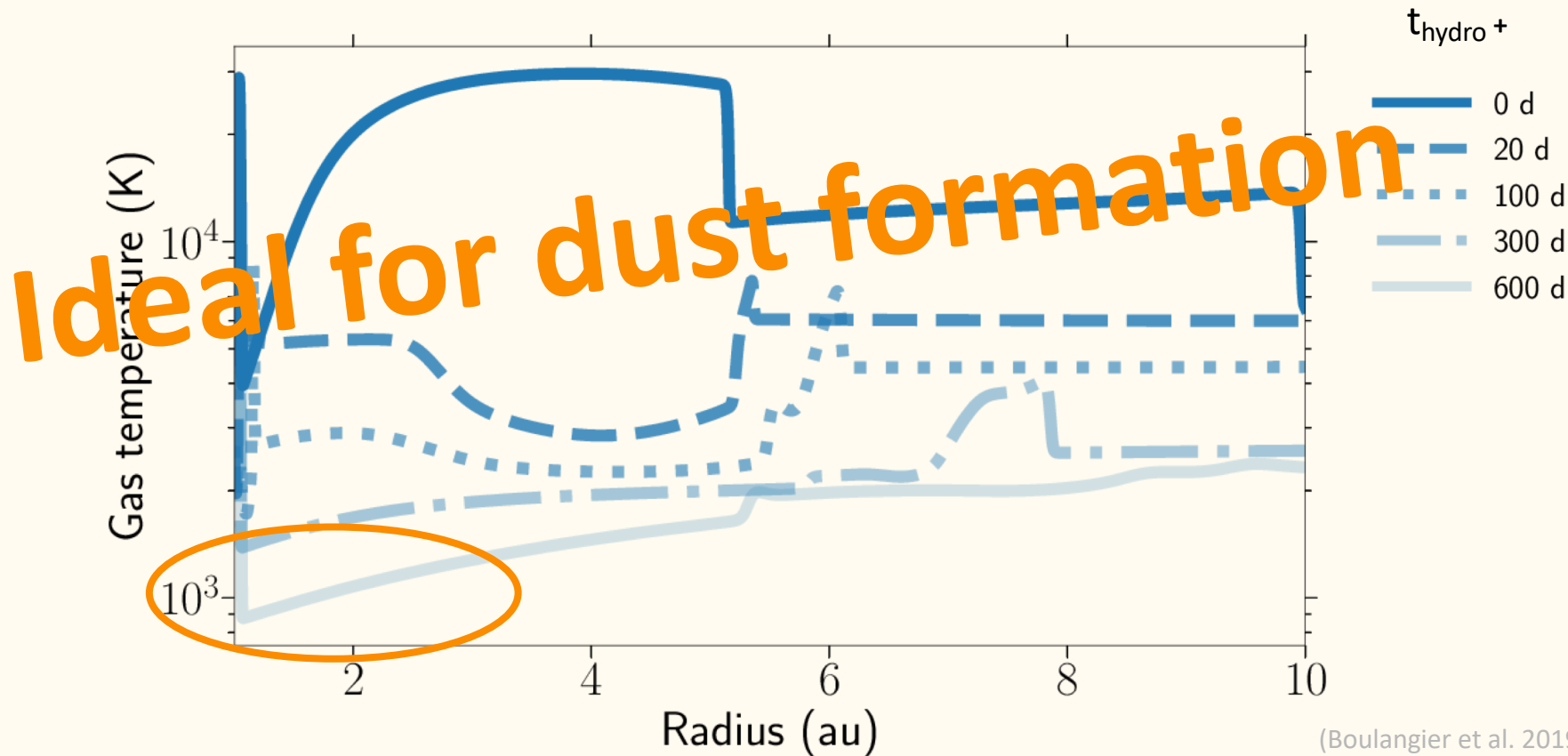


Current chemistry

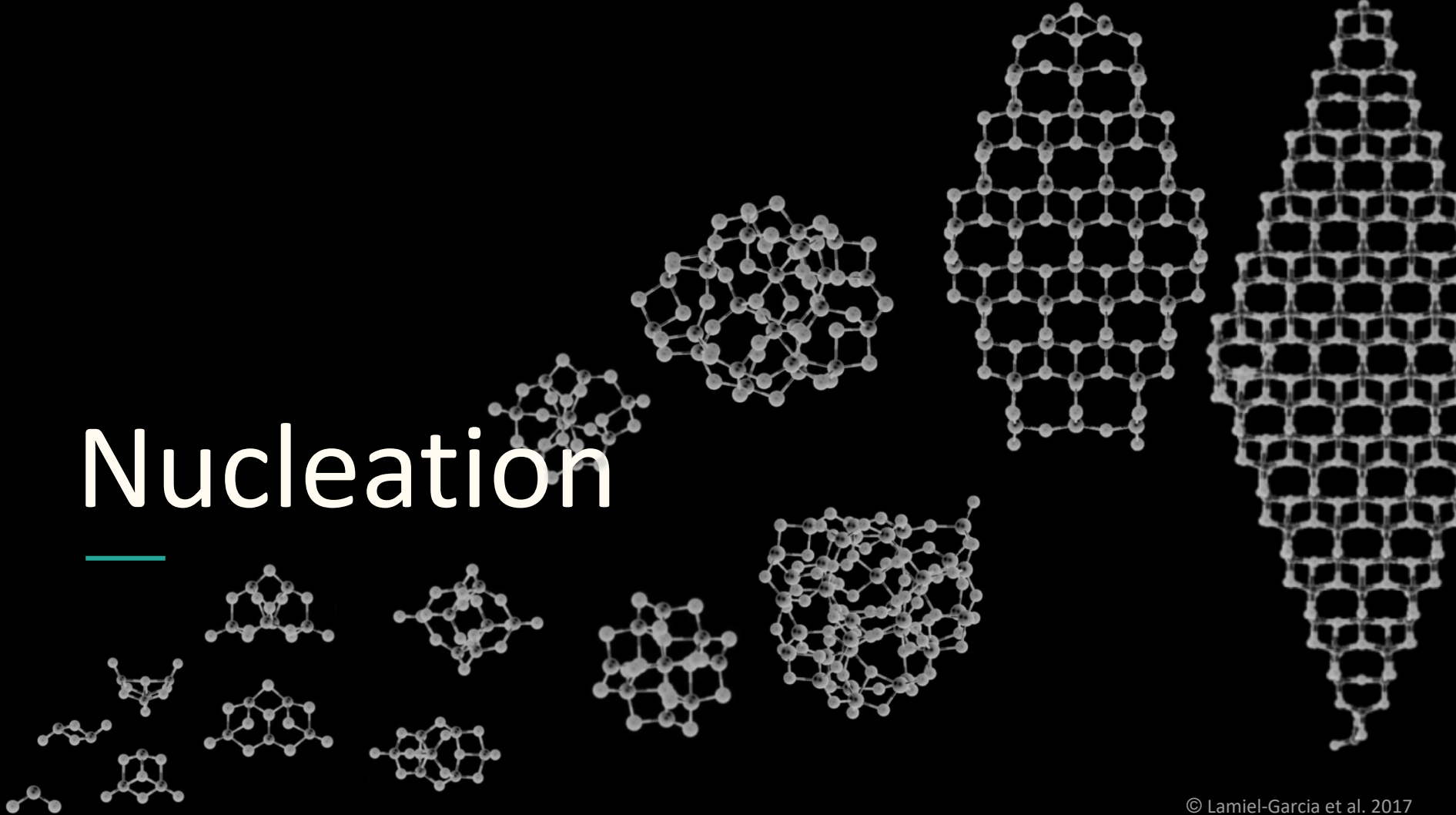
2 step improvement



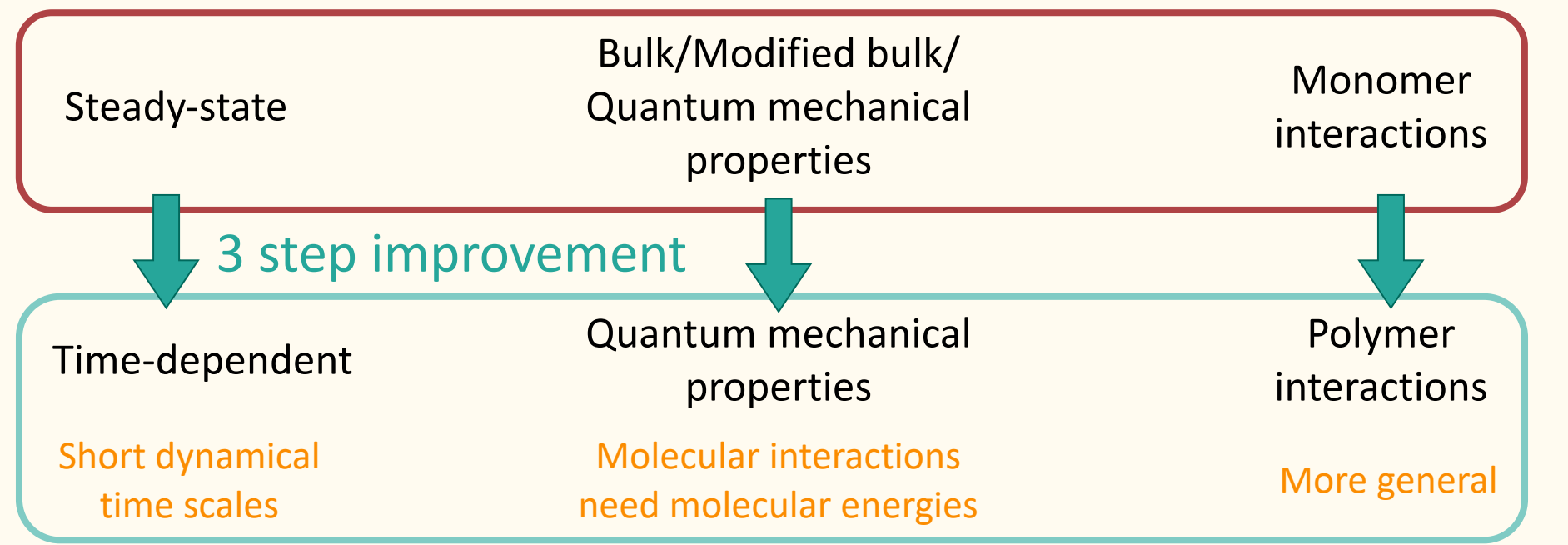
Cooling is super efficient



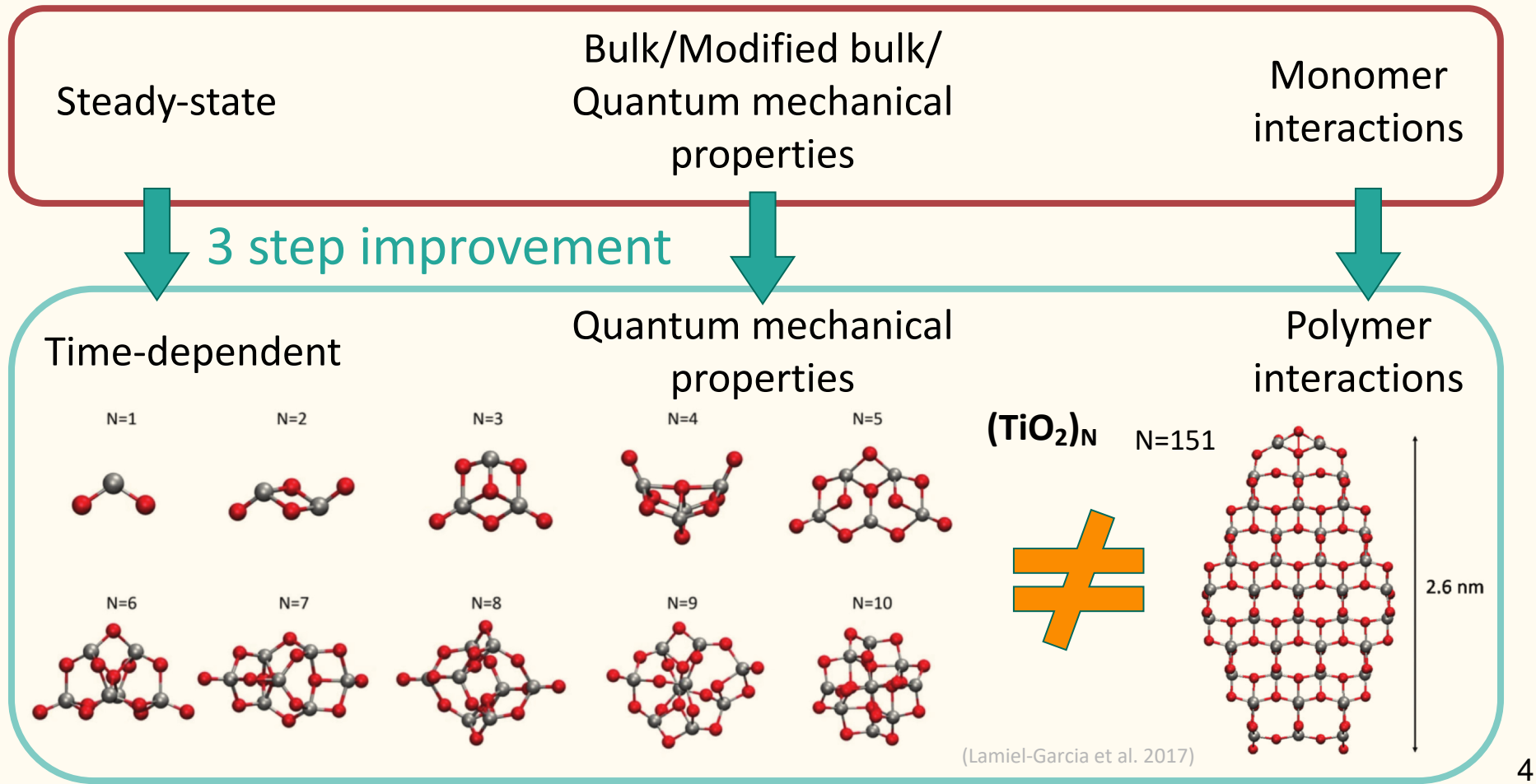
Nucleation



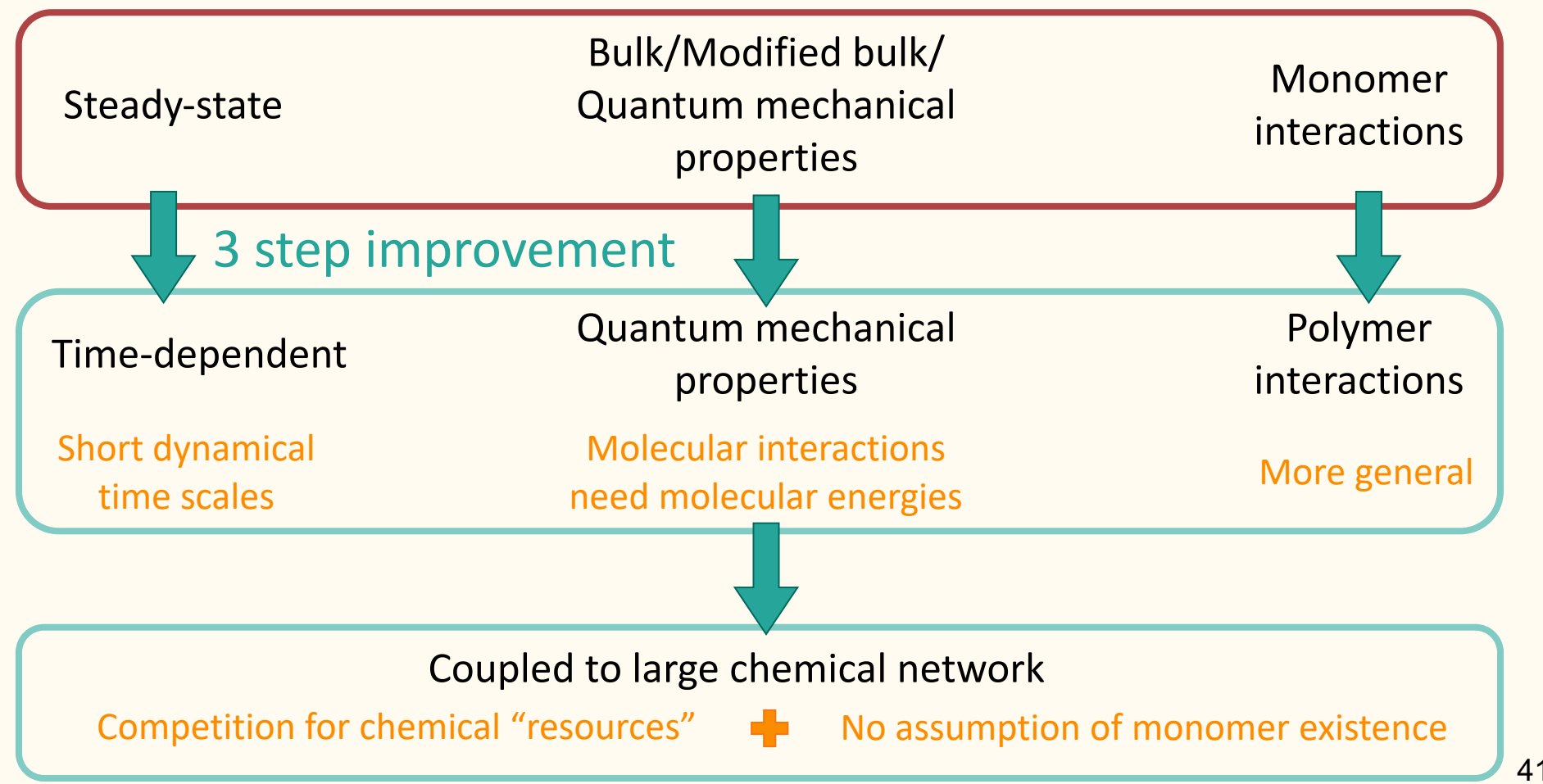
Current nucleation



Current nucleation



Current nucleation



Nucleation candidates choice based on

Presolar grains



High bond energies



Atomic abundances

$(\text{TiO}_2)_N$

$(\text{SiO})_N$

$(\text{MgO})_N$

$(\text{Al}_2\text{O}_3)_N$

N_{max}

10

10

10

8

Quantum
mechanical
properties

DFT

lowest energy isomer $\rightarrow$ Gibbs free energy $\rightarrow$ reversed reaction rate

Extra
reactions

~20

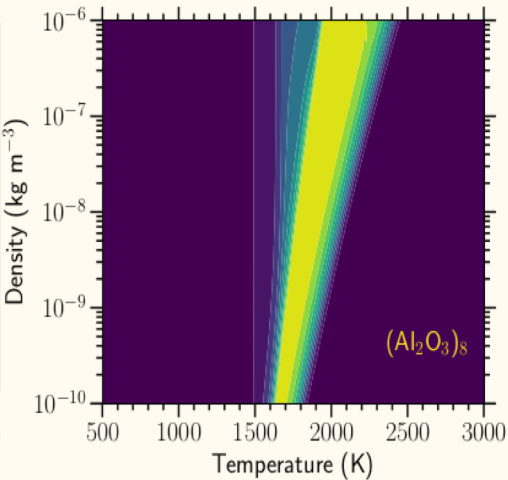
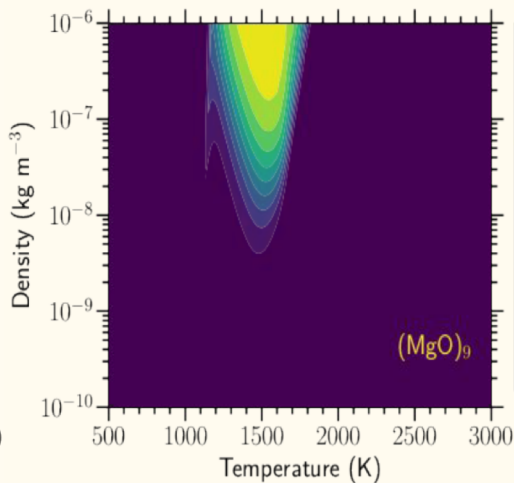
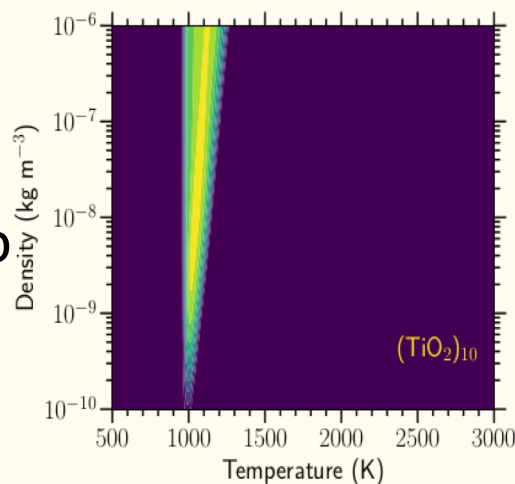
1

~50

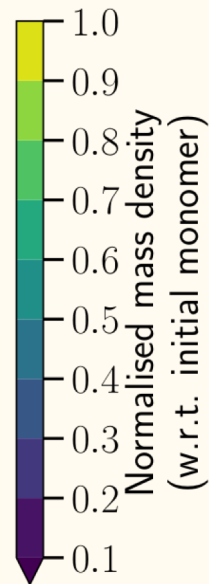
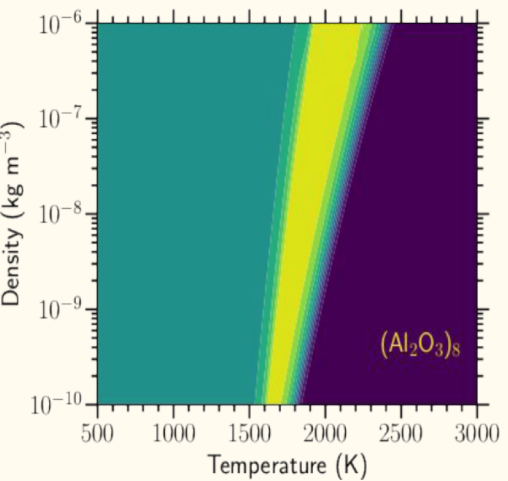
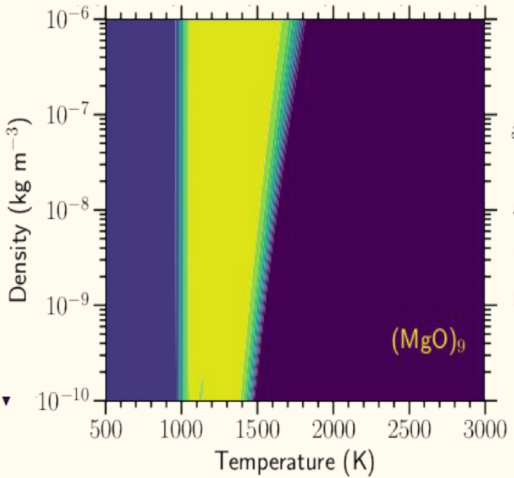
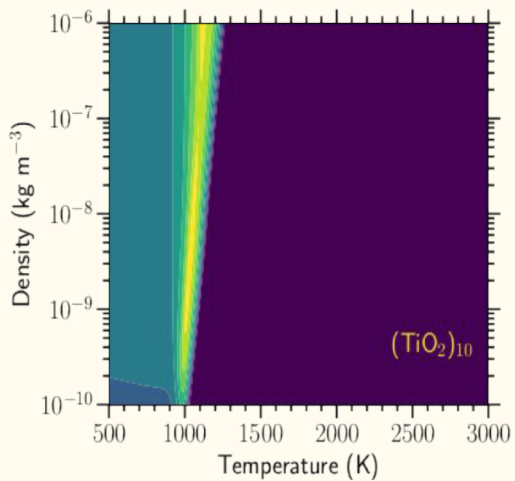
~100



Mono



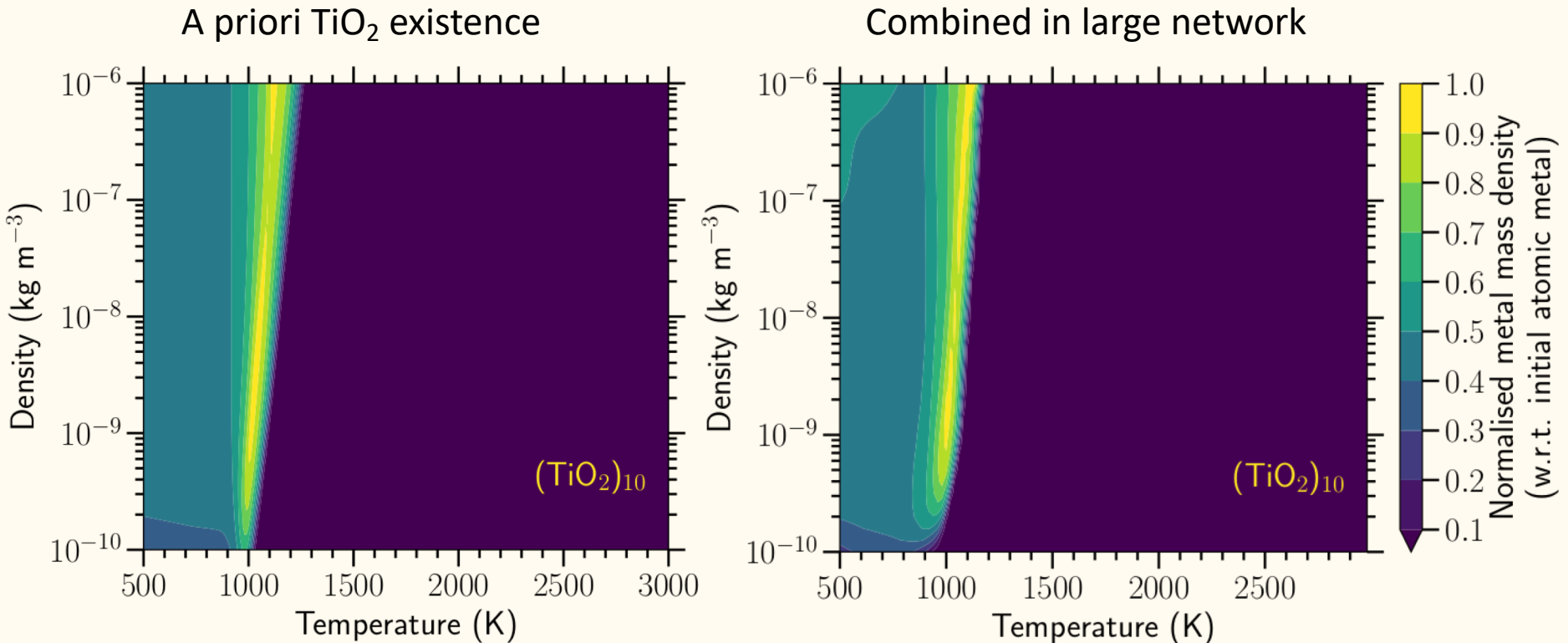
Poly



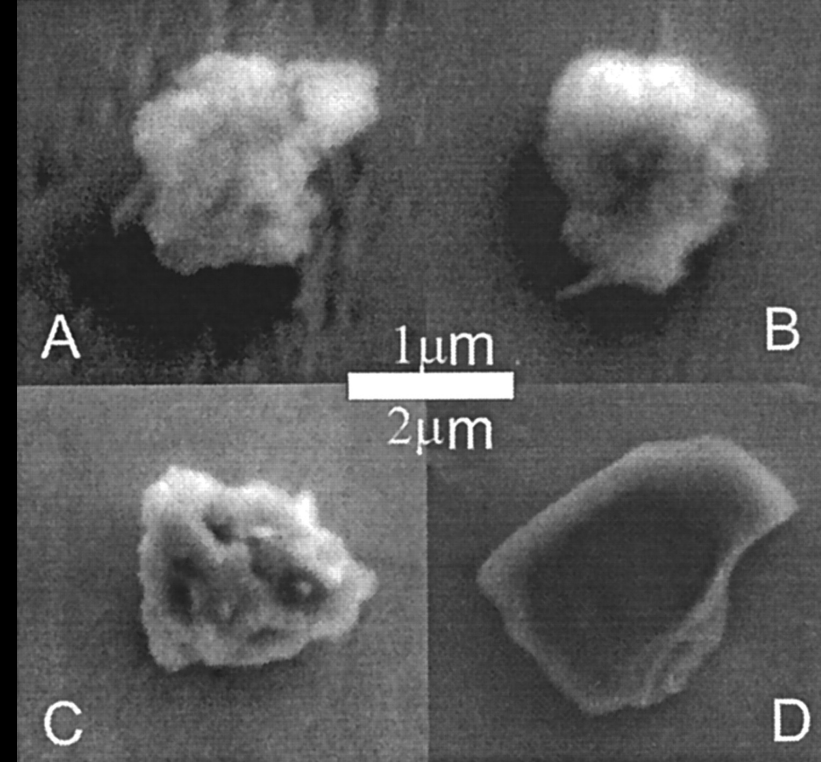
What if combined with network?

1. No Al_2O_3 → No Al_2O_3 -clusters
2. No MgO → No MgO -clusters
3. SiO -clusters equally inefficient
4. TiO_2 -clusters equally efficient

TiO₂-clusters are the best candidate



Planet Earth — Meteorites



Al_2O_3 -clusters are best candidate

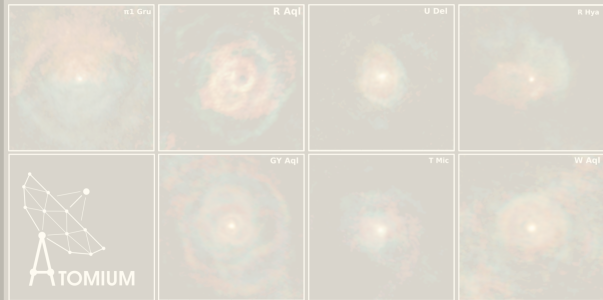
- Abundant in **presolar grains**
(much more than Ti-oxides)
- **Dust** observed close to the star
(at **high temperature**)
Only feasible for Al_2O_3
- Need for **revision of Al-reactions** or
circumvent $(\text{Al}_2\text{O}_3)_{n=1}$

Corundum = Conundrum

Future



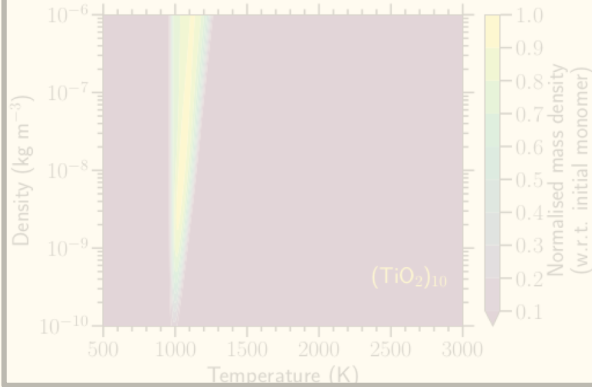
Observations



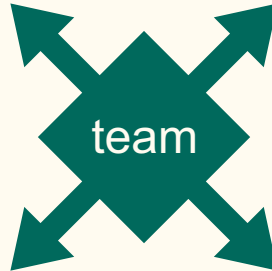
Gallery of the winds of red giant stars
ALMA – ATOMIUM Large Program

- Under embargo -

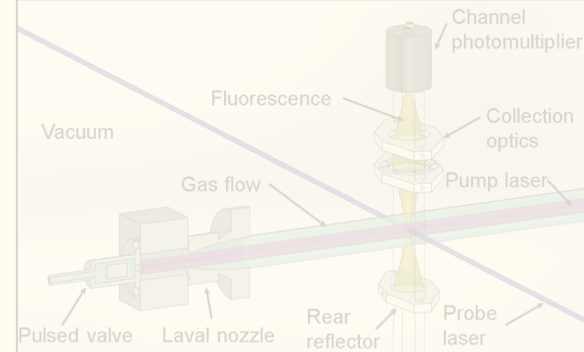
parsec



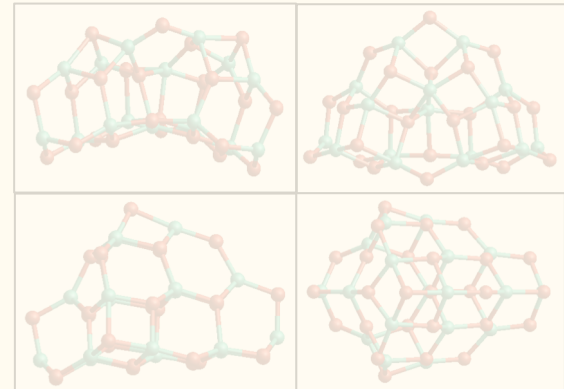
Simulations



Laboratory

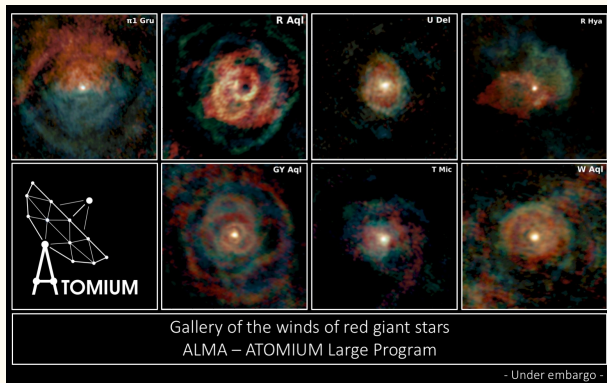


nanometer

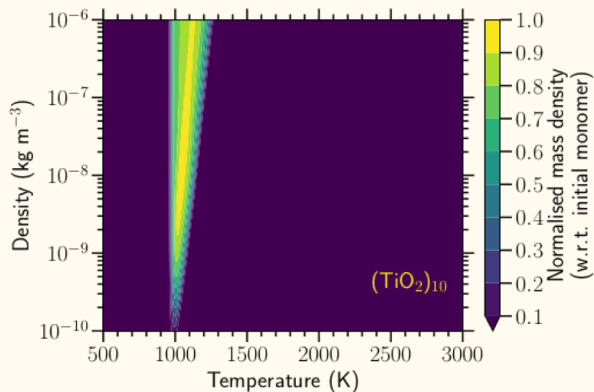


Theory

Observations



parsec



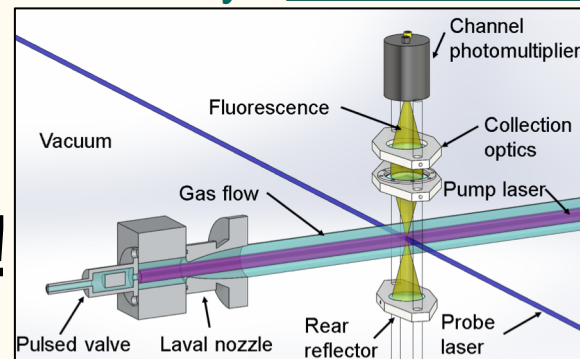
Simulations

THANKS!

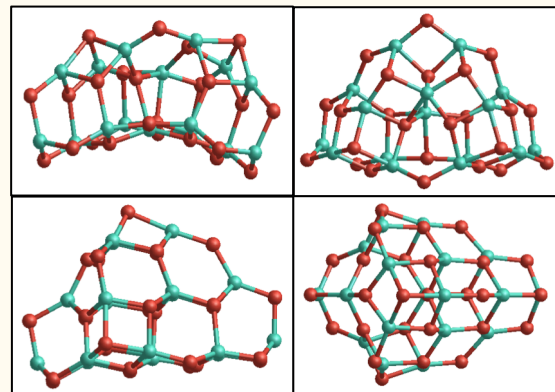
team

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Laboratory



nanometer



Theory