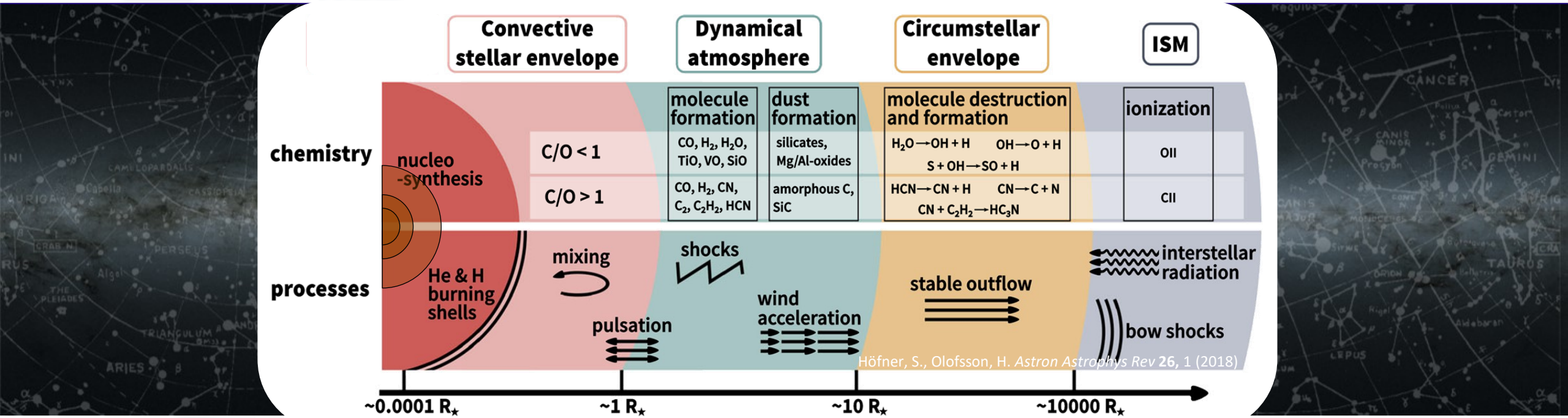
Radioactive Molecules in Space

A. A. Breier, T. F. Giesen

June 30, 2021



Höfner, S., Olofsson, H. *Astron Astrophys Rev* **26,** 1 (2018)

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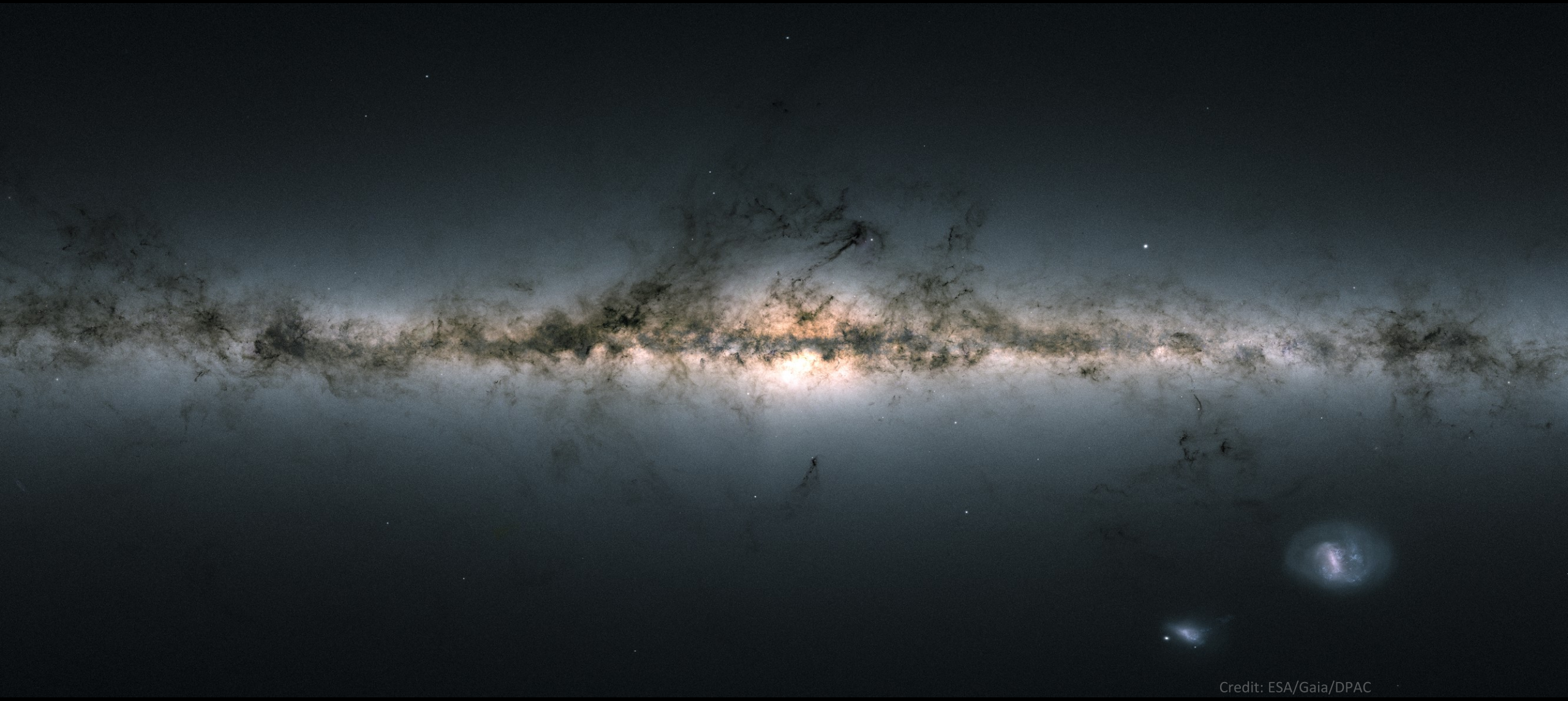
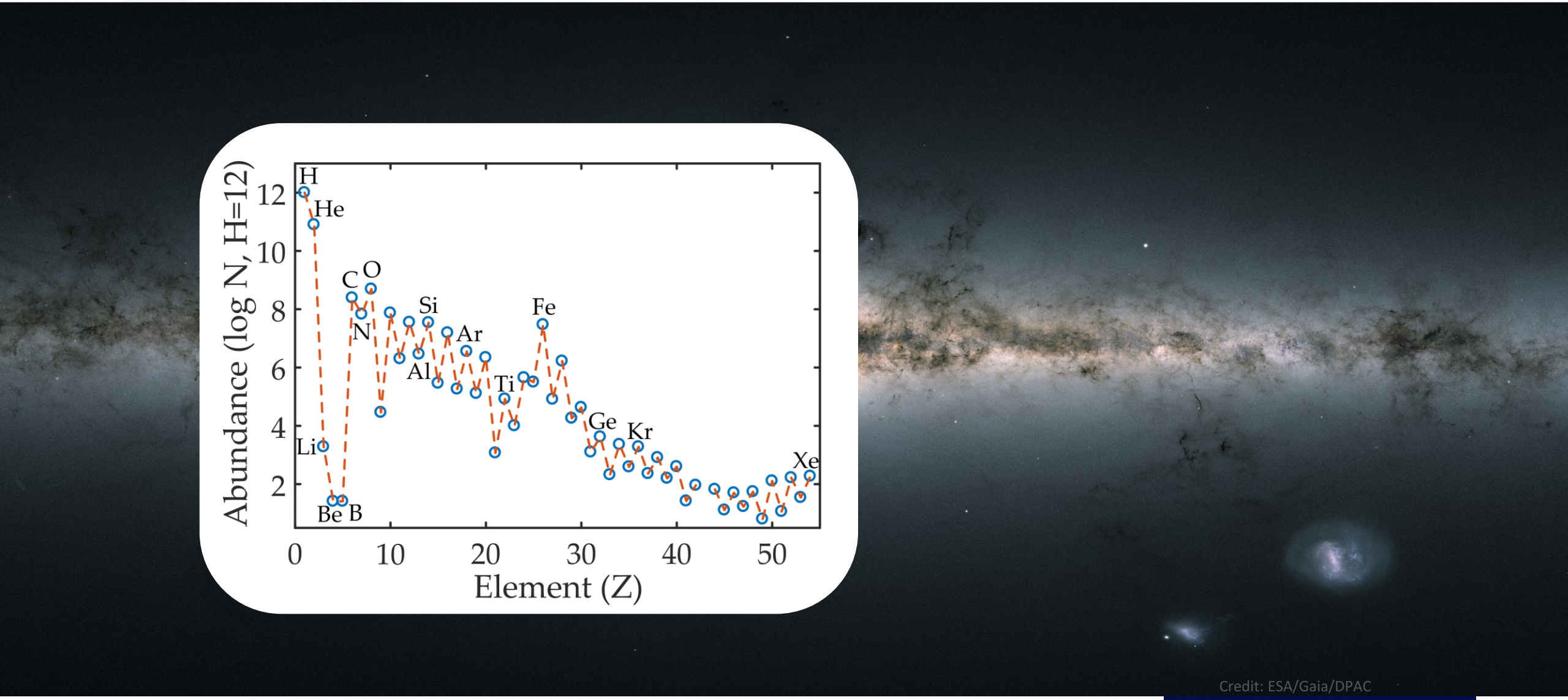
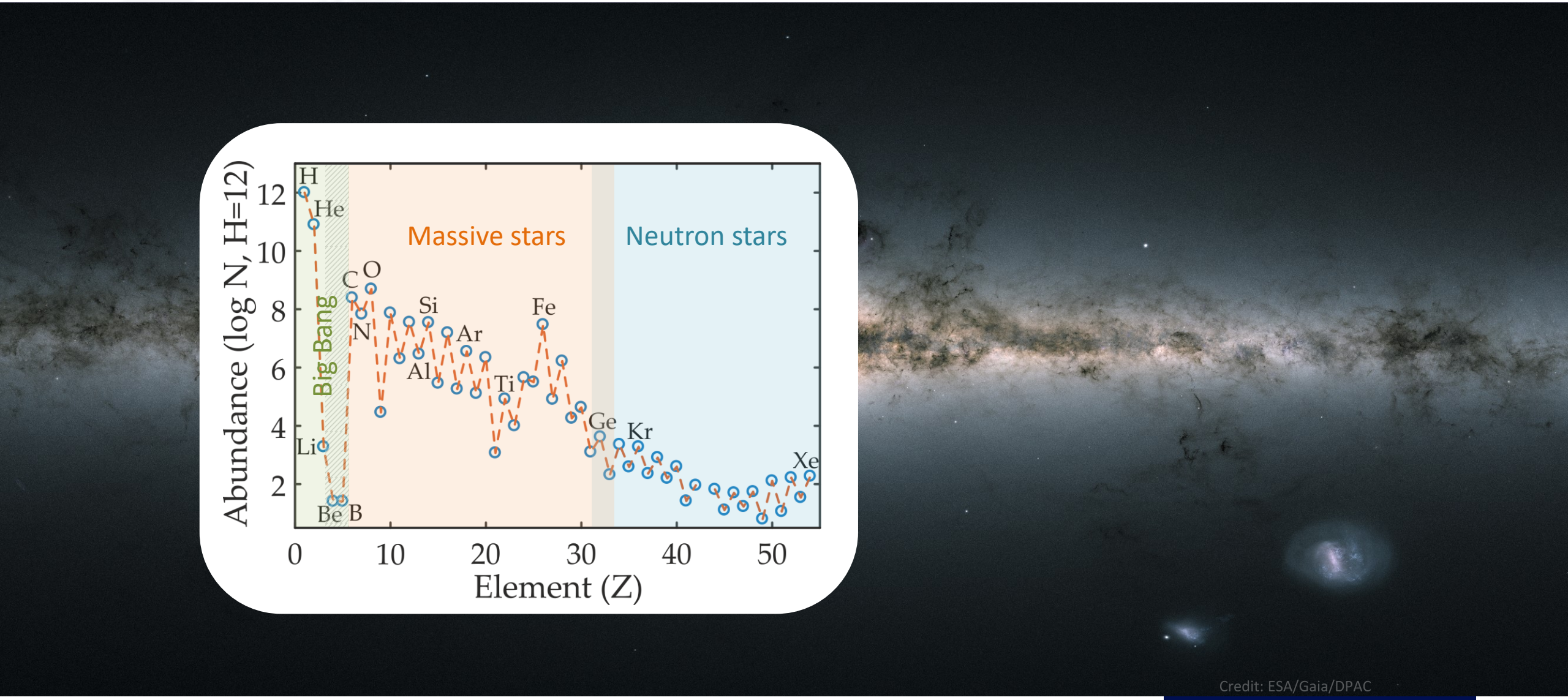

Credit: ESA/Gaia/DPAC



Credit: ESA/Gaia/DPAC



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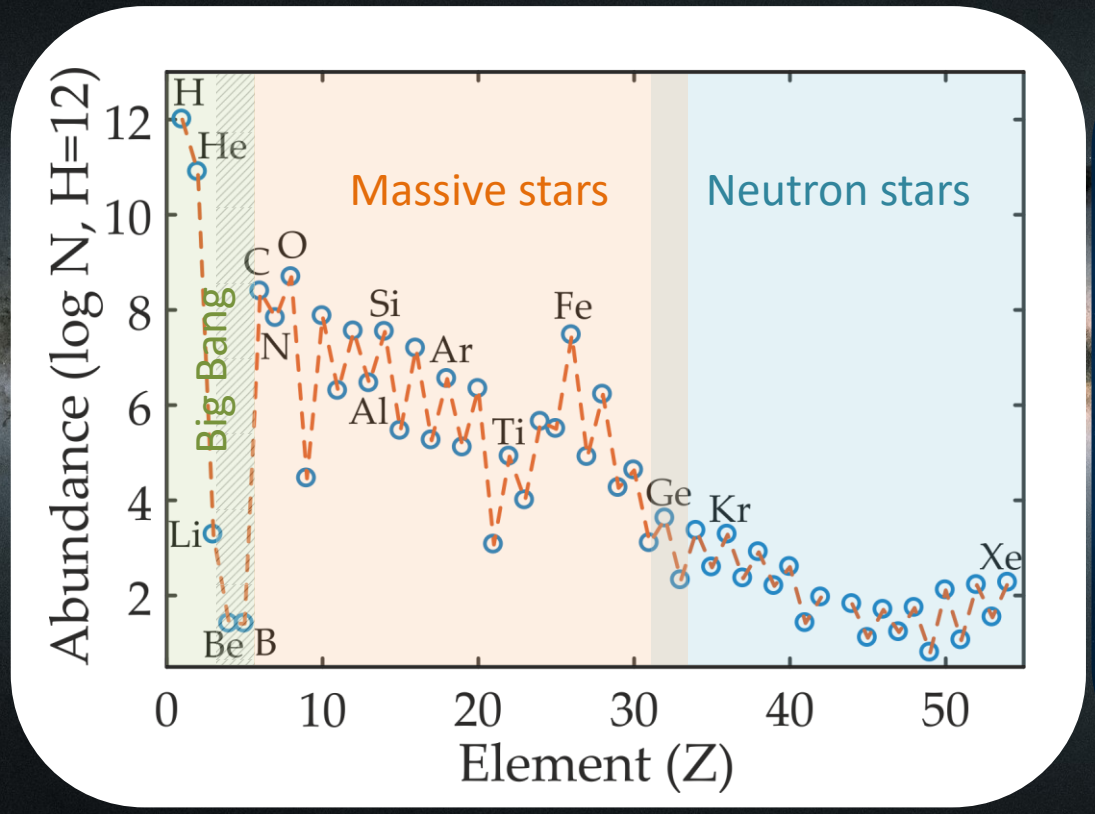
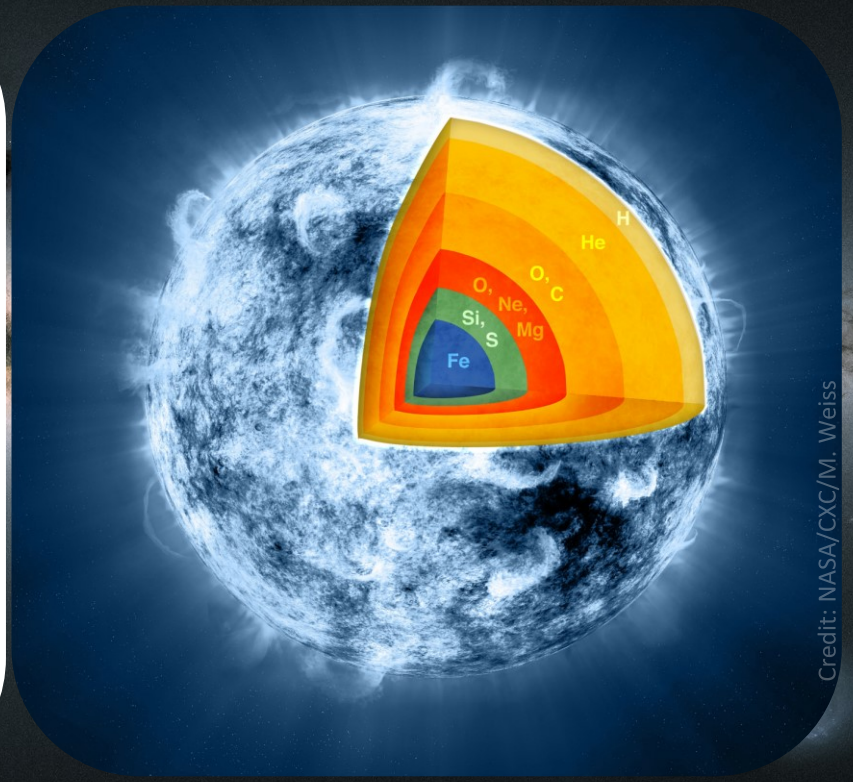
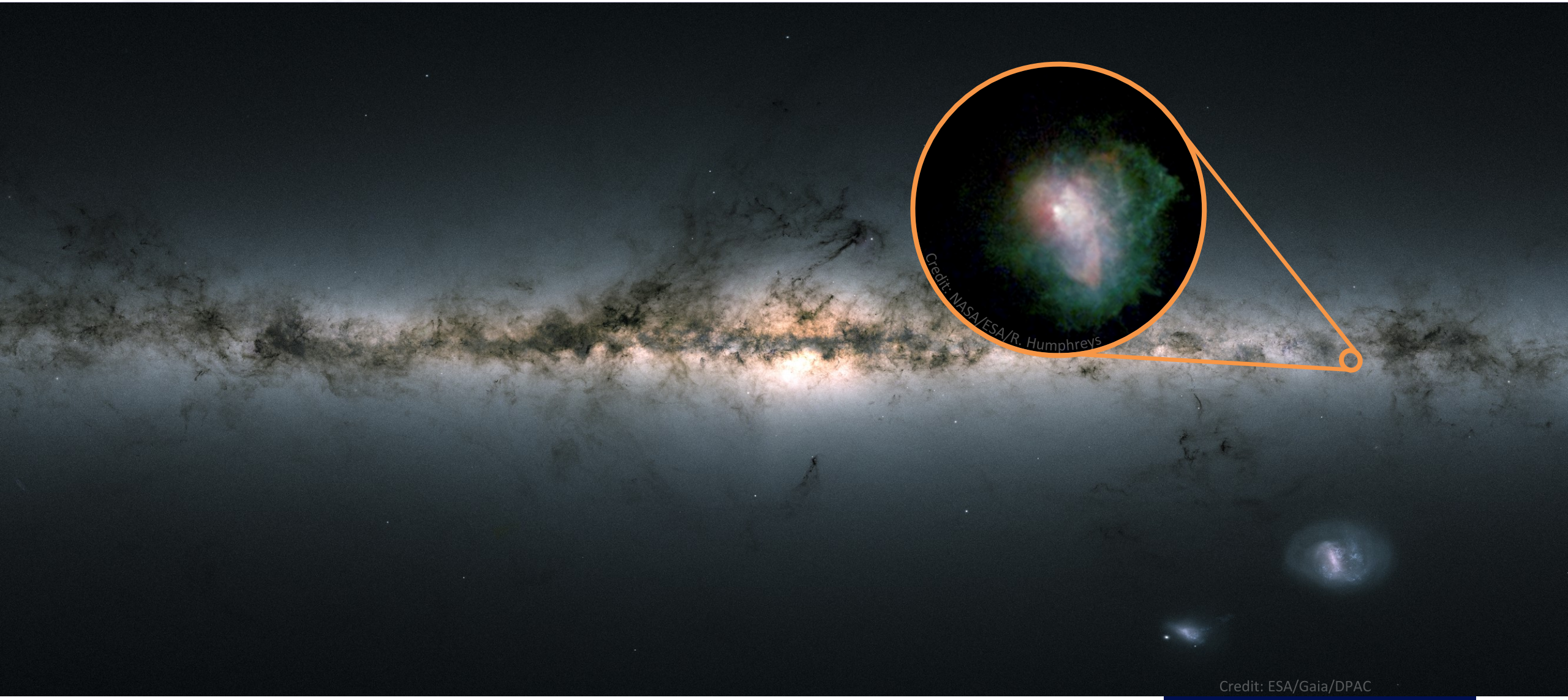
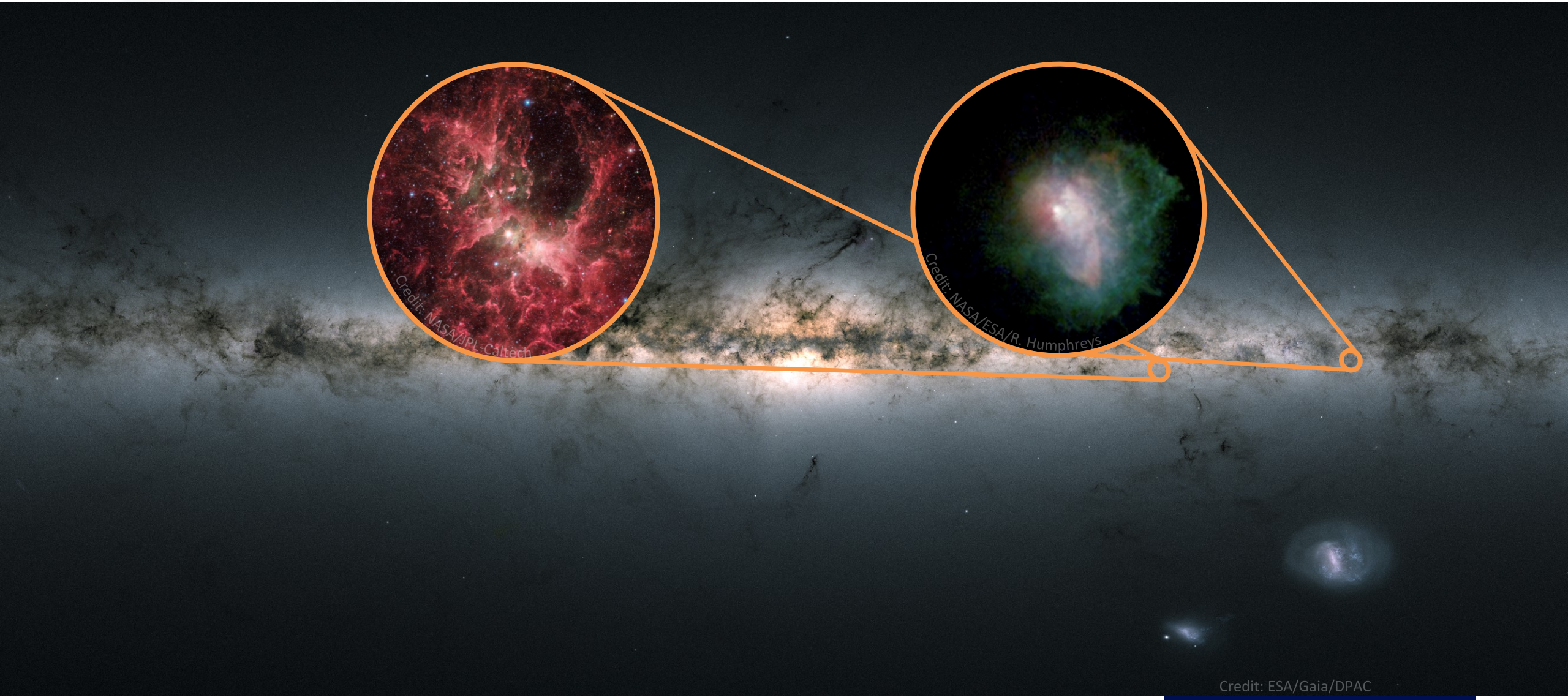


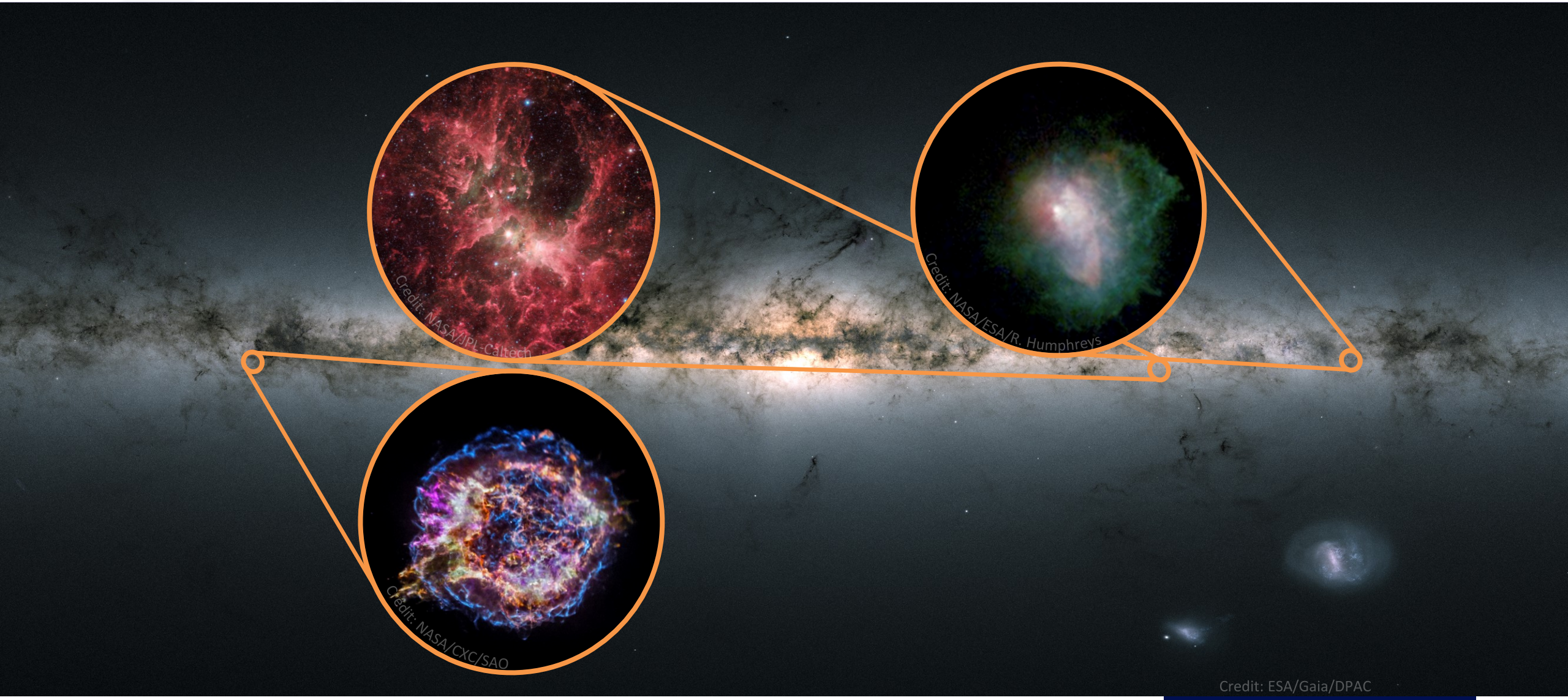


Credit: NASA/CXC/M. Weiss

Credit: ESA/Gaia/DPAC


Credit: NASA/ESA/R. Humphreys
Credit: ESA/Gaia/DPAC


Credit: NASA/JPL-Caltech
Credit: NASA/ESA/R. Humphreys
Credit: ESA/Gaia/DPAC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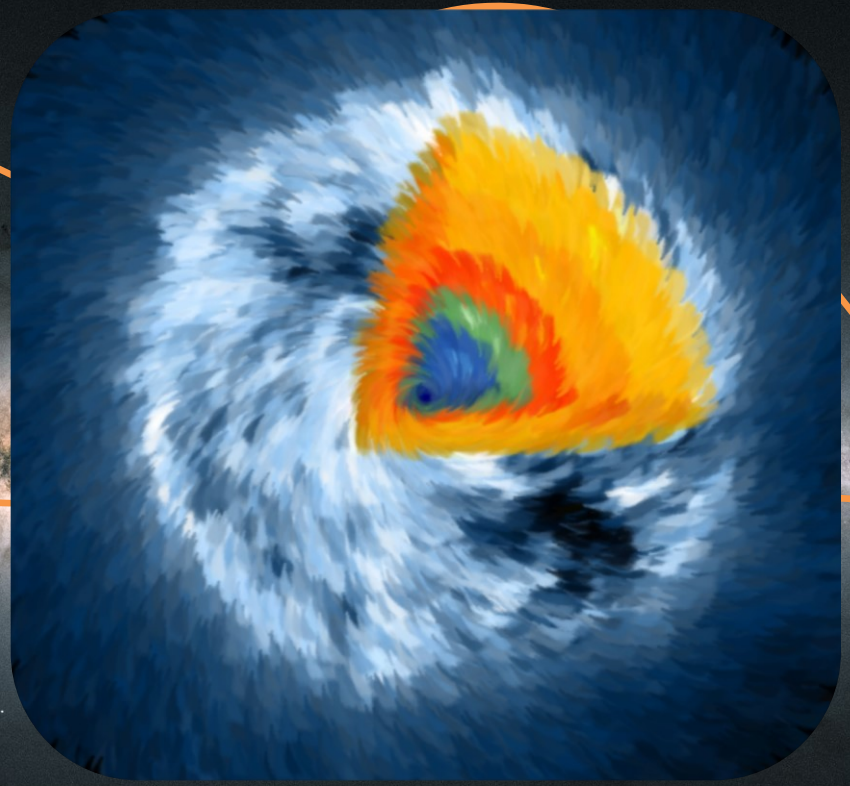
Credit: NASA/ESA/R. Humphreys
Credit: NASA/CXC/SAO
Credit: ESA/Gaia/DPAC

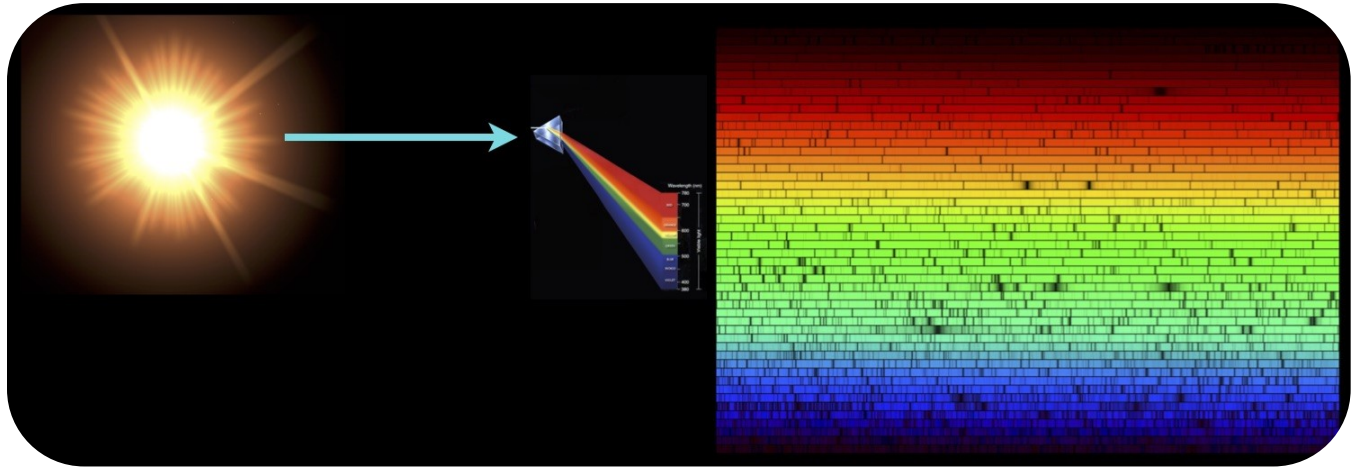
Credit: NASA/CXC/M. Weiss



Understanding stellar evolution by observing radioactive nuclei

Credit: ESA/Gaia/DPAC

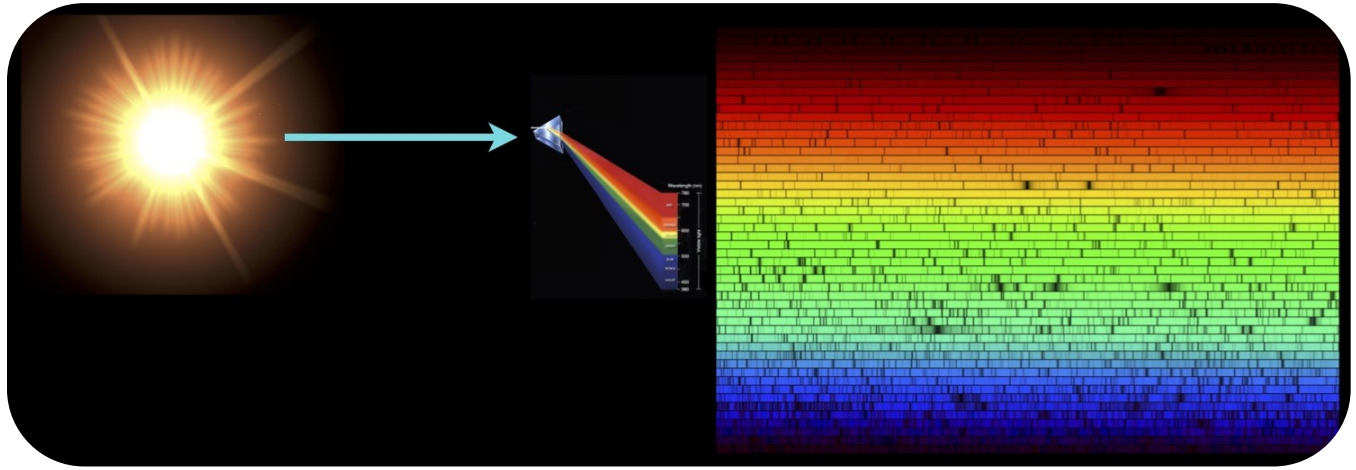
Radioactive atoms in space



Radioactive atoms in space

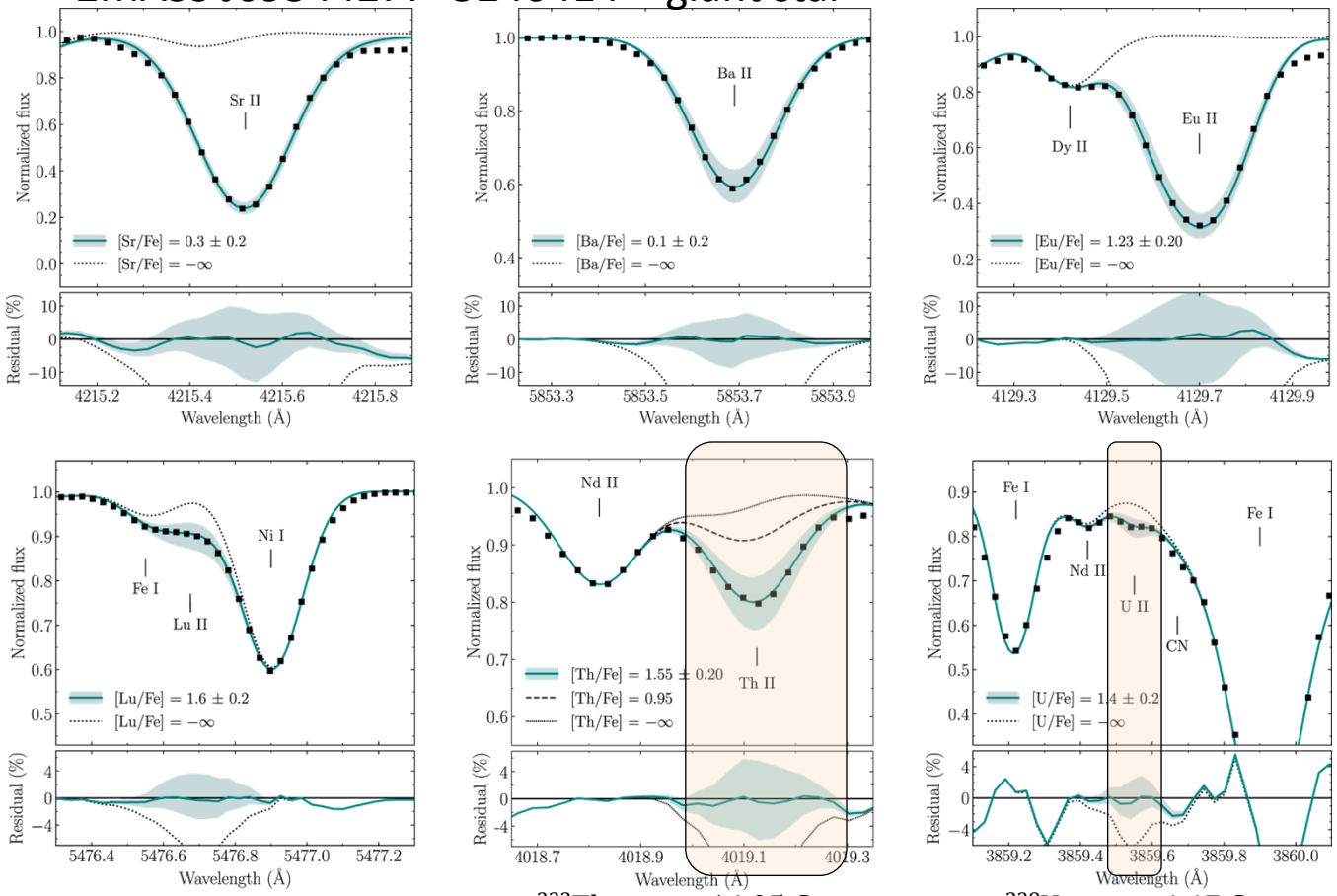
2.7 m (107") Harlan J. Smith Telescope

- Photon energy range: 340 nm -1000nm (R~60000)
- Spatial resolution: >10“ (crater on the moon)



Radioactive atoms in space

2MASS J09544277+5246414 – giant star



^{232}Th: $\tau_{1/2} = 14.05$ Gyr

^{238}U: $\tau_{1/2} = 4.47$ Gyr

E. M. Holmbeck *et al.* 2018 *ApJL* **859** L24

Radioactive atoms in space

Decaying chain			Lifetime τ [yr][a]	Sources	Decay process[b]
^{7}Be	$\rightarrow$ ^{7}Li		0.21	Novae	EC
^{56}Ni	$\rightarrow$ ^{56}Co	$\rightarrow$ ^{56}Fe	0.33	SNe	β^+
^{57}Co	$\rightarrow$ ^{57}Fe		1.07	SNe	EC
^{49}V	$\rightarrow$ ^{49}Ti		1.30	SNe	EC
^{22}Na	$\rightarrow$ ^{22}Ne		3.75	Novae	β^+
^{3}H	$\rightarrow$ ^{3}He		17.8	CR,AGB	β^-
^{44}Ti	$\rightarrow$ ^{44}Sc	$\rightarrow$ ^{44}Ca	85.0	SNe	EC,β^+
^{32}Si	$\rightarrow$ ^{32}P	$\rightarrow$ ^{32}S	221	SNe,AGB	β^-
^{63}Ni	$\rightarrow$ ^{63}Cu		144	SNe	β^-
^{39}Ar	$\rightarrow$ ^{39}K		388	SNe	β^-
^{14}C	$\rightarrow$ ^{14}N		8.27×10^{3}	CR	β^-
^{59}Ni	$\rightarrow$ ^{59}Co		1.10×10^{5}	SNe	EC
^{41}Ca	$\rightarrow$ ^{41}K		1.47×10^{5}	SNe,AGB	EC
^{36}Cl	$\rightarrow$ ^{36}Ar		4.34×10^{5}	Ane,AGB	β^-
^{26}Al	$\rightarrow$ ^{26}Mg		1.03×10^{6}	SNe,WR,AGB	β^+
^{10}Be	$\rightarrow$ ^{10}B		2.01×10^{6}	CR	β^-
^{60}Fe	$\rightarrow$ ^{60}Co	$\rightarrow$ ^{60}Ni	3.75×10^{6}	SNe	β^-
^{53}Mn	$\rightarrow$ ^{53}Cr		5.34×10^{6}	SNe	EC

Radioactive atoms in space

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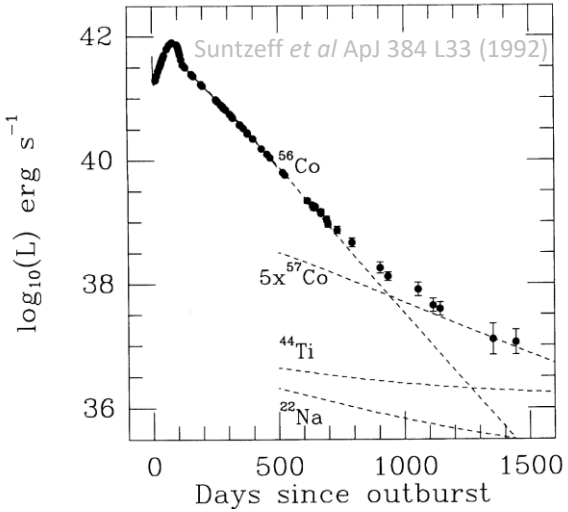

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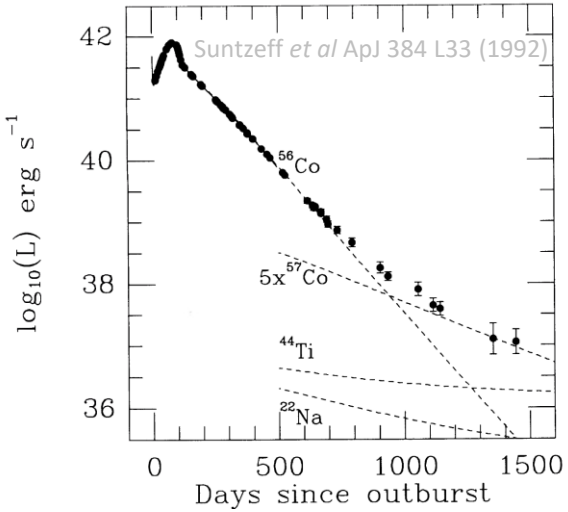
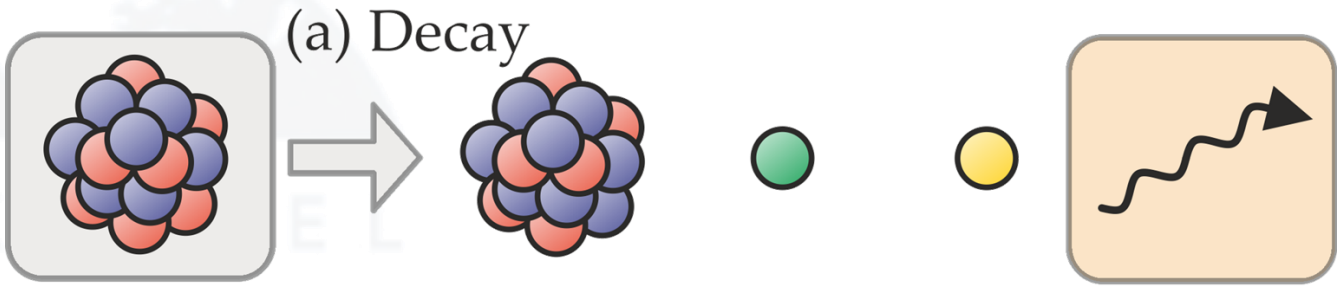
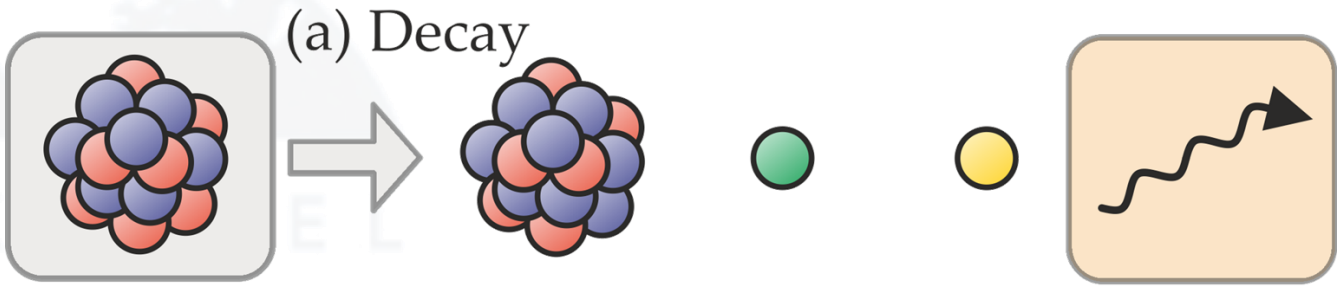


Radioactive atoms in space

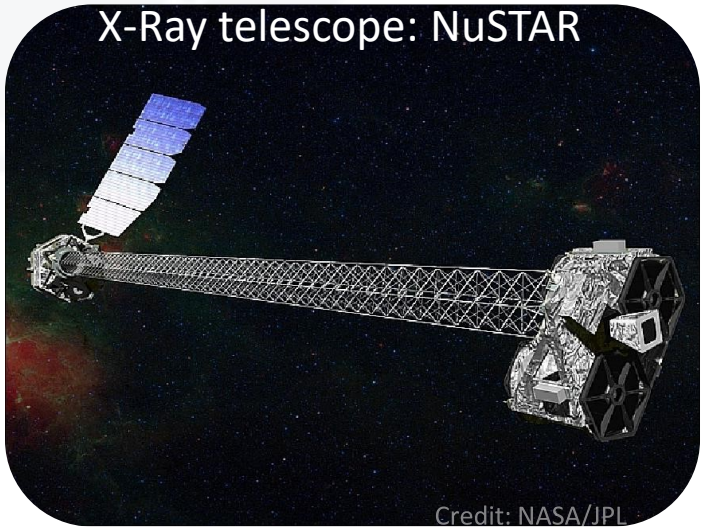


$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z\mp1}Y + e^{\pm} + \upsilon_e/\overline{\upsilon}_e + \gamma $$

Radioactive atoms in space



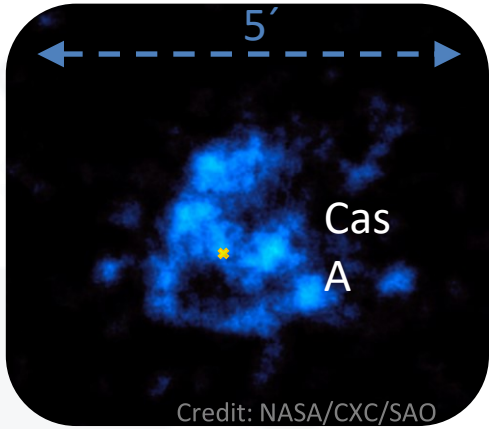
$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z\mp1}Y + e^{\pm} + \nu_e/\overline{\nu}_e + \gamma $$



- Single photon event wrt τ
- Photon energy range: keV - MeV
- Spatial resolution: >10“

Radioactive atoms in space

^{44}Ti



Mean lifetime

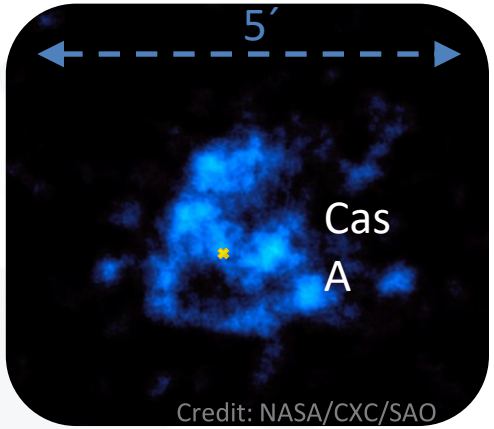
$\tau = 85$ y

Spatial resolution

Objects

Radioactive atoms in space

^{44}Ti



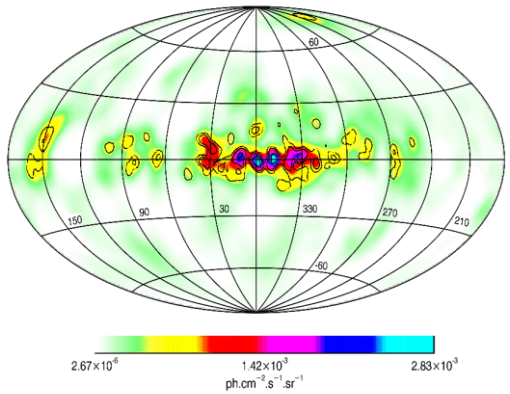
Mean lifetime

τ = 85 y

Spatial resolution

Objects

^{26}Al



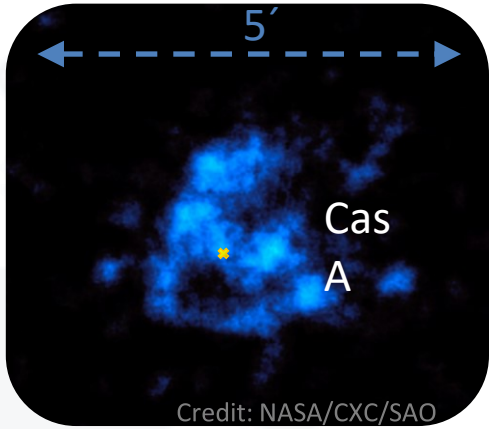
Bouchet *et al.*, *ApJ* **801**, 142 (2015)

τ = 1.0 My

Regions

Radioactive atoms in space

^{44}Ti



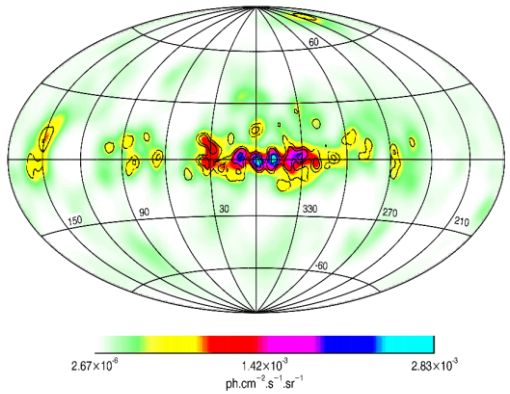
Mean lifetime

τ = 85 y

Spatial resolution

Objects

^{26}Al

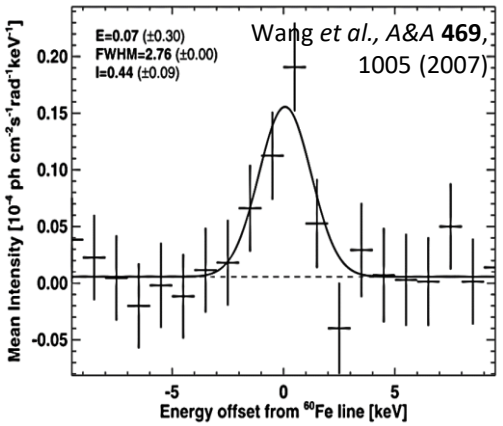


Bouchet *et al.*, *ApJ* **801**, 142 (2015)

τ = 1.0 My

Regions

^{60}Fe



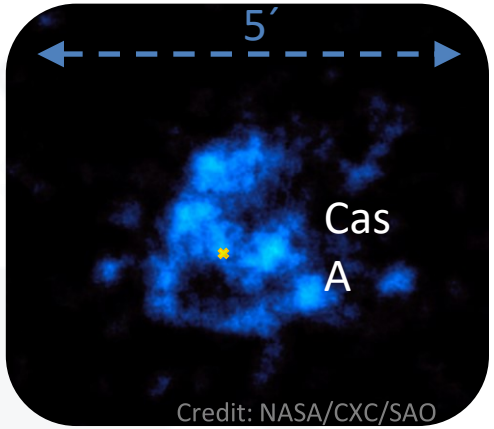
Wang *et al.*, *A&A* **469**, 1005 (2007)

τ = 3.8 My

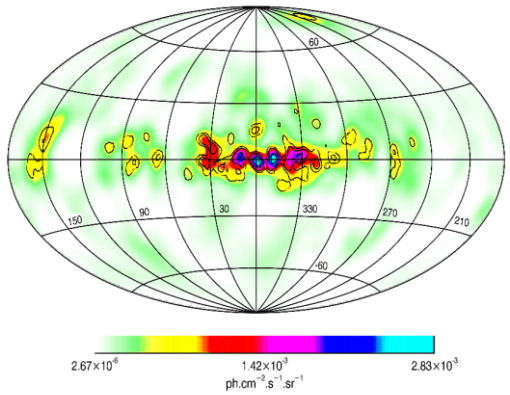
vanishing

Radioactive atoms in space

^{44}Ti

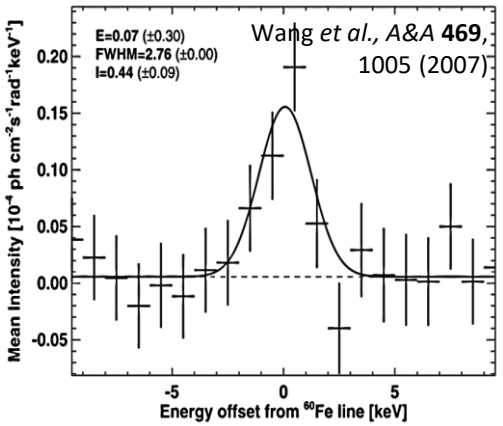


^{26}Al



Bouchet *et al.*, *ApJ* **801**, 142 (2015)

^{60}Fe

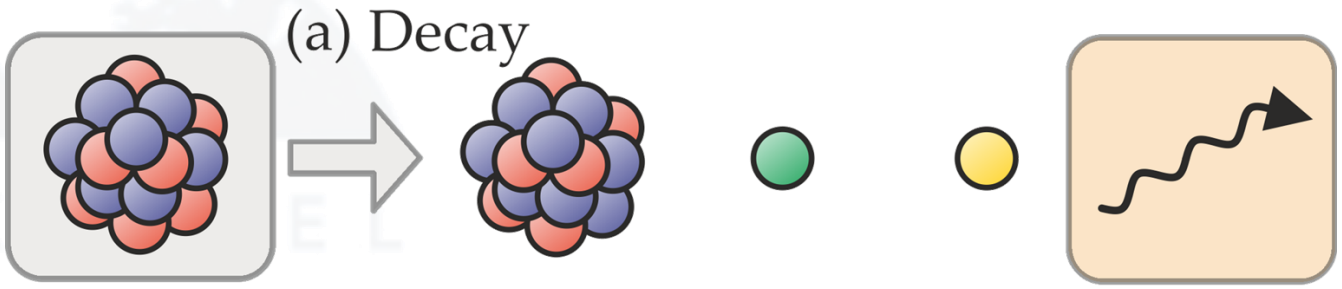


	^{44}Ti	^{26}Al	^{60}Fe
Mean lifetime	τ = 85 y	τ = 1.0 My	τ = 3.8 My
Spatial resolution	Objects	Regions	vanishing

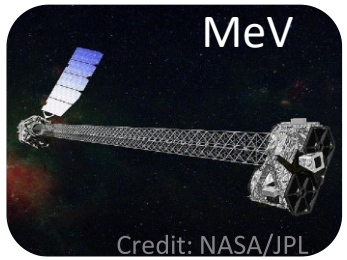
increases

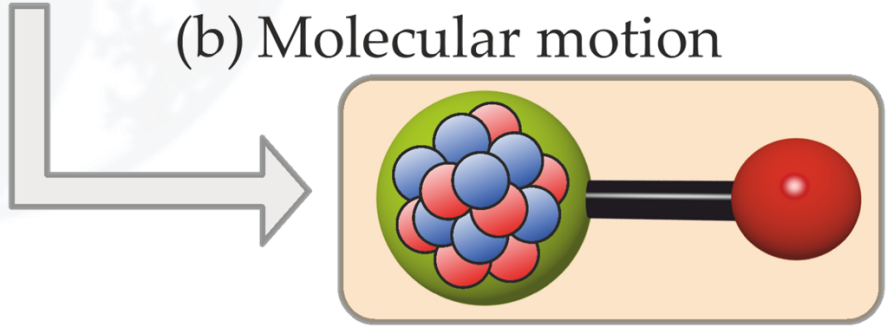
increases

From MeV to meV



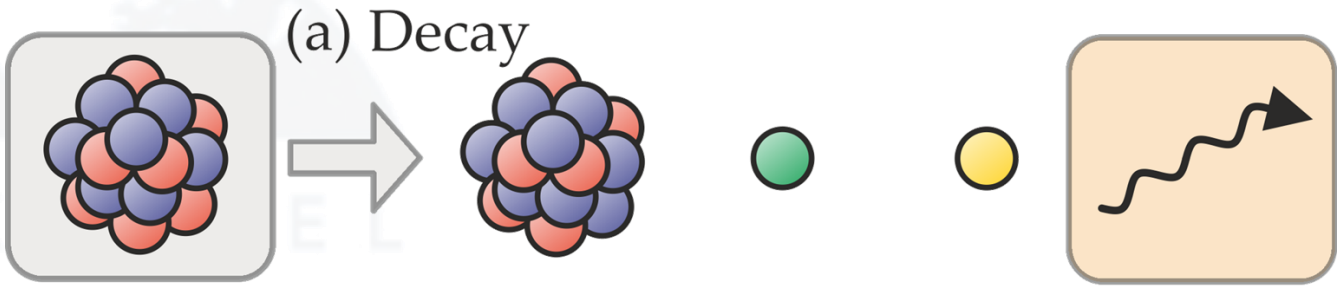
$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z\mp1}Y + e^{\pm} + \nu_e/\overline{\nu}_e + \gamma $$



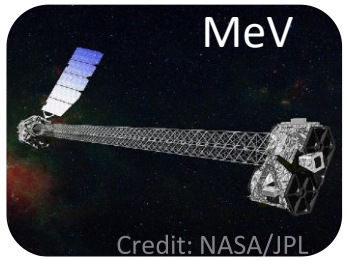


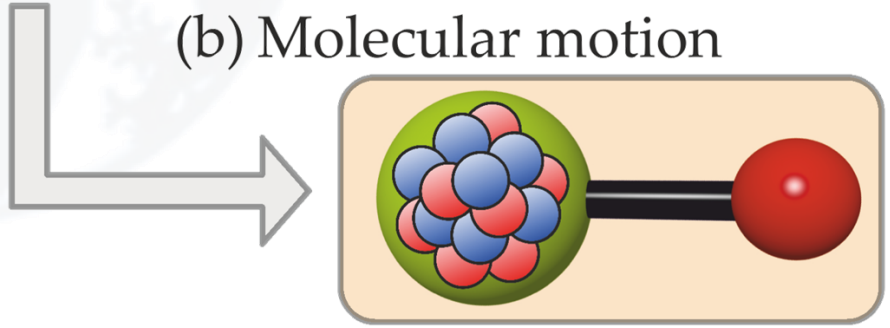
$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z}X - B $$

From MeV to meV

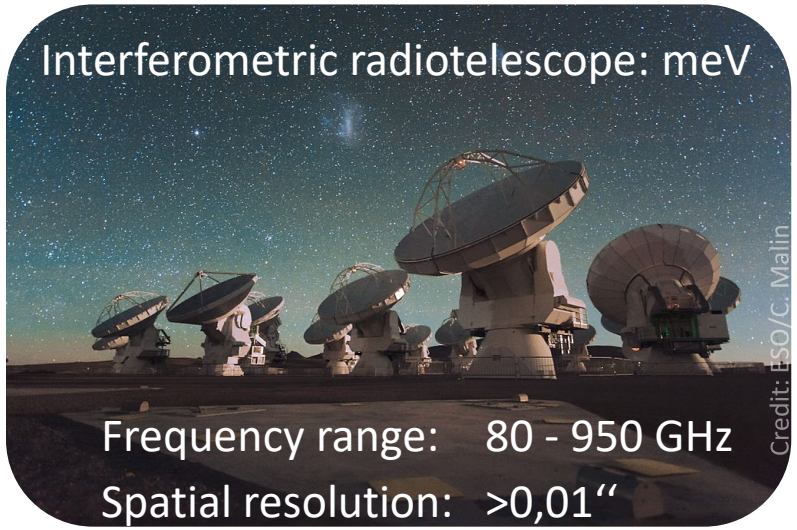


$$^{A}_{Z}X \longrightarrow {}^{A}_{Z\mp1}Y + e^{\pm} + \nu_e/\overline{\nu}_e + \gamma$$





$$^{A}_{Z}X \longrightarrow {}^{A}_{Z}X - B$$



- Continuous photon flux
  (^{26}Al:^{26}AlF ≙ 1 : 10^{12})

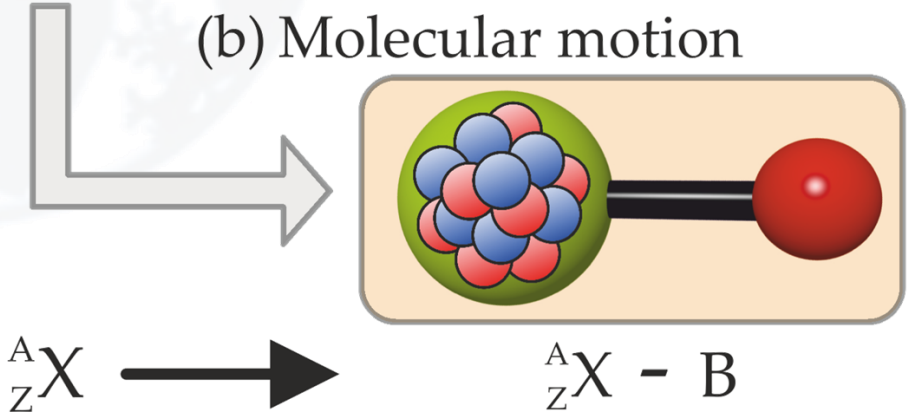
From MeV to meV

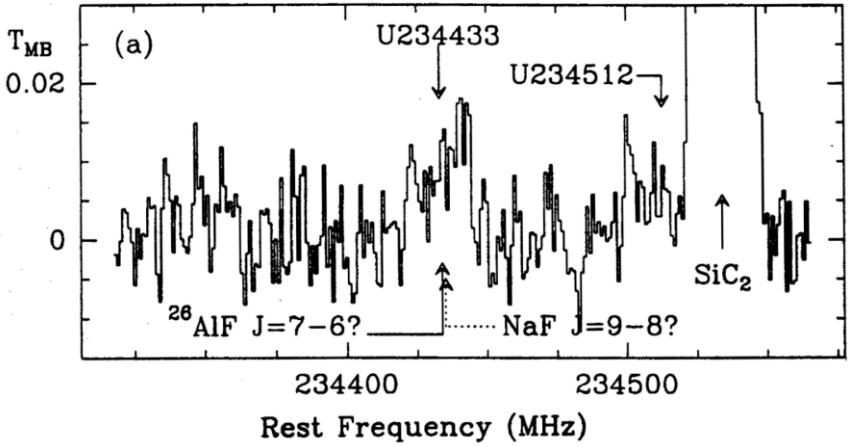
Nucleosynthesis in AGB stars: observation of ^{25}Mg and ^{26}Mg in IRC+10216 and possible detection of ^{26}Al

M. Guélin[1], M. Forestini[2], P. Valiron[2], L. M. Ziurys[3], M.A. Anderson[3], J. Cernicharo[4], and C. Kahane[2]

[1] IRAM, 300 rue de la piscine, F-38406 St Martin d'Hères, France
[2] Laboratoire d'Astrophysique, Observatoire de Grenoble, Université Joseph Fourier, BP 53, F-38041 St Martin d'Hères Cedex 09, France
[3] Arizona State University, Dept. of Chemistry, Tempe, AZ 85287-1604, USA
[4] Centro Astronomico de Yebes, IGN, E-19080 Guadalajara, Spain

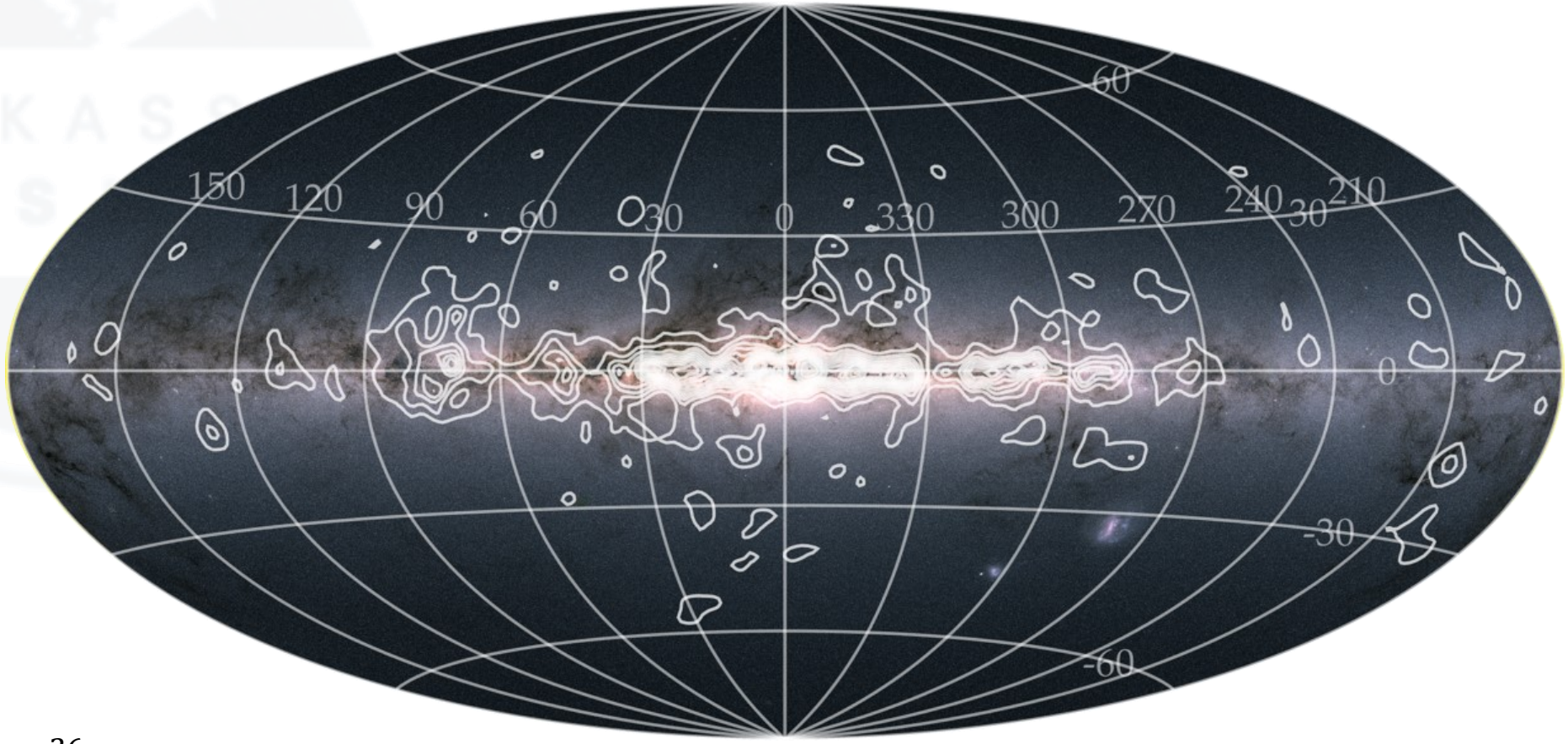
Received 12 August 1994 / Accepted 7 October 1994





- Continuous photon flux
  (^{26}Al:^{26}AlF ≙ 1 : 10^{12})

Galactic ^{26}Al distribution



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Diehl *et al.*, Nature **439**, 45 (2006)

Credit: ESA/Gaia/DPAC & Plüschke (2001)

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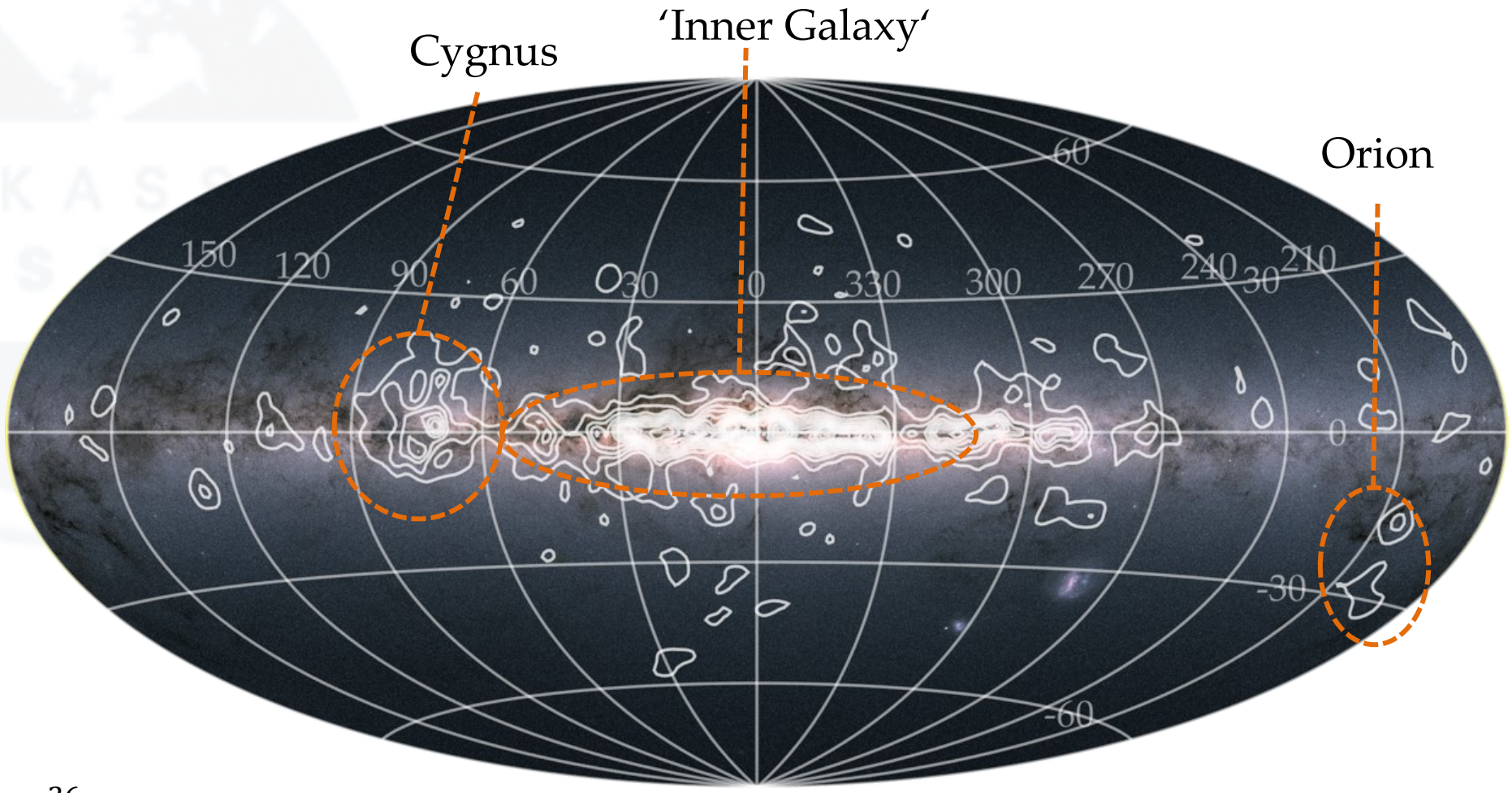

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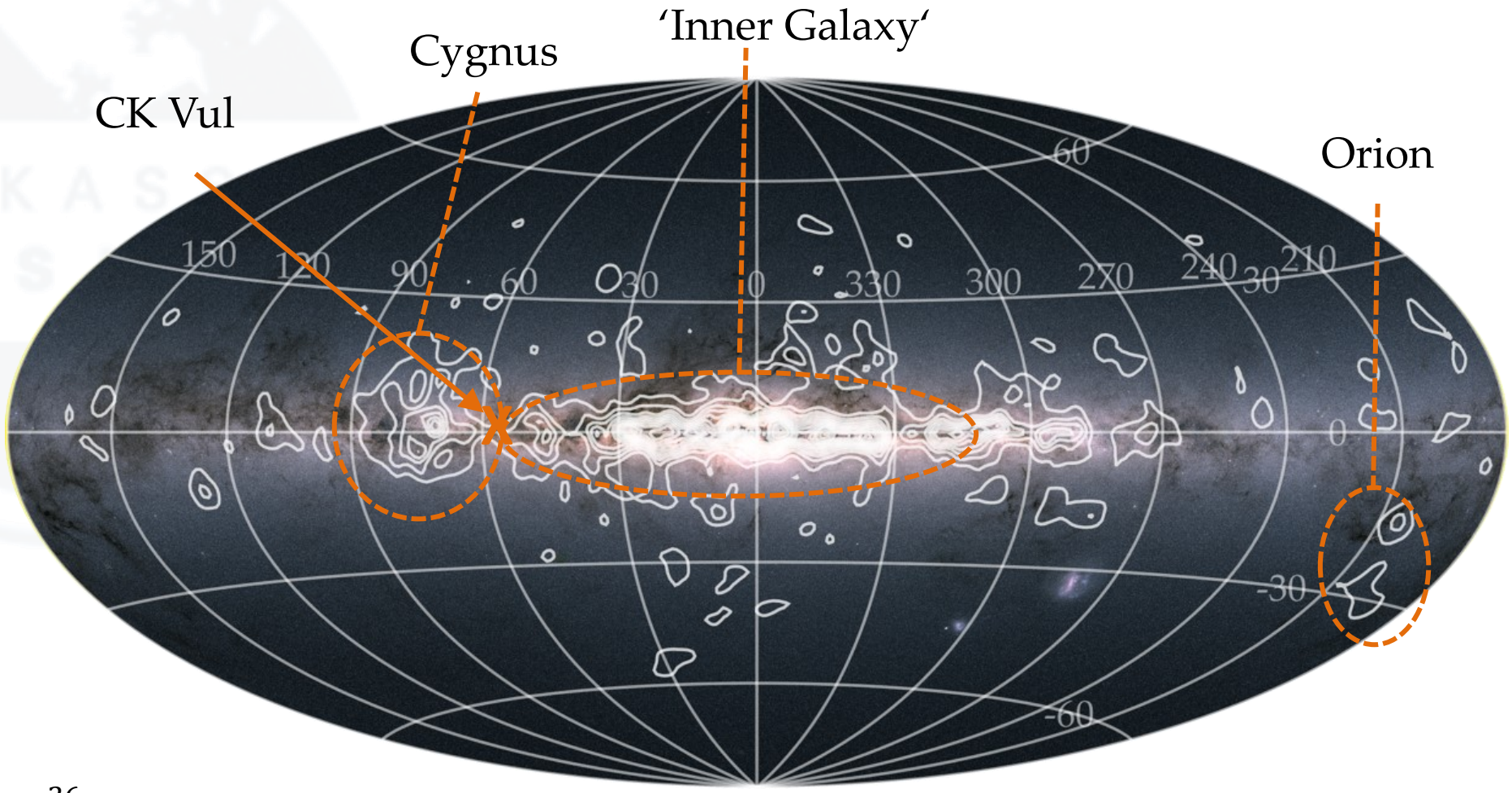

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CK Vulpeculae (CK Vul)

Key facts

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- ‘Red’ nova object

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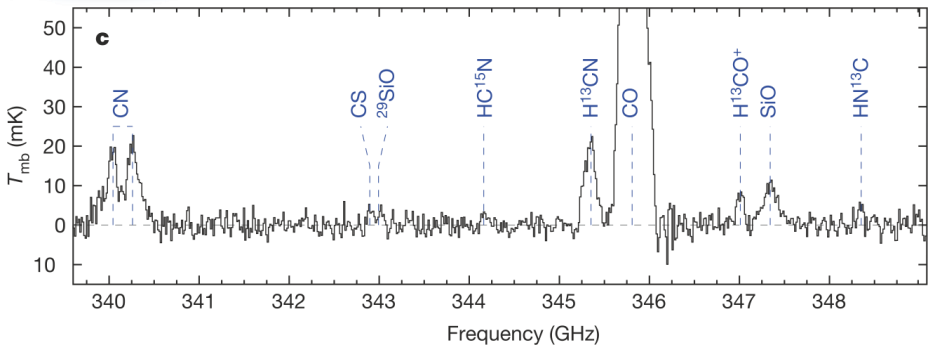
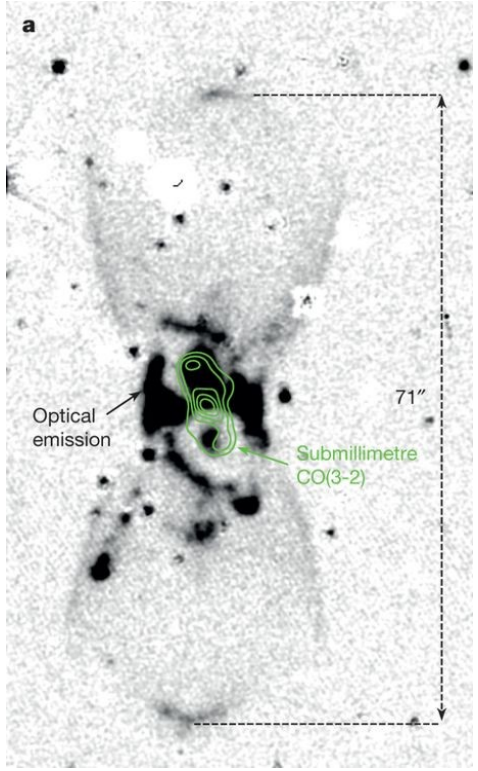


Nuclear ashes and outflow in the eruptive star Nova Vul 1670

Tomasz Kamiński[1,2], Karl M. Menten[2], Romuald Tylenda[3], Marcin Hajduk[3], Nimesh A. Patel[4] & Alexander Kraus[2]



Nature **520**, 322 (2015)

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Isotopic ratios

	CK Vul	Solar
$^{12}C/^{13}C$	~3	~89
$^{14}N/^{15}N$	~16	~272
$^{16}O/^{18}O$	~36	~499
$^{28}Si/^{29}Si$	~7	~20

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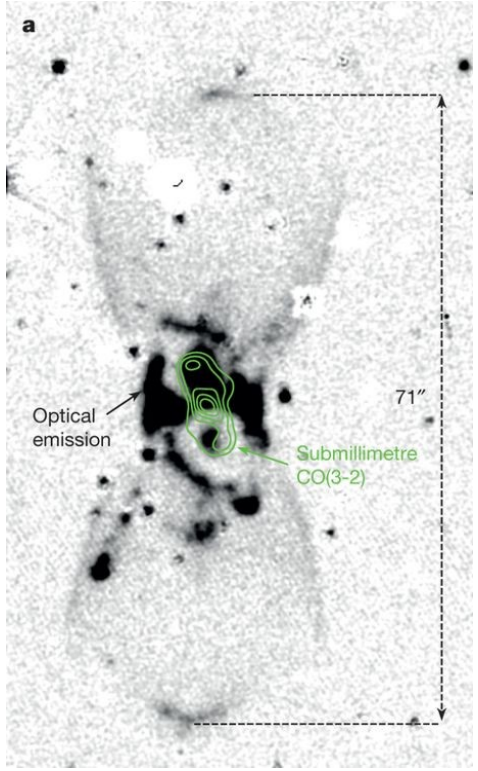

Nature **520**, 322 (2015)

Molecule: ^{27}AlF

Spectroscopic facts

Observed in Lab since	1939
Valence conf.	$2\sigma^2 2\pi^4$
Ground state	$X\,^1\Sigma^+$
Dipole moment [D]	1.53
Nuclear spin I (^{27}Al/^{19}F)	2.5/0.5
Q(^{27}Al) [mb]	147(1)

Molecular parameterization

Dunham parameterization

$$
\begin{aligned}
B_v &= Y_{01} + Y_{11}(v+1/2) + Y_{21}(v+1/2)^2 + Y_{31}(v+1/2)^3 + \cdots \\
&= \sum_{k1} Y_{k1}(v+1/2)^k.
\end{aligned}
$$

Astronomical observation

- C-rich environment: IRC+10216
  8 transitions
- Planetary nebular: CRL 2688
  3 transitions

Molecule: ^{27}AlF

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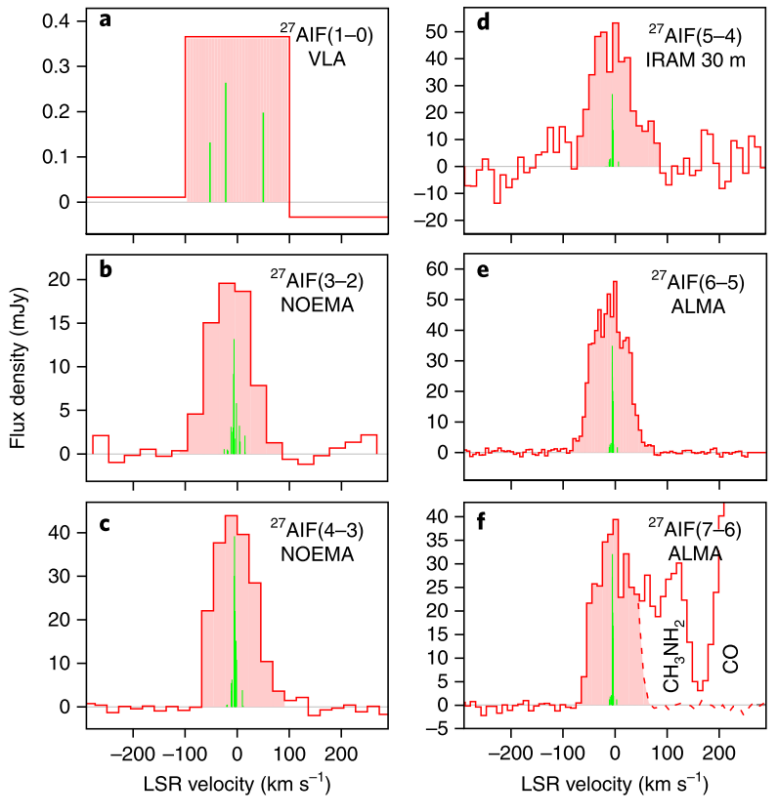
Astronomical observation

- $T_{ex} = 12.9^{+2.4}_{-1.8}$K; Line width:~ 140 $^{km}/_{s}$



Kamiński ...,Breier,..., Nature Astronomy **2**, 778 (2018)

Mass-independent description of AlF

AlF

$$B_\nu = \sum_k \mu^{-(k/2+1)} \left(1 + \sum_{i=A,B} \frac{m_e}{M_i} \Delta^i_{k1}\right) U_{k1} \left(\nu + \frac{1}{2}\right)^k$$

$$U_{01} = 184655.12(23)\ \mathrm{MHz} \cdot \mathrm{u}$$

$$r_e^{BO} = 1.65435196(103)\ \text{Å}$$

AB	Δ^A_{U01}	Δ^B_{U01}
BF	-1.84(6)	-1.4*
AlF [theo]	[-0.96]	[-1.45]
GaF	-0.66(20)	-1.5*

*Using wobble-stretch theory

I (^{26}Al/^{19}F)	5/0.5
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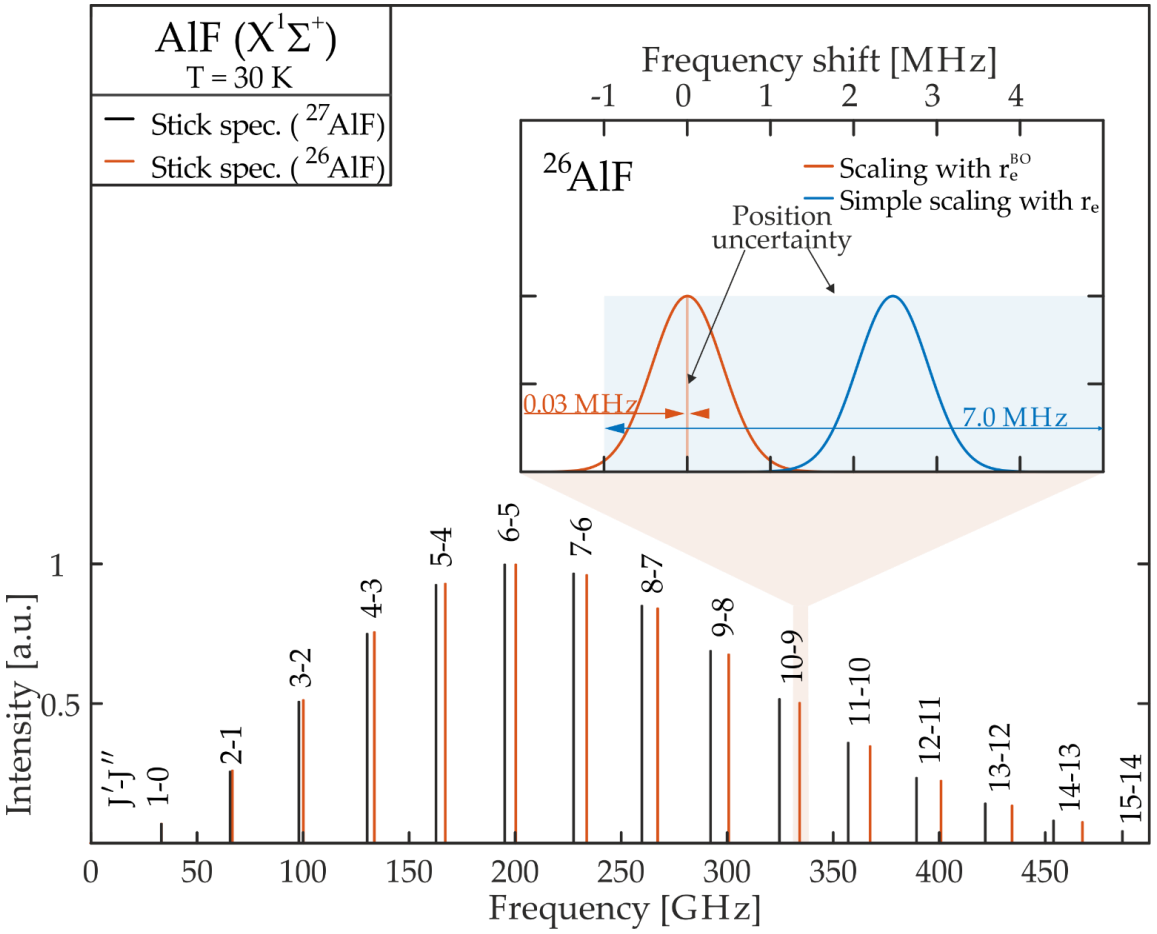

→Reducing uncertainty from 10^{-5} to 10^{-7}

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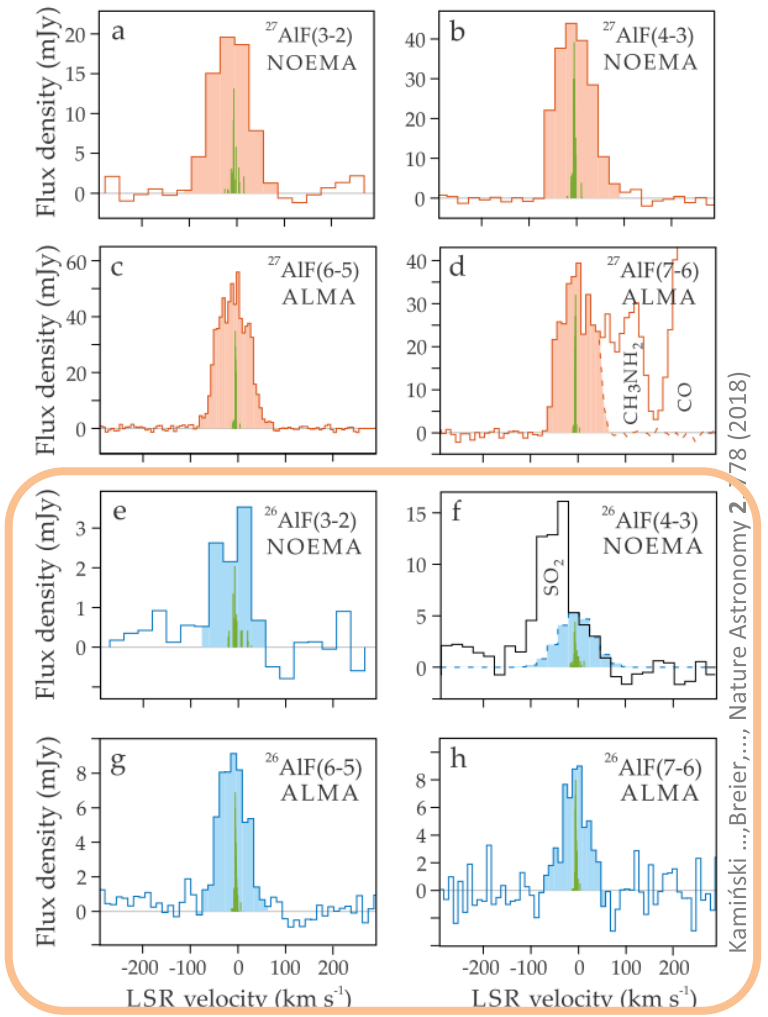

Kamiński ...,Breier,..., Nature Astronomy 2, 178 (2018)

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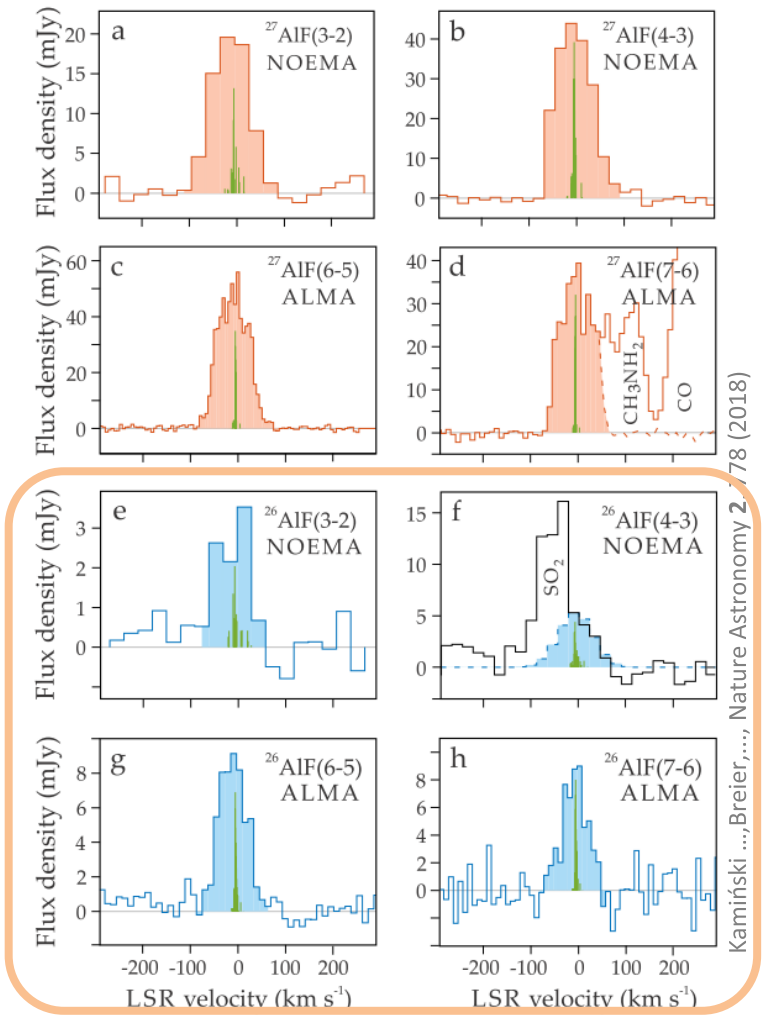

Kamiński ...,Breier,..., Nature Astronomy 2, 178 (2018)

Why so much ^{26}AlF ?

The origin of ^{26}Al

CK Vul

$$N_{27} = 3.0^{+0.5}_{-0.6} \times 10^{15}\ \mathrm{cm}^{-2}$$

$$N_{27}/N_{26} = 7.1^{+3.2}_{-2.2}$$

AGB

$$\bar{N}_{27}/\bar{N}_{26} \approx 120000$$

Diehl *et al.*, Nature **439**, 45 (2006)

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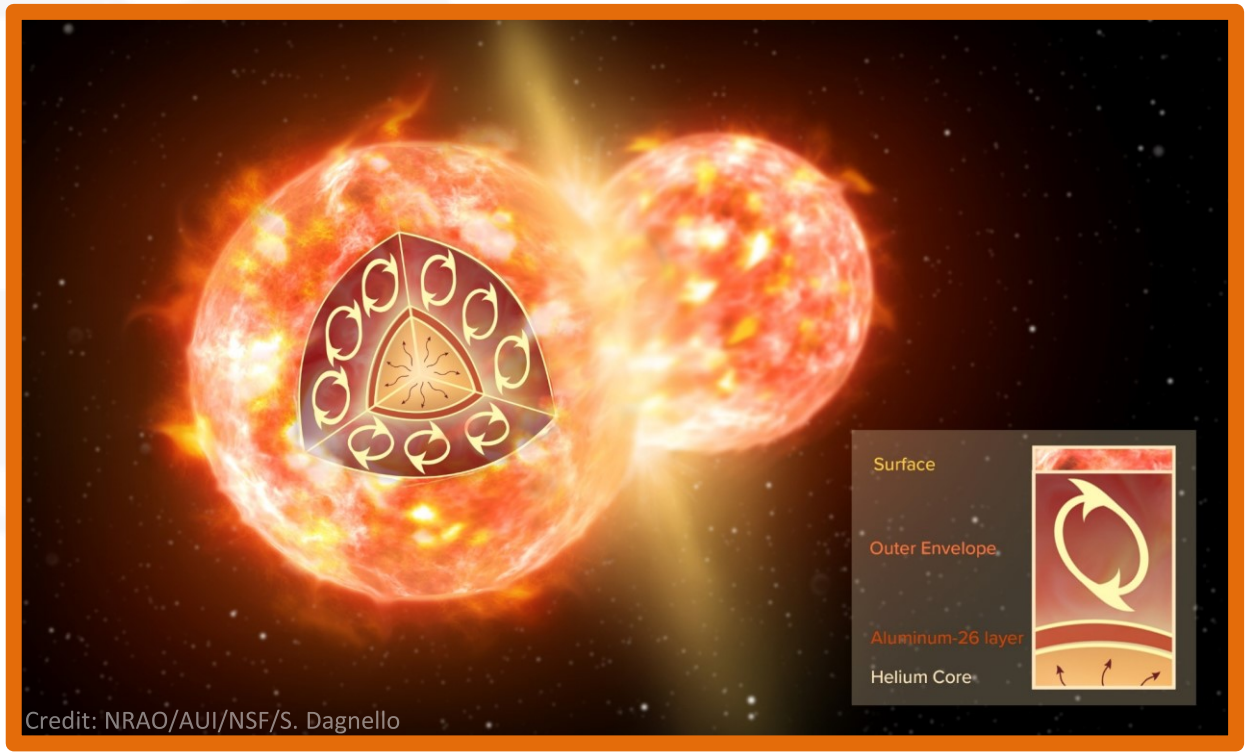

Merging scenario

- Stellar Merger: two low mass star being one in the RGB phase

Kamiński *et al.*, Nature Astronomy **2**, 778 (2018)

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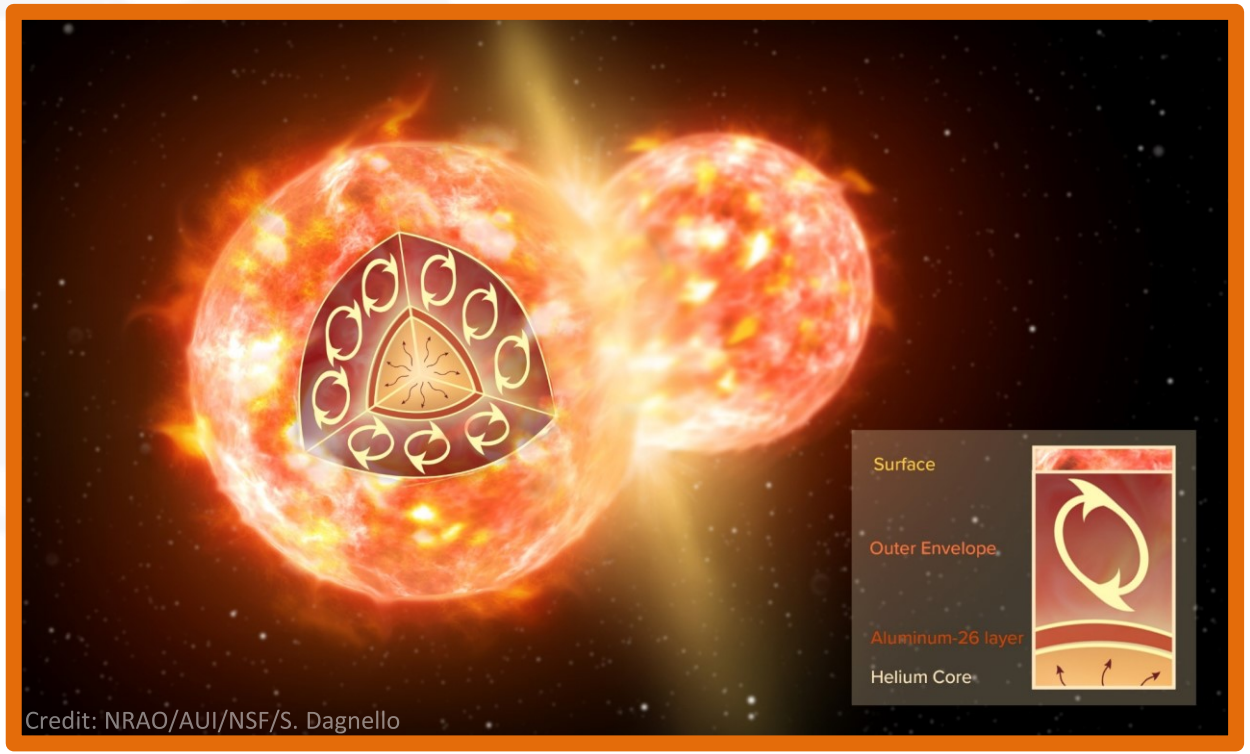


Merging scenario

- Stellar Merger: two low mass star being one in the RGB phase

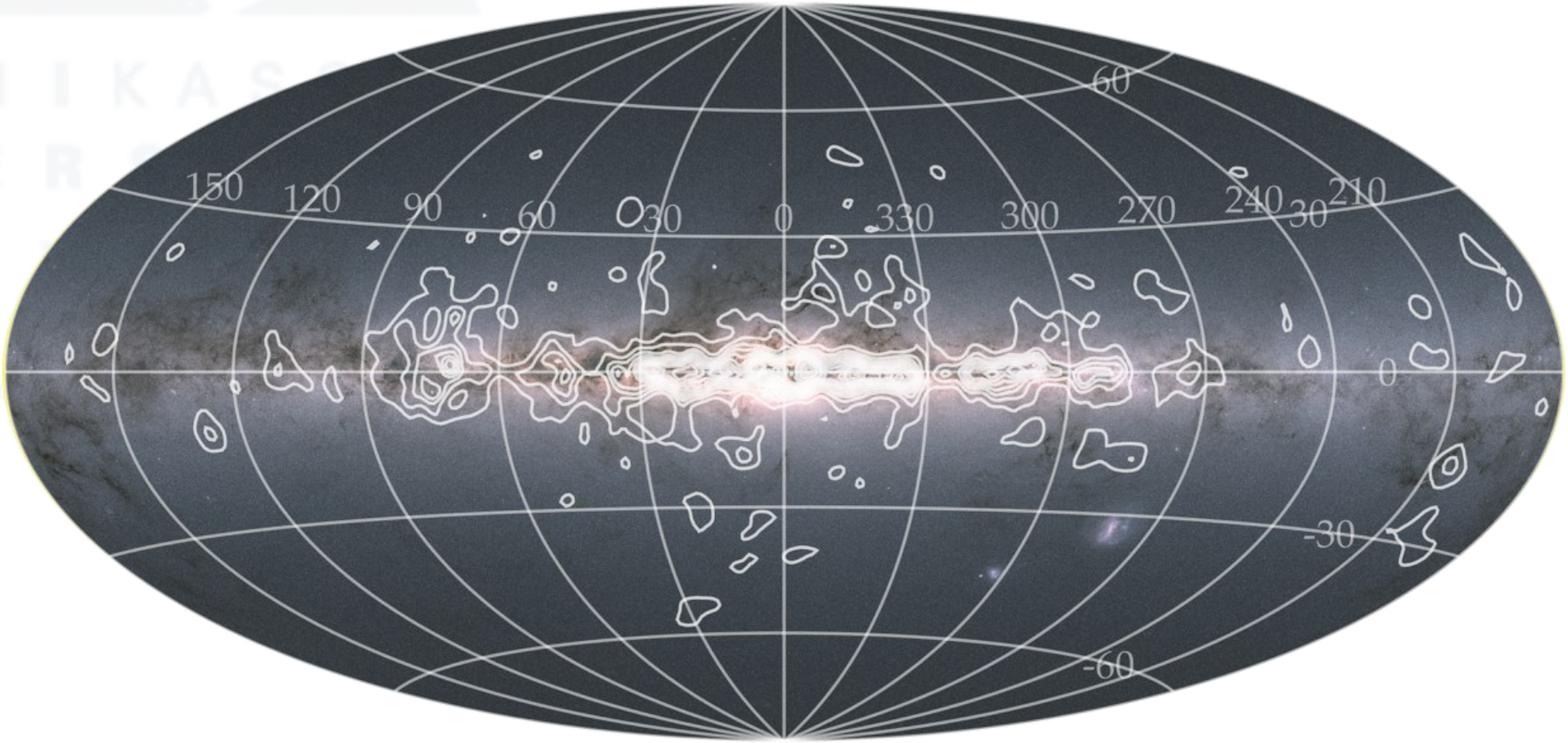
  Kamiński *et al.*, Nature Astronomy **2**, 778 (2018)

  Or

- Merger event between a white and brown dwarf

  Eyres *et al.*, MNRAS **481**, 4931 (2018)

Are there more possible sources?



Credit: ESA/Gaia/DPAC & Plüschke (2001)

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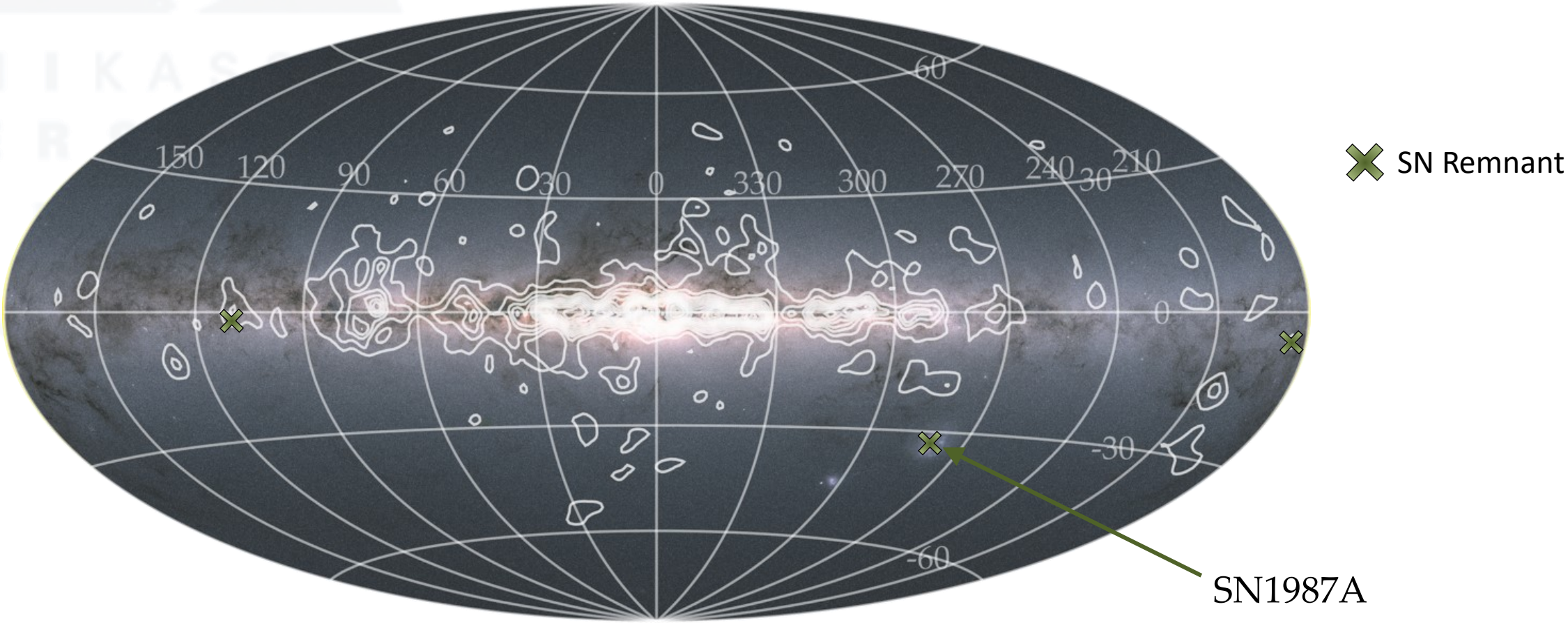

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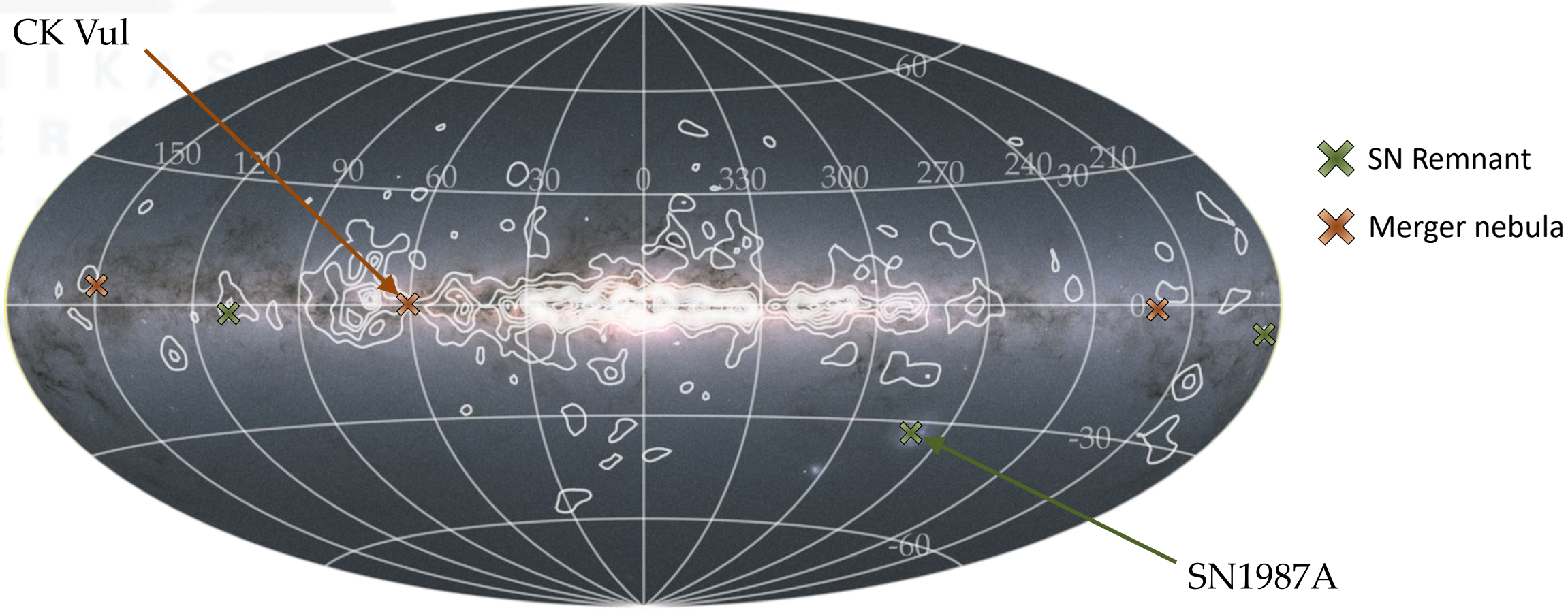

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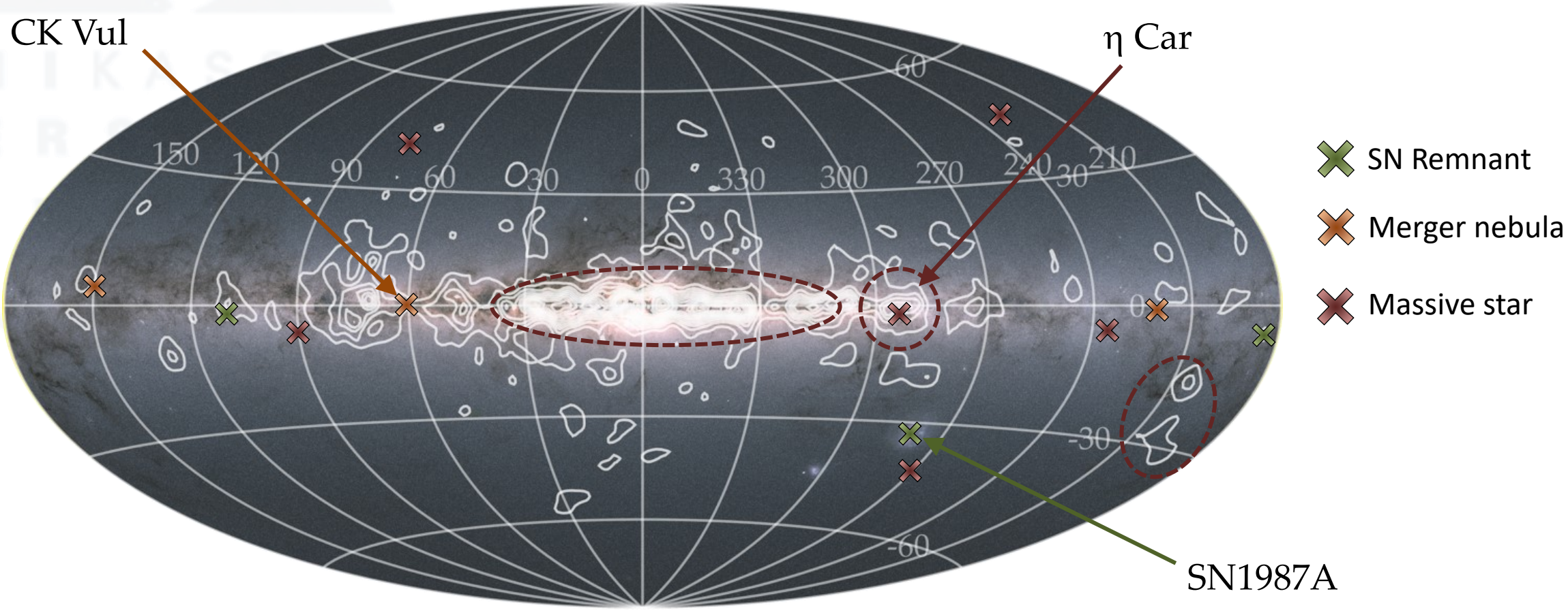

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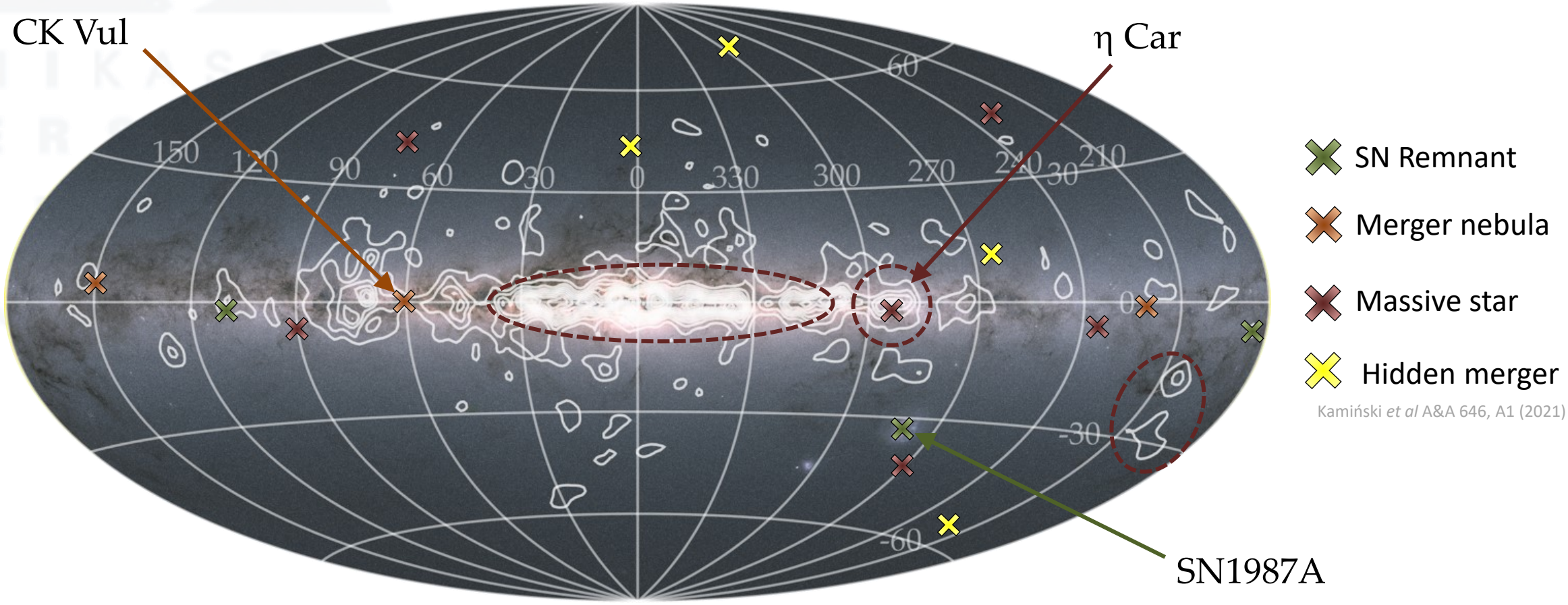


Kamiński *et al* A&A 646, A1 (2021)

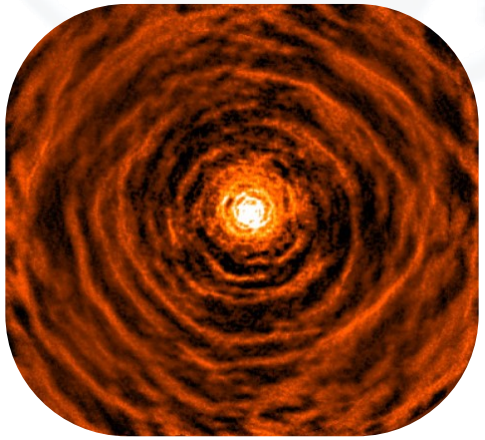
Credit: ESA/Gaia/DPAC & Plüschke (2001)

Stellar environments: Astrochemistry

Credit: NASA/ESA/R. Humphreys

C/O <1

Guélin *et al* A&A 610, A4 (2018)



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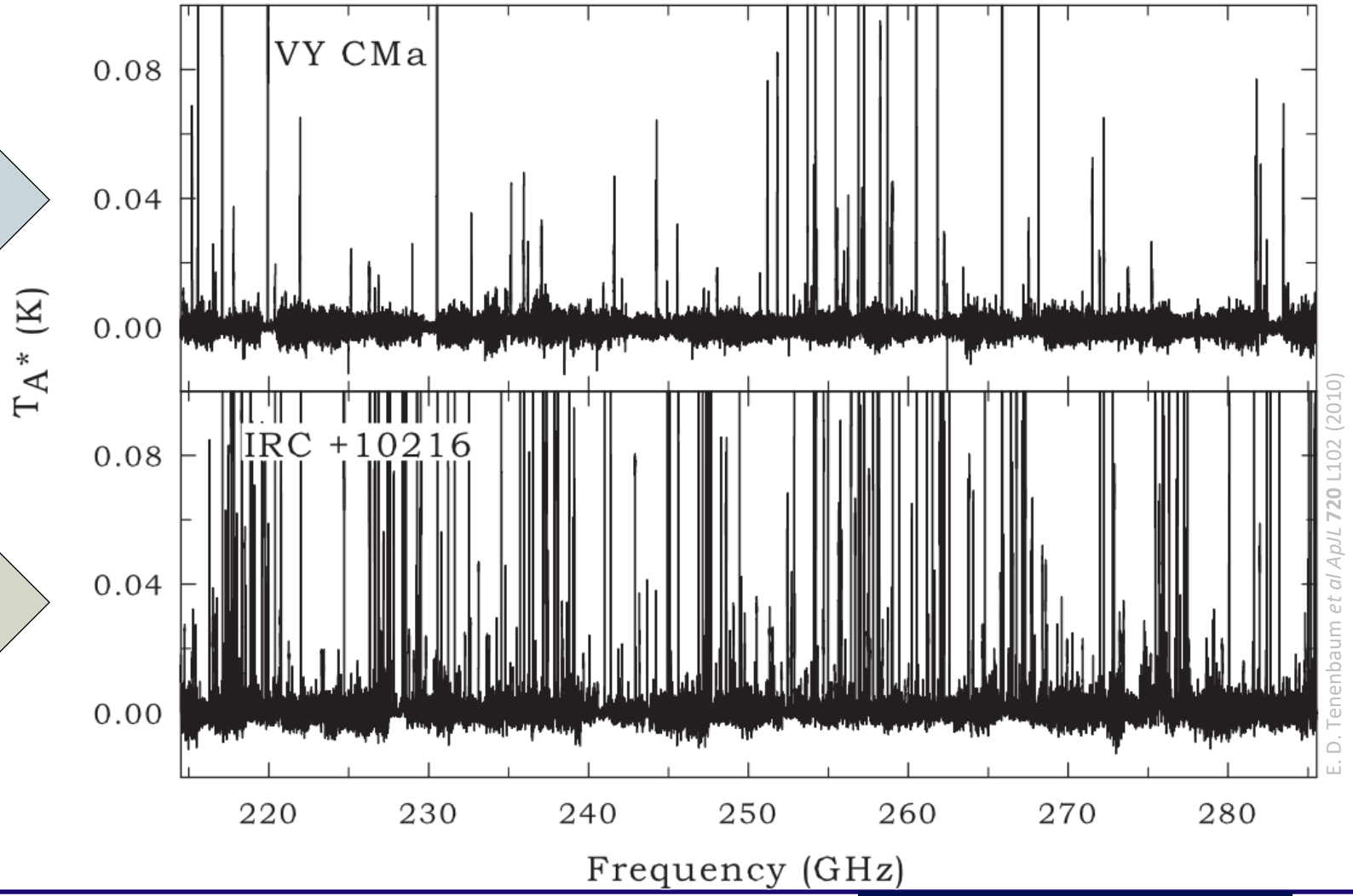

E. D. Tenenbaum *et al* *ApJL* **720** L102 (2010)

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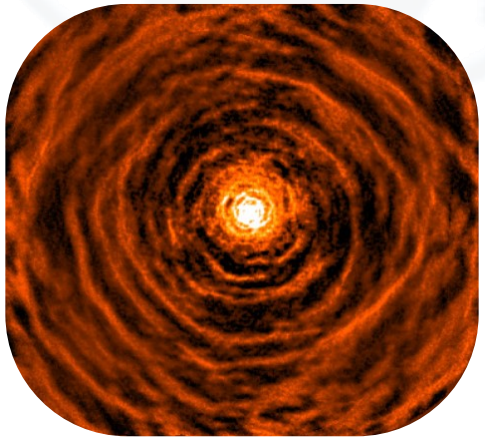

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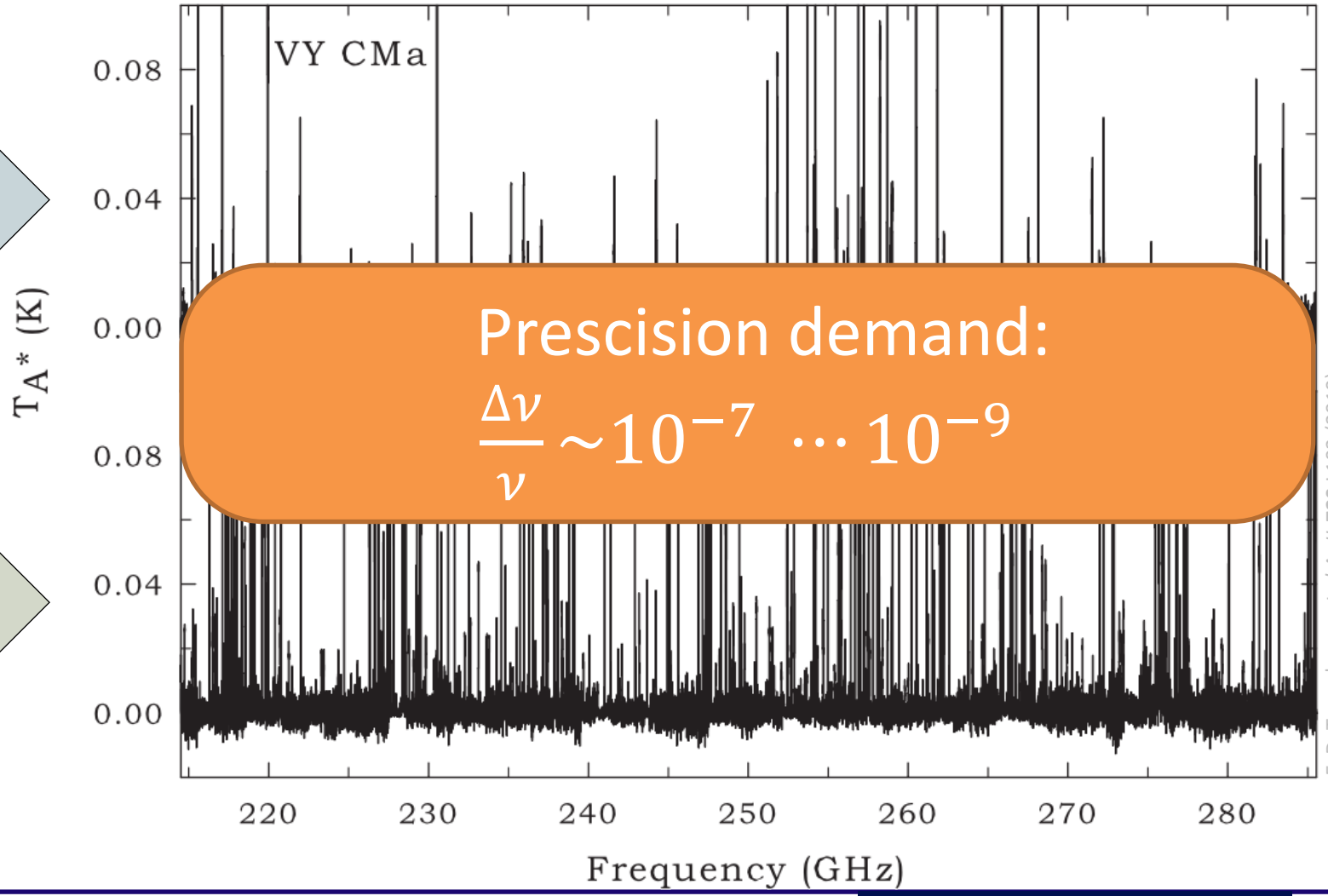

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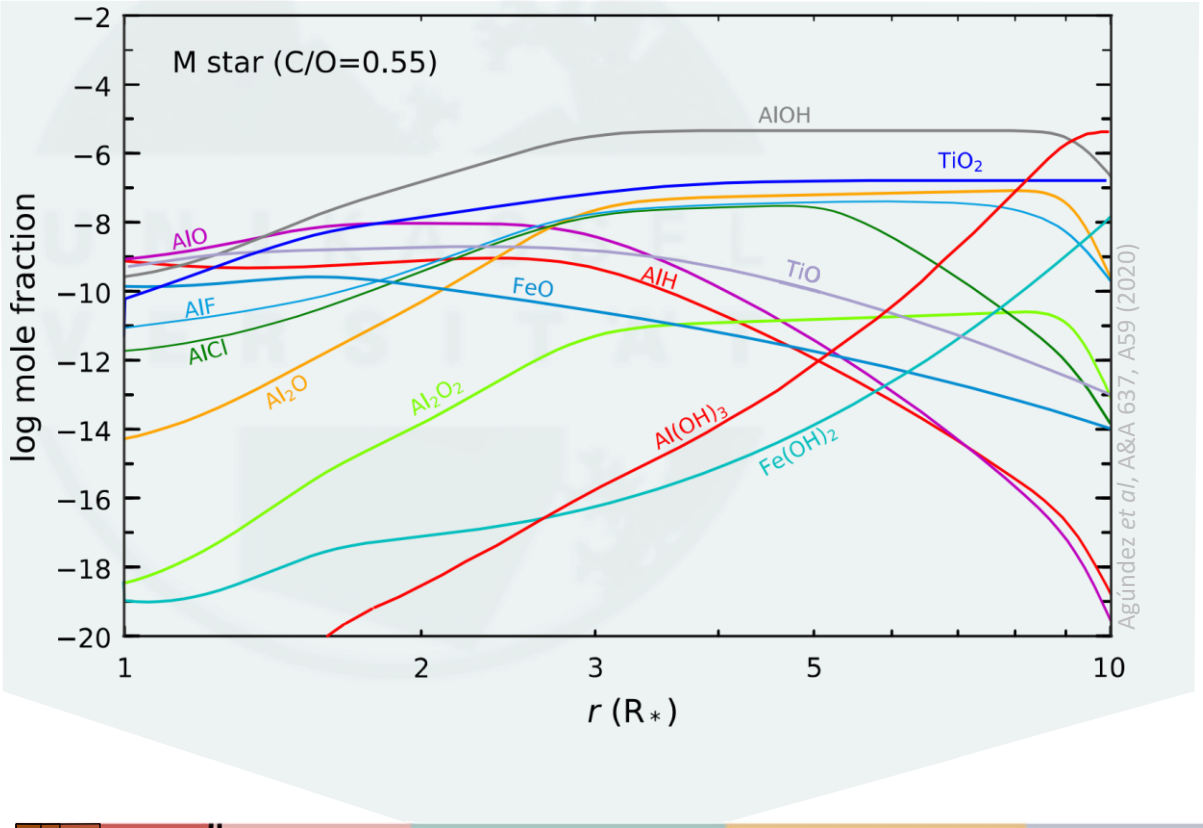
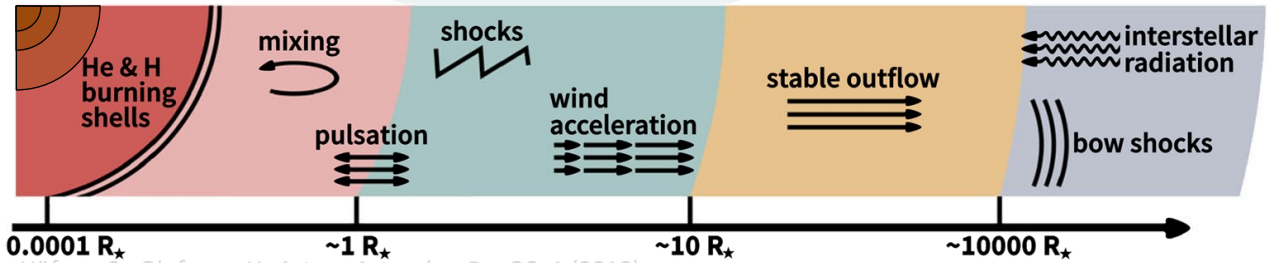
Prescision demand:

$$\frac{\Delta\nu}{\nu} \sim 10^{-7} \cdots 10^{-9}$$

Further Molecular Species





Höfner, S., Olofsson, H. *Astron Astrophys Rev* **26**, 1 (2018).

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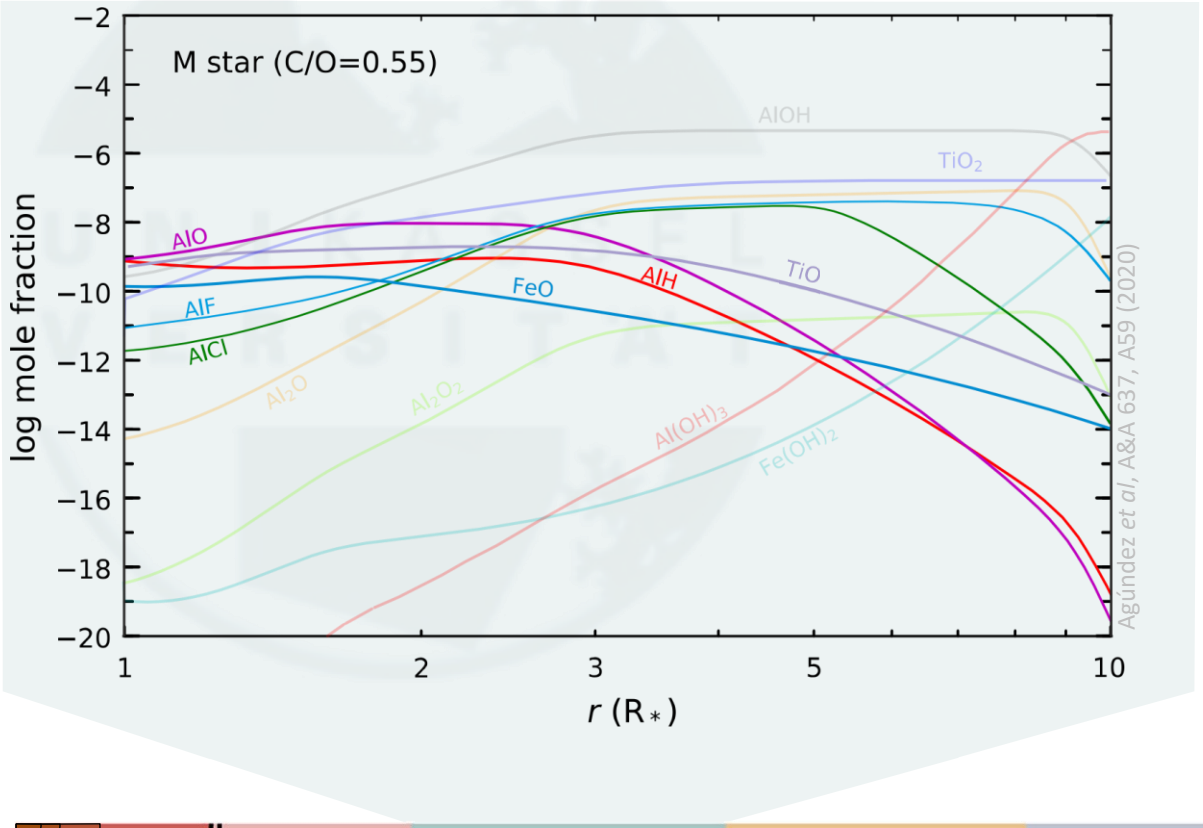

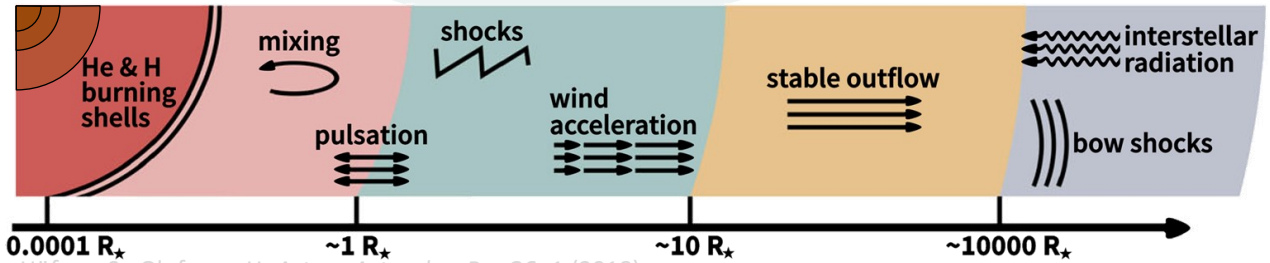

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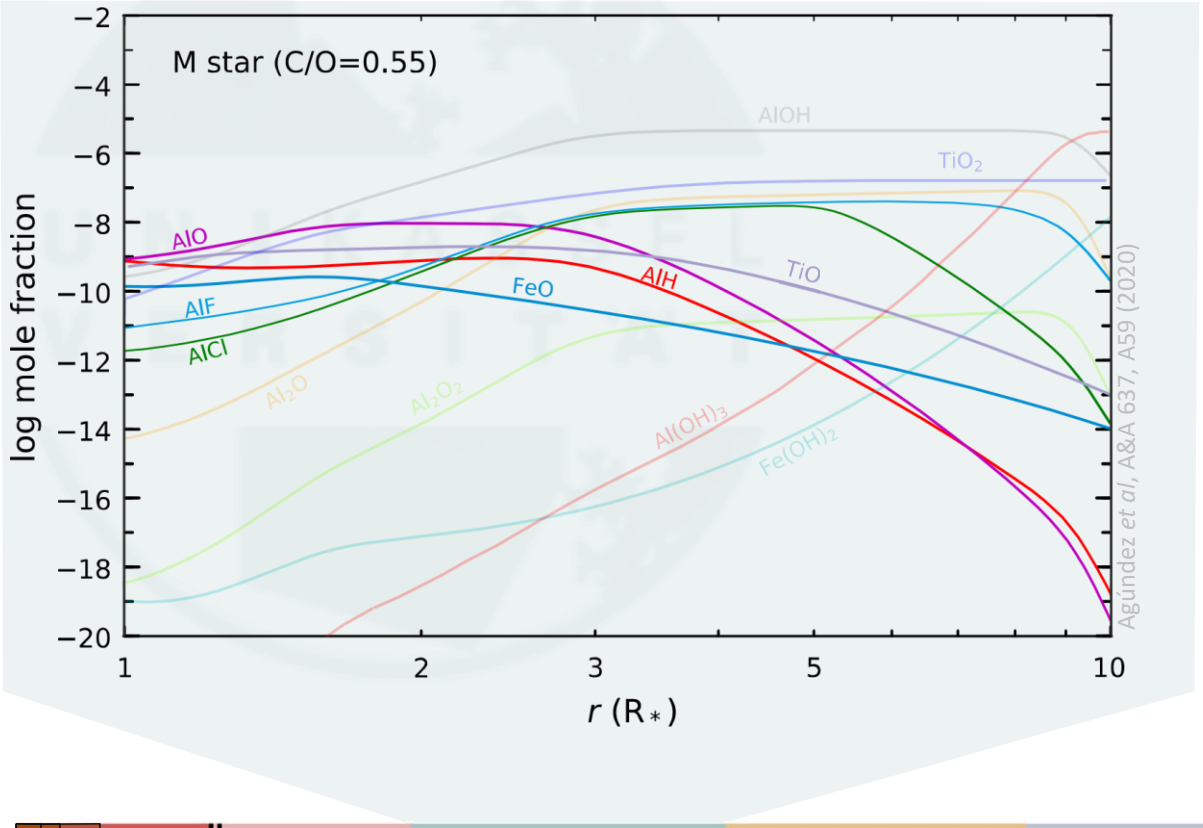

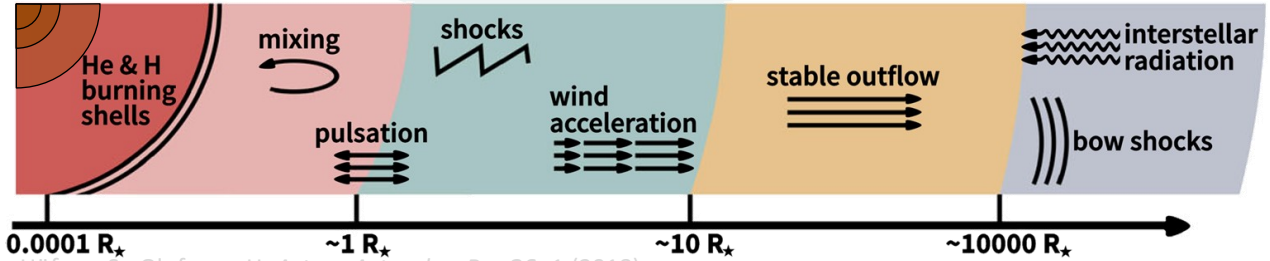

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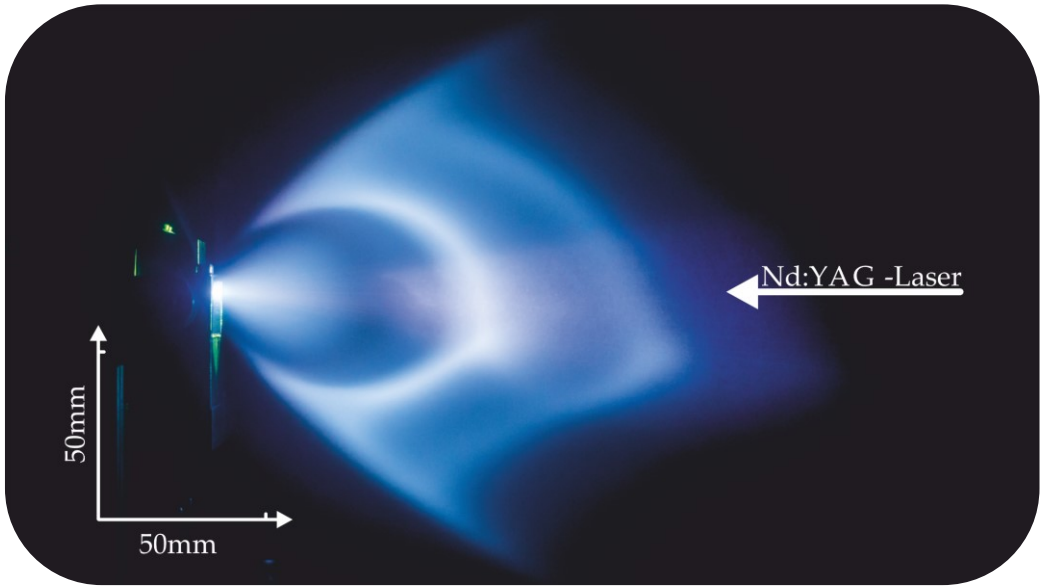

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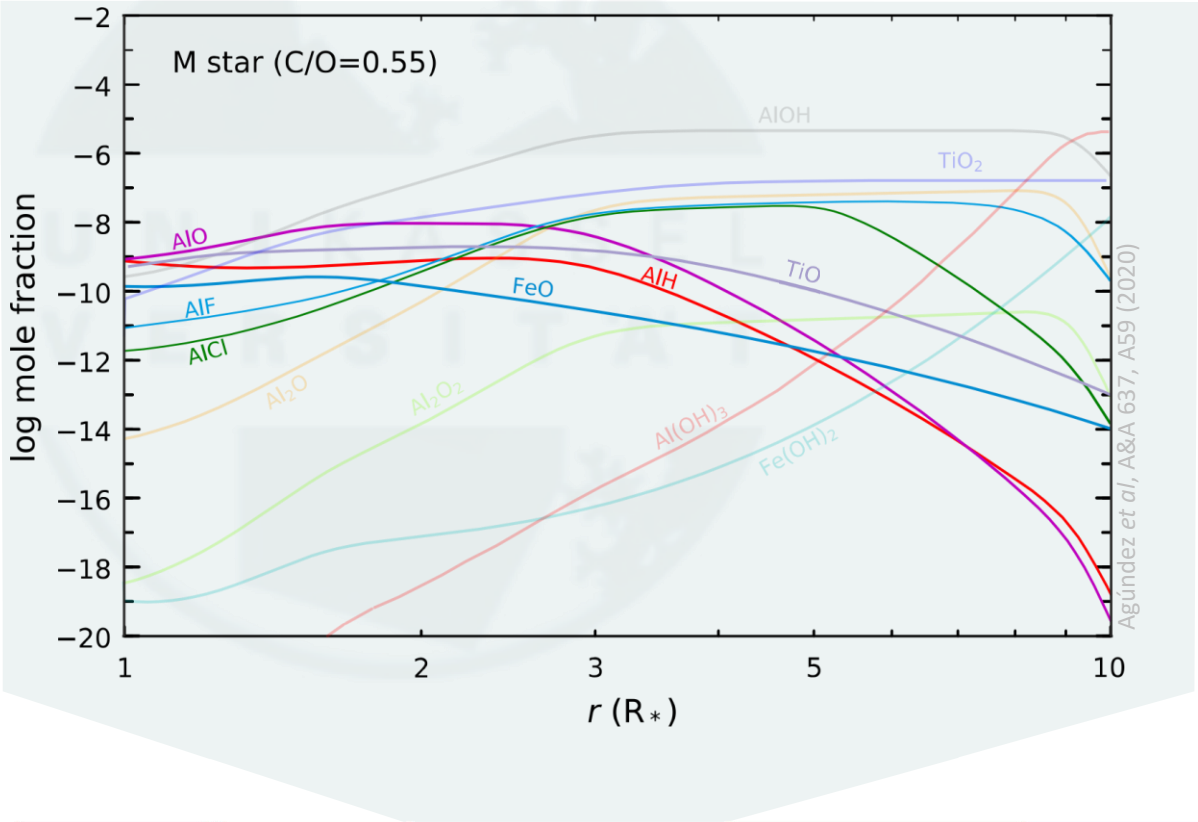
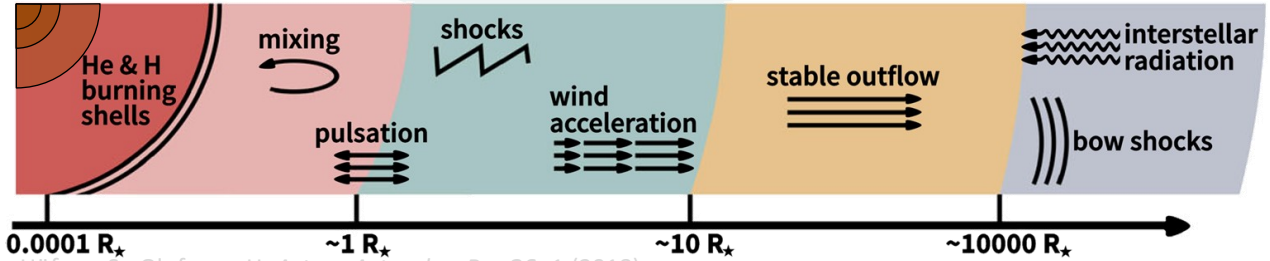


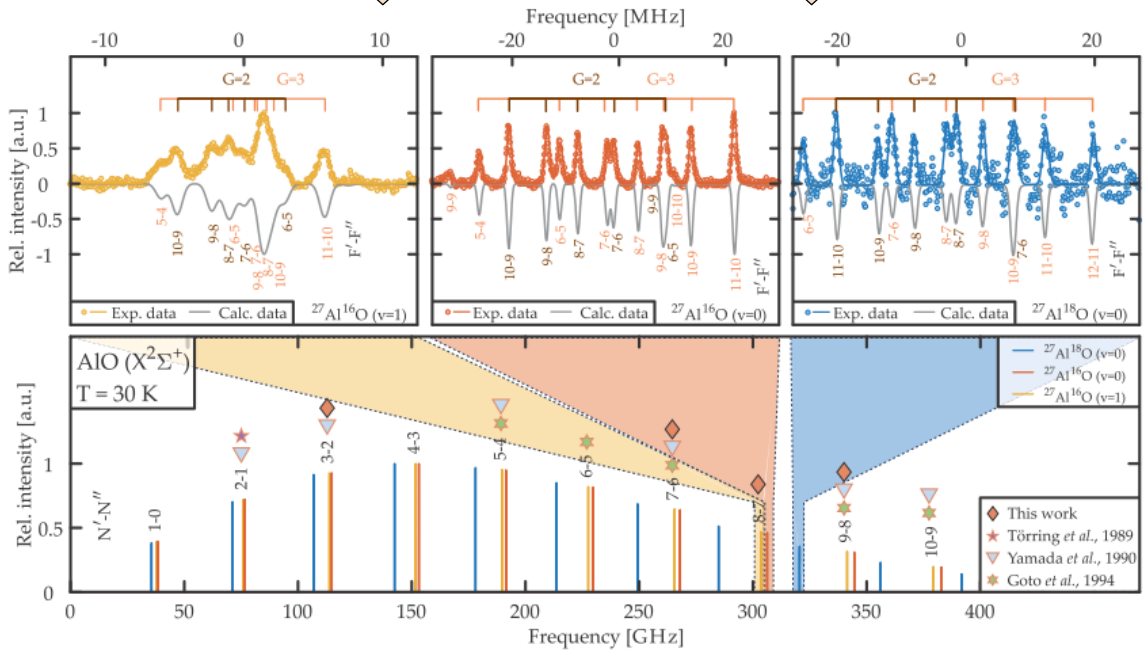


Höfner, S., Olofsson, H. *Astron Astrophys Rev* **26**, 1 (2018).

Radioactive diatomic molecules

- ^{26}AlO
- ^{44}TiO
- ^{26}AlF
- ^{60}FeO

scalable



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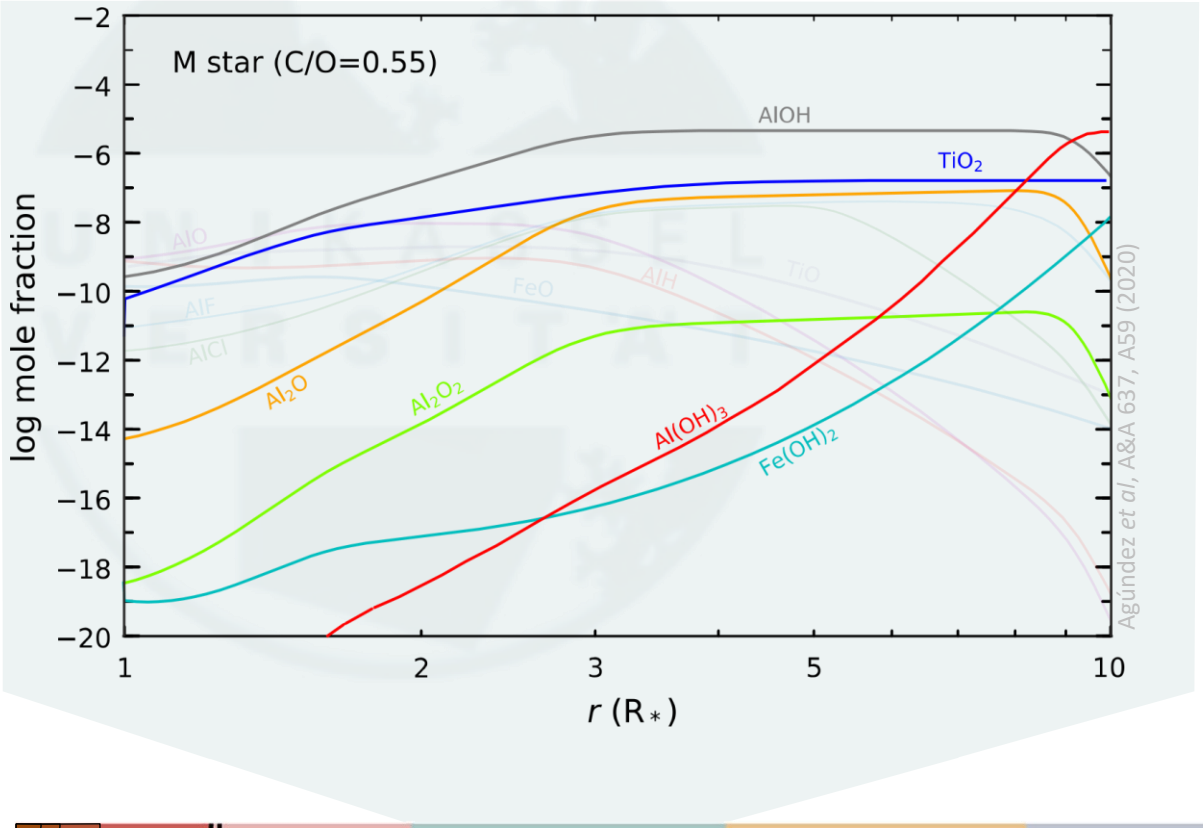

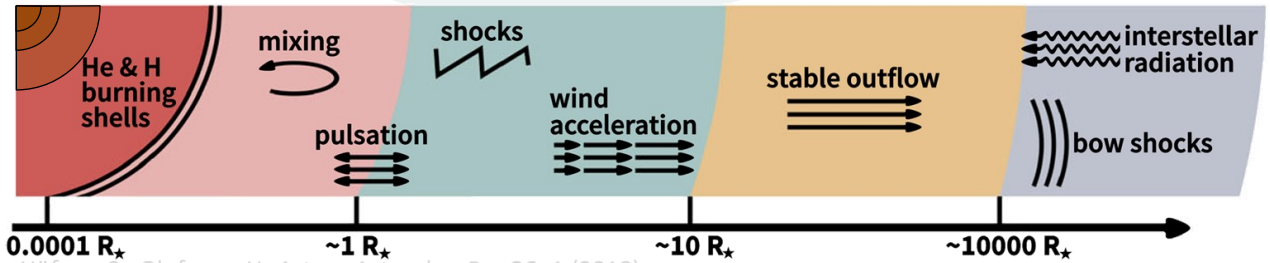

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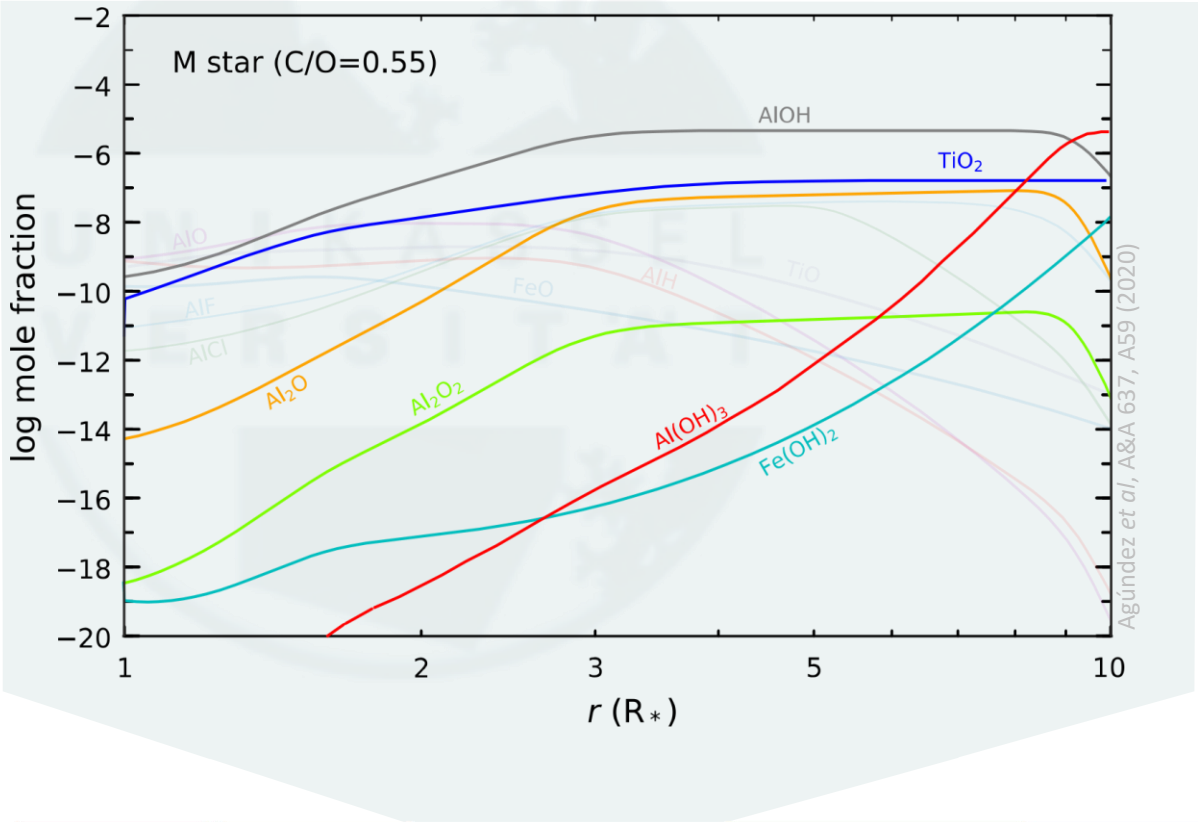

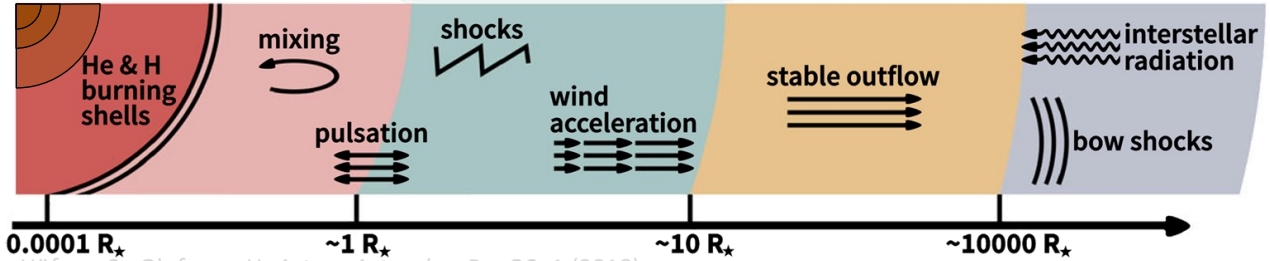

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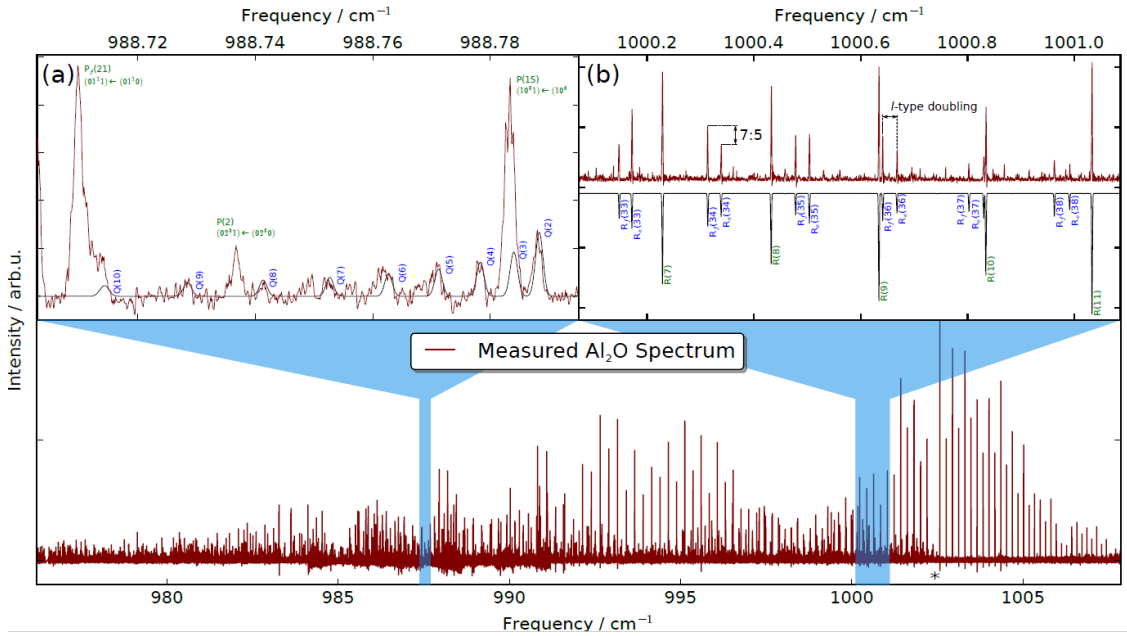
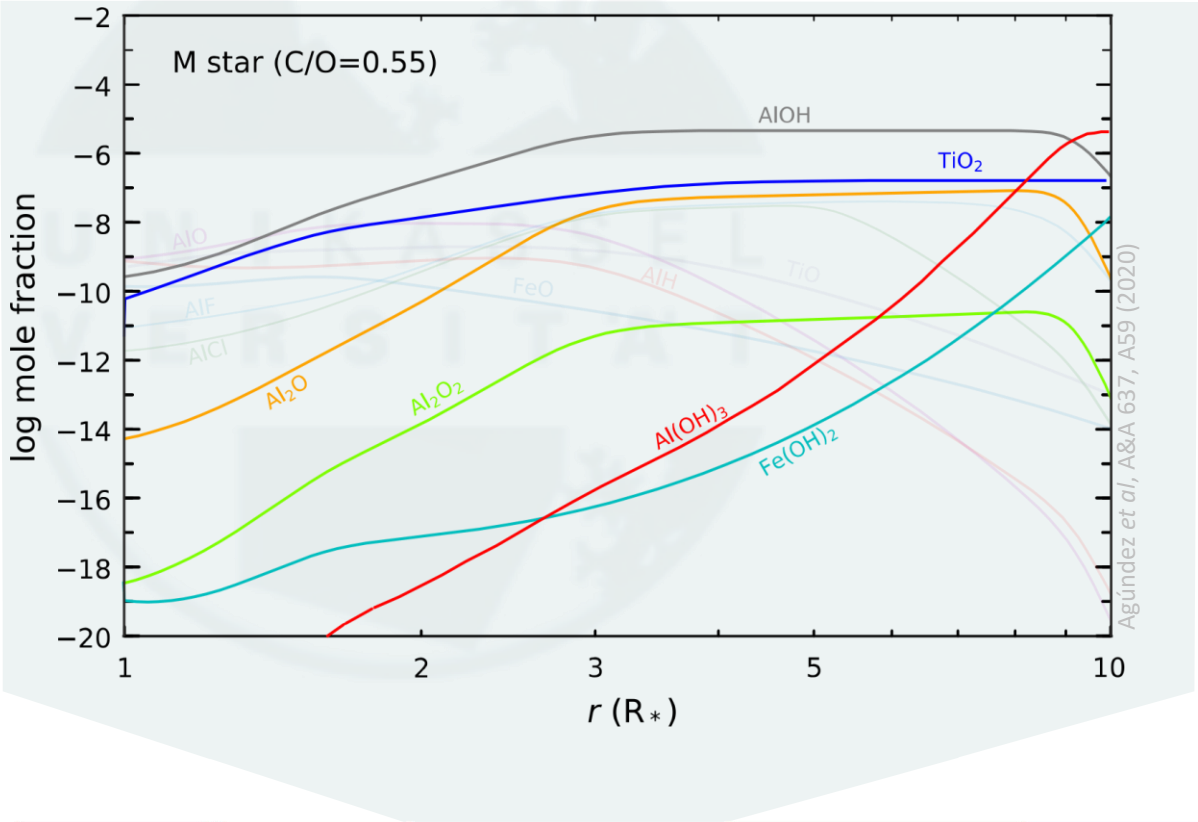
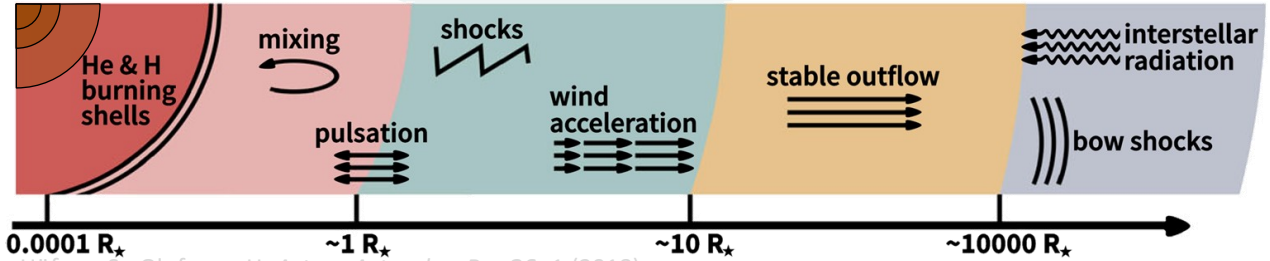


Further Molecular Species

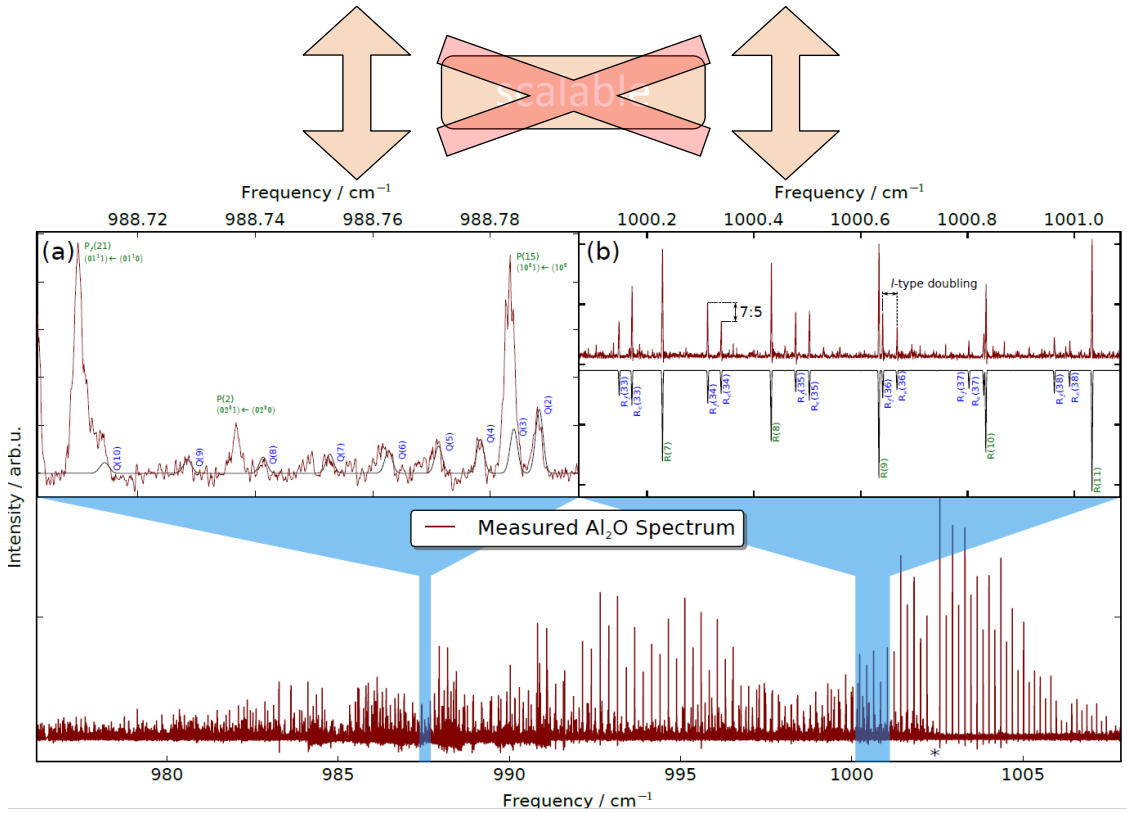




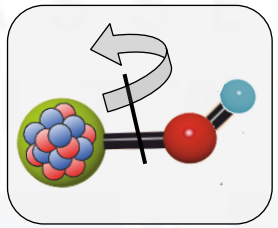
Höfner, S., Olofsson, H. *Astron Astrophys Rev* **26**, 1 (2018).

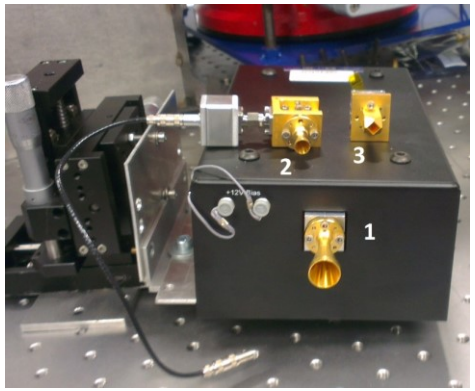
Radioactive polyatomic molecules

- $^{26}AlOH$
- $^{44}TiO_2$
- $^{26}Al_2O$
- $^{60}Fe(OH)_2$

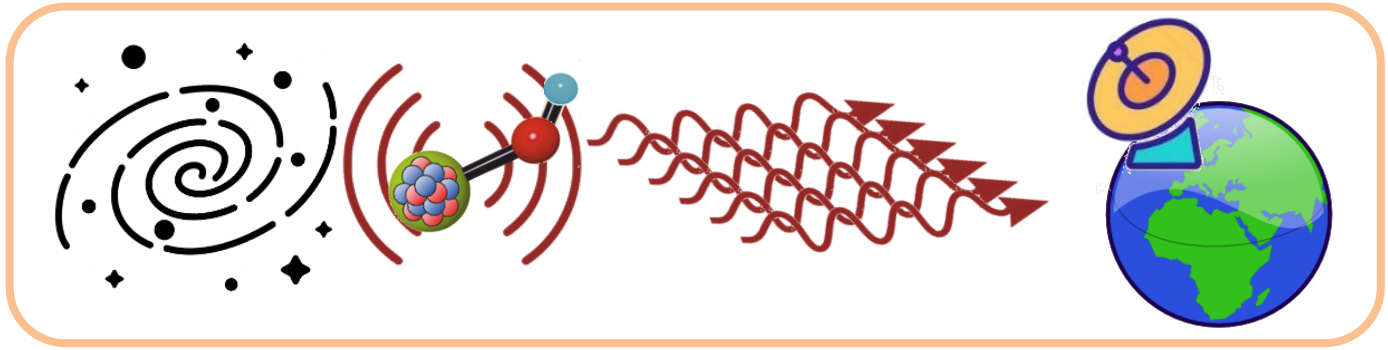


New opportunities: Laboratory astrophysics



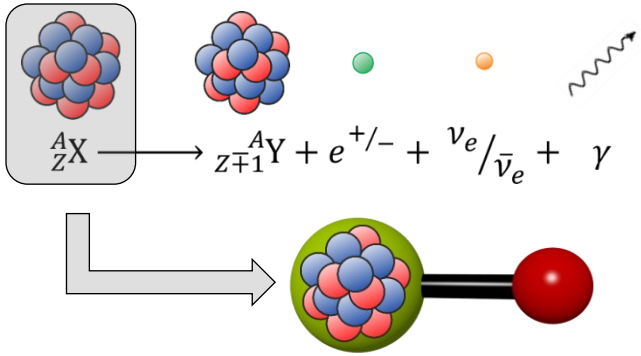


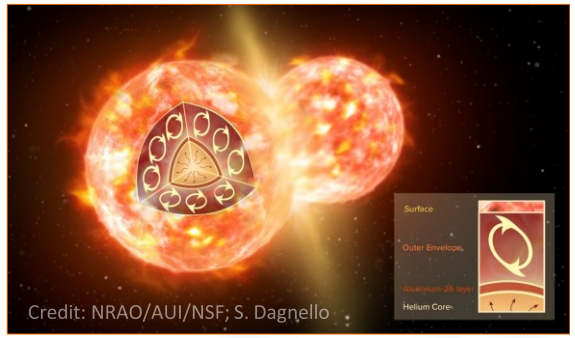
C/O <1 | $^{26}AlOH$ | $^{44}TiO_2$ | $^{60}Fe(OH)_2$ | $^{26}Al_2O$ | $^{32}Si_2C$ | $^{32}SiC_2$ | C/O >1

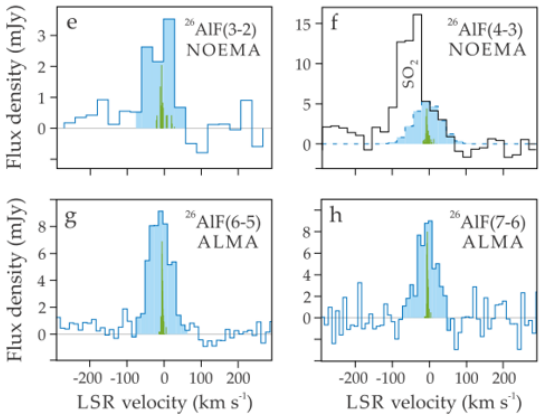


Conclusion

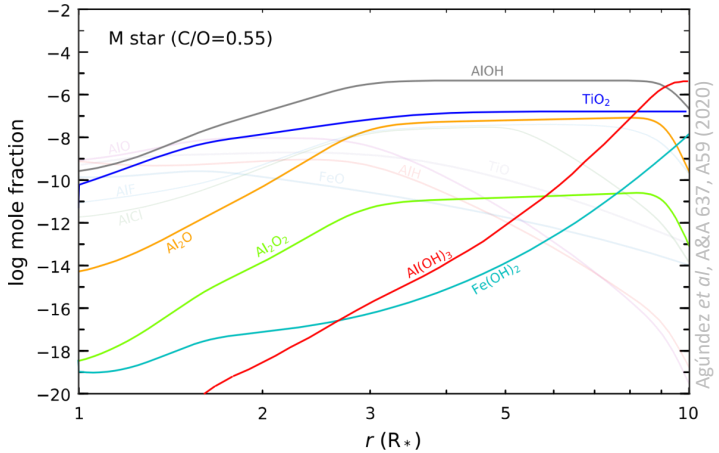
- Radioactive molecule:
  as tracer for stellar dynamics







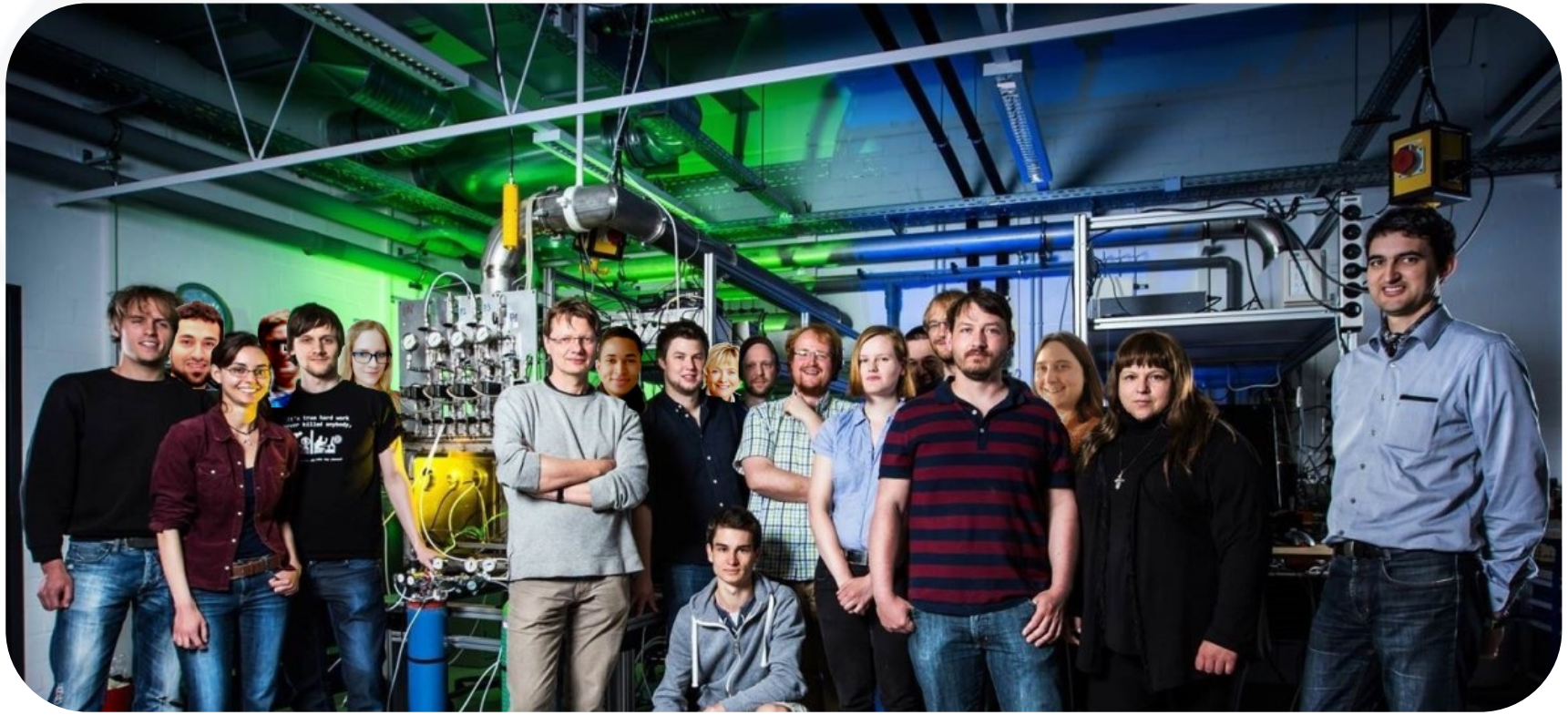
- Mass-independent description on diatomic molecules,…



- …but radioactive polyatomic molecules need direct measurments

C/O <1 | ^{26}AlOH | $^{44}TiO_2$ | $^{60}Fe(OH)_2$ | $^{26}Al_2O$ | $^{32}Si_2C$ | $^{32}SiC_2$ | C/O >1

Thank you



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DFG Priority Program 1573 ISM-SPP Interstellar Medium

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