19th Russbach School on Nuclear Astrophysics

Mar 3 – 9, 2024, Russbach Parish Center

COSMIC ALCHEMY

Elusive Nature of Post-Asymptotic Giant Branch Chemical Distribution

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MACQUARIE University
Astrophysics and Space Technologies Research Centre

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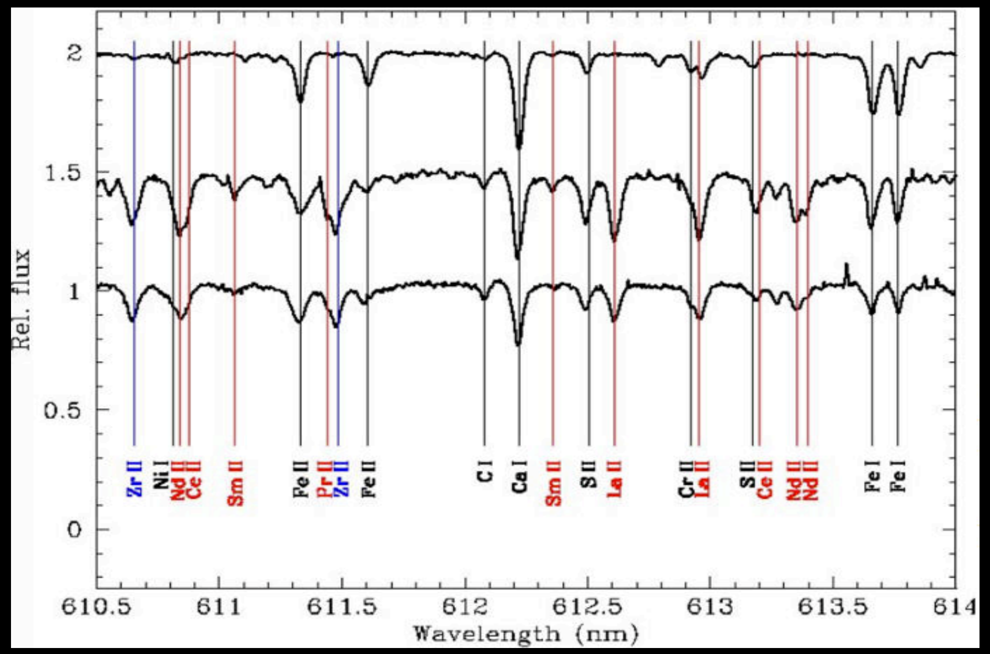
Amanda Karakas, Orsola De Marco, Mark Wardle*

INAF ISTITUTO NAZIONALE DI ASTROFISICA

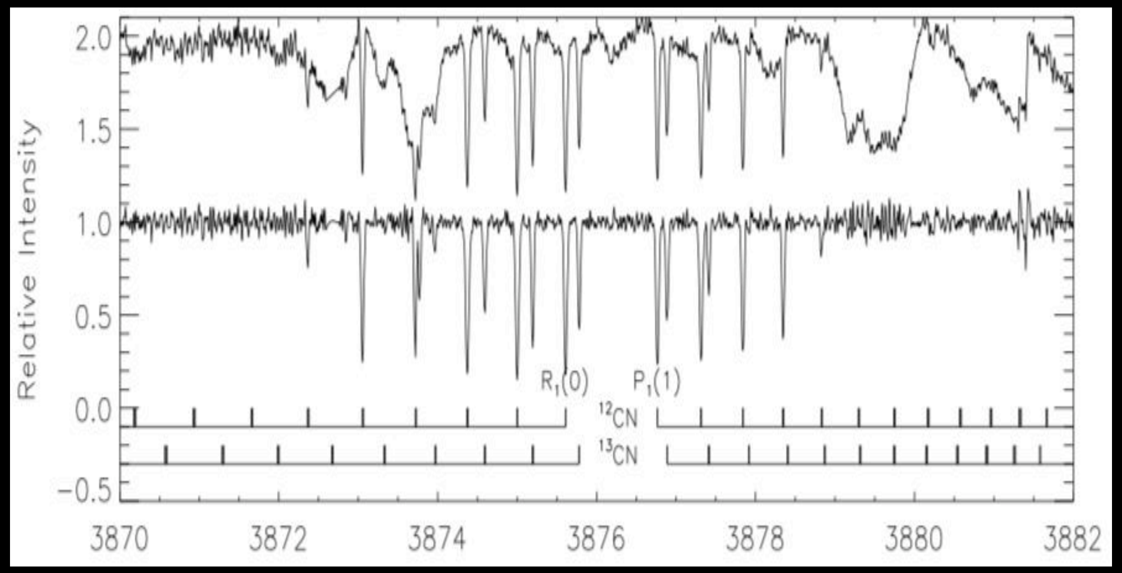
KU LEUVEN

INSTITUTO D ASTROFISICA D CANARIAS · IAC ·

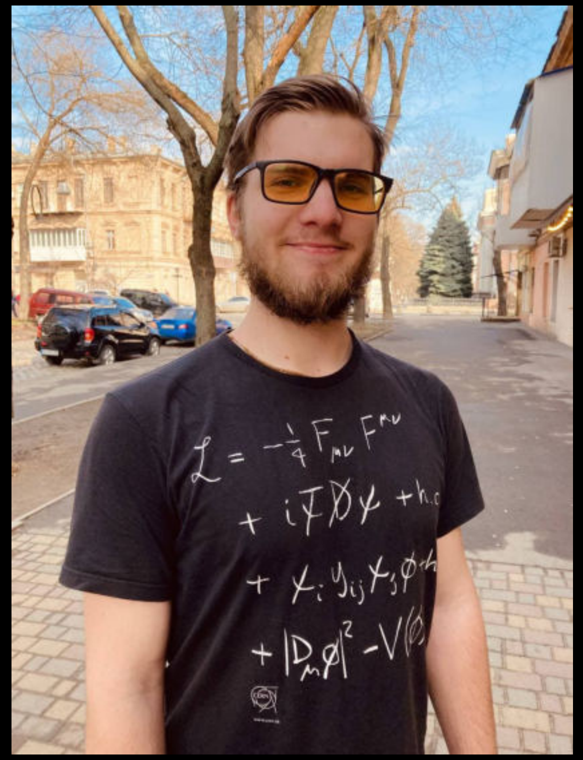
1. Evolved stars as tracers for AGB nucleosynthesis



Optical spectra - UVES/VLT



CN Violet System (0,0) band towards HD 56126
(Bakker et al., 1997)



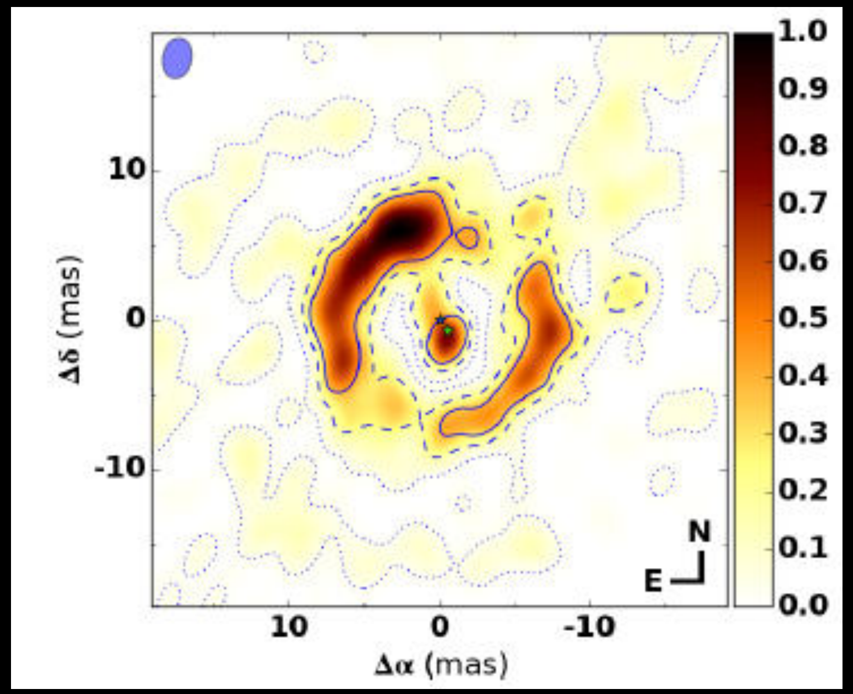
Maksym Mohorian

Meghna Menon

Silvia Tosi

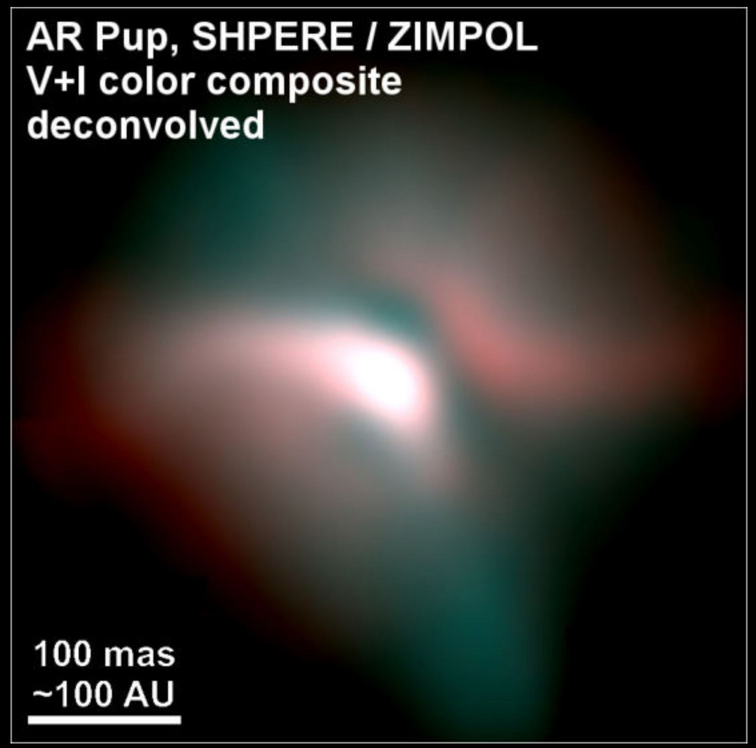
Zara Osborne

2. Investigating the second-generation proto-planetary disks



Hillen et al., 2016

H-band reconstruction PIONIER/VLTI



Ertel, Kamath, et al., 2018

Kateryna Andrych

Toon de Prins

Kayla Martin

3. Chromospheric activity in stars

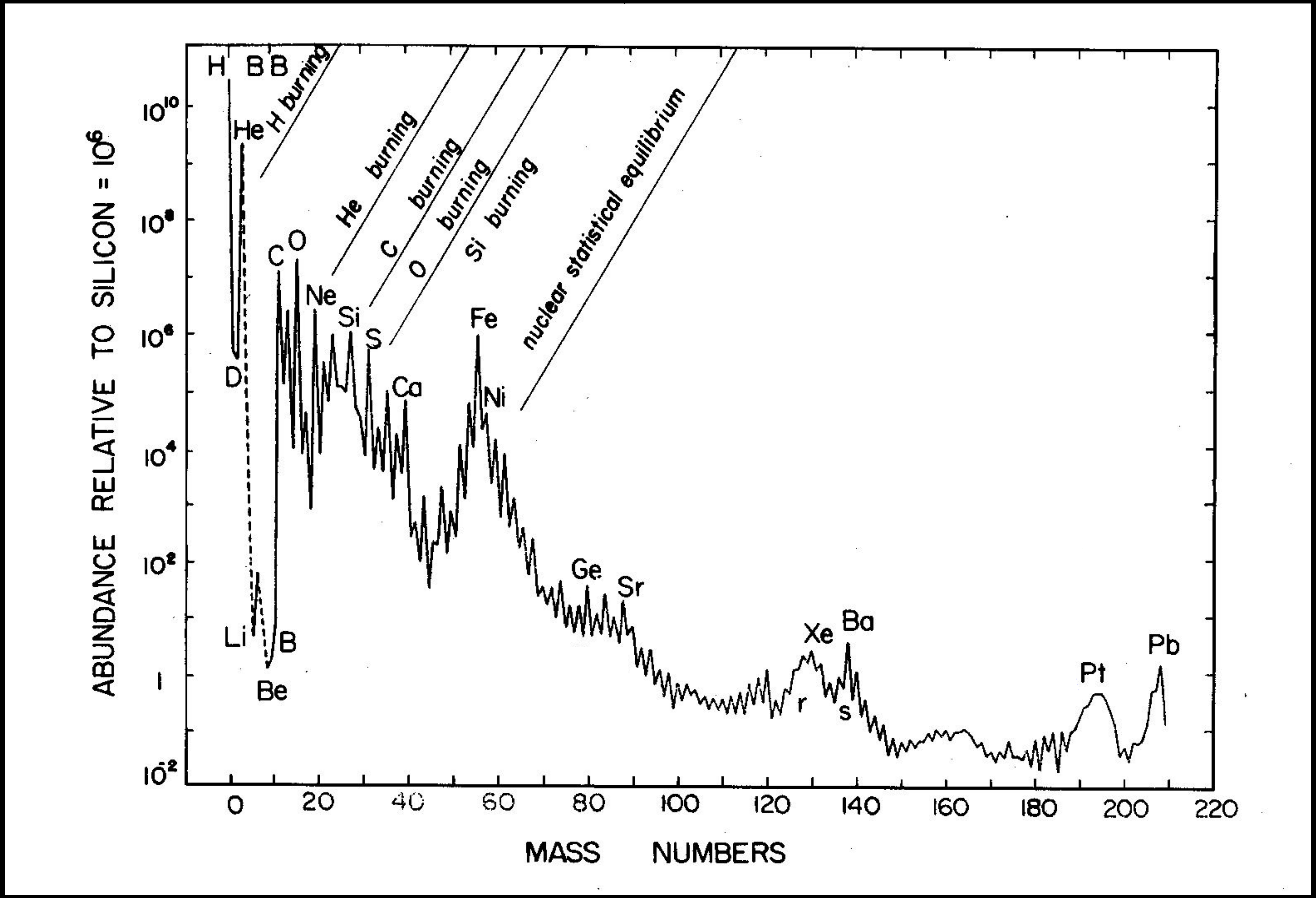
Deepak Chahal

Astro Speak…

- Mass fraction: Mass of H + He + 'metals' = 1
- $[a/b] = \log_{10}(a/b)_{star} - \log_{10}(a/b)_{sun}$
- "Metal" content usually defined according to [Fe/H]
- A metal-poor star has $[Fe/H] < 0$
- [Fe/H] is also a proxy for time (age)

Scientific Background: The Origin Of Elements

Abundances of the Chemical Elements in the Solar System



adapted from Cameron (1982)

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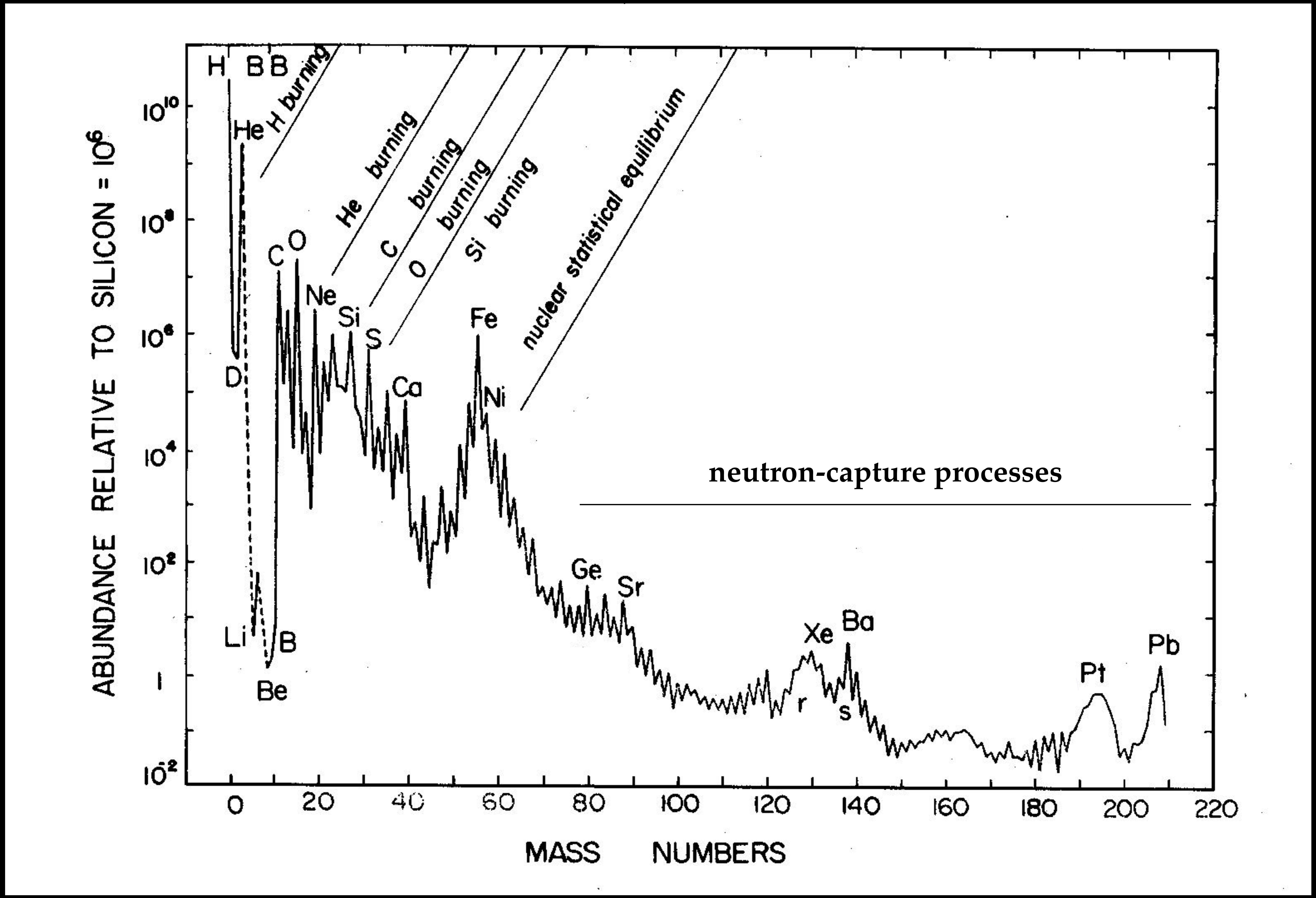

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Making Heavy Elements by Neutron Capture

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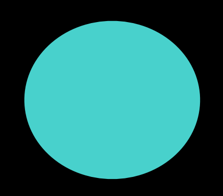
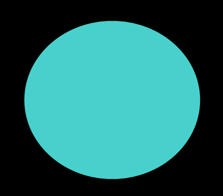


Making Heavy Elements by Neutron Capture

seed
Fe



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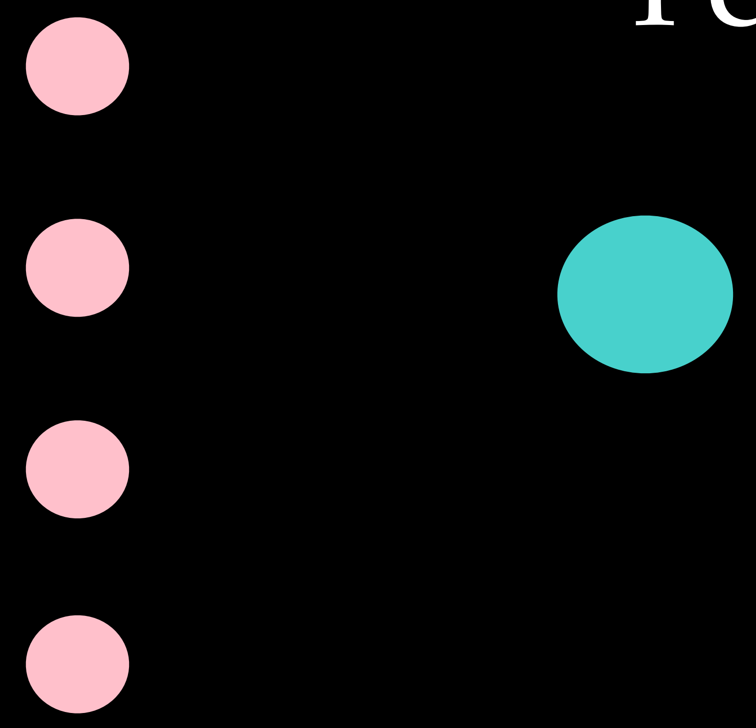

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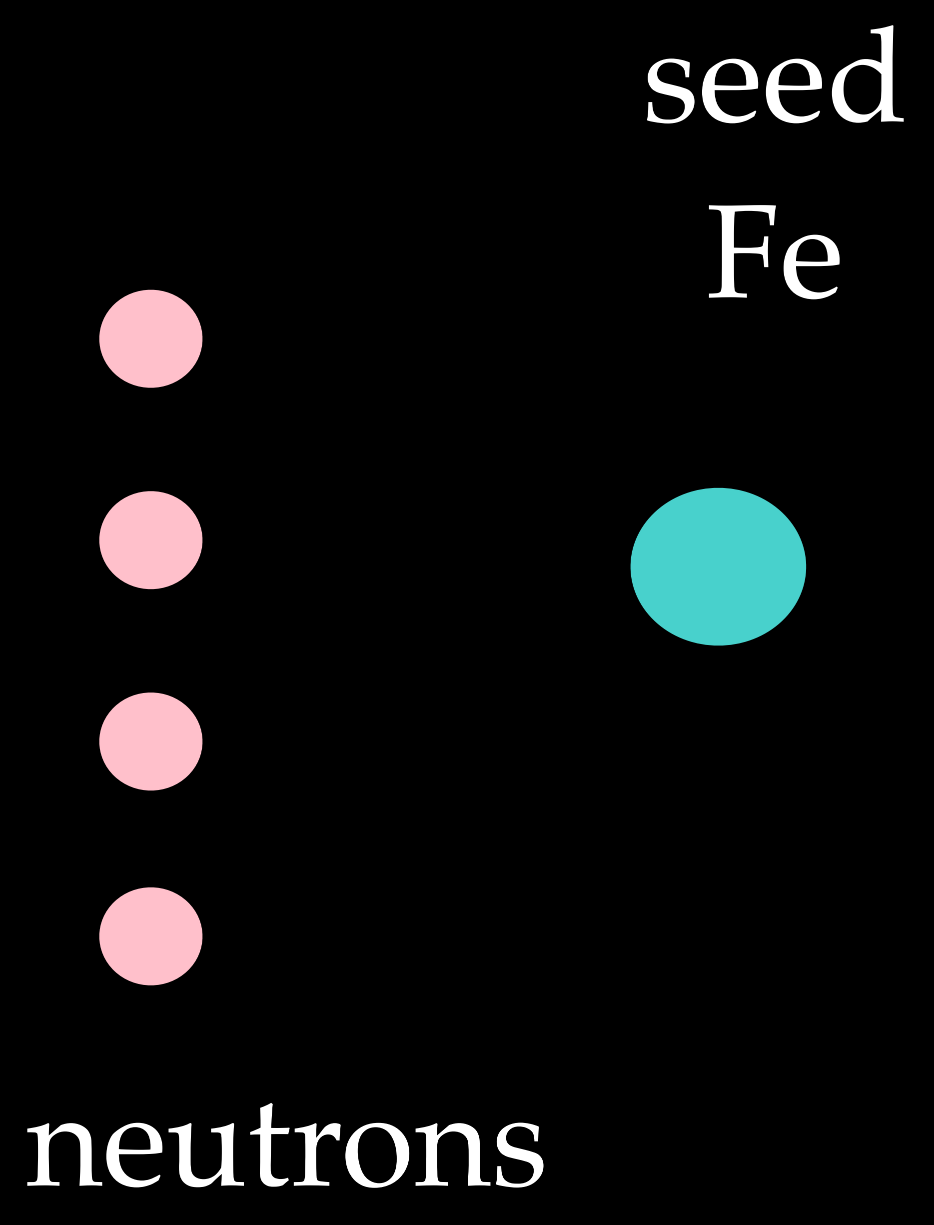

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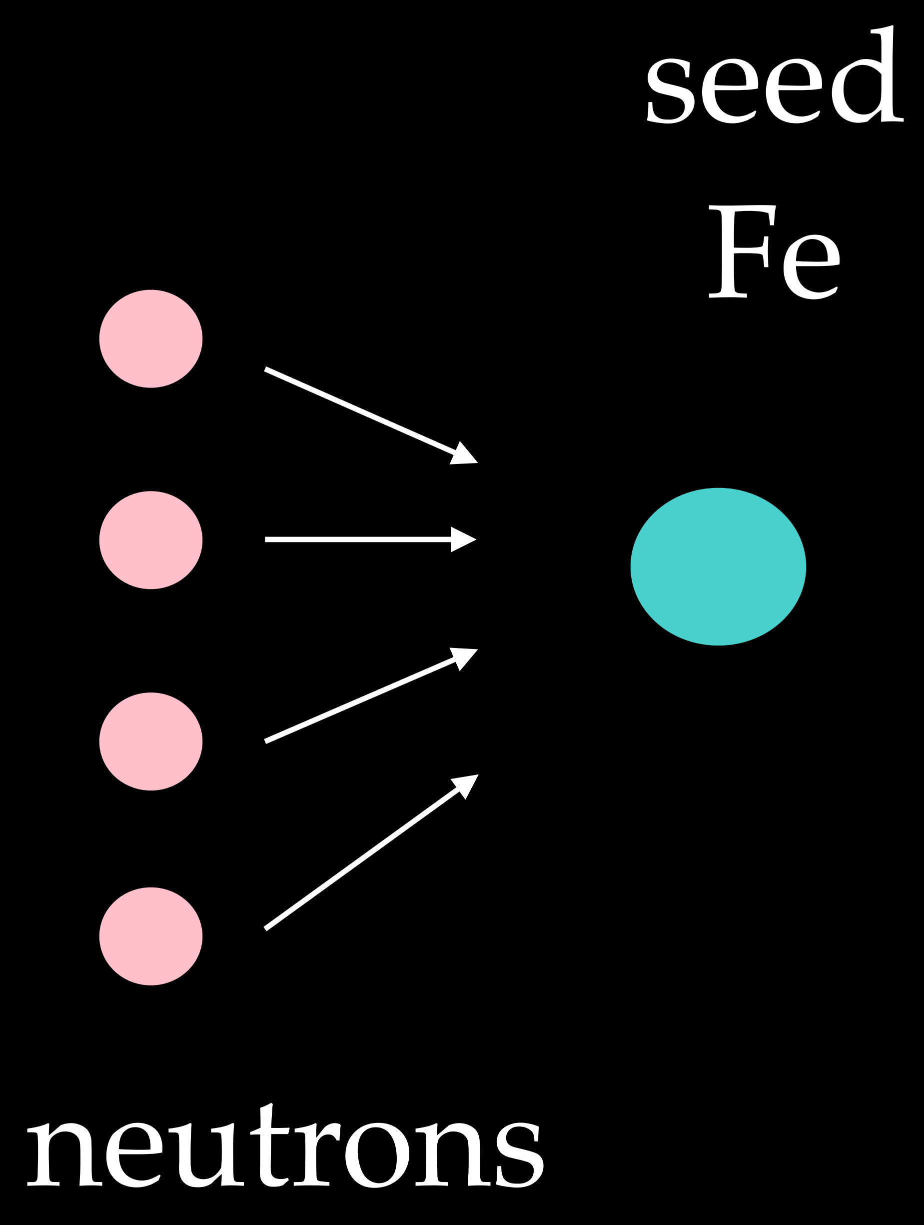

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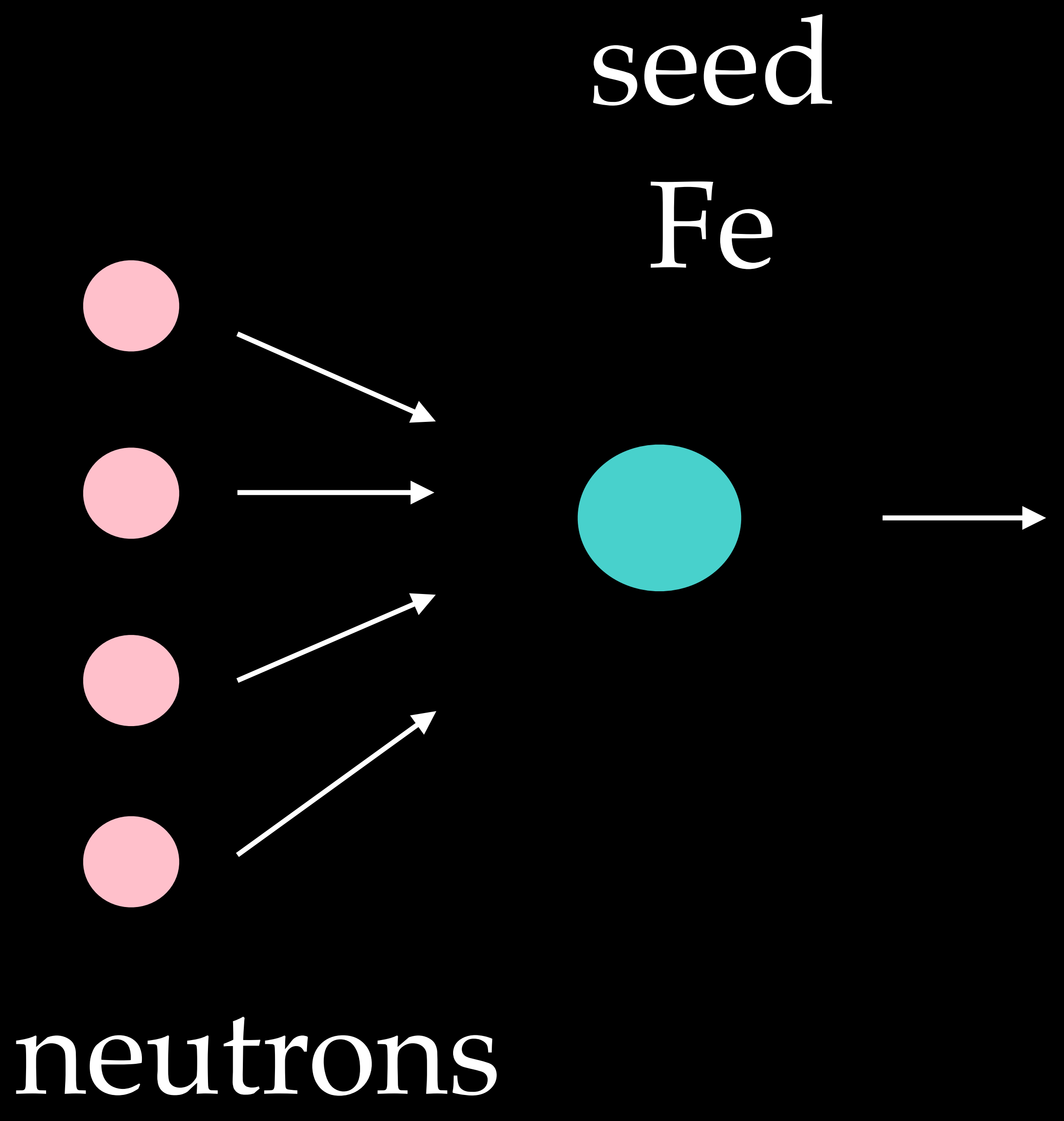

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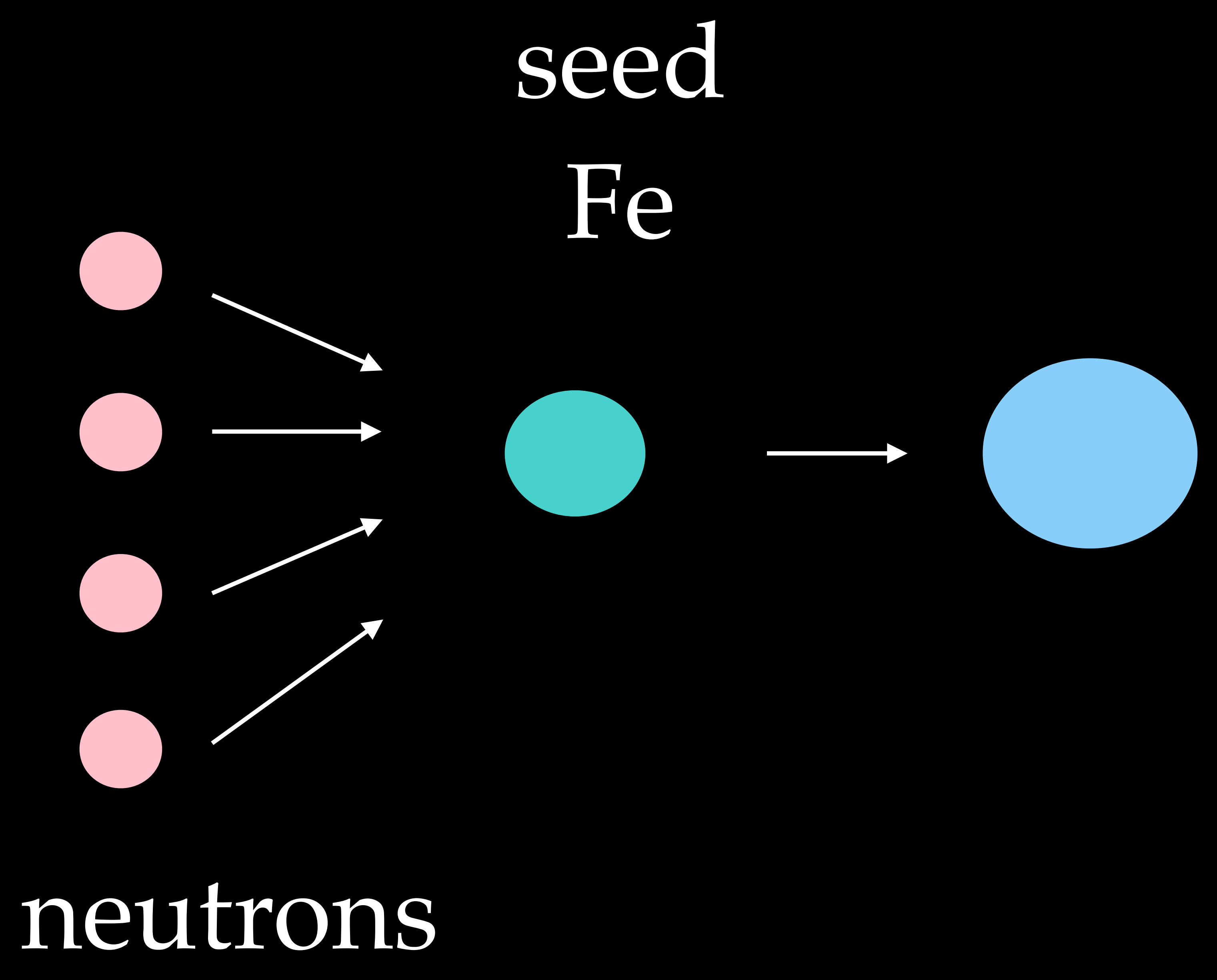

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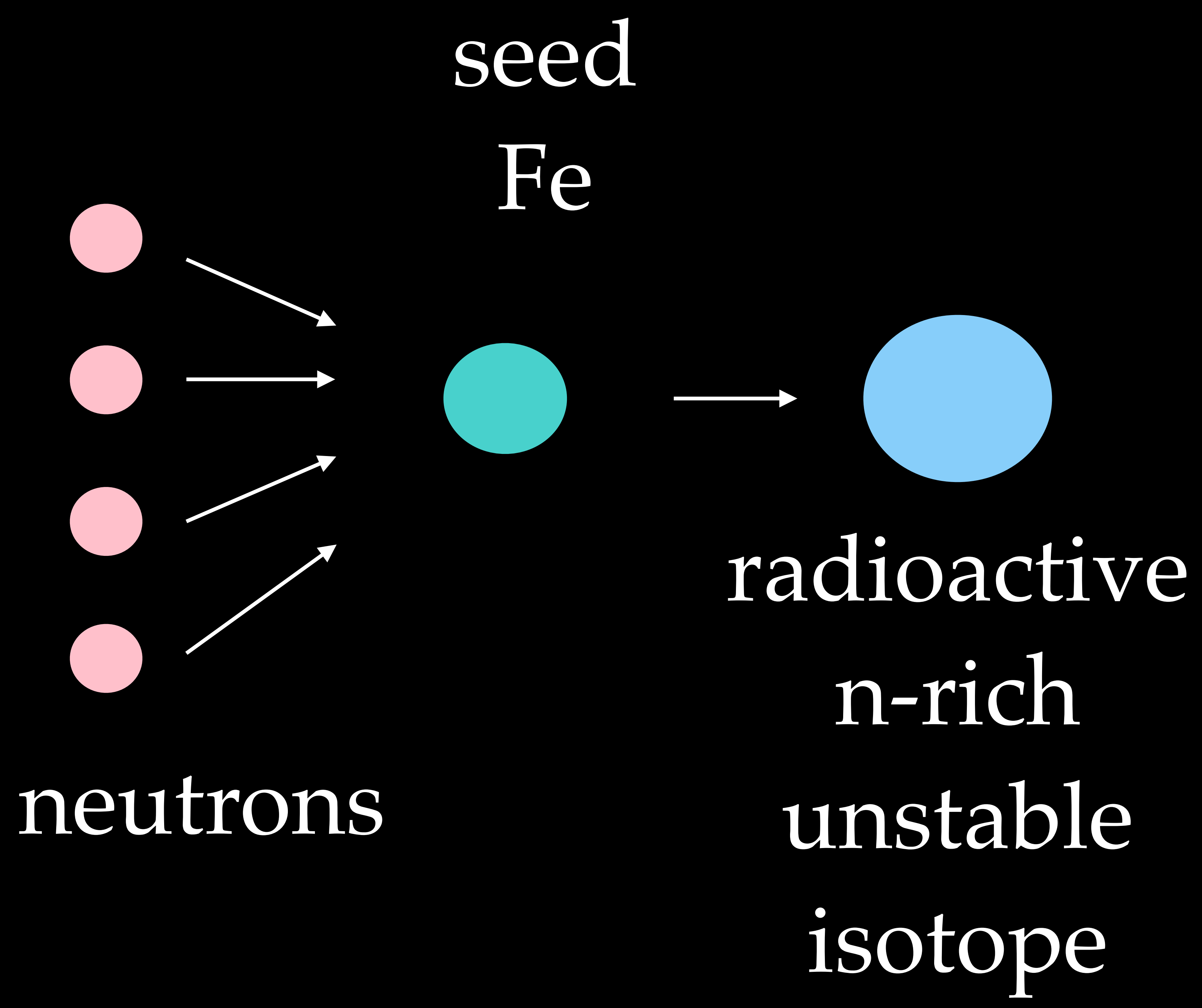

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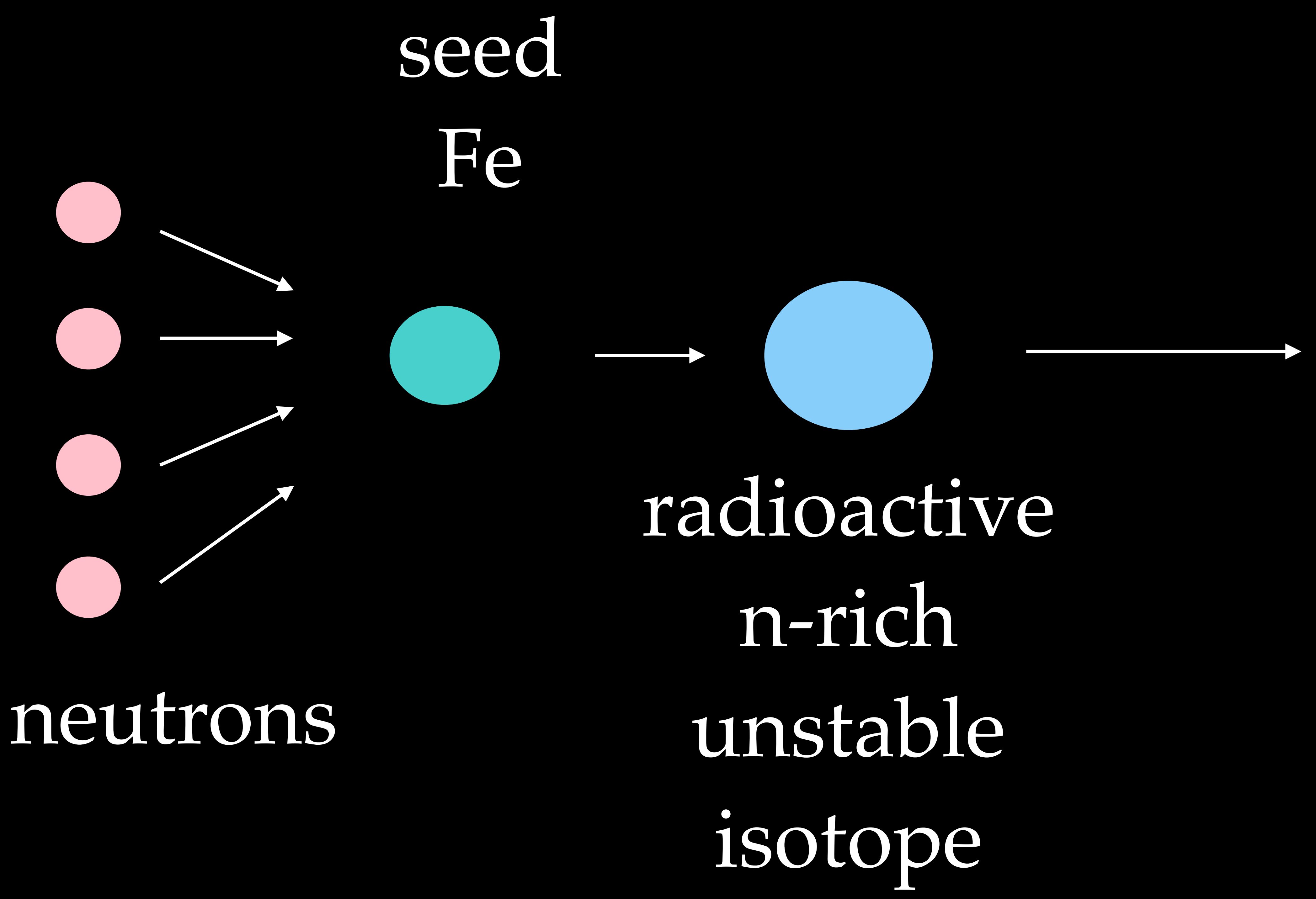

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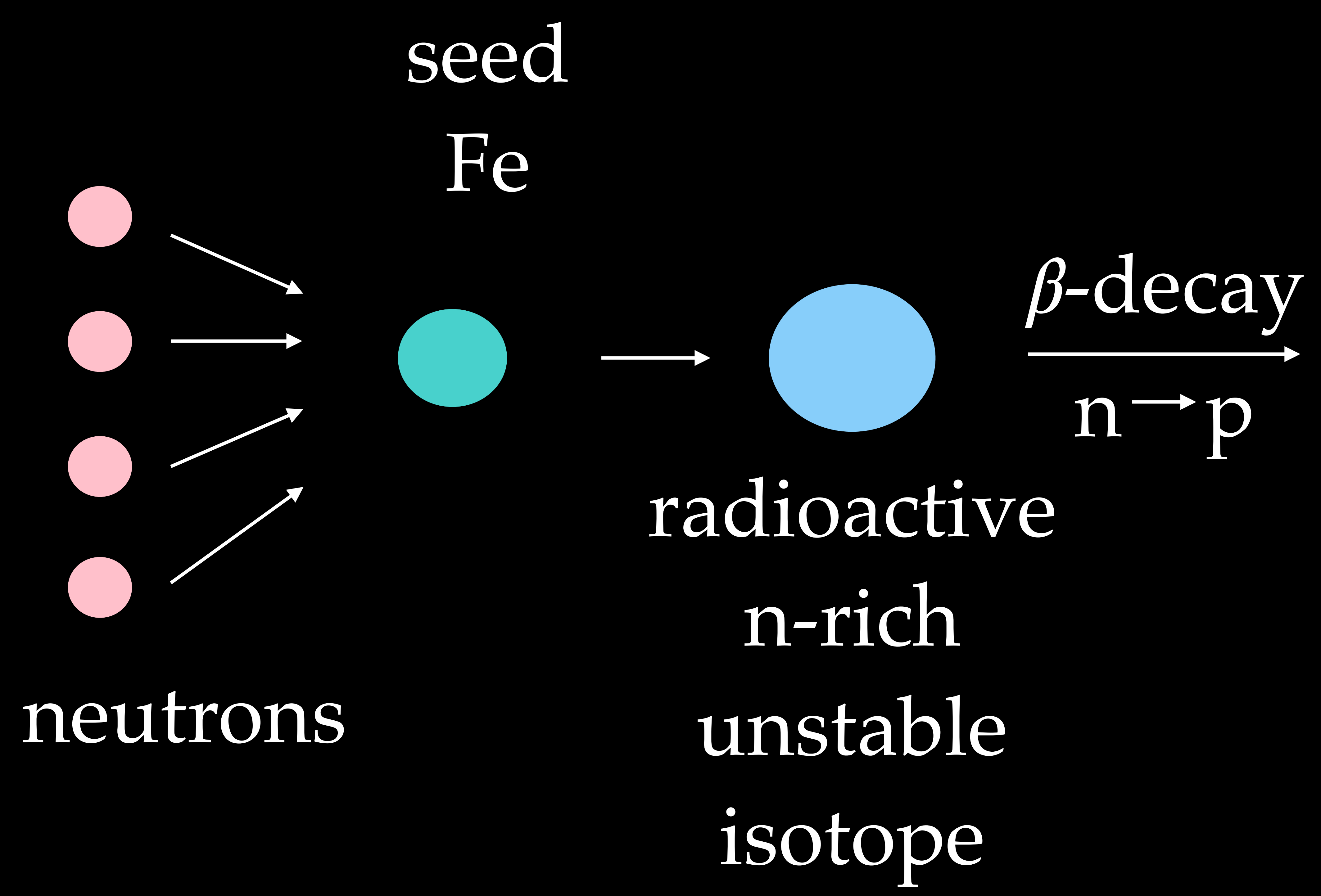

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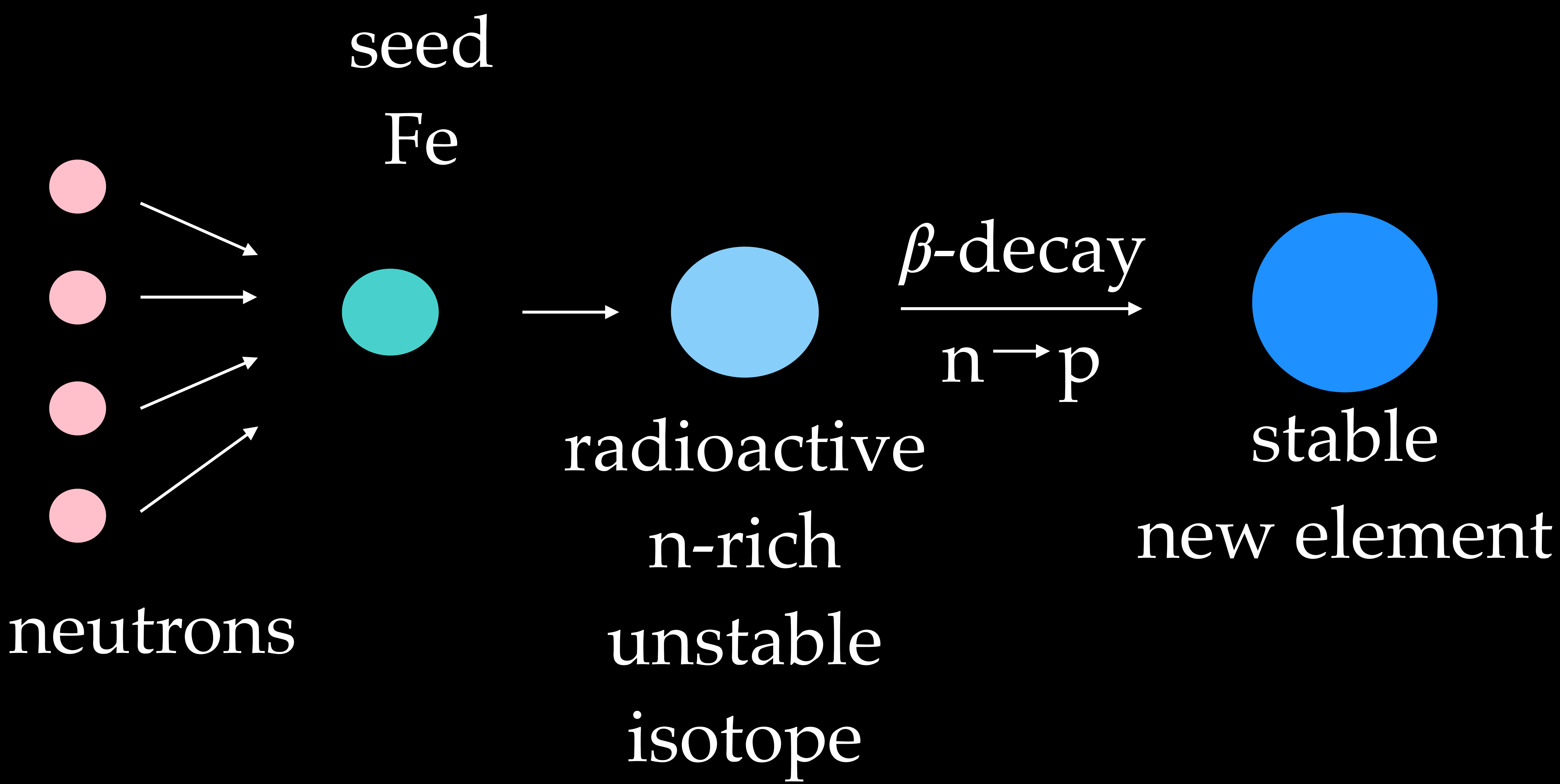

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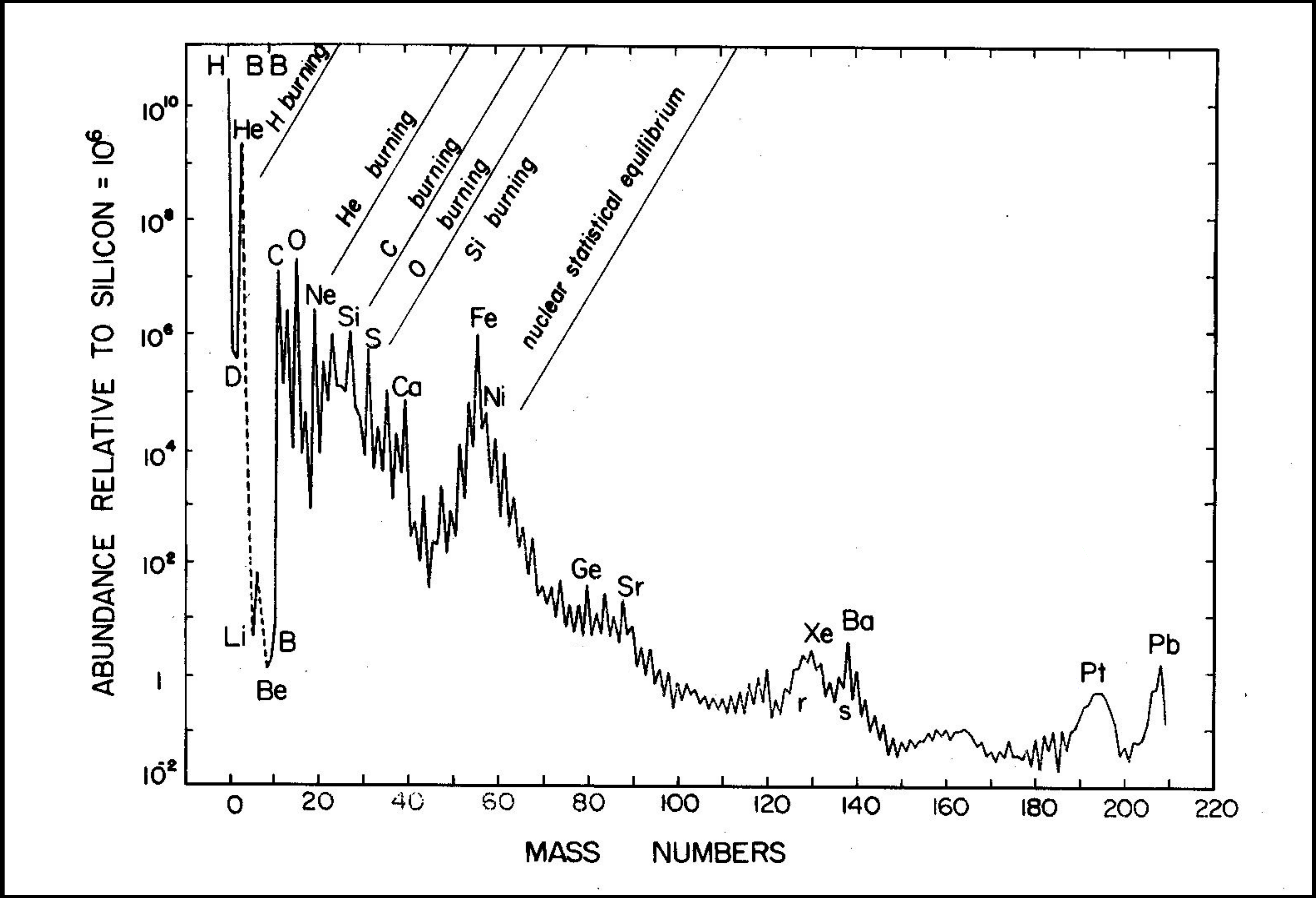

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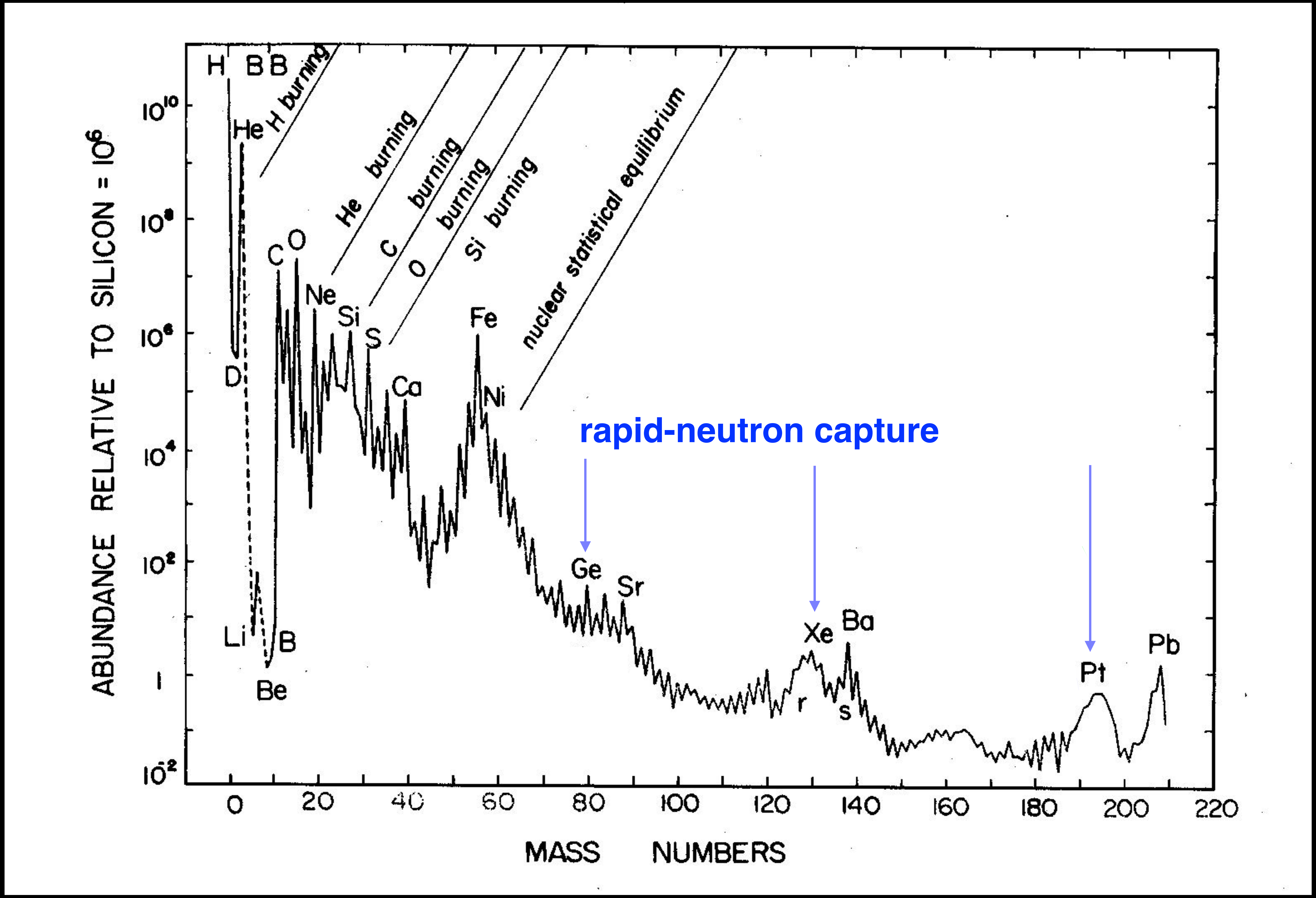

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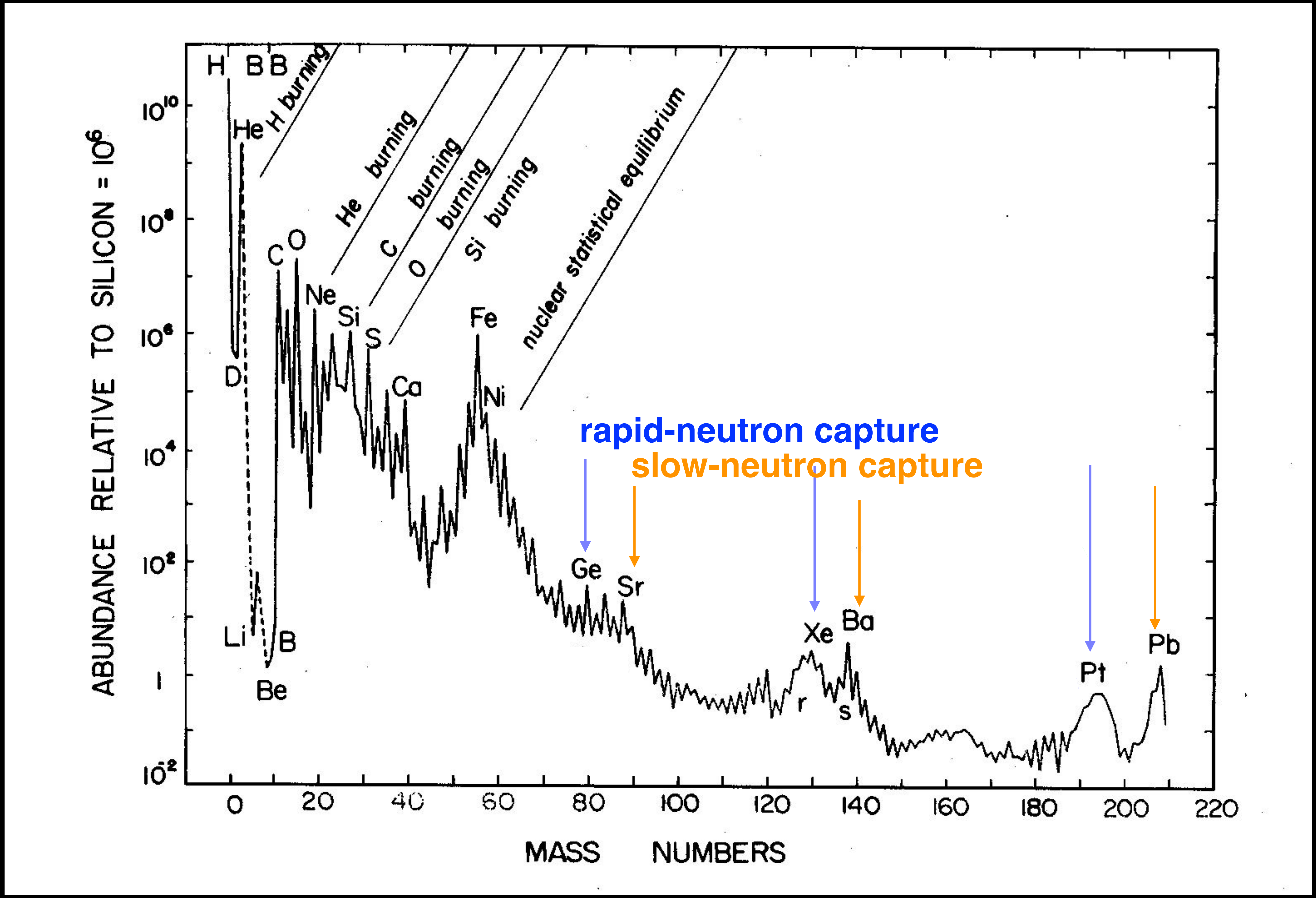


RAPID

NEUTRON CAPTURE PROCESS

n-capture rate < β-decay rate

$N_n > 10^{20}$ n/cm^3

SLOW

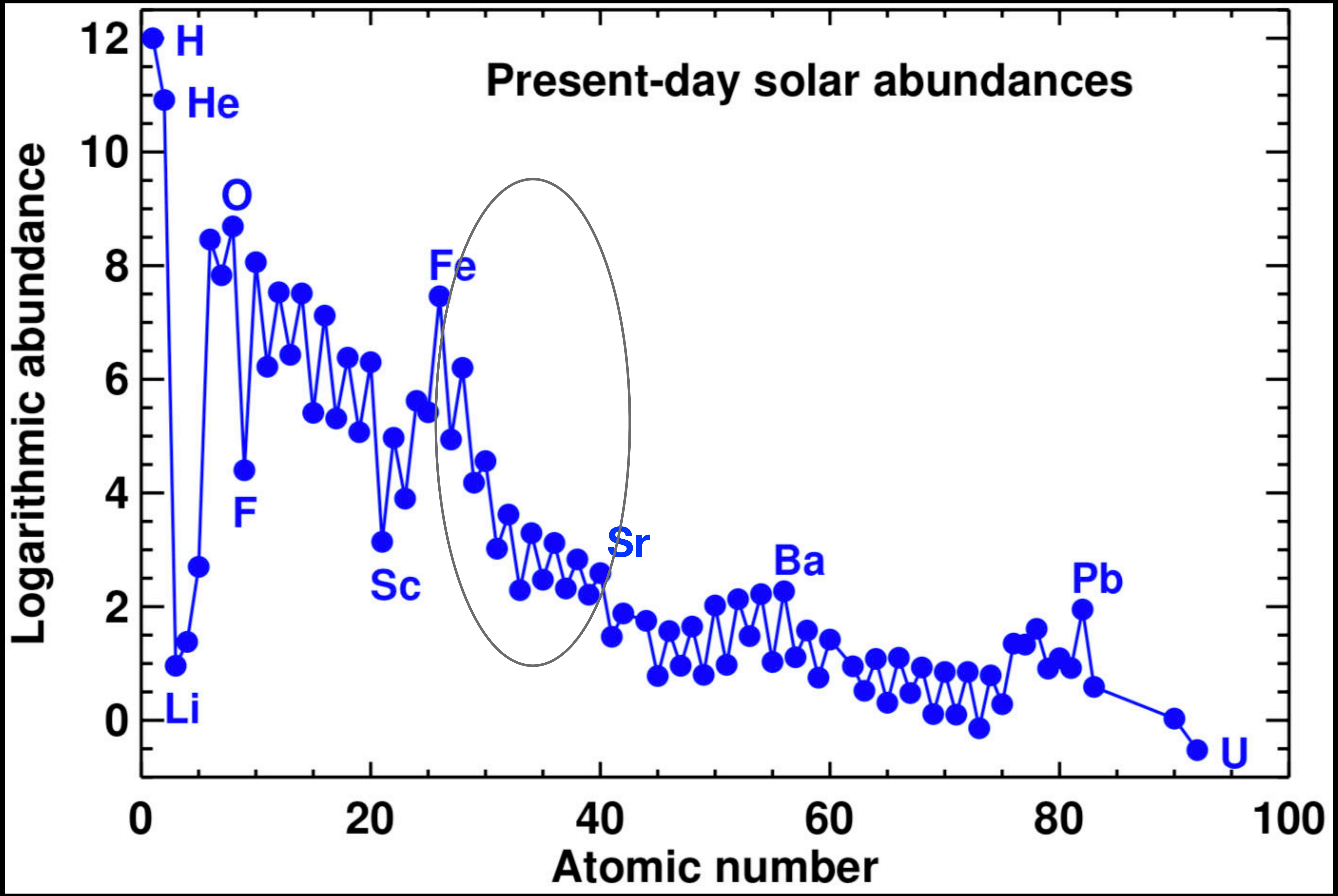
NEUTRON CAPTURE PROCESS

n-capture rate >> β-decay rate

$N_n \sim 10^8$ n/cm^3

Origins from Low- and Intermediate-Mass Stars: CNO, Iron-Peak, *s*-Process Elements

Present-day solar photospheric logarithmic abundances



Weak component

from Fe to Sr

τ ≈ 0.06 mbarn−1

Massive stars

Asplund et al., 2021

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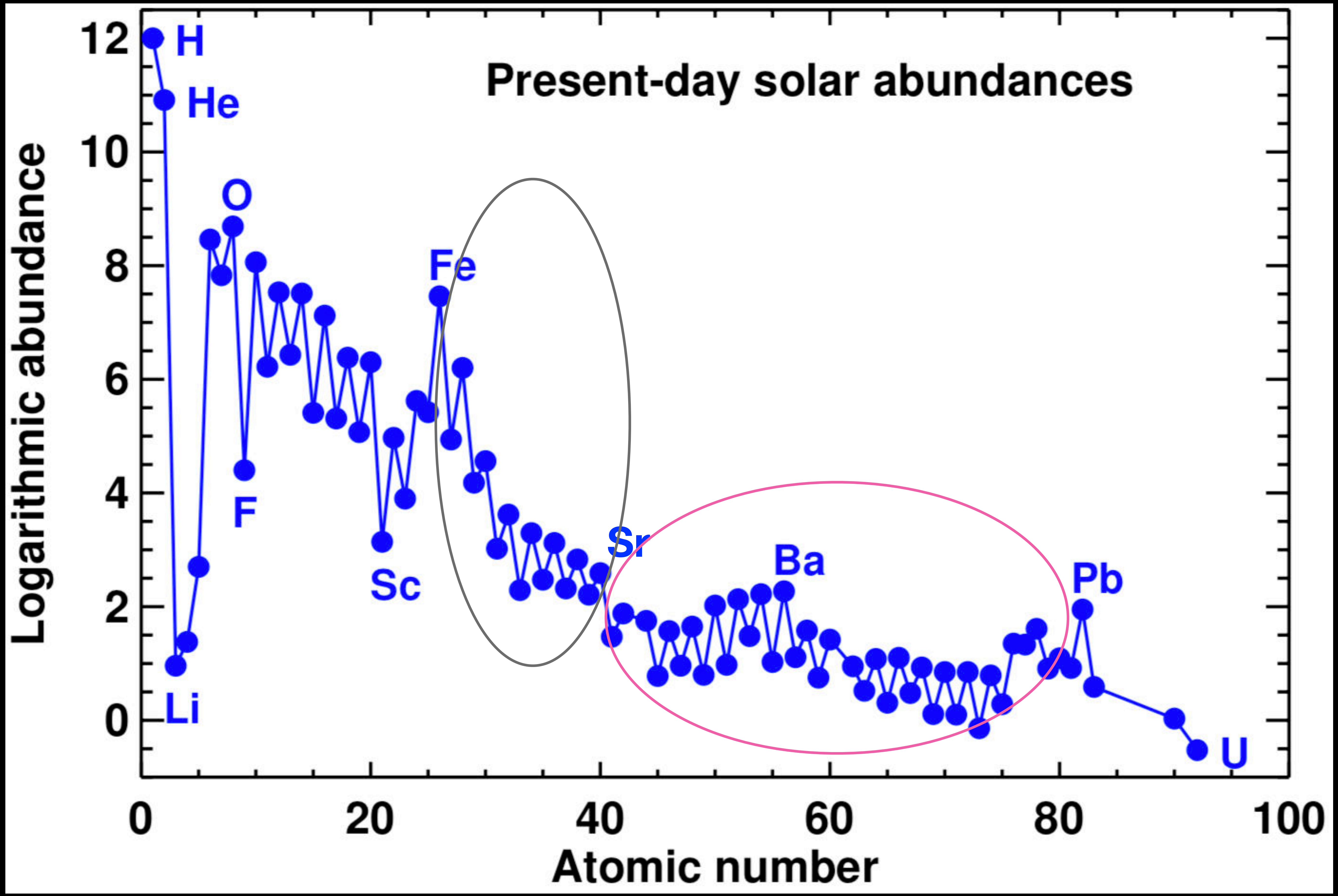

Asplund et al., 2021

Weak component
from Fe to Sr
$\tau \approx 0.06$ mbarn−1
Massive stars

Main component
from Sr to Pb
$\tau \approx 0.3$ mbarn−1
Low-mass AGBs

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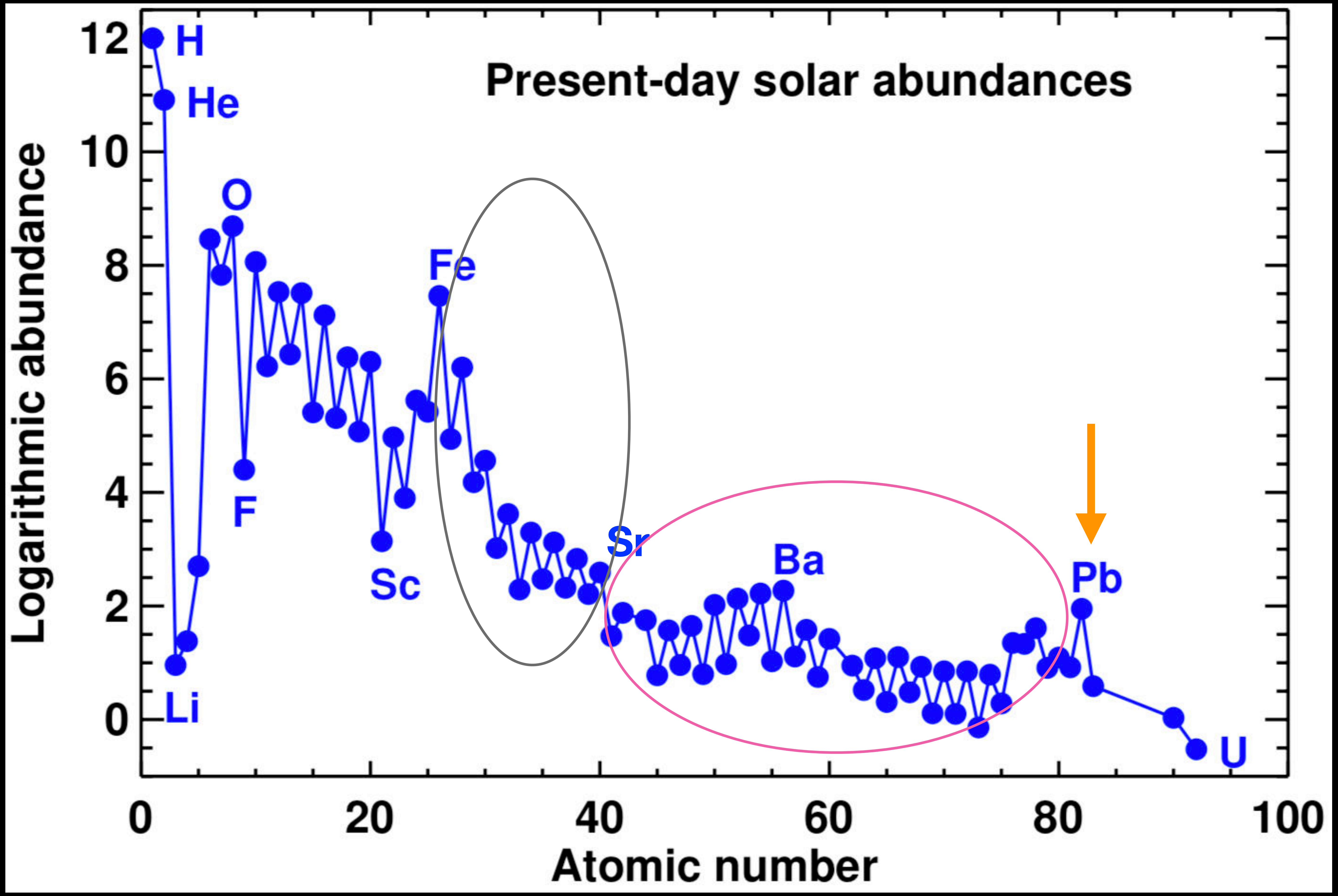


Asplund et al., 2021

Weak component

from Fe to Sr

τ ≈ 0.06 mbarn−1

Massive stars

Main component

from Sr to Pb

τ ≈ 0.3 mbarn−1

Low-mass AGBs

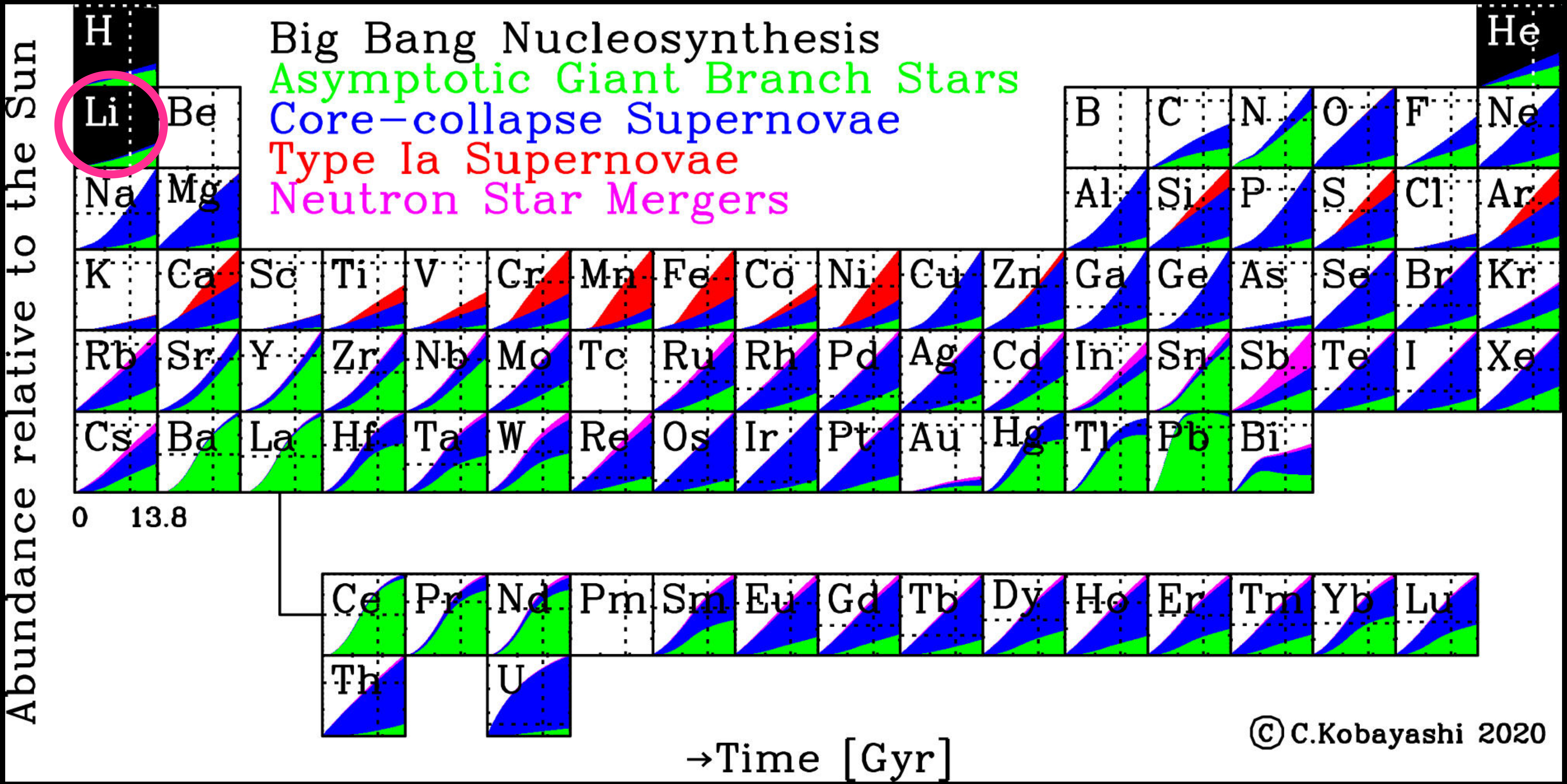
Strong component

Pb

τ ≈ 7.0 mbarn−1

Low-mass, Low-metallicity AGBs

Limitations in Current AGB Yields…



N, Li - INTERMEDIATE MASS STARS!

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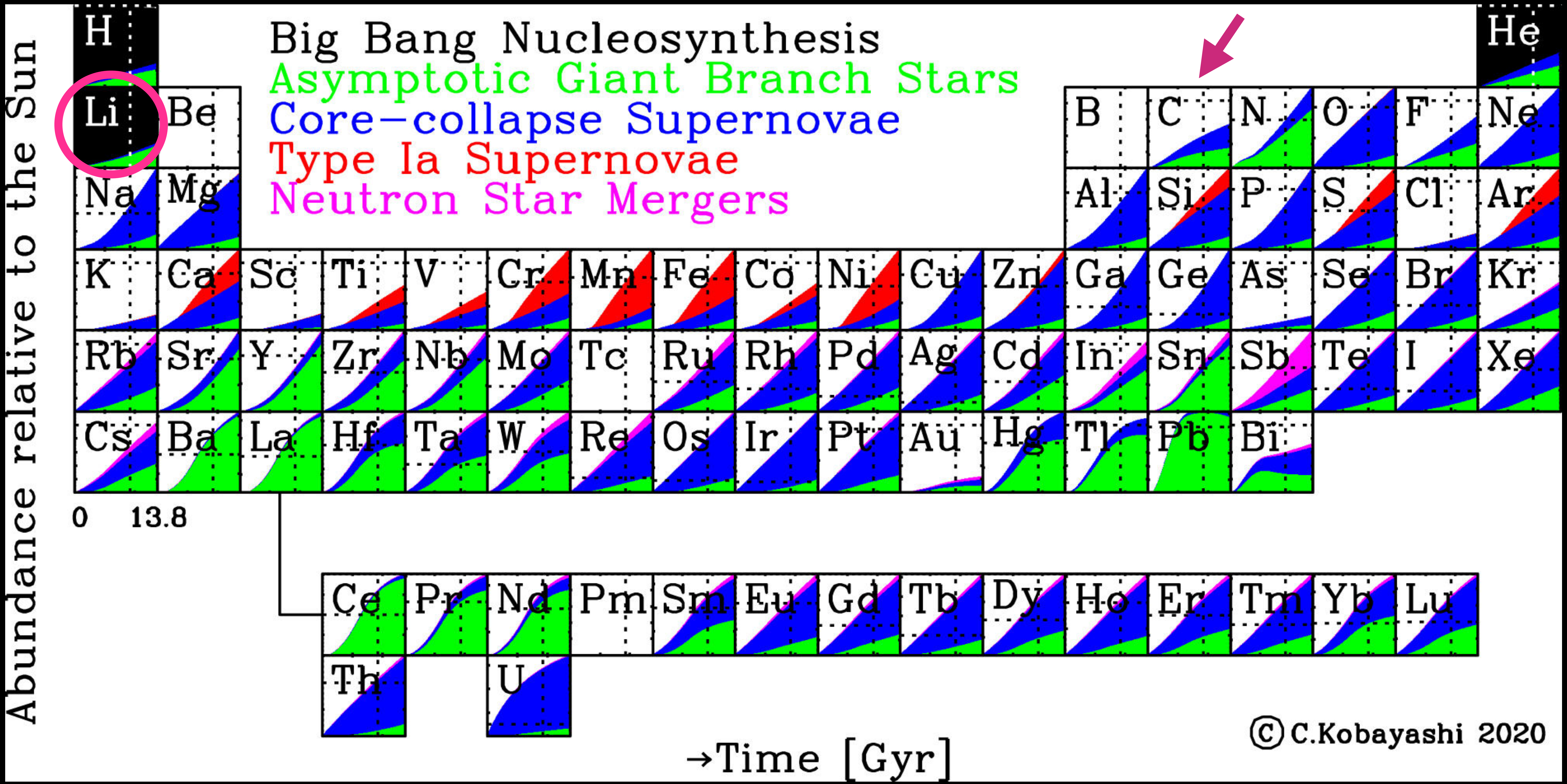

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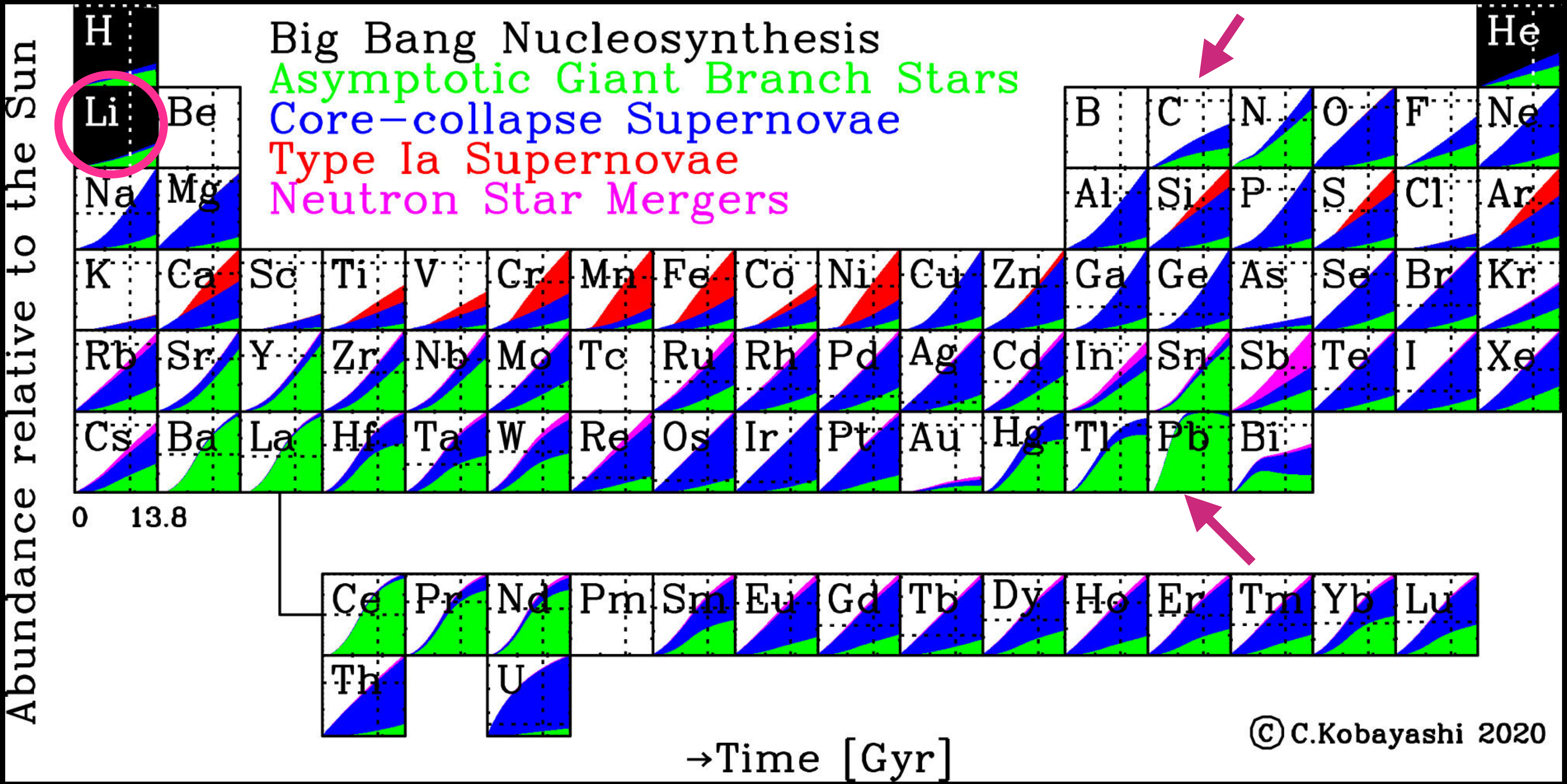

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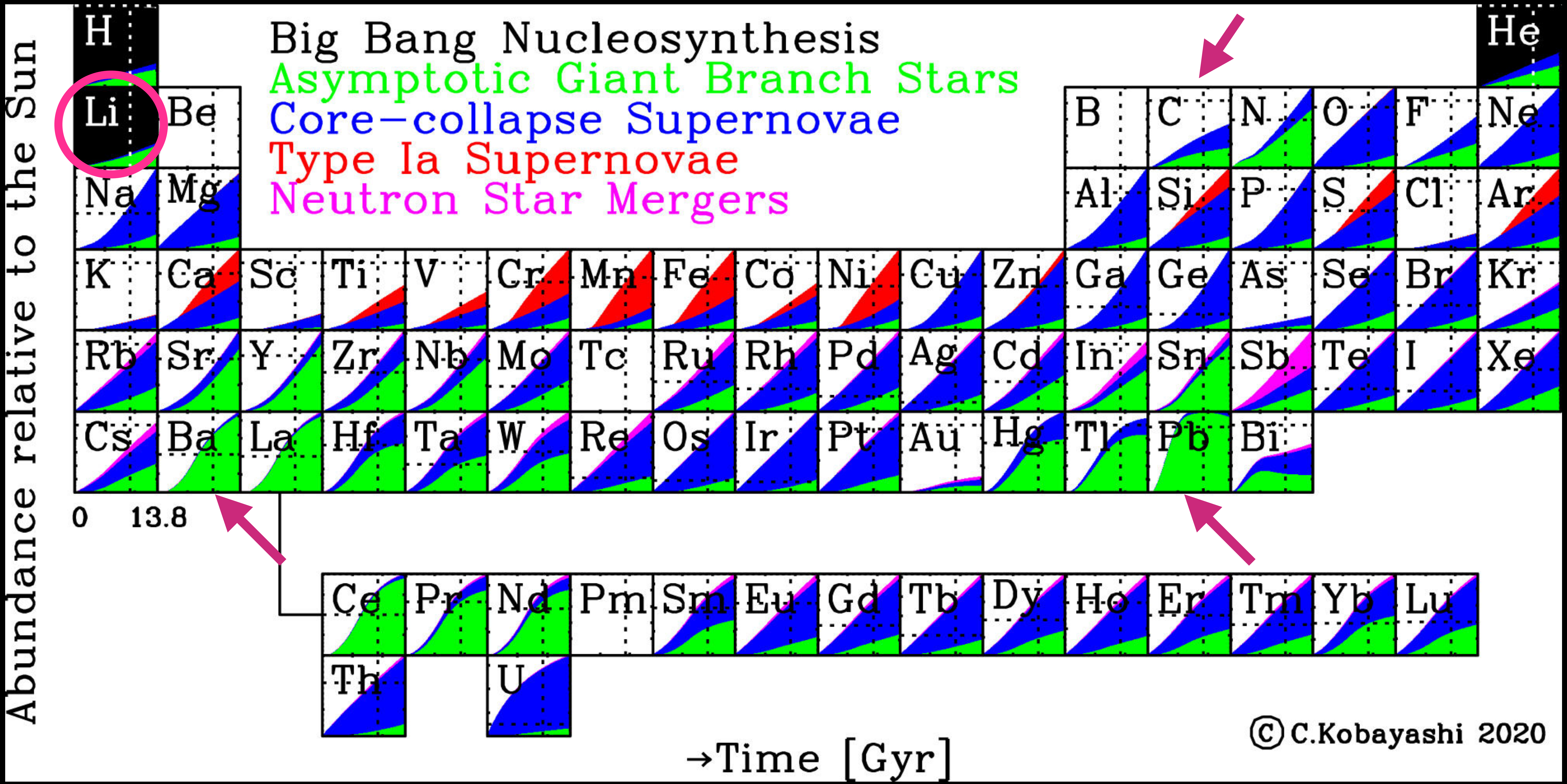

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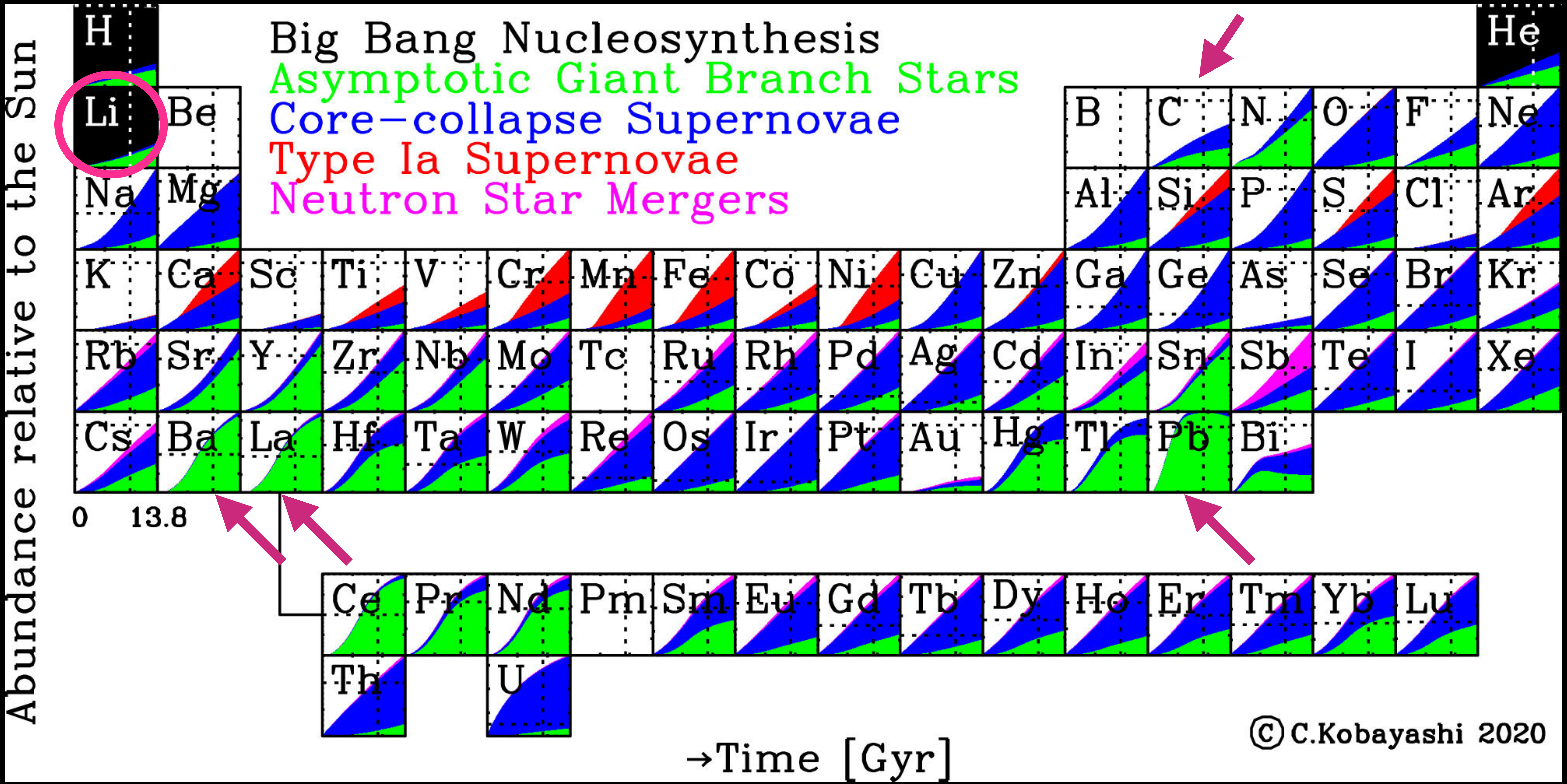

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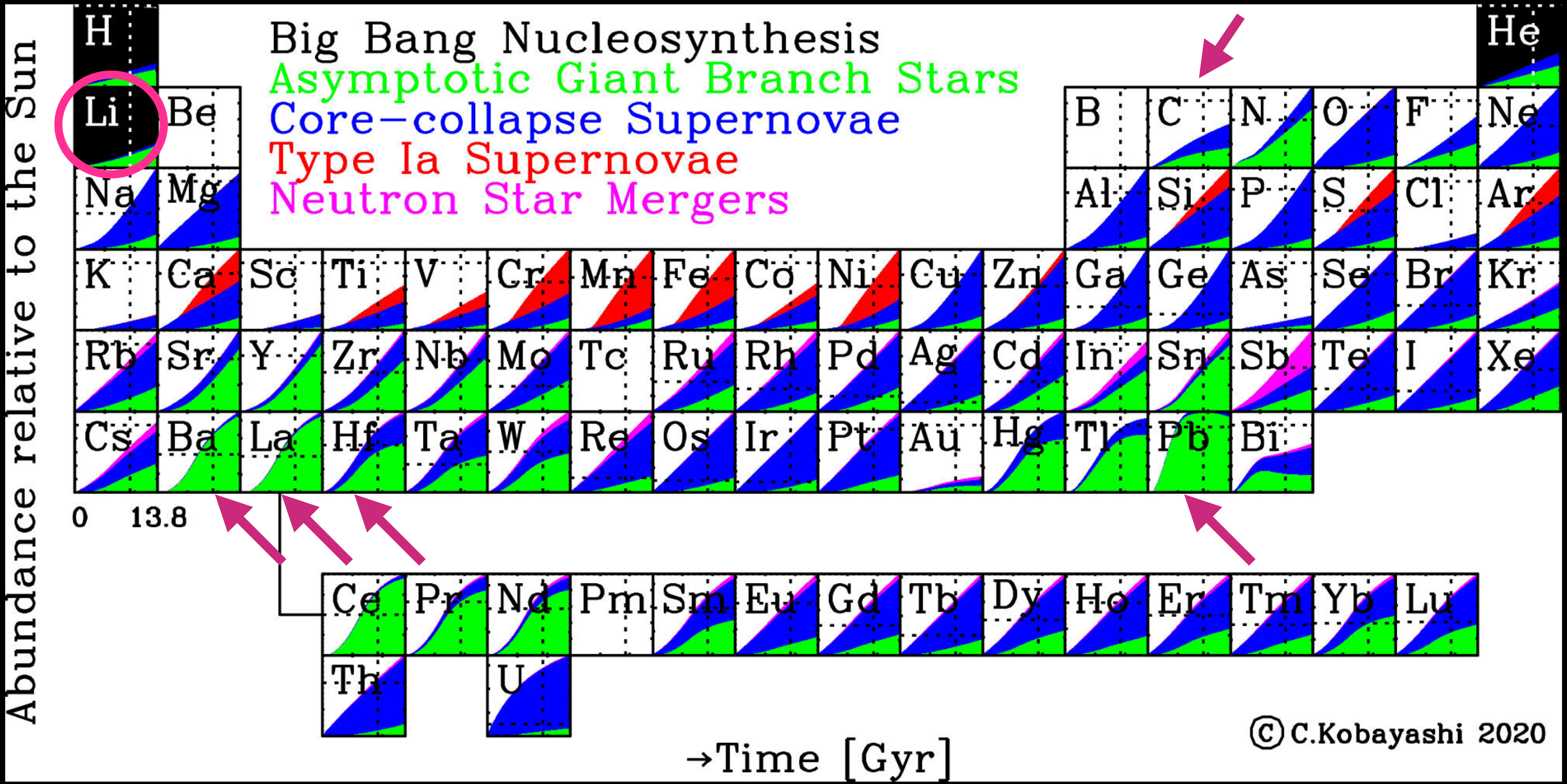

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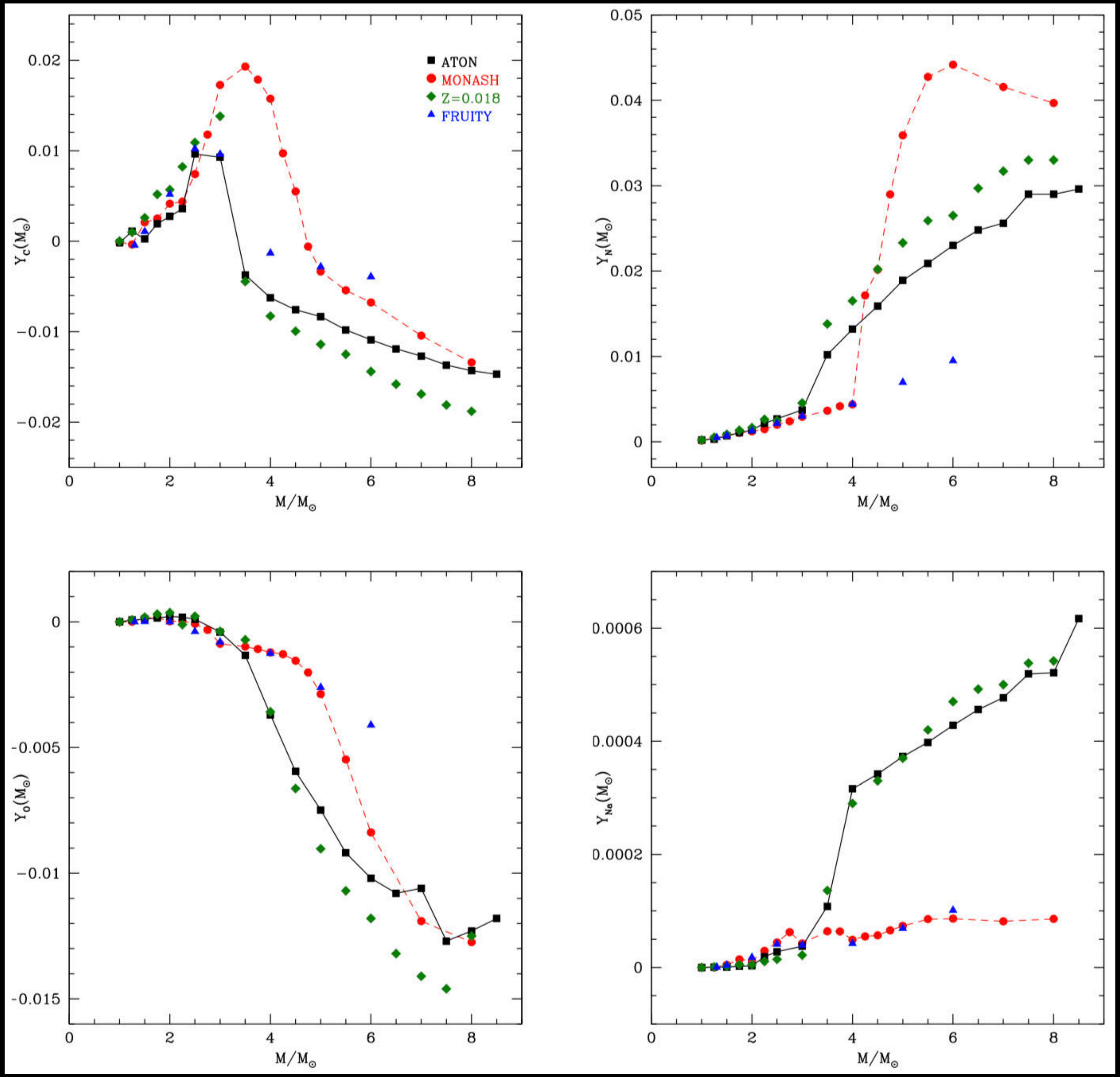
Yields of the CNO Elements and Sodium for Different AGB Models…



Ventura et al., 2017

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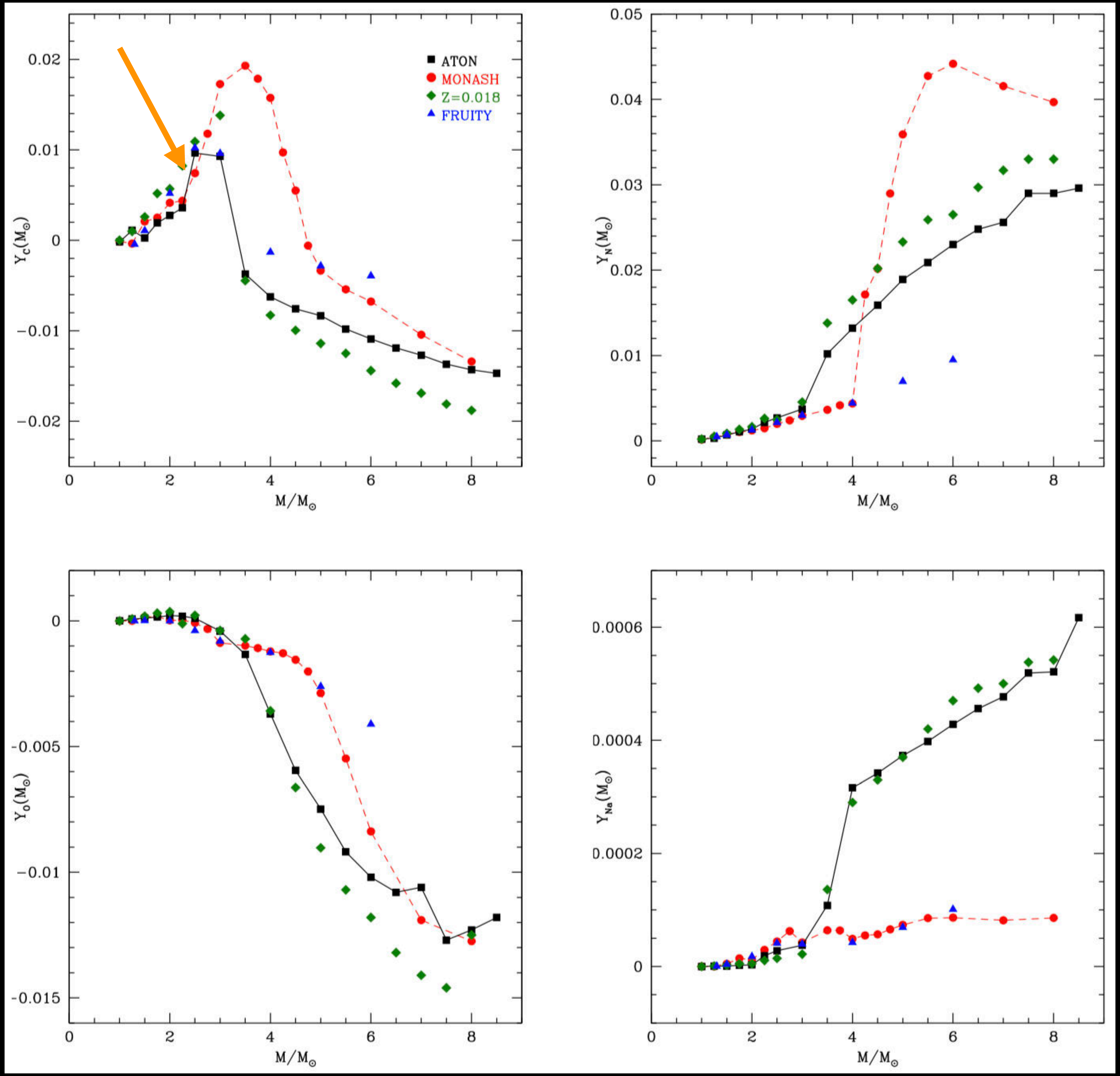

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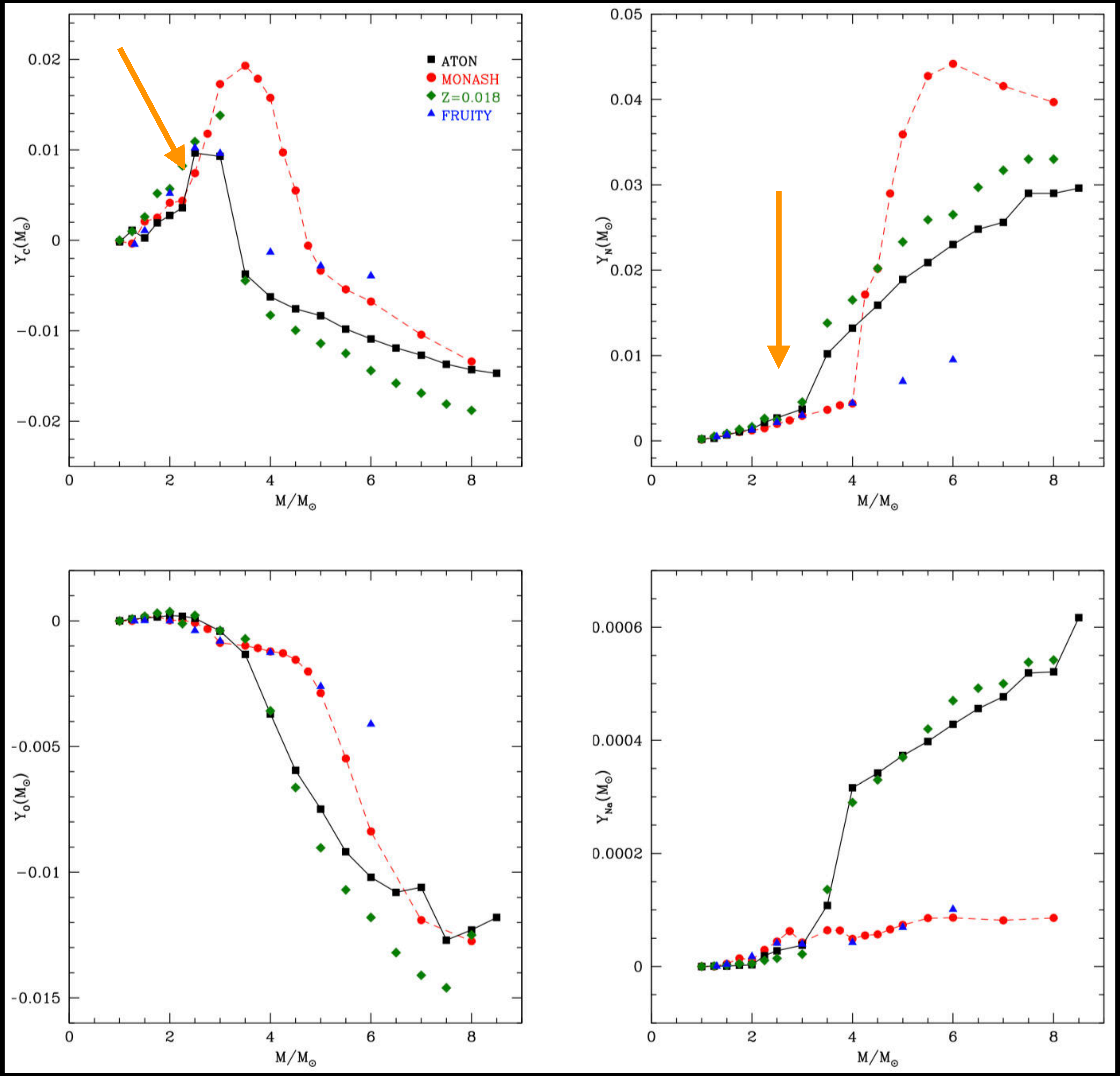

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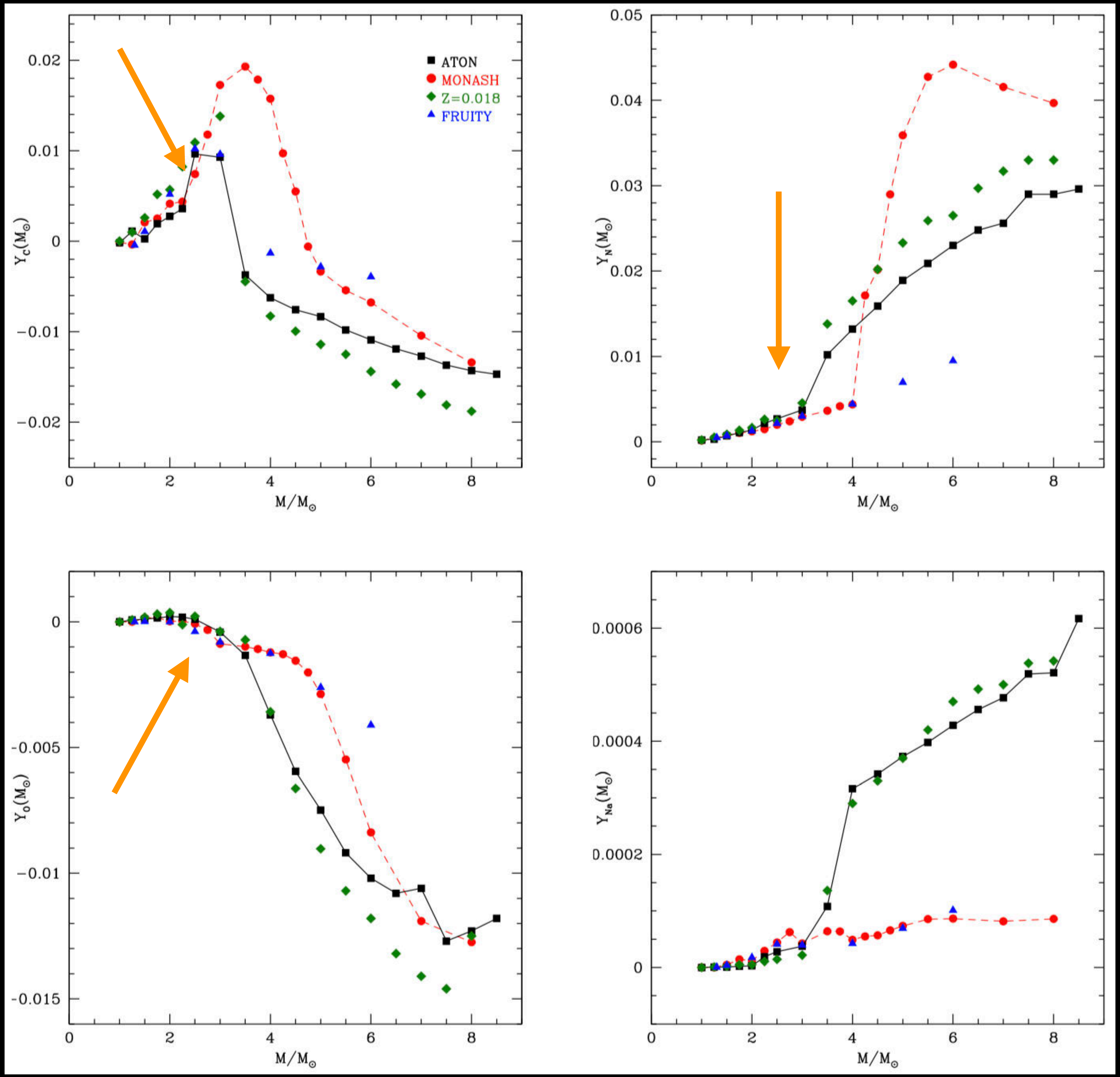

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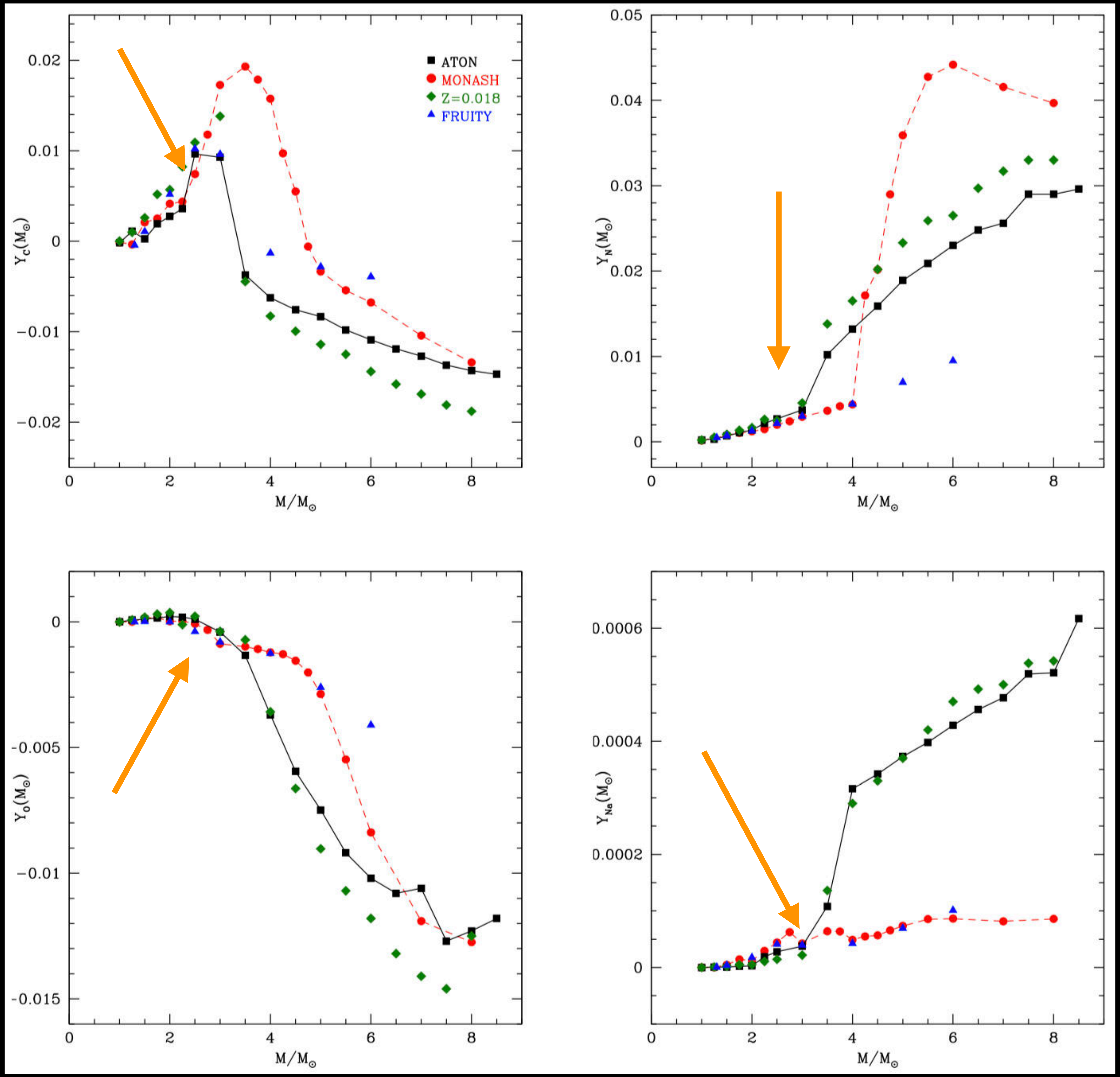
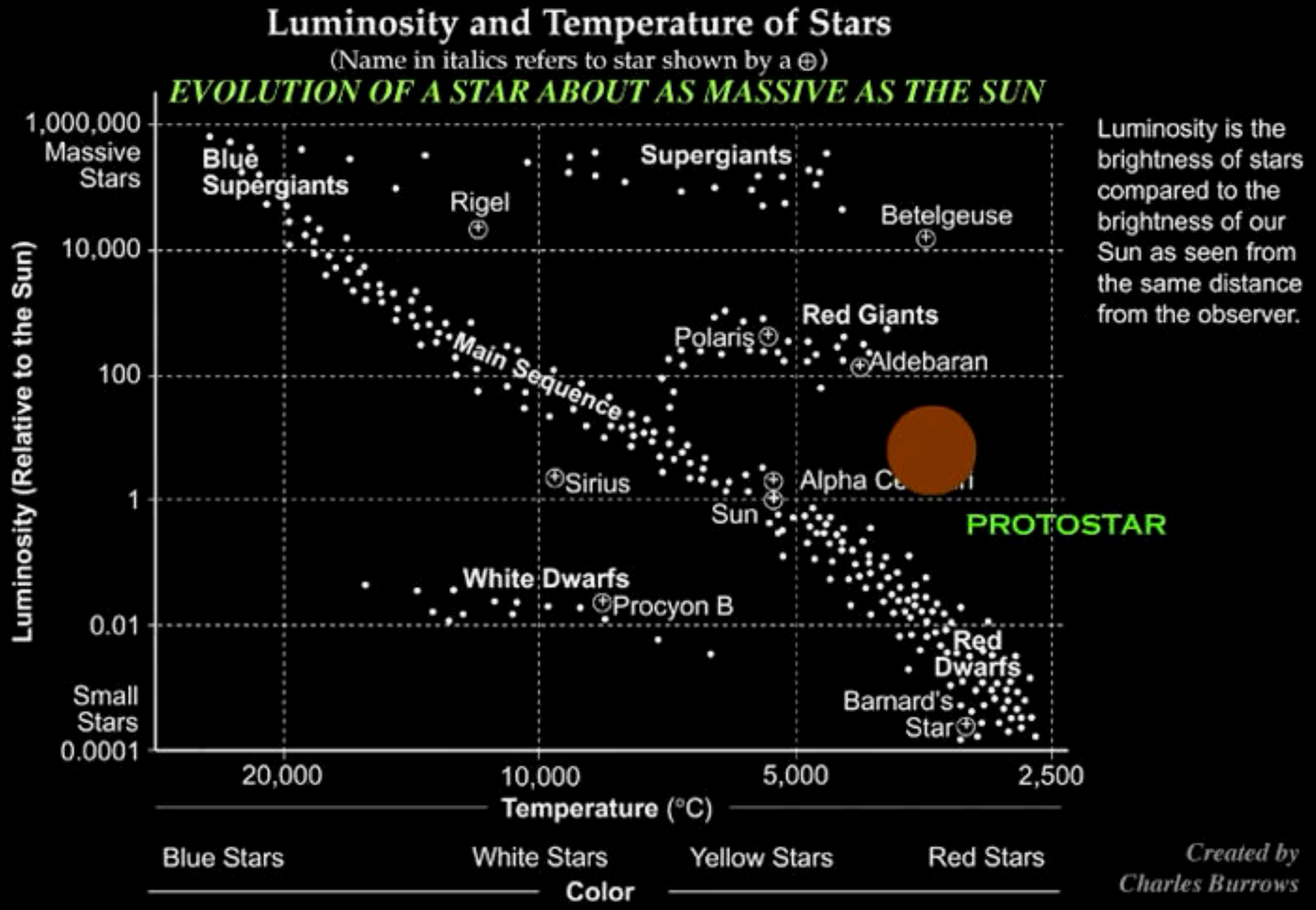


Ventura et al., 2017

Low- and Intermediate-Mass Single Star Evolution



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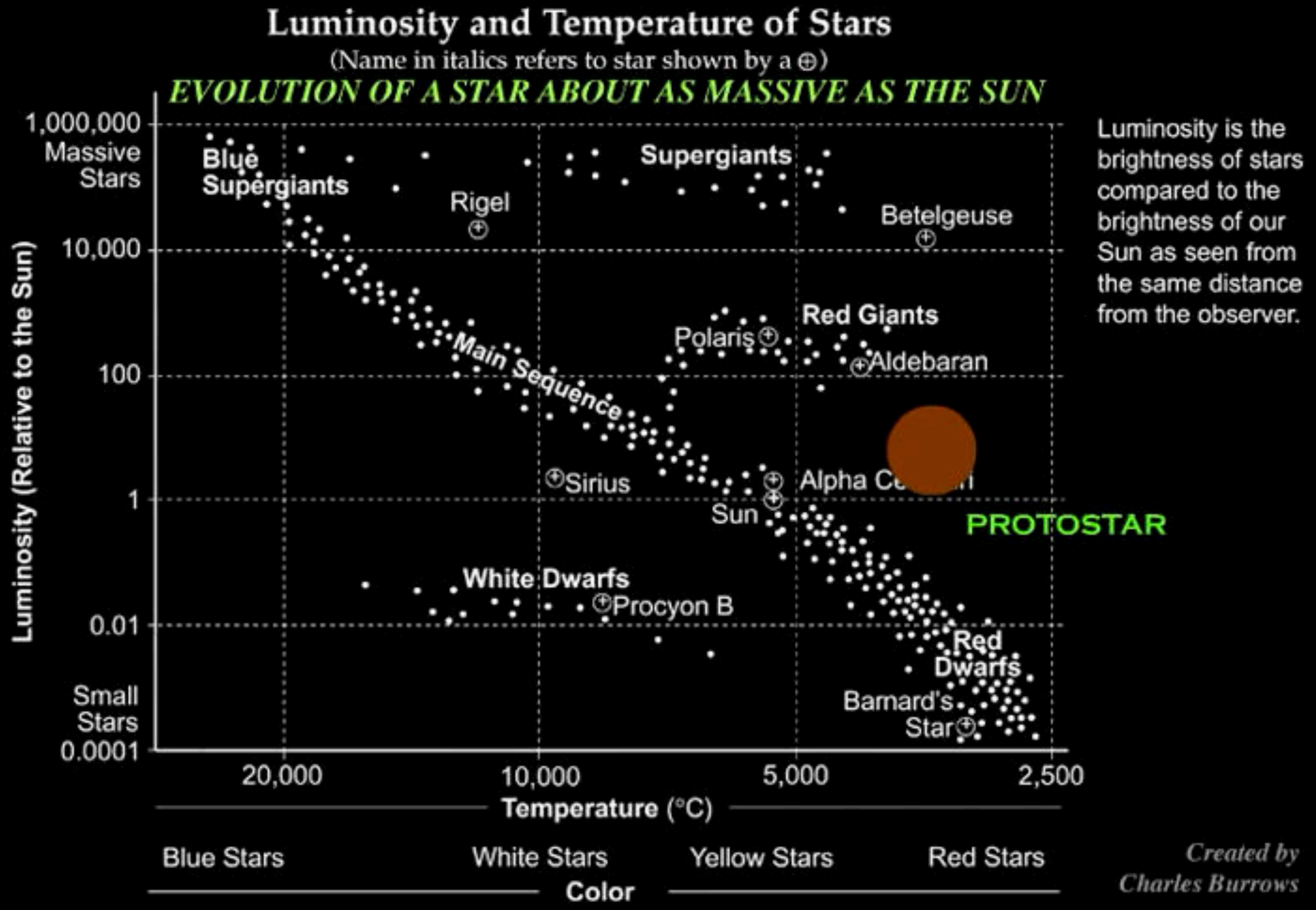
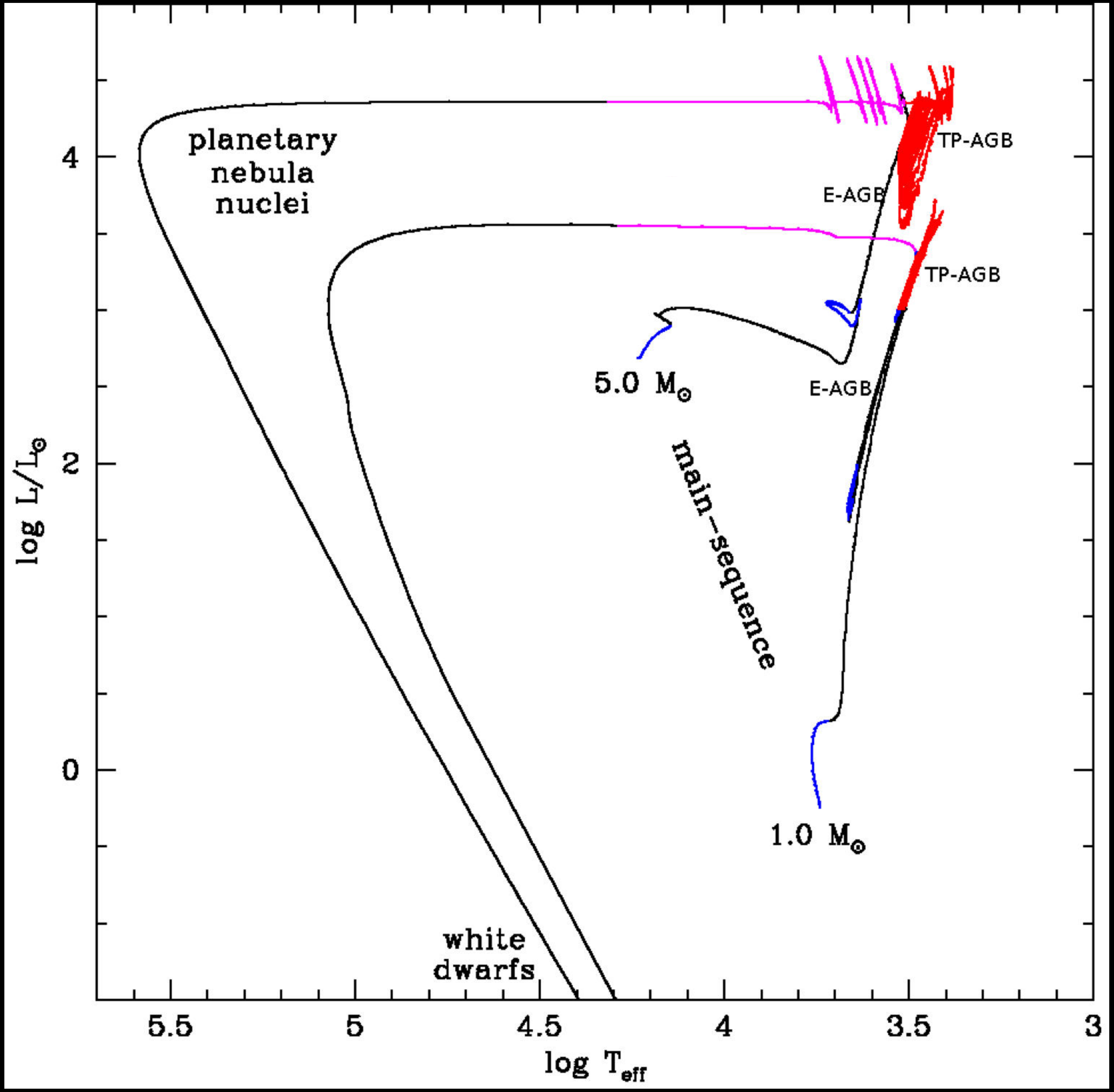


AGB Nucleosynthesis



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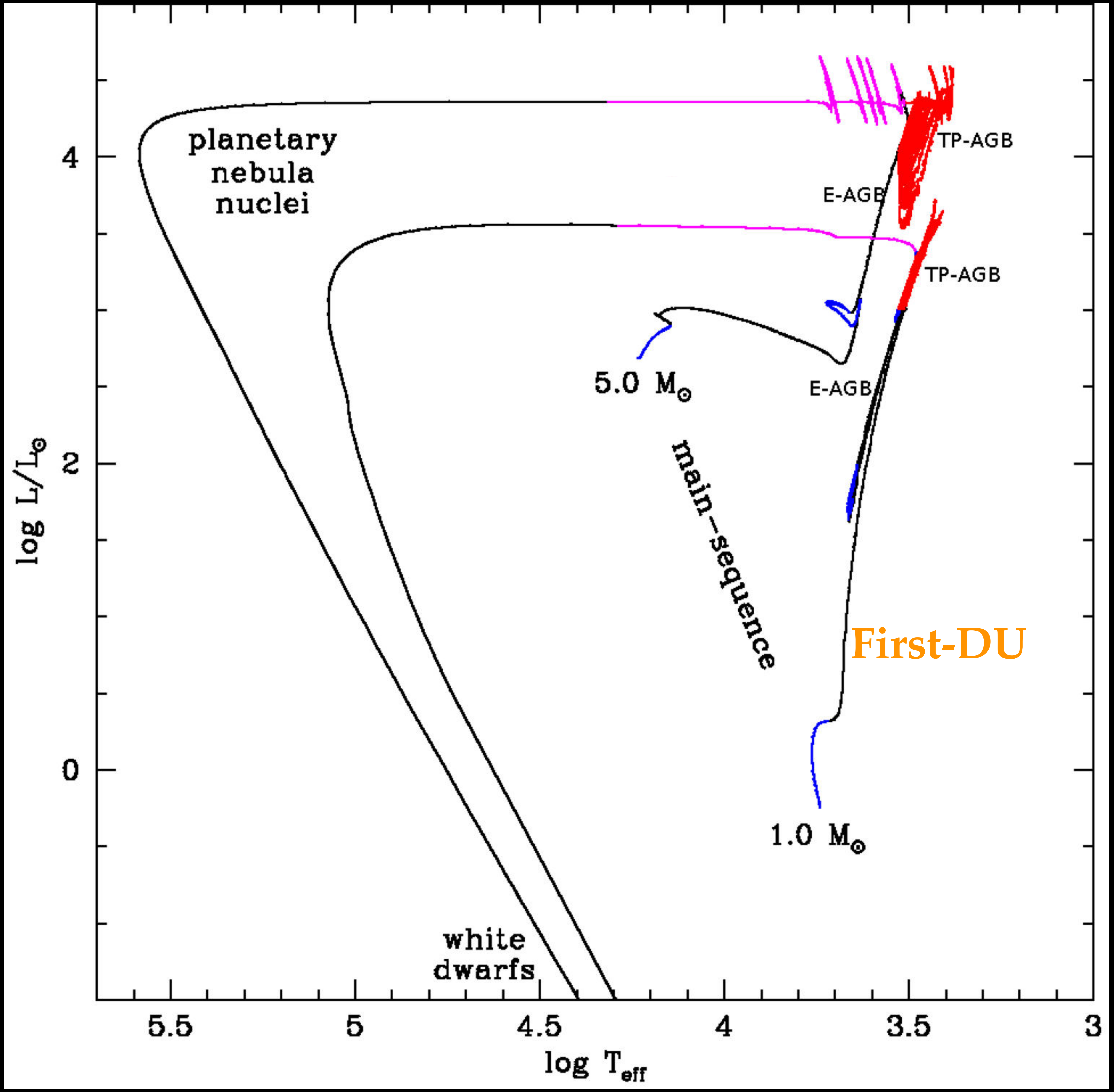

First-DU
increase in 4He, 13C, 14N, 17O
decrease in 12C, 16O and 18O

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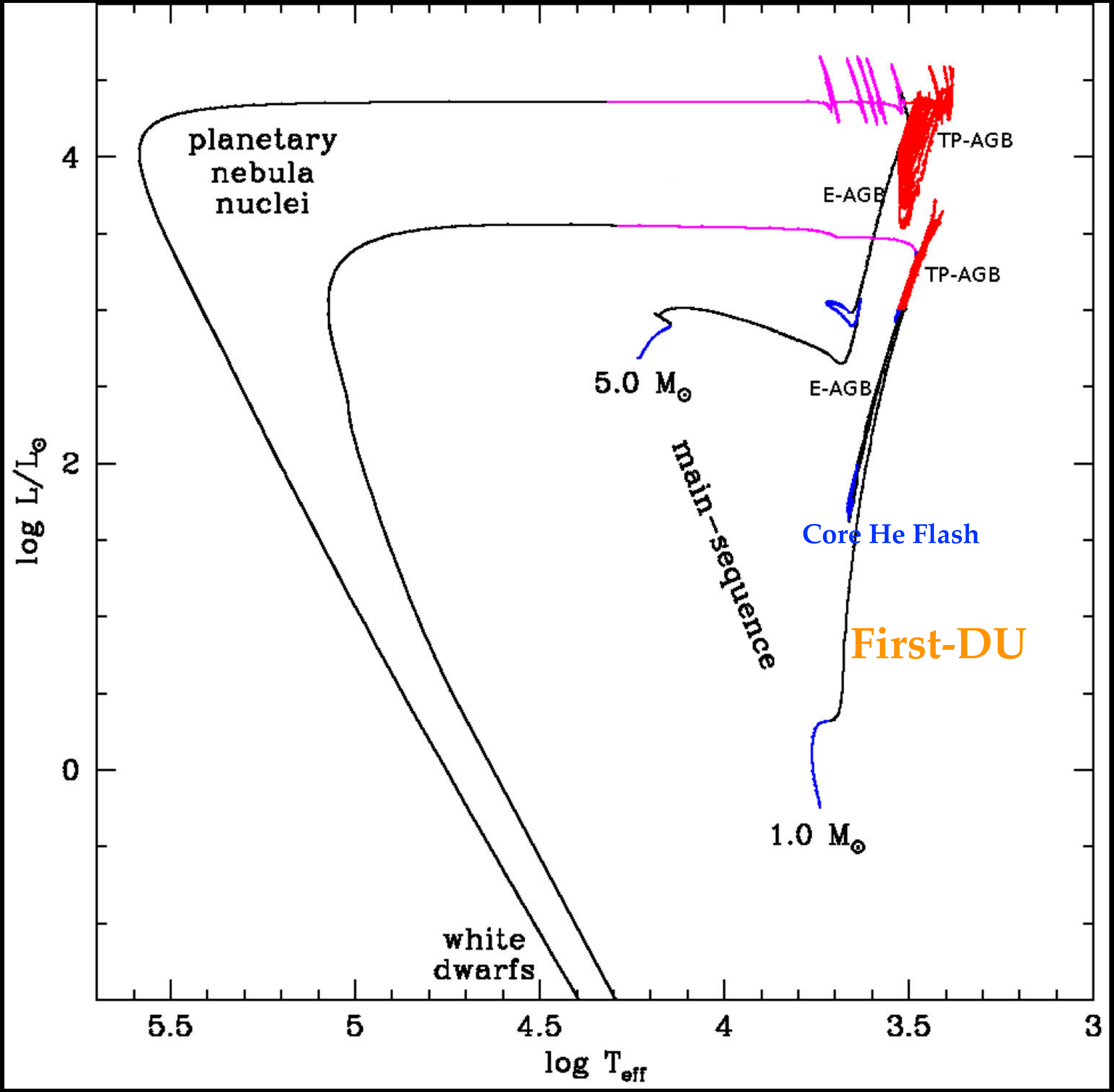

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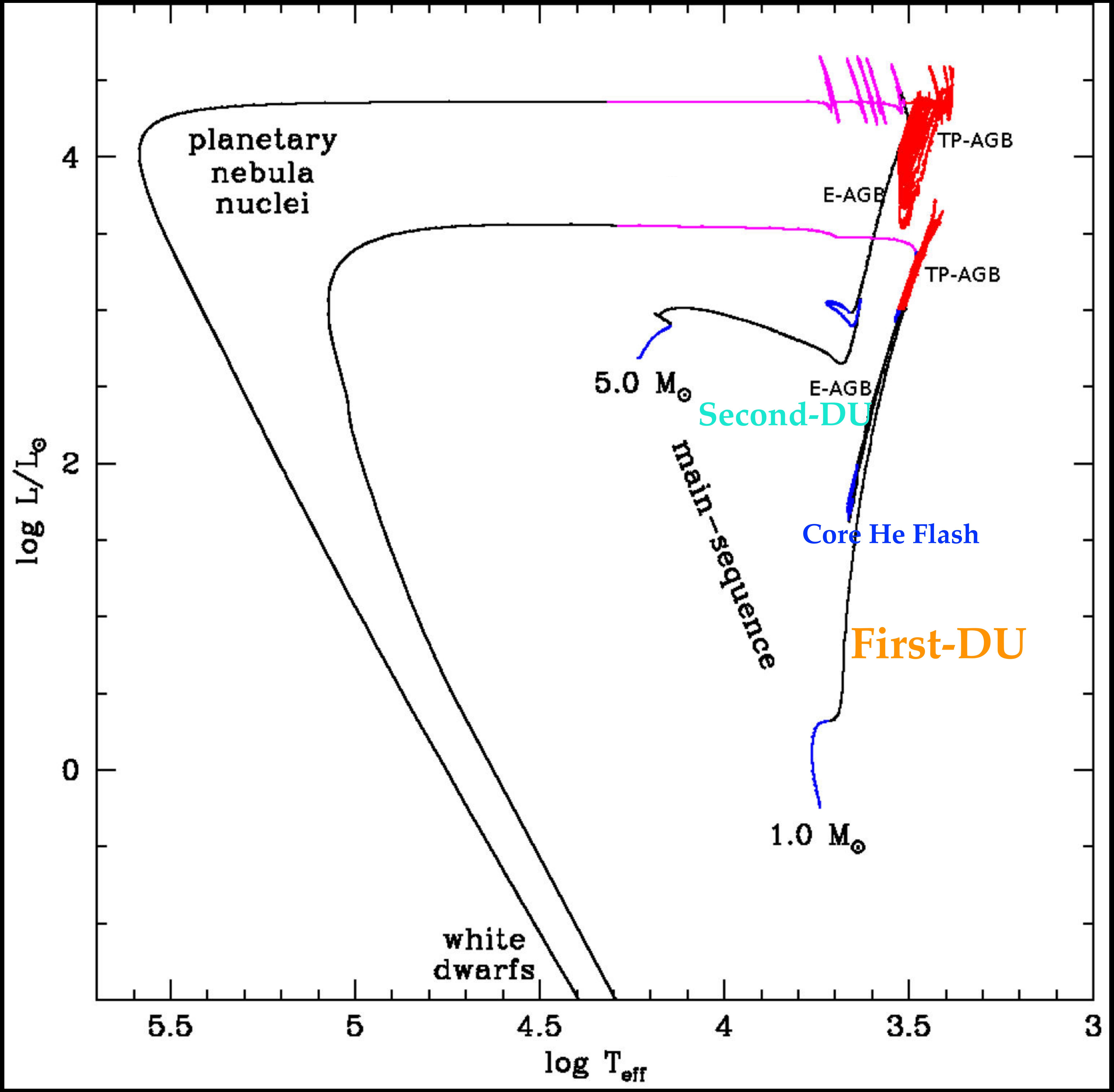
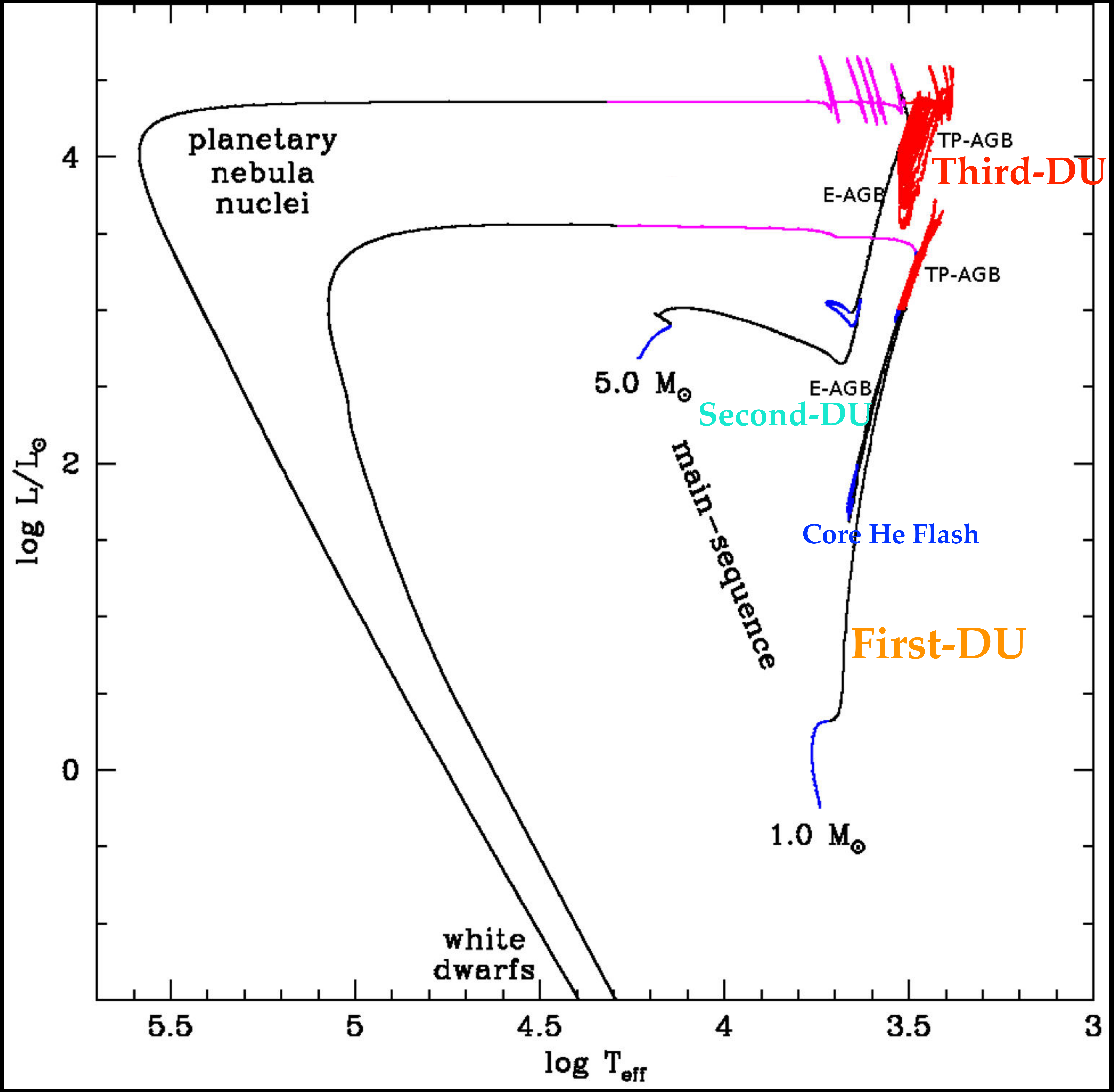


First-DU
increase in 4He, 13C, 14N, 17O
decrease in 12C, 16O and 18O

Second-DU in M > ~3$M_\odot$
increase in 4He and 14N

AGB Nucleosynthesis



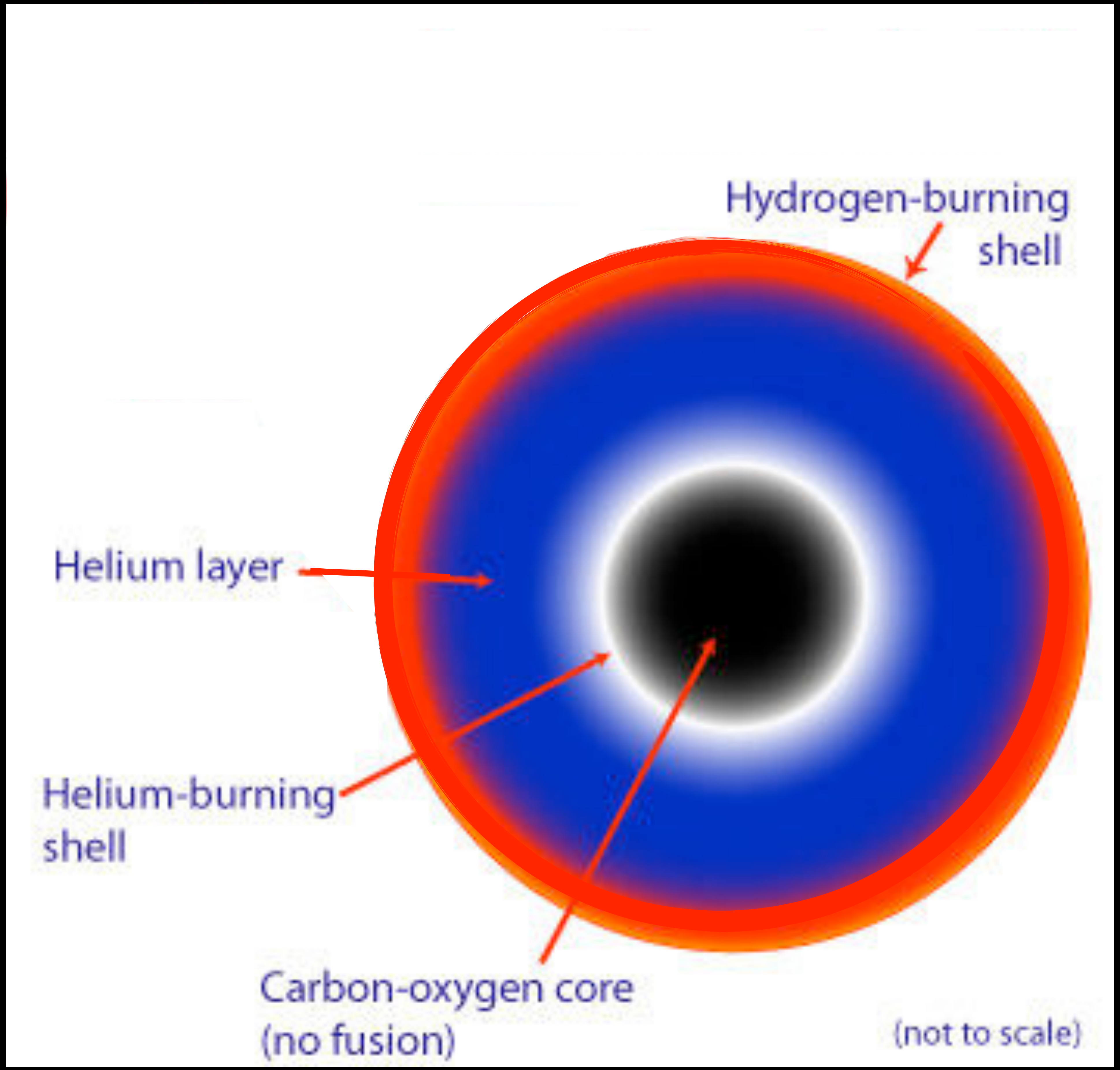
First-DU
increase in 4He, 13C, 14N, 17O
decrease in 12C, 16O and 18O

Second-DU in M > ~3M☉
increase in 4He and 14N

Third-DU increase in 4He and 12C and heavy elements (s-process elements)

Hot Bottom Burning (in M > ~3M☉)
decrease in 12C
increase in 13C and 14N
7Li, Na, Mg, Al

AGB Stars as Tracers of AGB Nucleosynthesis…



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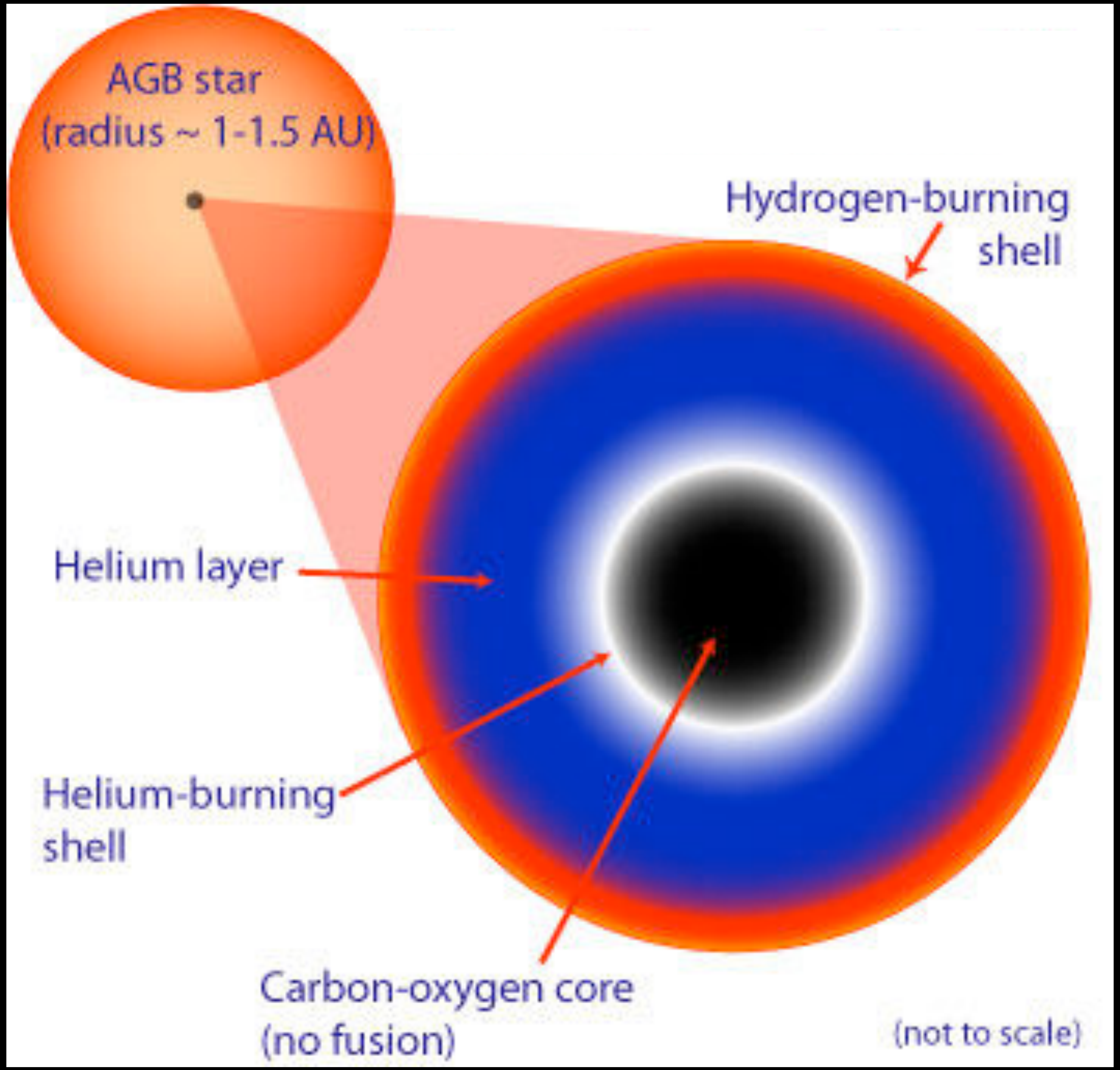

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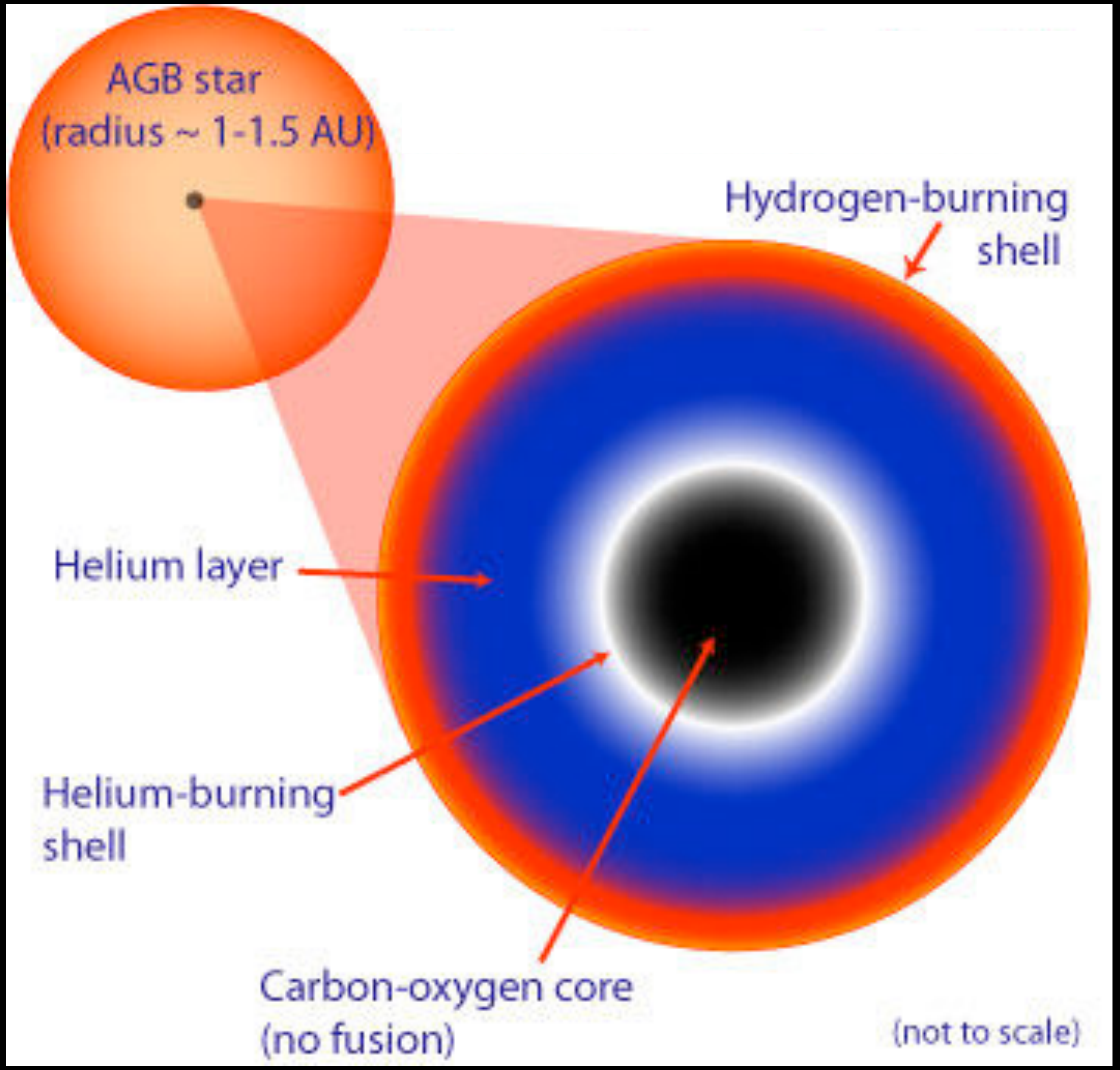

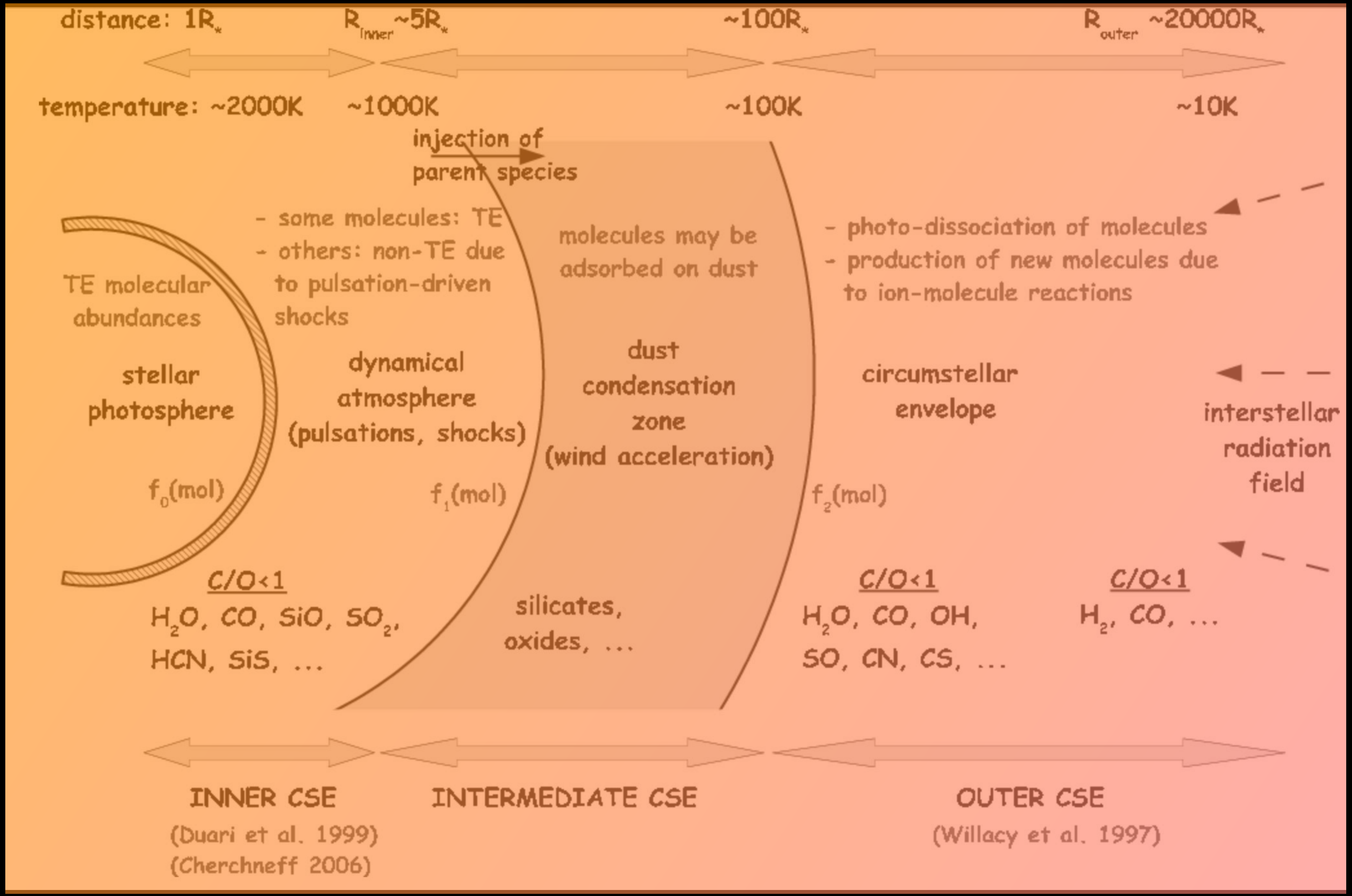

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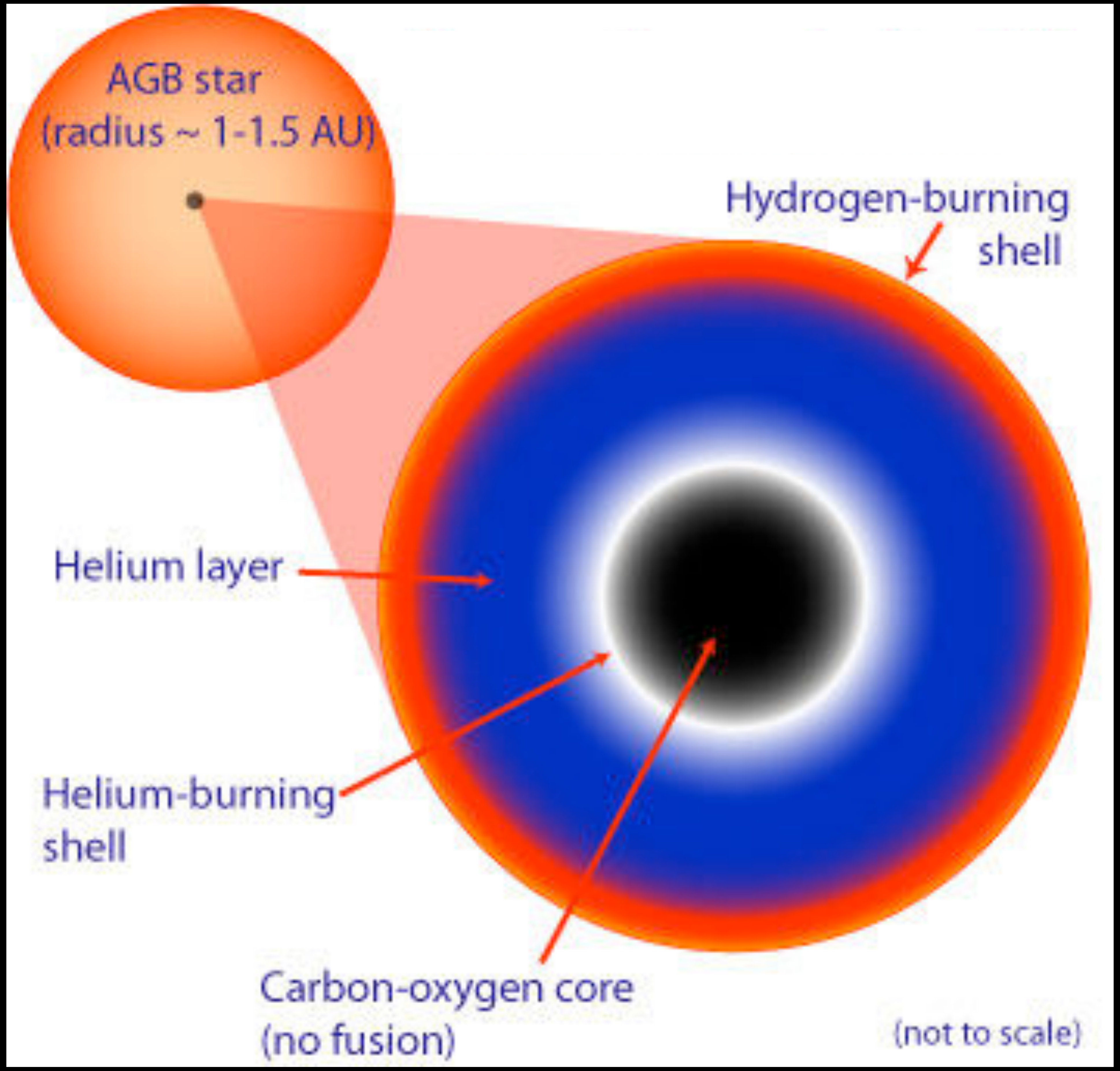
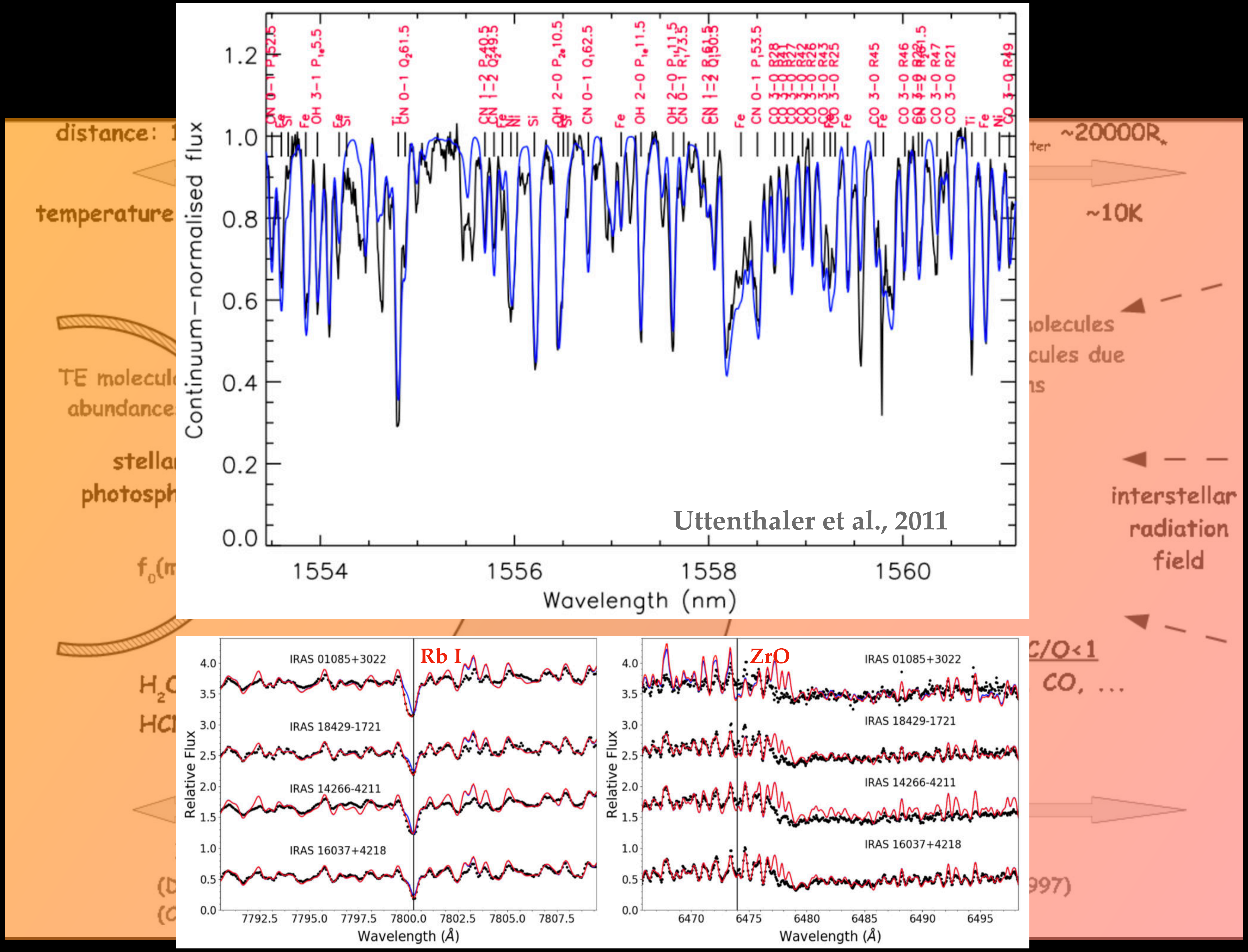
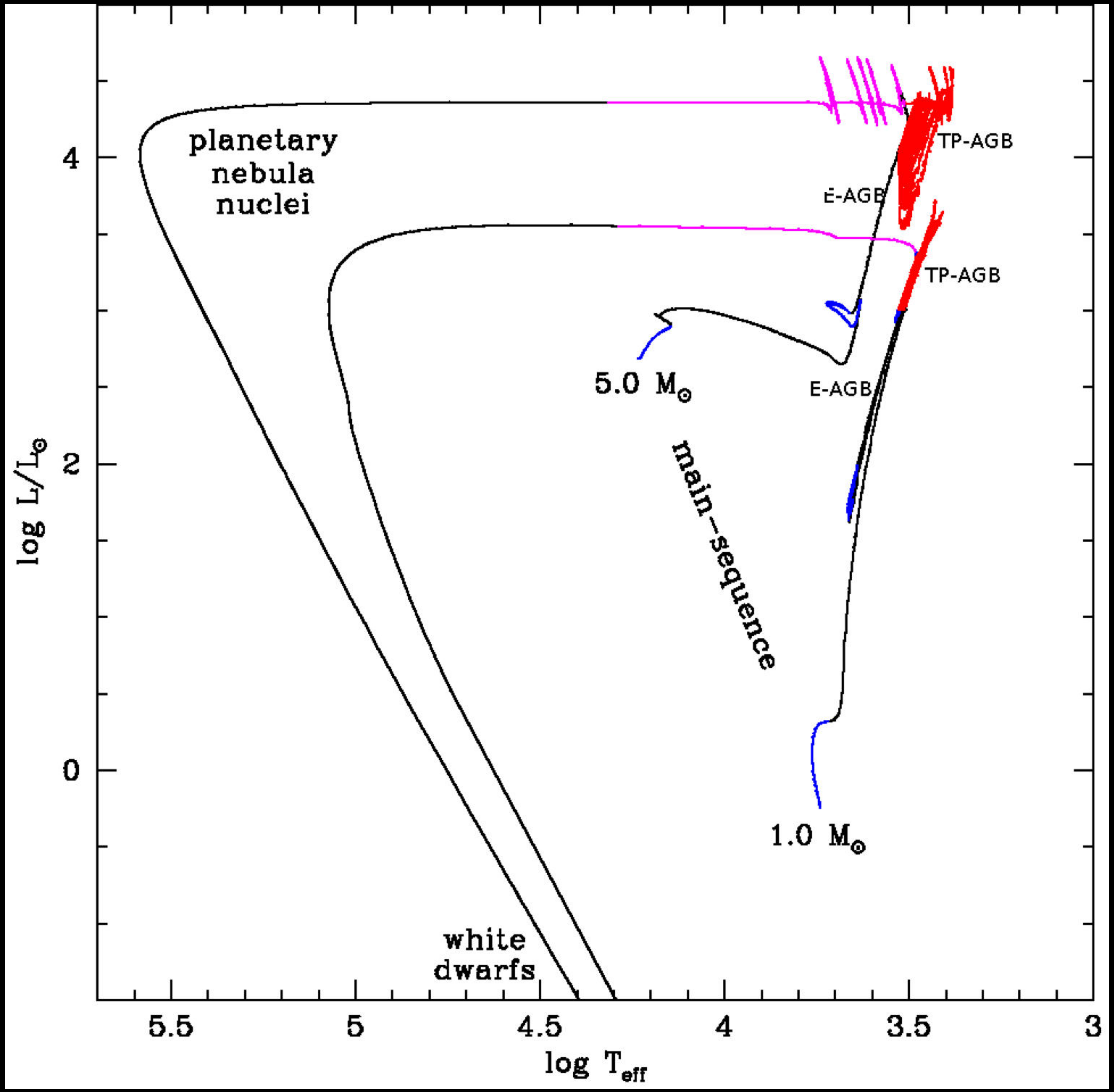




García-Hernández, D. A et al., 2011; 2017

Introducing: Post-AGB Stars!



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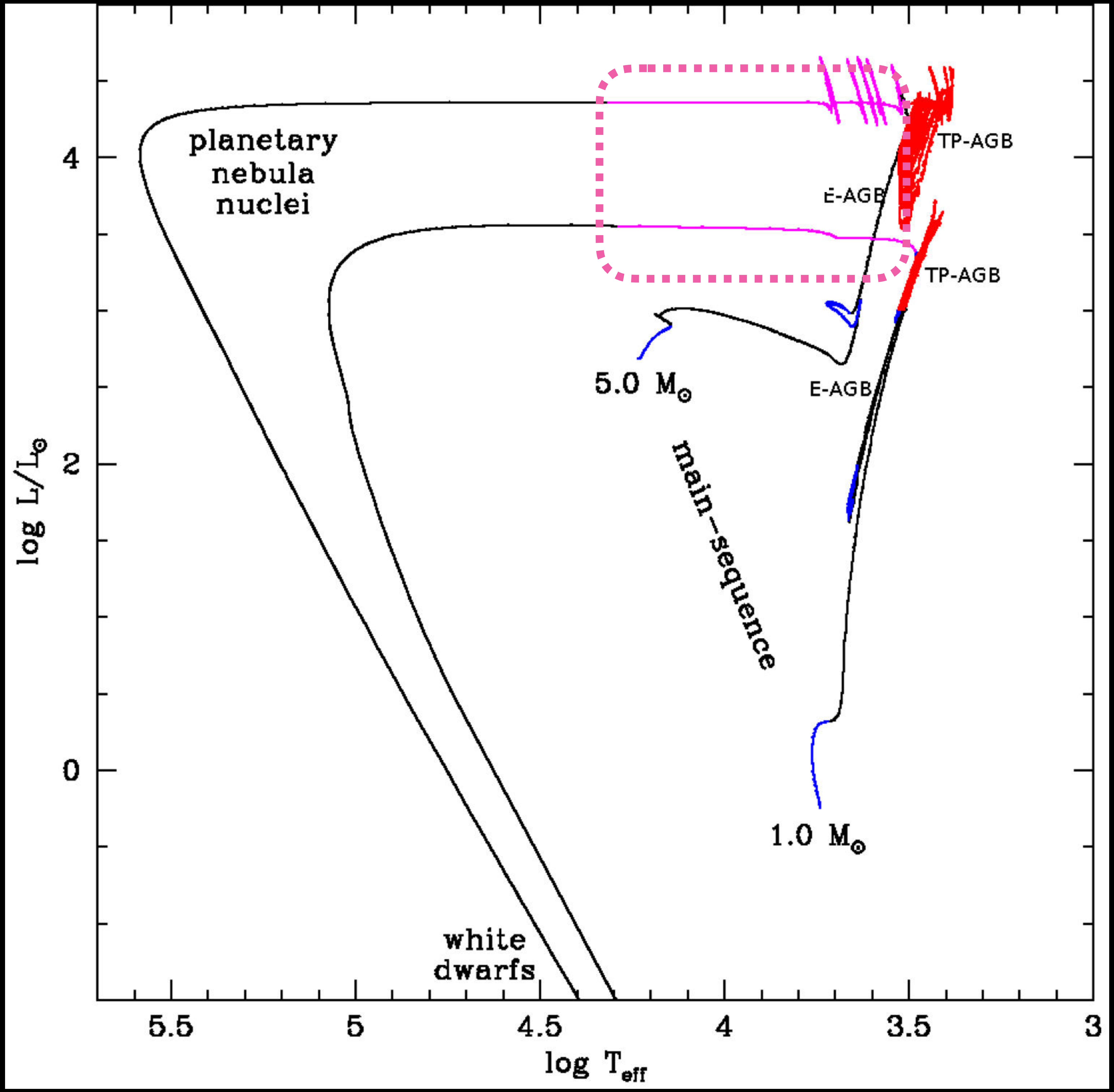

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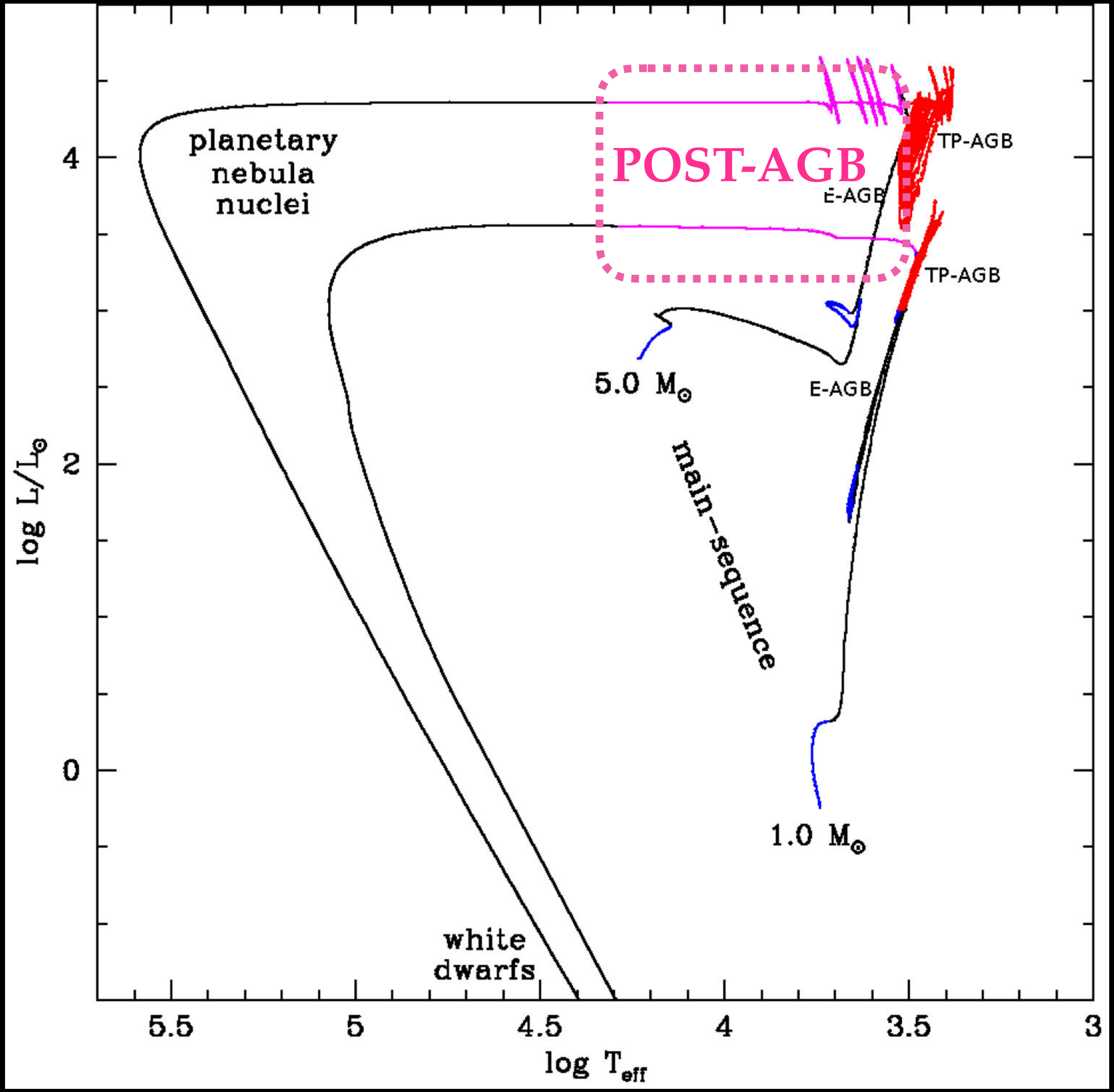

Single Post-AGB Stars

Kwok et al., 1980; Reddy et al., 1999; Bakker et al., 1997; Bakker & Lambert 1998; Van Winckel 2003; Van Winckel et al., 2009; Rao et al., 2012; Sczerba et al., 2009; and all others…

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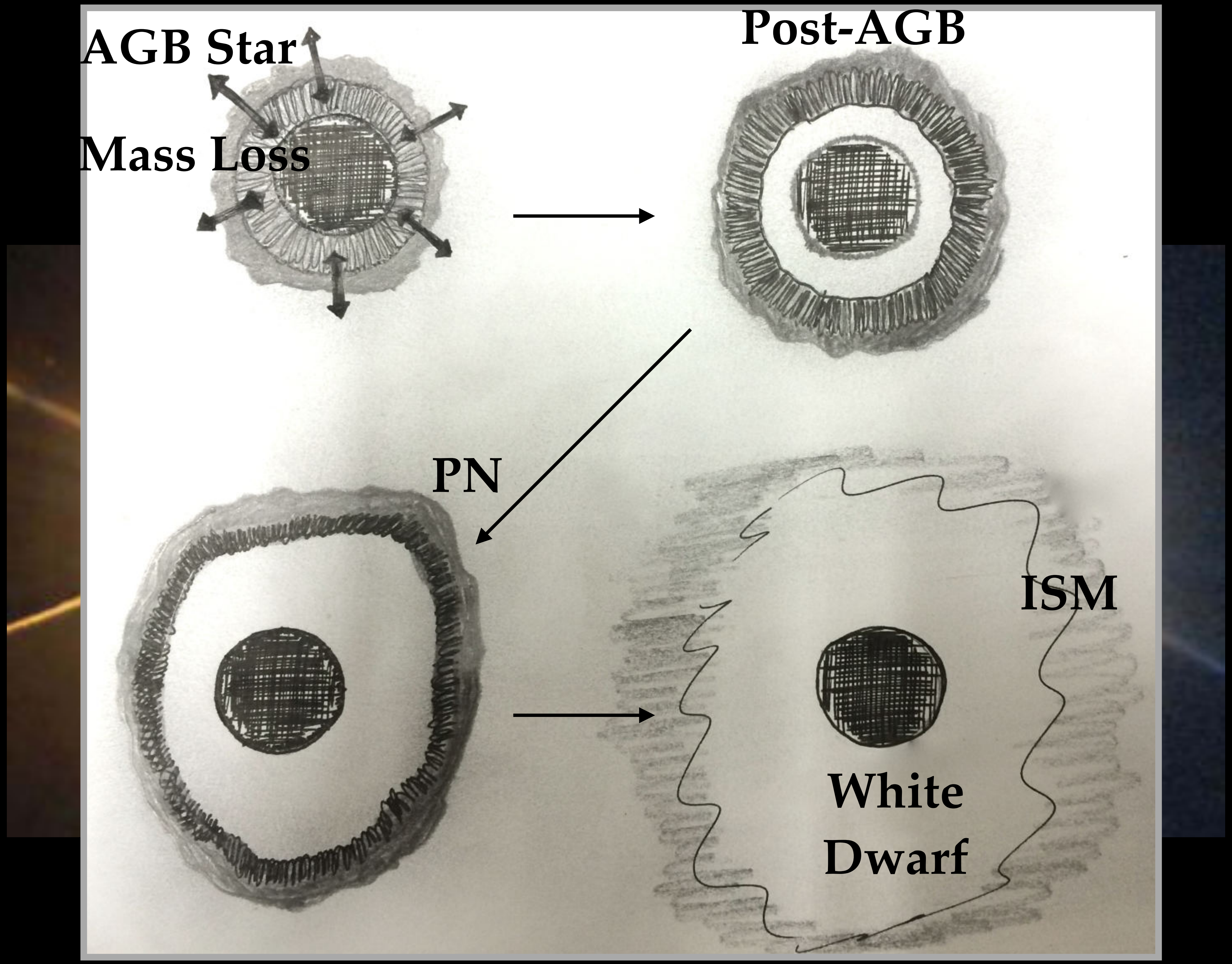

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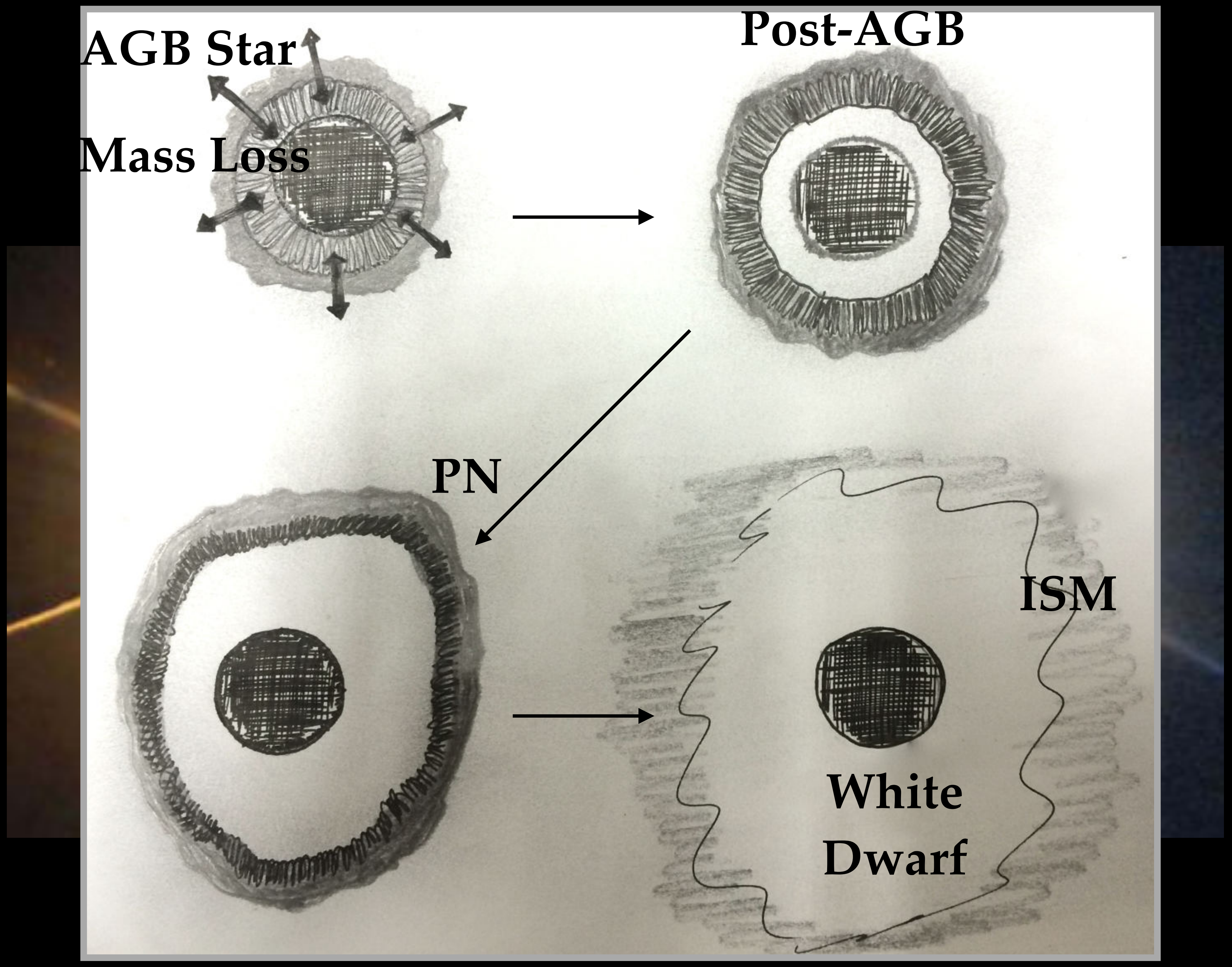

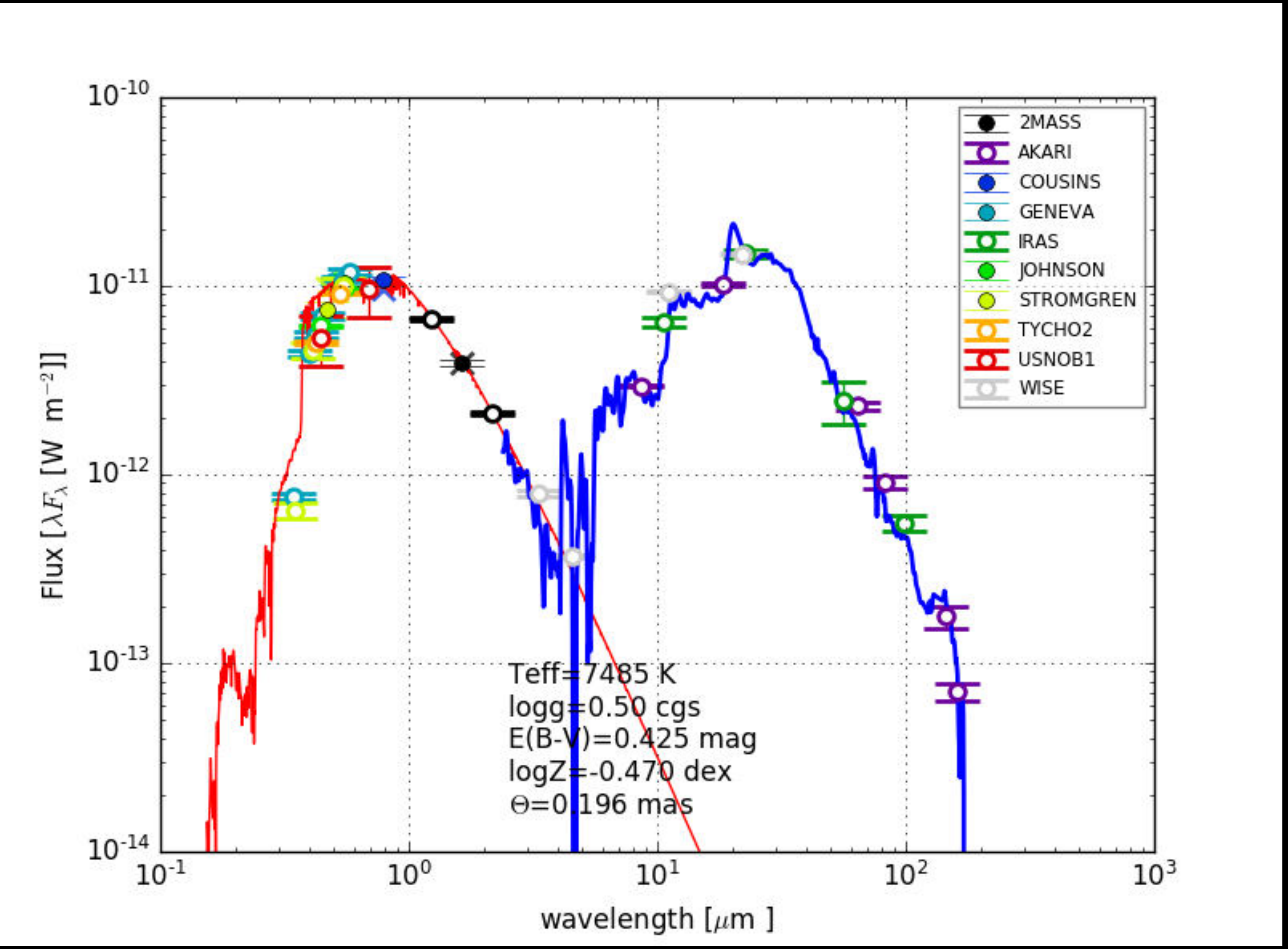

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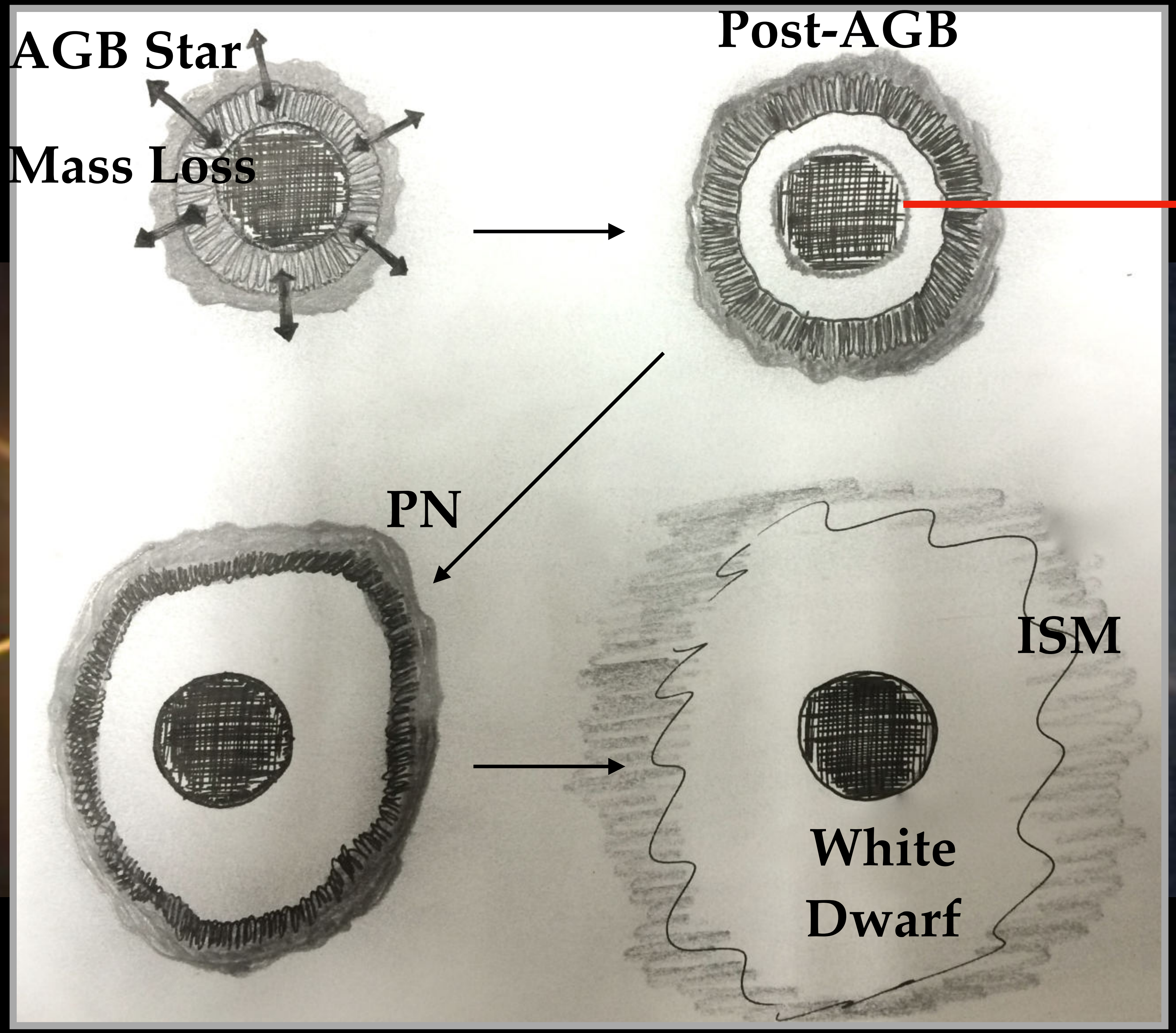

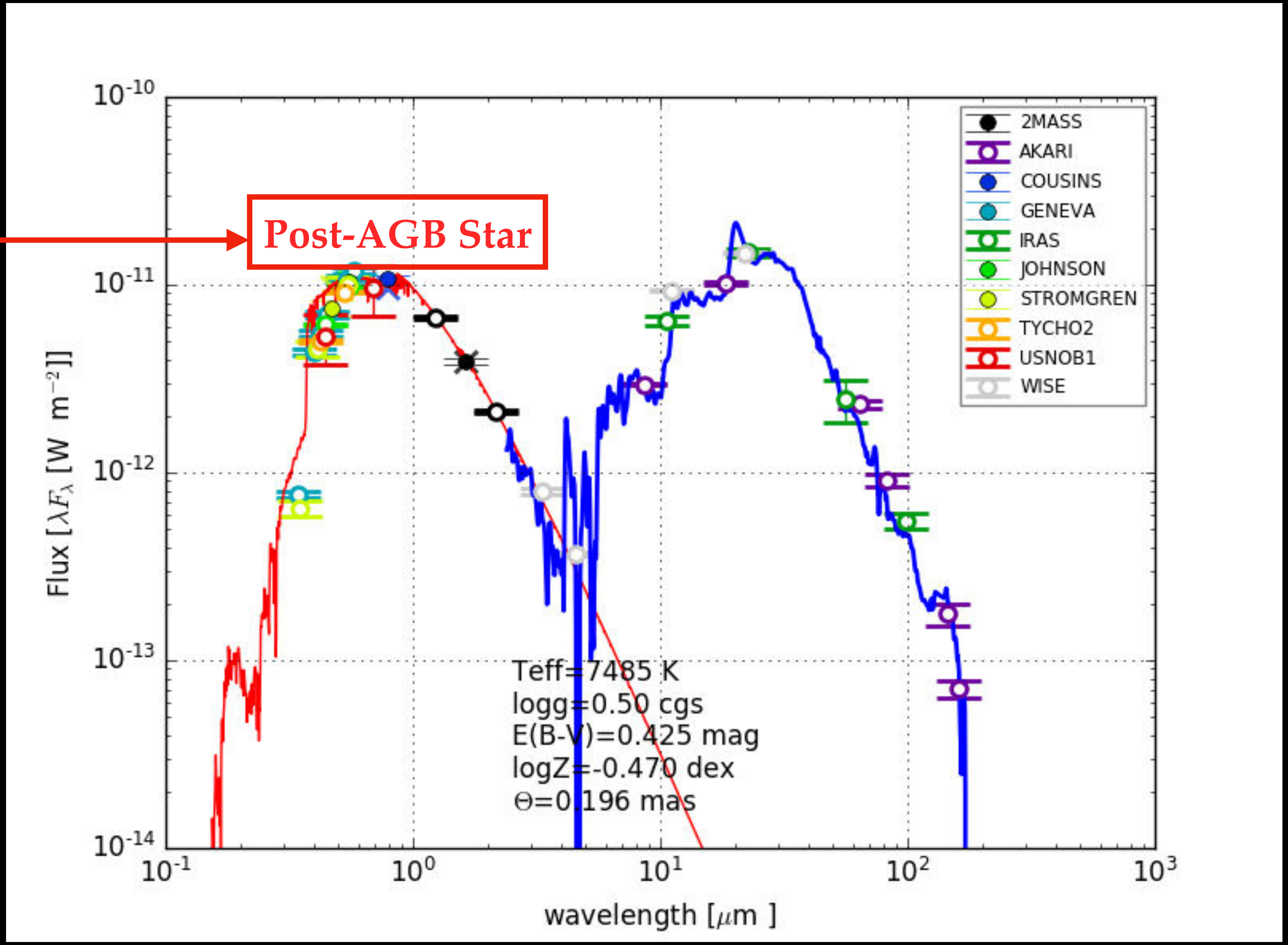

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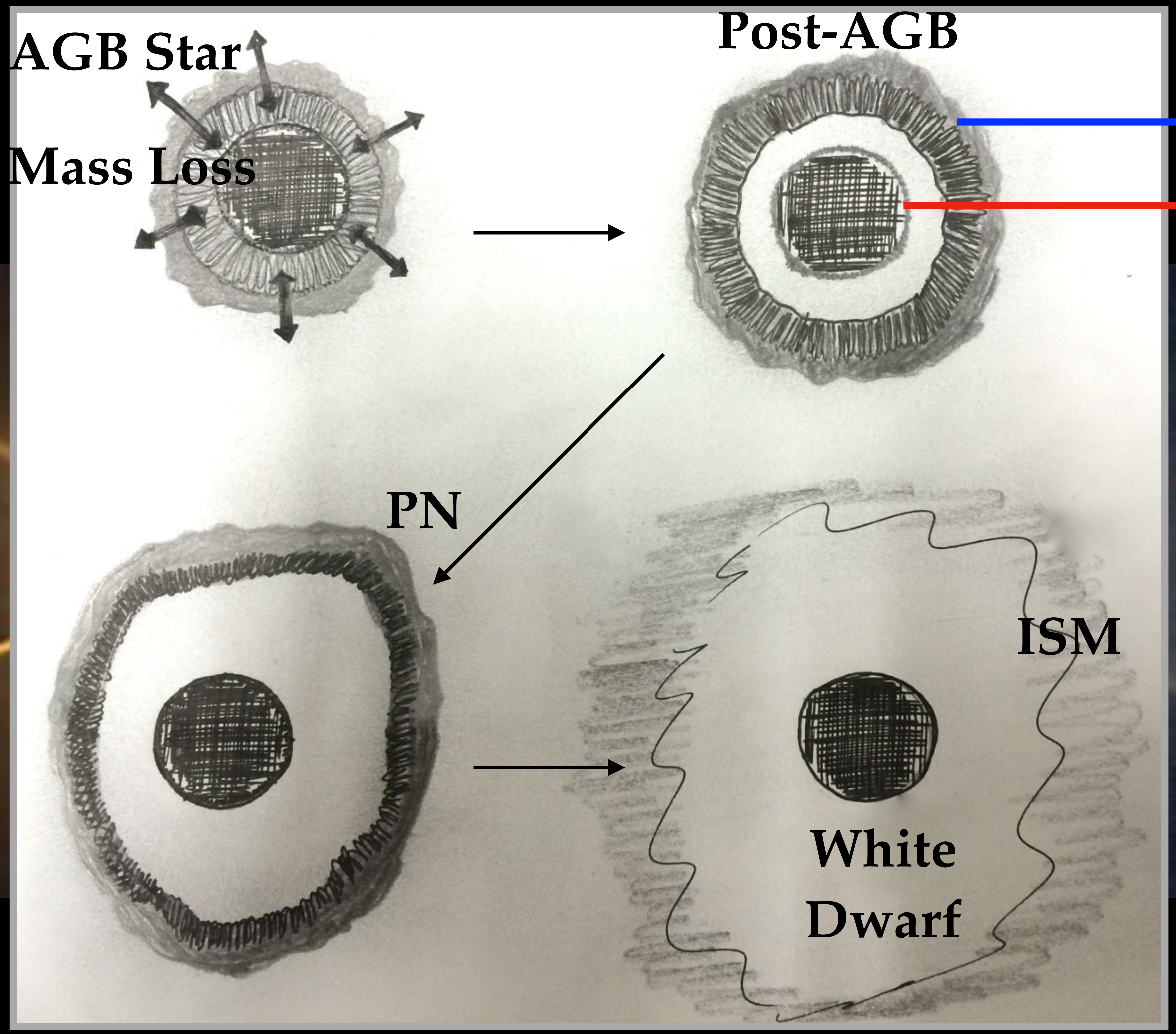
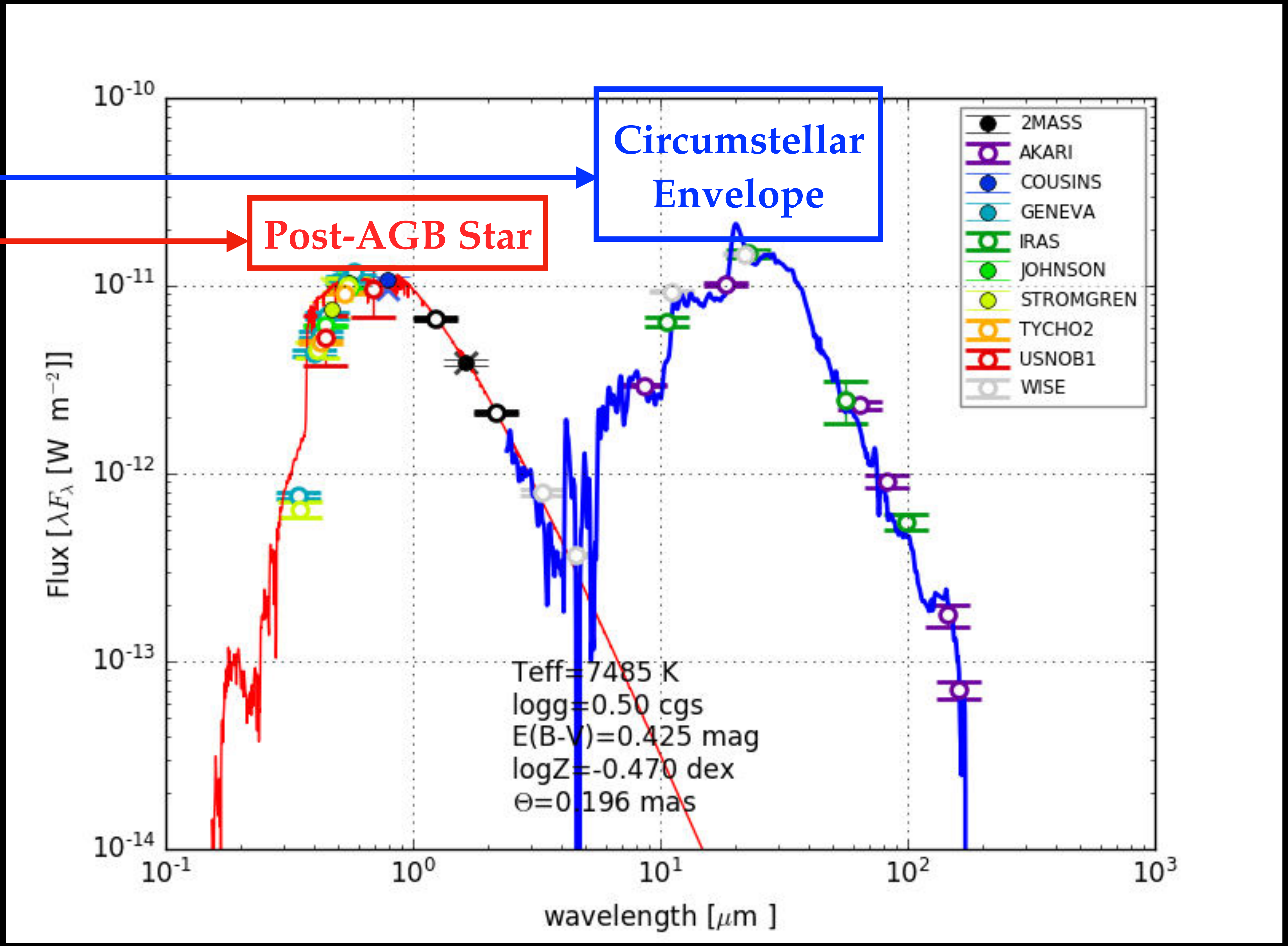
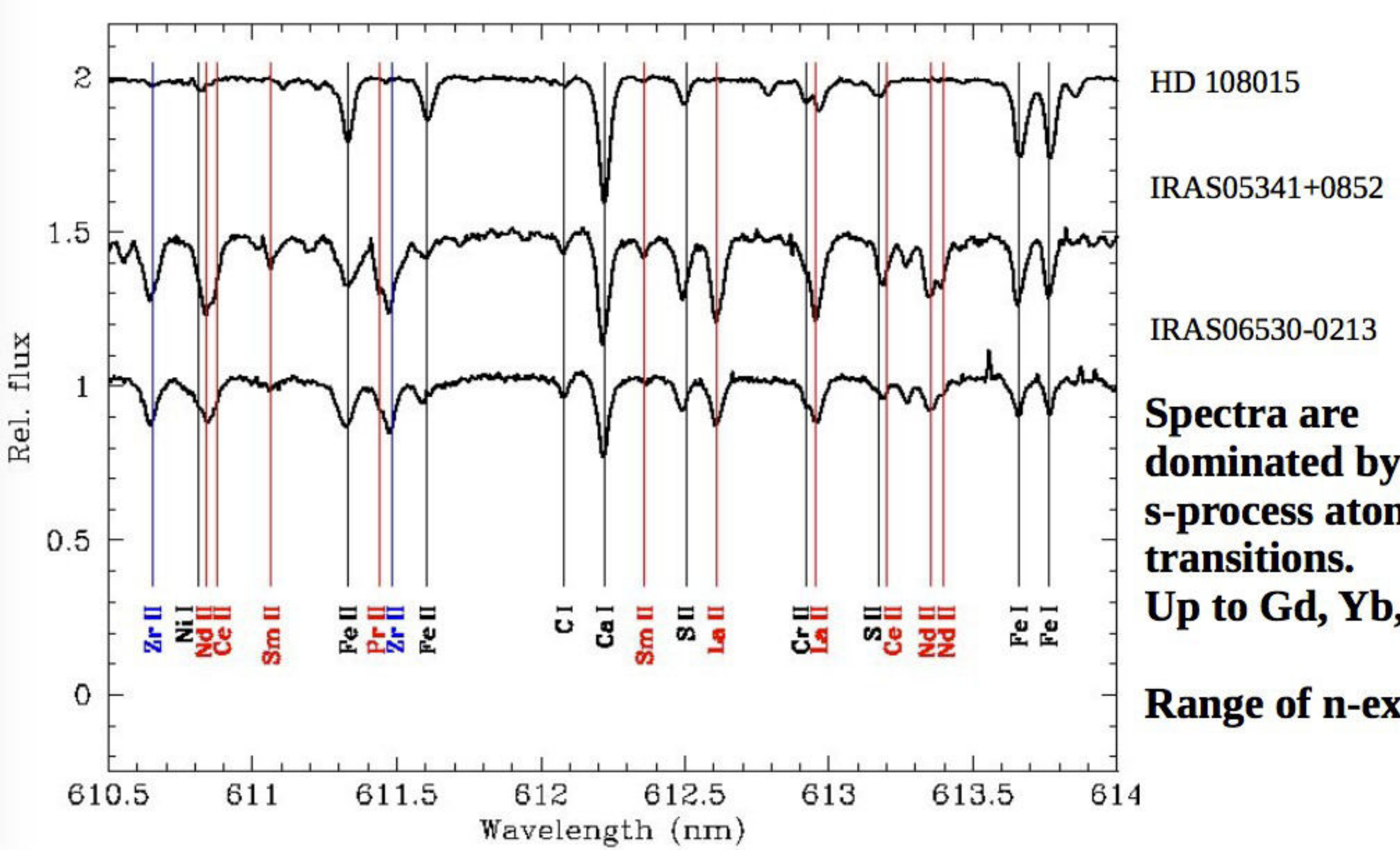




Kwok et al., 1980; Reddy et al., 1999; Bakker et al., 1997; Bakker & Lambert 1998; Van Winckel 2003; Van Winckel et al., 2009; Rao et al., 2012; Sczerba et al., 2009; and all others…

Single Post-AGB Stars as Exquisite Tracers of CNO, Fe-peak & *s*-process elements



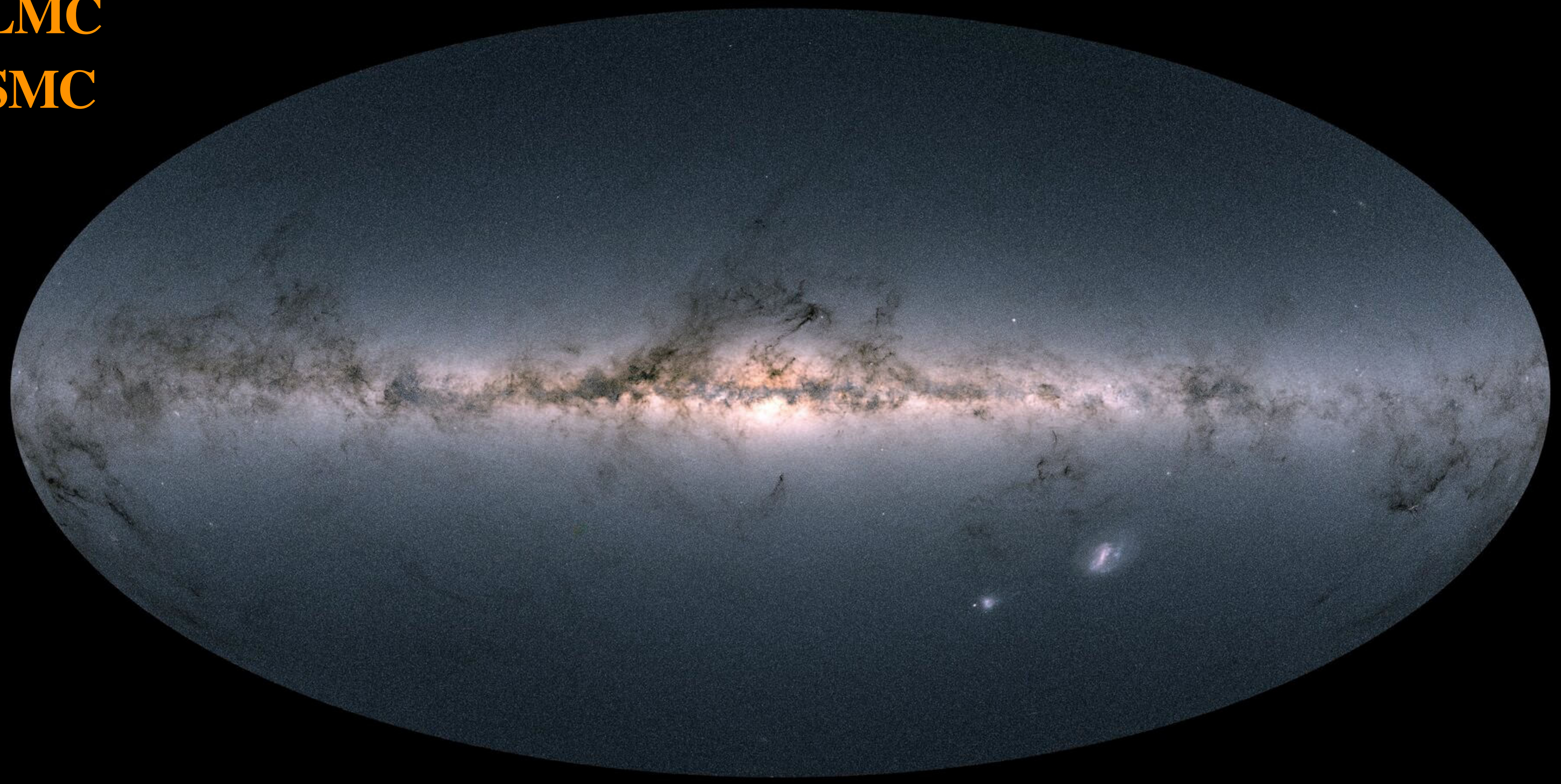
Spectra are dominated by s-process atomic transitions.
Up to Gd, Yb, Lu, W

Range of n-exposures

+ LUMINOSITY (PROGENITOR MASS)

The Hunt for Post-AGB Stars

MILKY WAY
LMC
SMC



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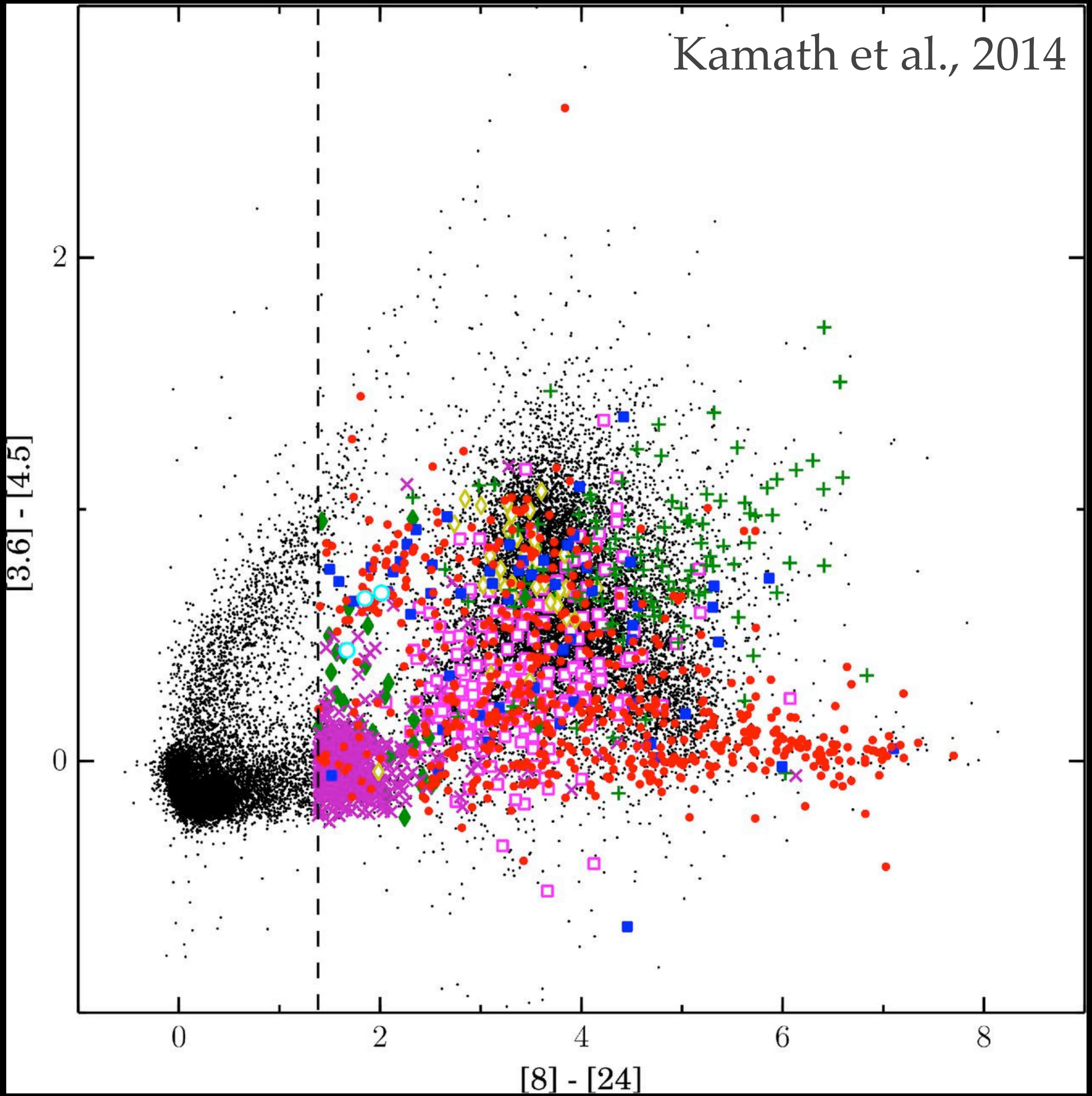

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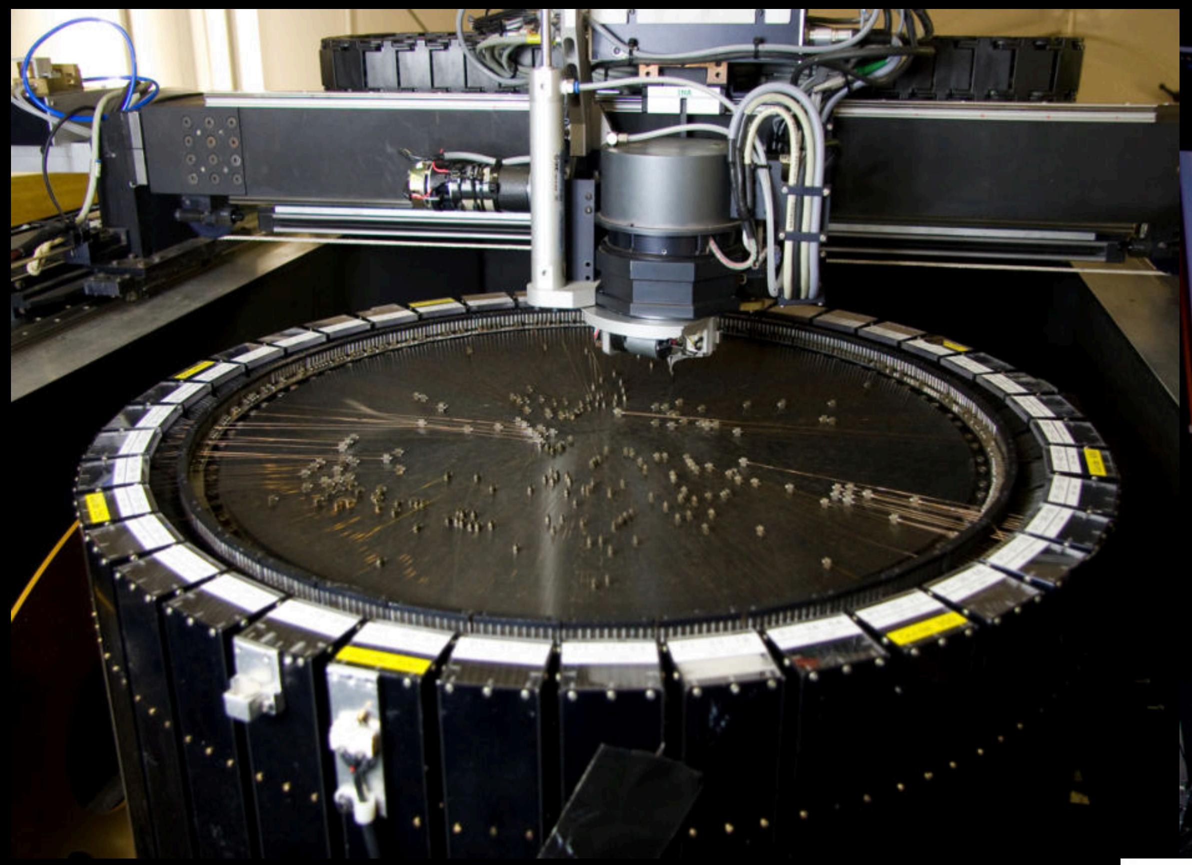

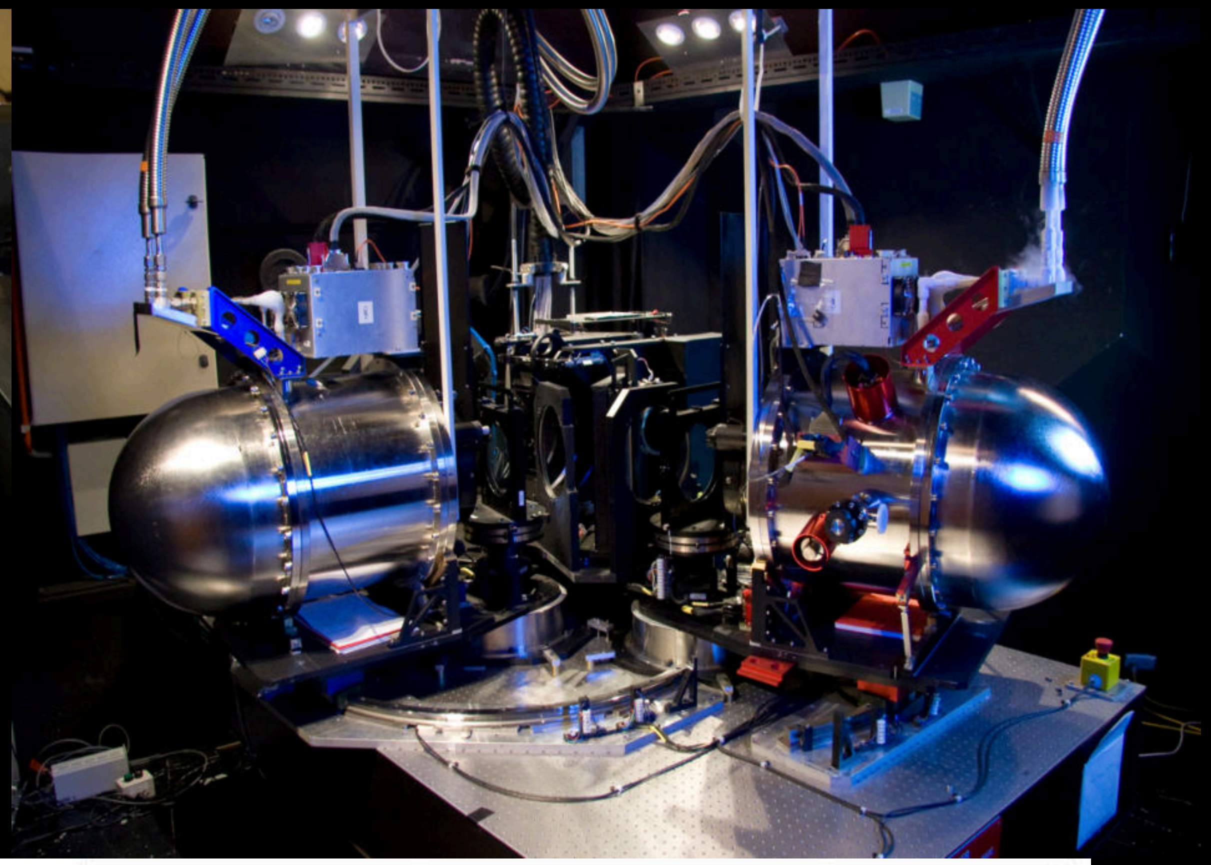

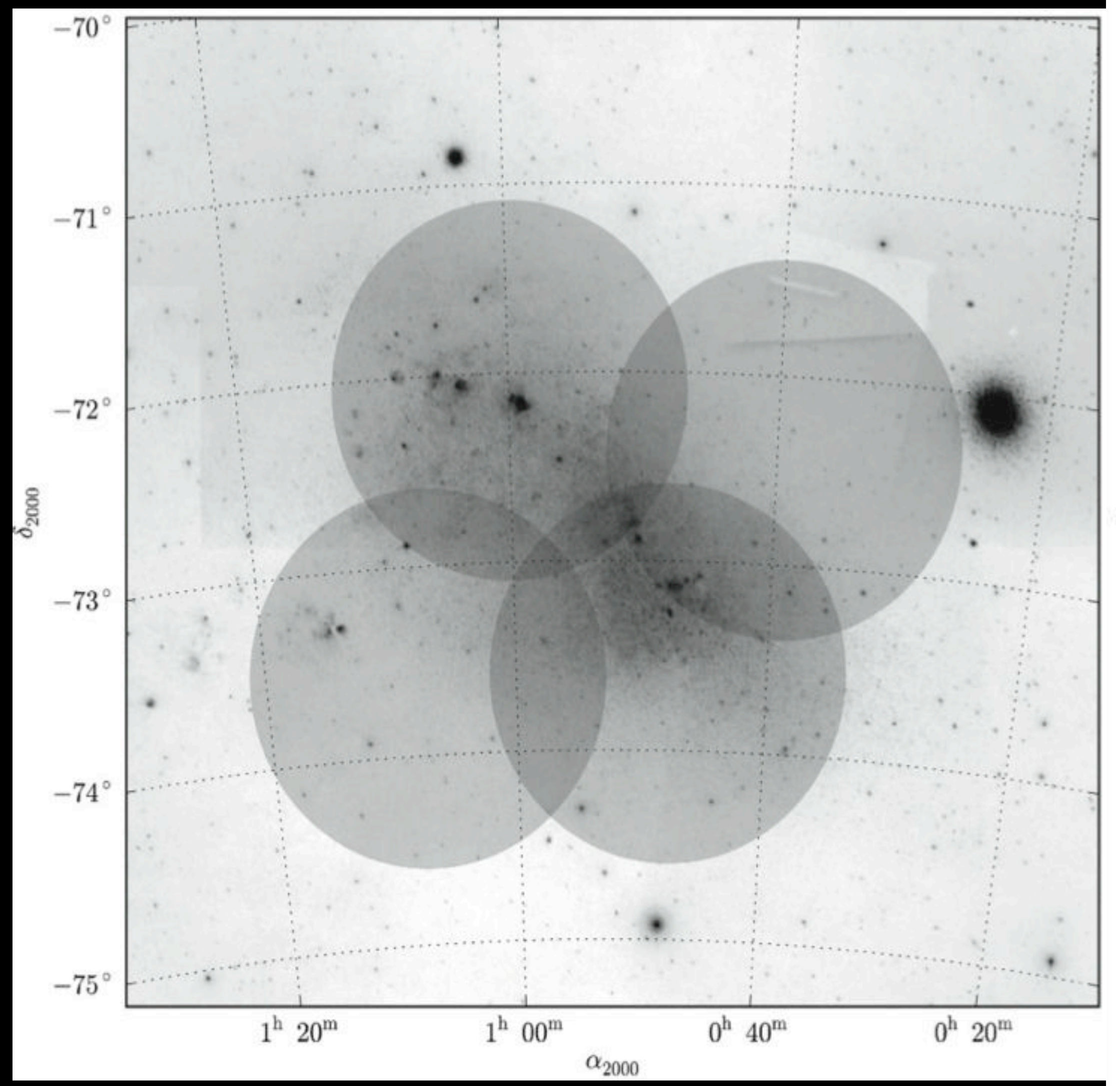

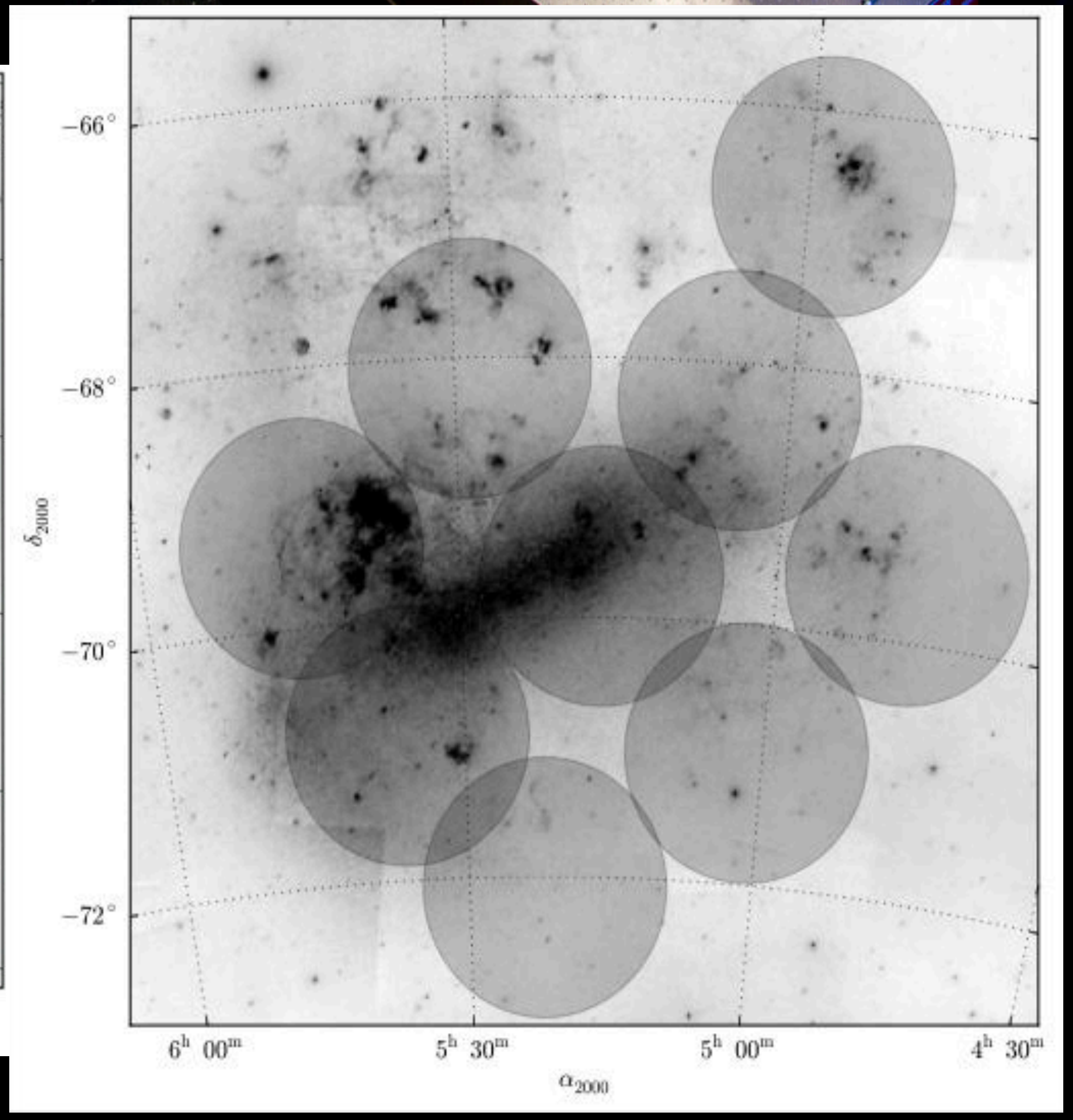

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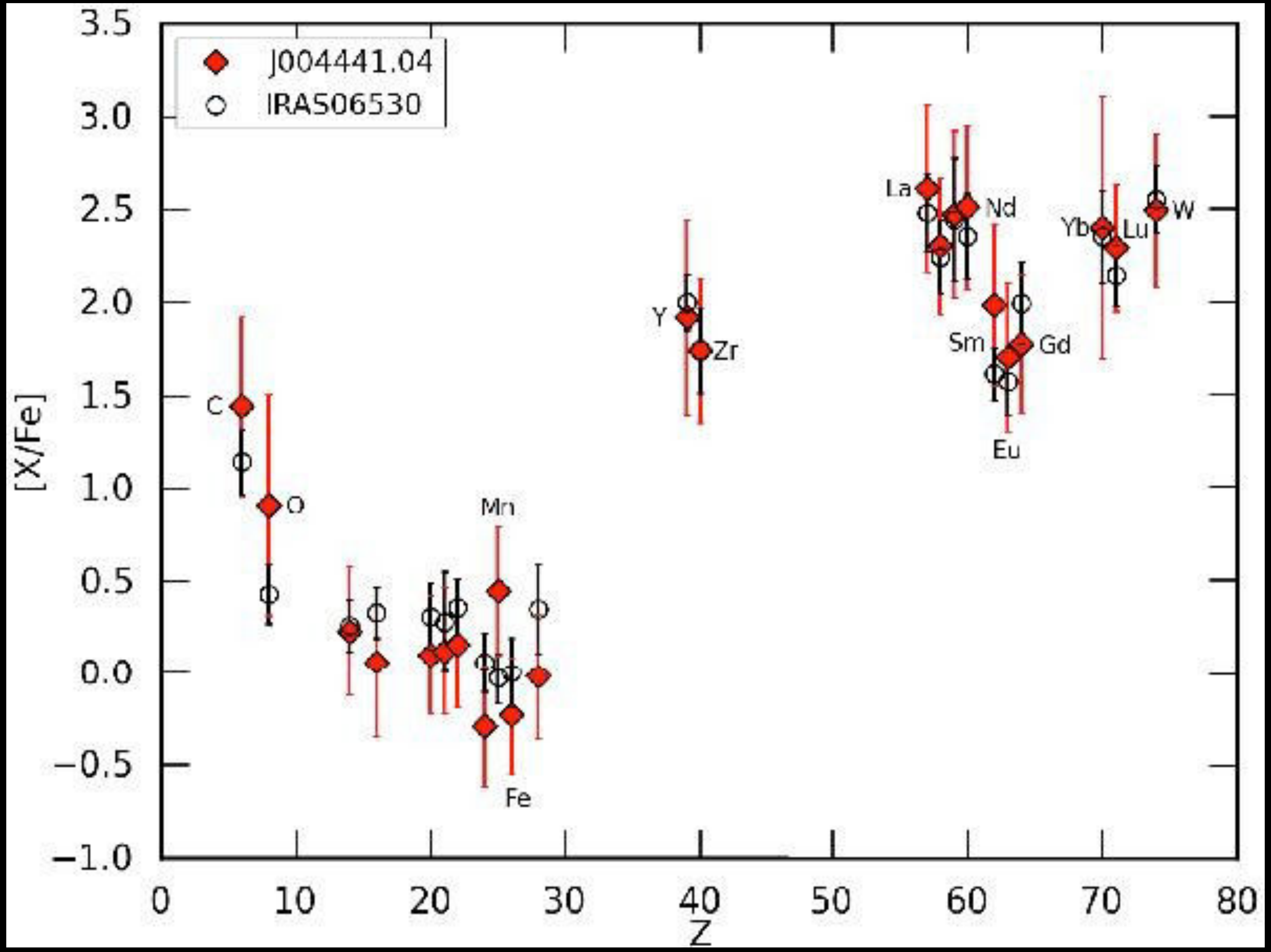
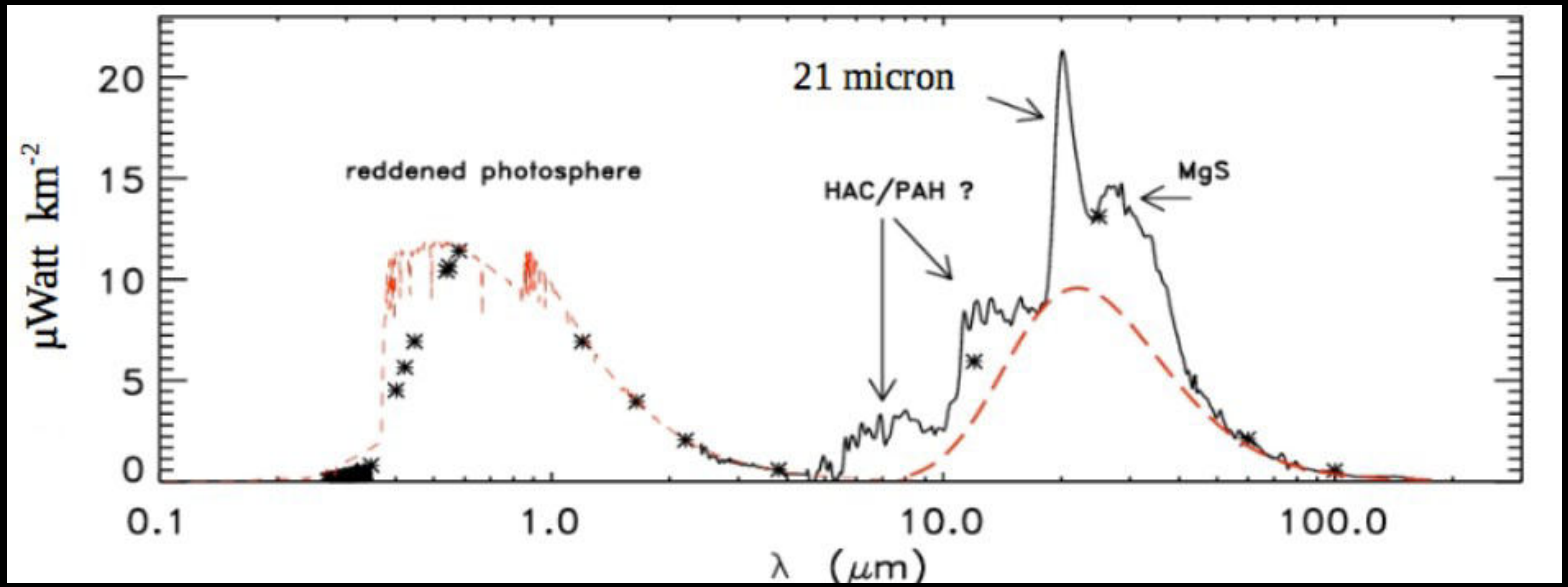
Single Post-AGB Stars as Exquisite Tracers of CNO, Fe-peak & *s*-process elements

Carbon and *s*-process rich stars:



De Smedt et al., 2012, 2015

- $M_{initial}$ ~ 1 to 1.5 Msun
- [Fe/H] = -1.0 to -1.5
- Z ~ 0.001
- T_{eff} ~6000 K
- Log g ~1 to 1.5 dex



Van Winckel 2003

All C-rich and *s*-process rich post- AGB stars show the <u>21-micron feature</u>!

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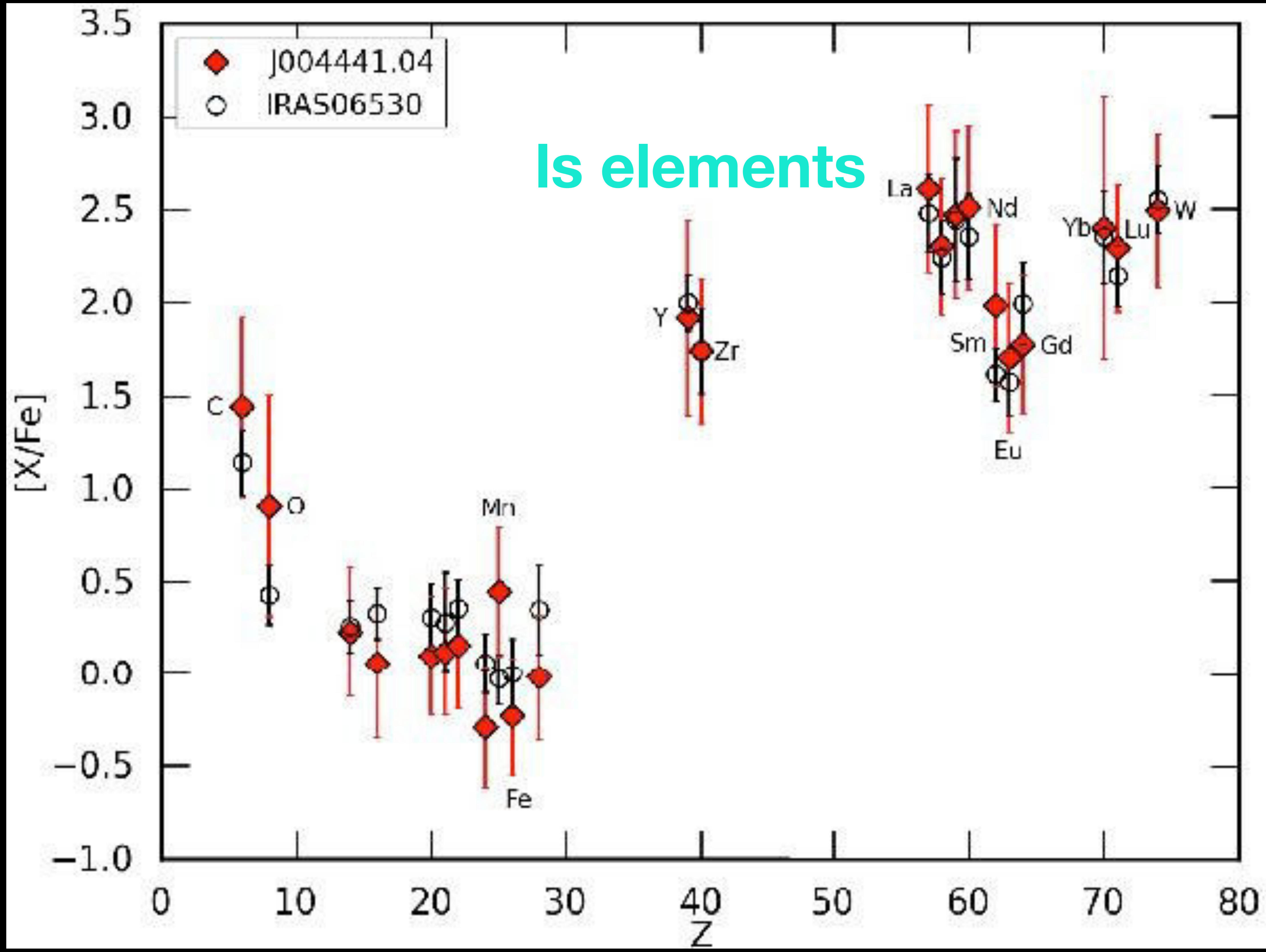

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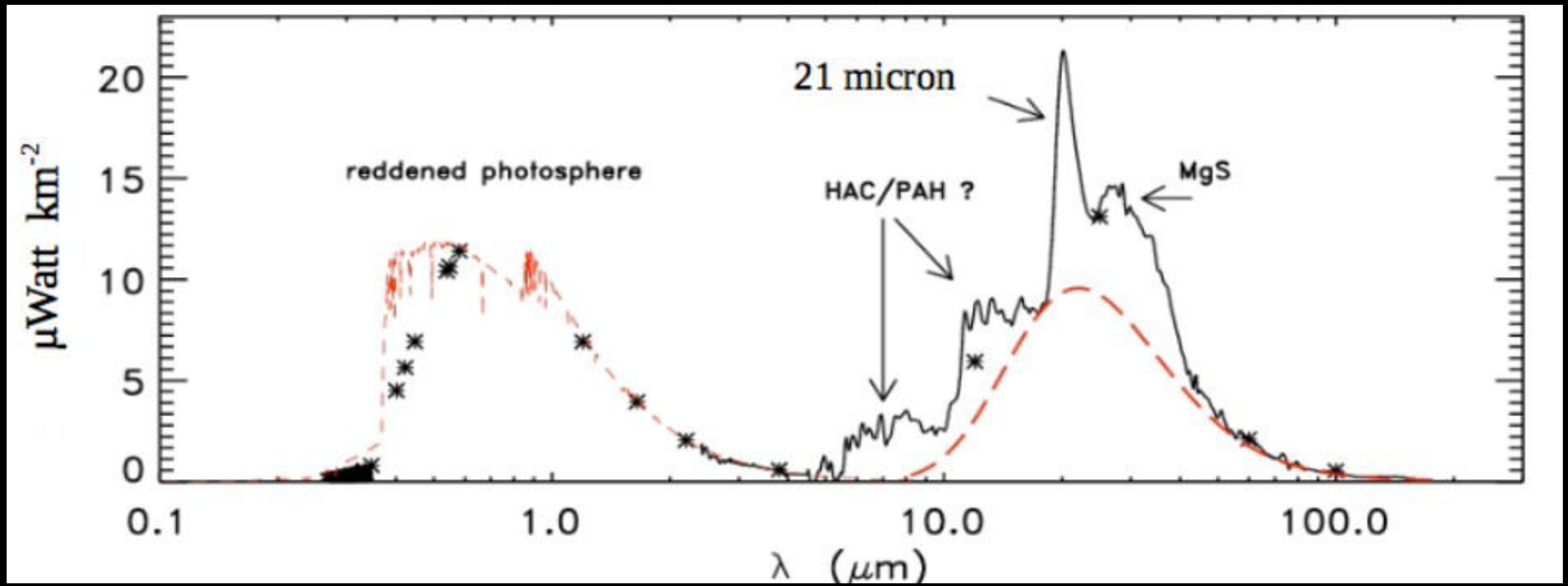

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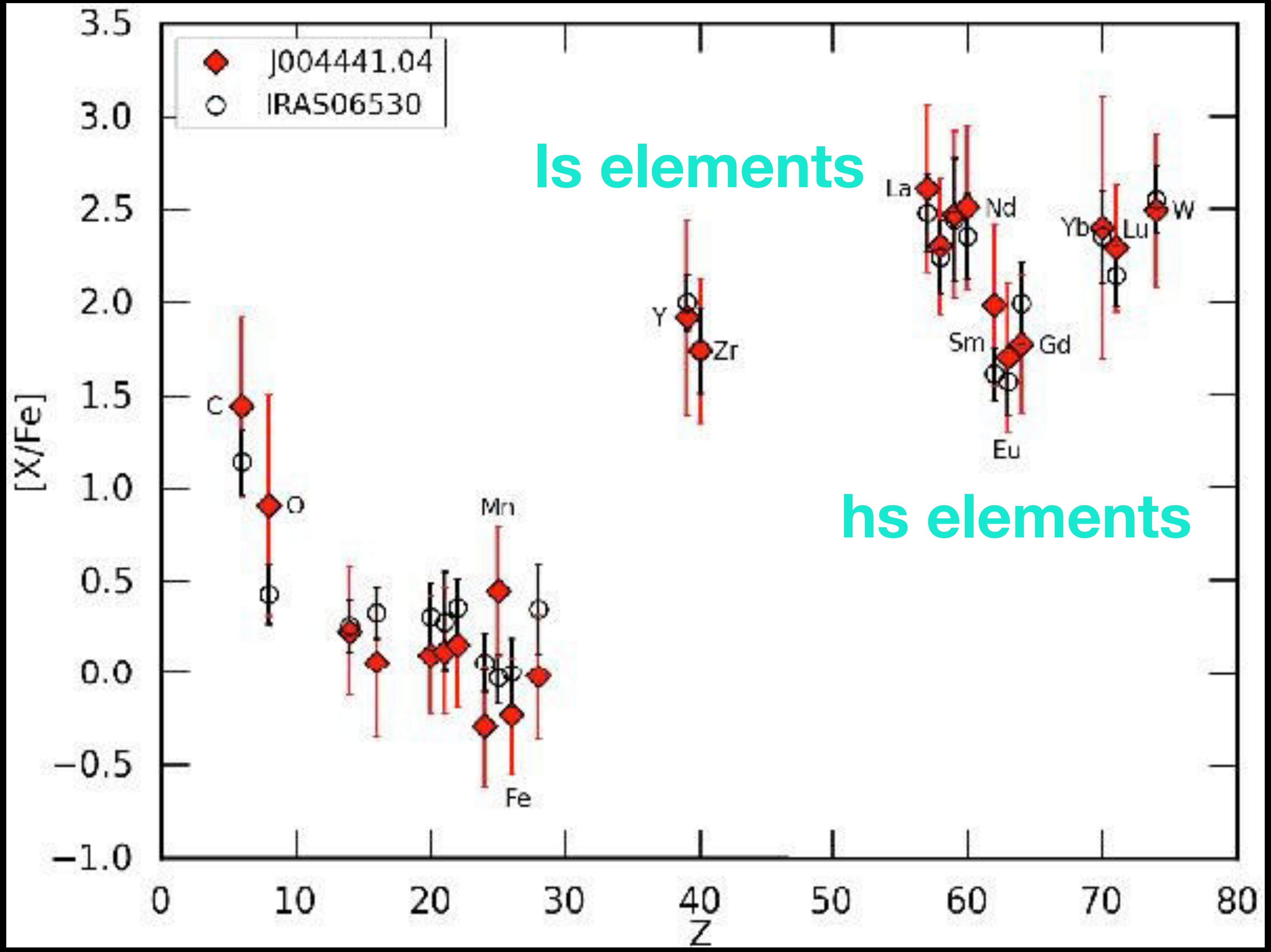

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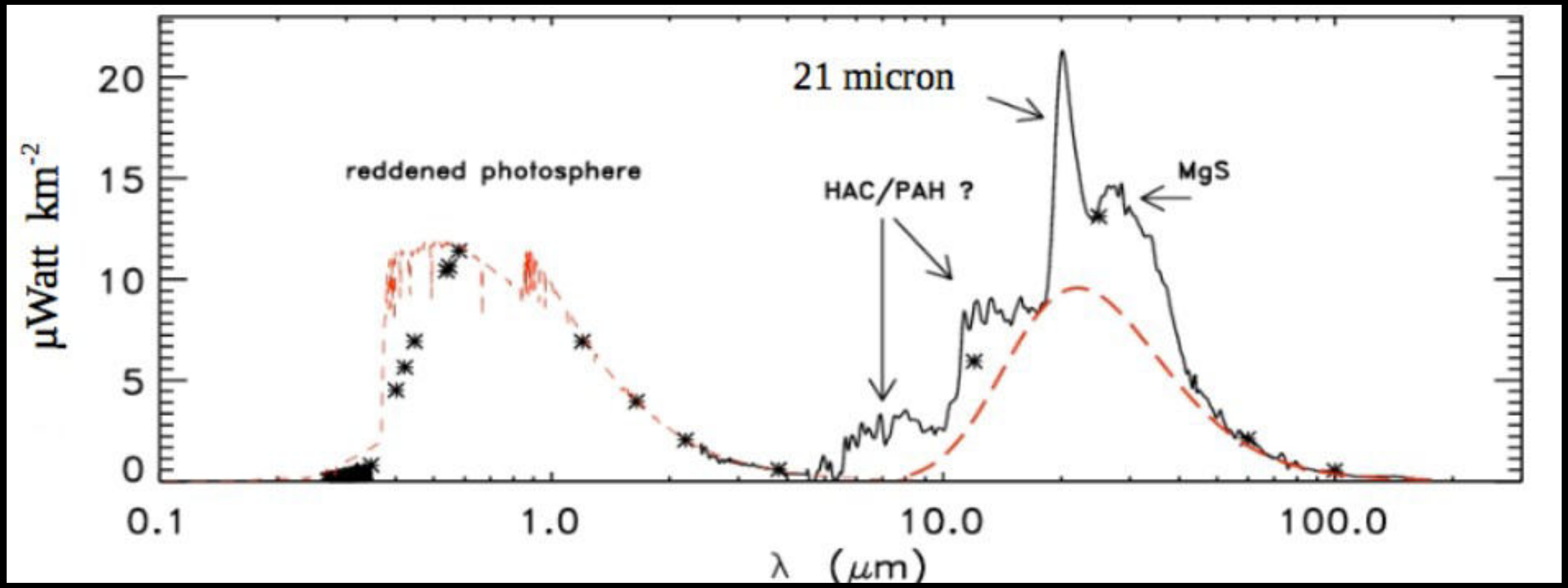

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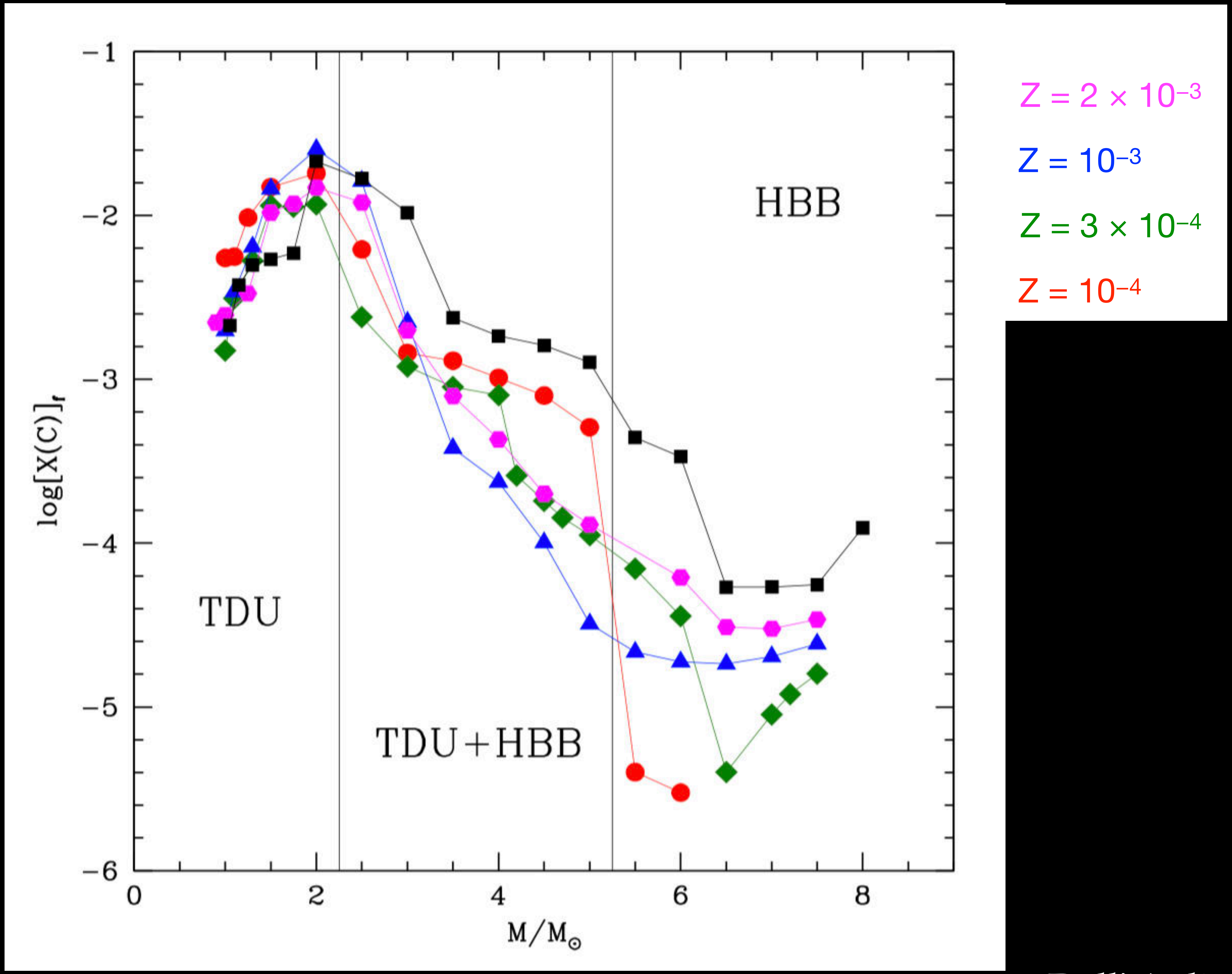
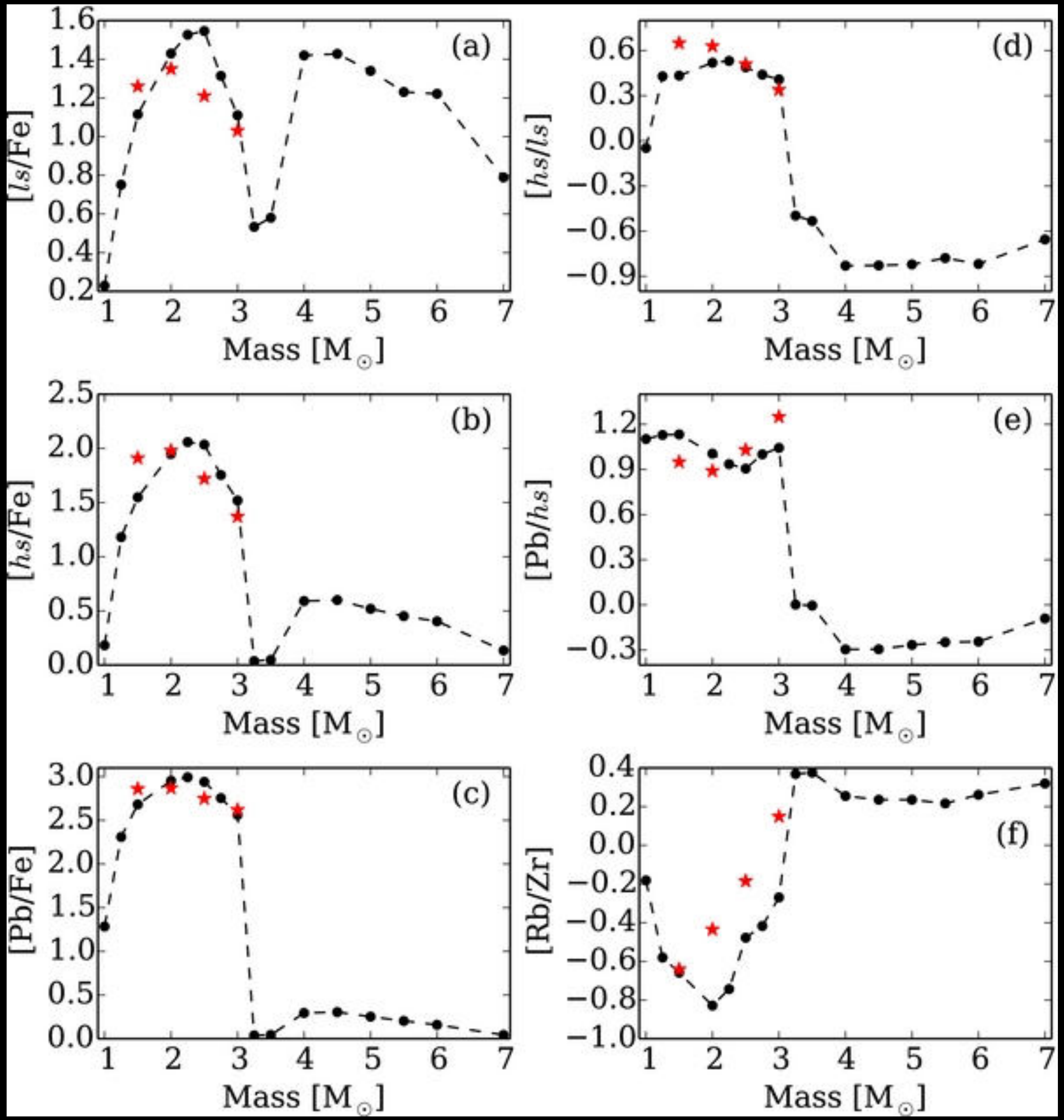
Nucleosynthetic Yields from Stellar Models



Dell' Agli et al., 2019

Nucleosynthetic Yields from Stellar Models

ls = Y, Sr, Zr, Rb
hs = Ba, La, Nd



Fishlock et al., 2014

The revelation of chemical diversities in AGB nucleosynthesis…

Van Winckel 2003; Kamath et al., 2017; 2020; 2022; 2023

THE STATE-OF-THE-ART: COMPLEXITIES IN SINGLE STAR AGB NUCLEOSYNTHESIS

The State-of-the-art: **Complexities** in Single Star AGB Nucleosynthesis

A subset of post-AGB stars reflect a lack of carbon production during the AGB phase

Kamath et al.,2018

efficiency of the third dredge-up

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***s*-process nucleosynthesis**

Observed C/O and 12C/13C ratios significantly lower than predictions *De Smedt et al., 2012; Van Aarle et al., 2014; Kamath et al., 2014; 2015*
convection, mixing, and mass-loss

Complexities in Single Star AGB Nucleosynthesis

- **Failed third dredge-up**

Lack of carbon production during the AGB phase for stars that are predicted to have efficient TDU

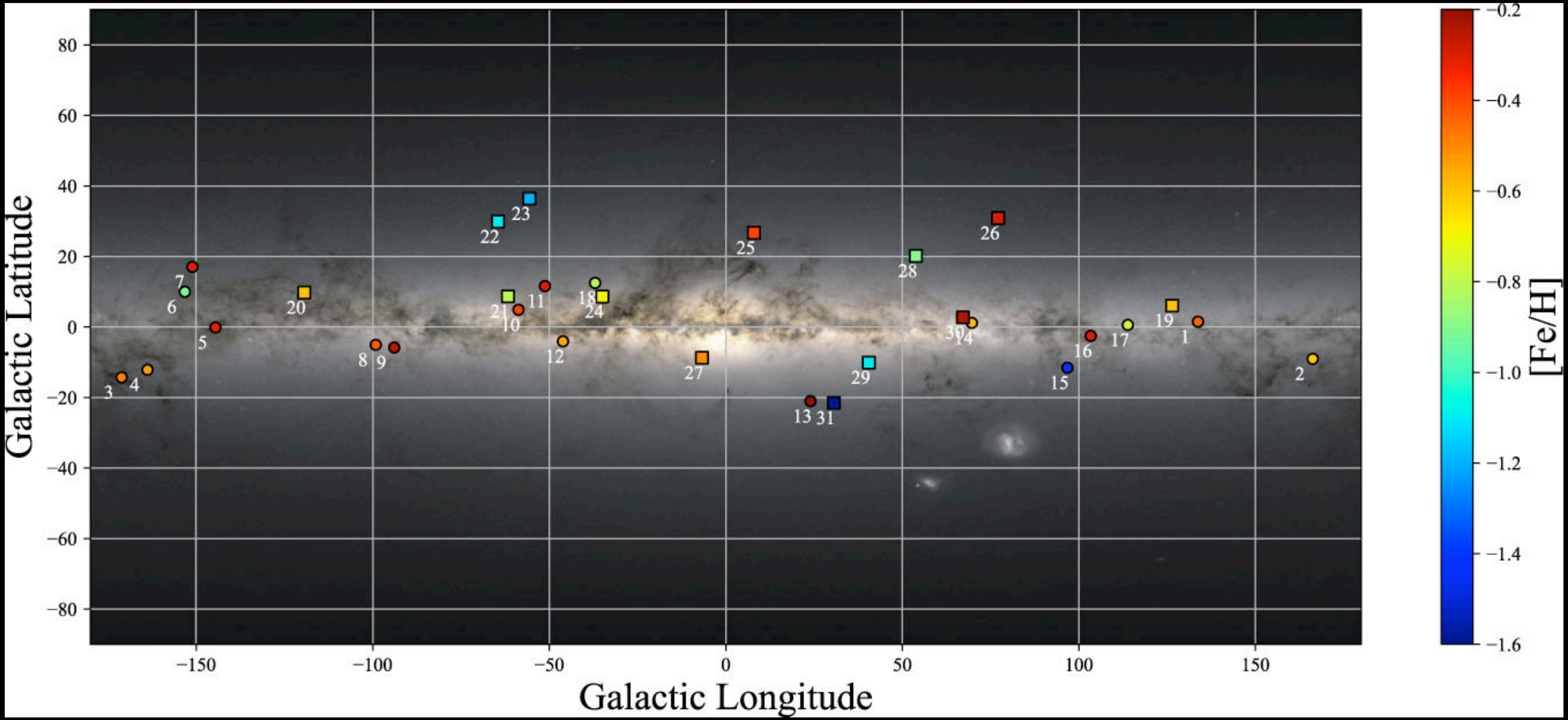
Kamath et al., 2017

- **Diverse AGB nucleosynthesis**

Non-uniform *s*-process production

Van Winckel 2003; Kamath et al.,2022; Kamath et al., 2023

Chemical Diversities Within the Galactic Single Star Sample

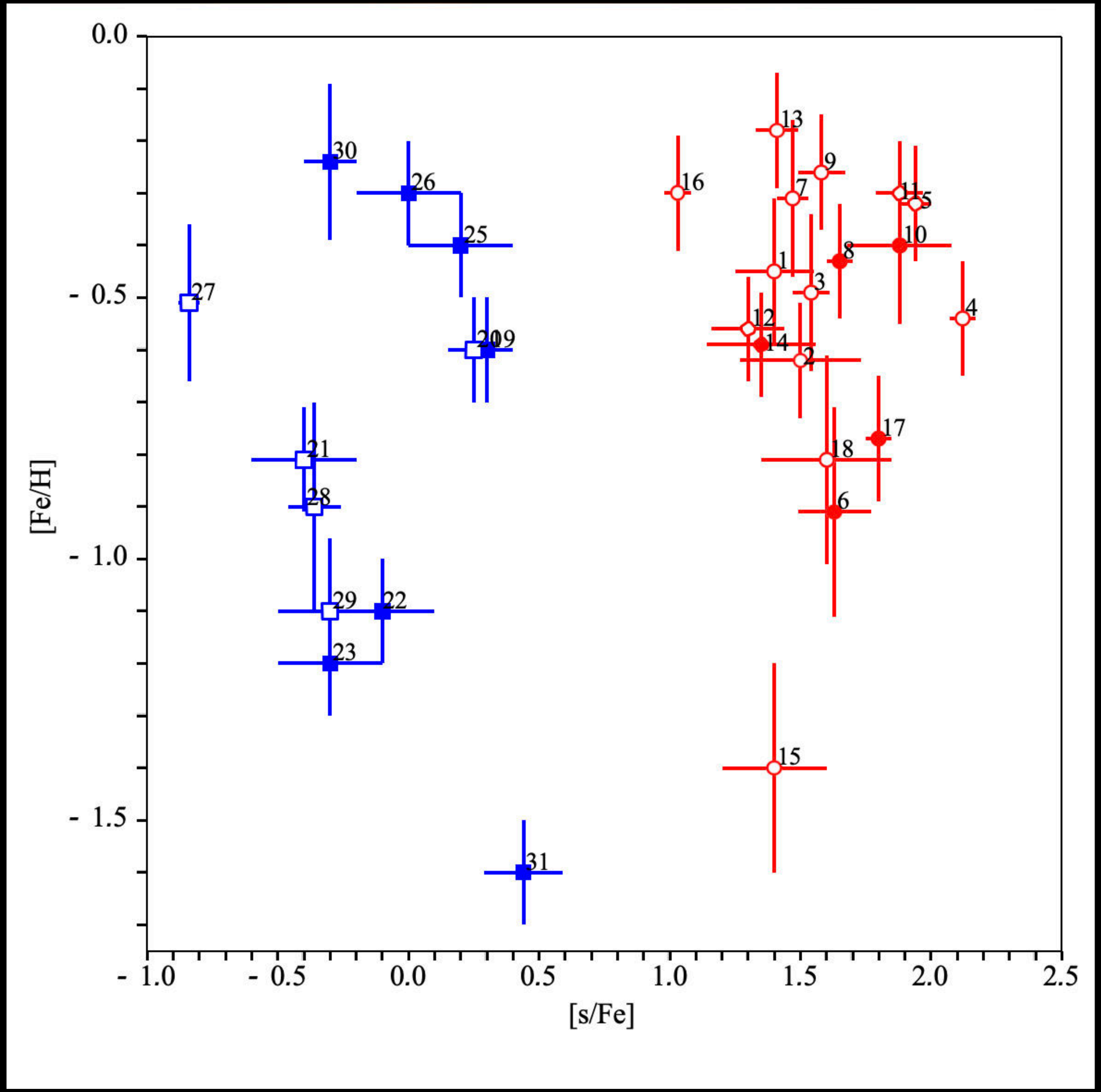


Chemical Diversities Within the Galactic Single Star Sample

Chemical Diversities Within the Galactic Single Star Sample

s-process rich versus non-enriched:

s-process rich
non s-process enriched



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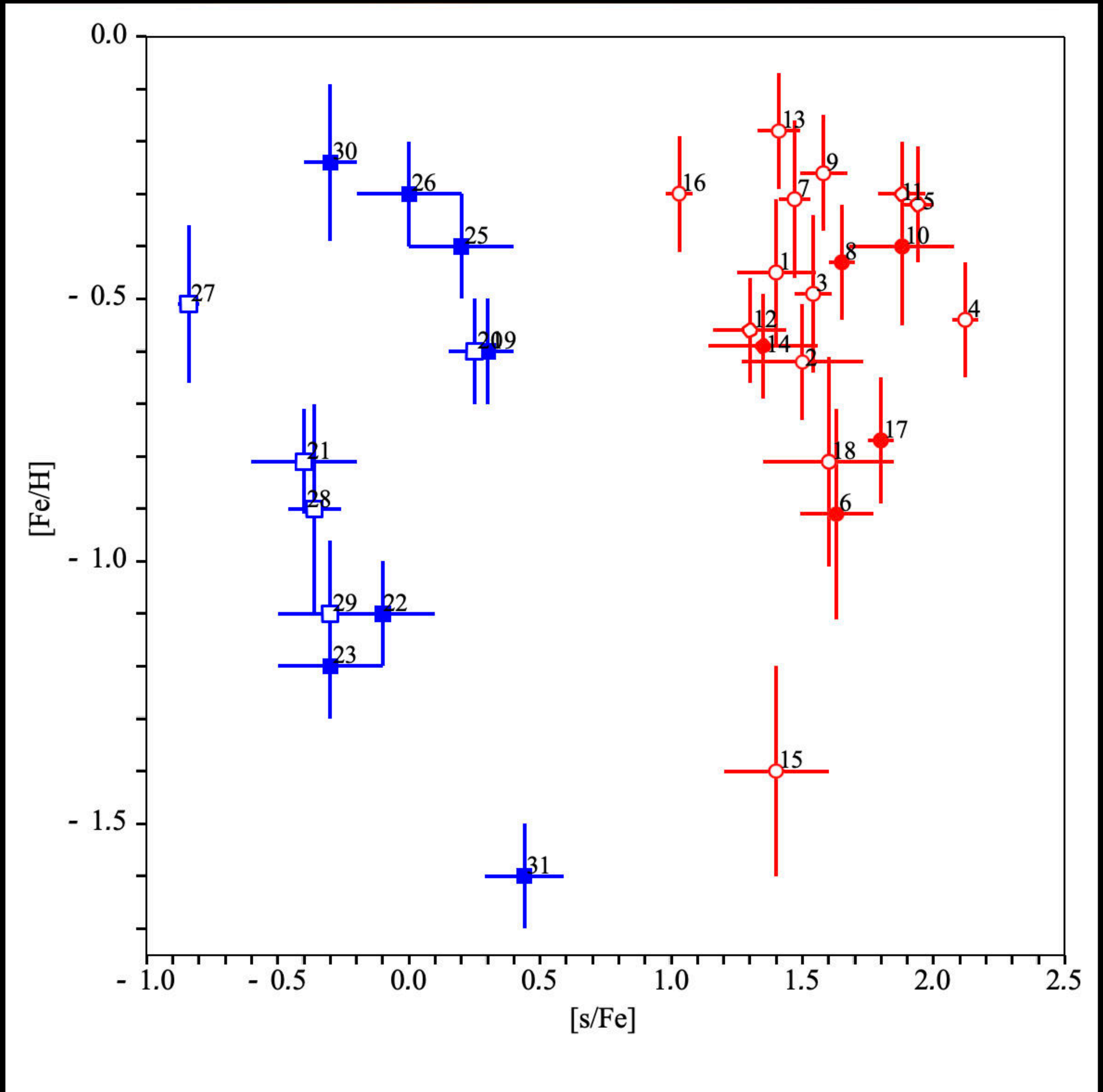
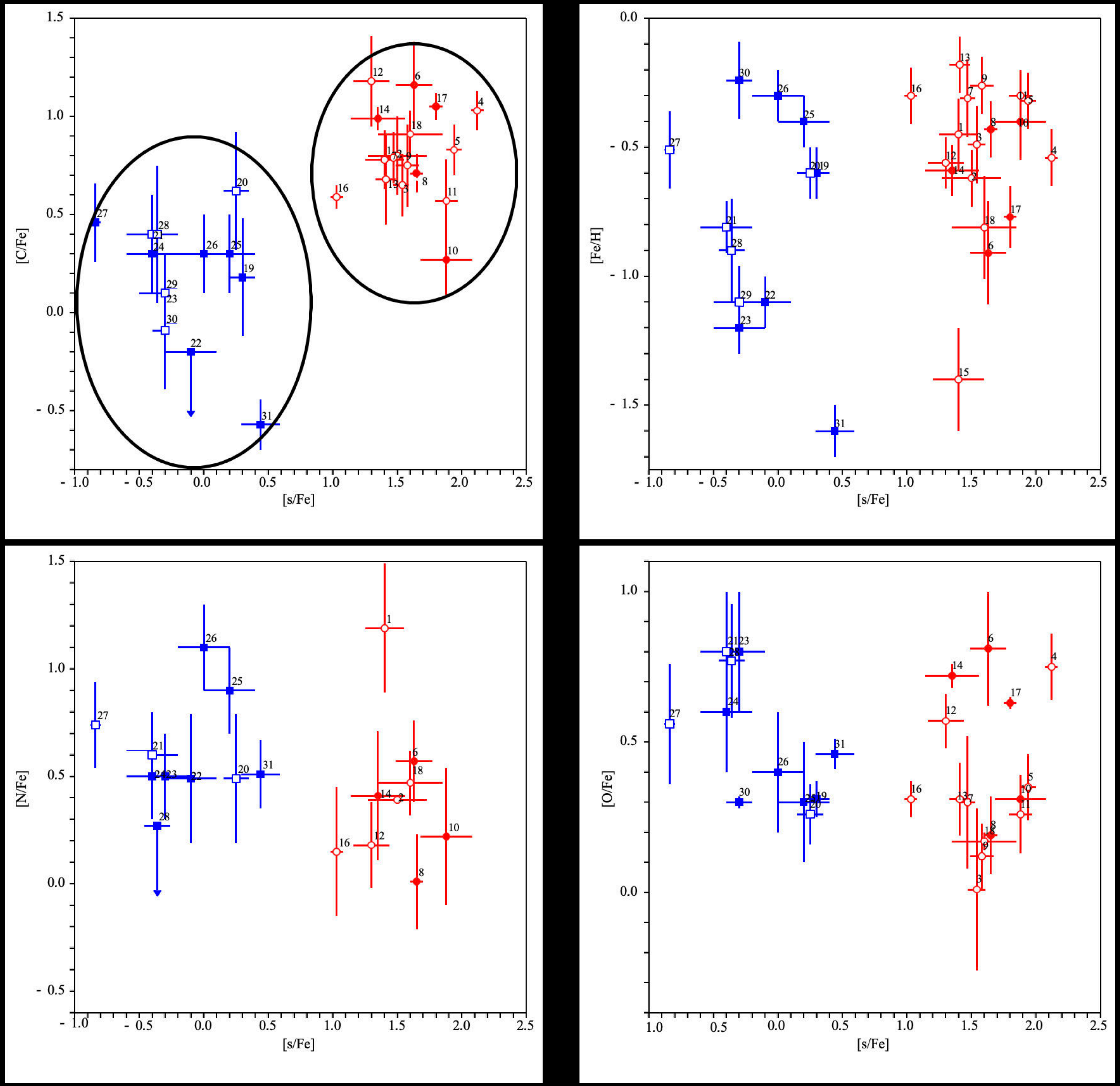


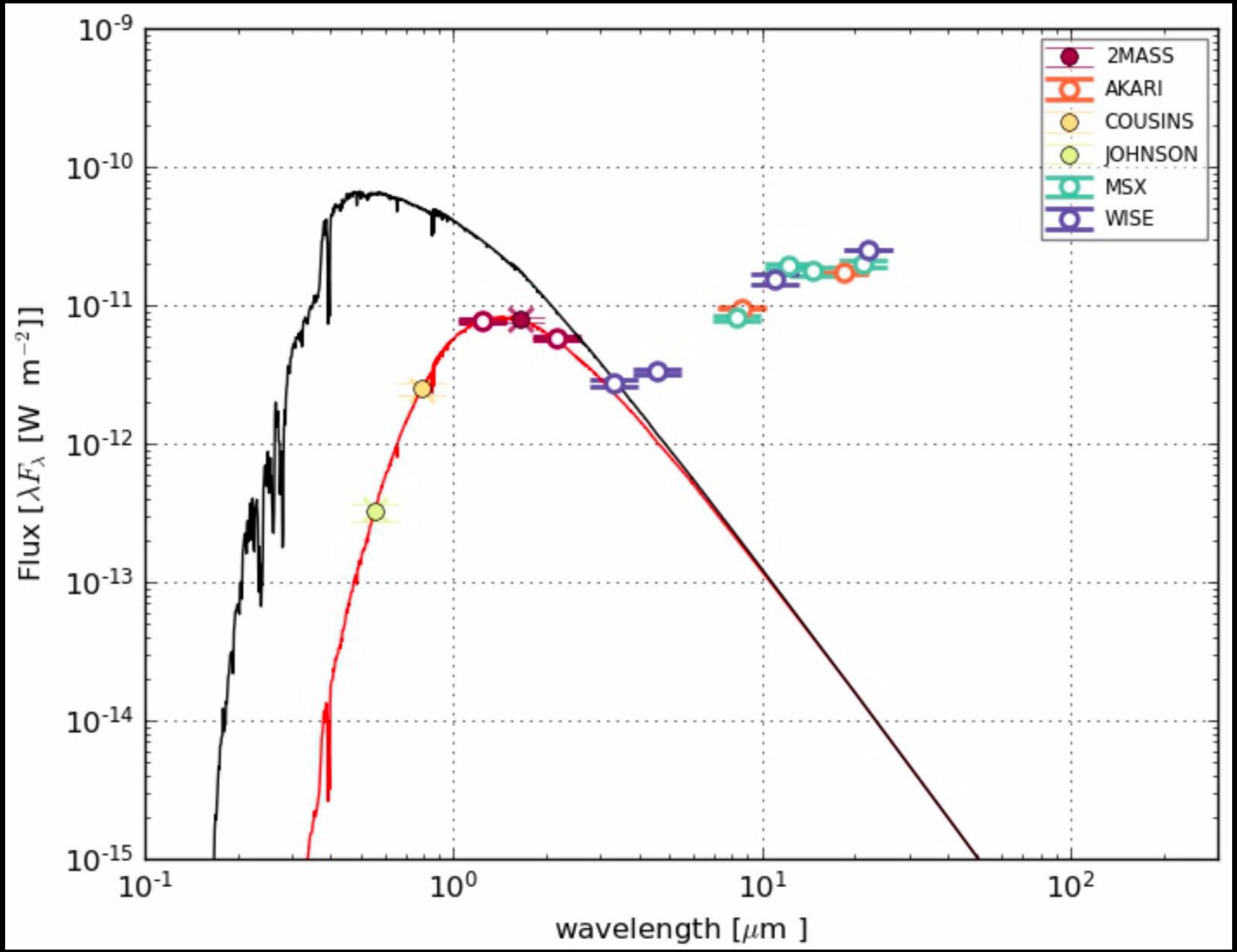
AGB Nucleosynthesis is NOT homogenous!

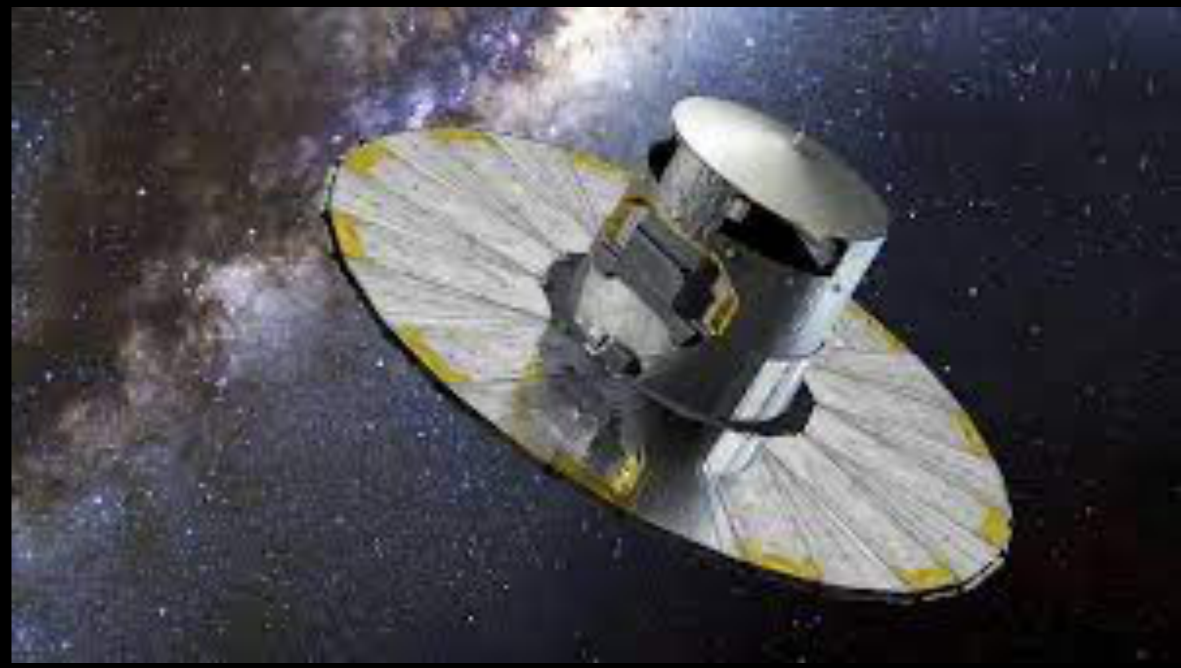
Red: s-process enriched
Blue: non s-process rich



- A chemical dichotomy in the C and *s*-process abundances: enriched and non-enriched (in disagreement with models!)
- No obvious trends in O and N

Luminosities for Single Galactic Post-AGB Stars with GAIA





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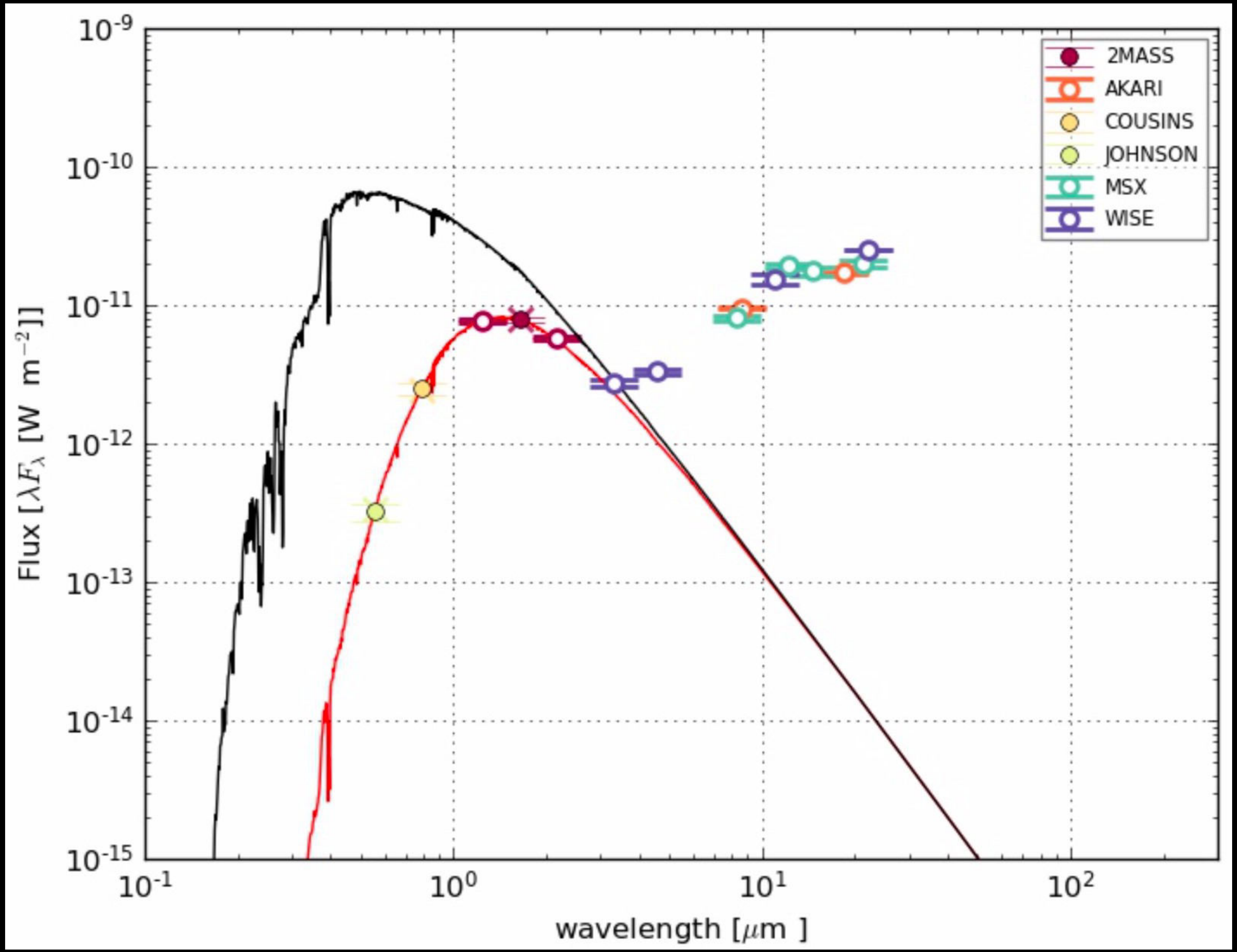

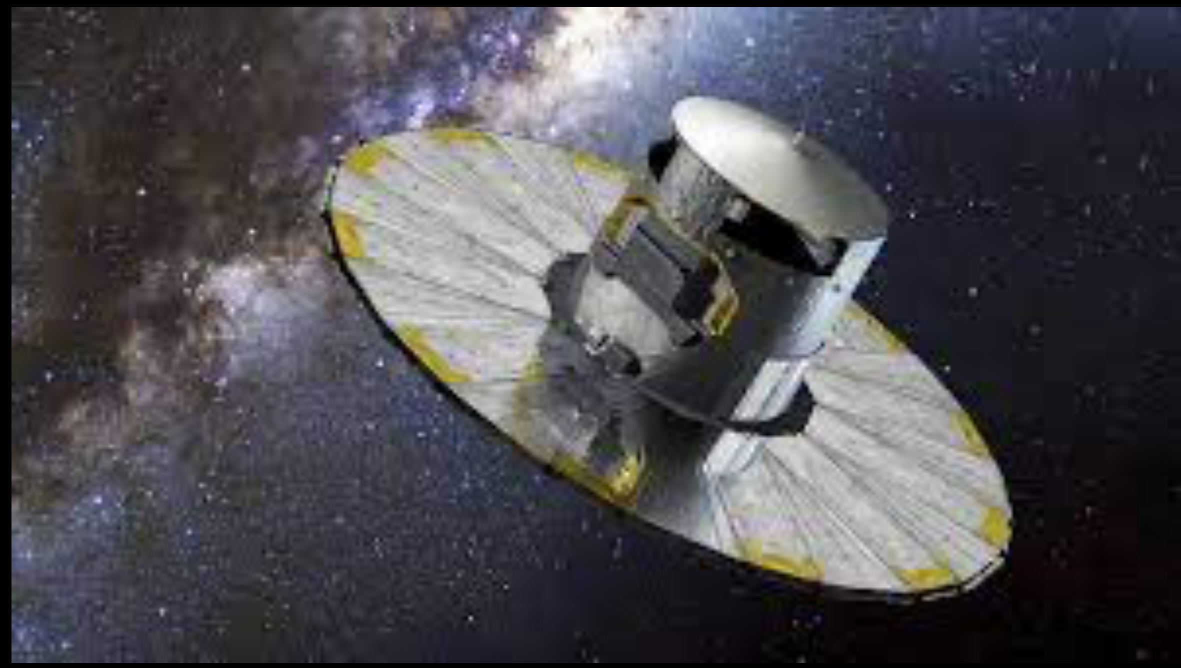

- Parallaxes from Gaia EDR3

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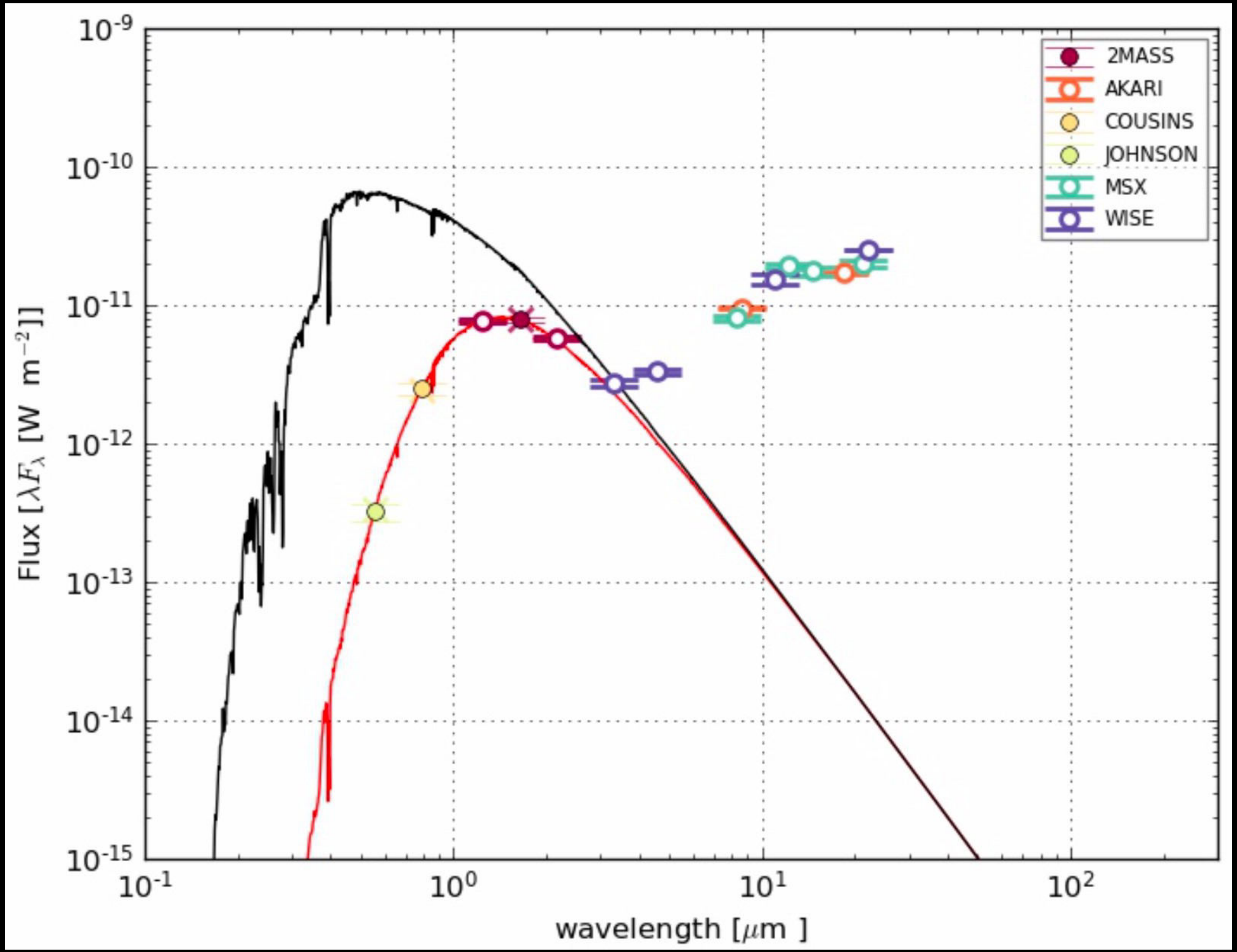

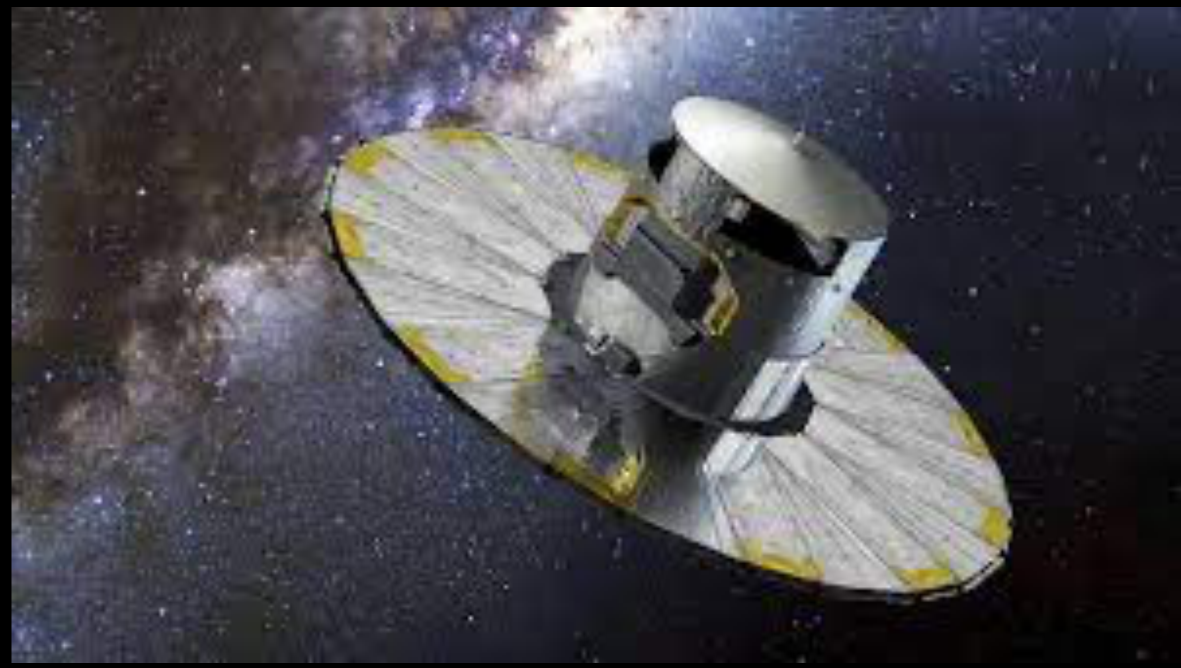

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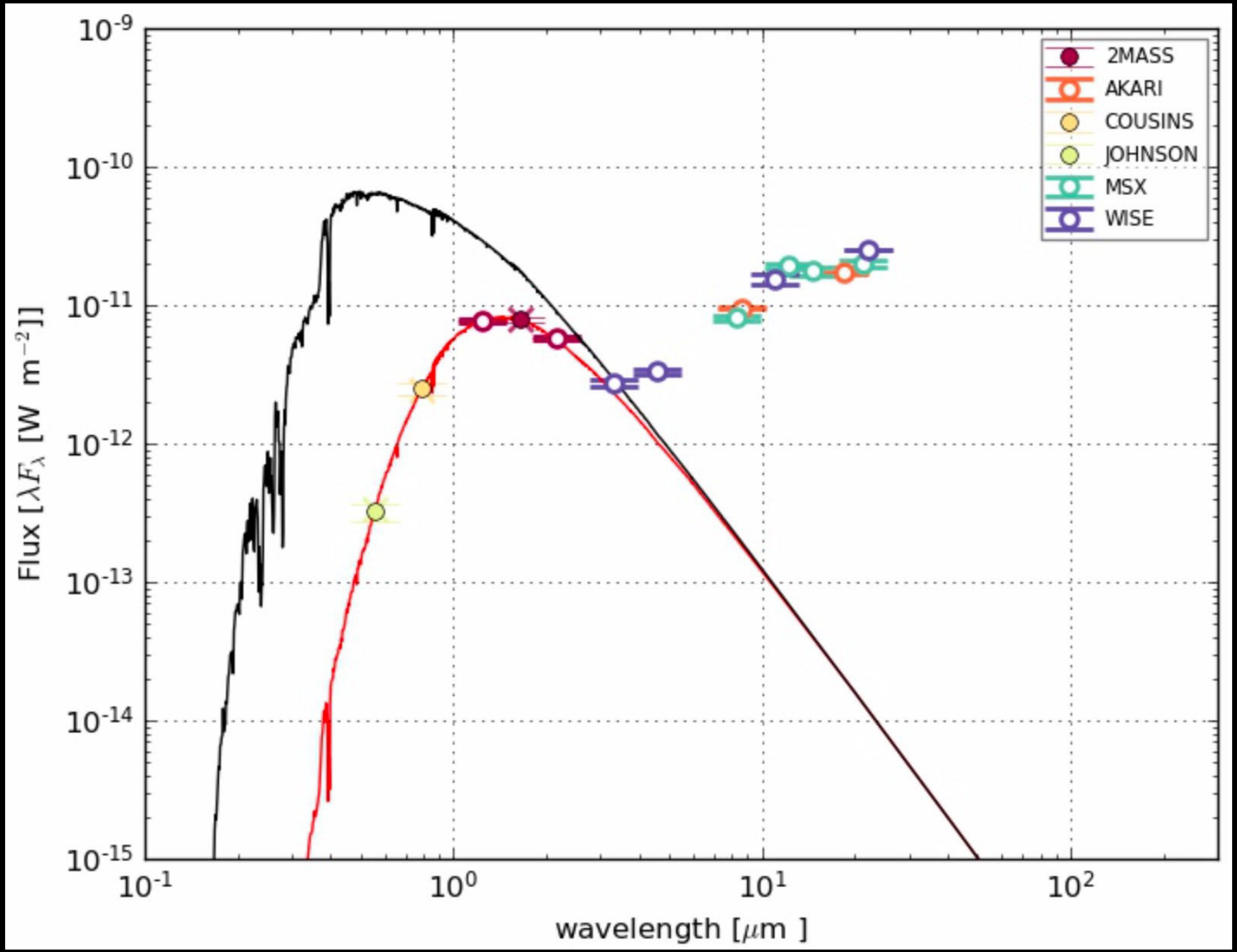

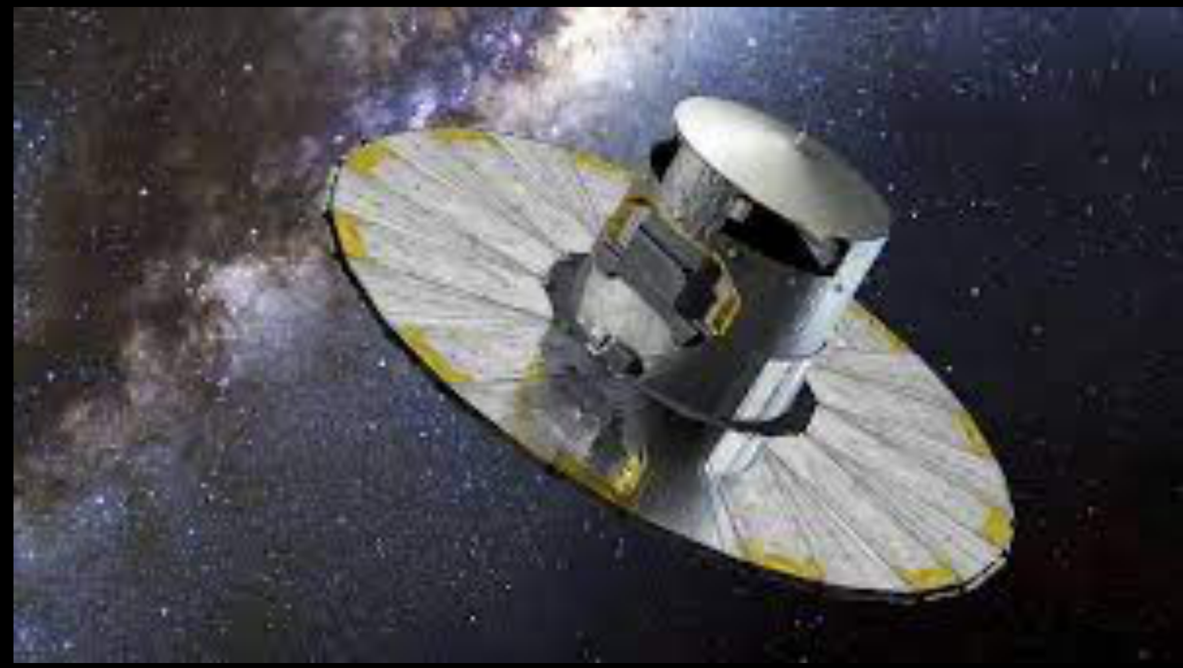

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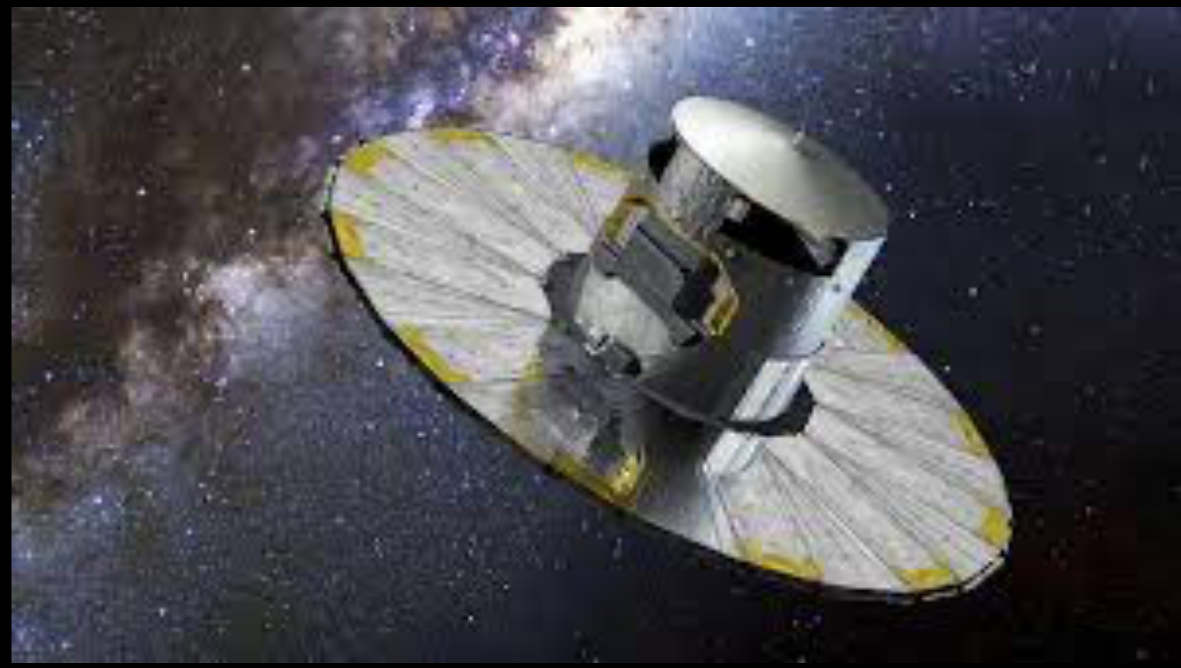

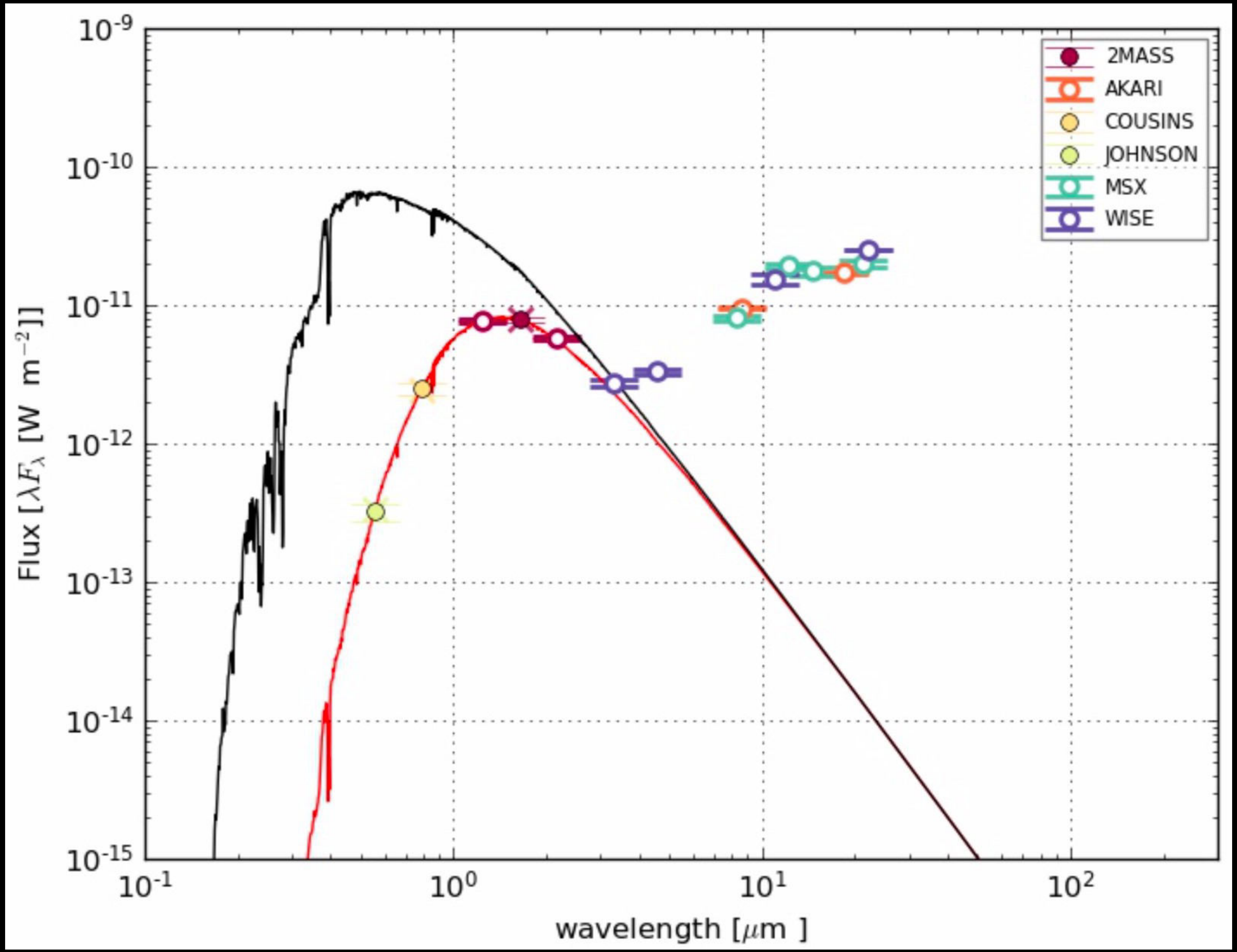

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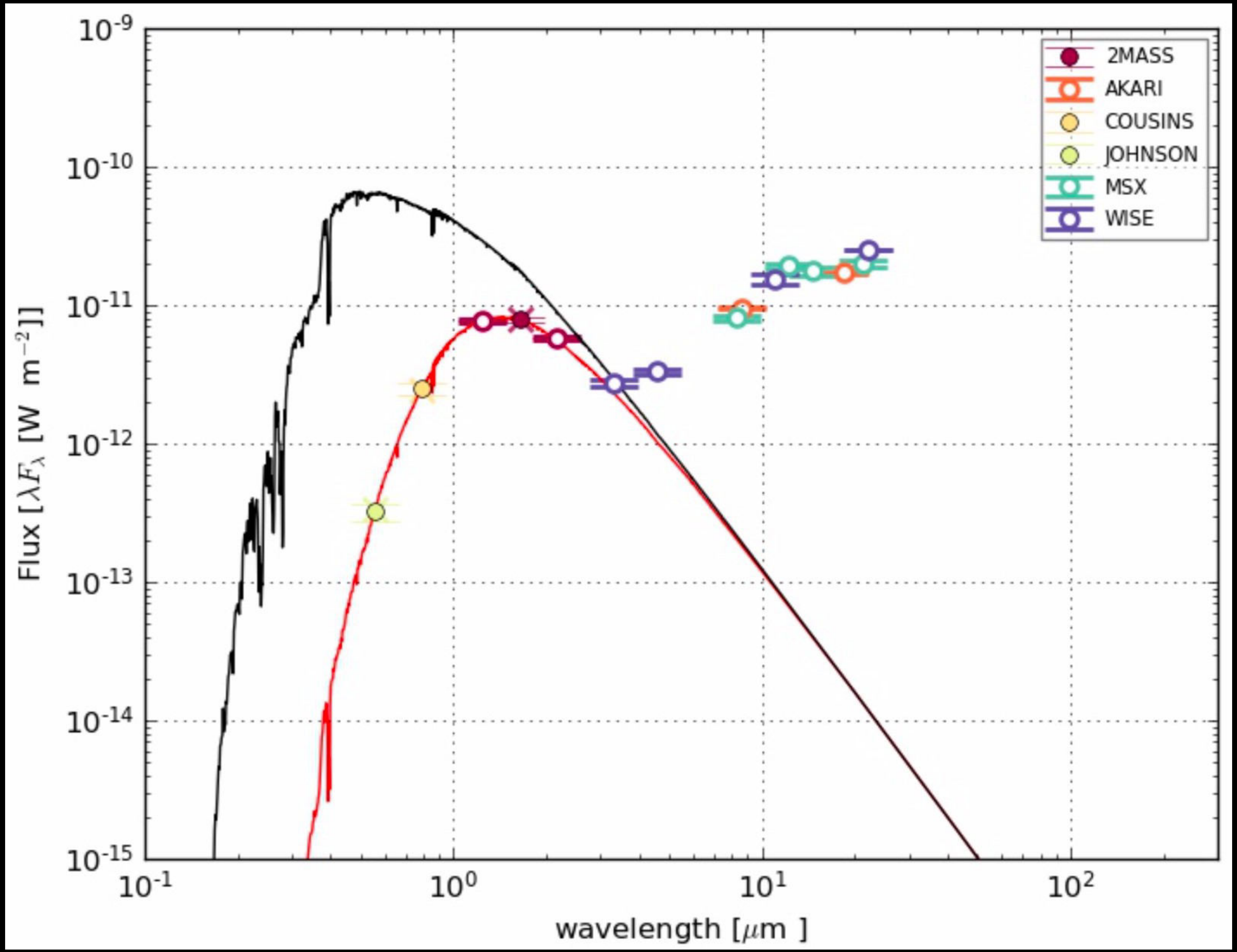

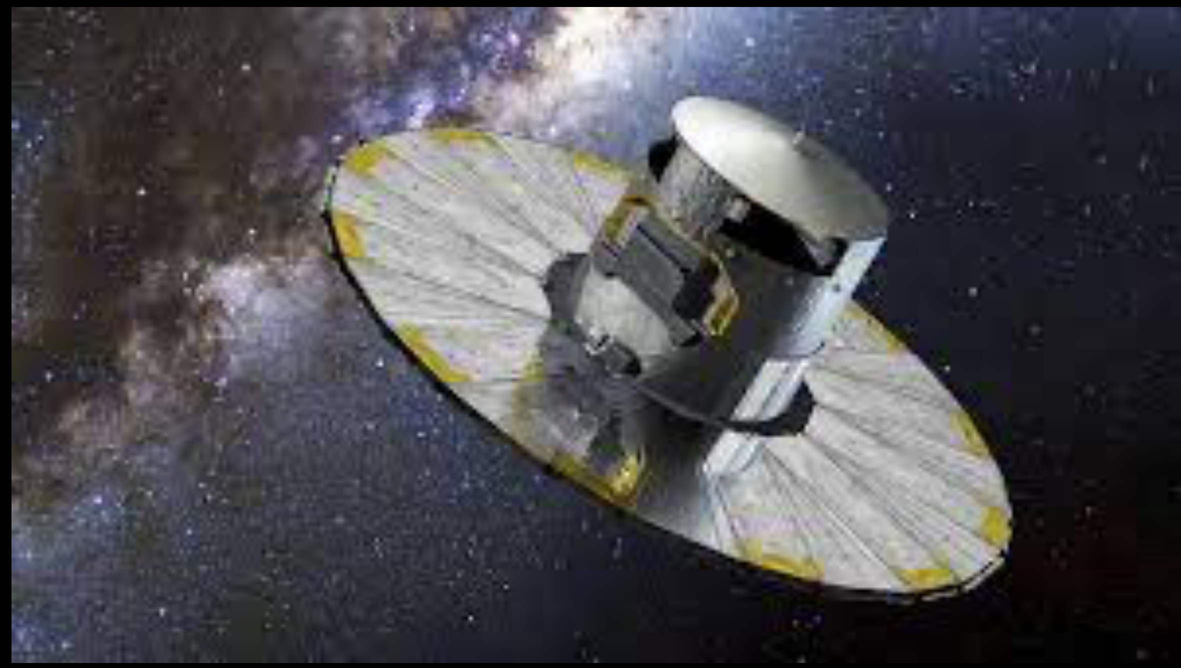

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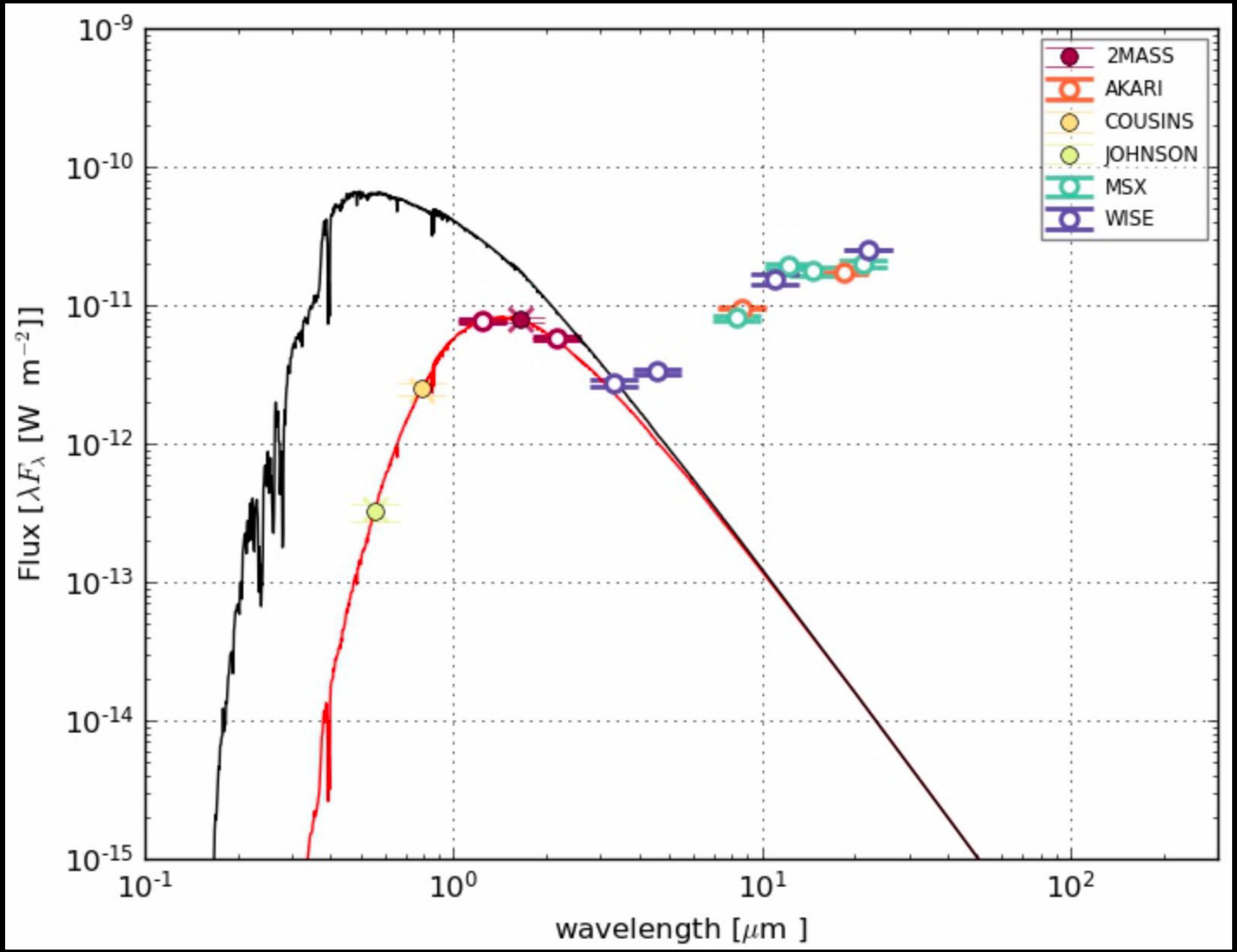

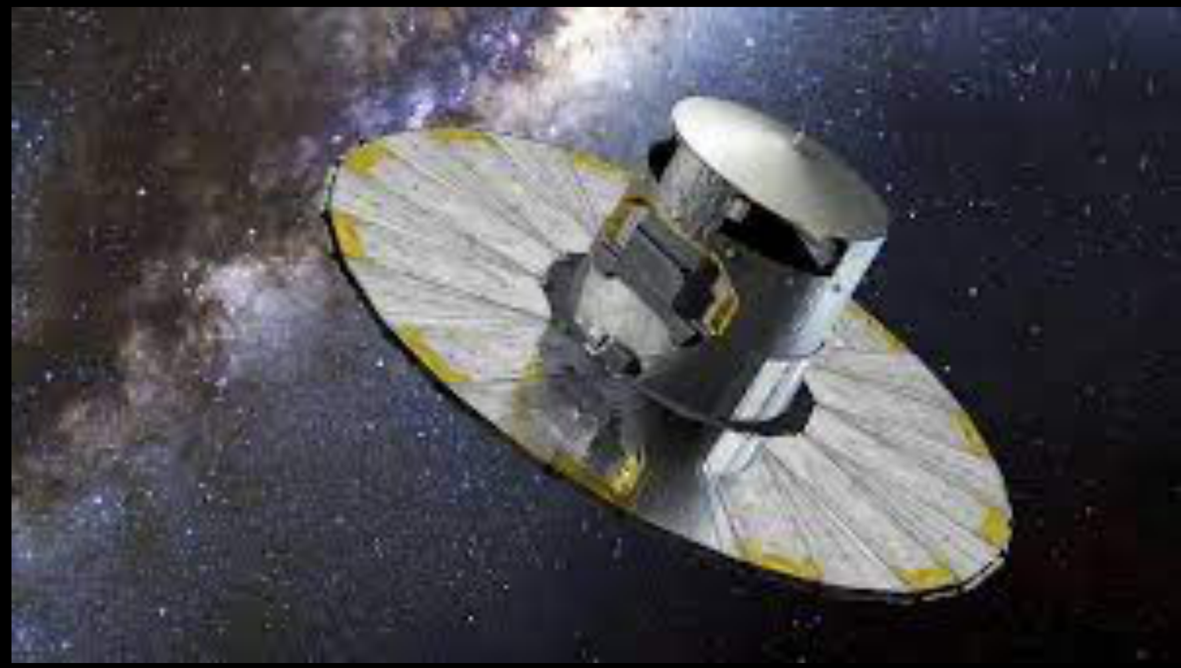

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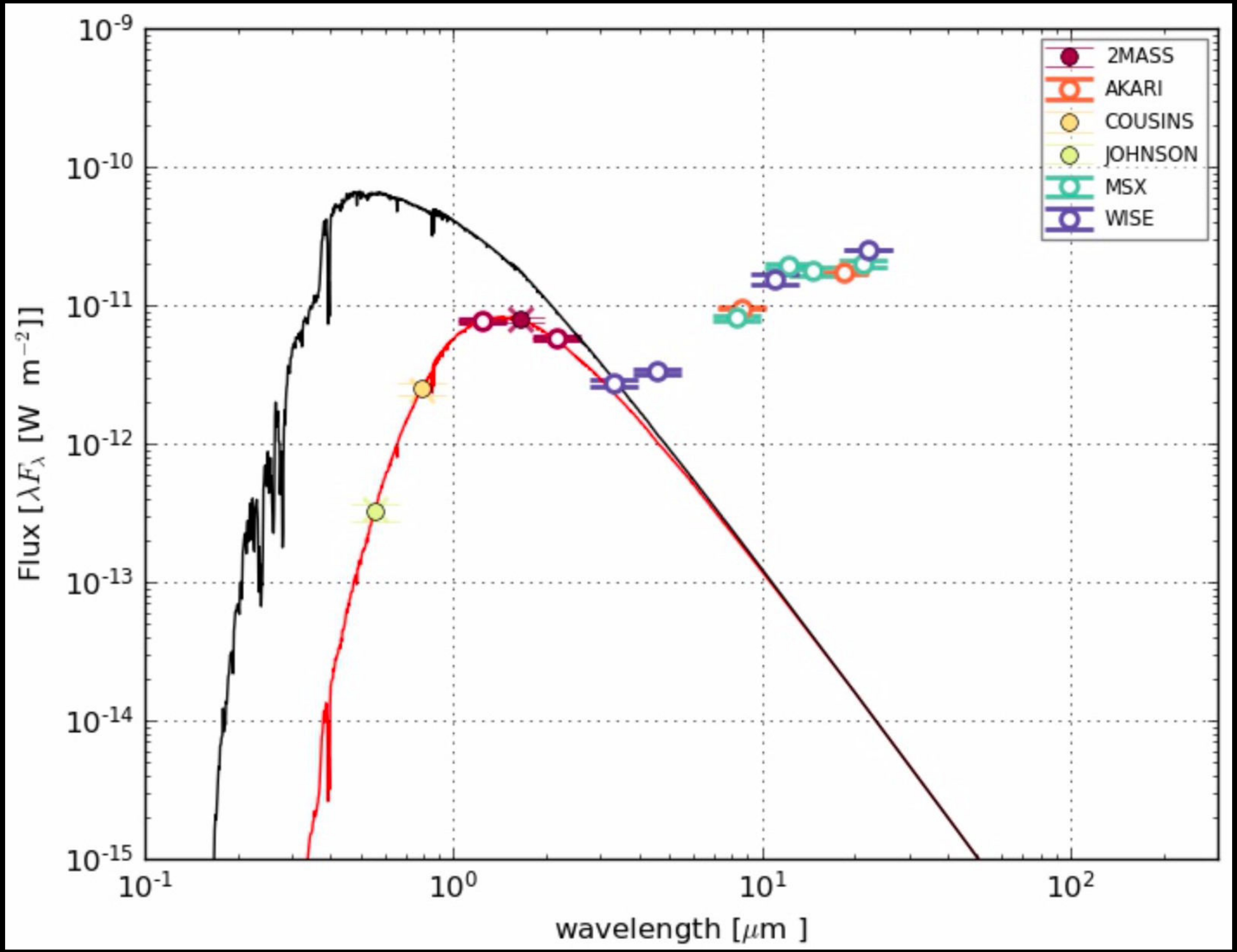

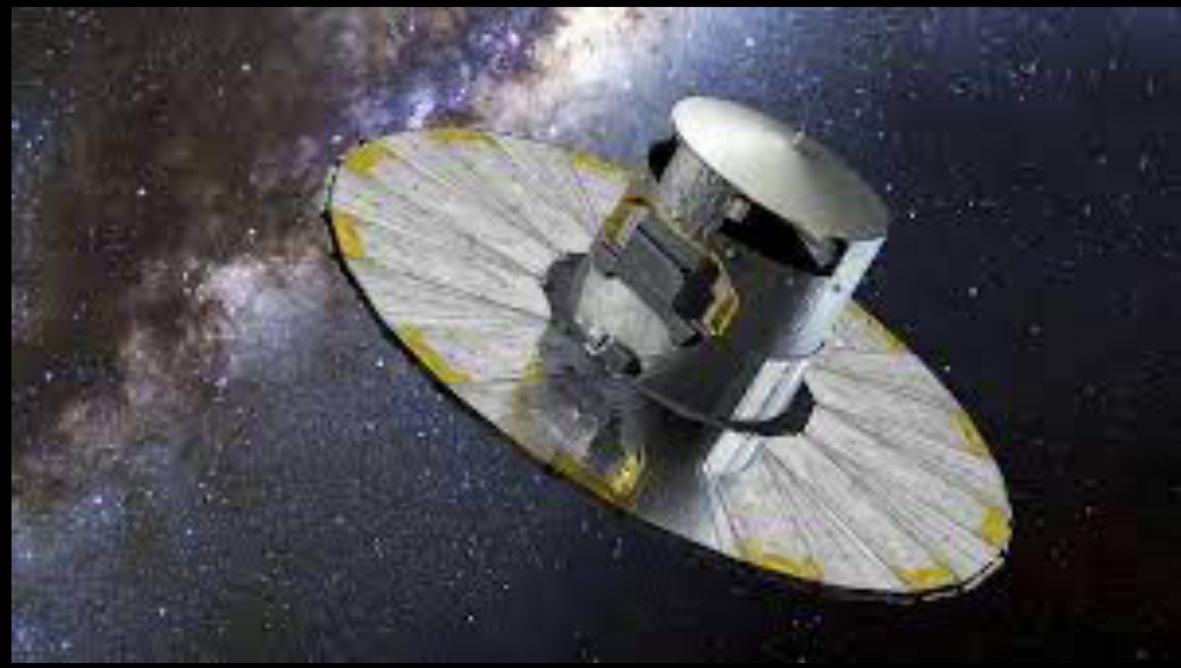

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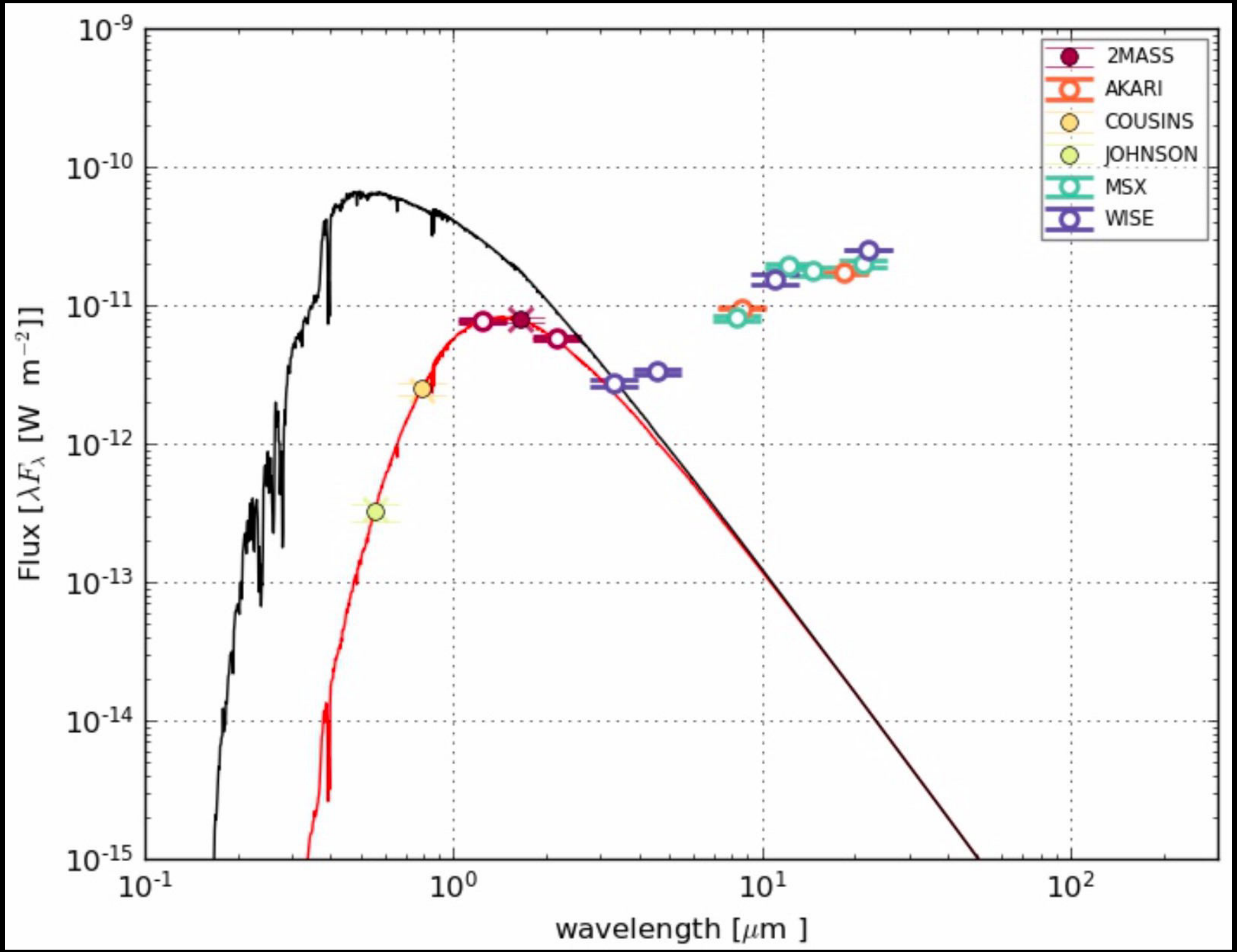

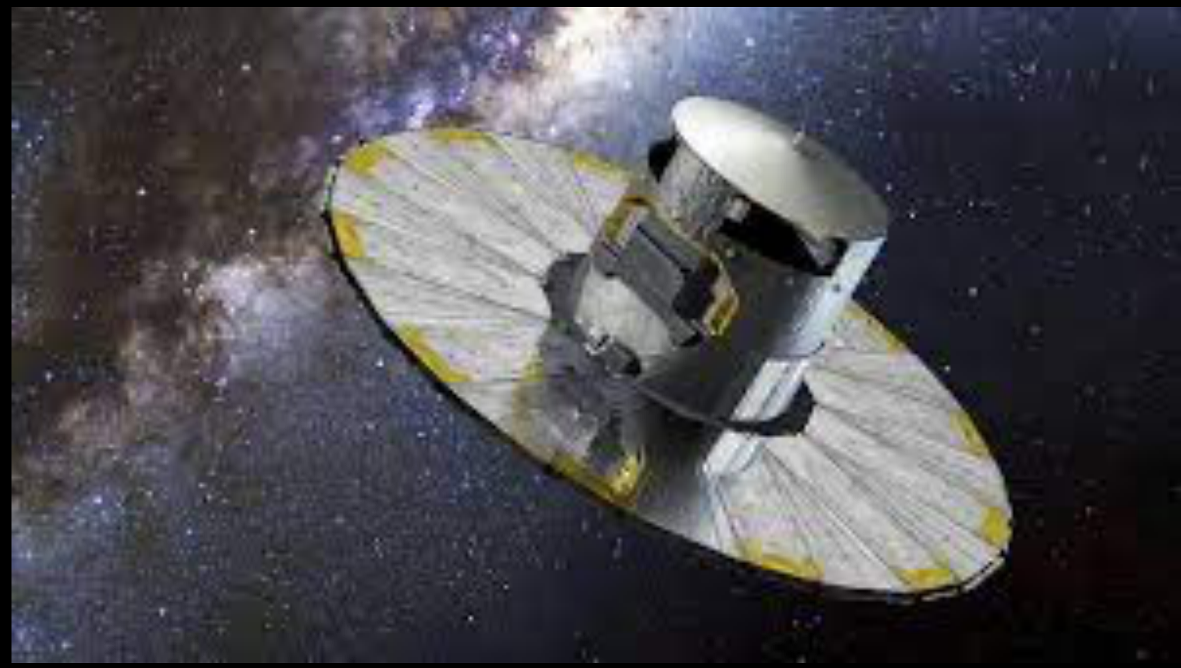

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  ↓
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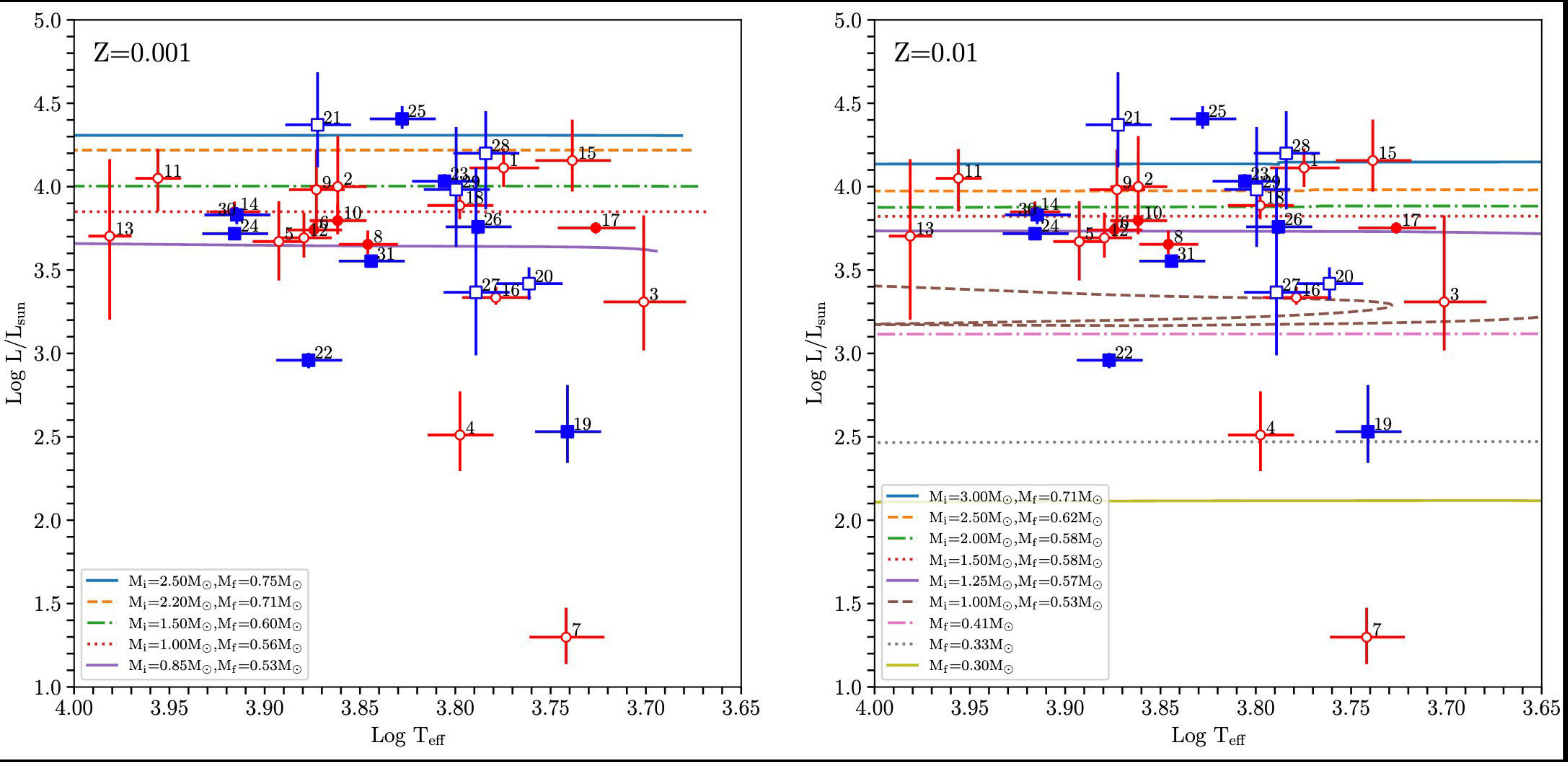
Positions of Galactic Post-AGB Stars in the HR-Diagram



Filled: Quality 1 - Filled, Open: Quality 2 (based on GAIA astrometric data)

Red circles: s-process enriched Blue squares: non s-process rich

Kamath et al., 2022

Chemistry of Stars Evolving from AGB to Post-AGB

STANDARD AGB EVOLUTION AND NUCLEOSYNTHESIS SCENARIOS

Chemistry of Stars Evolving from AGB to Post-AGB

STANDARD AGB EVOLUTION AND NUCLEOSYNTHESIS SCENARIOS

Case 1: Progenitor mass below ~1 Msun (FDU)

- **Few thermal pulses before envelope is lost**
- **Evolve as M-stars**
- Little to no C and s-process Some N (~0.5 dex) from FDU

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Case 3: Progenitor mass of ~3 - 4 Msun (TDU + HBB)

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- N is ~a factor of 10 higher than initial

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- N is ~a factor of 10 higher than initial

Case 4: Progenitor mass of > 4 Msun (HBB)

- Dominated by HBB
- N enhancement, neither C nor *s*-process

Chemistry of Stars Evolving from AGB to Post-AGB

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Case 3: Progenitor mass of ~3 - 4 Msun (TDU + HBB)

- Experience both TDU and HBB Enhanced in C and *s*-process.
- N is ~a factor of 10 higher than initial

Case 4: Progenitor mass of > 4 Msun (HBB)

- Dominated by HBB
- N enhancement, neither C nor *s*-process

Chemistry of Stars Evolving from AGB to Post-AGB

STANDARD AGB EVOLUTION AND NUCLEOSYNTHESIS SCENARIOS

Case 1: Progenitor mass below ~1 Msun (FDU)

- **Few thermal pulses before envelope is lost**
- **Evolve as M-stars**
- Little to no C and s-process Some N (~0.5 dex) from FDU

Case 2: Progenitor mass of ~1 - 3 Msun (TDU)

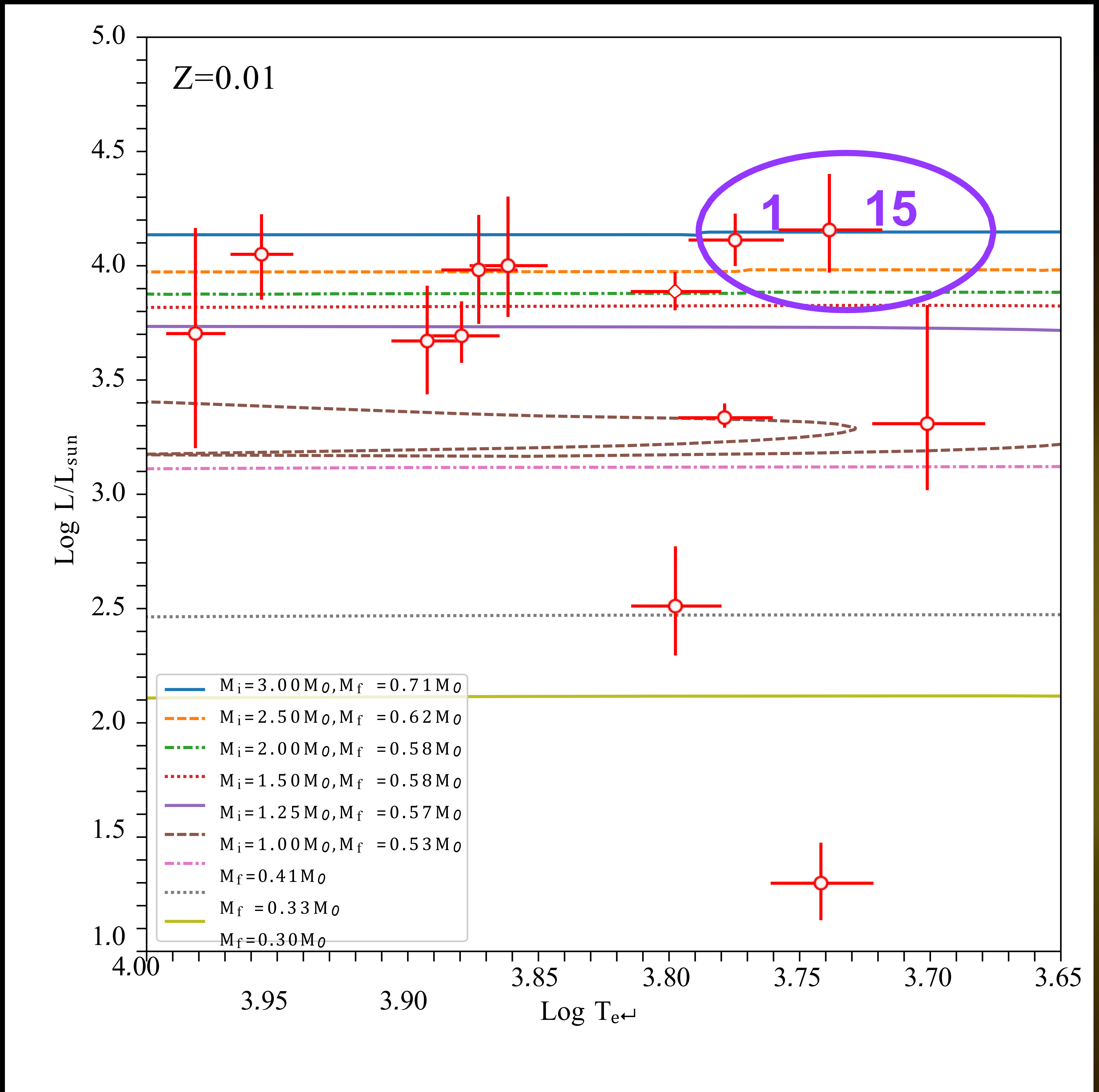
- Series of thermal pulses Evolve as C-stars Significant C and *s*-process
- Some N (from FDU), mild O-enrichment

Case 3: Progenitor mass of ~3 - 4 Msun (TDU + HBB)

- Experience both TDU and HBB Enhanced in C and *s*-process.
- N is ~a factor of 10 higher than initial

Case 4: Progenitor mass of > 4 Msun (HBB)

- Dominated by HBB
- N enhancement, neither C nor *s*-process



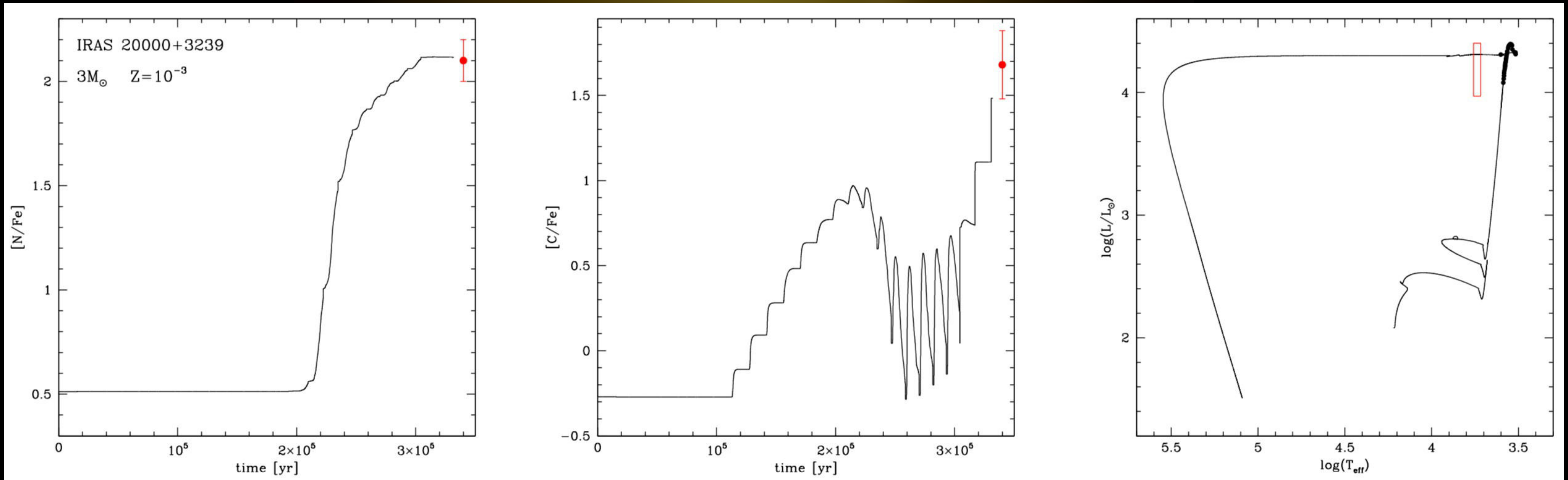
Case 3: TDU + HBB

Progenitor mass of ~3 - 4 Msun

- Experience both TDU and HBB
- Enhanced in C and *s*-process.
- N is ~a factor of 10 higher than initial

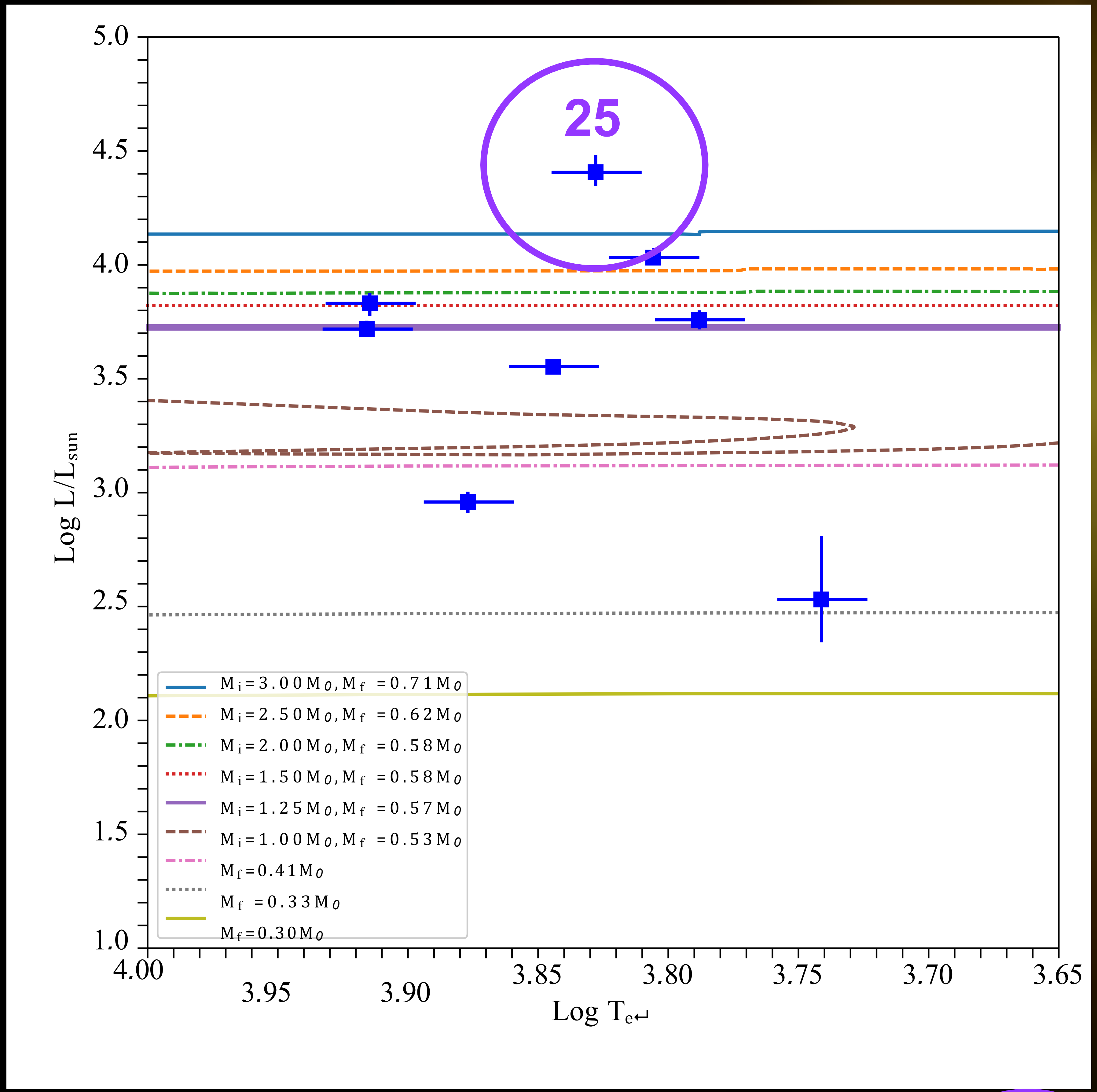
Index	Object	T_{eff}	$L/L_{\odot}$	[C/Fe]	[N/Fe]	[O/Fe]	Flag	M_{init}	chemistry
				s-process enriched stars					
1	IRAS Z02229+6208	5952 ± 250	12959	0.78 ± 0.15	1.19 ± 0.15	...	Q2	$3-3.5\ M_{\odot}$	TDU+HBB
15	IRAS 20000+3239	5478 ± 250	14342	1.7 ± 0.2	2.1 ± 0.2	...	Q2	$3-3.5\ M_{\odot}$	TDU+HBB

- **Case 3: TDU + HBB**
- **Progenitor mass of ~3 - 4 Msun**
  - Experience both TDU and HBB
  - Enhanced in C and *s*-process.
  - N is ~a factor of 10 higher than initial



Case 4: HBB
Progenitor mass of > 4 Msun

- Dominated by HBB
- N enhancement, neither C nor *s*-process

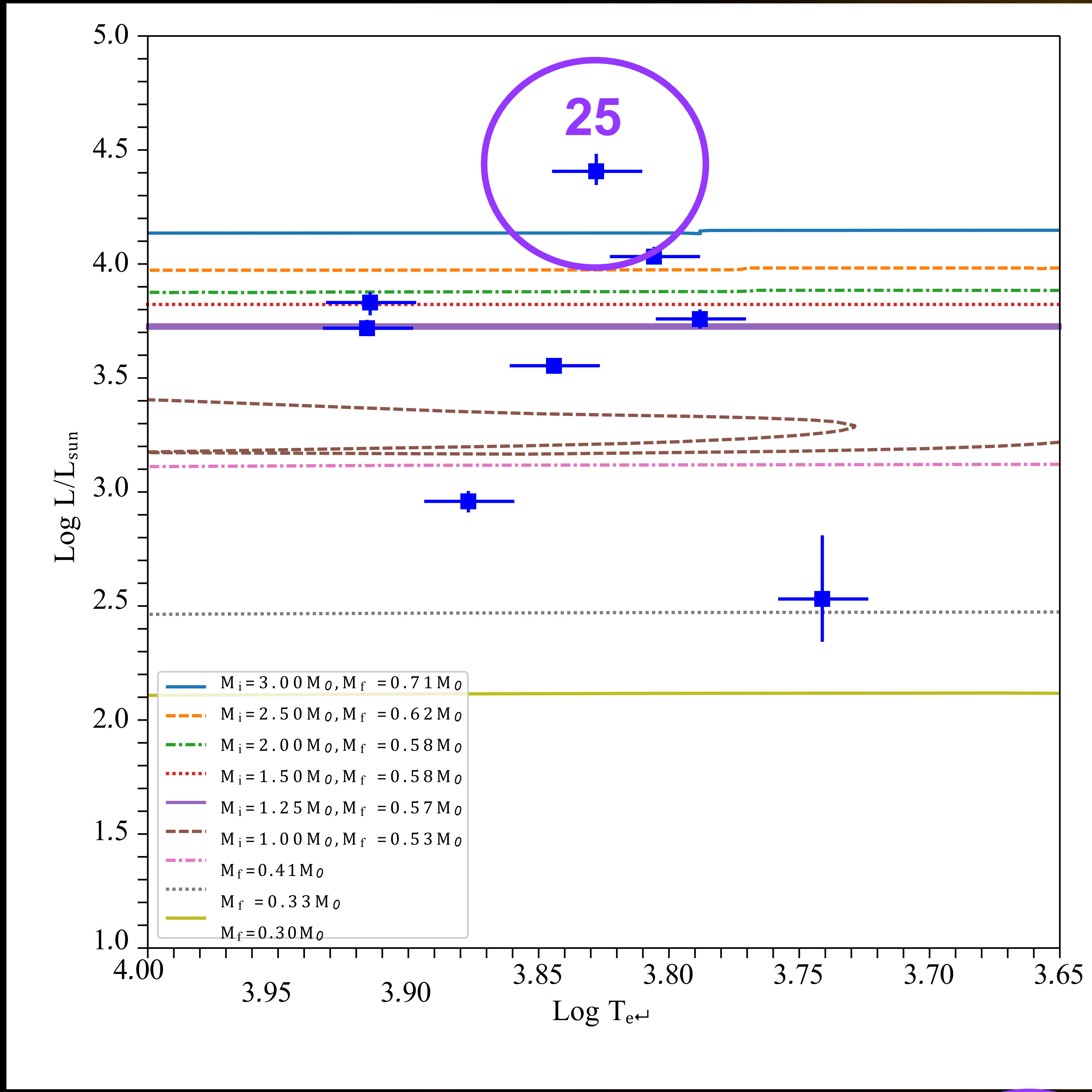


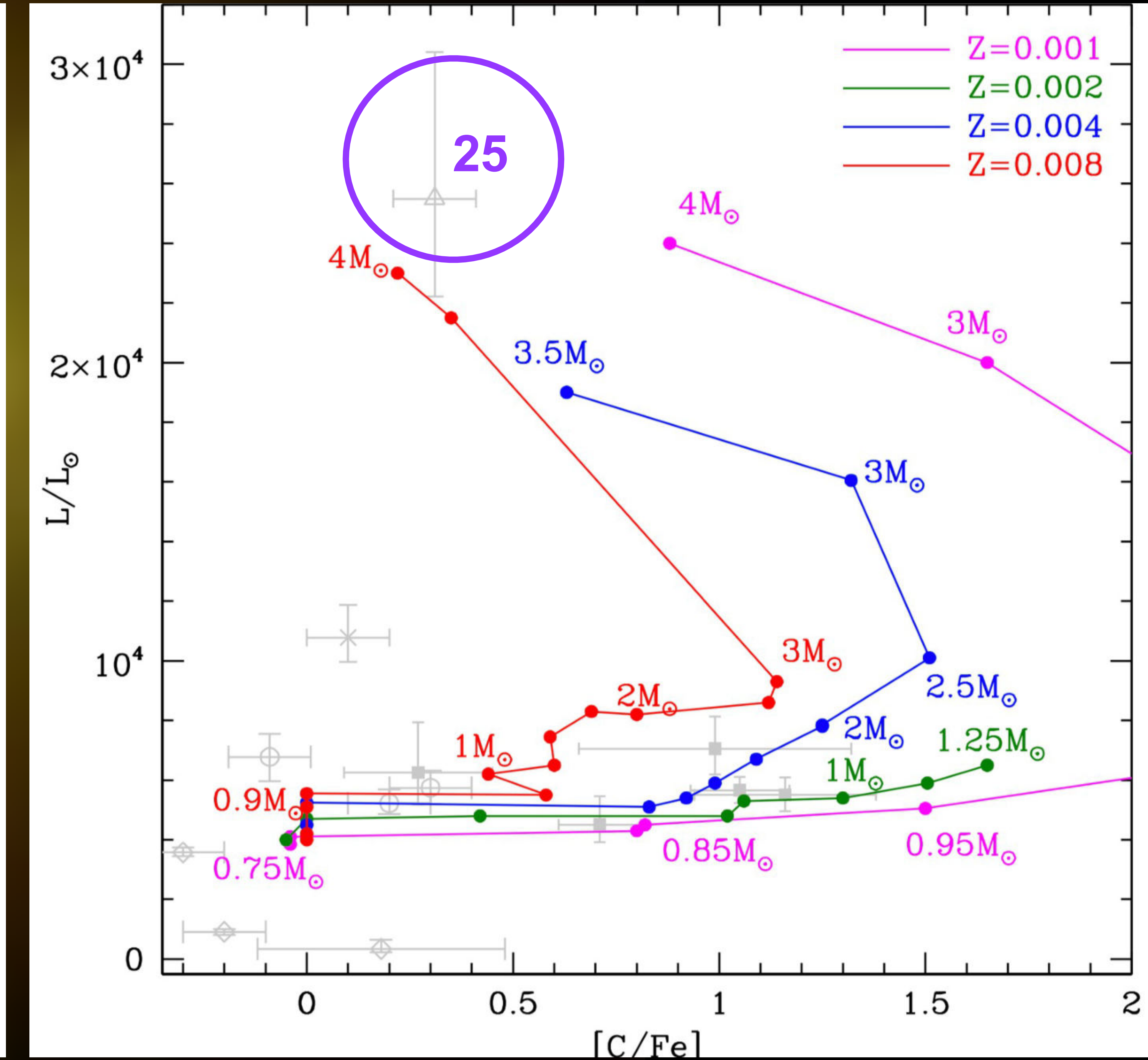
Index	Object	T_{eff}	$L/L_\odot$	[C/Fe]	[N/Fe]	[O/Fe]	Flag	M_{init}	chemistry
25	HR 6144	6728 ± 250	25491	0.3 ± 0.2	0.9 ± 0.2	0.3 ± 0.2	Q1	$4 - 5\ M_\odot$	HBB

Case 4: HBB

Progenitor mass of > 4 Msun

- Dominated by HBB
- N enhancement, neither C nor *s*-process





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Progenitor mass of > 4 Msun

- Dominated by HBB
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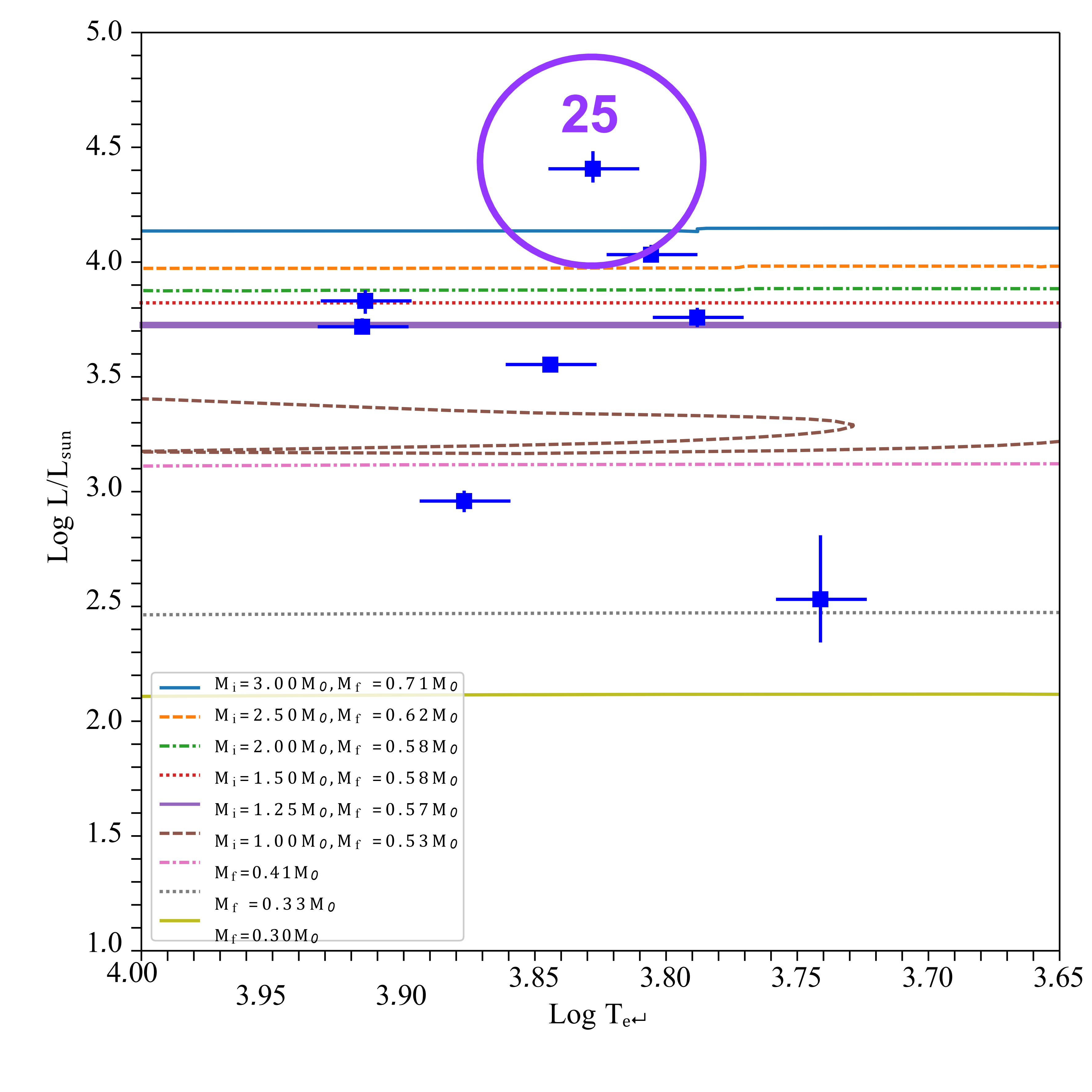

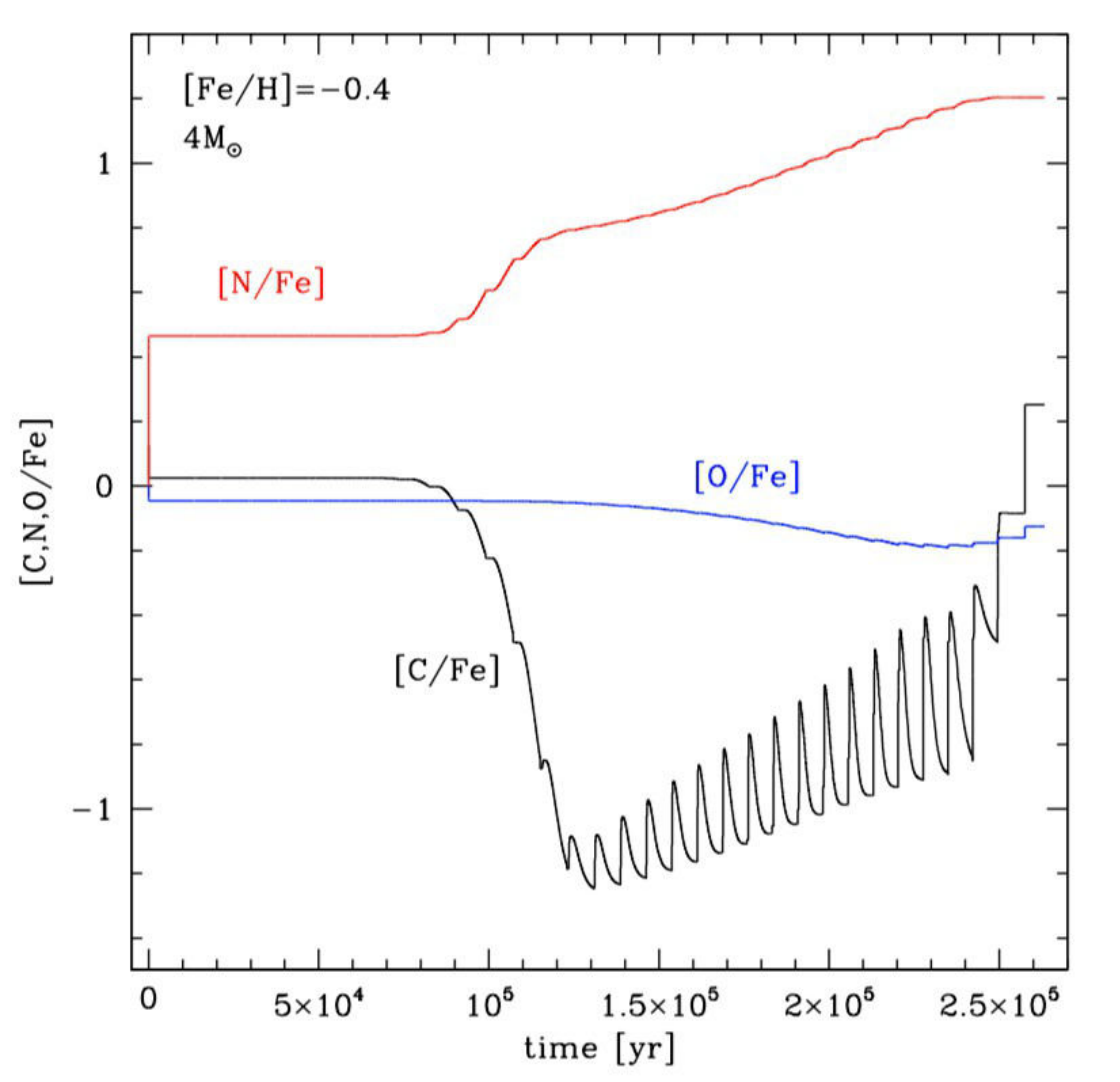

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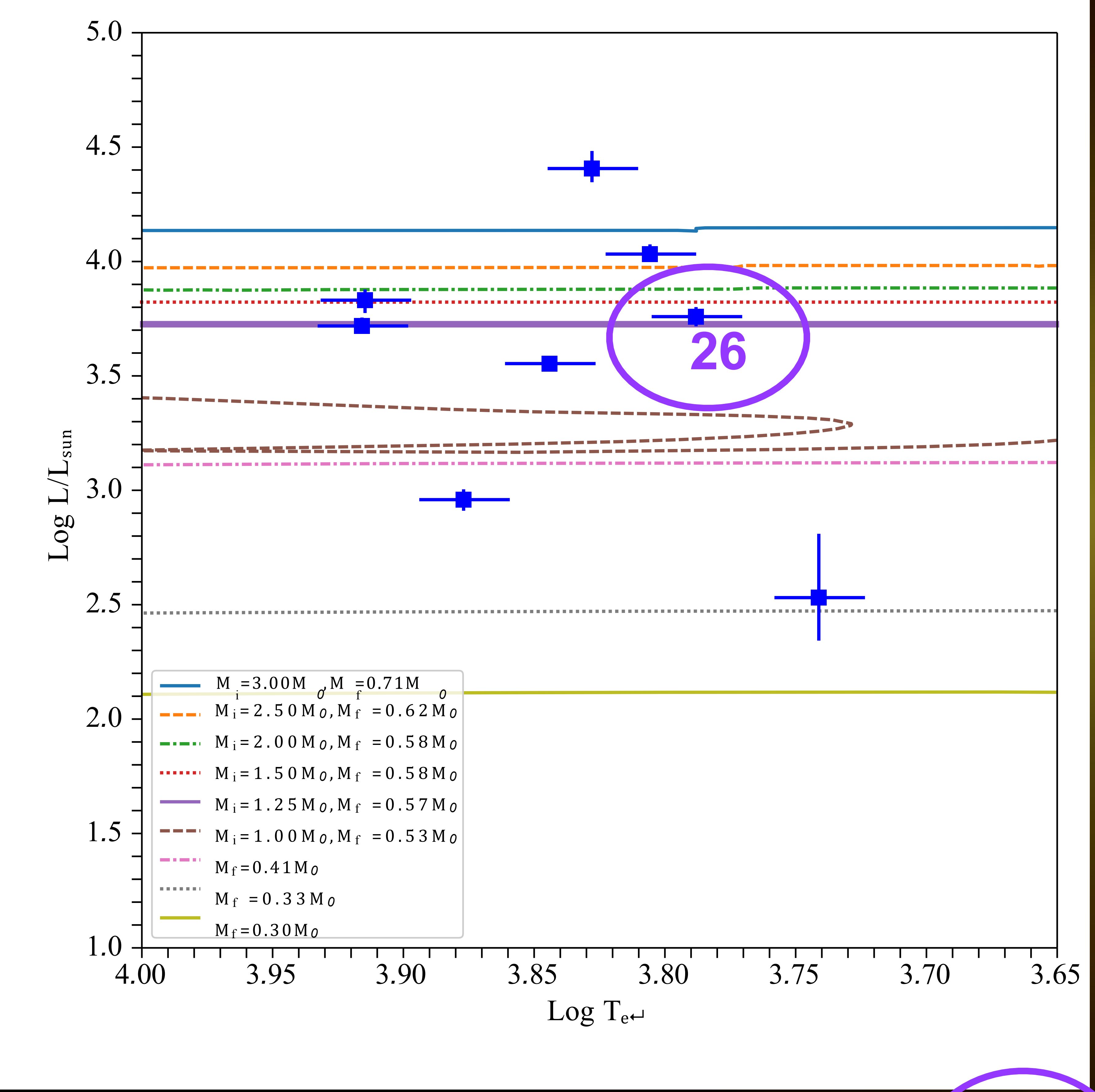
NON-STANDARD AGB EVOLUTION AND NUCLEOSYNTHESIS SCENARIOS

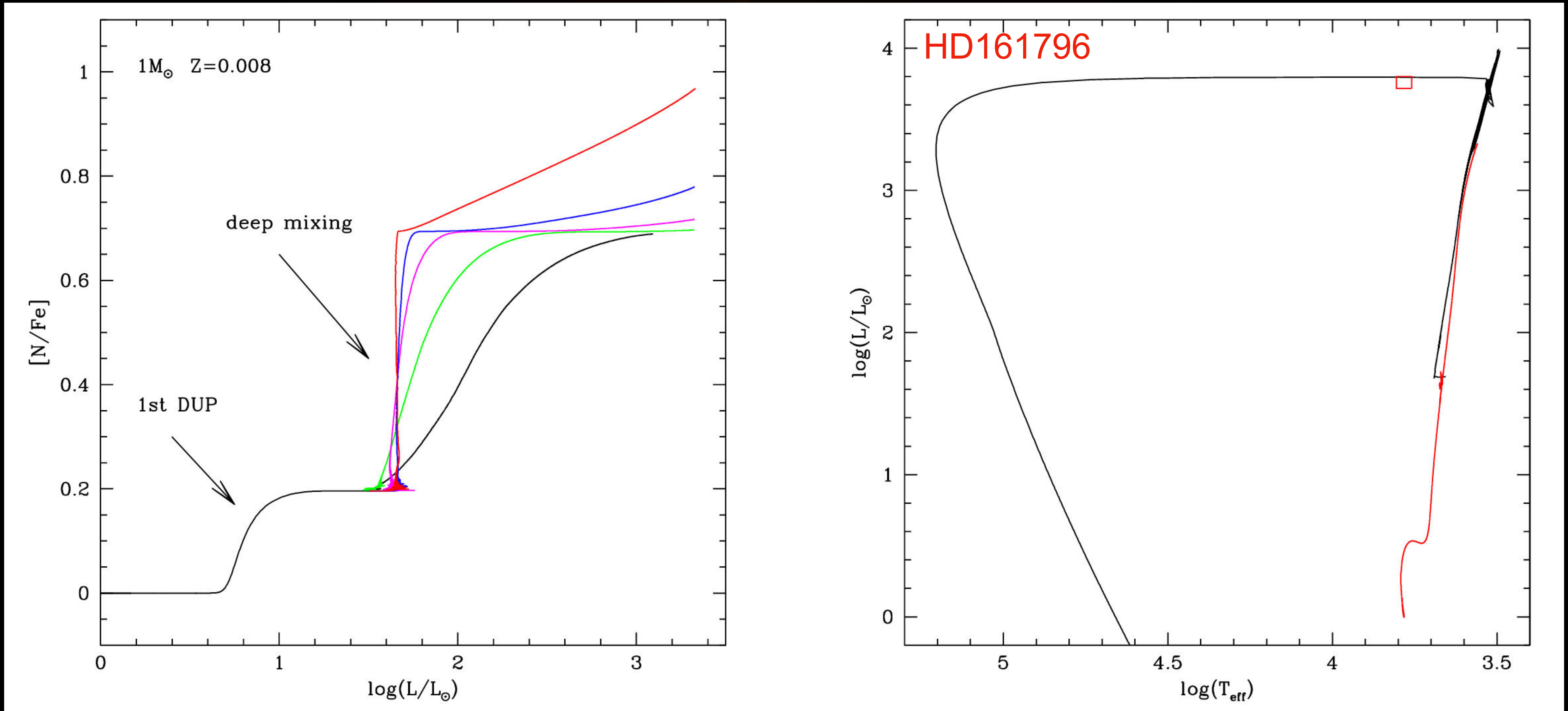
A Signature of Deep Mixing During the RGB?



- ★ No *s*-process enhancements
- ★ luminosity: 5000–6300 Lsun
- ★ Extremely large surface nitrogen, [N/Fe] = 1.1
- ★ Possibility explored: extremely deep mixing during the RGB ascending
- ★ e.g., D'Antona & Ventura 2007

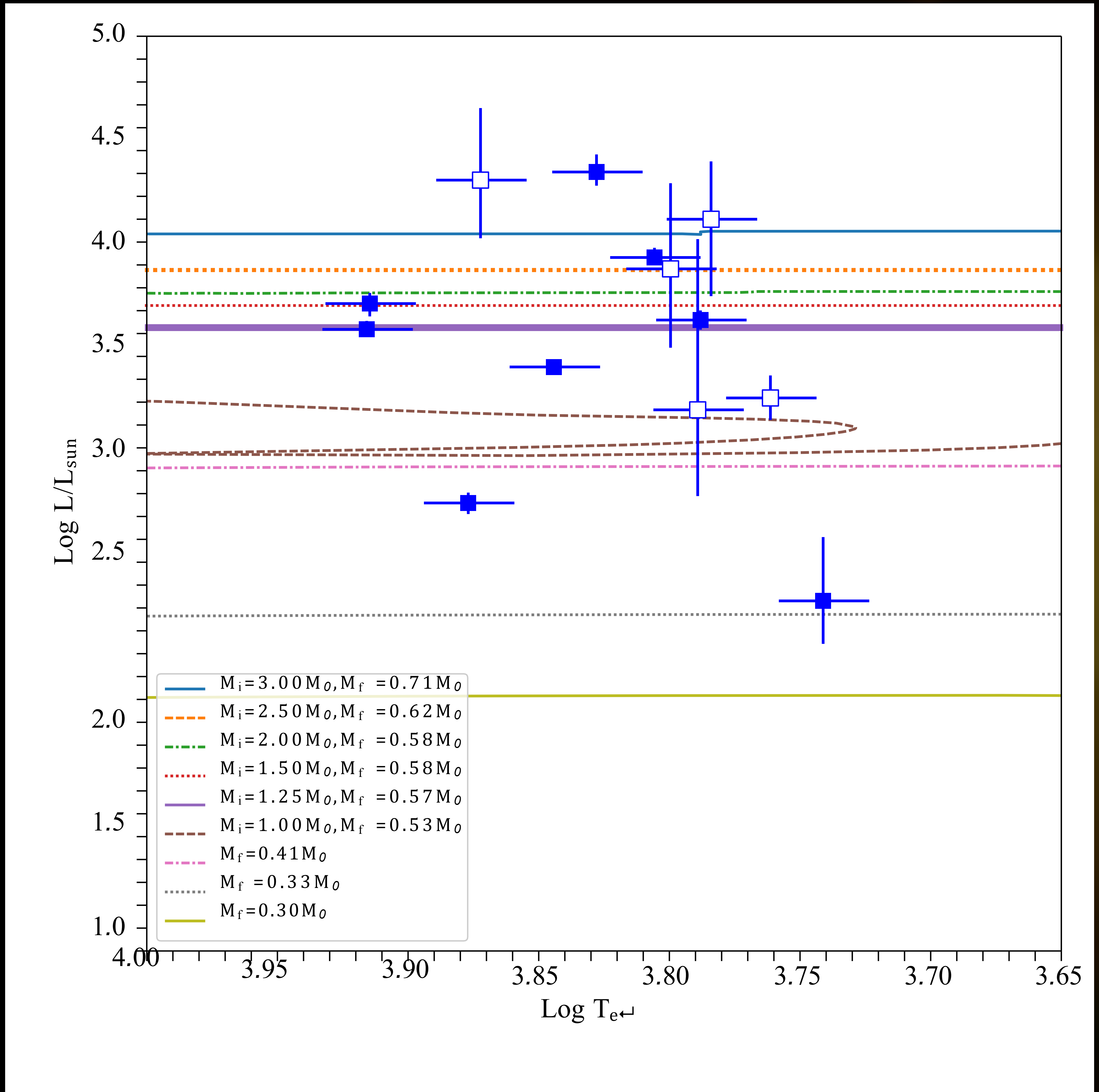
Index	Object	T_{eff}	$L/L_{\odot}$	[C/Fe]	[N/Fe]	[O/Fe]	Flag	M_{init}	chemistry
26	HD 161796	6139 ± 250	5742	0.3 ± 0.2	1.1 ± 0.2	0.4 ± 0.2	Q1	$1 - 1.2\ M_{\odot}$	FDU

A Signature of Deep Mixing During the RGB?



- ★ AGB phase with a mass in the 1 – 1.1 M⊙ range
- ★ Assuming a ~ 0.1 M⊙ mass loss during the RGB, this corresponds to age 4 – 5 Gyr Star
- ★ must have experienced one or 2 TDU events before entering the post-AGB phase (observed value [N/Fe] = 1.1, [C/Fe] = 0.3 + lack of s-process enhancement)

Stars that Failed the Third Dredge-Up



Index	Object	T_{eff}	$L/L_\odot$	[C/Fe]	[N/Fe]	[O/Fe]	Flag	M_{init}	chemistry
21	SAO 239853	7452 ± 250	23490	0.4 ± 0.15	0.6 ± 0.2	0.8 ± 0.2	Q2	$\sim 3\ M_\odot$	TDU
23	HD 112374	6393 ± 250	10777	0.1 ± 0.2	0.5 ± 0.2	0.8 ± 0.2	Q1	$2.5 - 3\ M_\odot$	TDU

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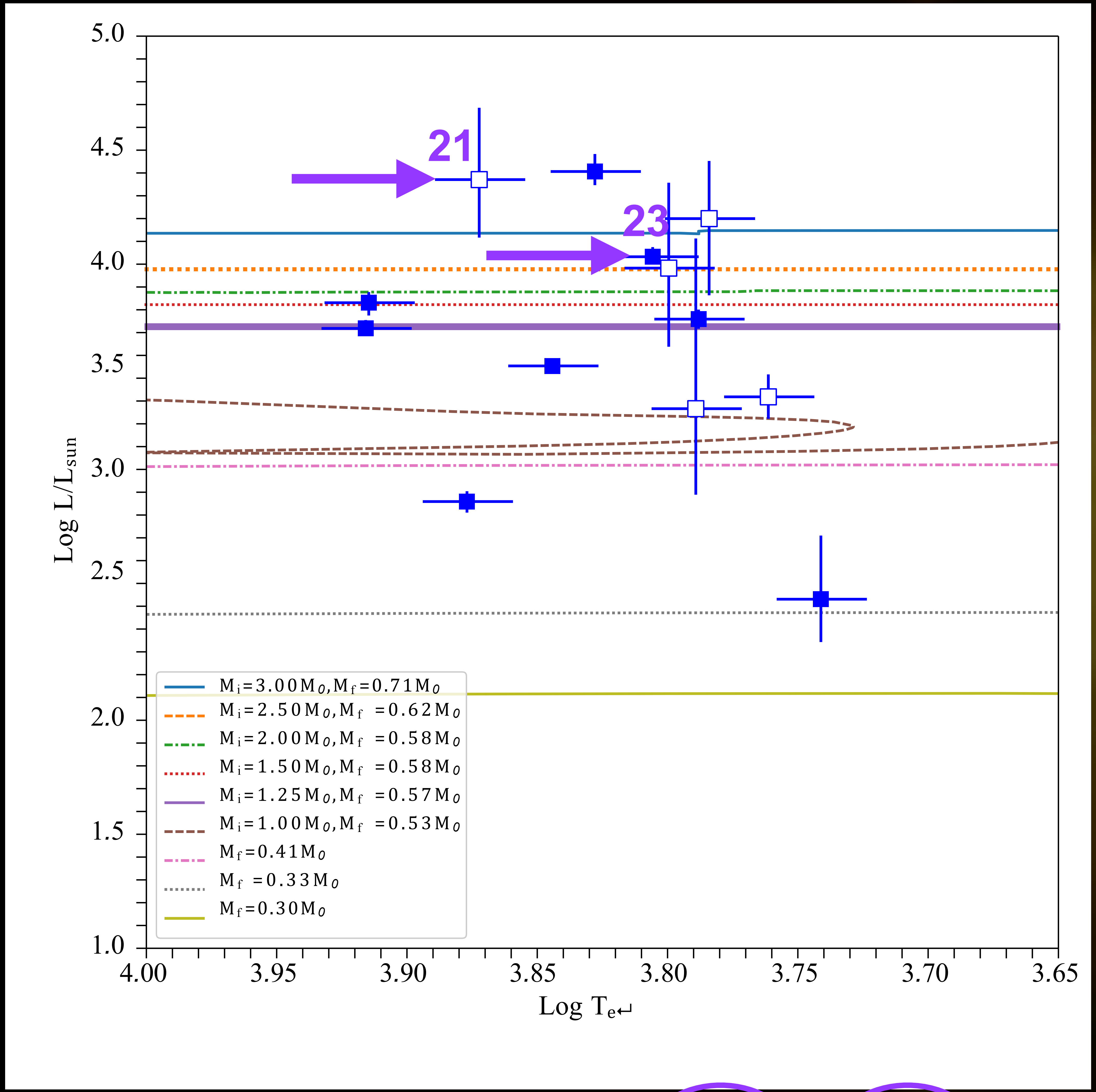

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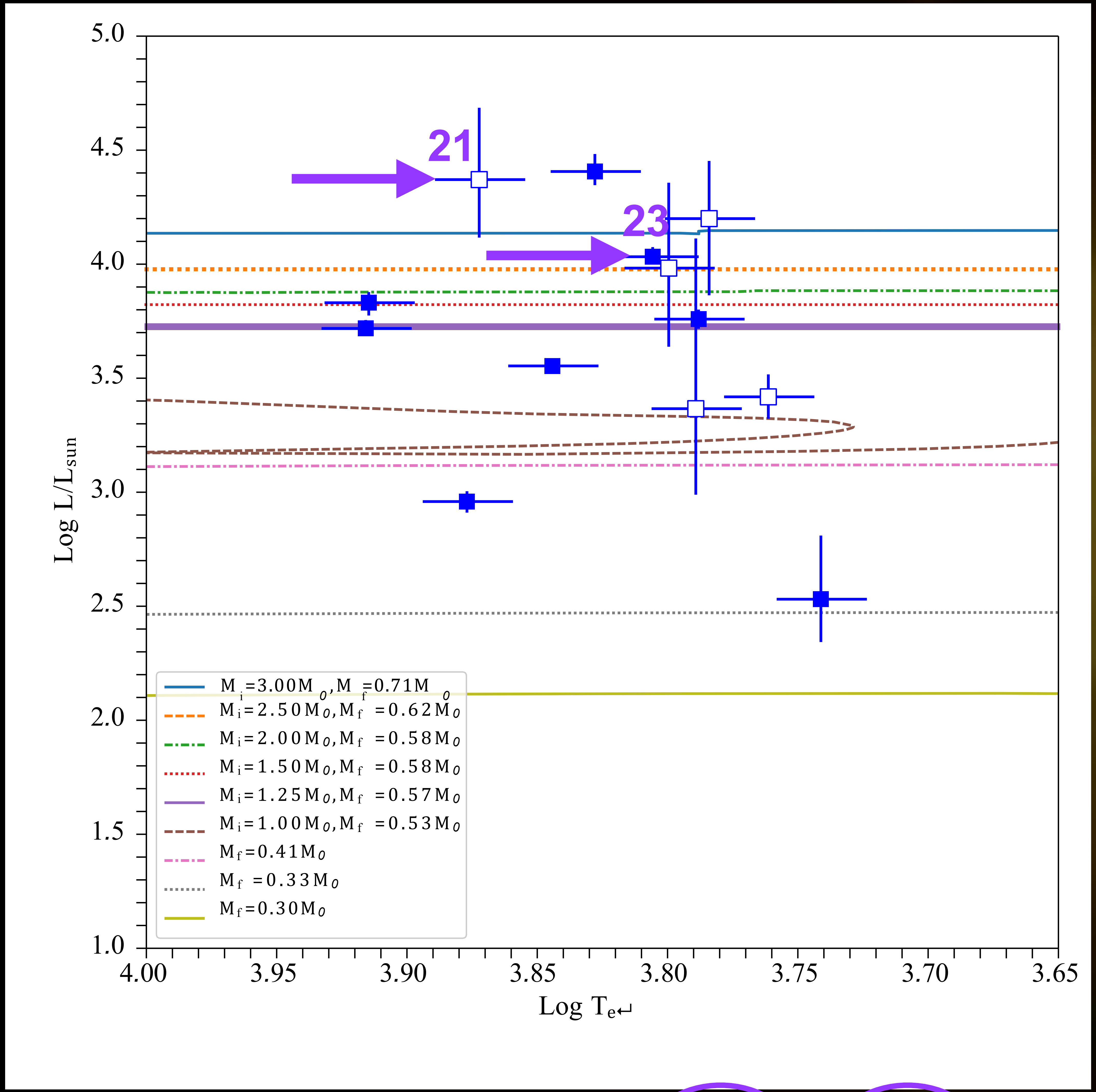

- A fast loss of the external envelope halted further growth of the core mass and increase in the surface carbon and prevented *s*- process enrichment

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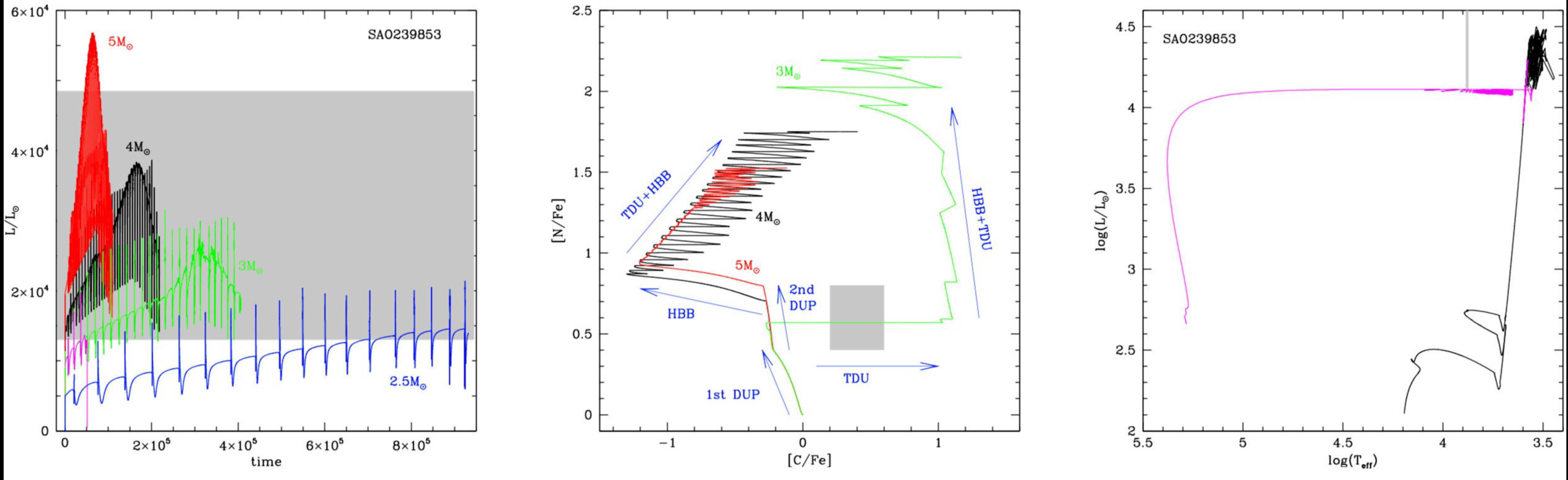
STARS THAT FAILED THE THIRD DREDGE-UP



- SAO239853: uncertain luminosity, given in the 13000 – 48500 L⊙ range.
- The 3 Msun model star evolves to surface C and N abundances consistent with those observed during the first part of the AGB phase, after the star experienced a couple of TDU events
- We artificially removed the envelope of the stars from this point on

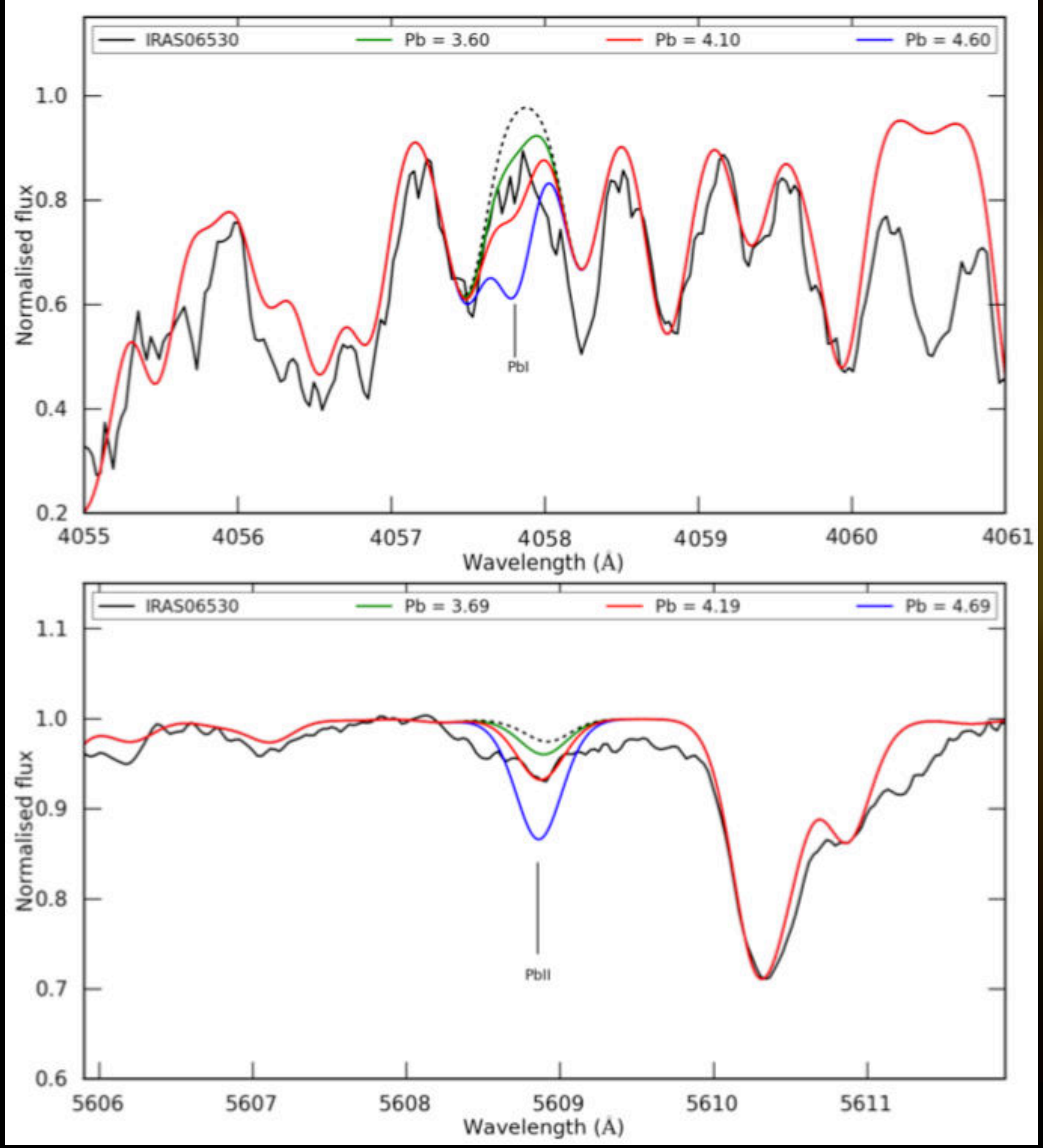
Post-AGB stars are exquisite tools to reconstruct the evolution of the stars through the post-MS phases.

- **~ 40%** of the single post-AGB stars in the sample **descend from 1 − 3 M⊙ progenitors**
- **5 sources are the progeny of low-mass stars,** that started the AGB phase with mass below ~ 1 M⊙
- **The three brightest stars,** whose surface chemical composition shows up the signature of proton-capture processing, are identified as the youngest stars in the sample, **descending from 3 − 4 M⊙ progenitors** that experienced both third dredge-up and hot bottom burning
- **A few low luminosity sources are tentatively identified as the progeny of low- mass (~ 0.5 − 0.7 M⊙),** post core helium burning stars, which after a short expansion phase lost the entire envelope and failed to reach the AGB
- **Surface carbon + luminosity** -> best indicator of the past history and nature of their progenitors

Complexities in Single Star AGB Nucleosynthesis

- ⋆ Under-abundance of lead (Pb)
  De Smedt et al., 2014, 2015; Kamath et al., 2021
  ***s*-process nucleosynthesis**

LEAD (Pb): A TRACER OF S-PROCESS AND I-PROCESS IN AGB STARS



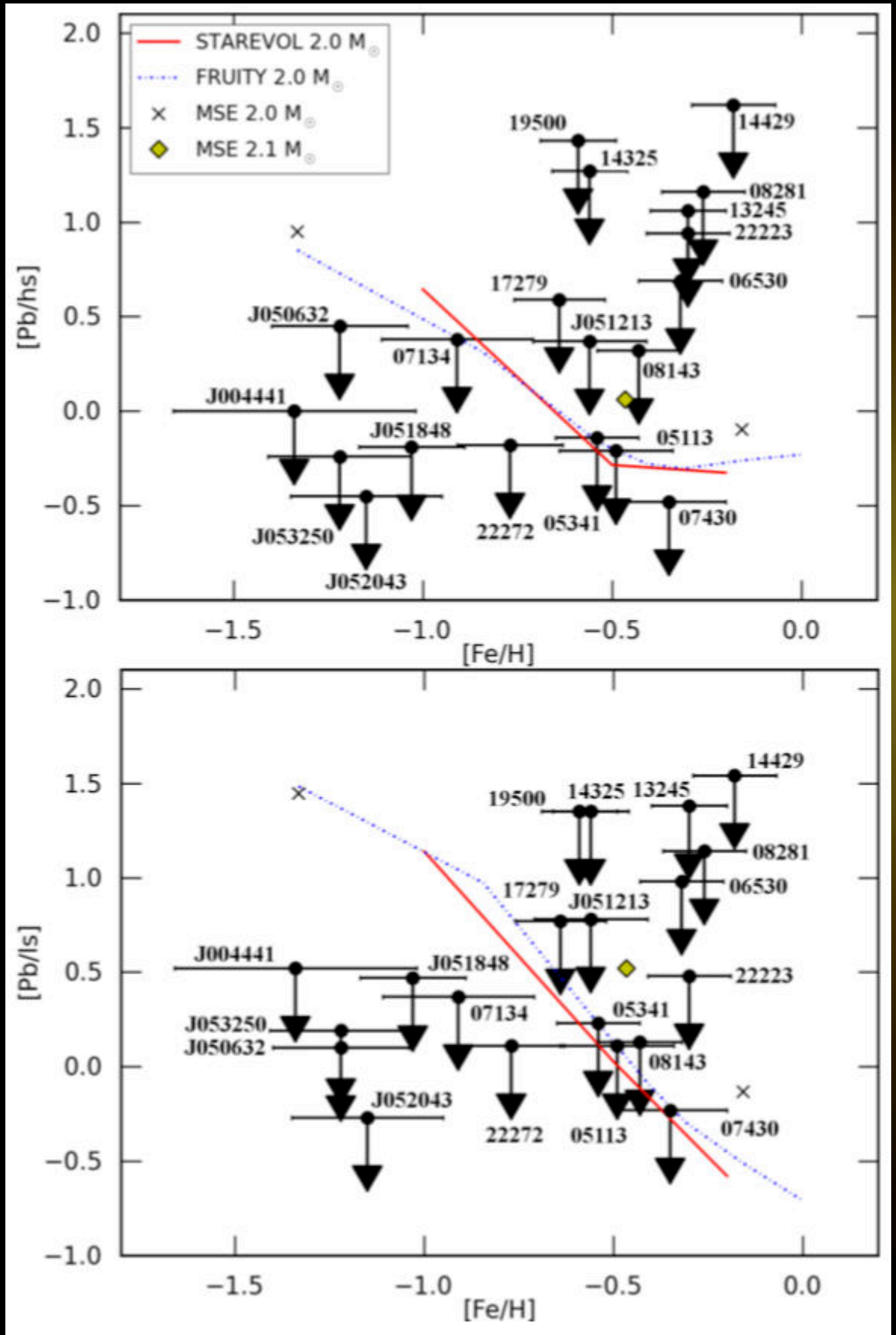
Strong component

Pb

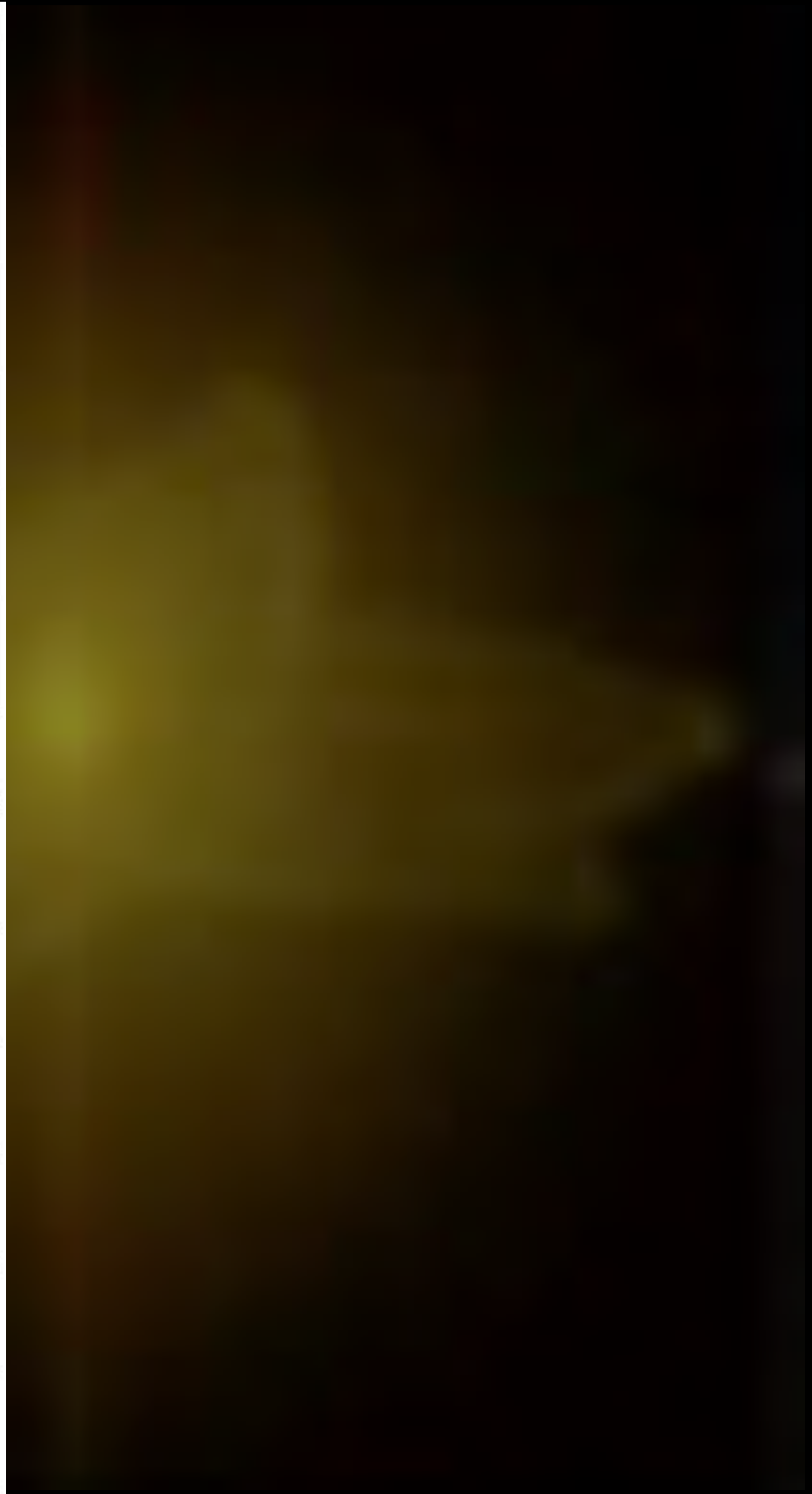
τ ≈ 7.0 mbarn−1

Low-mass, Low-metallicity AGBs

LEAD (PB): A TRACER OF S-PROCESS AND I-PROCESS IN AGB STARS



De Smedt et al., 2016



Kamath & Van Winckel 2021

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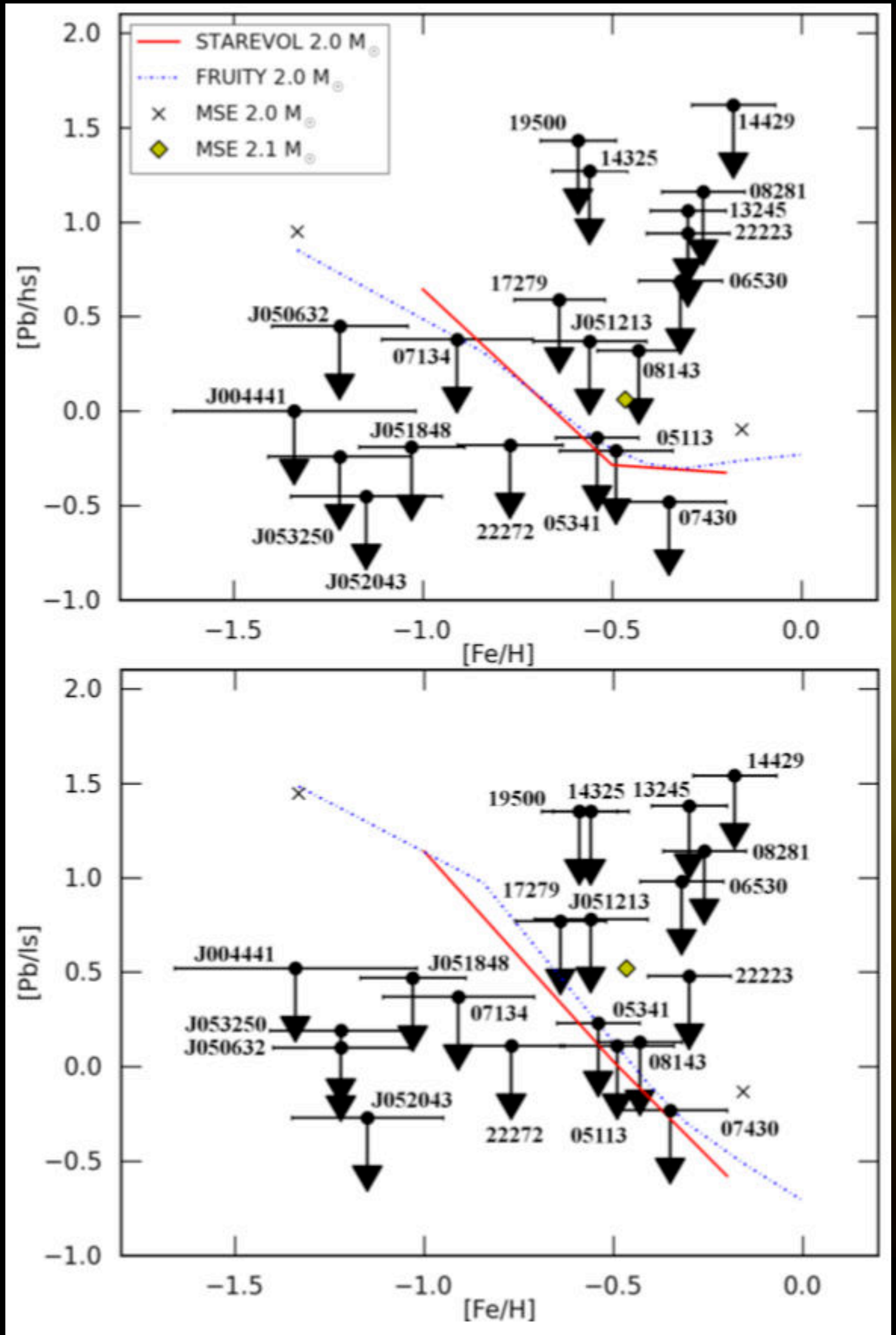

De Smedt et al., 2016

Discrepancy between the observed and predicted Pb over-abundances in single, low-metallicity ([Fe/H]<– 0.7 dex) post-AGBs

Kamath & Van Winckel 2021

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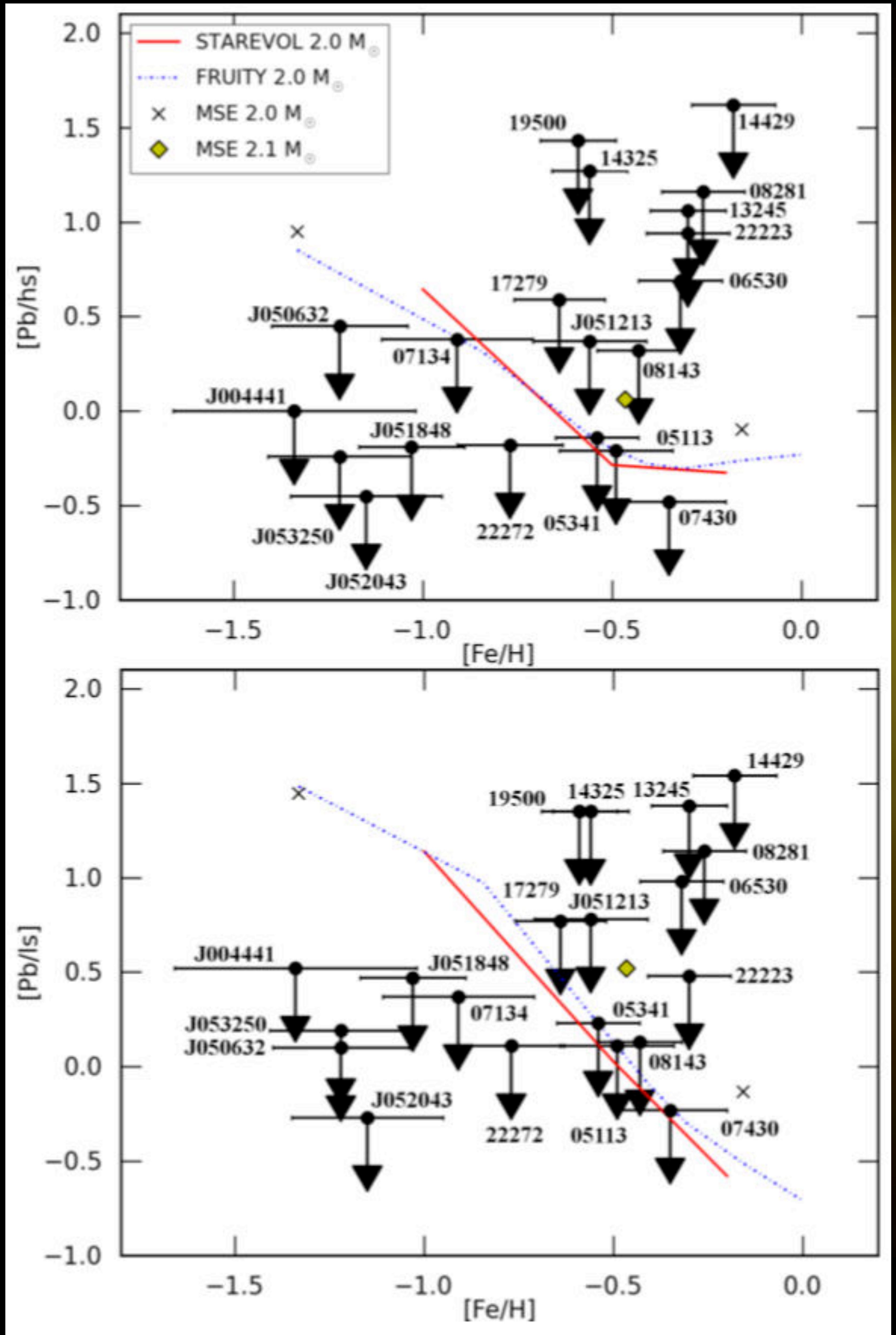

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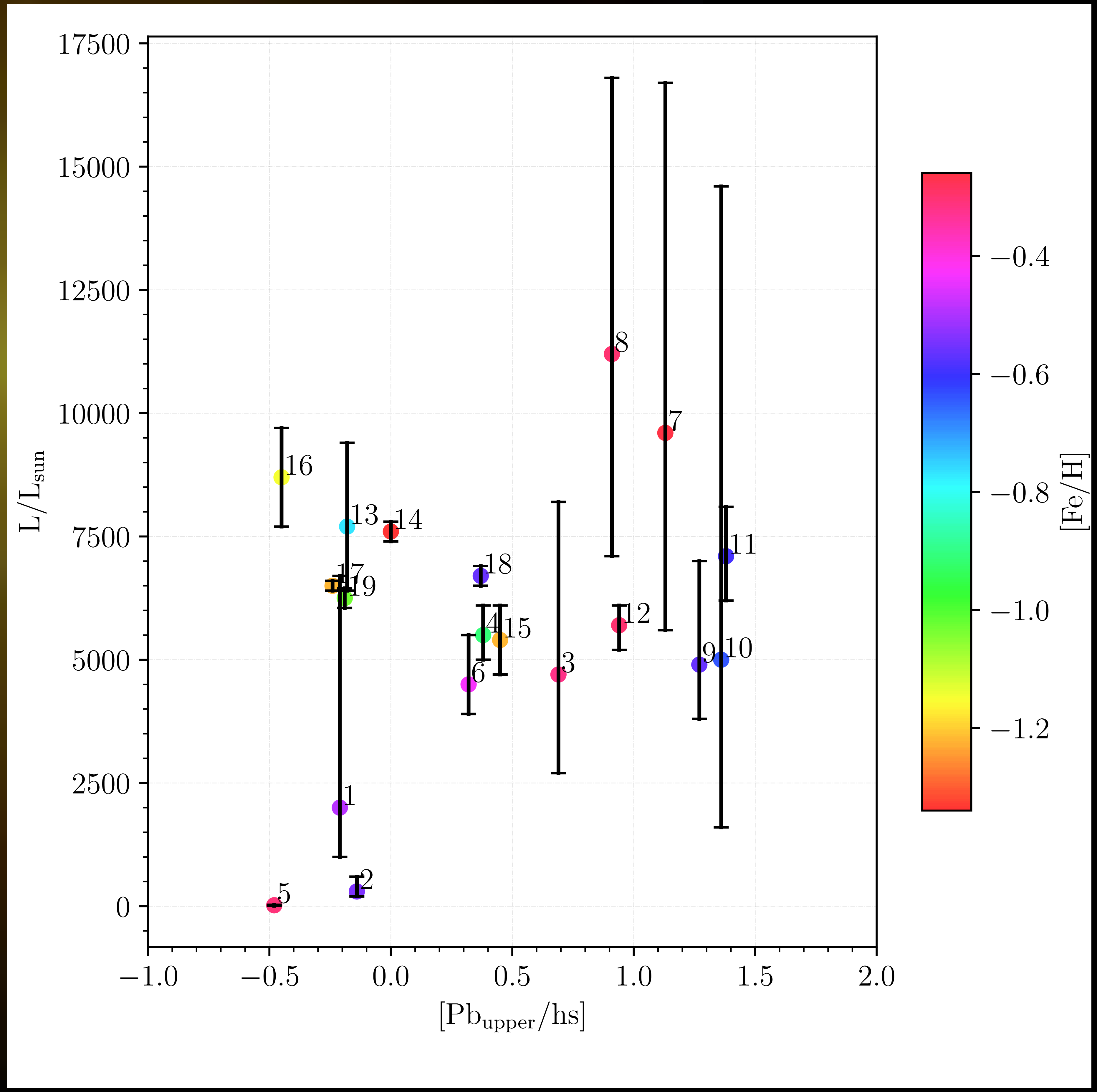


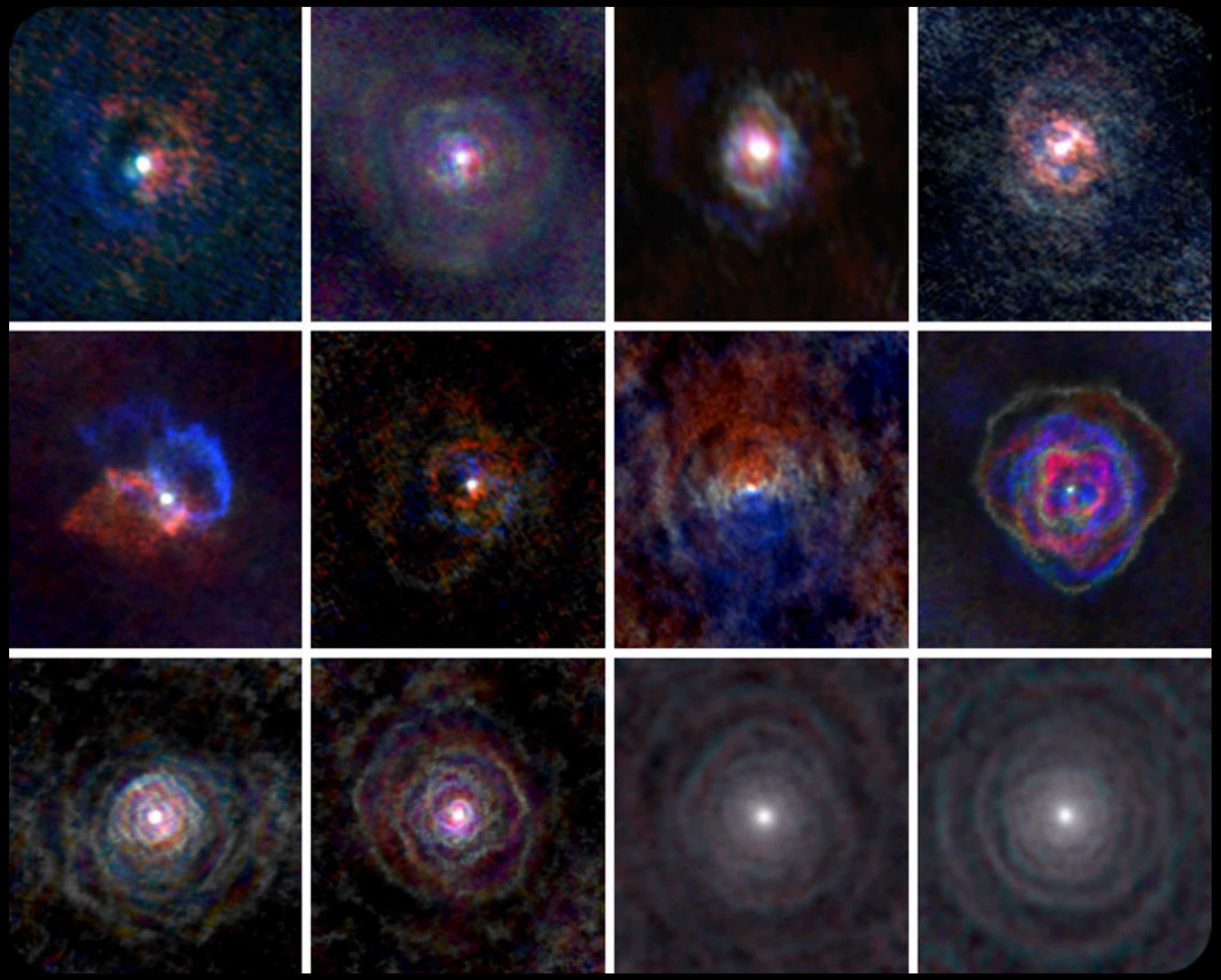
Kamath & Van Winckel 2021

The Effect of Binarity on Element Production

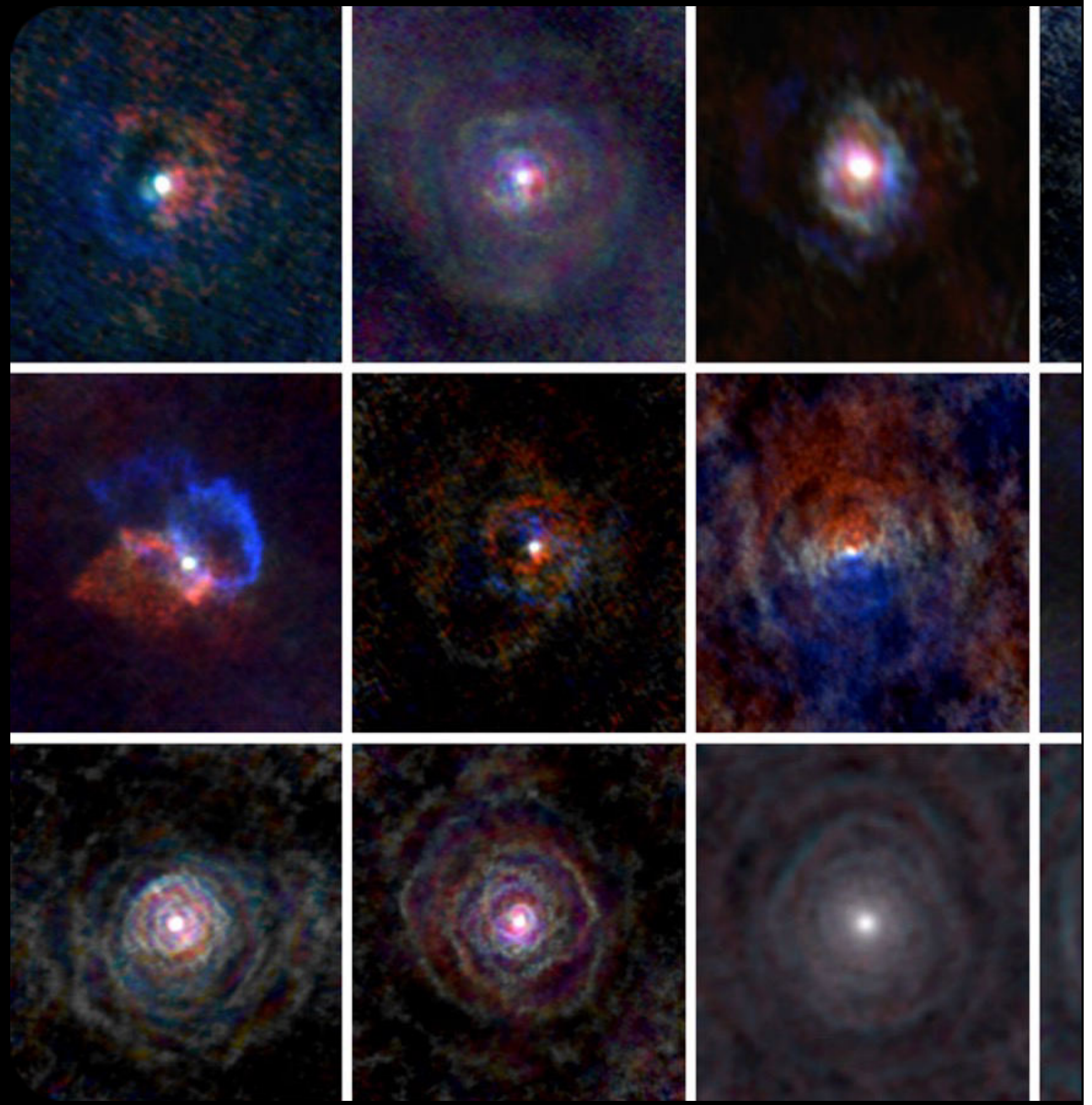
35

Breaking Symmetry

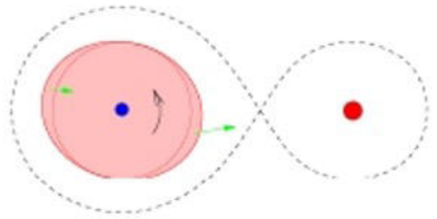
79.90



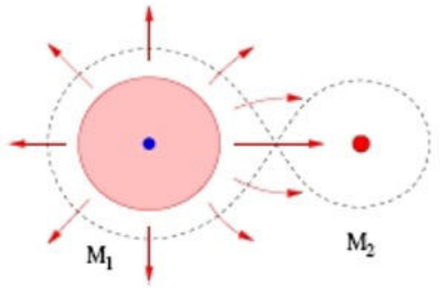
35 Br 79.90 eaking Symmetry



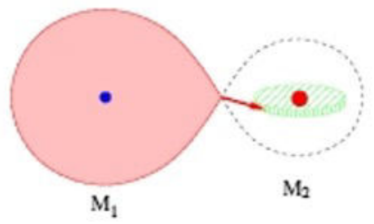
stars in binary systems can interact in various ways:



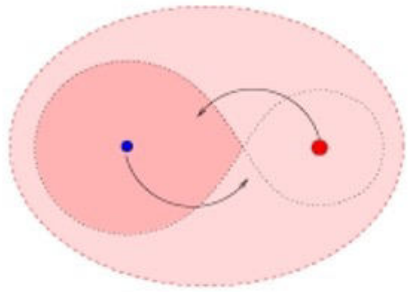
tidal interaction



wind accretion & tidally enhanced winds

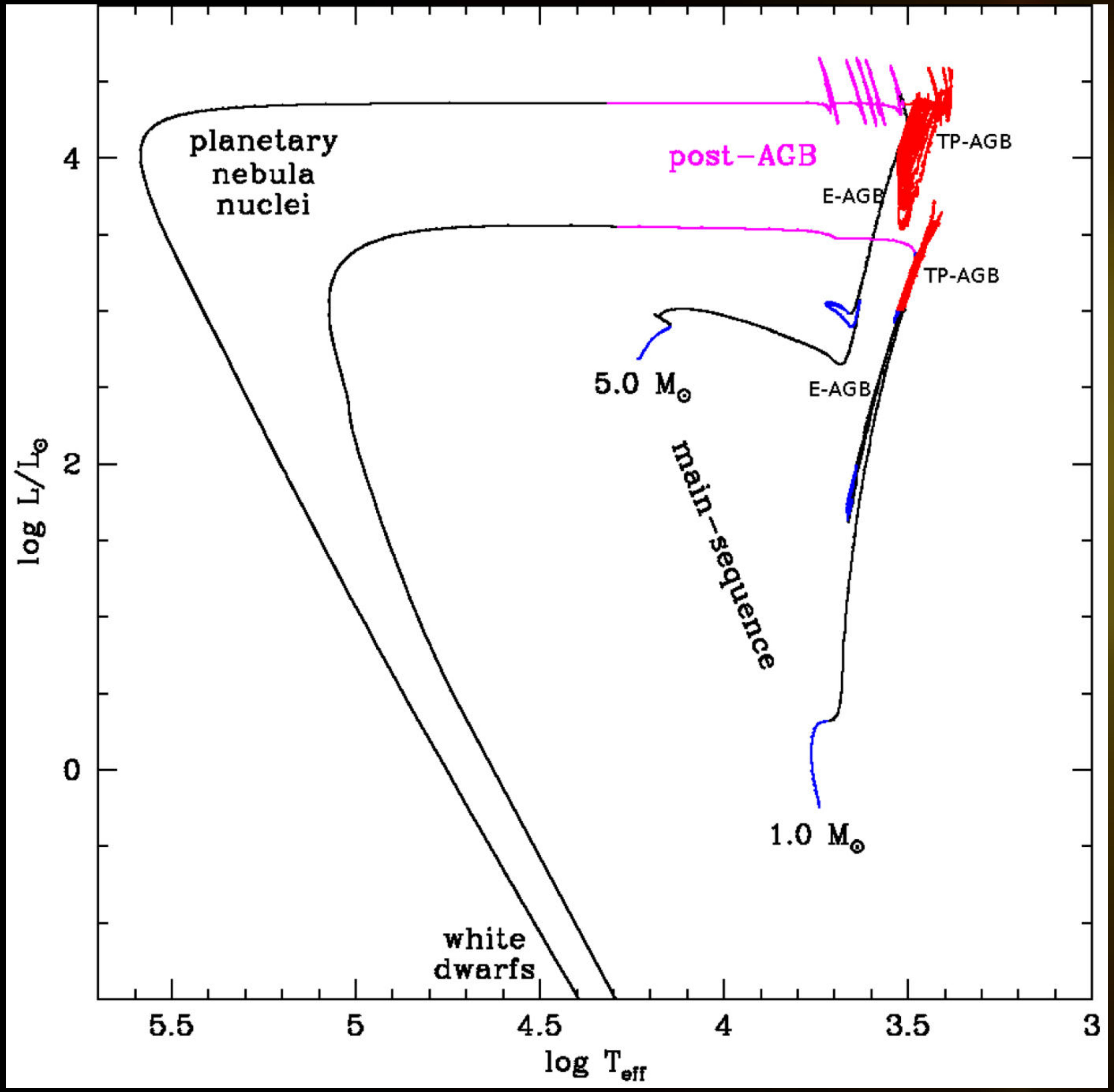


Roche-lobe overflow



common envelope evolution

The Effect of Binarity:



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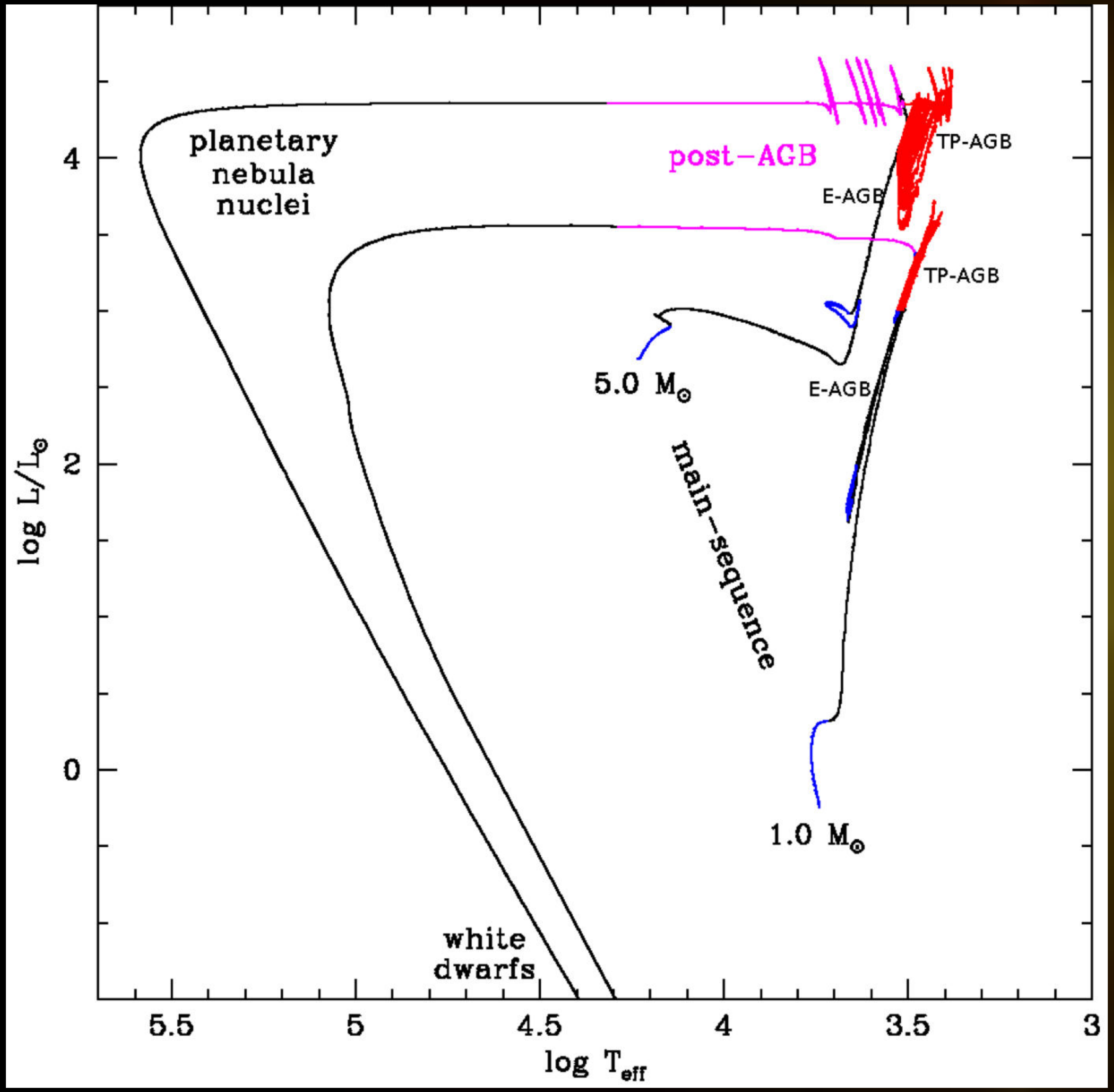

RocheLobe Filling on the Giant Branches

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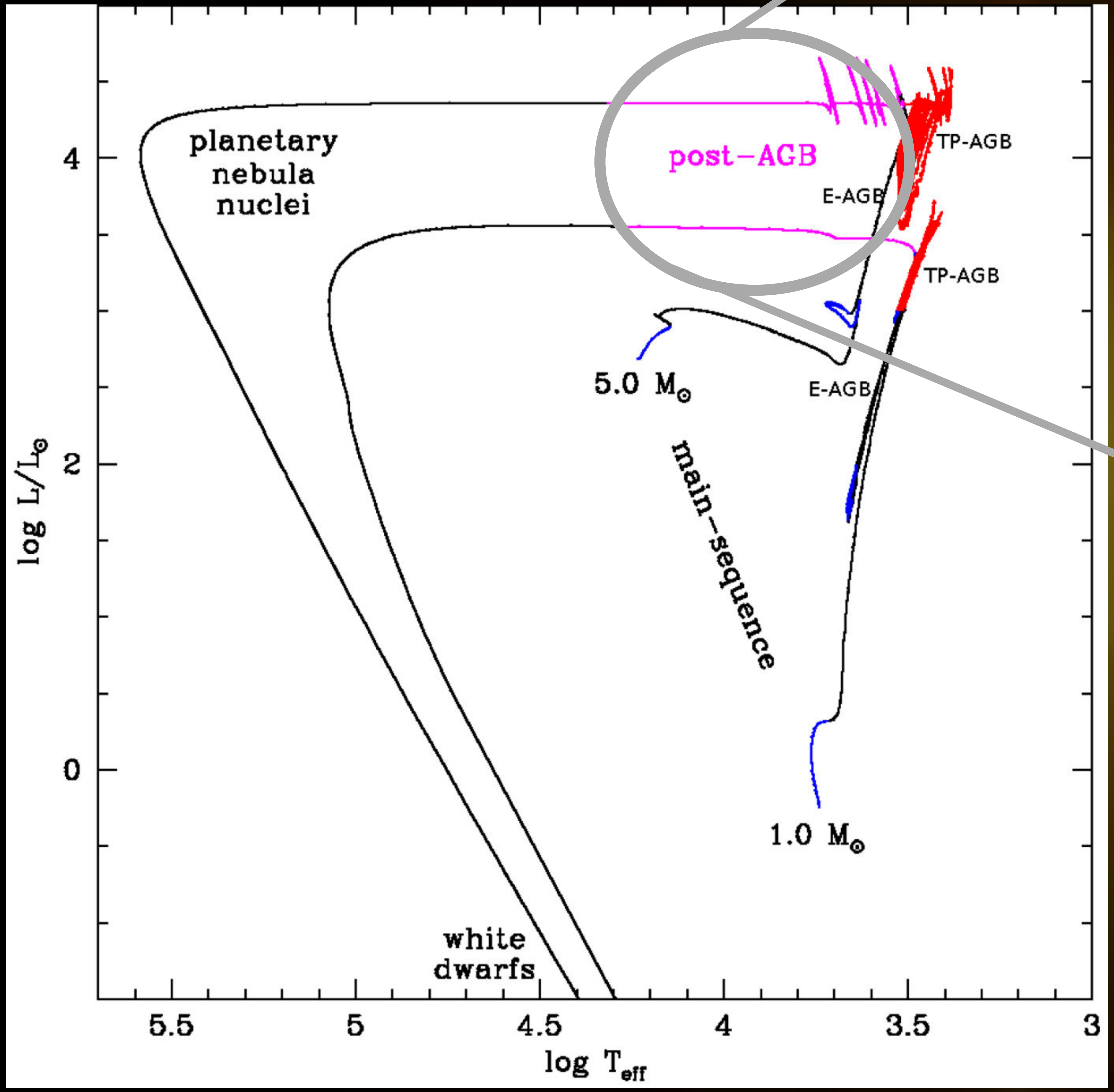
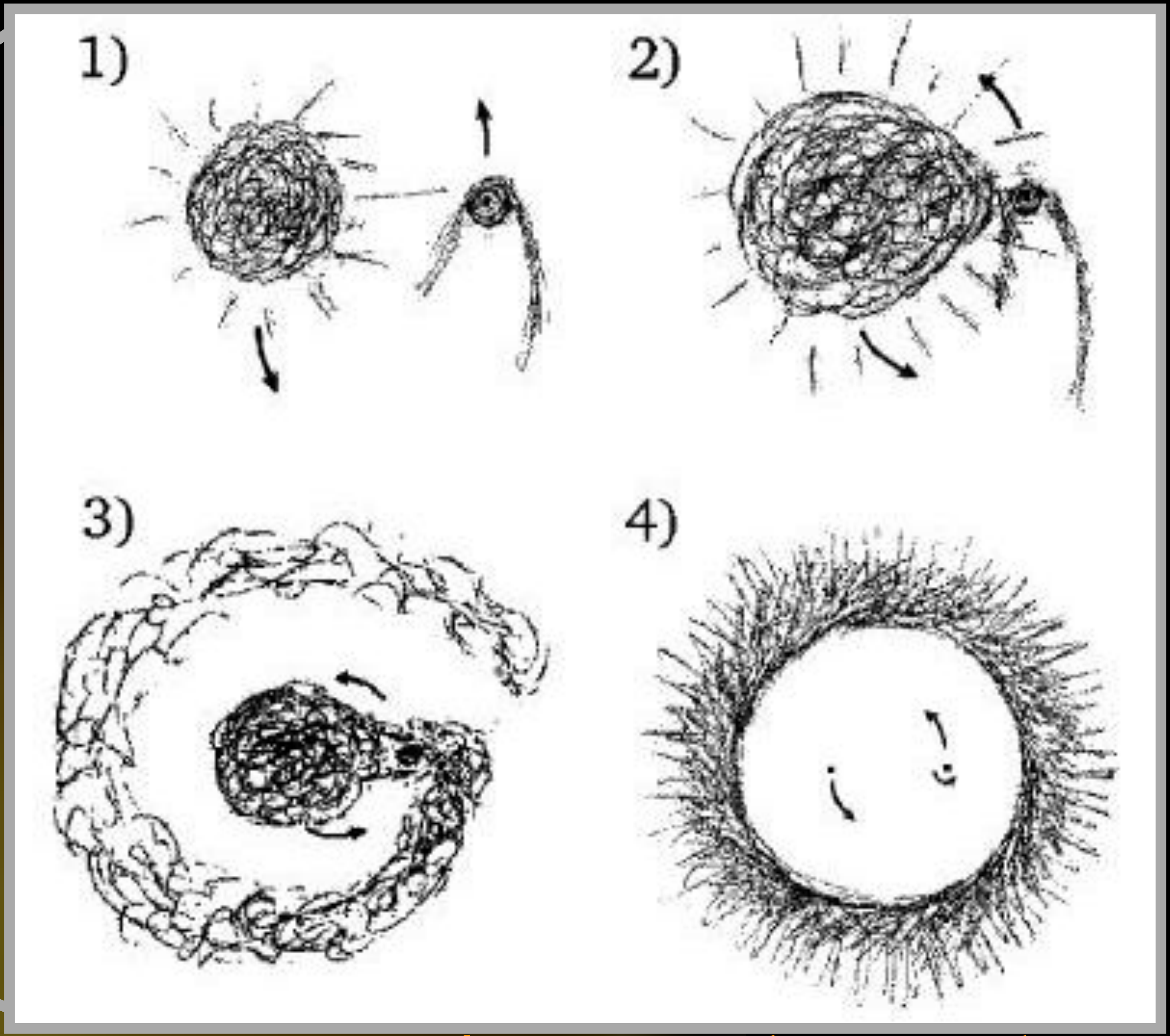


RocheLobe Filling on the Giant Branches



Formation of a circumbinary disc

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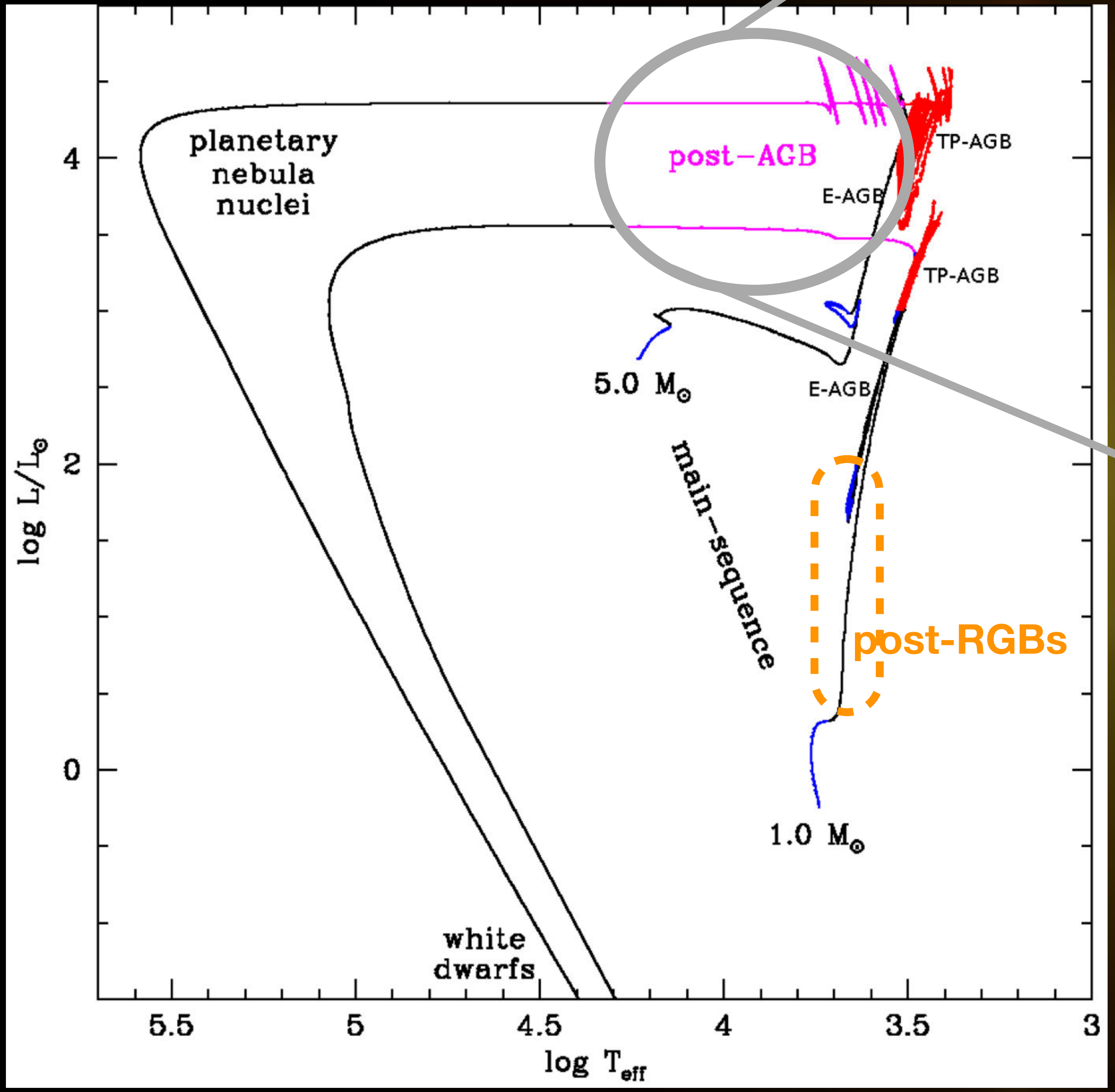

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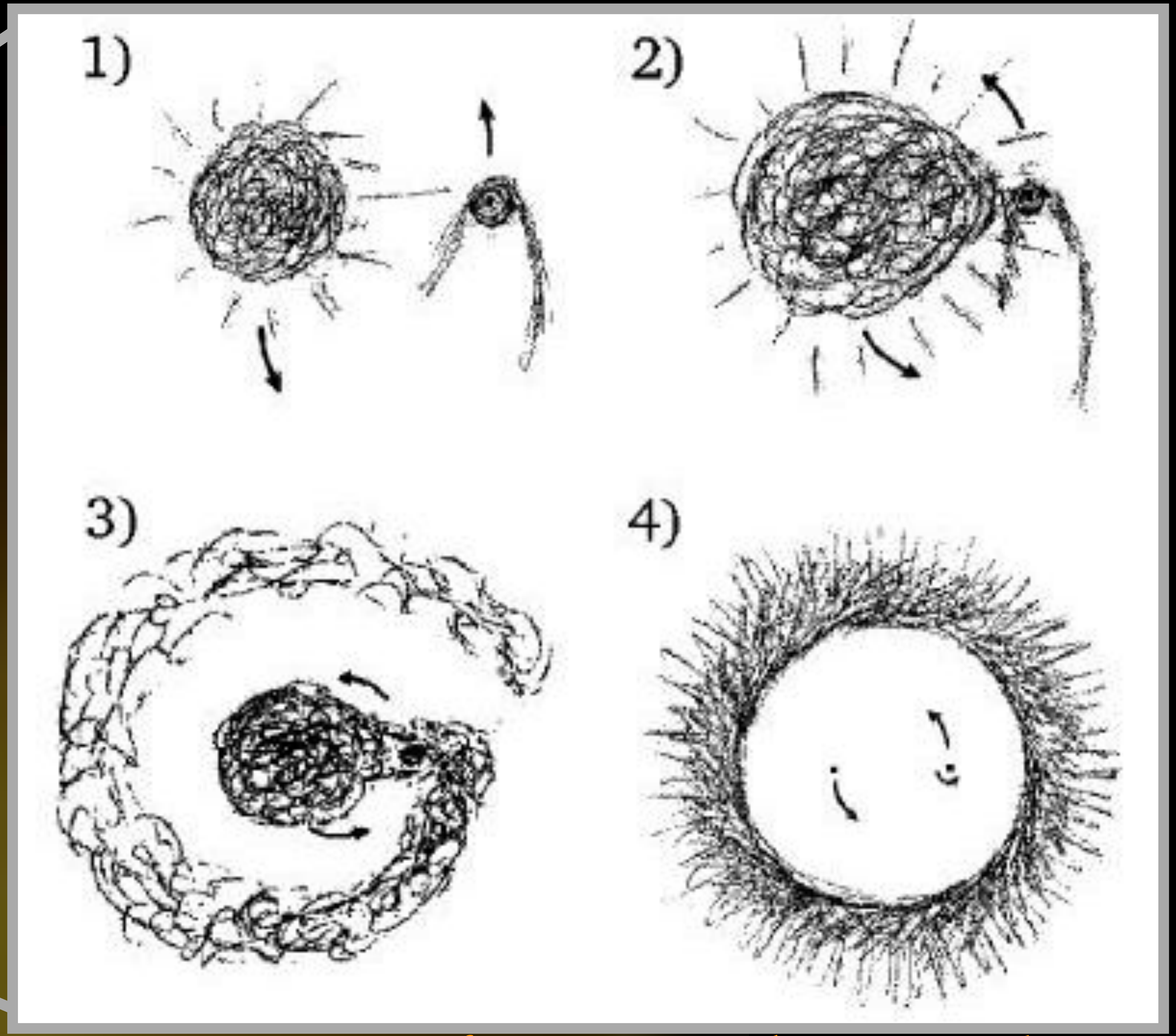

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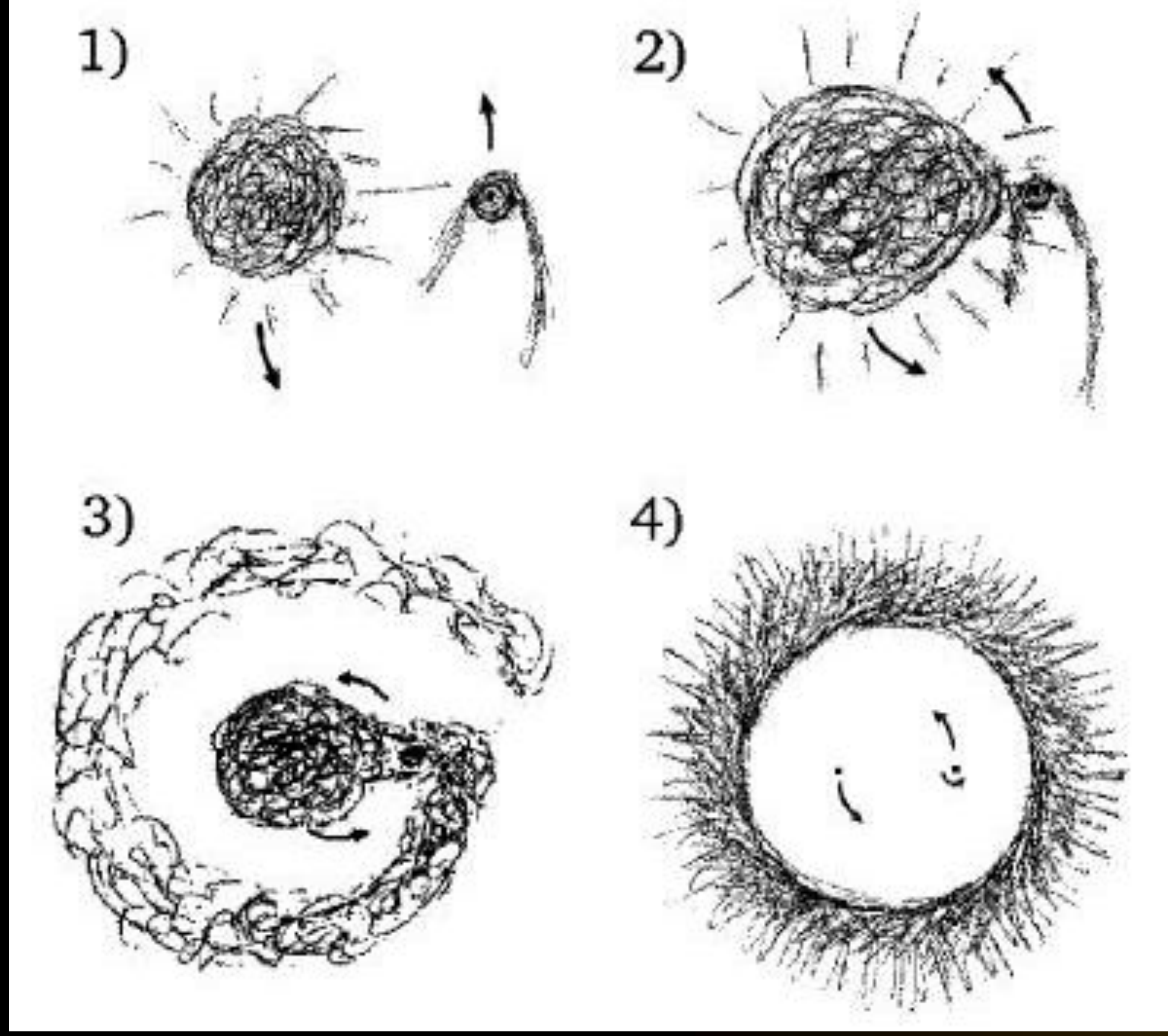
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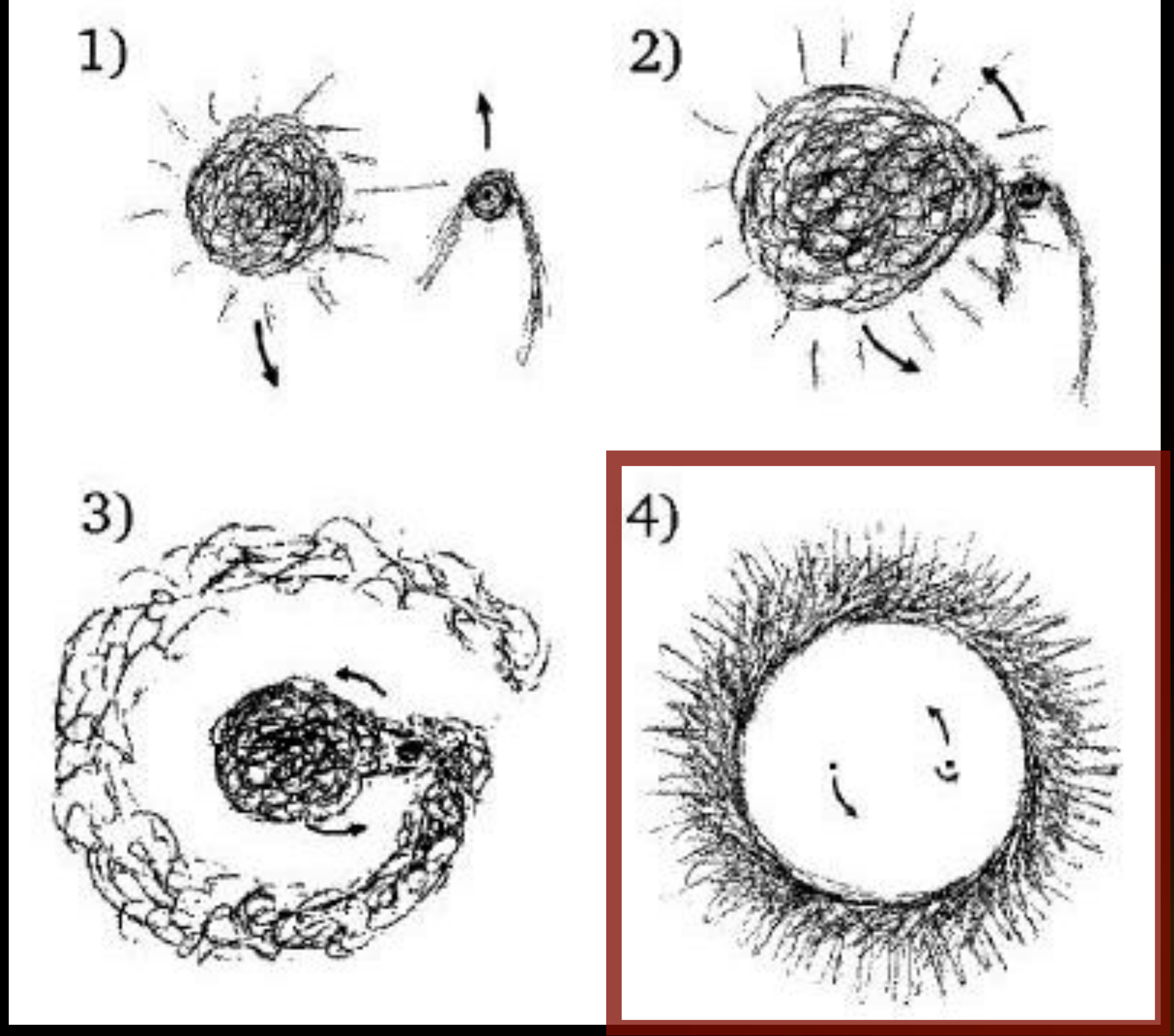
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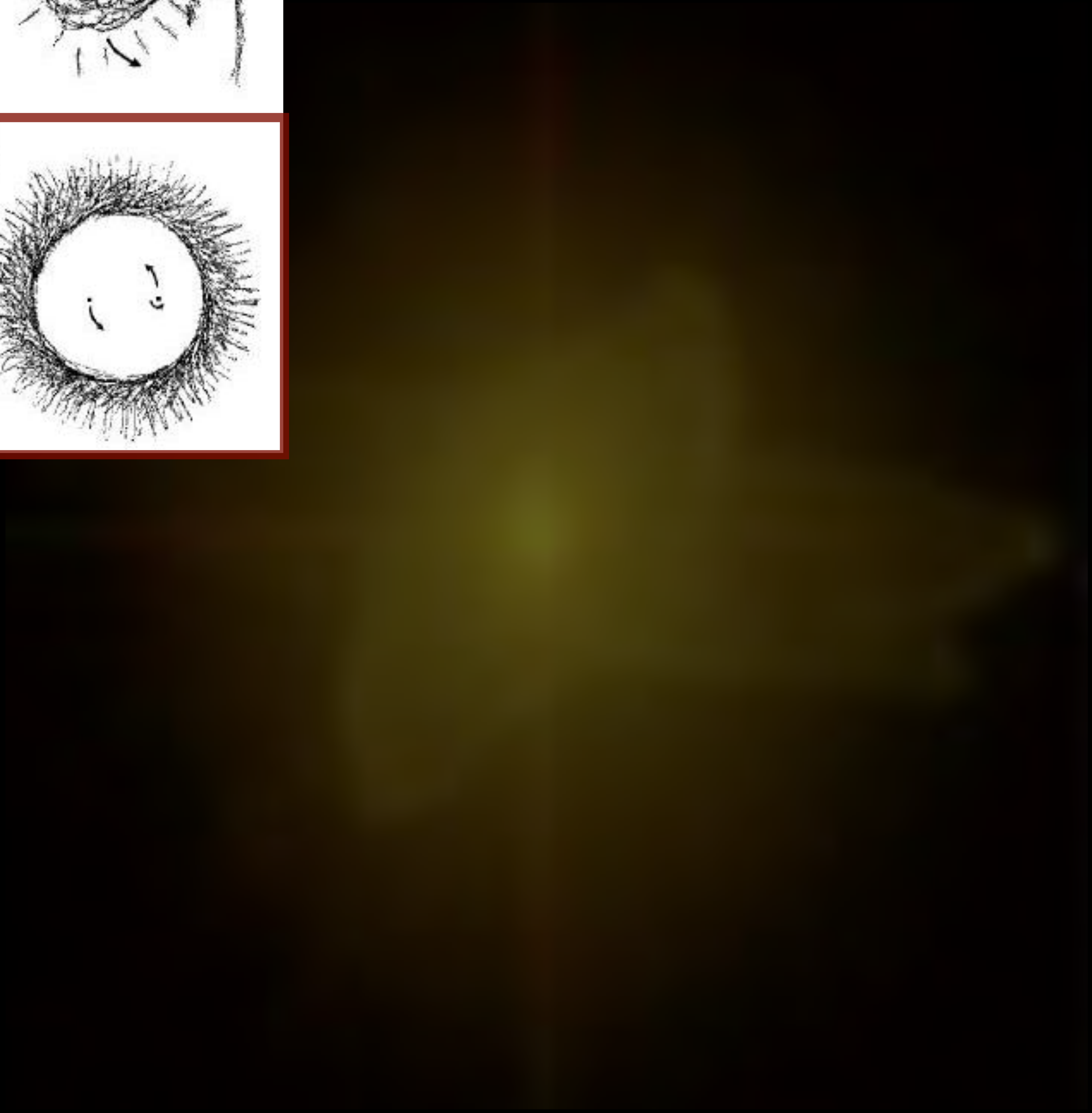
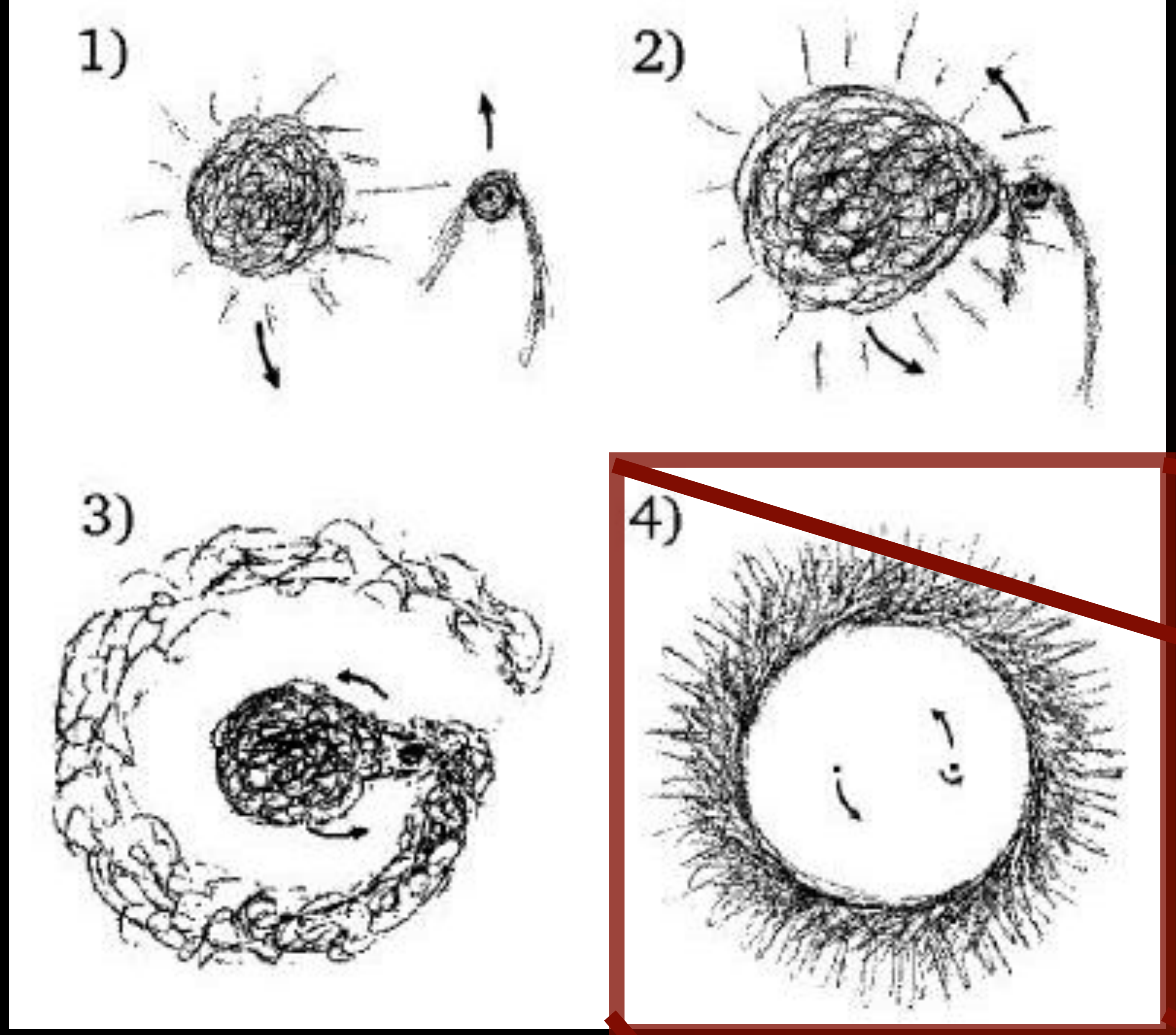
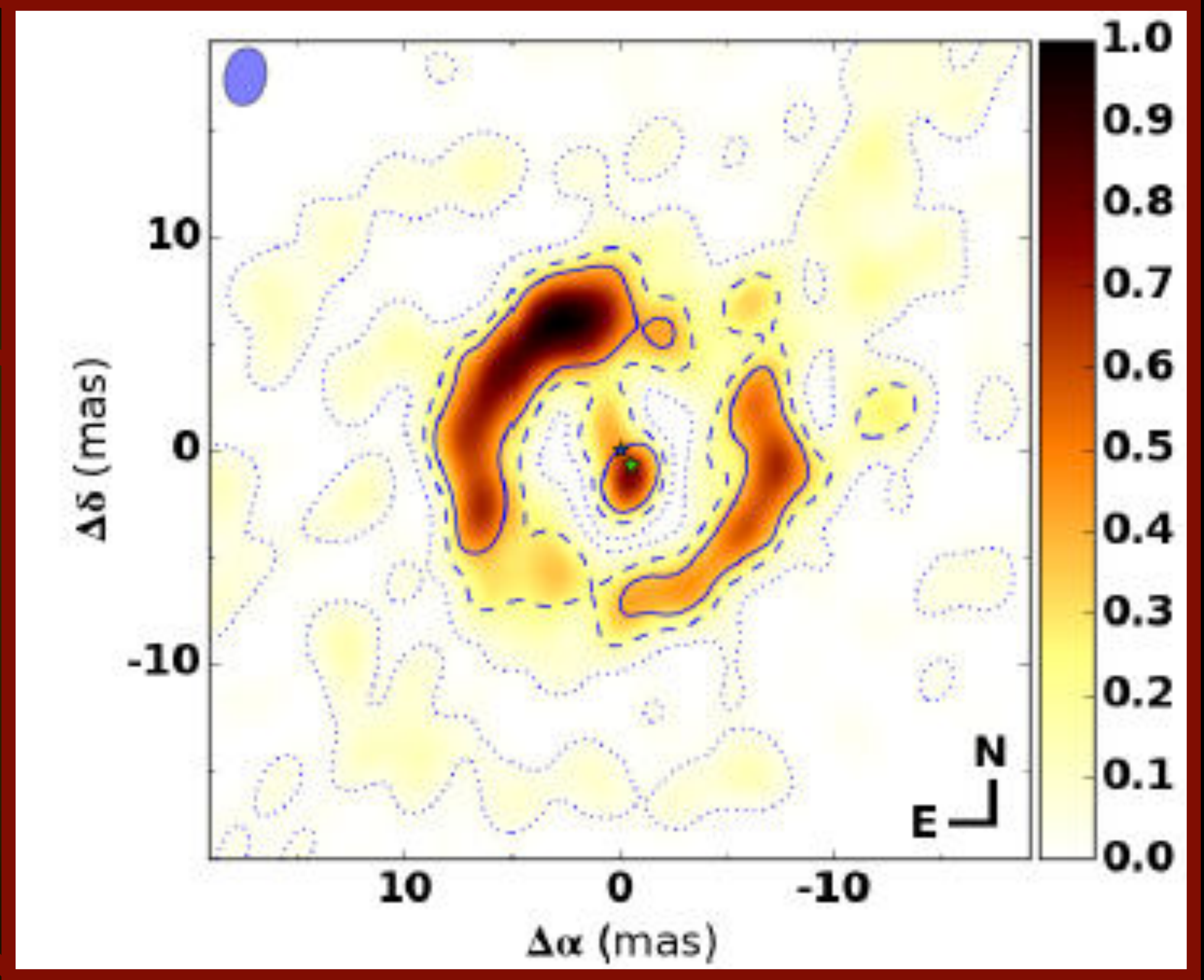
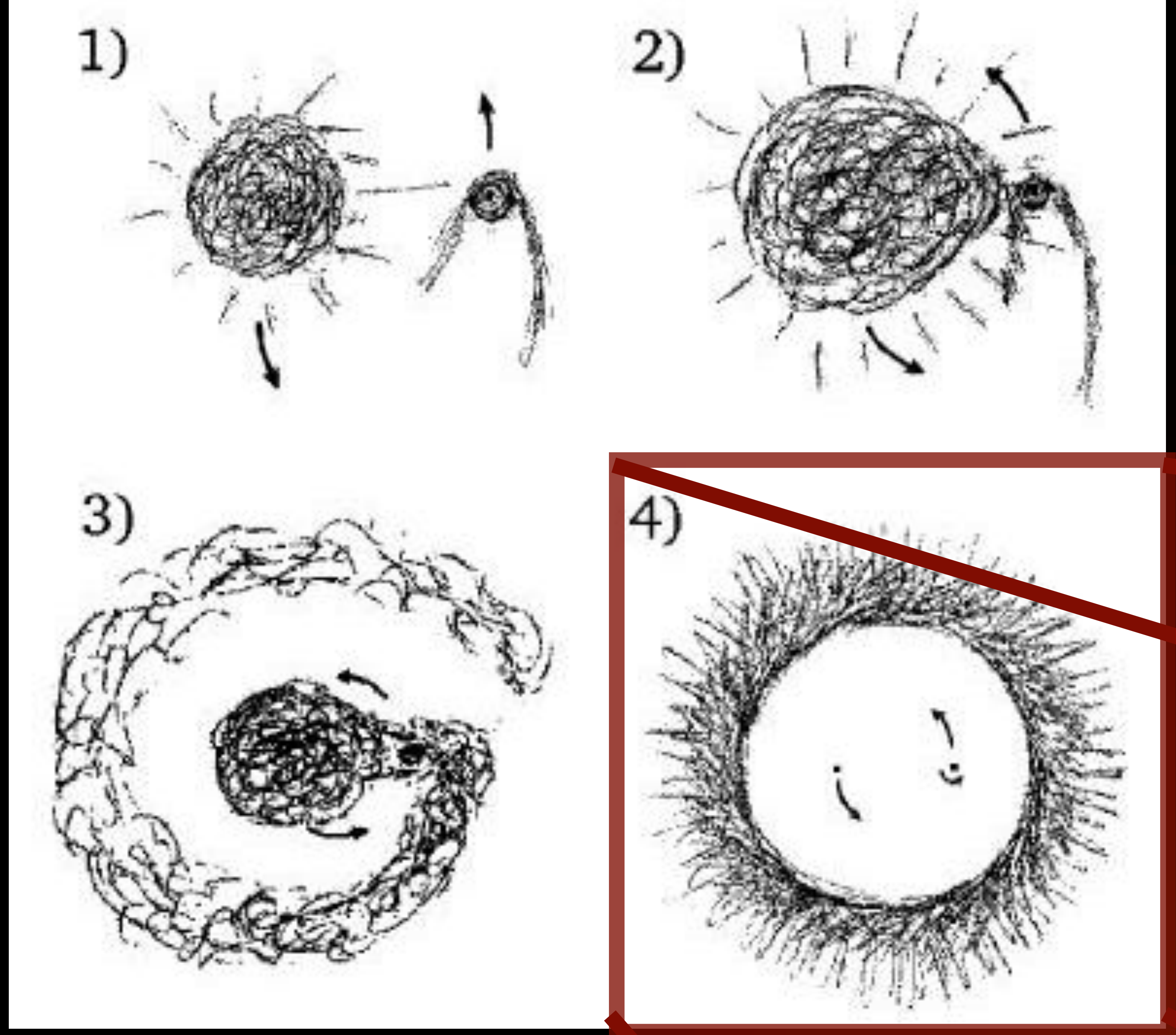




H-band reconstruction PIONIER/VLTI



Kluska et al., 2018



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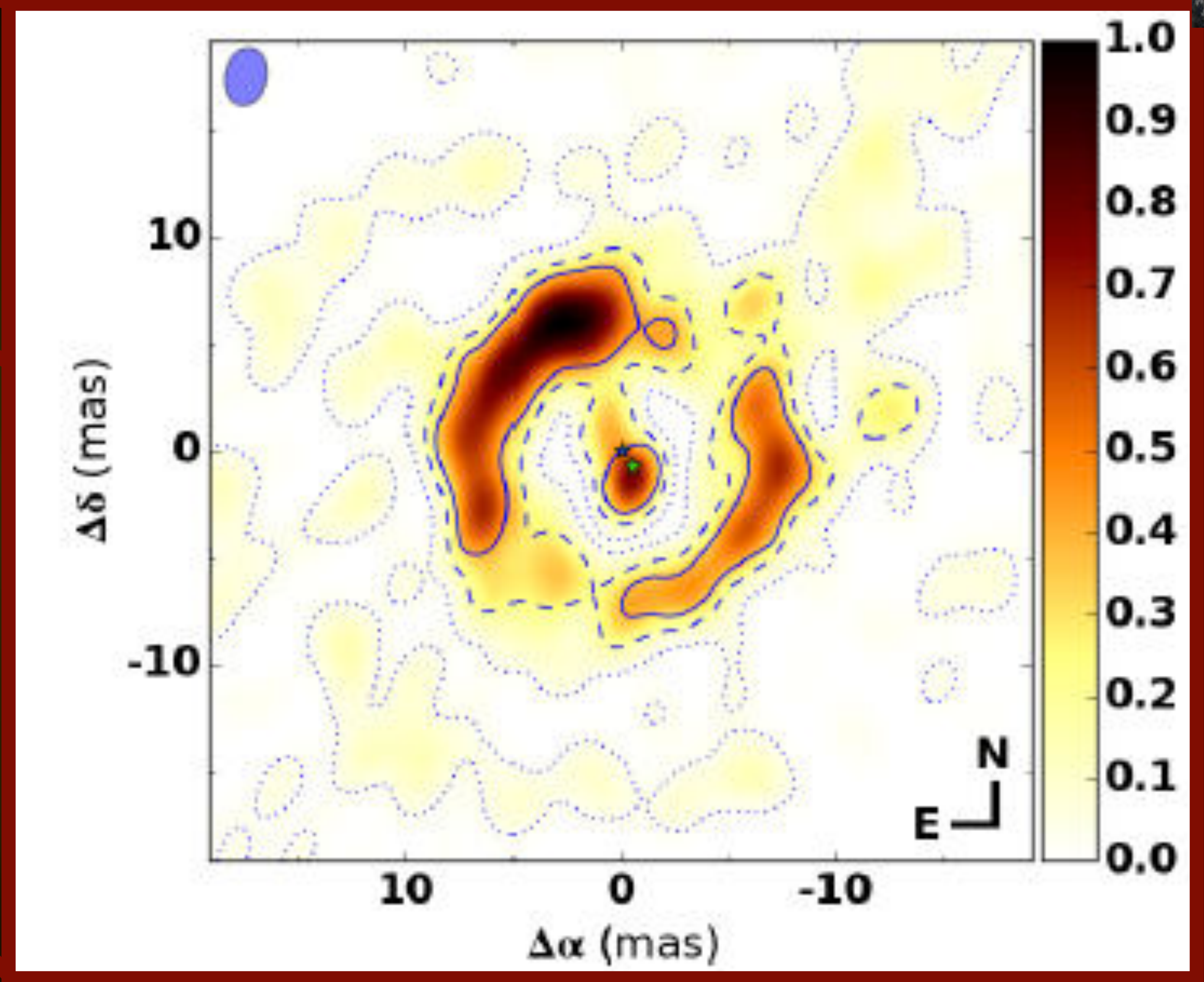

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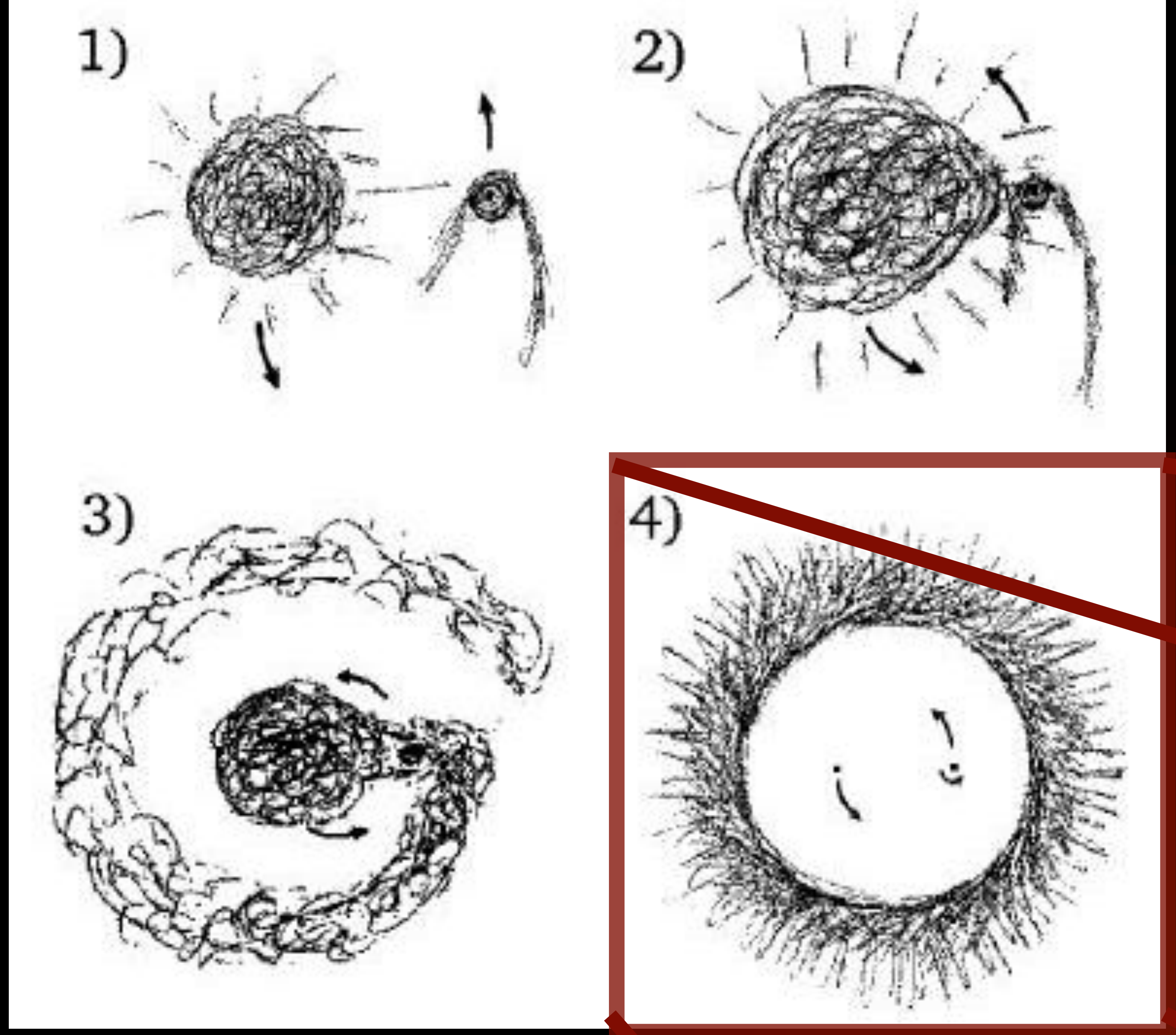

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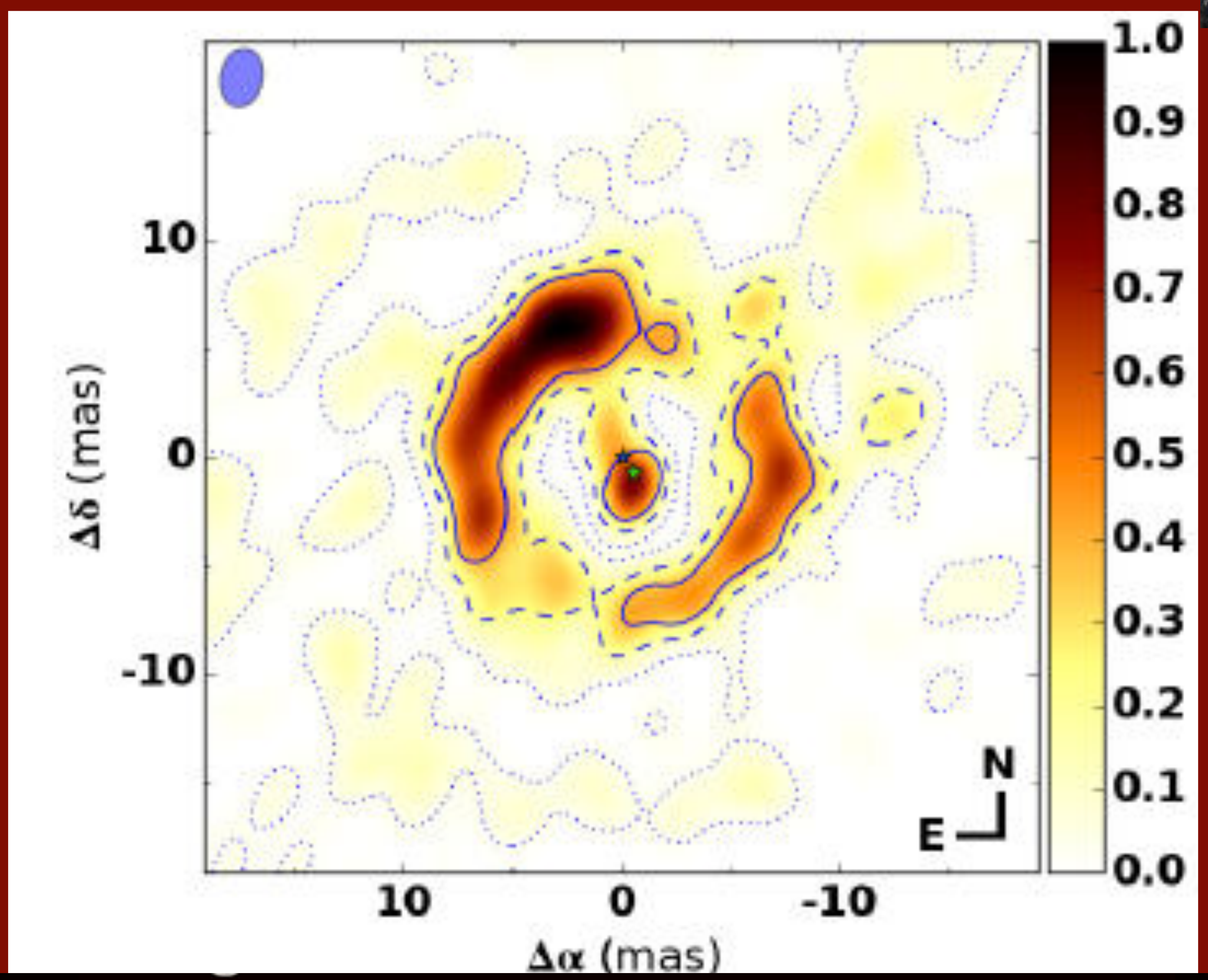
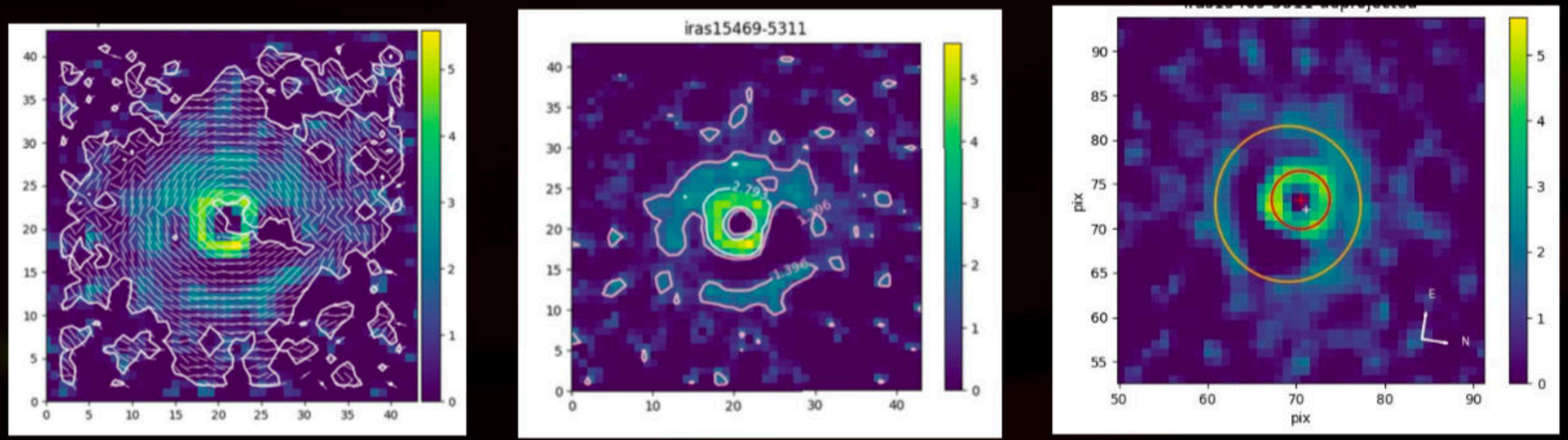
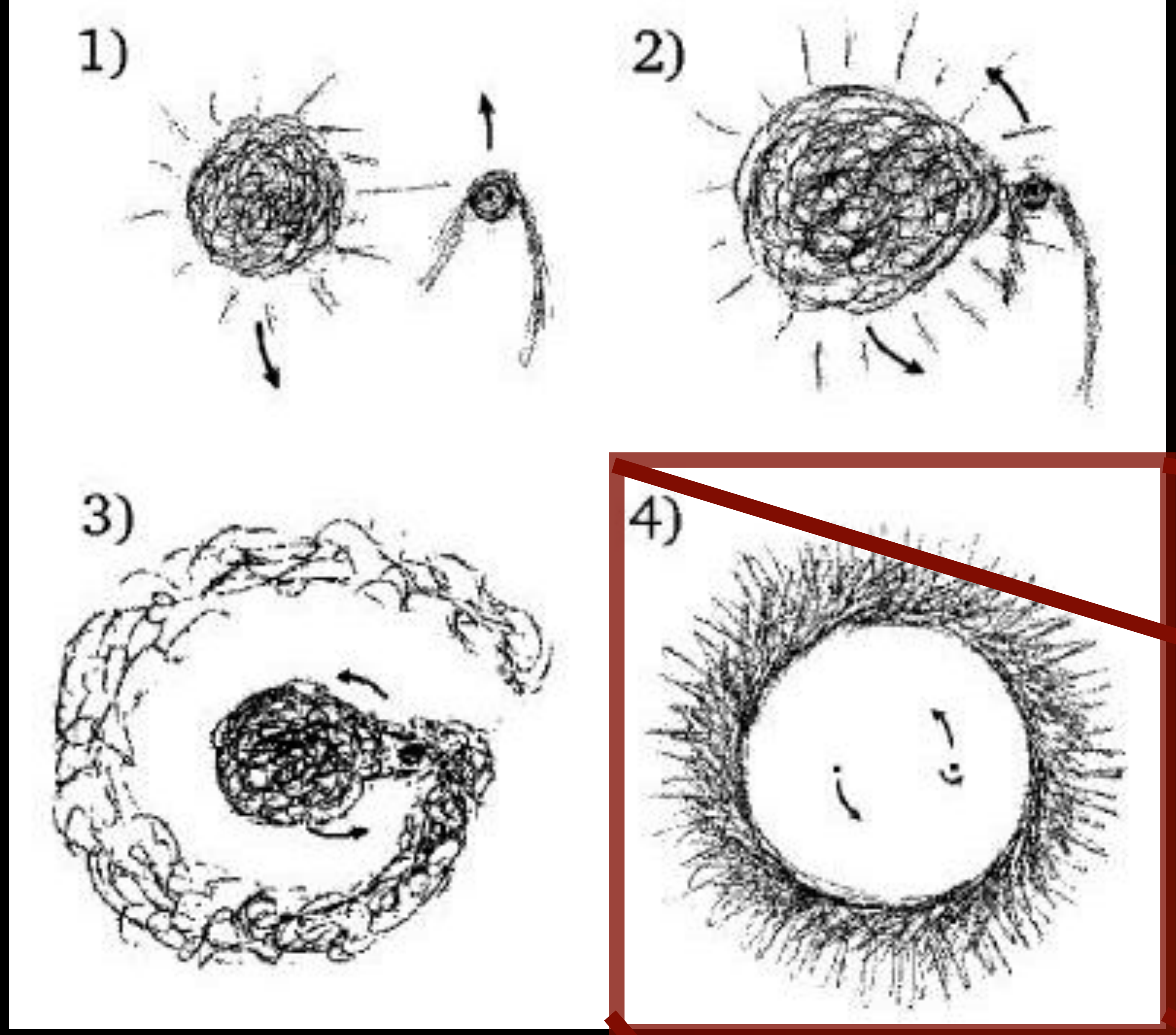


Kluska et al., 2018

Imaging and Polarimetry
K band VLT/SPHERE/IRDIS



Andrych et al., 2023



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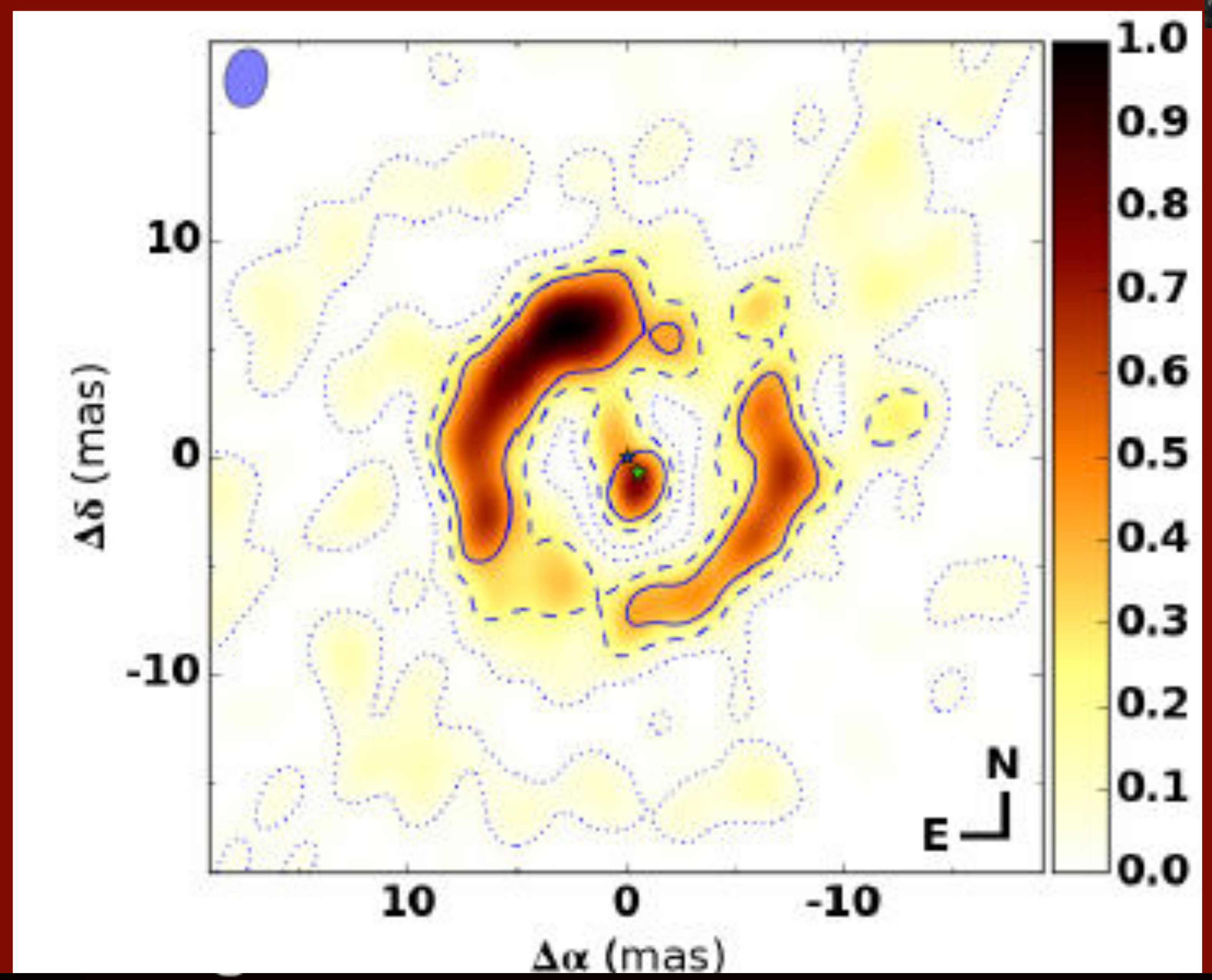

Kluska et al., 2018

SPHERE/VLT/ESO

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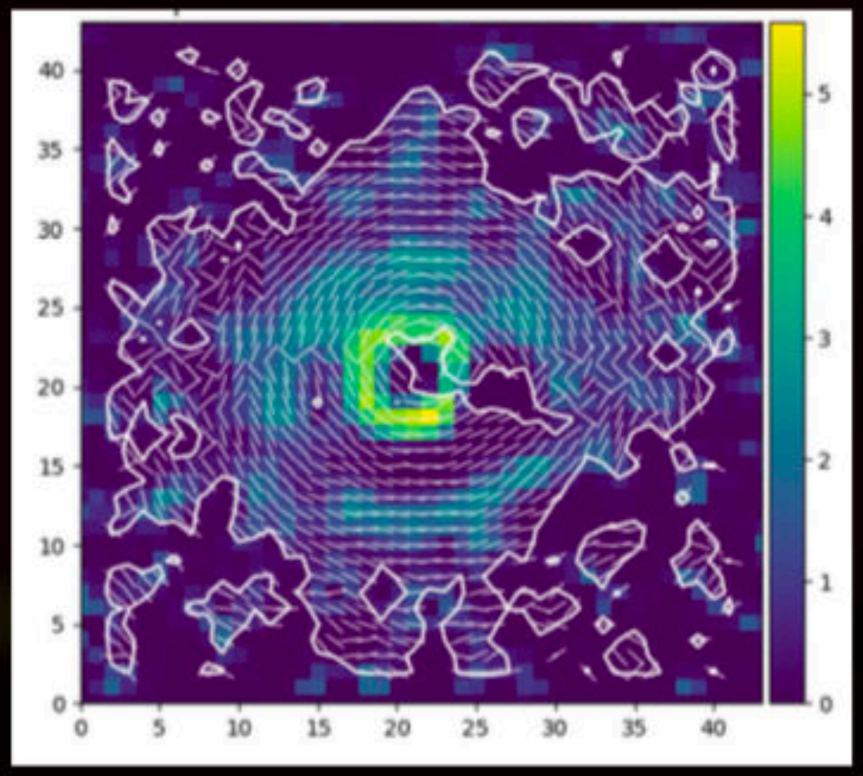
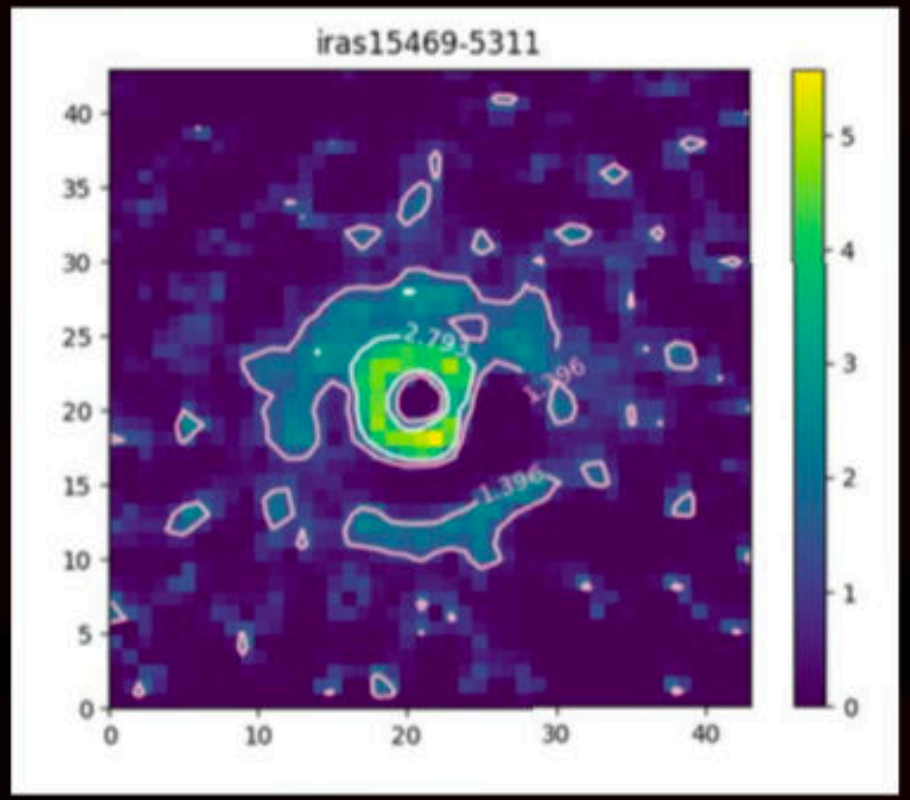
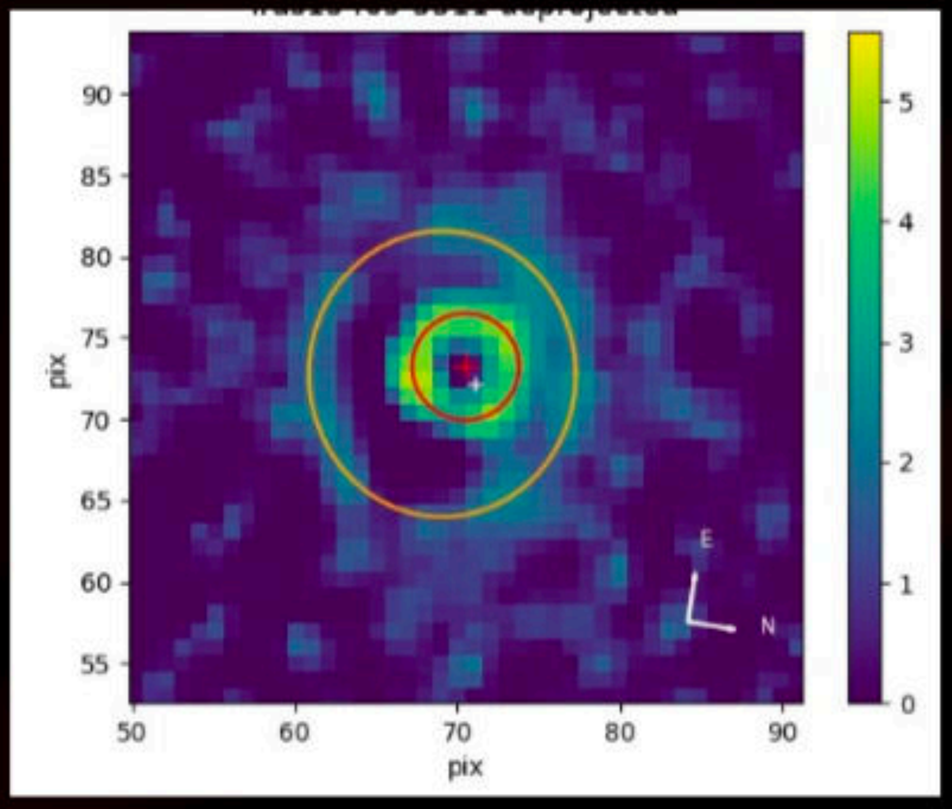
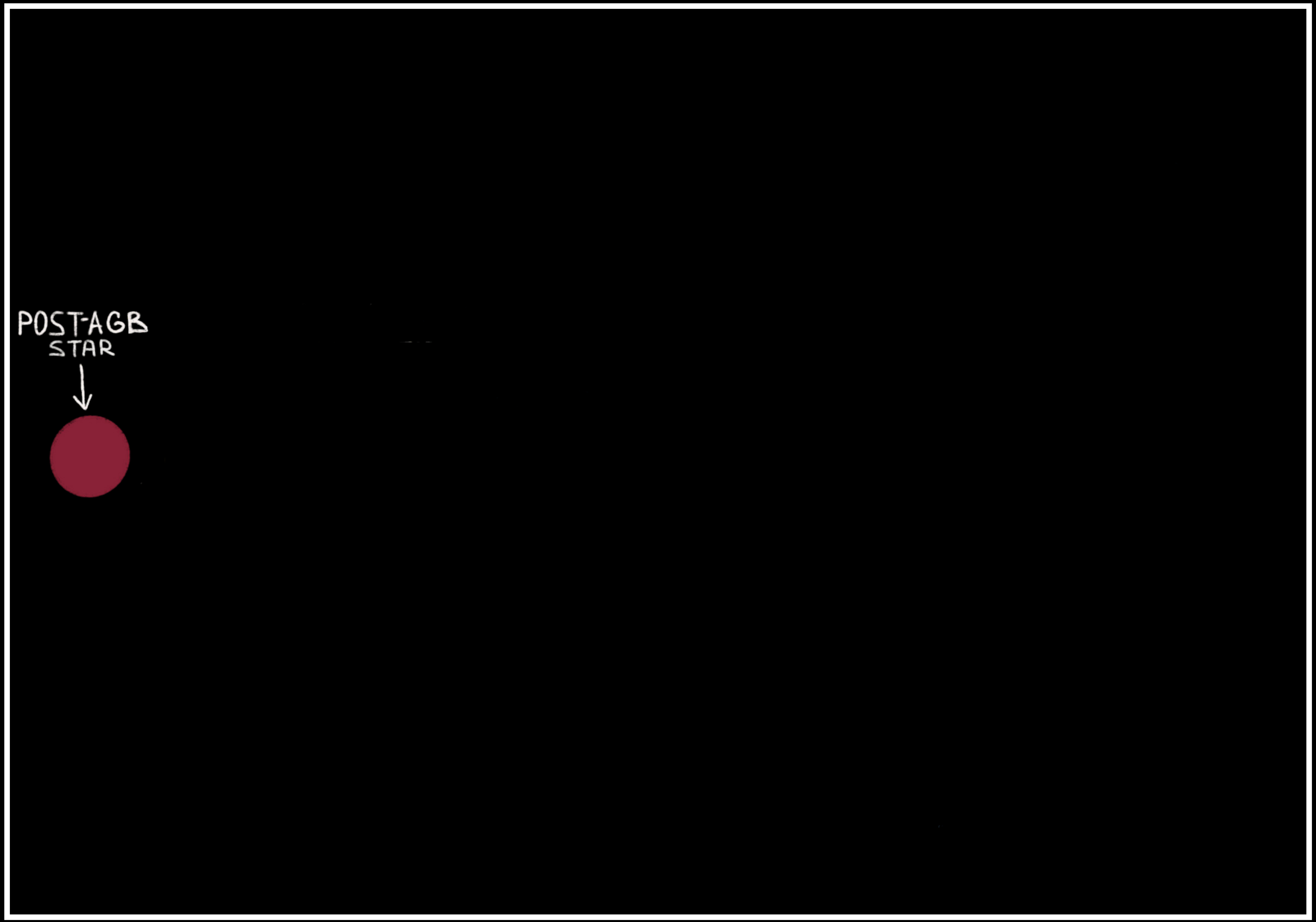






Andrych et al., 2023

The Post-AGB Binary System



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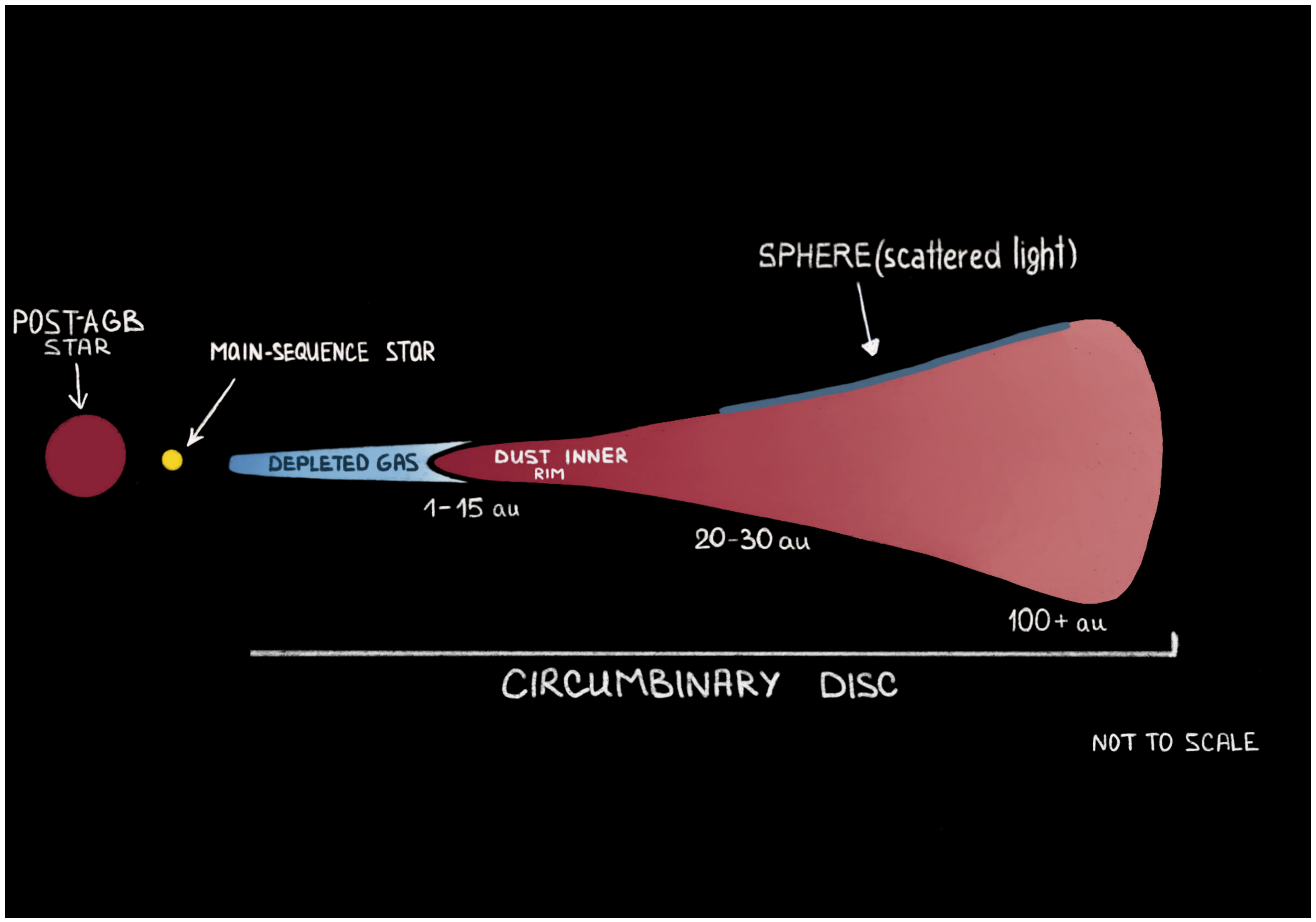

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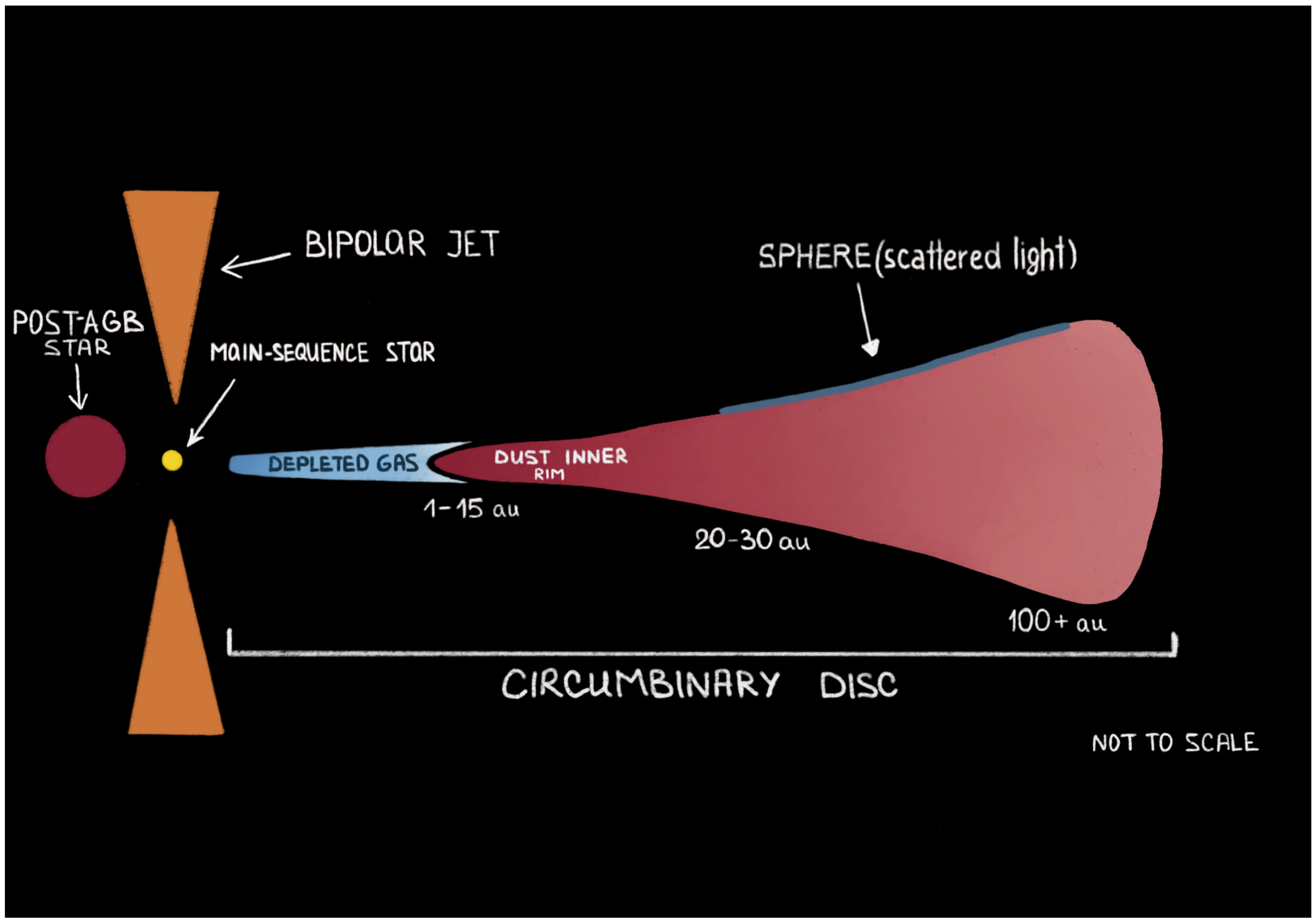
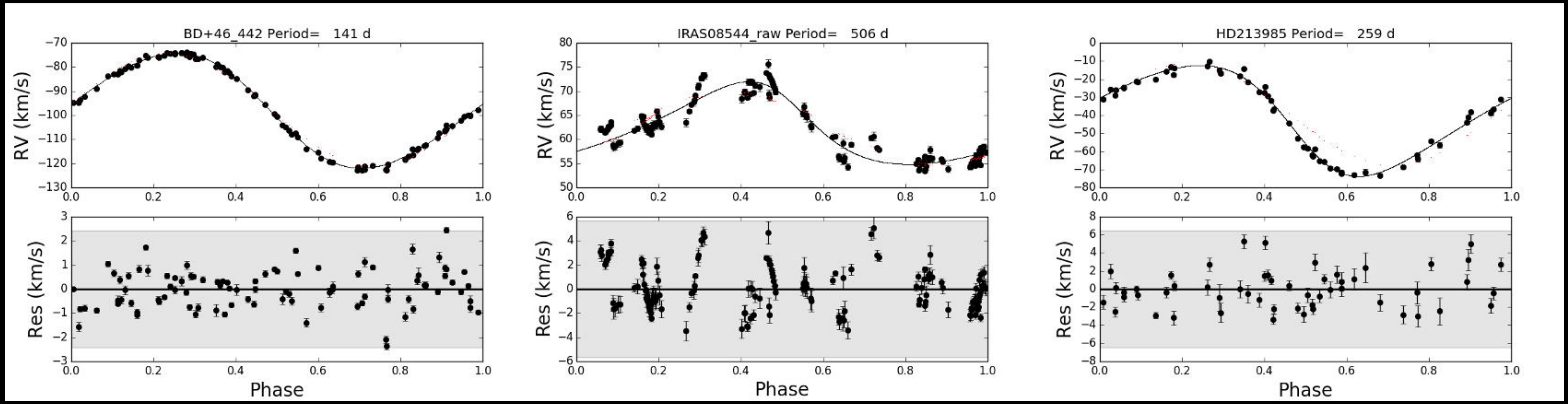
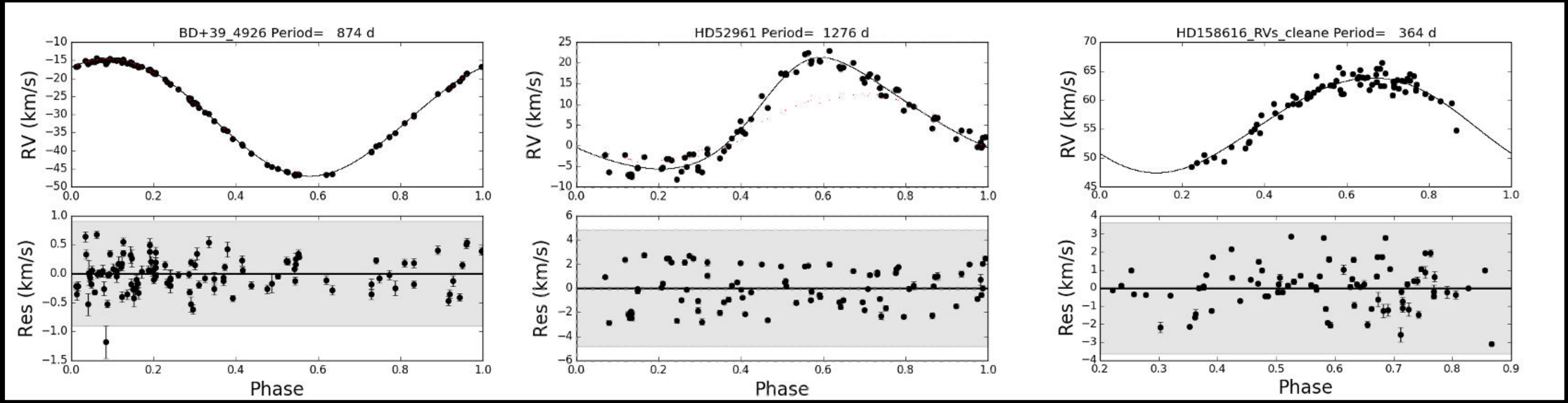
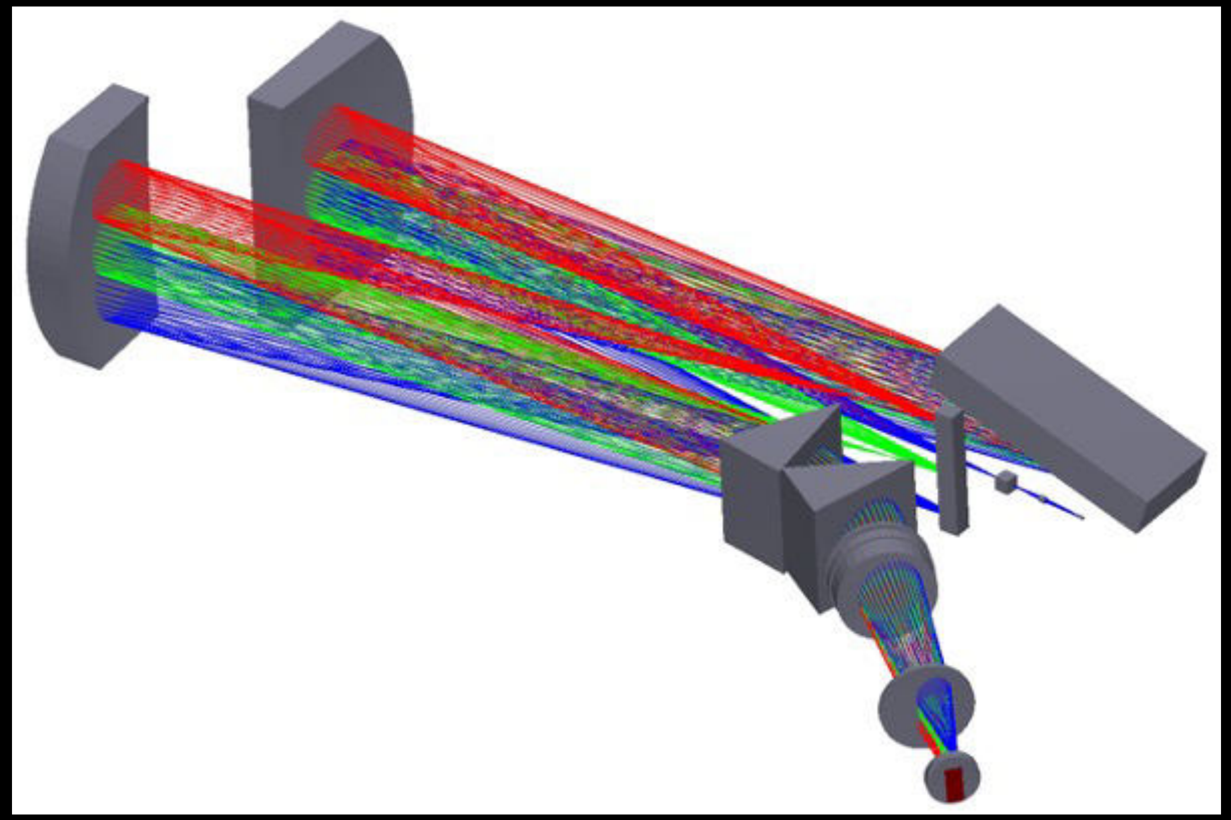


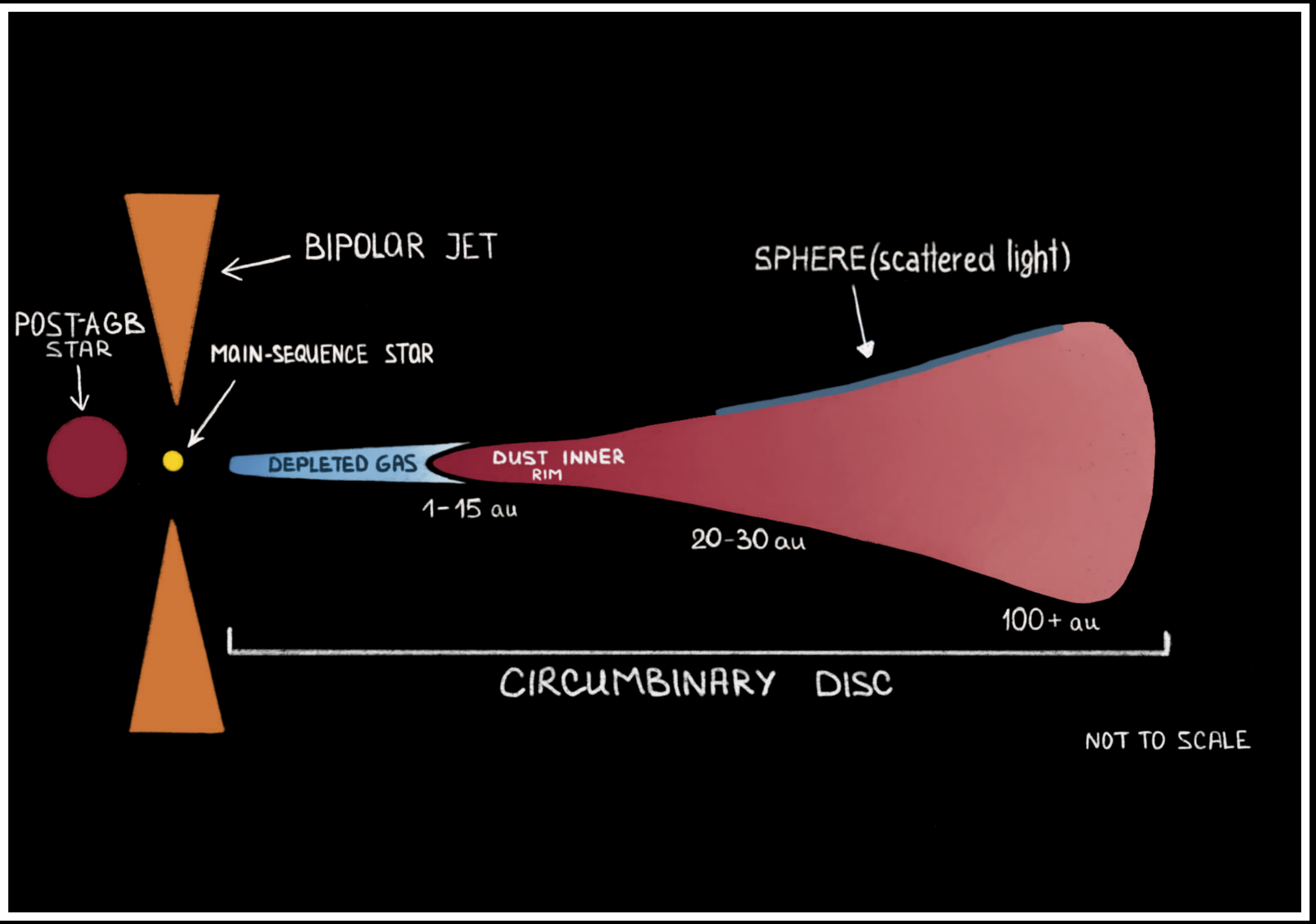
Spectroscopic binaries - time resolved spectroscopy

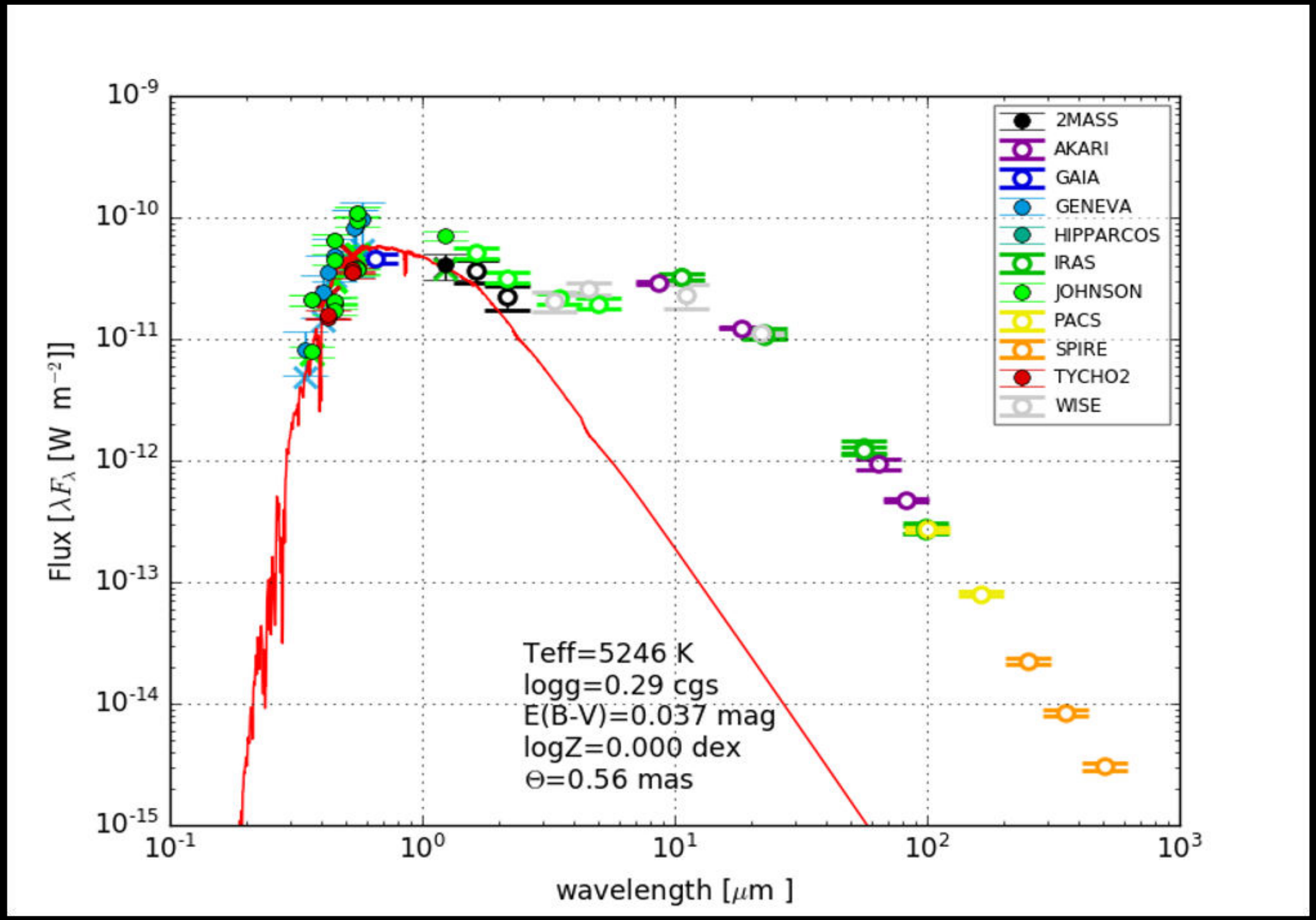




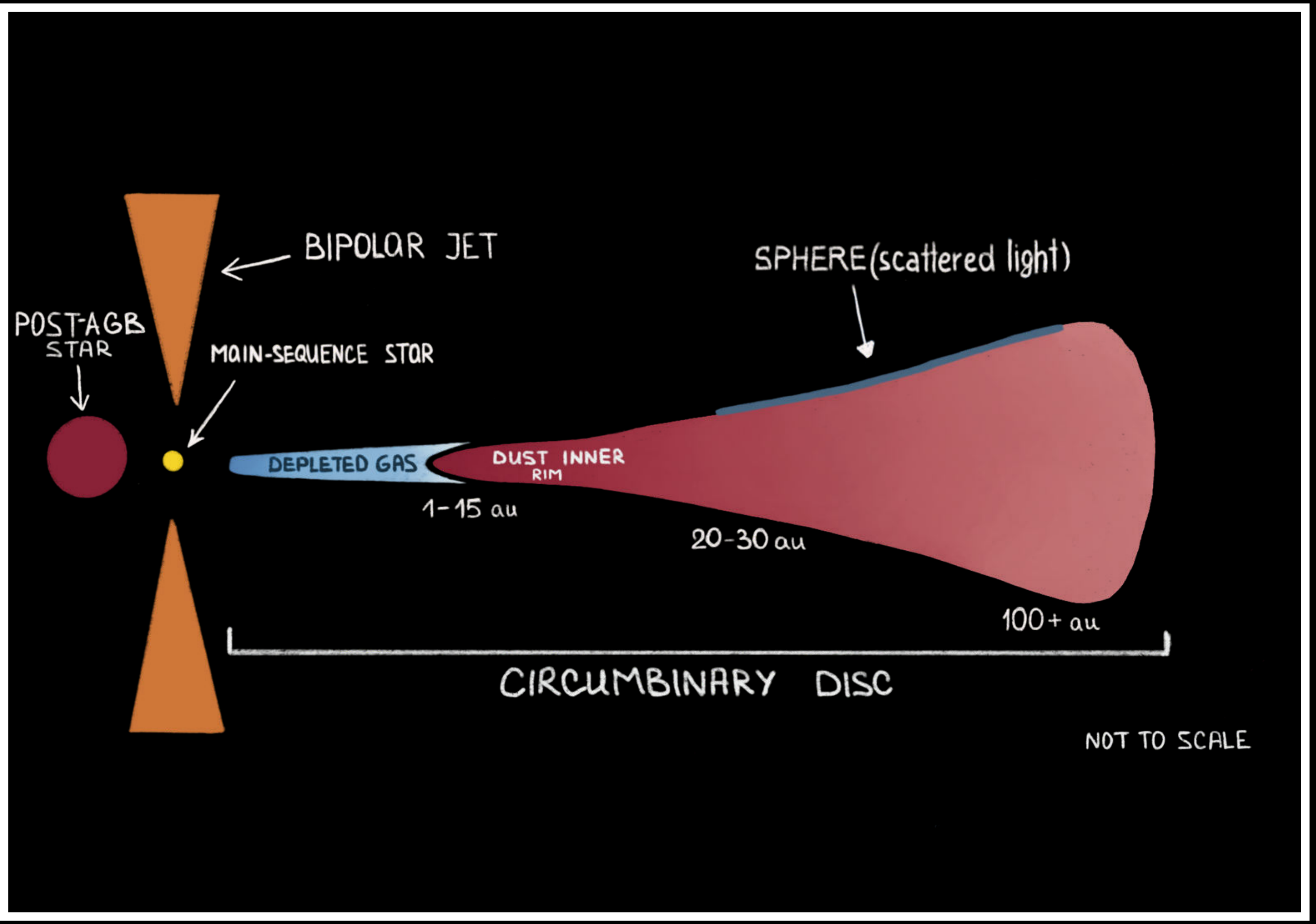


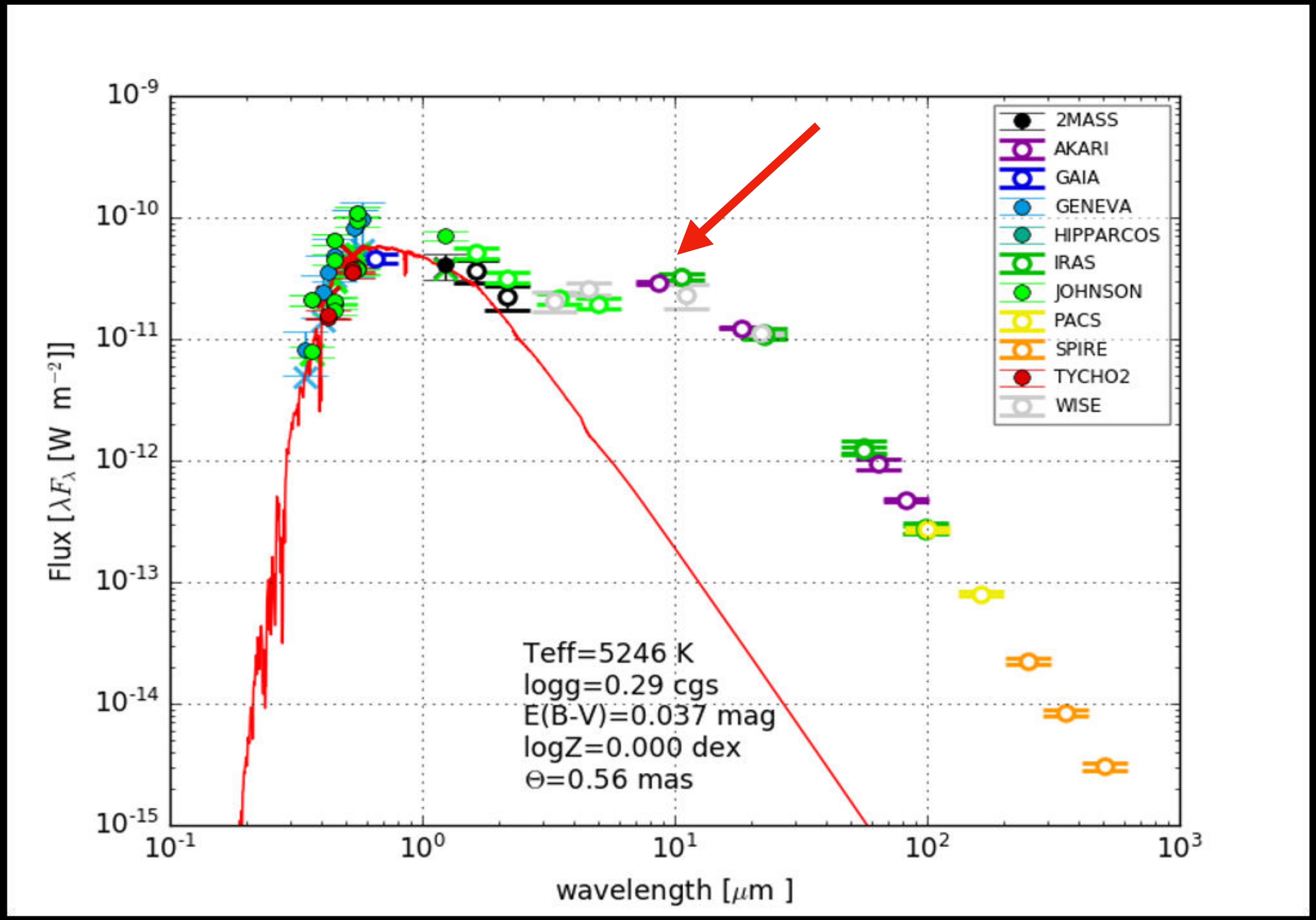
Van Winckel et al., 2009, Oomen et al., 2019





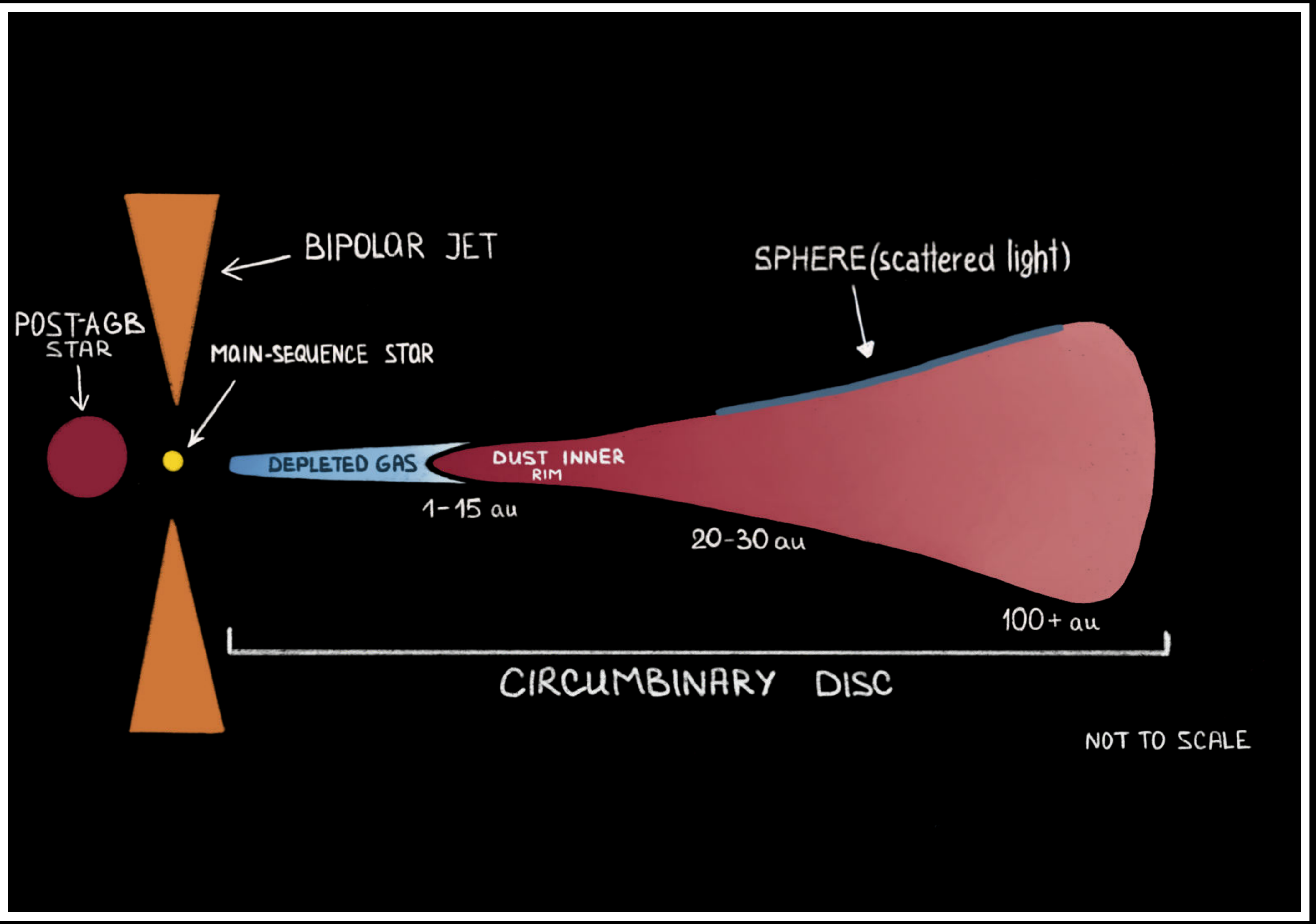
Kluska et al., 2022; Kamath et al., 2014, 2015, 2022

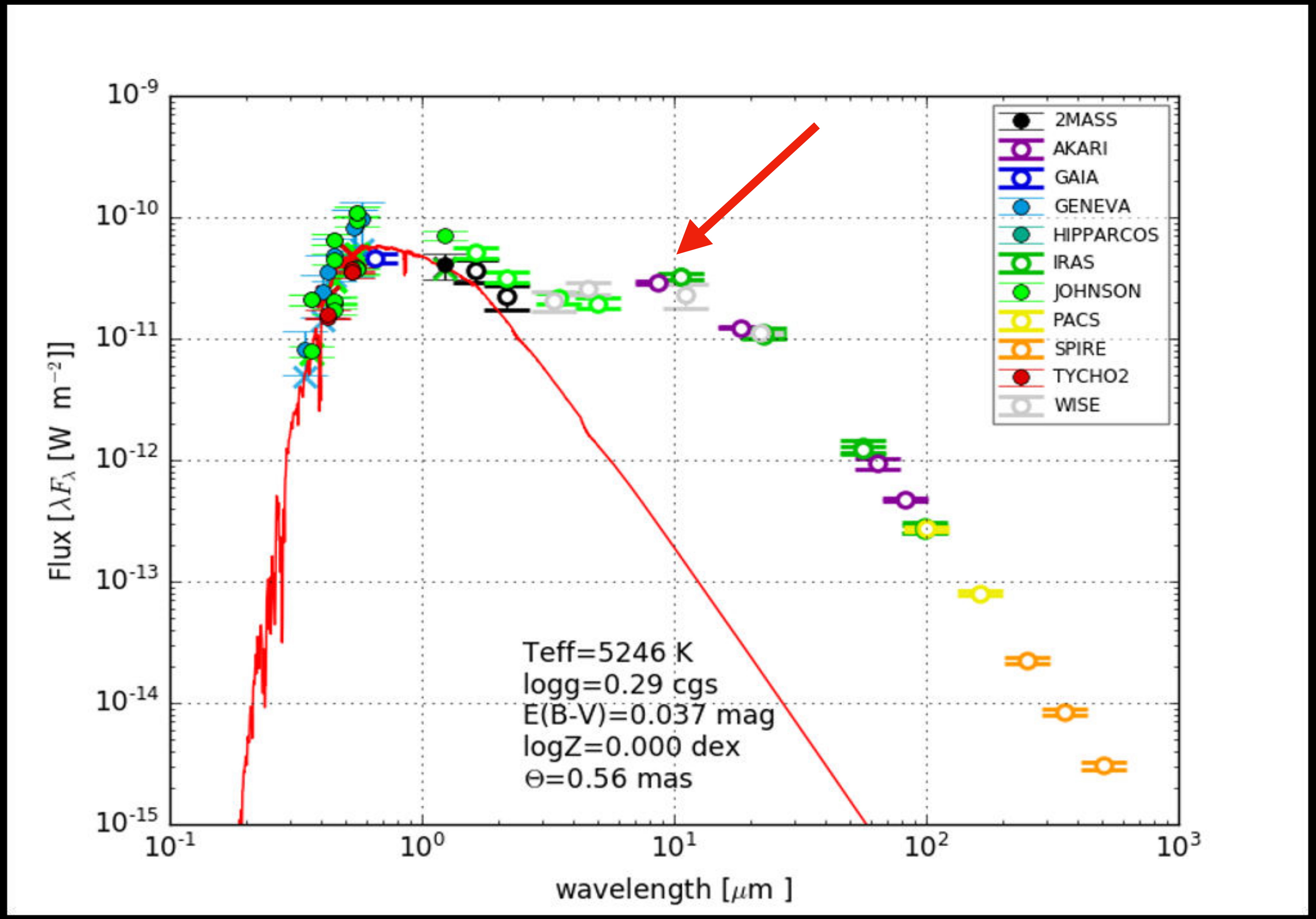




- NearIR excess with a broad onset: hot dust component is indicative of Keplerian disc

Kluska et al., 2022; Kamath et al., 2014, 2015, 2022





- NearIR excess with a broad onset: hot dust component is indicative of Keplerian disc
- Discs are fat
- L(IR) is large fraction of L(star) and the disc evolves…
- Long wavelength spectral index: large grains

Kluska et al., 2022; Kamath et al., 2014, 2015, 2022

The Effect of Binarity:

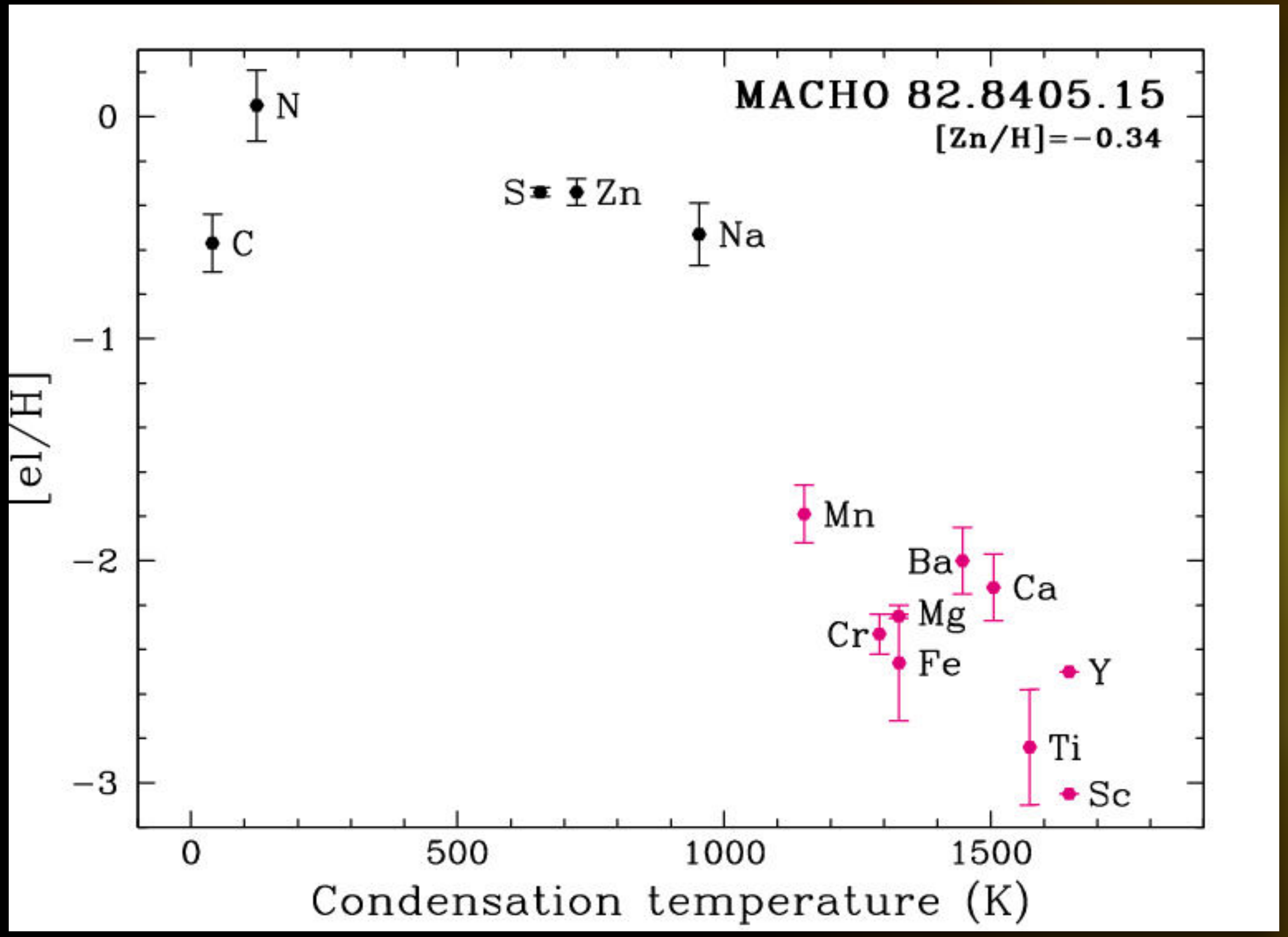
Photospheric Chemical Depletion in post-AGB binaries

Kamath & Van Winckel 2019; Oomen et al., 2021; Mohorian et al., 2024; Menon et al., 2024

The Effect of Binarity:

Photospheric Chemical Depletion in post-AGB binaries

Feedback from disc =>
Loss of nucleosynthetic history



- [C/Fe]>0
- Depletion of refractory elements
- Refractory elements scale with Fe

Kamath & Van Winckel 2019; Oomen et al., 2021; Mohorian et al., 2024; Menon et al., 2024

The Effect of Binarity:

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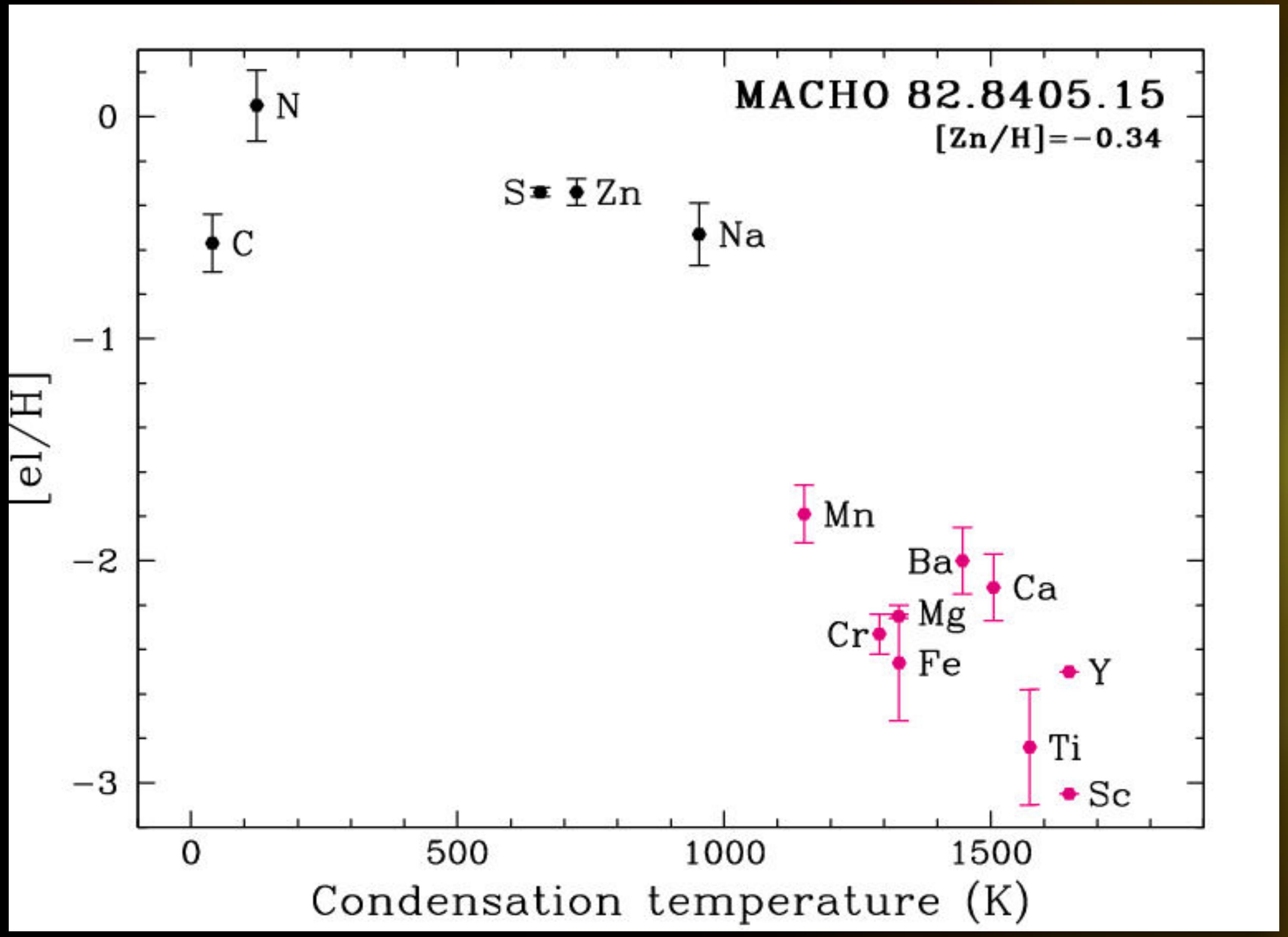

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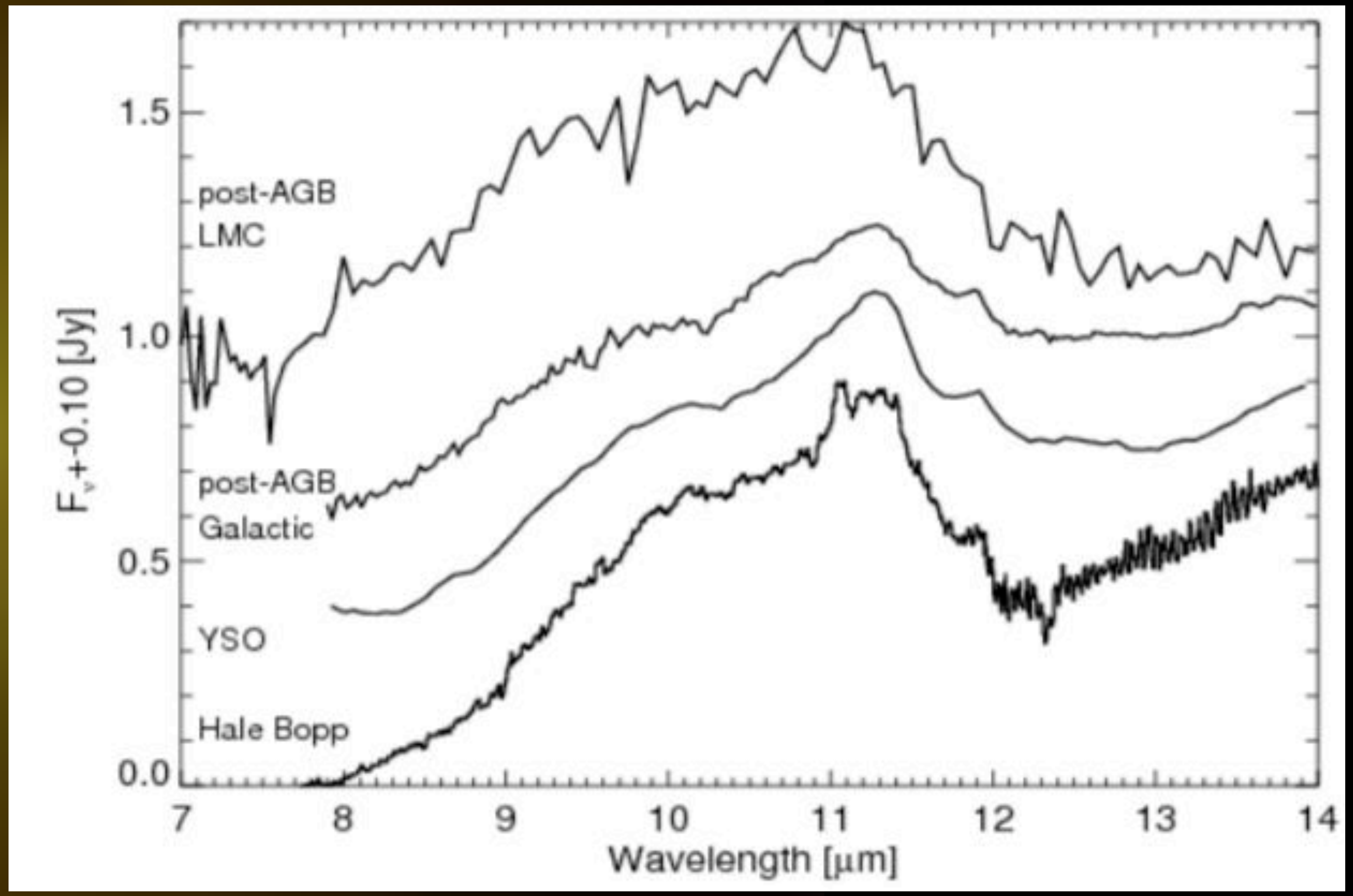


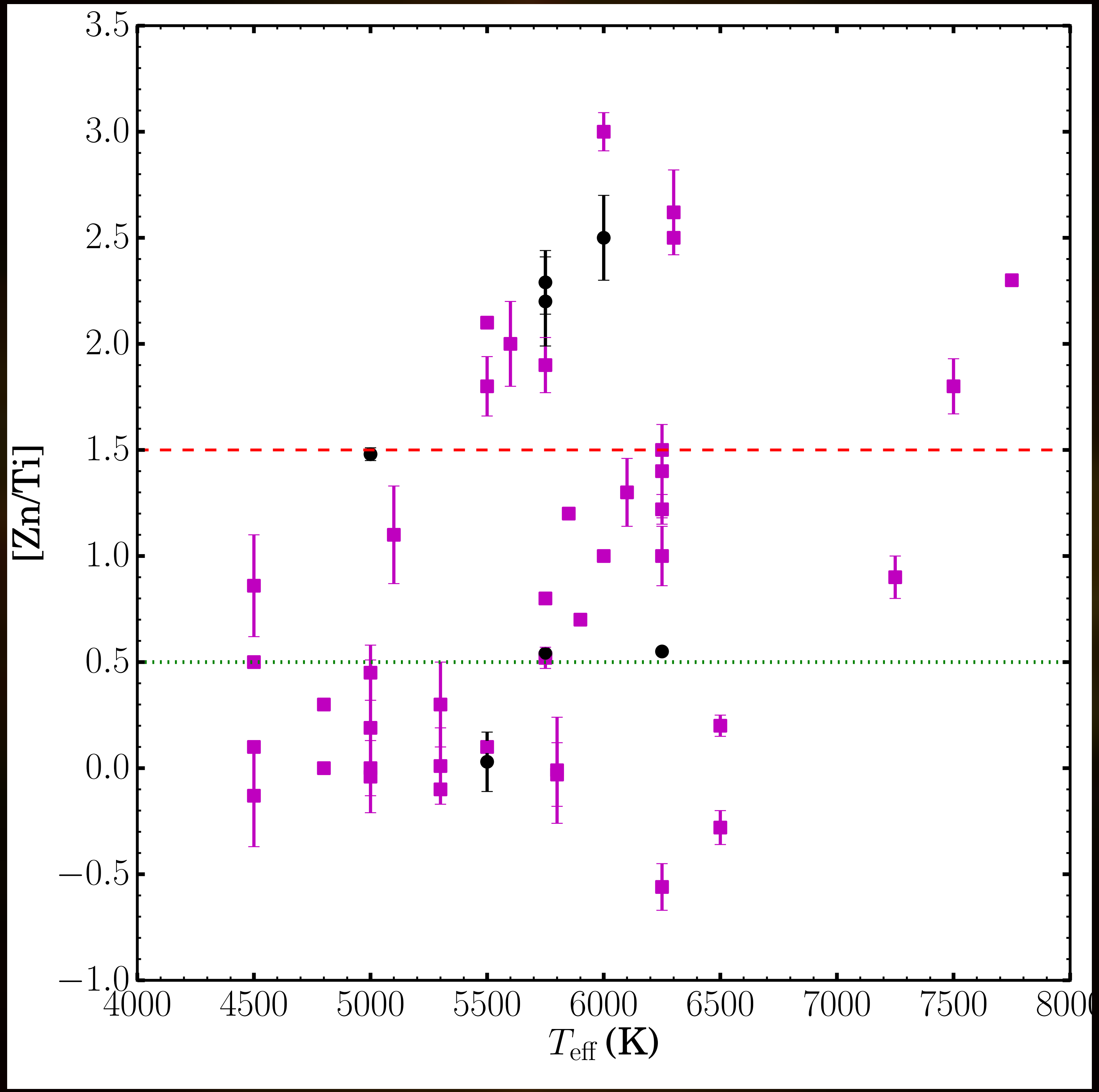
10-micron silicate feature

IR spectra are very rich and strongly crystalline

Kamath & Van Winckel 2019; Oomen et al., 2021; Mohorian et al., 2024; Menon et al., 2024

The Effect of Binarity:

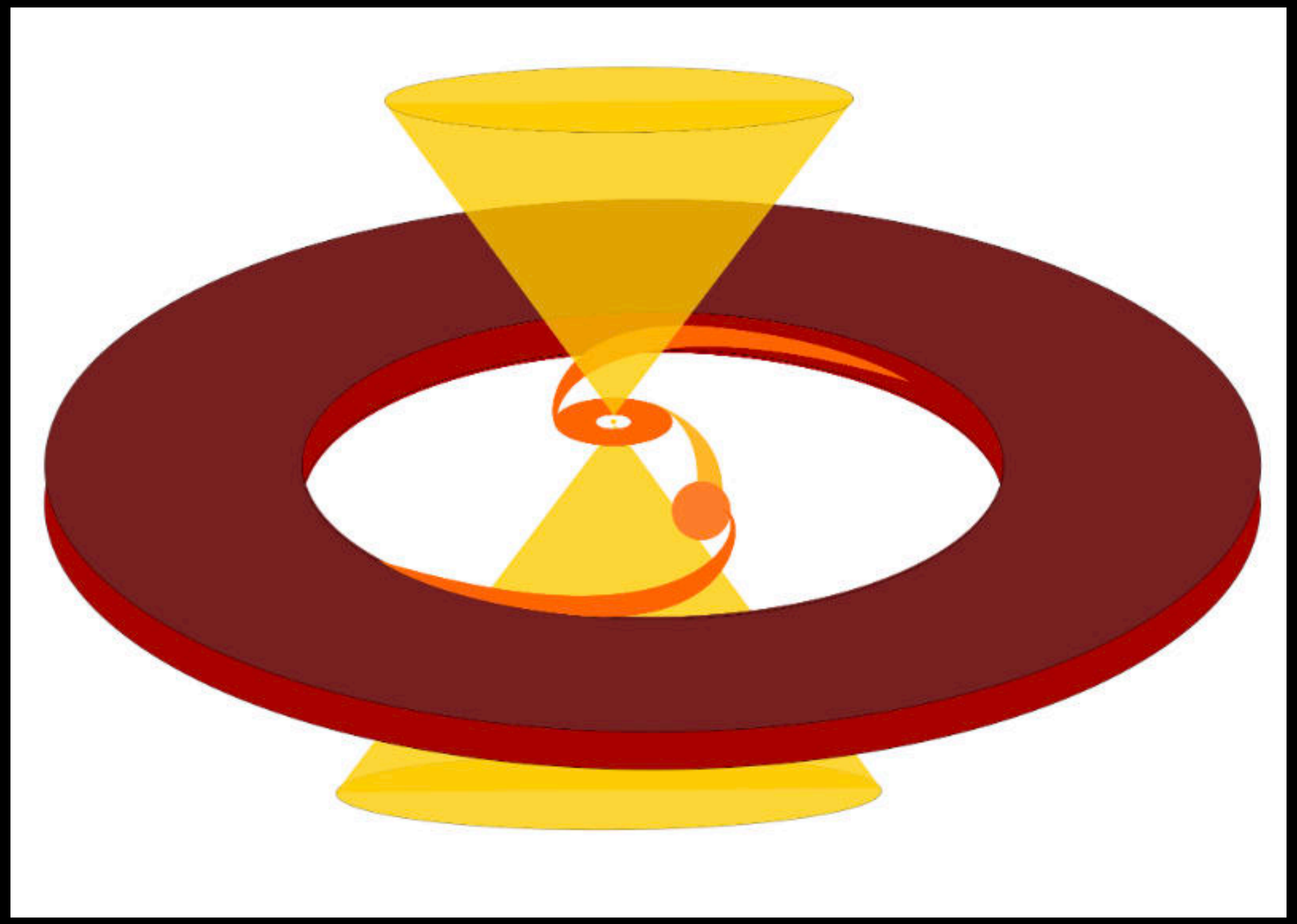
Photospheric Chemical Depletion in post-AGB binaries

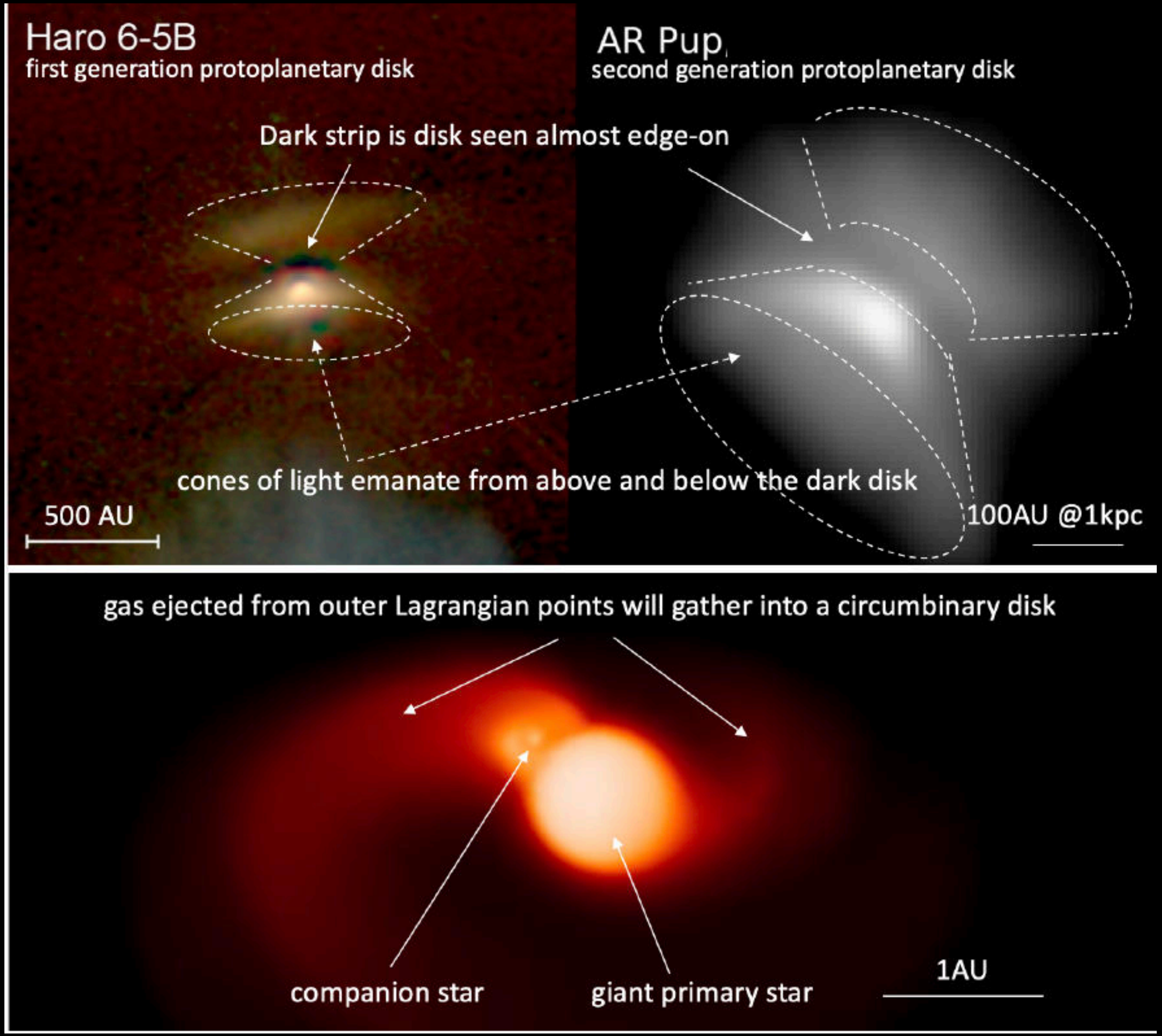


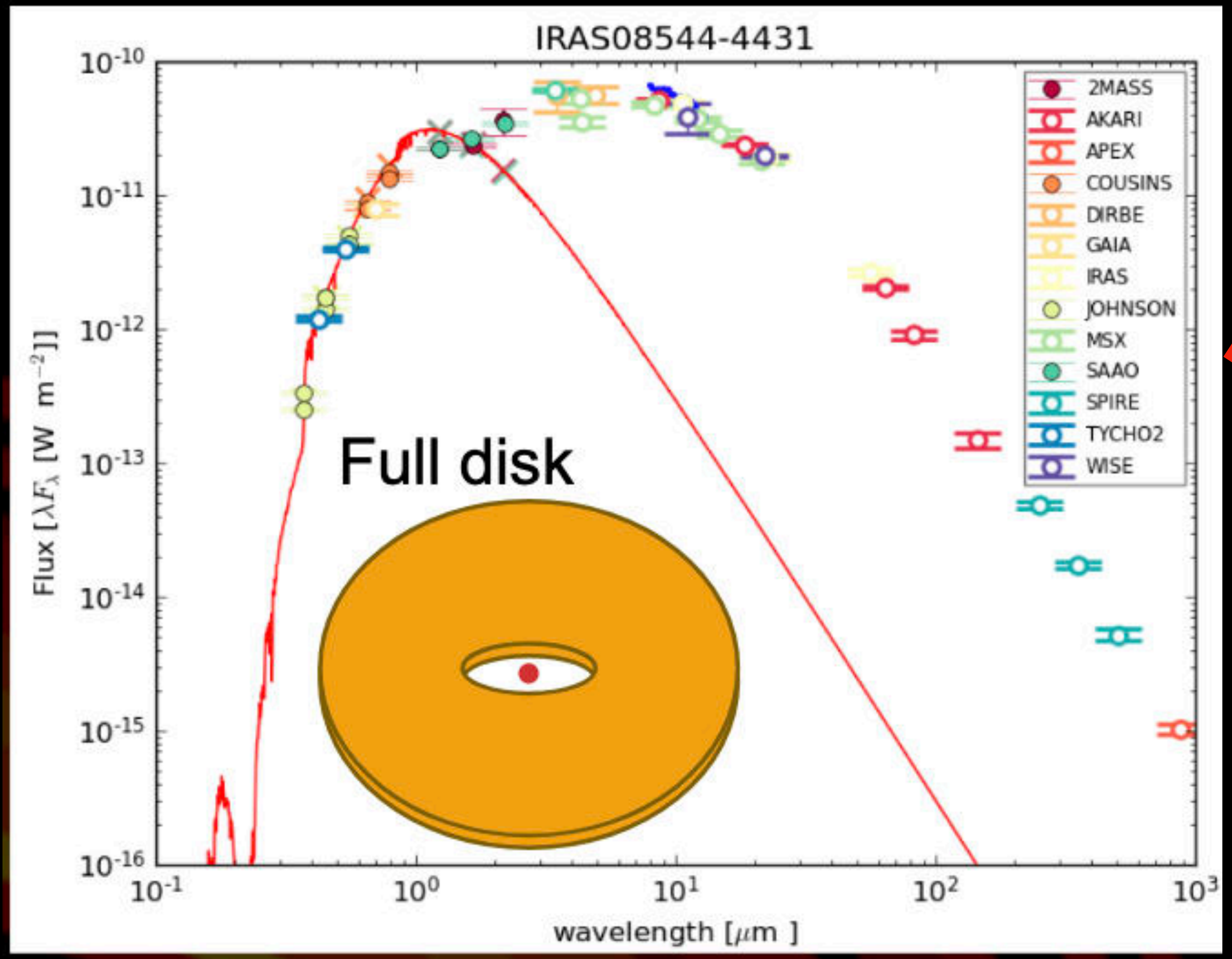
Depletion is efficient over a wide range of luminosities AGB/RGB!

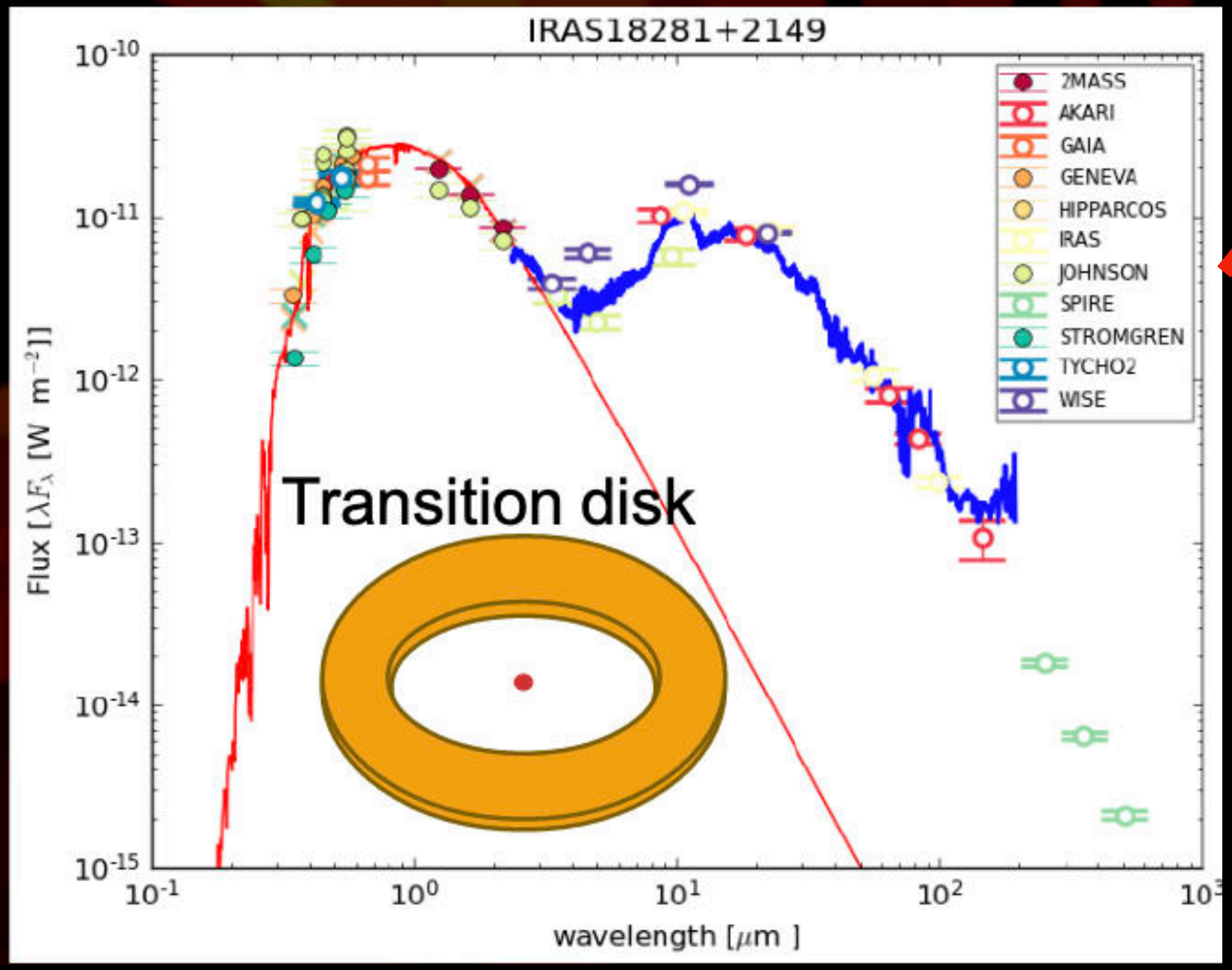
Van Winckel et al., 2009; Oomen et al., 2019; Kamath & Van Winckel 2019

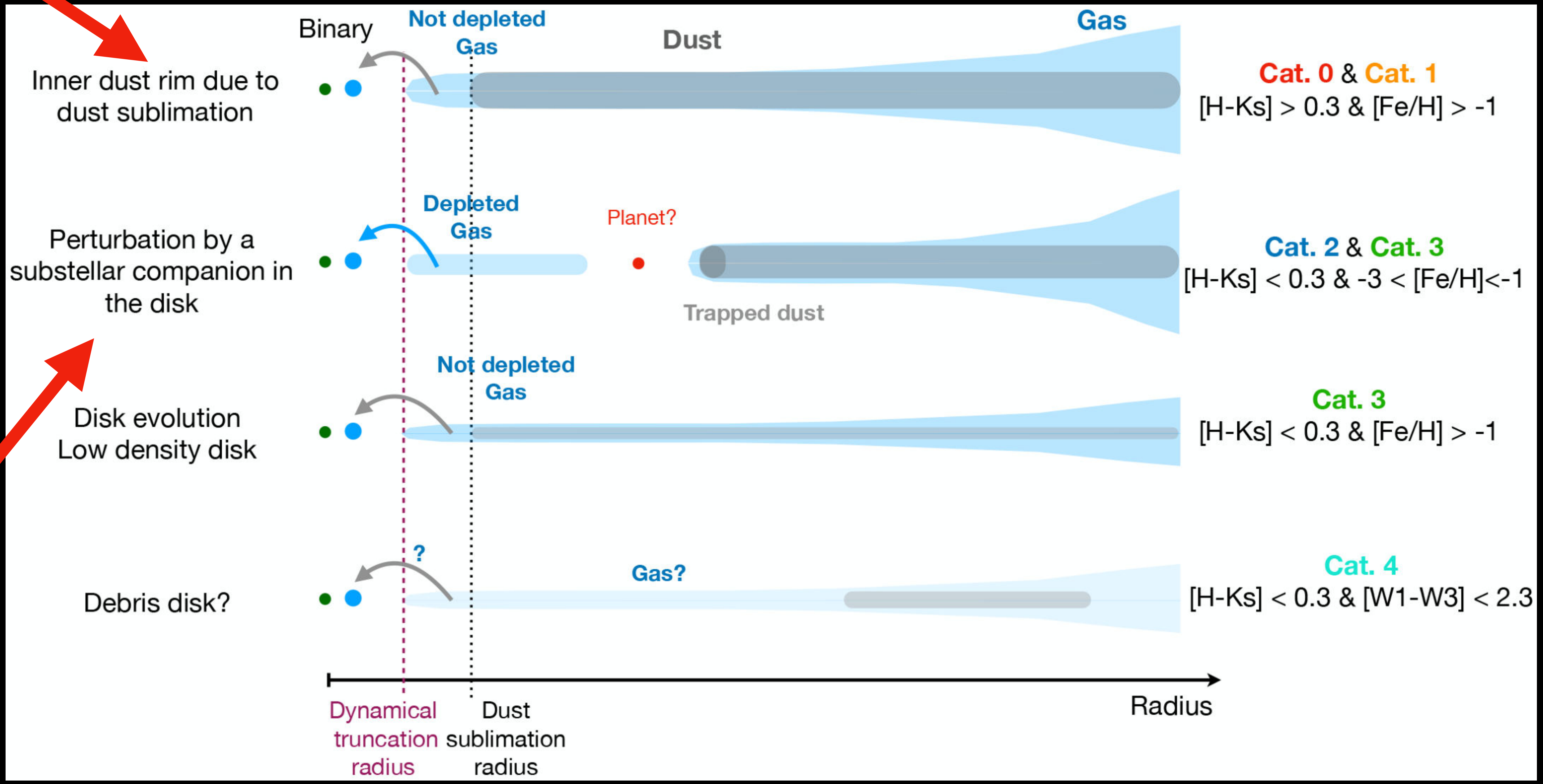
A second chance for planet formation!?




Haro 6-5B
first generation protoplanetary disk
AR Pup
second generation protoplanetary disk
Dark strip is disk seen almost edge-on
cones of light emanate from above and below the dark disk
500 AU
100AU @1kpc
gas ejected from outer Lagrangian points will gather into a circumbinary disk
companion star
giant primary star
1AU



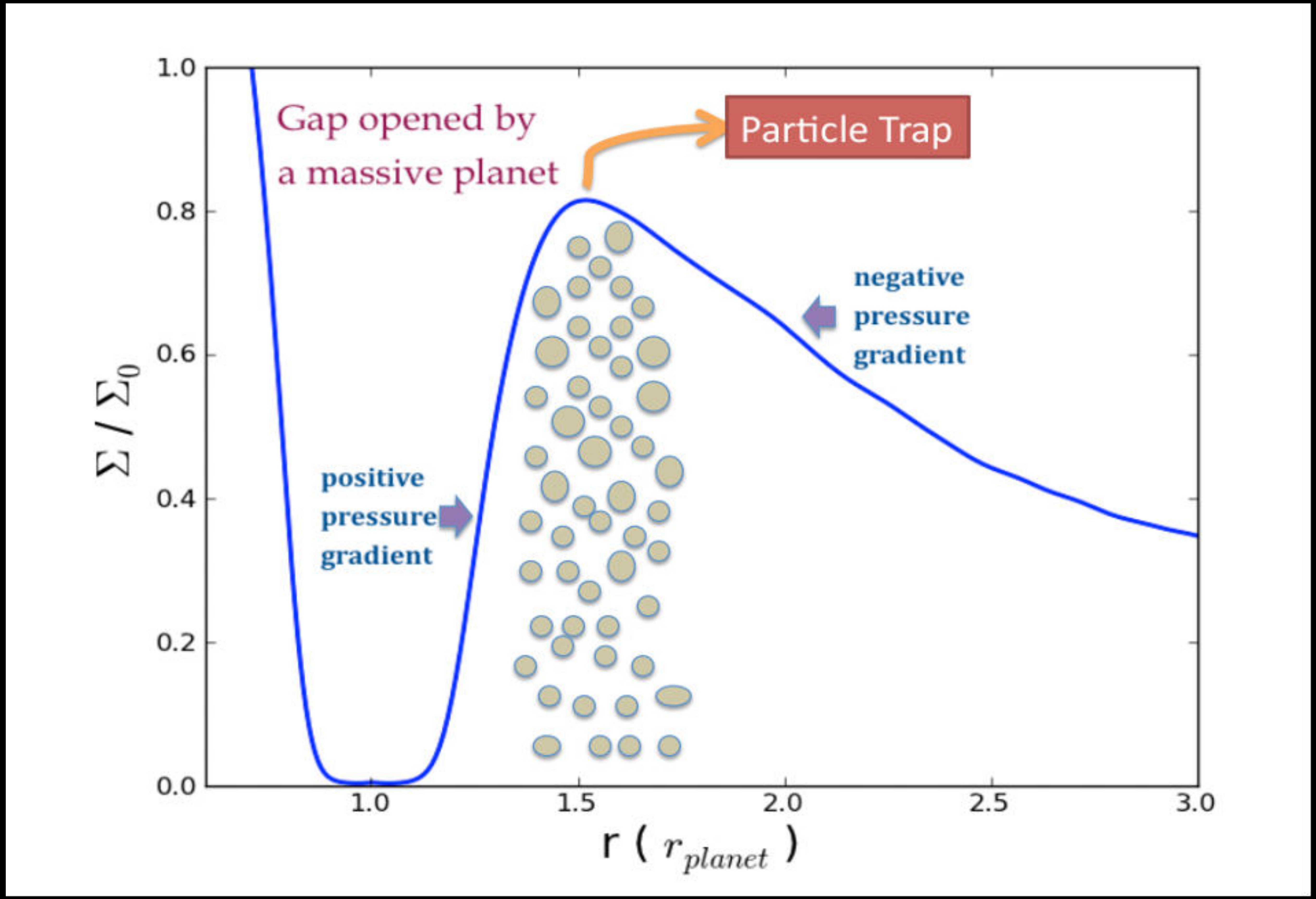




Kluska et al., 2022

- Most discs (Full discs) start at <u>sublimation</u> temperature
- Transition discs (10%) start at larger radii

Gas-Dust Separation and Dust Trapping



Britain et al. 2023; Kluska et all 2022

- Another similarity with YSO:
- Depletion in YSO is thought to be by dust trapping by planet formation
- Dust is trapped, clean gas can be accreted
- Depletion is correlated with SED shape (transition discs in Post-AGB stars are more depleted)
- Planet-Disc interaction also in post-AGB binaries?

INSPI**RING**: **IN**terferometric **S**urvey of **P**ost-agb b**I**naries with their **RING** an imaging VLTI Large Programme

PI: Kluska, CI: Van Winckel, Kamath, …

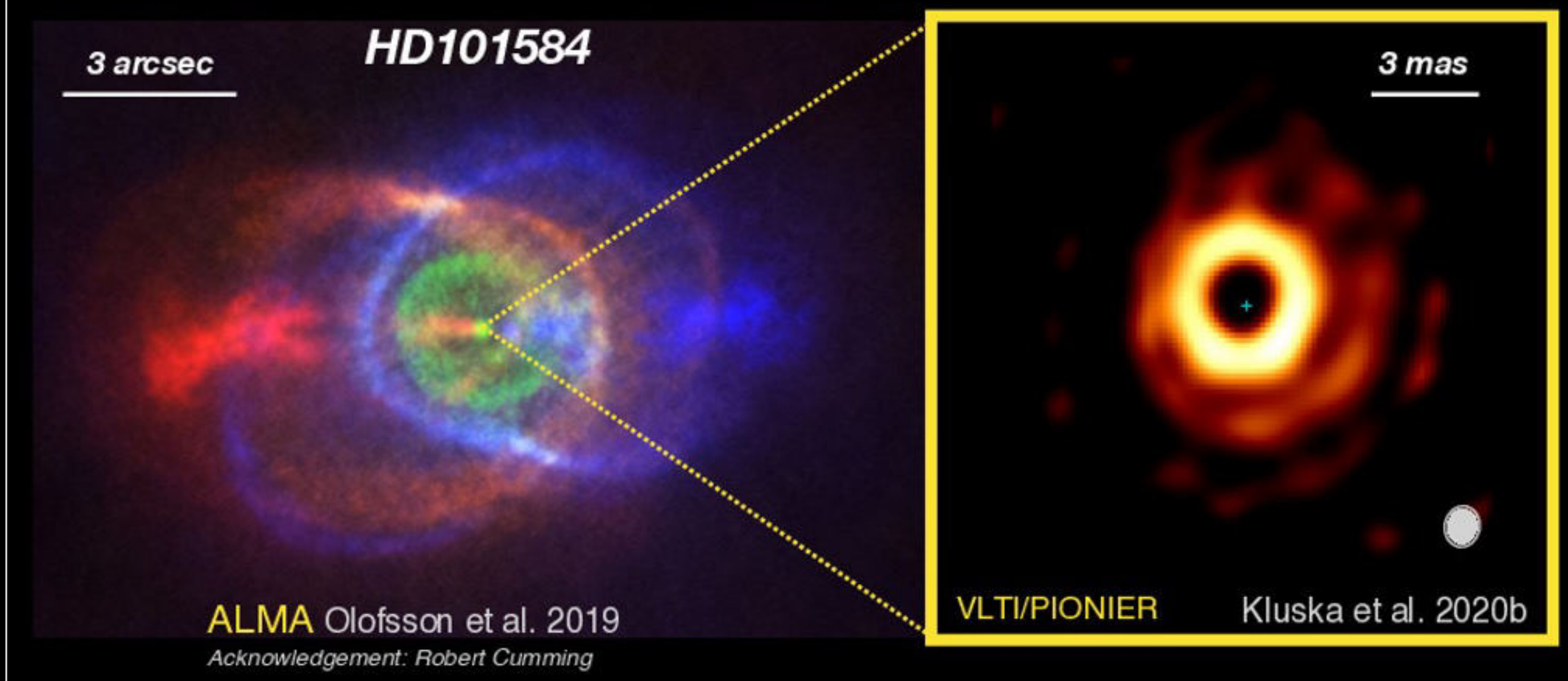
250h with PIONIER and GRAVITY - 11 targets

Main goals:

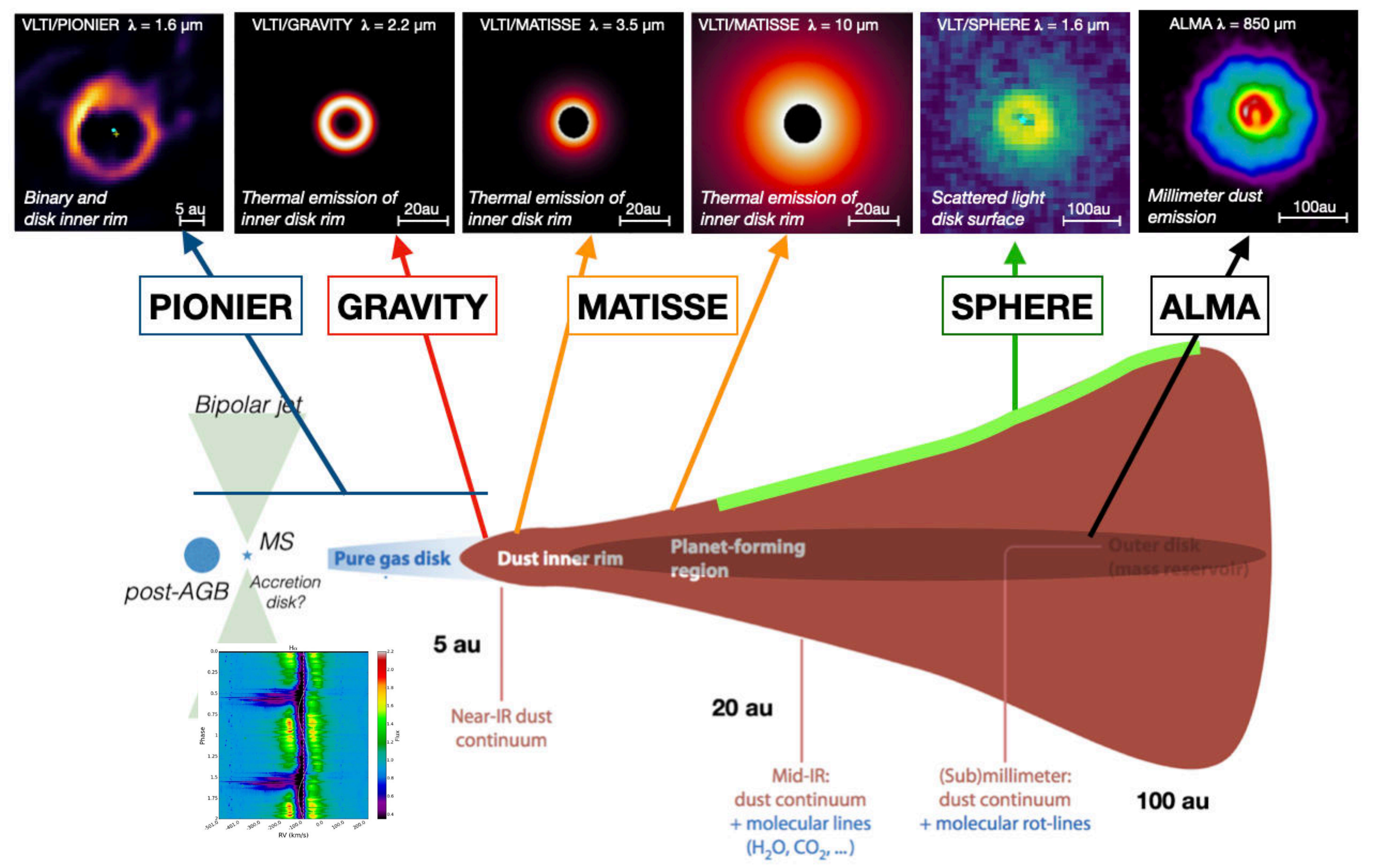
- Structure of the inner rim vs. binary phase
- Circum-secondary accretion

Methodology:

- Image reconstruction
- Geometrical modelling
- Radiative transfer modelling



Kluska et al., 2020, 2021, 2022



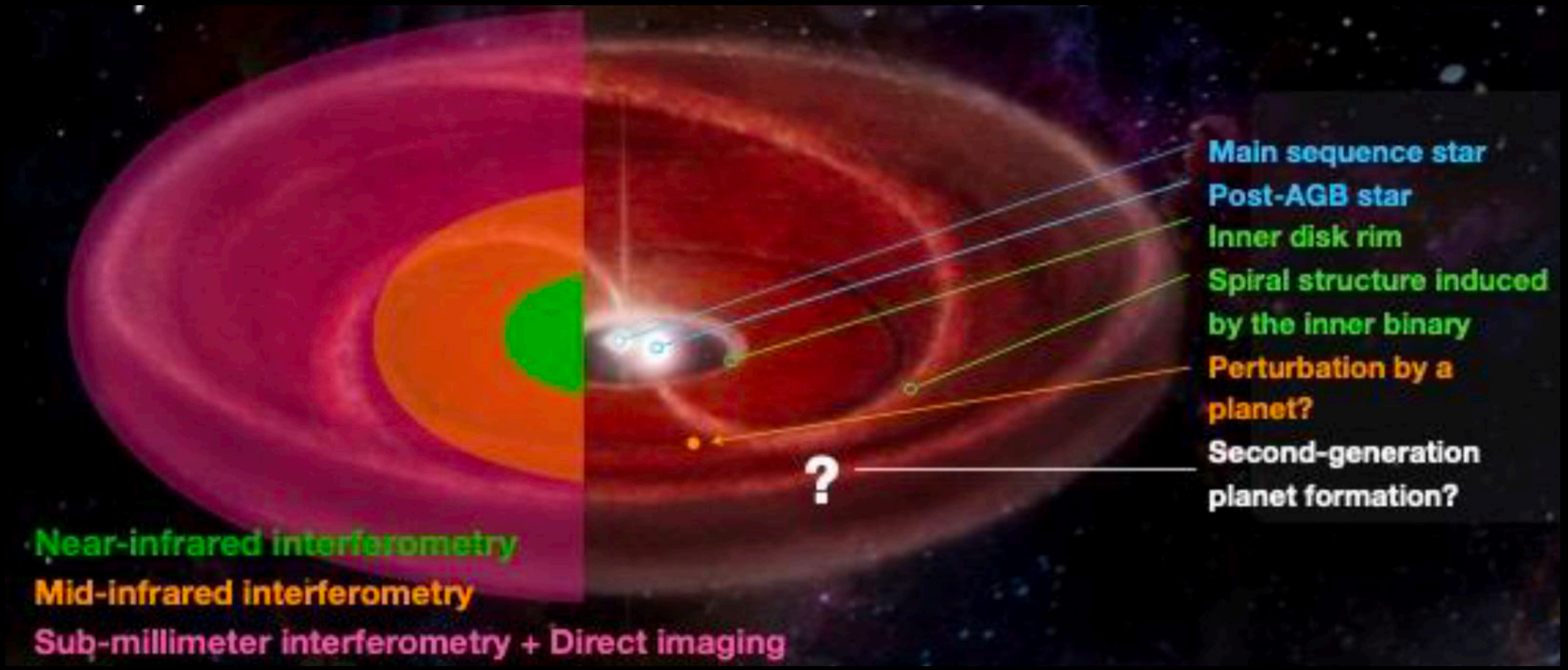
VLTI/PIONIER λ = 1.6 μm
Binary and disk inner rim
5 au
VLTI/GRAVITY λ = 2.2 μm
Thermal emission of inner disk rim
20au
VLTI/MATISSE λ = 3.5 μm
Thermal emission of inner disk rim
20au
VLTI/MATISSE λ = 10 μm
Thermal emission of inner disk rim
20au
VLT/SPHERE λ = 1.6 μm
Scattered light disk surface
100au
ALMA λ = 850 μm
Millimeter dust emission
100au
PIONIER
GRAVITY
MATISSE
SPHERE
ALMA
Bipolar jet
MS
post-AGB
Accretion disk?
Pure gas disk
Dust inner rim
Planet-forming region
Outer disk (mass reservoir)
5 au
20 au
100 au
Near-IR dust continuum
Mid-IR: dust continuum + molecular lines (H_2O, CO_2, ...)
(Sub)millimeter: dust continuum + molecular rot-lines
Hα
Phase
RV (km/s)
Flux

- Measuring the morphology and properties of observed planet-forming disks surrounding evolved binary stars

- Investigating the formation and evolution of second-generation proto-planetary disks

- Building a theoretical model for second-generation planet formation

- Establishing the nexus between planet formation in young and evolved systems

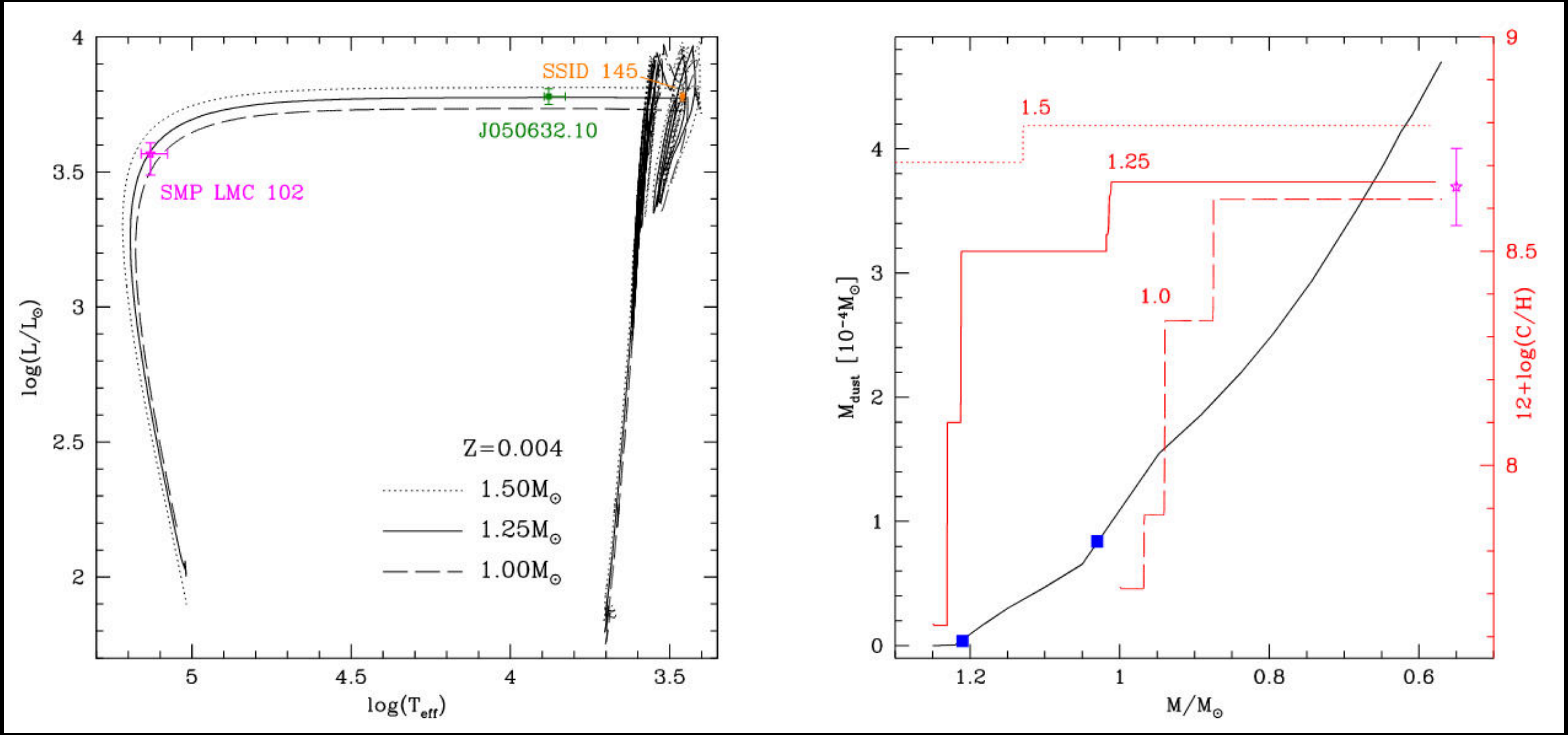


Evolved Stars' Metamorphosis: a Comprehensive Analysis of The AGB to PN Transition

MACQUARIE University
Astrophysics and Space Technologies Research Centre

INAF ISTITUTO NAZIONALE DI ASTROFISICA

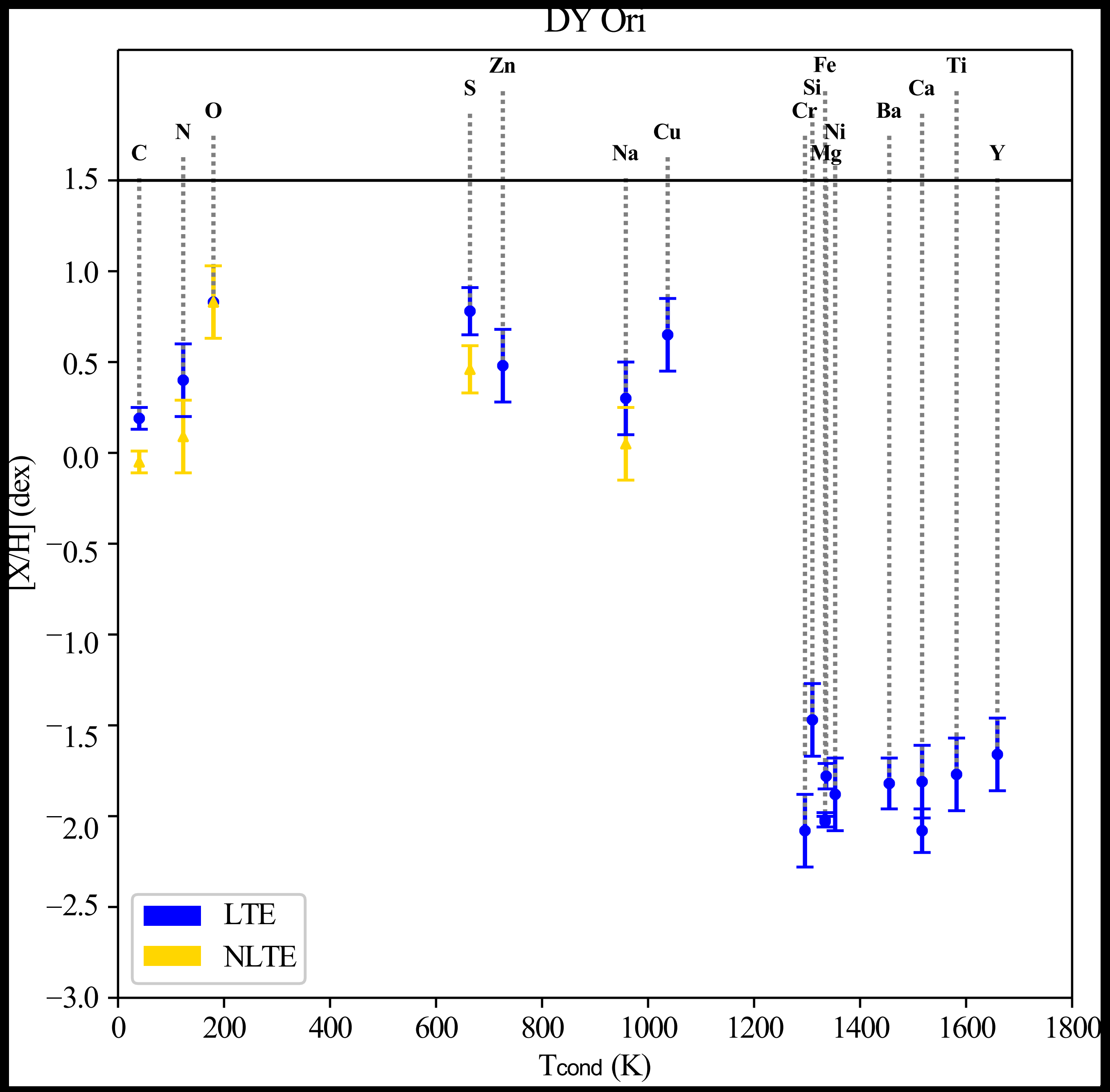
Evolved Stars' Metamorphosis: a Comprehensive Analysis of The AGB to PN Transition

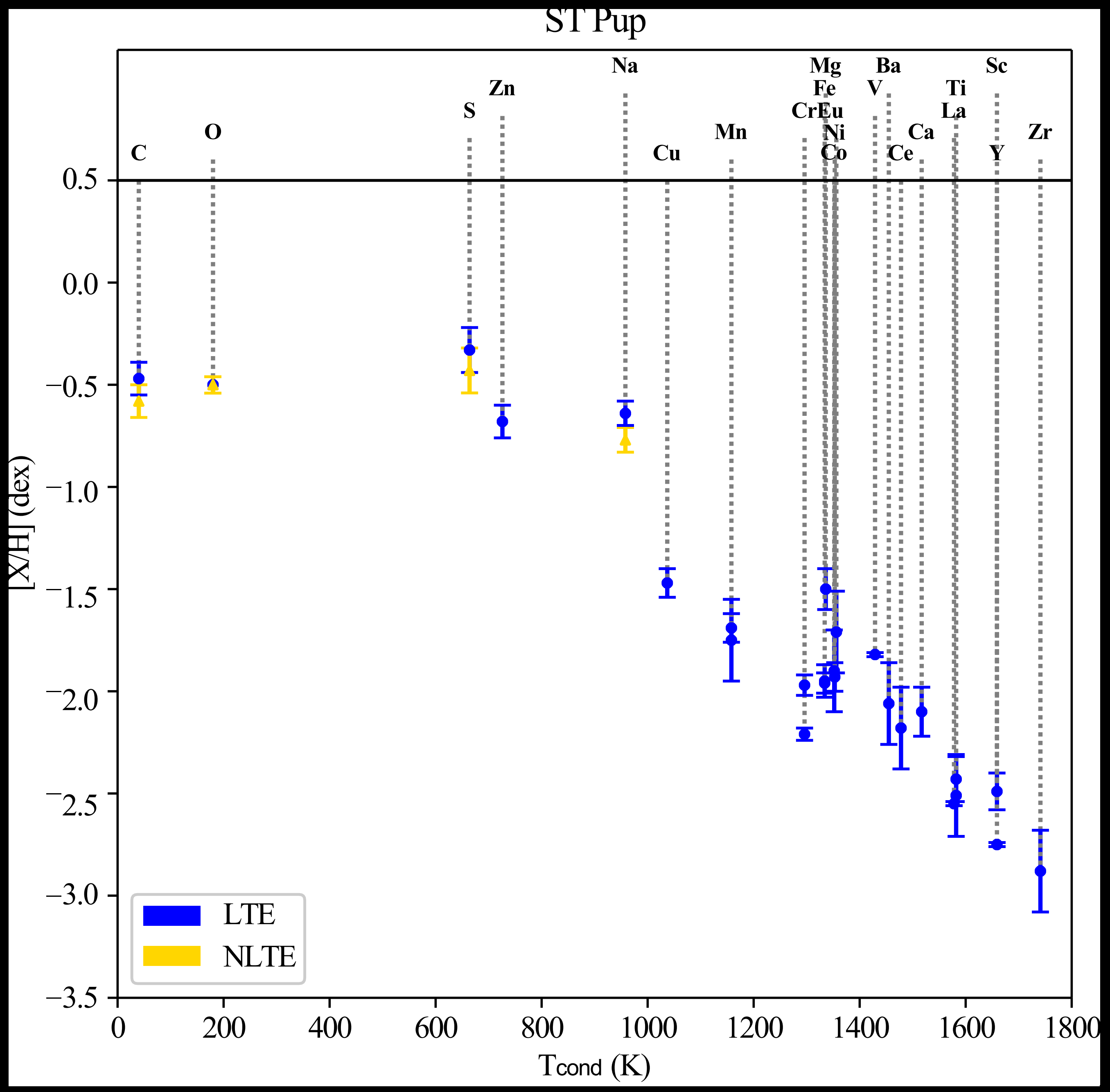


Mon. Not. R. Astron. Soc. **000**, 1–7 (2012) Printed 31 July 2023 (MN LaTeX style file v2.2)

Dust from evolved stars: a pilot analysis of the AGB to PN transition

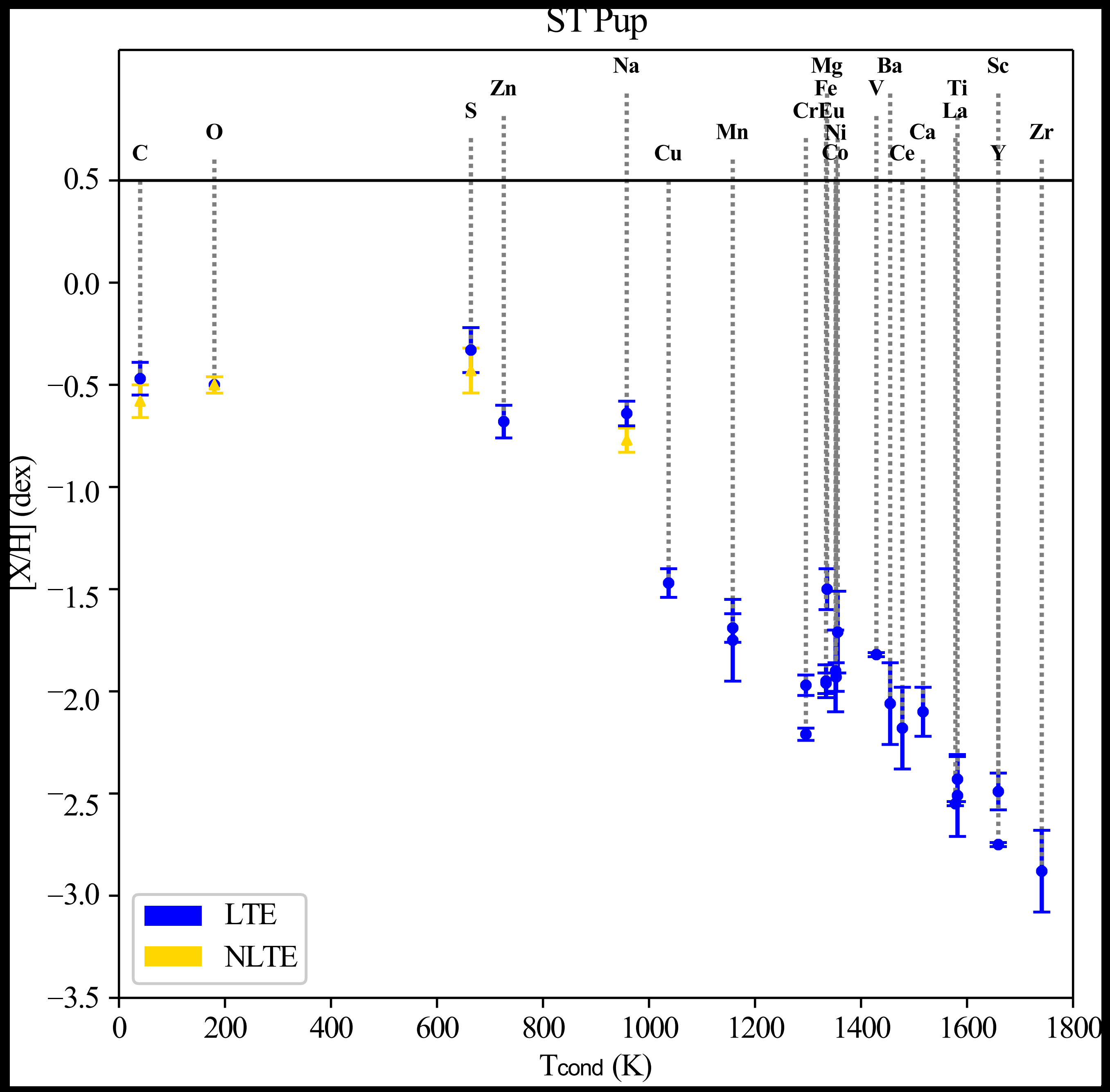
F. Dell'Agli[1★], S. Tosi[1,2], D. Kamath[1,3], L. Stanghellini[4], S. Bianchi[2], P. Ventura[1,5], E. Marini[1], D. A. García-Hernández[6,7]
[1]*INAF, Osservatorio Astronomico di Roma, Via Frascati 33, 00077, Monte Porzio Catone, Italy*
[2]*Dipartimento di Matematica e Fisica, Universitá degli Studi Roma Tre, via della Vasca Navale 84, 00100, Roma, Italy*
[3]*Department of Physics and Astronomy, Macquarie University, Sydney, NSW 2109, Australia*
[4]*NSF's NOIRLab, 950 Cherry Ave., Tucson, AZ 85719, USA*

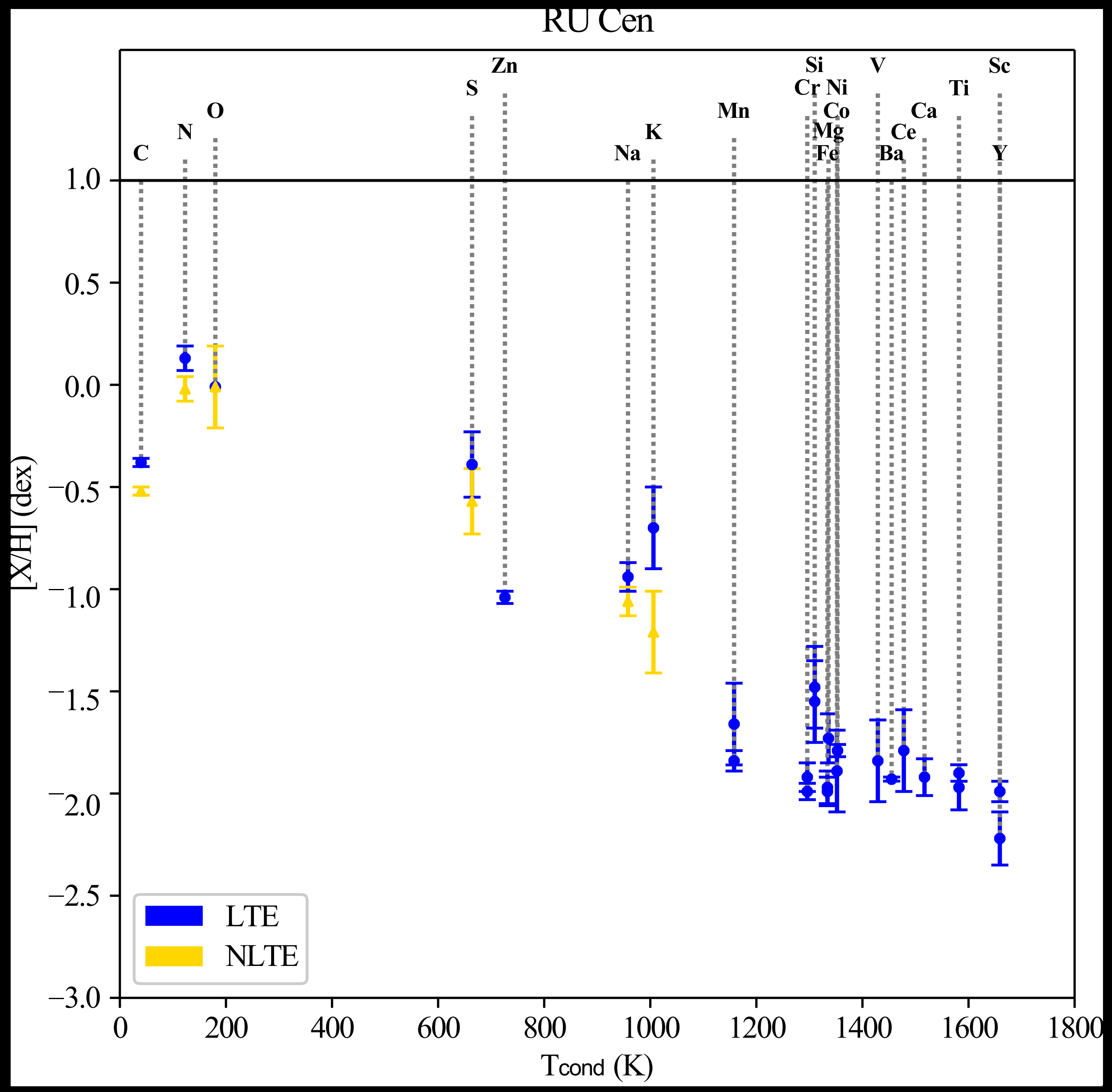




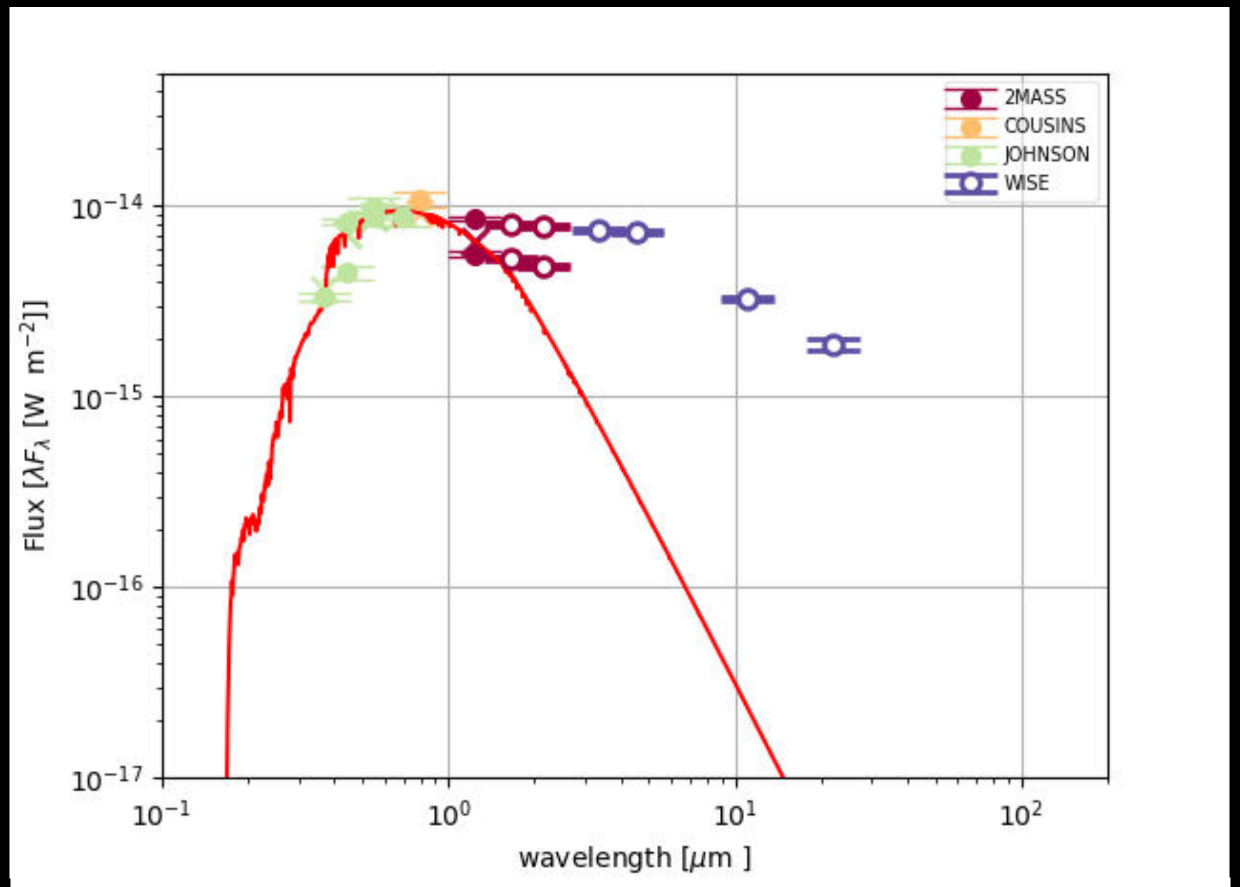
Chemical Depletion in Evolved Stars with Planet Forming Disks!

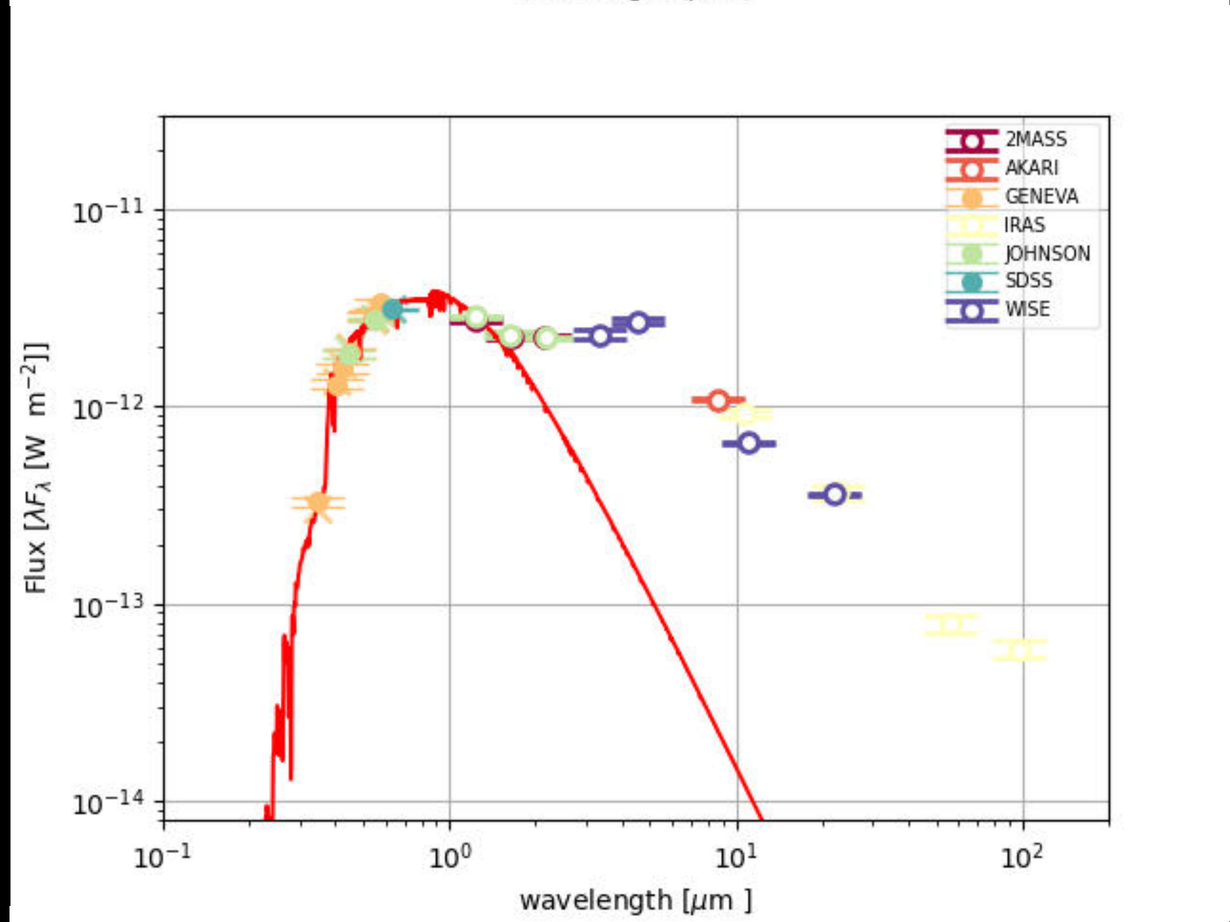
Mohorian et al., 2024; in-prep

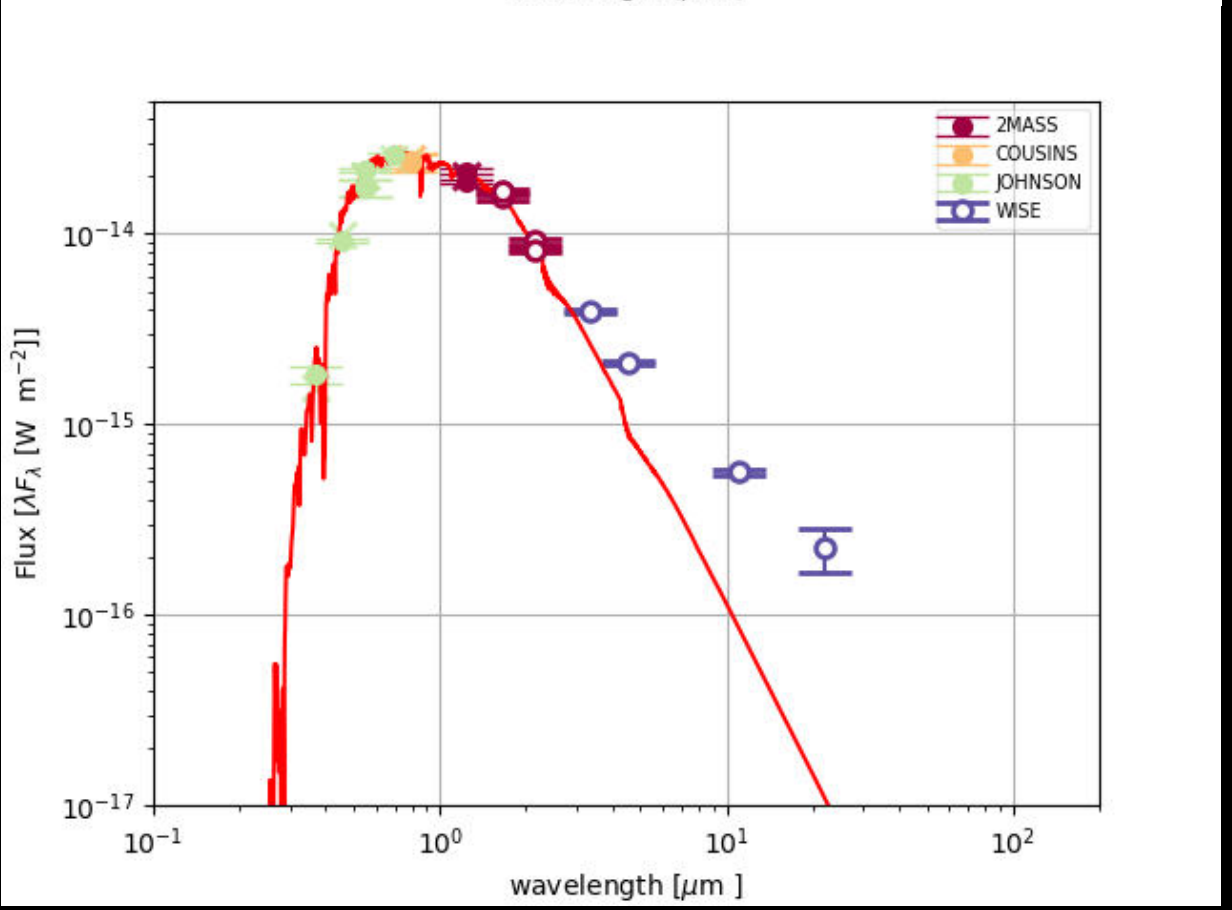


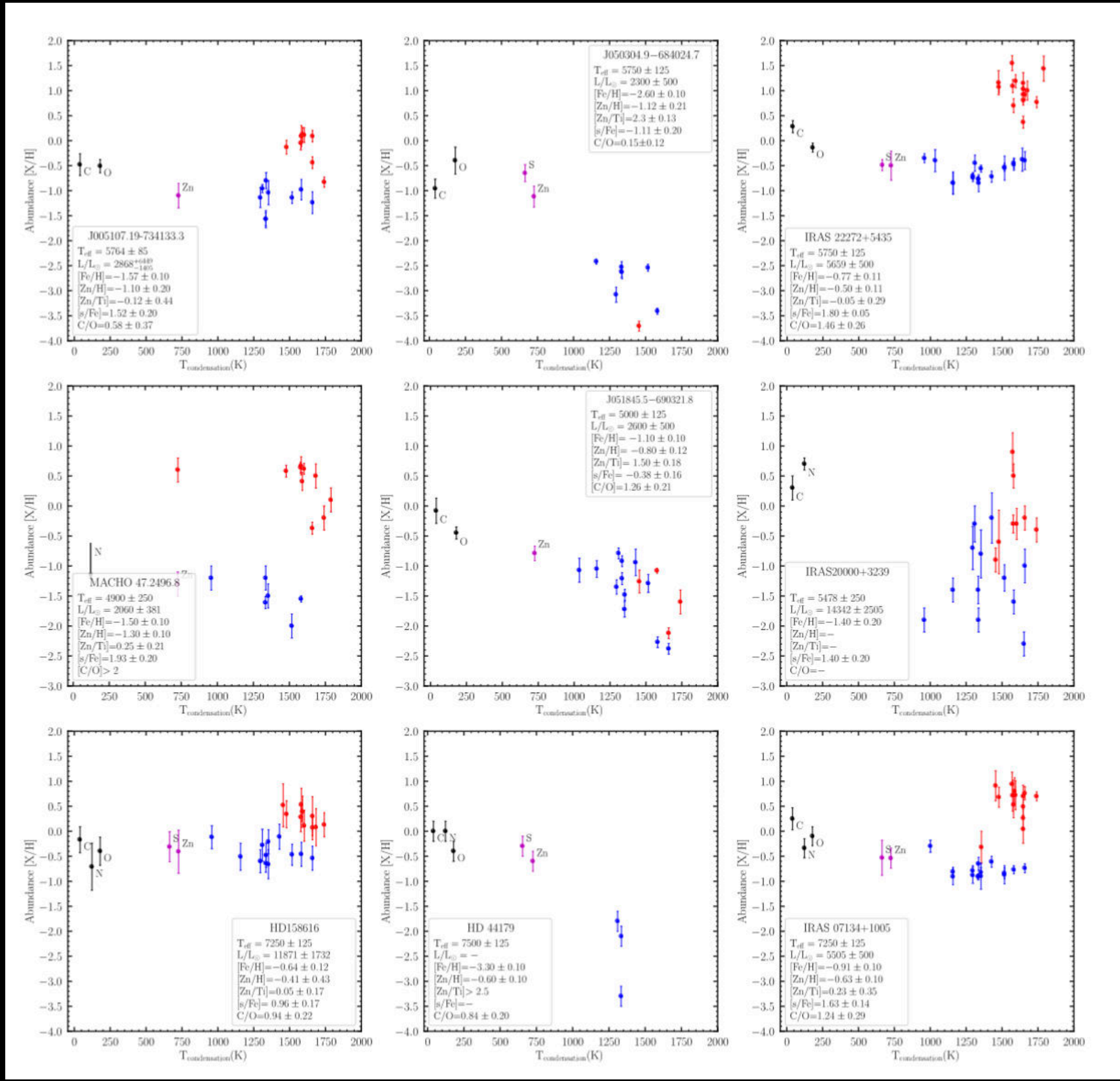


Intrinsically s-Process Enhanced Evolved Binaries



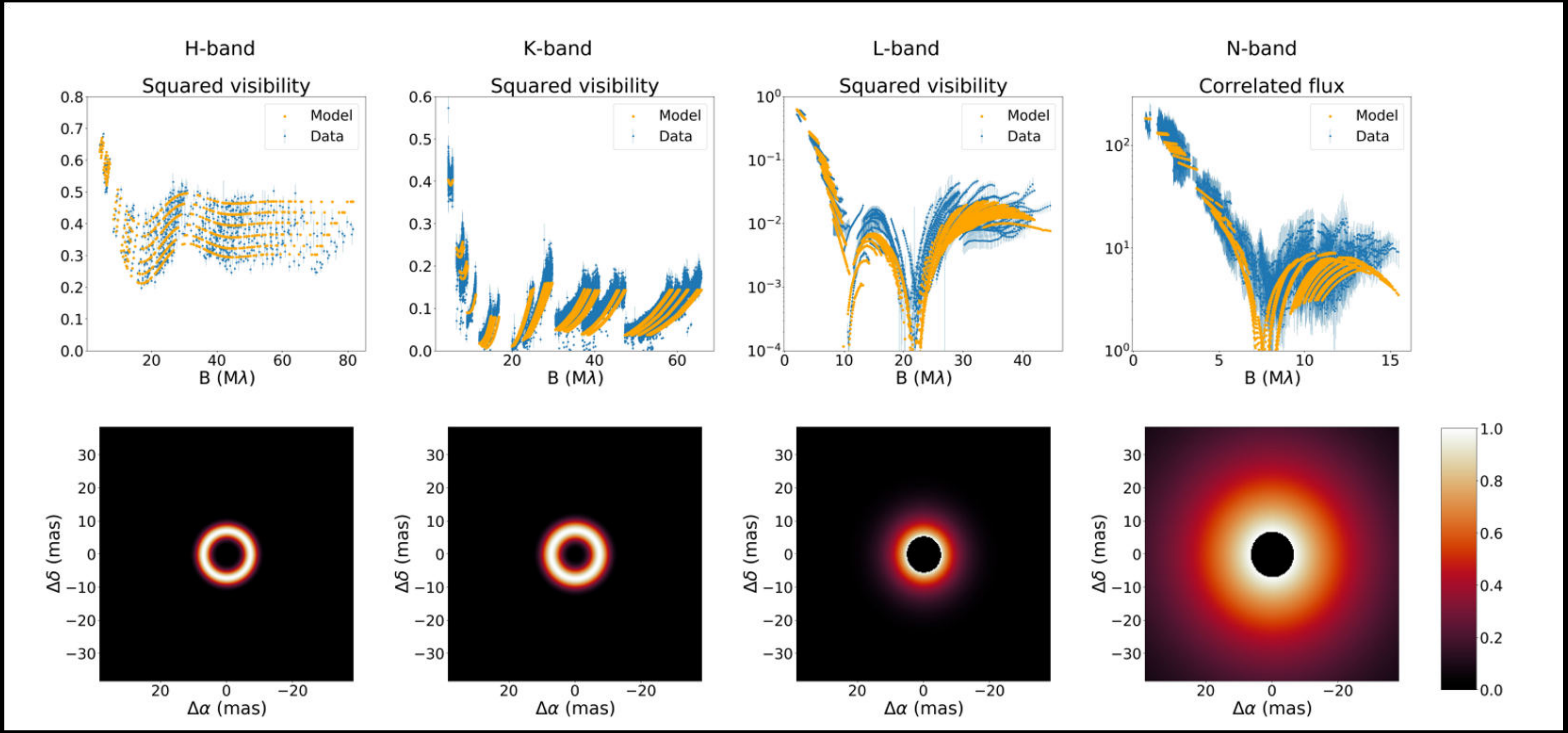






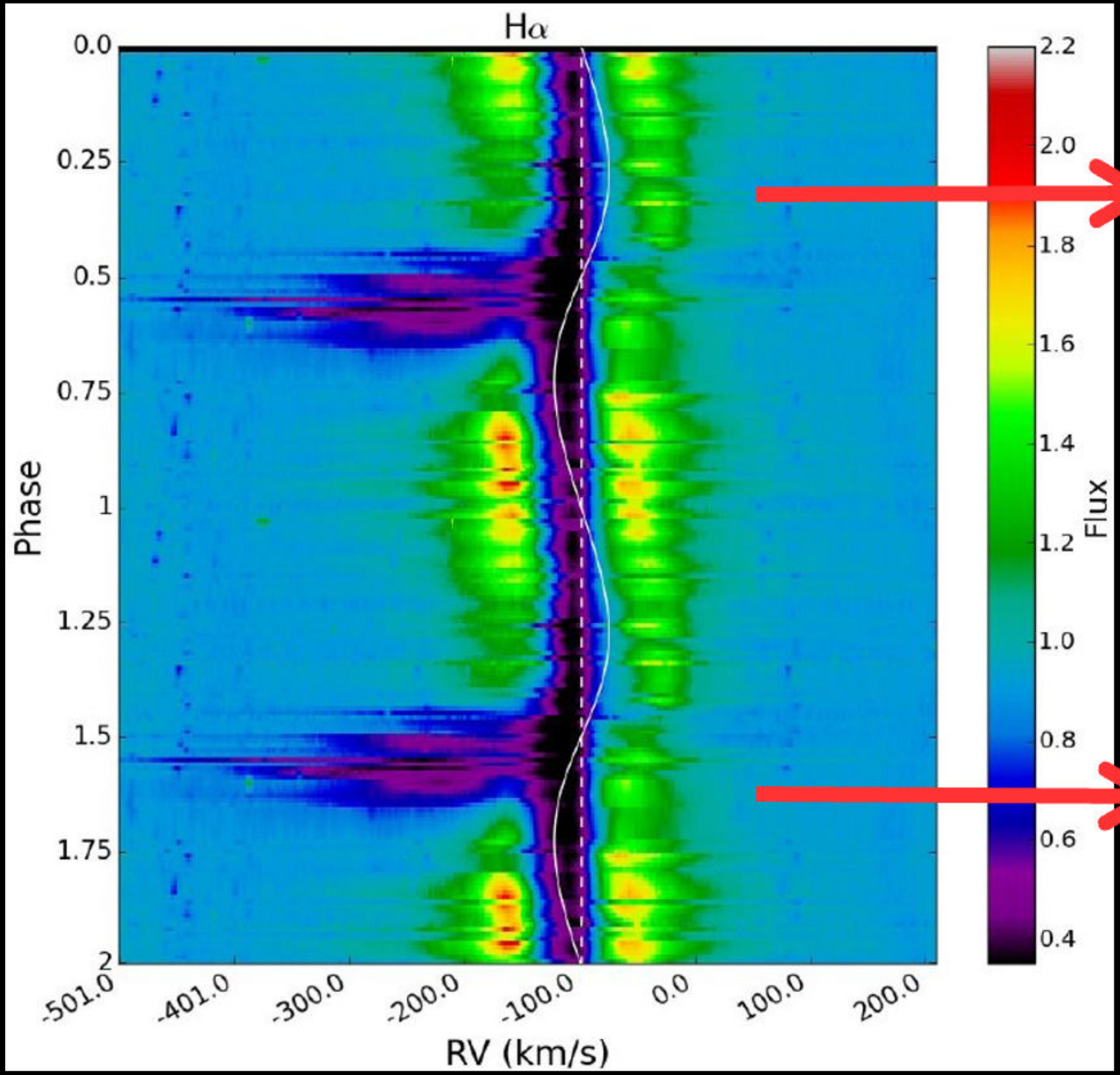
Menon et al., 2024

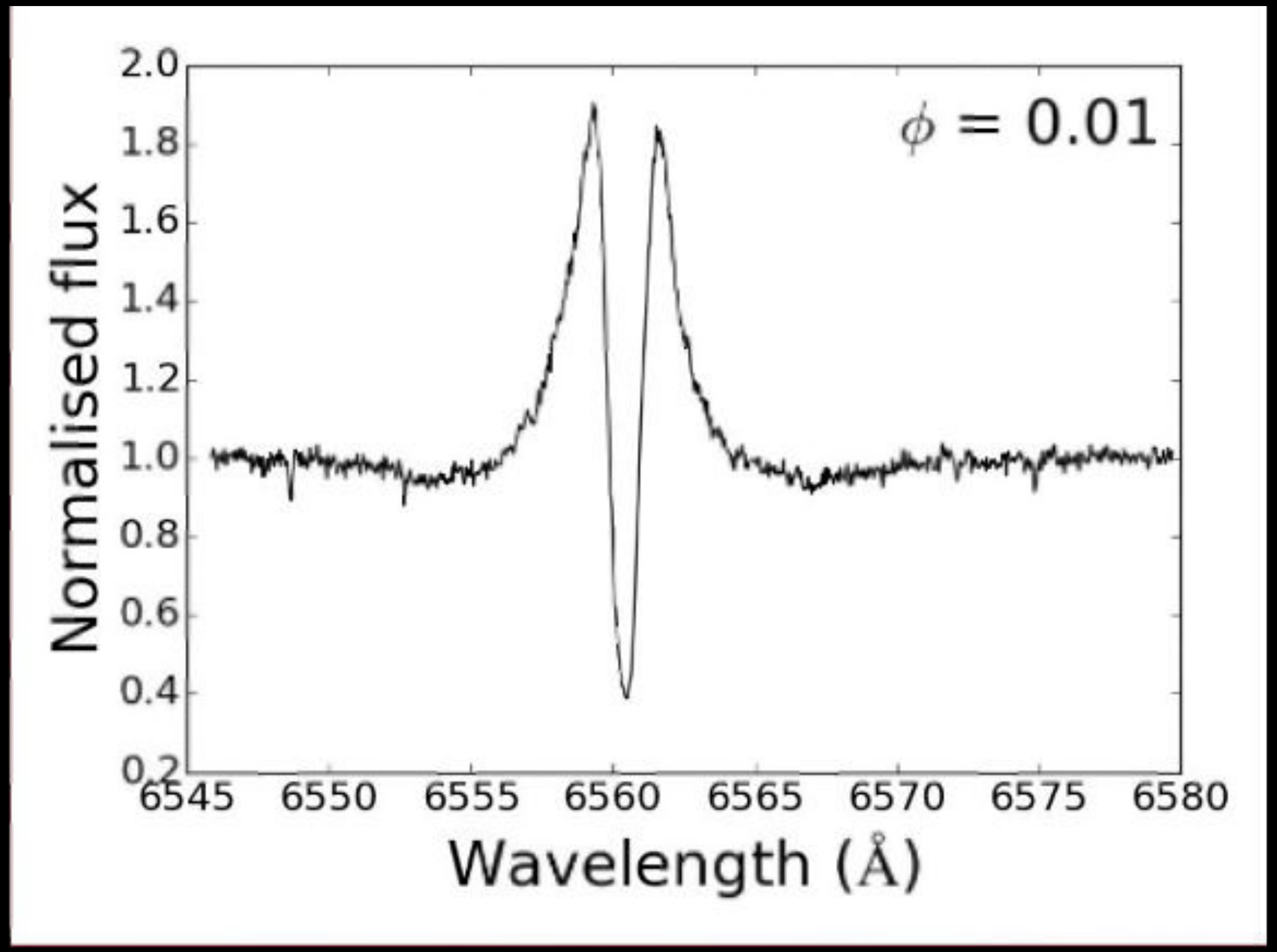
post-AGB circumbinary discs: near & mid-IR interferometry

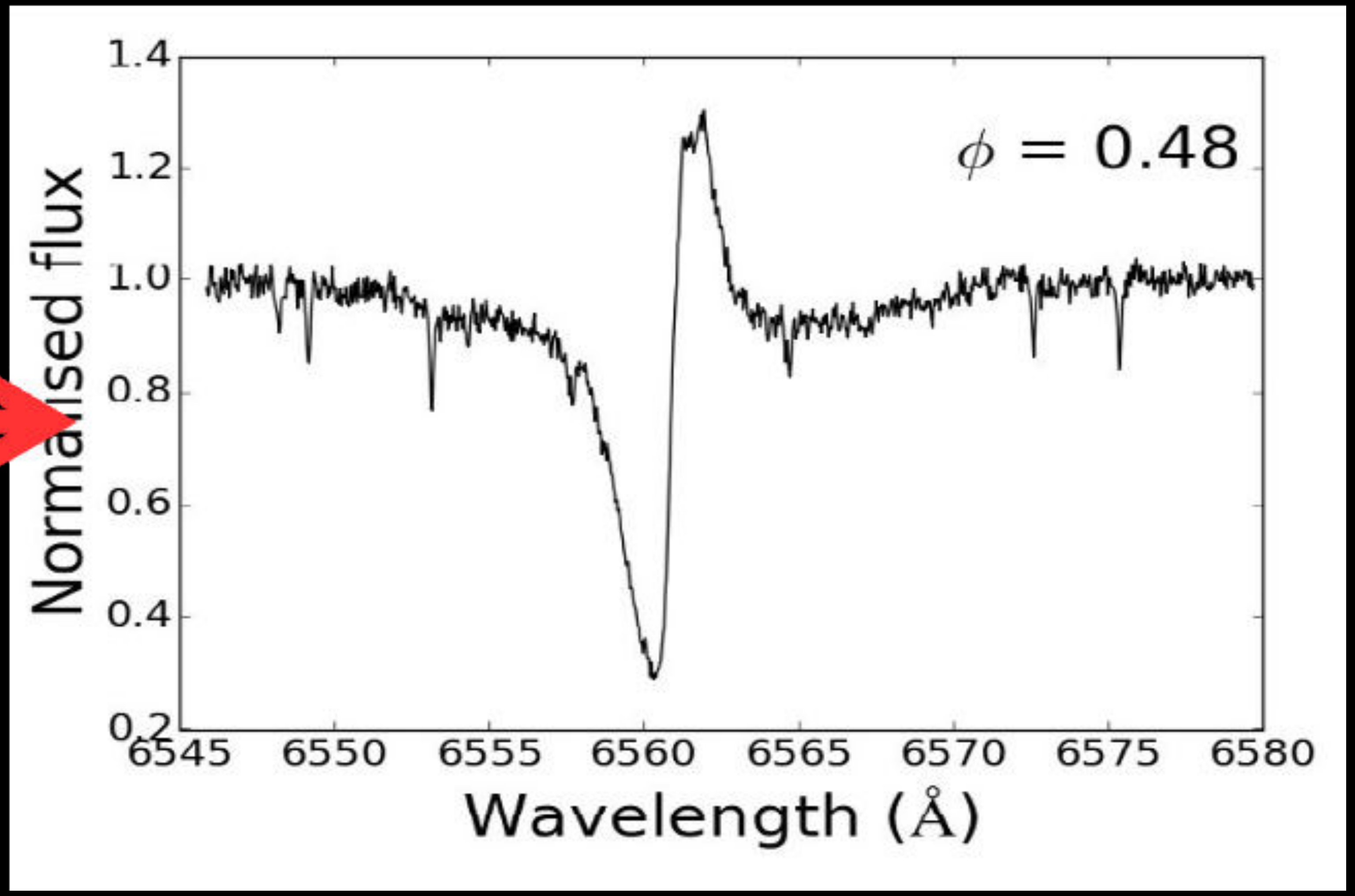


RT models of protoplanetary discs adapted to central luminous source fit very well.

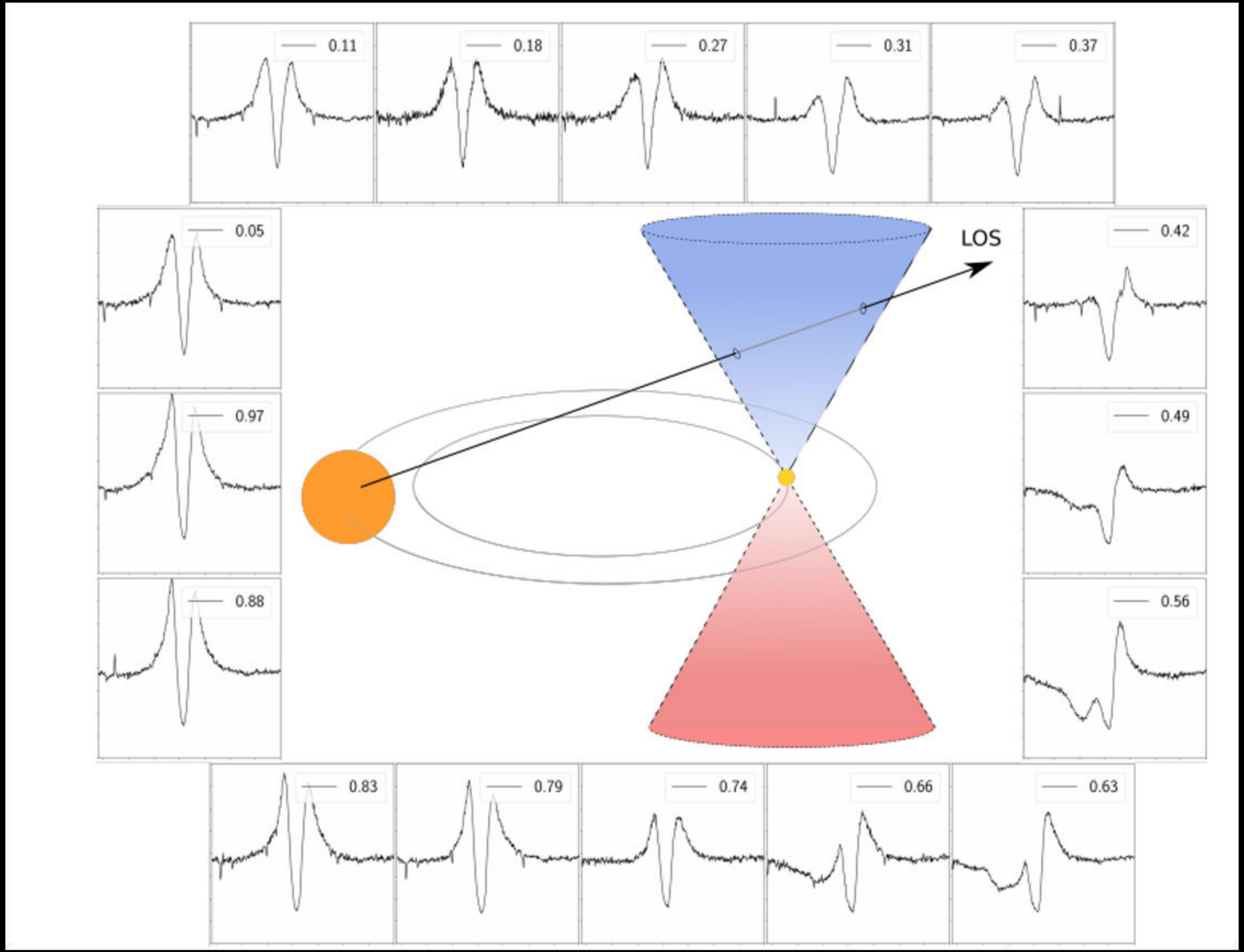
Detection of JETS from Dynamic Spectra







Bollen et al., 2019, 2020, 2022

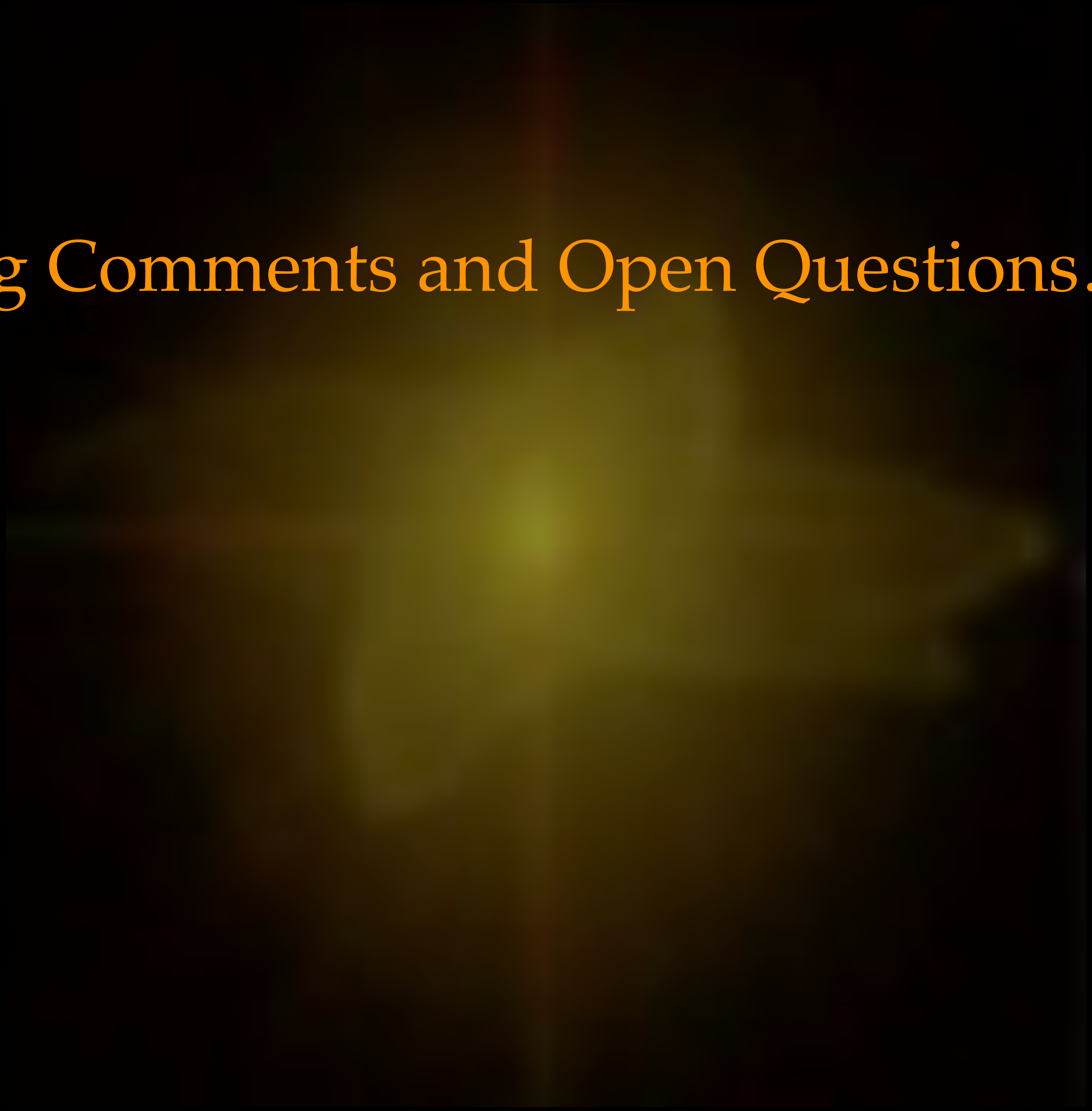


Time-resolved spectroscopy:
- spatio-kinematic (geometric modelling)
- RT (constrains are the Balmer lines)

- Jet opening angle
- Jet tilt
- Angular Velocity structure
- Density structure
- Binary (radius components, orbit)

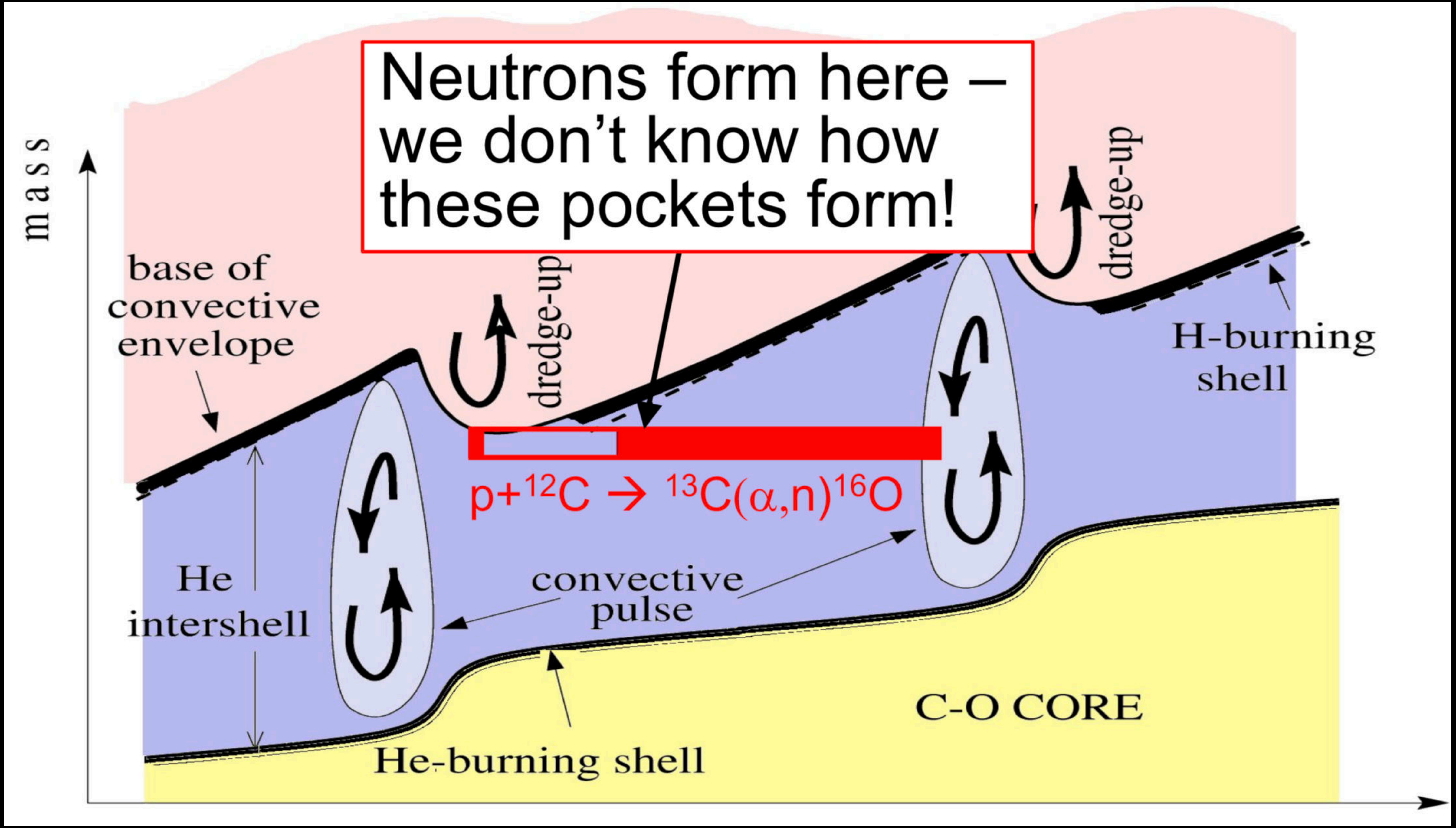
- Wavelength Coverage: 380nm to 900nm
  - C I lines at 5380˚A(left panel) and 6587˚A(right panel)
  - High excitation oxygen multiplet at 6156 Å and/or the forbidden oxygen lines at 6300 and 6363 Å.
  - N I lines at 7423.64˚A, 8223.128˚A, 8655.878˚A and 8728.91˚A.
  - Ba II lines (e.g., at 4554.03˚A and at 6496.89˚A)
  - Pb I line at 4057.807 Å; Pb II line at 5608.853 Å
  - Zn I line at 4810.540˚A

Closing Comments and Open Questions…



Closing Comments and Open Questions…

- ★ AGB nucleosynthesis is not homogenous (even within a mass and metallicity range)
- ★ Not all AGB stars are producers of C and *s*-process elements.
- ★ How does this affect Galactic chemical enrichment models?


Neutrons form here – we don't know how these pockets form!
mass
base of convective envelope
dredge-up
dredge-up
H-burning shell
p+12C → 13C(α,n)16O
He intershell
convective pulse
C-O CORE
He-burning shell