50th Anniversary of the Inauguration of the Anglo-Australian Telescope

Advancing Our Understanding of Cosmic Origins: Insights from AAT's Multi-object Spectroscopy

Dr Devika Kamath

MACQUARIE University
Astrophysics and Space Technologies Research Centre

Students: Kateryna Andrych, Meghna Menon, Maksym Mohorian, Silvia Tosi, Toon De Prins, Kayla Martin, Zara Osborne

Collaborators: Hans Van Winckle, Paolo Ventura, Flavia Dell'Agli, Anish Amarsi, Amanda Karakas, Orsola De Marco, Mark Wardle, Anibal Garcia Hernandez

INAF ISTITUTO NAZIONALE DI ASTROFISICA

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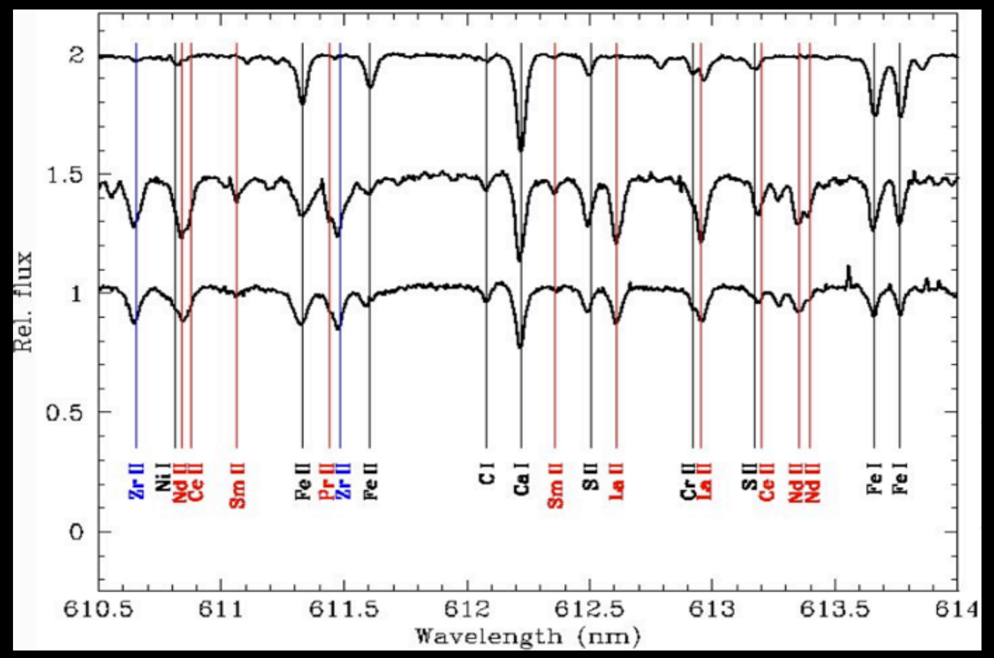
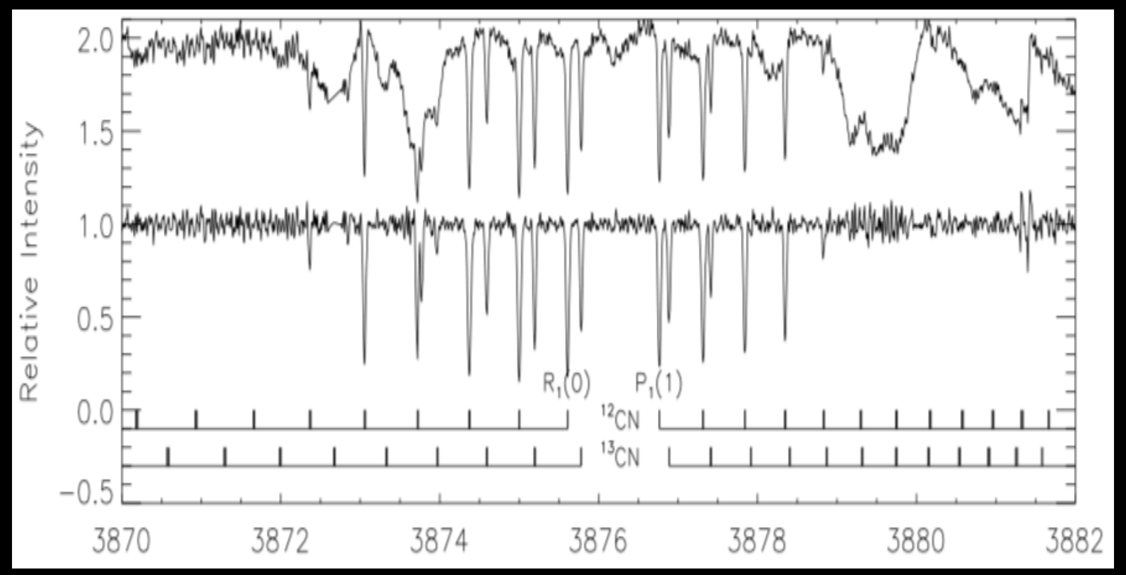
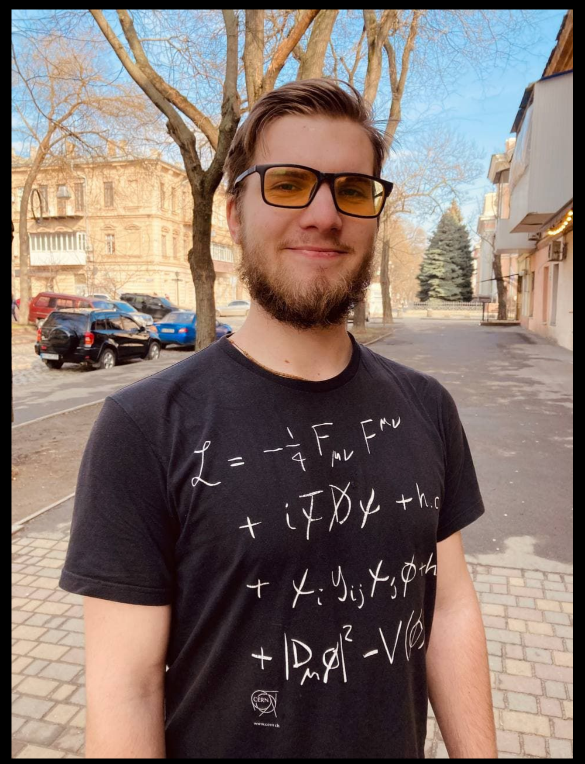
Evolved stars as tracers for AGB nucleosynthesis



Optical spectra - UVES/VLT



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


Maksym Mohorian


Meghna Menon


Silvia Tosi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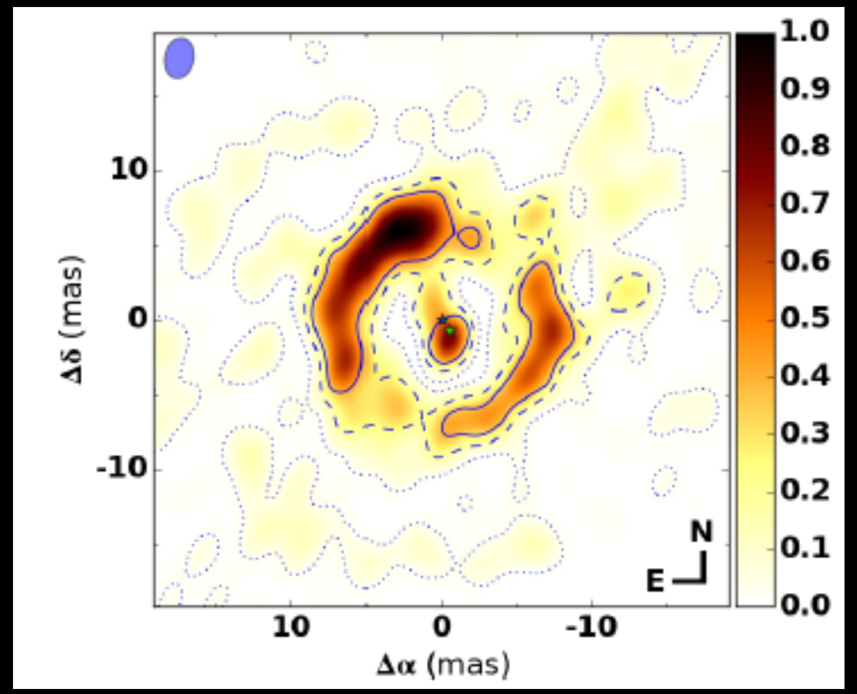
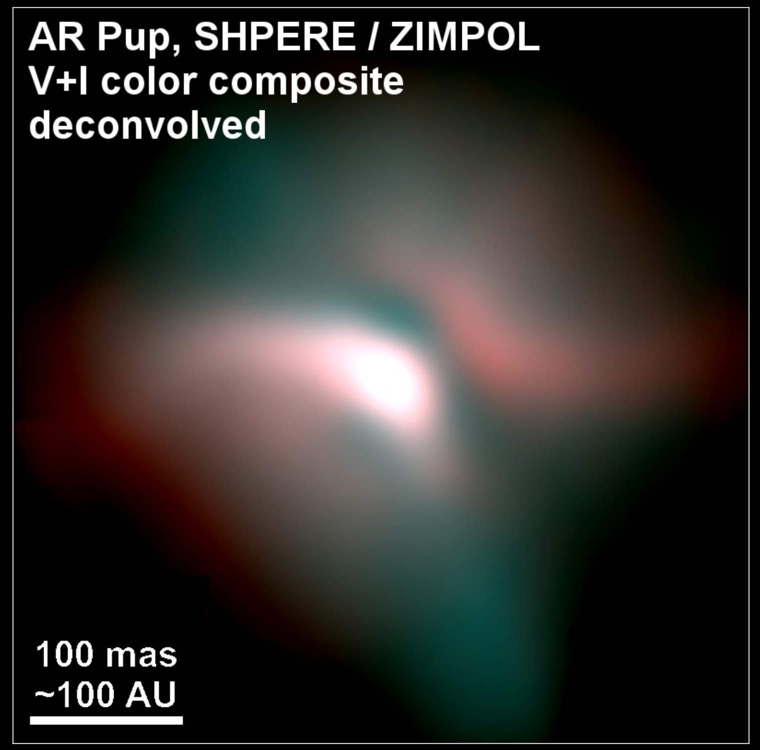
Investigating the second-generation proto-planetary disks



Hillen et al., 2016

H-band reconstruction PIONIER/VLTI



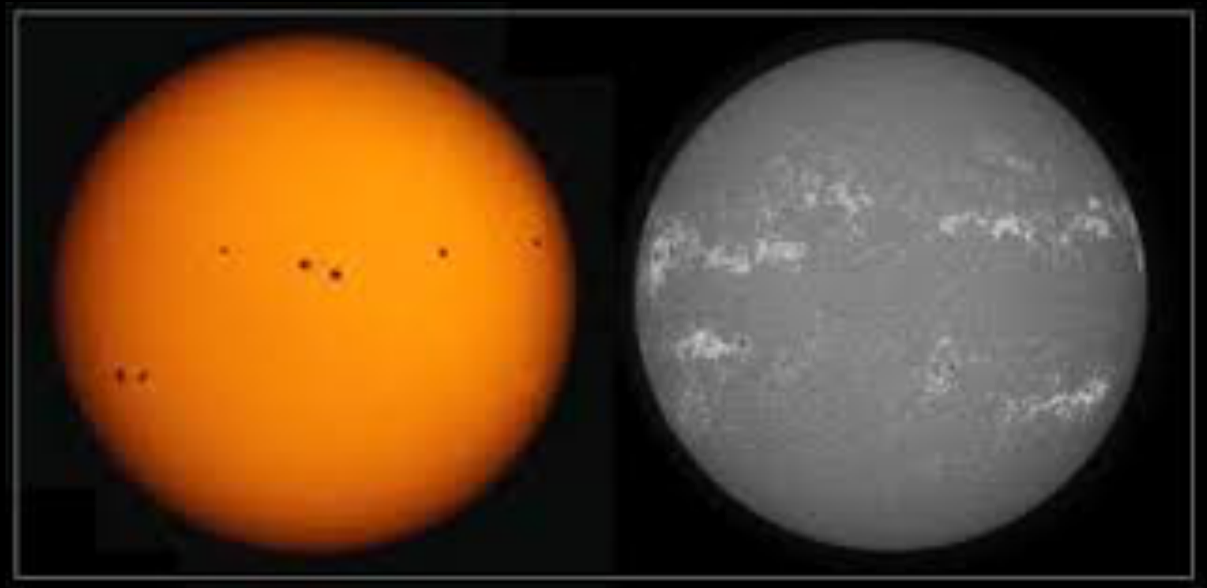
Ertel, Kamath, et al., 2018


Kateryna Andrych


Toon de Prins


Kayla Martin

Chromospheric activity in stars




Deepak Chahal

Key Questions Explored through AAT Observations

1. Origin of elements and refining stellar yields: How do low- and intermediate-mass stars contribute to cosmic chemical budget?
2. Dust production and evolution in evolved stars: How does dust form and evolve during and after the AGB phase?
3. Binary interactions in evolved stars: How do binary interactions shape the evolution of low- and intermediate-mass?
4. Second-generation proto-planetary disks: Can these astrophysical sites host planets?

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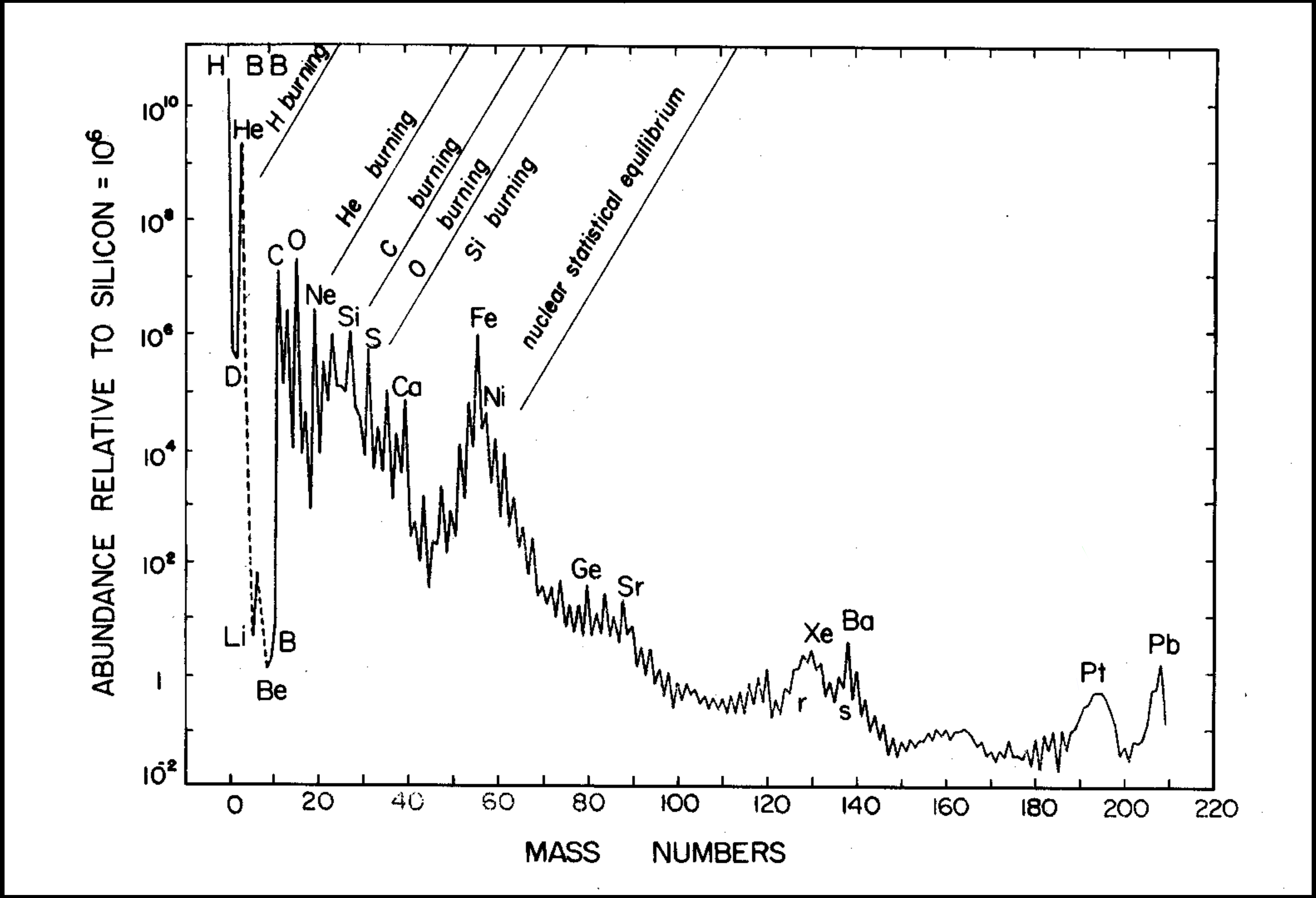
Making Heavy Elements by Neutron Capture



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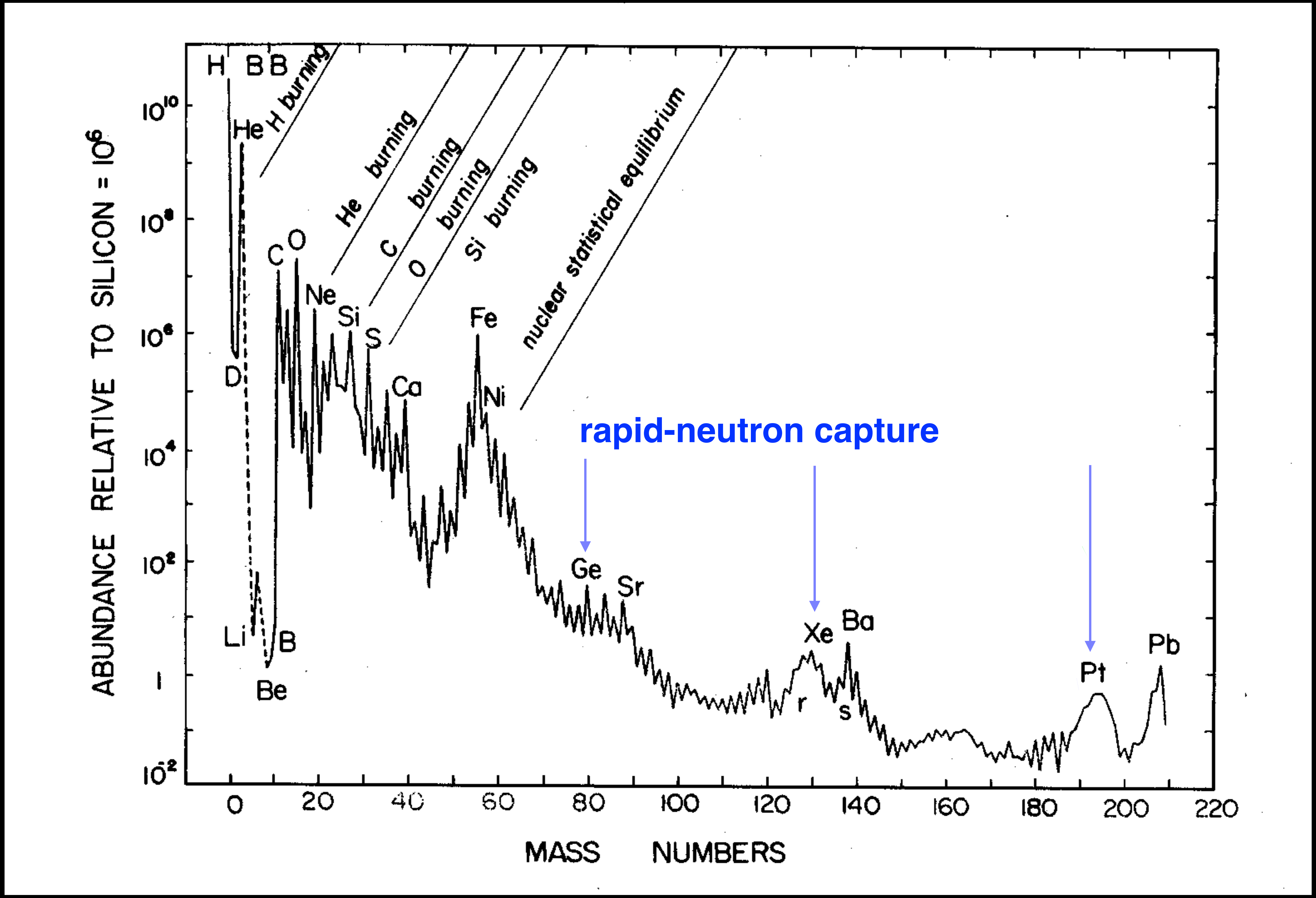
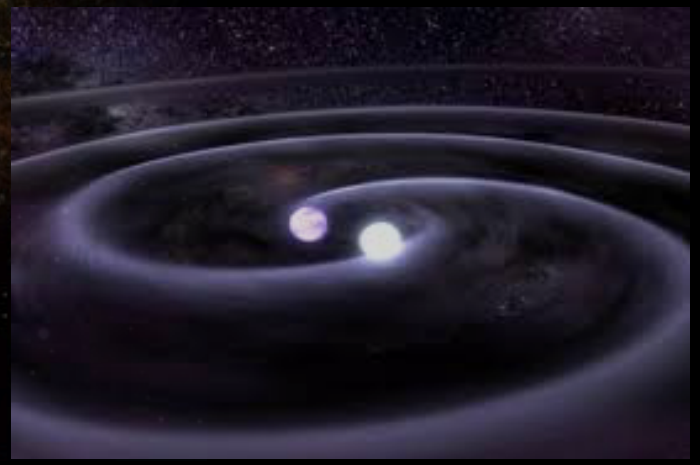


RAPID

NEUTRON CAPTURE PROCESS

n-capture rate < β-decay rate

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



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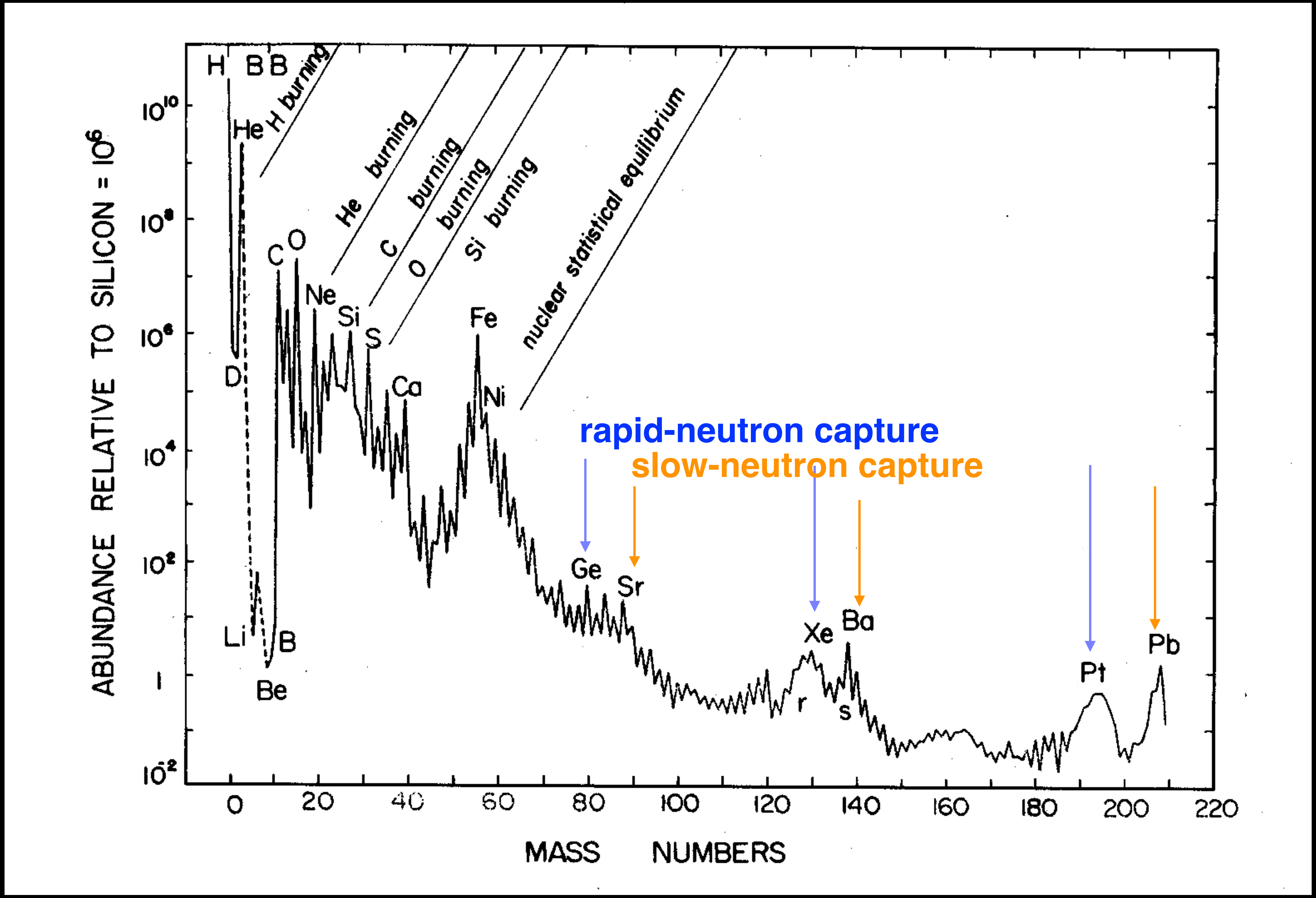

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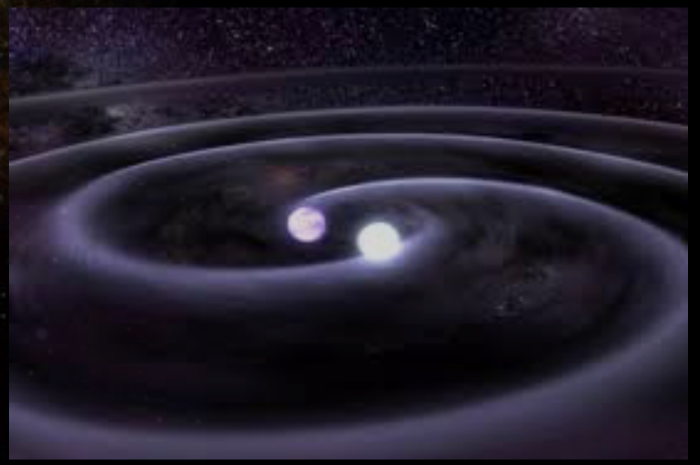


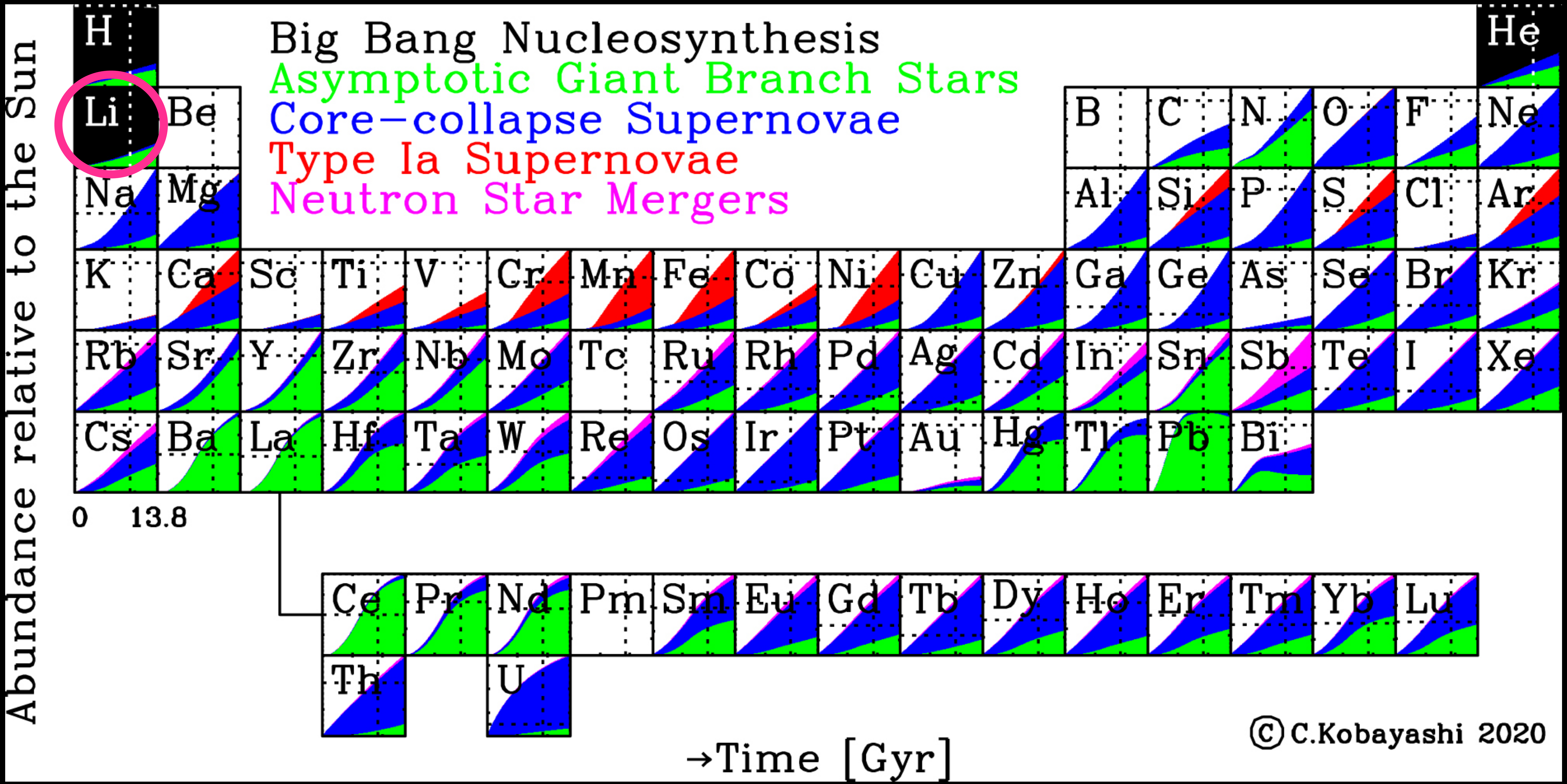
SLOW

NEUTRON CAPTURE PROCESS

n-capture rate >> β-decay rate

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

Limitations in Current Stellar Yields…



N, Li - INTERMEDIATE MASS STARS!

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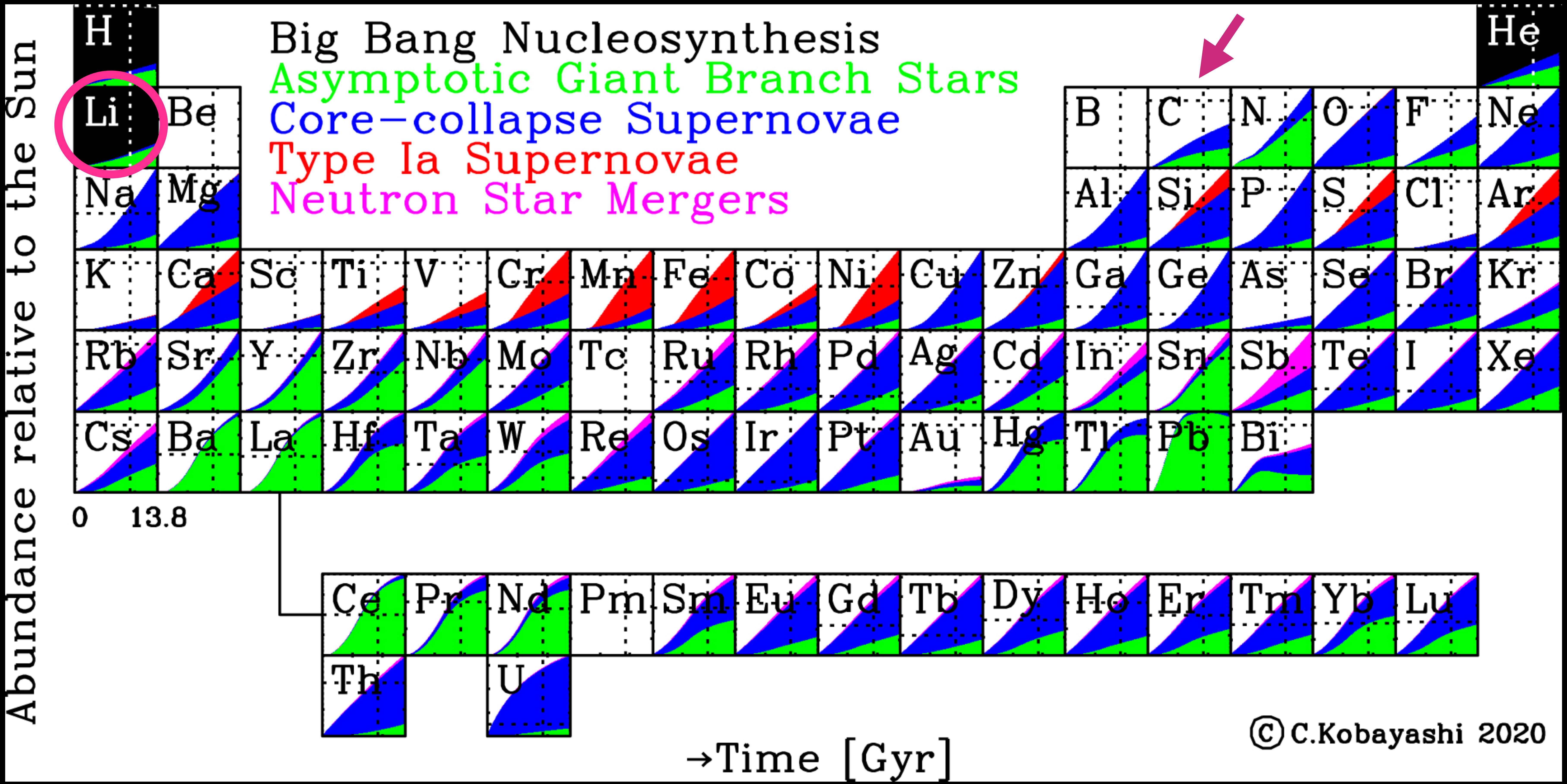

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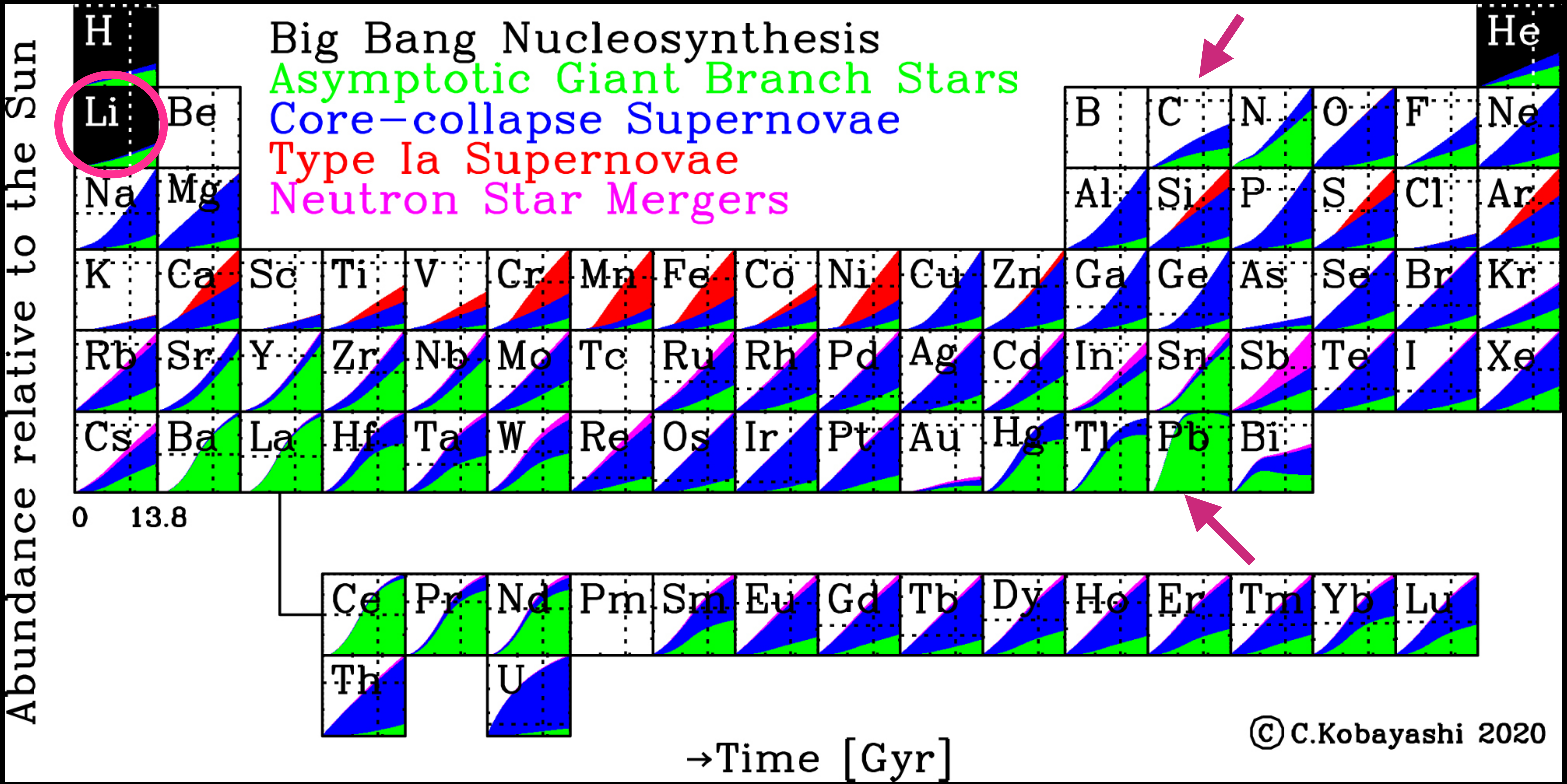

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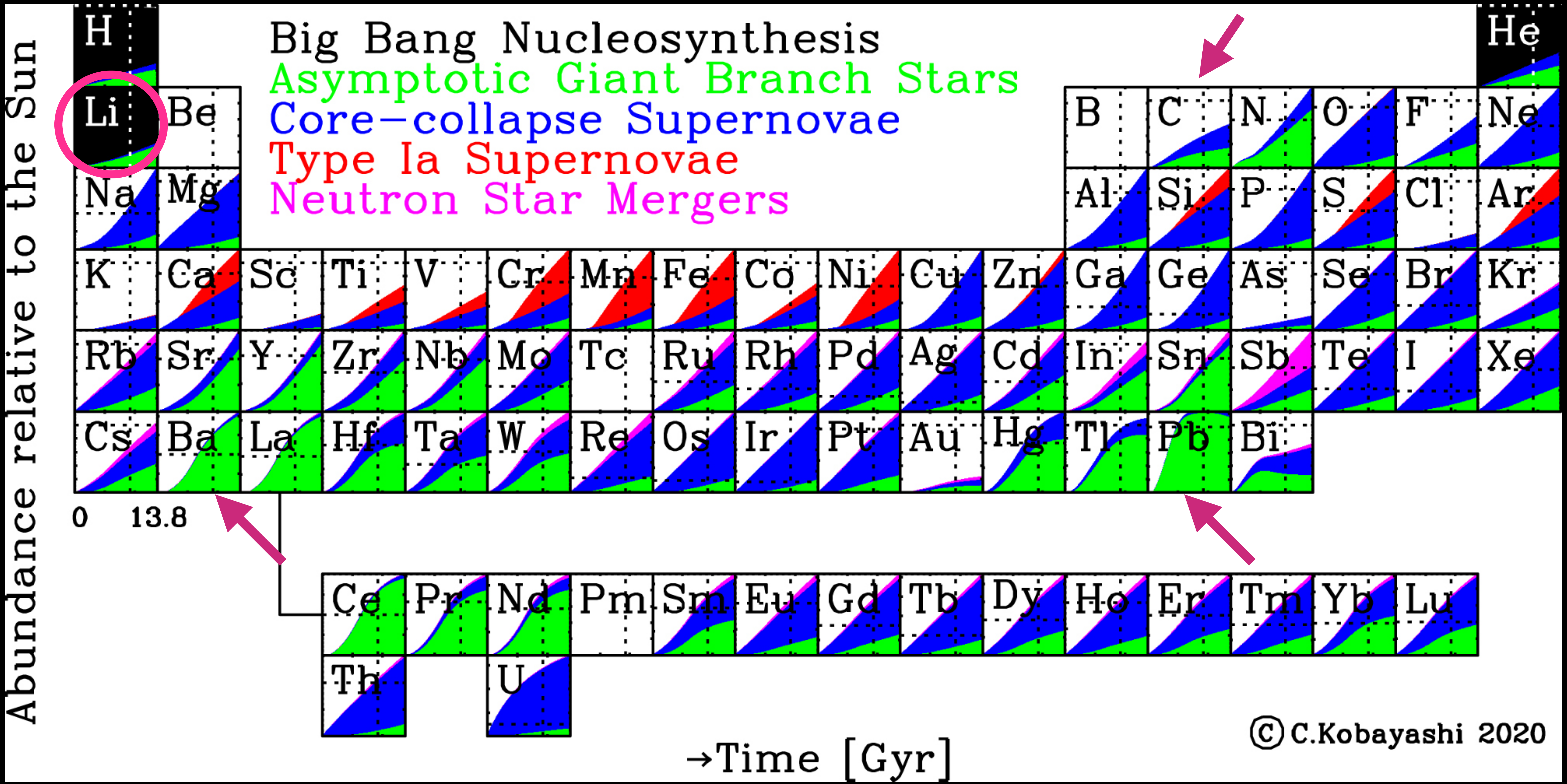

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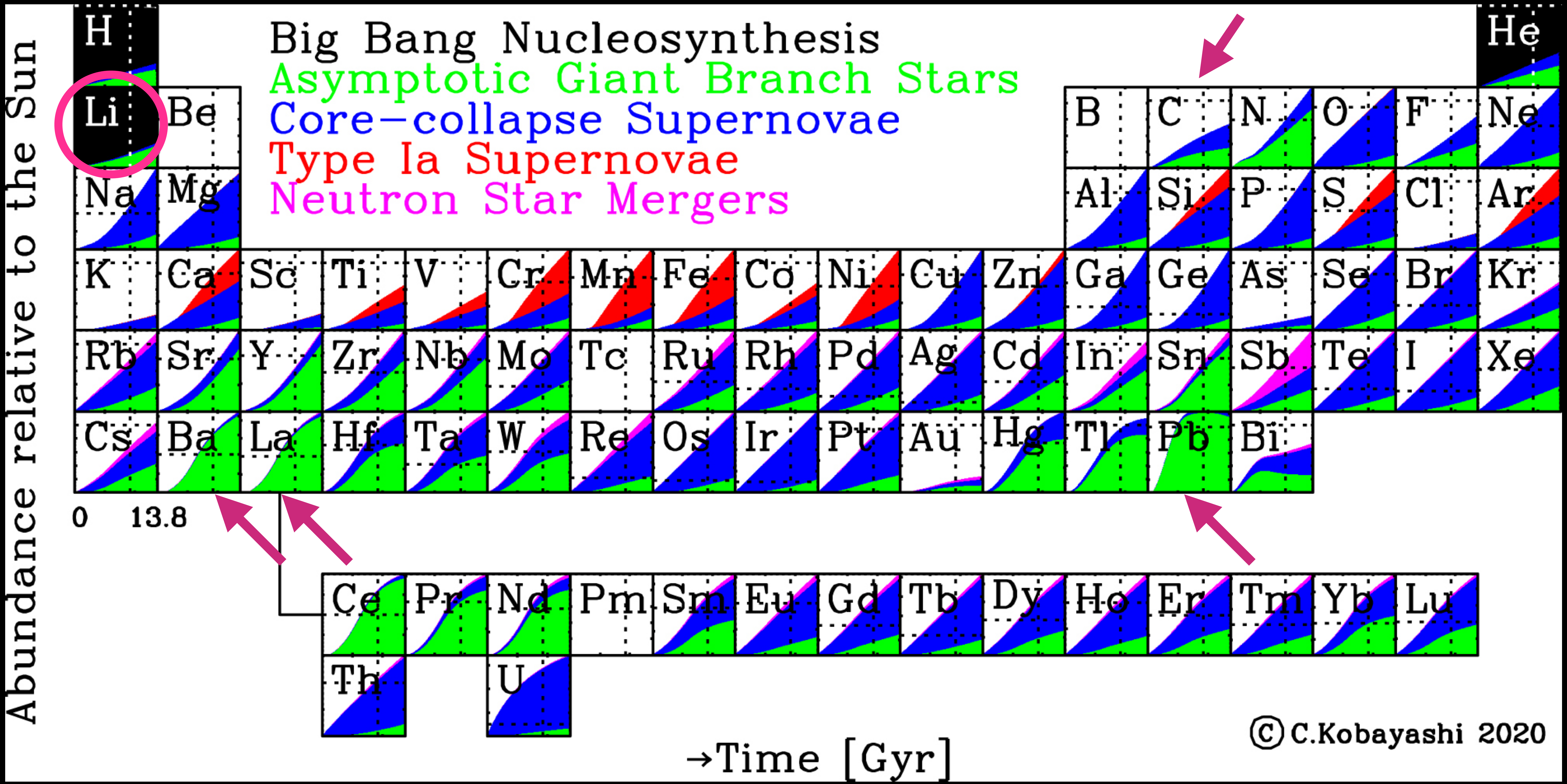

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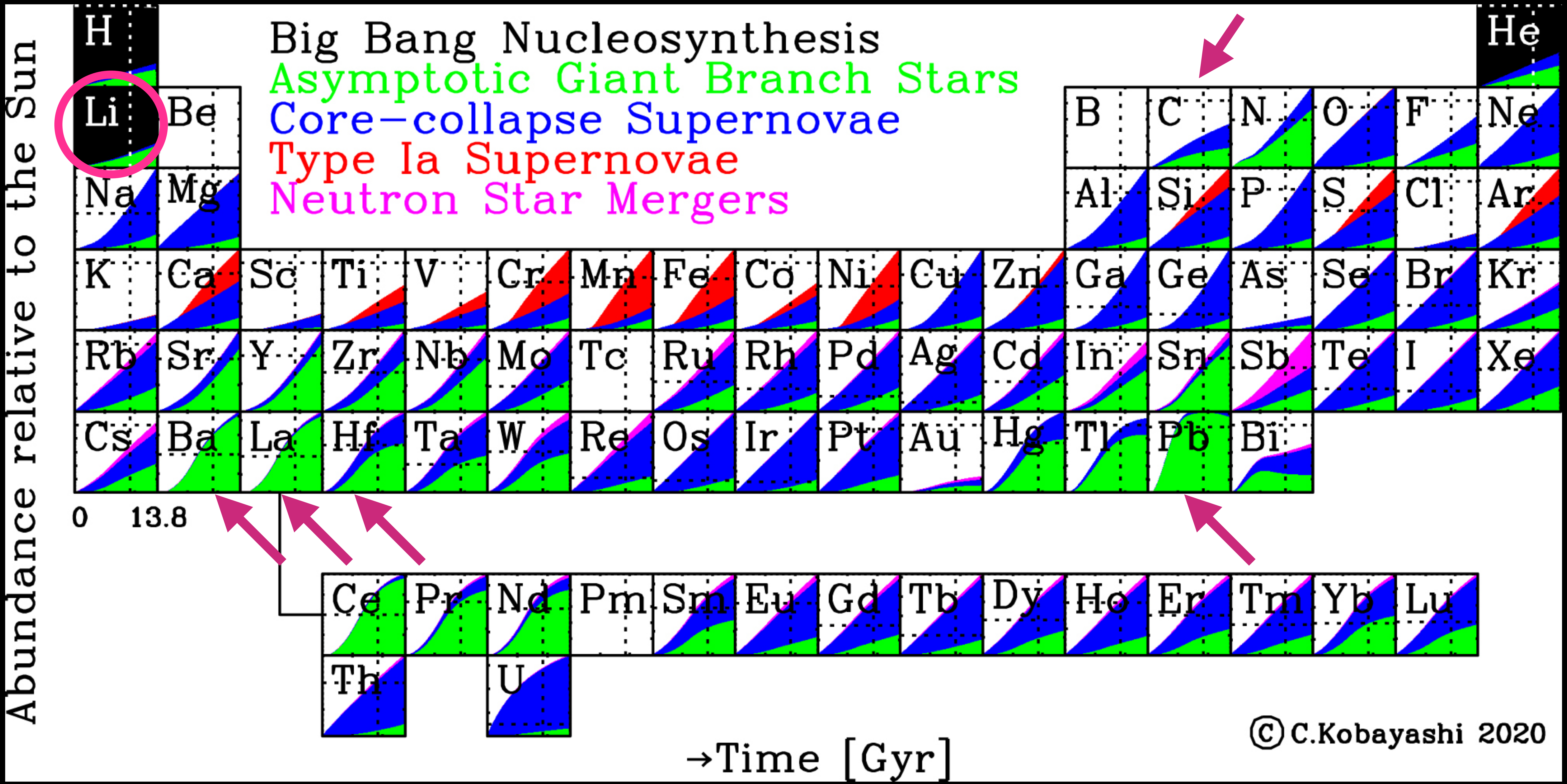
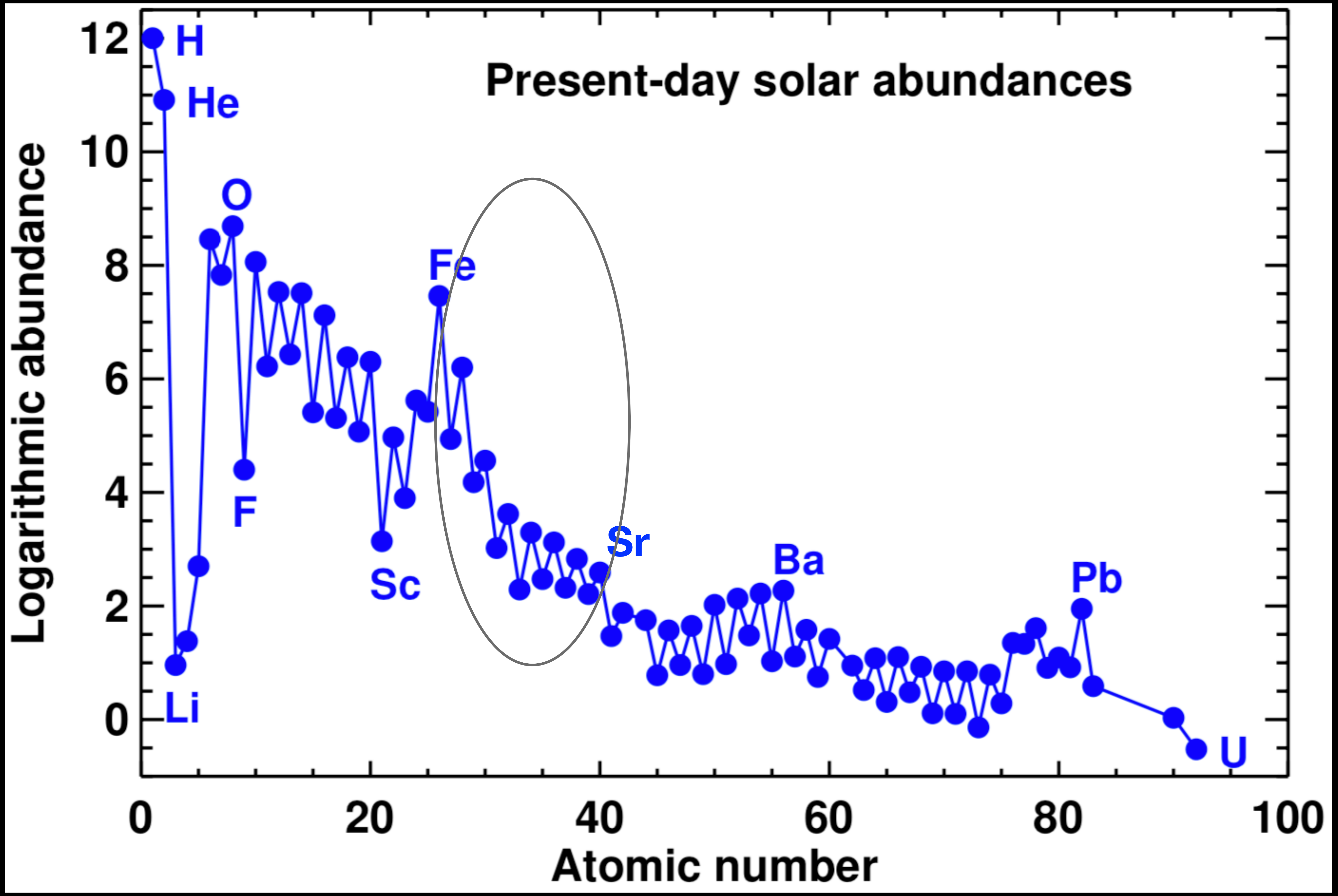


N, Li - INTERMEDIATE MASS STARS!

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

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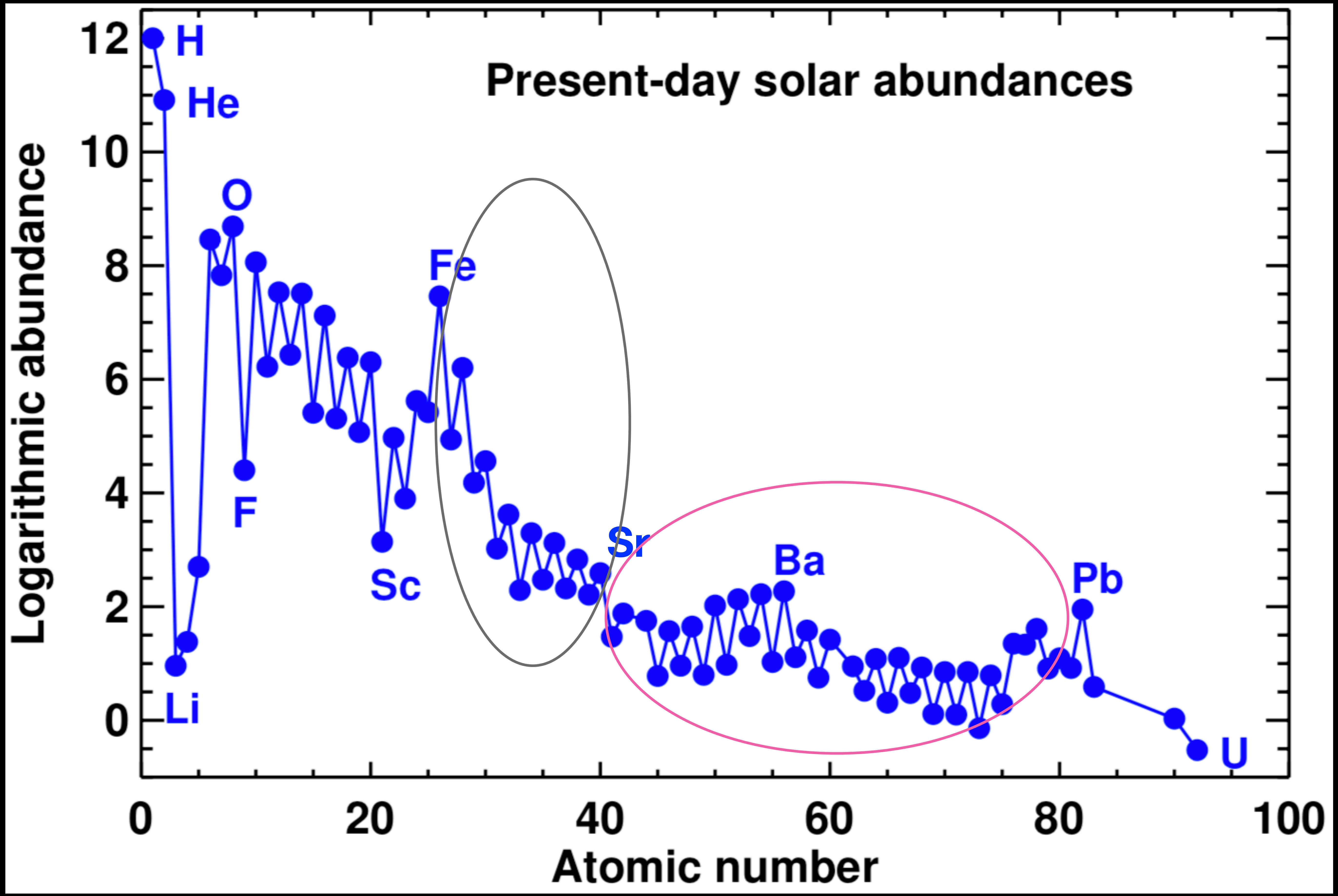

Weak component
from Fe to Sr
$\tau \approx 0.06$ mbarn−1
Massive stars

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

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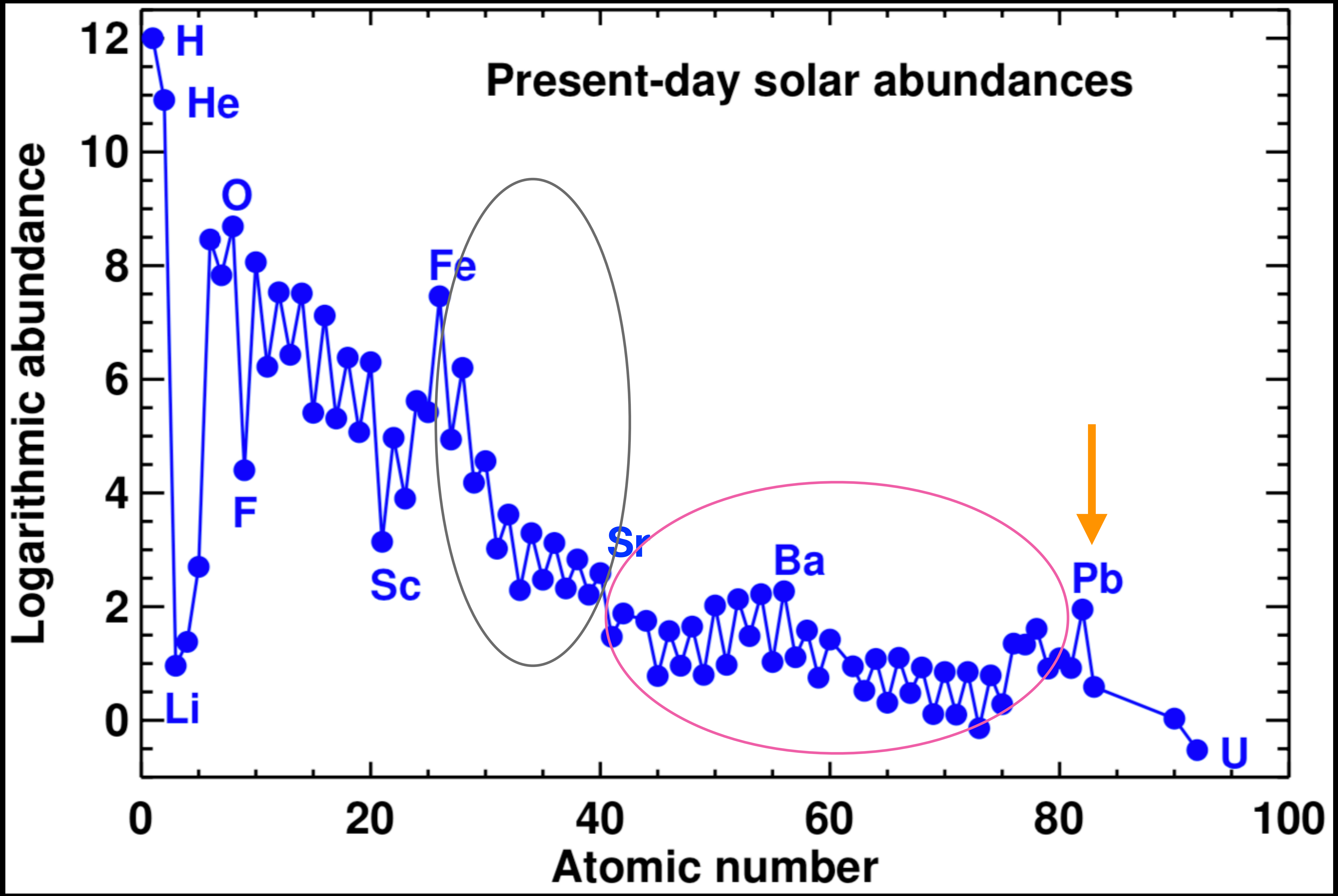

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Low-mass AGBs

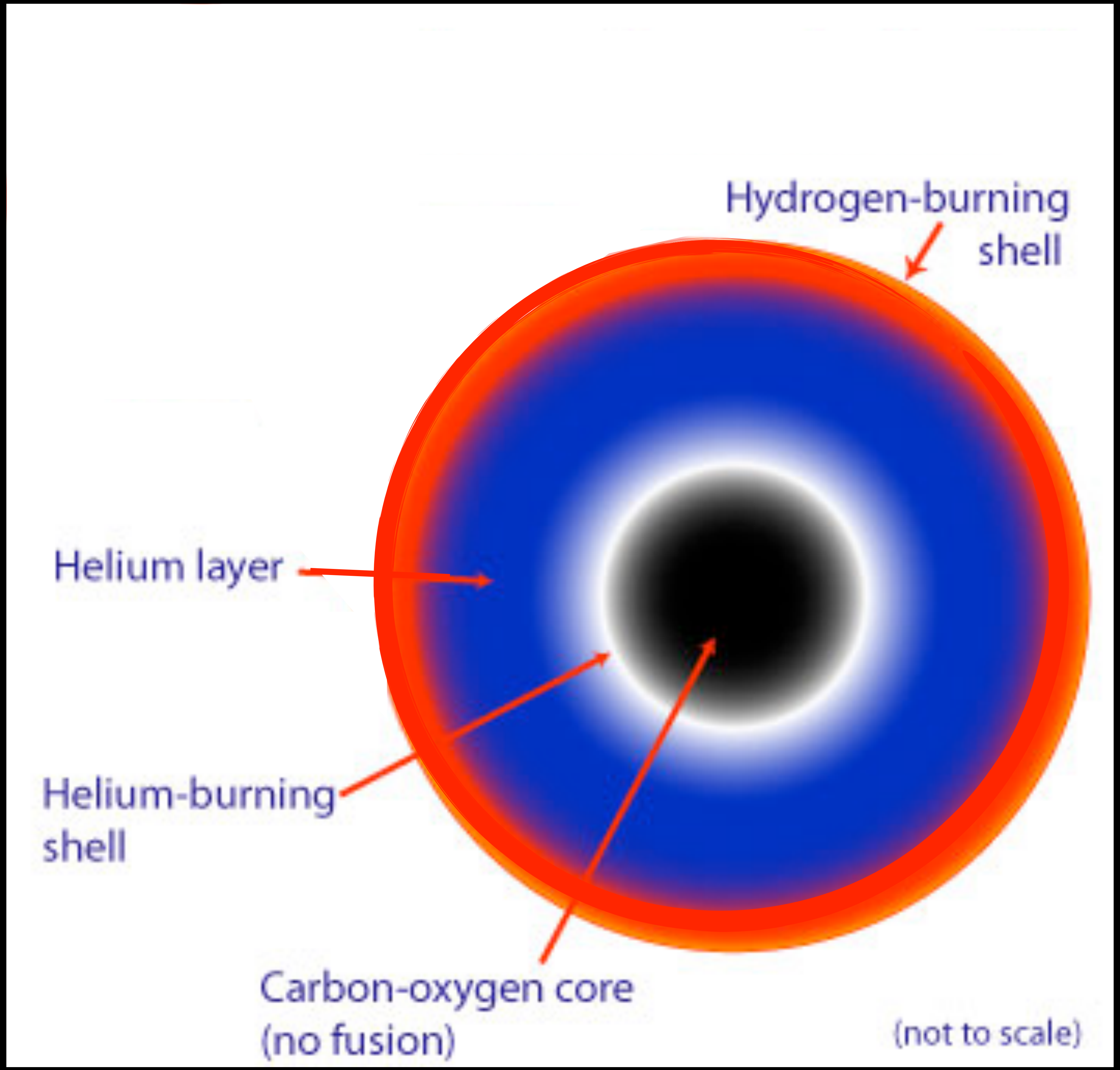
Strong component

Pb

τ ≈ 7.0 mbarn−1

Low-mass, Low-metallicity AGBs

AGB Stars as Tracers of AGB Nucleosynthesis…



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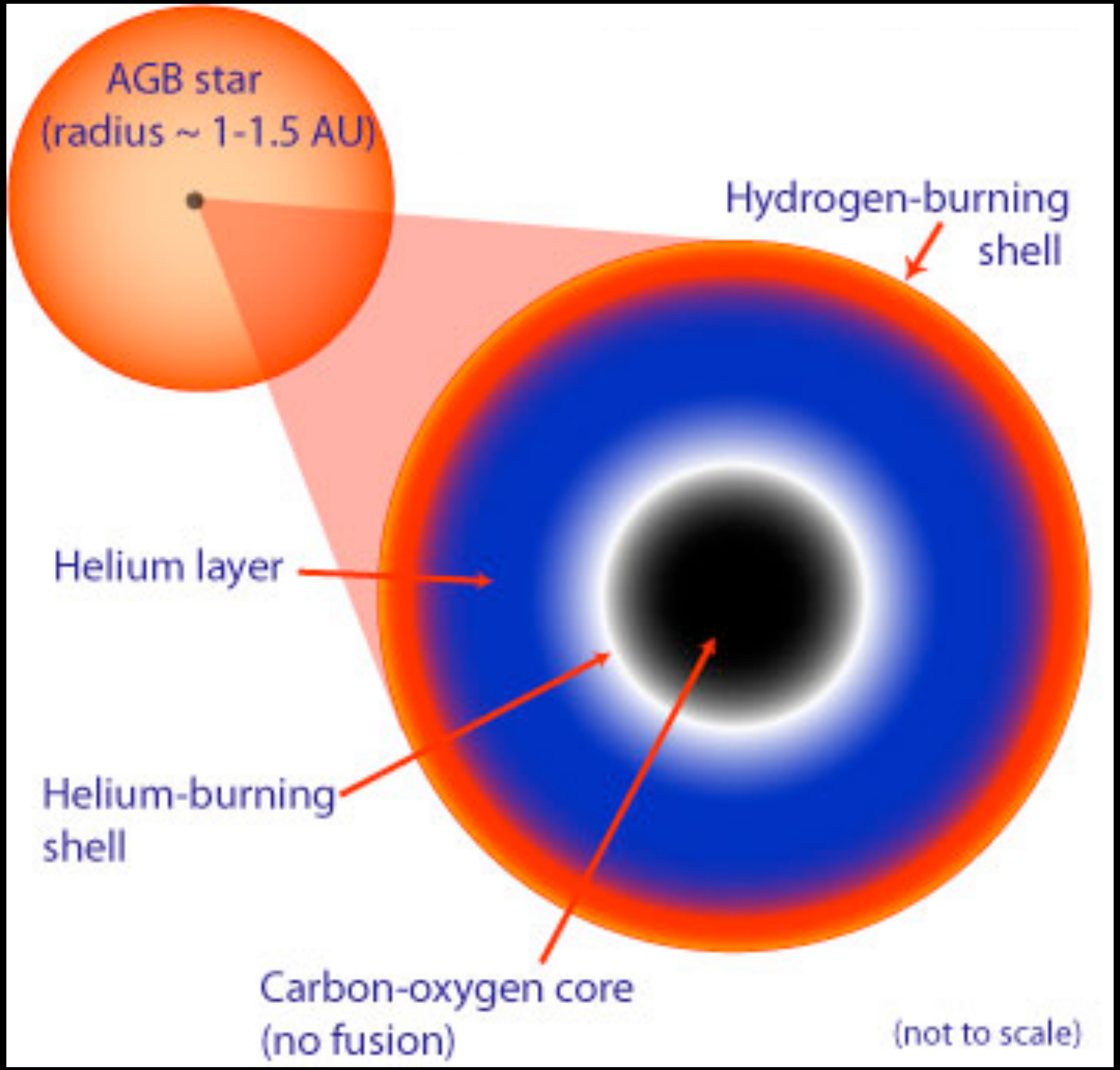

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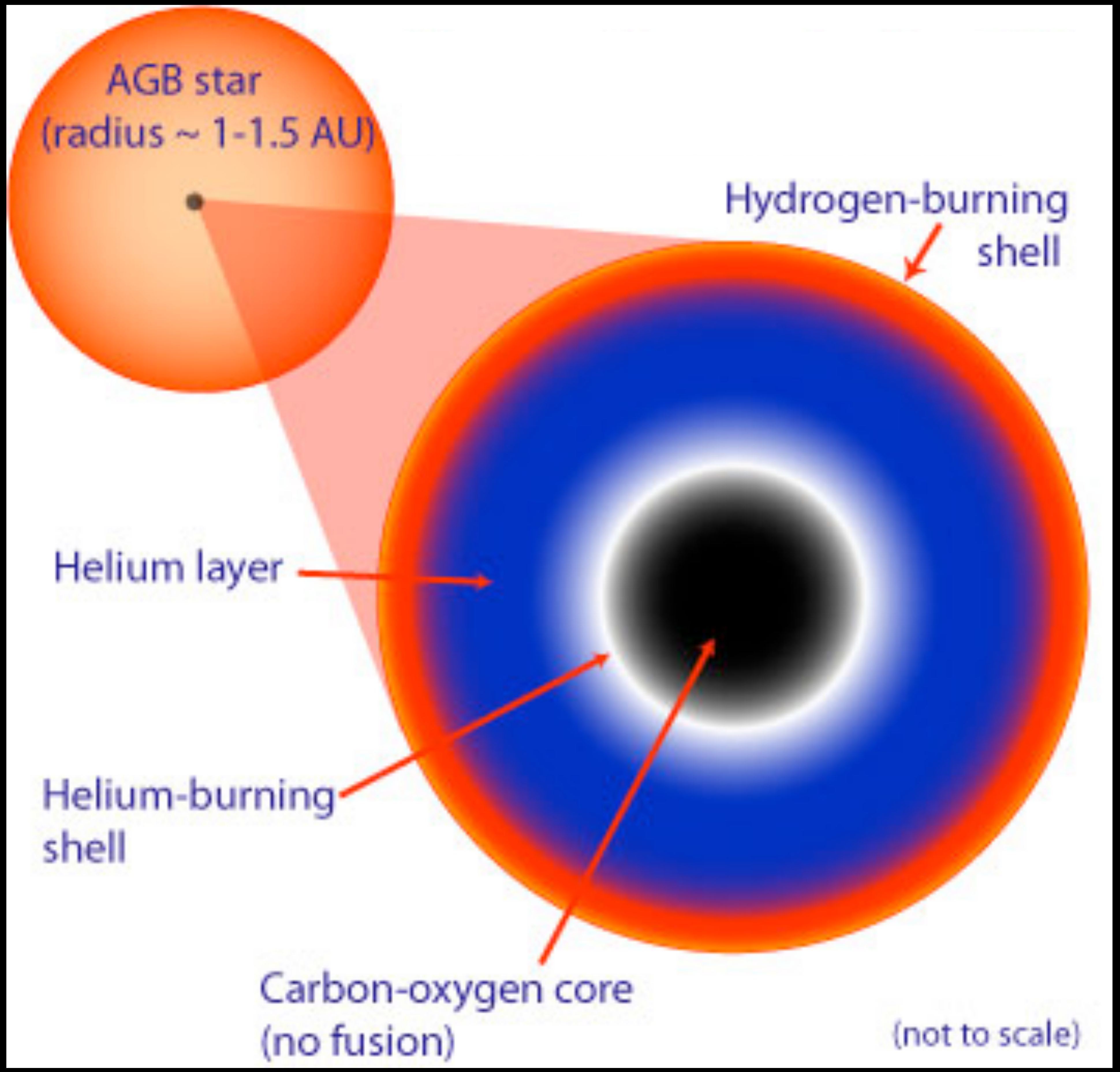

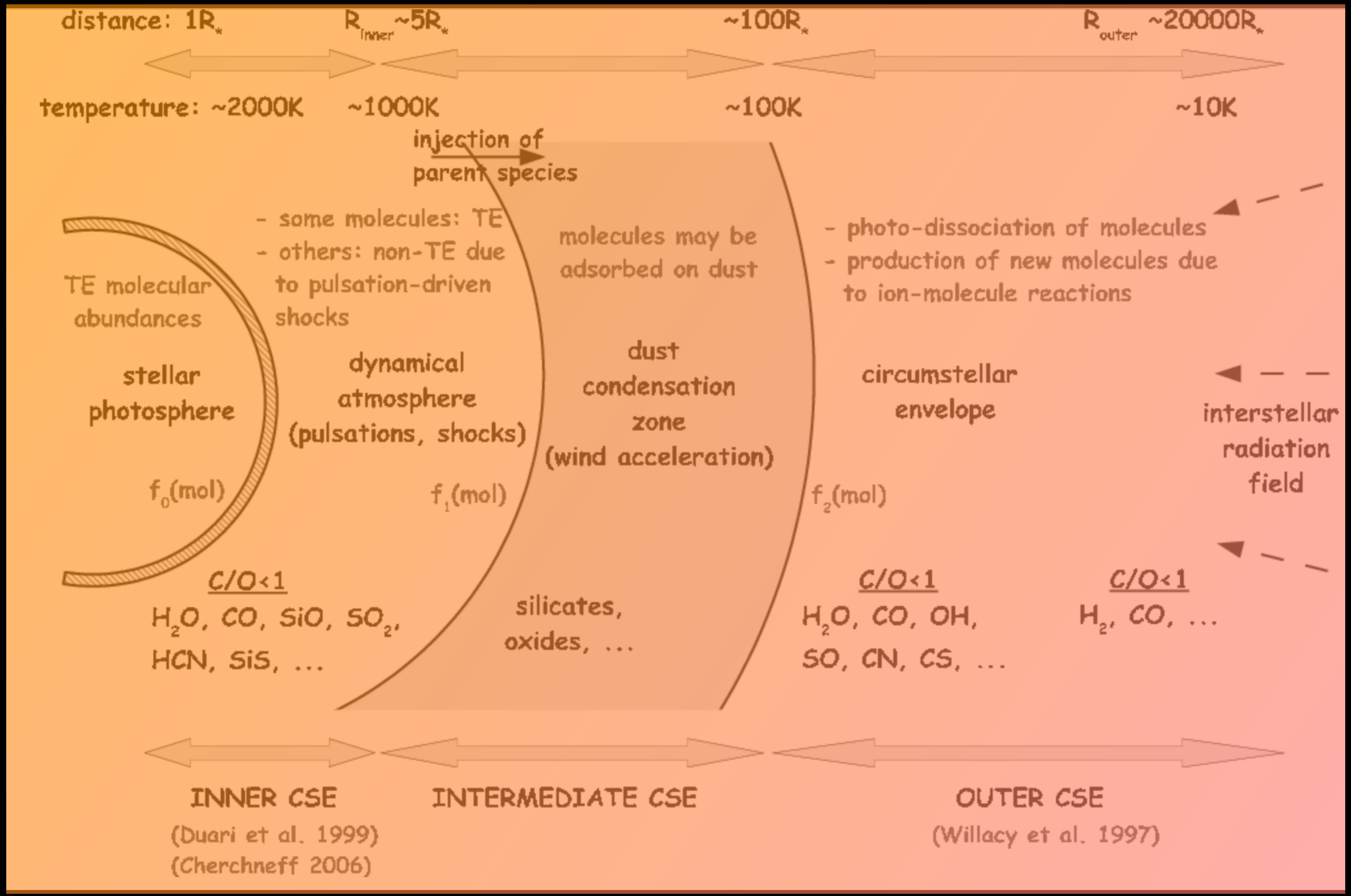

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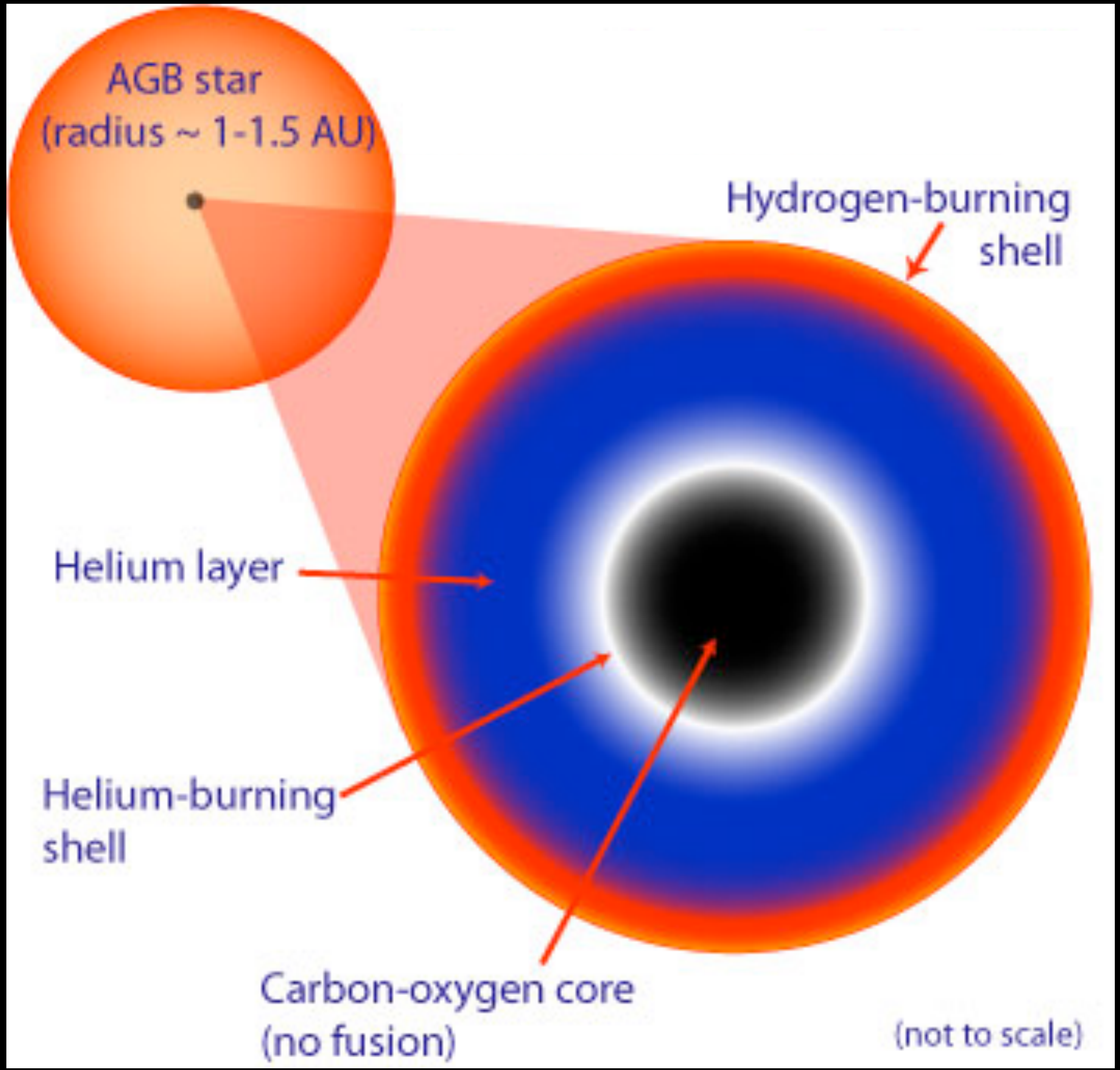
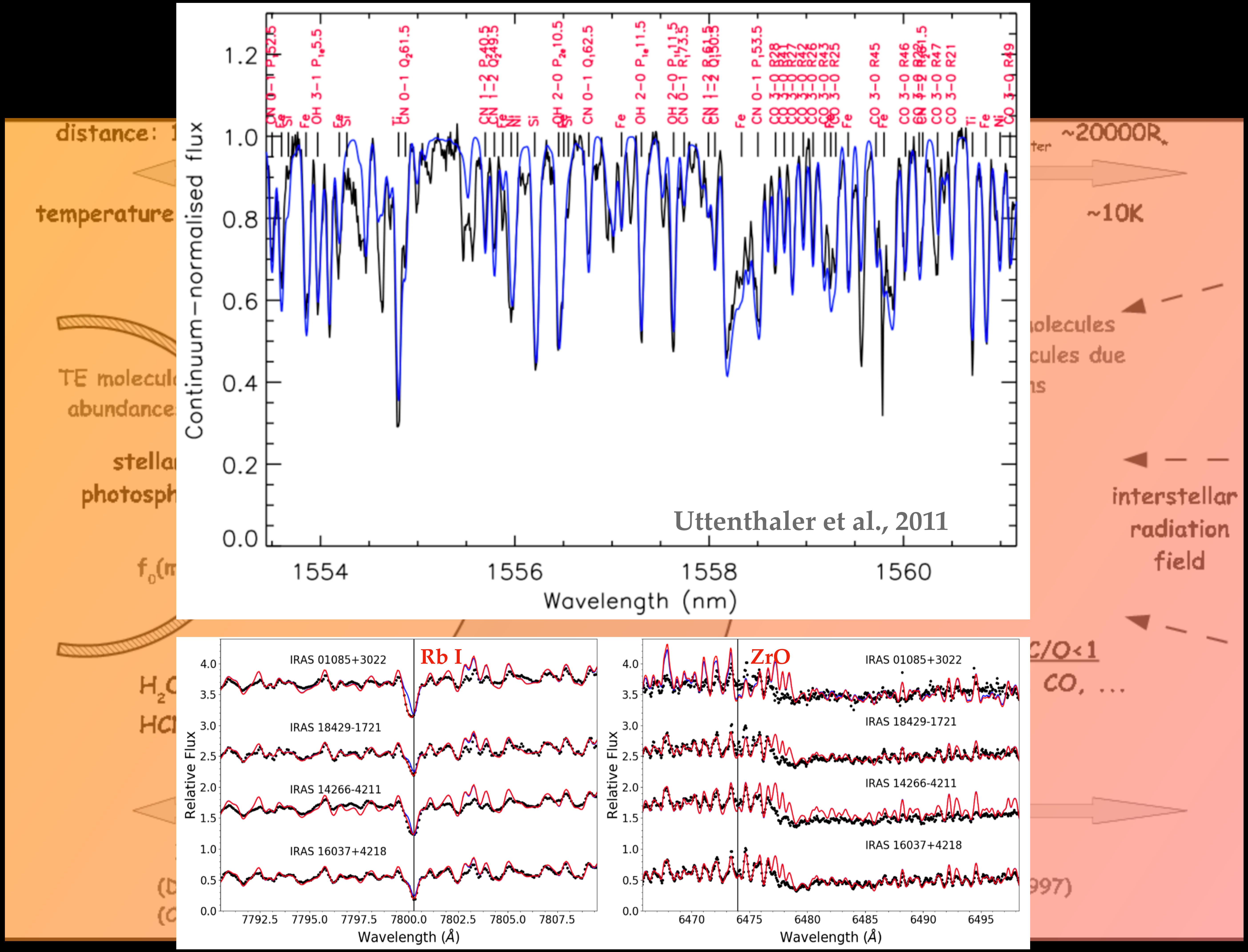
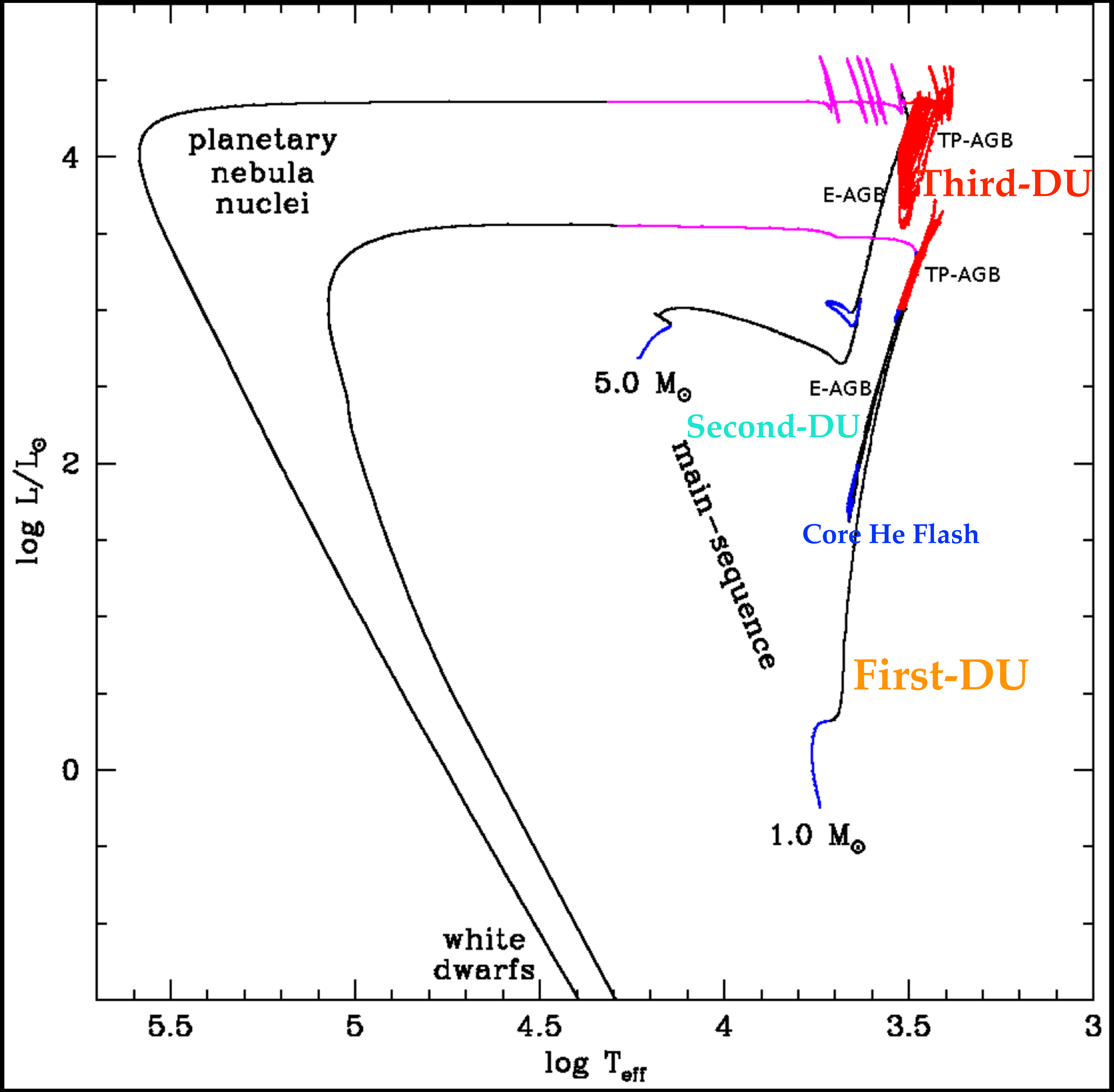




García-Hernández, D. A et al., 2011; 2017

Post-AGB Stars: Exquisite Tracers of the Origin of Elements



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

Second-DU in M > ~3M☉

increase in 4He and 14N

First-DU

increase in 4He, 13C, 14N, 17O

decrease in 12C, 16O and 18O

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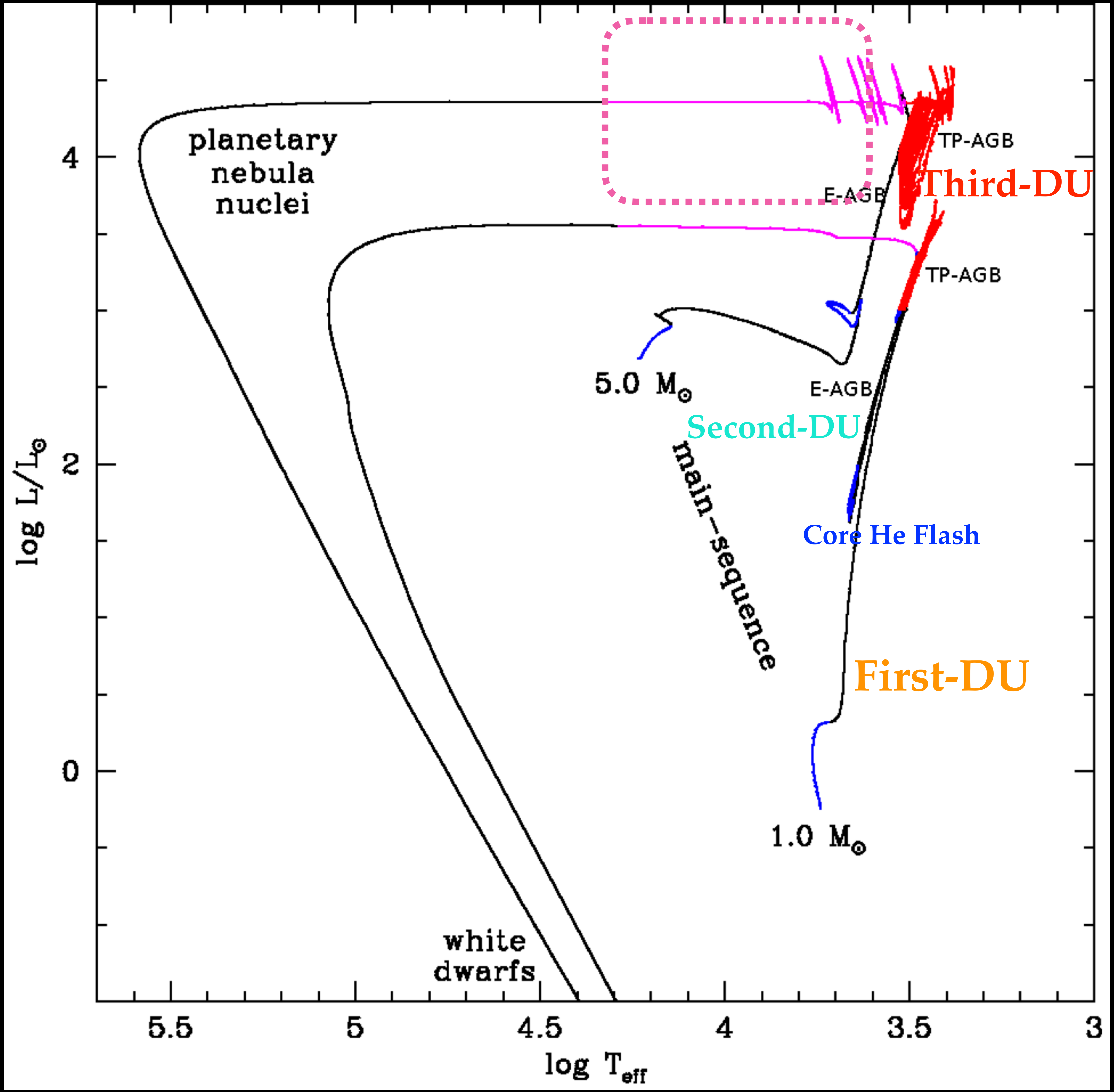

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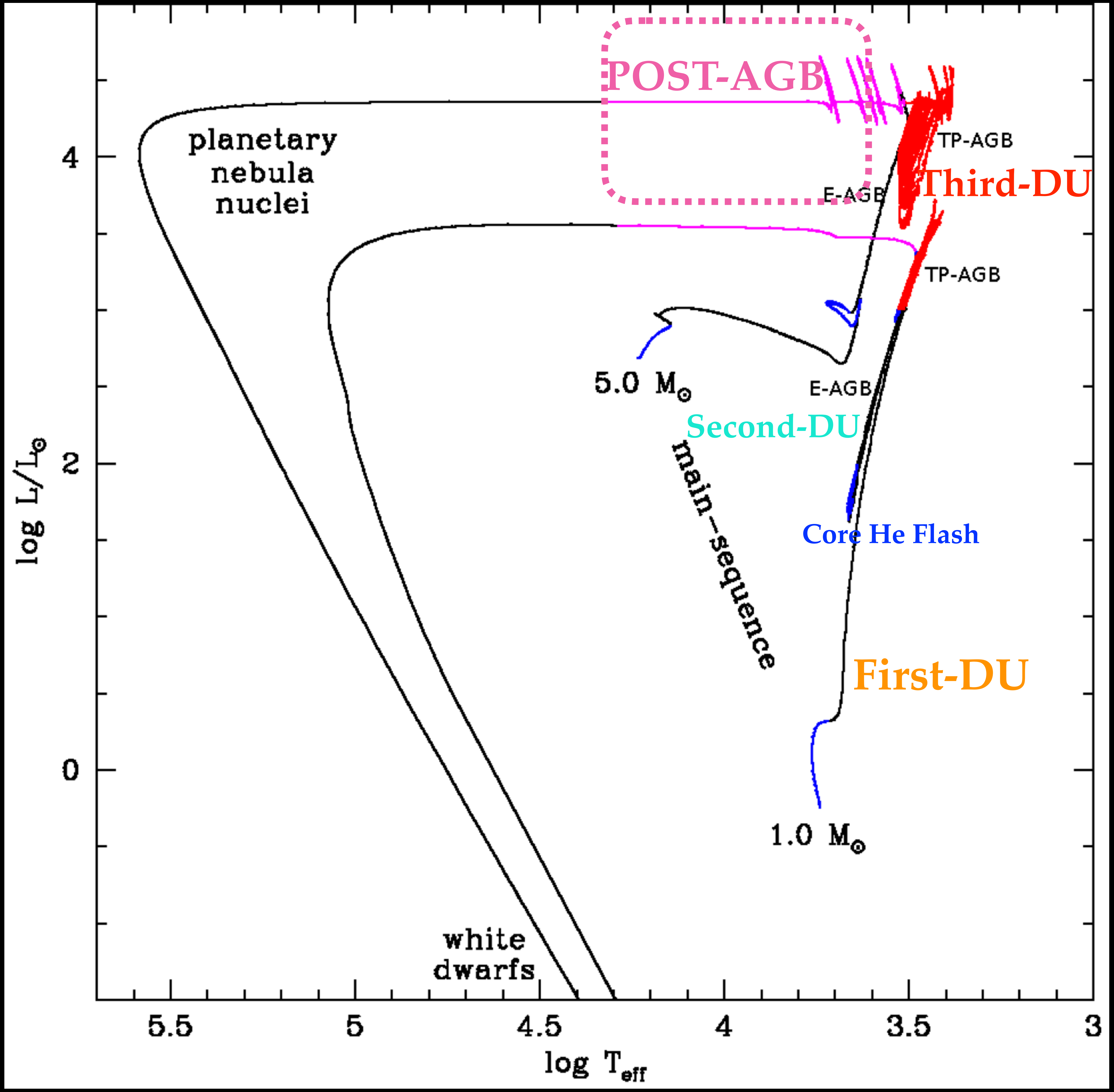

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Single Post-AGB Stars in the Galaxy

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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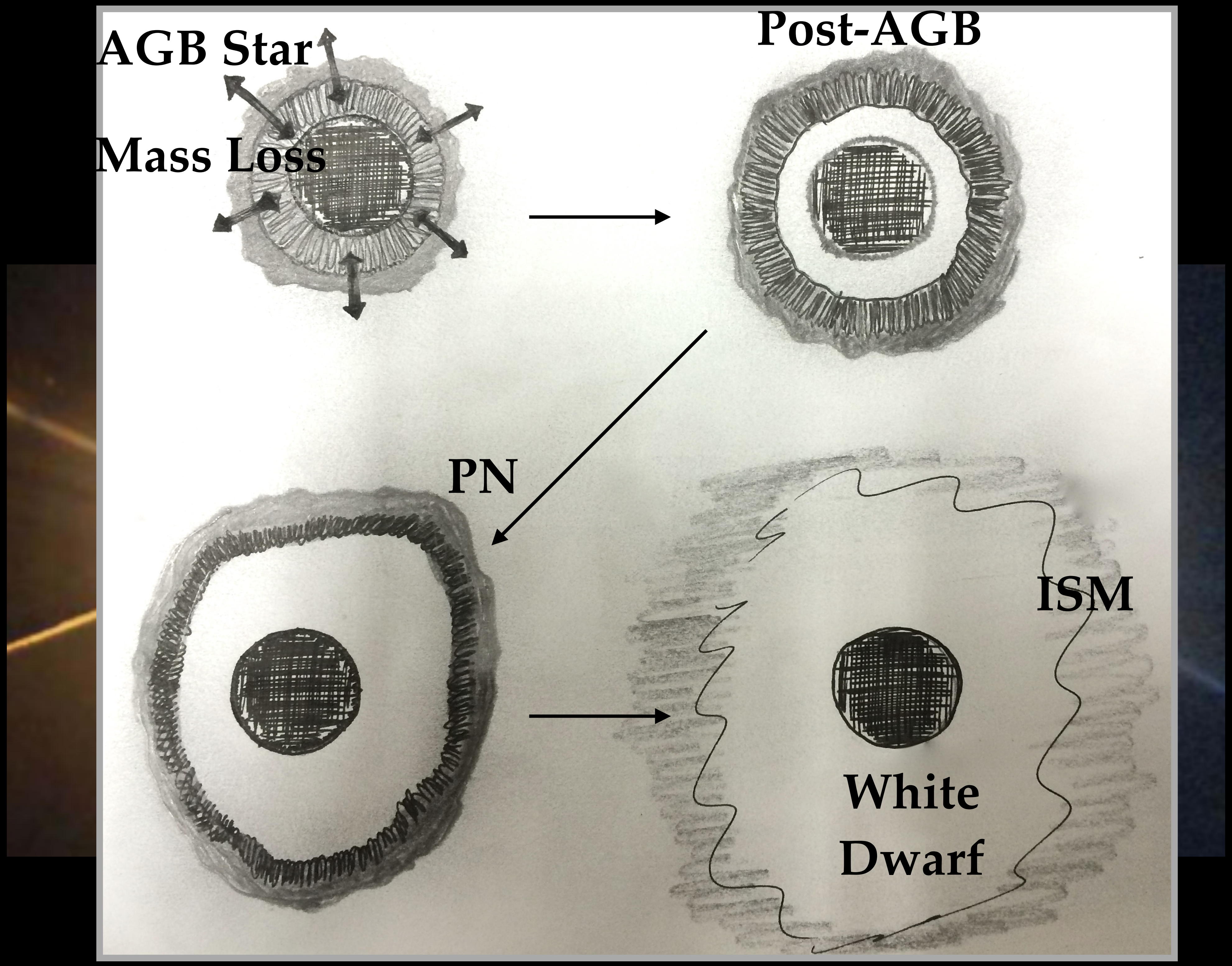

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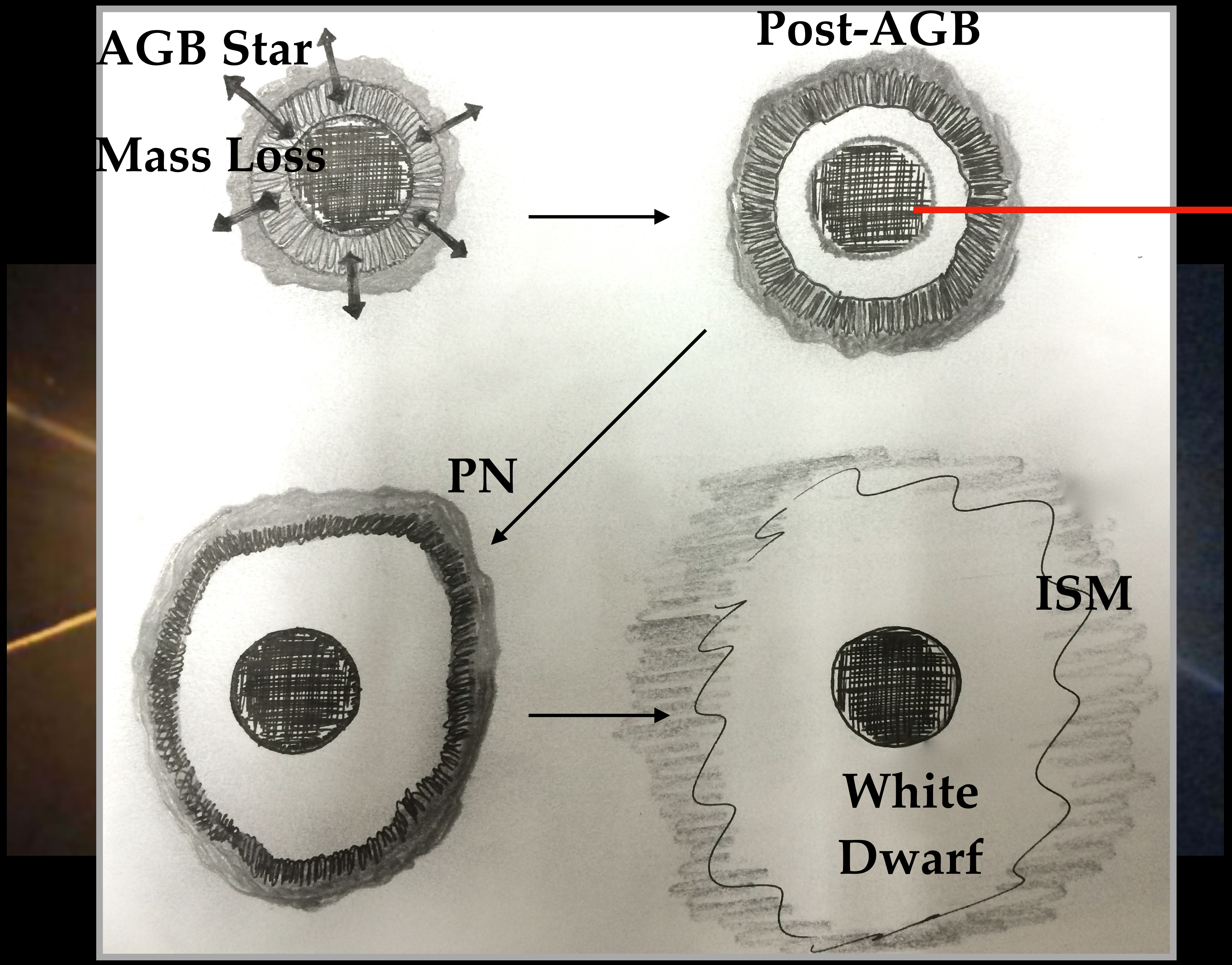

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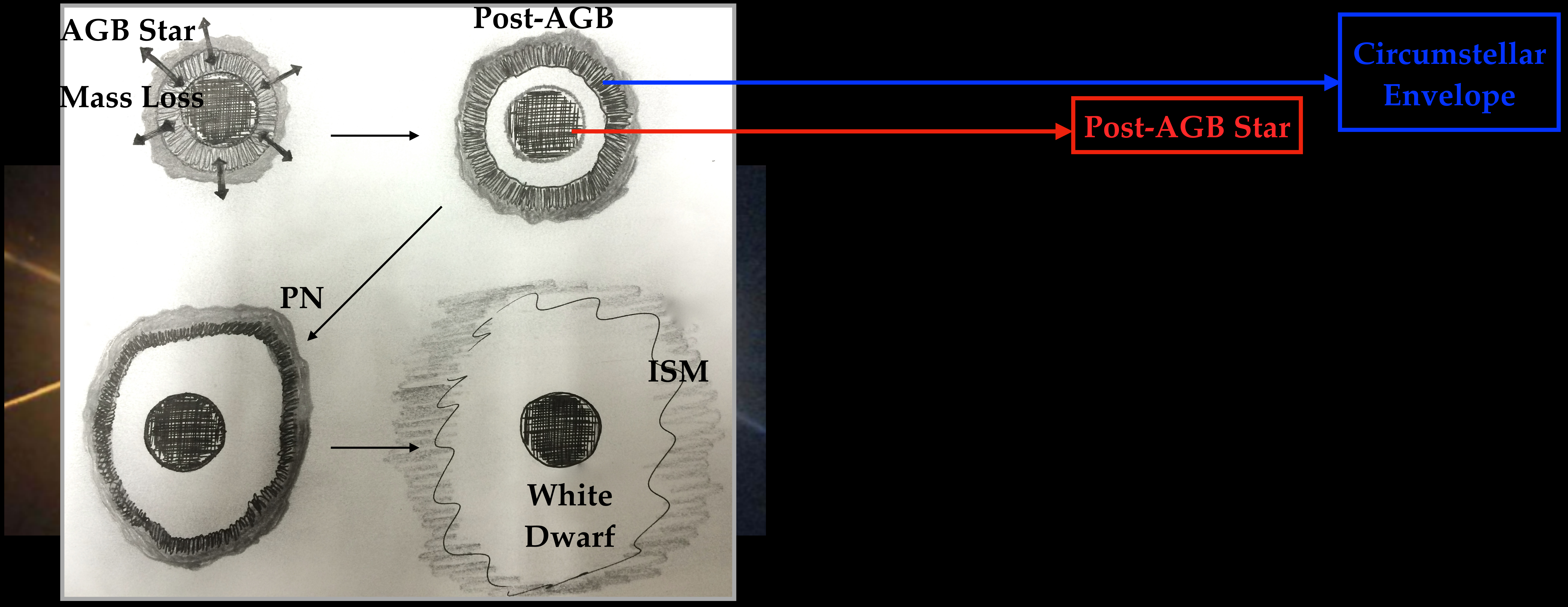

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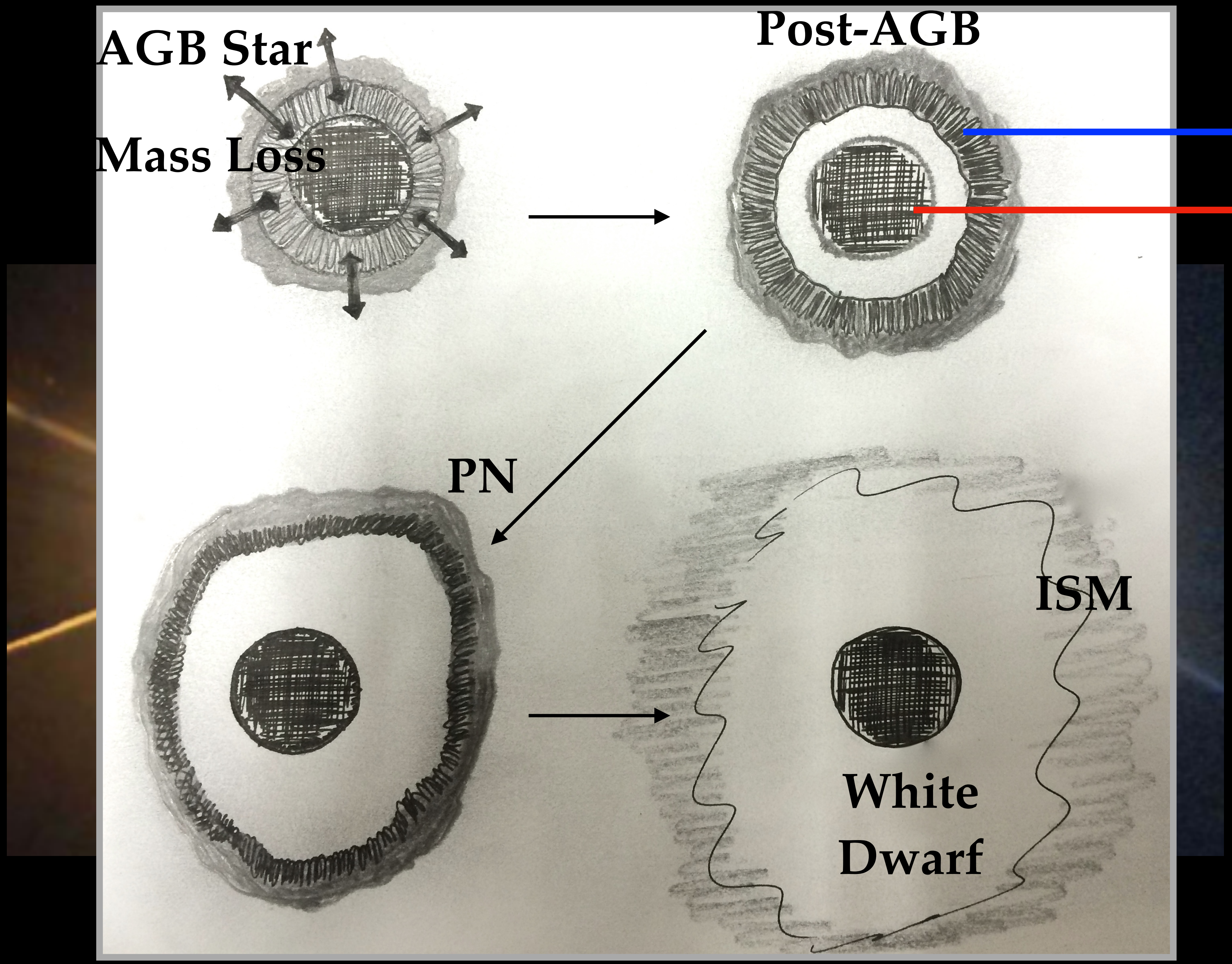

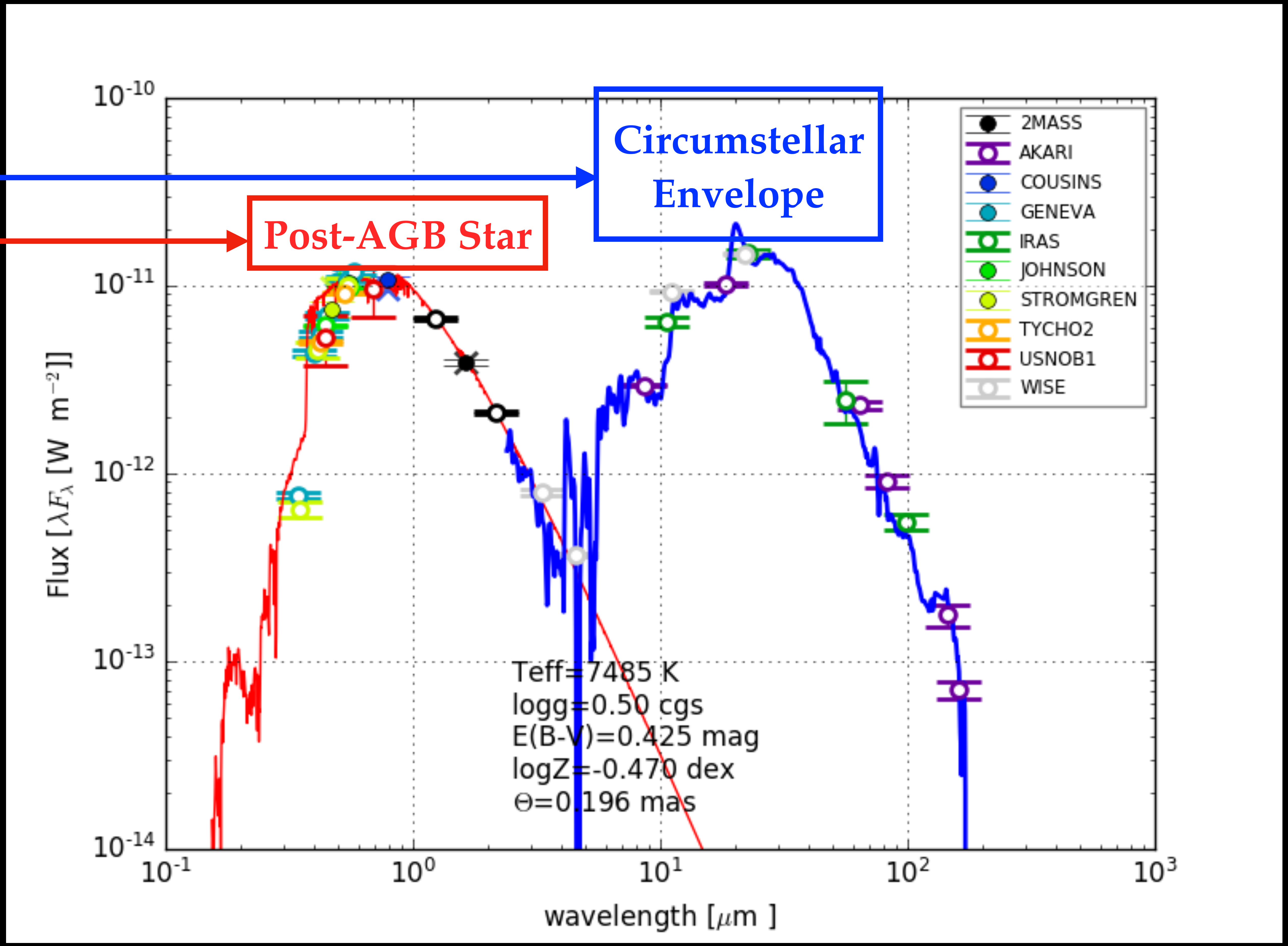

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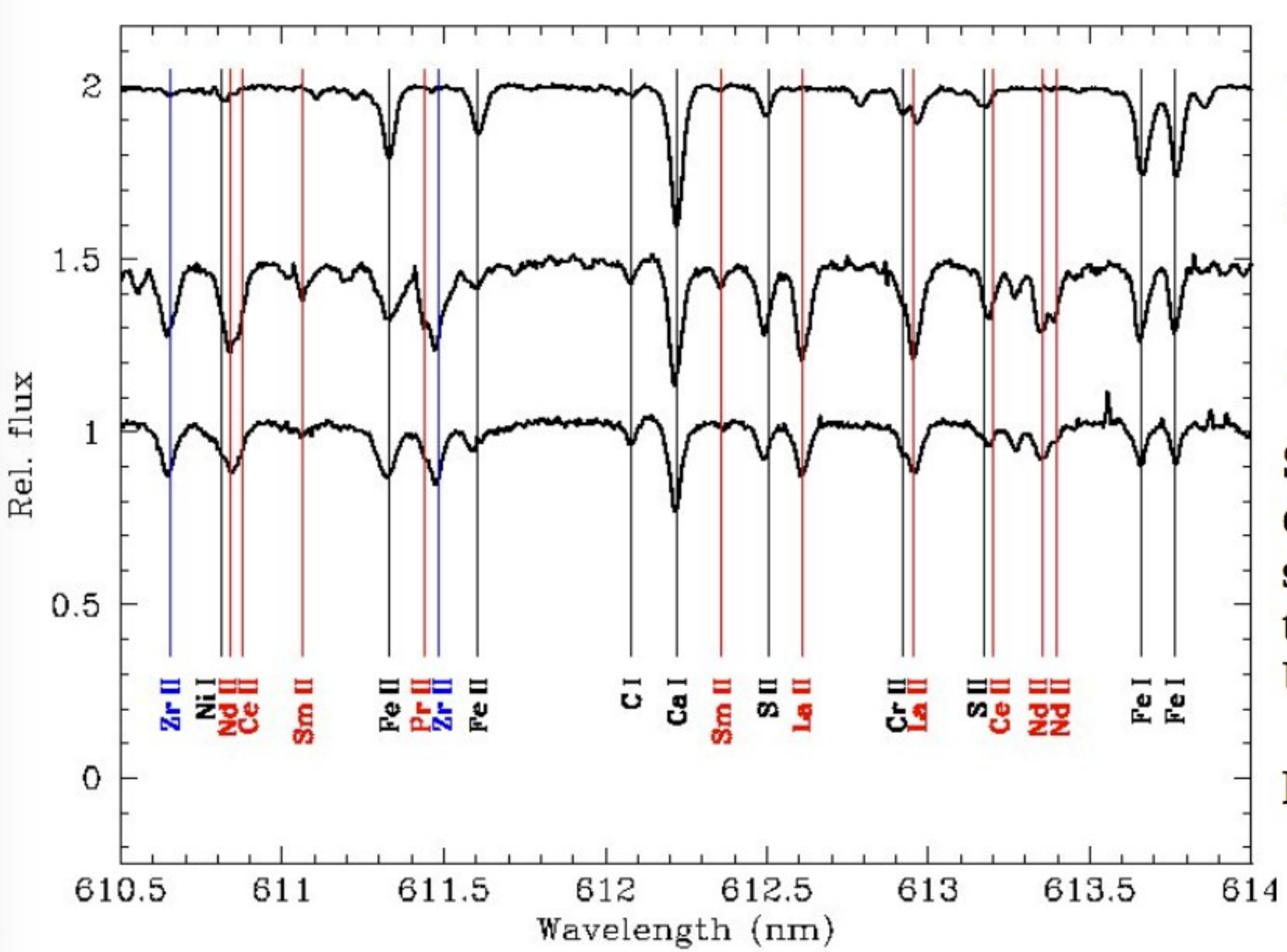
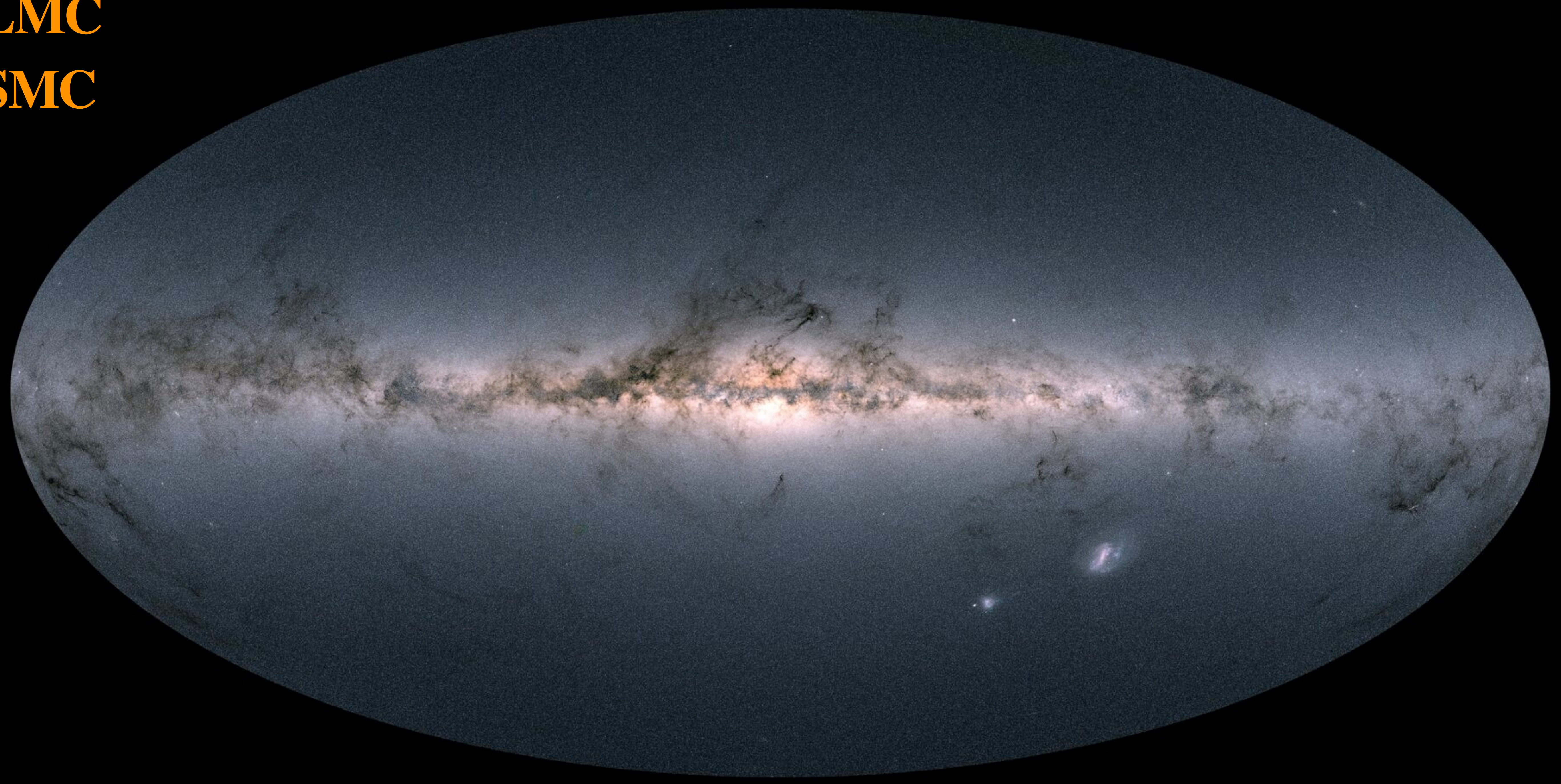


Spectra are dominated by s-process atomic transitions.
Up to Gd, Yb, Lu, W

Range of n-exposures

The Hunt for Post-AGB Stars

Milky Way
LMC
SMC



Galaxy: Van Winckel 2003; Szczerba et al., 2007; Kamath et al., 2022; Kluska et al., 2022
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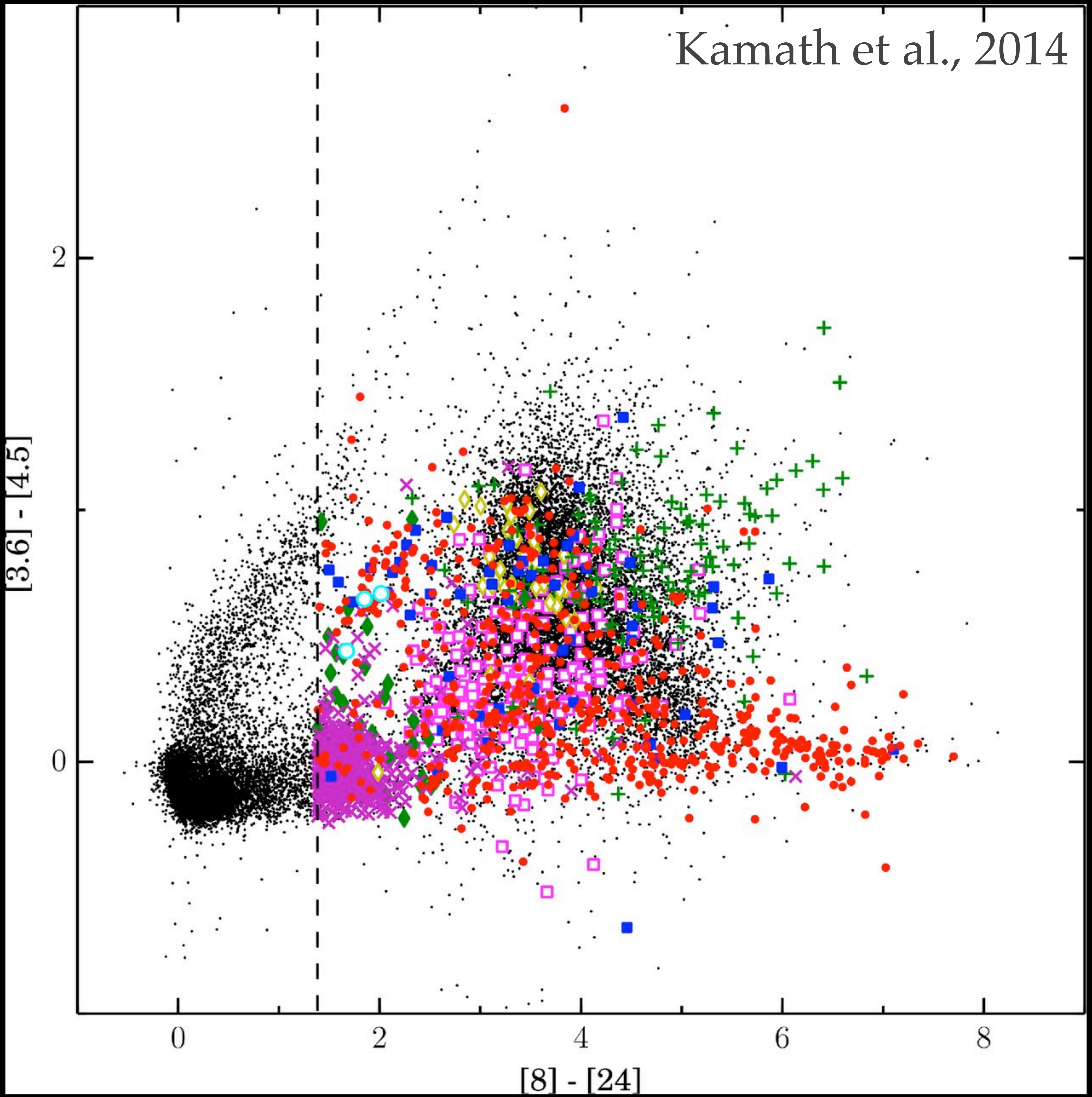

- **Initial Sample: Combination of UV, Optical and IR Photometry**
- **Candidate List: Low-Resolution Spectroscopic Analyses**

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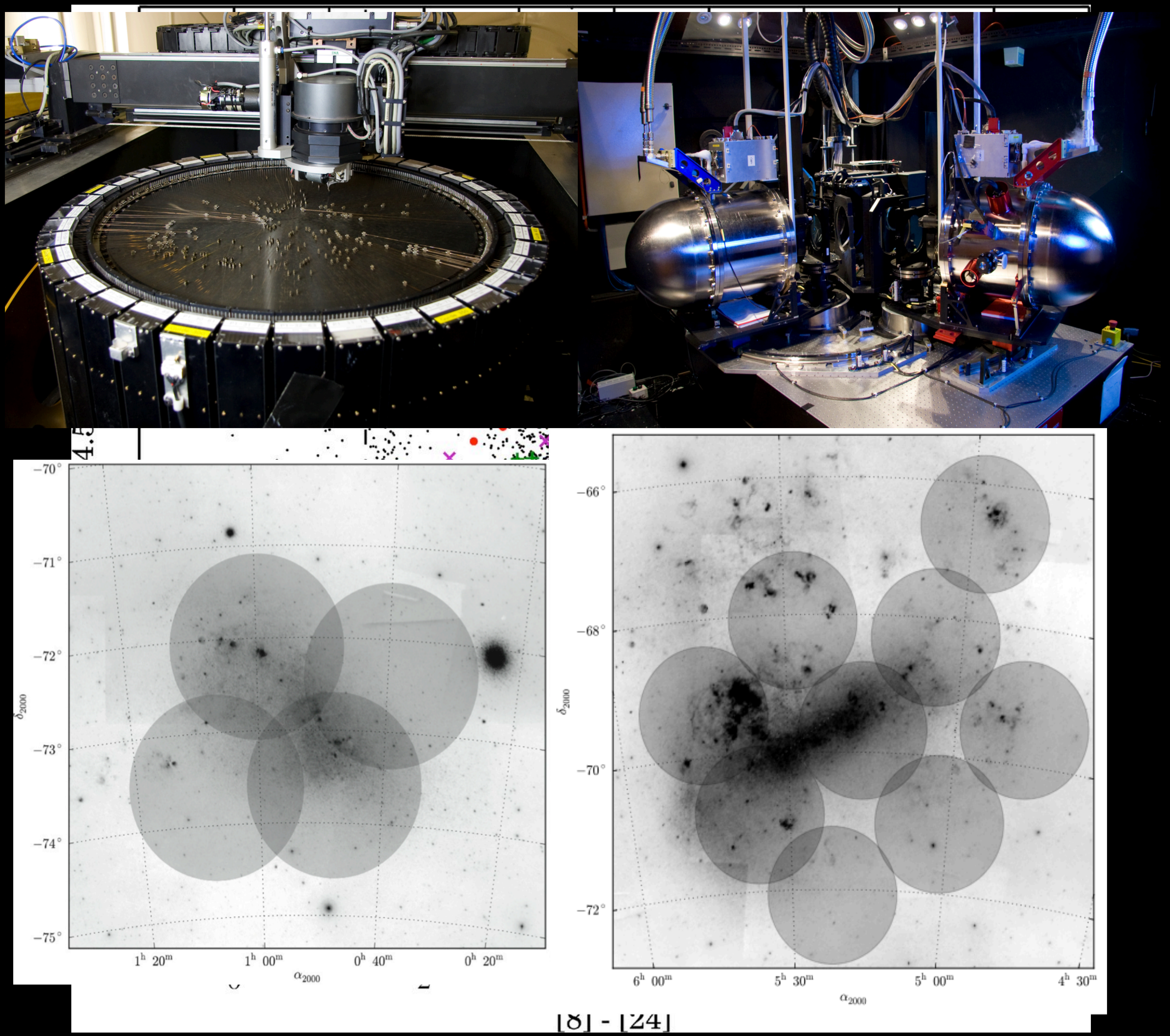

- **Initial Sample: Combination of UV, Optical and IR Photometry**
- **Candidate List: Low-Resolution Spectroscopic Analyses**
- **Final Catalogue: High-resolution Spectroscopic Analyses**

<u>Current Sample:</u>
Galaxy: 300 candidates
LMC: 150 candidates
SMC: 50 candidates

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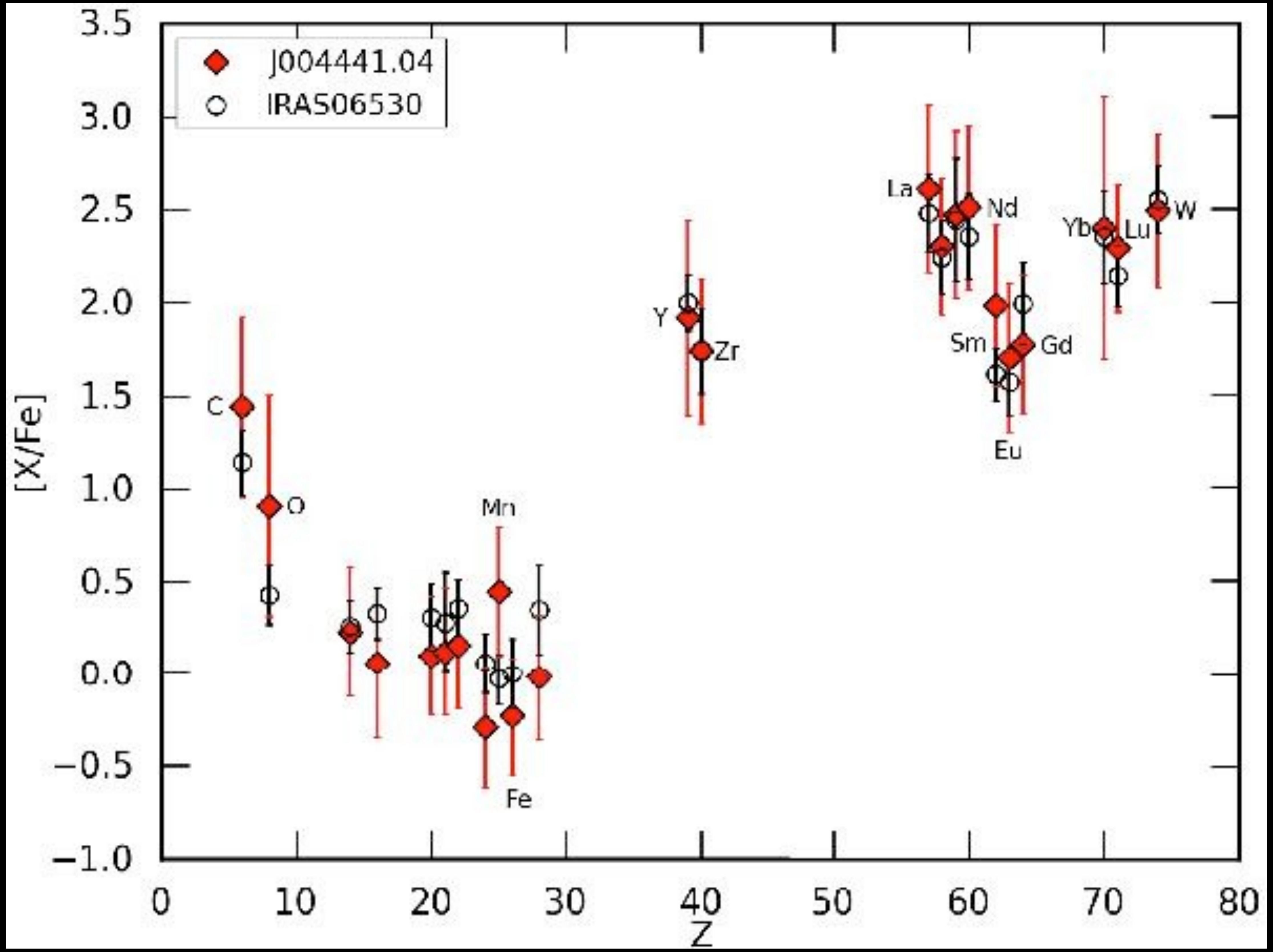
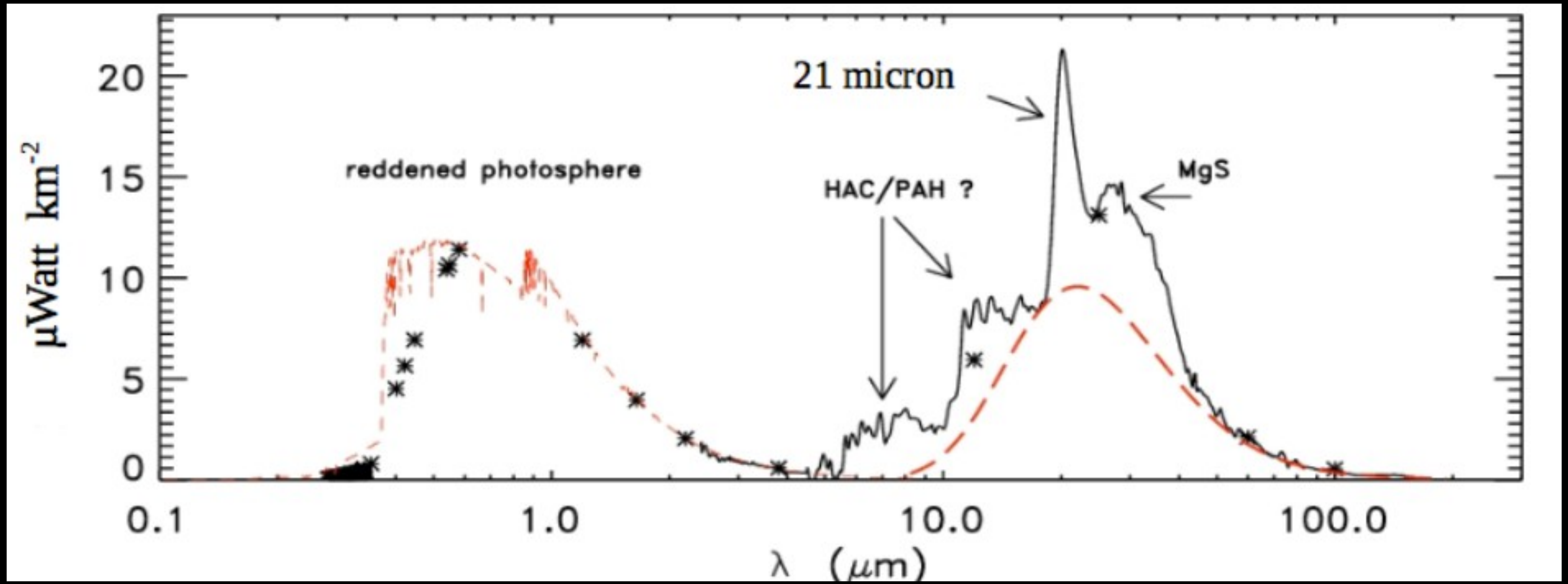
Single Post-AGB Stars as Exquisite Tracers of CNO, Fe-peak & *s*-process elements

Carbon and *s*-process rich stars:



- $M_{initial}$ ~ 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, Volk et al., 2020

All C-rich and *s*-process rich post- AGB stars show the 21-micron feature.

De Smedt et al., 2012, 2015; Kamath et al., 2017, Menon et al., 2023

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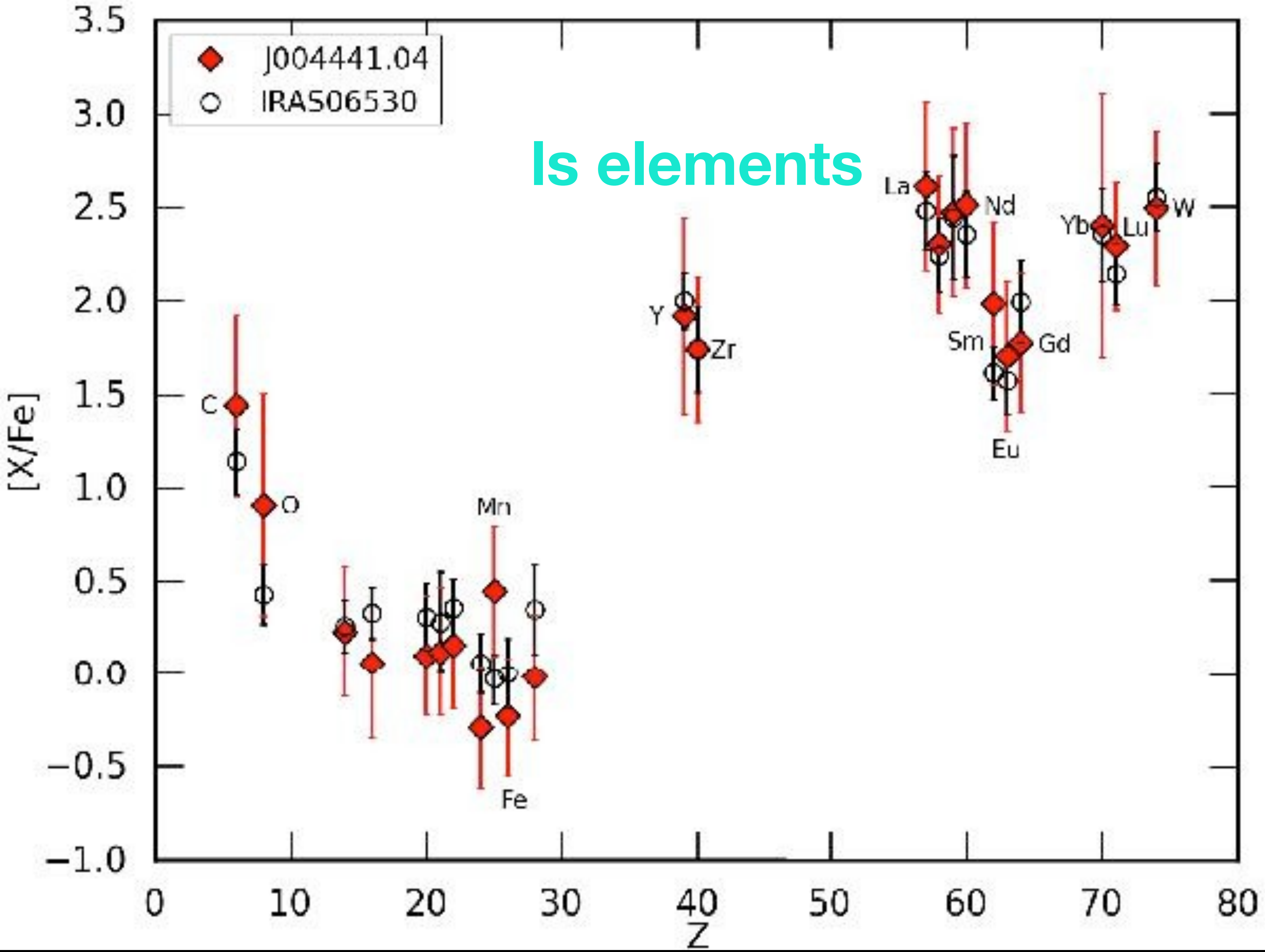

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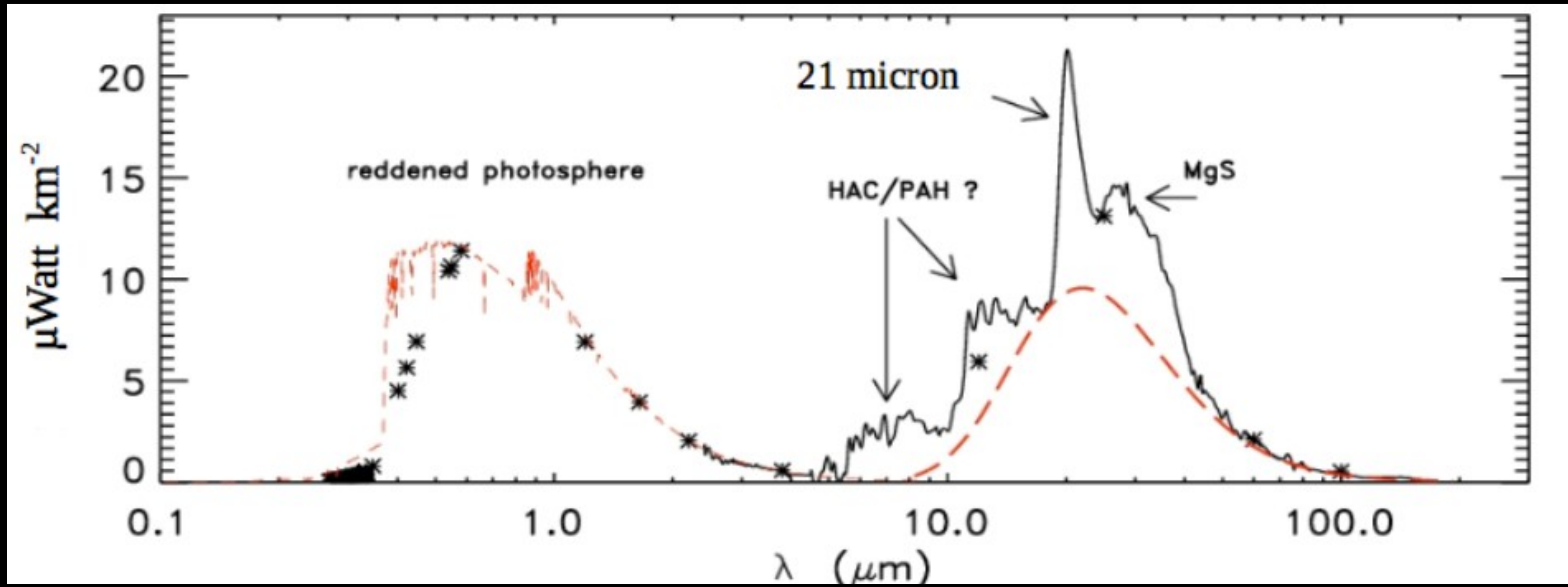

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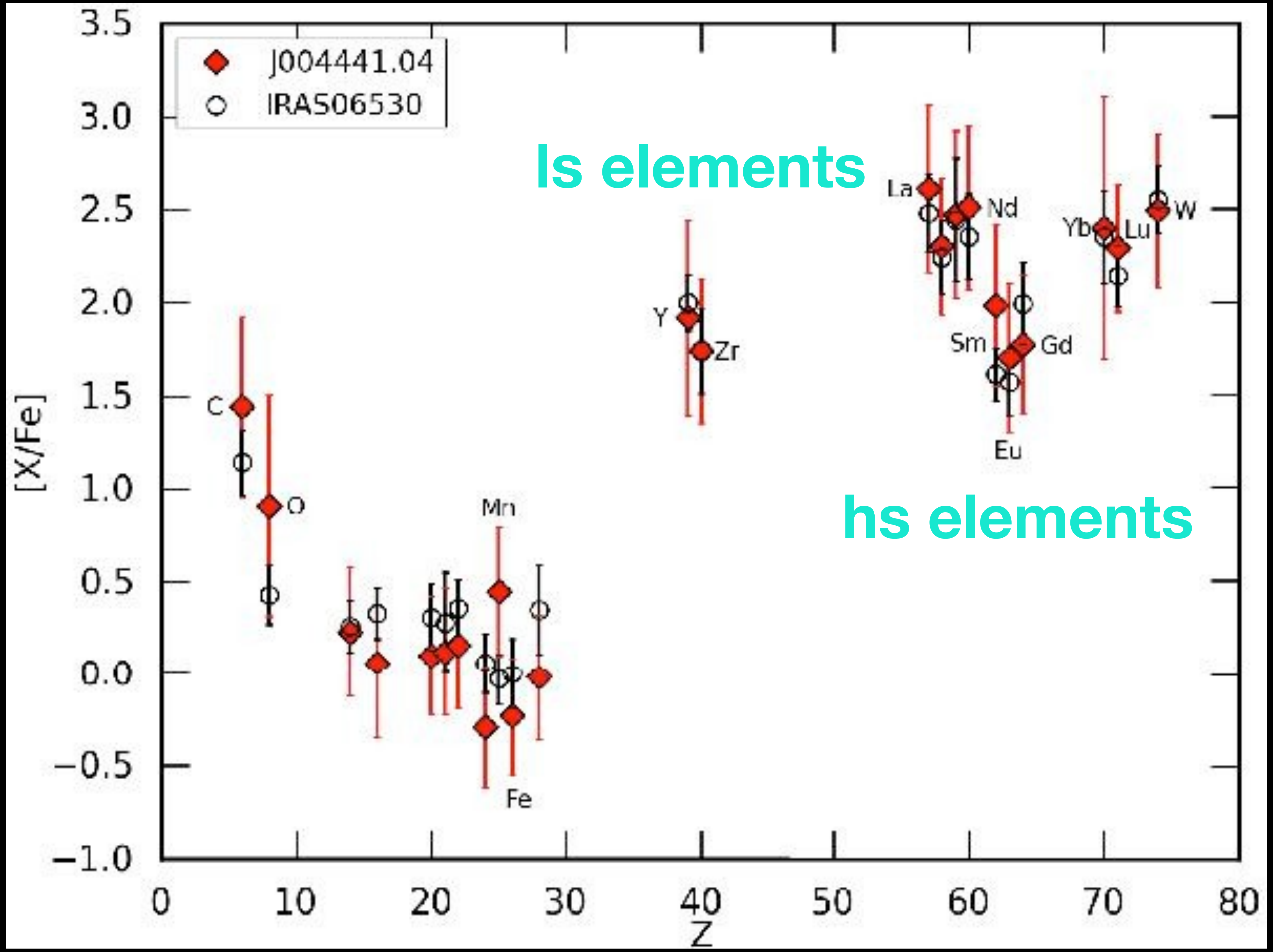

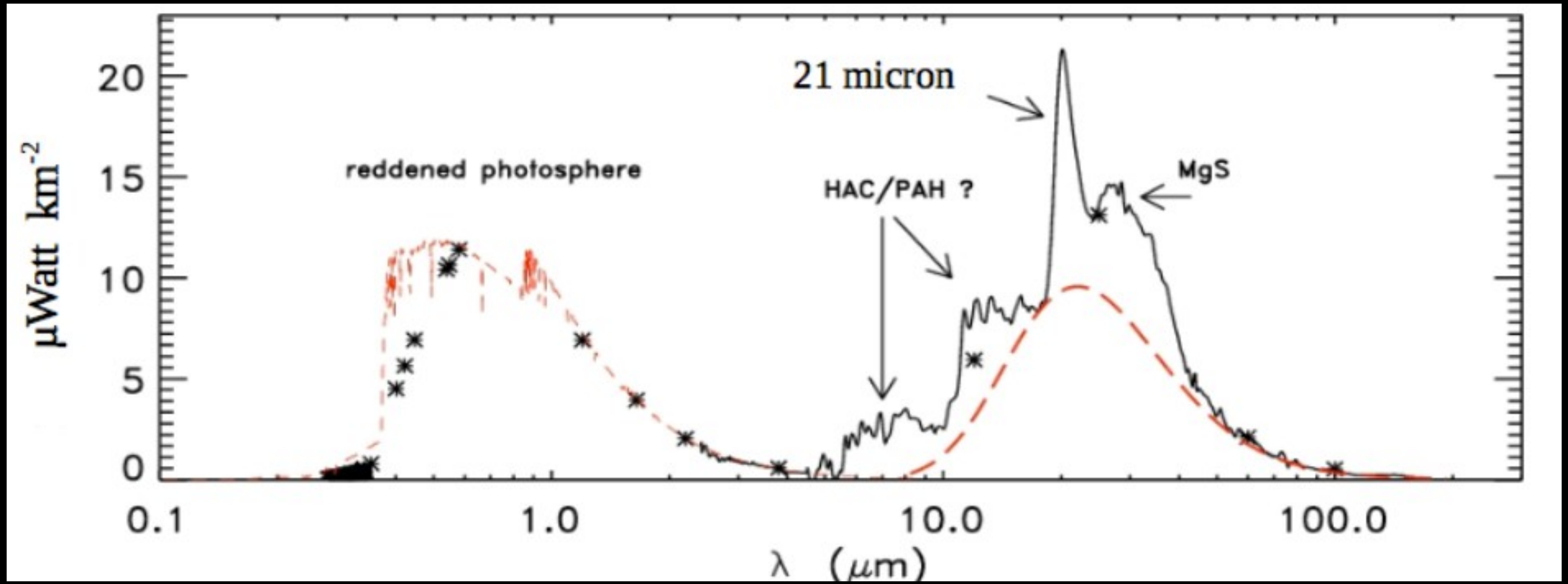

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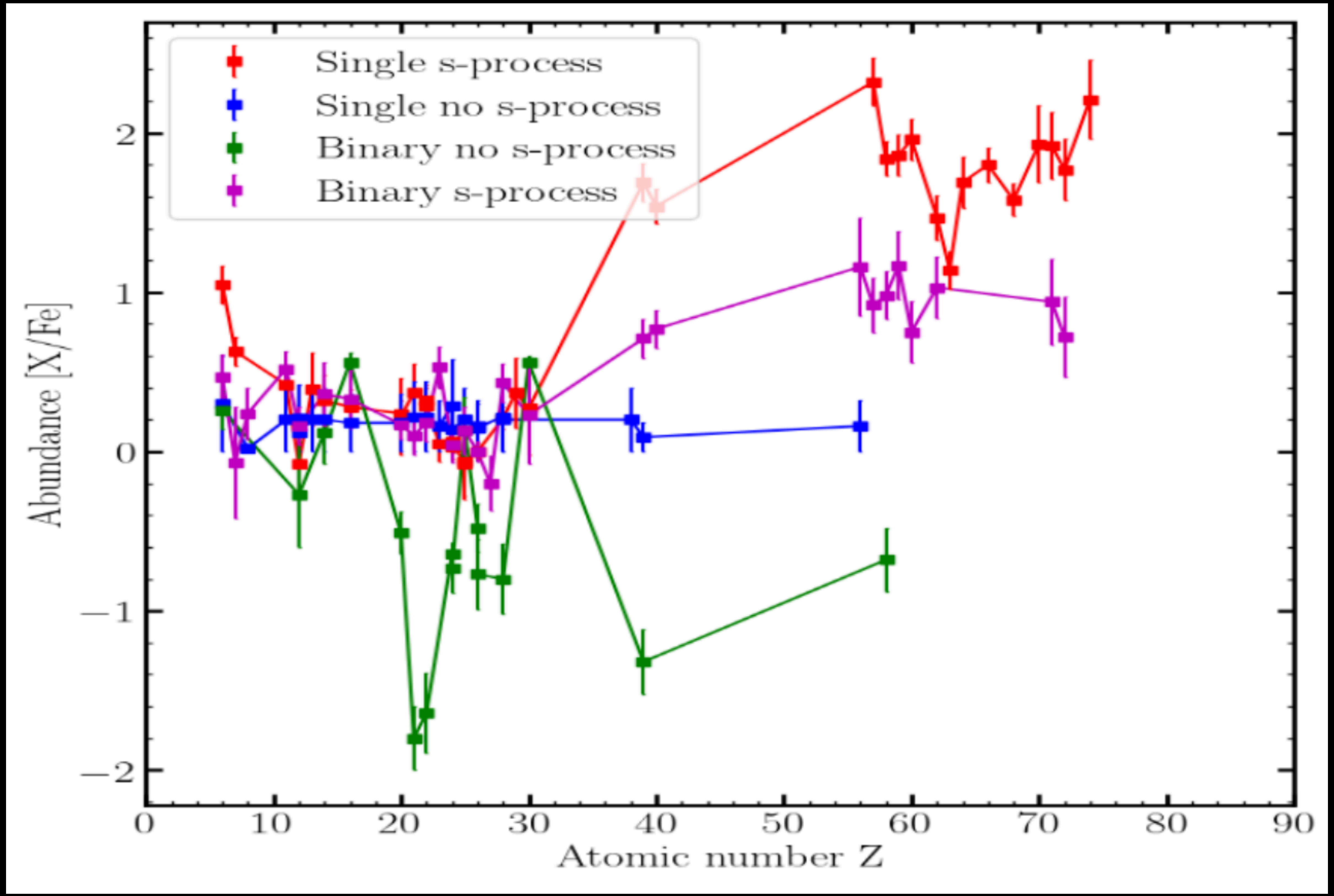
The revelation of chemical diversities in AGB nucleosynthesis…



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Chemical Diversities Within the Galactic and LMC/SMC Single Star Sample

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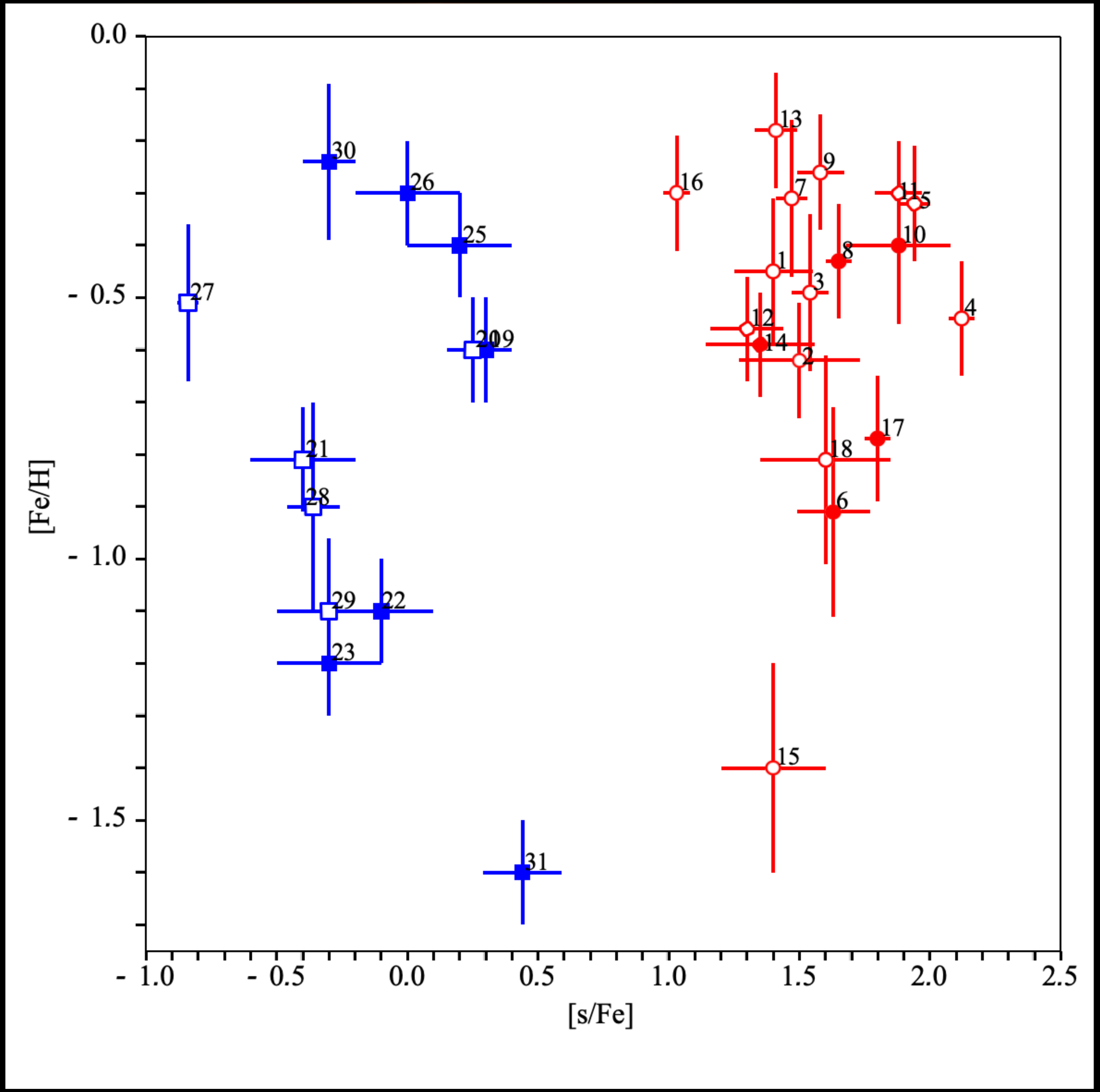
s-process rich versus non-enriched:

s-process rich
non s-process enriched



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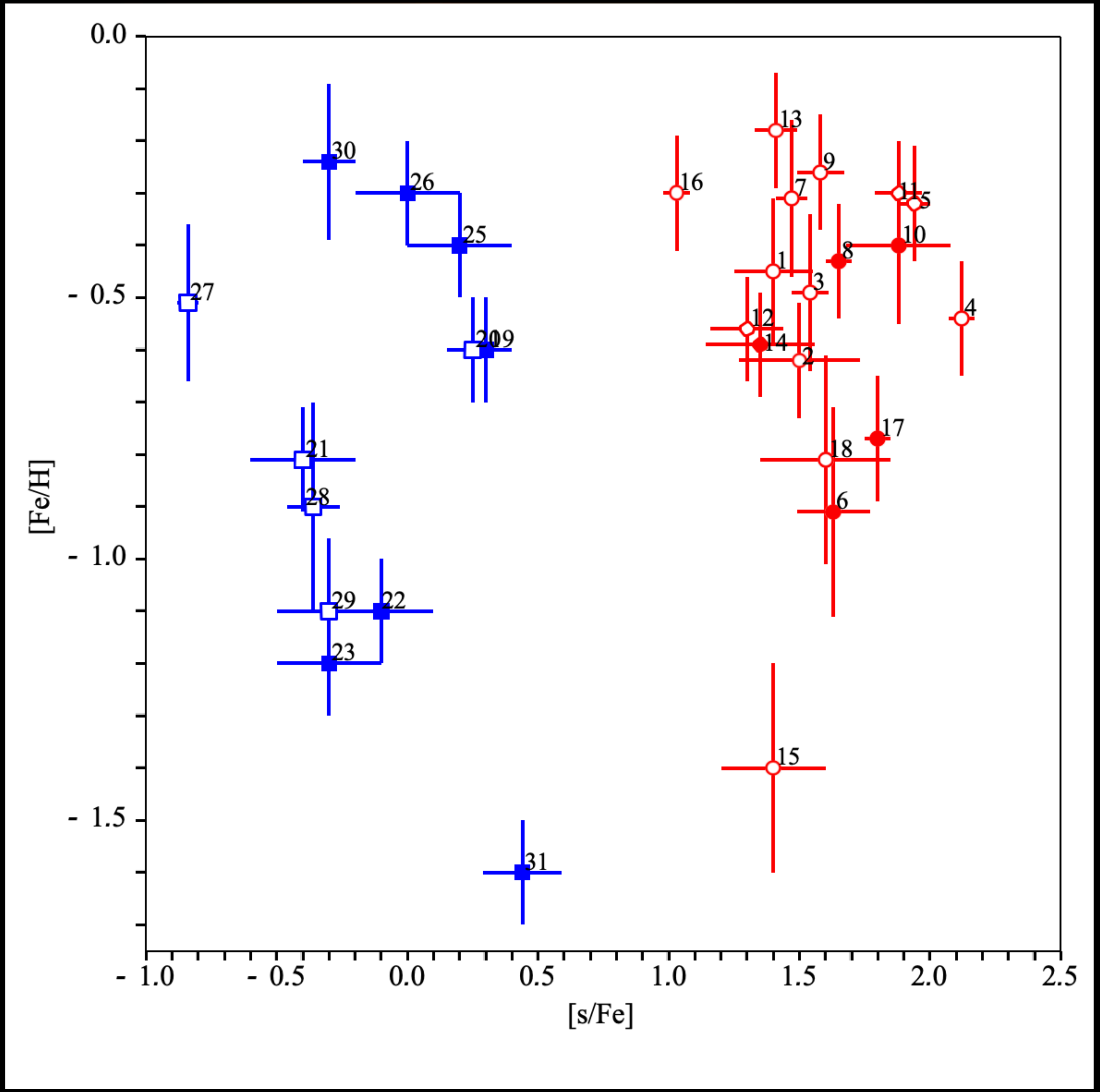
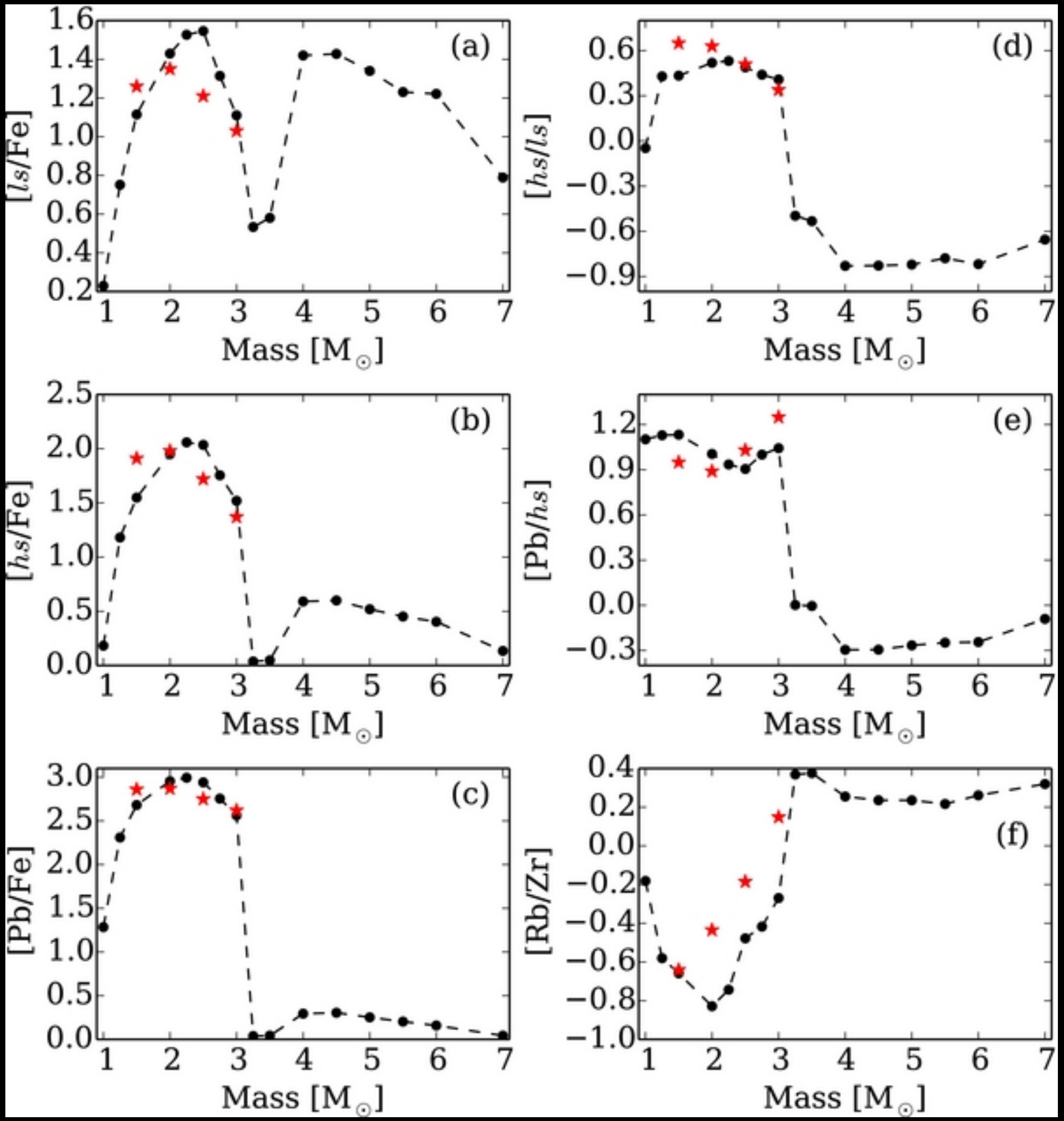


AGB Nucleosynthesis is NOT homogenous!

Nucleosynthetic Yields from Stellar Models

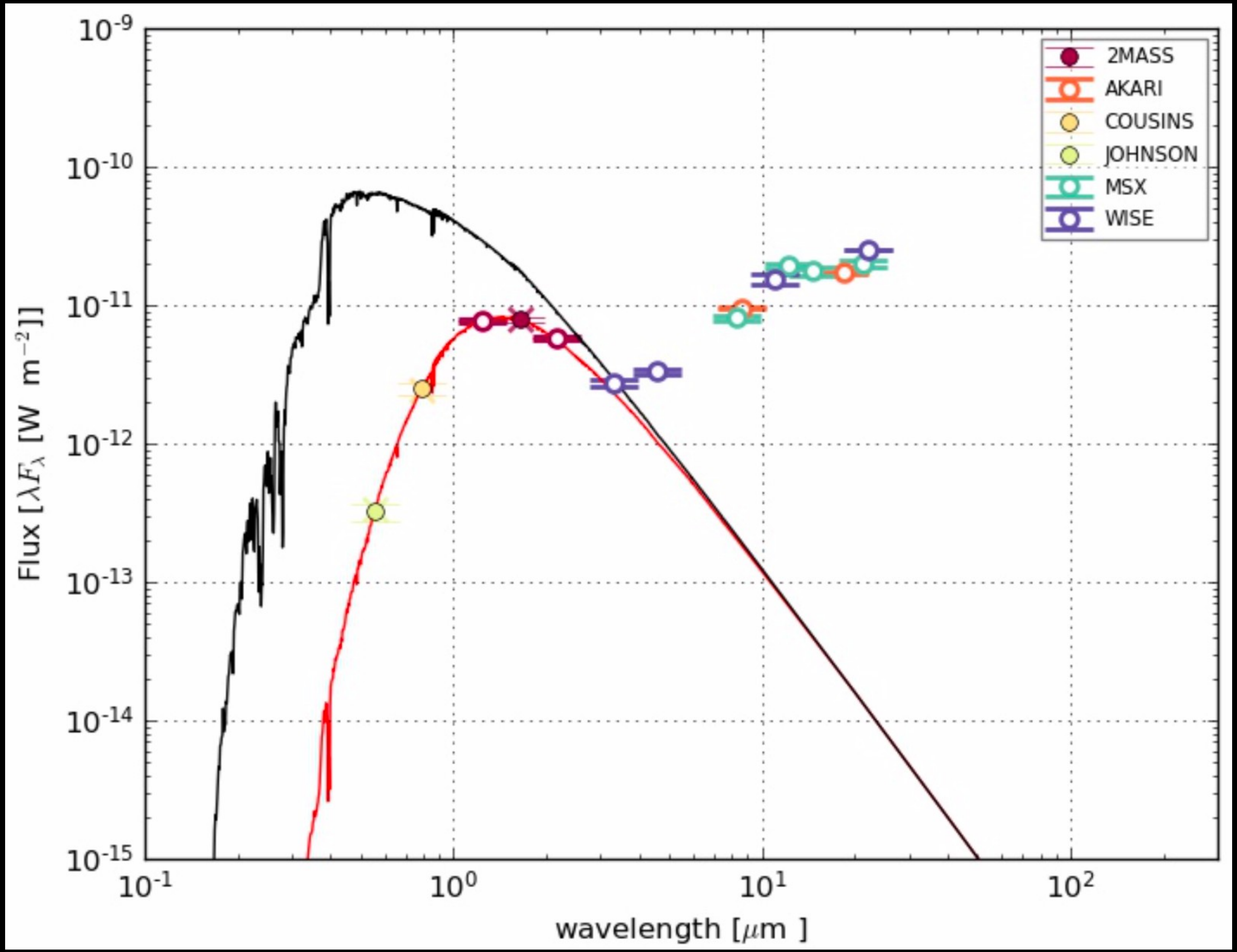


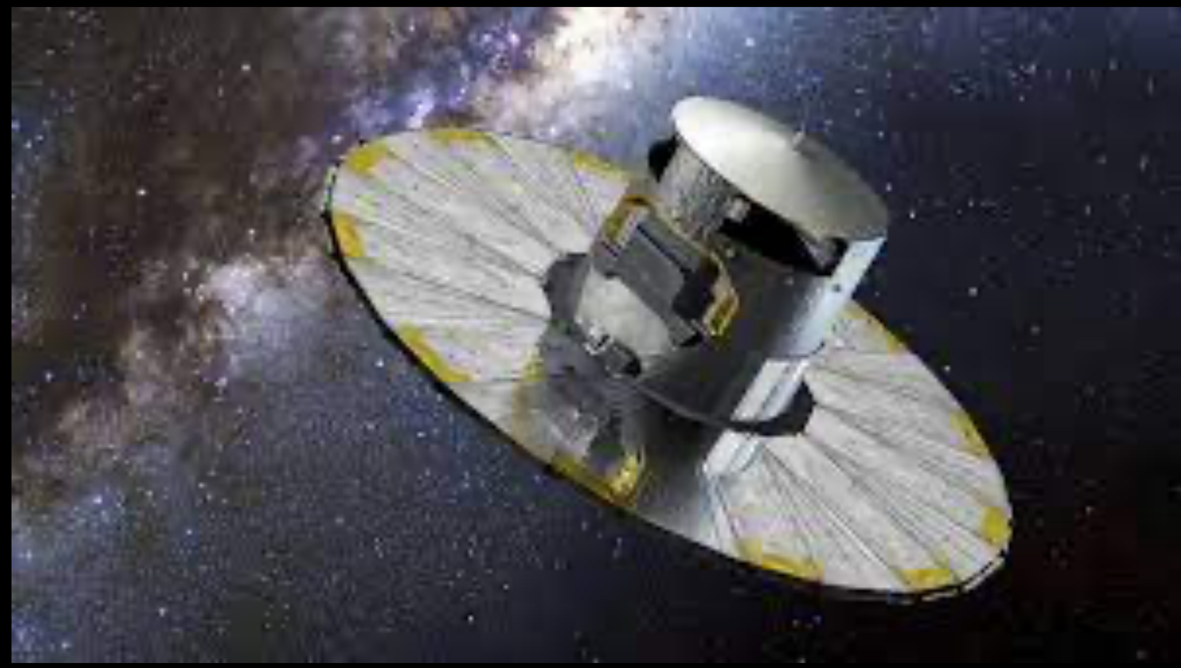
ls = Y, Sr, Zr, Rb

hs = Ba, La, Nd

Fishlock et al., 2014

Luminosities for Single Galactic Post-AGB Stars with GAIA





Kamath et al., 2022

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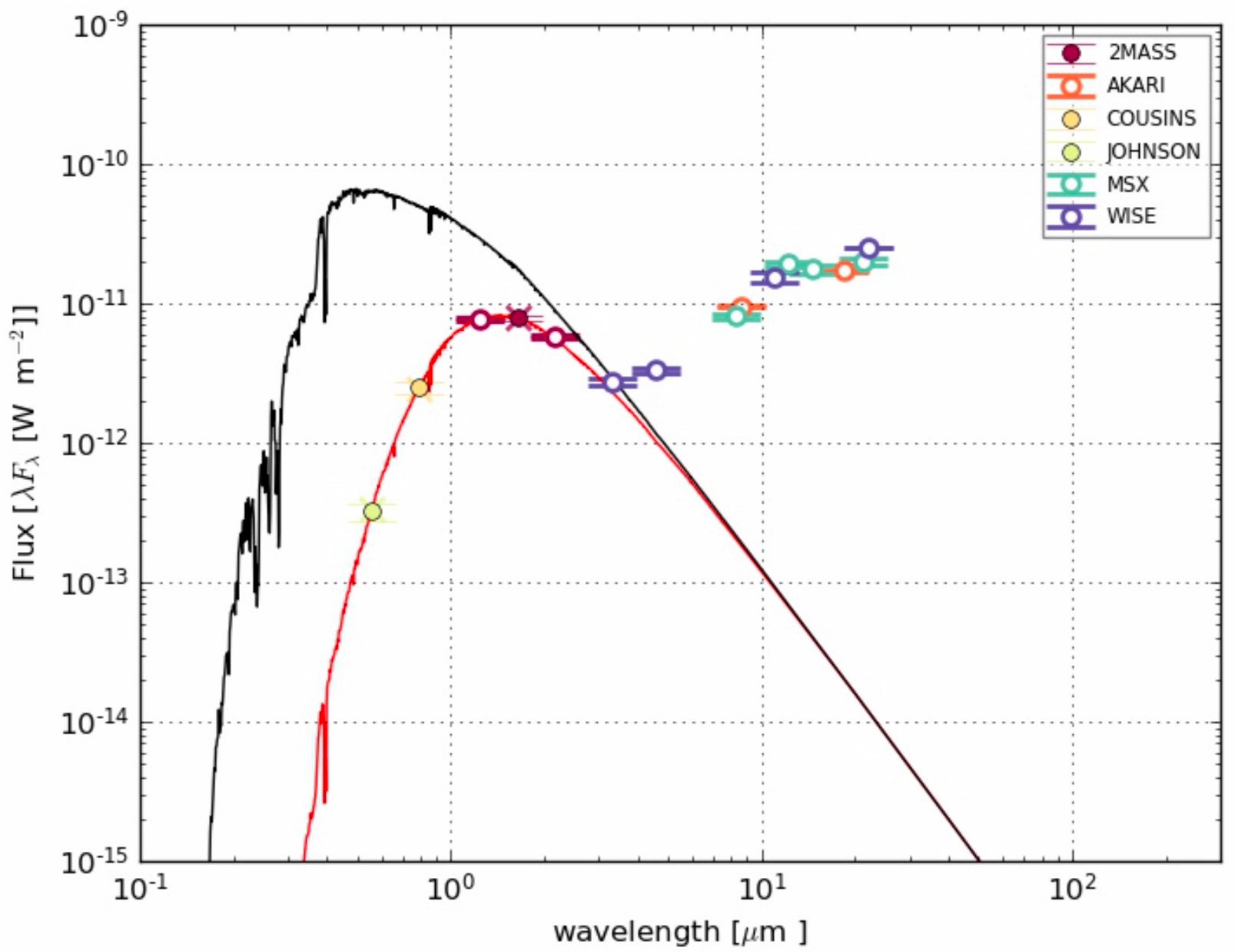

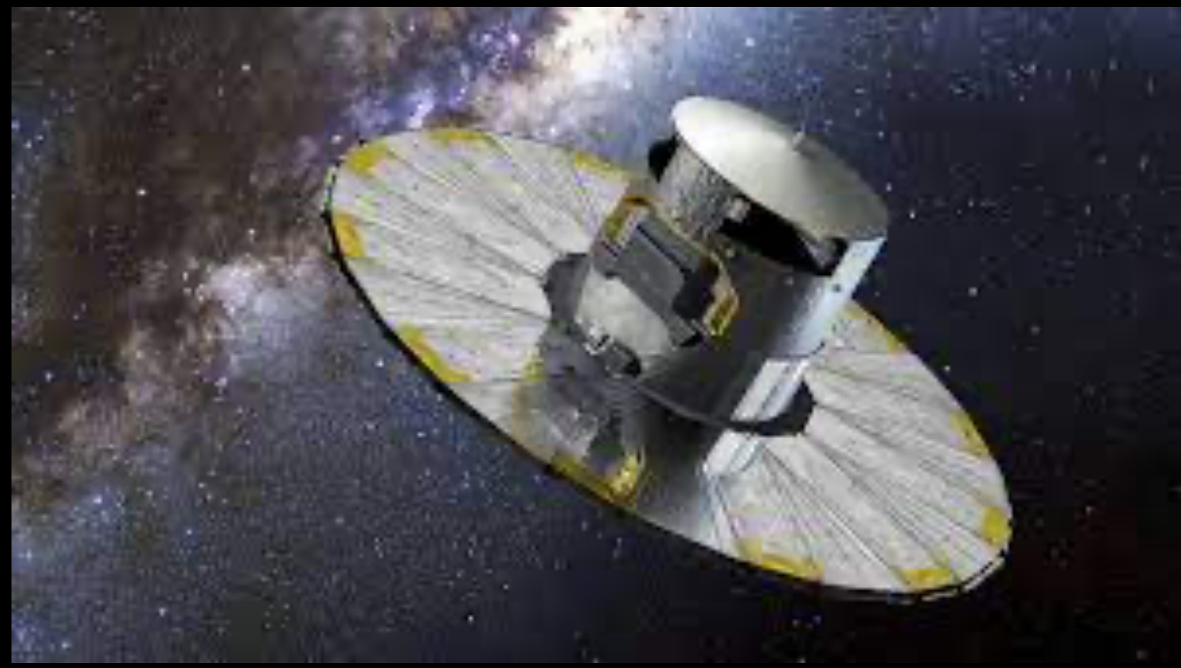

- Parallaxes from Gaia EDR3

Kamath et al., 2022

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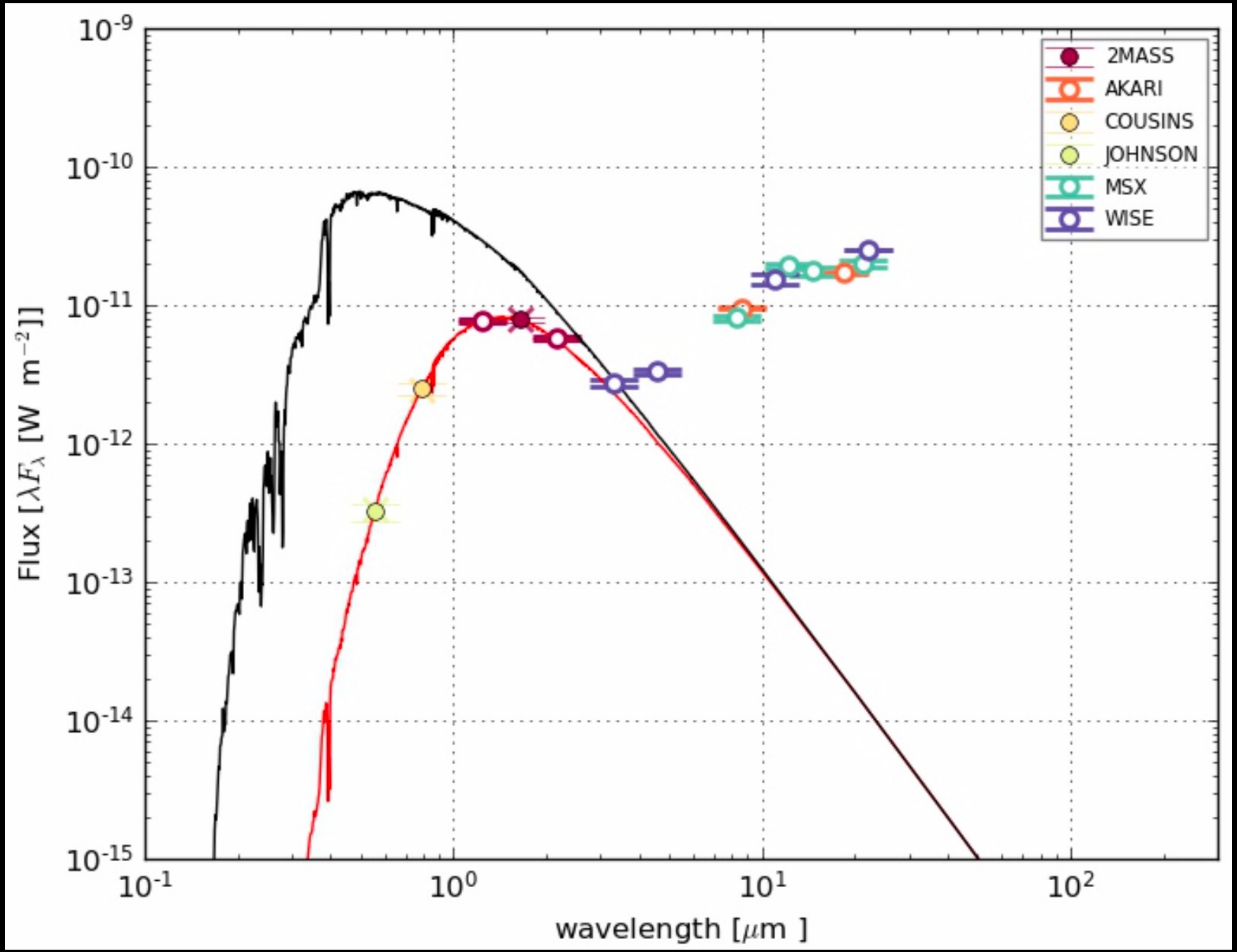

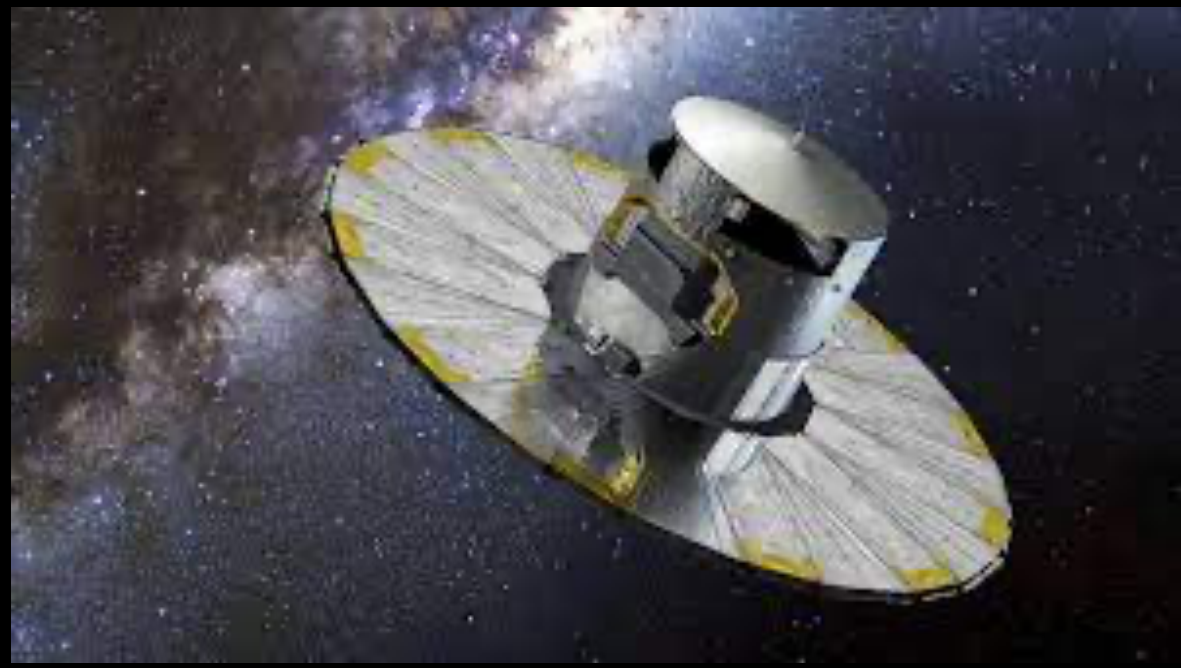

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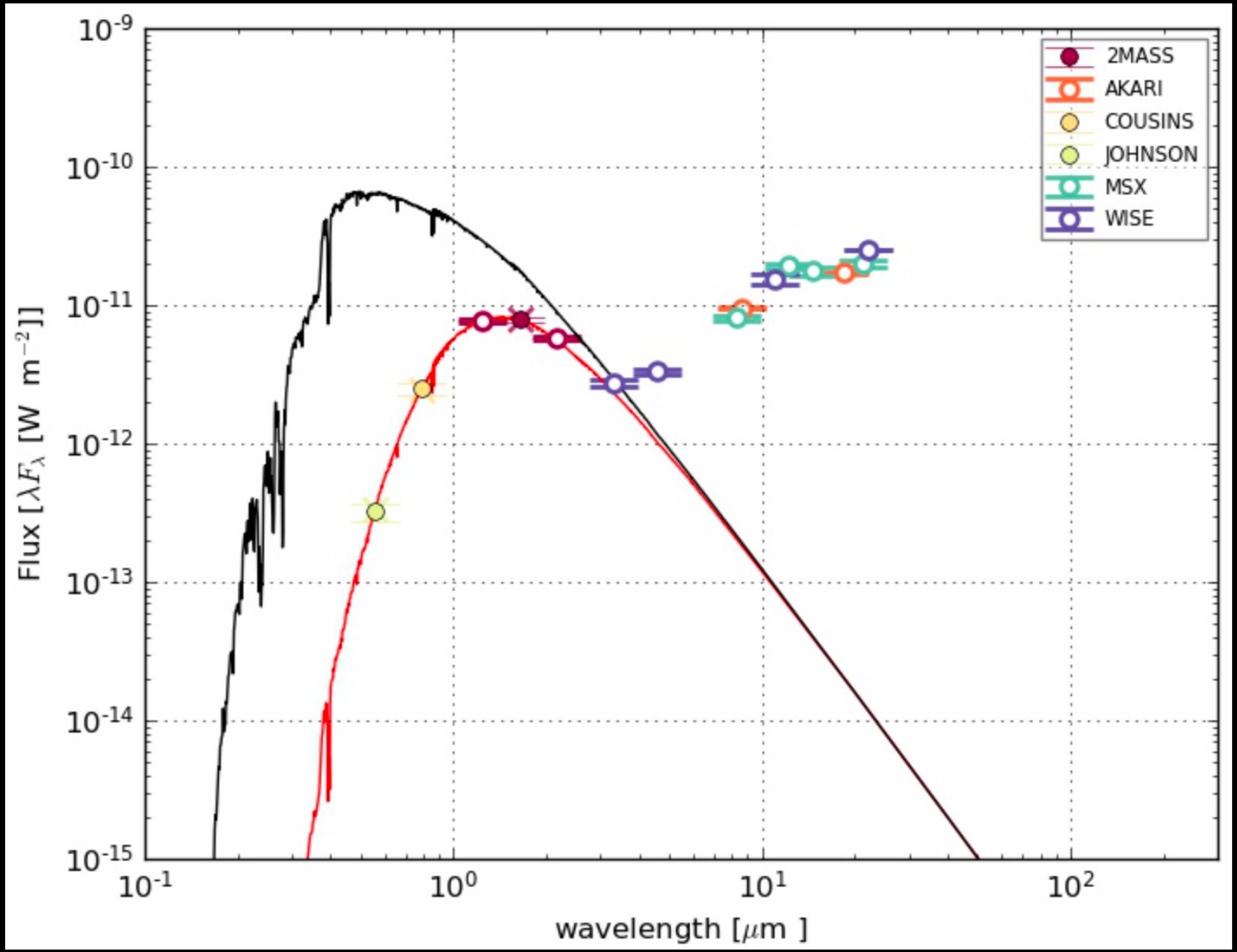

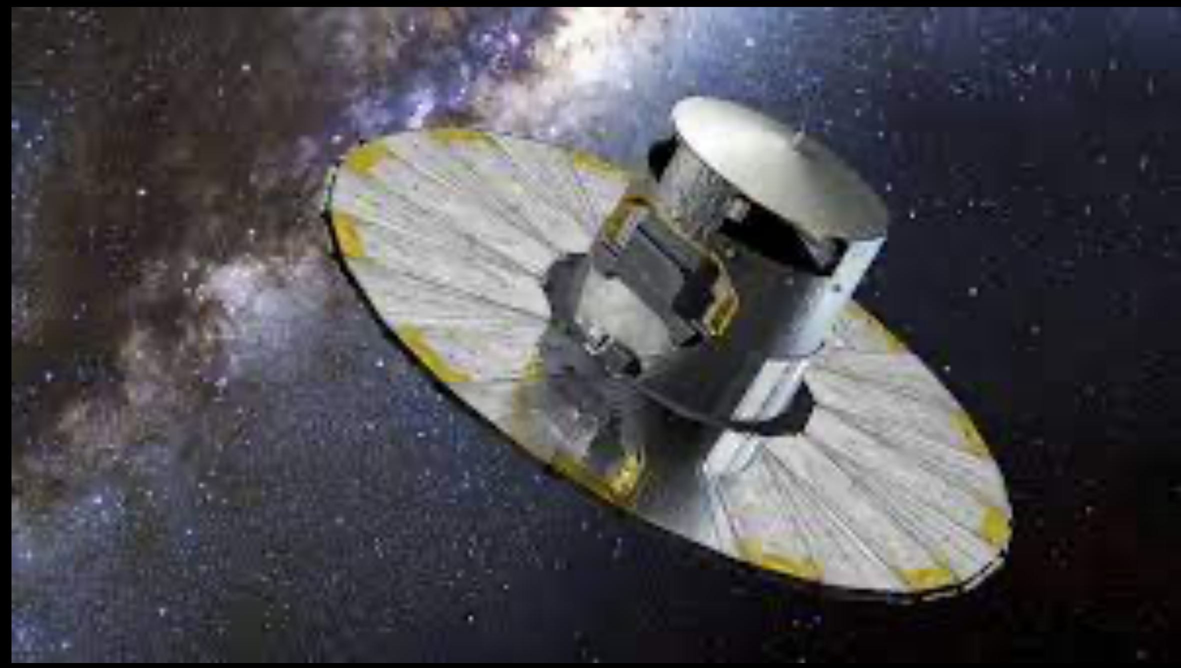

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Kamath et al., 2022

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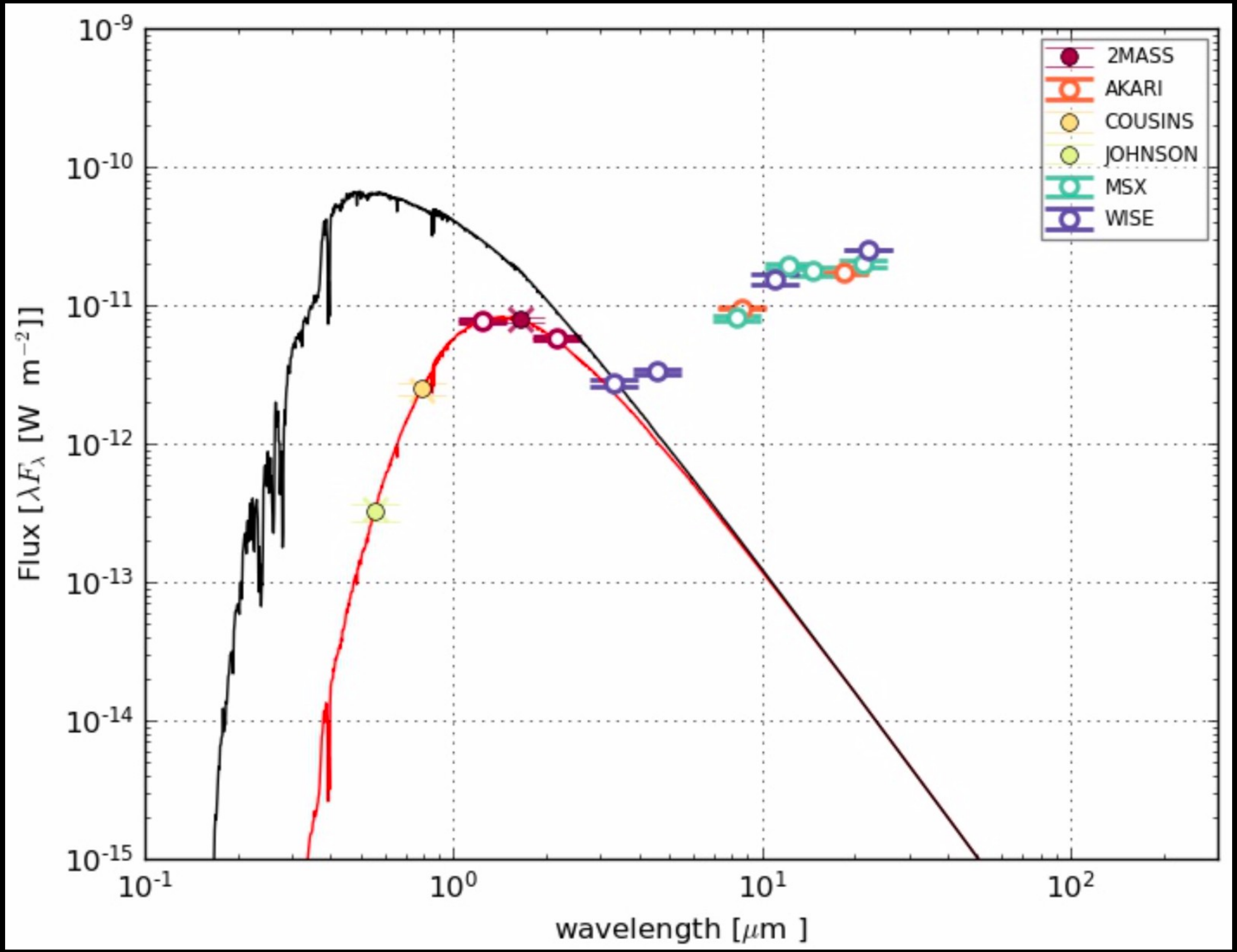

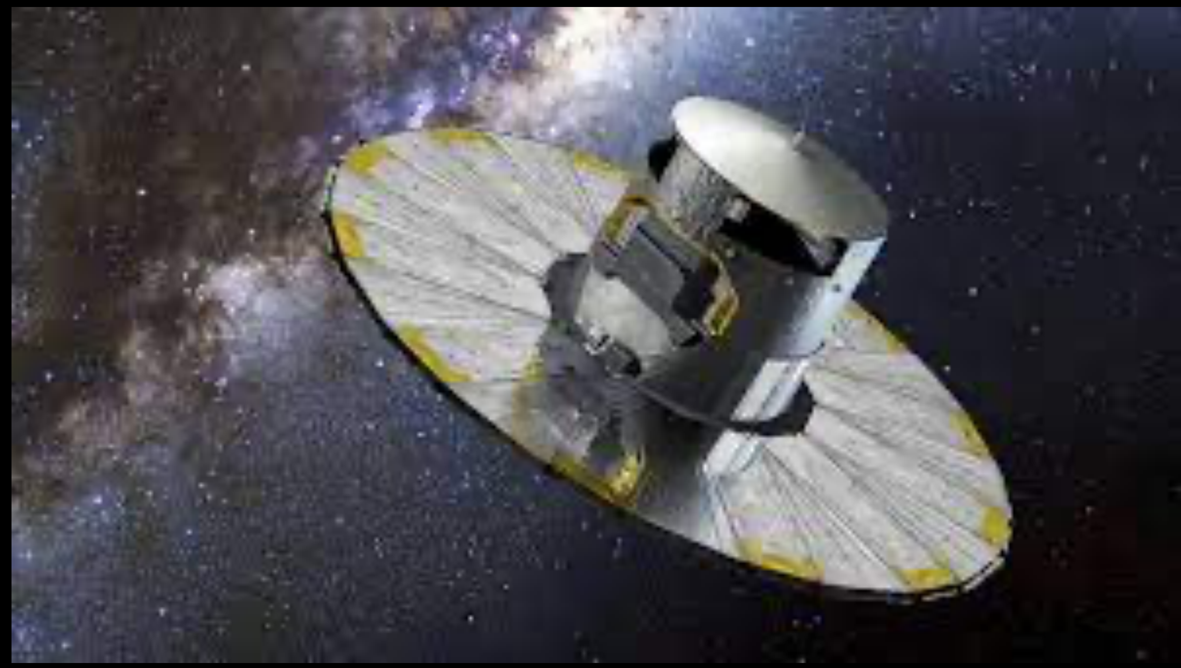

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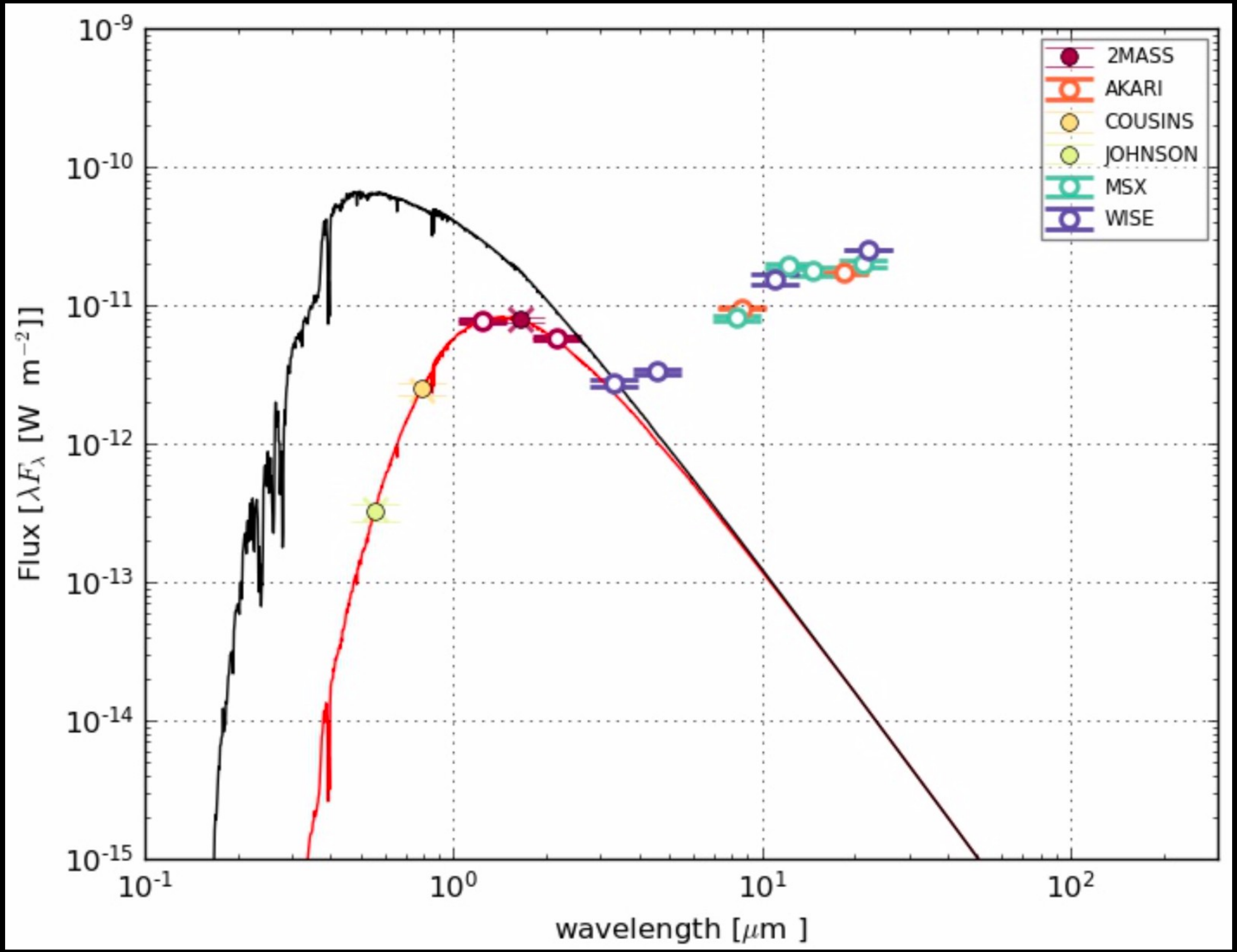

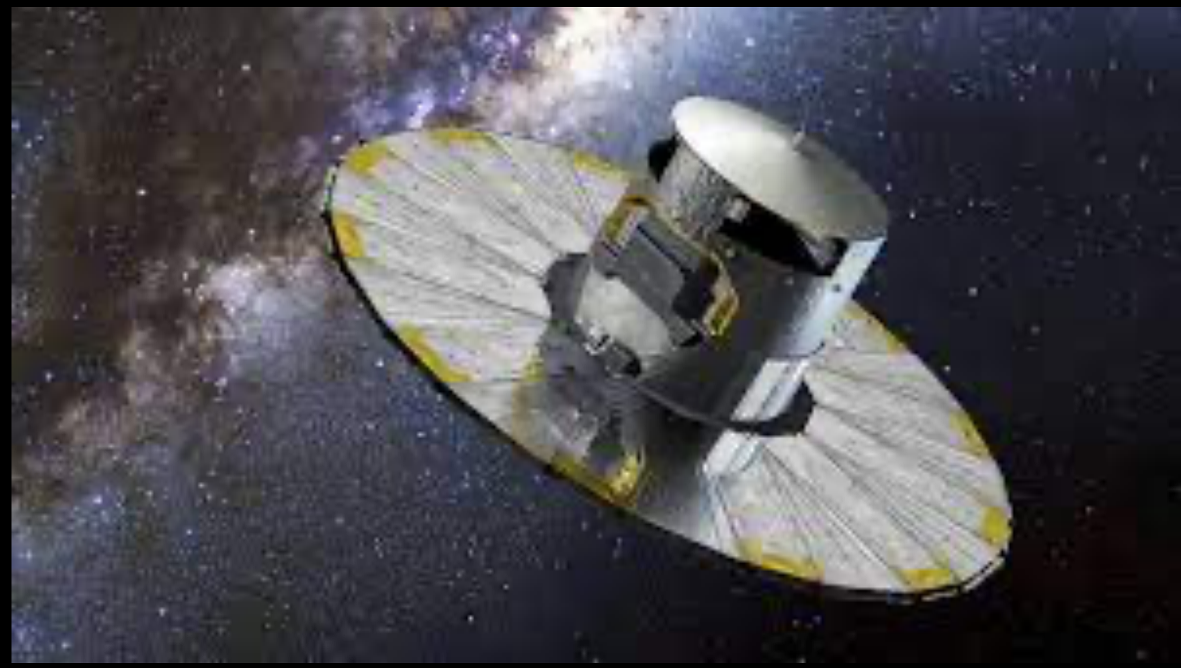

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Kamath et al., 2022

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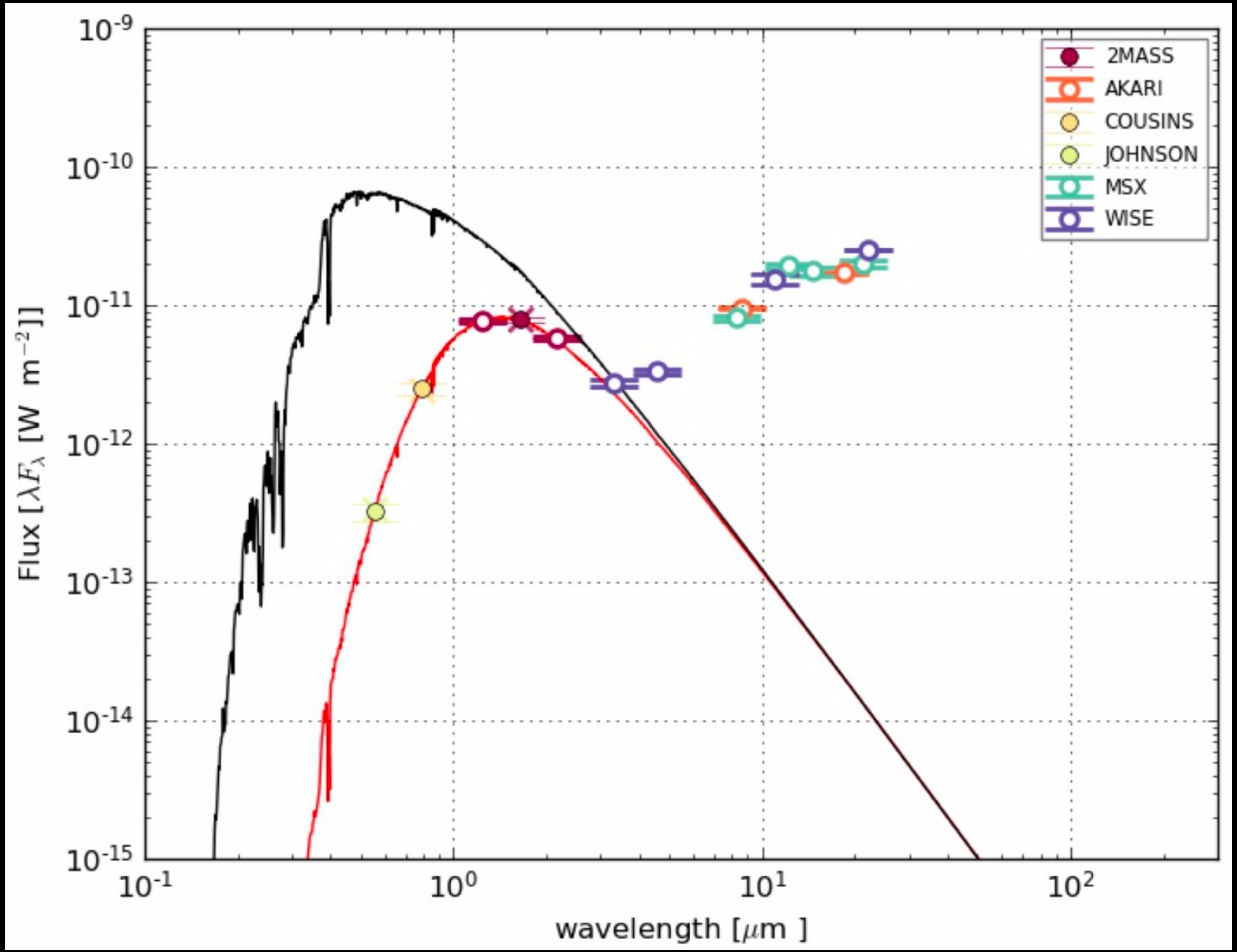

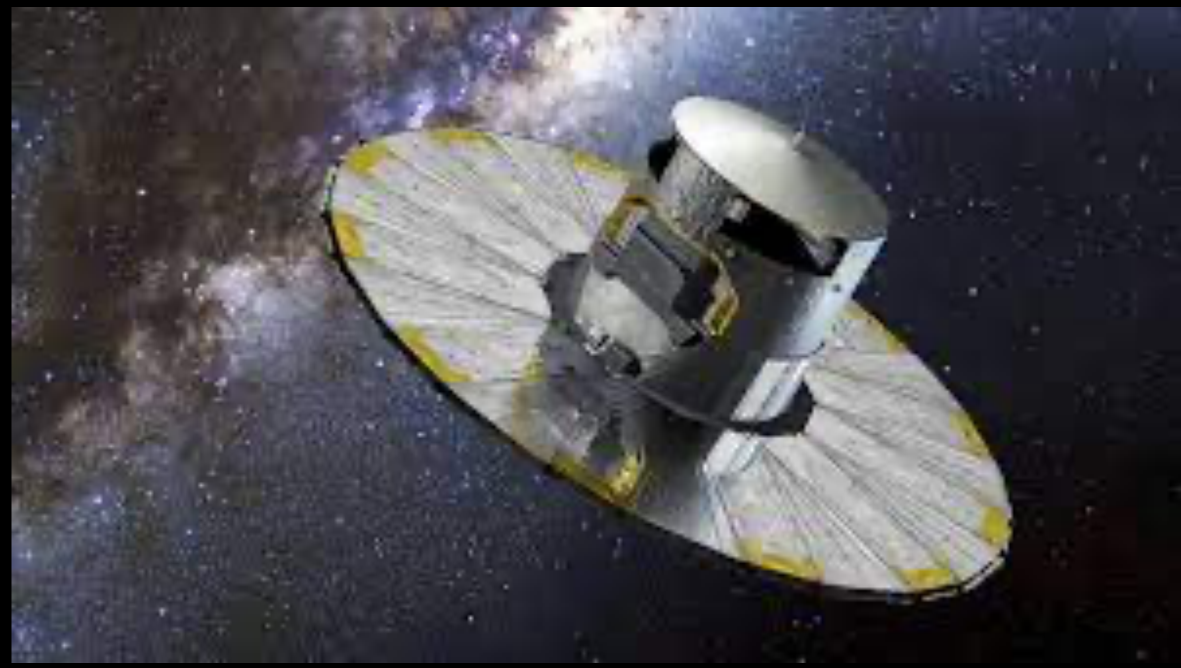

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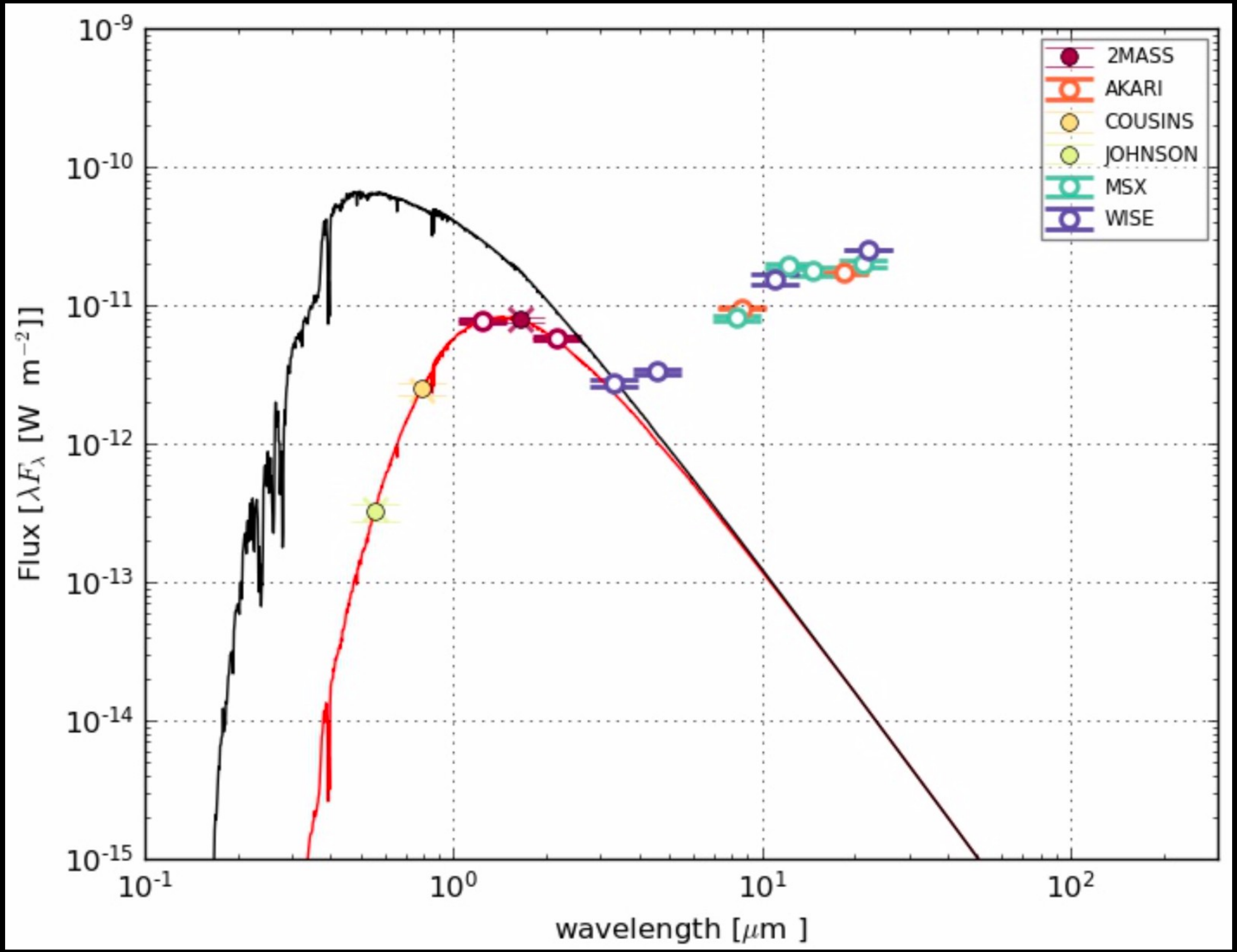

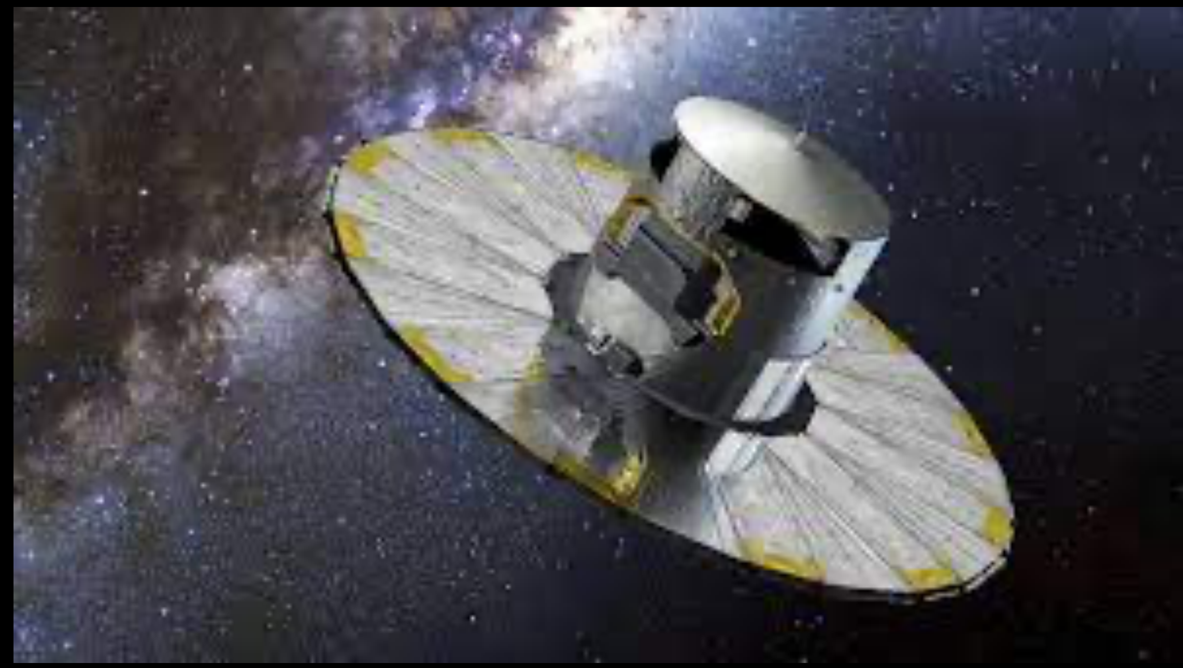

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Kamath et al., 2022

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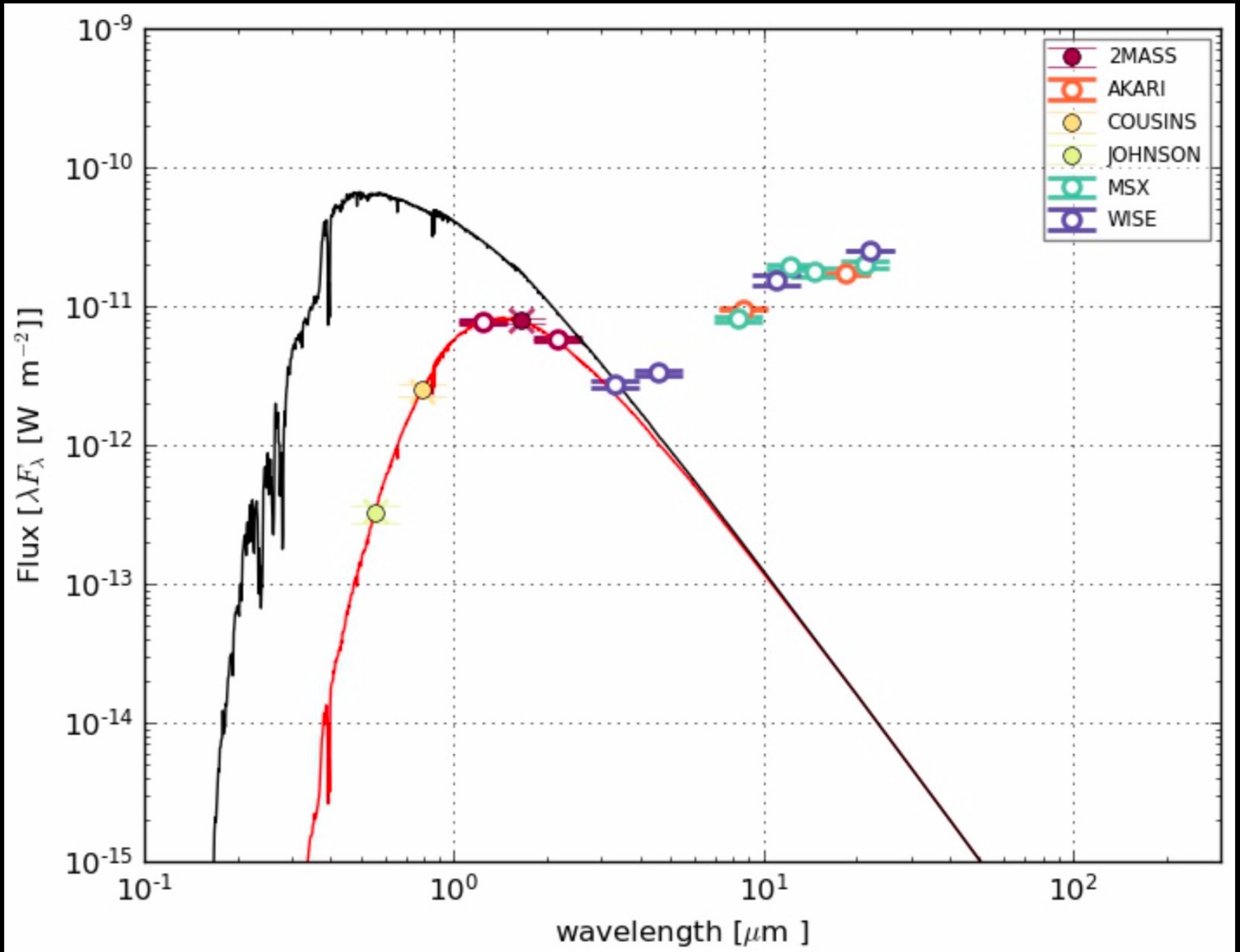

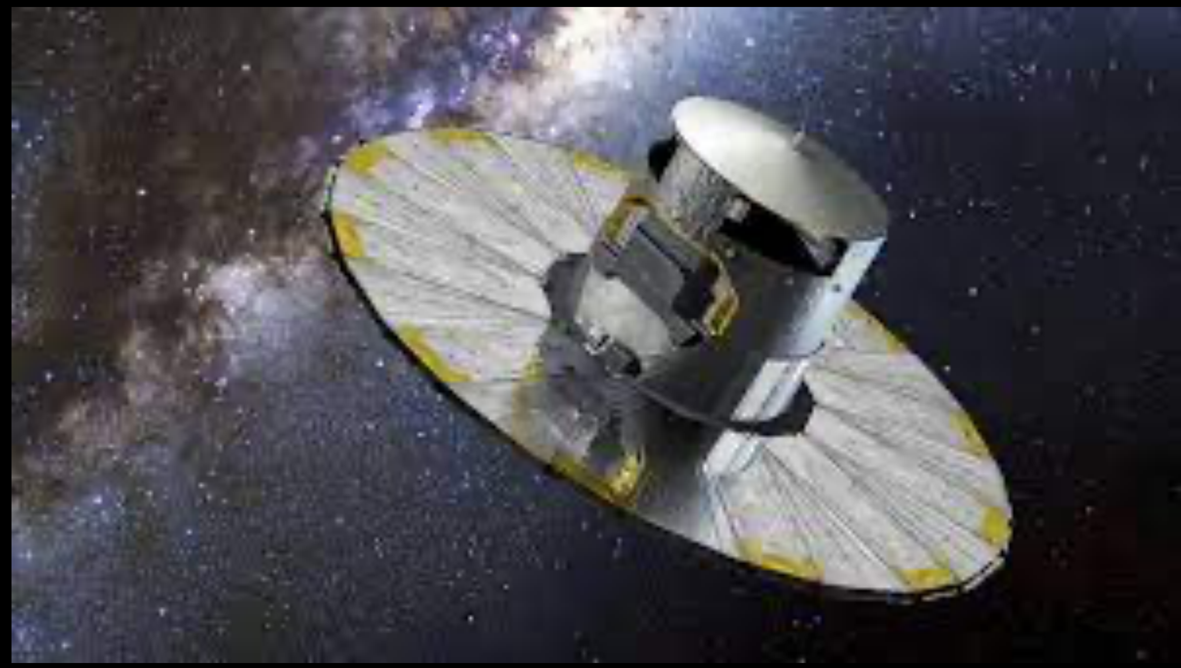

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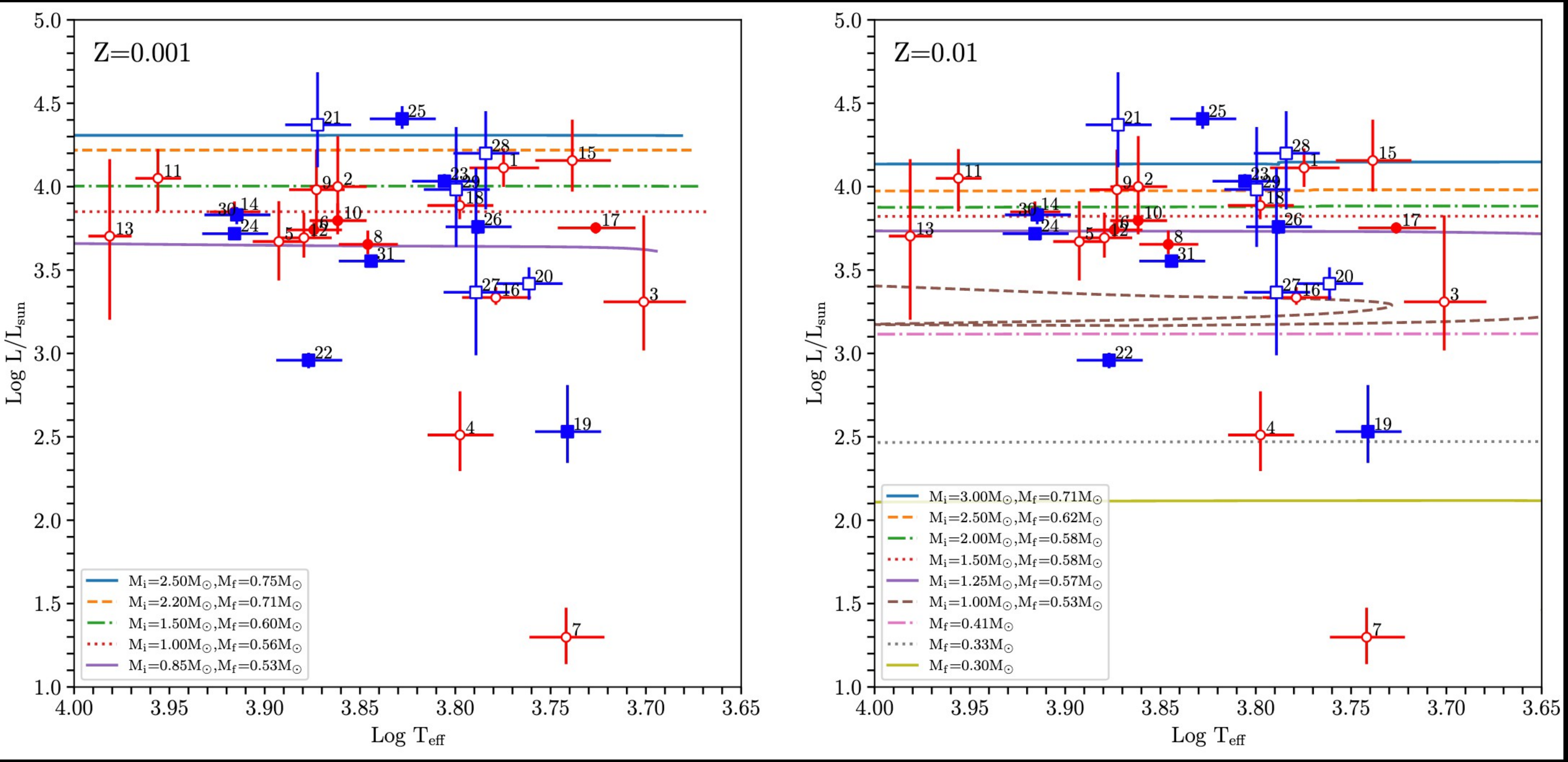
↓

- Luminosity

Kamath et al., 2022

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; Kamath et al., 2023

Key Questions Explored through AAT Observations

1. Origin of elements and refining stellar yields: How do low- and intermediate-mass stars contribute to cosmic chemical budget?
2. Dust production and evolution in evolved stars: How does dust form and evolve during and after the AGB phase?
3. Binary interactions in evolved stars: How do binary interactions shape the evolution of low- and intermediate-mass?
4. Second-generation proto-planetary disks: Can these astrophysical sites host planets?

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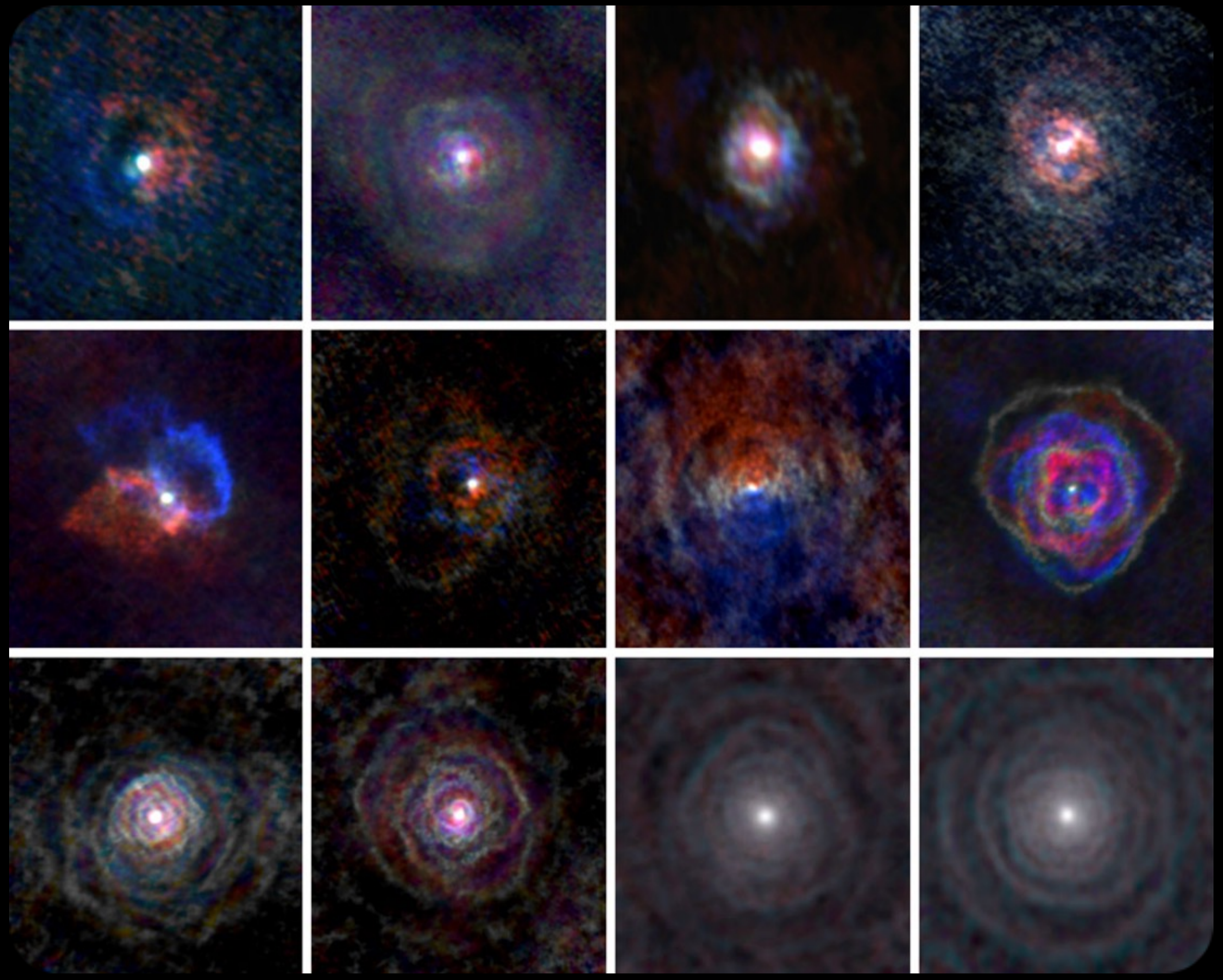
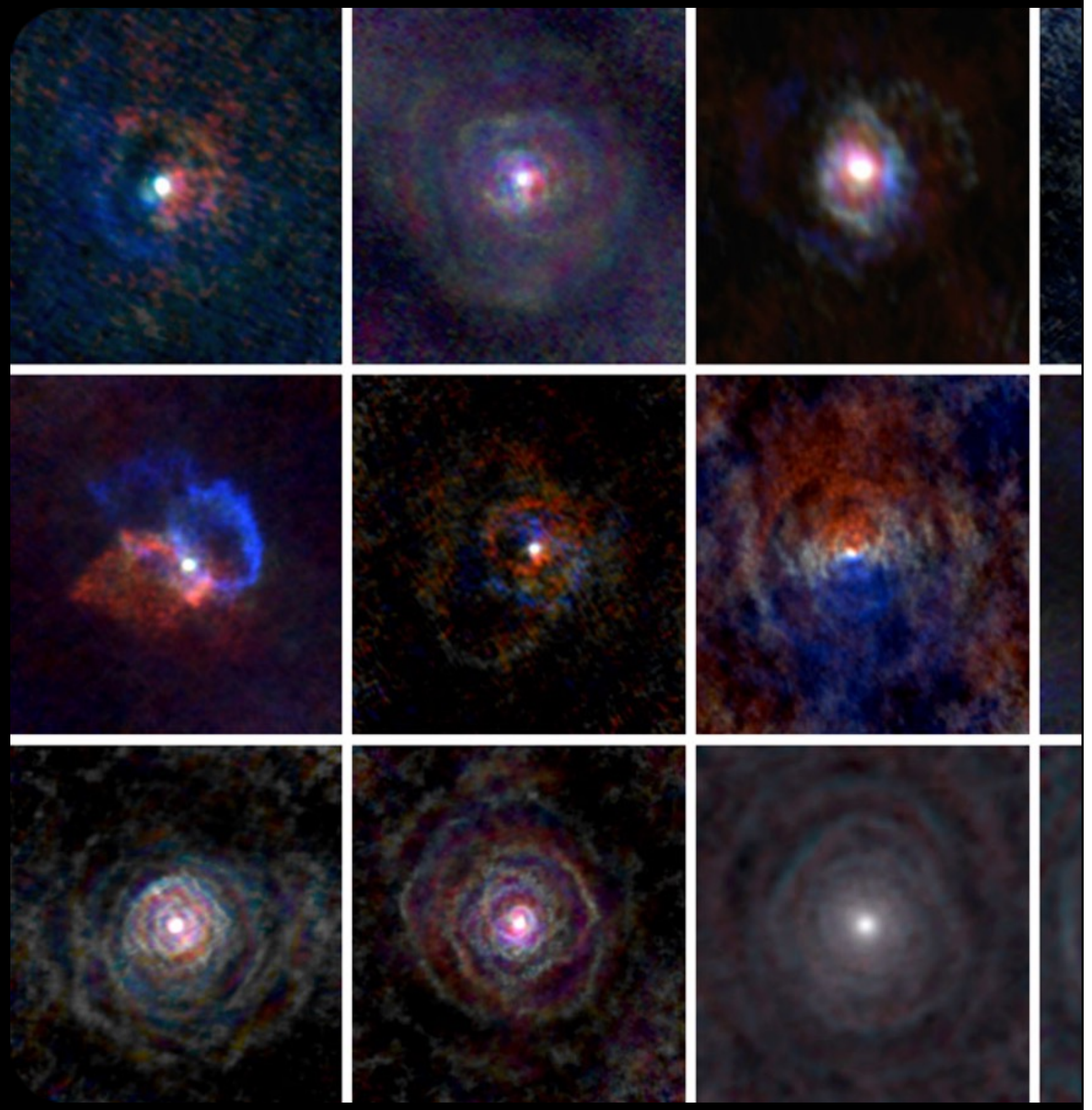
35 Br 79.90 eaking Symmetry

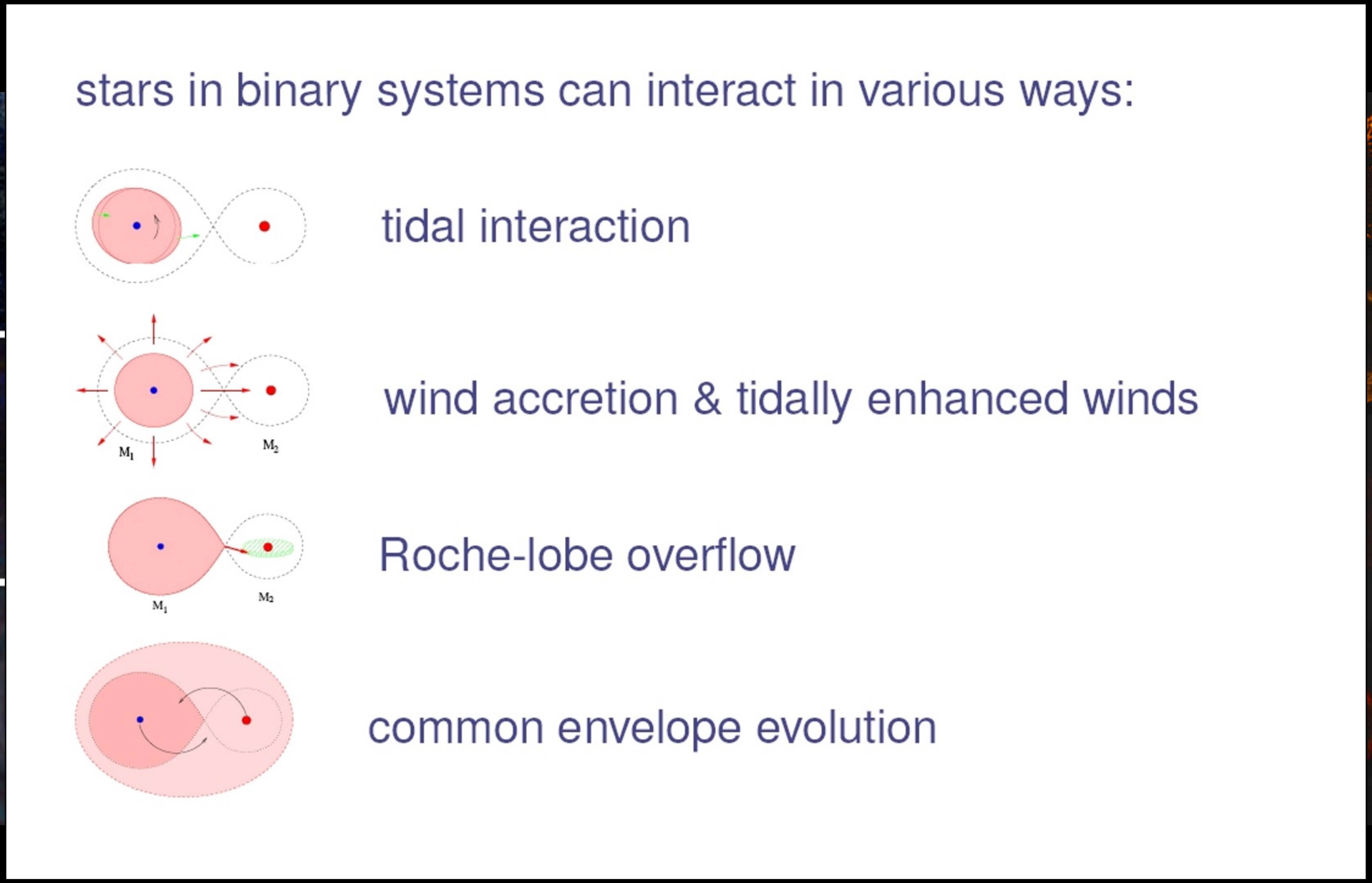


Breaking Symmetry

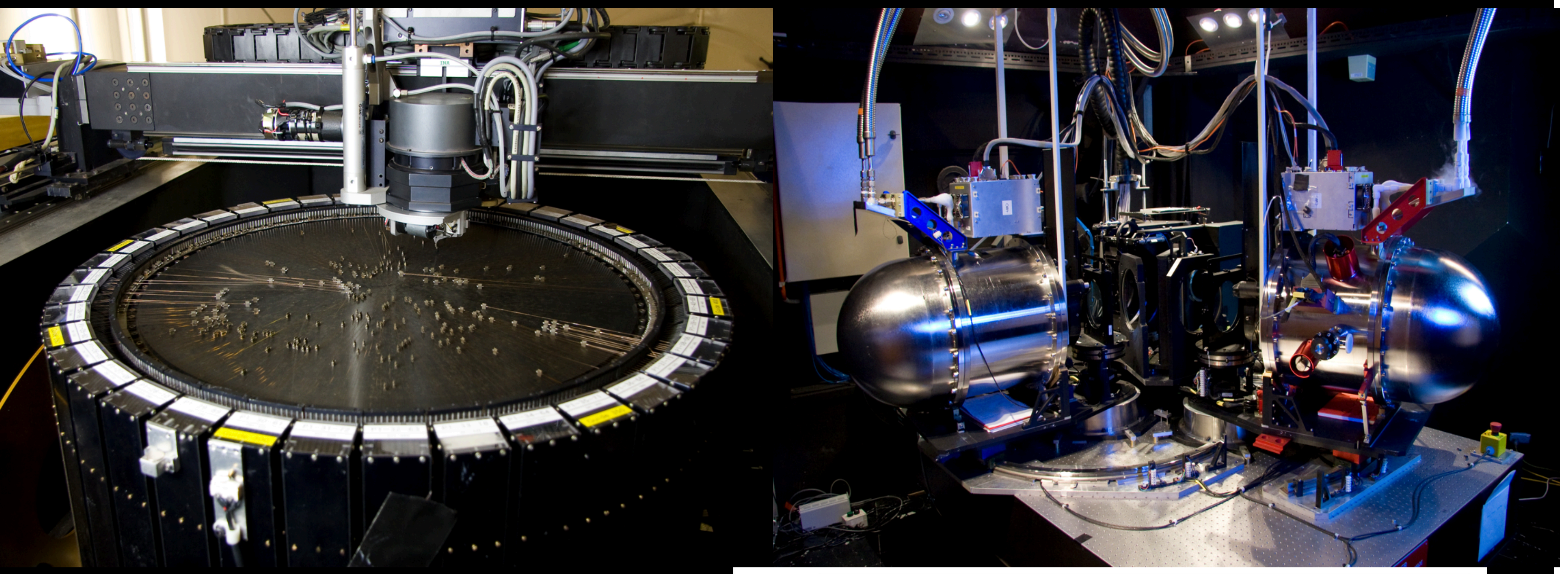
35

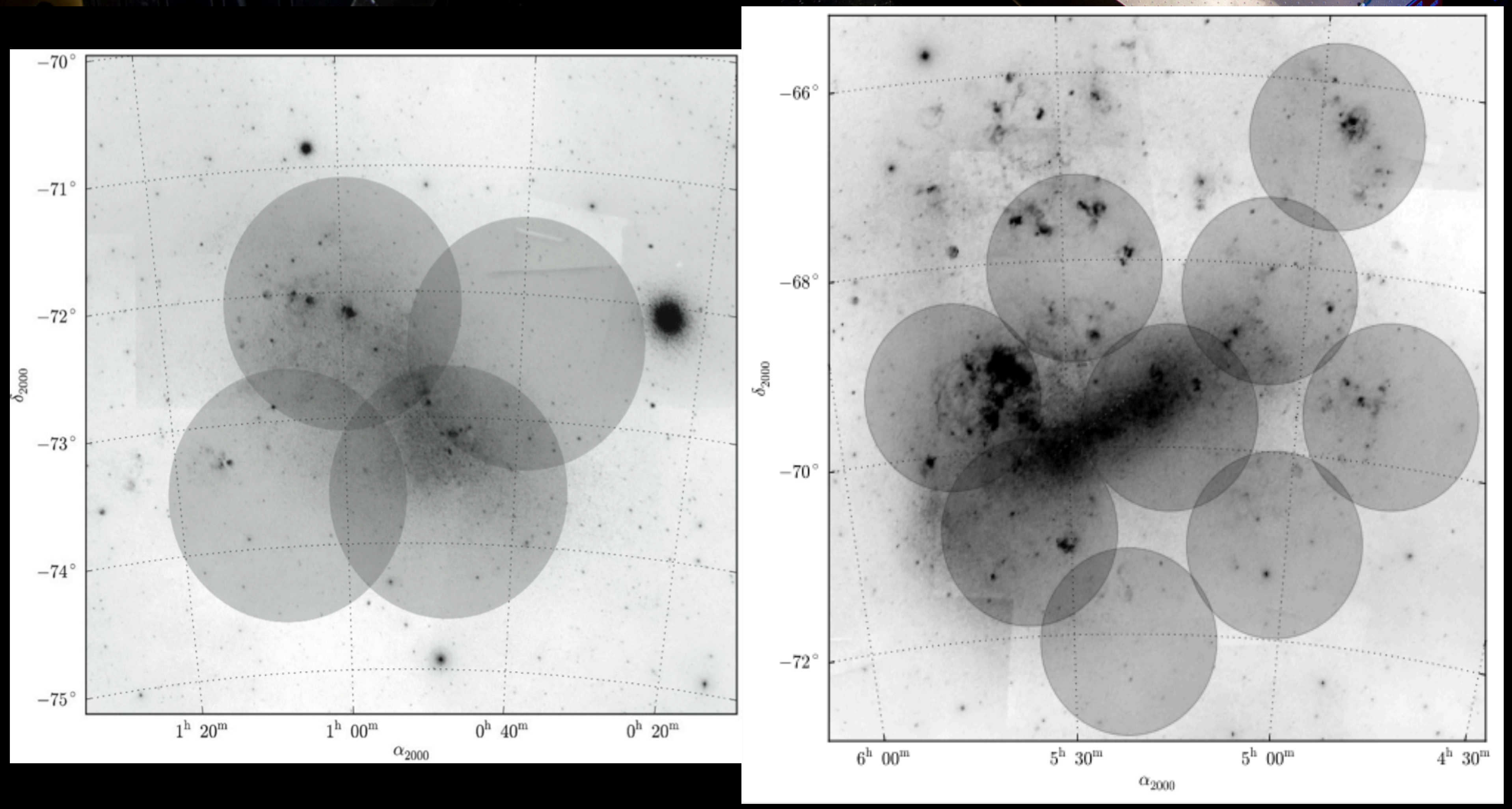
79.90

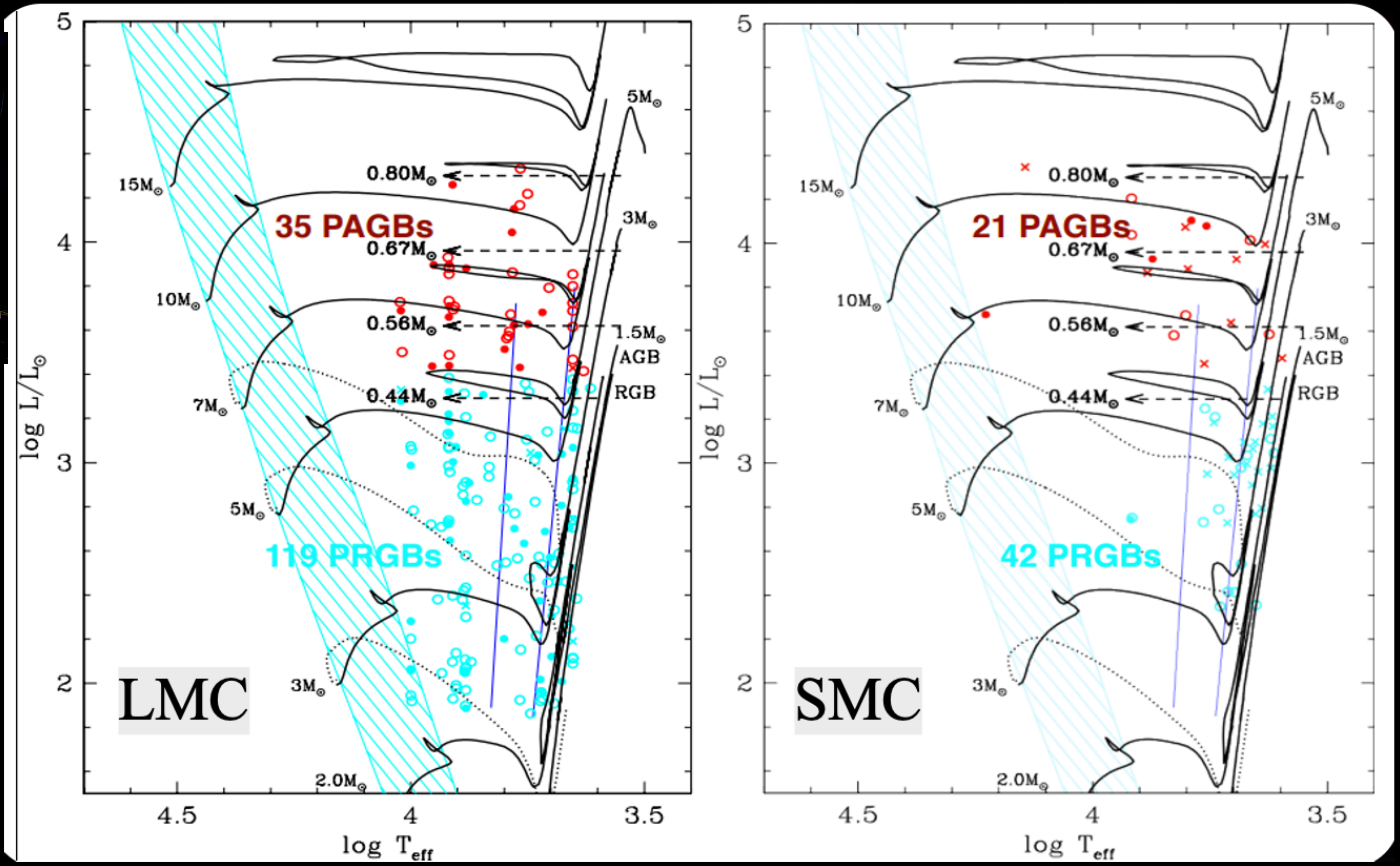




The Discovery of post-RGB Stars (in binary systems)

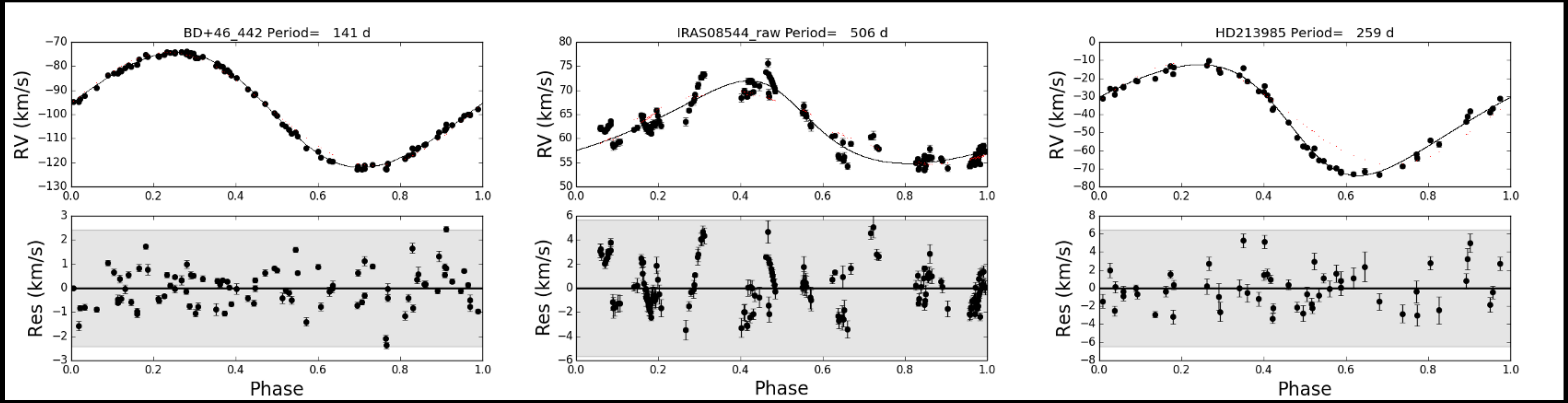


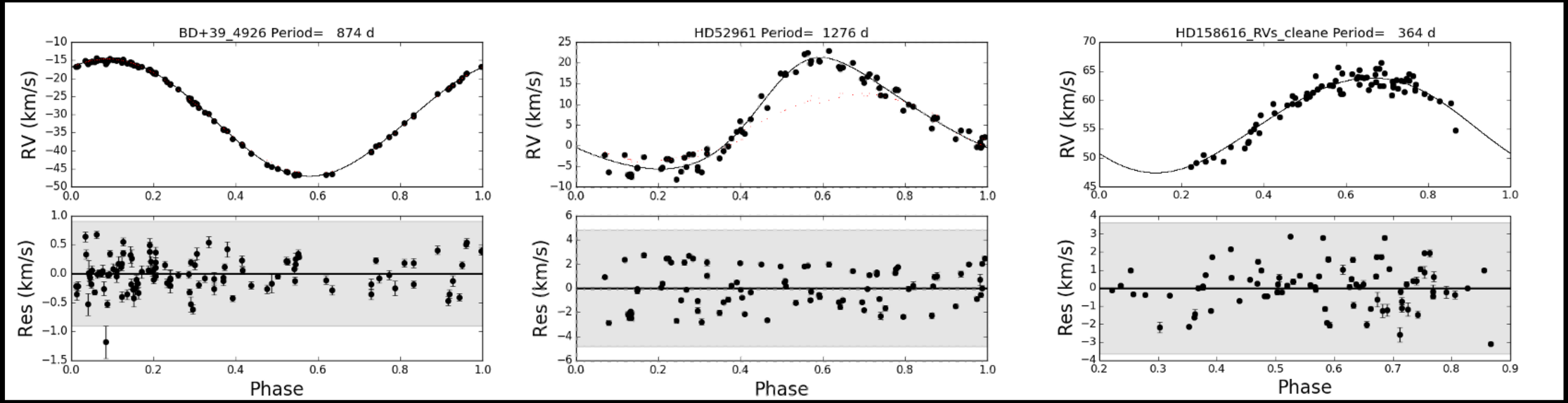


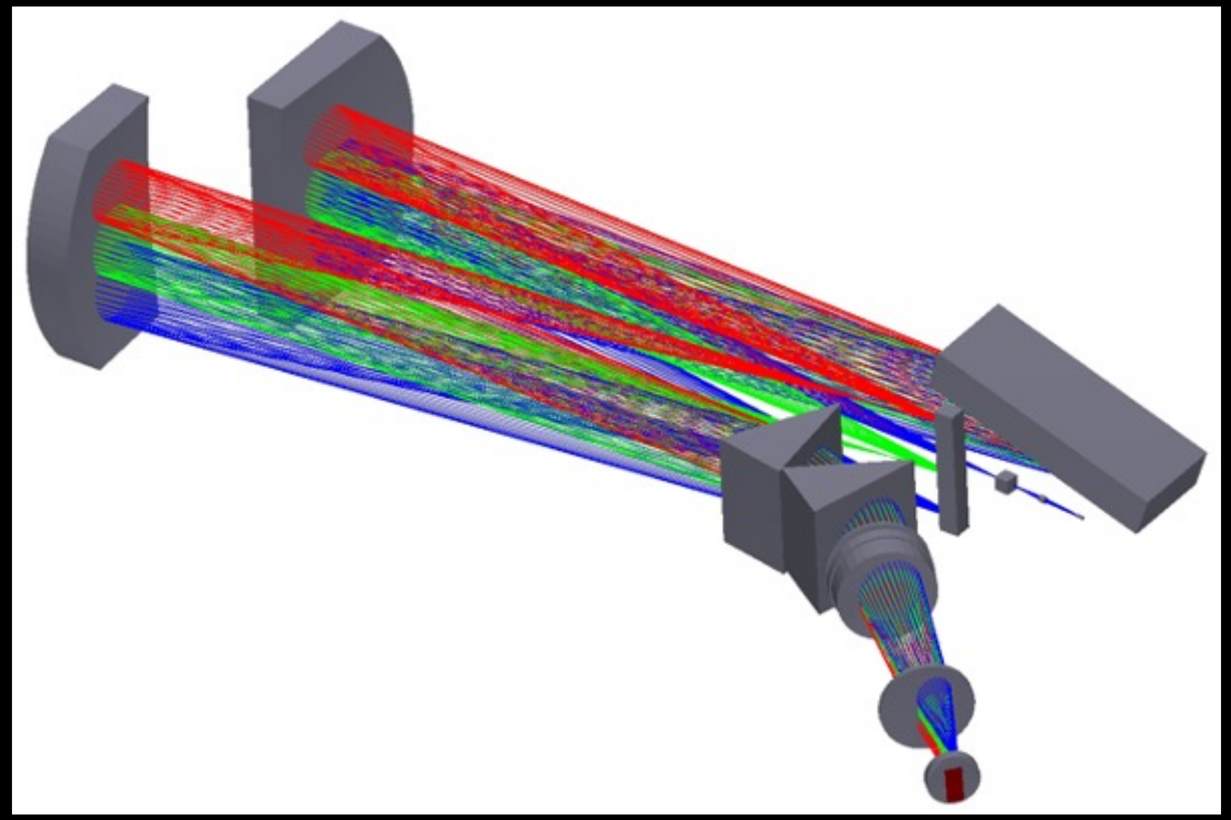


Kamath+2014, 2015, 2016

Spectroscopic binaries - time resolved spectroscopy

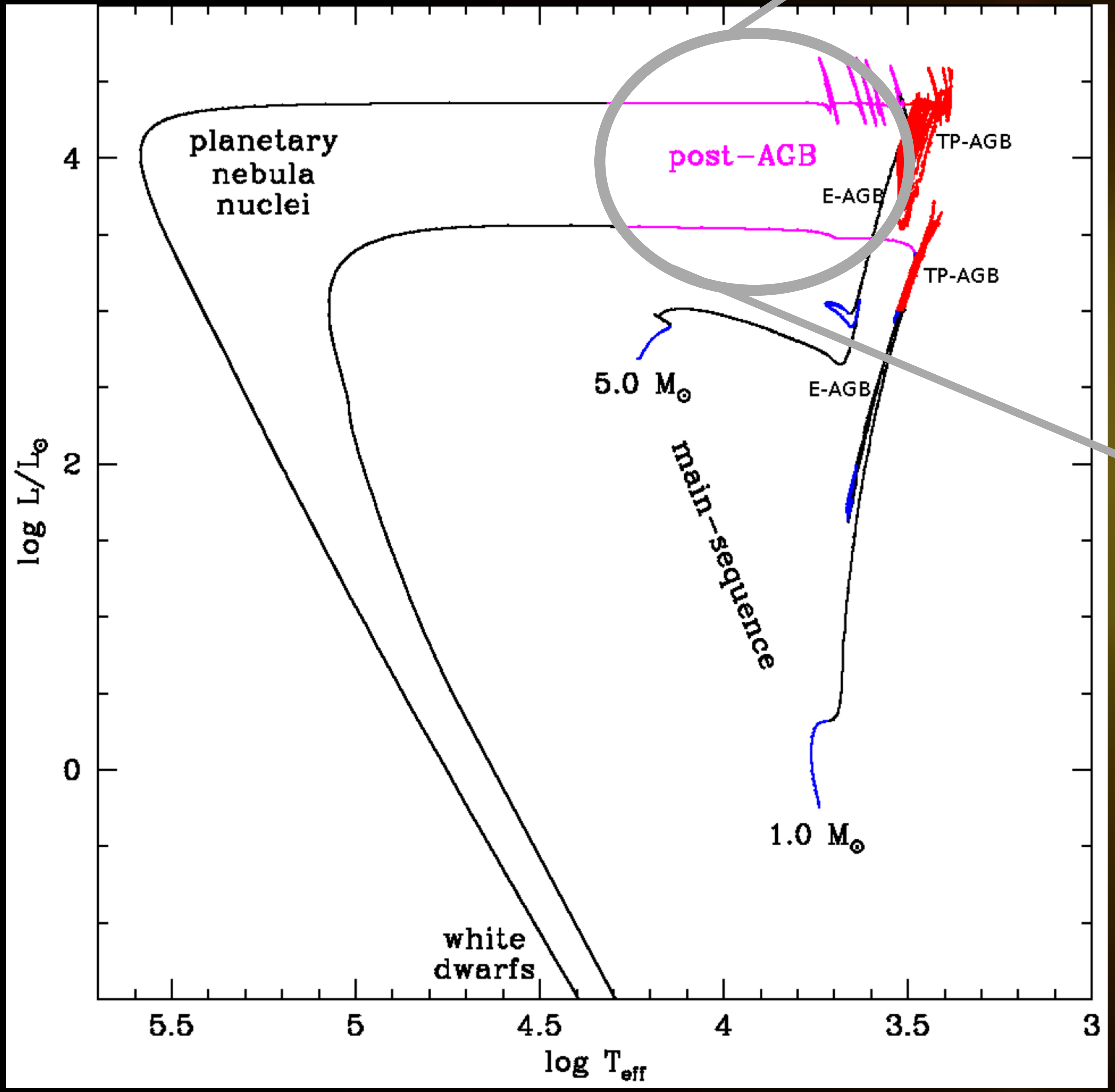


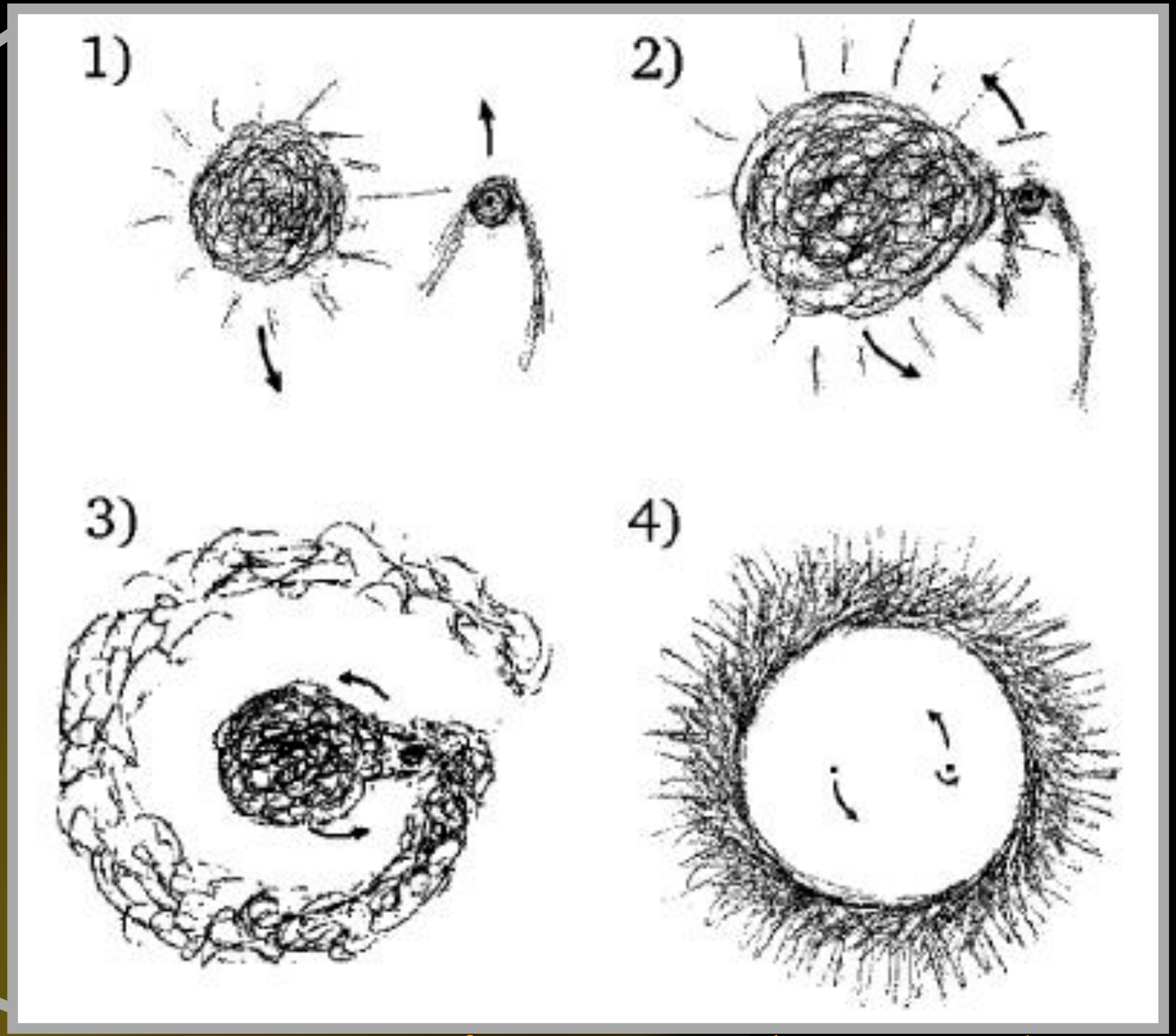




Van Winckel et al., 2009, Oomen et al., 2019

The Effect of Binarity:





Formation of a circumbinary disc

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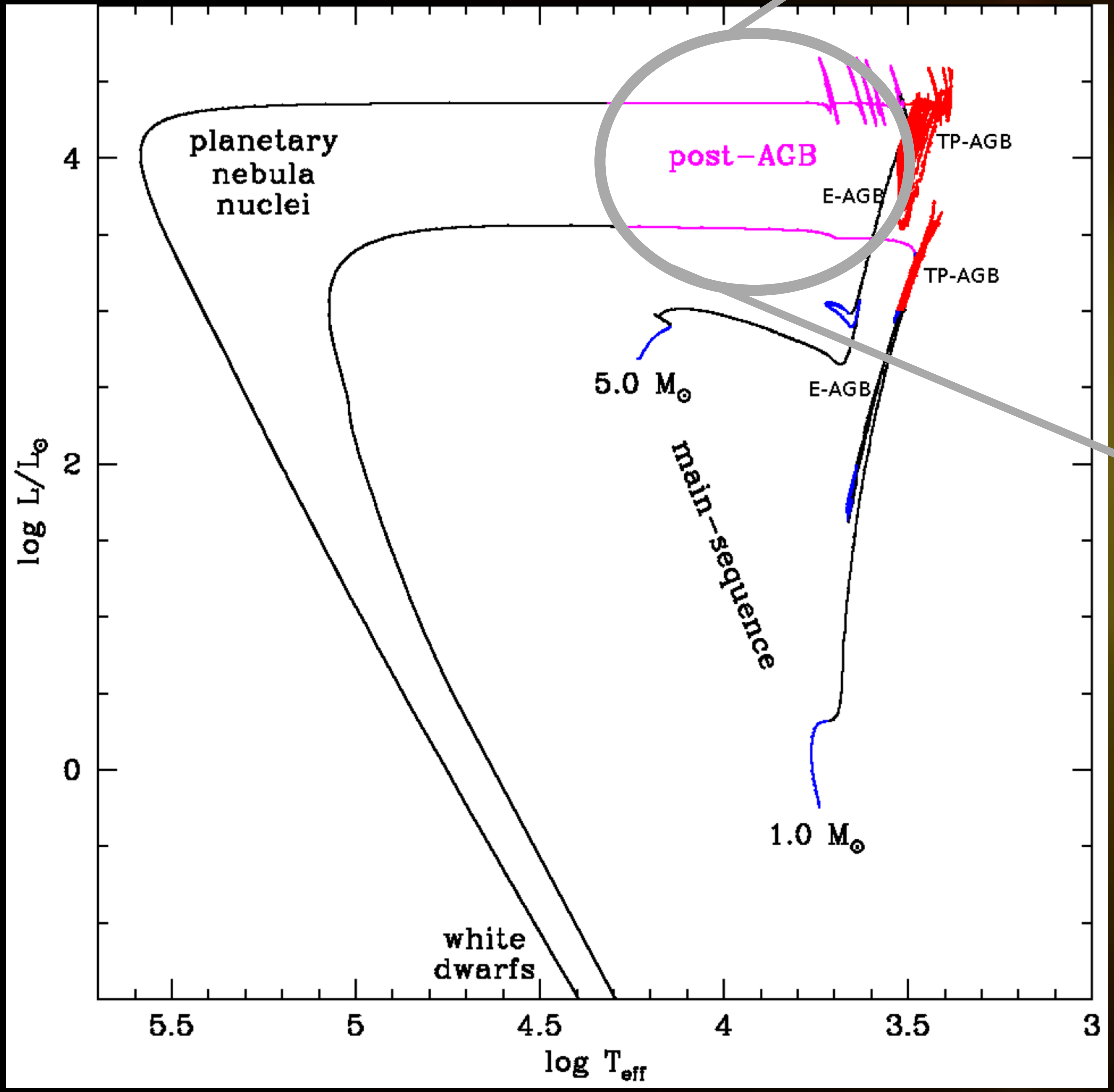
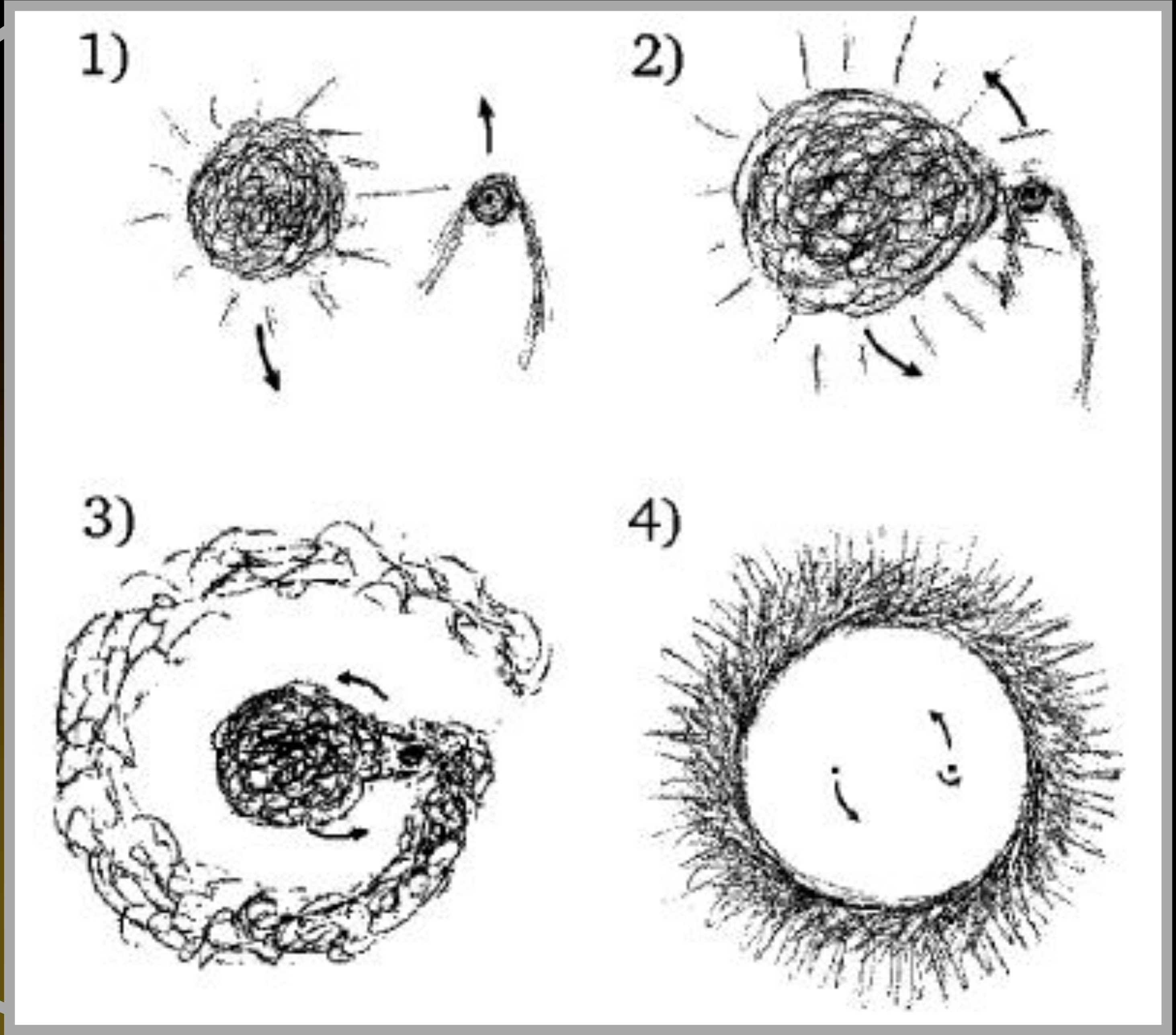


RocheLobe Filling on the Giant Branches



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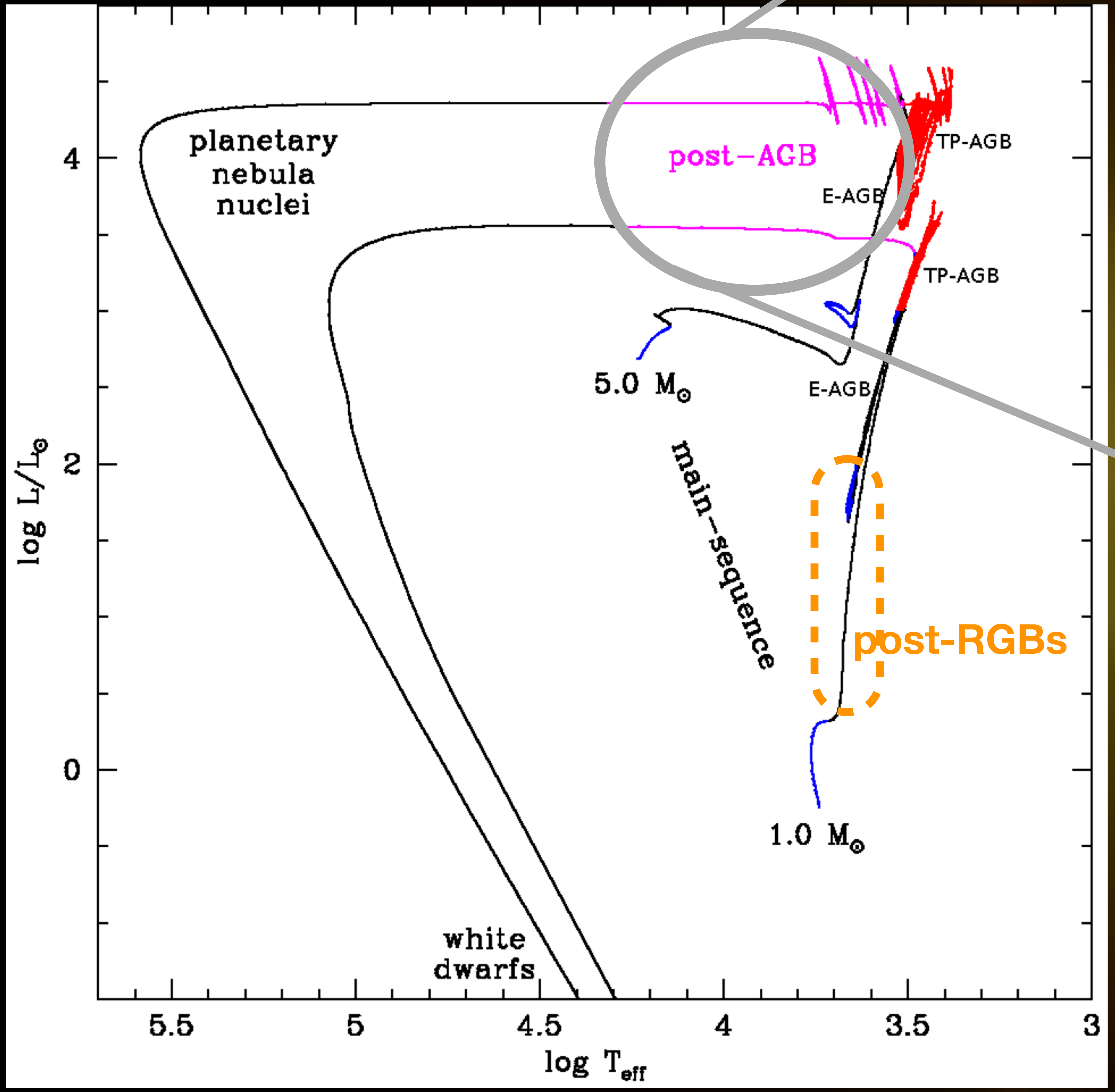

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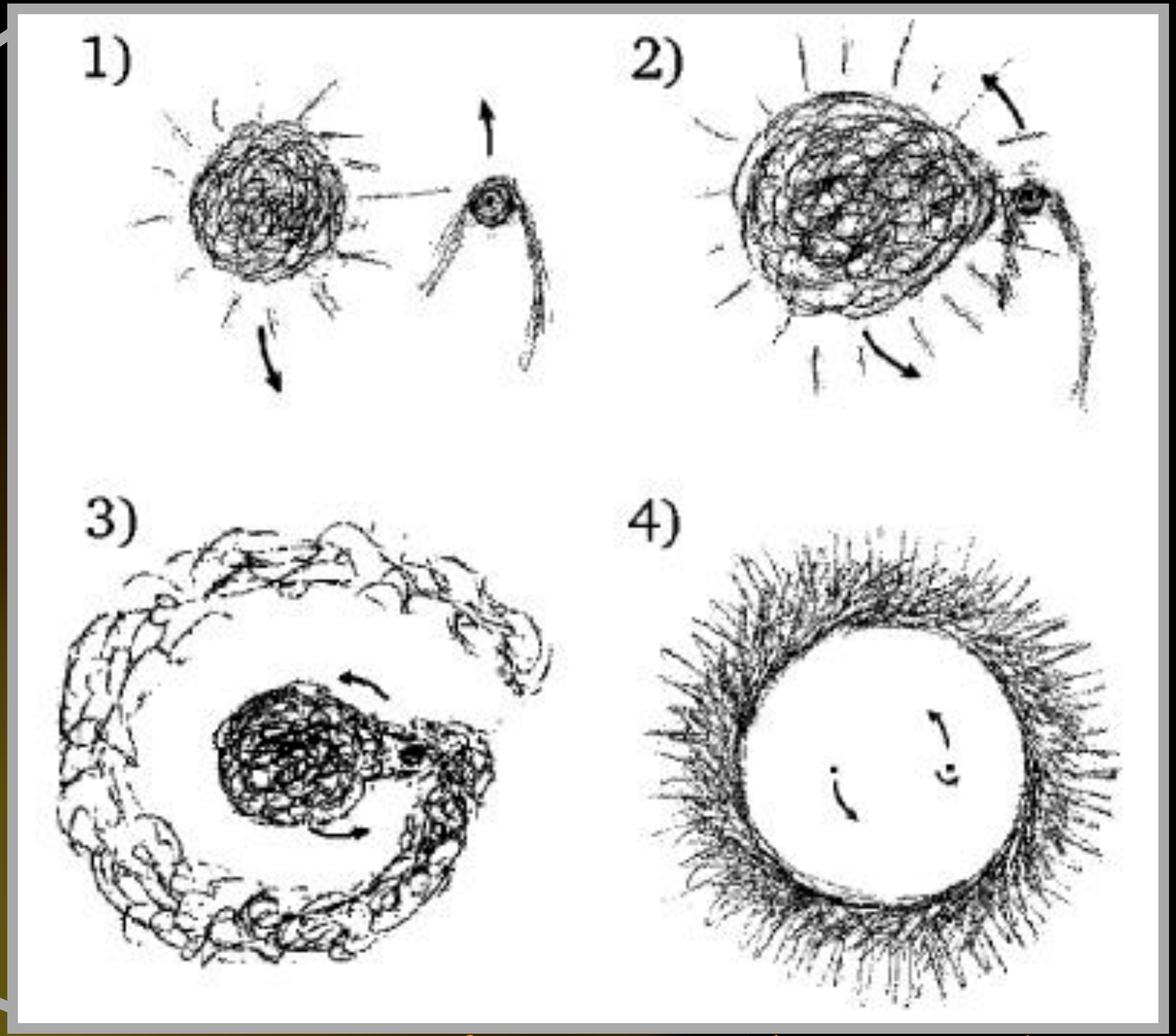

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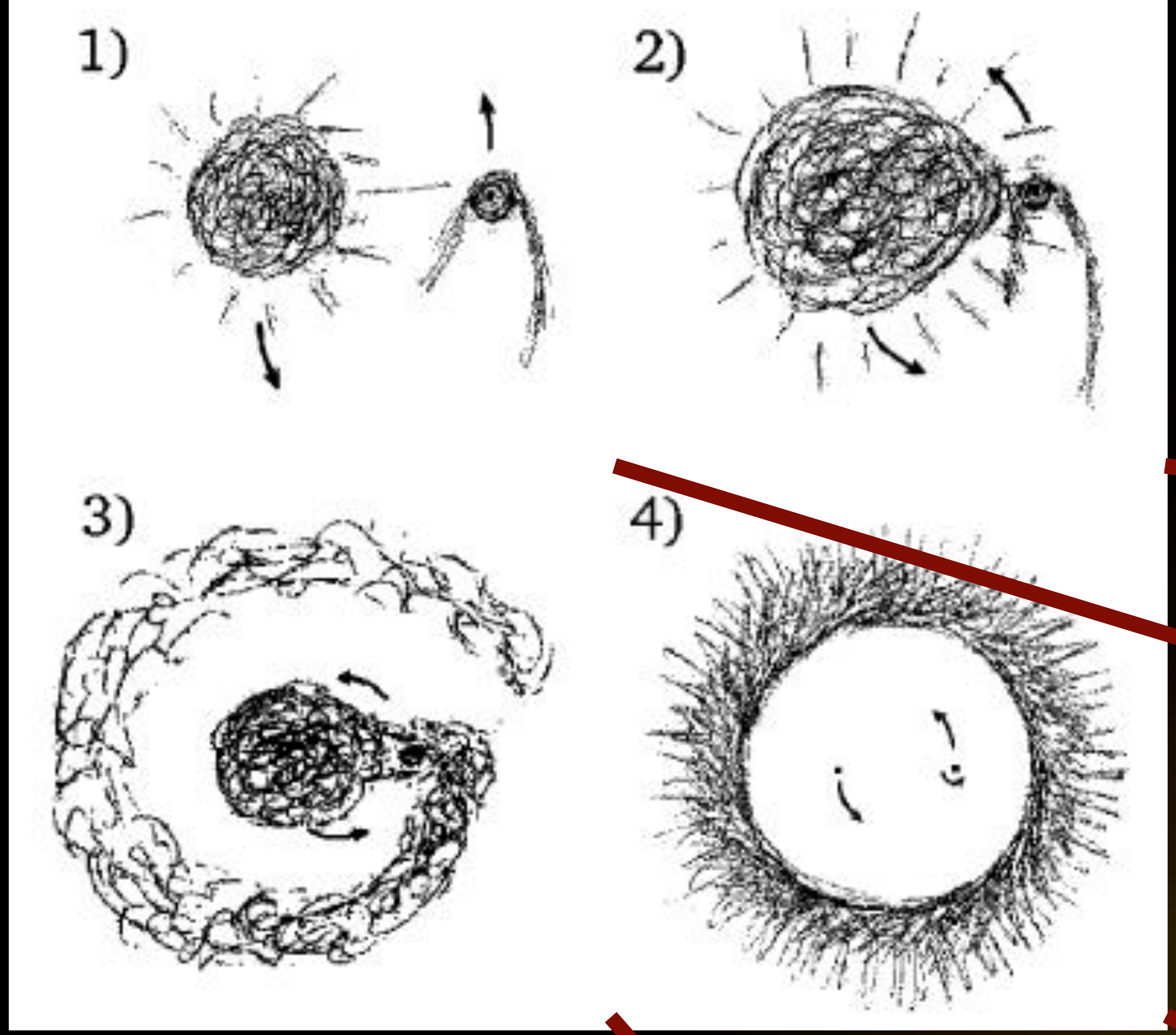
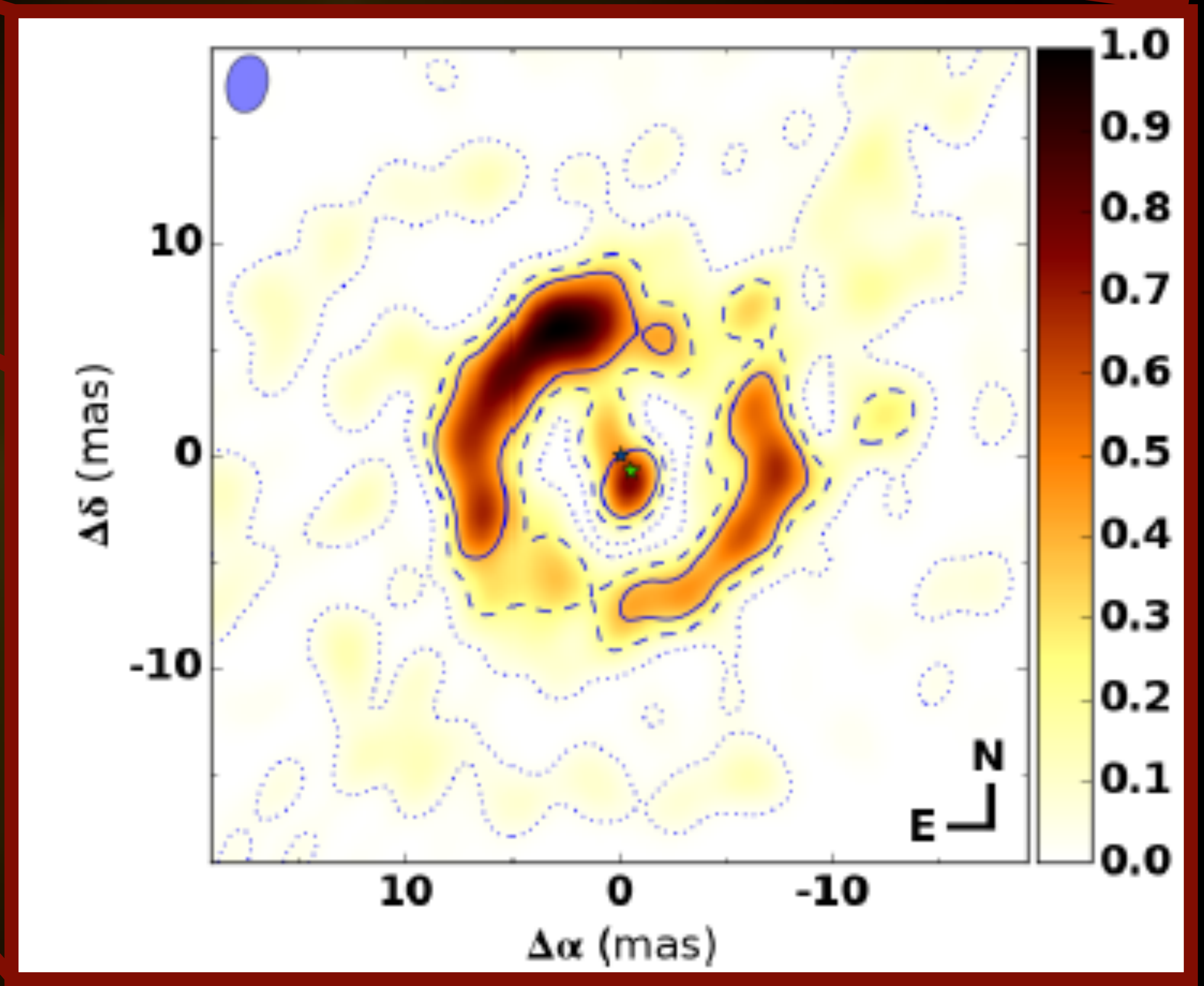


H-band reconstruction PIONIER/VLTI



Kluska et al., 2018

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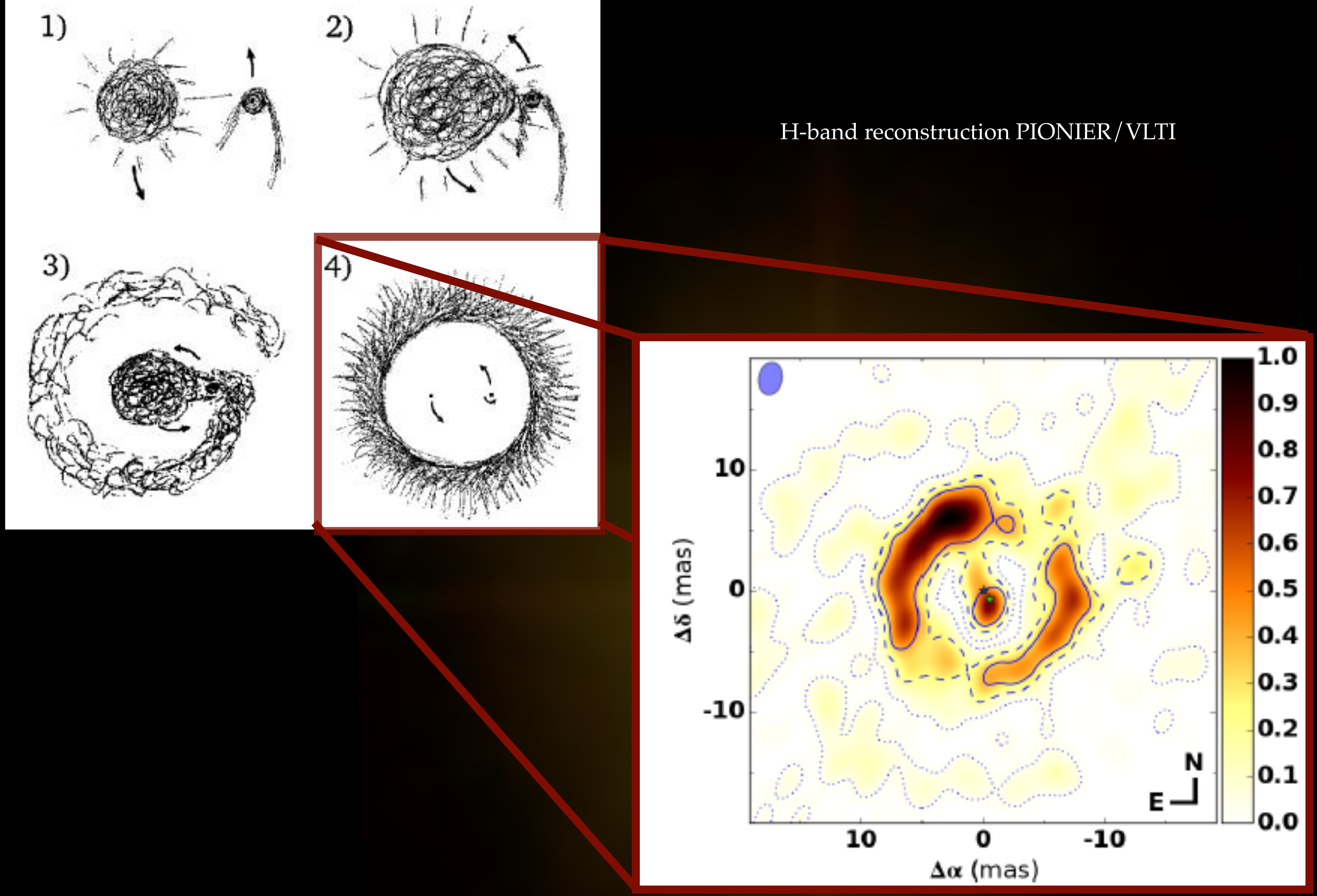

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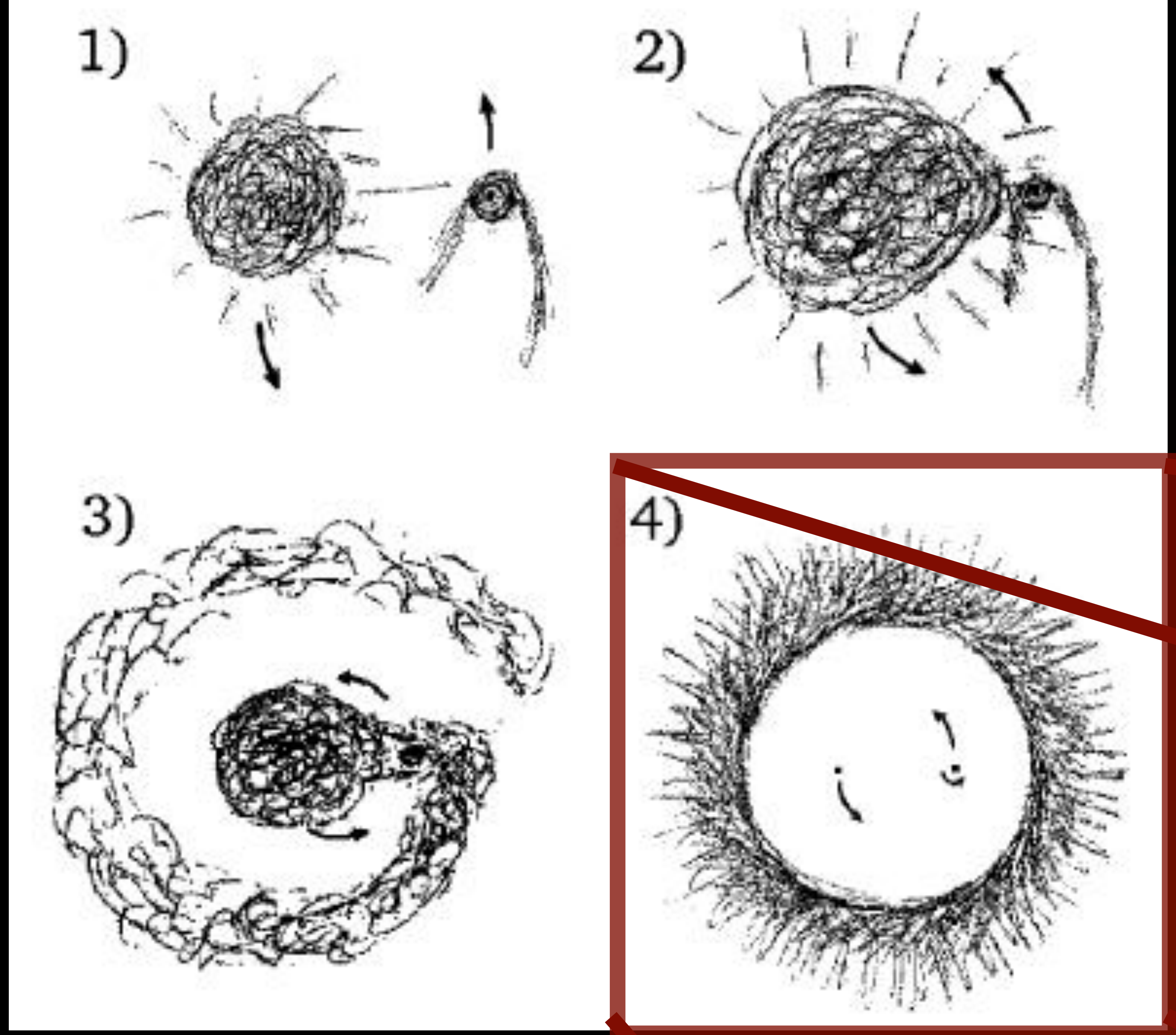

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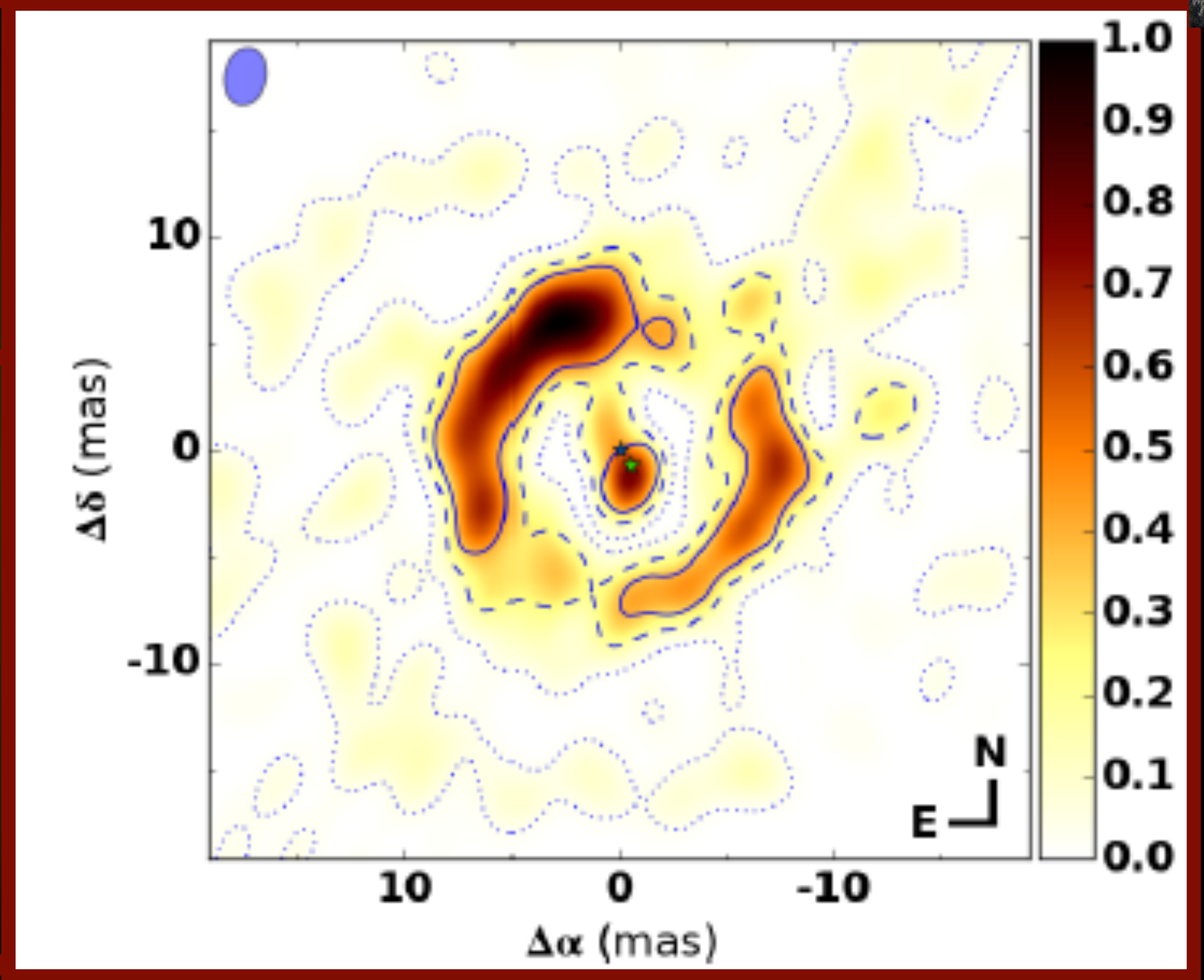

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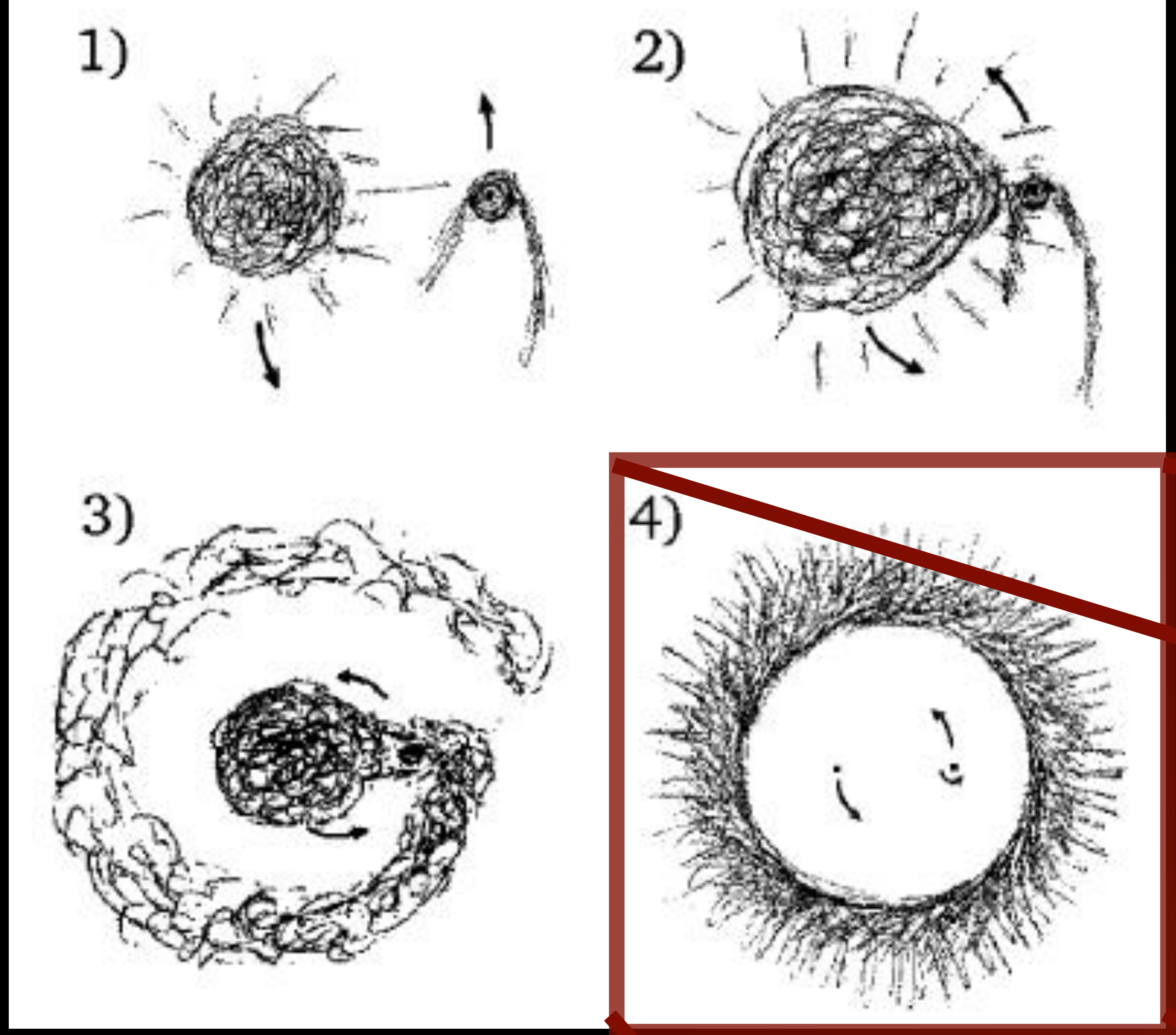

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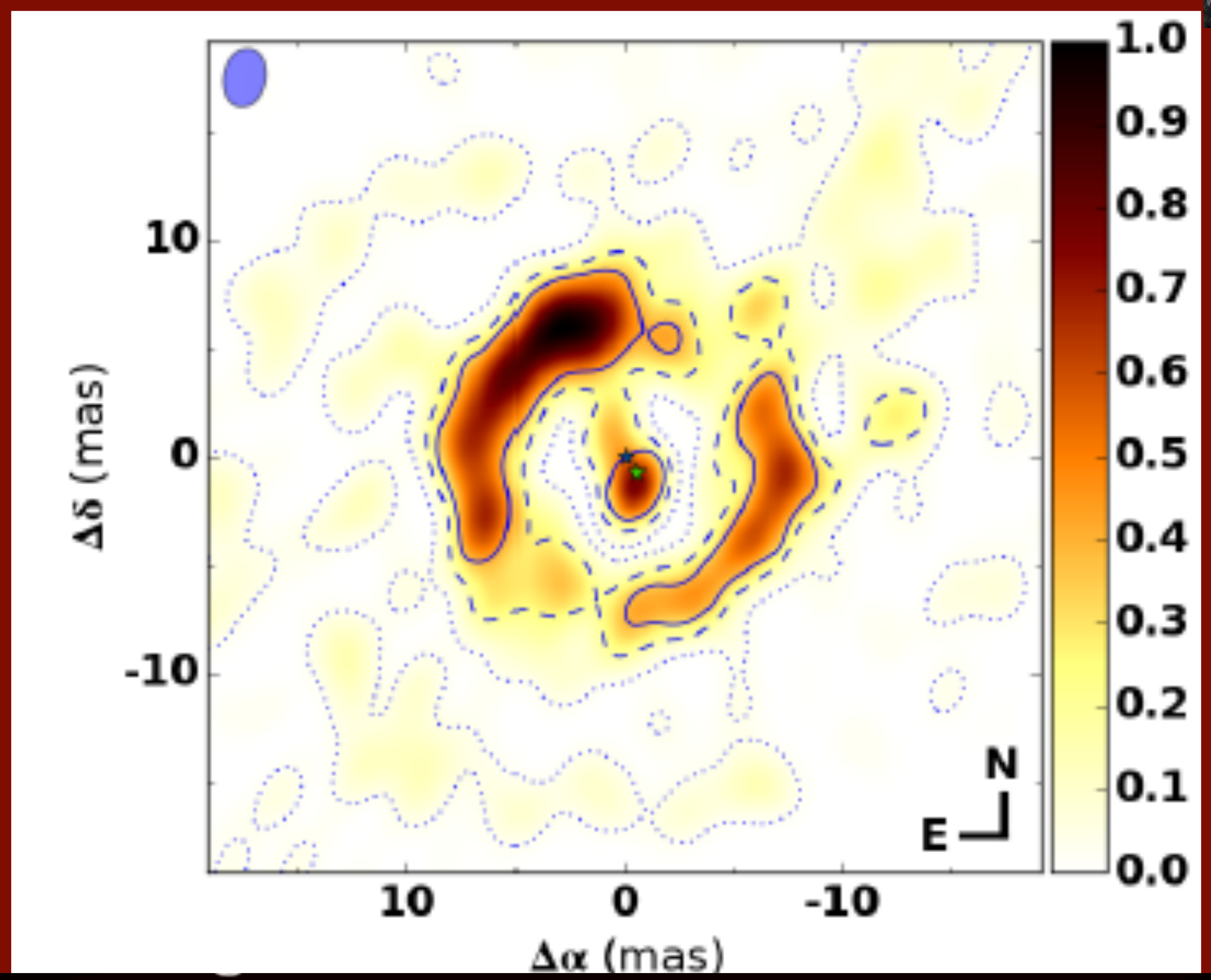
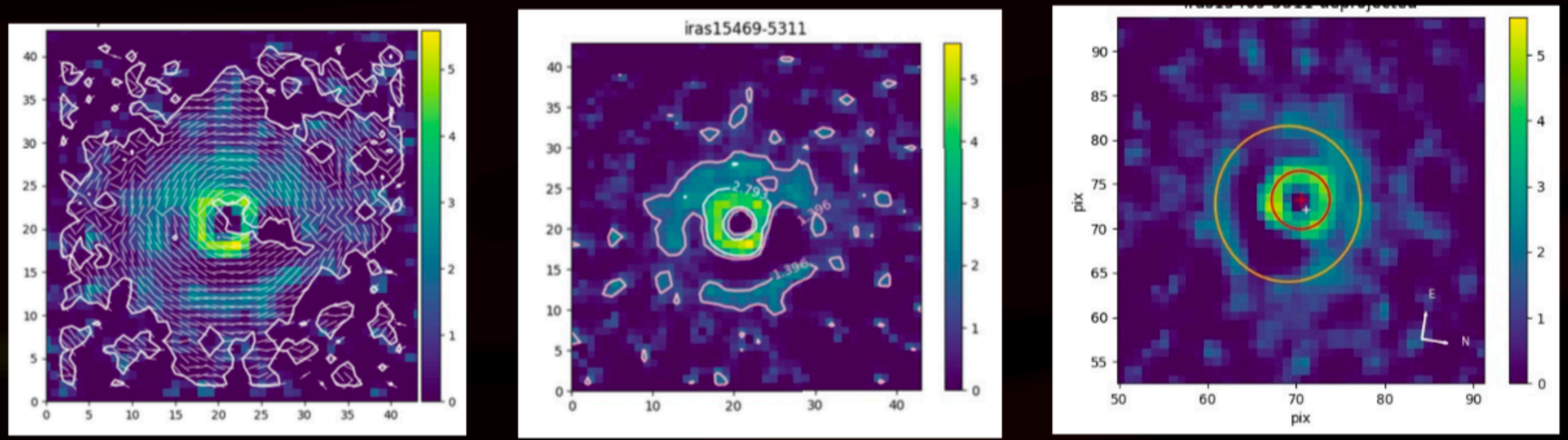
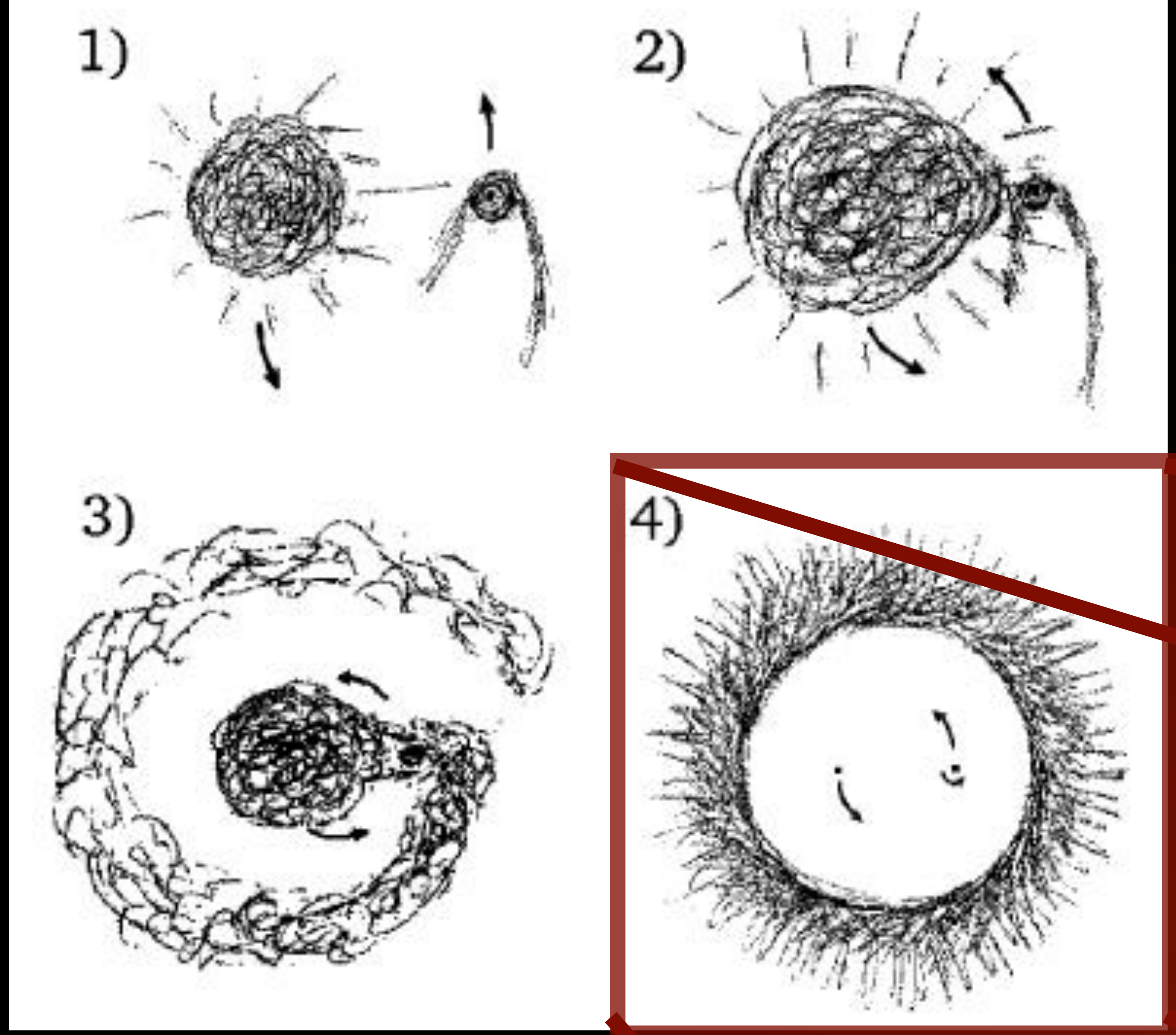


Kluska et al., 2018

Imaging and Polarimetry
K band VLT/SPHERE/IRDIS



Andrych et al., 2023



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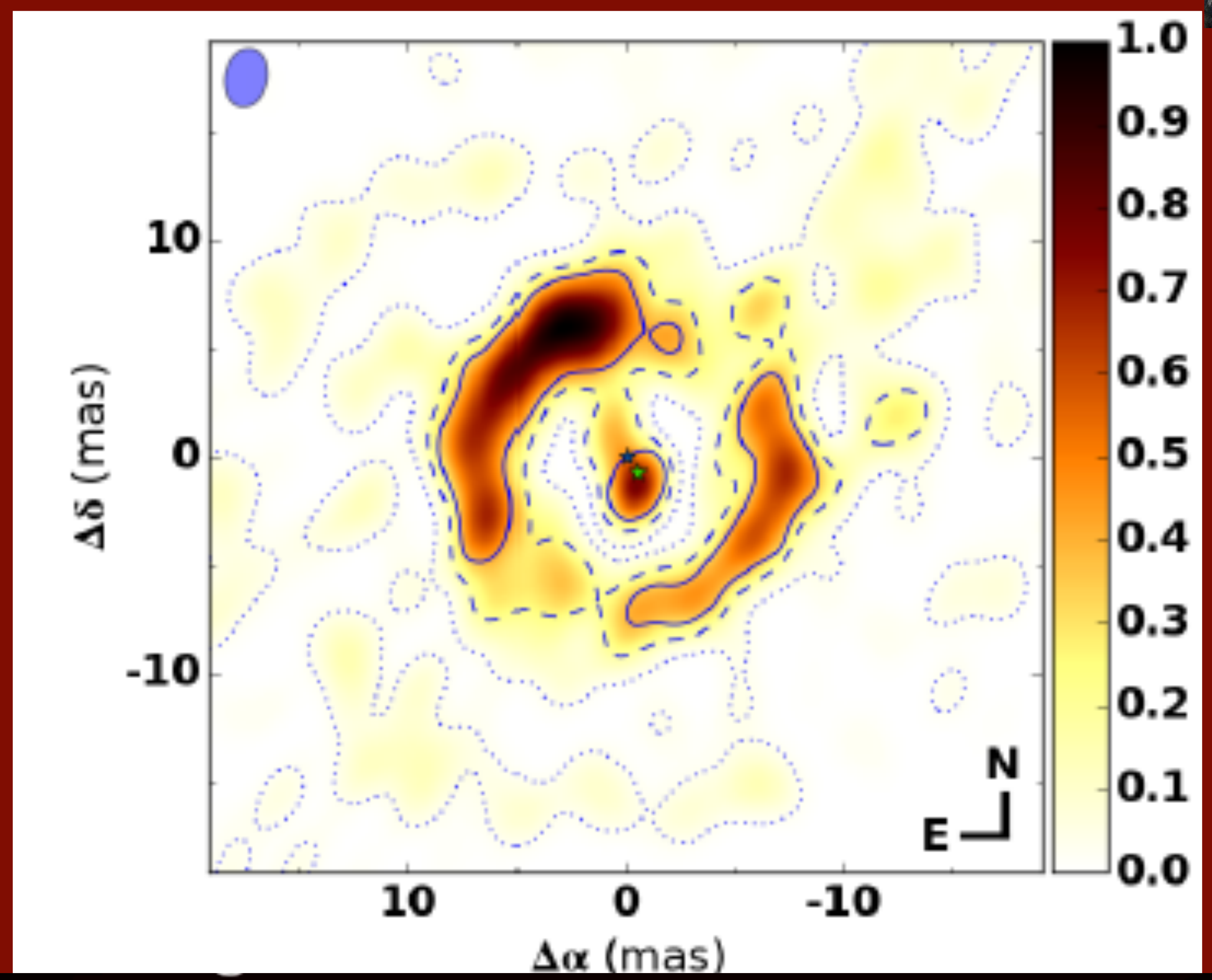

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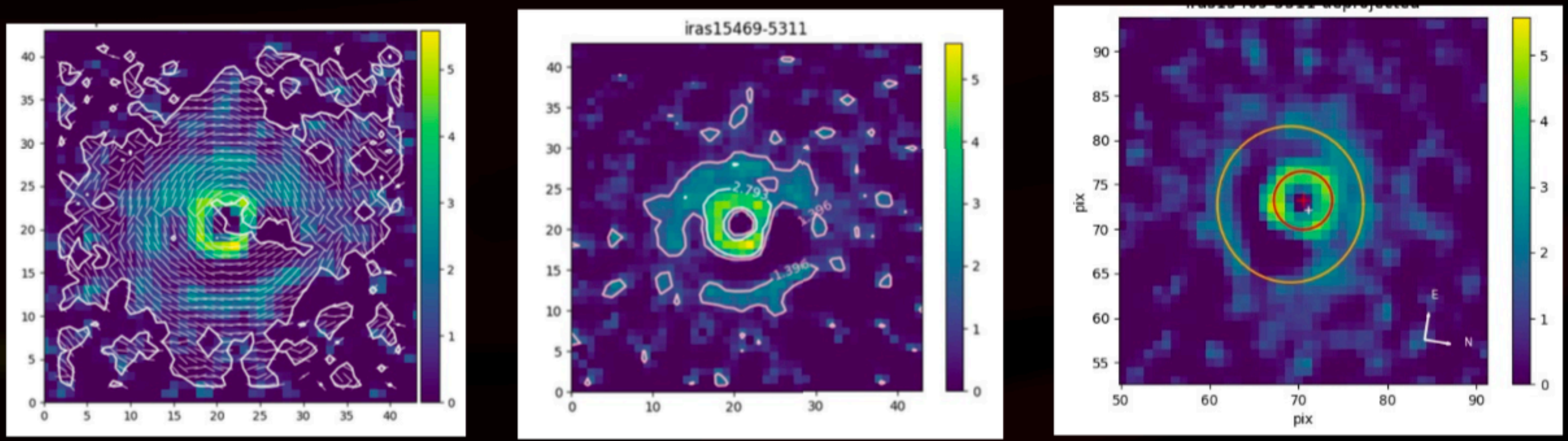
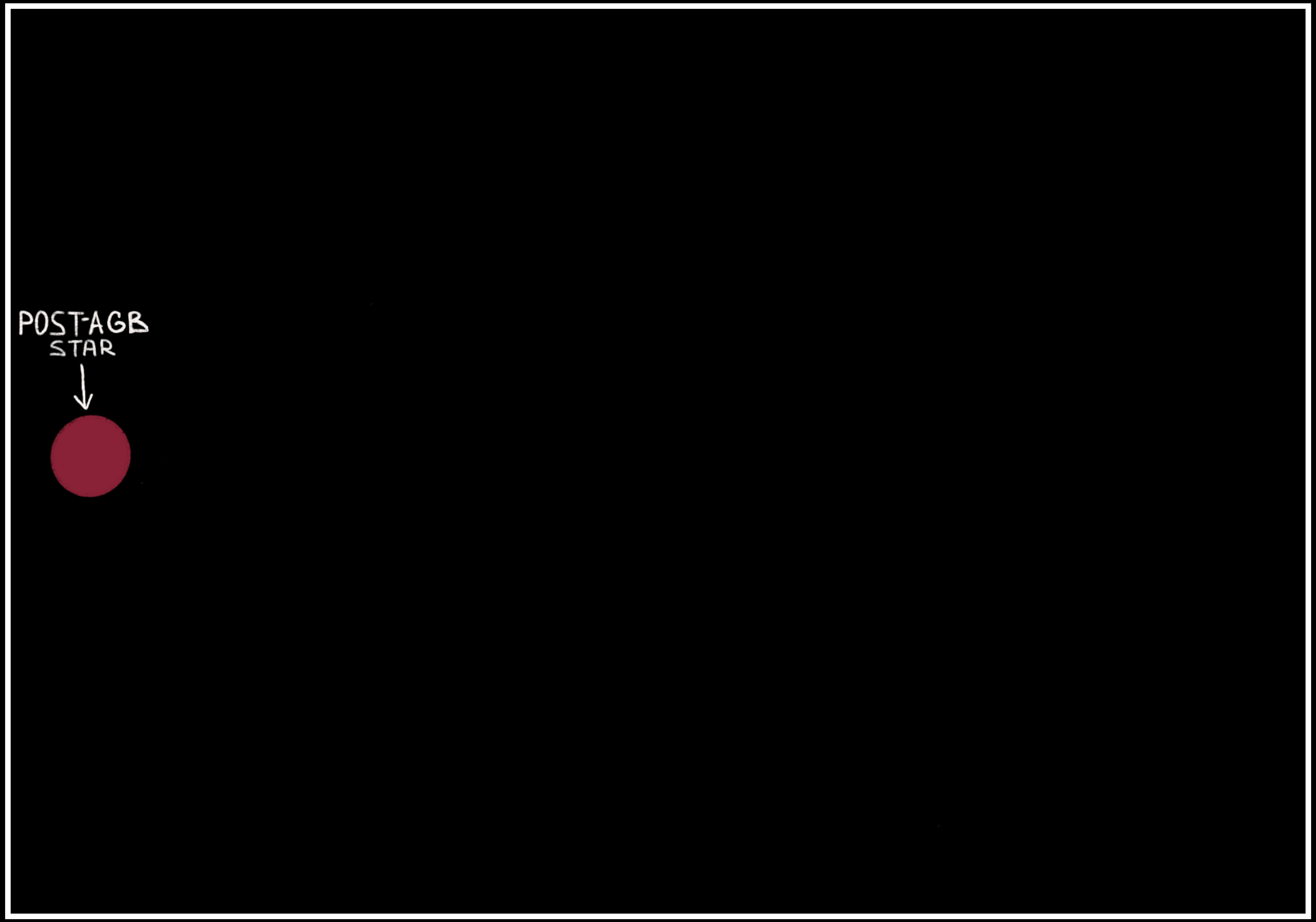


Andrych et al., 2023

The Post-AGB Binary System



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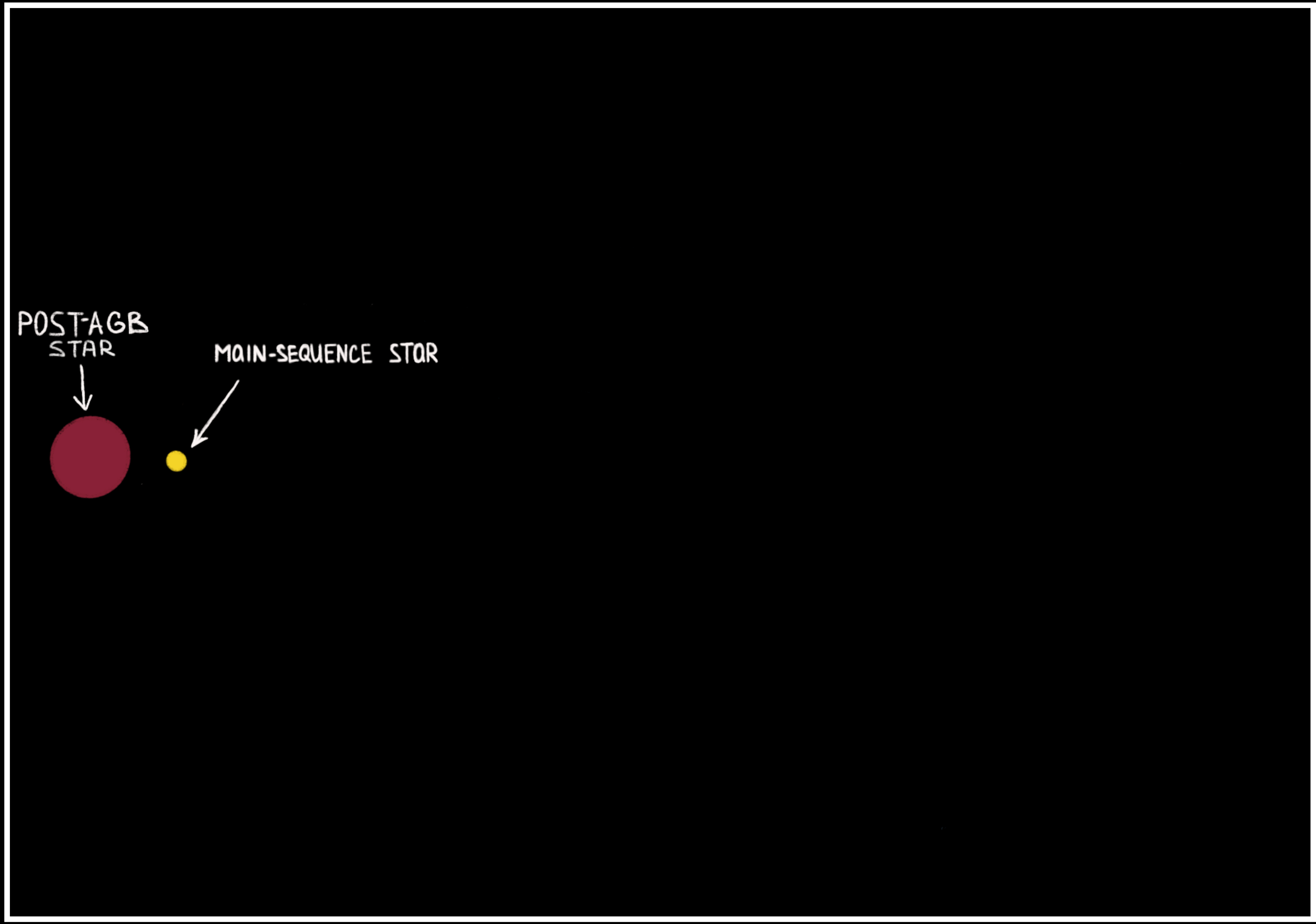

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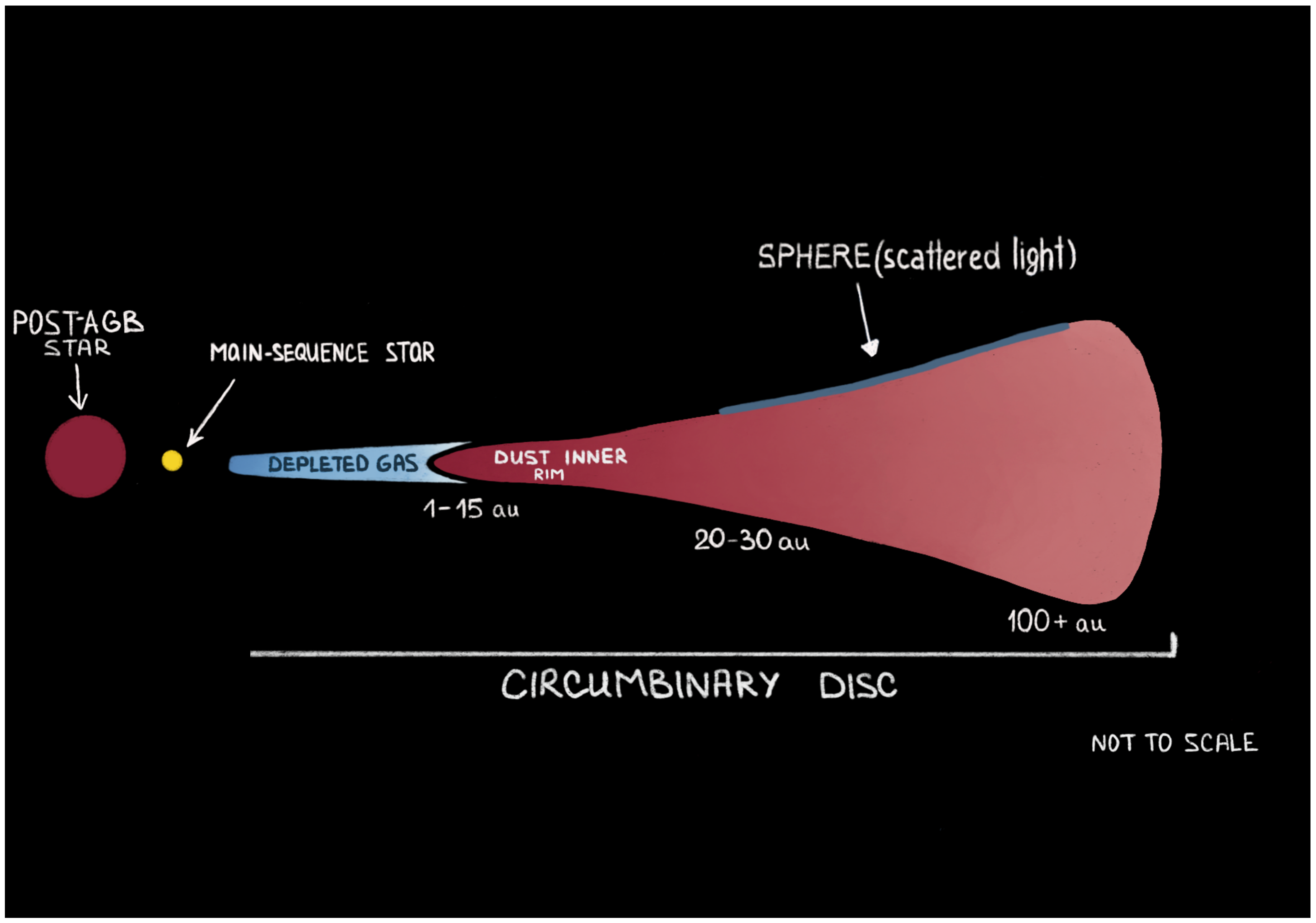

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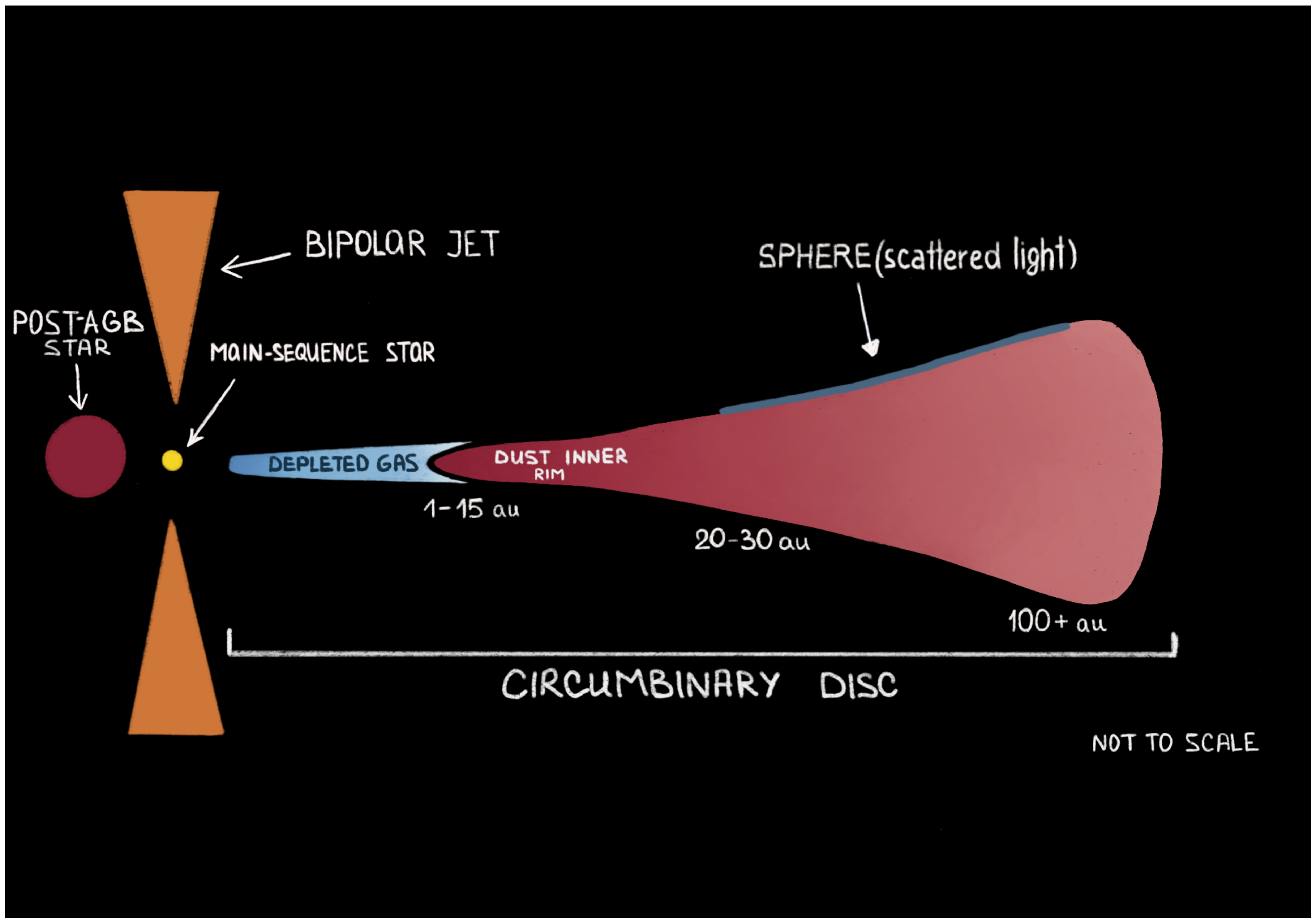
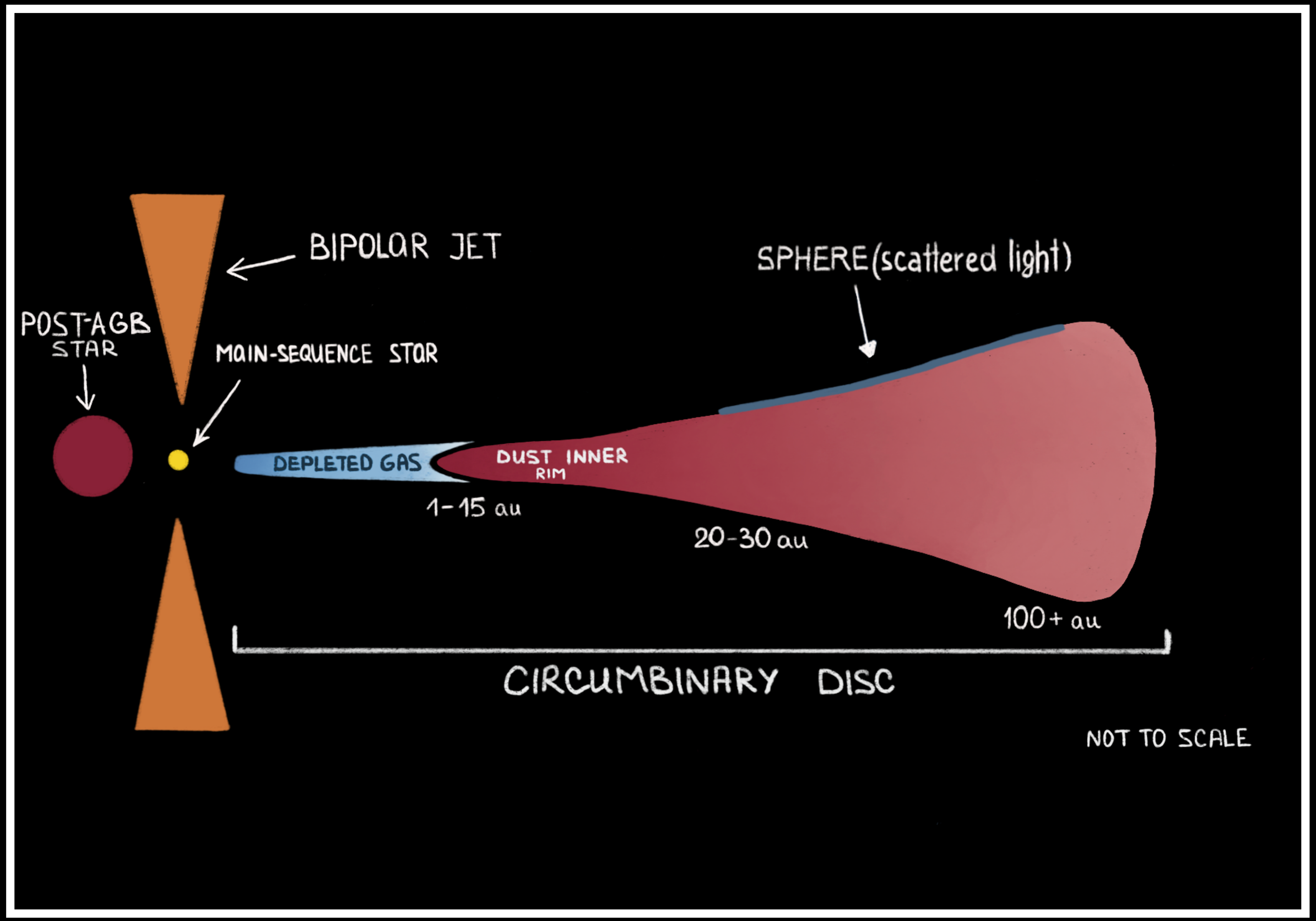
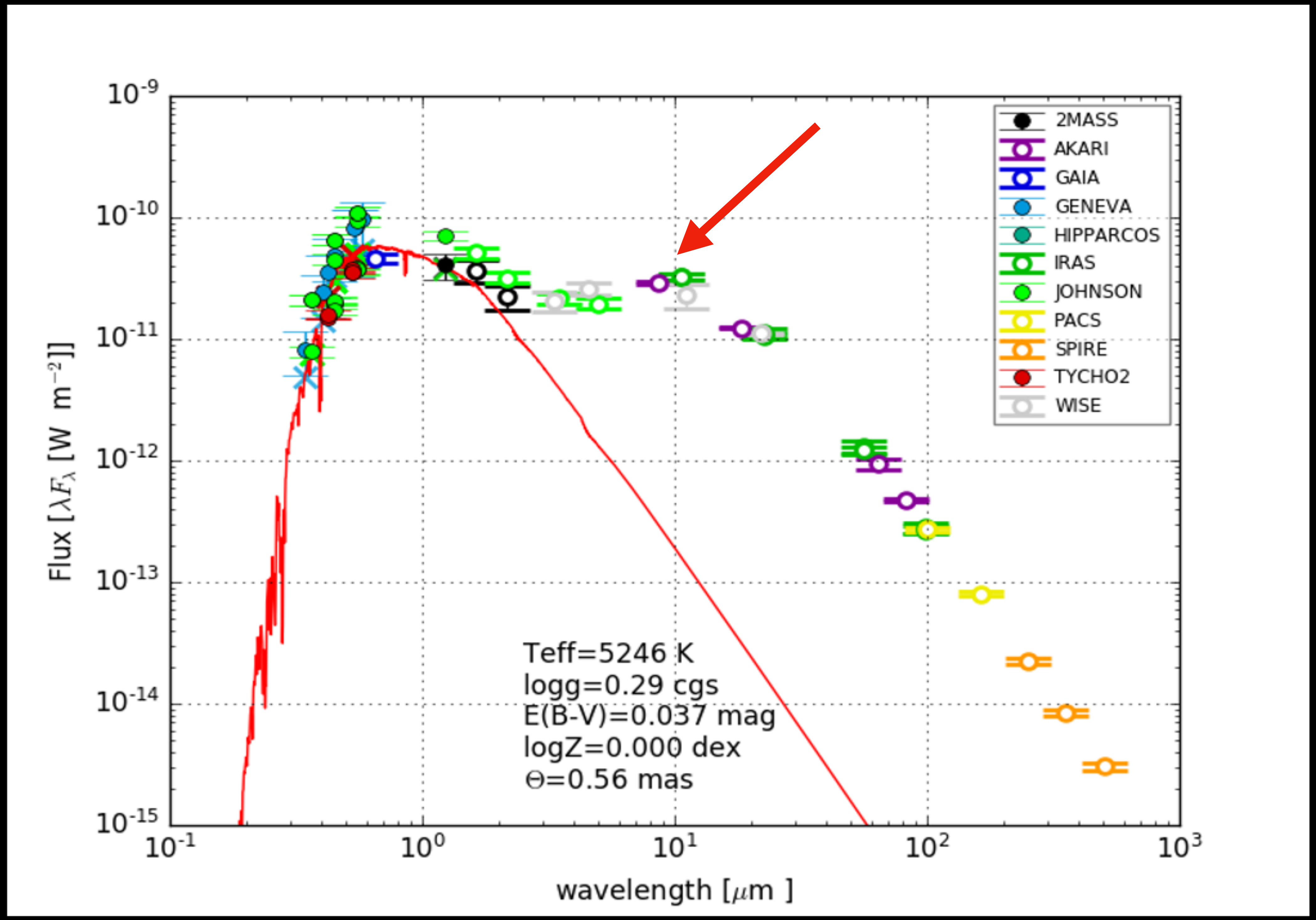
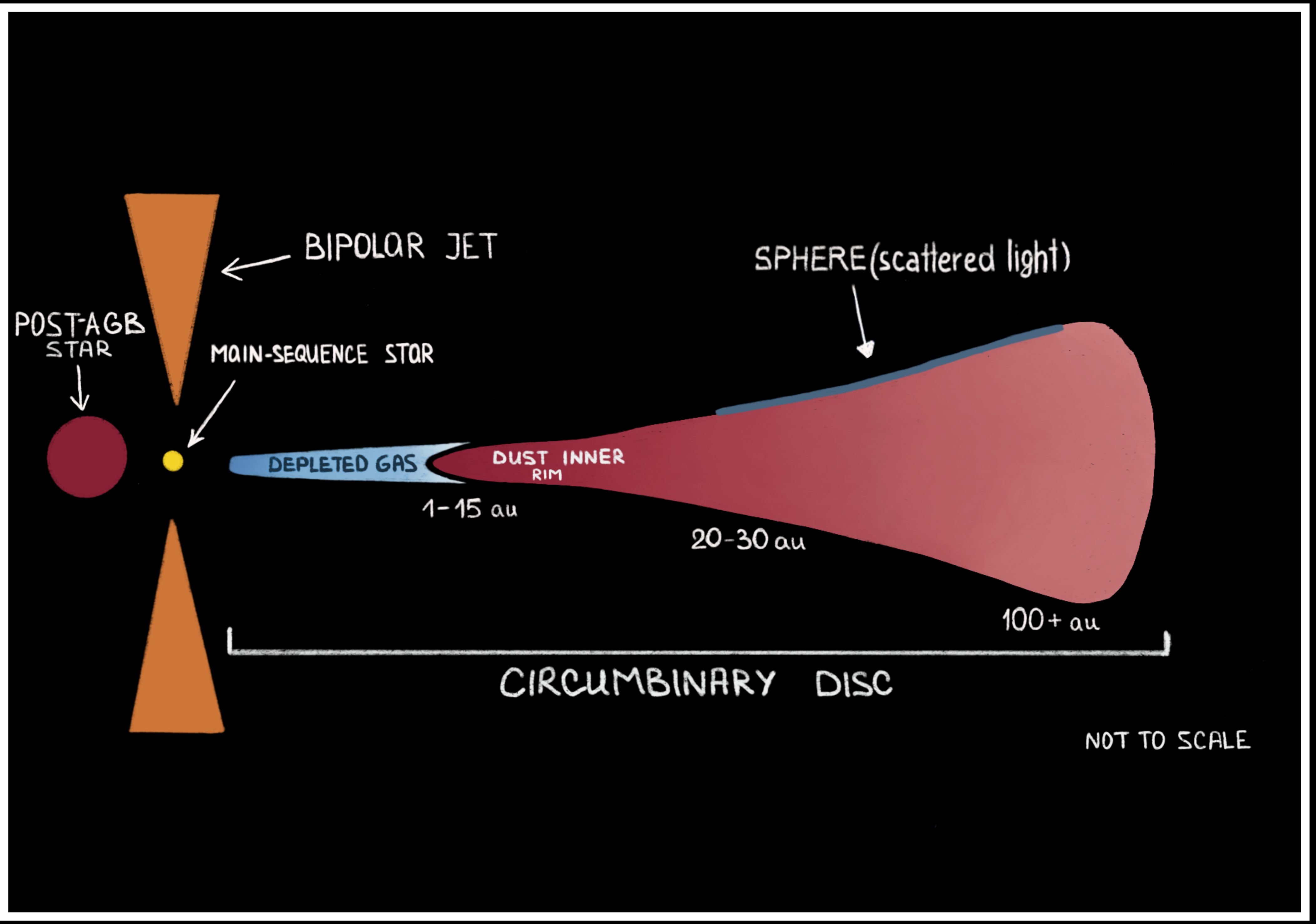


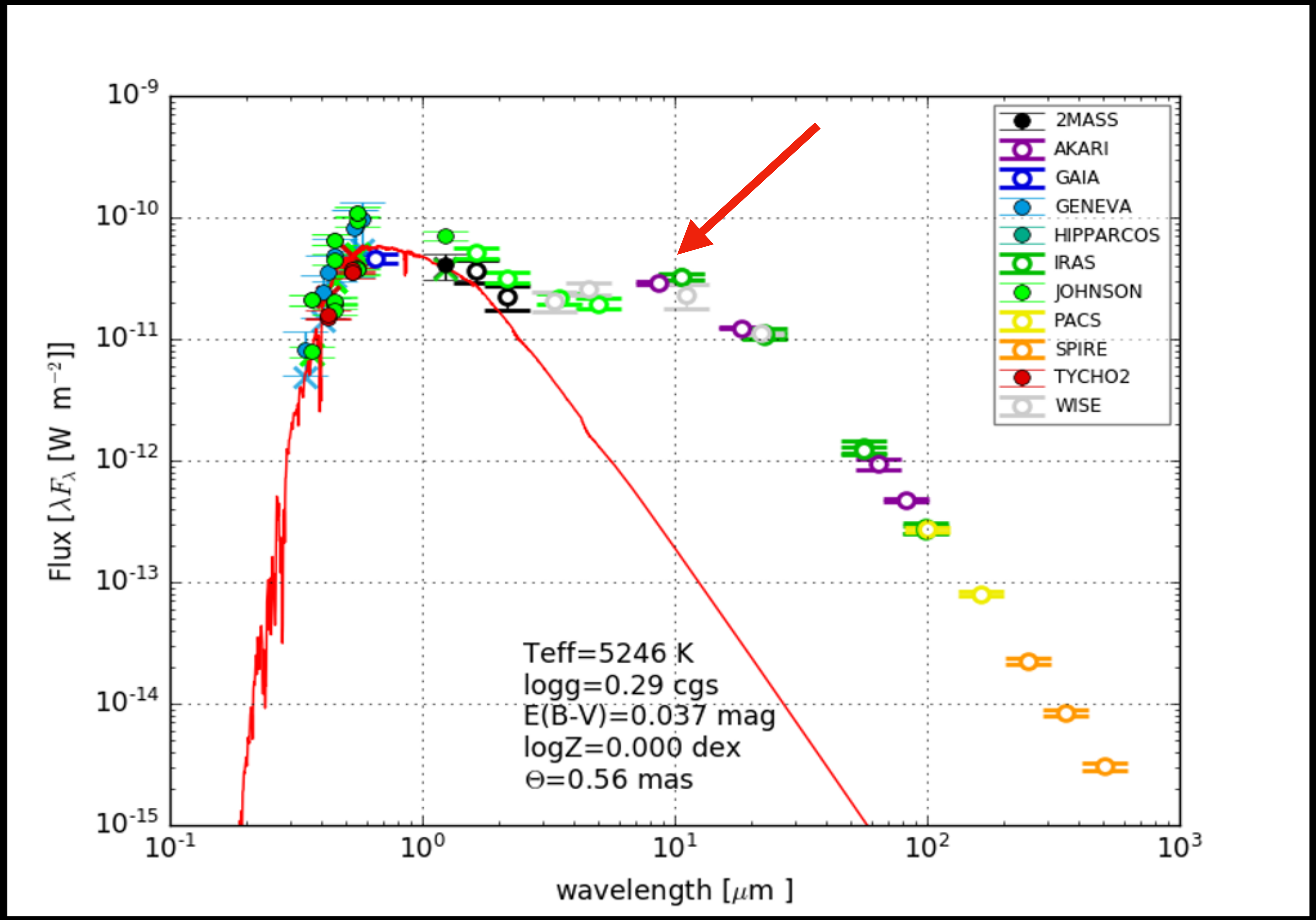




- NearIR excess with a broad onset: hot dust component is indicative of Keplerian disc

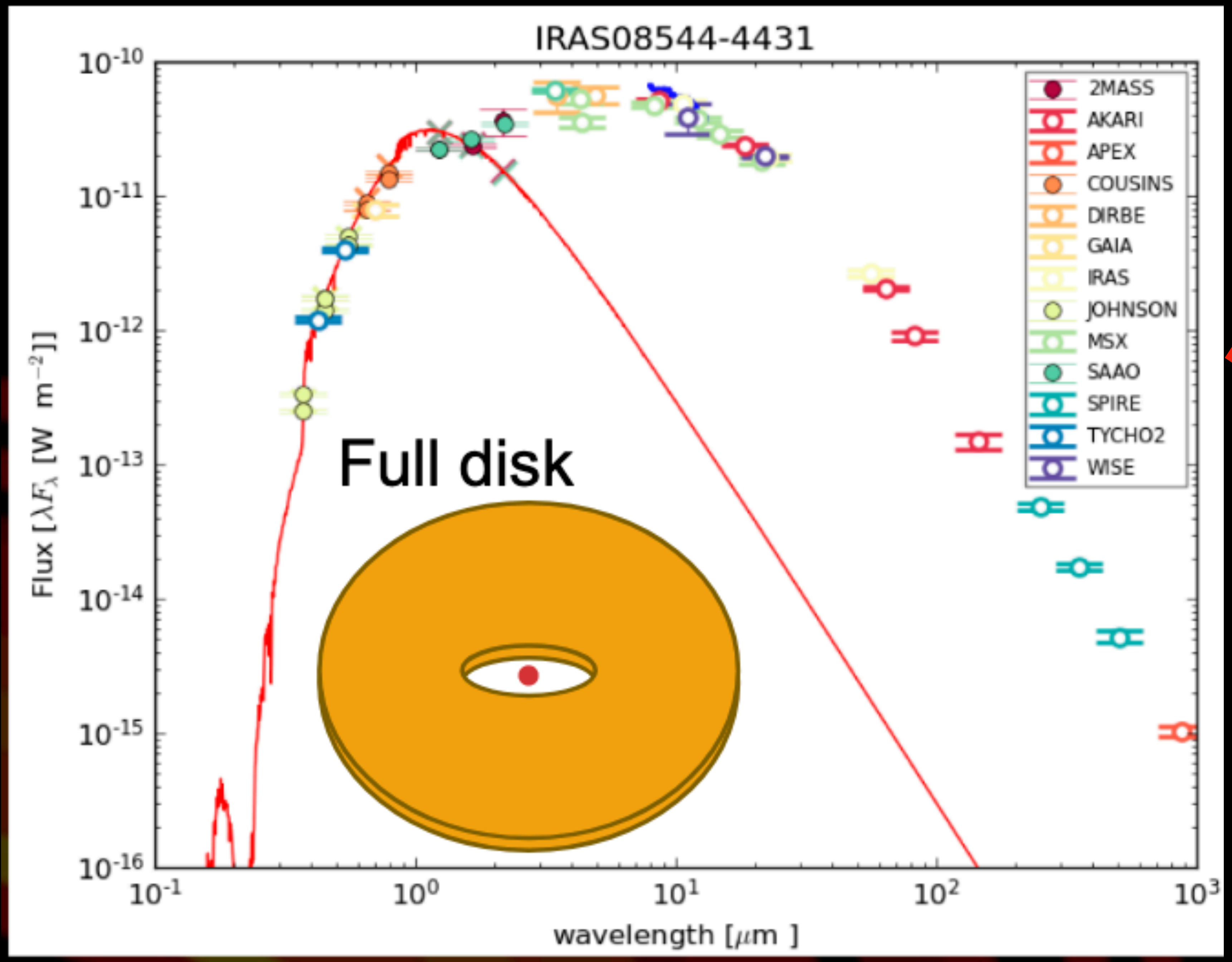
Kluska et al., 2022; Kamath et al., 2014, 2015, 2022

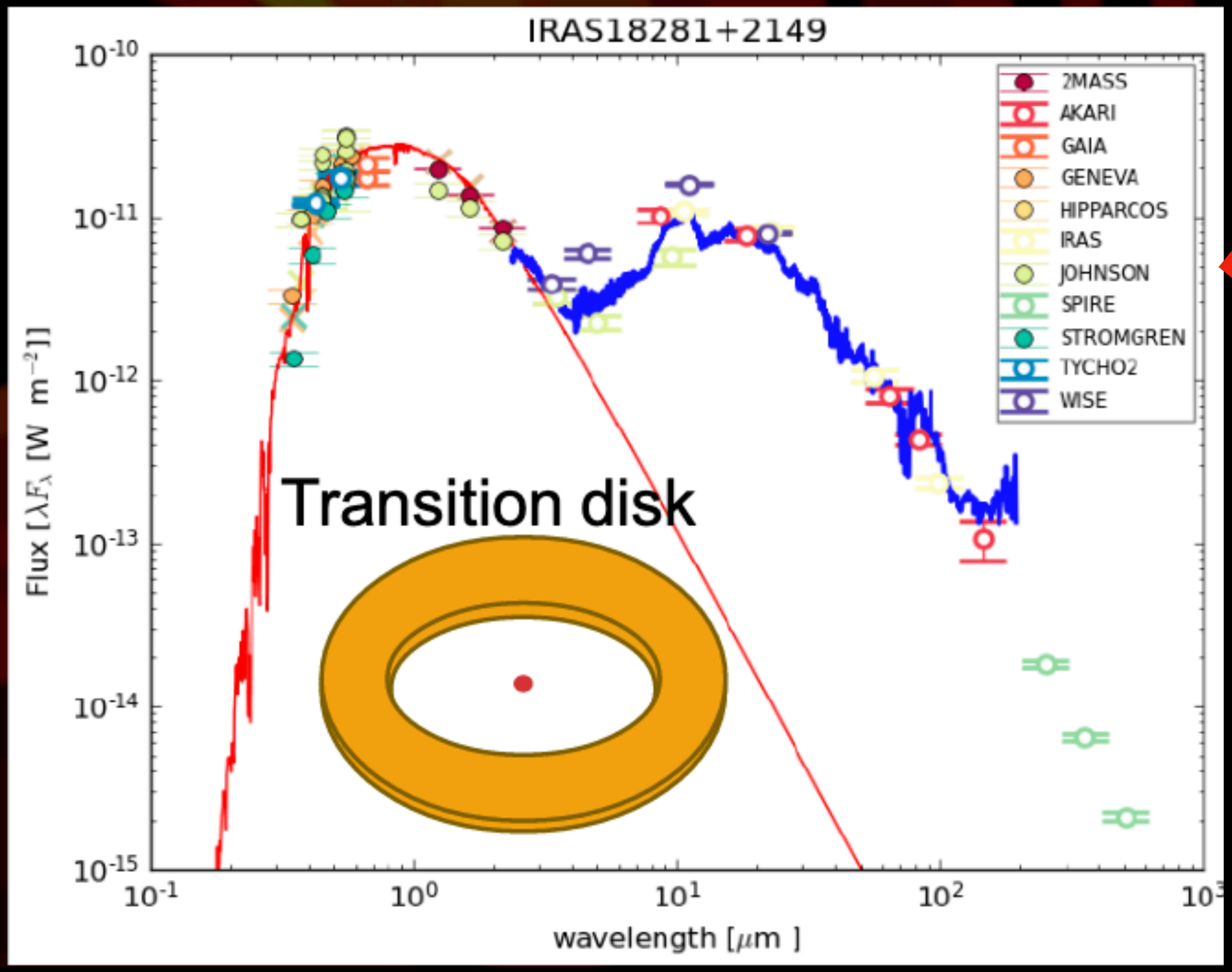


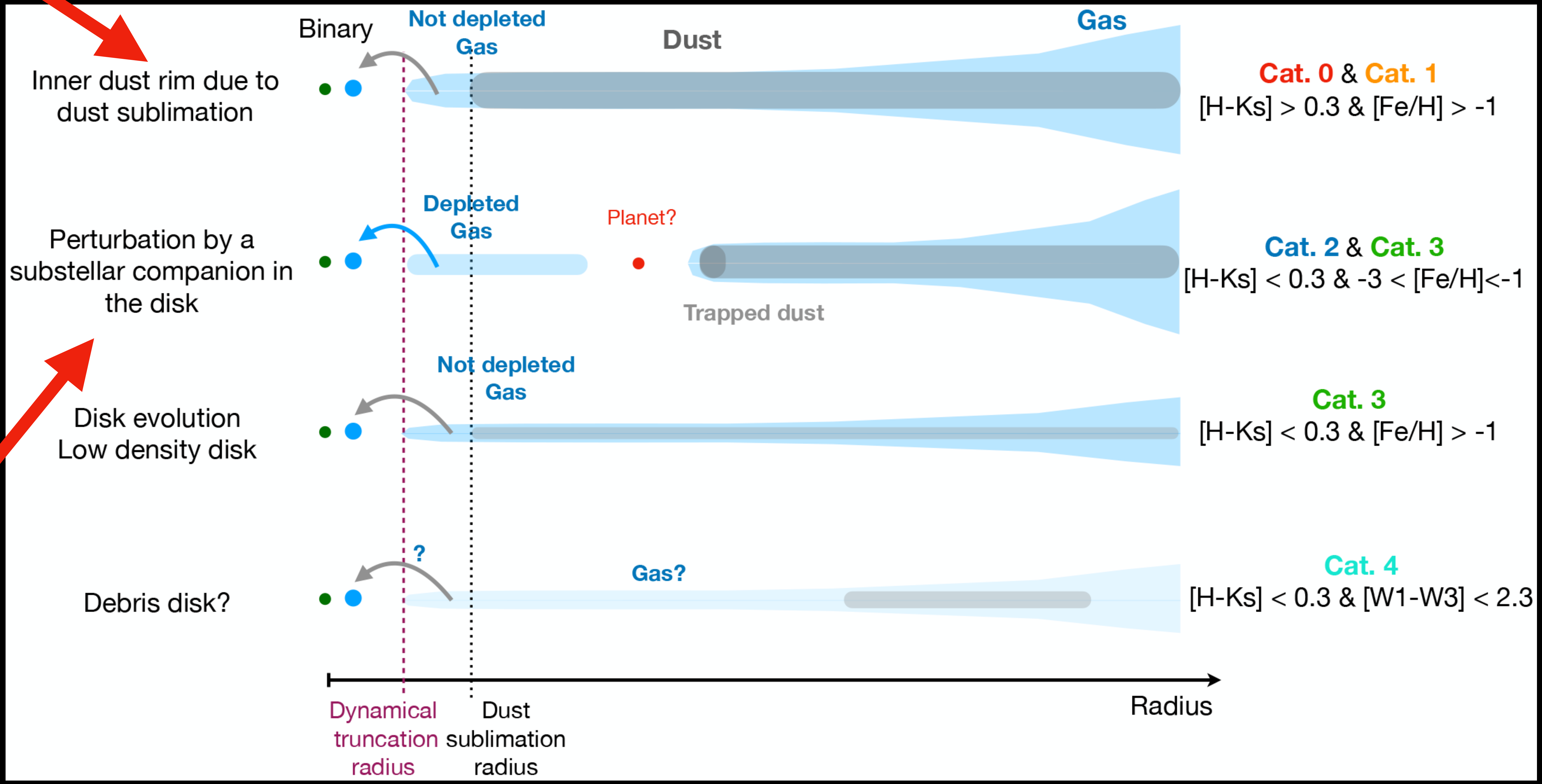


- NearIR excess with a broad onset: hot dust component is indicative of Keplerian disc
- Discs are fat
- L(IR) is large fraction of L(star) and the disc evolves…
- Long wavelength spectral index: large grains

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







Kluska et al., 2022

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

The Effect of Binarity:

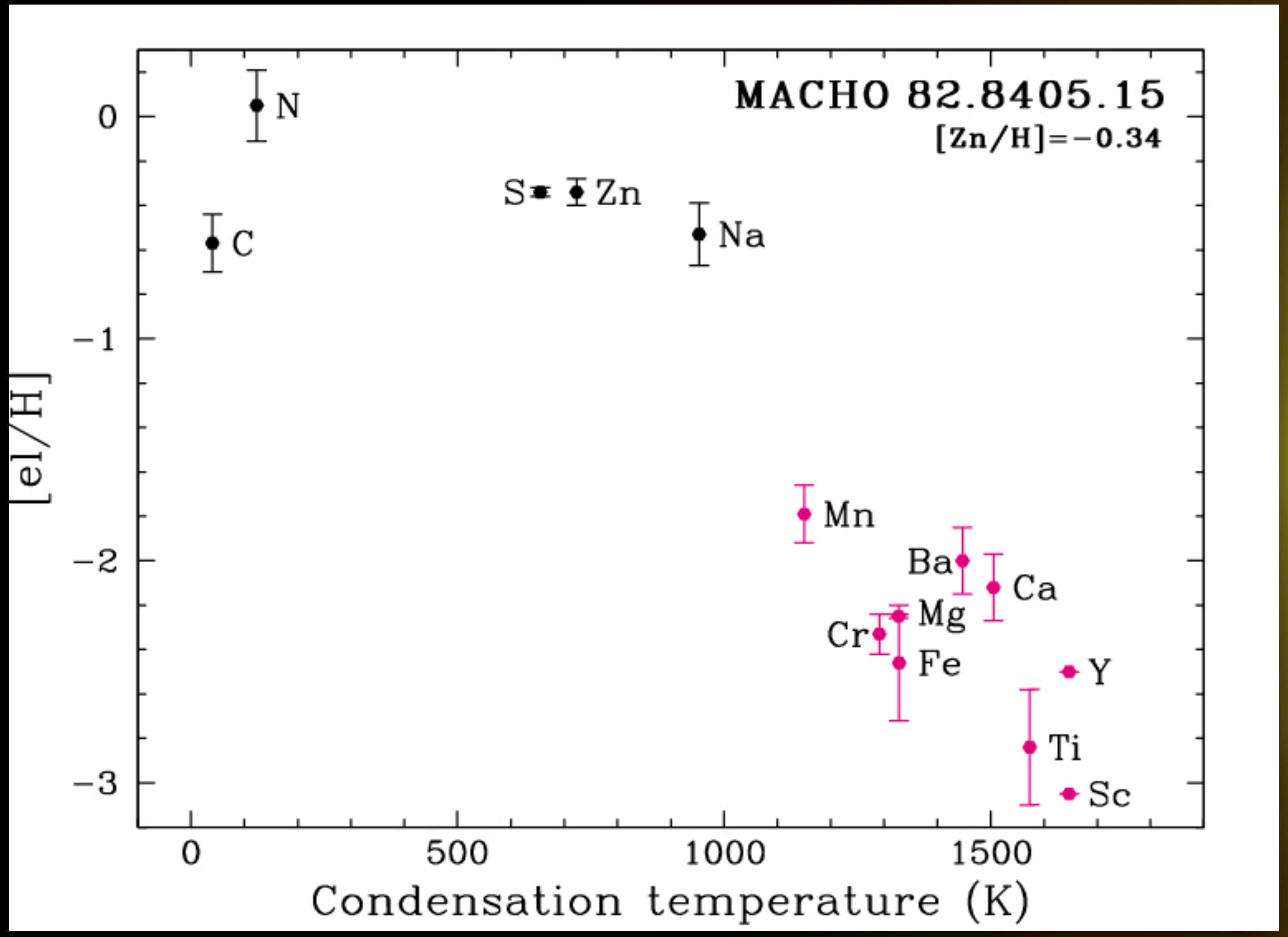
Photospheric Chemical Depletion in post-AGB binaries

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

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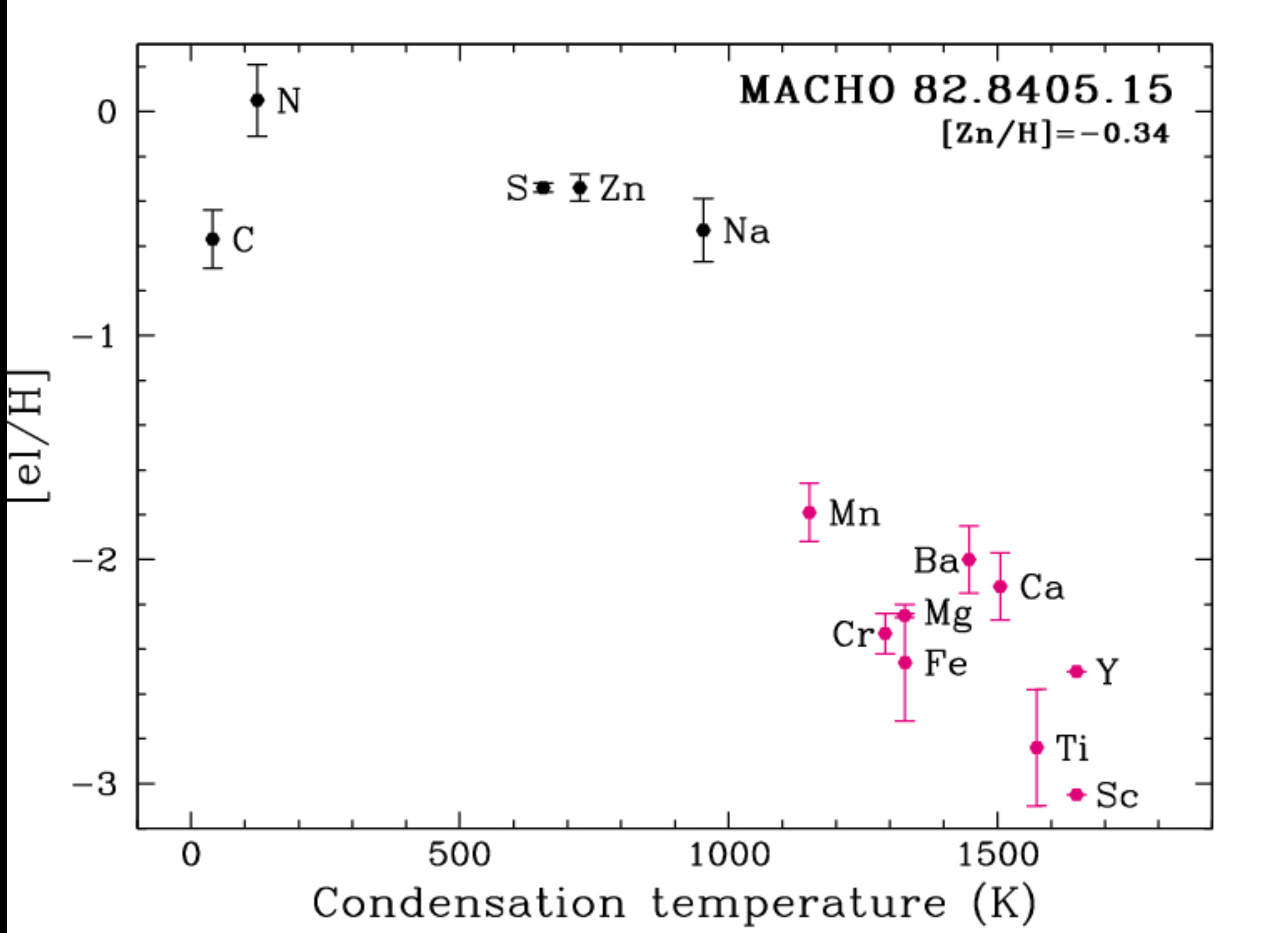

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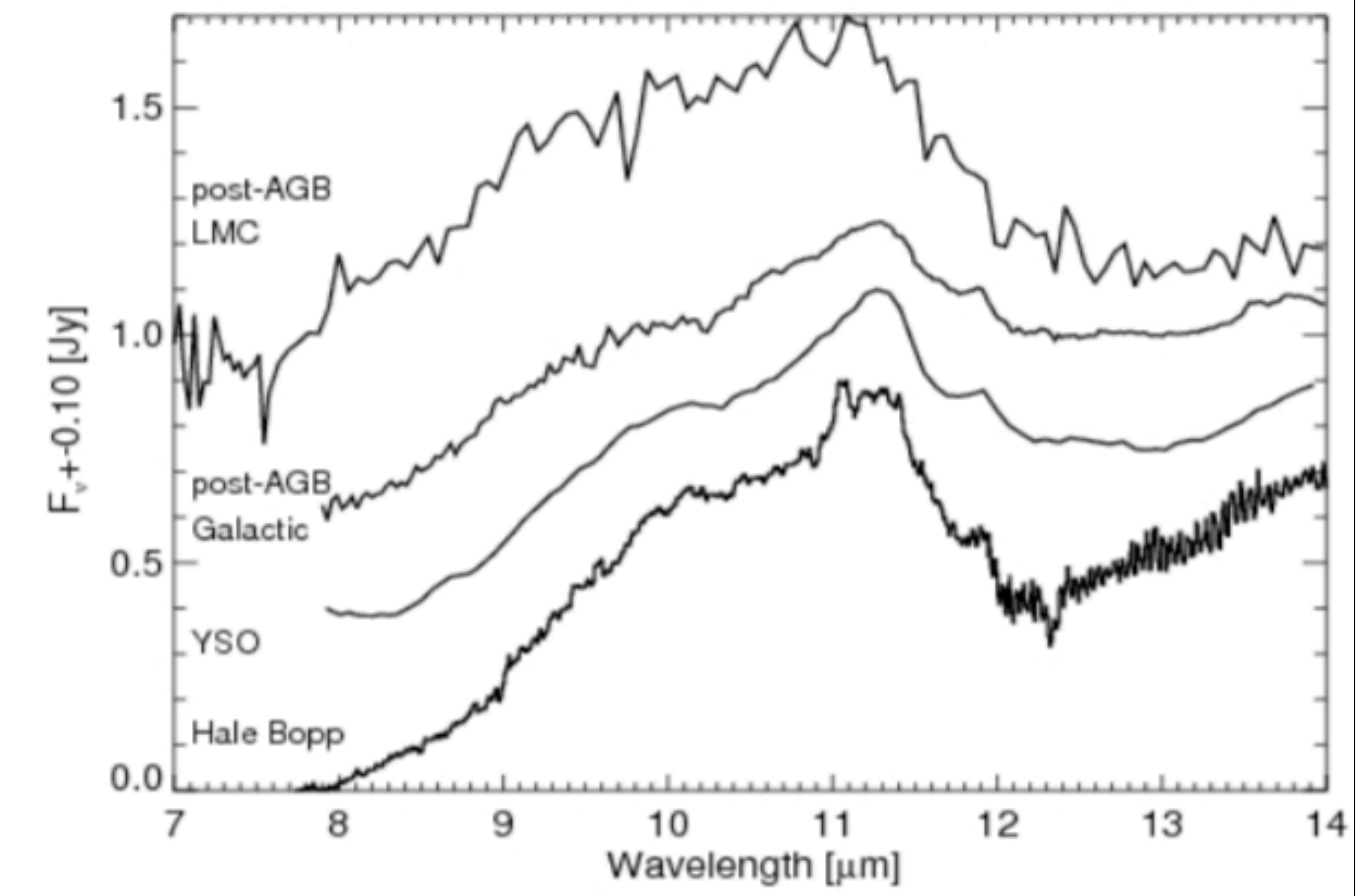


10-micron silicate feature

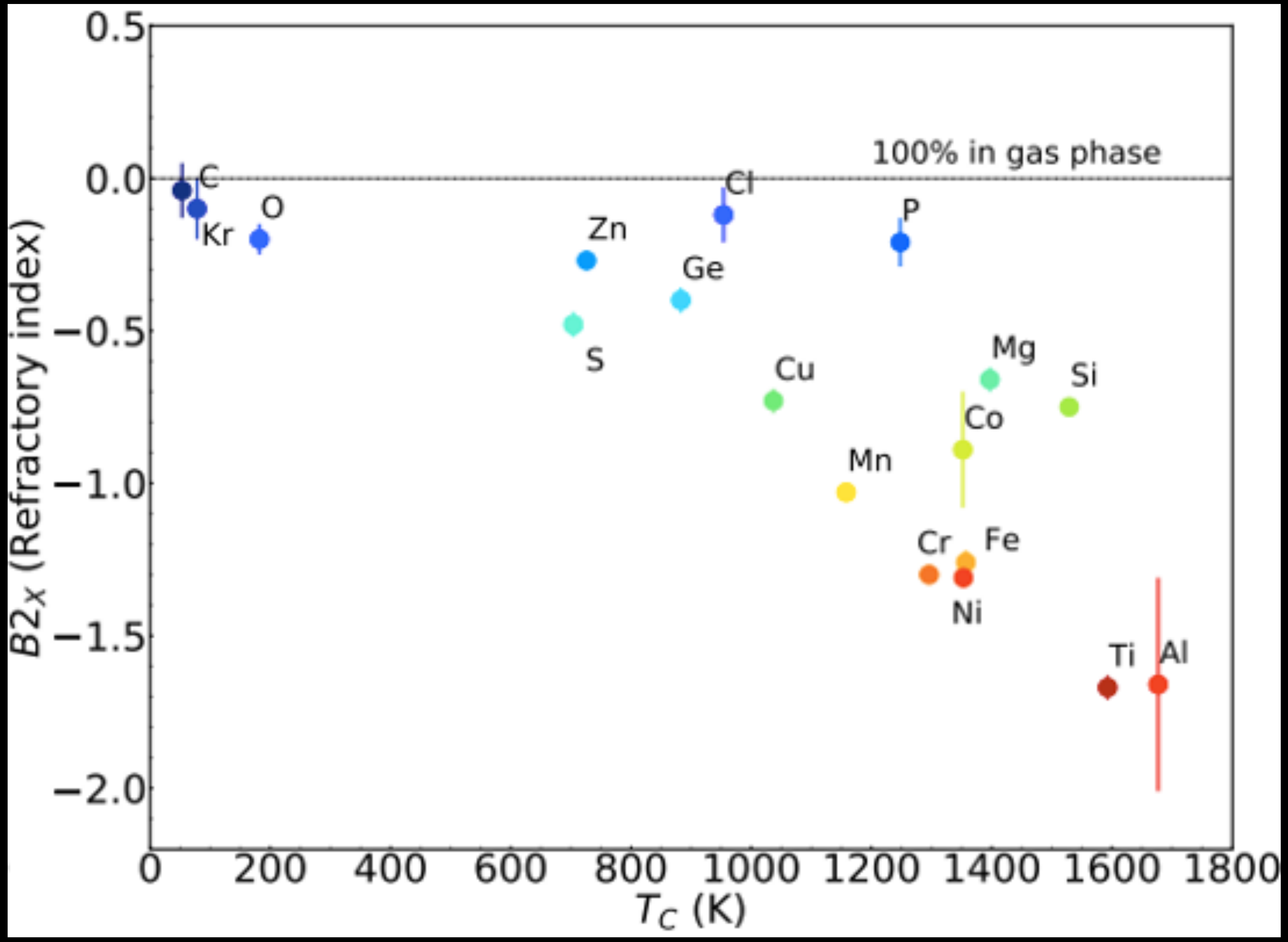
IR spectra are very rich and strongly crystalline

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

Chemical Depletion Across the HR Diagram

Chemical Depletion Across the HR Diagram

ISM



Konstantopoulou+2022

Chemical Depletion Across the HR Diagram

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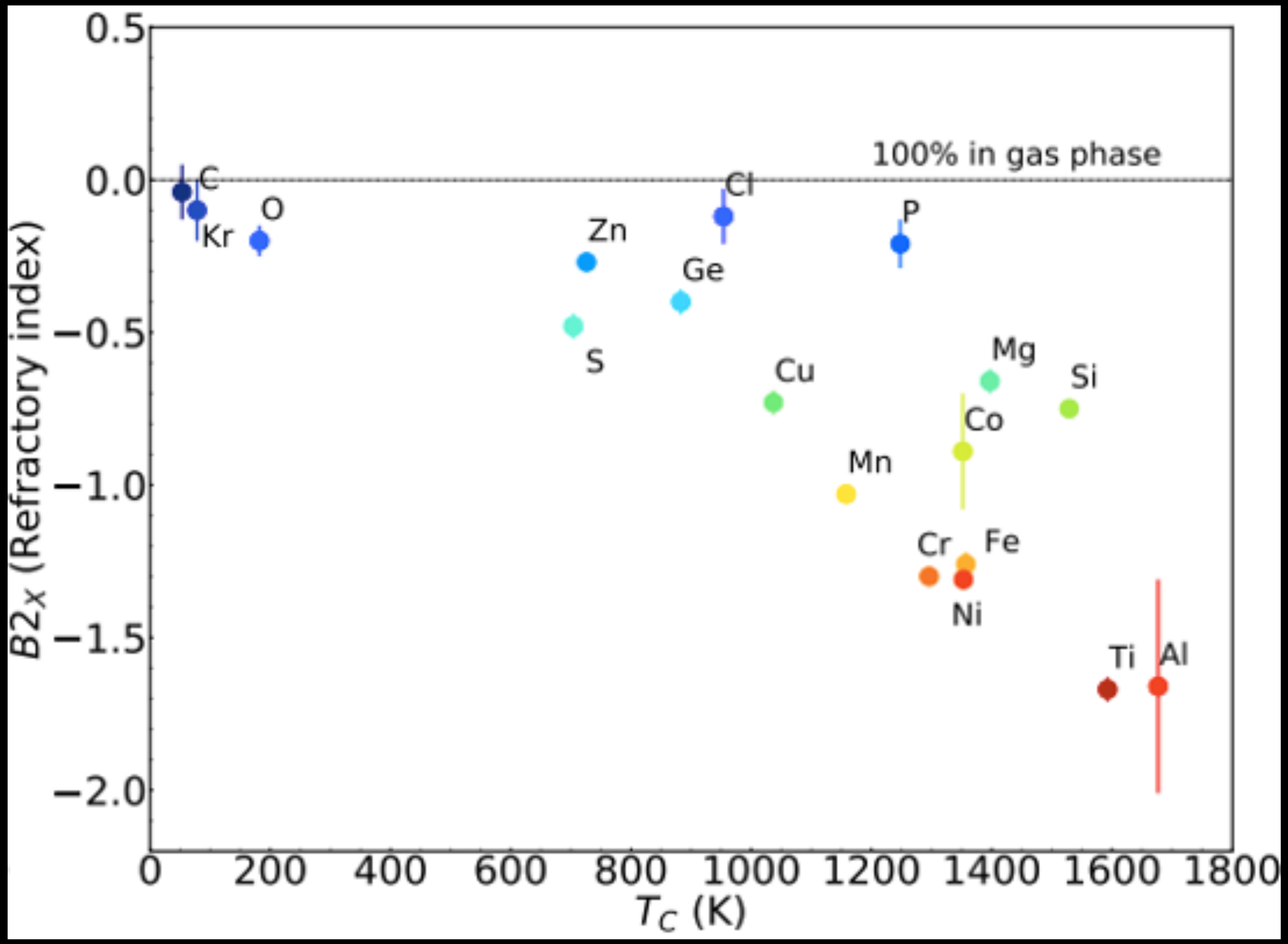
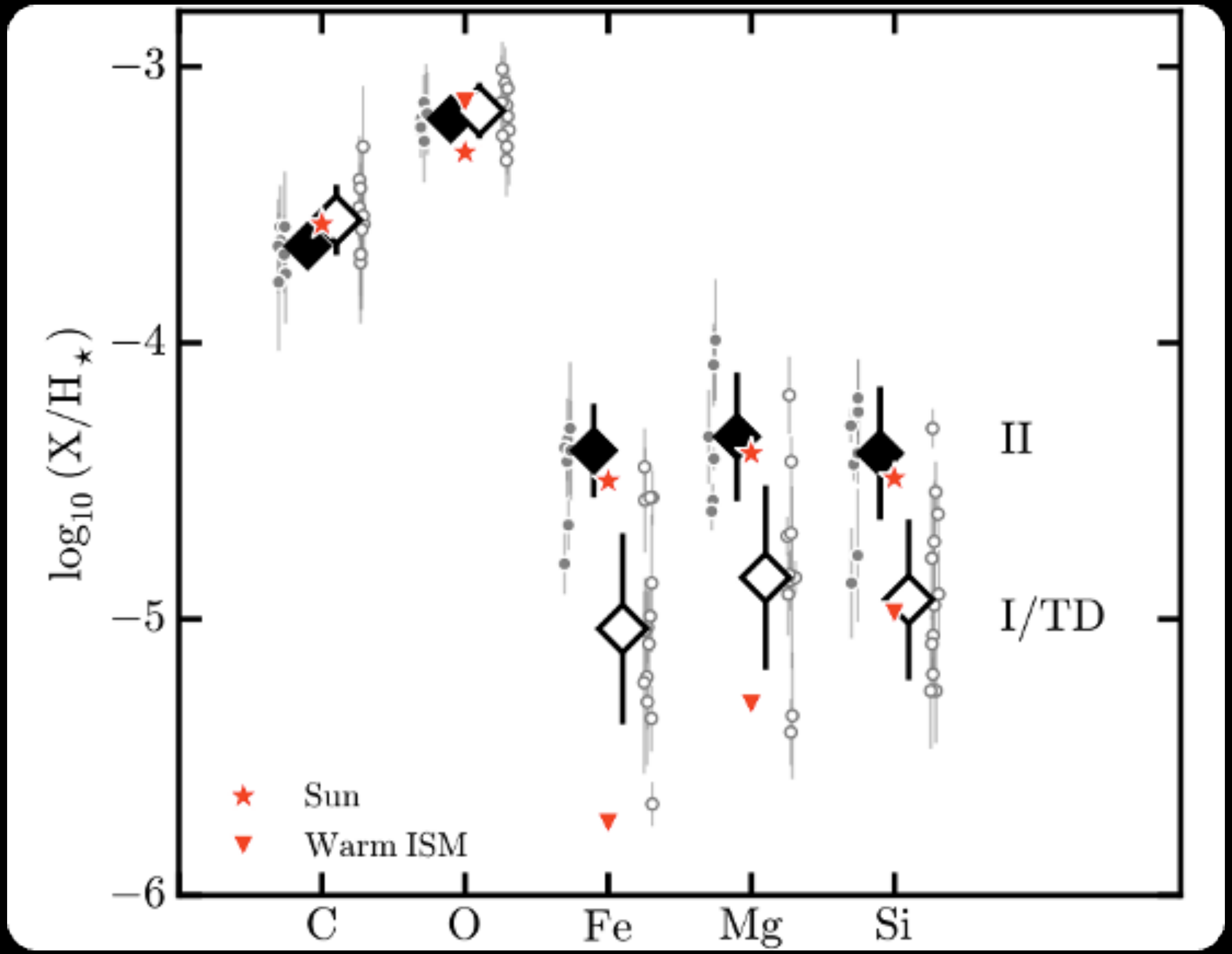


Konstantopoulou+2022

Young Stars

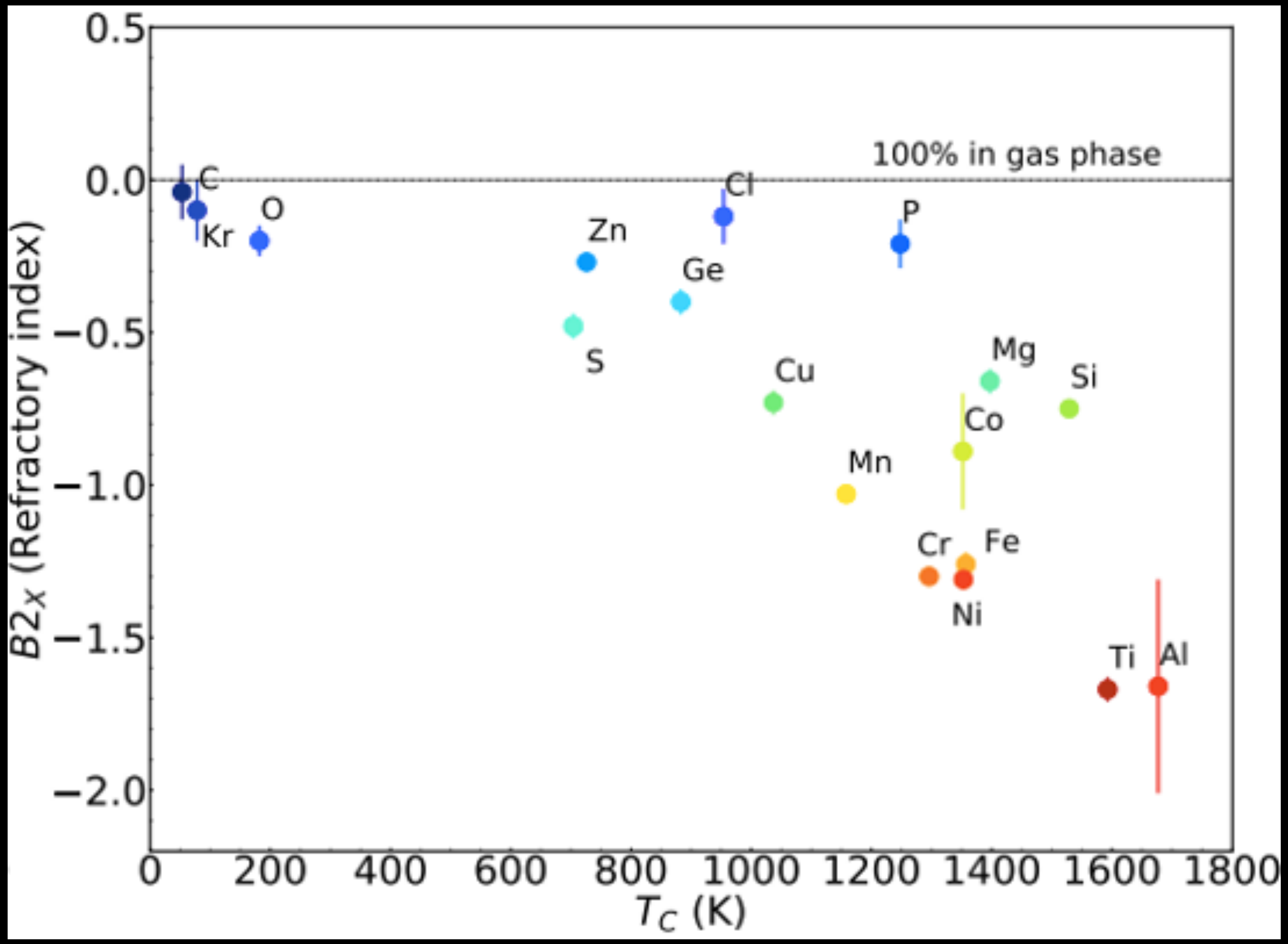


Kama+2015

Note: for young stars,
II are full discs,
I/TD are transition discs

Chemical Depletion Across the HR Diagram

ISM



Konstantopoulou+2022

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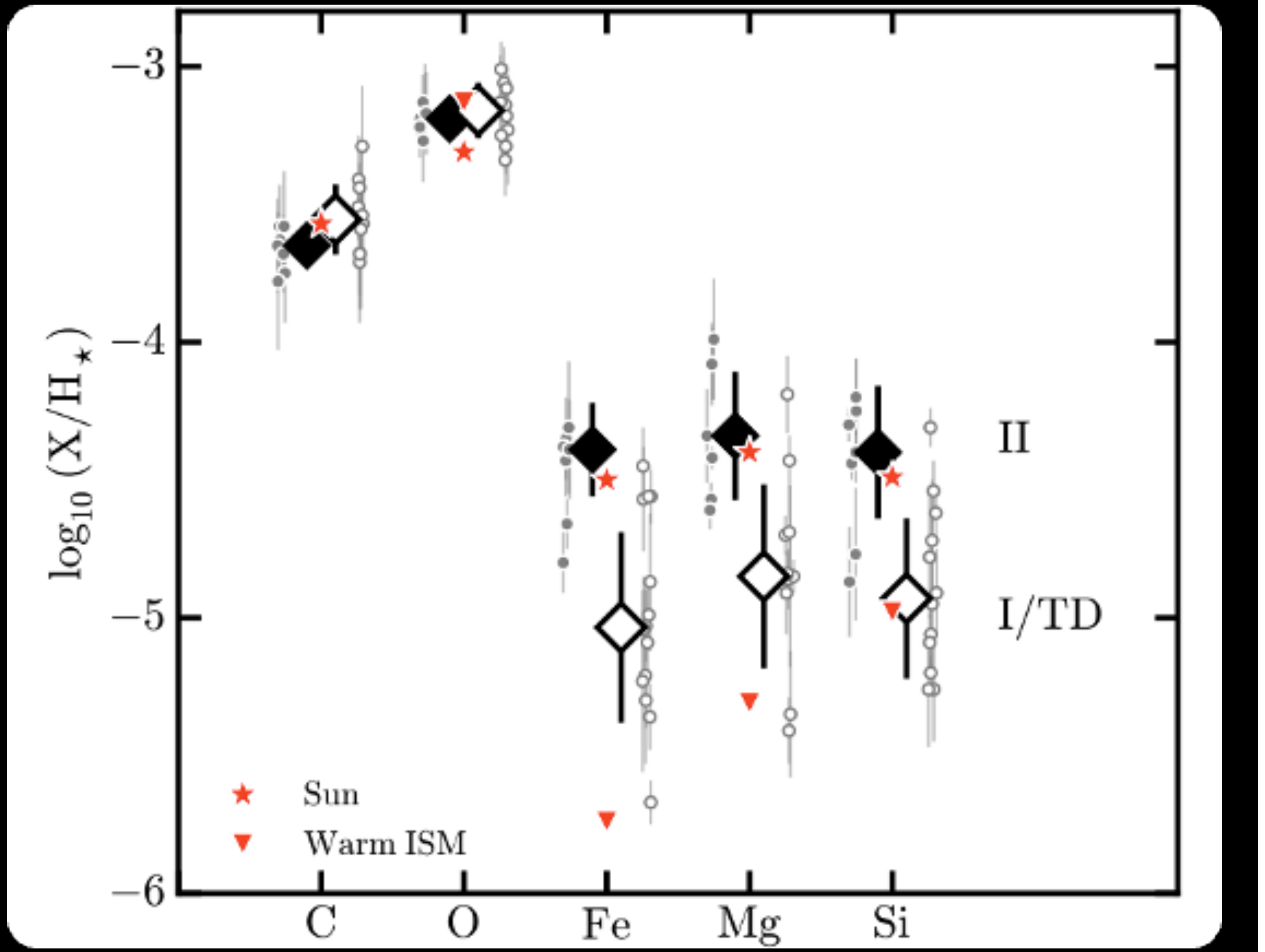
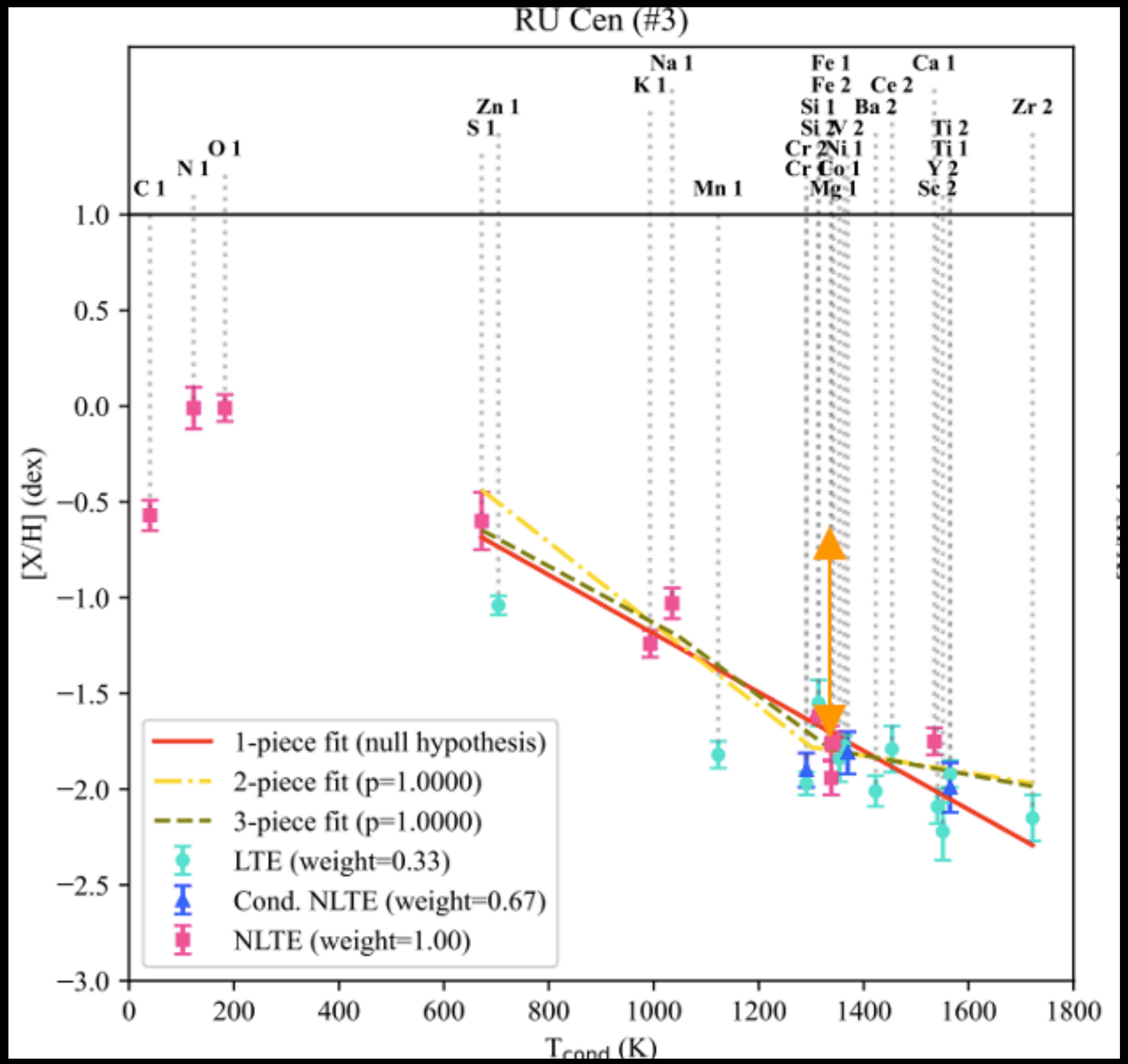


Kama+2015

PAGB/PRGB Binaries



Mohorian et al., 2024 to-be-submitted

Note: for young stars,
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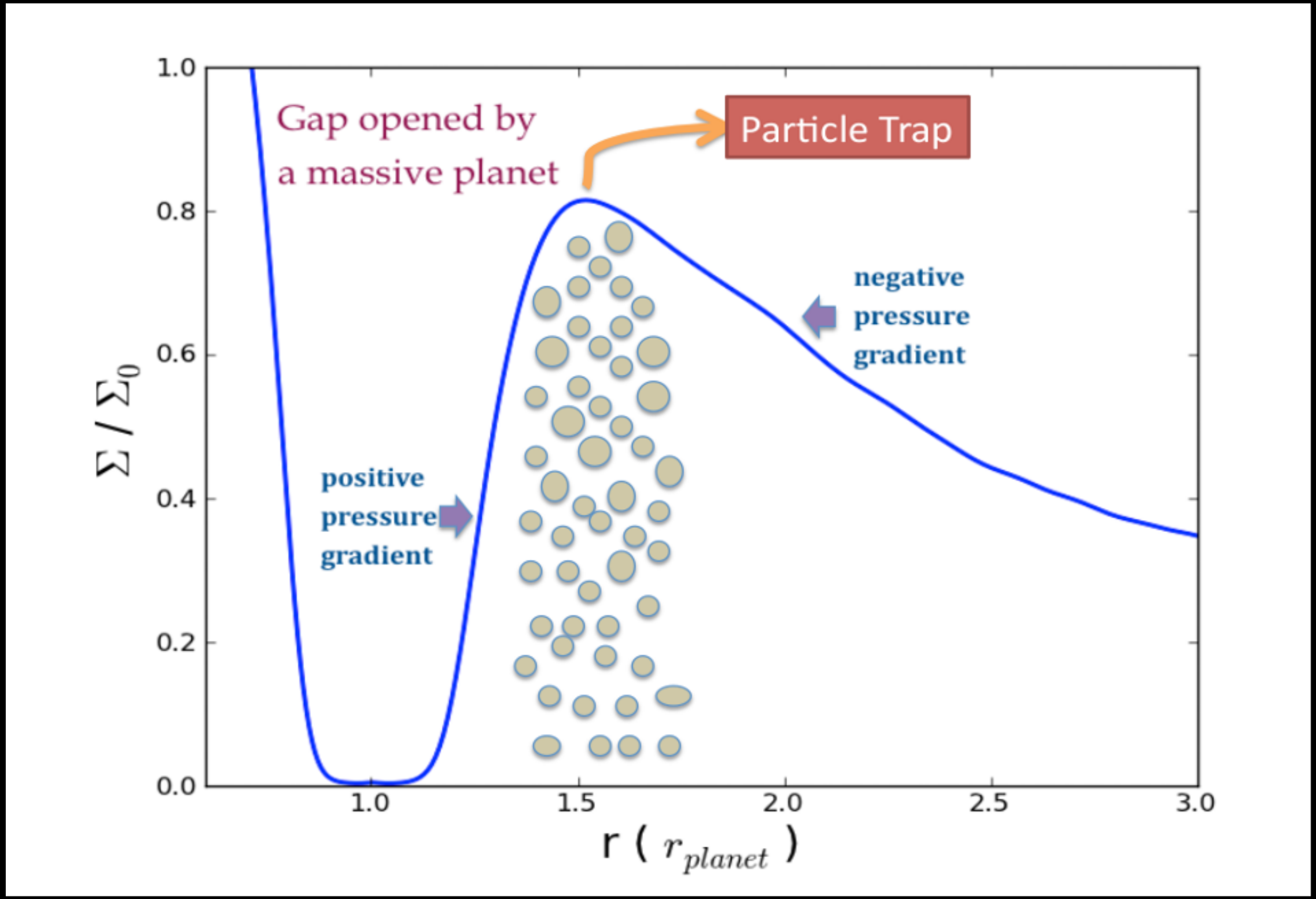
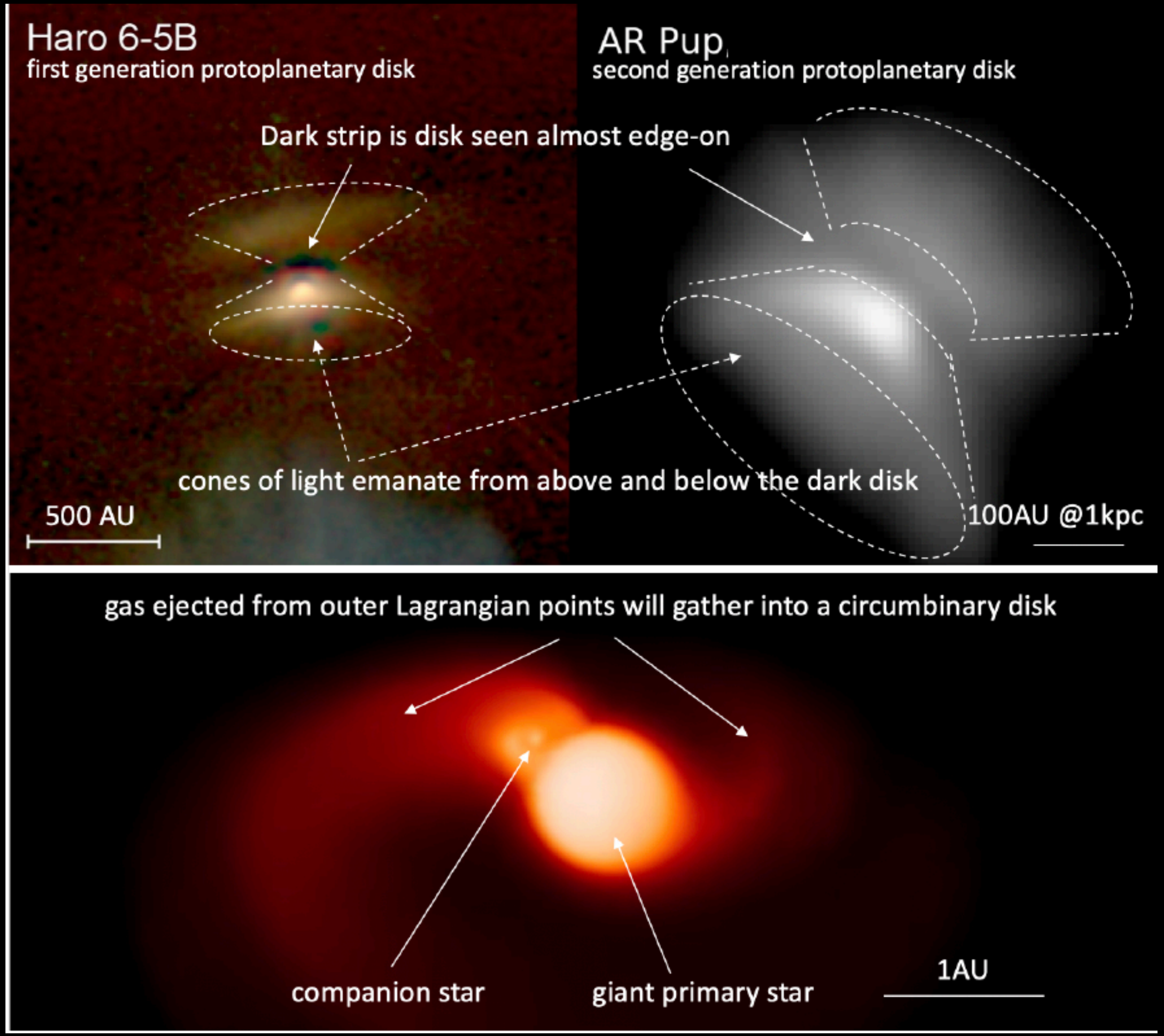
Gas-Dust Separation and Dust Trapping



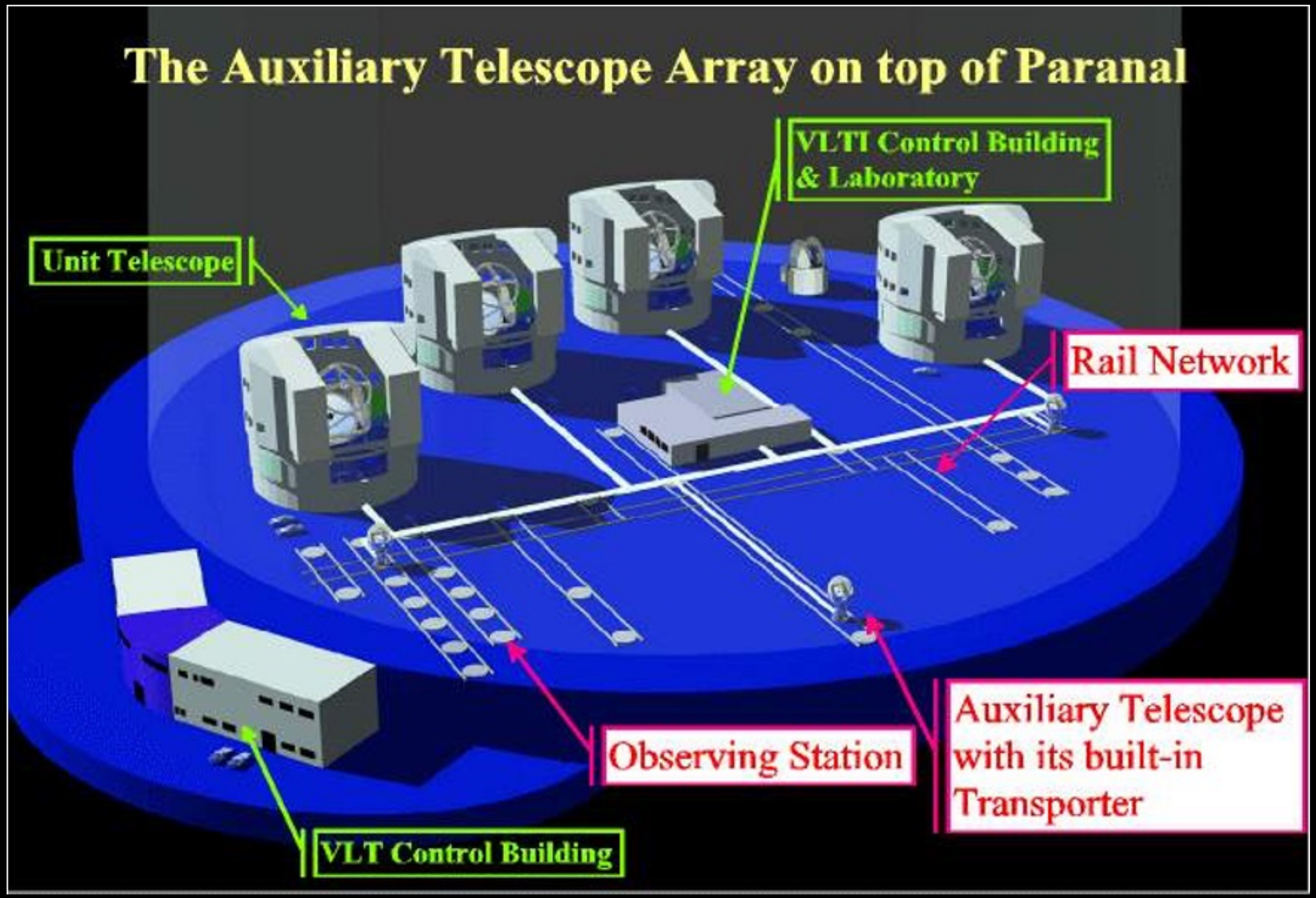
Britain et al. 2023; Kluska et all 2022

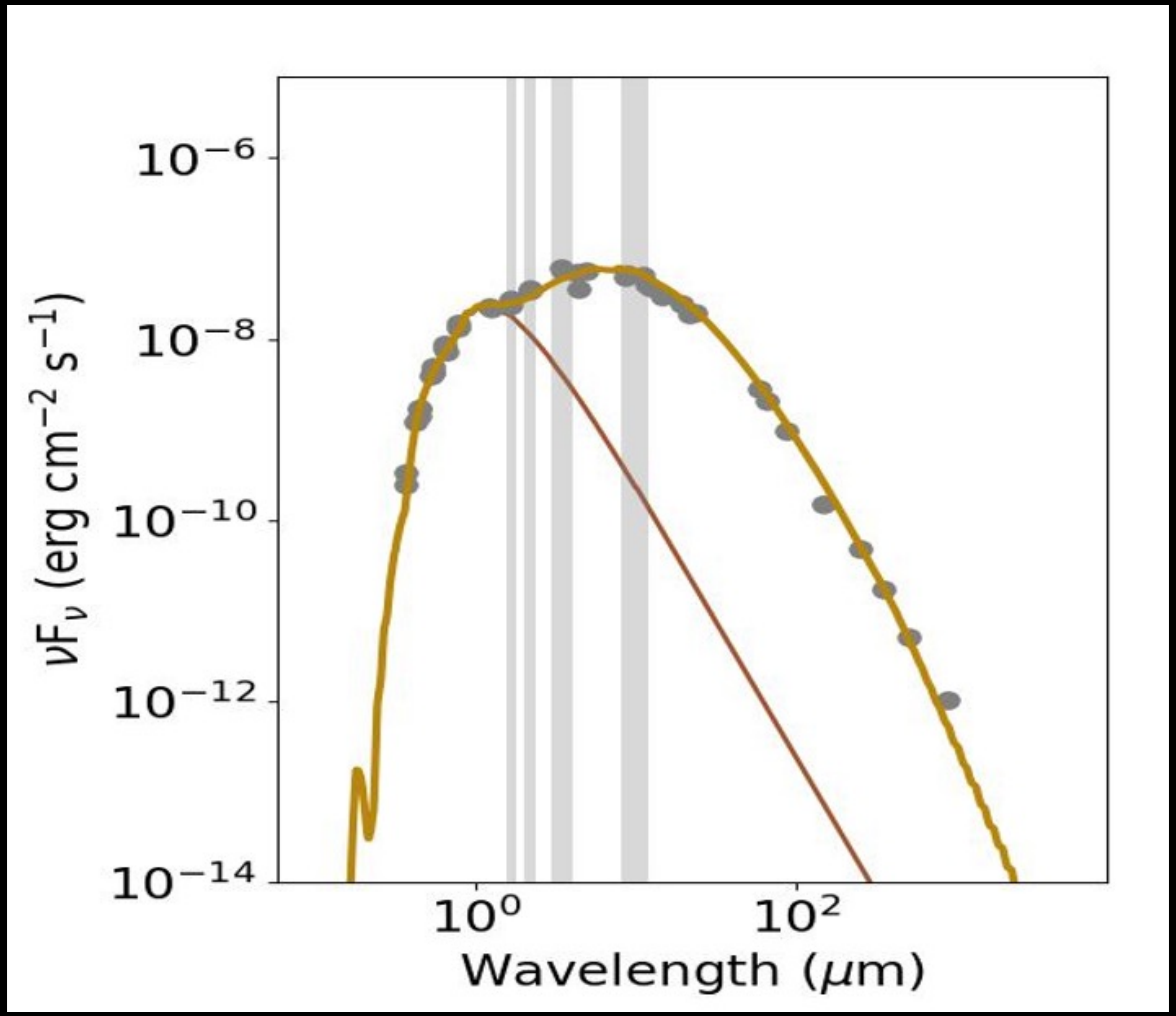
- Another similarity with YSO:
- Depletion in YSO is thought to be by dust trapping by planet formation
- Dust is trapped, clean gas can be accreted
- Depletion is correlated with SED shape (transition discs in Post-AGB stars are more depleted)
- Planet-Disc interaction also in post-AGB binaries?

A second chance for planet formation!?



Unravelling the Circumbinary Disk Structure: Near+Mid-IR Interferometry





- Interferometric Image Reconstruction: 1mass resolution!
- Several instruments now (H to N band)
- 4-telescope combiners (Pionier, Gravity, Matisse)

Kluska et al., 2021, 2020, 2019, 2018 ; Hillen et al., 2016

INSPIRING: INterferometric Survey of Post-agb bInaries with their RING an imaging VLTI Large Programme

PI: Kluska, CI: Van Winckel, Kamath, et al.,

250h with PIONIER and GRAVITY - 11 targets

Main goals:

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Methodology:

- Image reconstruction
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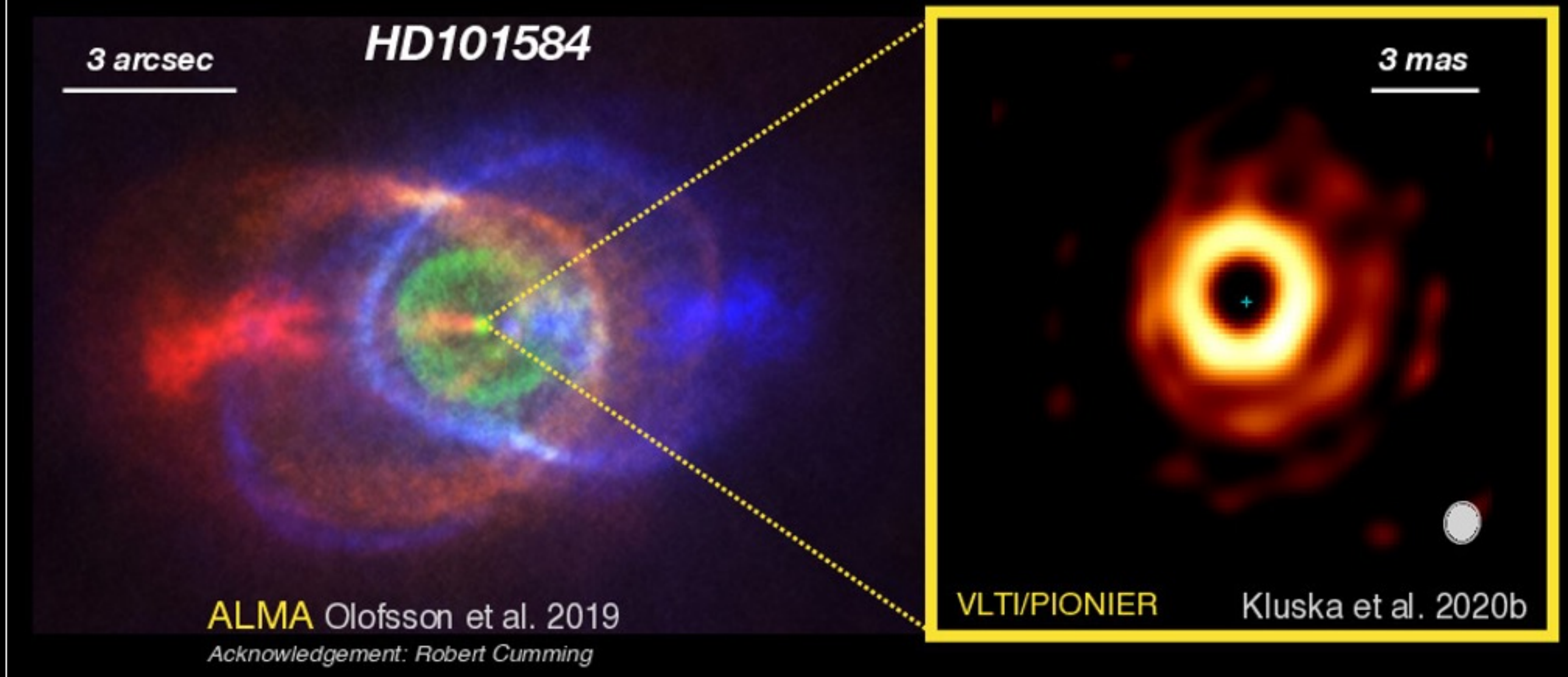
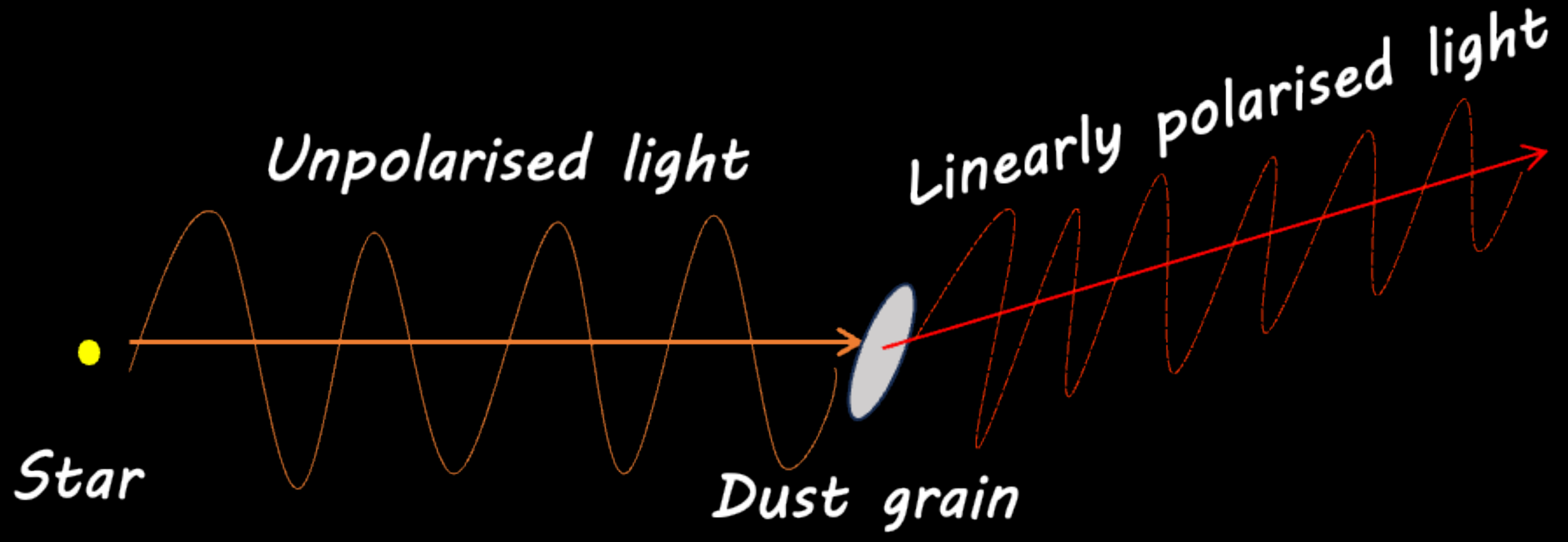
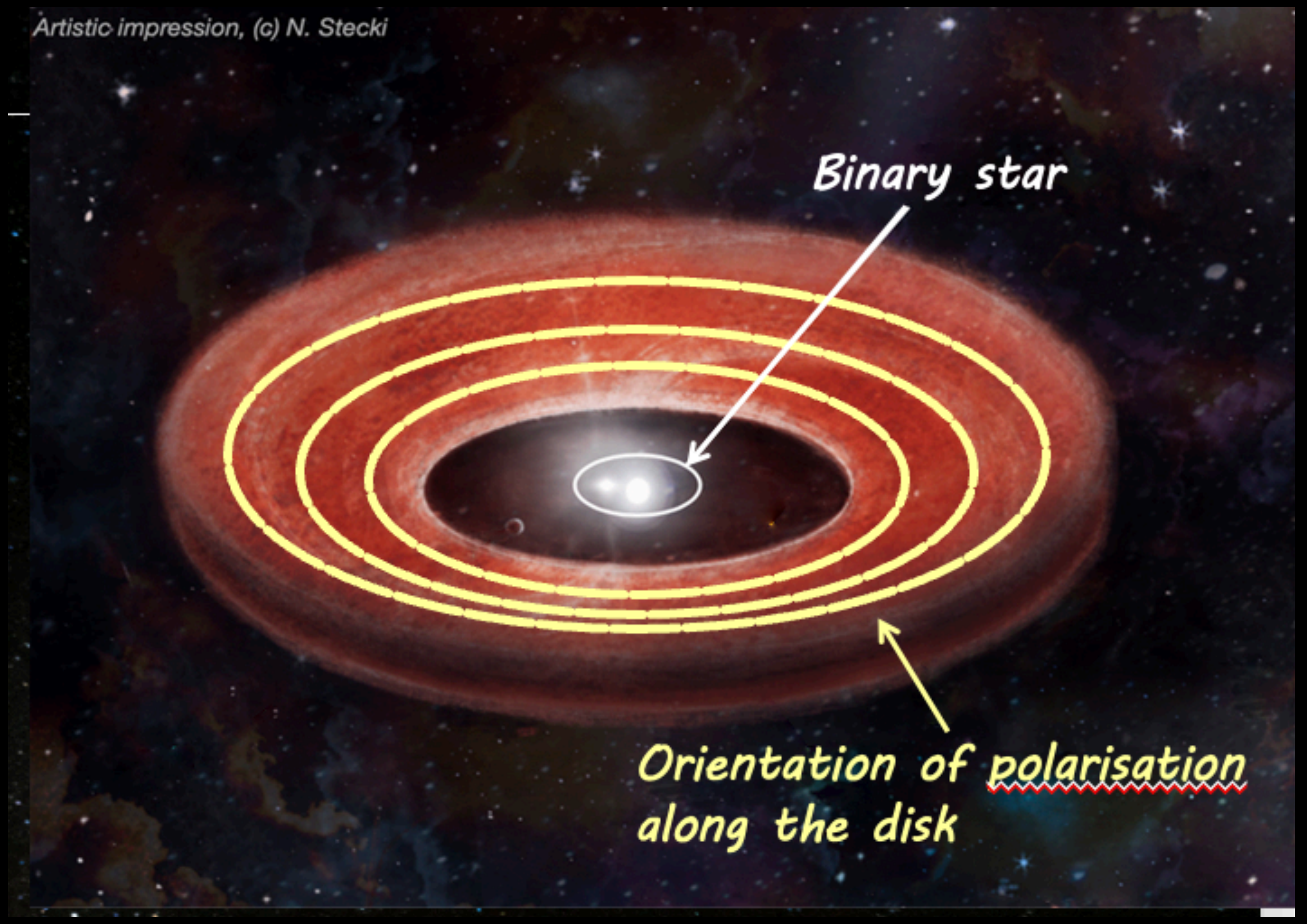


Kluska et al., 2020, 2021, 2022

Unravelling the Circumbinary Disk Structure: High resolution imaging and polarimetry

VLT/SPHERE





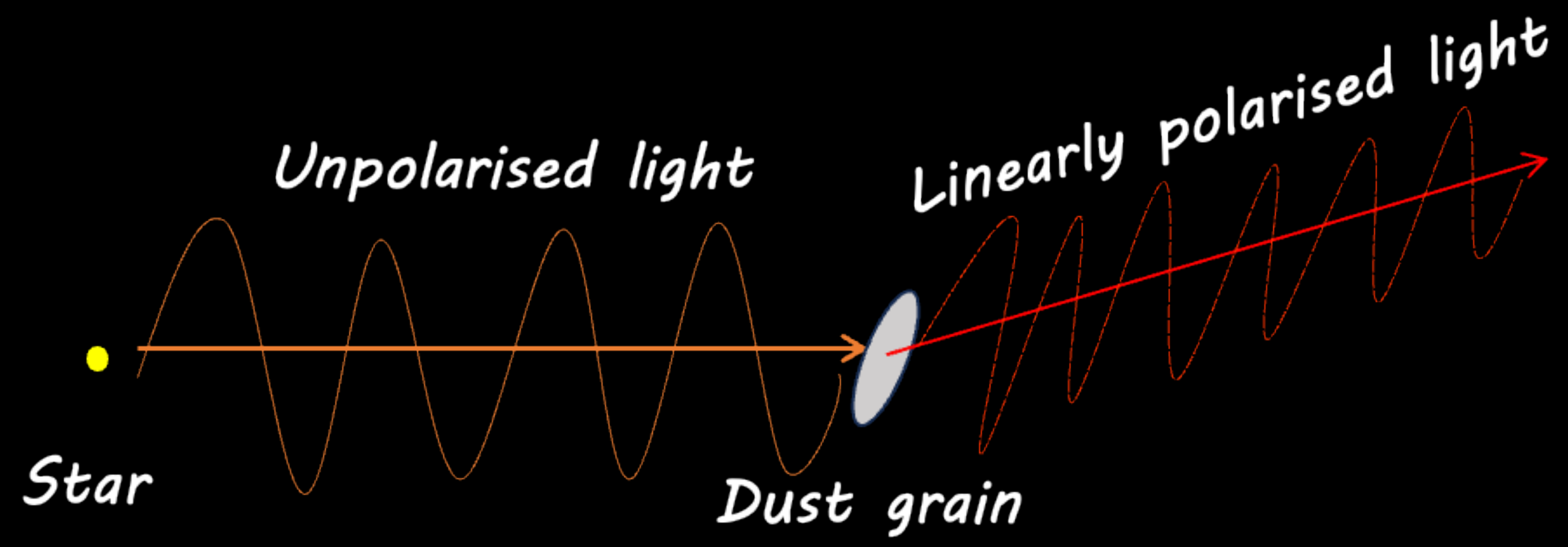
Observational data:

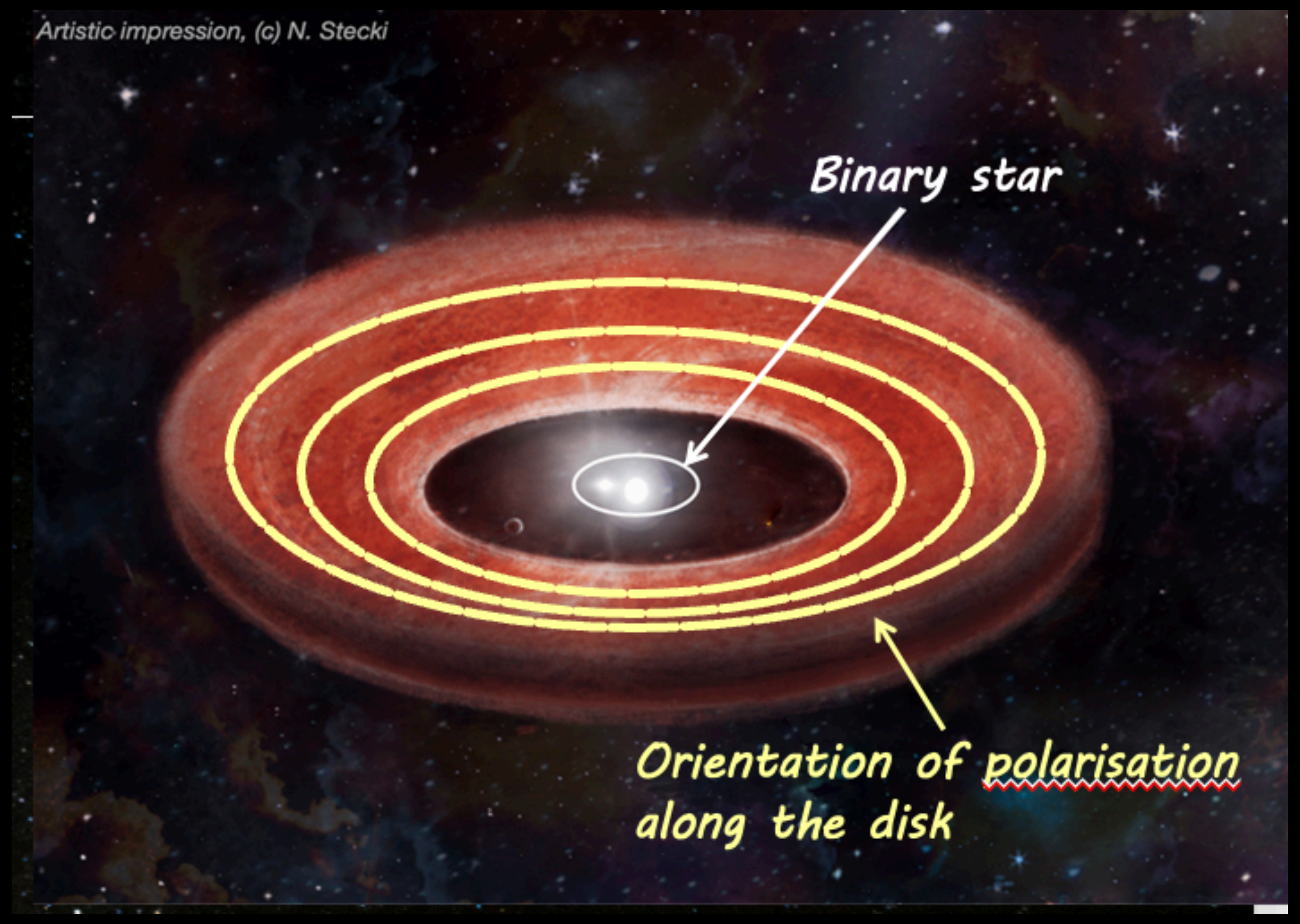
Stokes components I Q U V

Unpolarised (I) · Linearly polarised (Q, U) · Circularly polarised (V)

Andrych et al., 2023, 2024 submitted

Unravelling the Circumbinary Disk Structure: High resolution imaging and polarimetry





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PI: Kamath
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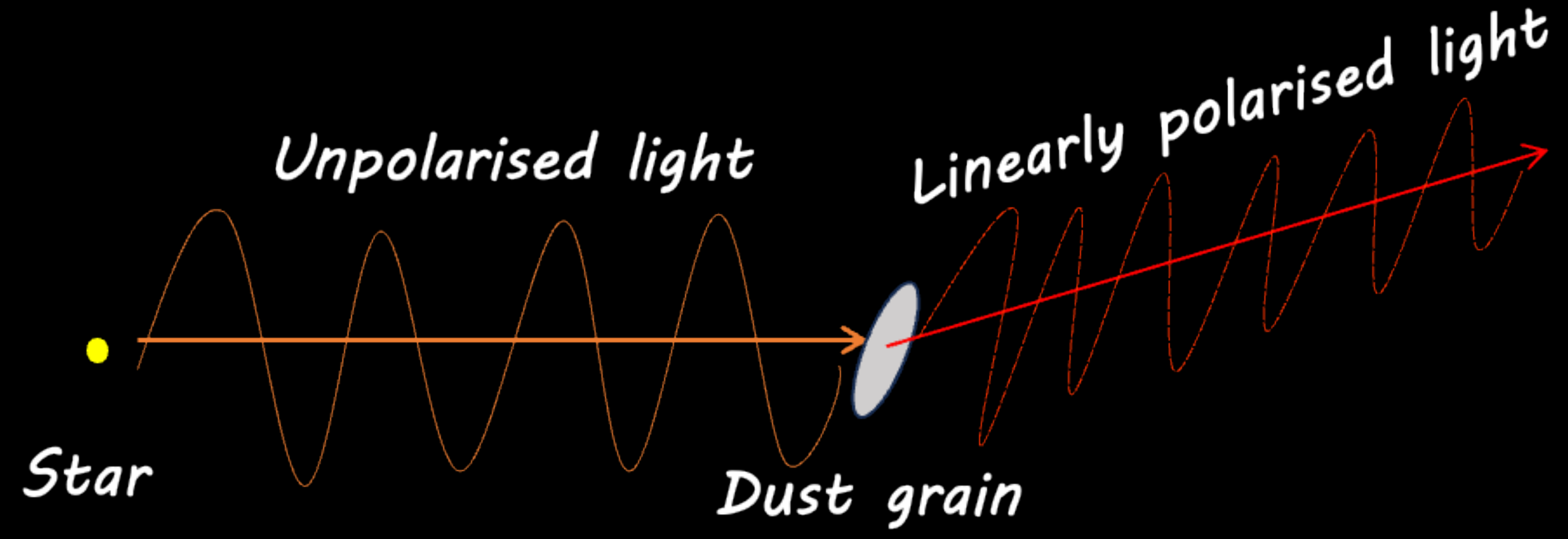

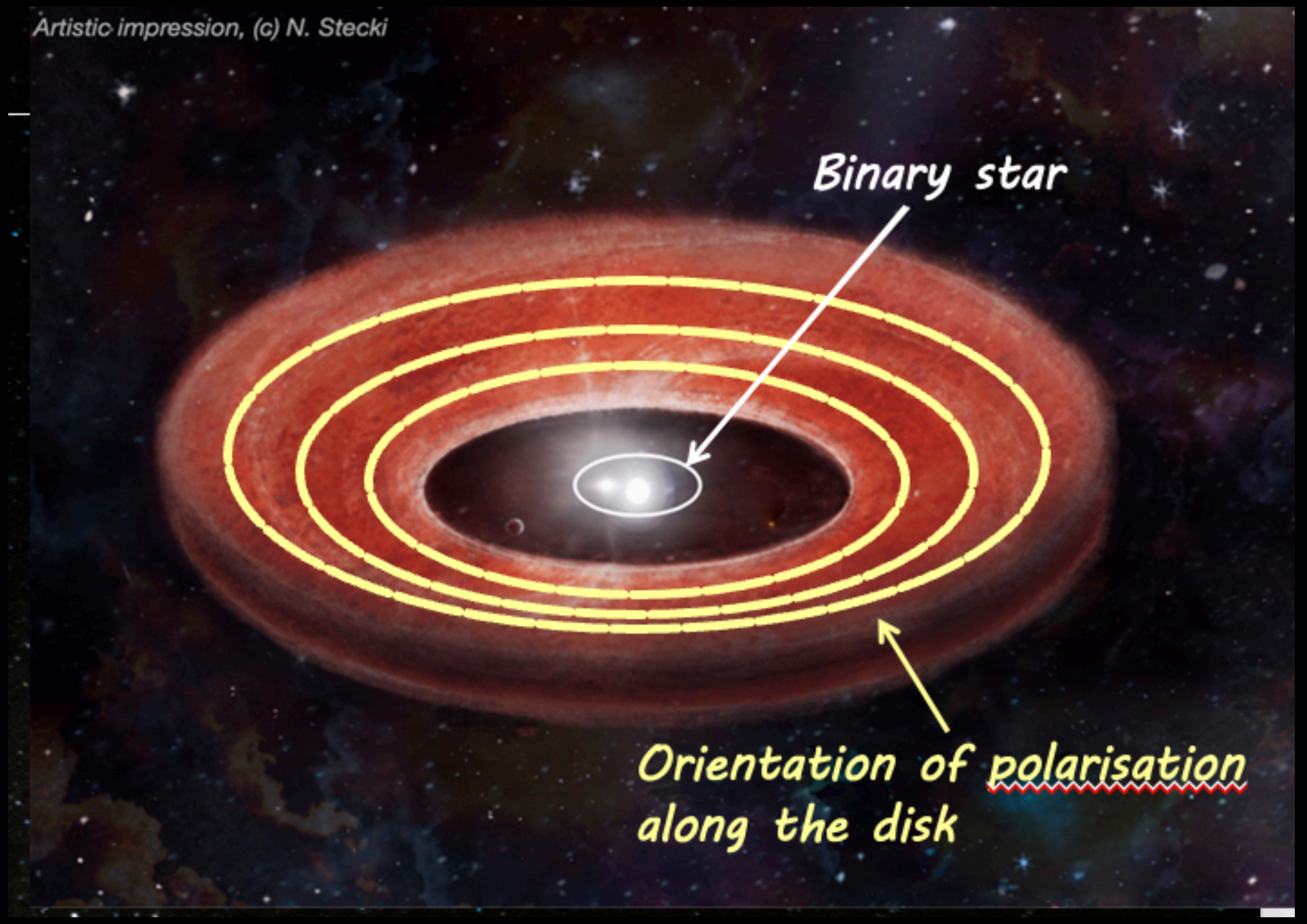

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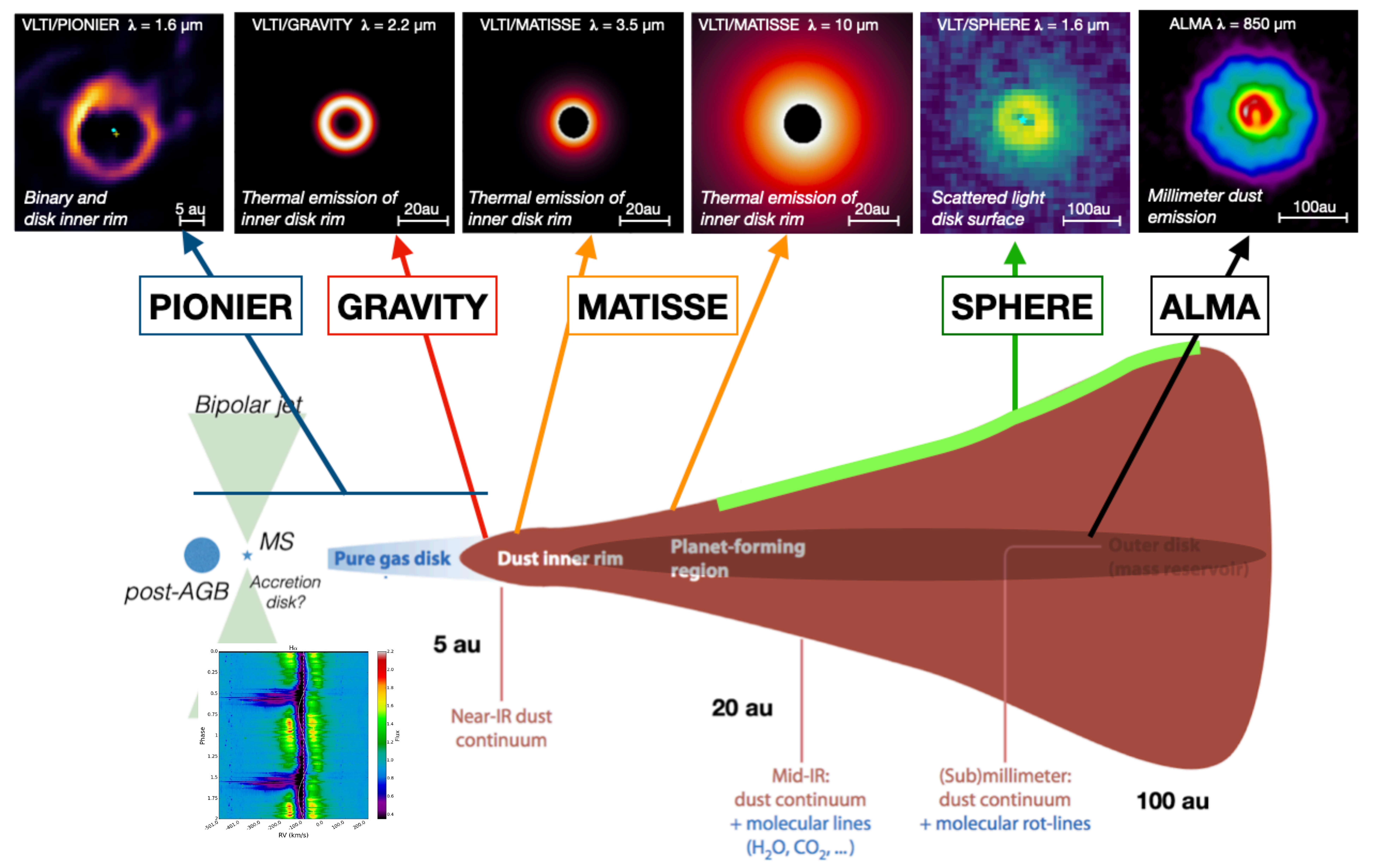

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VLT/SPHERE λ = 1.6 μm
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100au
ALMA λ = 850 μm
Millimeter dust emission
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post-AGB
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Planet-forming region
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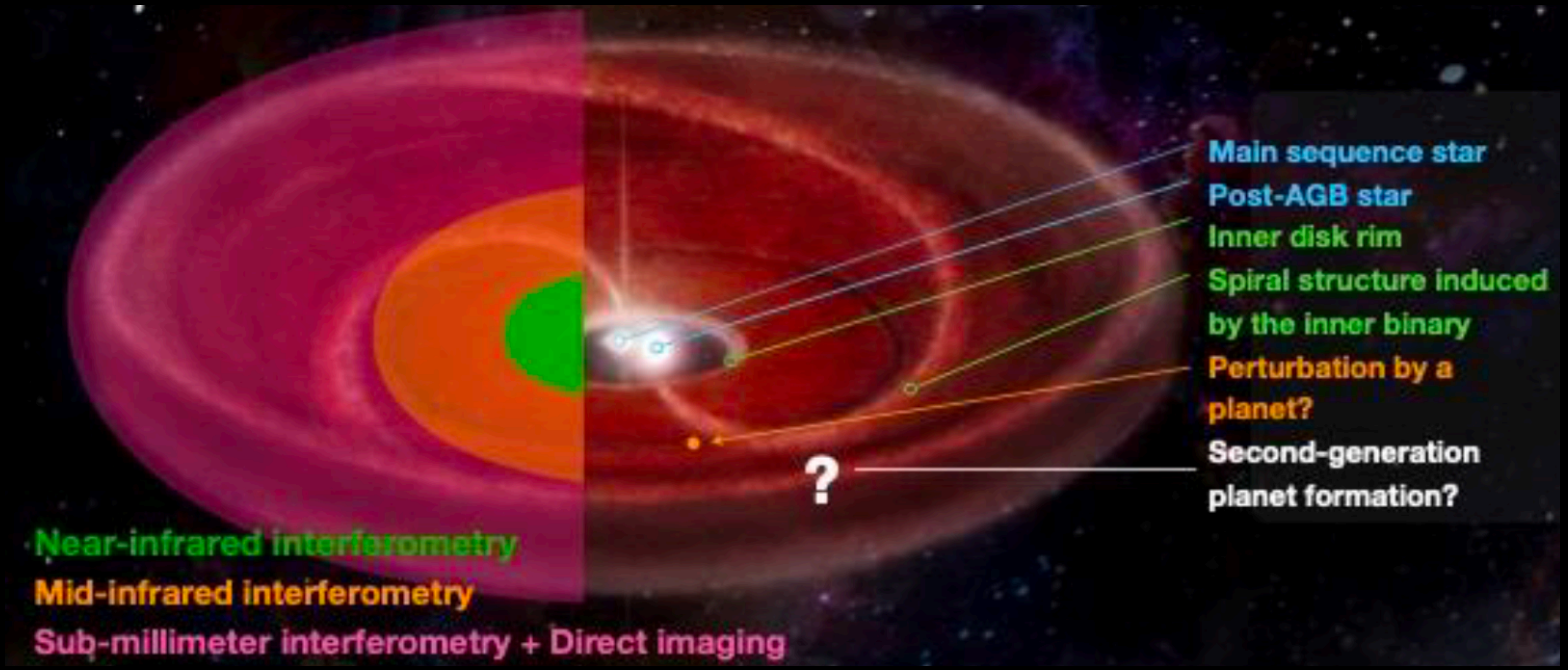
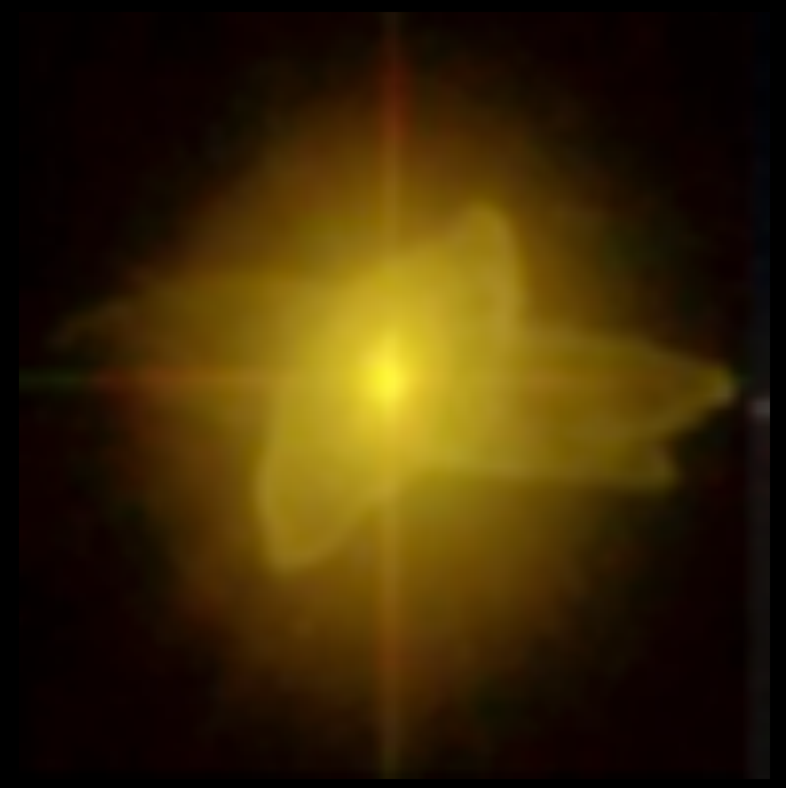
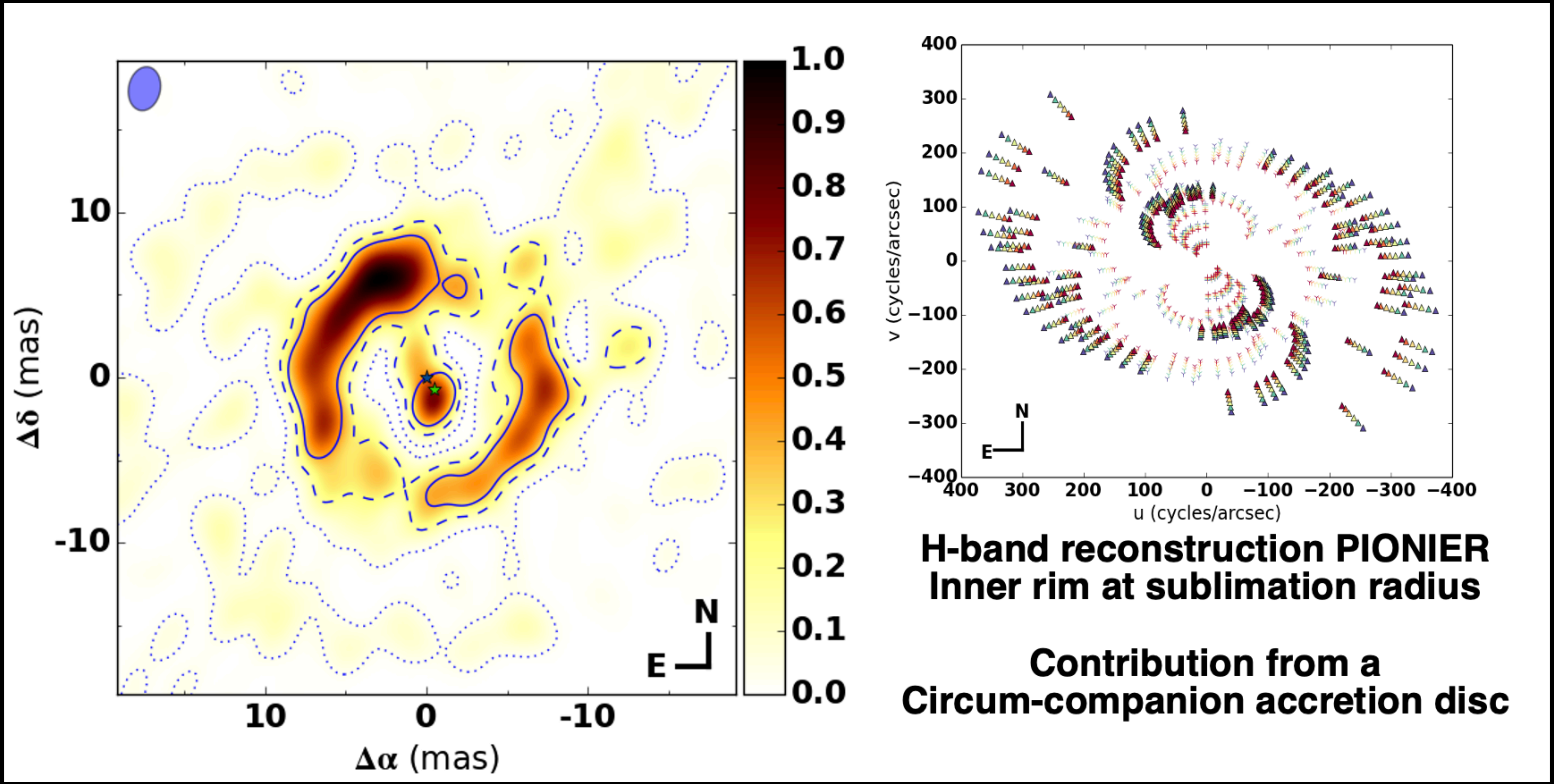


Evolved Stars' Metamorphosis: a Comprehensive Analysis of The AGB to PN Transition



MACQUARIE
University
Astrophysics and
Space Technologies
Research Centre

IRAS08544-4431: interferometric imaging



Hillen et al., 2016; Kluska et all 2018

ESO press release: eso1608a

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

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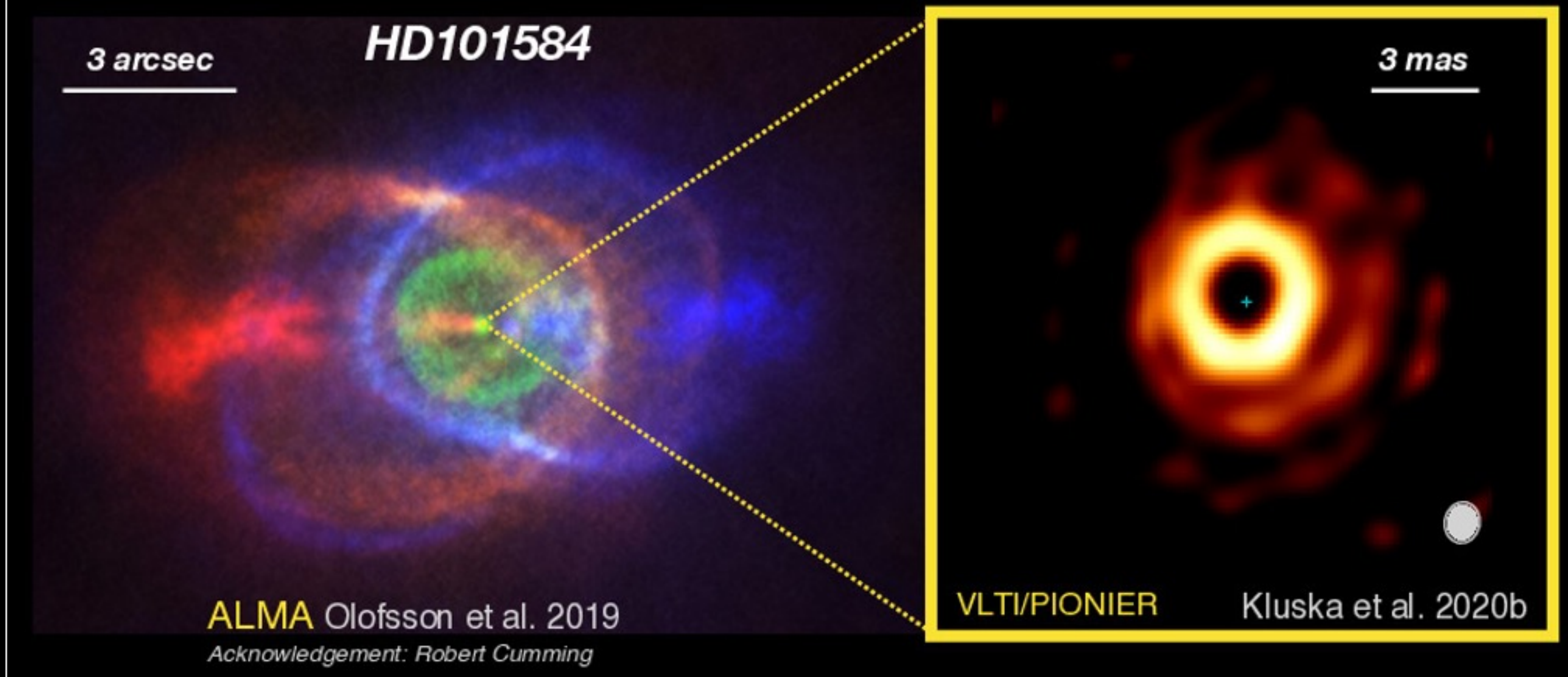
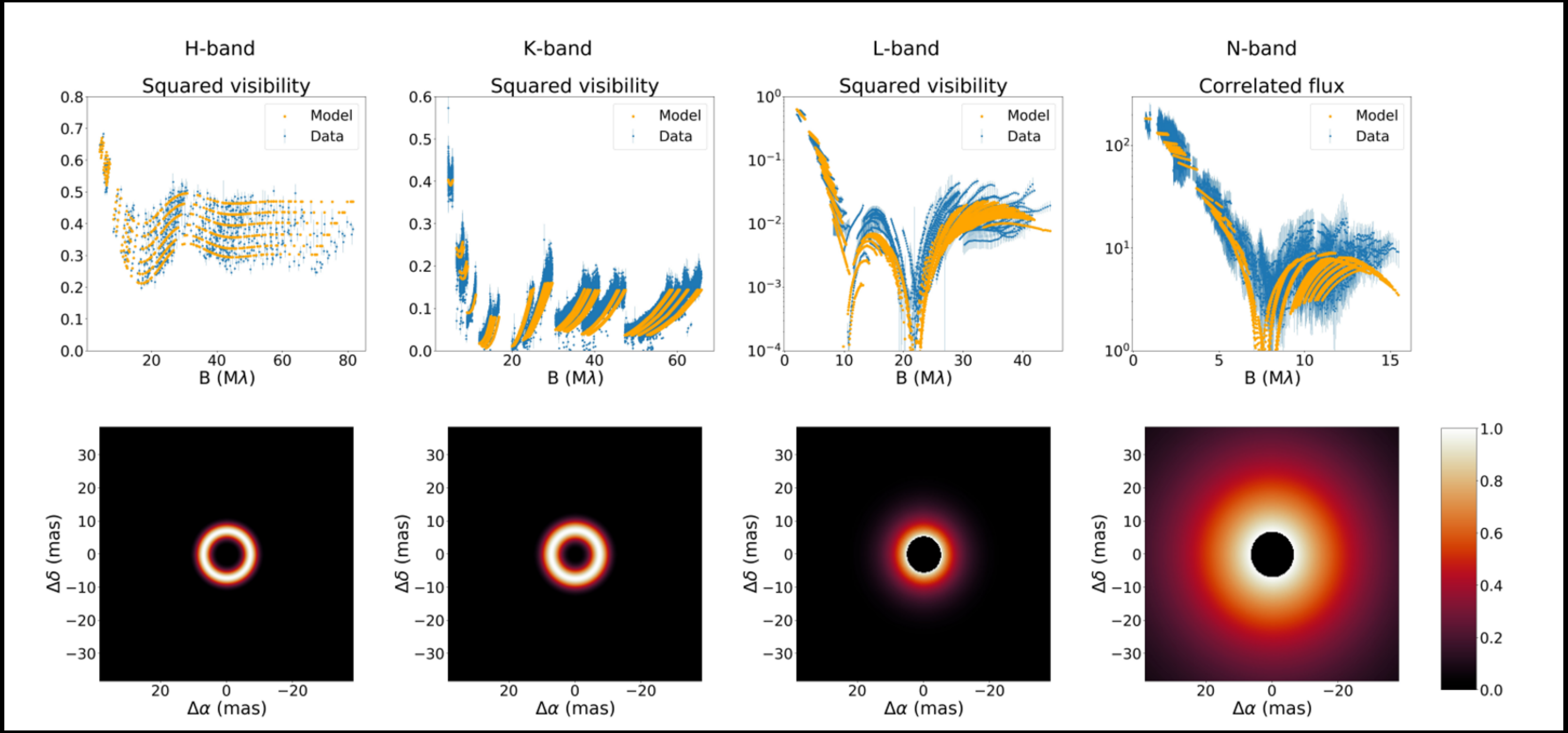


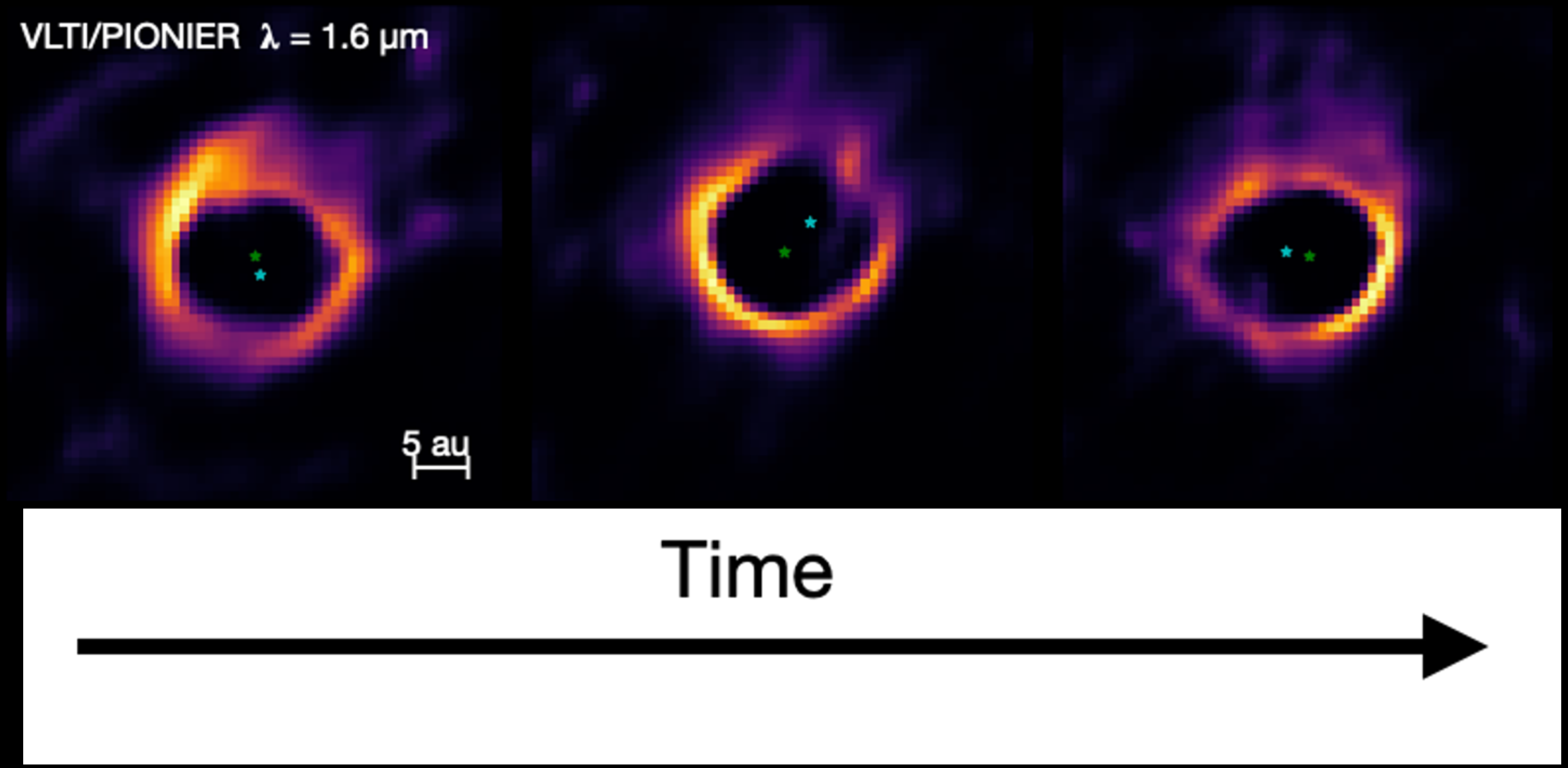
Kluska et al., 2020, 2021, 2022

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



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

CB-discs: time-resolved interferometry



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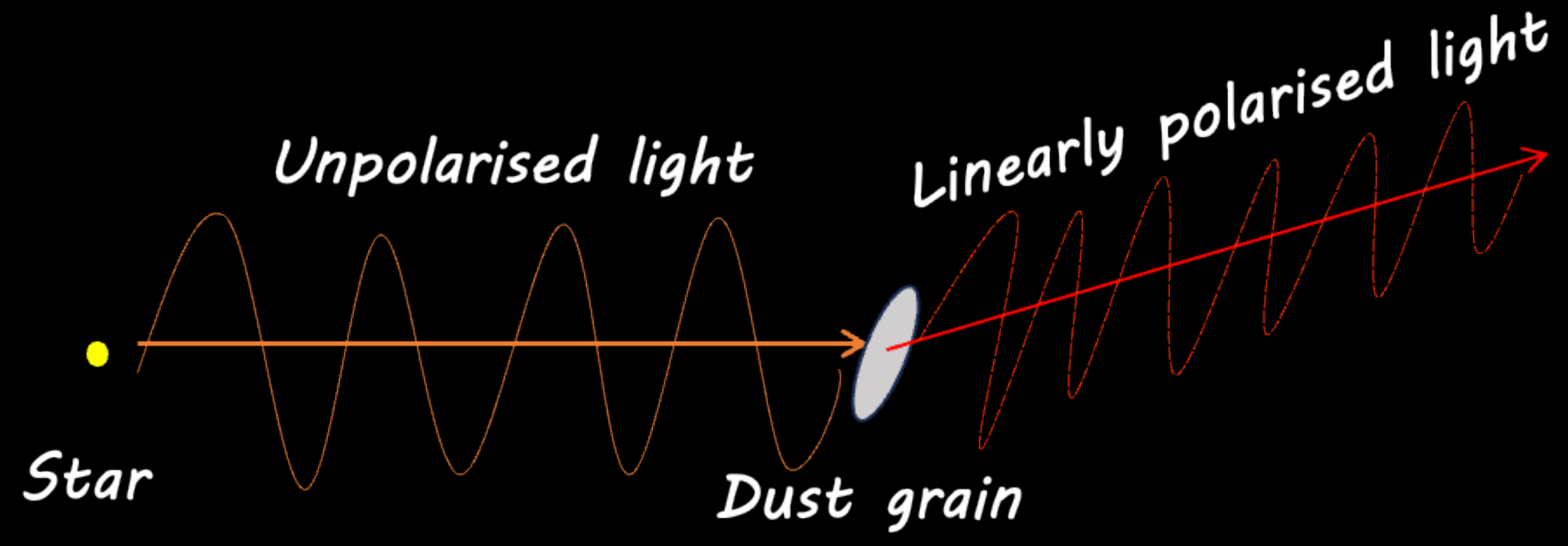

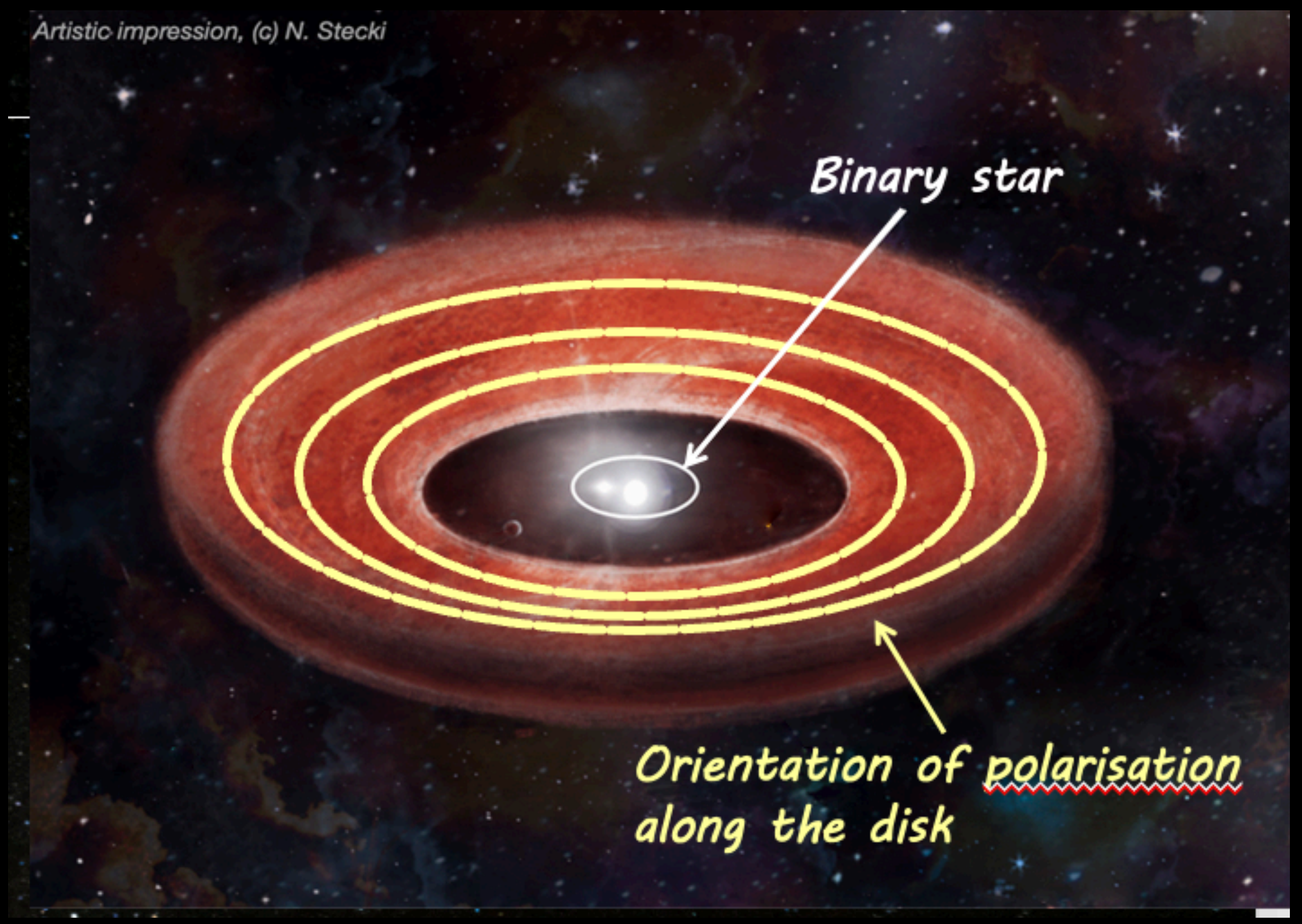

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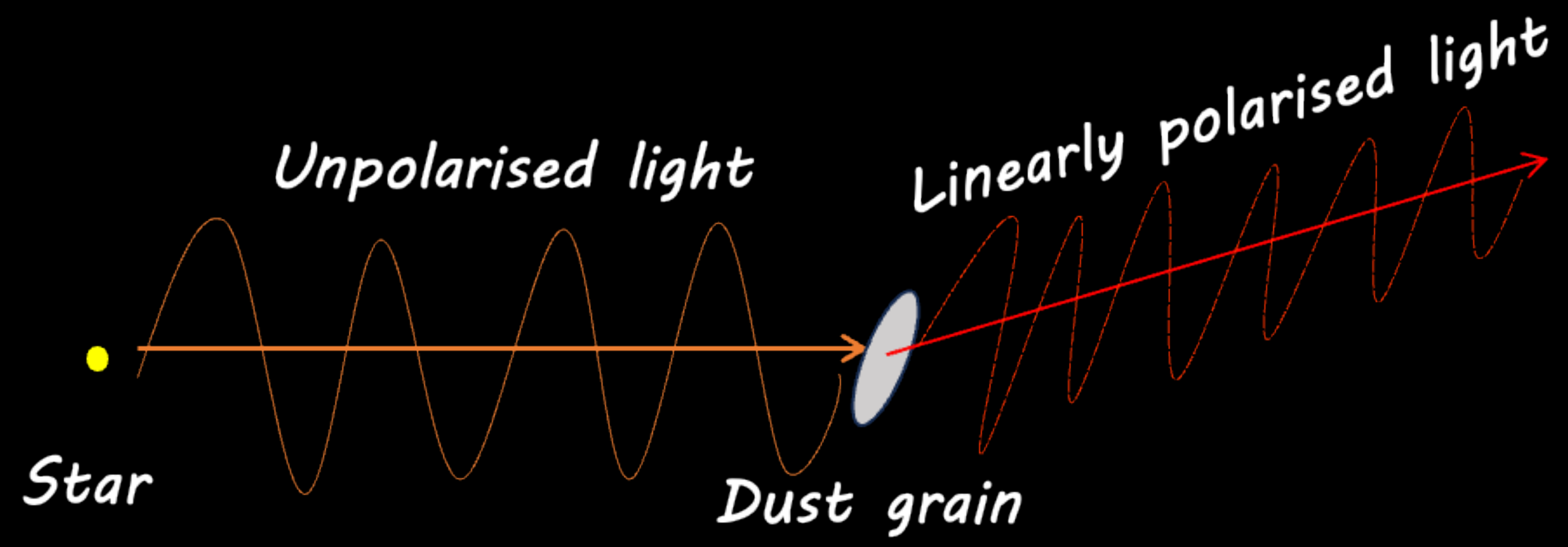

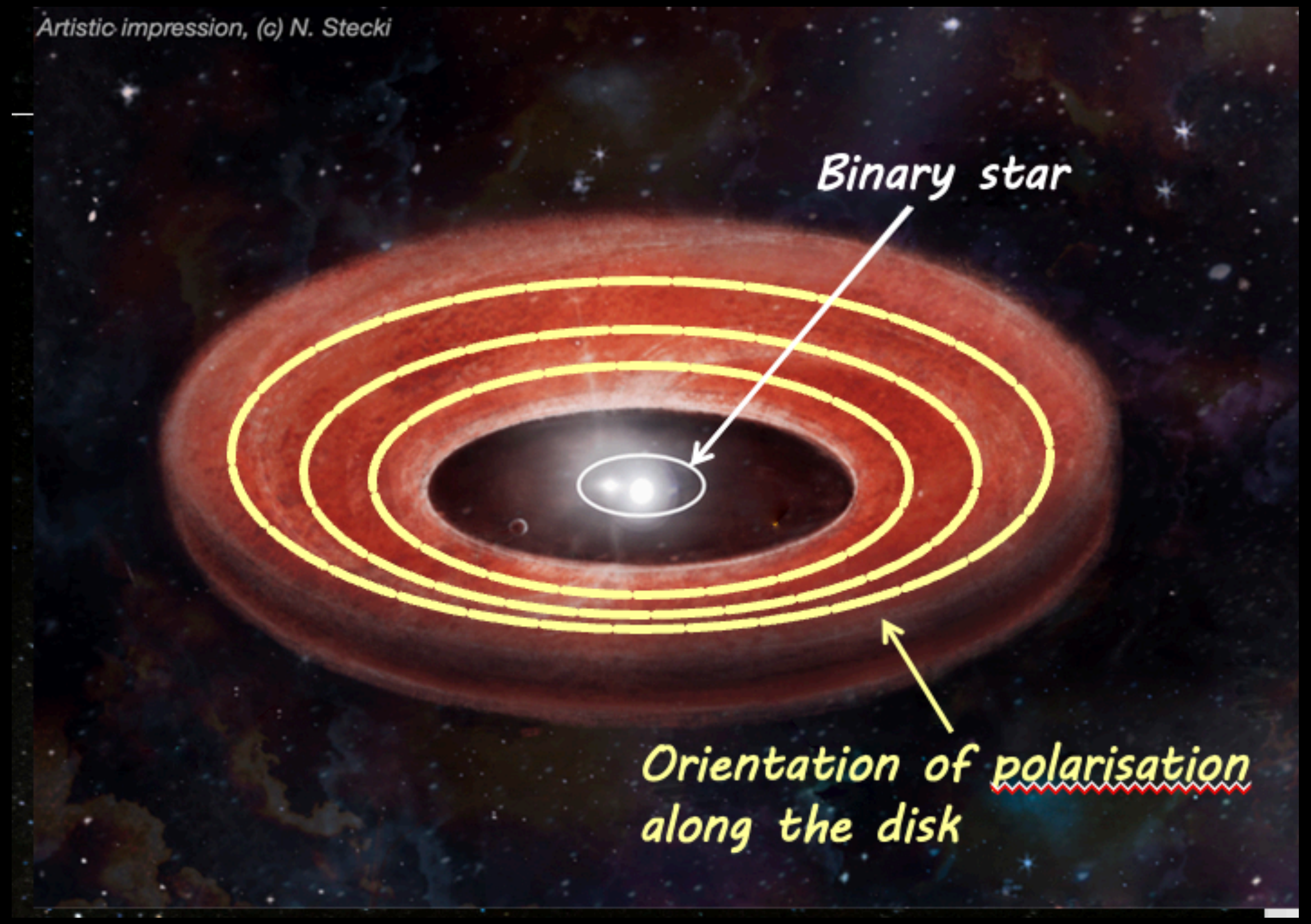

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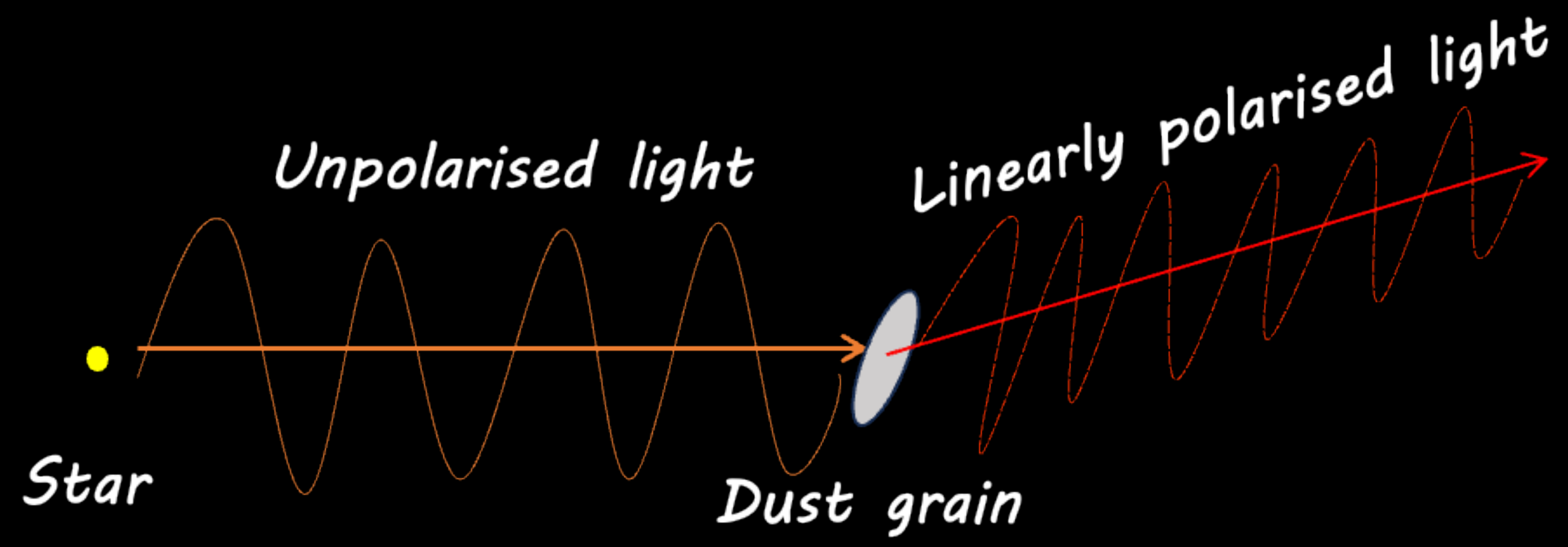
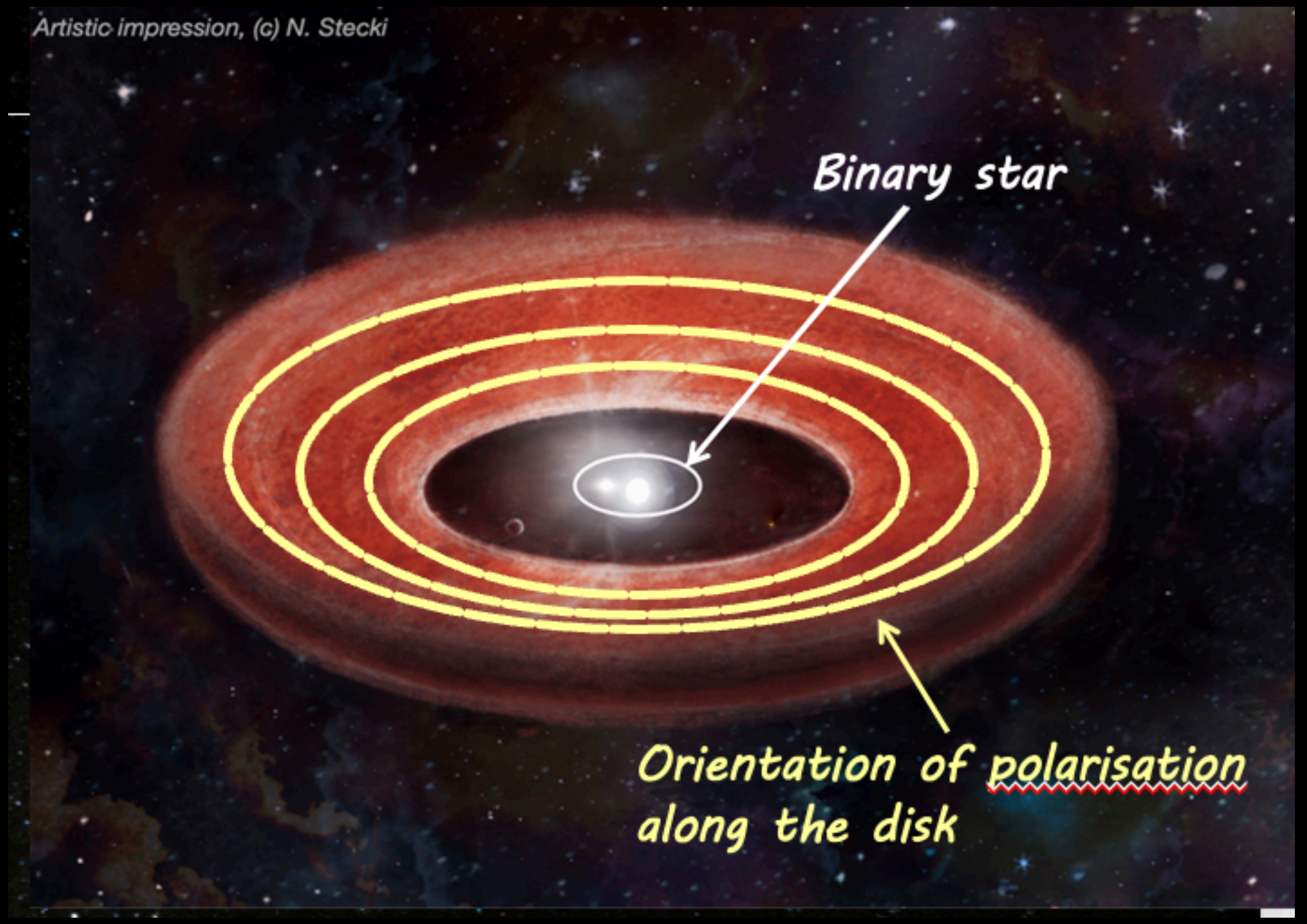




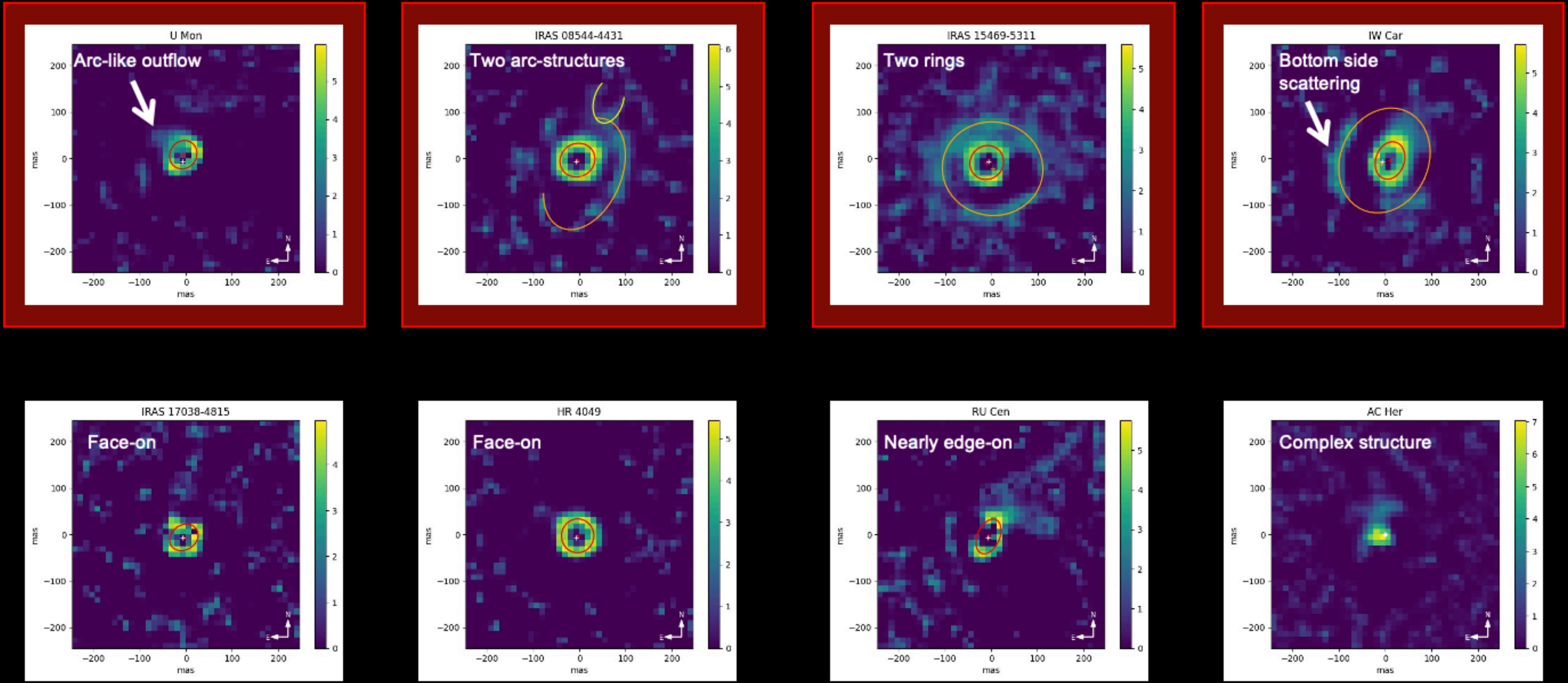
Observational data:

Stokes components I Q U V

Unpolarised — I; Linearly polarised — Q U; Circularly polarised — V

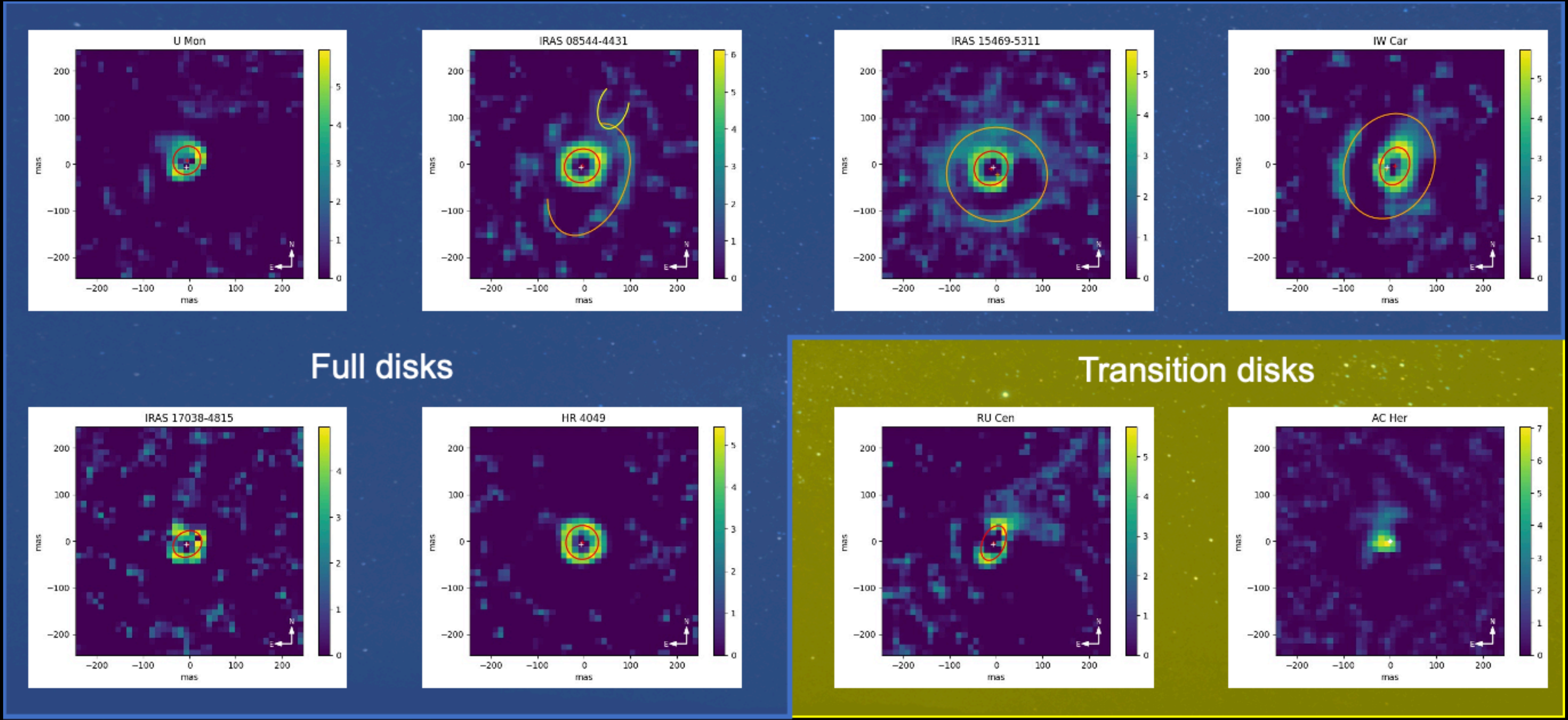
Extended Disc Structure: Complex Morphologies

IRDIS
H-band



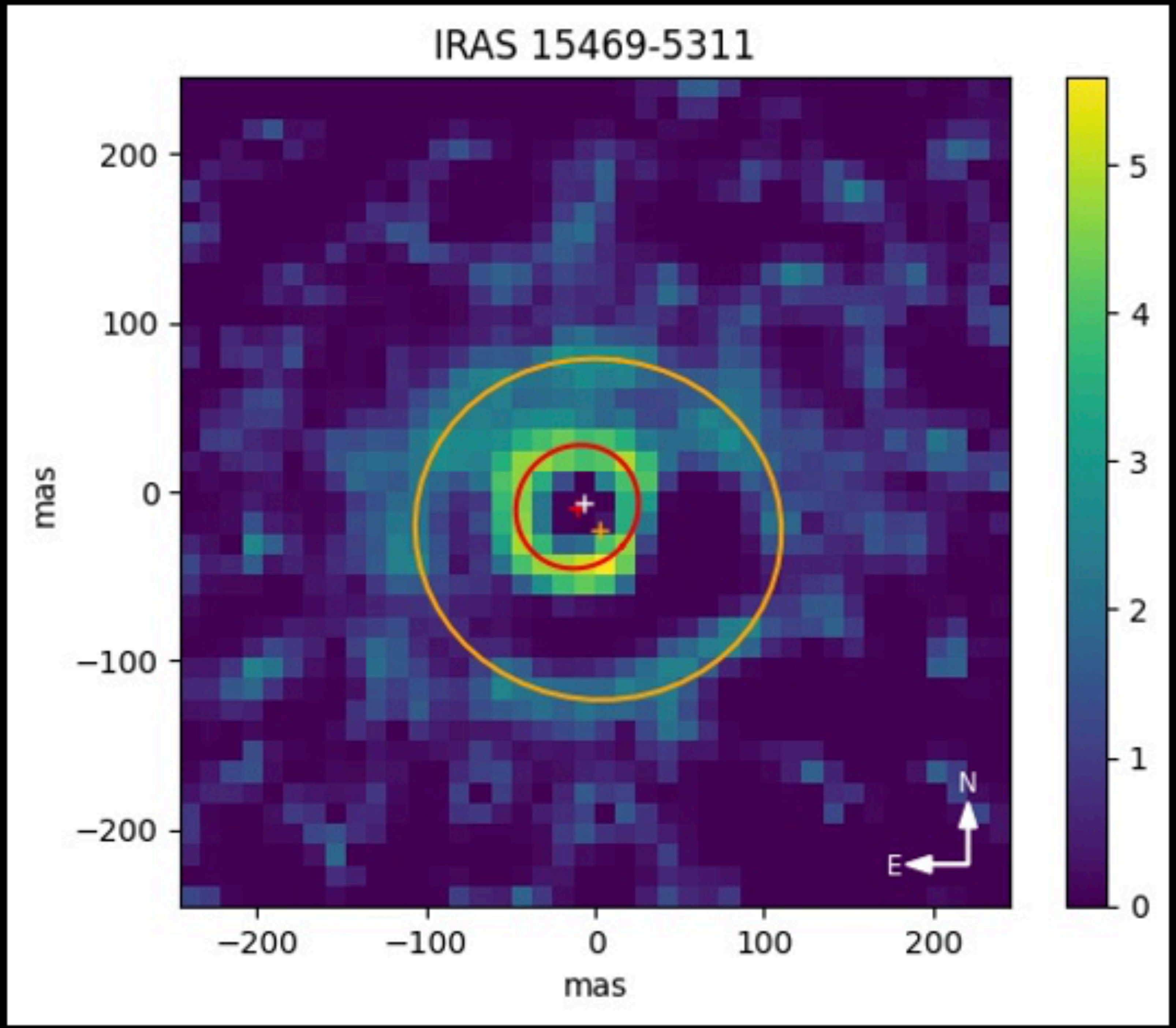
Andrych et al., 2023

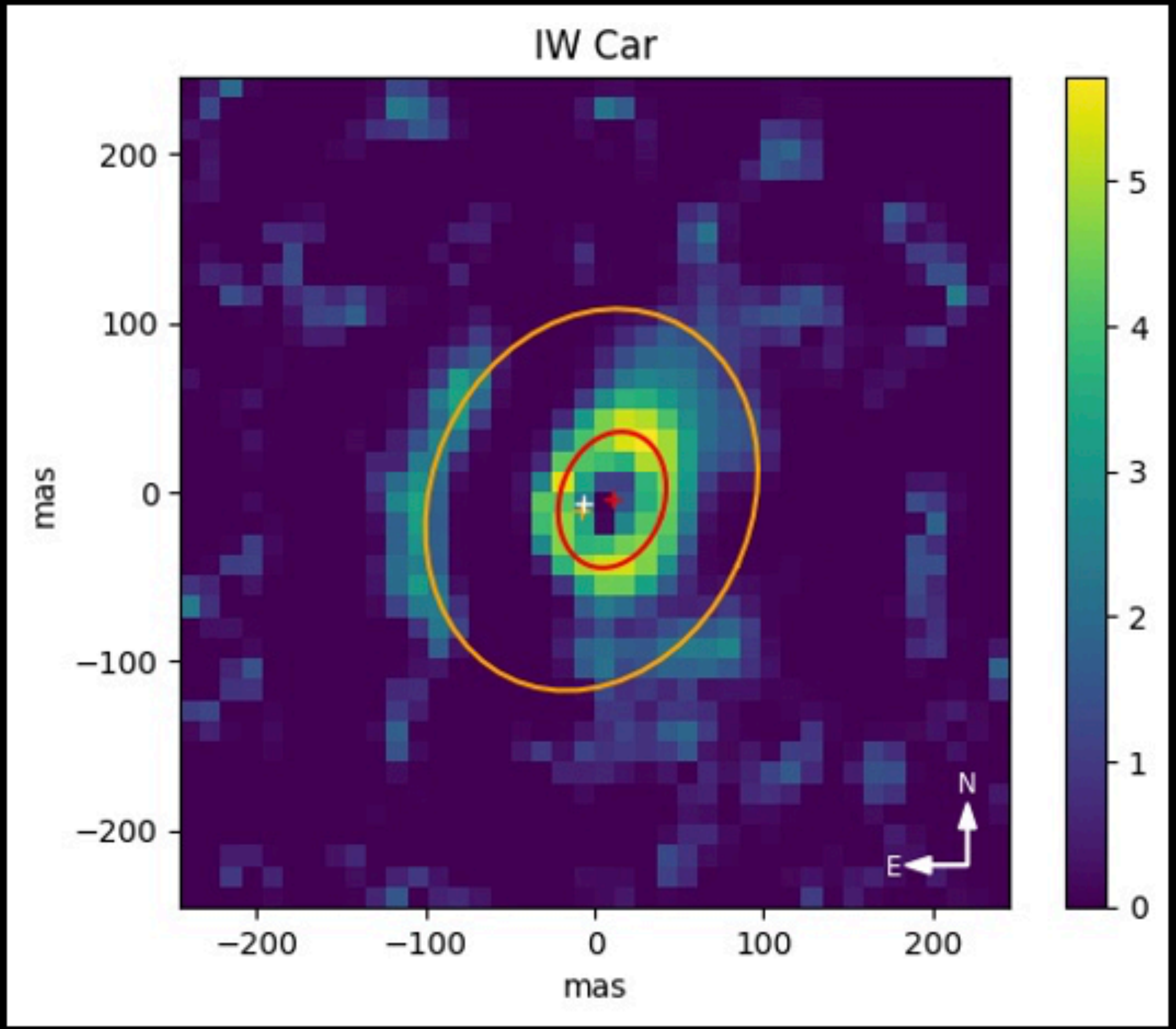
Transition discs show more asymmetries than full disks!



Andrych et al., 2023

First direct measurement of the post-AGB disk scale-height



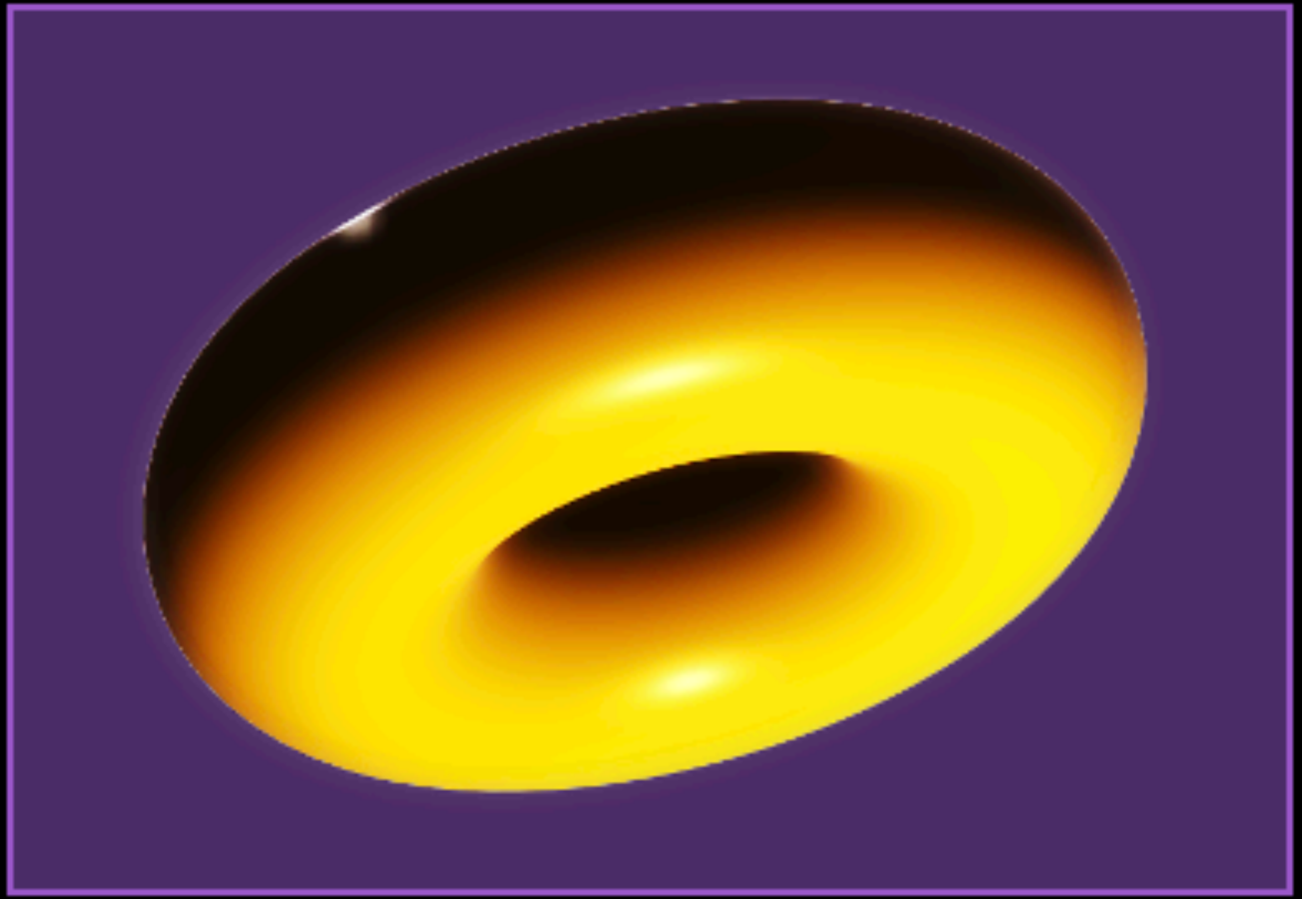


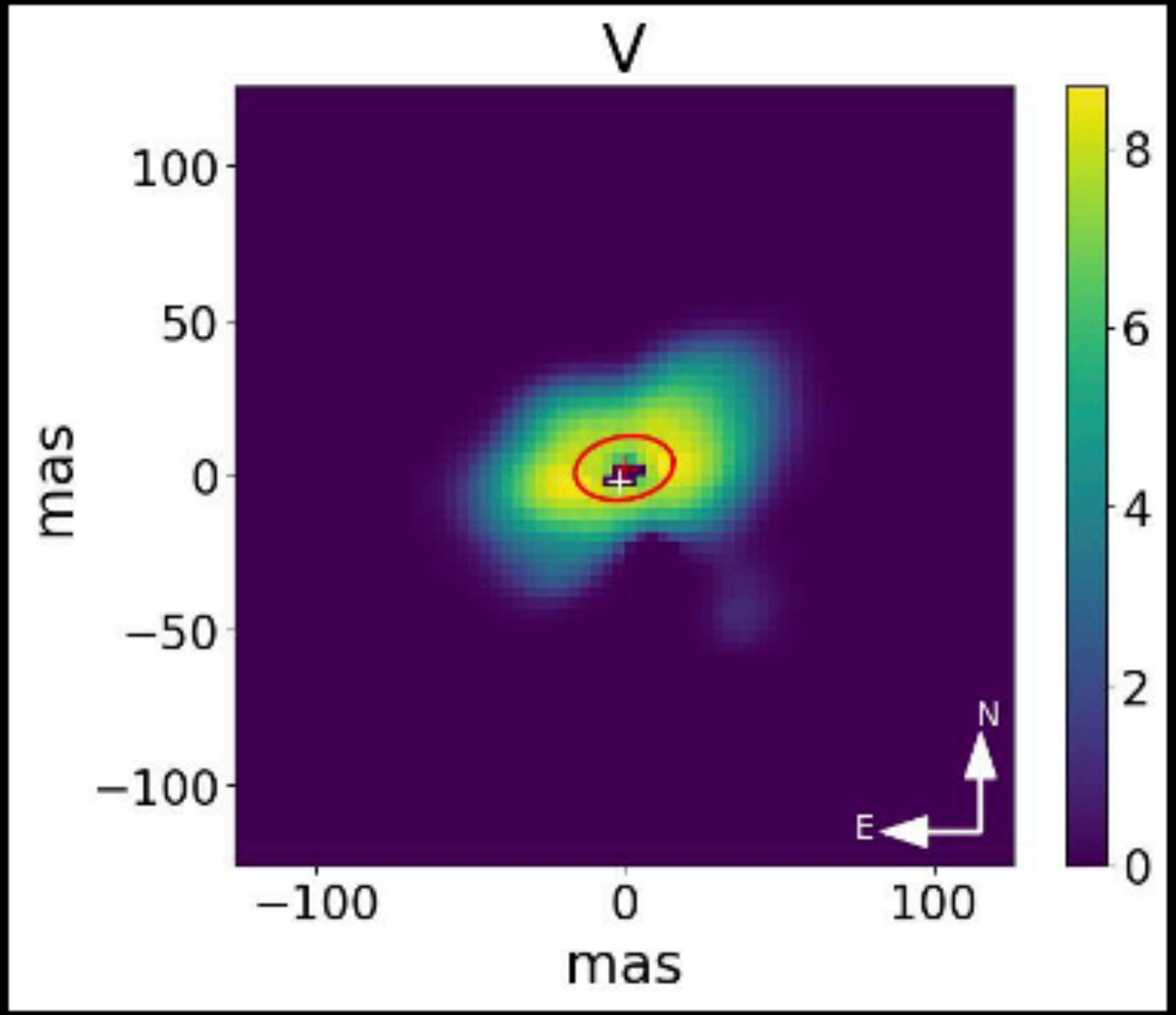
height above the mid-plane ~ 190AU for the separation from the central binary of ~ 1100AU

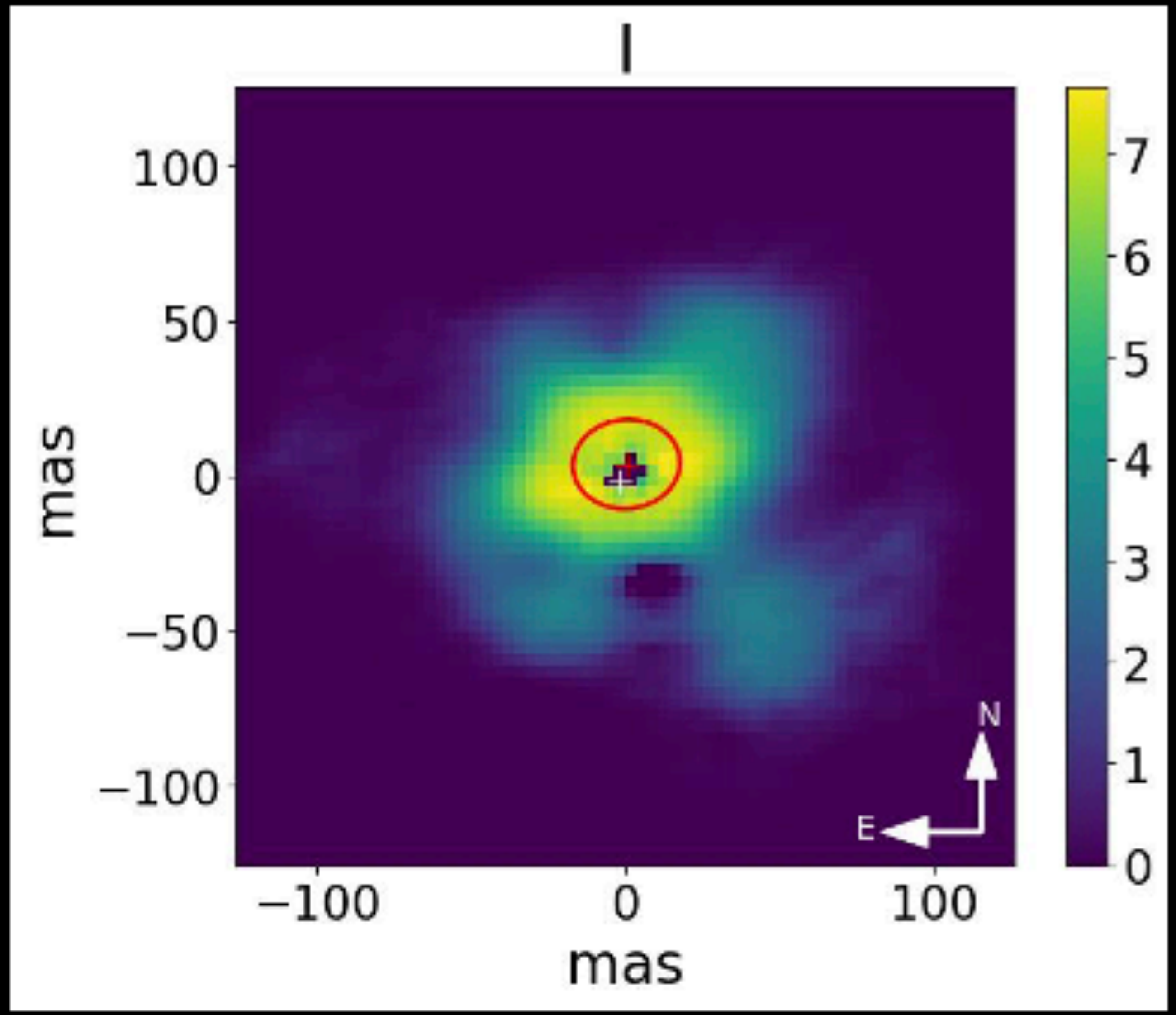
total height of the disc ~ 90AU
detected scattered emission to ~ 250AU

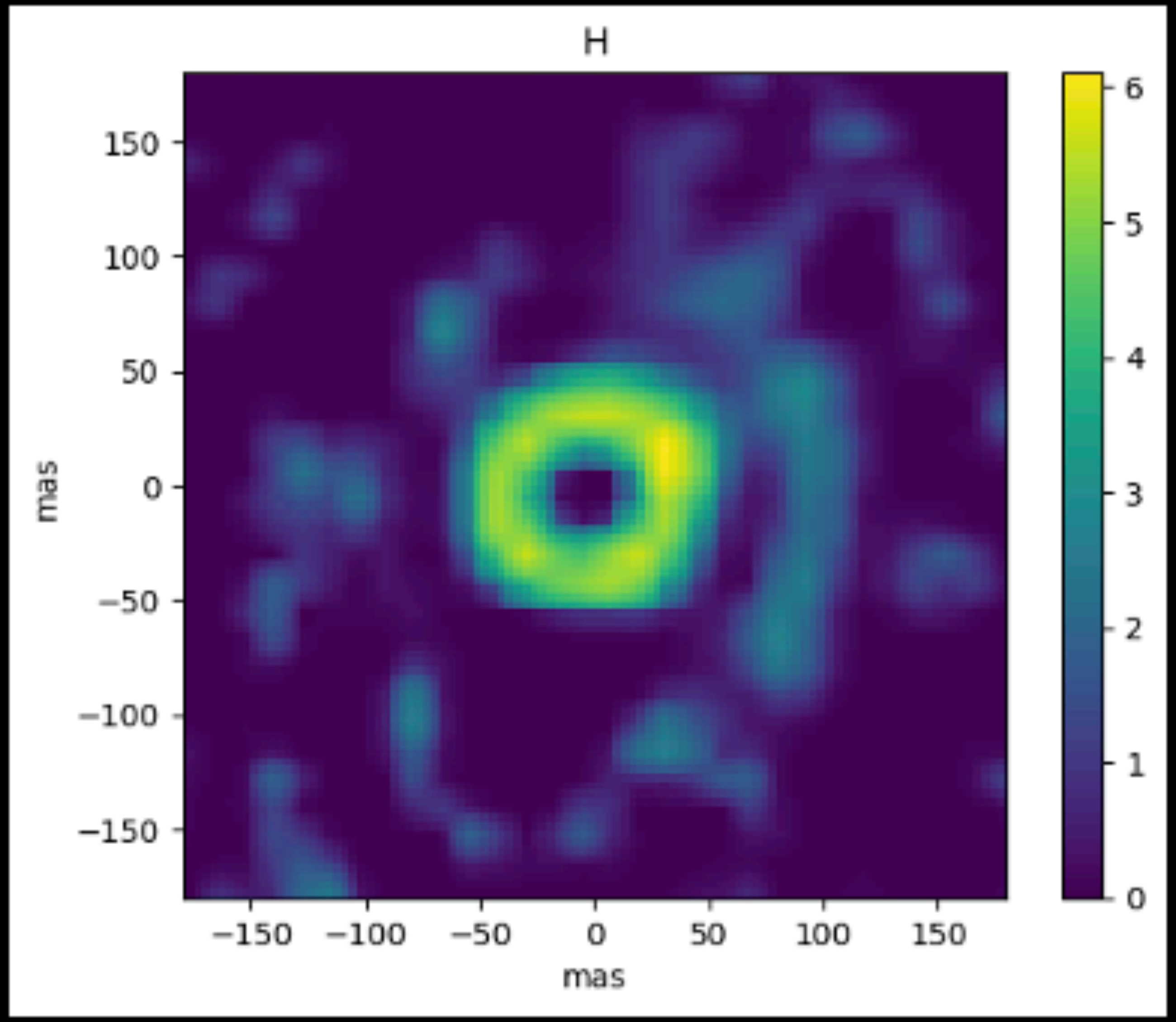
Multiwavelength results: IRAS 08544-4431

Presence of forward scattering peak is consistent with the porous dust aggregates of ~ 1μm size and suggest the northern part of the disk being closer to the observer!









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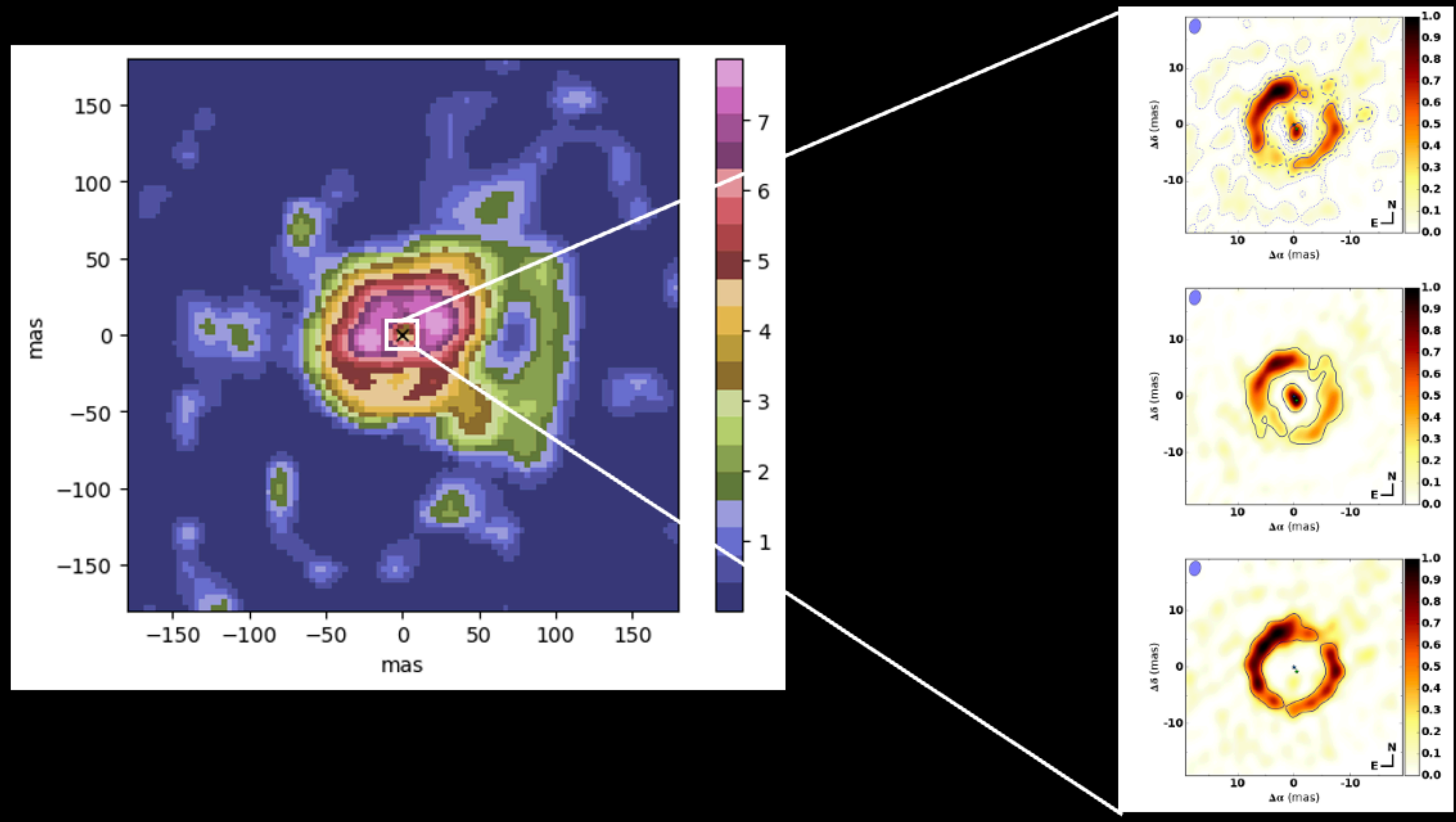
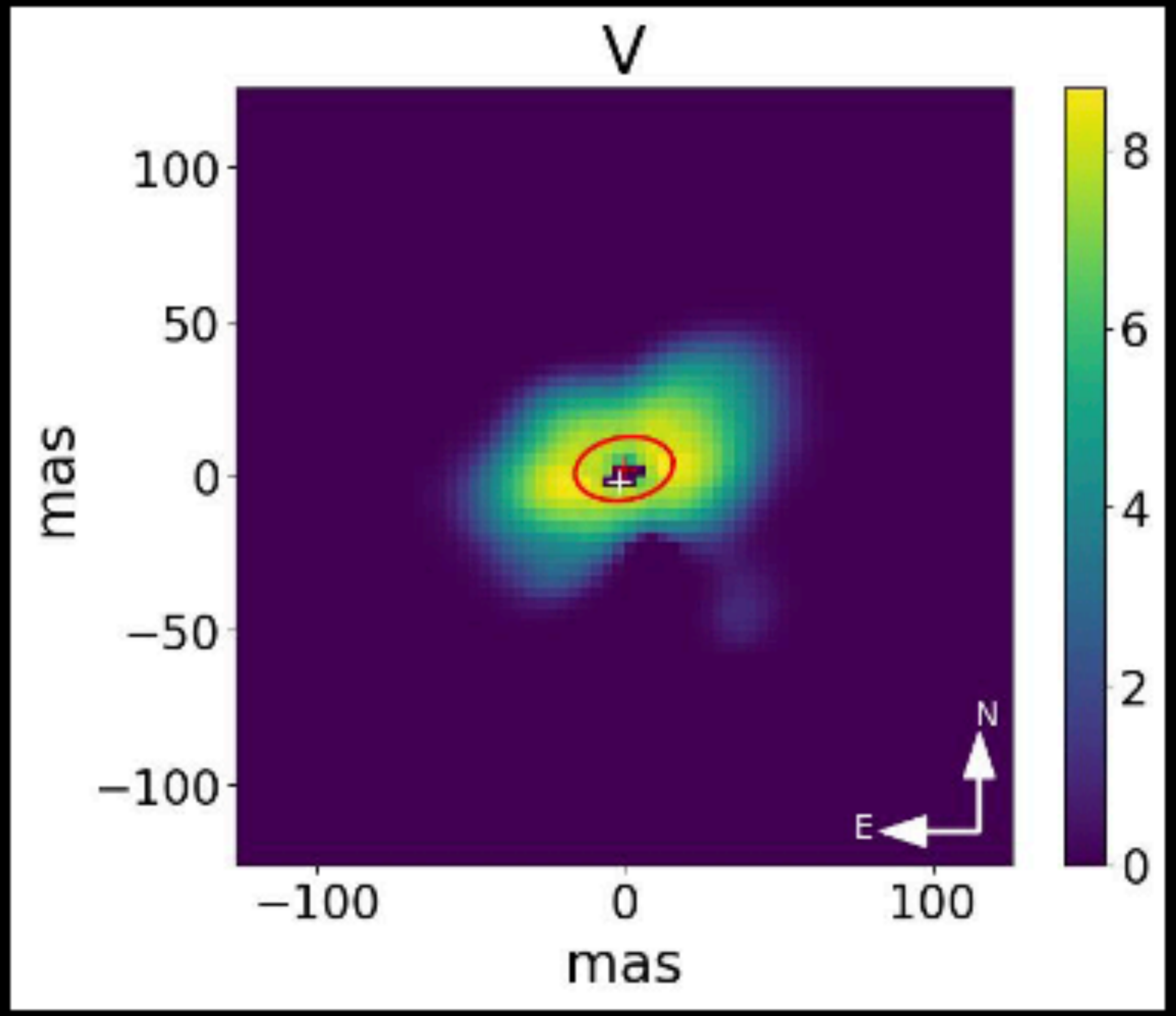
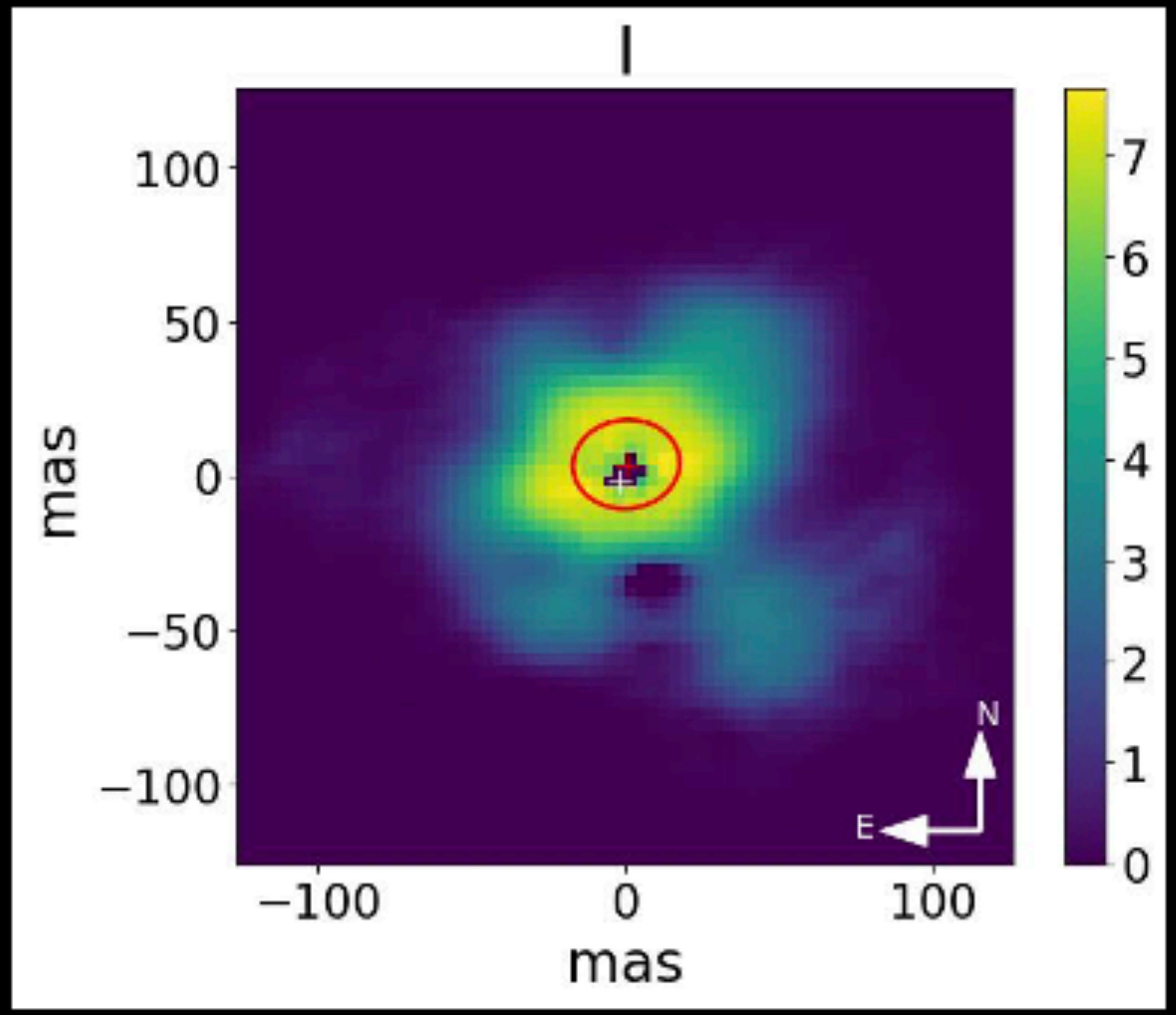
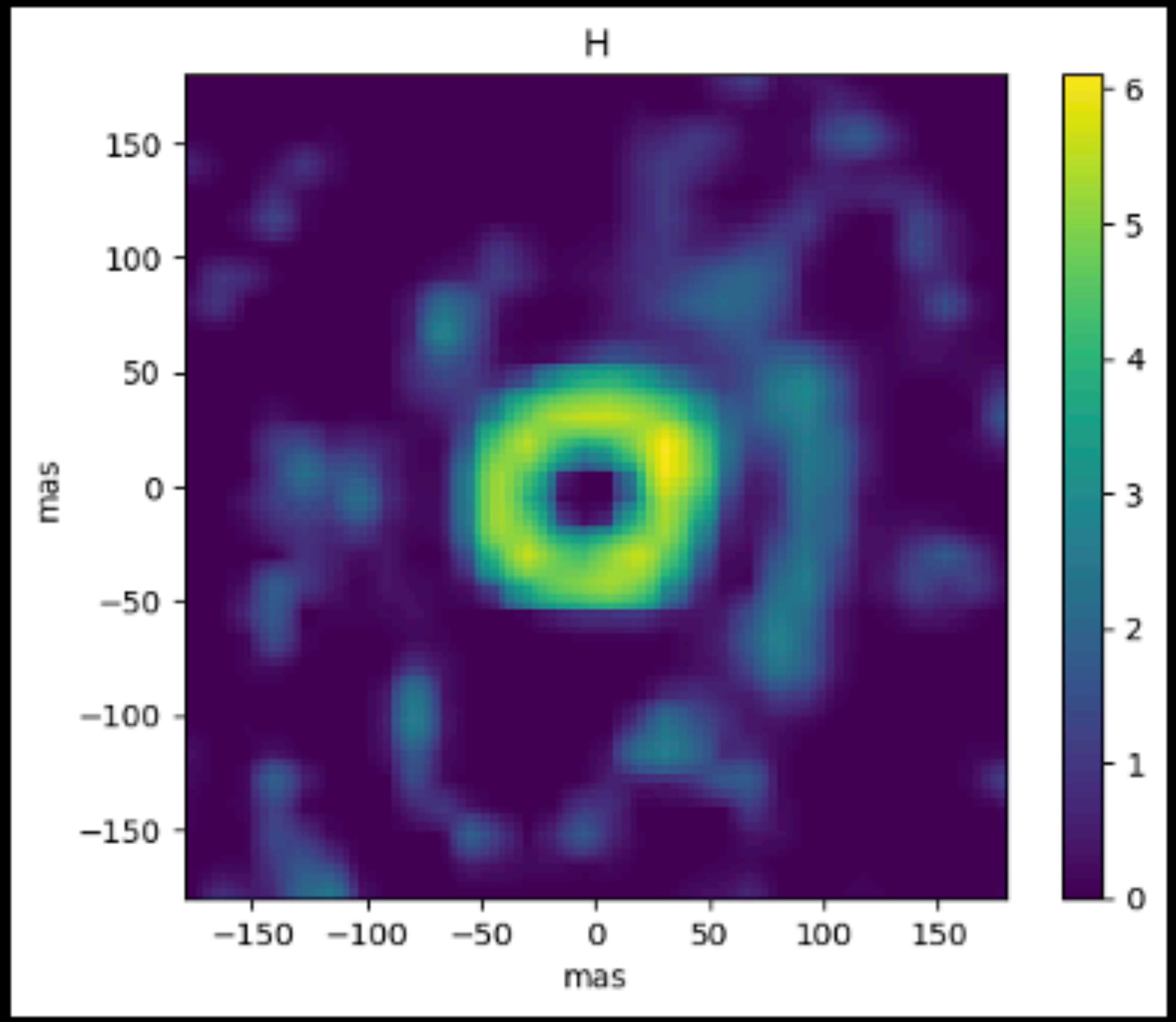


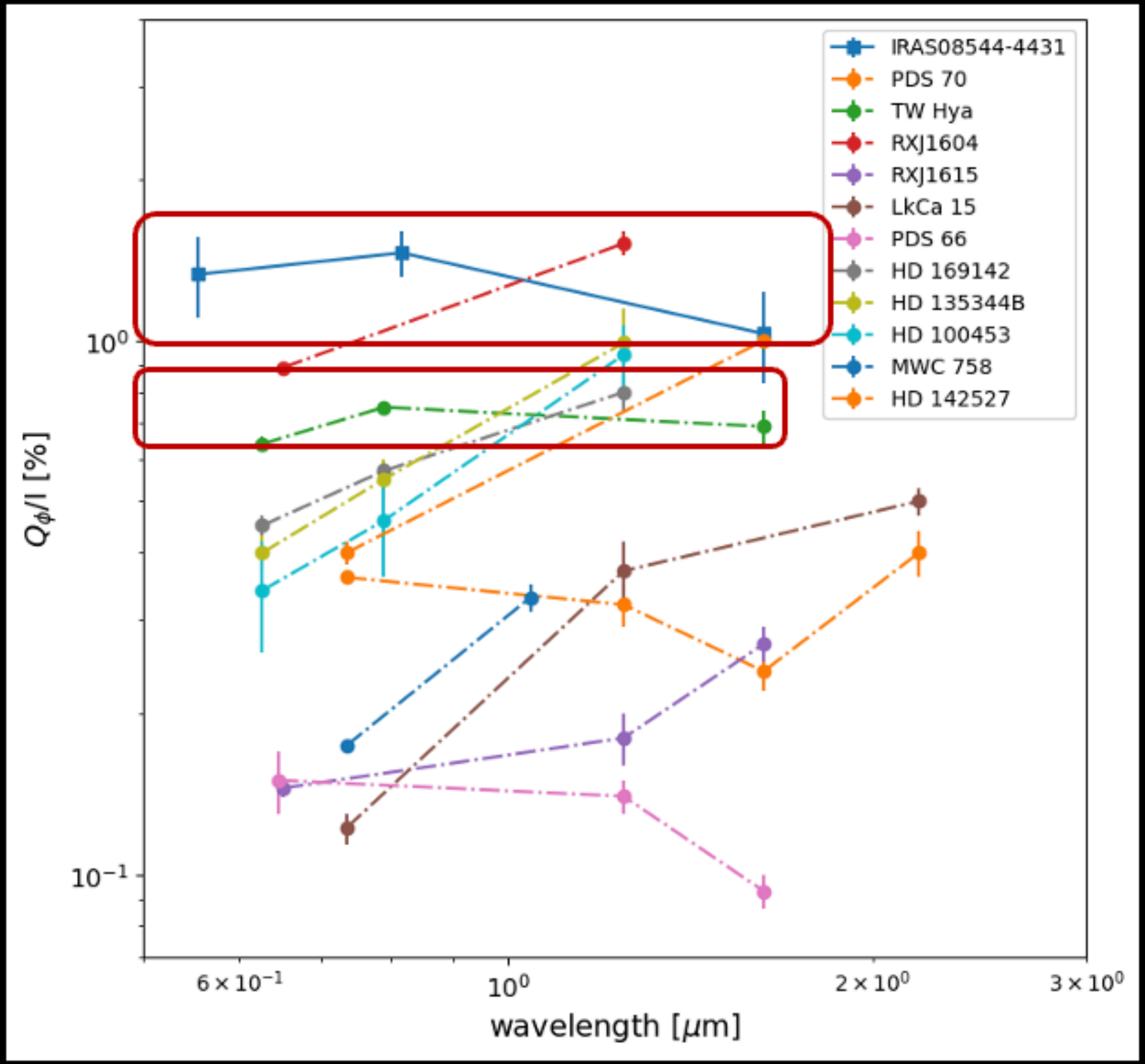




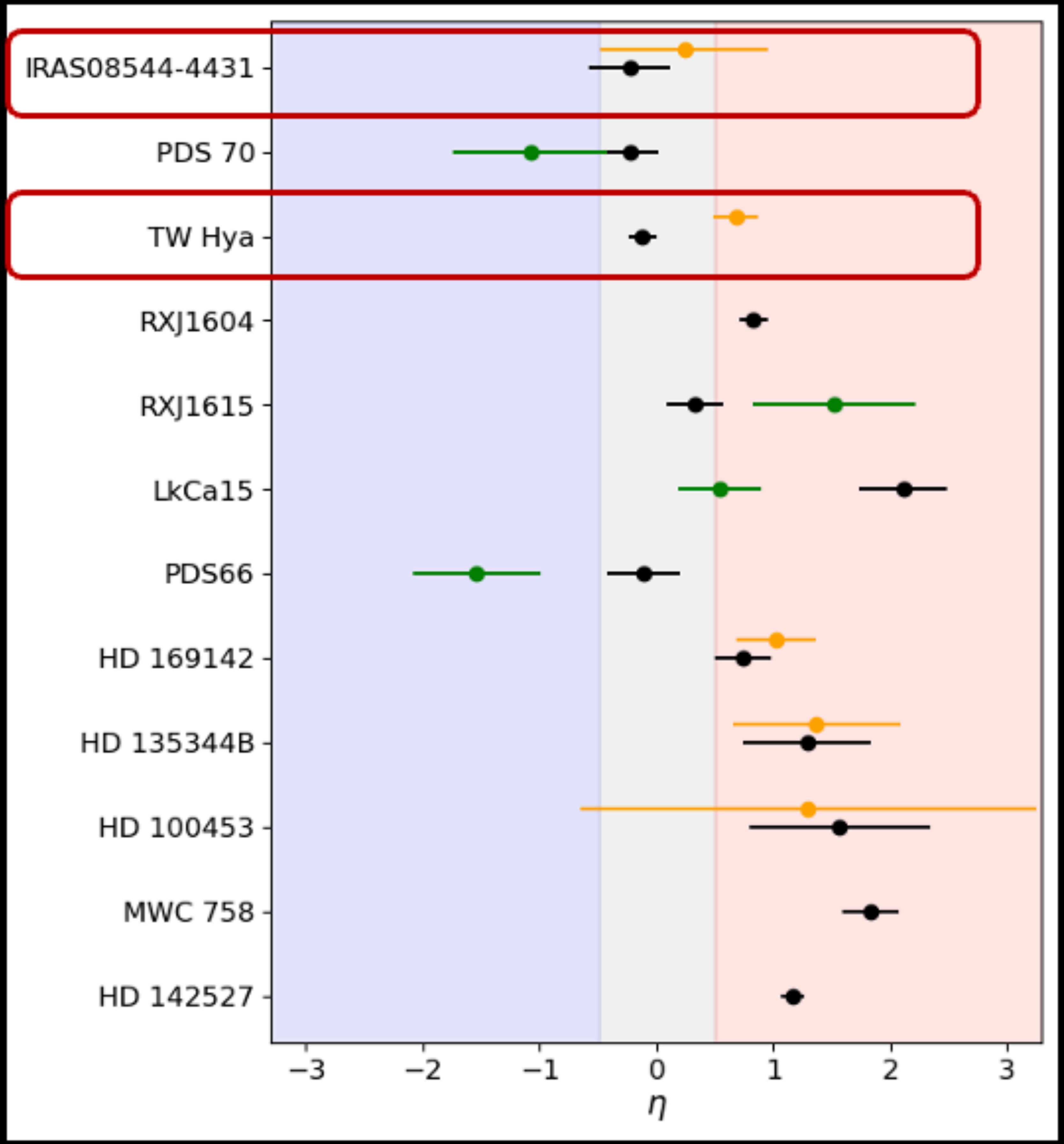


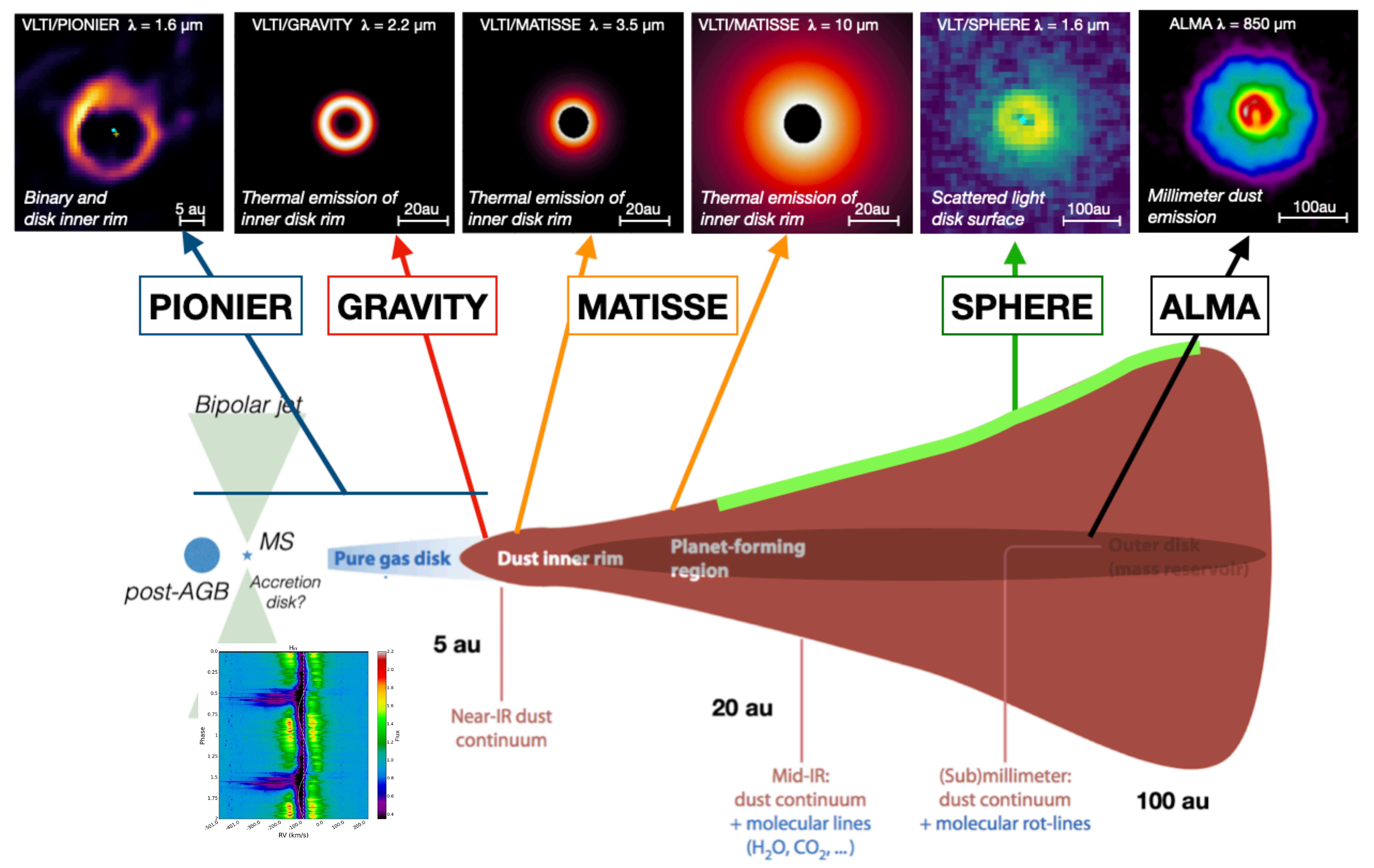
Comparison of post-AGB system IRAS 08544-4431 with protoplanetary disks

Post-AGB system shows relative polarized brightness similar to the brightest PPDs!



Grey polarized disc color is consistent with dust aggregates instead of single monomers!

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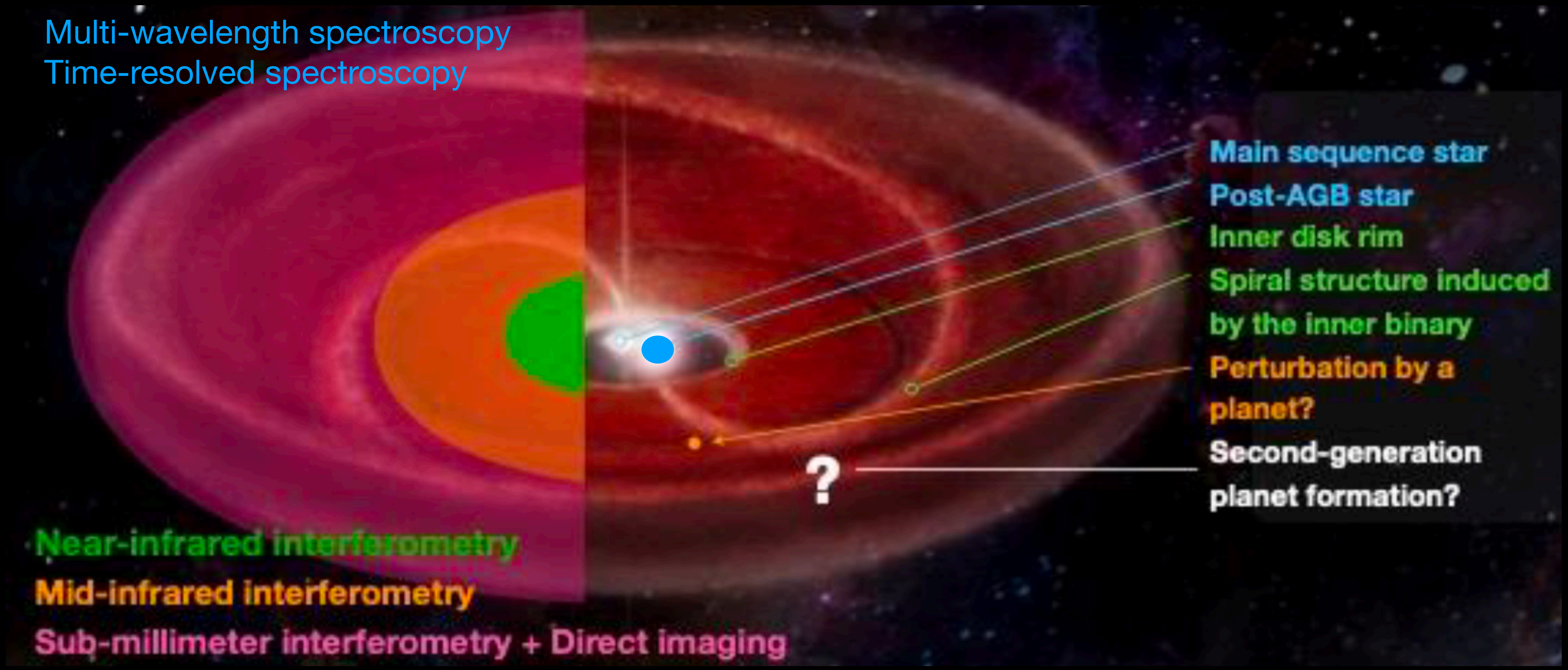
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Main sequence star
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Spiral structure induced by the inner binary
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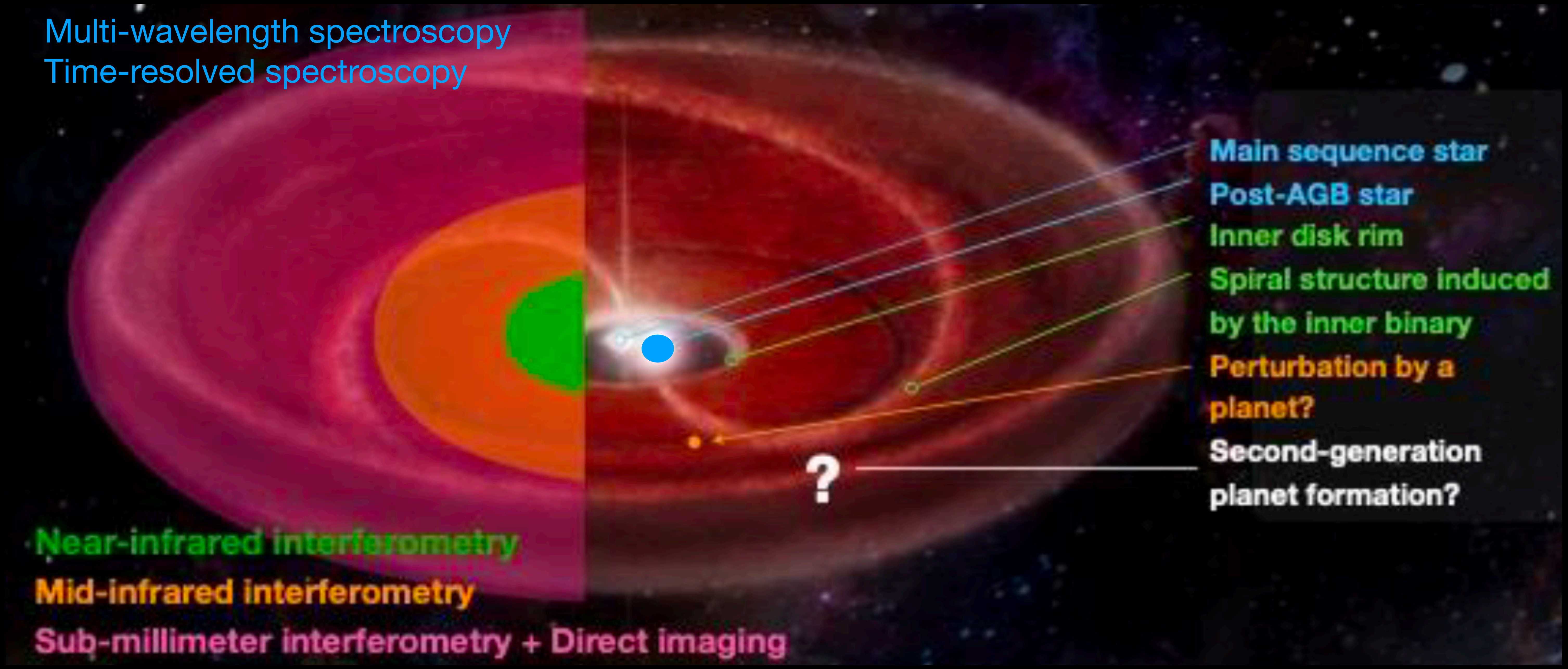
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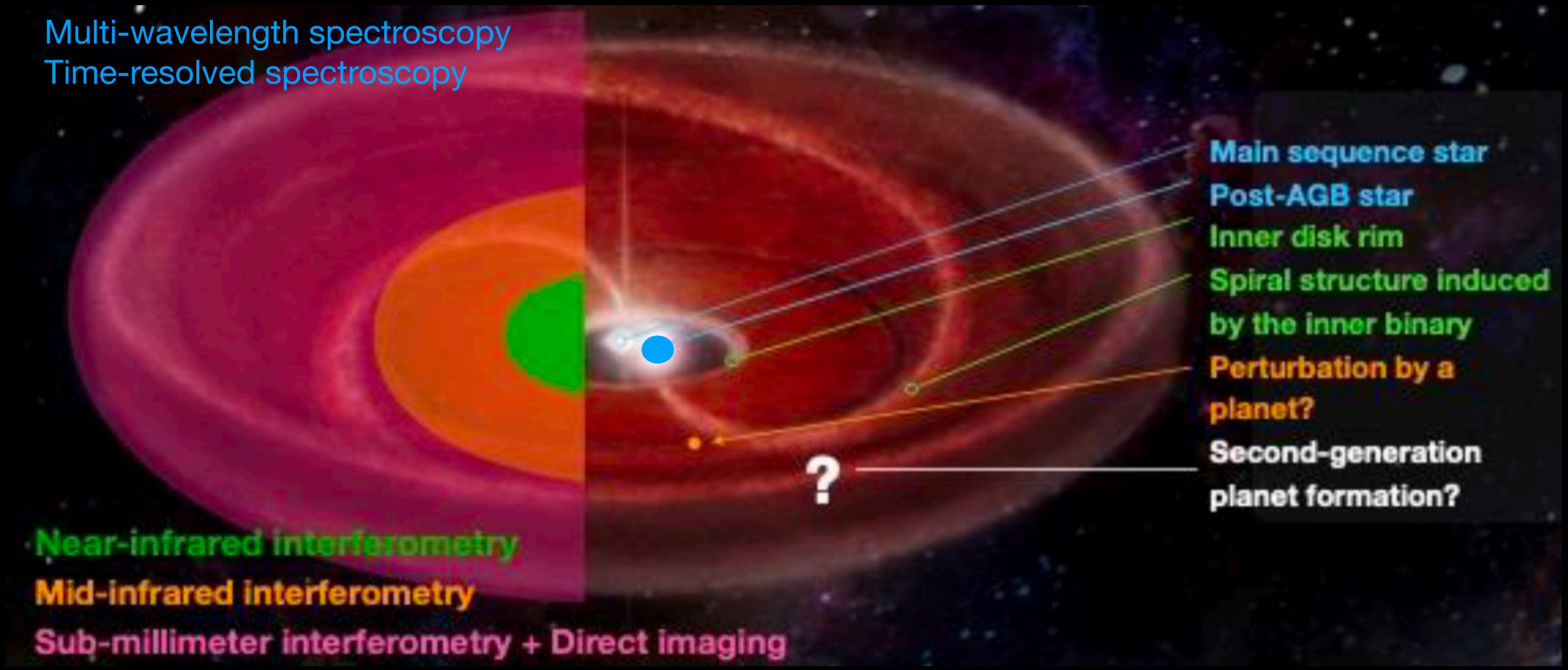

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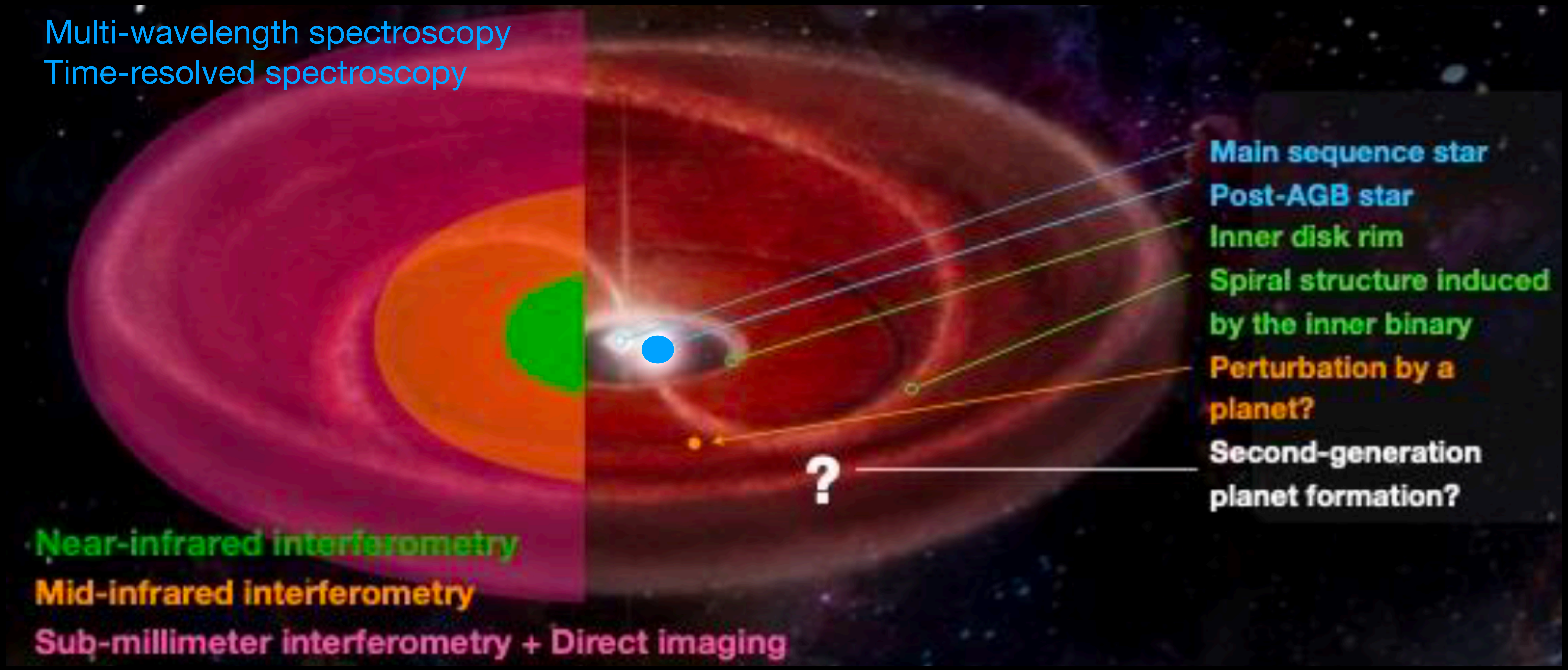

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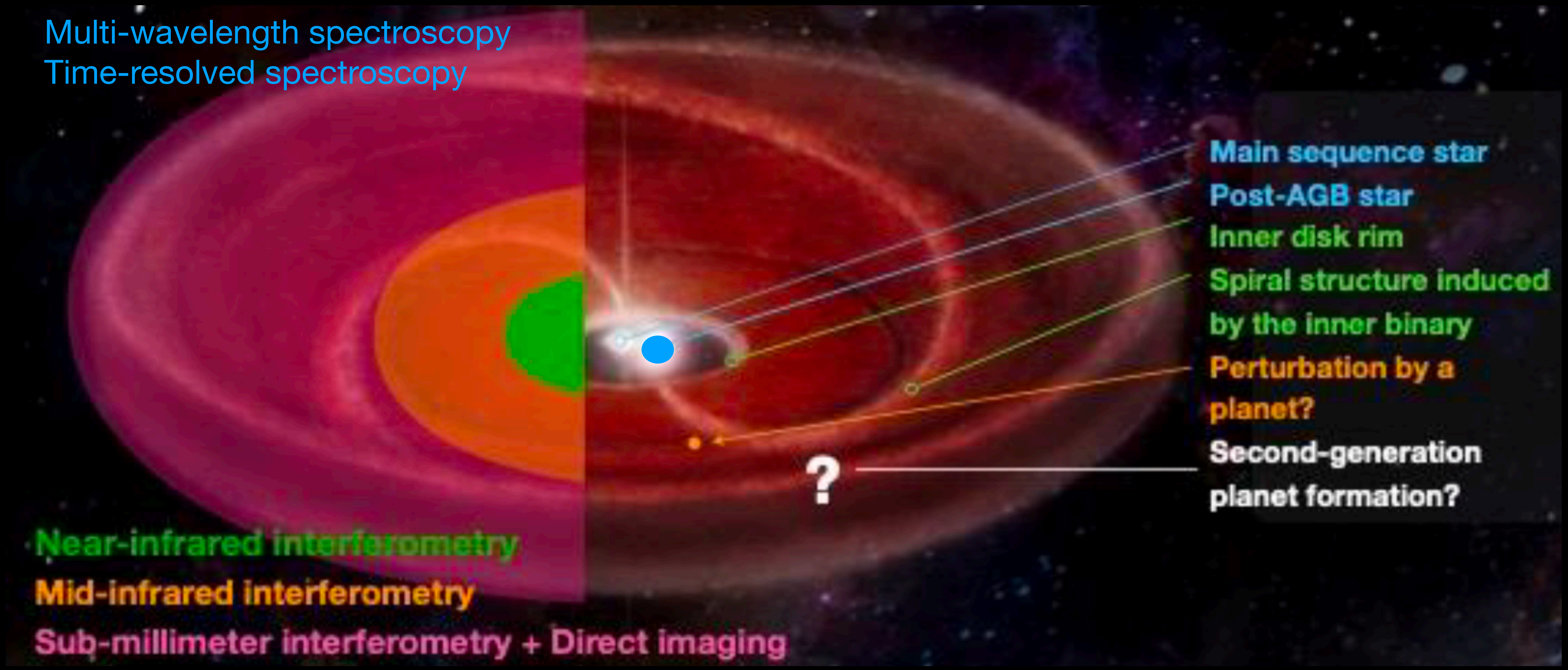

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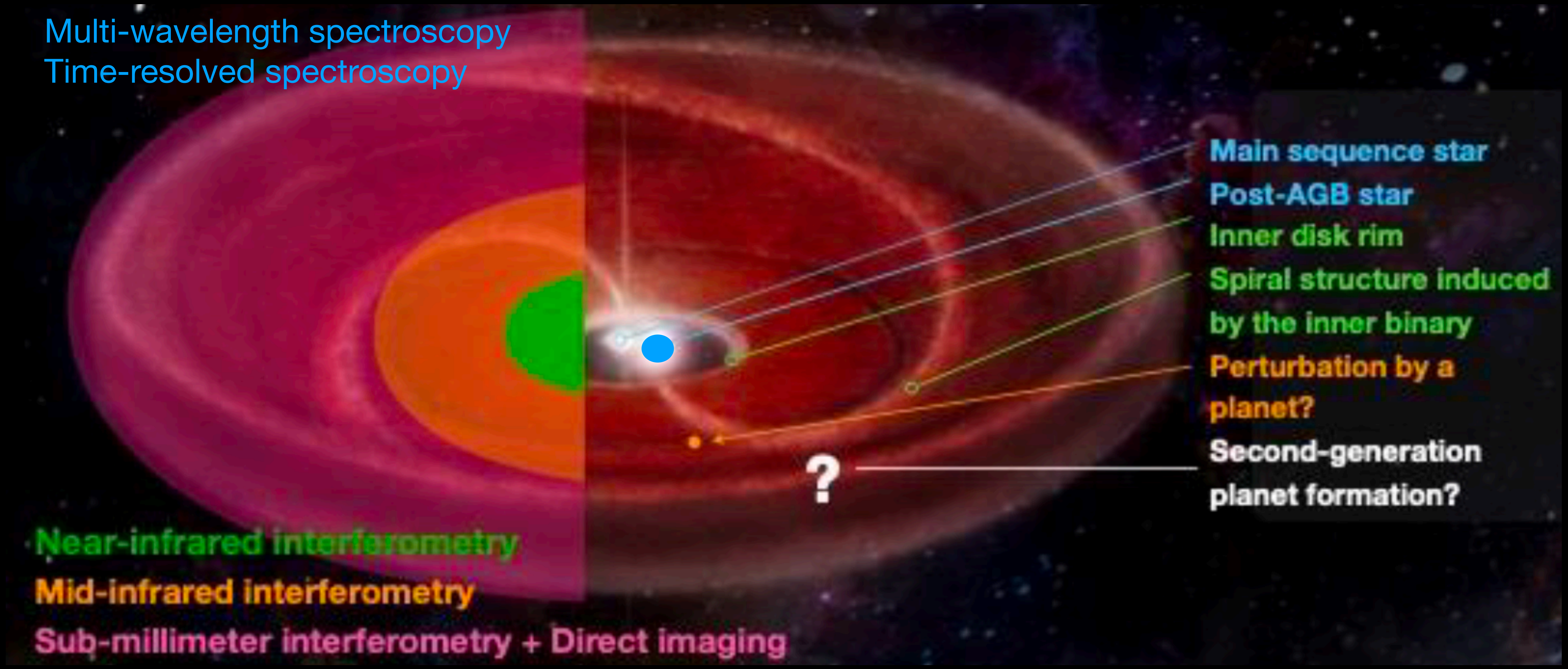

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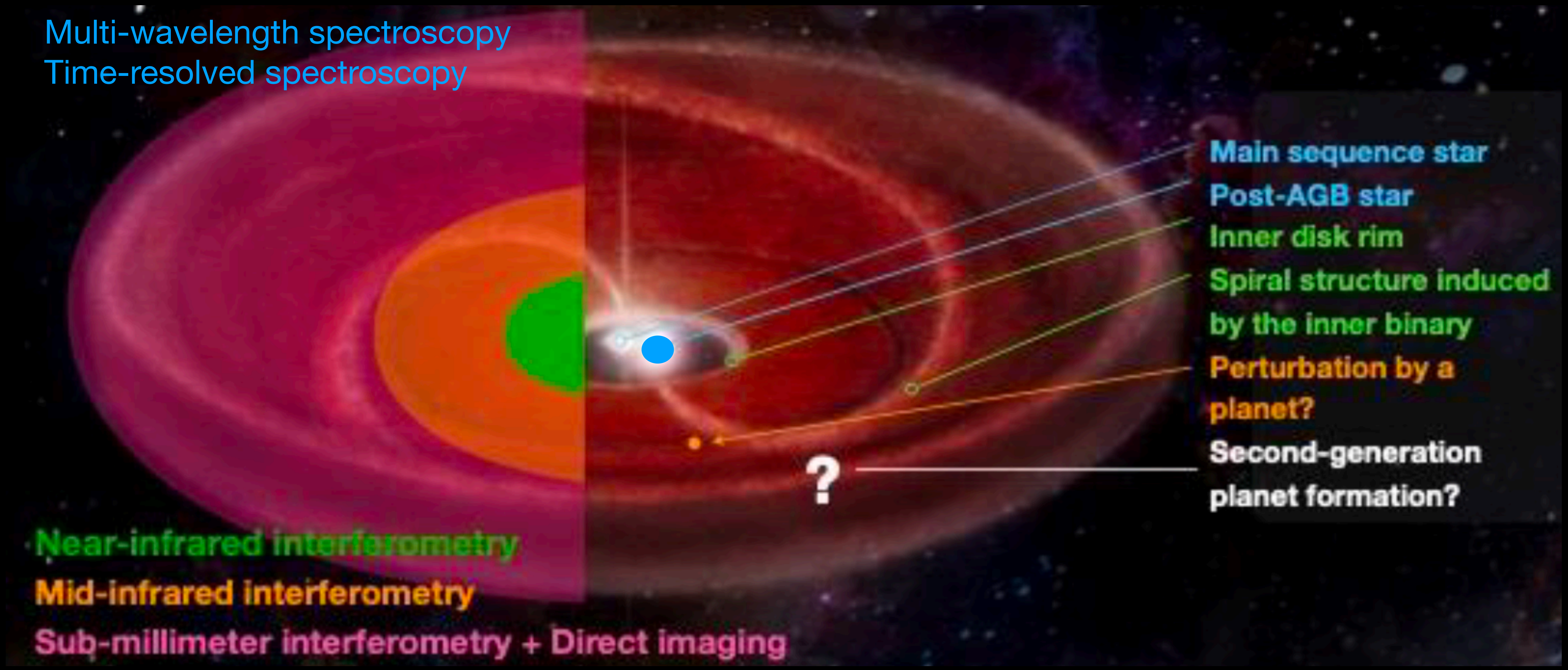

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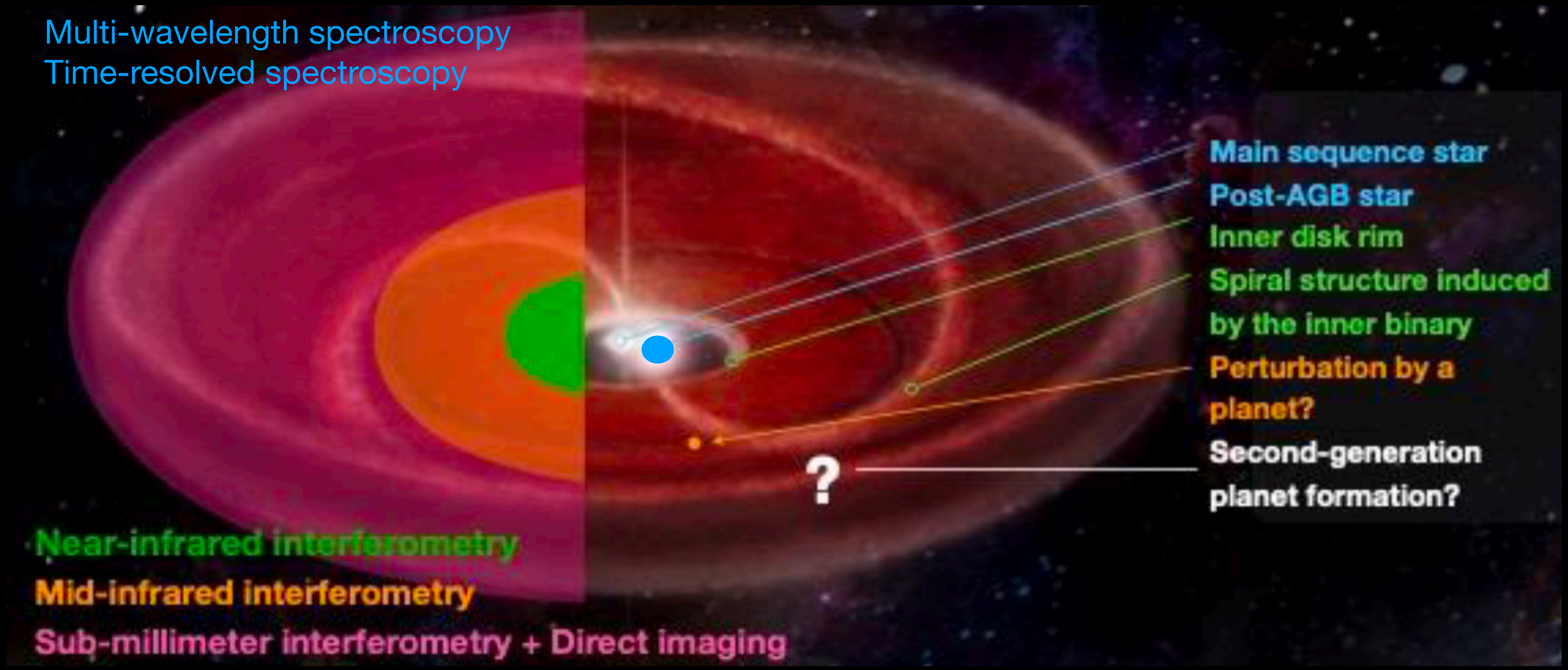

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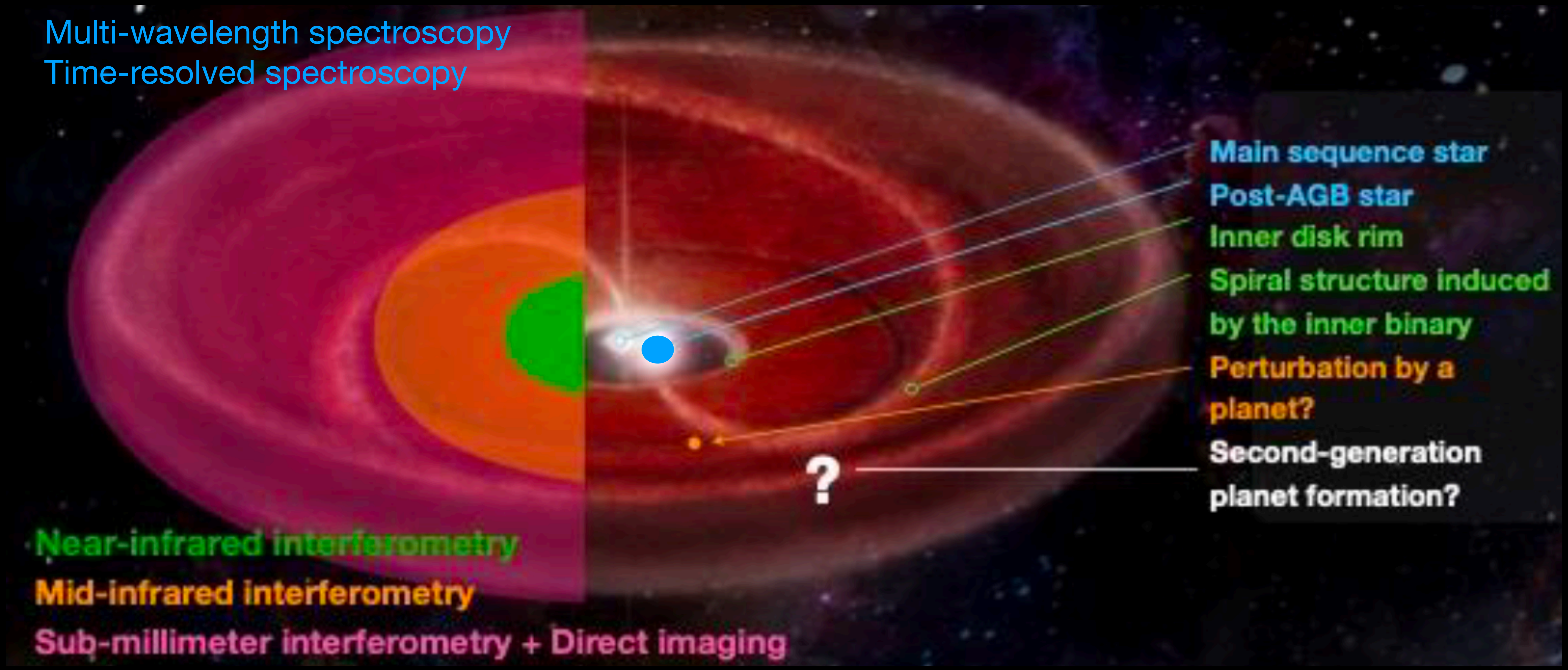

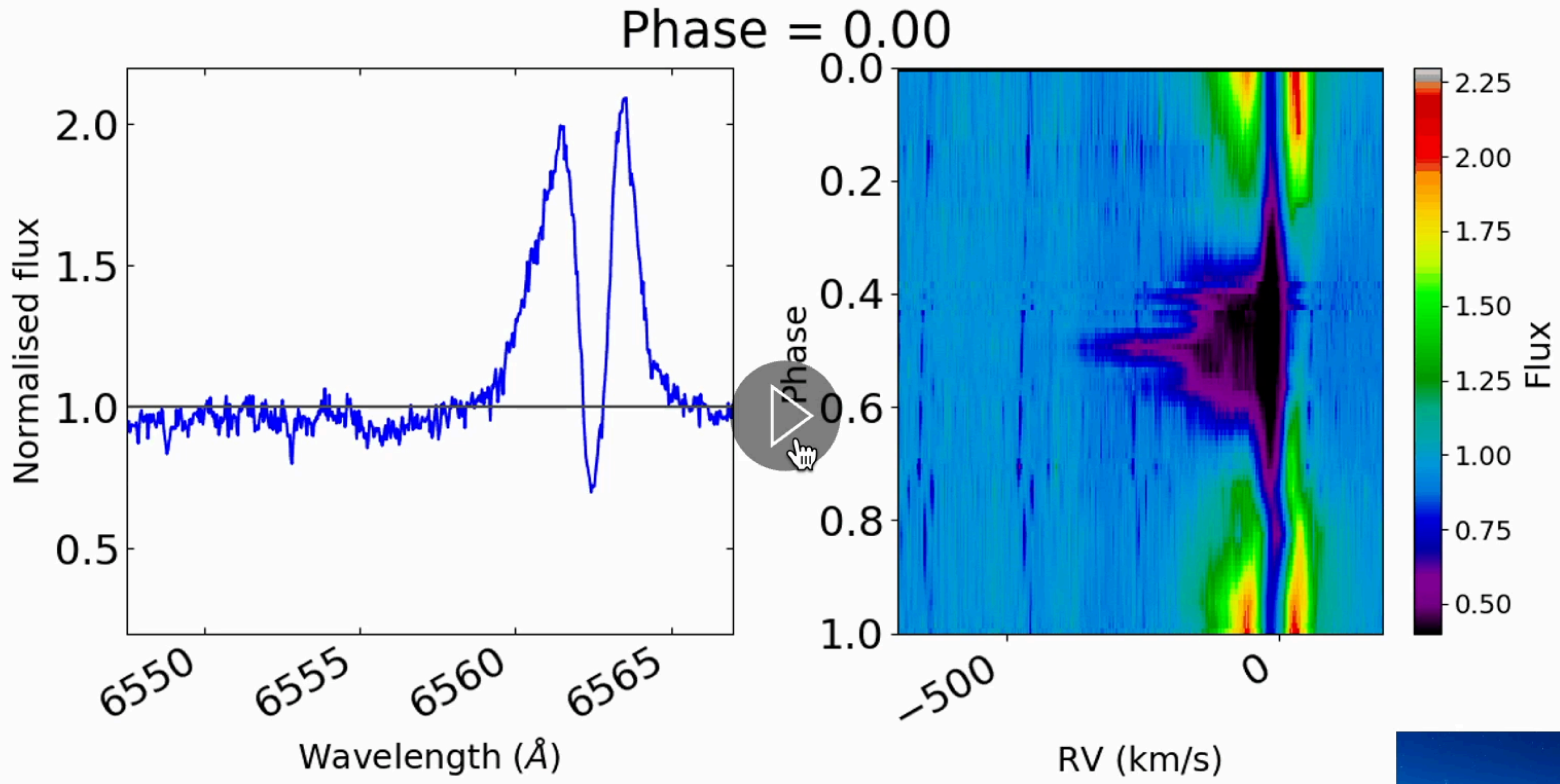
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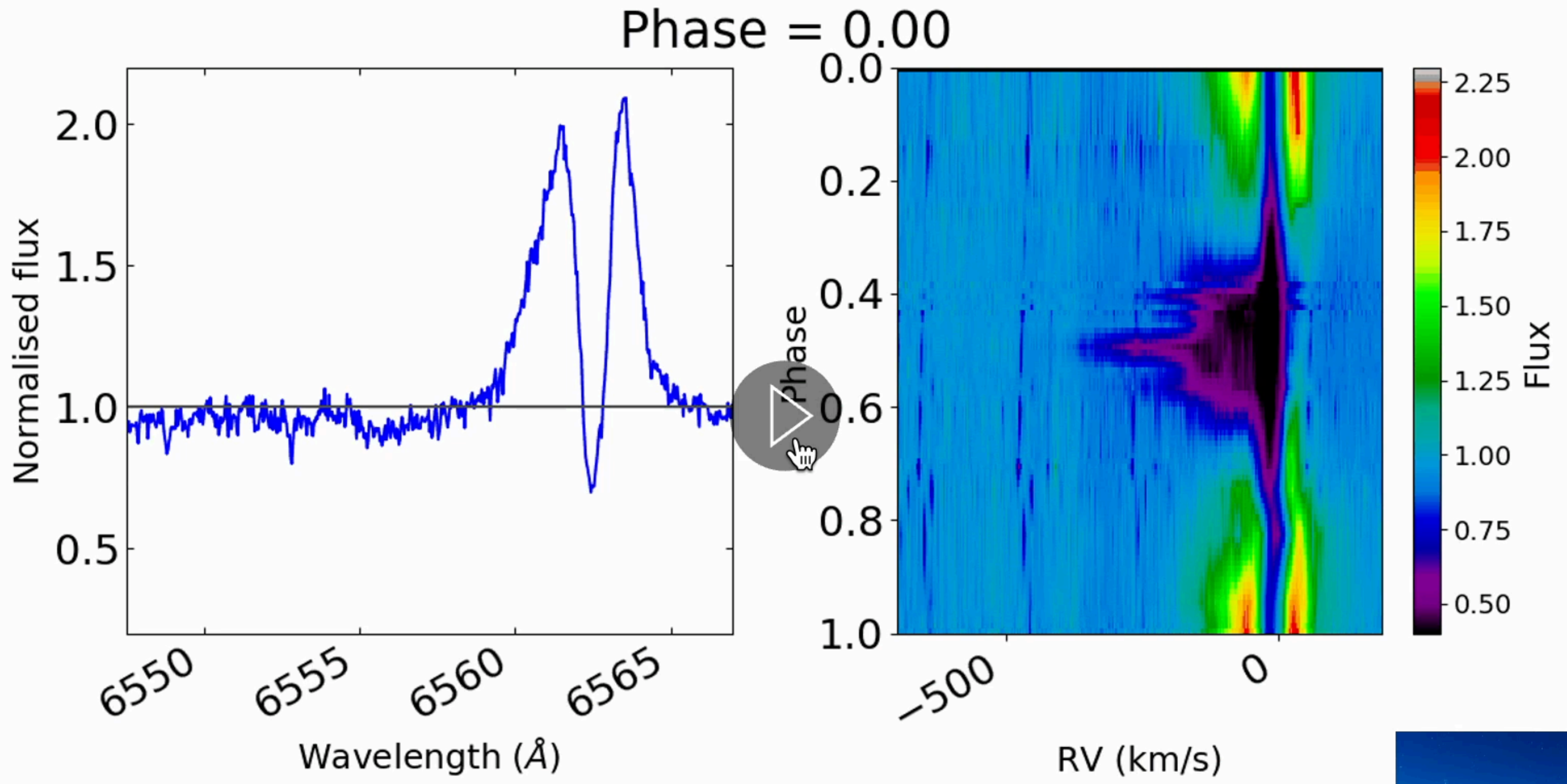
Normalised flux
2.0
1.5
1.0
0.5
6550
6555
6560
6565
Wavelength (Å)
Phase
0.0
0.2
0.4
0.6
0.8
1.0
−500
0
RV (km/s)
Flux
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50


MERCATOR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Normalised flux
2.0
1.5
1.0
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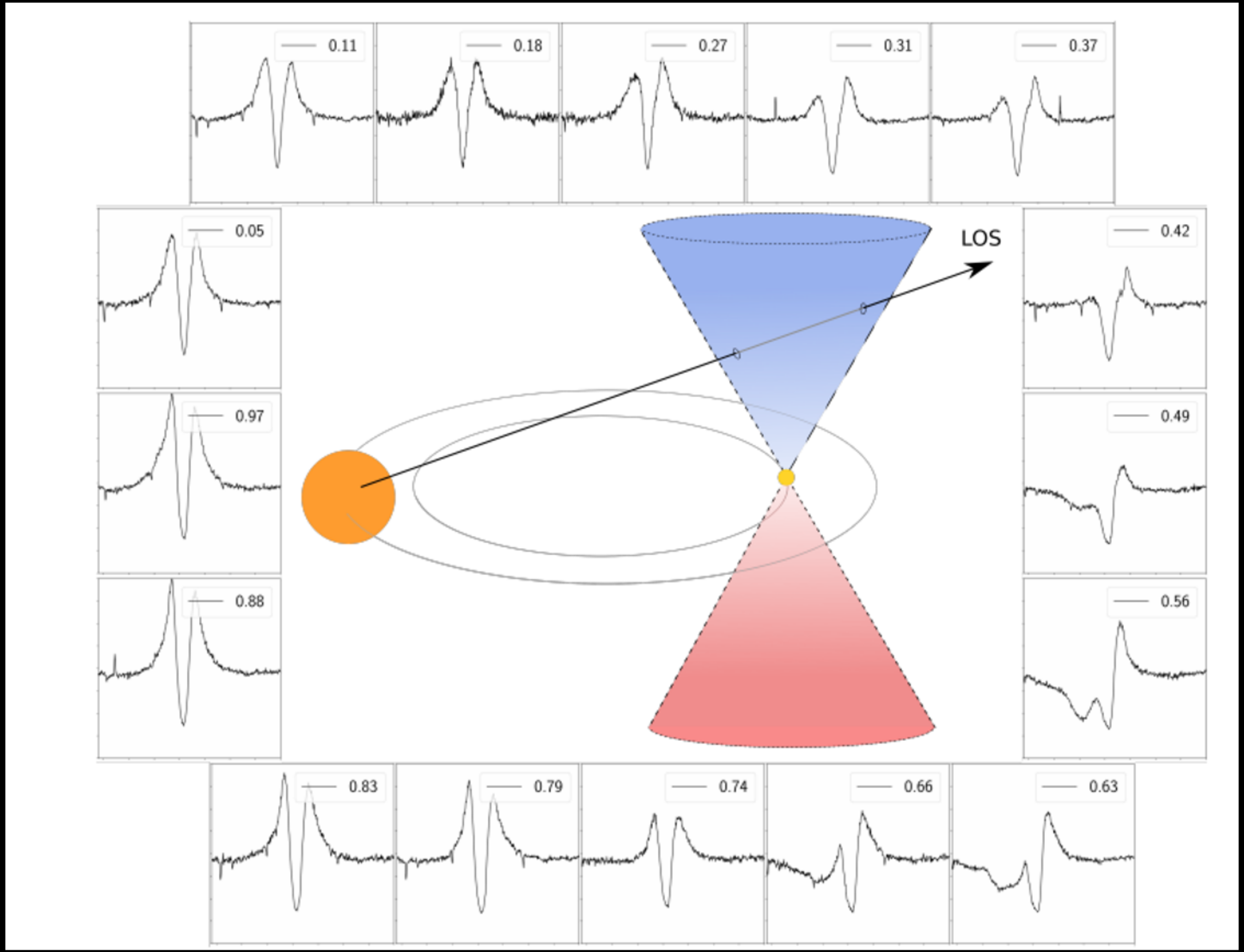
6555
6560
6565
Wavelength (Å)
Phase
0.0
0.2
0.4
0.6
0.8
1.0
−500
0
RV (km/s)
Flux
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50

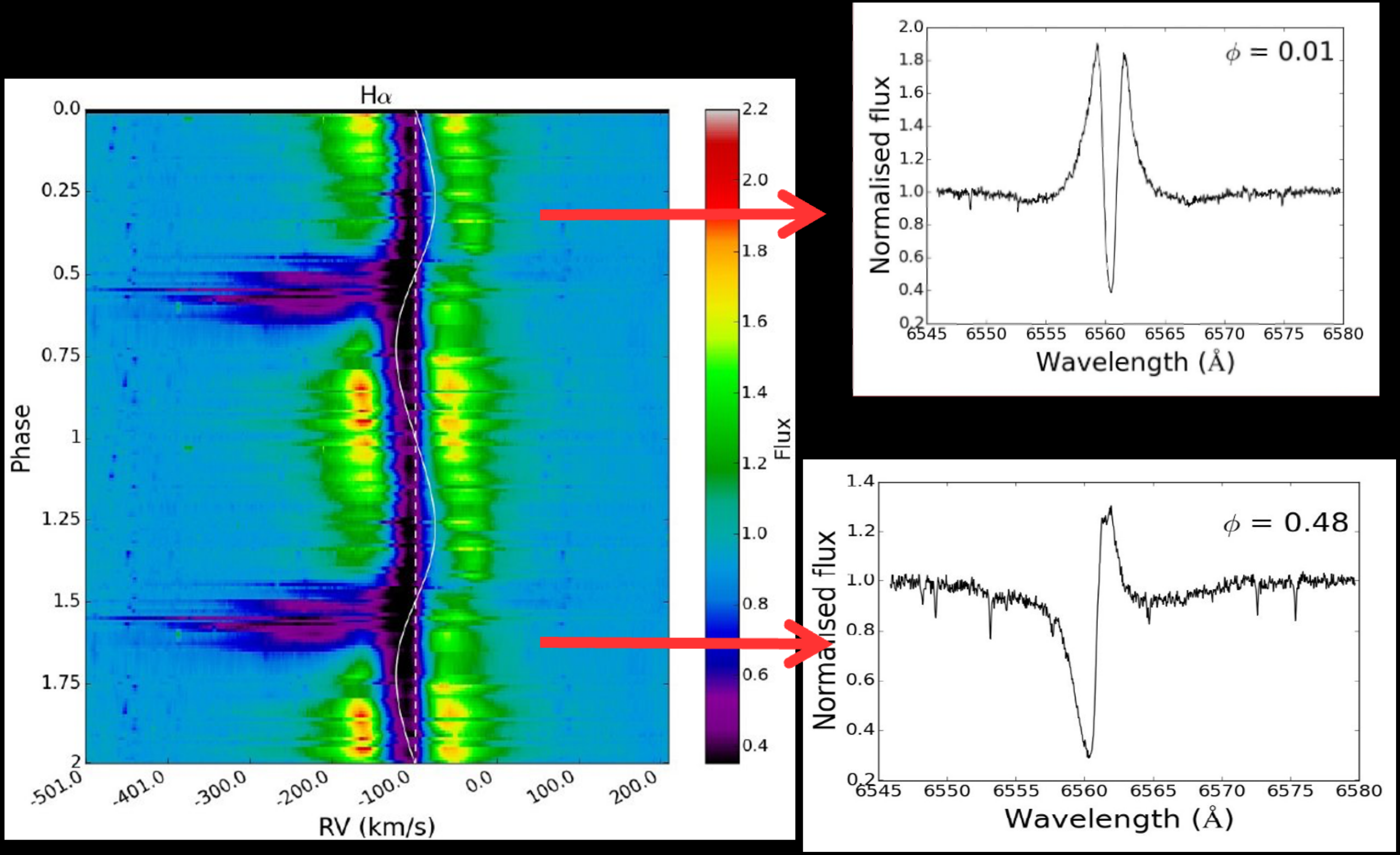

MERCATOR



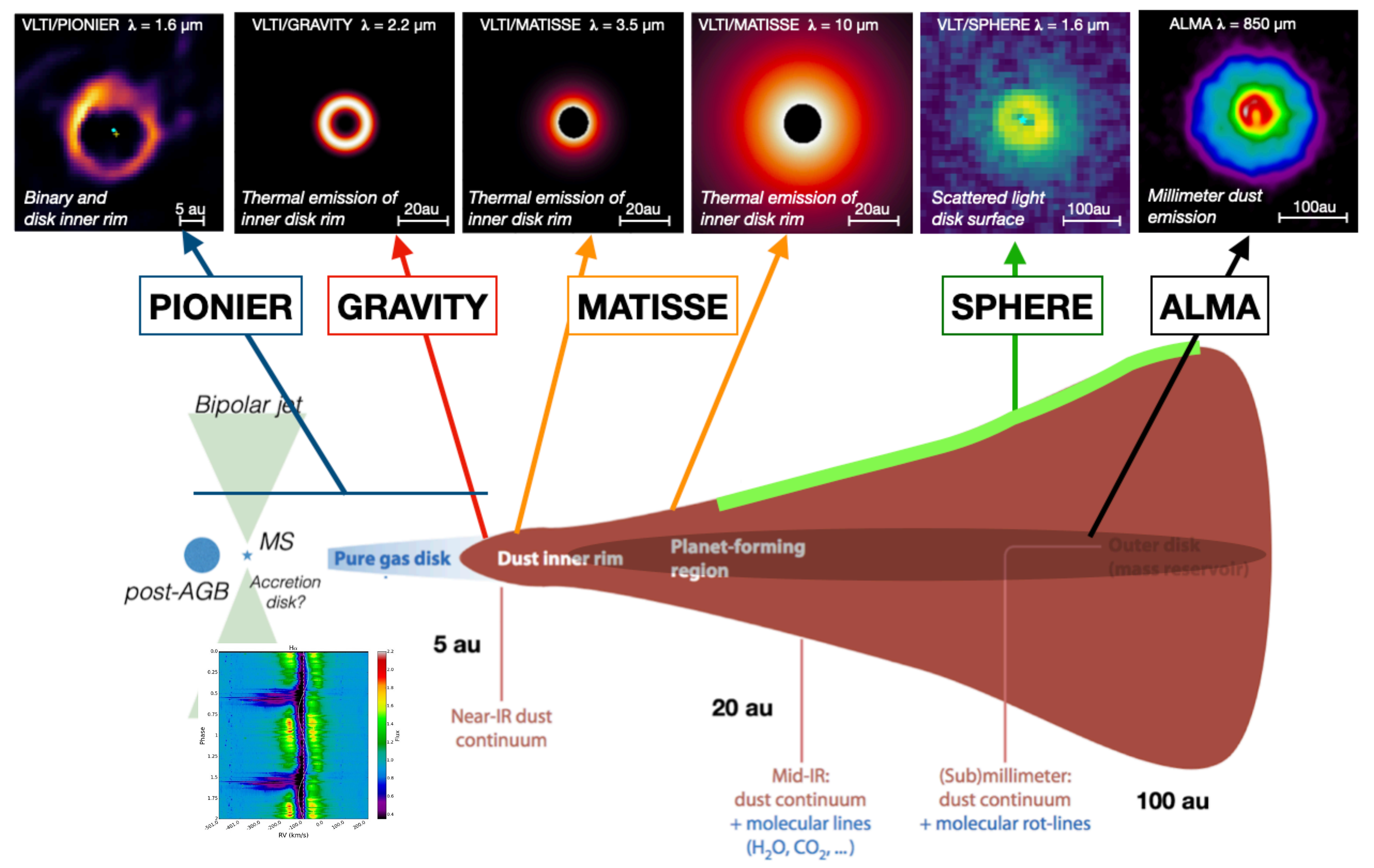
Time-resolved spectroscopy:
- spatio-kinematic (geometric modelling)
- RT (constrains are the Balmer lines)

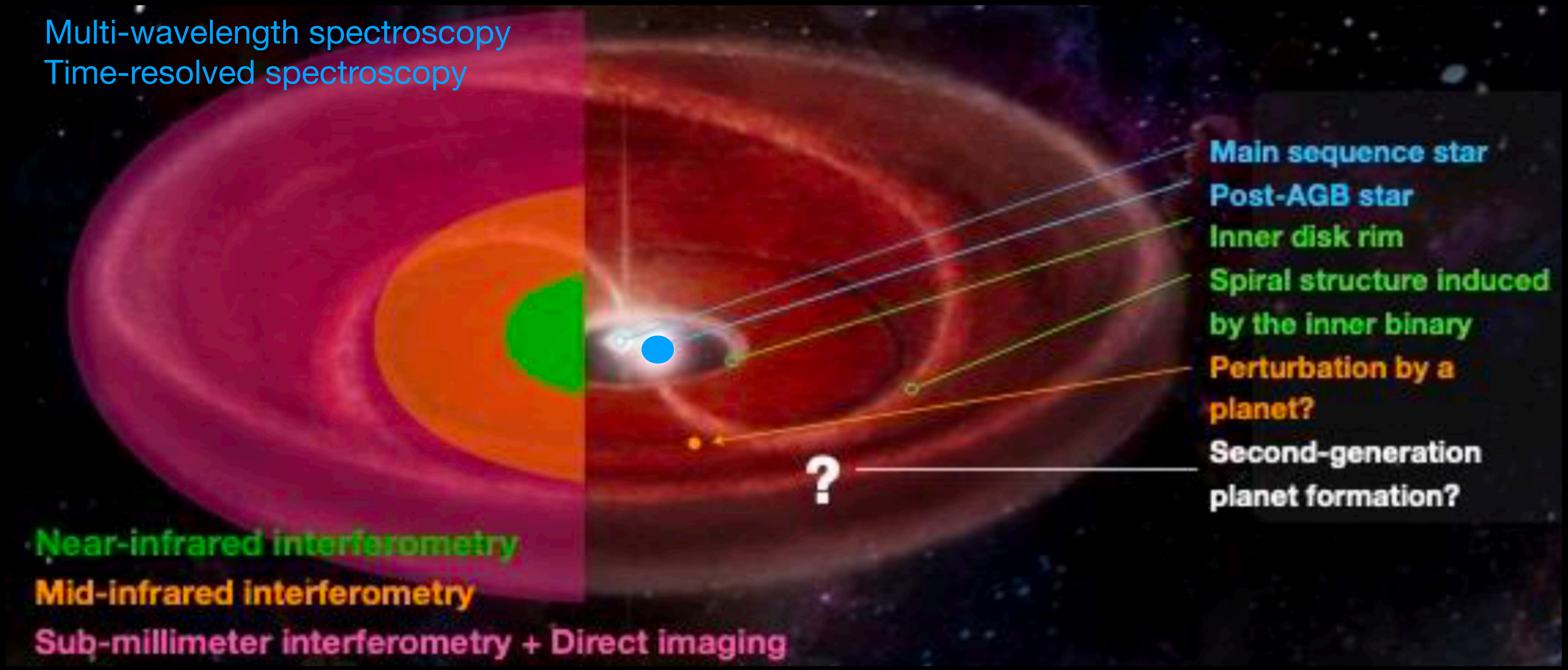
- Jet opening angle
- Jet tilt
- Angular Velocity structure
- Density structure
- Binary (radius components, orbit)

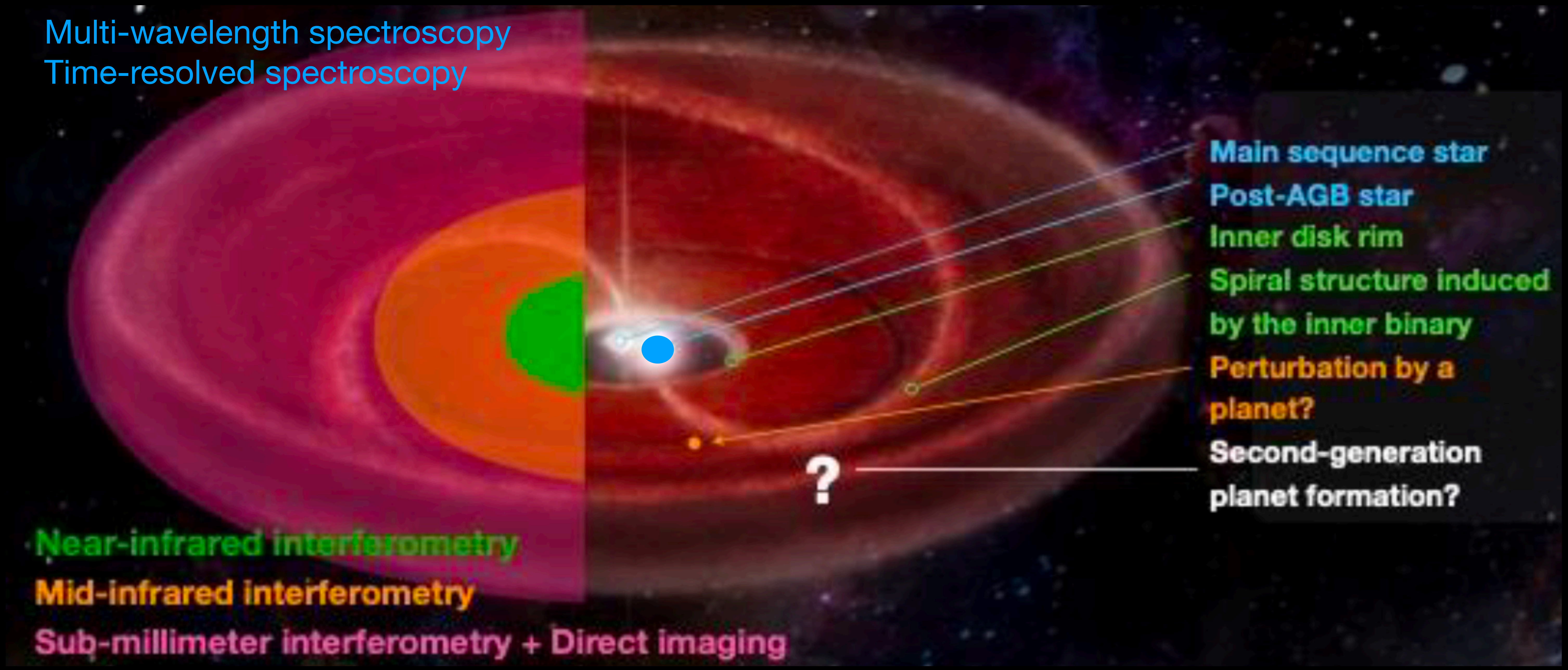
Detection of JETS from Dynamic Spectra



Bollen et al., 2019, 2020, 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


Multi-wavelength spectroscopy
Time-resolved spectroscopy
Main sequence star
Post-AGB star
Inner disk rim
Spiral structure induced by the inner binary
Perturbation by a planet?
Second-generation planet formation?
Near-infrared interferometry
Mid-infrared interferometry
Sub-millimeter interferometry + Direct imaging


Multi-wavelength spectroscopy
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Inner disk rim
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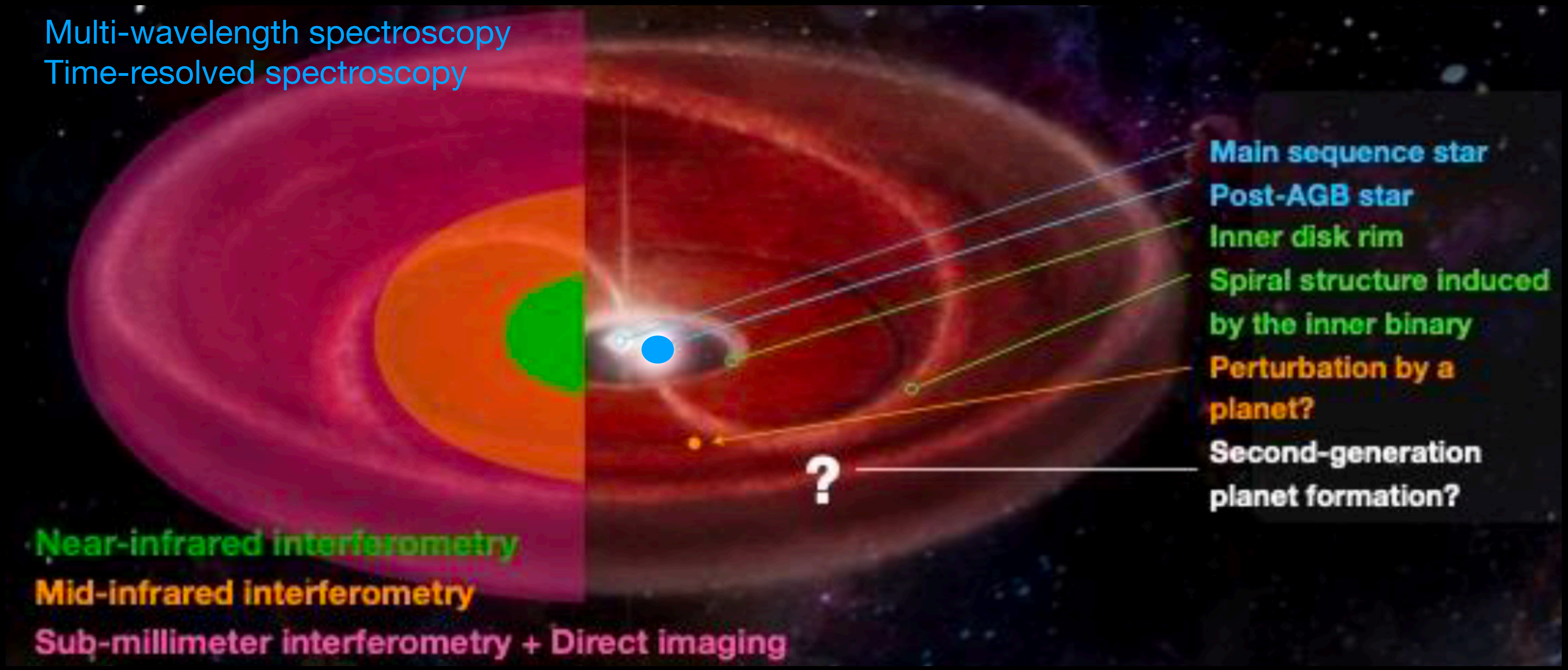
Perturbation by a planet?
Second-generation planet formation?
?
Near-infrared interferometry
Mid-infrared interferometry
Sub-millimeter interferometry + Direct imaging

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



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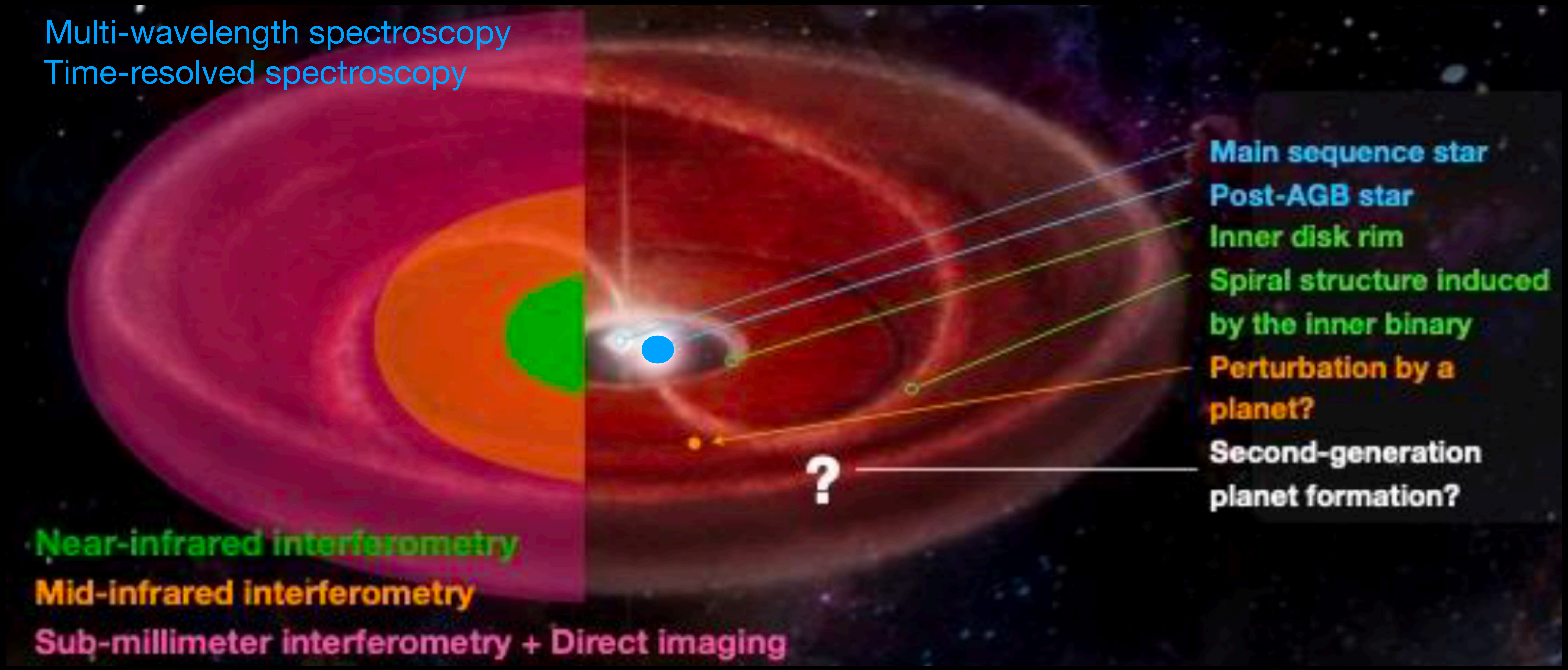
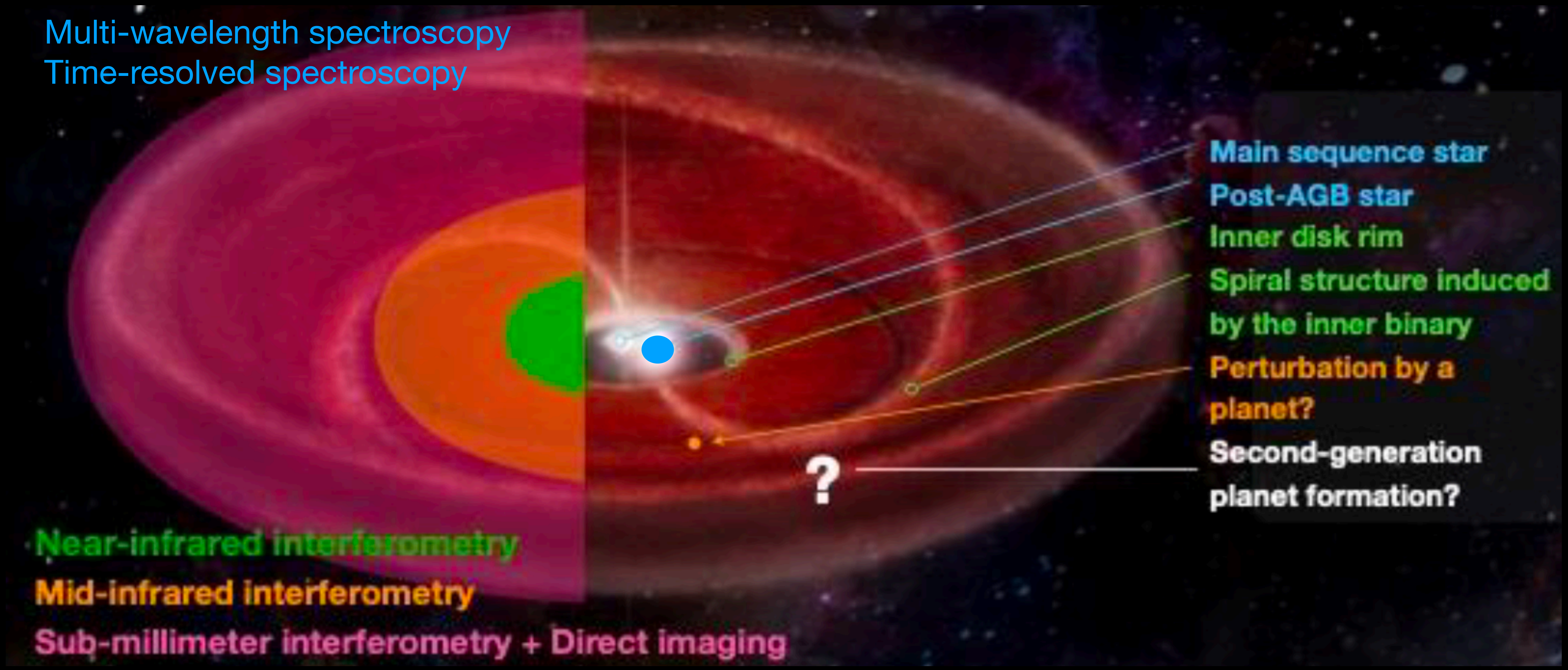


- Measuring the morphology and properties of observed planet-forming disks surrounding evolved binary stars

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



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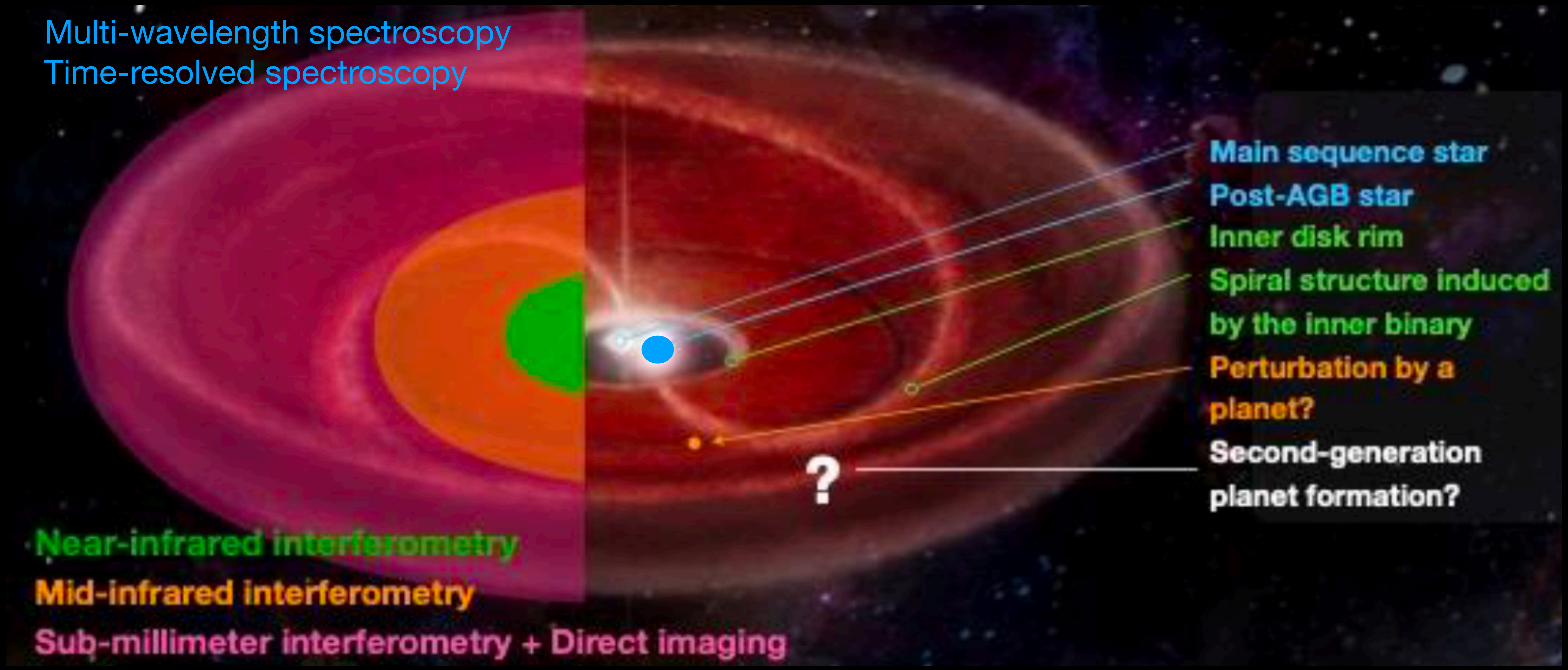
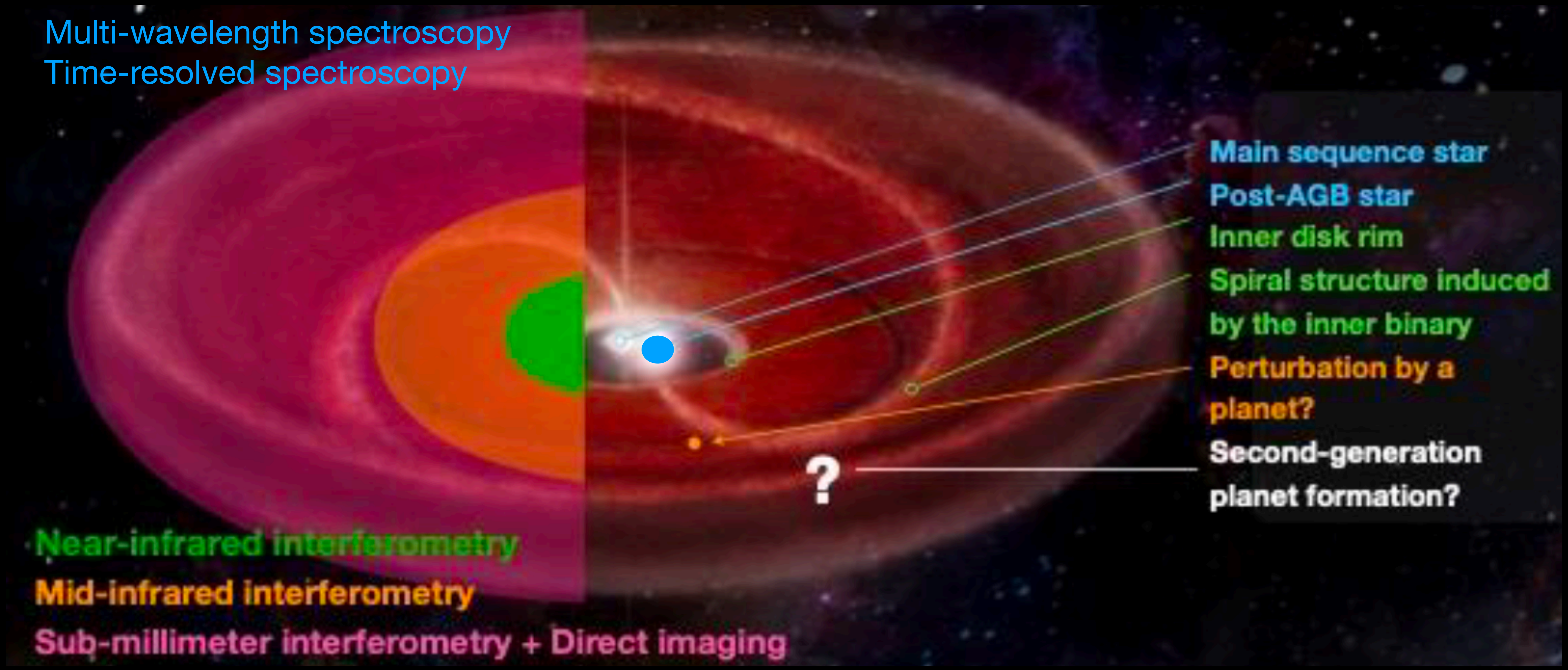


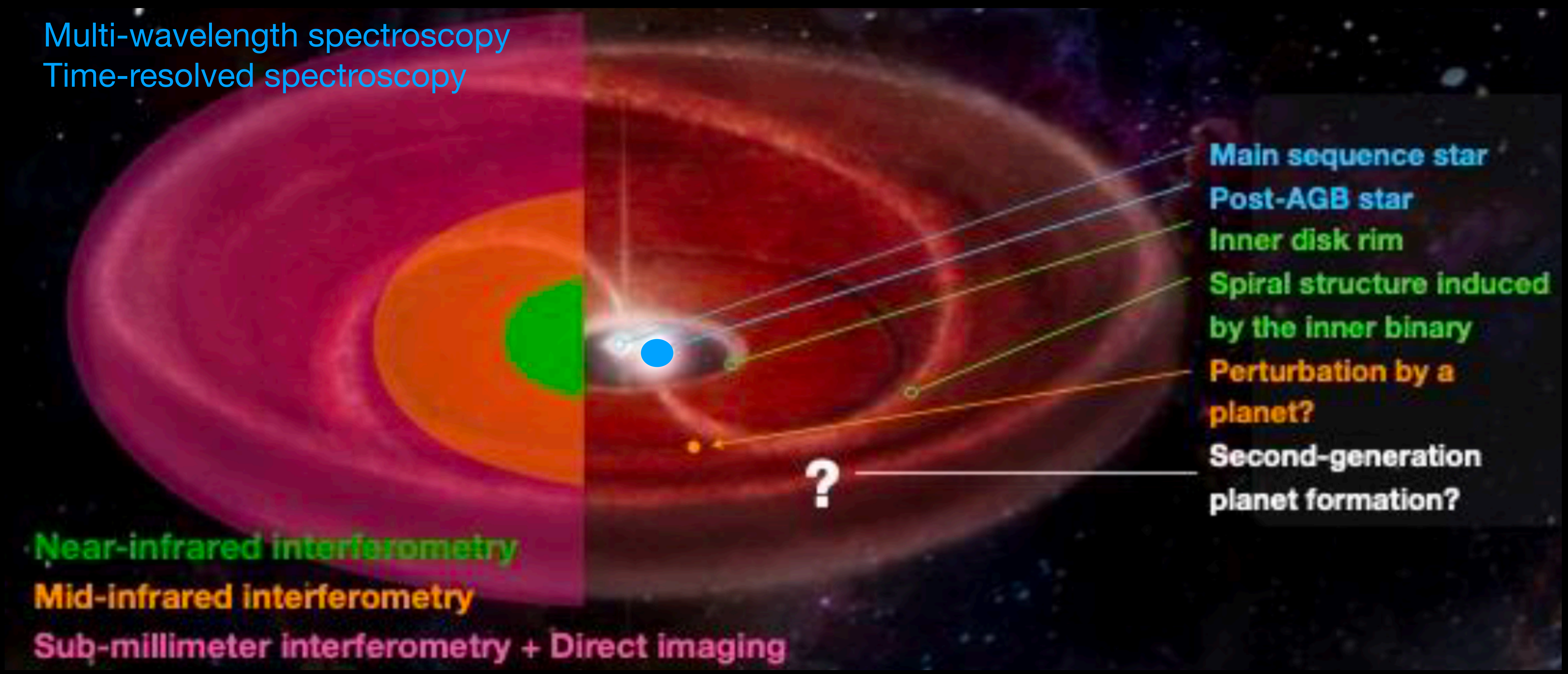
- Measuring the morphology and properties of observed planet-forming disks surrounding evolved binary stars
- Investigating the formation and evolution of second-generation proto-planetary disks
- Building a theoretical model for second-generation planet formation



- 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

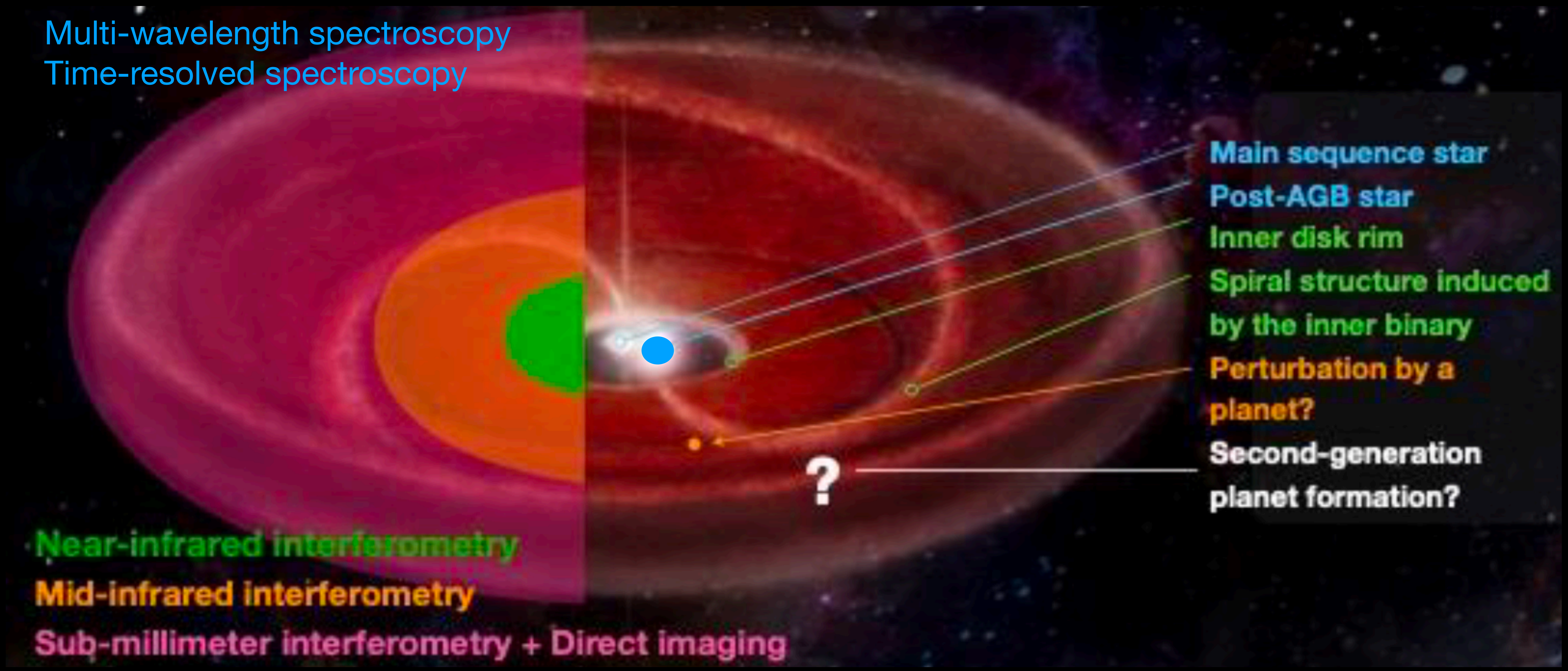


- Measuring the morphology and properties of observed planet-forming disks surrounding evolved binary stars

- 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



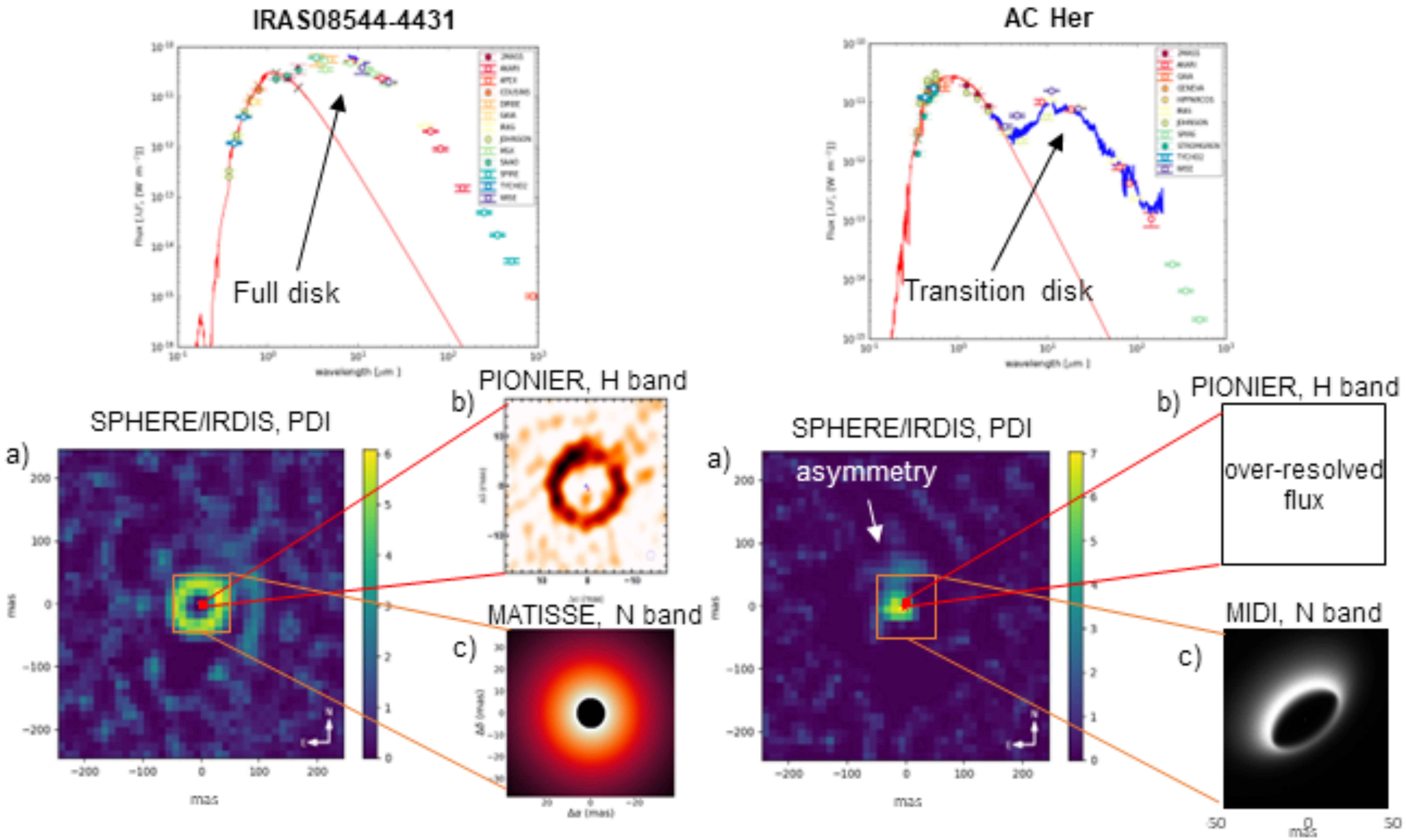


Fig.1: **Left Panel:** SED and disk images of a PAGB binary with non-transition disk: IRAS08544-4431. **Right Panel:** SED and disk images of a PAGB binary with transition disk: AC Her. **Top Panel:** SEDs for both objects. **Bottom Panel:** Montage of disk images: **a)** SPHERE/IRDIS polarimetric differential imaging (PDI) in H band, **b)** near-infrared interferometric image reconstruction using PIONIER in H band: the disk inner rim for IRAS 08544-4431 (Kluska et al. 2018, A&A, 616A, 153) and star with over-resolved component for AC Her (Kluska et al. 2019, A&A, 631A, 108K), **c)** geometric model of the interferometric data in N band showing the extended disk structure for IRAS08544-4431 (MATISSE, Corporaal et al. 2021, A&A 650, L13) and the inner gap for AC Her (VLT/MIDI, Hillen et al. 2015, A&A, 578, A40).