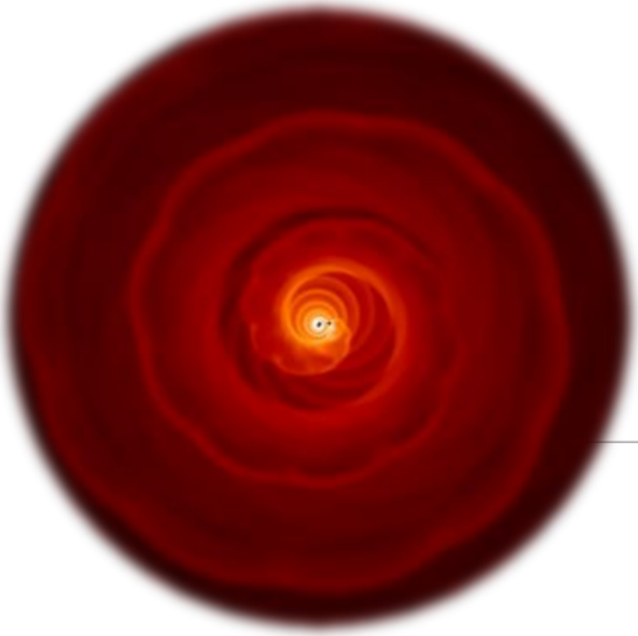
Shaping of AGB outflows by wind-companion interactions



Jolien Malfait

Leen Decin, Lionel Siess (ULB),
Frederik De Ceuster, Silke Maes,
Mats Esseldeurs, Thomas Ceulemans

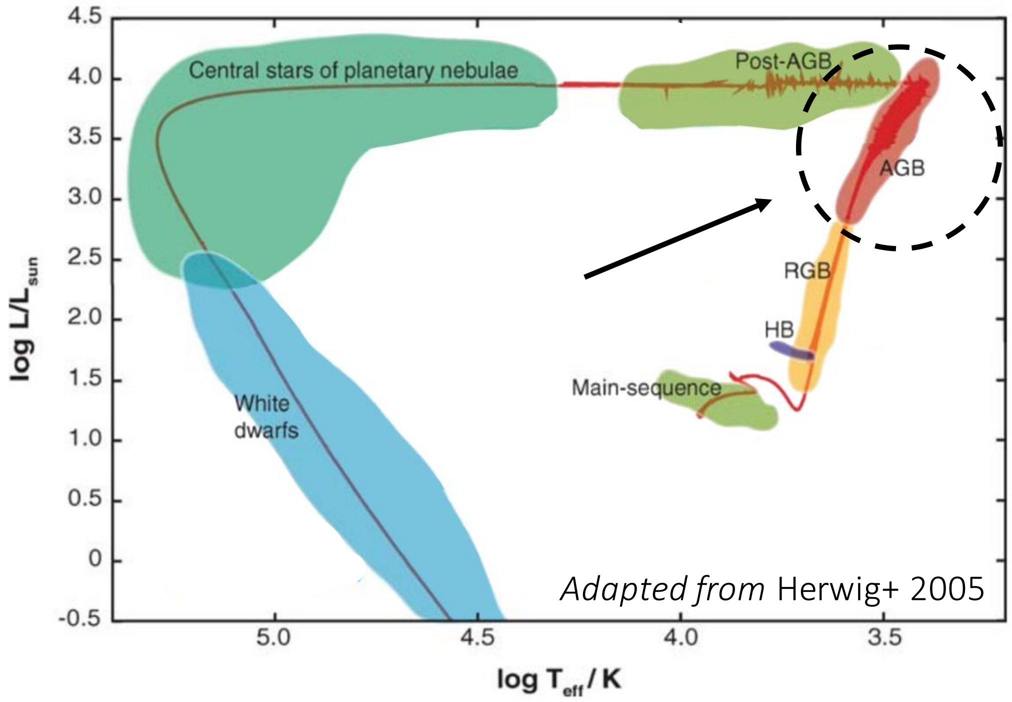
Institute of Astronomy, KU Leuven, Belgium

Phantom users workshop

Monash University, Melbourne, Australia
Feb 13-17, 2023

AGB stars

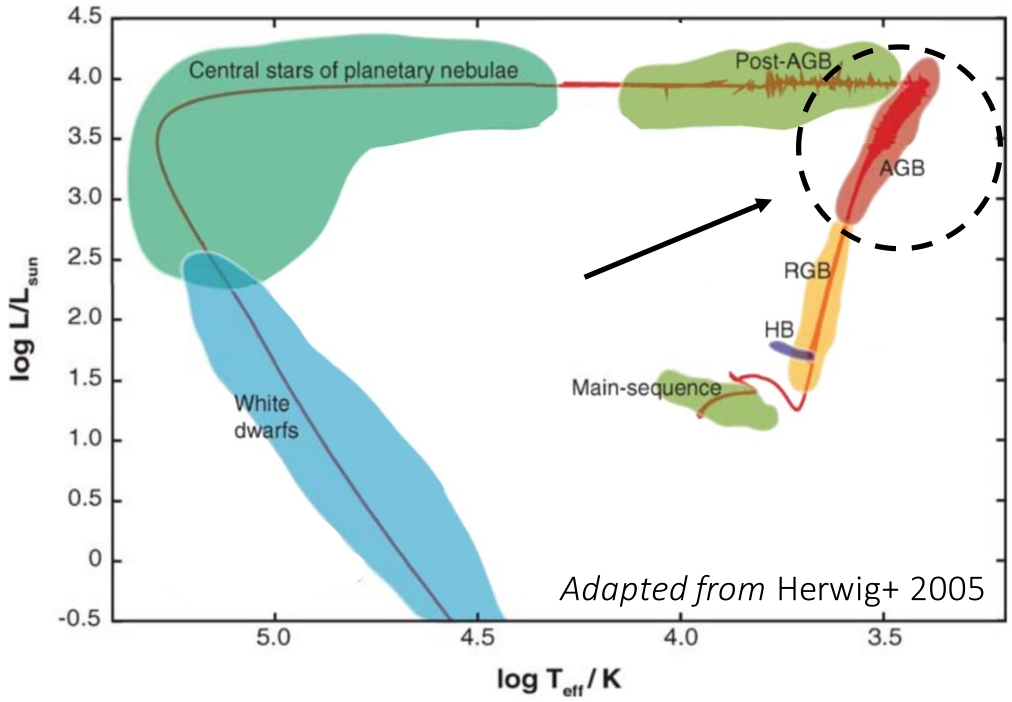
- Evolved low- and intermediate mass stars
  Initial mass : ~ 0.8 - 8 $M_{\odot}$



Adapted from Herwig+ 2005

AGB stars

- Evolved low- and intermediate mass stars
  Initial mass : ~ 0.8 - 8 $M_\odot$
- Pulsation-enhanced dust-driven stellar wind
  v_∞ ~ 5 - 30 km/s , $\dot{M}$ ~ 10^{-8} - 10^{-5} $M_\odot$/yr



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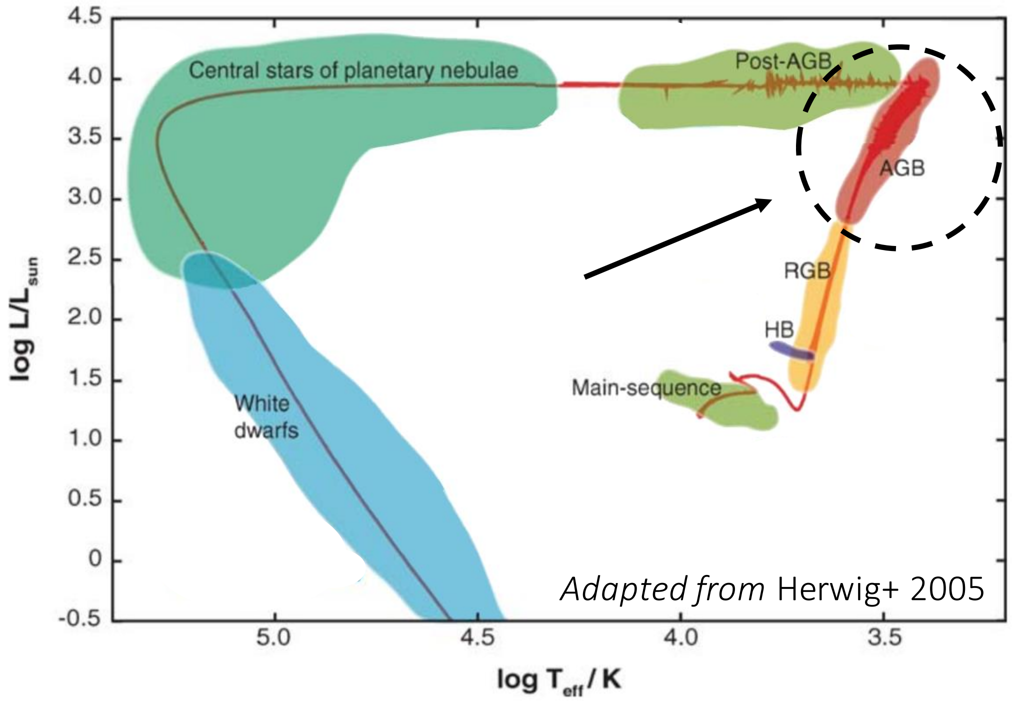

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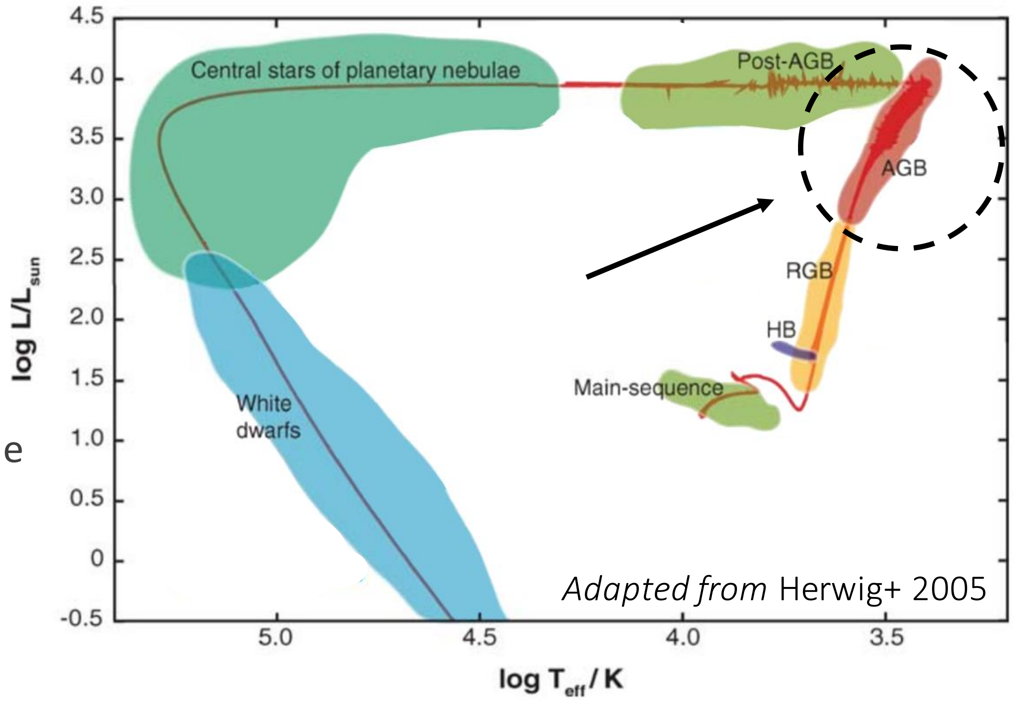
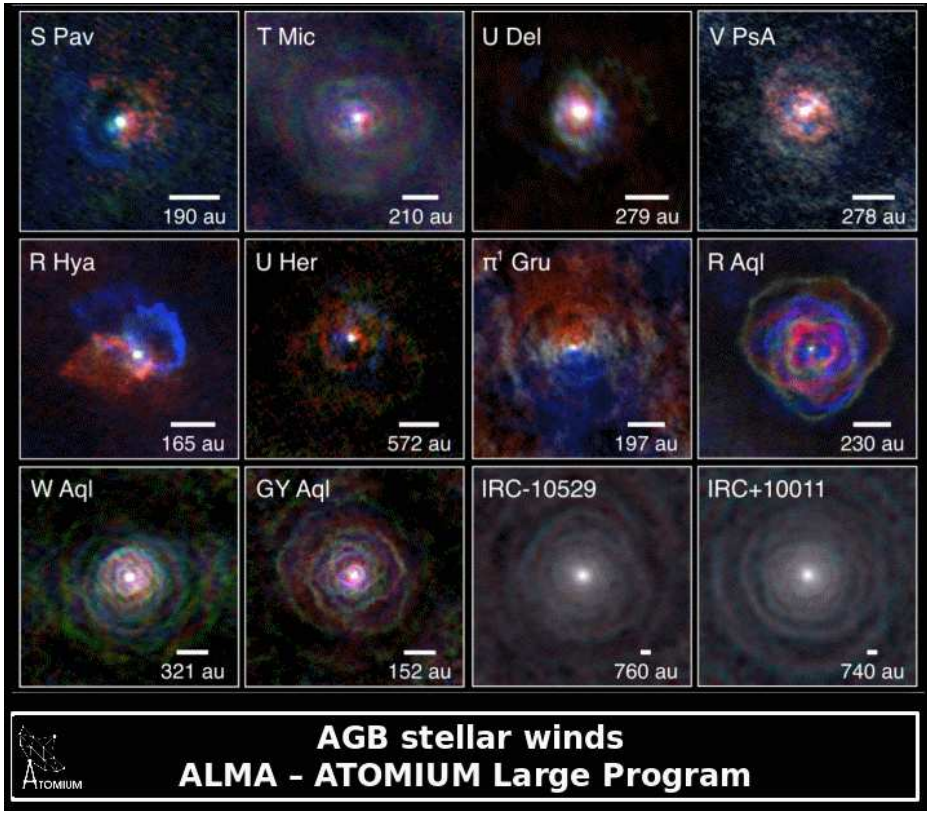
- For decades outflows assumed to be spherically symmetric --> 1D models
- Progenitors of post-AGB stars & planetary nebulae with asymmetric morphologies
  (e.g. Van Winckel+ 2003, Jones & Boffin 2017)



Adapted from Herwig+ 2005

Complex-structured AGB outflows



Decin+ 2020

- ALMA large program ATOMIUM (Decin+ 2020)
- Complex structures in AGB outflows:
  - spirals, arcs, bipolarity, …
- Primary cause: **wind-companion interaction**
  - population synthesis (*Moe & Di Stefano 2017, Decin+ 2021,…*)
  - Observations (indirect!) (e.g. Previous talk by *Taissa Danilovich*)
  - simulations (e.g. *Malfait+ 2020, Maes+ 2020, …*)

Challenges & opportunities: 3D

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I. Incorrect 1D prescriptions for **AGB Mass loss rate**, impacted by companion and 3D morphology

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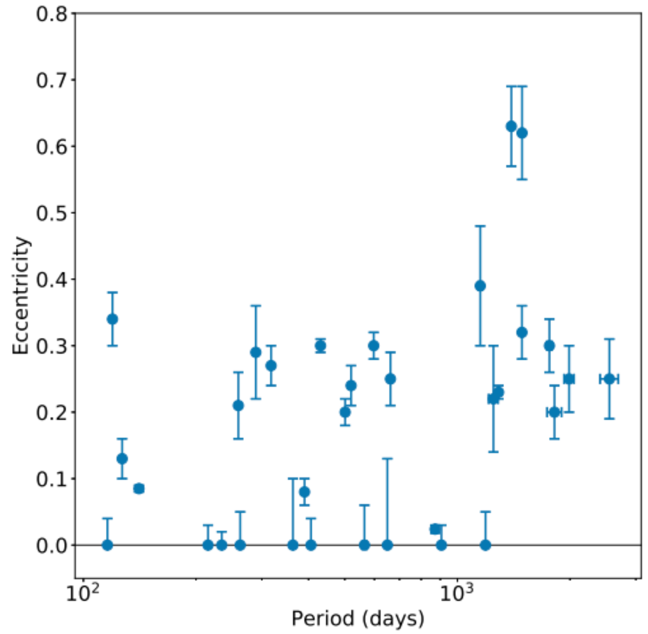
- Understand **orbital evolution**, e.g. highly eccentric orbits *(Oomen+ 2018)*



e-log *P* distribution of post-AGB stars
Oomen+ 2018

Challenges & opportunities: 3D

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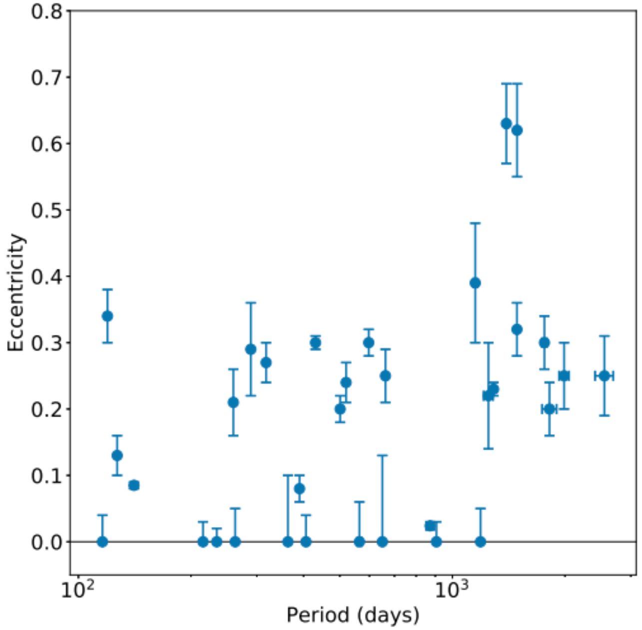
- **Complex-structured morphologies**

Cartoon of structural elements of Post-AGB binary
Bollen+ 2022



e-log *P* distribution of post-AGB stars
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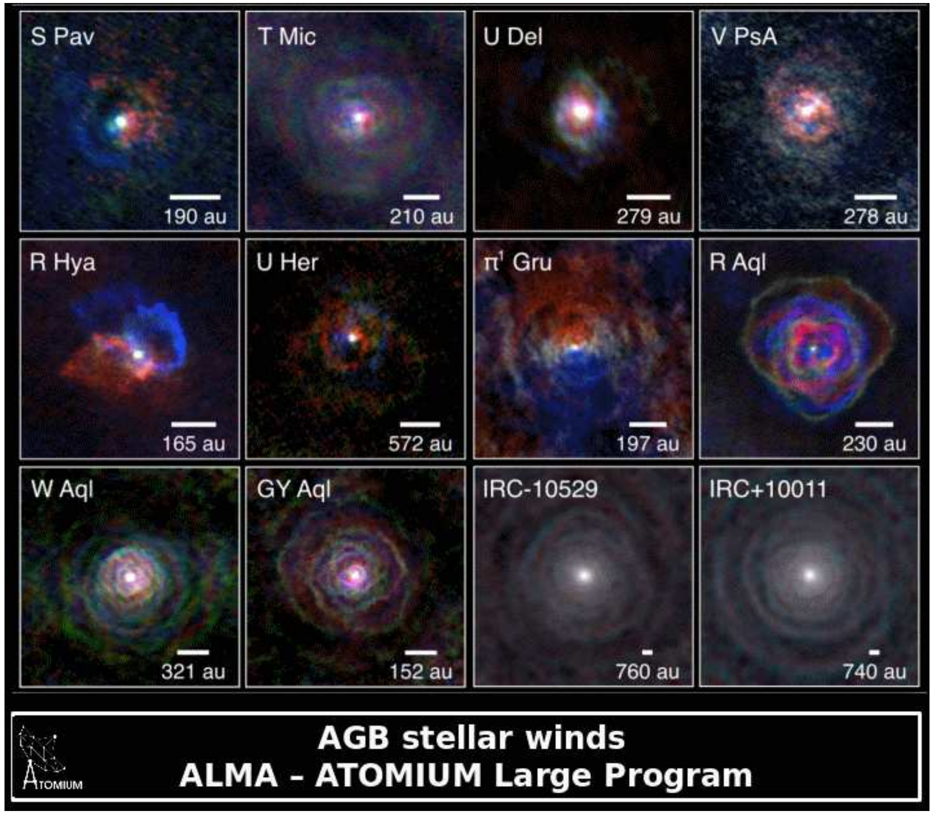
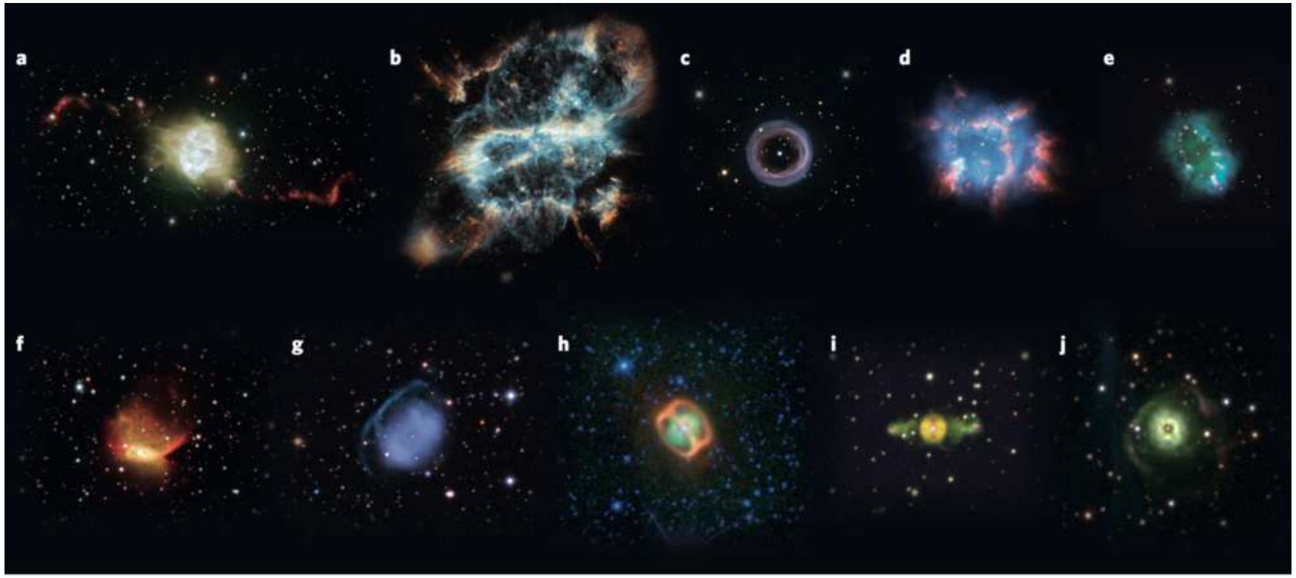
AGB outflows vs Planetary nebulae



Decin+ 2020



Planetary nebulae known to host binary central stars

Jones and Boffin 2017

a) Fleming 1, b) NGC 5189, c) Shapley 1, d) NGC 6326, e) The Necklace, f) Henize 2-428, g) Abell 65, h) NGC 1514, i) ETHOS 1, and j) Henize 2-39. Panels reproduced with permission from: ESO [57] (a); NASA, ESA, and the Hubble Heritage Team (STScI/AURA) (b,e); ESO (c,f); ESA/Hubble and NASA (d); Don Goldman (g); NASA/JPL-Caltech/UCLA, [102], AAS/IOP (h); [55], Oxford Univ. Press (i); [69], Oxford Univ. Press (j)

Challenges & opportunities: 3D

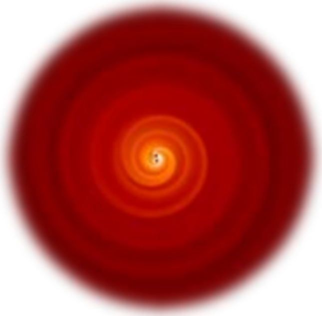
I. Incorrect 1D prescriptions for **AGB Mass loss rate**, impacted by companion and 3D morphology

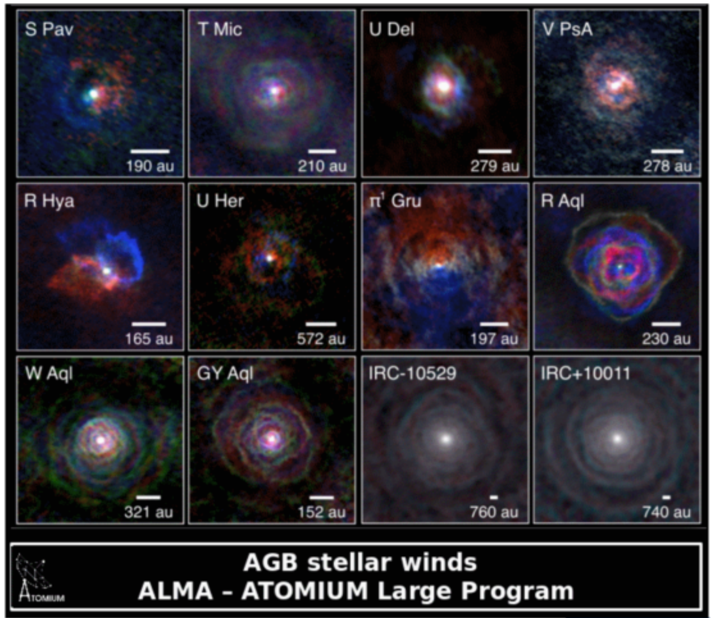
II. Bridge gap with **Post-AGB stars** & **Planetary Nebulae:**

- Understand **orbital evolution**, e.g. highly eccentric orbits *(Oomen+ 2018)*
- **Complex-structured morphologies**

III. **Study AGB outflows** through observations & modelling

- ATOMIUM collaboration (PI Leen Decin)



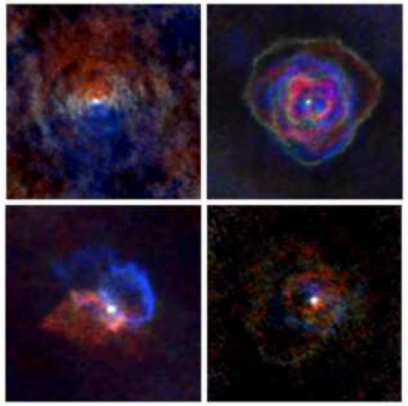


Leen Decin

Lionel Siess

What are we working on?

ATOMIUM
ALMA **observations**



...

Sofia Wallström   Taissa Danilovich

Radiative transfer +
link observations - simulations

Magritte

Thomas Ceulemans

Frederik De Ceuster

Jolien Malfait

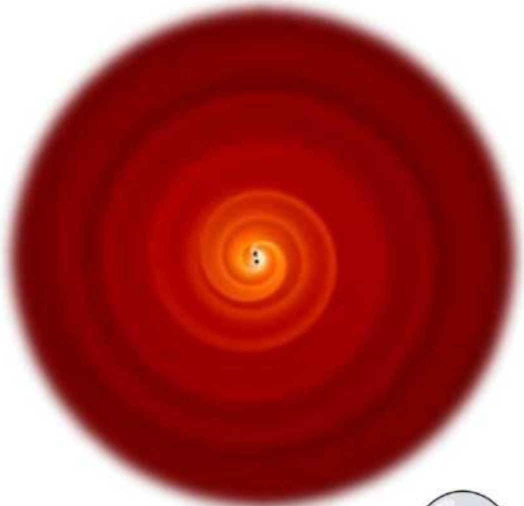
Mats Esseldeurs

Speed up **chemical simulations**
in 3D models

In coll. with Marie Van de Sande et al.

Silke Maes

Development **AGB wind model**
+ analysis of hydro-models



Daniel Price

AGB wind model

Leen Decin

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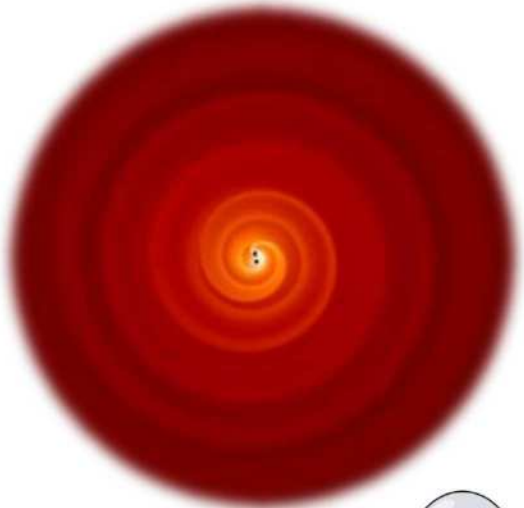


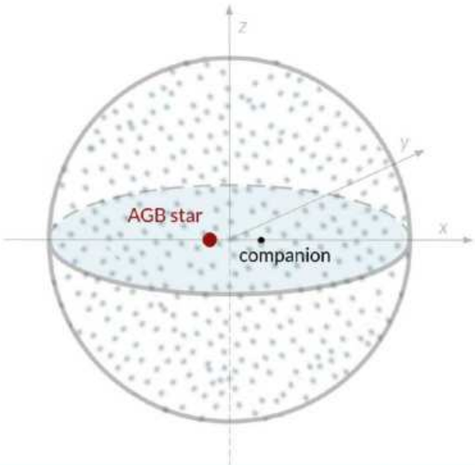
Daniel Price

AGB wind model

Leen Decin  KU LEUVEN

Lionel Siess  ULB

- 3D Smoothed Particle Hydrodynamic (SPH) models with ***Phantom*** *(Price+ 2018, Siess+ 2022)*
- Gravity-only AGB star & companion
- Free-wind *(Malfait+ 2021, Maes+ 2021)*
- HI cooling *(Malfait+ in prep.)*



Jolien Malfait

Frederik De Ceuster

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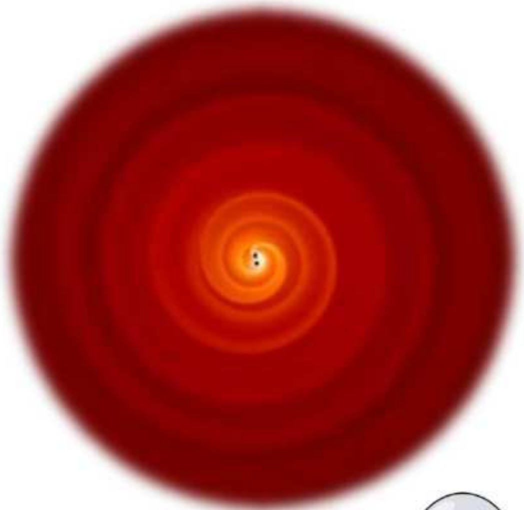


Daniel Price

AGB wind model

Leen Decin

KU LEUVEN

Lionel Siess

ULB

Esseldeurs+ (in prep.), Siess+ 2022

! See talk by Lionel Siess ! (Wednesday 10 AM)

- More accurate wind launching (not free wind):
  - Use of ray tracer to better estimate radiation force & dust T *(Esseldeurs+ In prep)*
  - Dust nucleation *(Siess+ 2022)*
  - Pulsations
- More accurate cooling/heating
- ...

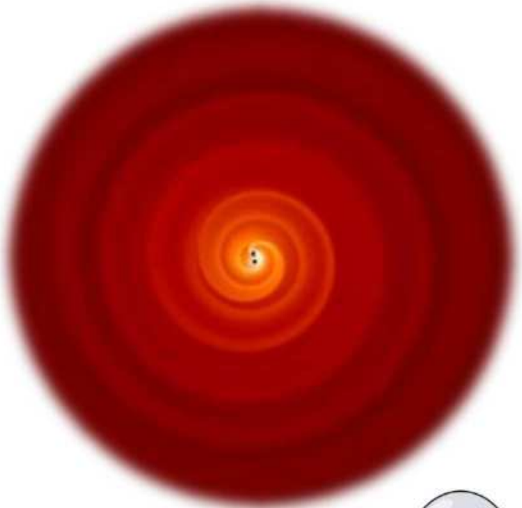
Jolien Malfait

Frederik De Ceuster

Mats Esseldeurs

Silke Maes

Development **AGB wind model** + analysis of hydro-models



Daniel Price

AGB wind model

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KU LEUVEN

ULB

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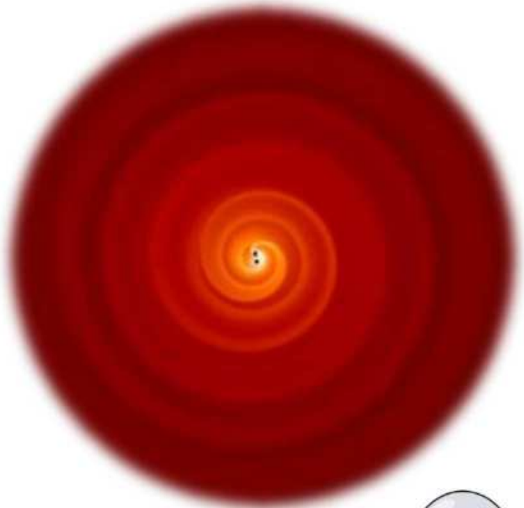
Development AGB wind model
+ ***analysis of hydro-models***



Frederik De Ceuster

Mats Esseldeurs

Silke Maes

Daniel Price

Malfait+ 2021
Maes+ 2021

AGB wind model: Previous work

Binary parameter space explored:

- Semi-major axis — a
- Wind velocity — v_w
- Companion mass — m_c
- Eccentricity — e

No HI cooling included yet

A&A 652, A51 (2021)
https://doi.org/10.1051/0004-6361/202141161

Astronomy & Astrophysics

SPH modelling of wind-companion interactions in eccentric AGB binary systems

J. Malfait[1], W. Homan[2,1], S. Maes[1], J. Bolte[1], L. Siess[2], F. De Ceuster[3,1], and L. Decin[1,4]

[1] Institute of Astronomy, KU Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium
e-mail: jolien.malfait@kuleuven.be
[2] Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles (ULB), CP 226, 1050 Brussels, Belgium
[3] Department of Physics and Astronomy, University College London, Gower Place, London WC1E 6BT, UK
[4] School of Chemistry, University of Leeds, Leeds LS2 9JT, UK

Received 23 April 2021 / Accepted 1 July 2021

Malfait+ 2021:
Focus on **eccentric orbits** and how various **wind structures** close to companion star shape wind

A&A 653, A25 (2021)
https://doi.org/10.1051/0004-6361/202140823

Astronomy & Astrophysics

SPH modelling of companion-perturbed AGB outflows including a new morphology classification scheme

S. Maes[1], W. Homan[2,1], J. Malfait[1], L. Siess[2], J. Bolte[1], F. De Ceuster[3,1], and L. Decin[1,4]

[1] Instituut voor Sterrenkunde, KU Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium
e-mail: silke.maes@kuleuven.be
[2] Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles (ULB), CP 226, 1050 Brussels, Belgium
[3] Department of Physics and Astronomy, University College London, Gower Place, London, WC1E 6BT, UK
[4] School of Chemistry, University of Leeds, Leeds LS2 9JT, UK

Received 17 March 2021 / Accepted 30 June 2021

Maes+ 2021:
Focus on **terminal wind velocity**
and **morphology classification parameter**

Malfait+ *2021*
Maes+ *2021*

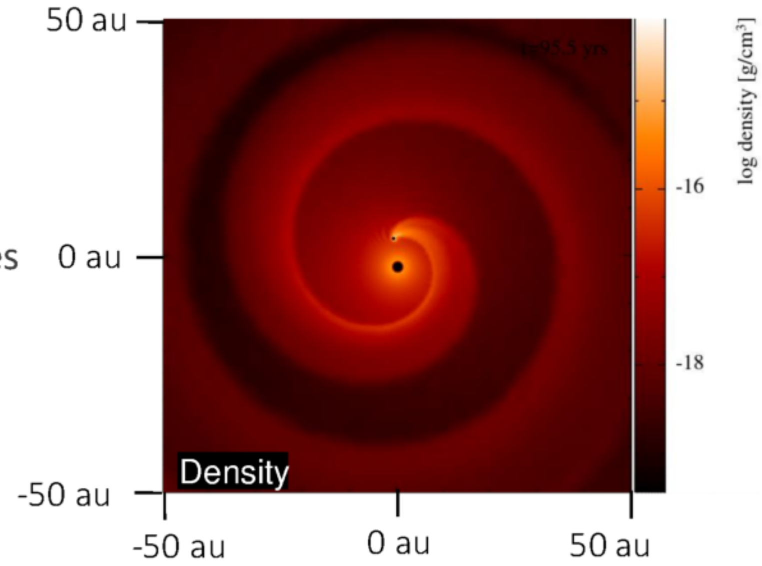
Wind-companion interaction

Wind-companion interactions

- Induced orbital motion & gravitational attraction of wind particles
- Stronger impact for
  (i) larger M_{comp} , (ii) smaller a, (iii) lower v_w , (iv) higher e
- Classification parameter (*Maes*+ *2021*):

$$\varepsilon \equiv \frac{e_{\rm grav}}{e_{\rm kin}} = \frac{(24G^3 m_{\rm comp}^2 m_{\rm AGB})^{1/3}}{v_{\rm wind}^2 a(1-e)}$$

$$\begin{cases} \varepsilon \lesssim 1 & \text{: limited impact companion => Regular spiral morphology} \\ \varepsilon \gg 1 & \text{: stronger impact companion => Rather irregular morphology} \end{cases}$$



AGB wind model

Binary systems: setup

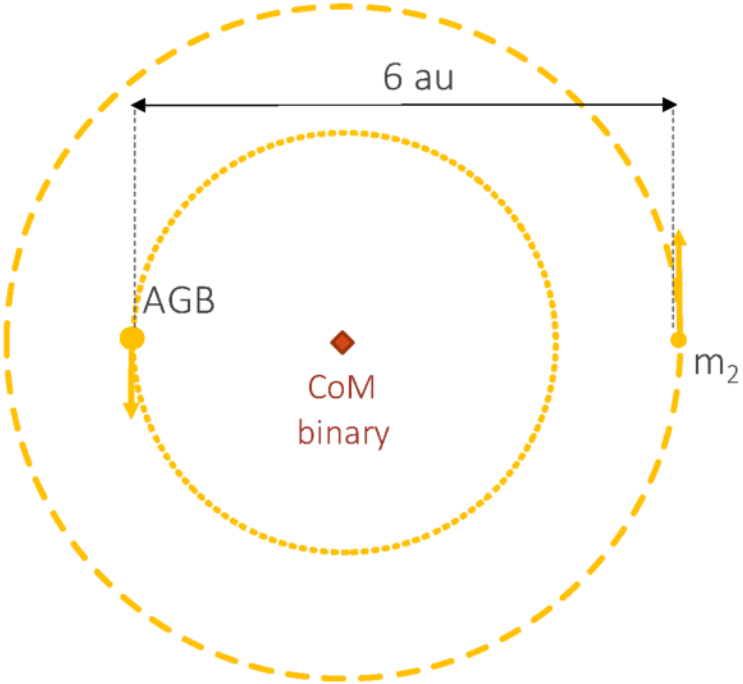
Malfait+ 2021
Maes+ 2021
Malfait+ 2023 (in prep)

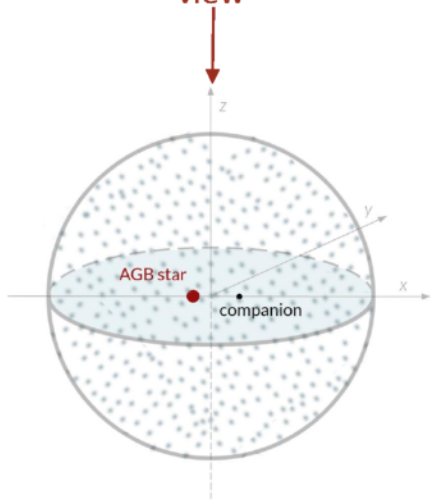
AGB
$M_{AGB} = 1.5\ M_{sun}$

companion
$m_2 = 1.0\ M_{sun}$

$e = 0.0\ -\ 0.5$

$v_w = 5\ -\ 10\ -\ 20$ km/s

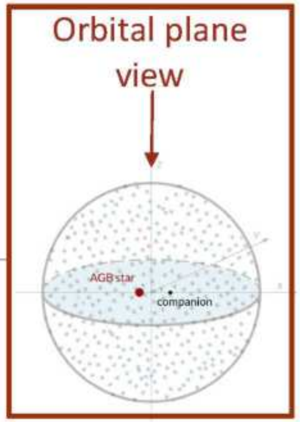




AGB wind model

Malfait+ *2023 (in prep)*

Morphology types: binary systems



$a = 6$ au
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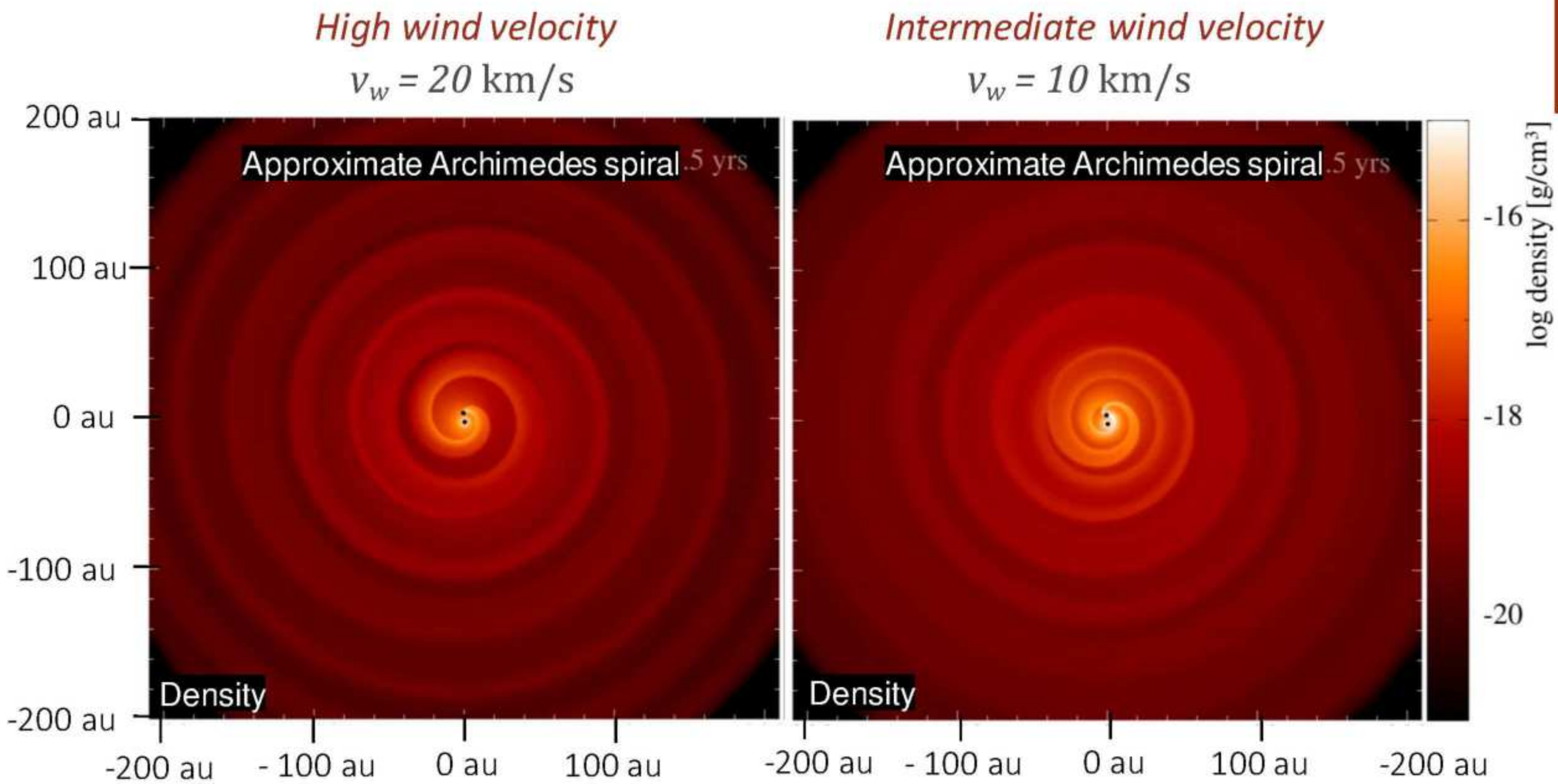
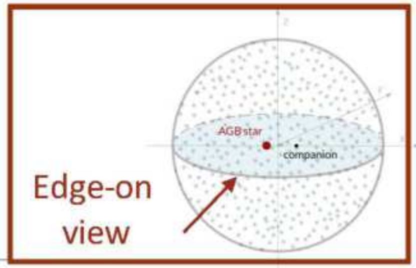
$M_{comp} = 1\ M_{sun}$



AGB wind model

Malfait+ 2023 (in prep)

Morphology types: binary systems



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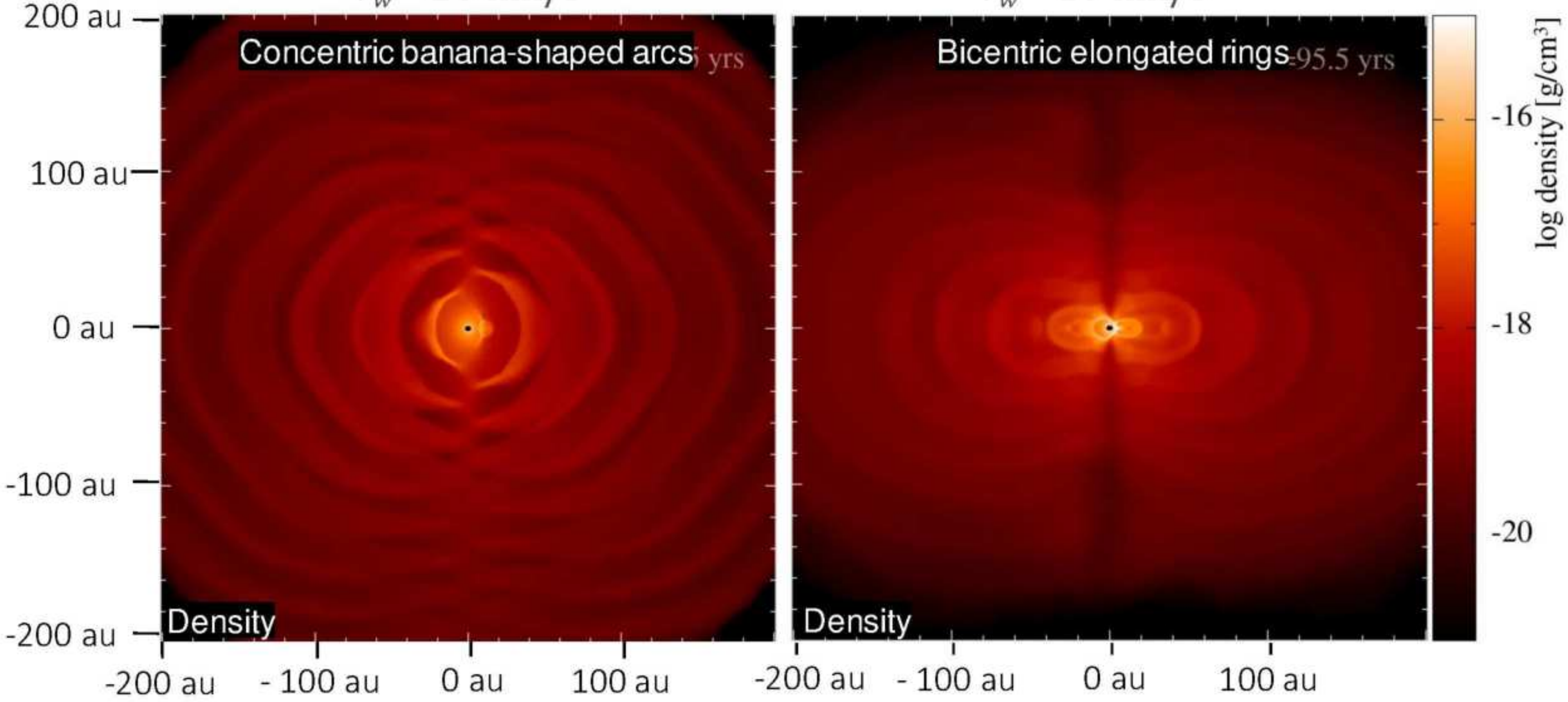
High wind velocity $v_w = 20$ km/s

Intermediate wind velocity $v_w = 10$ km/s



AGB wind model

Malfait+ 2023 (in prep)

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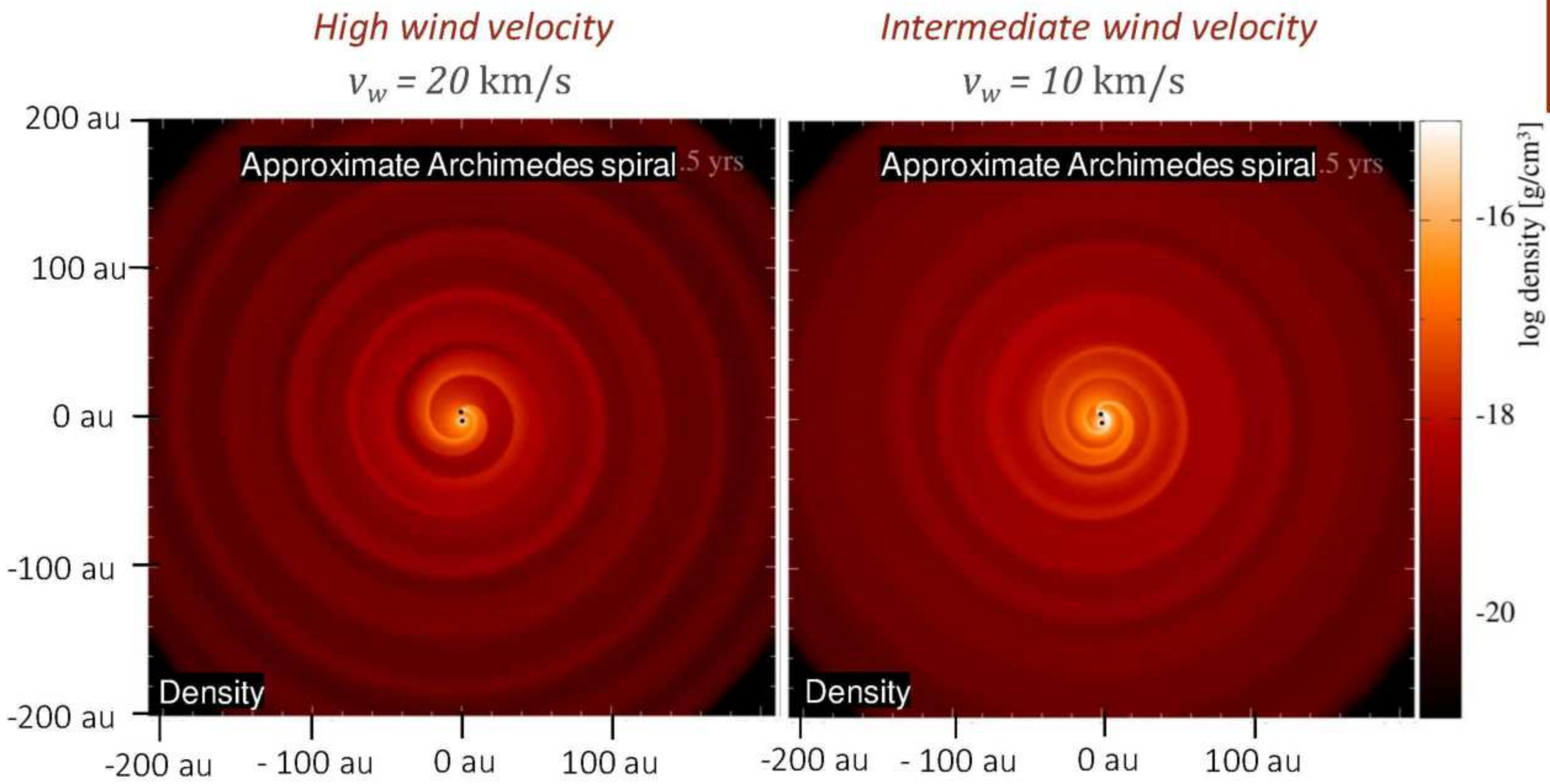
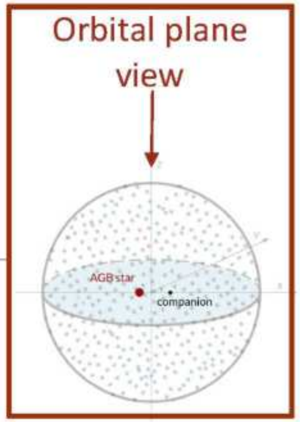
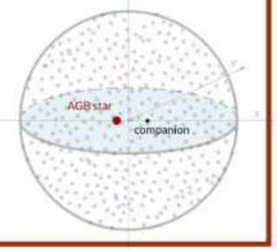




AGB wind model

Malfait+ *2023 (in prep)*

Orbital plane view



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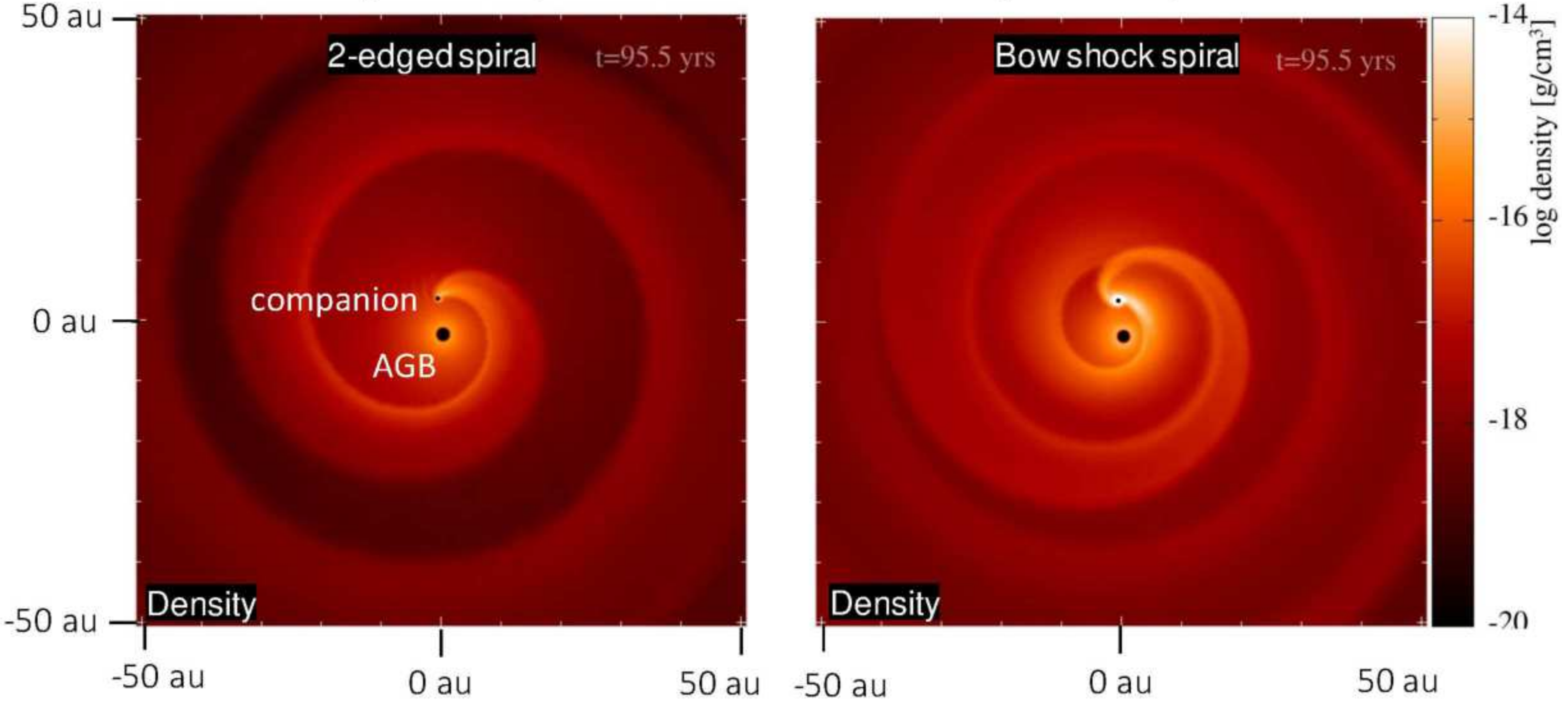

AGB wind model

Malfait+ 2023 (in prep)

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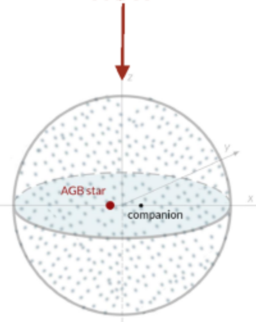

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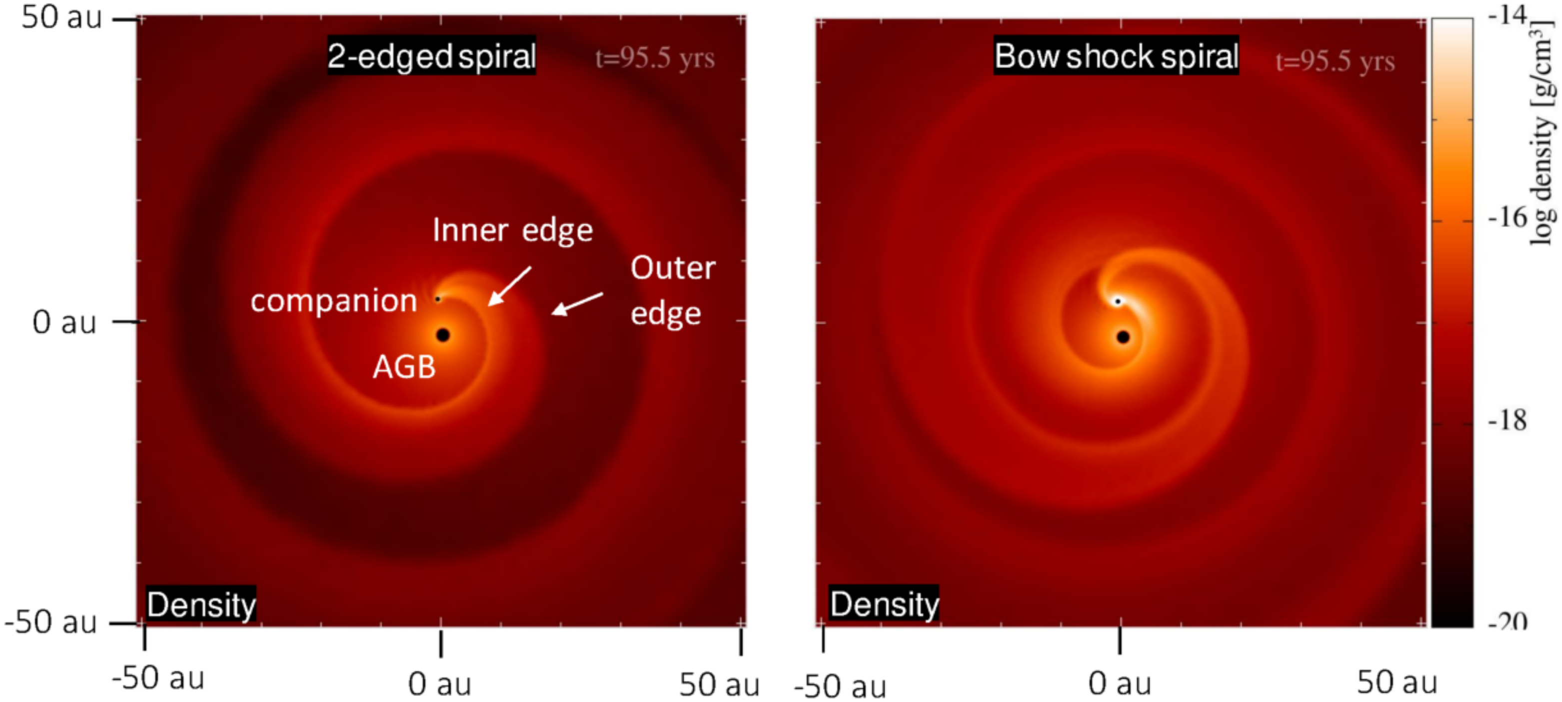

AGB wind model

Malfait+ 2023 (in prep)

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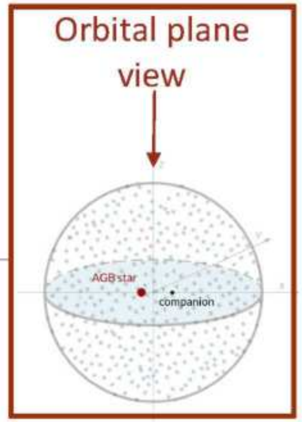

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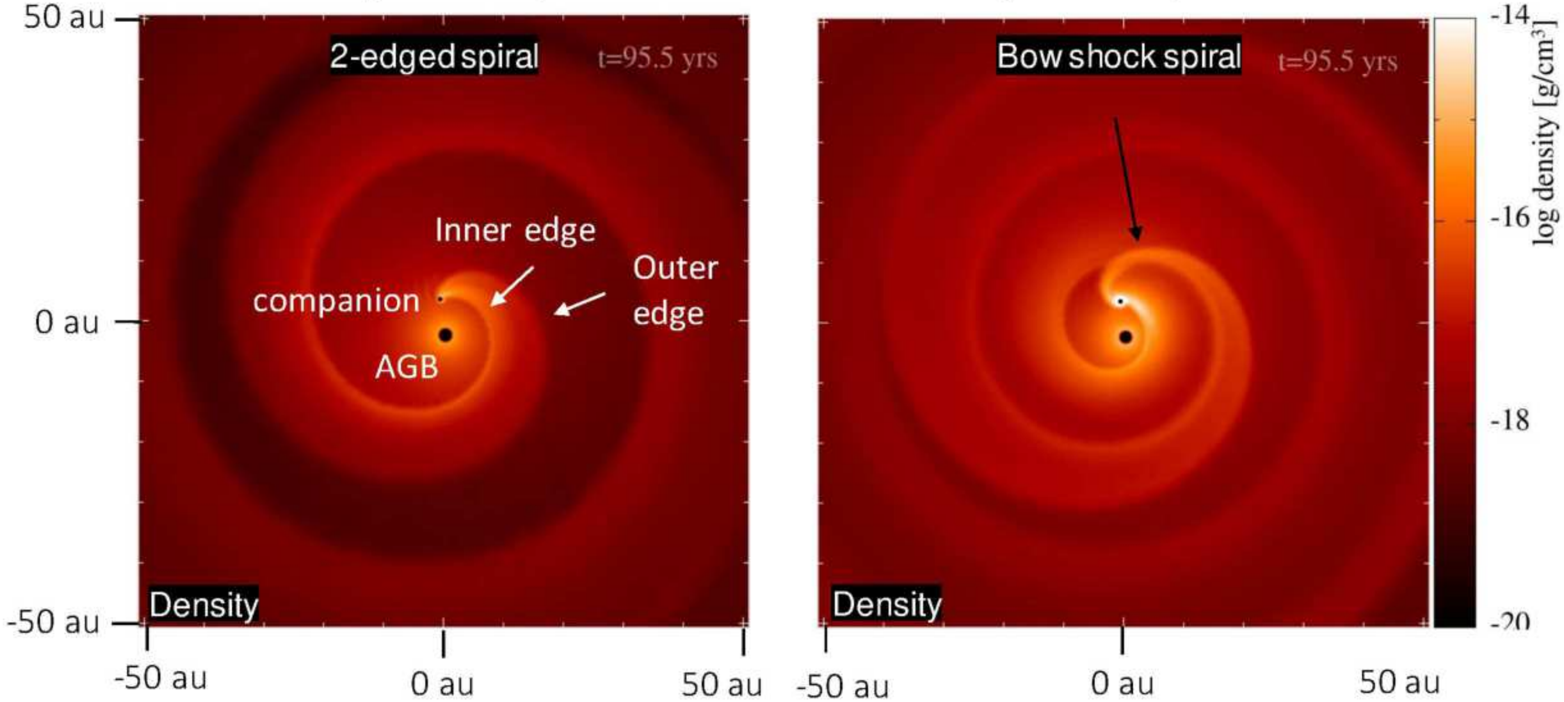

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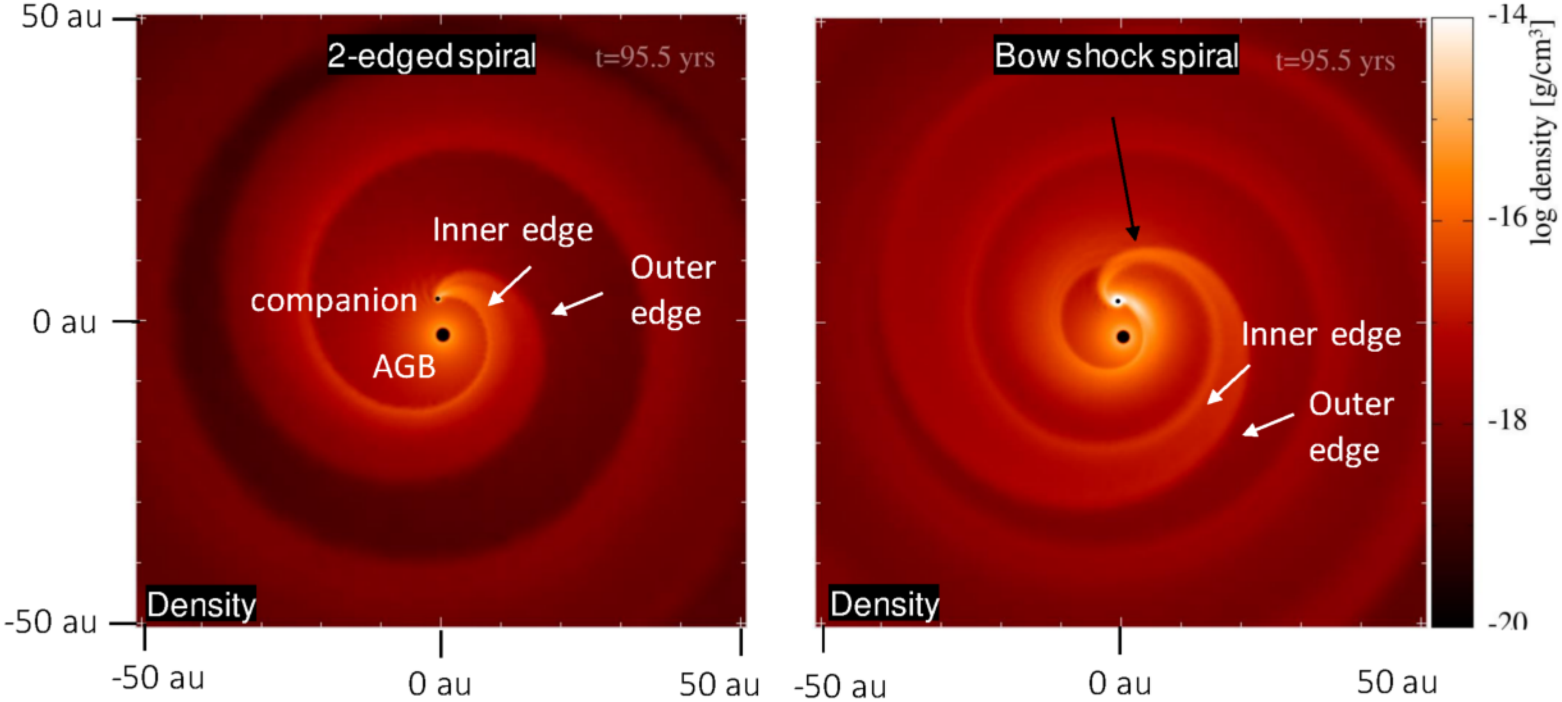
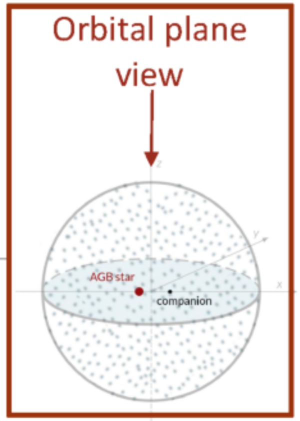
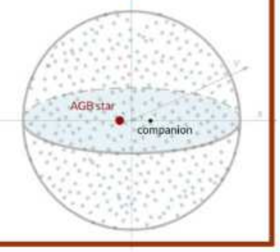




AGB wind model

Malfait+ 2023 (in prep)

Orbital plane view



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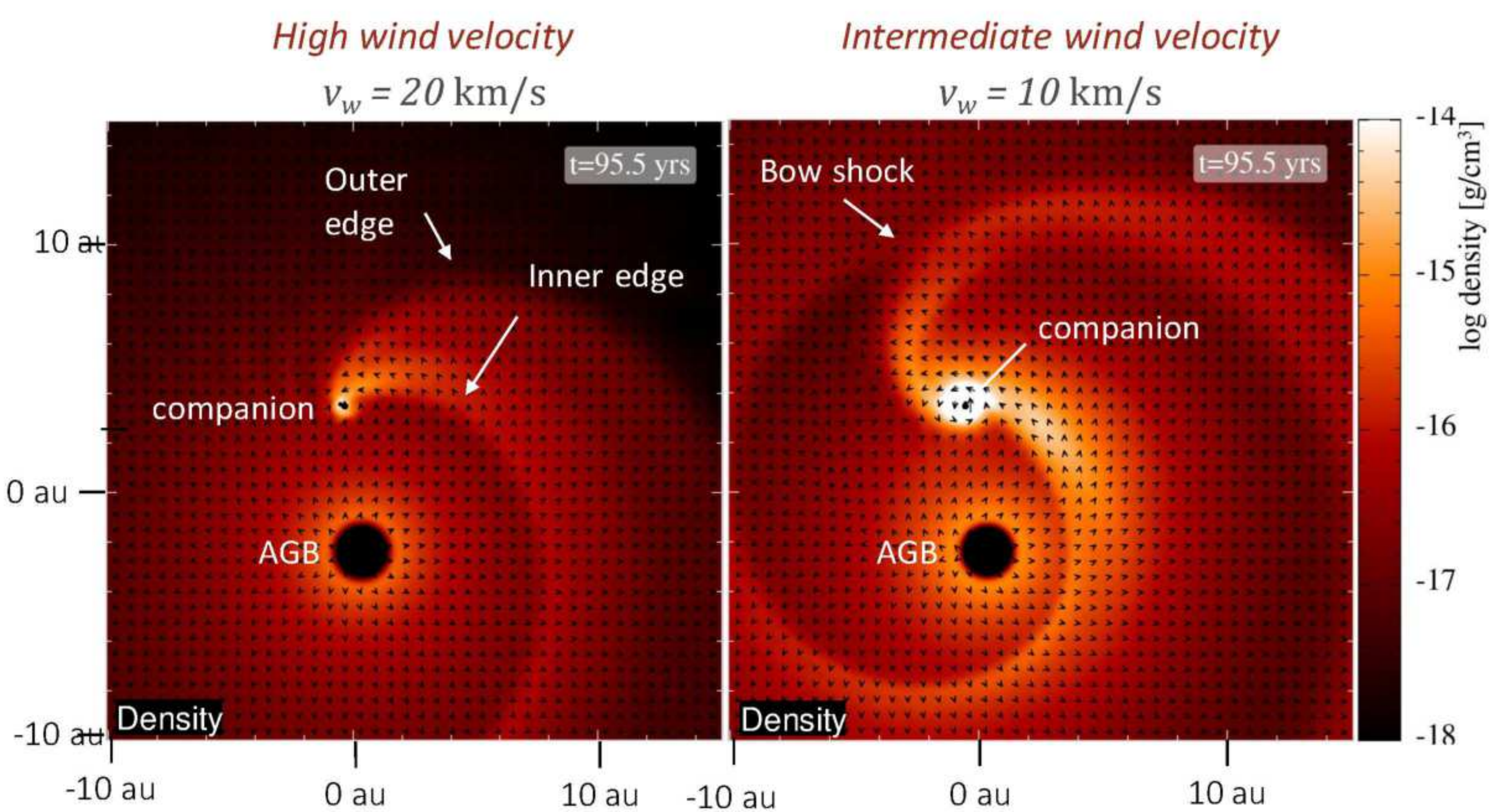

AGB wind model

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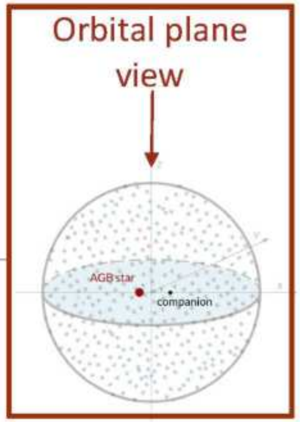

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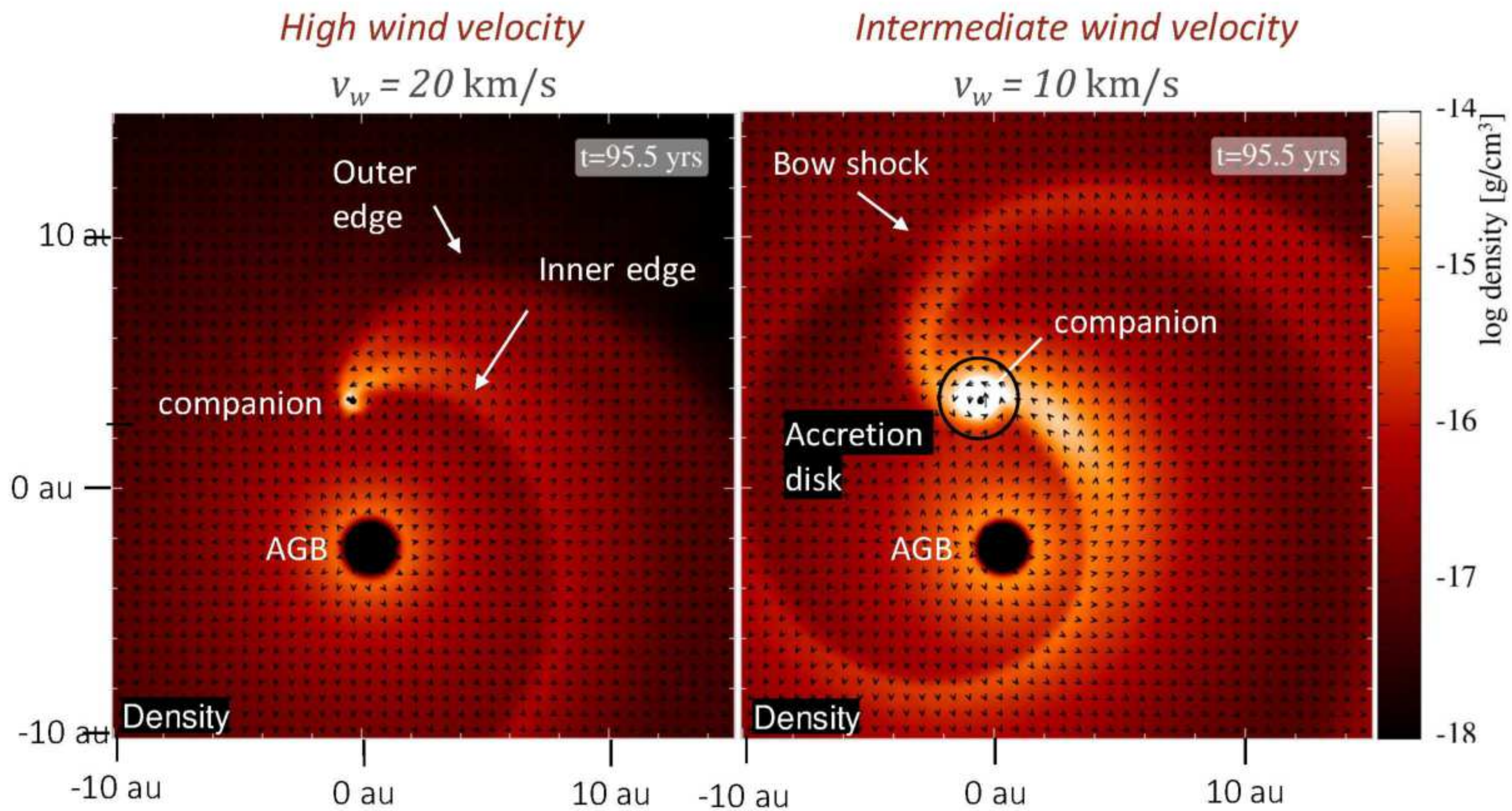

AGB wind model

Malfait+ 2023 (in prep)

Morphology types: binary systems

$a = 6$ au
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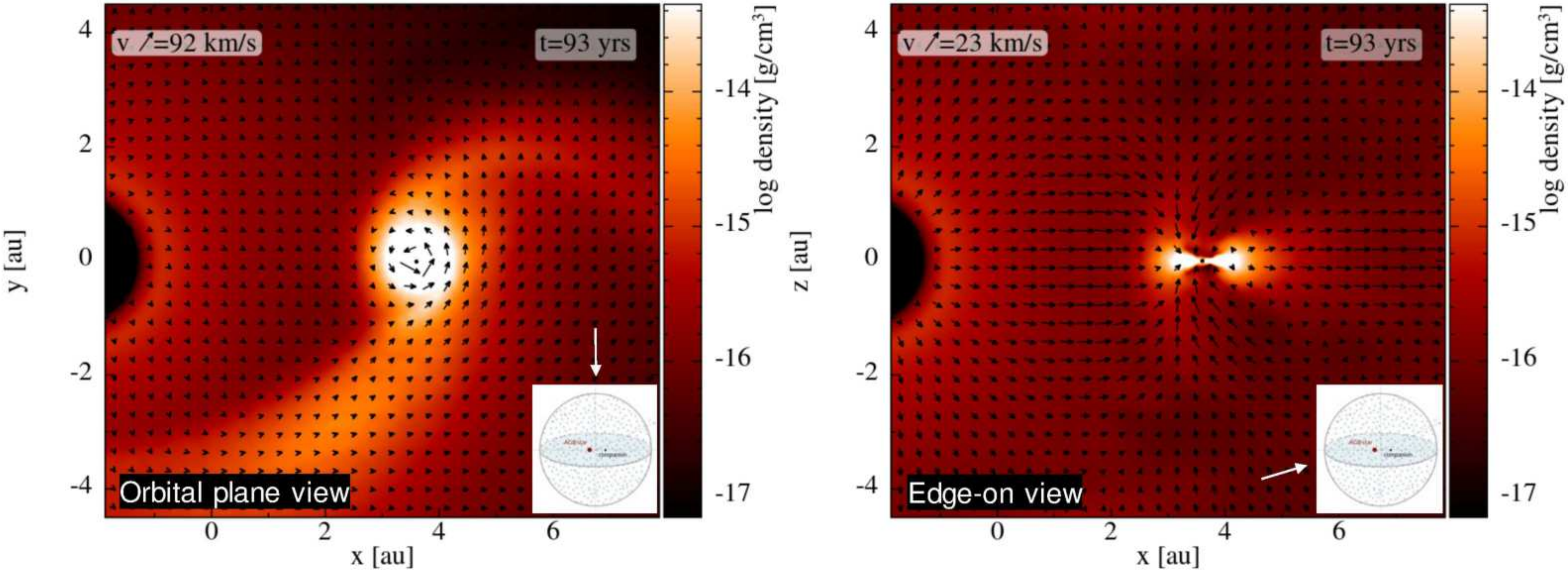
Accretion disk

Intermediate wind velocity $v_w = 10$ km/s

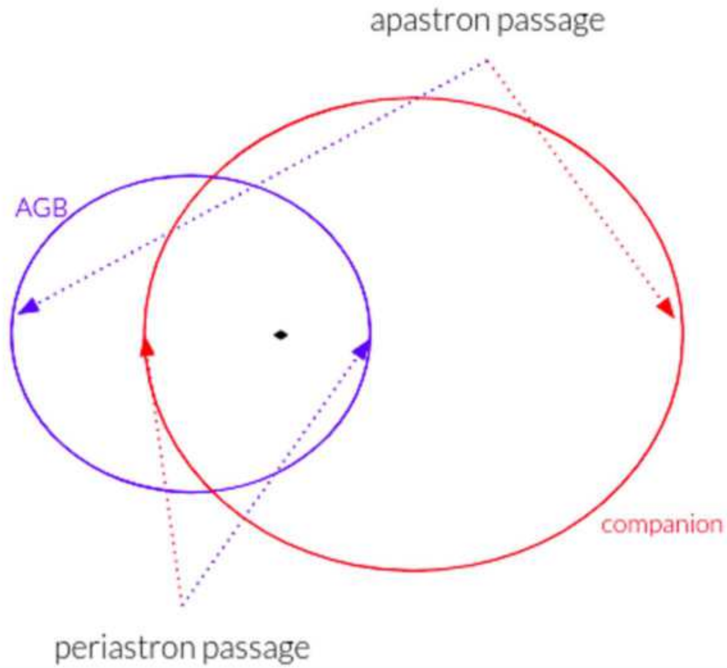


Morphology types: eccentric binaries

- (Progeny of) binary AGB stars with high *e* (e.g. *Oomen+ 2018*)
  Highly asymmetric AGB structures observed *(Previous talk by Taissa Danilovich, Decin+ 2020)*

- Varying orbital separation and orbital velocities

- -> **Phase-dependent**
  wind-companion interaction intensity



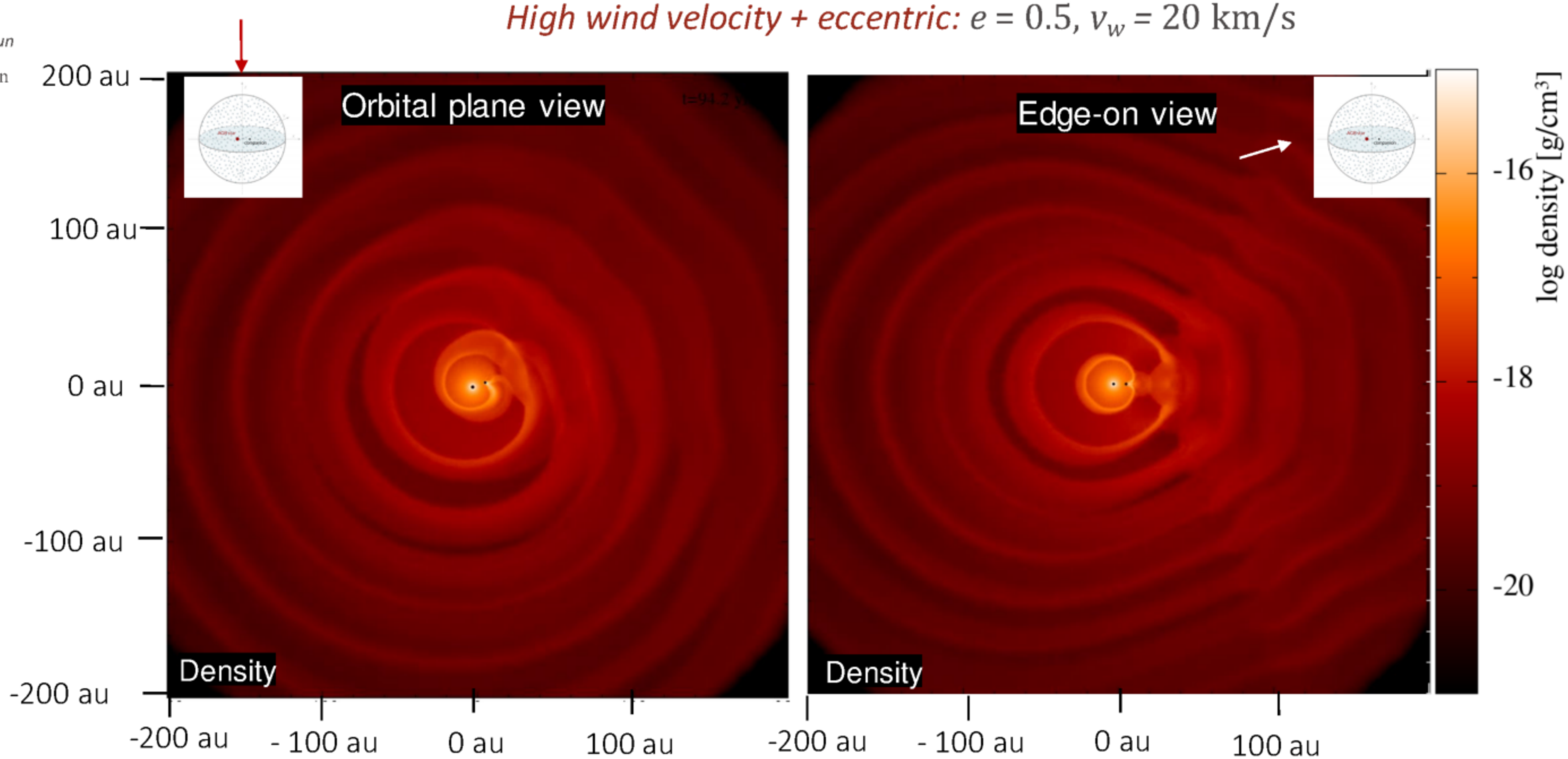
AGB wind model

Malfait+ *2023 (in prep)*
Malfait+ *2021*

Morphology types: eccentric binaries

$a = 6$ au
$M_{AGB} = 1.5\, M_{sun}$
$\mathrm{M_{comp}} = 1\ \mathrm{M_{sun}}$

High wind velocity + eccentric: $e = 0.5$, $v_w = 20$ km/s



AGB wind model

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Malfait+ 2021

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a = 6 au
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M_{comp}= 1 M_{sun}

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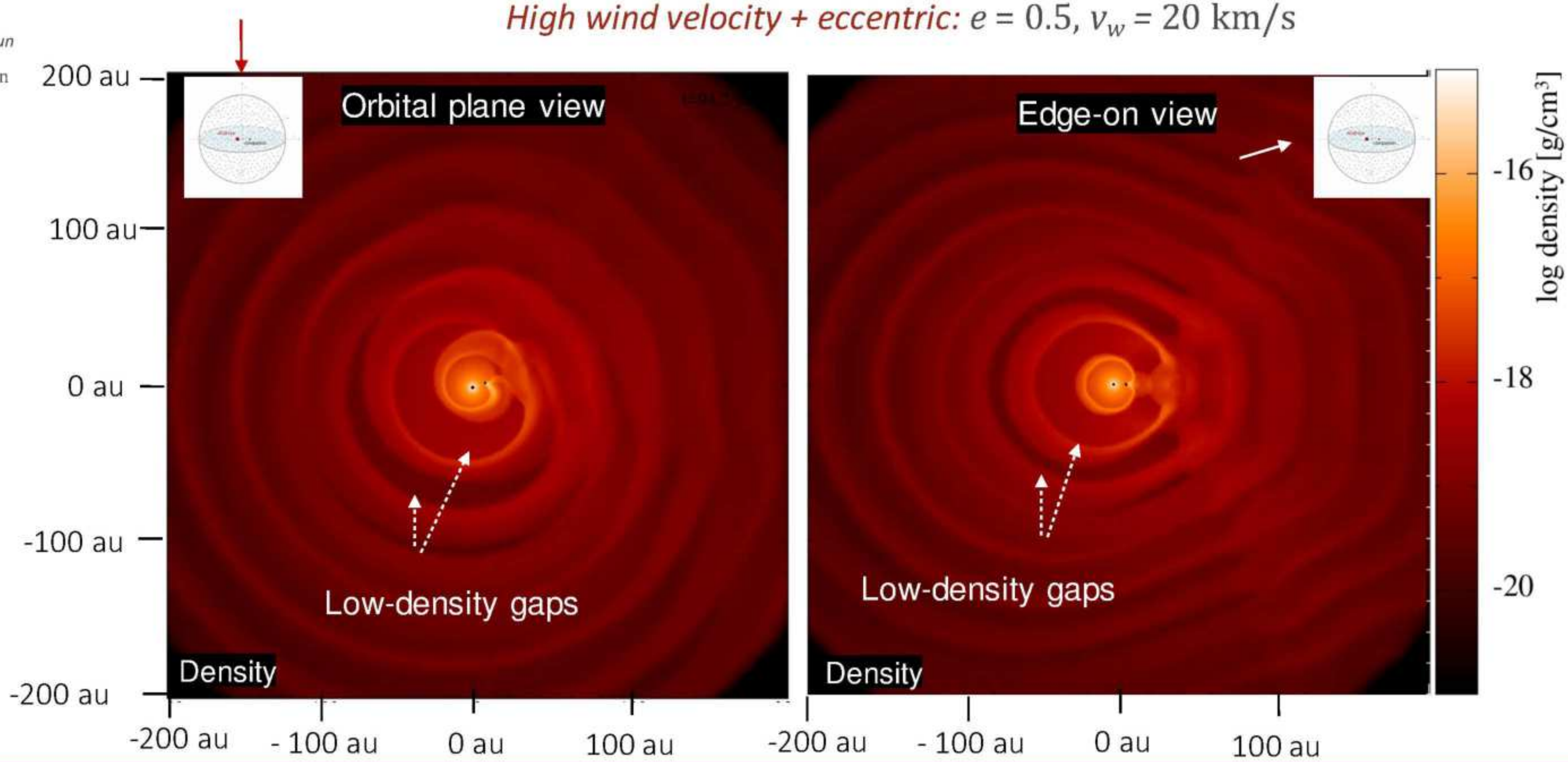

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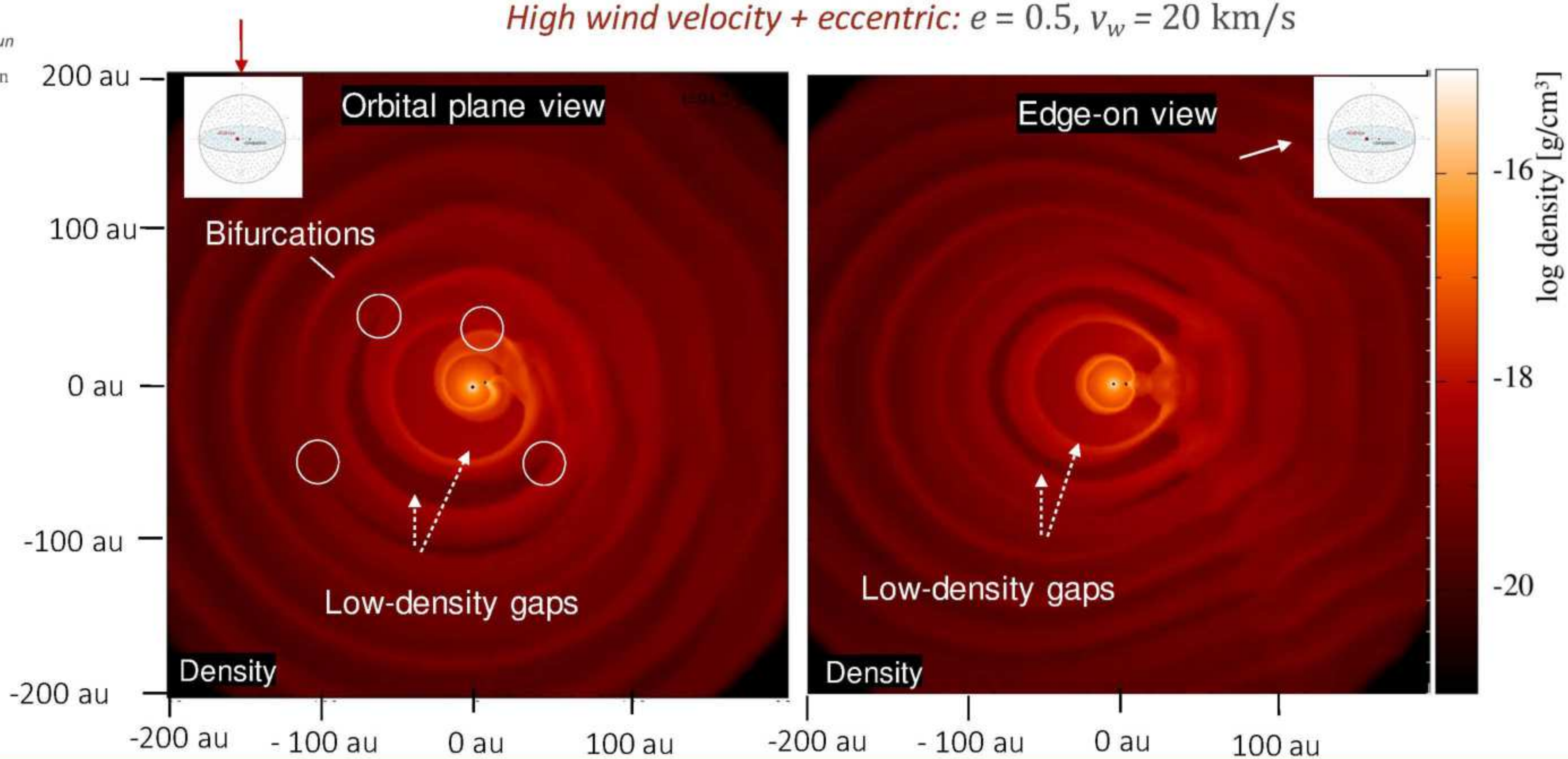
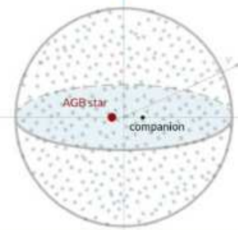


AGB wind model

Malfait+ *2023 (in prep)*
Malfait+ *2021*

Morphology types: eccentric binaries

Orbital plane view



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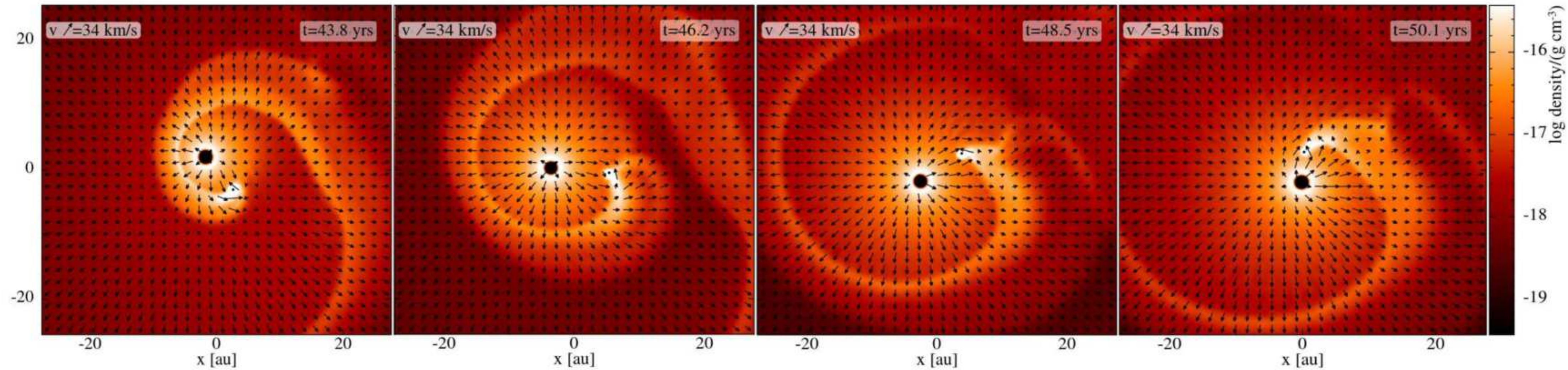
High wind velocity + eccentric: $e = 0.5$, $v_w = 20$ km/s

Bow shock | Bow shock gets detached from companion | 2 - edged spiral forms



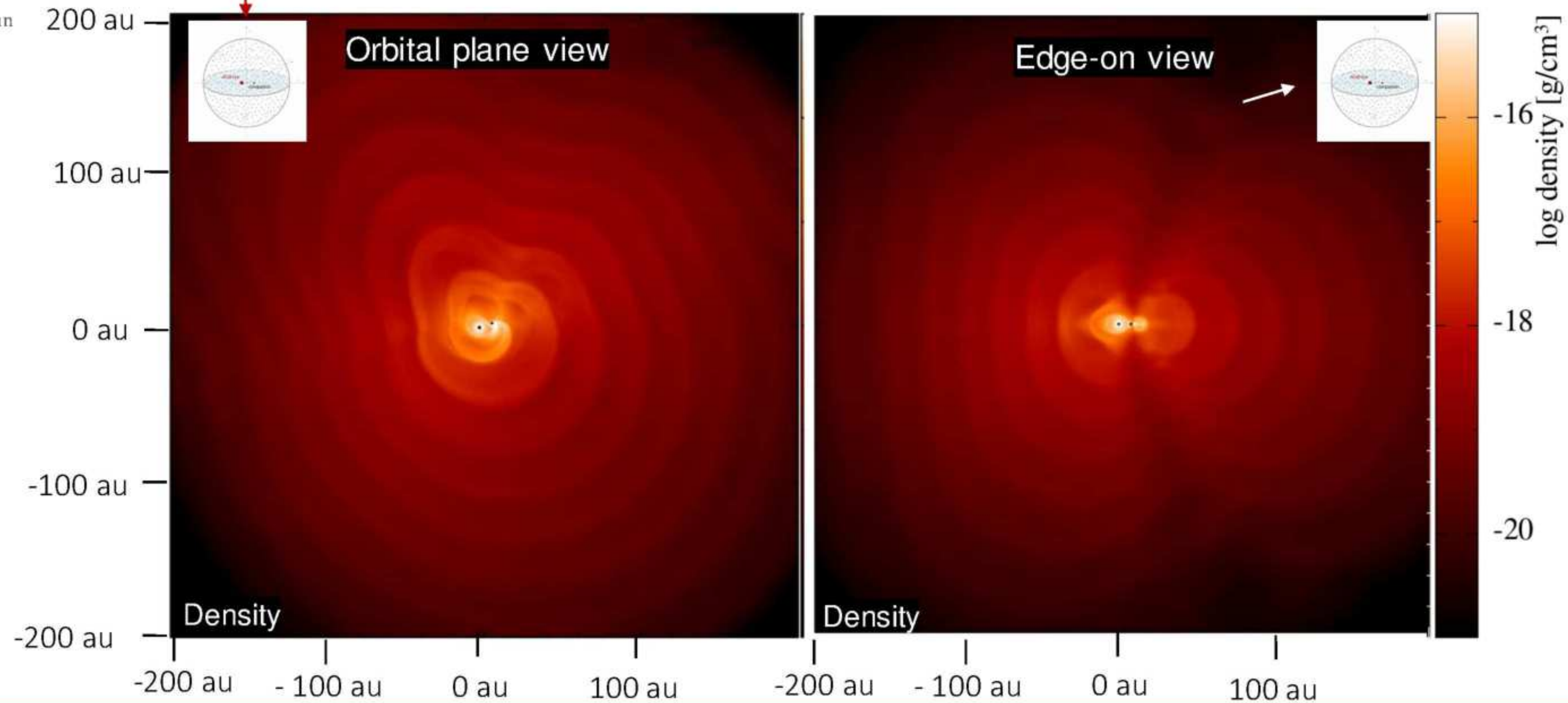
AGB wind model

Malfait+ 2023 (in prep)

Morphology types: eccentric binaries

$a = 6$ au
$M_{AGB} = 1.5\ M_{sun}$
$M_{comp} = 1\ M_{sun}$

Low wind velocity + eccentric: $e = 0.5$, $v_w = 5$ km/s



AGB wind model

Malfait+ 2023 (in prep)

Morphology types: eccentric binaries

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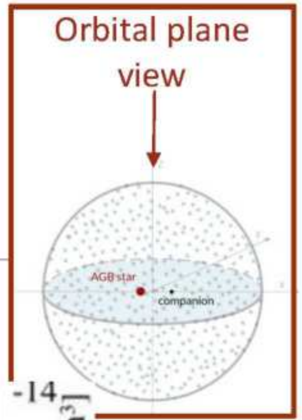
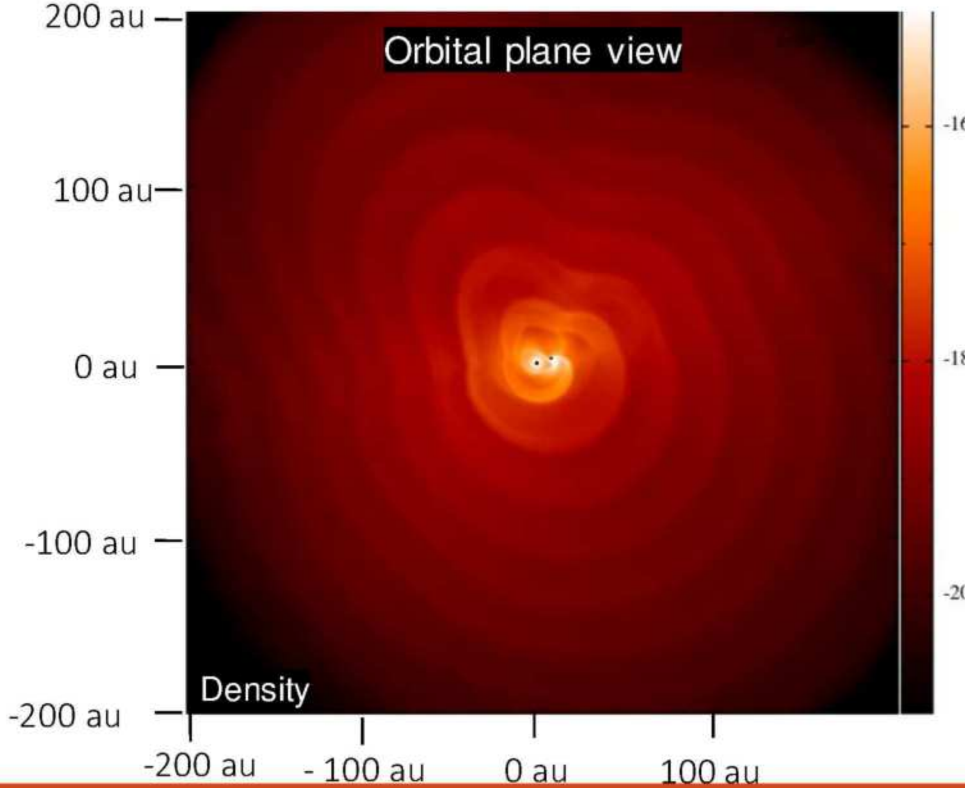
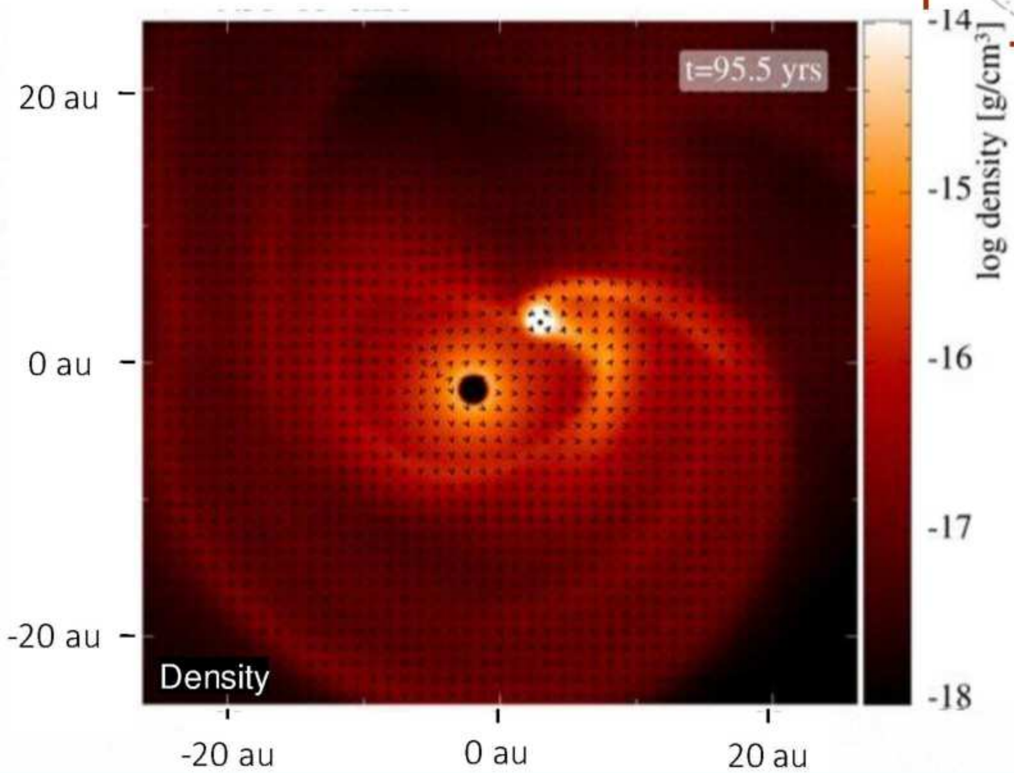
$M_{comp} = 1\ M_{sun}$

Low wind velocity + eccentric: $e = 0.5$, $v_w = 5$ km/s





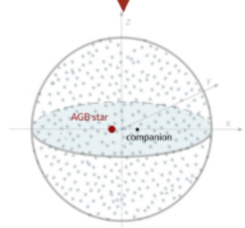


AGB wind model

Malfait+ 2023 (in prep)

Hierarchical triple simulations

Orbital plane view



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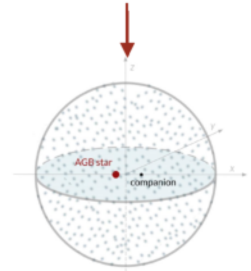

AGB wind model

Malfait+ 2023 (in prep)

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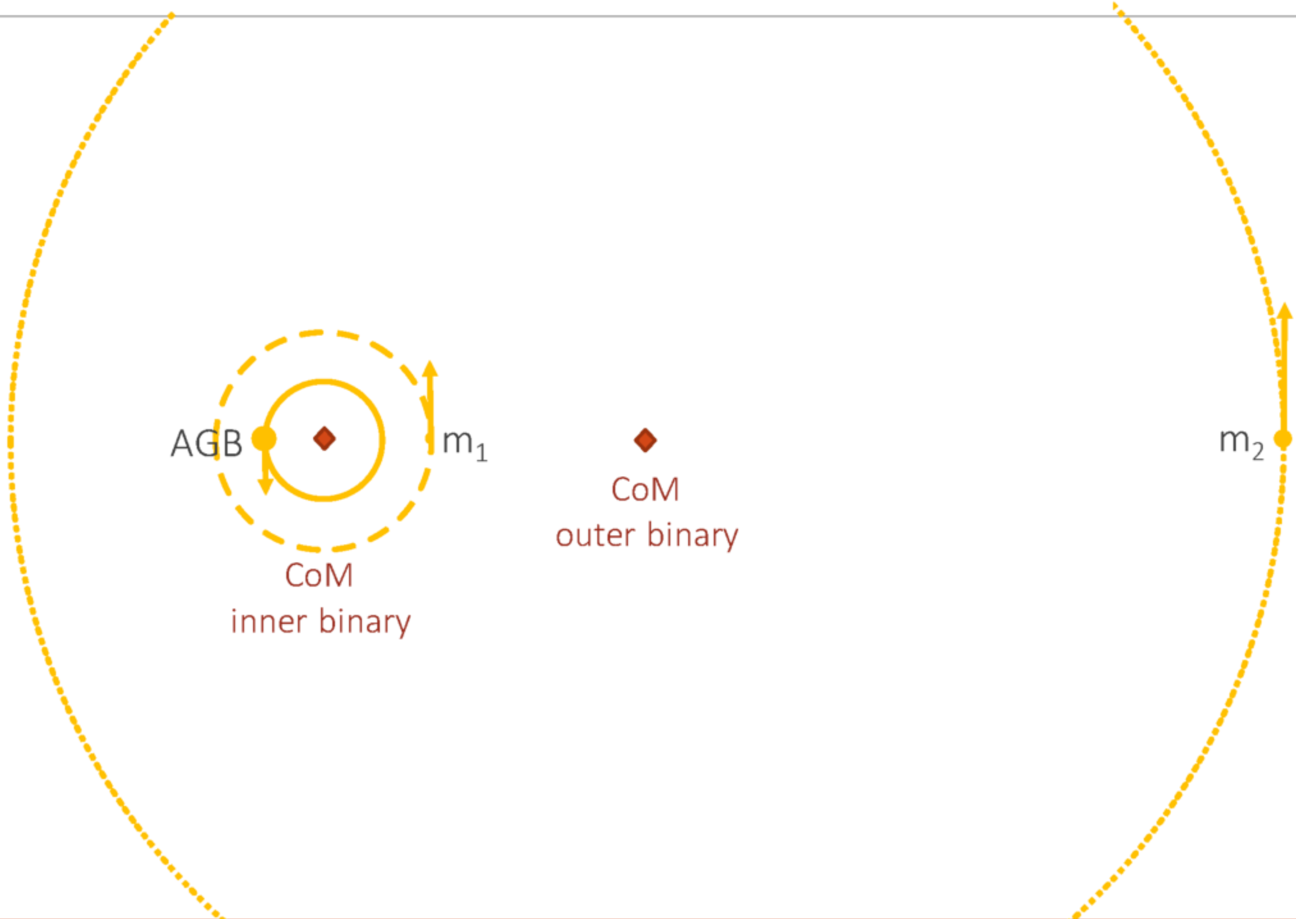
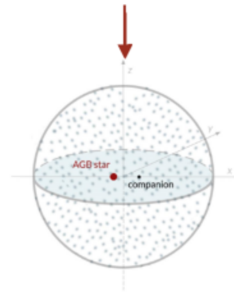


Orbital plane view



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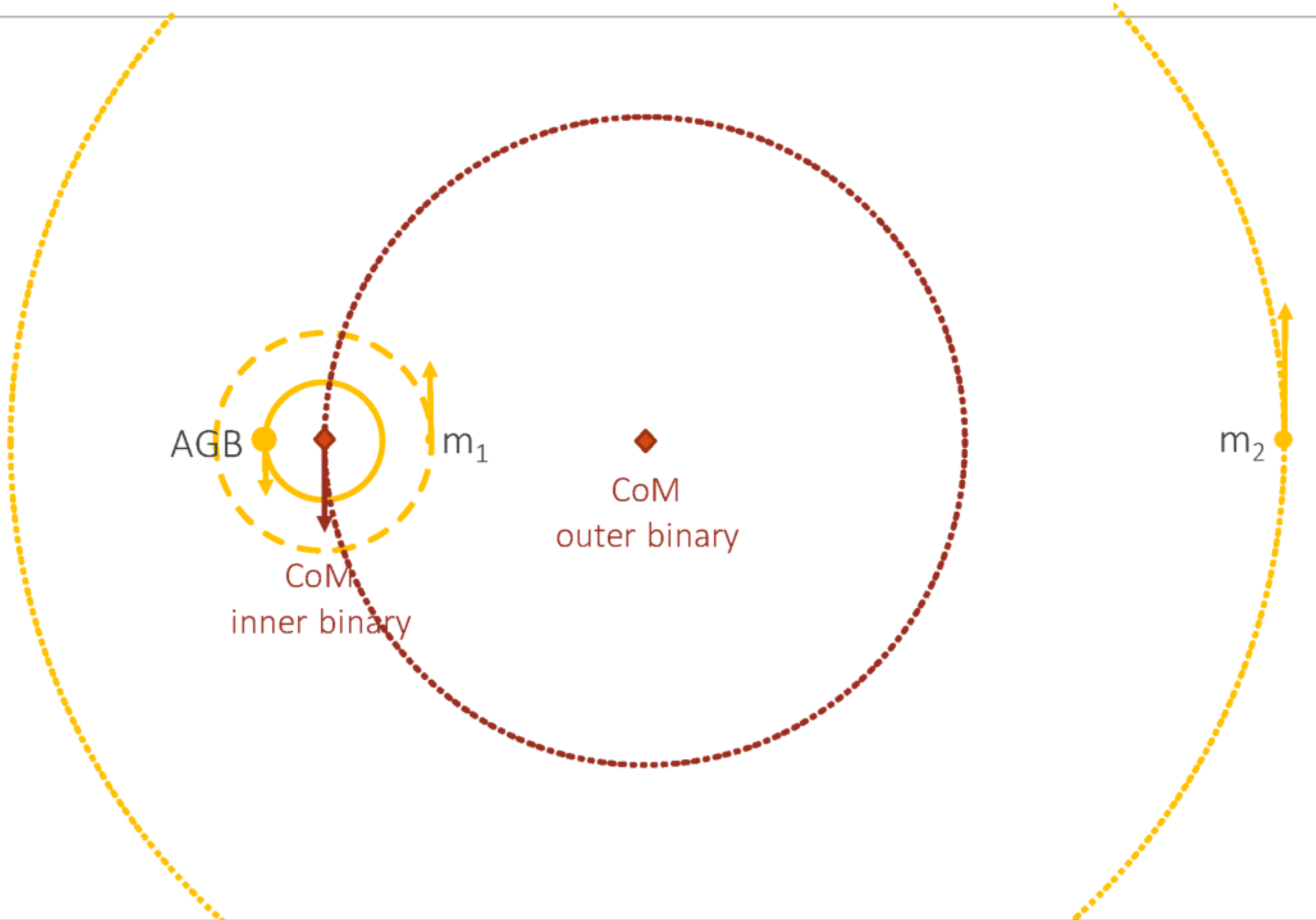
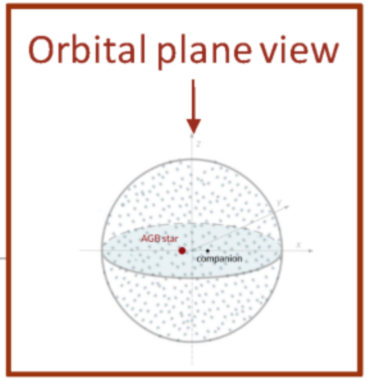
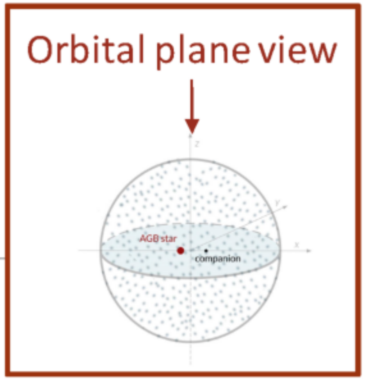


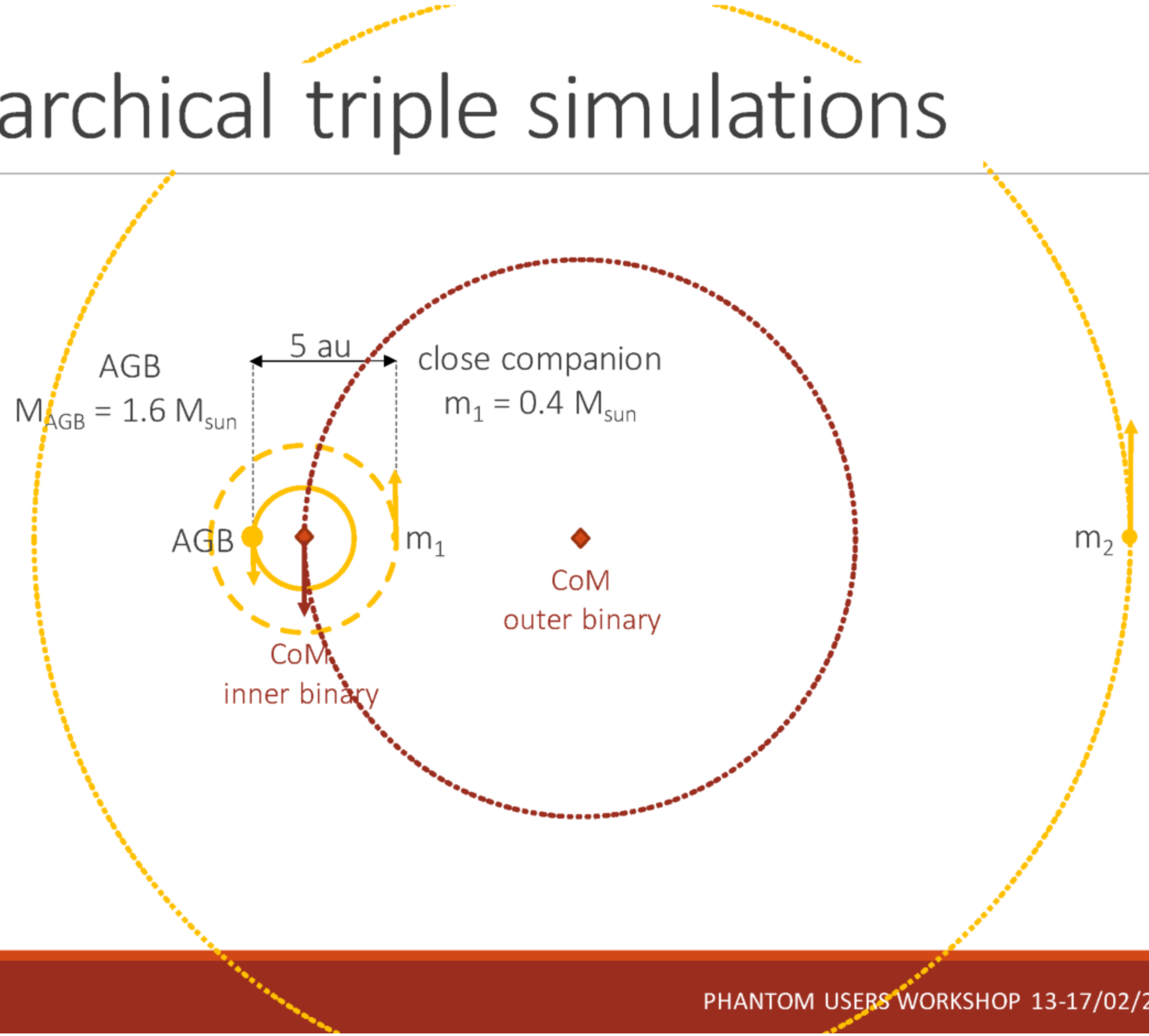


AGB wind model

Malfait+ *2023 (in prep)*

Hierarchical triple simulations





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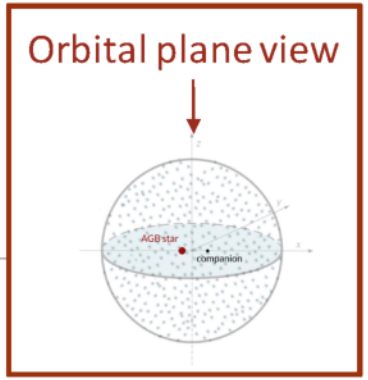
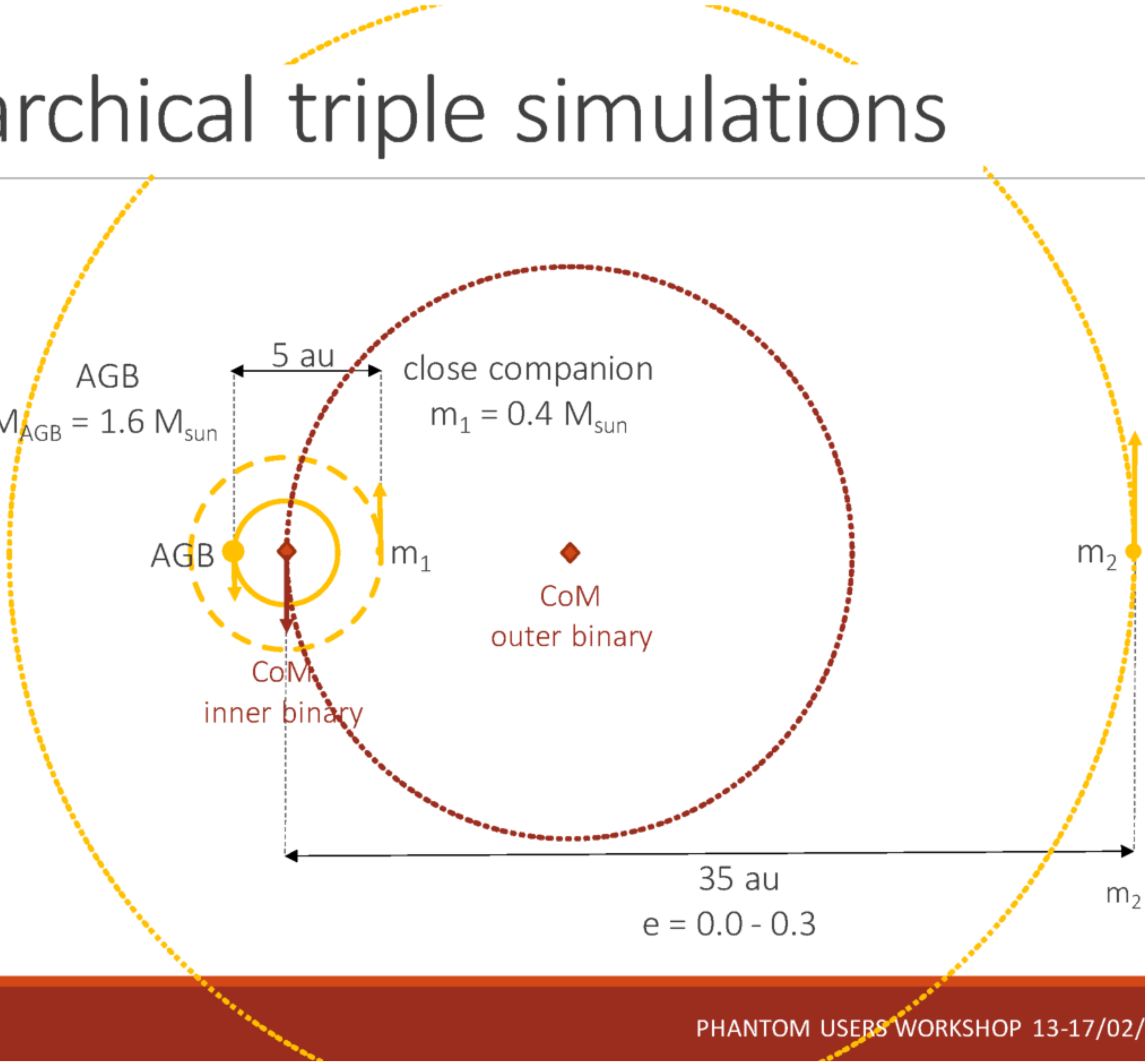
Malfait+ 2023 (in prep)

Hierarchical triple simulations





AGB wind model

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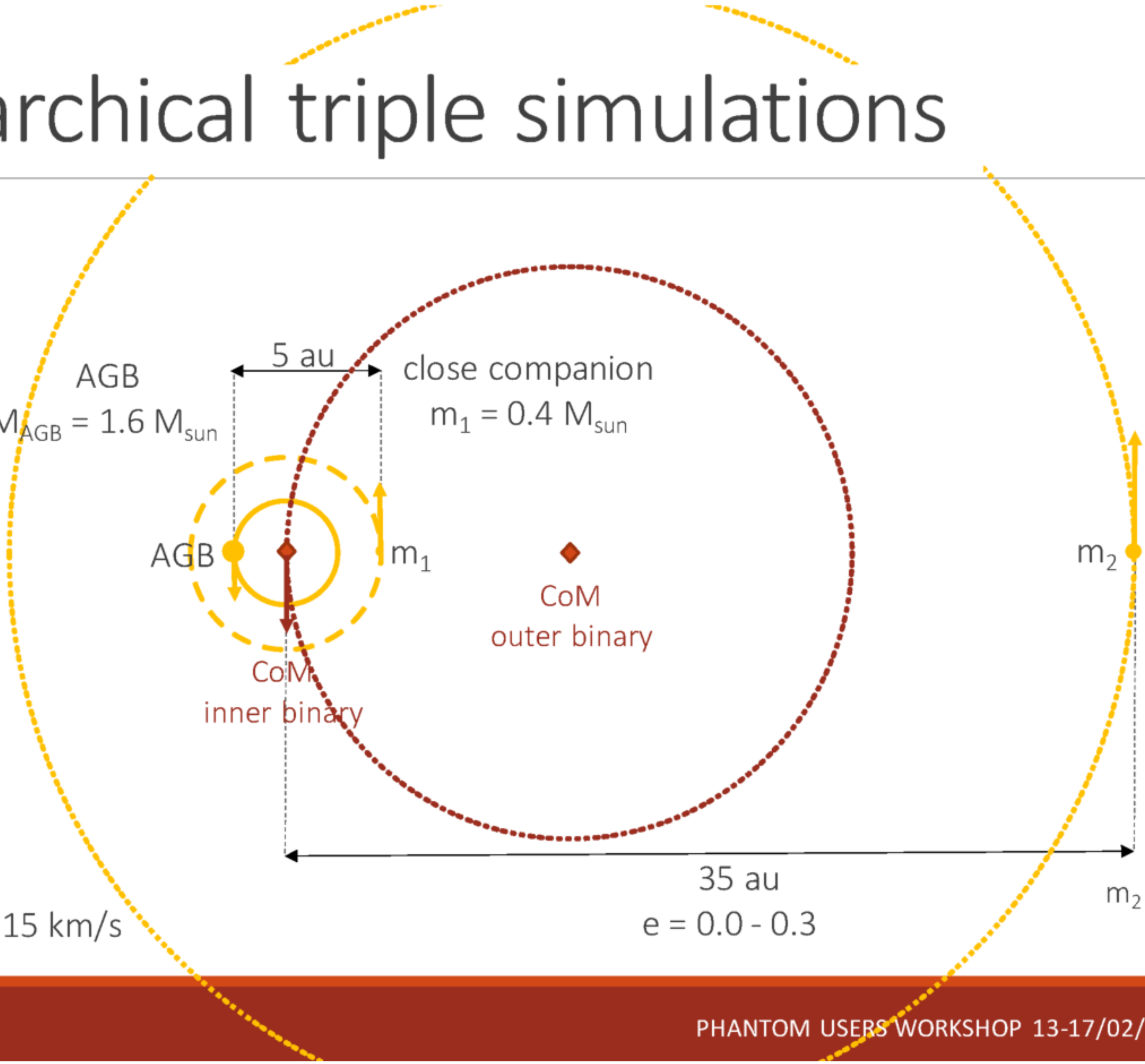
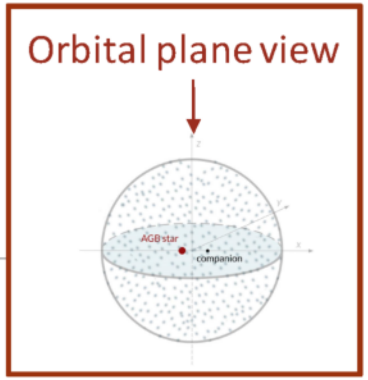


v_w = 8 - 10 - 15 km/s



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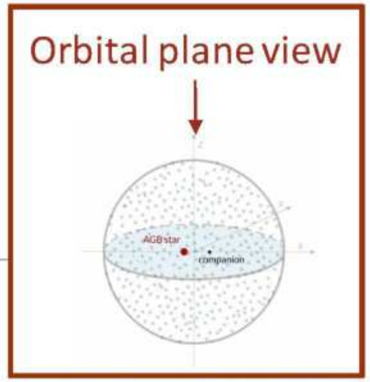
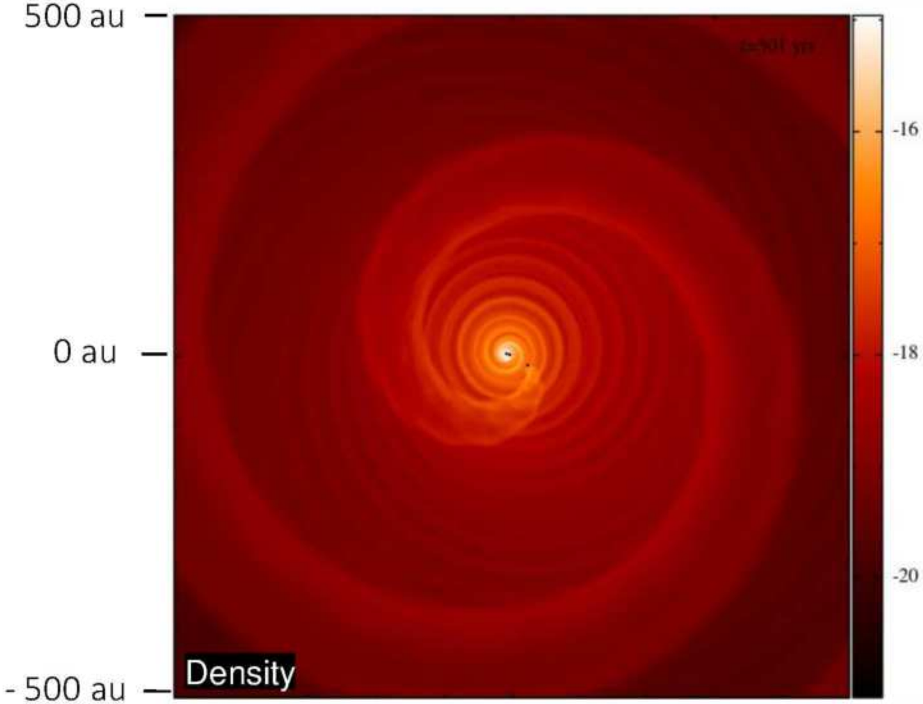
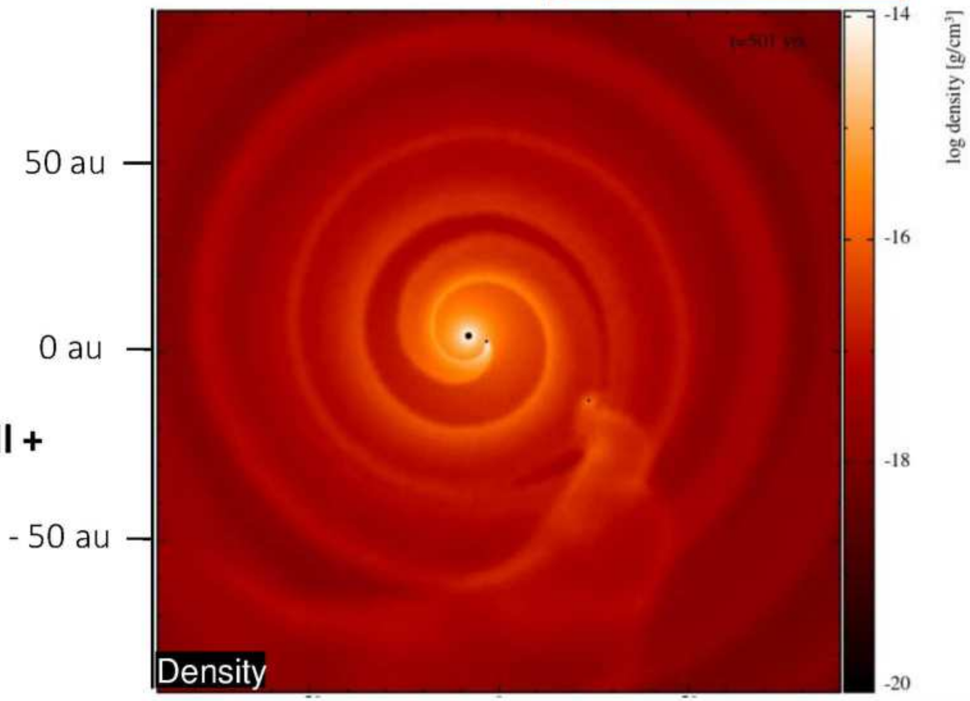




v_w = 15 km/s
e_2 = 0
m_2= 0.6 M_{sun}
a1 = 5 au
a2 = 35 au
M_{AGB}= 1.6 M_{sun}
m_1= 0.4 M_{sun}

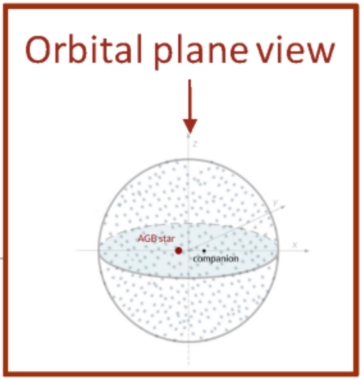
Inner snail shell + outer spiral

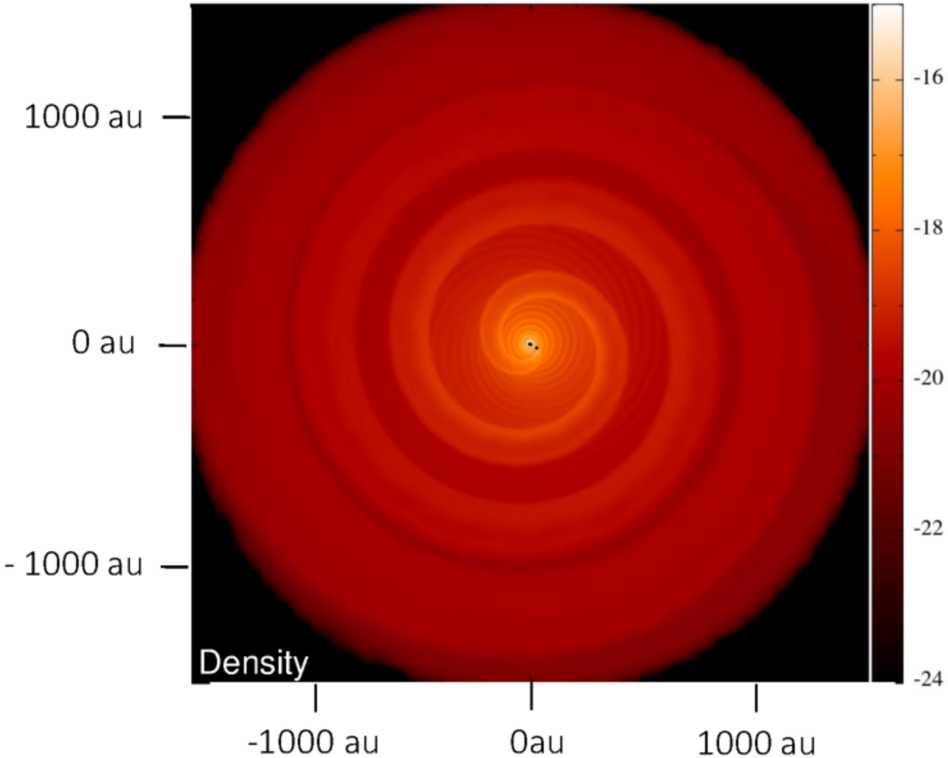


AGB wind model

Malfait+ 2023 (in prep)

Hierarchical triple simulations





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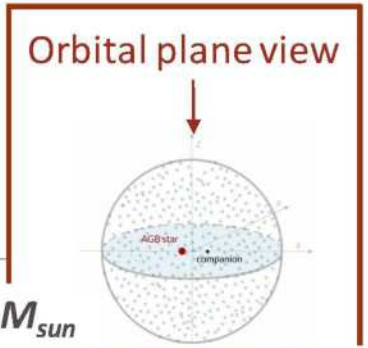
Inner snail shell + outer spiral

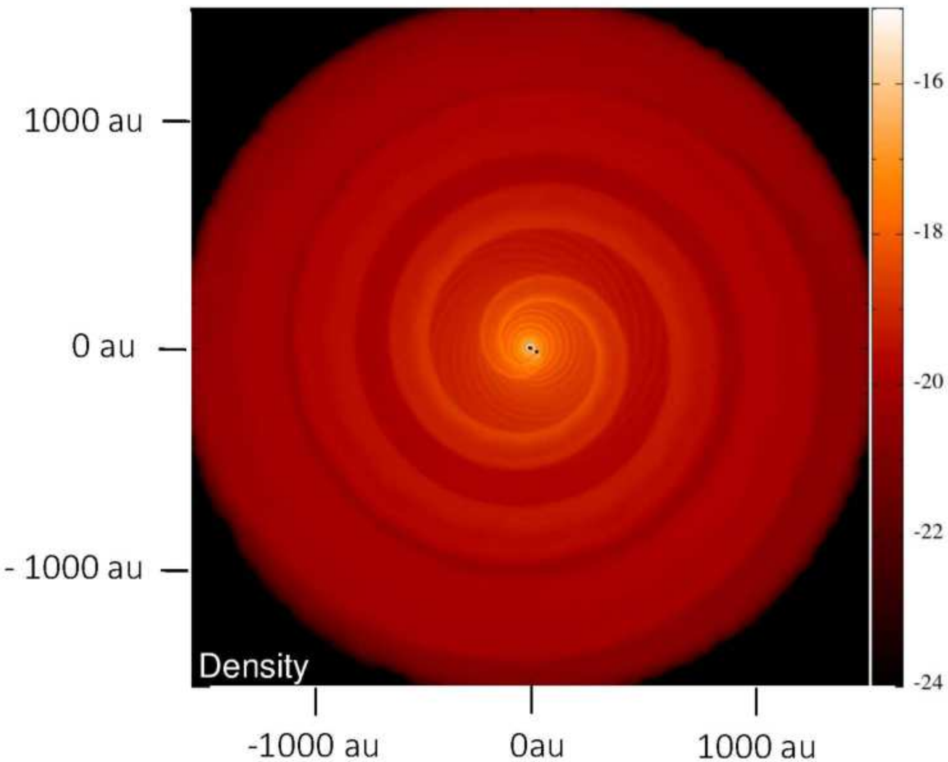
AGB wind model

Malfait+ 2023 *(in prep)*

Hierarchical triple simulations



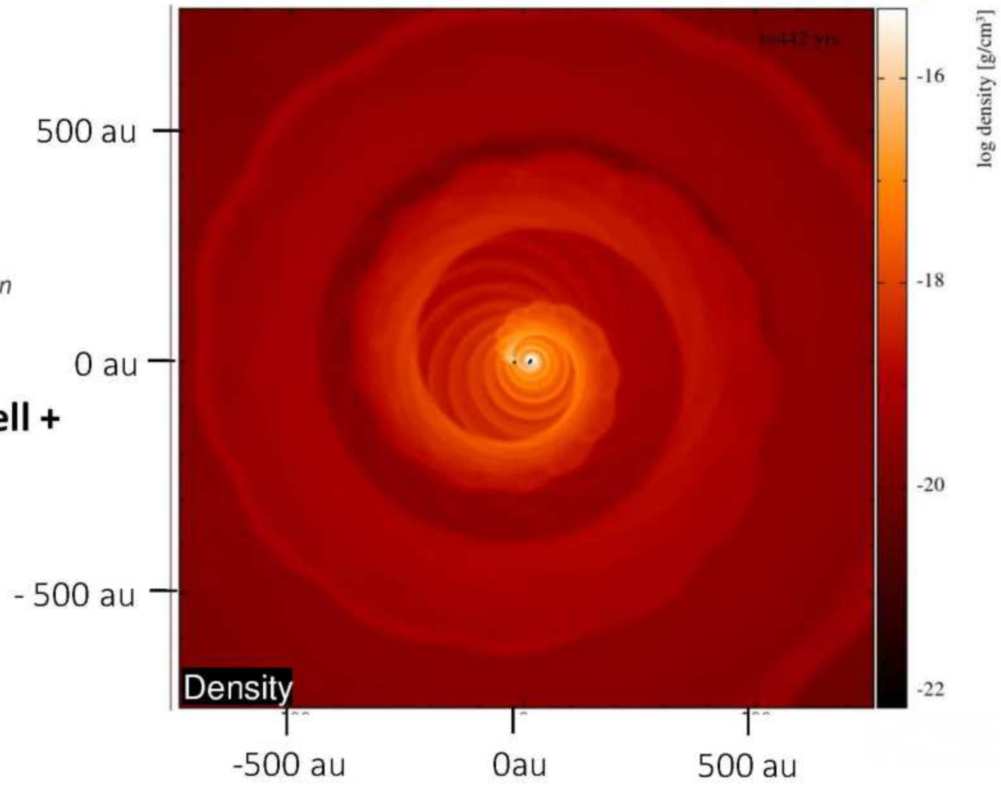
m_2= 0.6 M_{sun}



v_w = 15 km/s
e_2 = 0
a1 = 5 au
a2 = 35 au
M_{AGB}= 1.6 M_{sun}
m_1= 0.4 M_{sun}

Inner snail shell + outer spiral

m_2= 1.5 M_{sun}



What are we working on?

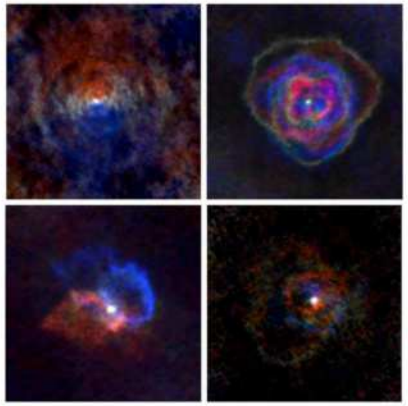
Leen Decin

Lionel Siess

KU LEUVEN

ULB

ATOMIUM
ALMA **observations**



...

Sofia Wallström

Taissa Danilovich

Radiative transfer +
link observations - simulations

Magritte

Thomas Ceulemans

Frederik De Ceuster

Jolien Malfait

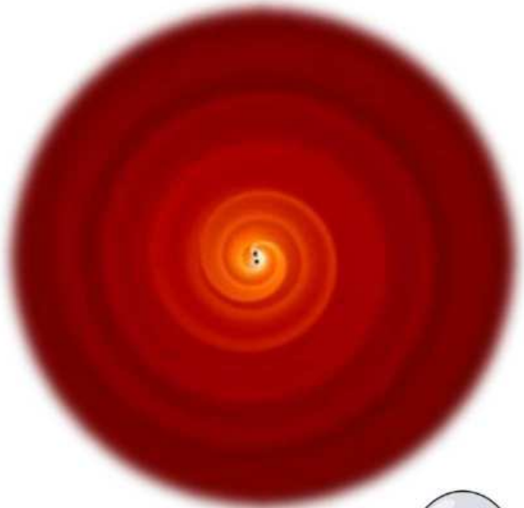
Mats Esseldeurs

Speed up **chemical simulations** in 3D models

In coll. with Marie Van de Sande et al.

Silke Maes

Development **AGB wind model**
+ analysis of hydro-models



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Daniel Price

Chemistry model

Leen Decin

Lionel Siess

What are we working on?

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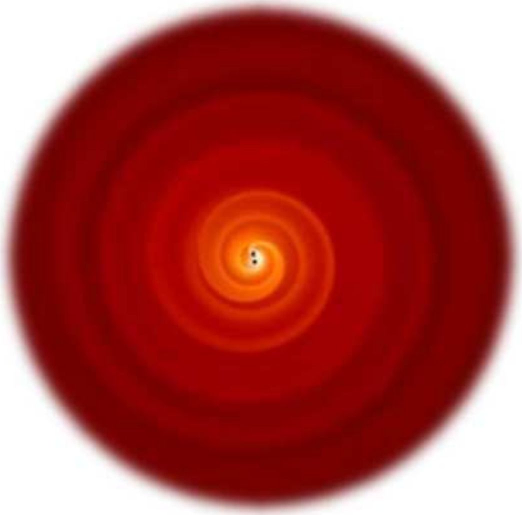
+ analysis of hydro-models



Frederik
De Ceuster

Speed up **chemical simulations**
in 3D models

In coll. with Marie Van de Sande et al.

Silke
Maes

3D chemistry modelling

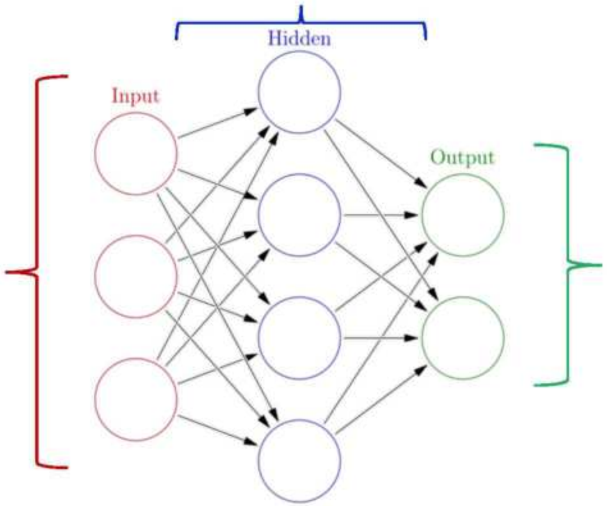
Speed up **chemical simulations** in 3D models

Maes+ (in prep.)

- ***Goal:*** Acceleration of **solving chemistry in 3D** + coupling to hydro
- ***Issue:*** chemical kinetics = solving ODE's --> **computationally infeasibly in 3D** with complex dynamics
- ***Way forward:*** emulate chemical calculations using a **neural network** (*e.g. de Mijola+ 2019, Holdship+ 2021*)

surrogate of chemical kinetics model

physical state & abundances at time *t*



physical state & **new** abundances at time $t + \Delta t$

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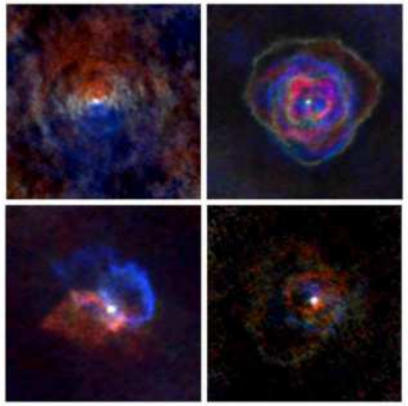
What are we working on?

ATOMIUM
ALMA **observations**



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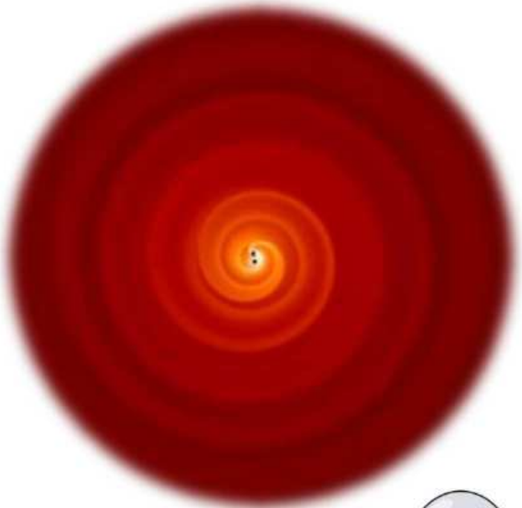

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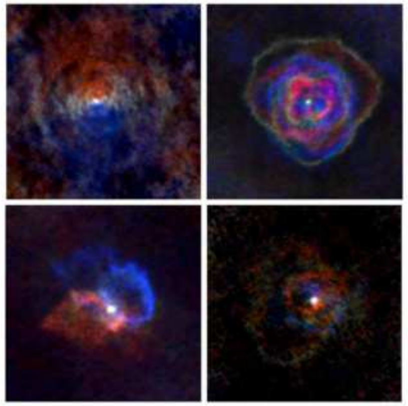

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Magritte for synthetic observations

De Ceuster+ (2020a,b; 2022), Ceulemans+ (in prep.), github.com/Magritte-code/Magritte

An open-source software library for 3D radiative transfer,
e.g. tailored to Phantom models!

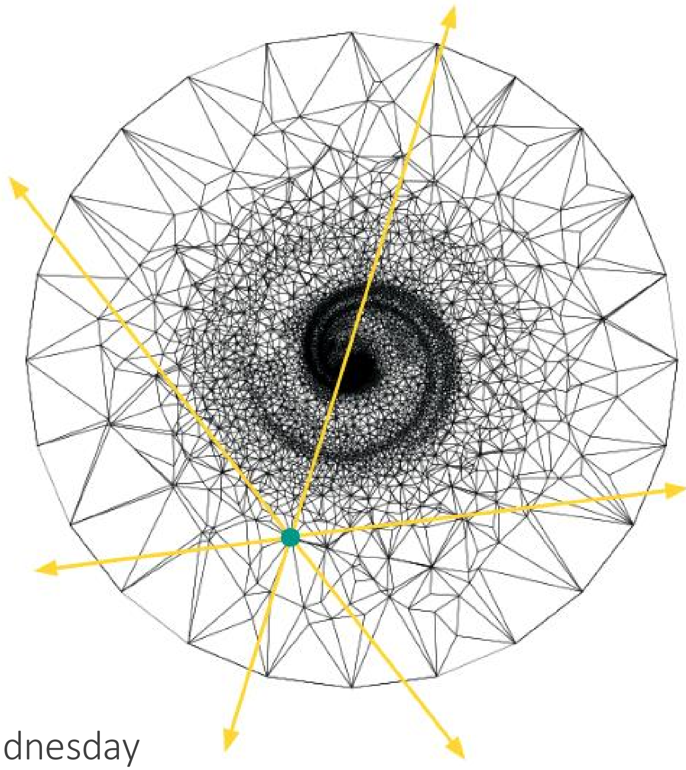
Features

- NLTE **line** radiative transfer
- **Optimize discretization** for RT *(De Ceuster+ 2020b)*

How it works

- Only uses **point cloud with nearest neighbor information** (no grid)
- **Traces rays** and **solves RT equation** along each ray

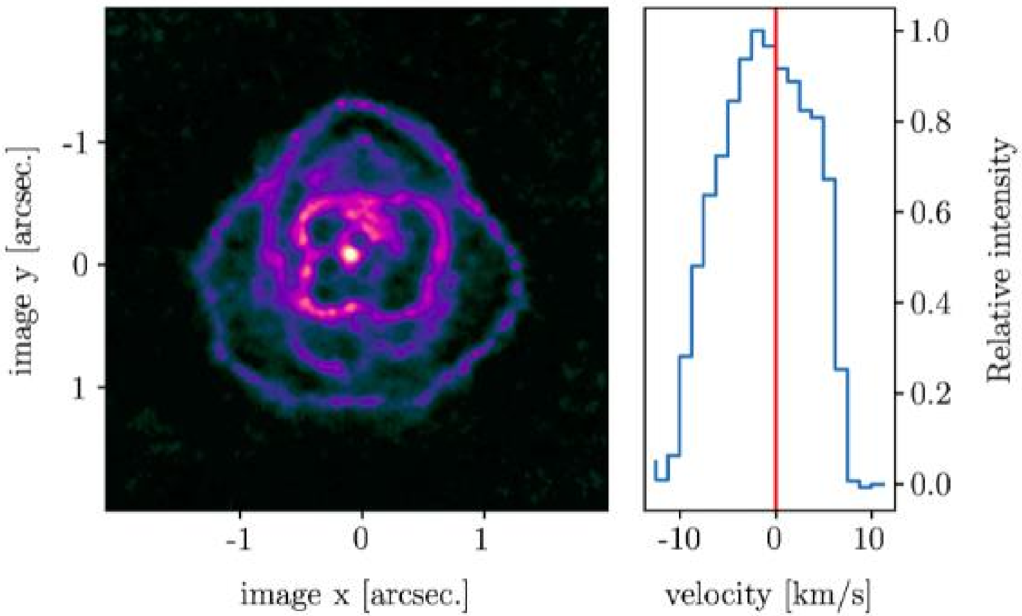
Used in Phantom *(Esseldeurs+ In prep)* & See talk Lionel on Wednesday

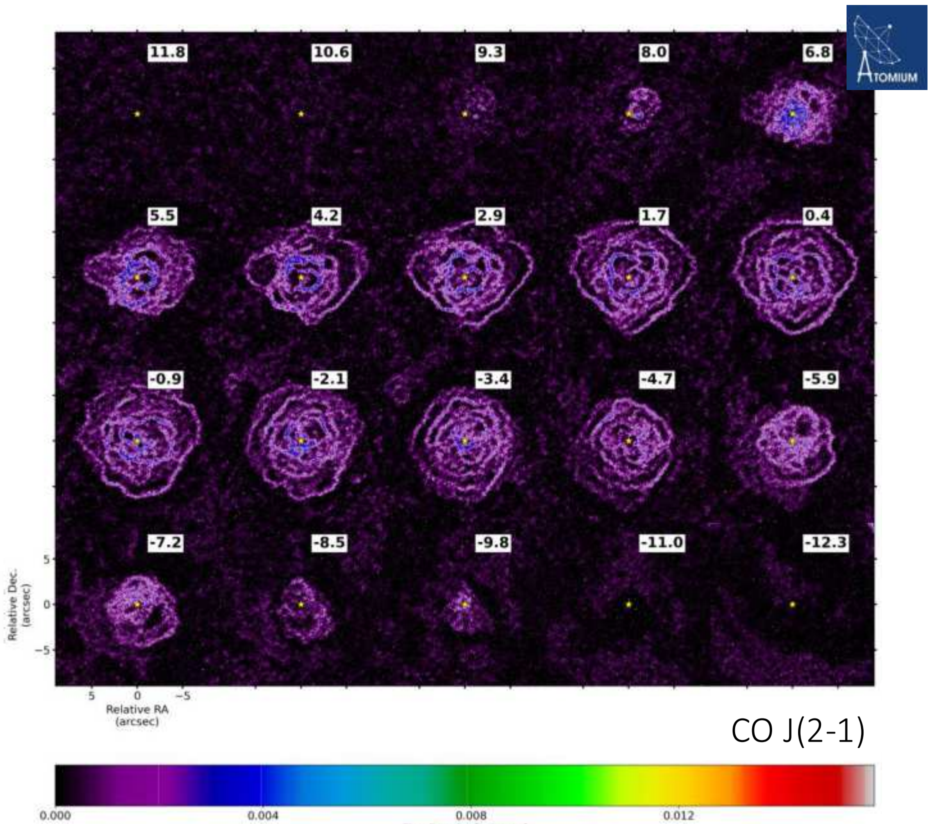


Example: R Aquilae

(ALMA observation, *Decin+ 2020*)

Velocity channel maps





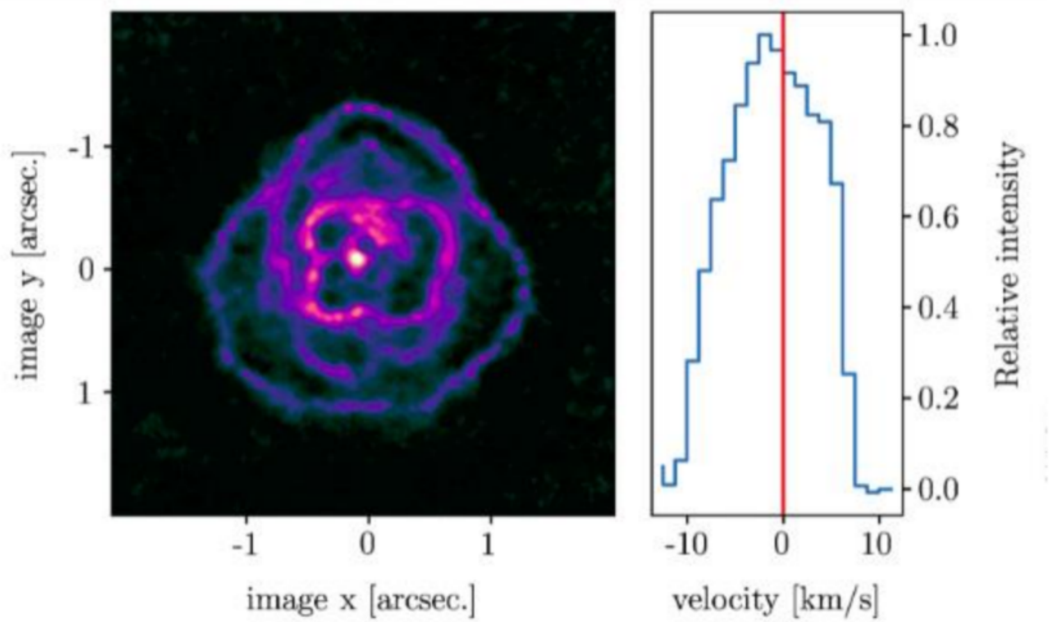
CO J(2-1)

Flux Density [Jy/beam]

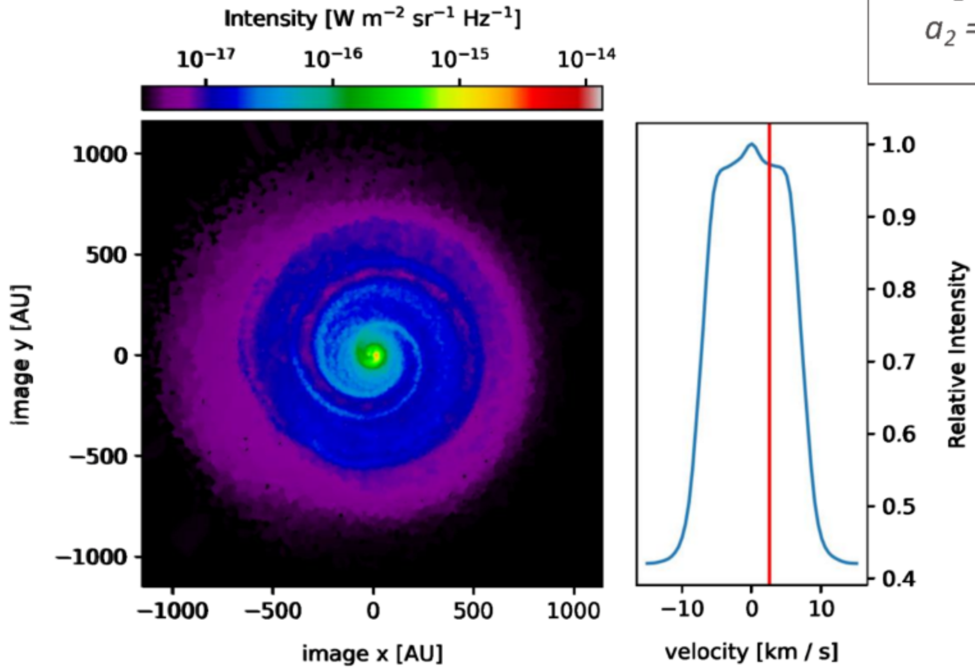
Example: RT forward model

M_{AGB}= 1.6 M_{sun}
m_1= 0.4 M_{sun}
m_2= 1.5 M_{sun}
v_w = 8 km/s
a_1 = 5 au
a_2 = 35 au

R Aql observation



Triple system synthetic observations



(+ casa simulator should still be applied)

Magritte

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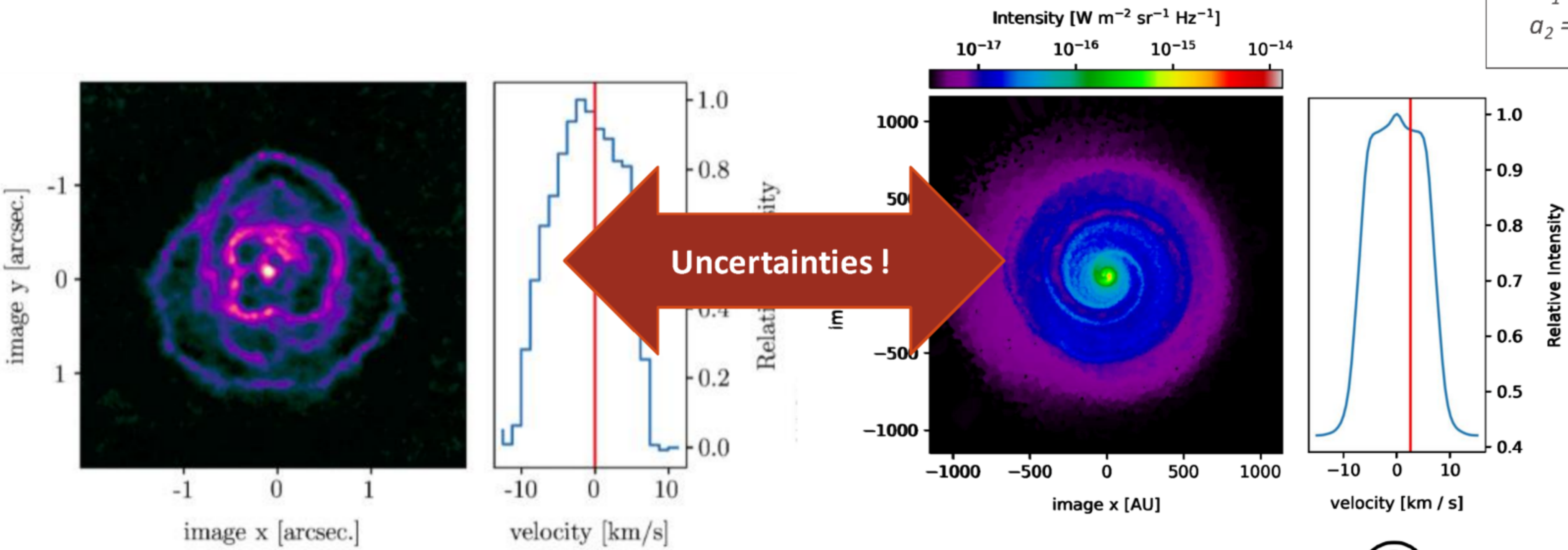

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De-projecting observations into models

Frederik
De Ceuster

De Ceuster+ (in prep.), Coenegrachts+ (in prep., previous talk by Taissa), Malfait+ (in prep.)

Forward modeling: from models to (synthetic) spectral line observations

- Difficult to create models that resemble observations, and thus difficult to compare them

Frederik De Ceuster

De-projecting observations into models

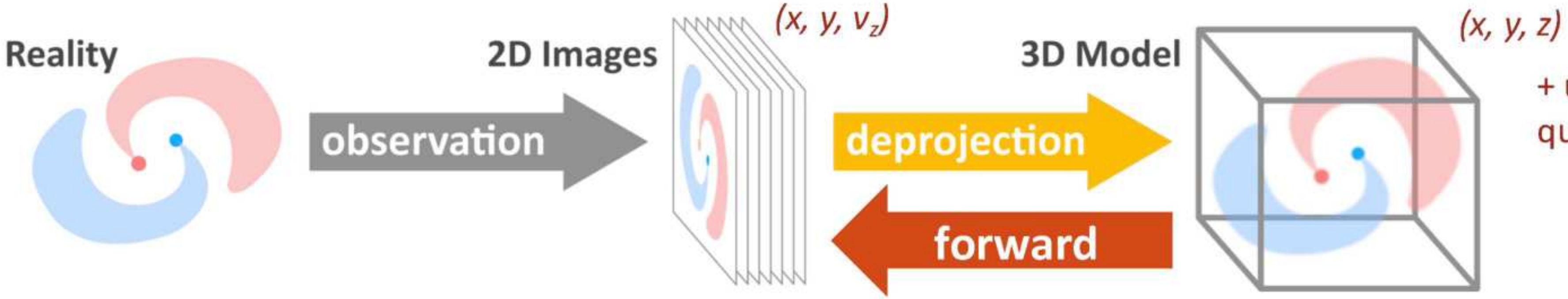
De Ceuster+ (in prep.), Coenegrachts+ (in prep., previous talk by Taissa), Malfait+ (in prep.)

Forward modeling: from models to (synthetic) spectral line observations

- Difficult to create models that resemble observations, and thus difficult to compare them

Inverse (de-projection) modeling: turning (real) spectral line observations into models

- Use information encoded in the frequency-dependence to infer the depth-dependence



What are we working on?

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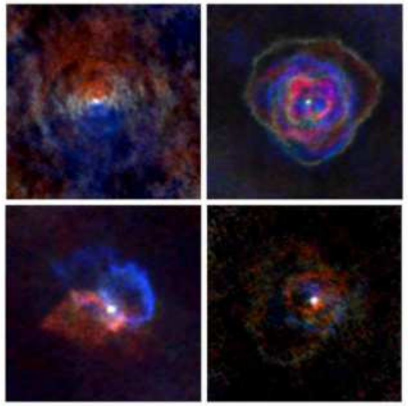
Lionel Siess

ULB

ATOMIUM
ALMA **observations**



Sofia Wallström

Taissa Danilovich

...

Radiative transfer +
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Magritte

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Silke Maes

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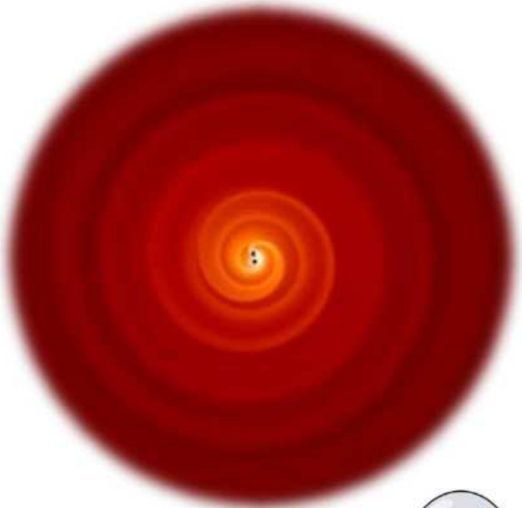

PHANTOM

Daniel Price

Conclusions

Phantom Users Workshop
Monash University, Melbourne, Australia
Feb 13-17, 2023

jolien.malfait@kuleuven.be

- AGB outflows are complex, impact from **wind-companion interactions**
- Hydro-models help us understand **structure formation in binary and triple systems**
- Development of **improved AGB-wind model**, with **chemistry coupling**
- Radiative transfer solver **Magritte** + ALMA simulator + deprojection help to **compare simulations & observations**
- MCFOST?
- *! Post-doc vacancy on theoretical and hydrodynamic modelling @KU Leuven !*

PHANTOM

Magritte

github.com/Magritte-code/Magritte

In collaboration with:
Leen Decin
Lionel Siess (ULB)
Frederik De Ceuster
Silke Maes
Mats Esseldeurs
Thomas Ceulemans

KU LEUVEN
ULB
ATOMIUM