# THE ROLE OF AN ASYMMETRIC RADIATION FIELD IN SHAPING PROTOPLANETARY DISC CHEMISTRY AND DYNAMICS IN STELLAR BINARY SYSTEMS

PHANTOM WORKSHOP 2025

**SPEAKER:**

**PEDRO P. POBLETE**

Université Grenoble Alpes

IPAG

Institut de Planétologie et d'Astrophysique de Grenoble

# PHANTOM-MCFOST IN BINARIES

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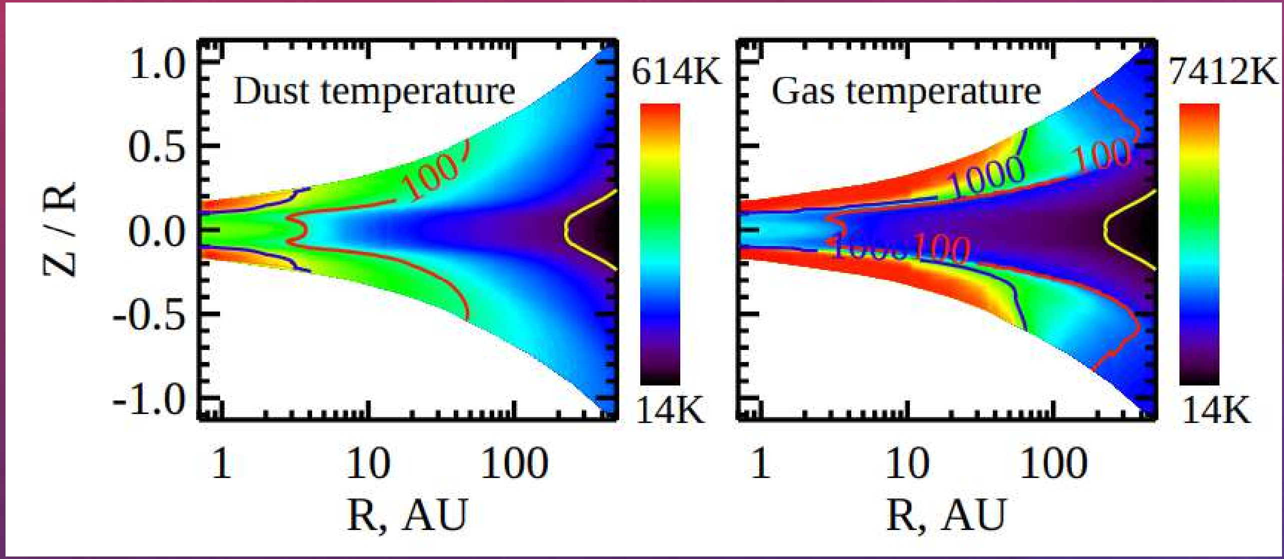
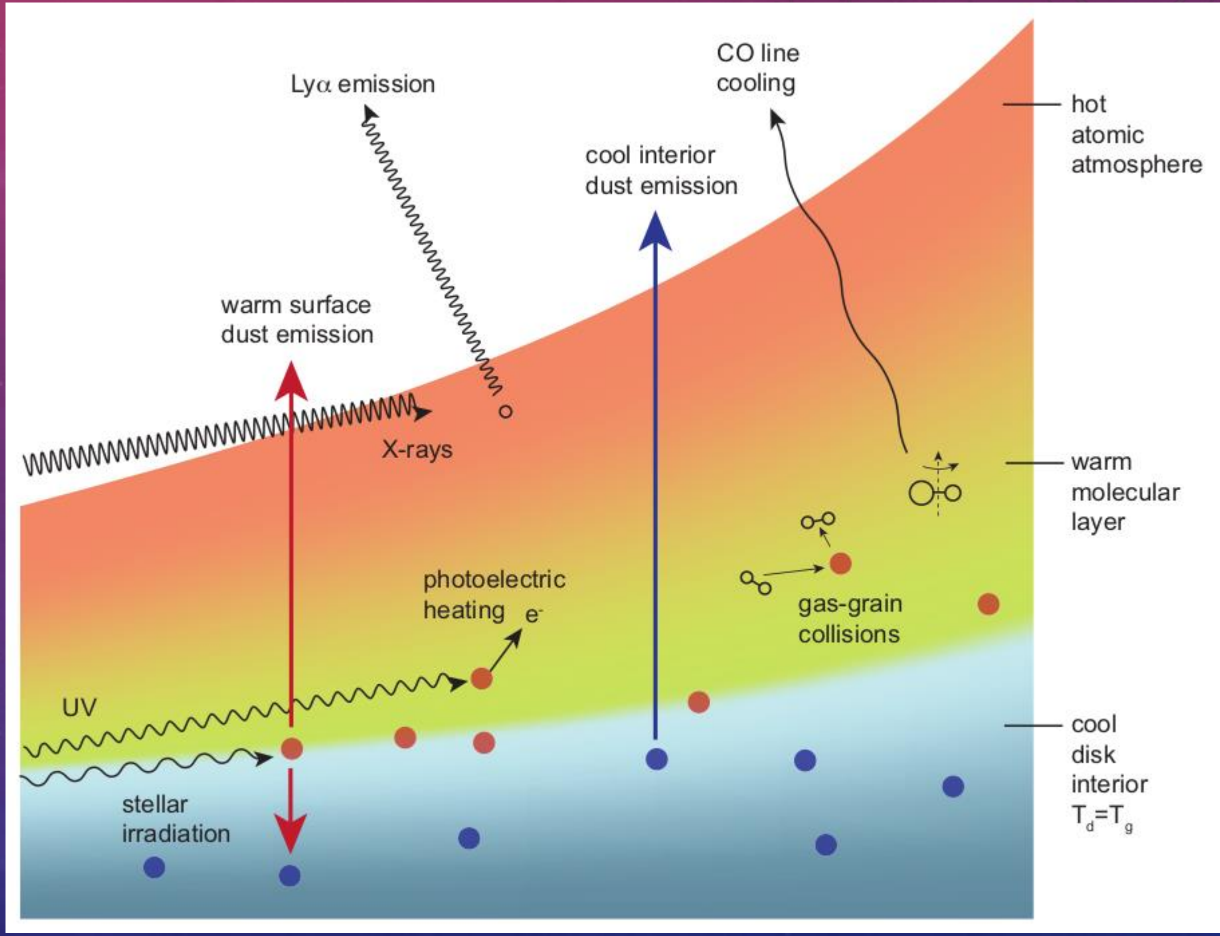
# INTRODUCTION
## THERMAL STRATIFICATION




*Henning & Semenov 2013*




*Armitage 2019*

Accurate modelling of the disc temperature profile is essential for properly simulating the disc's dynamics and chemistry.

# INTRODUCTION

## PHANTOM & MCFOST


Hydrodynamic simulations (PHANTOM)
+
Temperature profile computed by Monte Carlo + ray tracing (MCFOST)

# INTRODUCTION
## PHANTOM & MCFOST

Letter | Published: 12 August 2019

**Kinematic detection of a planet carving a gap in a protoplanetary disk**

C. Pinte, G. van der Plas, F. Ménard, D. J. Price, V. Christiaens, T. Hill, D. Mentiplay, C. Ginski, E. Choquet, Y. Boehler, G. Duchêne, S. Perez & S. Casassus

*Nature Astronomy* **3**, 1109–1114 (2019) | Cite this article

**1927** Accesses | **87** Altmetric | Metrics


Previous PHANTOM+MCFOST coupled implementations

Pinte+2019

# INTRODUCTION
## PHANTOM & MCFOST

JOURNAL ARTICLE

**Rocking shadows in broken circumbinary discs** FREE

Rebecca Nealon, Daniel J Price, Christophe Pinte

*Monthly Notices of the Royal Astronomical Society: Letters*, Volume 493, Issue 1, March 2020, Pages L143–L147, https://doi.org/10.1093/mnrasl/slaa026

**Published:** 11 February 2020 **Article history** ▾


Previous PHANTOM+MCFOST coupled implementations

Pinte+2019
Nealon+2020

# INTRODUCTION
## PHANTOM & MCFOST

JOURNAL ARTICLE

**On the rise times in FU Orionis events** FREE

Elisabeth M A Borchert ✉, Daniel J Price, Christophe Pinte, Nicolás Cuello

*Monthly Notices of the Royal Astronomical Society: Letters*, Volume 510, Issue 1, February 2022, Pages L37–L41, https://doi.org/10.1093/mnrasl/slab123
**Published:** 27 November 2021 **Article history ▾**


Previous PHANTOM+MCFOST coupled implementations

Pinte+2019
Nealon+2020
Borchert+2022a

# INTRODUCTION

## PHANTOM & MCFOST


JOURNAL ARTICLE

**Sustained FU Orionis-type outbursts from colliding discs in stellar flybys** FREE

Elisabeth M A Borchert ✉ , Daniel J Price , Christophe Pinte , Nicolás Cuello

*Monthly Notices of the Royal Astronomical Society*, Volume 517, Issue 3, December 2022, Pages 4436–4446, https://doi.org/10.1093/mnras/stac2872

**Published:** 07 October 2022 **Article history** ▾

Previous PHANTOM+MCFOST coupled implementations

Pinte+2019
Nealon+2020
Borchert+2022a
Borchert+2022b

# INTRODUCTION
## PHANTOM & MCFOST


JOURNAL ARTICLE

**Short-lived gravitational instability in isolated irradiated discs**

Sahl Rowther, Daniel J Price, Christophe Pinte, Rebecca Nealon, Farzana Meru, Richard Alexander

*Monthly Notices of the Royal Astronomical Society*, Volume 534, Issue 3, November 2024, Pages 2277–2285, https://doi.org/10.1093/mnras/stae2167

**Published:** 18 September 2024 **Article history** ▾

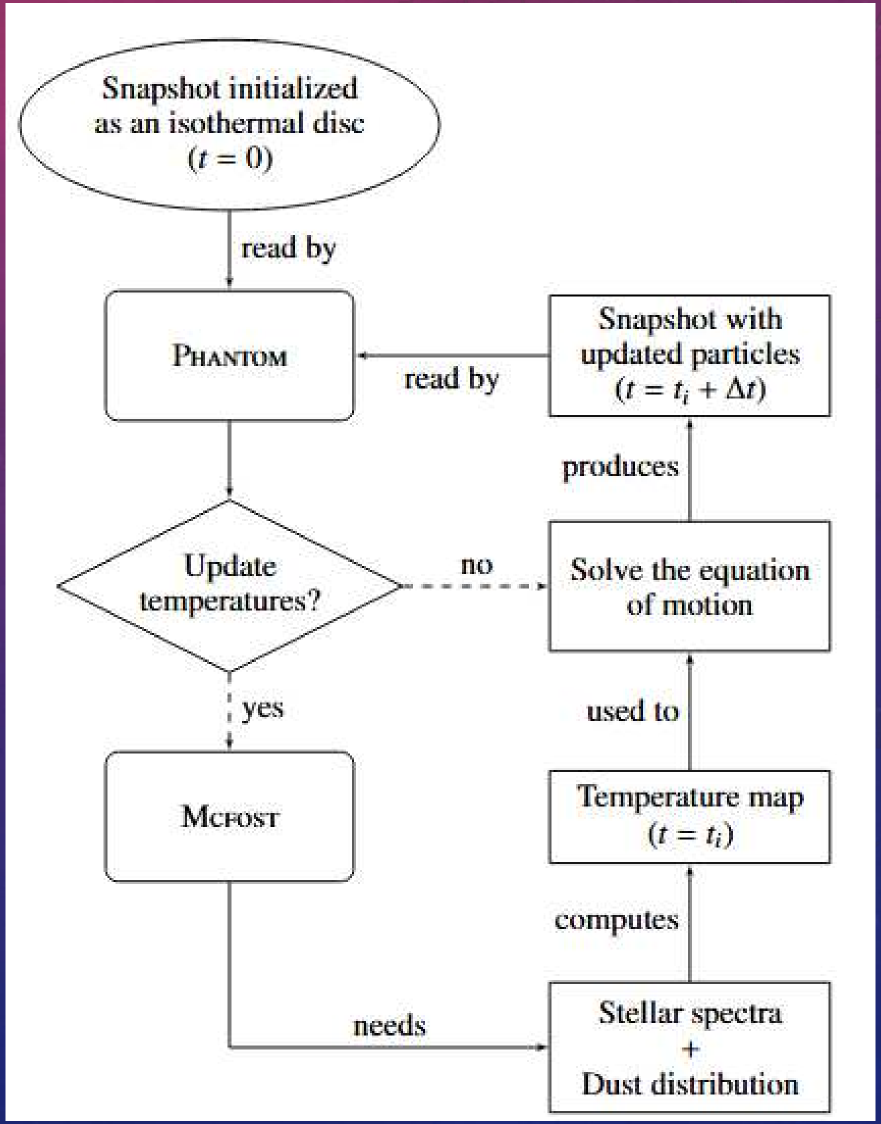
Previous PHANTOM+MCFOST coupled implementations

Pinte+2019
Nealon+2020
Borchert+2022a
Borchert+2022b
Rowther+2024

The unofficial PHANTOM+MCFOST “how it works” documentation

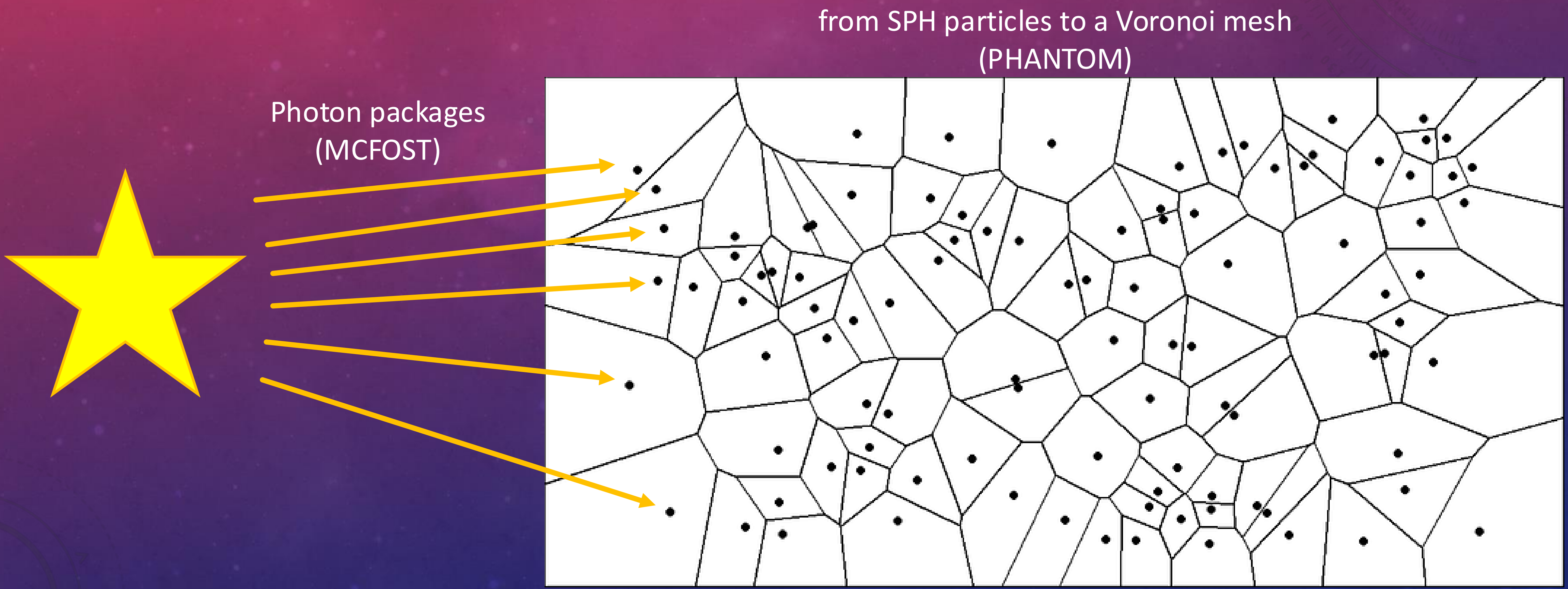
# INTRODUCTION

## PHANTOM & MCFOST – HOW IT WORKS

# INTRODUCTION

## PHANTOM & MCFOST – HOW IT WORKS






*made by Francesco Bellelli*

# METHODS

## SIMULATION SETUP

$M_{\text{disc}} = 2 \cdot 10^{-3} M_{\odot}$

Dust-to-gas ratio $= 0.01$

**Perfect dust to gas coupling**

**&**

**One-fluid simulations**

Bin 1: $1.0\ \mathrm{M}_{\odot}/1.0\ L_{\odot}$

Bin 2: $0.5\ \mathrm{M}_{\odot}/0.036\ L_{\odot}$

$a = 50$ au

$e = 0.50$

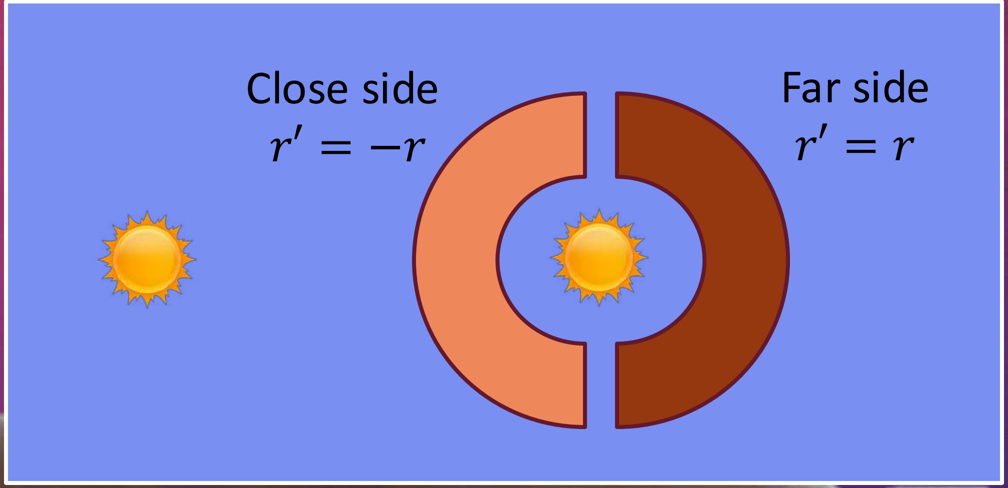
$i = 0°/30°$

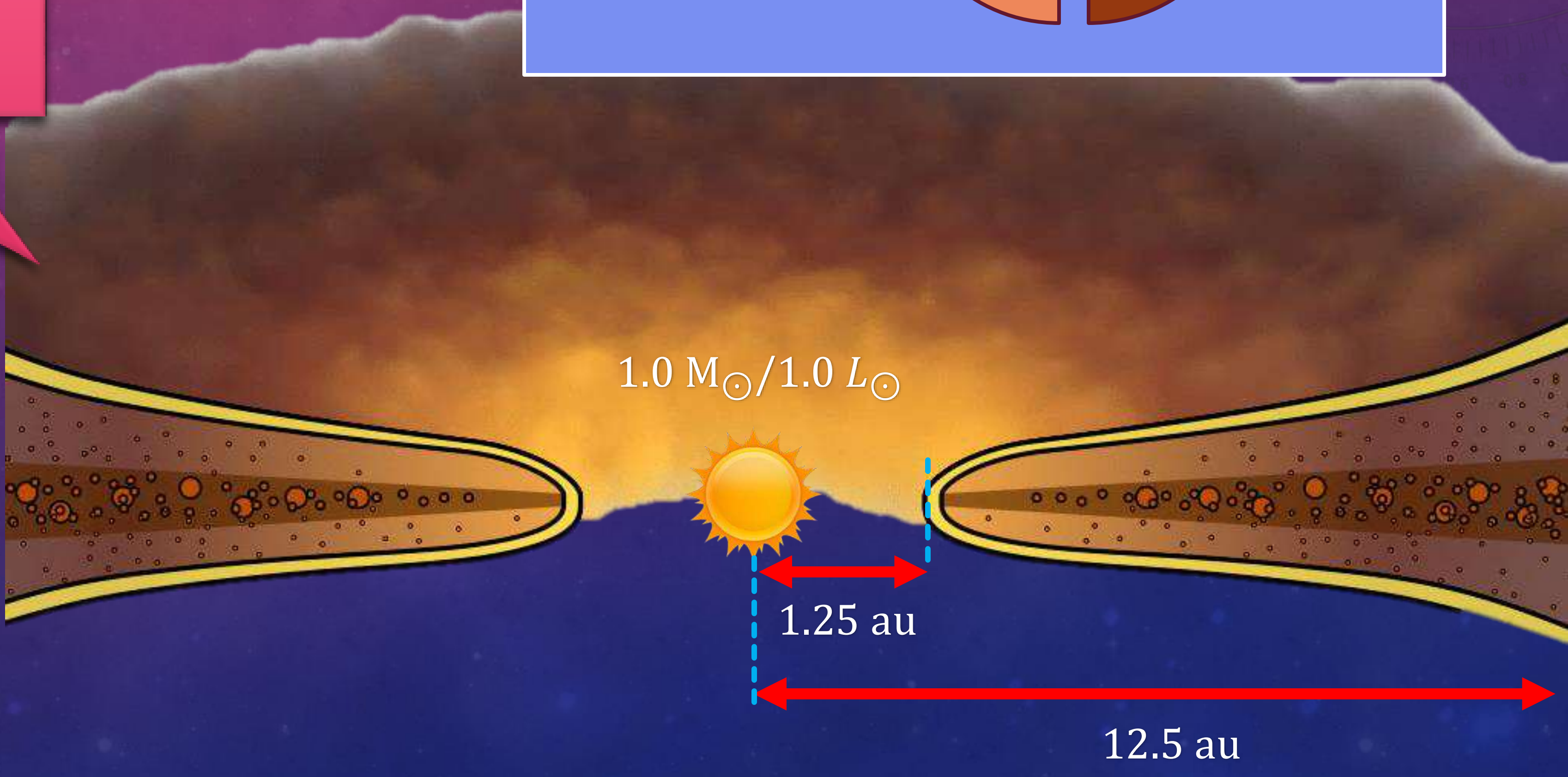
$\omega = 0°$

$\Omega = 0°$

T ~ 250 yr

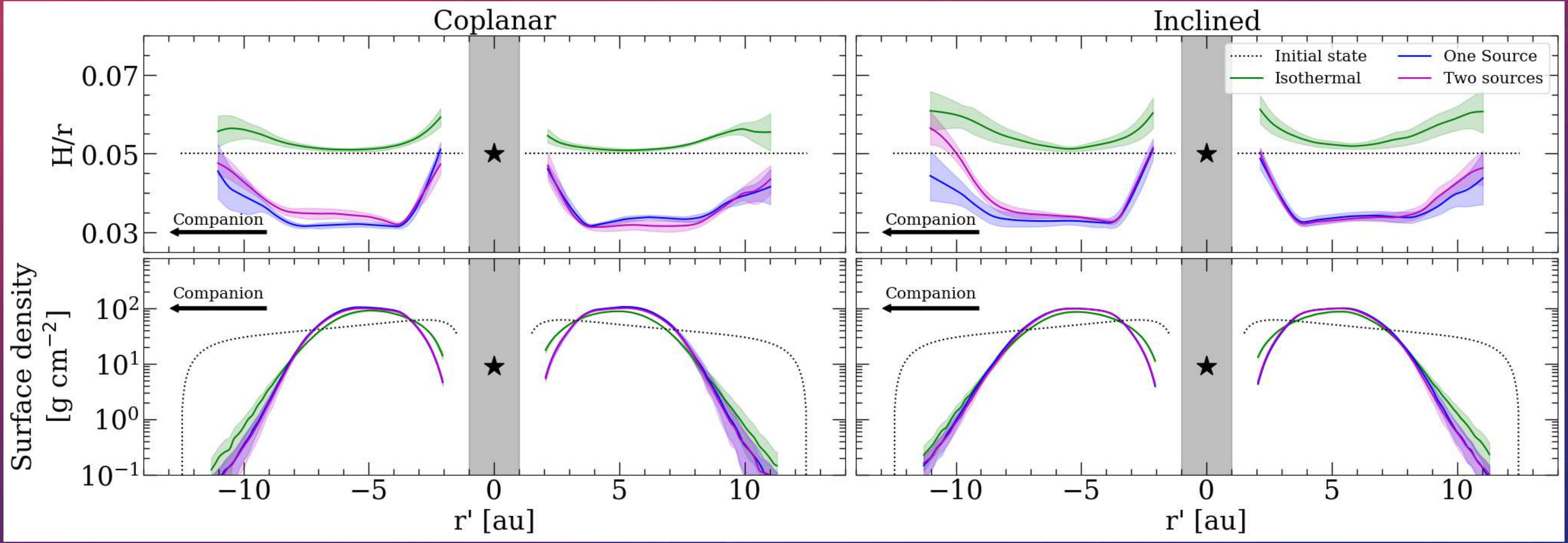
***Notation***



# RESULTS
## DYNAMICS – SCALE HEIGHT & SURFACE DENSITY

Isothermal: Classical temperature prescription.
One source: Only the primary star irradiates.
Two sources: Both stars irradiate.

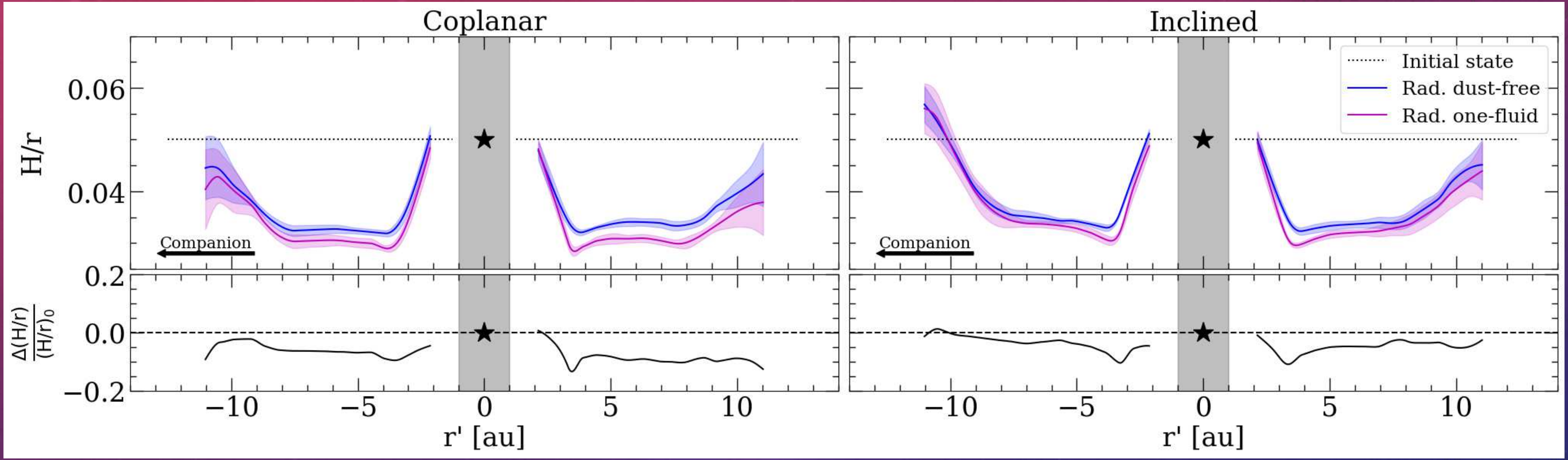



*Poblete + in prep*

- Allow to evolve the H/r value from the initial value.
- Relevance of the secondary star to irradiate the disc.
- **More important, the inclination of the binary.**

# RESULTS

## DYNAMICS – SCALE HEIGHT IN ONE-FLUID DUST

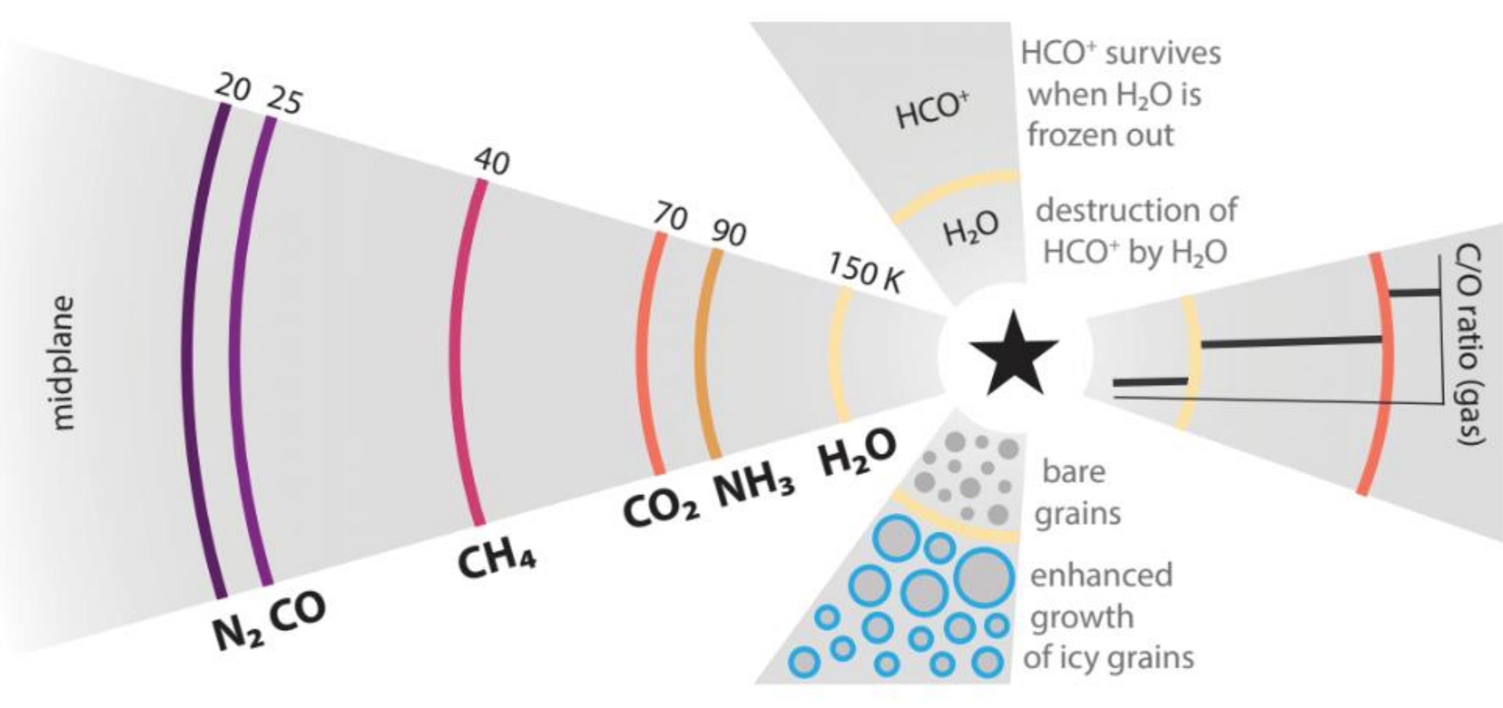



*Poblete + in prep*

- Dust can settle in the disc's midplane.
- Increase the disc's optical thick and become the disc cooler.
- **Result: the disc becomes more compact due to dust settling and add more extinction on the disc plane.**

# RESULTS

## CHEMISTRY– SNOW LINES




*van 't Hoff & Bergner 2024*

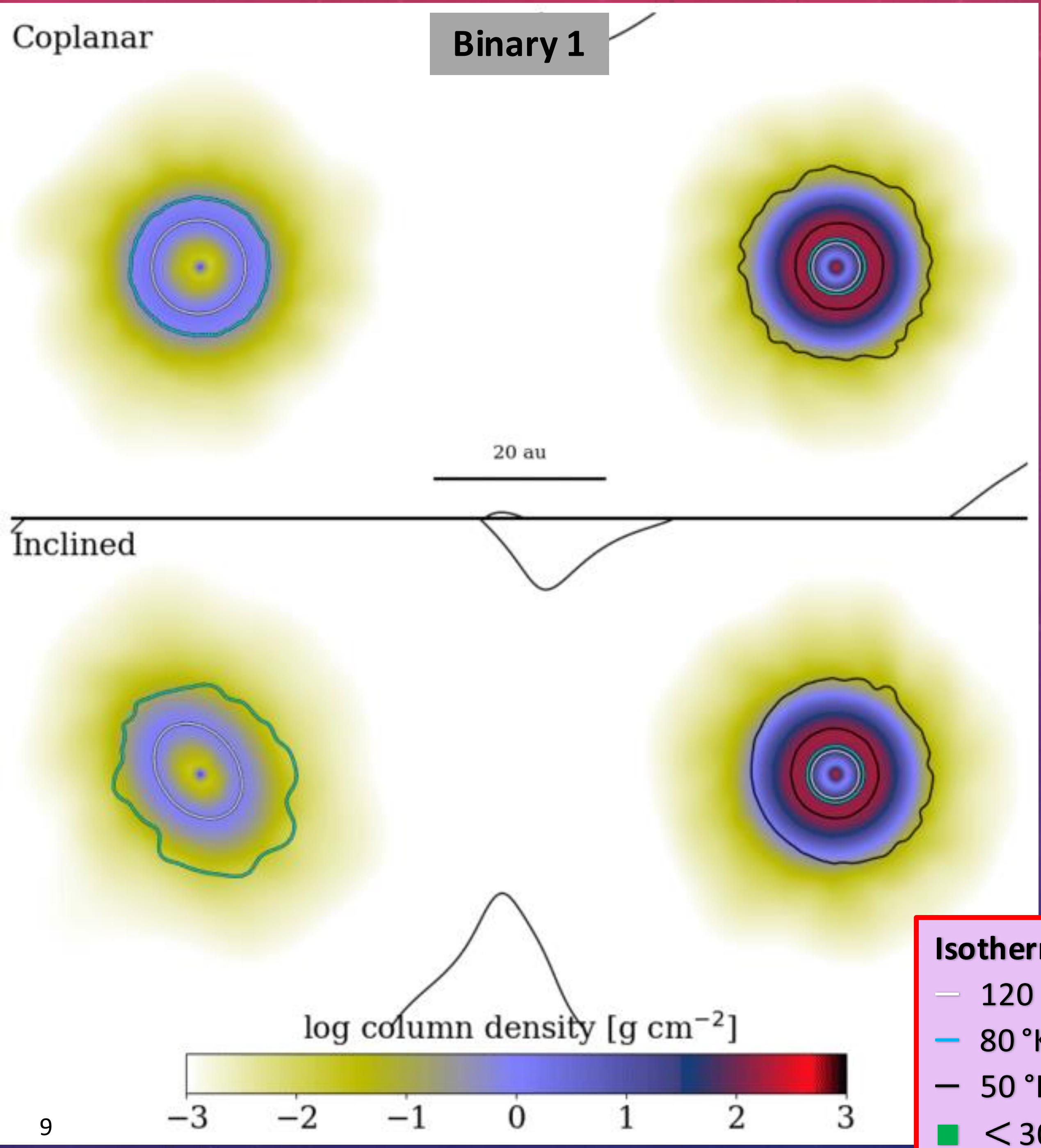
Table A.1: Adopted molecular vibrational frequency, desorption energy, atomic mass, and freeze-out temperature.

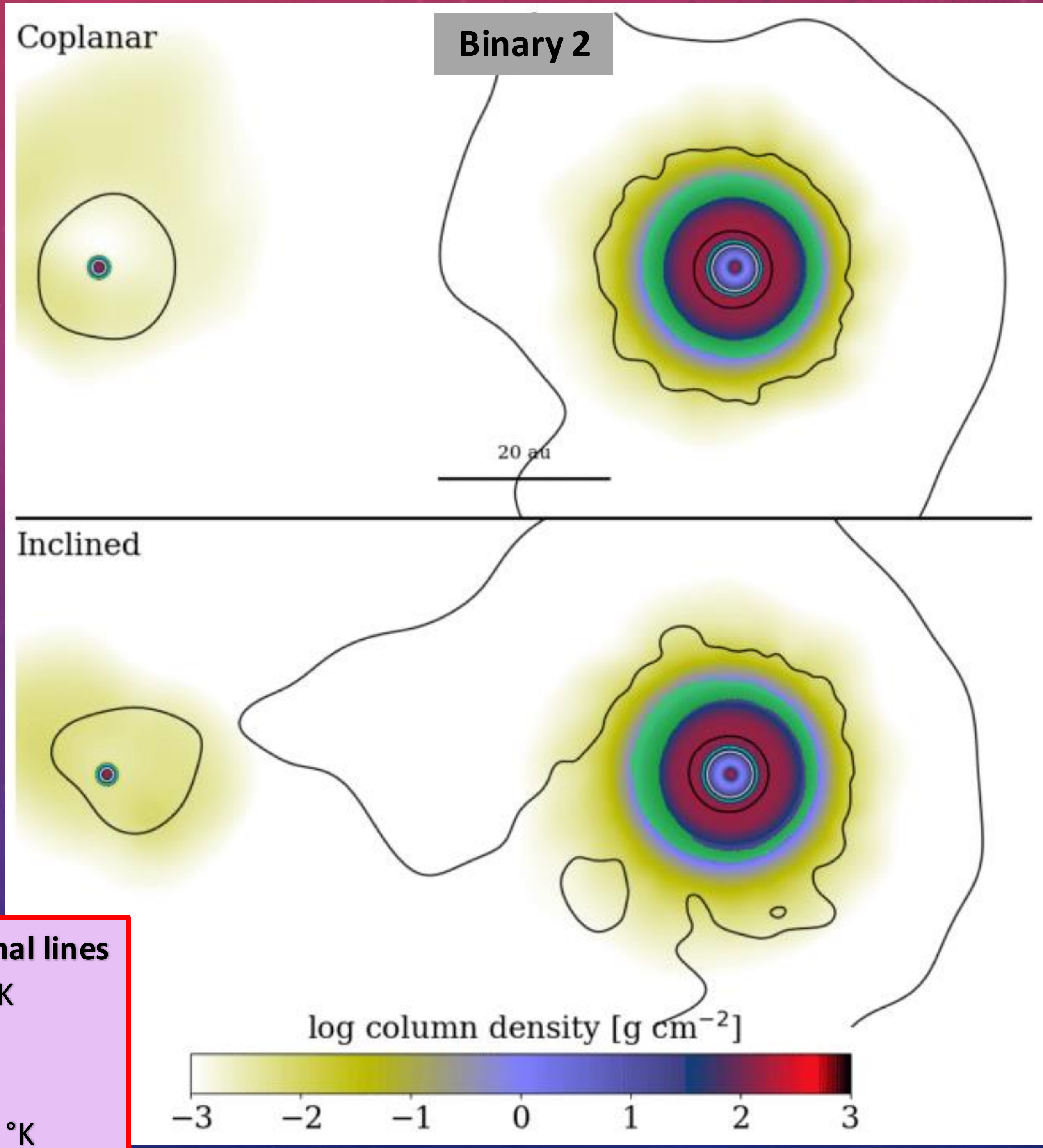
| Molecule | $\nu_i$ [a] [Hz] | $E_i$ [a] [K] | $m_i$ [$m_H$] | $T_{fo,i}$ [b] [K] |
|---|---|---|---|---|
| $H_2O$ | $4 \times 10^{13}$ | 5800 | 17.84 | 123 (120) |
| $CO_2$ | $1 \times 10^{13}$ | 2700 | 43.56 | 58 (50) |
| CO | $7 \times 10^{11}$ | 1180 | 27.72 | 27 (30) |
| $N_2$ | $8 \times 10^{11}$ | 1050 | 27.72 | 24 (30) |
| $NH_3$ | $1 \times 10^{13}$ | 3800 | 16.83 | 83 (80) |

**Notes.**
[a] Values adopted from table 1 of (Öberg & Wordsworth 2019).
[b] Values computed by assuming $s = 0.1$ μm, $d_{gr} = 10^{-14}$, and $n_H = 10^{12}$ cm$^{-3}$. We obtain this last value directly from our simulations. Adopted values are in parentheses.

*Poblete + in prep*

- Snow line: limit where the temperature is equal to the freeze-out temperature of a molecular species.
- The freeze-out temperature depends on the disc's local gas/dust conditions.



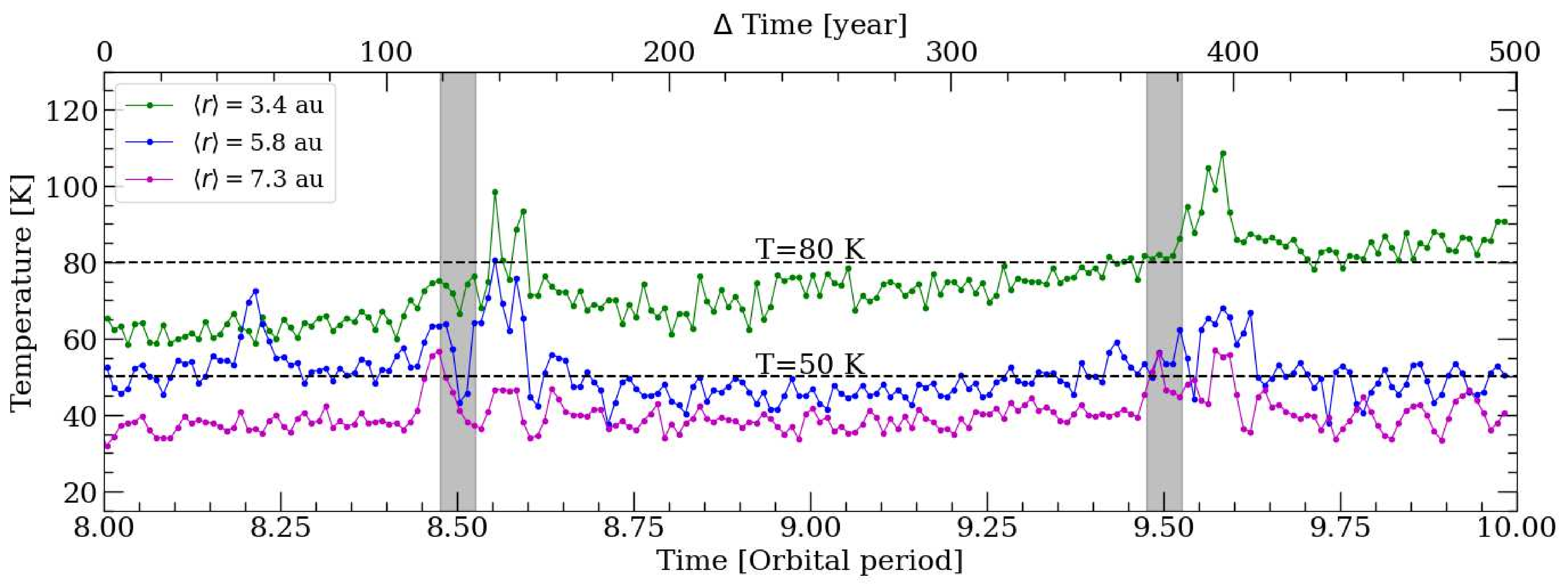




**Isothermal lines**

- 120 °K
- 80 °K
- 50 °K
- < 30 °K

# RESULTS

## CHEMISTRY– HEATING ALONG THE BINARY'S ORBITAL PHASE

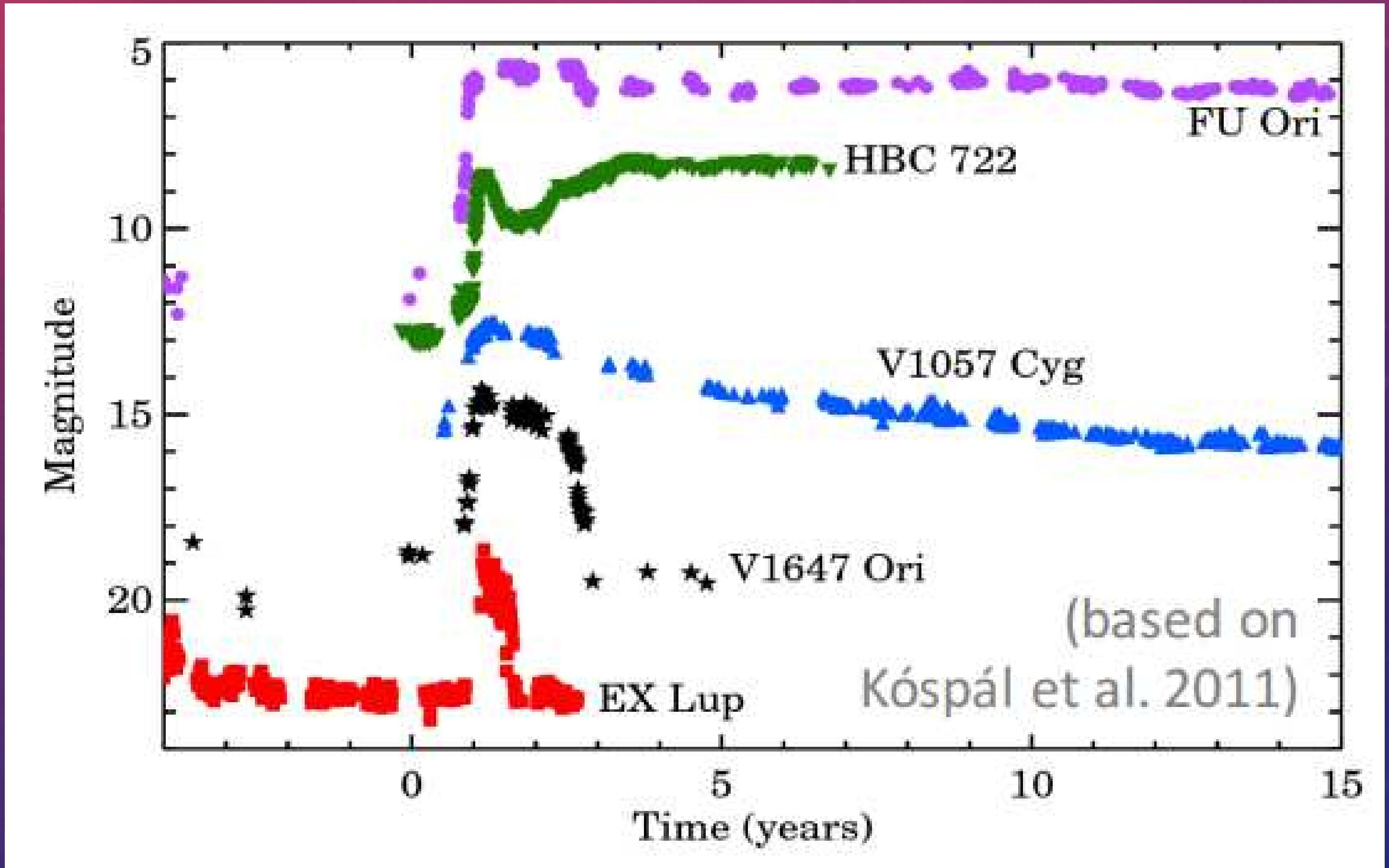



*Poblete + in prep*

- Individual particles in the disc experience cycles of heating/cooling as a function of the binary's orbital phase.
- **Implications for freezing-out/sublimation cycles.**

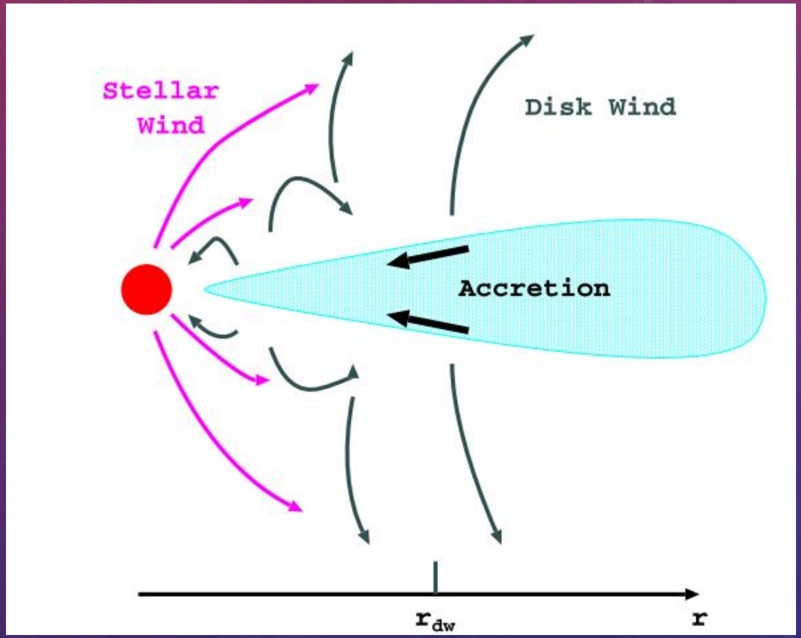
# RESULTS

## VARIABLE STARS – TYPES OF OUTBURST

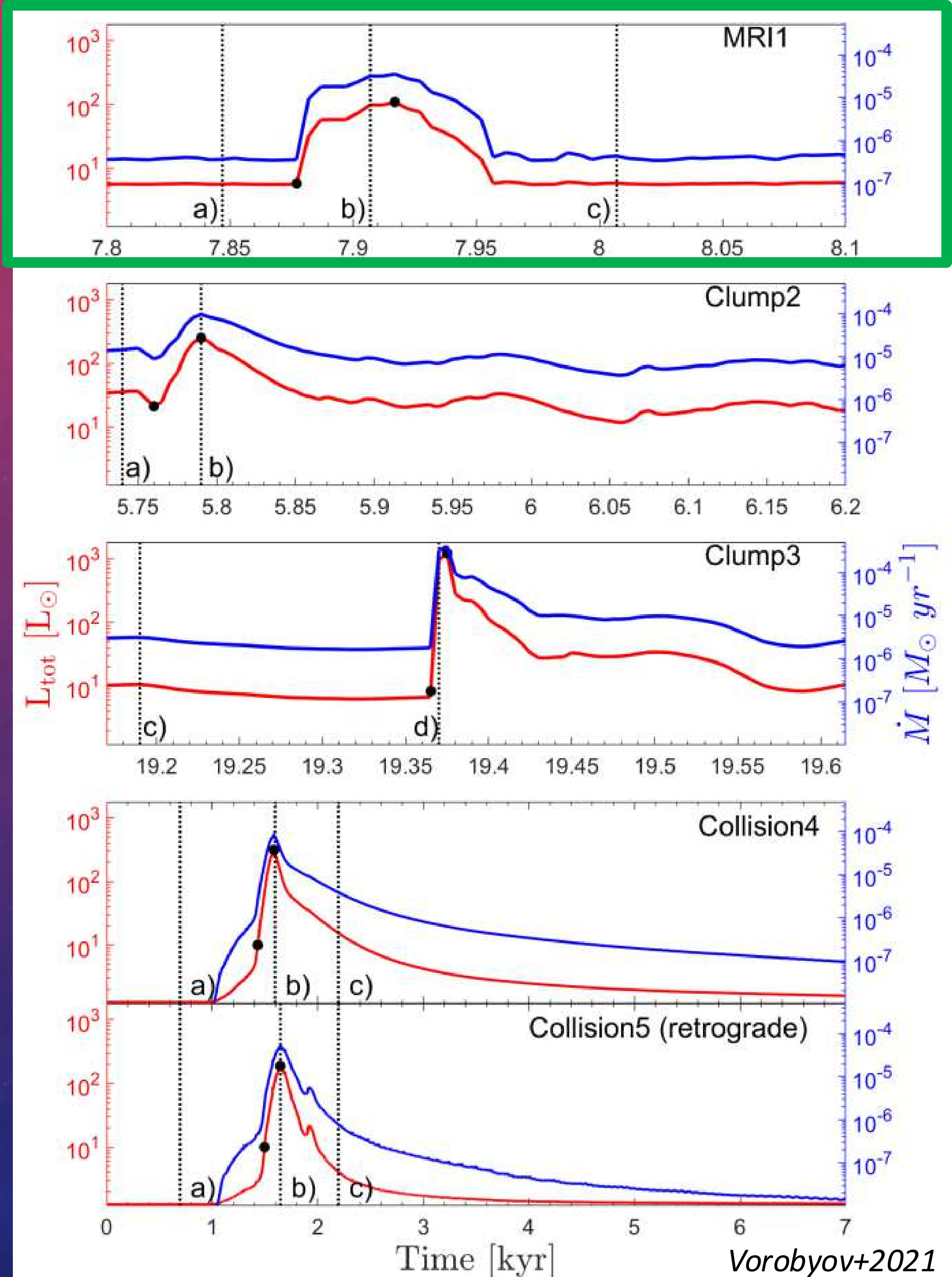


# RESULTS
## FU ORIONIS EVENTS - DETONATING

- **Magnetorotational instability (MRI)**



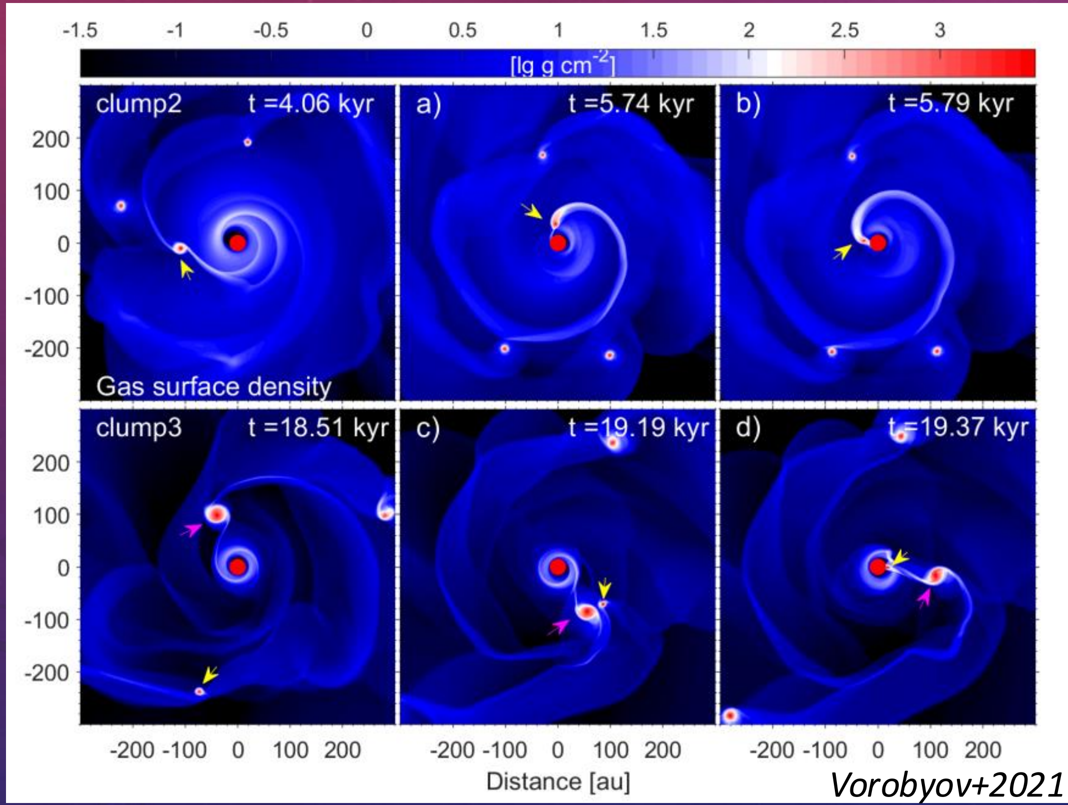

*Suzuki+2010*

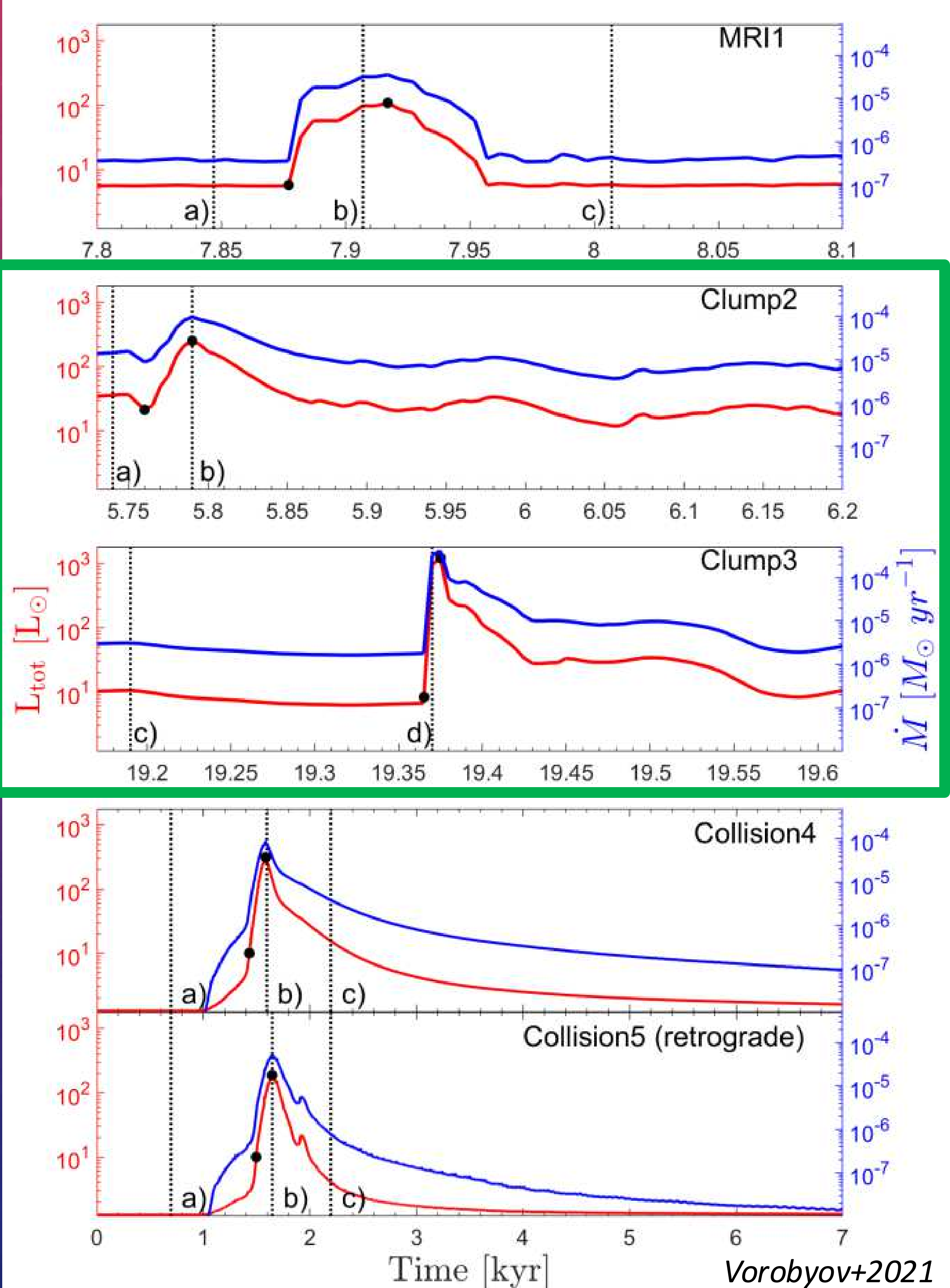



*Vorobyov+2021*

# RESULTS
## FU ORIONIS EVENTS - DETONATING

- Magnetorotational instability (MRI)
- **Clumps accretion**

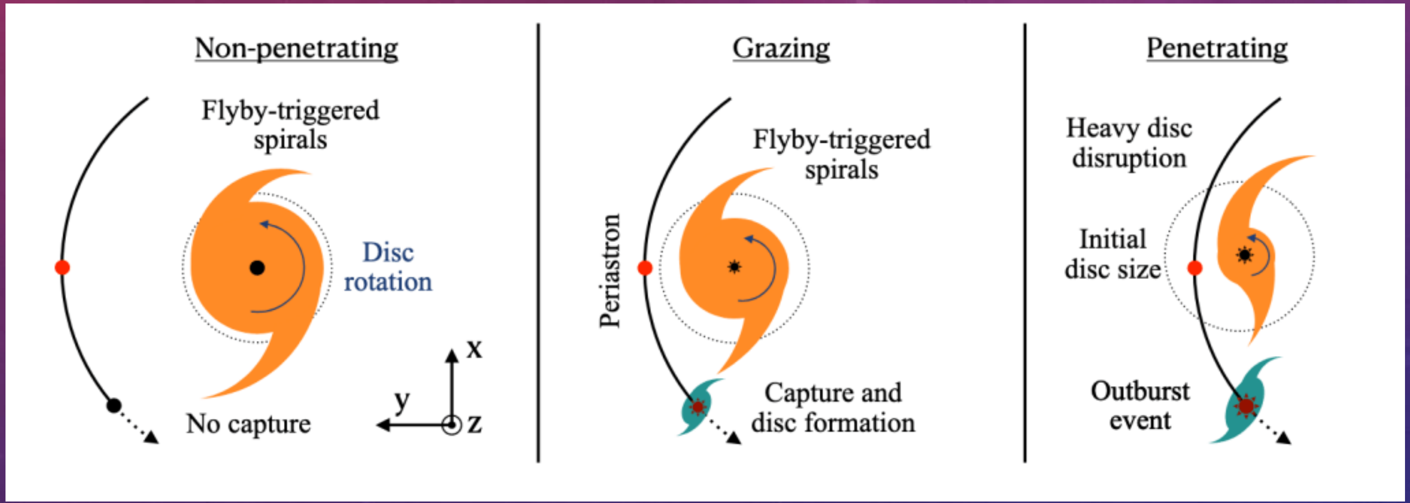


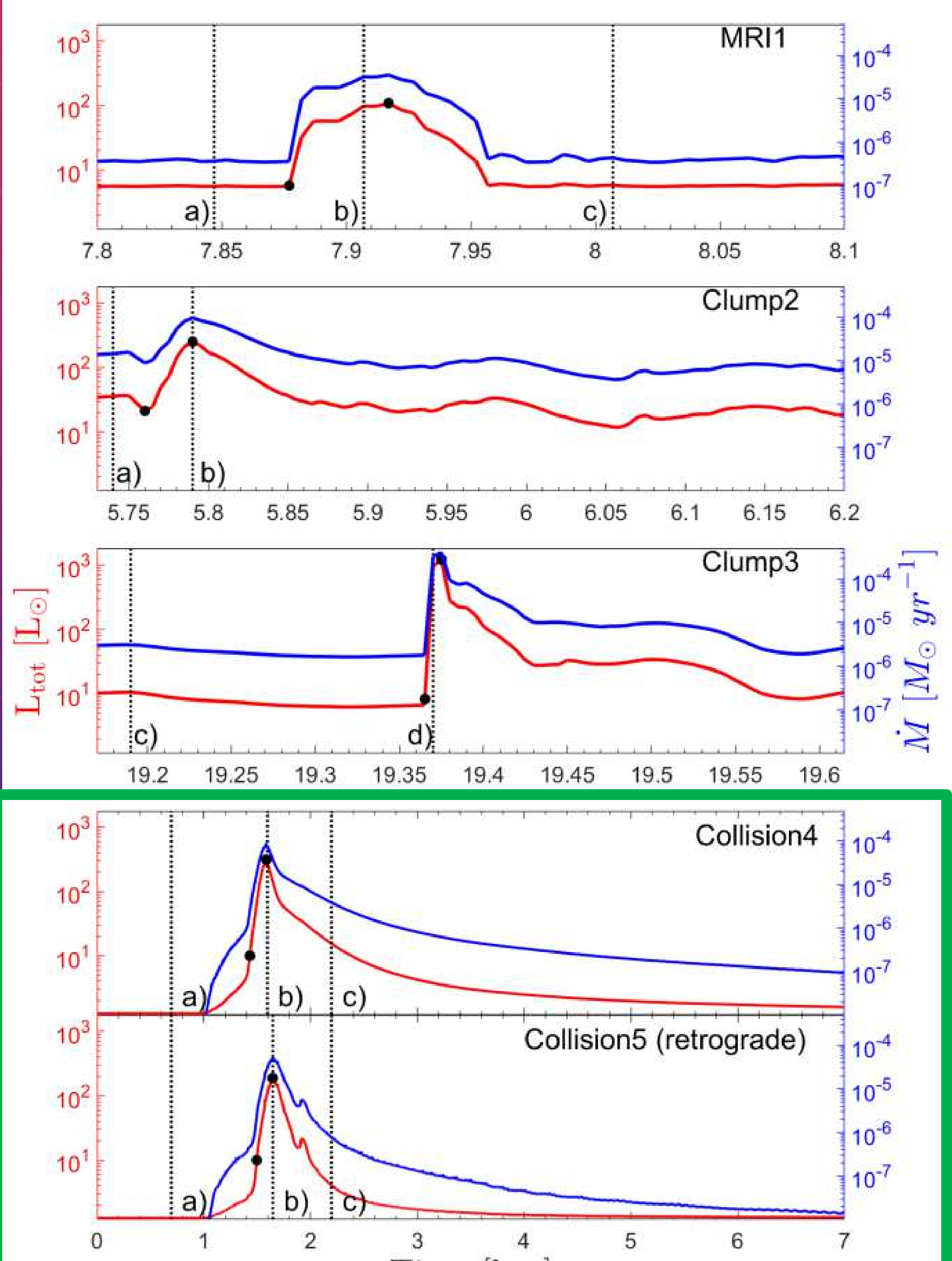
# RESULTS

## FU ORIONIS EVENTS - DETONATING

- Magnetorotational instability (MRI)
- Clumps accretion
- **Flyby**

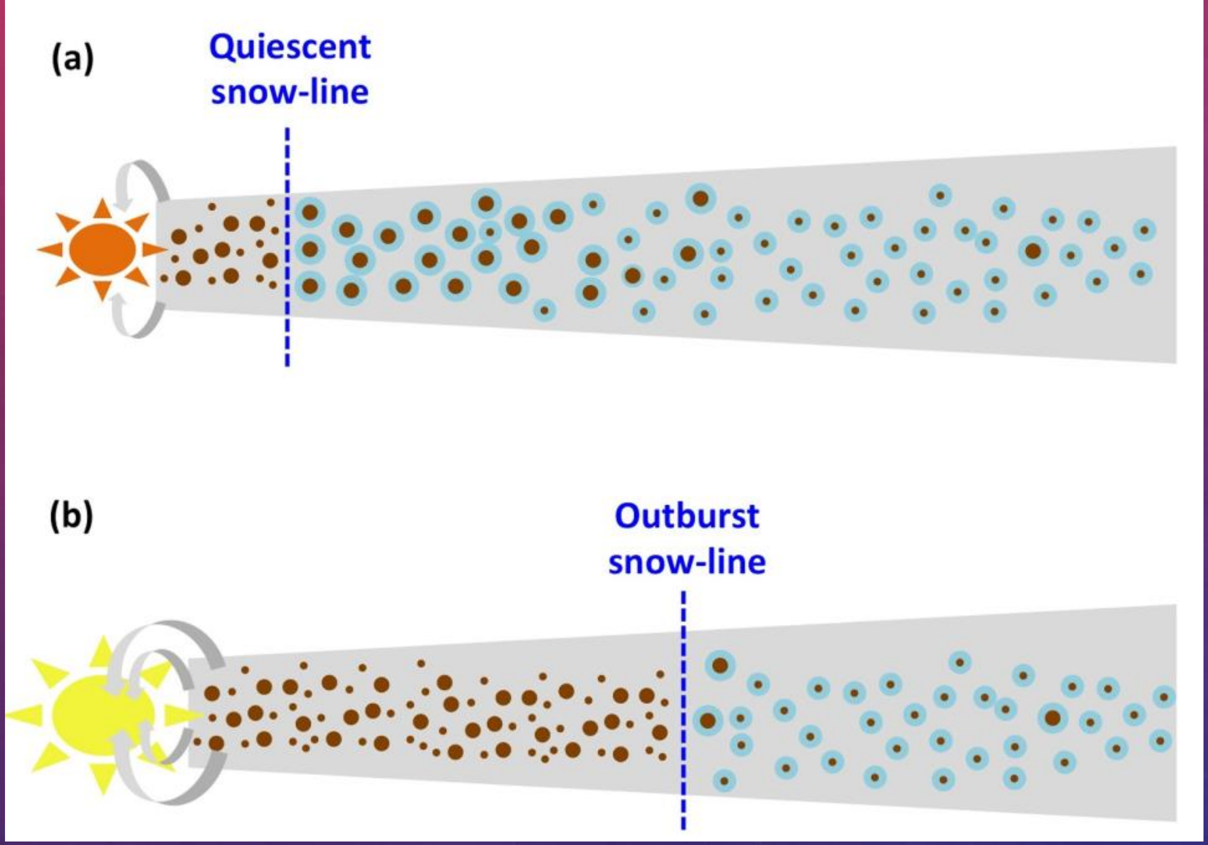



*Cuello+2023*

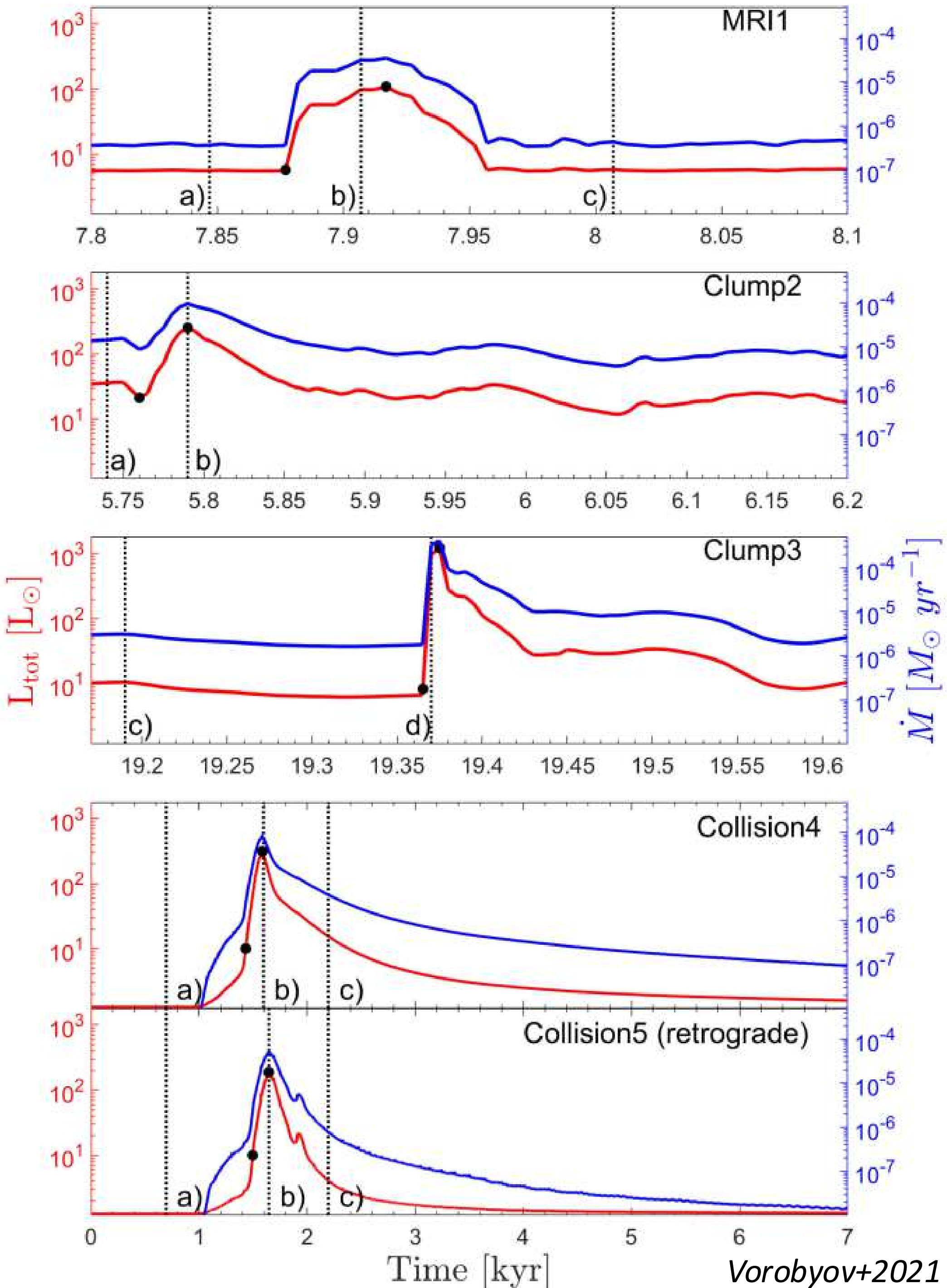



*Vorobyov+2021*

# RESULTS
## FU ORIONIS EVENTS - AFTERMATHS



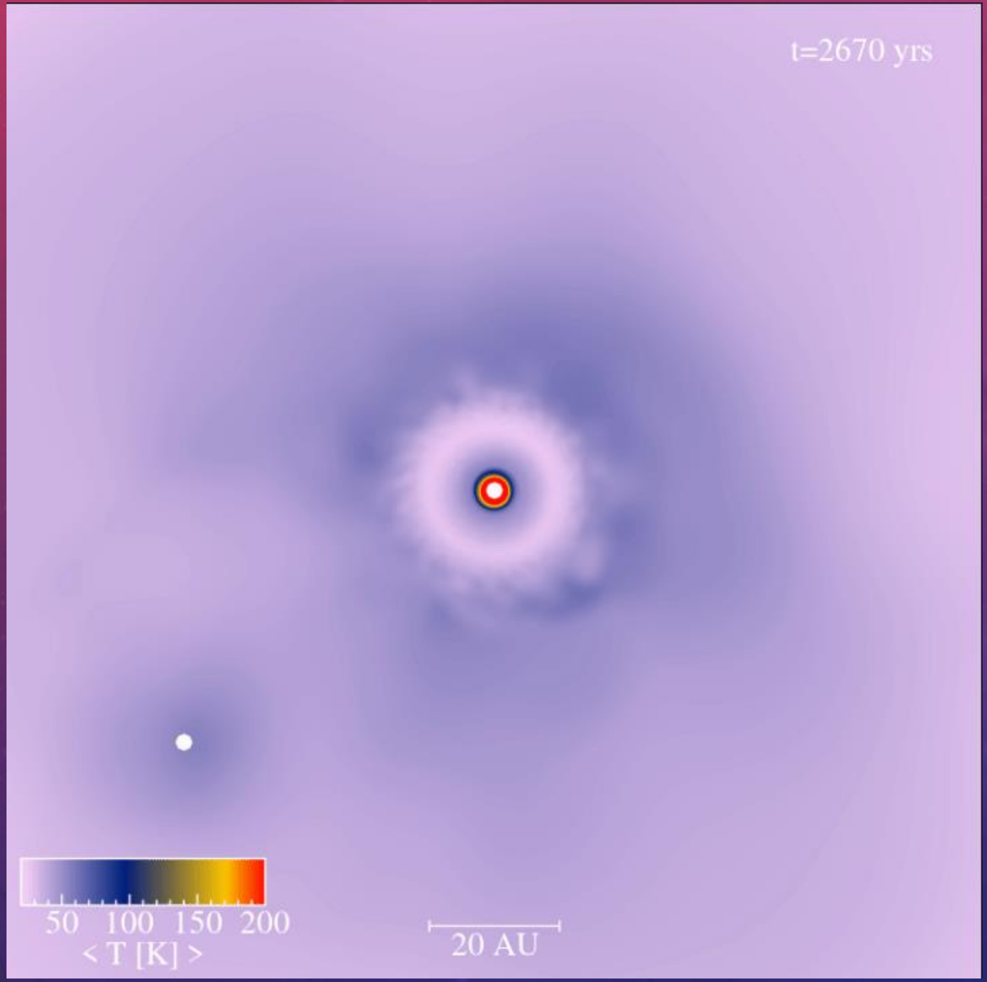

*Cieza+2016*



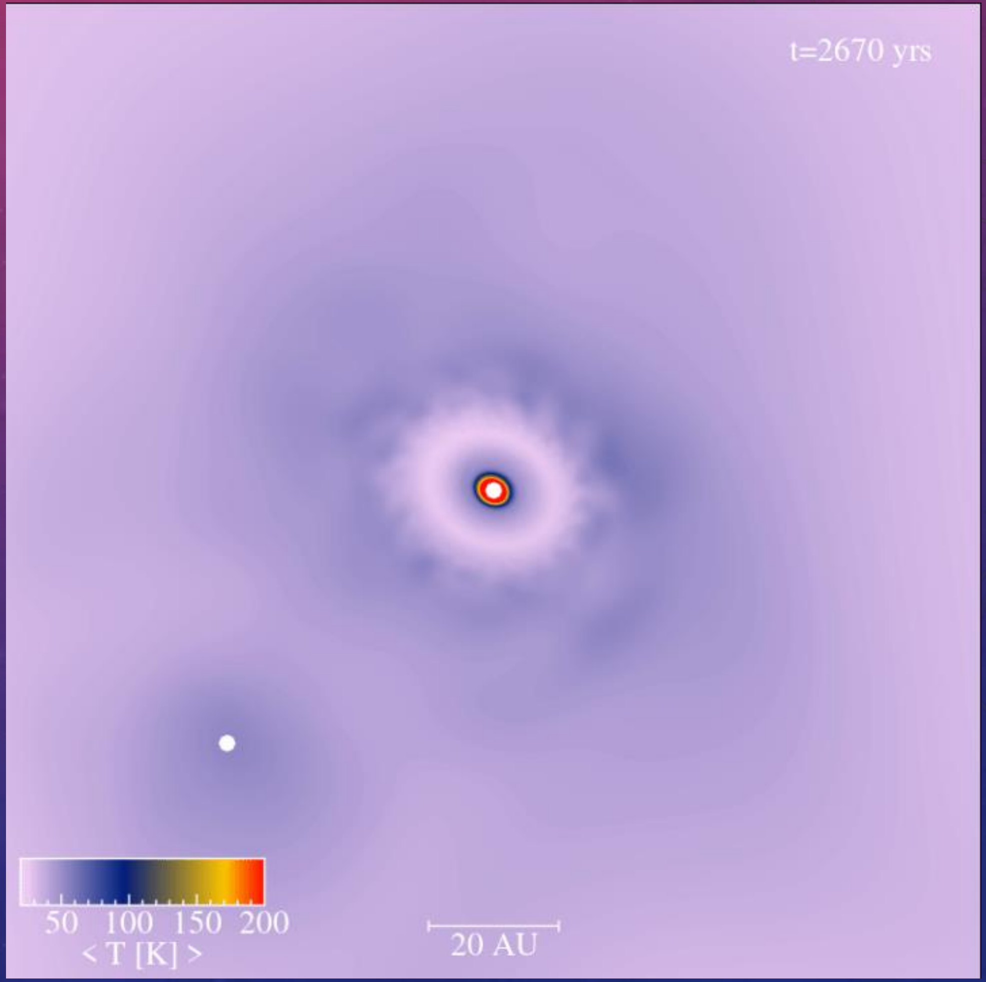

*Vorobyov+2021*

# RESULTS
## OUTBURST

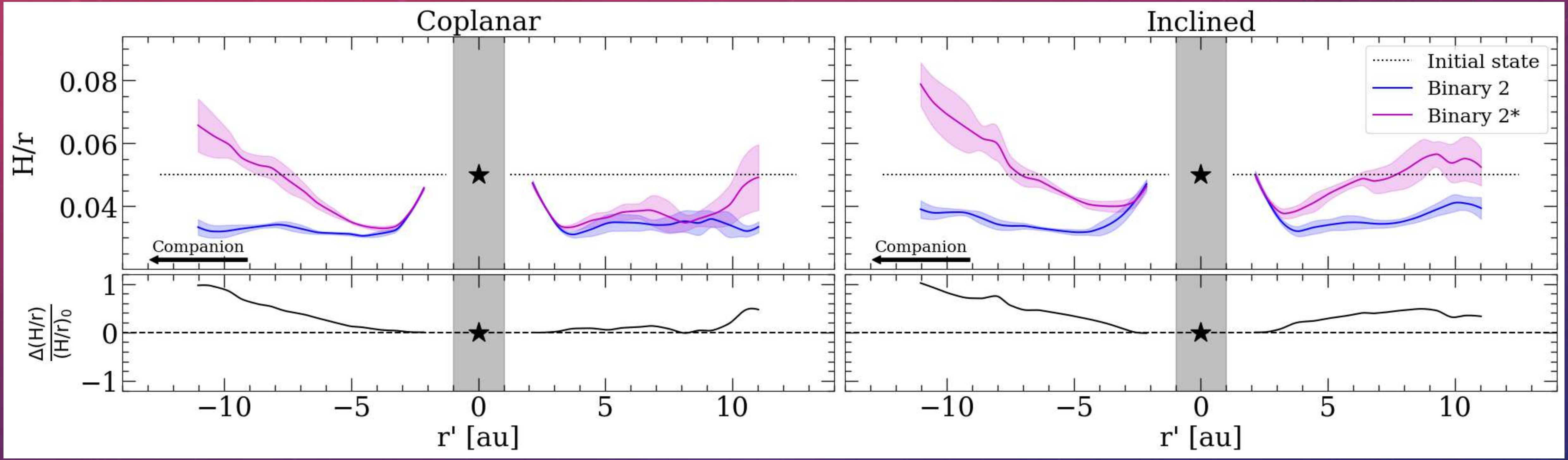
**Coplanar**




**Inclined**



# RESULTS
## DYNAMICS– OUTBURST




*Poblete + in prep*

- The disc is significantly puffed up at the facing region of the companion.

- The puffing up is also evident in the opposite region.

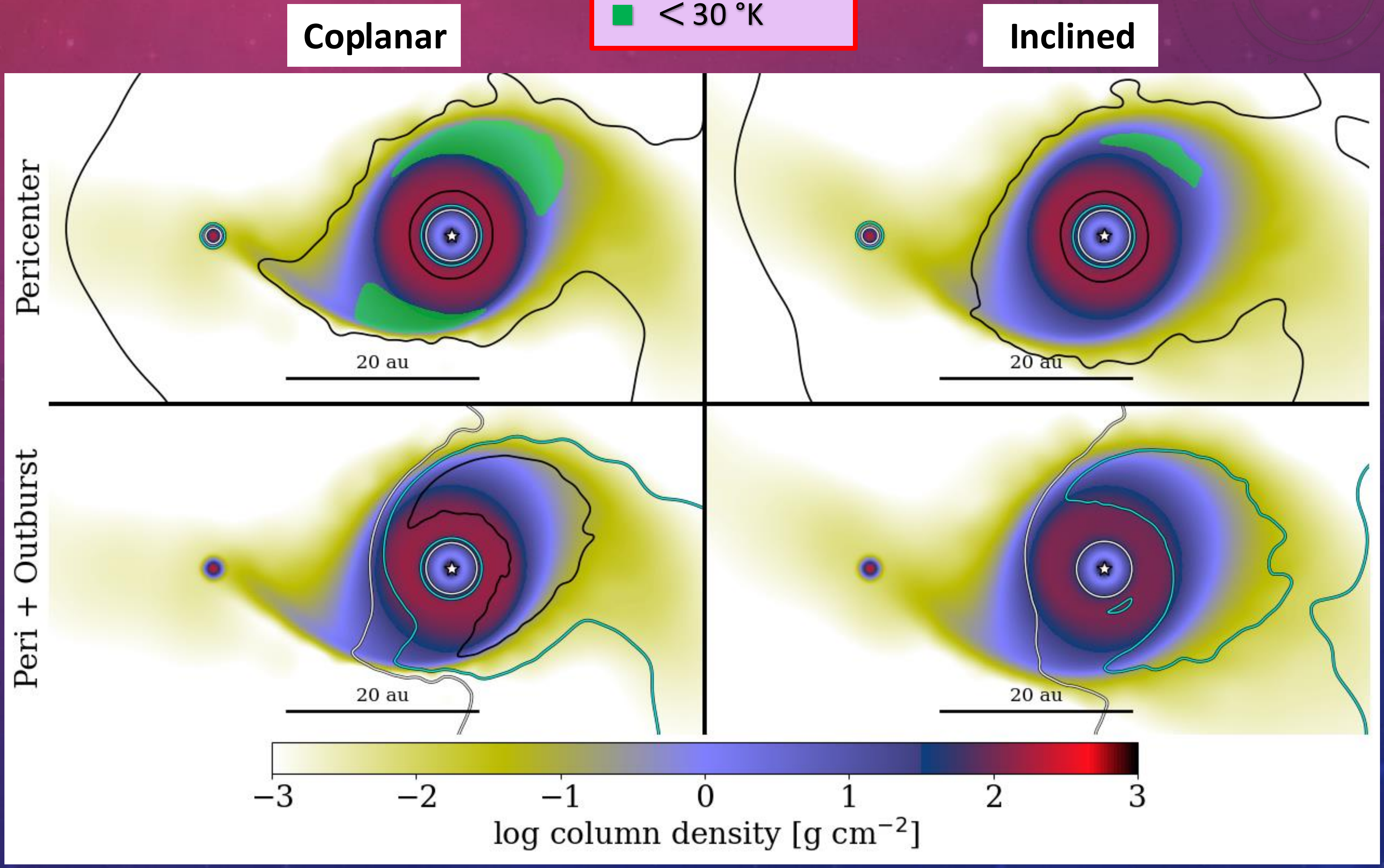
# RESULTS
## CHEMISTRY– OUTBURST

$L_{sec} = \sout{0.036}\ 30\ L_{\odot}$

**Extreme heating of the disc.**

- Coplanar: the disc's temperature is above 30° K.
- Inclined: : the disc's temperature is above 50° K.

Isothermal lines
120 °K
80 °K
50 °K
< 30 °K



# SUMMARY

- Phantom-mcfost allows us to model the disc dynamics of an asymmetric radiation field.
- Applicable for modelling multiple stellar systems where the radiation field is not radially central.
- The temperature profile depends on the stellar and disc parameters. The temperature is no longer a power law.
  - Compute a more realistic evolution of the H/r profile.
  - Relevance of dust settling and dust sub-structures.
- Suitable to model outburst events where the temperature profile changes drastically.
  - Allows us to trace snow lines and link them to the binary’s orbital phase.
  - Allows us to study the evolution of the chemical interest regions.

# THANK YOU!

The Andes at night

The Andes at day