Setting discs on fire with stellar flybys

2nd European Phantom code family users workshop
Grenoble, France

Shot down in flames
Shot down in flames
Ain't it a shame
To be shot down in flames?
No! Shot

Nicolás Cuello, 2 June 2025

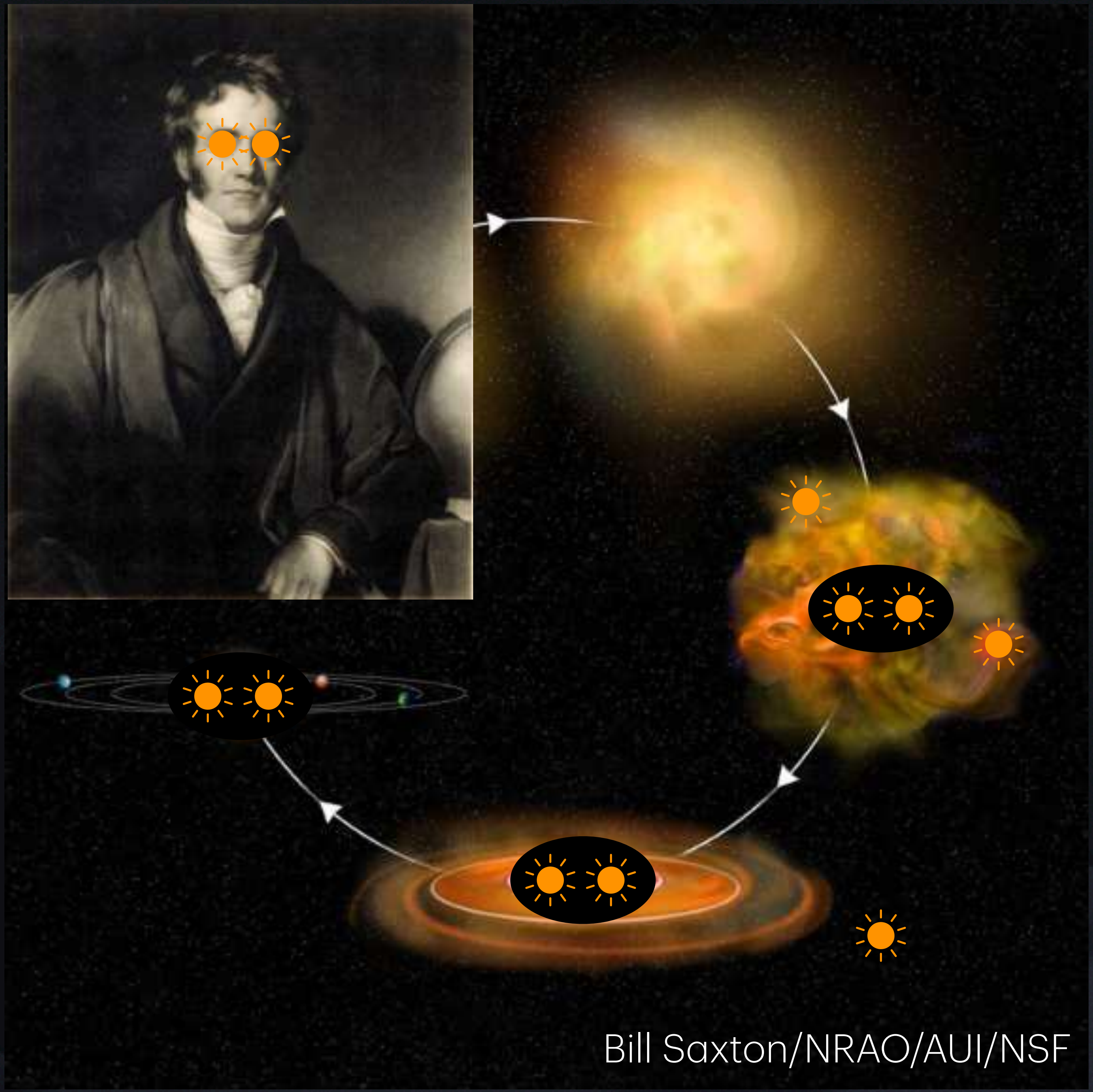
Take-away of this talk

- A broad range of dramatic accretion events may be linked to stellar multiplicity & stellar flybys with discs
- Flybys are not necessarily harmful for planet formation: context matters
- Flyby models may help to better interpret the emerging population of outbursting stars: link to be established

Part I:
Why should discs & planets care about stellar flybys?

Stellar multiplicity is unavoidable

- For simplicity, it is often assumed that disc & planet formation occur in isolation.
- Picture of the "typical scenario" needs to be revised
- John Hershel: mapped and characterised binary stars in the early XIX century
- Stellar multiplicity is key: drives accretion & precession, sets disc sizes & masses



STELLAR MULTIPLICITY MUST BE TAKEN INTO ACCOUNT IN OUR MODELS

"All stars are born as binaries or multiples" (Larson, 1970s)

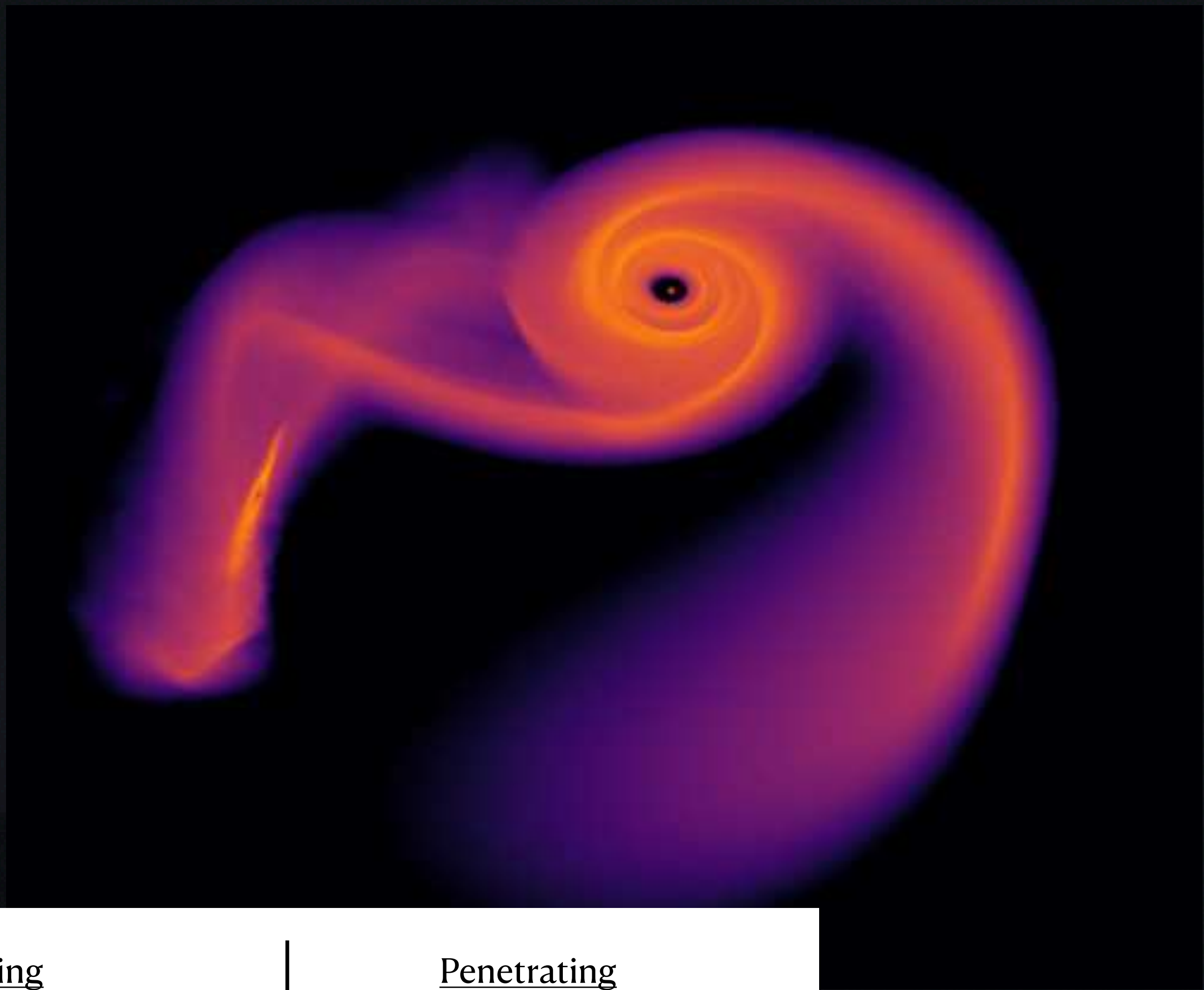
Implication #1: Most (if not all) single stars were once part of multiple stellar systems

Implication #2: Ejection and stellar encounters are common in active SFRs

Useful flyby definitions & parameters

<u>Definition</u>: A flyby occurs whenever a star on a parabolic or hyperbolic orbit (e≥1) perturbs another star (w/ or w/o a disc)

<u>Types</u>: Prograde & retrograde; Non-penetrating, grazing, disc-penetrating flybys



<u>Effects</u>: ...) au
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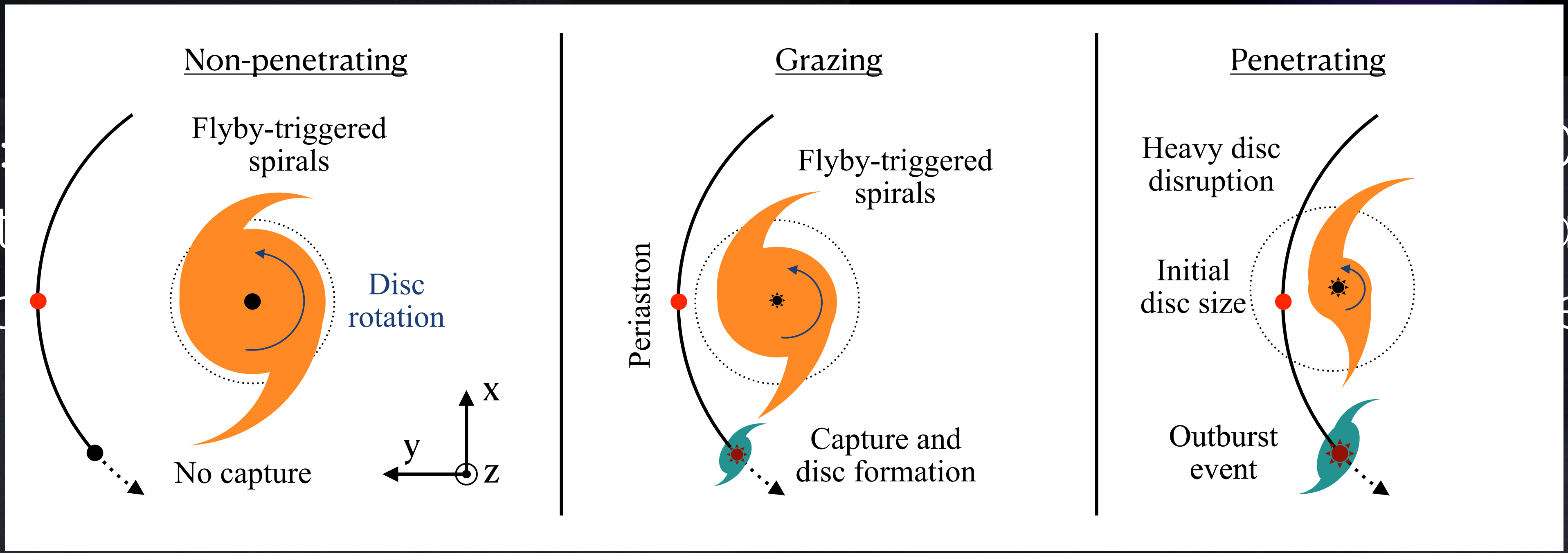
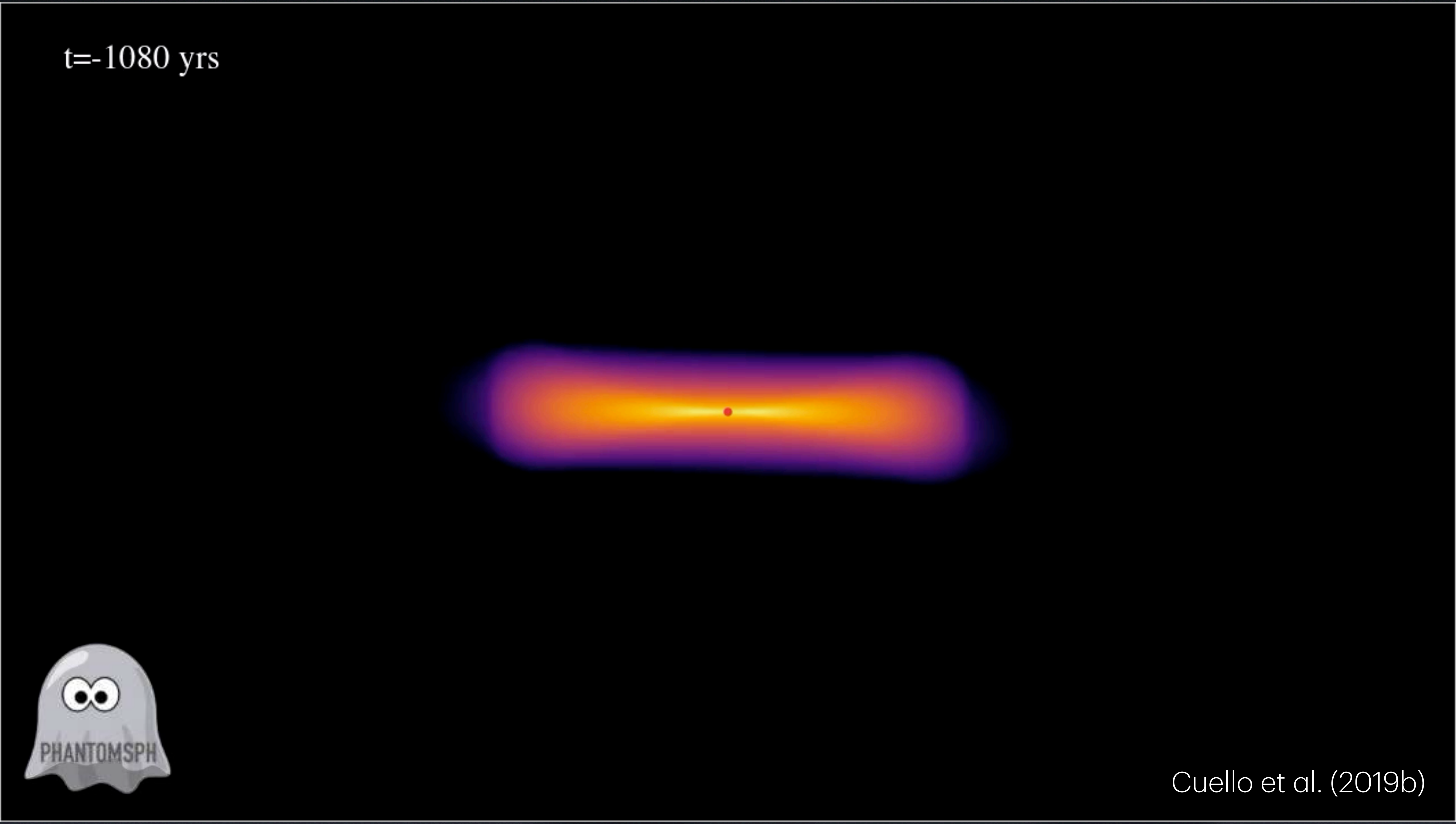
dust tr ... e (2023)



Example: inclined prograde orbit



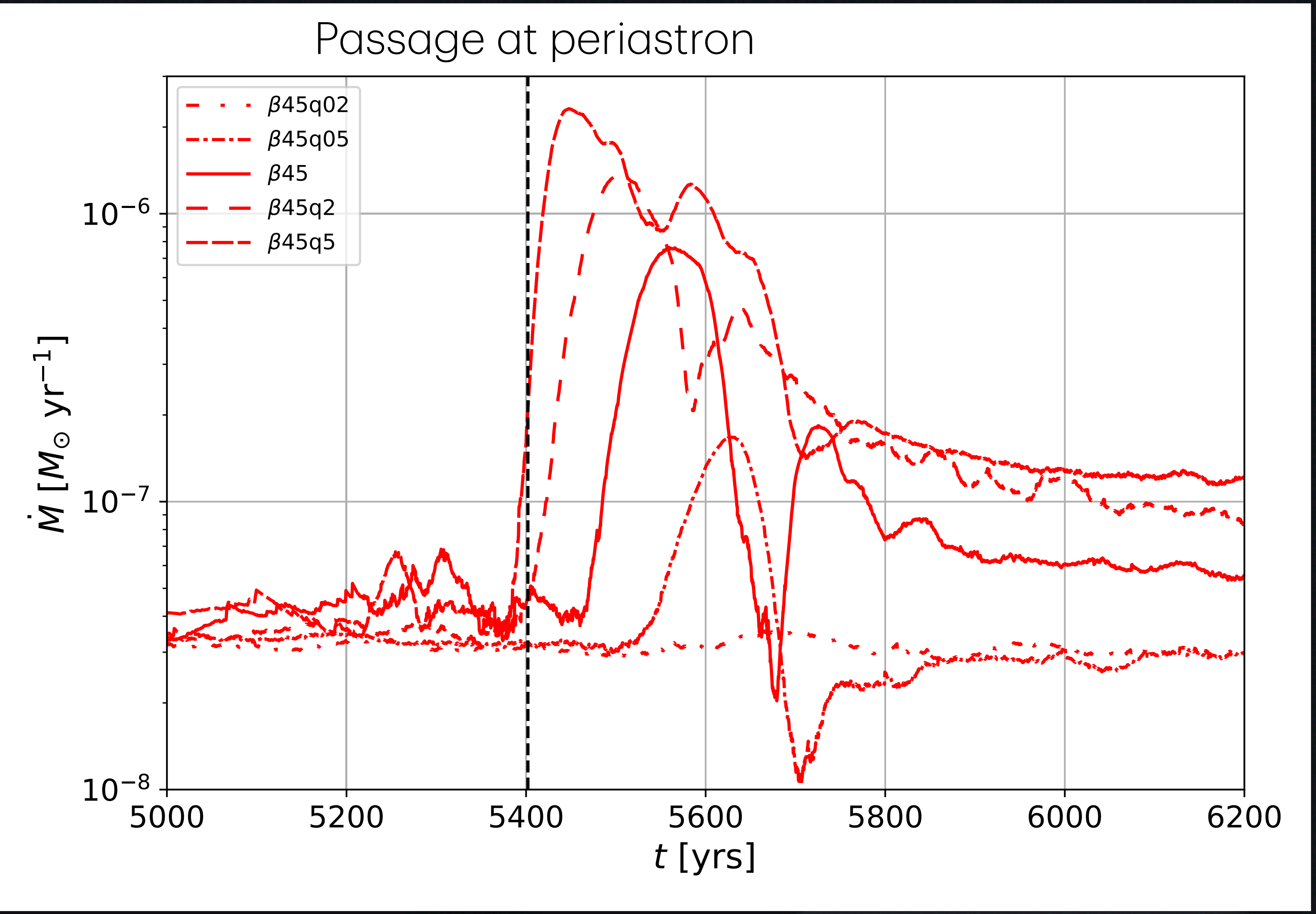
PROGRADE & RETROGRADE CREATE DIFFERENT SUBSTRUCTURES → FLYBY FINGERPRINTS

Part II: The powerful link between accretion and stellar flybys

Measuring flyby-induced accretion

Cuello et al. (2019b)

- Flyby orbital inclination critically depends on β: inclined prograde flybys
- But, there is a delay of ~100 yrs between the periastron and the outburst…
- Increasing intruder's mass speeds up the process: faster rise & higher peak
- NB: Thermal & magnetic effects not considered here
  ➞ Recent work by Vorobyov



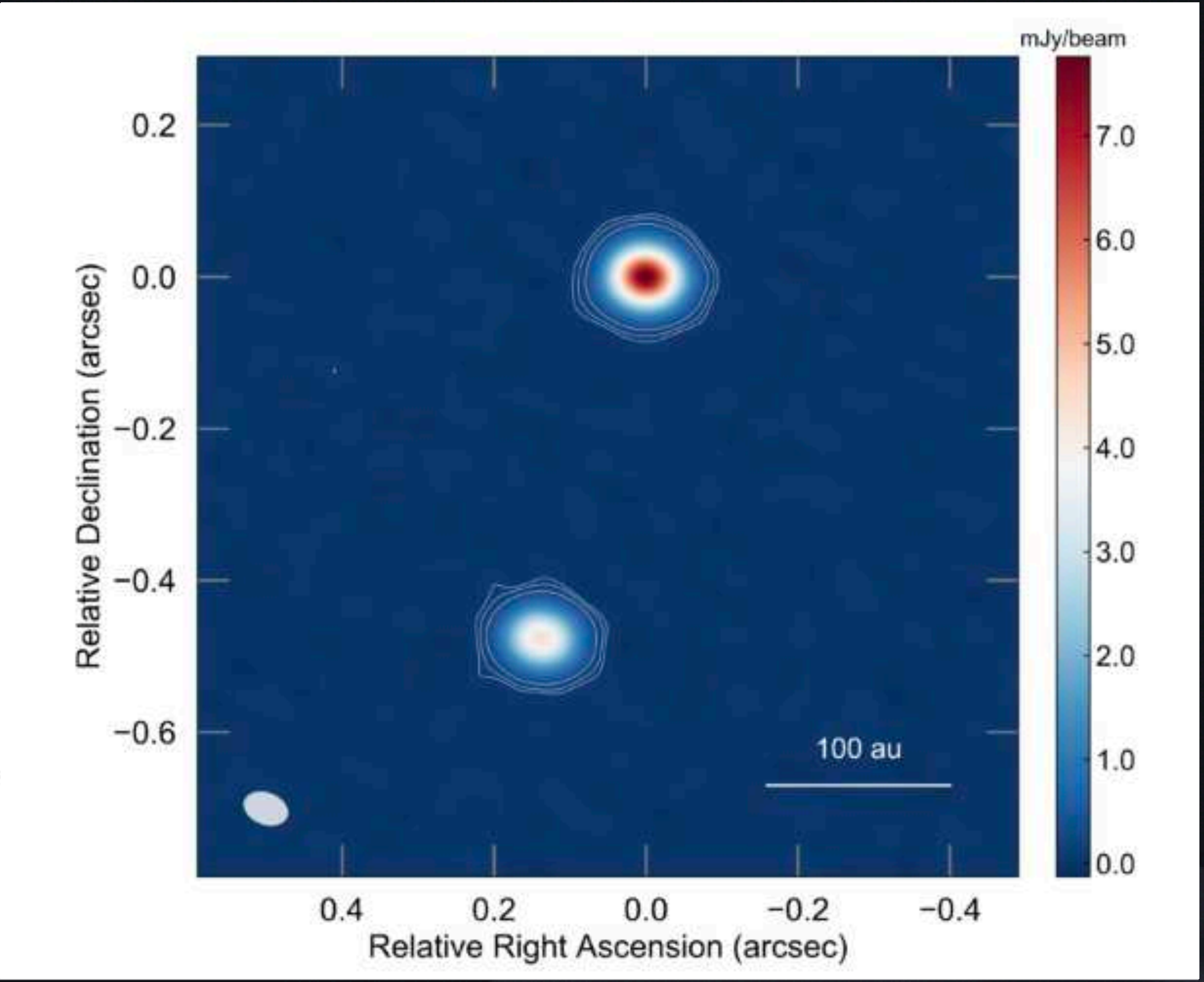
$$L_{\rm acc} = \frac{1}{2}\frac{GM_*\dot{M}}{R_*}$$

$$T_{\rm acc} = \left(\frac{L_{\rm acc}}{4\pi\sigma R_*^2}\right)^{1/4}$$

Distant flyby-triggered outbursts in tension with the FU Orionis outburst

Changing the approach with FU Ori in mind

- Outburst reported in 1937. Rise time very short ~ 1 yr. Factor x 100 in accretion !!!
- M(FU Ori N) < M(FU Ori S): **the less massive star (N) is the strong accretor**
- Separation between the two stars, disc individual sizes, morphology, spiral, outflows
- Models w/ a short timescale: Projects led by Elisabeth Borchert (Monash, Australia)

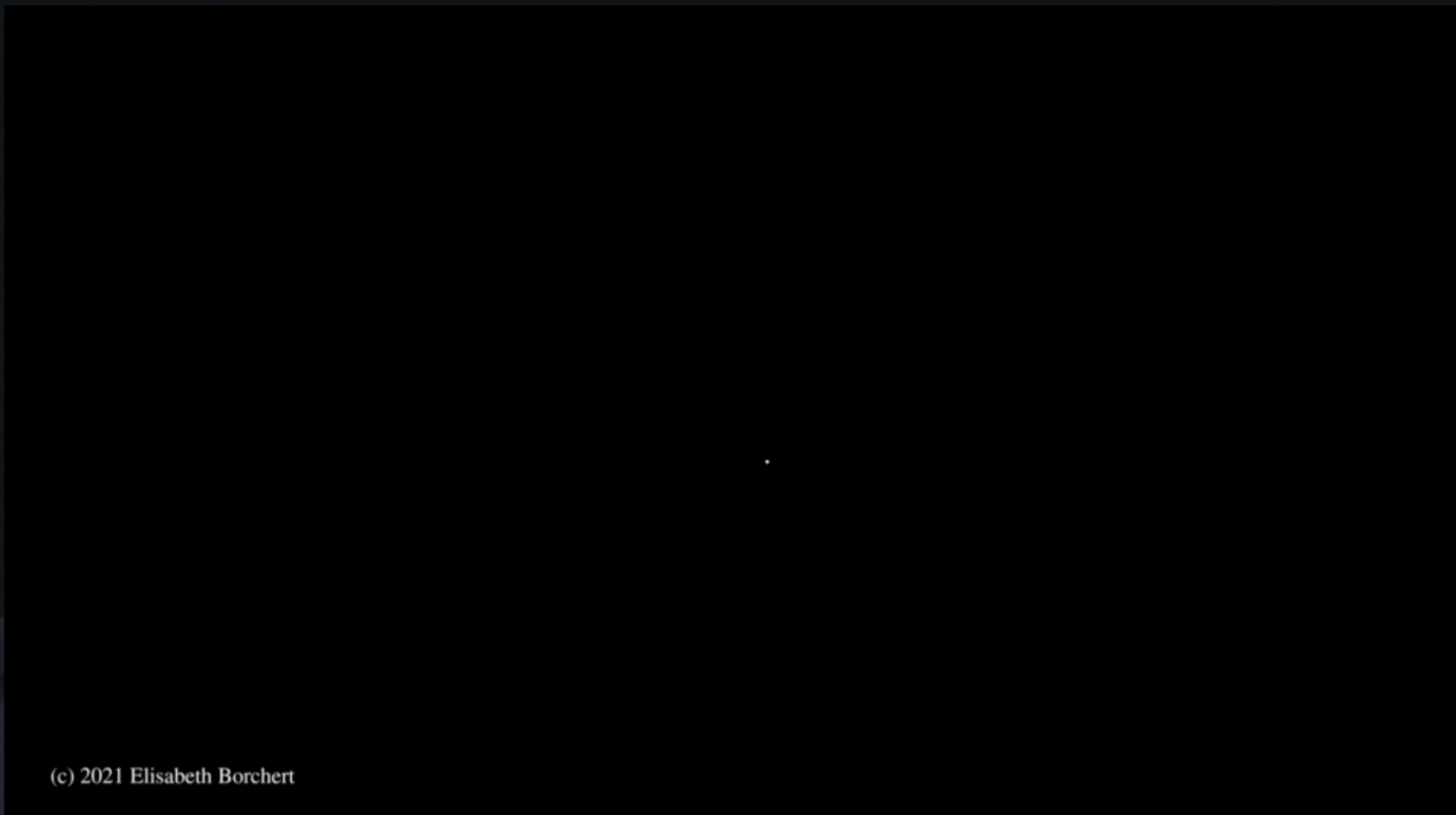


Weber et al. (2023), Pérez et al. (2020)

WHAT IF WE THROW THE STAR AT THE DISC & WE MAKE MATERIAL RAIN DOWN ON IT?

Outburst during disc-penetrating flybys

Novelty: Phantom-MCFOST simulations, T field updated every few hydro steps



Borchert et al. (2022a)

A DISC PENETRATING FLYBY COULD GENERATE THE MORPHOLOGY & THE FLASH

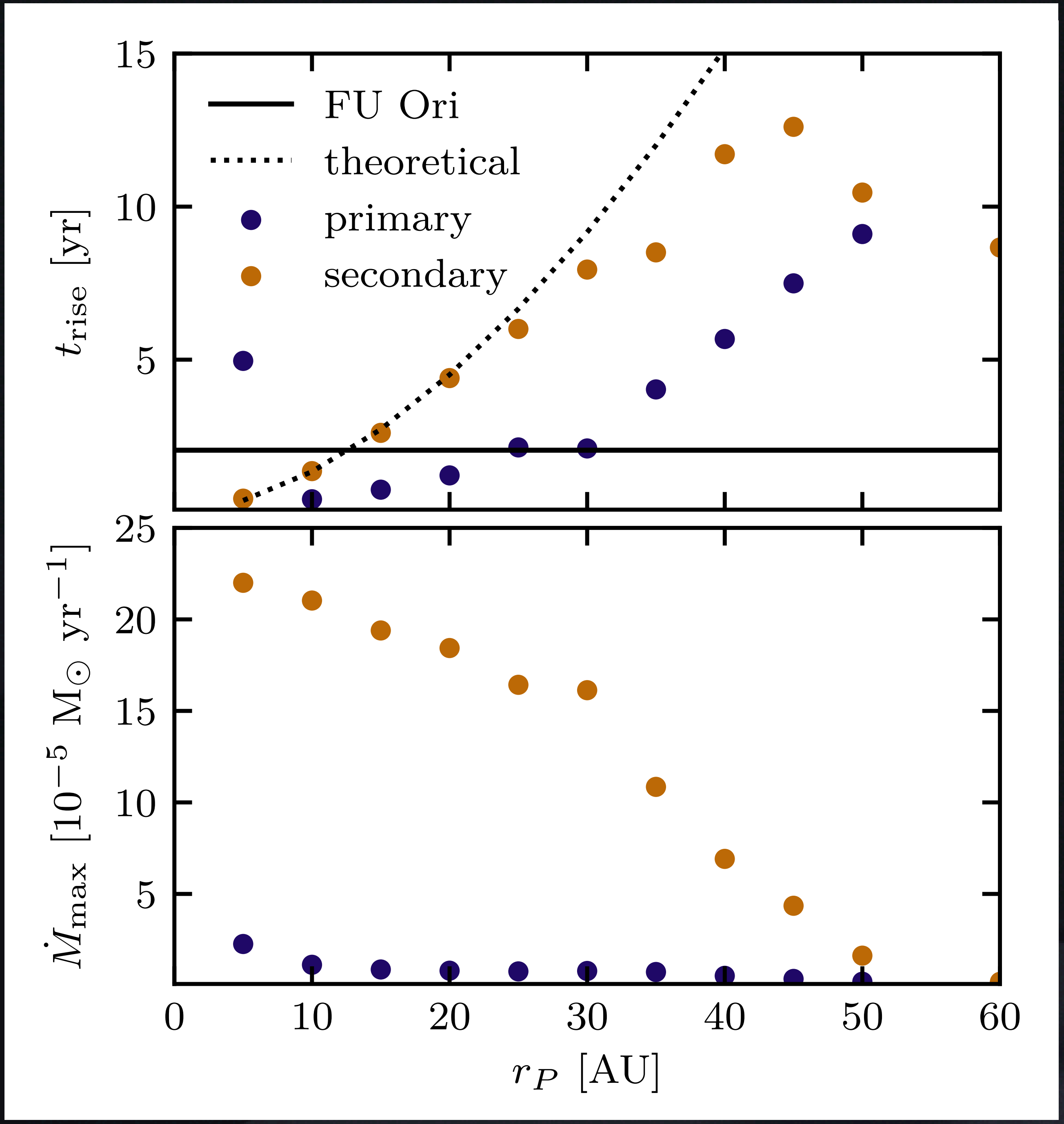
Flyby-induced FU Ori-like outburst

- As the disc-less intruder travels through the disc, it accretes material in a 3D fashion and forms a circumsecondary disc

- The rise time and maximum value of the stellar accretion are in agreement with FU Orionis

$$t_{\rm rise} = \frac{L(r_{\rm p})}{\sqrt{2GM/r_{\rm p}}}$$

- This requires a very close flyby ~20 au, so less likely encounter



Borchert et al. (2022a)

A DISC PENETRATING FLYBY COULD GENERATE THE ACCRETION BURST

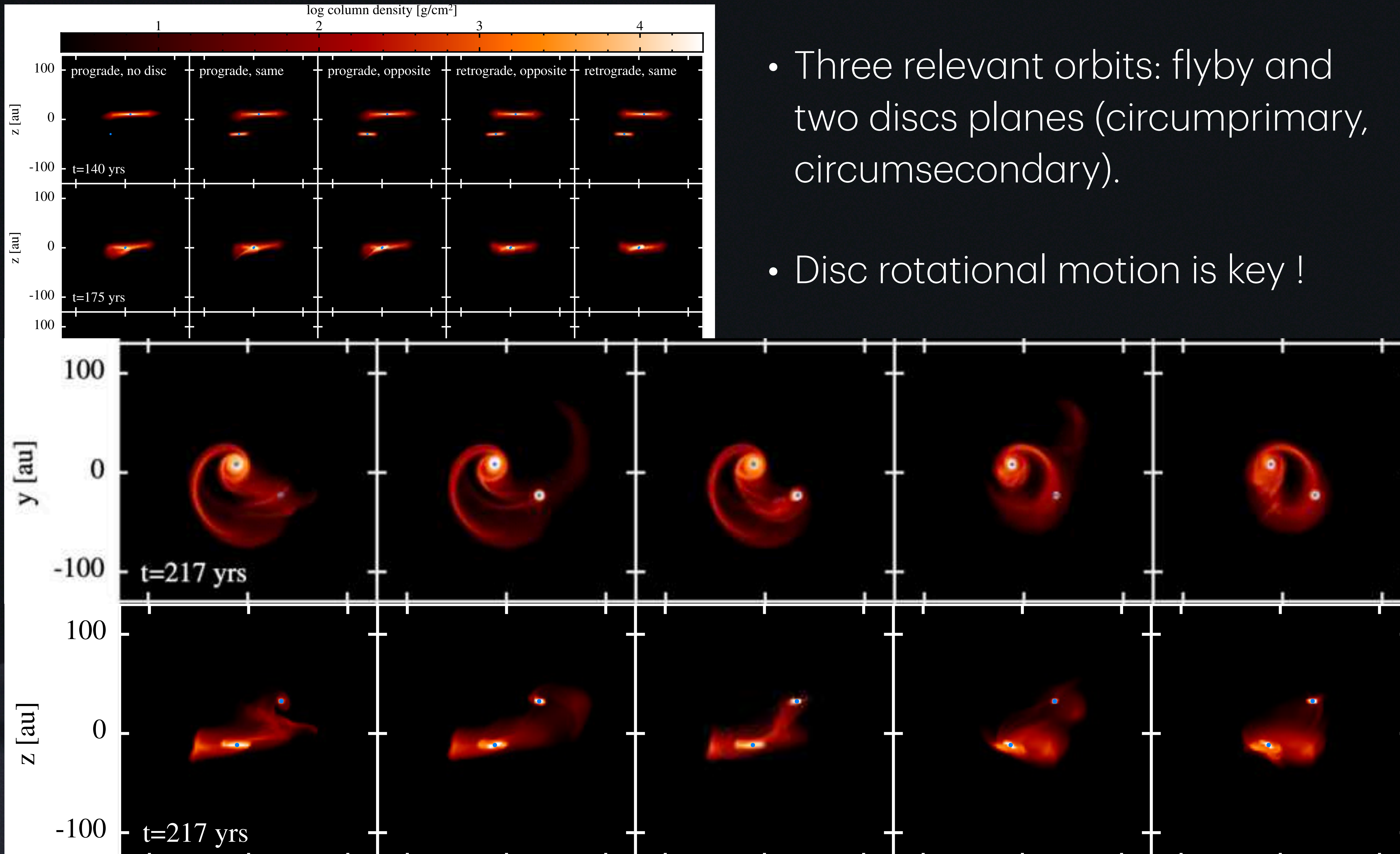
What if both stars participating in a flyby have discs?

Fact #1: In FU Ori, both stars have discs (see observations by Pérez+2020 & Weber+2023)

Fact #2: For a given star, + likely to encounter stars which are around the same age

Does disc-disc-flyby orientation matter?

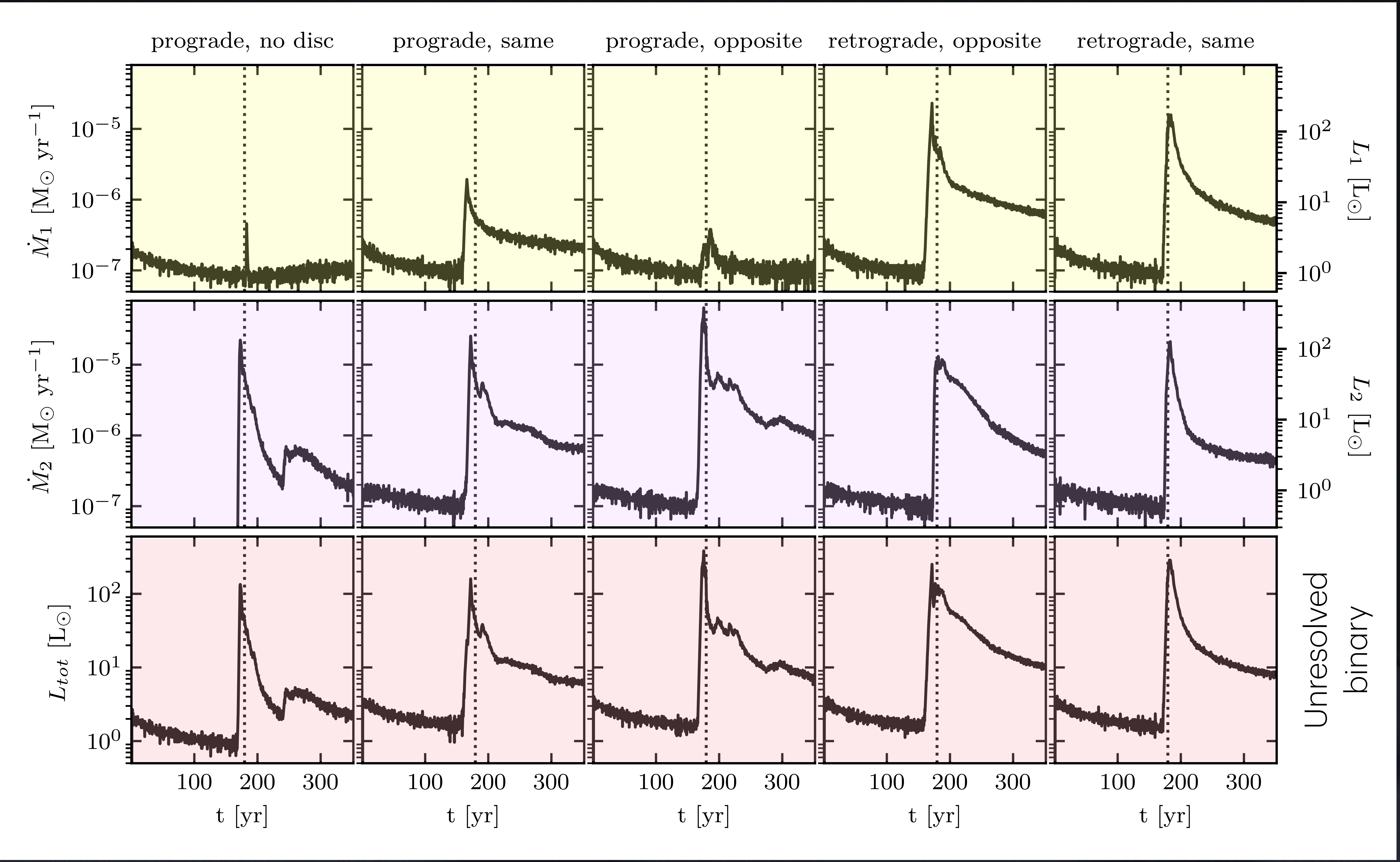
Borchert et al. (2022b)



- Three relevant orbits: flyby and two discs planes (circumprimary, circumsecondary).
- Disc rotational motion is key !

RELATIVE ORIENTATIONS MATTER FOR DISC MORPHOLOGY AND ACCRETION

Different types of accretion events

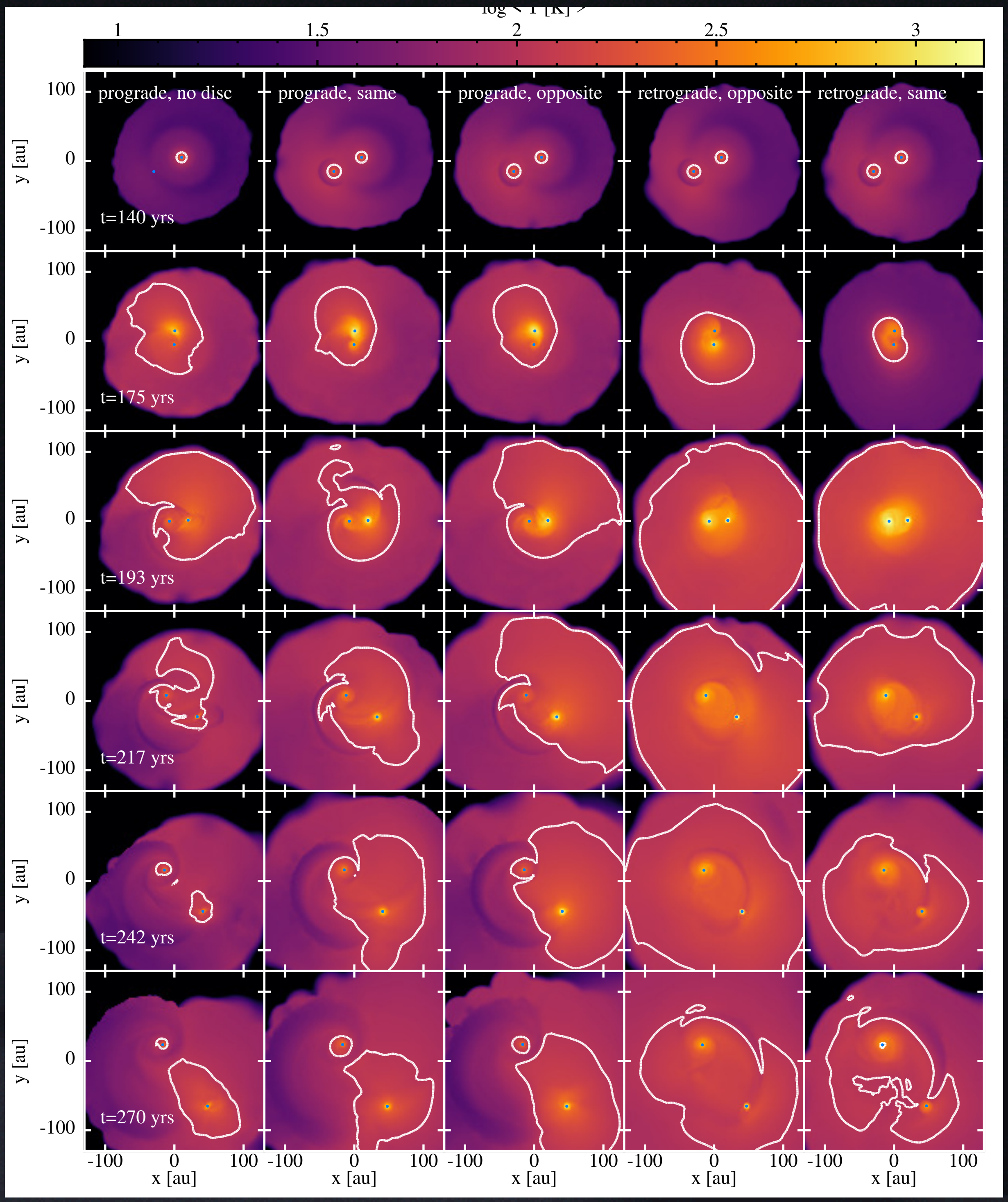


Borchert et al. (2022b)

HAVING A DISC PRIOR TO THE ENCOUNTER CHANGES THE ACCRETION TREND

Flybys move the ice-lines within the disc

Borchert et al. (2022b)

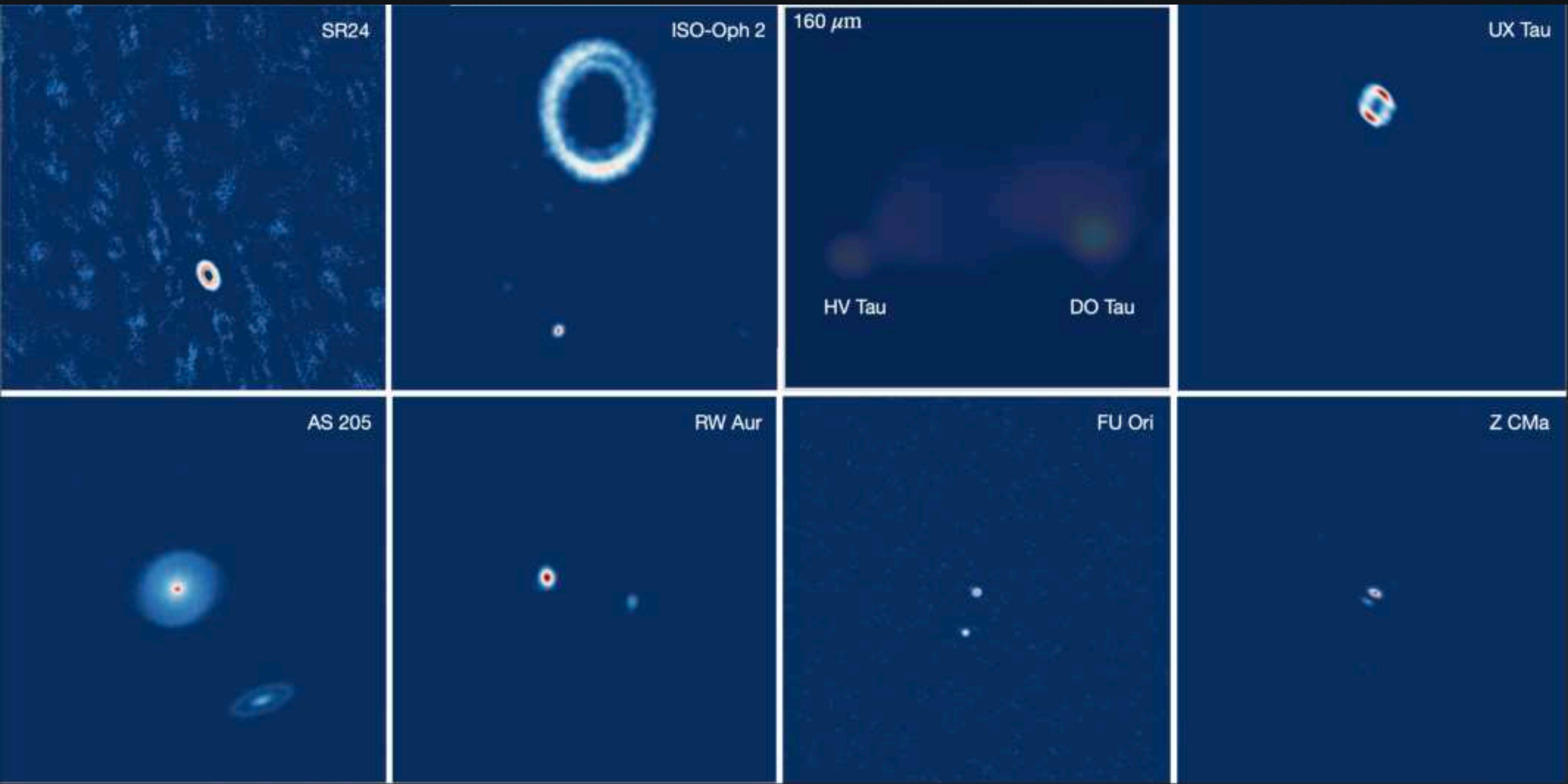


- Changing encounter parameters and the circumsecondary disc rotation, the ice-surface moves !
- ❄️🥶 scenario: prograde, no disc
- 🔥🥵 scenario: retrograde, opposite
- Ice-surfaces are highly dynamic and evolve during the encounter, hence dust is reprocessed / cooked
- Check upcoming talk by P. Poblete

ICE SURFACES CAN BECOME HIGHLY ASYMMETRIC AND IMPACT DUST COMPOSITION

Part III:
Are stellar flybys a nightmare or a dream for planet formation?

Bestiary of stellar flybys with discs

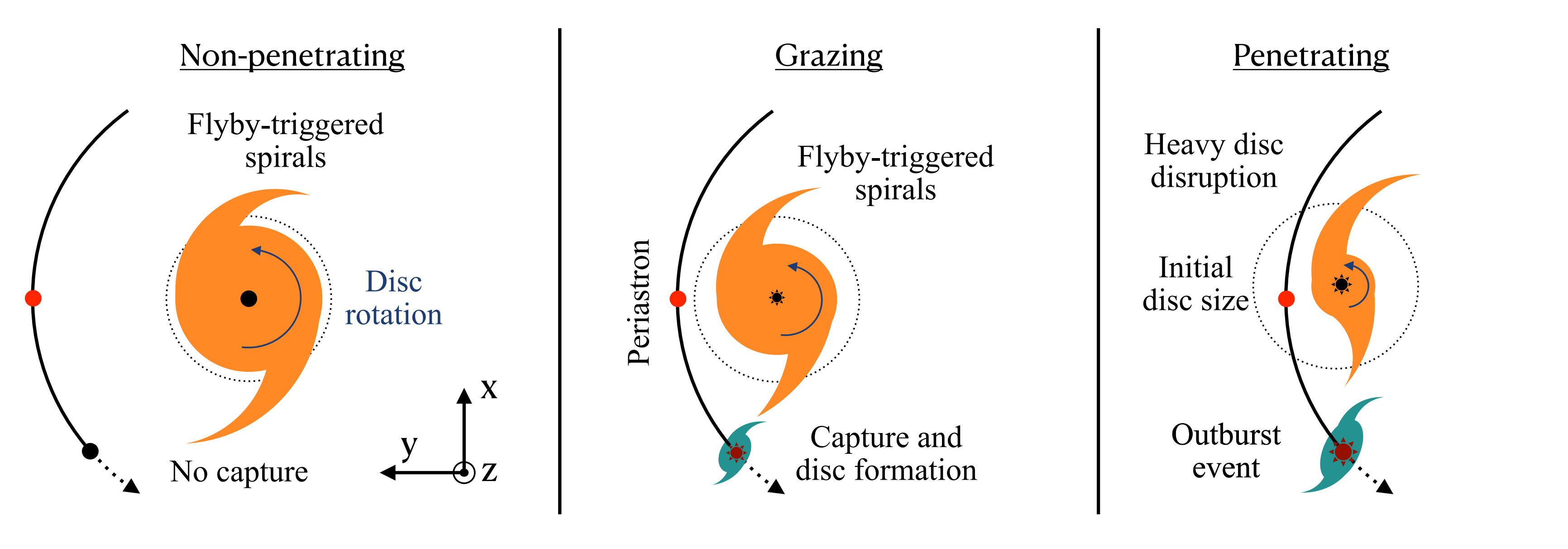


Gallery from recent review on stellar flybys: Cuello, Ménard & Price 2023
<u>Observations by</u>: Mayama+,2010/20 Weber+2023, González-Ruilova+2020, Winter+2018, Ménard+2020, Kurtovic+2018, Cabrit+2006, Rodriguez+2018, Takami+2018, Dong+2022

Our current list of suspects

Name	Distance	Mass ratio: $q = M_2/M_1$	Projected sep.	$r_{\rm flyby} = r_{\rm peri}/R_{\rm disc}$	Orbit: β, e
SR 24	100 ± 2 pc	0.95/1.4=0.7	520 au	~ 1	Prograde, e?
ISO-Oph 2	134 ± 8 pc	0.08/0.5=0.16	240 au	~ 2.5	Prograde, e?
HV & DO Tau	138 ± 1 pc	0.5/1.35=0.37	12 600 au	$285/320 \approx 0.9$	$\beta = 28^{\rm o}$, $e \sim 1$
UX Tau	142 ± 1 pc	0.2/1.0=0.2	383 au	$100/90 \approx 1.1$	$\beta \approx 45^{\rm o}$, $e \sim 1$
AS 205	142 ± 3 pc	1.28/0.87=1.47	168 au	~ 1	Prograde, e?
RW Aur	156 ± 1 pc	0.9/1.4=0.64	234 au	$70/60 \approx 1.2$	$\beta \approx 20^{\rm o}$, $e = 1$
FU Ori	408 ± 3 pc	1.2/0.6=2.0	204 au	$20/50 = 0.4$	$\beta \approx 45^{\rm o}$, $e \gtrsim 1$
Z CMa	1125 ± 30 pc	1.8/6.0=0.3	4725 au	$3000/840 \approx 3.6$	$\beta \approx 45^{\rm o}$, $e \sim 1$
Sag. C cloud	8100 pc	3.2/31.7=0.1	≈ 8000 au	$2000/3000 \approx 0.7$	$\beta \approx 45^{\rm o}$, $e \sim 1$

Cuello, Ménard & Price (2023)



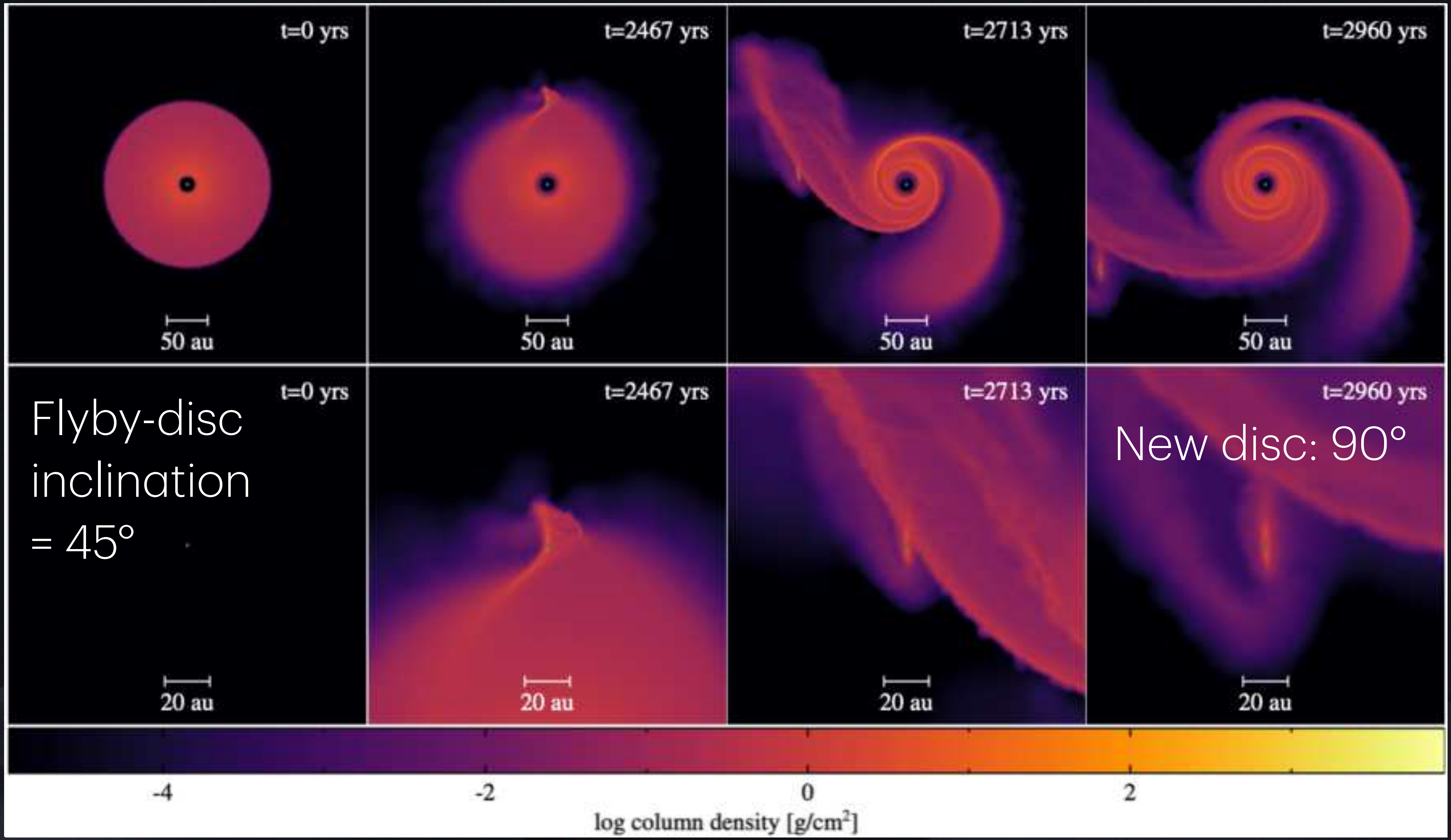
ARE ALL THESE SUSPECTS ERUPTIVE OR WILL THEY BE?

Some related questions in light of the previous content

Q#1: What happens to the material captured around the intruder star?

Q#2: Can flybys help to form planets and reprocess solids within protoplanetary discs?

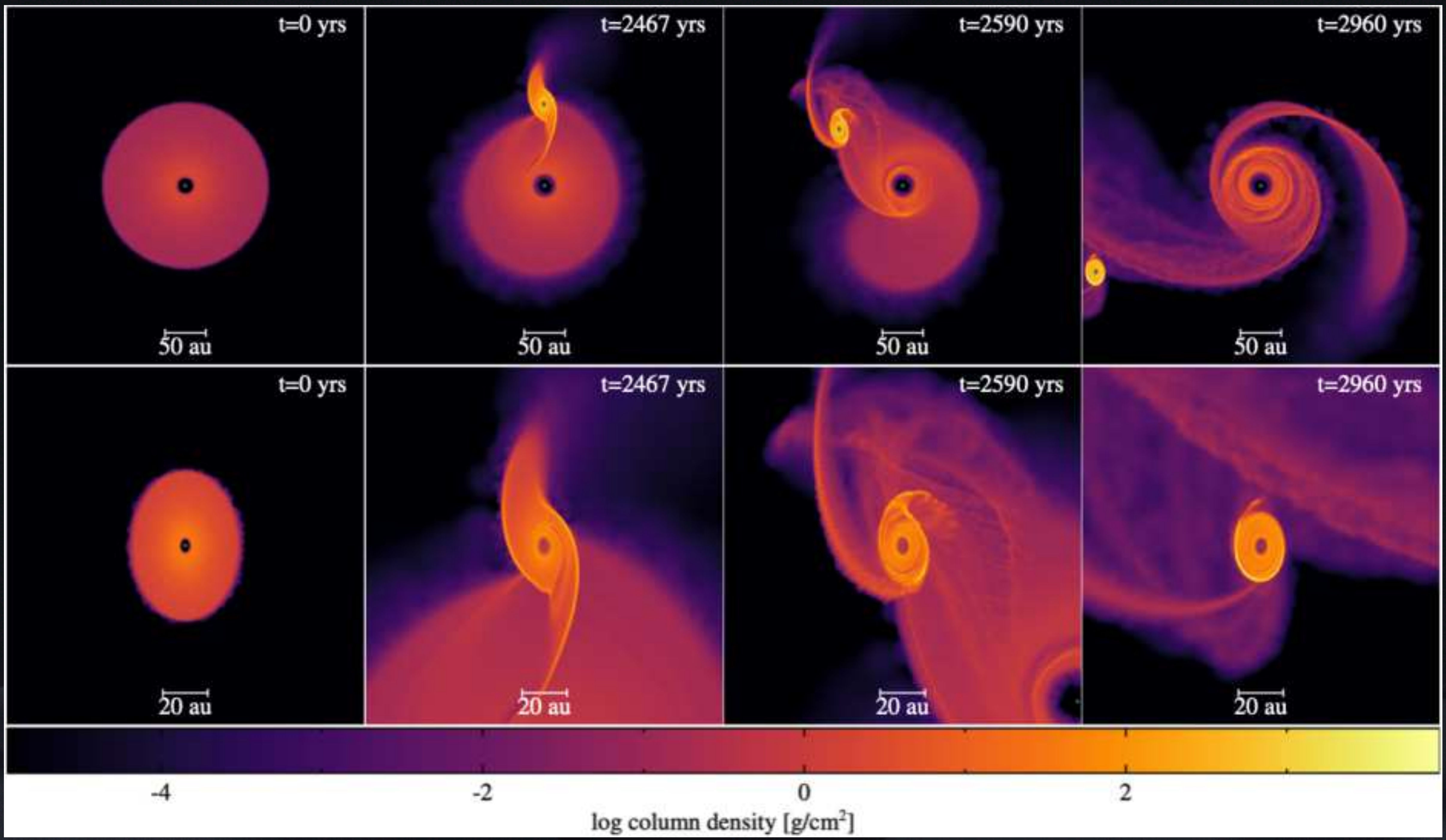
Formation of 2nd generation discs



Smallwood et al. (2024)

THE SECONDARY DISC INCLINATION IS TWICE THE INTRUDER'S ORBITAL INCLINATION

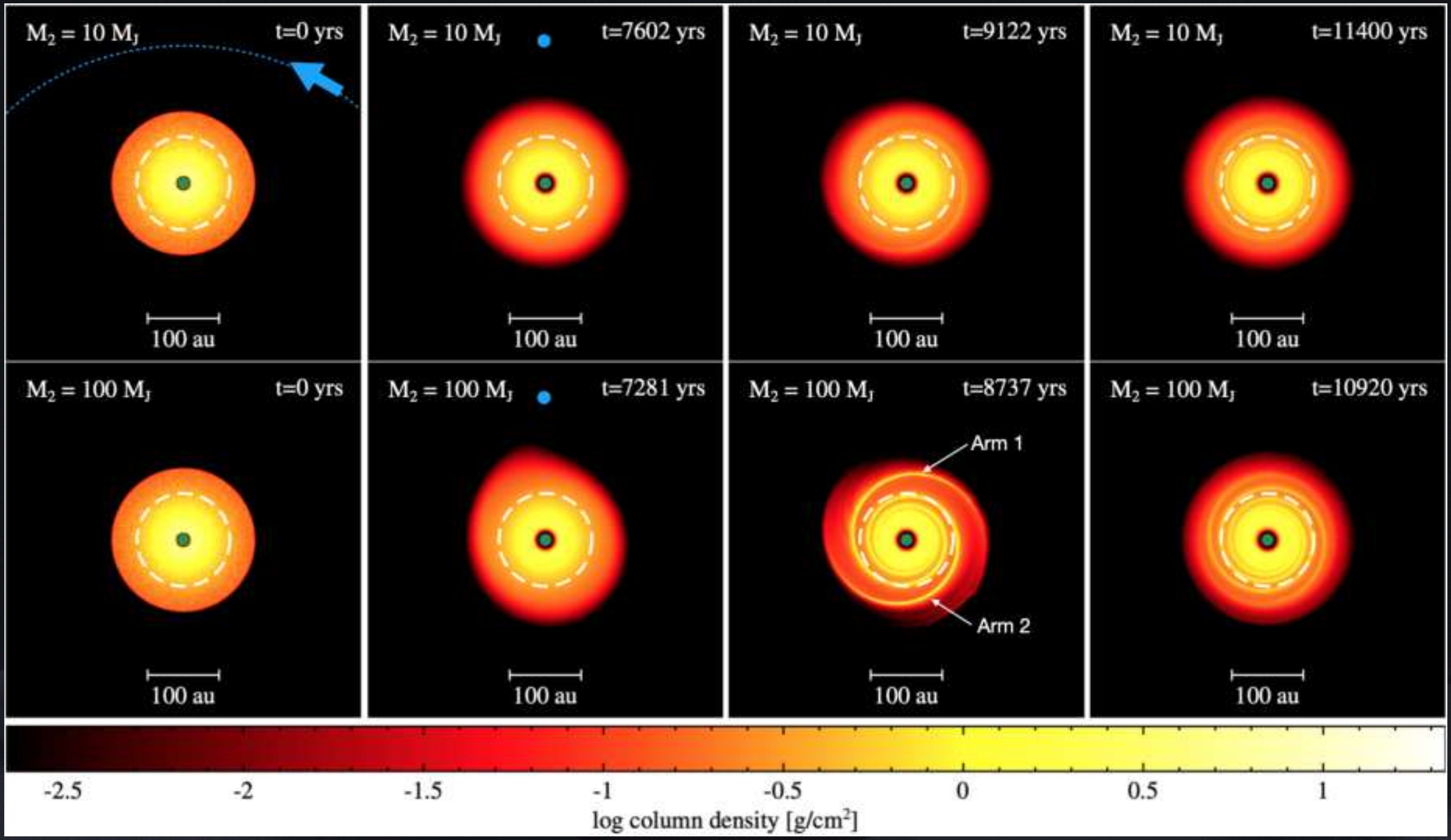
Accretion onto an existing disc



Smallwood et al. (2024)

THE ACCRETED MATERIAL IS FORCED TO ACCRETE ONTO THE PRE-EXISTING DISC

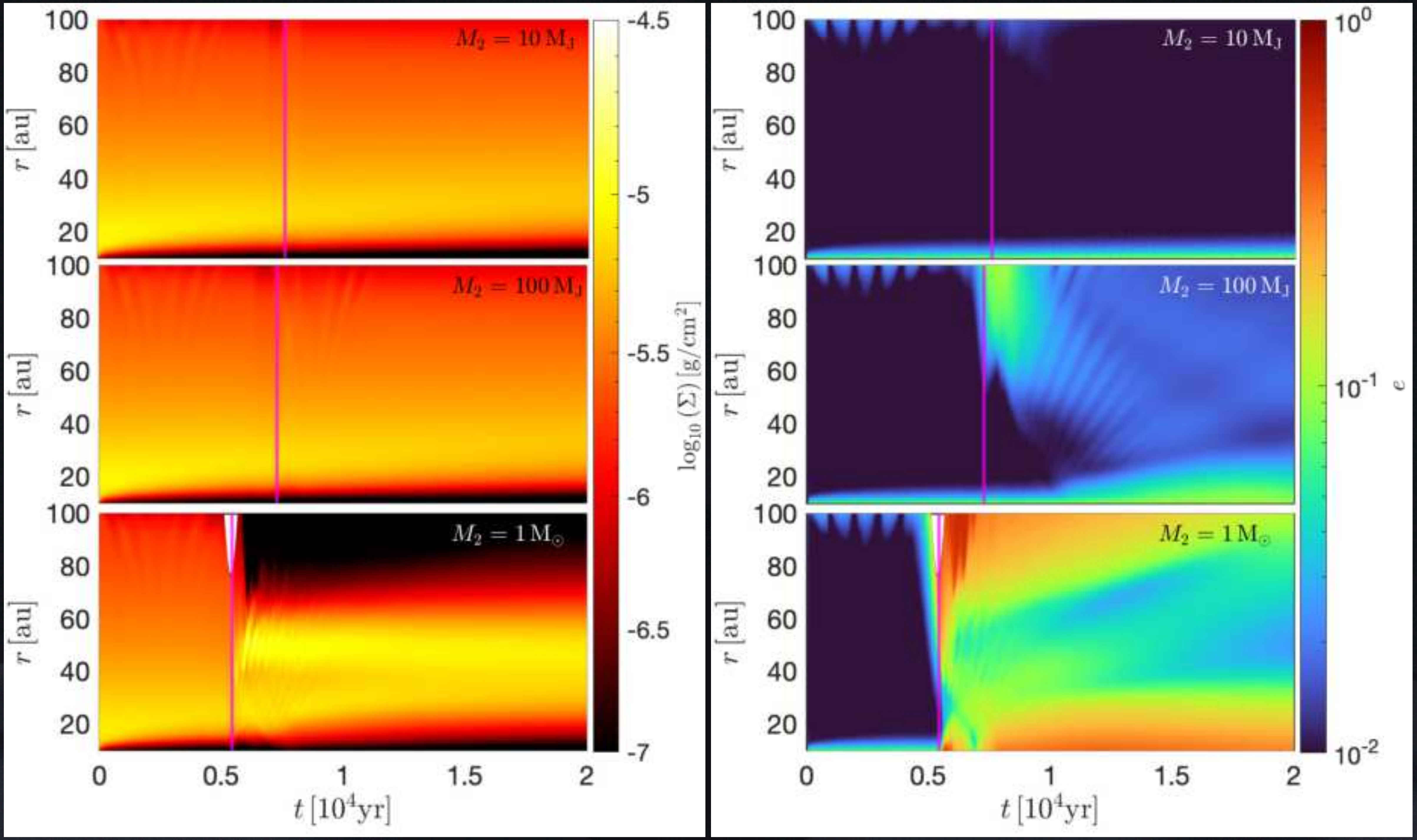
Flyby-induced spirals



Smallwood et al. (2023)

SPIRALS IN THE DISC CAN ACT AS DUST TRAPS AND TYPICALLY LIVE FOR SOME KYRS

Density & eccentricity increase



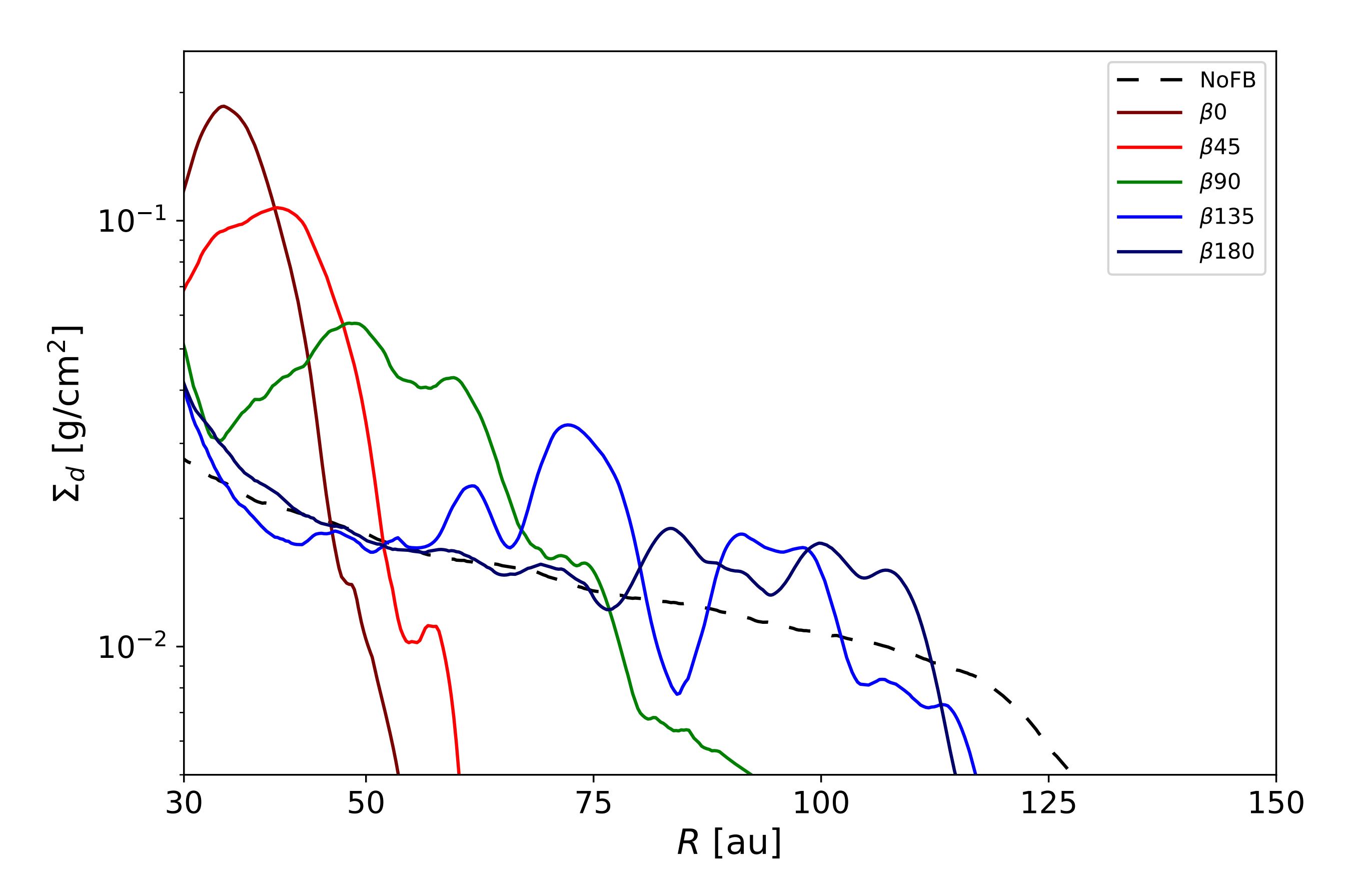
Smallwood et al. (2023)

GRAZING FLYBYS ARE ABLE TO CONCENTRATE AND EXCITE PARTICLES IN THE DISC

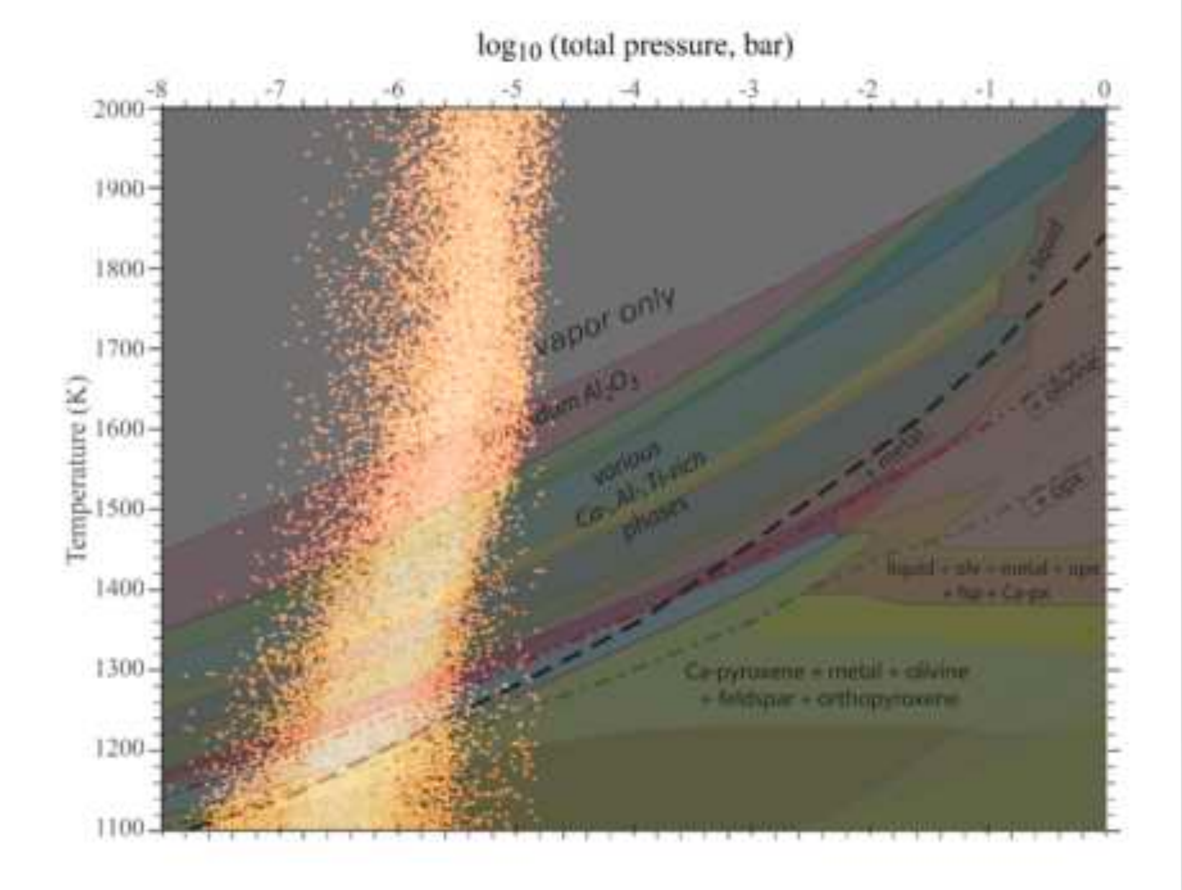
Planet formation aided by flybys

- Flybys cause tidal truncation and lead to steeper surf. dens. profiles
- Dust drift & traps: streaming inst.?

- Disc-penetrating encounters lead a dramatic increase in T
- Dust particles > 1000 K: CAIs?



Cuello et al. 2019b



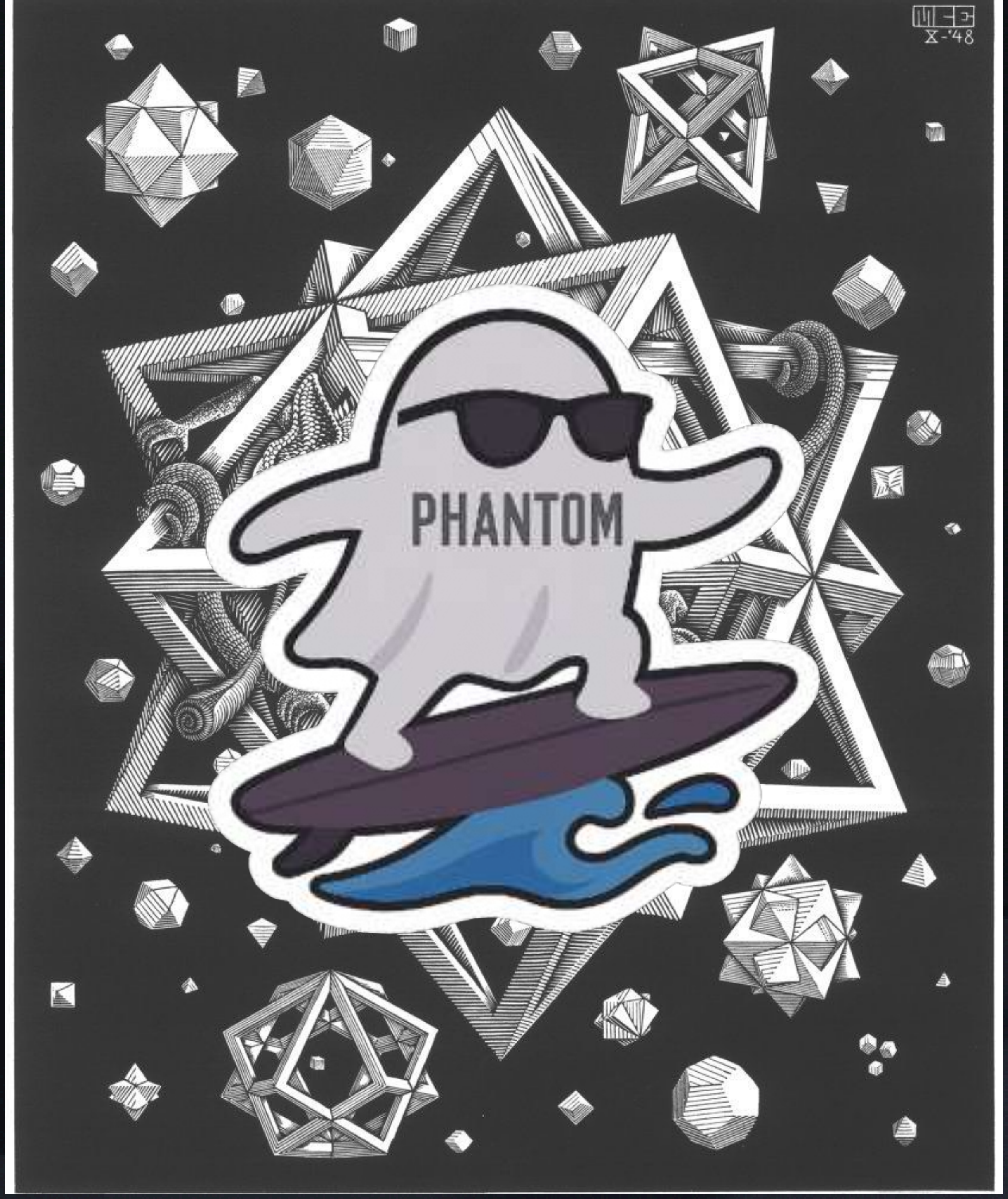
Price, Borchert, Cuello & Pinte (in prep?)

For resonant planetary chains perturbed by Stellar Flybys:
Check recent work by Charalambous, Cuello & Petrovich (2025)

Epilogue: Flybys, accretion & planets

A nightmare or a dream?

- Flybys (=gravitational vandals) are a natural way to trigger outbursts & substructure around young stars
- Flybys (=cosmic midwives) trigger gravitational instabilities, concentrate dust (mix & cook), accelerate PF.
- Important to consider both discs (rotation matters), radiative effects & "chemistry" during the flyby
- Search for a more systematic link between flyby candidates and recent/ ongoing outburst. For instance: Are outbursting stars the norm rather than the exception? Outbursting Sun?

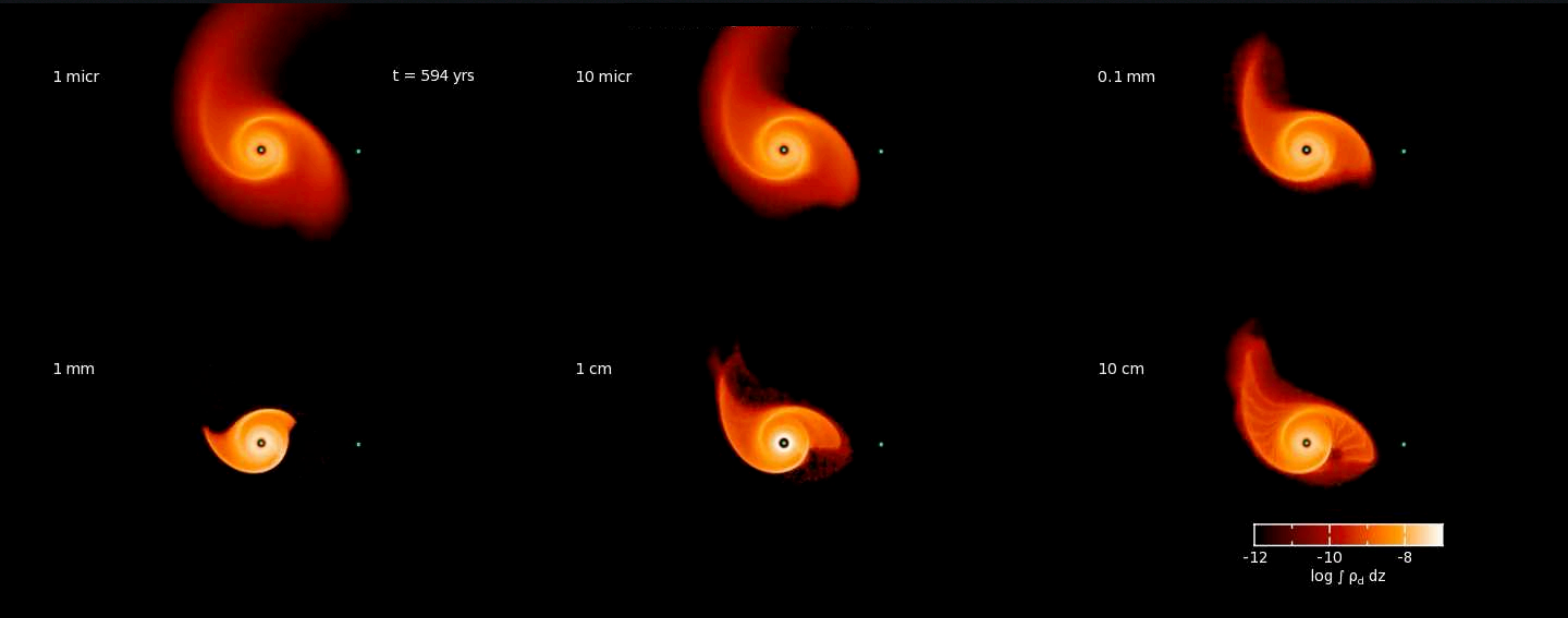


Escher

FLY-BYE BYE AND THANKS FOR YOUR ATTENTION !

Bonus slides:
Extra content on flybys

Dust dynamics during flybys



Cuello et al. (2019b)

Due to radial drift, different dust species have different cross sections

Dust response depends on gas coupling & flyby parameters

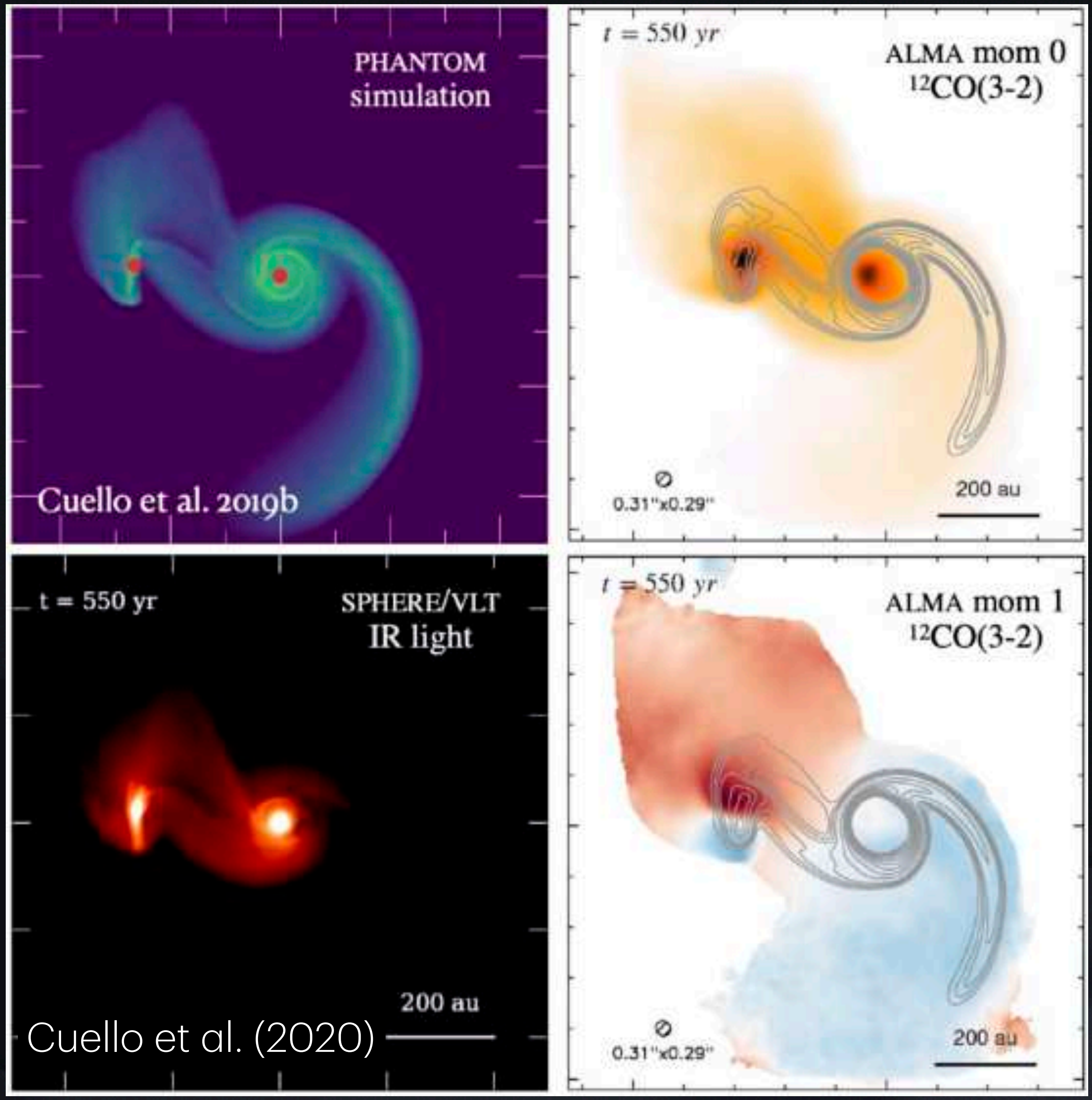
Connecting hydro to observations

- **Models ↔ Observations**

  Hydrodynamics w/ PHANTOM
  Radiative transfer w/ MCFOST
  NB: Gas & Dust separately

- Emission at ≠ λ: IR, mm, lines
  Catalogue of synthetic obs.
  ➙ Search for perturbers

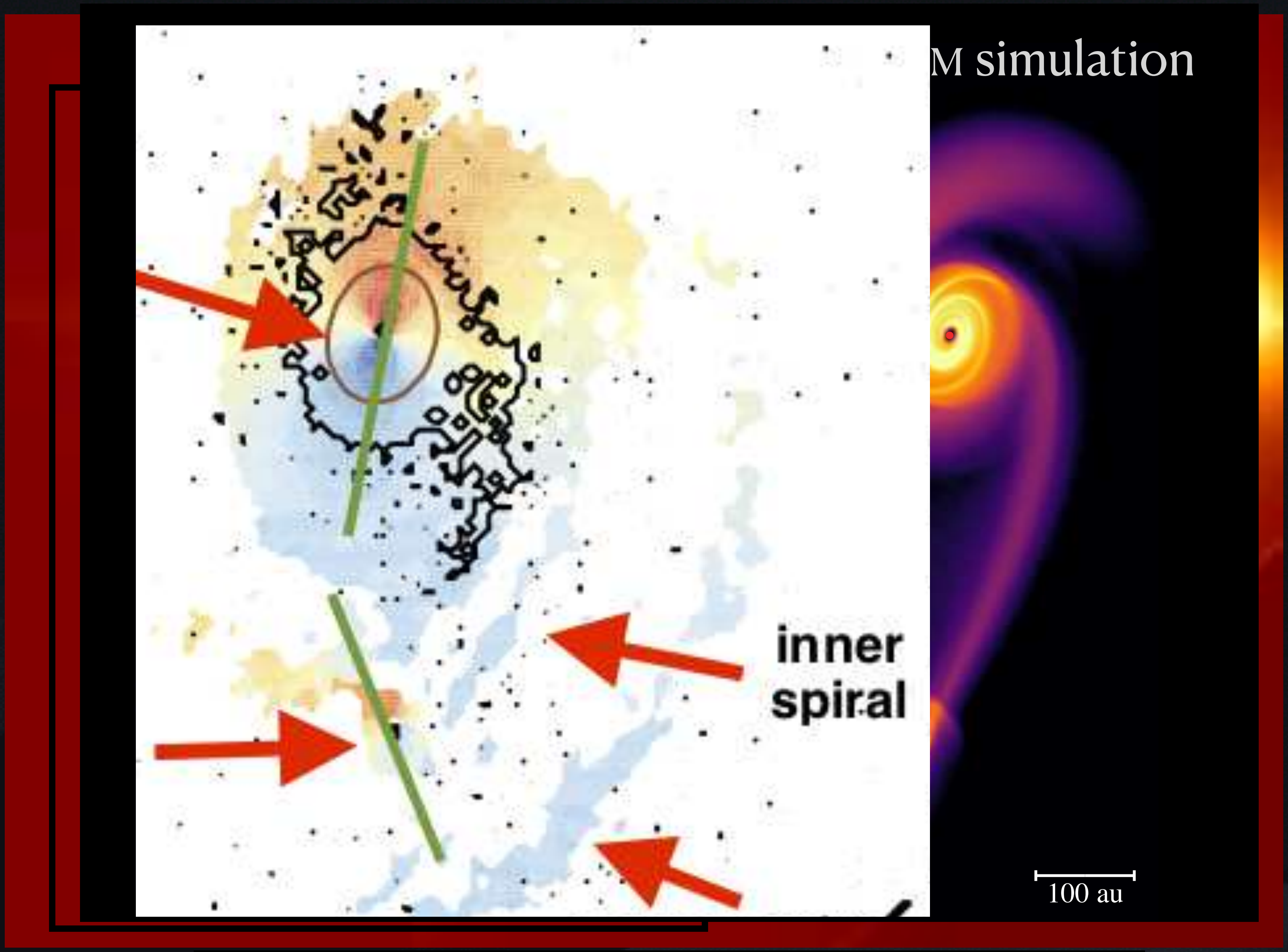
- <u>Analogy</u>: flyby = crime scene
  Perturber has already left
  or (if lucky) caught in the
  field of view



INTERPRETATIVE FRAMEWORK FOR RECENT OBSERVATIONS OF PERTURBED DISCS

A flyby in a quadruple stellar system

- Inclined prograde flyby
  ➙ Spirals + Bridge
- Mass ratio M_C/M_A=0.2
  R_P = 100 au, R_{out} = 90 au
  ➙ Grazing encounter
- Disc capture scenario
  Disc misalignment
  2nd generation PPDs ?
- Recent works (incl. NC)
  by Borchert+2023 and
  Smallwood+2023, 2024



Ménard, Cuello et al. (2020, SPHERE consortium)

A PROGRADE INCLINED FLYBY REPRODUCES THE OBSERVATIONS