PLANET FORMATION AND DISC EVOLUTION

Daniel Price
Monash University
Melbourne, Australia

DUST BUSTERS

Olympian Symposium "Star formation in the era of JWST",
29th May - 2nd June 2023, Katerini, Greece

Australian Government
Australian Research Council

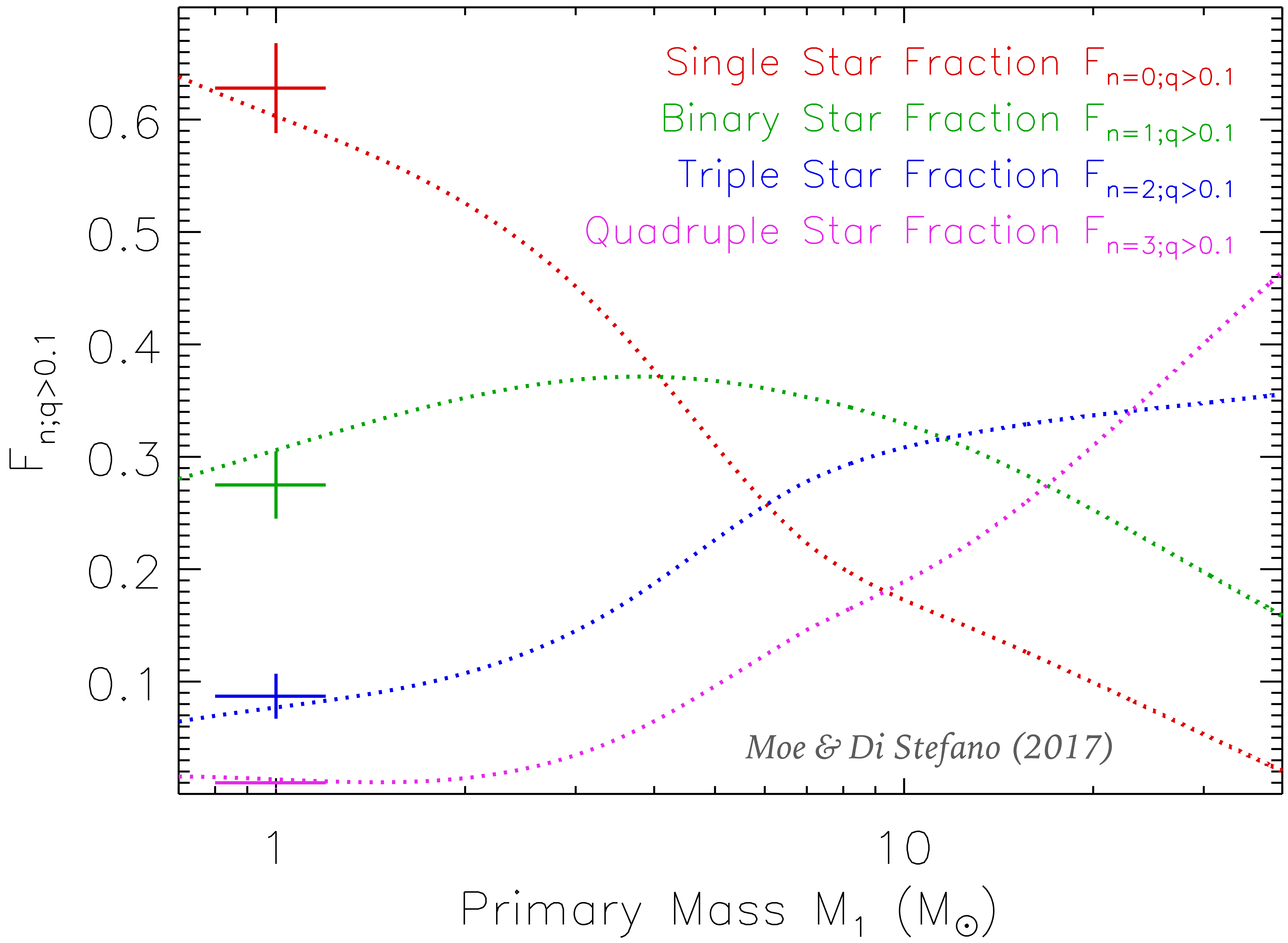
MONASH University

HOW DO YOU FORM A SOLAR SYSTEM LIKE OURS?

Chrondrules everywhere: Dust has been melted

Credit: wikipedia/CactiStaccingCrane

PROBLEM 1: HOW TO MAKE THE SUN?



I. Need to make a SINGLE star

II. Need to accrete 1Msun of gas

IS STAR FORMATION EVER ISOLATED?

Credit: NASA/ESA/M... Orion Treasury Project

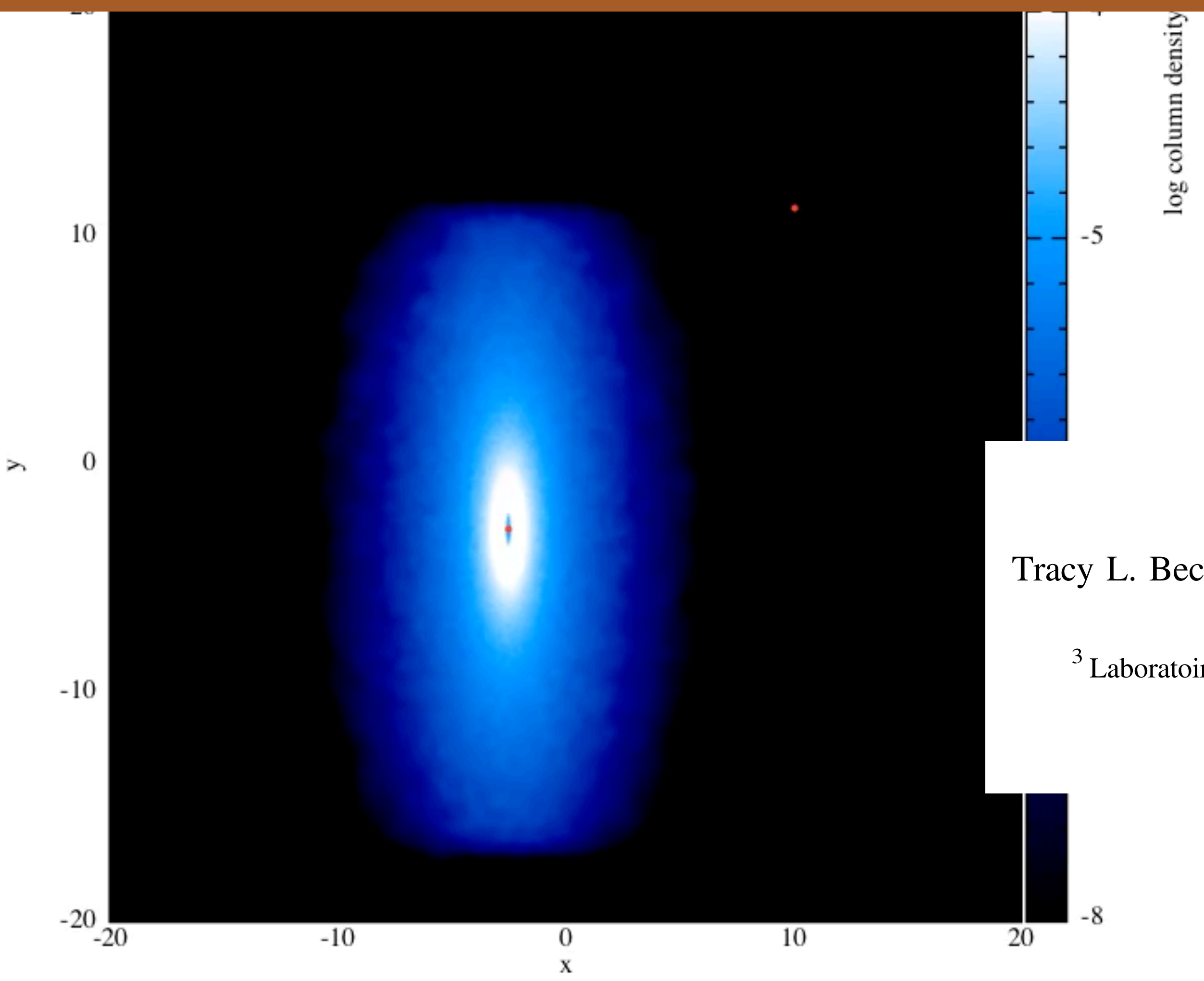
Credit: Adam Block/wikipedia

The Astrophysical Journal, 859:150 (16pp), 2018 June 1
https://doi.org/10.3847/1538-4357/aac08f
© 2018. The American Astronomical Society. All rights reserved.

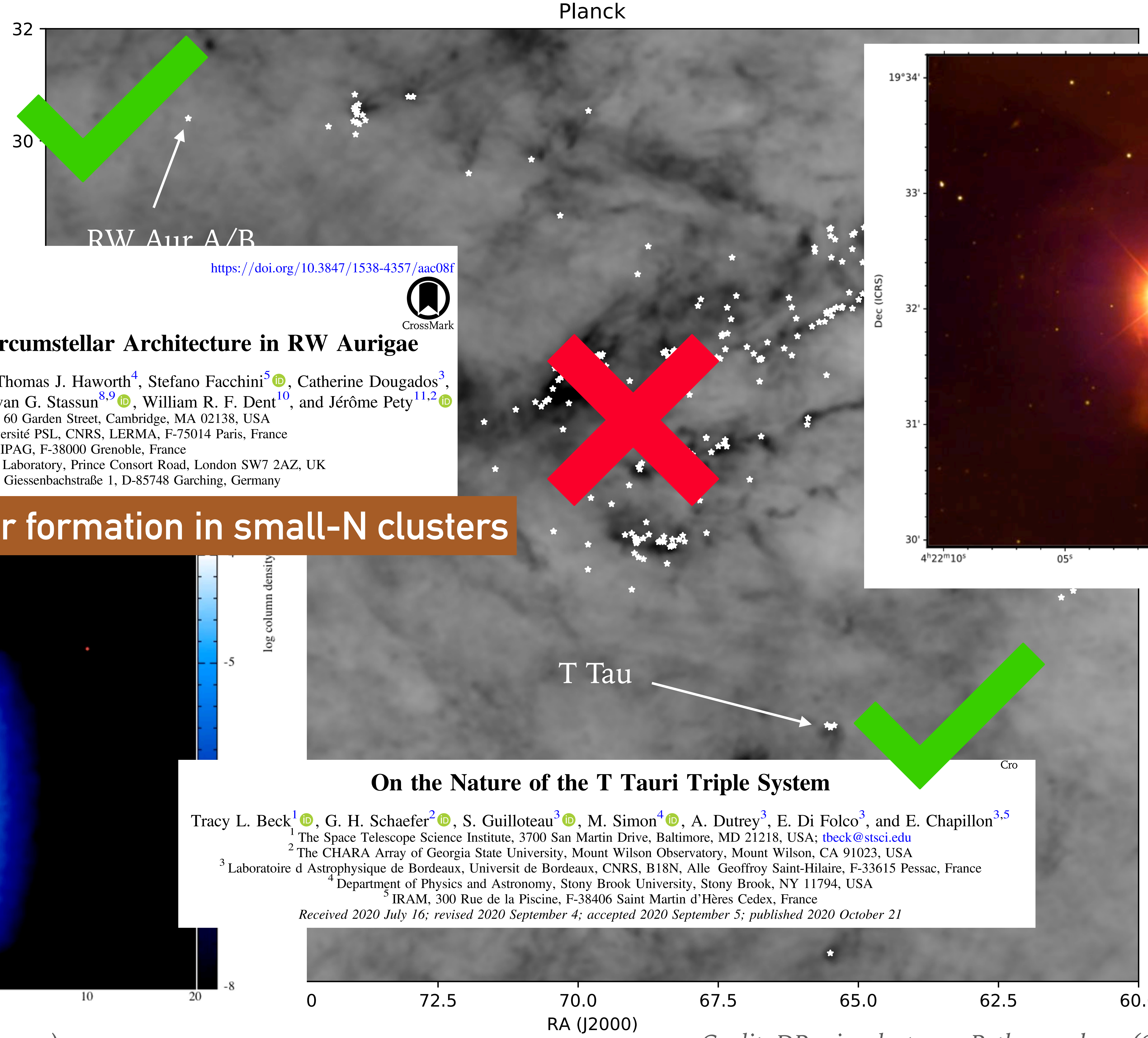
Multiple Stellar Flybys Sculpting the Circumstellar Architecture in RW Aurigae

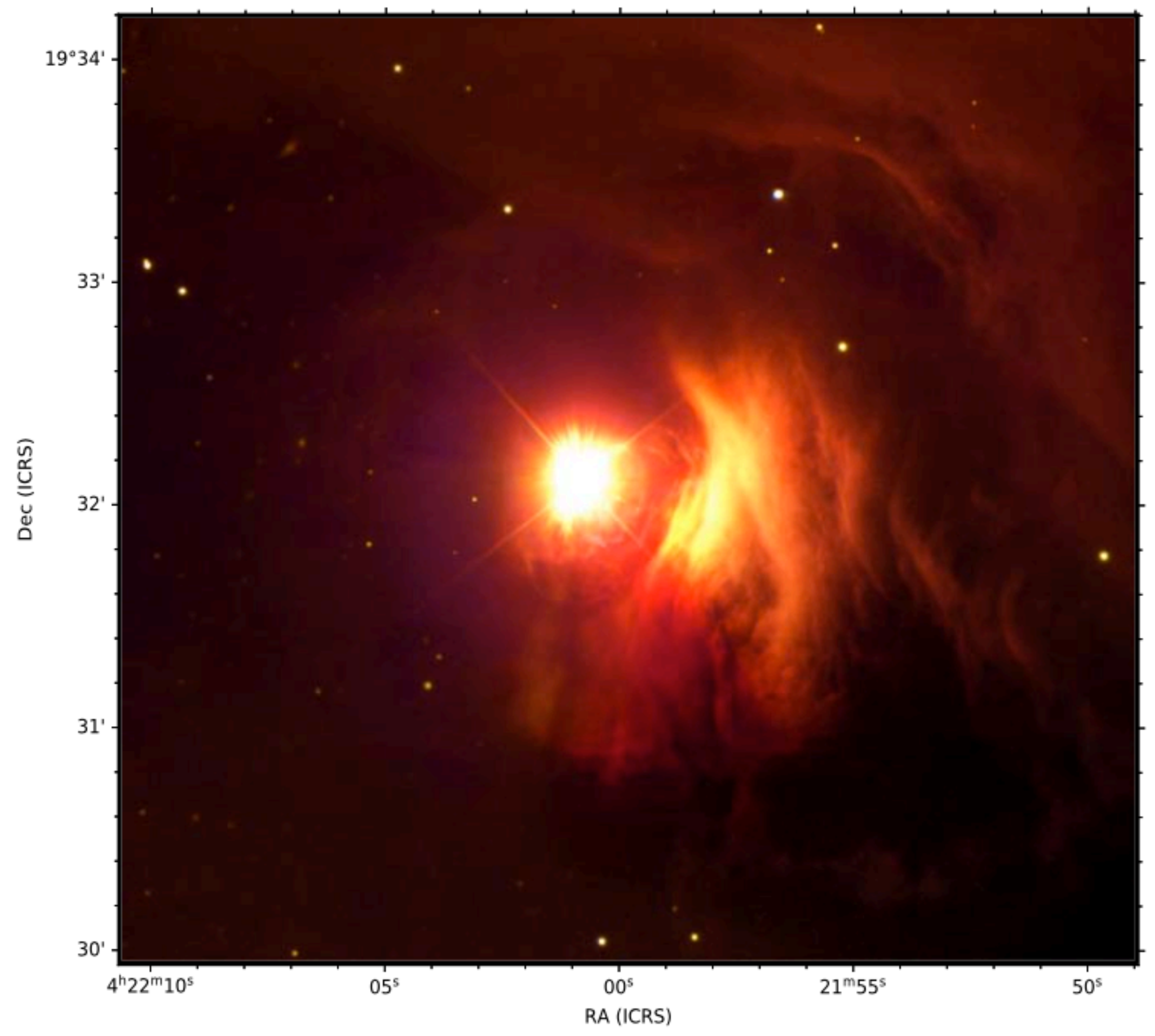
Joseph E. Rodriguez[1], Ryan Loomis[1], Sylvie Cabrit[2,3], Thomas J. Haworth[4], Stefano Facchini[5], Catherine Dougados[3], Richard A. Booth[6], Eric L. N. Jensen[7], Cathie J. Clarke[6], Keivan G. Stassun[8,9], William R. F. Dent[10], and Jérôme Pety[11,2]
1 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
2 Sorbonne Université, Observatoire de Paris, Université PSL, CNRS, LERMA, F-75014 Paris, France
3 Univ. Grenoble Alpes, CNRS, IPAG, F-38000 Grenoble, France
4 Astrophysics Group, Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, UK
5 Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstraße 1, D-85748 Garching, Germany

See Ambrose poster on star formation in small-N clusters



Credit: Nicolás Cuello (in prep)





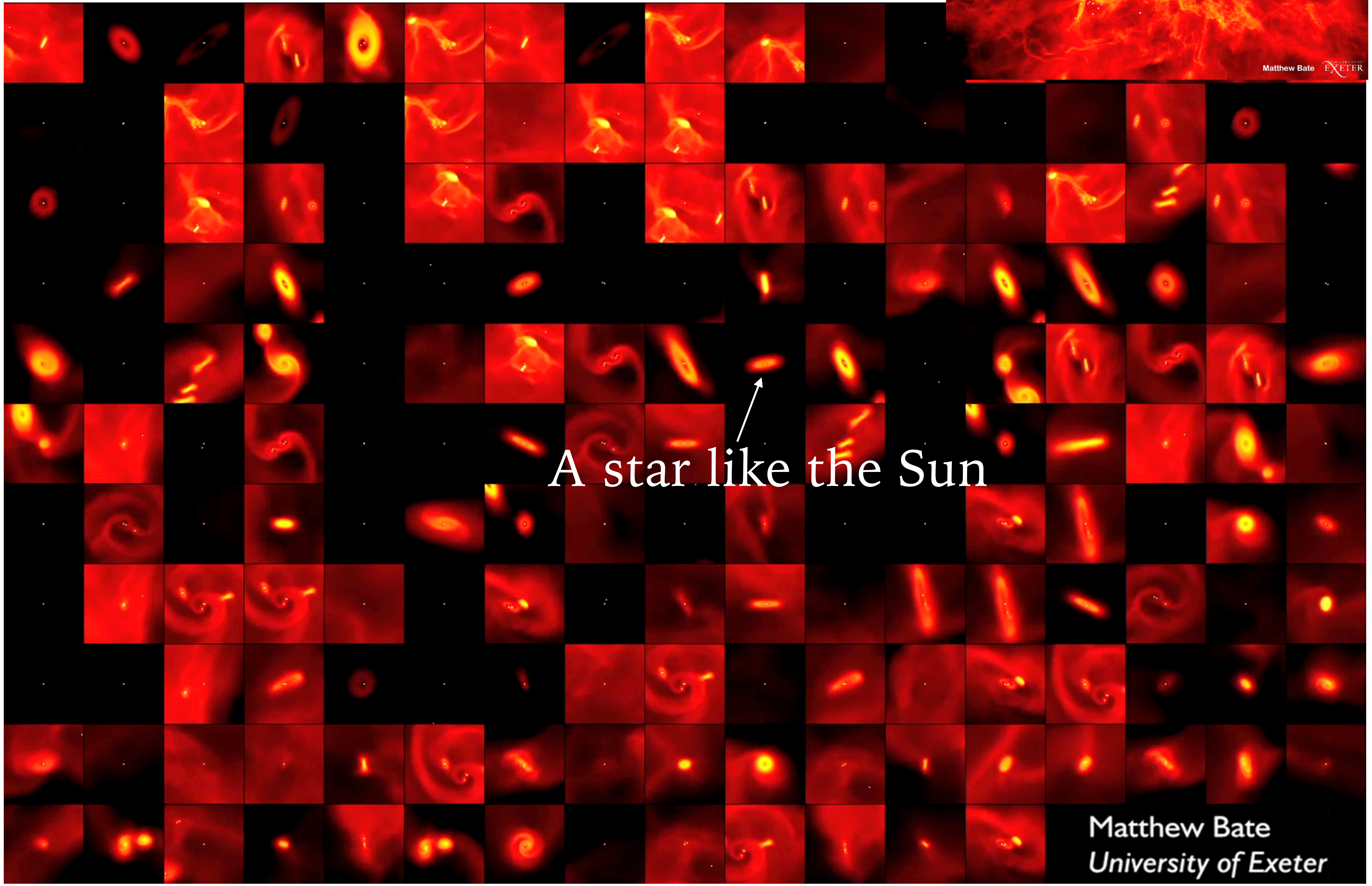
On the Nature of the T Tauri Triple System

Tracy L. Beck[1], G. H. Schaefer[2], S. Guilloteau[3], M. Simon[4], A. Dutrey[3], E. Di Folco[3], and E. Chapillon[3,5]
1 The Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA; tbeck@stsci.edu
2 The CHARA Array of Georgia State University, Mount Wilson Observatory, Mount Wilson, CA 91023, USA
3 Laboratoire d Astrophysique de Bordeaux, Universit de Bordeaux, CNRS, B18N, Alle Geoffroy Saint-Hilaire, F-33615 Pessac, France
4 Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA
5 IRAM, 300 Rue de la Piscine, F-38406 Saint Martin d'Hères Cedex, France
Received 2020 July 16; revised 2020 September 4; accepted 2020 September 5; published 2020 October 21

Credit: DP using dustmaps Python package (Green 2018 JOSS)

1. HOW TO MAKE A SINGLE STAR

Bate (2012, 2018)



- Form single stars by ejecting them from unstable multiple systems
- Almost every star has multiple infall events or stellar flybys in the Class 0 stage
- Naturally explains misalignment between disc and stellar spin axes

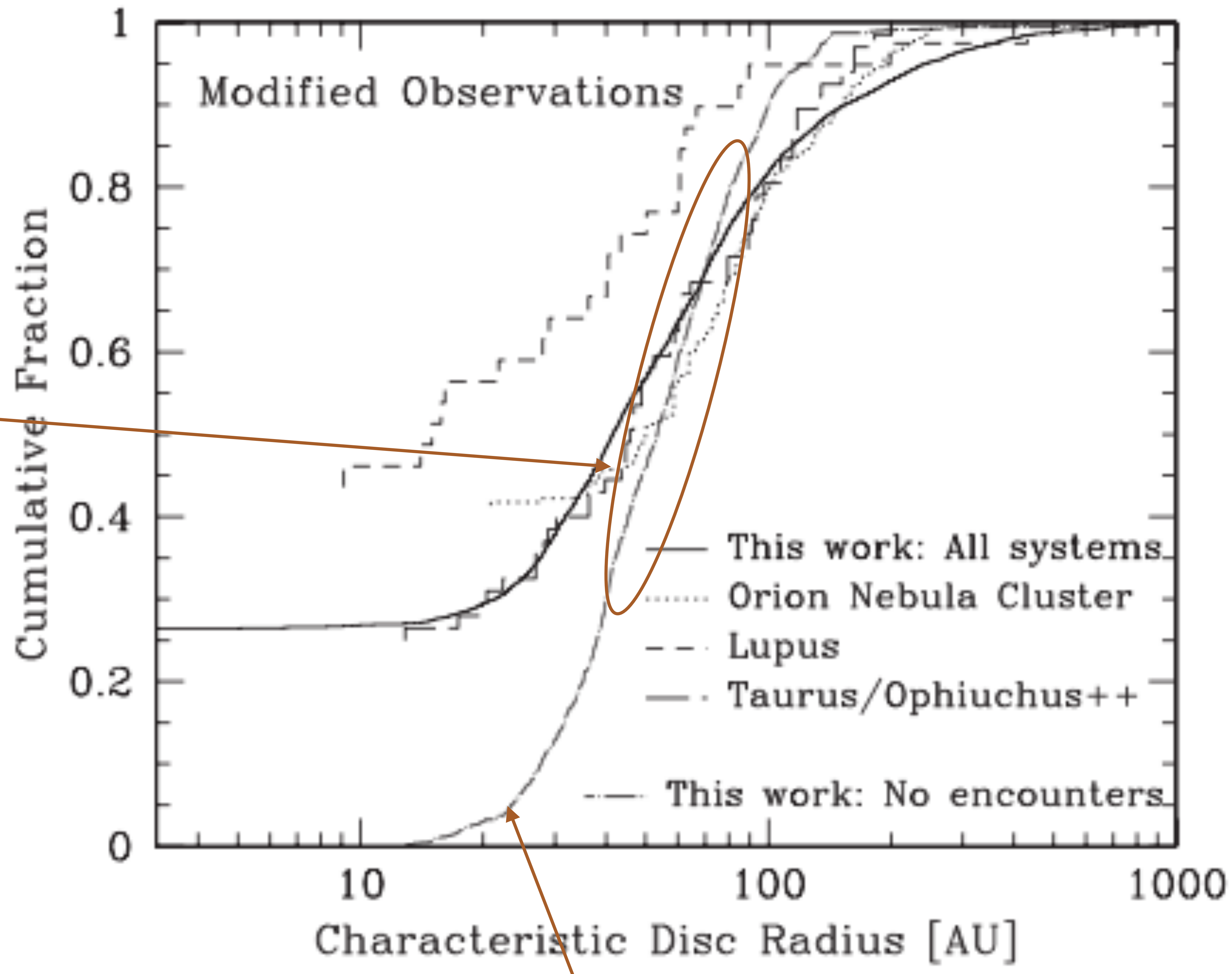
See Elsender talk

DISC SIZES ARE SET BY TIDAL TRUNCATION

Bate (2018) compared to observations by Vicente & Alves (2005); Tazzari et al. (2017); Tripathi et al. (2017); Andrews et al. (2009, 2010)

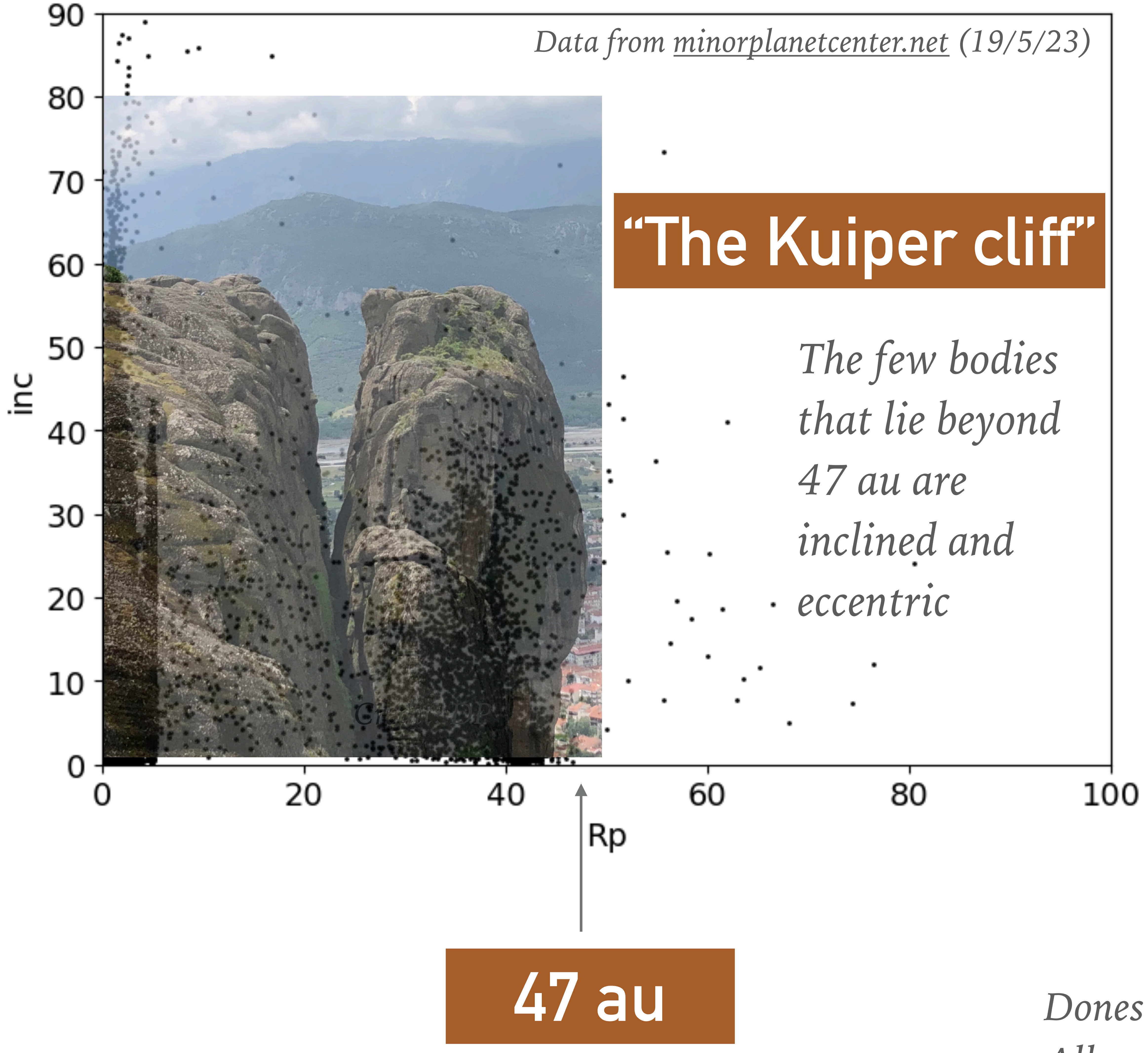
- Disc size distribution in cluster formation simulations matches the observed (mm-continuum) size distributions
- How can the distribution in Taurus, Ophiuchus & Orion be the same if dynamical interaction is important?

Ans: dynamical interaction occurs in small groups independent of large-scale stellar density (Bate 2018)



Stars with no interactions do not match the observed population

HOW DID THE SOLAR SYSTEM GET ITS SIZE?

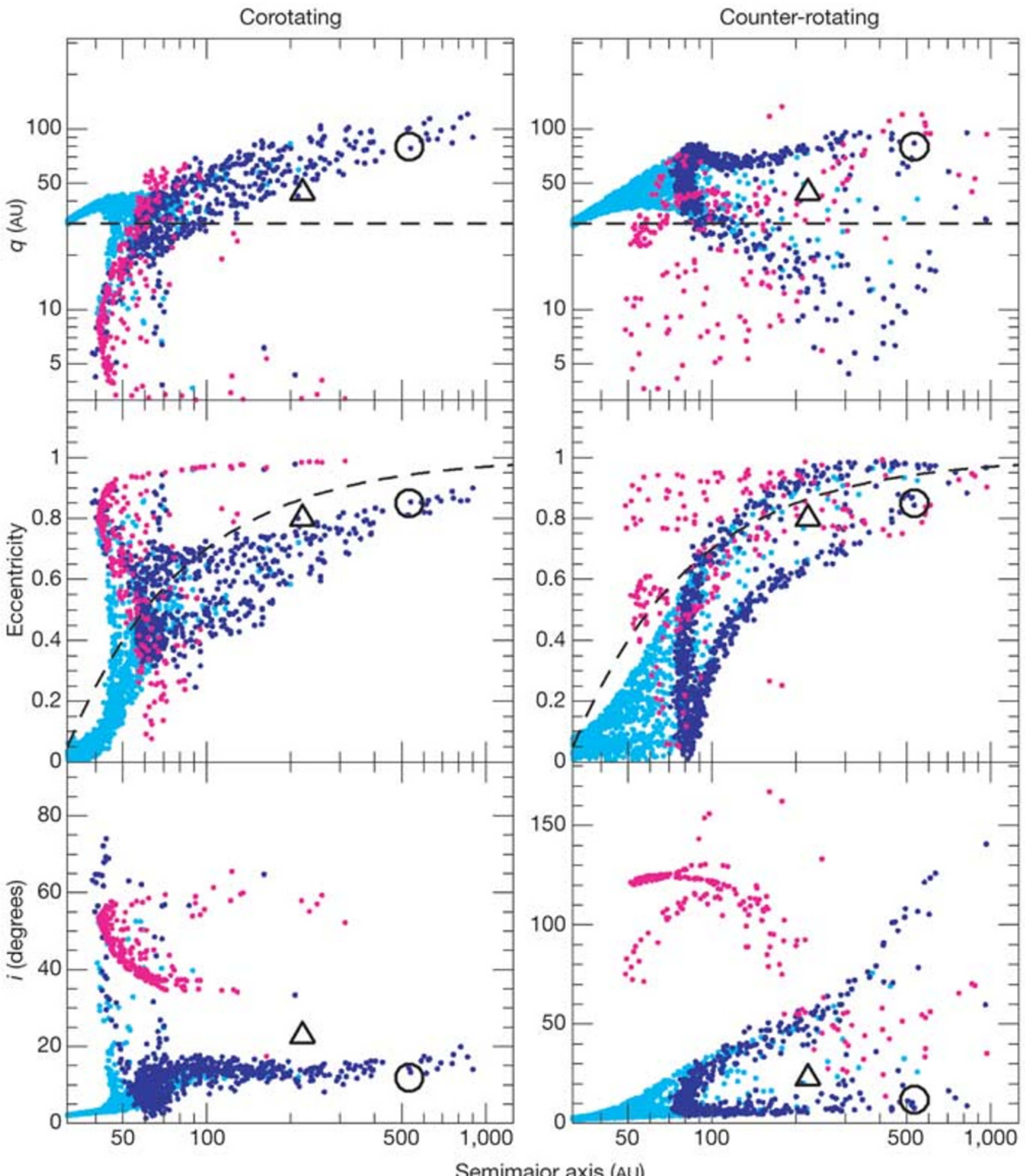


- Distribution of minor bodies sharply truncated at ~47 au
- Very difficult to explain in standard models
- Would be naturally explained by a stellar flyby, like every other disc (Ida+2000; Kenyon & Bromley 2004)

Dones 1997; Jewitt et al. 1998; Chiang & Brown 1999; Trujillo & Brown 2001; Allen et al. 2001; Gladman et al. 2001; Petit et al. 2006, Larsen et al, 2007

A FLYBY IN THE OUTER SOLAR SYSTEM?

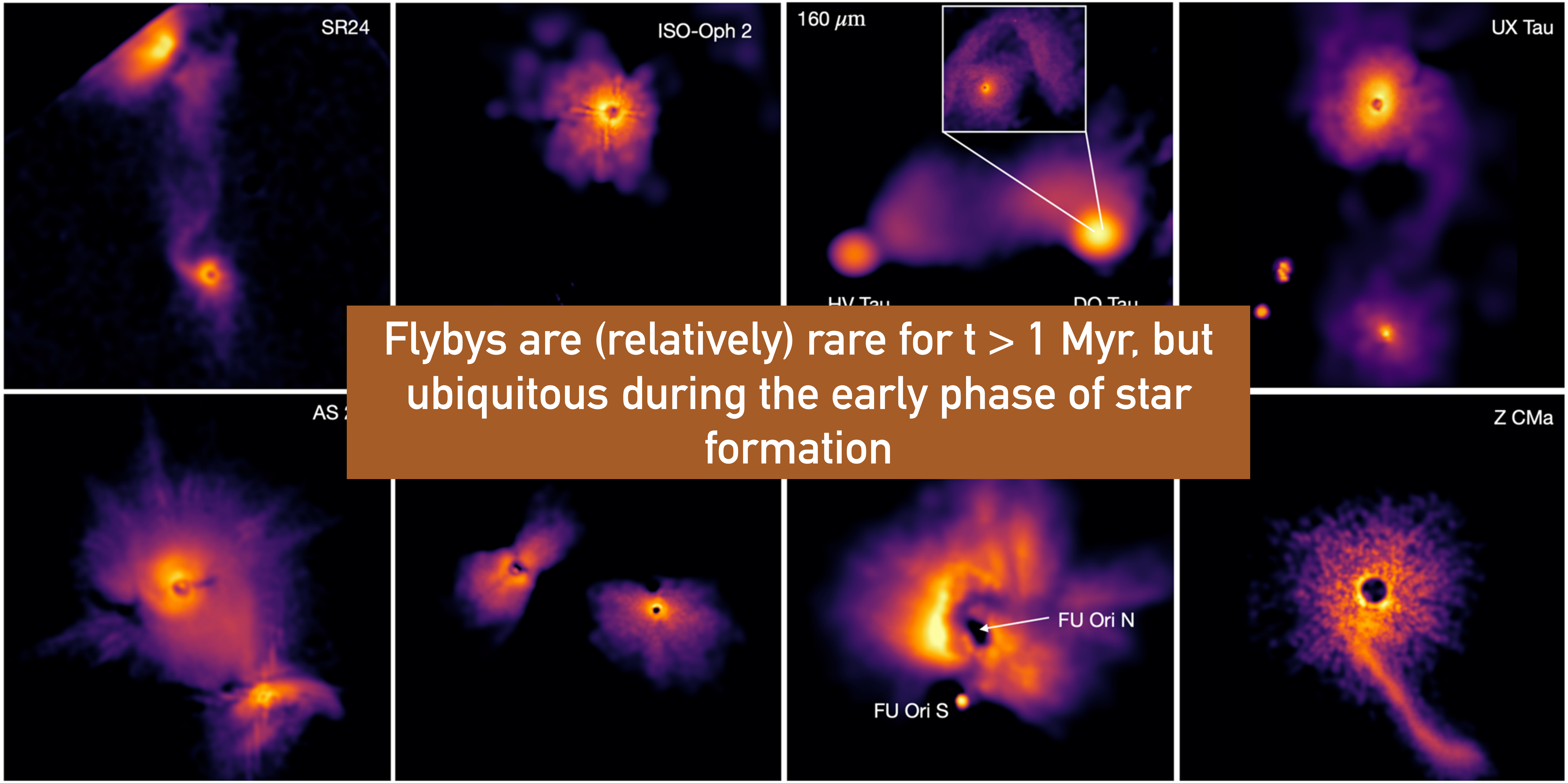
Kenyon & Bromley (2004)
See also Pfalzner et al. (2018)



- ➤ Naturally truncate the (dust) disc
- ➤ Stir particles beyond 50 au into inclined and eccentric orbits, matching those of the trans-Neptunian objects

EVIDENCE FOR LATE FLYBYS

Cuello, Ménard & Price (2023)



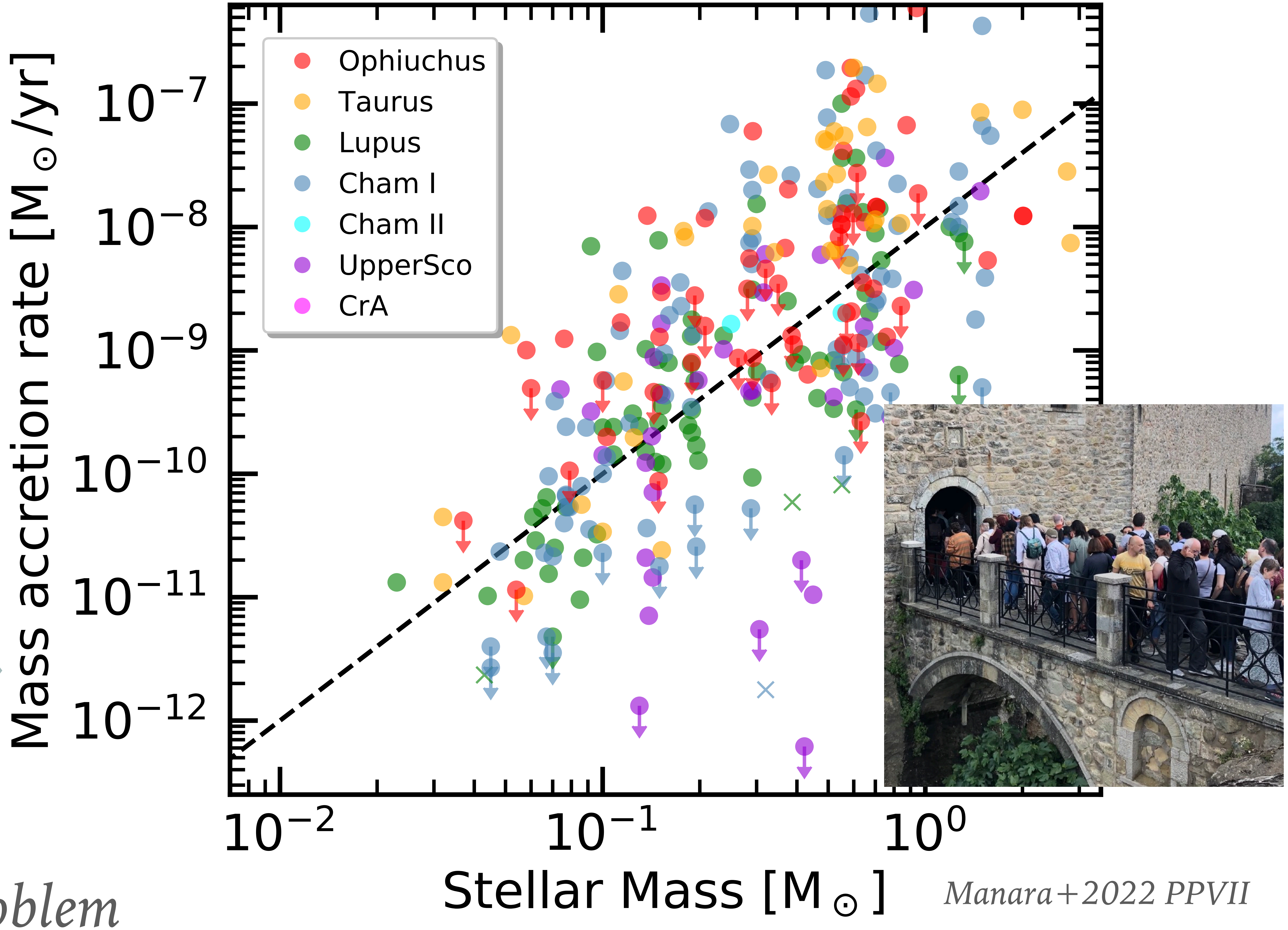
Flybys are (relatively) rare for t > 1 Myr, but ubiquitous during the early phase of star formation

2. CAN WE GROW A STAR TO 1 SOLAR MASS BY DISC ACCRETION?

The best accretion discs can offer: $1M_{\odot}$ in 3Myr ~ c_s^3/G

Typical disc-driven $\dot{M}$

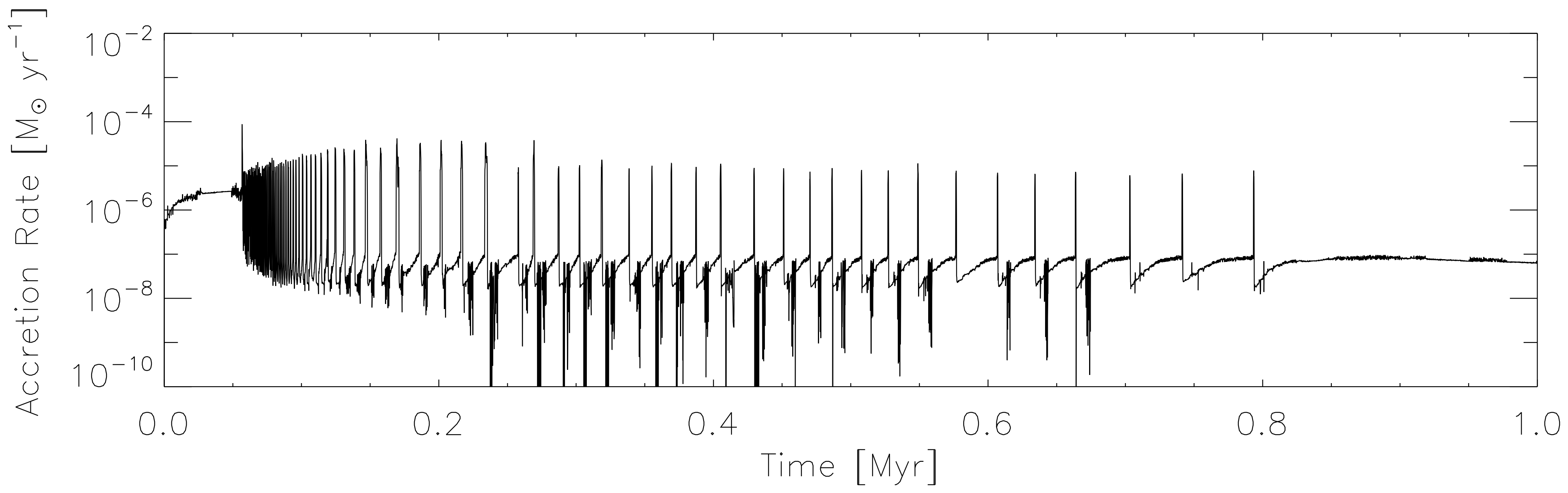
Low mass stars have even lower $\dot{M}$, they are not growing!



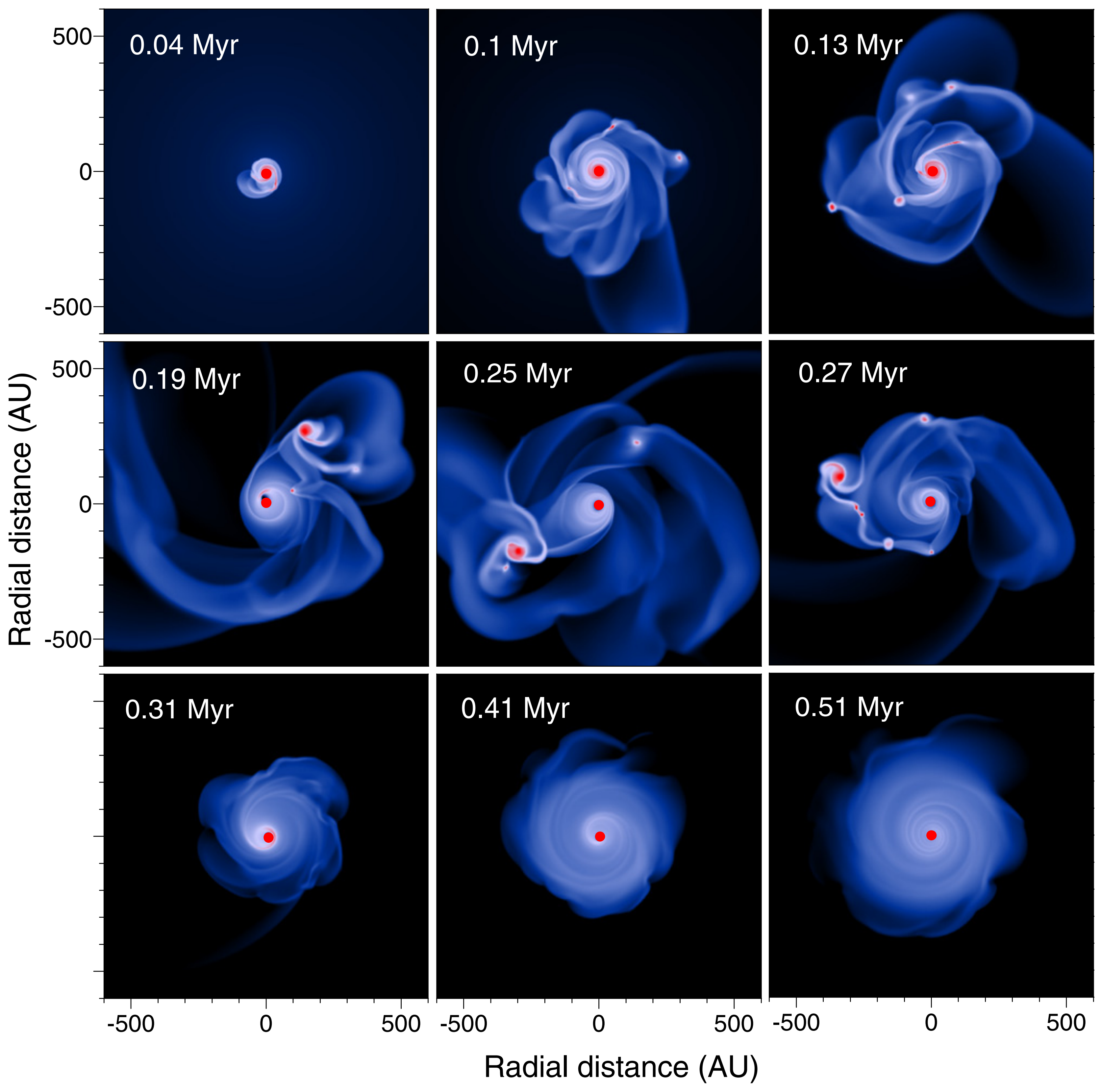
Manara+2022 PPVII

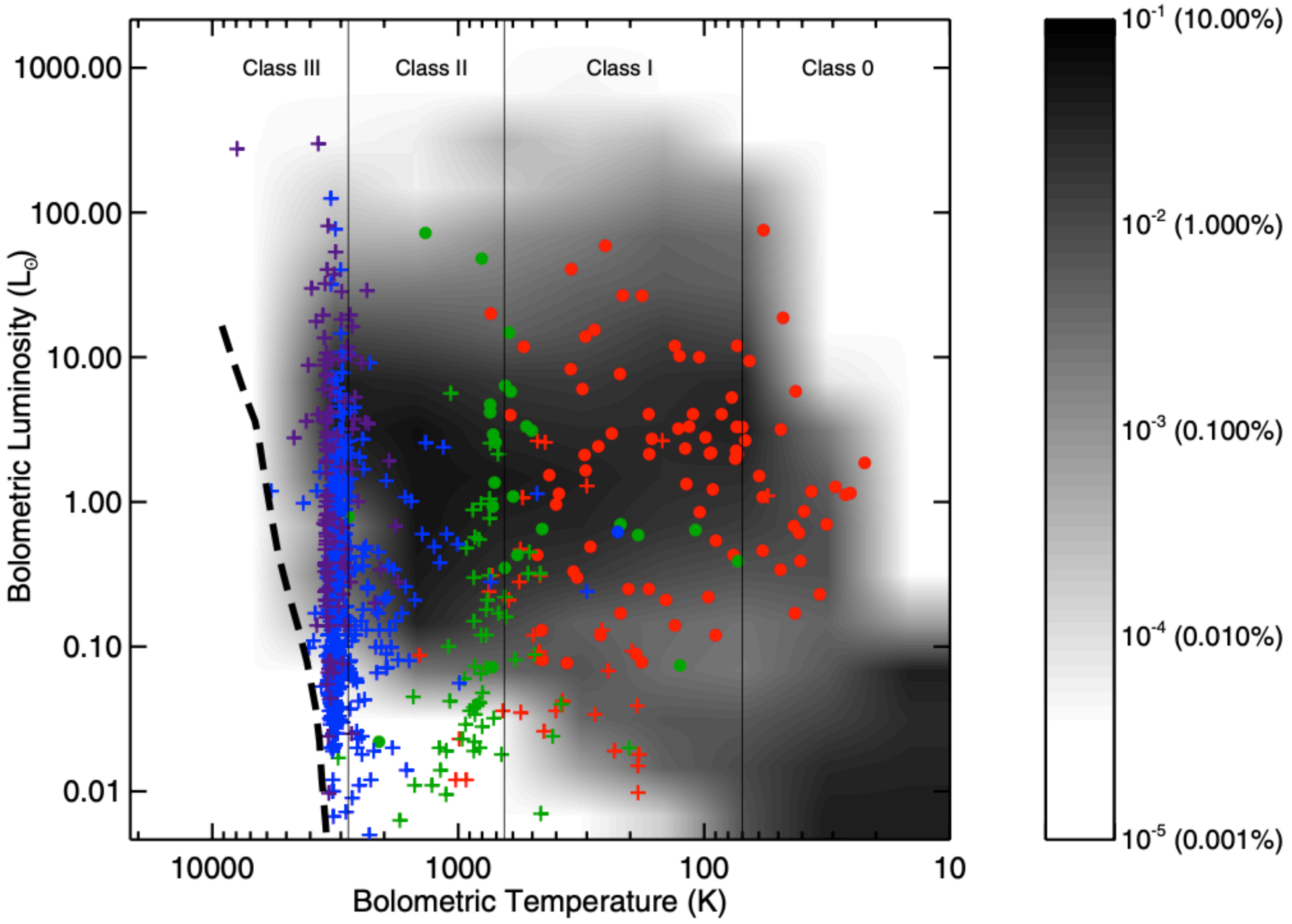
Aka: Protostellar luminosity problem

SOLUTION: EPISODIC ACCRETION VIA FU ORIONIS-TYPE OUTBURSTS?



Bae+(2014)





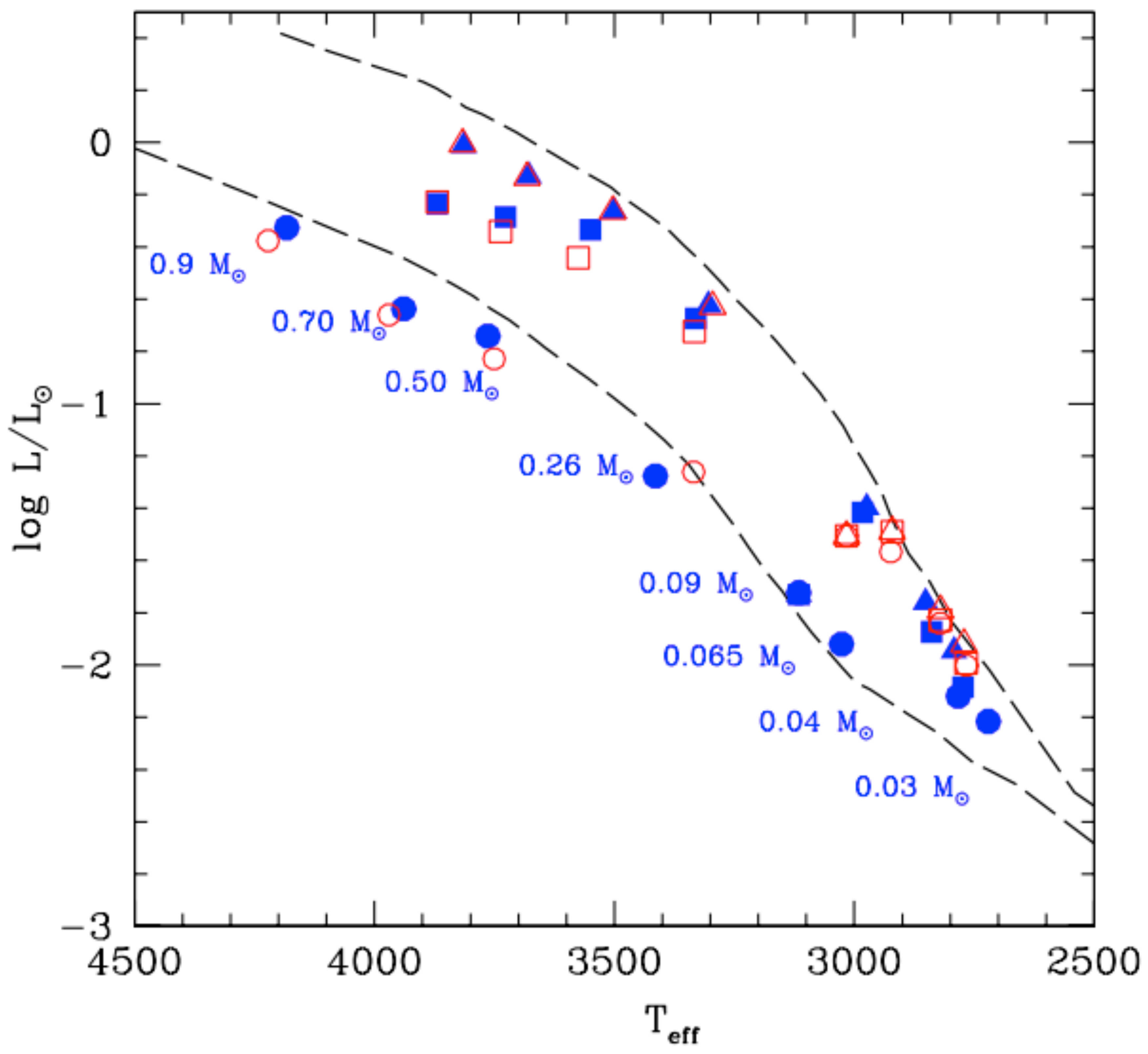
Offner & McKee (2011); Vorobyov (2010); Dunham & Vorobyov (2012); Padoan+(2014); Inutsuka+(2010); Stamatellos+(2011,2012); Kuffmeier+(2019)

SOLUTION: EPISODIC ACCRETION?

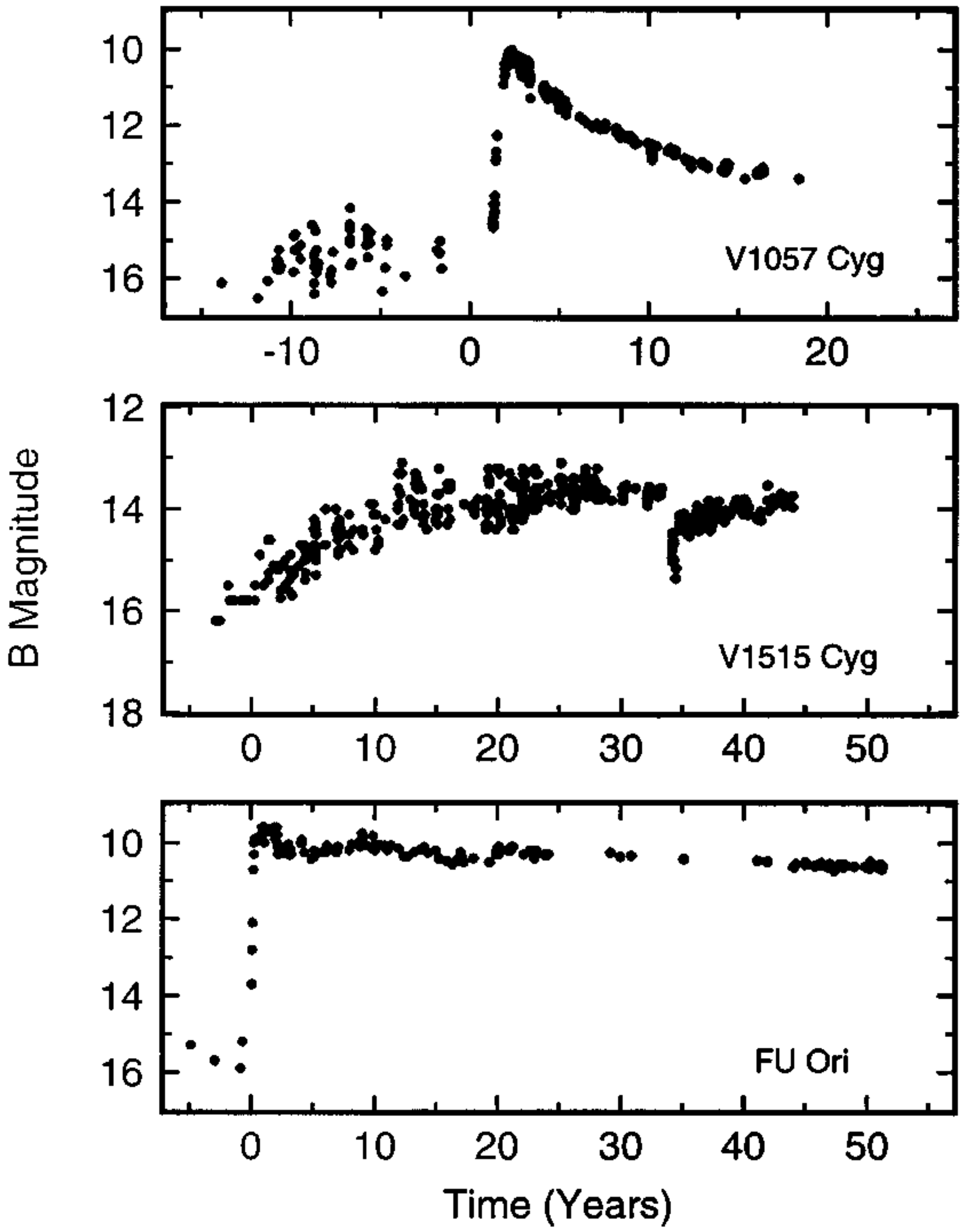
OBSERVED LUMINOSITY SPREAD IN YOUNG CLUSTERS AND FU Ori STARS: A UNIFIED PICTURE

I. Baraffe[1], E. Vorobyov[2,3], and G. Chabrier[1,4]
[1] Astrophysics Group, University of Exeter, EX4 4QL Exeter, UK; i.baraffe@ex.ac.uk
[2] Institute of Astrophysics, The University of Vienna, Vienna A-1180, Austria; eduard.vorobiev@univie.ac.at
[3] Research Institute of Physics, Southern Federal University, Rostov-on-Don, Russia
[4] École Normale Supérieure, Lyon, CRAL (UMR CNRS 5574), Université de Lyon, F-69364 Lyon Cedex 7, France; gilles.chabrier@ens-lyon.fr
Received 2012 February 22; accepted 2012 June 10; published 2012 August 21

Can produce luminosity spread in HR diagram using non-steady accretion, but require a transition from "cold" to "hot" accretion above some threshold ($\sim 10^{-5} M_\odot/\mathrm{yr}$)



BUT WHAT CAUSES FU ORIONIS OUTBURSTS?

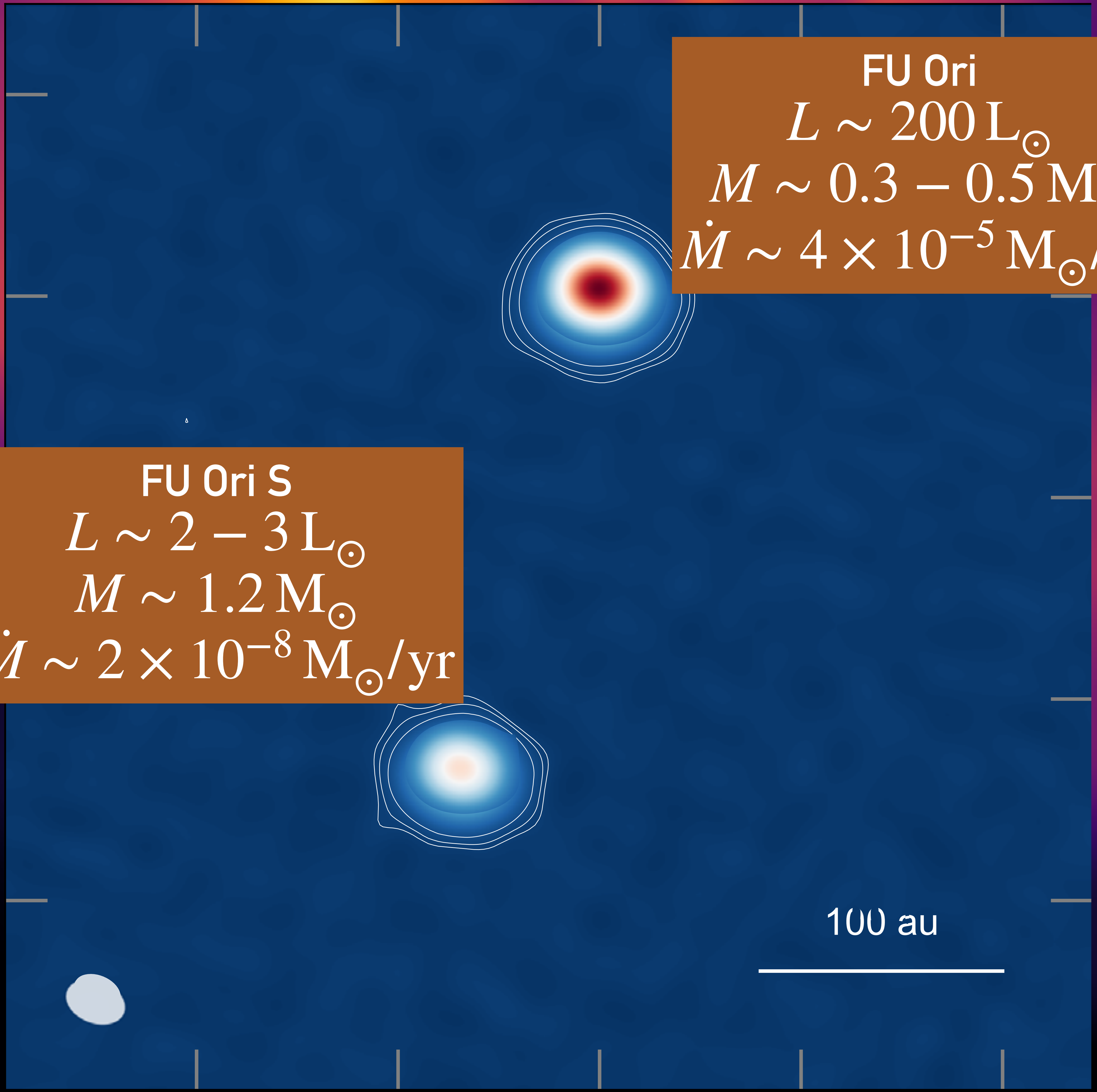


Hartmann & Kenyon (1996)

- *Disc thermal instability (Clarke et al. 1990; Bell & Lin 1994; Bell+1995; Kley & Lin 1999)*
- *Binary-disc interaction? (Bonnell & Bastien 1992). Possibly triggering thermal instability?*
- *Planet-disc interaction triggering thermal instability (Clarke & Syer 1996; Lodato & Clarke 2004)*
- *Tidal disruption of young, massive planets (Nayakshin & Lodato 2012)*
- *Pile-up of material due to dead zones/layered accretion (Martin, Lubow & Livio 2012; Martin & Livio 2014; Kadam+2020; Vorobyov+2020)*
- *Accretion outbursts in self-gravitating discs (Bae+2014)*
- *Sudden increase in turbulence due to transition between gravitational instability and magnetic instability (Martin & Lubow 2013; Martin & Livio 2014)*
- *Cloud Capture (Dullemond et al. 2019)*

FU ORIONIS

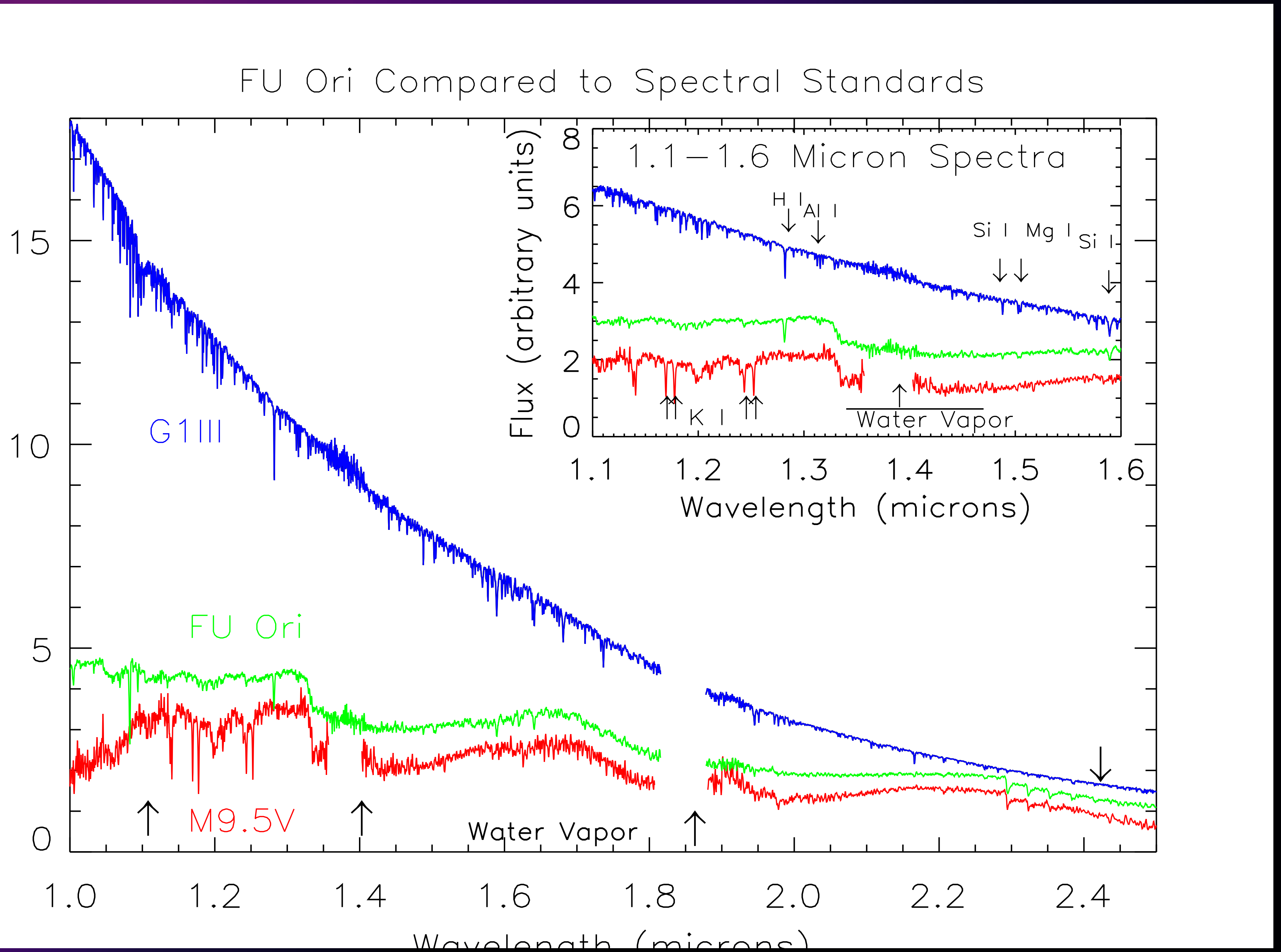
Reipurth & Aspin (2004); Malbet et al. (2005); Beck & Aspin (2012); Takami et al. (2018); Laws et al. (2020); Perez et al. (2020); Labdon et al. (2021)



FU Ori
$L \sim 200\,L_\odot$
$M \sim 0.3 - 0.5\,M_\odot$
$\dot{M} \sim 4 \times 10^{-5}\,M_\odot/yr$

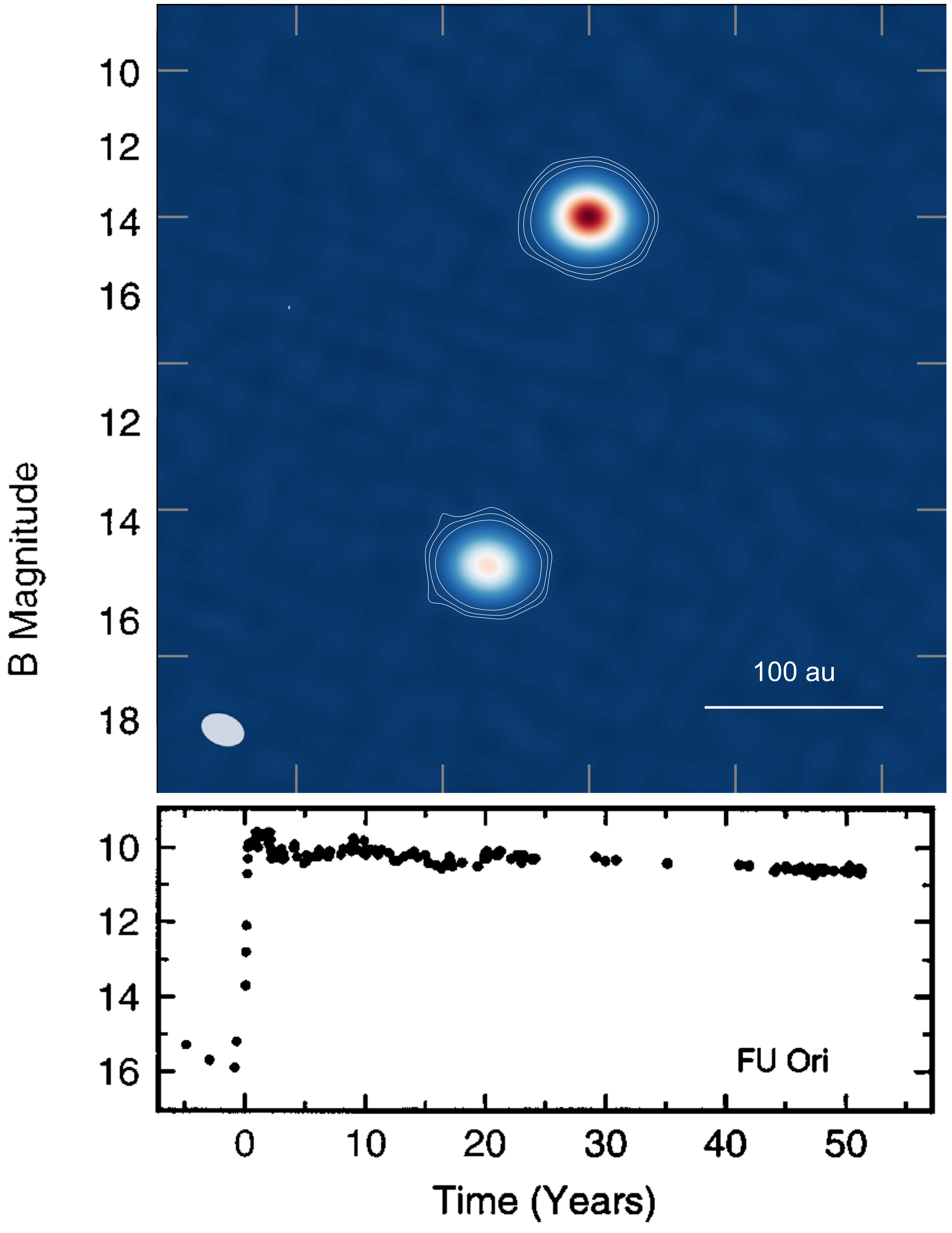
FU Ori S
$L \sim 2 - 3\,L_\odot$
$M \sim 1.2\,M_\odot$
$\dot{M} \sim 2 \times 10^{-8}\,M_\odot/yr$

ALMA continuum image at 1mm (Perez+2020)



Poor spectral fits: FU Ori N fit by M-dwarf spectra in IR but a G-type giant in optical?? (Beck & Aspin 2012)

BUT WHAT CAUSES FU ORIONIS OUTBURSTS?



Hartmann & Kenyon (1996)

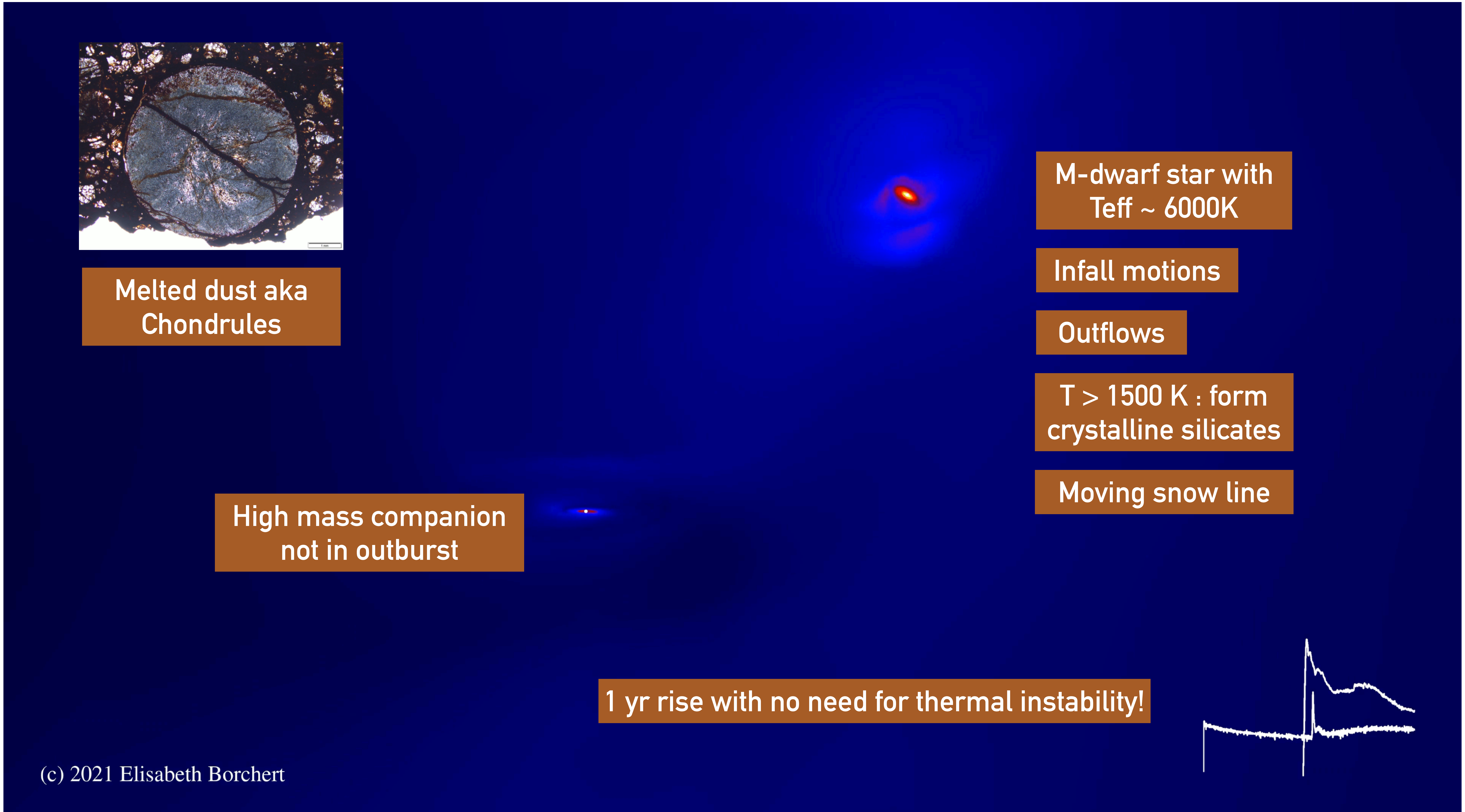
- *Disc thermal instability (Clarke et al. 1990; Bell & Lin 1994; Bell+199*
- *Binary-di* *92). Possibly triggering thermal i*
- *Planet-dis* *bility (Clarke & Syer 1996; Lo*
- *Tidal disr* *akshin & Lodato 2012)*
- *Pile-up of* *cretion (Martin, Lubow & Livio 2012; Martin & Livio 2014; Kadam+2020; Vorobyov+2020)*
- *Accretion* *e+2014)*
- *Sudden in* *between gravitational instability* *ubow 2013; Martin & Livio 2014)*
- *Cloud Capture (Dullemond et al. 2019)*

YOU ARE LOOKING AT THE WRONG STAR!

Outburst is on the LOW MASS object!

FU ORI AS A FLYBY

Borchert, DP et al. (2022a,b)
See also Vorobyov+2021

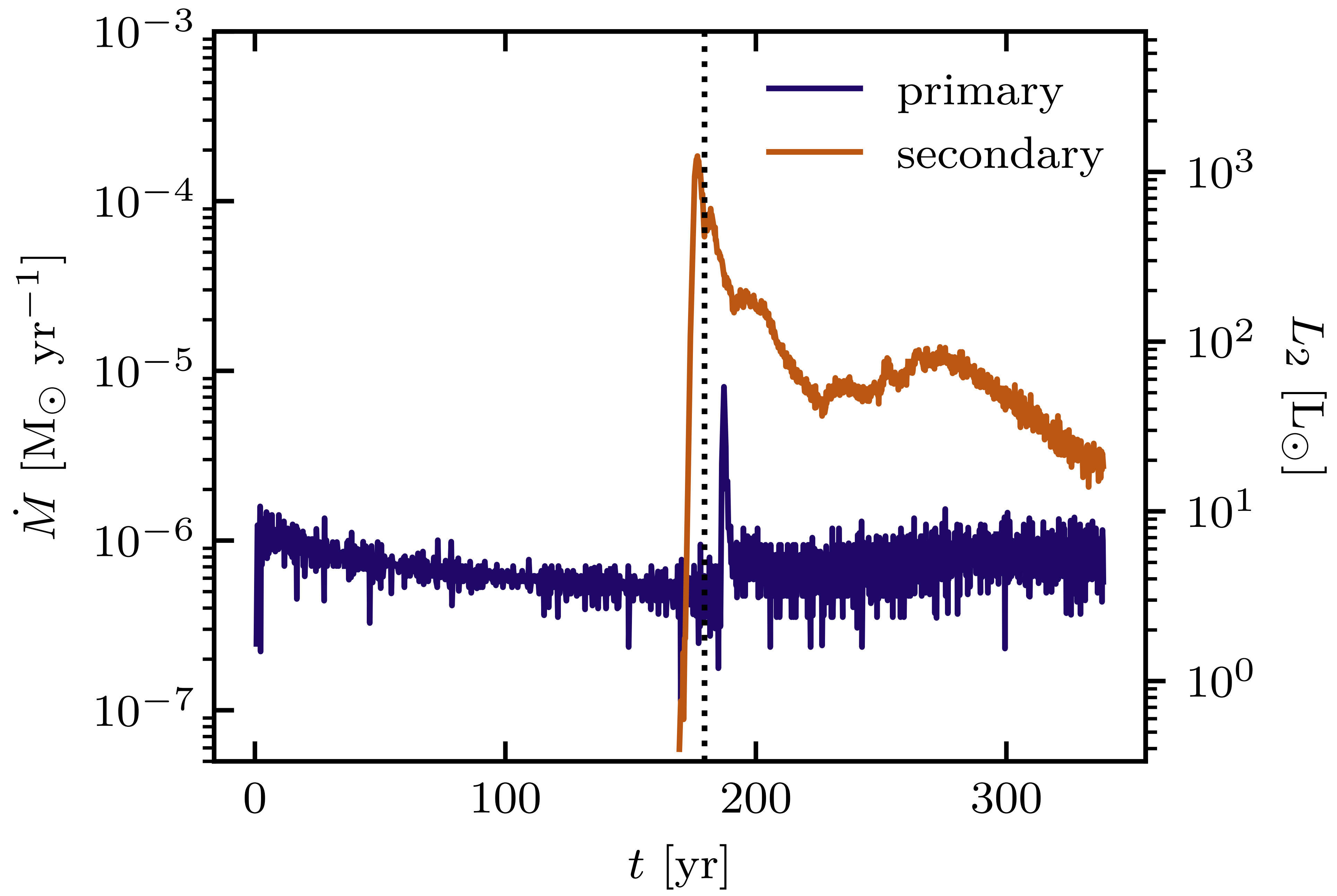


PHANTOM

+ live MCFOST radiative transfer with L=Lstar + $GM\dot{M}/R_*$

HOW TO ACCRETE LIKE HELL

Borchert, DP et al. (2022a,b)



High $\dot{M}$ occurs when accretion flows are misaligned!

Episodic accretion: the interplay of infall and disc instabilities

Michael Kuffmeier,[1★] Søren Frimann,[2] Sigurd S. Jensen[1] and Troels Haugbølle[1]
[1]*Centre for Star and Planet Formation, Niels Bohr Institute and Natural History Museum of Denmark, University of Copenhagen, Øster Voldgade 5-7, DK-1350 Copenhagen K, Denmark*
[2]*Institut de Ciències del Cosmos, Universitat de Barcelona, IEEC-UB, Martí Franquès 1, E-08028 Barcelona, Spain*

HYPOTHESIS:

Stars grow via misaligned flows

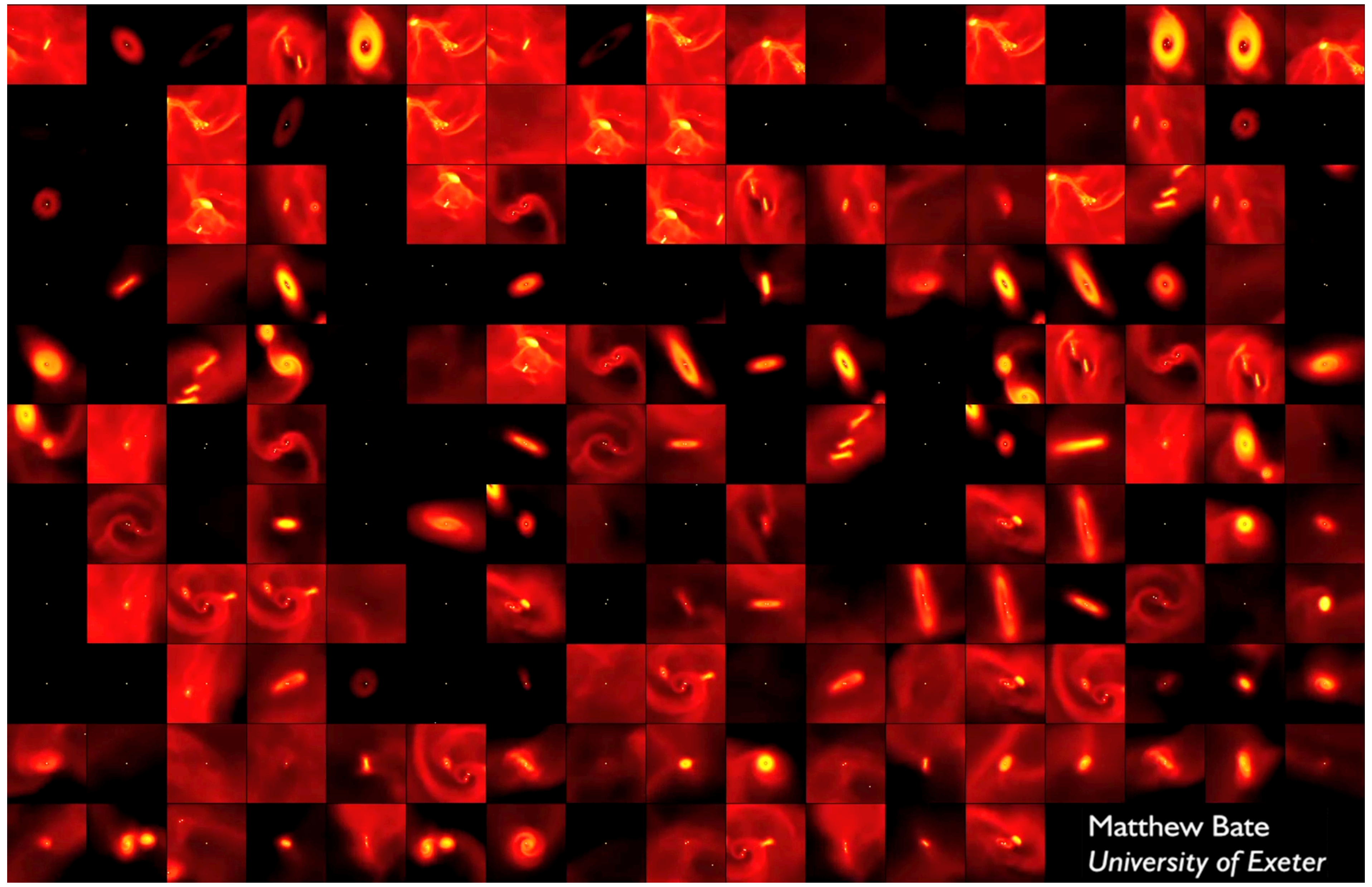
See Kuffmeier talk + papers (Kuffmeier+2017; 2018; 2021)

Corollaries:

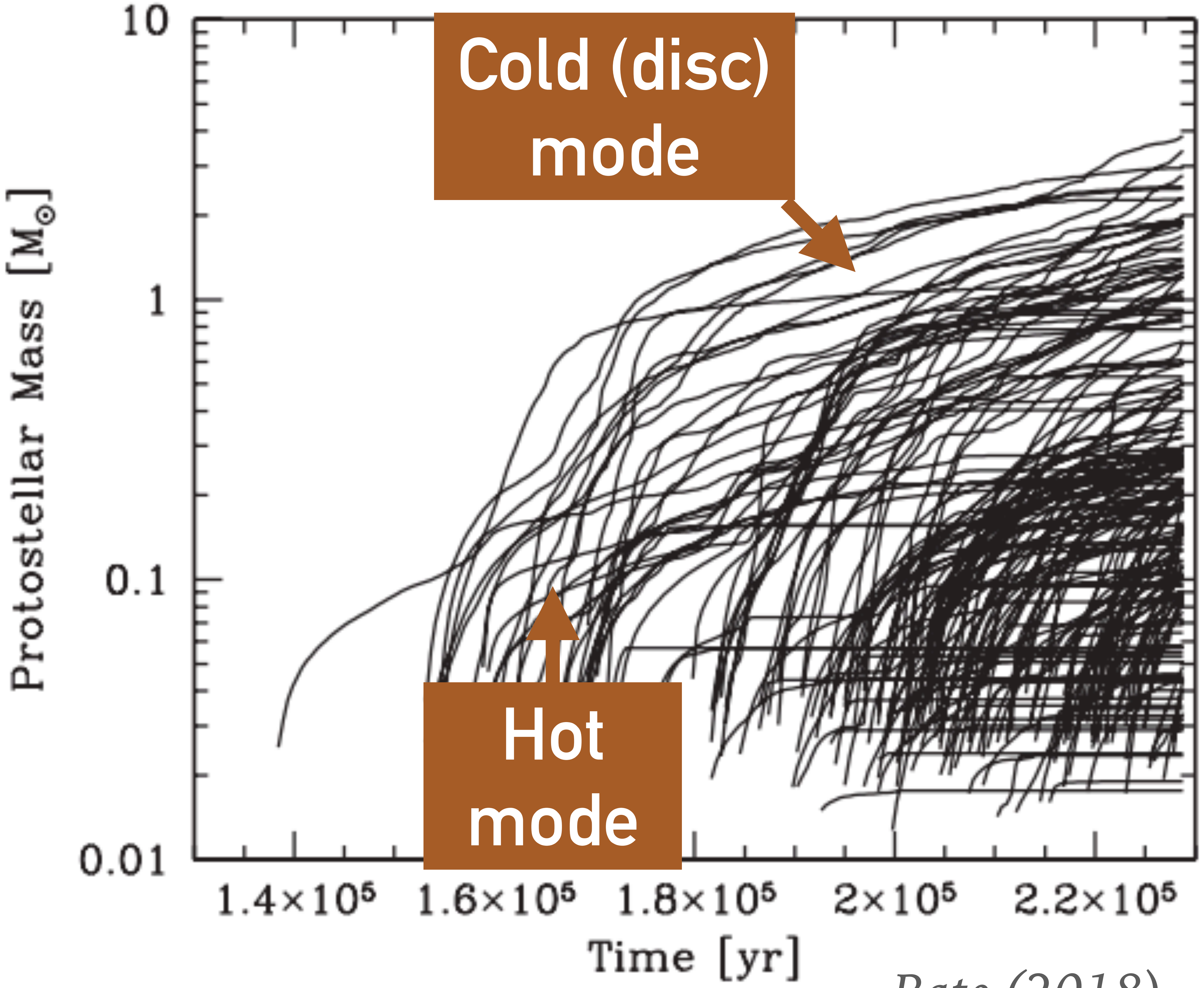
1. *FU Orionis outbursts are misaligned flow accretion events*
2. *Accretion occurs this way during the entire Class 0/1 phase should be associated with jets/outflows*
3. *BY DEFINITION there is infalling envelope material when stars accrete in this "hot" mode*

GROWING STARS VIA MISALIGNED FLOWS: THEORY

- Hot mode = *misaligned infall producing direct cancellation of angular momentum*



Bate (2018); see also Kuffmeier et al. (2017, 2018, 2021)



Bate (2018)

GROWING STARS VIA MISALIGNED FLOWS: L1527 WITH JWST

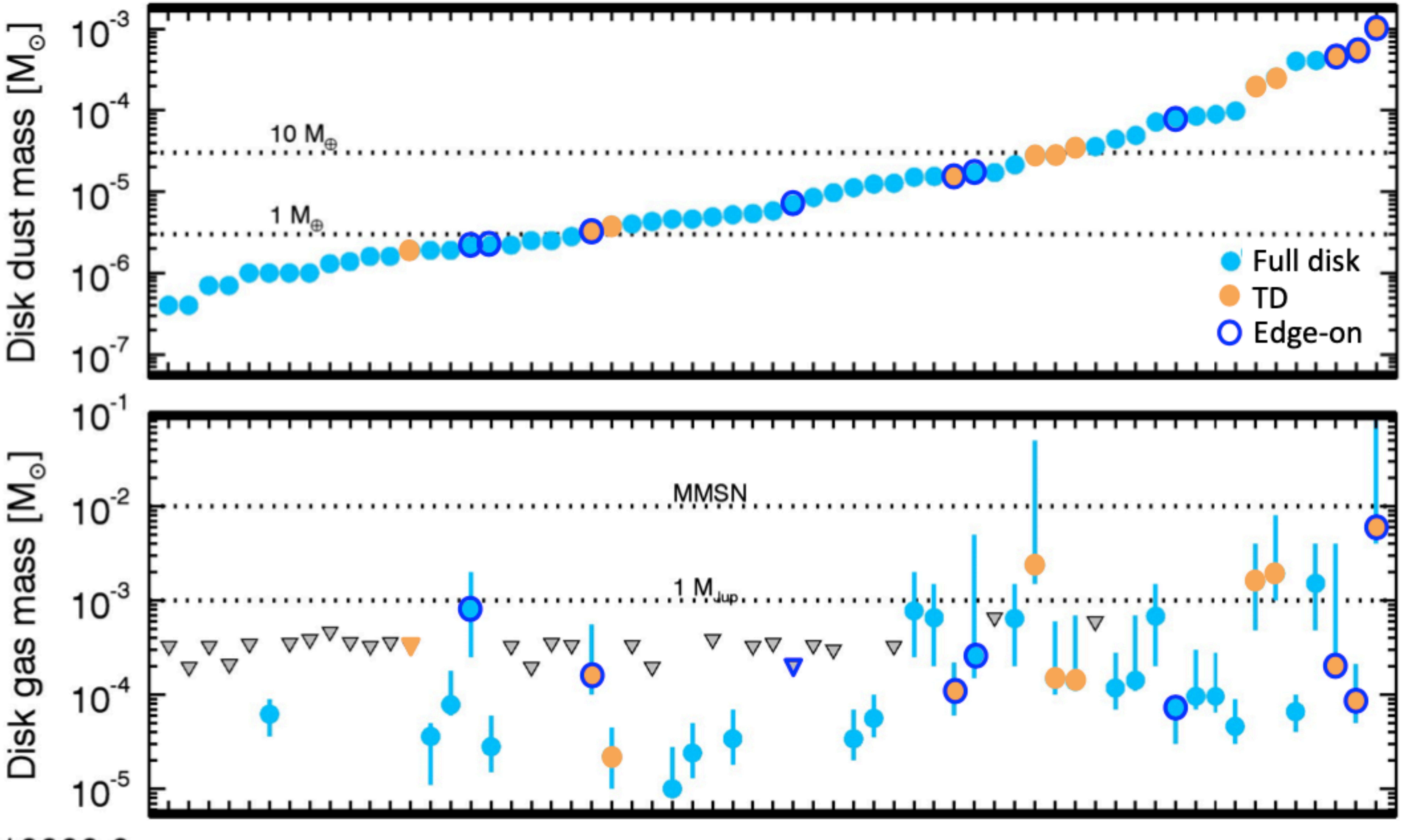
This is how most of the mass accretion happens!

Credits: NASA, ESA, CSA, and STScI. Image processing: J. DePasquale, A. Pagan, and A. Koekemoer (STScI)

Tobin+2013:

Parameter	Description	Paper I Model	Best-fit Model
$\dot{M}_{disk}$ ($M_\odot$ yr^{-1})	Disk accretion rate	3.0×10^{-7}	1.5×10^{-6}

PROBLEM 2: HOW TO MAKE THE PLANETS?



- Not enough dust or gas mass to form observed exoplanet systems (or the solar system)

Miotello+2017 for discs in Lupus

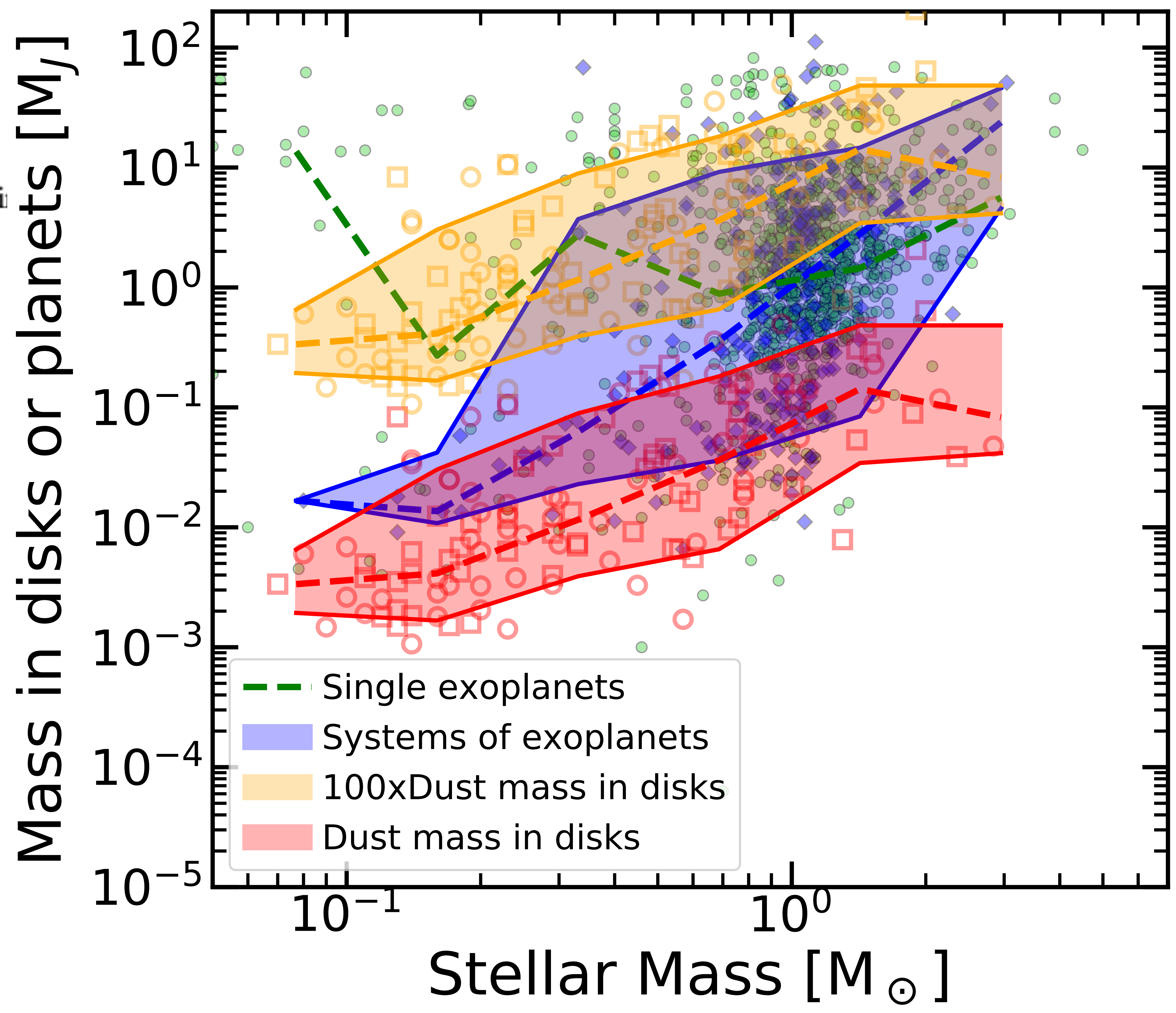
PROTOPLANETARY DISCS ARE NOT PROTO-PLANETARY…

Letter to the Editor

Why do protoplanetary disks appear not massive enough to form the known exoplanet population?

C. F. Manara[1,⋆], A. Morbidelli[2], and T. Guillot[2]

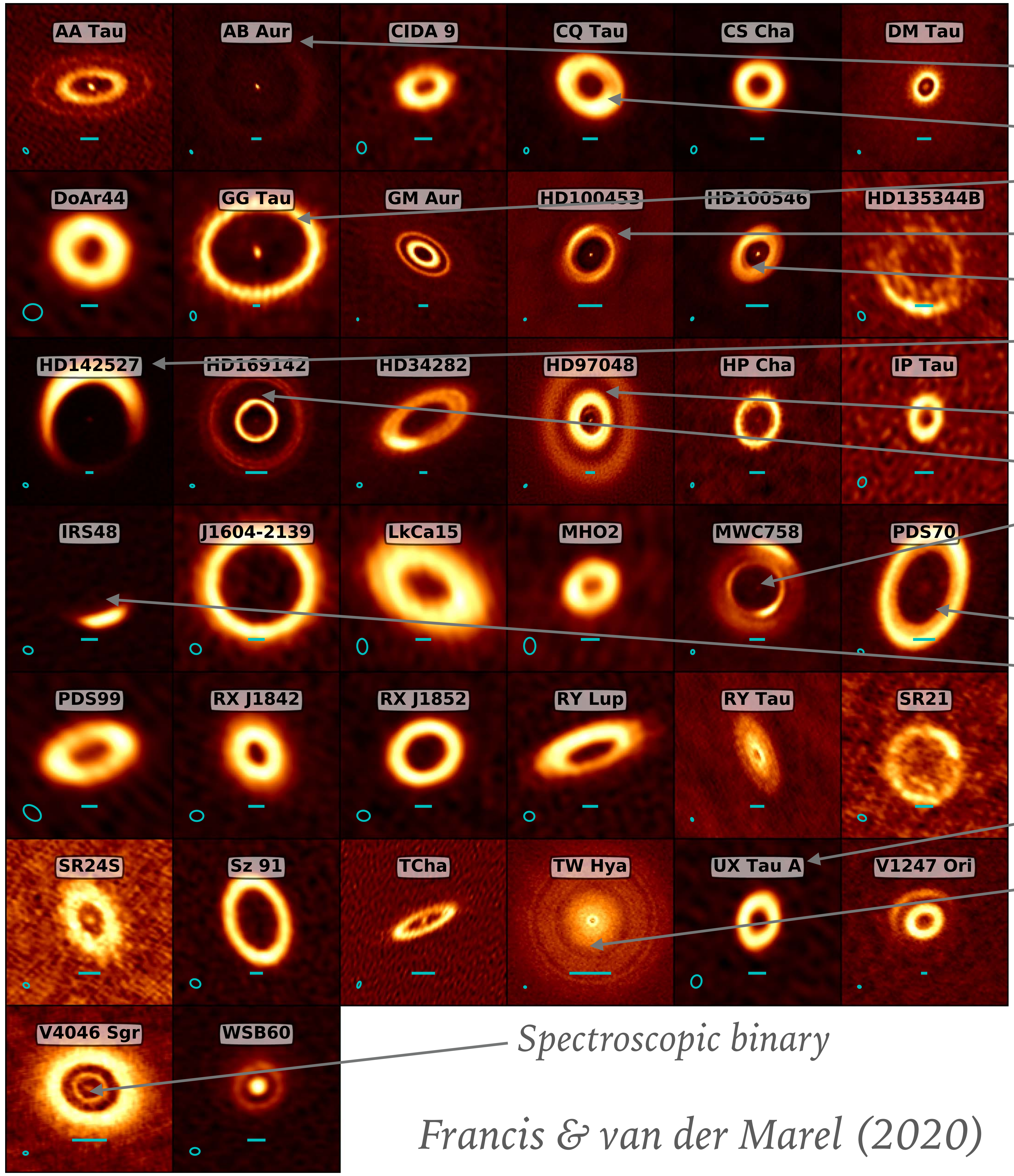
[1] European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching bei München, Germany
e-mail: cmanara@eso.org
[2] Laboratoire Lagrange, Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Boulevard de l'Observatoi
06304 Nice Cedex 4, France



Planets must be already made!

Manara et al. (2018); Mulders et al. (2021)

MULTIPLICITY IS PRINTED ALL OVER THE DISC POPULATION: TRANSITION DISCS



Probable binary (Poblete+2020)

Probable binary (Hammond+2022)

Hierarchical quintuple (Di Folco et al. 2014)

Misaligned binary (Rosotti+2020)

Probable binary (Norfolk+2022)

Circumbinary / misaligned (Lacour+16,Price+18)

Kinematic detection of planet in gap (Pinte+2019)

Planet imaged in gap (Hammond+2023)

Probable binary (Calcino et al. 2022) or massive planets (Dong+2015, Ren+2018)

Two giant planets (Mueller+ 2018, Keppler+2018)

Probable binary (Calcino et al. 2019)

Ongoing stellar flyby (Ménard+2020)

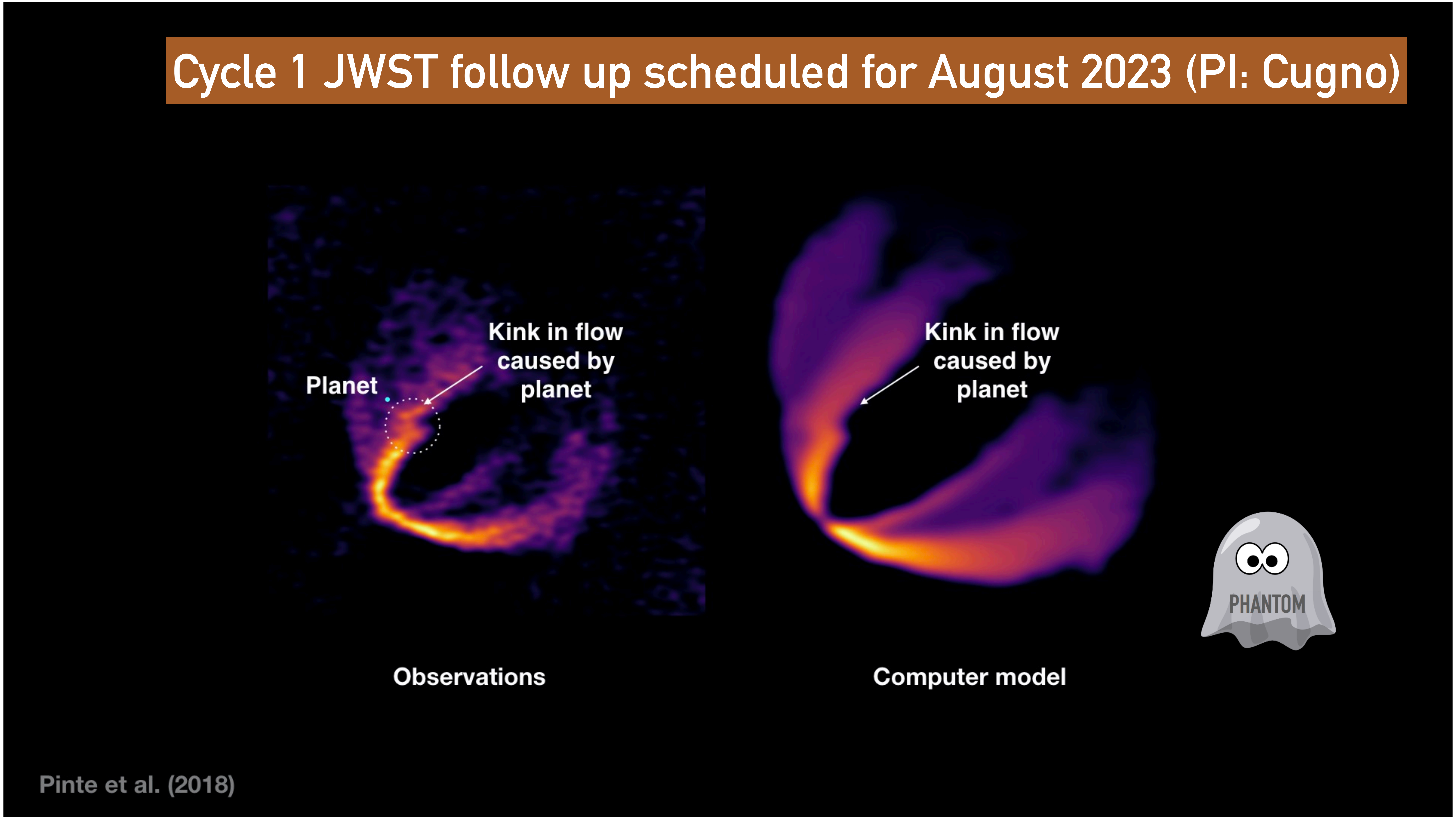
Warped disc/moving shadows (Debes+2017) suggesting massive inner companion (Nealon+2018) + super-Earths (Mentiplay+2019)

Spectroscopic binary

Francis & van der Marel (2020)

PLANETS REVEALED BY KINEMATIC PERTURBATIONS…

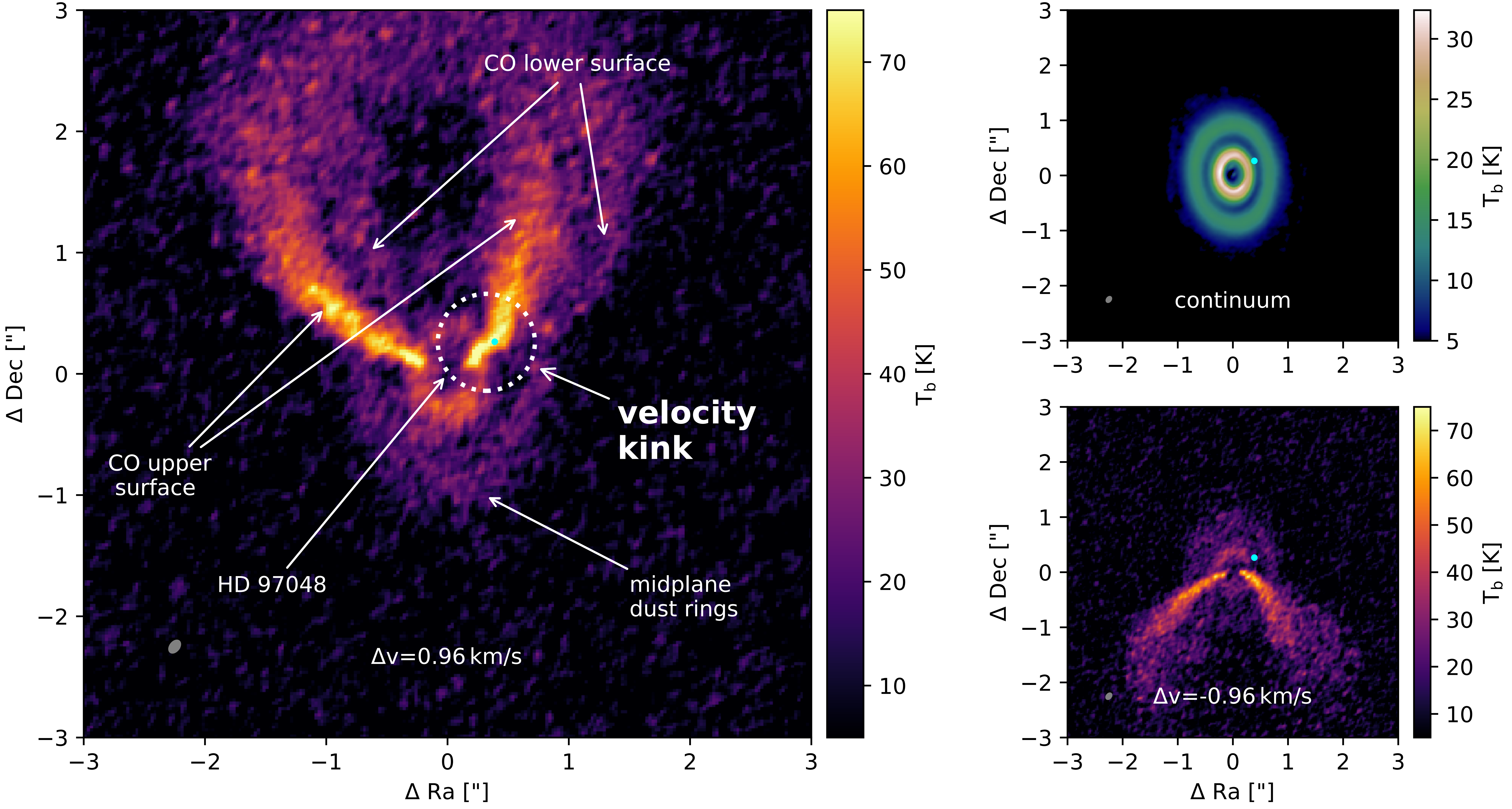
Pinte, DP et al. (2018)



Best match with models using $M \approx 2 - 3\ M_{\rm Jup}$

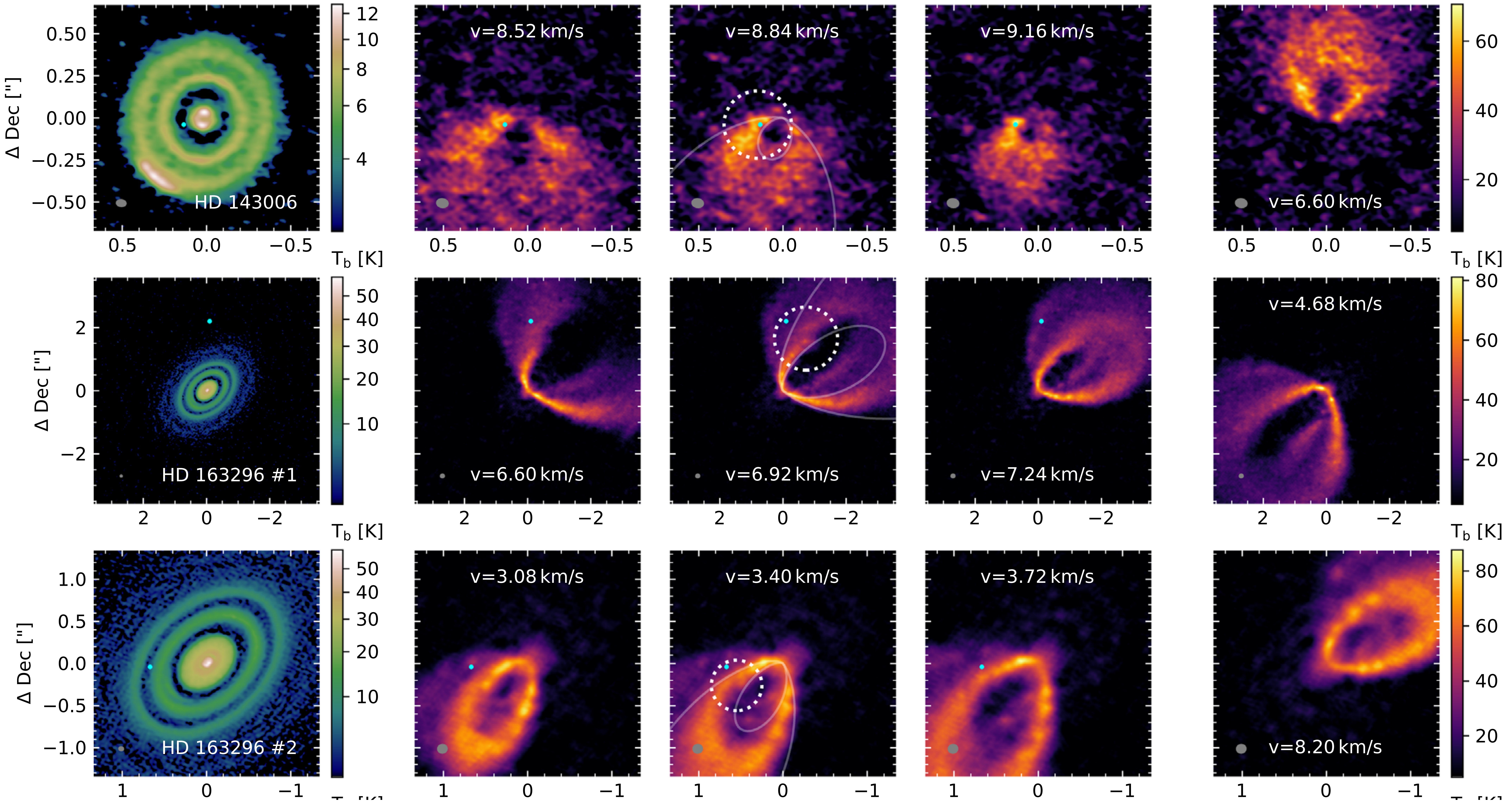
PLANETS REVEALED BY KINEMATIC PERTURBATIONS…

Pinte et al. (2019)



PLANETS REVEALED BY KINEMATIC PERTURBATIONS…

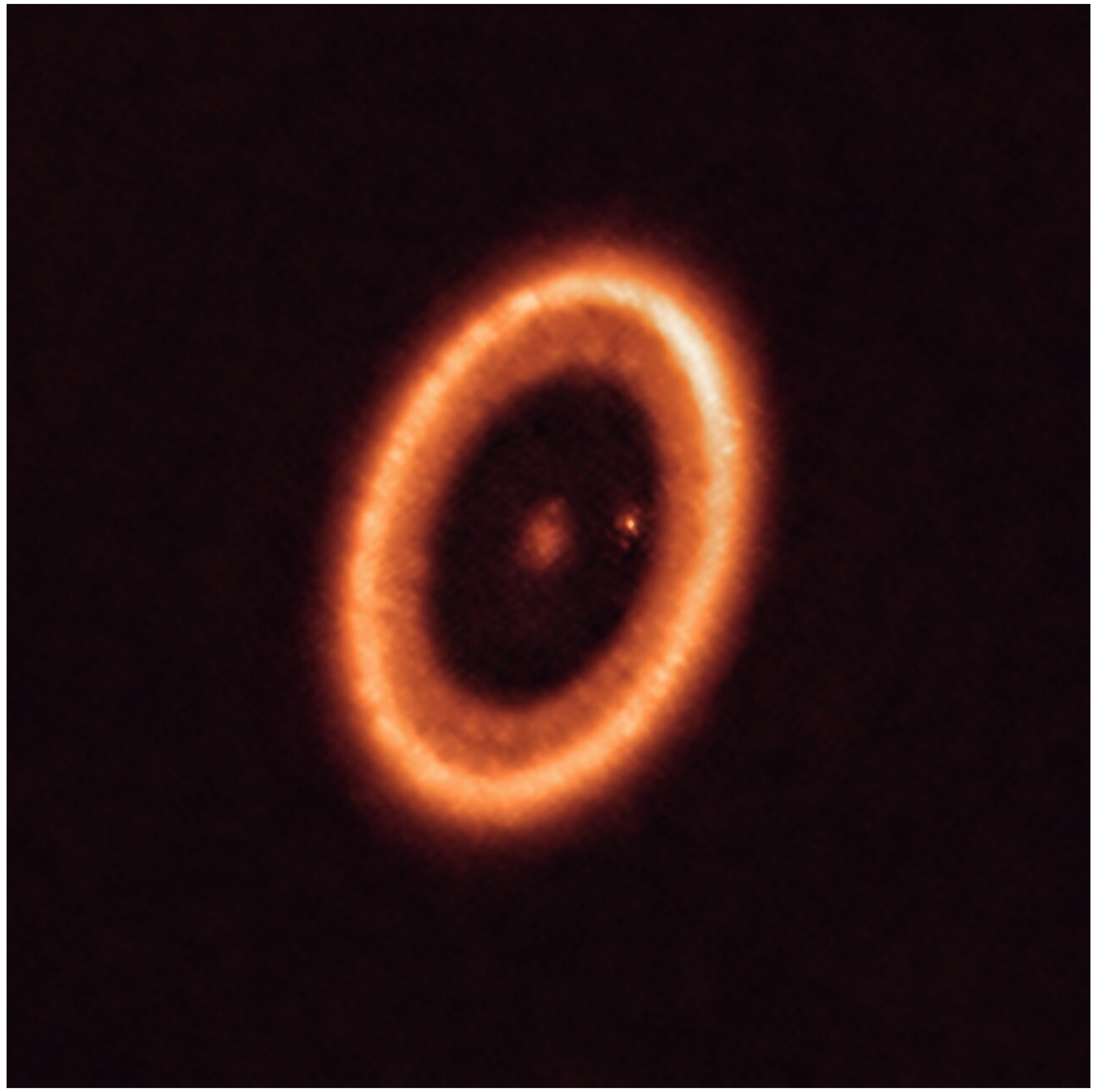
Pinte, DP et al. (2020)
Verrios, DP et al. (2022)



See PPVII review by Pinte et al. (2023)

...AND ALSO DIRECT IMAGING

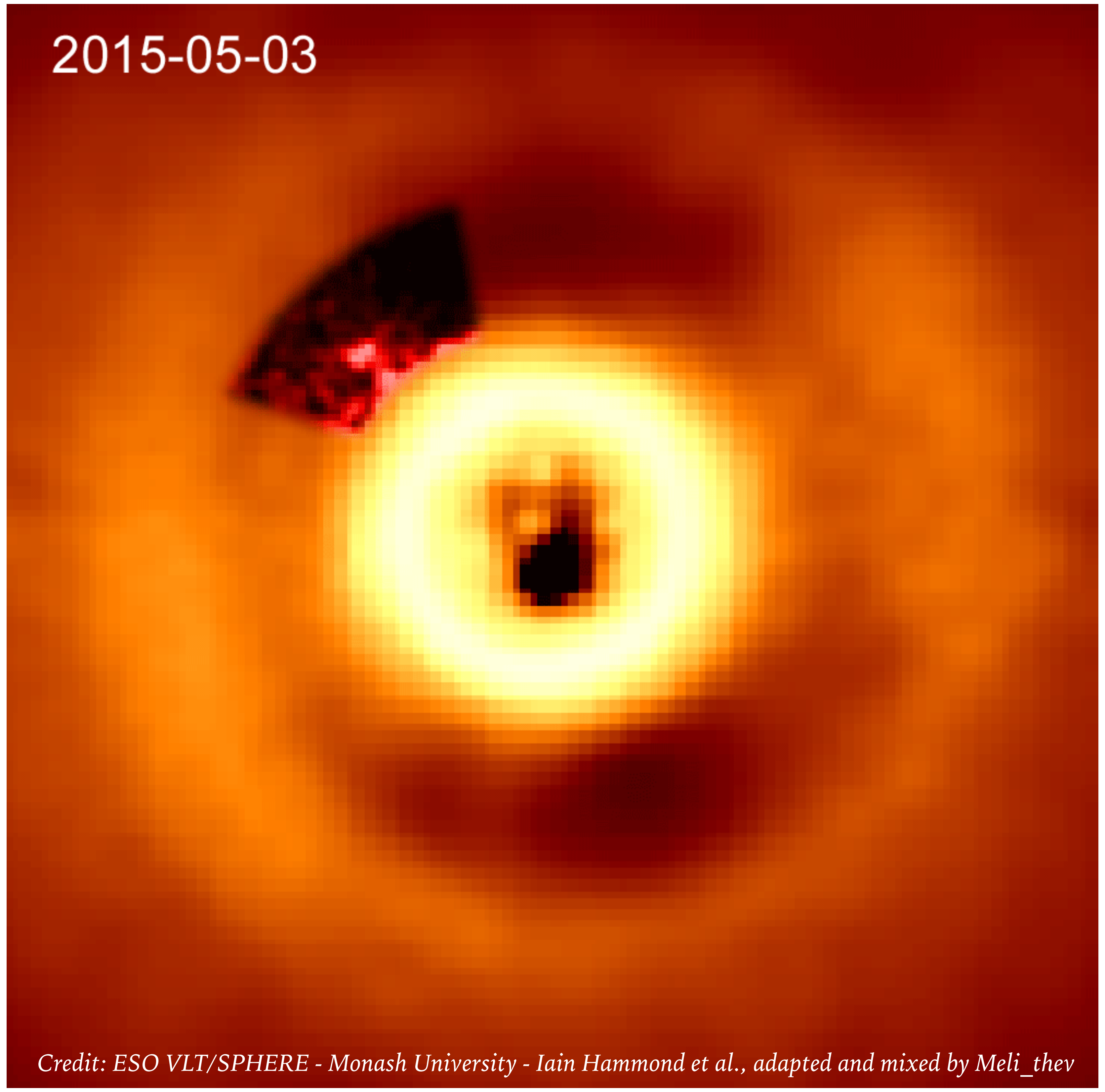
PDS 70



Benisty et al. (2021)

Also Müller et al. (2018); Keppler et al. (2018, 2019), Haffert et al. (2019); Christiaens et al. (2019a,b)

HD 169142



Hammond et al. (2023 incl. DP)

Direct evidence for circumplanetary discs

HOW DO YOU FORM A SOLAR SYSTEM LIKE OURS?

Fresh infall / late flyby

7° Solar obliquity

Trans-Neptunian objects are highly inclined and eccentric

Naturally explained by late flyby

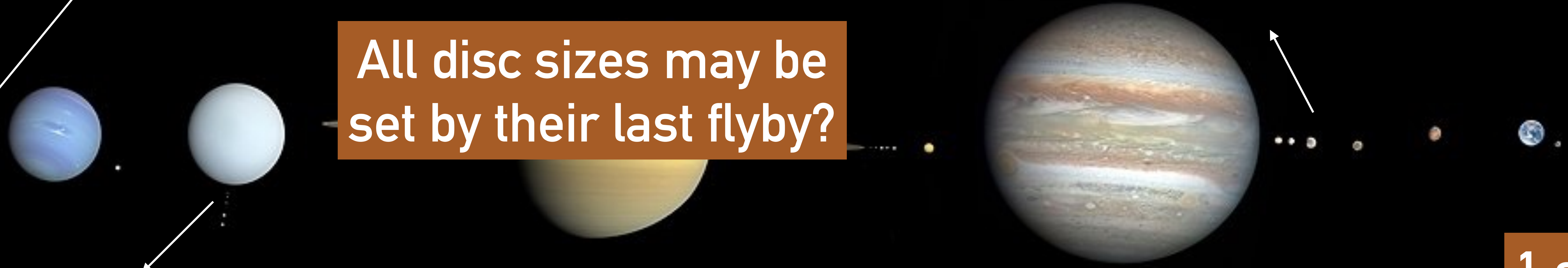
Formation in cluster

Radioactive elements: nearby massive stars?

Solar system is sharply truncated at ~47 au

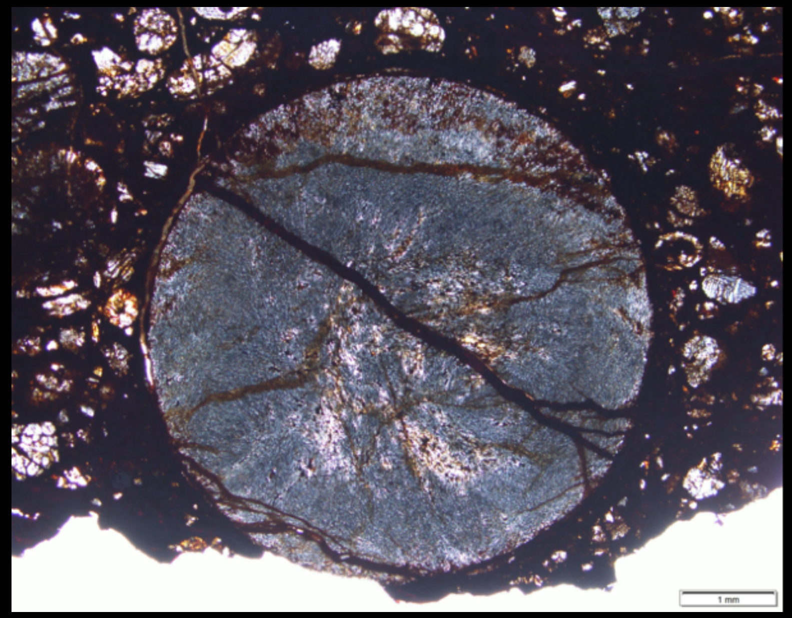
Single star = loser in an unstable triple

All disc sizes may be set by their last flyby?



Uranus rolls along its orbit

1 solar mass can only be accreted via misaligned flows



Chrondrules fall into two families: late infall?

Chrondrules everywhere: Dust has been melted

Natural in accretion bursts caused by misaligned flows

Credit: wikipedia/CactiStaccingCrane

CONCLUSION: THIS IS THE ENVIRONMENT IN WHICH STARS AND PLANETS FORM

Disc observations tell us that:

- ➤ Stars grow via misaligned flows, NOT by disc accretion
- ➤ Planets form early, when disturbances, fresh infall and flybys are common
- ➤ Planets form readily, even at large orbital separations
- ➤ The solar system reveals hints of the same processes, indicating universal formation process

Credits: NASA, ESA, CSA, and STScI. Image processing: J. DePasquale, A. Pagan, and A. Koekemoer (STScI)