Disk tearing in a young triple star system with misaligned disk/orbit planes

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CfA: David Wilner, Sean Andrews

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UNIVERSITY OF EXETER

EAS meeting
2020 June 30

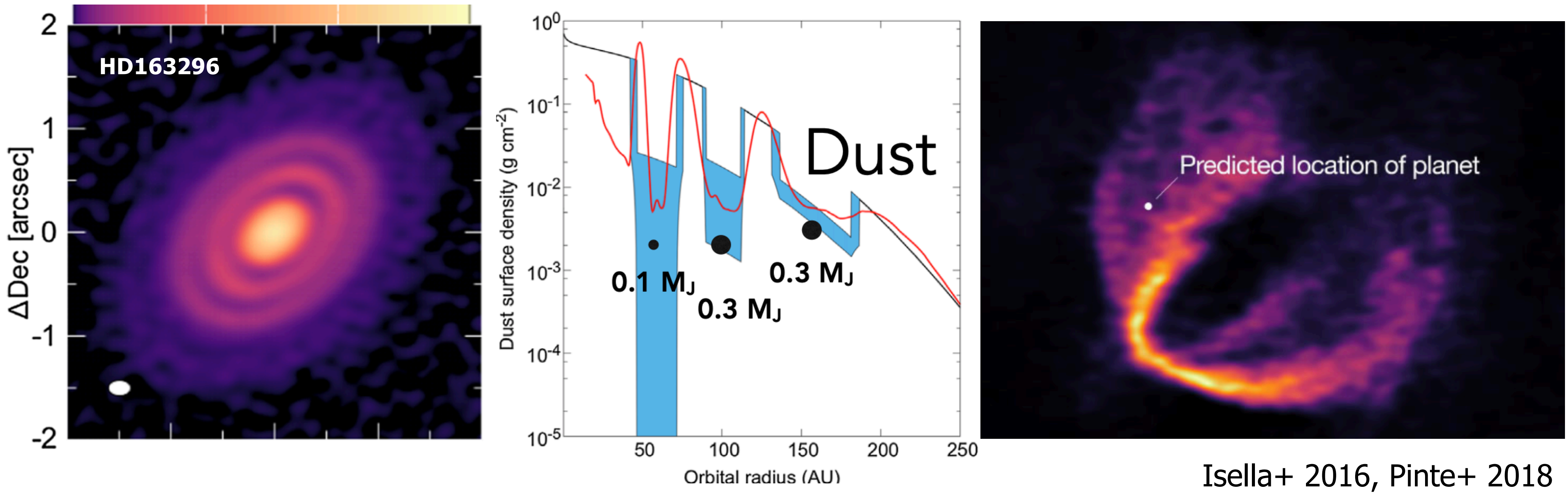
erc

PMS multiples as laboratory for planet formation

Imaging forming planets remains hard!

Most planets are **inferred indirectly from disk structures,**
but with **far too many free parameters & untested assumptions on basic disk physics**

➜ Disk truncation/gap-opening processes in PMS binaries resemble conditions found in planet formation



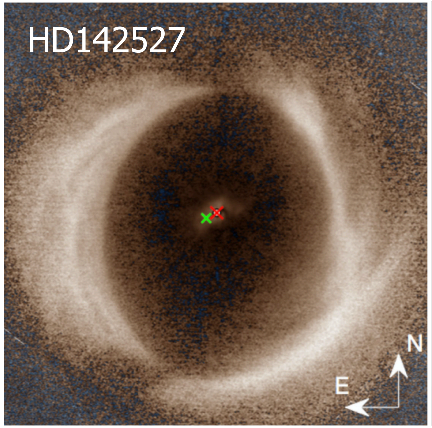
Isella+ 2016, Pinte+ 2018

PMS multiples as laboratory for planet formation

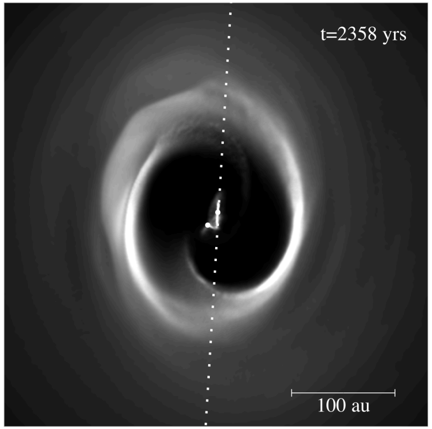
Stellar multiplicity might be responsible for many structures observed in protoplanetary disks:

- Dust-cleared gaps and cavities
- Gas kinematics signatures (e.g. spirals)
- Dust asymmetries (e.g. horseshoes)
- Misaligned disk components (warps, shadows)

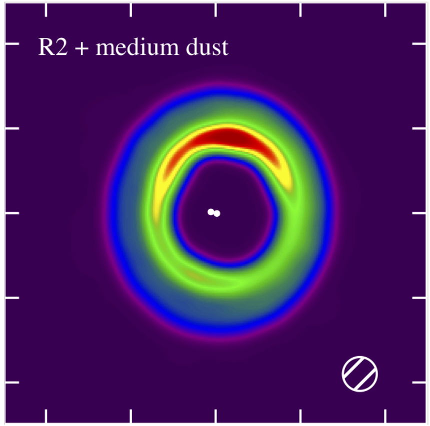
Observation: Scattered light

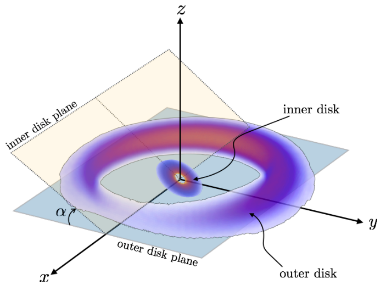


Simulation: Scattered light



Simulation: Dust horseshoe

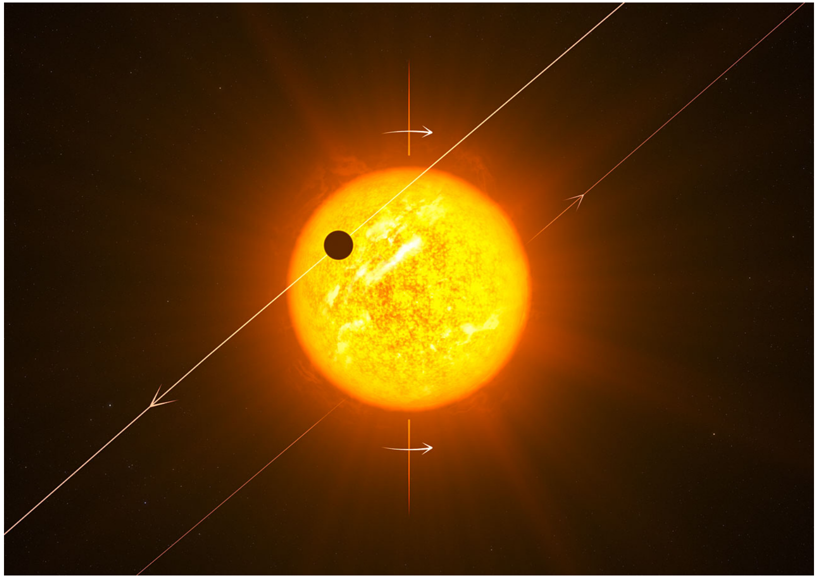




Price+2018; Marino+ 2015

PMS multiples as laboratory for planet formation

…and might be needed to explain the obliquity observed in planetary systems



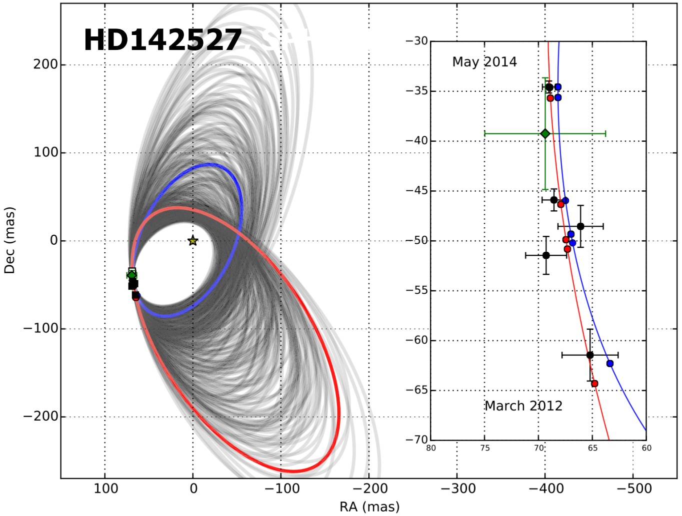
…and Tatooine-like planets

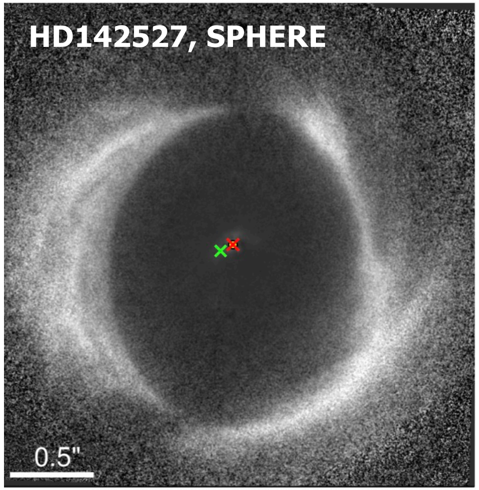
ESO, Lucasfilm

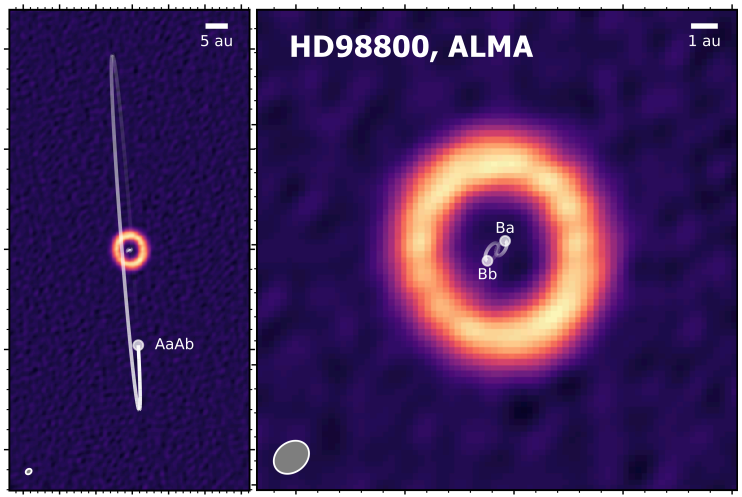
PMS multiples as laboratory for planet formation

Need for a ‘benchmark’ system that ticks all boxes to be useful for modelers:

- **global properties** (distance, dust mass, …)
- **well-constrained 3-D orbits** (RV + astrometry)
- **3-D disk orientation well-constrained on all scales**
- **System properties just in the ‘goldilock’ zone**, where hydrodynamical effects are maximal (separation, eccentricity, mutual inclination, …)





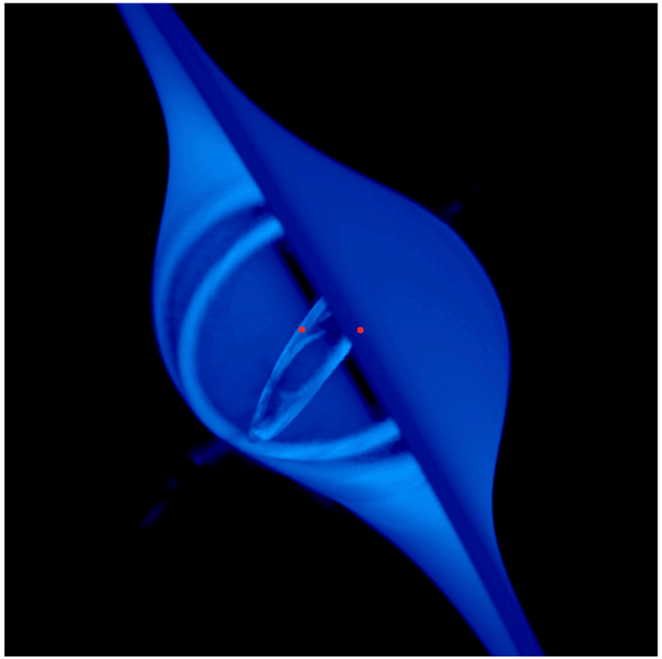


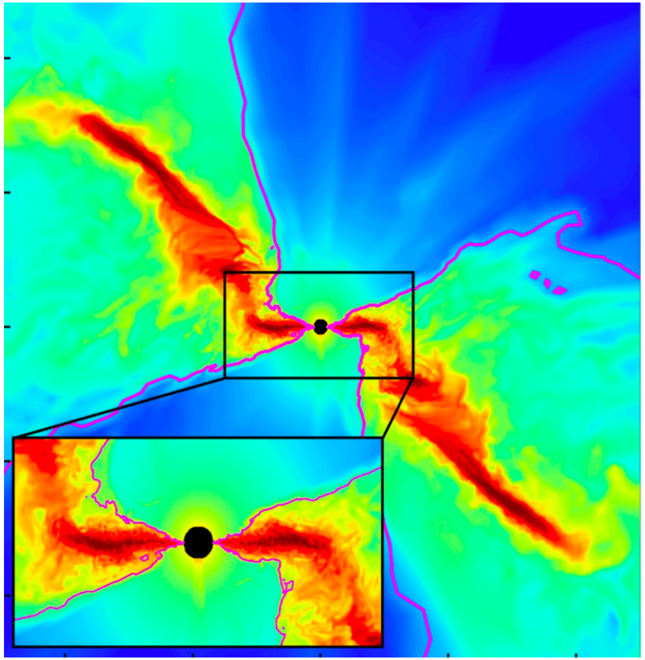
Price+2018, Avenhaus+ 2017, Kennedy+ 2019

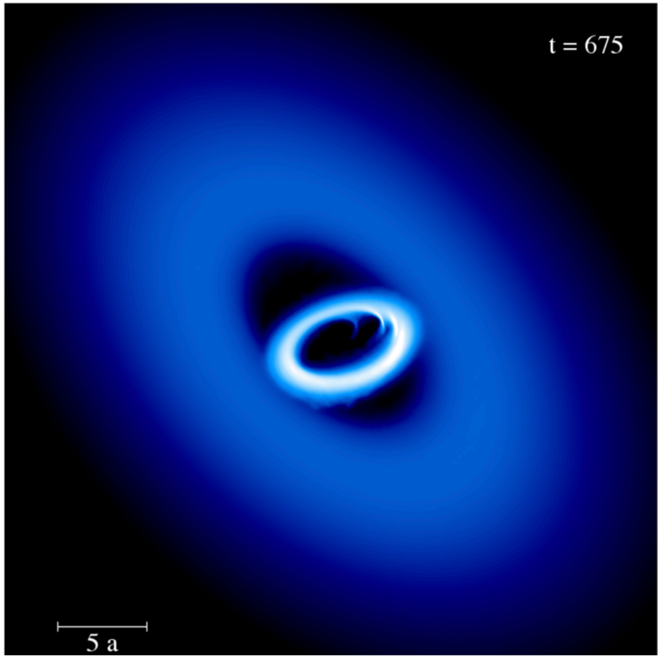
Theory predictions for disc tearing

Binaries whose orbital plane is misaligned with disk plane:

Gravitational torque can tear the disk apart into multiple, precessing rings
(e.g. Nixon+ 2012, 2013, Dogan+2015, Liska+ 2019, Nealon+ 2019, Facchini+ 2019, ...)







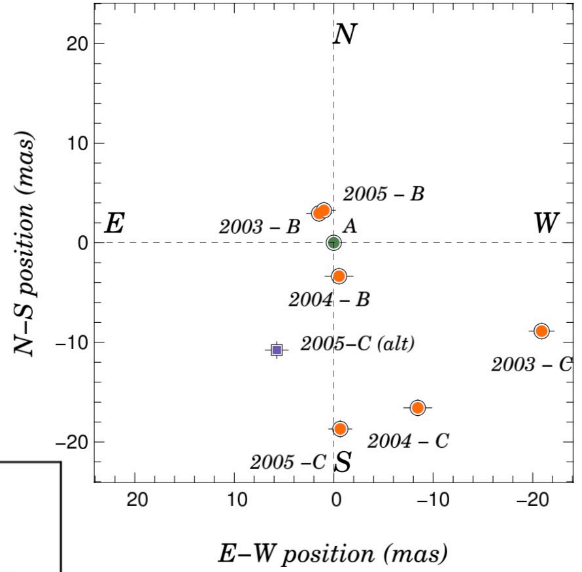
Nixon+ 2012, Liska+ 2019; Facchini+ 2019

GW Orionis: PMS triple system

Hierarchical pre-main-sequence triple system in λ Orionis (388 pc)

Spectroscopic binary: P_{AB}=242d, e_{AB}=0.04
(Mathieu+ 1991; Prato+ 2018)

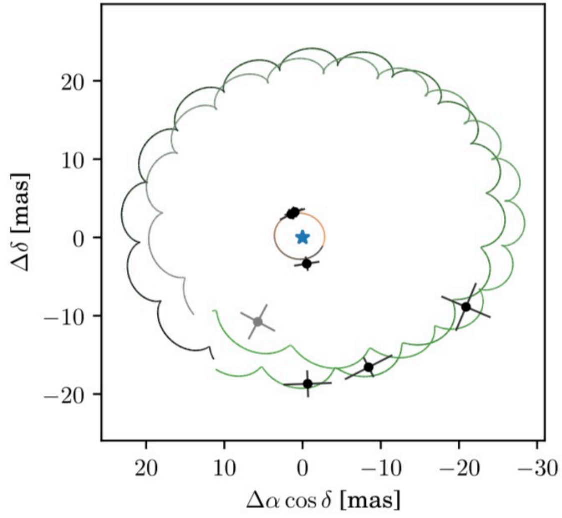
3rd star discovered with IOTA interferometry in H-band
(Berger+ 2011)



Berger+ 2011

Preliminary RV+astrometry orbit
(Czekala+ 2017):

- P_C=11.5 yrs
- e_{AB}=0.13 a_{AB}=1.25 au
- e_C=0.25 a_C=9.1 au
- Masses 2.7 M_{sun}, 1.7 M_{sun}, 0.9 M_{sun}

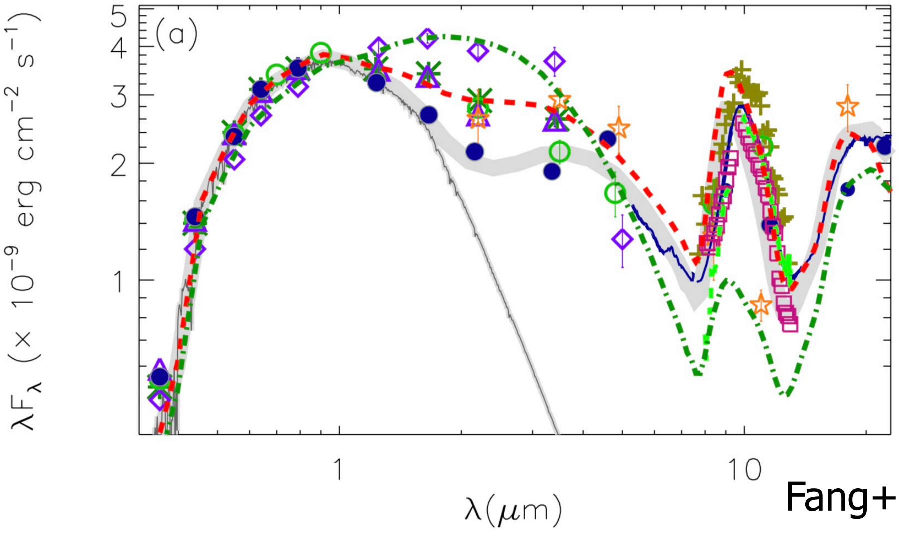


Czekala+ 2017

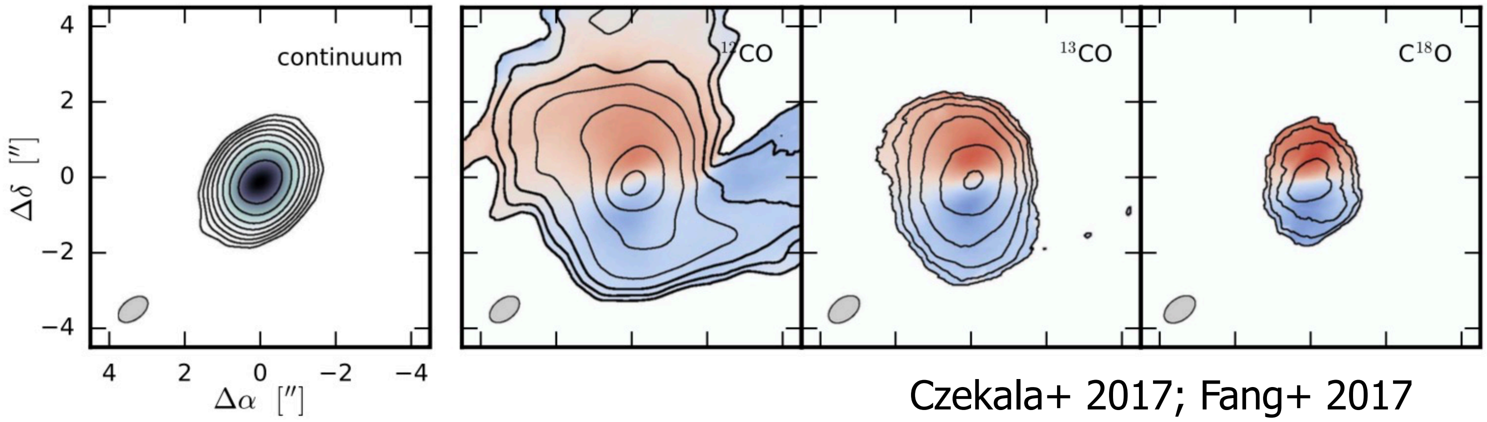
Earlier disk observations

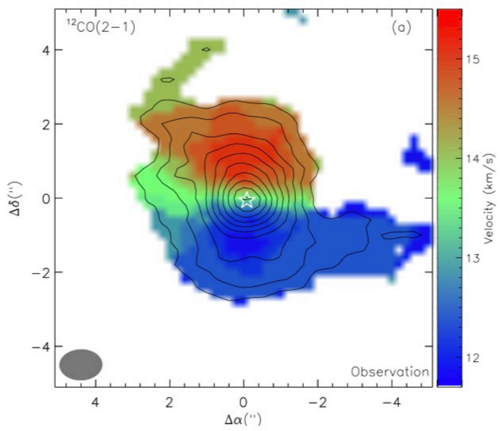
Massive (~0.03 M_{sun}) circumstellar disk oriented North-South, resolved with SMA (Fang+ 2017) and ALMA (Czekala+ 2017)

SED between 1-3.5 μm variable on timescales of years, suggesting inner disk realignments (Fang+ 2014)



Fang+ 2014

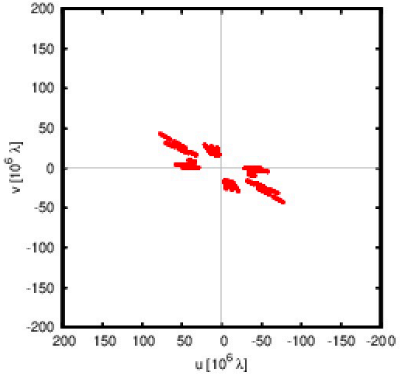


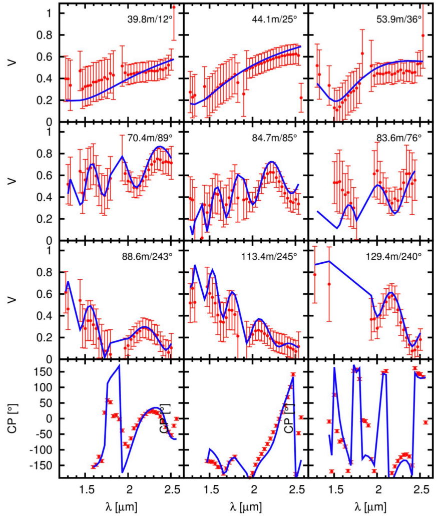


Czekala+ 2017; Fang+ 2017

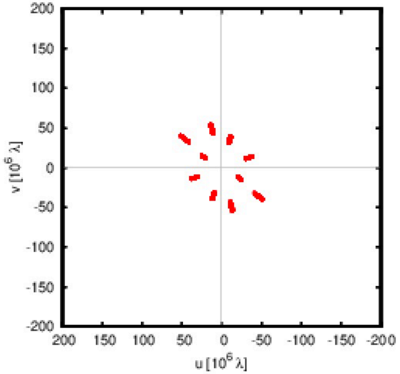
GW Orionis: astrometric orbit monitoring 2008-2019

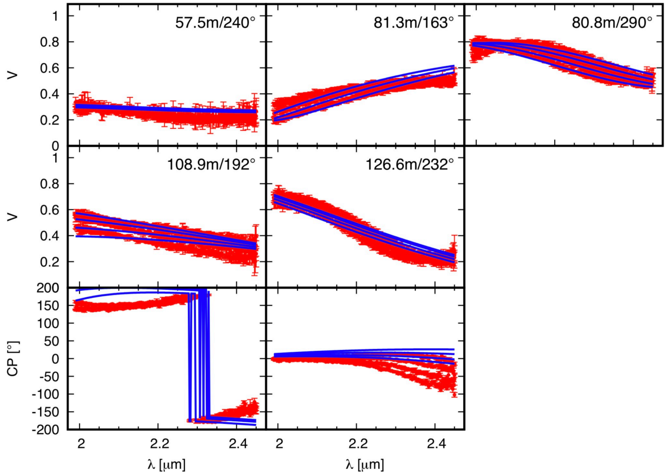
VLTI/AMBER (2008-15): **3×8.2m**



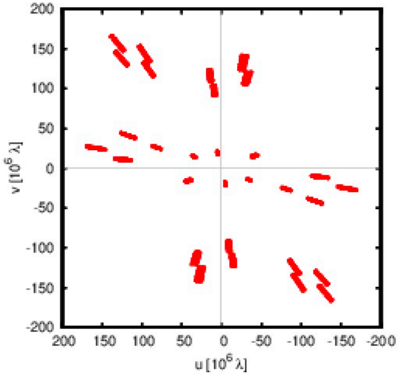


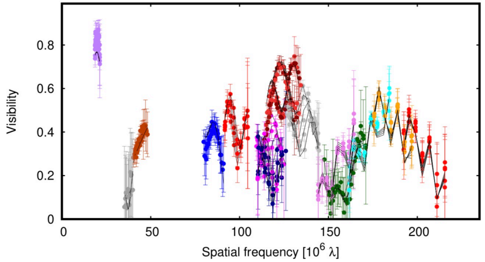
VLTI/GRAVITY (2017/18): **4×1.8m**

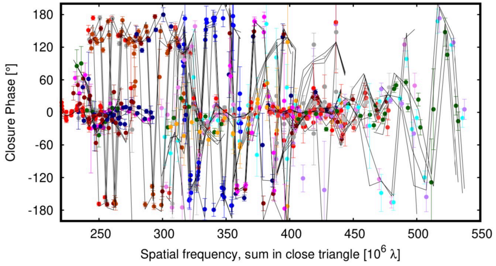




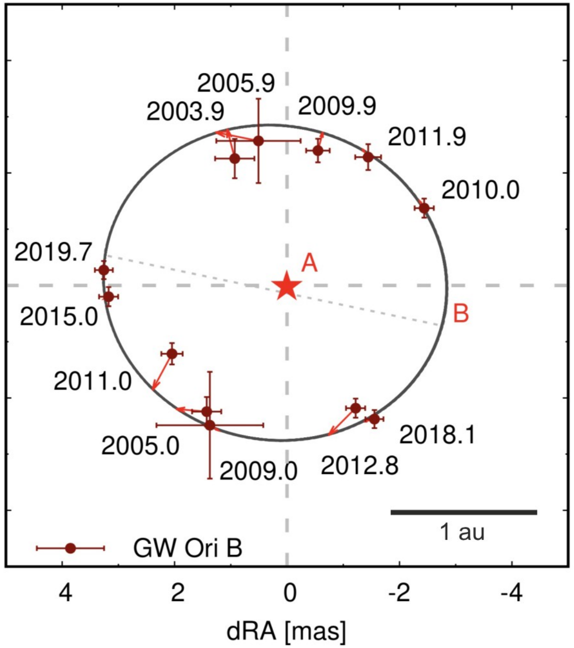
CHARA/MIRC-X (2019): **6×1m**

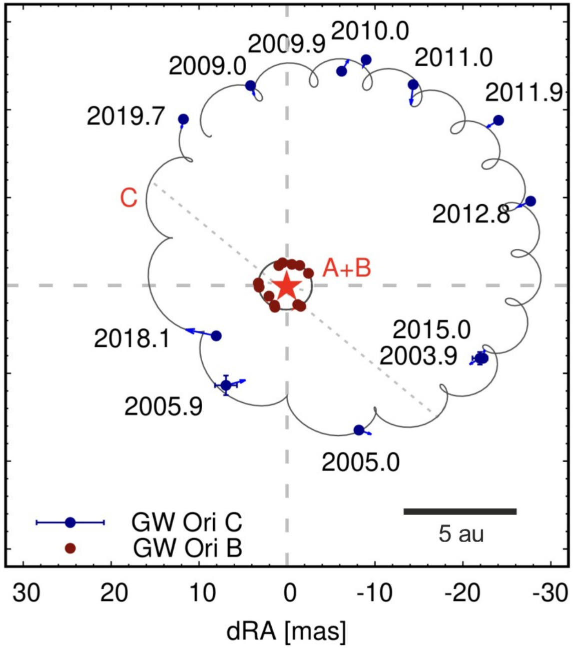


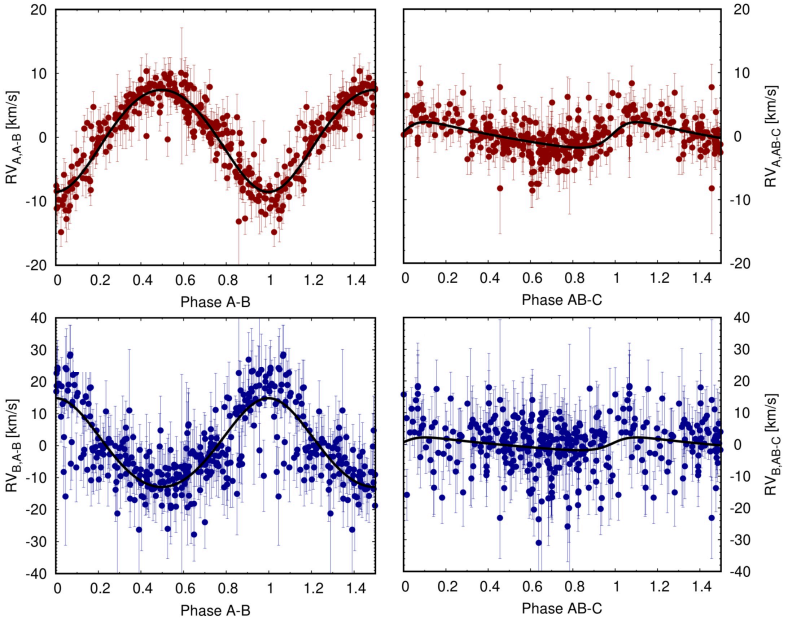




GW Orionis: astrometric orbit monitoring 2008-2019







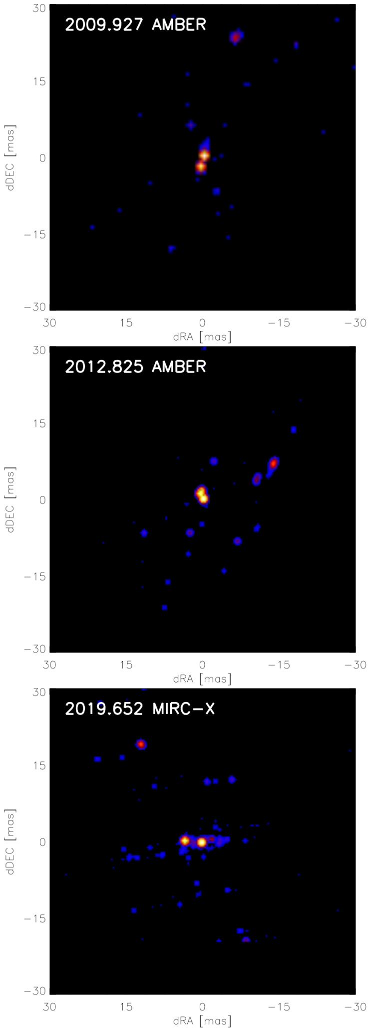
Full 3D orbit solution based on astrometry (VLTI+CHARA) + radial velocities (from Czekala et al. 2017):

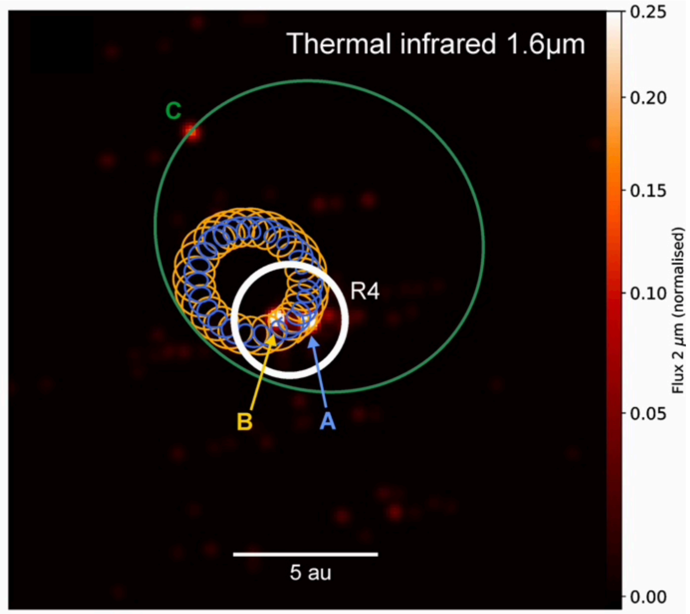
Inner binary:	*P=241.62±0.05 d*	*a=1.2±0.04 au*	*e=0.069±0.009*
Tertiary:	*P=11.55±0.01 yrs*	*a=8.89±0.04 au*	*e=0.379±0.003*

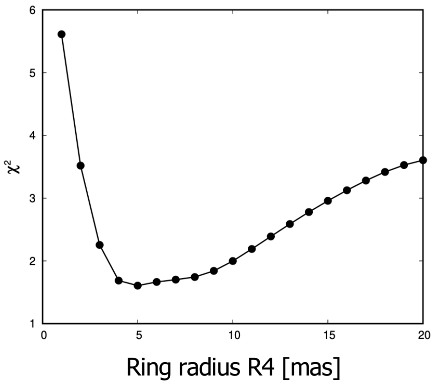
Dynamical masses/distance: *2.5±0.3* $M_\odot$ *1.4±0.2* $M_\odot$ *1.4±0.3* $M_\odot$ *387±27 pc*

Kraus+ 2020

Evidence for circumbinary disk from VLTI/CHARA



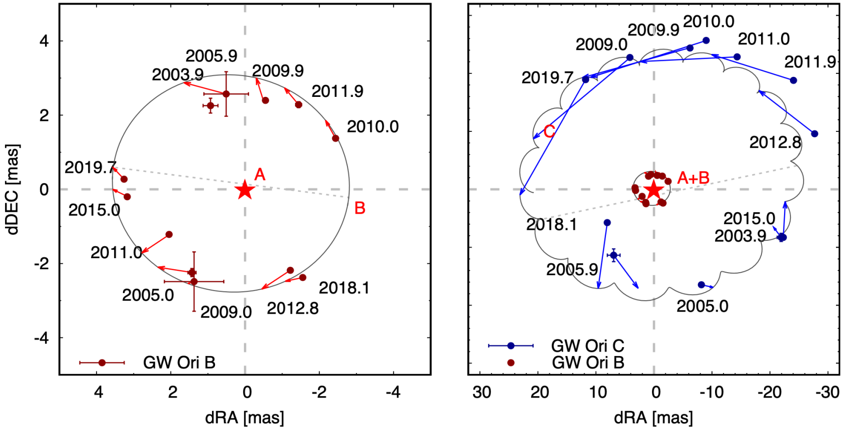




Visibility profile shows extended flux on scales of ~5 mas (~2 au)

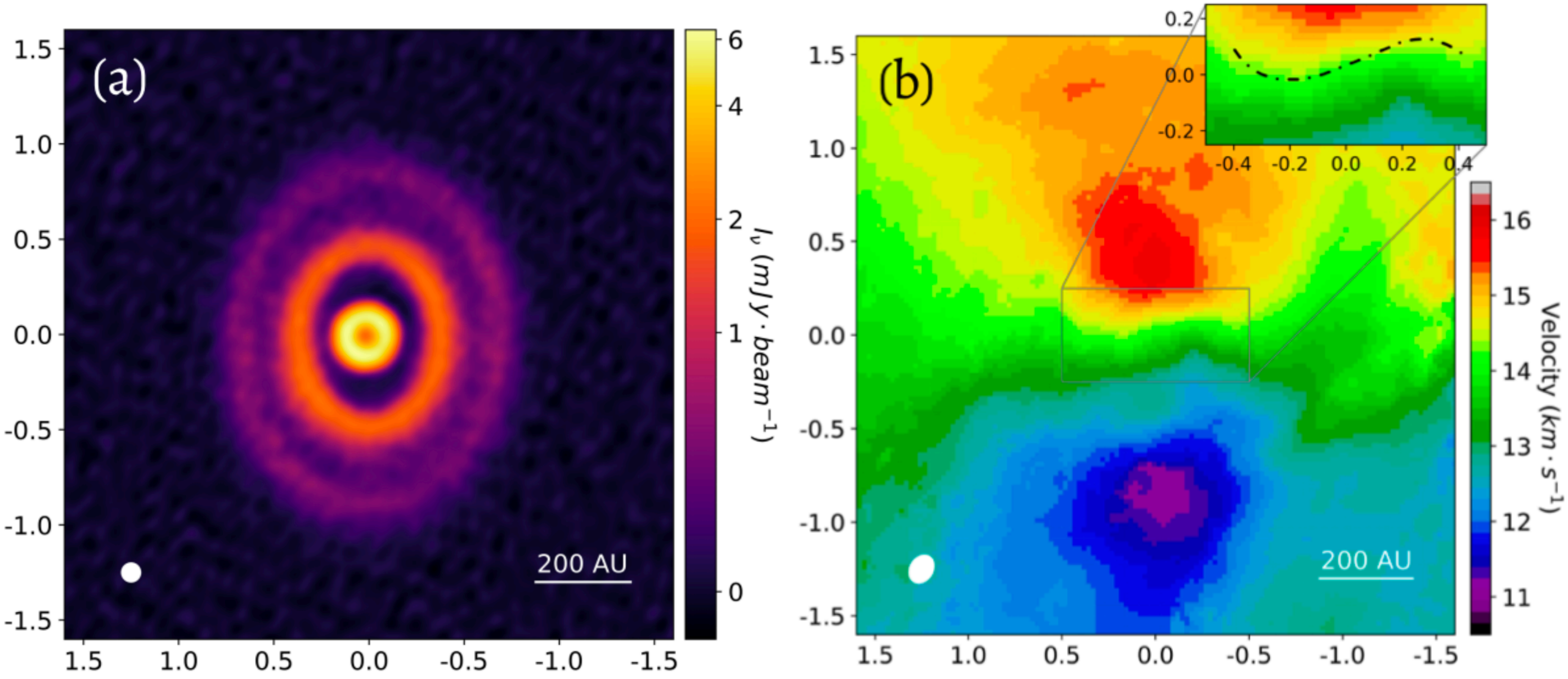
➜ Geometry still unconstrained, but likely circumbinary disk

Comparison with one of Czekala+ 2017 orbit solutions



Kraus+ 2020

ALMA dust imaging 0.1" resolution (Bi+ 2020)



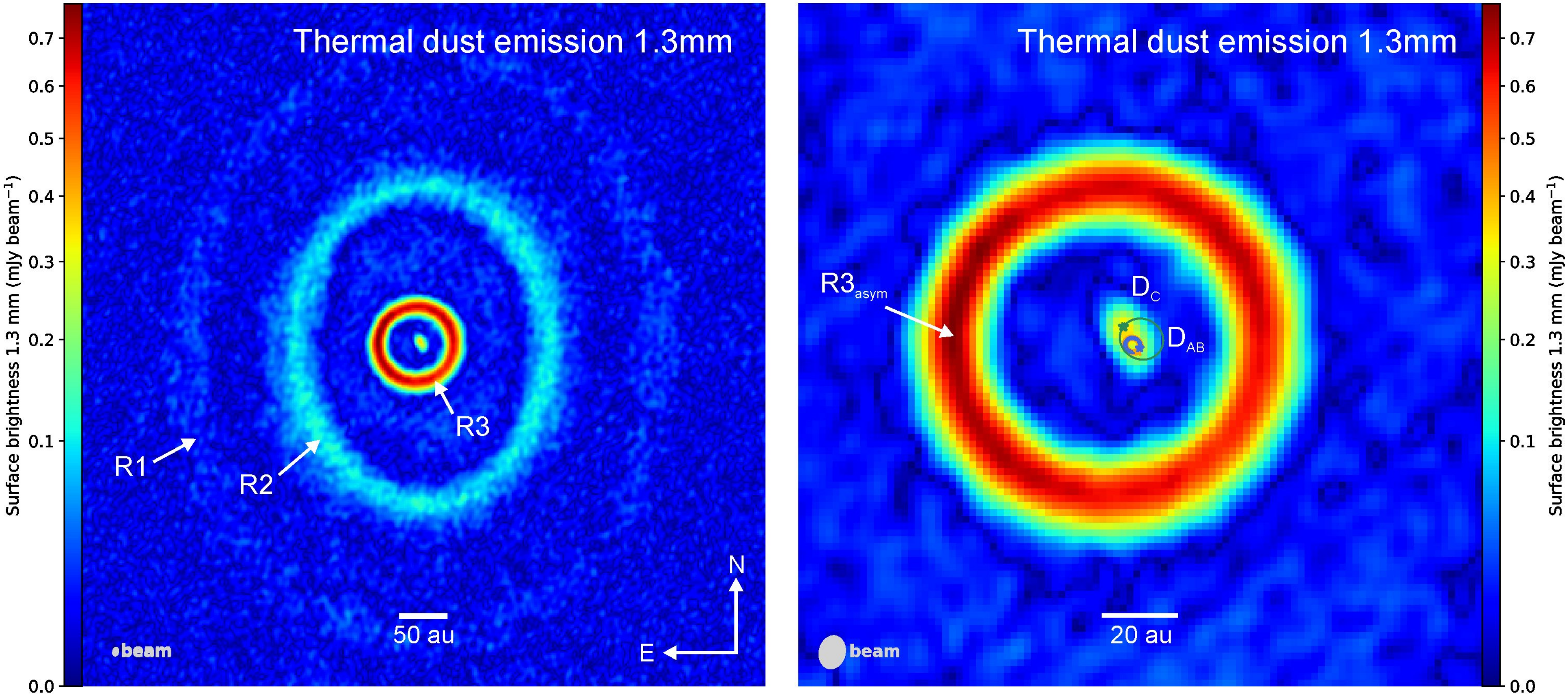
Inner ring at different orientation and offset with respect to the outer rings

Twists in ^{12}CO moment 1 map

- ➜ Misalignment in inner disk
- ➜ Companion in outer disk cause for misalignment?

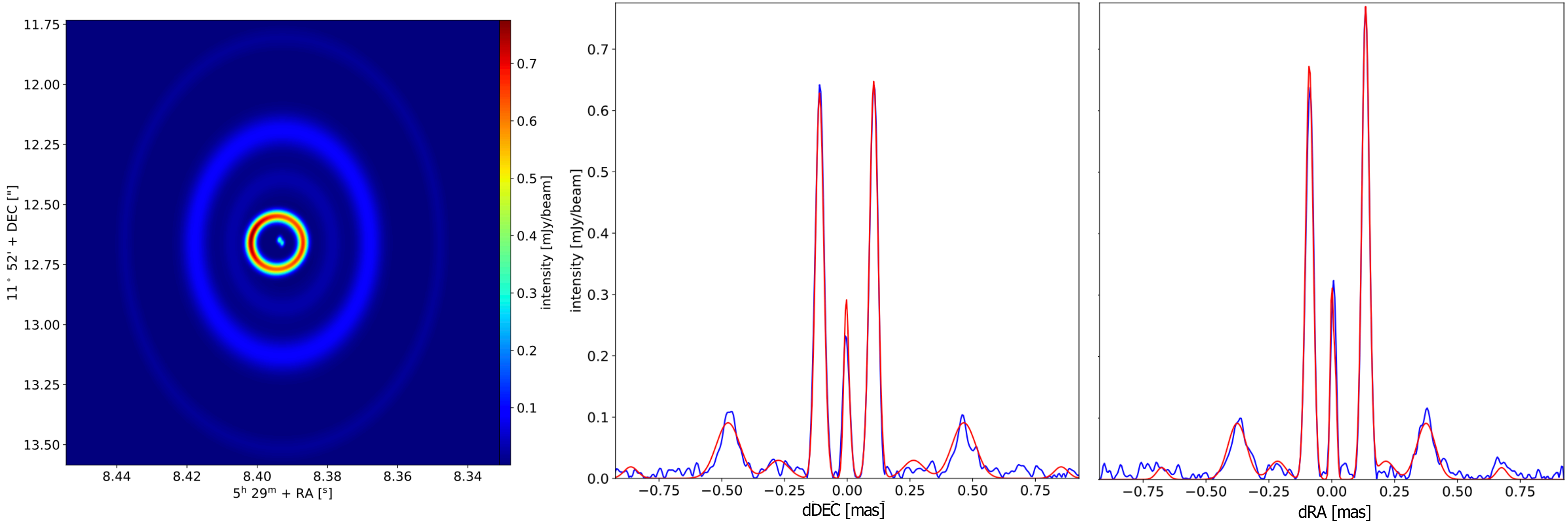
Bi+ 2020

ALMA dust imaging 0.02" resolution



Kraus+ 2020

ALMA dust imaging 0.02” resolution



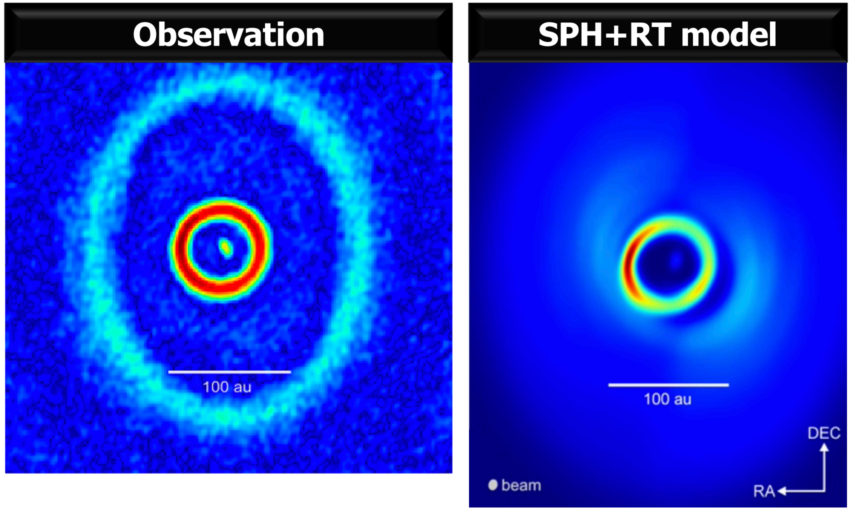
Geometric model:

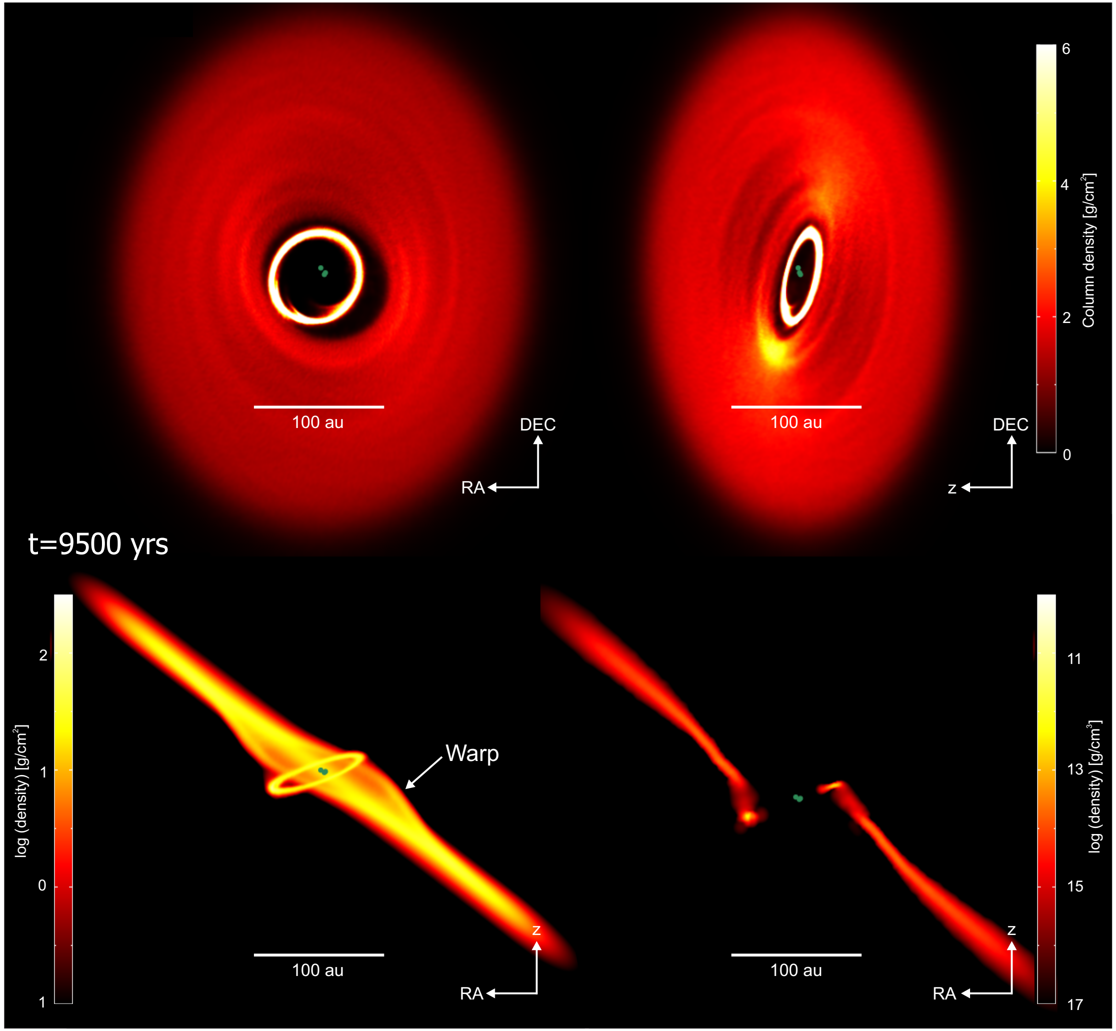
- Rings with radius 334±13, 182±12, 46±1 au, circumbinary/circumtriple disk spatially unresolved
- Dust mass estimates for rings (≳46, 153, 18 M_{Earth}) and circumbinary/circumtriple disk (≳ 0.02 M_{Earth})
- Inclination for outer rings 142º, 143º
- **Sky-projected shape** of inner ring

  ➜ get 3D shape by fitting **sky-projected shape and shadow patterns**

Kraus+ 2020

SPH simulation based on actual orbits + disc properties

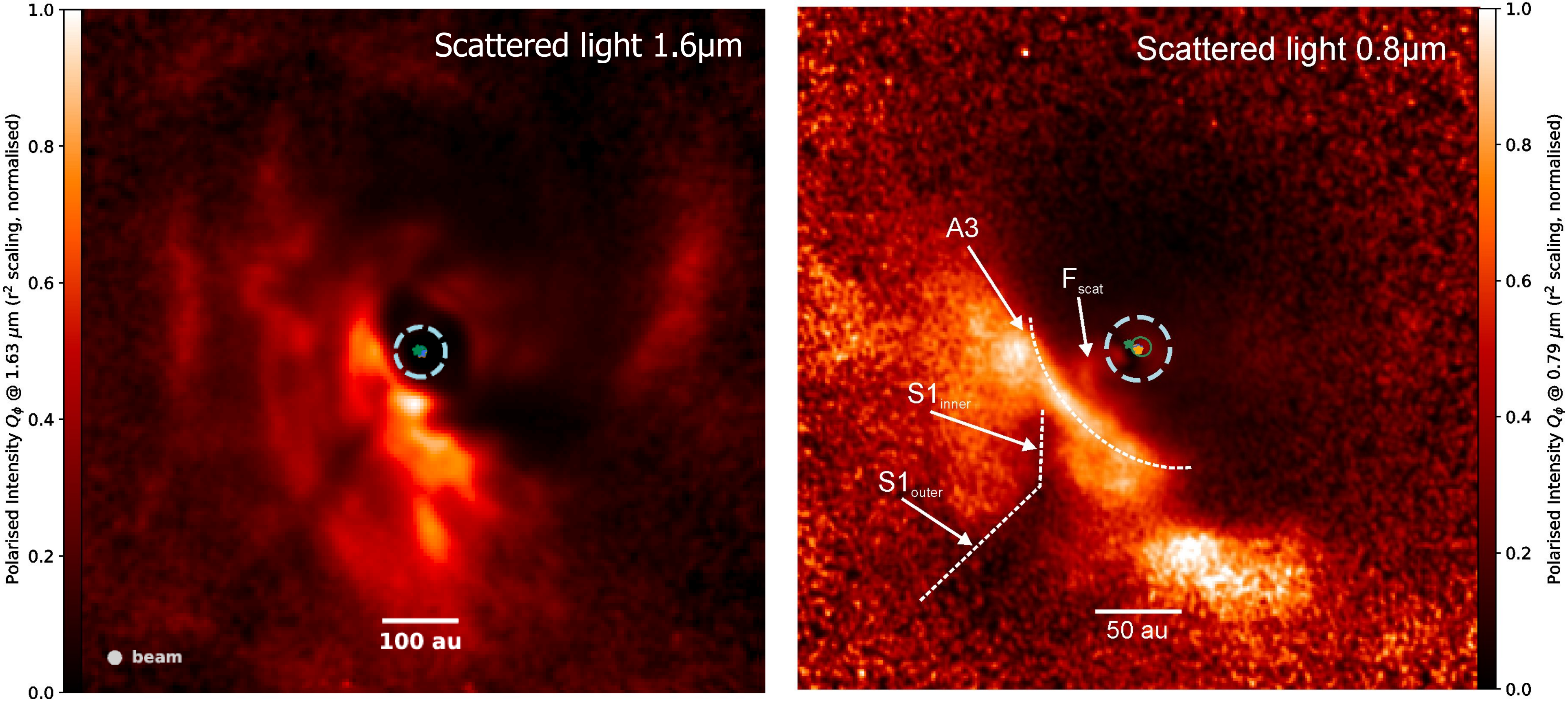




SPH model reproduces
key characteristics of ring R3:

- Size of ring
- Eccentricity
- Mutual inclination
- Density enhancement near apoastron of ring

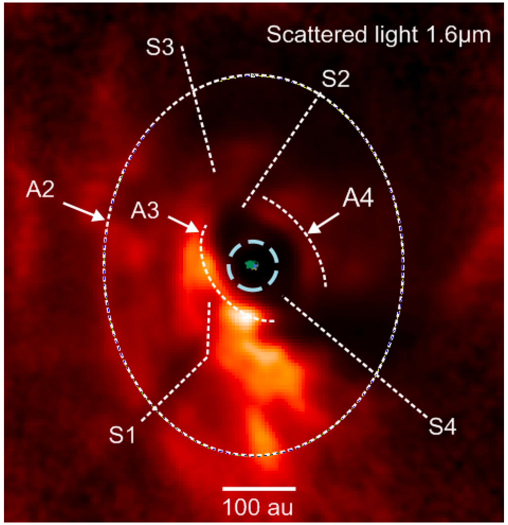
SPHERE/GPI polarimetric imaging

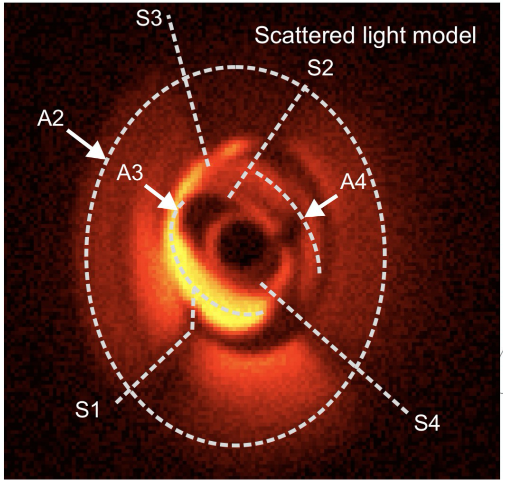


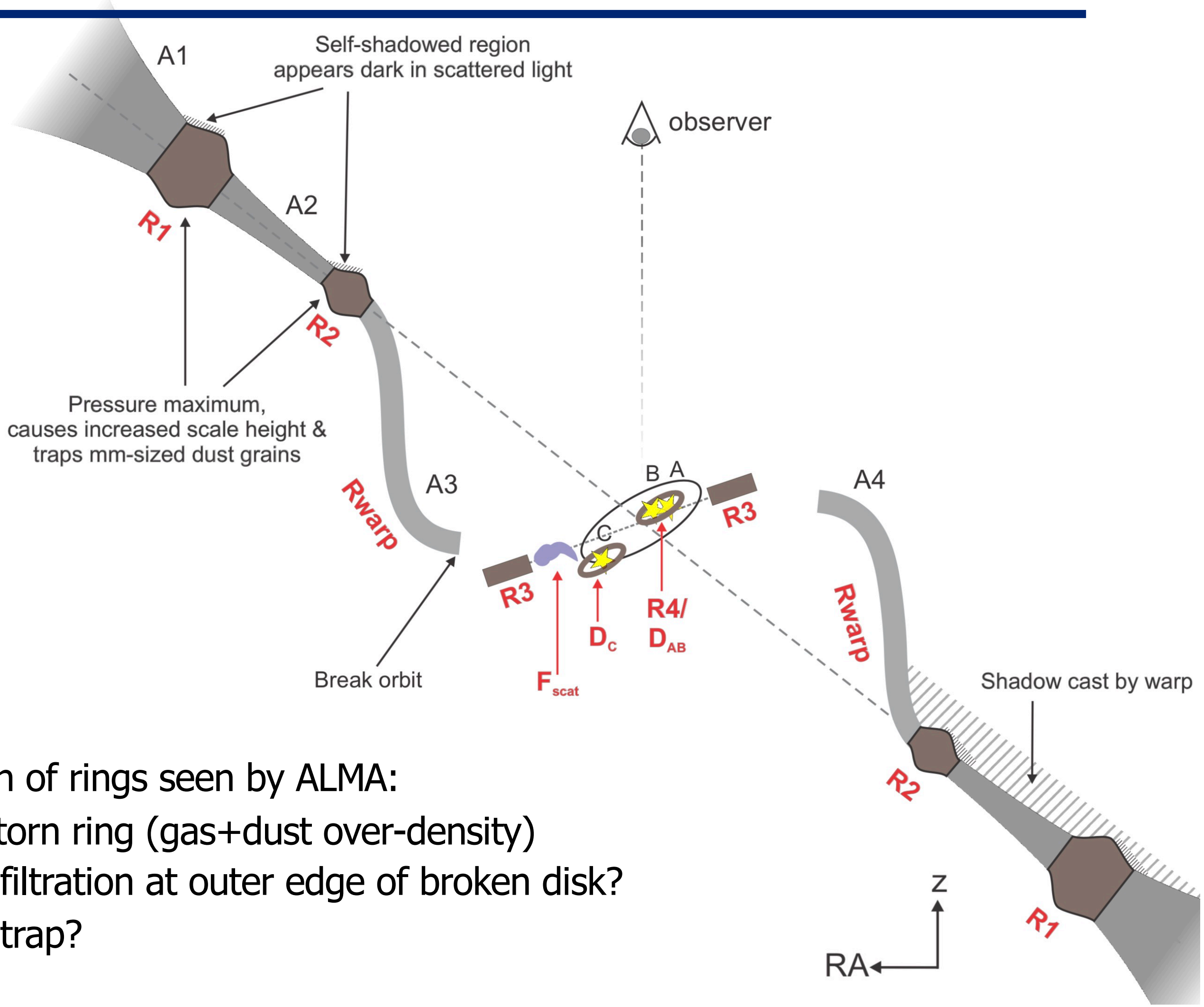
Sub-mm rings correspond to regions with low scattered light

Kraus+ 2020

3D orientation of misaligned ring + disc warp







Possible origin of rings seen by ALMA:

- R3: Disk-torn ring (gas+dust over-density)
- R2: Dust filtration at outer edge of broken disk?
- R1: Dust trap?

Summary

- GW Orionis: **benchmark for studying hydrodynamical effects** in PMS multiples
- **Disk tearing in action: Mechanism for forming "Tatooine" planets on oblique orbits**
- Combining different wavelengths & techniques crucial
  (even if it can be frustrating & tedious):
  - **VLTI/CHARA:**
    Astrometric monitoring over 11 years
  - **ALMA:**
    inclination of outer disk
    + sky-projected shape of 'occulter ring'
  - **GPI/SPHERE:**
    warped disk surface
    + orientation of 'occulter ring'
- Combining shadows + resolved imaging of occulter
  ➜ **3D structure of warp/misaligned disk**