

Optical interferometric images



Welcome to the museum

Tour guide: Jacques Kluska

KU LEUVEN



Why interferometric imaging?

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- ❖ Our brain is used to images

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- ❖ Be (less) model independent

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- ❖ Excellent to communicate results

Why interferometric imaging?

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- ❖ Be (less) model independent
- ❖ Excellent to communicate results
- ❖ Deciphering the interferometric code
 - ❖ From $V_2, CP, d\Phi \dots$ to an image

Why interferometric imaging?

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- ❖ Be (less) model independent
- ❖ Excellent to communicate results
- ❖ Deciphering the interferometric code
- ❖ From $V_2, CP, d\Phi \dots$ to an image



Katie Bouman after performing the first image reconstruction of the M87 black hole

Museum collection

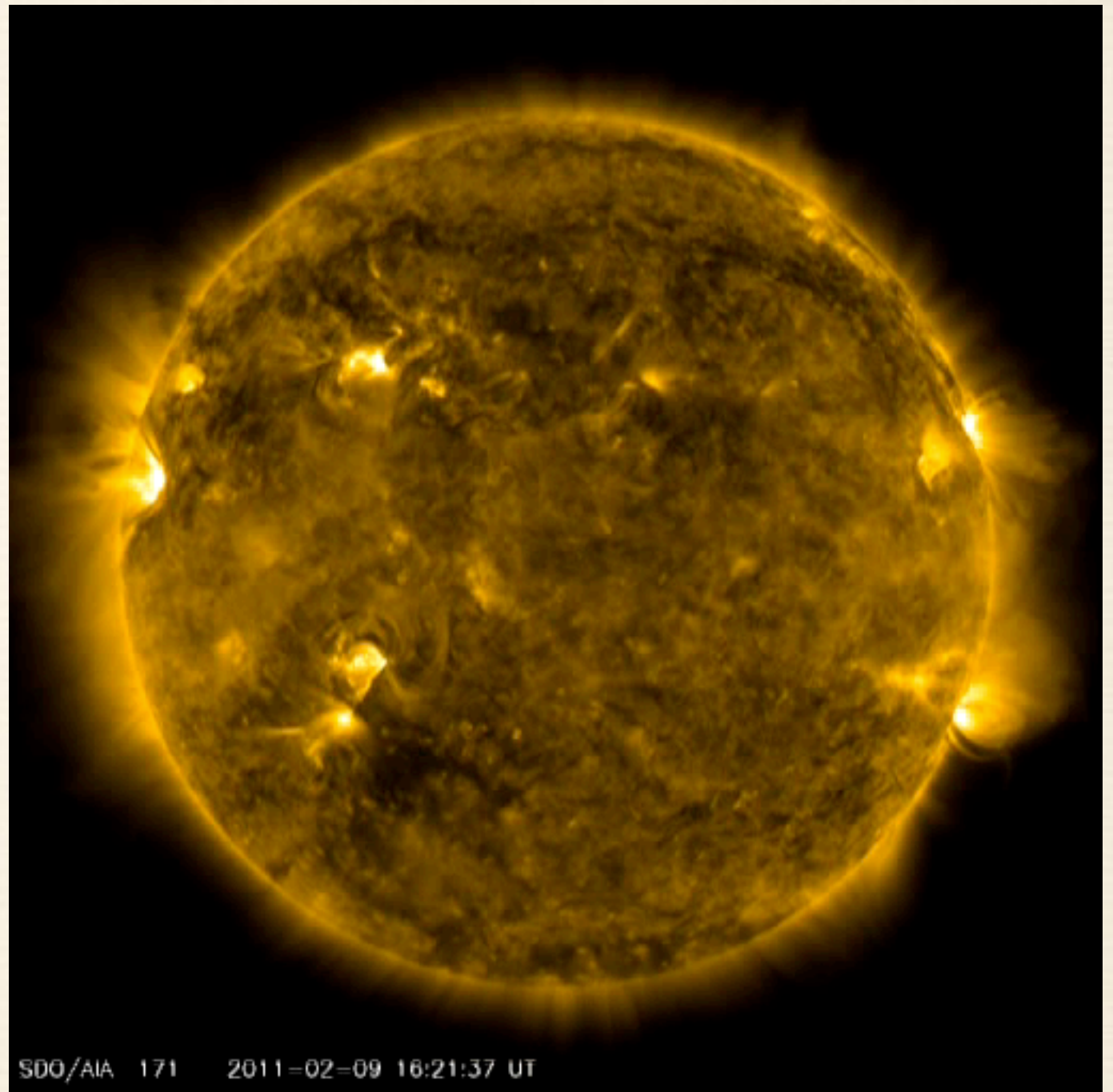


- ❖ Stellar surfaces
- ❖ Binaries
- ❖ Extra-galactic science
- ❖ Circumstellar disks

Stellar surfaces

Stellar surfaces

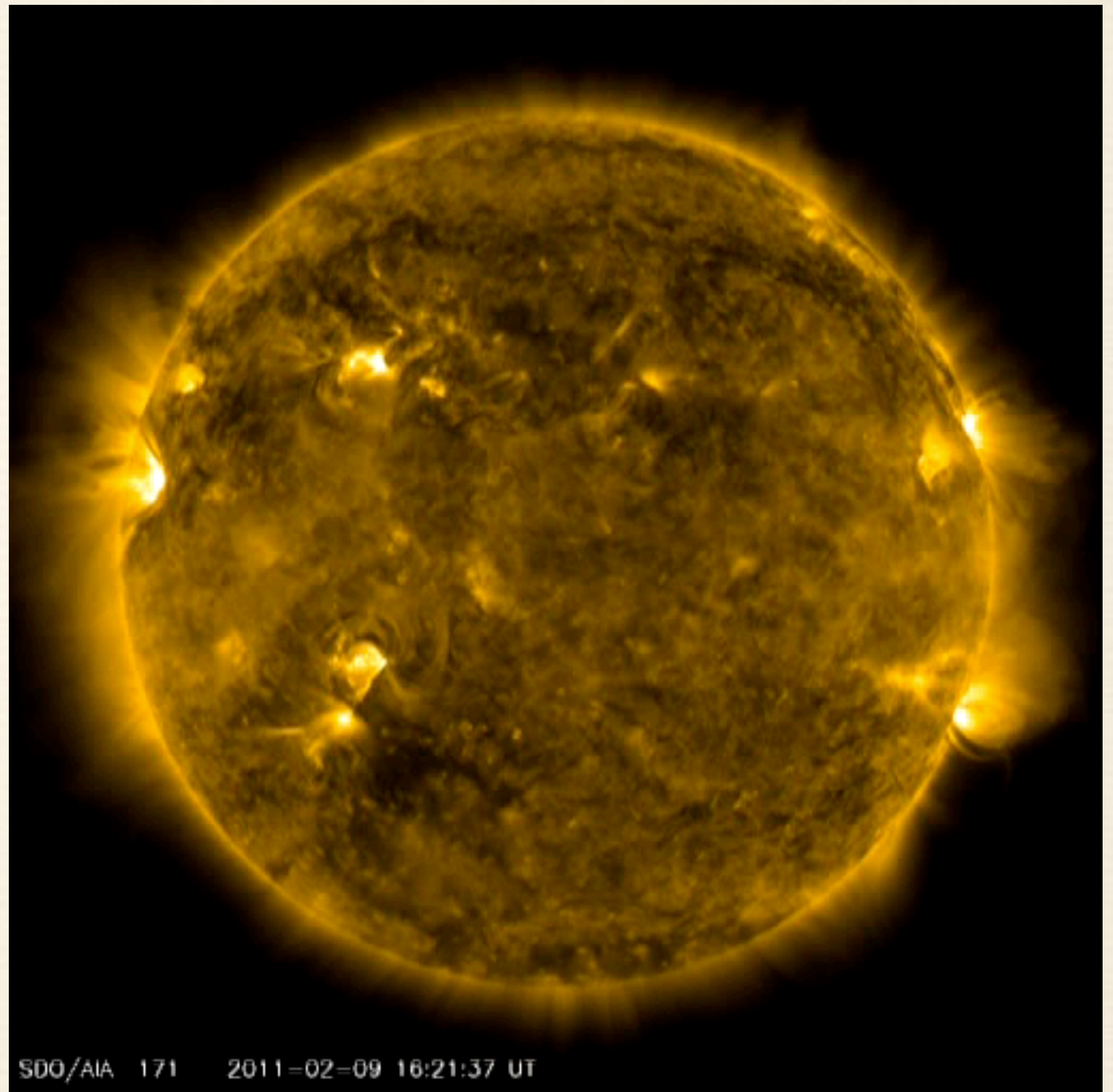
- ❖ Stellar physics
- ❖ Magnetic activity
- ❖ Convection
- ❖ Flares/winds



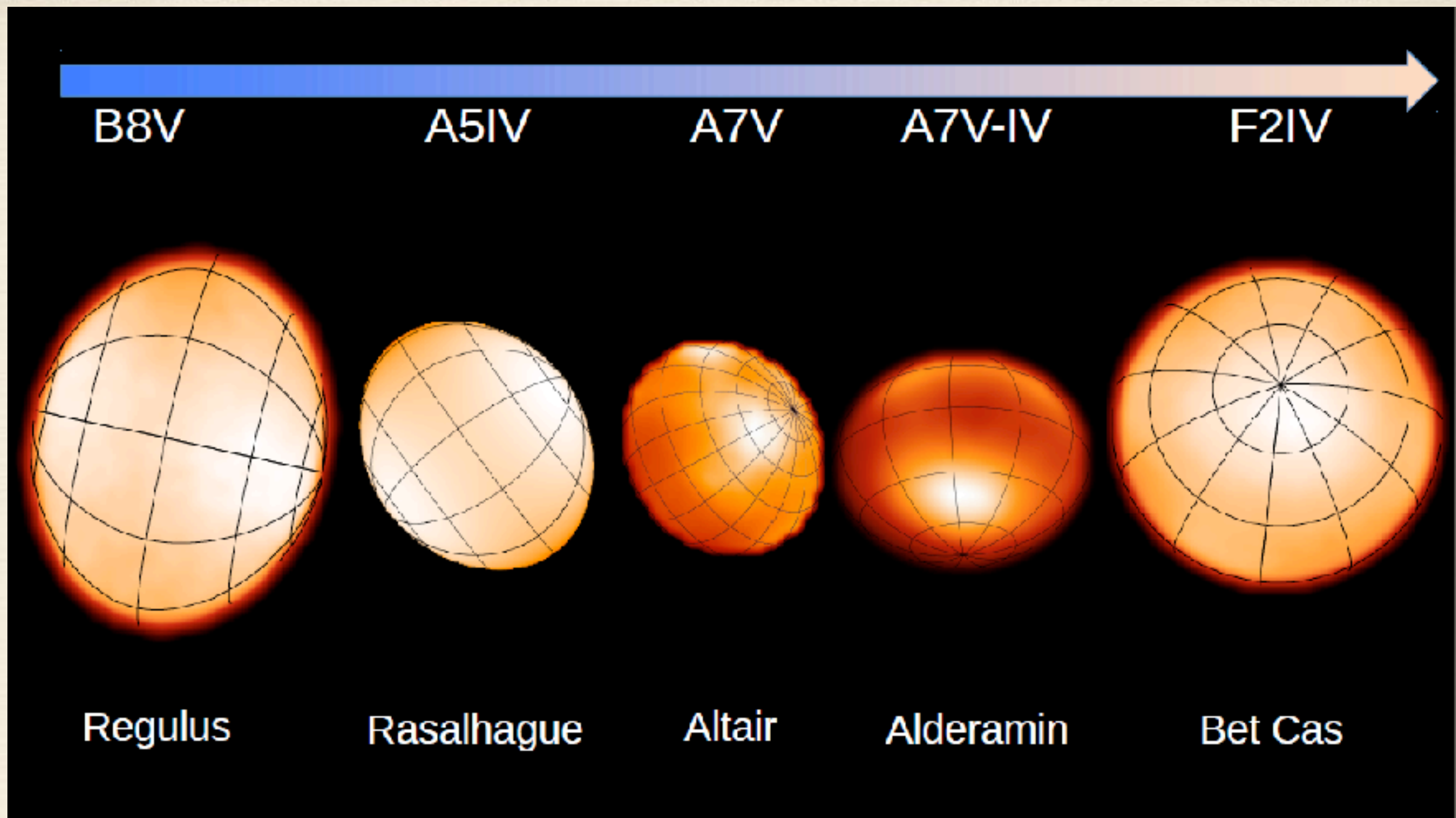
The Sun seen by Soho; (c)NASA/Soho

Stellar surfaces

- ❖ The main difficulty
- ❖ Sharp edge
- ❖ Smooth features on the surface



The Sun seen by Soho; (c)NASA/Soho



Title: **Family of rapid rotators**

Artists: **Che et al., Zhao et al., Monnier et al.**

Year: **2007 -2009 - 2011**

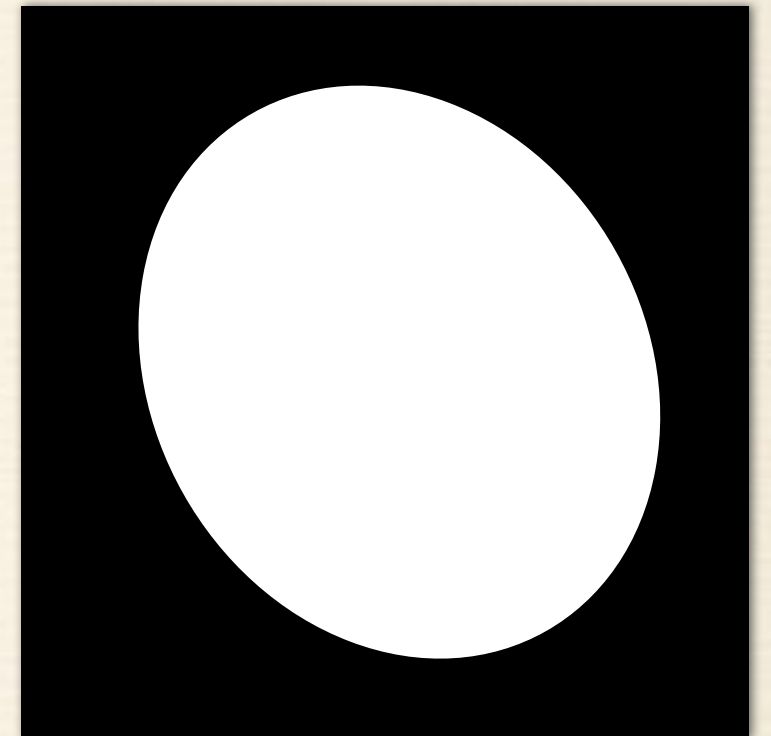
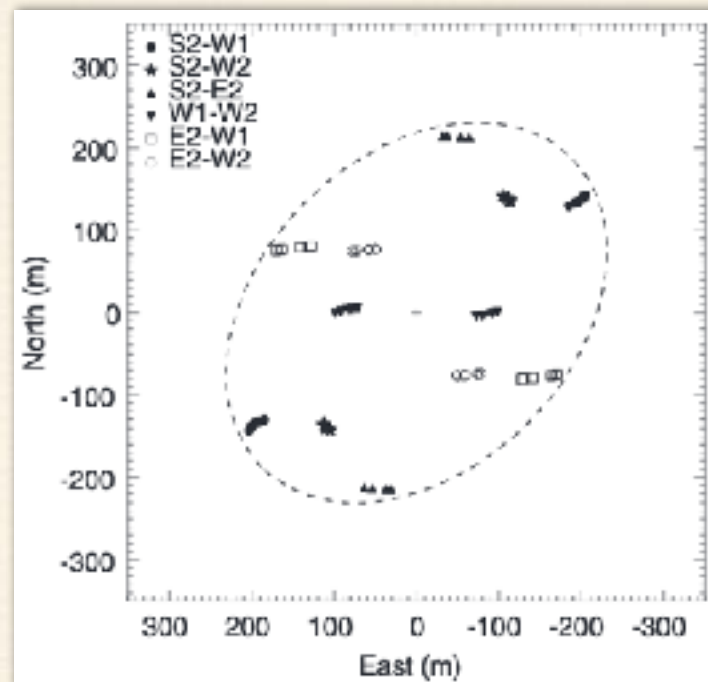
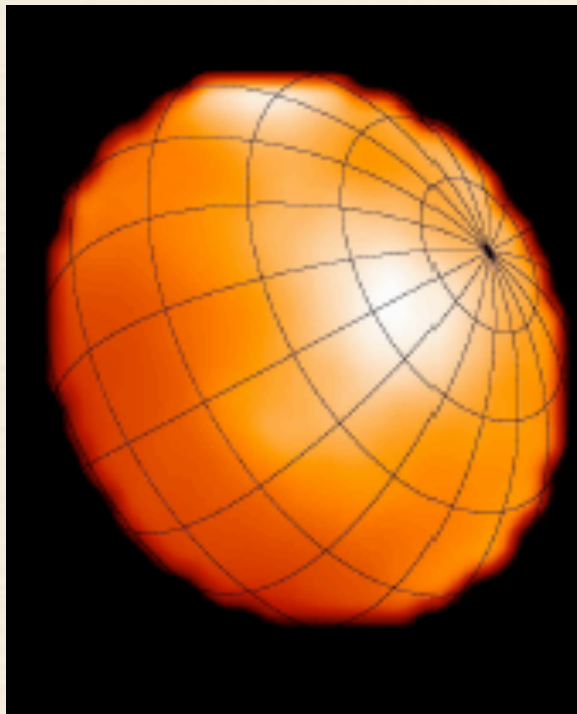
Technique: **MACIM (old Squeeze)**

Instrument: **CHARA/MIRC**

Stellar surfaces

(u, v)-plane

Mask



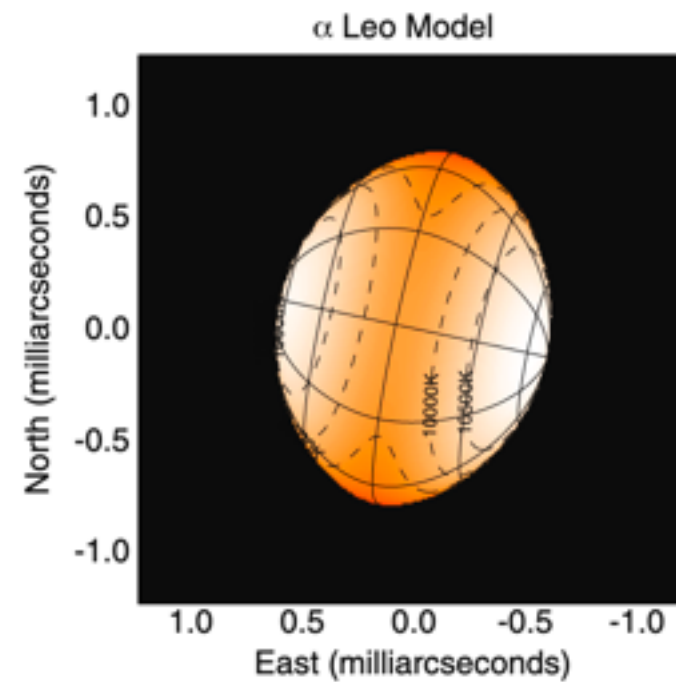
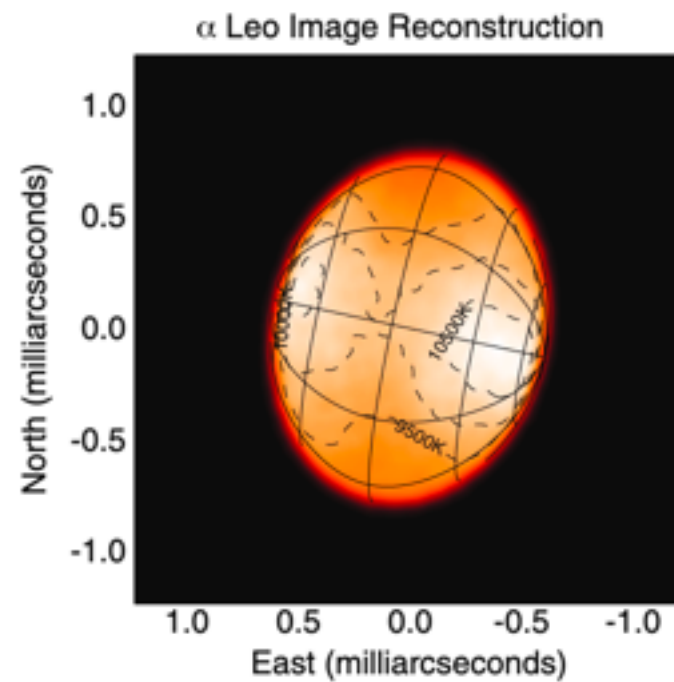
Title: **Altair**

Artists: **Monnier et al. (Science)**

Year: **2007**

Technique: **MACIM (old Squeeze)**

Instrument: **CHARA/MIRC**



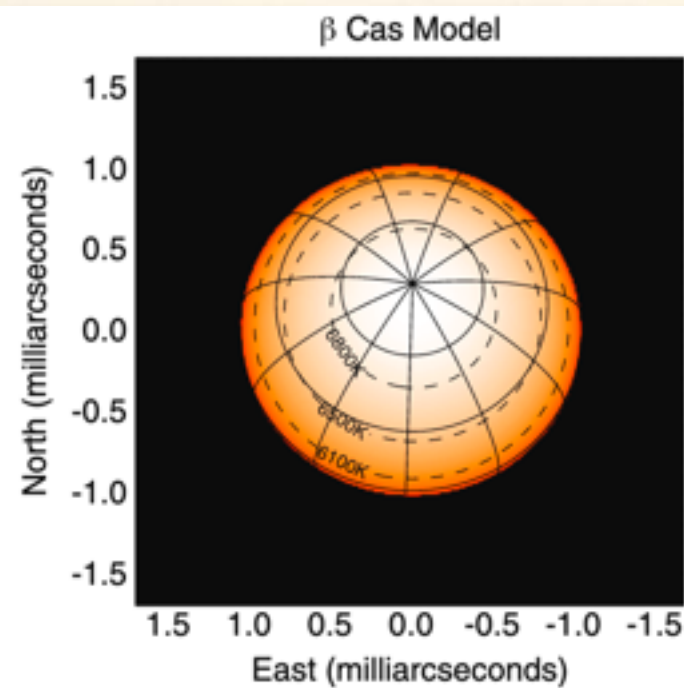
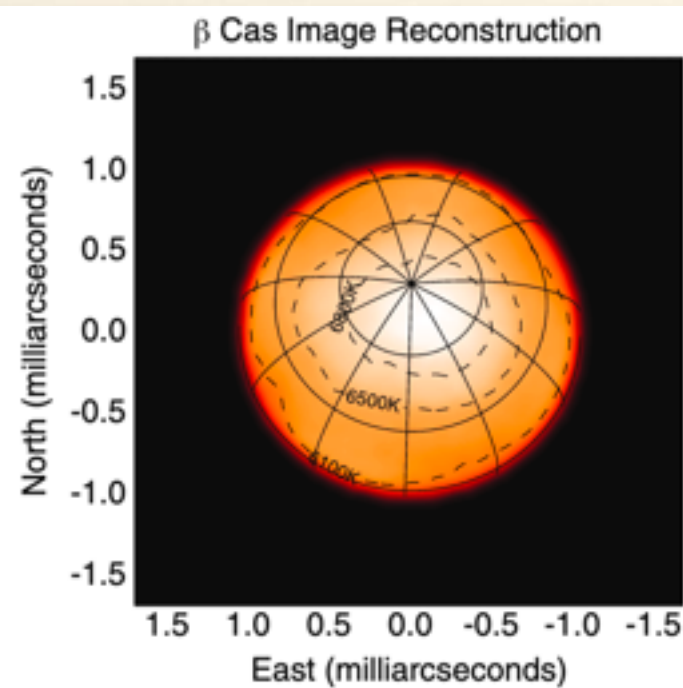
Title: α Leo & β Cas

Artists: Che et al.

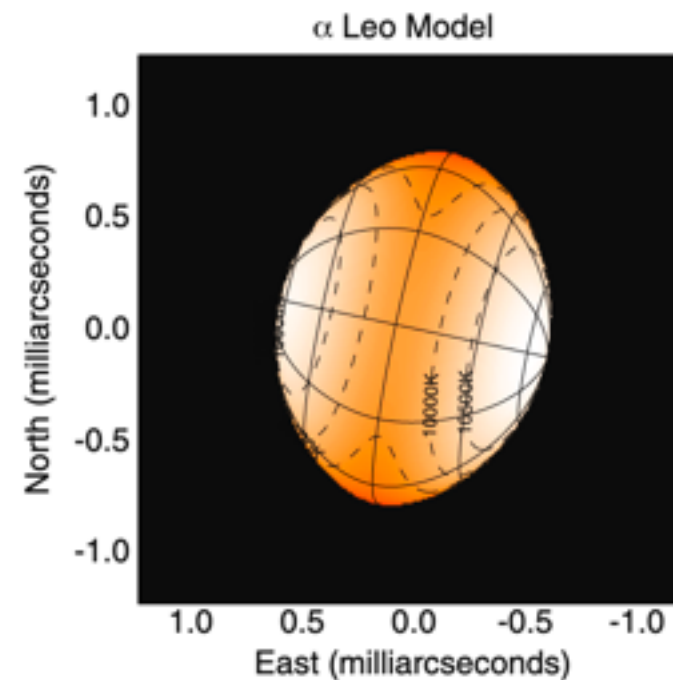
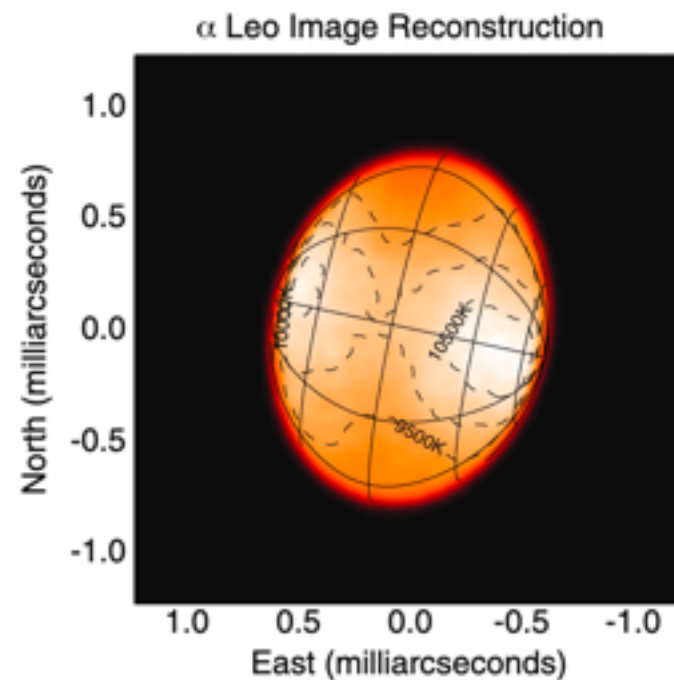
Year: 2011

Technique: MACIM (old Squeeze)

Instrument: CHARA/MIRC



Gravity darkening



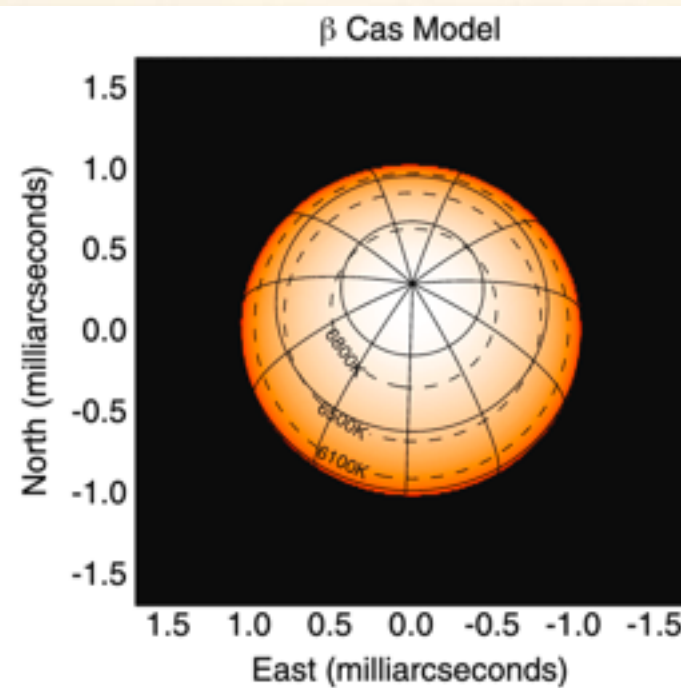
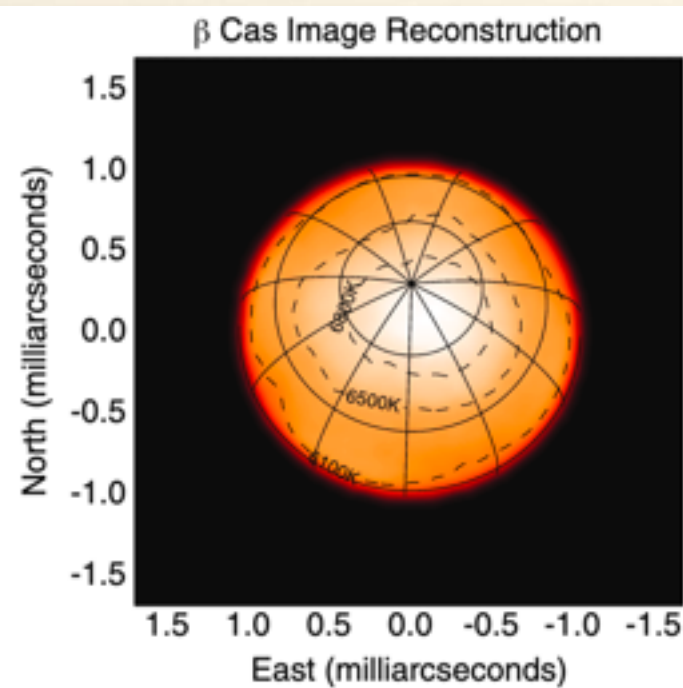
Title: α Leo & β Cas

Artists: Che et al.

Year: 2011

Technique: MACIM (old Squeeze)

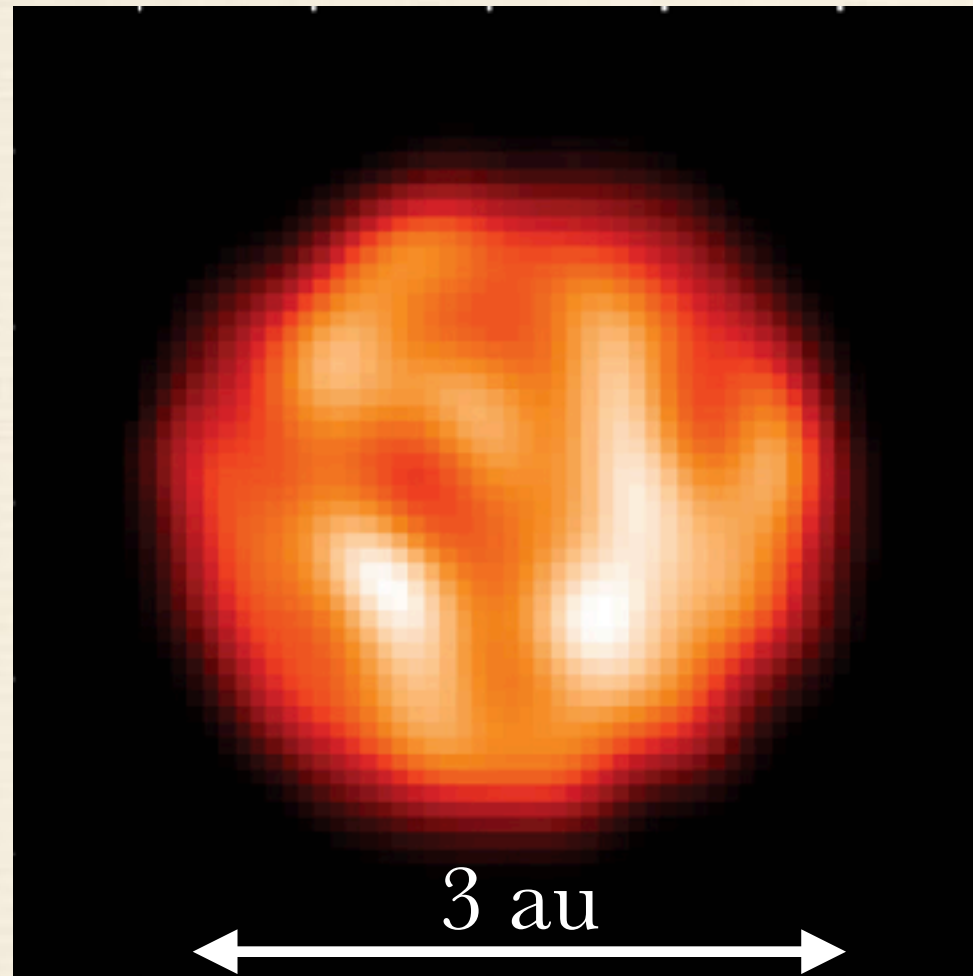
Instrument: CHARA/MIRC



Gravity darkening

Image used to confirm the model

Stellar surfaces



Title: π^1 Gruis

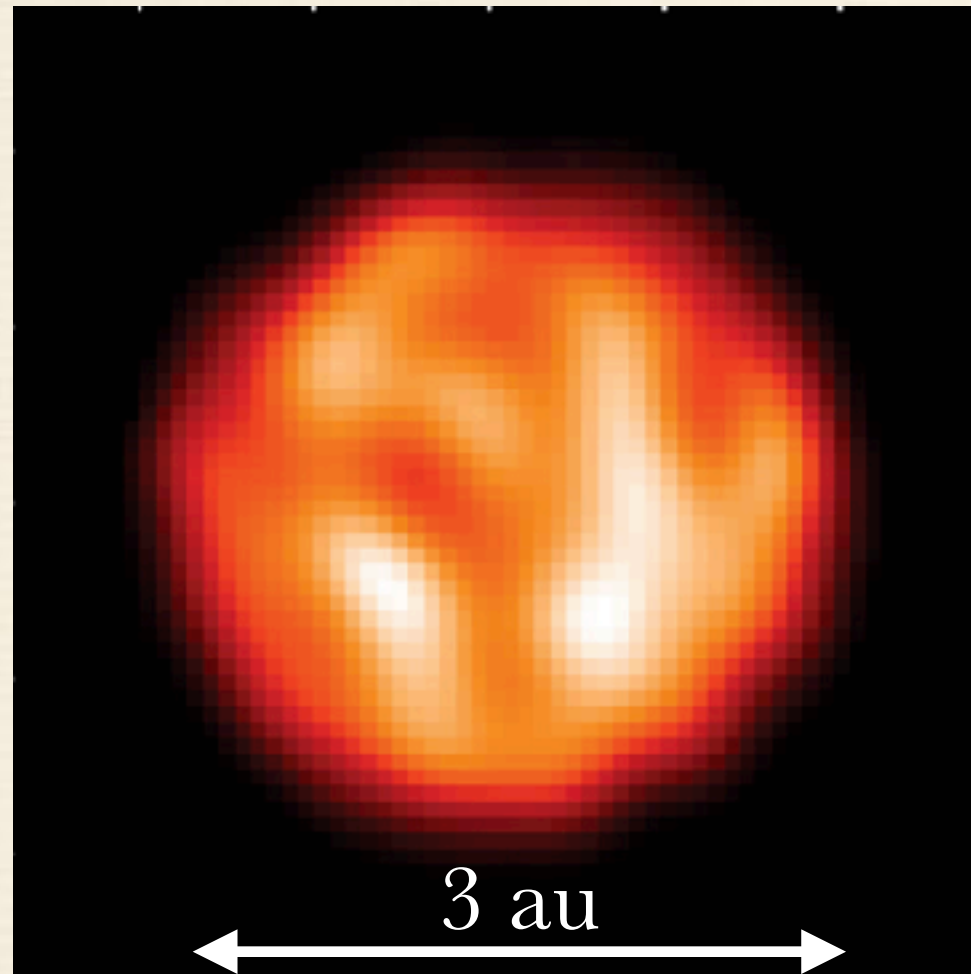
Artists: Paladini et al. (Nature)

Year: 2017

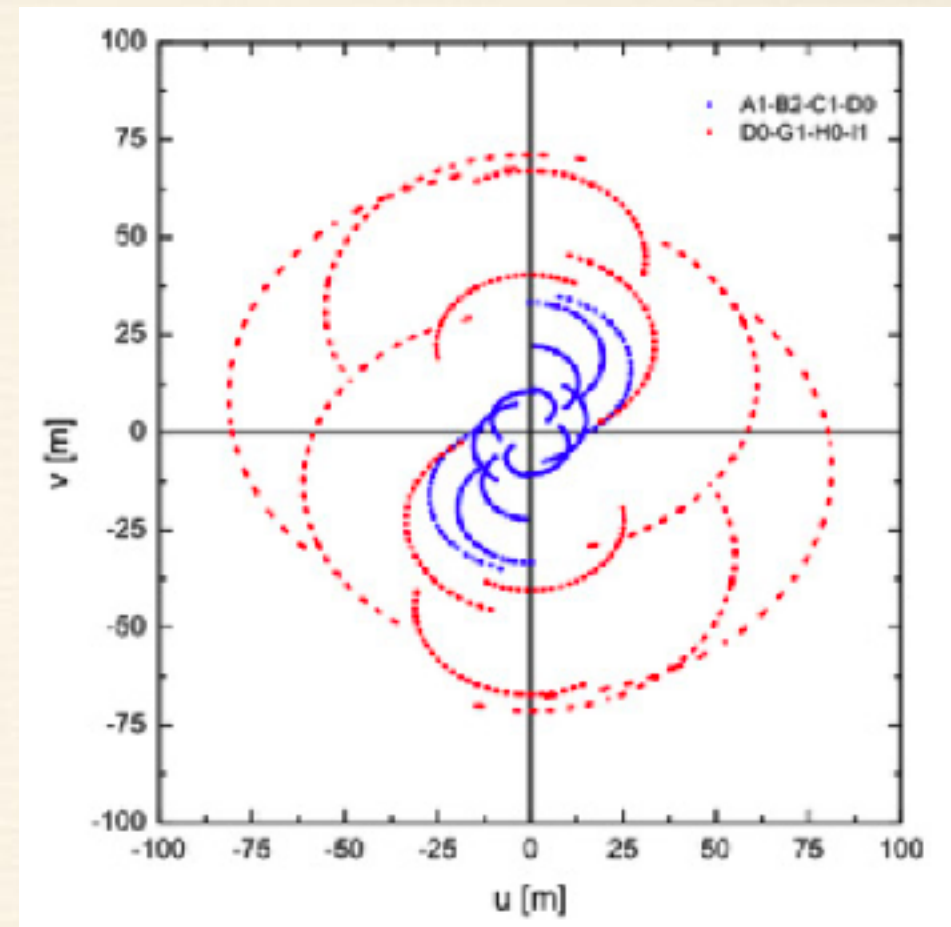
Technique: Squeeze & MiRA

Instrument: VLT/PIONIER

Stellar surfaces

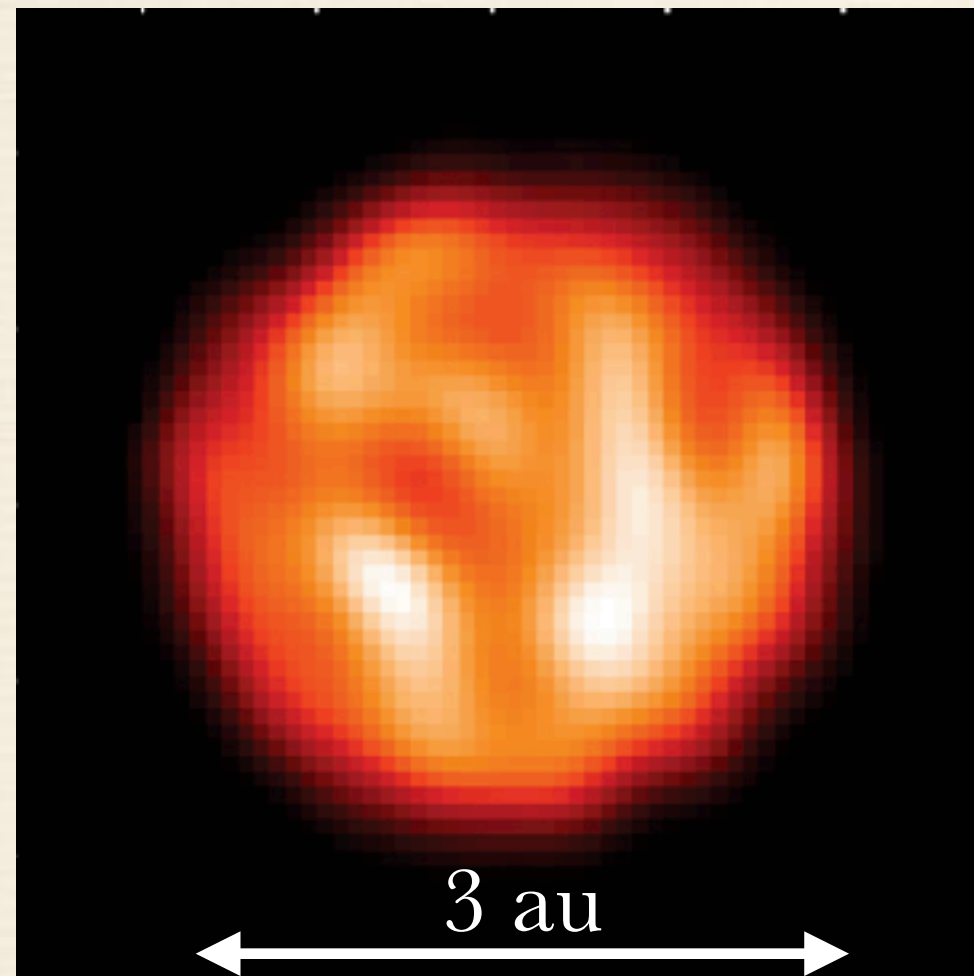


Title: π^1 Gruis
Artists: Paladini et al. (Nature)
Year: 2017
Technique: Squeeze & MiRA
Instrument: VLT1/PIONIER



No mask was used

Stellar surfaces



Title: π^1 Gruis
 Artists: Paladini et al. (Nature)
 Year: 2017
 Technique: Squeeze & MiRA
 Instrument: VLTi/PIONIER

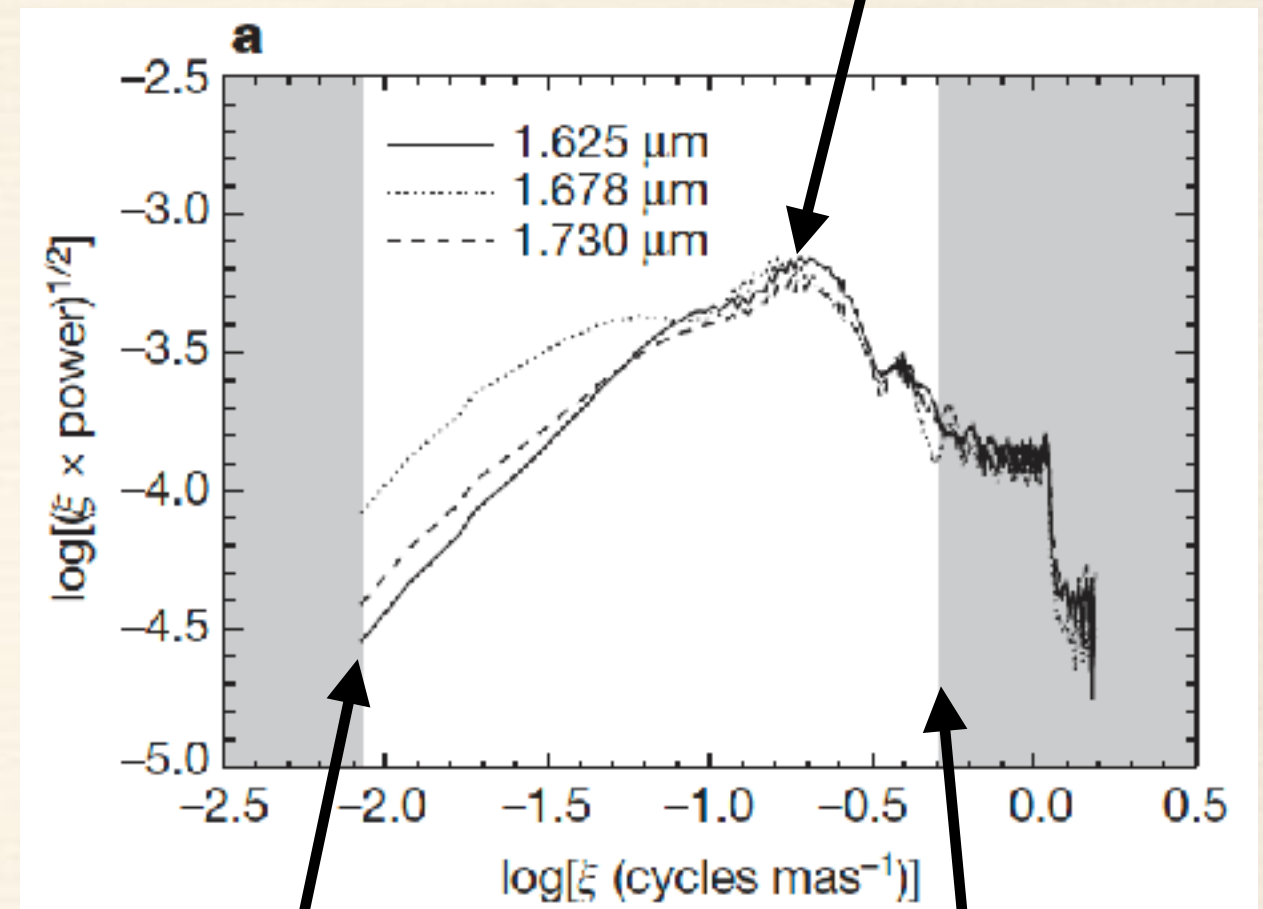
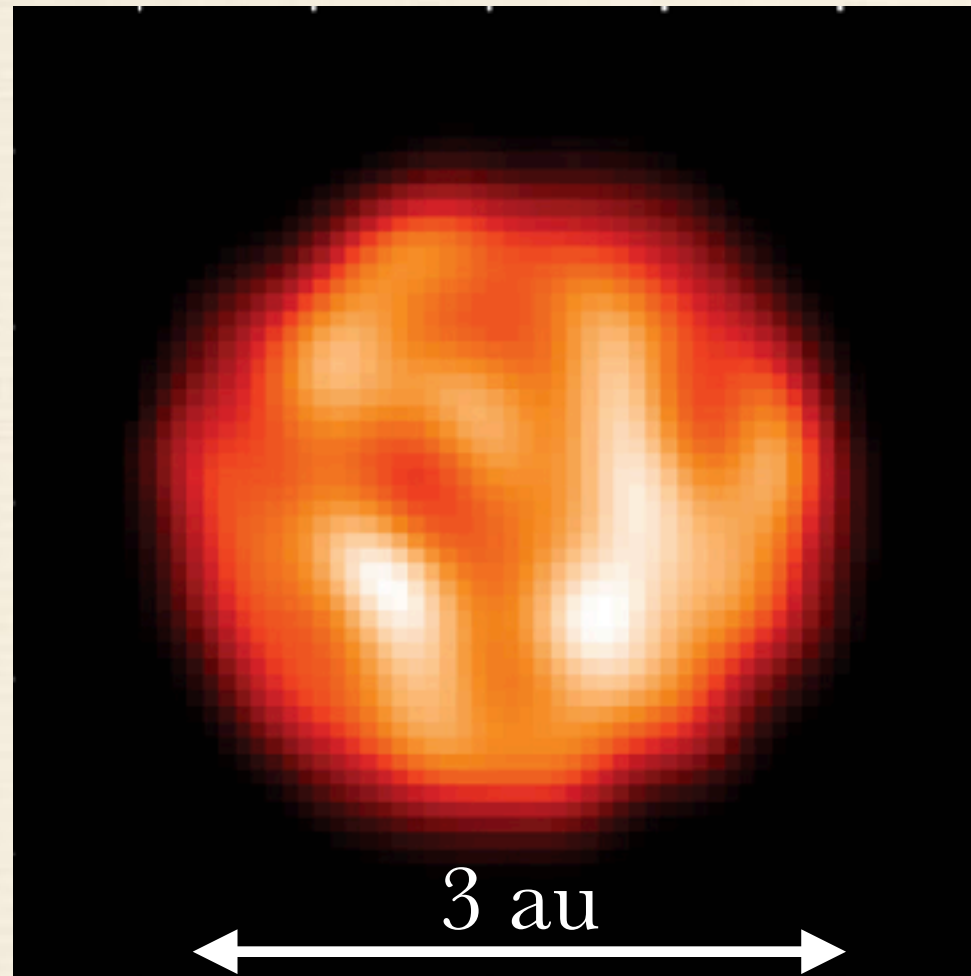


Image
Size

Smallest recoverable
angular scale
(u,v)-plane

Typical size of the
convection cell

Stellar surfaces



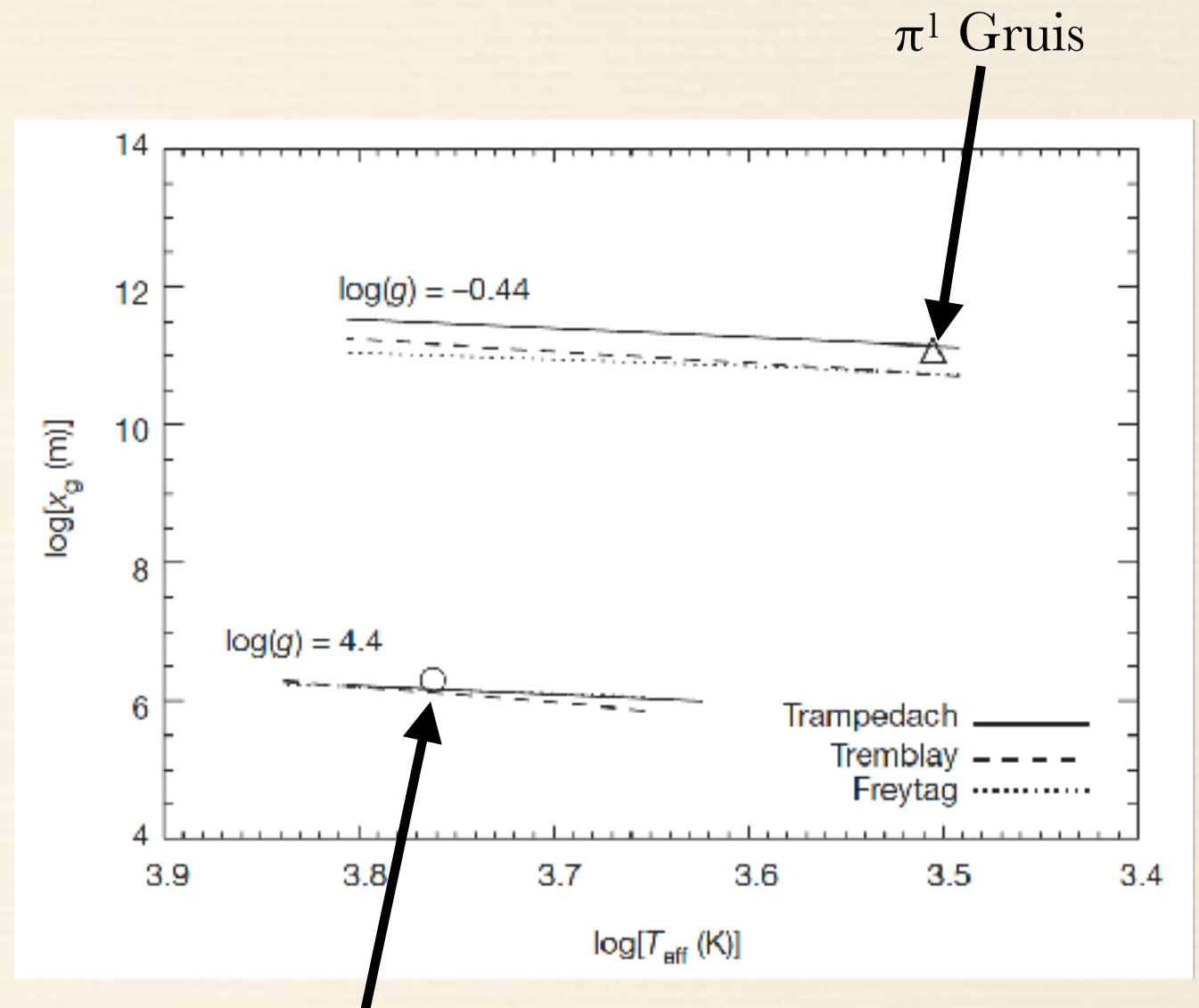
Title: π^1 Gruis

Artists: **Paladini et al. (Nature)**

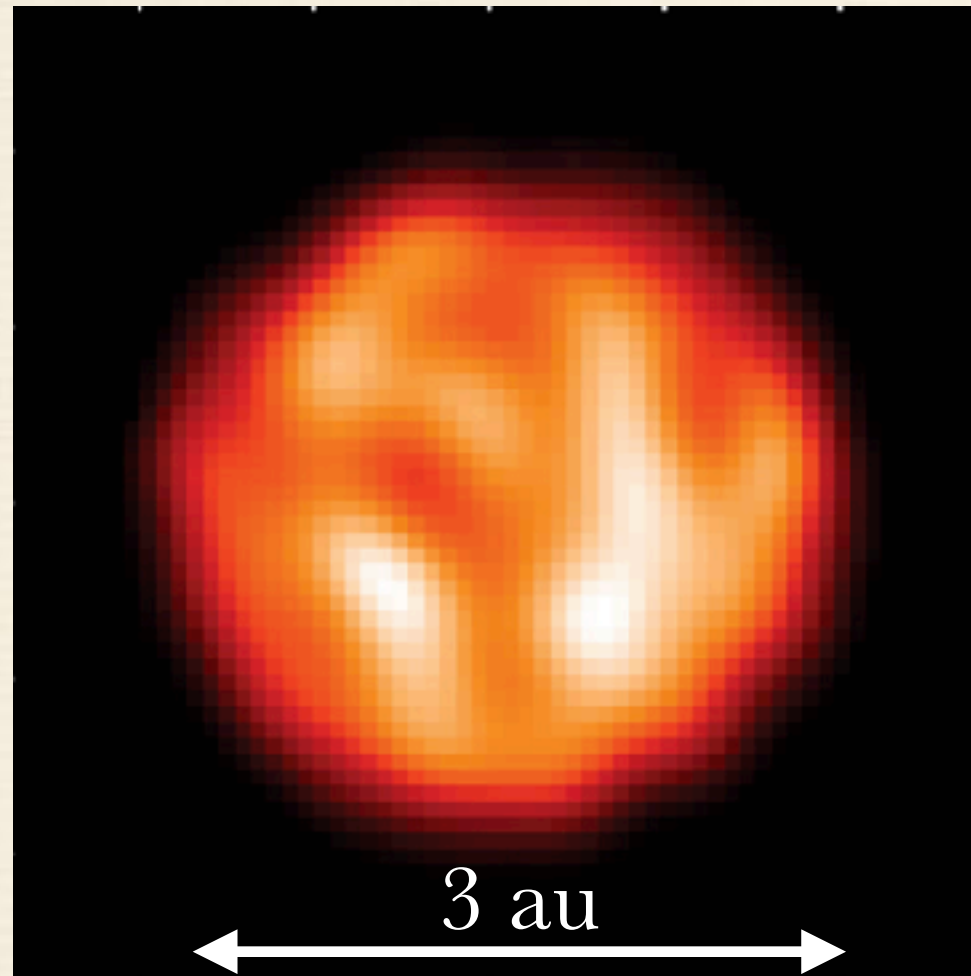
Year: **2017**

Technique: **Squeeze & MiRA**

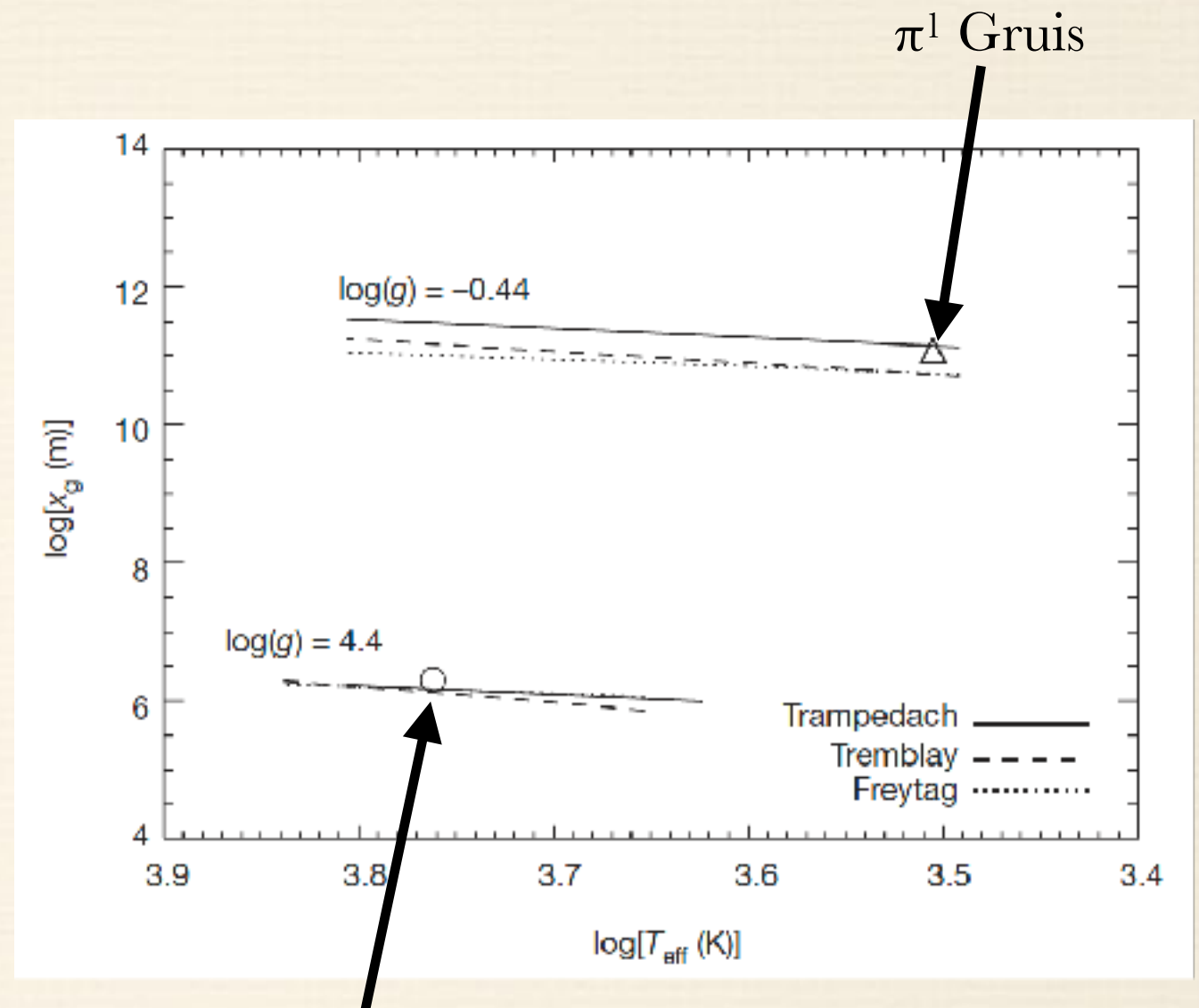
Instrument: **VLTI/PIONIER**



Stellar surfaces



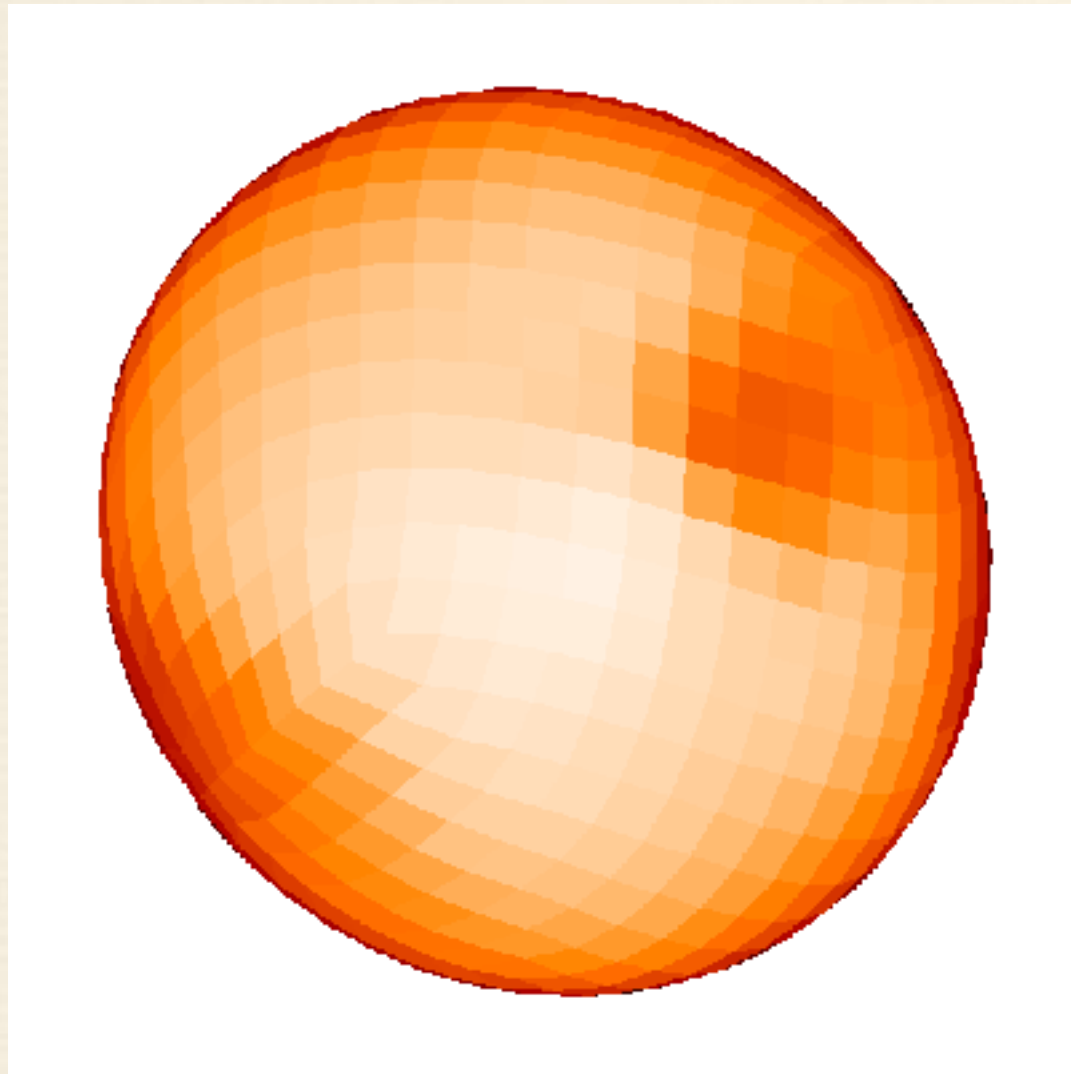
Title: π^1 Gruis
Artists: **Paladini et al. (Nature)**
Year: **2017**
Technique: **Squeeze & MiRA**
Instrument: **VLT/PIONIER**



Sun

Directly using images to determine
scientific information

Stellar surfaces



Title: **Zeta Andromeda**

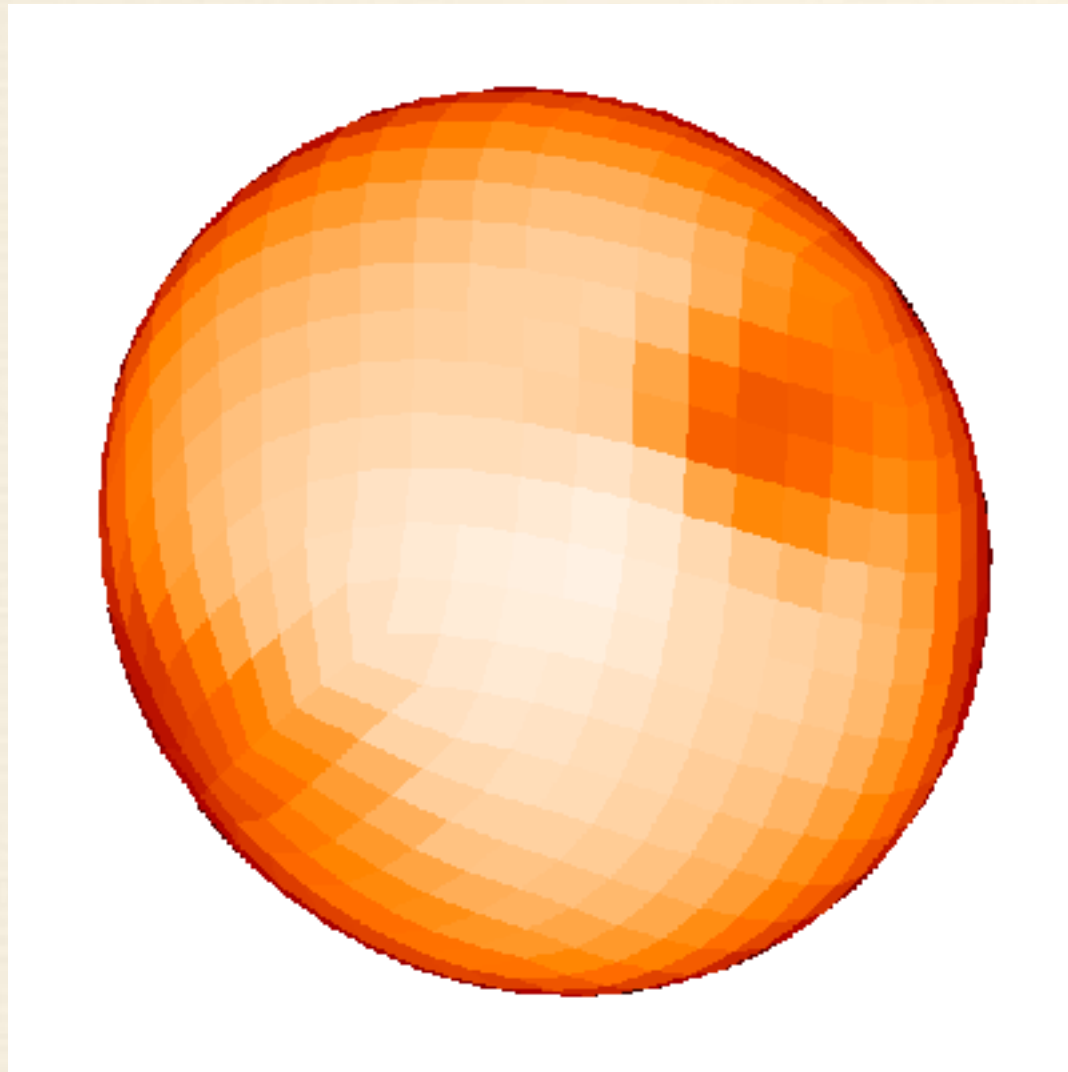
Artists: **Roettenbacher et al. (Nature)**

Year: **2016**

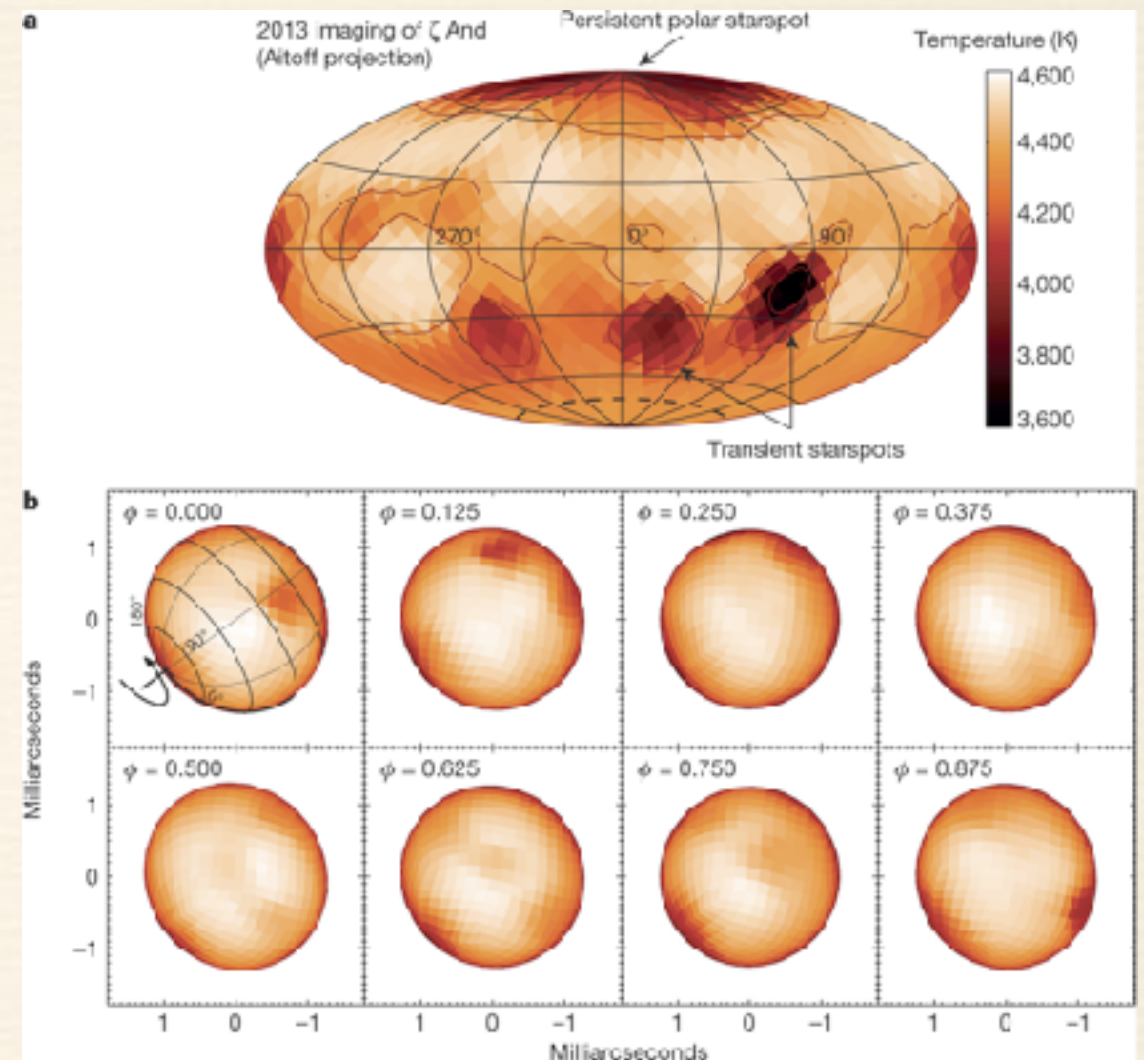
Technique: **Surfing**

Instrument: **CHARA/MIRC**

Stellar surfaces



Title: **Zeta Andromeda**
Artists: **Roettenbacher et al. (Nature)**
Year: **2016**
Technique: **Surfing**
Instrument: **CHARA/MIRC**



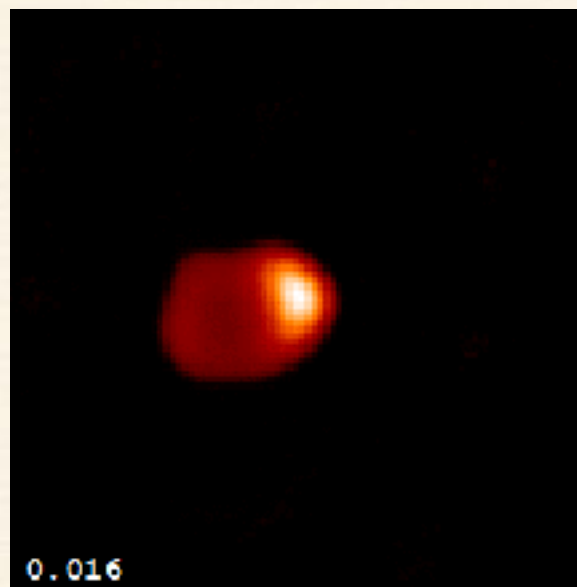
No solar type dynamo producing spots in a magnetically active star
N-S asymmetry

Binaries

Binaries



Title: **Beta Lyrae**
Artists: **Zhao et al.**
Year: **2008**
Technique: **Macim (old Squeeze)**
Instrument: **CHARA/MIRC**



Title: **Algol**
Artists: **Baron et al.**
Year: **2012**
Technique: **Squeeze**
Instrument: **CHARA/MIRC**

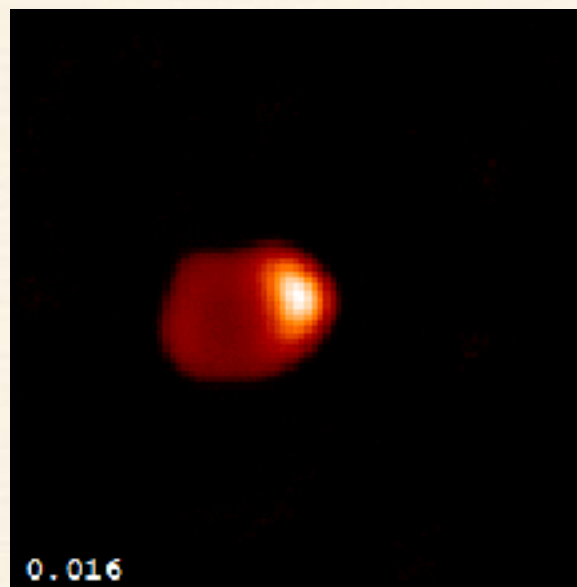


Title: **SS Leporis**
Artists: **Blind et al.**
Year: **2008**
Technique: **MiRA**
Instrument: **VLT/PIONIER**

Binaries



Title: **Beta Lyrae**
Artists: **Zhao et al.**
Year: **2008**
Technique: **Macim (old Squeeze)**
Instrument: **CHARA/MIRC**



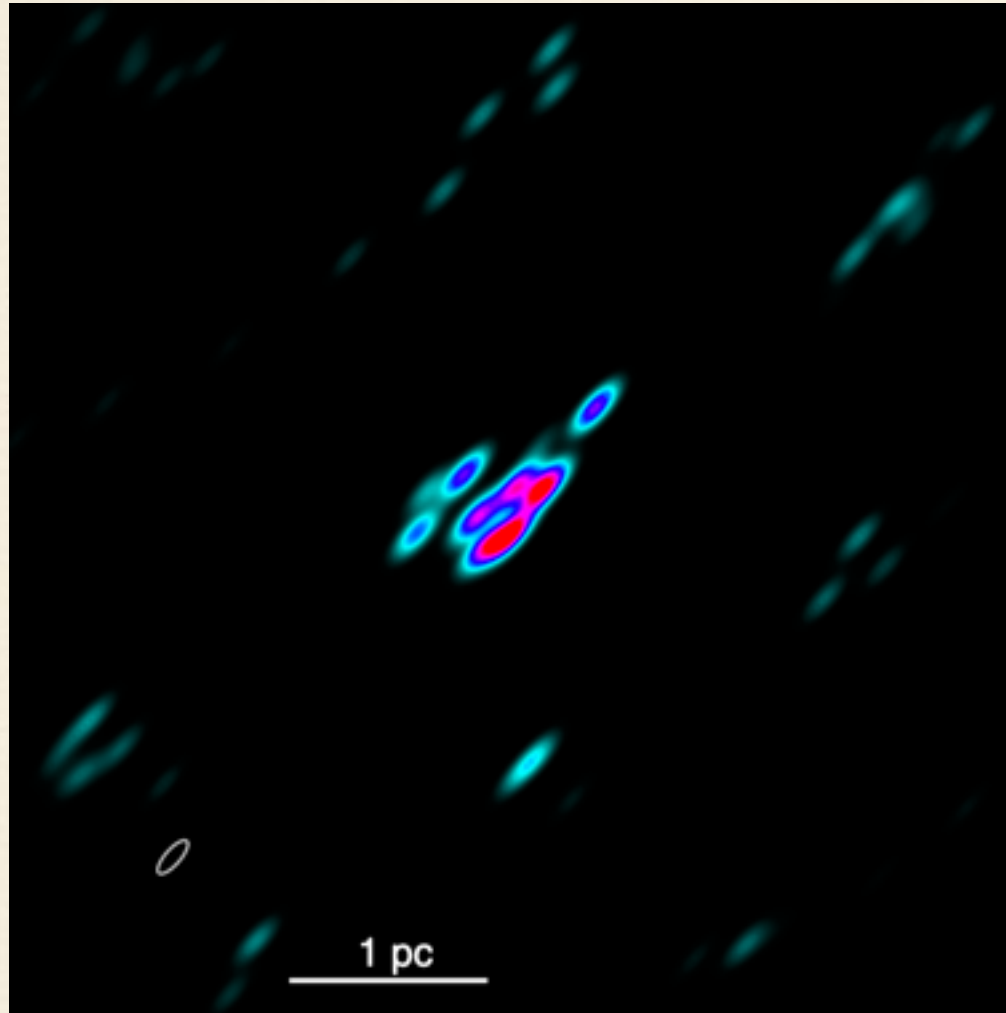
Title: **Algol**
Artists: **Baron et al.**
Year: **2012**
Technique: **Squeeze**
Instrument: **CHARA/MIRC**



Title: **SS Leporis**
Artists: **Blind et al.**
Year: **2008**
Technique: **MiRA**
Instrument: **VLT/PIONIER**

Extra-galactic science

Extra-galactic science



Title: **NGC 1068**

Artists: **GRAVITY coll., Pfuhl et al.**

Year: **2019**

Technique: **MiRA**

Instrument: **VLTI/GRAVITY**

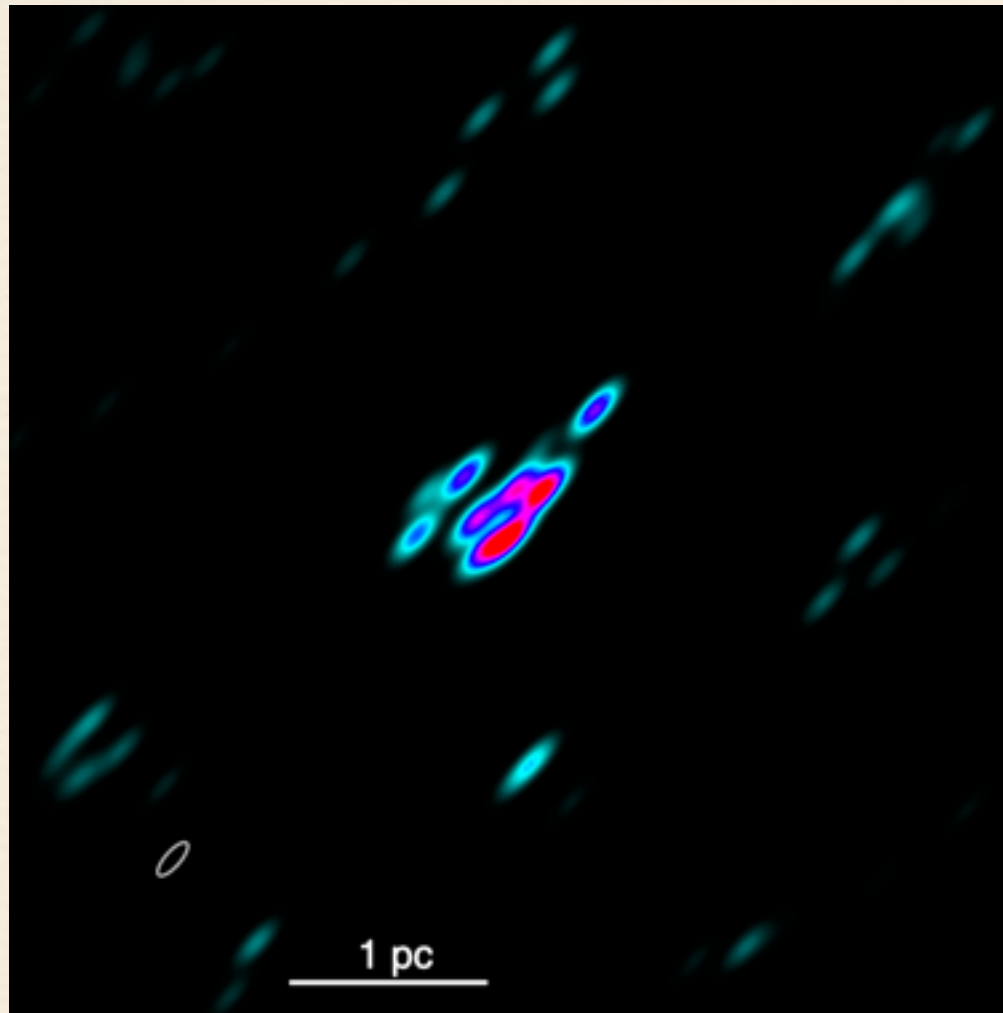
Extra-galactic science

Active Galactic Nuclei

Resolving the broad line emission region (BLR)

Dust sublimation region around the galactic centre

- a dusty torus



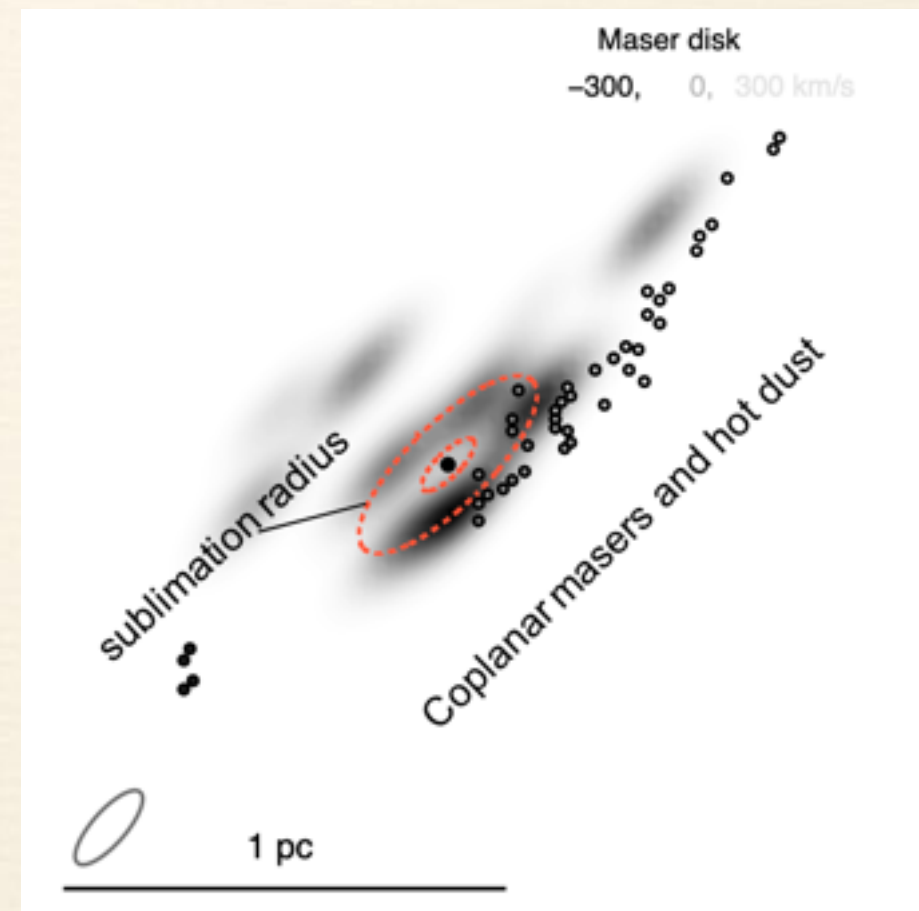
Title: **NGC 1068**

Artists: **GRAVITY coll., Pfuhl et al.**

Year: **2019**

Technique: **MiRA**

Instrument: **VLT/GRAVITY**



Circumstellar disks

Circumstellar disks

- ❖ Planet formation and stellar evolution
- ❖ What is the structure and temperature of the circumstellar disk?



A circumbinary disk (c) N. Stecki

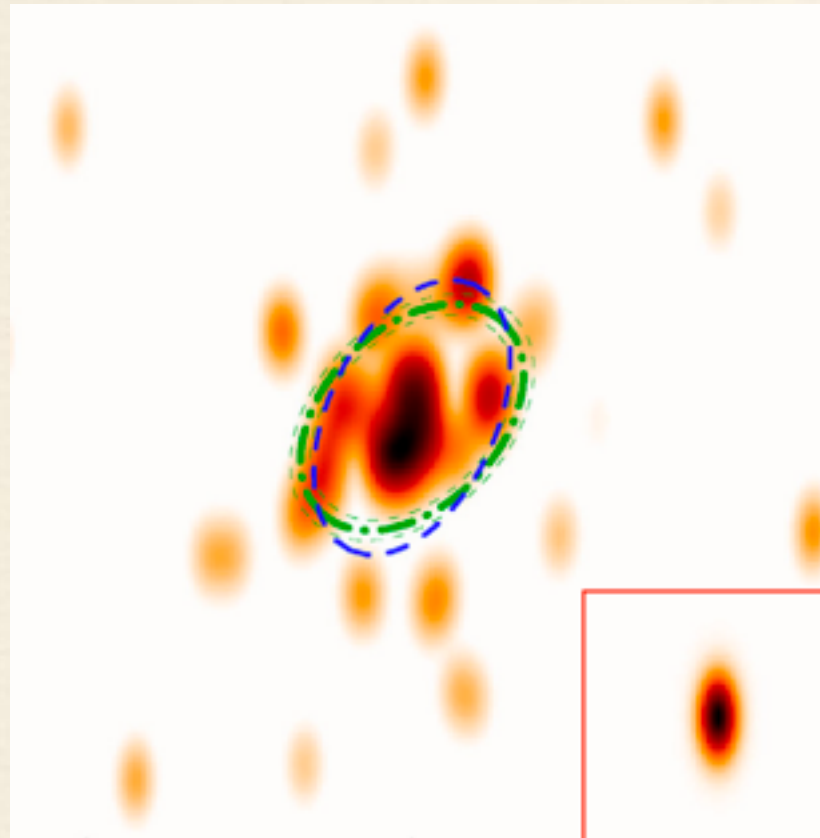
Circumstellar disks

- ❖ Difficulty:
- ❖ Bright and hot central star
- ❖ Smooth cold disk with a sharp inner edge



A circumbinary disk (c) N. Stecki

Circumstellar disks

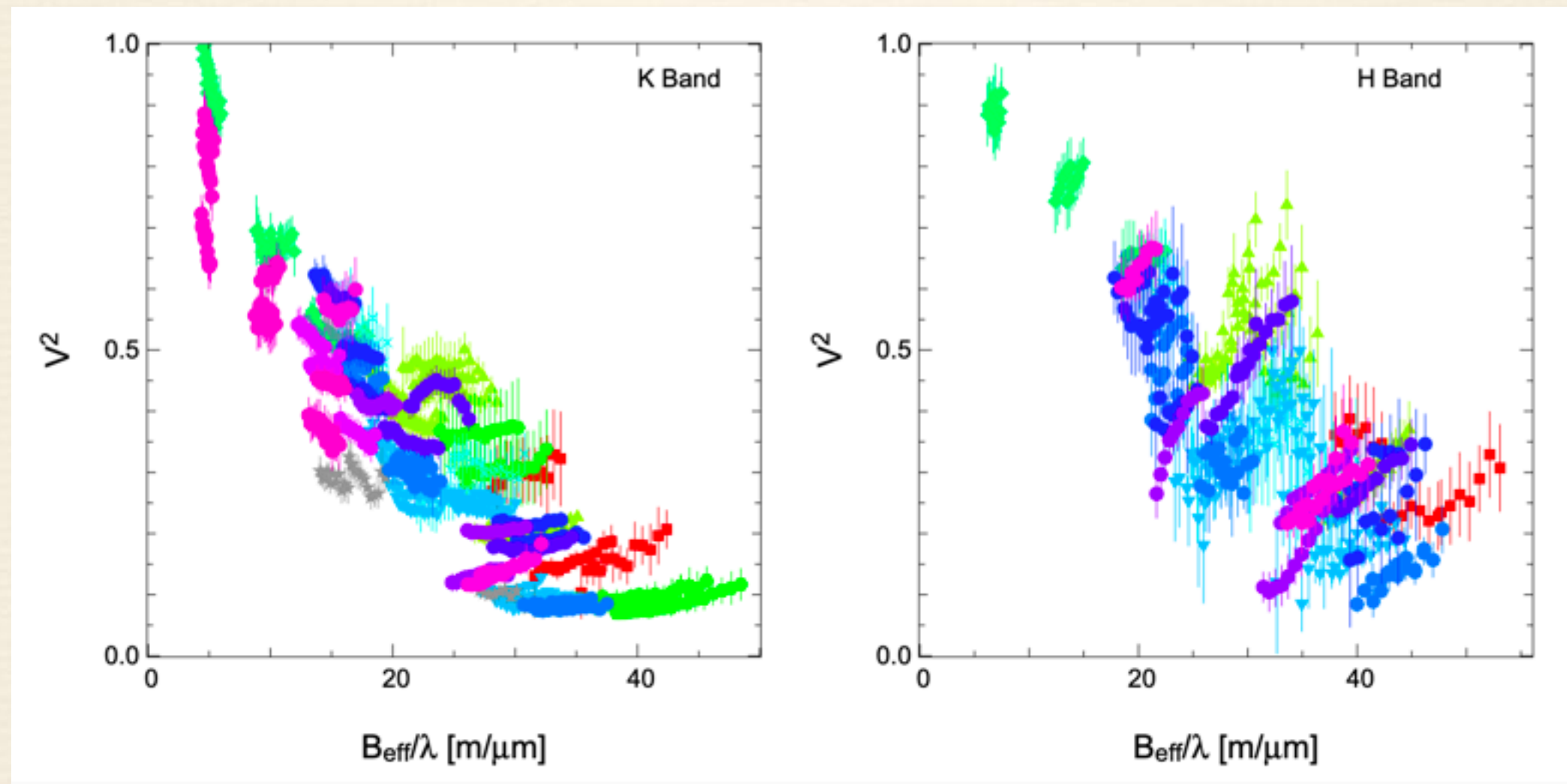


Title: **HD163296**
Artists: **Renard et al.**
Year: **2010**
Technique: **MiRA**
Instrument: **VLTI/AMBER**

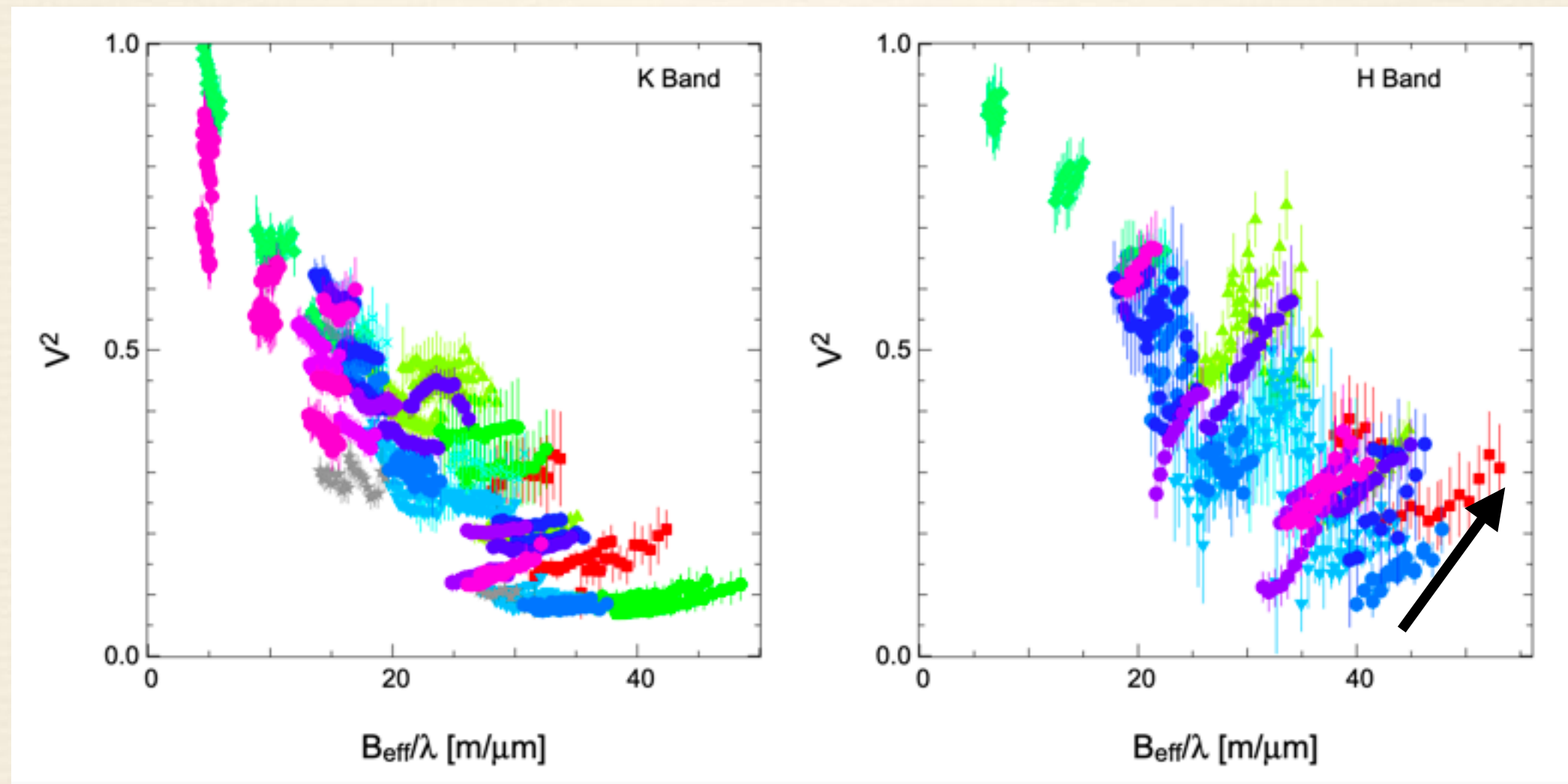


Title: **HD 144668**
Artists: **Benisty et al.**
Year: **2011**
Technique: **MiRA**
Instrument: **VLTI/AMBER**

Circumstellar disks

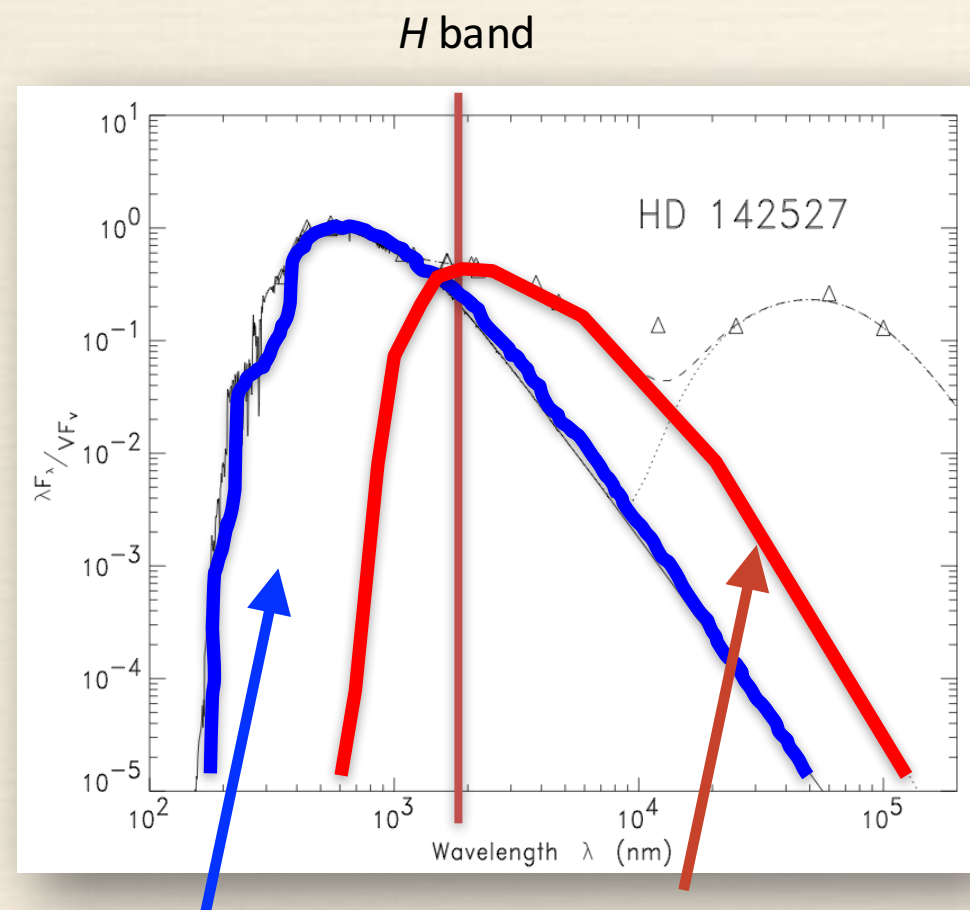


Circumstellar disks

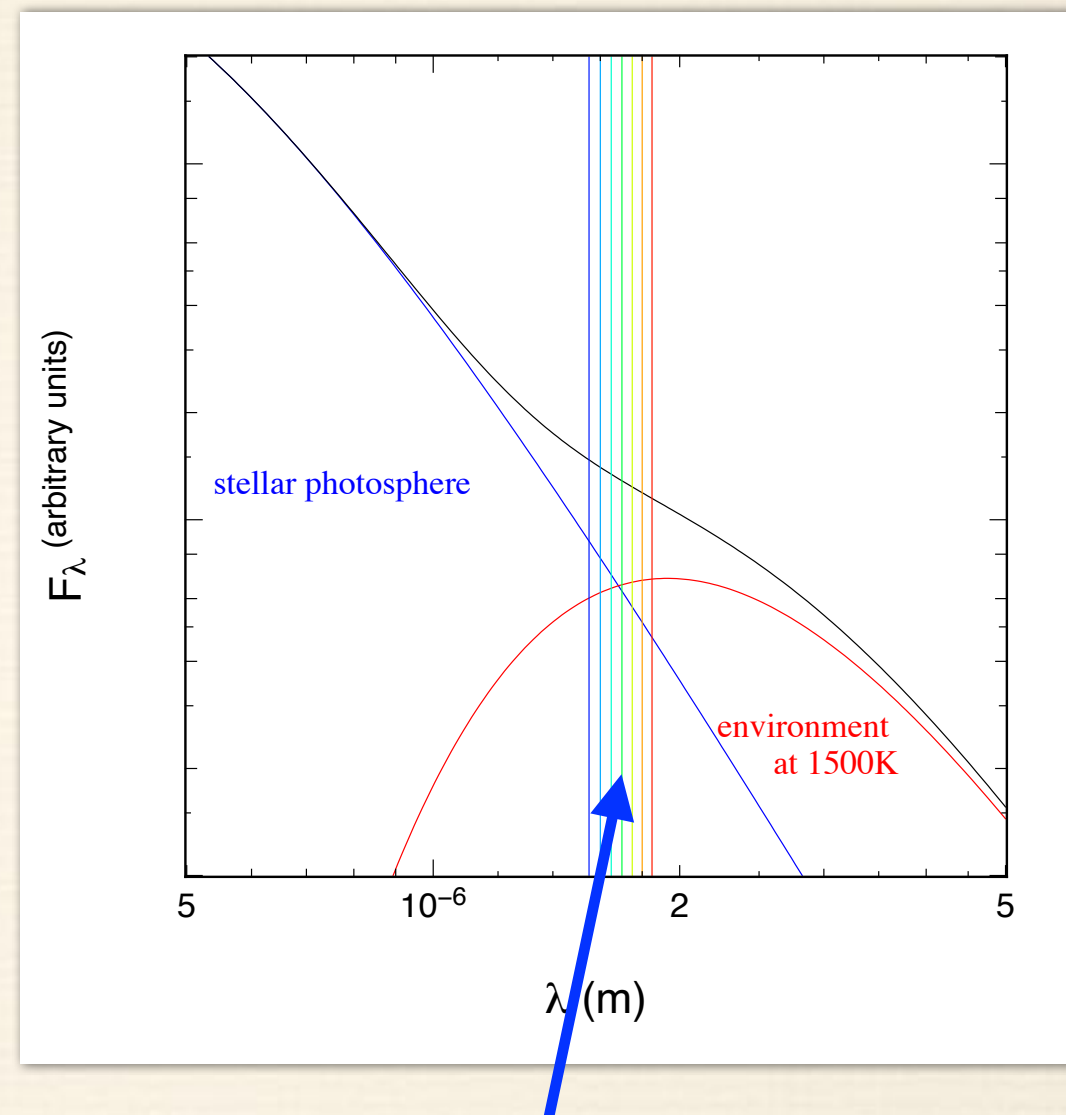
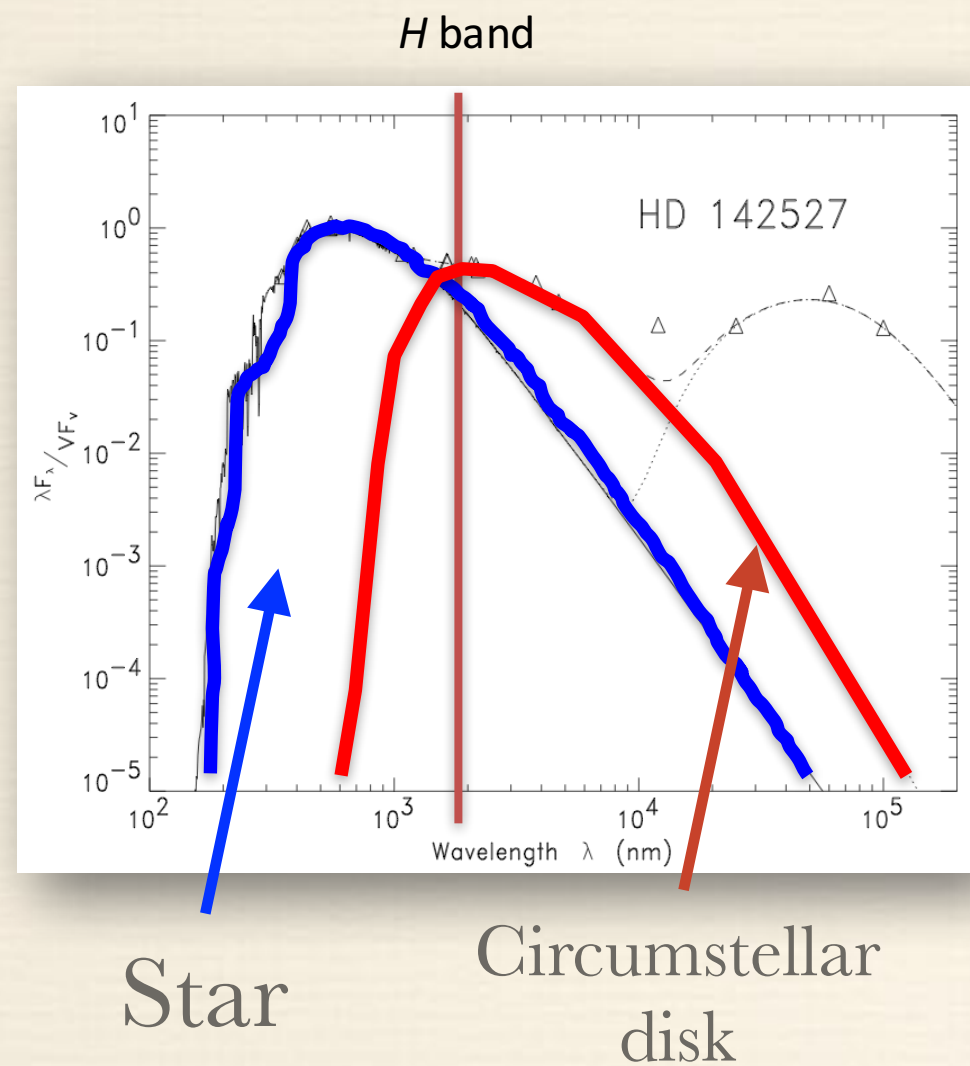


Chromatic effect

Circumstellar disks

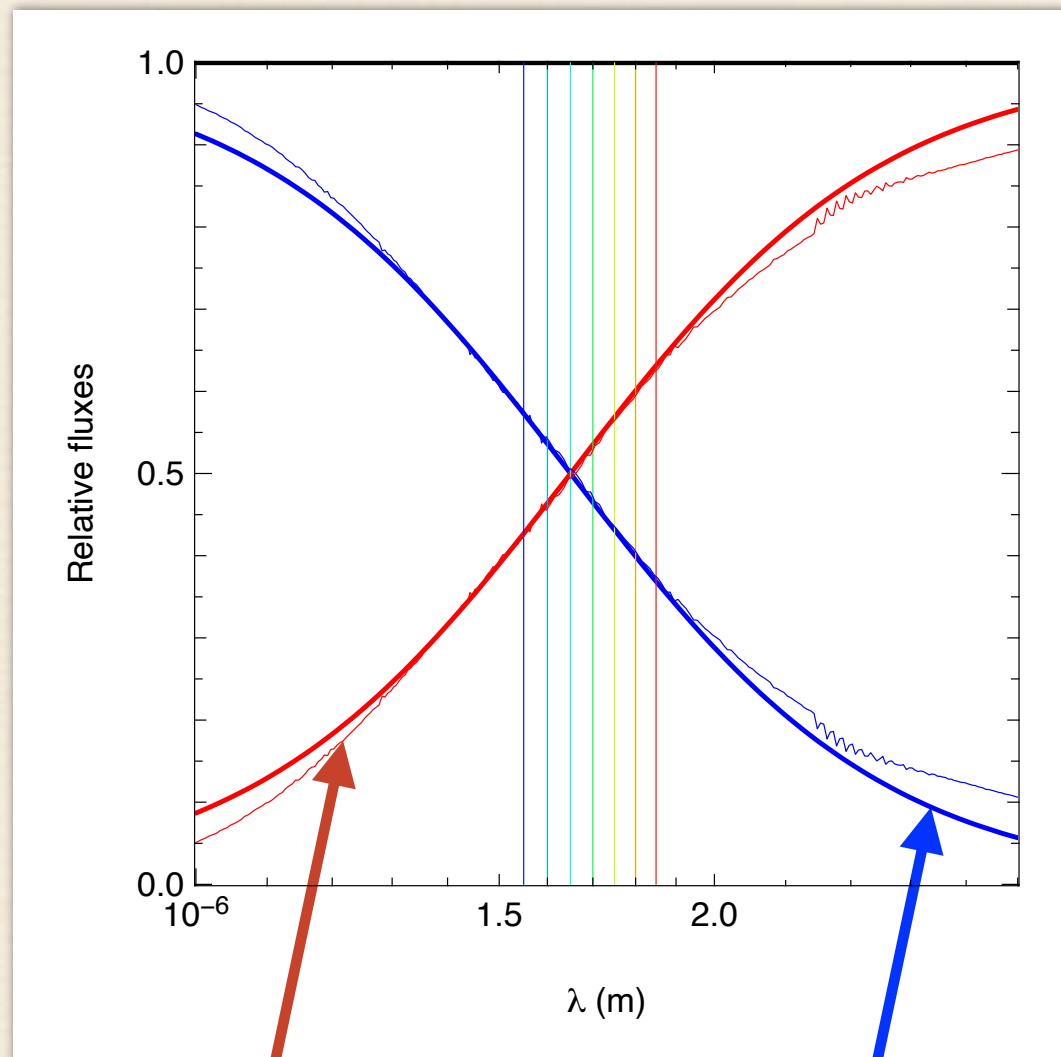


Circumstellar disks



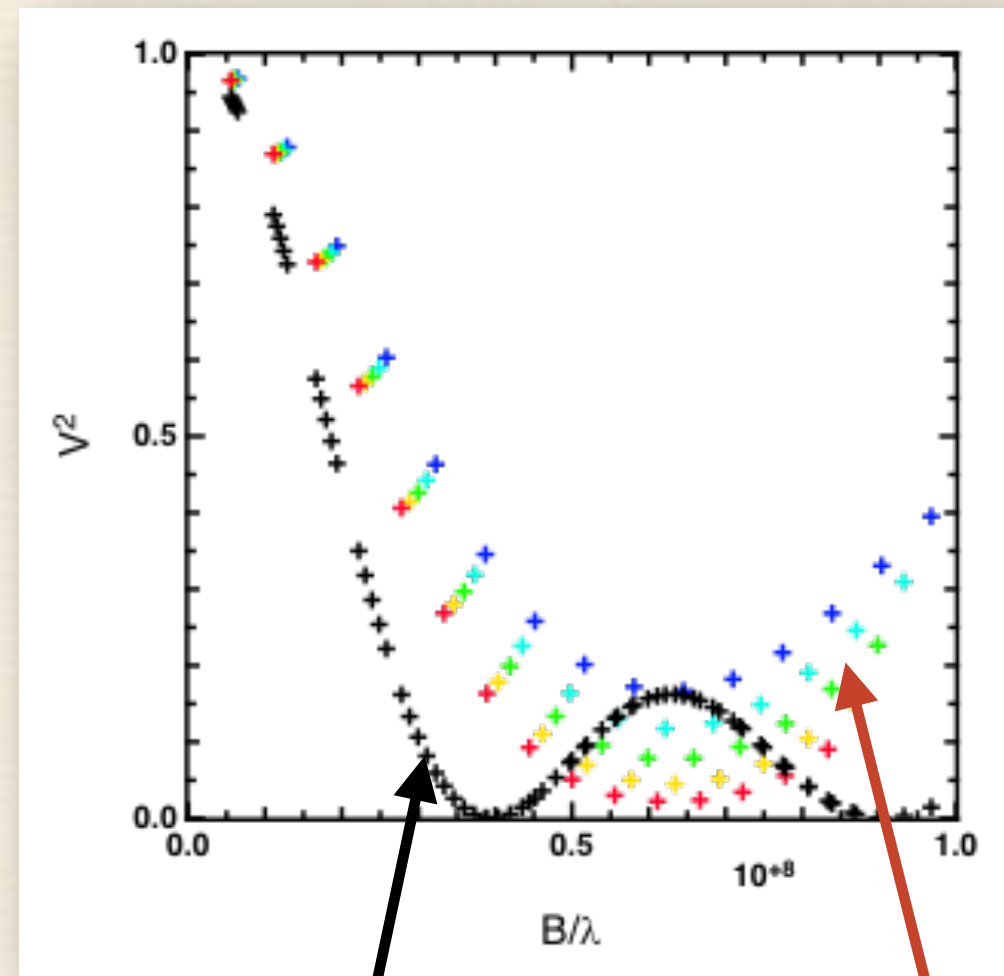
Spectral channels of
the interferometer

Circumstellar disks



Circumstellar
disk

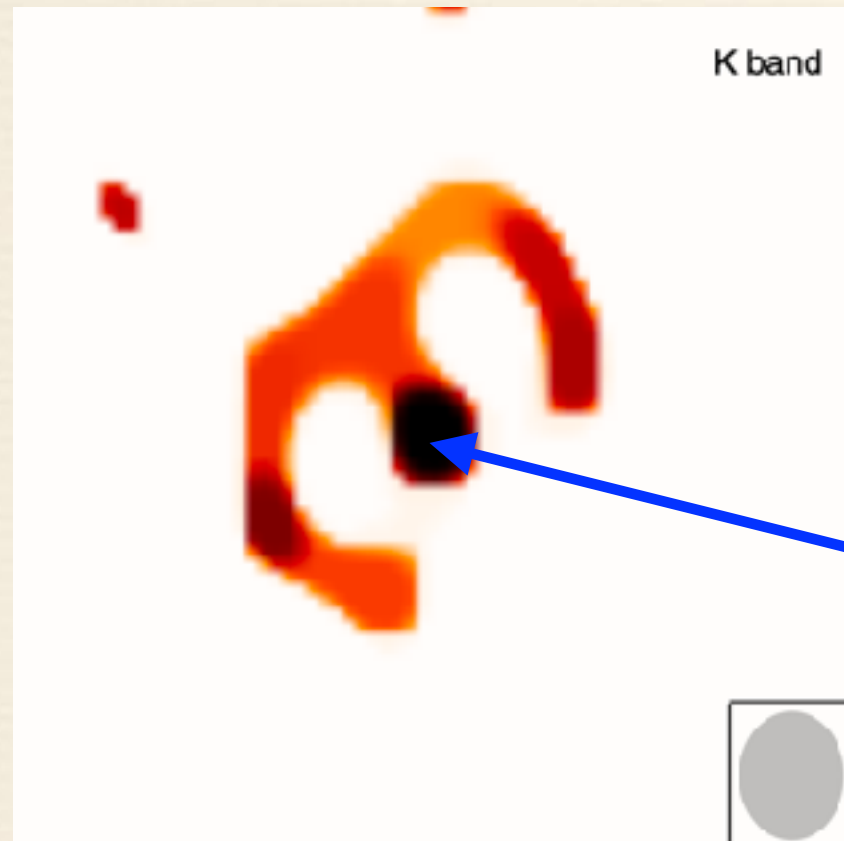
Star



Disk alone

Disk + star

Circumstellar disks



Star has high surface brightness

Title: **HD 144668**

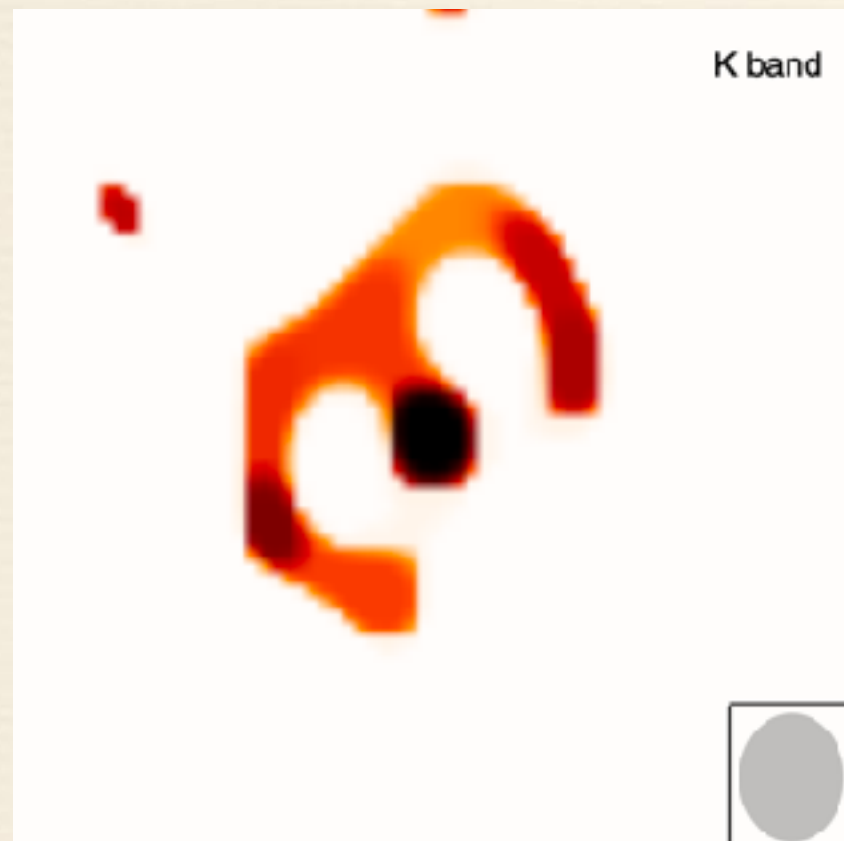
Artists: **Benisty et al.**

Year: **2011**

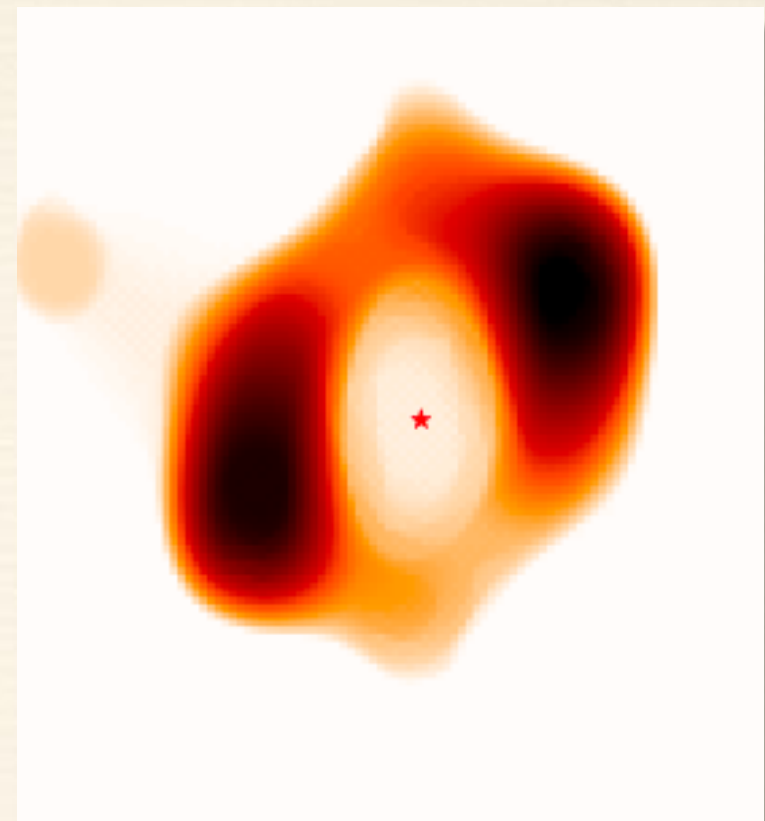
Technique: **MiRA**

Instrument: **VLTI/AMBER**

Circumstellar disks



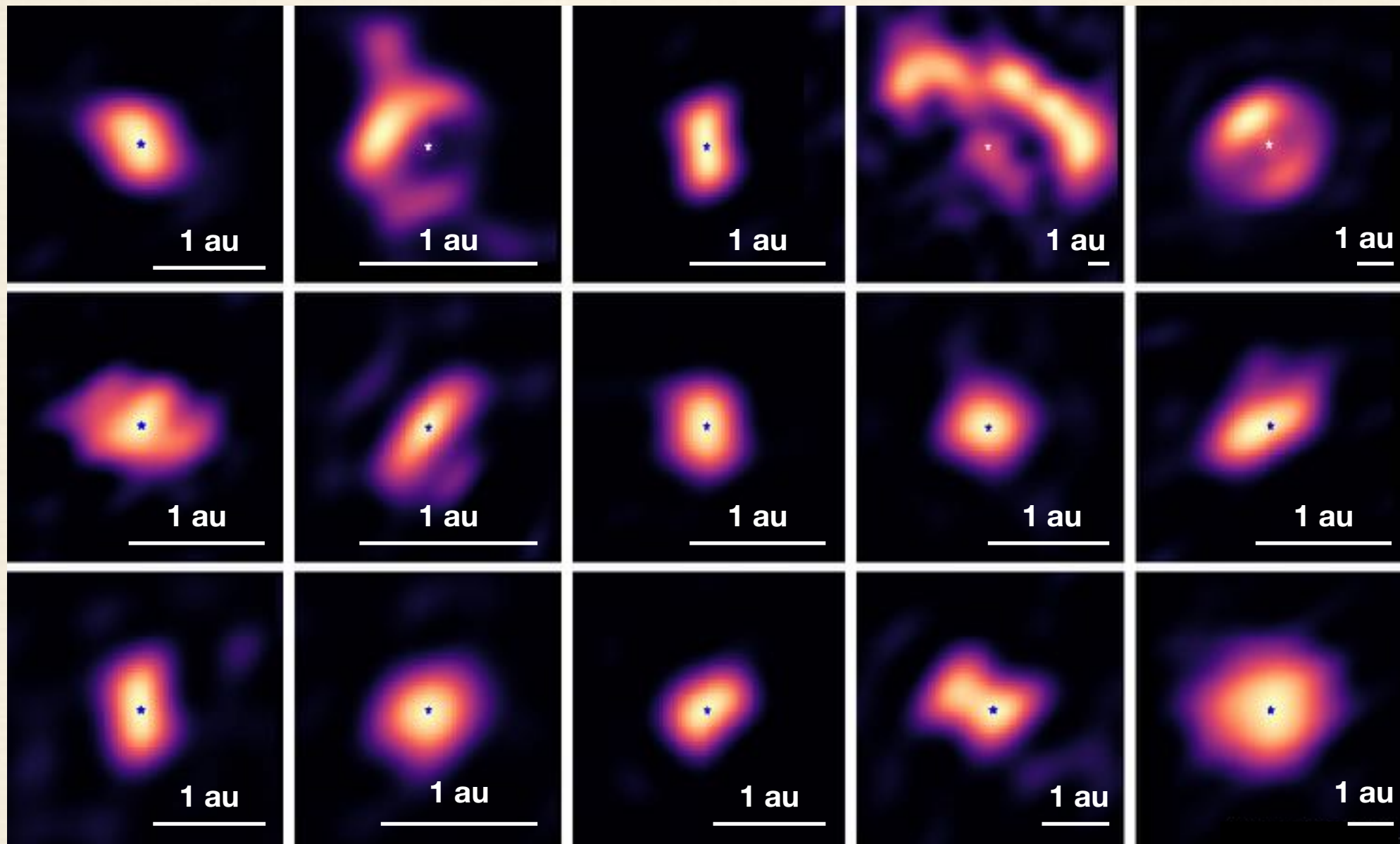
Title: **HD 144668**
Artists: **Benisty et al.**
Year: **2011**
Technique: **MiRA**
Instrument: **VLTI/AMBER**



Title: **HD 144668**
Artists: **Kluska et al.**
Year: **2014**
Technique: **MiRA/SPARCO**
Instrument: **VLTI/AMBER**

SPARCO reconstruction
Star modelled as a point source and
withdrawn from the image

Circumstellar disks



Title: **Family portrait of disks around Herbig Ae/Be stars**

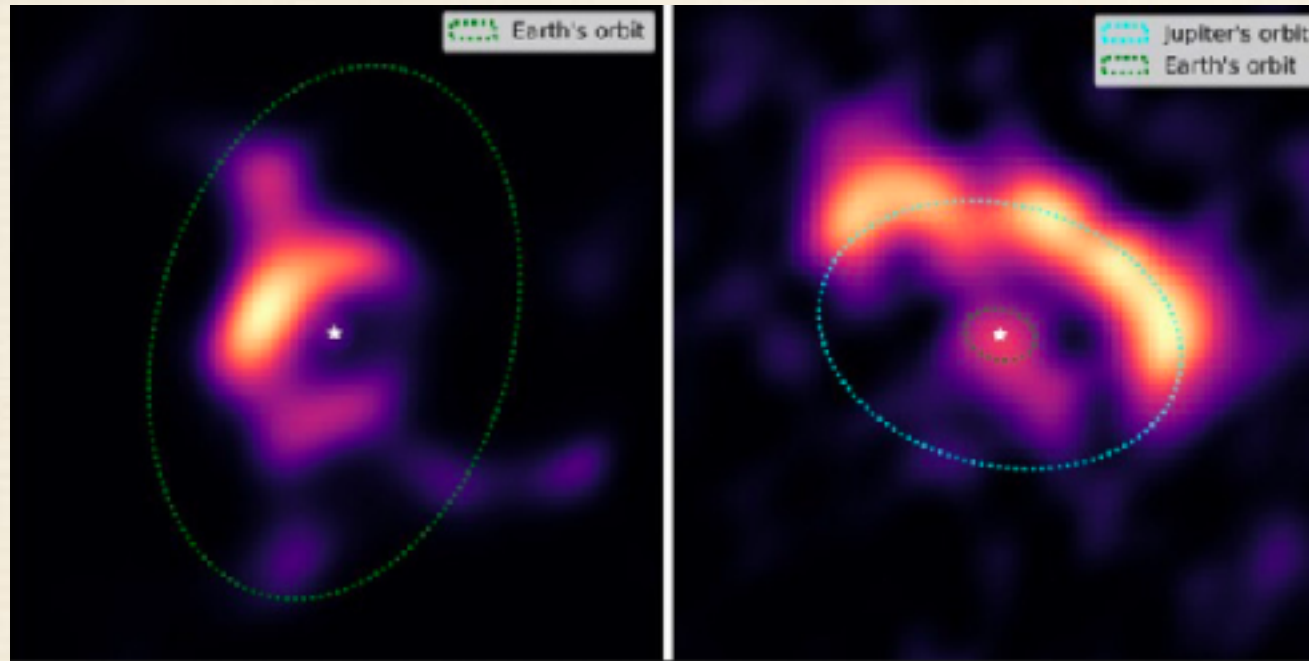
Artists: **Kluska et al.**

Year: **2020**

Technique: **MiRA/SPARCO**

Instrument: **VLT/PIONIER**

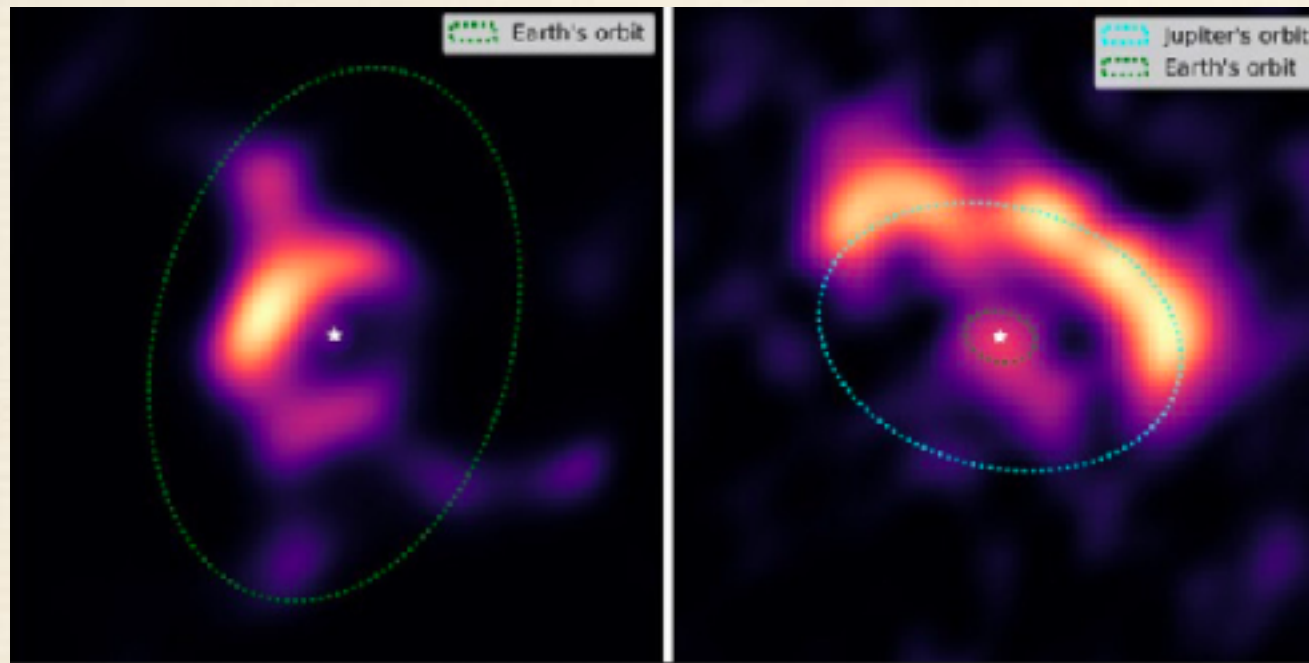
Circumstellar disks



Title: **R CrA & HD45677**
Artists: **Kluska et al.**
Year: **2020**
Technique: **MiRA/SPARCO**
Instrument: **VLTI/PIONIER**

- ❖ Location of the emission
- ❖ Dust sublimation location, geometry, temperature
- ❖ Information on mineralogy
- ❖ Azimuthal structure

Circumstellar disks



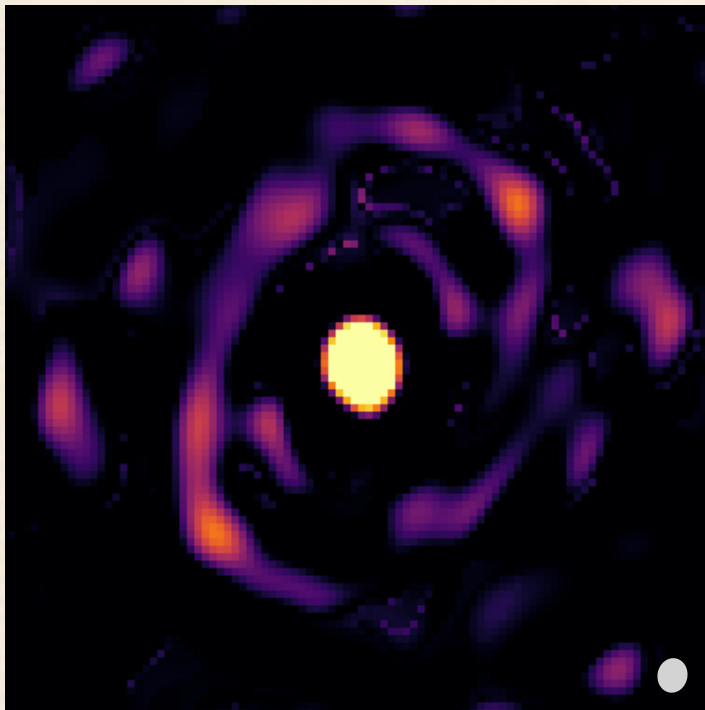
Title: **R CrA & HD45677**
Artists: **Kluska et al.**
Year: **2020**
Technique: **MiRA/SPARCO**
Instrument: **VLTI/PIONIER**

- ❖ Location of the emission
- ❖ Dust sublimation location, geometry, temperature
- ❖ Information on mineralogy
- ❖ Azimuthal structure

In parallel to model fitting

Circumstellar disks

Disks around post-AGB binaries



Title: **IRAS08544-4431**

Artists: **Hillen et al.**

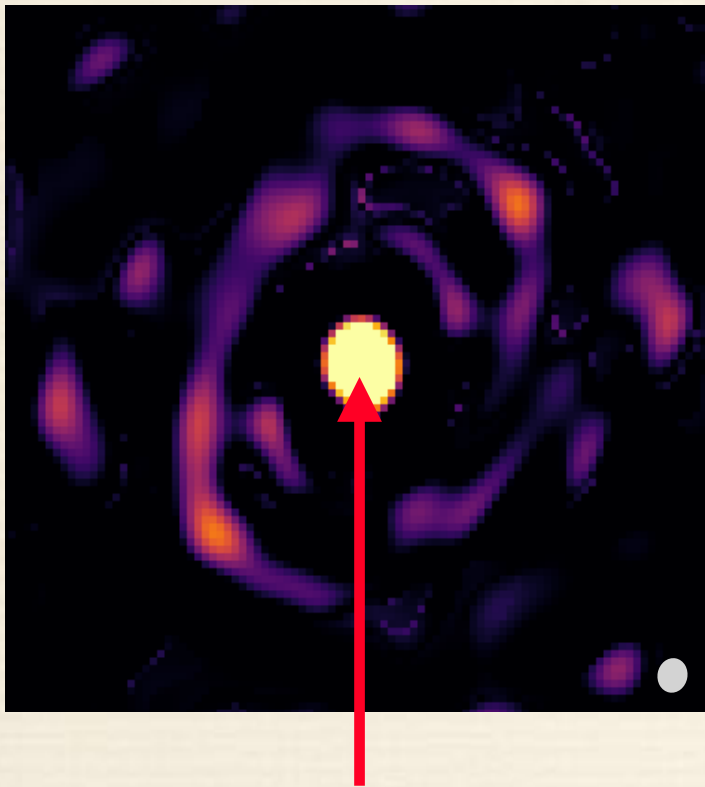
Year: **2016**

Technique: **MiRA/SPARCO**

Instrument: **VLT/PIONIER**

Circumstellar disks

Disks around post-AGB binaries

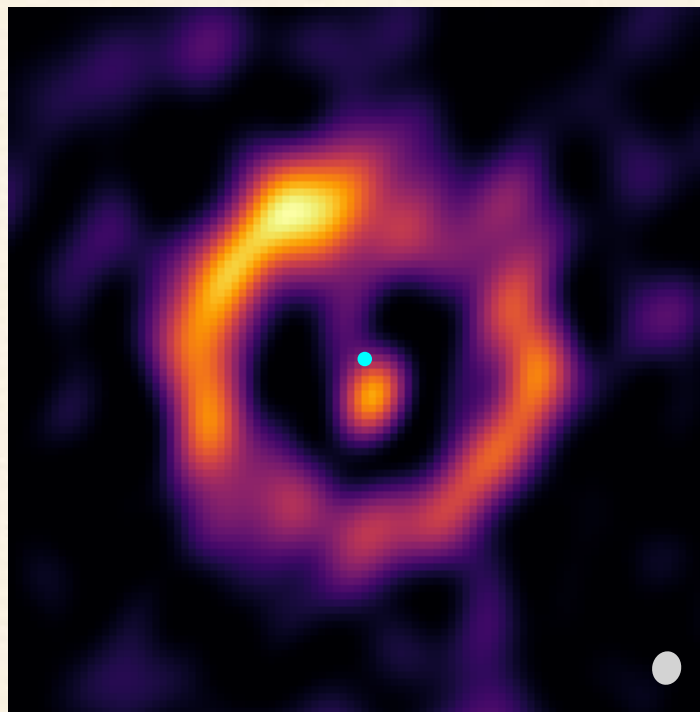
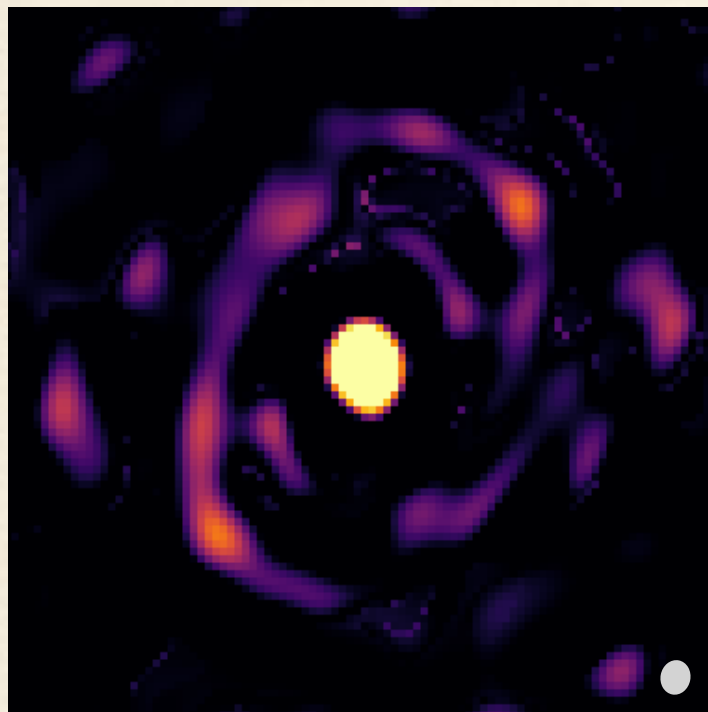


Primary star

Title: **IRAS08544-4431**
Artists: **Hillen et al.**
Year: **2016**
Technique: **MiRA/SPARCO**
Instrument: **VLT/PIONIER**

Circumstellar disks

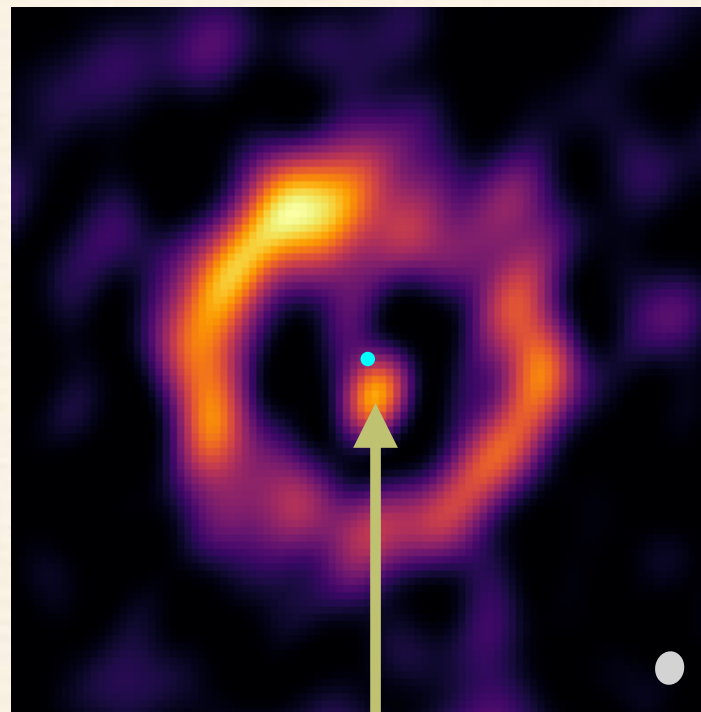
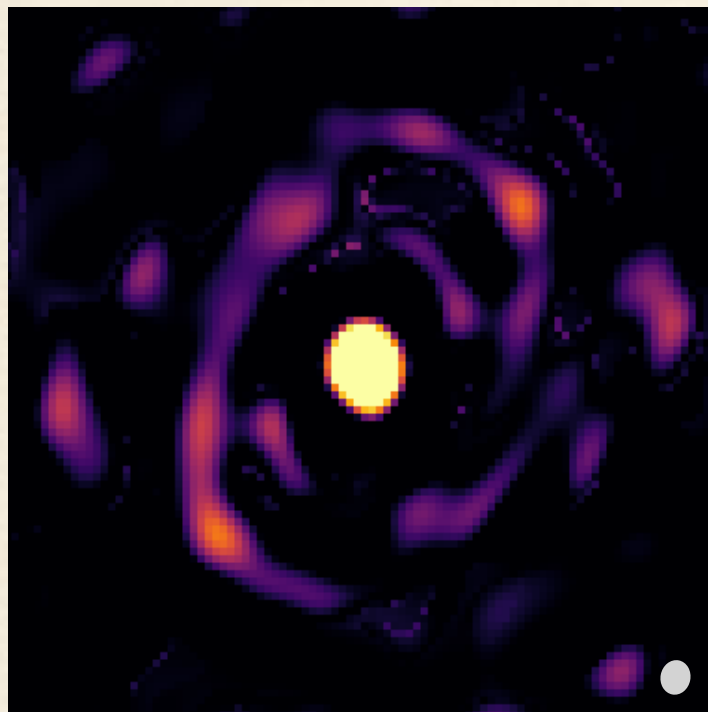
Disks around post-AGB binaries



Title: **IRAS08544-4431**
Artists: **Hillen et al.**
Year: **2016**
Technique: **MiRA/SPARCO**
Instrument: **VLT/PIONIER**

Circumstellar disks

Disks around post-AGB binaries



Secondary star

Title: **IRAS08544-4431**

Artists: **Hillen et al.**

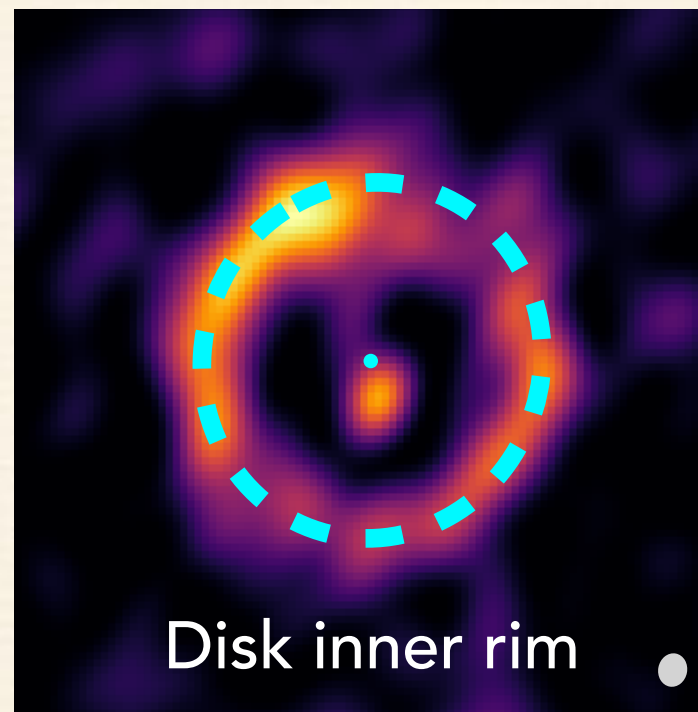
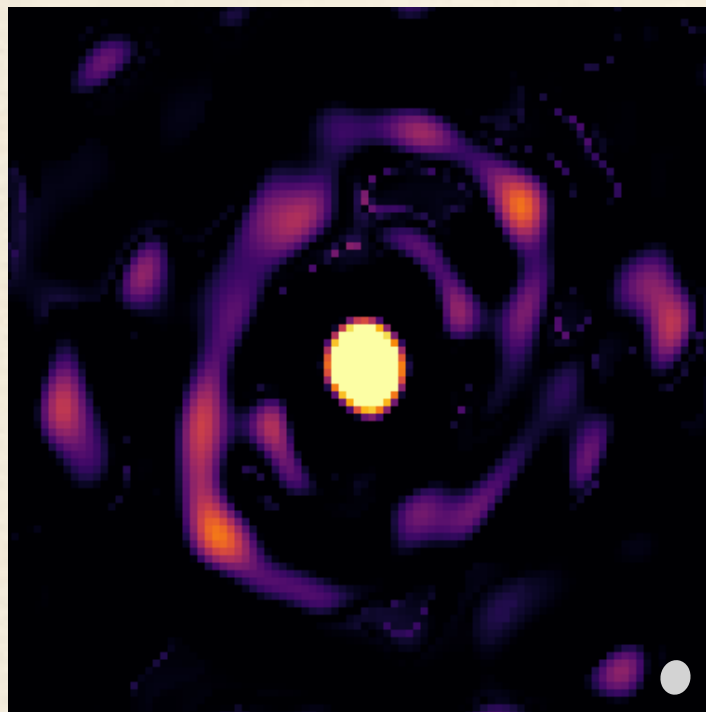
Year: **2016**

Technique: **MiRA/SPARCO**

Instrument: **VLT/PIONIER**

Circumstellar disks

Disks around post-AGB binaries



Disk inner rim

Title: **IRAS08544-4431**

Artists: **Hillen et al.**

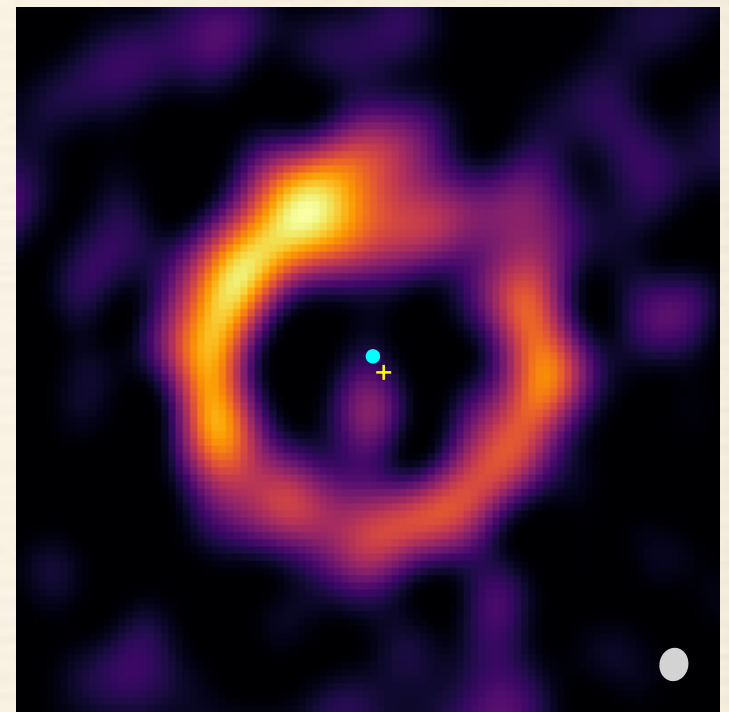
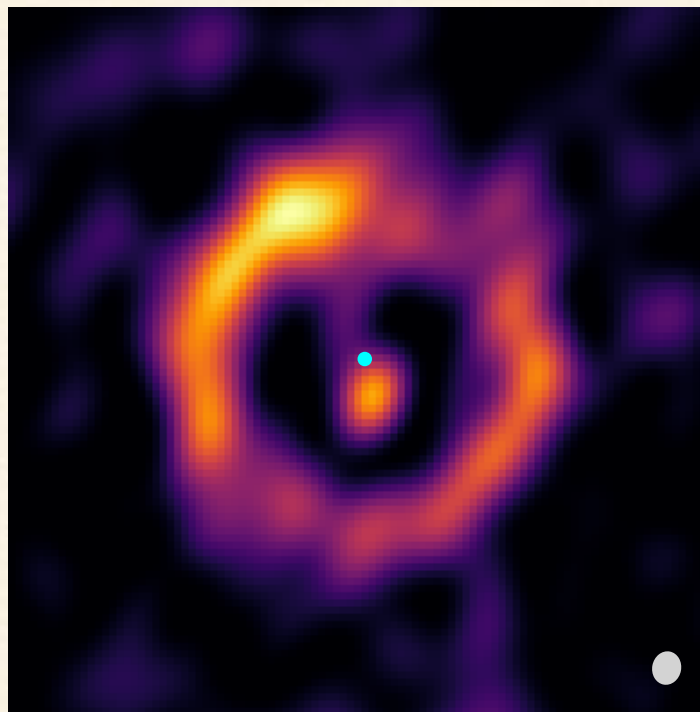
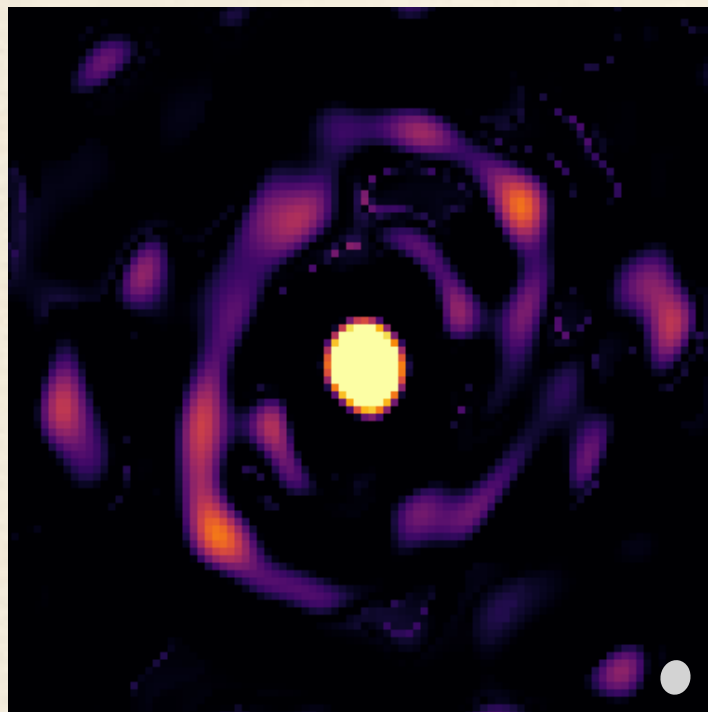
Year: **2016**

Technique: **MiRA/SPARCO**

Instrument: **VLT/PIONIER**

Circumstellar disks

Disks around post-AGB binaries

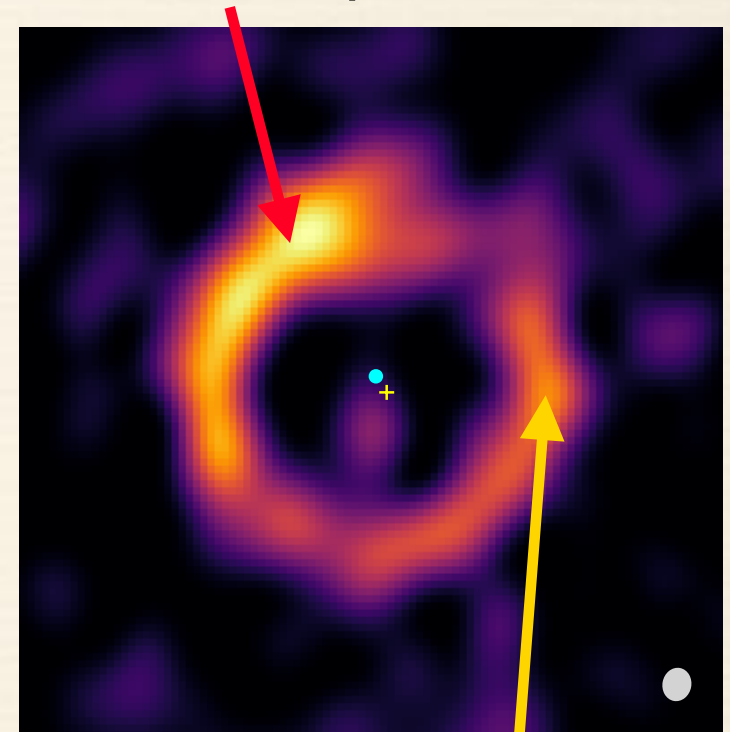
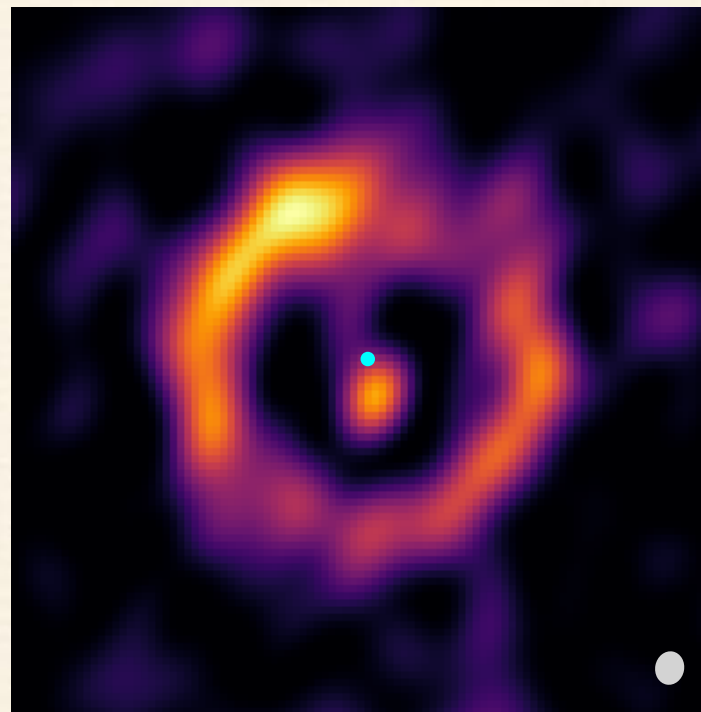
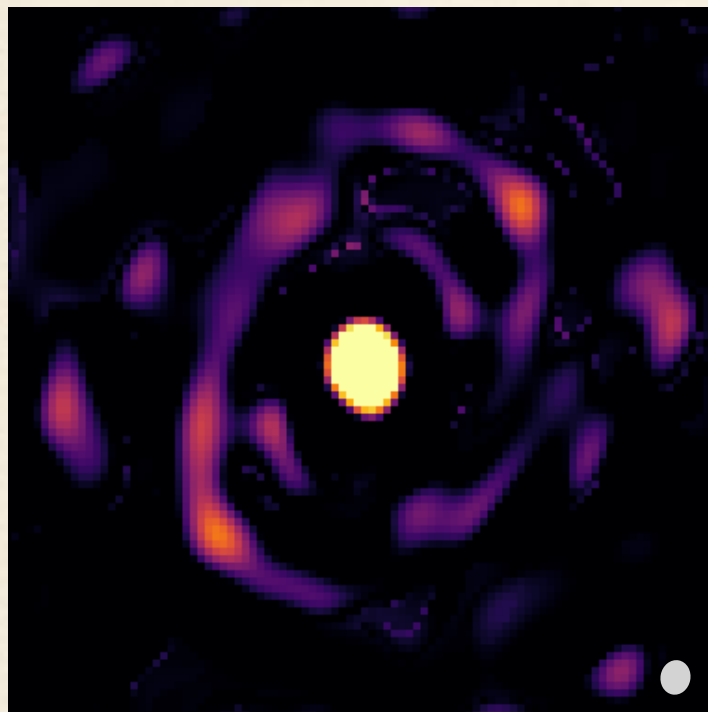


Title: **IRAS08544-4431**
Artists: **Hillen et al.**
Year: **2016**
Technique: **MiRA/SPARCO**
Instrument: **VLT/PIONIER**

Circumstellar disks

Disks around post-AGB binaries

Illumination from primary



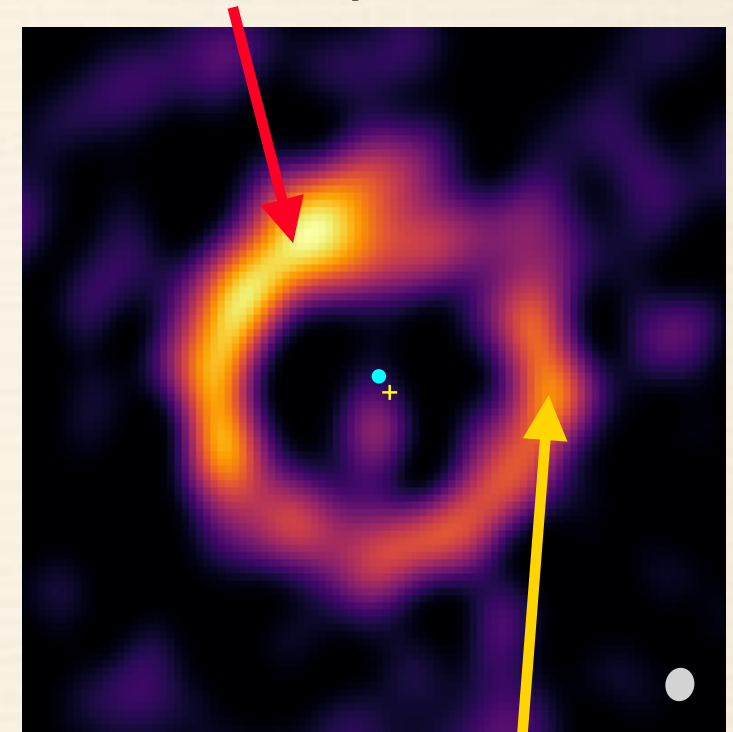
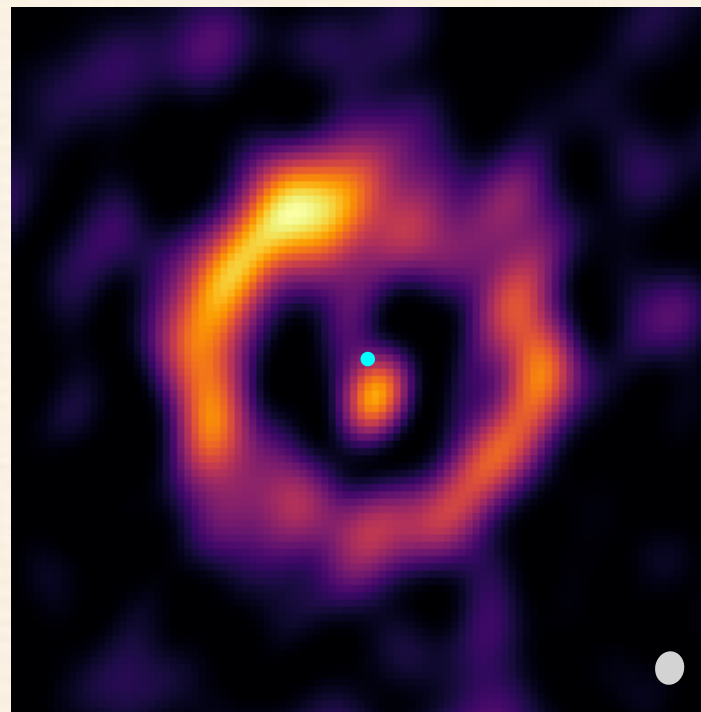
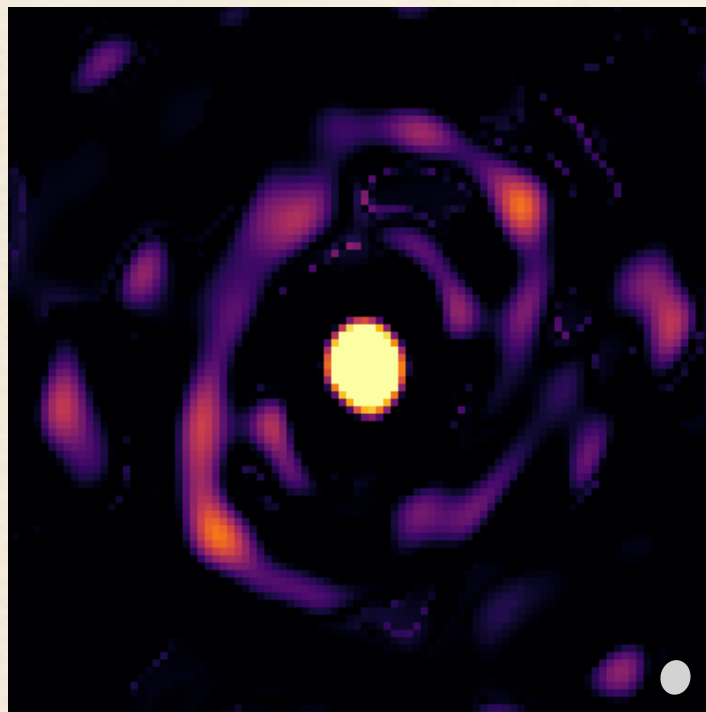
Spiral wave?

Title: **IRAS08544-4431**
Artists: **Hillen et al.**
Year: **2016**
Technique: **MiRA/SPARCO**
Instrument: **VLT/PIONIER**

Circumstellar disks

Disks around post-AGB binaries

Illumination from primary



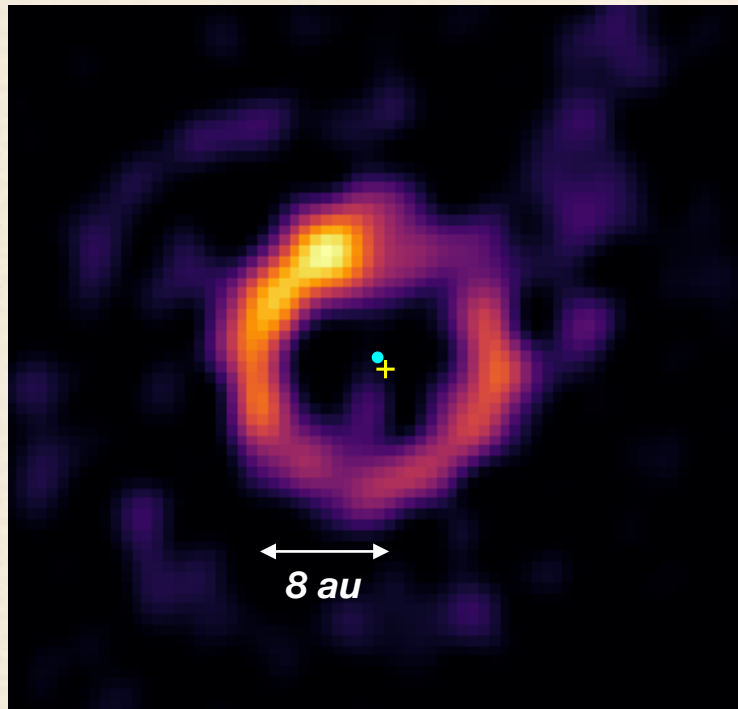
Spiral wave?

Title: **IRAS08544-4431**
Artists: **Hillen et al.**
Year: **2016**
Technique: **MiRA/SPARCO**
Instrument: **VLT/PIONIER**

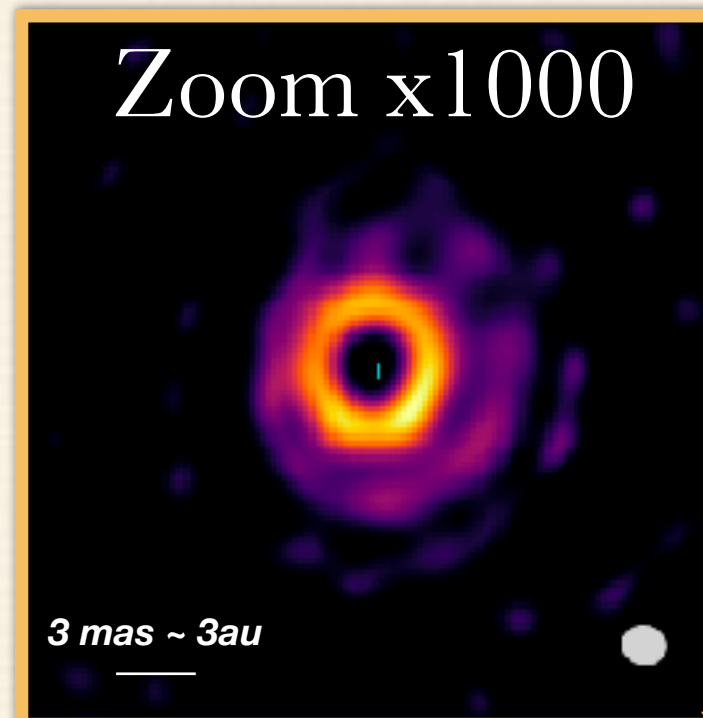
From the image to models

Circumstellar disks

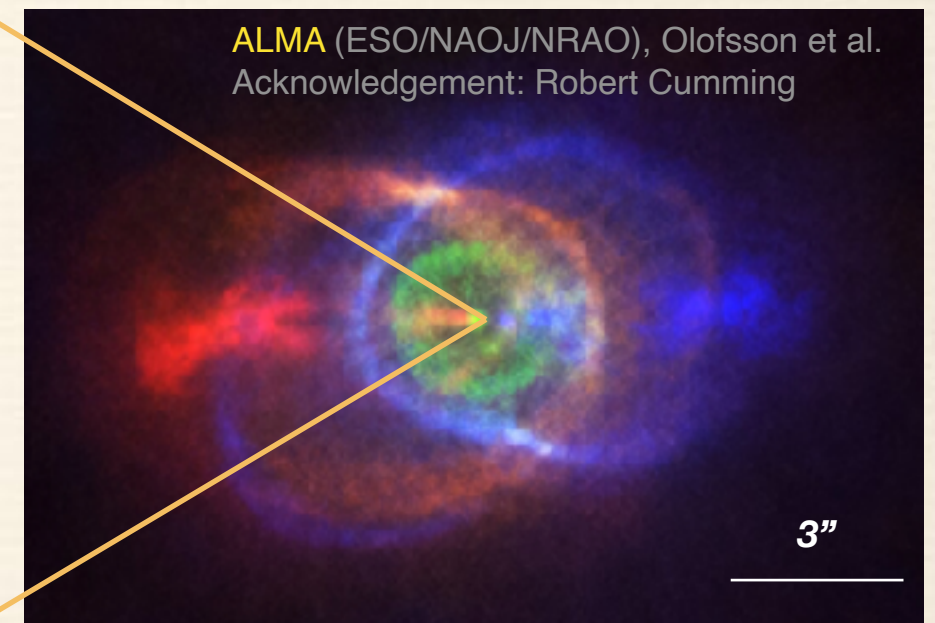
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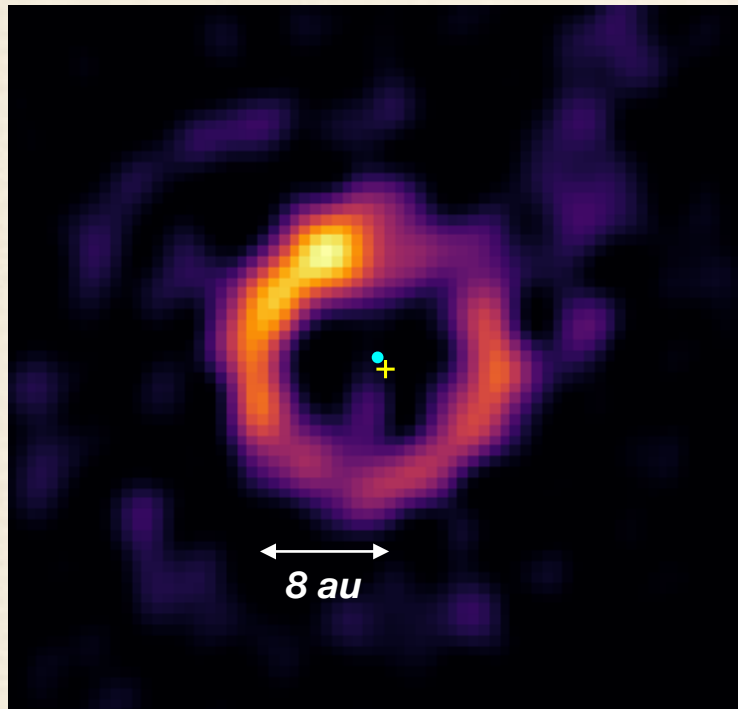


Title: **HD101584**
Artists: **Kluska et al.**
Year: **2020**
Technique: **MiRA/SPARCO**
Instrument: **VLTI/PIONIER**



Circumstellar disks

Disks around post-AGB binaries



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Artists: **Hillen et al.**

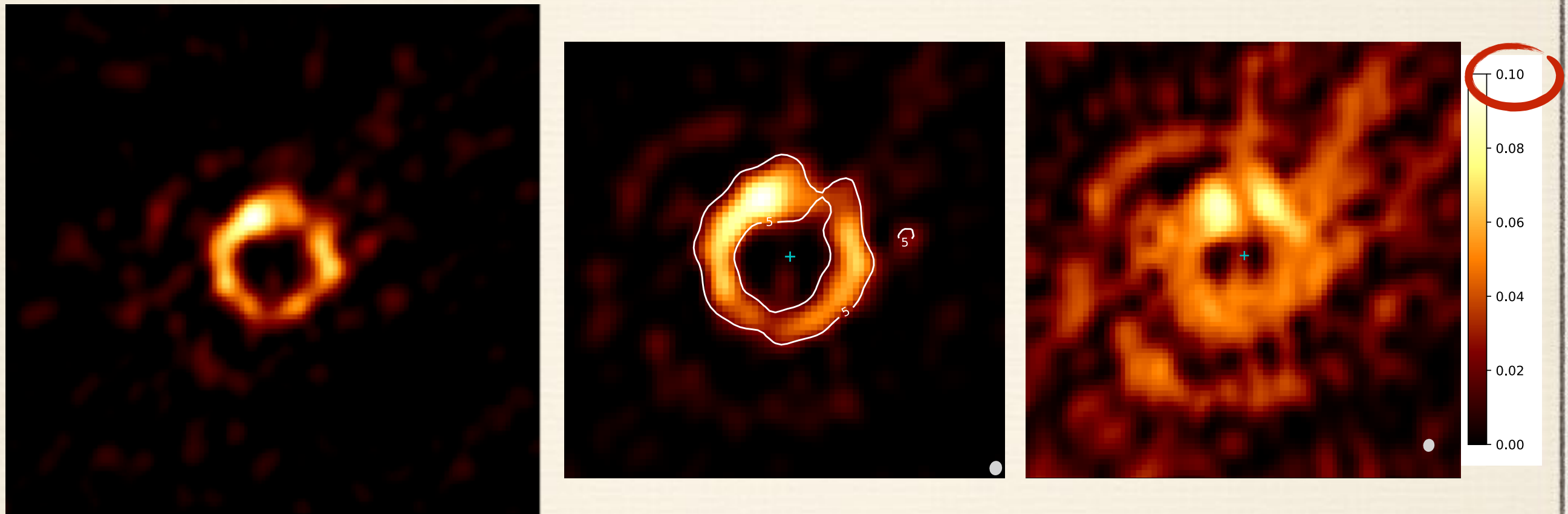
Year: **2016**

Technique: **MiRA/SPARCO**

Instrument: **VLT/PIONIER**

Circumstellar disks

(If I have time...)

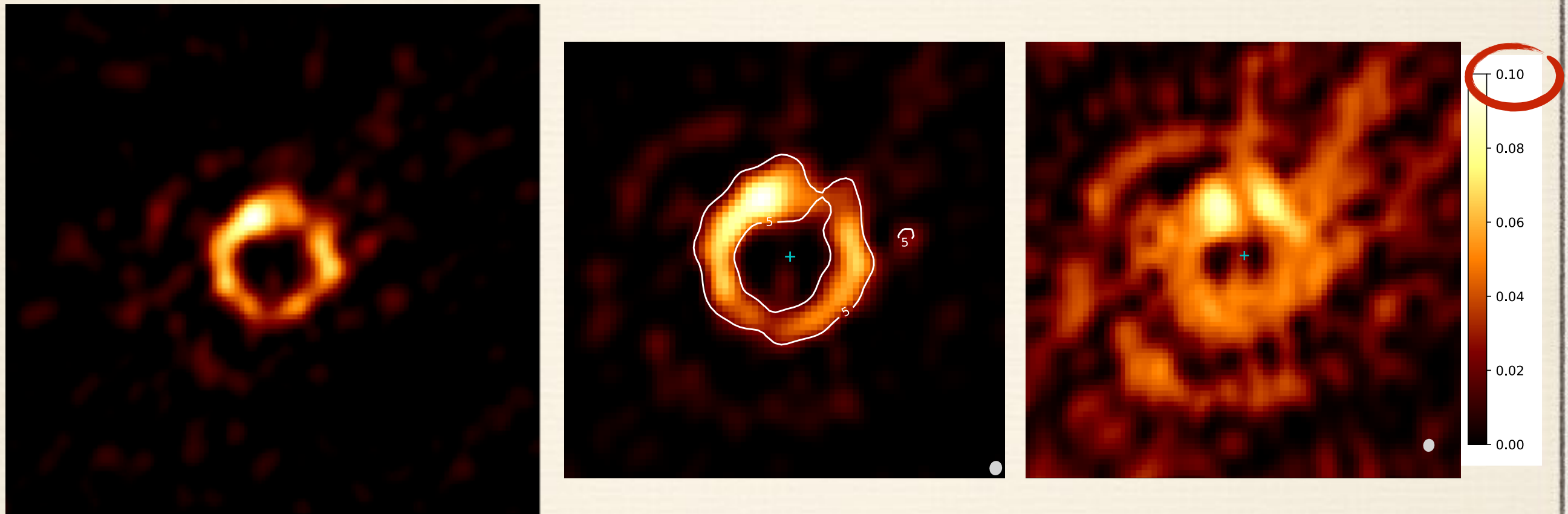


How to investigate the noise in the image?

Bootstrapping: random construction of a new dataset from existing data points

Circumstellar disks

(If I have time...)



How to investigate the noise in the image?

Bootstrapping: random construction of a new dataset from existing data points

End of the visit

To conclude

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- ▶ A lot of interferometric images
 - ▶ Stellar surfaces, circumstellar environments, binaries, extragalactic sources
 - ▶ We only enter the imaging era: VLTI (PIONIER, GRAVITY, **MATISSE**) + CHARA (MIRC-X, MYSTIC, SPICA)

To conclude

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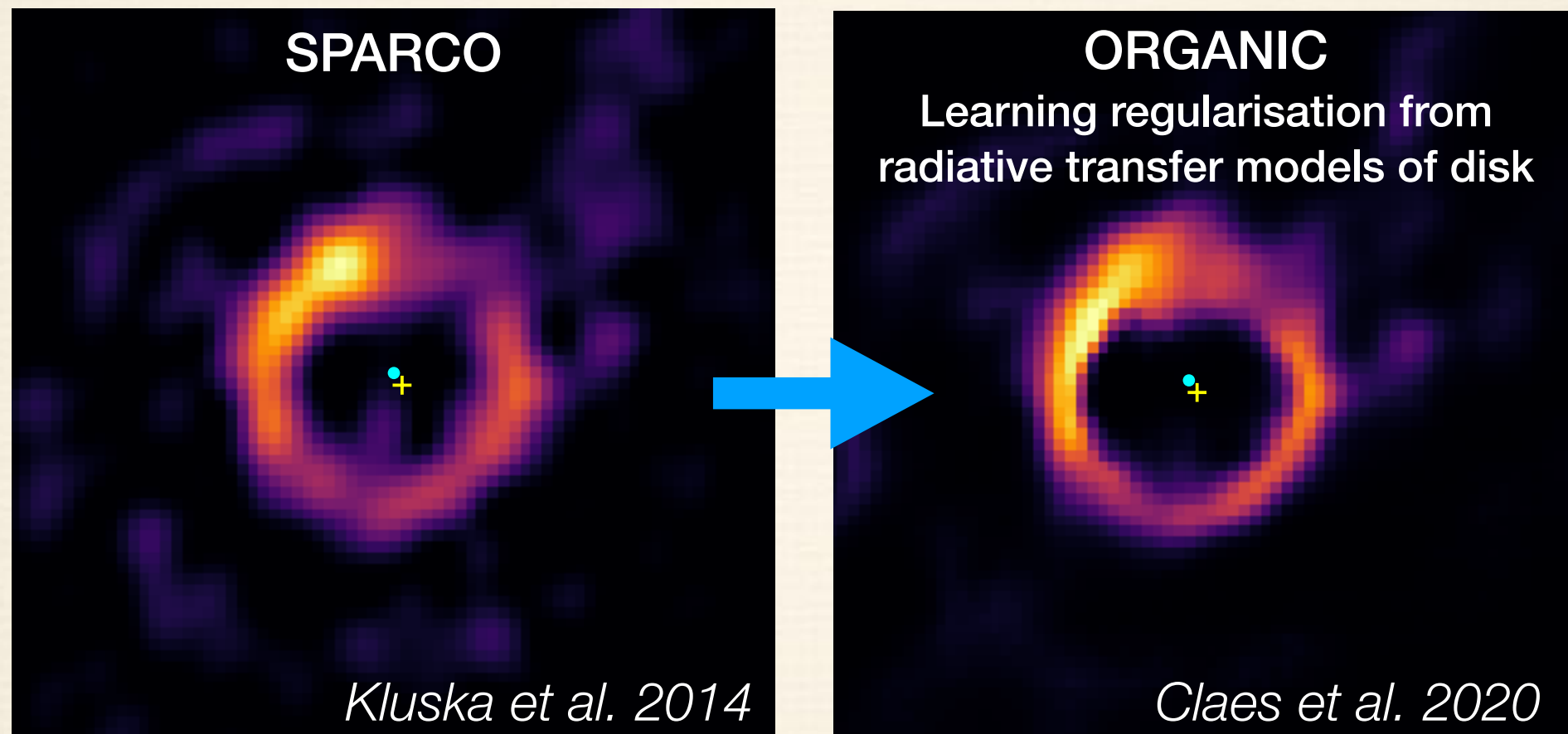
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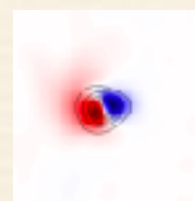
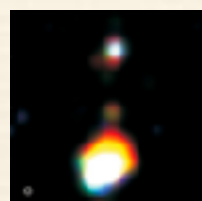
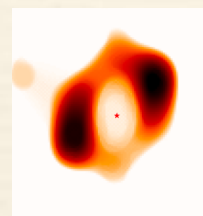
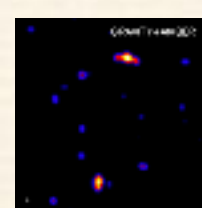
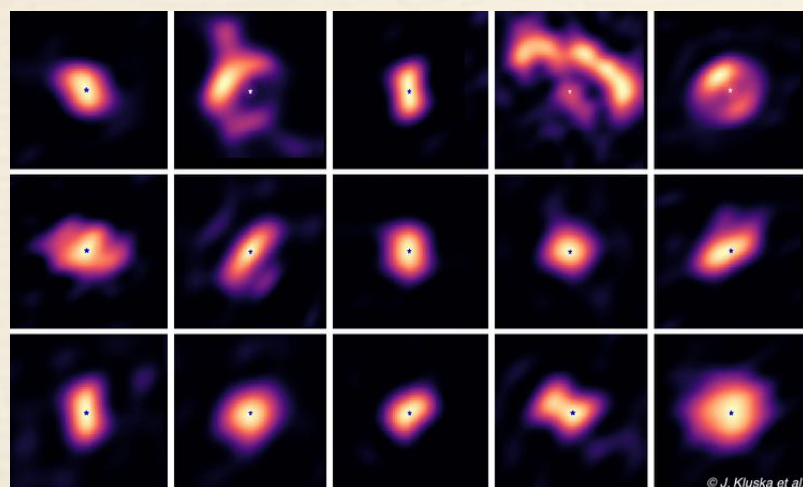
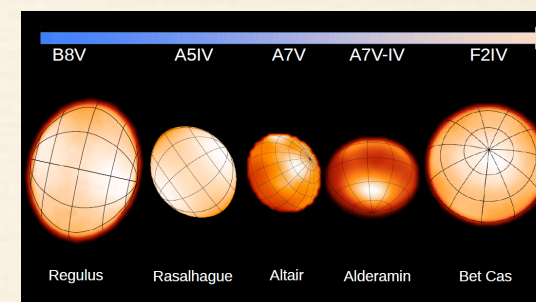
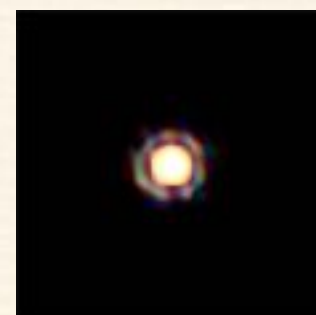
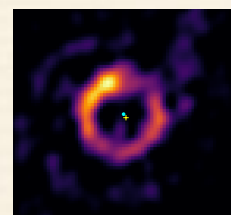
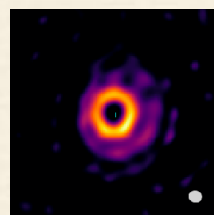
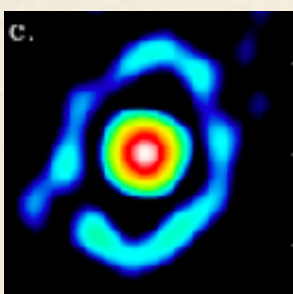
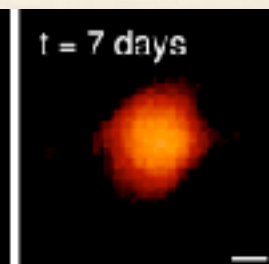
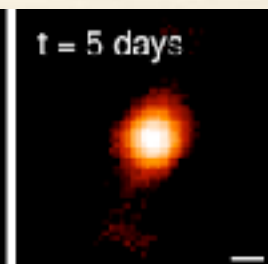
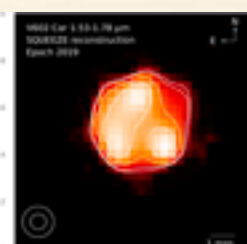
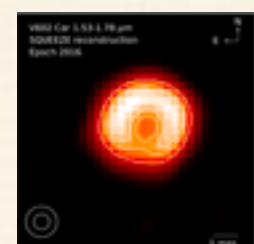
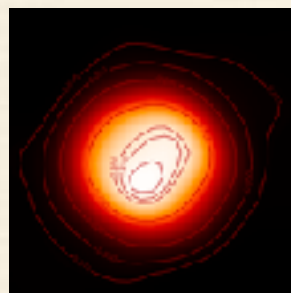
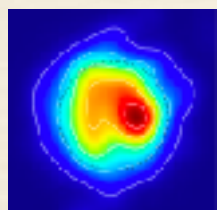
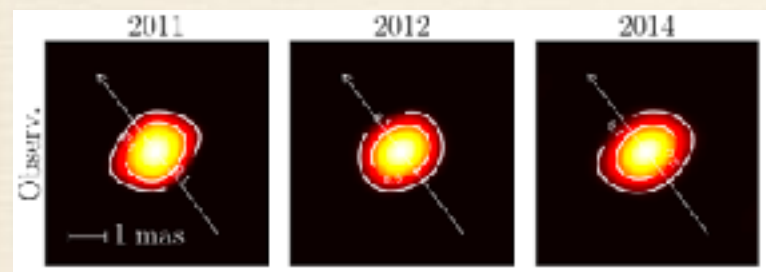
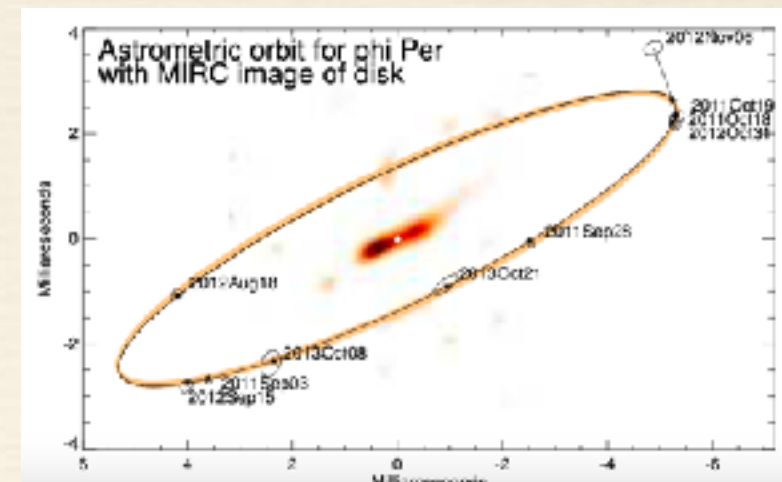
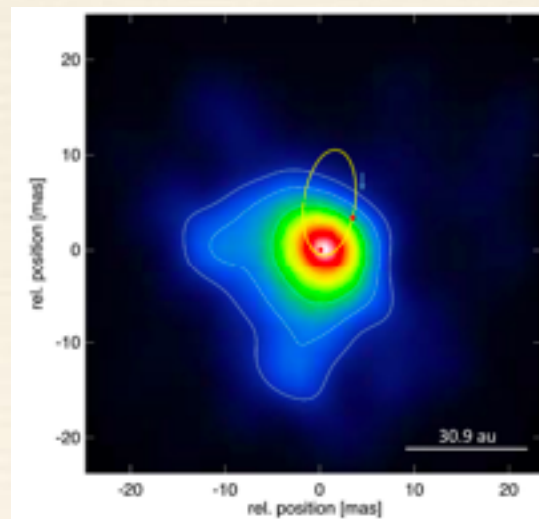
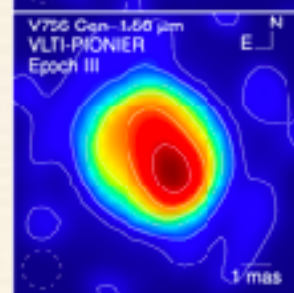
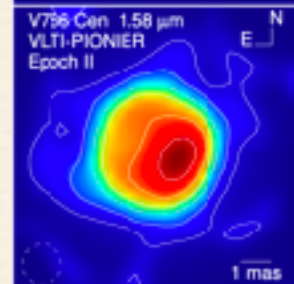
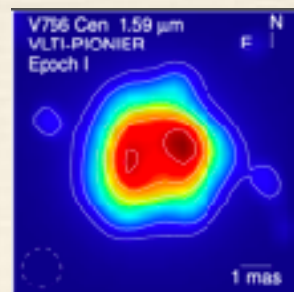
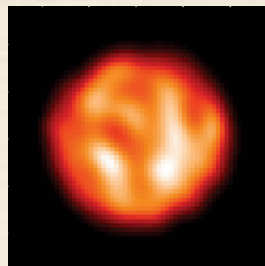
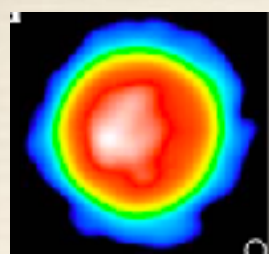
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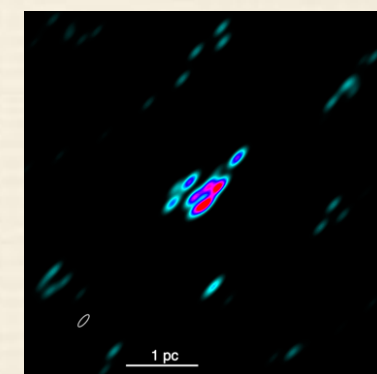
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- ▶ Future with neural networks!

To conclude





Thank you!



Le Bouquin+2009, Ohnaka+2019, Wittkowski+2017, Mourard+2015, Weigelt+2016, Ohnaka+2017, Dalla Vedova+2017, Kraus+2017,2012, Hone+2017, Ohnaka+2020, Climent+2020, Chiavassa+2020 and many more....