Observing the birth of planets

Valentin Christiaens
Postdoctoral researcher - Monash University

University of Melbourne - 17 October 2018

Outline

- I. Introduction
  - High-contrast imaging of exoplanets
  - Transition disks
- II. Direct search for protoplanets
  - In thermal-IR
  - In NIR with an IFS
- III. Indirect constraints: spiral arms and hydro-dynamical simulations
- IV. Future of the search for protoplanets
- V. Conclusions

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Challenge of high-contrast imaging

Credit: G. Duchêne

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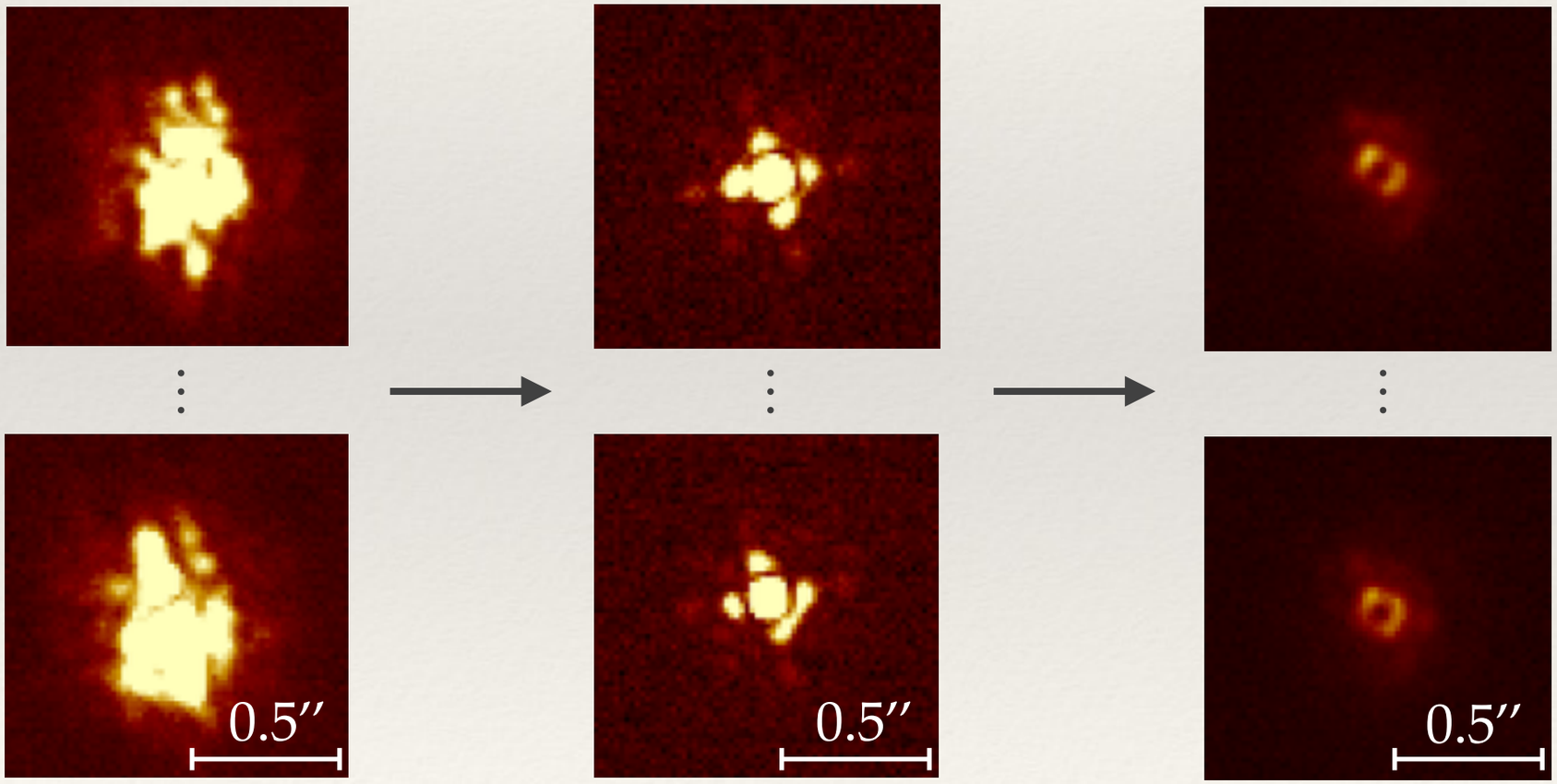
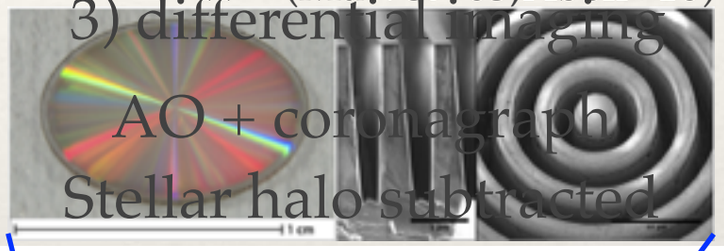
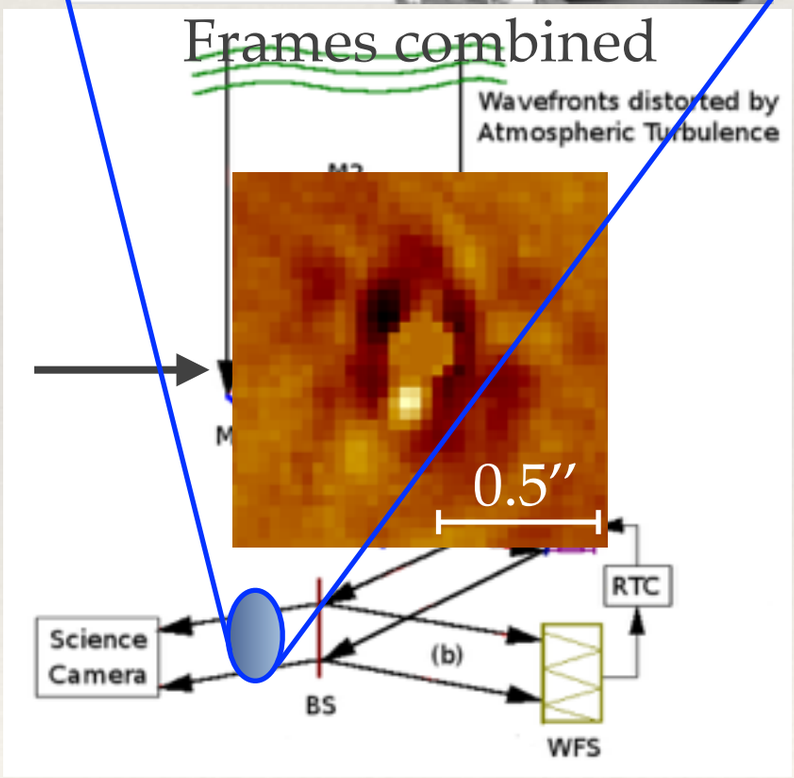
Challenge of high-contrast imaging

- 2 major hurdles to directly image exoplanets: **contrast** and **angular resolution**
- HCI techniques: 1) adaptive optics 2) coronagraphy 3) differential imaging



(Mawet+05,Absil+16)

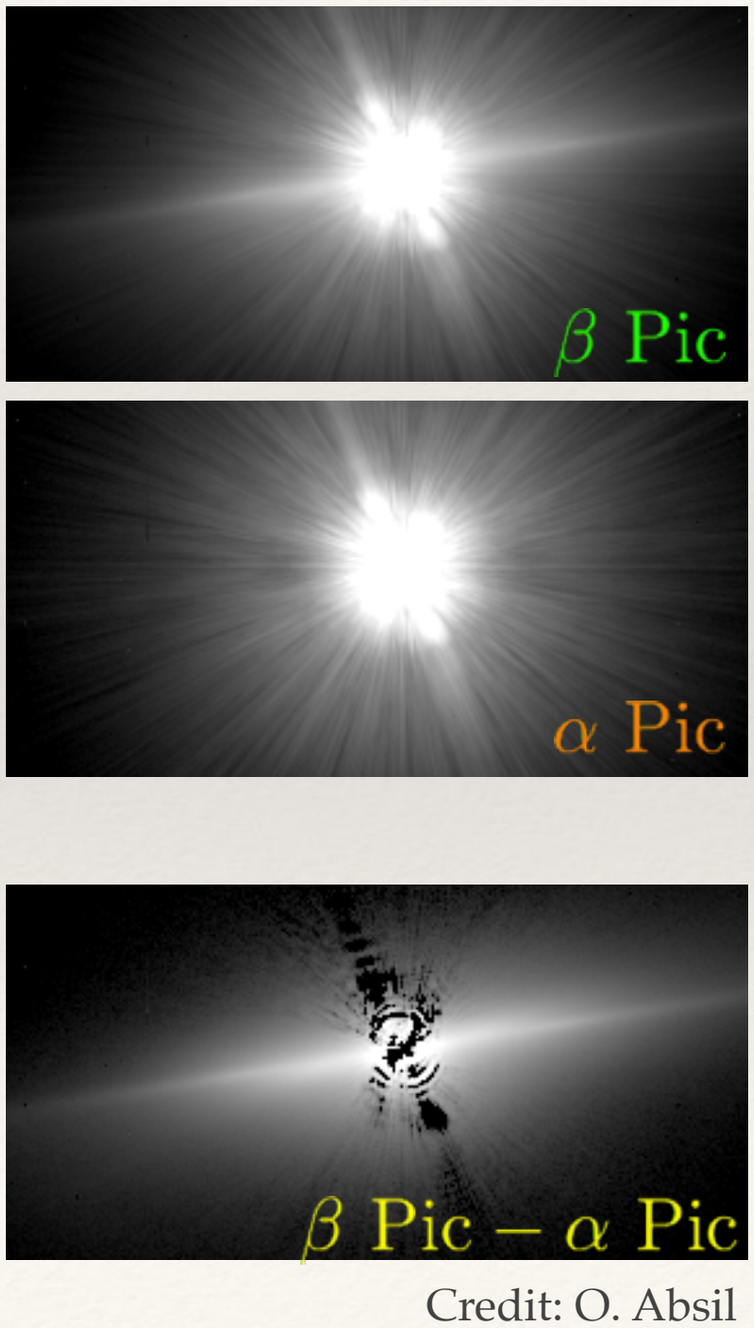




- Residual hurdle: (quasi-static) **speckles**

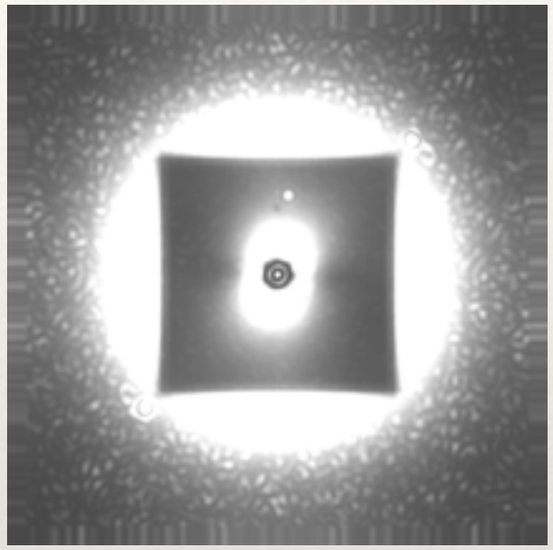
PSF modeling + differential imaging

Reference star Differential Imaging (RDI)



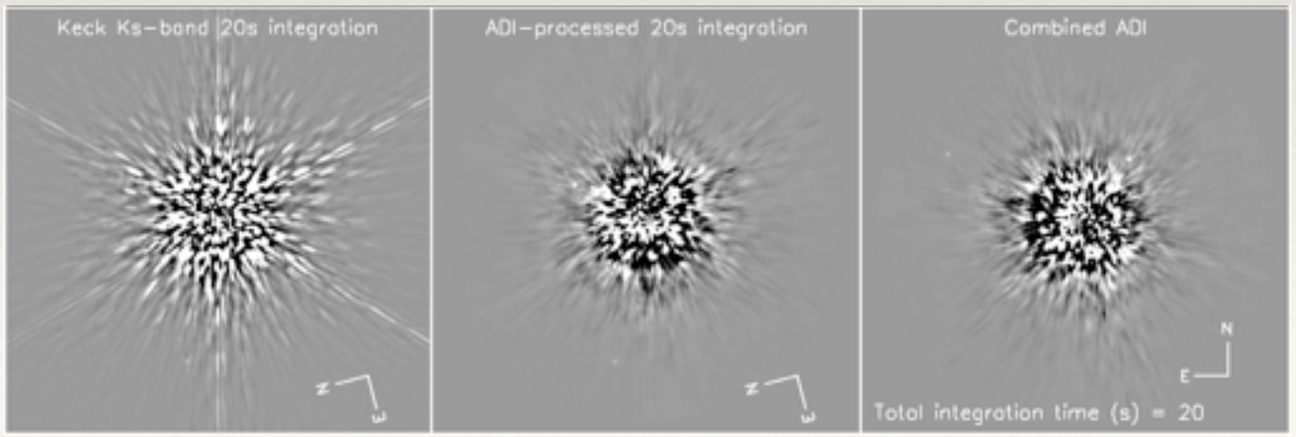
Credit: O. Absil

Spectral Differential Imaging (SDI)



Credit: B. Macintosh

Angular Differential Imaging (ADI)



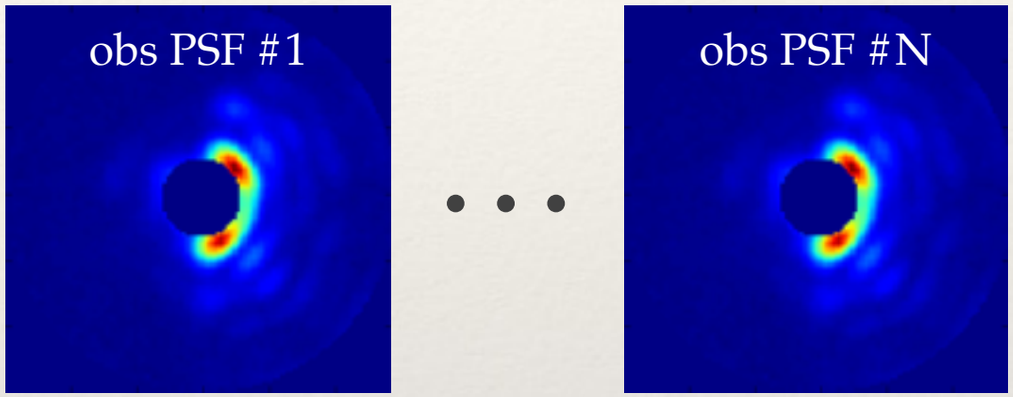
Credit: C. Marois

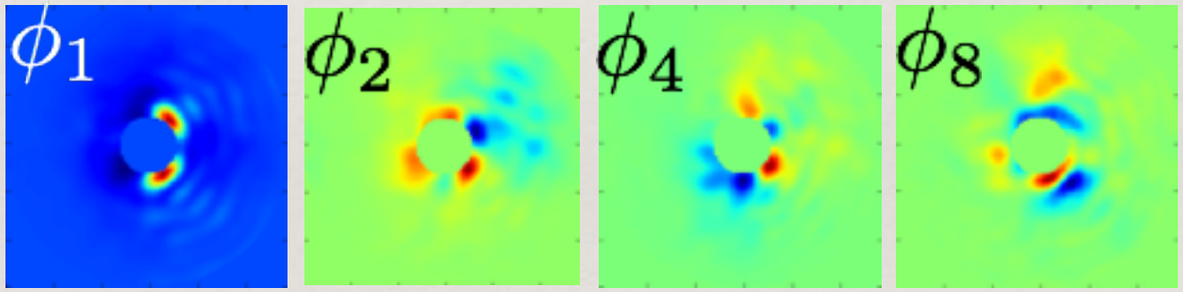
Principal component analysis (PCA)

- Build an orthogonal basis to reproduce the observed PSFs
- Analogy:

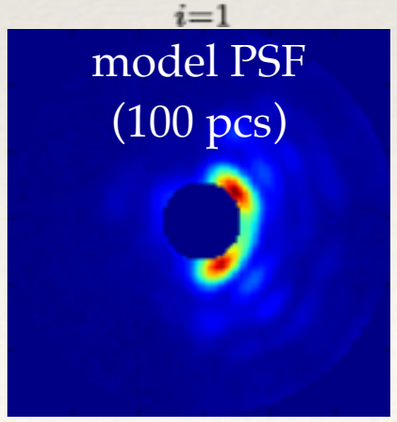
Male face model built from a basis of female faces

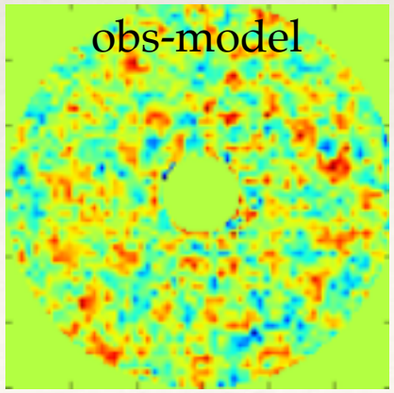
PSFs



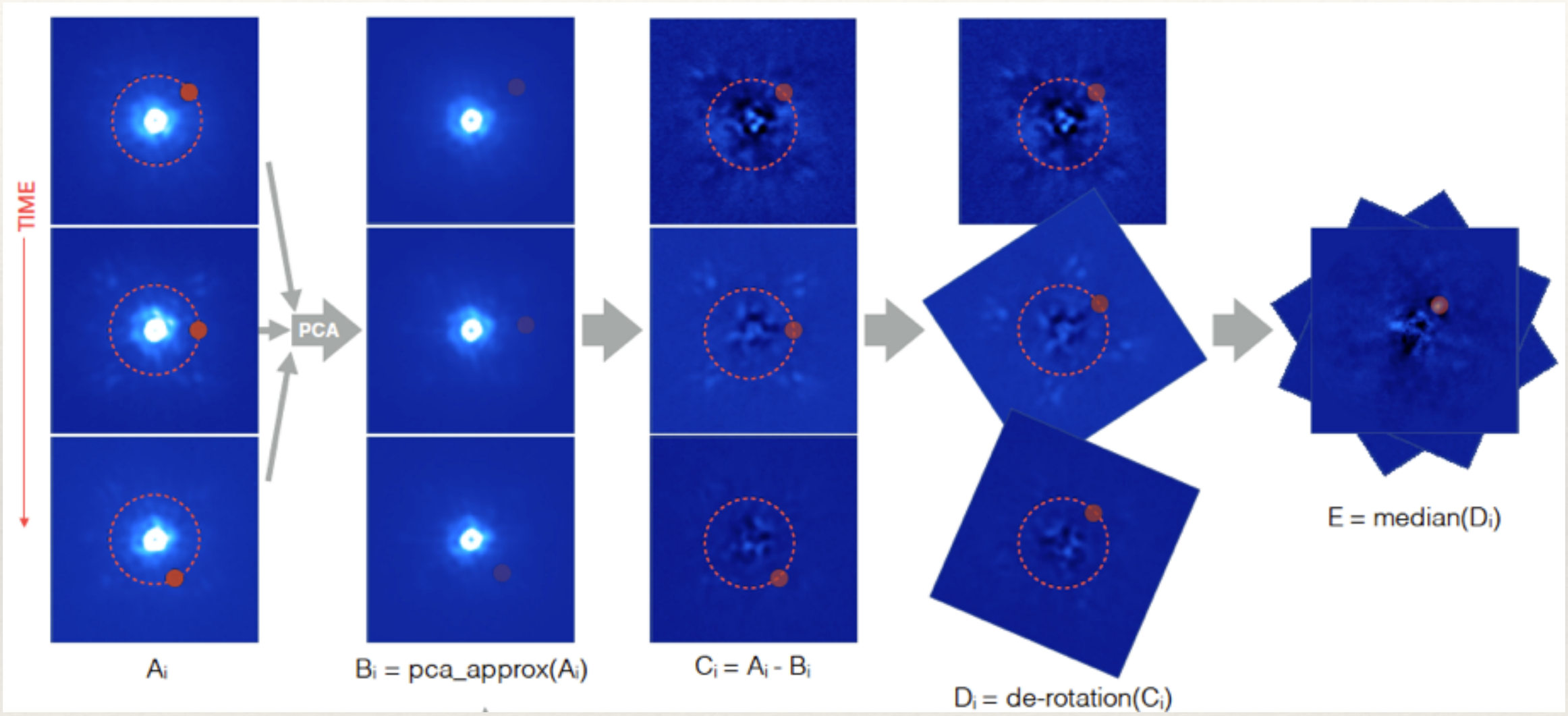


$$R(\vec{x}) = \sum_{i=1}^{n_{\rm pc}} a_i \phi_i(\vec{x})$$





Principal component analysis (PCA) + ADI

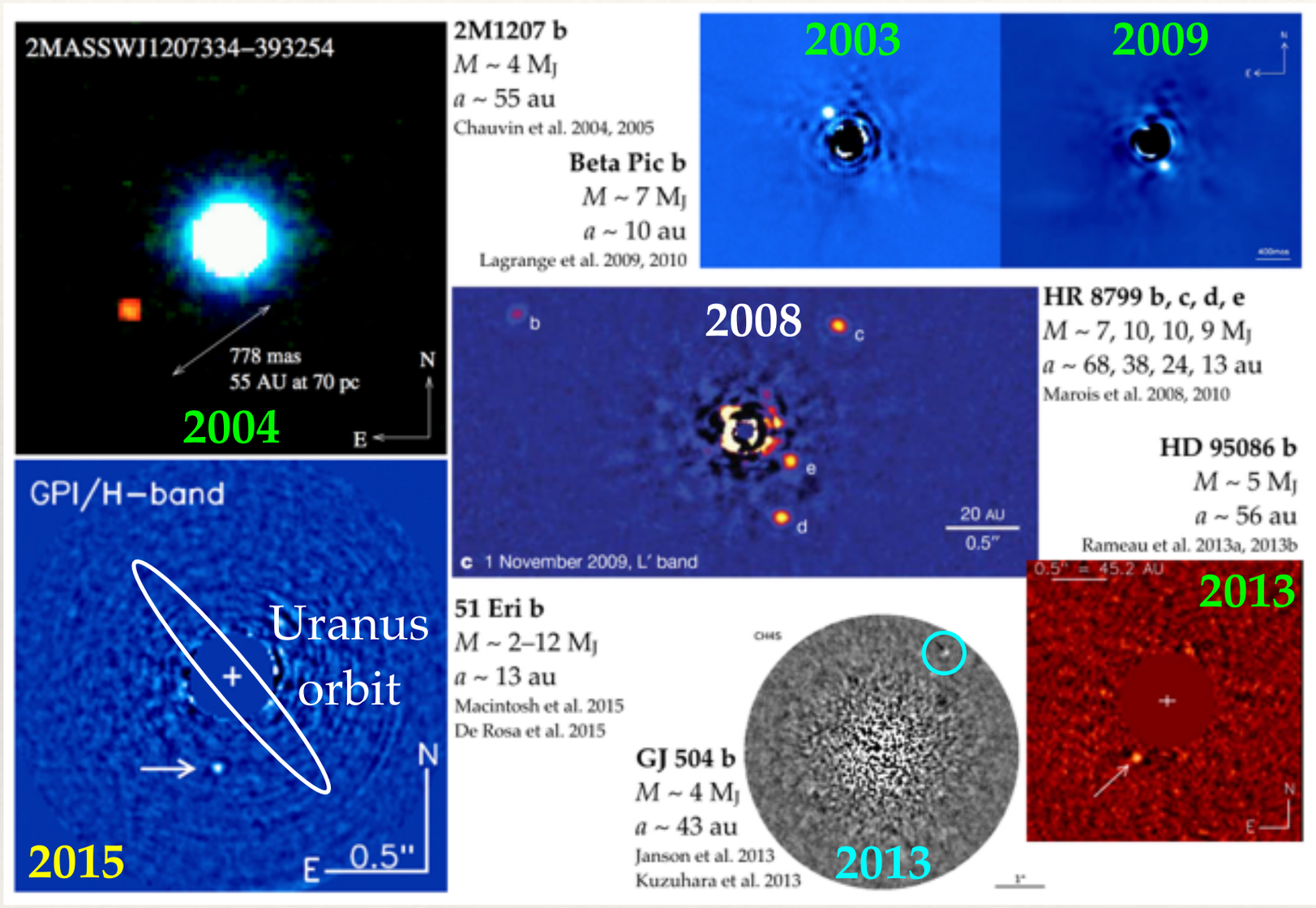


Credit: C. Gomez

$$B_i = \sum_{j=1}^{n_{\mathrm{pc}}} < A_i, \phi_j > \phi_j,$$

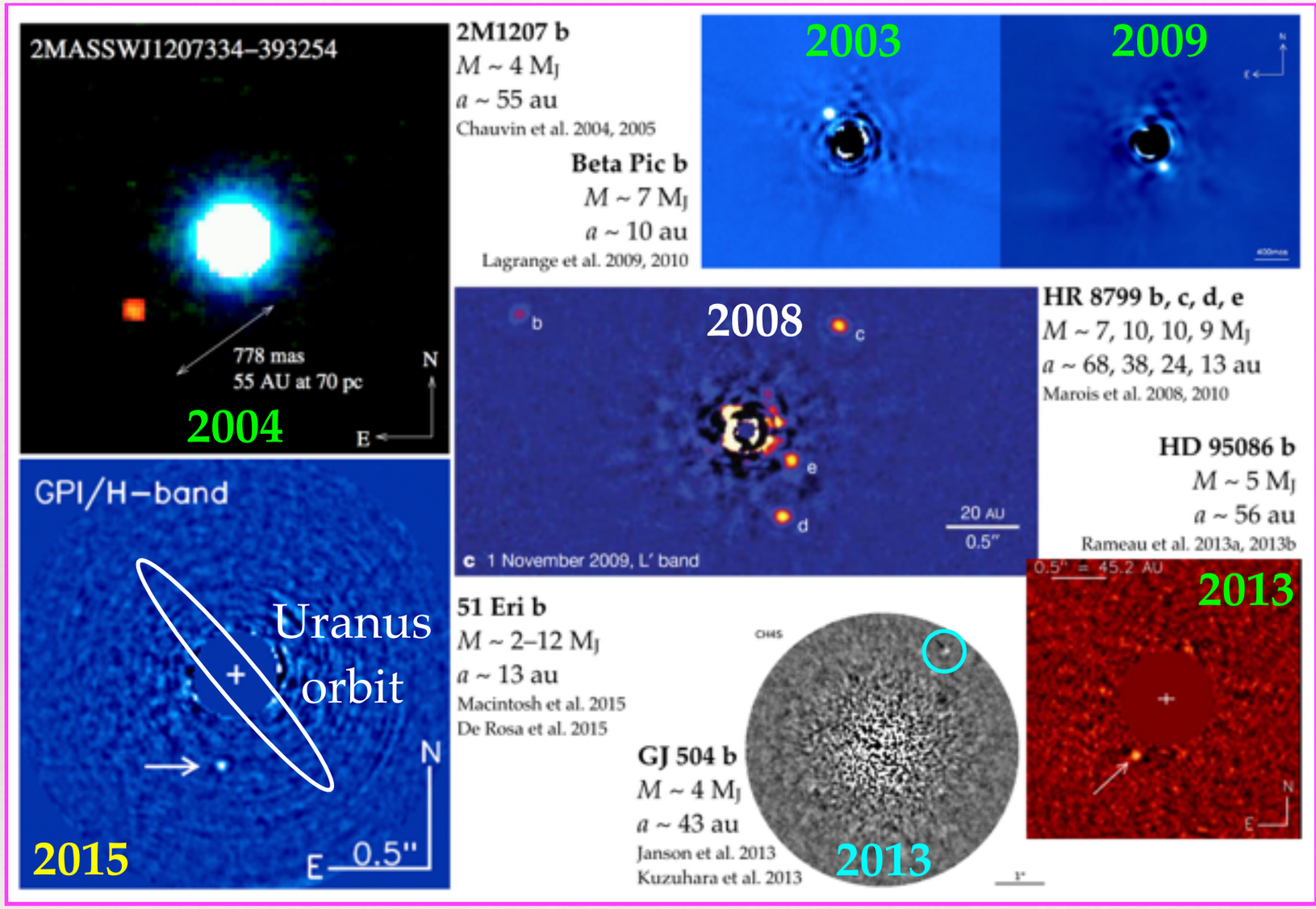
where ϕ_j are a set of orthonormal eigenvectors of $\mathbf{A}^{\mathrm{T}}\mathbf{A}$.

Exoplanet direct images

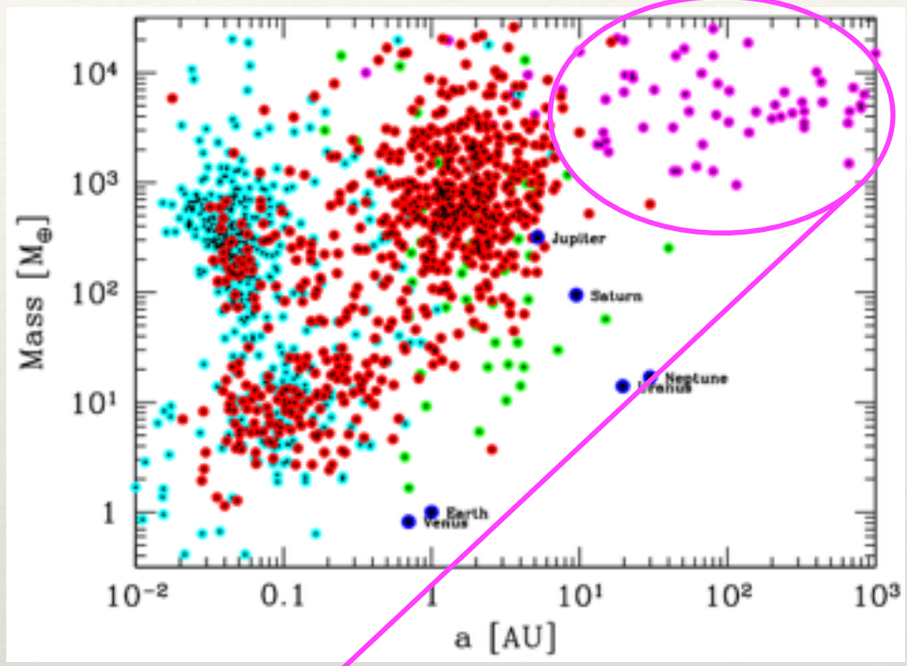


10m-class telescopes

Exoplanet direct images



Directly Imaged



Mordasini+18

- Directly imaged exoplanets provide invaluable information:
  - parameter space inaccessible with other techniques
  - spectrum => T_{eff}, log(g), atmosphere composition
  - exact orbital architecture of exoplanetary systems

} Niche: young giant planets (on wide orbit)

=> constraints on planet formation models

Formation of giant planets

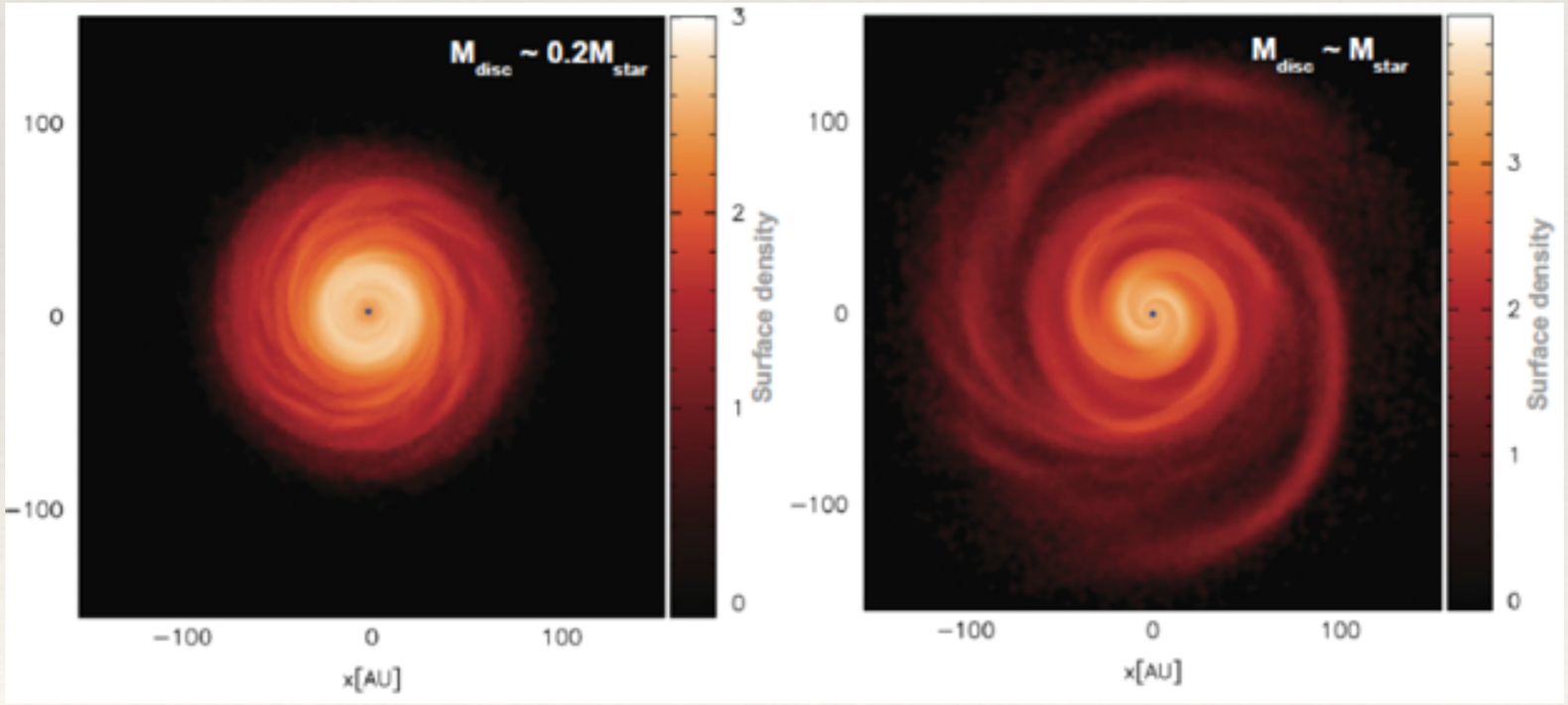
Core accretion **Gravitational instability**

Gravitational instability

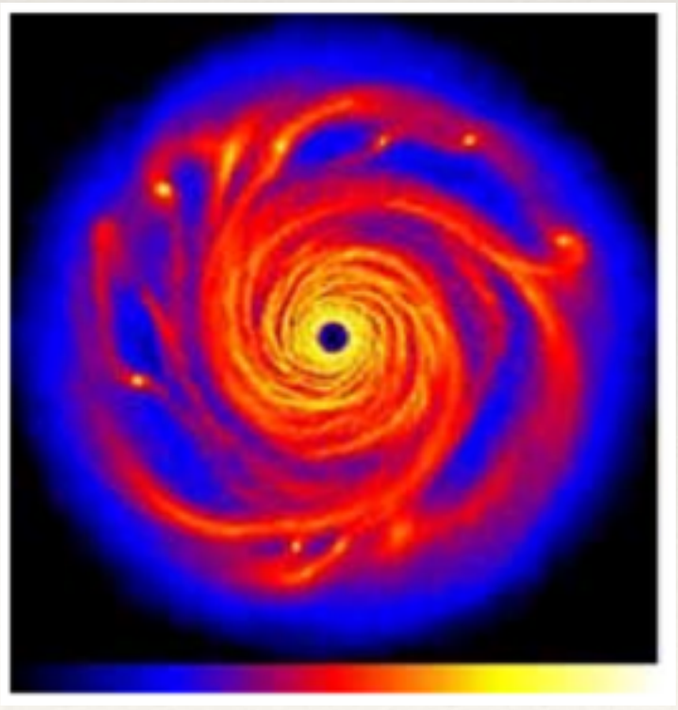
- If $Q \equiv \frac{c_s \Omega}{\pi G \Sigma} < Q_{\rm crit} \approx 1$ AND $t_{\rm cool} \equiv \frac{U}{2\sigma T_{\rm disk}^4} \lesssim \beta_{\rm crit} \Omega^{-1}$

GI condition (Toomre 1964) Cooling condition (Gammie 2001)

=> **gravitational fragmentation**

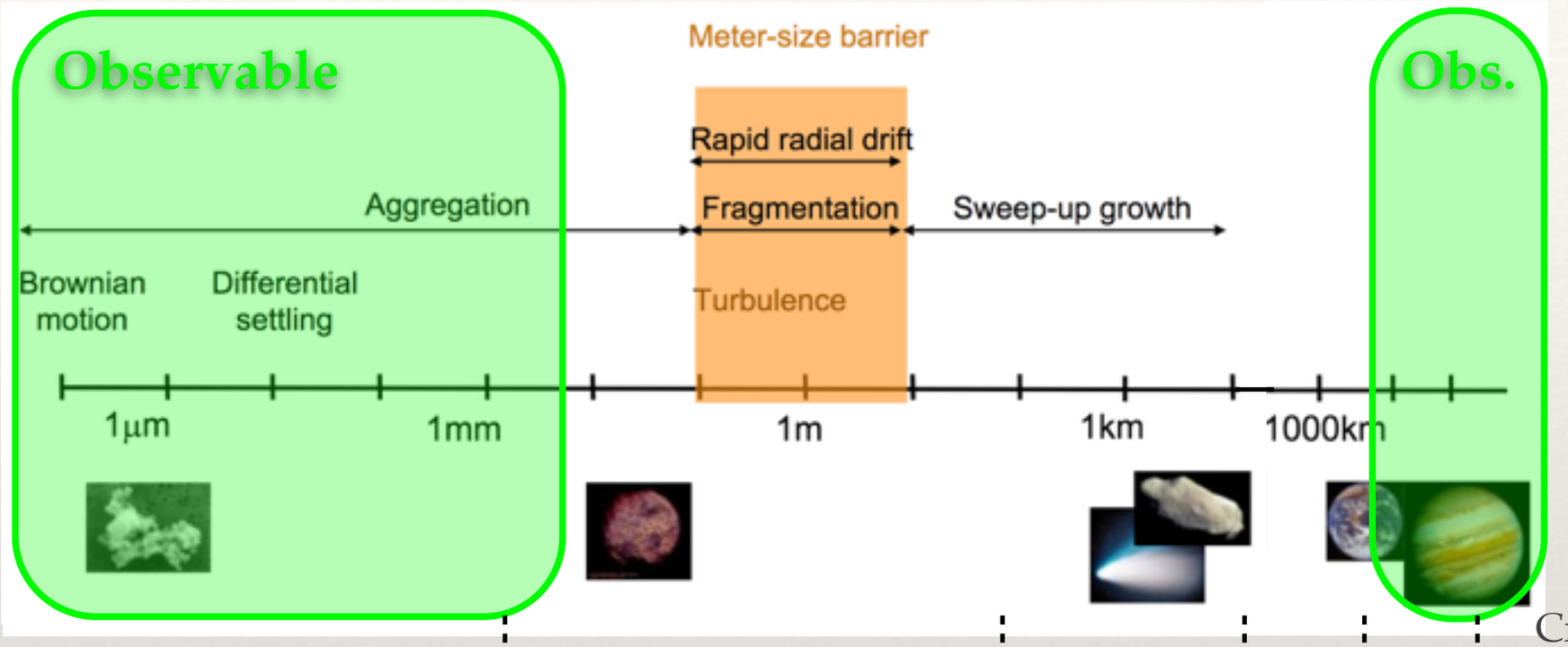


Forgan & Rice 2013



Rice+2003

Core accretion

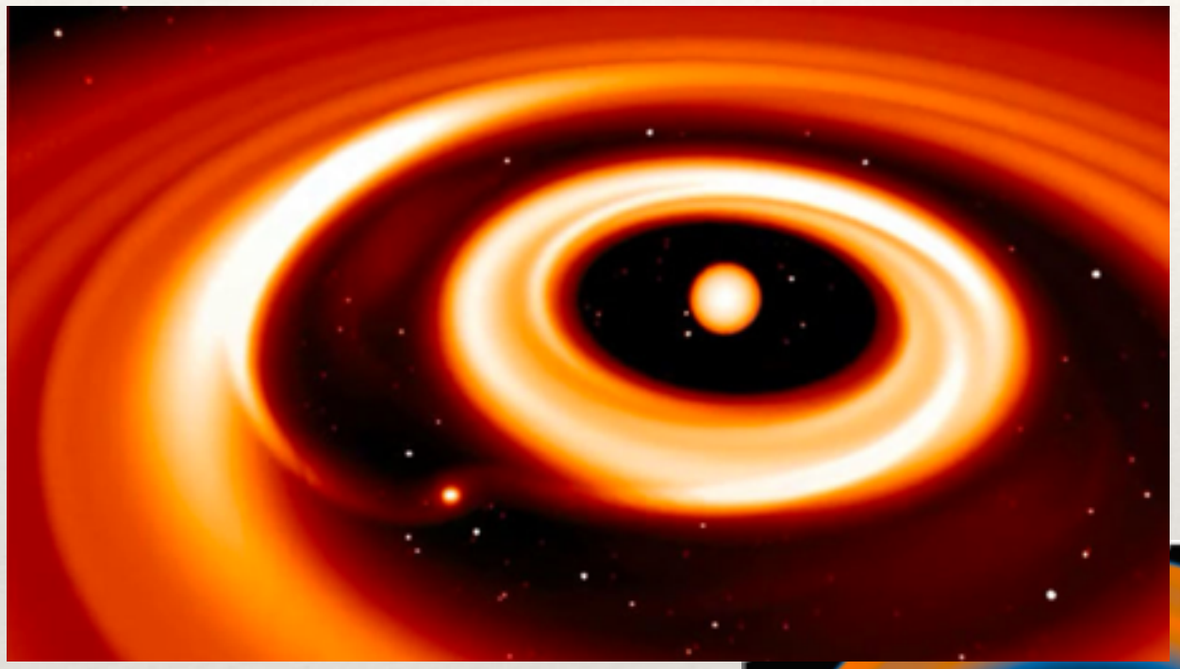


Credit: C. Dullemond

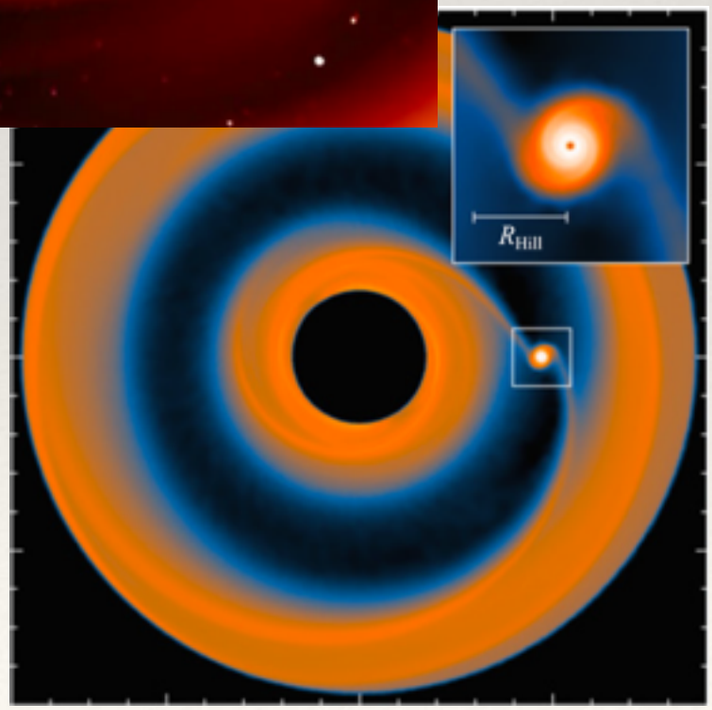
- 5 main steps: 1) Grain growth
  2) Planetesimal formation?
  3) Core formation
  4) Hydrostatic growth
  5) Runaway accretion

Circumplanetary disk (CPD)?

- CPD at the scale of the protoplanetary disk

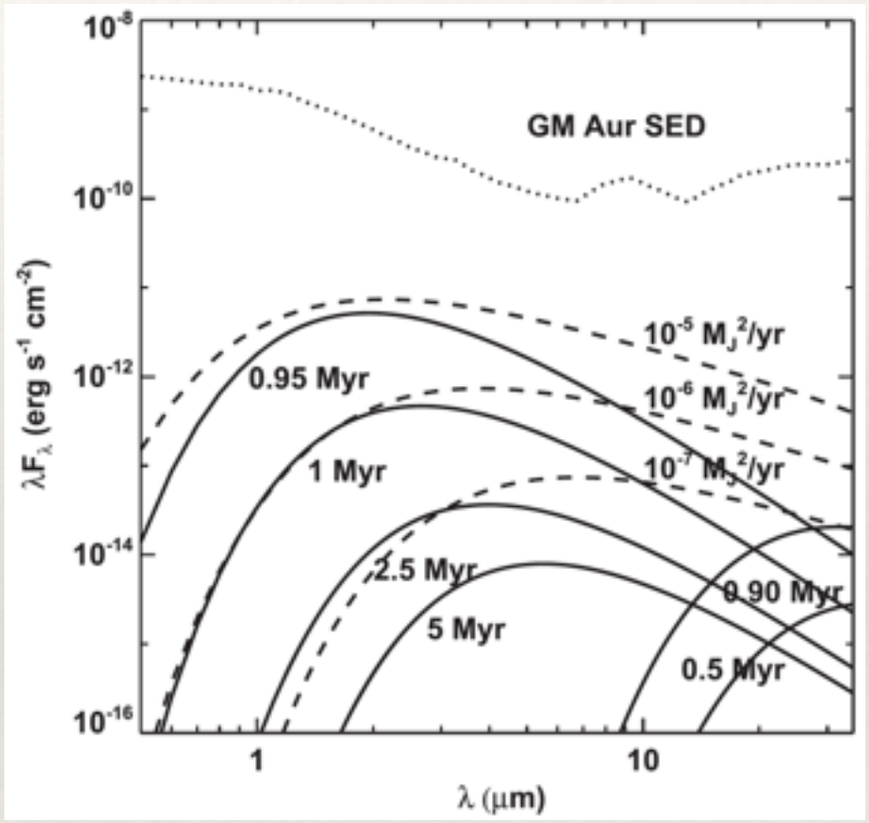


Credit: SNSC



Perez+2015

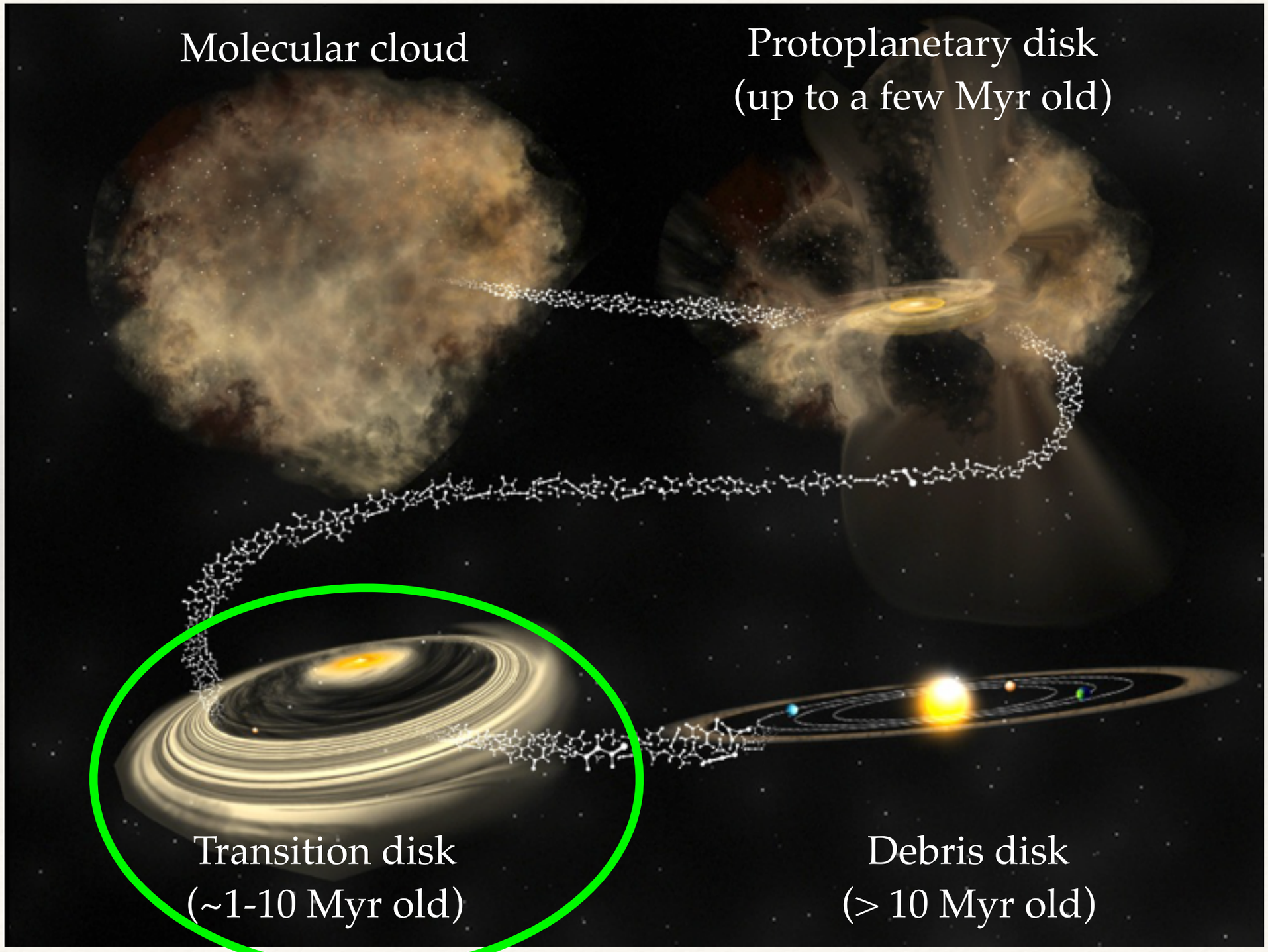
- Expected SED



Eisner 2015

solid: protoplanet alone
dashed: protoplanet + CPD

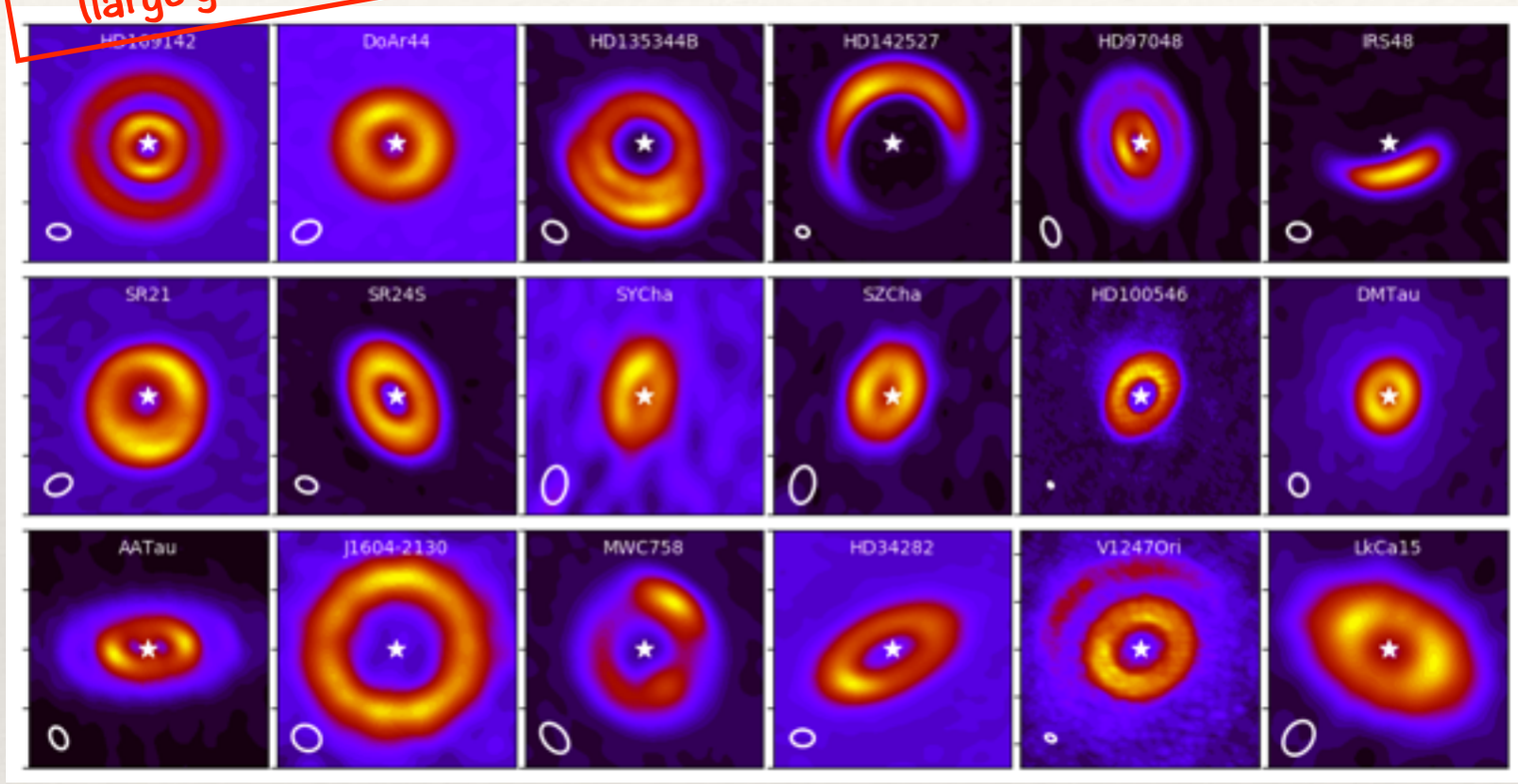
Where to look for protoplanets?



Possible companion signposts in TDs

Sub-mm continuum (large grains)

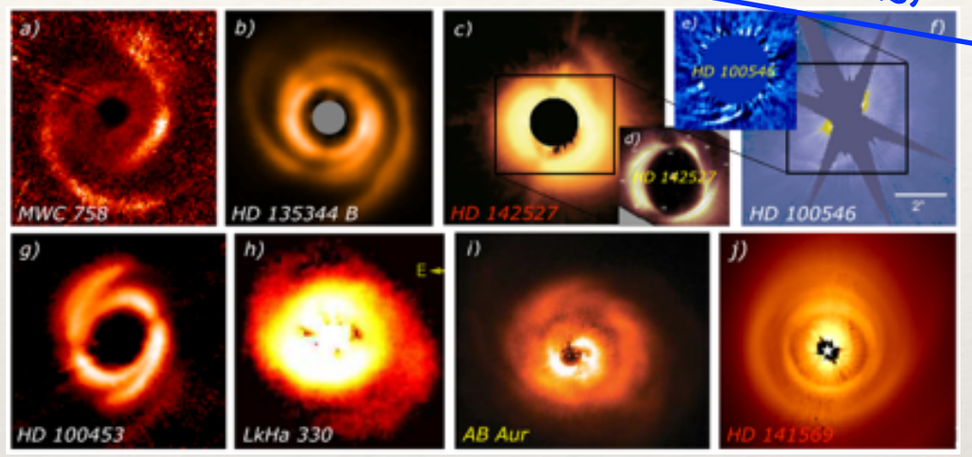
Large cavities+asymmetries



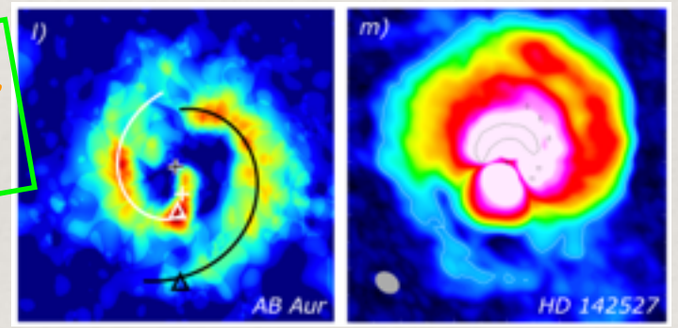
Credit: N. van der Marel

NIR polarized light (small grains)

Spiral arms

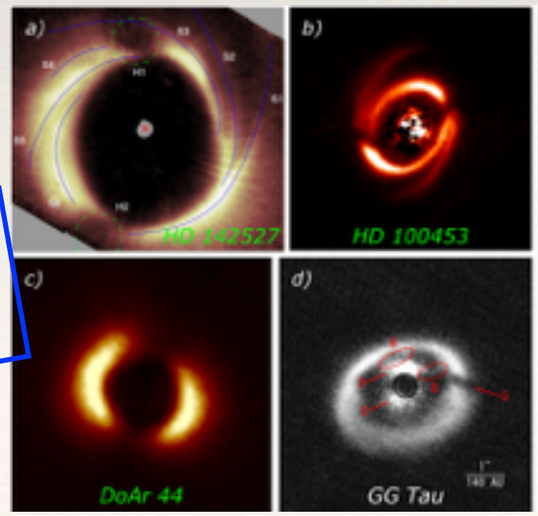


Sub-mm lines (gas)



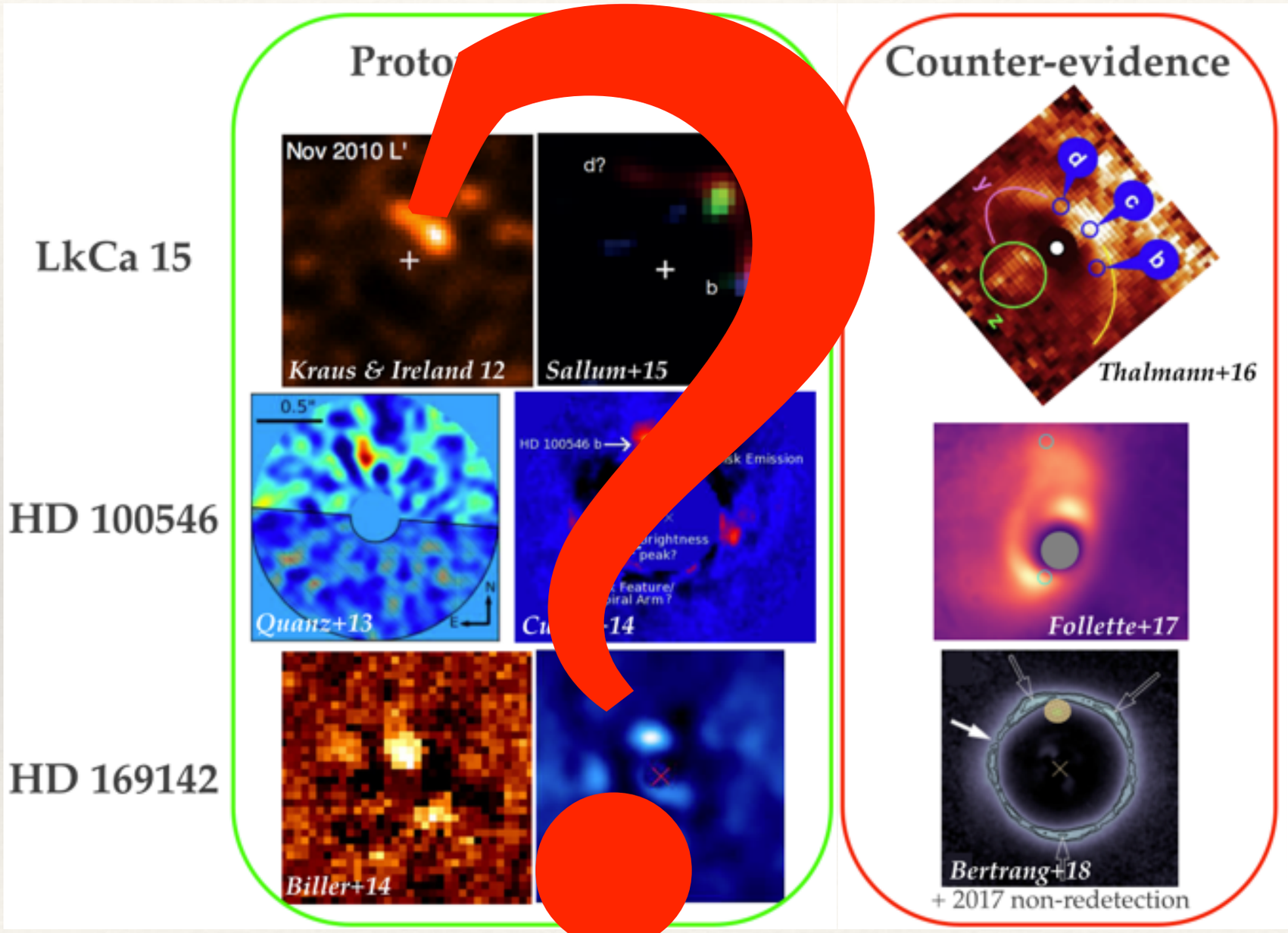
Shadows / Inner Warps

NIR polarized light (small grains)



Several mechanisms can induce these disk features…
but a single one might be enough: the dynamical interaction with embedded companion(s)

Protoplanet candidates?



=> First bona fide detection required (as of 6 months ago)

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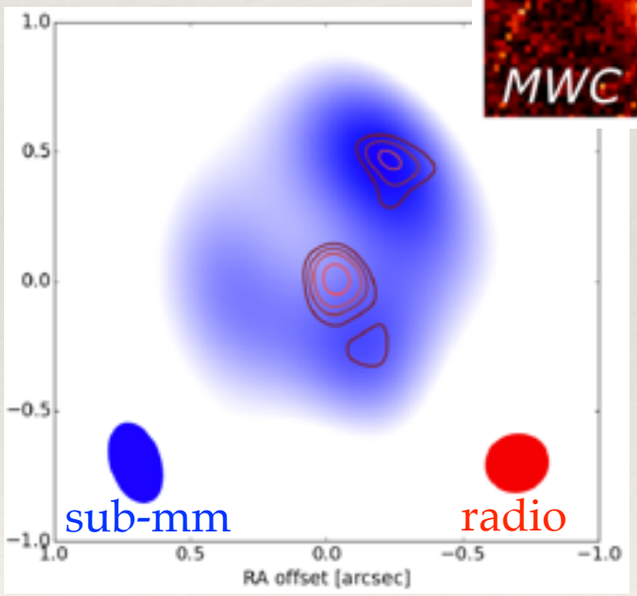
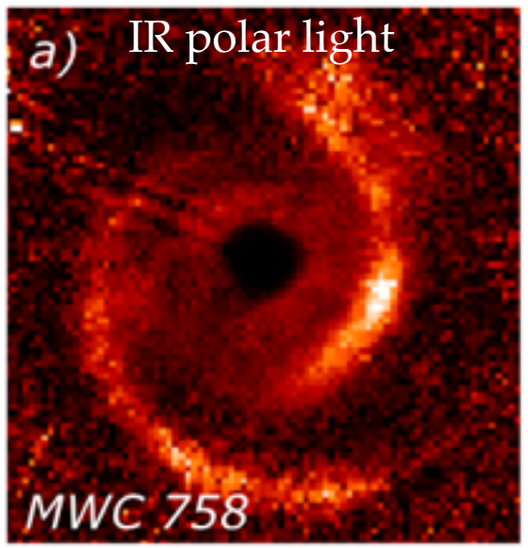
Protoplanet candidate MWC 758 b

(Reggiani, Christiaens+ 2018)

Previous observations

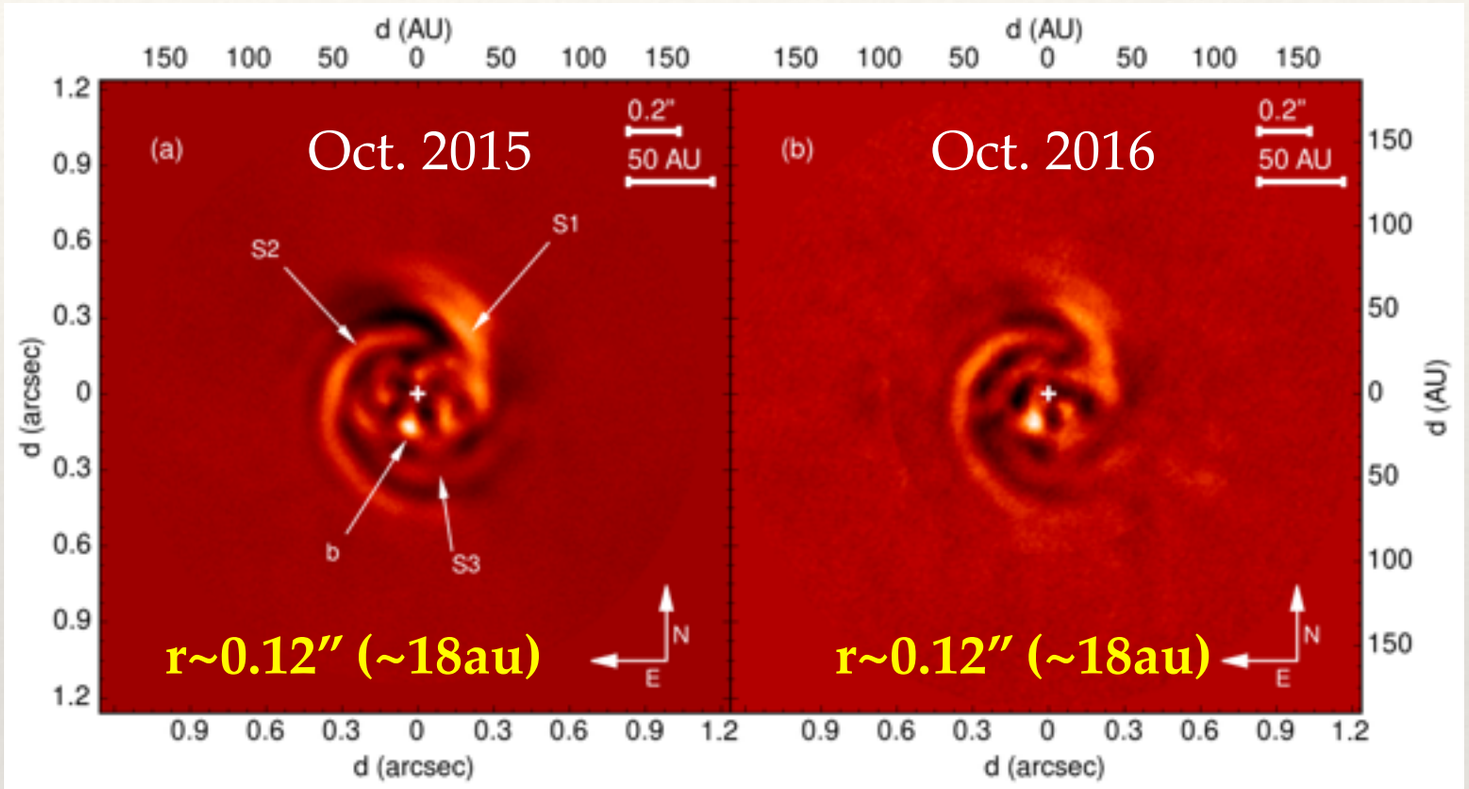
Marino+15





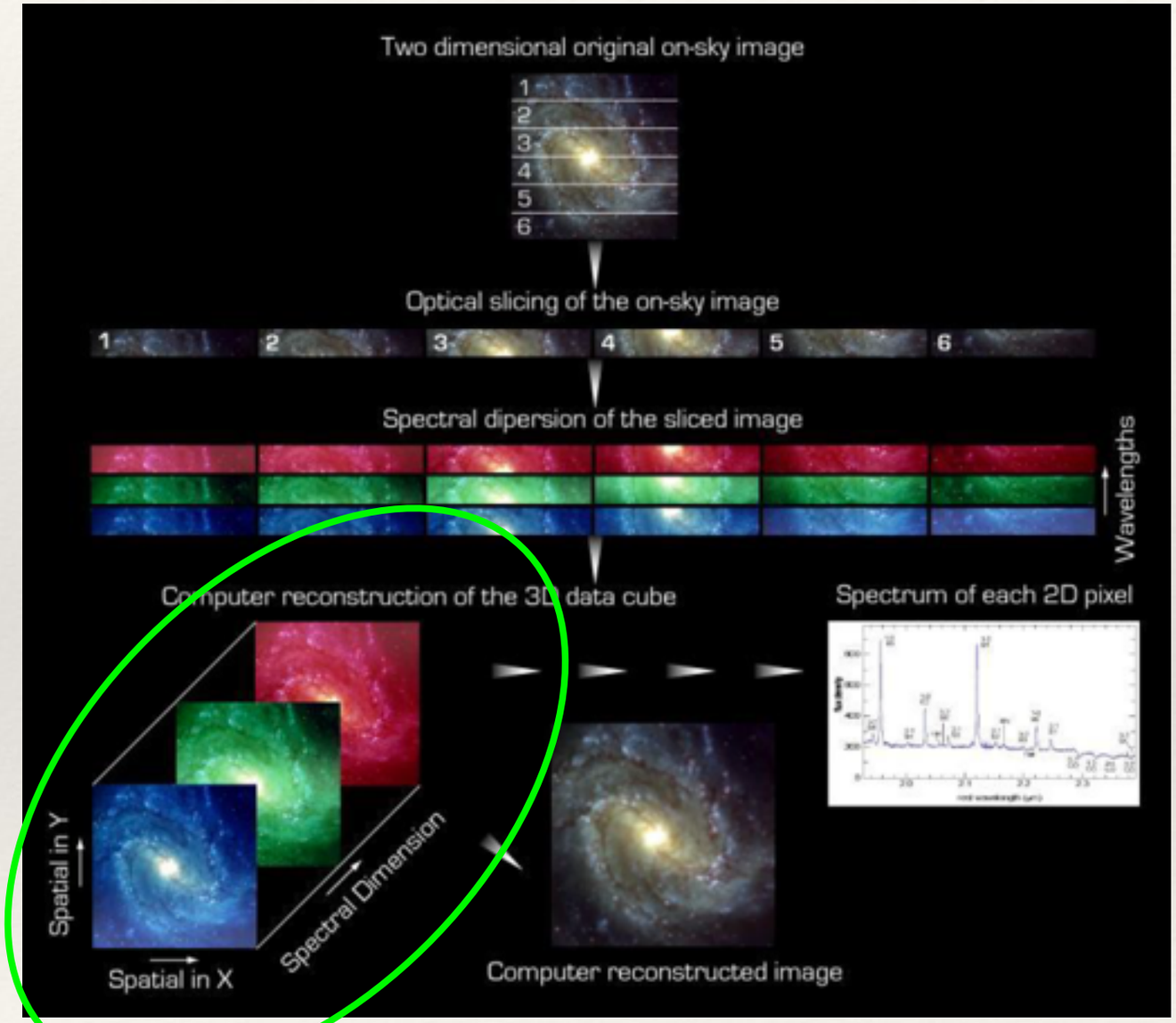
Benisty+15

Keck/NIRC2 (L'-3.8μm) - PCA-ADI

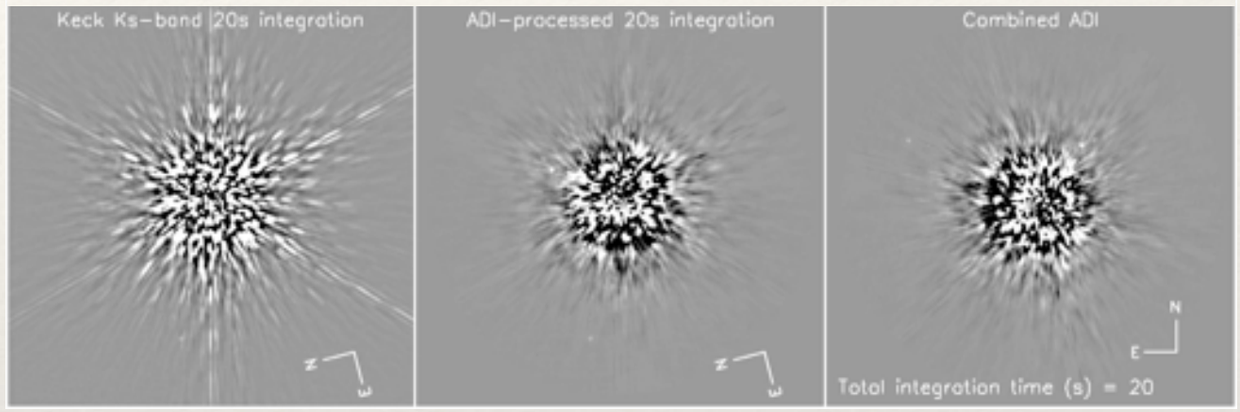


- BRIGHT! Protoplanet with CPD: 4 M_{Jup} accreting at 10^{-5} M_{Jup} yr^{-1}? (based on models in Zhu 2015)

Integral field spectroscopy

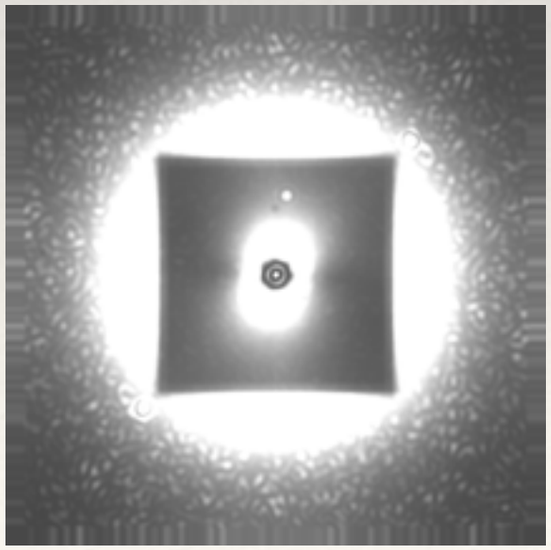


Angular Differential Imaging (ADI)



Credit: C. Marois

Spectral Differential Imaging (SDI)

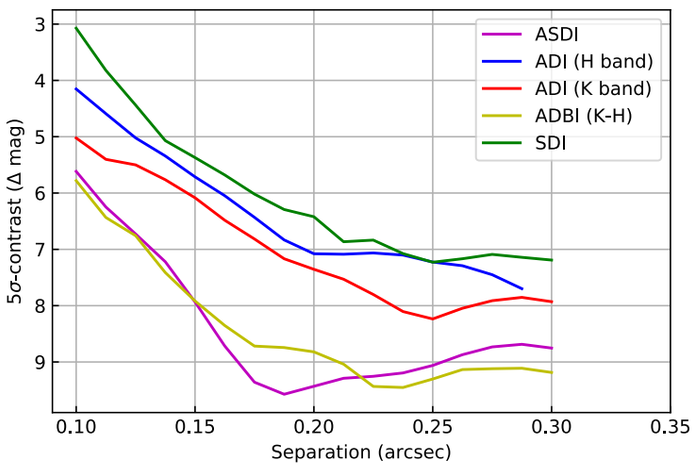


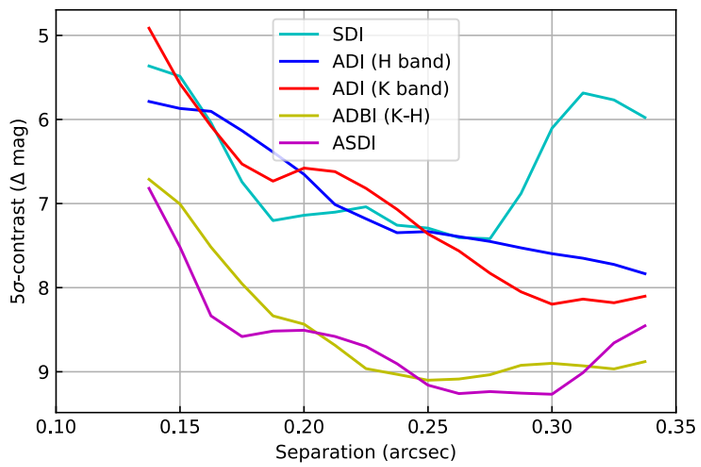
Credit: B. Macintosh

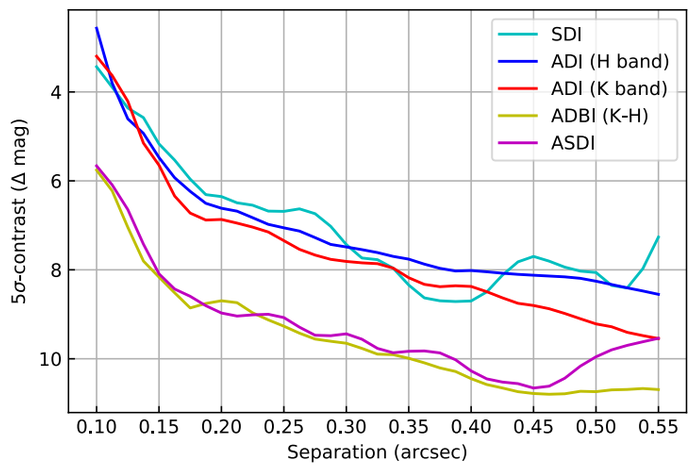
Mini-survey of transition disks with VLT/SINFONI

(Christiaens+ in prep.)

- **VLT/SINFONI**, *H*+*K* band (2000 channels in 1.45–2.45 μm)
- Targets: 5 transition disks with large gaps and signposts of companion presence
- Post-processing using PCA-ADI, -SDI, -ASDI and -ADBI







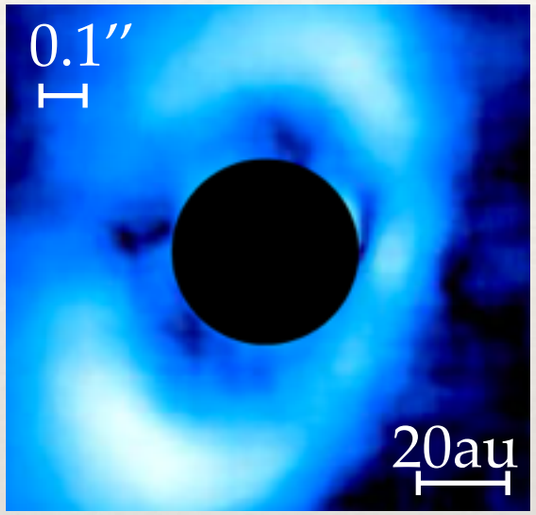
=> At 0.15”–0.20” separation, similar contrast as newer instruments (e.g. **VLT/SPHERE**)

Results of the VLT/SINFONI survey: PDS 70

(Christiaens+ 2018b, subm. to MNRAS)

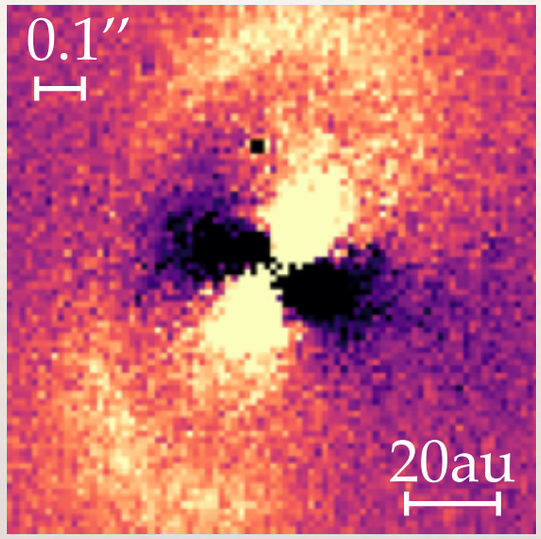
Disk

Polarized light - 1.66 μm



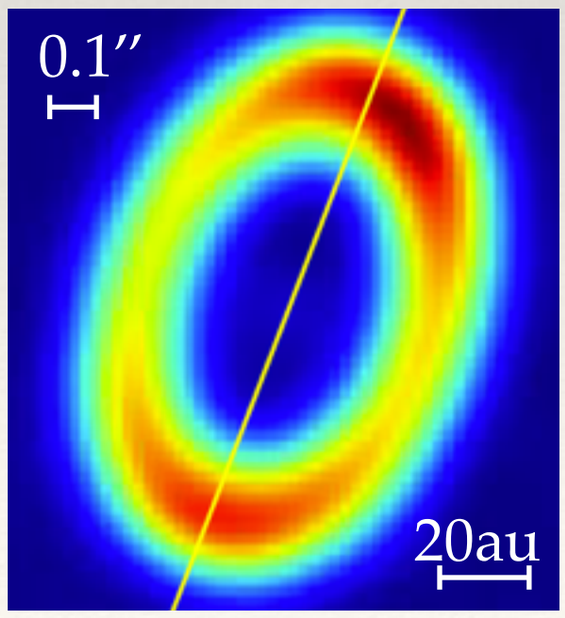
Hashimoto+2012

Polarized light - 1.2 μm



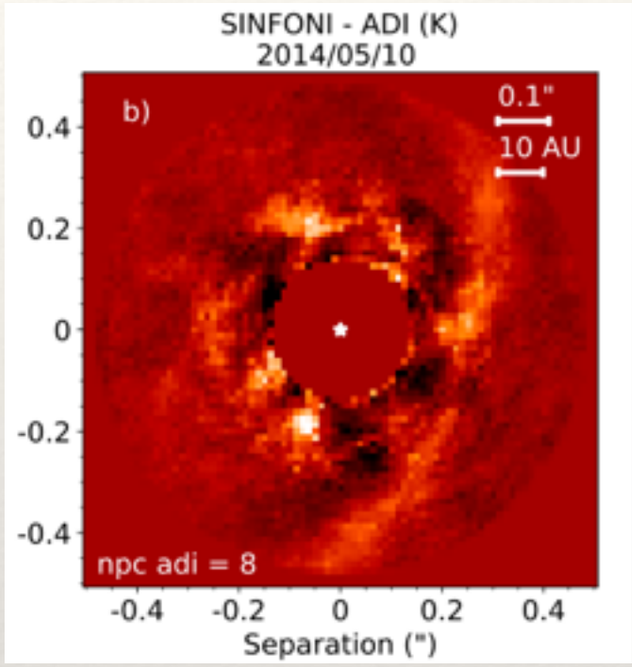
Keppler+2018

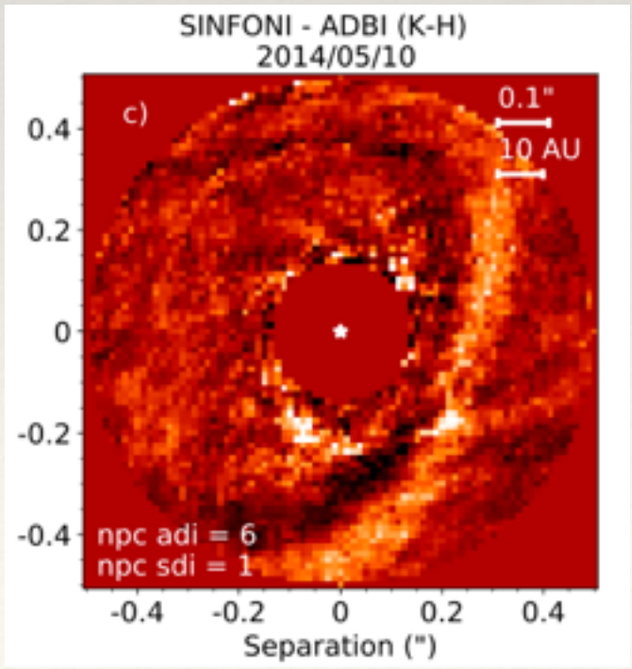
Continuum
0.88 mm



Long+2018

Companion candidate or gap-crossing bridge?





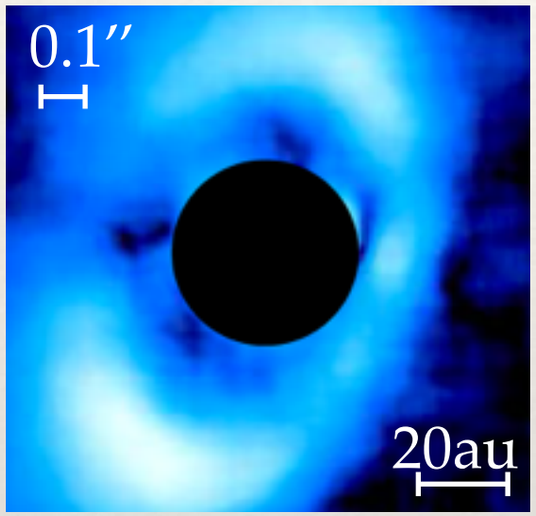
(Christiaens+ 2018b, subm. to MNRAS)

PDS 70 b?

(Keppler+ 2018; Müller+2018)

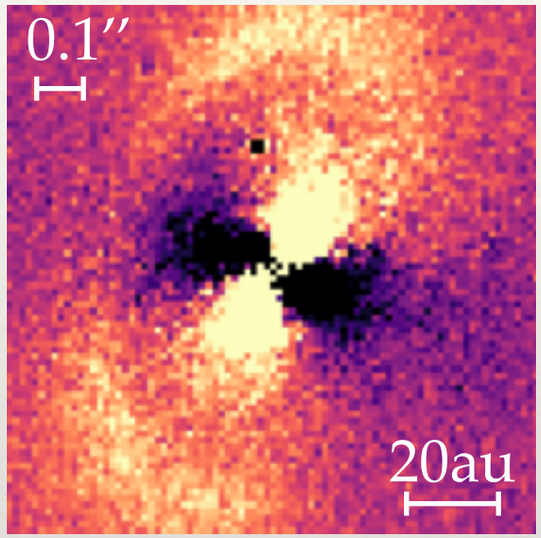
Disk

Polarized light - 1.66 μm



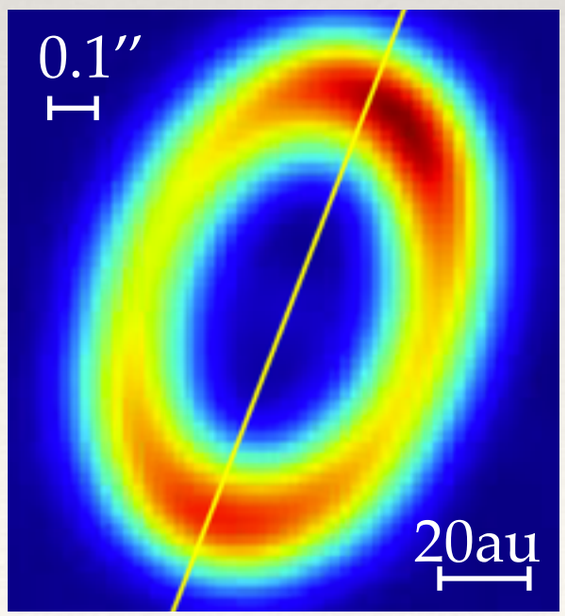
Hashimoto+2012

Polarized light - 1.2 μm



Keppler+2018

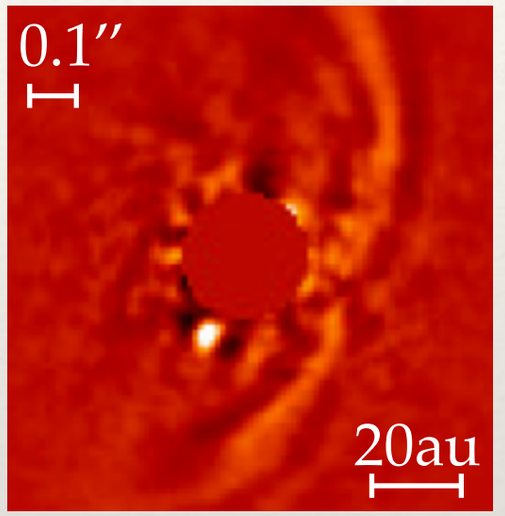
Continuum
0.88 mm



Long+2018

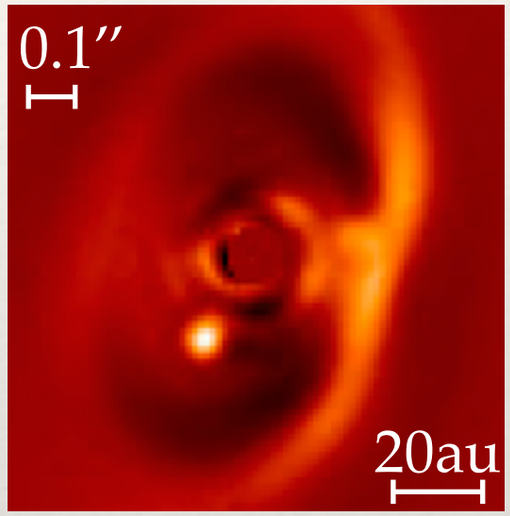
Protoplanet?

PCA-ADI - 2.2 μm

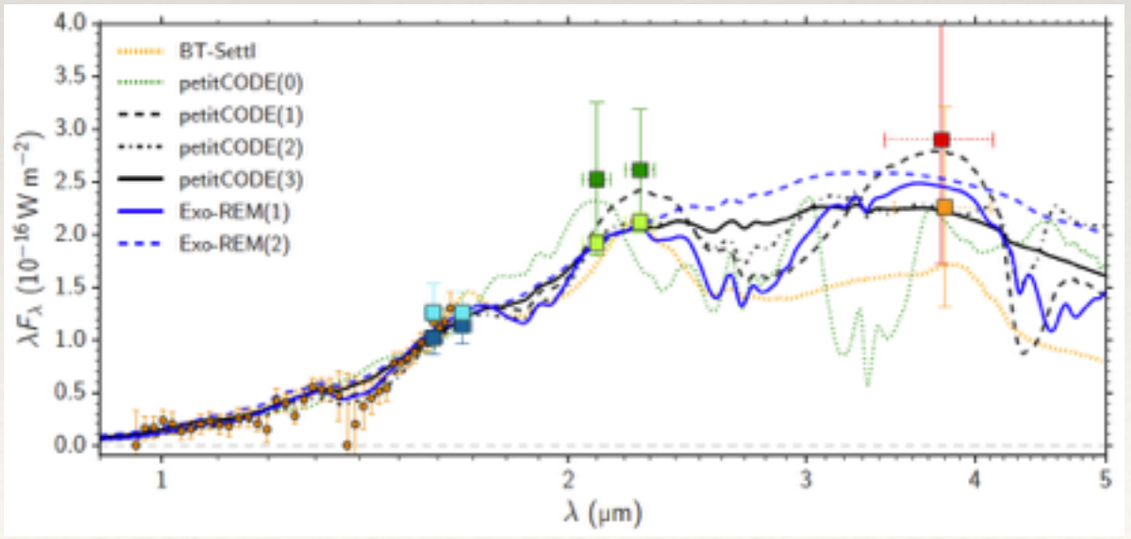


Keppler+2018

m-ADI - 2.2 μm



Müller+2018



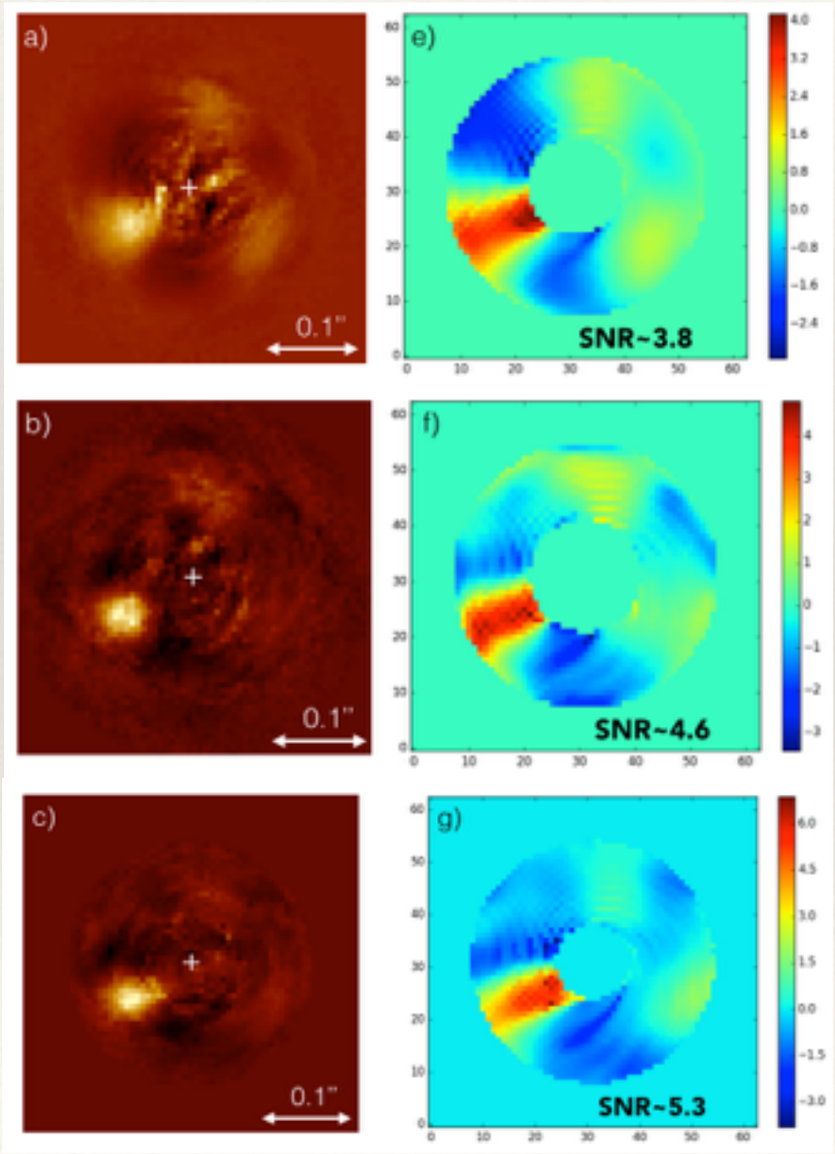
=> 0.2-55 M_{Jup}

Müller+2018

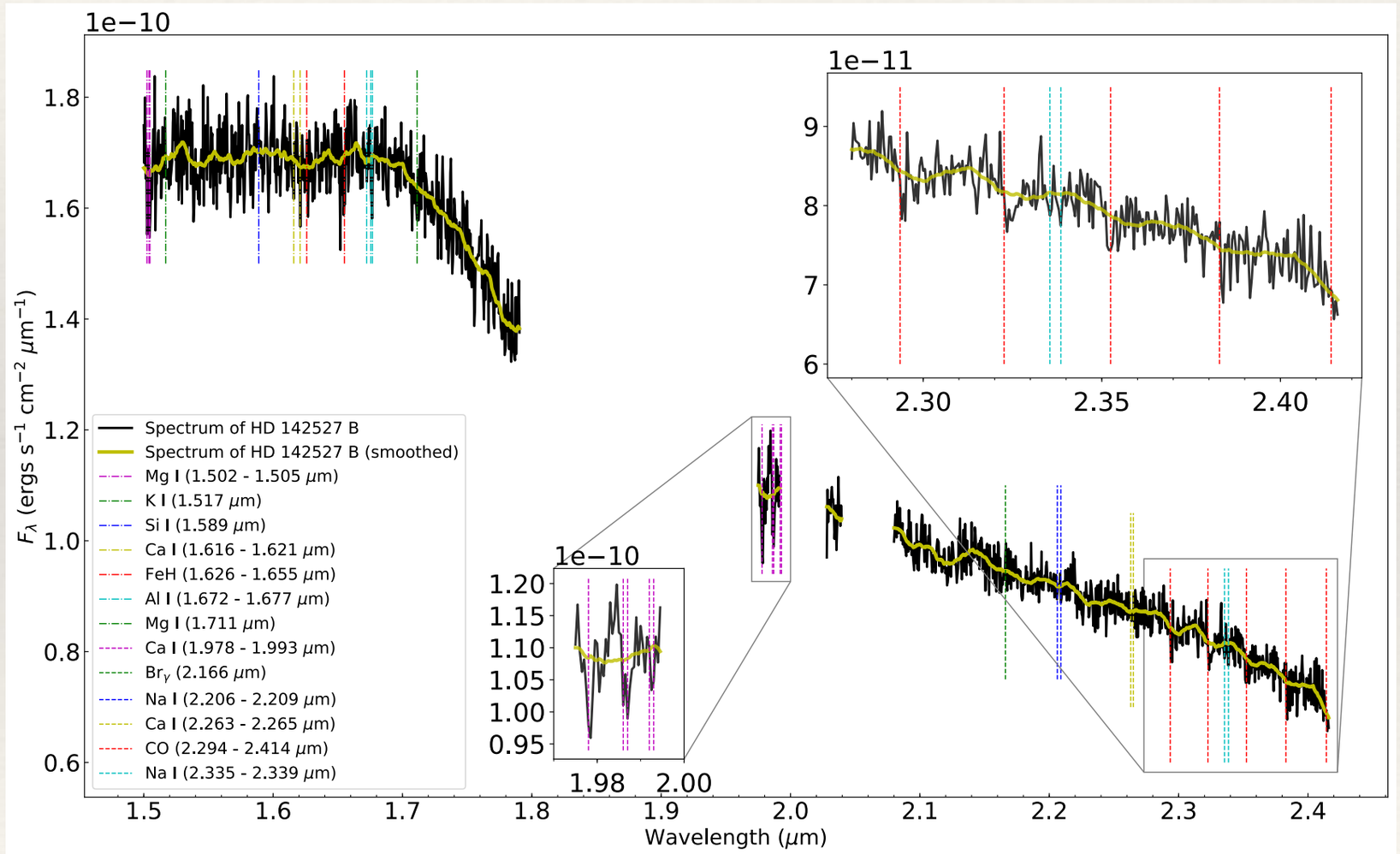
Results of the VLT/SINFONI survey: HD 142527

(Christiaens+ 2018a)

- PCA-ADI: detection in ~2000 individual spectral channels, e.g.:



- First extraction of the medium resolution spectrum of a companion at < 0.1”

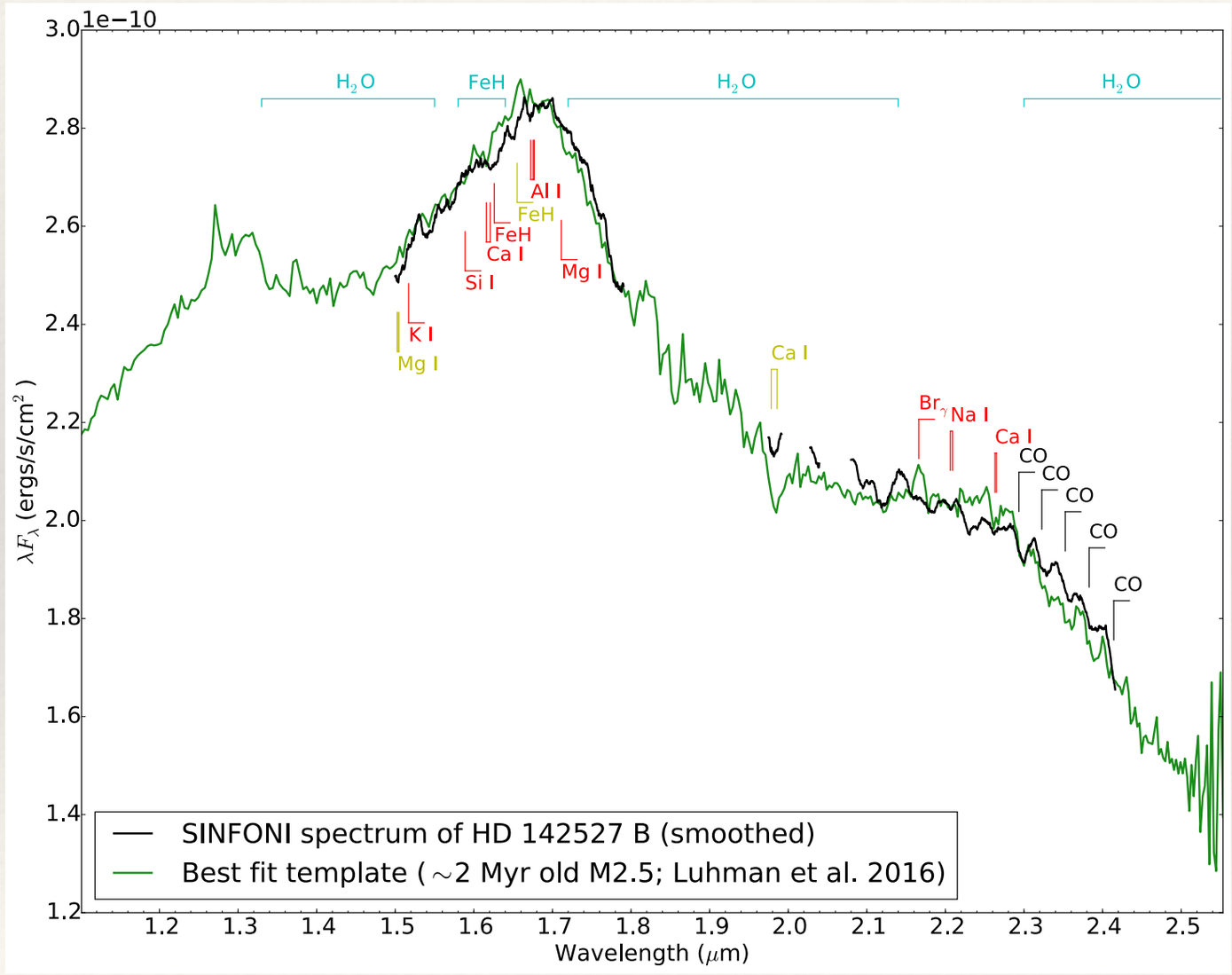


=> Confirmation of first detections in Biller+2012 and Close+2014

Results of the VLT/SINFONI survey: HD 142527

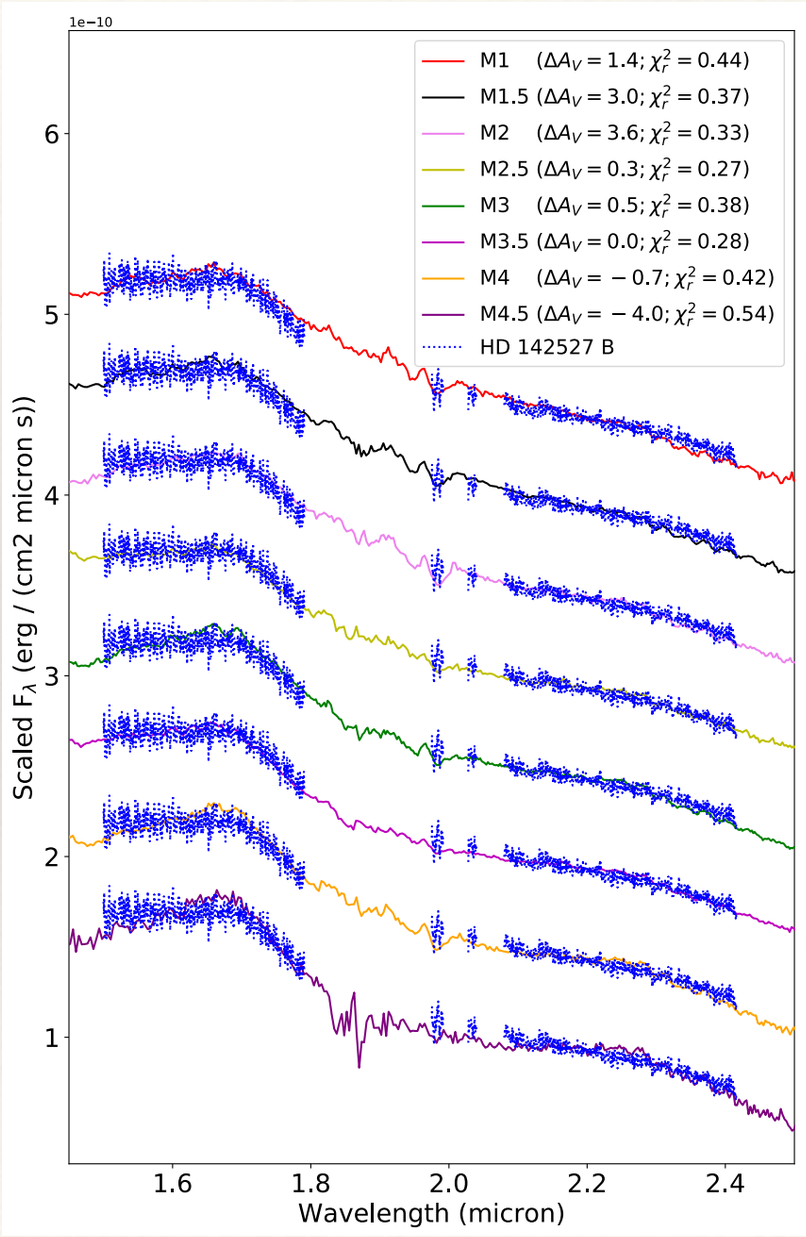
(Christiaens+ 2018a)

- Spectral characterization of the companion
  - Best-fit template spectrum from SpeX library



=> M2.5

- Comparison to a template library



=> M2.5±1.0

Results of the VLT/SINFONI survey: HD 142527

(Christiaens+ 2018a)

- Spectral characterization of the companion
  - Temperature and surface gravity estimated using BT-SETTL synthetic spectra:

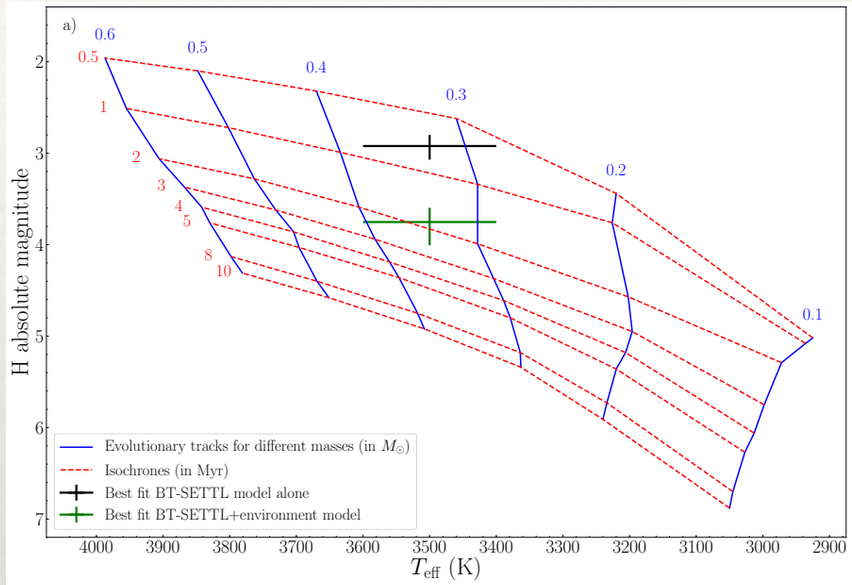
Best-fit photospheric model

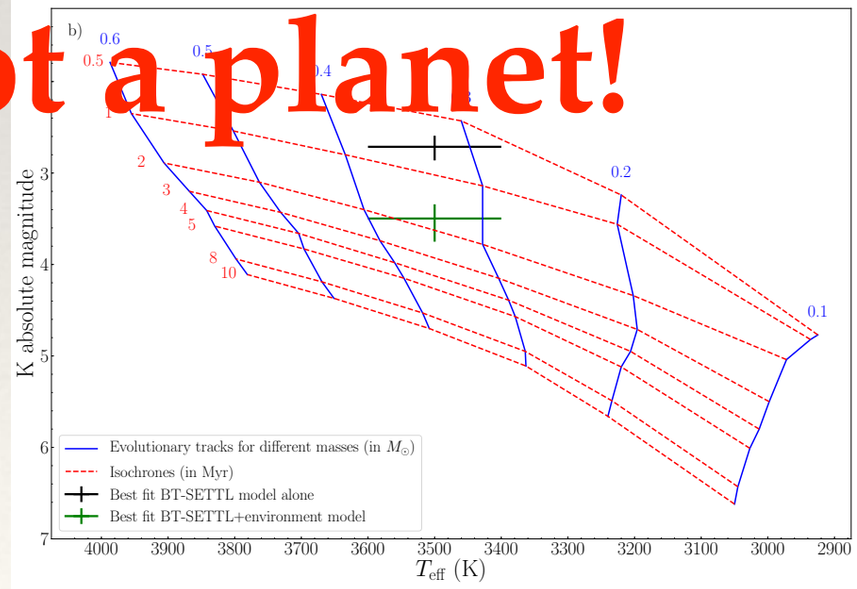
Best-fit model including a hot circum-secondary environment

It's a small star... not a planet!

=> T=3500±100K (T_{envt} ~ 1700K)

- Mass and age estimates based on evolutionary tracks in HR diagrams





=> M~0.35±0.05 M_{Sun}; Age~1–3 Myr

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  - High-contrast imaging of exoplanets
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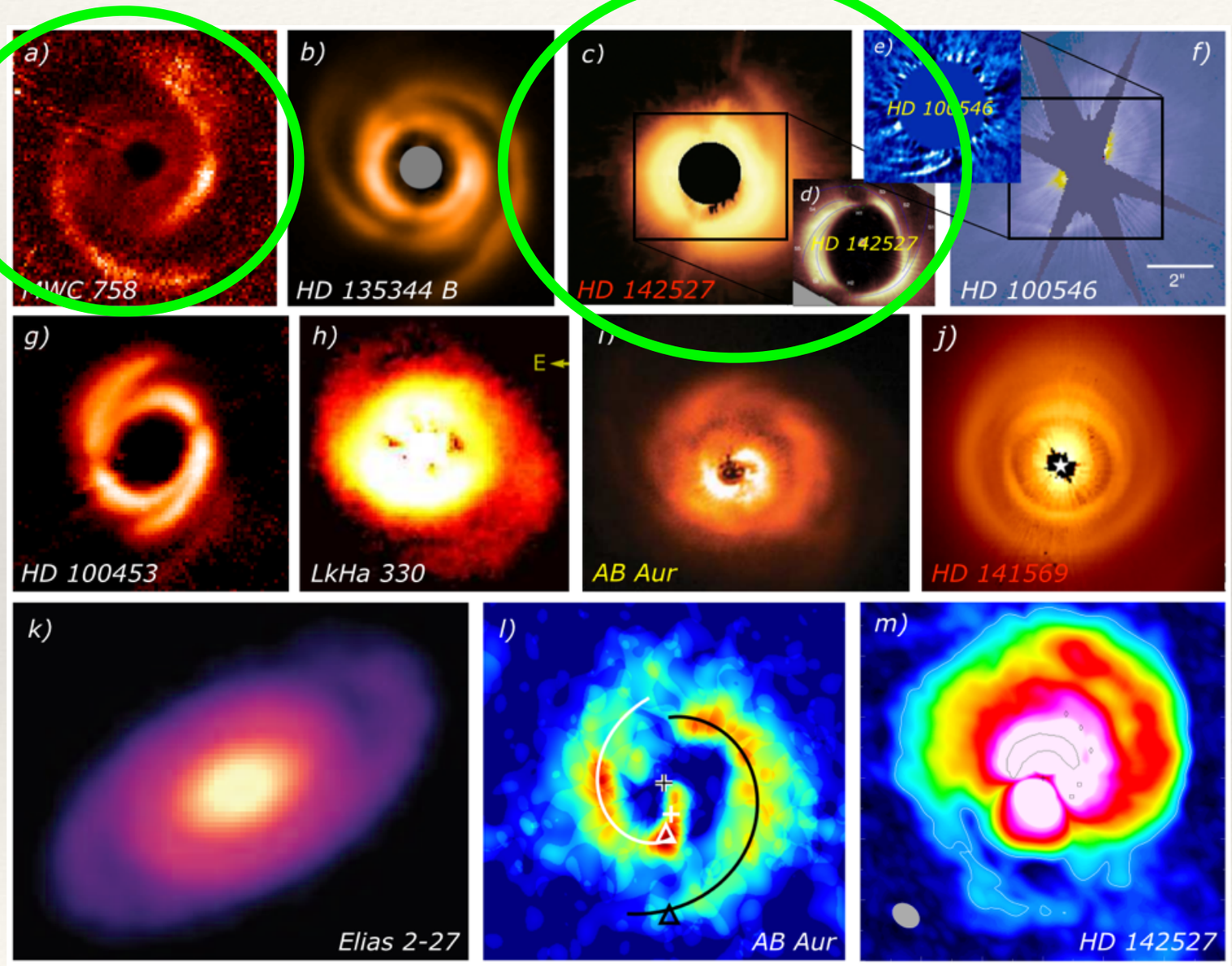
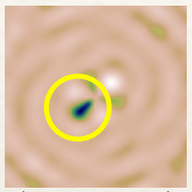
Spiral arms in TDs



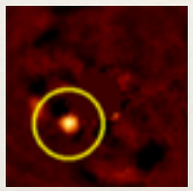
- Companion-induced density waves?
  (Lin & Papaloizou 79, Rafikov 02)
- Gravitational instability?
  (Durisen+07, Tomida+17)
- Stellar flyby?
  (Pfalzner+03, Quillen+05)
- Shadow-induced spirals?
  (Montesinos+16,+18)

IR spiral arms of HD 142527

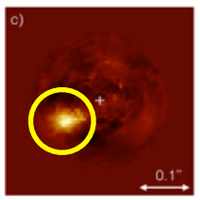
(Price+18)



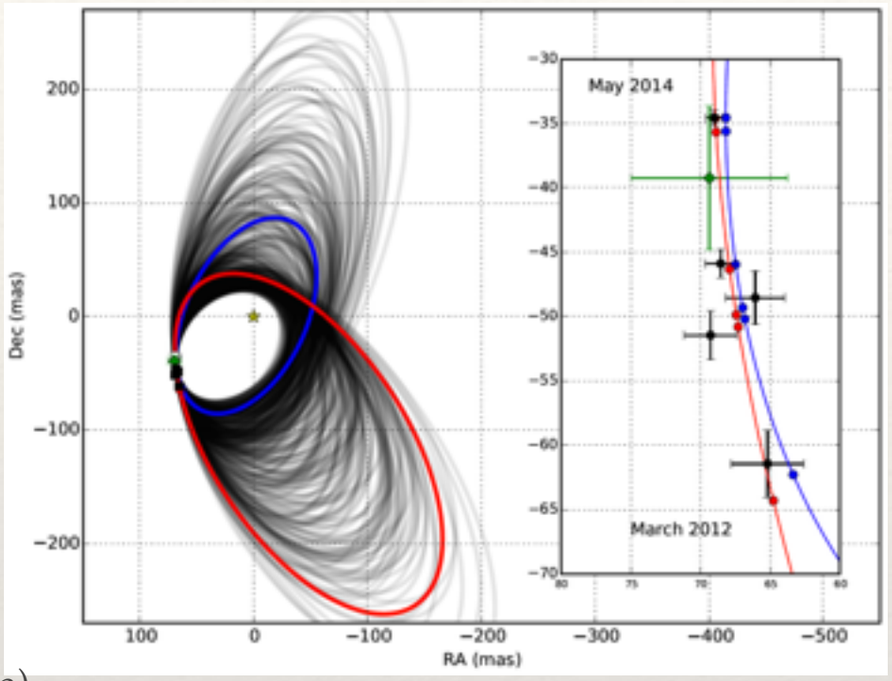
(Biller+12)



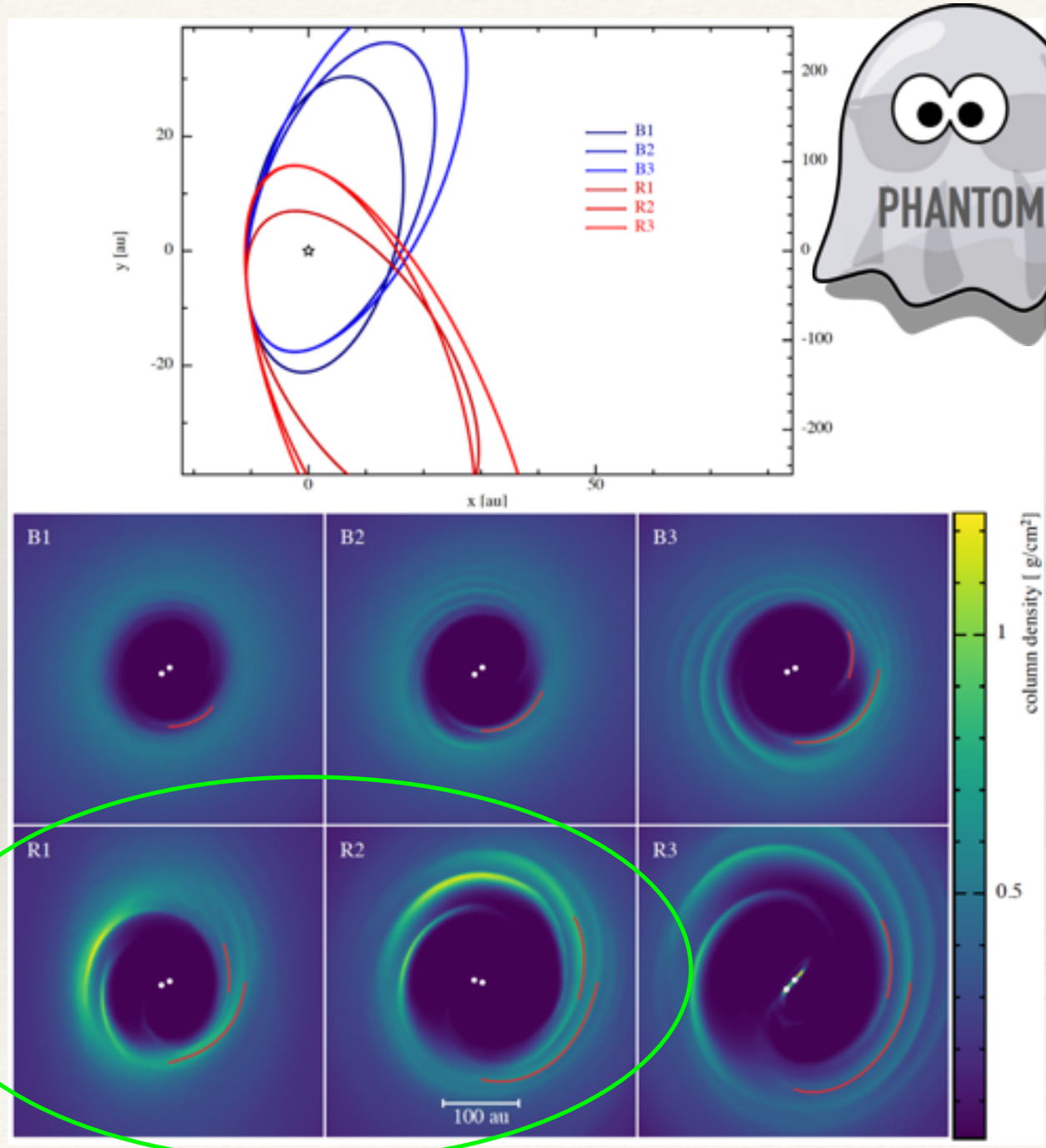
(Close+14)



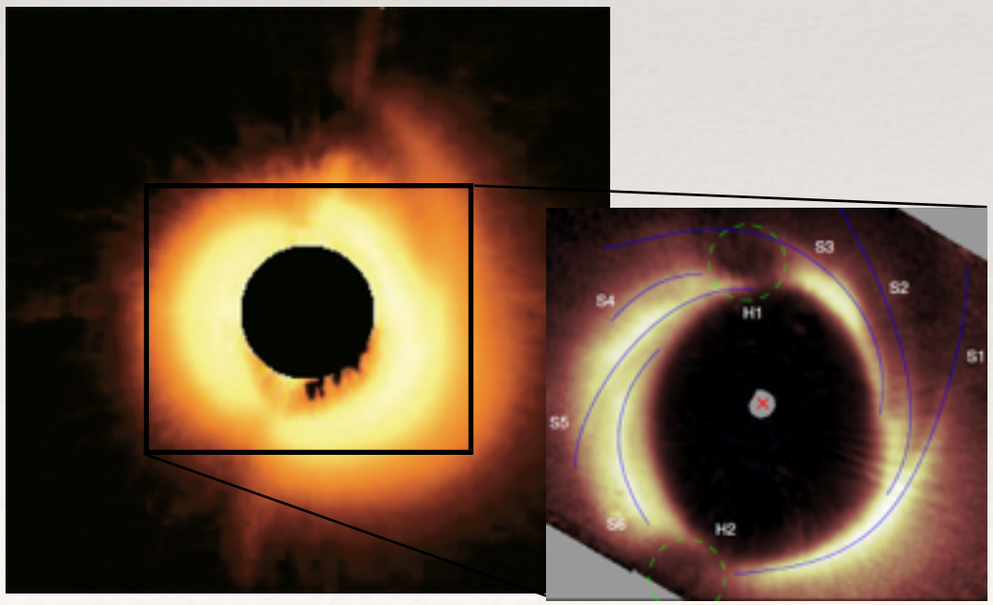
(Christiaens+18a)



Multi-epoch astrometry of the companion (Lacour+16)



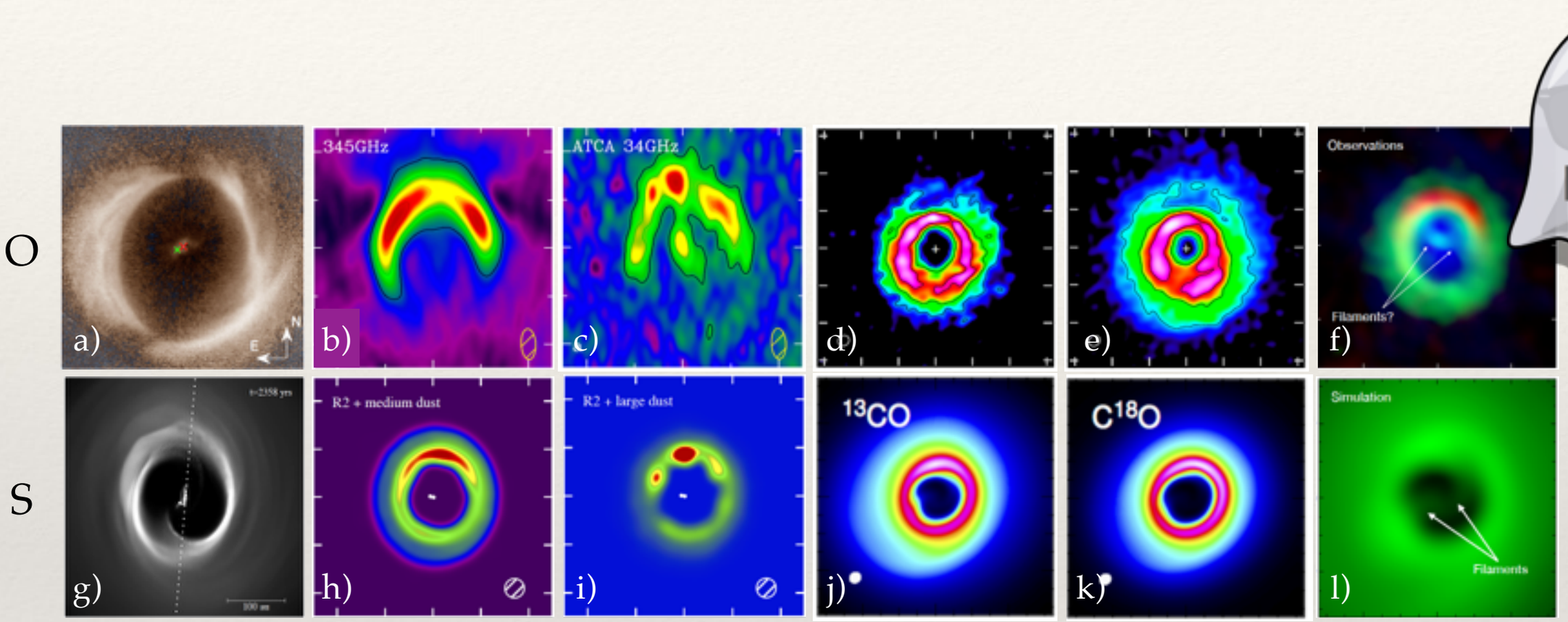
Hydro-dynamical simulations for different orbits of the companion



Observations: spirals and shadows
(Fukagawa+06, Avenhaus+13)

HD 142527: a resolved case

(Price+18)

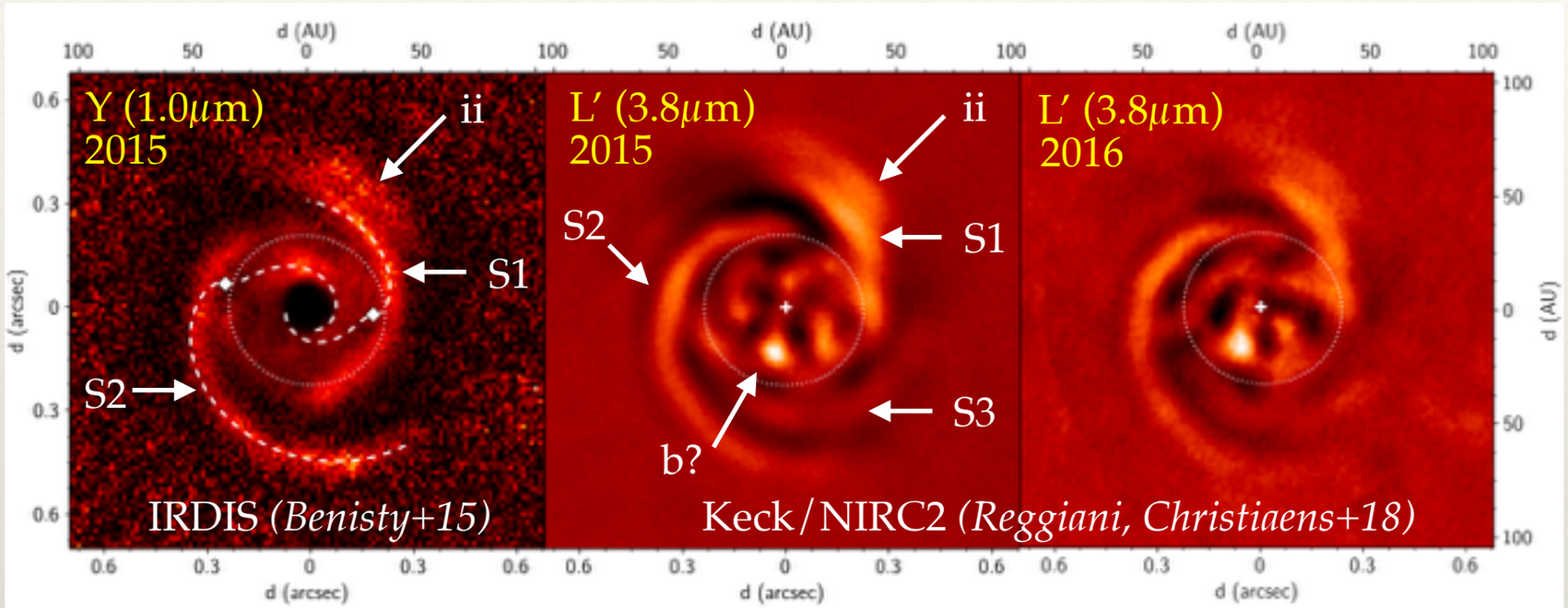


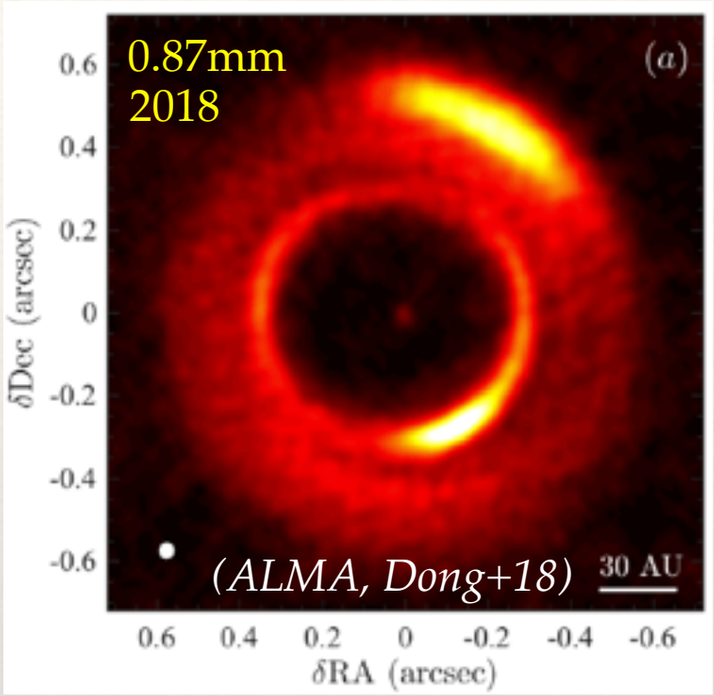
- All features of the disk can be qualitatively interpreted as disk-binary interaction:
  - mm- and cm-size grains crescent-shape distribution
  - CO distribution
  - possible gap-crossing filaments

Spiral arms of MWC 758

(Reggiani, Christiaens+18)

Observations





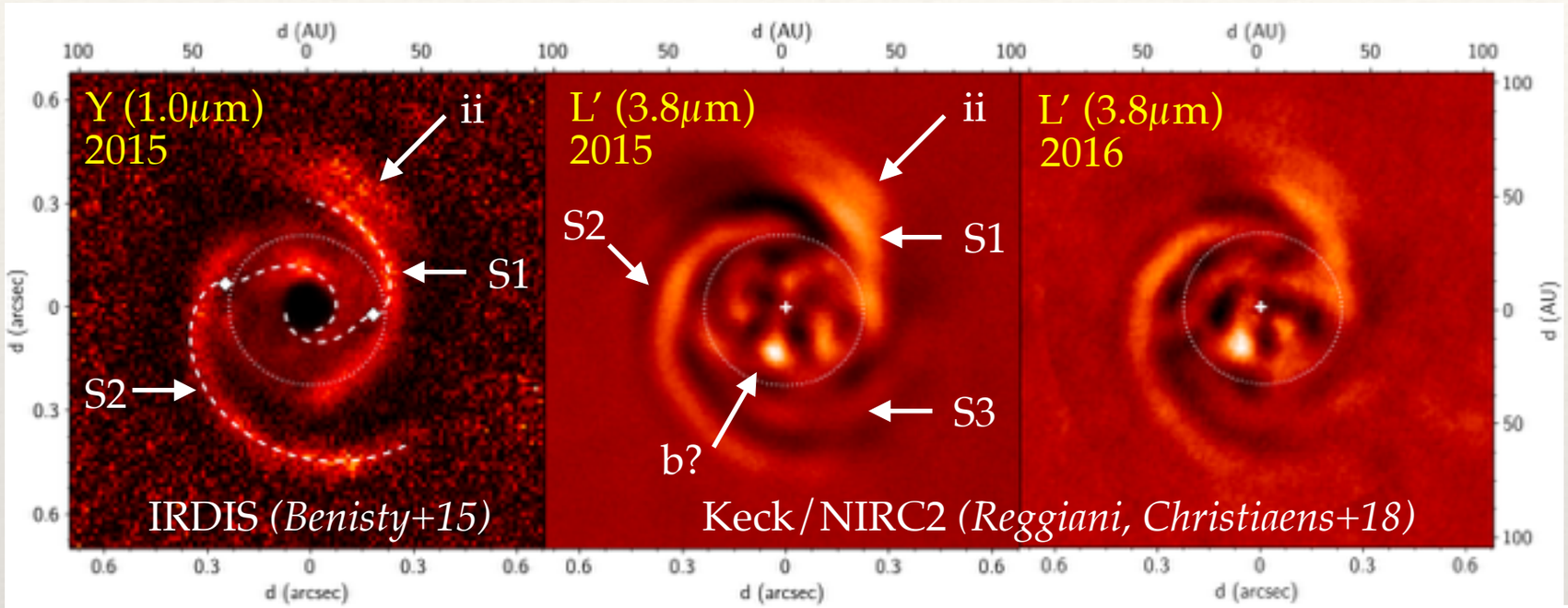
Origin of the spirals?

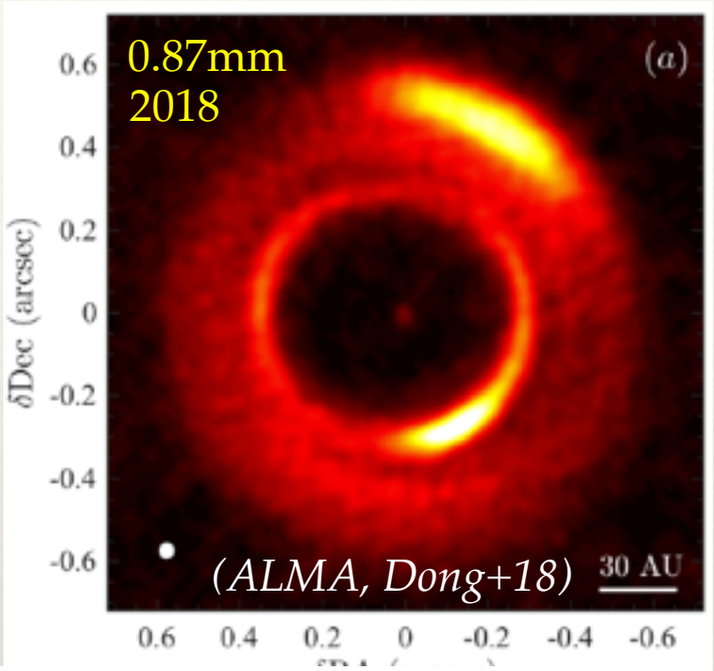
- ~~Gravitational instability?~~
- ~~Shadows/warp?~~
- ~~Flyby?~~
- Embedded giant planet?

Spiral arms of MWC 758

(Reggiani, Christiaens+18)

Observations

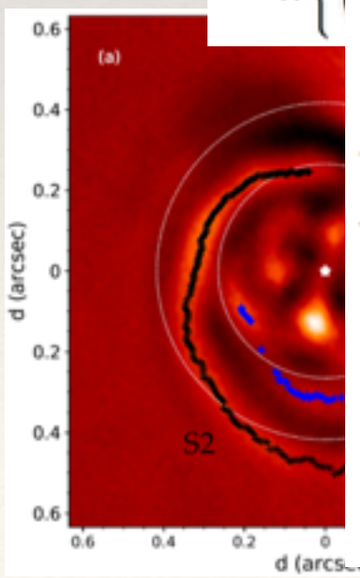


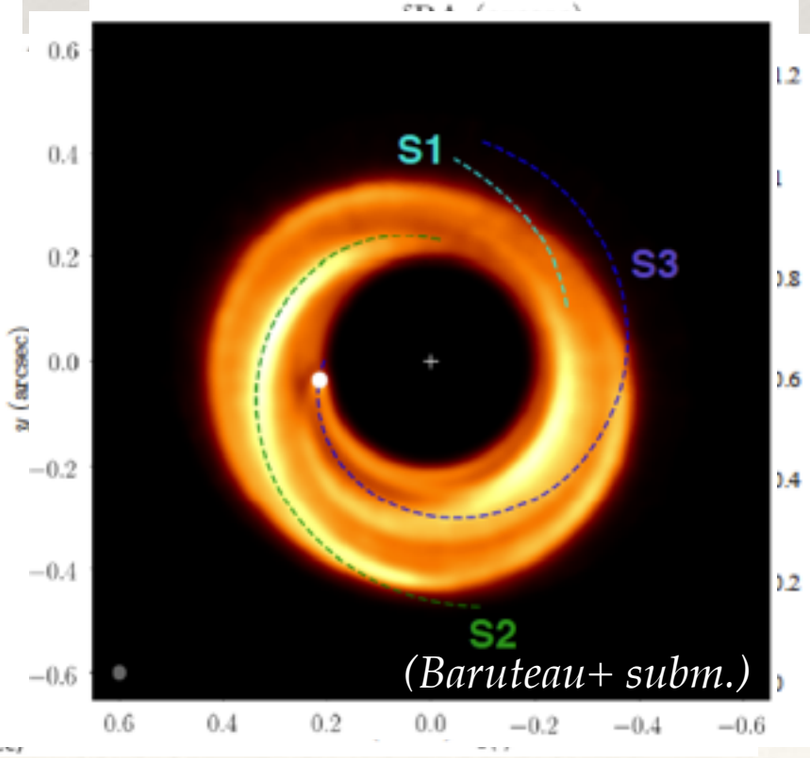


Origin of the spirals - embedded giant planet?

- ~~GP in the cavity on circular orbit?~~
- ~~GP in the outer disk?~~
- (1 GP in the outer disk and 1 in the cavity?)
- GP in the cavity on an eccentric orbit?

$$\theta(r) = \theta_p \times \left\{ \right.$$





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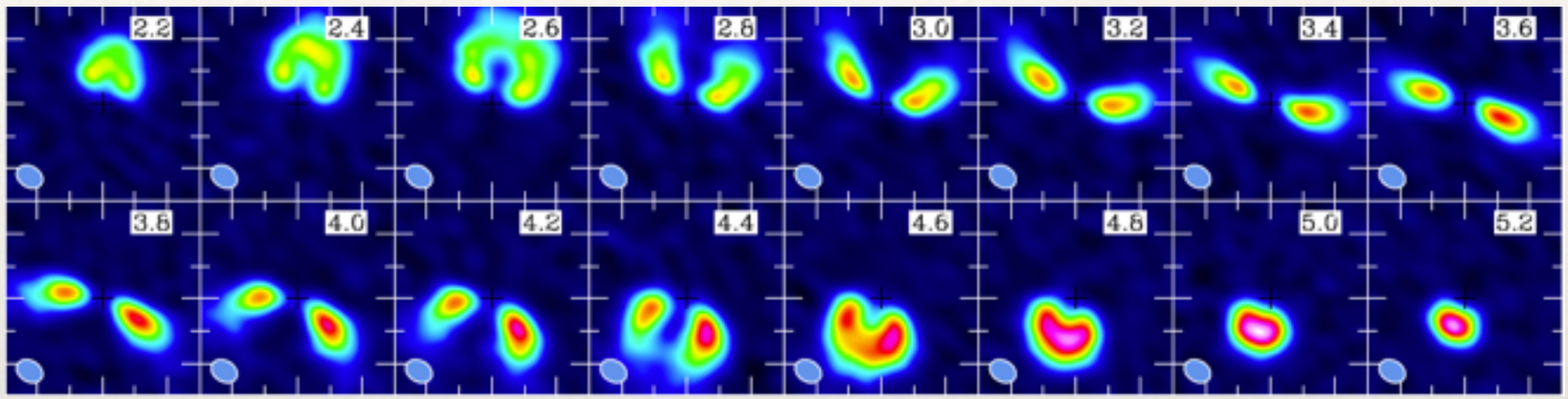
Disk kinematics

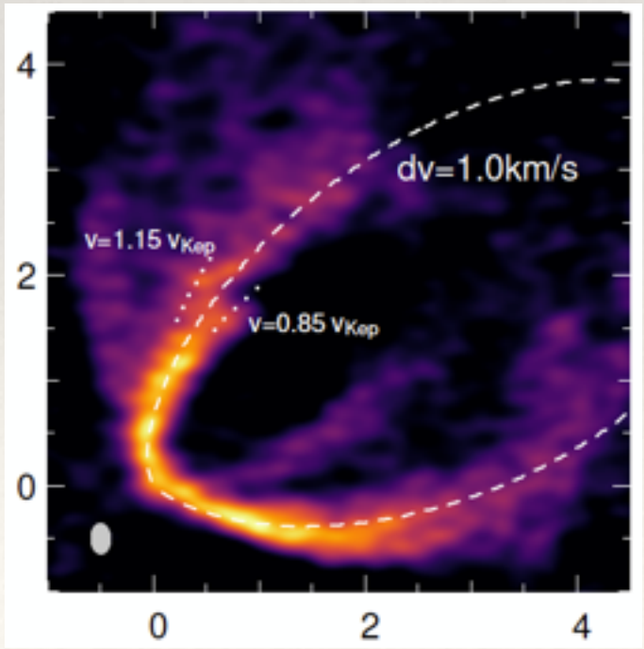
(Perez+15, Pinte+18)

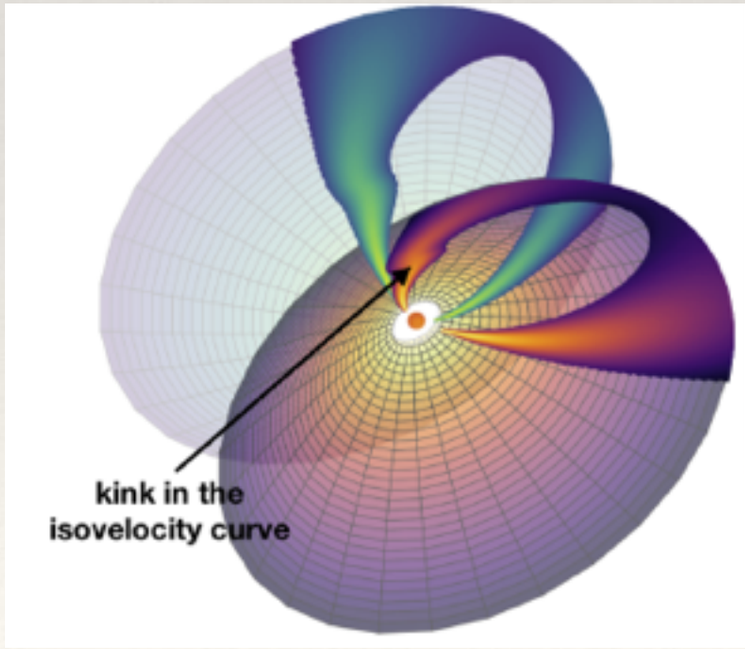
- Channel maps



Perez+15

- **HD 163296 b?**





=> ~2 M_{Jup} @ 290 au

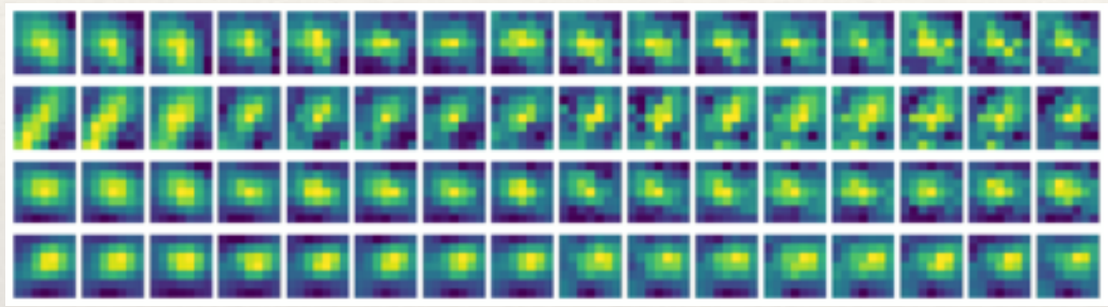
Pinte+2018

Machine learning

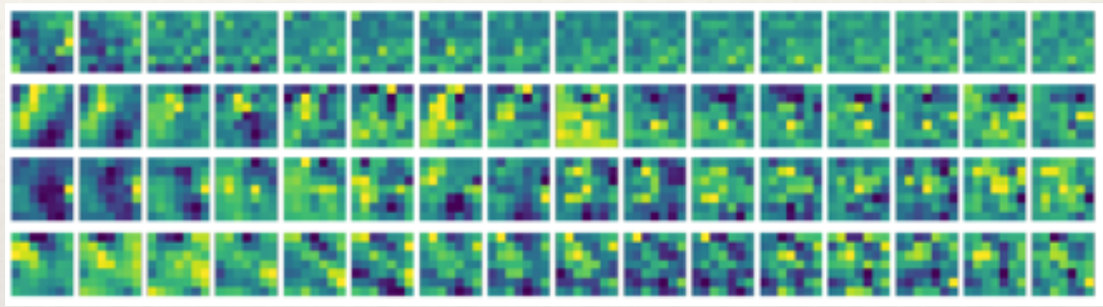
(Gomez Gonzalez+18)

- Machine trained with post-processed patches of images:

Positive samples (companions)

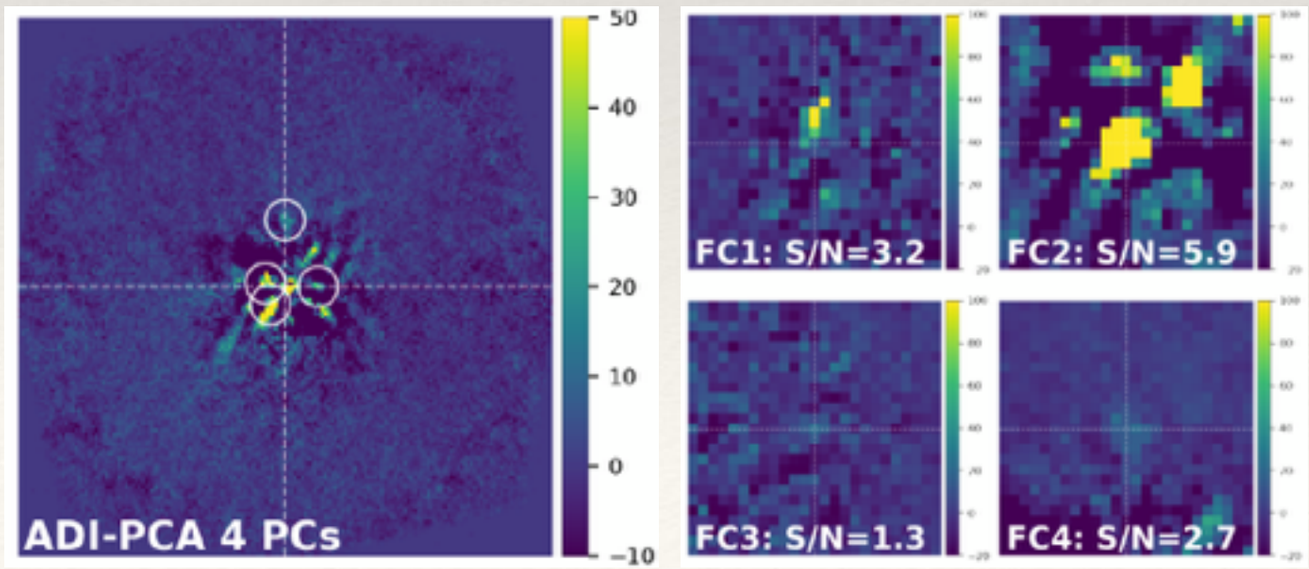


Negative samples (speckle+bkg)

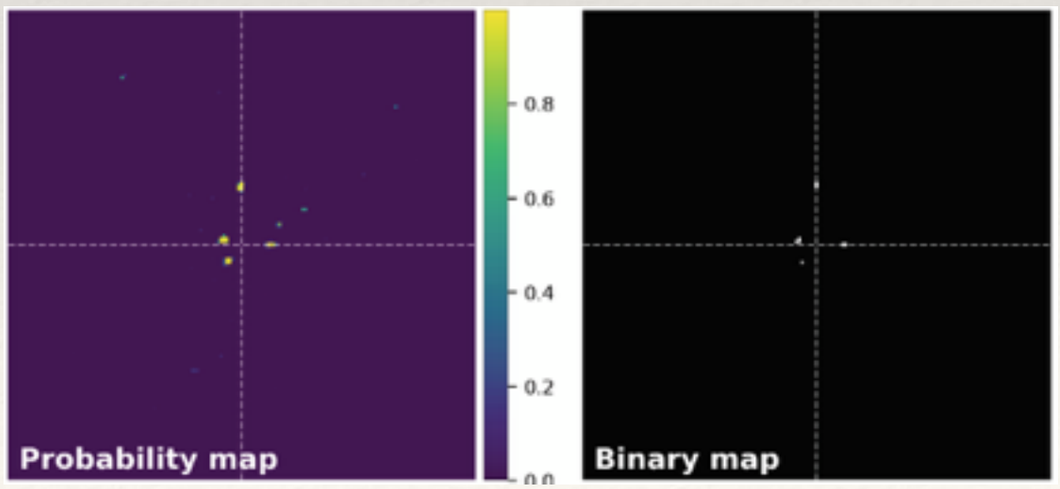


- Comparison to classical post-processing:

PCA-ADI



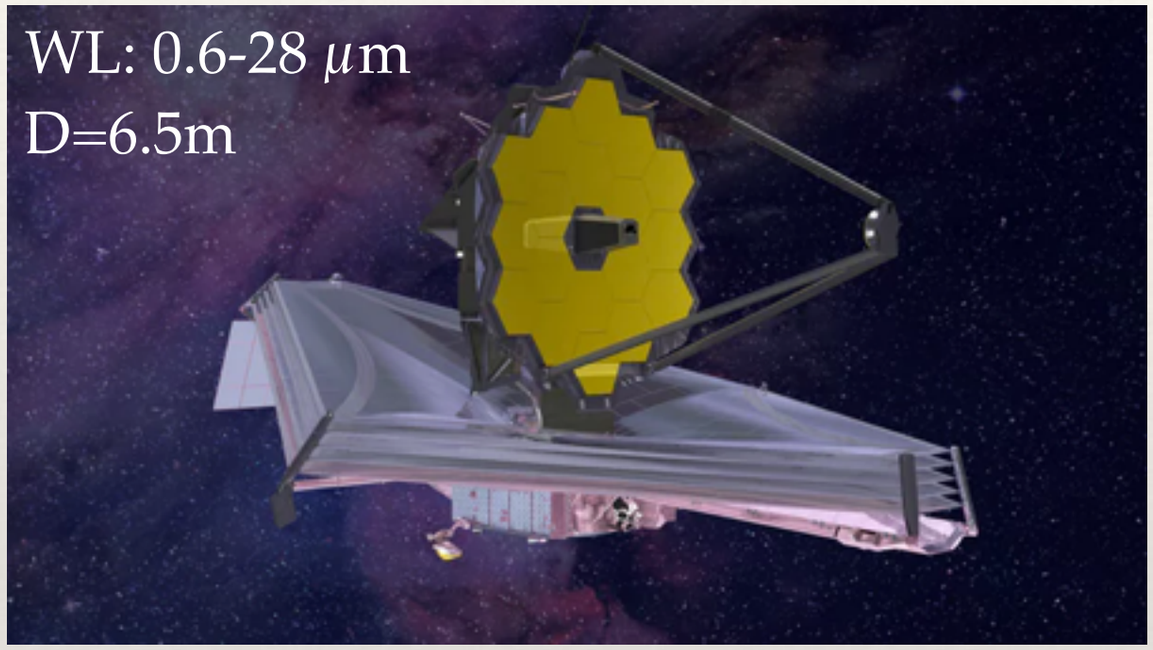
Machine learning



=> 1.0-2.5 mag contrast improvement!

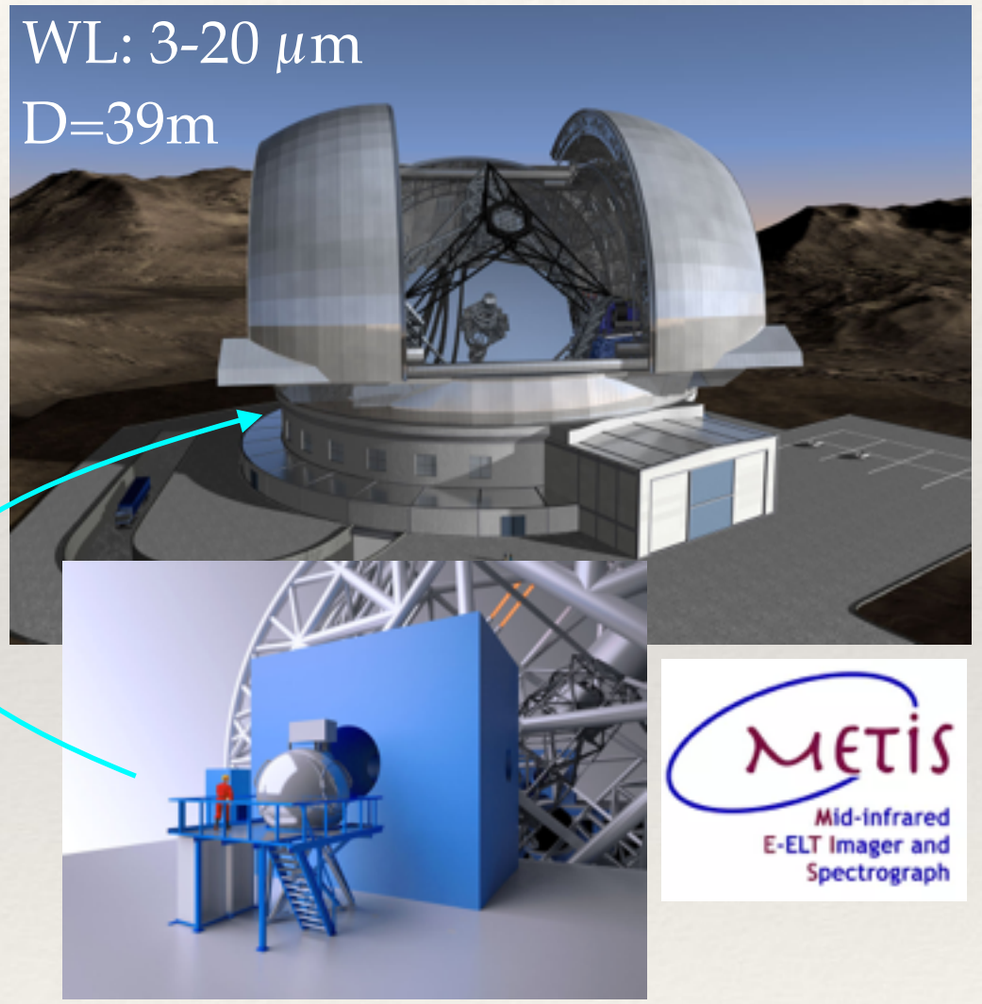
Future instruments

- JWST (?)



- Characterization of protoplanets and young Neptunes far from their star
  - Confirmation of HD 163296 b?

- ELT / METIS (~2025)



- Imaging and characterization of:
  - protoplanets (140 pc)
  - nearby (<10pc) exo-Earths? (Quanz+15)

Take away message

- Puzzle of planet formation?
  - Lot of new results brought with new instrumentation and techniques in the past years.
  - Are TDs carved by embedded GPs or small stars?
  - **Global multi-wavelength and multi-technique approach required!**

DIRECT DETECTION

<u>IR HC imaging</u>

- First detection
- Flux/color measurement

<u>IR spectroscopy</u>

- Spectral characterization
- First estimates of *T*, *M* and age

INDIRECT CONSTRAINTS

<u>IR polarimetric observations</u>

- Imaging of disk features (spirals, gap, asymmetries)

<u>Sub-mm observations</u>

- *Continuum* => imaging of disk features
- *Gas lines* => independent mass estimates from disk kinematics

<u>Hydro-dynamical + RT simulations</u>

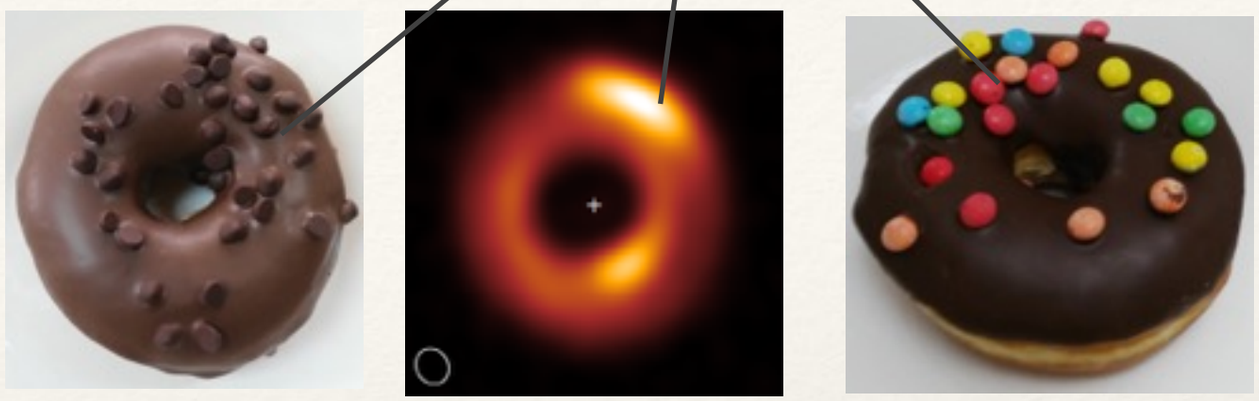
- Reproduction of disk features

=> independent mass and orbit estimates

Transition disks… everywhere

Squares with concentric circles (Kandinsky 1913)

clumps of mm-size grains



asymmetric mm-size grain distribution

residual fluid in the cavity

Thank you for your attention!