Exocomets, planets and resonant phenomena in the β Pictoris disk

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Outline of the talk

1. β Pictoris and debris disks
2. β Pictoris : Dust dynamics
3. Gas in the β Pictoris disk : FEBs (Exocomets)
4. FEBs and resonances
5. β Pictoris and Falling Evaporating Bodies in the presence of β Pic b & c
6. Conclusions

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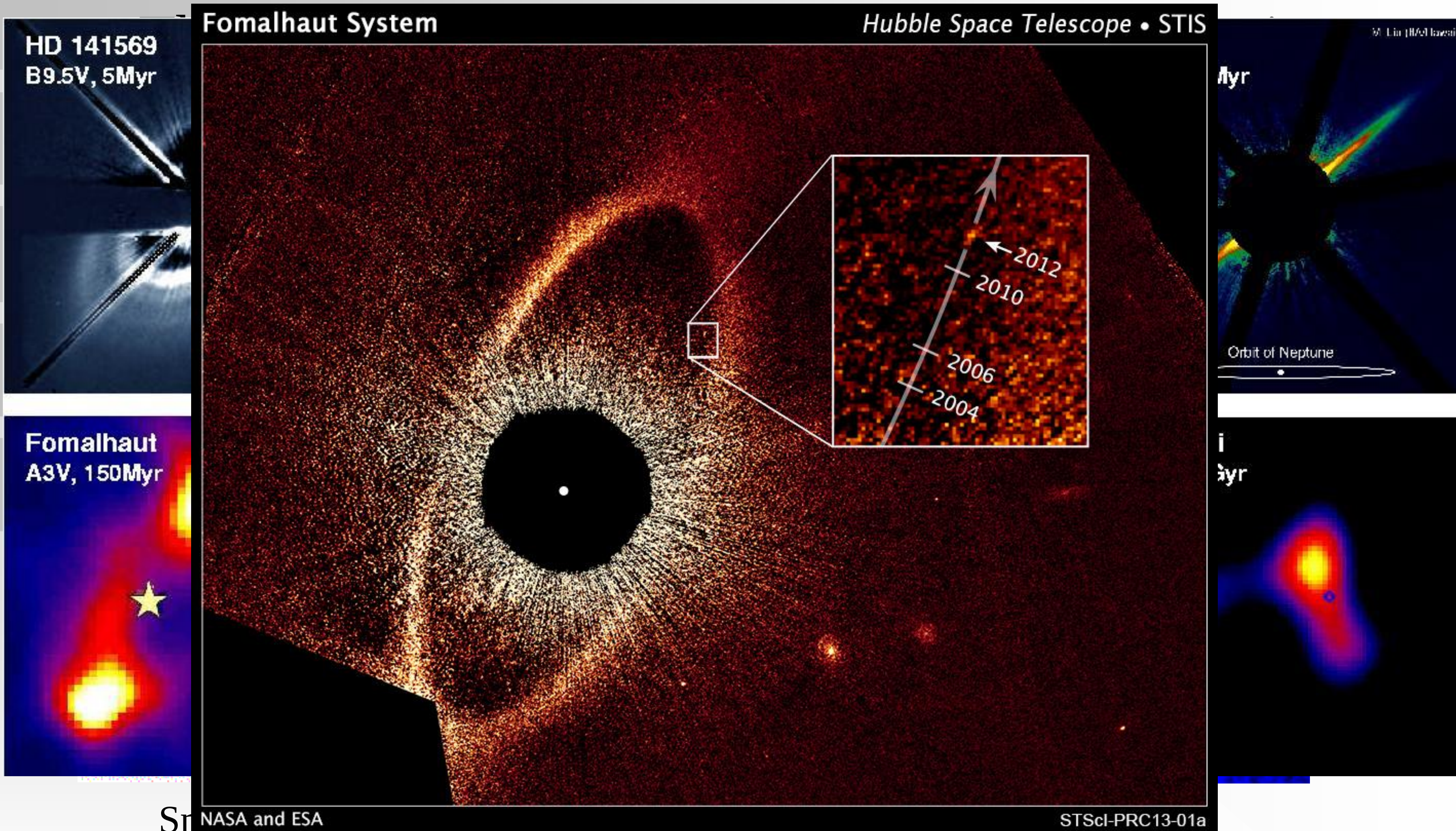
β Pictoris : the star

- An A5V type main-sequence star / $\delta = -51°$
- Magnitude m=3.86
- Mass ~1.75 $M_\odot$, Luminosity = 8.7 $L_\odot$
- Distance = 19.4 pc (Hipparcos) (van Leeuwen et al. 2007)
- Effective Temperature T_{eff} = 8050 K
- Radius ~ 1.7 $R_\odot$; *v*sin i = 130 km/s
- Age ~ 10—20 Myr (β Pic moving group) (Zuckerman et al. 2001; Ortega et al. 2004)
  - Most recent determination : 22±6 Myr (Binks & Jeffries 2014; Shkolnik+ 2017) (Lithium depletion in β Pic moving group)

  → Used to be estimated up to 200 Myr in the past !

β Pictoris : the dust disk



Mouillet et al. 1997

Debris disks

- = Dusty disks imaged around (mostly) young main sequence stars.
- The dust is short lived vs. Collisions & Radiation Pressure ⇒ Need for a reservoir = a disk of planetesimals (parent bodies).
- They nearly all present structures: asymmetries, gaps, warps,spirals… usually associated to the perturbing action of hidden planets.
- Planets have been indeed detected associated to some of them (β Pictoris, Fomalhaut, HD106906…)
- ⇒ Debris disks = The visible parts of young planetary systems.
- Dynamics in debris disks = dynamics in young planetary systems
- Solar analogue ~ Kuiper belt & Asteroid belt (=remnants)

Contents of debris disks

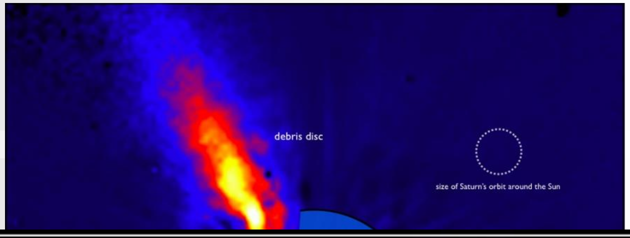
- Dust : the visible part (but short-lived)
- Planetesimals : Necessary as a collisional source of dust
- Planets : Necessary to explain asymmetries
- Circumstellar gas : Not much, but can be seen in absorption in the stellar spectum when the disk orientation is favourable.

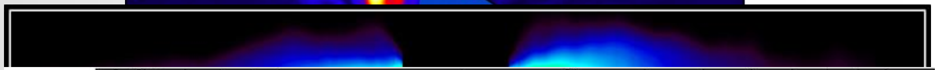
Active processes in debris disks

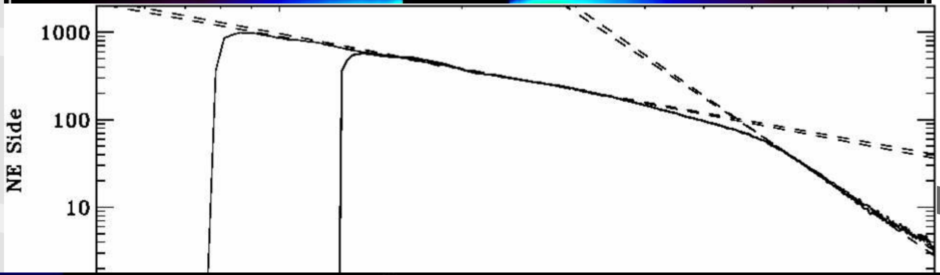
- Gravitational processes : chaotic, secular, resonant; planets (+companions) ⇒ planetesimals ⇒ dust particles ⇒ generation of asymmetries
- Radiative processes : Star ⇒ Dust particles + gas (radiation pressure) ⇒ transport of asymmetries
- Collisional processes : Planets + planetesimals ⇒ generation of dust ⇒ Collisional cascade
- Other : magnetic, sticking…

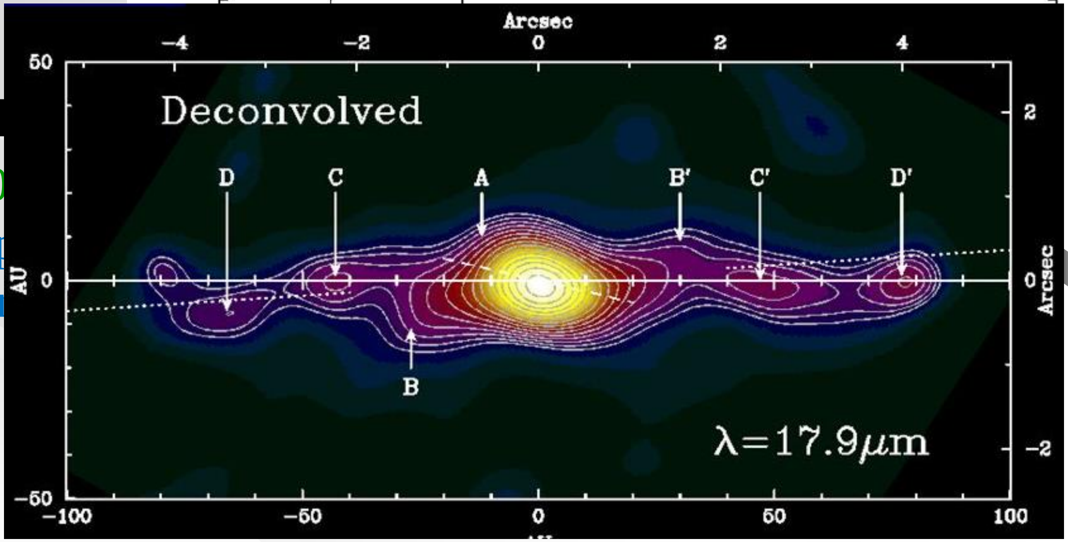
Characteristics of the β Pic disk

- Extending over hundreds of AUs
- The imaged dust is not primordial (Radiation pressure/ collisional erosion; Thebault et al. 2003)
  - ⇒ Need for an internal reservoir
  - ⇒ Disk of colliding planetesimals
- Many asymmetries between both branchs + warp inner part / outer part
  - ⇒ Indication of gravitational perturbations
- Dual power law radial profile wit break at ~120 AU (Heap et al. 2000
  - ⇒ Model : Disk of planetesimals u 120 AU + radiation pressure (Auge et al. 2001)
- Deconvolution ⇒ Many rings ? (Wahhaj et al. 2003)









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β Pictoris : Dust dynamics

- The dust particles are subject to gravity + radiation pressure + collisions/erosion + Poynting-Robertson drag
- Stellar radiation pressure : For any particle,

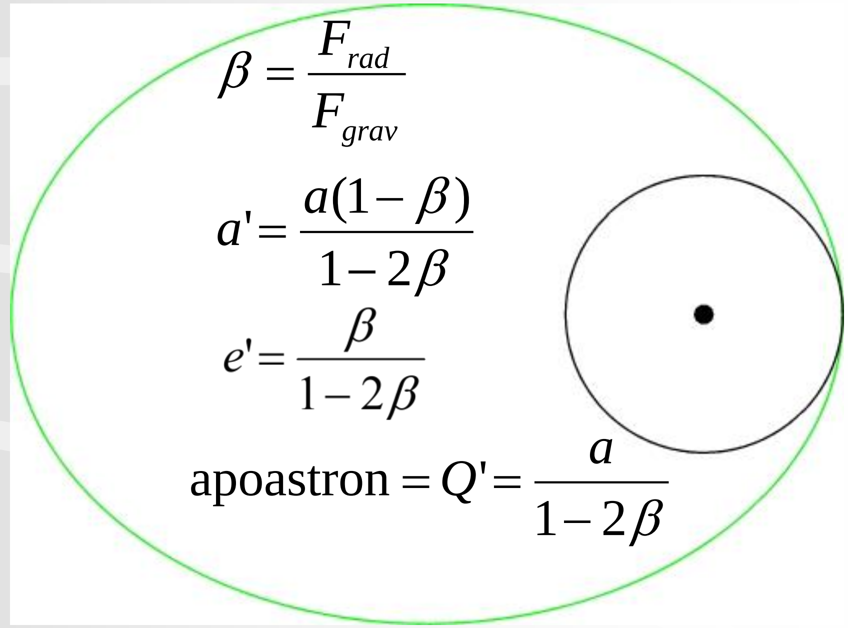
$$F_{\mathrm{grav}} \propto \frac{1}{r^2} \quad \text{and} \quad F_{\mathrm{rad}} \propto \frac{1}{r^2} \Rightarrow \beta = \frac{F_{\mathrm{rad}}}{F_{\mathrm{grav}}} = \text{constant}$$

$$\Rightarrow \quad \ddot{\vec{r}} = -\frac{GM_*(1-\beta)}{r^3}\vec{r}$$

- Under the action of radiation pressure, each particle follows a pure Keplerian orbit, but feeling an effective central mass $M_*(1-\beta)$

Dust particles orbits

- Dust particles are produced by planetesimals on ~circular orbits (black).
- Due the radiation pressure, they move on another, wider orbit (green)
- Dust particles can be transported very far away, ejected if β > 0.5 .
- This fully explains the radial profile of β Pic's disk : The 120 AU break corresponds to the edge of the planetesimal belt
- Asymmetries in the parent bodies distribution (due to planets…) are transported outwards this way.



$$\beta = \frac{F_{rad}}{F_{grav}}$$

$$a' = \frac{a(1-\beta)}{1-2\beta}$$

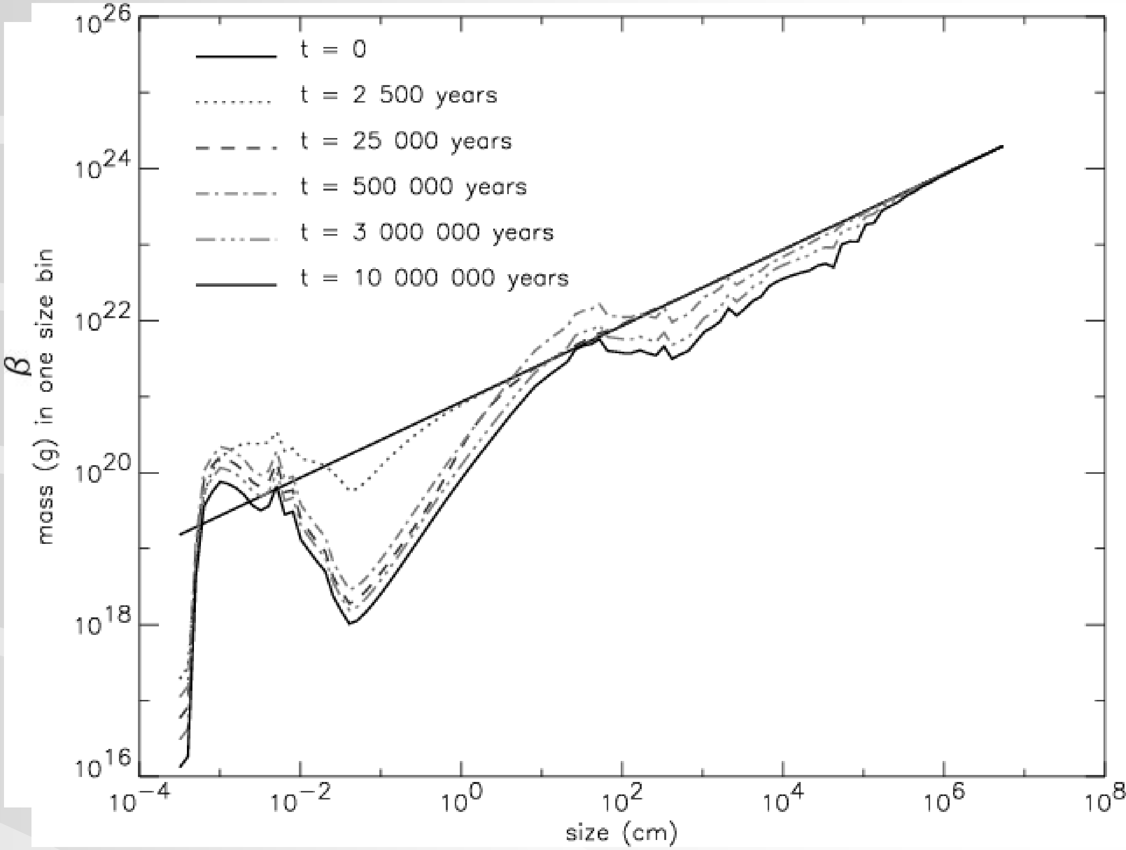
$$e' = \frac{\beta}{1-2\beta}$$

$$\text{apoastron} = Q' = \frac{a}{1-2\beta}$$

Lecavelier et al. (1996)
Augereau et al. (2001)

β values

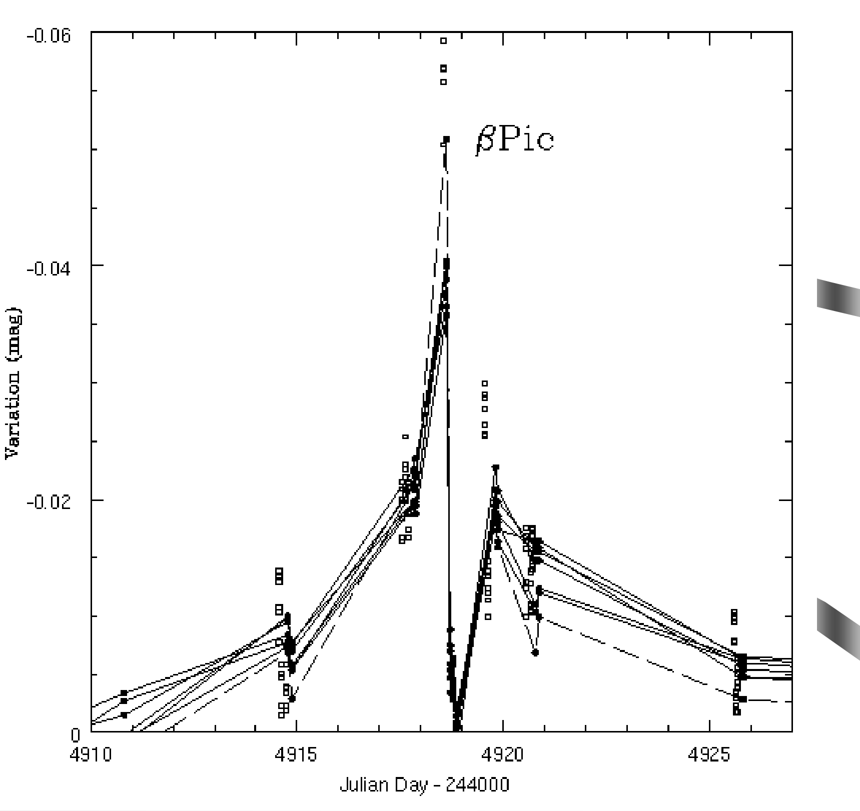
- β depends on the grain size. For large grains, $\beta \propto r^{-1}$
- For A type stars like β Pic, all grains below a threshold size are ejected.
- Due to erosion, smaller grains are continuously produced and ejected.
- Consequence : Wavy size distribution
- Need for a reservoir to replenish the disk.



Thébault et al. (2003)

β Pictoris before β Pic b and c : Clues for the presence of planets

- The various asymmetries….
- The rings ?
- The inner warp : could be caused by an inclined planet (Mouillet et al. 1999; Augereau et al. 2001)
- The « transit » = A photometric event in November 1981 ⇒ Transit of the Hill sphere of a Jovian planet at ~10 AU ? (Lecavelier et al. 1996)
- The star-grazing exocomets (FEBs)



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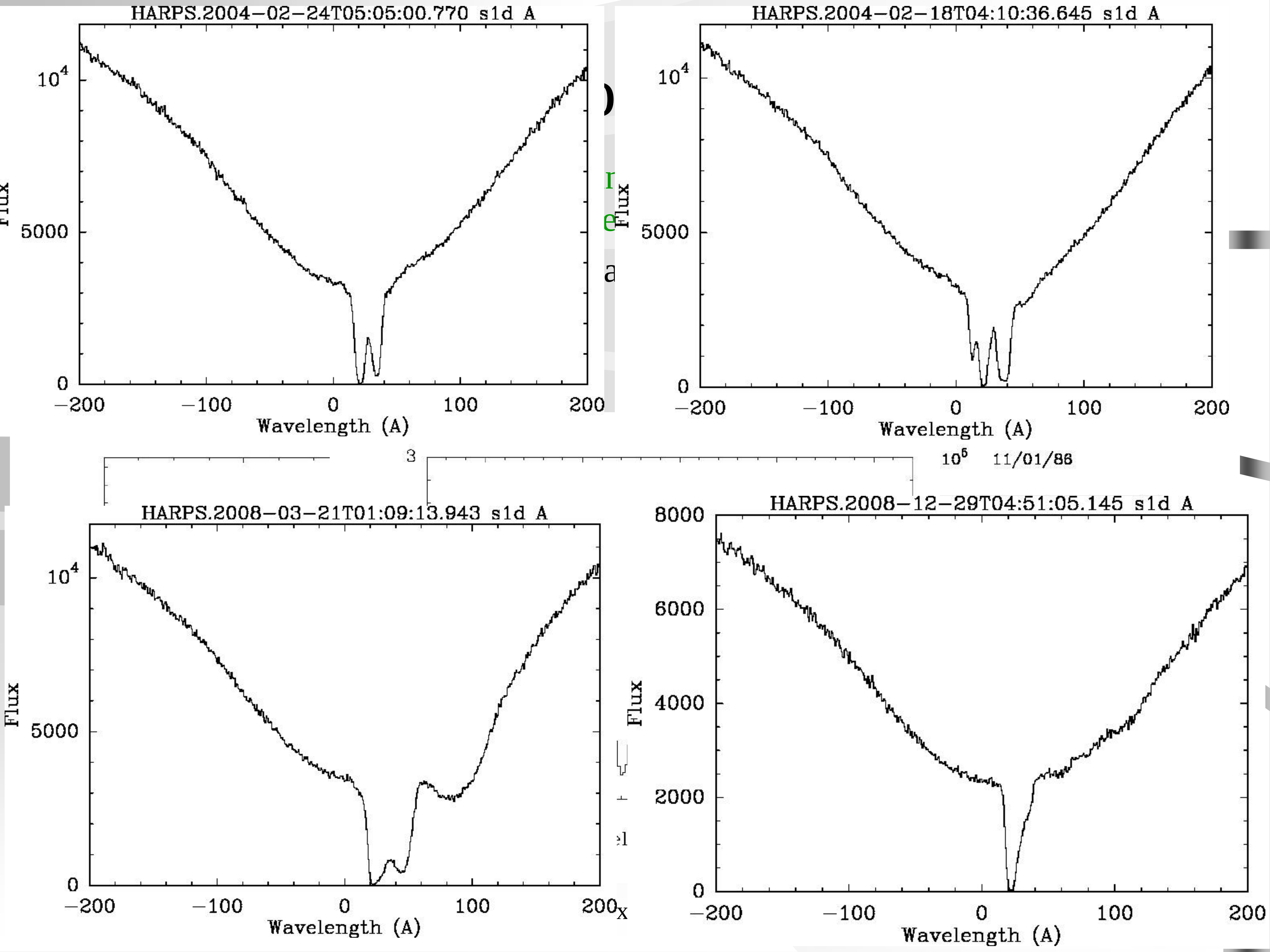
Gas in the β Pictoris disk

- Circumstellar gas is detected in absorption in the spectrum of the star (thanks to edge-on orientation) : C, Na, Mg, etc… (Roberge et al. 2006), H I, H_2 (Freudling et al. 1995; Lecavelier et al. 2001), O (Brandeker et al. 2016)
- Most ionized species in Keplerian motion, despite strong radiation pressure
- The abundance of Carbon can render the whole gas self-braking (Fernandez et al. 2006; Brandeker 2011)
- Different species at different latitudes in the outer disk (Na I in the mid-plane, Ca II above (Brandeker et al. 2004)

- Model : The gas is not primordial (as the dust). The gas disk must be continuously replenished from a inner reservoir, by evaporating planetesimals (Lagrange et al. 1998), or by grain-grain collisions or photodesorption (Kral et al. 2015)


HARPS.2004-02-24T05:05:00.770 s1d A
HARPS.2004-02-18T04:10:36.645 s1d A
HARPS.2008-03-21T01:09:13.943 s1d A
HARPS.2008-12-29T04:51:05.145 s1d A
Flux
Wavelength (A)
10^4
5000
0
8000
6000
4000
2000
−200
−100
100
200
11/01/86

Characteristics of the transient events

- Detected in many spectral lines, but not all (Ca II, Mg II, Al III…) : only moderately ionized species (Ferlet+ 1987; Lagrange+ 1992; Vidal-Madjer+ 1994; Petterson & Tobin 1999; Kennedy 2018; Tobin+ 2019; Pavlenko+ 2021)
- Most of the time reshifted (tens to hundreds of km/s), but some blueshifted features
- The higher the velocity, the shorter the variation time-scale
- Comparison between features in doublet lines → saturated components that do not reach the zero level → The absorbing clouds do not mask the whole stellar surface
- ~Regularly observed for >30 years, but their bulk frequency is erratic

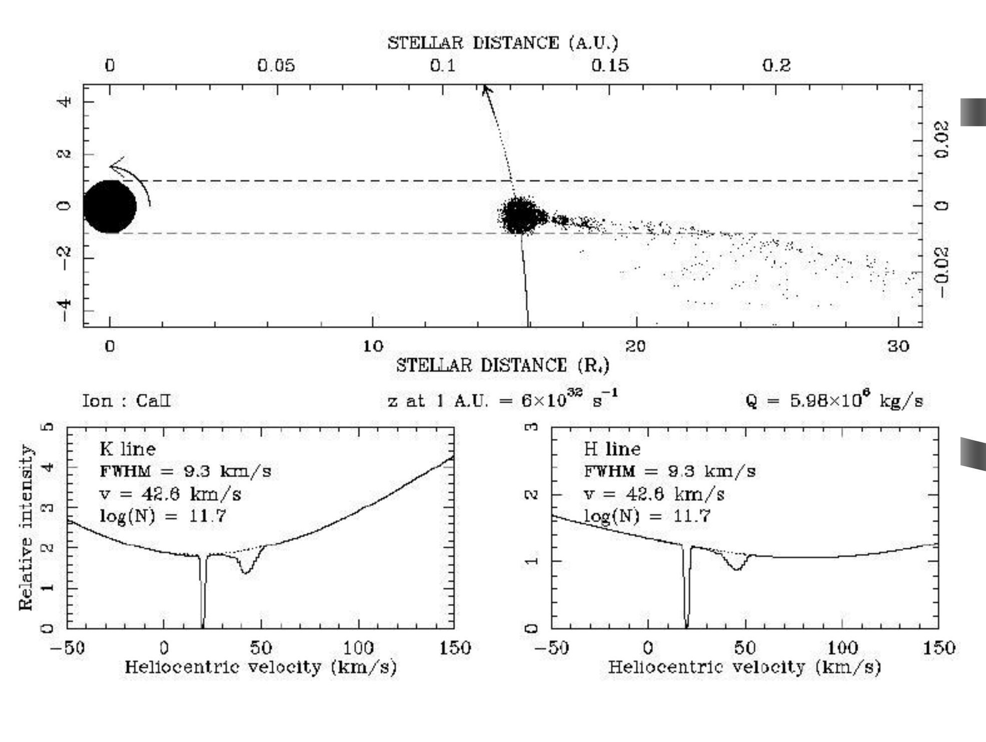
The FEBs (=exocomets)
(*Falling Evaporating Bodies*) scenario

(Beust et al. 1990, 1995, 1998…)

- Each of these events is generated by an evaporating body (comet, planetesimal) that crosses the line of sight.
- These objets are star-grazing planetesimals (comets) (<0.5 AU).
- At this short distance the dust sublimates → metallic ions in the coma.
- This model naturally explains :
  - The infall velocities : projection of the velocity onto the line of sight → close to the star
  - The time variability : time to cross the line of sight
  - The limited size of the clouds = size of the coma
  - The chemical issue : not all species are concerned

Physics involved in the FEBs scenario

- The ions are subject to the radiation pressure and to a drift force by the other species
- If the gas composition is carbonaceous enough, il can be self-braking (Fernandez et al. 2006)
- The different kinds of variable features (high velocity, low velocity…) are well reproduced if we let the periastron distance vary.
- The longitude of periastrons are not randomly distributed (predominance of redshifted features)



- Several hundreds of FEBs per year
- Possibly several families of FEBs (Kiefer et al. 2014)
- Question : why so many star-grazers ? What is their dynamical origin ?

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FEB dynamics : How do you generate star-grazers from a disk ?

- A requirement : planetary perturbations ⇨ need for planets !
- Direct scat… …nt and short lived…
- Kozai reso… …eferred orientation…
- Mean-mot… …l
  - Bodies … …vian planet s…
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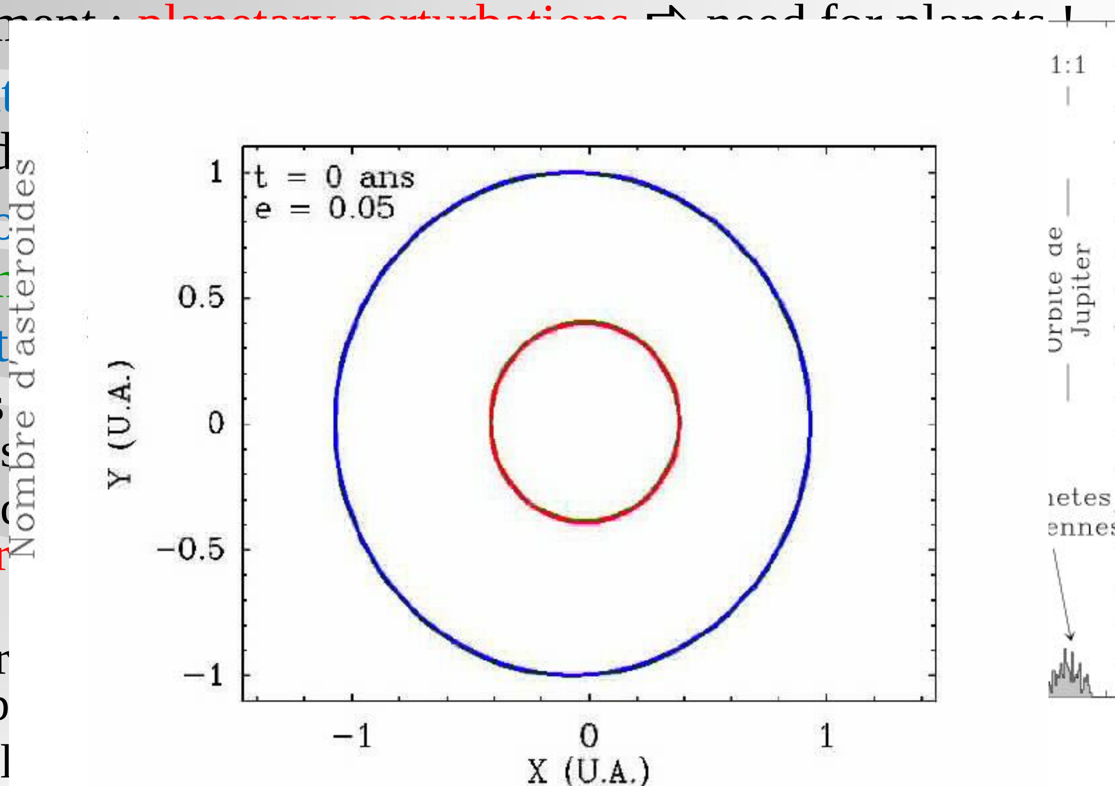
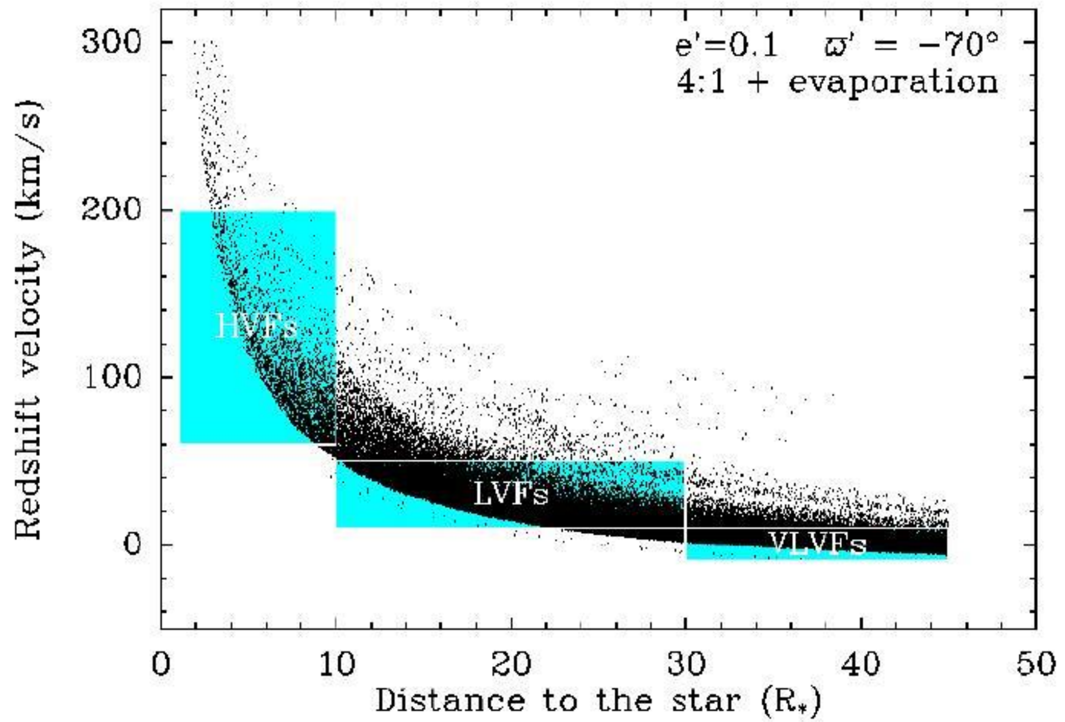
  - The or… …on of the perturb… …cs.
  - A simil… …lar asteroid belt



FEBs : Mean-motion resonances (MMRs)

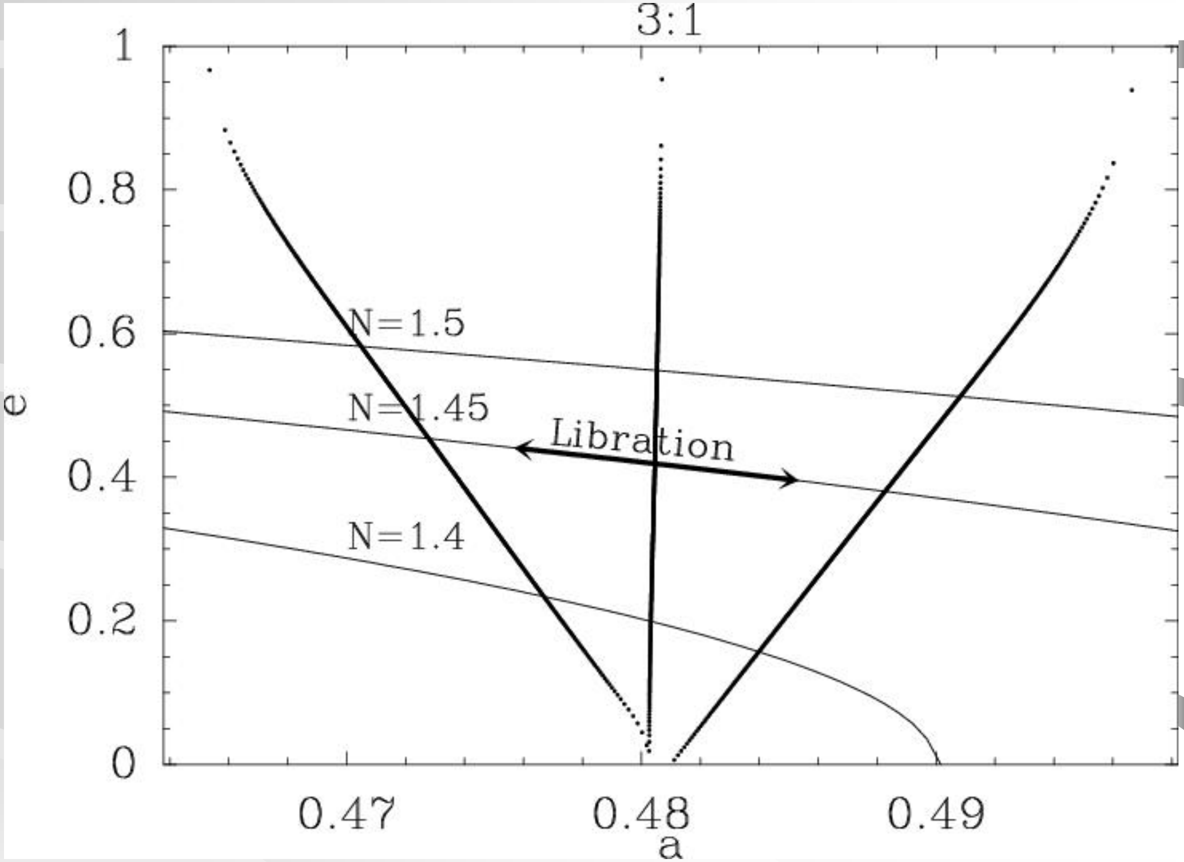
(Beust & Morbidelli 1996, 2000, Thébault et al 2001, 2003)

- Model as of 2001 (fits the statistics of velocity events) : FEBs progenitors= planetesimals trapped in MMR (4:1,3:1) with a moderately eccentric (e>0.05) Jovian planet
- Best model (2001) : a ~2 M_J planet, a≃ 10 AU, e ≃ 0.1, ϖ = -70°±20°



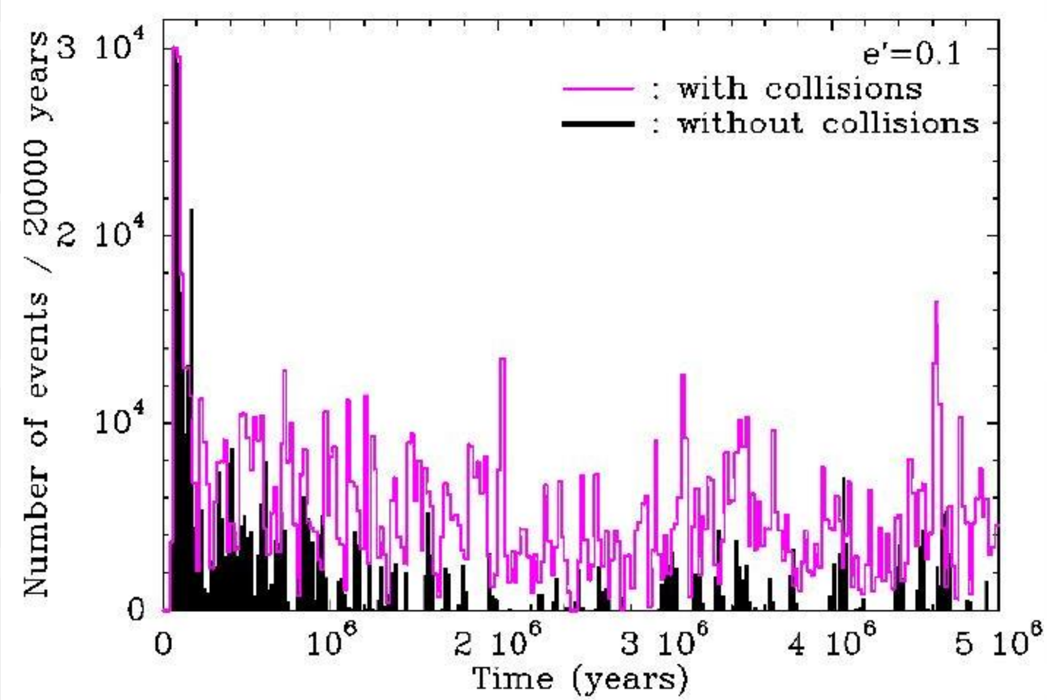
Resonant motion

- Resonant motion ⇔ secular libration of the critical argument of the resonant
- ⇒ Libration in *(a,e)* space, but keeping a secular invariant *N* constant, if the perturbing planet'orbit is circular
- If $e' \neq 0$, *N* can change ⇒ possibility to reach high eccentricities



Duration of the phenomenon

- Best planet to match the FEB statistics : ~ a few Jupiter masses @ 10 AU (Beust & Morbidelli 2000; Thébault & Beust 2001).
- But the resonances clear out quickly (< 1 Myr) ➩ Need for refilling to sustain the process
- Collisions between planetesimals are a good candidate to refill the resonances and make it last several Myrs (Thébault & Beust 2001)



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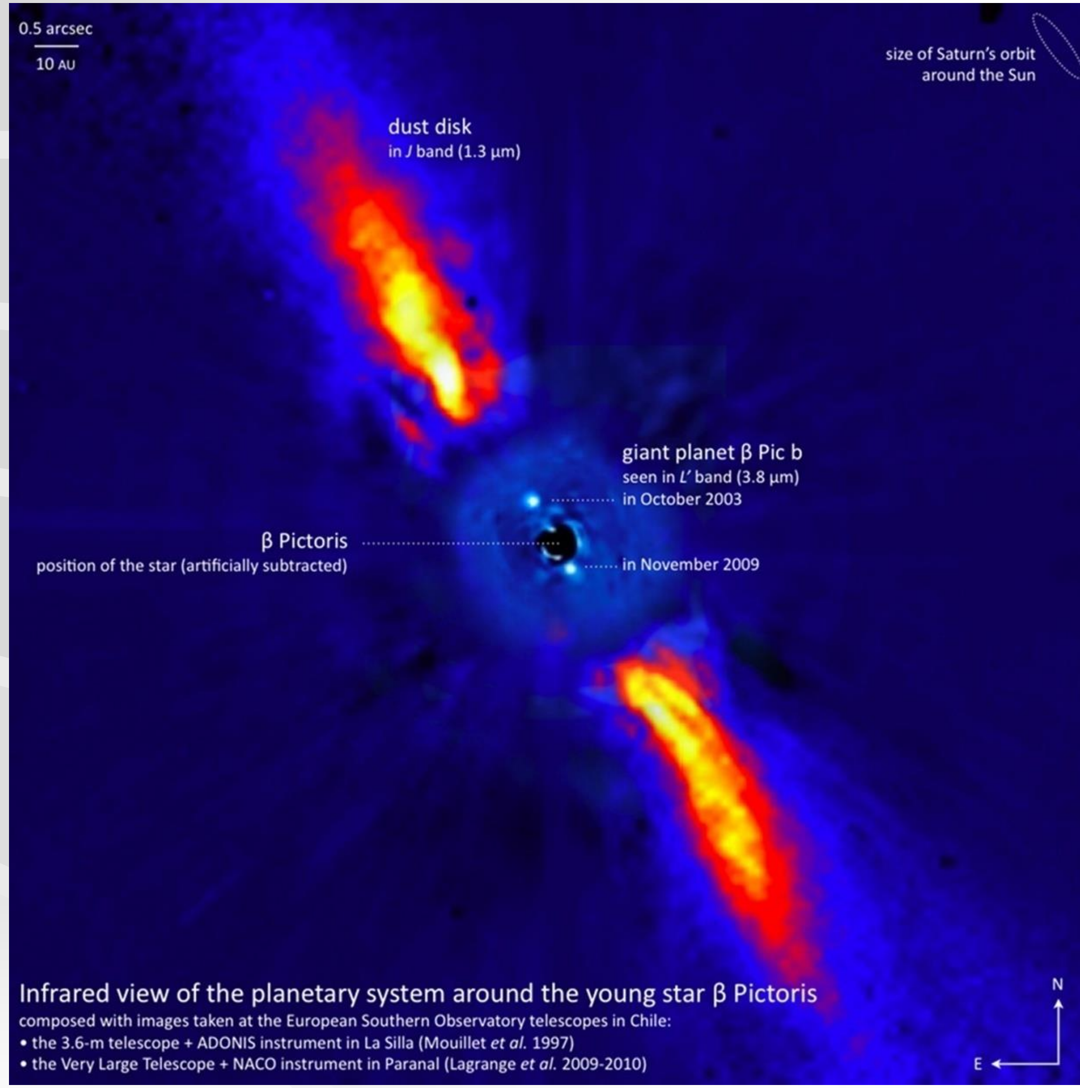
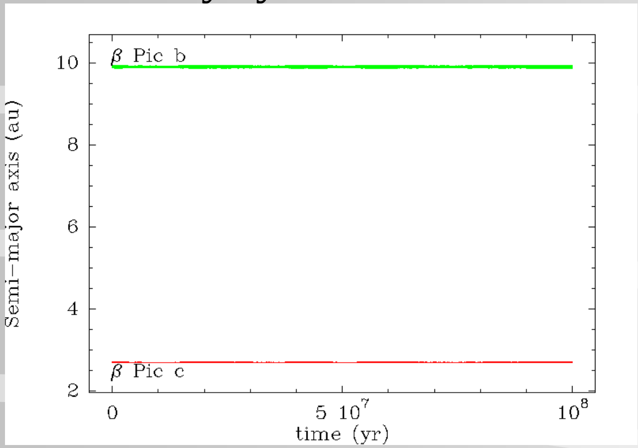
β Pictoris b and c

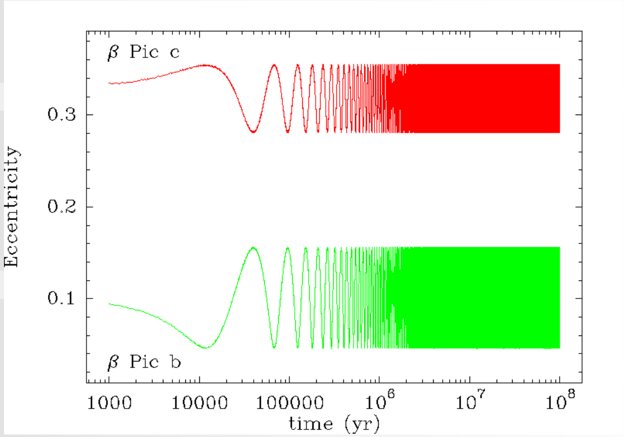
- β Pic b = Giant planet *(~11 M_J, a~9 AU, e~0.1)* imaged in 2009, followed by NACO, SPHERE, GPI, GRAVITY… ⇒ orbital fit ! *(Lagrange et al. 2009, 2010, 2018…)*
- Does it match the FEB model prediction : Quite well, actually !
- β Pic c = Second planet *(~8 M_J, a~2.7 AU, e > 0.2)* detected via radial velocity, confirmed by direct imaging *(Lagrange, Nowak et al. 2019-2020)*
- Regarding to the FEB issue, the presence of this planet is puzzling…



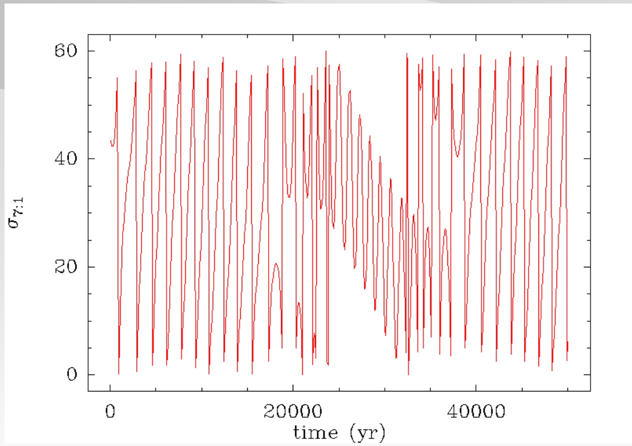
β Pictoris b & c

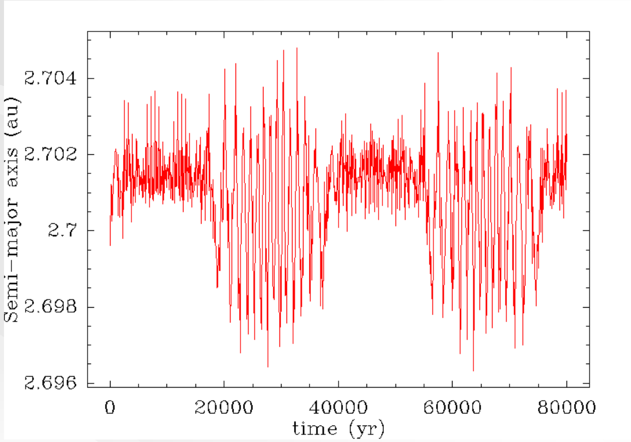
- The 3-body system is stable





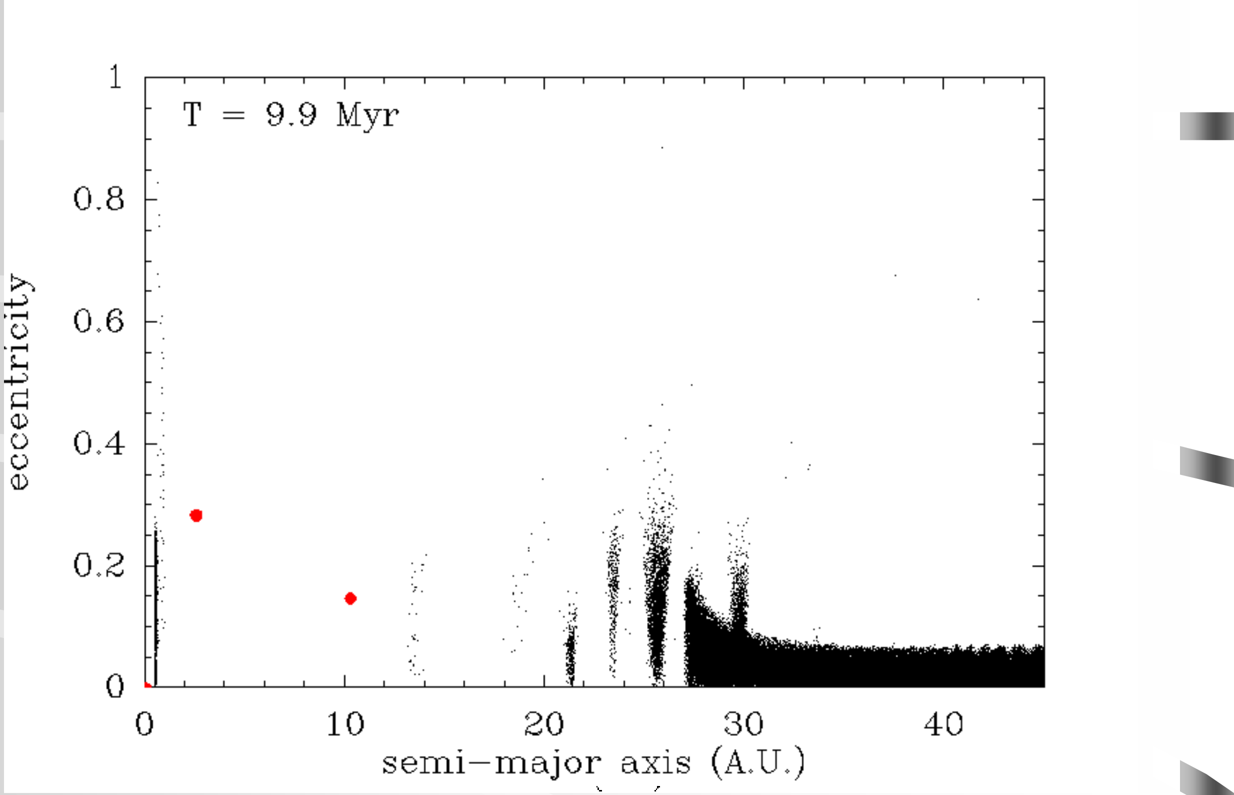
- But both planets could temporarily be trapped in 7:1 MMR ! (Lacour+ 2021; Beust+ 2022, in prep)





FEBs and β Pic b & c

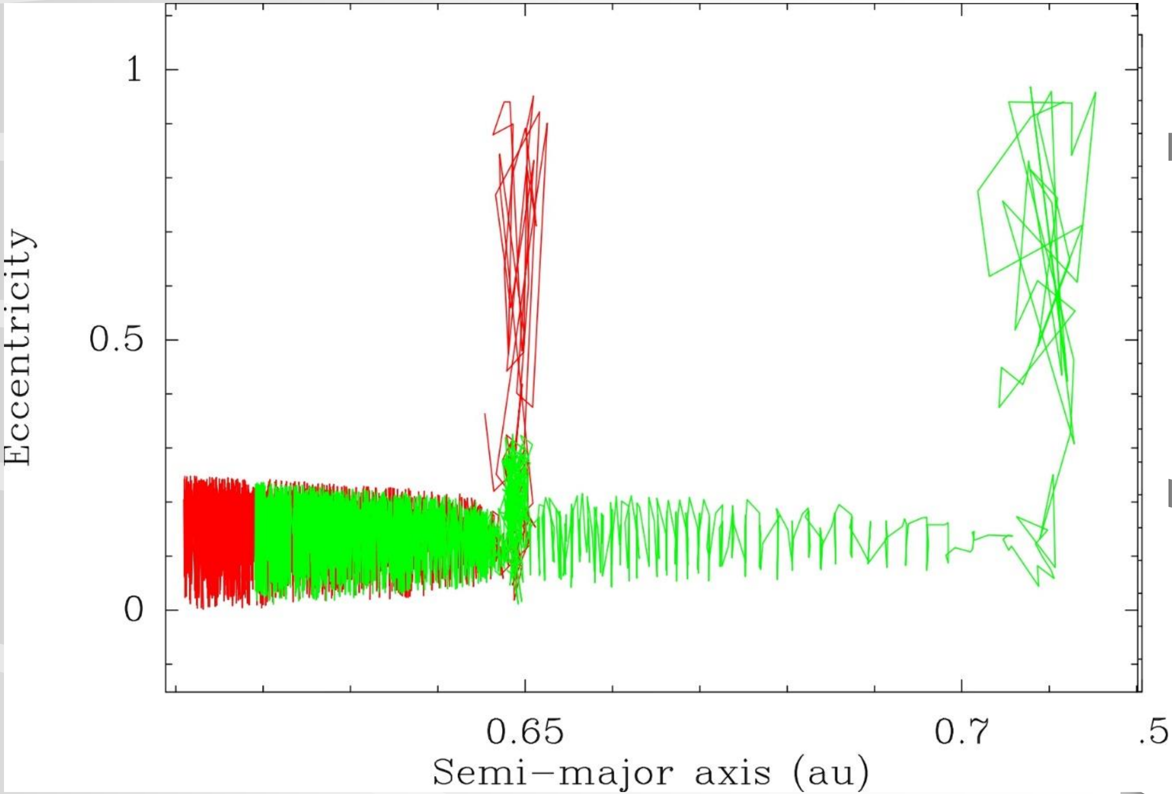
- β Pic c is a potential barrier for proto-FEBs trapped in MMR with β Pic b as their eccentricity increase ⇒ orbit crossing & ejection
- Simulate (N-body) a disk of planetesimals ranging from 0.5 to 50 AU in the presence of the two planets *(orbital solution from Lacour et al. 2021)*
- Result : The whole disk between ~1 AU and ~20 AU is unstable *(Beust et al. 2022, in prep)*
- This concerns in particular the quoted MMR zone with β Pic b (~4 AU)



Consequence : No FEBs can arise from this zone !

Focus on the inner disk

- Redo a simulation with more particles in the inner zone (Beust+ 2022)
- High order (5:1,6;1, 7:1…) MMRs with β Pic c are active sources of FEBs !
- The resonances are active sources of FEBs because the eccentricity of β Pic c is high (0.33 here)
- Perturbations from β Pic b help to enhance the mechanism ⇒ Many particles undergo a semi-major axis drift before falling into a MMR with β Pic c
- This helps the mechanism
  1. to concern many more particles (the whole disk around 1 au)
  2. to naturally last longer, up to the present age of the star



Consequence : FEBs can arise from the inner zone !

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Conclusions

- Debris disks are the visible part (dust) of young planetary systems.
- β Pictoris is the historical prototype of debris disk, associated with a planetary system holding at least two giant planets.
- Falling Evaporating Bodies (Stargrazing exocomets) in the β Pictoris system is an example of extreme small bodies dynamics in a young system
- The dynamical origin of FEBs was associated to Mean-Motion Resonances with a giant planet long before the discovery of Pic b & c
- The presence of both planets complicates the model initially built with one single planet.
- Dedicated simulations show that high order Mean Motion Resonances with β Pic c now seem better suited to act as a dynamical source of FEBs.
- β Pic b plays an enhancing role in this mechanism that helps it to last longer.