debris disc modelling

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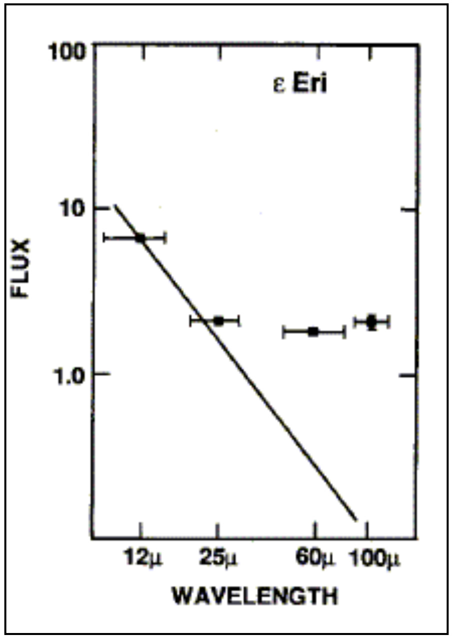
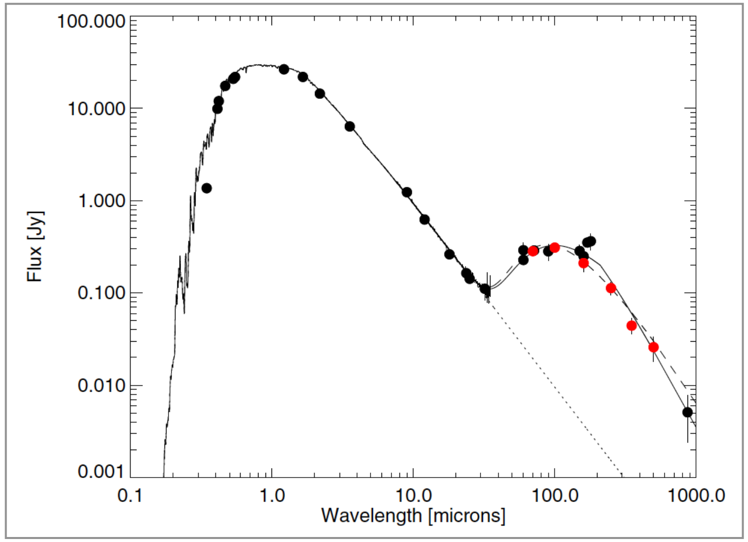
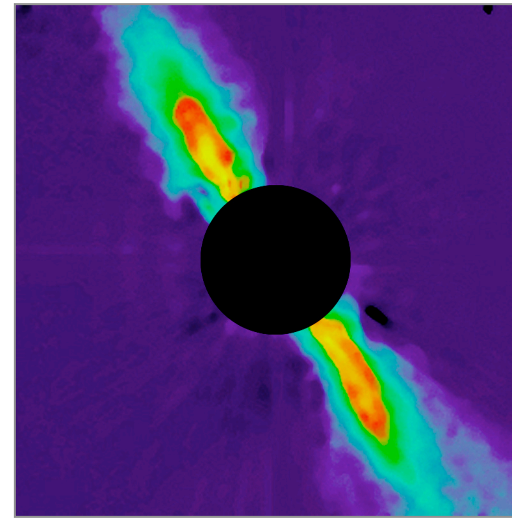
outline

- Introduction: there is more than meets the eye
- Grain population « best fit » models
- Statistical (collisional) models
- *N*-body codes
- *Coupled* collision+dynamics models
    - first efforts
    - perspectives

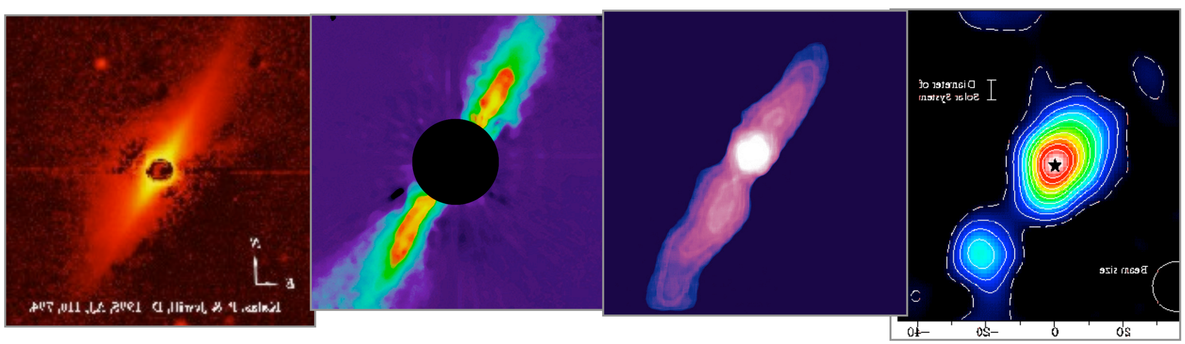
Debris discs: what do we see?

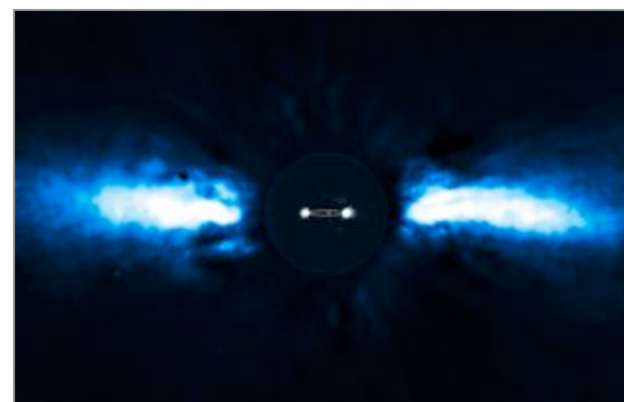






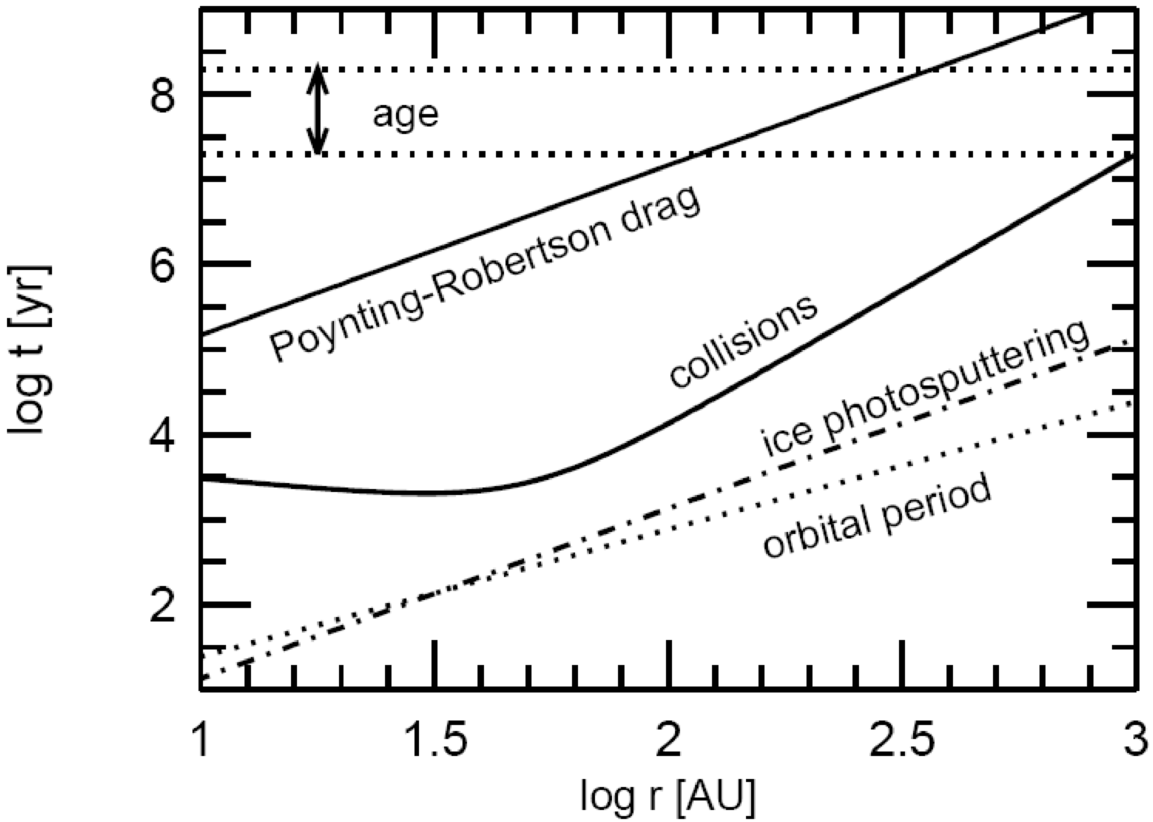
Small (<1cm) DUST particles





Debris discs: what do we see?

DUST that is ***not*** primordial ⟷ $t_{removal} \ll t_{disc}$



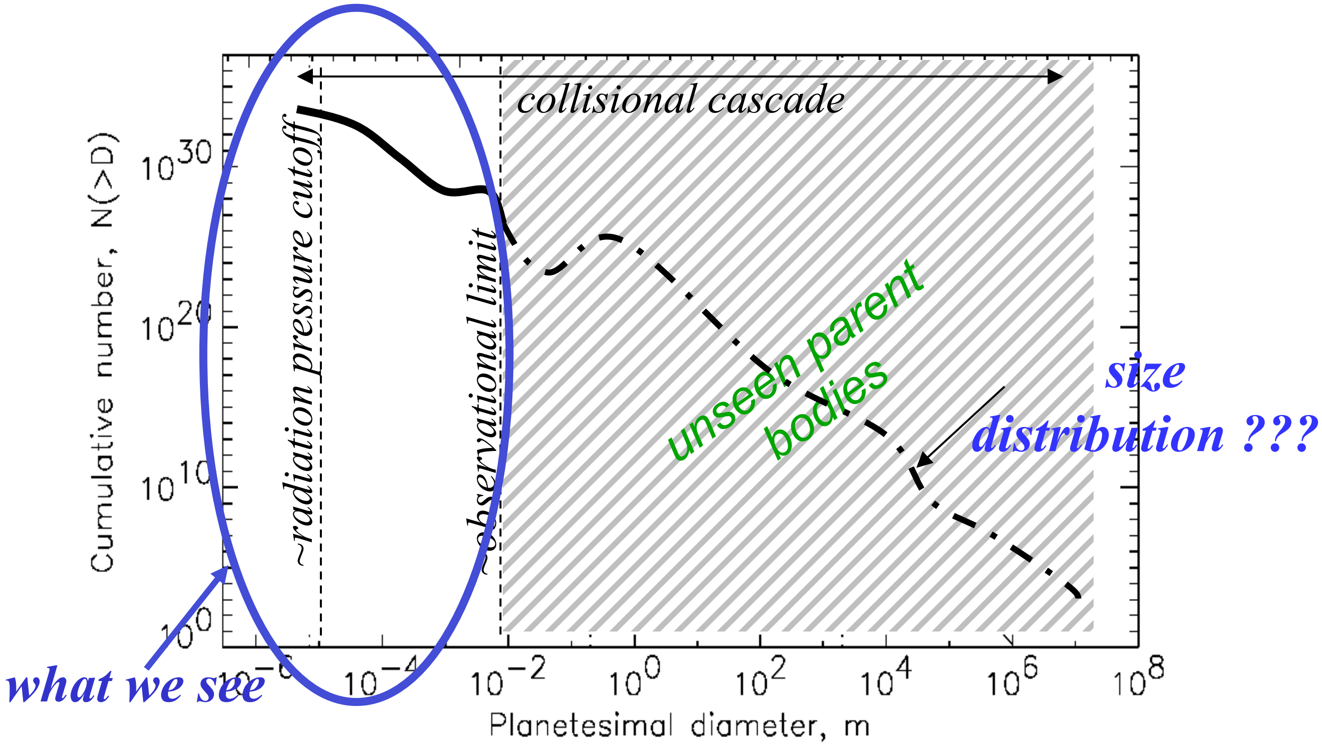
Relative timescales in the beta Pic disc

(Artymowicz, 1997)

dust grains steadily produced by collisions from larger unseen « parent bodies »

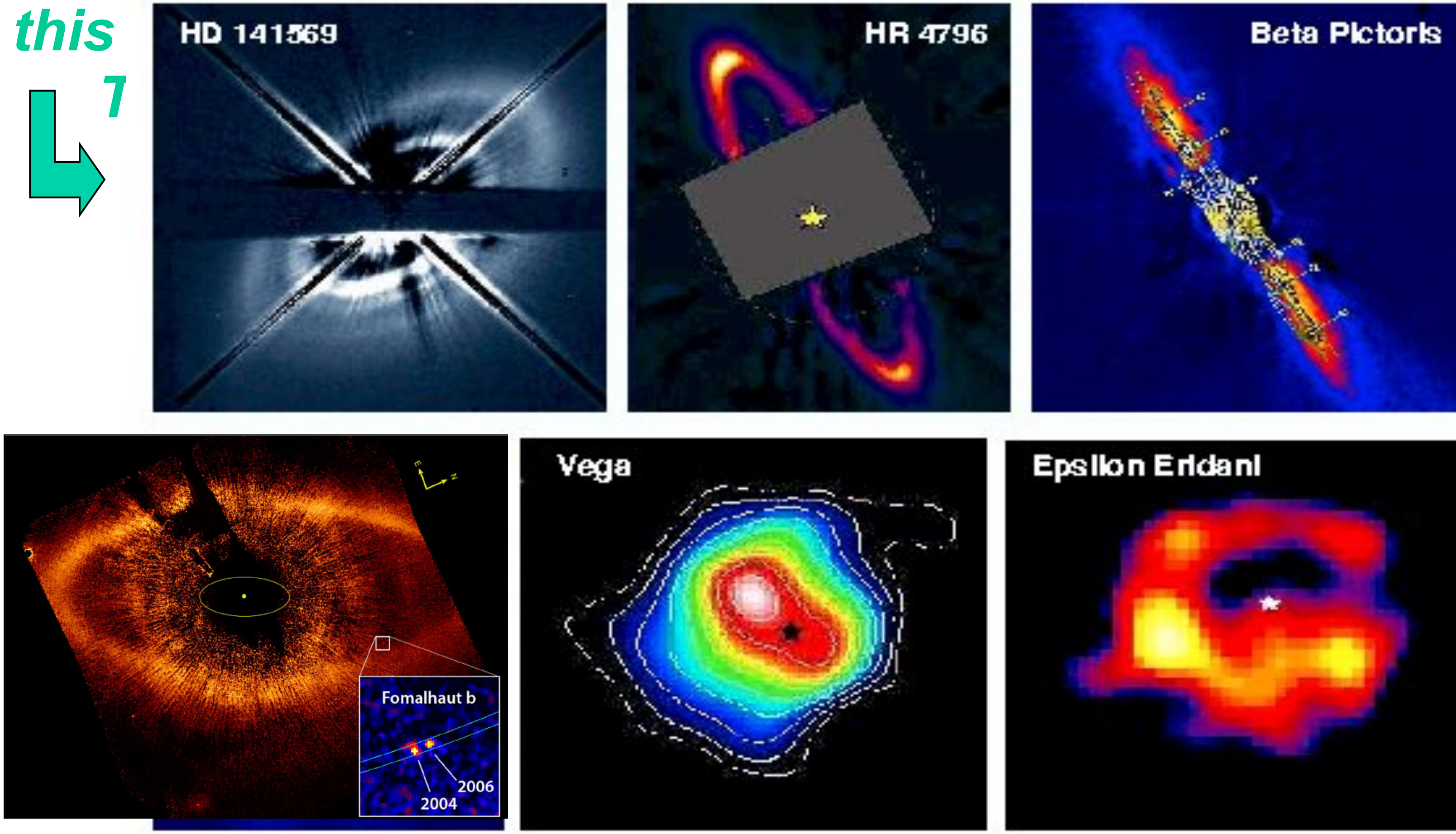
Debris discs: what do we see?

The tip of the collisional iceberg



- **Imaged debris discs show pronounced structures**

They rather look like this



"something" is shaping them: planets? companion star? Transient events?

Grain population « best fit » models

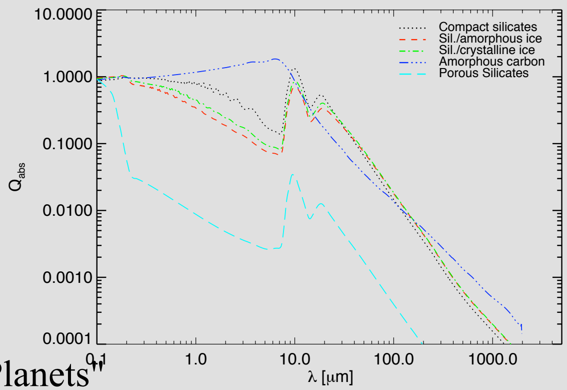
(see also posters by Booth; Olofsson, Lestrade; Ertel; Donaldson, Stapelfeldt, Broekhoven-Fiene)

- No assumptions about what is going on in the system
- ***Aim***: fit SEDs or/and resolved images
- Find the best spatial and size distributions for the grains
- Based on radiative transfer models
- Chemical composition and grain structure

the GRaTer code (Augereau et al., 1999)

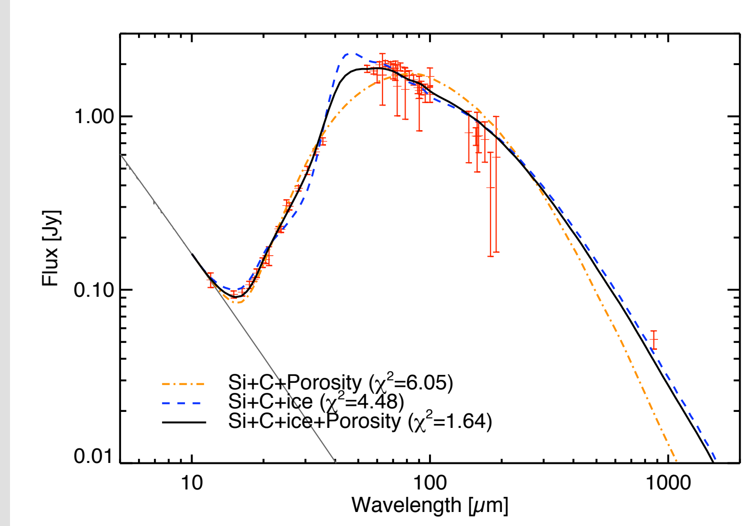
- Star properties
  - Spectral type, magnitude, distance
  - NextGen synthetic stellar spectrum
- Disk Geometrical properties
  - Surface density profile: 2-power law (r_0, α_{in}, α_{out}): Ring-like discs
  - Inclination
- Grain properties
  - Hard, spherical grains
  - Grain size distribution

    $dn/da \propto a^{-\kappa}$, from a_{min} to a_{max}
  - Grain composition
    - Optical indexes available for various materials (silicates, organic refractories, ices, etc.)
    - Multi-material, possibly porous, grains: use of an effective medium theory



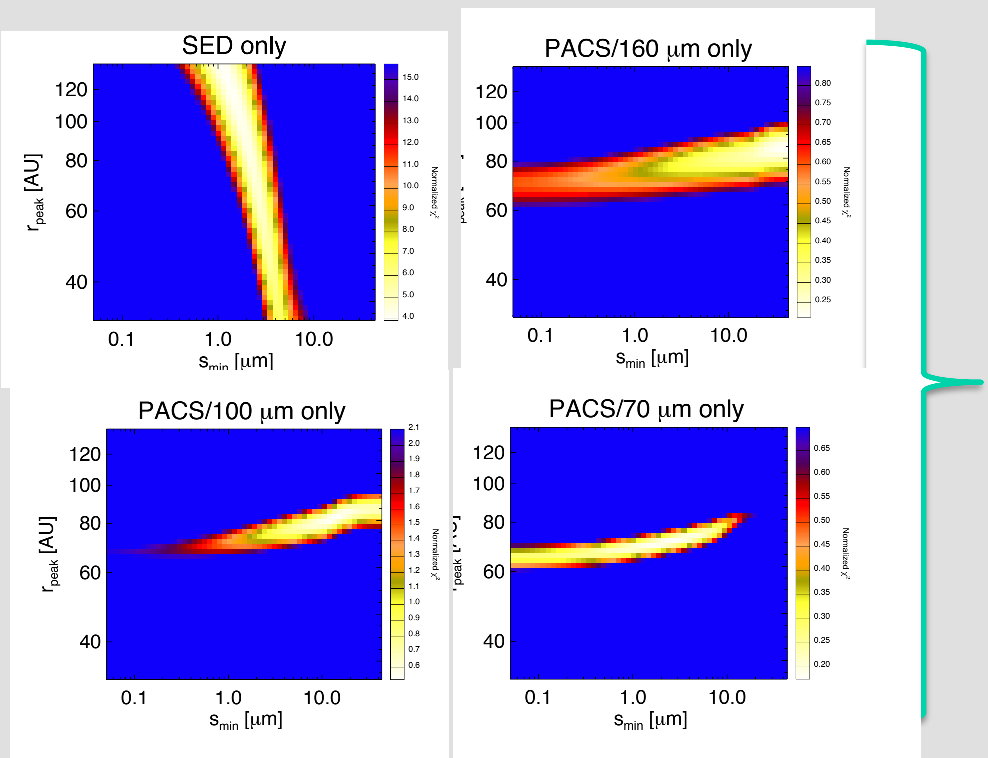
GRaTer method & results

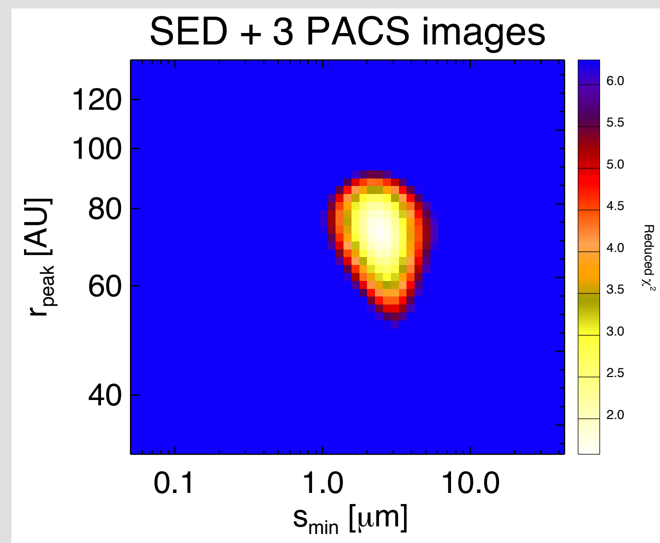
- Fitting strategy:
  - Chi-square minimization
  - Bayesian analysis



Kuiper belt around HD181327

(Lebreton et al., 2012)

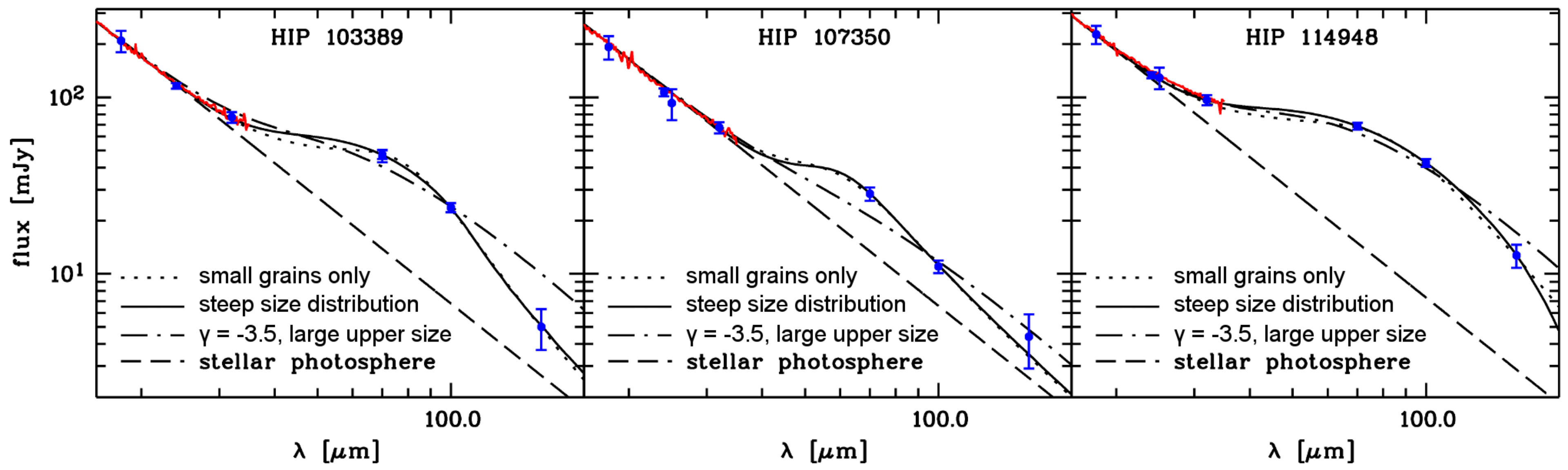




q1 Eridani

(Augereau et al., in prep)

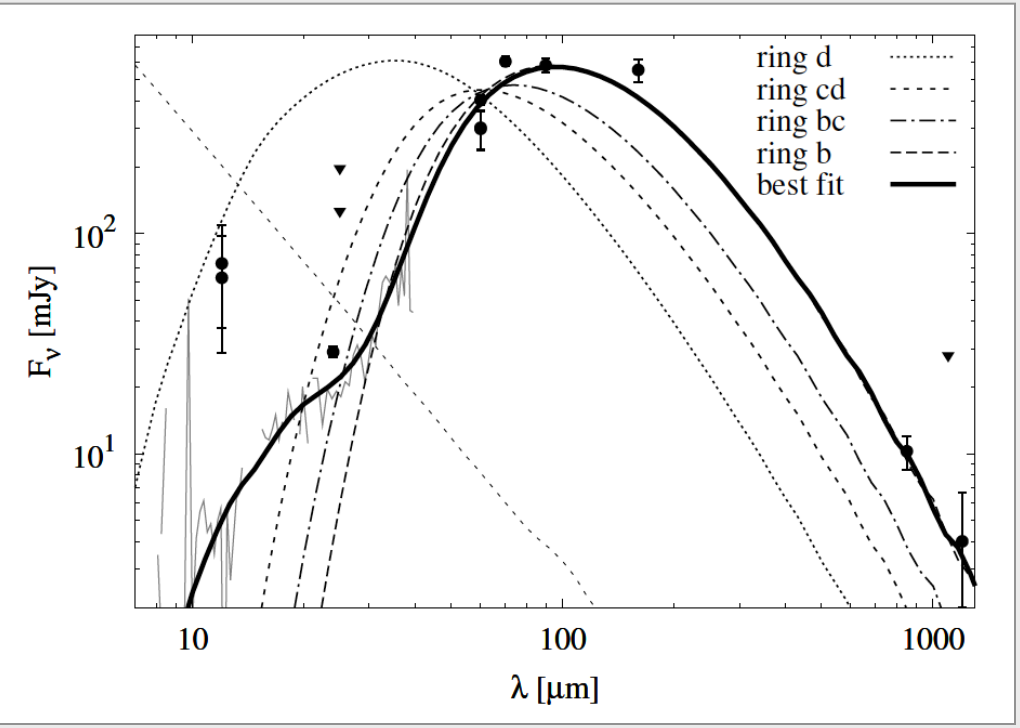
SAnD (Ertel et al., 2012)



SEDs with steep decrease at long wavelengths

Grain size distribution steeper than -3.5 (no coll. Equilibrium!)

« A new mechanism to produce the dust in the presented debris disks, deviations from the conditions required for a standard equilibrium collisional cascade (grain size exponent of −3.5), and/or significantly different dust properties are necessary to explain the SED shape of the three debris disks presented »



SEDUCE & SUBITO

(Müller, 2011)

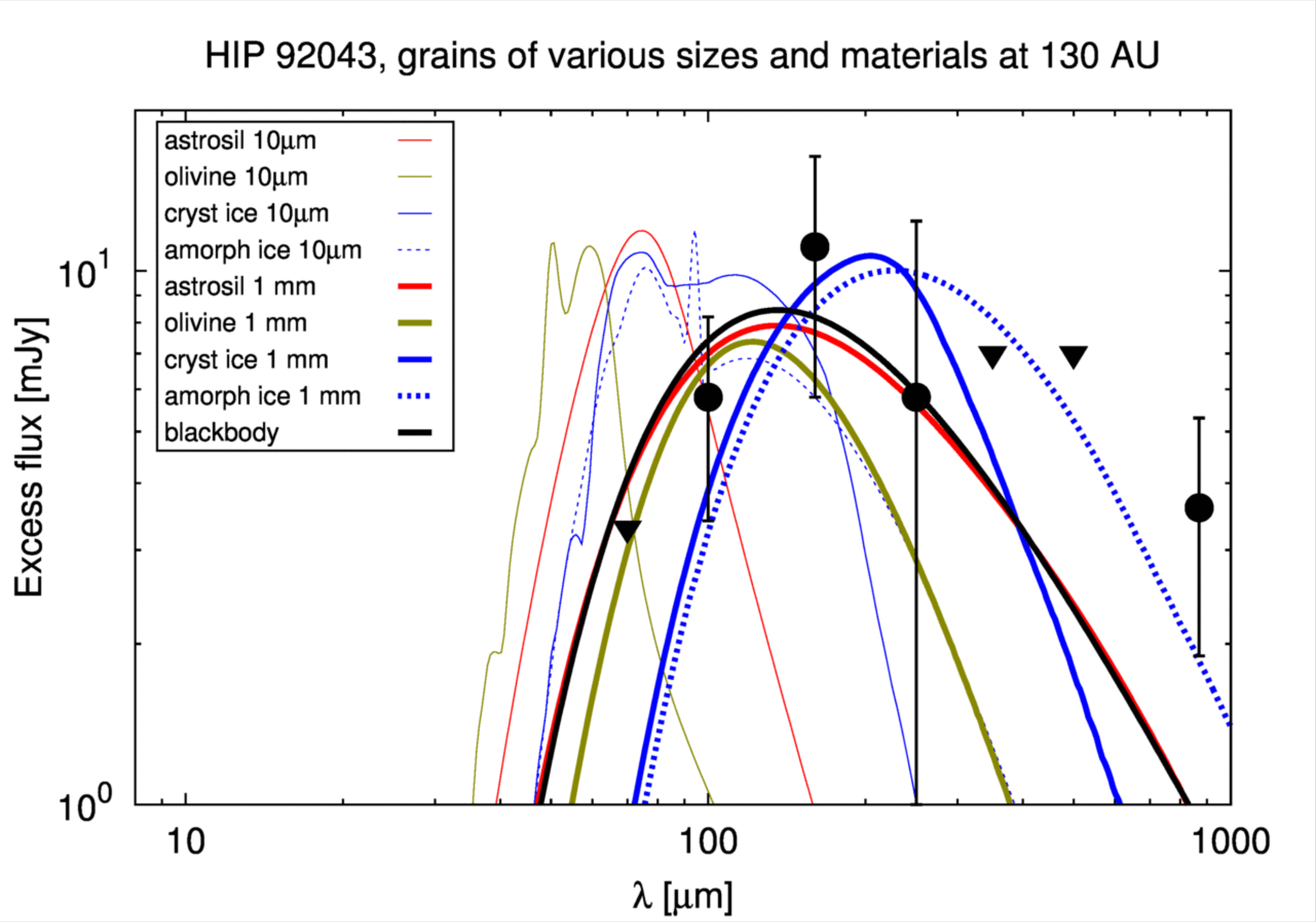
Can also be used taking as an input the results of the ACE collisional model

Table 4.2: Locations and names of the first-guess dust rings.

ring location	ring extension [AU]	name
inside d	3 – 15	ring d
between d and c	28 – 32	ring cd
between c and b	45 – 60	ring bc
outside b	75 – 125	ring b

Ultra-cold discs

(see also talk by Krivov)

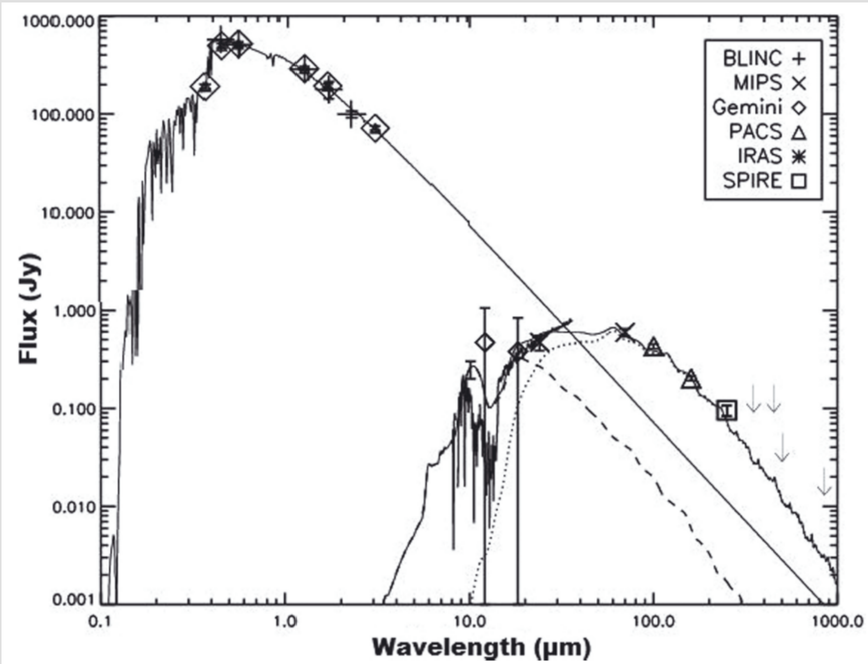


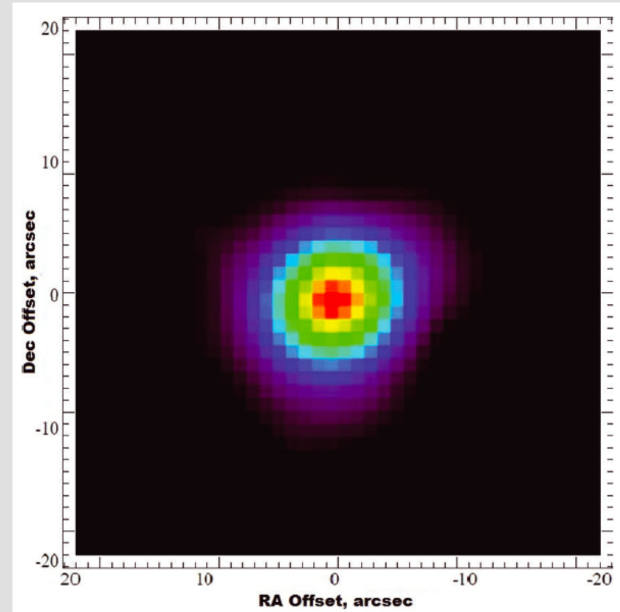
Marshall et al.(2012)

Links to planets

fit of the β-Leo debris disc

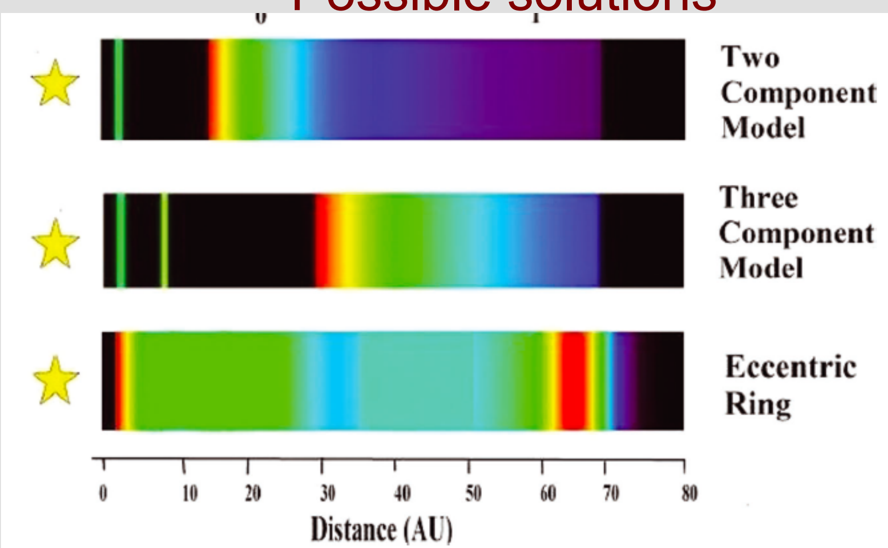
Churcher et al.(2011)





Possible solutions

Planetary system architecture?



Planet(s) in the 2-15AU region

Planet(s) in the 2-30AU region

No planet in the 2-65AU region

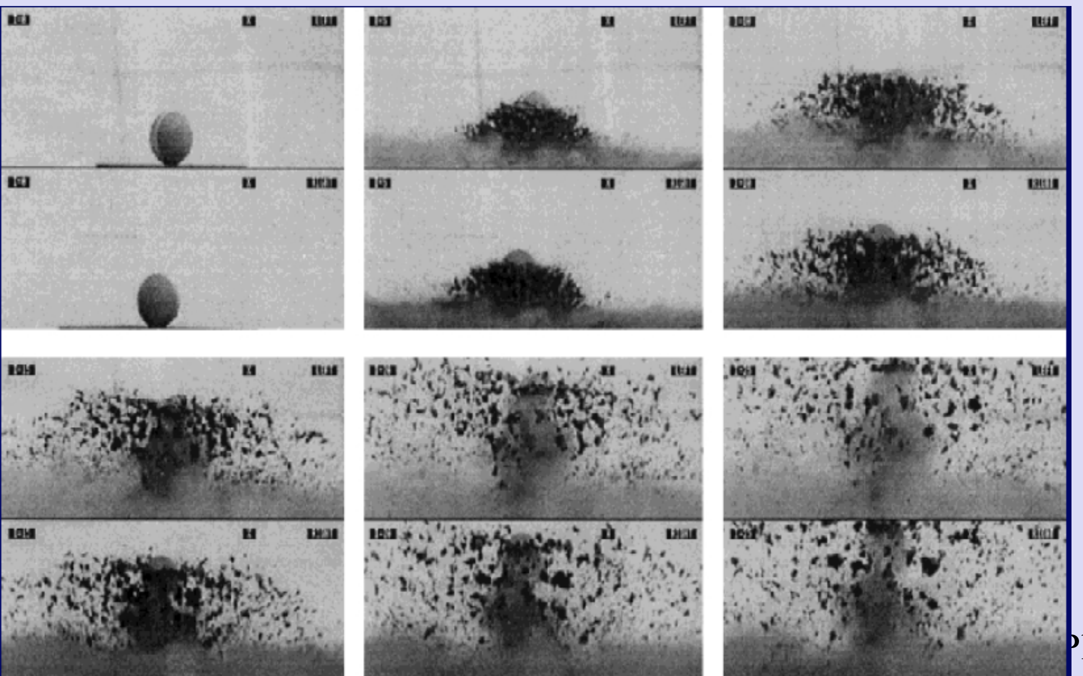
Statistical collisional models

Principle

- *Poor Spatial resolution, poor dynamics*
- *Dust grains distributed in Size Bins (and possibly spatial/velocity bins)*
- *"Collision" rates between all size-bins*
- *Each bin$_i$-bin$_j$ interaction produces a distribution of bin$_{l<max(i,j)}$ fragment*

$$dN_k = \sum_{i,j=1}^{n} n_{i,j,k} p_{i,j} N_i N_j dt - \sum_{l=1}^{n} \gamma_{l,k} p_{l,k} N_l N_k dt$$

- Collision Outcome prescription (lab.experiments, simulations)

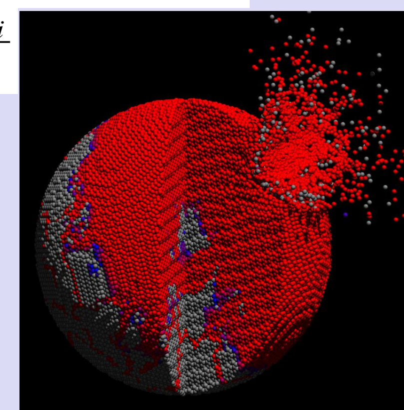


$$M_{1i} = \left[\frac{q_{1i} M_{lf(i)}^{q_{1i}}}{(1-q_{1i})} \left(M_{lf(i)}^{(1-q_{1i})} - M_{sl(i)}^{(1-q_{1i})} \right) + M_{lf(i)} \right]$$

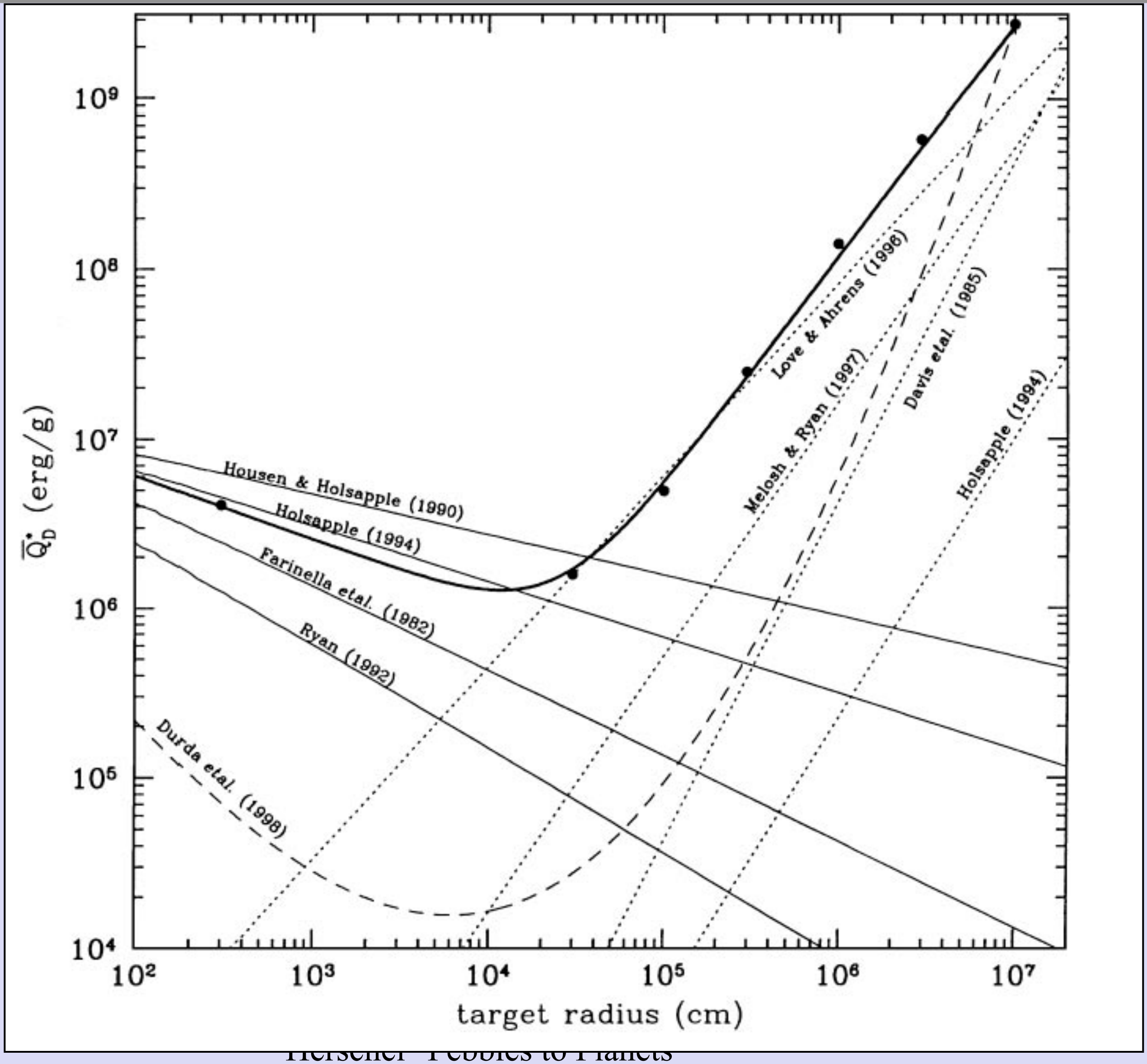
$$C_{1i} = 3 q_{1i} R_{lf(i)}^{3q_{1i}} \qquad C_{2i} = \frac{C_{1i}}{R_{sl(i)}^{3(q_{1i}-q_{2i})}}$$

$$\frac{C_{2i}}{(3-3q_{2i})} R_{sl(i)}^{-3q_{2i}} = \frac{M_i - M_{1i}}{M_{sl(i)}}$$

Planets"



Critical fragmentation Energy (Q*)
conflicting estimates



Benz&Asphaug, 1999

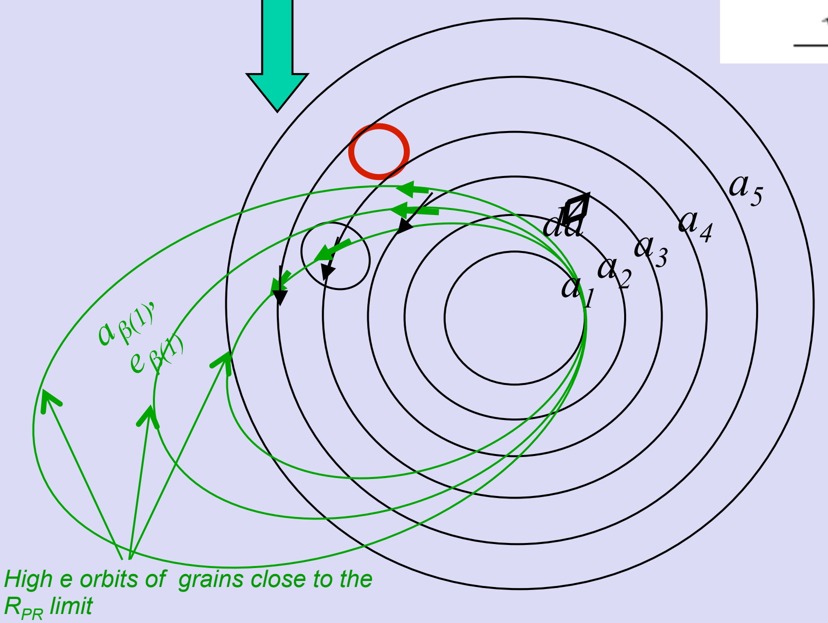
Multi-annulus code (Thebault&Augereau, 2007)

Table 1. Nominal case setup. The fields marked by a √ are explored a[s] free parameters in the simulations. See text for details.

	Radial extension	$10 < a < 120$ AU
	Number of annuli × radial width	11×10 AU
√	Initial surface density profile	$\Sigma(a) \propto a^{-1.5}$
√	Total "dust" mass ($R < 1$ cm)	$0.1\,M_{\oplus}$
	Size range modelled	$3\,\mu$m $< R < 50$ km
	Number of size bins	103
	Initial size distribution	$dN \propto R^{-3.5}dR$
√	Sublimation distance (water ice)	$a_{sub} = 20$ AU
√	Dynamical excitation	$\langle e \rangle = 0.1 = 2\langle i \rangle$
√	Stellar type	A5V
√	Blow-out size	$R_{PR} = 5\,\mu$m
√	Collision outcome prescription	(see Appendix B)

takes into account

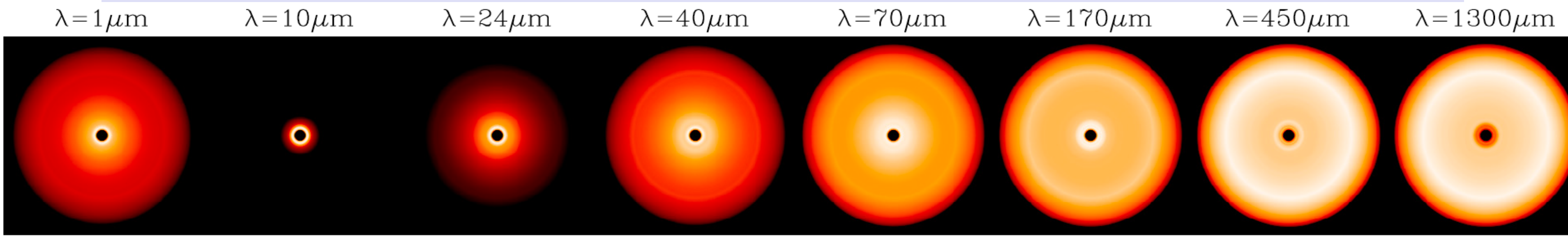
- ***Collisions (fragmentation, cratering, re-accretion)***
- ***simplified, non-evolving dynamics***
- ***Radiation pressure effects***

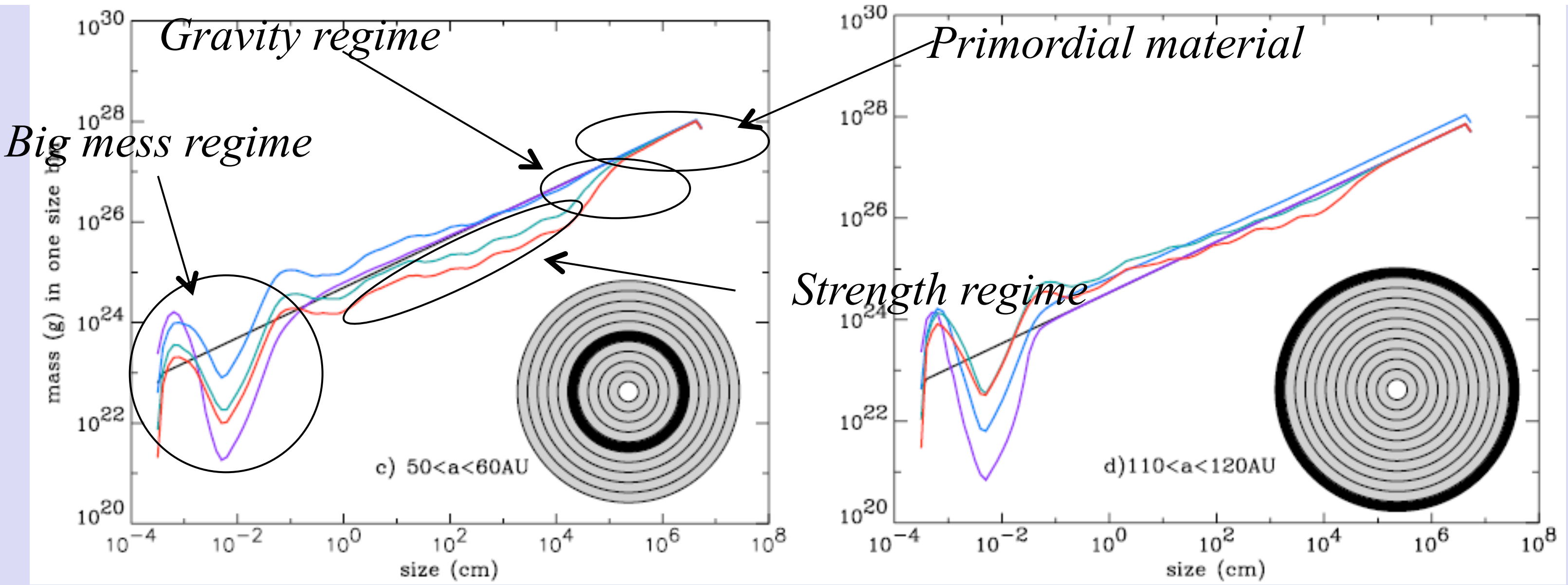


- ***Extended Disc: 10-120AU***
- ***Size range: 3µm – 50km***

Evolution of an extended disc

Synthetic Images (1D) with GRaTer





size distribution evolution (Thebault&Augereau, 2007)

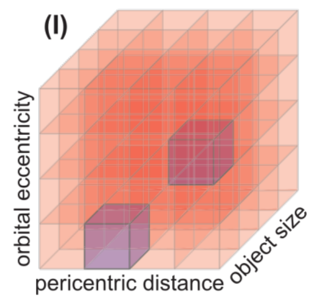
The ACE code (Jena group)

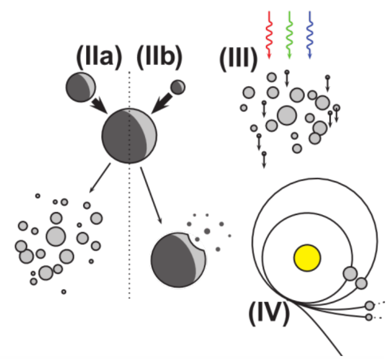
Initial belt of planetesimals

Debris disc at subsequent time instants

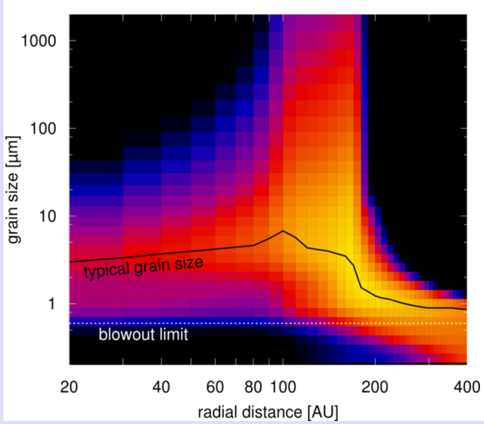
Features:

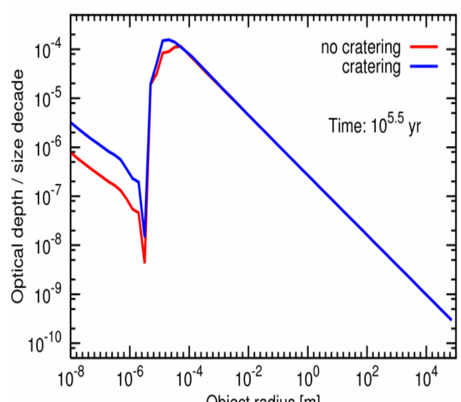
- *statistical code on an (m,q,e)-mesh*
- *stellar gravity & radiation pressure*
- *diffusion by P-R, stellar wind, gas drag*
- *sticking, bouncing, cratering, disruption*
- *distributed parallel computing*

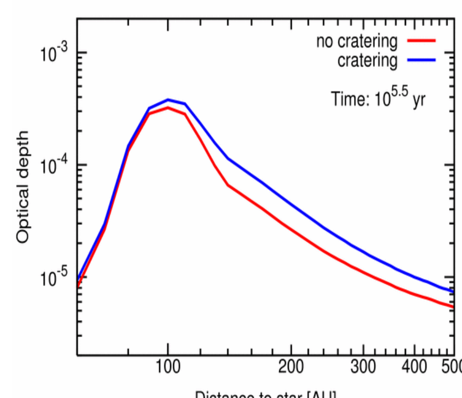




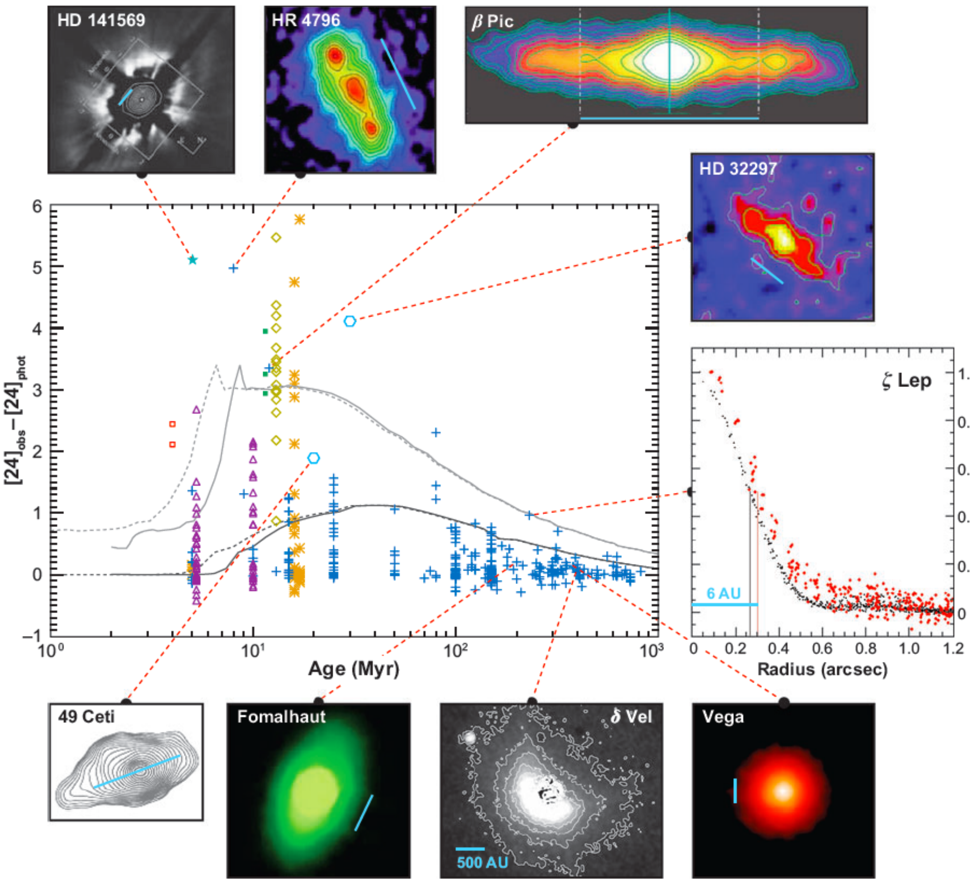
Developed by:
Krivov & Sremčević (2003-2004),
Löhne (2005-2012)





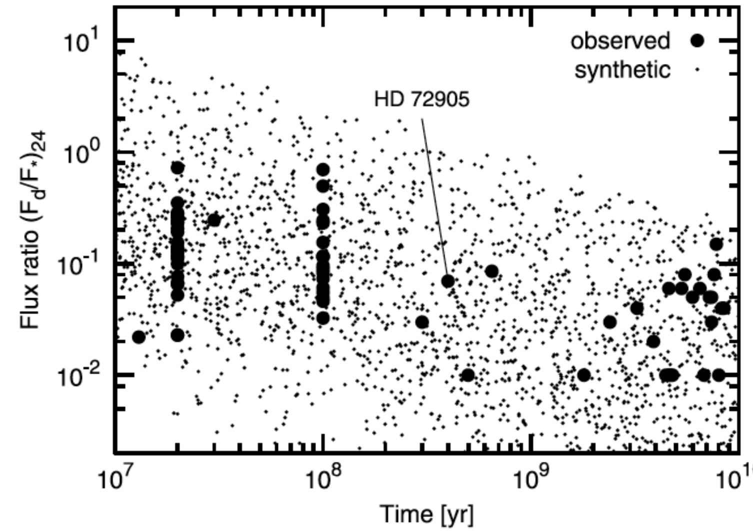


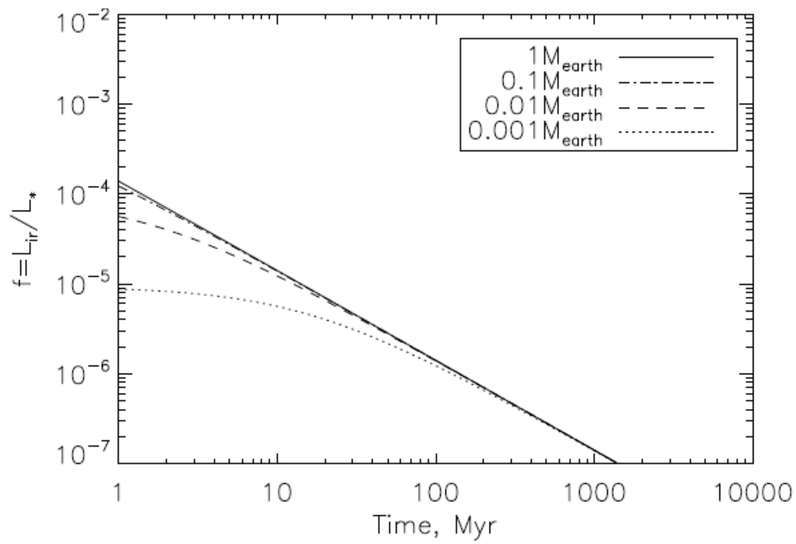
Long-term collisional evolution



Wyatt (2008) (Kenyon&Bromley runs)

Löhne et al.(2008)

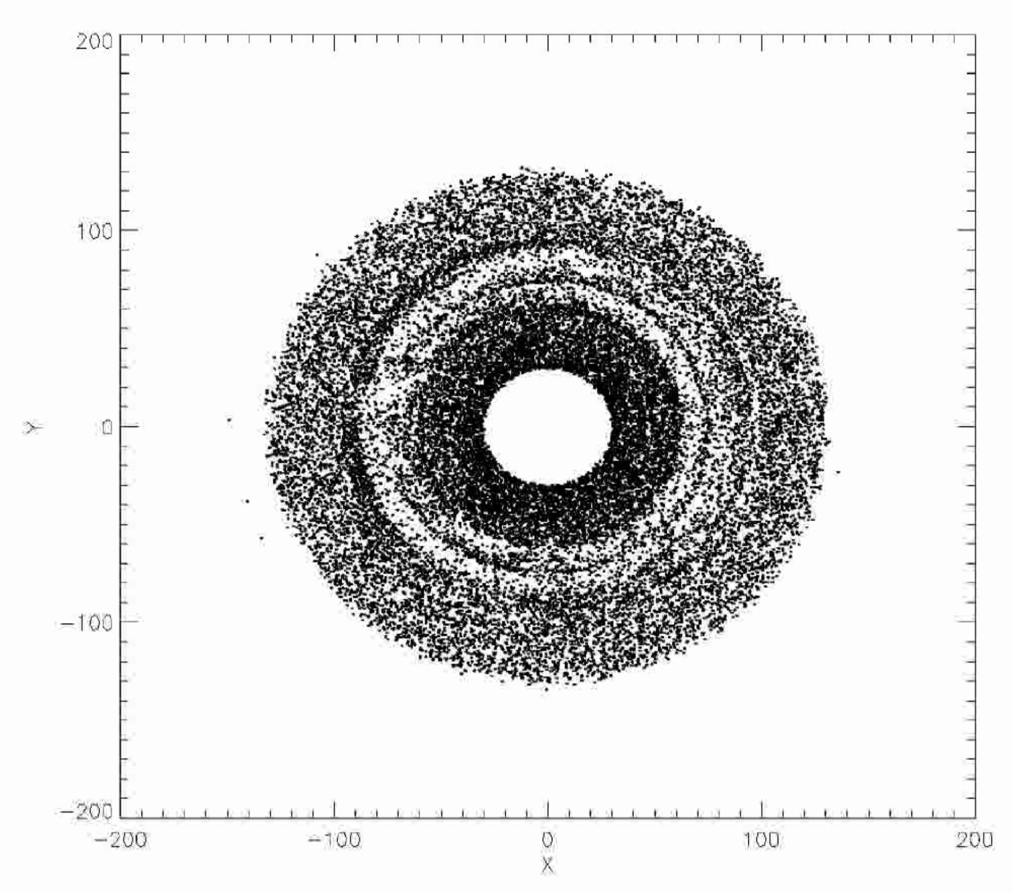




Steady state evolution models predict that there is an L_{max} for a disc of a given radius and age ***(Wyatt, 2007)***

Dynamical models

(see also posters by Bonsor; Faramaz; Morey; Kennedy)

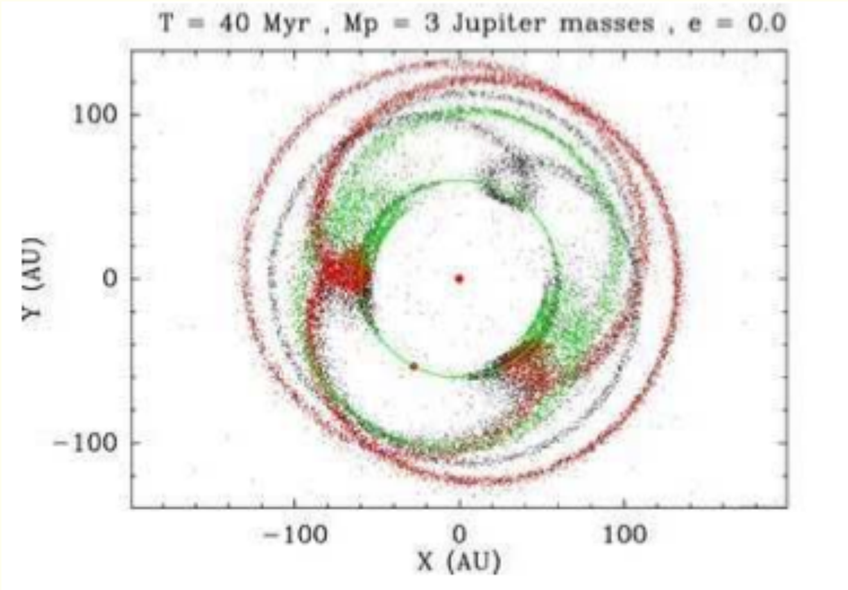


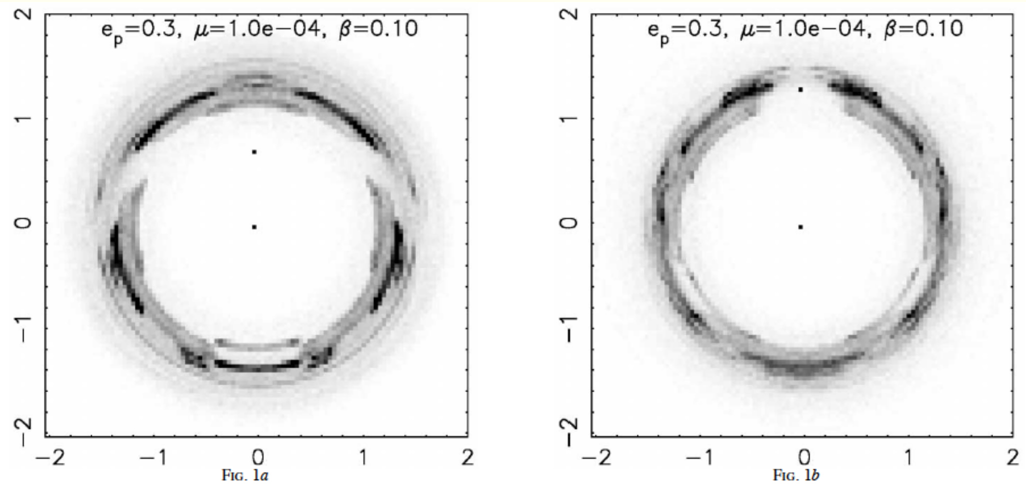
Ingredients

- ***N*-body integrator**
- **Gravity from central star**
- **Gravity from perturber(s)**
- Radiation Pressure
- PR-drag
- Gas drag
- ….NO COLLISIONS

Resonant capture of planetesimals

Rèche et al. (2007)

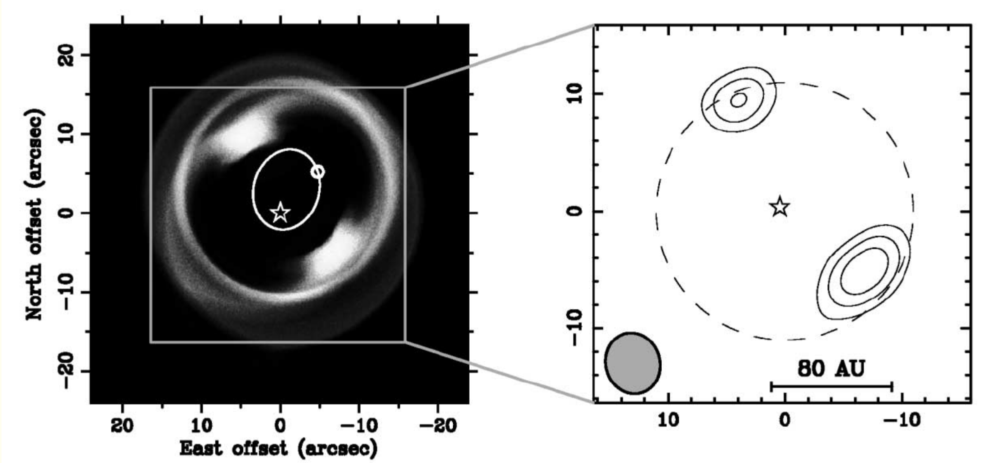




Quillen & Thorndike (2002)

Easy trapping when :

- planets migrate
- dust drifts inward (PR drag)
- Planets increase in mass

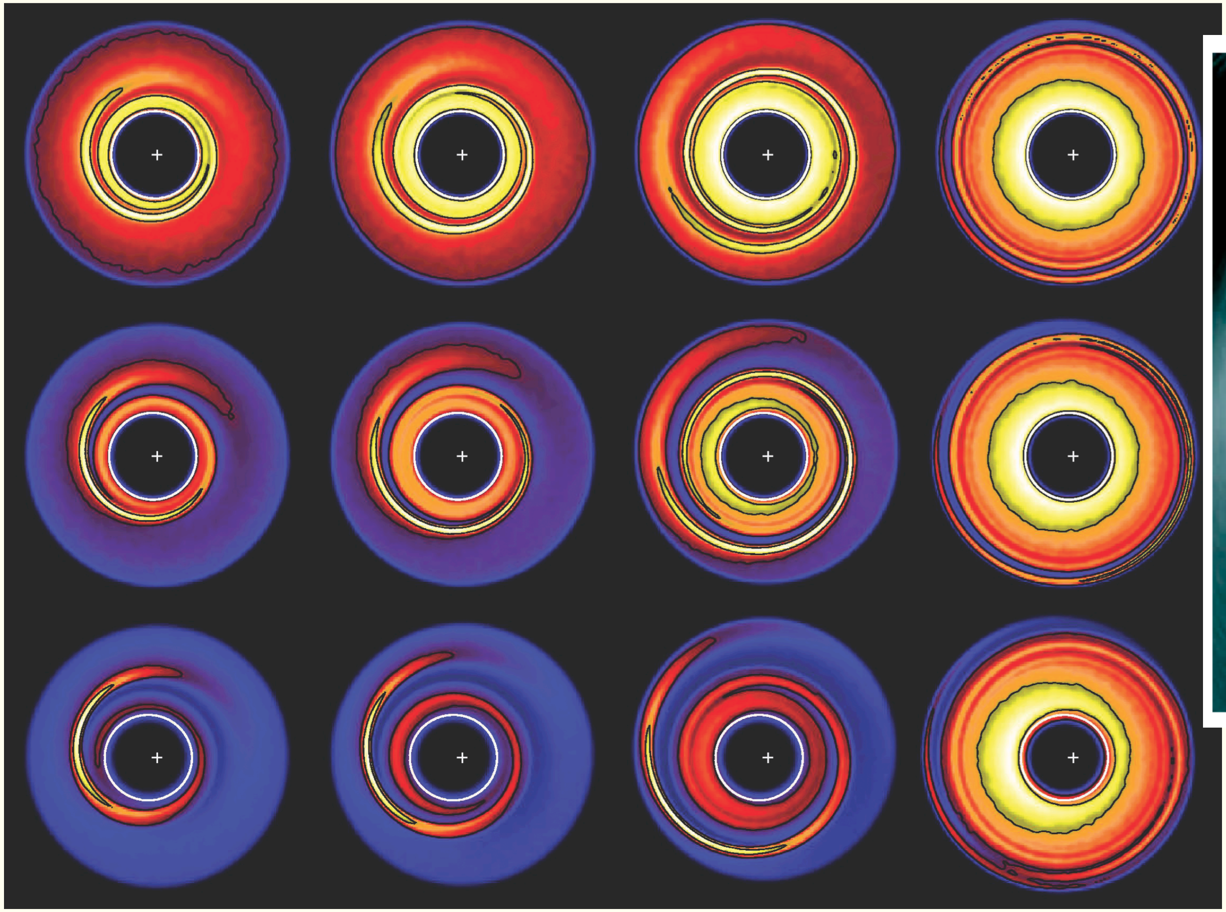


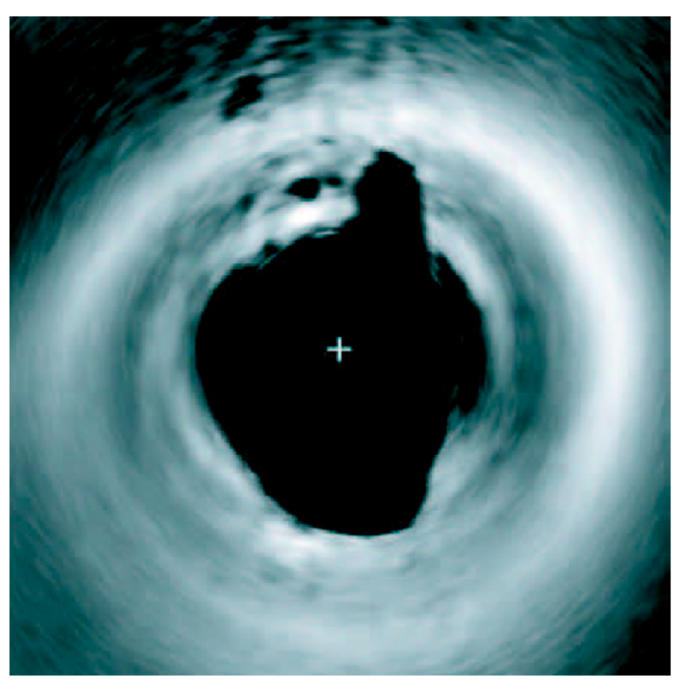
Vega 1.3mm emission (*Wilner et al. (2002)*)

Secular response of a disc to an eccentric planet

- Differential precession of planetesimal orbits
- Transient spiral features
- Pericentre glow

(See also poster by V.Faramaz on zeta Ret.)





Spiral structures in HD141569 (Wyatt et al., 2005)

Linking planets to the radial distribution of dust

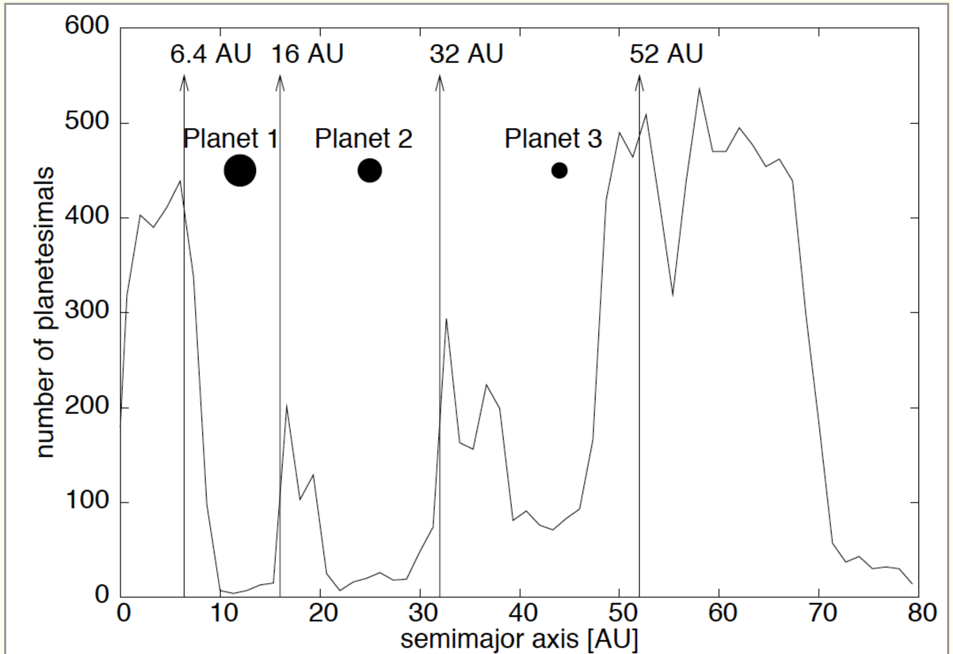
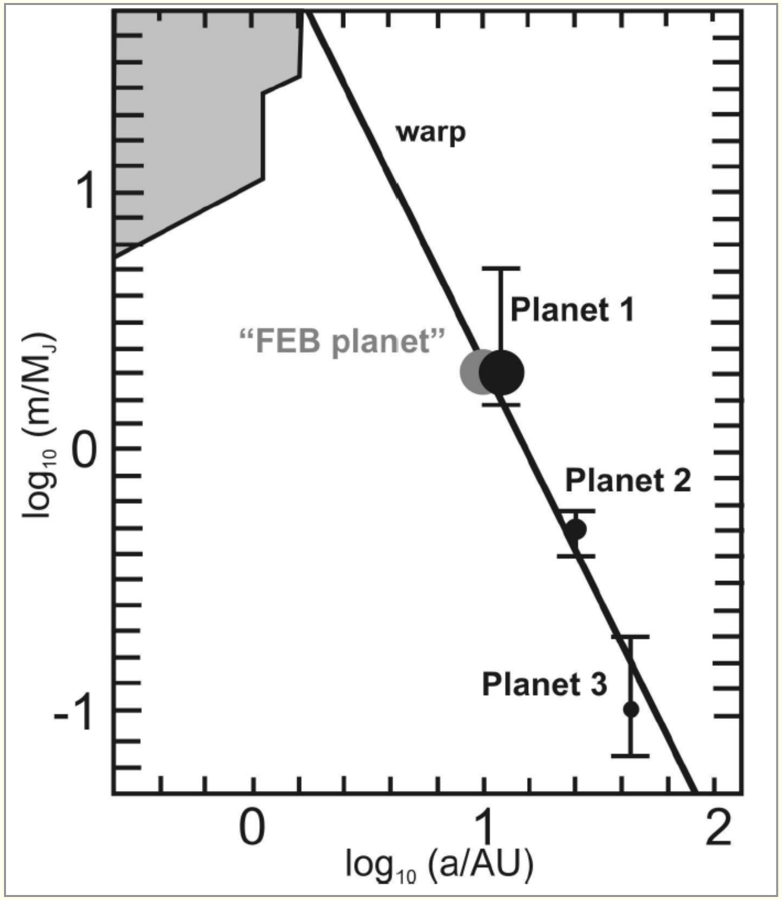
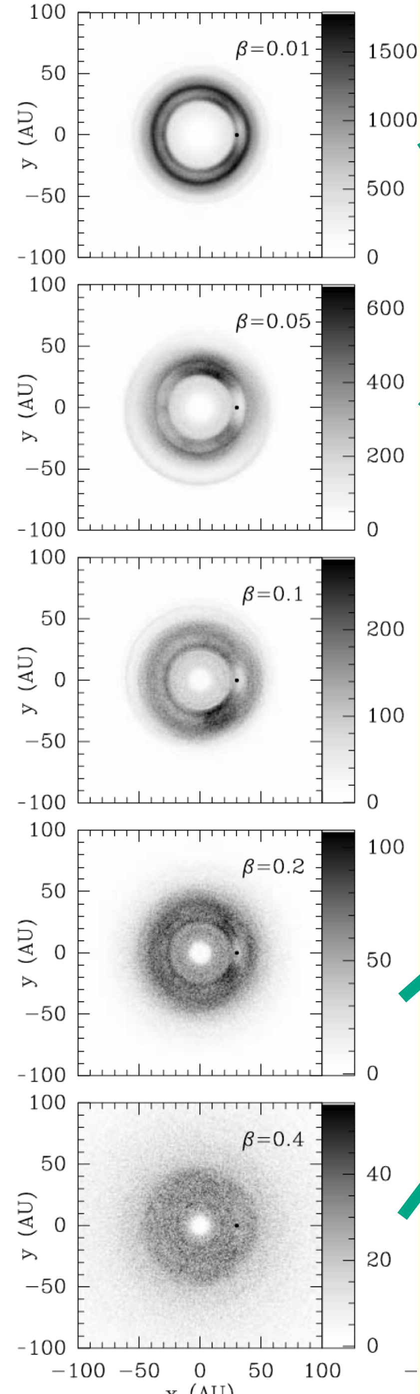


Fig. 6. Effect of three planets at 12, 25 and 44 AU with $m = 2M_J$, $0.5M_J$ and $0.1M_J$ (all with $e = 0.01$) on the disc.

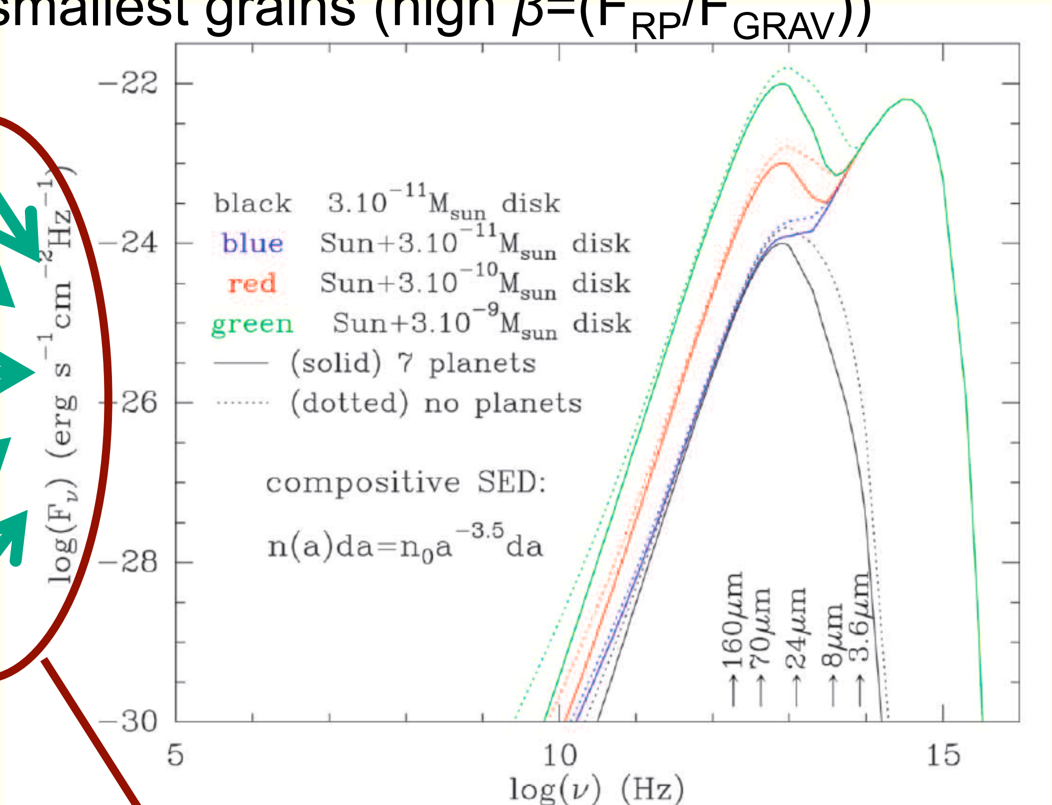


Freistetter et al.(2007)

Accounting for size distributions



Because Radiation Pressure & PR drag induce a *size-dependent* dynamics for the smallest grains (high β=(F_{RP}/F_{GRAV}))

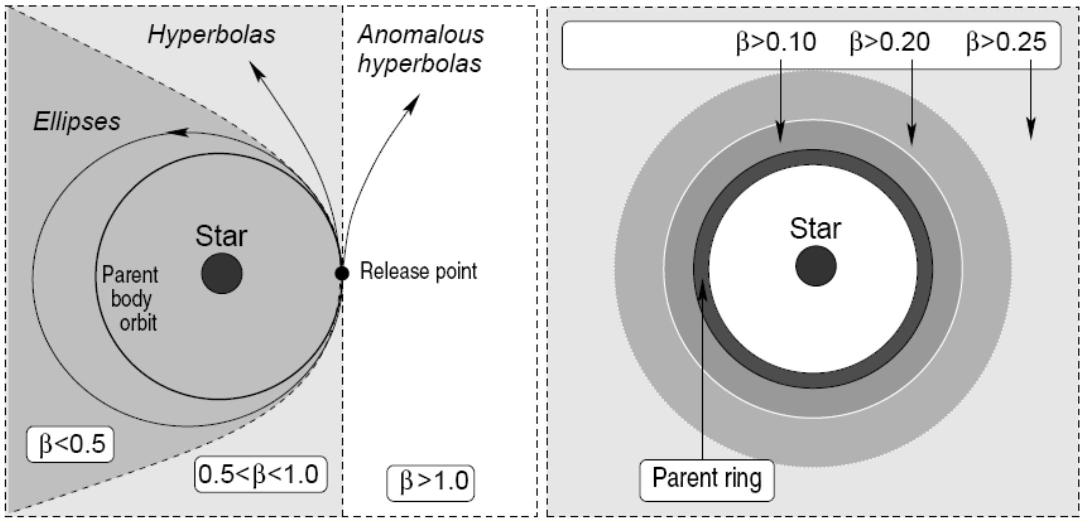


Moro-Martin et al.(2002)

dN α $r^{-3.5}dr$ (collisional « equilibrium »)

N-body models are not enough: NO COLLISIONS!

- Collision timescales can be < dynamical timescales ➡ Prevent the building of spatial structures



steady **collisional production** of small grains placed on high-*e* orbits by **radiation pressure**

(Krivov, 2010)

- Spatial segregation according to sizes => different collisional behaviour/evolution (and thus size distribution) depending on location => -3.5 law no longer valid
- Feedback of collisions on the dynamics
- RP places grain in potentially unstable regions

The dust grains that are (usually) observed are the troublemakers (smallest bound particles)

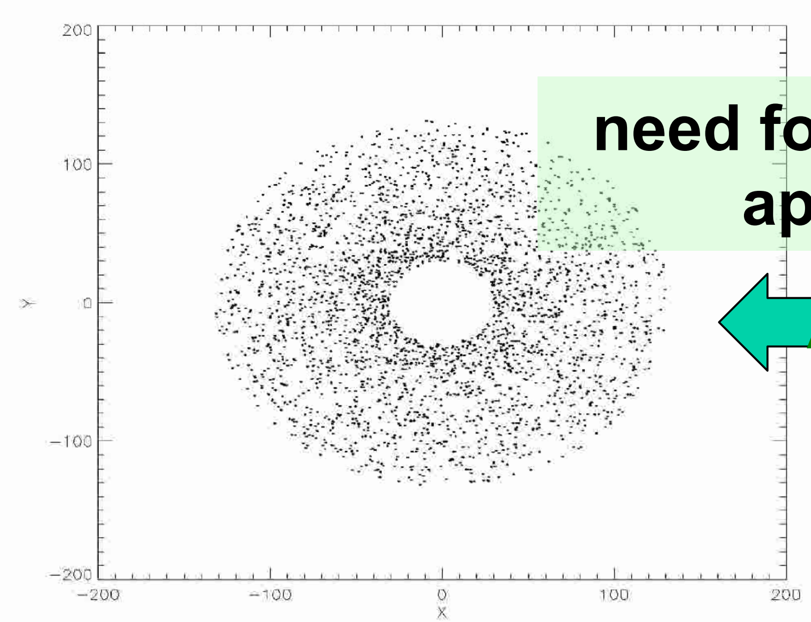
~~either~~ ~~or~~

N-body runs: spatial structures ***but*** no collisional evolution or size distribution

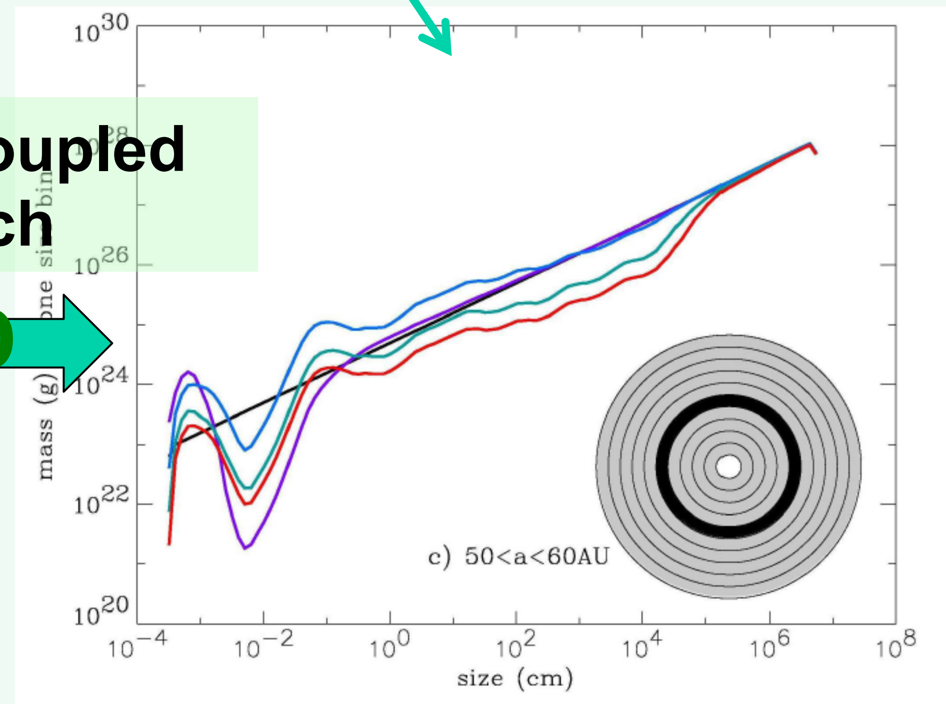
Statistical simulations: collisional evolution, (detailed collision prescriptions), size distribution ***but*** no (or poor) dynamics

need for a coupled approach

AND

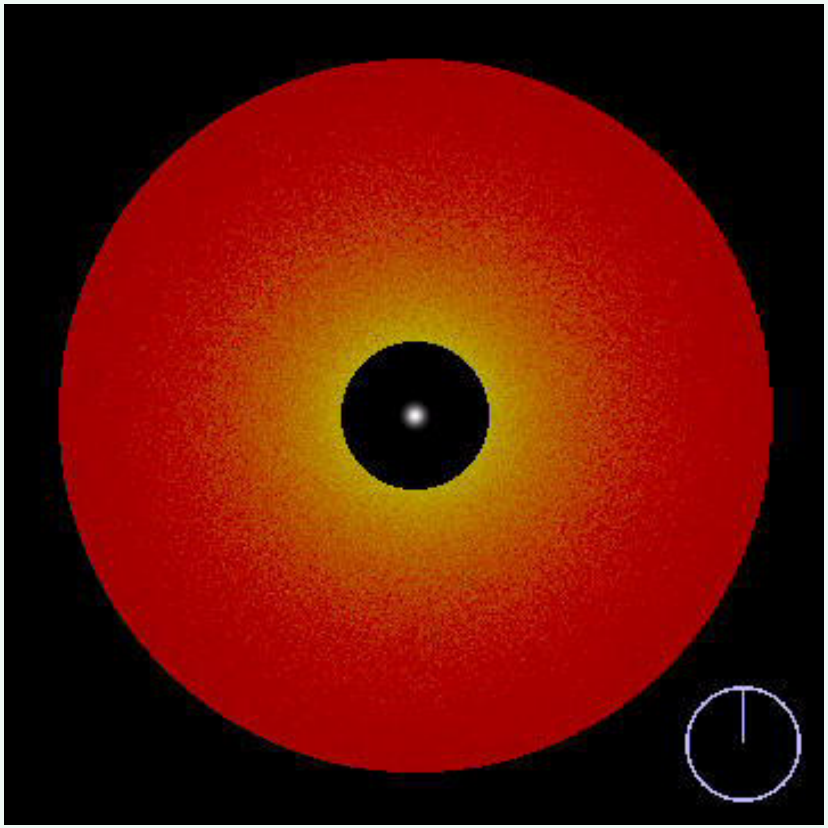


OK if only large particles (sub-mm images)



OK if no perturbations

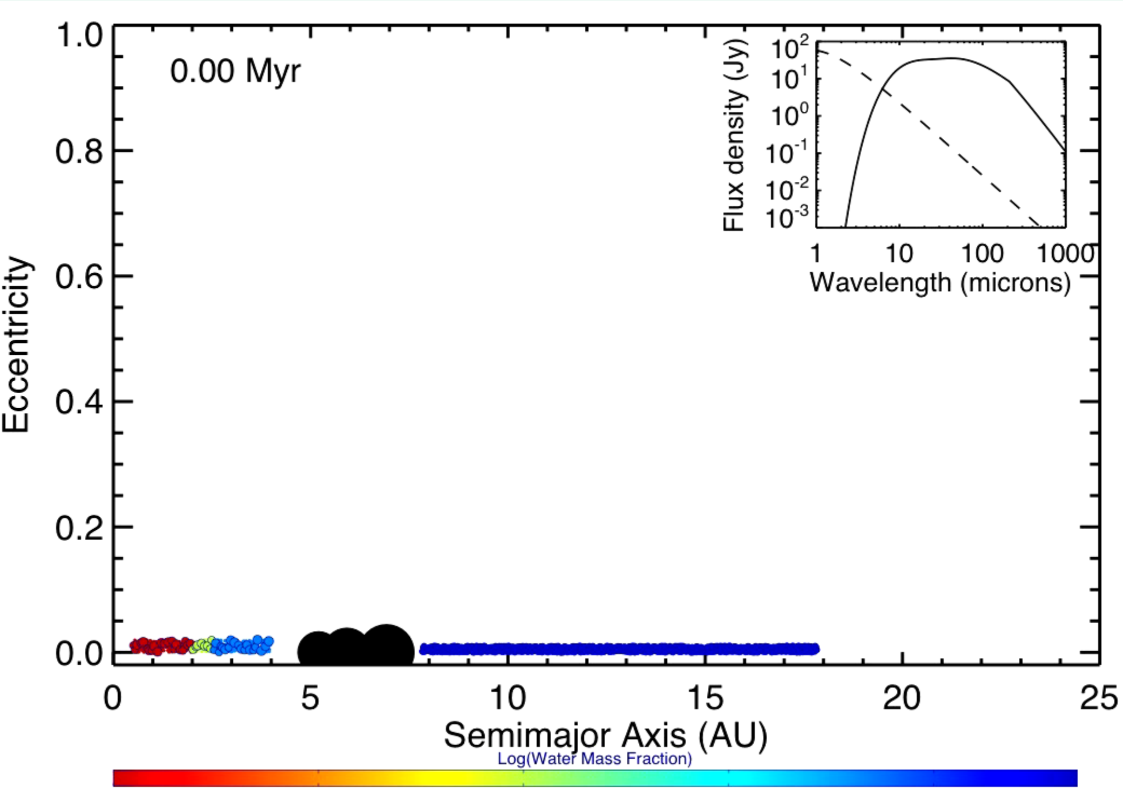
Multi-annulus hybrid code (Kenyon&Bromley)



- Multiannulus coagulation/ fragmentation code (masses <0.01 M_{earth})
- N-body code (masses > 0.01 M_{earth})

Debris disc as signposts of planet forming discs

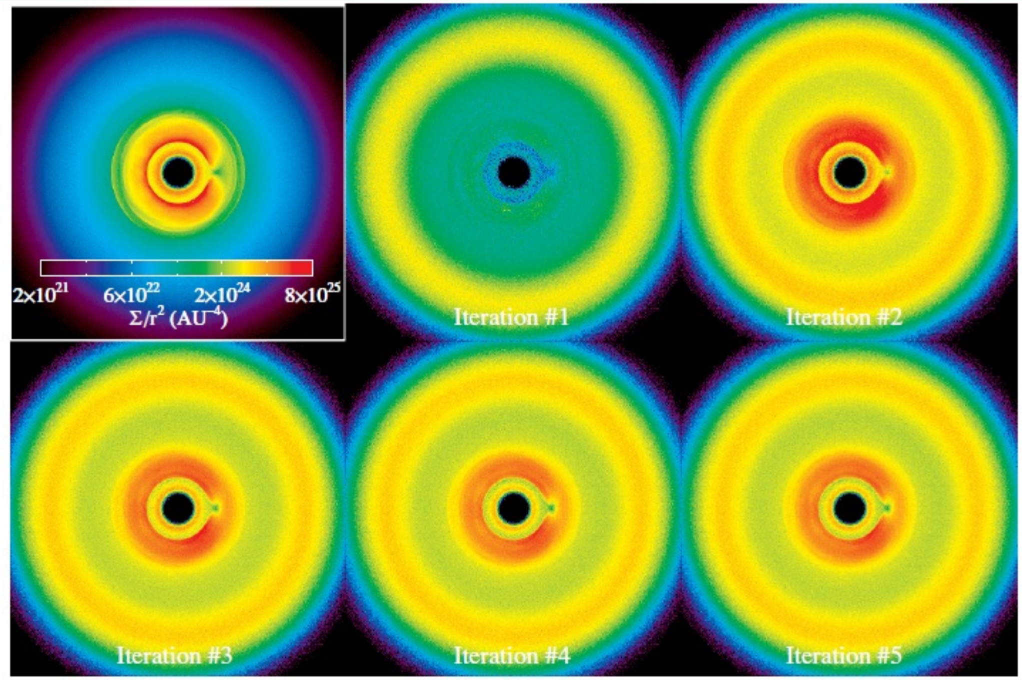
Raymond et al. (2011)



- Hybrid model from Booth et al. (2009)
- 4 populations:
  - Planets
  - Embryos
  - Planetesimals
  - Dust

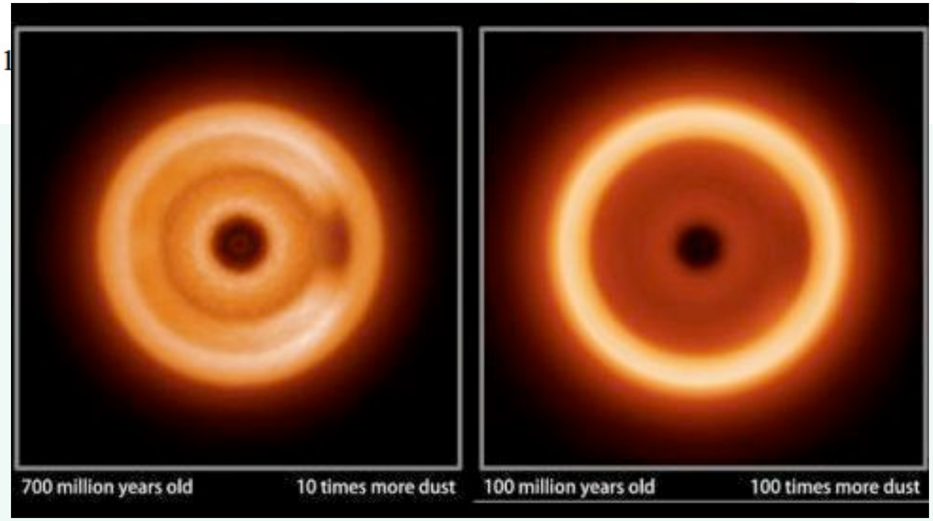
Collisional grooming model (Stark & Kuchner)

Create successive streams of particle trajectories, that are used as collision maps for successive iterations.

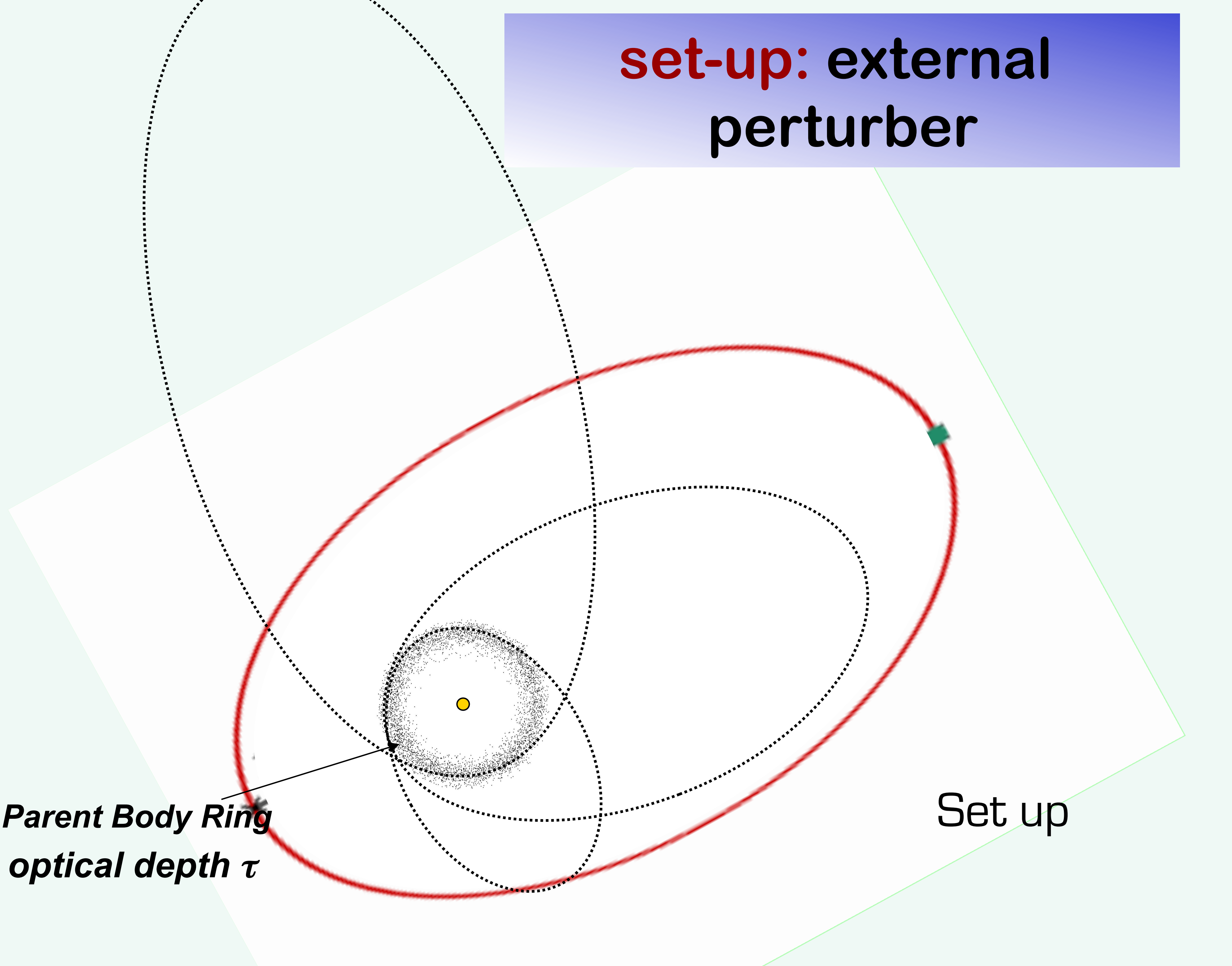


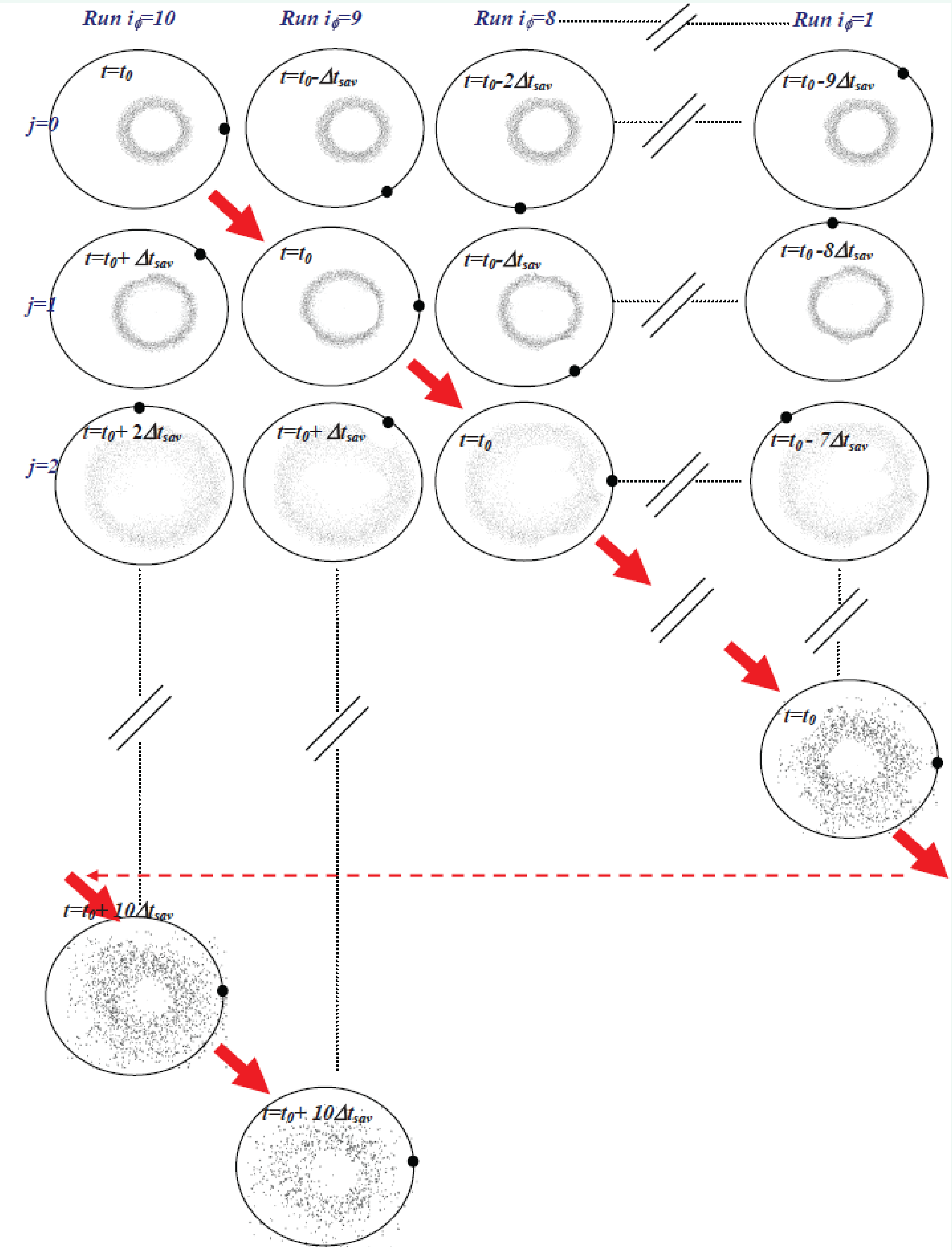
- Adapted to PR-drag drifting grains captured by a planet
- Impressive results for the Kuiper Belt

- Works only (so far) for one circular perturber
- No fragmentation (fully destructive collisions)



set-up: external perturber





DyCoSS Code (Thebault, 2012)

- System at ***steady state***
- One perturber on any orbit
- Self-consistent size distribution

3 steps

- **1) Parent Body run**: for β=0 particles, until *dynamical steady state* is reached. Save10 PB disc profiles for 10 ≠ positions of the companion on its orbit separated by $dt_{sav}=t_{orb}/10$

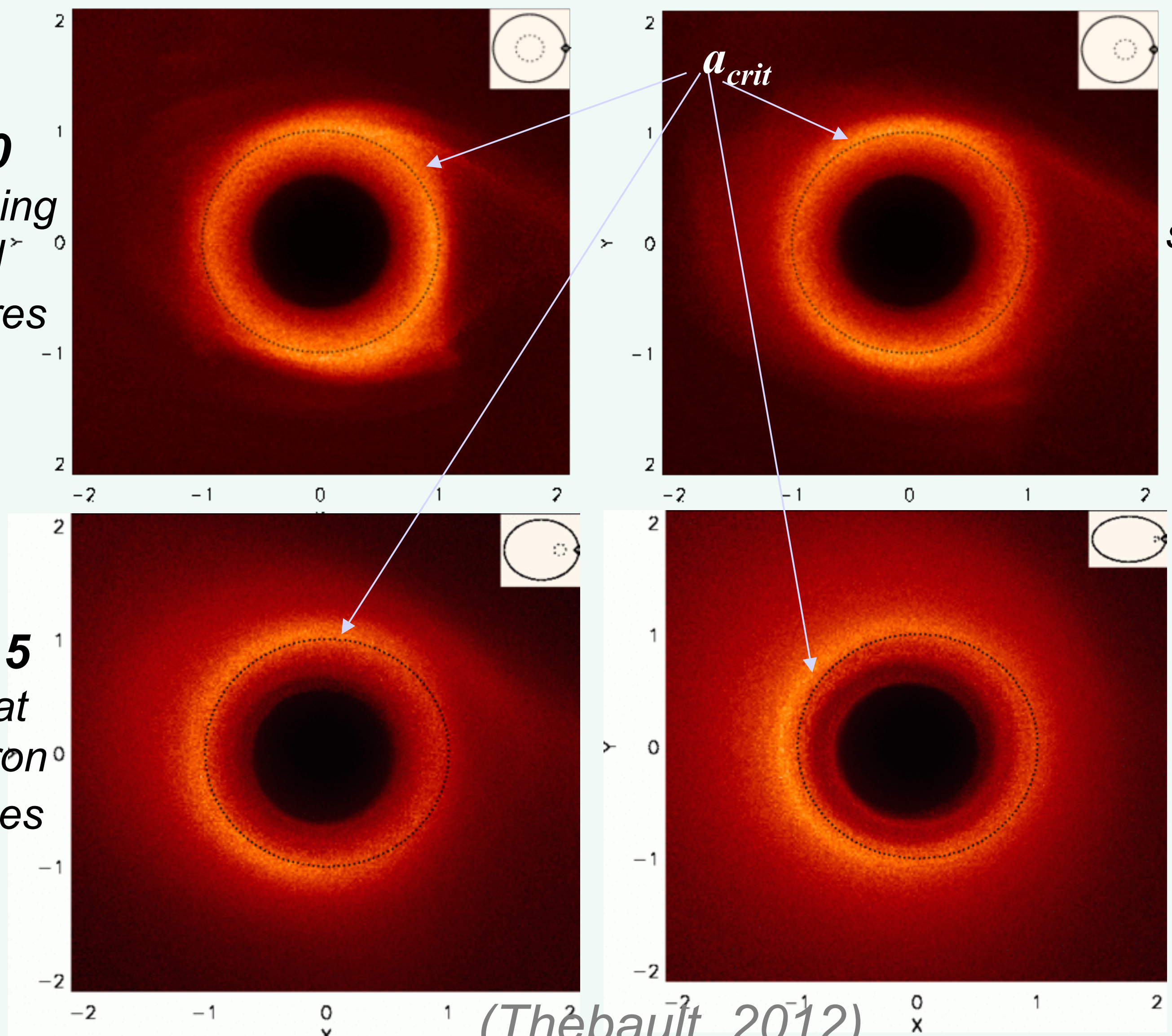
- **2) Collisional Runs**: From each of the10 PB discs, 10^5 small grains are released following $dN \alpha\ s^{-3.5}ds$. They are assigned a *collision destruction probability* as a function of size and location. All particle positions are recorded at each dt_{sav}. Runs are stopped when all particles have been removed by ejection or collisions

- **3) Recombining:** Use all collisional runs to reconstruct the dust distribution, **at steady state**, for each orbital position of the perturber.

Response of a collisional disc to binary perturbations

e_B=0
precessing spiral structures

e_B=0.2
precessing spirals for half the orbit

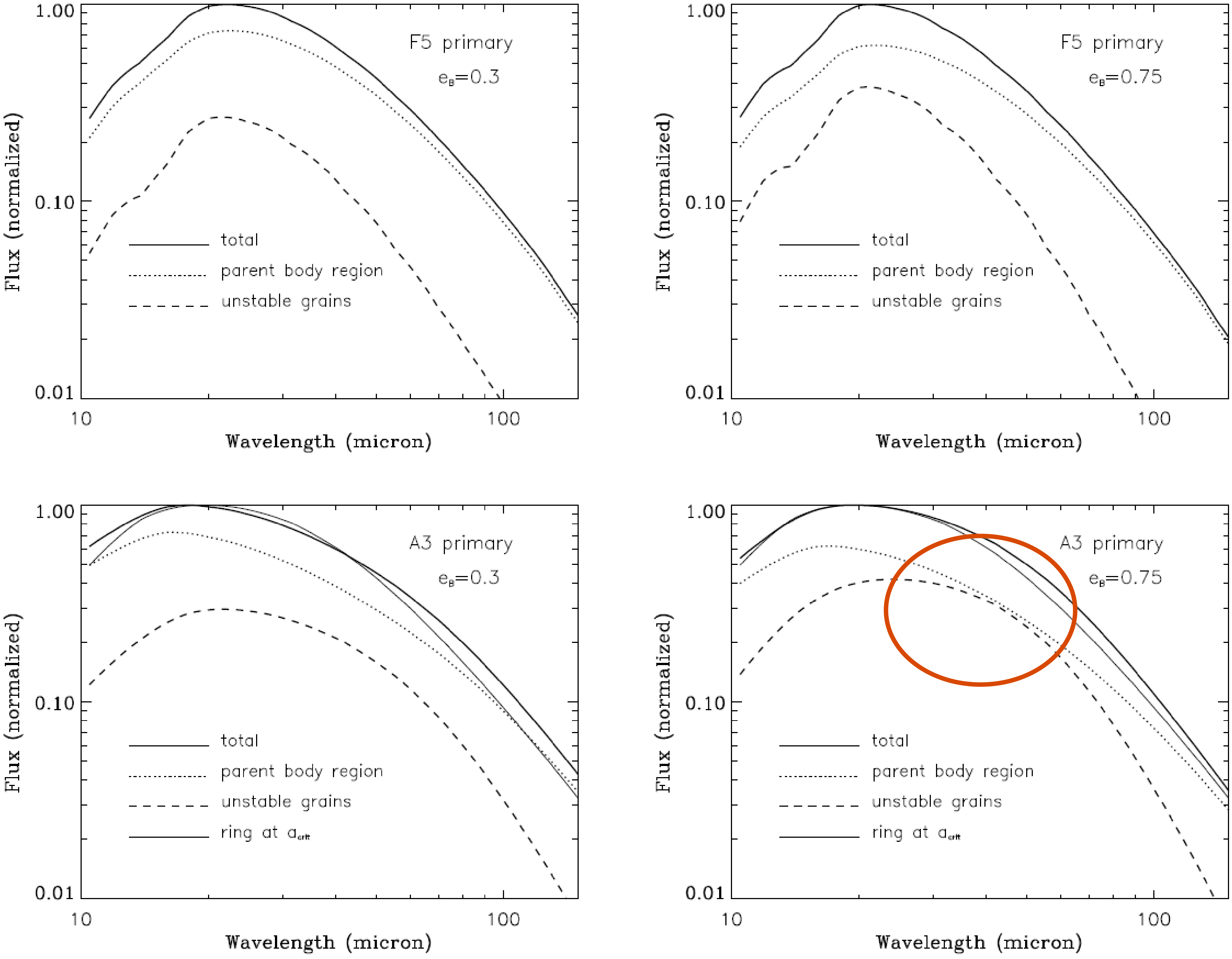


e_B=0.5
spiral at periastron passages

e_B=0.75
Invariant asymmetric disc

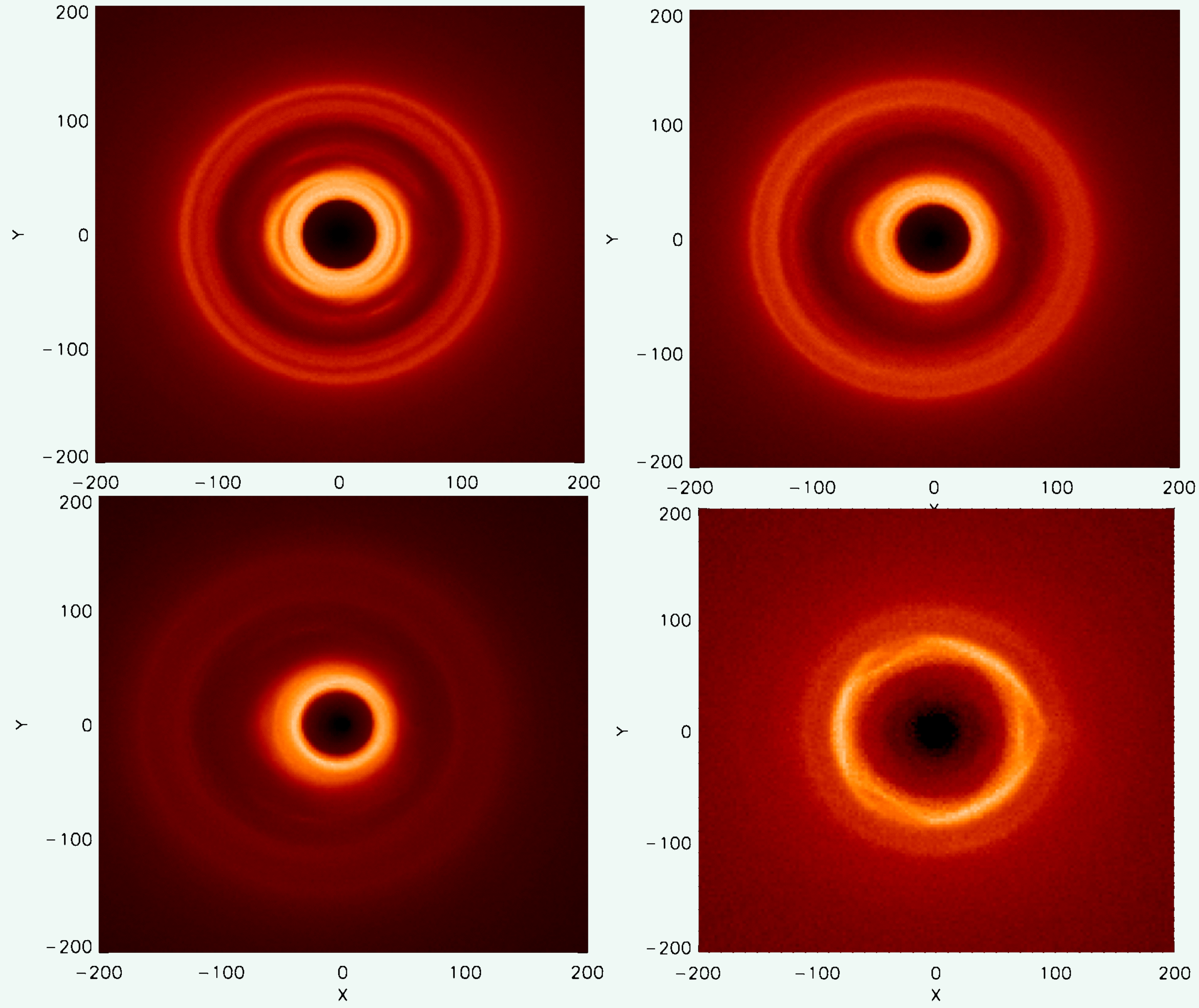
(Thébault, 2012)

Discs in binaries: SEDs (using GRaTEr)



Planets in collisionally active discs

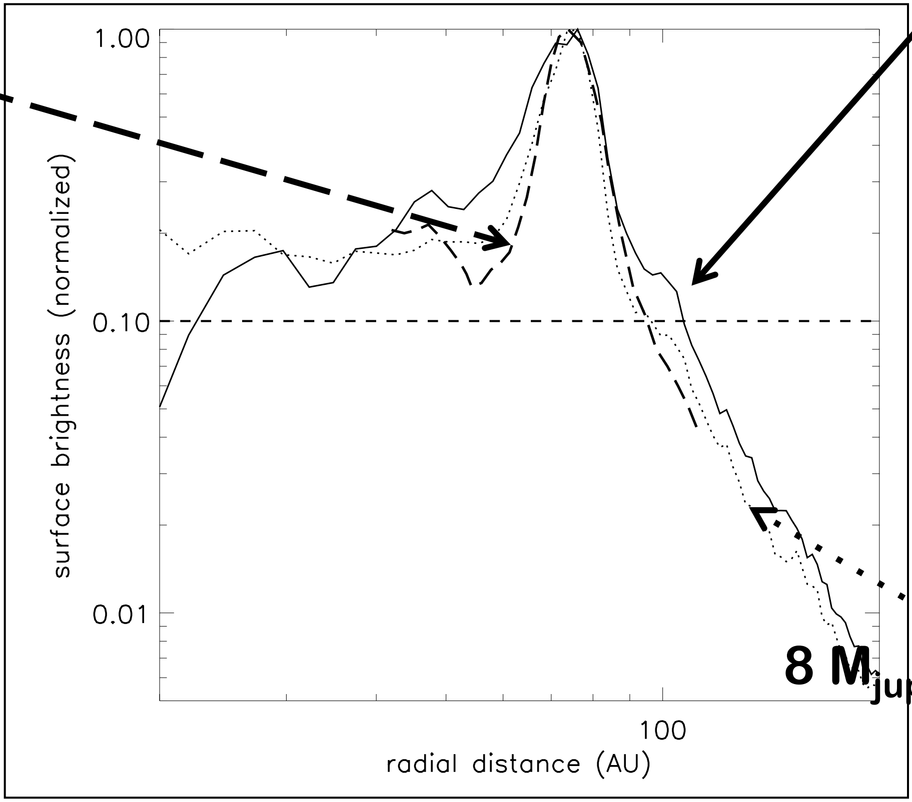
at steady state



Fitting the HR4796 disc?

5 M_{jup} planet at 98 AU

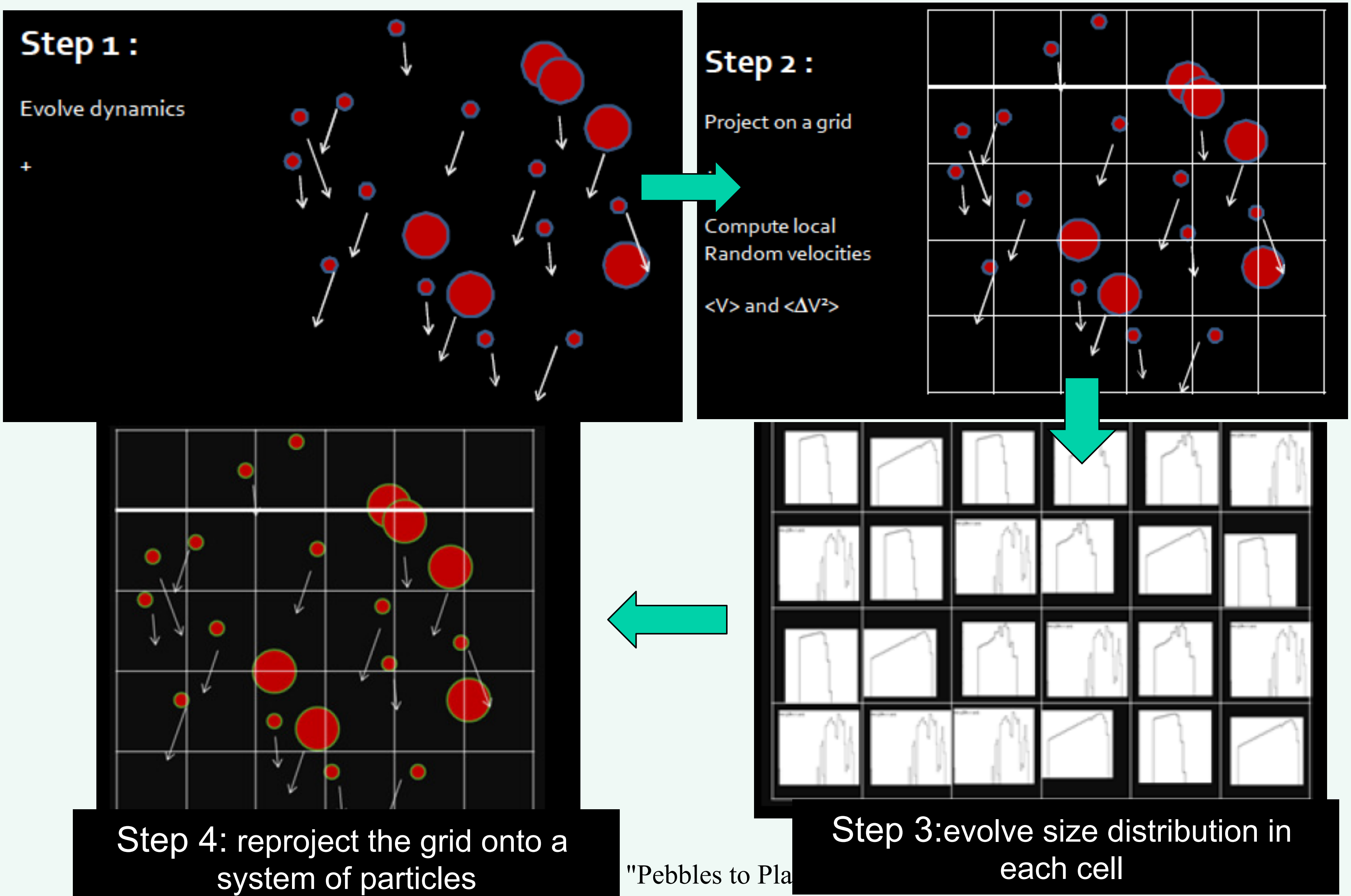
Observed profile (Schneider et al., 2009)



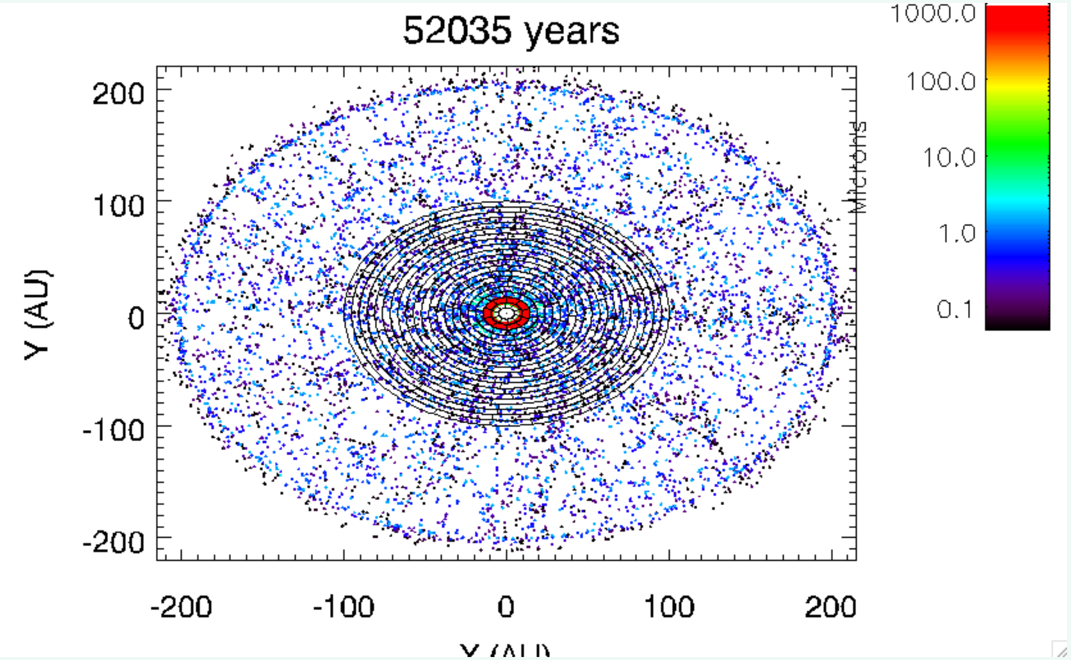
8 M_{jup} planet at 102 AU

(Lagrange et al., submitted)

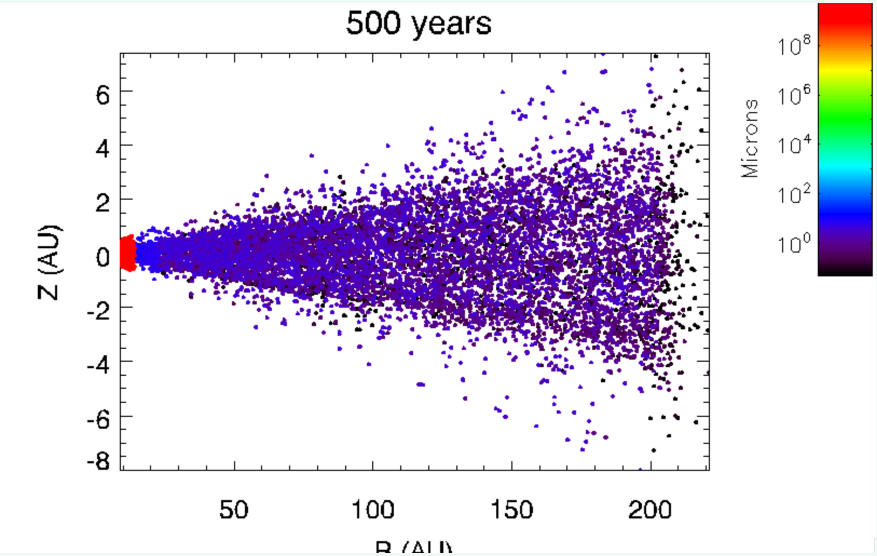
The first fully coupled collisions+dynamics code: LIDT (Charnoz, 2012)

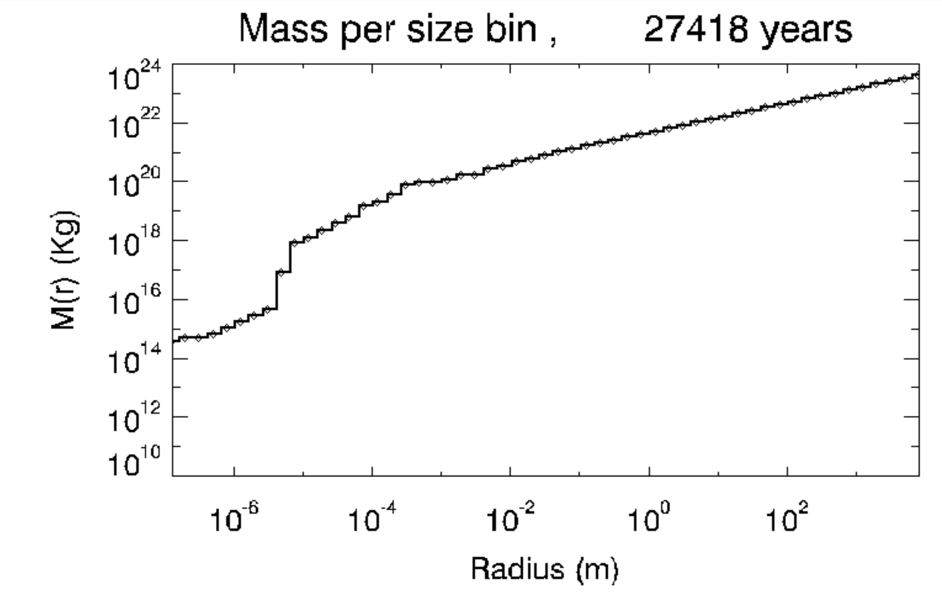


Debris disc version of LIDT (Kral/Thebault)



- *First test:* *reproduce well known robust results*





FIN