Debris Disks and Planetary Systems

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Outline

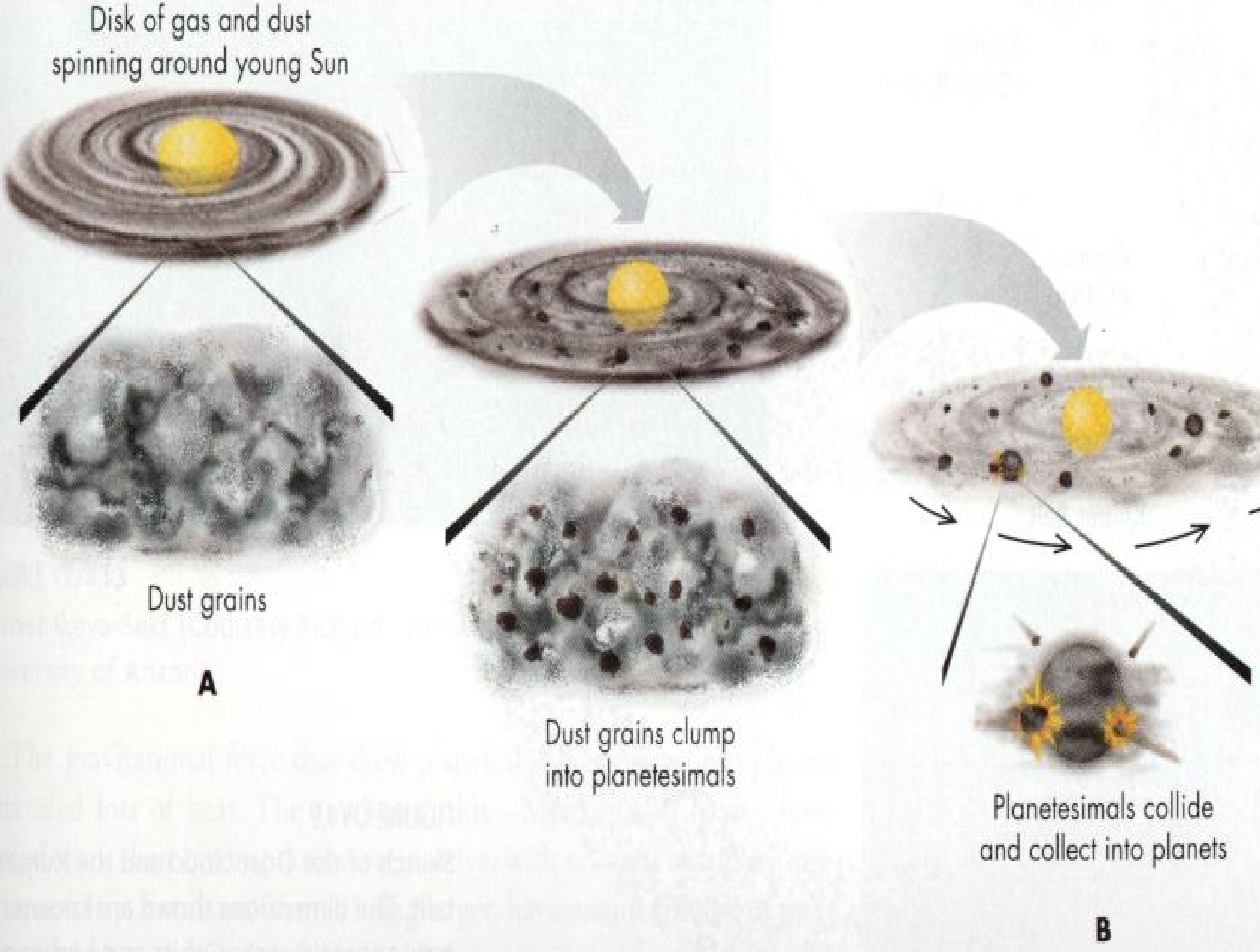
- Part 1 Introduction of Debris Disks
- Part 2: The Vega Puzzle
- Part 3: Extra-Solar Planetary Systems
- Part 4: Conclusions and Challenges

Debris Disks

- Definition: dust grains and small bodies (planetesimals, asteroids, Kuiper-Belt objects) on the disk of a planetary system.
- That is, except the planets , those non-gaseous parts are referred as the debris disk
- Sizes: dust grains are 0.1 to 10 micro-meter, planetesimals are cm to km
- The first extra-solar debris disk: the Vega system
- Around 20 directly imaged debris disks

Formation of a Debris Disk

- The remnants of the protoplanetary disk
- The gaseous part of disk has a lifetime of about 1 to 6 Myrs (Meyer et al. 2007)
- After the gas is cleared out, a debris disk is there with a mass only a small fraction of original protoplanetary disk
- Typically, debris disk is around Earth Mass


Disk of gas and dust spinning around young Sun
Dust grains
A
Dust grains clump into planetesimals
Planetesimals collide and collect into planets
B

Replenishment

- Small dust grains are blown out continuously by radiation pressure
- Small grains exist in imaged debris disks
- A replenishment mechanism is necessary
- Collisions between planetesimals can produce small dust grains
- Planetesimals and/or asteroids shall exist in the system, and have enough collision rates

Simulations of Debris Disks

- Observations of imaged debris disk give: information of grain sizes, disk structure
- 1st Goal: to produce the grain size distributions
- 2nd Goal: to model the structures of debris disks
- One has to model the collisional events and also orbital evolution of dust grains
- A very difficult task
- Most works focus on one aspect only: collisional cascade or orbital (disk structure) evolution

Collisional Cascades

- method: particle-in-a-box
- Include catastrophic and erosive collisions
- Use a system of equations governing the number densities of different sizes of grains
- Analytic work: Dohnanyi (1969), Hellyer (1970), Bandermann (1972)
- Numerical Codes: Krivov et al. (2008), Kuchner & Stark (2010), Gaspar et al. (2012)

Disk Structure Modeling

- Dust grains are moving as test particles, under the influence of gravitational force and radiation pressure of the central star
- Dust grains are also affected by the existing planets’ gravity
- All dust grains’ orbits are determined
- Surface mass density of grains on debris disk is calculated, so gives disk structures (Deller & Maddison 2005)

The Vega Puzzle

- Through their own Spitzer data, Su et al. (2005) showed the Vega’s debris disk’ dust are small (1 micro-meter) blowout grains
- Krivov et al. (2006) pointed out the mass budget problem if blowout grains all the time, so favor larger (10 micro-meter) long-lived grains
- Muller et al. (2010) showed that if Vega star’s luminosity is much smaller than what was used, larger long-lived grains can still fit Spitzer data
- The Puzzle/Debate: short lived or long lived ?.

Su, Rieke et al. (2005)

- What we see are mostly small dust grains
- At R > 200 AU, surface density: 1/R profile
- A ring of planetesimals and asteroids between 86 and 200 AU
- The ring region produces new dust grains
- Dust grains are blown out continuously
- We witness a recent collisional outcome

Jiang & Yeh (2009)

- In a blowing out picture, investigate the condition to produce 1/R density profile
- Investigate the effect of chemical compositions
- Investigate the effect of cut-off of grain size distribution
- Investigate the necessary dust production rate through collisions

The Details

$$\frac{dN}{da} = Ca^{-3.5}$$

$$\Sigma_1(R) = \begin{cases} \frac{\Sigma_0}{100^2} & \text{when } 86 \leq R \leq 100, \\ \frac{\Sigma_0}{R^2} & \text{when } 100 < R \leq 200, \end{cases}$$

Chemical Compositions

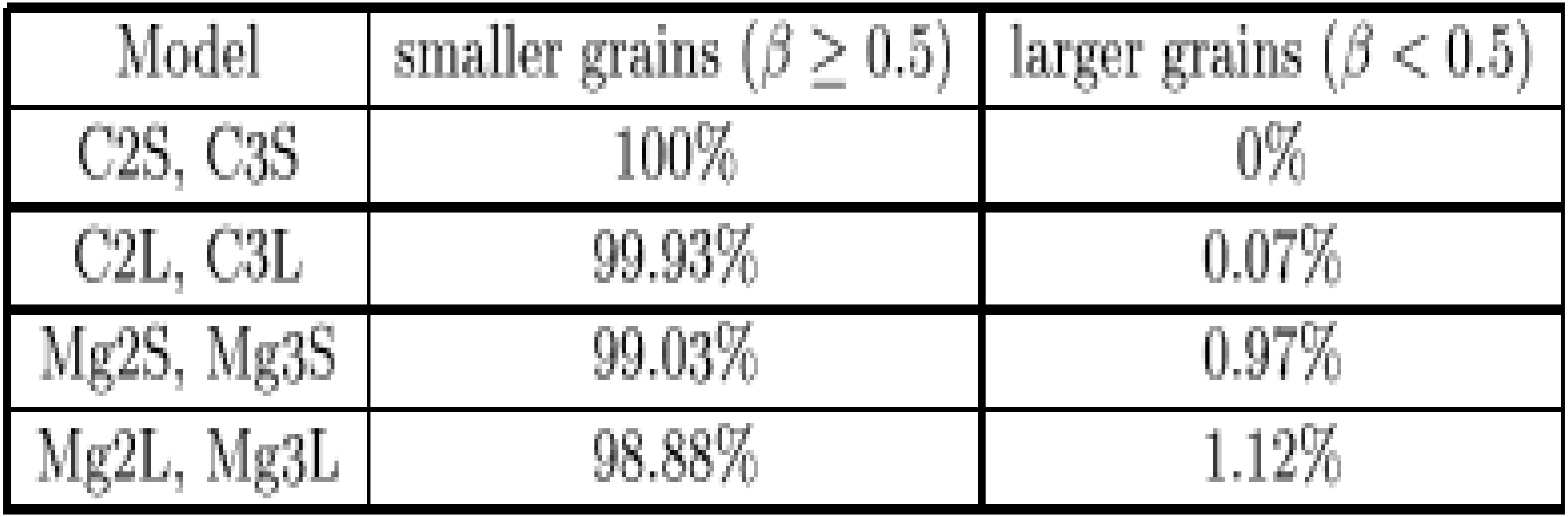
- C400 and MgFeSiO4

$$\beta = \frac{3L}{16\pi G m_0 c \rho a} \frac{\int Q_{pr}(a, \lambda) F_\lambda d\lambda}{\int F_\lambda d\lambda}$$

Table 1 The Ingredients of Models

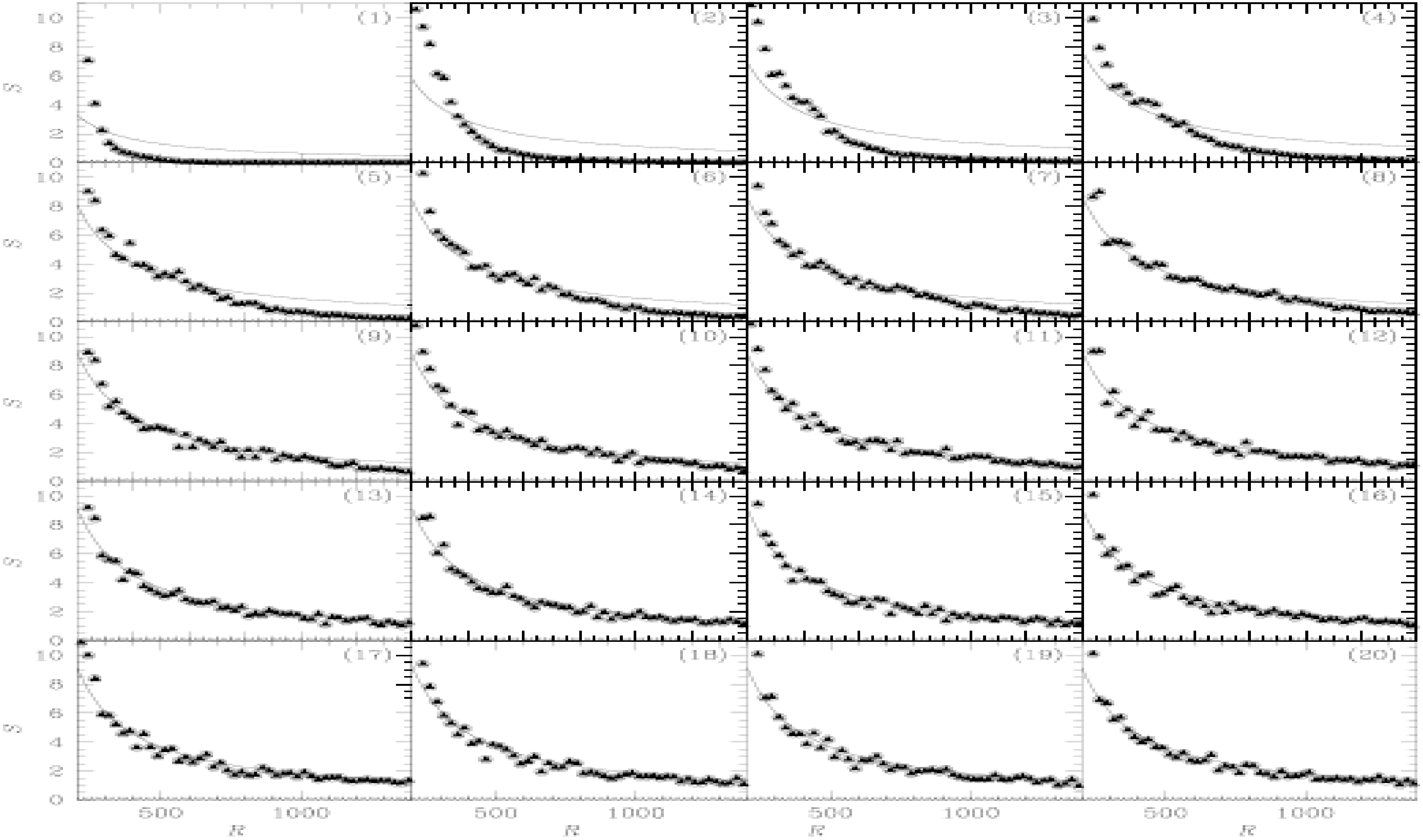
Model	Composition	Grain Density	Time Interval	$a_{\max}$	$\beta_{\min}$
C2S	C400	$2.26(\mathrm{g/cm^3})$	100 (years)	9.57 (μm)	0.62
C2L	C400	$2.26(\mathrm{g/cm^3})$	100 (years)	14.04 (μm)	0.42
C3S	C400	$2.26(\mathrm{g/cm^3})$	1000 (years)	9.57 (μm)	0.62
C3L	C400	$2.26(\mathrm{g/cm^3})$	1000 (years)	14.04 (μm)	0.42
Mg2S	$MgFeSiO_4$	$3.3(\mathrm{g/cm^3})$	100 (years)	9.57 (μm)	0.28
Mg2L	$MgFeSiO_4$	$3.3(\mathrm{g/cm^3})$	100 (years)	14.04 (μm)	0.19
Mg3S	$MgFeSiO_4$	$3.3(\mathrm{g/cm^3})$	1000 (years)	9.57 (μm)	0.28
Mg3L	$MgFeSiO_4$	$3.3(\mathrm{g/cm^3})$	1000 (years)	14.04 (μm)	0.19

The Grain Number Percentage

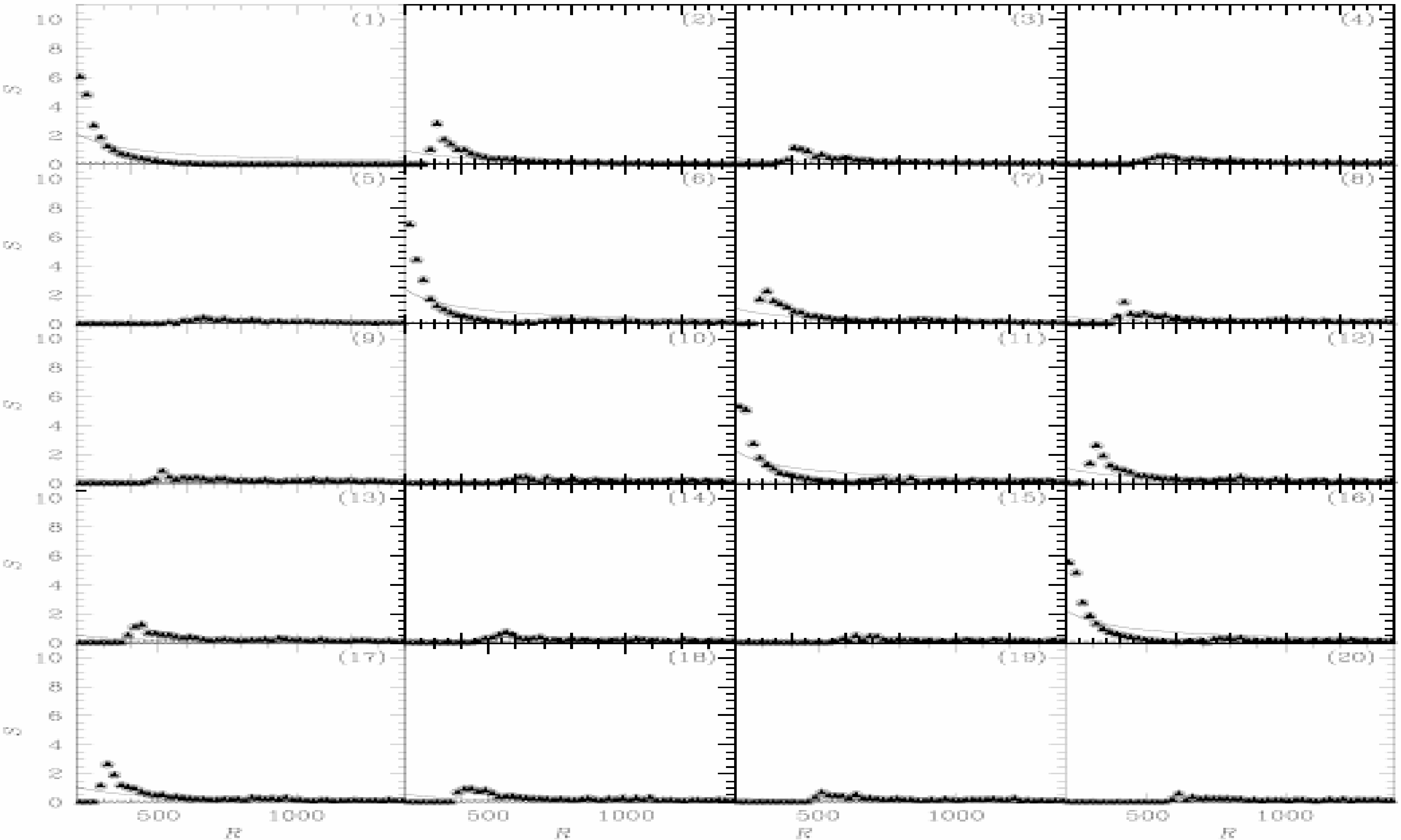


Model	smaller grains ($\beta \geq 0.5$)	larger grains ($\beta < 0.5$)
C2S, C3S	100%	0%
C2L, C3L	99.93%	0.07%
Mg2S, Mg3S	99.03%	0.97%
Mg2L, Mg3L	98.88%	1.12%

Model C2S



Model C3S



Remarks

- The self-consistent dynamical model can be constructed for the blowing-out picture
- Model C2S gives the best fit to 1/R profile
- average dust production rate:
  0.001 Earth Mass every 1000 years

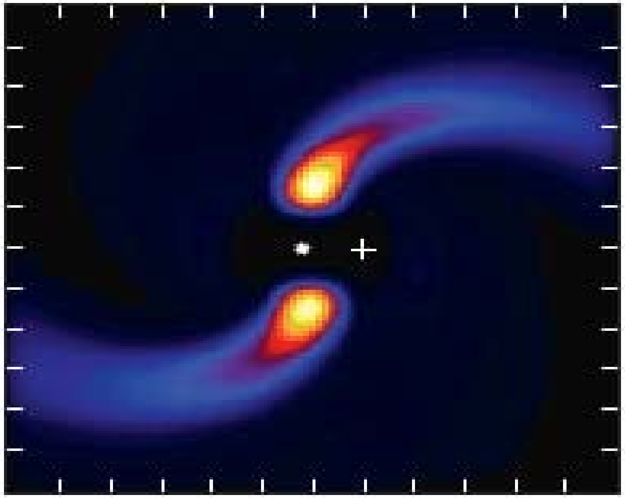
The Inner Vega Disk

- Holland et al. (1998) show two Clumps
- Although coronagraphic search on this region gave negative result (Itoh et al. 2006)
- To explain clumps, need models with planetesimals/grains in resonance with a planet
- A Migrating Neptune (Wyatt 2003)
- A Jupiter Mass Planet on eccentric orbit (Wilner et al. 2002)

Wyatt (2006)

- For one recent collision event, non-axis-symmetric structures shall be on outer disk

Small Grains from One Collision
(Wyatt 2006)

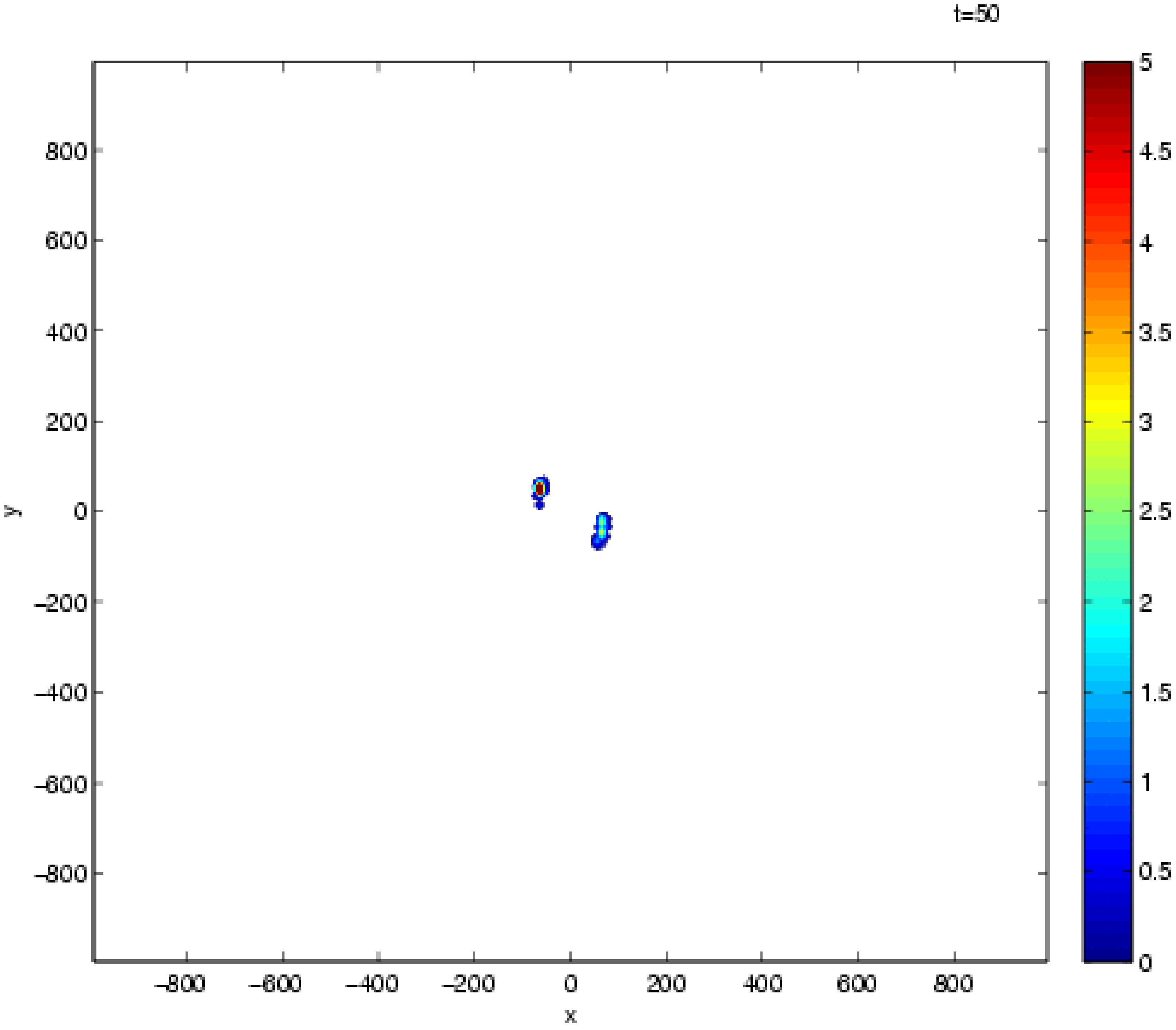


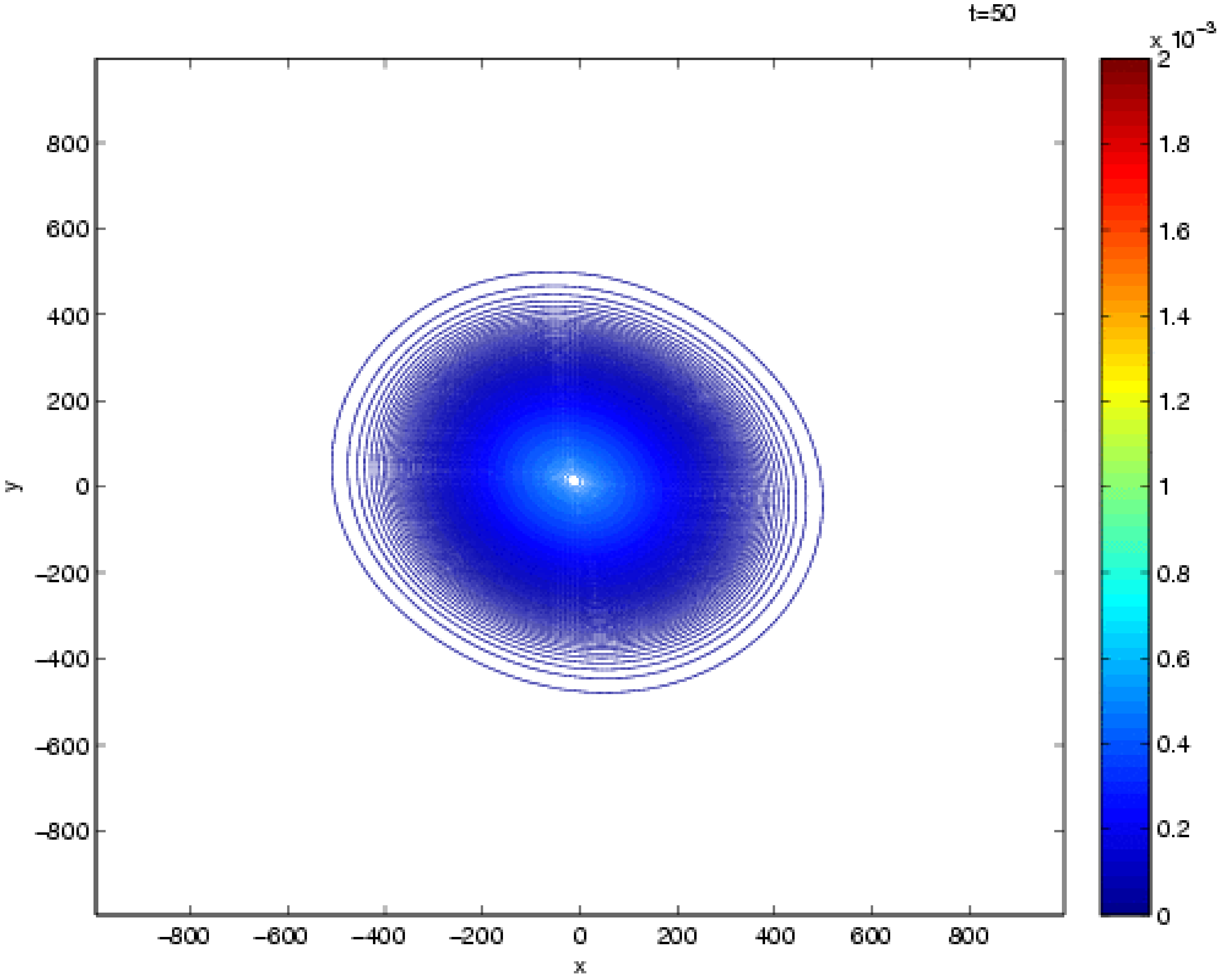
Possible Solution to Vega Puzzle: a quasi-steady state picture

- Adopting the grain sizes in Su et al. (2005), i.e. the Spitzer observational results
- Planetesimals get captured into resonanes gradually, then form inner two clumps
- Not always in high dust production rate, only approach to recent rate gradually
- A large number of arms become an axis-symmetric structure at outer Vega disk

Jiang & Yeh (2011)

- Two clumps rotate with a planet
- Planetesimals in the two clumps might collide with each other (as a stochastic process), and produce small grains
- Grains are blown out continuously, and form many arms


t=50
y
x
800
600
400
200
0
−200
−400
−600
−800
−800
−600
−400
−200
0
200
400
600
800
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0

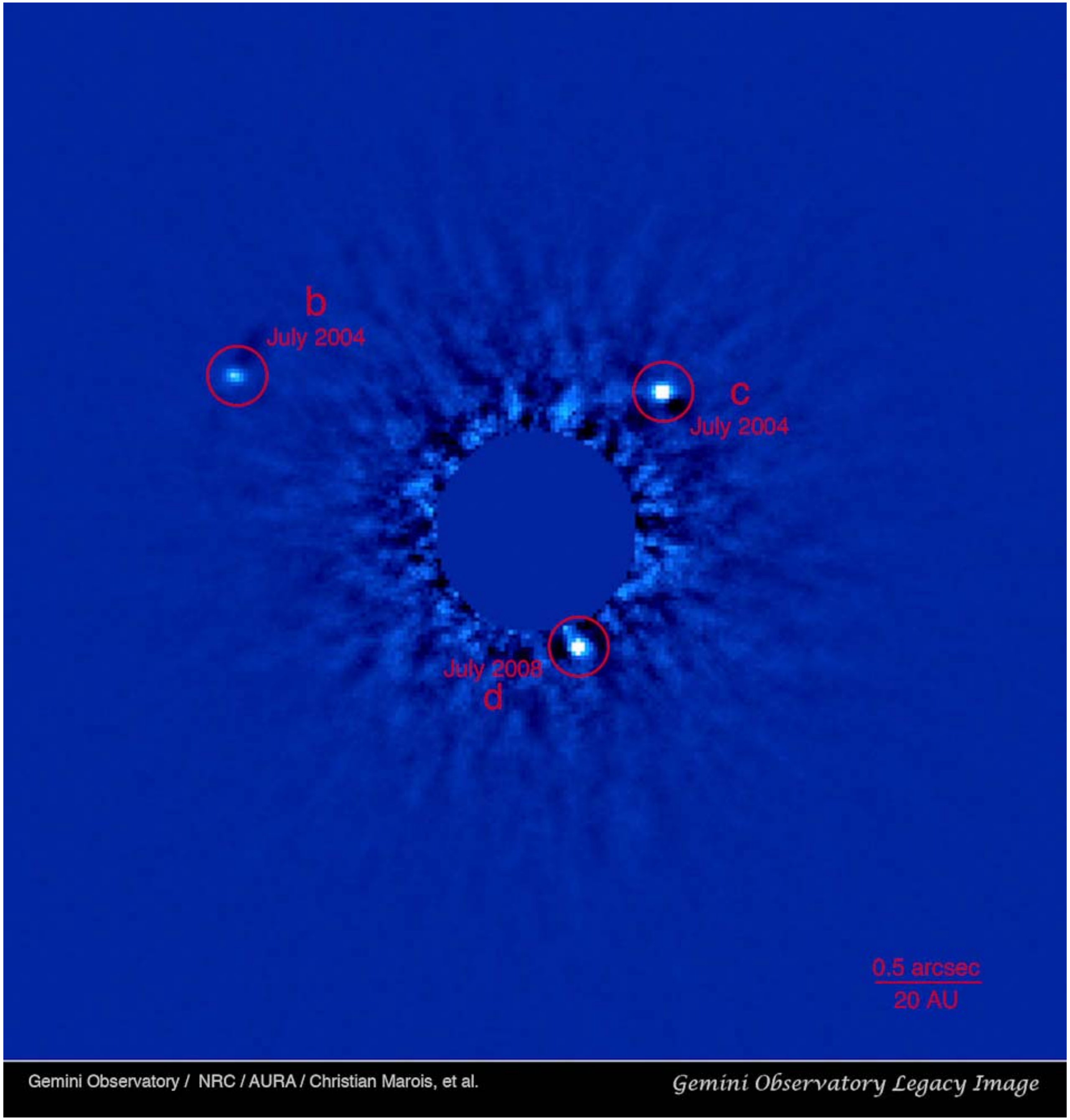

t=50
x 10^-3
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
800
600
400
200
0
−200
−400
−600
−800
y
−800
−600
−400
−200
0
200
400
600
800
x

Remarks

- This picture adopts small grain size but use different interpretation, i.e. not just a recent collision
- This picture can solve mass budget problem
- This picture produce symmetric-looking debris disk as seen by Spitzer
- Future state-of-art simulations are necessary: resonant capture, collisions, disk structures

Debris Disks versus Exoplanets

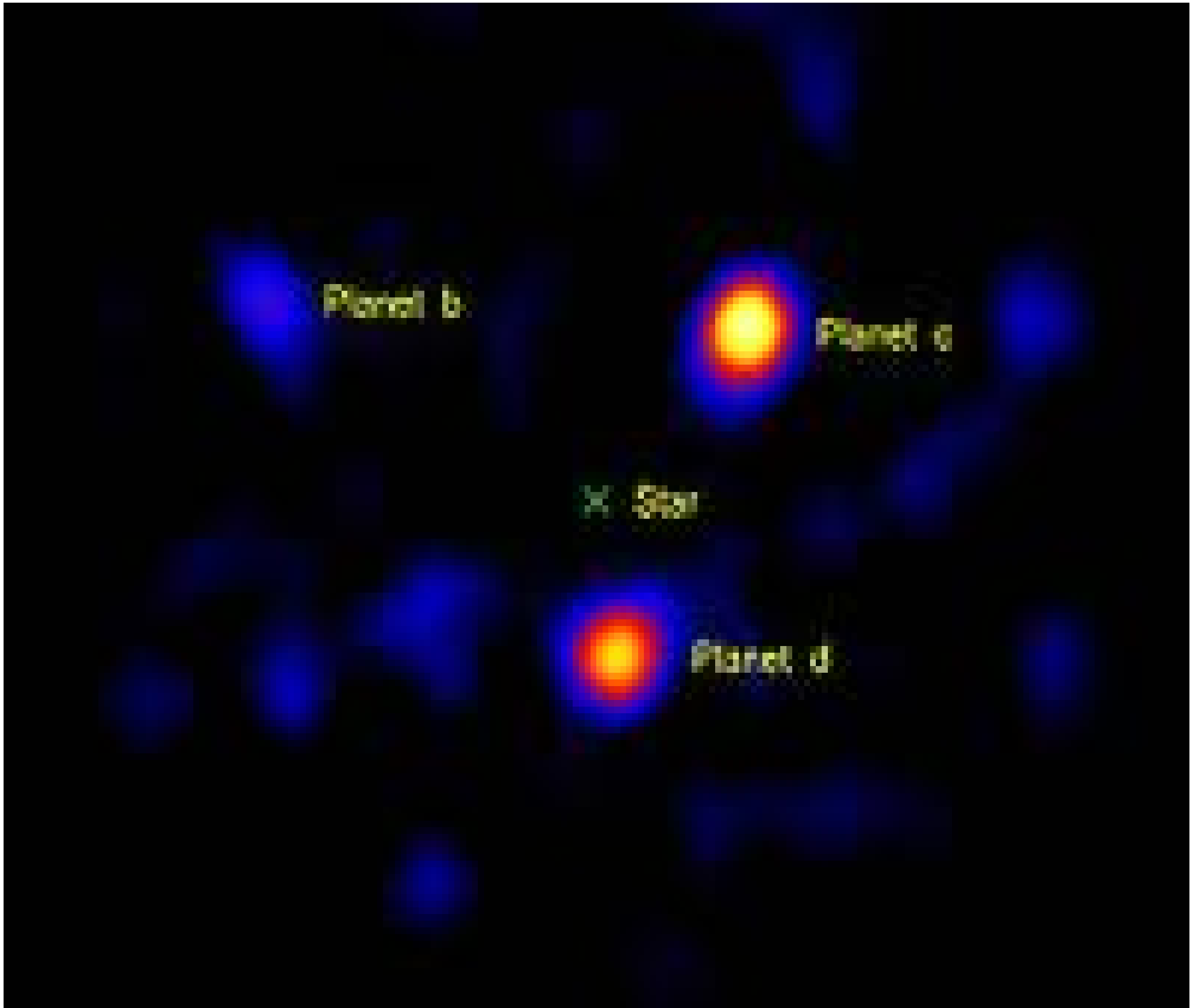
- More than 800 detected exoplanets
- At least, 2.5 to 5.5 % of stars might have planets (Jiang et al. 2010)
- Most are detected by Doppler-shift method, transit, direct imaging, and transit timing variation (Lissauer et al. 2011, Jiang et al. 2012)
- Exoplanets can be hidden in debris disk if grains are small short-lived ones (Jiang & Yeh 2009)
- The ones with debris disk: HR8799 system, Beta Pic System, Fomalhaut system

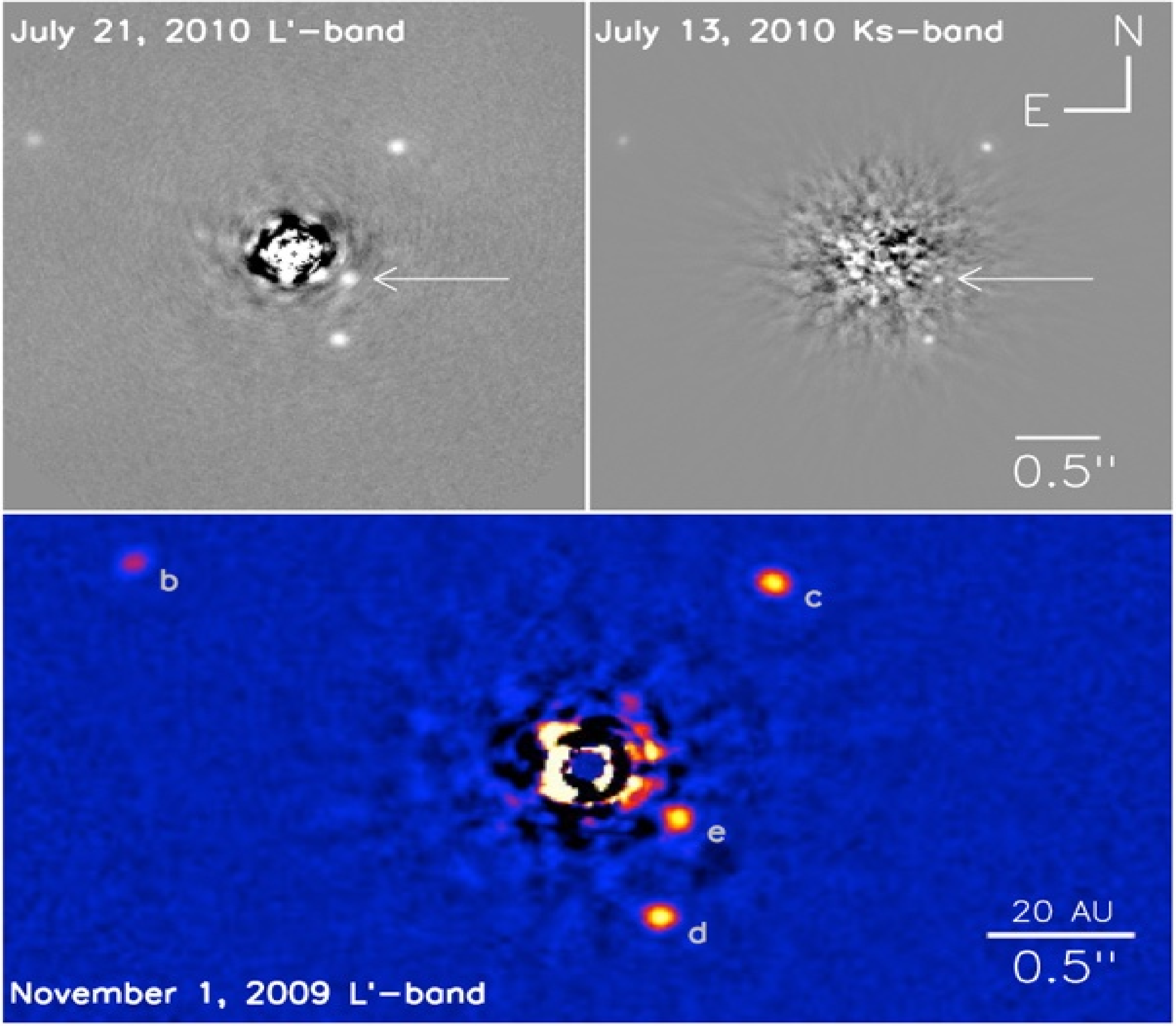


Gemini Observatory / NRC / AURA / Christian Marois, et al.

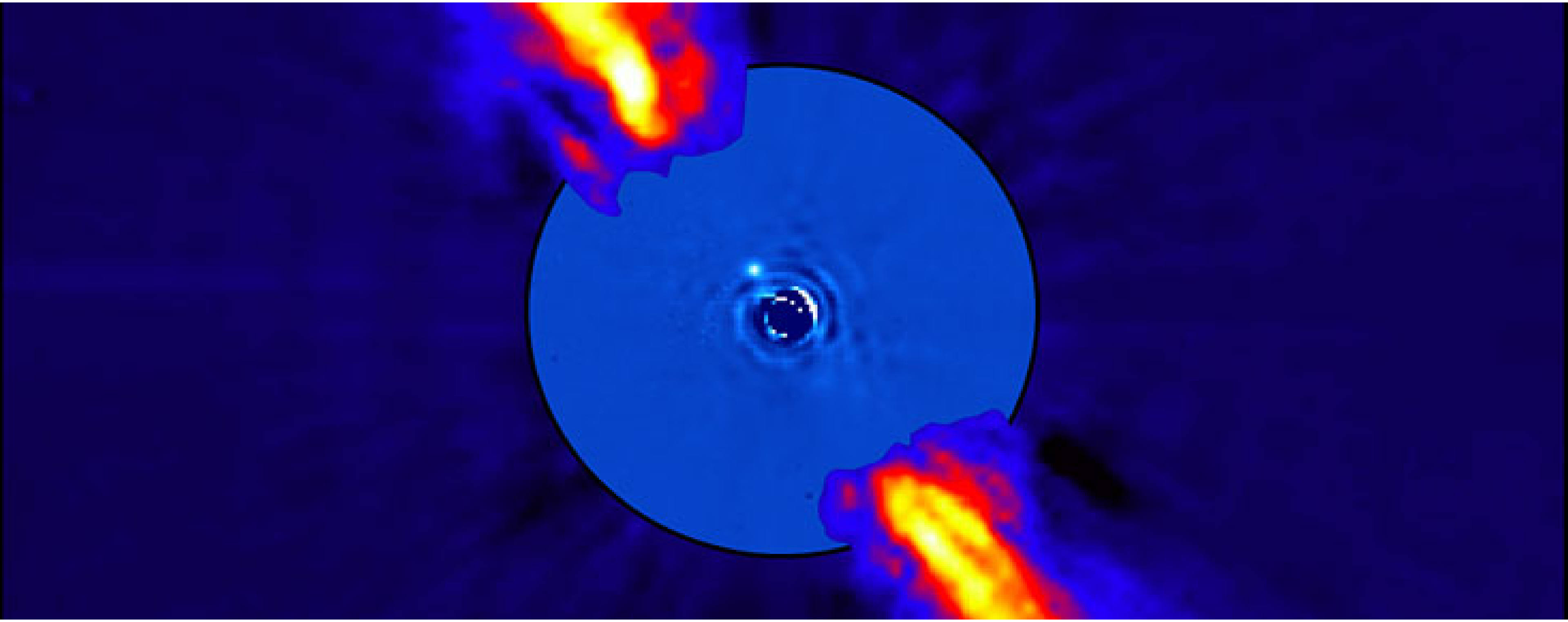
Gemini Observatory Legacy Image

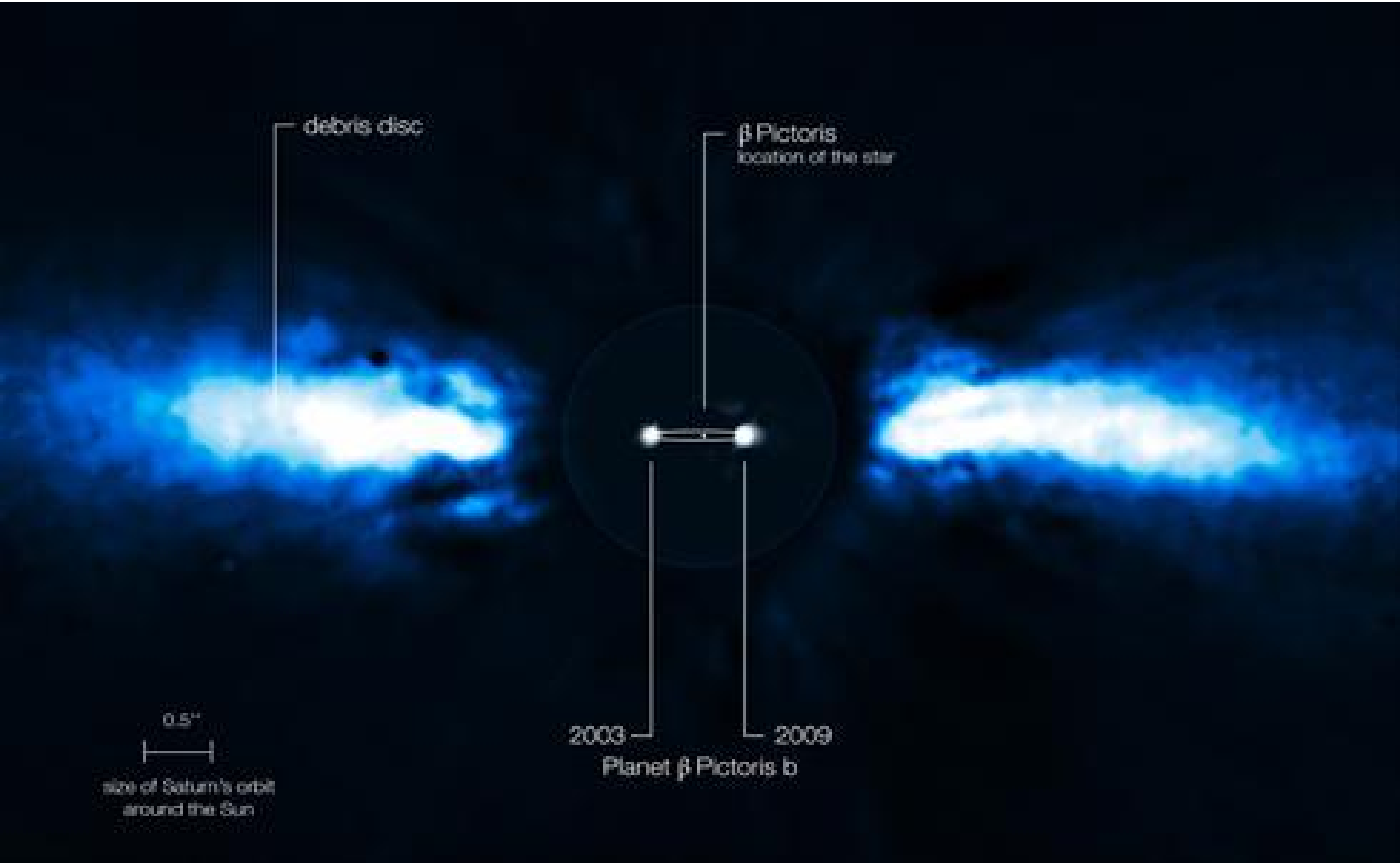
HR8799



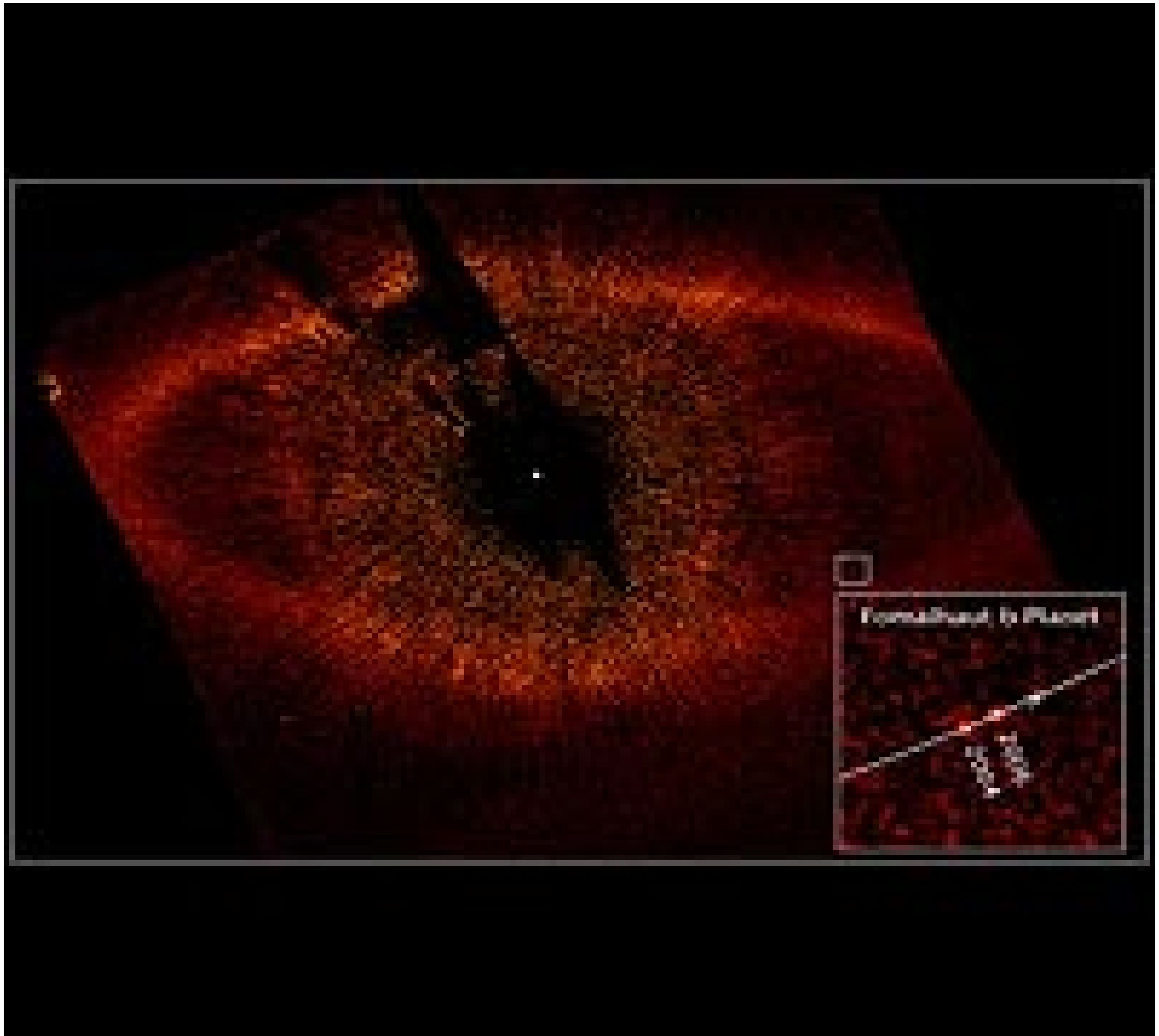

July 21, 2010 L'-band
July 13, 2010 Ks-band
N
E
0.5''
b
c
e
d
20 AU
0.5''
November 1, 2009 L'-band

Beta Pic Planet




debris disc
β Pictoris
location of the star
0.5''
size of Saturn's orbit around the Sun
2003
2009
Planet β Pictoris b

Fomalhaot System



Conclusions and Challenges

- Further detail numerical simulations are necessary to build up our knowledge
- With more observations, huge number of simulational investigations will lead to more reasonable results
- To deal with collisions in smaller scale and orbital evolution in larger scale at the same time is the challenge in this field