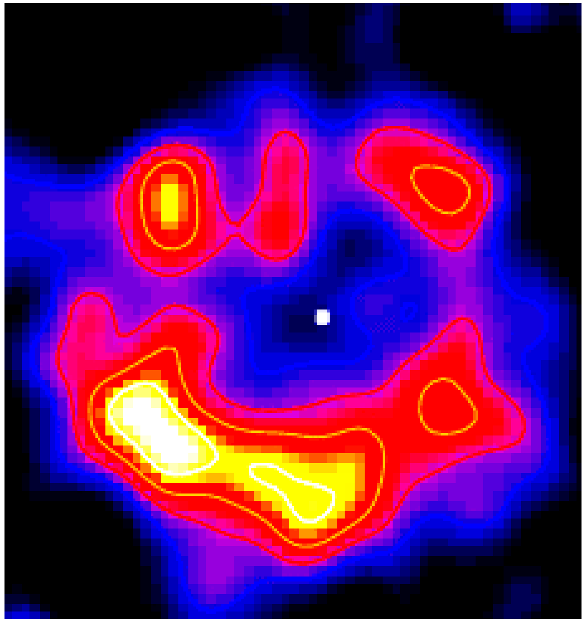
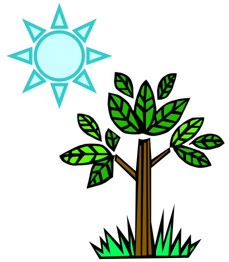
Debris disks: detecting planets and their environments

Jane Greaves

St Andrews



questions

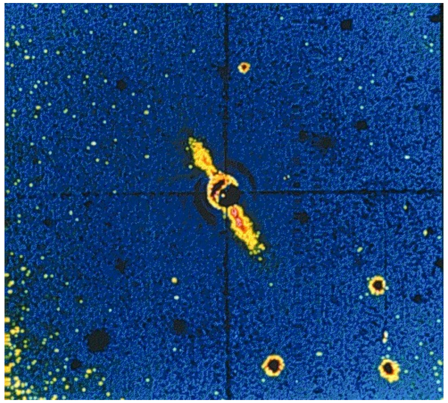


1) what is the nature of debris disks?

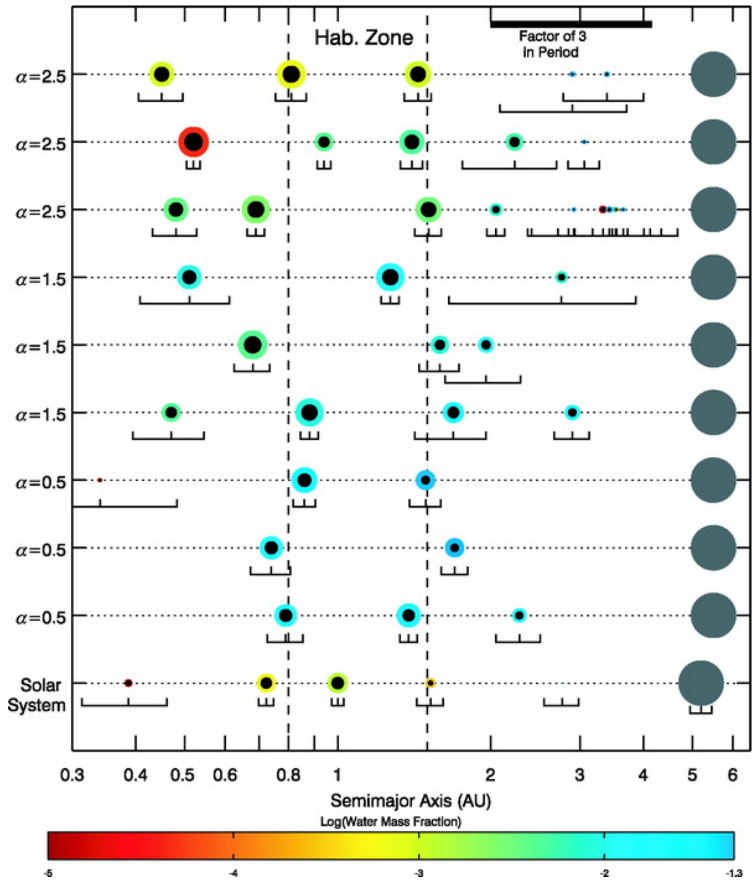
2) what do they tell us about planet formation histories of nearby stars?

3) a new method of planet detection?

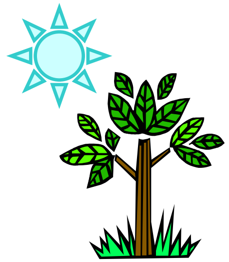
continuation…

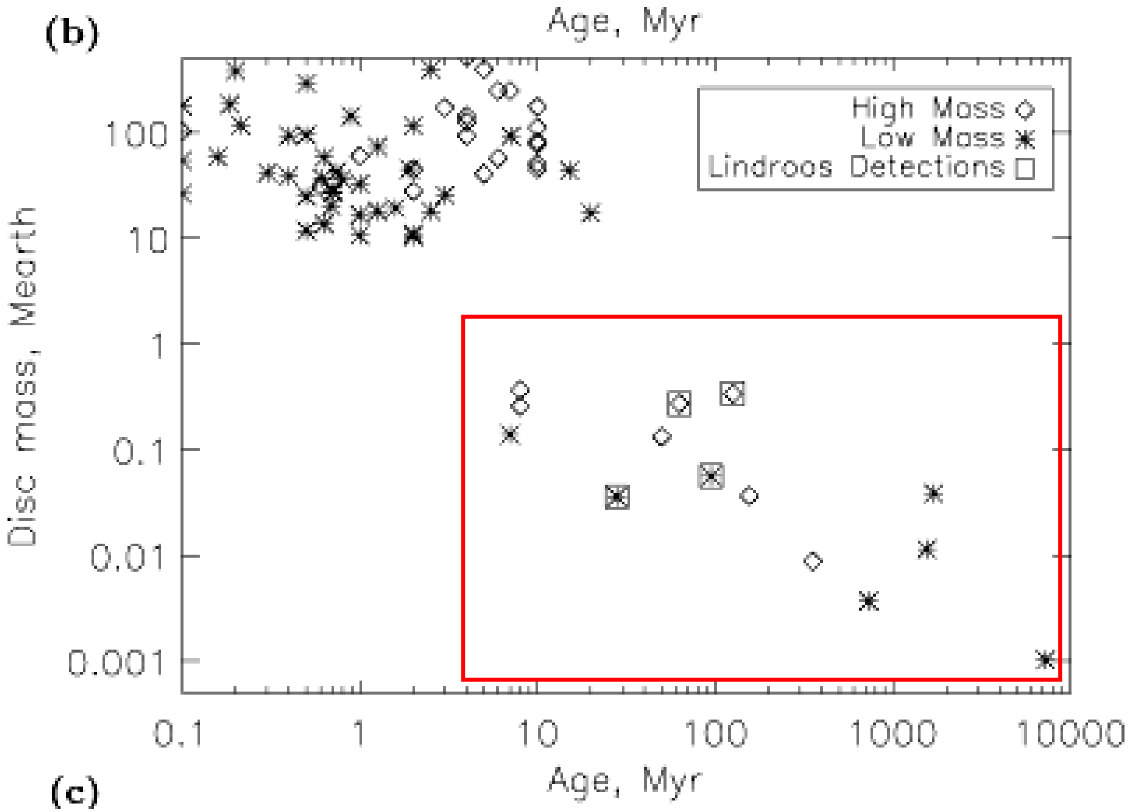


- from the proto-planetary disks lecture:
  - no gas seen after ~10-15 Myr; very little dust
    - but why is there Solar System dust at ~4.5 Gyr?
  - what about the late stages of planet formation?
    - main Earth-assembly phase at ~15-40 Myr

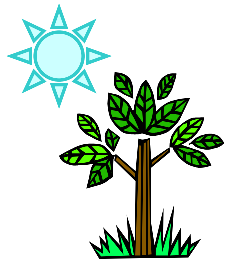


- systems in this lecture have much fainter dust, on more compact scales, seen at much older ages   Wyatt, Dent & Greaves 2003

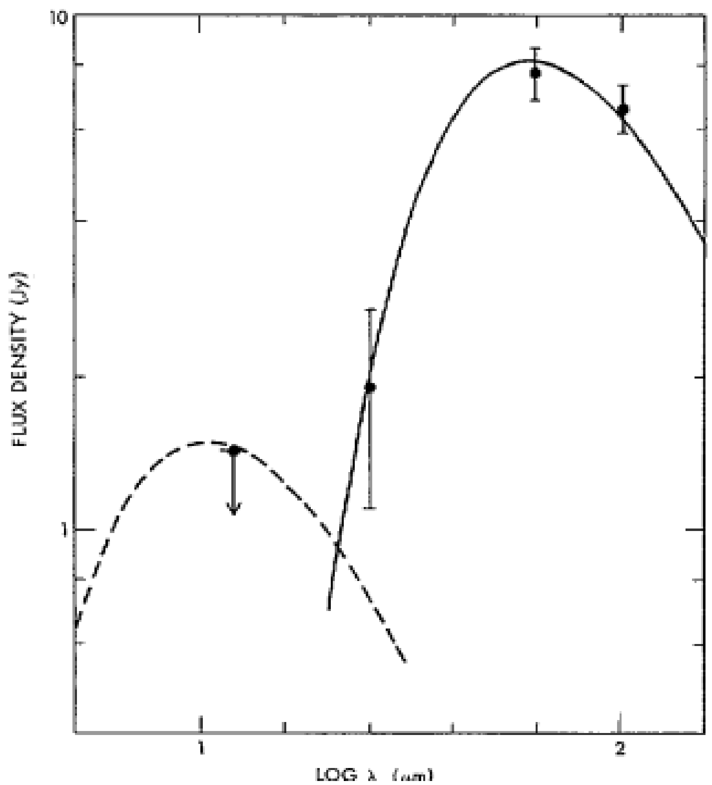




nature of debris disks

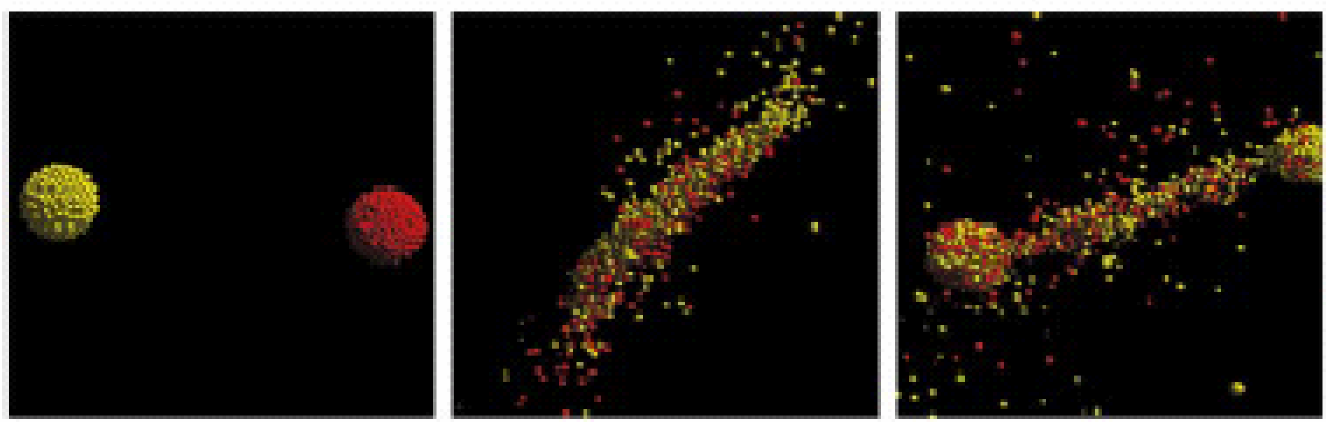


- discovery:
  - calibration observations of IRAS in 1984 discovered a huge 'excess' towards Vega, the standard A0 star
    - but main sequence, ~350 Myr
  - primordial dust should not survive so long - in a gas-free disk, strong effects of:
    - radiation pressure
    - Poyting-Robertson drag
    - break-up in collisions

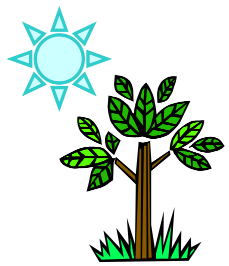


origin of debris

- short destruction timescales mean that dust around main-sequence stars must be *continually regenerated*
  - from collisions among comets or asteroids
    - producing large dust fragments within thermal emission in the mid-infrared to millimetre



epochs

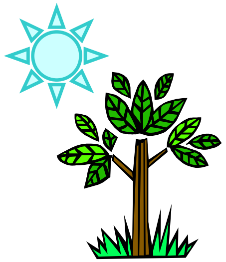


- ~10 Myr: end of 'proto-planetary disk'
  – large, massive disks… some remnant gas… structure shaped by newly-formed giant planets?
- 10's to 100's Myr: completing terrestrial planets
  – debris common… fixing final planet locations? … cataclysms?
- Gyr's: main epoch for Solar analogues
  – debris rarer… steady grinding … impacts on planets

observations

- from space or high mountain sites
  - wavelengths strongly absorbed by atmospheric H_2O etc.

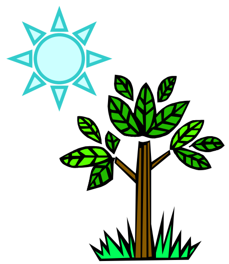
observing limitations



- angular resolution
  - typically a few arcsec, or tens of AU at distances to nearest stars… only resolve major features
- background confusion
  - e.g. high redshift starburst galaxies: similar dust SED
- photospheric flux
  - dust fluxes are a few mJy; stellar light is dominant in mid-/far-infrared (ok in submillimetre)
    - can not detect IR excesses ~20% or less: e.g. stellar atmosphere model uncertainties ~5%

    … higher resolution needed to separate star and disk

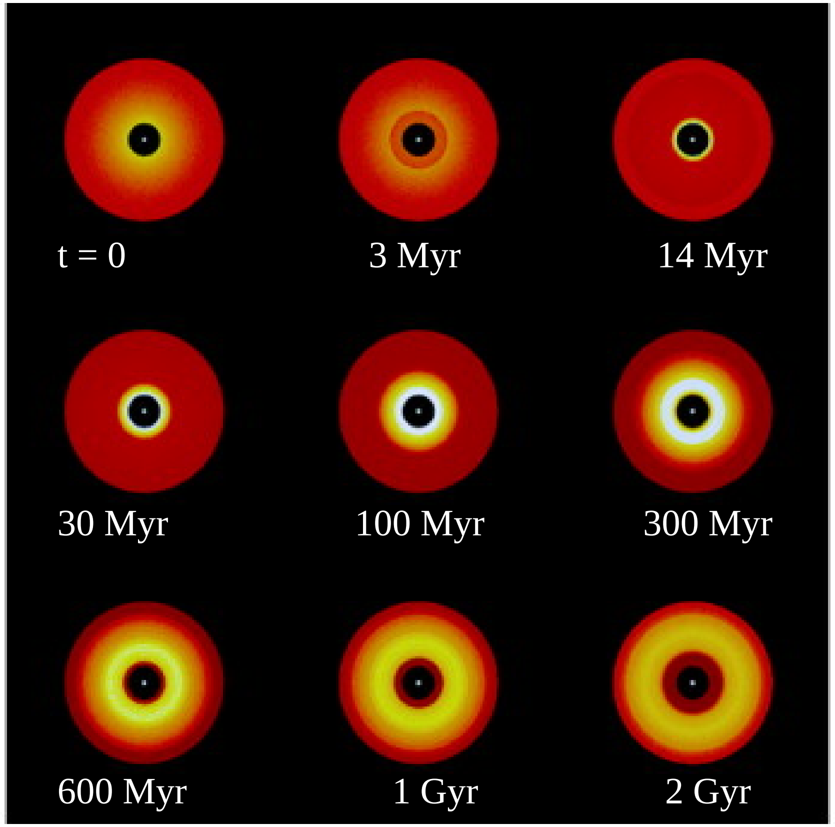
expectations

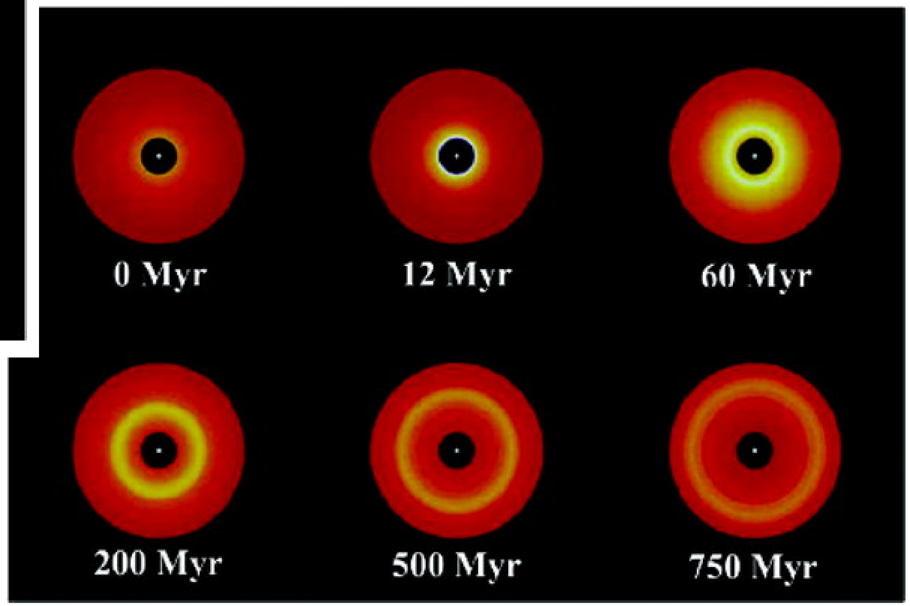


- within ~1st Gyr:
  - enhanced (i.e. detectable) dust production after:
    - stirring by migrating planets
    - catastrophic collisions (~1000 km bodies?)
  - dust rings can be a sign of planet formation
    - once a body ~Pluto size forms, it stirs up the orbits of surrounding planetesimals: more collisions
    - speed of formation depends on dynamical time (period ~ $M_*^{1/2}$ $a^{3/2}$): waves of dust appear moving outwards
- at later times:
  - steady-state levels of dust from random collisions?
    - but can be >> than in Solar System

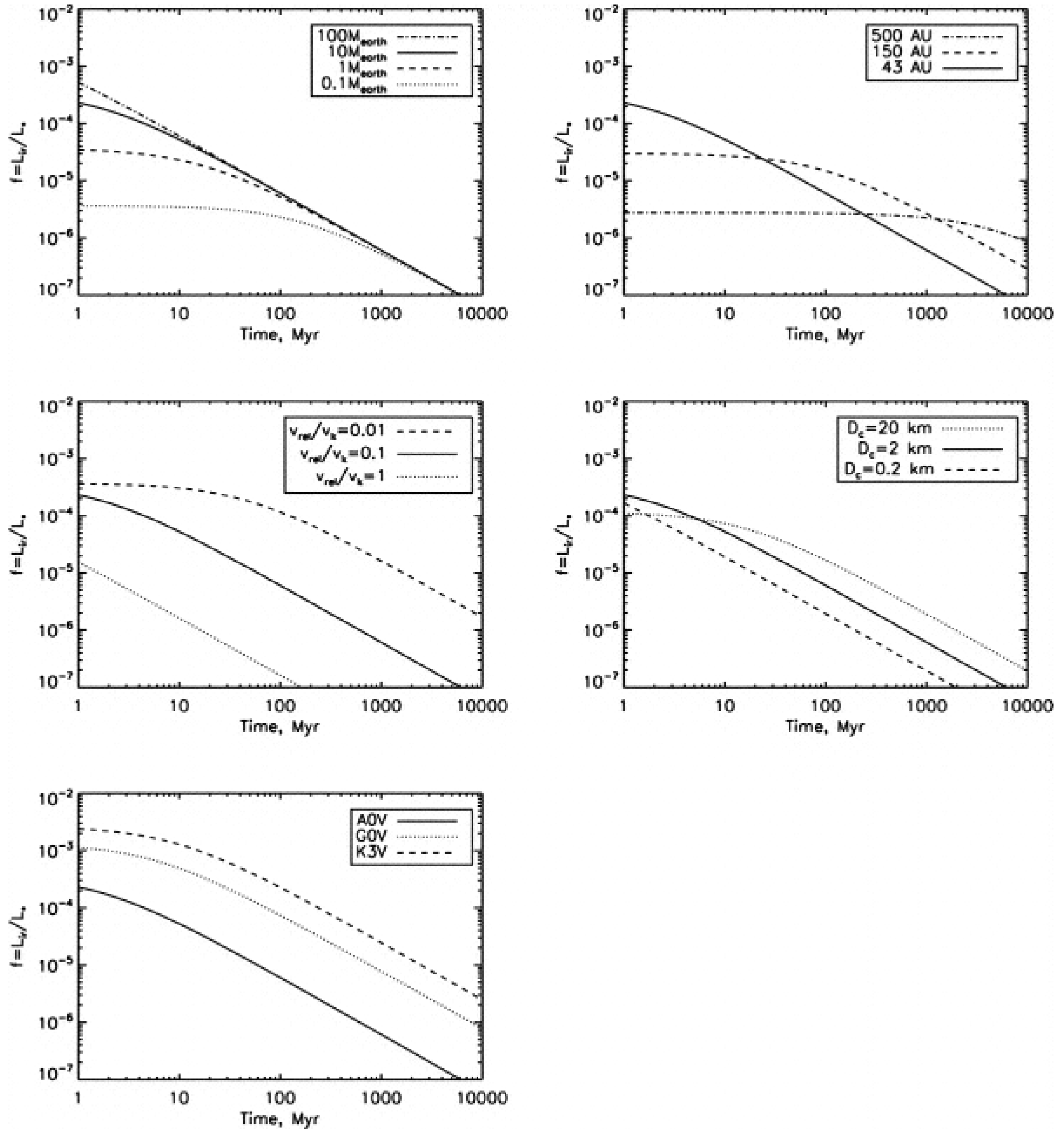
Kenyon & Bromley 2002, 2004

left: planetesimals; right: with planets (radii to 3000 km)

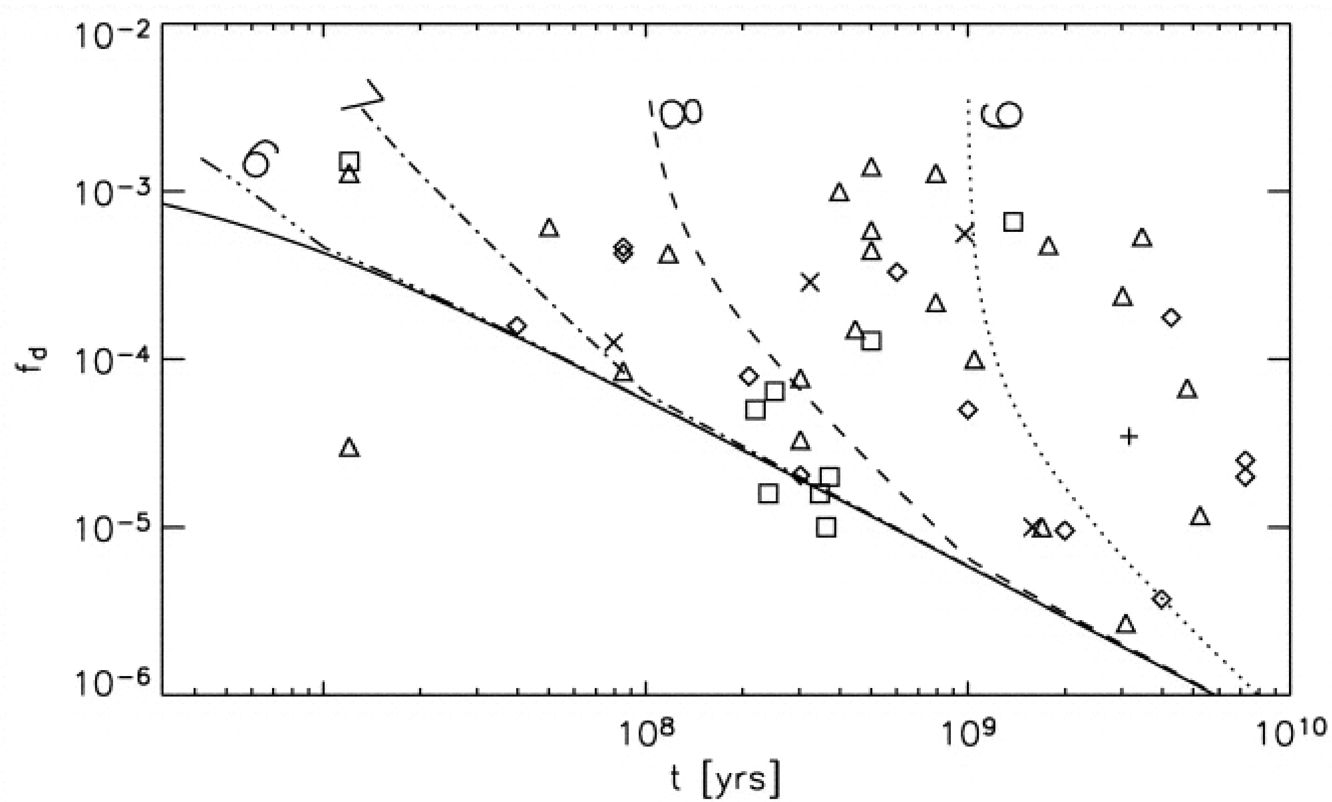




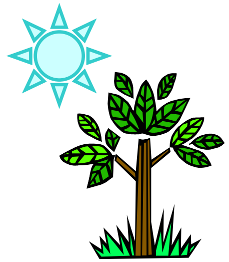
- actual timescales depend on M*, disk radius + initial disk mass   Wyatt et al. 2007
  - in the Solar System, formation of large bodies finished early because the radius is only ~50 AU
    - so, similar stars with larger primordial disks could *still be forming planets* at Gyr ages



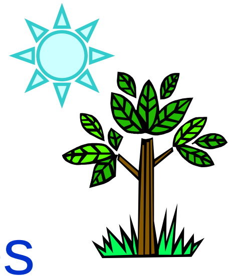
- late stirring by planets could explain why only some stars have detectable debris at late times
  Dominik & Decin 2003
  - curves show log(start time in yrs) for delayed stirring events; symobols are observed debris systems



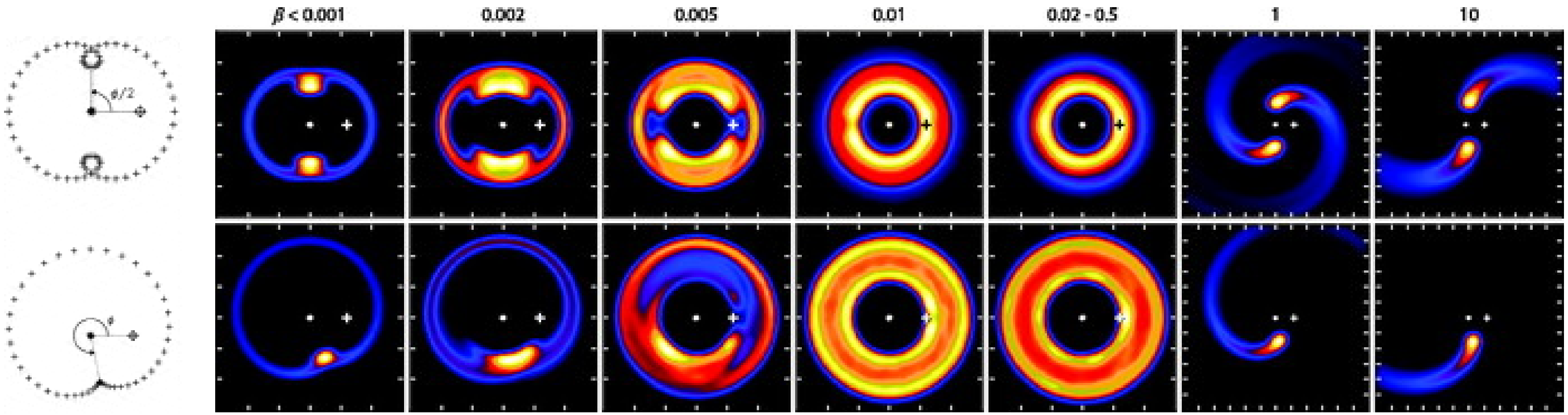
signs of planets



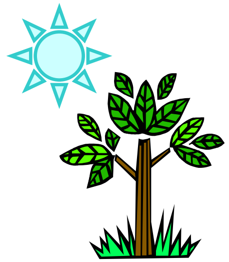
- clues from seeing debris:
  - evidence that planetesimal formation got started! … and reached sizes of at least 10's km
    - largest bodies to have undergone one collision at Gyr-ages of stars
  - estimate of the size of the primordial disk
    - important for the surface density and so the planet forming history
  - disk structure that requires planets to explain
    - offset, cavity, spiral, warp…
    - clearest examples are resonances



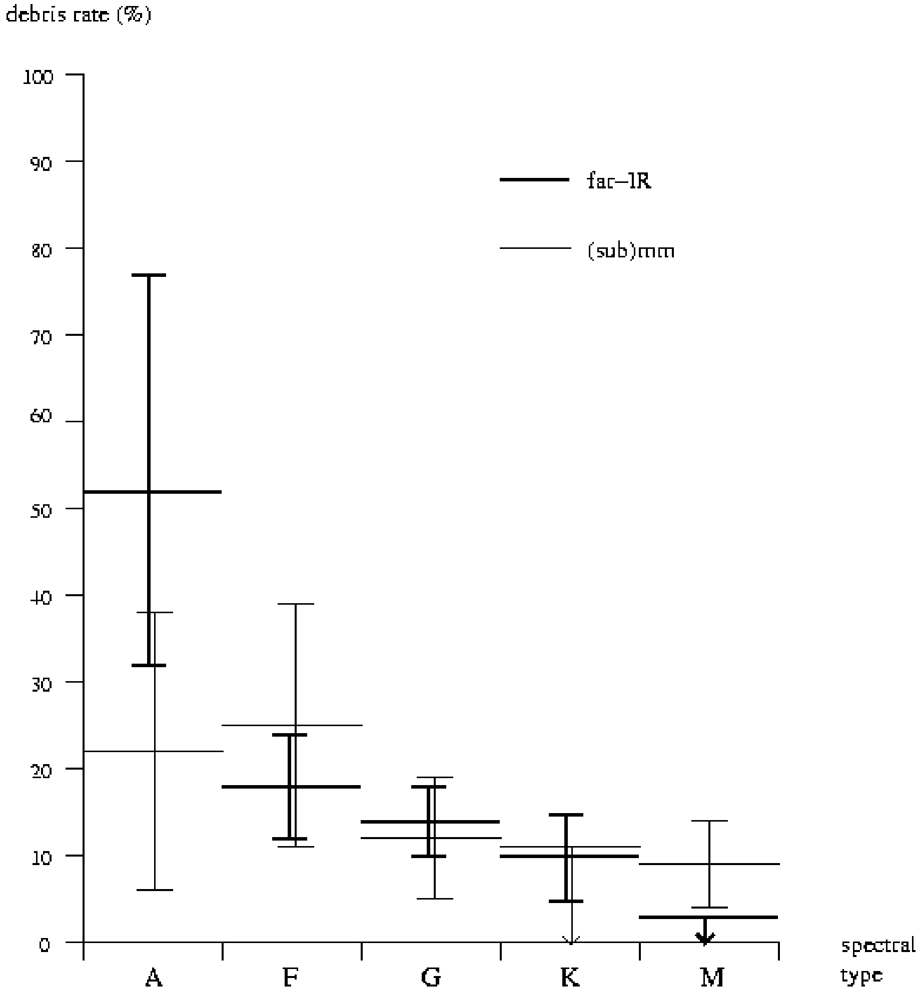
- NB, disk structure varies with wavelength
  - different sized grains are trapped in resonances more or less effectively by gravity of planet
    - plot shows different beta values, which is ratio of stellar radiation force to stellar gravity   Wyatt 2006



observed systems

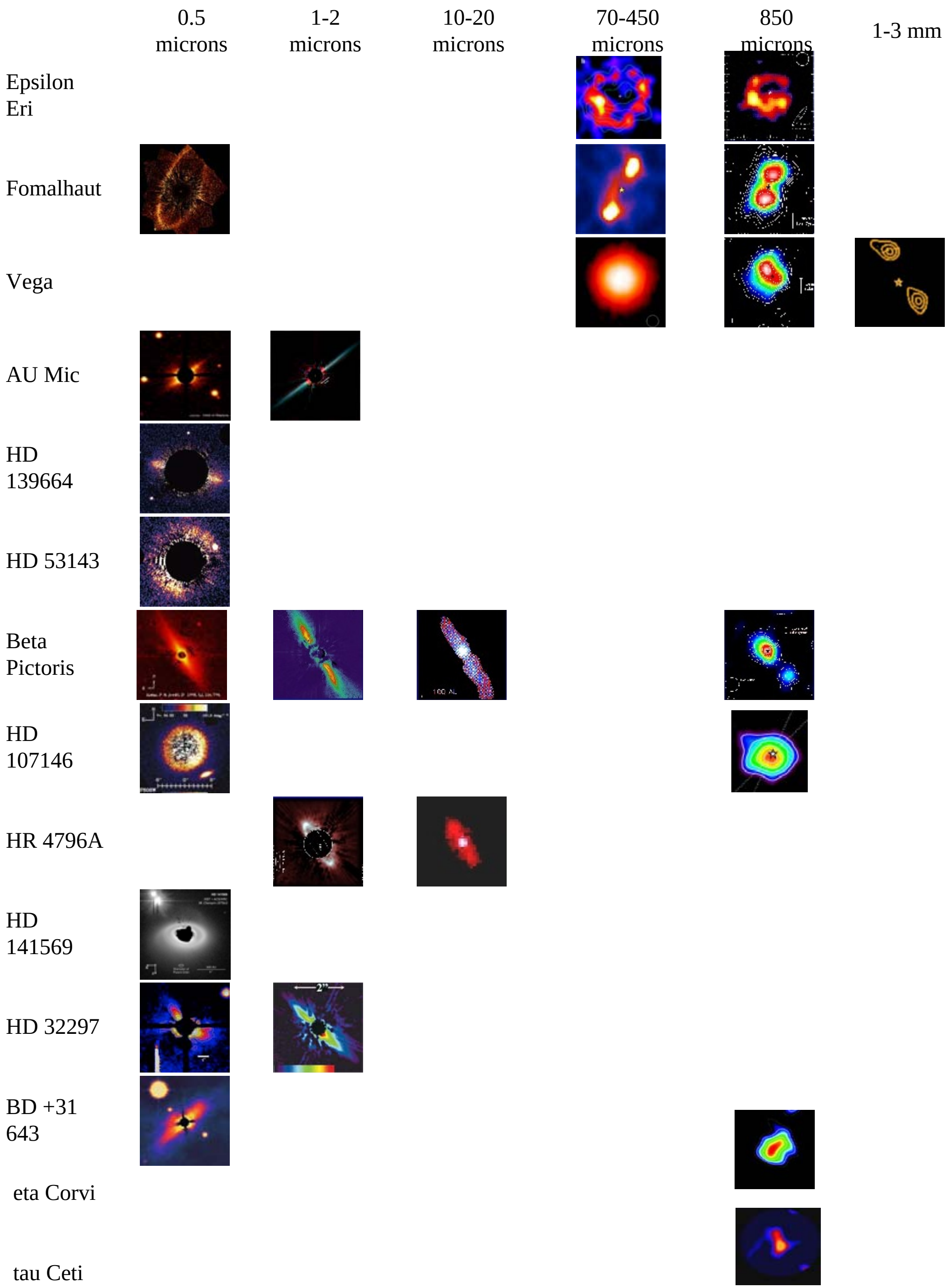


- stars ~3-30 pc from the Sun
- ~20% of normal main-sequence stars
  - the Sun is in the other ~80% of 'clean' systems



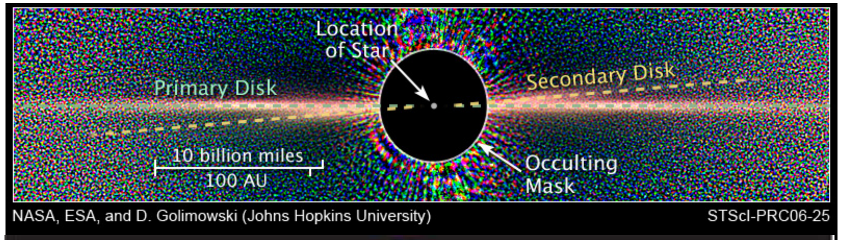
'rogues gallery'

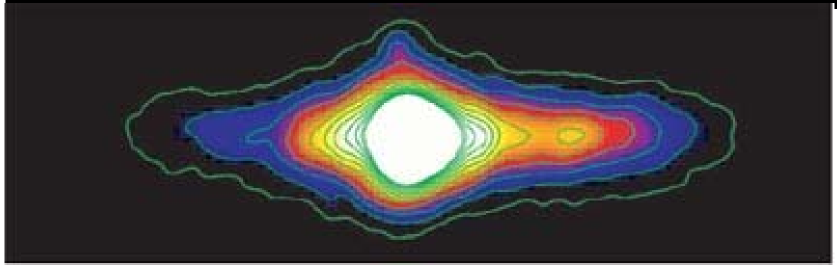
(Paul Kalas website)

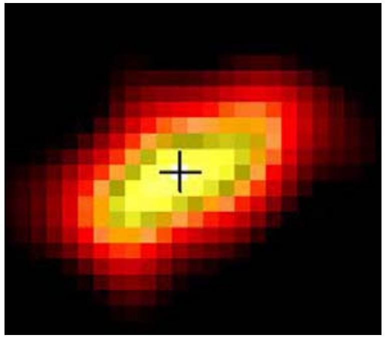


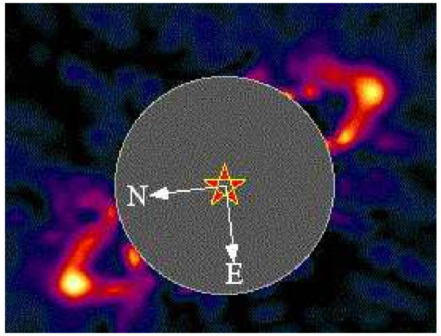
early stage

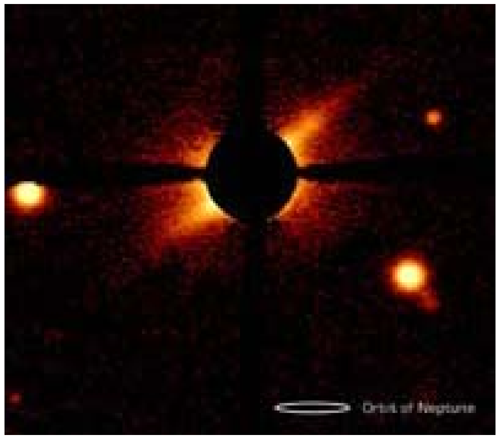
- at ~10 Myr: beta Pic and HR4796 A already show signs of perturbations by planets
    - both are A-stars
  - only similarly young low-mass object is the M-star AU Mic
    - asymmetric disk





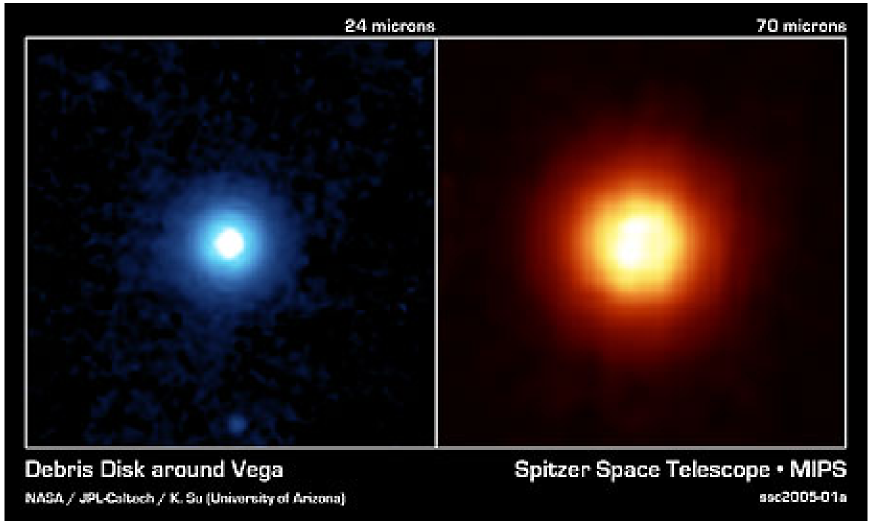


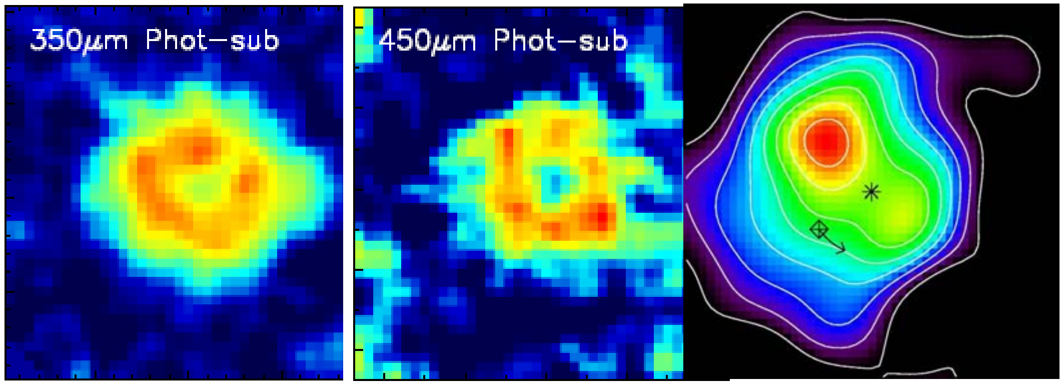


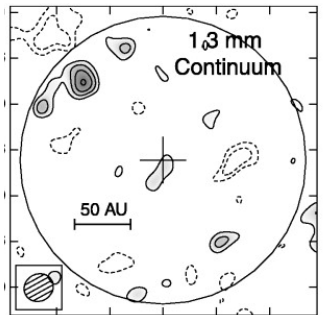


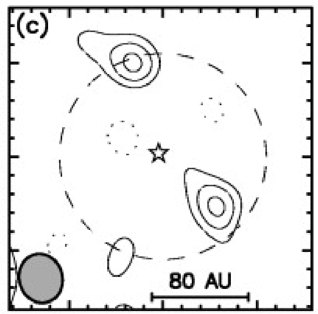
Vega

- archetype - but <u>not</u> typical structure
- halo of blown-out grains (mid-IR)… vs. distinct clumps (submillimetre)
  - effects of planetary migration, stirring of planetesimals, and trapped vs escaping particles



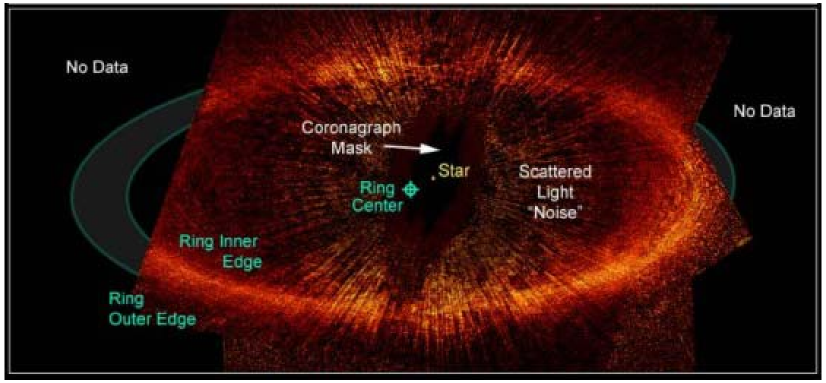


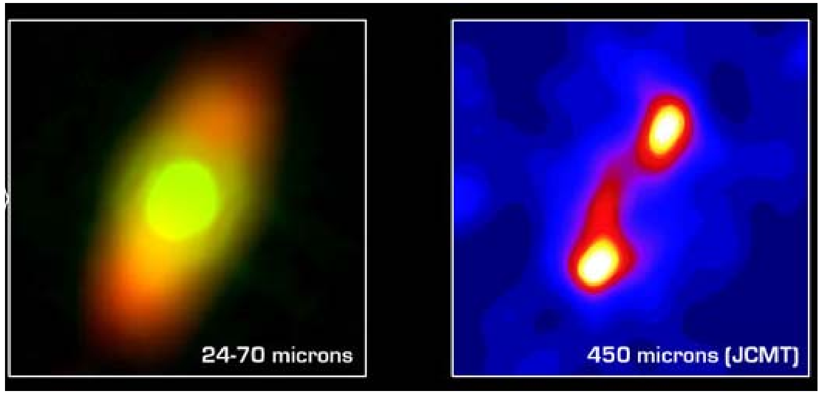


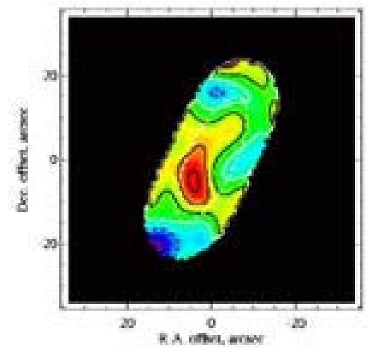


Fomalhaut

- both A-stars ~200-300 Myr old… but Fomalhaut disk is unlike Vega's
  - – no halo
  - – narrow ring system
    - ~25 AU wide at 140 AU
  - – single distant clump
    - suggests a very distant planet, at ~100 AU?

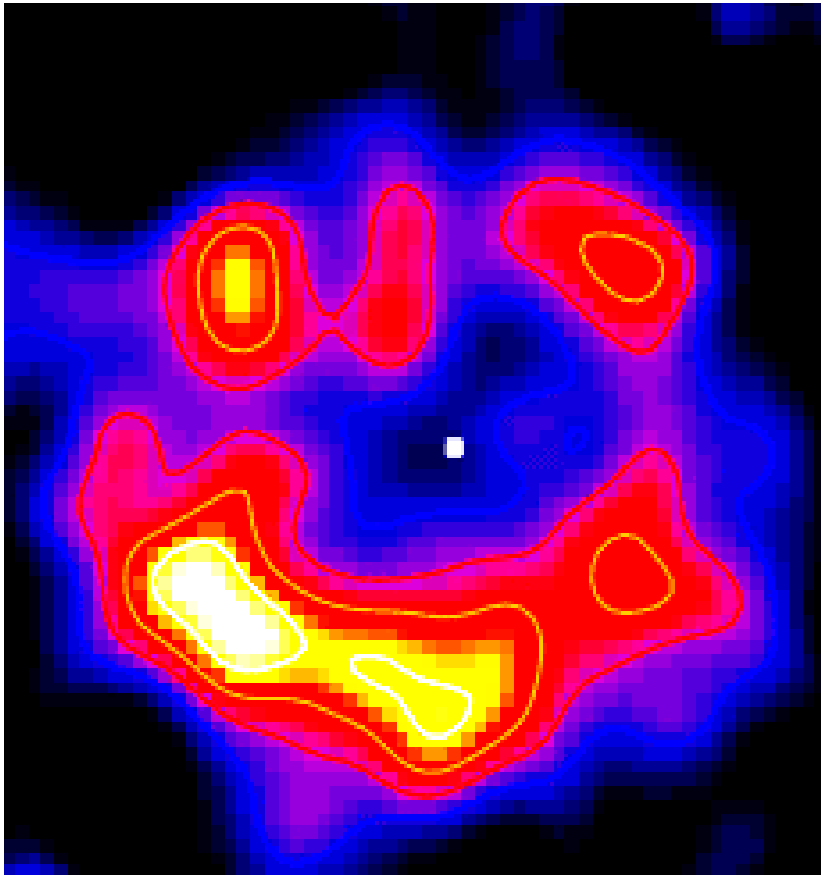




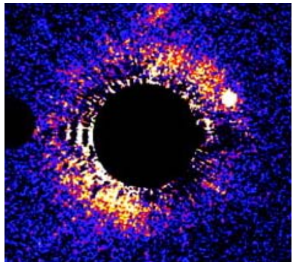


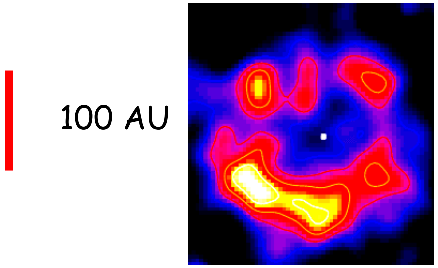
epsilon Eridani

- K2 star, 0.85 Gyr old
  - dust extends to ~100 AU (about twice as large as Solar System Kuiper Belt)
  - central cavity to ~30 AU
  - multiple clumps
  - only system with time-resolved motion



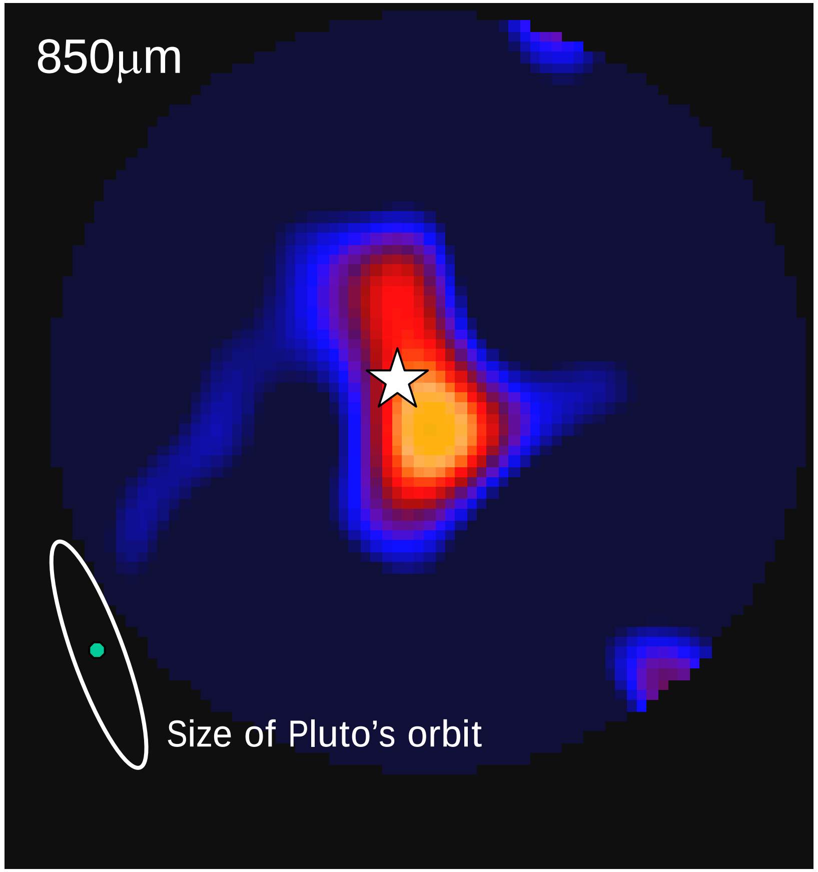
- archetype of many?
  - e.g. recent HST image of HD 53143



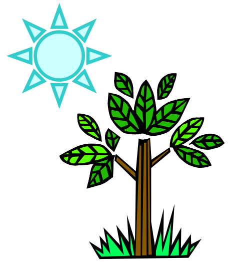


tau Ceti

- G8 star, 10 Gyr old
  - most like the Solar System in size, with radius ~55 AU
  - but, 20x dust flux of Kuiper Belt
    - many more comets, at *twice age* of Sun
  - no analogue to Jupiter… many infalling comets?



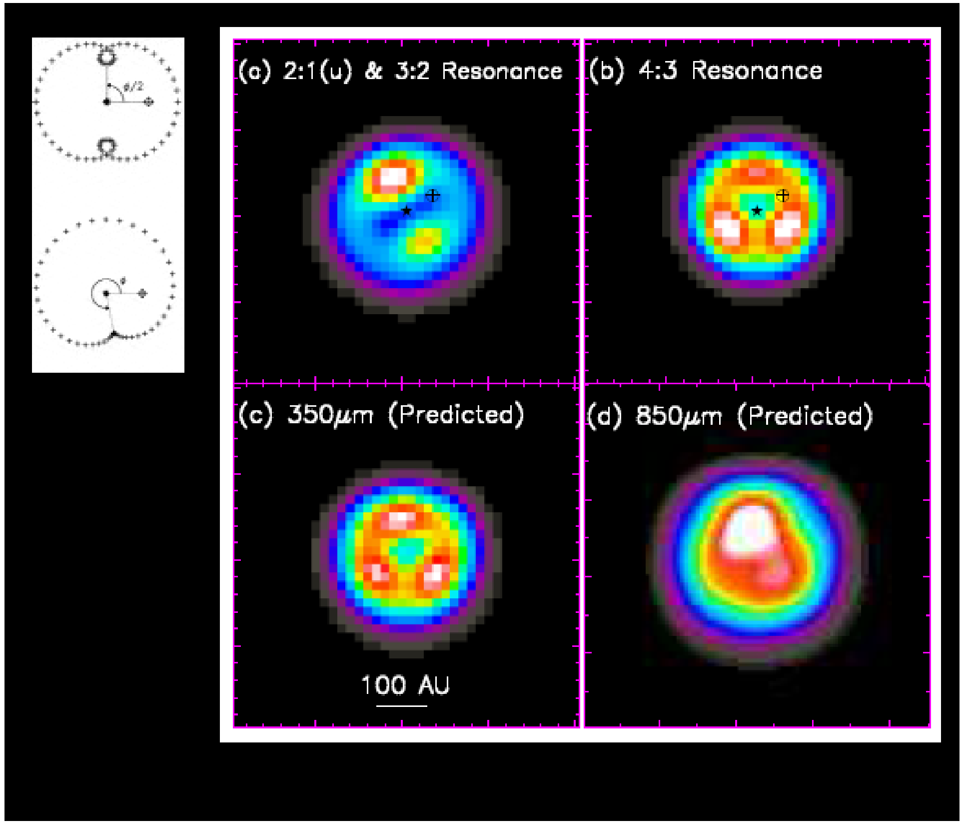
global properties



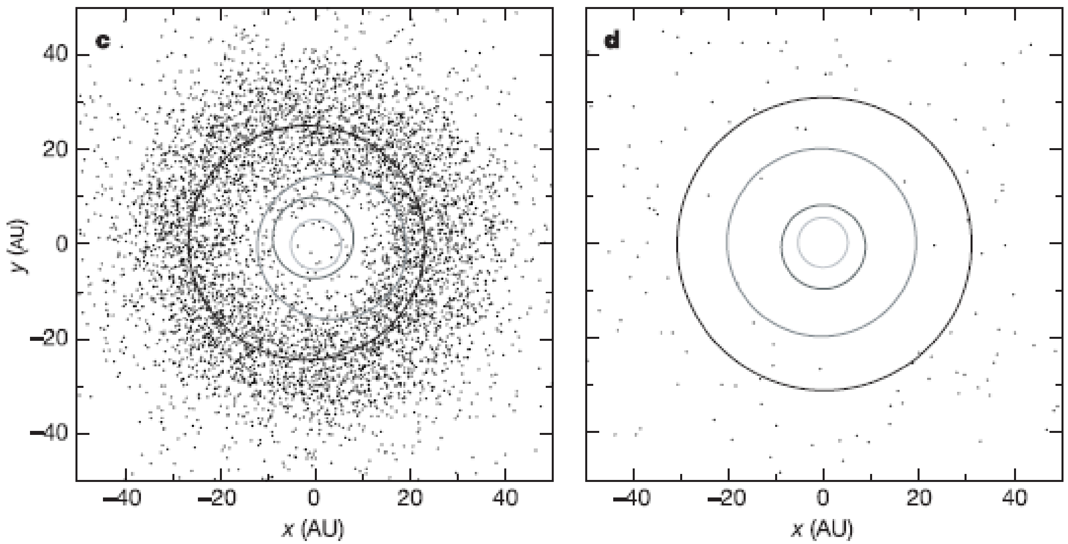
- rings, not filled disks
    - also infered from SED's of unresolved systems
- many perturbed disks
    - – planets at tens of AU… needs outwards migration?
- most disks larger than Solar System
    - – radii up to 300 AU; descendants of T Tauri disks?
- little connection to
    - – age, spectral type, metallicity, rotation, companion stars, planets

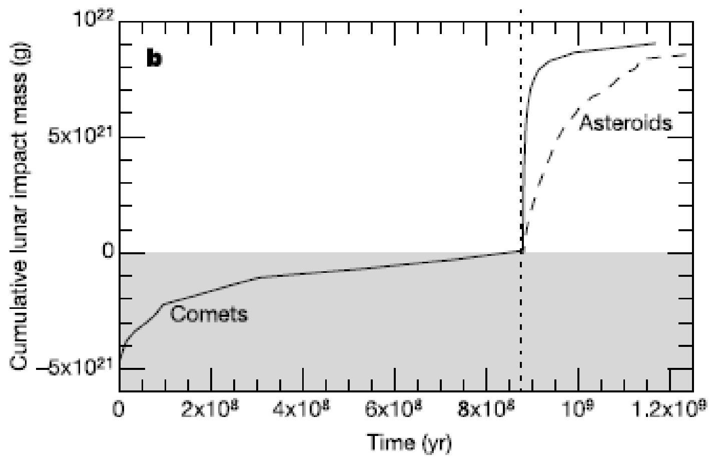
planet formation and migration

- outwards migration increases planetesimal collisions + traps dust
  - in resonant positions, e.g. 2 orbits of comets for 3 orbits of planet
  - hence, infer position of planets! … uniquely sensitive at tens of AU
    - example: a *Neptune*-mass planet that is now at 65 AU from Vega

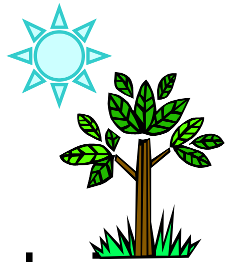


- a similar process may have happened in the Solar System *(Eric's lecture)*
  - comet belt was stirred by shifting orbits of the gas giants, resulting in the Late Heavy Bombardent of the Earth and Moon, at ~700 Myr? Gomes et al. 2005



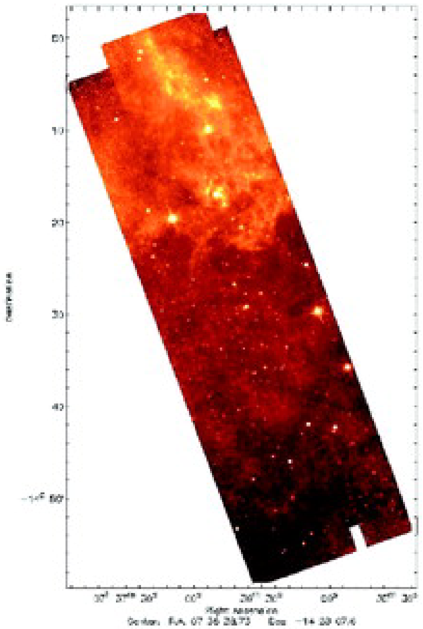


terrestrial planet construction

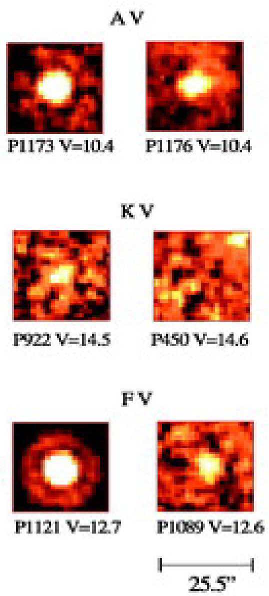


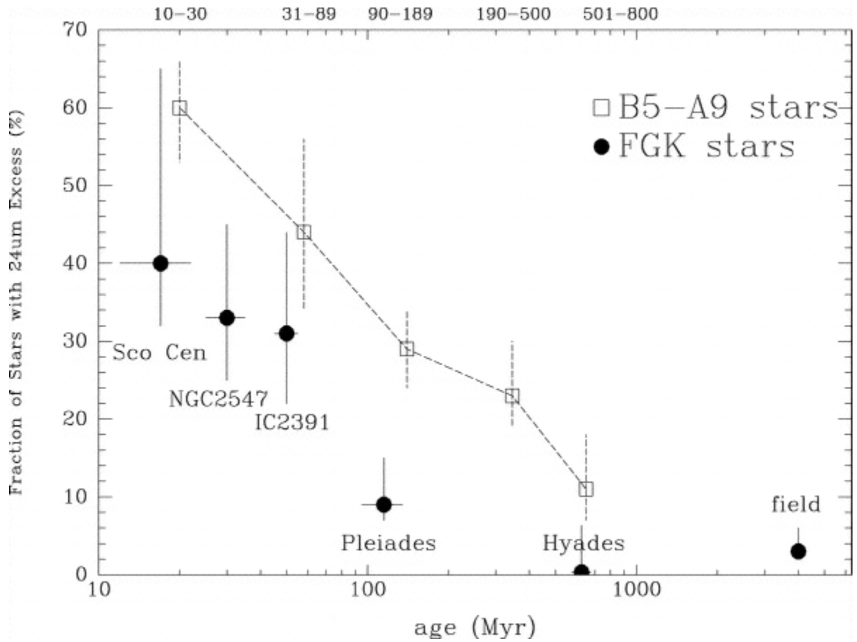
- some stars in clusters at 10's Myr show debris
  - possibly a signature of collisions among big planetesimals, in the terrestrial planet building epoch

MIPS image of M47 at 24μm

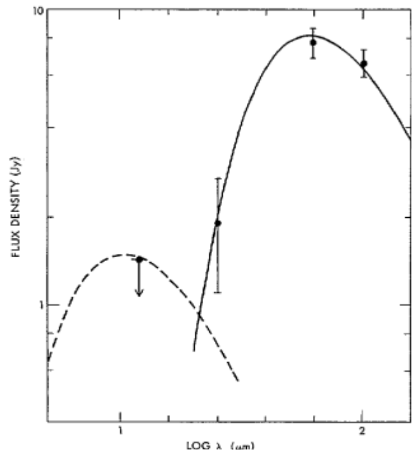


Excess vs. non-excess stars:





planet detection

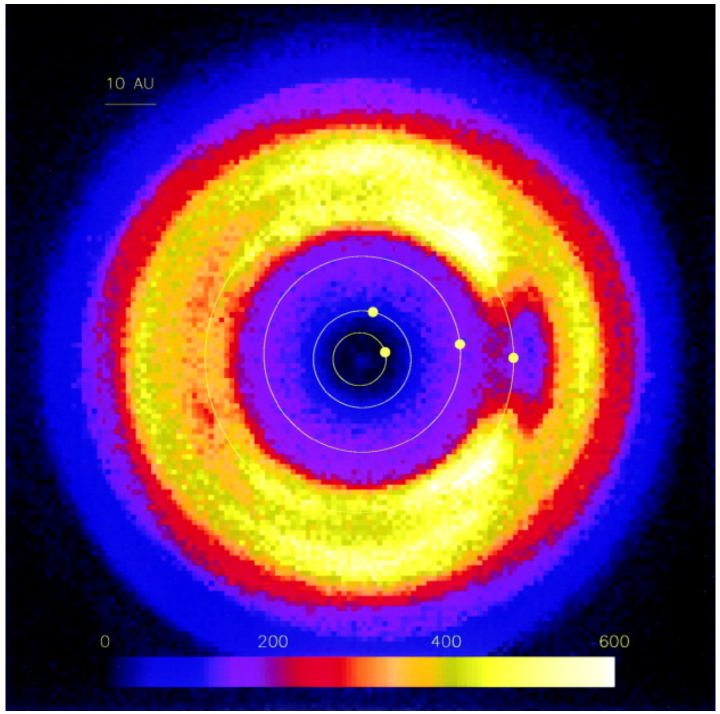


- central clearing in debris disks
  - either imaged, or infered from the SED: lack of hot dust near the star

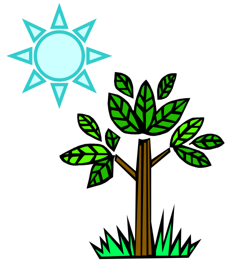
  …but, this is ambiguous re planetary systems

    - planet eject particles crossing their orbit   Liou & Zook 1999

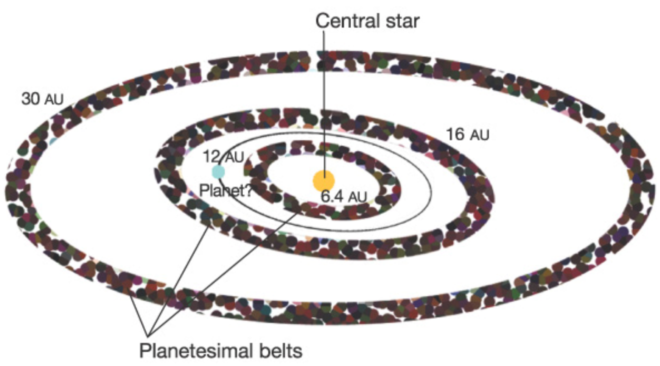
  - but in detectable debris disks, collisional grinding will also remove grains near the star
    Wyatt 2006

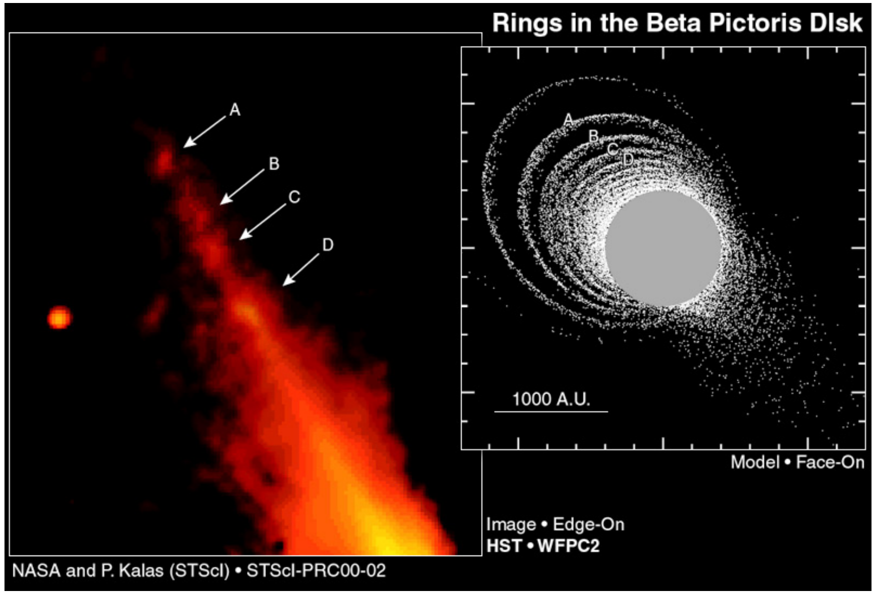


warping



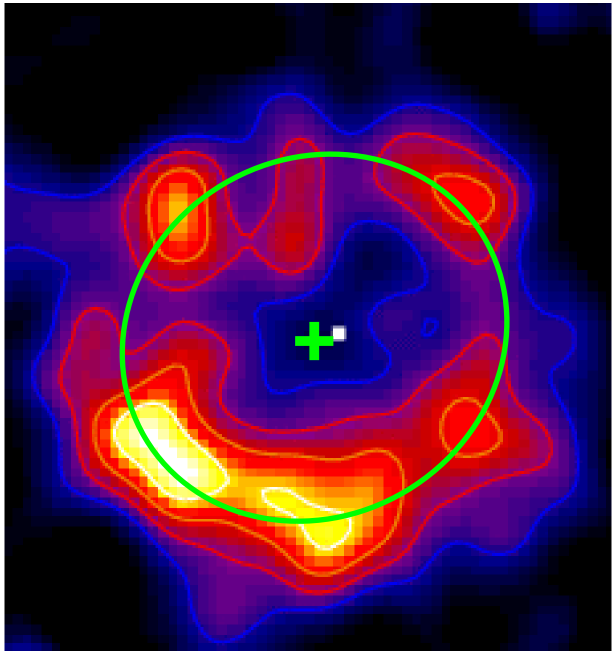
- distortions of disk plane could be due to planet on inclined orbit
  - but also (at large distances) disk can be perturbed by fly-by of another star, e.g. beta Pictoris Kalas et al. 2000

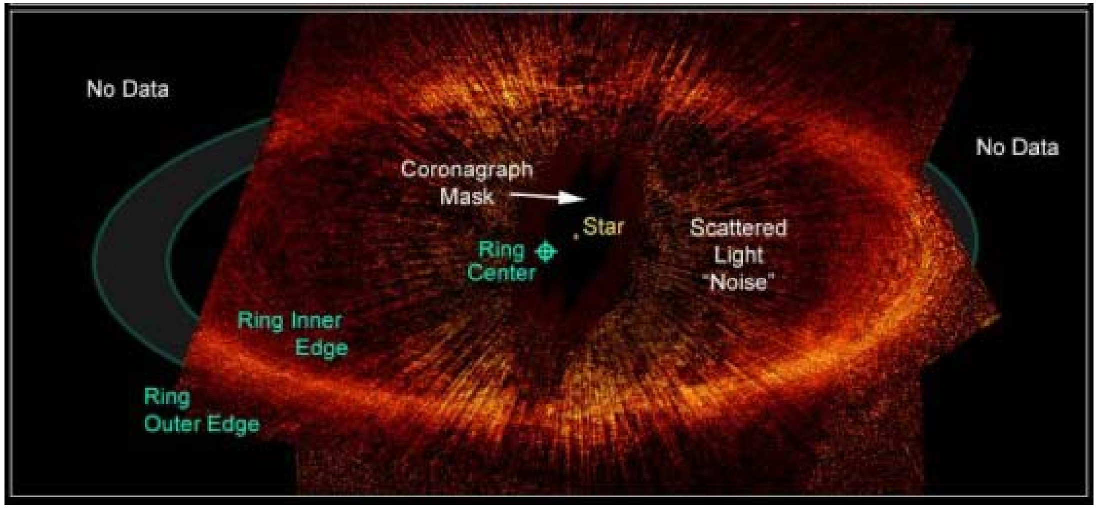




offsets

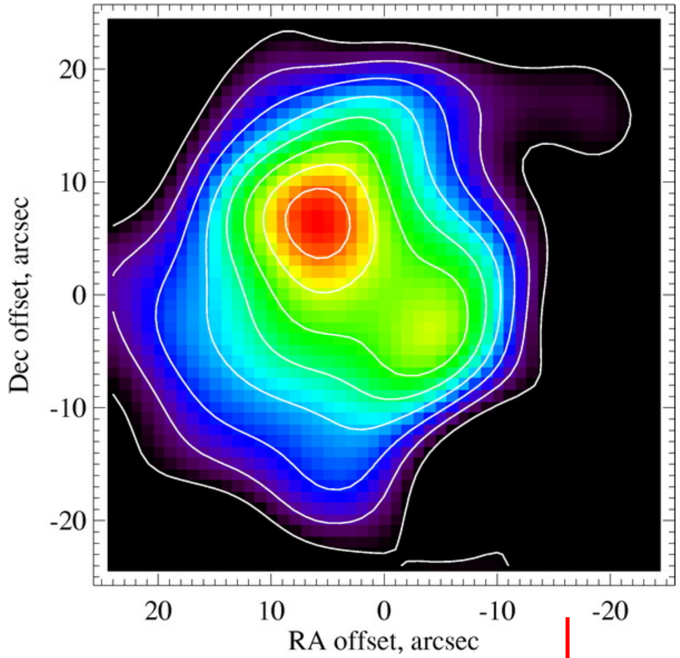
- a planet on an eccentric orbit can force dust orbits to be offset with respect to the star
  - (approximately?) solvable for planet orbit

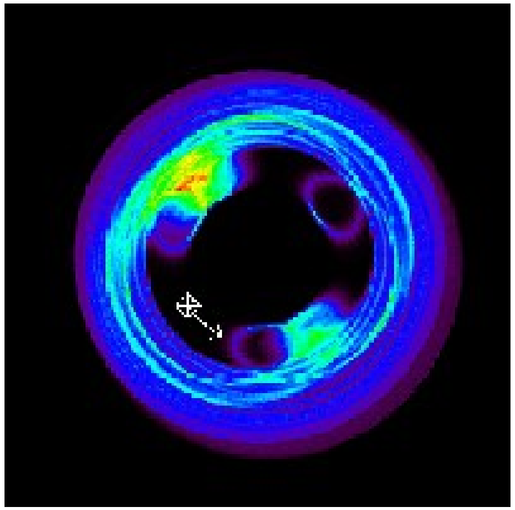


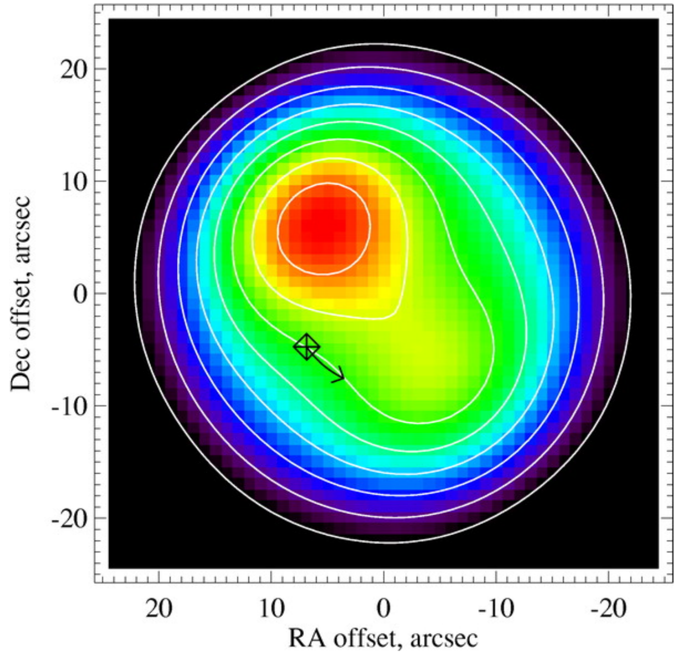


resonances

- resonant clumps require a planet
  - can be rather proces solutions, e.g. in the case of Vega, position and direction of motion of planet   Wyatt 2003

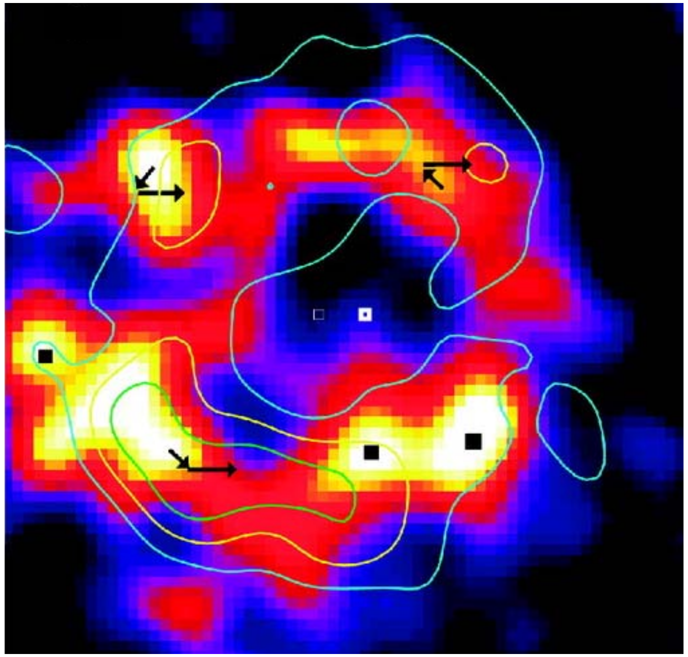


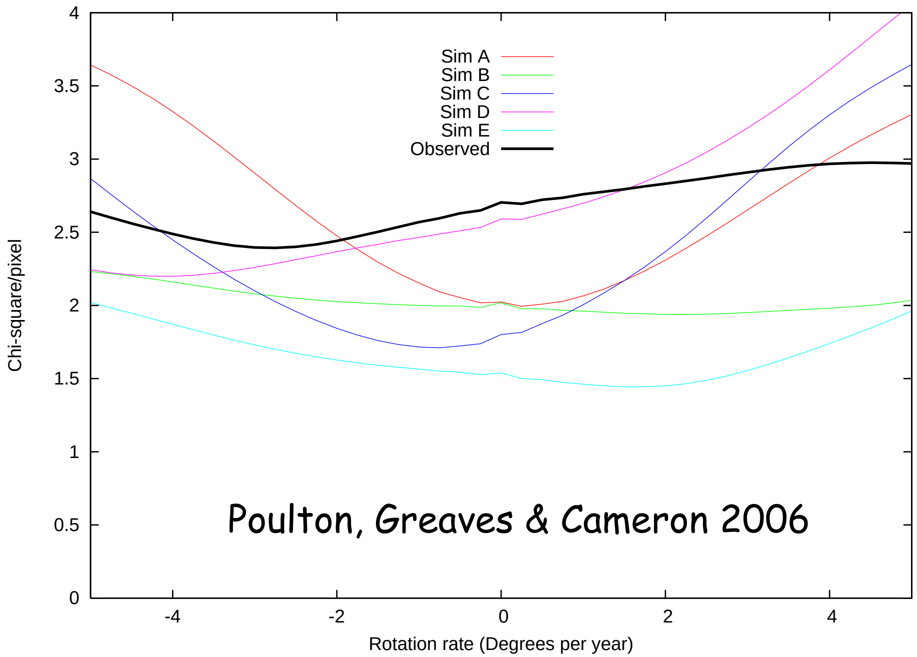




tracking rotation

- for one system so far: rotation of the clump pattern in the epsilon Eridani ring over 5 years
  - consistent with a planet at ~30 AU that both 'drags' the clumps at its own period, and clears the inner edge of the dust ring





future


SCUBA-2 undergoing testing in the laboratory at UK ATC

- higher-resolution imaging
  - Herschel, JWST: fine structure of (warm) disks
  - ALMA at <0.1": confirm rotations within ~ 1 month!
- unbiased surveys: what makes a star have debris?
  - e.g. SCUBA-2 survey of 500 nearby main-sequence stars, 2008-2009 *(see Neil's poster upstairs)*
    - origin of debris, system properties, effects of debris on future planet-finding missions targeting nearby stars

SUPA Astrobiology

- comet belts and habitability
  - many comets means high impact rates on terrestrial planets, such that land masses could all be molten… even at low Kuiper Belt-levels of comets, need a Jupiter analogue to deflect infalling comets or life could be very dangerous!
    - nearest system identified with both low debris and a 'shield planet' is 47 UMa at 14 pc
    - need to find some closer targets for 'habitable Earths'!