Scottish Universities Physics Alliance

Proto-planetary disks:
observing planet-forming material

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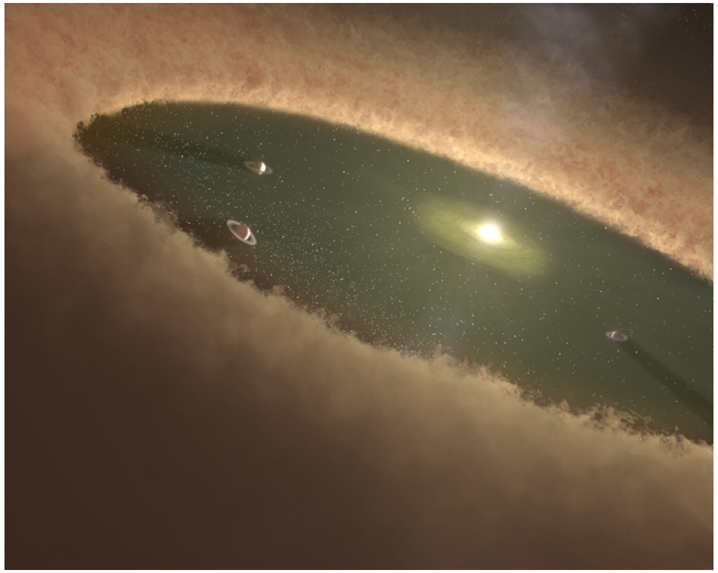
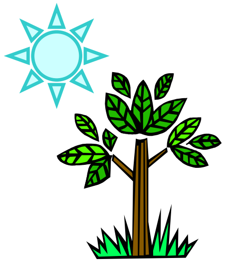
(with thanks to
Kenny Wood)

St Andrews



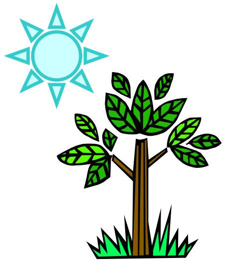
questions



1) are the observed disks suitable for planets to form?

2) are there signs of ongoing planet formation?

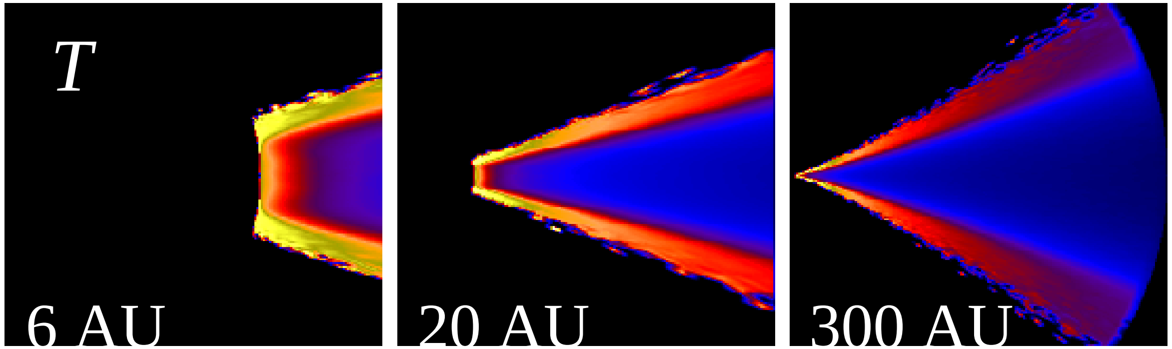
3) can we observe the young planets?



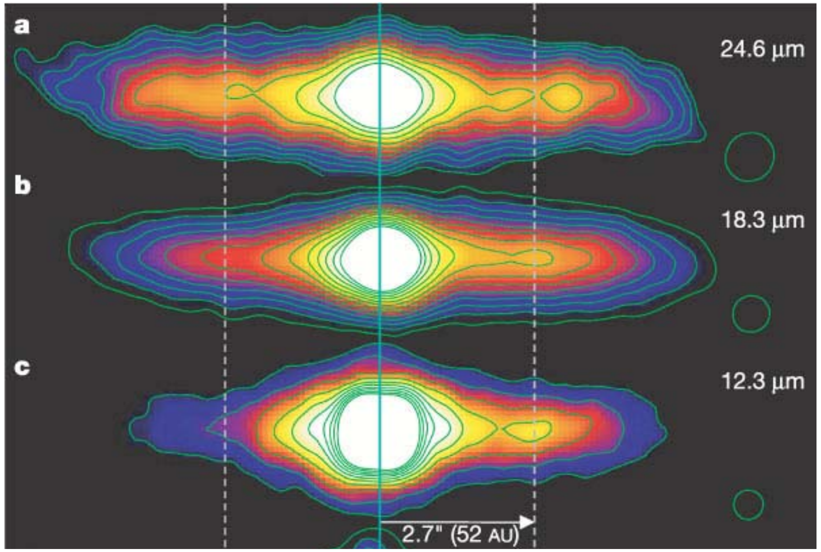
(1) suitability of disks

observing the disks

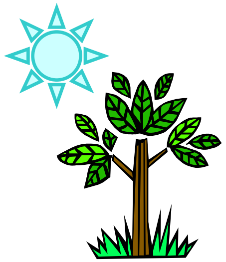
- scattered light images
  - disks that are rather edge-on block the direct star-light, while scattering light towards us that traces the disk geometry
    - mainly optical, so high angular resolution e.g. with HST

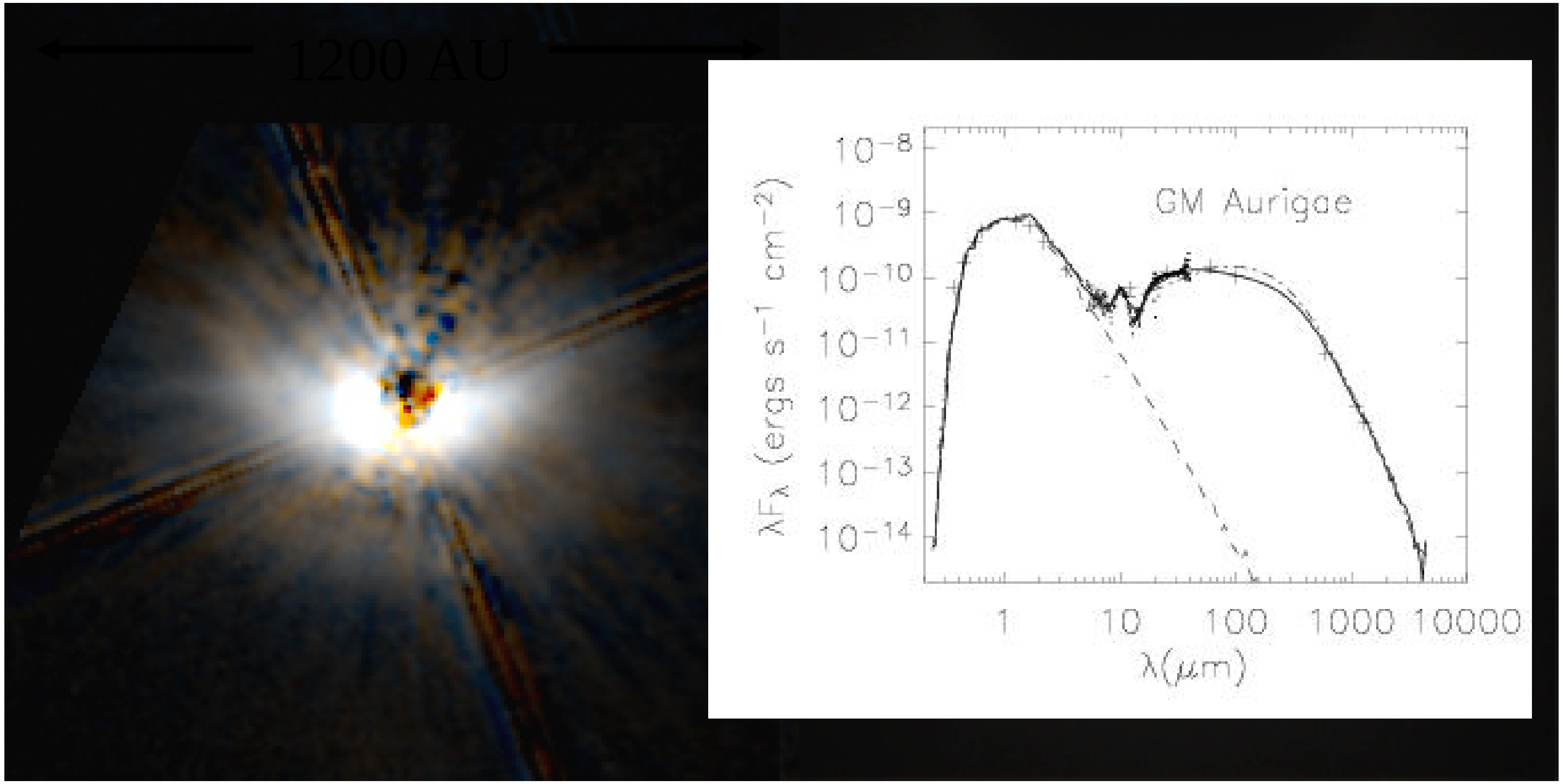


- thermal emission
        - worse angular resolution
    - optically thick from near- to mid-infrared, optically thin in far-IR and (sub)millimetre
    - former traces warm dust from the sublimation point out to tenths of AU; latter traces zone of formation of planets out to comets
        - c.f. Earth ~280 K / 10 micron

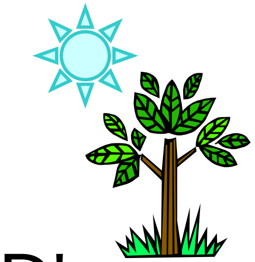


- spectral energy distributions (SED's)
  - plot of flux against wavelength, very useful for unresolved disks

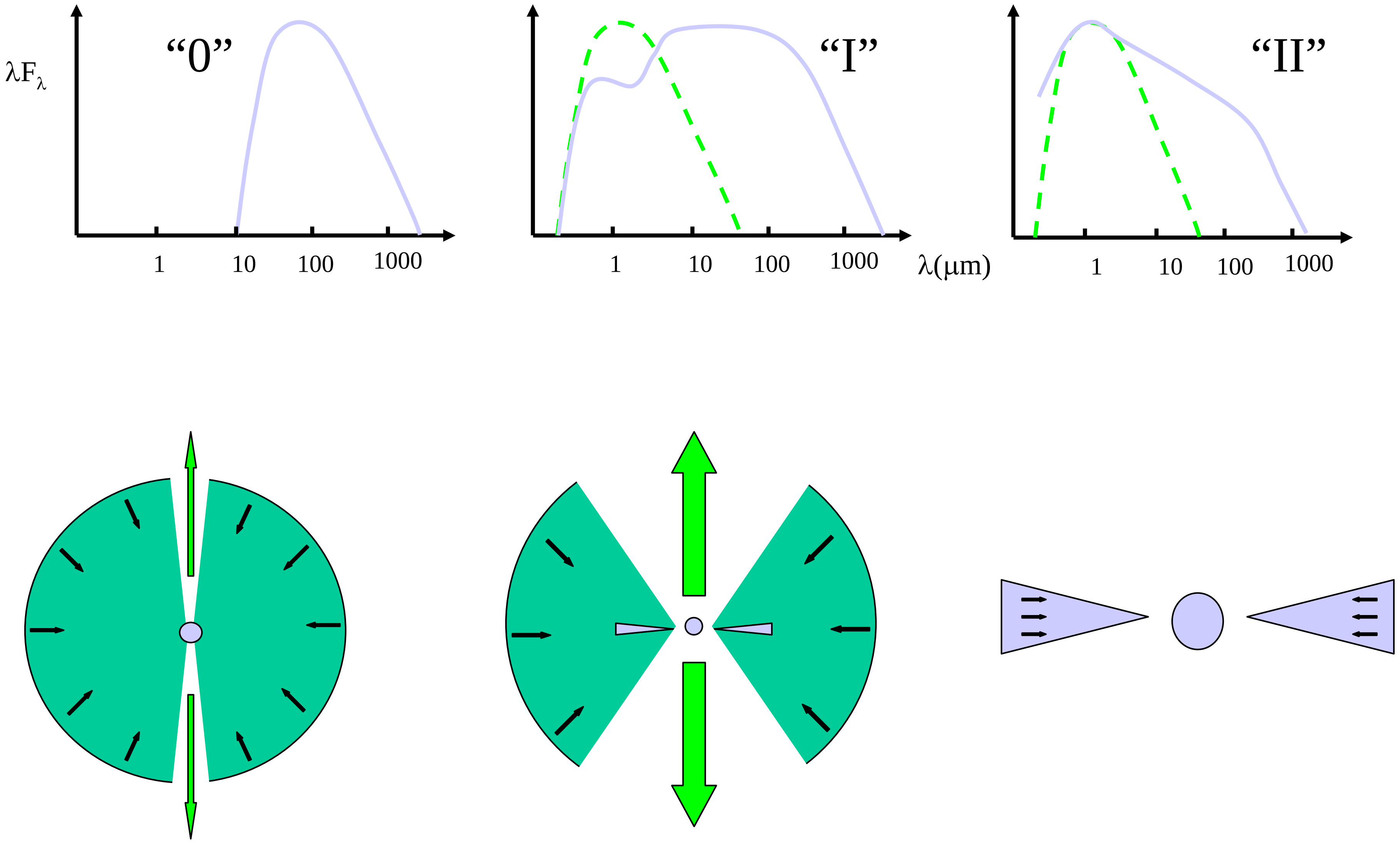




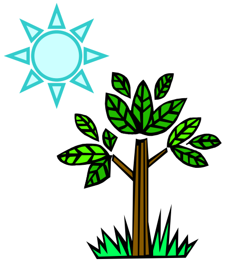
general phenomena



- simple YSO classification scheme via SED's
    - Class 0 = protostar (powered by gravitational contraction) with massive envelope (and disk)
    - Class I = protostar (>90% assembled) with diffuse envelope and substantial disk
    - Class II = pre-main sequence star with substantial disk and strong accretion
    - Class III = pre-main sequence star with remnant disk and weak accretion
  - evolution from dominated by the cool envelope to dominated by the hot star

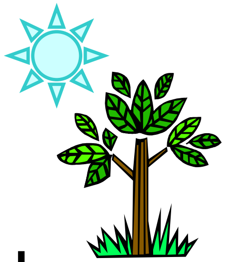

λF_λ
“0”
“I”
“II”
1
10
100
1000
λ(μm)

timescales



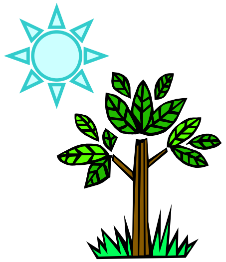
- relative timescales from counts of each type
    - assumes steady rate of star formation
- boot-strapped to 'real' ages from plotting pre-main sequence stars on Hayashi tracks:
    - Class 0 stage lasts few 10^4 years, Class I few 10^5 years, Classes II and III ~10^{6-7} years (overlapping)
- but planet formation needs few 10^{6-7} years?
    - so expected to be mainly ongoing in Class II YSO's (insufficient disk in Class III)

disk processes: dust



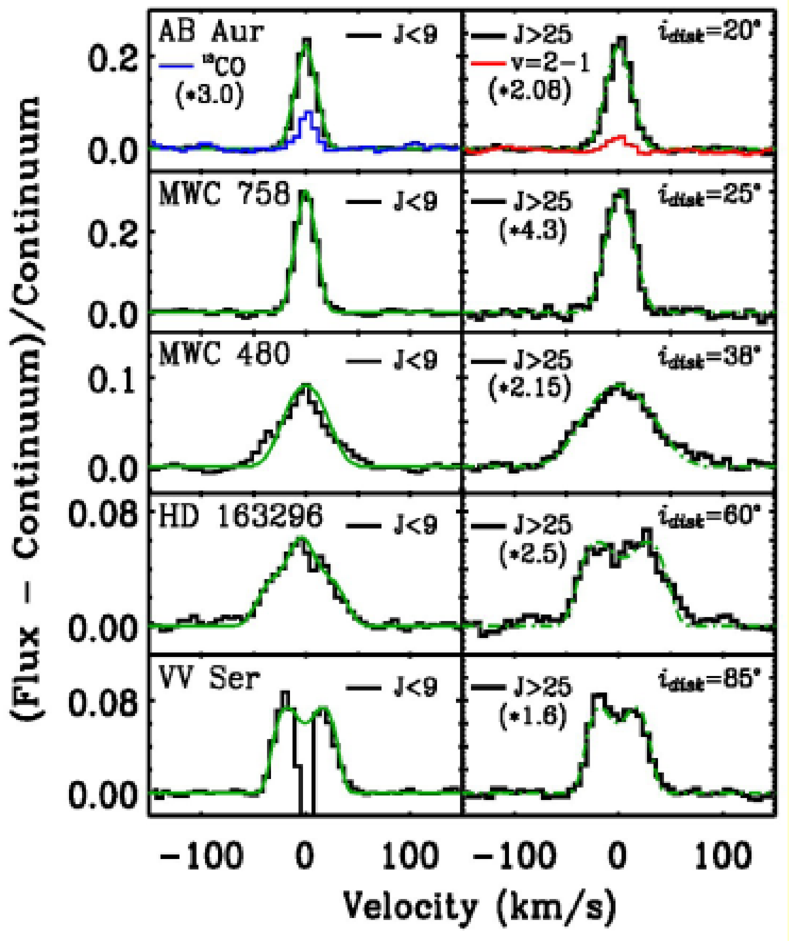
- in the dense disk environment, dust should grow
  - – from sub-micron ISM size to micron sizes, then gravel, boulders, planetesimals… *(Eric's lecture)*
    - some difficulties, e.g. break-up at the cm-stage
  - – balance of growth and destruction with growth dominating
  - – heavier particles 'rain out' to disk mid-plane, where planet cores can start to build up
- later on:
  - – radiation pressure, light drag, trapping by planets…

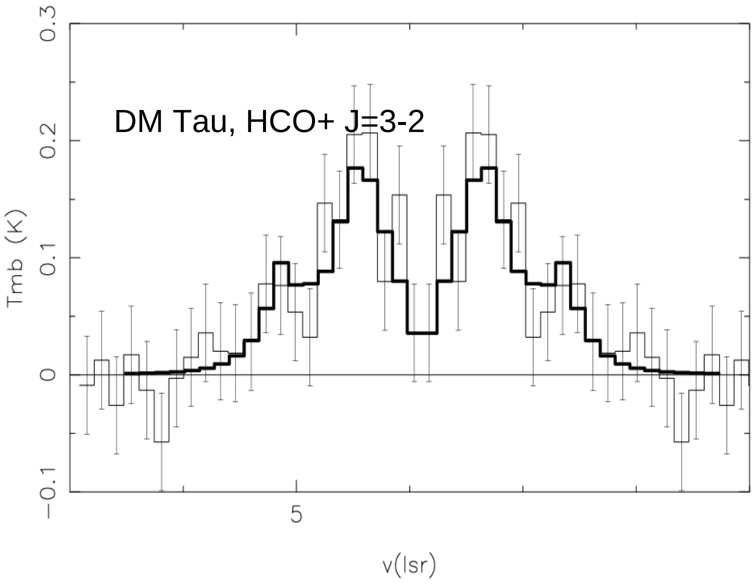
disk processes: gas



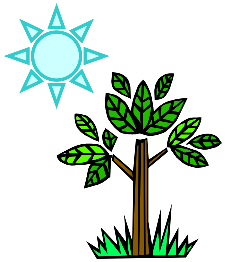
- mainly molecular near the cool dark midplane
  - reservoir with ~100x the mass of the dust
- dispersal:
  - within a few AU, photodissociation produces atoms of much higher energy that are not bound to the disk
  - at the largest radii, can be photo-dissociated by other stars in a cluster (e.g. irradiated by O,B stars)
    - unclear which is typically dominant
- gas seen up to 10-15 Myr although not for all stars, and with very uncertain disk masses
  - trace lines depend on abundance, temperature…

CO v=1-0

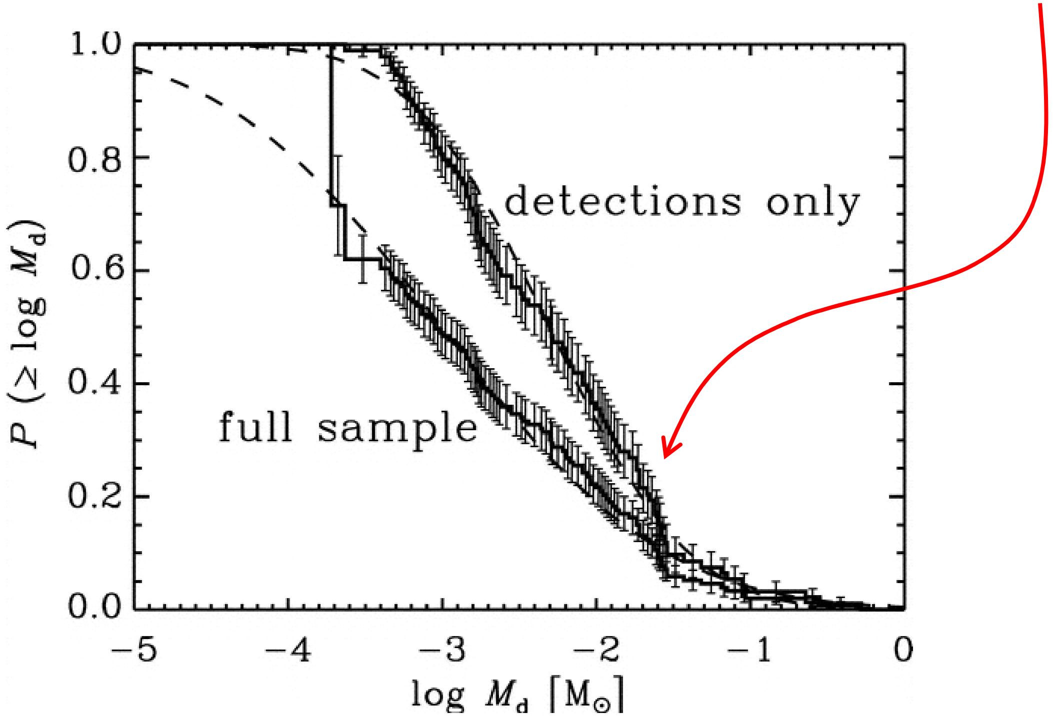

AB Aur
J<9
^{13}CO
(*3.0)
J>25
v=2−1
(*2.08)
i_{disk}=20°
MWC 758
J<9
J>25
(*4.3)
i_{disk}=25°
MWC 480
J<9
J>25
(*2.15)
i_{disk}=38°
HD 163296
J<9
J>25
(*2.5)
i_{disk}=60°
VV Ser
J<9
J>25
(*1.6)
i_{disk}=85°
0.2
0.0
0.1
0.08
0.00
(Flux − Continuum)/Continuum
−100
0
100
Velocity (km/s)

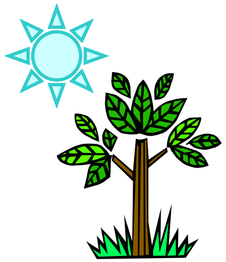

DM Tau, HCO+ J=3-2
Tmb (K)
0.3
0.2
0.1
0
−0.1
5
v(lsr)

actual disk properties

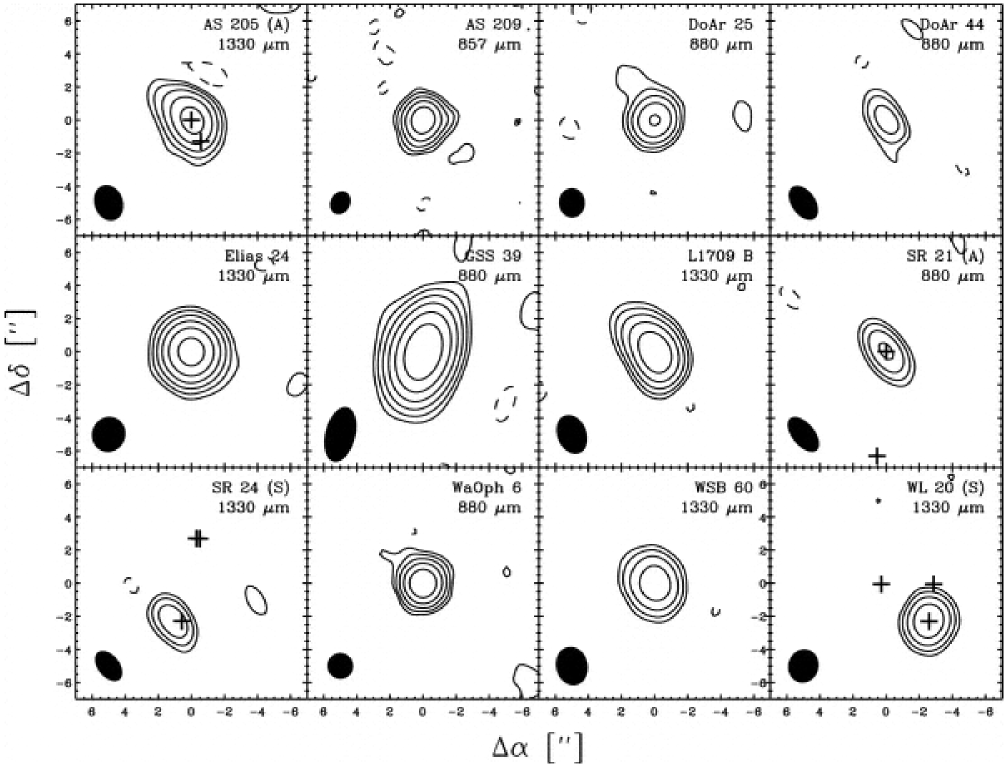


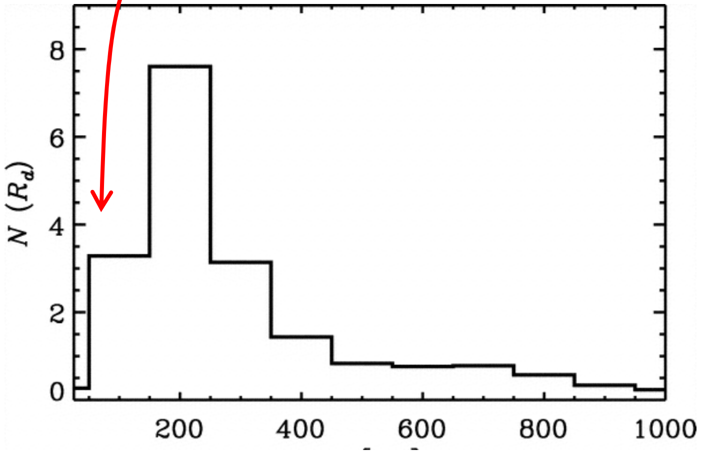
- masses of disks
  - e.g. submm survey of Taurus: Andrews & Williams 2005
  - note that many of the disks are *much less massive* than the Minimum Mass Solar Nebula (~0.02 M_{sun})



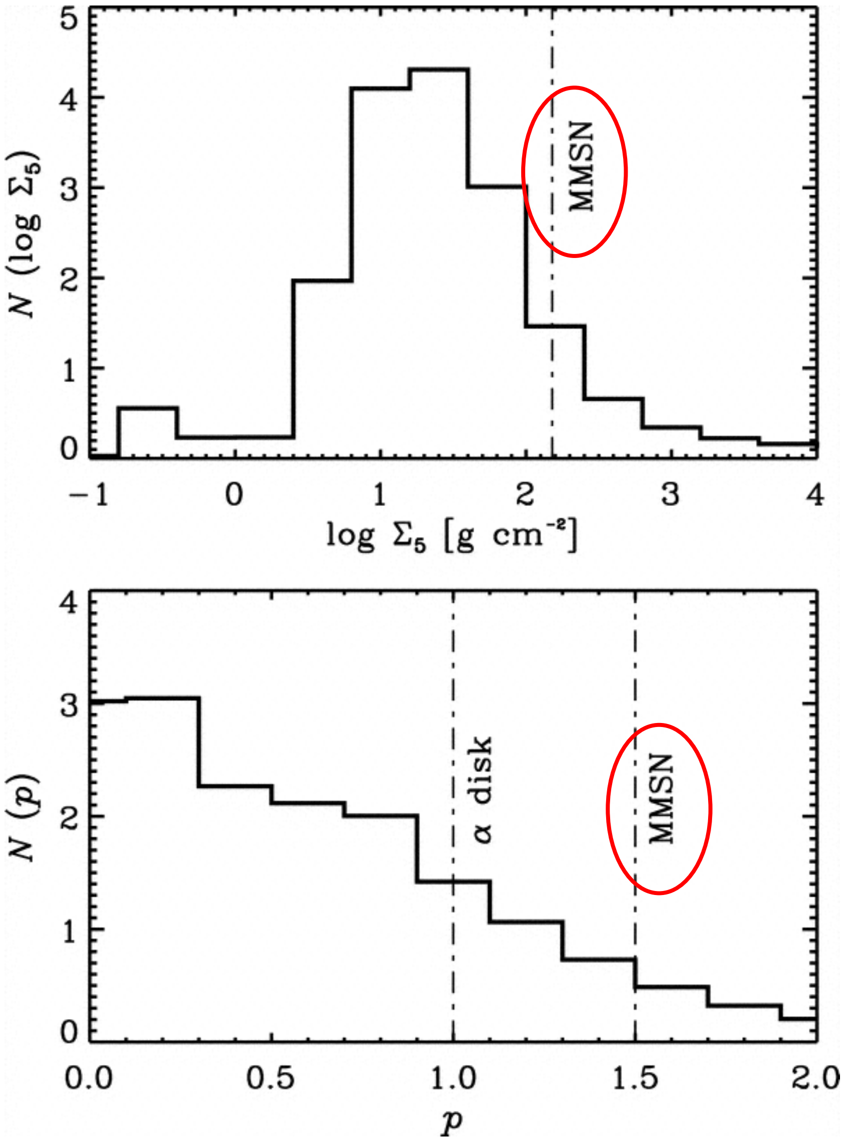


- sizes of disks, e.g. by submillimetre interferometry: Andrews & Williams 2007
- typical disk radius of ~200 AU
  - this is 4x larger than the Solar System
    - although observed for disks of ~few MMSN

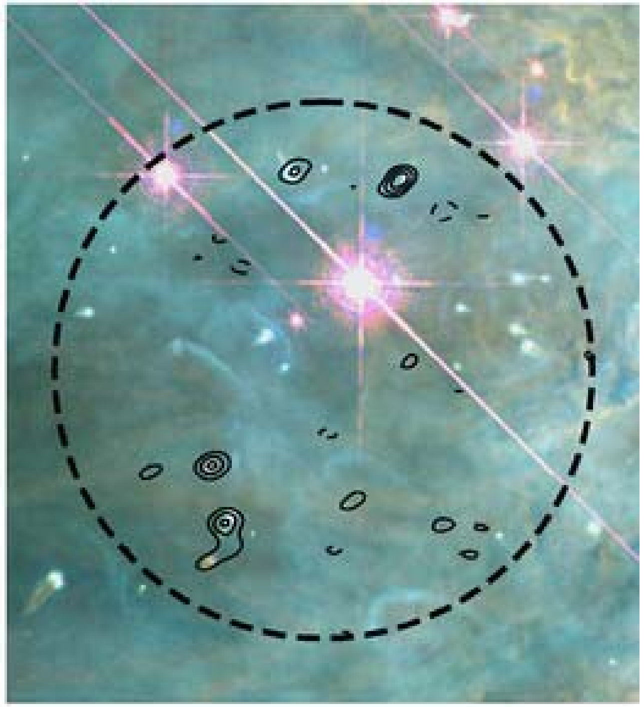


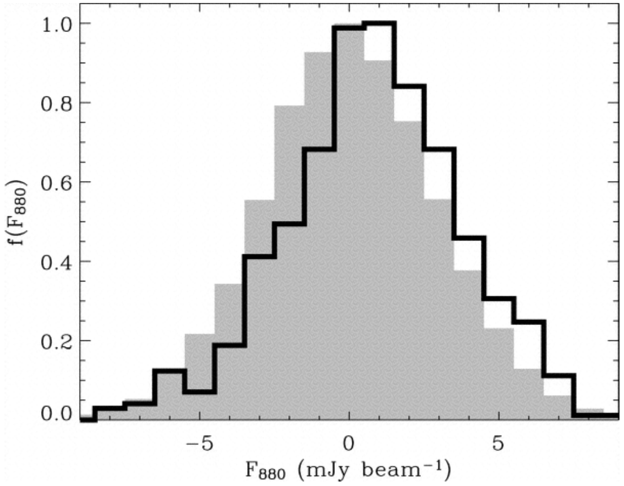


- surface densities (column through disk)… large low-mass disks: *low* values
  - a problem for standard core accretion models
- the profiles may also be flatter than expected
  - surface density ~ $r^{-1.5}$ in the Solar System
    - masses in planet cores
  - if flatter, e.g. r^{-1}: moves more mass further out, away from where it is needed to form planets



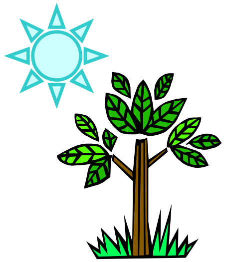
- environment effects:
  - dense clustering of stars may affect disk survival, e.g. by photoevaporation or truncation
    - NB, disks in loose clusters easier to image! but many less stars than in dense clusters like Orion
  - evidence of bimodal disk population in Orion
    - in which case, maybe few planets in such clusters? … this would mean planets of mature stars are a *biased* sub-population from among disks of young stars



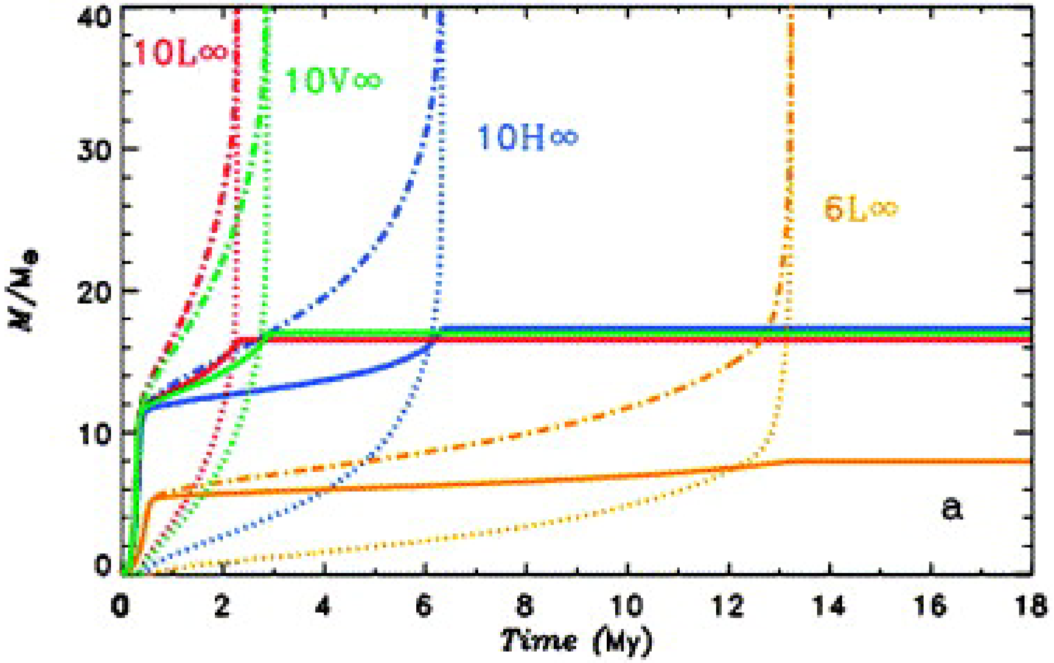


comparison to models

(only basics covered here!)

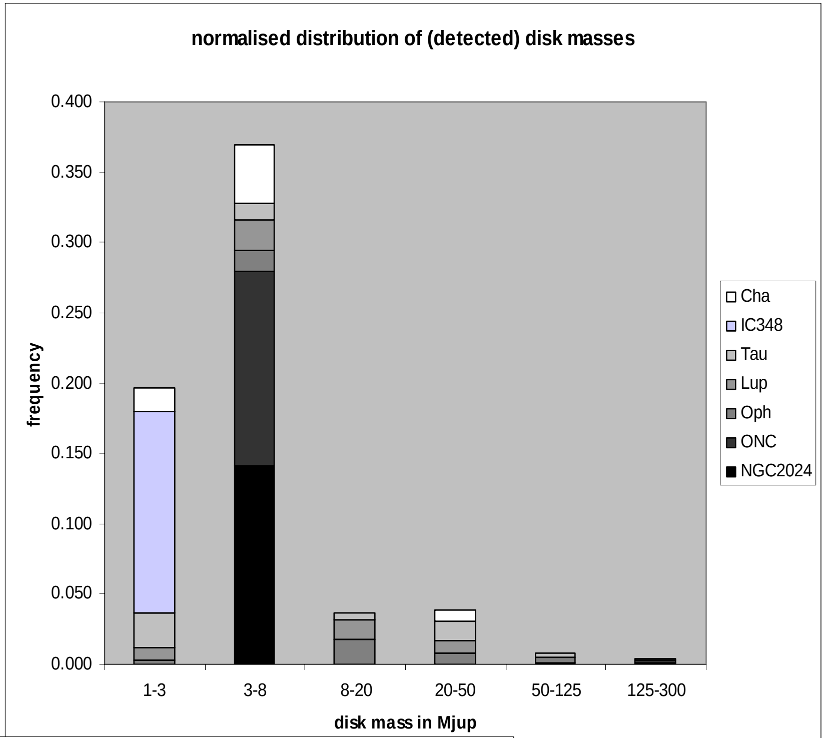


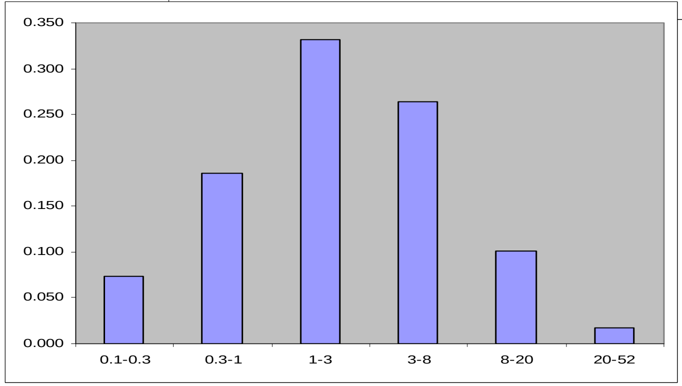
- giant planet formation via core accretion
  - threshold of surface density, and minimum timescales to work: Hubickyj et al. 2005



masses vs. models

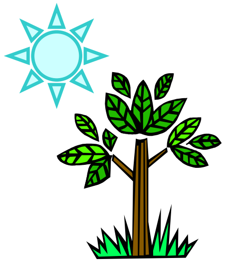
- *few* disks have the ~0.06 M_{sun} mass that models need for giant planet formation to work
  - maybe only 'top-end' disks form ~5-15% incidence of gas giants that we see? … but still need higher 'usage' of disk than the few-% in the Solar System



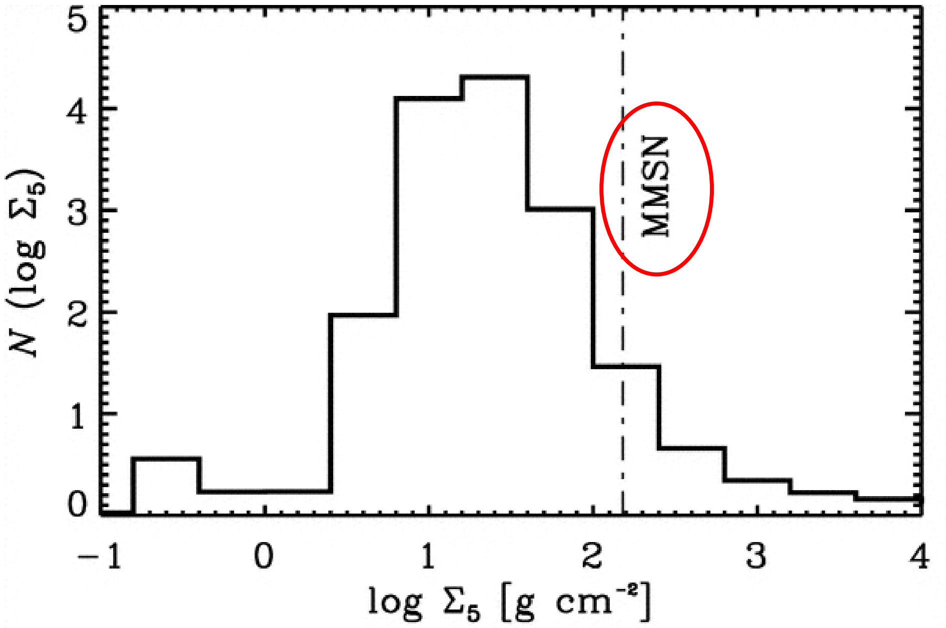


planetary system masses

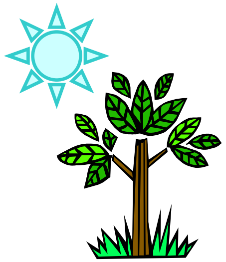
surface densities



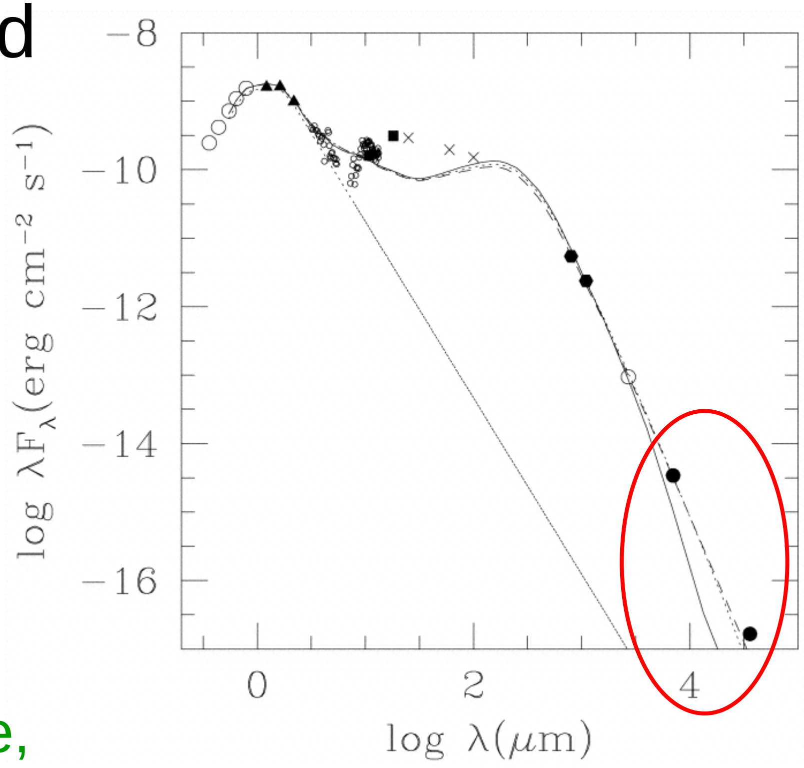
- surprisingly low if the observed disks are the ones that will form gas giants
  - if surface density~ $r^{-1.5}$, then disk with 20 M_{Jup} and 200 AU implies ~1 g/cm^2 at 5 AU
  - cf. 5-10 g/cm^2 needed in models

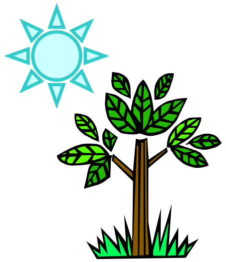


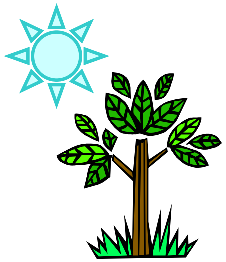
missing mass?



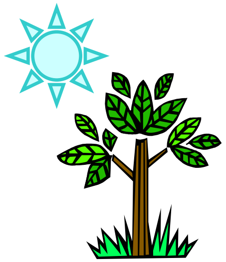
- NB, total mass is estimated from M(dust) x100… so *all* dust grains must be counted
  - – large 'pebbly' grains should dominate mass
    - *radio* thermal emission
  - – new cm-data suggests factors-of-few missed dust mass… could scale many disks nearer to MMSN
    - but can't scale most massive, to keep $M_{disk} << M_{star}$





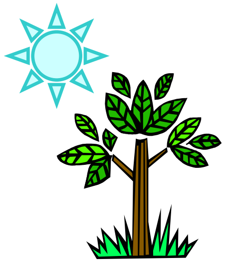


- summary on disks:
  - some, but not the majority, of disks around young stars appear to be suitable for forming gas giants
  - there are some significant differences between models based on the Solar System and the observed properties of exo-disks
  - the disks last at most 10-15 Myr, which requires cores of giant planets to form quickly (there must still be gas around to add the atmospheres)



(2) signs of planet formation

expectations

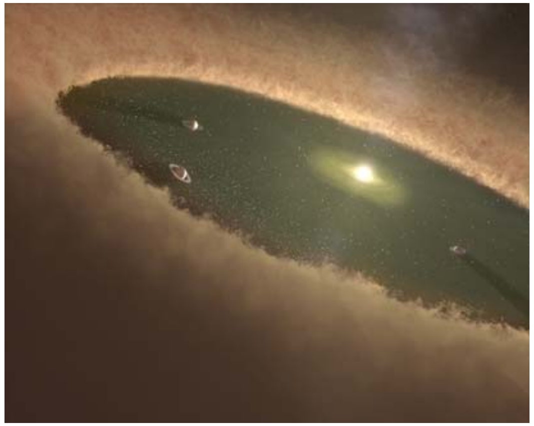


- for gas giants (e.g. Hubickyj, Bodenheimer & Lissauer 2005)
  - dust coagulates into planetesimals

    ~10^5 years
  - planetesimals merge into planet core

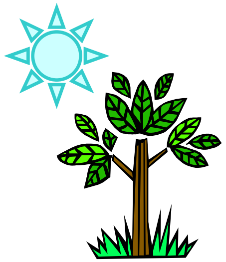
    a few 10^6 years
  - core accretes thick gas atmosphere

    ~10^6 years

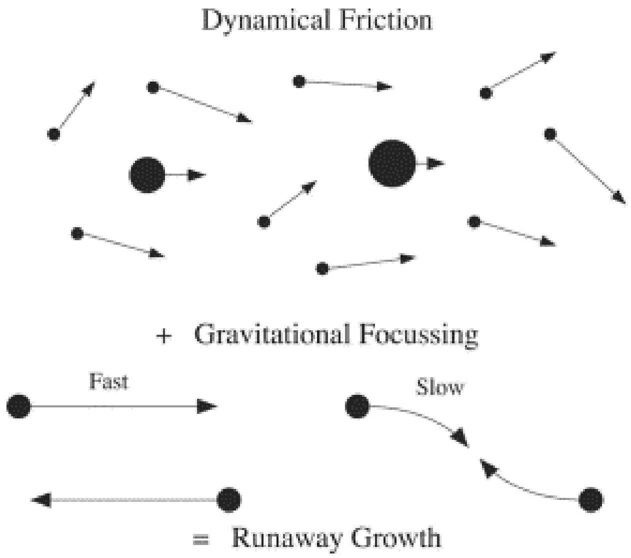


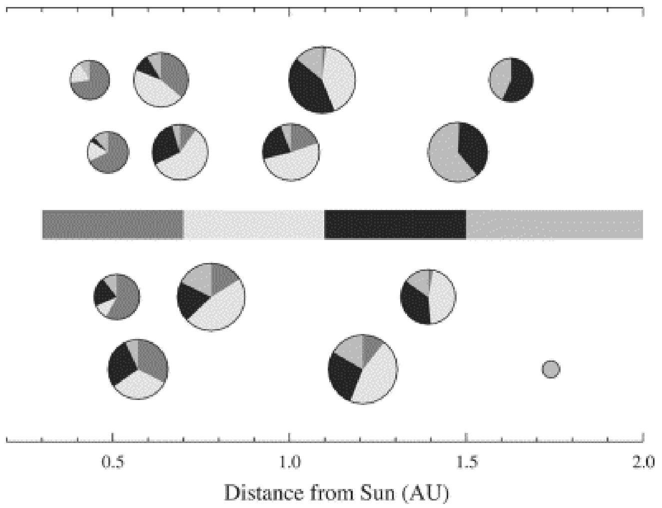
- timescales are reasonable (just) compared to disk lifetimes
  - if opacity of dust is << ISM dust (larger grains)

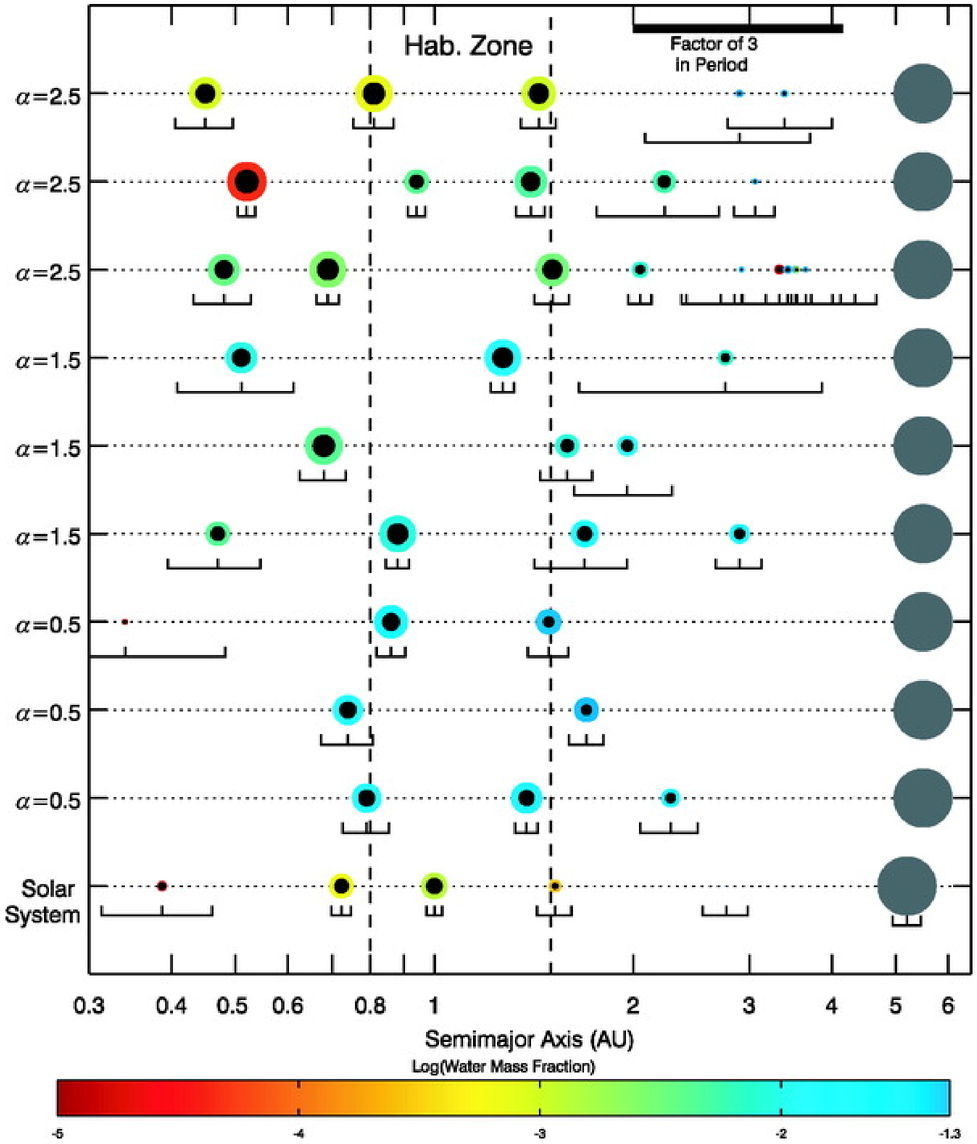
expectations



- terrestrial planets
  - starts with planetesimals as for the gas giants
    - inside 'snow line': rocky grains stick slower?
  - random collisions of a few bodies to form planet
    - one-off events e.g. forming Earth's large moon
      - exact architecture of Solar System should be rare
    - takes $10^{7\text{-}8}$ years, so little gas left
- materials for one planet can come from all over the disk, so compositions are quite random
  - e.g. water content of Earth's oceans could have been much lower or higher

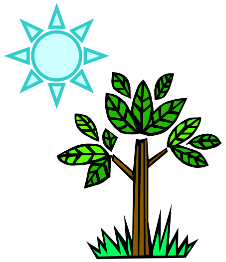




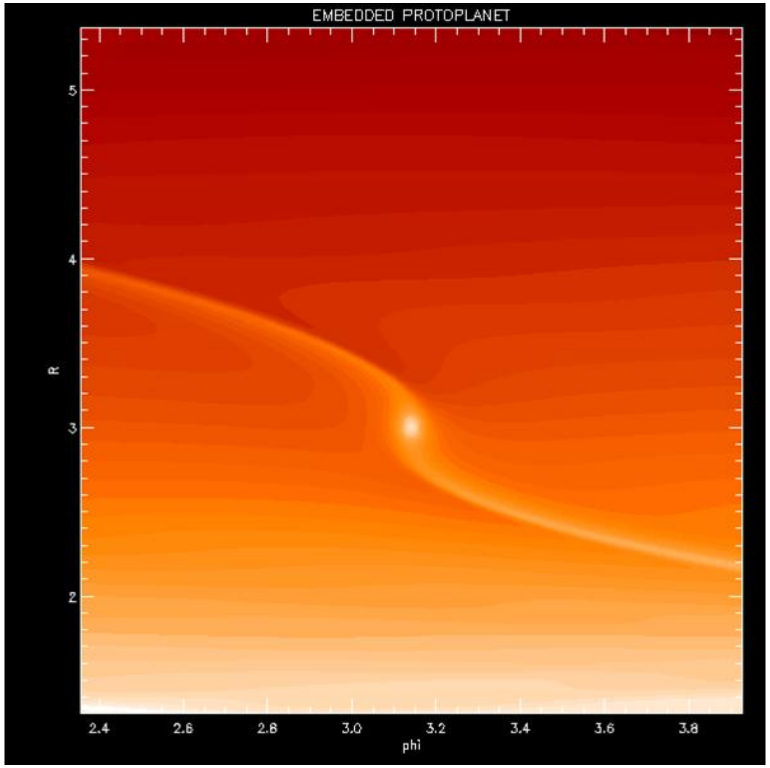


Chambers 2004; Raymond, Quinn & Lunine 2005

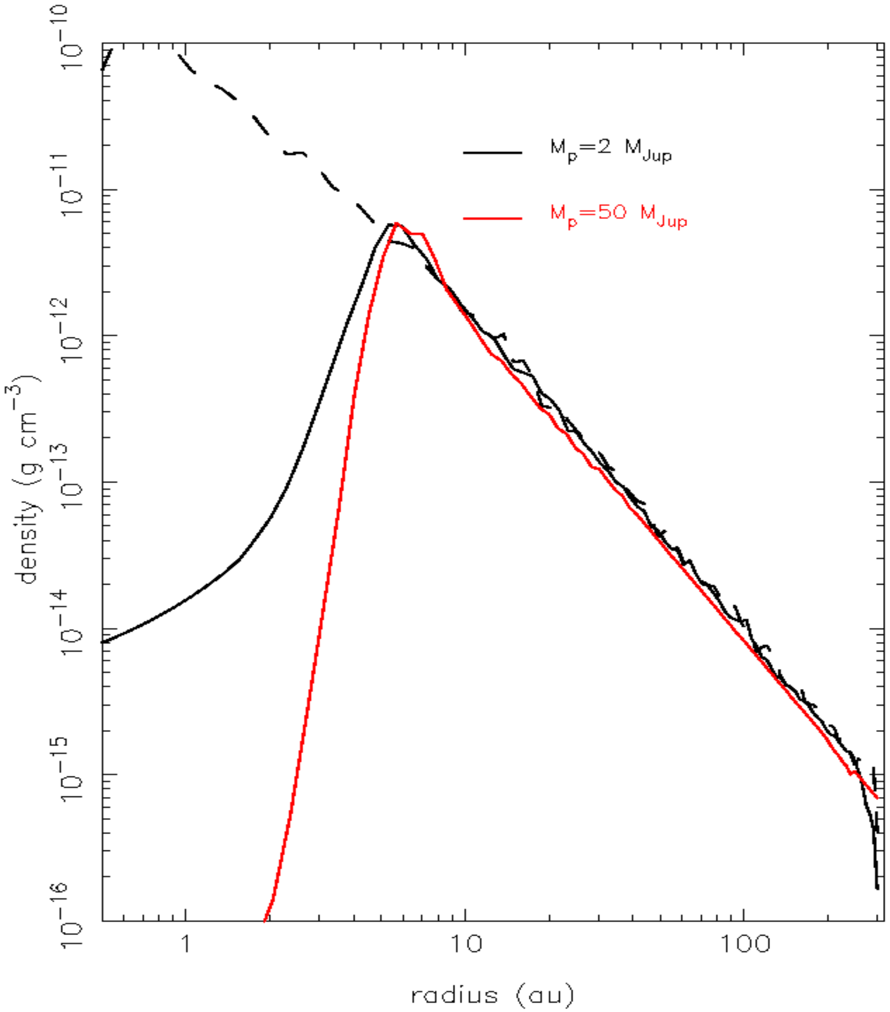
effect on disks



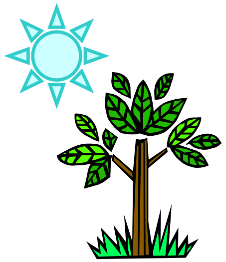
- dust and gas should clear on different timescales
  - dust first, going into planetesimals
- planet formation should sweep clear the vicinity
  - forming an inner hole or a cleared ring
    - e.g. an inner hole will reduce level of near-IR dust emission
  - not all dust is affected: e.g. small grains may be swept across gaps by accreting gas
    - useful clue to planet mass: if it's large, only small dust can filter across



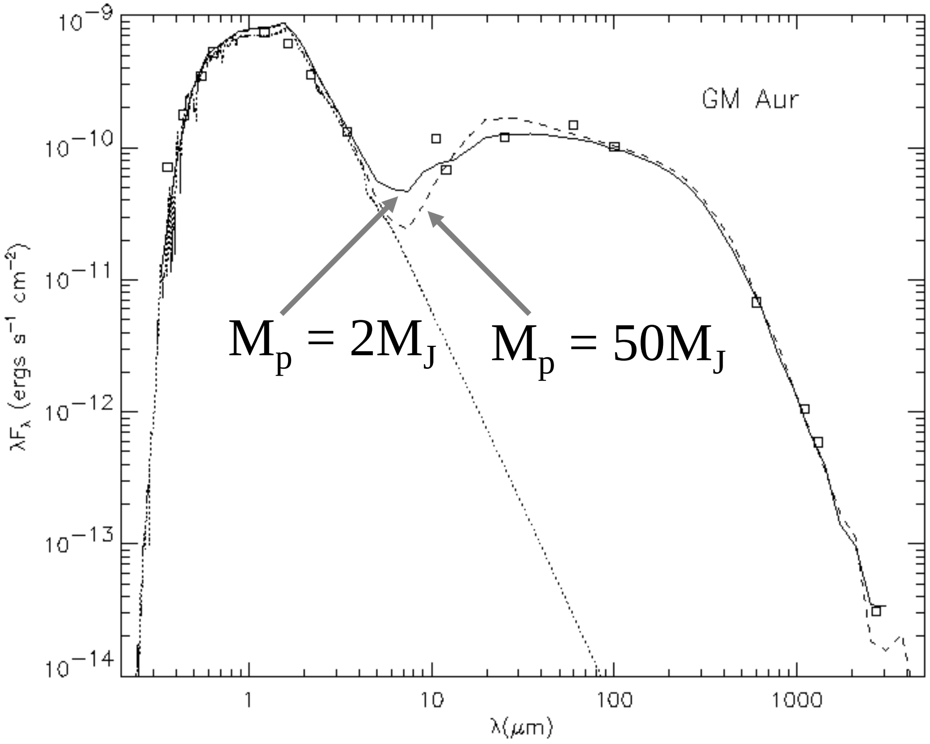
Richard Nelson, QMUL: simulation of planet accreting from disk

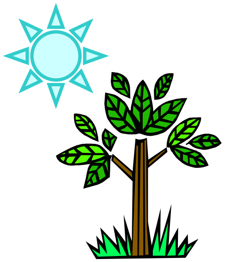


3D SPH calculation by Ken Rice: planet at 2.5 AU clears inner 4 AU in ~2000 yr

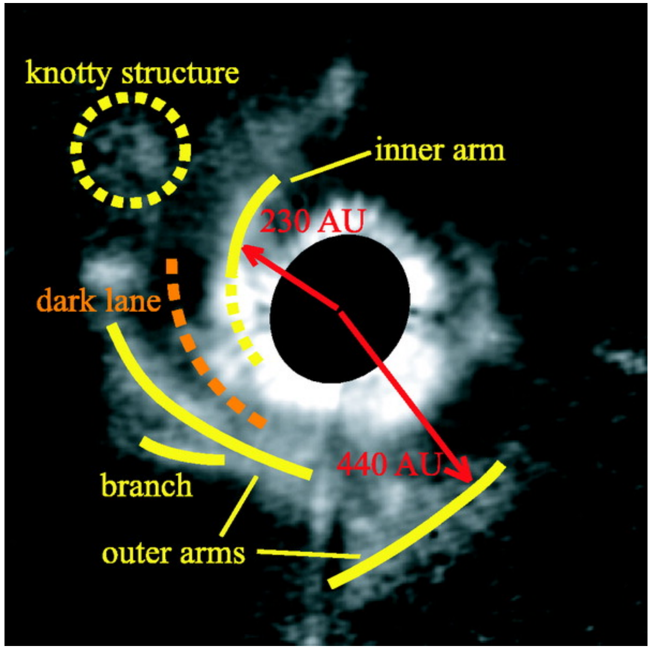


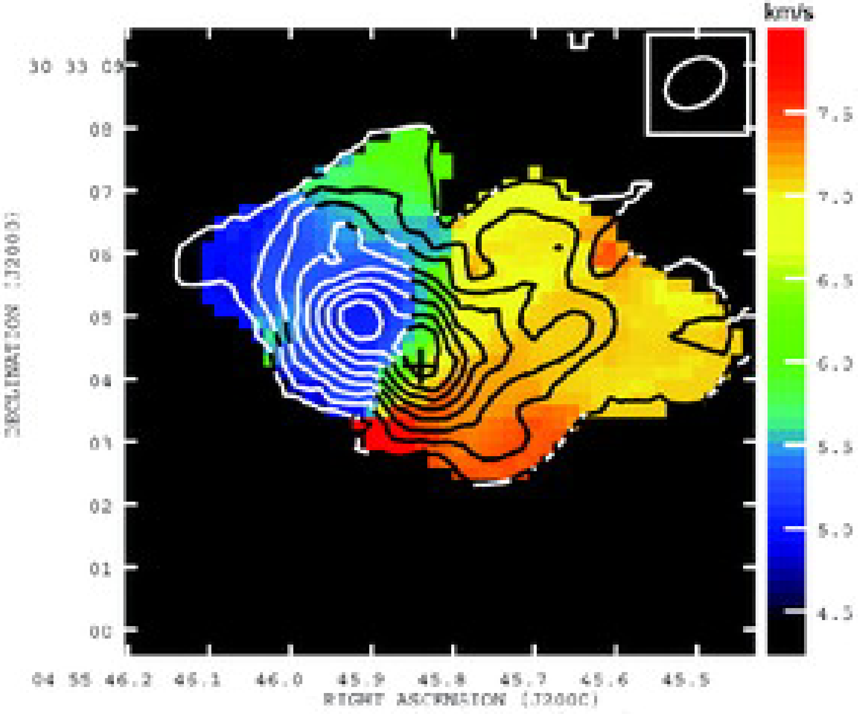
- evidence for inner gaps seen in SED's
- but cleared rings may be ambiguous
  - radiation pressure forces grains out while viscosity drags grains in (Takeuchi & Lin 2003)
    - so cleared rings might form *without* a planet



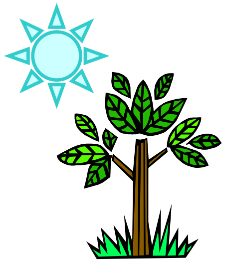


- planets can also perturb the disk
  - some observational evidence for this, e.g. star AB Aur (~2 M_{sun}) Fukugawa et a. 2004, Lin et al. 2006
    - asymmetries, spiral arms…
    - also look for non-Keplerian velocities of gas

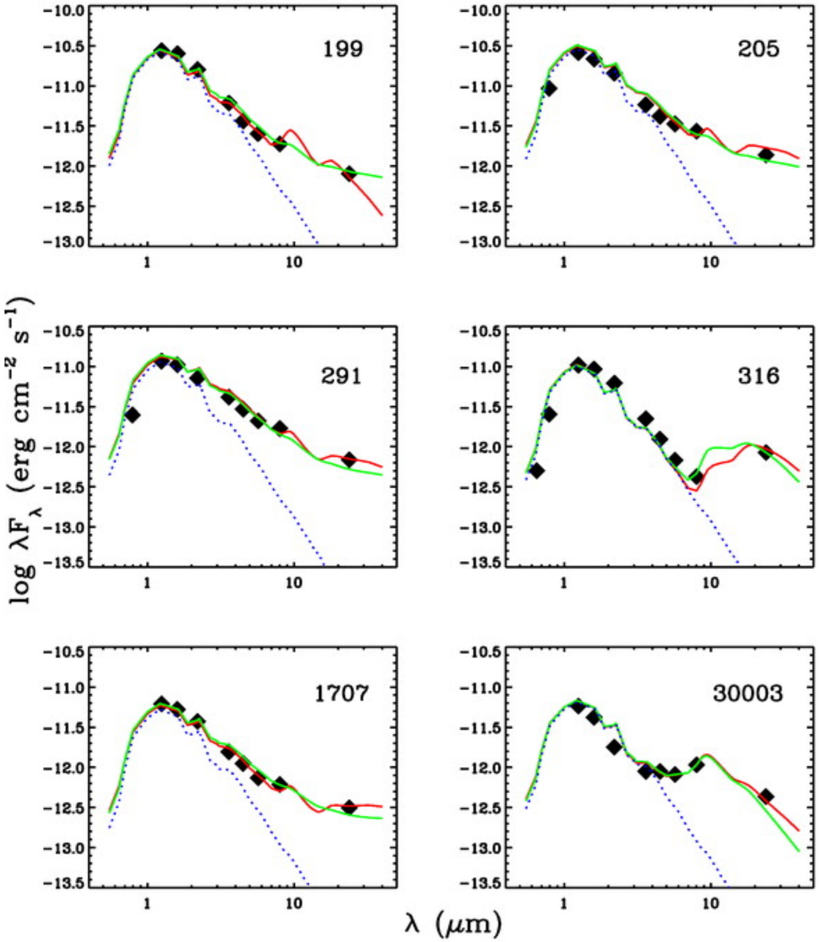


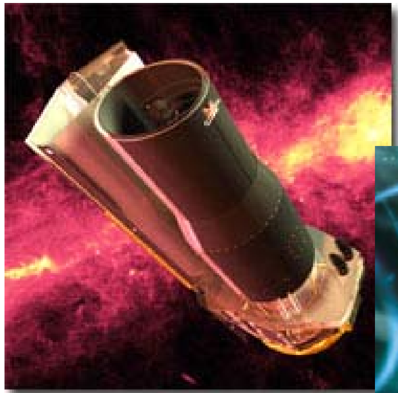


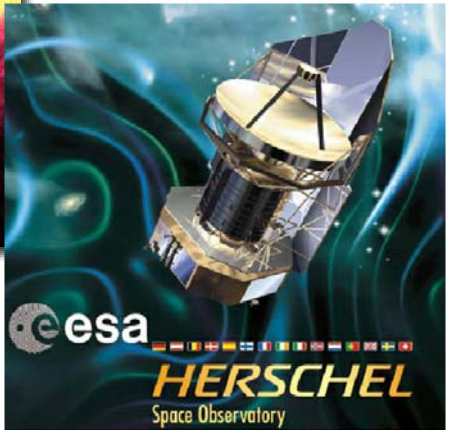
input from observations



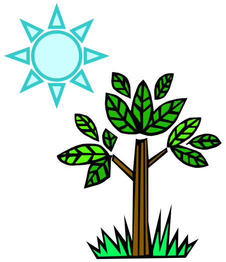
- now: mainly SED's
  - e.g. Spitzer IR satellite, 2003-2008
    - also soon Herschel IR satellite 2008+



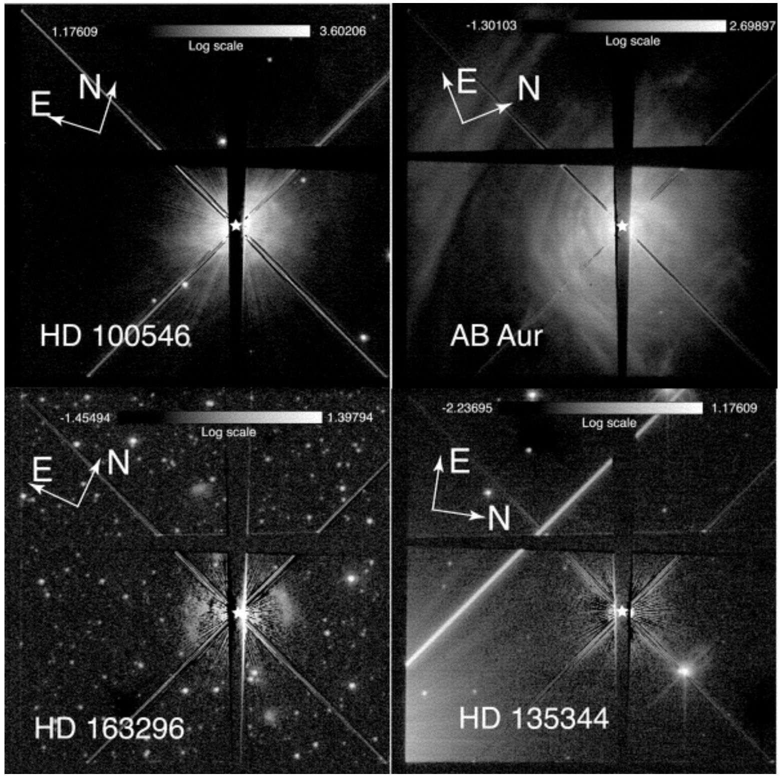


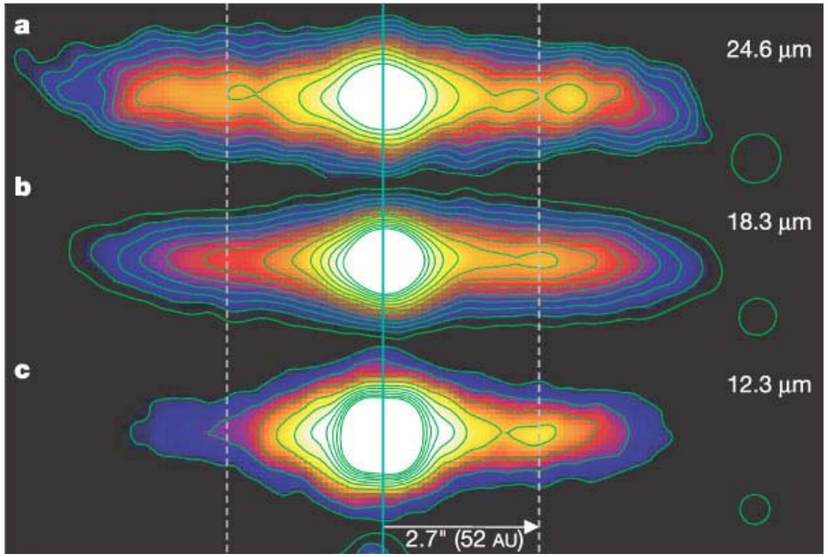


observations

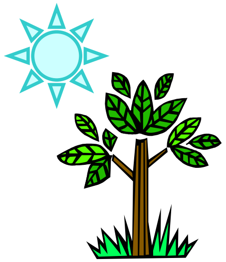


- now / near-future:
  - imaging of possible planetary perturbations
    - e.g. HST, 10m-class telescopes on the ground

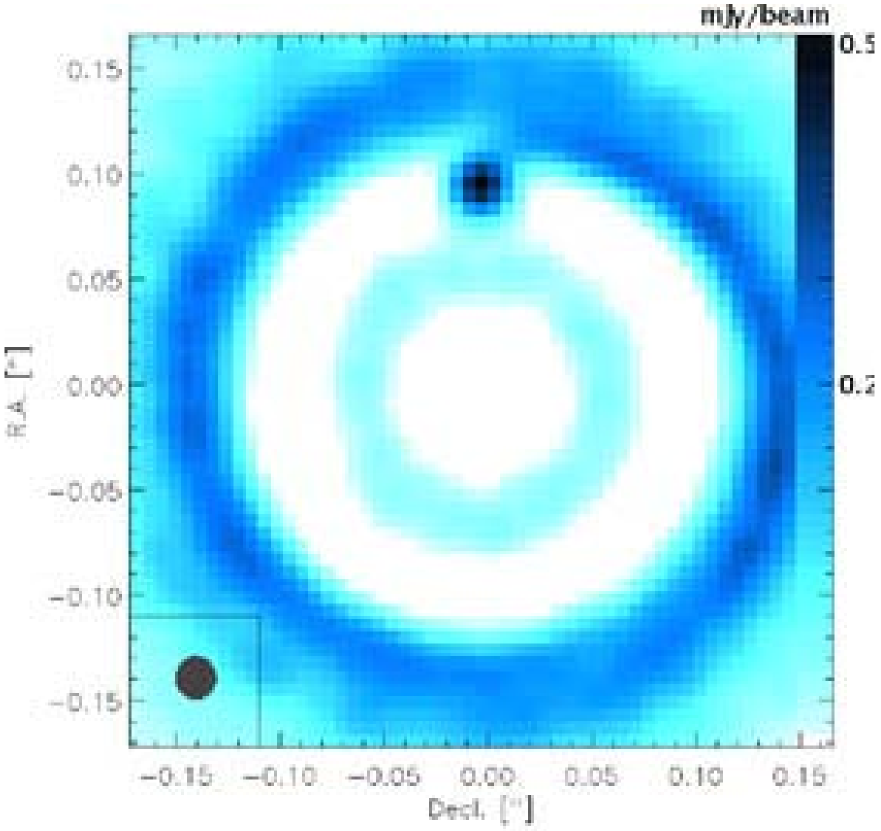


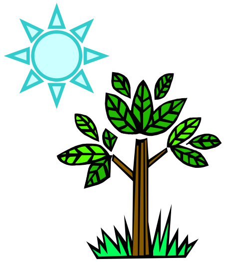


observations

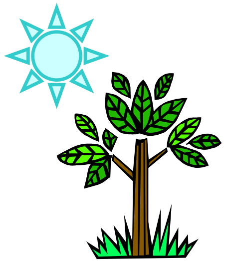


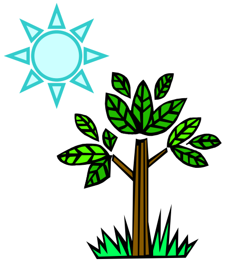
- medium-term future:
  - JWST IR satellite ~2012
    - much more detailed disk images
  - ALMA millimetre interferometer ~2010
    - direct imaging of cleared rings?





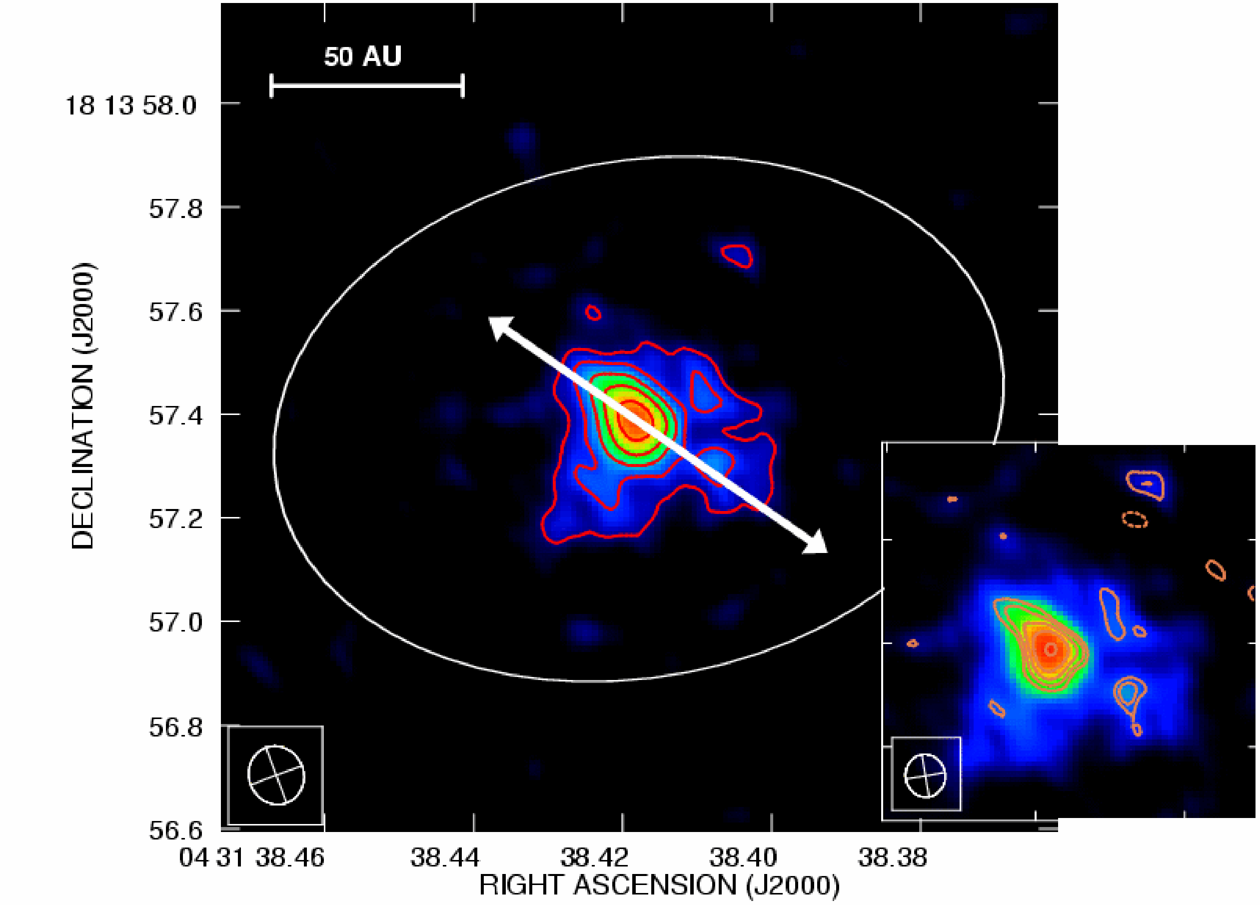
(3) imaging planets

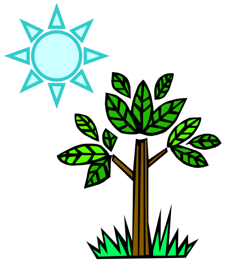




radio detection

- – low-mass companion seen! … with max. resolution of VLA (0.1" at 1.3 cm) Greaves, Richards, Rice & Muxlow 2007





- summary of planet detection:
  - disks disappear - but *not* predominantly accreted into planets: not a planet signature
  - gas and dust redistributed by stellar forces: e.g. ring structure *not* necessarily by planets
  - inner holes and perturbations in disks: hard to explain by non-planet mechanisms
  - direct detection of emission from planets forming in disks: in the near future!