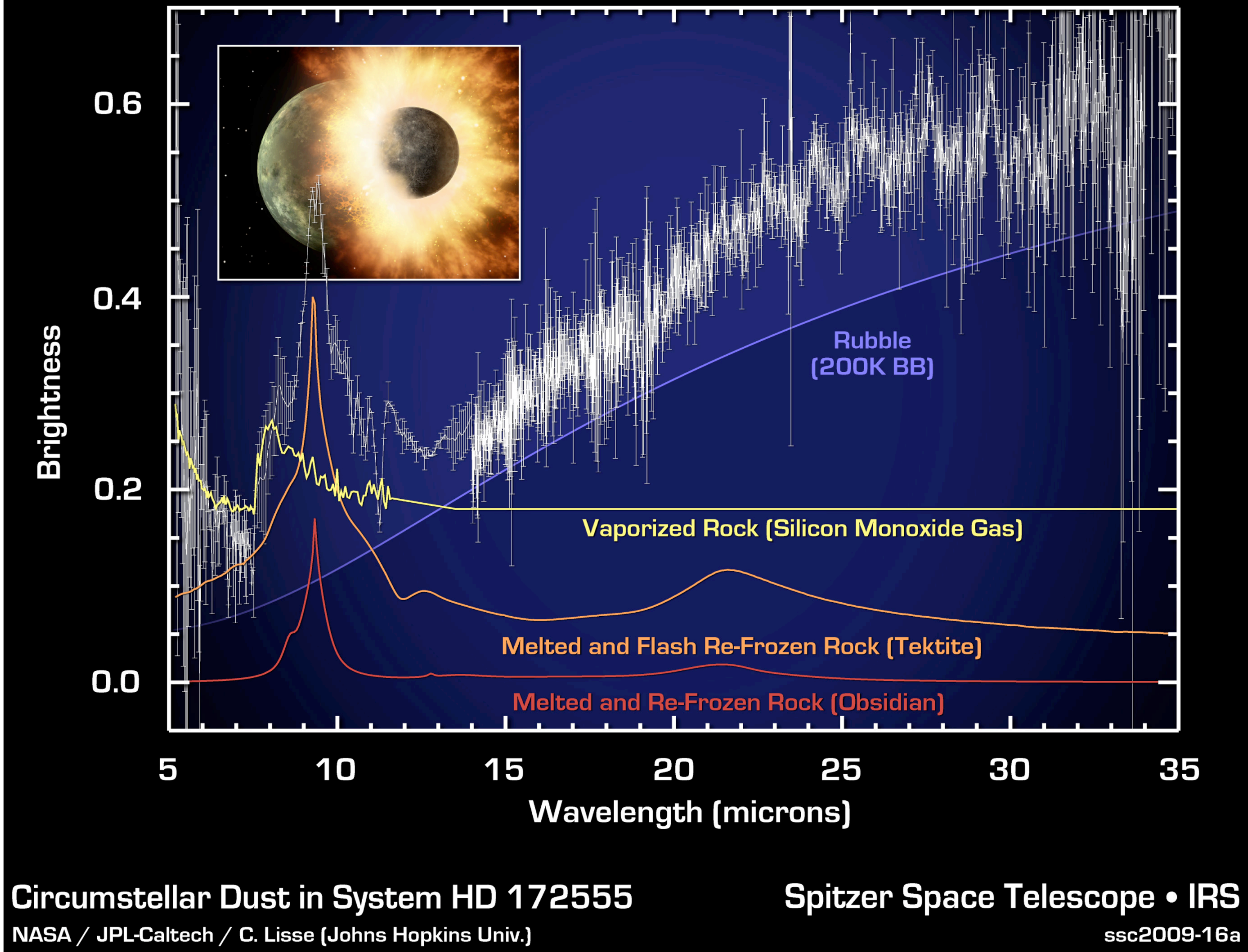
HD172555 : Spitzer Evidence for Abundant Circumstellar Silica and SiO Gas Created by a Giant Hypervelocity Collision



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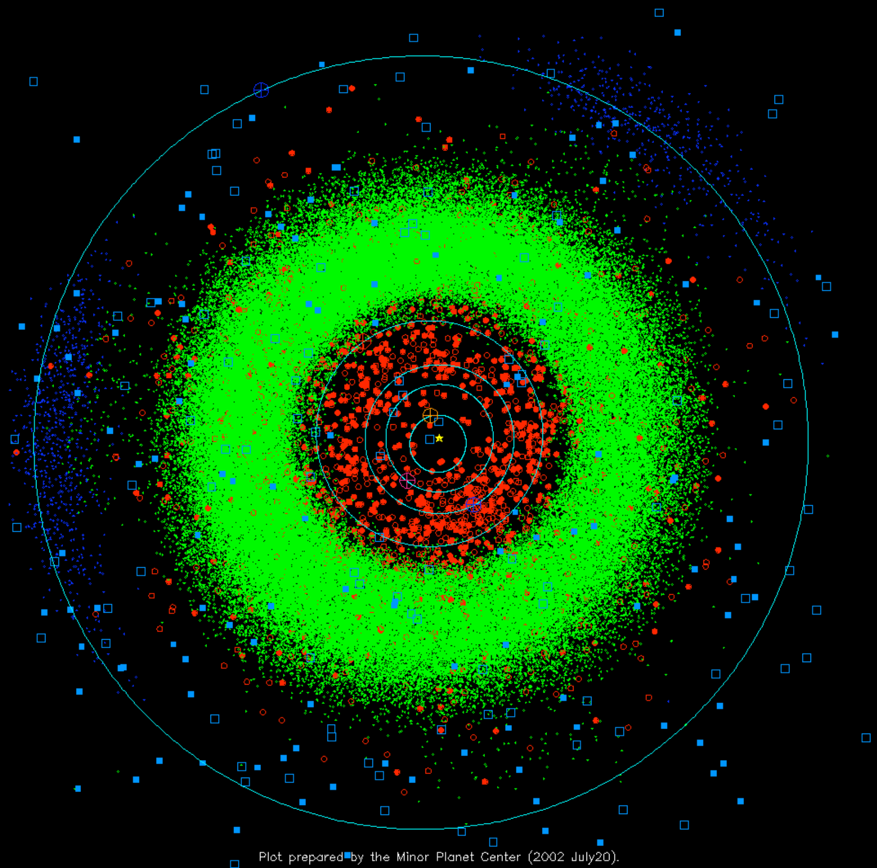
Nov 2009

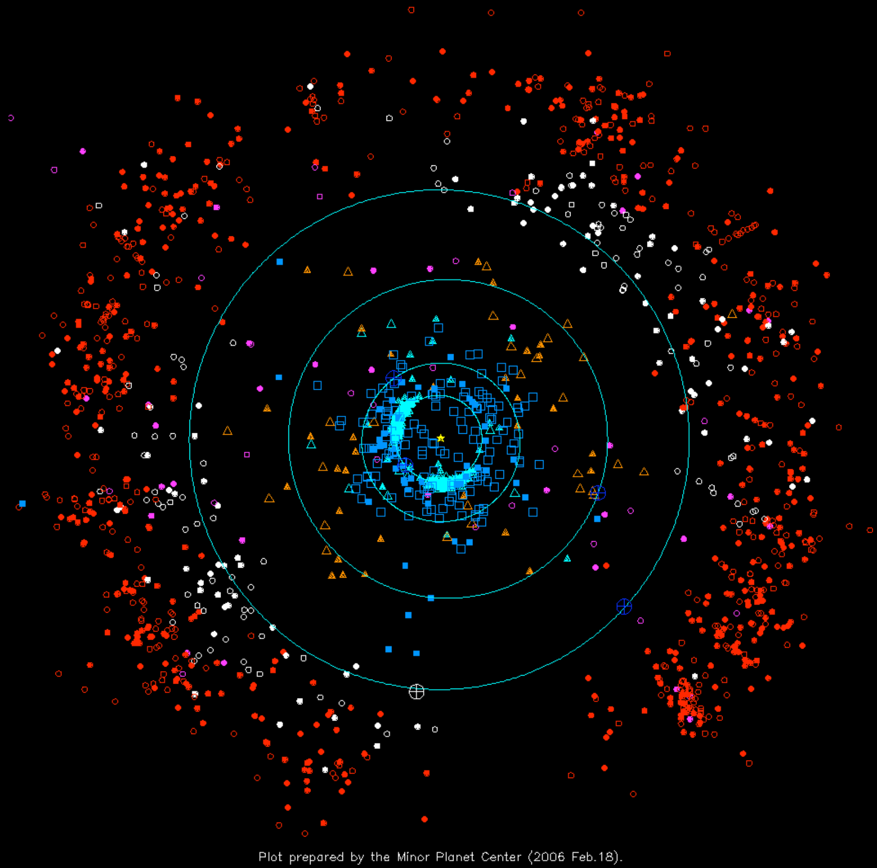
While mostly cleared out, the Solar System does contain 2 sparse (< 1% of original density) Debris Disks & an Oort Cloud (not shown)

Inner System
(green = asteroid belt)



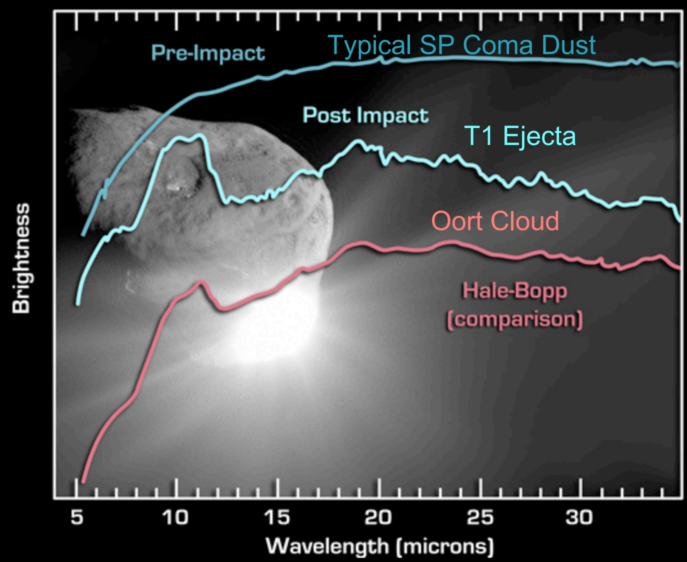
|----------- 10 AU -----------|

Outer System
(red = Kuiper Belt)

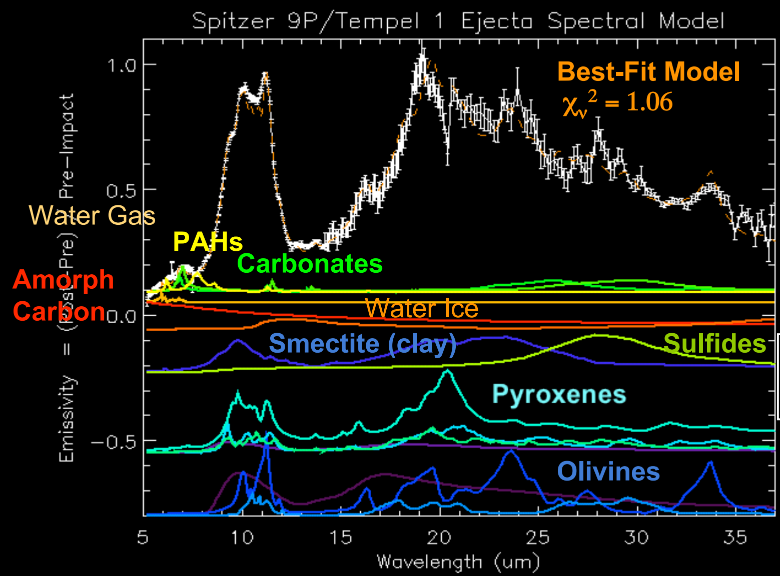


|------------100 AU ------------|

Deep Impact and the STARDUST Comet Sample Return Have Created A New Era of IR Dust Compositional Studies - Comets Are Now Known to Be Processed Mixes of ISM Material.



Comet dust only reveals its compositional signatures on remote IR observations when finely divided, as in the Deep Impact experiment or in the violent outflow from hyperactive comets like C/Hale-Bopp 1995 O1

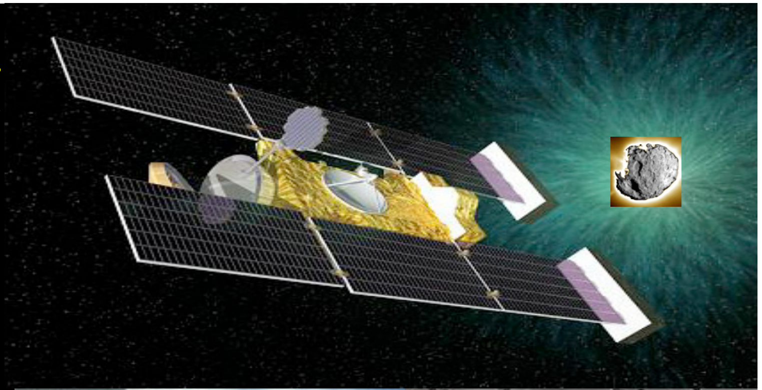


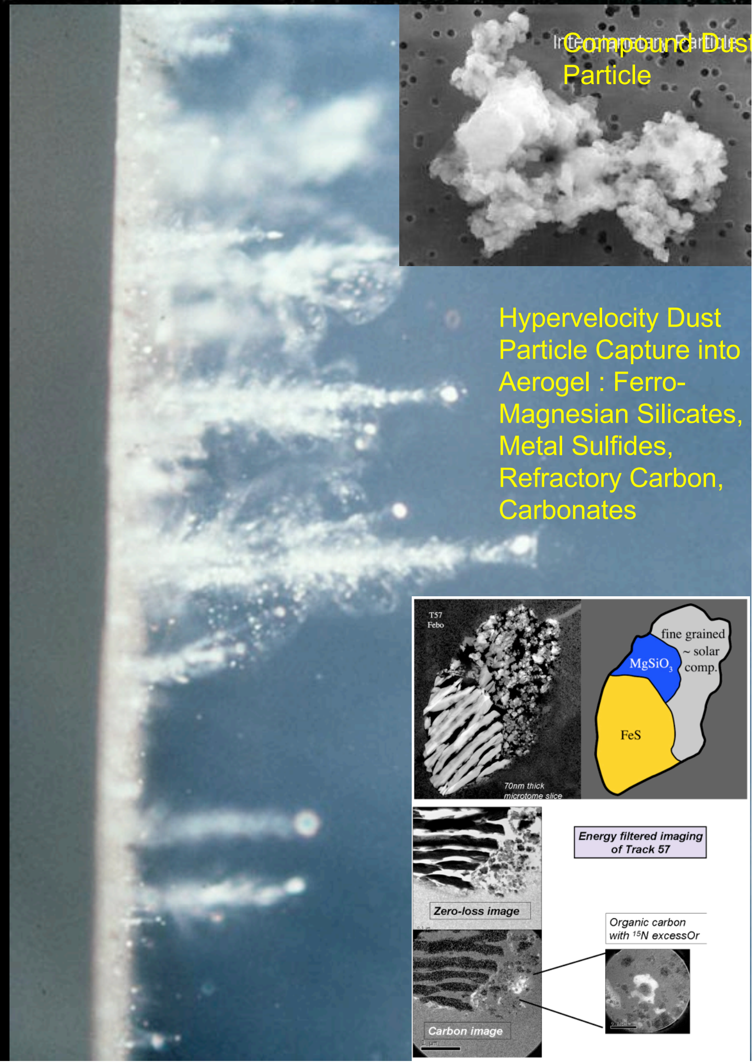
Spitzer IRS I+45 Min

344 Spectral Points
SNR 5 - 30 (2σ errors)
➢16 Sharp Features
95% C.L. = 1.13

Laboratory Powder Emission Spectra

Lisse *et al.* 2006

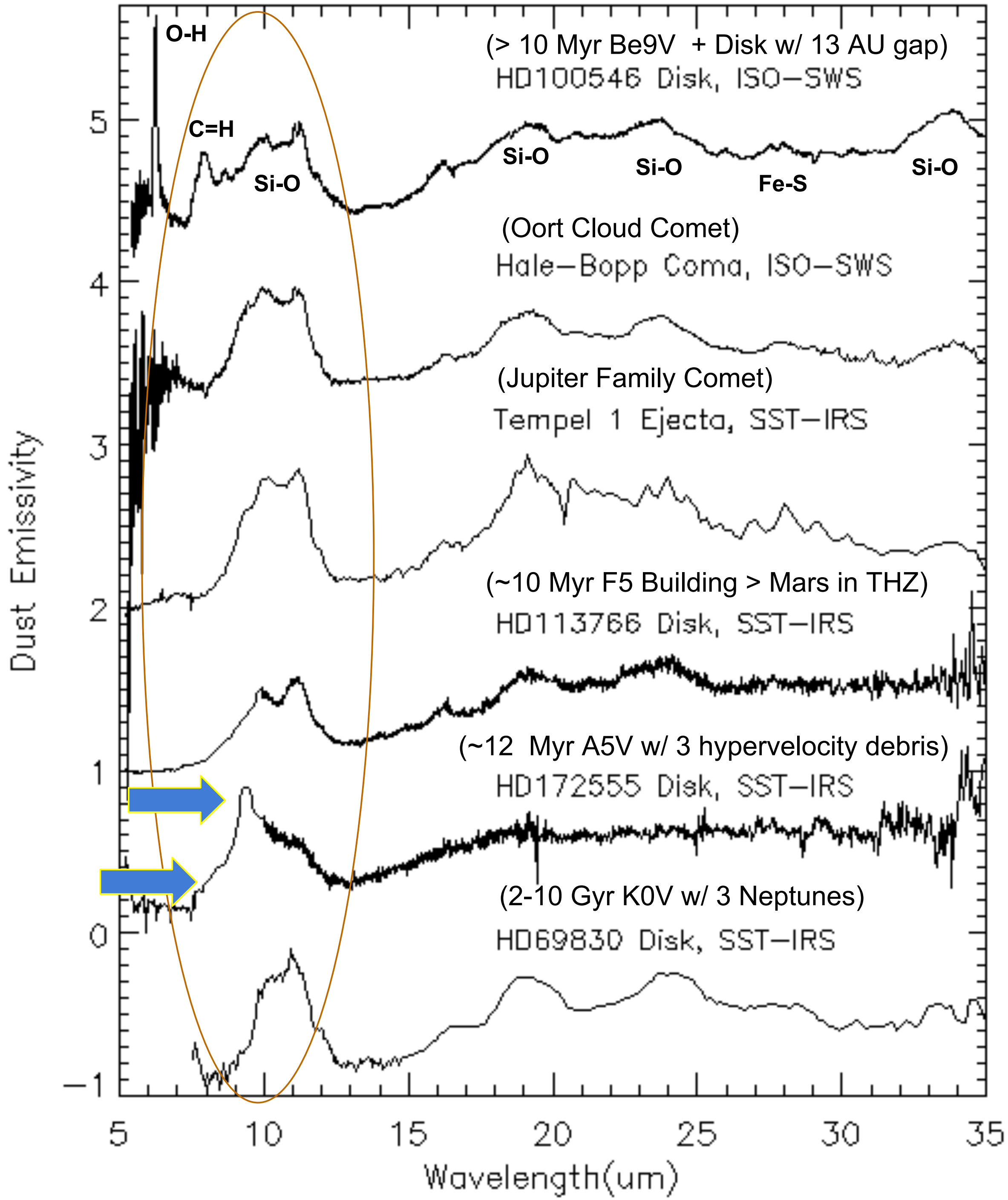




HD172555 *Spitzer* circumstellar excess spectrum compared to selected *Spitzer/ISO* Exo-System & Comet spectra.

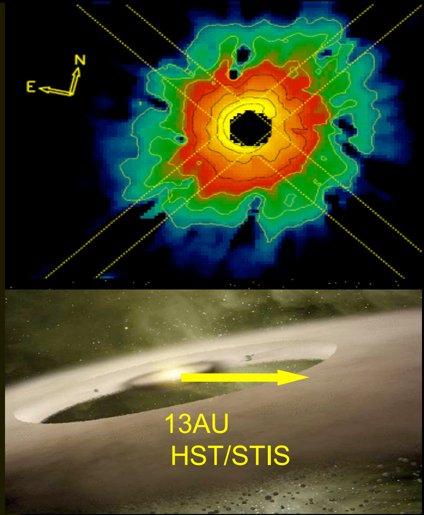
While all systems studied to date have similar spectral features due to the ubiquitous presence of silicates, PAHs, water gas and ice, carbonates, and metal sulfides, the HD17255 spectrum is very peculiar.

We know of only 1 other system, out of hundreds, that show a pronounced 9 µm crystalline Si-O feature, and the 8-9 µm emission signature is unique.

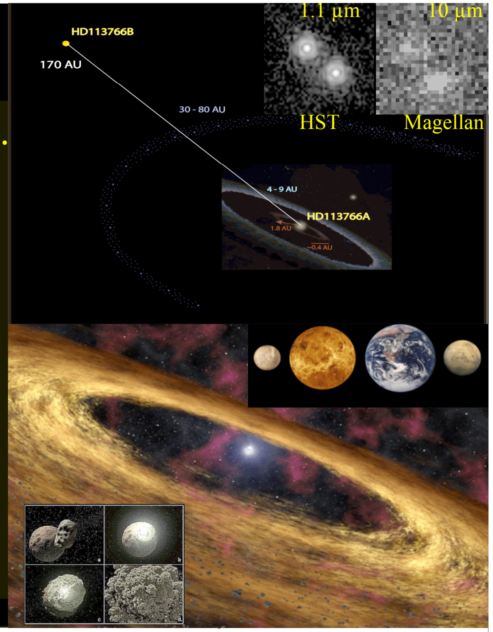


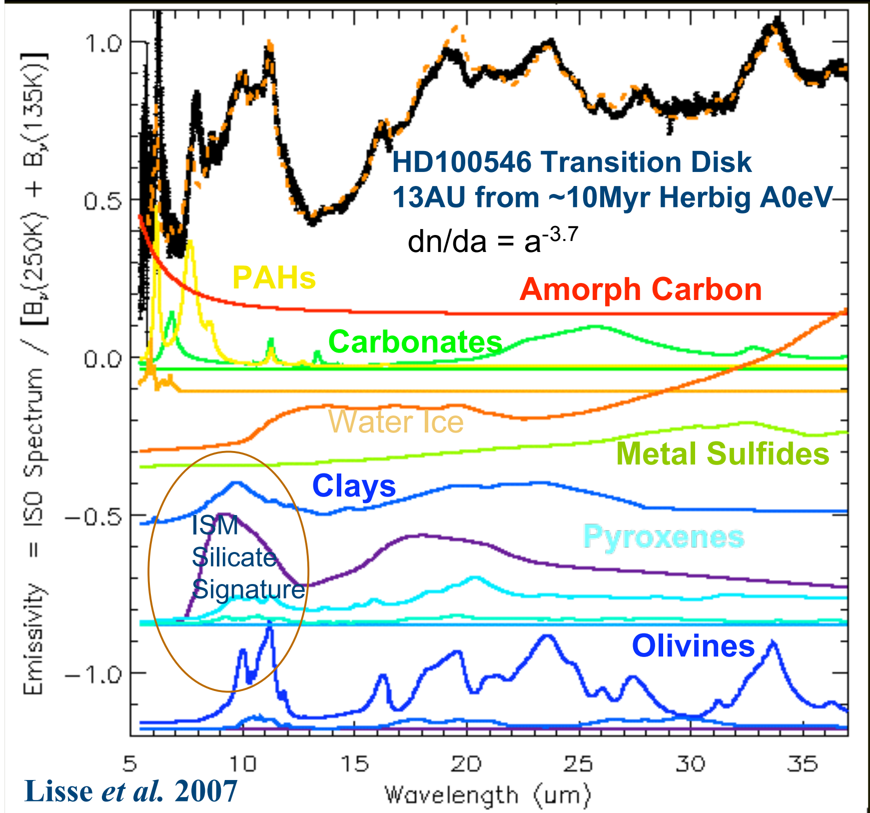
Maturing ('Teenage') Stellar Objects

Herbigs HD100546 & 163296: Comet-like system spectra. Especially rich in Mg-rich olivine and amor-phous ISM pyroxene, water ice. ~10 My old, >> M_{earth} of material at ~13/7 AU at an inner disk cavity edge (c.f. Grady *et al.* 2005).
=> Building Giant Planets w/ cometary planetisimals.



HD113766 : 10-16 My old.
➢0.5M_{Mars} of Dust @ ~1.9 AU from HD113766A, has Mg-rich olivine, Fe-rich sulfides, amorph carbon, and xtal pyroxene. Solar abundance, S-type asteroid composition in the heart of the terrestrial planet zone.
=> Ongoing Rocky Planet Formation.

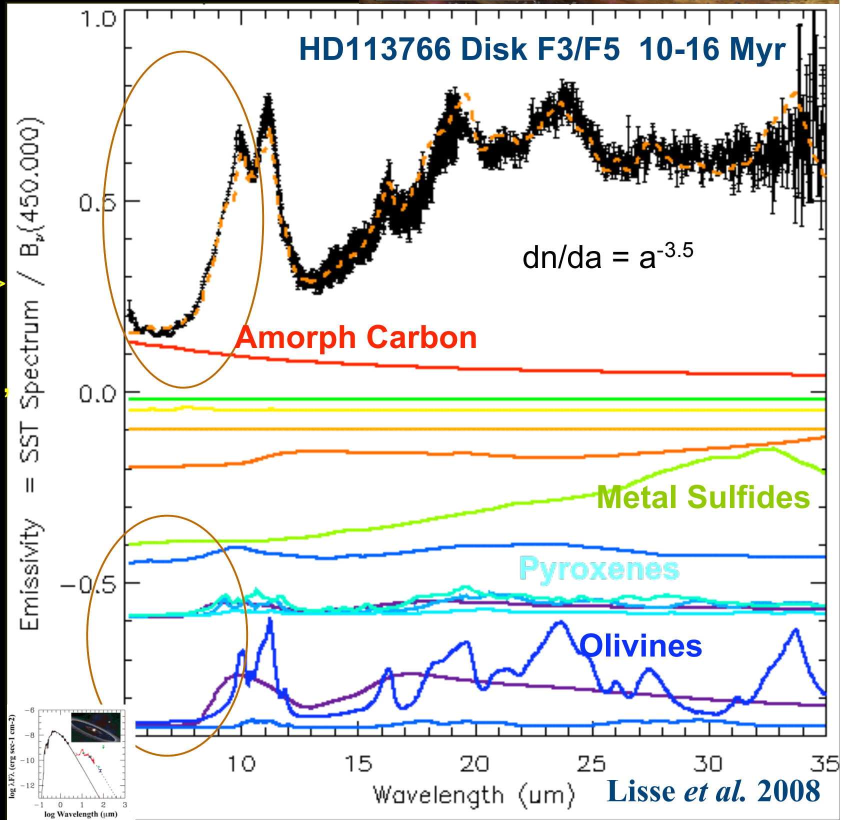




Lisse *et al.* 2007

???

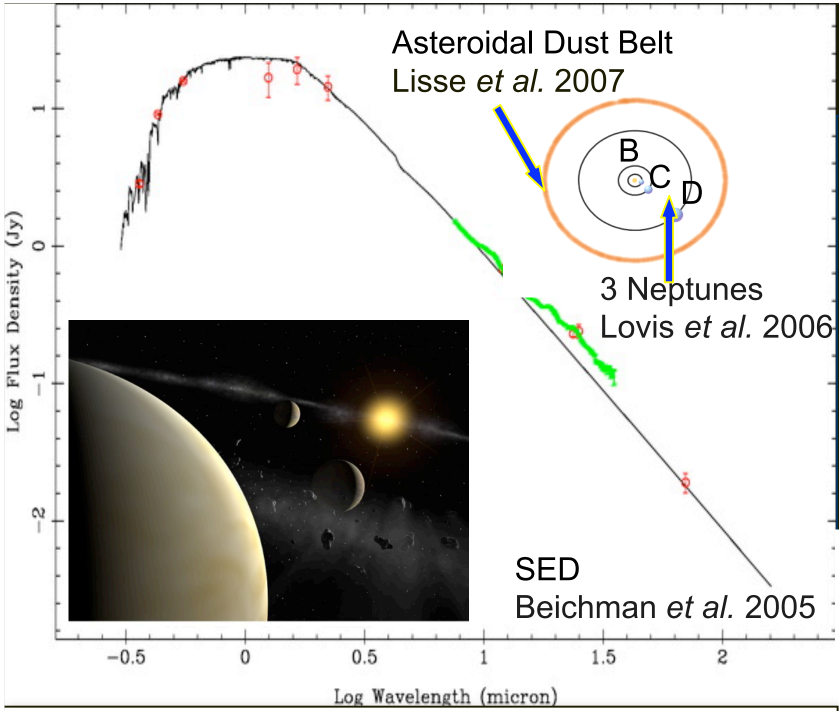
Disk Evaporation, Gas Depletion

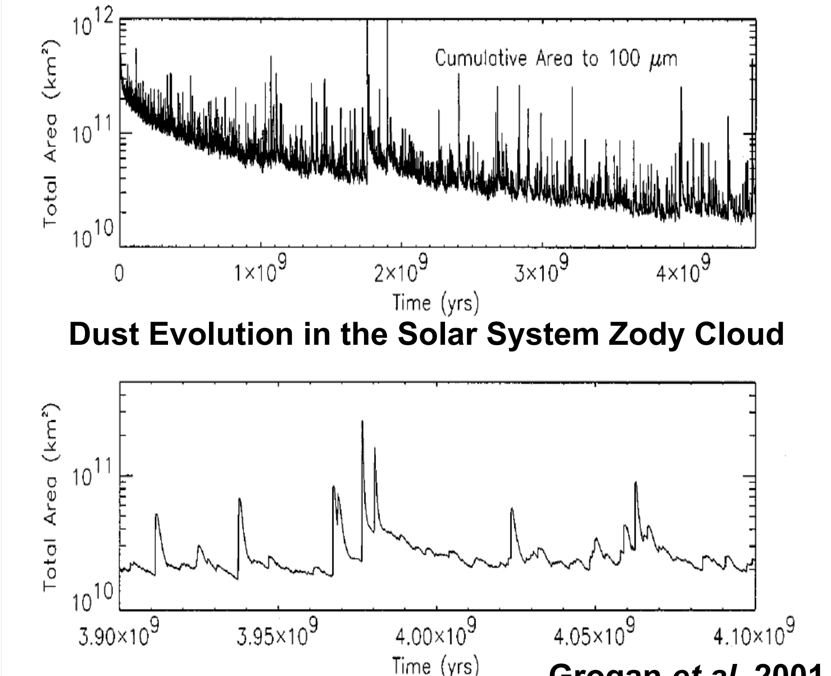


Lisse *et al.* 2008

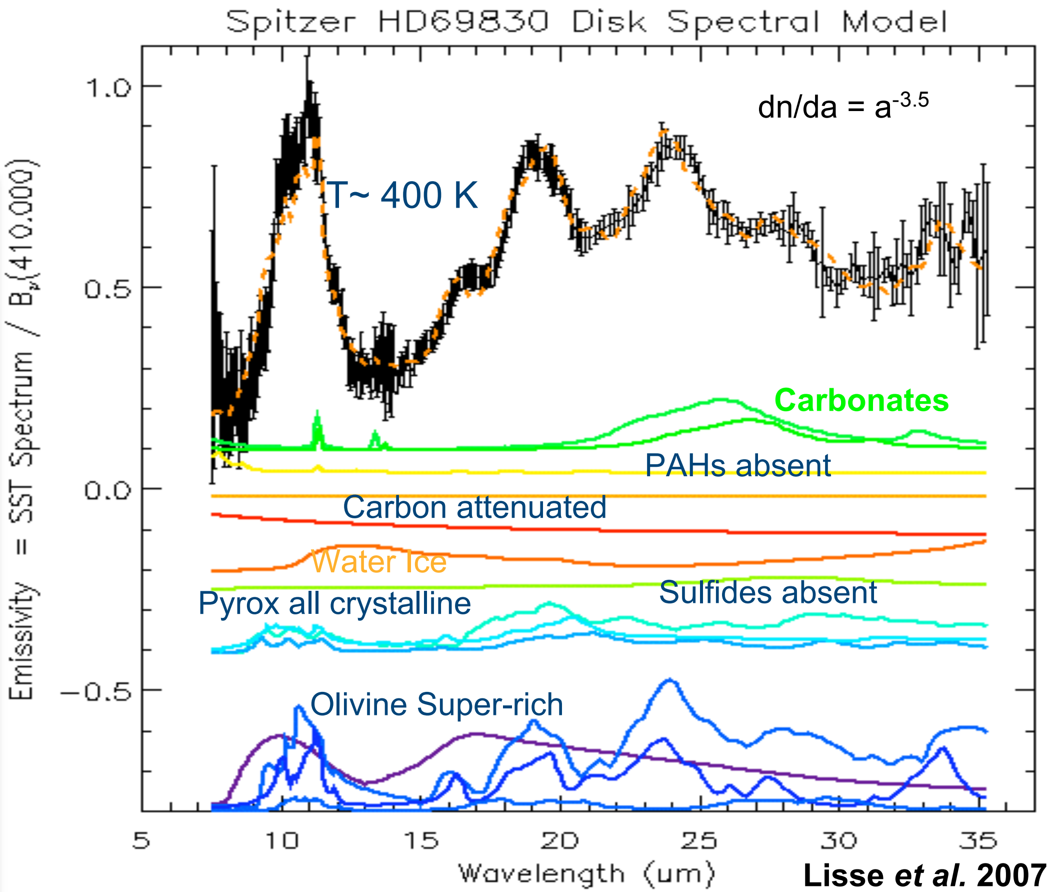
Dense, Mature Debris Disk of HD69830

- •K0V, T = 5400 K, 2 - 10 Gyr old, 12 pc distant
- •Small, icy, ephemeral dust replenished by ongoing fragmentation of an ~30 km radius P/D asteroid disrupted @ 1 AU. (Like Karins/Veritas asteroids in the solar system 5-8 Mya?)
- •3 Neptune Sized Planets @ 0.08, 0.16, 0.63 AU



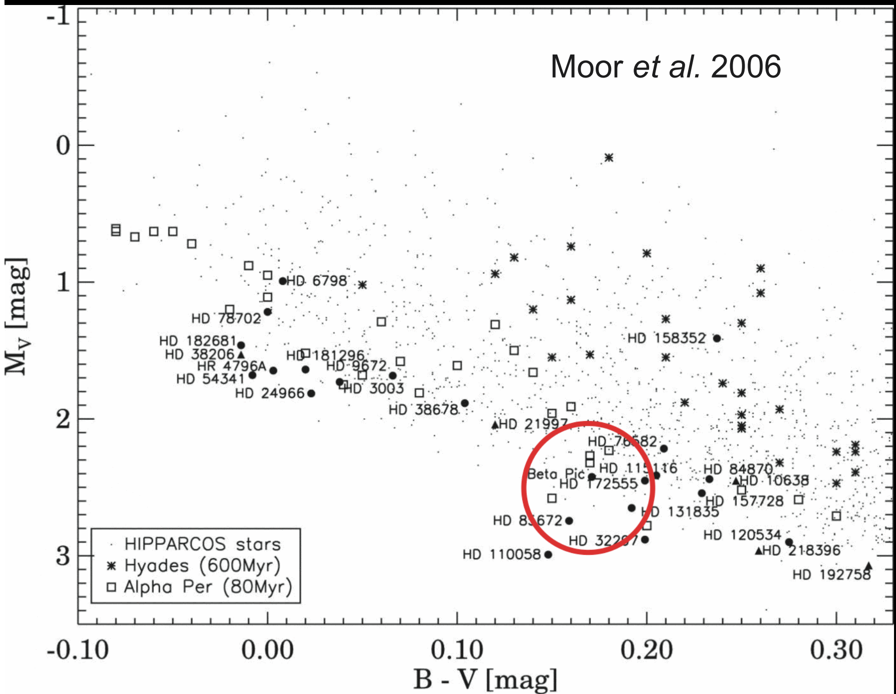


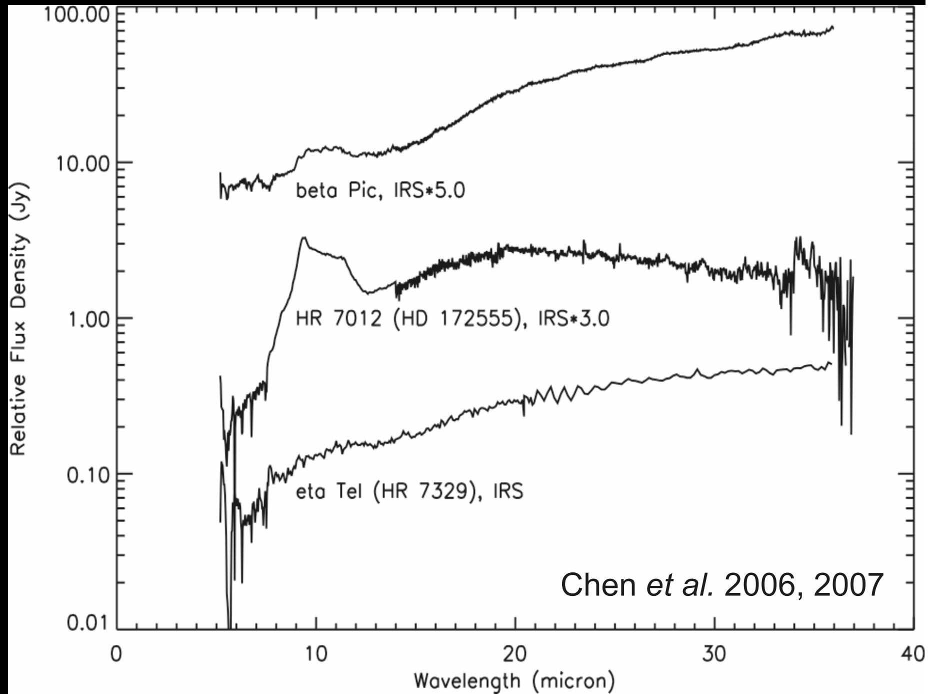
Grogan *et al.* 2001

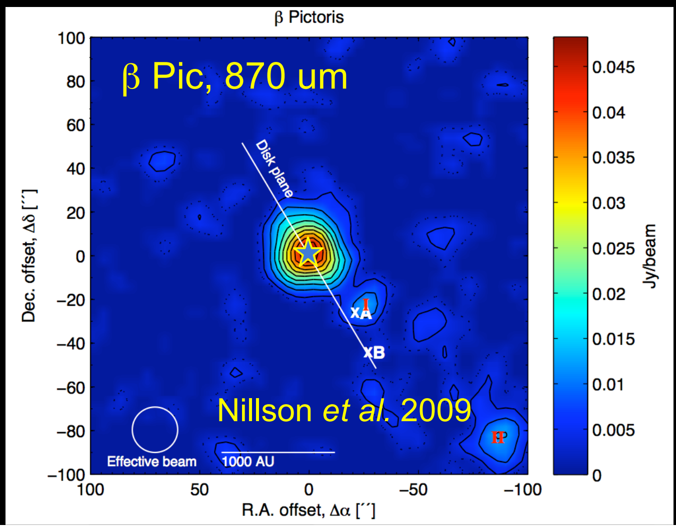


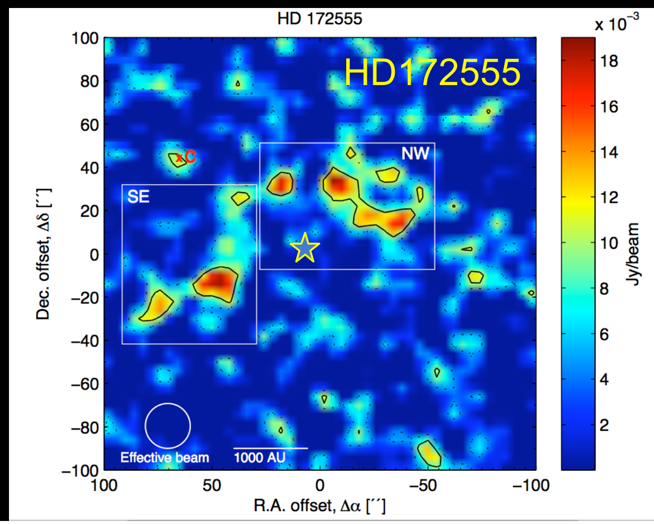
Lisse *et al.* 2007

HD172555 – a 29.2 pc distant, 10-12 Myr old A5V star in the β Pic moving group. Similar in the Optical, Wide Variance in the IR/Sub-mm from coeval β Pic (A5V) & η Tel (A2V)

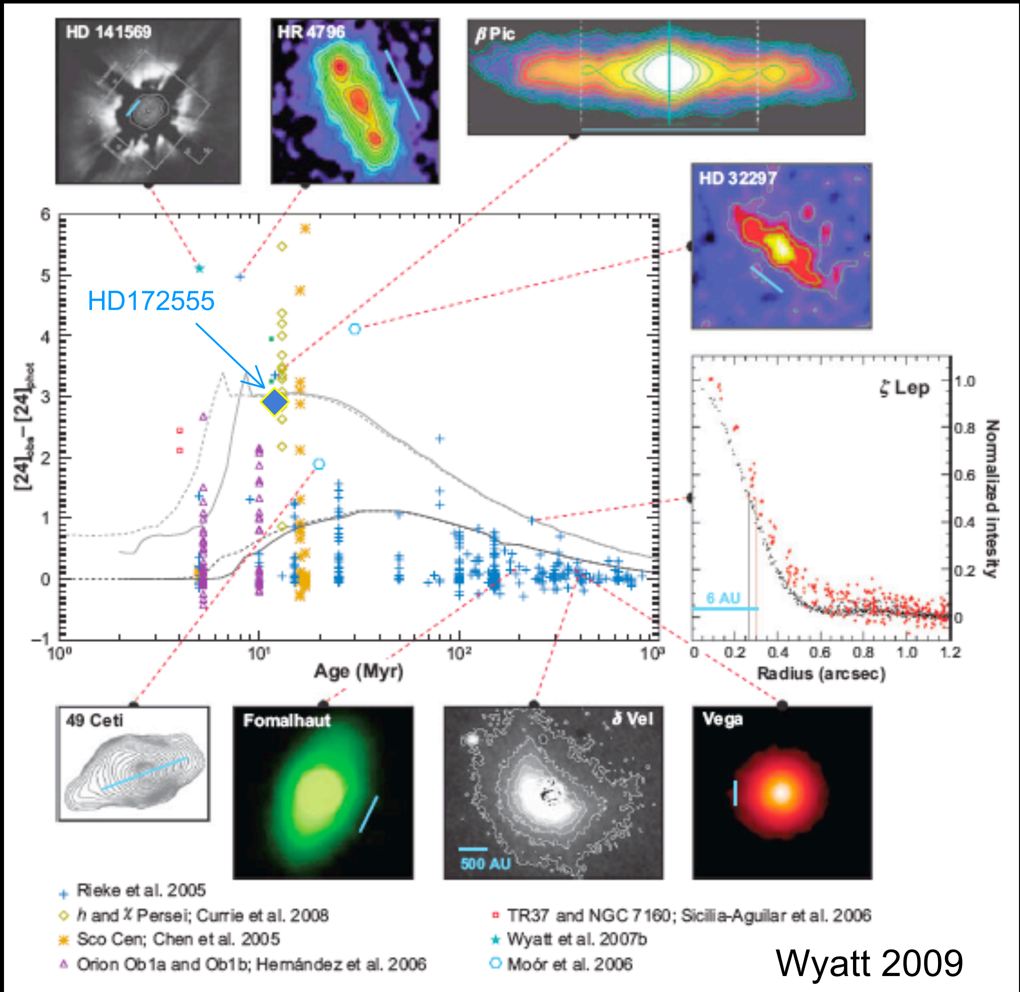


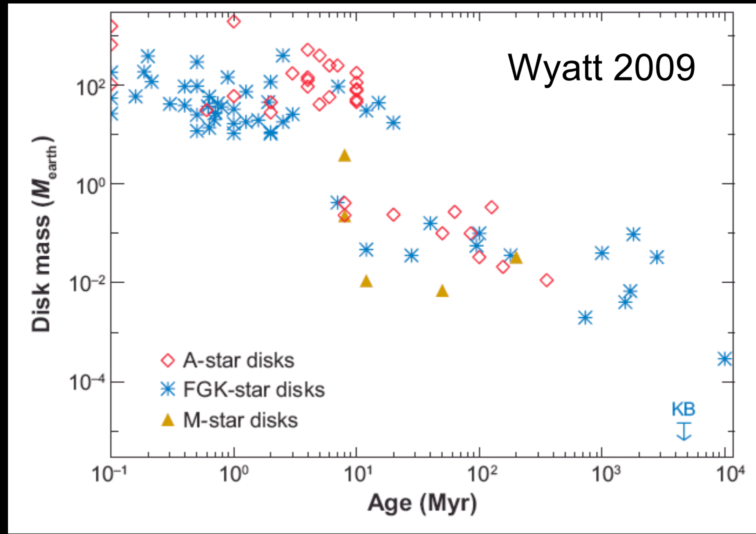


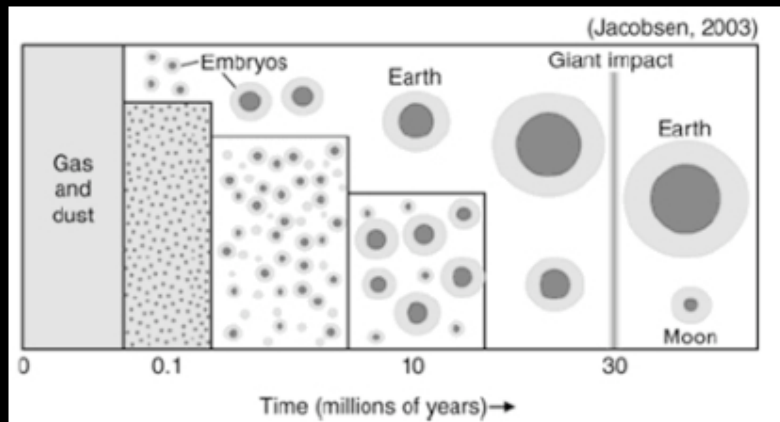




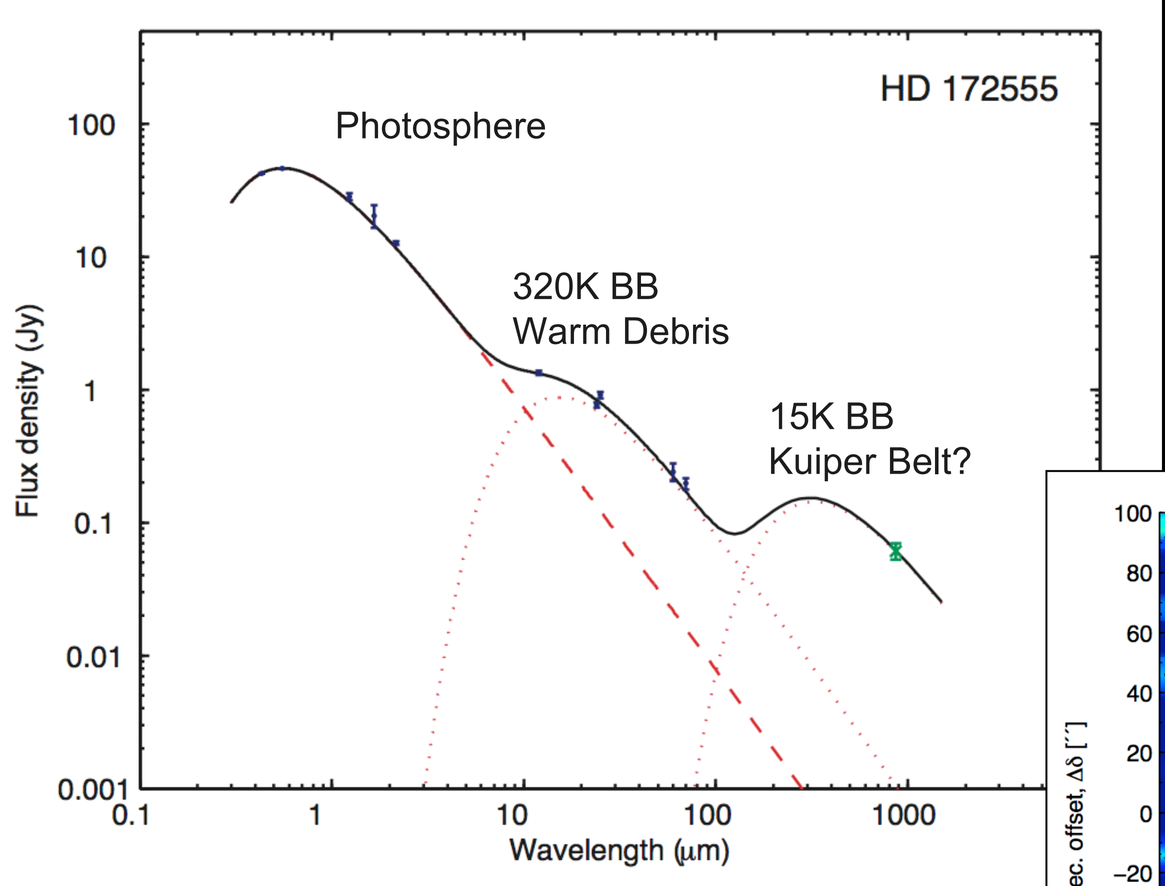
HD17255 is Very Dusty, & at 12Myr Age at an Interesting Time for an A-star Debris Disk



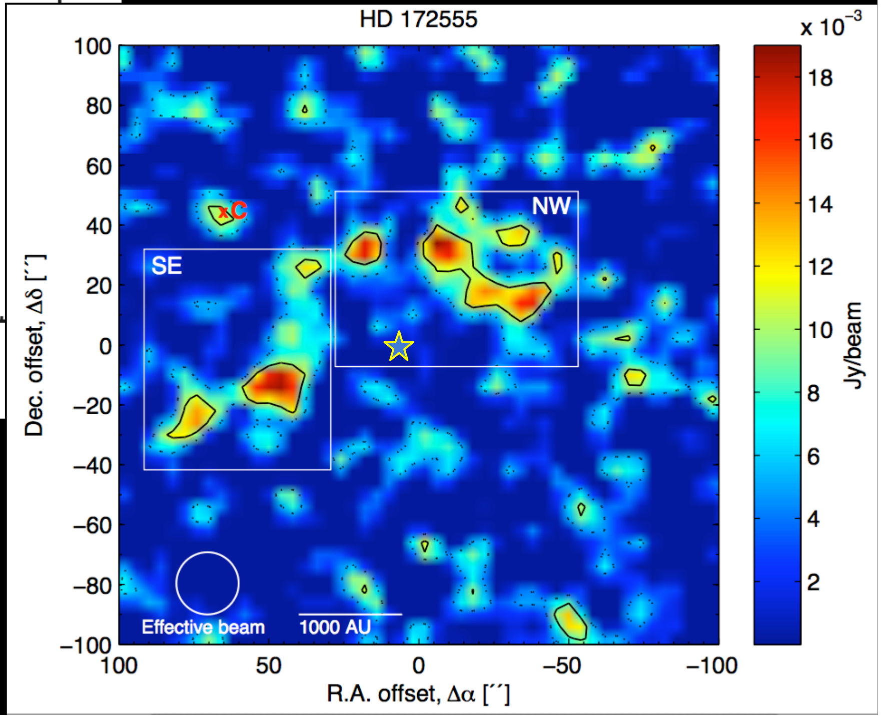




IRAS/2MASS/MichiganCat/APEX total Spectral Energy Distribution (SED) for HD172555. L_{IR}/L_{bol} is high, ~7×10^{-4}, implying significant reprocessing of star light into thermal emission from dust.

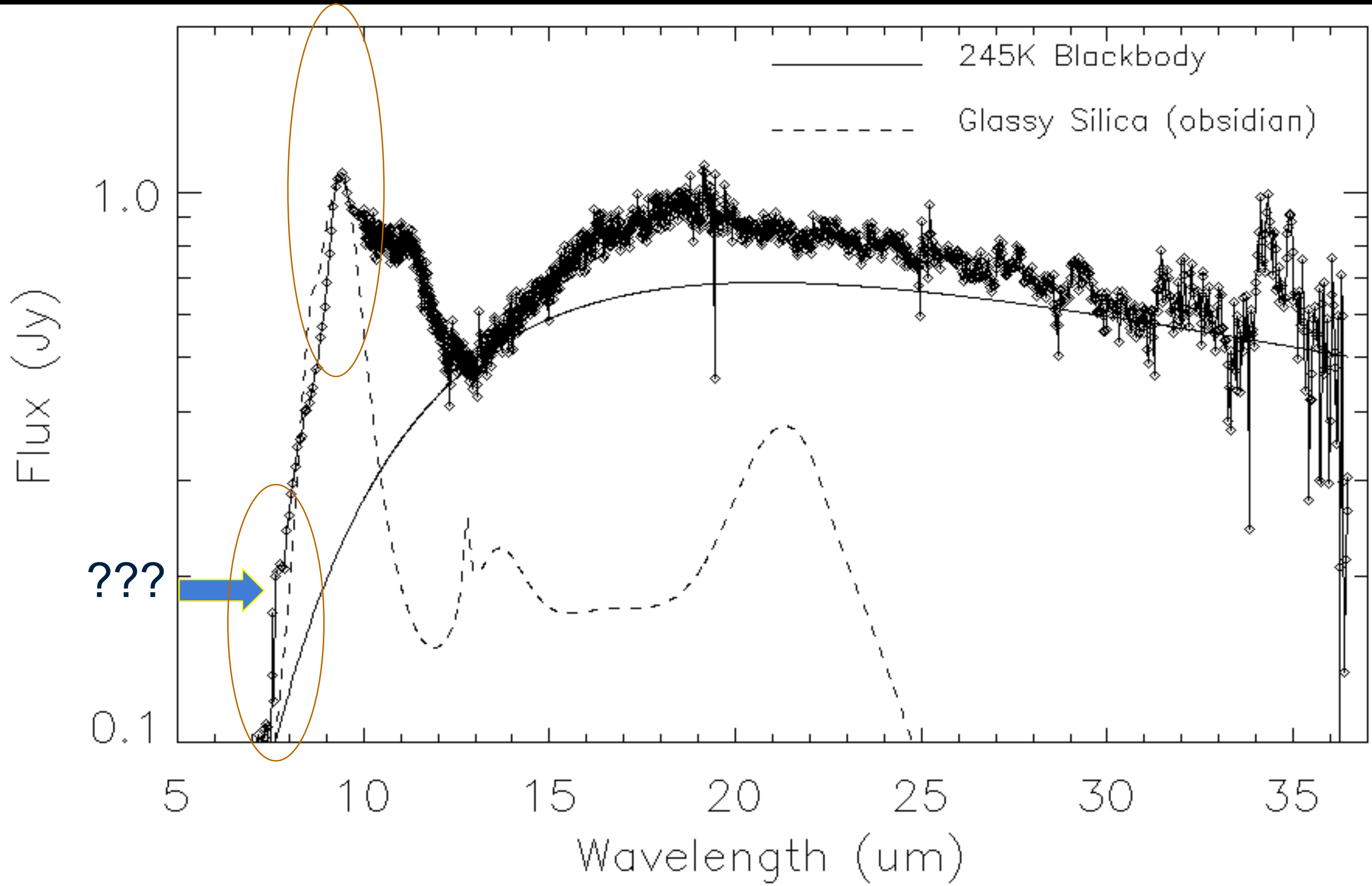


870 um imaging shows extended cold dust ring (Kuiper Belt?), no optical dust disk detected by HST (dust already highly aggregated?).

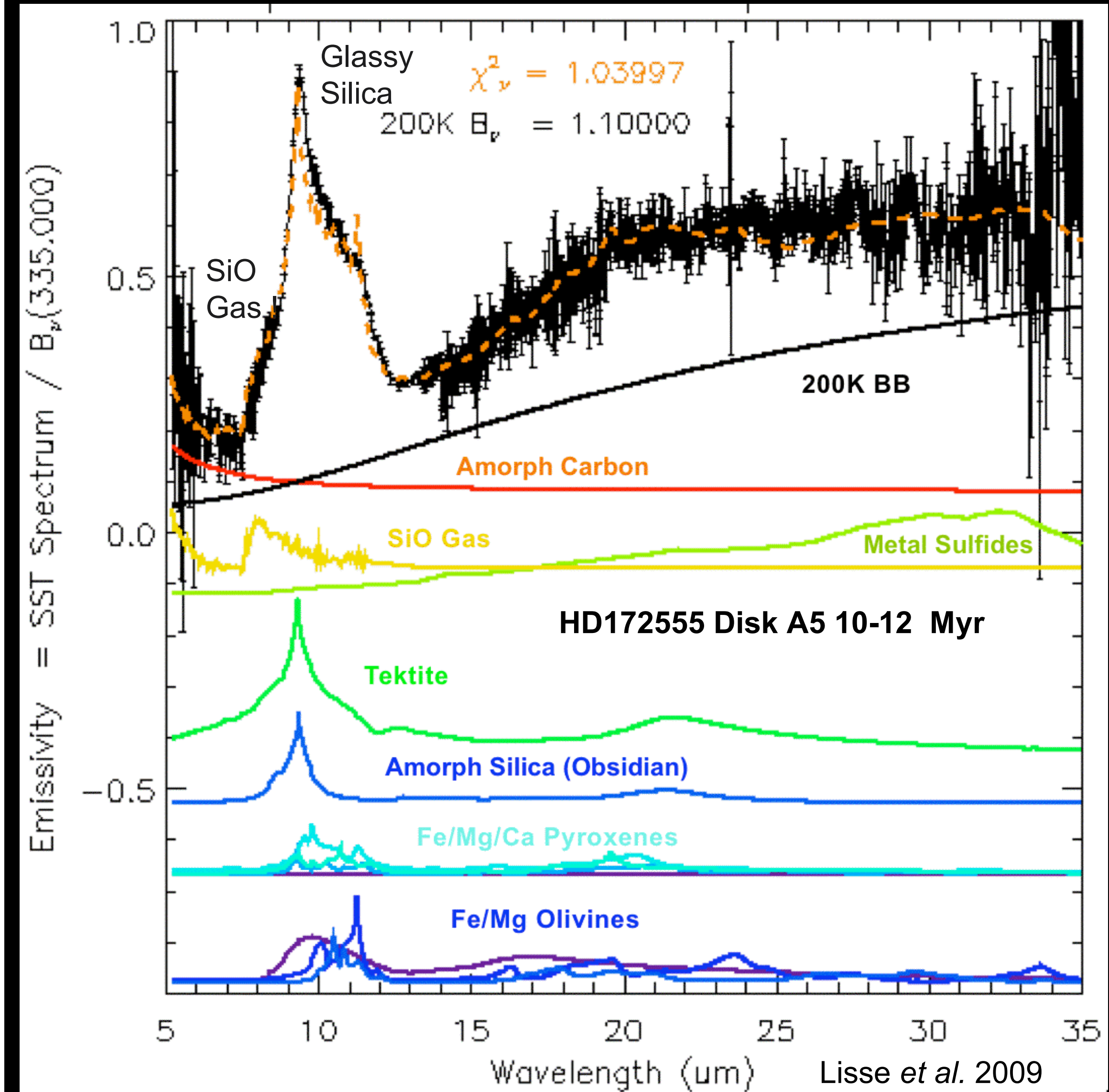


IR SED shows evidence for close in (~ 6 AU) warm dust excess and distant cold dust excess.

HD172555 *Spitzer* circumstellar dust excess, showing pronounced 9 μm feature matching Amorphous Silica but not Silicate (olivine, pyroxene) nor Crystalline Silica (quartz/cristobalite) emission.



Using thermal emission modeling, we find the circumstellar dust rich in ***silica and SiO gas***. Abundant Tektite & Obsidian amorphous silica are required to fit the data. There are almost no pyroxenes present, suggesting these have been destroyed to make silica. No good parent body match. M_{total} similar to 5×10^{-3} M_{Earth} predicted for lunar formation event (Canup 2004).



Tektite and Obsidian Dust : products of quick quenching of molten rock at high T, low P.

SiO gas : produced by vaporizing rock. Requires v_{impact} >10 km/s. SiO Gas/Dust = 1 – 10.

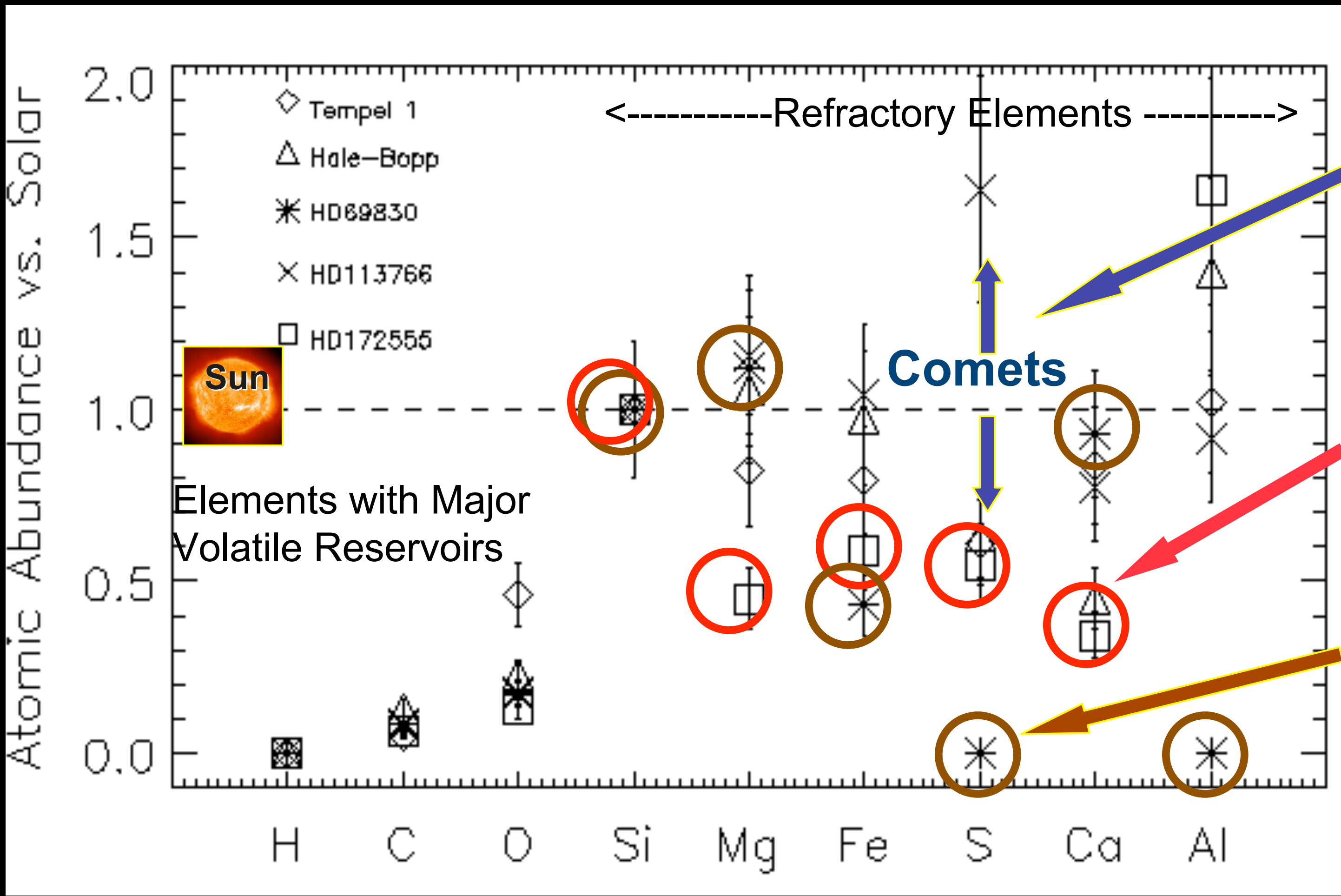
Large Dust : there is also a large quantity of dust at LTE at 6 AU.

Mass : 150 - 200 km radius asteroid's worth (4×10^{19} – 2×10^{20} kg) of fine silica rich material; ~500 km radius worth (10^{21} –10^{22} kg) of large rubble; and ~10^{22} kg of SiO gas at ~5.6 AU. 10^{-3} to 10^{-2} M_{Earth} total.

Mineralogy: Parent object does not seem like any known taxonomy, asteroid or comet. No cometary water carbonates, phyllosilicates or amorphous carbon is present. ***If one has to be selected, the parent is closest to an A-type igneous asteroid*** : there is copious metal sulfide and olivine-type rock. **However, it is not easy to show where the sizeable silica content originates - A-types not known for this.**

Atomic Abundances from the Compositional Model

Comets, and Earth-Building Systems are Near-Solar in Dominant Refractory Elements, but HD69830 asteroidal silicates and HD172555 impact/chondrule silicas are not.



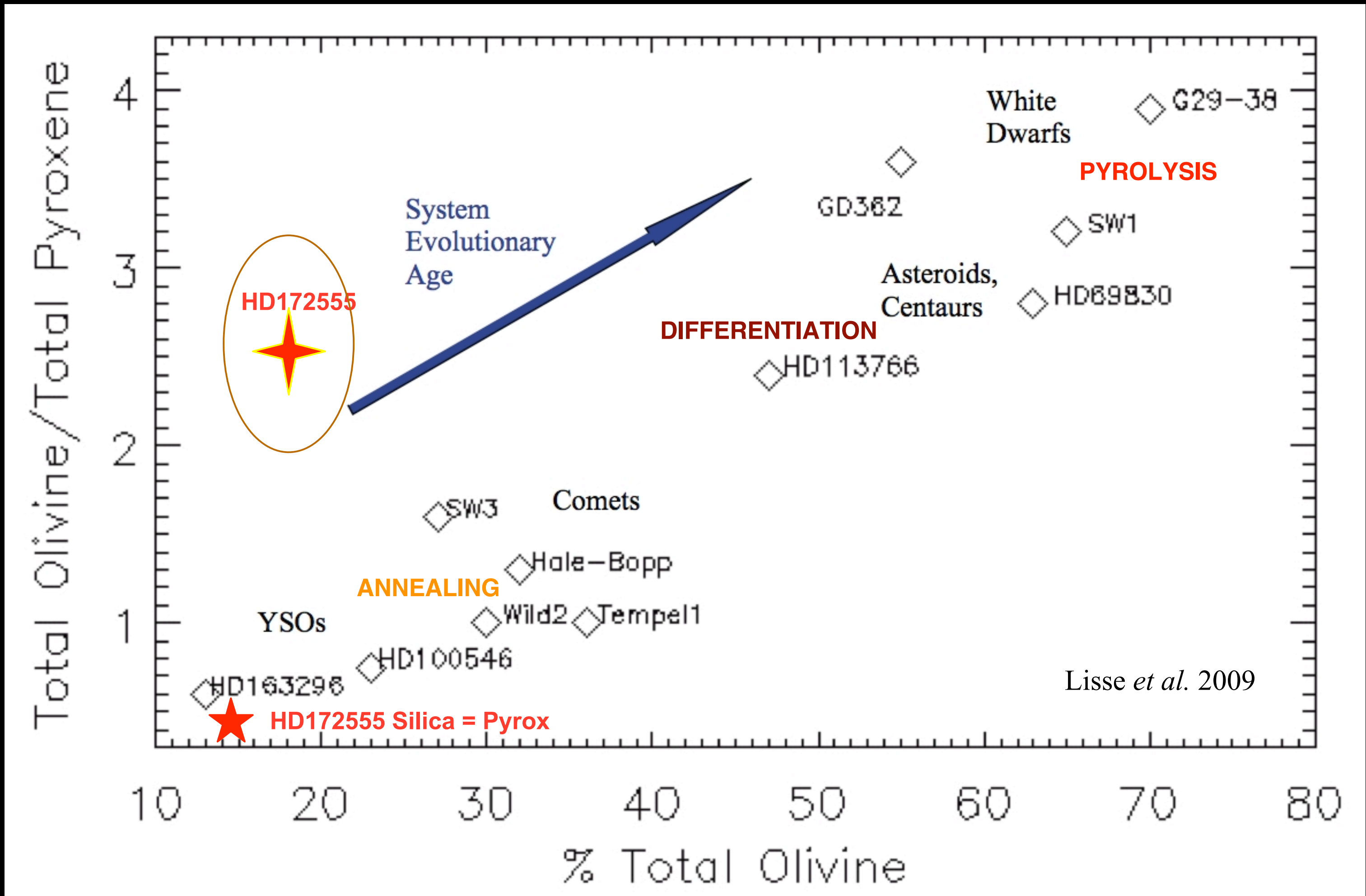
Abundances : Comets are Near-Solar in Dominant Refractory Elements, as is the HD113766 Earth-Building System.

HD172555 Material is strongly depleted in all species except Si and O. Melt and vapor differentiation/ purification?

Main sequence, mature HD69830 P/D type Asteroid Rubble is Not. The composition shows similarity to highly differentiated bodies.

System Silicate Trends from the Compositional Mo

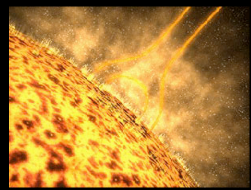
Pyroxenes, are preferentially destroyed as ISM dust becomes more and more crystallized in primordial disks, as olivine grows in differentiated mantles during planet formation, and as WDs further roast the remnant bodies in their systems. But HD172555's dust lies far from the normal trend line.

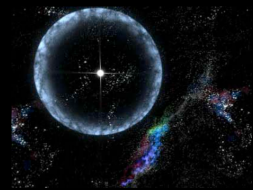


Source of the HD172555 Silica + SiO Gas

◆Primordial Material

T Tauri, Herbig Ae/Be systems show good evidence for silica material in their spectra (Sargent et al. 2006, Bouwman et al. 2008).
=>BUT system old, cleared & w/o any gas (Chen *et al*. 2006)





◆Chondrule Formation Due to Giant Stellar Flare or Nebular Shock

UV/Xray photon heating and stellar wind energy deposition dominate optical/IR photon insolation and gas/dust collisions in YSOs. ~10 Myr old stars can have ~10^3 times more UV/Xray flux and stellar wind density. A flare/CME/ejection event could melt and vaporize large quantities of *distributed* material. Nebular shocks play a similar role (Harker & Desch 2002). => BUT: Cleared system, A-star $L_x / L_{bol} < 10^{-5}$

=> Hypervelocity Impact(s)!!!

Large collisions are expected during the 10 - 100 My era of terrestrial planet building, and there is abundant circumstantial evidence for impacts with specific energy (**V** > 10 km/s) to create silica/SiO gas in the Solar System : Mecury's high density; Venus' retrograde spin (could also be due to atmospheric interactions); Earth's Moon; Vesta's igneous composition; Mars' North/South hemispheric cratering anisotropy; Uranus' spin axis in plane of ecliptic. 10^2 yr < SiO gas lasts < 10^5 yrs

Hypervelocity Impact Scenario :

At least one body in a 2-body collision is disrupted at a relative velocity large enough to transform the normal silicate material into silica, similar to the processes that created shocked quartz & tektites around impact craters on Earth. Efficient melting/vaporization requires Δv > 10 km/sec. For HD172555, $V_{keplerian}$ @ 5.6 AU ~ v_{MBA} = 19 km/s, need high-inclination collision in excited (|i| < 45°) oligarch system (Kenyon & Bromley 2006).

Svetsov 2005

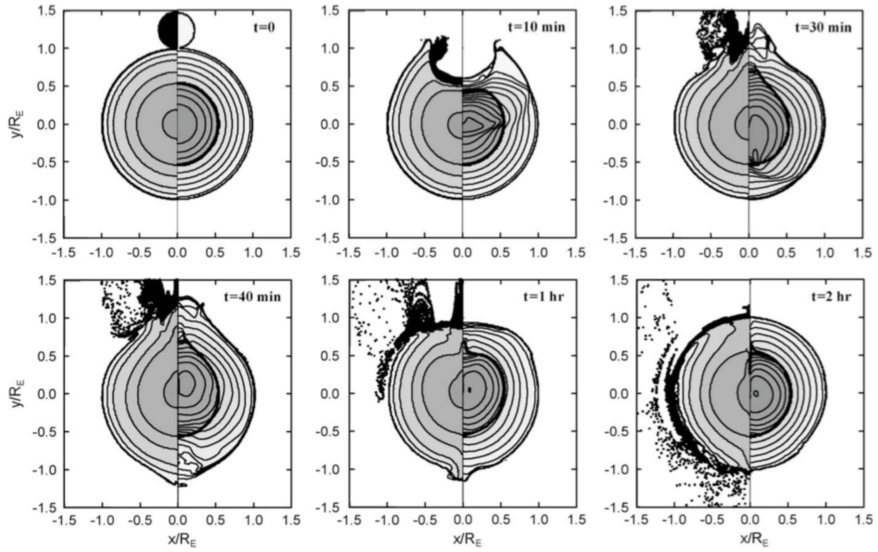
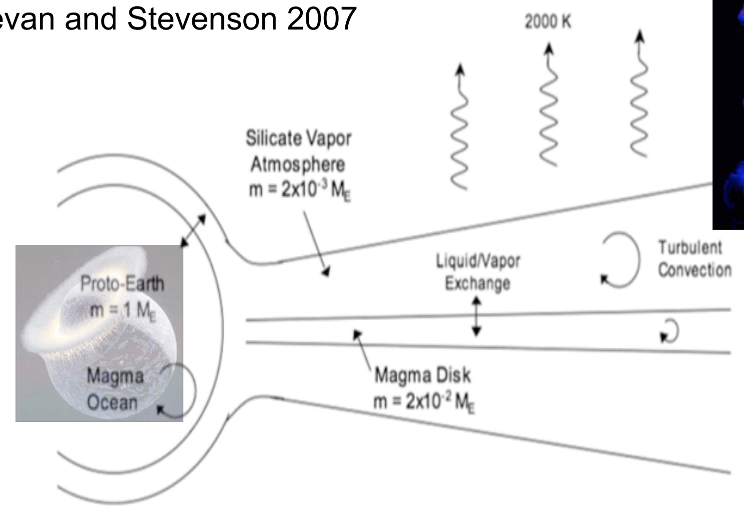


Fig. 1. The impact of a 3000-km-diameter asteroid at 15 km/s. The right sides of the plates show contours of constant densities which are plotted with an interval 0.5 g/cm³, the minimum density level is 2 g/cm³ at the surface. Nine contours coincide and look like one at the mantle/core boundary where the density jumps from 5.9 to 10.3 g/cm³. The left sides of the plates show the motion of the Earth and asteroid material. The lines are boundaries between initially spherical layers inside the Earth. The asteroid particles are shown by black spots. R_E is the Earth's radius.

Possible Sceanrio : Hot Torus of Liquid/Gaseous Rock Formed During a 'Lunar Formation Event'

Pahlevan and Stevenson 2007



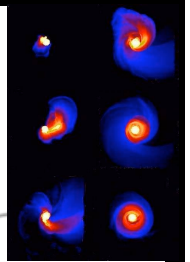
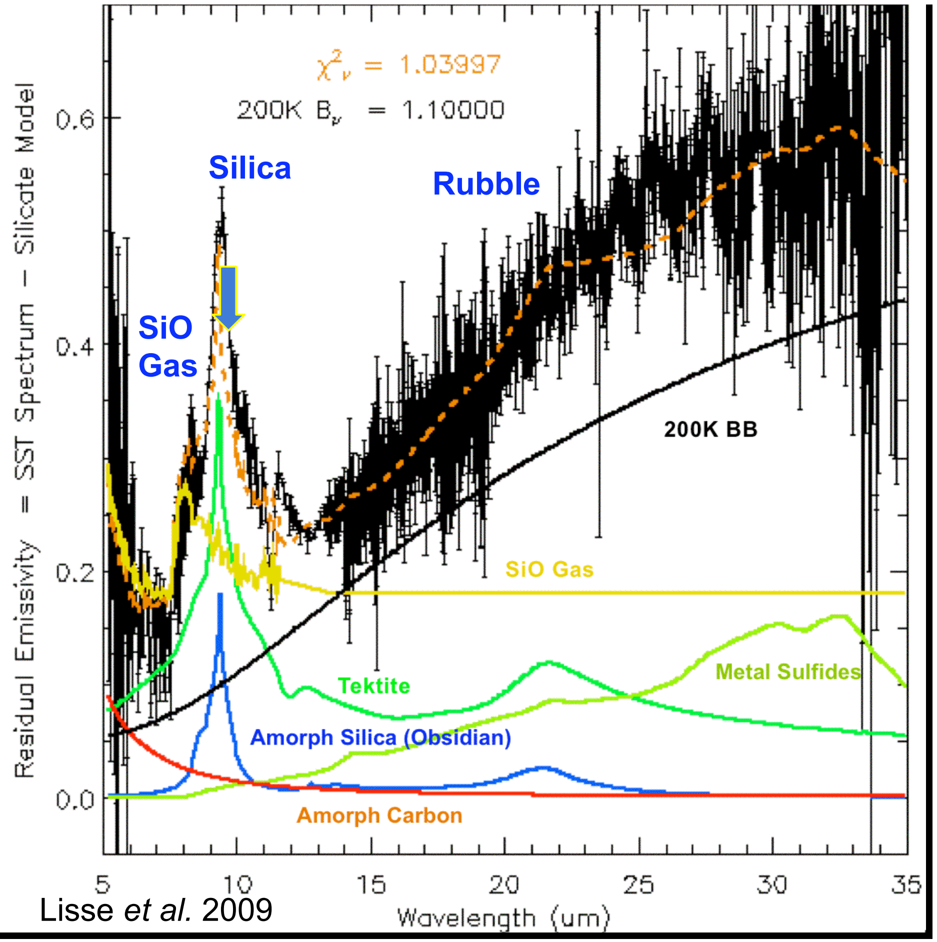


Fig. 3. Schematic of Earth and proto-lunar disk immediately after the giant impact. High radiative heat loss guarantees convection in the silicate Earth, disk and atmosphere. Liquid/vapor exchange with a common silicate vapor atmosphere makes it possible for the two massive liquid reservoirs to equilibrate. Convection within the Earth allows the entire terrestrial silicate reservoir to be tapped.

Glassy Silica, SiO gas required to fit HD172555 Disk Spectra



Lisse *et al.* 2009

Consider, if you will : An unsuspecting Proto-Planet, in a β Pic moving group system 29 pc away quietly going on about its daily business orbiting 5.6 AU from a 12 Myr old A5 star when….

HD172555 Impact Movie (made by the Spitzer Science Center in LA, where else?)

Accretional Energy

(Fegley and Schaefer 2005)

- Some theories suggest that a magma ocean formed as Earth accreted
  - Suggested magma ocean temperatures are > 2000 K
- Energy released by accretion of an Earth-like planet (1 $M_\oplus \sim 6 \times 10^{24}$ kg & 1 $R_\oplus \sim 6370$ km) is:

$$\frac{GM_\oplus^{\ 2}}{R_\oplus} = \frac{(6.67\times10^{-11} m^3 kg^{-1} s^{-2})(6\times10^{24} kg)^2}{(6370\times10^3 m)} \sim 4\times10^{32}\,Joules$$

- Energy to heat up and vaporize bulk silicate Earth (BSE) is:

$$E_{vap} = \frac{M_{BSE}}{\bar{\mu}} \times \Delta_{vap}H = \frac{(4\times10^{27} g)}{(140\ g\ mol^{-1})} \times 1180\ kJ\ mol^{-1} \sim 3\times10^{31}\,Joules$$

Liquidus temperatures for possible magma ocean

Magma type	T_{liq} (K)[1]	$T_{b.p.}$ (K)[2]
Tholeiite	1433	3270
Komatiite	1838	3341
Dunite	1954	3294
Forsterite	2163	3540
Bulk silicate Earth	1892	3361
Bulk silicate Mars	1844	3269

[1] computed using Magfox code

[2] computed using MAGMA code

$$\frac{E_{accretion}}{E_{vap}} = \frac{GM_\oplus^2}{R_\oplus E_{vap}} = \frac{4\times10^{32}\,Joules}{3\times10^{31}\,Joules} \sim 10$$

→ Accretion of an Earth-like planet easily vaporizes the silicate portion!

Impact Energy

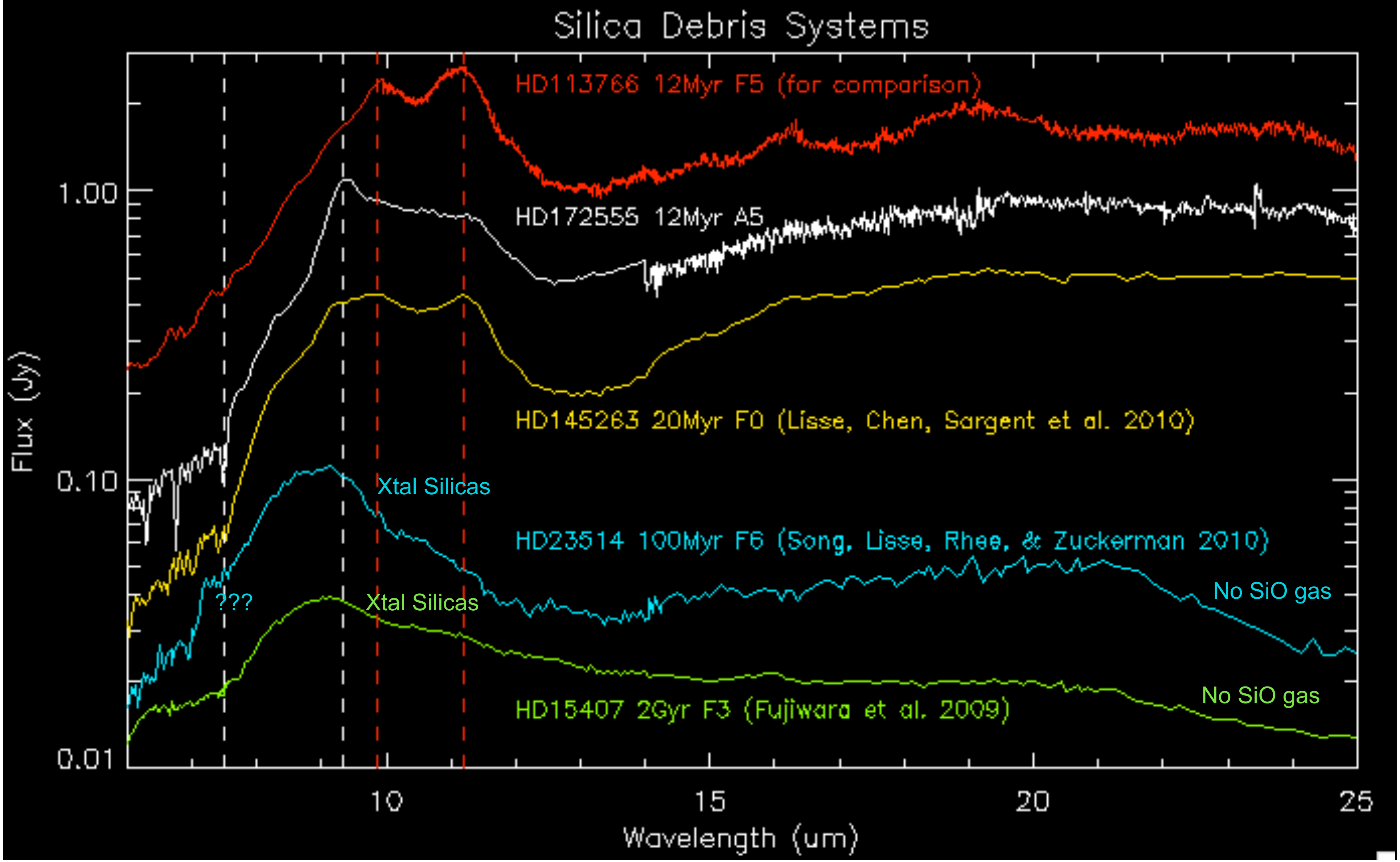
(Fegley and Schaefer 2005)

ΔE (J)	Size of impactor	Thermal effects
7×10^{27}	1.4×10^{20} kg (~mass of asteroid 2 Pallas)	Boil oceans and heat to 2000 K
5×10^{28}	1×10^{21} kg (~mass of asteroid 1 Ceres)	Melt crust and heat to 2000 K
2×10^{29}	4×10^{21} kg (~5% mass of Earth's moon)	Vaporize crust and heat to 3200 K
3×10^{31}	6.8×10^{23} kg (~mass of Mars)	Vaporize silicate Earth and heat to 3540 K

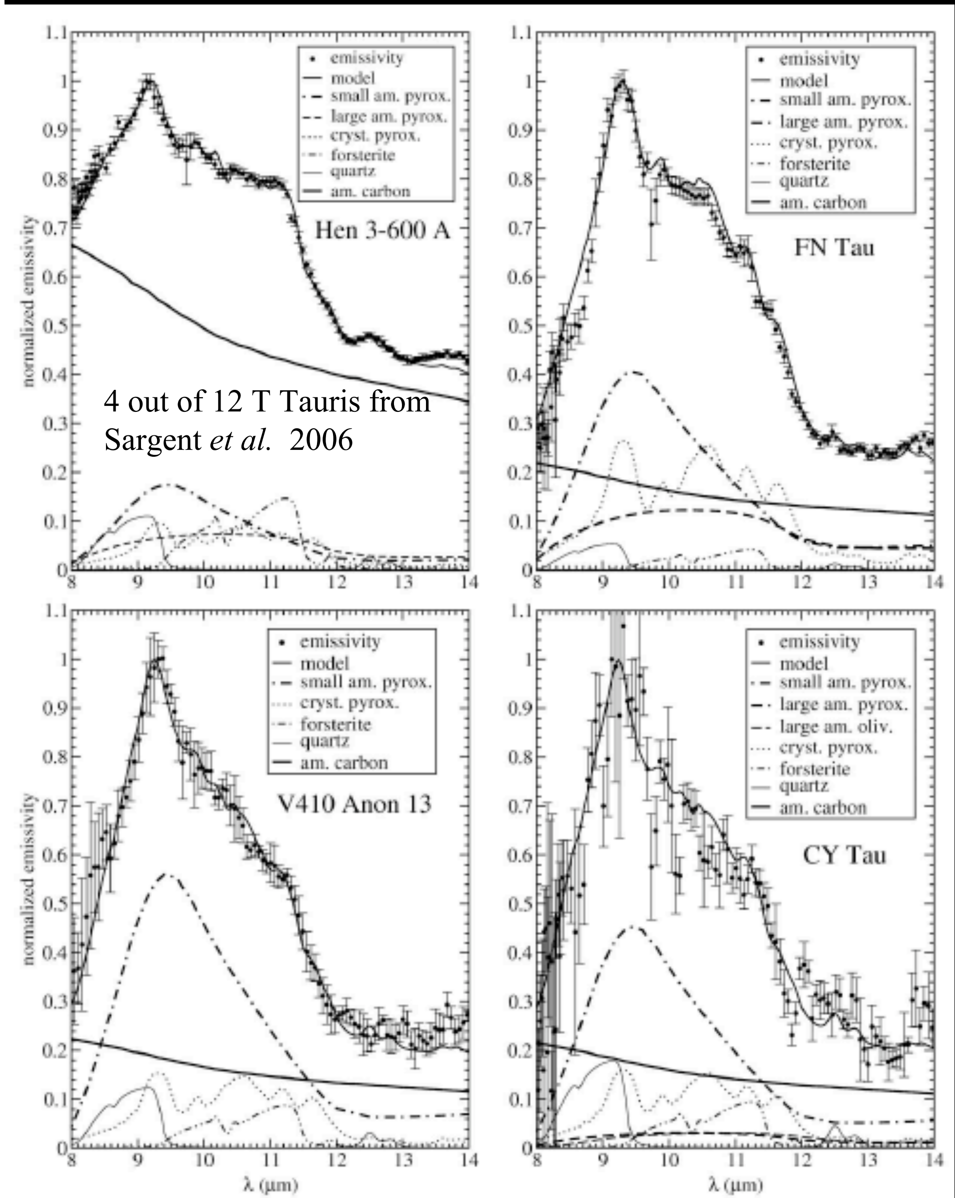
- Giant impact models give temperatures of 4000 – 5000 K
  - Some accretion models now suggest that impacts between large bodies may be ubiquitous
- Kinetic energy ($\frac{1}{2}mv^2$) converts into thermal energy after an impact
  - Thermal energy is used to sequentially heat up solids, melt solids, heat liquids, vaporize liquids, and then heat the gas
- Assuming an impact velocity of 10 km s^{-1}, the energy of impact is:
  - ΔE_{impact} (J) = $5\times10^7 M$, where M = mass of impactor (in kg)
  - Table illustrates the effects of various sized impactors
  - Cooling times for these impacts range from on the order of 10 years for the smallest impact to 10^3 – 10^4 years for the Mars-sized impact

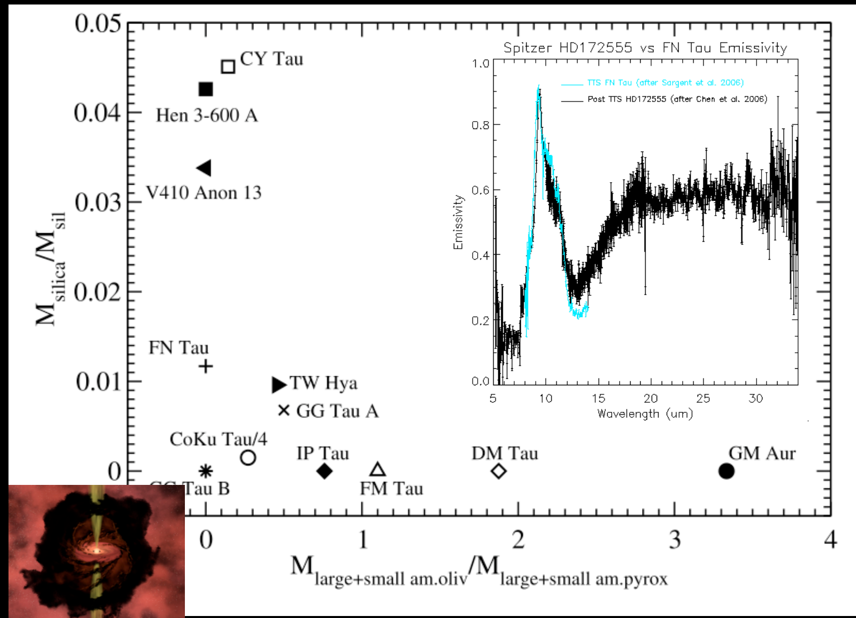
More to come for a new class of silica rich objects?

Spitzer excess spectra of the ~20 Myr HD145263 (aka “the Lobclaw”, Chen *et al.* 2007)
the ~100 Myr HD23514 (aka the Pleiades dust star, Song *et al.* 2009)
& the mature 2Gyr old Akari star HD15407 (Fujiwara *et al.* 2009)



Is the HD172555 silica primordial? I.e. is HD172555 a mis-identified TTS? Sargent *et al.* found ~1/3 of T Tauris have silica, and the FN Tau 8-13 μm spectrum looks *very* similar to the *Spitzer* HD172555 spectrum in the same region.

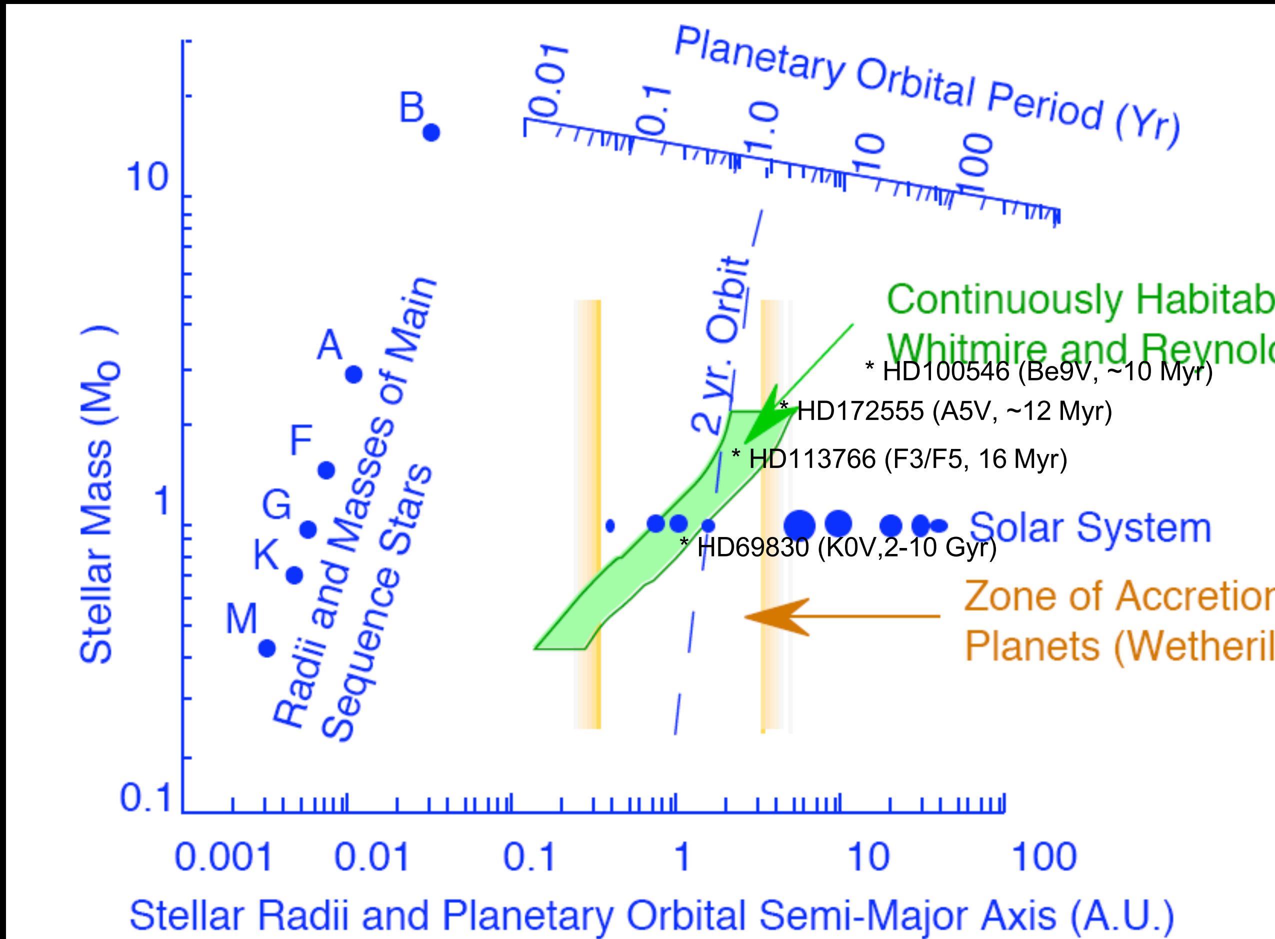




- HD172555 is too old (β Pic Moving Group)
- L_x/L_{bol} is too low (2×10^{-6})
- No mid-IR gas lines at 5-8 μm and 15 μm

=> HD172555 is Not a T Tauri Star! But what then do TTSs and a 12 Myr A5 star have in common? E.g., do T Tauris create Silica from ISM material by massive in-disk collisions, as expected in planet building systems?

HD172555 Circumstellar Excess Location with respect to the System's Terrestrial Accretion & Habitability Zones



Circumstellar material is at outer edge of the terrestrial planet forming & habitable zones.
Parent star, A5/7, $2M_{solar}$, $9.5L_{solar}$, is too early a type to allow life to develop for long. :)

Conclusions & Speculations

- The circumstellar material detected by Spitzer around HD172555 is dominated by amorphous silica, SiO gas, and large dark pieces of dust.
- The HD17255 excess masses about 10^{-3} to 10^{-2} M_{earth} (Pluto to Moon mass).
- At ~12 Myr, the excess is occurring when terrestrial planets are built, => ***at least*** 2 rocky bodies ≥ Pluto-Moon size. Method of planet detection?
- Lunar formation event easily detectable by Spitzer (Meyer 2009). Hot magma ocean (1000 – 2000 K) remnant – can observe? 6 AU from an A5 star….
- 10^2 < Time scale for SiO removal < 10^5 yr, expect < $10^5/10^7 = 10^{-2}$ probability of detection, know of ~$4/10^3$ systems.
- 3 other similar SiO dominated mature systems? SiO gas only found in other very young system. HD172555 SiO gas/Dust = 1-10 => recent impact. Gas recondenses to form crystalline silicas?
- HD17255b is not a very good place to live, even after it cools off.

Fin.