PROTOPLANETARY DISKS

AND THE IRS ‘LO-RES’ LEGACY

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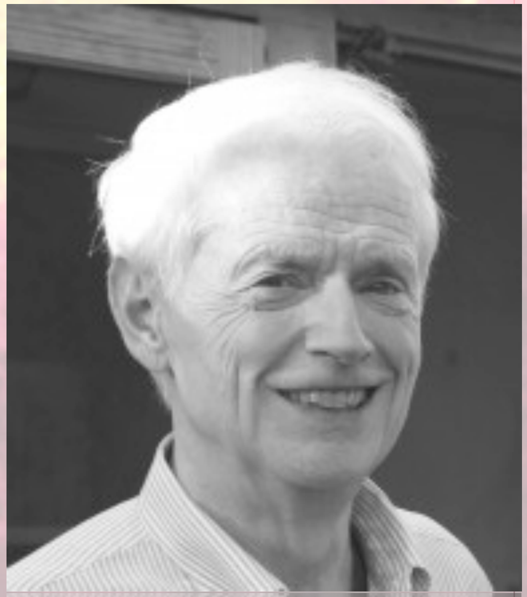
Science Enabled by Novel Infrared Instrumentation, 26 June 2017, Cornell University

Credit: NASA/FUSE/Lynette Cook

SPITZER SPACE TELESCOPE
INFRARED SPECTROGRAPH (IRS)

- Last NASA “Great Observatory”
- Cryo mission 2003-2009
- IRS (PI Houck)
  - 5-40μm, low-res (SL, LL)
  - 9-35μm, hi-res (SH, LH)
- Protoplanetary disks:
  - GTO: IRS_Disks (PID 2)
  - Legacy program: c2d
  - many GO programs…

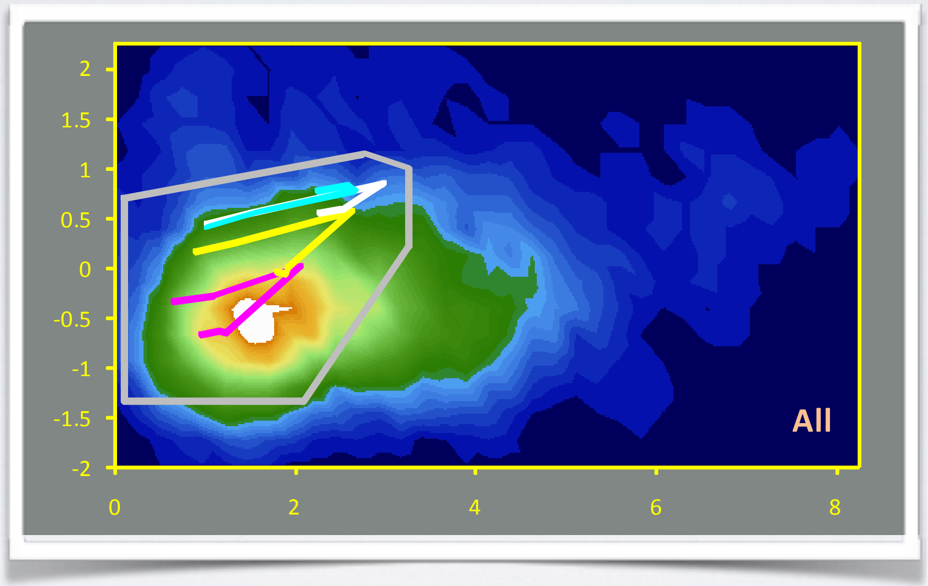


IRS_Disks team leaders, 2003?

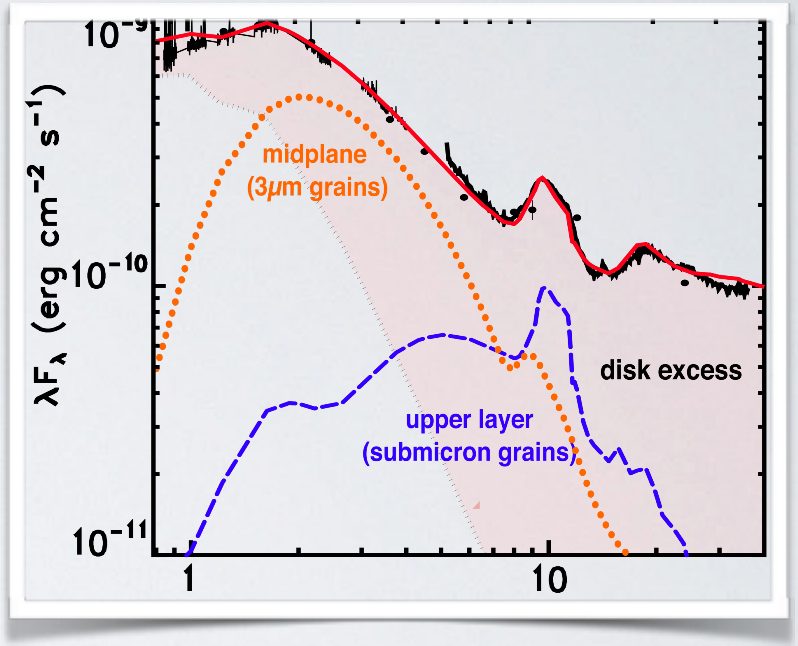
OUTLINE

Theory/motivation

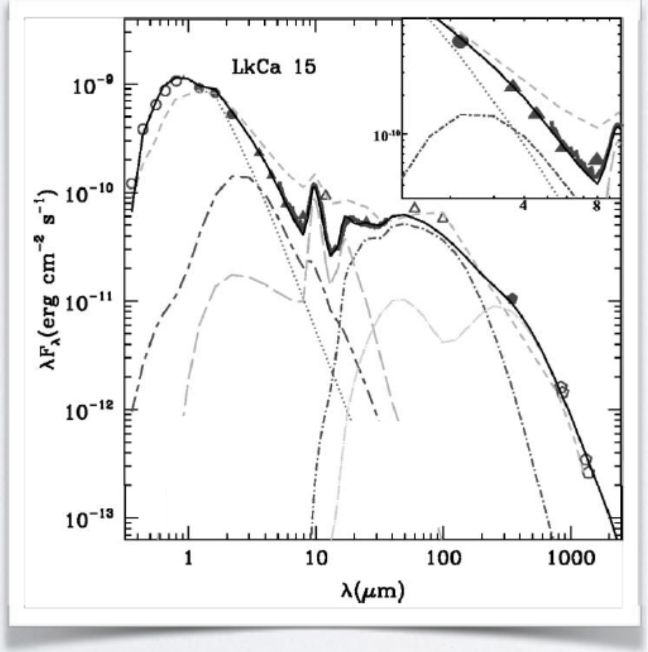
Dust settling



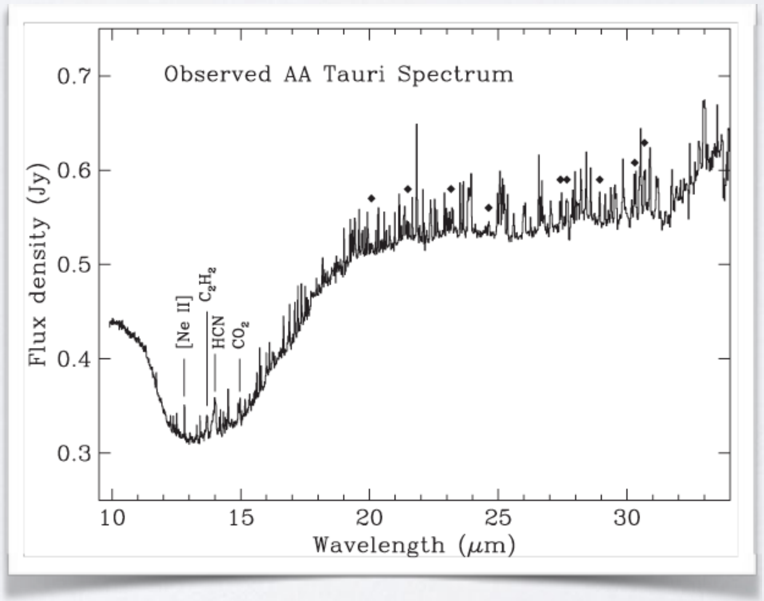
Grain growth



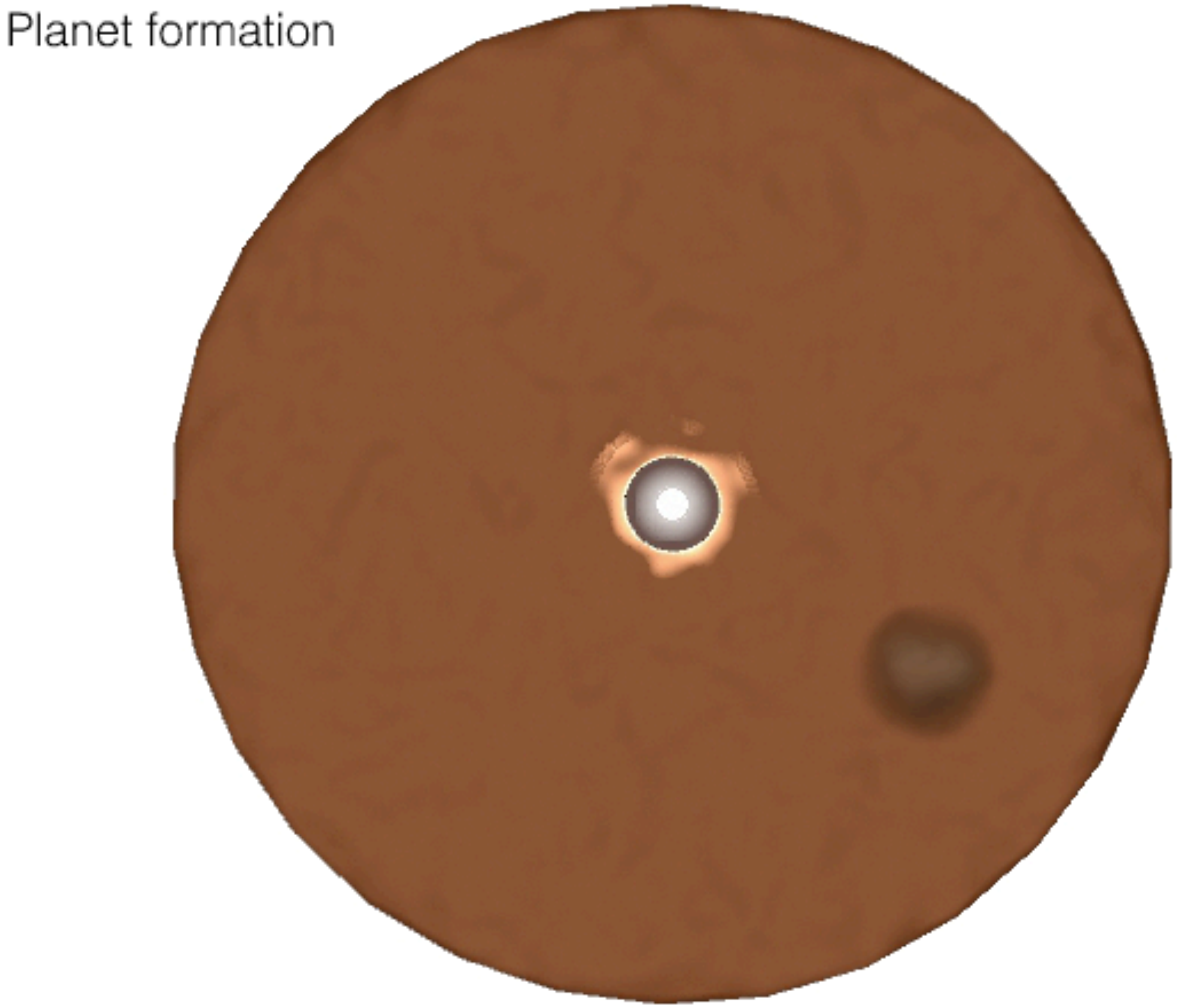
Planet formation



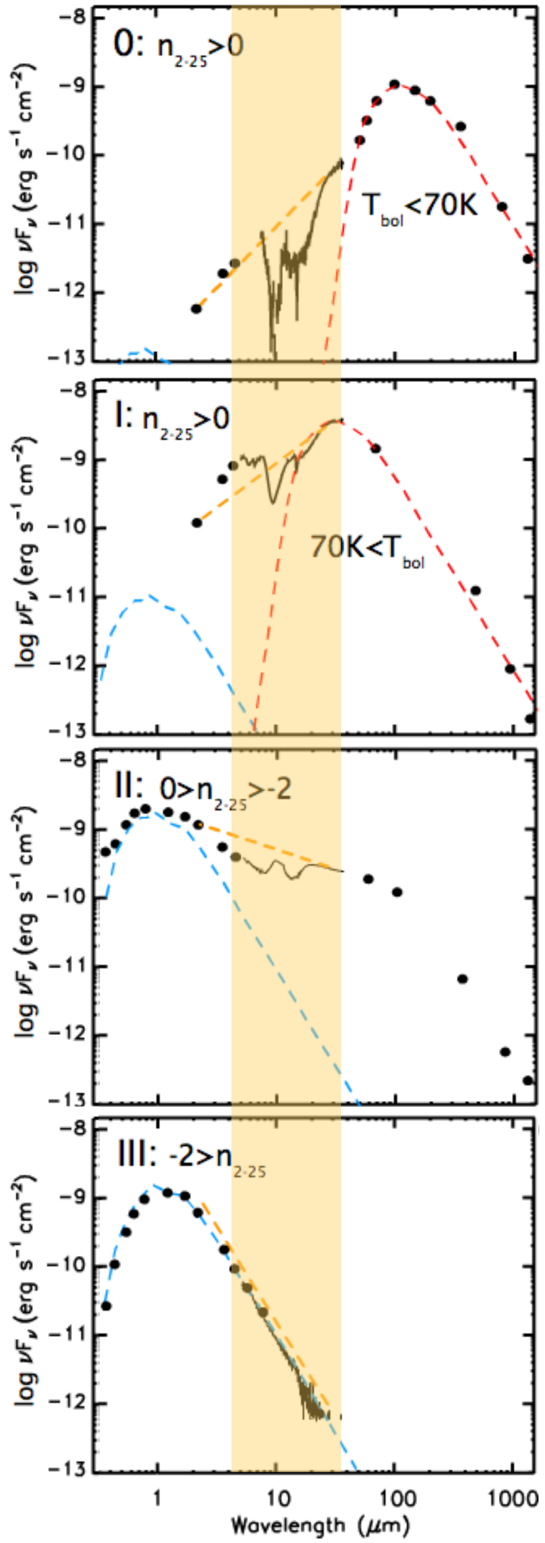
Organics



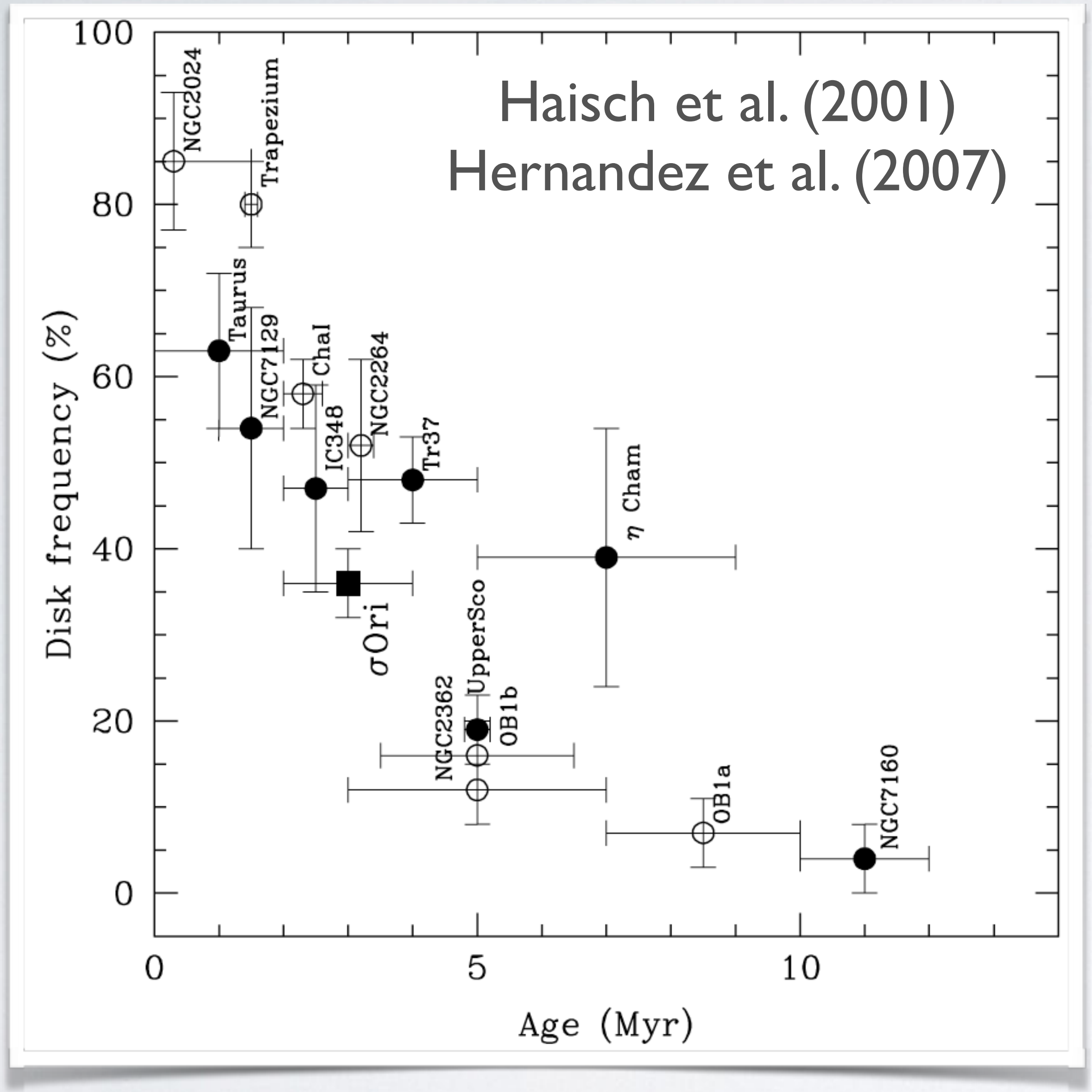
STAR FORMATION OVERVIEW



Credit: M. K. McClure



DISK EVOLUTION



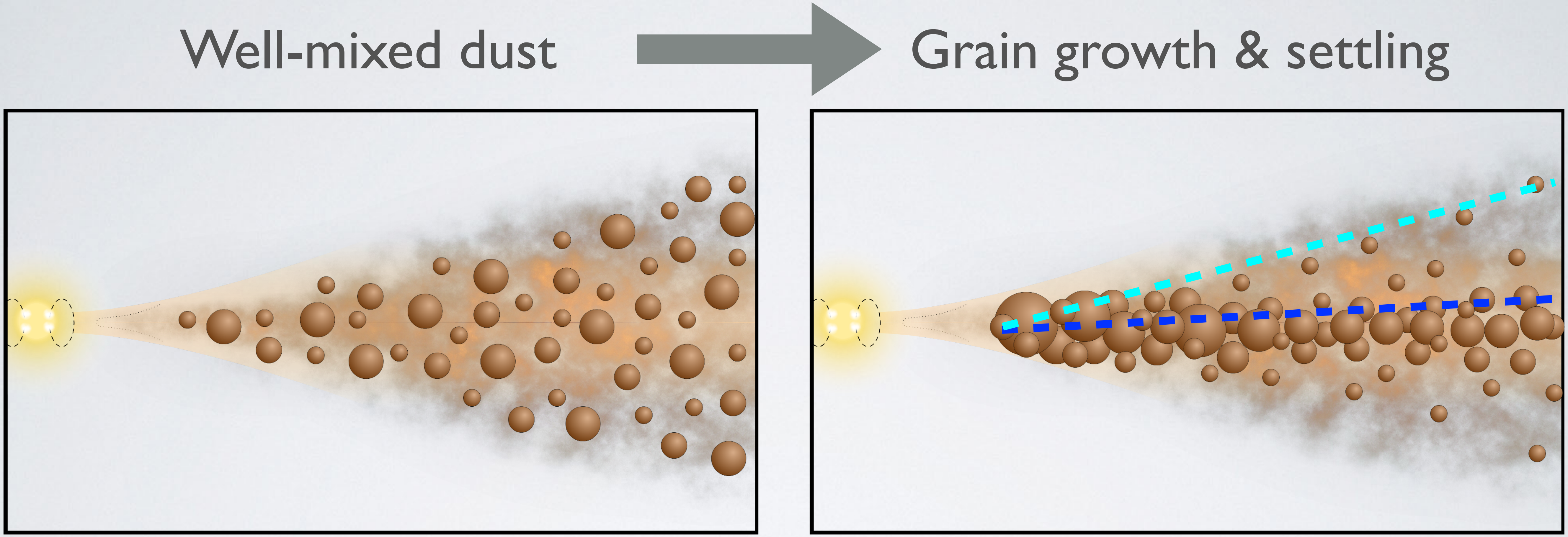
Haisch et al. (2001)
Hernandez et al. (2007)

- primordial (protoplanetary) disk stage lasts up to 10 Myr
- dominated by viscous evolution, but other physical processes affecting disks during their lifetime include:
  - dust settling
  - grain growth
  - planet(esimal) formation
  - appearance of building blocks of life

Spitzer IRS provided first evidence for what these processes look like in real life (vs theory).

DUST GROWTH & SETTLING

Dust spatial distribution and grain size evolves over time.



Well-mixed dust

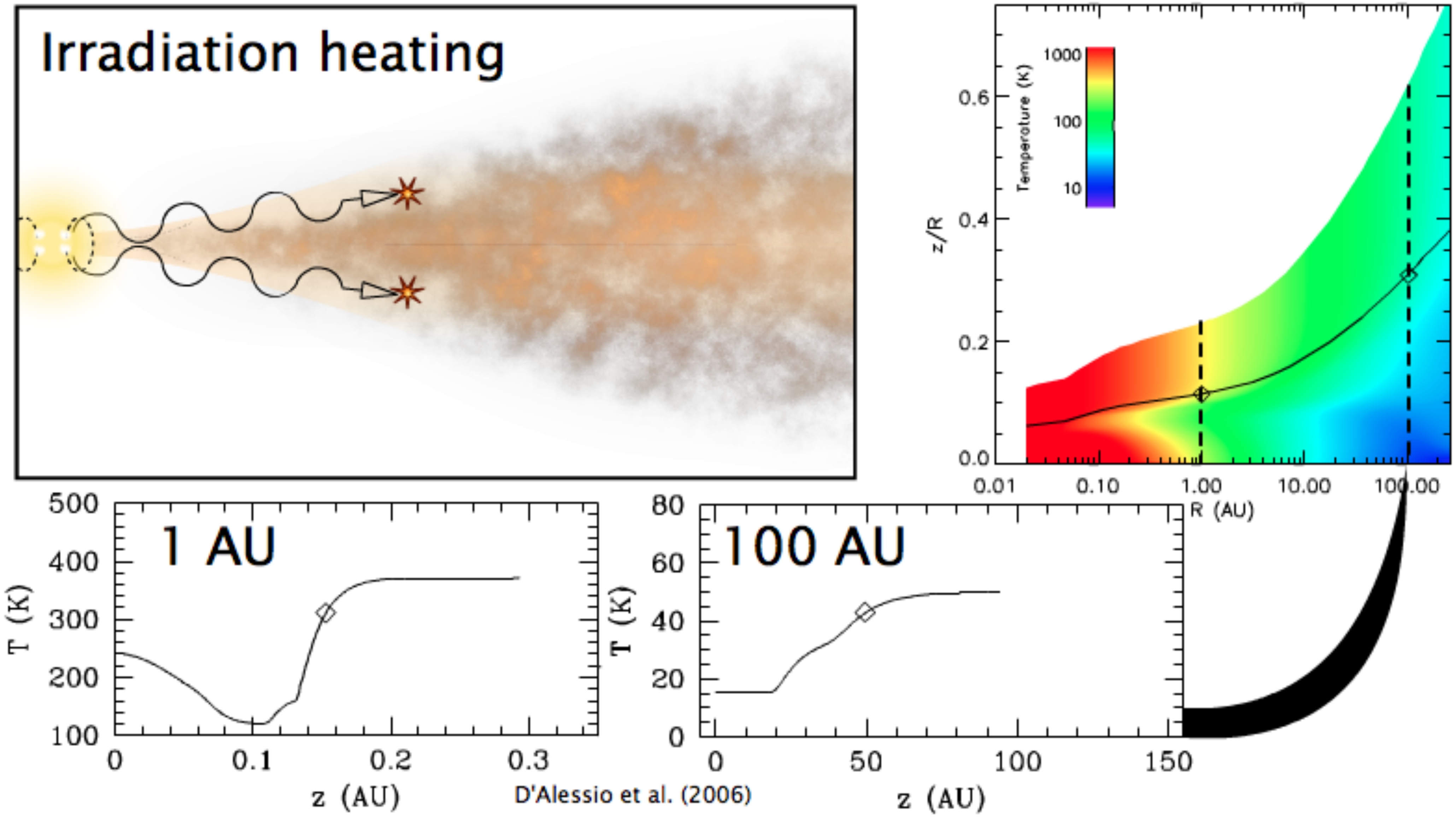
Grain growth & settling

1) Large grains concentrate at midplane with dust/gas >> 0.01: Important step towards planetary core formation!
2) Population of small grains with dust/gas << 0.01

How does grain segregation affect the disk structure?

DUST SETTLING SETS T(z,R)

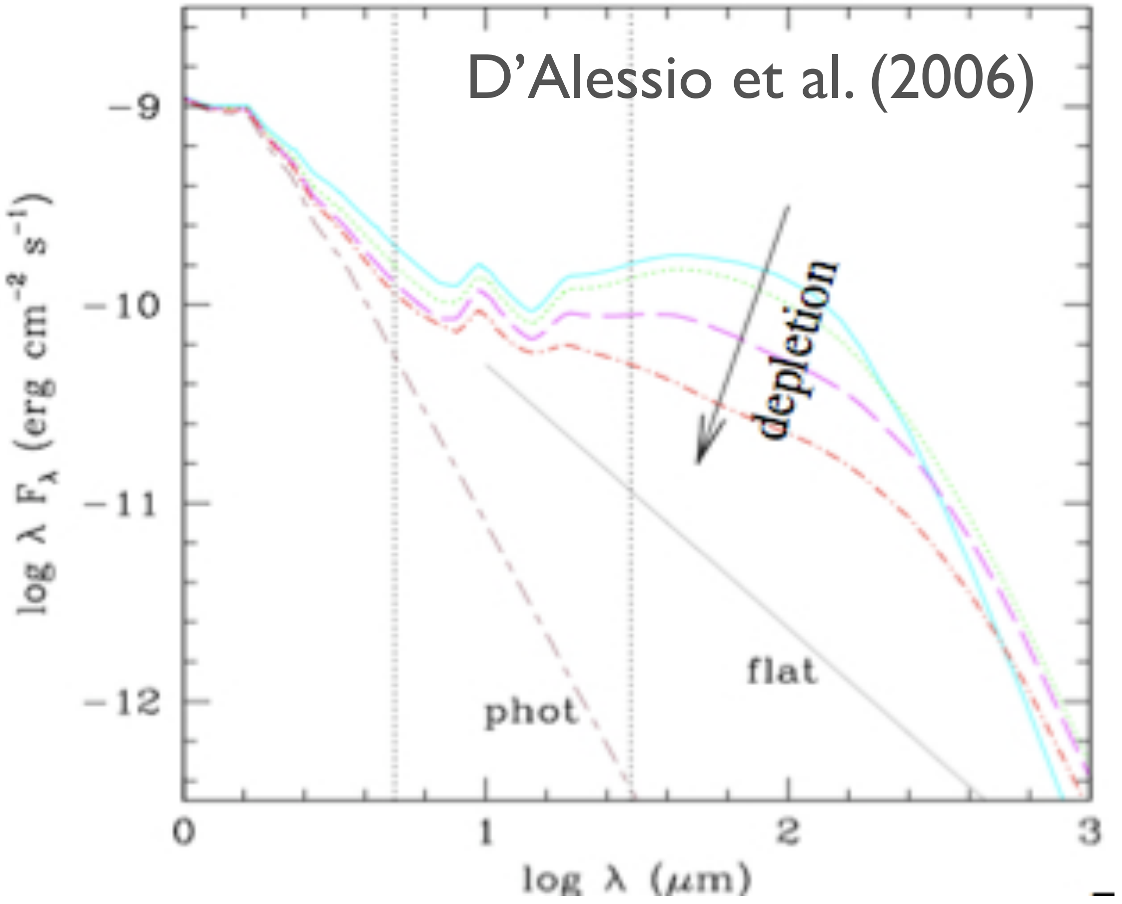
Small dust grains heat disk upper layers, causing disk to flare (Kenyon & Hartmann 1987).



D'Alessio et al. (2006)

Changes in T(z,R) produce measureable mid-IR characteristics.

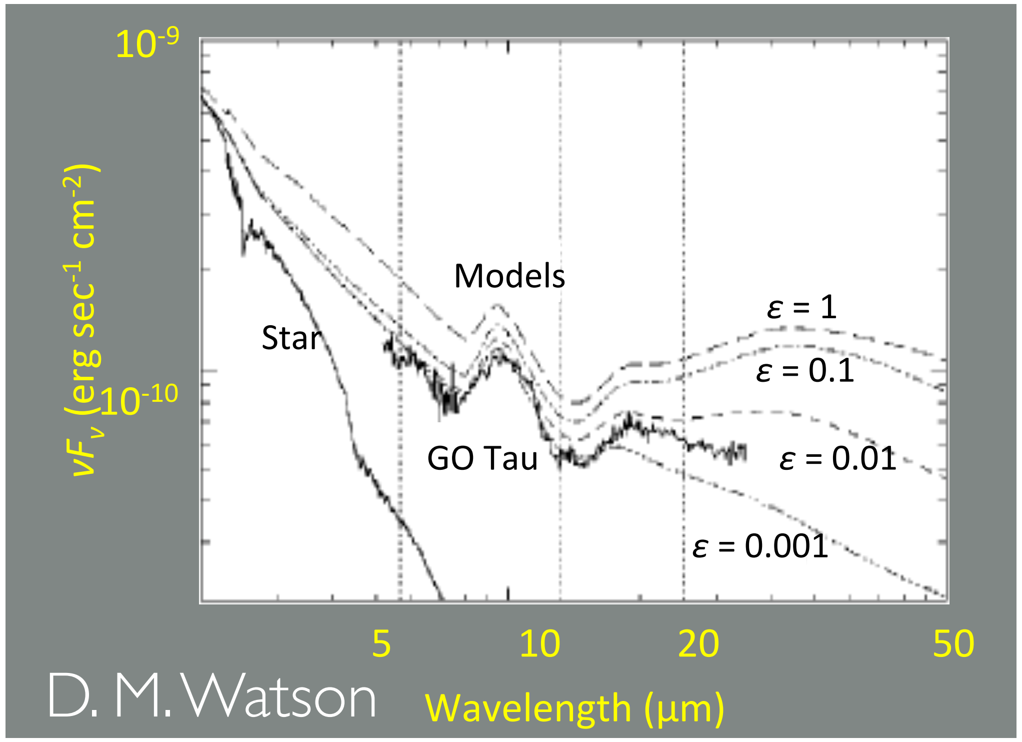
PREDICTED SETTLING SIGNATURES



- less opacity → cooler upper layer → lower continuum flux >30μm
- less optically thin small grain dust mass → smaller 10μm feature

- Spitzer IRS spectra show range of continuum levels
- comparison of model settling indicator for disks in many regions

D'Alessio et al. 1998, 2006; Furlan et al. 2006, 2011.



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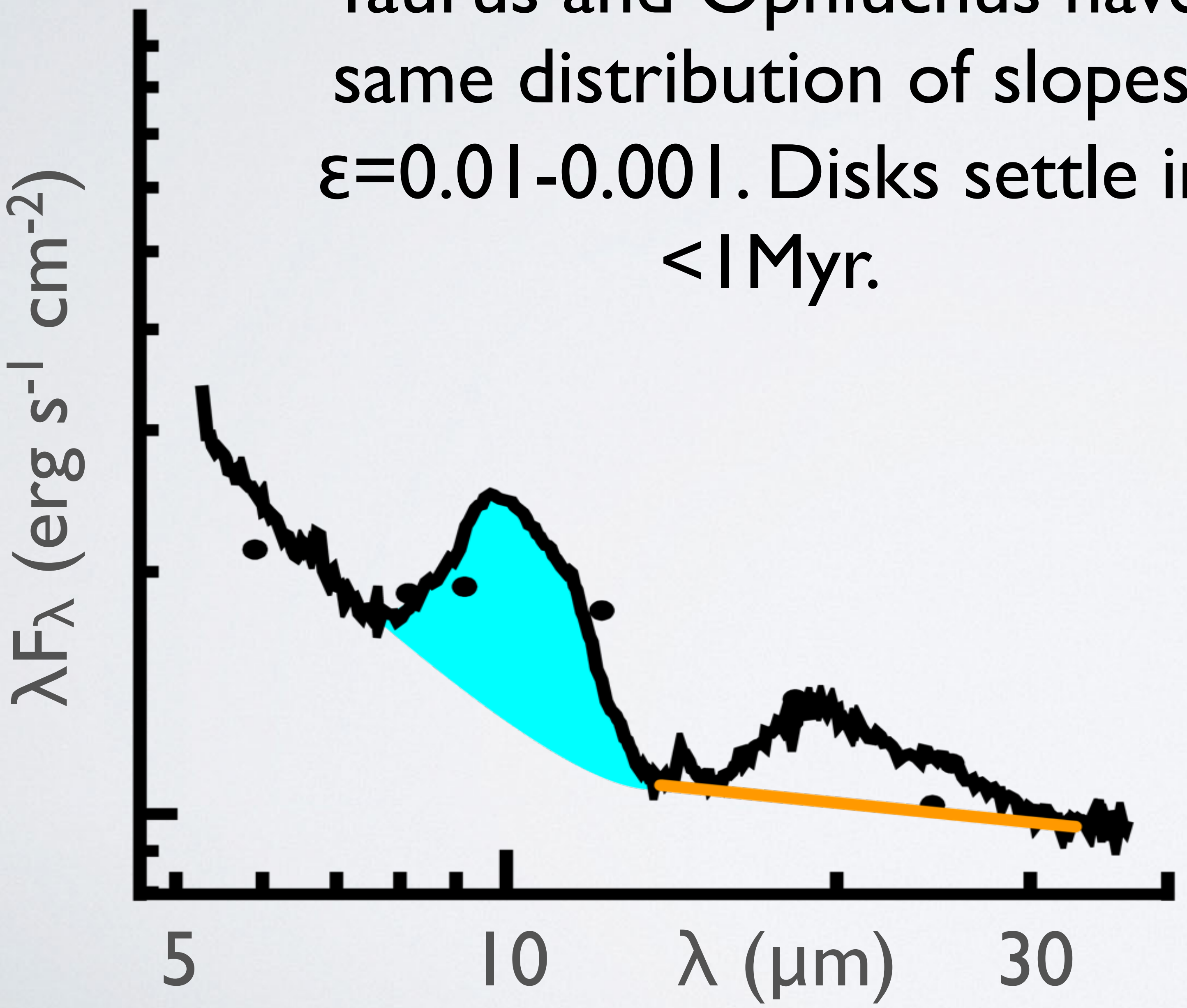
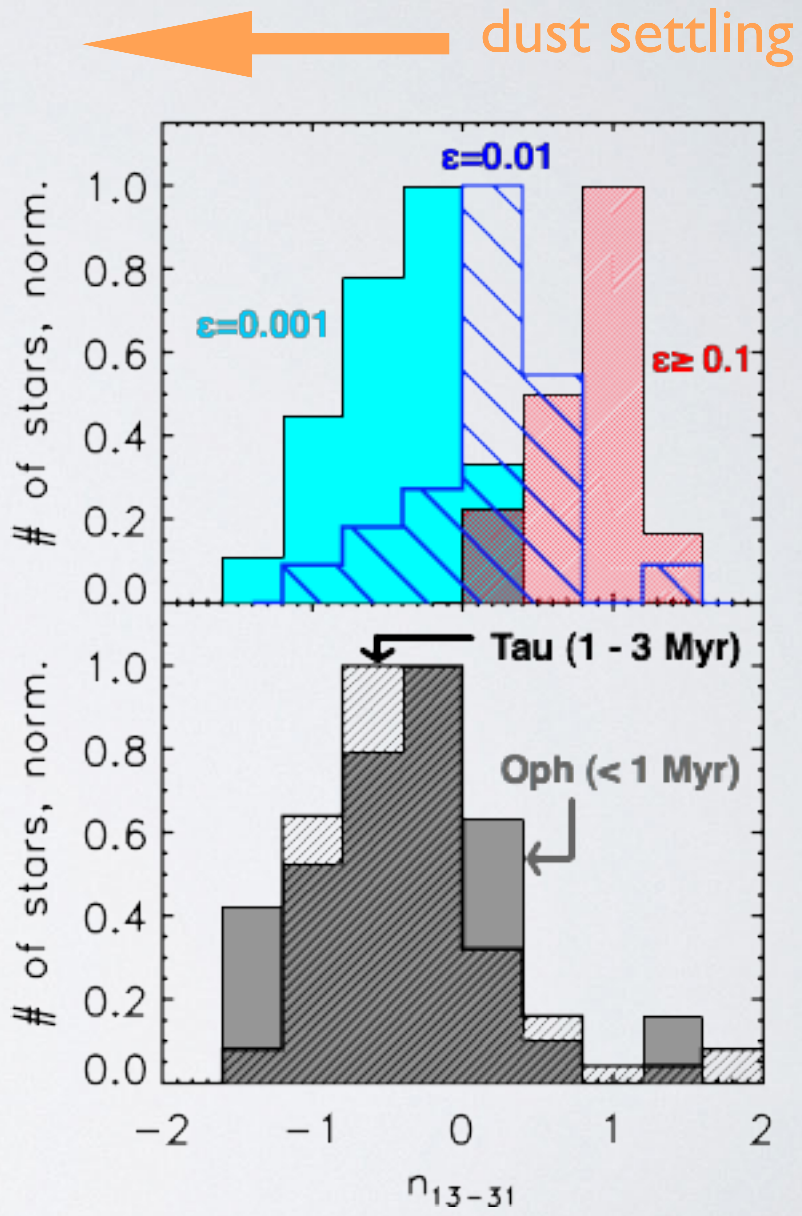
SETTLING OCCURS BY 1 MYR

Slope between continuum bands indicates degree of dust settling.

Taurus and Ophiuchus have same distribution of slopes: ε=0.01-0.001. Disks settle in <1Myr.

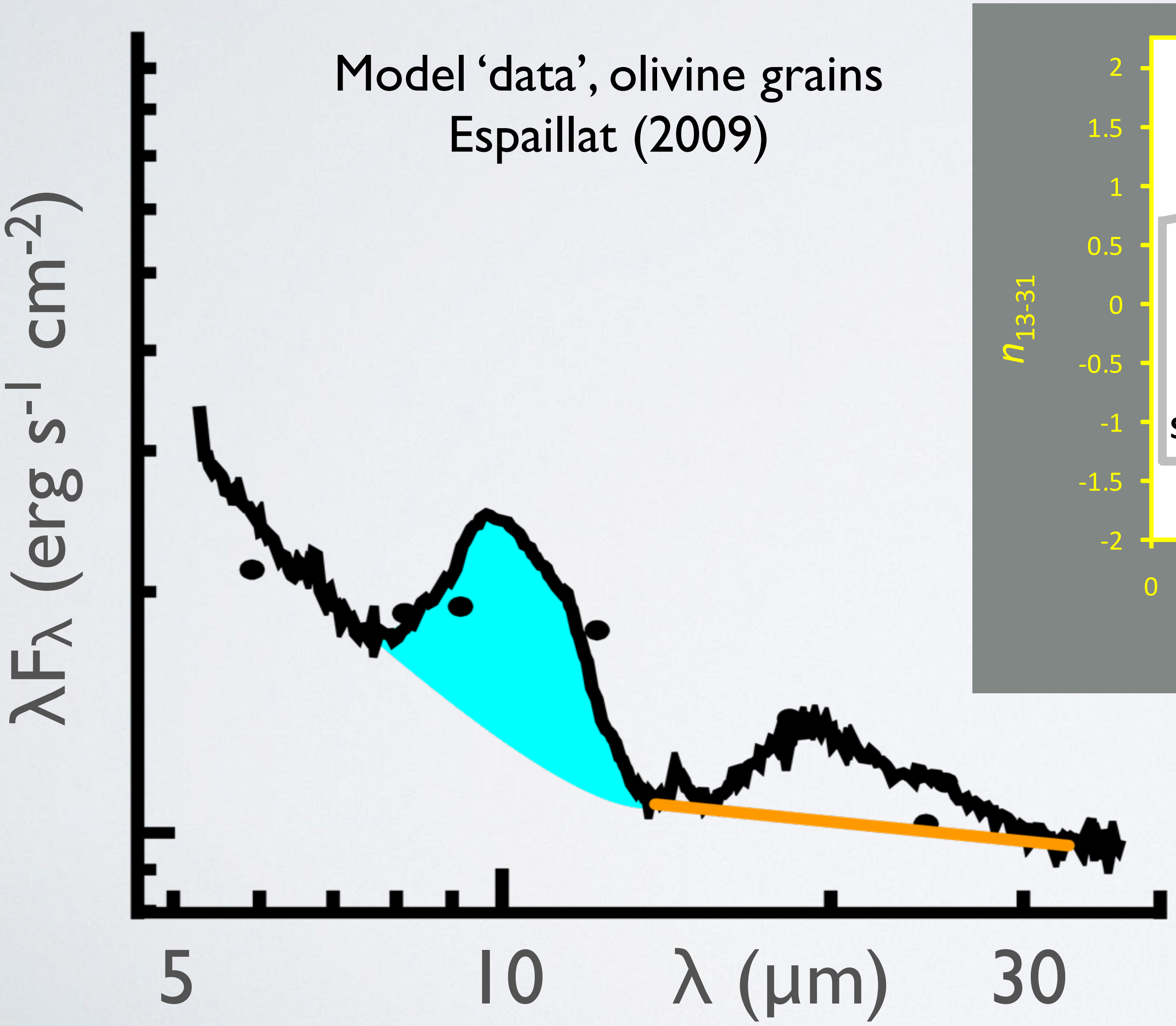


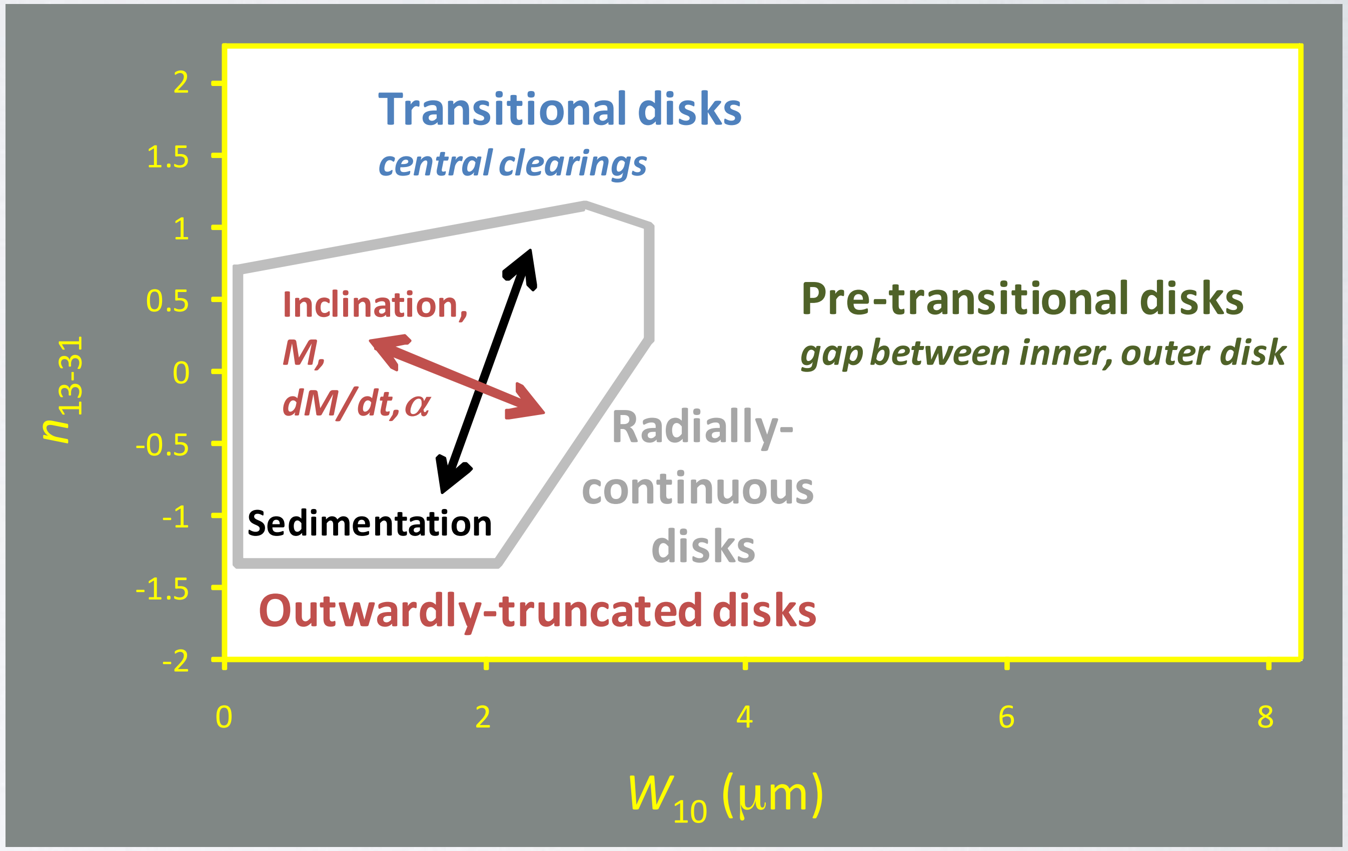


McClure et al. (2010), Furlan et al. (2006)

SETTLING OCCURS BY 1 MYR

Slope between continuum bands vs equivalent width of 10μm silicate feature separates effects of dust settling from planet formation:


Model ‘data’, olivine grains
Espaillat (2009)



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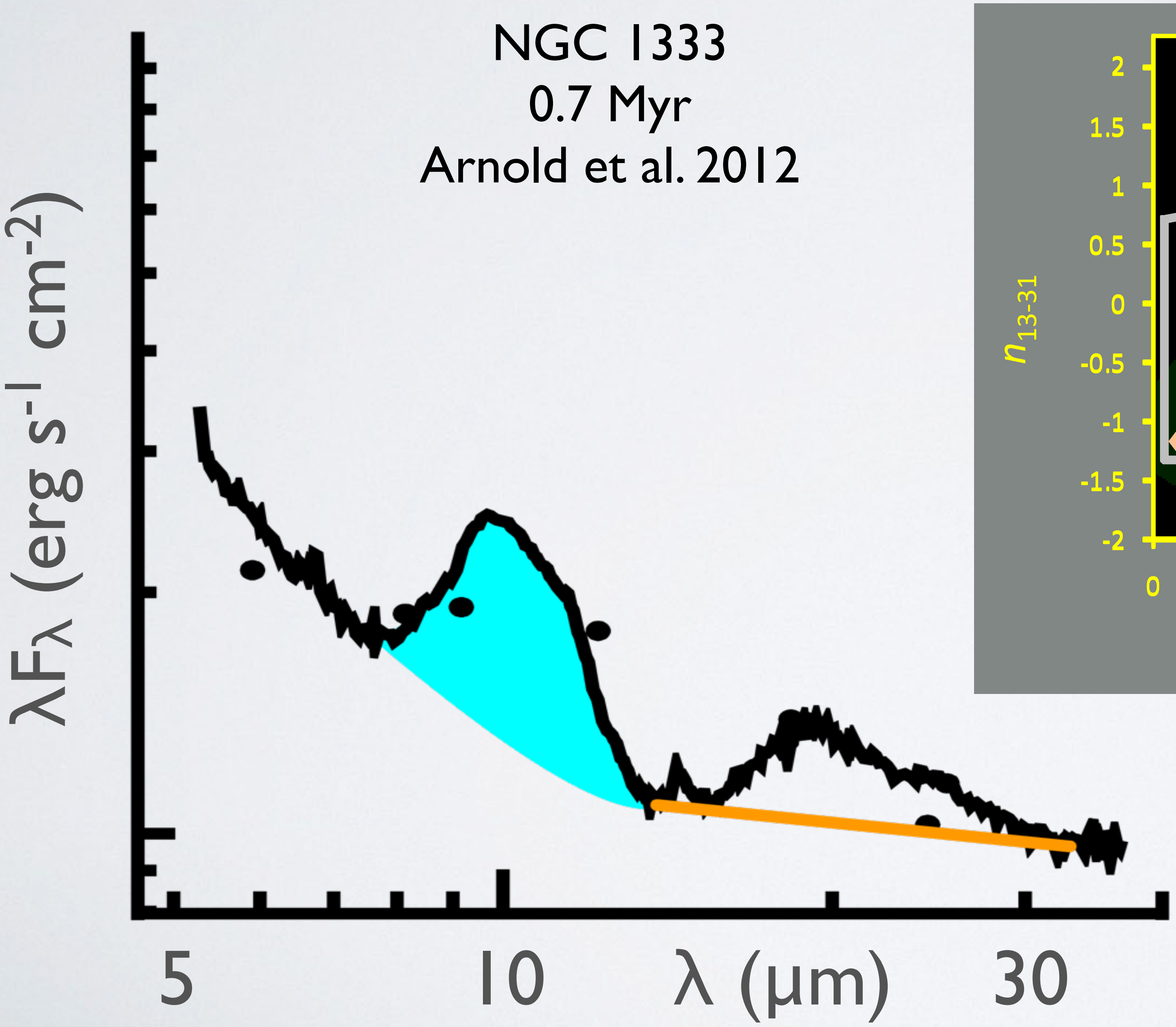
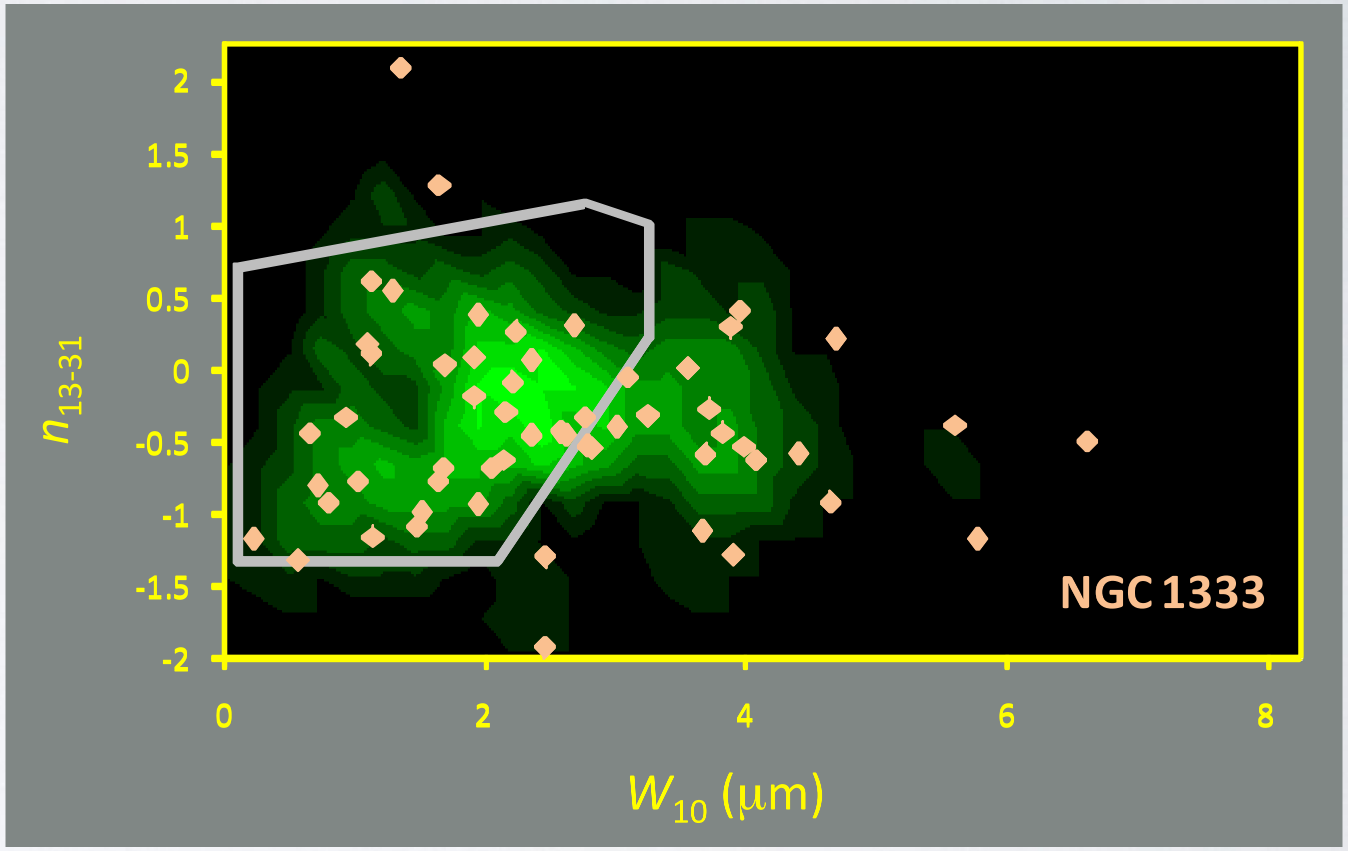

NGC 1333
0.7 Myr
Arnold et al. 2012



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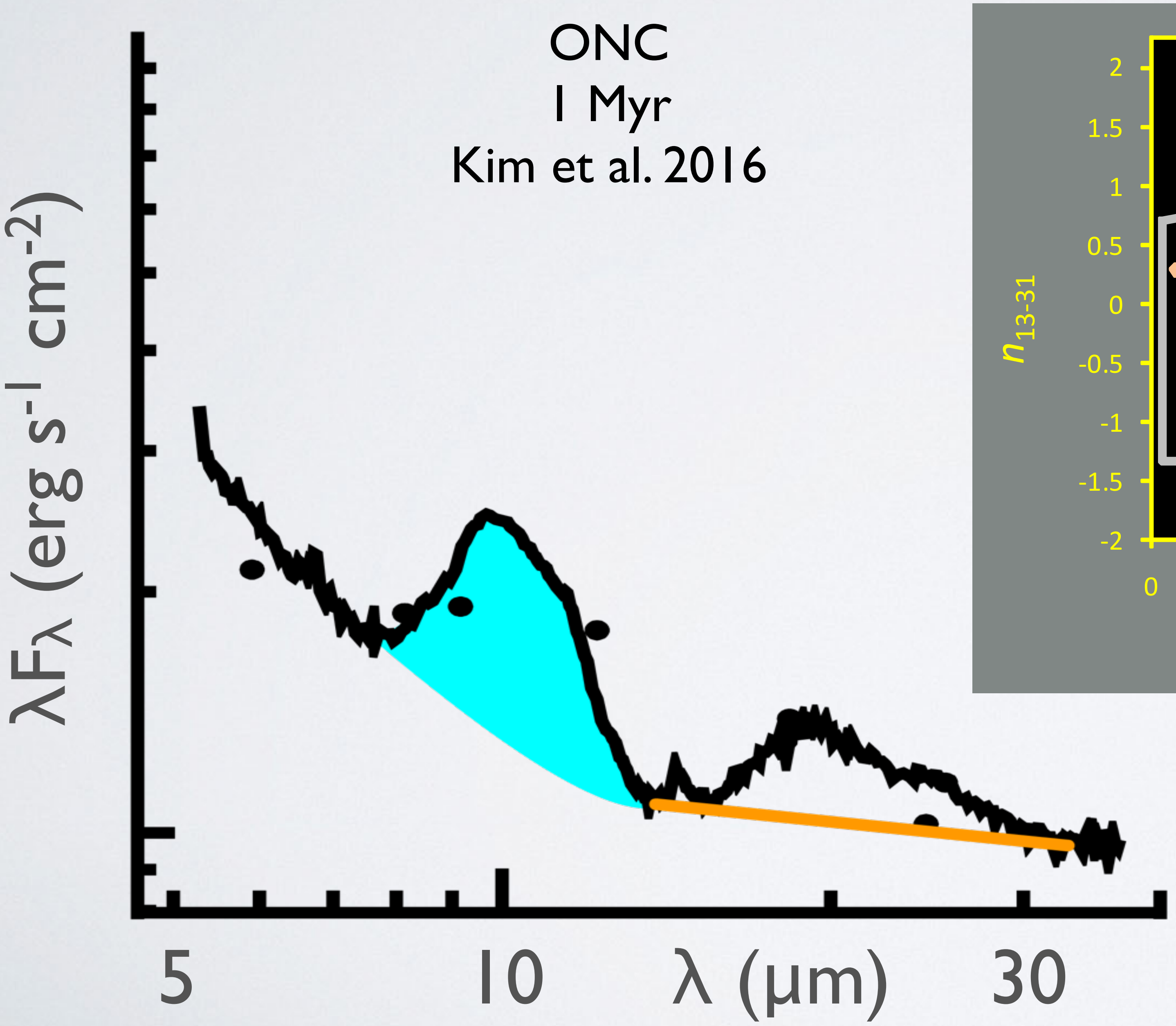

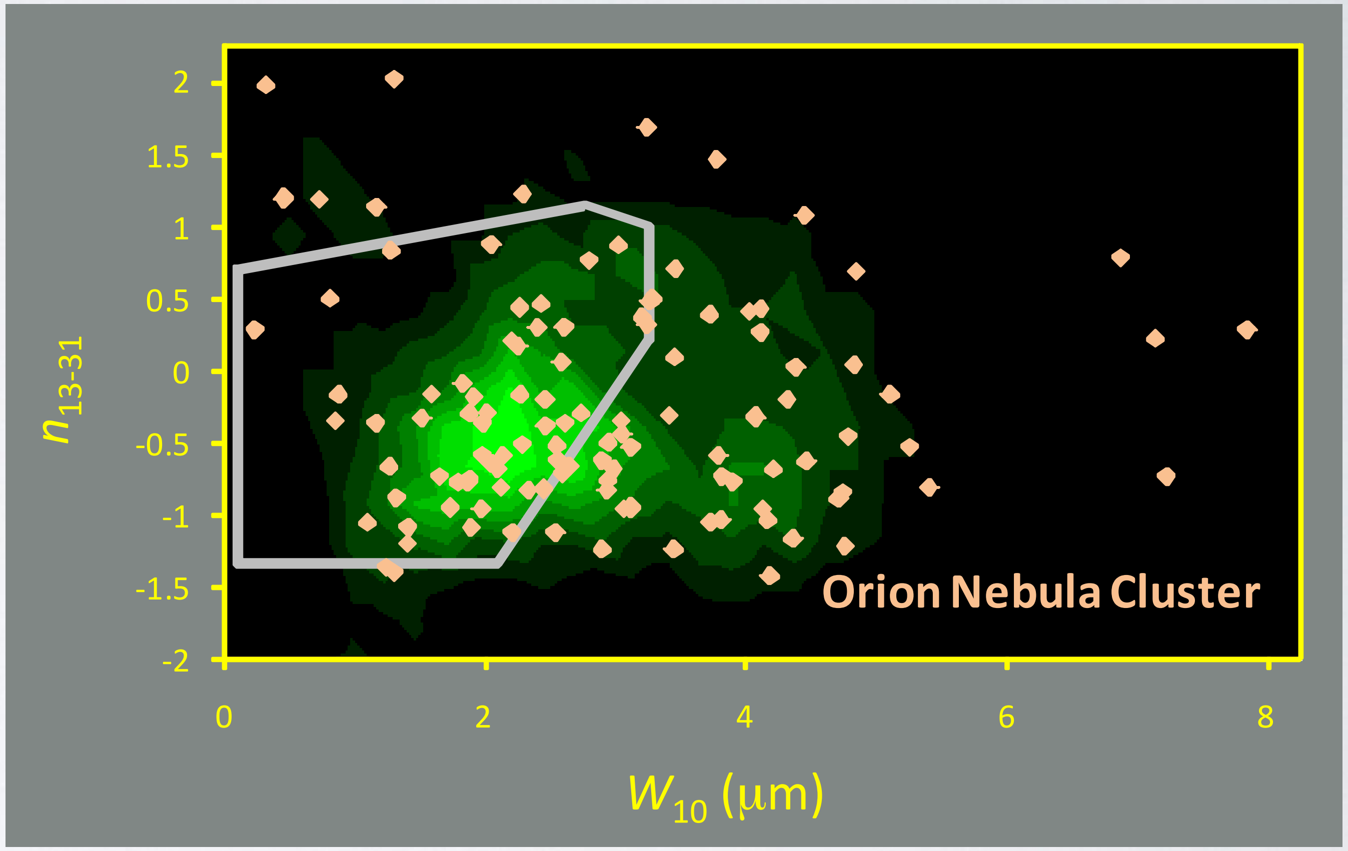

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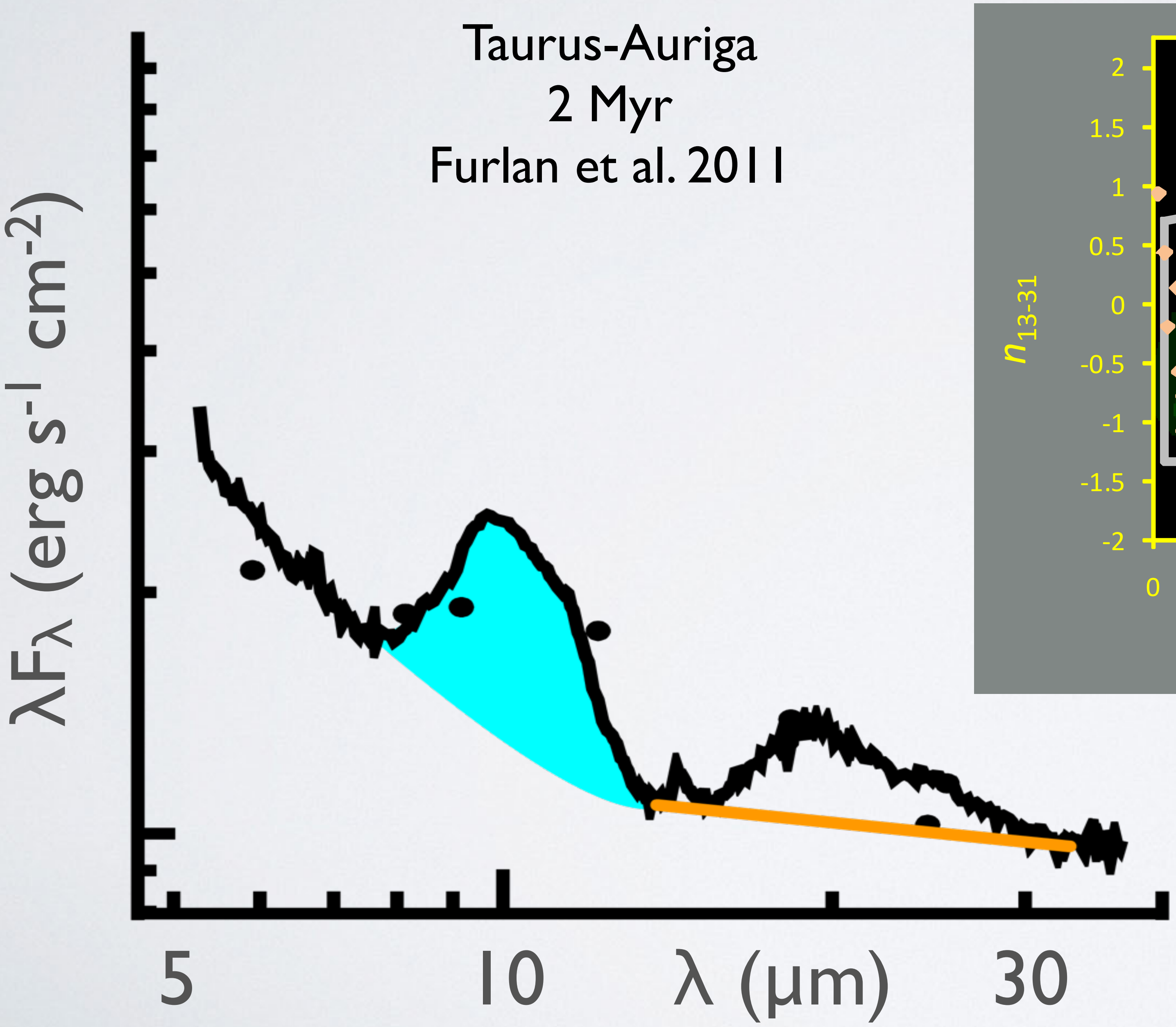

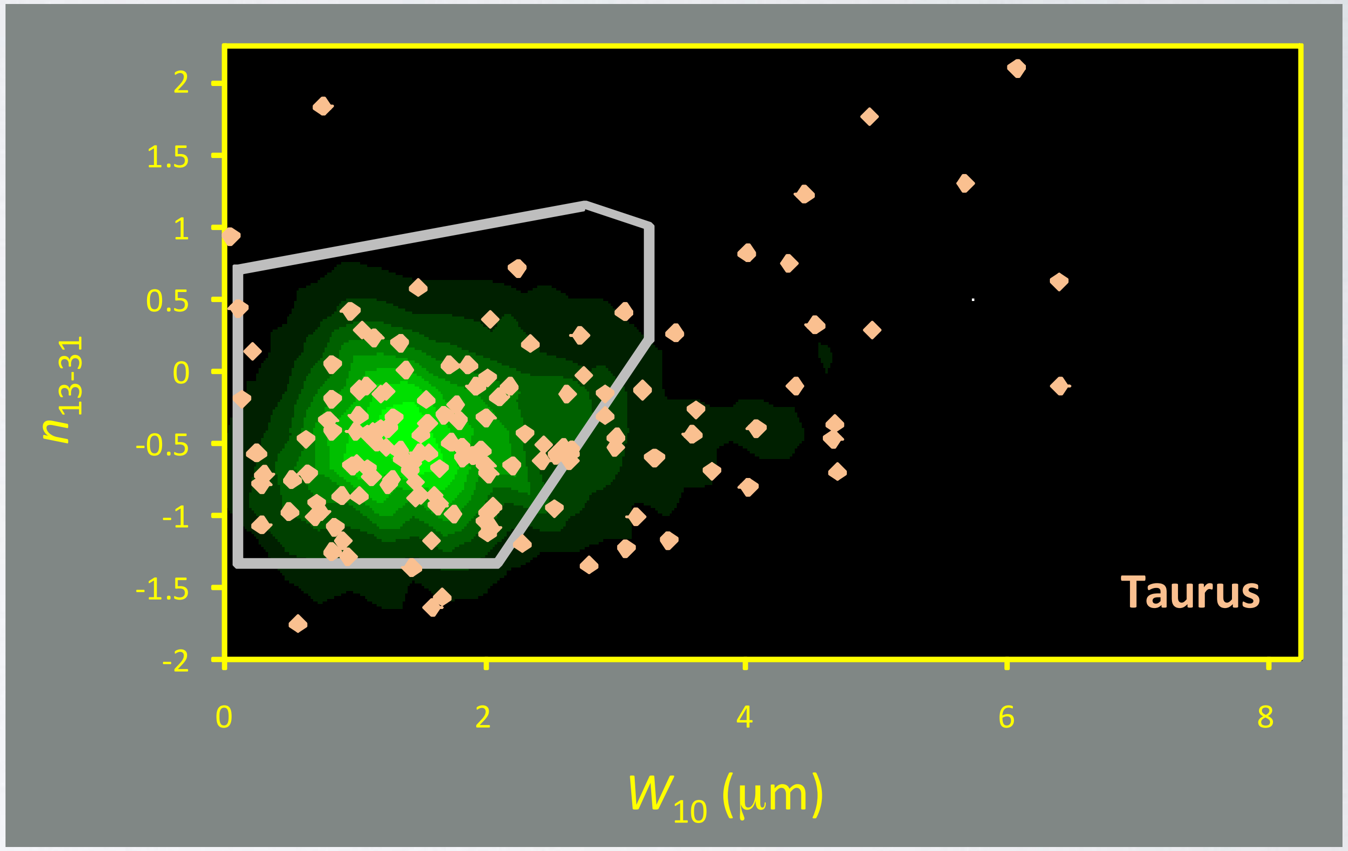

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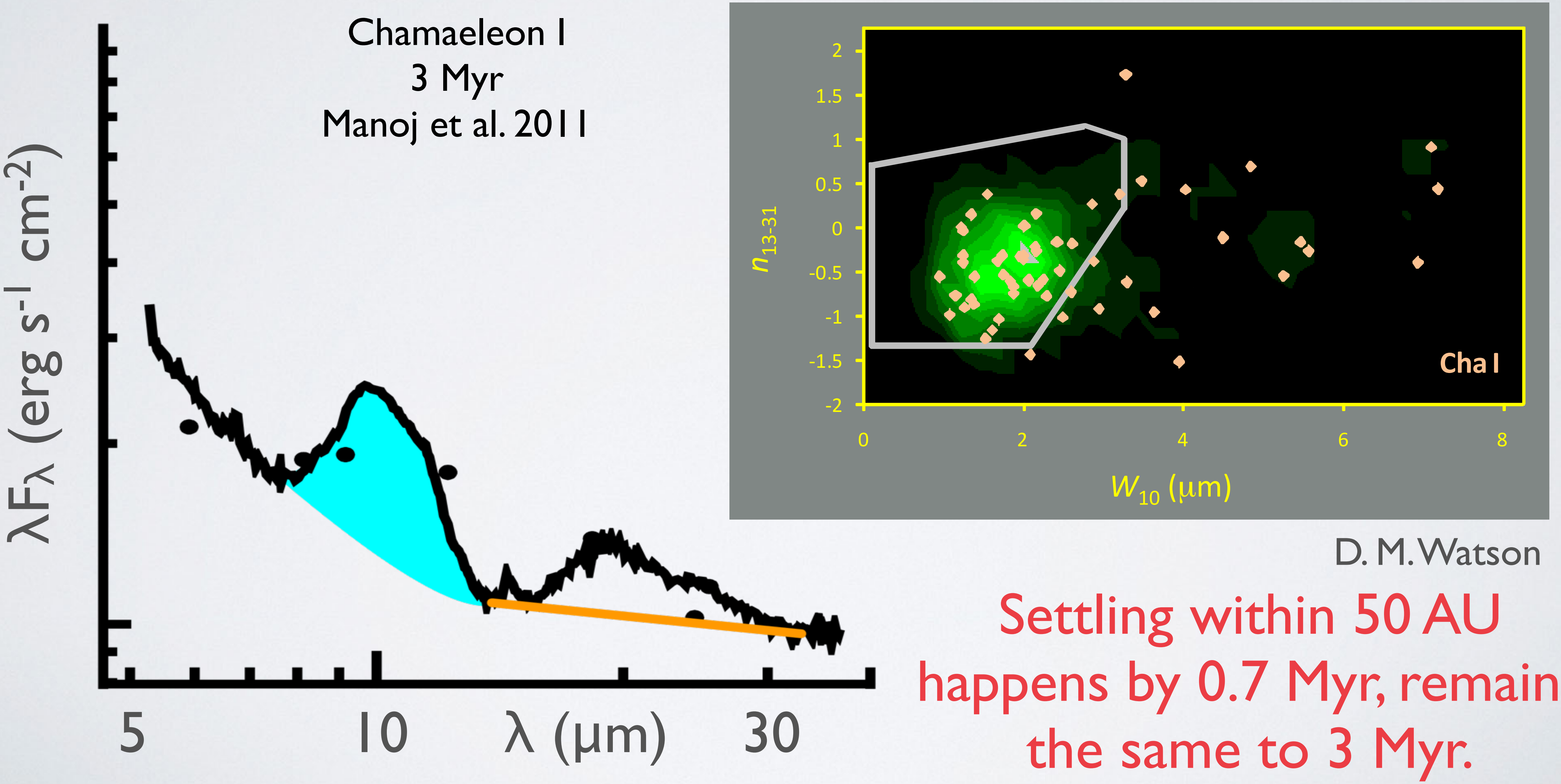

Chamaeleon I
3 Myr
Manoj et al. 2011

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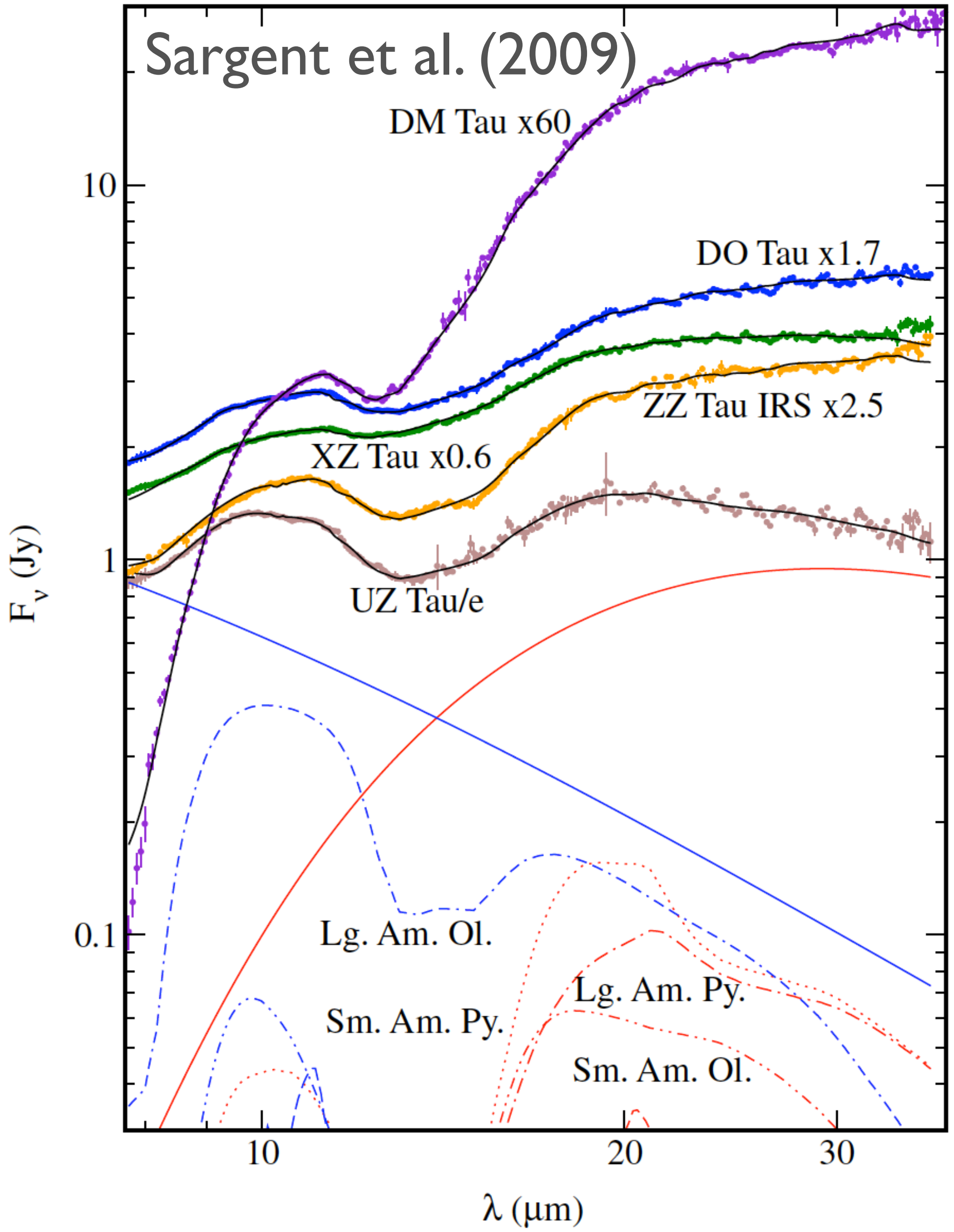
Settling within 50 AU happens by 0.7 Myr, remains the same to 3 Myr.

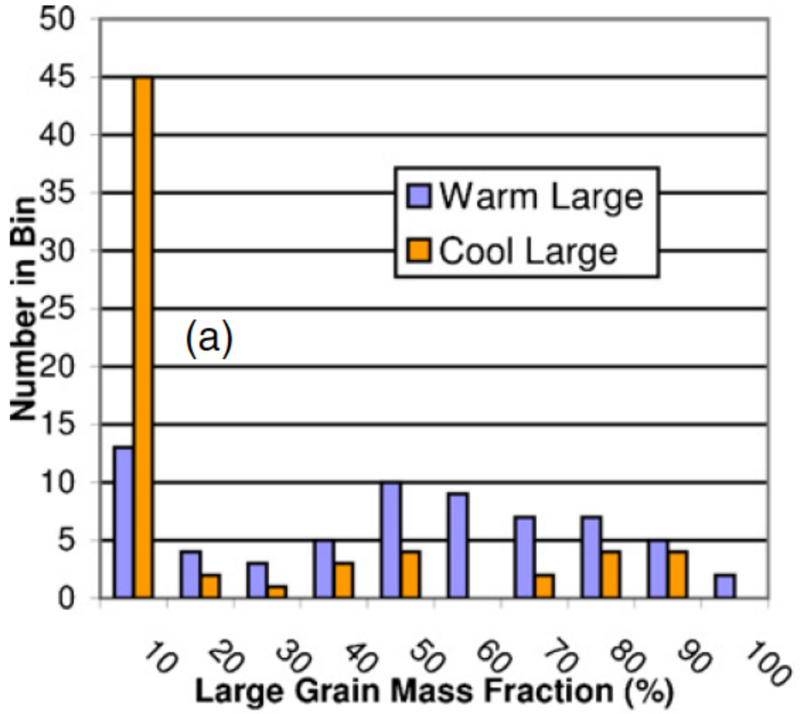
GRAIN GROWTH IN DISKS

Two-temperature, many species, fits:

(Sargent et al. 2009, Olofsson et al. 2010, Koch et al. 2017)



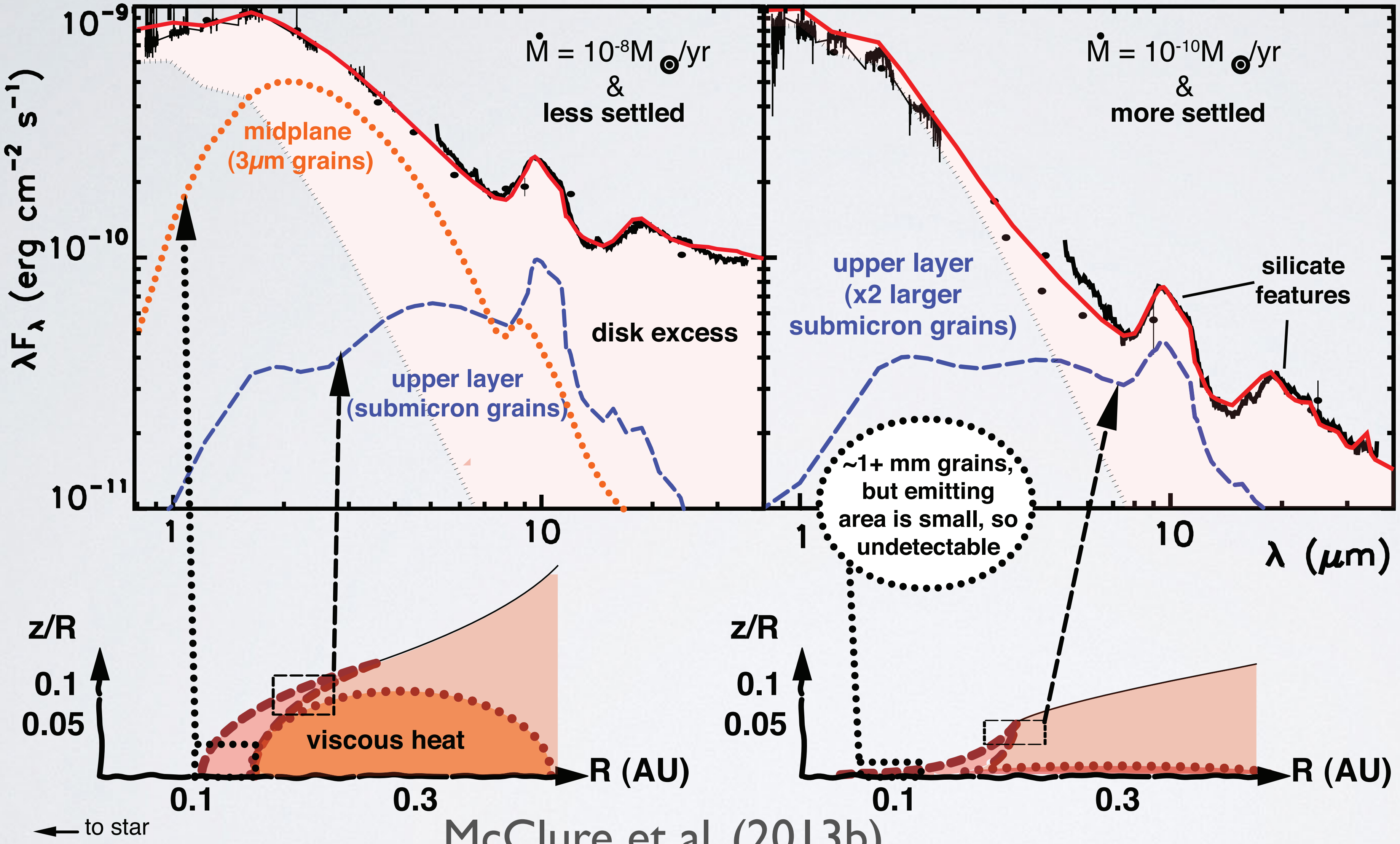
- warm (~700K) & cool (~125K) blackbodies
- warm & cool optically thin dust of large/small amorphous silicates and 3 crystalline silicate species.
- more large warm grains consistent with expectation of faster timescales in inner disk.
- little variation as a function of age.



But is this the whole picture?

EVIDENCE FOR FRAGMENTATION?

Self-consistent disk + silicate sublimation rim models.



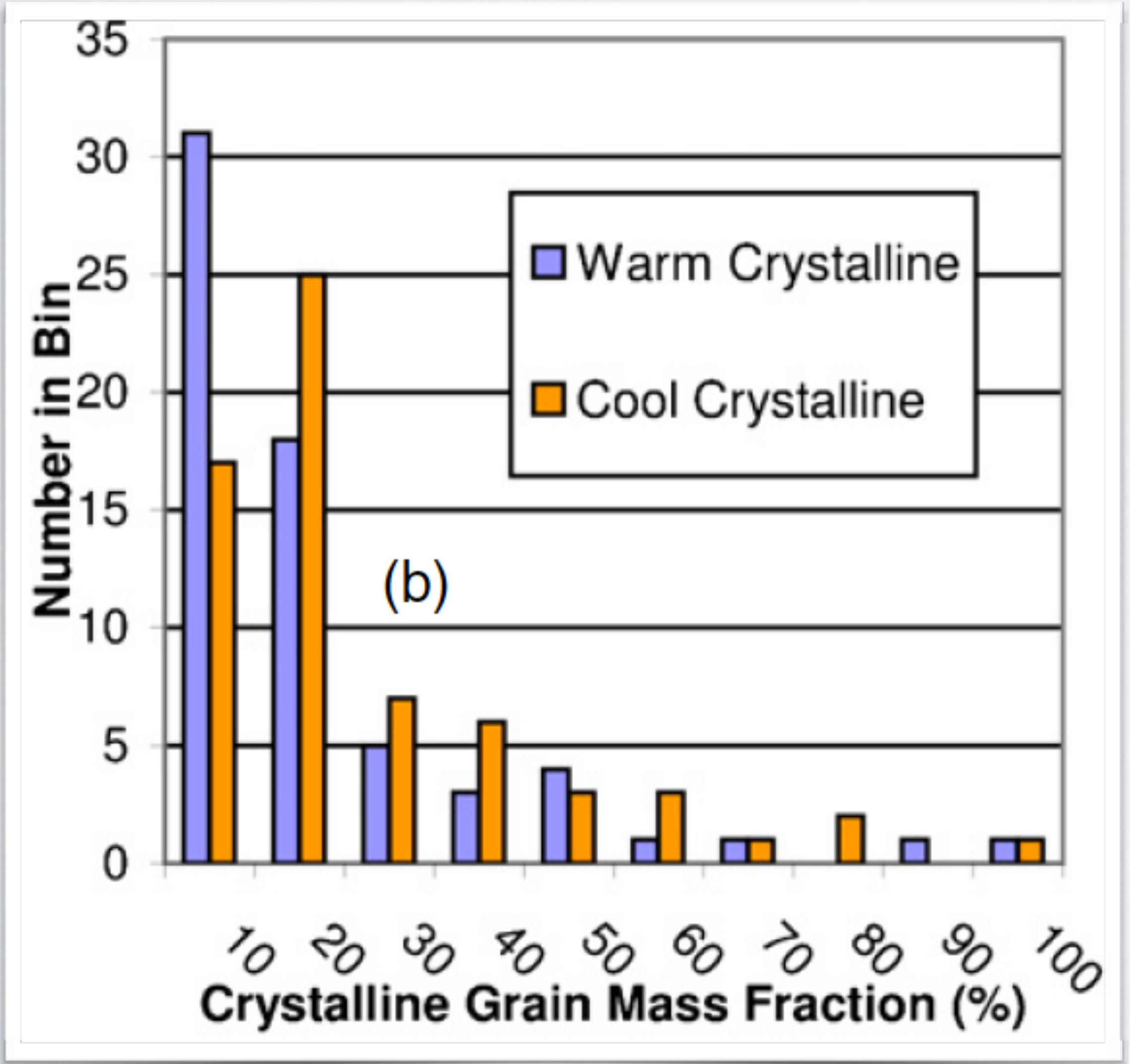
McClure et al. (2013b)

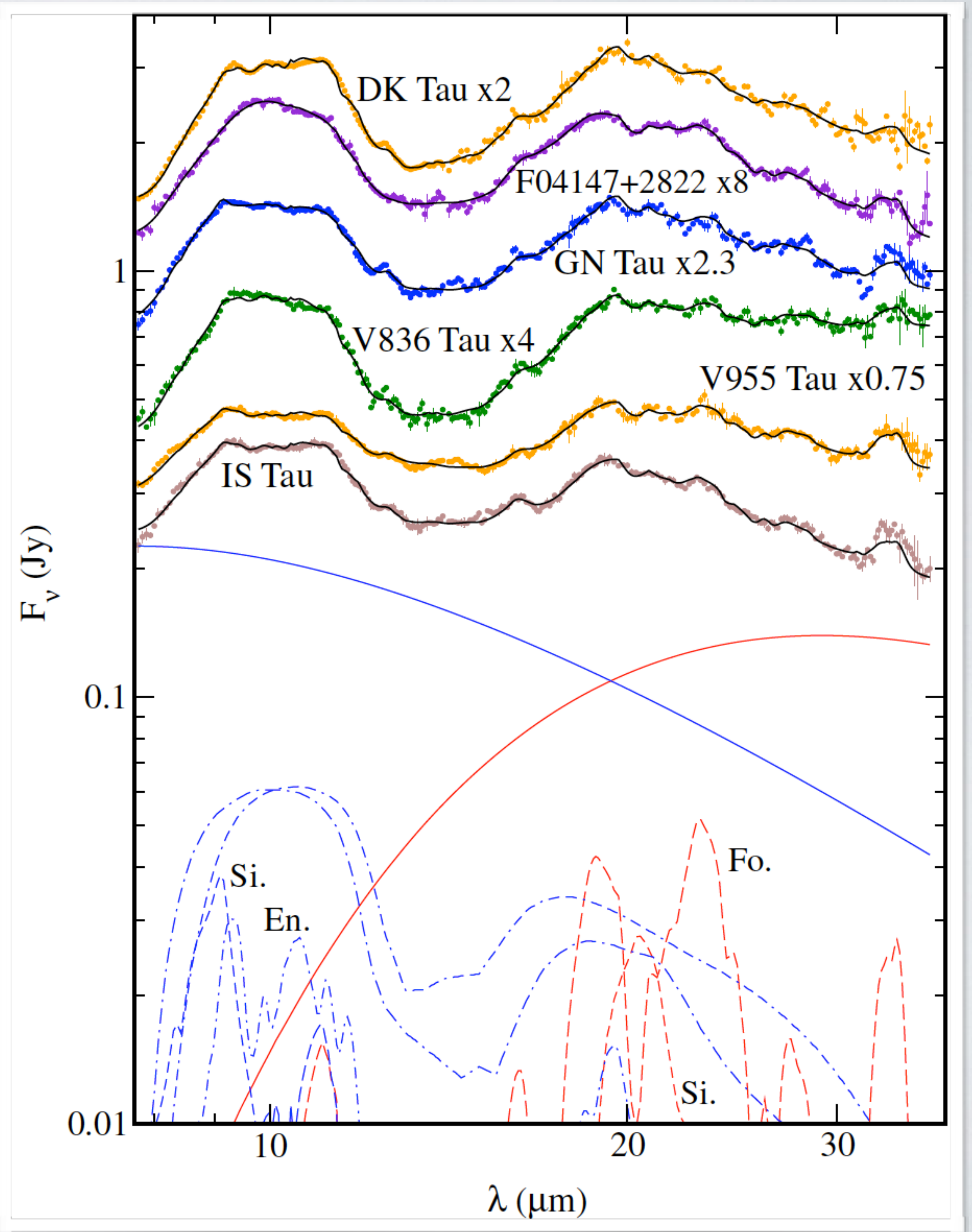
- Larger Mdot, hotter disk, more fragmentation
- cooler disk, more grain growth

Small grains in 10μm feature may indicate increased settling and "hidden" grain growth.

DUST MINERALOGY - PLANETESIMAL FORMATION?

- Two-temperature fits find cool forsterite, silica.
- Silica fraction increases with disk age.
- Sign of planetesimals?

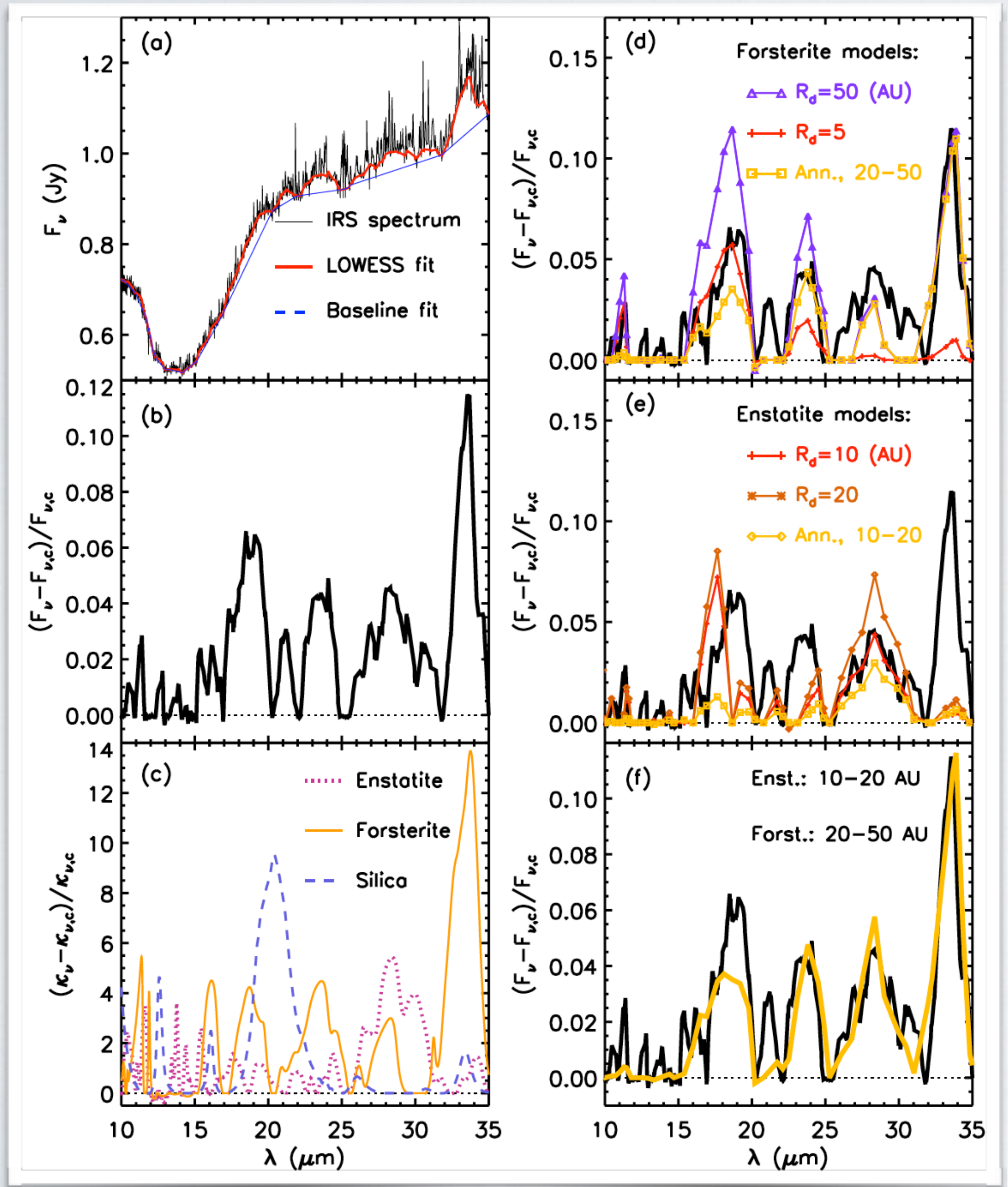




Sargent et al. (2006, 2009); Olofsson et al. (2013), Koch et al. (2017)

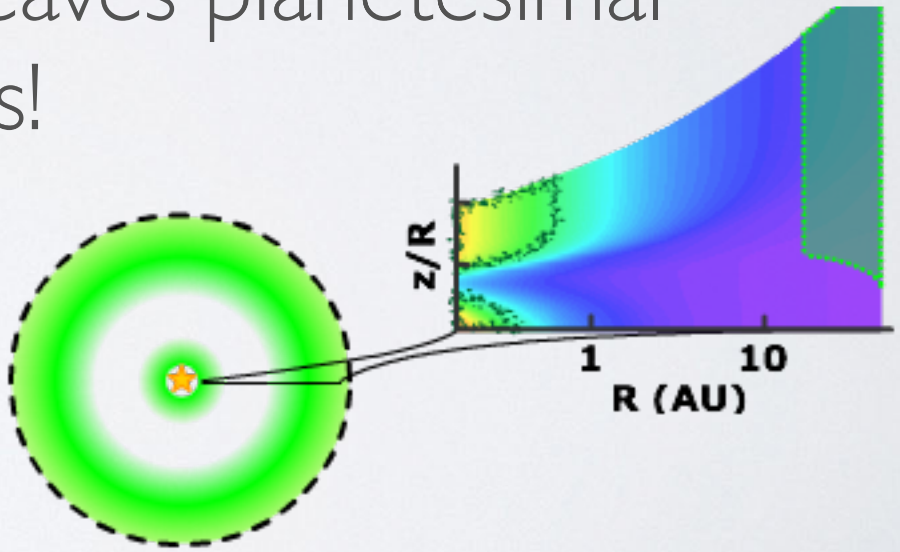
DUST MINERALOGY - PROTO-KUIPER BELT?

Self-consistent disk models to simulate crystalline annuli at different radii.



McClure et al. (2012)

- Best fit is crystalline ring between 20-50 AU
- Too far out for innate temperature structure or shock formation (Harker & Desch 2002); leaves planetesimal collisions!



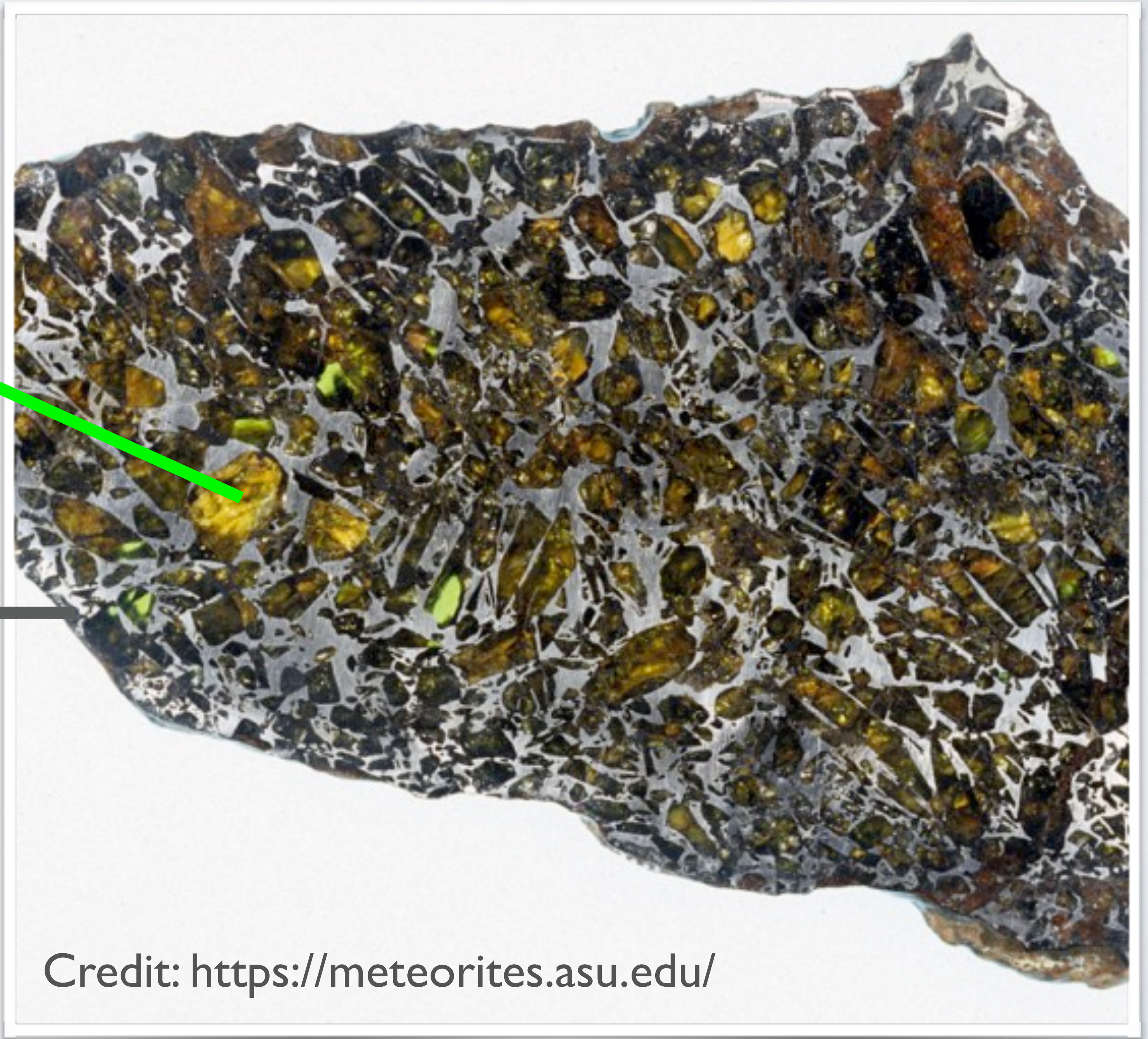
Is this scenario common?

SOLAR SYSTEM ANALOG

Pallasite meteorite family: collisions between *differentiated* planetesimals.

Forsterite inclusions (green)
vaporized crust

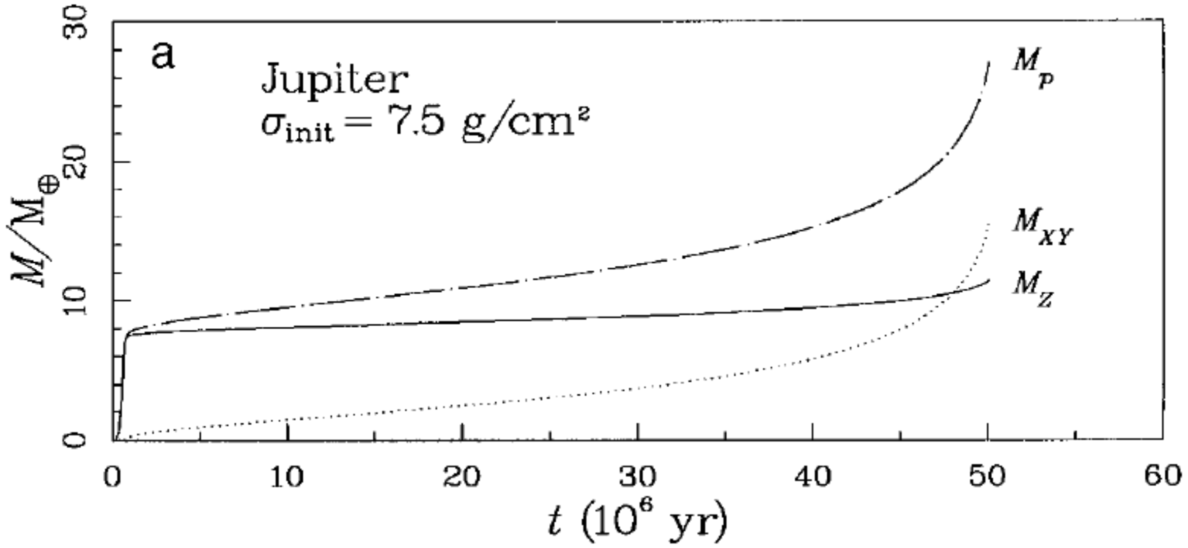
Iron-nickel matrix (silver)
molten core

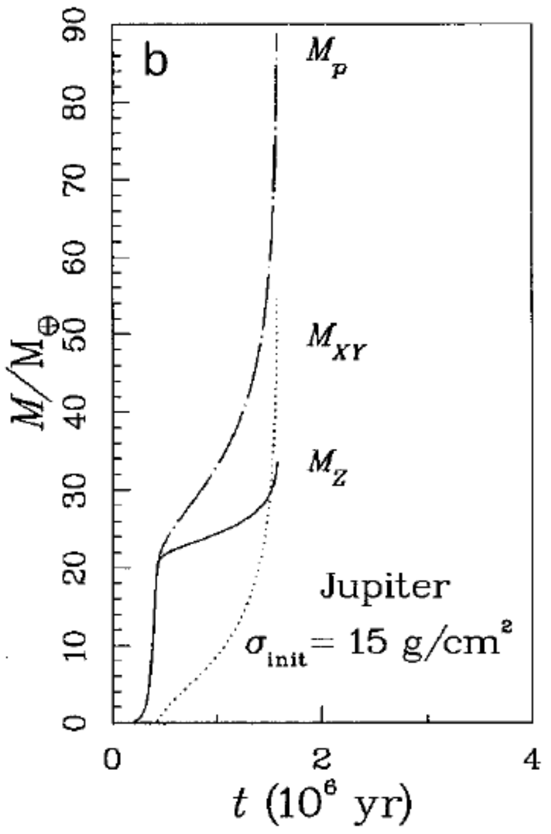


Credit: https://meteorites.asu.edu/

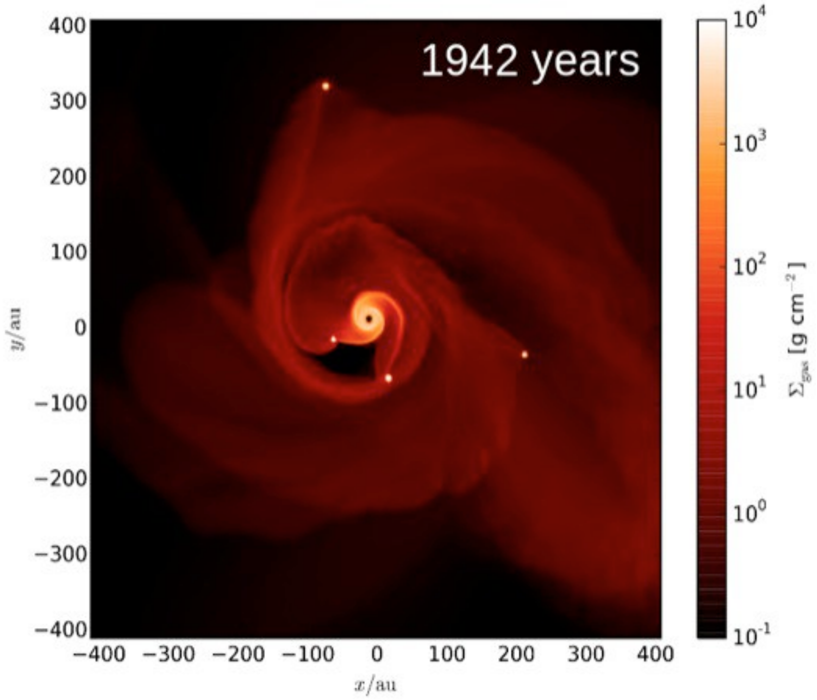
Have mature planets formed in disks as well?

GIANT PLANET FORMATION





Pollack et al. (1996)



Szulágyi et al. (2017)

Core accretion:

- planetesimal sticking/growth
- slow: ~ few Myr to form giant planets (Σ dependent)
- works in inner disk, produces cold planet

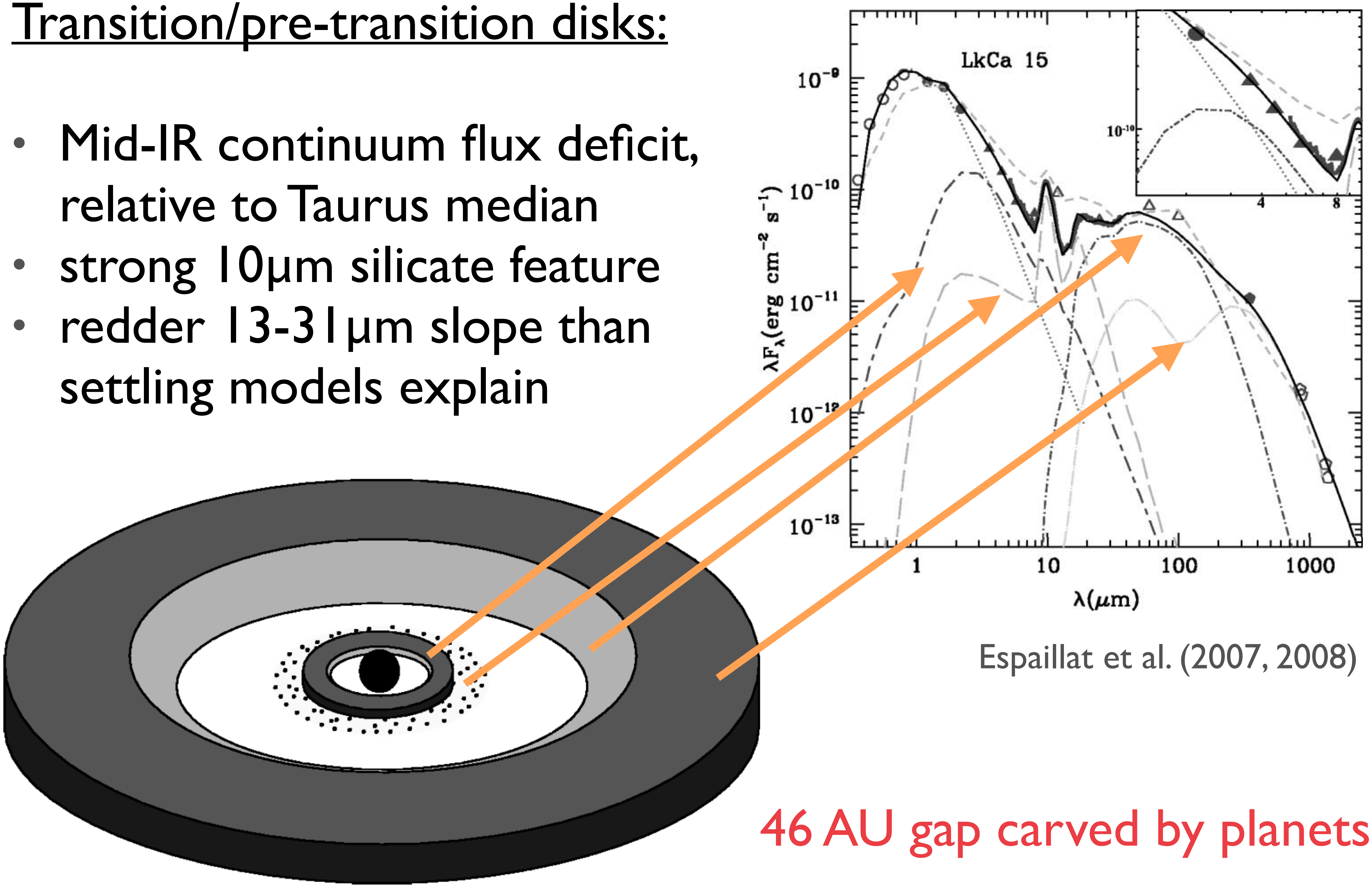
Gravitational instability:

- collapse of unstable region in outer disk
- shorter timescale
- hotter planet

SIGNS OF GIANT PLANET FORMATION?

Transition/pre-transition disks:

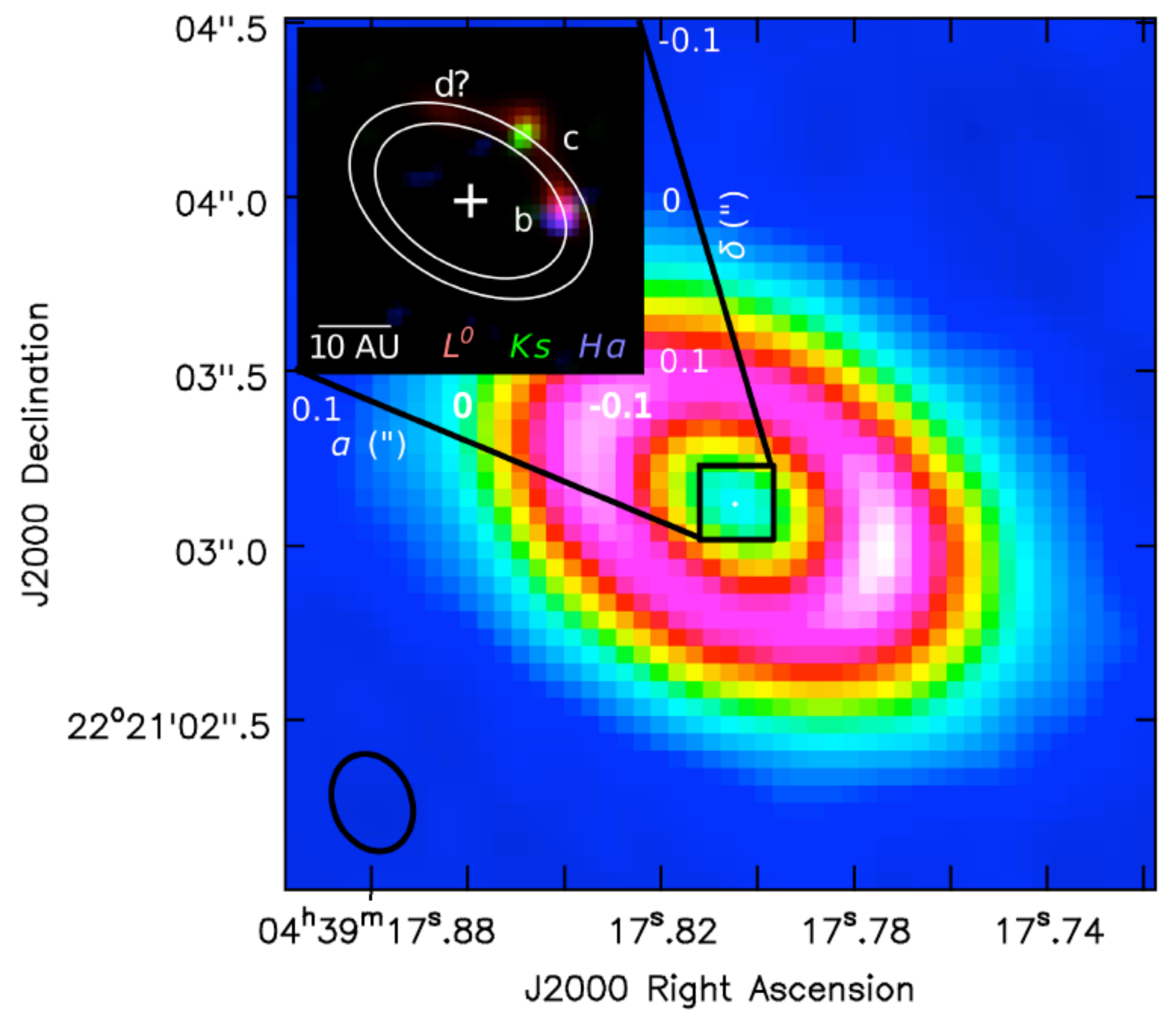
- Mid-IR continuum flux deficit, relative to Taurus median
- strong 10µm silicate feature
- redder 13-31µm slope than settling models explain



Espaillat et al. (2007, 2008)

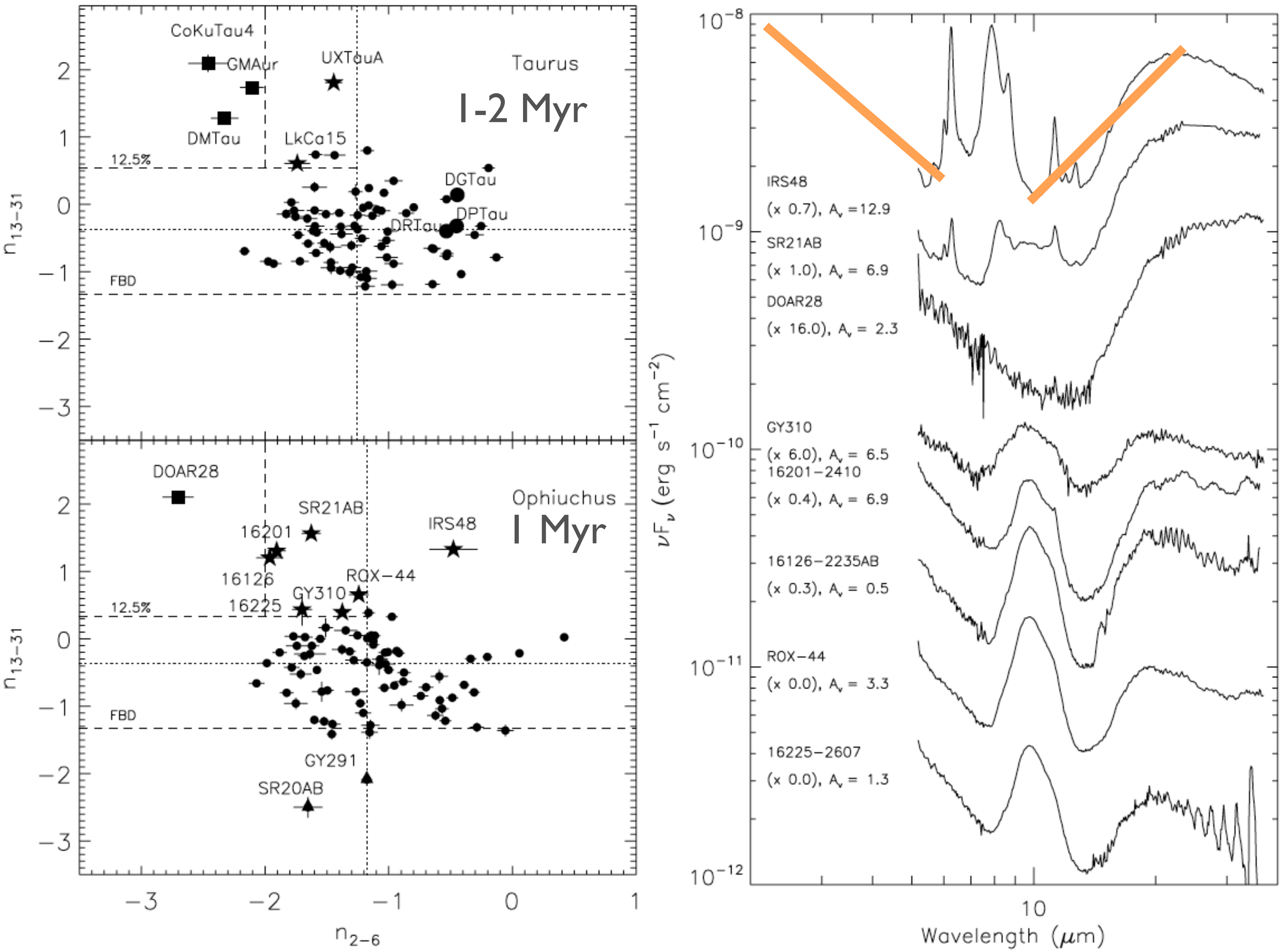
46 AU gap carved by planets?

CONFIRMATION OF GIANT PLANETS IN LKCA 15!



- ALMA gap ~50 AU (similar to SED)
- planet candidates imaged at Ks, L0, and Hα (Kraus & Ireland 2011, Sallum et al. 2015)
- large gaps may require multiple >1Mjup planets to open

TRANSITION DISKS POPULATIONS: TIMESCALE FOR GIANT PLANET FORMATION



1-2 Myr

1 Myr

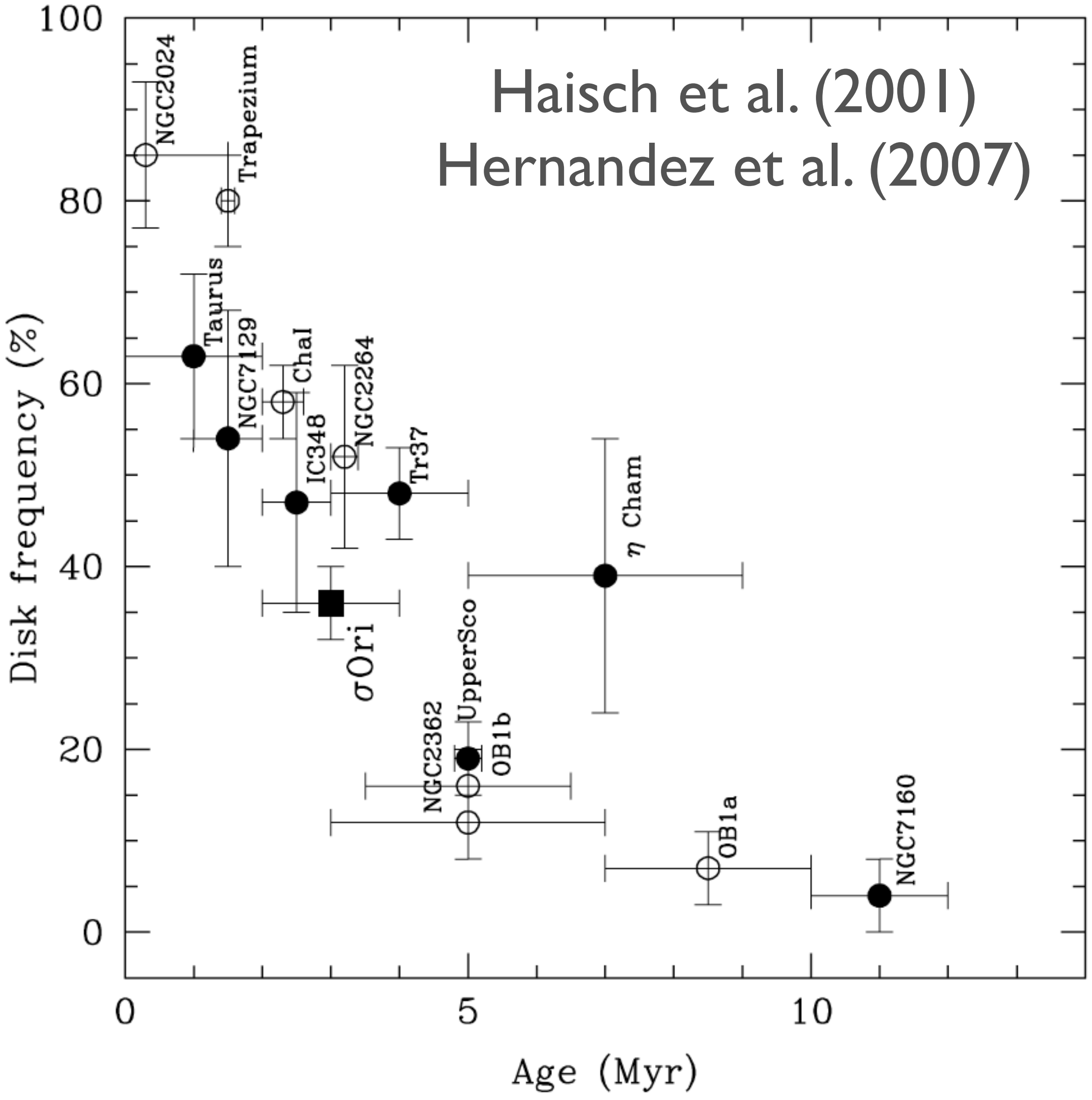
McClure et al. (2010)

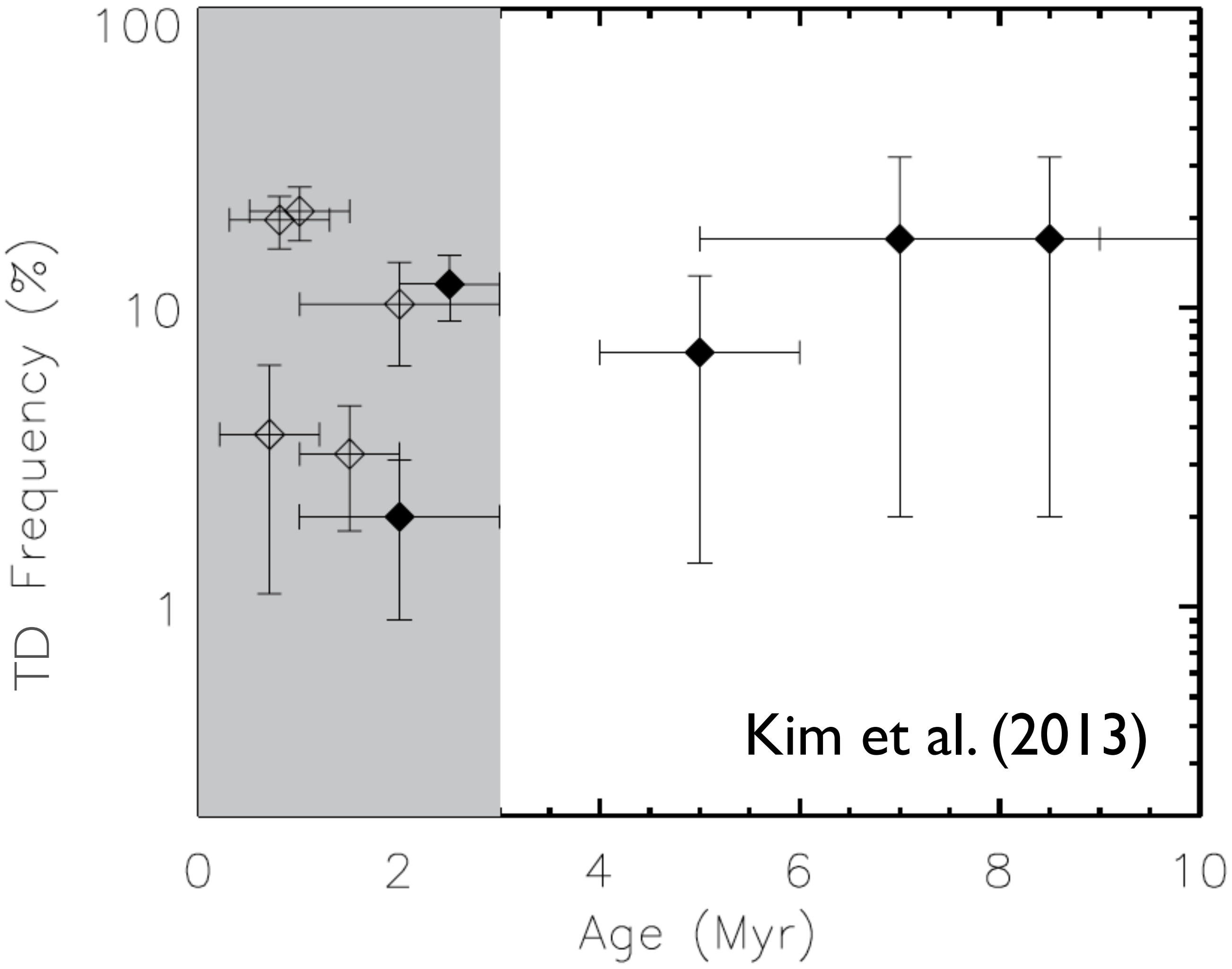
TDs disks relatively common at range of ages

How early do they occur?

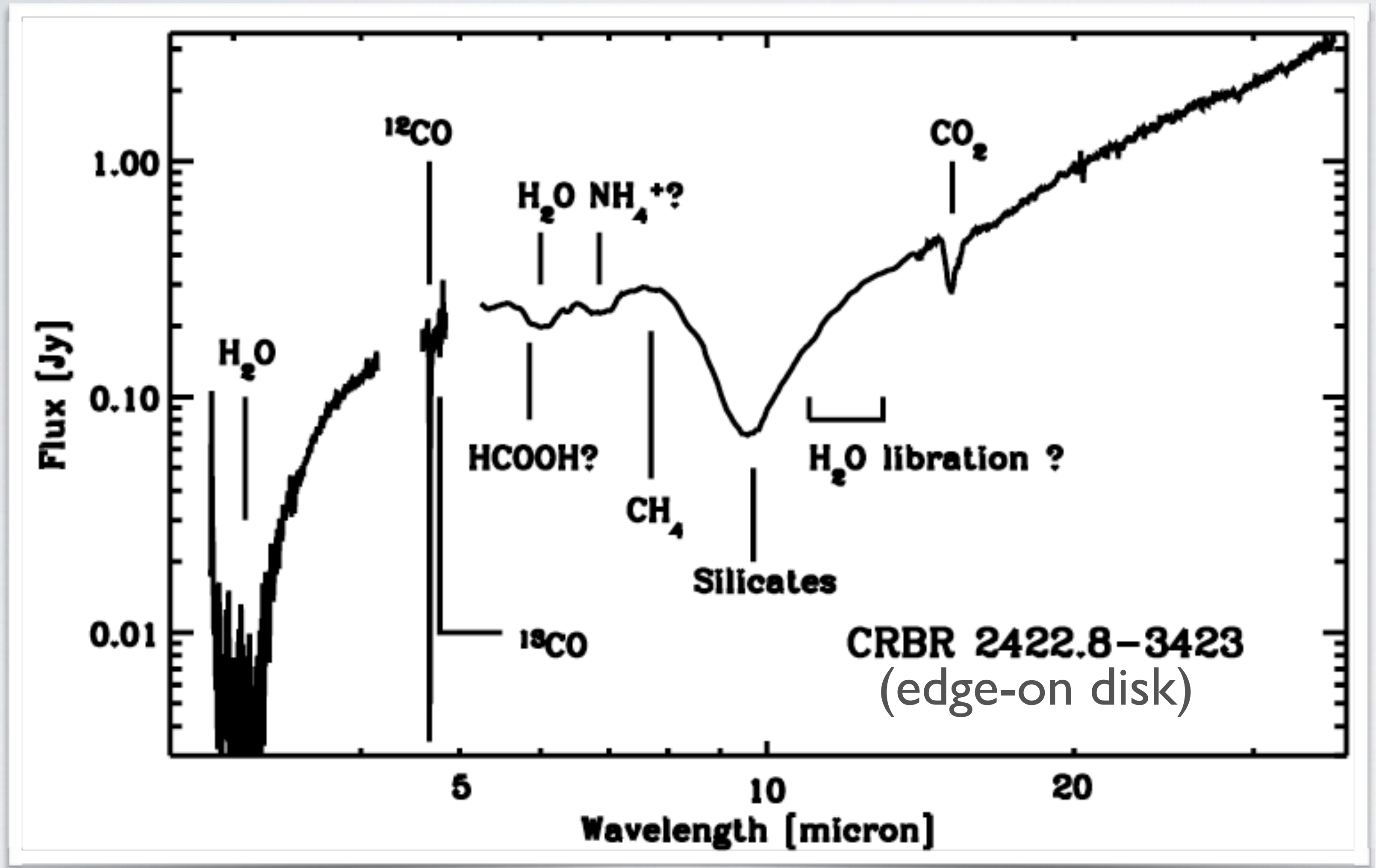
TRANSITION DISKS POPULATIONS: TIMESCALE FOR GIANT PLANET FORMATION

Transition disks stage represents ~10-25% of disks. It begins early, continues at similar rate over disk lifetime. Combined with large gap sizes, suggests gravitational instability?





CRITICAL PLANET-FORMING INGREDIENTS IN DISKS: ICES

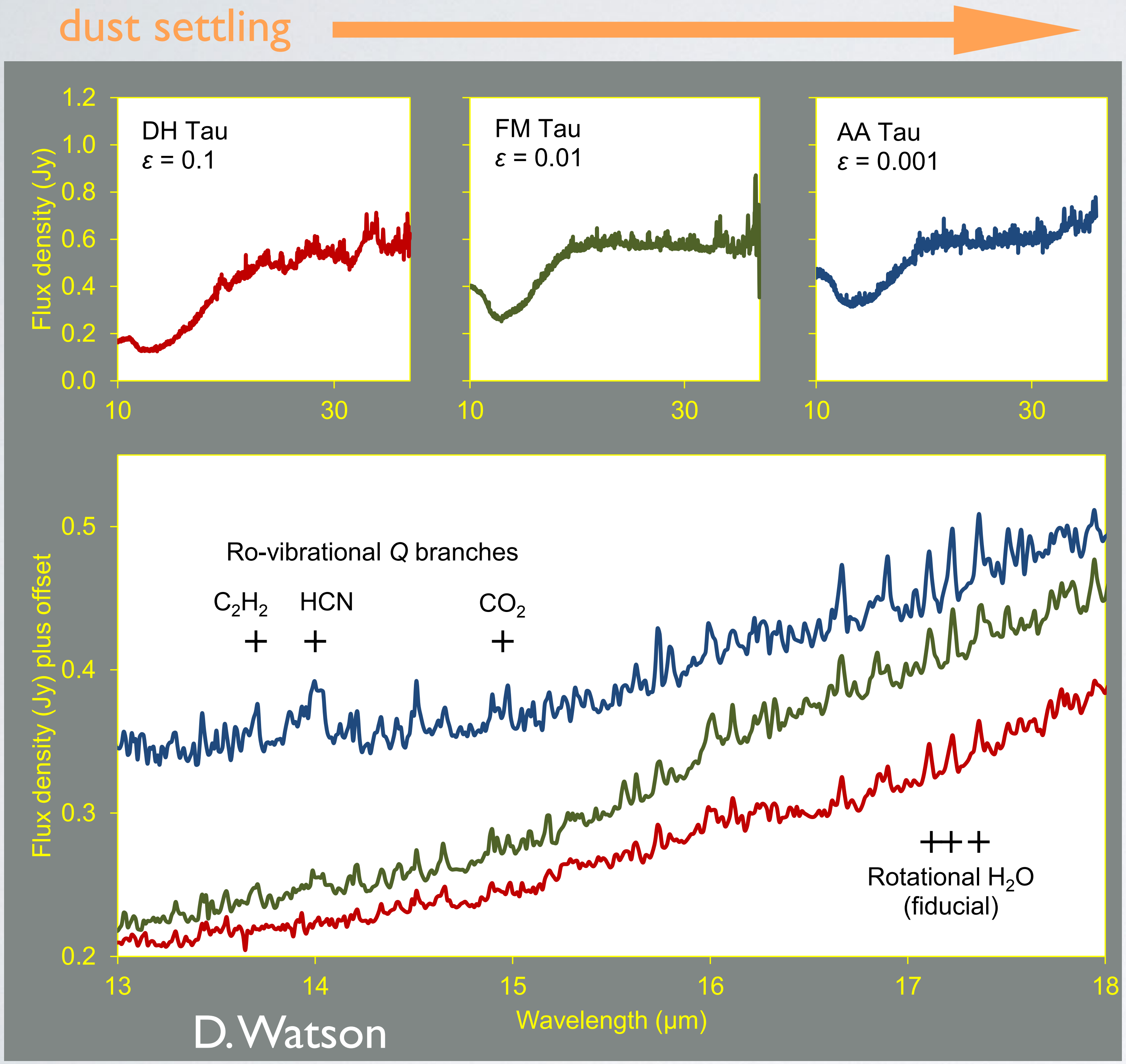


Pontopiddan et al. (2005)

- Presence of many ices in edge-on disks, including more complex organics like methanol
- Mixing of complex organics in CO_2 ice feature
- Processing of 6-8μm complex

JWST will be able to disentangle ice blends to trace ice evolution from clouds to disks (GTO, ERS proposals). HIRMES & OST will be able to detect thermal ice emission seen with Herschel (McClure et al. 2015).

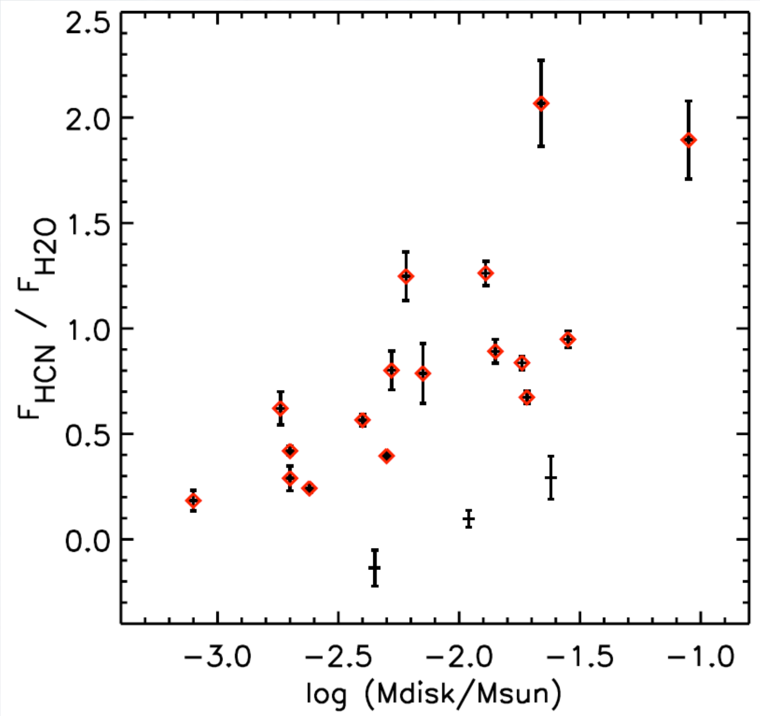
CRITICAL PLANET-FORMING INGREDIENTS IN DISKS: GAS PHASE ORGANICS AND WATER



- *Spitzer* hi-res: extensive H2O & OH emission line forest, select organics (blended)
- T~300-1000 K (inner 4 AU)
- Strength increases with settling (less dust extinction)

Carr & Najita (2008); Pontopiddan et al. (2010)

CRITICAL PLANET-FORMING INGREDIENTS IN DISKS: SOLIDS LOCKED IN THE OUTER DISK?



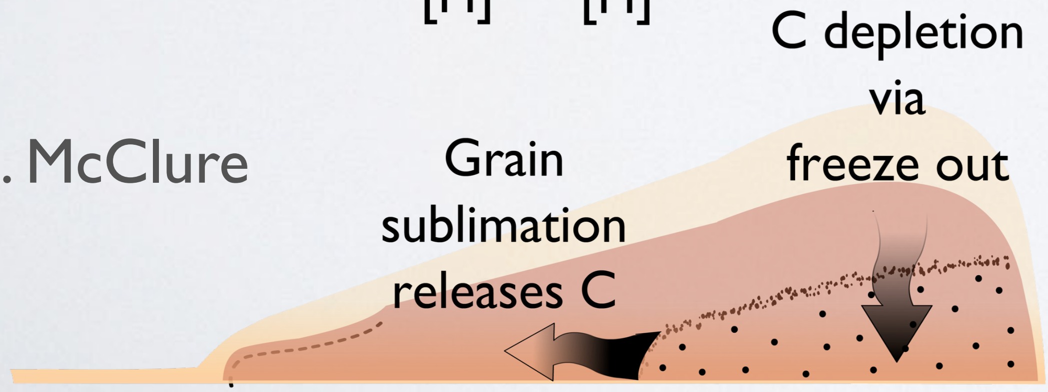
Najita et al. (2011, 2013)
Kama et al. (2016)

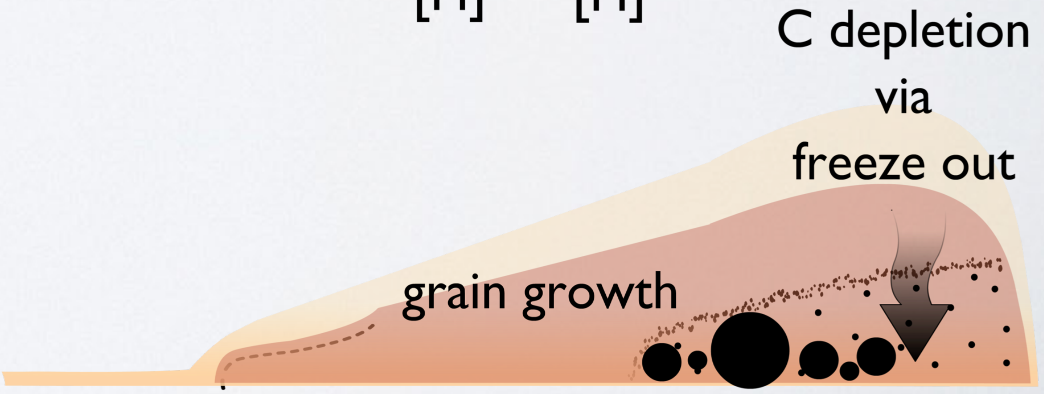
- F_{HCN}/F_{H2O} (inner disk) correlates with sub-mm flux (outer disk)
- Volatile locking could cause C/O variation, explaining some of the spread in flux ratios
- evidence for locking in complex organic signatures…

1) Volatile release: $\frac{[C_{in}]}{[H]} > \frac{[C_{out}]}{[H]}$

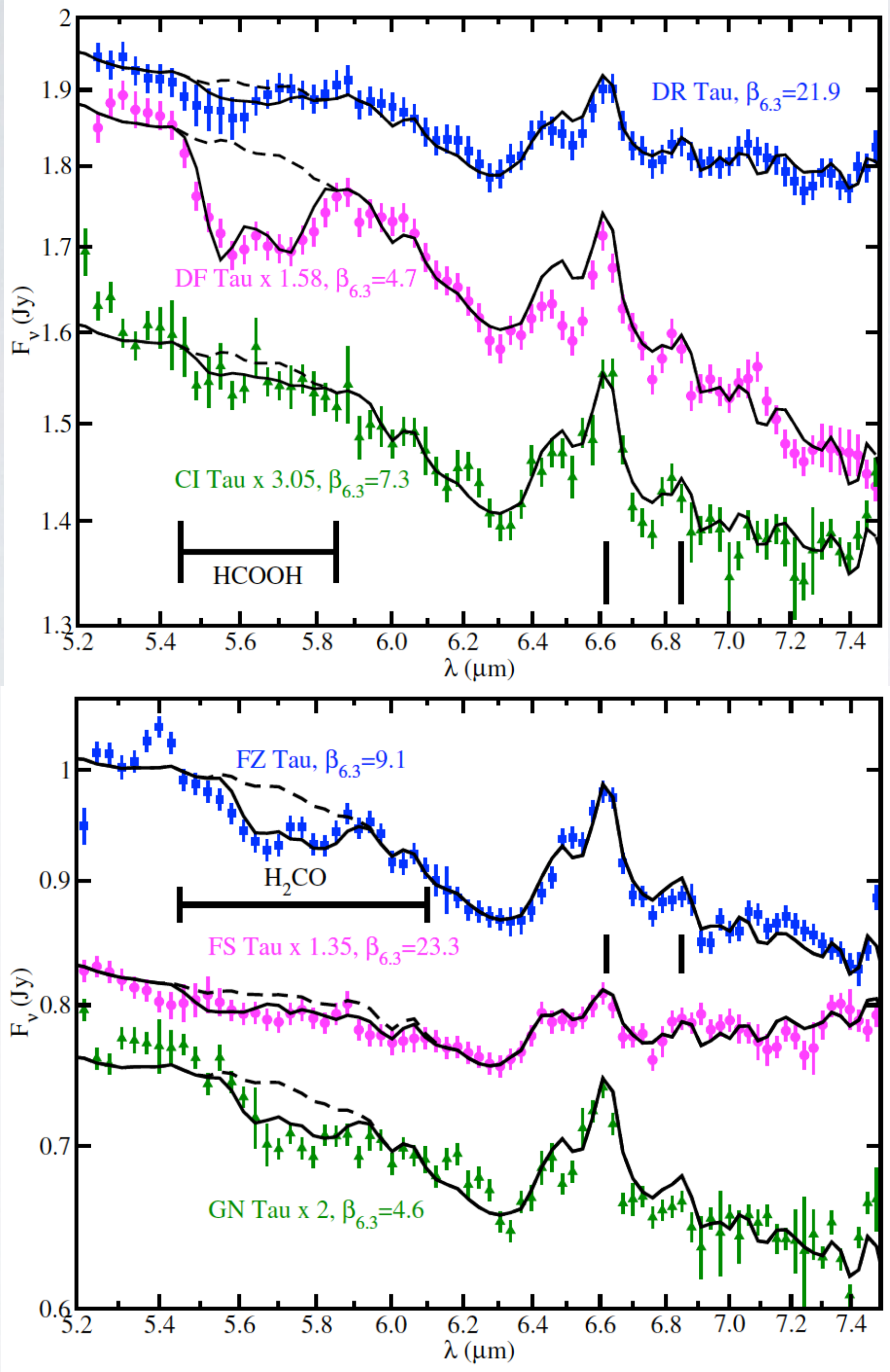
2) Volatile locking: $\frac{[C_{in}]}{[H]} \leq \frac{[C_{out}]}{[H]}$

M.K. McClure





Critical planet-forming ingredients in disks: Complex organics



Sargent et al. (2014)

- *Spitzer* low-res: hot H_2O emission line and more complex organics formaldehyde (H_2CO) and formic acid (HCOOH)
- T~1200 K (inner 0.2 AU) for water, T~500-1000 K.
- Formaldehyde produced by CO ice hydrogenation: consistent with CO depletion mechanism proposed to explain low CO/H2 ratio for TW Hya (ALMA; Schwarz et al. 2016)

Really need JWST to disentangle bands.

SUMMARY

Spitzer IRS showed us that protoplanetary disks:

✓ can settle dust to the midplane by 0.7 Myr

✓ experience grain growth even in upper layers, but 10μm feature is tricky to interpret due to silicate rim contribution

✓ show evidence for high velocity planetesimal collisions in a substantial population

✓ have giant planets already by 0.7 Myr.

✓ display strong lines of water and organics that are building blocks for the more complex molecules necessary for life.

Look for future progress with JWST, HIRMES, and OST.