Radial Dust Migration in the TW Hydra protoplanetary disk

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Theory of radial dust migration

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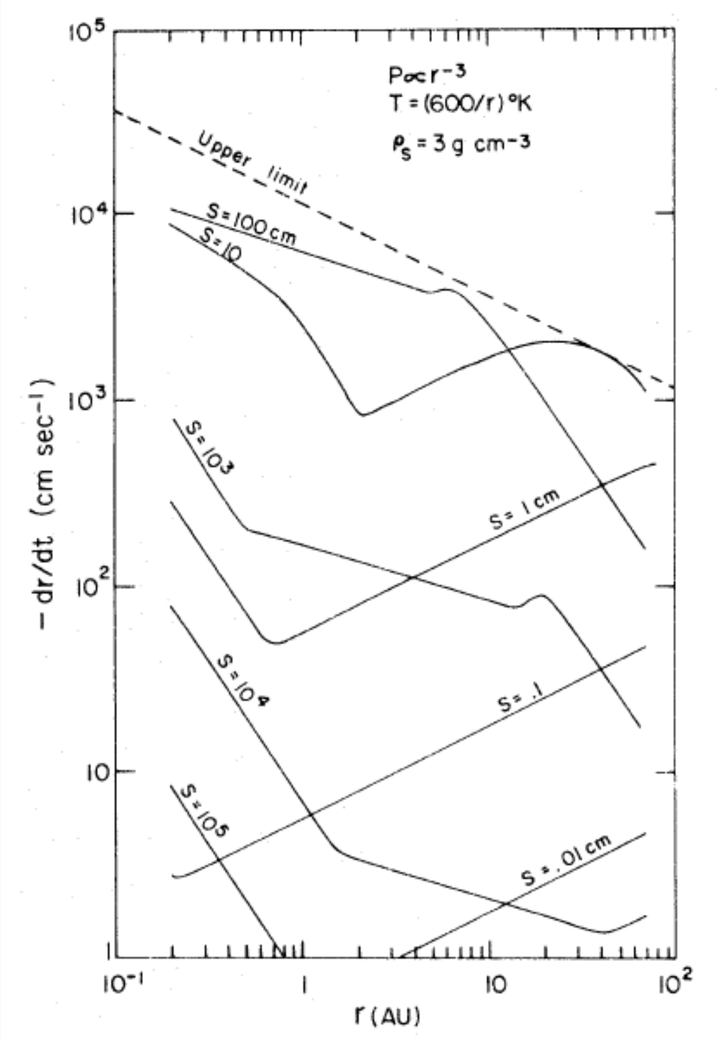
- Grains < 1 m migrate very fast – too rapid for planets to form! Yet they do.... (Weidenschilling 1977, Nakagawa 1986)

assuming MMSN



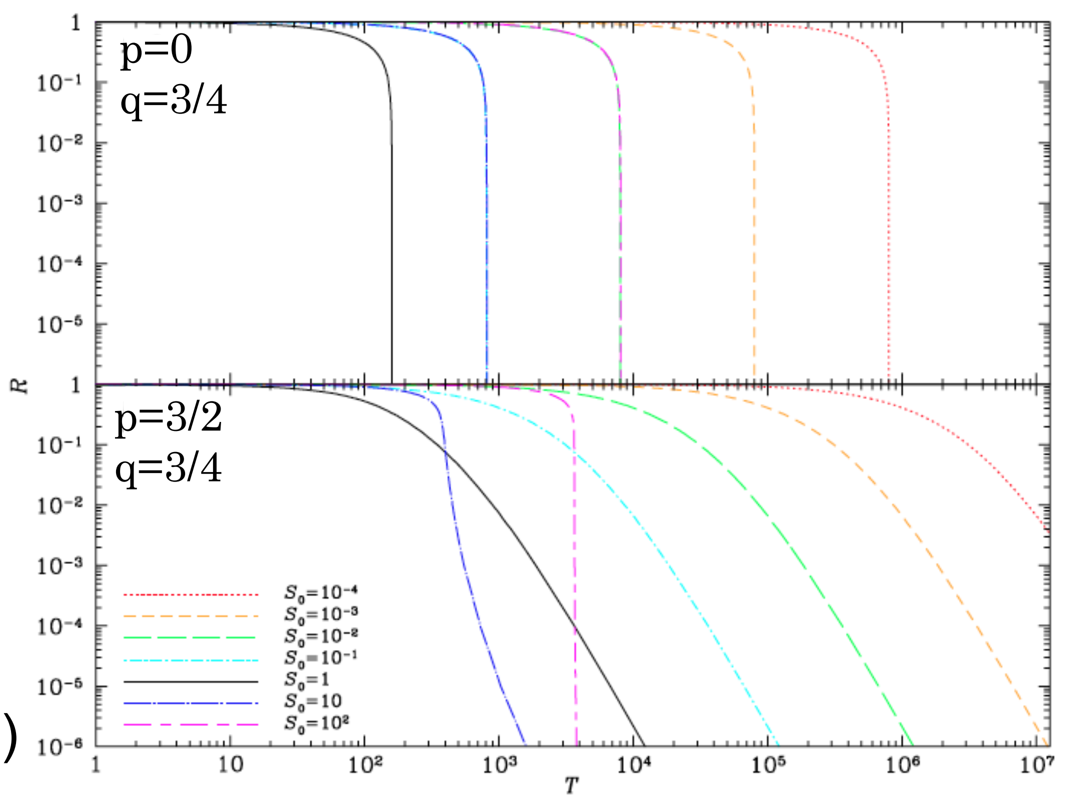
Small particles coupled with gas, large particles decoupled

(Weidenschilling 1977)

Theory of radial dust migration

- Grains < 1 m migrate very fast – too rapid for planets to form! Yet they do.... (Weidenschilling 1977, Nakagawa 1986) *assuming MMSN*
- Recent improvements:
  - depending on Σ(r), T(r) and grain growth, can keep dust for longer than disk lifetime

(Youdin & Shu 2002, Dullemond & Dominik 2004, Birnstiel et al. 2009, Youdin 2011, Laibe et al. 2012)



(Laibe et al. 2012)

Obs of radial dust migration

- Some 1.3−3 mm observations suggest larger grains centrally concentrated (Isella et al. 2010, Guilloteau et al. 2011)

→ But generally lack observational constraints

TW Hydra ideal to study migration

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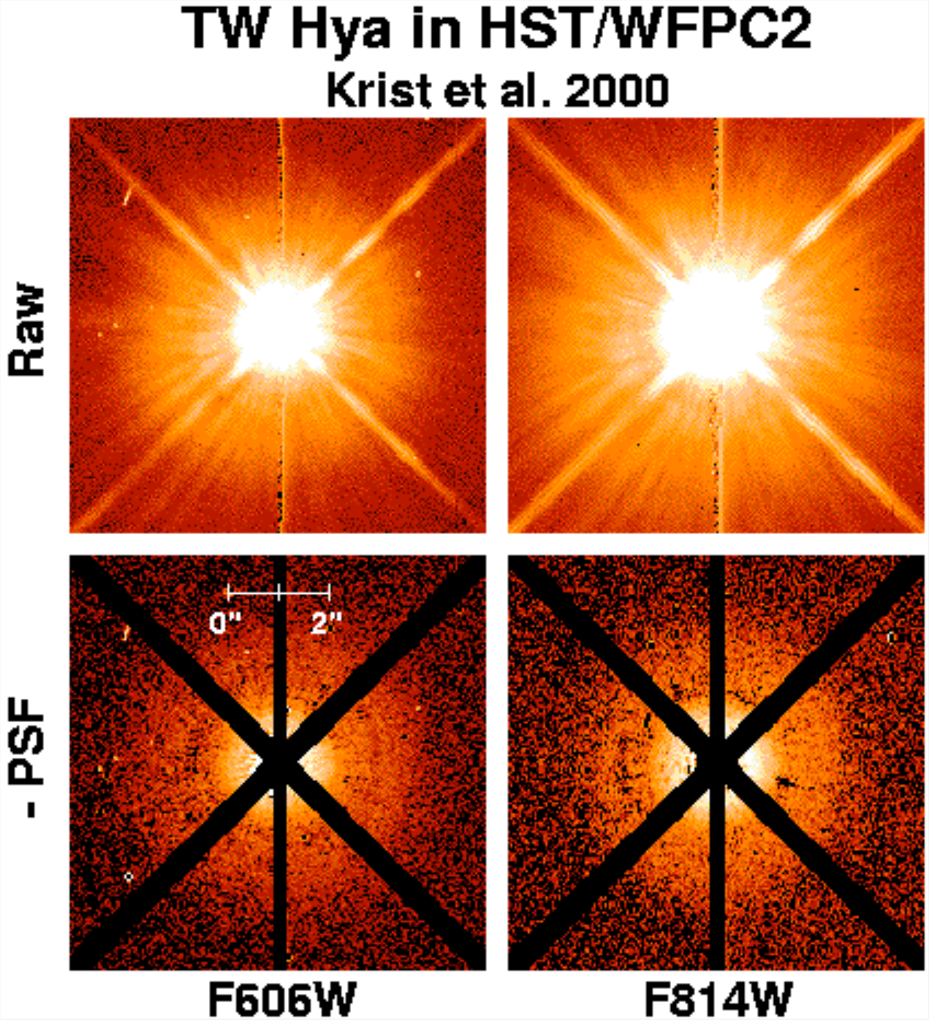
- Nearest T Tauri star, massive gas-rich disk
  - d = 56pc
  - age= 3-20 Myr (ave. 10 Myr)
- Disk **very** well studied:
  - discovered in scattered light (Krist et al. 2000)
  - dust continuum and molecular line images @ several λ
- Multi-epoch, multi-λ studies [sub-mm and mm]:
  - 870 μm @ SMA (Qi et al. 2004; Andrews et al. 2012)
  - 1.3 mm @ SMA/CARMA (Hughes et al. 2008; Isella et al. 2009)
  - 3 mm @ ATCA (Wilner et al. 2003)
  - 7 mm @ VLA (Wilner et al. 2000, Hughes et al. 2007)
- Extensive models exist (Thi et al. 2010, Gorti et al. 2011)

TW Hya in scattered light



Disk pole-on!

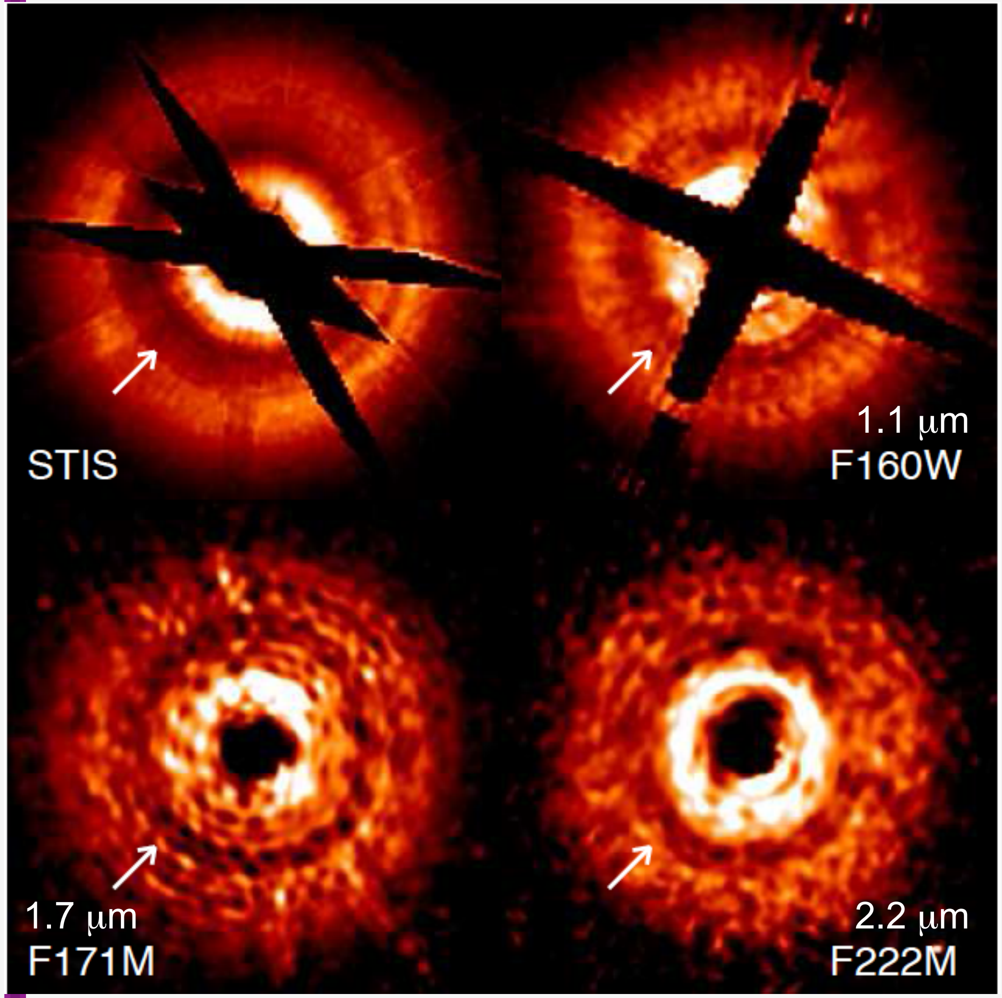
- (useful → use visibility profiles instead of images)

R_{out} > 200 AU

Break in surface brightness ≈ 60 AU (1'')

- colour change @ break(Roberge et al. 2005)

TW Hya in scattered light



(Debes et al. submitted)

Disk pole-on!
- (useful → use visibility profiles instead of images)

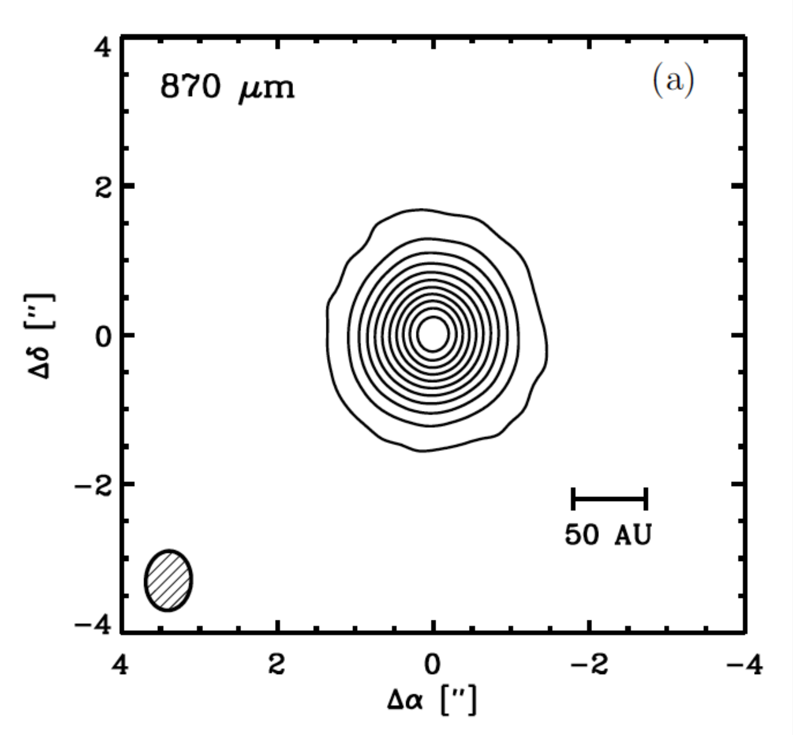
R_{out} > 200 AU
- (sensitivity limited)

Break in surface brightness ≈ 60 AU (1'')
- colour change @ break(Roberge et al. 2005)

Recent HST obs dip in surface brightness ~80 AU and sharp cutoff ~150 AU

870 μm data & results

(Andrews et al. 2012)



Emission @ 870 μm compact

- all emission within 60 AU
- sharp edge @ 60 AU provides better model fit

870 μm data & results

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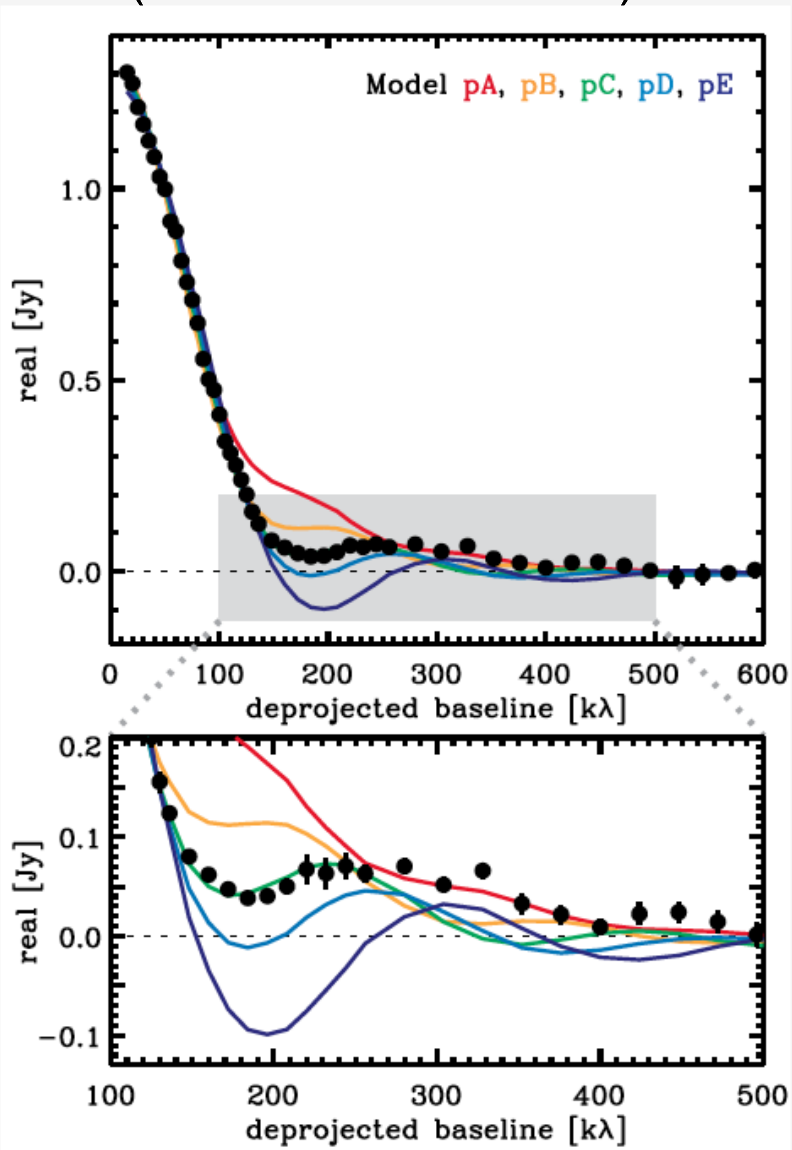

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870 μm emission much more compact than scattered light or CO disk

- R_{out_870} ≈ 60 AU
- $R_{out\_scattered}$ > 200 AU
- R_{out_CO} > 215 AU

Previous 7mm data & results

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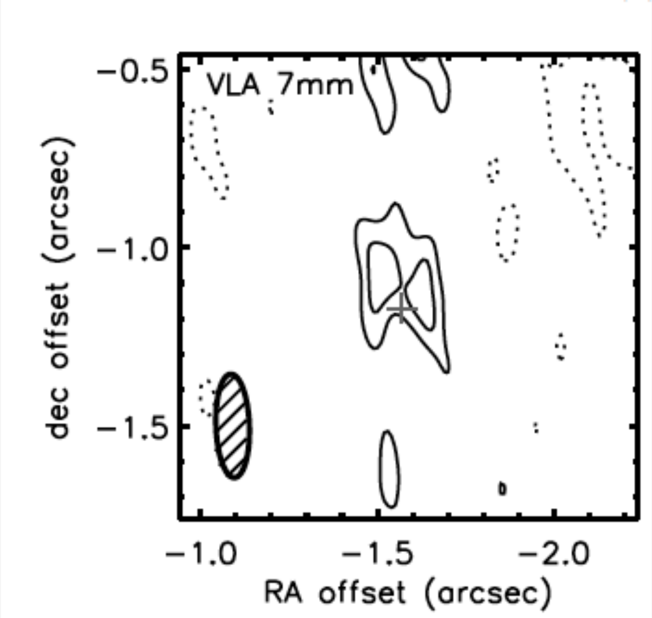
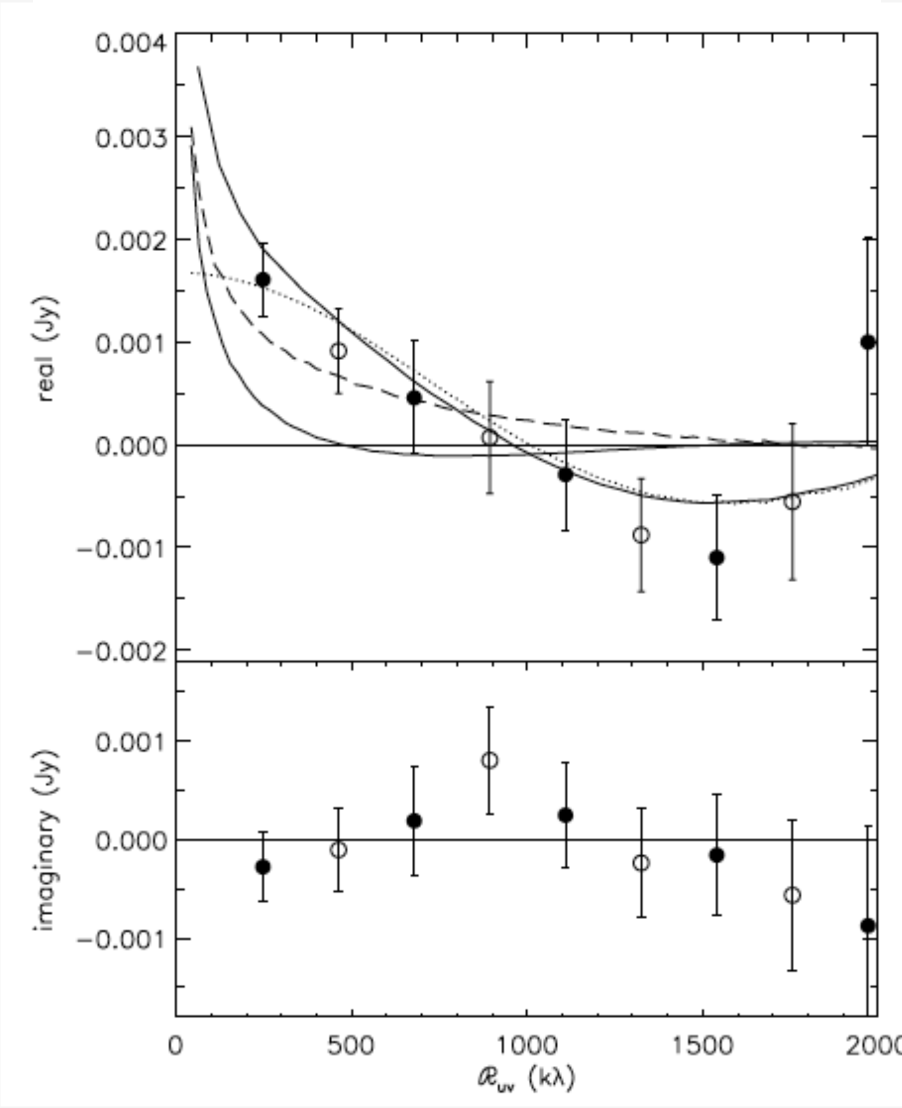
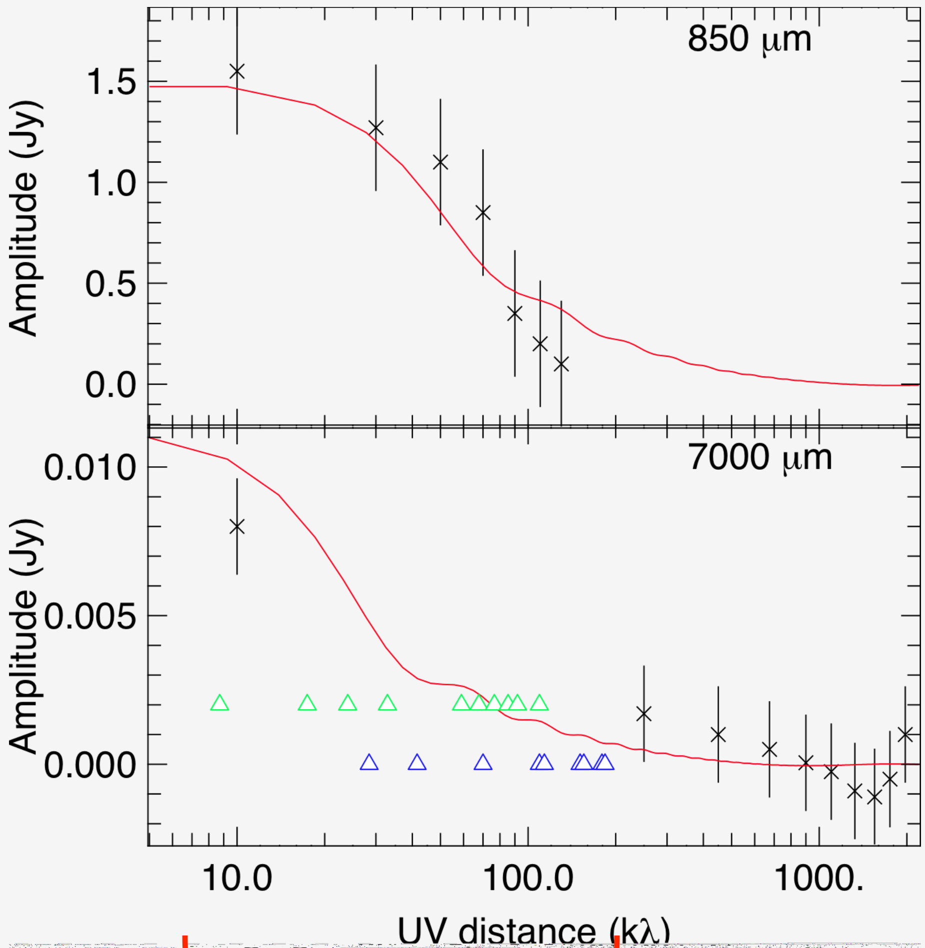
(Hughes et al. 2007)

- Inner hole in disk
- Visibility null shows peaked emission @ 4 AU (≈ 1000 kλ)
- Incomplete UV coverage
  - no info < 200 kλ
  - no info on larger scale

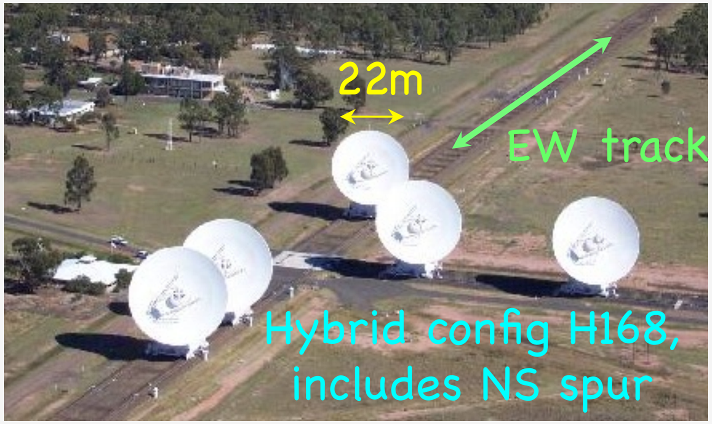




Filling the uv-plane at 7mm



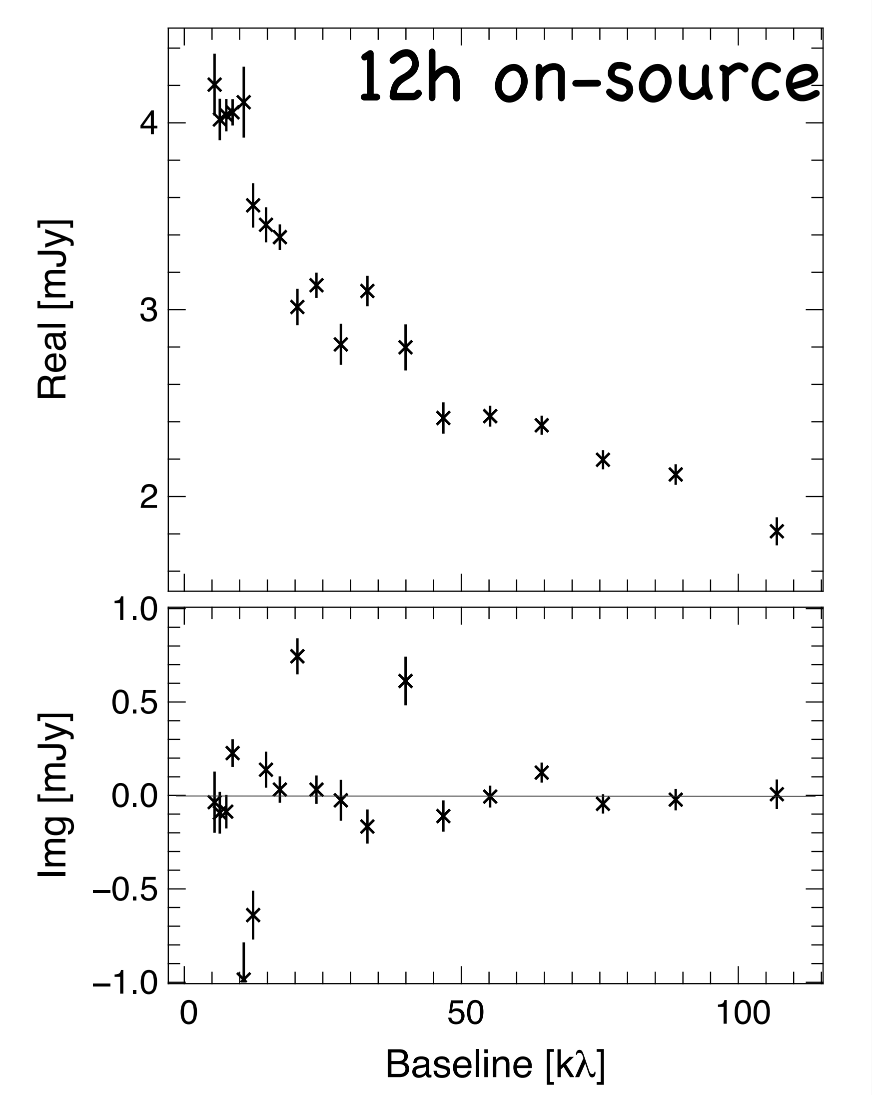
ATCA < 200 kλ



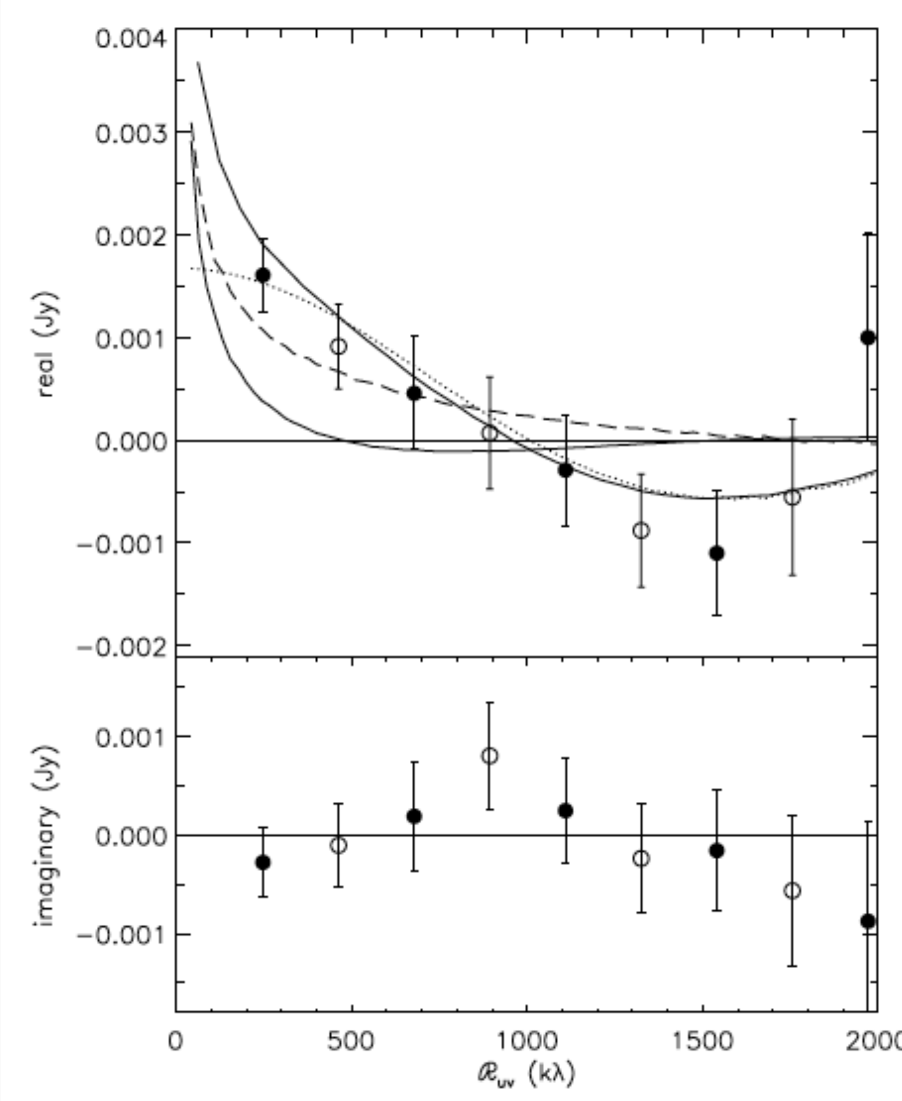
Australia Telescope Compact Array
- 6 element array
- mm bands: 3, 7, 15
 (and cm to 21cm)
- compact hybrid, extended 6km

Filling the uv-plane at 7mm

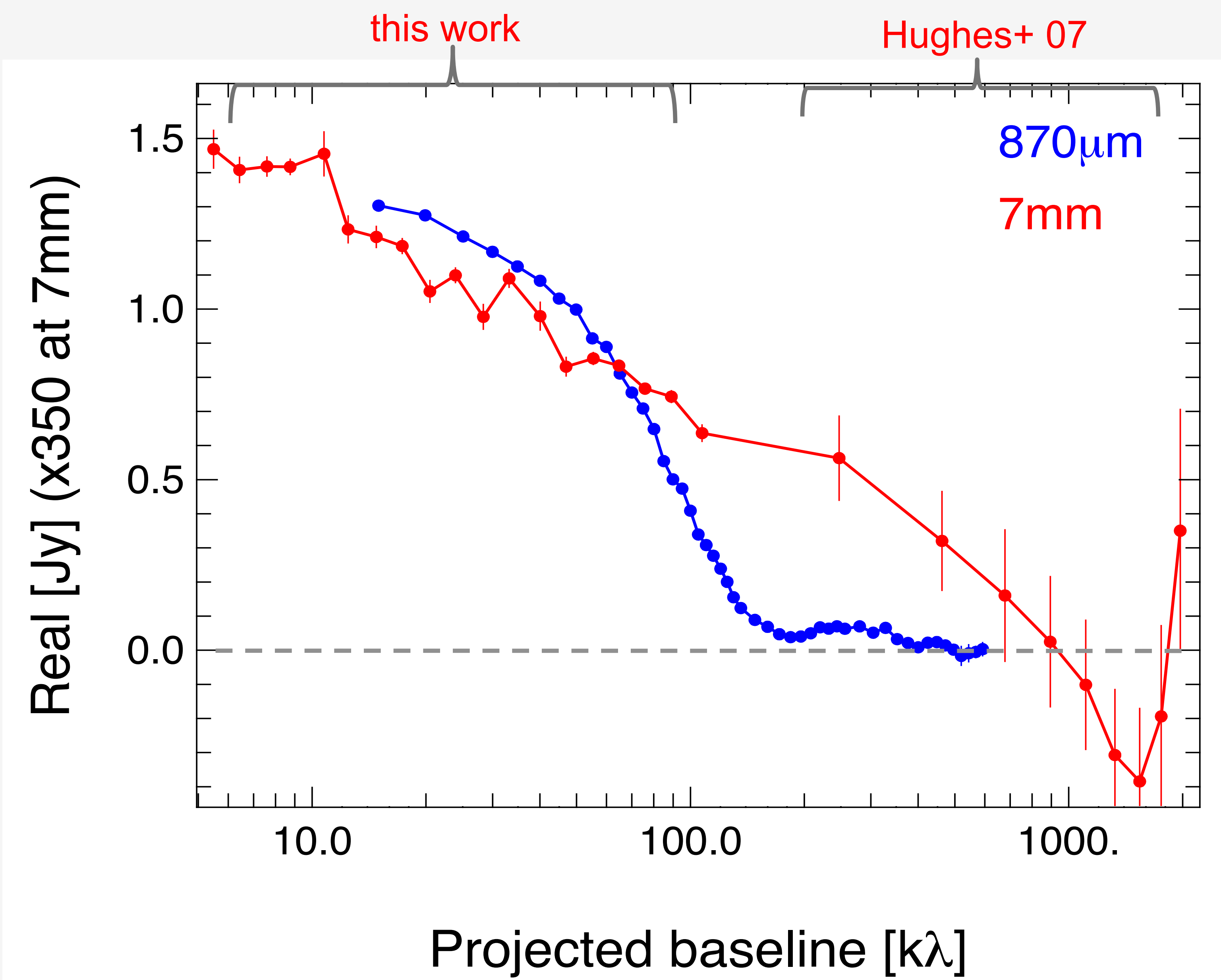
This work: ATCA 44 GHz



Hughes et al. (2007)



Putting it all together: 870μm vs 7mm



Interpretation:

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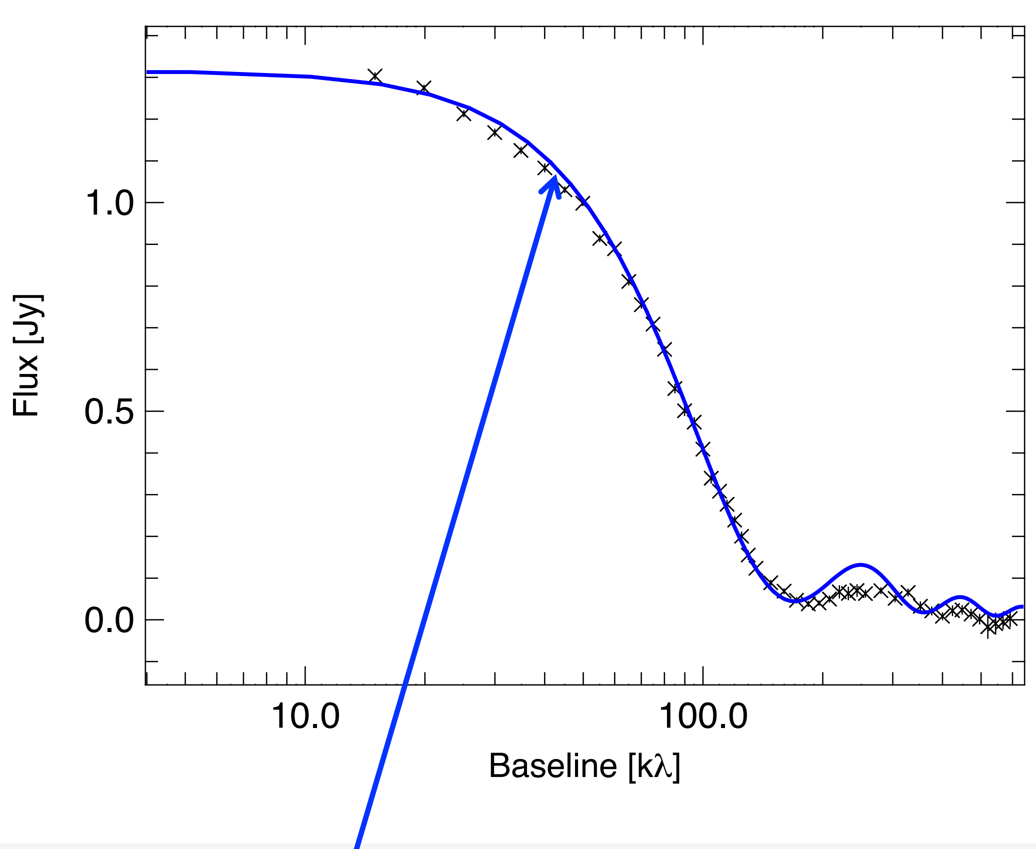
Surface brightness distribution model

870 μm

- R^{-1} profile needed
- with sharp cutoff @ 60 AU
- no need for significant emission outside

→ Same conclusions as Andrews et al. (2012)
no surprise !



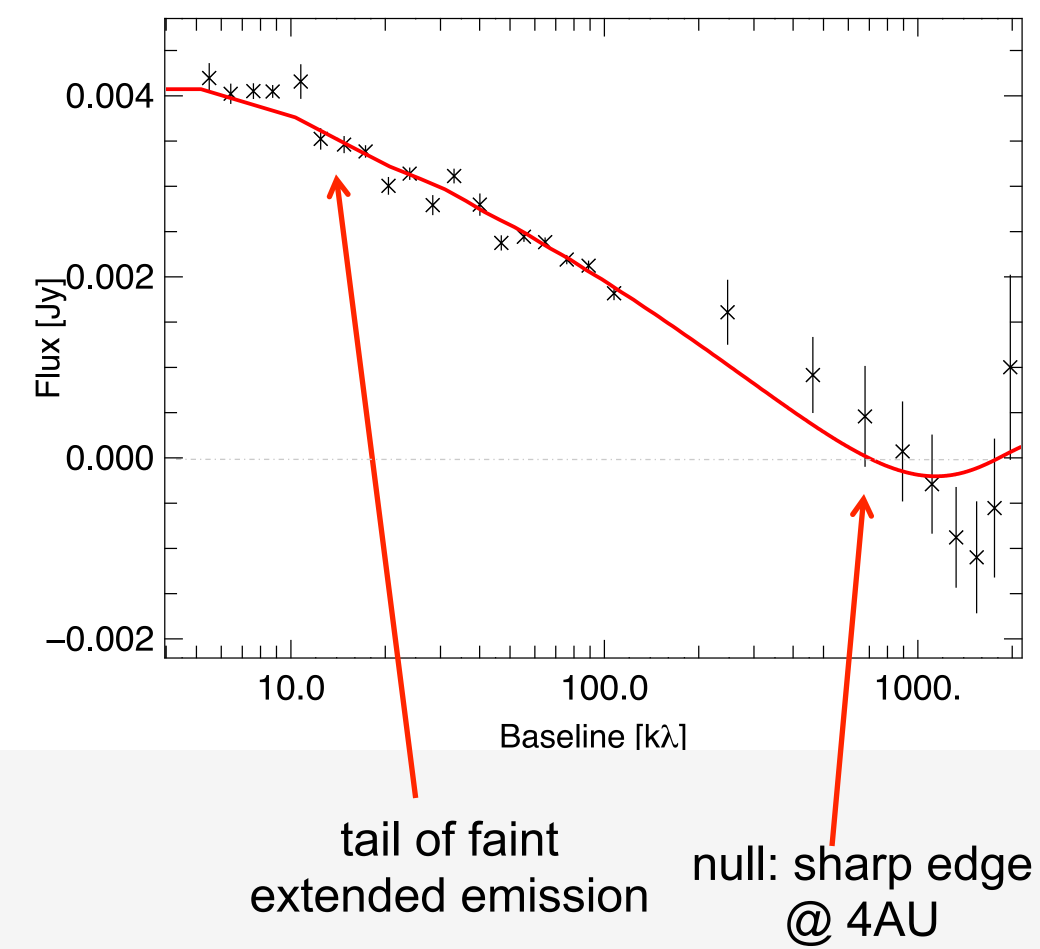
slope change :
60 AU cutoff

Interpretation:

Surface brightness distribution model

7 mm

- R^{-2} profile required
  very peaked inside
- $R_{in} \approx 4$ AU needed
  → something 'halting' the migration
- nothing special @60 AU
- includes tail of faint extended emission (similar to scattered light)
  → $R_{out} \geq 200$ AU



Interpretation:

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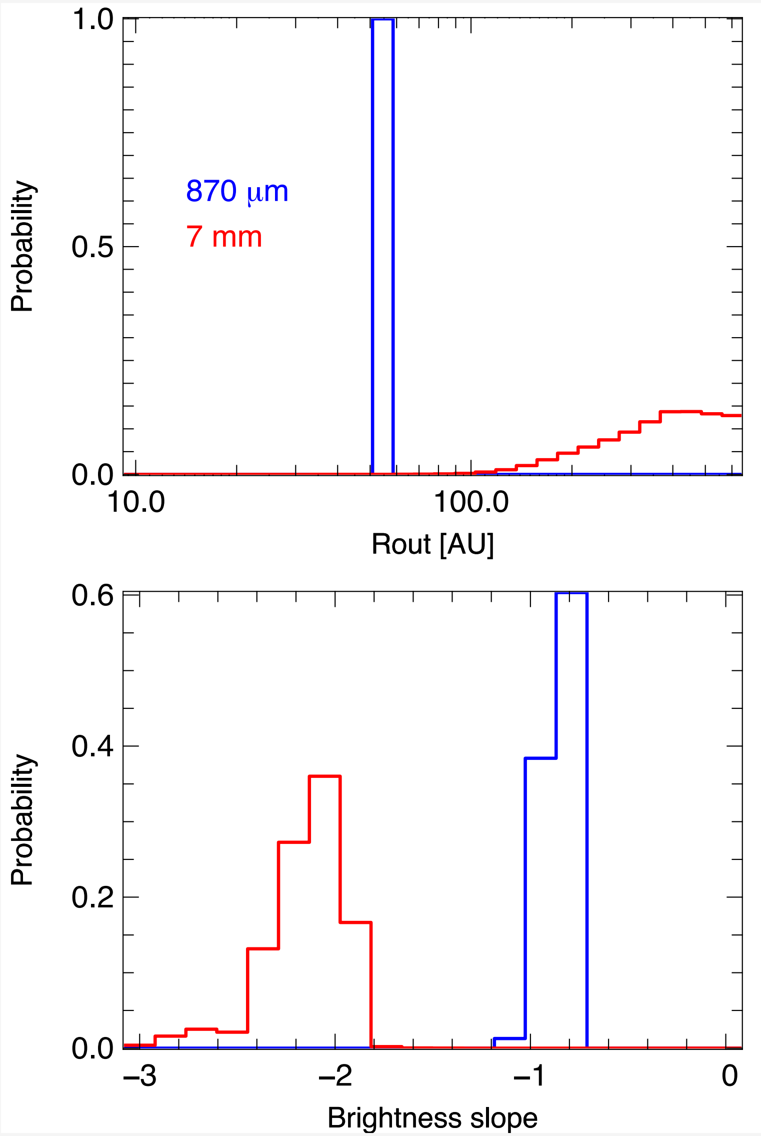
Separate dust populations needed **870 μm** + **7 mm**



Emission profiles different and trace different dust populations

- 870 μm : 50−300 μm grains
- 7 mm : 1 mm - 1cm grains

λ-ratio ≈ 10 : limited overlap

Models with radially well-mixed dust: ruled out!

Broad picture: radial migration

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Roughly we have:

- 7mm emission (large > mm grains): more peaked toward center, but extended to > 200 AU
- 870 µm emission (≈ 100 µm grains): emission with intermediate size & sharp cut-off
- Scattered light (µm-sized grains): extended over full disk

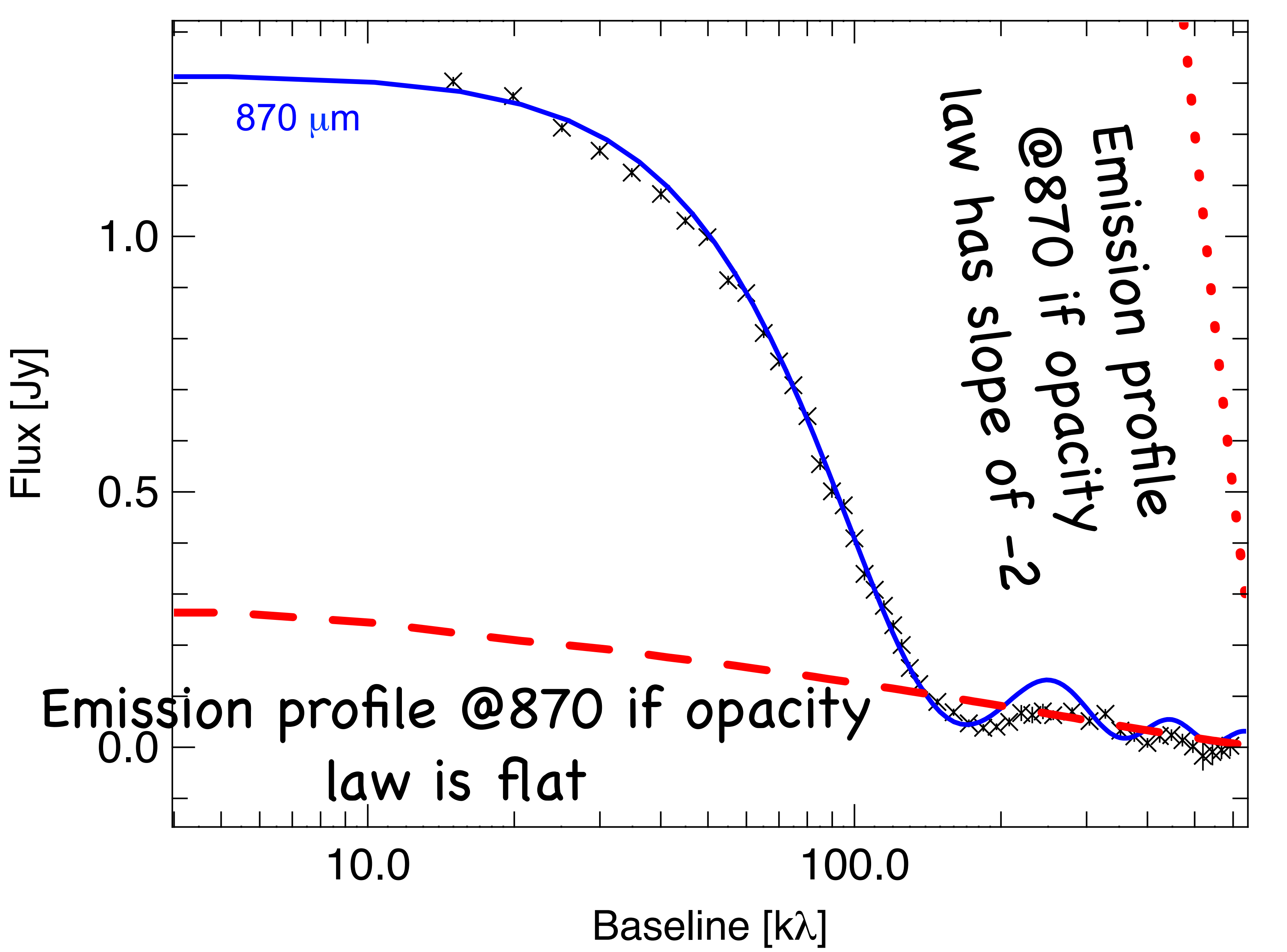
→ Big particles inside, small particles outside…

Discussion: the outer disk

Q: Why 7mm + scattered light extended over full disk (≥ 200 AU) like CO gas disk, but not 870 μm?

- Small grains (< 10 μm) present: won't emit significantly at 870 μm or 7 mm
- How large a grain would it take to emit at 7 mm (between 60−200 AU) and not at 870 μm?

Discussion: the outer disk



Discussion: the outer disk

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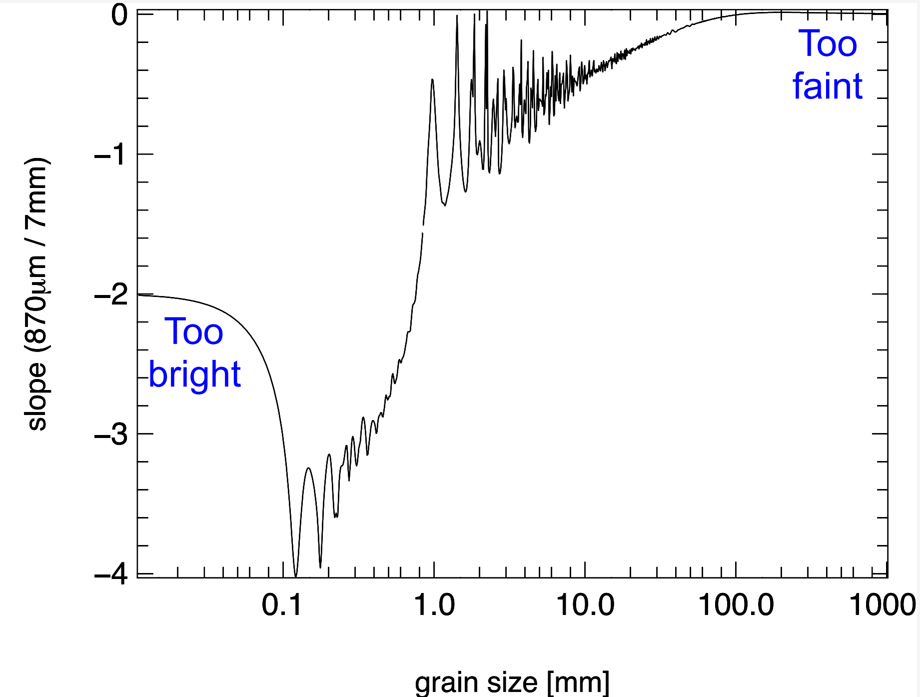
Q: Why 7mm + scattered light extended over full disk (≥ 200 AU) like CO gas disk, but not 870 μm?

- Small grains (< 10 μm) present: won't emit significantly at 870 μm or 7 mm
- How large a grain would it take to emit at 7 mm (between 60−200 AU) and not at 870 μm?

- if opacity ratio 870/7000 ≈ 1

→ implies grains ≥ 10 cm



FINE PRINT WARNING: strongly dependant on shape of visibility!

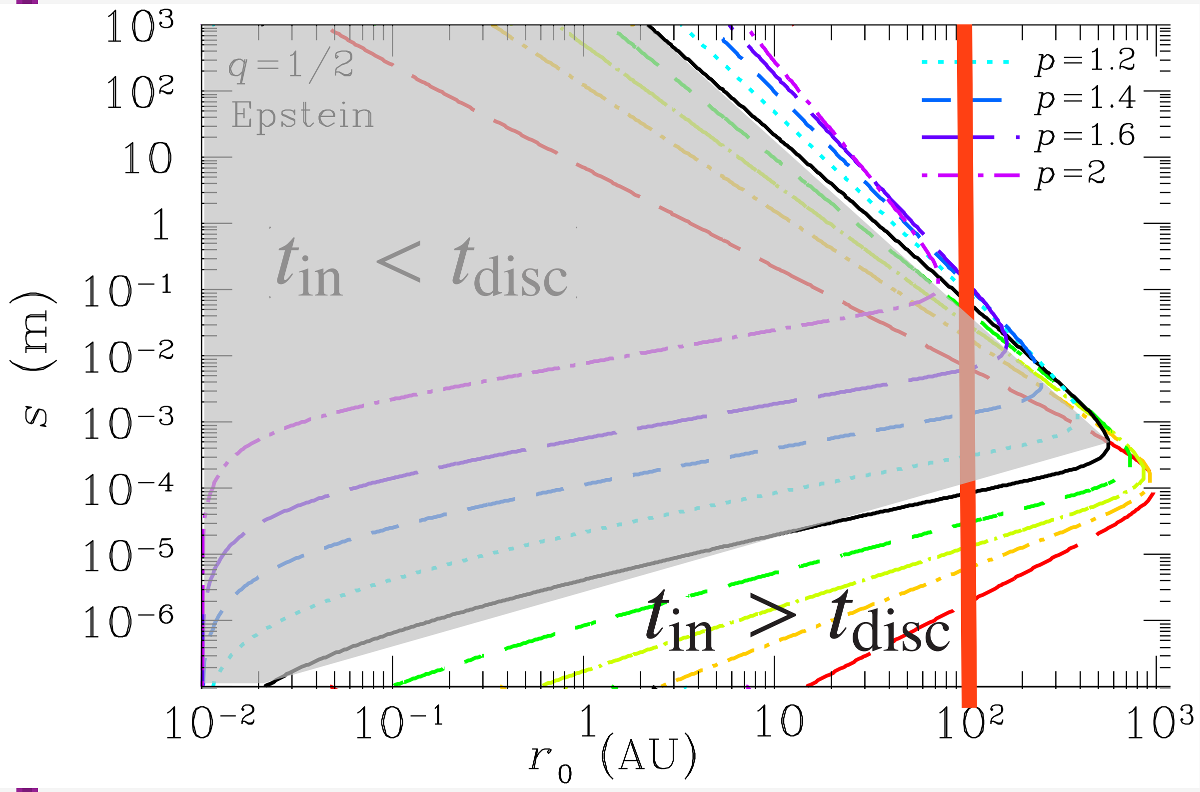
Discussion: the outer disk

Very small grains (≤ 10 µm)

- v. strongly coupled to gas
- agrees with scattered light
- don't emit much @ λ_{mm}

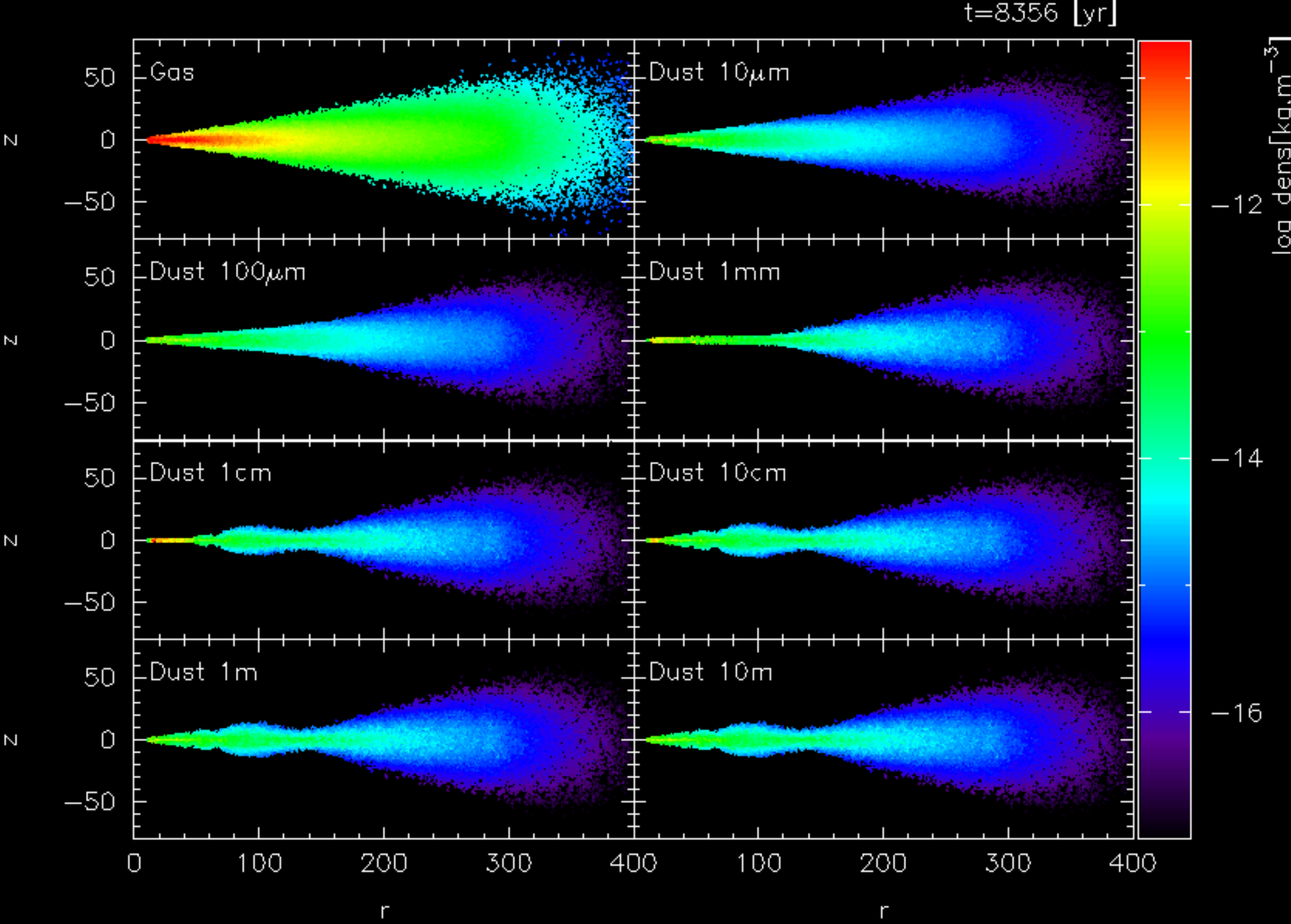
Big grains (≥ 10 cm)

- decoupled from gas
- similar extent 7mm emission
- remain undetected @ 870µm



≈ 100 µm−1mm optimal grain size for migration at R > 100 AU for this disk ??

(Laibe et al. 2012)


t=8356 [yr]
Gas
Dust 10μm
Dust 100μm
Dust 1mm
Dust 1cm
Dust 10cm
Dust 1m
Dust 10m
z
r
log dens[kg.m^-3]
-12
-14
-16
50
0
-50
0
100
200
300
400

s (m)

Concluding remarks: what we see

- Unambiguous evidence of radial migration in TW Hya ("easy" as it's nearby, good λ coverage). Clearly see:
  - Scattered light: μm grains well-coupled to extended gas -
    . disk > 200 AU
    . something funky at 60 AU…
  - 870 μm: 100 μm grains compact
    . disk within 60 AU
  - 7 mm: 10 cm grains very peaked
    . grain pile-up 4 AU
    . but extended tail with small grains > 200 AU
  - Dust @ 4 AU: something preventing inward migration
  - gas pressure max, hidden planet?
  - Transition @ 60 AU: "sweet spot" for rapid migration of 100μm – 1mm grains??

Concluding remarks: what it means!

- Dust pile-up @ 4 AU:
  - something preventing inward migration
  - gas pressure max, hidden planet?
- Transition @ 60 AU:
  - “sweet spot” rapid migration for 100μm–1mm grains??
  - Messy mix of migration, growth, fragmentation
- ALMA to the rescue!
  - 3 mm ALMA will help understand dust size distribution
  - plus tons of fun for dynamic modellers ☺

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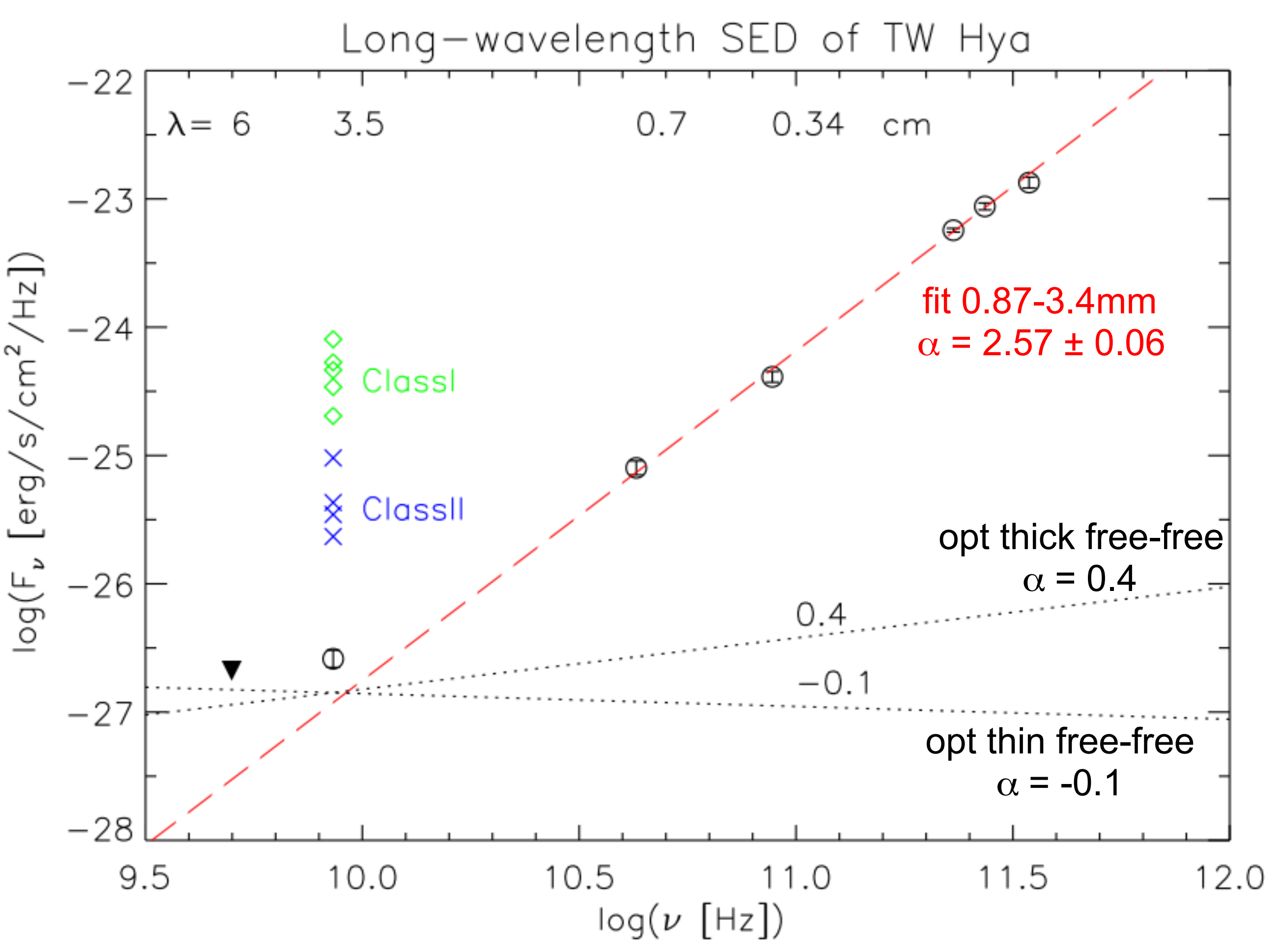
Thermal dust at 7mm



Pascucci et al. (2012)

→ free-free contributes @ 3.6 and 6 cm, but not 7 mm