Observing Accretion Disks I:

Basics of Observing Disks and Continuum Emission

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Topics I would like to cover

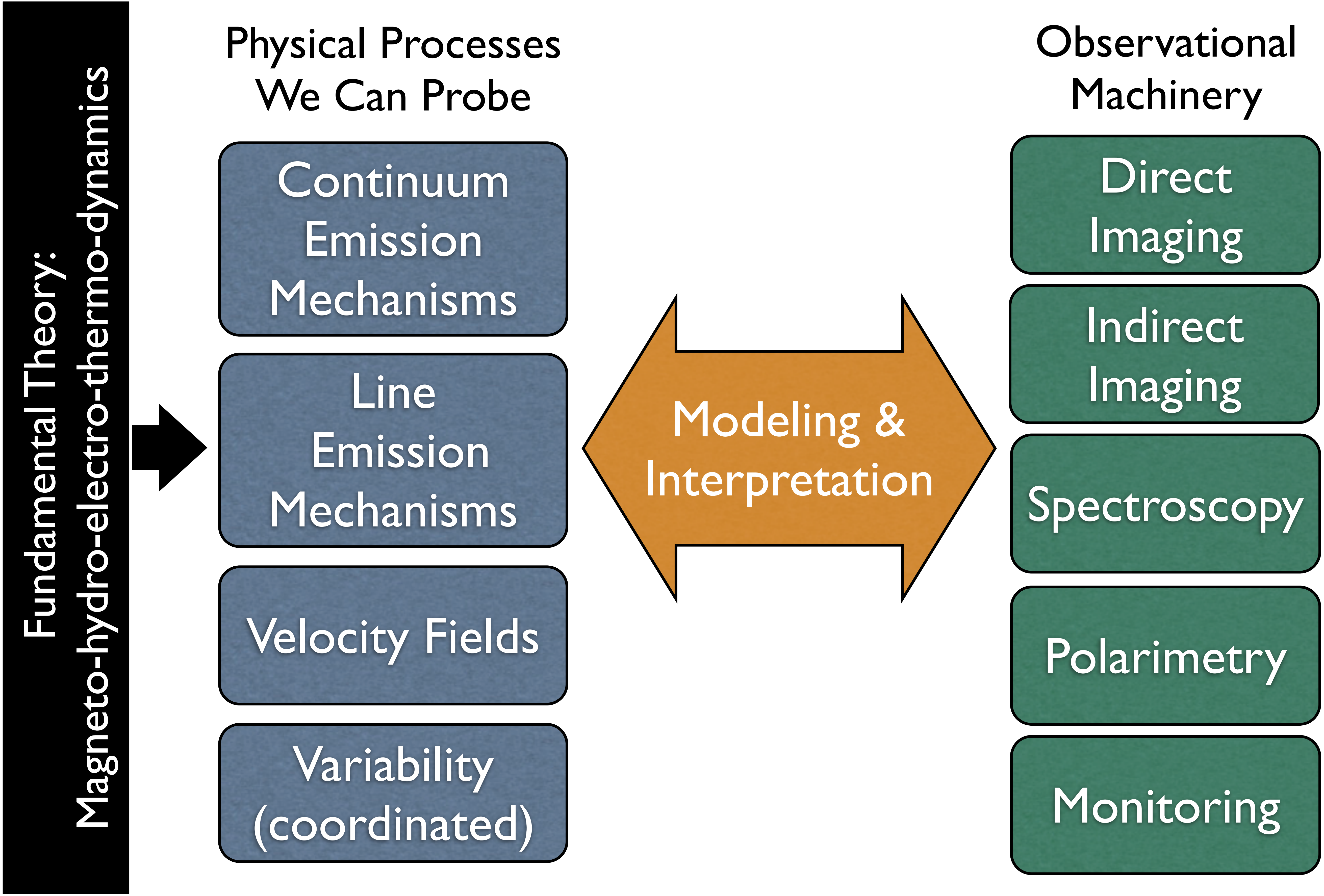
How we observe disks

- Spectral energy distributions → thermodynamics
- Emission lines → velocity field and structure
- Variability → time scales and instabilities
- Indirect imaging → spatially-resolved structure

Things we learn from observations

- What structures do we see in disks?
- How well does the theory work?
- How much faith should we have in the results?

General Philosophy



Fundamental Theory:
Magneto-hydro-electro-thermo-dynamics

Physical Processes We Can Probe

- Continuum Emission Mechanisms
- Line Emission Mechanisms
- Velocity Fields
- Variability (coordinated)

Modeling & Interpretation

Observational Machinery

- Direct Imaging
- Indirect Imaging
- Spectroscopy
- Polarimetry
- Monitoring

The Three Lectures

Intro and Continuum Emission

- The basics of observing disks
- Spectral energy distributions

Emission Lines and Indirect Imaging

- Eclipse mapping
- Emission lines from disks and diagnostic value
- Doppler tomography

AGN Disks and Their Emission Lines

- The disk as the source of the emission lines
- Outflows as seen through absorption lines

Organization of Lecture I

- **Basics First**
    - Sizes, masses, accretion rates, temperatures
    - Distinction between CVs, XRBs, AGNs, YSOs
- **Direct Imaging of Disks**
    - Rare but extremely valuable
- **Spectral Energy Distributions**
    - Assumptions and basic calculations
    - Applications to specific types of systems
    - Lessons from comparison of models with data

Basics First...

Where do we find accretion disks?

- Interacting binary stars
  - ✦ CVs, LMXBs, (short period) Algol binaries
  - ✦ perhaps some HMXBs and some symbiotic stars
- Active galactic nuclei (AGNs)
- Protostars (YSOs)

Other types of disks

- Debris disks in main seq. stars (e.g., β Pictoris)
- Outflow disks (Be and other hot stars)

Conventions

Measure lengths in units of the gravitational radius

$$r_{\rm g} \equiv \frac{GM_\bullet}{c^2} = M_\bullet \qquad (G = c = 1)$$

For the Sun (1 $M_\odot$) r_g = 1.5 km

For a 10^8 $M_\odot$ black hole r_g = 1 AU

For compact notation, adopt a dimensionless radial coordinate

$$\xi \equiv \frac{r}{r_{\rm g}} = \frac{r}{M_\bullet}$$

Kepler's laws take a very simple form (in Greek), for example

$$\beta = \frac{1}{\sqrt{\xi}}$$

$$(\text{where } \beta = v/c)$$

Geometry and Energetics

- **Inner disk radius:**

  radius of star or close to event horizon

- **Outer disk radius:**

  set by tidal truncation in binaries
  (or gravitational instability in case of AGNs?)

- **Mass of central object:**

  can be very hard to measure, especially in AGNs

- **Accretion rate:**

$$L_{\mathrm{bol}} = \boxed{\eta_{\mathrm{rad}}} \frac{G \boxed{M} \dot{m}}{r_{\mathrm{in}}} = 4\pi \boxed{d^2} \left(\frac{F_{\mathrm{obs}}}{\boxed{\zeta_{\mathrm{bol}}}} \right)$$

Inner Disk Radius

- **radius of a WD ~ 10^8–10^9 cm (M < 1.4 $M_\odot$)**

$$R_{\rm WD} \approx 5 \times 10^8 \left(M/{\rm M}_\odot\right)^{-0.8}$$

- **radius of a NS ~ 10–15 km (M=1.4–2.7 $M_\odot$)**

M/R depends on NS equation of state

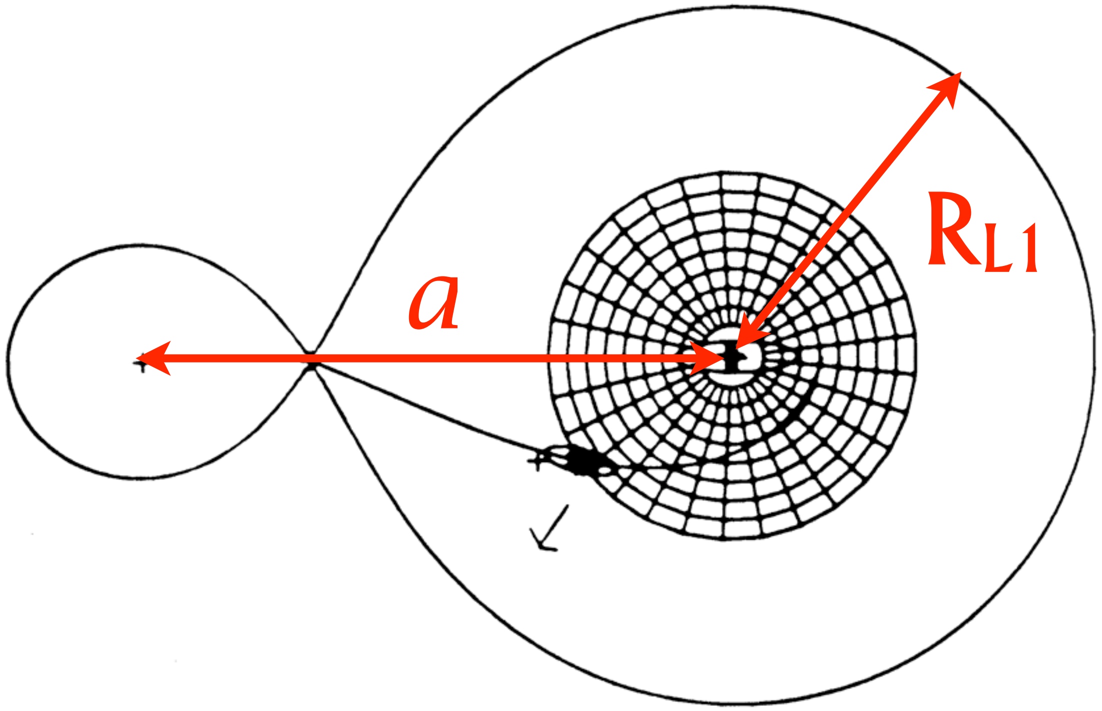
- **radius of event horizon for non-rotating BHs**

$R_S = 2GM / c^2$

~ 6 km for Stellar BH (M=4 $M_\odot$)

~ 2 AU for Massive BH (M=10^8 $M_\odot$)

Outer Disk Radius



- **CVs and LMXBs**

  $R_D \sim 0.6\,R_{L1} \sim 0.3\,a$

  $\sim R_\odot$

- **AGNs: ???**

  radius of marginal self gravity

  e.g., Goodman & Tan (2004, ApJ, 608, 108)

$$R_{\rm sg} \approx 3100 \left(\frac{\alpha_{0.3}}{\mu}\right)^{1/3} \left(\frac{\ell_E}{\epsilon_{0.1}}\right)^{1/6} \left(\frac{\kappa}{\kappa_{\rm es}}\right)^{1/2} M_8^{1/2}\,{\rm AU}$$

$R > R_{sg}$: terra incognita

	YSO	**CV**	**NS XRB**	**10^8 $M_\odot$ AGN**
ξ in	$\sim 10^7$	> 1800	4–7	2
ξ out	$\sim 10^{10}$	10^5–10^6	10^5–10^6	>1500

$$\xi = r/r_g = rc^2/GM$$

Temperature and Disk Mass

- **Temperature, non-rotating black hole disks,**

$$T_{\rm in} \propto M^{-1/4} \left(\frac{L}{L_{\rm Edd}}\right)^{1/4}$$

$$\approx 20 \left(\frac{M}{10^8\, M_\odot}\right)^{-1/4} \left(\frac{L}{L_{\rm Edd}}\right)^{1/4} \ {\rm eV}$$

- **Disk Mass:**
  - Estimate: mass should be accreted in a viscous time

$$M_{\rm D} \sim \dot{m}\, \tau_{\rm visc}(\xi_{\rm out})$$

  - Mass also derived from fits to the SED

	YSO	**CV**	**NS XRB**	**$10^8 M_\odot$ AGN**
M_D ($M_\odot$)	~ 0.1–1	~ 10^{-11}	~ 10^{-11}	~ 10^5
T_{max}	~ 10^2 K	~10^4 K few eV	~10^7 K 1–2 keV	~10^5 K ~20 eV
Ideal band	FIR	UV	X-ray	EUV

Can We Image Disks Directly?

Nearest CVs

- 1 $R_\odot$ @ 50 pc → 0.6 milli-arcsec

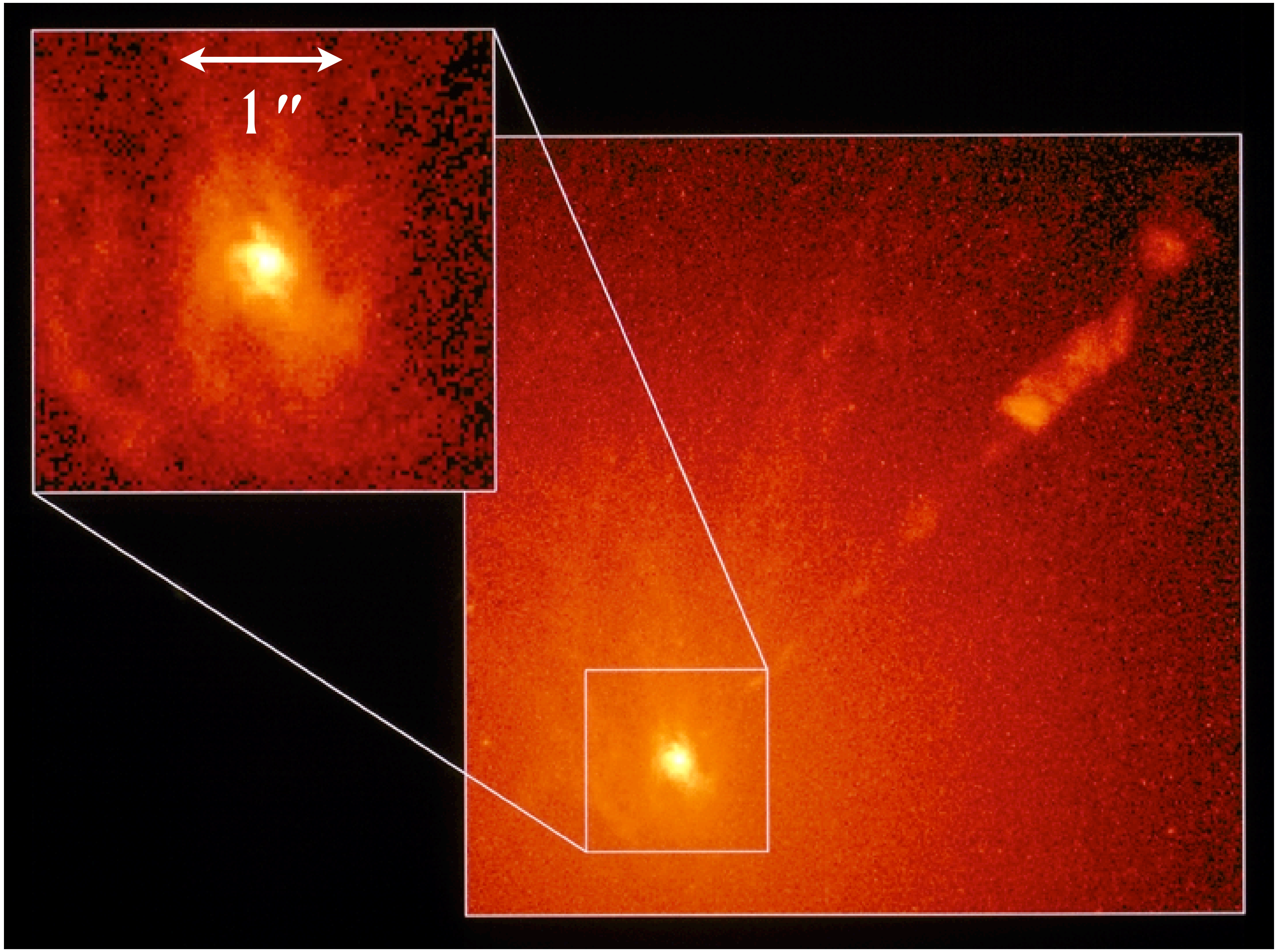
Nearest AGNs

- 1000 AU @ 1 Mpc → 1 milli-arcsec
- but a few large disks imaged with HST in optical

Nearest YSOs

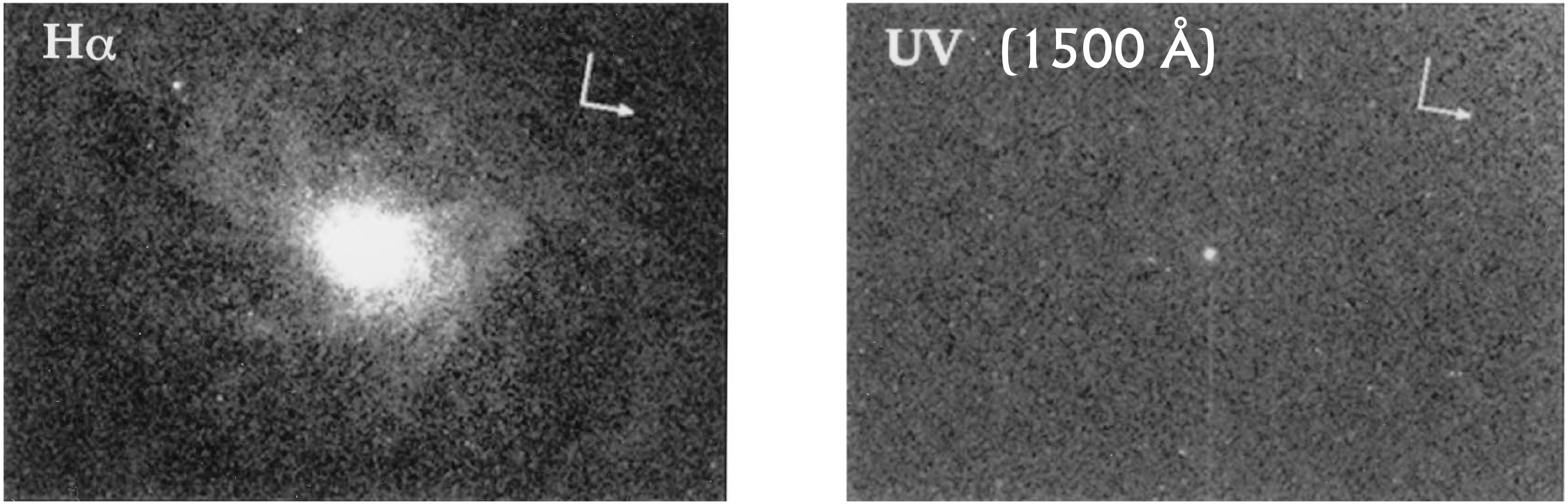
- 100 AU @ 150 pc → 0.6 arcsec
- imaged with the HST and with ground-based interferometers (near-IR and mm-wave bands)

Gaseous Disk in M87



HST/WFPC2 Hα+[N II] image
Ford et al. 1994, ApJ, 435, L27

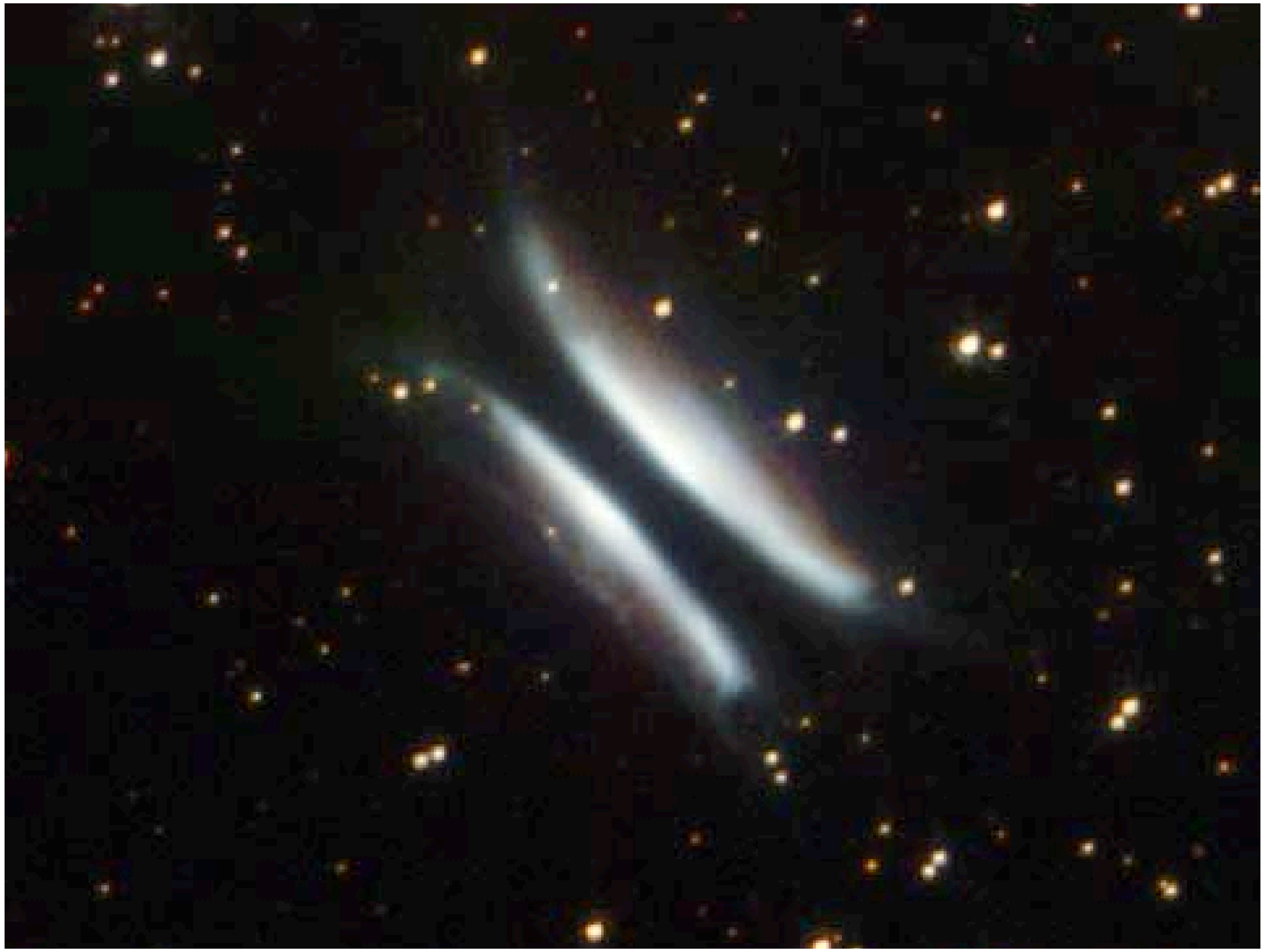
Gaseous Disk in M81



HST/WFPC2 images: 57.5 × 40.3 arcsec

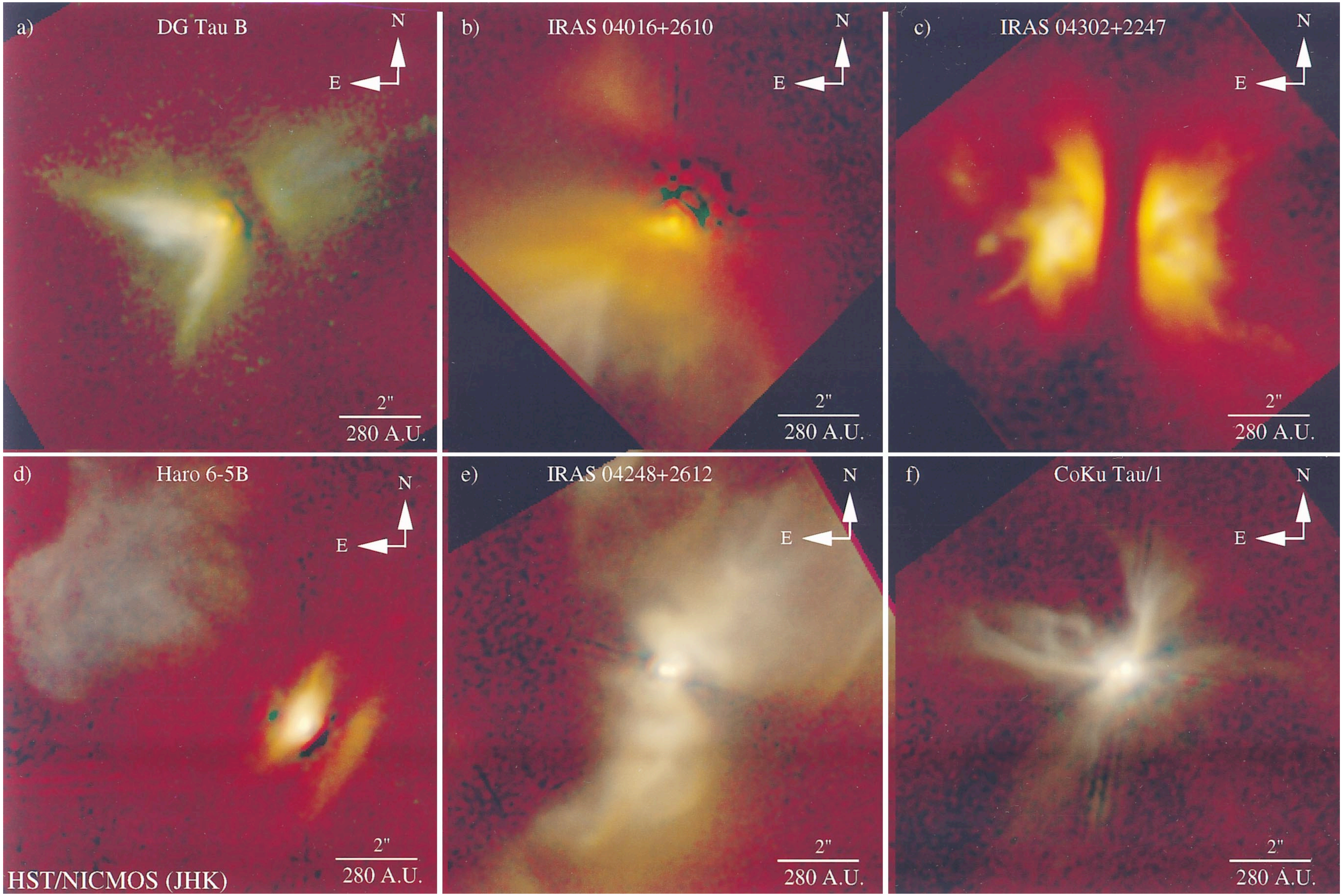
Devereux et al. 1997, ApJ, 481, L71

Direct Images of Protostellar Disks



Gomez's Hamburger
IRAS 18059-3211: disk in silhouette
(Hubble Heritage)

Direct Images of Protostellar Disks

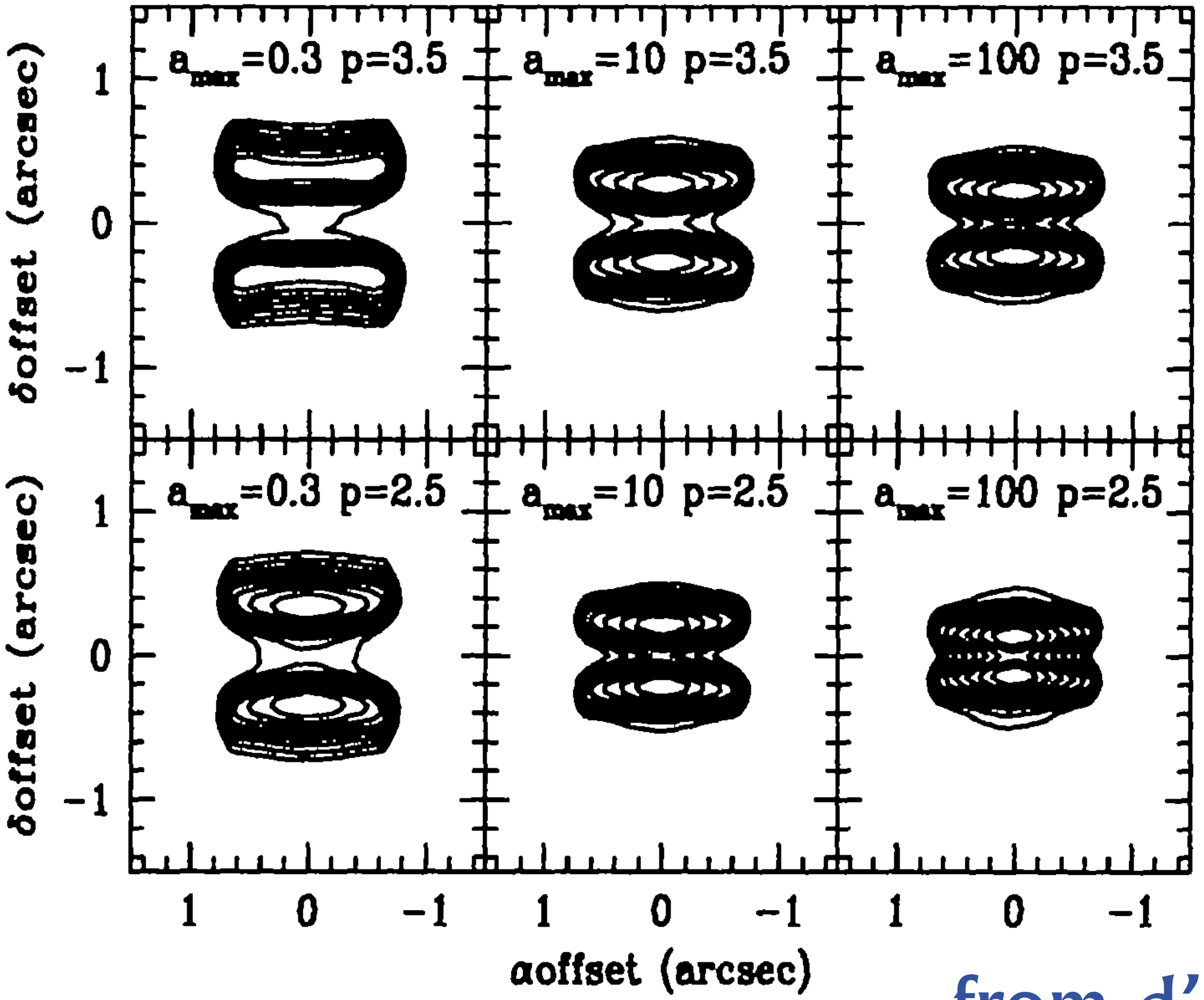


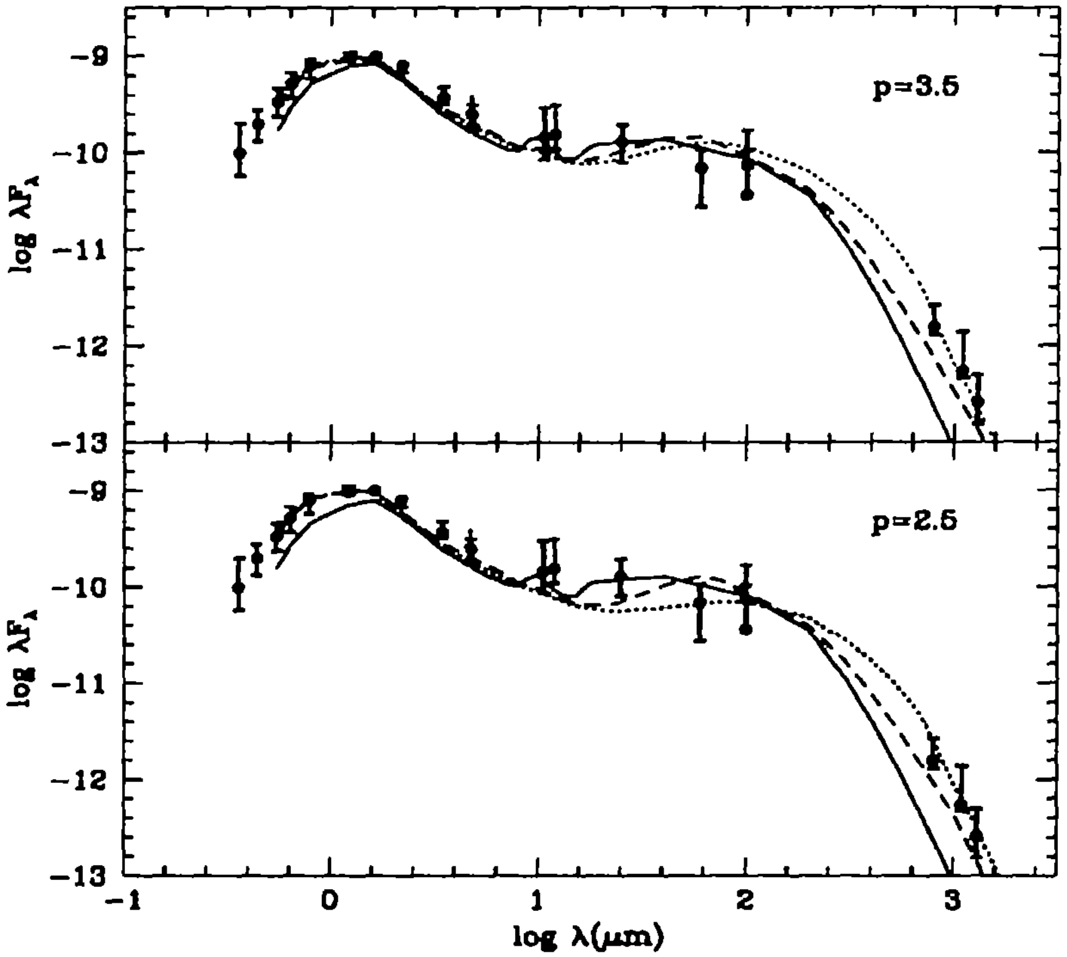
Padget et al. 1999, AJ, 117, 1490

HST/NICMOS images of YSOs in Taurus

The luxury of imaging...

- **Combine morphology and SED constraints to infer detailed sructure.**
  - e.g., dust properties from synthetic scattered light images and model S.E.D.s

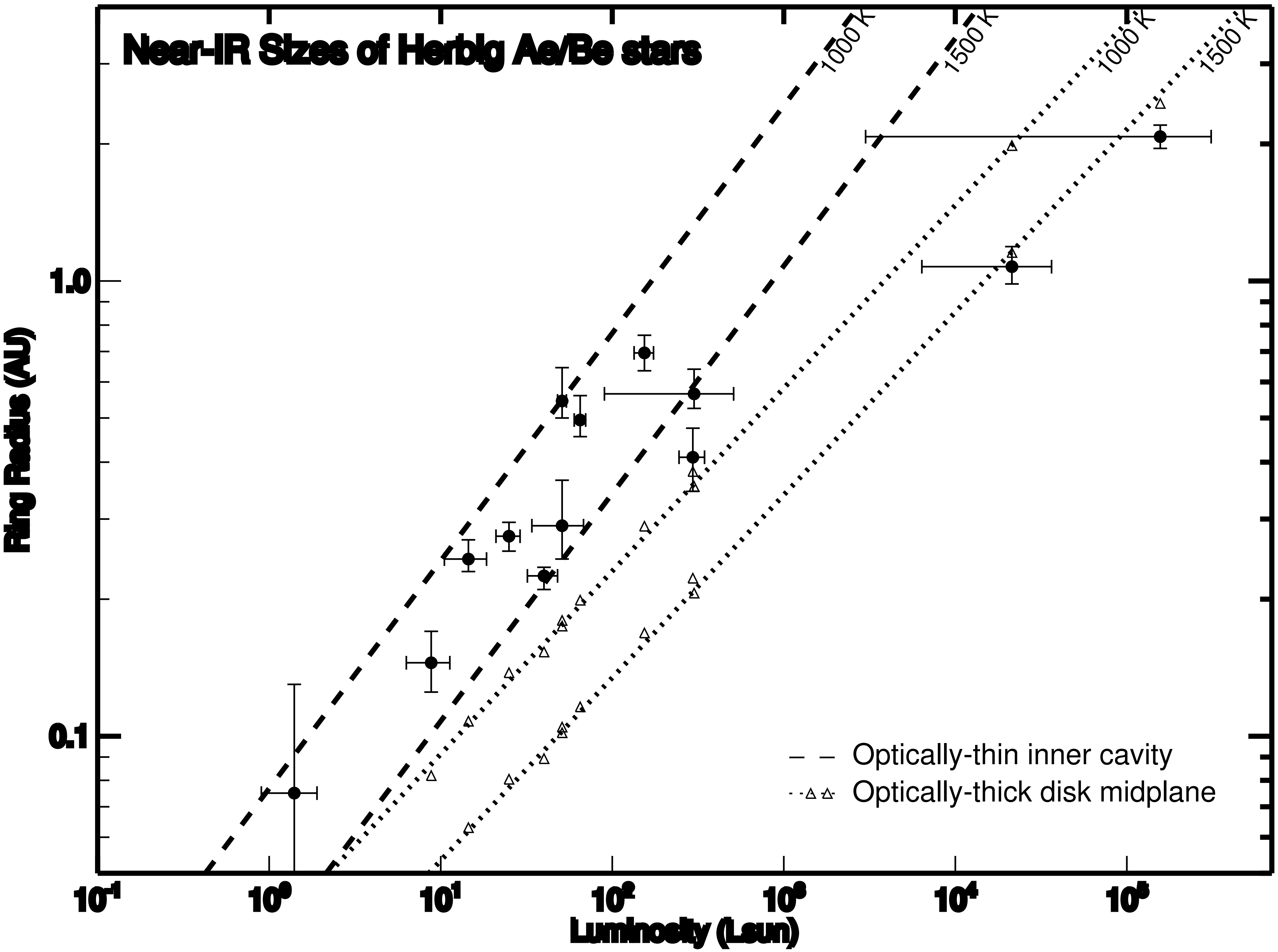




from d'Alessio et al.2001, ApJ, 553, 321

Sizes of Protostellar Disks from Interferometry

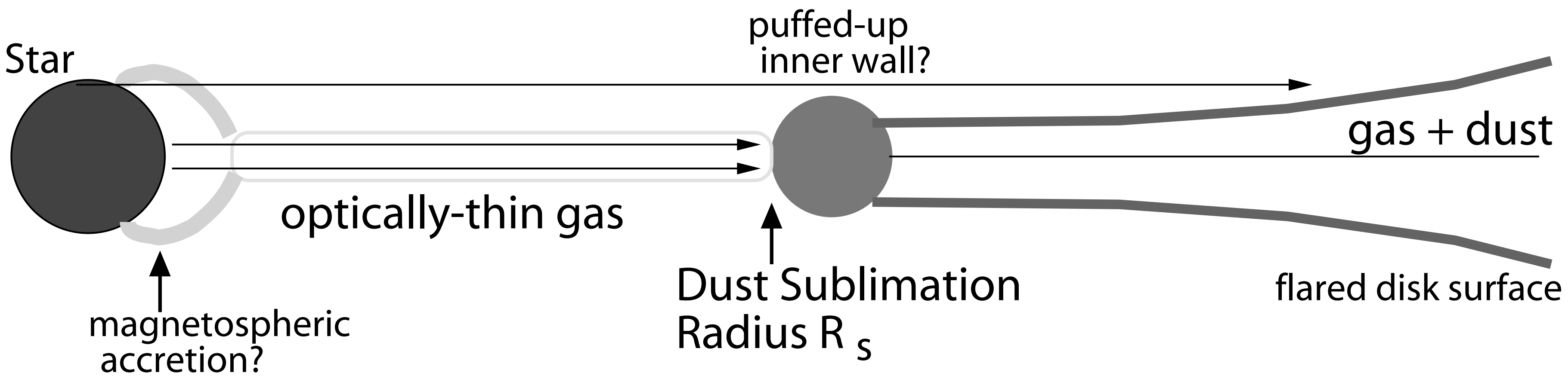
Size-luminosity relation in Herbig Ae/Be stars



Monier et al. 2005, ApJ, 624, 832

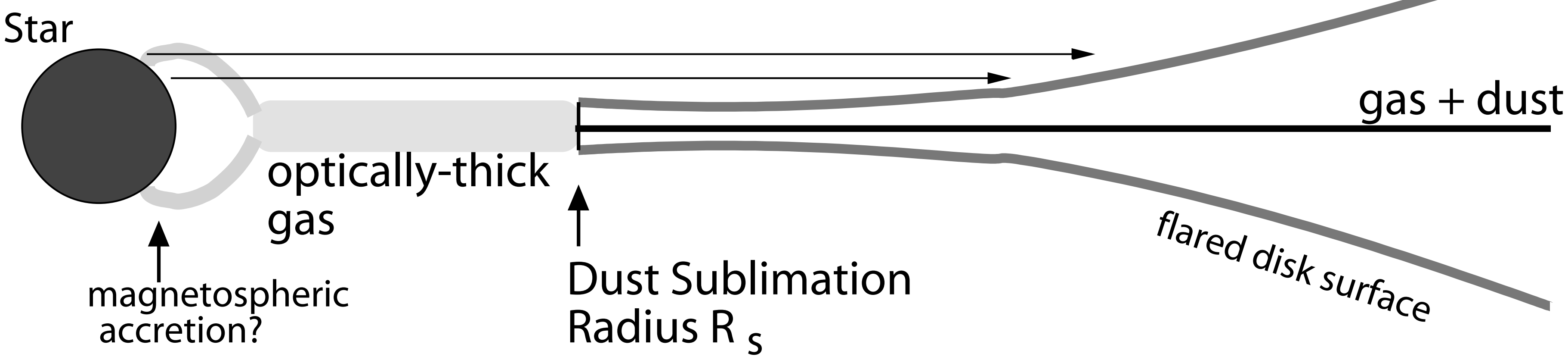
Disk structure from size measurements

"Optically-thin Cavity" Disk Model



Star
puffed-up
inner wall?
gas + dust
optically-thin gas
Dust Sublimation
Radius R $_s$
flared disk surface
magnetospheric
accretion?

"Classical" Disk Model



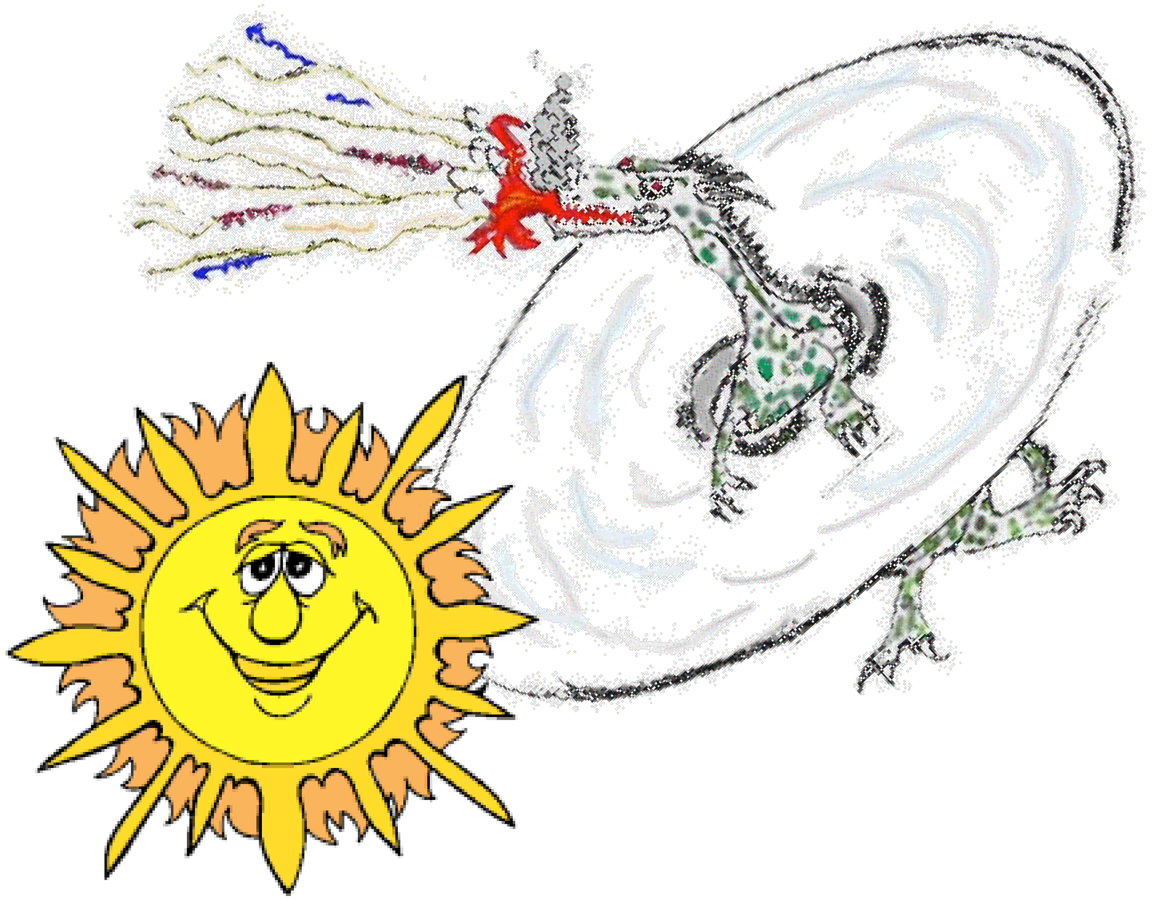
Star
gas + dust
optically-thick
gas
Dust Sublimation
Radius R $_s$
flared disk surface
magnetospheric
accretion?

Monier et al. 2005, ApJ, 624, 832

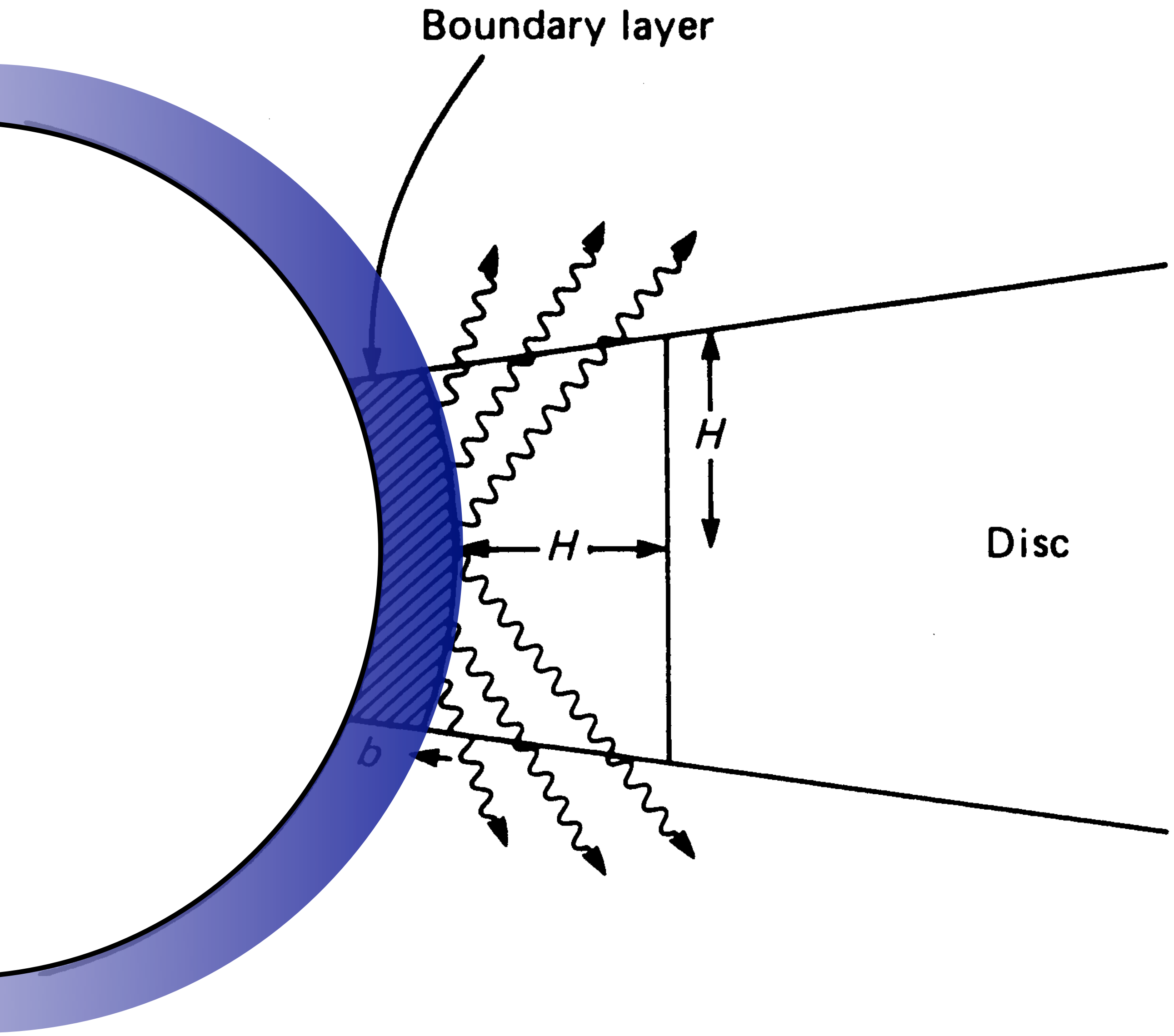
Can we isolate the disk without imaging it?

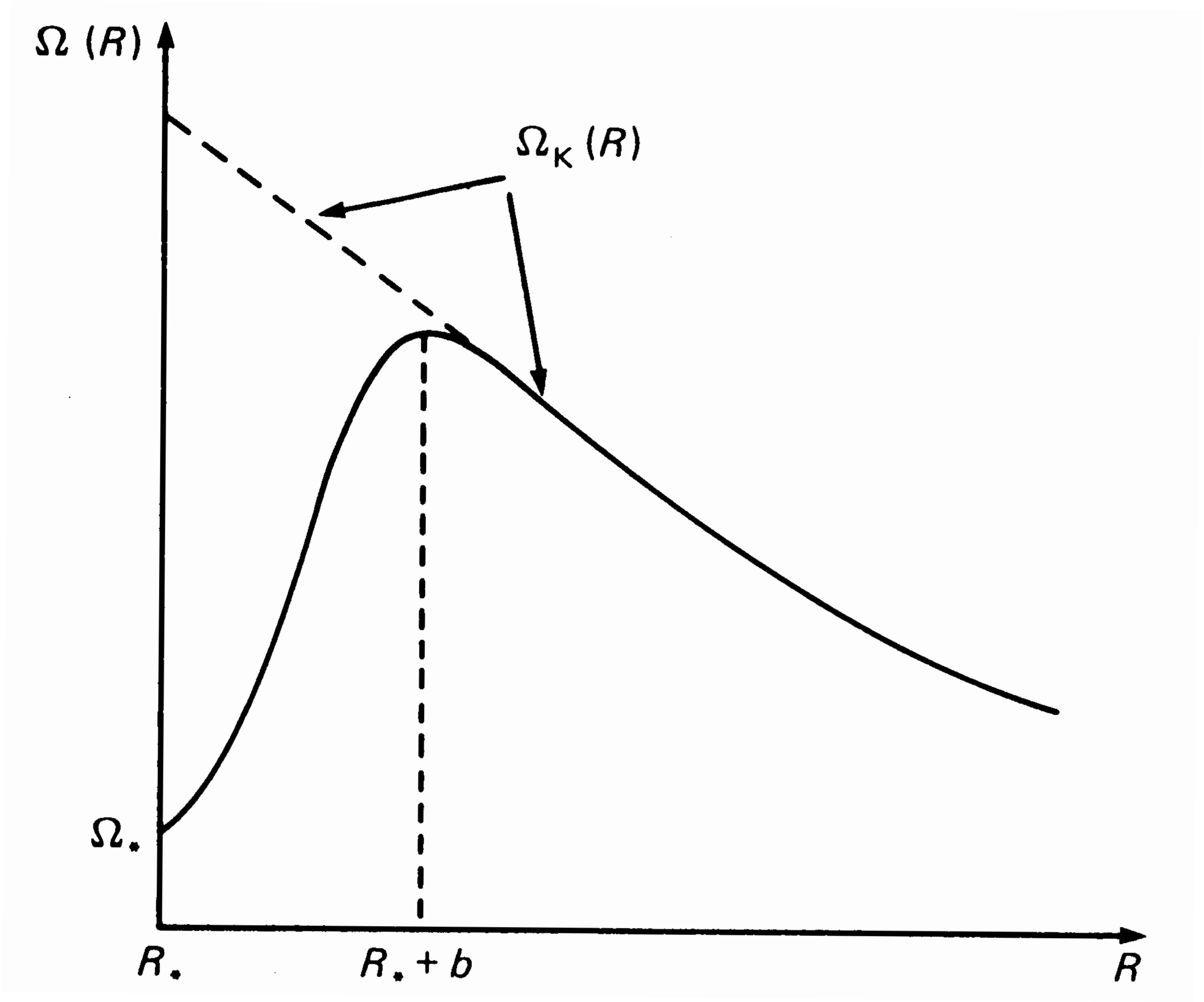
- **Observed light includes:**
  - ✦ Boundary Layer and central star
  - ✦ Jet (beamed)
  - ✦ Companion star
  - ✦ Host galaxy of AGN

- **Disk light passes through**
  - ✦ Atmosphere/wind
  - ✦ Curved spacetime



The Disk-Star Boundary Layer





Half of the accretion luminosity released in boundary layer

In CVs: $T \sim 10^8$ K if optically thin (e.g., Tylenda 1979)
$T \sim 10^5$ K if otically thick (e.g., Pringle 1977)

Spectral Energy Distributions (S.E.D.s)

- **Start with temperaure distribution of disk**

$$T(r) = T_* \left(\frac{r}{R_{\rm in}}\right)^{-3/4} \left[1 - \left(\frac{r}{R_{\rm in}}\right)^{-1/2}\right]^{1/4}$$

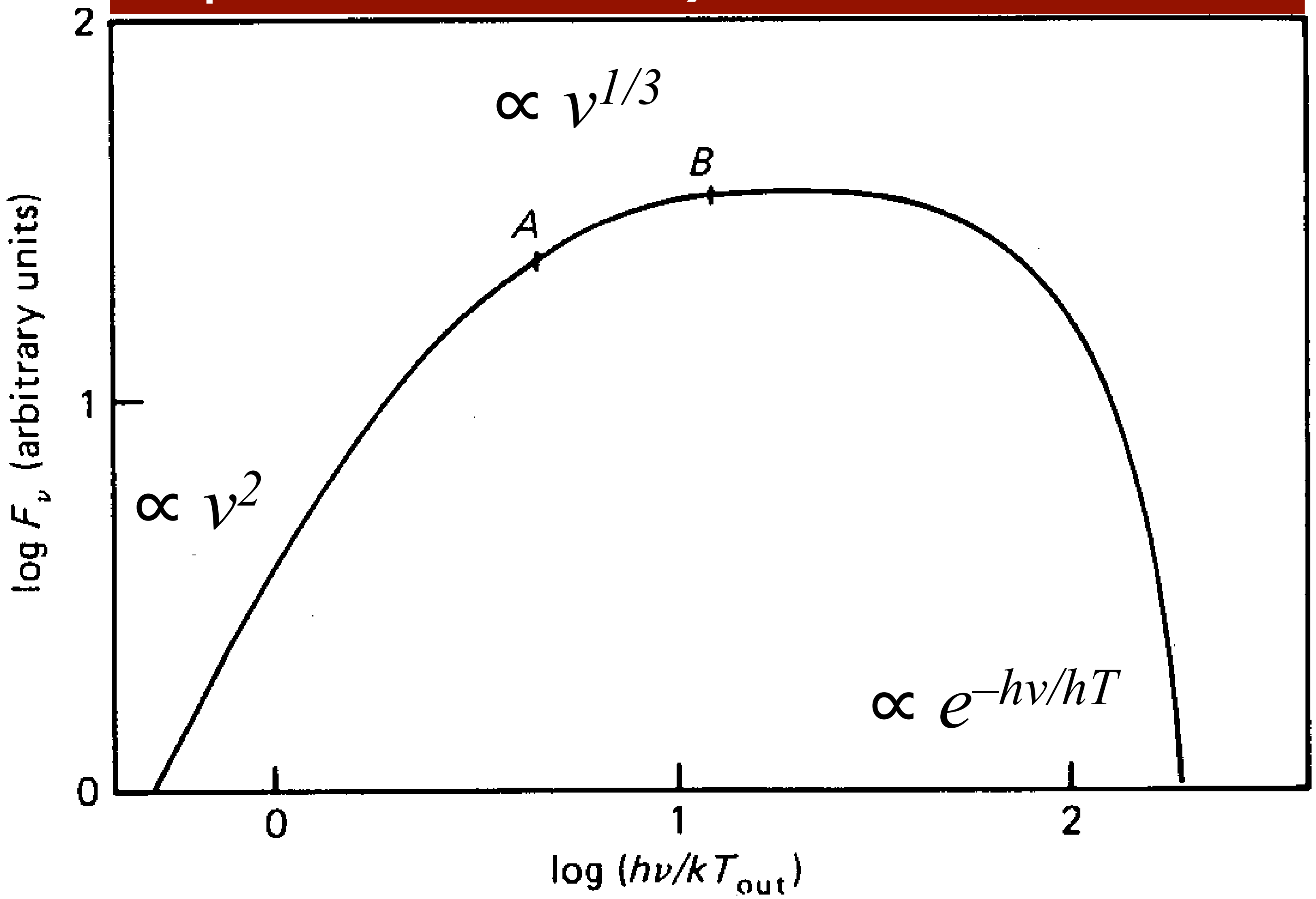
where $$T_* = \left(\frac{3\,G\,M\,\dot{m}}{8\pi\,\sigma_{\rm SB}\,R_{\rm in}^3}\right)^{1/4}$$

- **Assume local black body emission and integrate over the entire disk**

$$f_\nu = \frac{\cos i}{d^2} \int_{R_\star}^{r_{\rm out}} B_\nu[T(r)]\; 2\pi r dr$$

Resulting shape

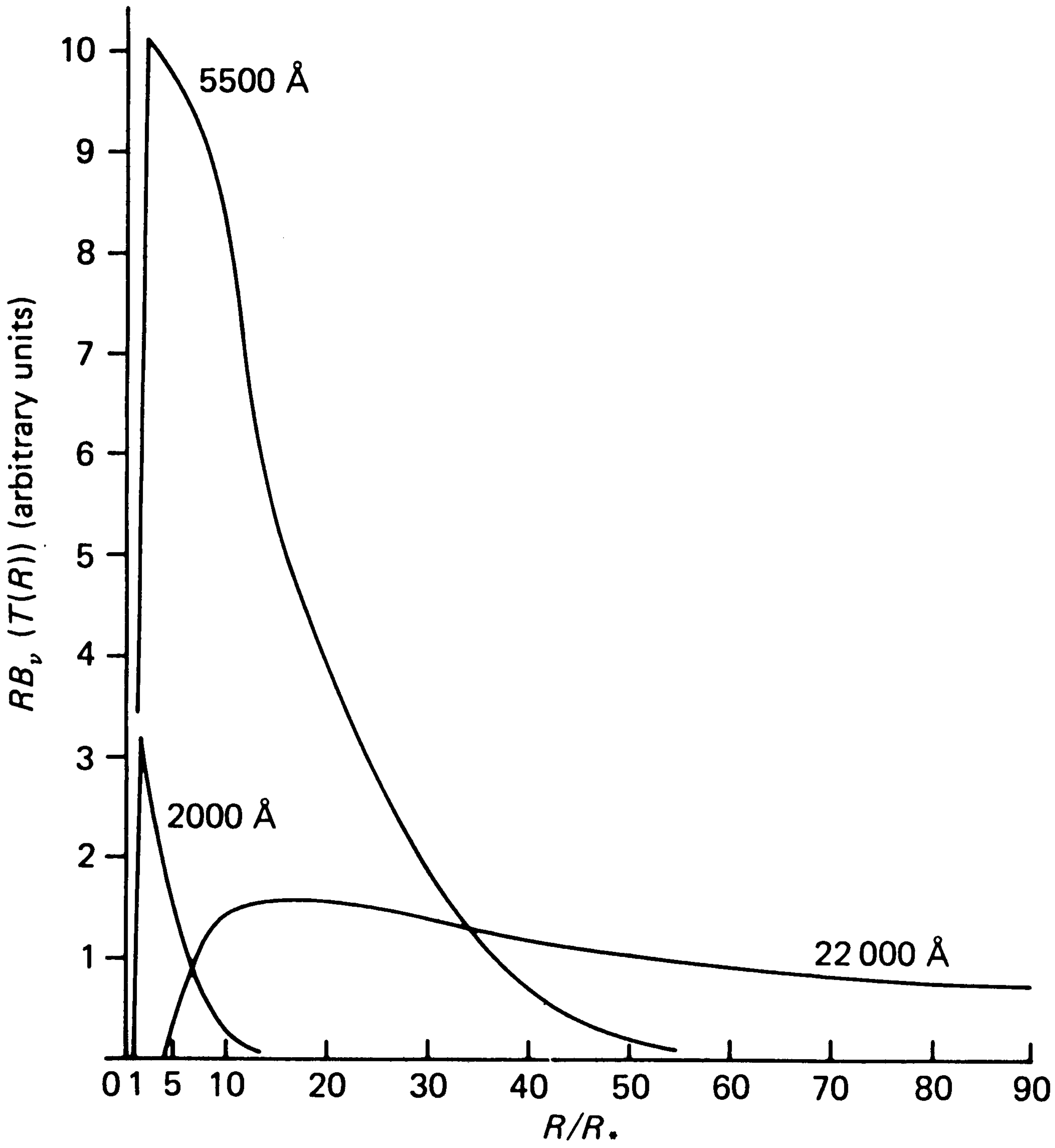
For XRBs	600 Å	200 eV	2 keV
For AGNs	6 µm	5000 Å	20 eV
For CVs	1 µm	1 Ry	3 eV



Wavelength dependent disk size

$$f_\nu(r) \propto 2\pi r \; B_\nu[T(r)]$$

- Disk should appear smaller at shorter wavelengths



In principle, we can learn a lot about the disks if we can measure their SEDs and fit them with models.

- test disk models
- infer accretion rate
- turn them into tools

Doing this in practice is not easy.

- need distances and masses
- need to observe in "difficult" bands
- need to do very messy physics, with many uncertainties...

How messy and how uncertain...

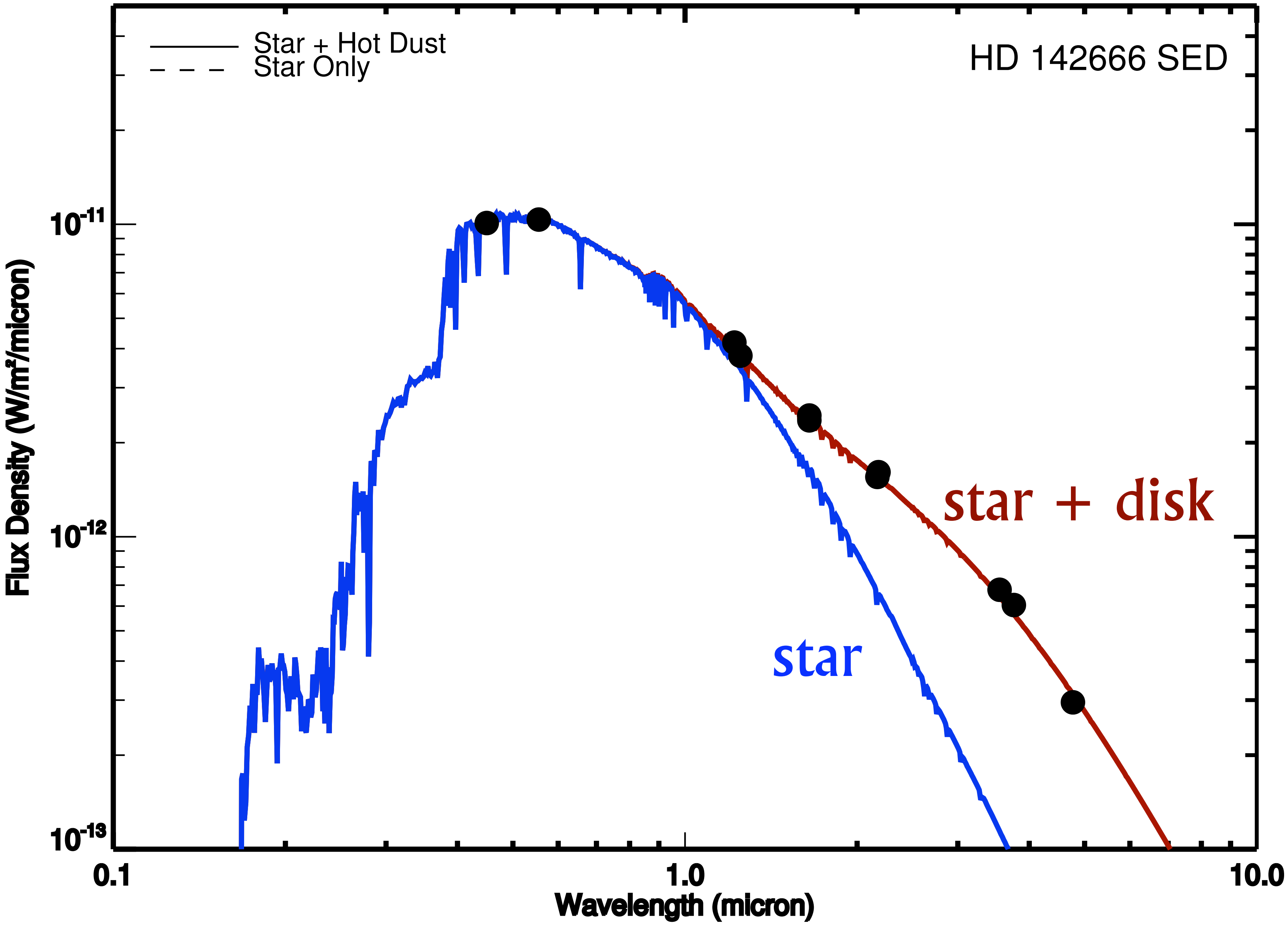
The use of black bodies is not adequate...

- Disks have atmospheres with vertical structure
- Scattering is important in very hot disks
- Dust is present in very cold disks
- Energy generation need not be concentrated in the mid-plane of the disk

Need sophisticated atmosphere models

- with proper radiative transfer
- and relativity (special and general)

Application to YSOs



SED models:
Radiative transfer in dusty disk, illuminated by central star

Monier et al. 2005, ApJ, 624, 832

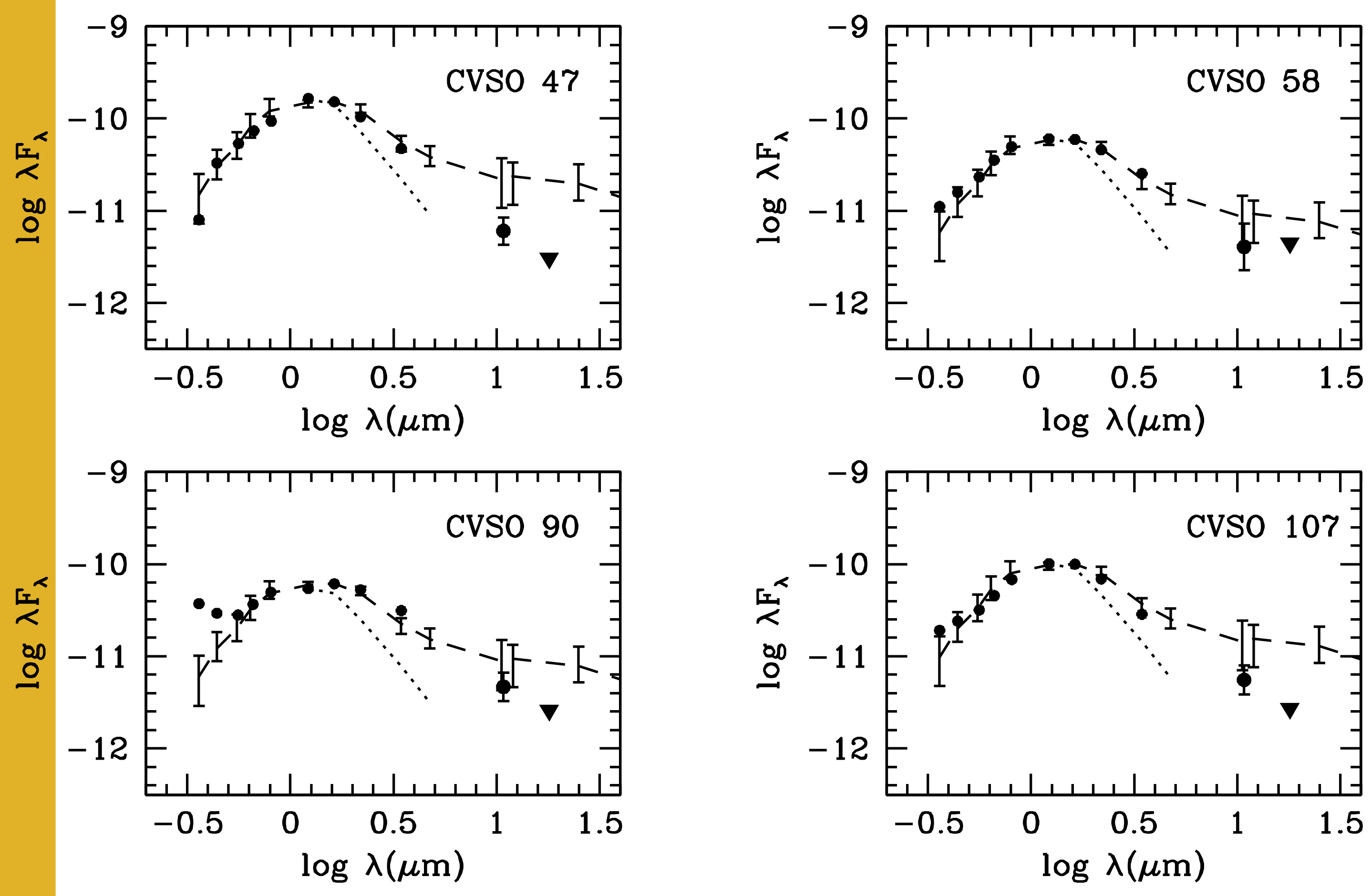
Accretion rates from SED fitting

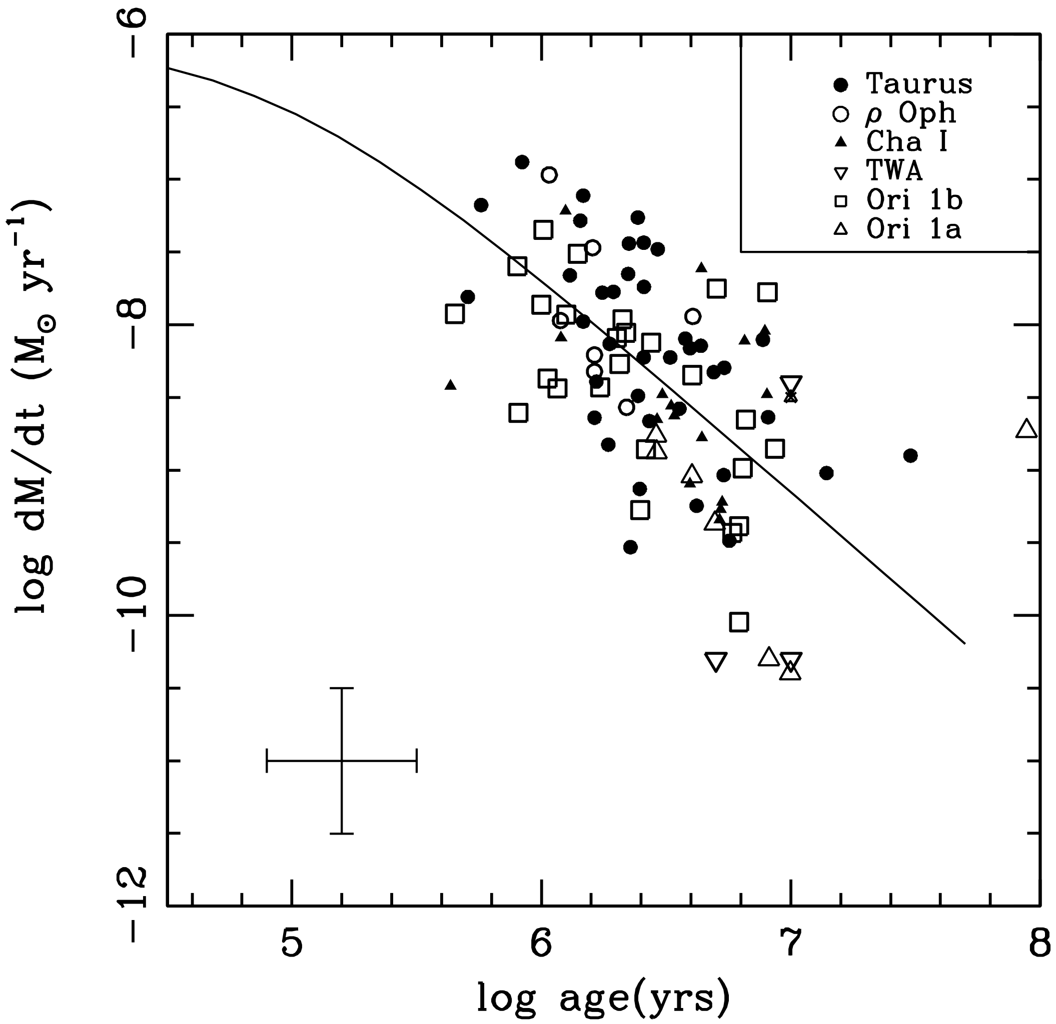
Evolution of protostellar disks in the Orion OB1 association.

Model fits to SEDs yield the accretion rate (among other parameters).

Accretion rate appears to drop as the stars age.

Disks are consumed ("viscous evolution").

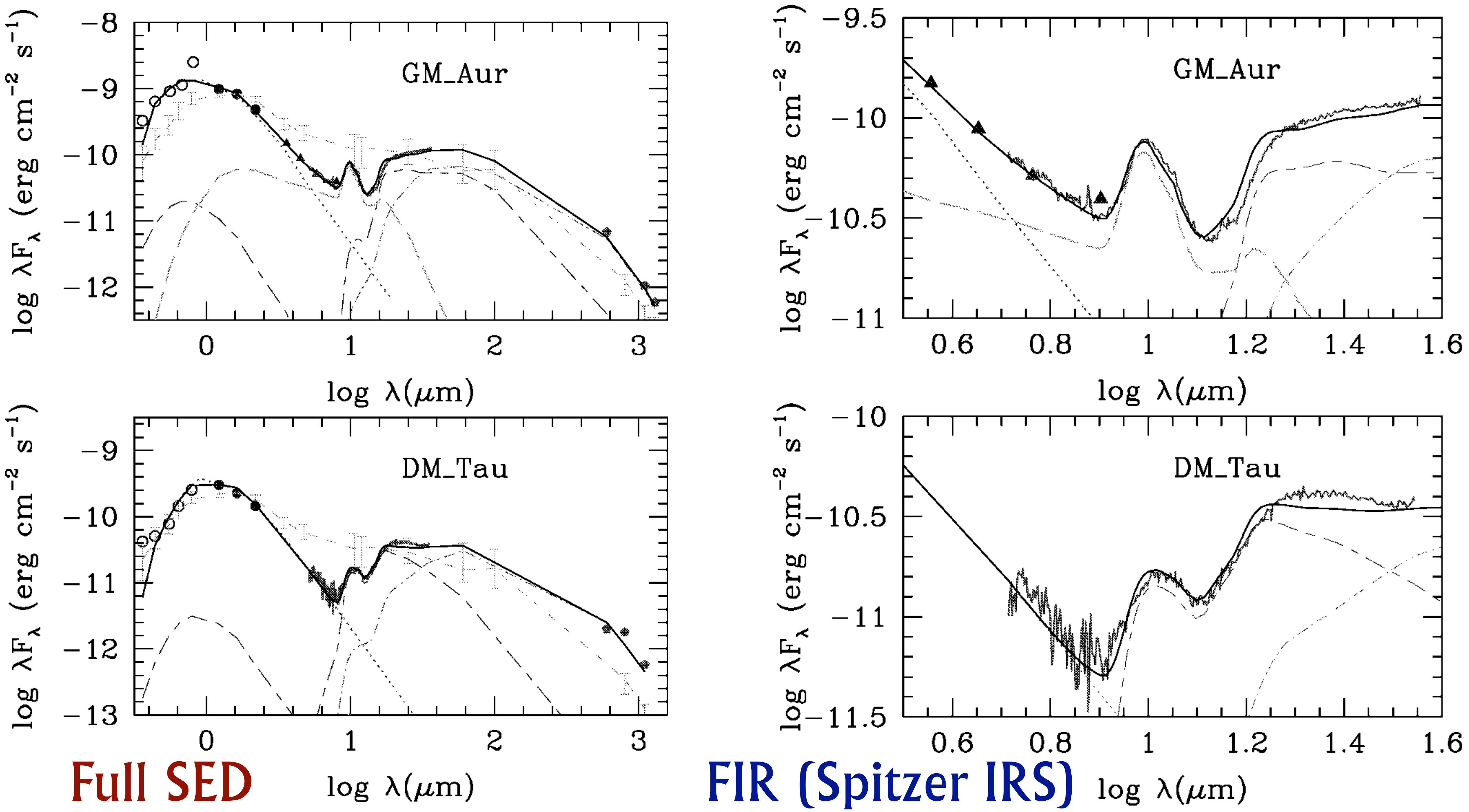




Calvet et al., 2005, AJ, 129, 935

Disk size & structure from SED fitting

Fits of SED models indicate a gap in the inner disk.
Gap manifests itself as a dip in the SED at 1 micron.
Spitzer IRS data constrain the SED at the crucial wavelength.



Full SED

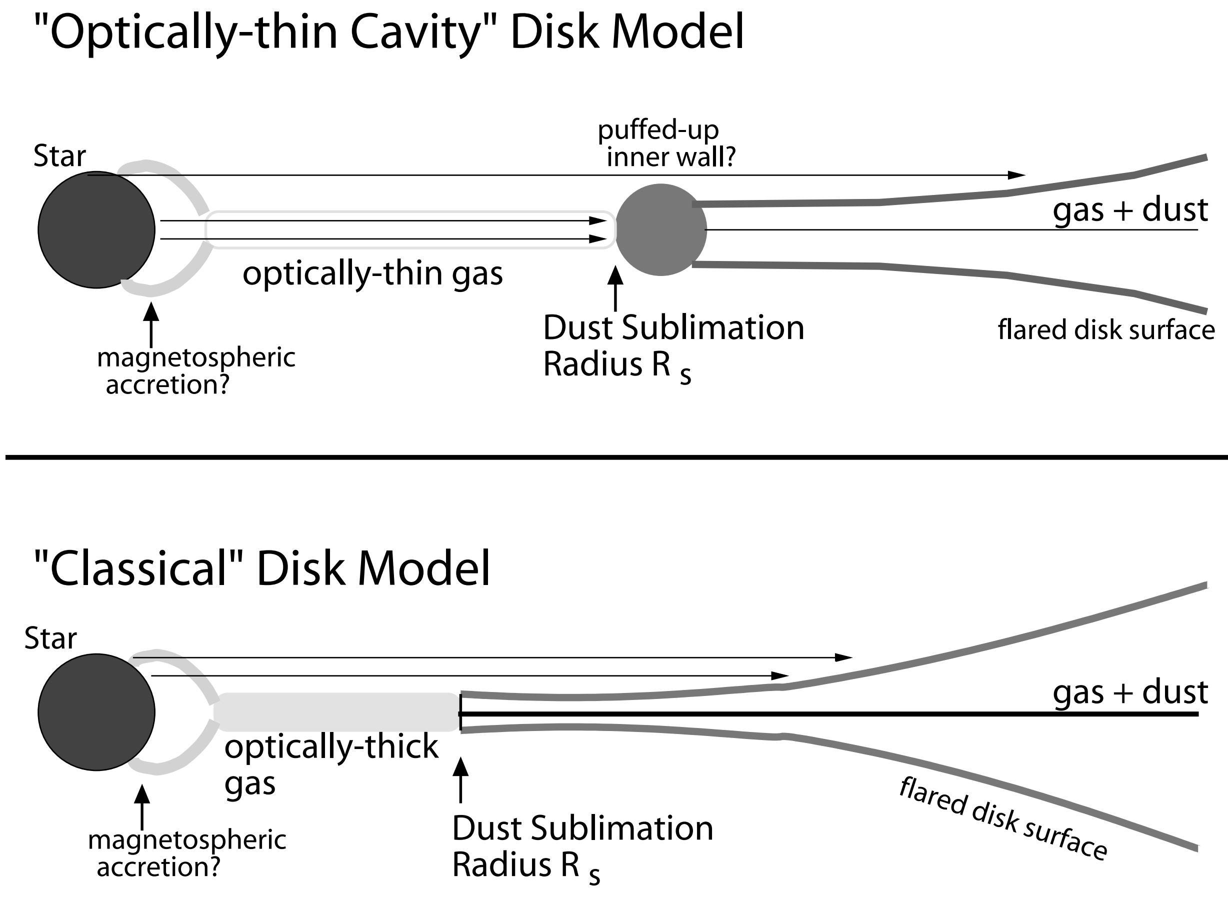
FIR (Spitzer IRS)

figures from Calvet et al. 2005, 630, L185

Imaging combined with SED fitting

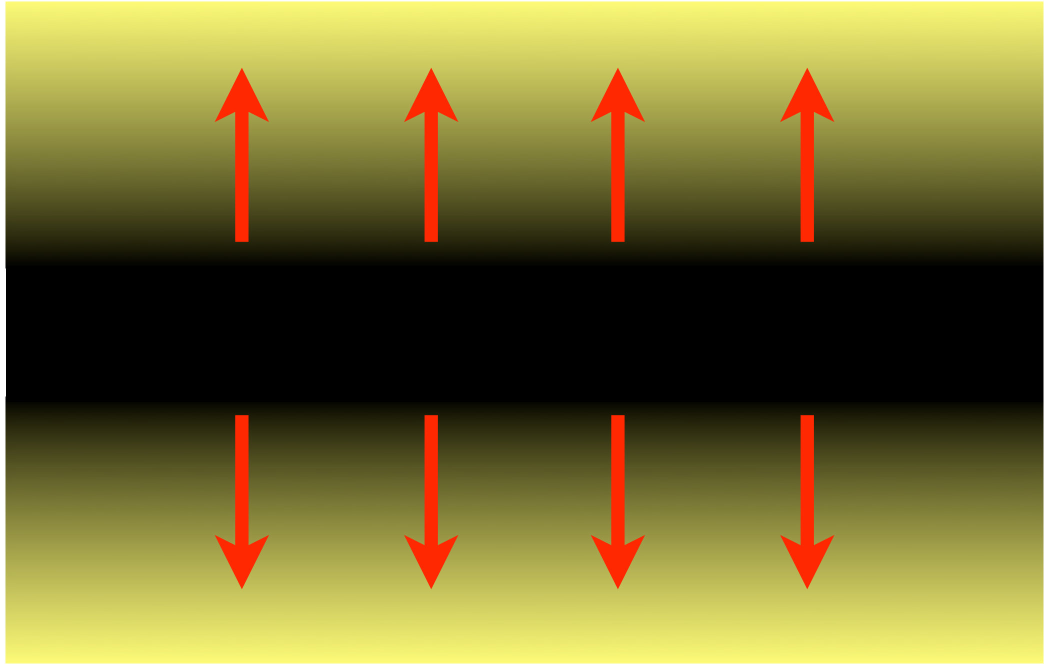
- Measurements of disk inner radii with Keck interferometer.
- Fix values in SED models.
- Infer vertical strucure of inner disk.

Eisner et al. 2004, ApJ, 613, 1049



sketch from Monier et al. 2005, ApJ, 624, 832

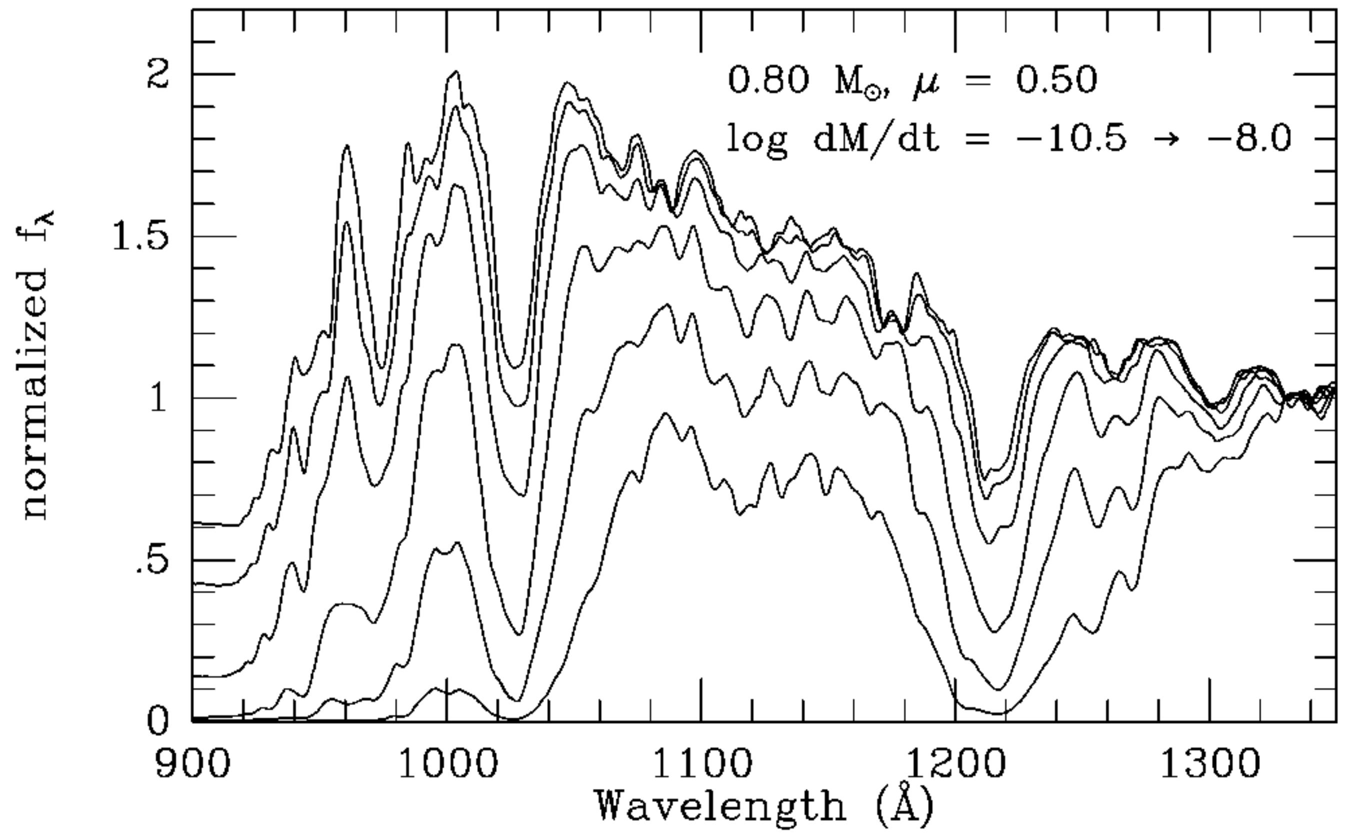
Applications to CVs

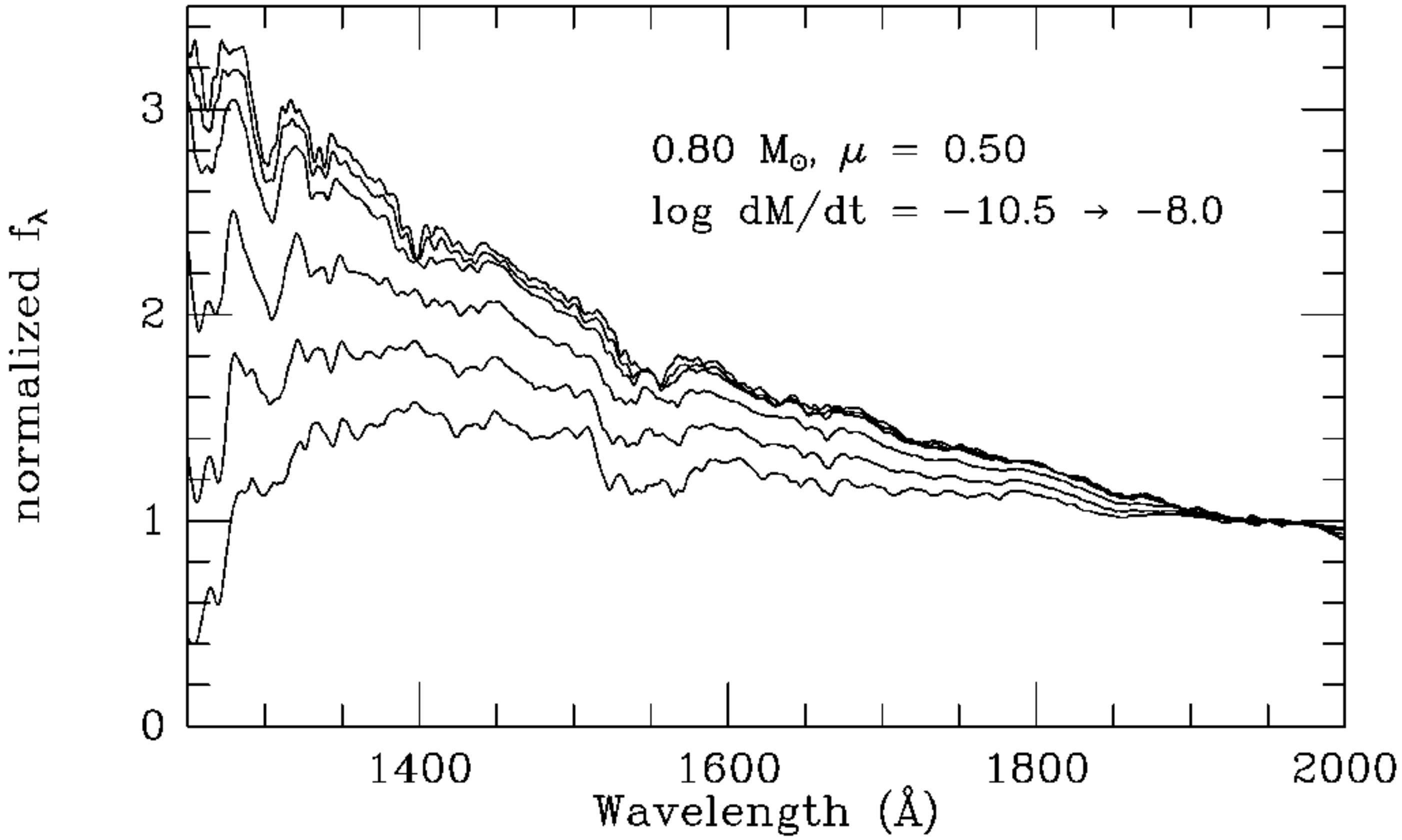


- Energy produced in disk midplane.
- Propagates through plane-parallel atmosphere.
- Limb darkening, foreshortening, rotational broadening of lines.
- Ideal range to observe: near-UV, 912–2000 Å
- Relativity not needed

Examples of resulting spectra

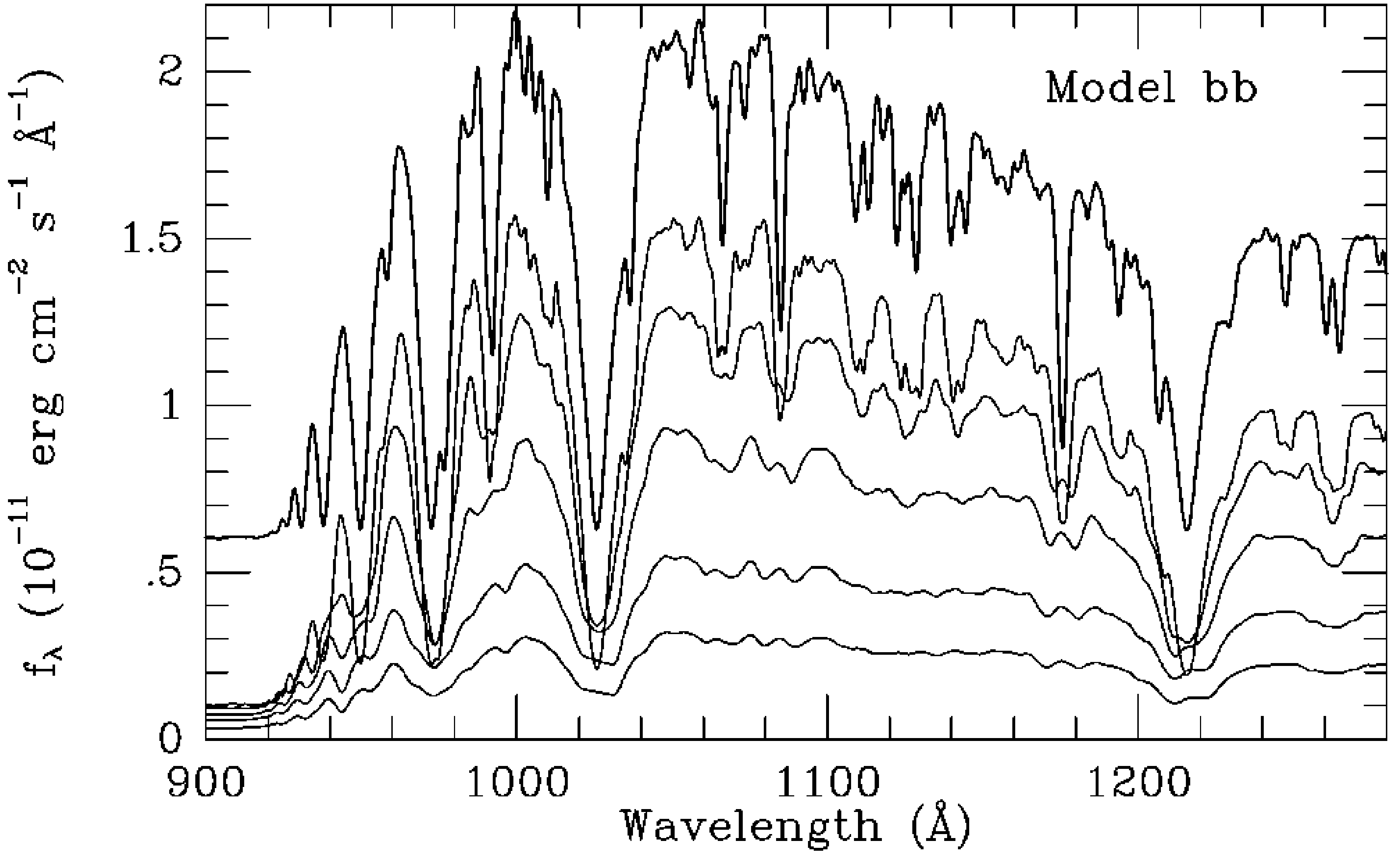
- Sequence of increasing dM/dt (bottom to top)
- Continua get bluer with dM/dt
- Absorption lines get shallower





from Wade & Hubeny 1998, ApJ, 509, 350

Effect of rotation and limb darkening



face-on
i = 8°

edge-on
i = 81°

Weak lines blend together into a pseudo-continuum

NOT A BLACKBODY!

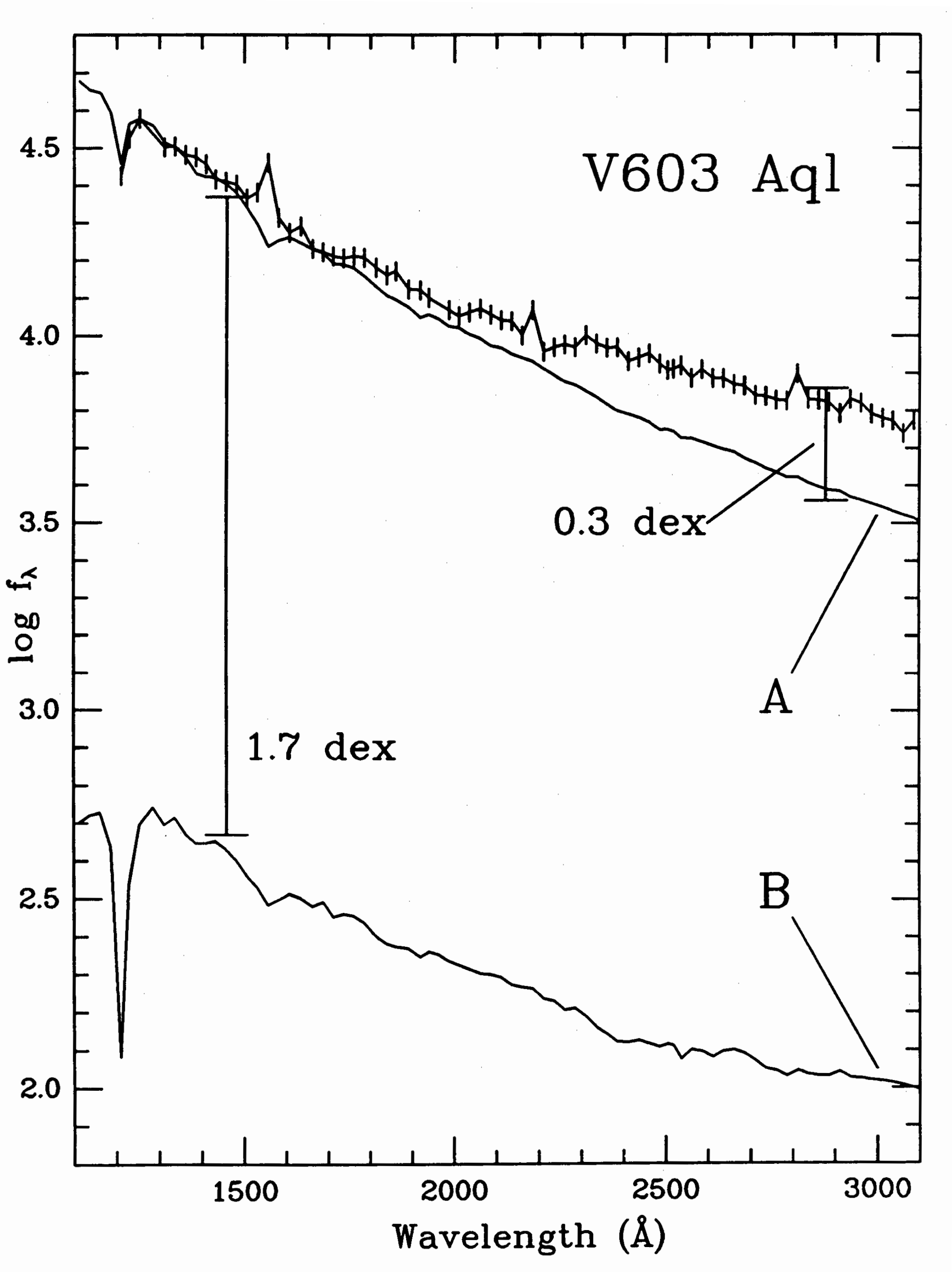
from Wade & Hubeny 1998, ApJ, 509, 350

Comparison with observations

- Cannot match flux and slope of UV spectra of CVs at the same time

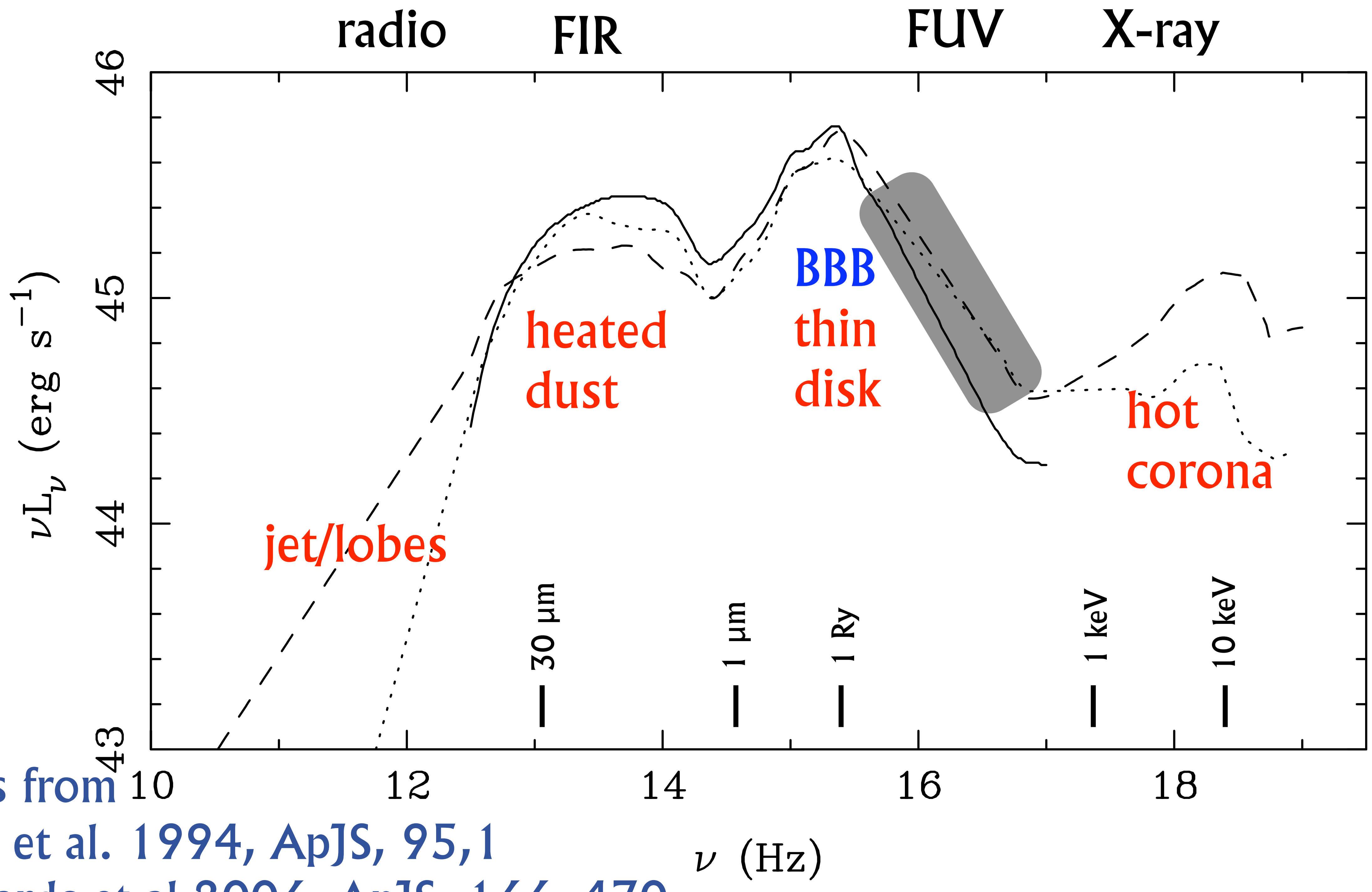
  Wade 1988, ApJ, 335, 394
  Puebla et al. 2008, AJ, 134, 1923

- Possible avenues to a solution:
  - Temperature profile of inner disk.
  - Optically thin gas in disk
  - Wind



Applications to Luminous AGNs

Average S.E.D.s of quasars



SEDs from
Elvis et al. 1994, ApJS, 95,1
Richards et al 2006, ApJS, 166, 470

Emission models for thin disks in AGNs

- **Historically, stellar atmospheres used to approximate disk atmosphere (matched in T and g). e.g., Sun & Malkan 1989, ApJ, 346, 68**
- **Shortcomings:**
  - Disks have a different density than stars for the same combination of T and g
    → different opacity
  - Temperature gradient of disk atmospheres different from stellar atmospheres
    → different absorption lines

Models for AGN accretion disk SEDs

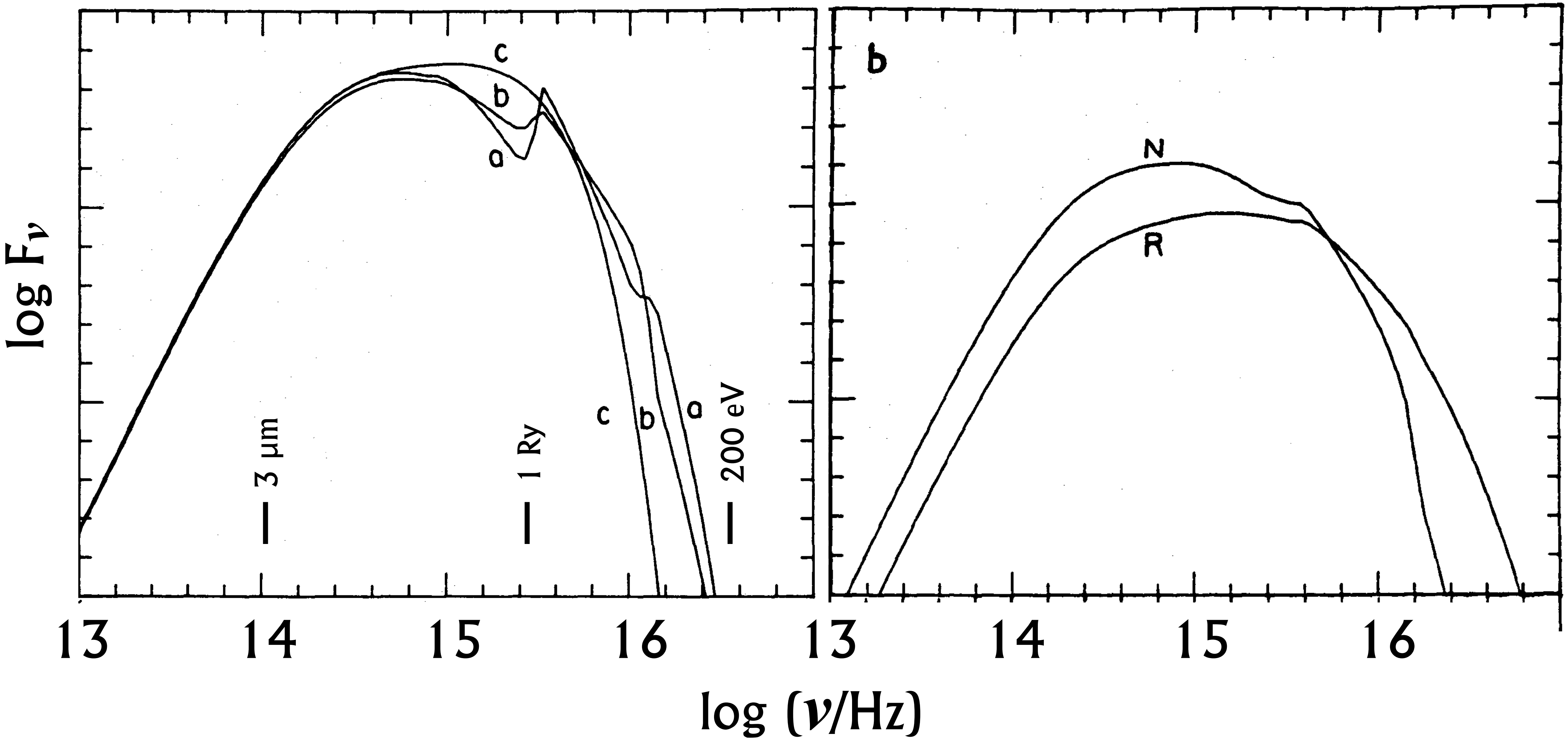
by Laor & Netzer 1989, MNRAS, 238, 897

- Calculation of H+He disk atmospheres based on vertical structure from α-disk models
  - free-free, bound-free opacity (latter is important)
  - comptonizaton, when necessary
  - various prescriptions for vertical temperature gradient
  - special and general relativity

Model examples

Vertical thermal structure:
a = isothermal
b = temp. gradient
c = black body (reference)

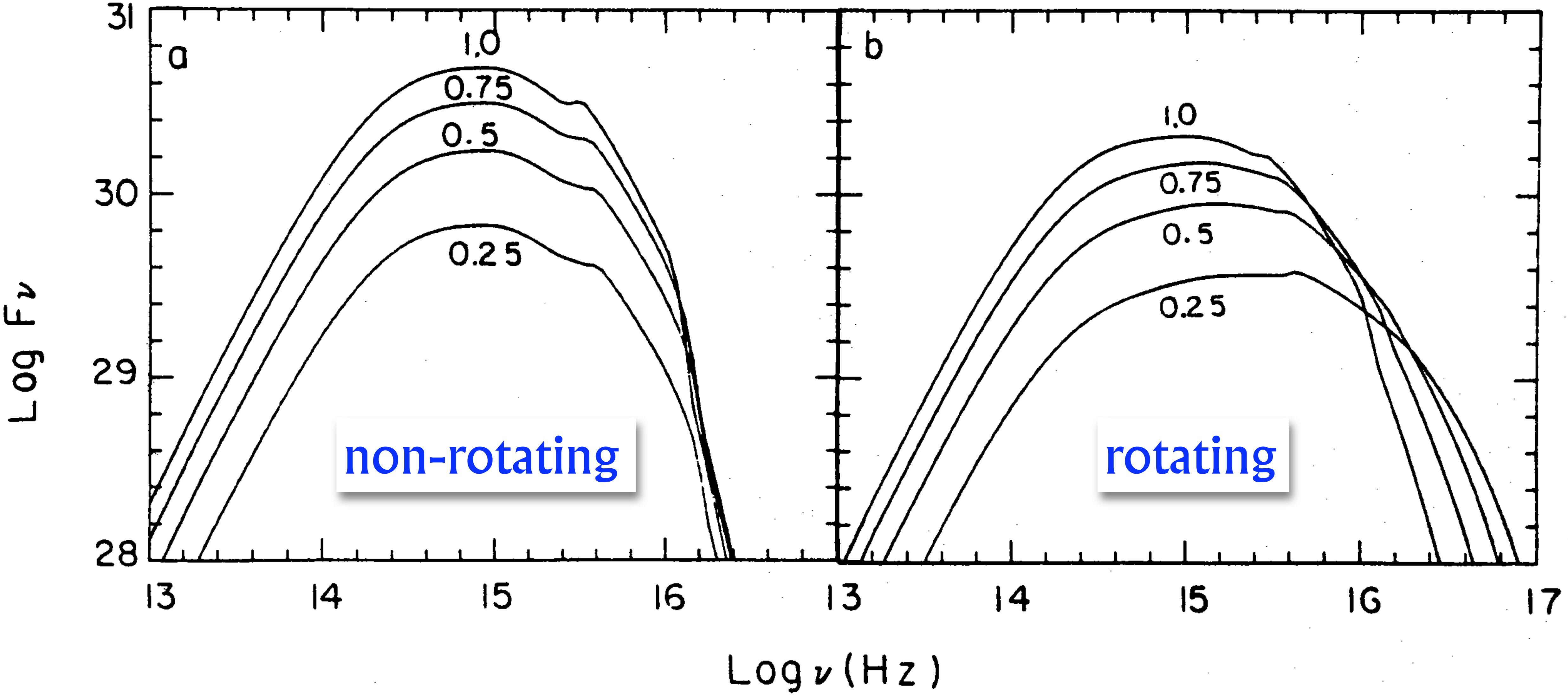
(R,N) = Rotating, non-rotating
black holes



from Laor & Netzer 1989, MNRAS, 238, 897

More examples: effect of inclination

Effect of inclination:
curves labeled by cos i, from face on to 75°

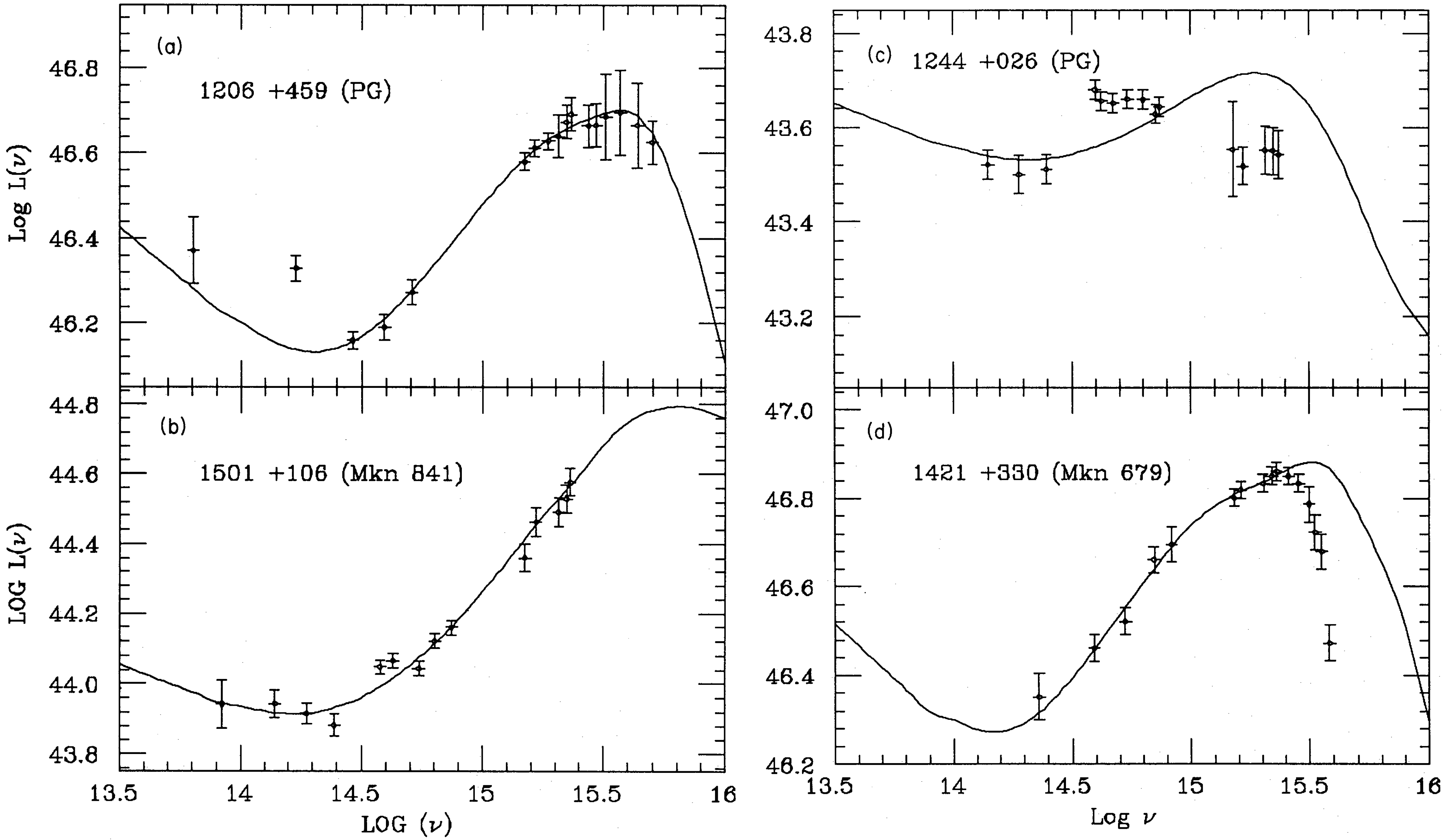


non-rotating

rotating

from Laor & Netzer 1989, MNRAS, 238, 897

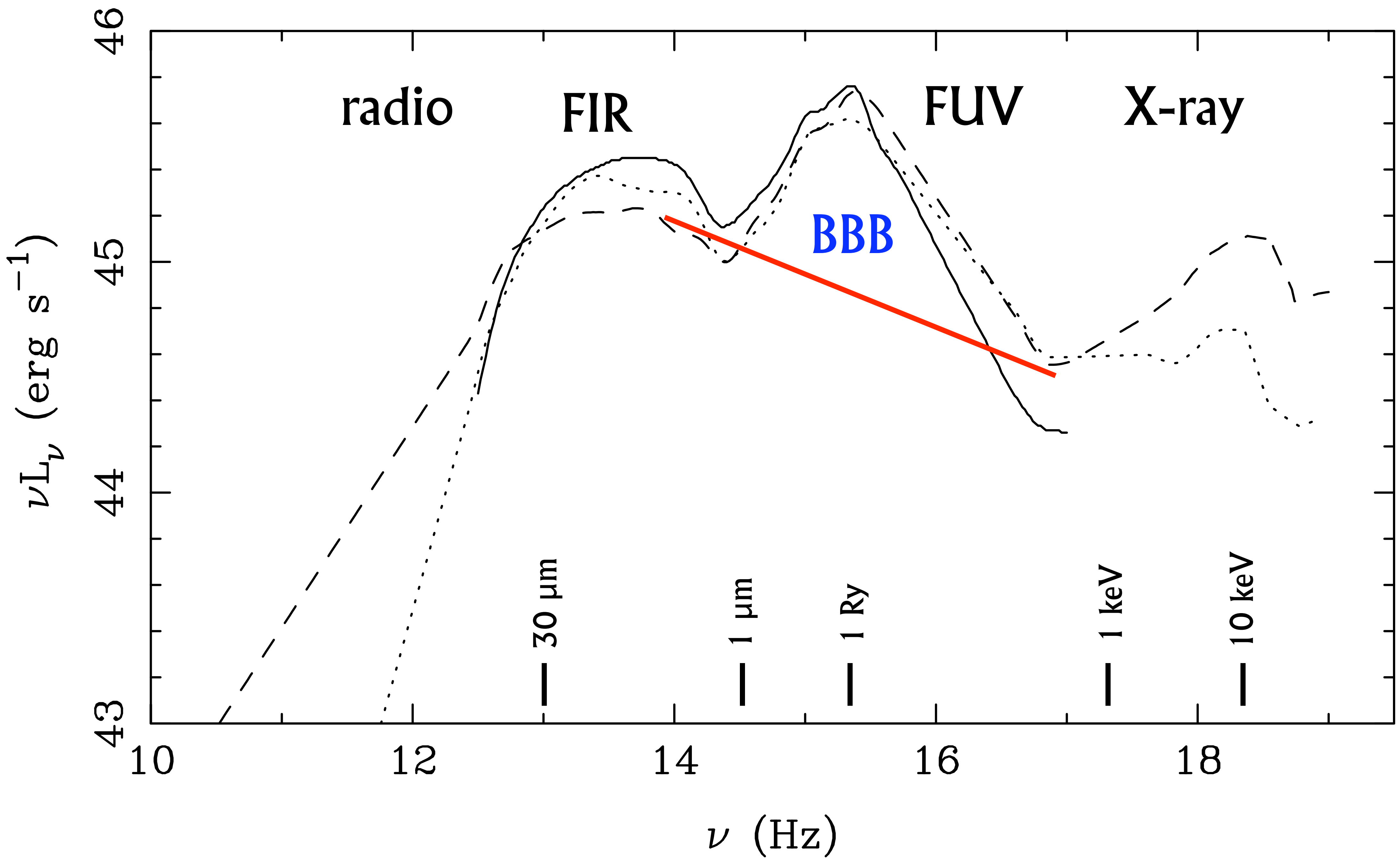
Comparison with data: mixed success



Laor 1990, MNRAS, 246, 369

- Fits not always good.
- Model parameters not well constrained

Comparison with data: issues

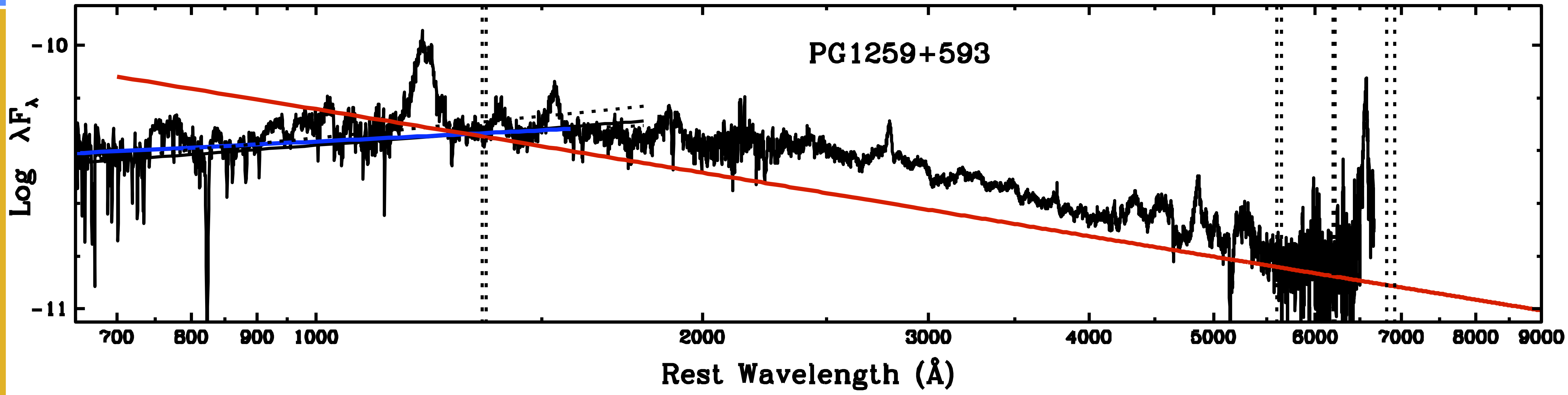


- FIR power-law needs to be invoked - ad hoc
- No smooth connection to X-ray data

Comparison with data: more issues

- **Ly edge: predicted but not observed. Breaks observed instead.**
  - Need even better atmosphere models.
- **Edges can be smoothed by scattering, but should lead to polarization.**
  - Early measurements of polarization did not agree with predictions (too high or too low).
  - Latest polarization observations (Kishimoto et al. 2003, 2004, 2005) may have uncovered Balmer edge and disk thermal emisson in polarized light.

High-Resolution UV Spectra of BBB



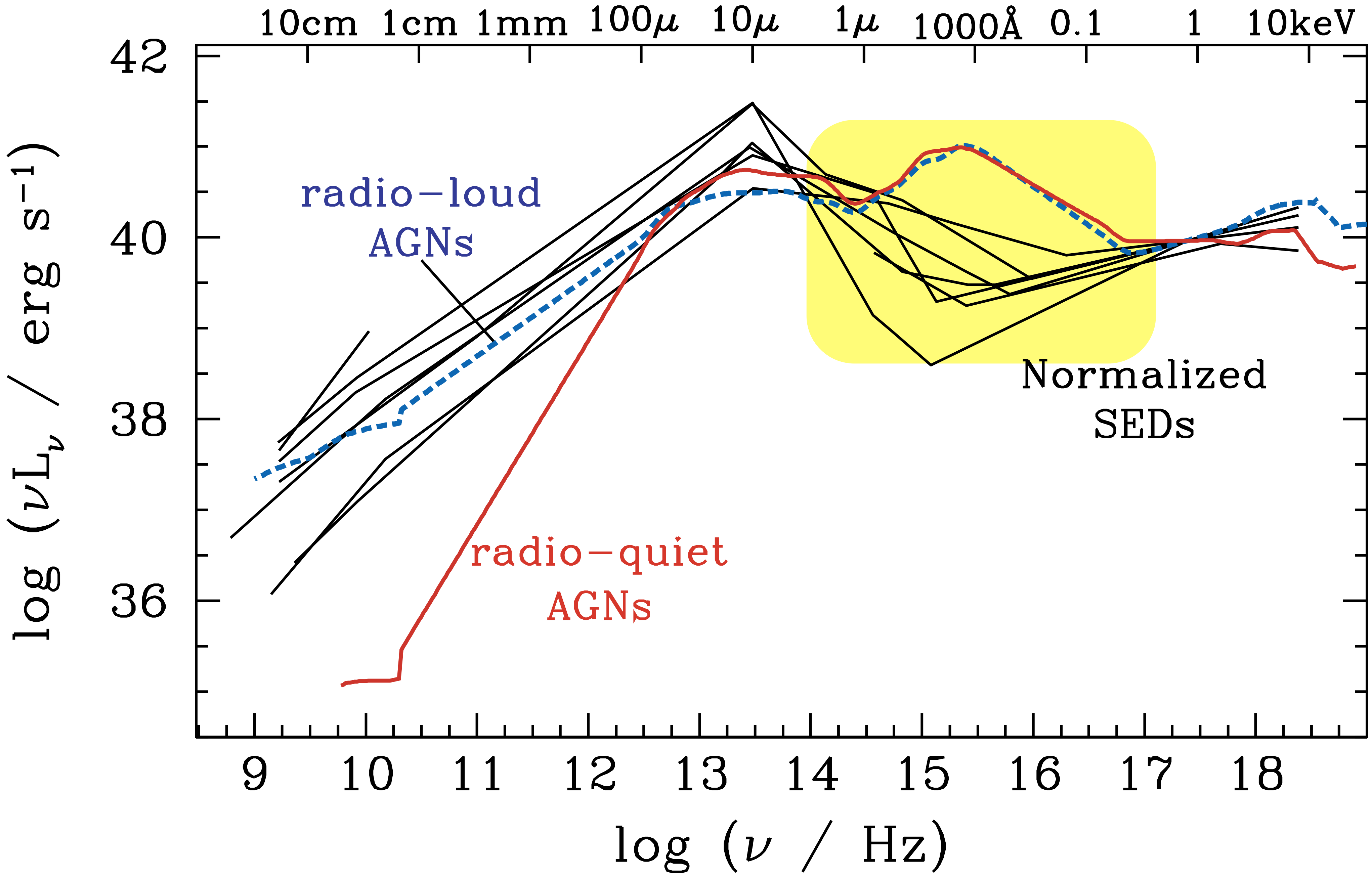
Shang et al. 2005, ApJ, 619, 41

- Find breaks in UV spectra of quasars and determine slope on either side
- Compare break wavelengths and slopes with hot atmosphere models (from Hubeny et al. 2001)
- Reasonable slopes but none of the expected correlations between model parameters found.

Application to Low-Luminosity AGNs

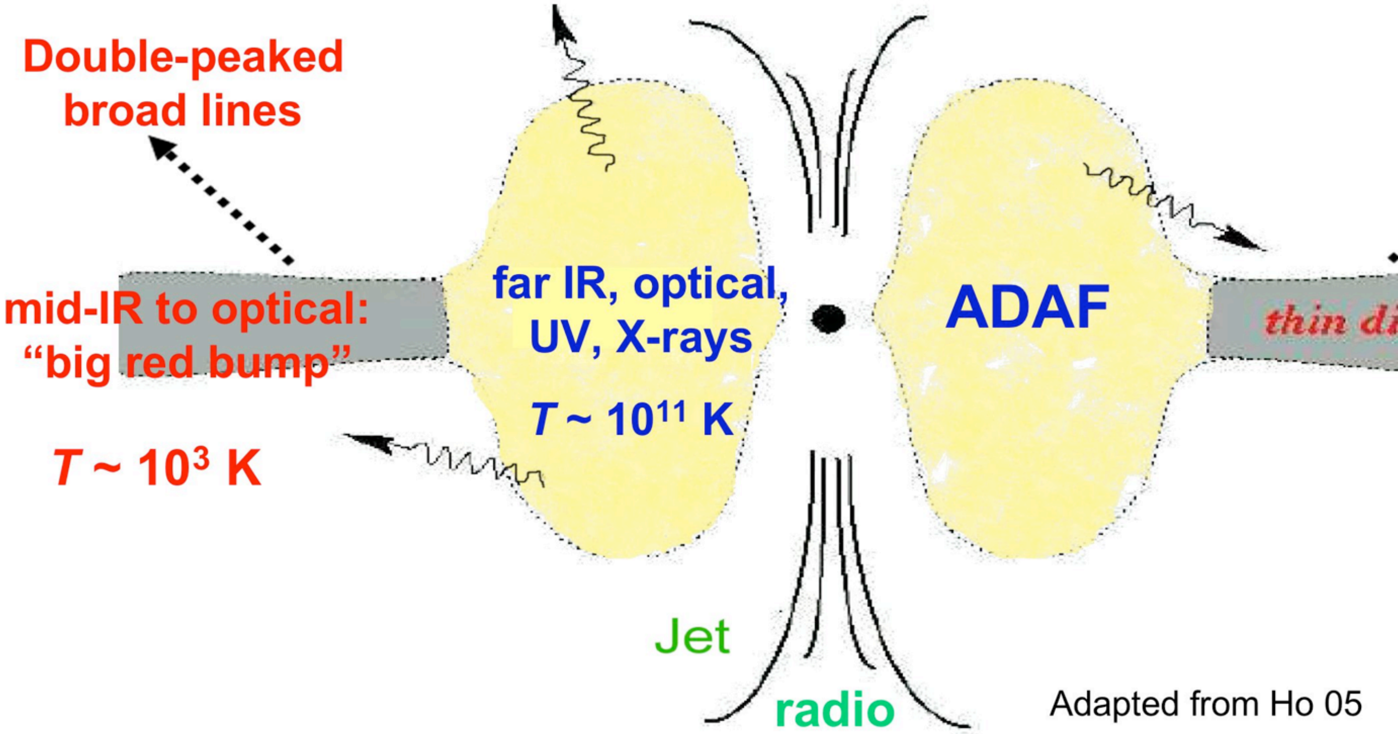
Collection of LL-AGN SEDs

from Ho 1999, ApJ, 516, 672



Main radiation processes involved

- From hot torus:
  - Synchrotron followed by inverse compton
  - Bremstrahlung
- From the thin disk
  - thermal emission (could be irradiated)
- From the jet
  - Synchrotron followed inverse compton

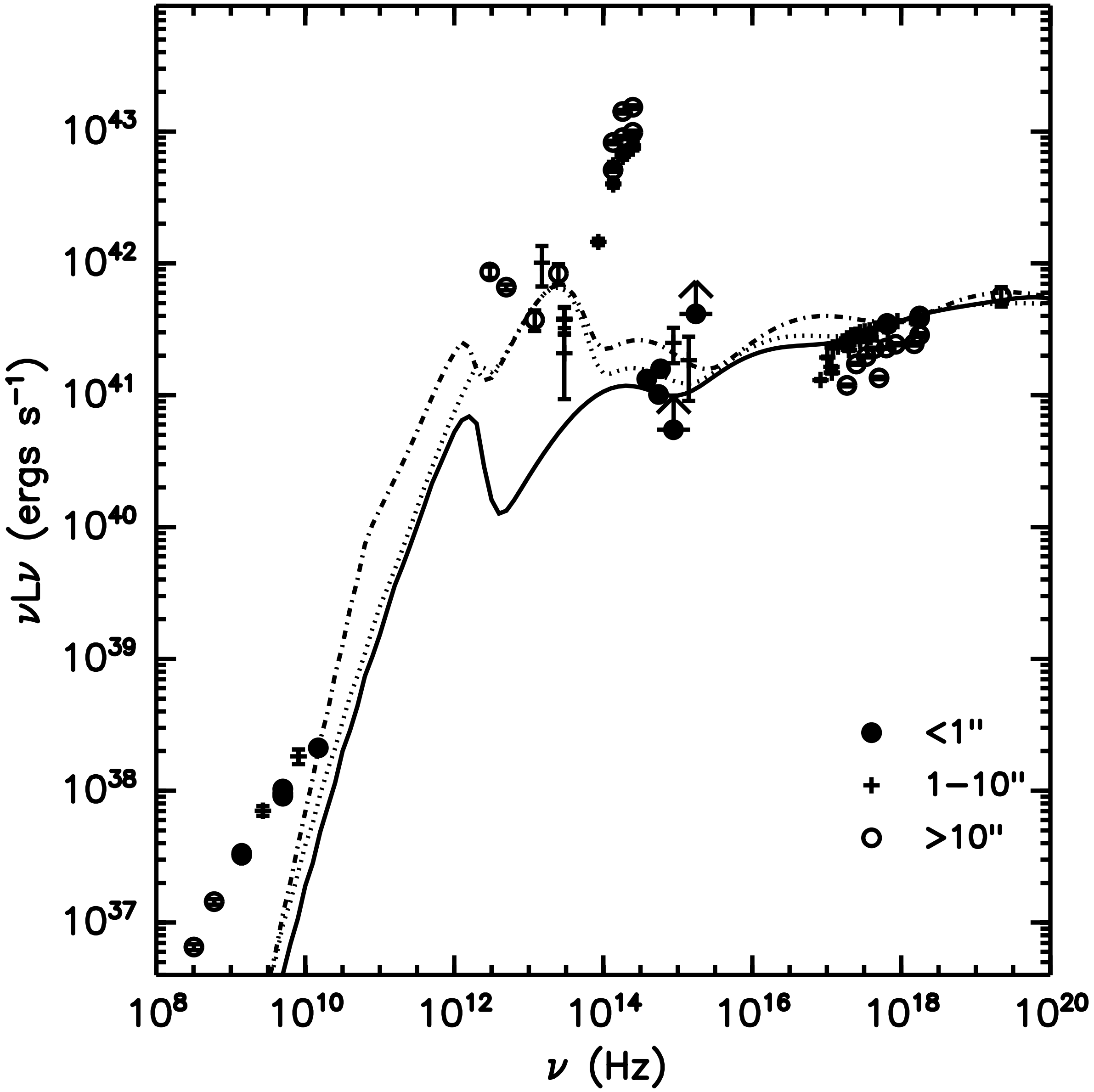


Adapted from Ho 05

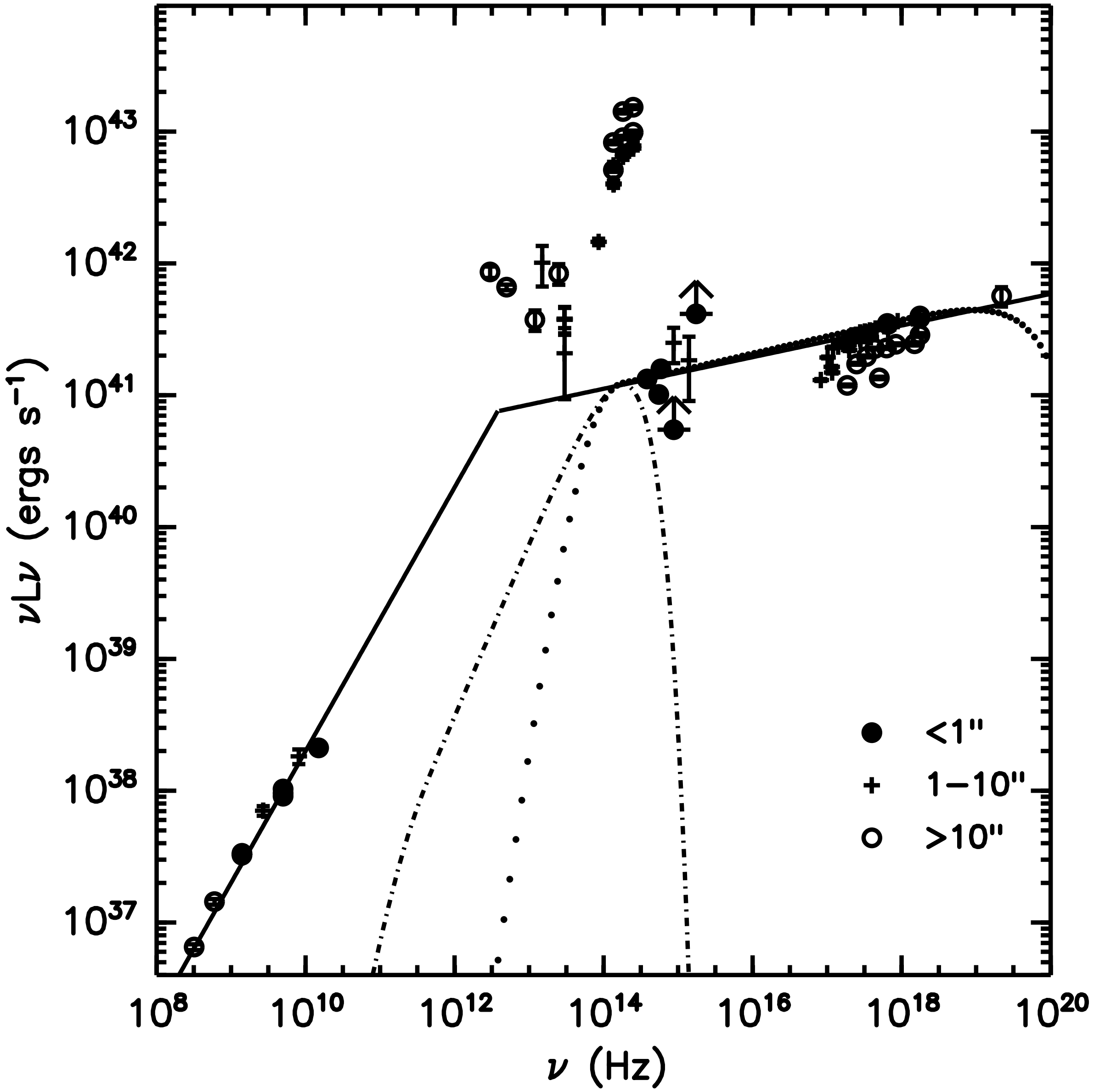
Fit to the SED of NGC 3998

from Ptak et al. 2004, ApJ, 606, 173

Fits with three different ADAF/ADIOS models plus thin outer disk.



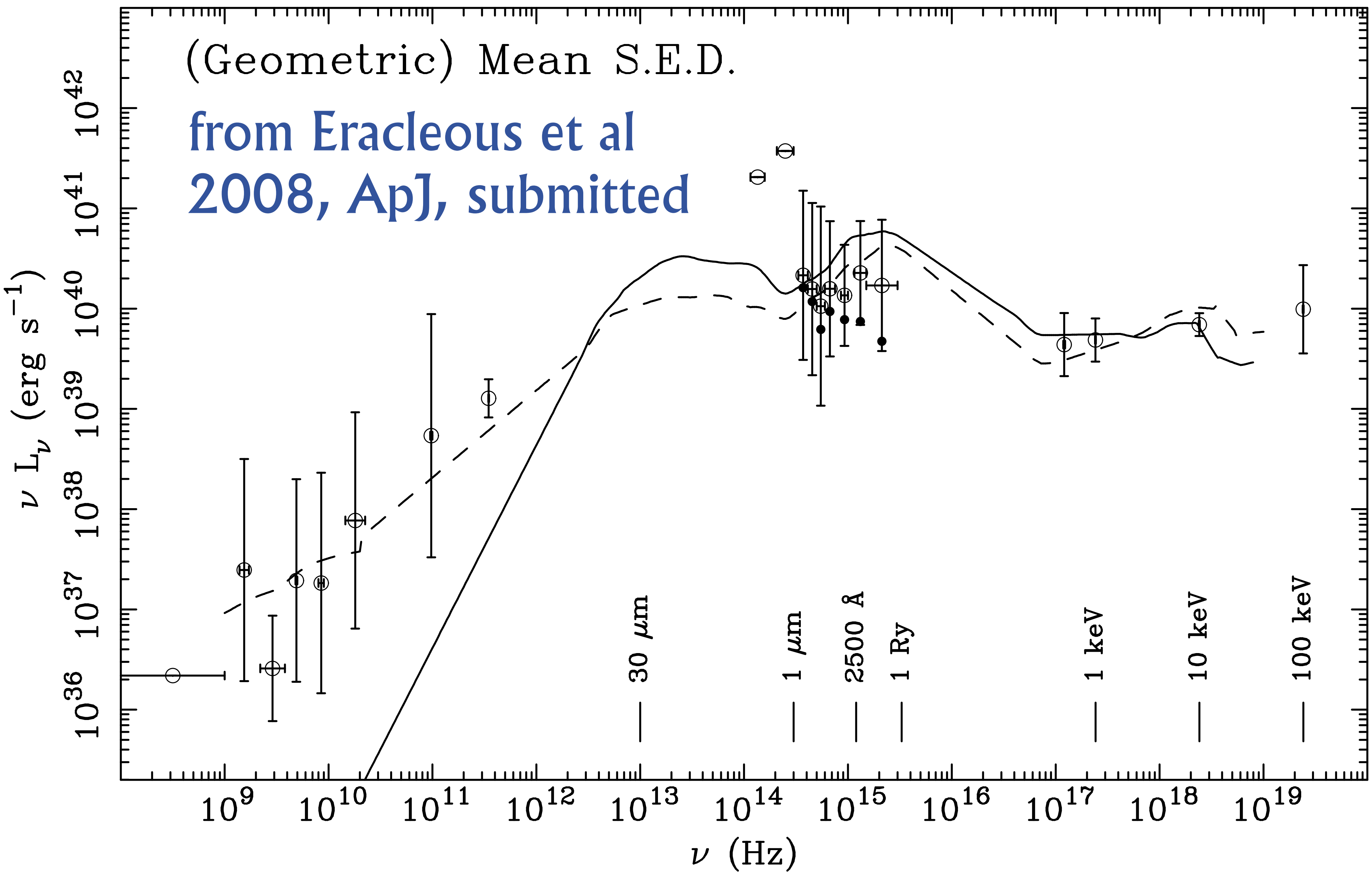
Comparison with thin comptonized disk model and broken power law



What we know about LL-AGN SEDs

- **VLA/VLBA observations**
  - compact, high-T_B radio cores and jets
  - jets required for radio portion of SED.
- **Chandra X-ray observations**
  - unresolved X-ray sources with power-law spectra
  - may be emission from ADAF/RIAF
- **HST UV Observations**
  - variable, unresolved sources at 2500 Å
  - does this agree with ADAF models?

New Average S.E.D. of LL-AGNs



from Eracleous et al 2008, ApJ, submitted

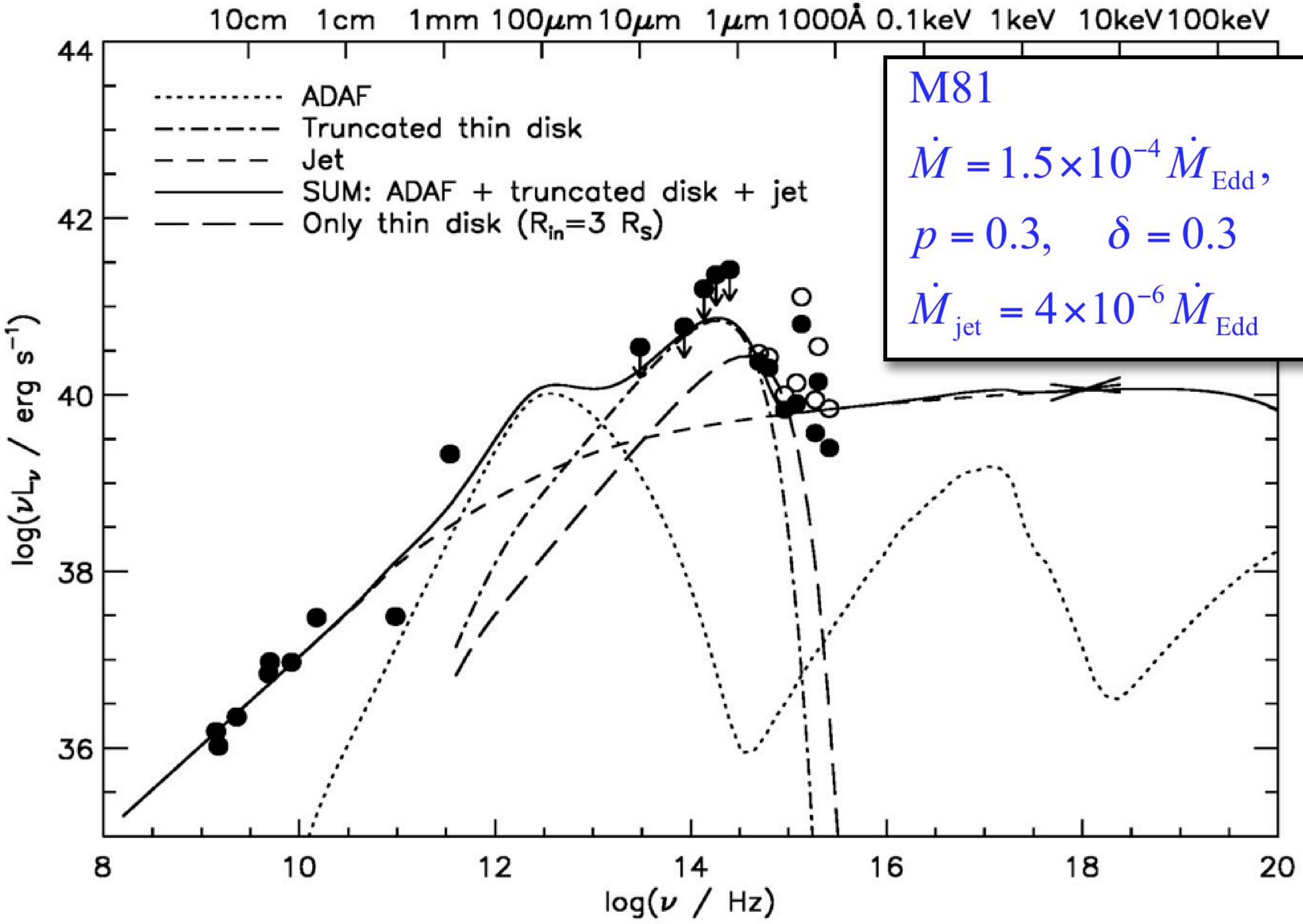
Fits to individual objects: M81

Jet explains radio and X-rays

Thin disk explains UV+optical

small contribution from ADAF

from Nemmen et al. 2008,
in preparation



M81

$\dot{M} = 1.5\times10^{-4}\dot{M}_{\rm Edd}$, $R_{\rm tran} = 50R_S$

$p = 0.3$, $\delta = 0.3$

$\dot{M}_{\rm jet} = 4\times10^{-6}\dot{M}_{\rm Edd}$

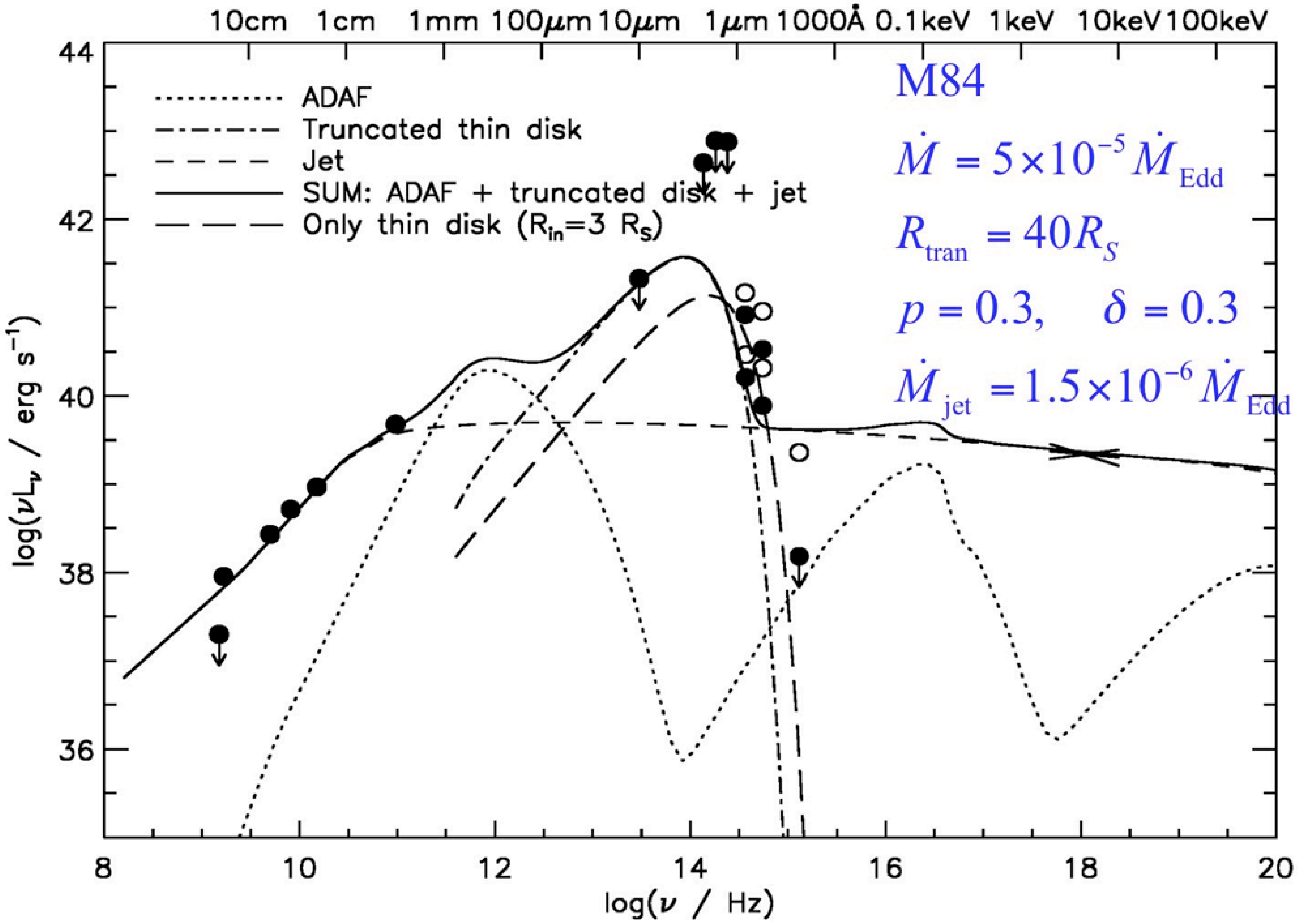
Fits to individual objects: M84

Jet explains radio and X-rays

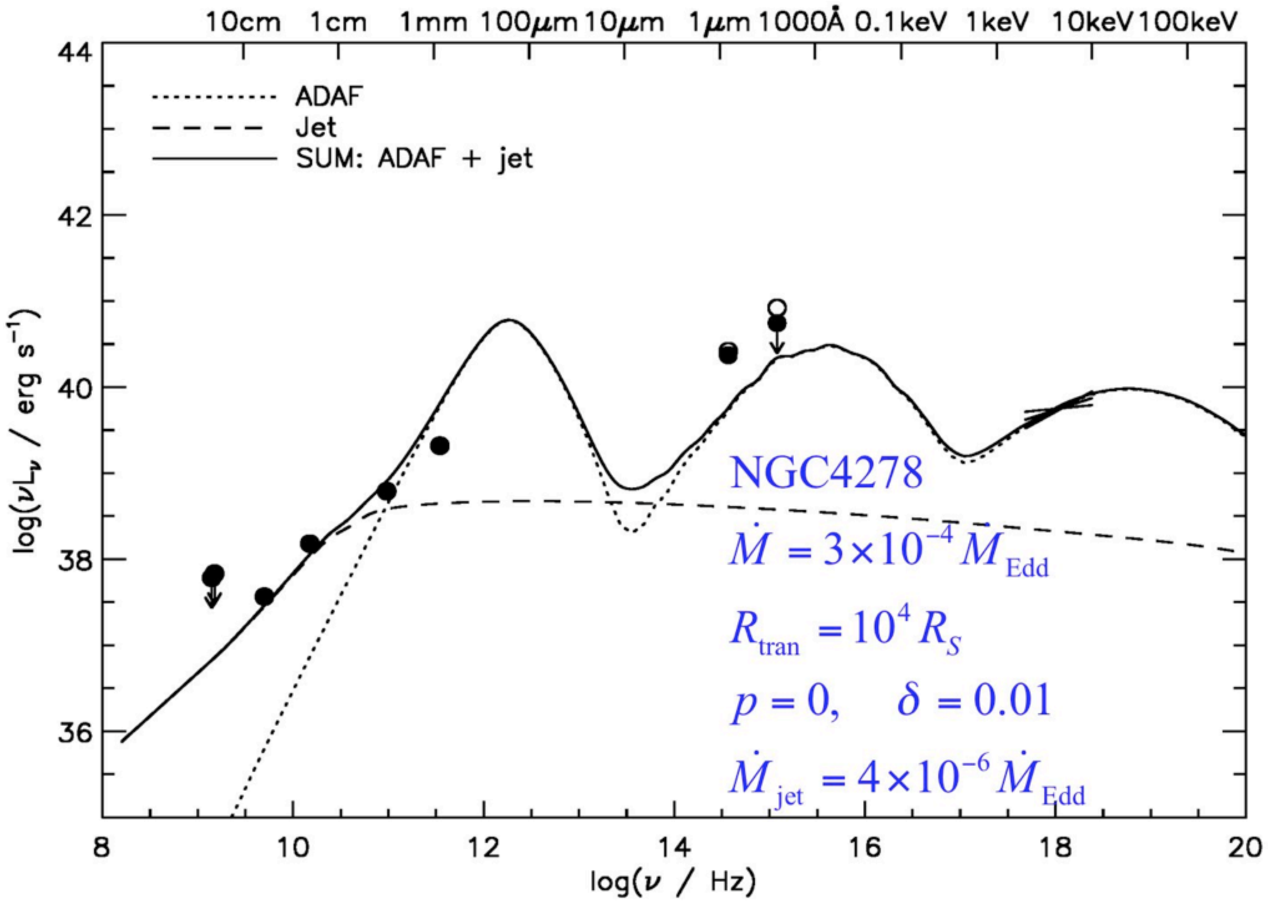
Thin disk explains UV+optical

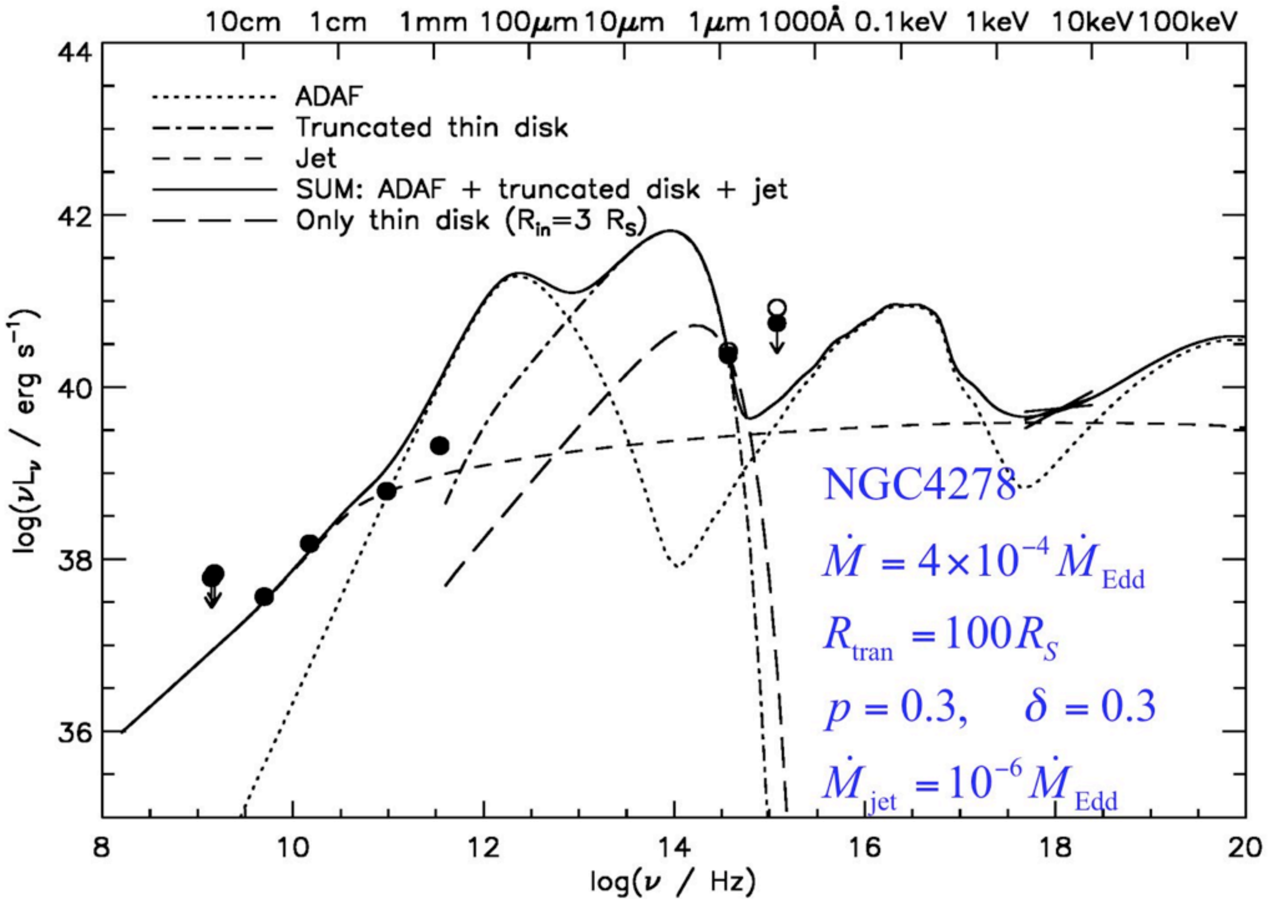
small contribution from ADAF

from Nemmen et al. 2008,
in preparation



Fits to individual objects: NGC 4274





- **Ambiguous case: more than one physically plausible solution possible**
- **Value of δ controls contribution of ADAF to the X-ray band and leads to different solutions**

Applications to XRBs

- **New generation of models based on latest theoretical developments.**
  - Most sophisticated atmosphere models yet
  - Electron scattering and comptonization
  - Fully relativistic ray propagation
  - Boundary conditions at inner disk edge
  - Vertical energy dissipation profile
- **Compare to BH-XRBs with known masses, distances, and inclinations**

Application to XRBs and the B. H. spin

- **Multi-color disk with modified blackbodies**

$$I_\nu \approx \frac{B_\nu(f_{\rm col}T)}{f_{\rm col}^4}$$

- **Adjust spin parameter to fit X-ray spectrum.**
- **Verify by checking if**

$$L(T) \propto T^4$$

as the system varies

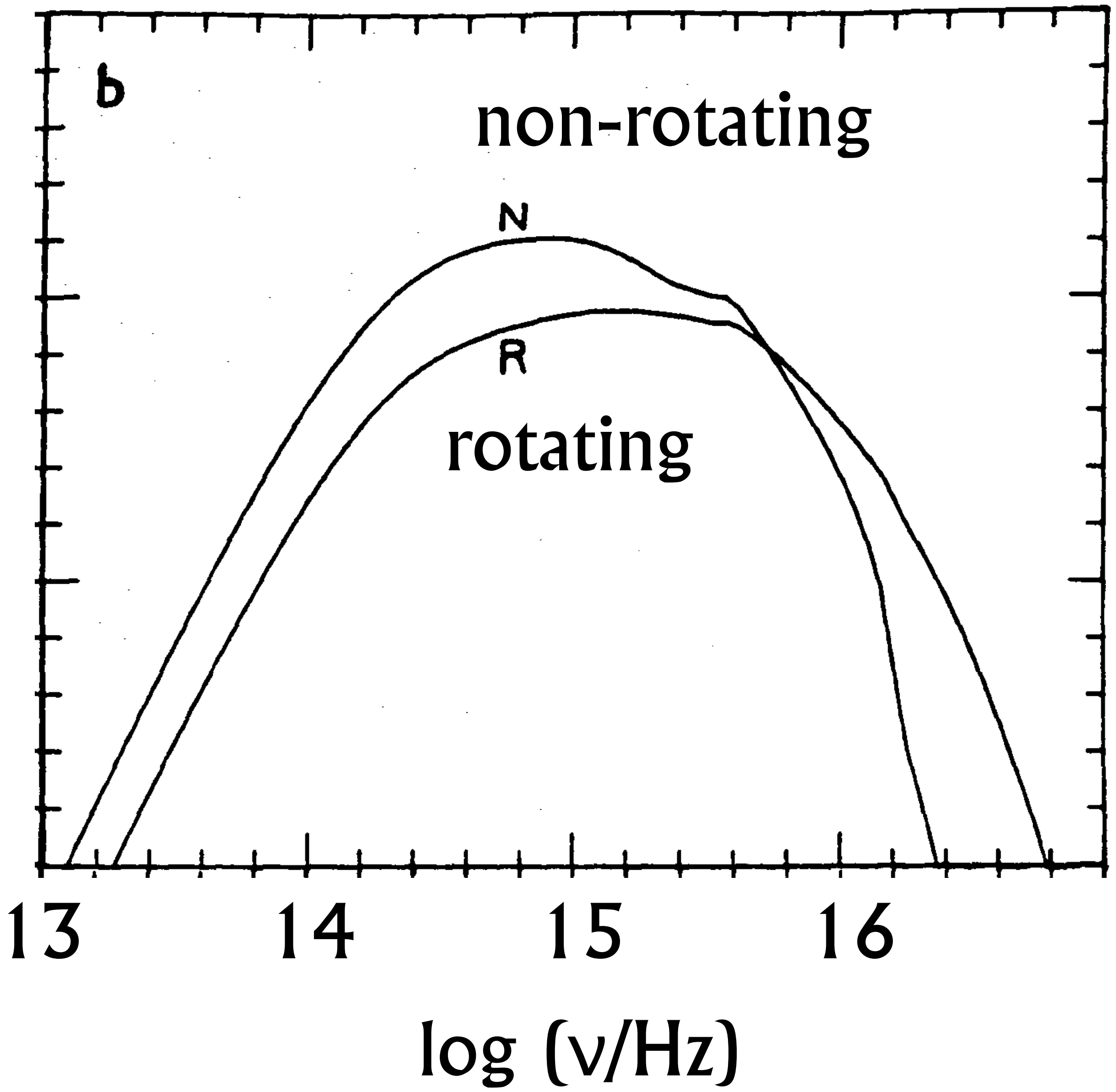


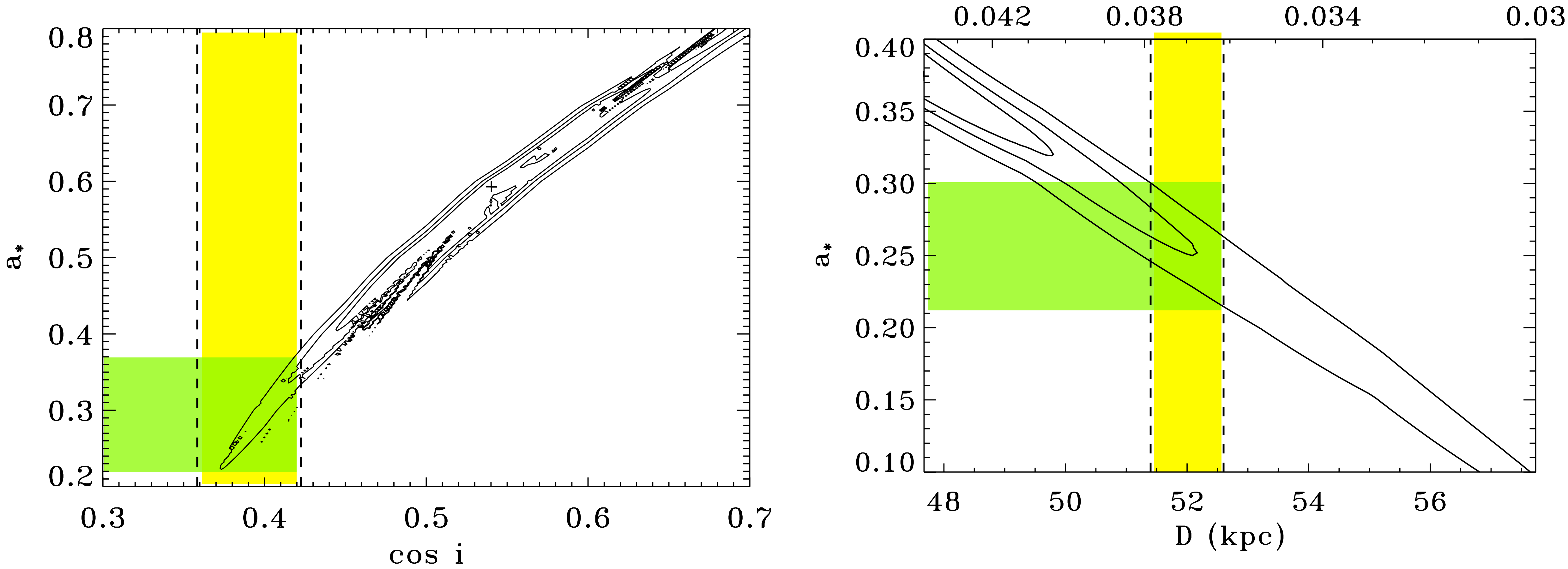
figure from Laor & Netzer 1989, MNRAS, 238, 897

Applications to XRBs: Recap

- **New generation of models based on latest theoretical developments.**
  Davies et al. 2006, ApJ 621, 372
  - Most sophisticated atmosphere models yet
  - Electron scattering and comptonization
  - Fully relativistic ray propagation
  - Boundary conditions at inner disk edge
  - Vertical energy dissipation profile
- **Compare to BH-XRBs with known masses, distances, and inclinations**

Results

from Davies et al. 2006, ApJ 621, 372



Can this method be applied to AGNs?

- Easier to measure distances to AGNs
- But BH masses and disk inclinations are very difficult to get
- AGN disks have kT ~ 20 eV; anathema!
  - radiate in FUV; thermal spectrum unobservable
  - atmosphere models more difficult (cf, CVs)
- If X-ray emission models are right (Lecture 3), disks must be intensely radiated.

Where do we stand?

- **SED models have only partial success.**
  - Qualititative features of the data are reproduced.
  - Most successful application is to hot XRB disks.
  - Spectacular failure in AGN SEDs.
- **Where could the problem be?**
  - Fundamental theory has open questions.
  - Atmosphere models are also incomplete (we know there are winds).
  - Irradiated atmospheres (e.g., current big picture in AGNs not self-consistent) !

End of Lecture I