Spectral Modeling of Protostars Associated with Taurus Molecular Cloud

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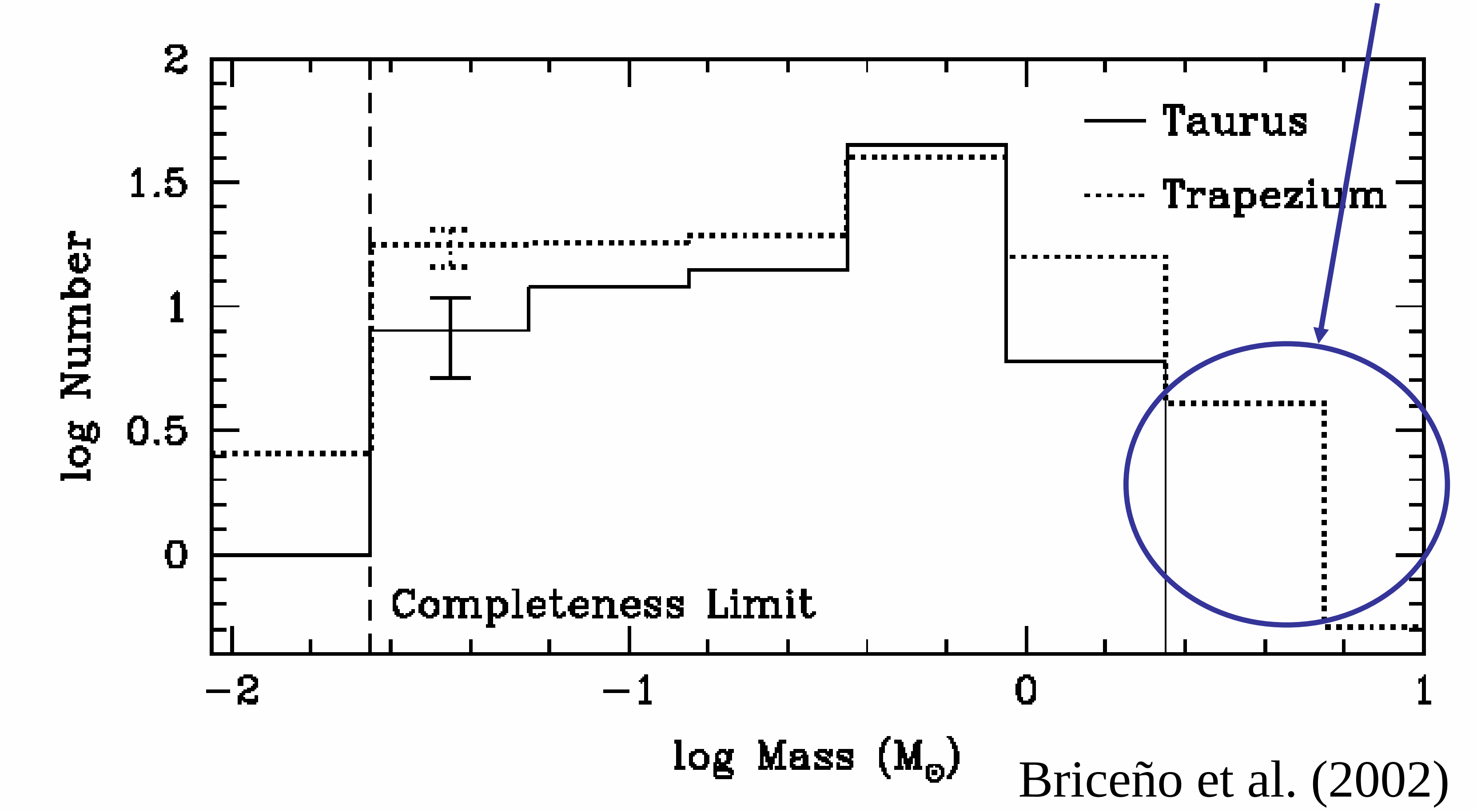
Motivation

- ➢ How circumstellar environment affects star formation?



There are no massive stars in Taurus

Briceño et al. (2002)

Purpose of This Work

➢ Properties of protostars should reflect on the circumstellar environment.

- luminosity function
- circumstellar mass (envelope, disk, mass ratio)
- outflow activity
- …

Research of the protostars with **spectral modeling**.

➢ for each star forming region.

➢ today’s talk is results for Taurus.

Past Works

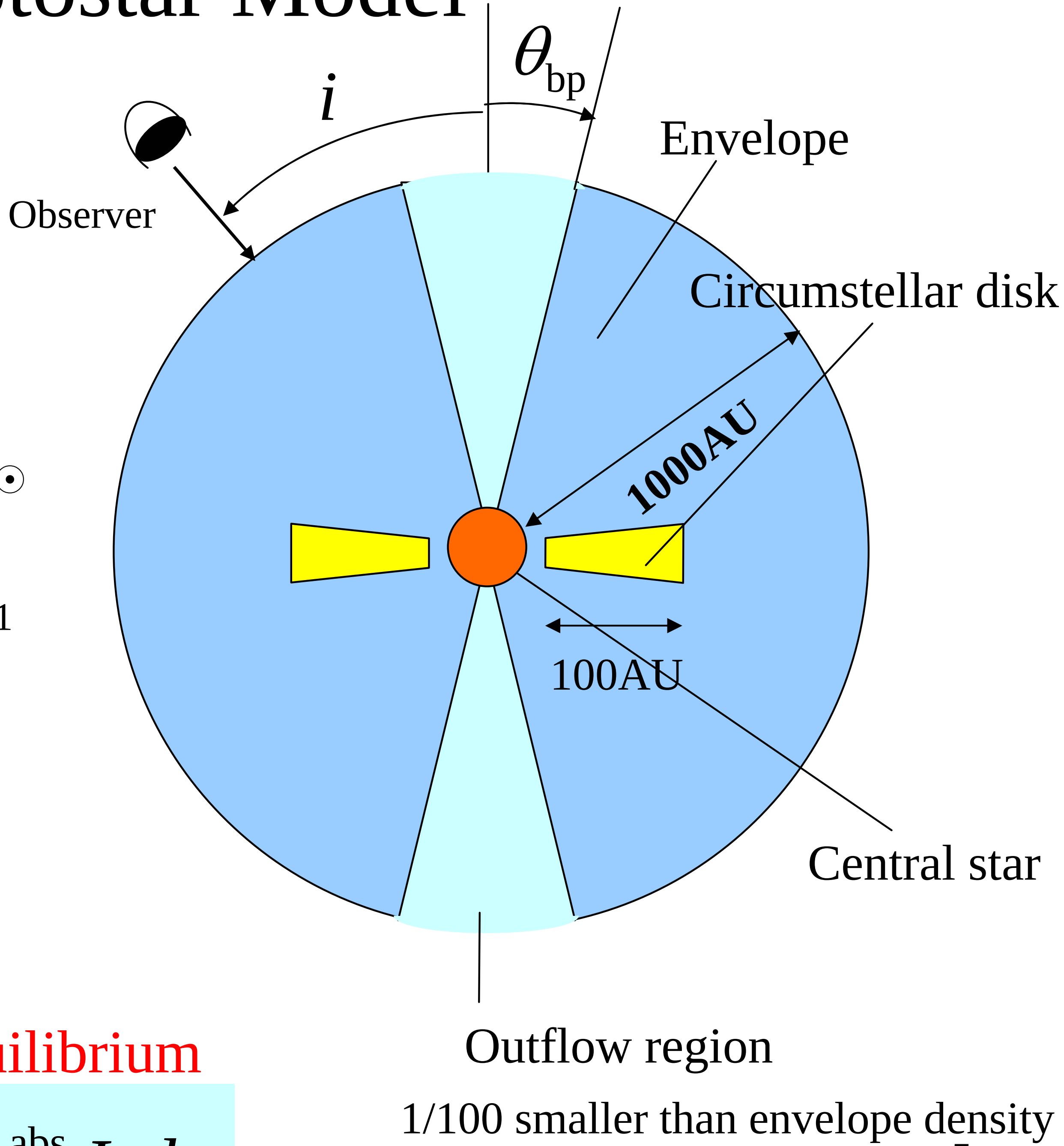
- Kenyon et al. (1993)
  - first (and only?) systematic research for SED of protostars.
  - sources are selected in Taurus.
  - spherically symmetric radiative transfer.
  - disk is not explicitly considered in their model.
- Osorio et al. (2003)
  - detailed modeling of L1551 IRS5.
  - multiplicity is considered.
  - circumstellar and circumbinary disks are considered.
  - approximate treatment of radiative transfer.

Systematic research of protostars with spectral modeling by using detailed protostar model is needed.

Protostar Model

- **2-D axisymmetric**
- Three components;
  - Central star: **single star**
    - Luminosity L_*
    - Temperature T_*
    - Mass $M_* = 0.5 M_\odot$
  - Circumstellar disk:
    - Surface density at 1AU Σ_1
    - Power law index $p = 1.5$
  - Envelope:
    - Density at 1AU ρ_1
    - Power law index $q = 1.5$
    - Semi-opening angle θ_{bp}
- Temperature: Radiative equilibrium

$$\int_0^\infty \chi_\nu^{\text{abs}} B_\nu d\nu = \int_0^\infty \chi_\nu^{\text{abs}} J_\nu d\nu$$



Treatment of Radiative Transfer

➢ Variable Eddington Factor Method (Stone, Mihalas, & Norman 1992; Kikuchi, Nakamoto, & Ogochi 2002)

- 0th, 1st, and 2nd moment equations of Radiation HydroDynamics (RHD) are solved.
- The Variable Eddington Factor (VEF) is introduced to close RHD moment equations.
- The VEF is calculated from the specific intensity which is determined by solving radiative transfer equation.

- In our scheme, velocity is set to 0.
  (our aim is to find the radiative equilibrium for given situation)

VEF method can treat the radiation transfer without any kind of approximation!

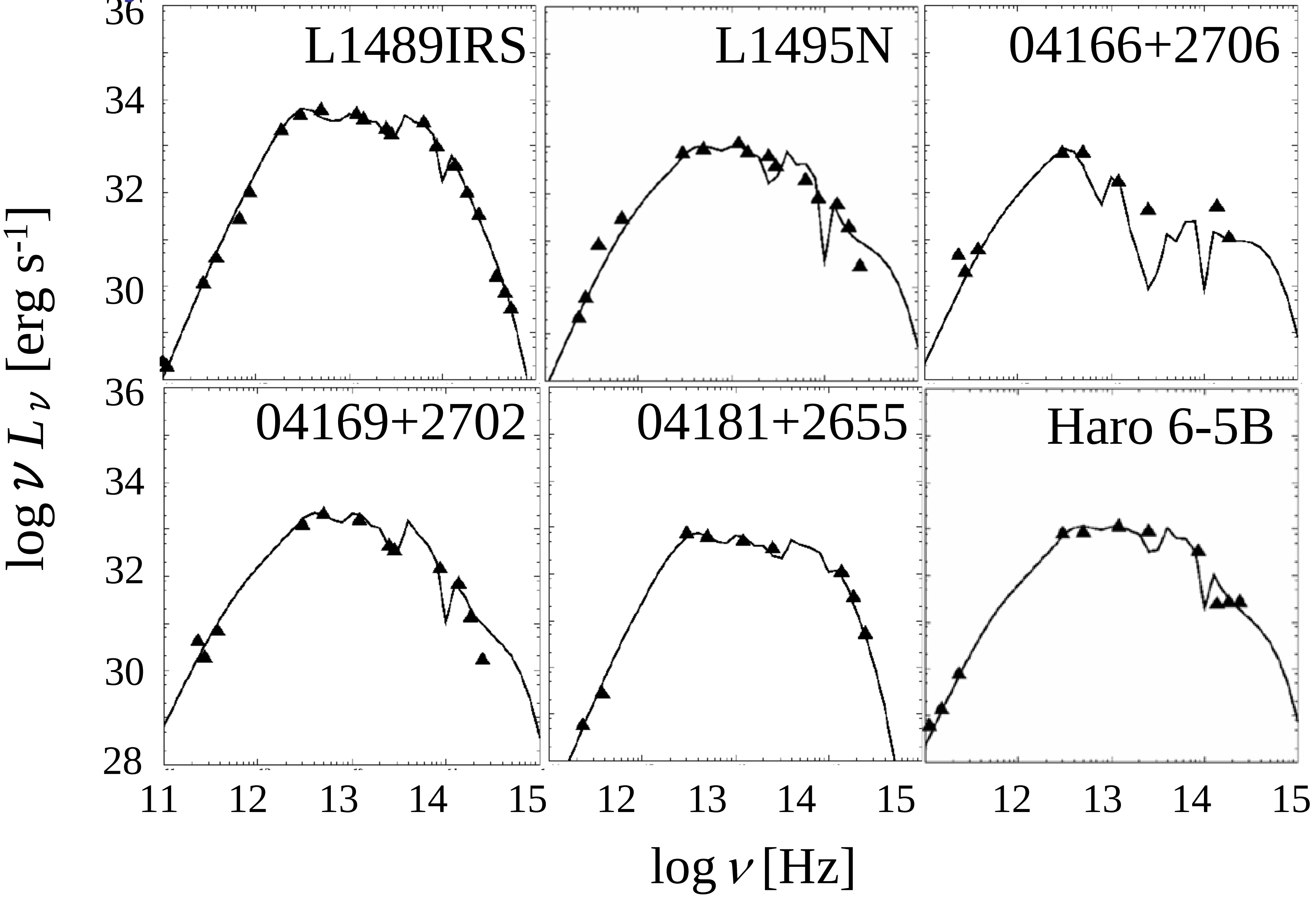
Source Selection

- associated with Taurus
- many observational point (roughly 10 or more)
- wide variety of wavelength (radio ~ NIR)

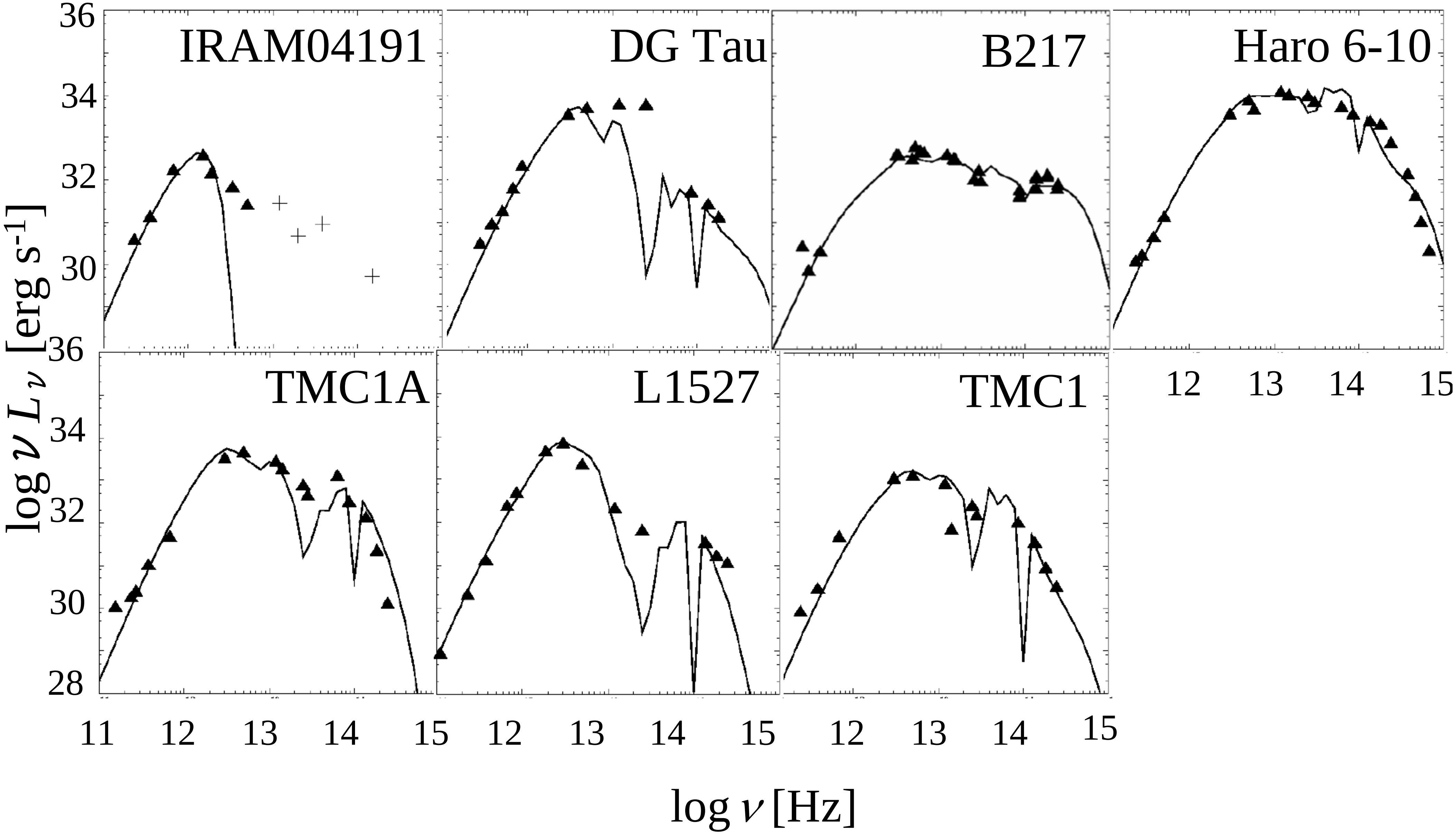
	Class	IRAS name	α (1950)	δ (1950)
L1489IRS	I	04016+2610	04h01m40s6	+26°10’49″
L1495N	I	04108+2803b	04h10m48s0	+28°03’49″
04166+2706	0/I	04166+2706	04h16m37s8	+27°06’29″
04169+2702	I	04169+2702	04h16m53s8	+27°02’48″
04181+2655	I	04181+2655	04h18m06s4	+26°55’01″
Haro6-5B	I	04189+2650	04h18m56s6	+26°50’28″
IRAM04191	0	-	04h19m06s4	+15°22’46″
DGTau	I	04240+2559	04h24m00s4	+25°59’30″
B217	I	04248+2612	04h24m53s2	+26°12’39″
Haro6-10	I	04263+2426	04h26m21s7	+24°26’26″
TMC1A	I	04365+2535	04h36m31s0	+25°35’52″
L1527	0/I	04368+2557	04h36m49s5	+25°57’16″
TMC1	I	04381+2540	04h38m07s6	+25°40’48″

Spectral Modeling

- We could reproduce observed SEDs almost all wavelengths for each objects.



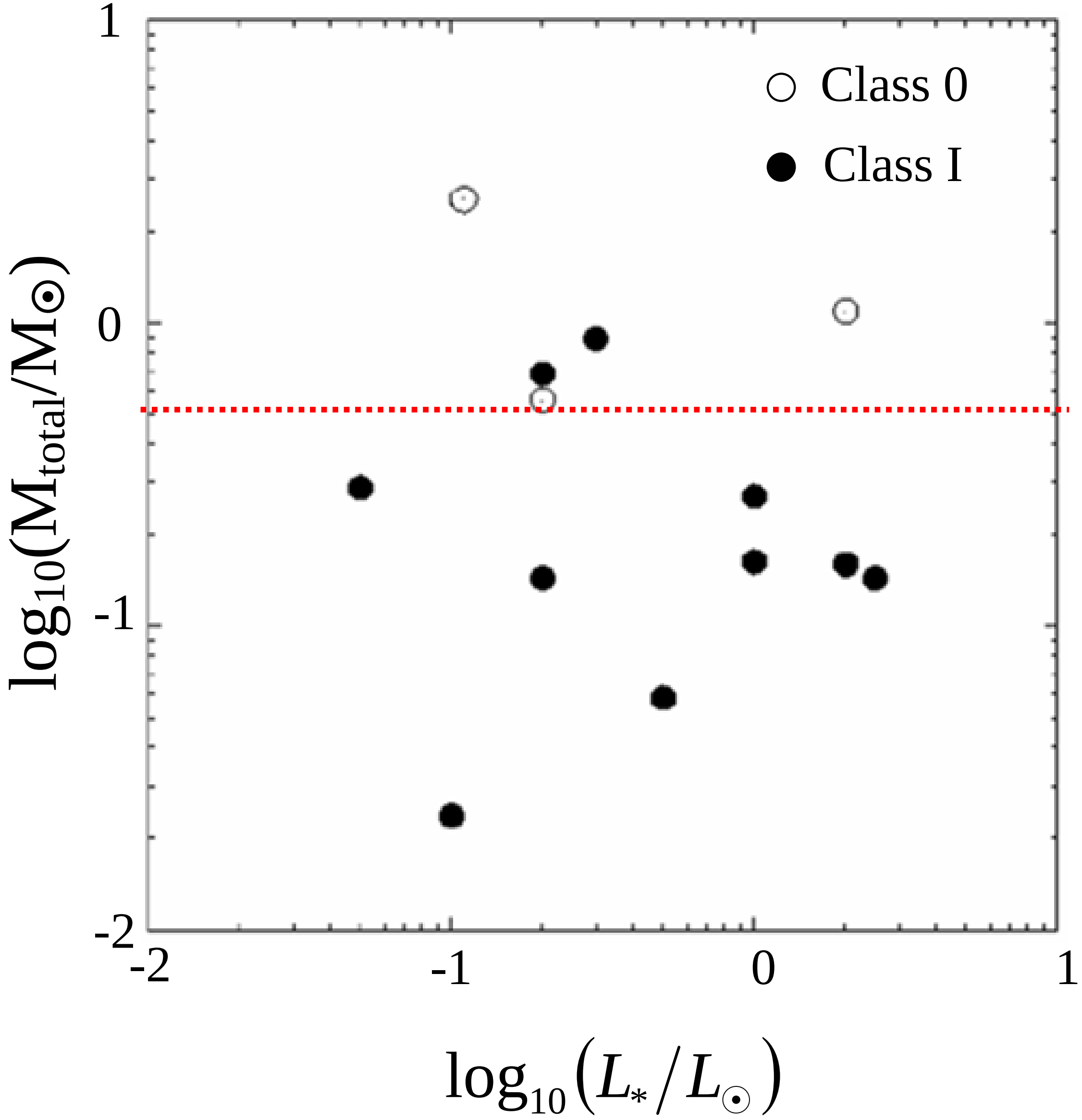
Spectral Modeling



Best Fitted Parameters for Each Objects

	L	rho_1	M_env	Sigma_1	M_disk	M_env/M_disk	M_total	theta_bp	inc
L1489IRS	1	−12.6	0.11	4000	0.054	2.03703704	0.164	15	10
L1495N	0.2	−14	0.0042	10000	0.14	0.03	0.1442	10	12
04166+2706	0.2	−13.3	0.021	40000	0.54	0.03888889	0.561	20	40
04169+2702	0.3	−13.52	0.013	65000	0.88	0.01477273	0.893	10	10
04181+2655	0.1	−13.34	0.017	500	0.0068	2.5	0.0238	13	10
Haro6−5B	0.2	−14	0.0042	50000	0.68	0.00617647	0.6842	10	11
IRAM04191	0.11	−11.22	2.5	6000	0.08	31.25	2.58	10	90
DGTau	2	−13.3	0.021	10000	0.14	0.15	0.161	10	60
B217	0.05	−13.34	0.017	20000	0.27	0.06296296	0.287	20	0
Haro6−10	2.5	−14	0.0042	10000	0.14	0.03	0.1442	10	12
TMC1A	1	−12.5	0.13	10000	0.14	0.92857143	0.27	20	22
L1527	2	−12	0.42	50000	0.68	0.61764706	1.1	22	60
TMC1	0.5	−14	0.0042	4000	0.054	0.07777778	0.0582	22	40

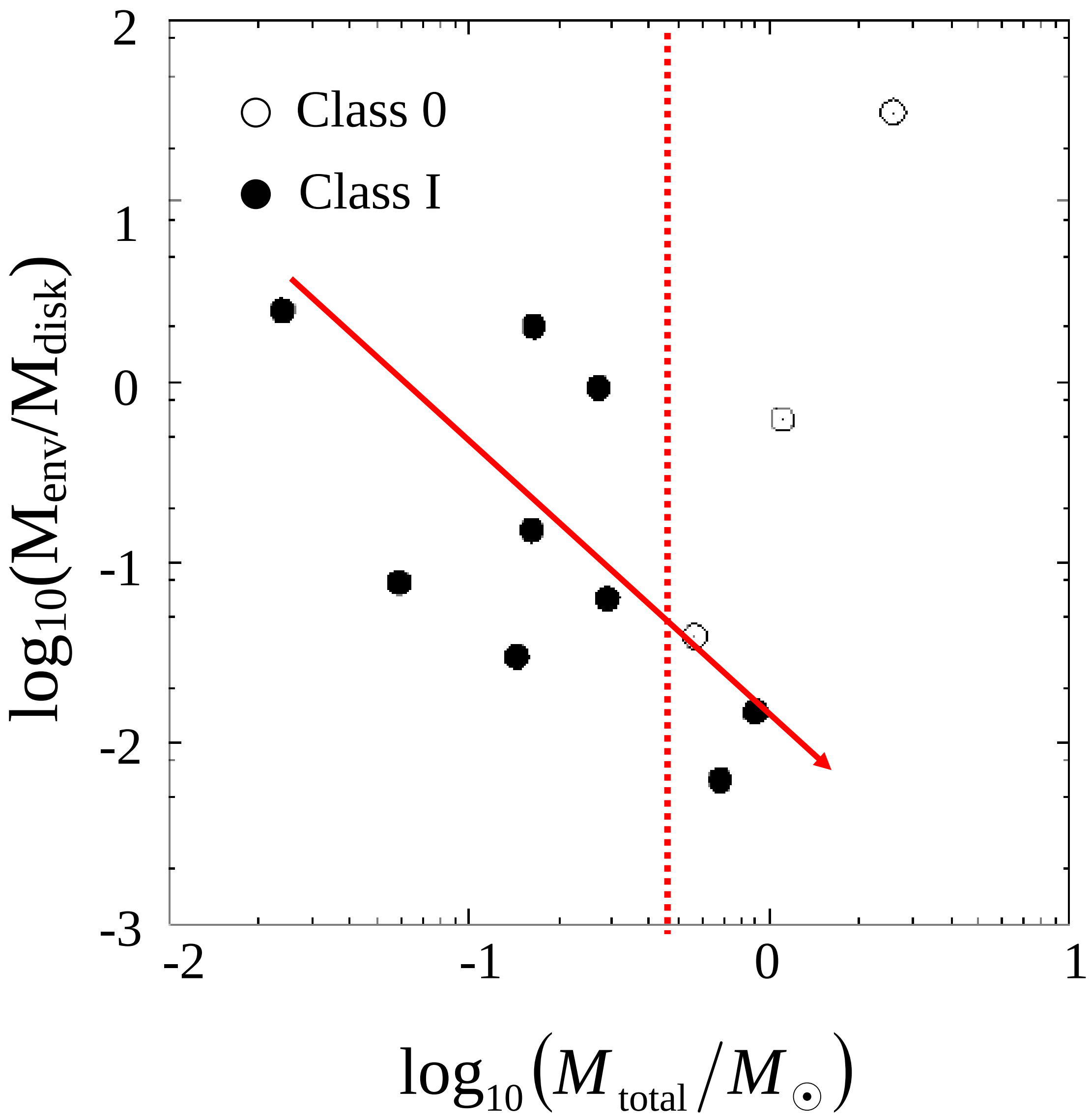
Correlation between Total Mass and Luminosity



- It seems that there are no correlation between these two values.

- The total circumstellar mass well separates Class 0 and I (also shown in Fig.1 of Bontemps et al. 1996).

Mass Ratio between Envelope and Disk



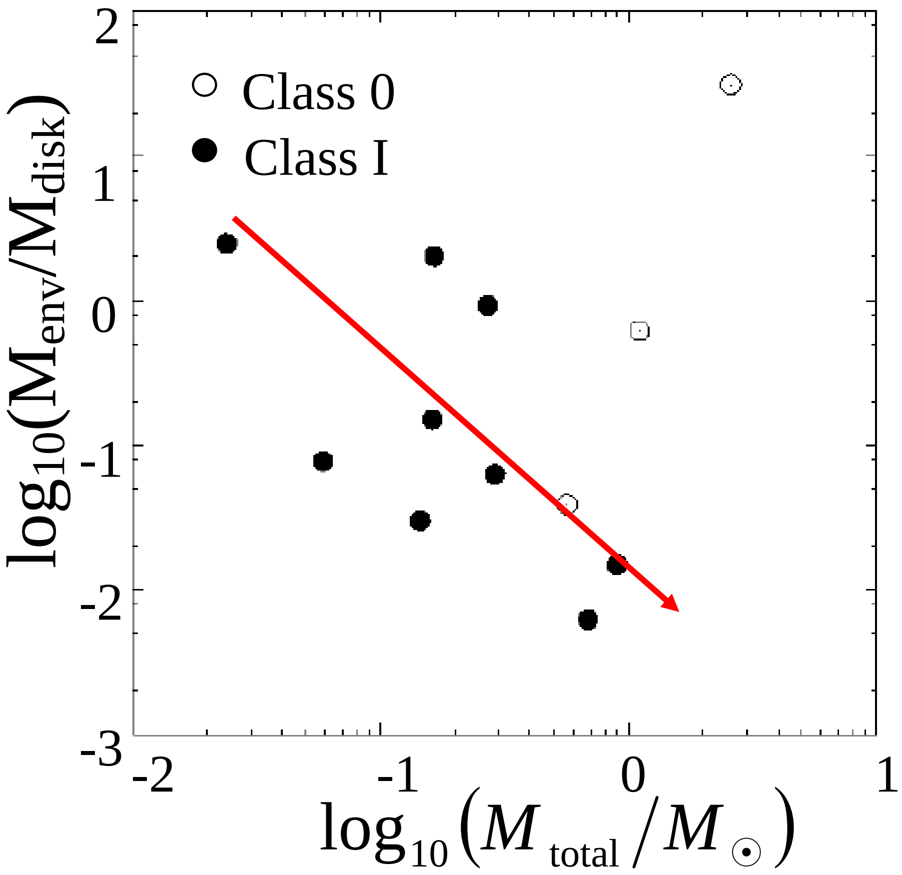
- A ratio M_{env}/M_{disk} has the value between 0.001 and 100. →reflecting the property of the star-forming region?

- Class 0 and Class I are well separated by the total mass rather than the mass ratio.

- mass ratio M_{env}/M_{disk} is decreasing with increase of the total mass M_{total}.

Interpretation of the Result

- In protostar phase, there is a certain amount of the mass in the envelope outer than 1000AU (Masunaga & Inutsuka 2000; Motte & André 2001)

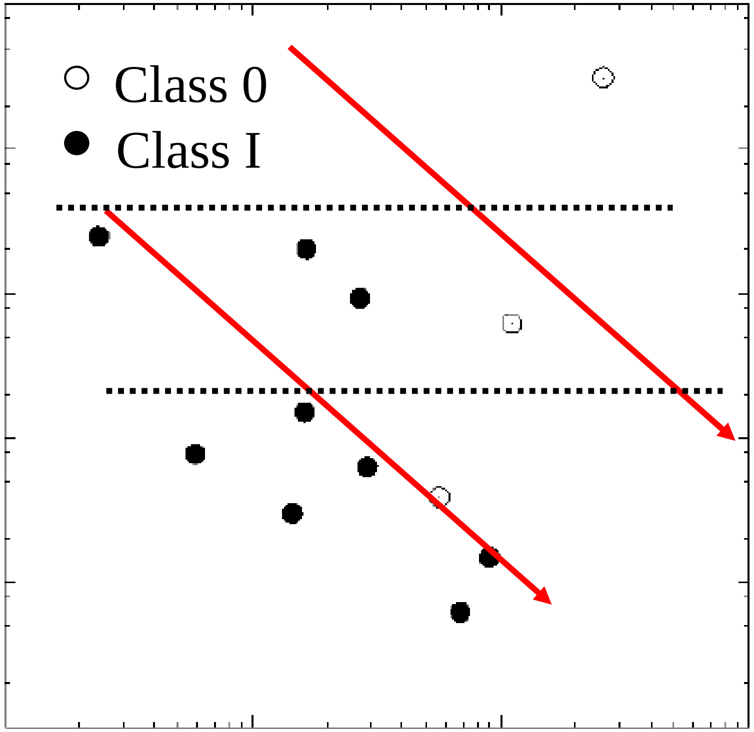


An increase of the total mass M_{total} arises from a mass infall from the outer envelope?

- Total (circumstellar) mass included into the radius 1000AU may be increasing with time at protostar phase.
- A decrease of the mass ratio indicates that an infalling material from the outer envelope would rapidly accrete onto the disk.

Substantial Difference between Class 0/I

1. Protostars classified into Class 0 are corresponding to a object which will evolve slightly massive stars than that of Class I.
   - large circumstellar mass.
   - low population (about 1/10 of Class I).
   - not contradict to youthfulness of Class 0?



2. Protostars classified into Class 0 are born into a core which initially has relatively large angular momentum than that forms Class I.
   - large circumstellar mass (accretion is prevented by the rotation?)
   - large outflow momentum (Bontemps et al. 1996)
   - correlation between outflow momnetum and initial rotational speed of the core (Tomisaka 2002)

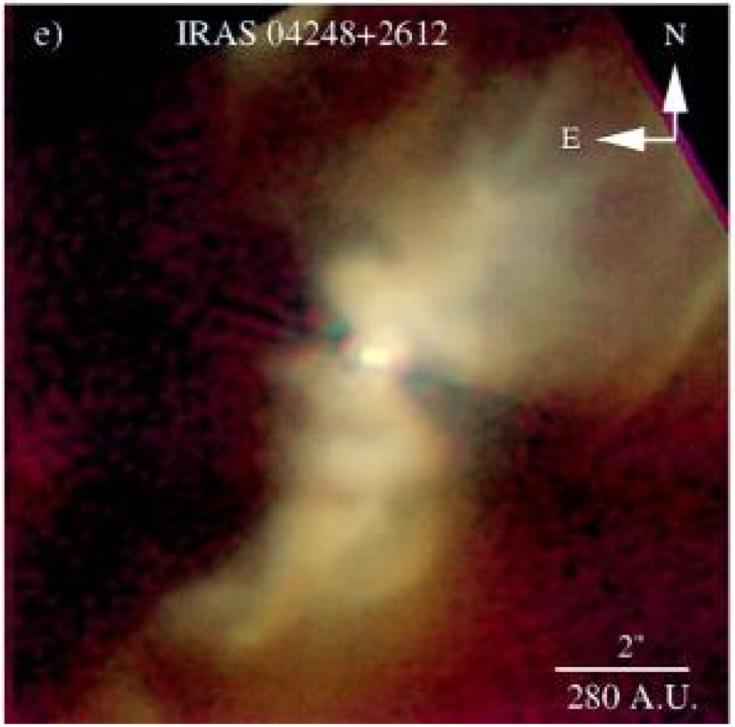
Summary

- We carried out the spectral modeling for 13 protostars associated with Taurus.
  - Our model could reproduce almost all observed SEDs.
  - mass ratio M_{env}/M_{disk}
    - $0.001 < M_{env}/M_{disk} < 100$
    - correlation between the total mass and the mass ratio
  - Class 0/I classification
    - differences between Class 0 and I are originated from initial condition (mass, angular momentum)?
- future work
  - comparison with other observation (imaging, line, etc.).
  - comparison with other star forming region.

Advantages of Spectral Modeling

- ➢ central star-disk system is invisible due to the thick envelope.
- ➢ spatial resolution is insufficient.

⇨ direct imaging of star-disk system is very difficult



HST /NICMOS images of Class I Object IRAS 04248+2612 (Padgett et al. 1999)

but spectral modeling do not need …

- ➢ high spatial resolution image.
- ➢ visibility of central region.

(instead, multi-frequency observation is essential.)

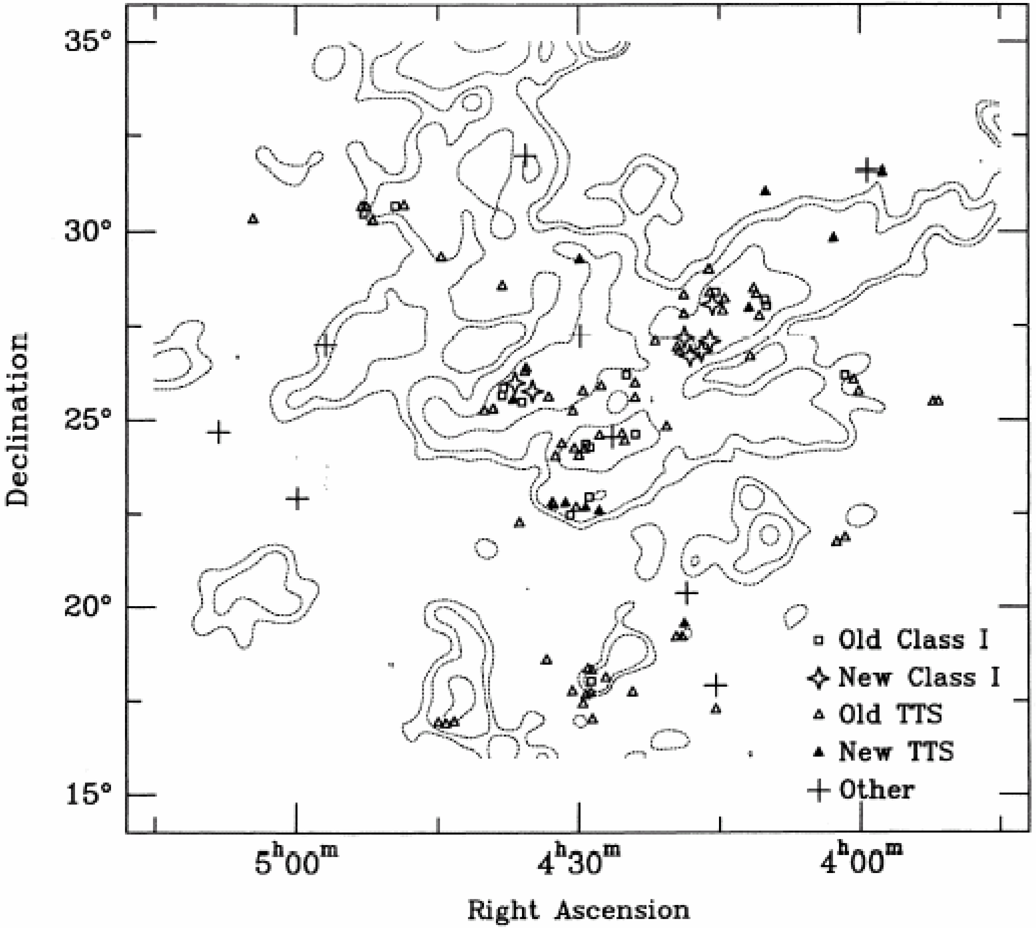
Taurus Molecular Cloud

- one of the nearest star forming region (140pc).

- no high-mass stars.

- roughly 30 protostar candidates (Class 0, I).

Spatial distribution of YSOs in Taurus



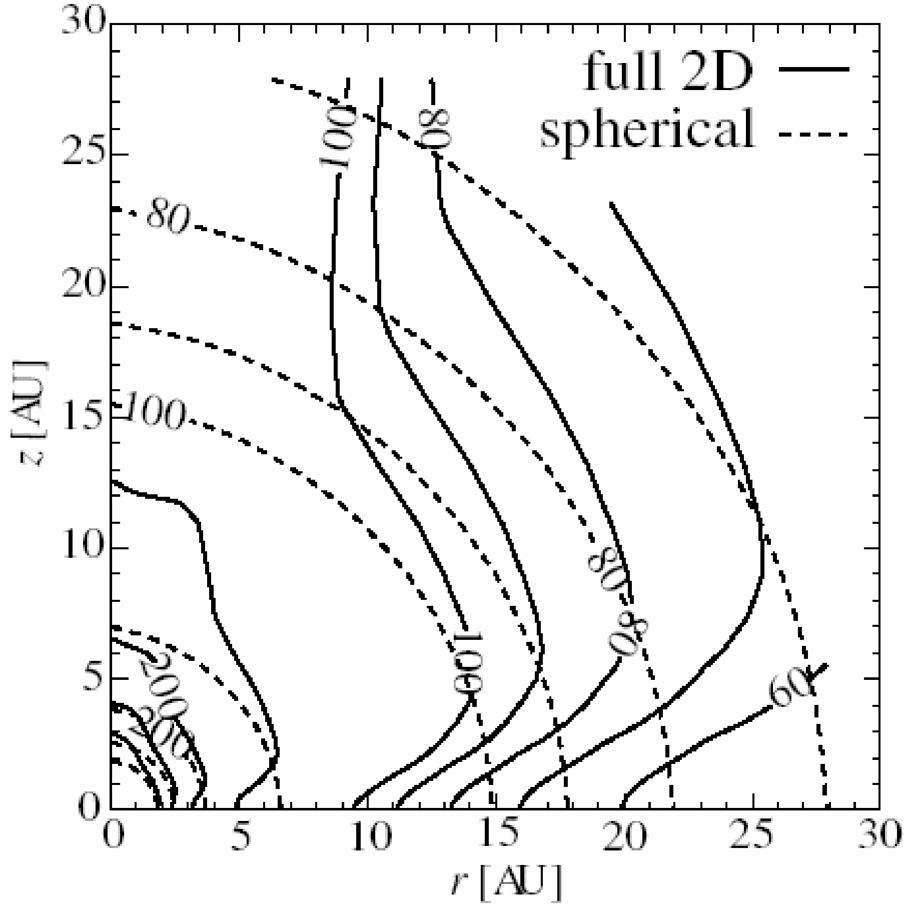
Kenyon et. al. 1990

Importance of Radiative Transfer

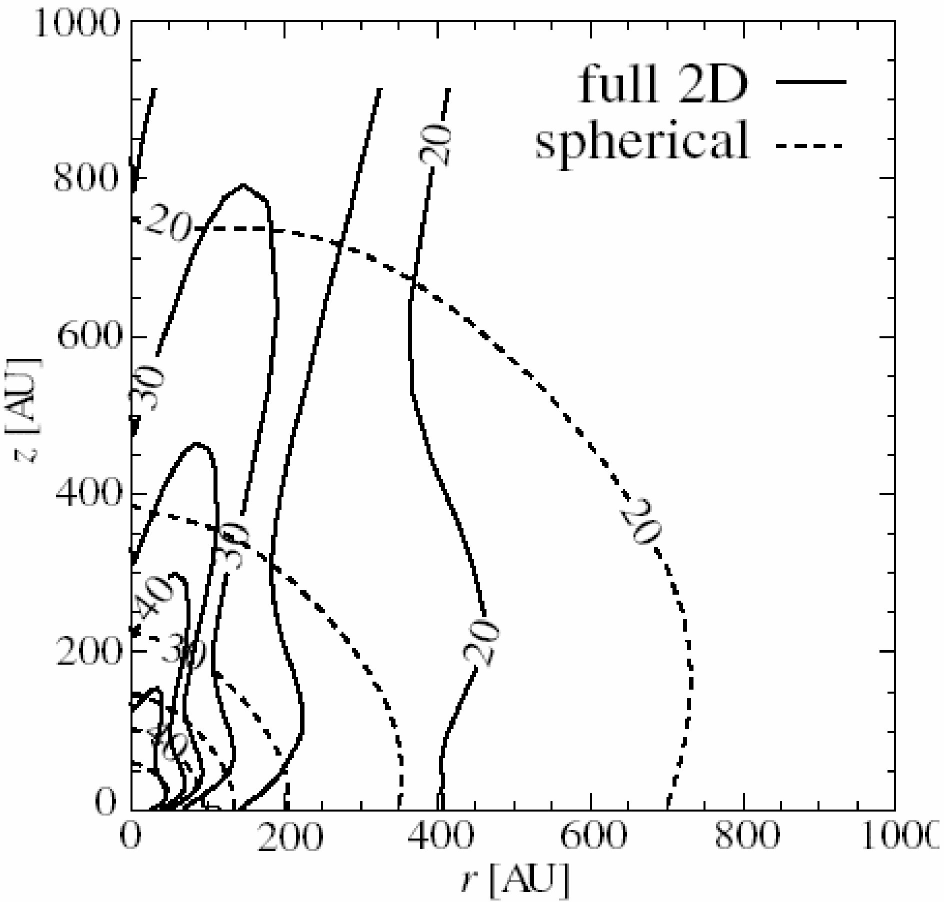
➢ Self-consistent treatment of radiation transfer is important (Nakazato, Nakamoto & Umemura 2003).

- temperature distribution

central 30 × 30 AU



1000 × 1000 AU



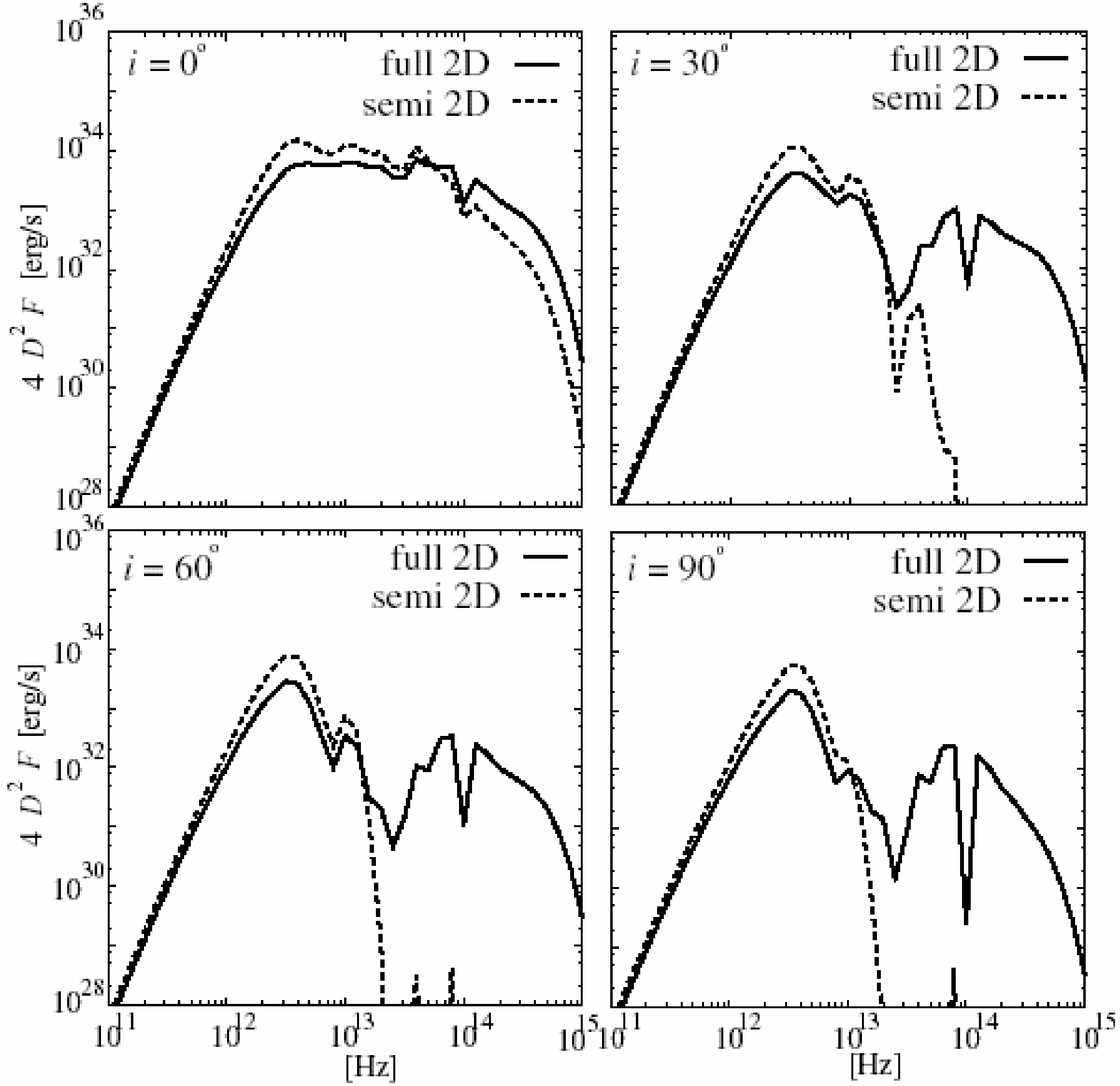
Nakazato, Nakamoto & Umemura (2003)

Importance of Radiative Transfer

➢ Self-consistent treatment of radiation transfer is important (Nakazato, Nakamoto & Umemura 2003).

- emerging SEDs

- outflow cavity is needed to reproduce the feature of NIR.



Basic Equations

- Energy Equation:

$$\frac{\partial e}{\partial t} = -4\pi\chi_P B + c\chi_E E$$

- Radiation Moment Equations:

$$\frac{\partial (e+E)}{\partial t} + \nabla \cdot F = 0$$

$$\frac{1}{c^2}\frac{\partial F}{\partial t} + \nabla \cdot (\mathrm{f}E) = \frac{1}{c}\chi_F F$$

- Variable Eddington factor

$$\mathrm{f} \equiv \frac{P}{E} = \frac{\oint nnI d\Omega}{\oint I d\Omega}$$

χ_P : Planck mean opacity

χ_E : energy mean opacity

χ_F : flux mean opacity

f : Variable Eddington factor

Calculate by solving radiation transfer equation

Radiative Transfer Equation
(Isotropic Scattering)

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = \underbrace{-(\chi_\nu^{\mathrm{abs}} + \chi_\nu^{\mathrm{sca}})I_\nu}_{\text{extinction (absorption+scattering)}} + \underbrace{\chi_\nu^{\mathrm{abs}} B_\nu}_{\text{emission}} + \underbrace{\chi_\nu^{\mathrm{sca}} \frac{1}{4\pi} \oint I_\nu d\Omega}_{\text{scattering}}$$

I_ν : specific intensity

ds : line element along the ray

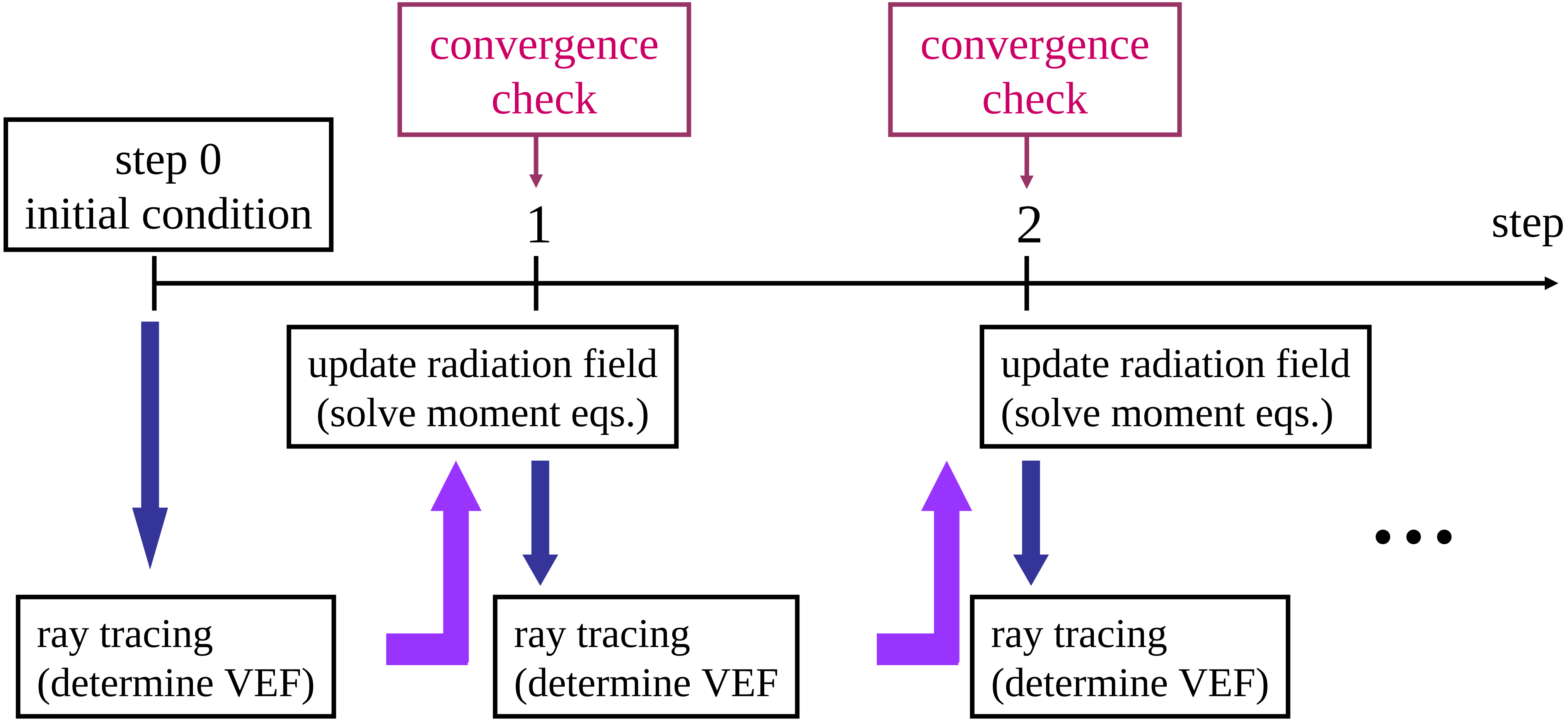
B_ν : Planck function

χ_ν^{abs} : absorption coefficient per unit volume

χ_ν^{sca} : scattering coefficient per unit volume

Flow Chart of the VEF Method

- Iterate following step until radiative equilibrium is achieved.



convergence check

convergence check

step 0
initial condition

1

2

step

update radiation field
(solve moment eqs.)

update radiation field
(solve moment eqs.)

…

ray tracing
(determine VEF)

ray tracing
(determine VEF

ray tracing
(determine VEF)

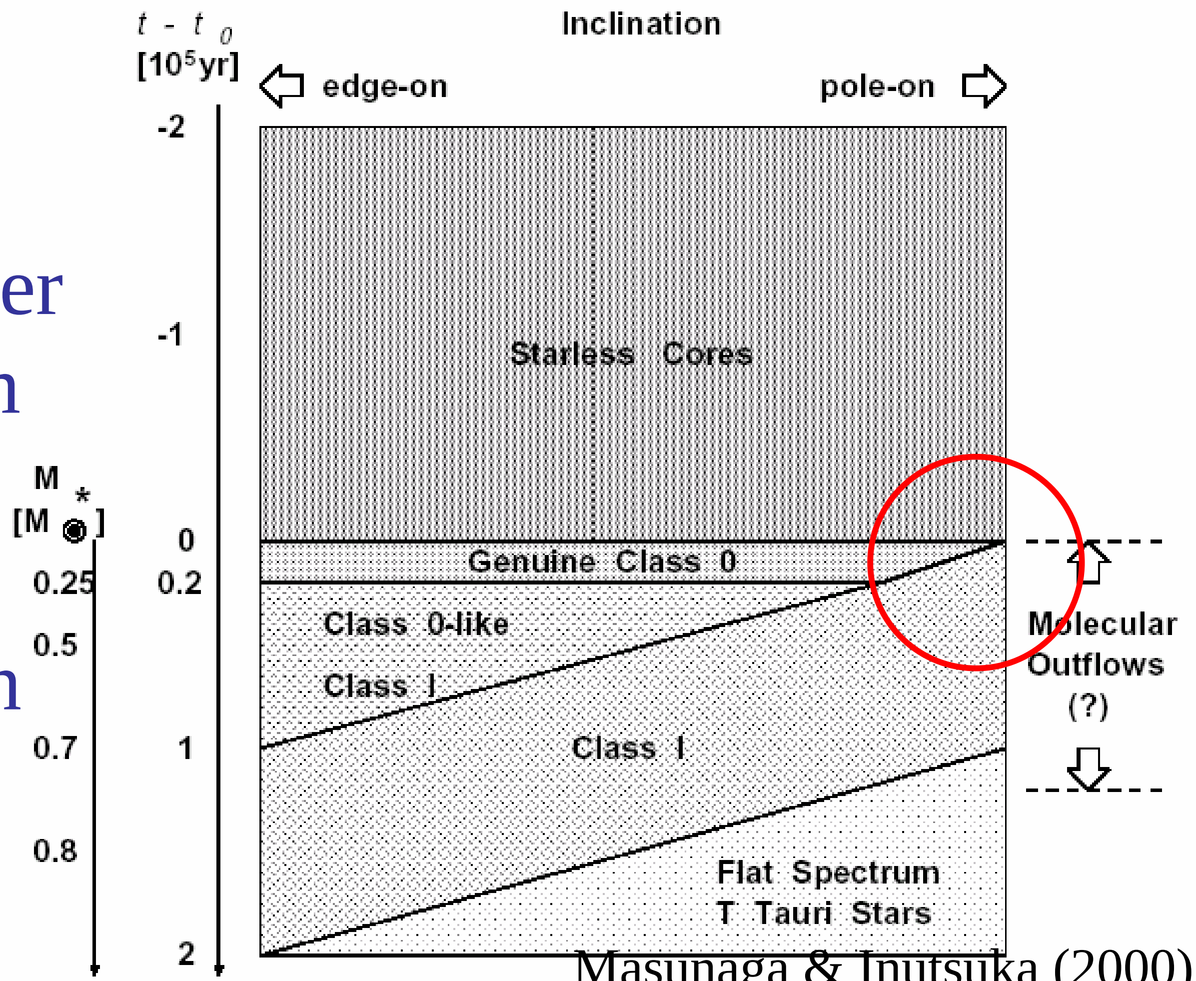
VEF method can treat the radiation transfer without any kind of approximation!

L1489IRS: Face-on View of Class 0?

- M_{env}/M_{disk} is large → accretion is not so proceeded?
- low inclination → tends to be observed as Class I

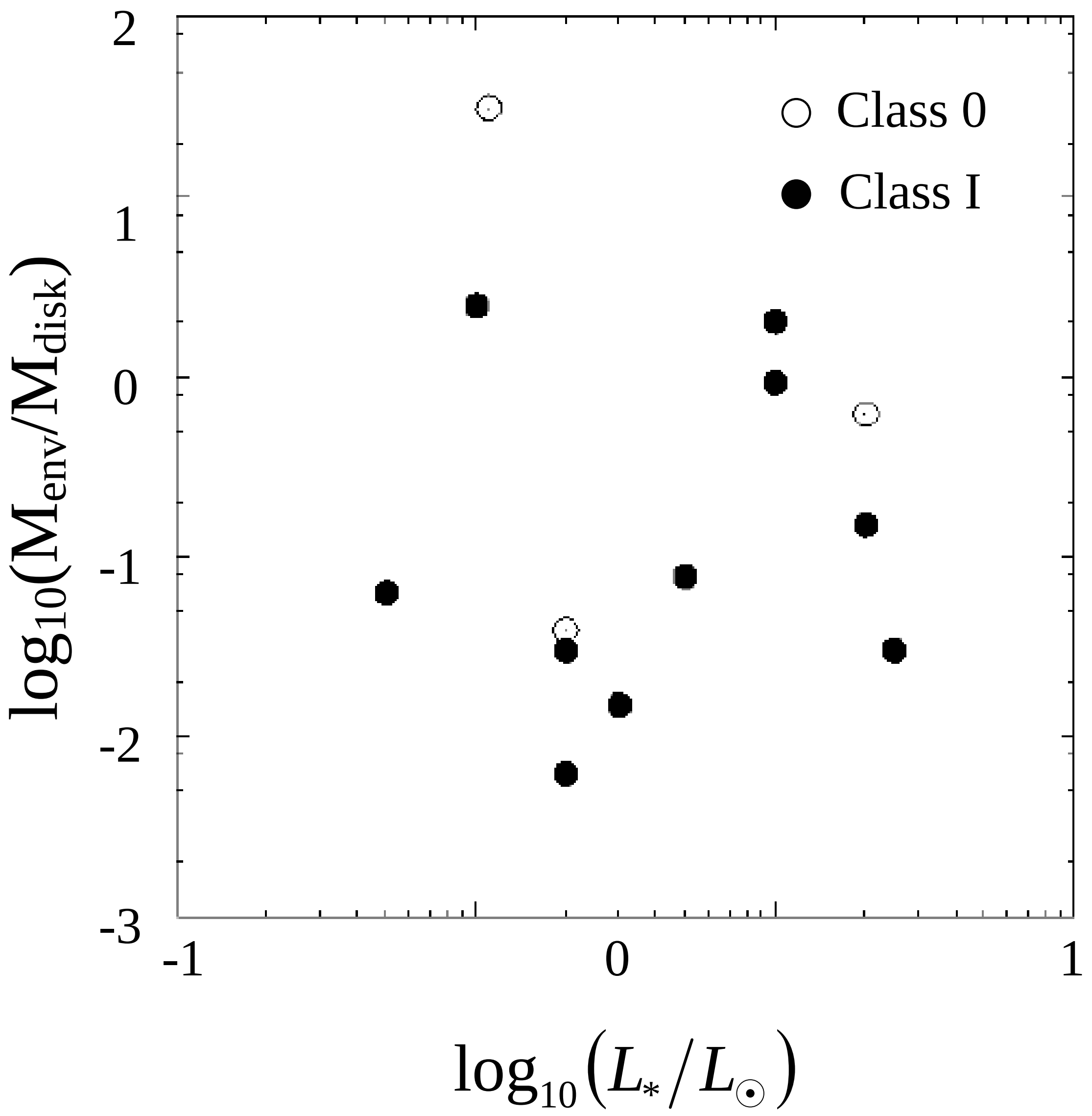
	Class	L	M_env	M_disk	M_env/M_disk	M_total	theta_bp	inc
L1489IRS	I	1	0.11	0.054	2.03703704	0.164	15	10

- L1489IRS may be younger than which is inferred from its apparent SED.
- An example which is not applied to the classification of the YSOs?



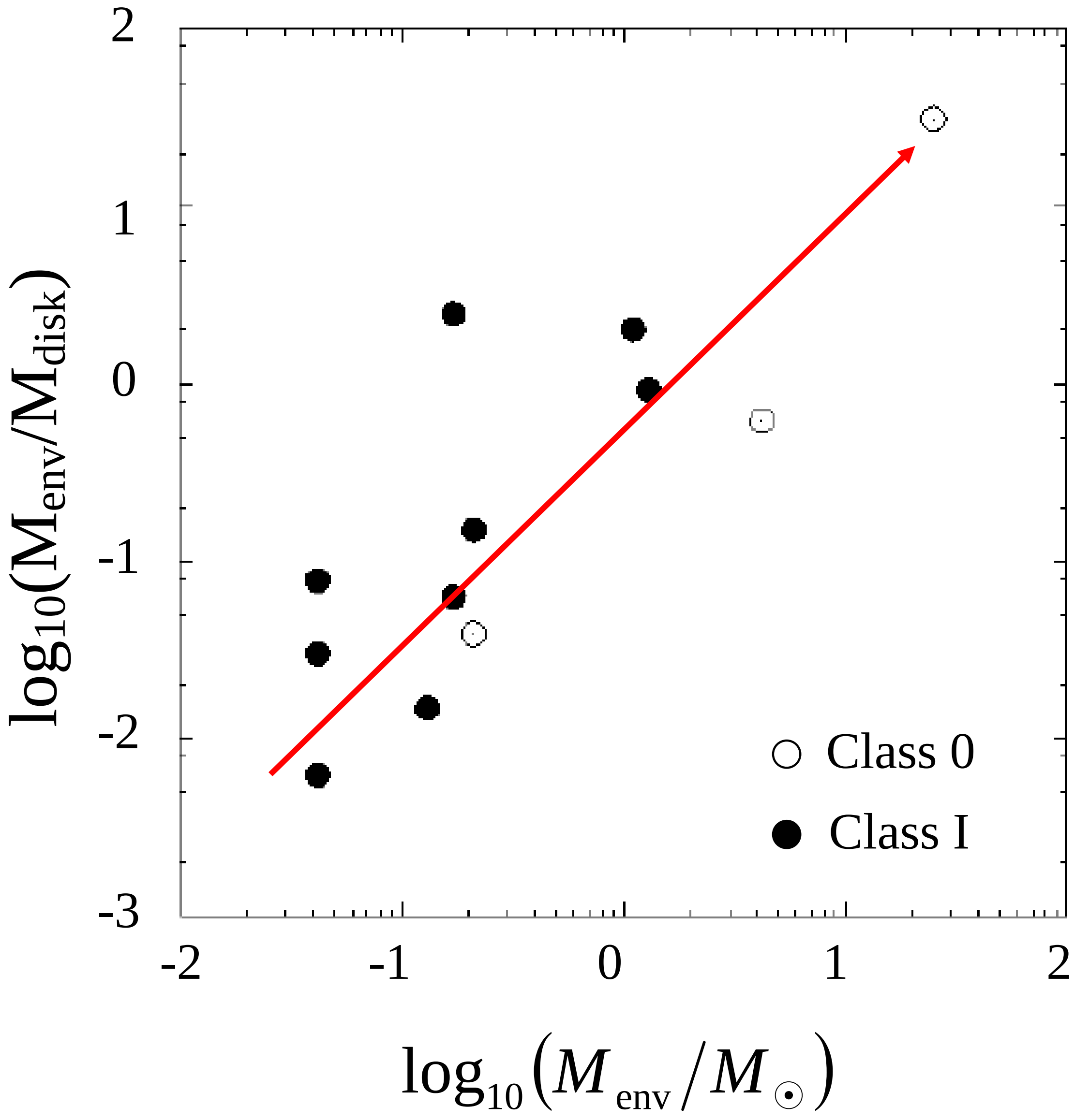
Masunaga & Inutsuka (2000)

Correlation between Mass Ratio and Luminosity



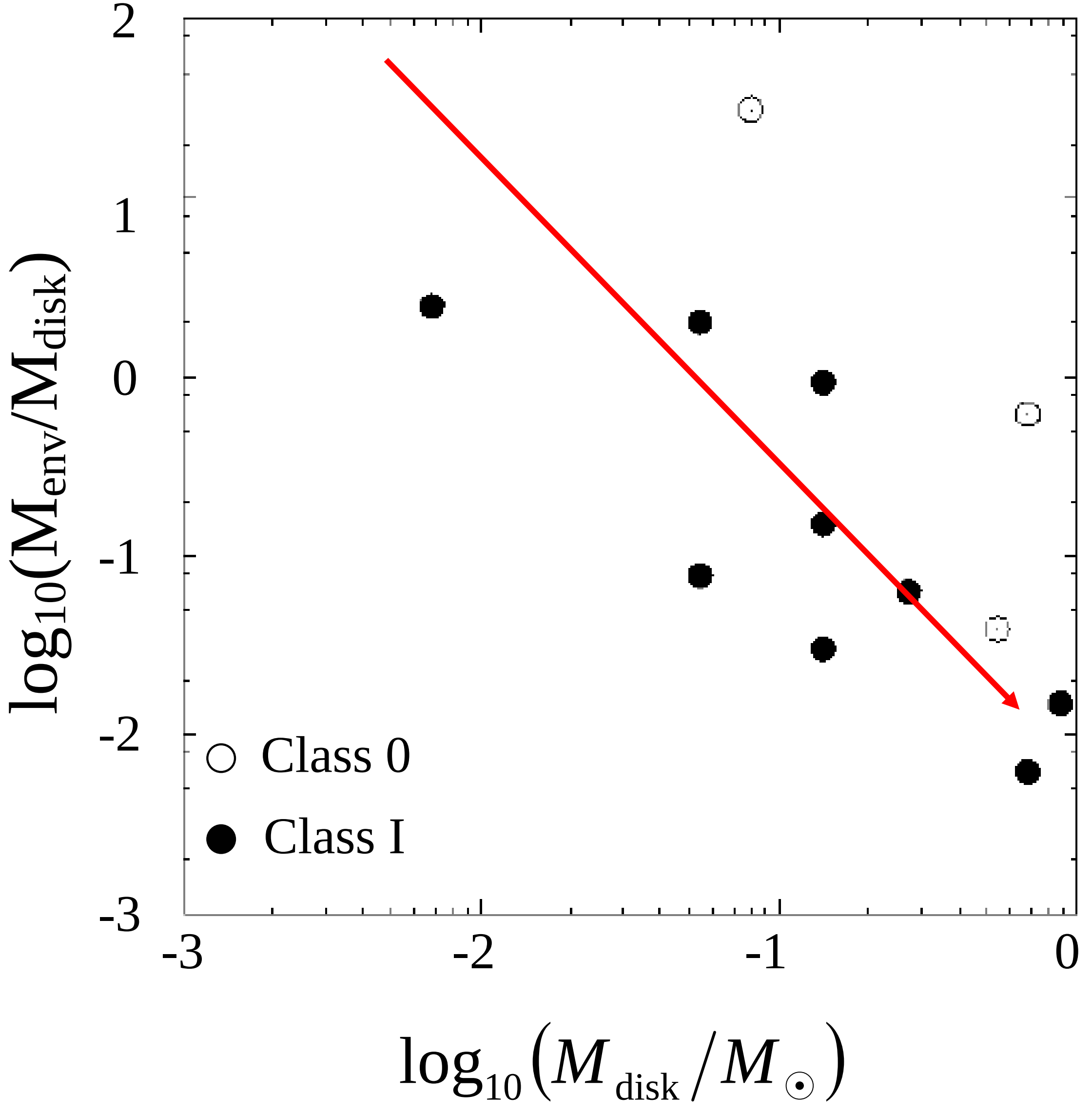
- The mass ratio is not correlated with the bolometric luminosity.

Mass Ratio between Envelope and Disk



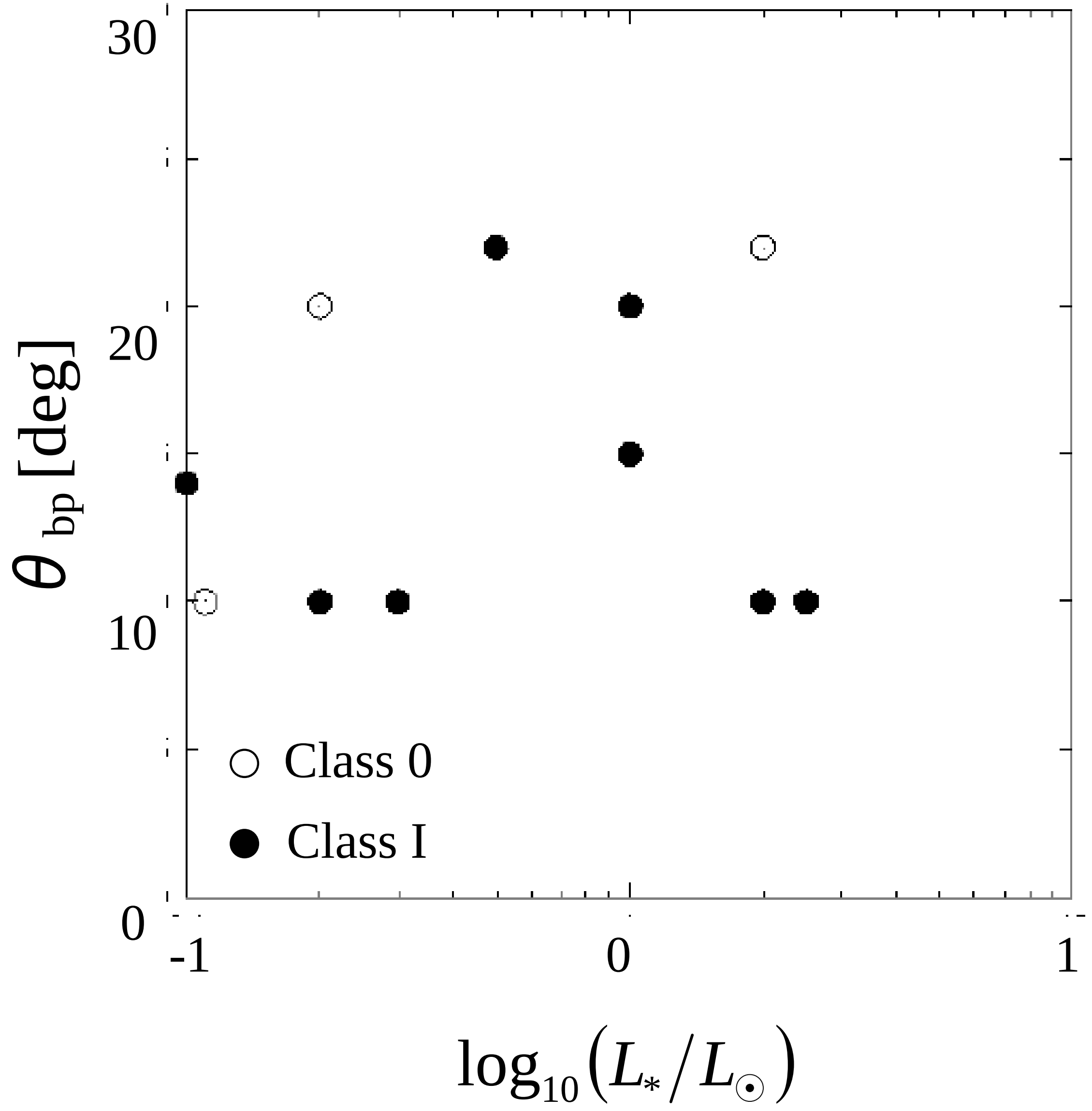
- envelope mass becomes large →mass ratio is large

Mass Ratio between Envelope and Disk

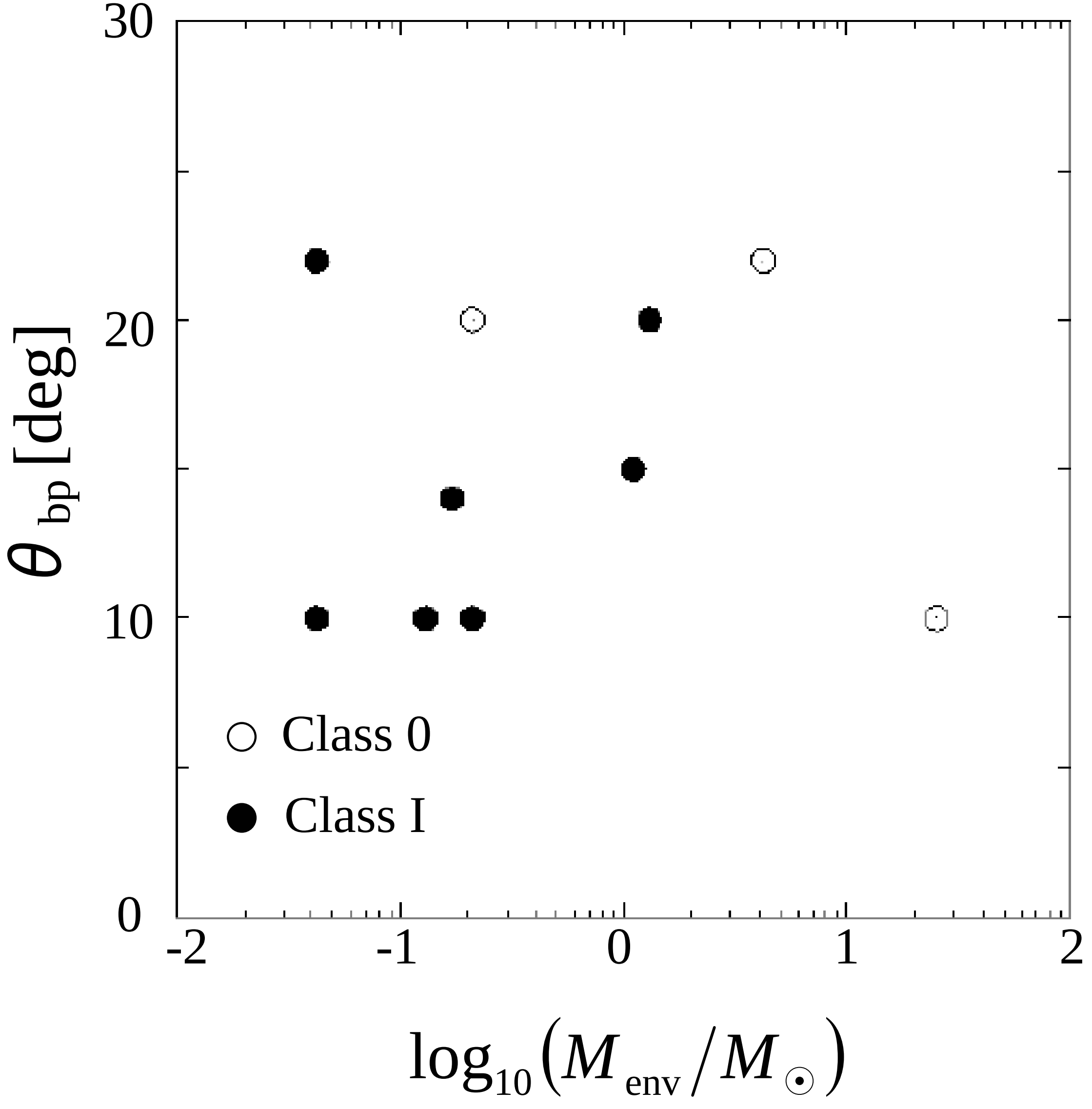


- disk mass becomes large
  → mass ratio is small

semi-opening angle of cavity

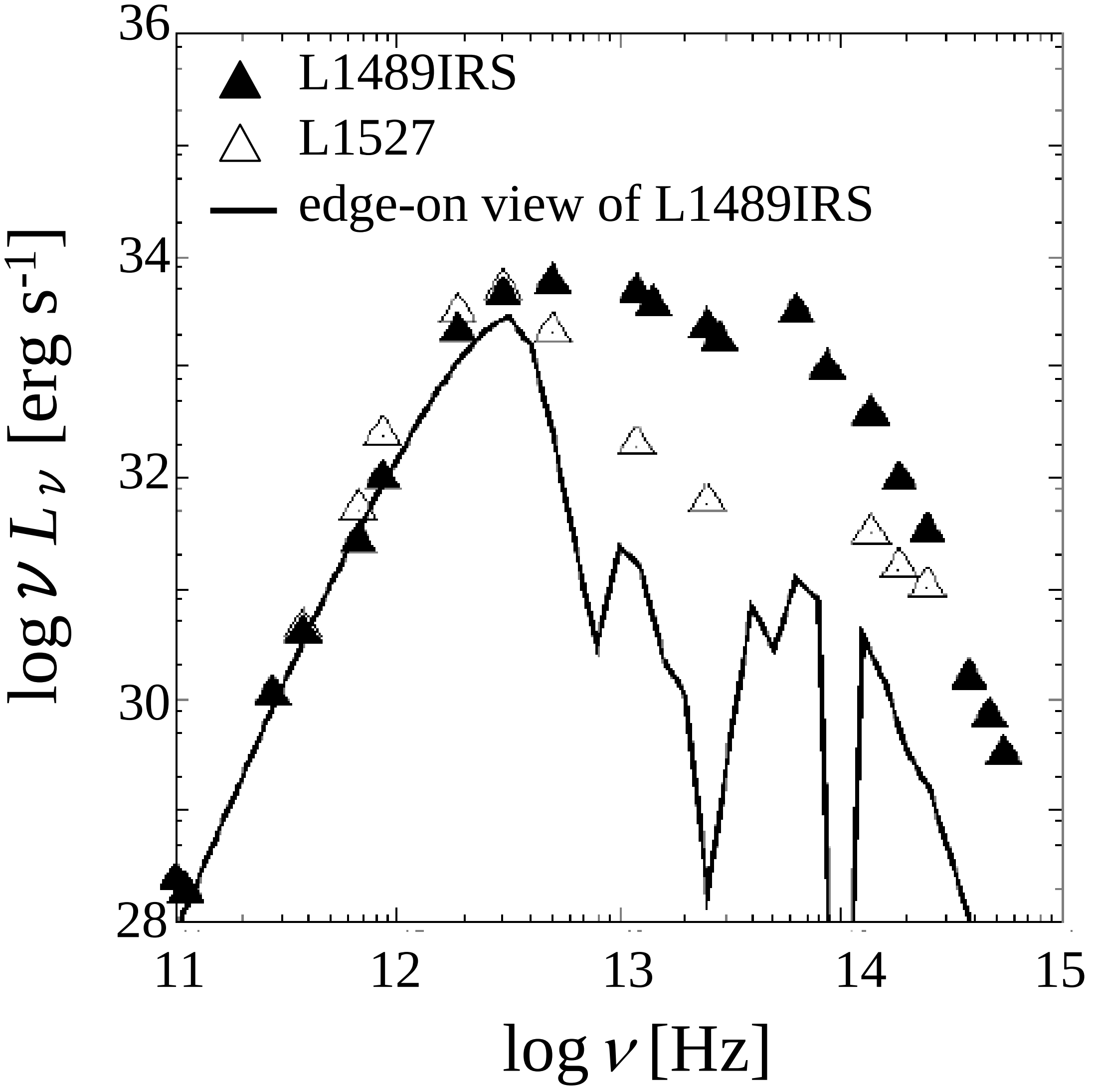


semi-opening angle of cavity

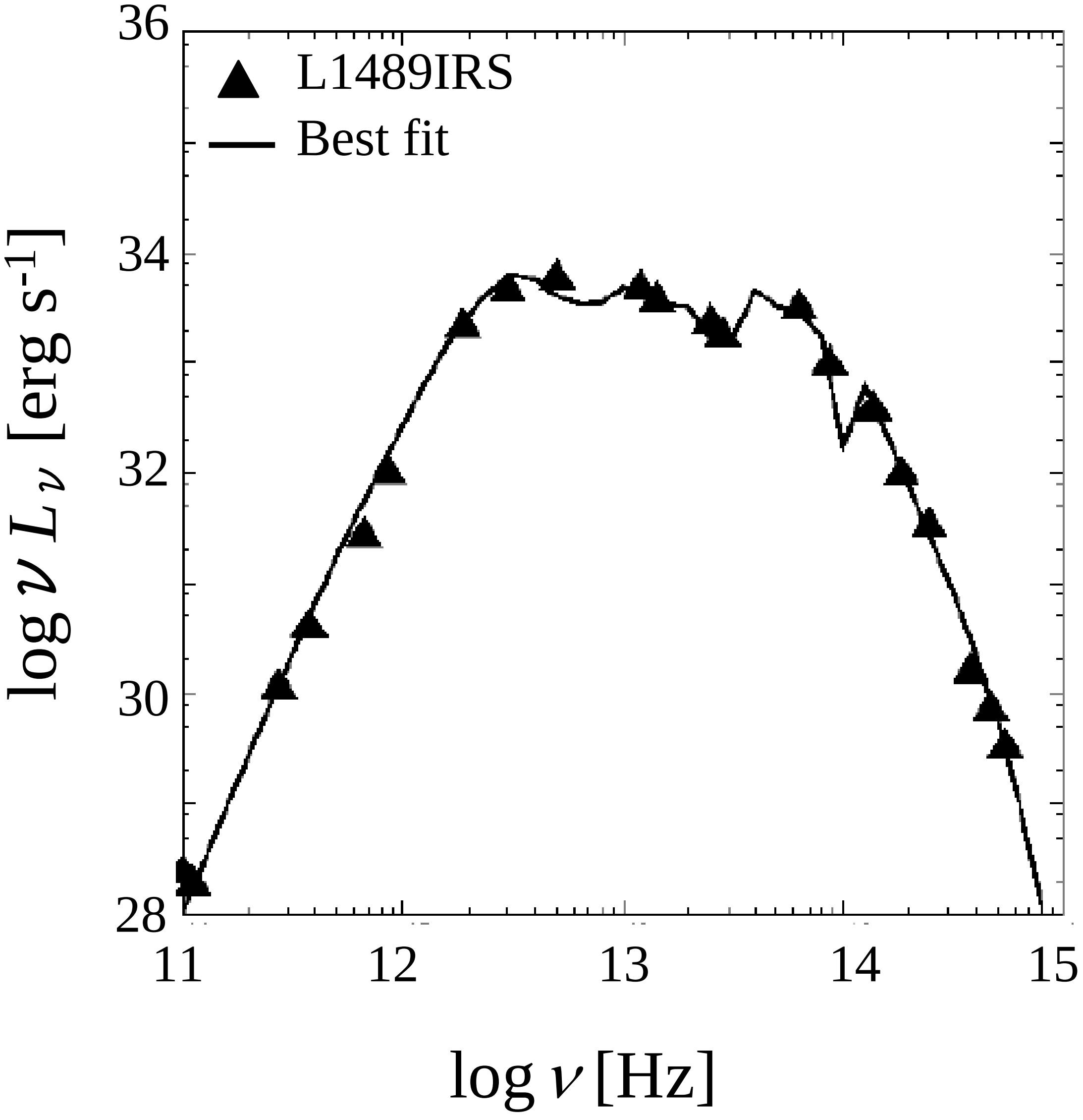


L1489IRS: Edge-on View

- Resemble to L1527



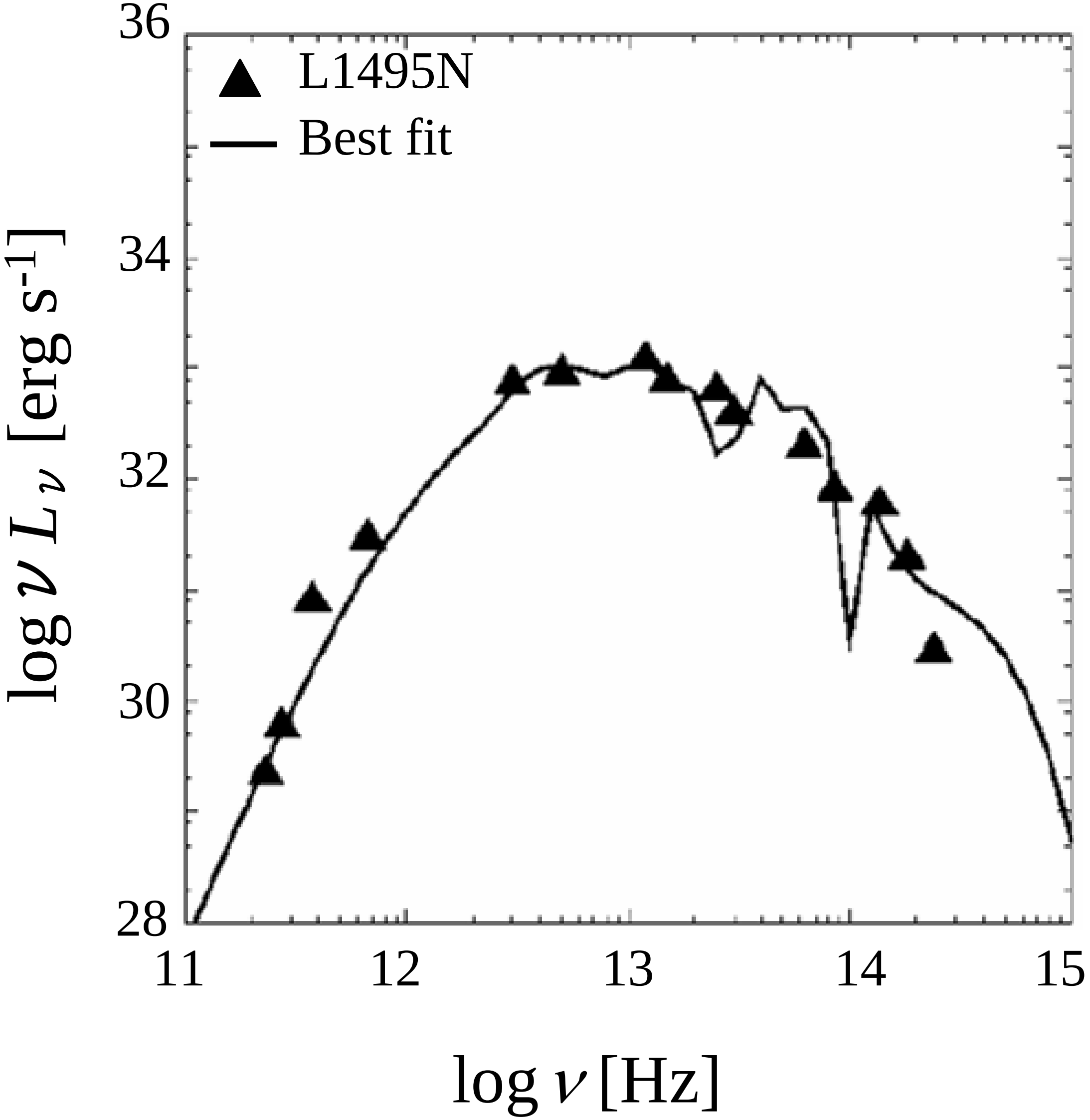
L1489IRS



best fitted parameters
$L_* = 1.0 L_\odot$
$\rho_1 = 2.5\times10^{-13}$ g cm^{-3}
$\left(M_{\rm env} = 0.11 M_\odot\right)$
$\Sigma_1 = 4\times10^{3}$ g cm^{-2}
$\left(M_{\rm disk} = 0.054 M_\odot\right)$
$\theta_{\rm bp} = 15^\circ$
$i = 10^\circ$

squared-residual = 0.021

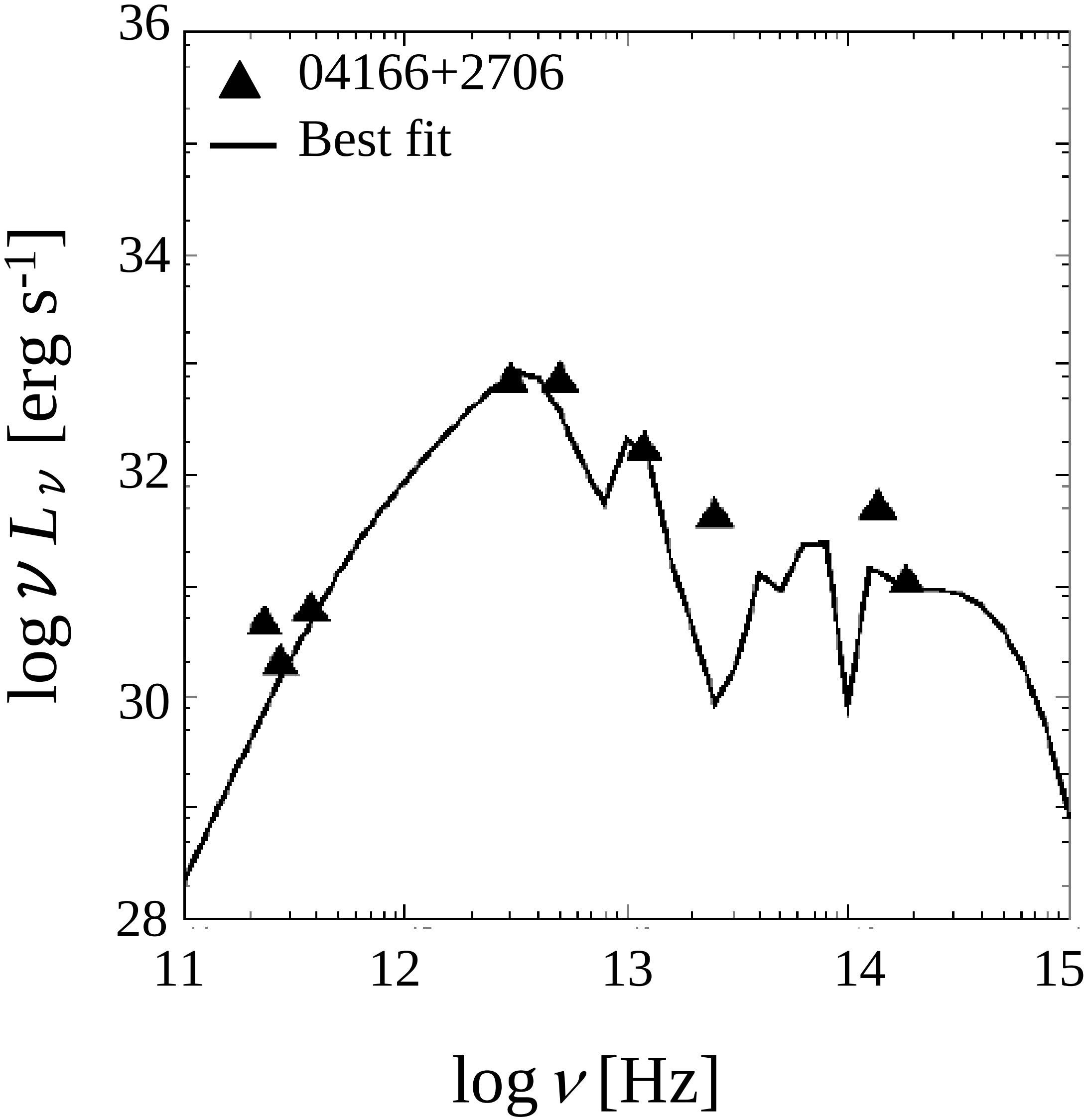
L1495N



best fitted parameters
$L_* = 0.2L_\odot$
$\rho_1 = 1.0\times10^{-14}$ g cm^{-3}
$(M_{\rm env} = 0.042M_\odot)$
$\Sigma_1 = 1\times10^4$ g cm^{-2}
$(M_{\rm disk} = 0.14M_\odot)$
$\theta_{\rm bp} = 10^\circ$
$i = 12^\circ$

squared-residual = 0.041

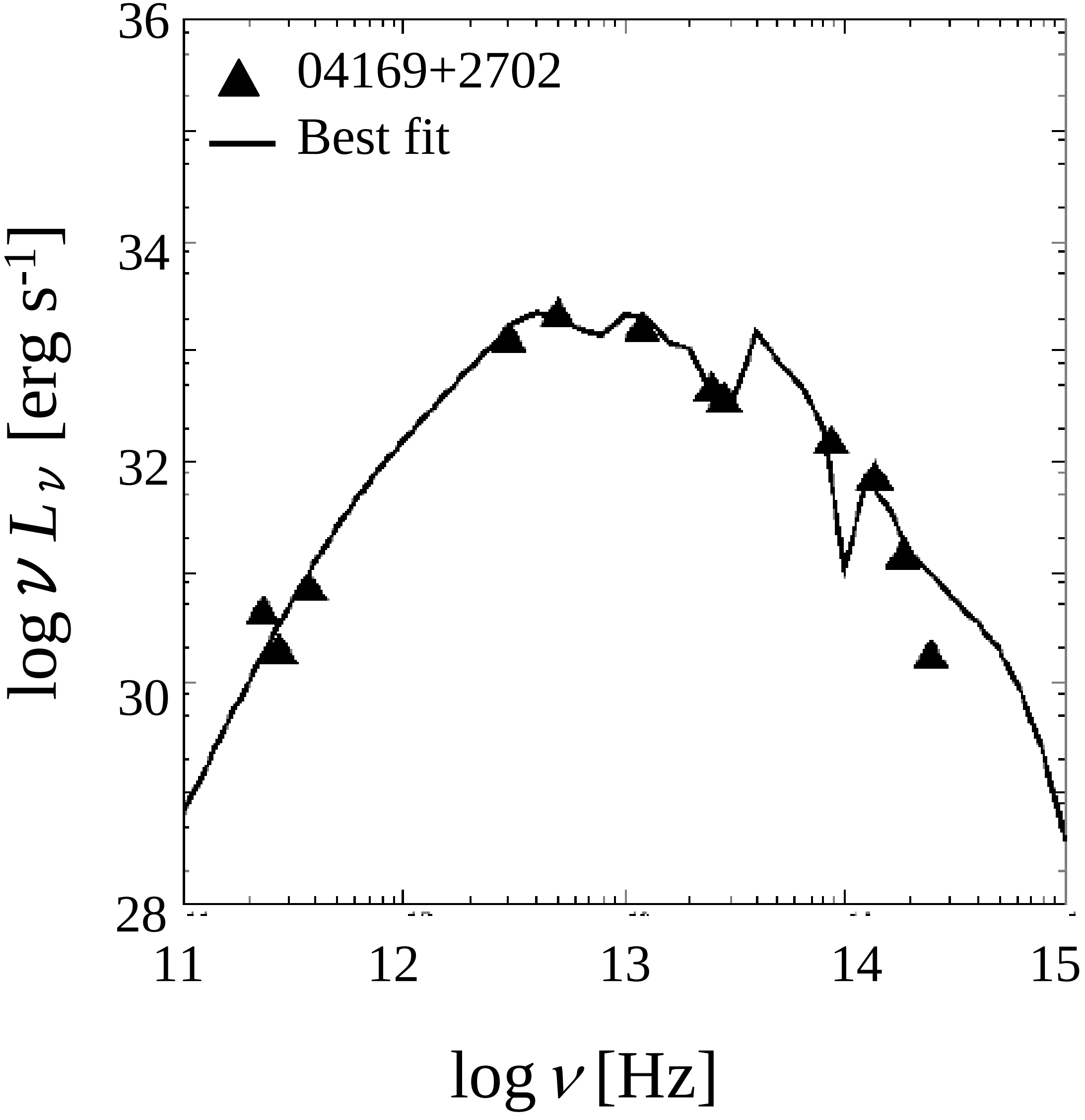
04166+2706



best fitted parameters
$L_* = 0.2 L_\odot$
$\rho_1 = 5.0\times10^{-14}$ g cm^{-3}
$\left(M_{\rm env} = 0.021 M_\odot\right)$
$\Sigma_1 = 4\times10^4$ g cm^{-2}
$\left(M_{\rm disk} = 0.54 M_\odot\right)$
$\theta_{\rm bp} = 20^\circ$
$i = 40^\circ$

squared-residual = 0.12

04169+2702



best fitted parameters

$L_* = 0.3 L_\odot$

$\rho_1 = 3.0 \times 10^{-14}$ g cm^{-3}

$\left(M_{\rm env} = 0.0013 M_\odot\right)$

$\Sigma_1 = 6.5 \times 10^{4}$ g cm^{-2}

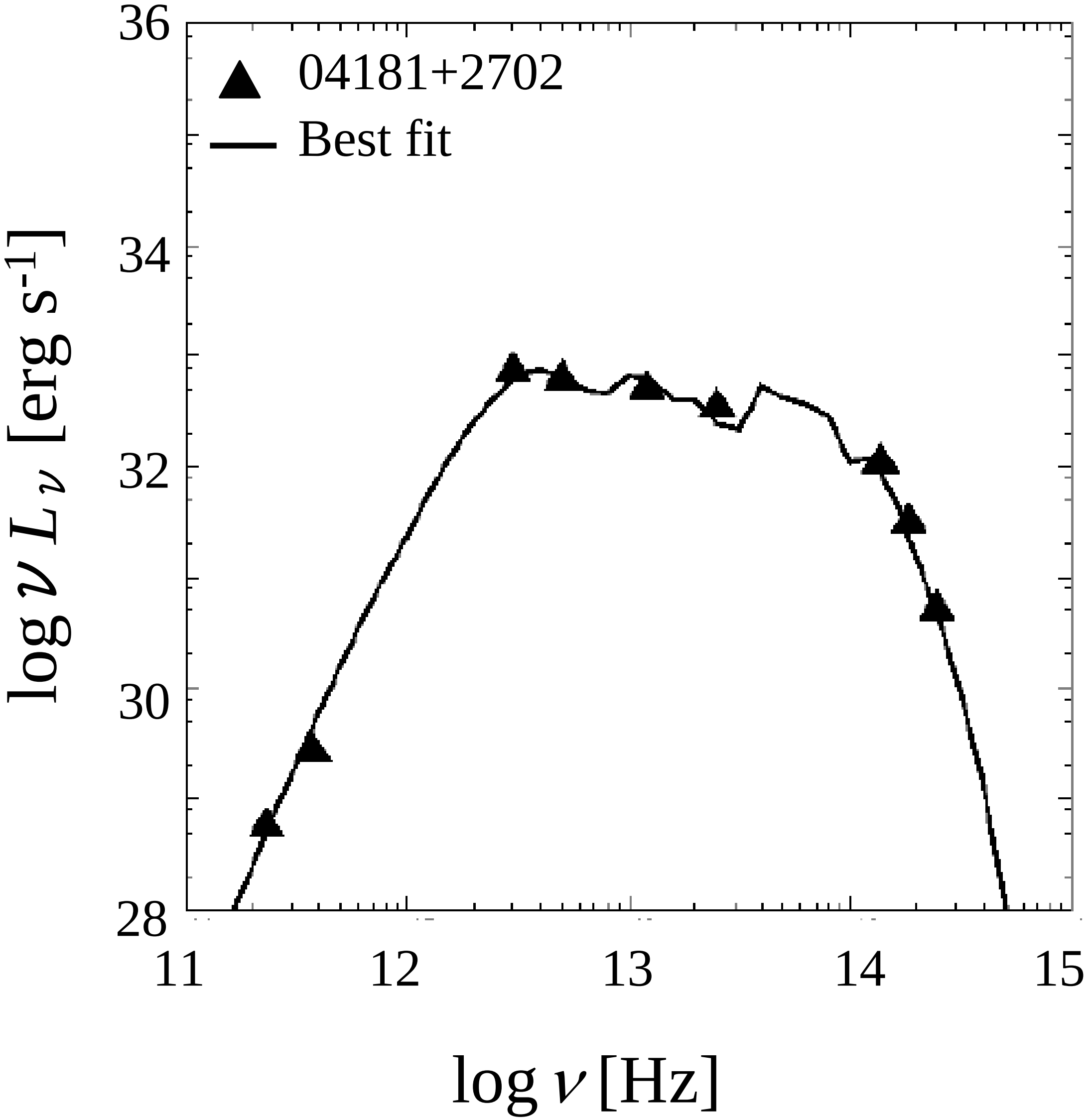
$\left(M_{\rm disk} = 0.88 M_\odot\right)$

$\theta_{\rm bp} = 10^\circ$

$i = 10^\circ$

squared-residual = 0.033

04181+2655



best fitted parameters

$L_* = 0.1 L_\odot$

$\rho_1 = 4.0\times10^{-14}$ g cm^{-3}

$\left(M_{\rm env} = 0.017 M_\odot\right)$

$\Sigma_1 = 5\times10^2$ g cm^{-2}

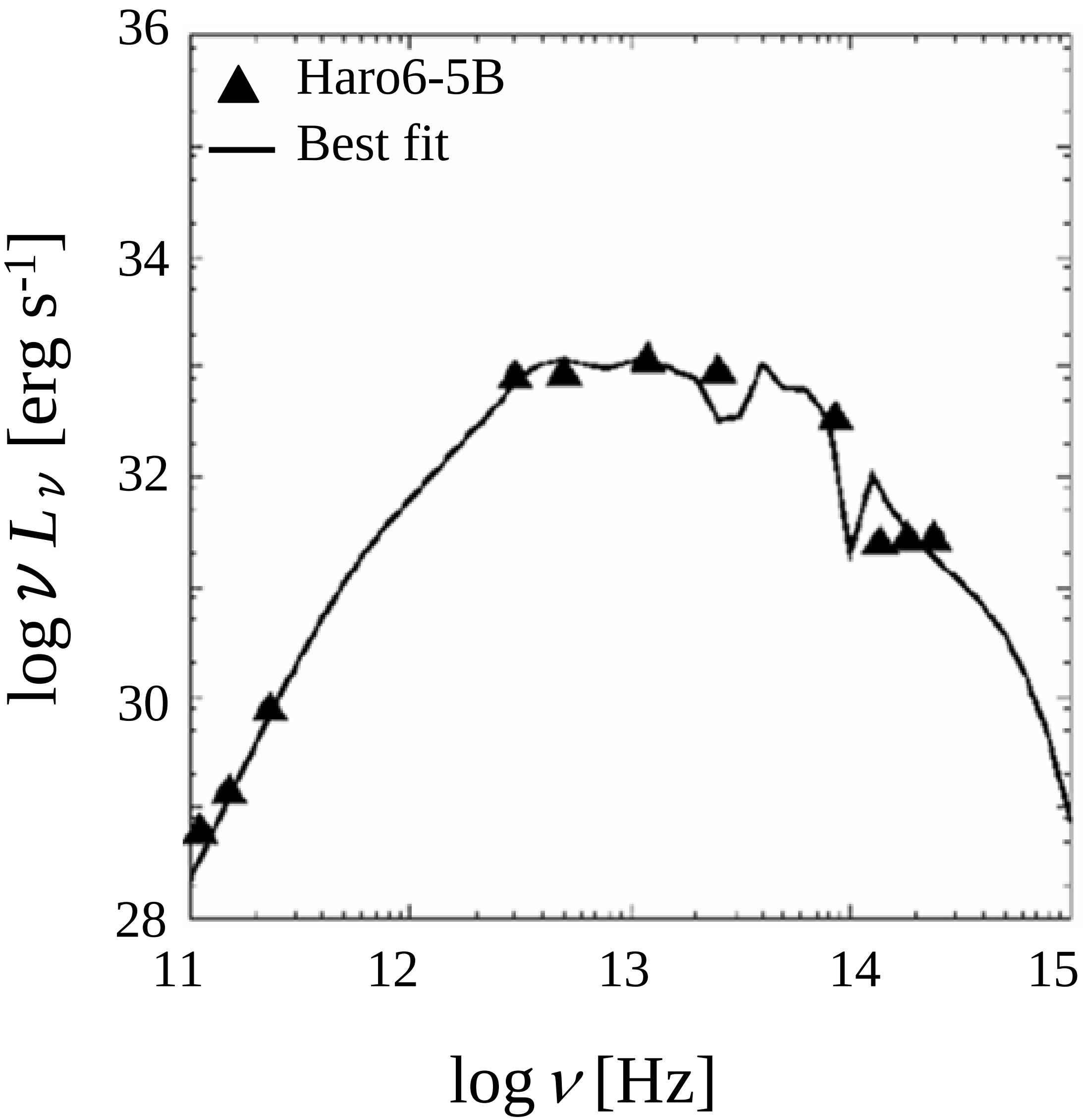
$\left(M_{\rm disk} = 0.0068 M_\odot\right)$

$\theta_{\rm bp} = 13^\circ$

$i = 10^\circ$

squared-residual = 0.0039

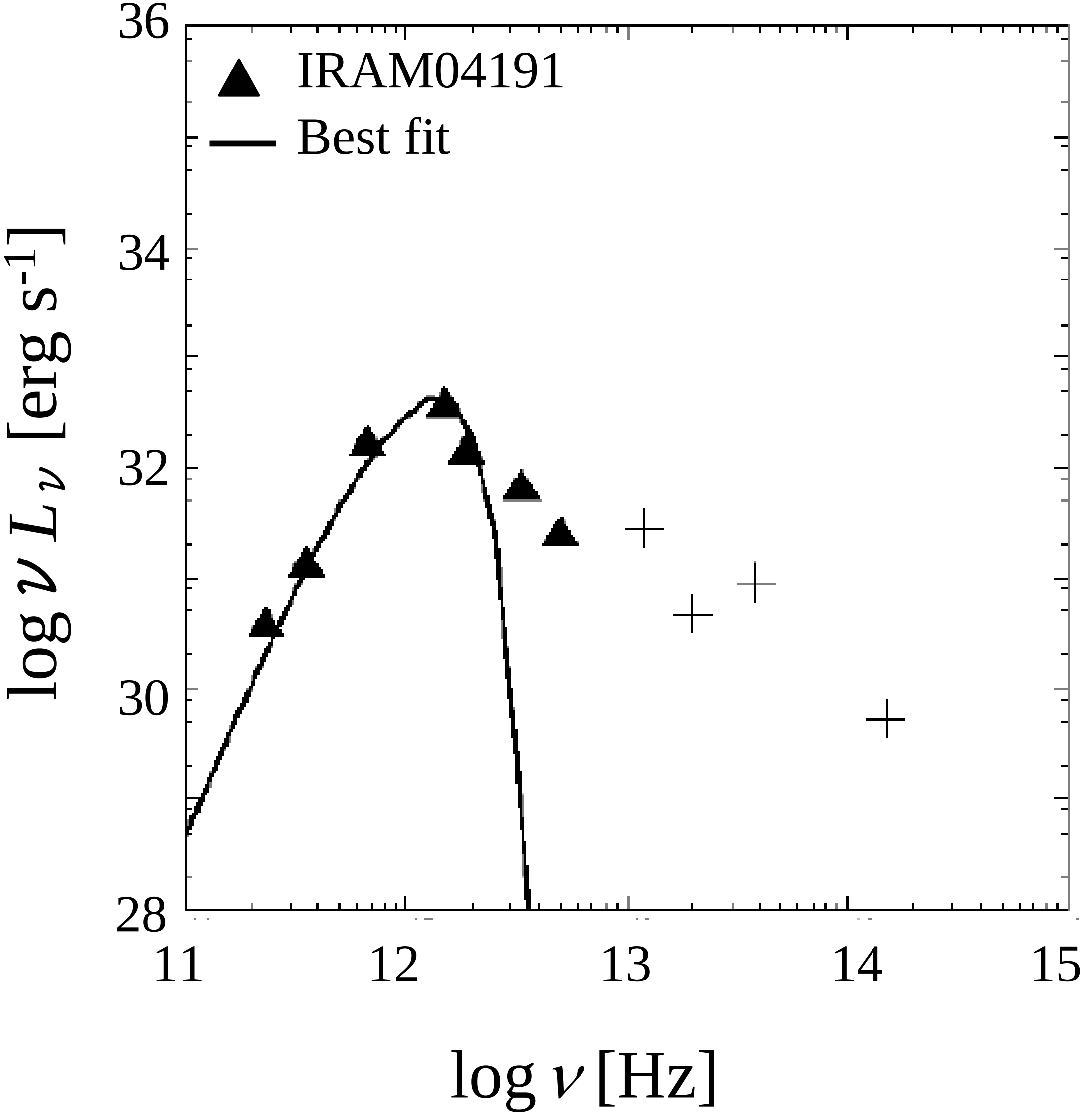
Haro6-5B



best fitted parameters
$L_* = 0.2 L_\odot$
$\rho_1 = 10^{-14}$ g cm^{-3}
$(M_{\text{env}} = 0.0042 M_\odot)$
$\Sigma_1 = 5\times10^4$ g cm^{-2}
$(M_{\text{disk}} = 0.68 M_\odot)$
$\theta_{\text{bp}} = 10^\circ$
$i = 11^\circ$

squared-residual = 0.022

IRAM04191



best fitted parameters

$L_* = 0.11 L_\odot$

$\rho_1 > 6.0 \times 10^{-12}$ g cm^{-3}

$\left(M_{\rm env} > 2.5 M_\odot\right)$

$\Sigma_1 < 6 \times 10^3$ g cm^{-2}

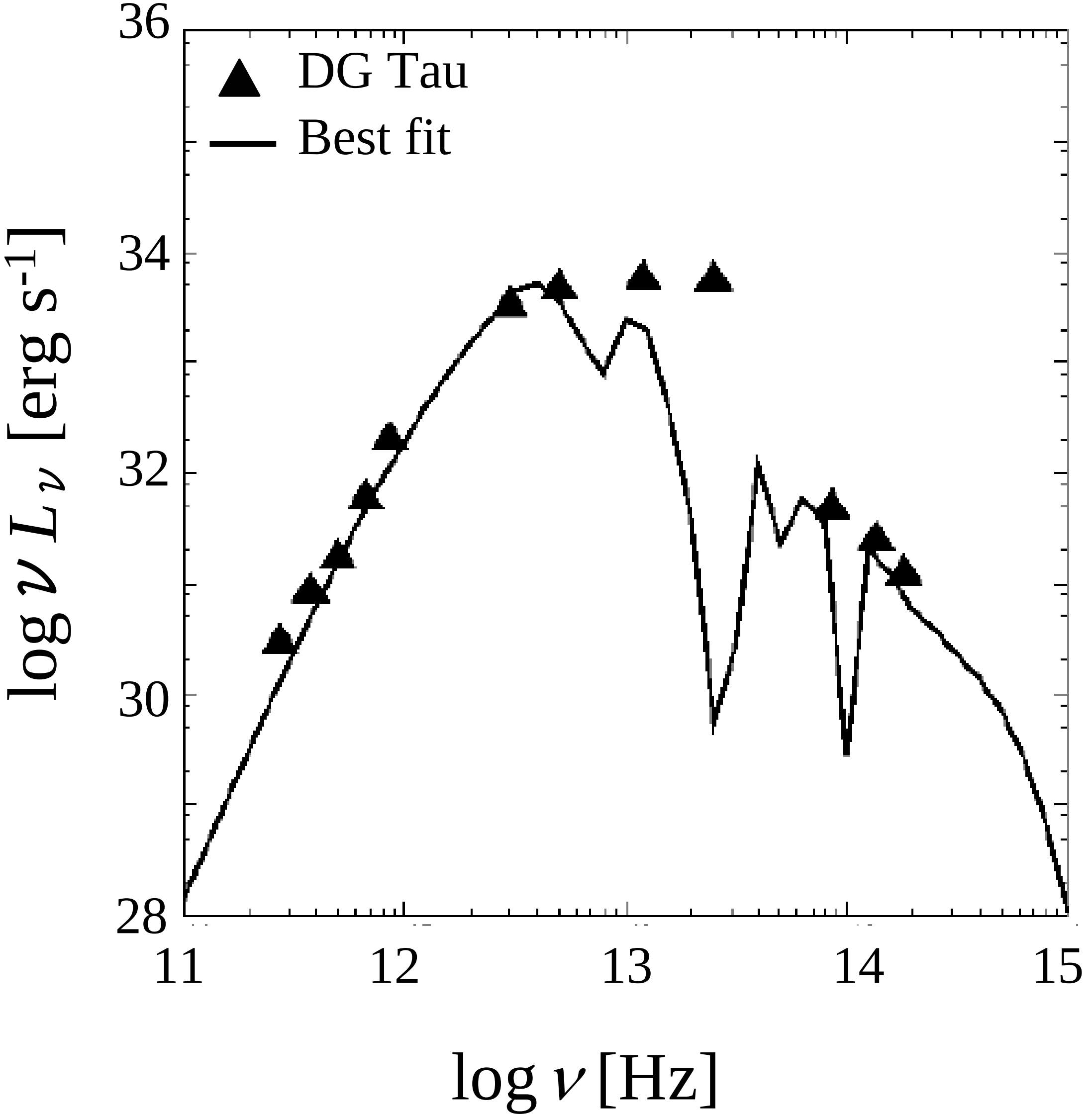
$\left(M_{\rm disk} < 0.08 M_\odot\right)$

$\theta_{\rm bp} = 10^\circ$

$i = 90^\circ$

squared-residual = 2.39

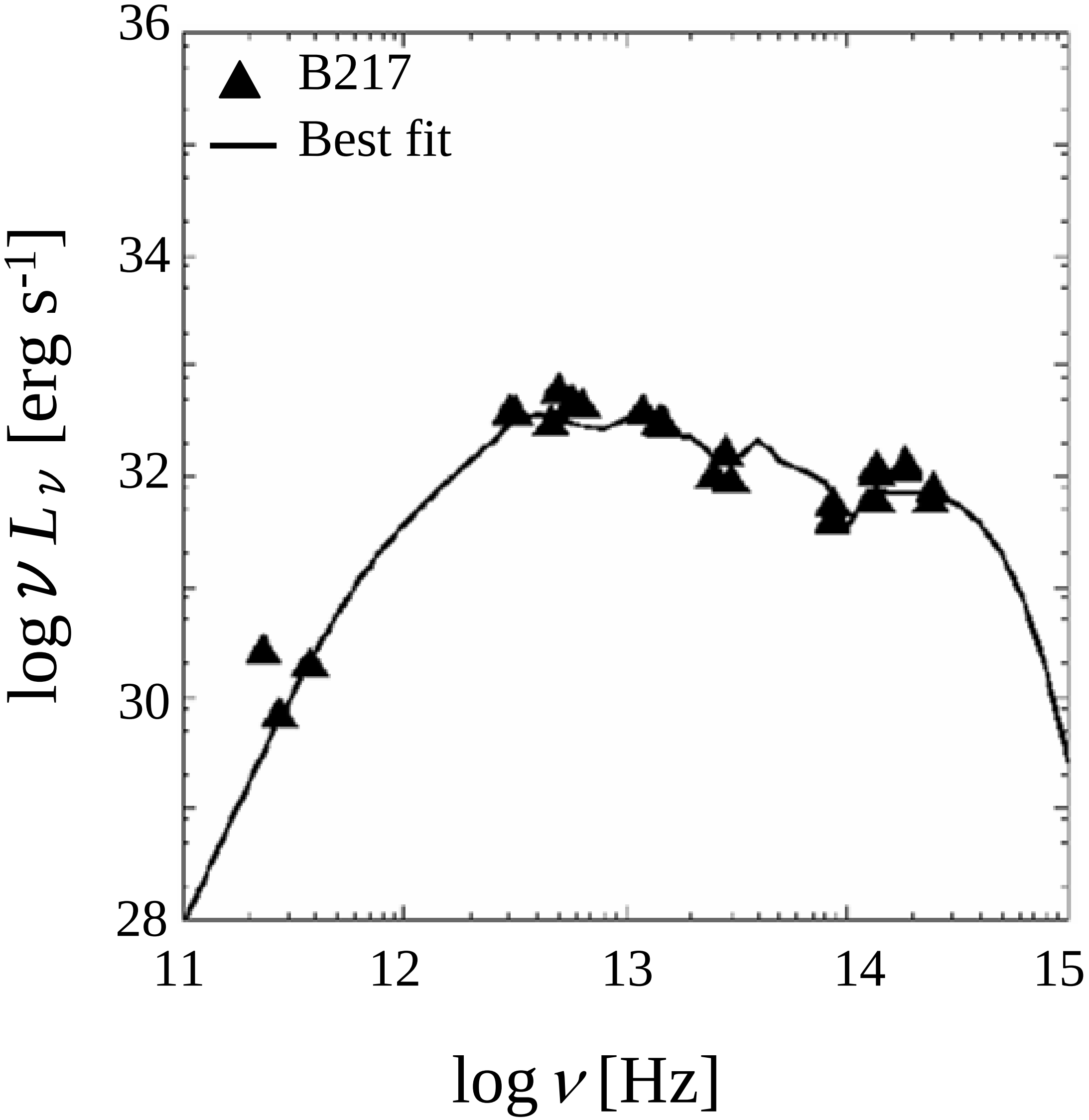
DG Tau



best fitted parameters
$L_* = 2.0 L_\odot$
$\rho_1 = 5.0\times10^{-14}$ g cm^{-3}
$(M_{\rm env} = 0.021 M_\odot)$
$\Sigma_1 = 10^4$ g cm^{-2}
$(M_{\rm disk} = 0.14 M_\odot)$
$\theta_{\rm bp} = 10^\circ$
$i = 60^\circ$

squared-residual = 0.52

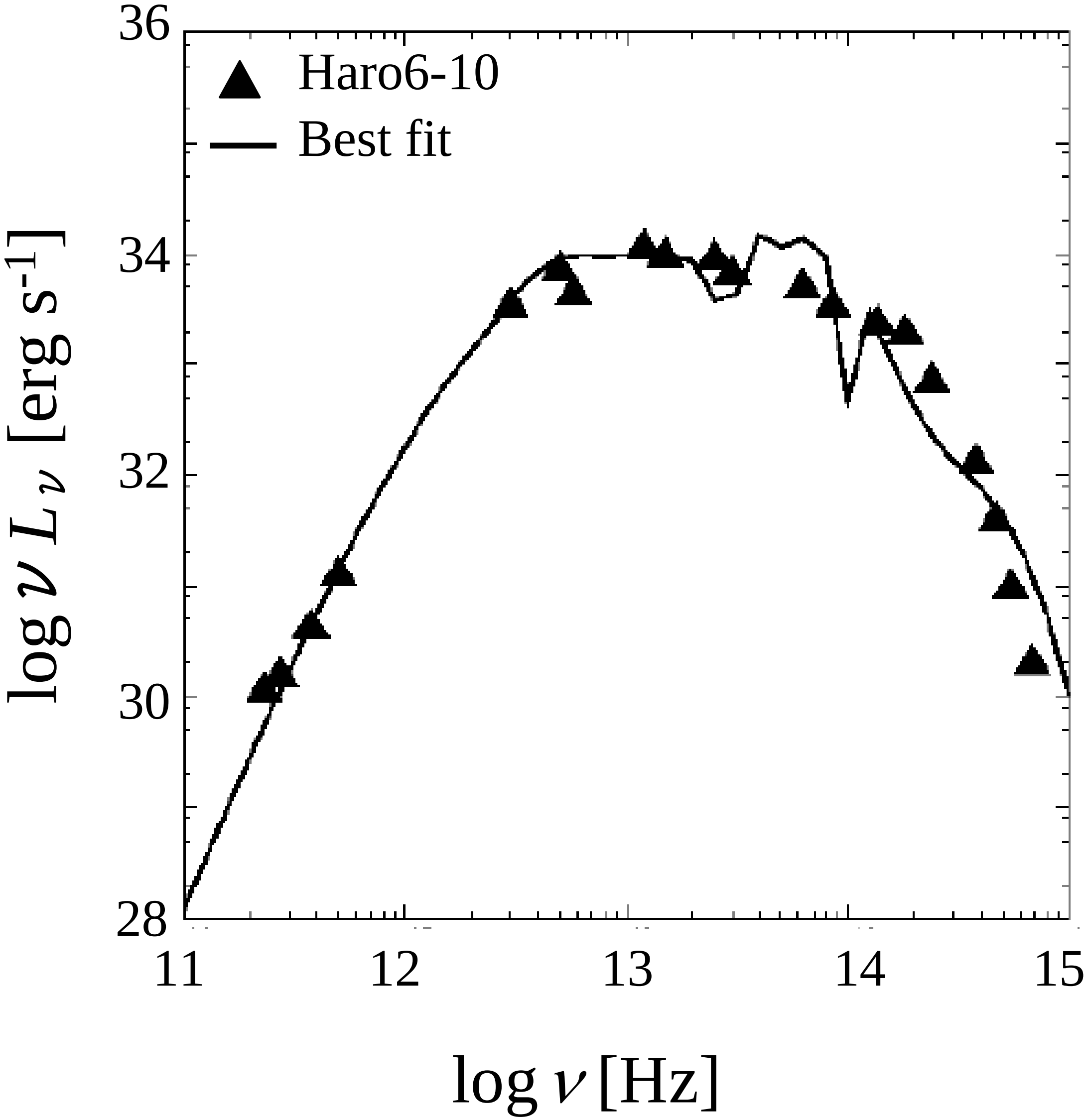
B217



best fitted parameters
$L_* = 0.05 L_\odot$
$\rho_1 = 4.0 \times 10^{-14}$ g cm^{-3}
$\left(M_{\rm env} = 0.017 M_\odot\right)$
$\Sigma_1 = 2 \times 10^4$ g cm^{-2}
$\left(M_{\rm disk} = 0.27 M_\odot\right)$
$\theta_{\rm bp} = 20^\circ$
$i = 00^\circ$

squared-residual = 0.014

Haro6-10



best fitted parameters

$$L_* = 2.5 L_\odot$$

$$\rho_1 = 10^{-14}\ \mathrm{g\ cm^{-3}}$$

$$\left(M_{\mathrm{env}} = 0.0042 M_\odot\right)$$

$$\Sigma_1 = 10^4\ \mathrm{g\ cm^{-2}}$$

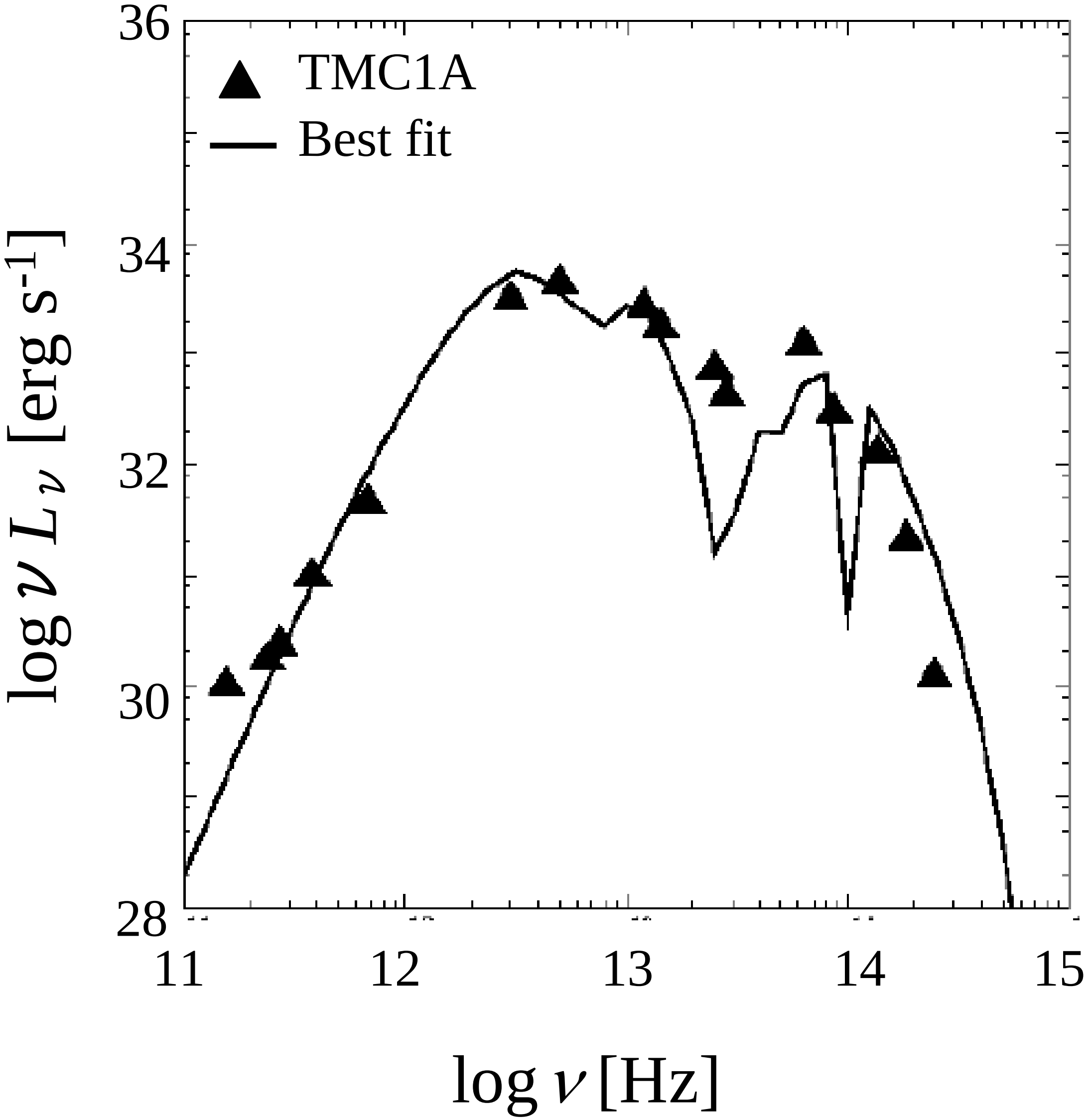
$$\left(M_{\mathrm{disk}} = 0.14 M_\odot\right)$$

$$\theta_{\mathrm{bp}} = 10^\circ$$

$$i = 12^\circ$$

squared-residual = 0.21

TMC1A



best fitted parameters

$L_* = 1.0 L_\odot$

$\rho_1 = 10^{-12.5}$ g cm^{-3}

$(M_{\rm env} = 0.13 M_\odot)$

$\Sigma_1 = 10^4$ g cm^{-2}

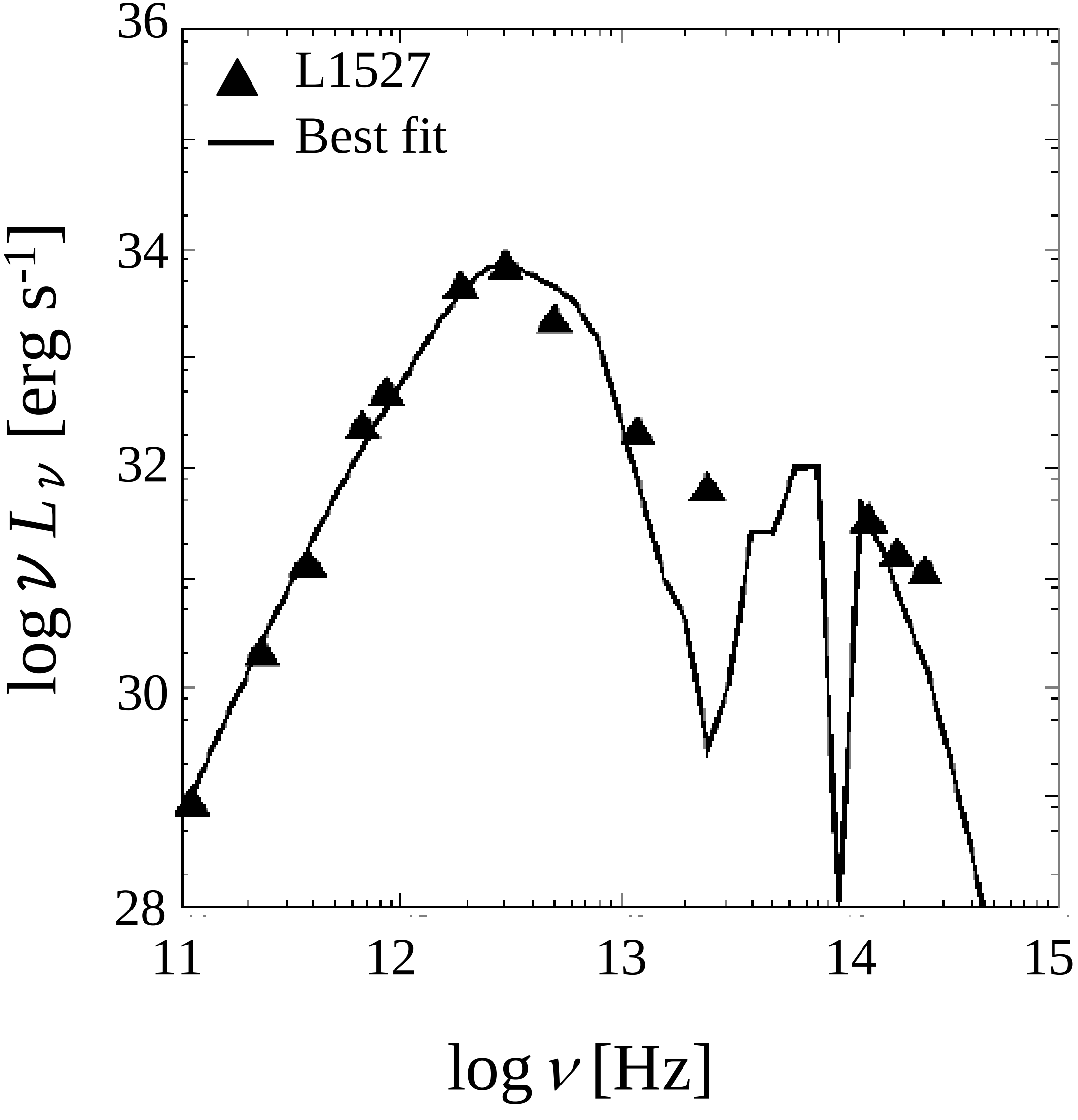
$(M_{\rm disk} = 0.14 M_\odot)$

$\theta_{\rm bp} = 20^\circ$

$i = 22^\circ$

squared-residual = 0.21

L1527



best fitted parameters

$$L_* = 2.0 L_\odot$$

$$\rho_1 = 10^{-12}\ \mathrm{g\ cm}^{-3}$$

$$\left(M_\mathrm{env} = 0.42 M_\odot\right)$$

$$\Sigma_1 = 5 \times 10^4\ \mathrm{g\ cm}^{-2}$$

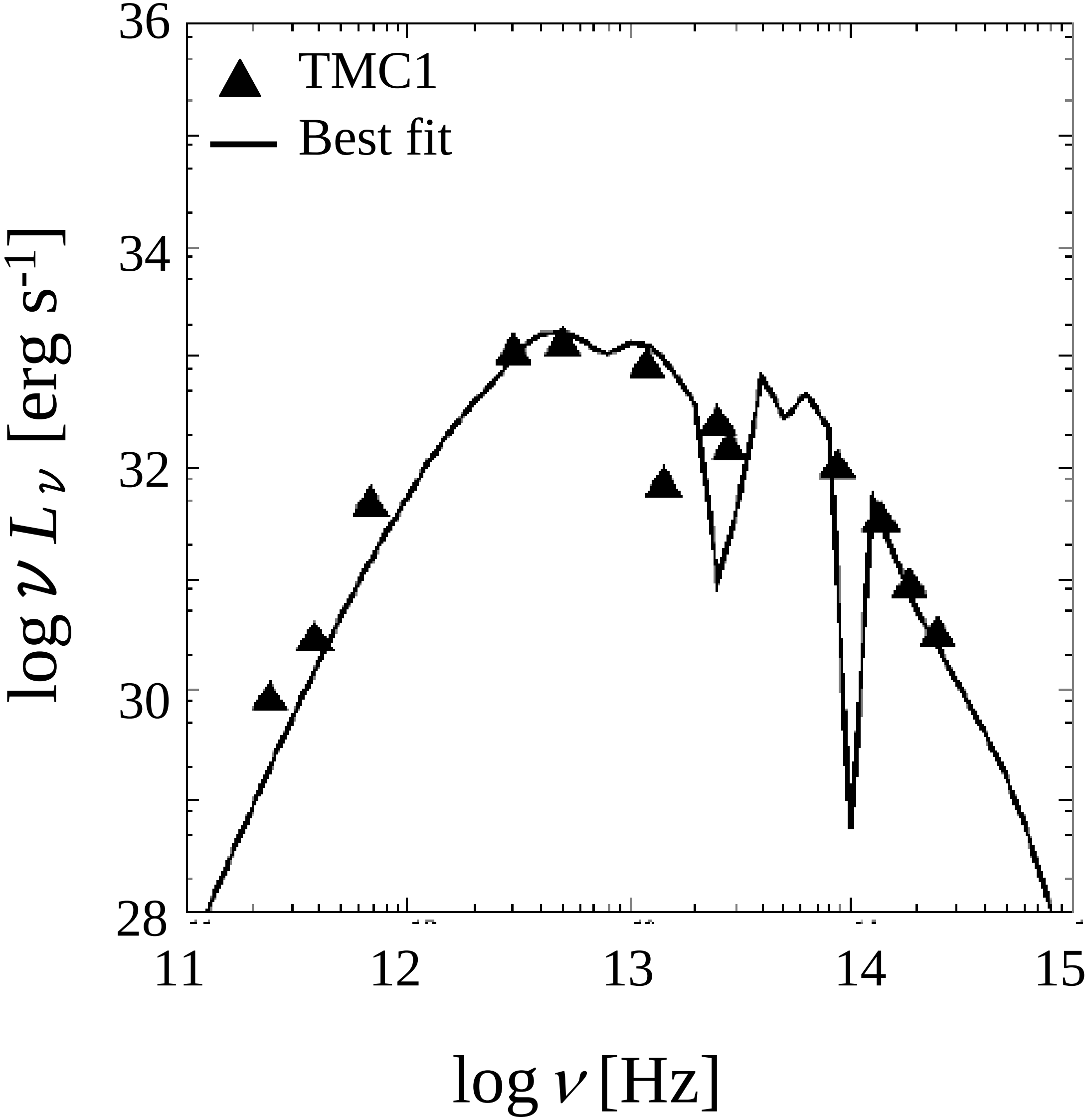
$$\left(M_\mathrm{disk} = 0.68 M_\odot\right)$$

$$\theta_\mathrm{bp} = 22^\circ$$

$$i = 60^\circ$$

squared-residual = 0.22

TMC1



best fitted parameters
$L_* = 0.5 L_\odot$
$\rho_1 = 10^{-14}$ g cm^{-3}
$(M_{\rm env} = 0.0042 M_\odot)$
$\Sigma_1 = 4 \times 10^3$ g cm^{-2}
$(M_{\rm disk} = 0.054 M_\odot)$
$\theta_{\rm bp} = 22^\circ$
$i = 40^\circ$

squared-residual = 0.18

Evaluation of Squared-Residual

$$s.r. = \sum_{\mathrm{n}=1}^{\mathrm{n}_{\mathrm{data}}} \frac{\left\{\log_{10}\left(4\pi D^2 \nu_{\mathrm{n}} F_{\nu_{\mathrm{n}}}^{\mathrm{obs}}\right) - \log_{10}\left(4\pi D^2 \nu_{\mathrm{n}} F_{\nu_{\mathrm{n}}}^{\mathrm{sim}}\right)\right\}^2}{\log_{10}\left(4\pi D^2 \nu_{\mathrm{n}} F_{\nu_{\mathrm{n}}}^{\mathrm{obs}}\right)}$$

$\mathrm{n}_{\mathrm{data}}$: number of data

ν_{n}: observed frequency

F_{ν}^{obs}: observed flux density

F_{ν}^{sim}: simulated flux density