Radiative Processes in the Interstellar Medium (III) Masers

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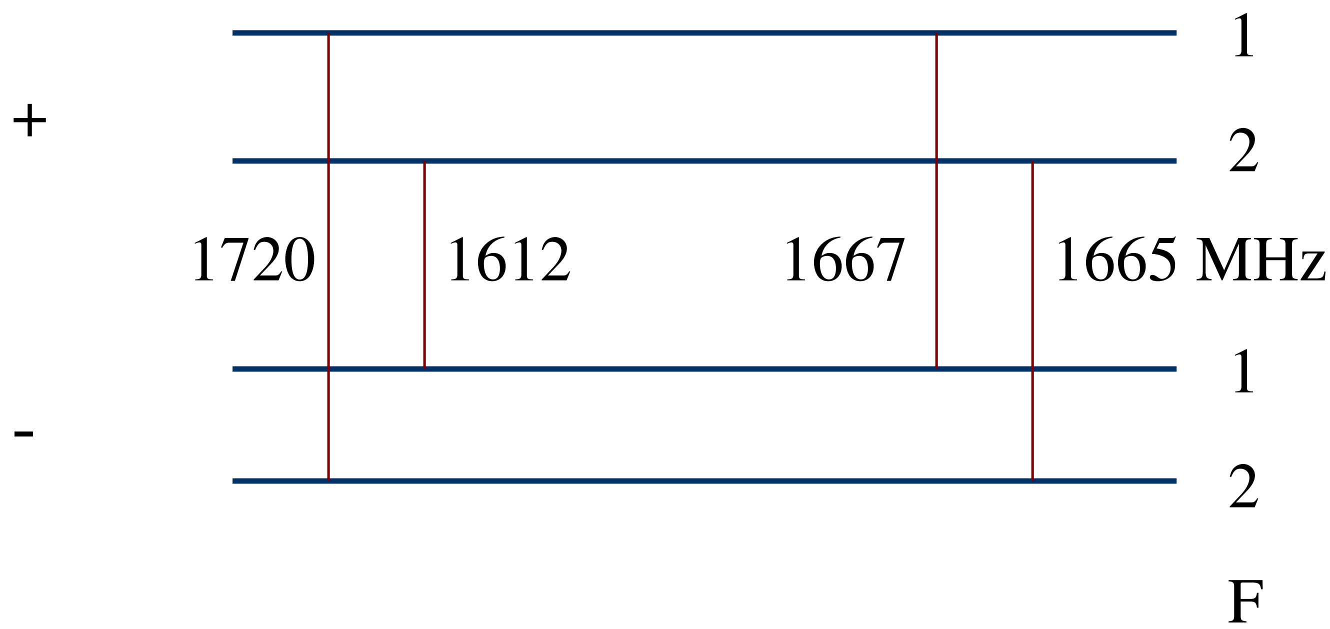
1st radio molecule (1963)



OH (18 cm)

Mysterium = OH Maser

MASER MOLECULES

- OH (hydroxyl)
- H_2O (water)
- SiO
- CH

- HCN
- NH_3 (ammonia)
- CH_3OH (methanol)
- H_2CO (formaldehyde)

$\lambda \sim$ 1mm — 30 cm

MASER ENVIRONMENTS

- Comets
- Molecular clouds
- Star-forming regions
- Red giant & supergiant stars
- Supernova remnants
- Galaxies (up to z = 0.265)
- H maser in MWC 349

Questions

- How do you know a maser when you see one?
- What IS a maser, anyhow?
- Why do they occur so readily in space?

“Mysterium”:

- Anomalous excitation pattern
- Narrow linewidths
- High polarization
- Extreme brightness

Brightness Temperature: $I_\nu = B_\nu(T_b)$

Excitation Temperature: $n_2/n_1 = \exp(-\Delta E/kT_x)$

$$\frac{dB_\nu(T_b)}{d\tau_\nu} = B_\nu(T_x) - B_\nu(T_b)$$

Generally: $T_b \leq T_x \sim T$

Masers: $T_b \sim 10^{10}$ — 10^{15} K !!!

Microwave

Amplification by

Stimulated

Emission of

Radiation

Radiative transfer: $\frac{dI}{d\ell} = \varepsilon - \kappa I$

$I = I_{in} e^{-\tau}$ $\tau = \int \kappa \, d\ell$

$\varepsilon \propto n_2 A$ $\kappa \propto (n_1 - n_2) B$

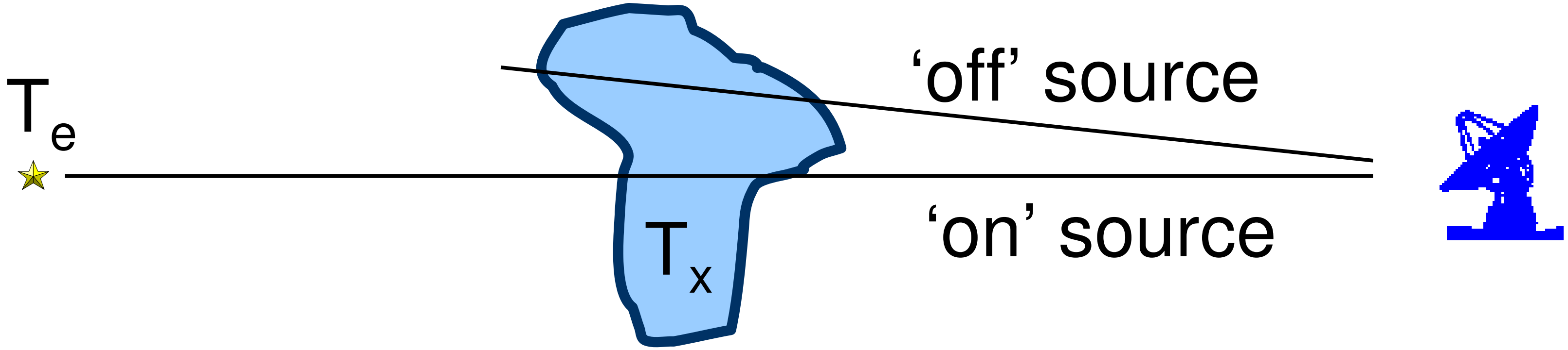
Normally: $n_2 << n_1 \Rightarrow$ absorption

Population Inversion: $n_2 > n_1$

$\kappa \propto n_1 - n_2 < 0!$

$I = I_{in} e^{+|\tau|}!$

absorption $\Rightarrow$ AMPLIFICATION!



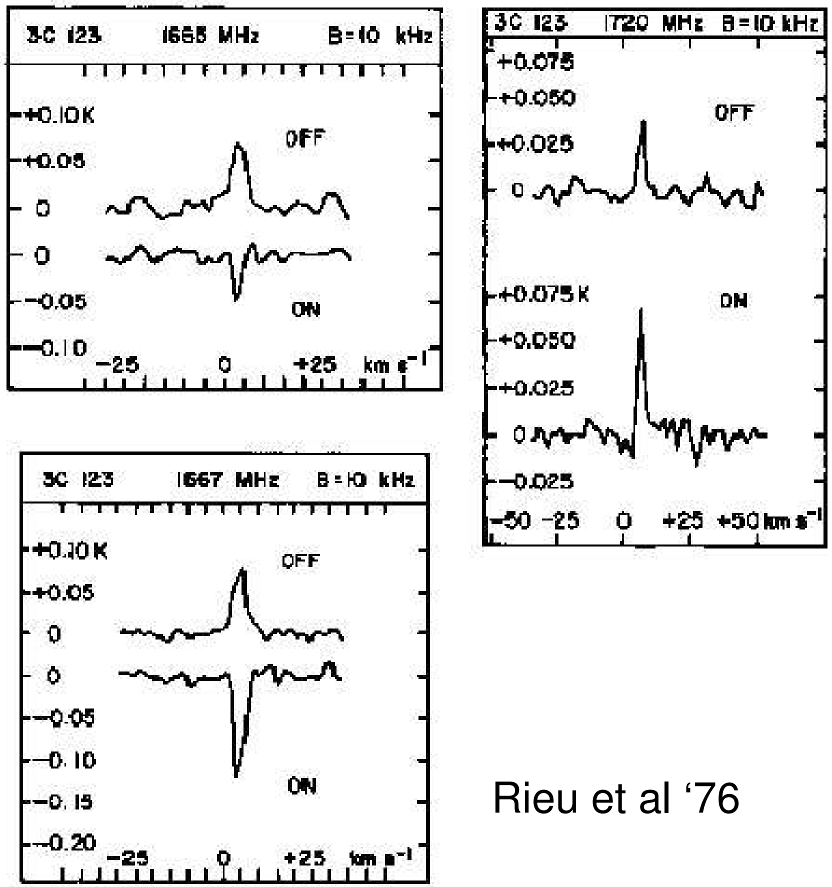
$$T_b^{line} = T_b - T_b^c$$

'off':

$$T_b^{line} = T_x(1 - e^{-\tau})$$

'on':

$$T_b^{line} = T_x(1 - e^{-\tau}) + T_e e^{-\tau} - T_e$$
$$= (T_x - T_e)(1 - e^{-\tau})$$



Rieu et al '76

$T_x(1665,1667) \sim 5–7$ K

$T_x(1720) \sim -10$K

Why ISM?

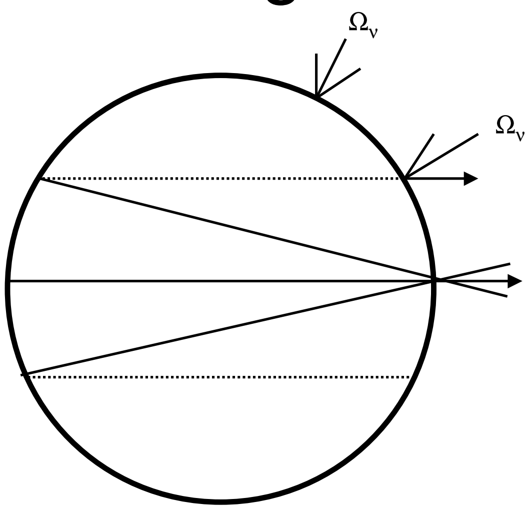
- Low densities –
  deviations from equilibrium
- Astronomical dimensions –
  large column densities

Natural environment for masers

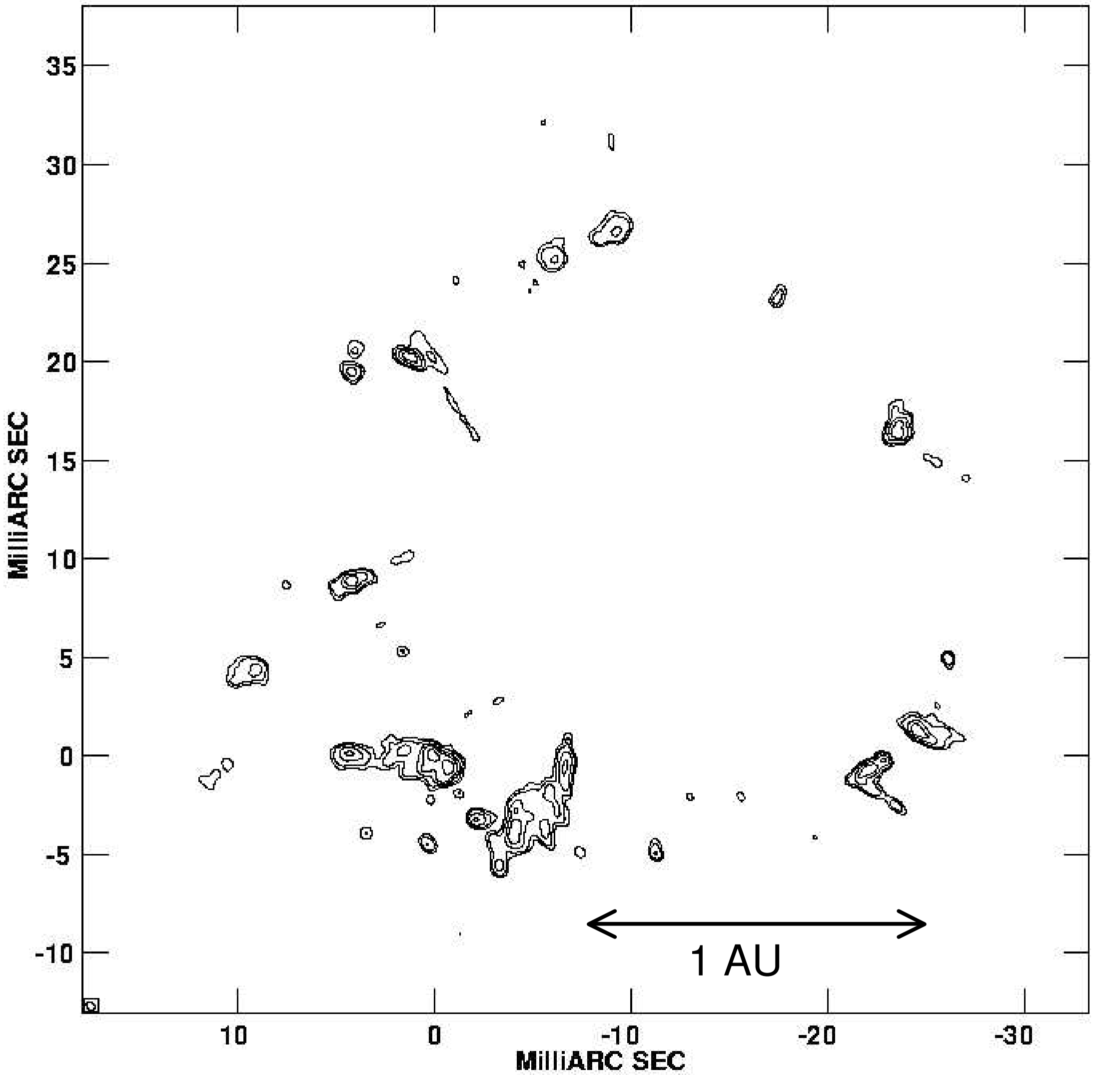
Amplified Radiation

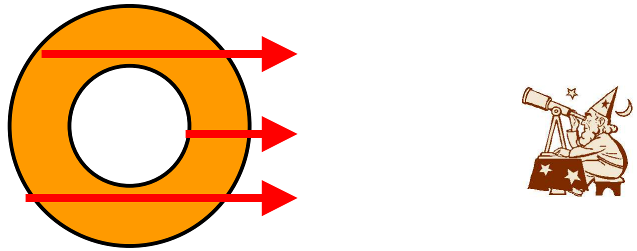
$$I(\ell) = I(\ell_0)\exp\left(\int_{\ell_0}^{\ell} \kappa d\ell\right)$$

- Velocity coherence along line-of-sight
- longer path, higher intensity
- Beaming



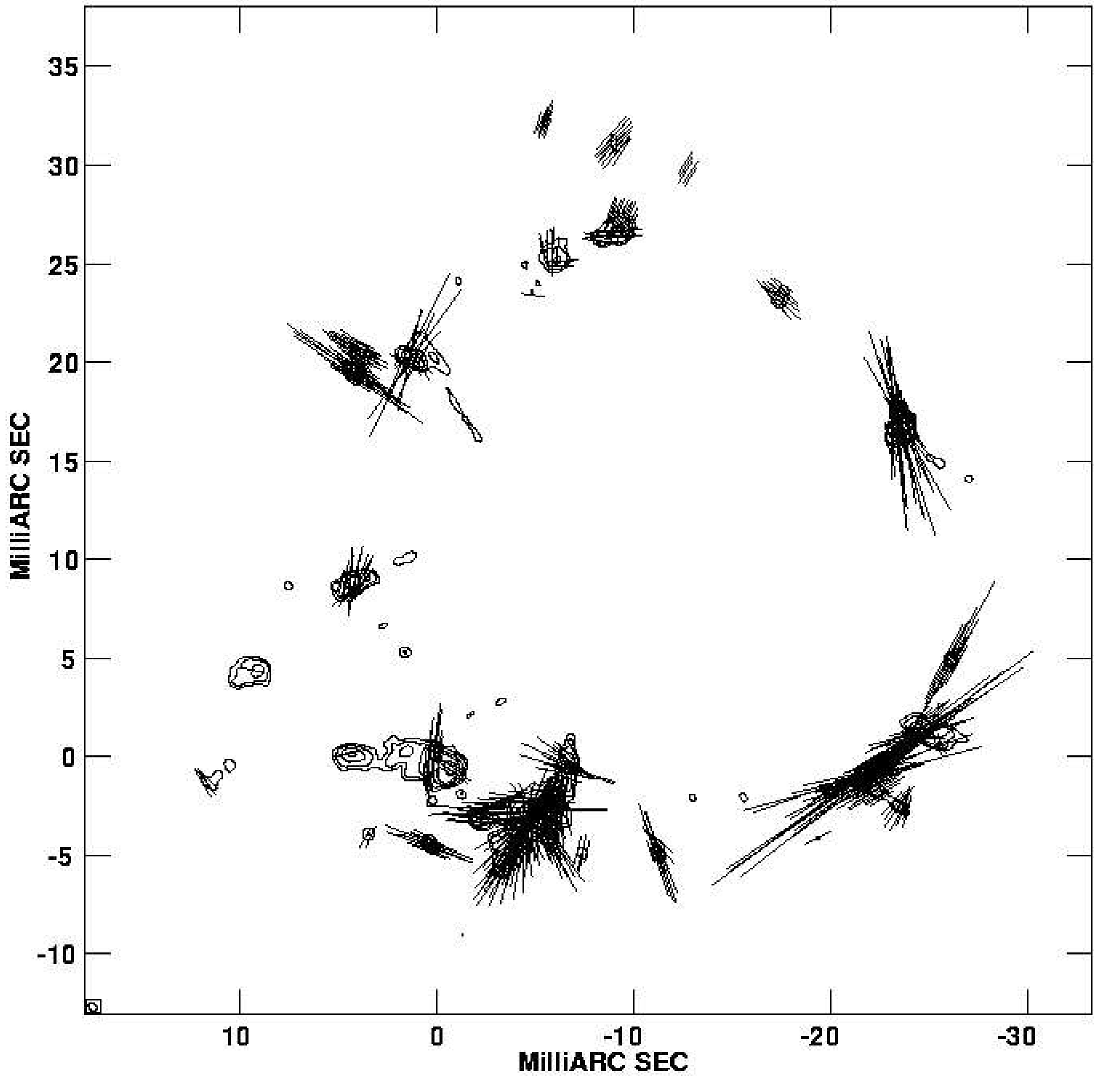
SiO masers in TX Cam

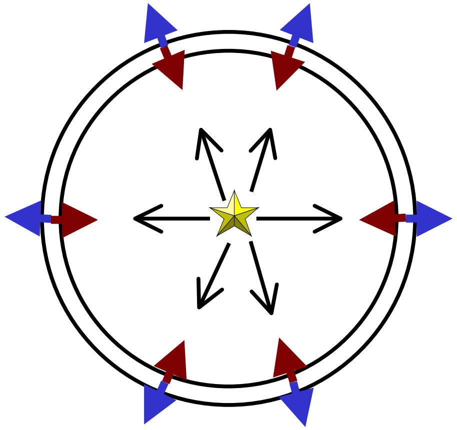


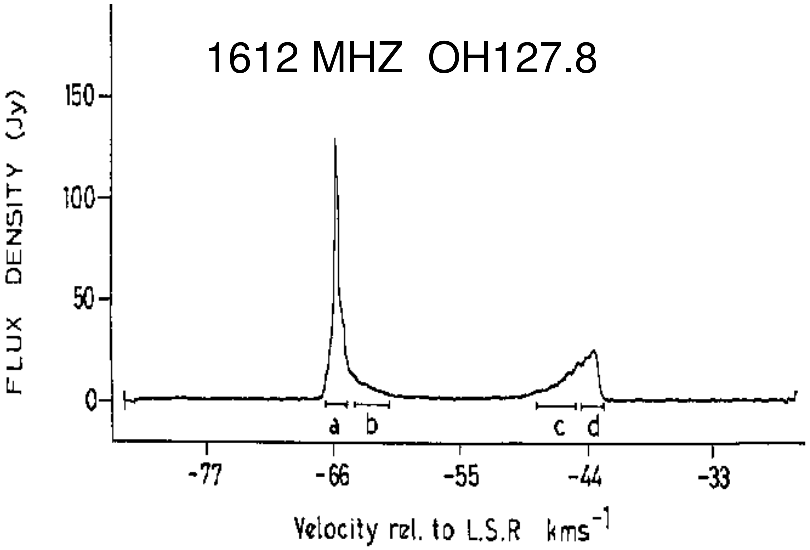


Kemball & Diamond '97

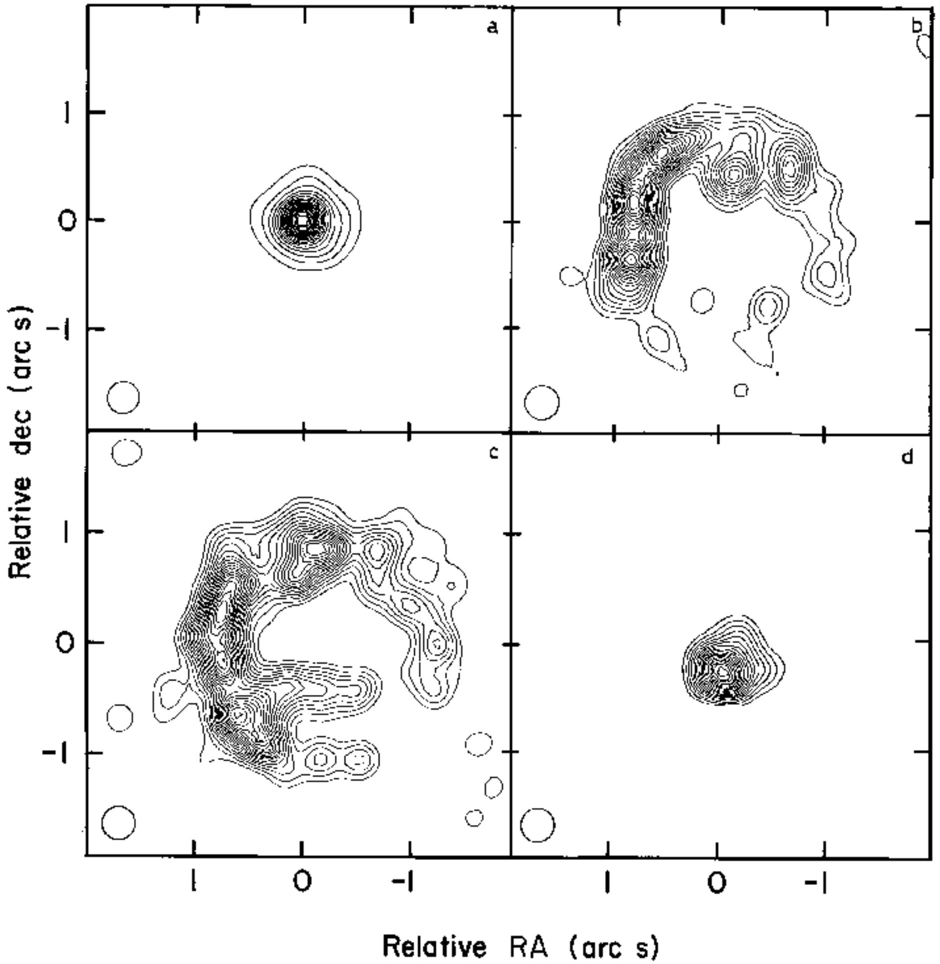
Polarization map:



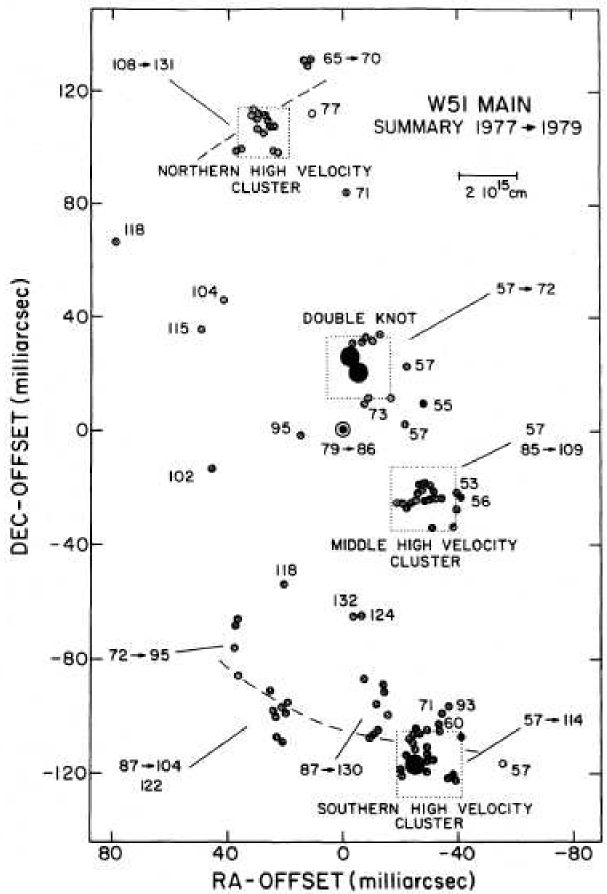


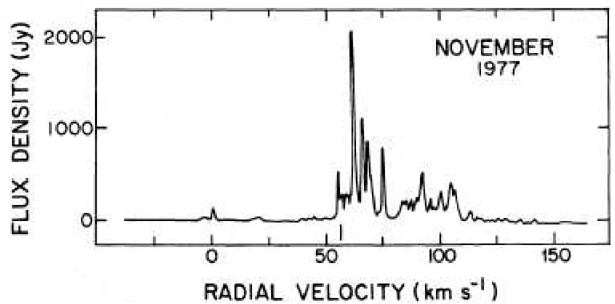


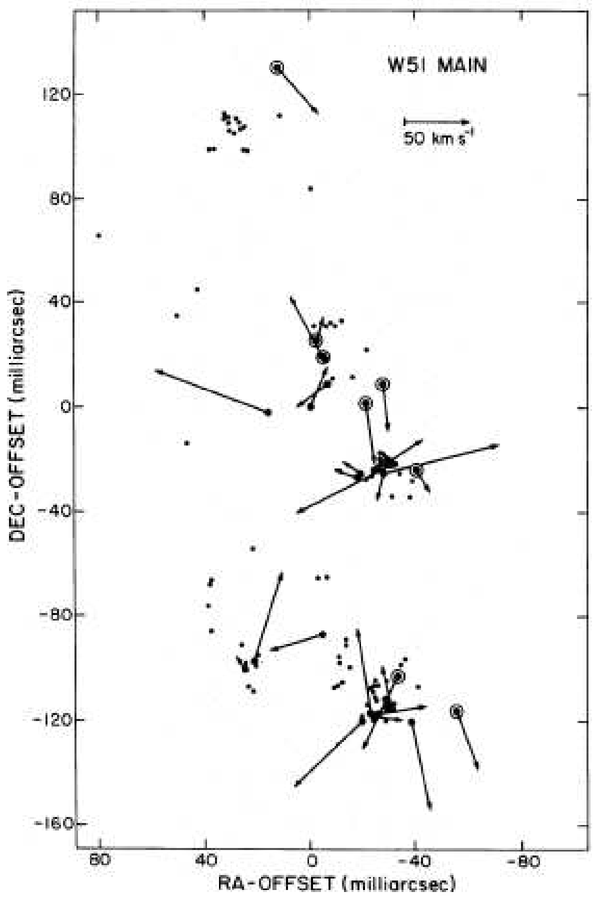
Booth et al ‘81



H_2O masers in W51

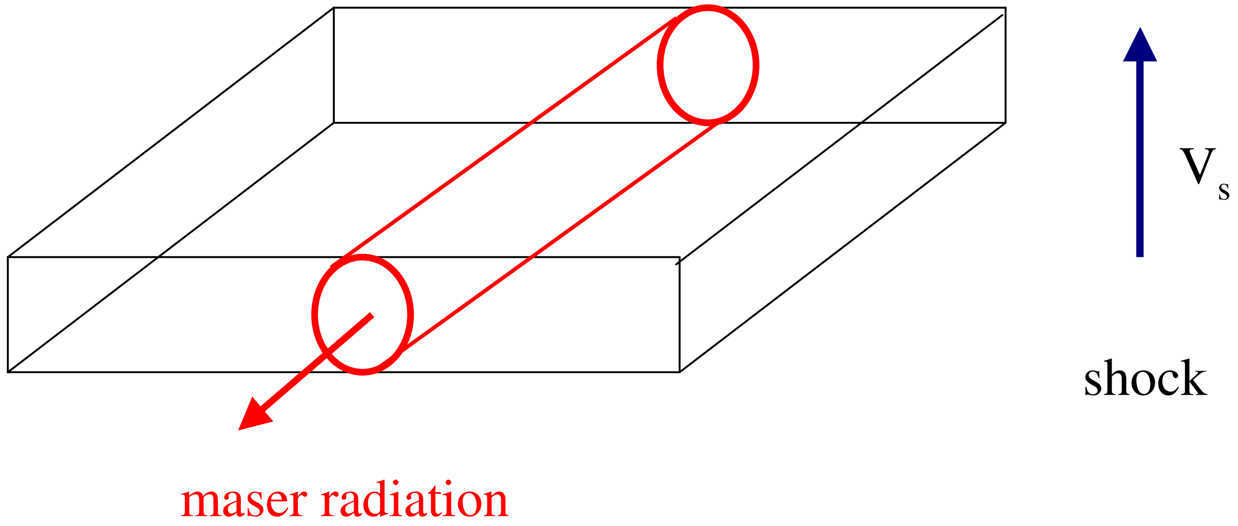




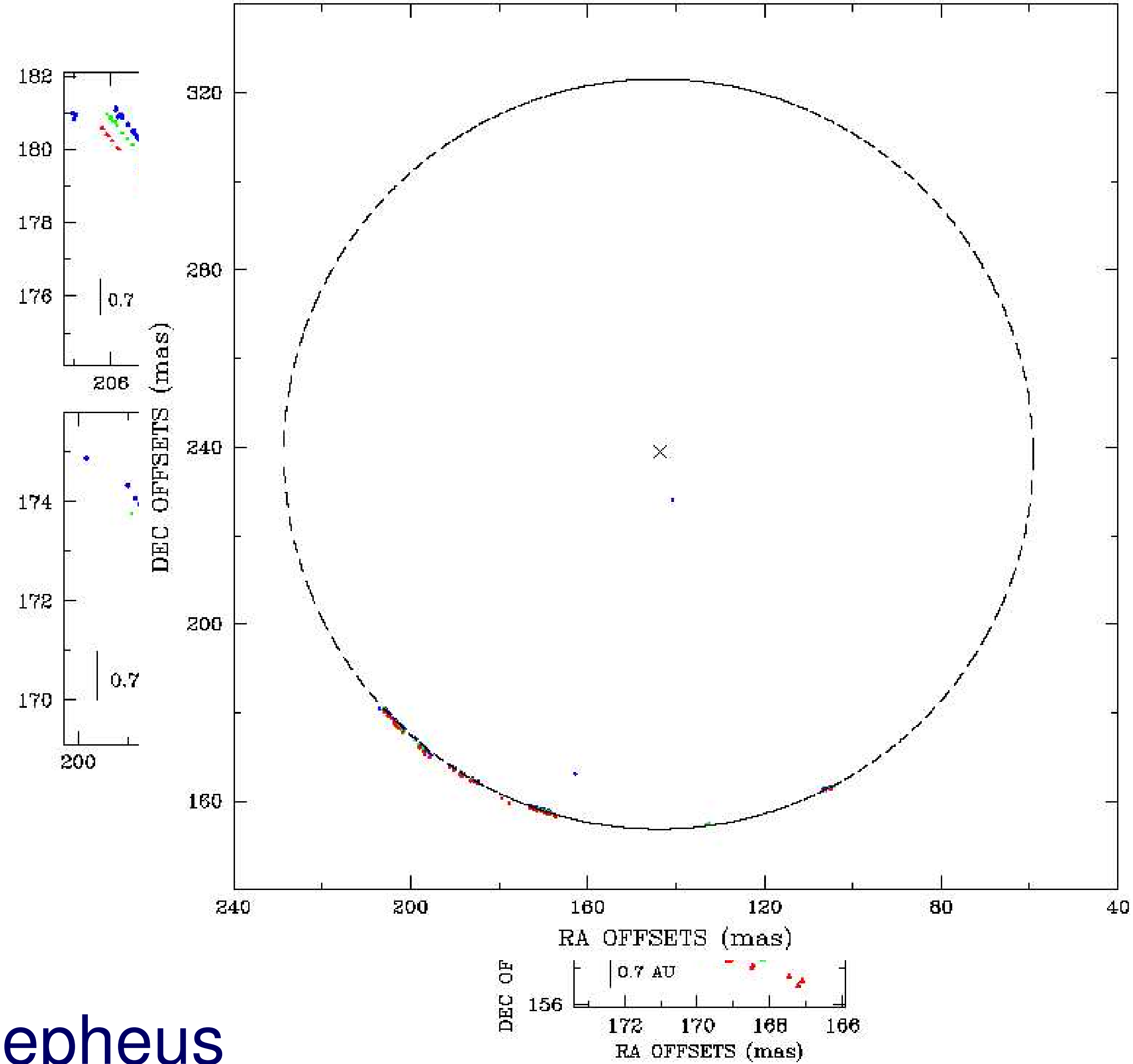


Genzel et al '81

Velocity-coherent regions in shocked gas!



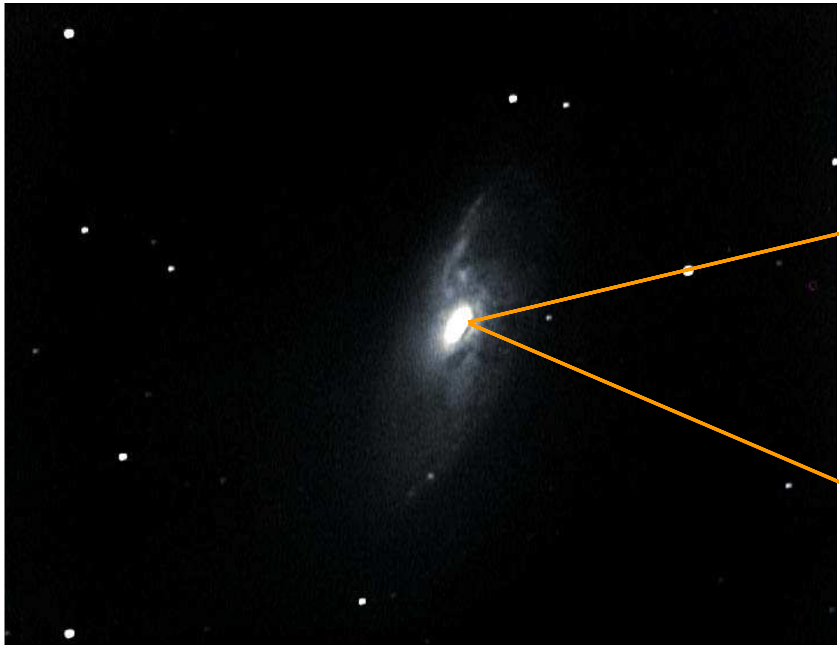
Elitzur, Hollenbach & McKee (89, 92)



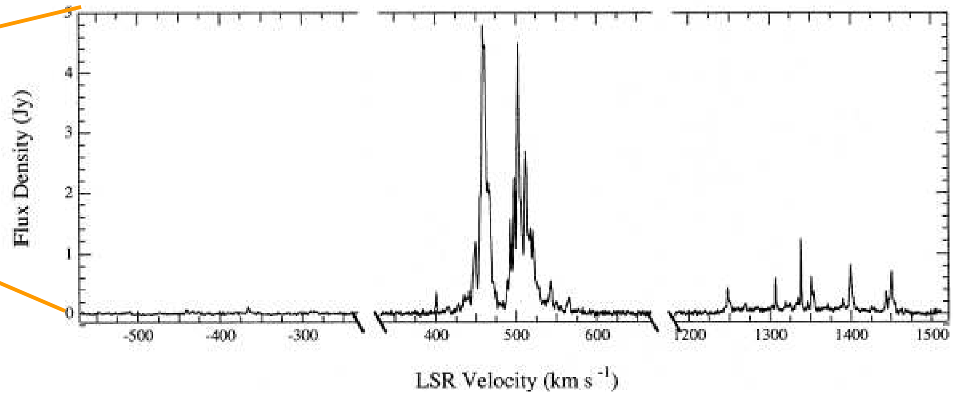
H_2O in Cepheus

Torrelles et al 2001

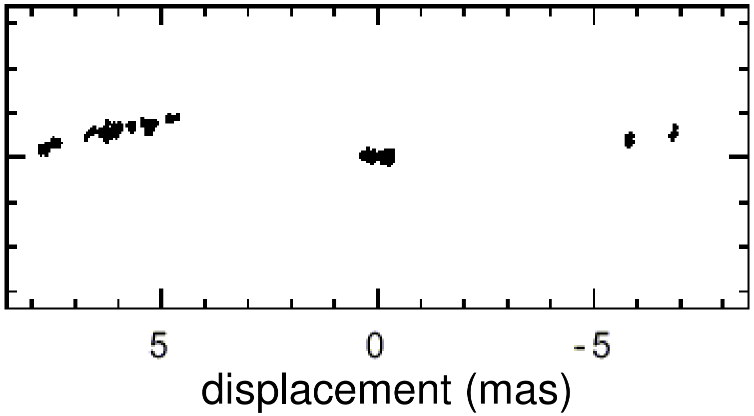
Black Hole in NGC4258

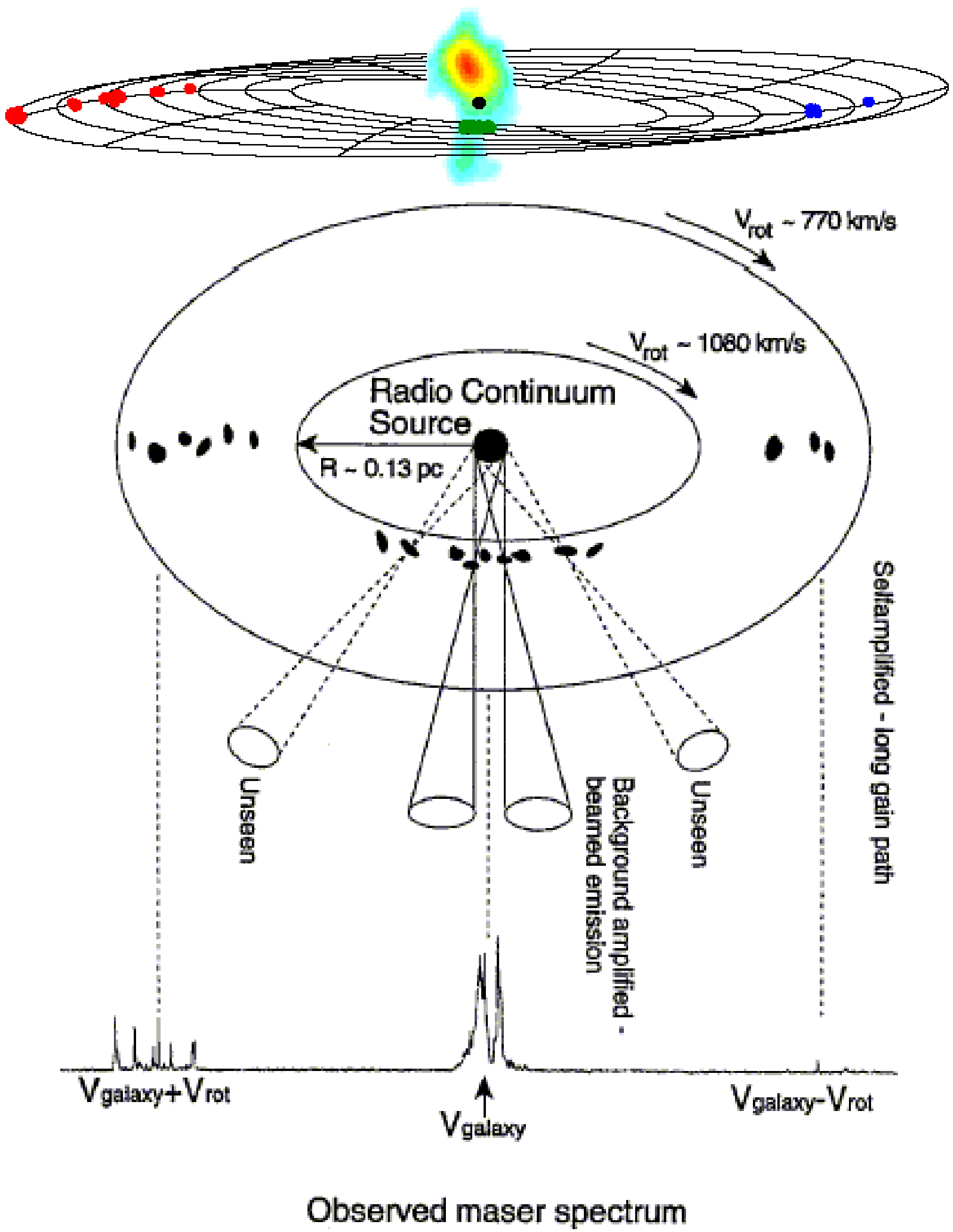


H_2O maser emission:

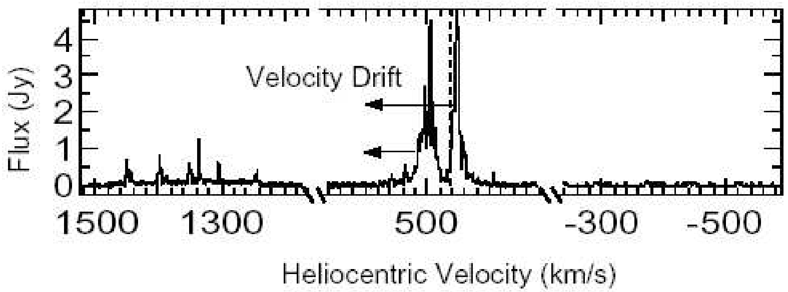


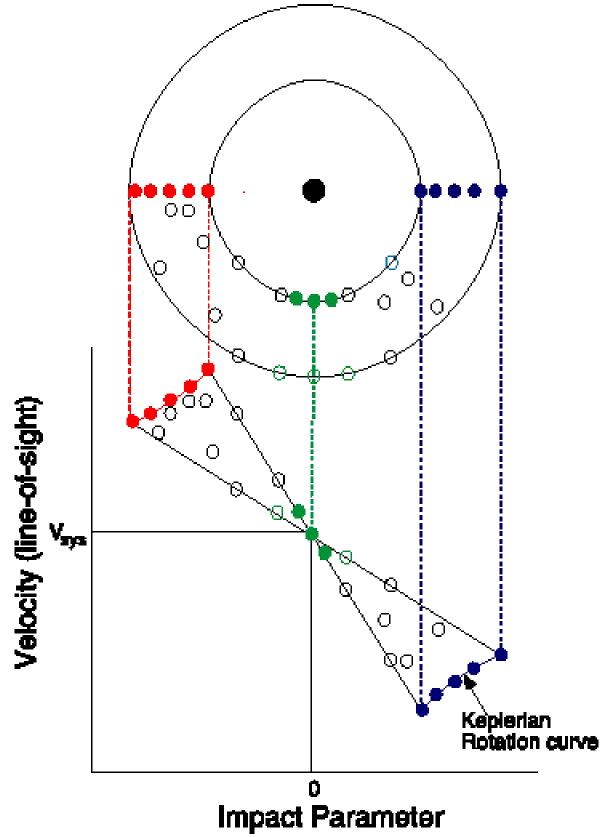
Mapping:





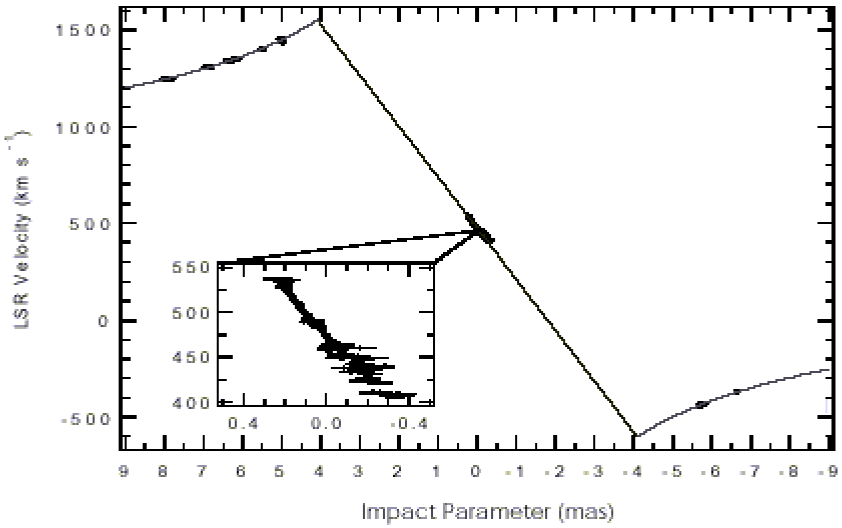
V_{rot} ~ 770 km/s
V_{rot} ~ 1080 km/s
Radio Continuum Source
R ~ 0.13 pc
Selfamplified - long gain path
Unseen
Background amplified - beamed emission
Unseen
$V_{galaxy}+V_{rot}$
V_{galaxy}
$V_{galaxy}-V_{rot}$
Observed maser spectrum





Keplerian Rotation:

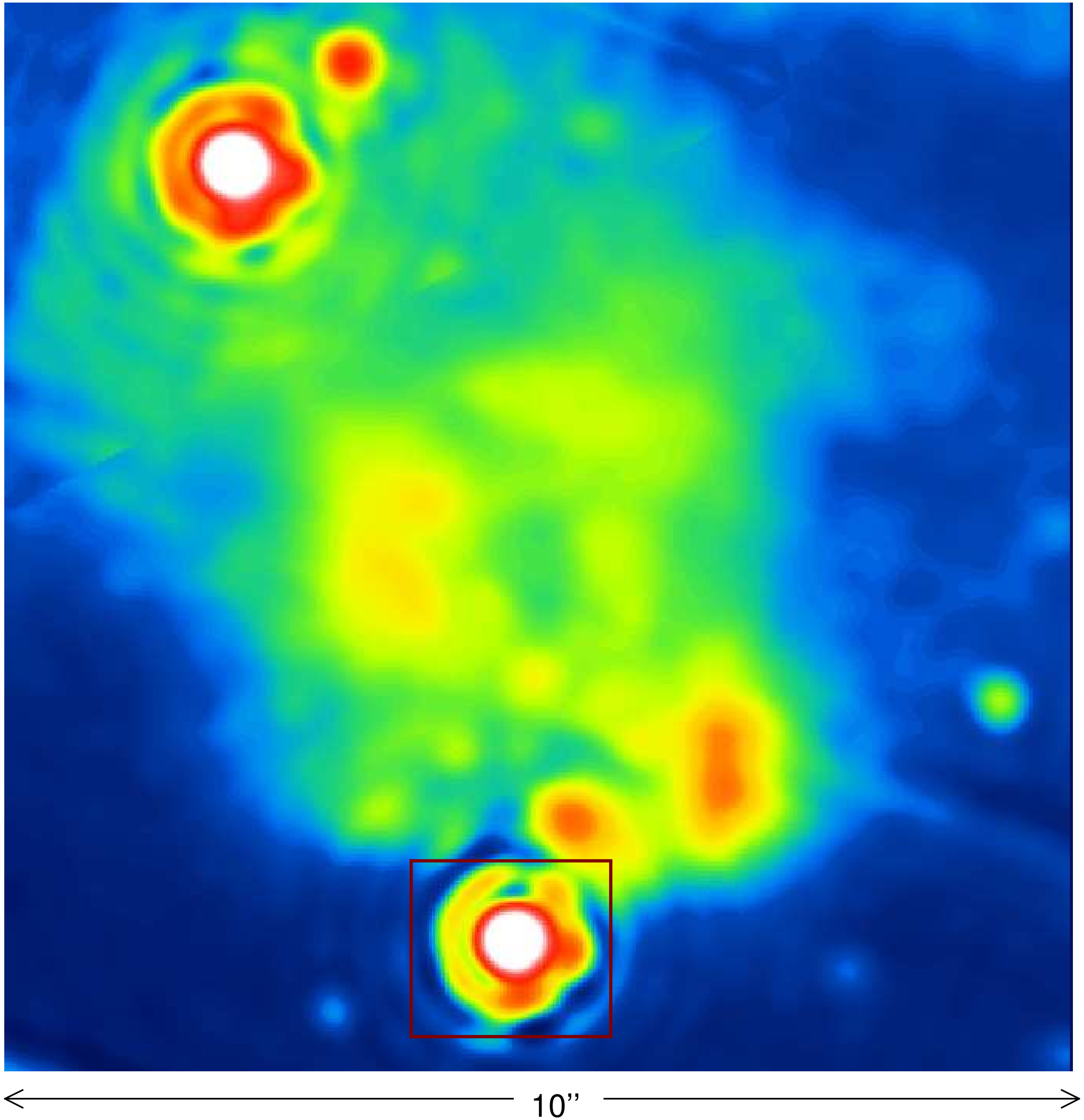
$$V_r^2 = \frac{GM}{r}$$



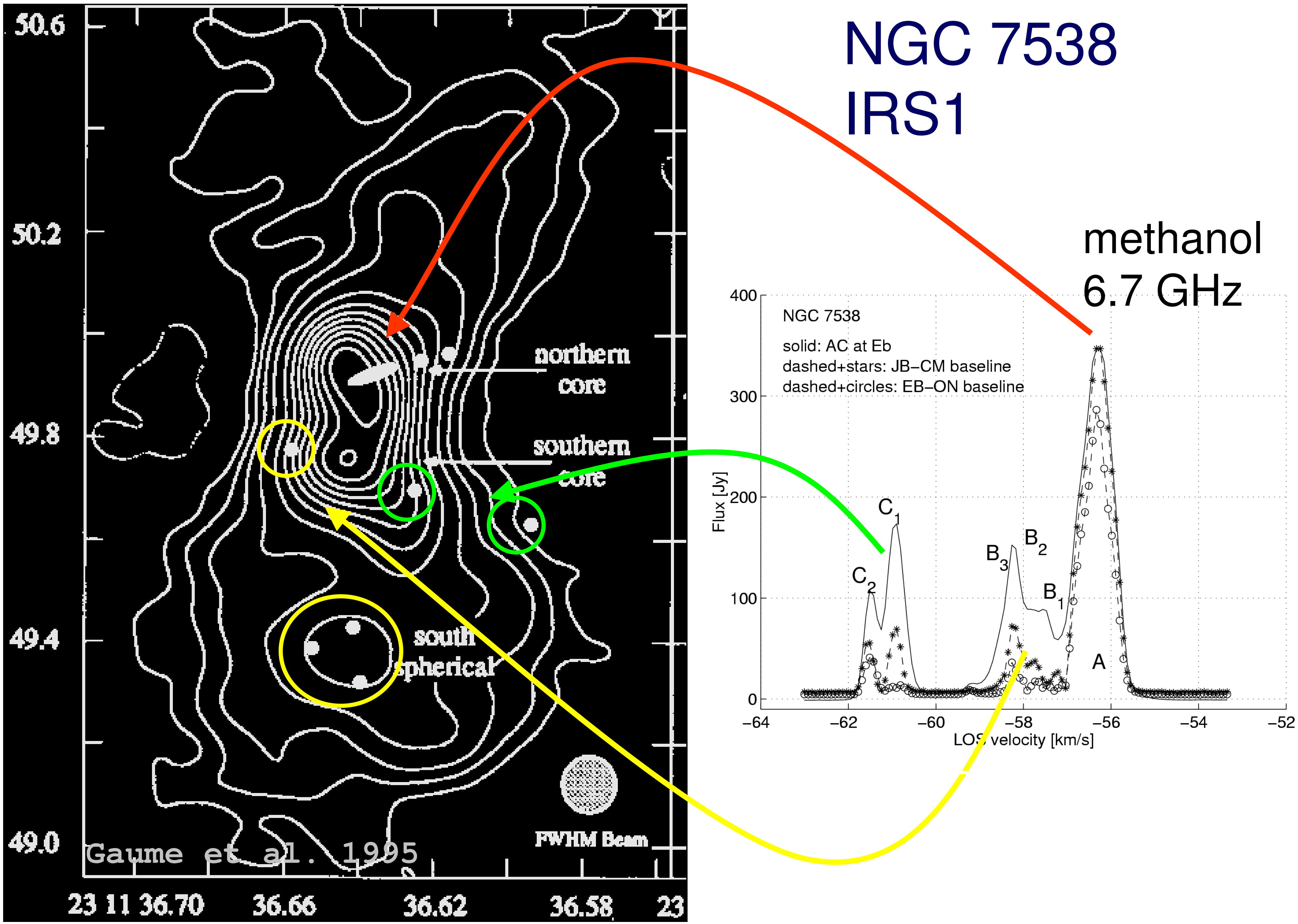
System Properties:

Central mass	$4\times10^7\ M_{\odot}$
Disk inner radius	0.14 pc
Disk thickness	<0.0003 pc
Distance	7.3 Mpc

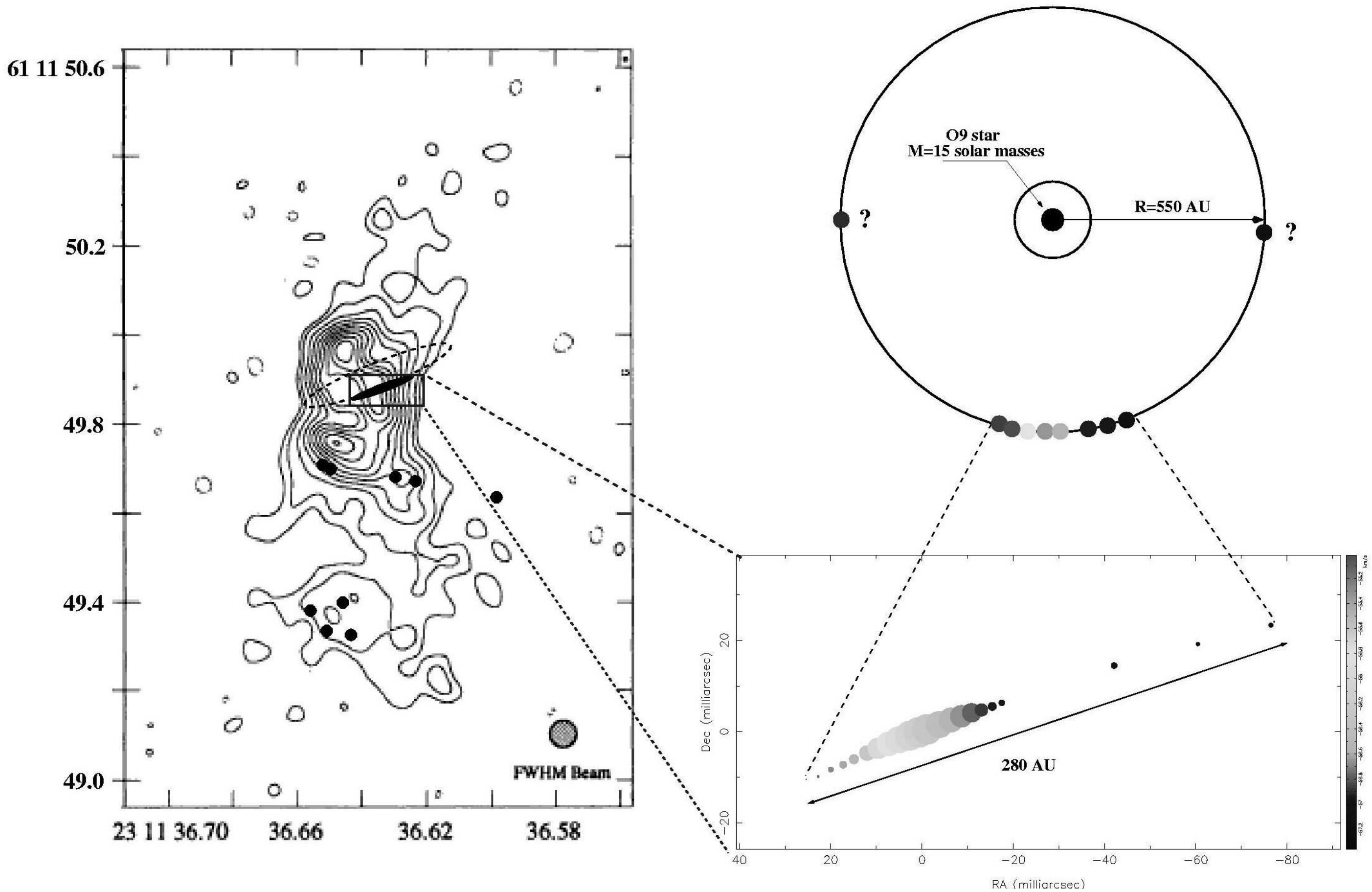
NGC7538
IRS1
K-image
(G. Weigelt)



M = 30 $M_\odot$
L = $8 \cdot 10^4$ $L_\odot$

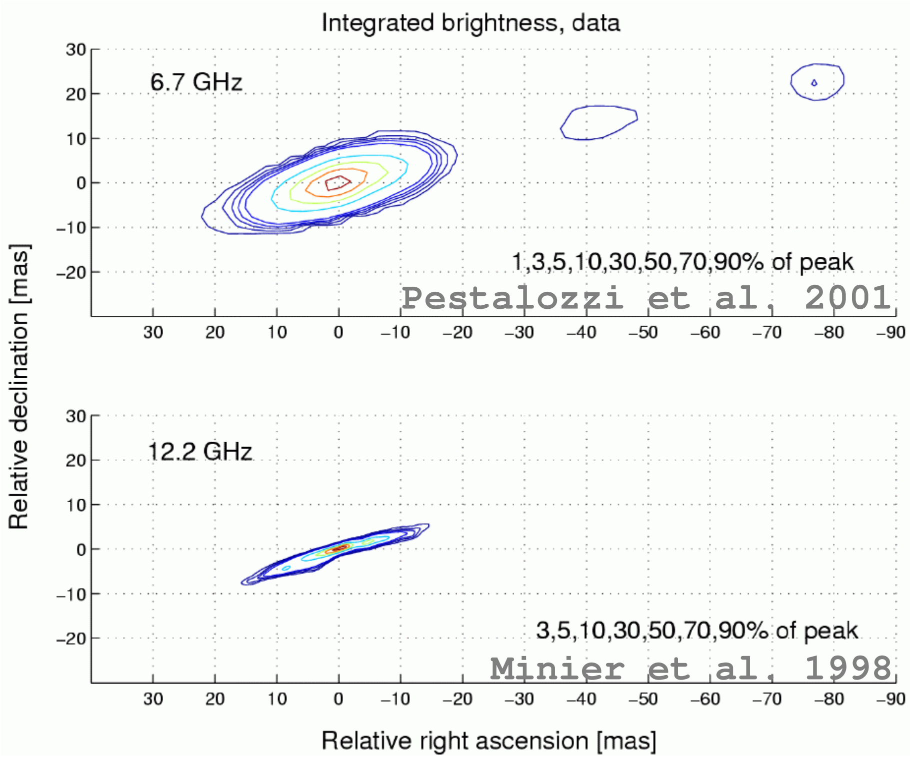

NGC 7538
IRS1
methanol
6.7 GHz
northern core
southern core
south spherical
FWHM Beam
Gaume et al. 1995
50.6
50.2
49.8
49.4
49.0
23 11 36.70
36.66
36.62
36.58
23
NGC 7538
solid: AC at Eb
dashed+stars: JB–CM baseline
dashed+circles: EB–ON baseline
Flux [Jy]
LOS velocity [km/s]
C1
C2
B1
B2
B3
A
400
300
200
100
0
−64
−62
−60
−58
−56
−54
−52

NGC 7538 – a disk?

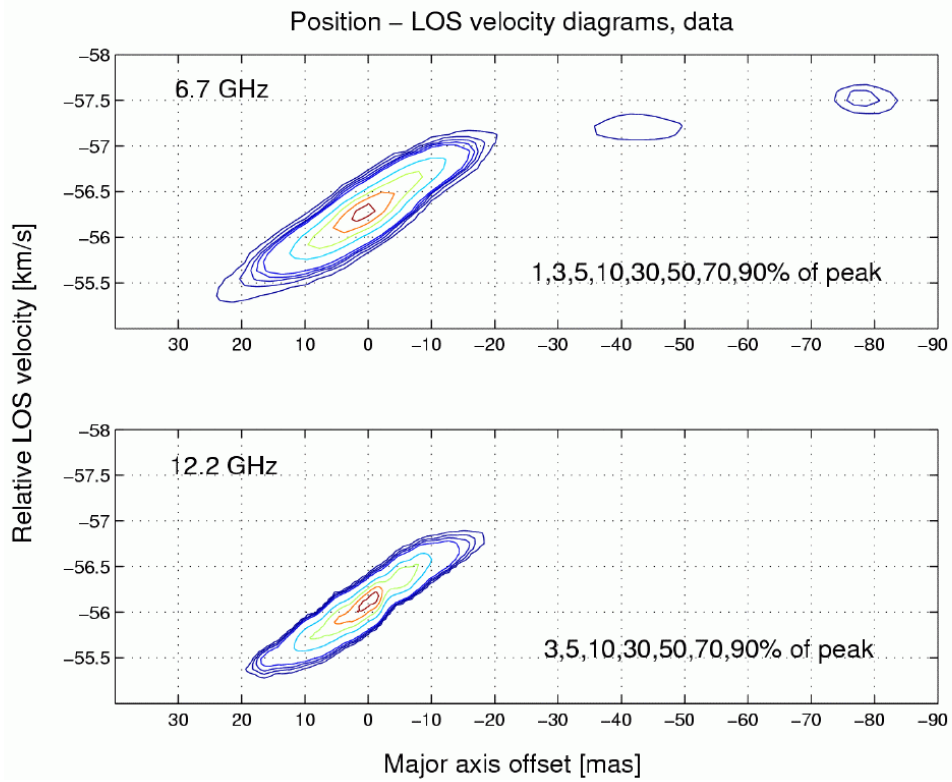


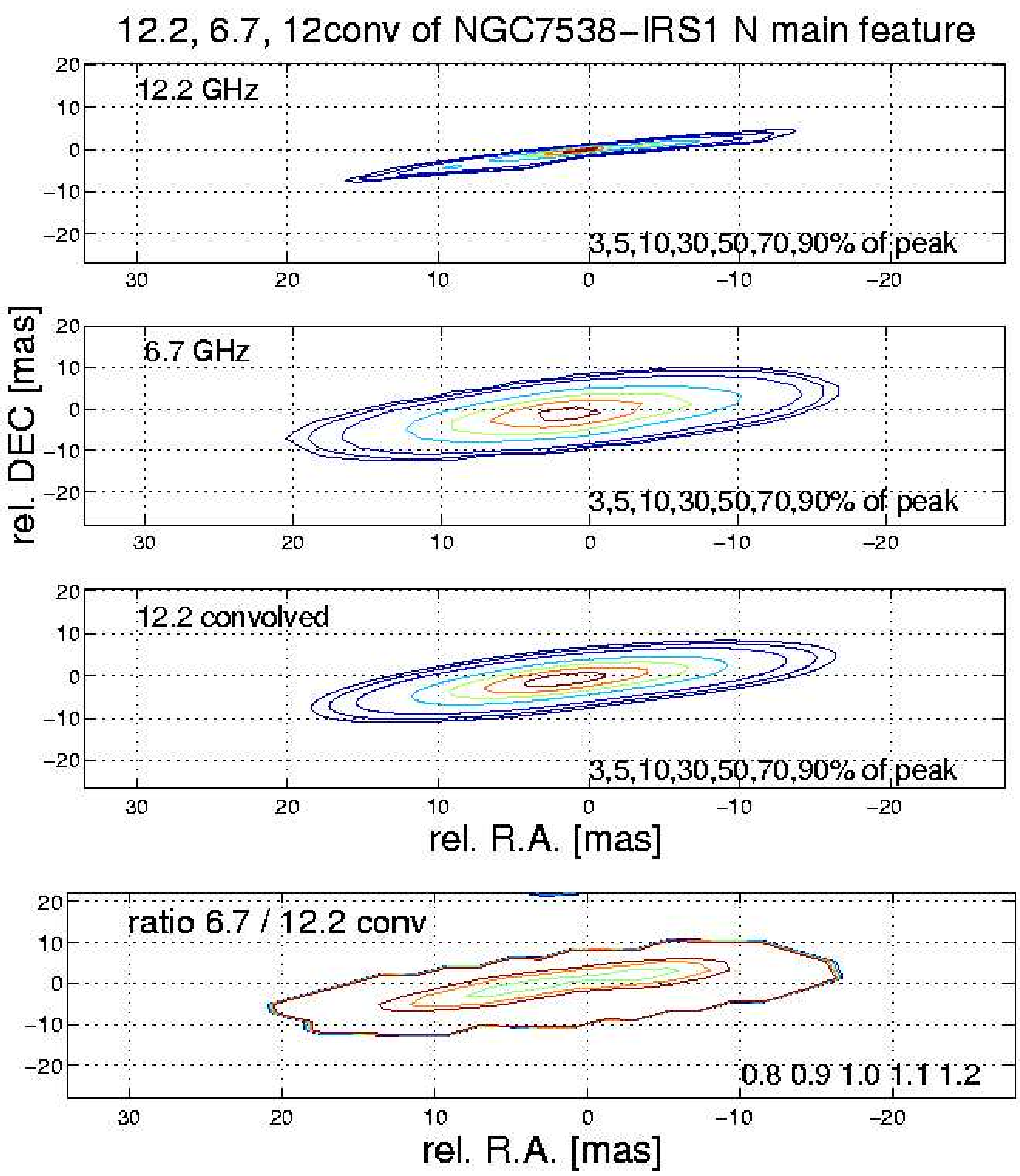
Minier, Booth, & Conway '98

Maps:



p-v diagrams:



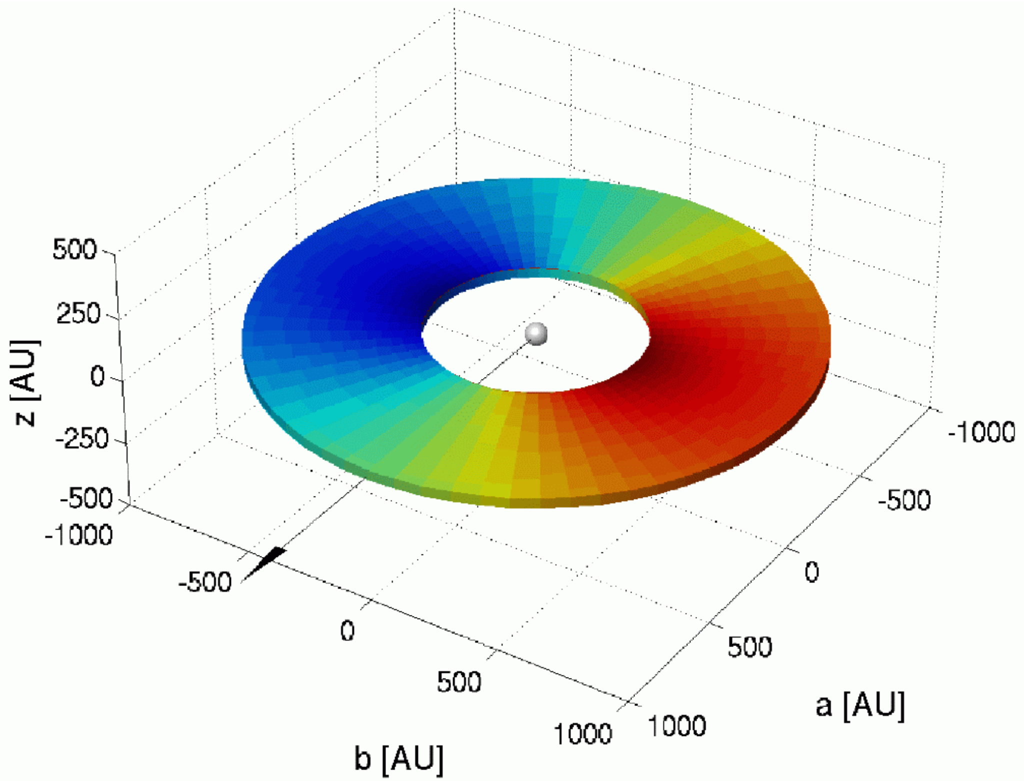


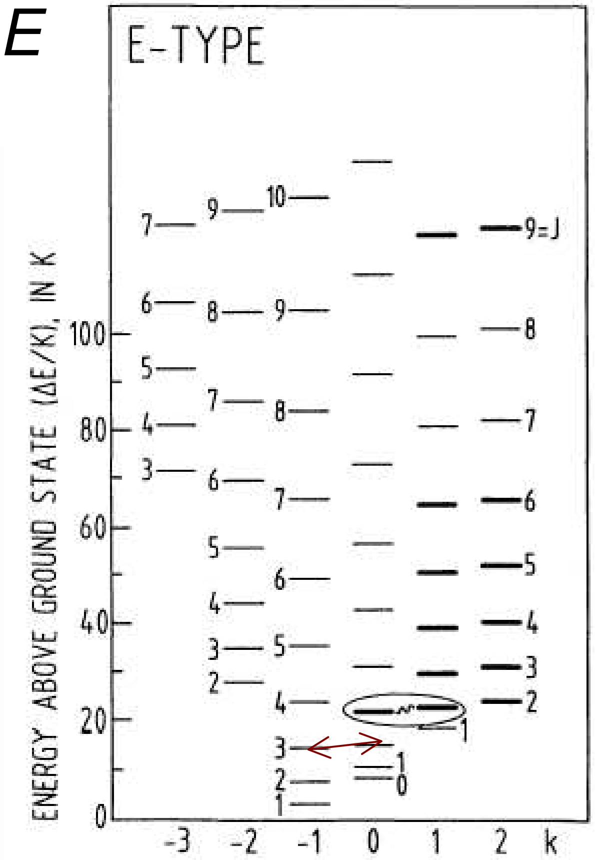
12.2, 6.7, 12conv of NGC7538-IRS1 N main feature
12.2 GHz
3,5,10,30,50,70,90% of peak
6.7 GHz
3,5,10,30,50,70,90% of peak
12.2 convolved
3,5,10,30,50,70,90% of peak
rel. DEC [mas]
rel. R.A. [mas]
ratio 6.7 / 12.2 conv
0.8 0.9 1.0 1.1 1.2
rel. R.A. [mas]

Different Species

6.7 GHz: $5_1 \rightarrow 6_0\ A^+$

12.2 GHz: $2_0 \rightarrow 3_{-1}\ E$

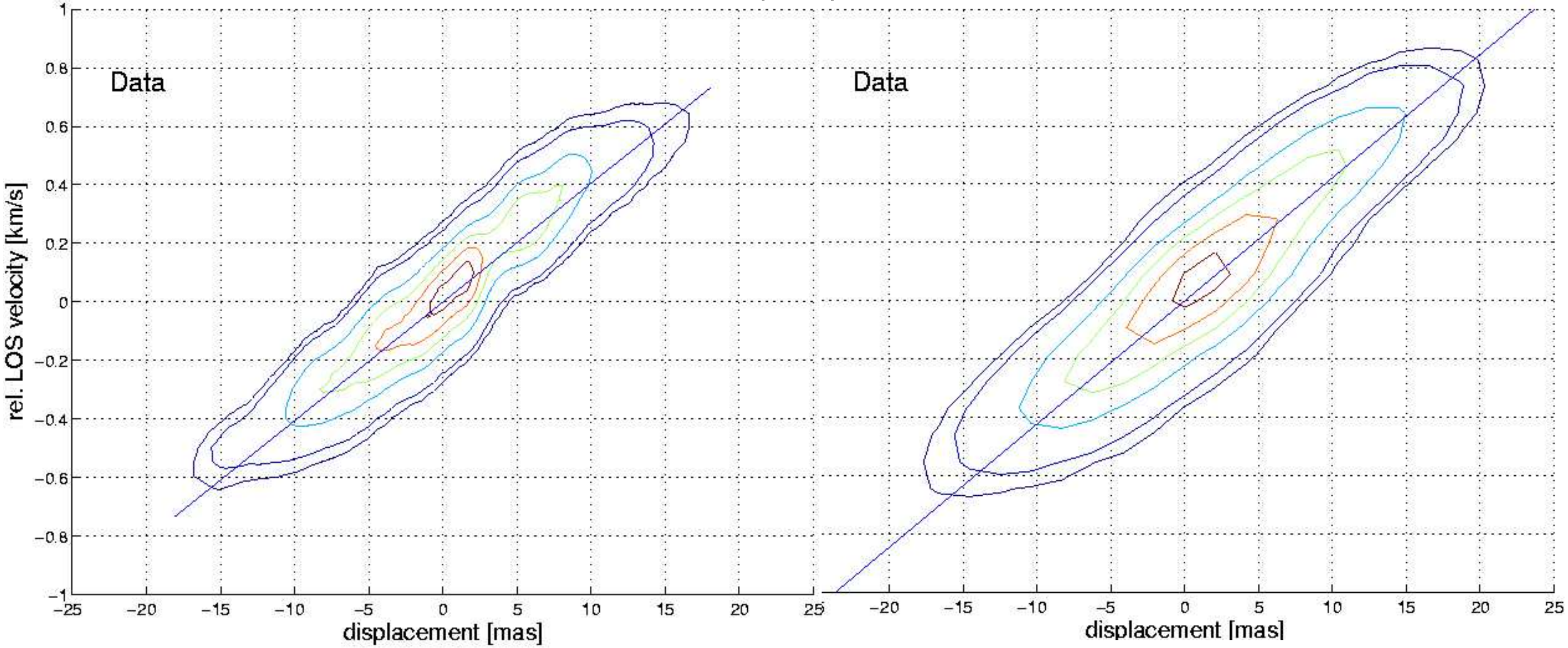




The Data

$$I(\theta,v) = I_B e^{\tau(\theta,v)} \Rightarrow \tau(\theta,v) = \ln[I(\theta,v)/I_B]$$

$\tau(\theta,v)$



12 GHz

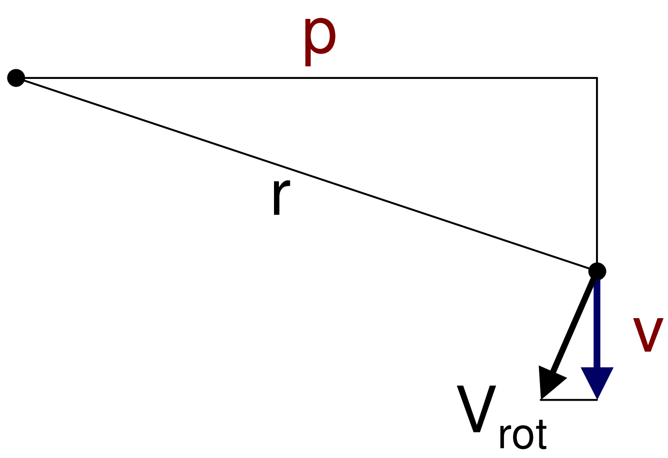
$\tau(0) = 16$

6.7 GHz

$\tau(0) = 18$

Pestalozzi et al ‘04

Position Velocity diagrams



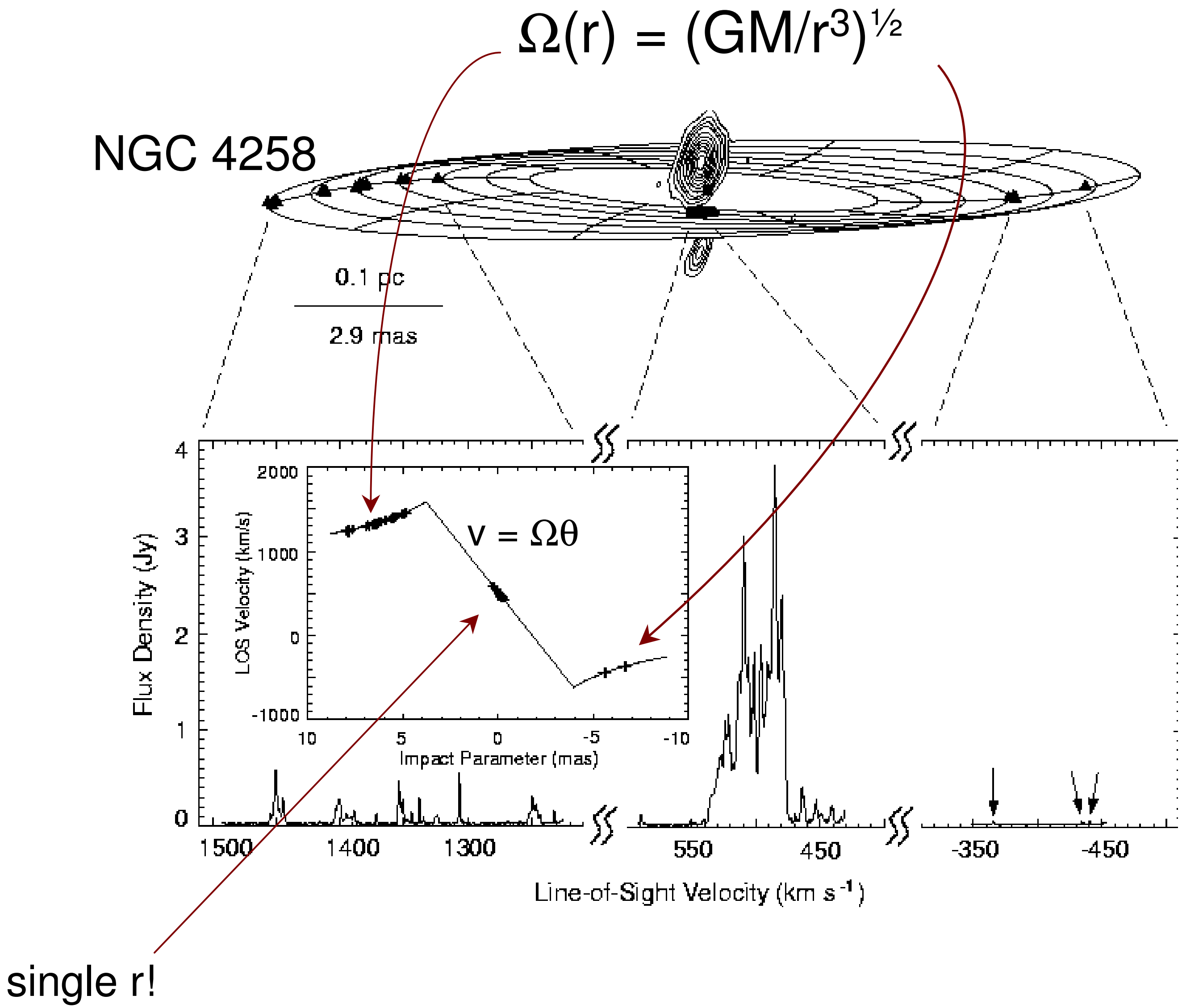
$$\frac{v}{V_{rot}} = \frac{p}{r}$$

$$\frac{v}{p} = \frac{V_{rot}}{r} = \Omega(r)$$

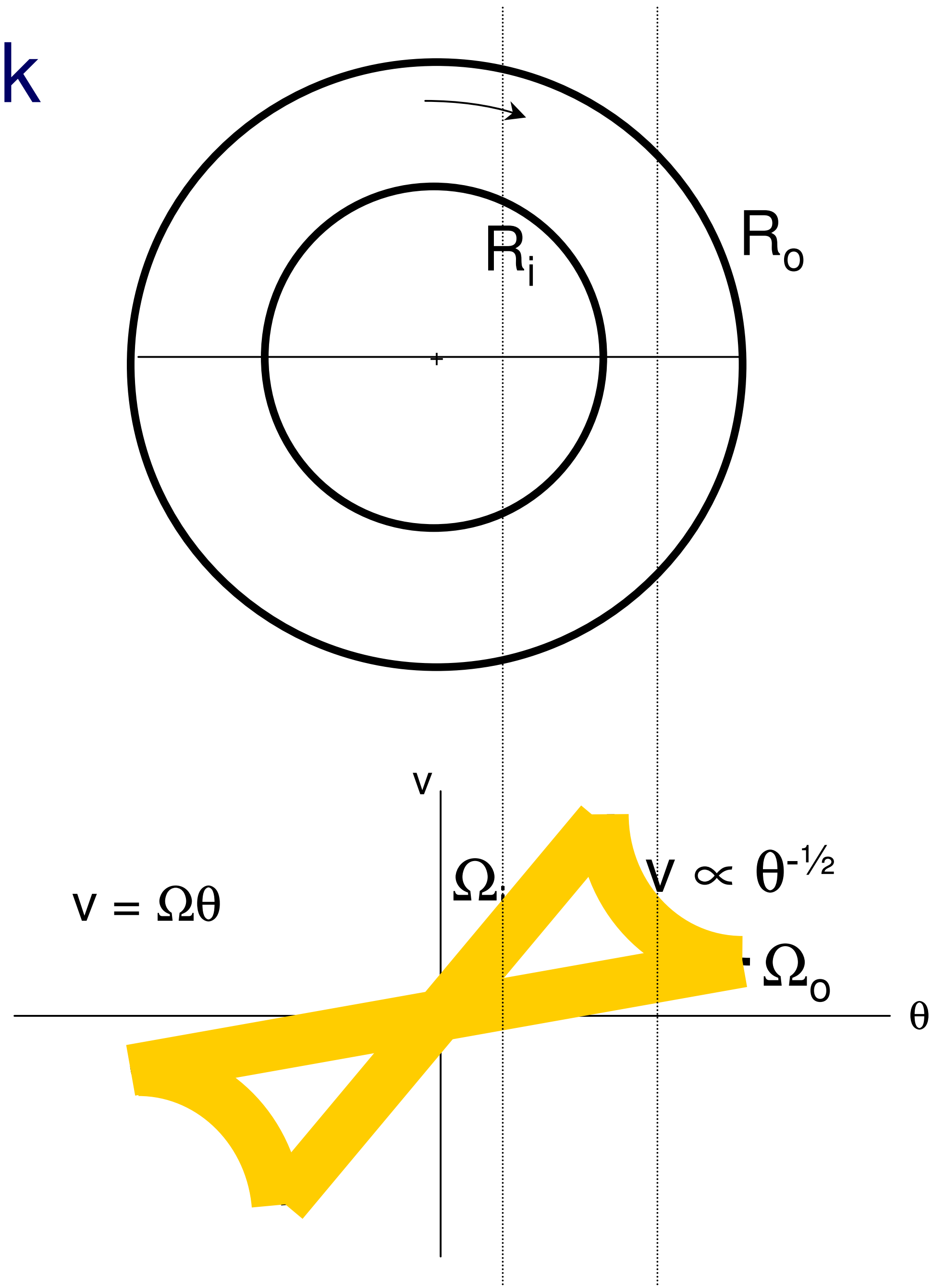
$$v = \Omega(r)\,p$$

- Straight line: single r <u>or</u> solid-body rotation
- Curvature $\Leftrightarrow$ Differential Rotation!

Keplerian Rotation



Smooth Disk

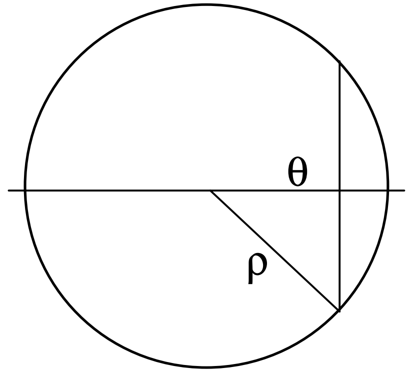


The Model

$\tau_\nu = \int \kappa_0(r)\phi(\nu)\, ds$

$\phi(\nu) = \phi_D[\nu - \nu_0(1 + v/c)]$

$v = \Omega\theta$



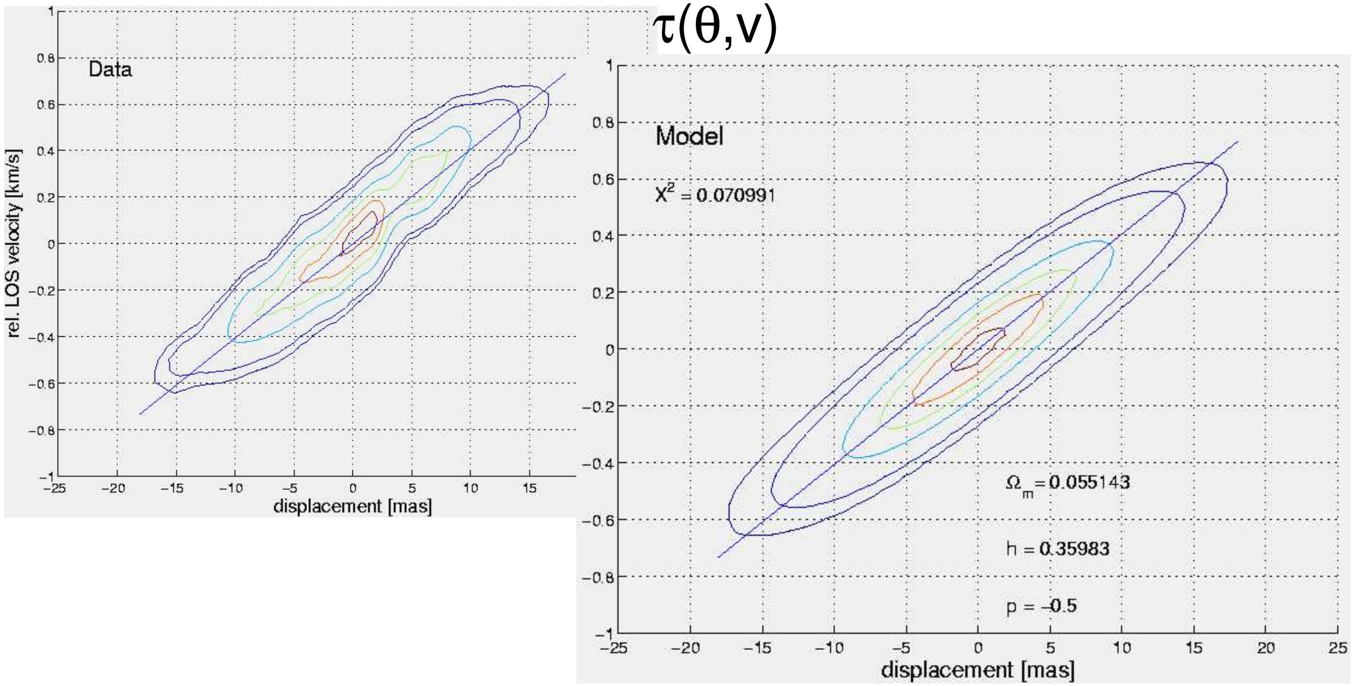
$$\tau(\theta, v) = \tau_0 \int \eta(\rho) \exp\left[-\frac{1}{2}\left(\frac{v - \Omega(\rho)\,\theta}{\Delta v_{\rm D}}\right)^2\right] \frac{d\rho}{\sqrt{1 - (\theta/\rho)^2}}$$

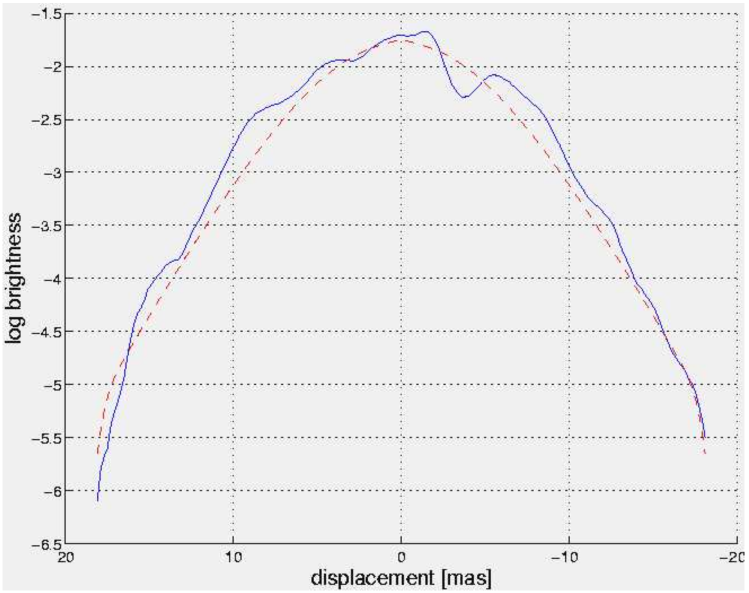
$\tau_0 = 18\ (16)$ $\Delta v_D = 0.4$ km s^{-1}

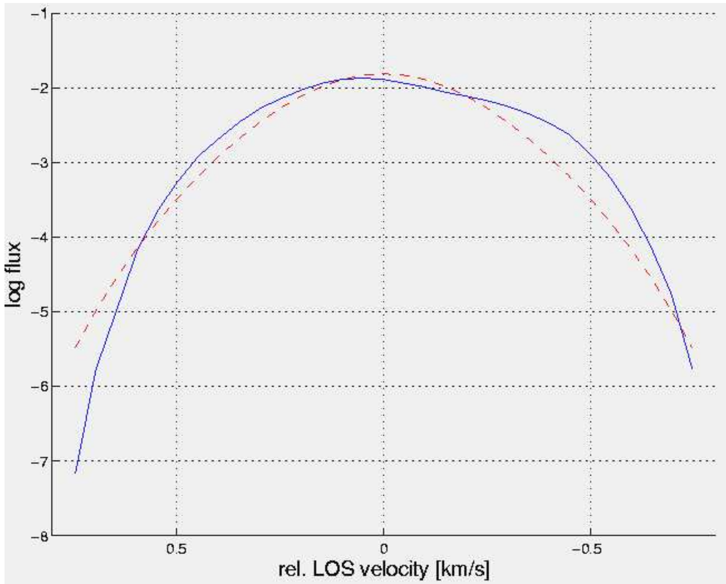
$\Omega = \Omega_o(\rho_o/\rho)^{3/2}$ $\eta \propto \rho^{-p}$ $h = R_i/R_o$

12 GHz fits

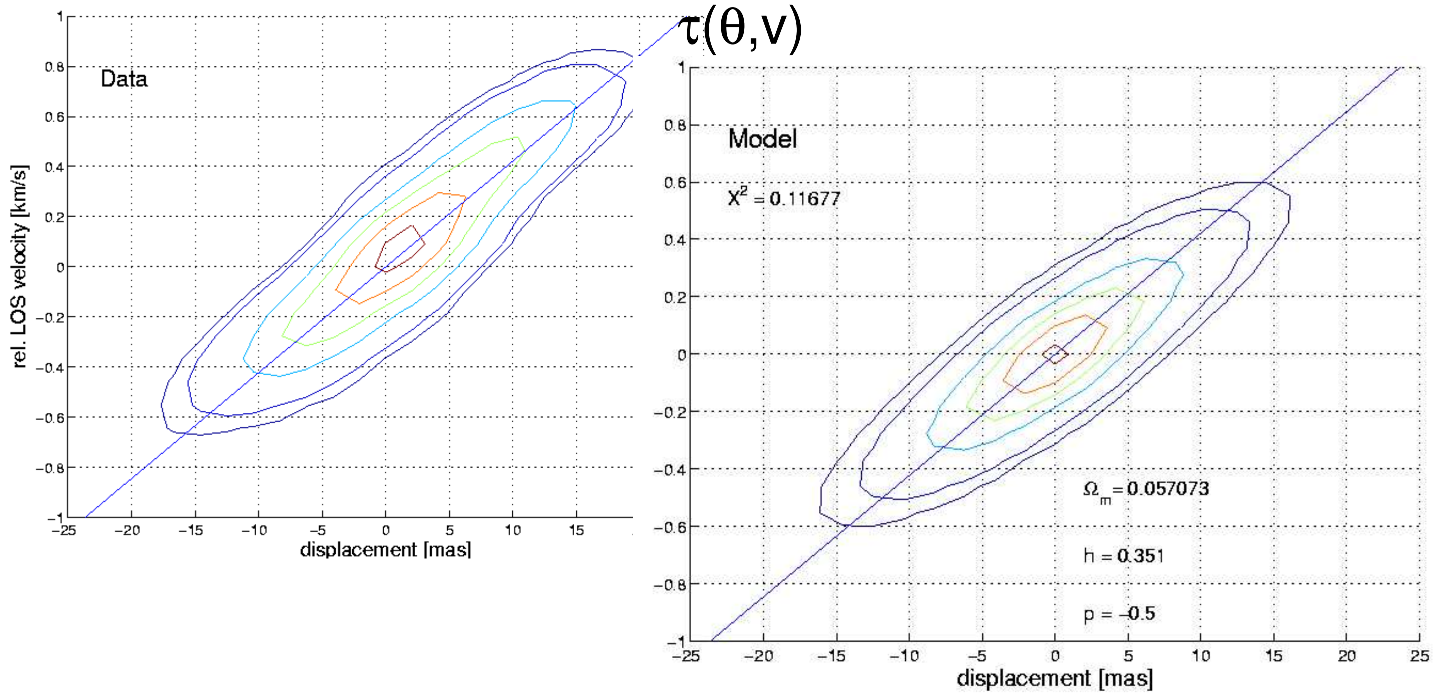
$\tau(\theta, v)$

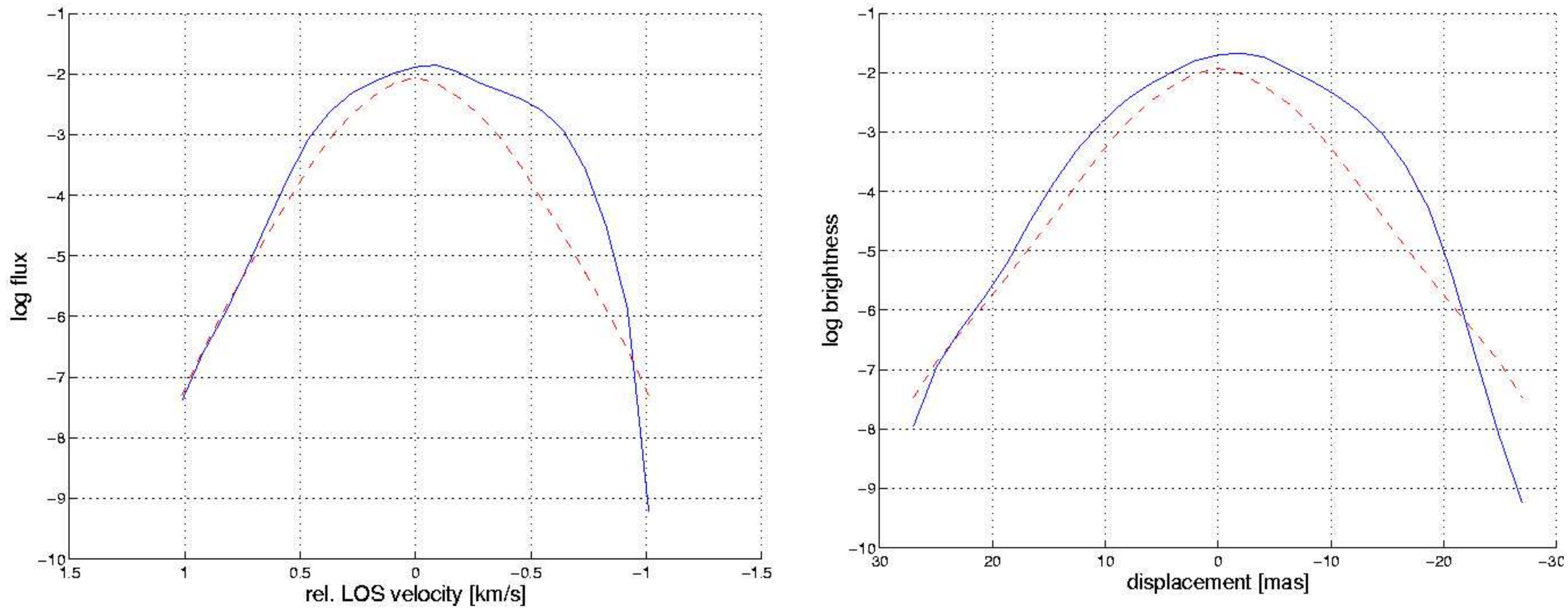






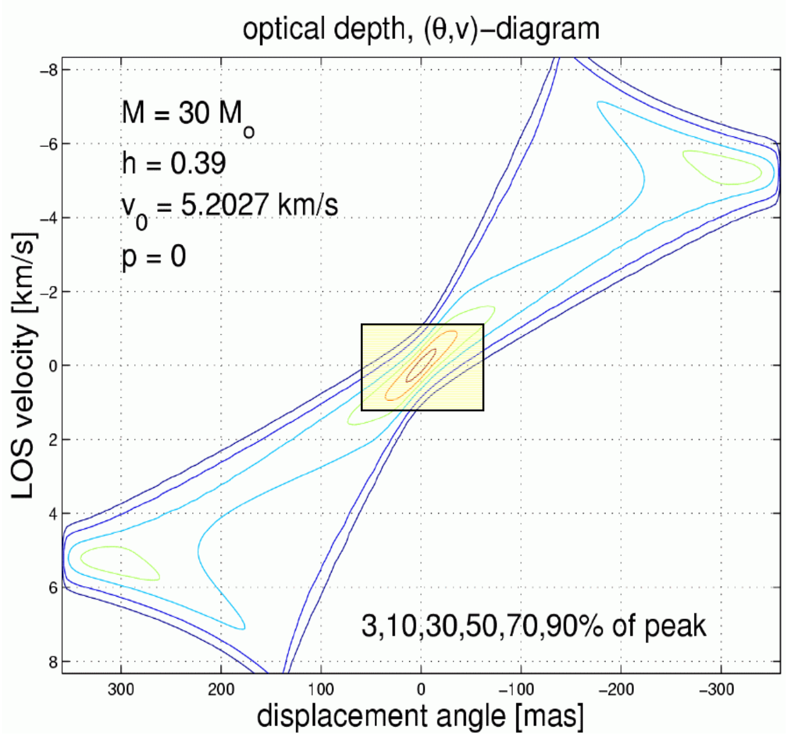
6.7 GHz fits


τ(θ,v)
Data
rel. LOS velocity [km/s]
displacement [mas]
Model
X² = 0.11677
Ω_m = 0.057073
h = 0.351
p = -0.5
displacement [mas]


log flux
rel. LOS velocity [km/s]
log brightness
displacement [mas]

Results

- $\Omega_m = ½(\Omega_i + \Omega_o) = 0.055$ km/s/mas
- $p = -0.5$
- $R_o/R_i = 2.9$
- $R_i, R_o = ?$

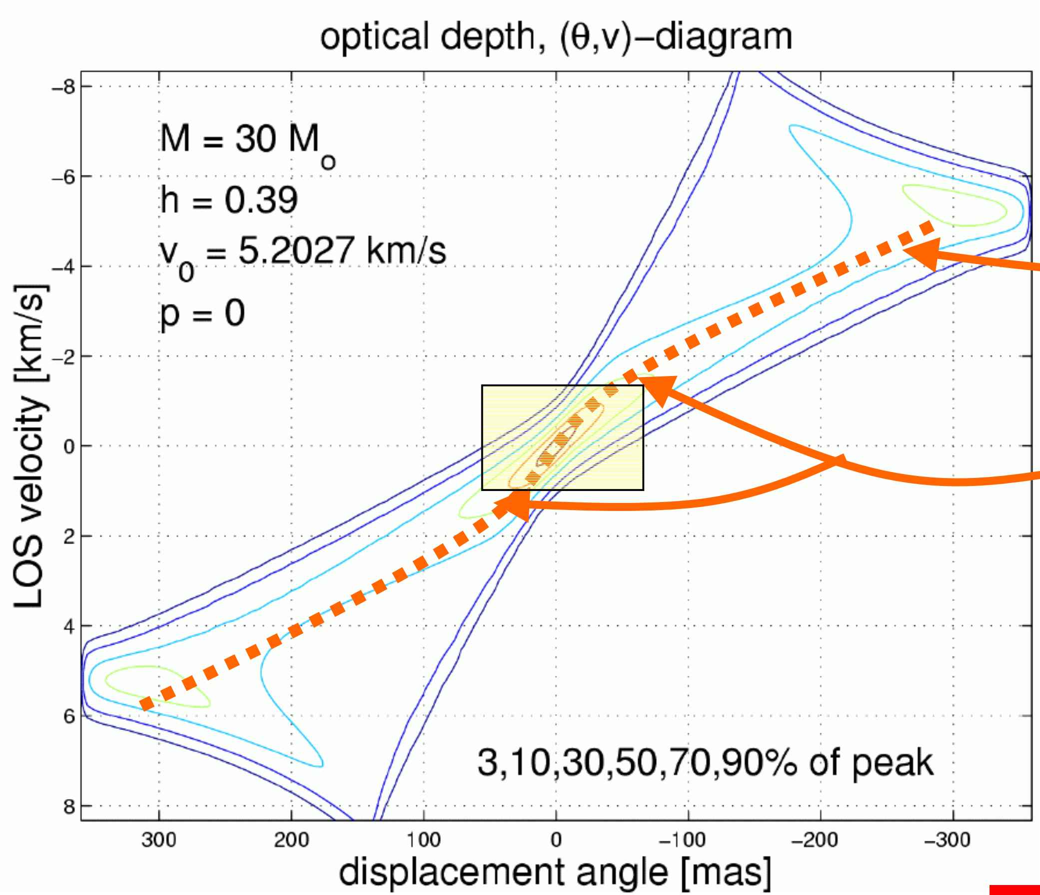


$\Omega = D(GM/R^3)^{½} \Rightarrow$

$M/R_o^3 = 30\ M_\odot/(750\ \mathrm{AU})^3$

$\tau = .7\tau_{peak} \Rightarrow I = 0.01\ I_{peak}$

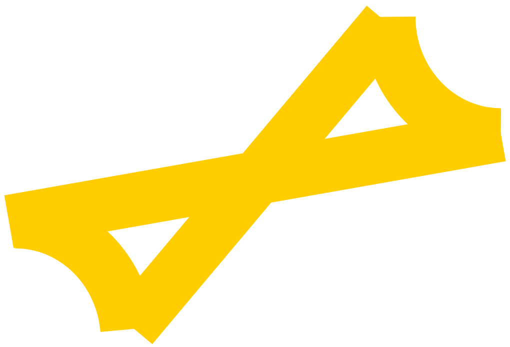
‘spine’, ‘kink’ & dynamic range



$$\frac{\partial}{\partial v}\tau(\theta, v)\Big|_{\theta} = 0$$

$$\theta_k = \frac{\Delta v_D}{\Omega_0}\,\frac{h^{3/2}}{1-h^{3/2}}$$

$$\tau = .7\tau_{peak} \;\Rightarrow\; I = 0.01\, I_{peak}$$



Protostellar Accretion Disks

- R ~ 10’s — 100’s AU
- M ~ .01 — .1 $M_{\odot}$

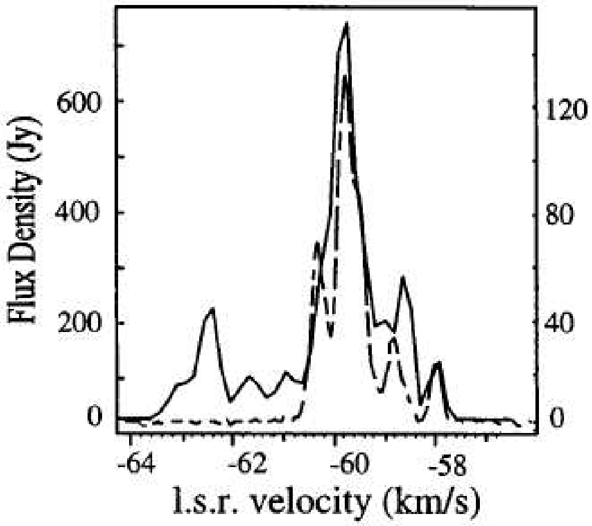
Observational Evidence:

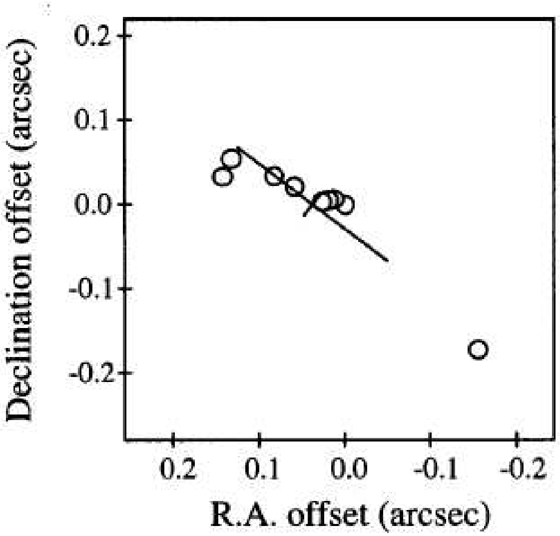
❾ T Tau stars (M $\leq$ 2 $M_{\odot}$)

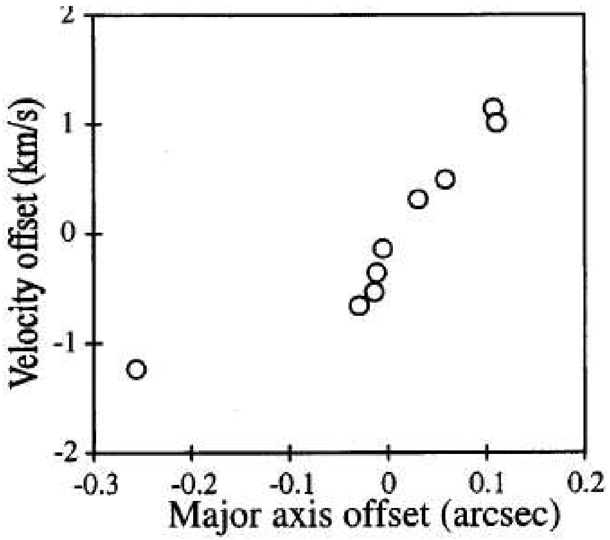
? Herbig Ae/Be stars
(2 $M_{\odot}$ $\leq$ M $\leq$ 10 $M_{\odot}$)

??? High mass (M $\geq$ 10 $M_{\odot}$)

Methanol Masers – Tracers of Circumstellar Disks?







6.7 GHz ————————

--------------- 12 GHz

Norris et al ‘98