dense ISM in ULIRG mergers : Arp 220 (and NGC 6240)

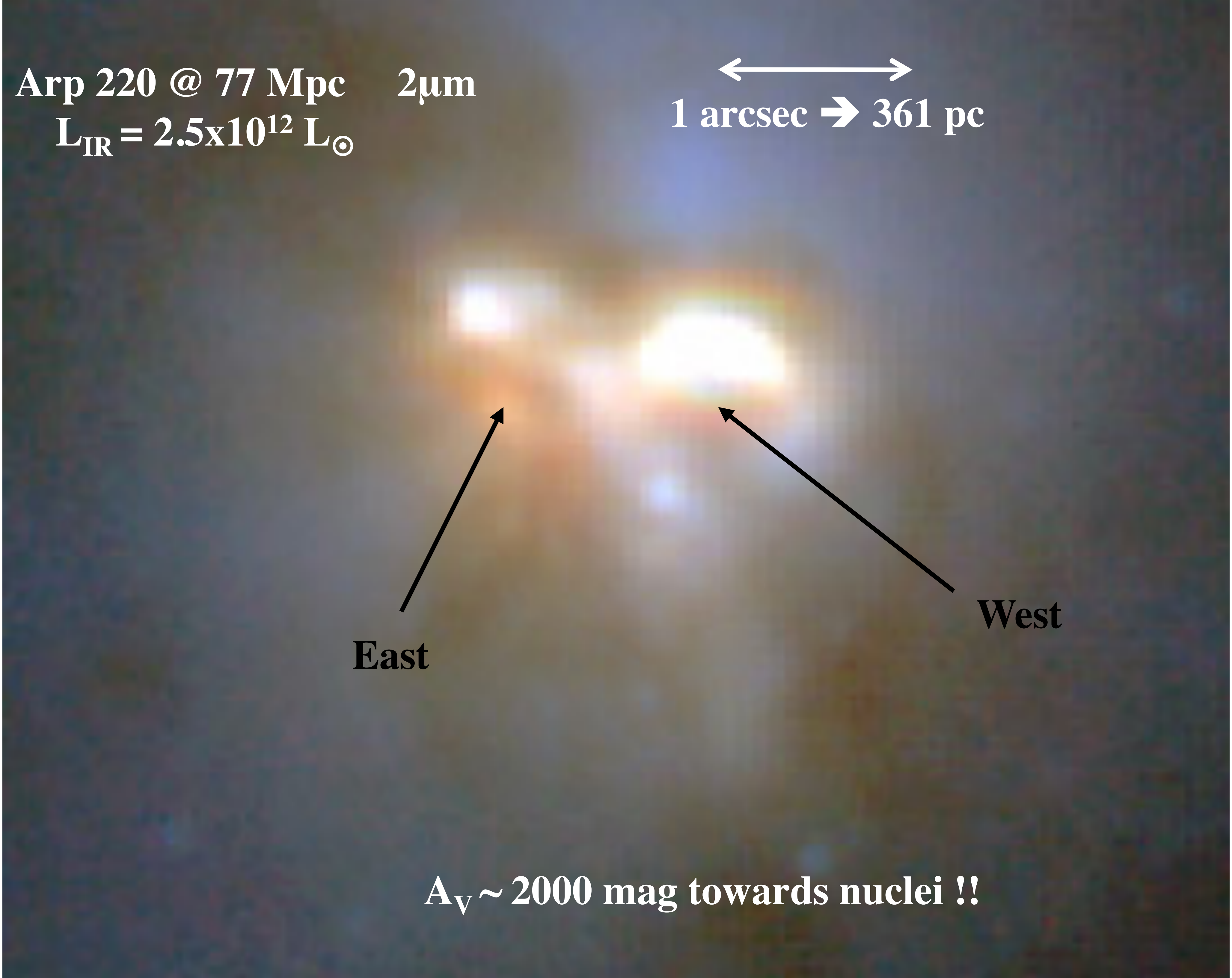
Cycle 0 ALMA --

Band 7 (0.5'') : HCN (4-3) , CS (7-6) , H26α
Band 9 (0.25'') : HCN (8-7)

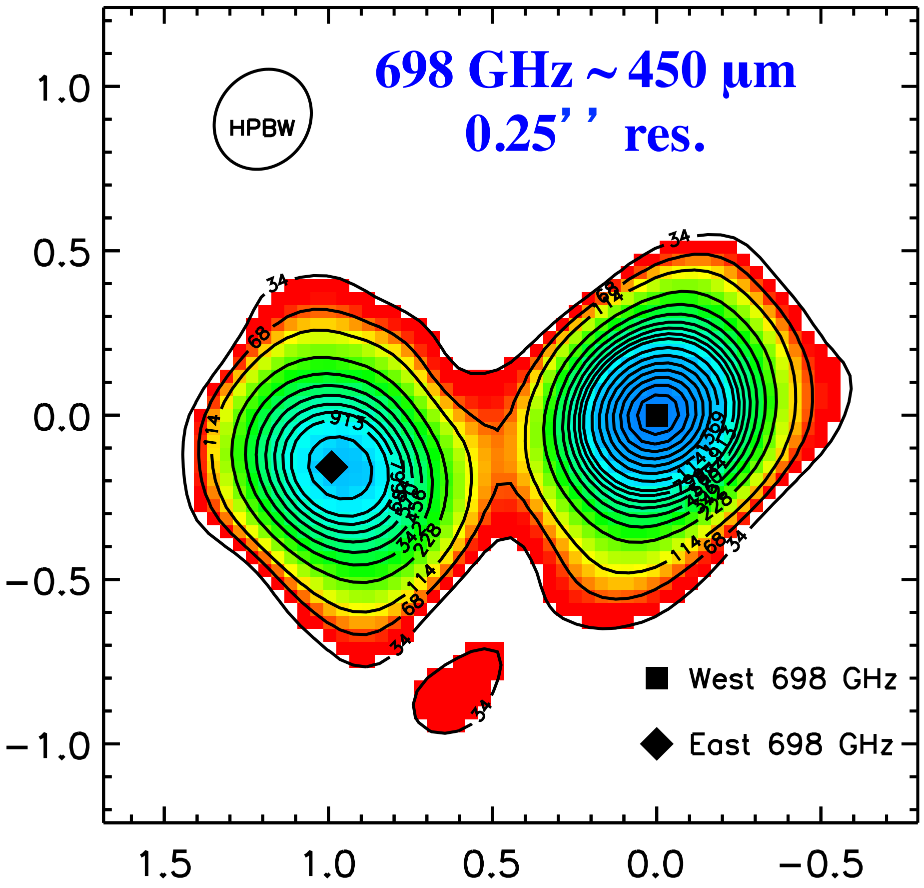
Cycle 1 ➔ Band 7 w/ 0.2''

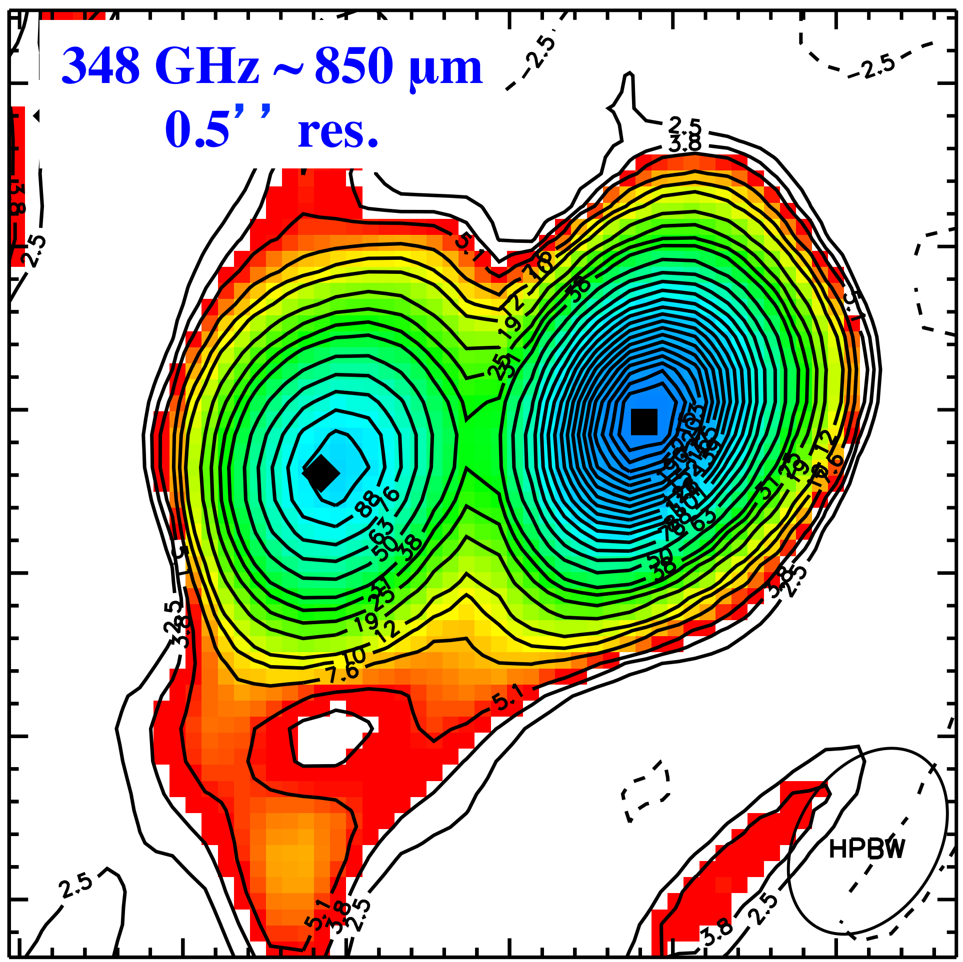
w/ K. Sheth, Manohar, Koda, Walter, Thompson, Barnes, Hernquist, Genzel, Robertson, van der Werf, Hayward, Narayanan, Brown, Tacconi, Fomalont, Sanders, Davies ApJ submitted

mass estimates – dust-based & dynamical
submm recomb lines – distinguishing SB & AGN
modeling of disks


Arp 220 @ 77 Mpc
2μm
L_IR = 2.5x10^12 L_⊙
1 arcsec → 361 pc
East
West
A_V ~ 2000 mag towards nuclei !!

Arp 220 dust continuum

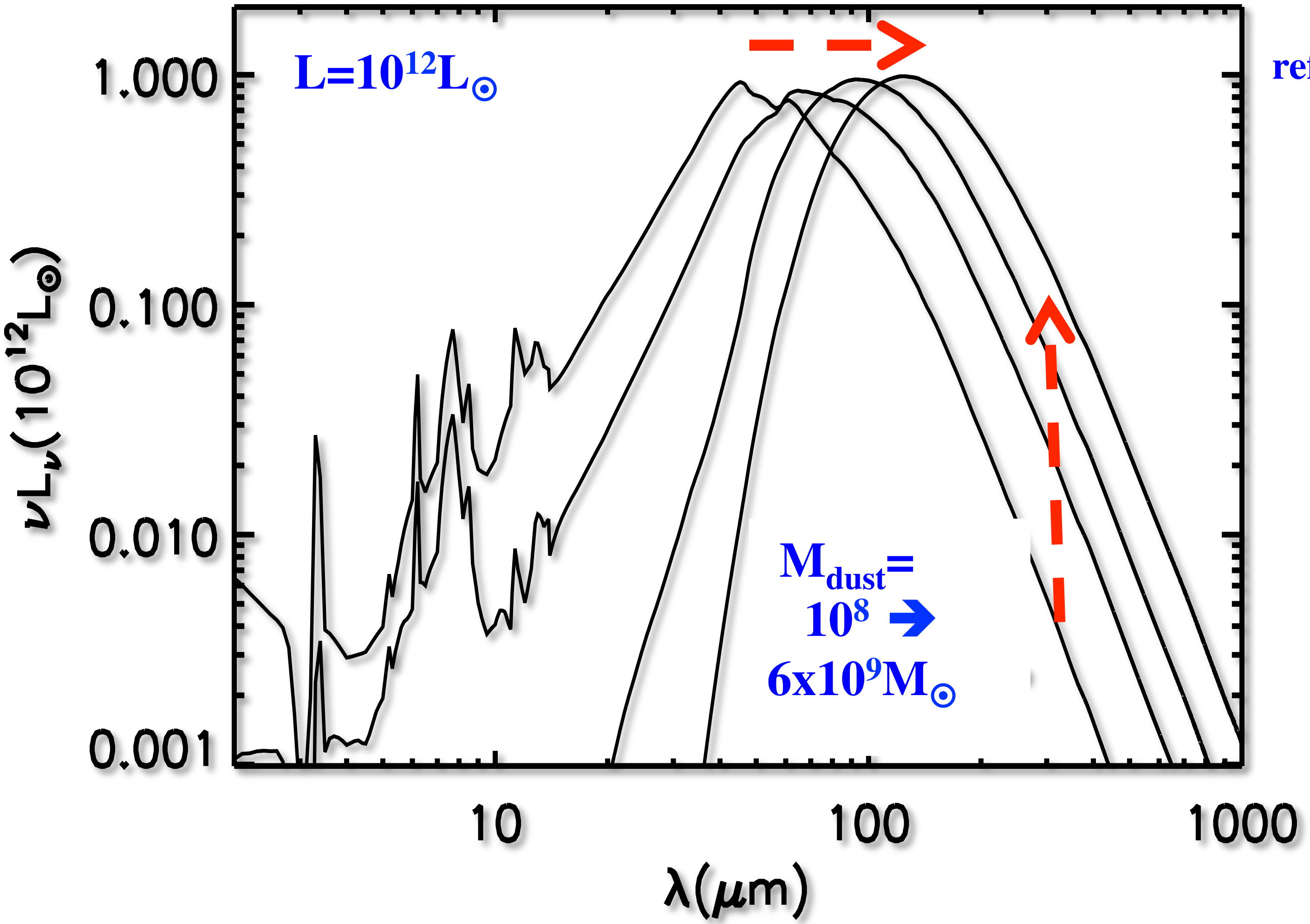




dust continuum
➔ISM mass

centrally heated dust cloud :

emitted SED as function of dust mass



ref.: Scoville, 2011 Canary I winter school lectures

models w/ increasing M_{dust}

- **peak shifts to longer λ for increased τ (or dust mass)**
- **flux on long λ tail scales linearly with M_{dust}**

R-J tail is optically thin,
therefore

$F_{RJ} = \varkappa_\nu \, T_{dust} \, \nu^2 \, M_{dust} \; / \; (4\pi d^2)$

$T_{dust} = 20\text{-}25$ K in Gal. SF ➔ little dep. on T_{dust}

if M_{ISM} / M_{dust} and $\varkappa_\nu$ are const. , F_{RJ} ➔ M_{ISM}

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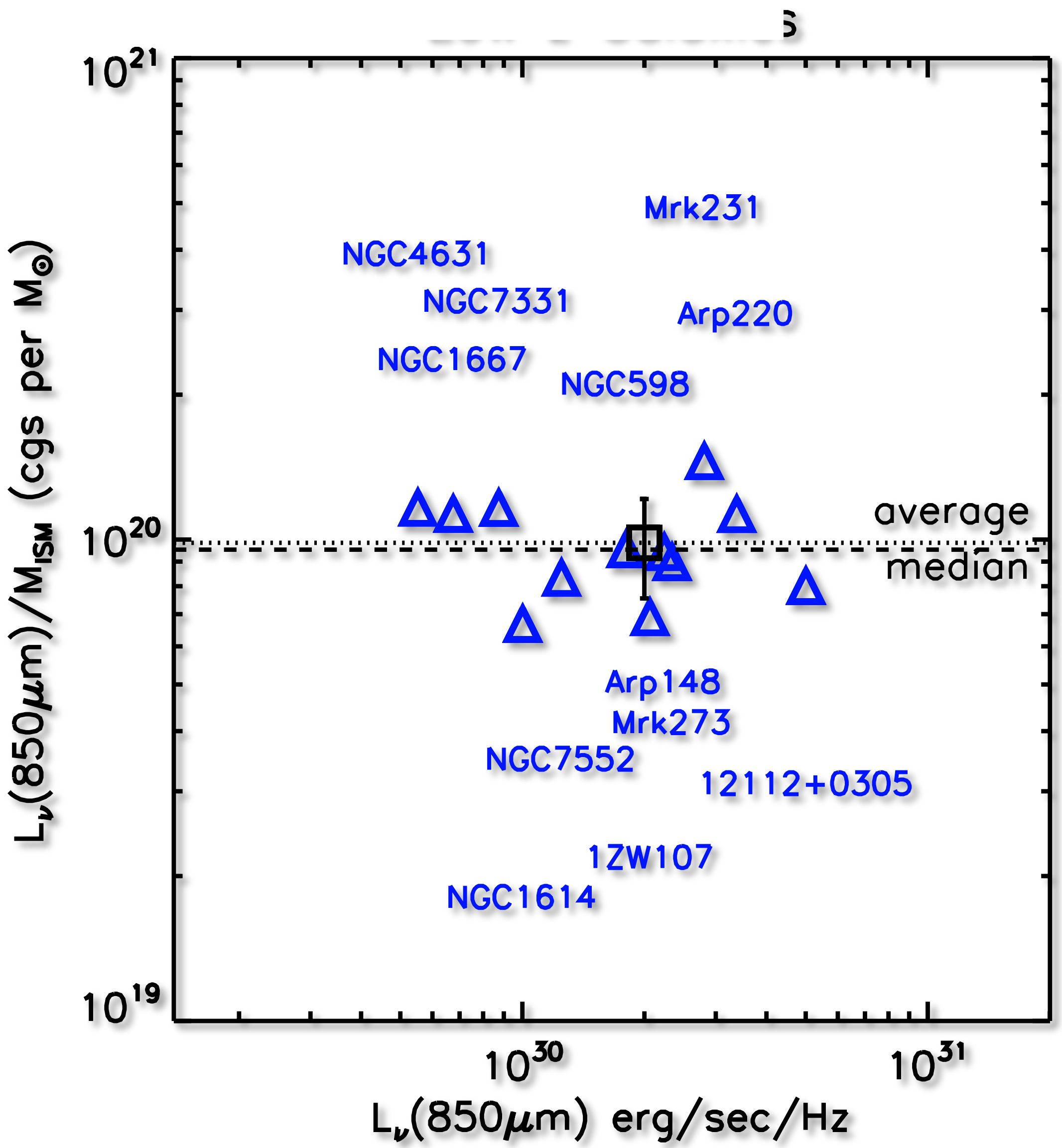
calibrate : $L_\nu / M_{ISM} = \langle \varkappa_\nu \, T_d \, M_{ISM} / M_{dust} \rangle$

local galaxies, Milky Way (Planck) & SMGs

local gal. w/ total 850μm fluxes & ISM masses



$1\mathrm{x}10^{20}$ erg/s/Hz/$M_\odot$

w/ less than factor 2 dispersion

Planck: Milky Way

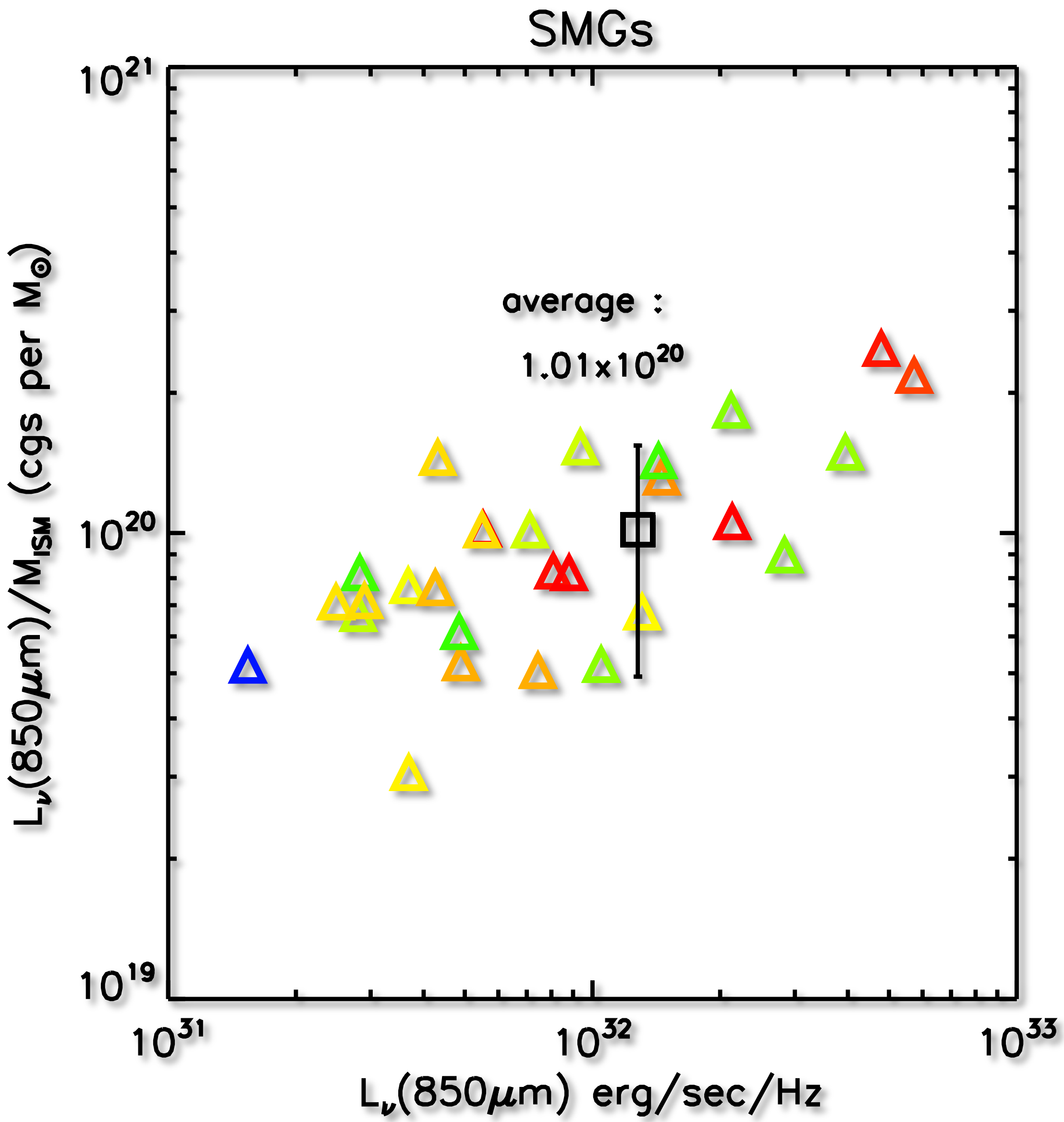
➔

$0.8\mathrm{x}10^{20}$ erg/s/Hz/$M_\odot$

$\beta = 1.8$ +- 0.1

850μm from Dale '05, Clements '09, Dunne & Eales '09)

z = 2 – 4 SMGs with CO (1-0) obs. :



➔ **same calibration as local gal. & MW**

ISM masses from RJ dust continuum :

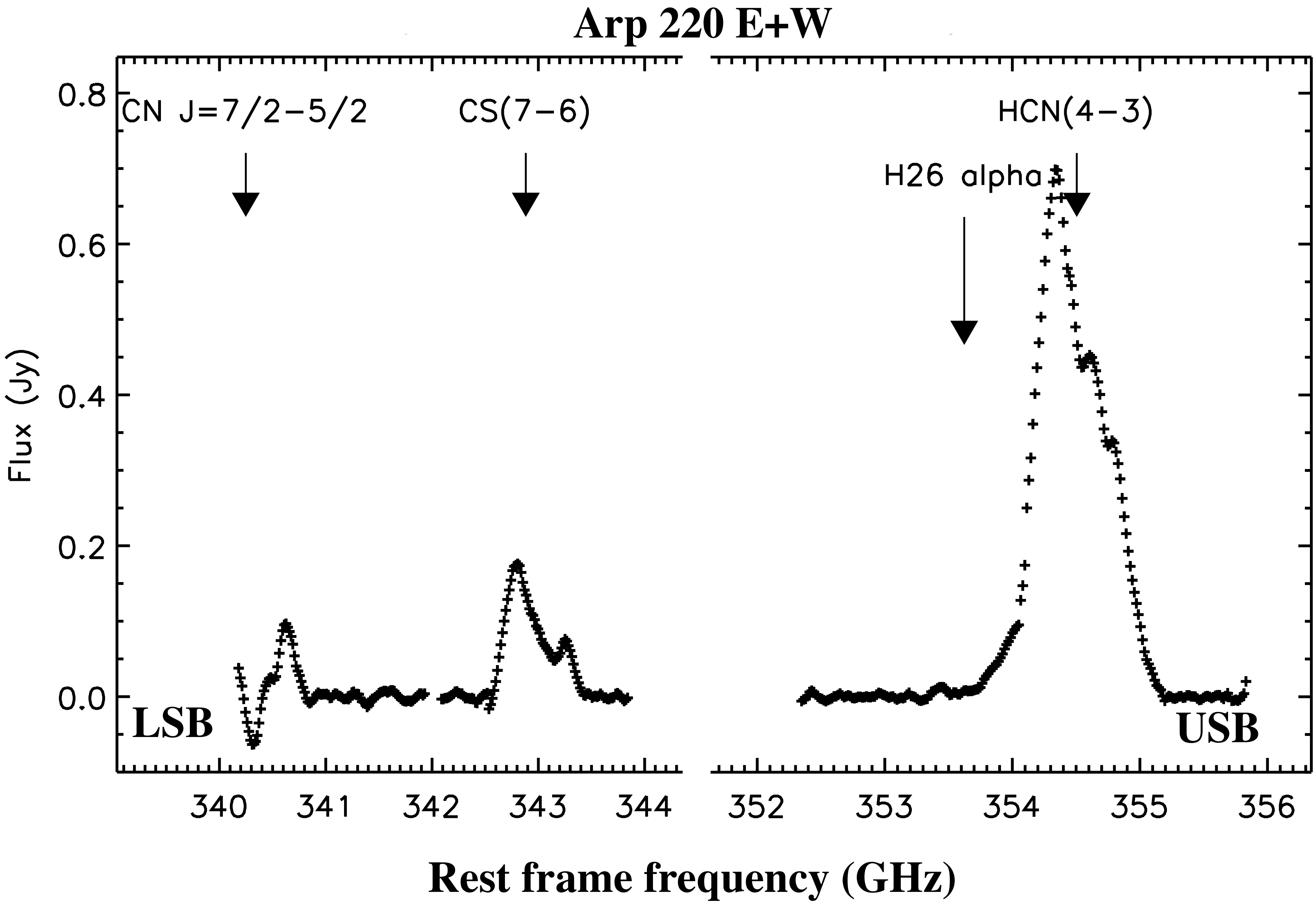
Scoville etal 2014, and Santini etal 2014 + friday talk

$$M_{ISM} = \frac{0.87\ S_\nu(\mathrm{mJy})d_{Gpc}^2}{(1+z)^{4.8}T_{25}\nu_{350}^{3.8}\Gamma_{RJ}} 10^{10} M_{sun}$$

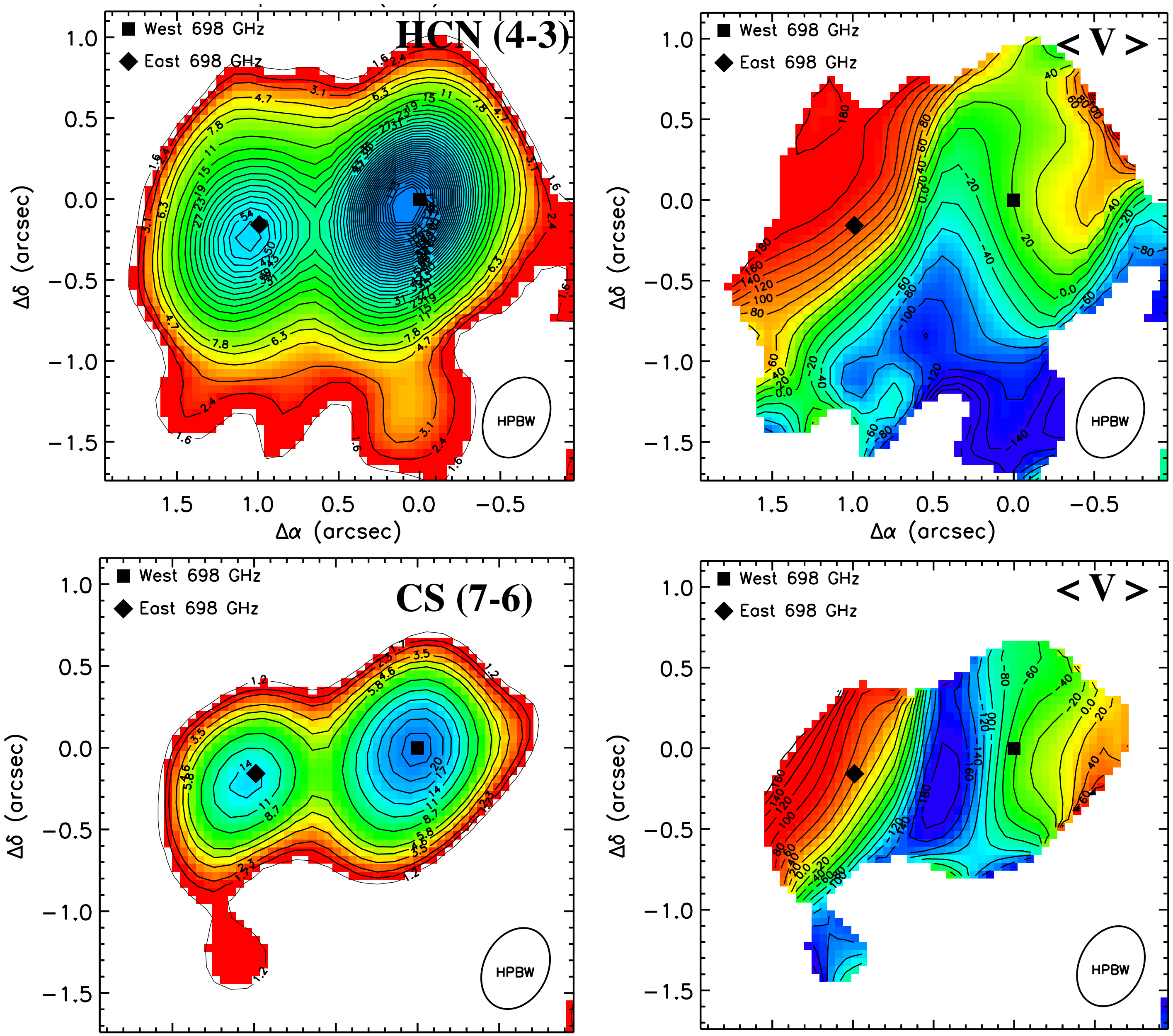
ISM Masses from Dust Continuum

Source	ν_{obs}	Flux	T_d a	Γ	Mass
	GHz	mJy	K		$10^9 M_\odot$
Arp 220 total	347.6	490	100	0.917	5.97
Arp 220 East	347.6	161	100		1.96
Arp 220 West	347.6	342	100		4.16
NGC 6240	693.5	126	25		1.64

lines ...


Arp 220 E+W
CN J=7/2-5/2
CS(7-6)
HCN(4-3)
H26 alpha
Flux (Jy)
0.8
0.6
0.4
0.2
0.0
LSB
USB
340
341
342
343
344
352
353
354
355
356
Rest frame frequency (GHz)

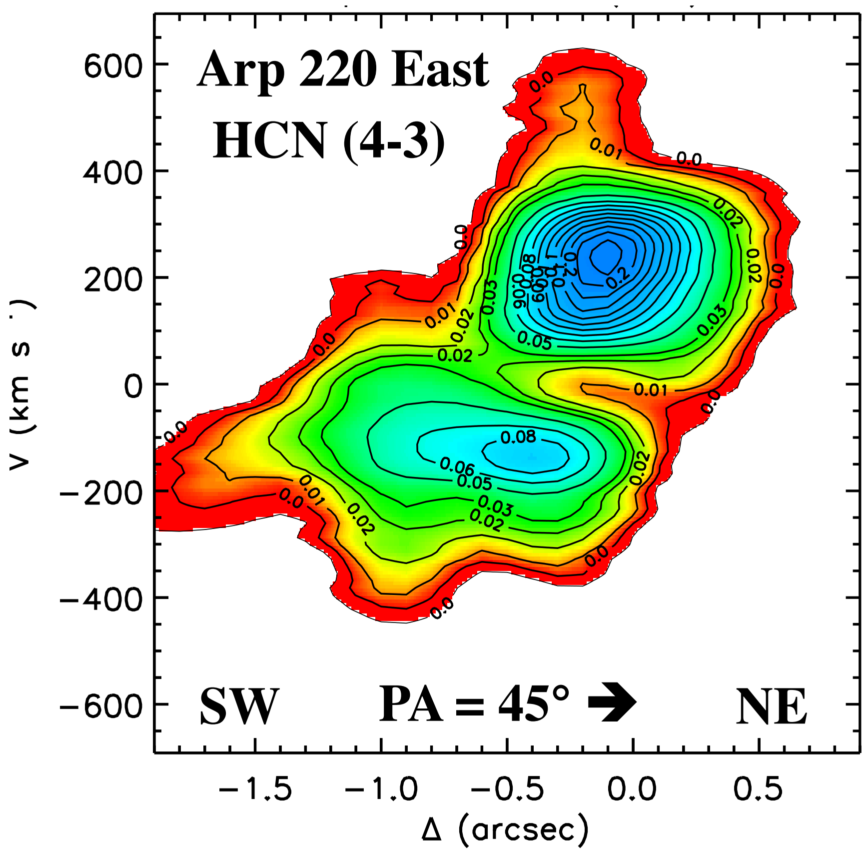
Arp 220



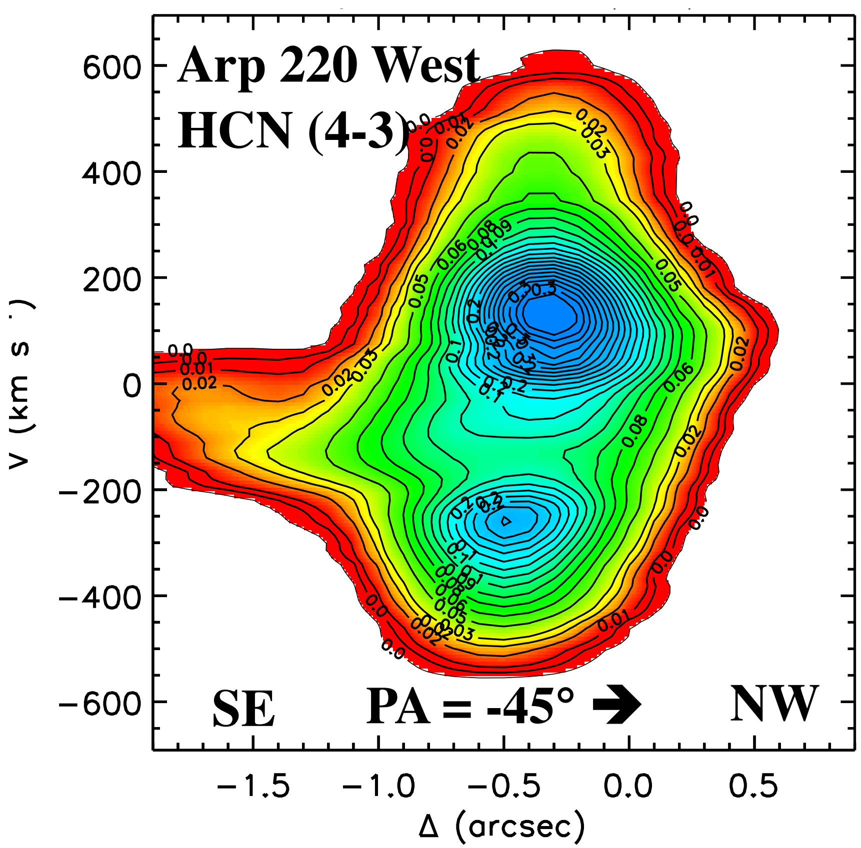
➔ counter-rotating disks (as in Sakamoto etal ‘98)

spatial – velocity strip maps along major axes

East



West



double Gaussian fits

Source		Beam major ″	Beam minor ″	Beam PA °	Deconvolved major ″	Deconvolved minor ″	Deconvolved T_B K
band 7 continuum							
Arp 220 W	continuum	0.60	0.42	-32.0	0.28	0.27	33
Arp 220 E	continuum	0.60	0.42	-32.0	0.37	0.27	11
Arp 220 W	continuum	0.52	0.39	-27.2	0.36	0.24	34
Arp 220 E	continuum	0.52	0.39	-27.2	0.38	0.32	9
band 9 continuum							
Arp 220 W	continuum	0.32	0.28	-38.6	0.23	0.19	148
Arp 220 E	continuum	0.32	0.28	-38.6	0.30	0.24	47
band 7 lines							
Arp220 W	CS (7 - 6)	0.60	0.42	-32.0	0.49	0.43	10
Arp220 E	CS (7 - 6)	0.60	0.42	-32.0	0.40	0.35	7
Arp220 W	HCN (4 - 3)	0.52	0.39	-27.2	0.57	0.41	39
Arp220 E	HCN (4 - 3)	0.52	0.39	-27.2	0.58	0.45	21

Dust : major axis radius ~ 0.12'' ➔ 40 pc

T_B ~ 148 & 47 K (450 µm)

HCN : major axis radius ~ 0.25'' ➔ 90 pc

T_B ~ 40 K

kinematic modeling

use kinematic deconvolution algorithm

Scoville, Young & Lucy '83

if vel. field known,

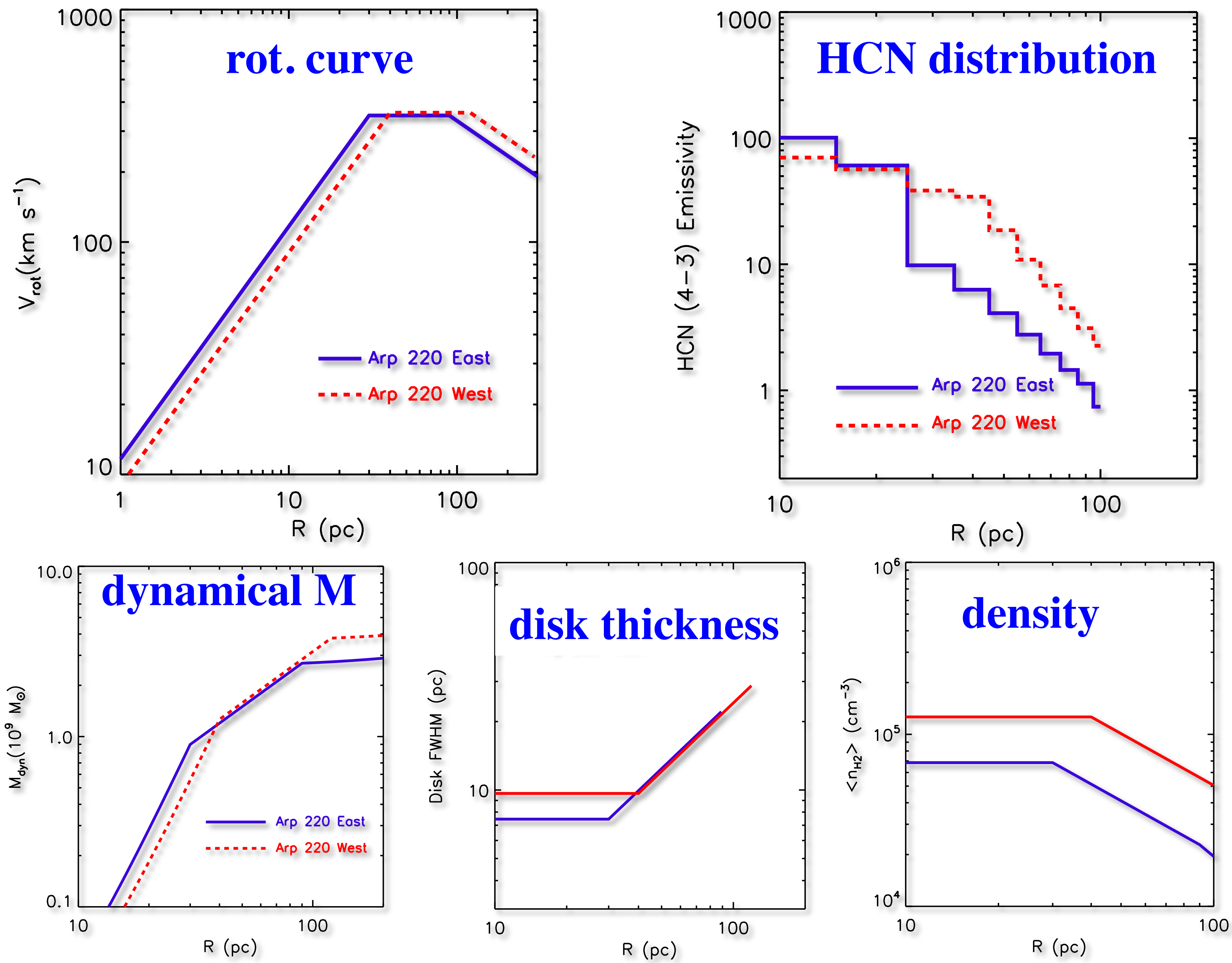
use observed line profiles

➔ super resolution much better than beam width

solve for rot. curve and emissivity (r)

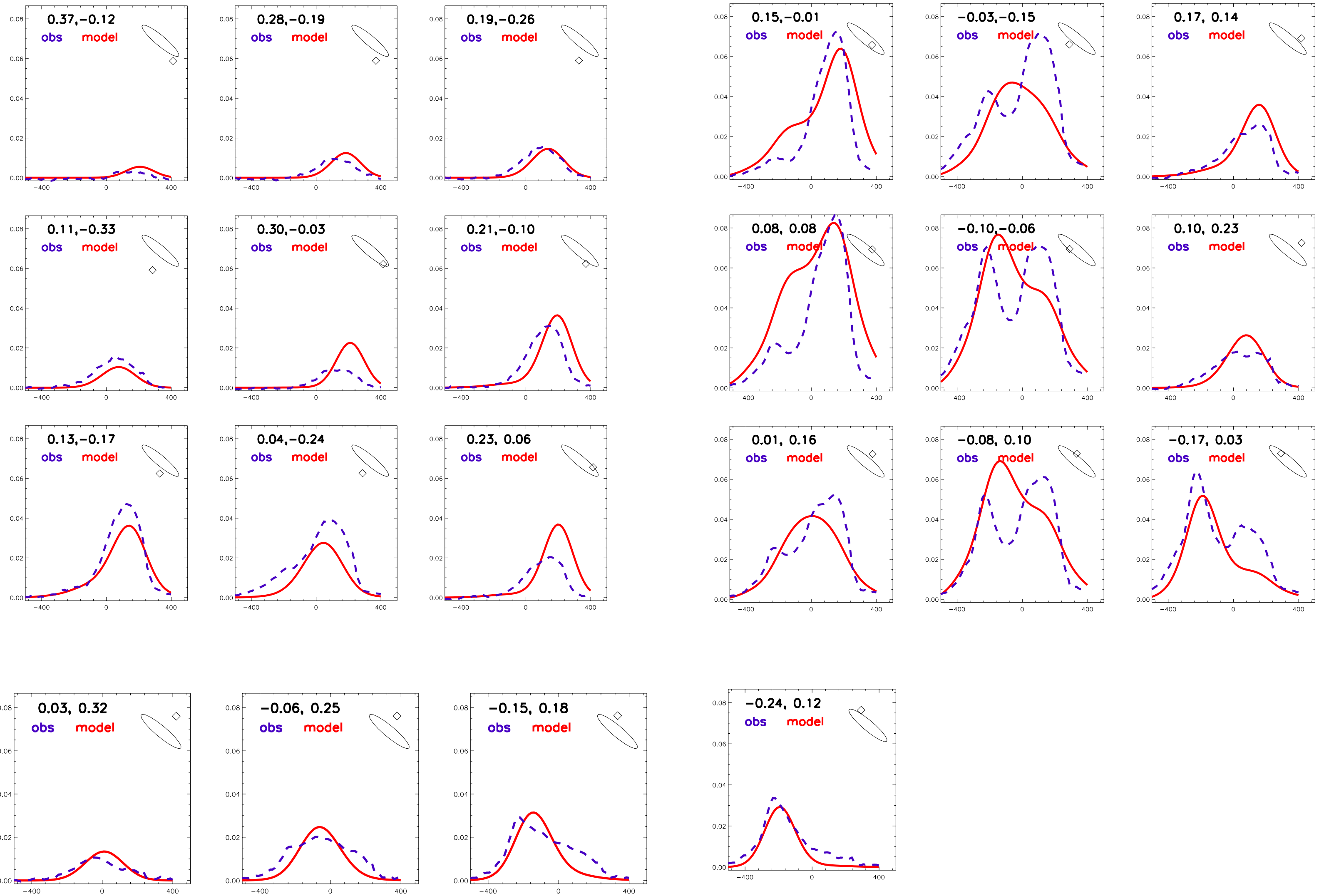
which give best fit between obs. and model line profiles

similar to doppler radar imaging of planets



rot. curve
Vrot(km s−1)
1000
100
10
1
10
100
R (pc)
Arp 220 East
Arp 220 West
HCN distribution
HCN (4−3) Emissivity
1000
100
10
1
10
100
R (pc)
Arp 220 East
Arp 220 West
dynamical M
Mdyn(10^9 M⊙)
10.0
1.0
0.1
10
100
R (pc)
Arp 220 East
Arp 220 West
disk thickness
Disk FWHM (pc)
100
10
10
100
R (pc)
density
<nH2> (cm−3)
10^6
10^5
10^4
10
100
R (pc)

Arp 220 East observed and model spectra

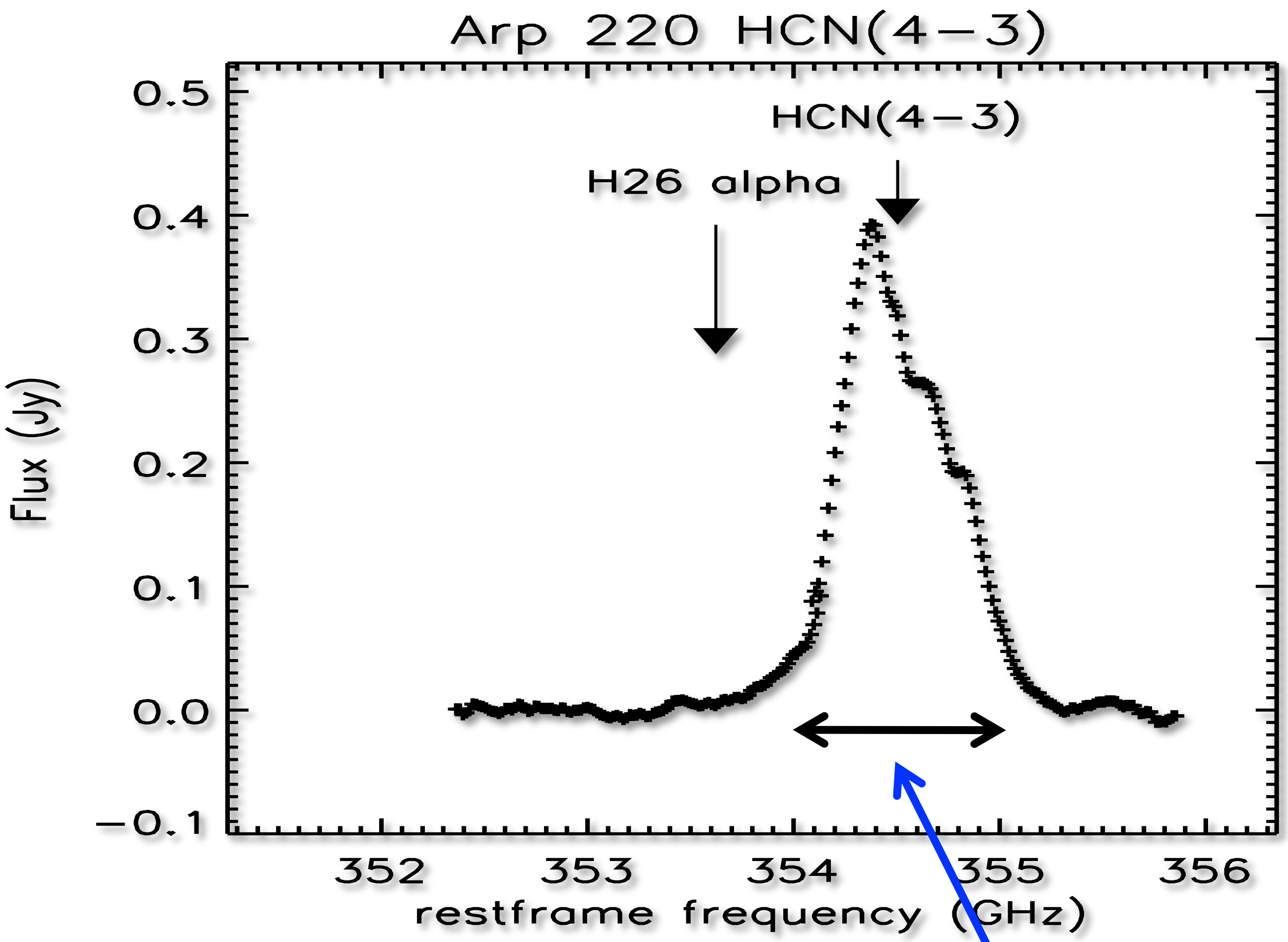


...diagnosing AGN vs Starbursts in dust obscured sources

how to tell AGN vs SB ??

diagnosing AGN vs Starburst Power

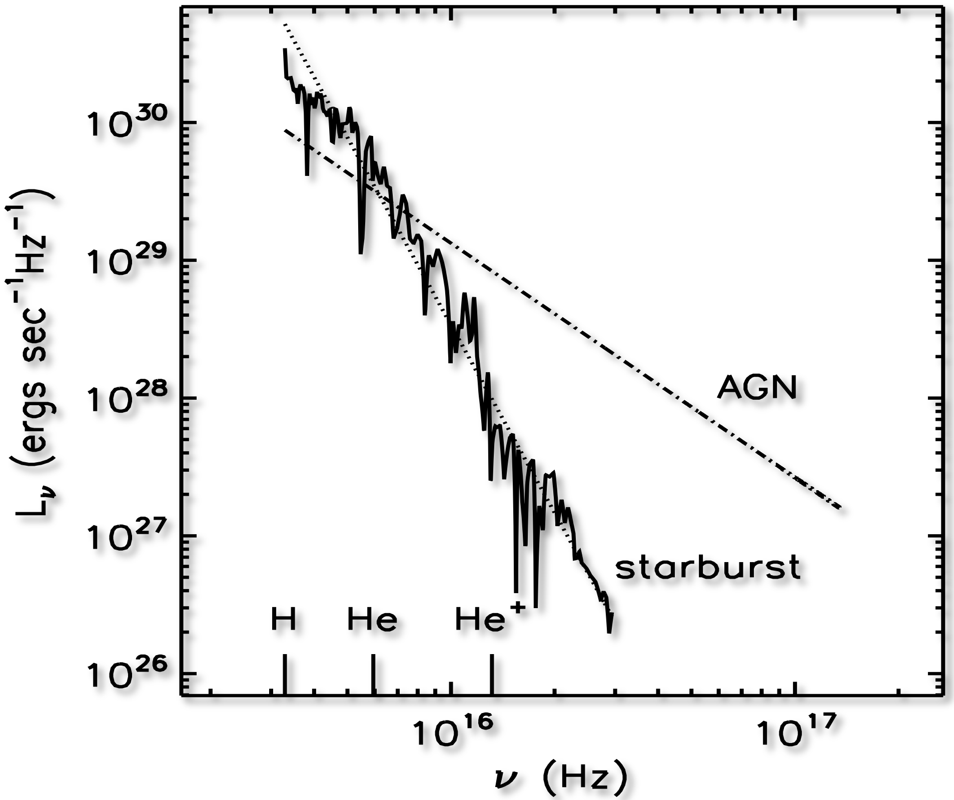
ALMA Band 7 -- 350 GHz integrated spectra



1000 km s^{-1}

diagnosing AGN vs Starburst Power

long standing issue with ULIRGs – AGN vs SB ??
ALMA can discriminate !!

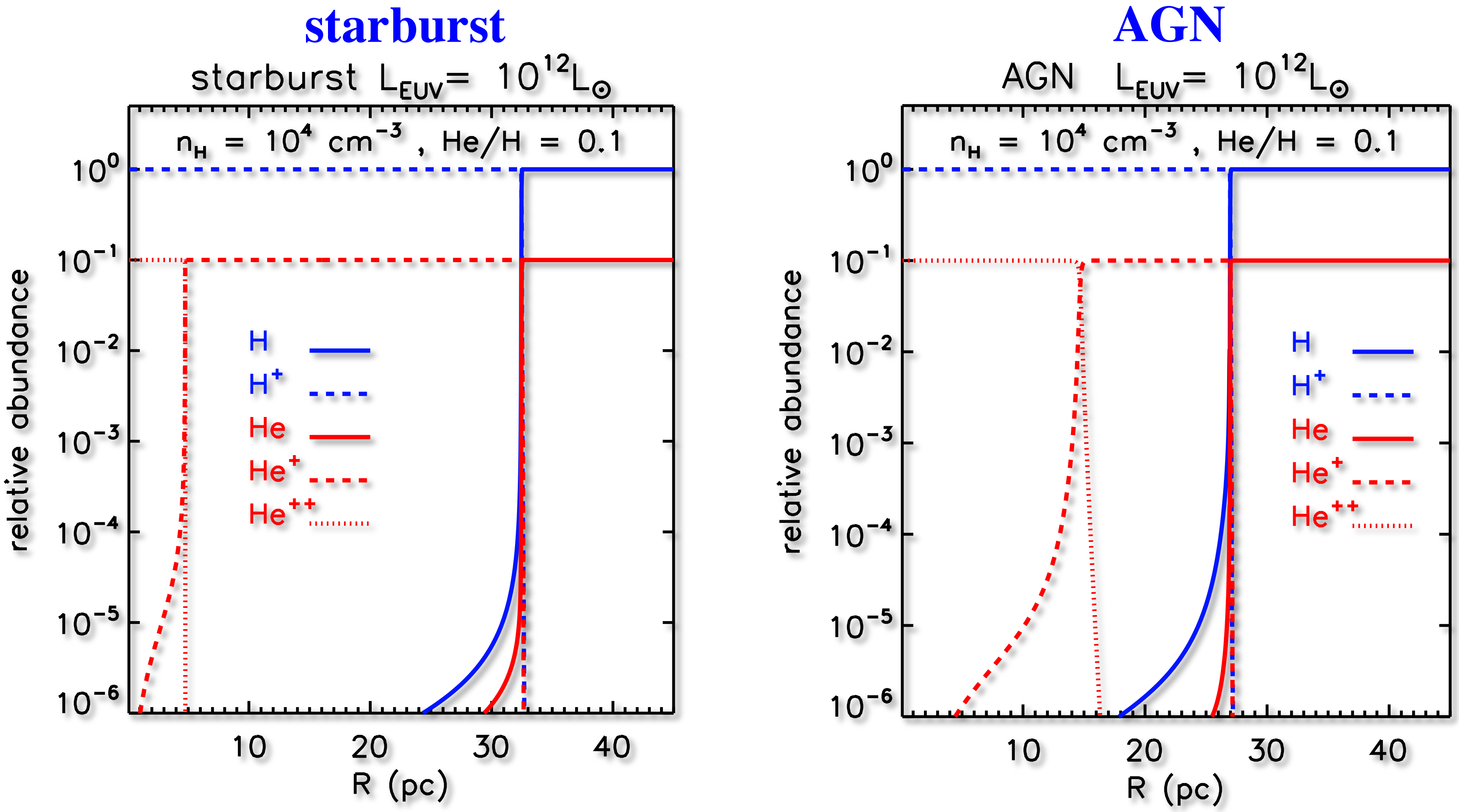


EUV spectra of SB & AGN are very different !!

H vs He$^+$ submm recomb. lines

Scoville & Murchikova '13 (ApJ)

ionization equilibrium :



➔ He^{++} / H^+ changes by 20x

relative strength of HI & HeII submm lines

quite independent of n_e & T_e

don't expect maser amplification

➔ lines fluxes ➔ UV luminosity & UV hardness

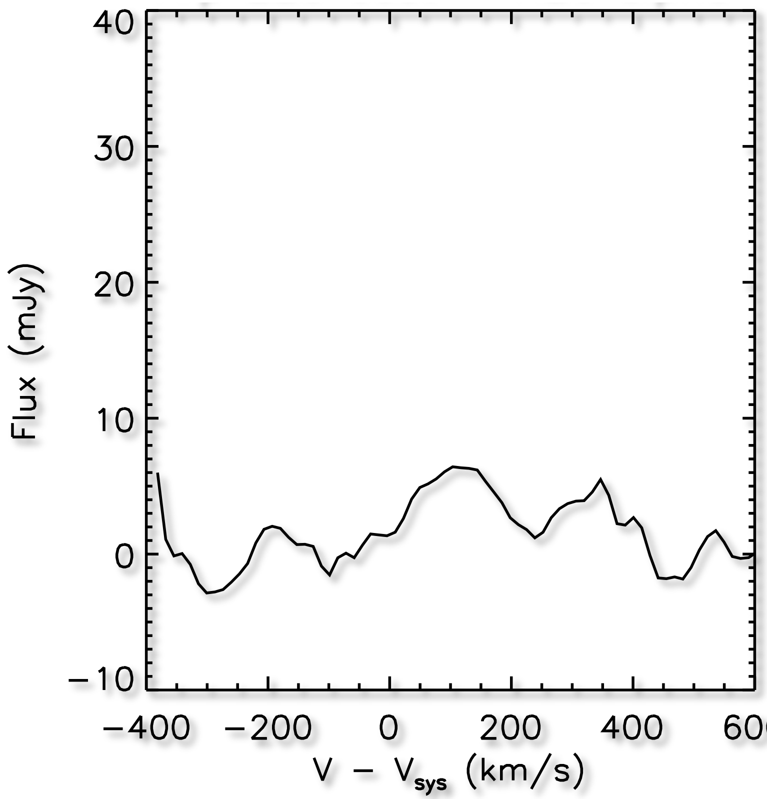
HI and HeII submm lines w/i single ALMA obs.

HI $n\alpha$	ν GHz	HeII $n\alpha$	ν (GHz) GHz	$\Delta\nu$ (GHz) GHz	ϵ_{HI} erg sec^{-1} cm^3	ϵ_{HeII} erg sec^{-1} cm^3
20	764.230	32	766.940	-2.710	1.21×10^{-30}	4.45×10^{-30}
21	662.404	34	641.108	21.296	9.05×10^{-31}	3.09×10^{-30}
22	577.896	35	588.428	-10.531	6.85×10^{-31}	2.59×10^{-30}
23	507.175	37	499.191	7.985	5.25×10^{-31}	1.85×10^{-30}
24	447.540	38	461.286	-13.746	4.06×10^{-31}	1.57×10^{-30}
25	396.901	40	396.254	0.647	3.17×10^{-31}	1.15×10^{-30}
26	353.623	42	342.894	10.729	2.50×10^{-31}	8.47×10^{-31}
27	316.415	43	319.781	-3.366	1.99×10^{-31}	7.32×10^{-31}
28	284.251	45	279.432	4.818	1.60×10^{-31}	5.50×10^{-31}
29	256.302	46	261.787	-5.485	1.29×10^{-31}	4.79×10^{-31}
30	231.901	48	230.713	1.187	1.05×10^{-31}	3.67×10^{-31}
31	210.502	50	204.370	6.132	8.67×10^{-32}	2.83×10^{-31}
32	191.657	51	192.693	-1.036	7.18×10^{-32}	2.48×10^{-31}

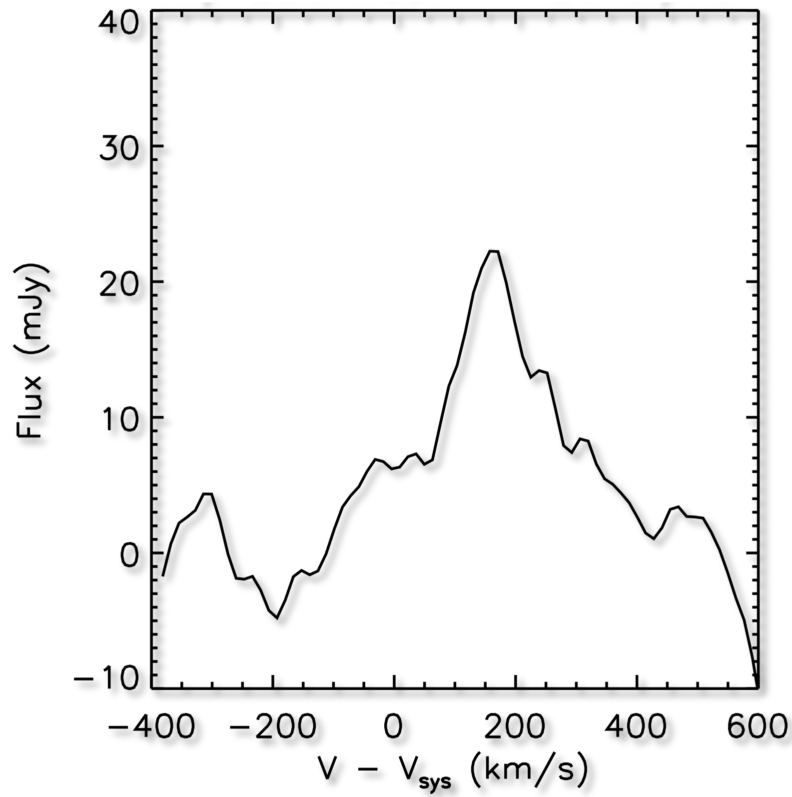
Scoville & Murchikova '13 (ApJ)

H 26α – a new probe of dust obscured SF !!

Arp 220 East



West



H 26α : 4 Jy km/s

low-n recomb. line flux ➔HII emission measure (n^2 x volume)

➔Lyc ν

4 Jy km/s ➔ 140 $M_\odot$ / yr

how much does α_{CO} change in ULIRGs ??

Arp 220 – CO and Dust Masses

	$S_{2-1}\Delta V$	$S_{1-0}\Delta V$	$ISM(CO)$	$ISM(dust)$
			$10^9 M_\odot$	$10^9 M_\odot$
East	120	30 – 46	3.9 – 6.0	2.0
West	187	47 – 72	6.0 – 9.2	4.2

using Galactic α_{CO}

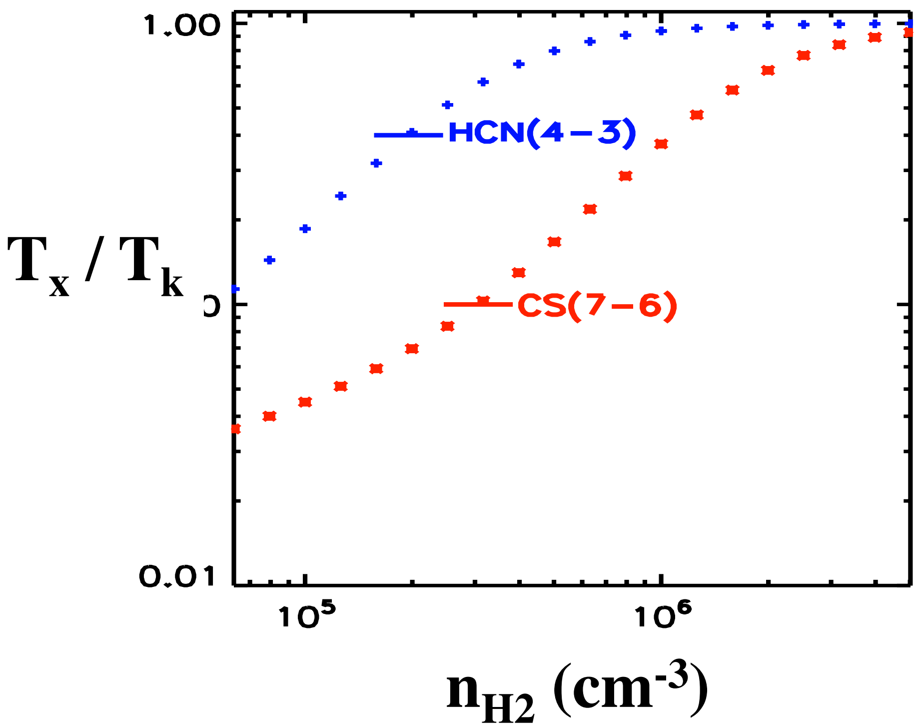
➔ CO-to-H_2 conversion factor only different by 2-3x densities from excitation of HCN (4-3) and CS (7-6) :

for optically thin lines, $n_{H2\ crit} > A/\langle\sigma v\rangle$

for thick lines, $A \rightarrow A\,\beta_{escape} \sim A/\tau$ w/ $\tau \propto A$

$\rightarrow$ $n_{H2\ crit} > A\beta / \langle\sigma v\rangle$ $\rightarrow$ reduced by τ

$\rightarrow$ $n_{H2\ crit}$ indep. of A !!



$\rightarrow$ HCN 3-2 and CS 7-6

~ 2-4 x 10^5 cm^{-3}

Arp 220 nuclei at radiation pressure limit for dust

Scoville 2001, 2003, Thompson+ 2005, Murray+3005

for self-gravitating sphere or disk,

$f_{rad} / g = \varkappa/c \, \Sigma_L / 4 \pi G \Sigma_M > 1$ if

Σ_L / Σ_M or $L/M > 500 \, L_\odot / M_\odot$

Arp 220 – $L / M \sim 2x10^{12} / 4x10^9 = 500 \, L_\odot / M_\odot$

➔ self-regulating SB

Edd. ratio increases to smaller r since rad. is harder

ULIRGs w/ ALMA :

probe ISM mass using RJ dust continuum
optically thin

use line profile modeling for super-resolution

submm H & He+ recomb. lines w/ ALMA
➔ dust obscured SF & AGN
(no metallicity and density dependence)

radii ~ 25 – 50 pc !! , M ~ 2-4x10^9 $M_\odot$, mostly gas
densities ~ 10^5 cm^{-3} (from dust, HCN, CO and grav.)

ALMA is revolutionary !!