Galaxy Evolution

interstellar matter (ISM) drives galaxy evolution, but ···

SFR evolution driven by gas supply ??

starburst vs main sequence ??

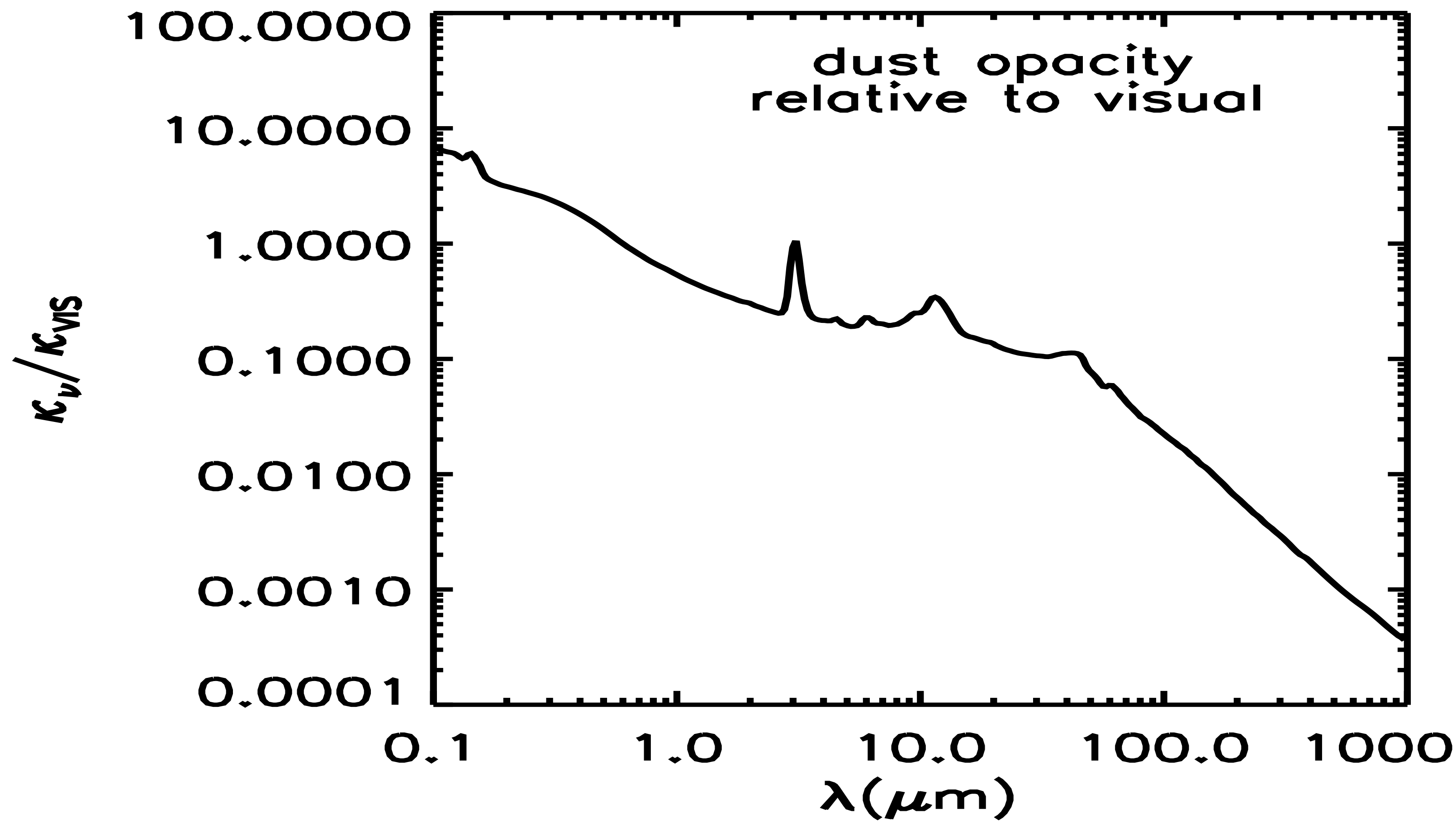
need to measure the mass of ISM gas or dust

CO / long λ dust em.

w/ ALMA ➔ high J CO ??

physical understanding of RJ

dust in rad. equil. -- heated by photons from :
stars + AGN
other dust, ie. secondary photons



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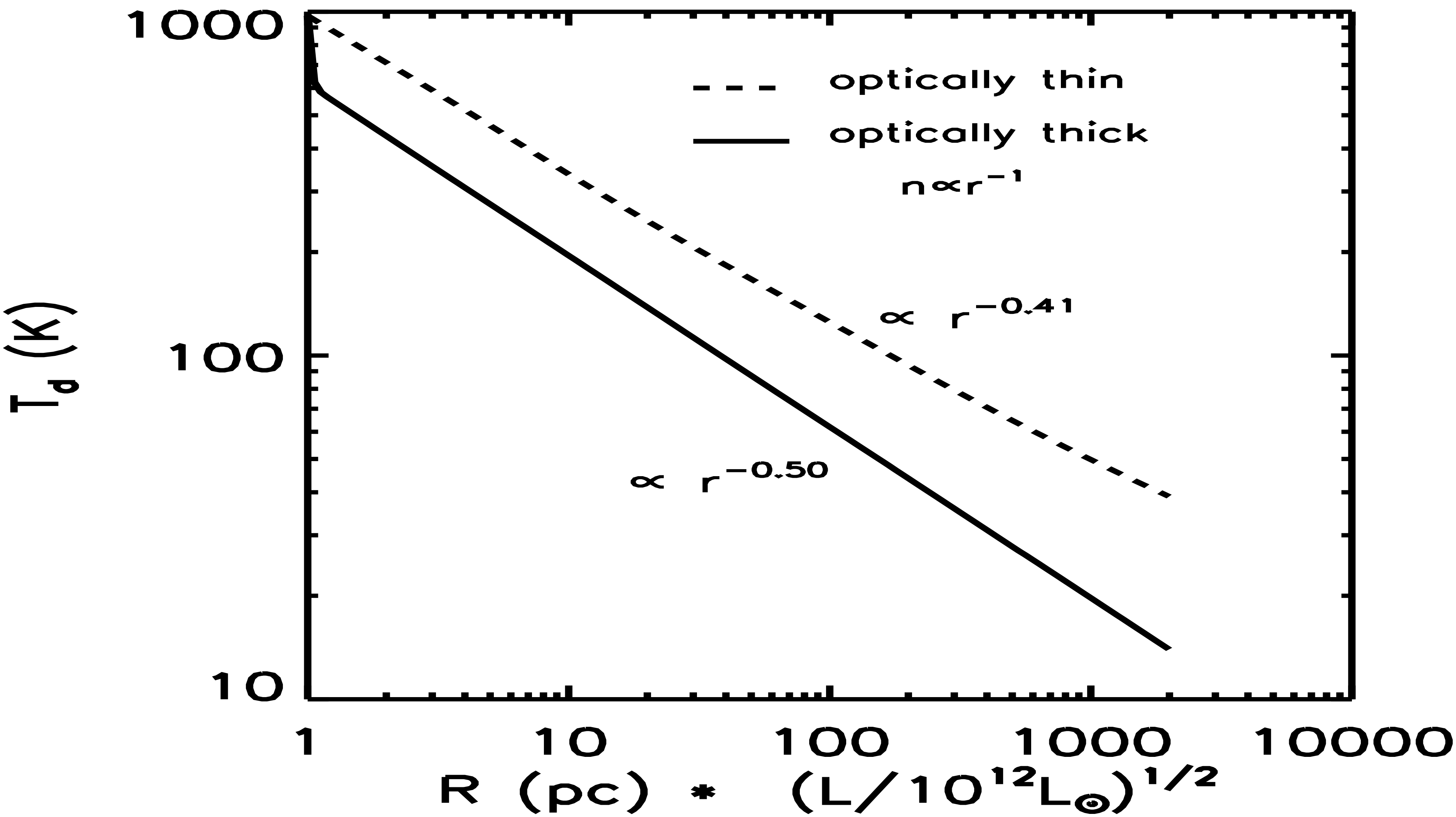
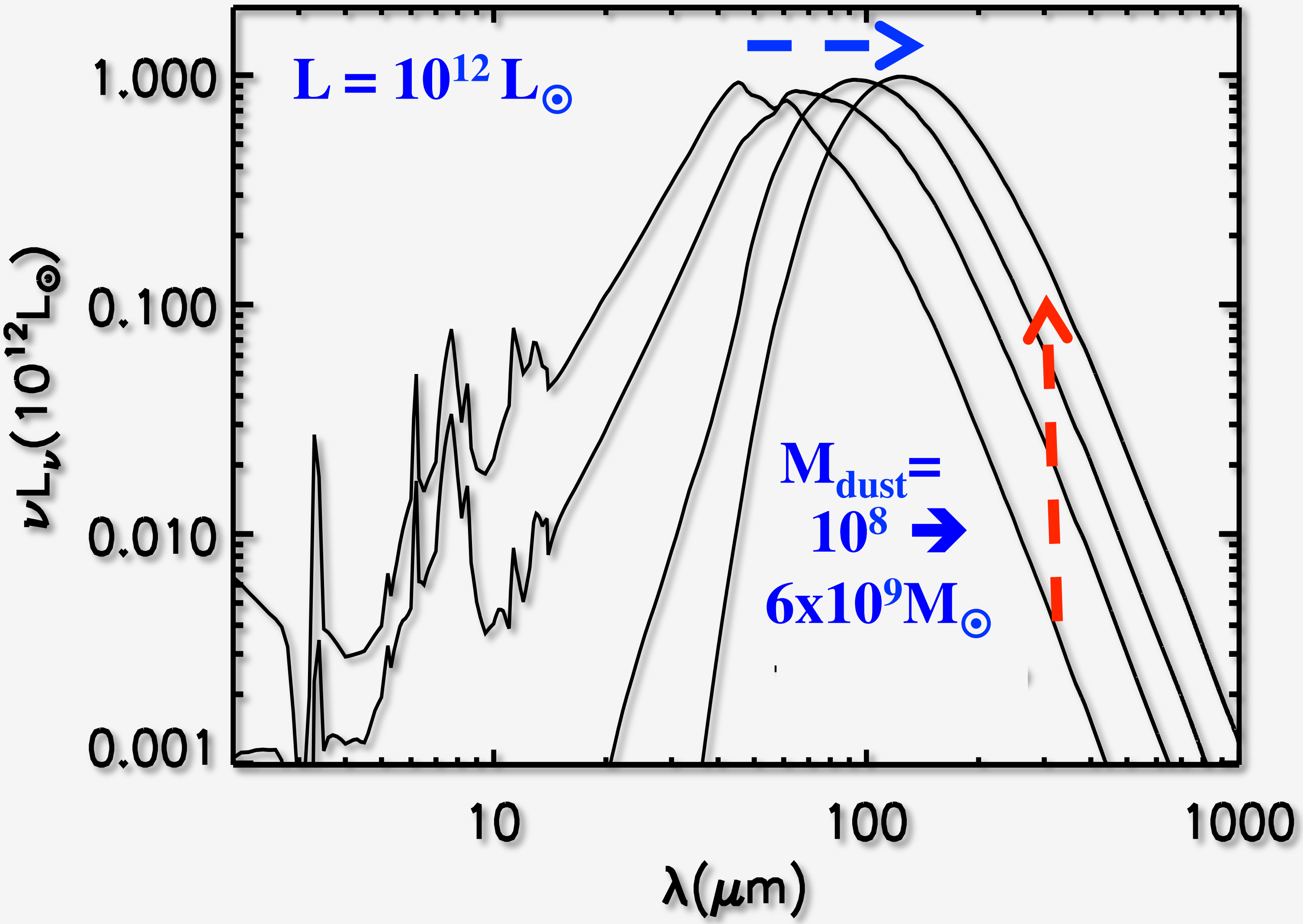


dust cloud spectrum -- w/ increasing M_{dust}



Scoville, 2011 Canary Is. winter school lectures

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

RJ dust continuum optically thin,

$$L_\nu \propto T_D \kappa_\nu \frac{\text{dust}}{\text{gas}} M_{gas}$$

empirically calibrate

w/ low z normal galaxies and ULIRGs + high z SMGs

What T_D ?

➔ adopt simple constant 25 K

regions of higher T relatively small frac. of mass

Orion GMCs
Lombardi etal 2014

Auriga-California GMC
Harvey etal 2013
only 2% of mass in high T (25 K) region of LkHα 101
most at ~15 K

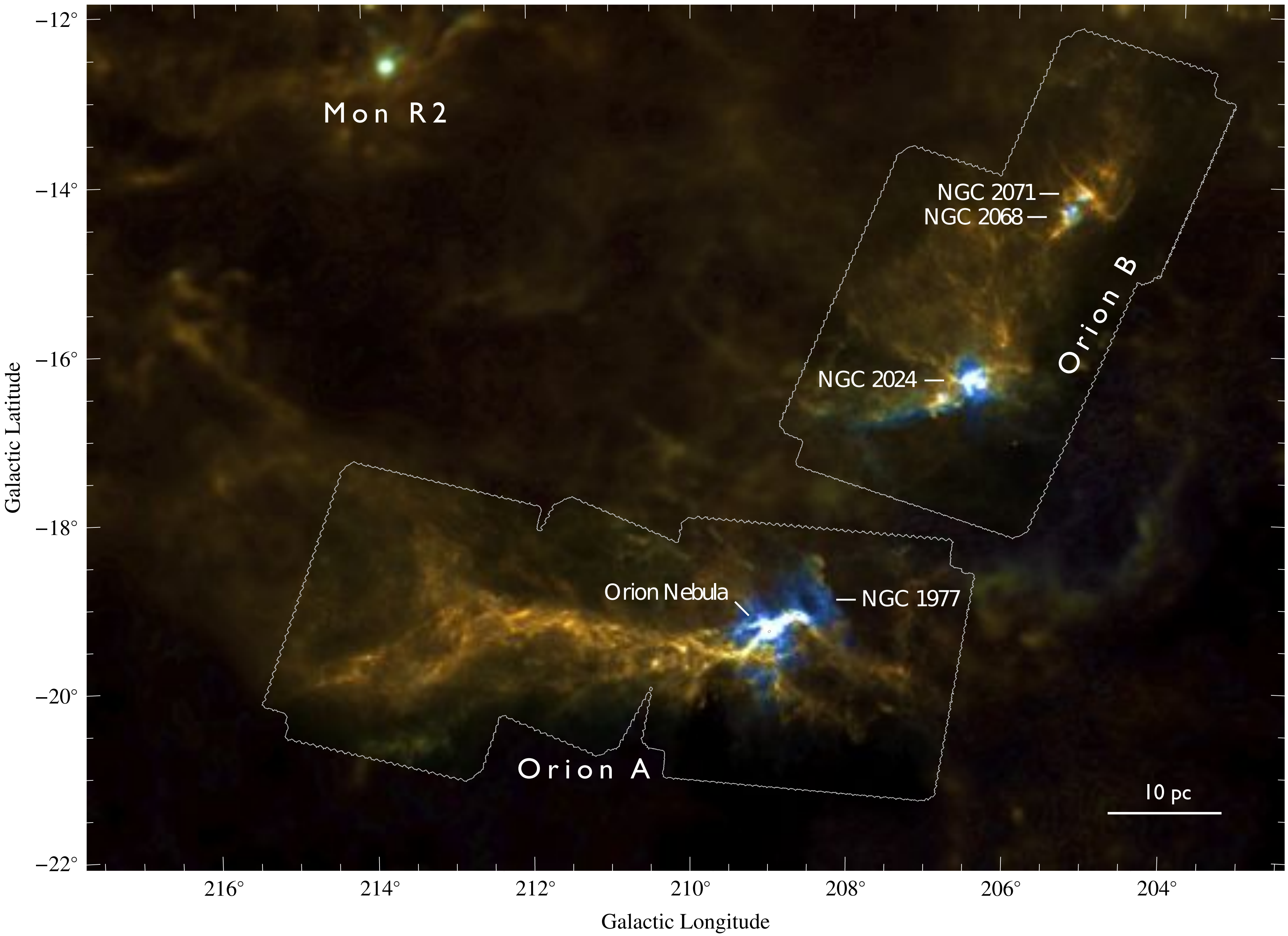
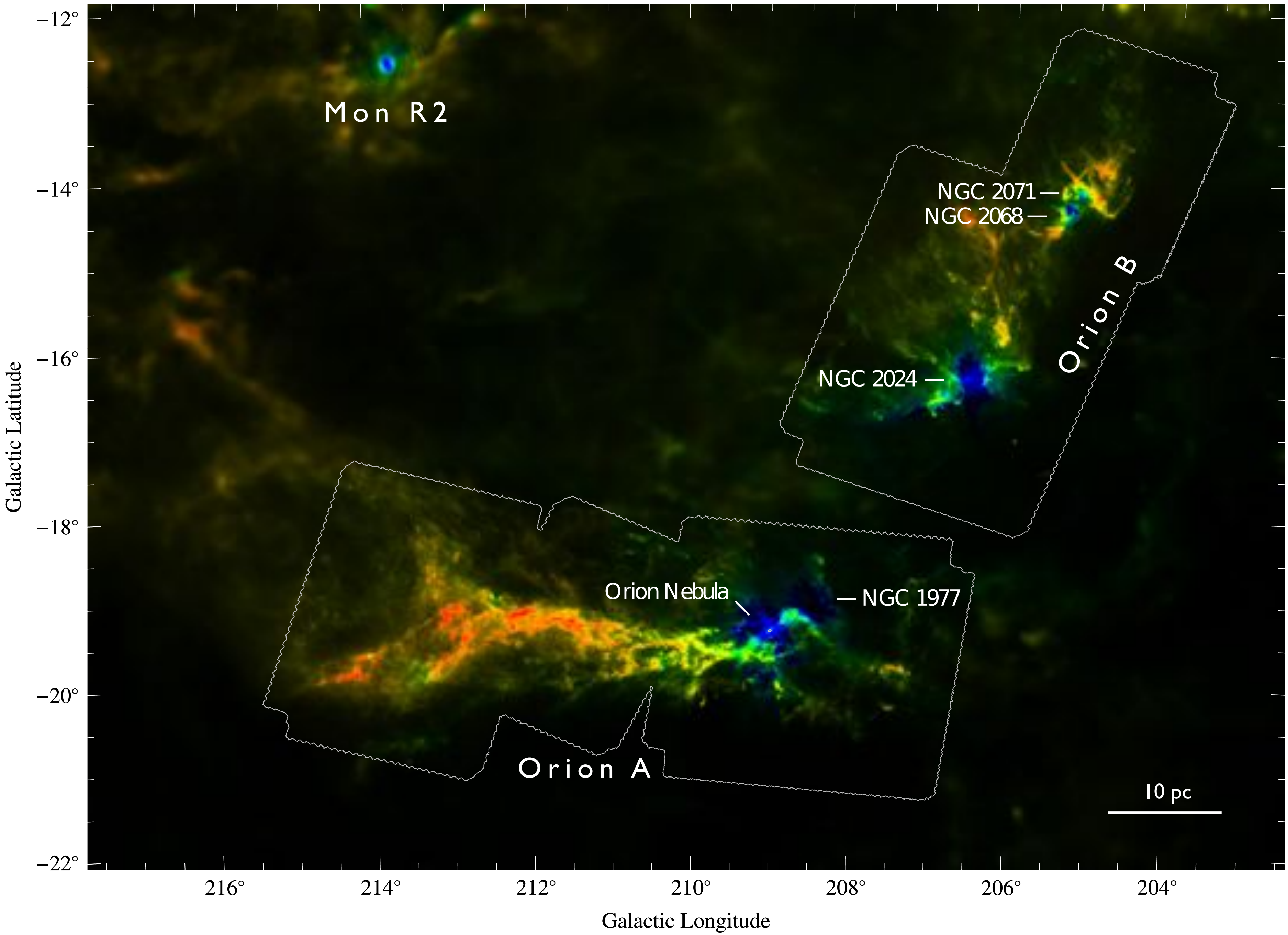
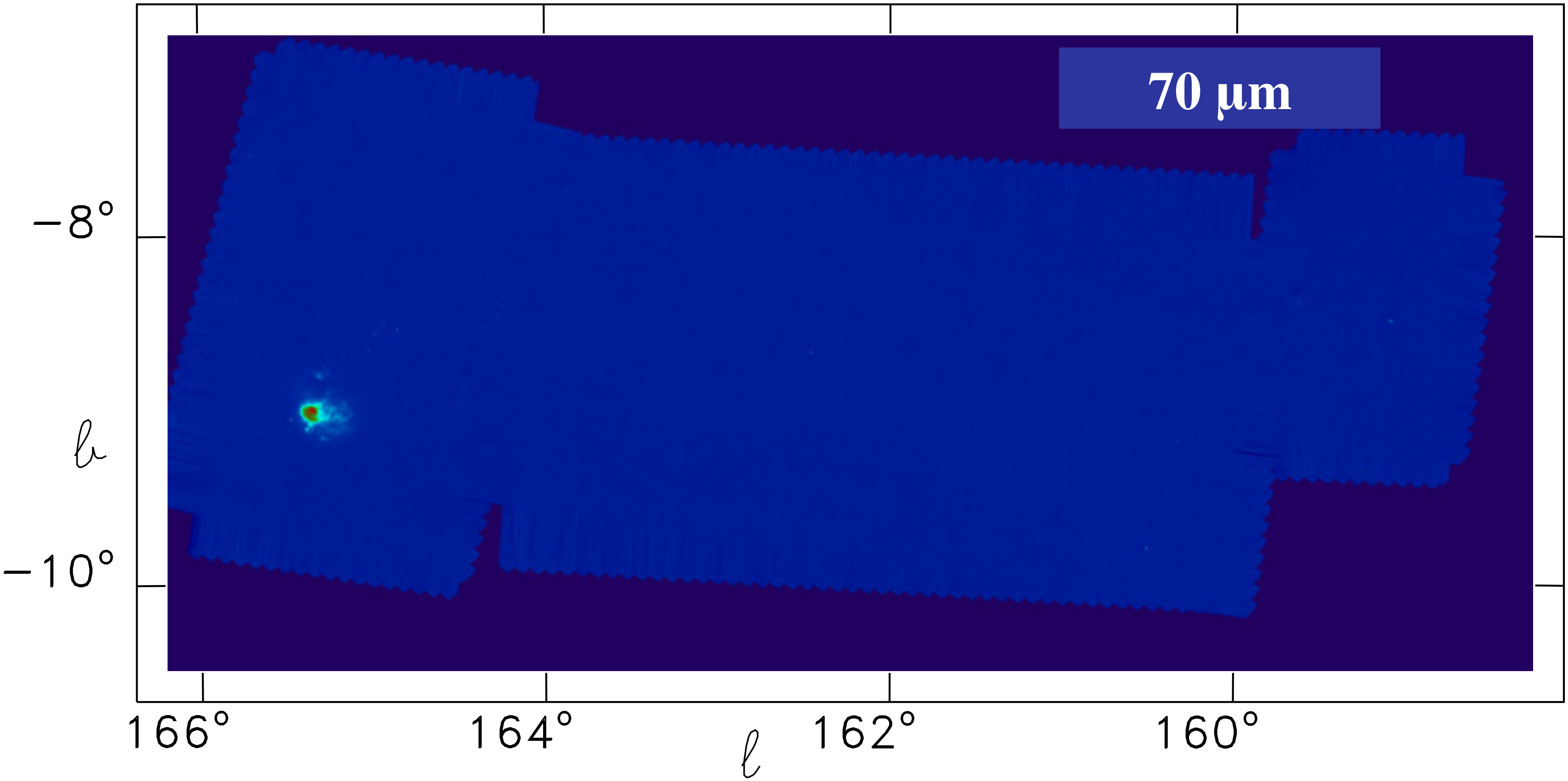


Fig. 2. Composite three-color image showing the *Herschel*/SPIRE intensities for the region considered, where available (with the 250 µm, 350 µm,



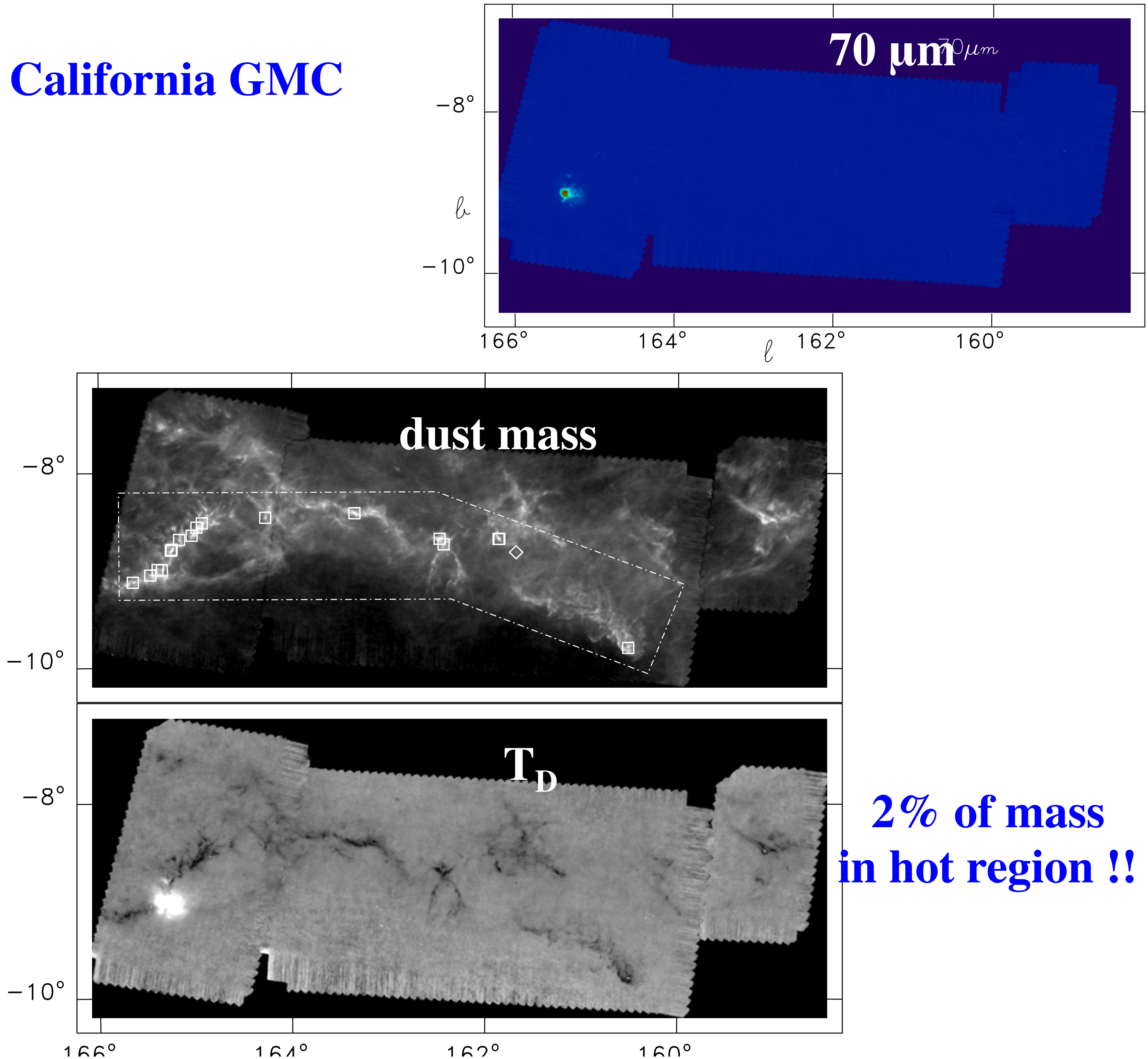
Mon R2
NGC 2071
NGC 2068
Orion B
NGC 2024
Orion Nebula
NGC 1977
Orion A
10 pc
−12°
−14°
−16°
−18°
−20°
−22°
Galactic Latitude
216°
214°
212°
210°
208°
206°
204°
Galactic Longitude

Auriga − California GMC (Harvey etal 2013)



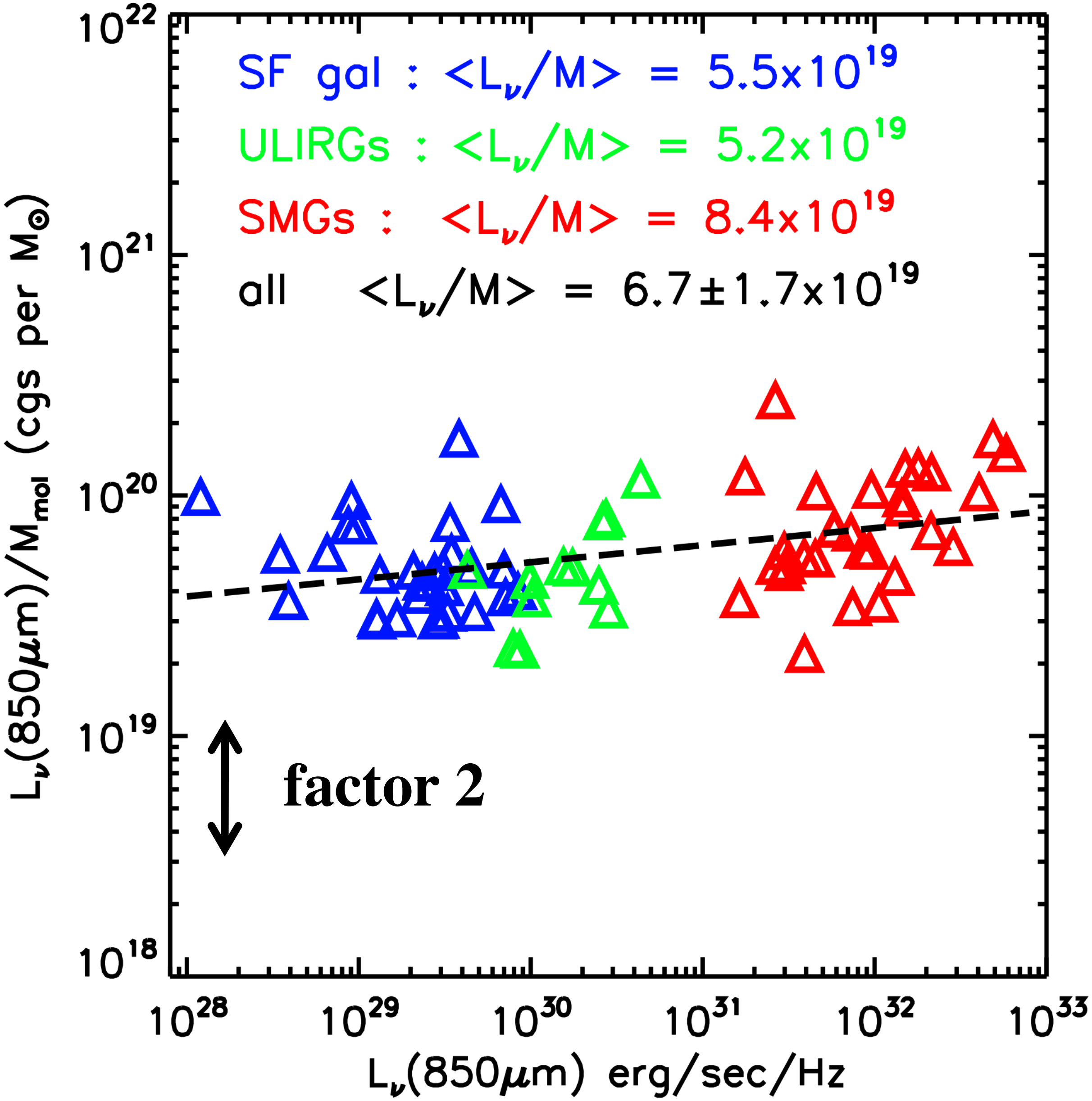
hot dust extended over ~10 arcmin, cold dust 6 deg

Auriga − California GMC



2% of mass in hot region !!

empirical basis for RJ continuum ➔ ISM masses



Hughes etal '17 get 6.4×10^{19} for 67 MS gal. @ $z < 0.3$

6.7×10^{19} erg/s/Hz/$M_\odot$

w/ less than factor 2 dispersion

Planck: Milky Way ➔ 6.2×10^{19} erg/s/Hz/$M_\odot$

$\beta = 1.8$ +- 0.1

quick and reliable !!

ISM evolution z = 0.3 to 3

RJ dust continuum ➔ ISM masses

ALMA w/ <u>~2 min integrations (CO 100x longer)</u>

1011 pointings w/i COSMOS field
➔ 687 detections of Herschel far infrared sources !!

w/ Vanden Bout, Lee, Sheth, <u>Aussel</u>, <u>Capak</u> , Sanders, Bongiorno, Diaz-Santos, Casey, <u>Murchikova</u>, Koda, Laigle, <u>Darvish</u>, Vlahakis, <u>McCracken</u>, <u>Ilbert</u>, Pope, Chu, Toft, Ivison, Morokuma-Matsui, <u>Armus</u>, Masters

- **Dunne etal mid z samples ➔ dust mass**
- **Fujimoto – sizes of dust em.**

logic of this work :

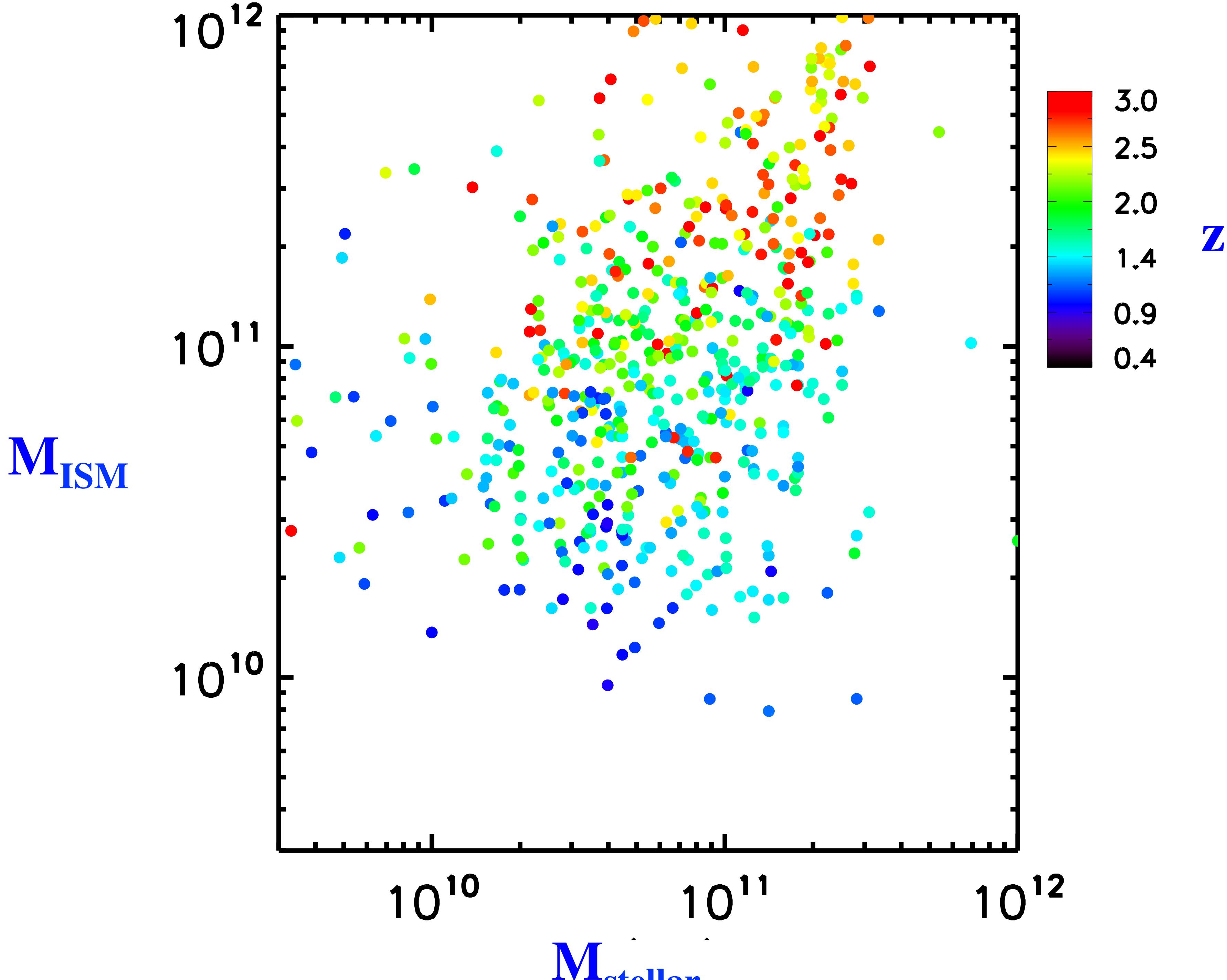
all ALMA 1.3 mm & 850 μm obs. in COSMOS field

search for sources at positions of Herschel FIR sources (14000)

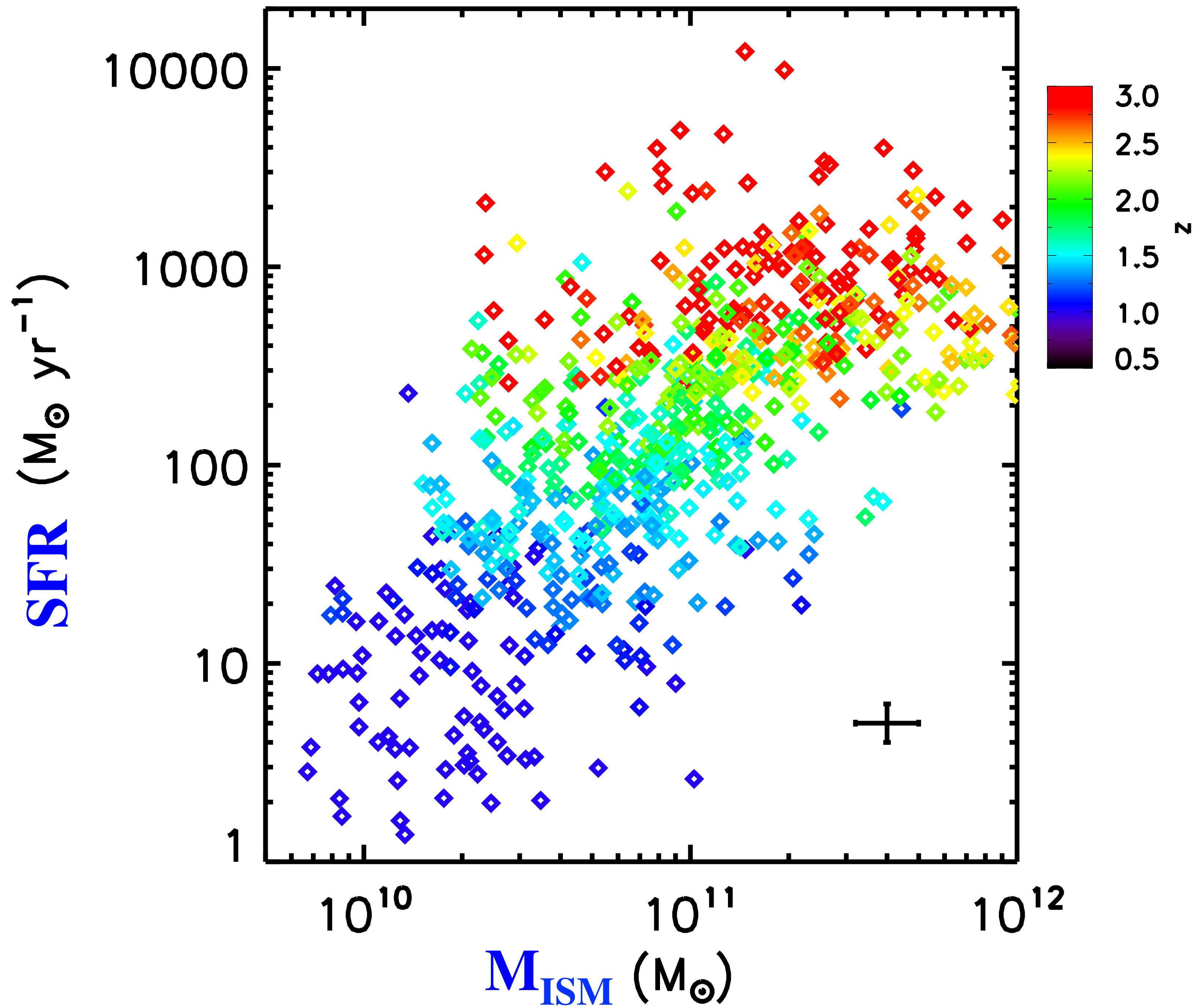
all Herschel sources w/i FOVs detected !! ➔ 687 detections

functional dependence of :

1. **ISM (z, M_*, sSFR rel. to MS)**
2. **SFR / ISM (z, sSFR rel. to MS, M_*)**
3. **Accretion rates needed to maintain SF**



10^{12}
10^{11}
10^{10}
M_{ISM}
10^{10}
10^{11}
10^{12}
$M_{stellar}$
3.0
2.5
2.0
1.4
0.9
0.4
z



10000
1000
100
10
1
SFR (M⊙ yr⁻¹)
10¹⁰
10¹¹
10¹²
M_ISM (M⊙)
3.0
2.5
2.0
1.5
1.0
0.5
z

gas contents correlated w/ ??

time in cosmic history (z)

mass of galaxy ($M_{stellar}$)

starburst vs main sequence ($sSFR$ / $sSFR_{MS}$)

gas contents correlated with :

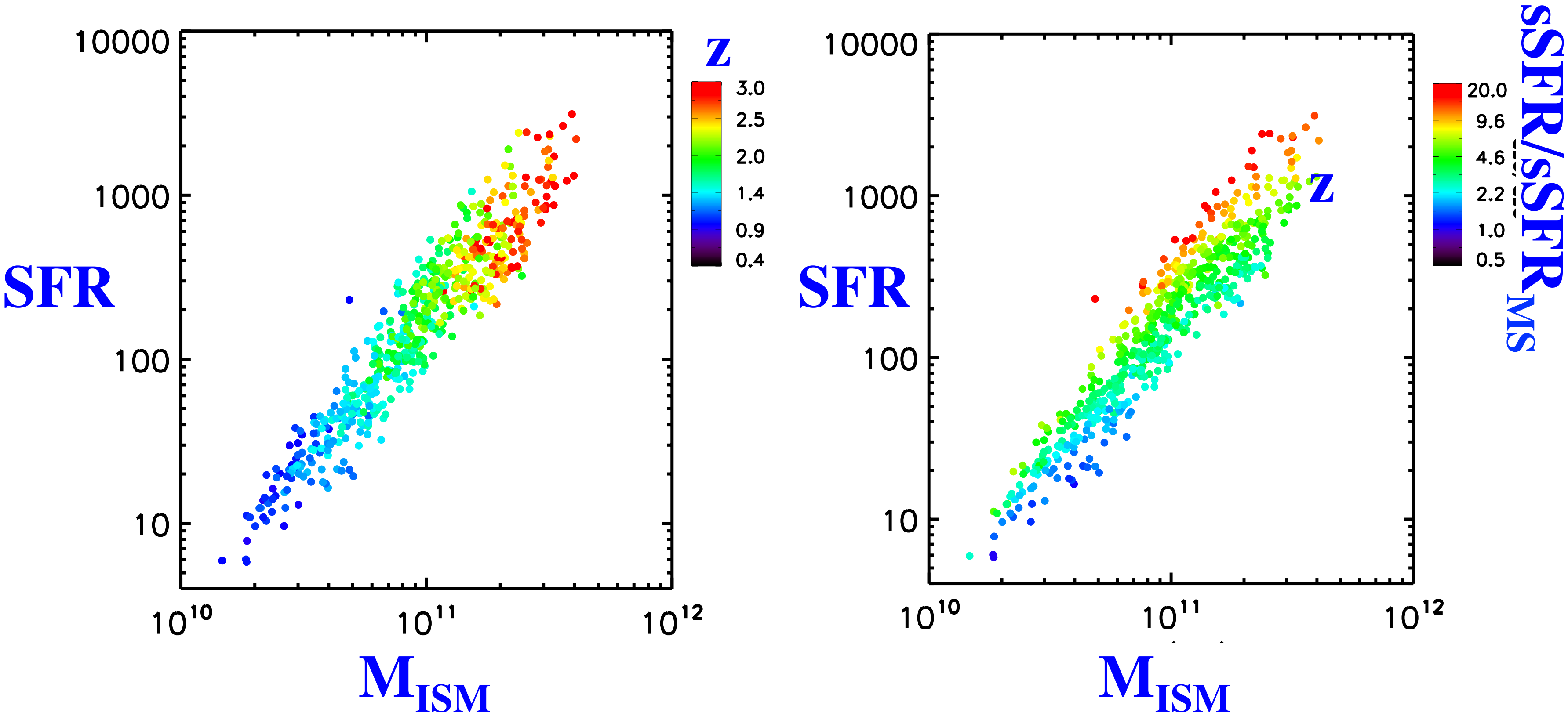
time in cosmic history (z)

mass of galaxy ($M_{stellar}$)

starburst vs main sequence (sSFR / $sSFR_{MS}$)

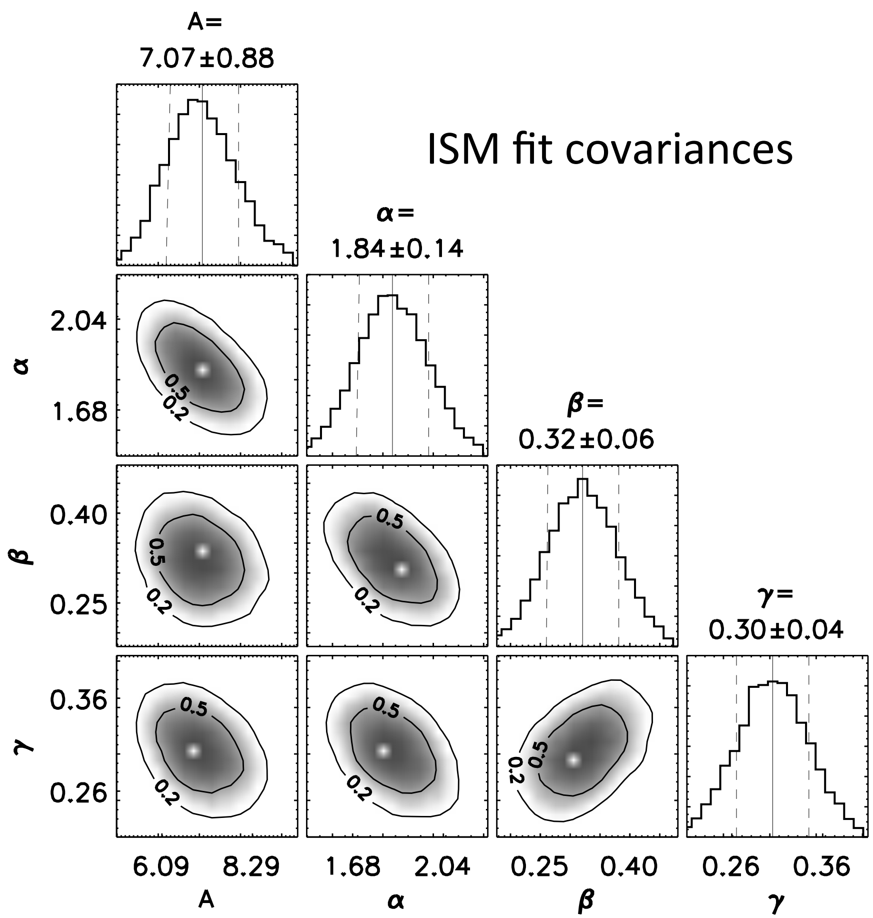
$$M_{ISM} = 7.07 \times 10^{9} M_{sun} \left(1+z\right)^{1.84} \left(\frac{sSFR}{sSFR_{MS}}\right)^{0.32} \left(\frac{M_{stellar}}{10^{10} M_{sun}}\right)^{0.30}$$

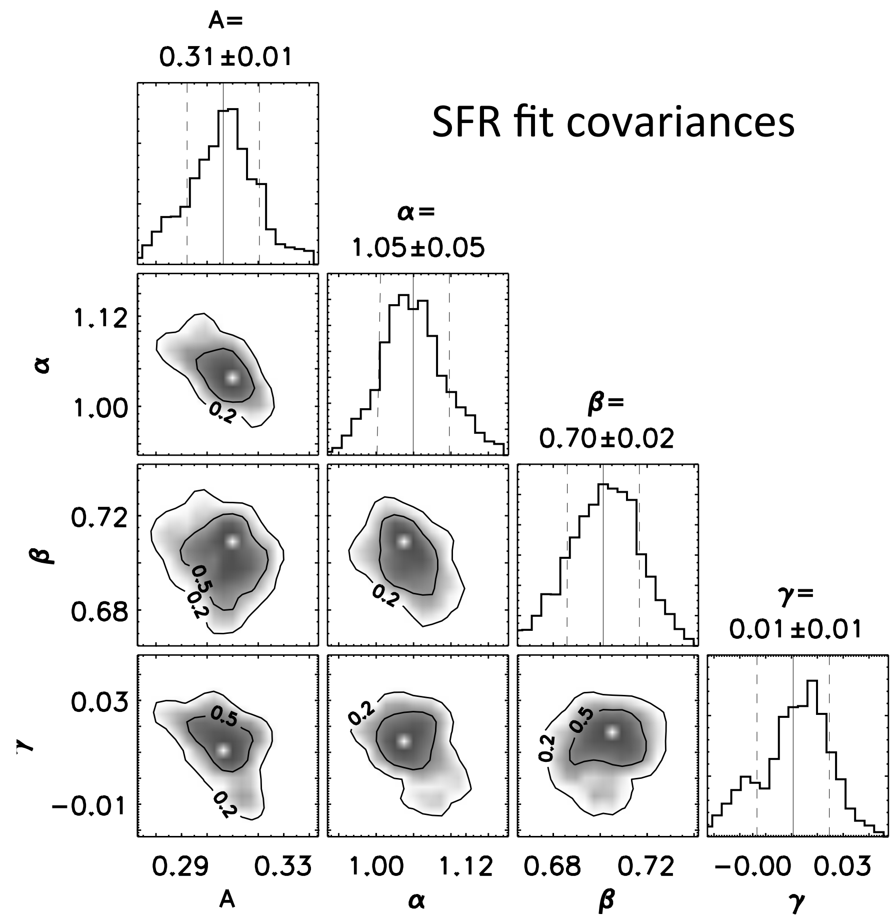
SF law :



$$\mathrm{SFR}\left(M_{sun}\,yr^{-1}\right) / \left(\frac{M_{ISM}}{10^{9}\,M_{sun}}\right) = 0.31\ \overbrace{(1+z)^{1.05}\left(\frac{sSFR}{sSFR_{MS}}\right)^{0.70}\left(\frac{M_{stellar}}{10^{10}\,M_{sun}}\right)}^{\text{efficiencies}}{}^{0.01}$$

covariances from Monte Carlo Markov Chain fitting



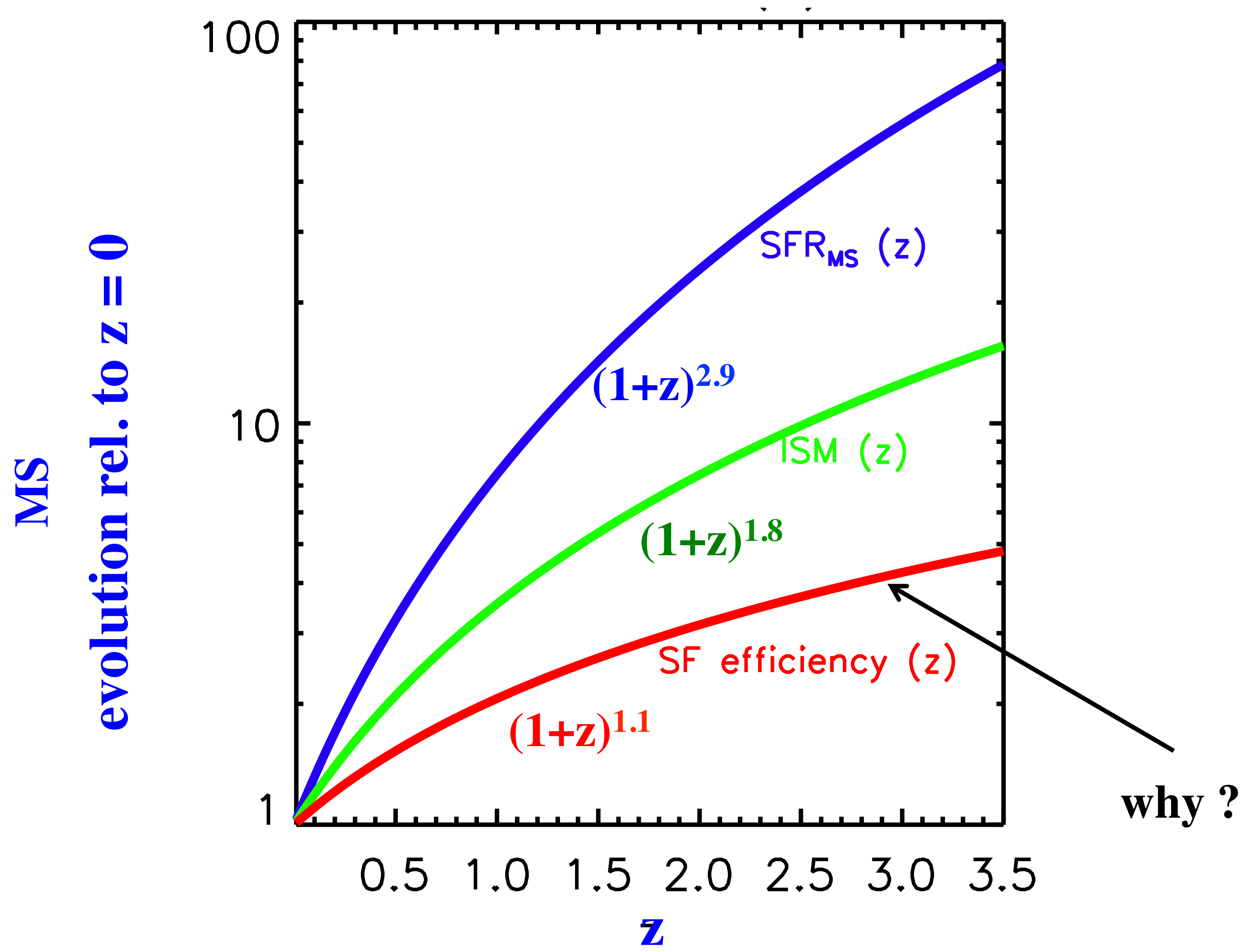


well-behaved w/ single values
uncertainties ~0.1 in exponents

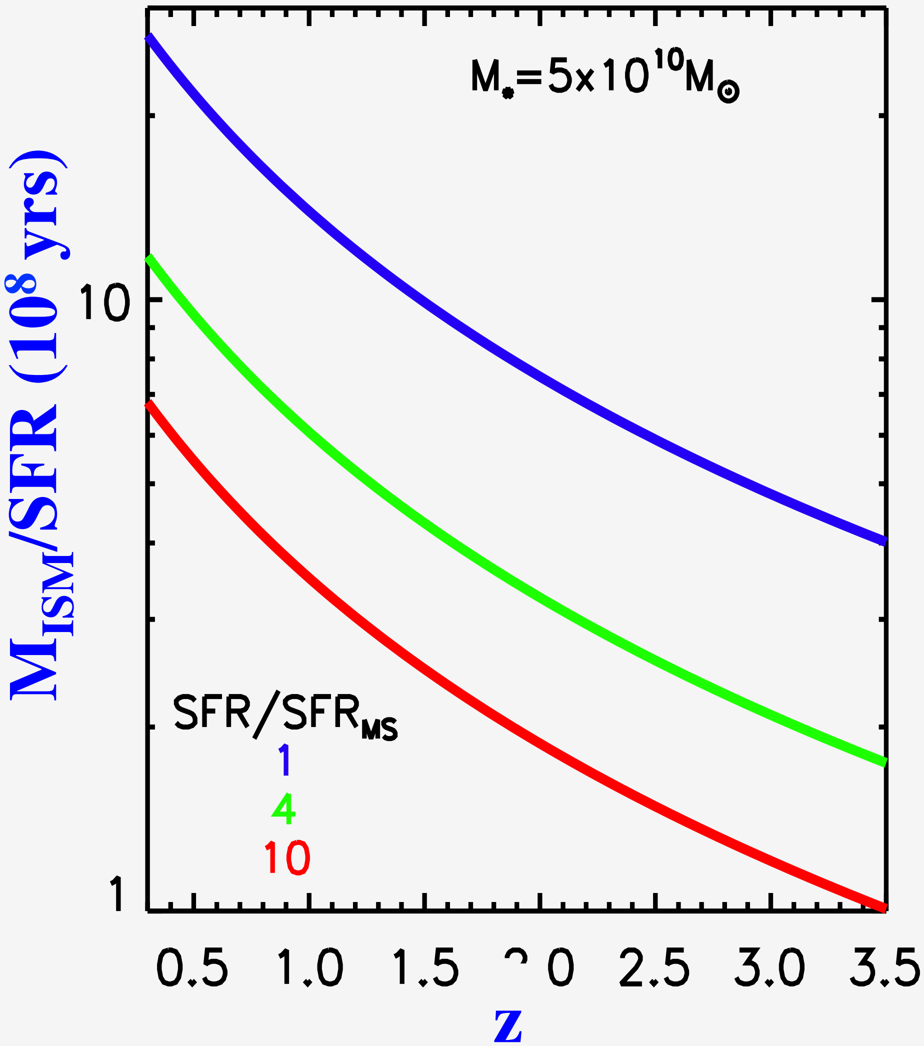
$$M_{ISM} = 7.07 \times 10^{9} M_{\Theta} \left(1+z\right)^{1.84} \left(\frac{sSFR}{sSFR_{MS}}\right)^{0.32} \left(\frac{M_{stellar}}{10^{10} M_{sun}}\right)^{0.30}$$

$$SFR\left(M_{sun} yr^{-1}\right) / \left(\frac{M_{ISM}}{10^{9} M_{sun}}\right) = 0.31 \underbrace{\left(1+z\right)^{1.05} \left(\frac{sSFR}{sSFR_{MS}}\right)^{0.70} \left(\frac{M_{stellar}}{10^{10} M_{sun}}\right)^{0.01}}_{\text{efficiencies}}$$

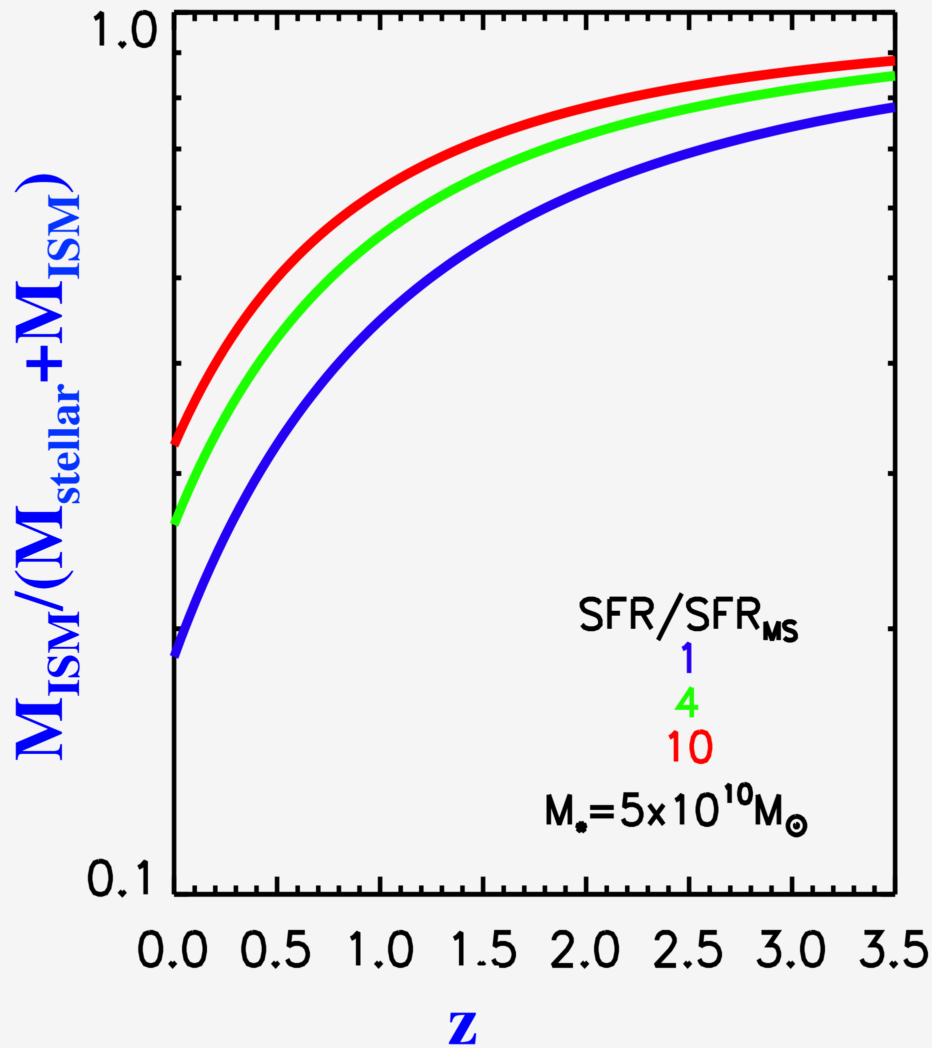
- **evolution w/ z : due to both increase in ISM and SF eff.**
- **increase above MS for SBs : higher ISM and SF eff.**
- **ISM varies as $M_{stellar}^{0.3}$ and SF eff. indep. of $M_{stellar}$**
- **not a simple low-z KS law -- higher efficiency $H_2 \rightarrow$ *'s**


MS
evolution rel. to z = 0
100
10
1
0.5
1.0
1.5
2.0
2.5
3.0
3.5
z
SFR$_{MS}$ (z)
$(1+z)^{2.9}$
ISM (z)
$(1+z)^{1.8}$
SF efficiency (z)
$(1+z)^{1.1}$
why ?

gas depletion times



ISM mass fractions

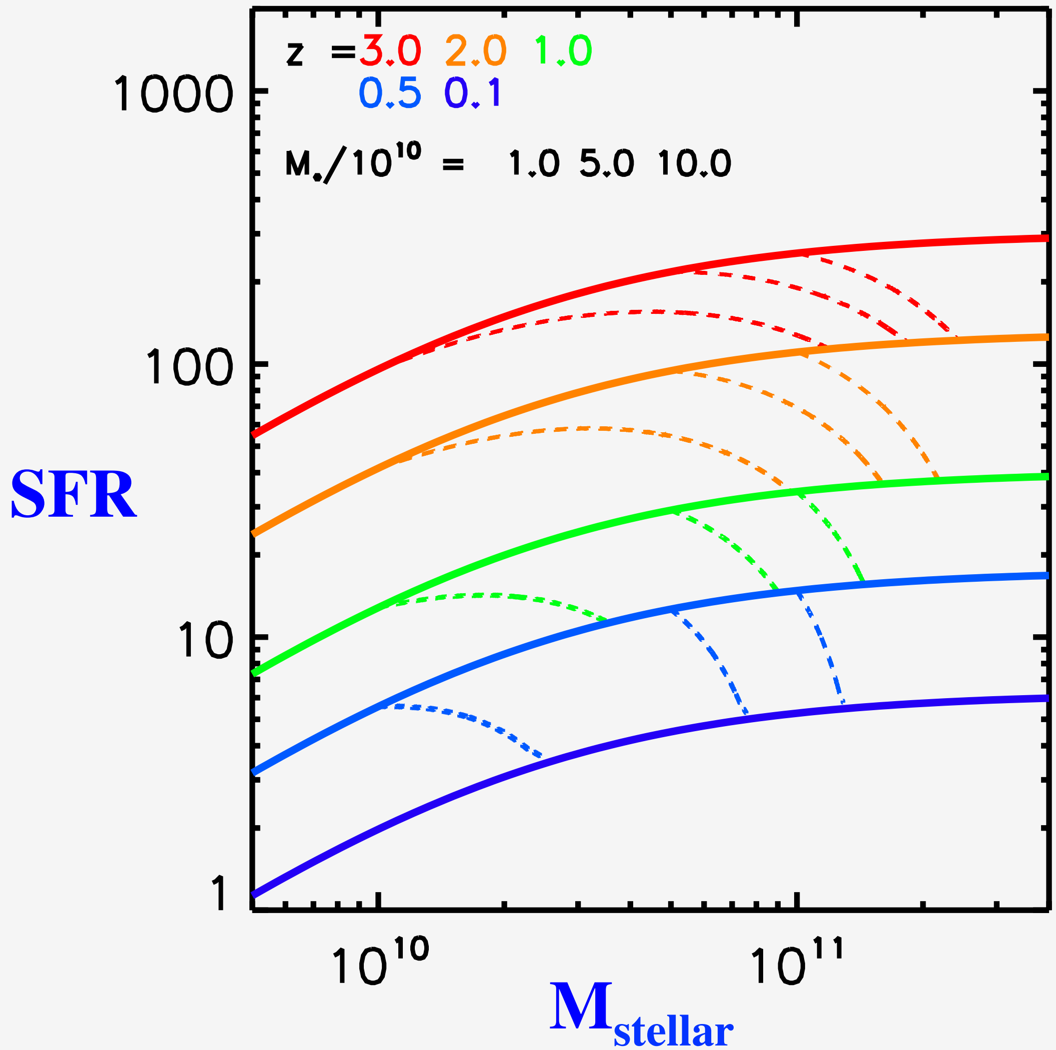


at z > 2, ~500 Myr MS

30% -- 80% above MS

➔ accretion

evolutionary continuity of MS

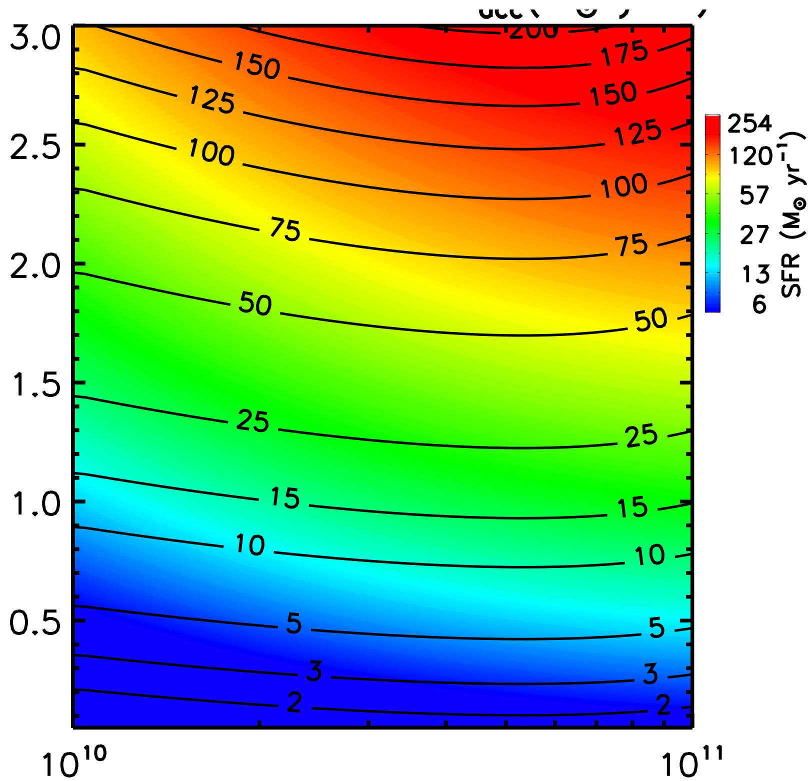


accretion needed to maintain SF :

$$\frac{dM_{ISM}}{dt} = -\ 0.7\ \mathrm{SFR} + \dot{M}_{accretion}$$

accretion rate ($M_\odot$ yr^{-1}) -- contours

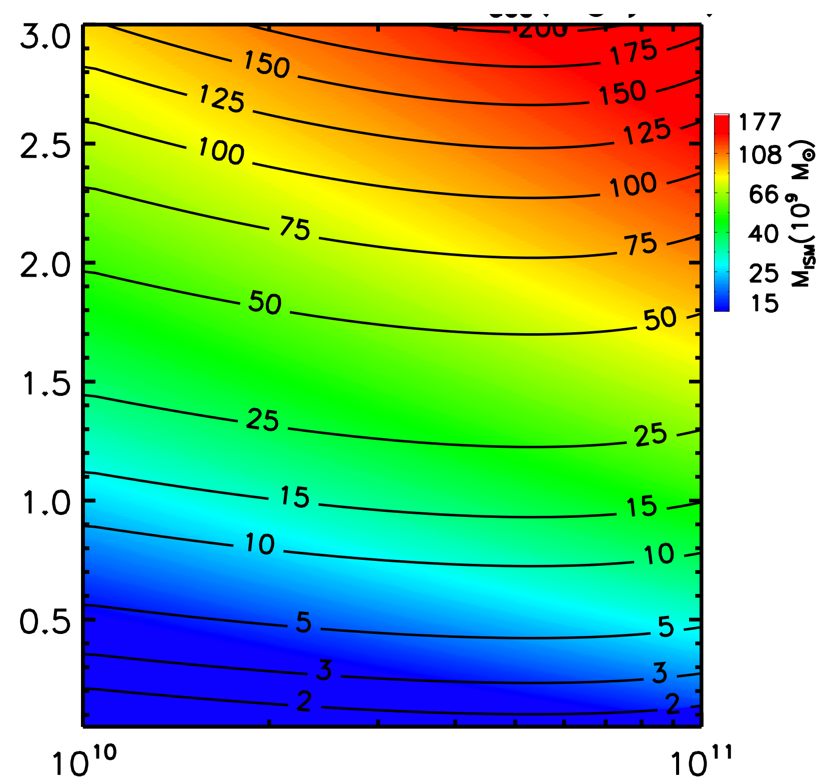
SFRs - color



z

$M_{stellar}$

ISM mass - color



z

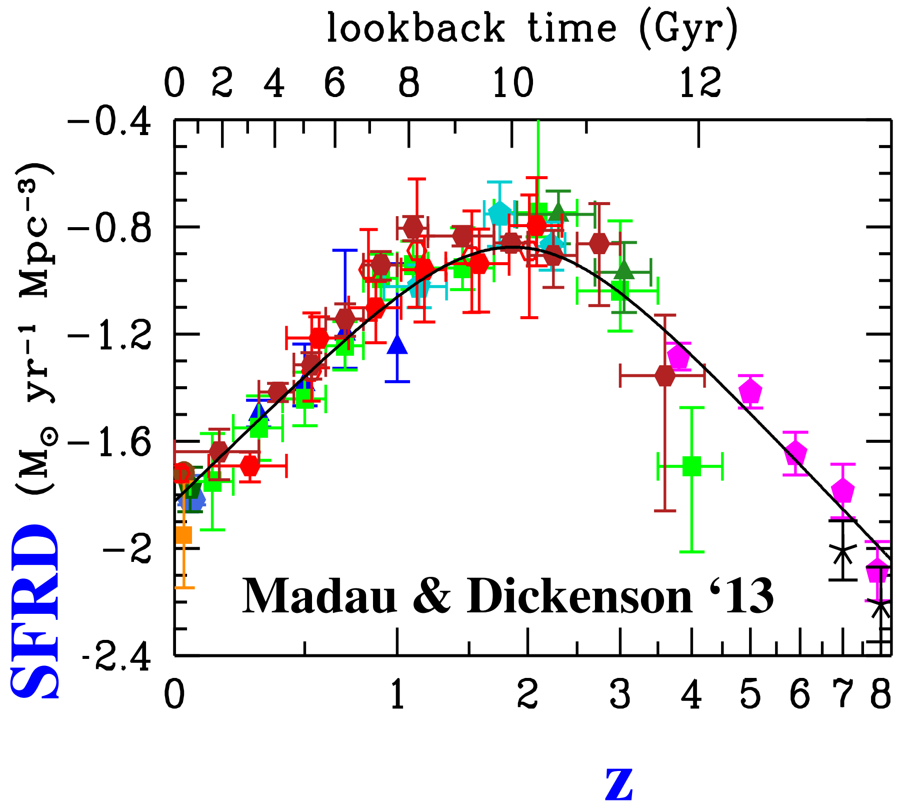
$M_{stellar}$

$$\dot{M}_{acc} = 1.12\, M_{sun} yr^{-1} \bullet (1+z)^{3.6} \left(\frac{M_{stellar}}{10^{10} M_{sun}}\right)^{0.44}$$

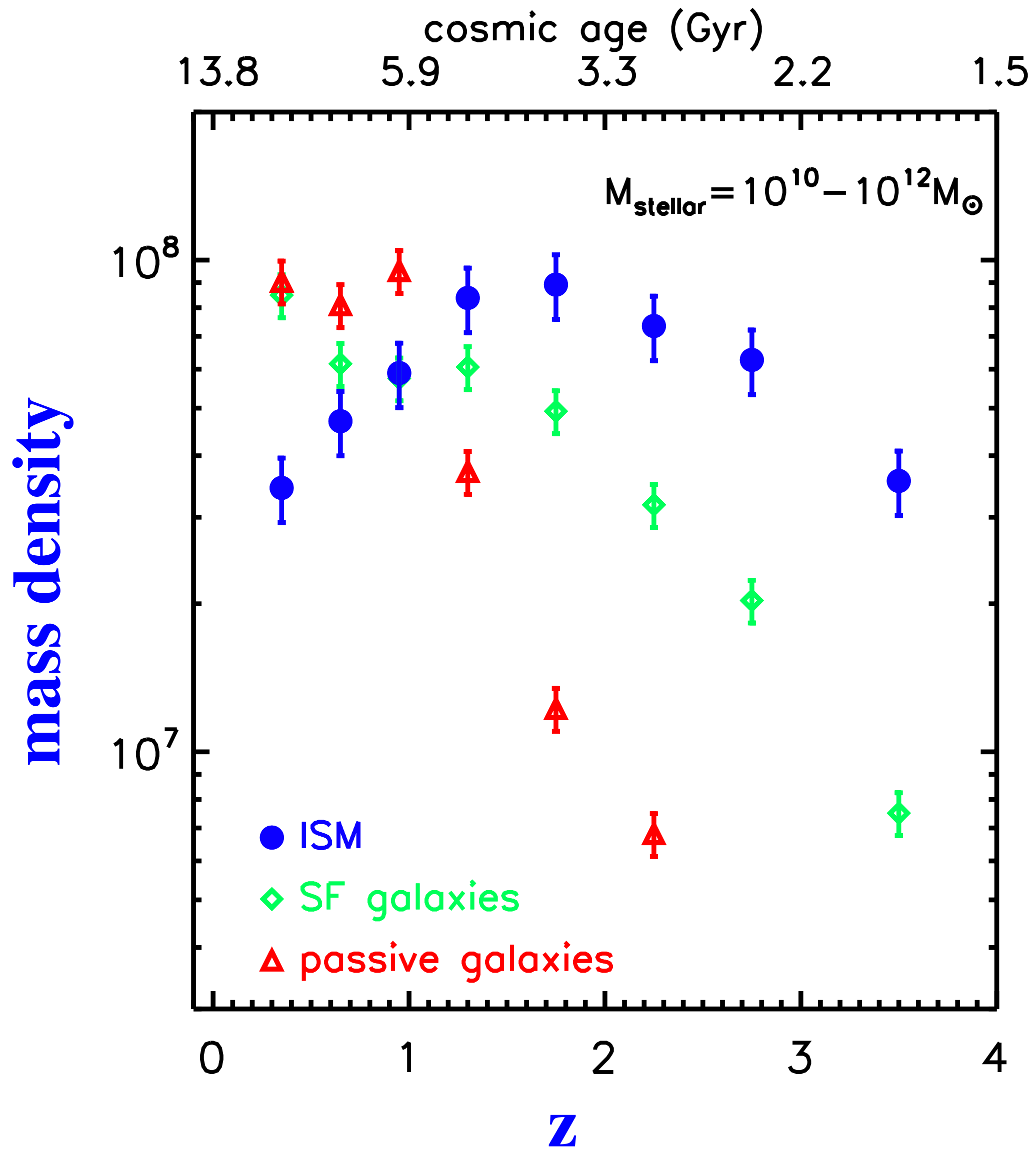
accretion rates are huge : 100 M_{sun}yr^{-1} at z > 2

overall cosmic evolution

cosmic evolution SF



cosmic evol. of ISM and stellar mass



summary :

1. RJ dust continuum is fast (2min) and reliable

2. ISM content and SFE evolve each less rapidly w/ z than SFR

3. ISM mass varies as $M_{stellar}^{0.3}$

4. above MS, SB due to both increased ISM and higher eff.

5. accretion rate are huge $\sim 100\ M_{sun}\ yr^{-1}$

specific accretion rate ($\dot{M}_{acc} / M_{stellar}$) :

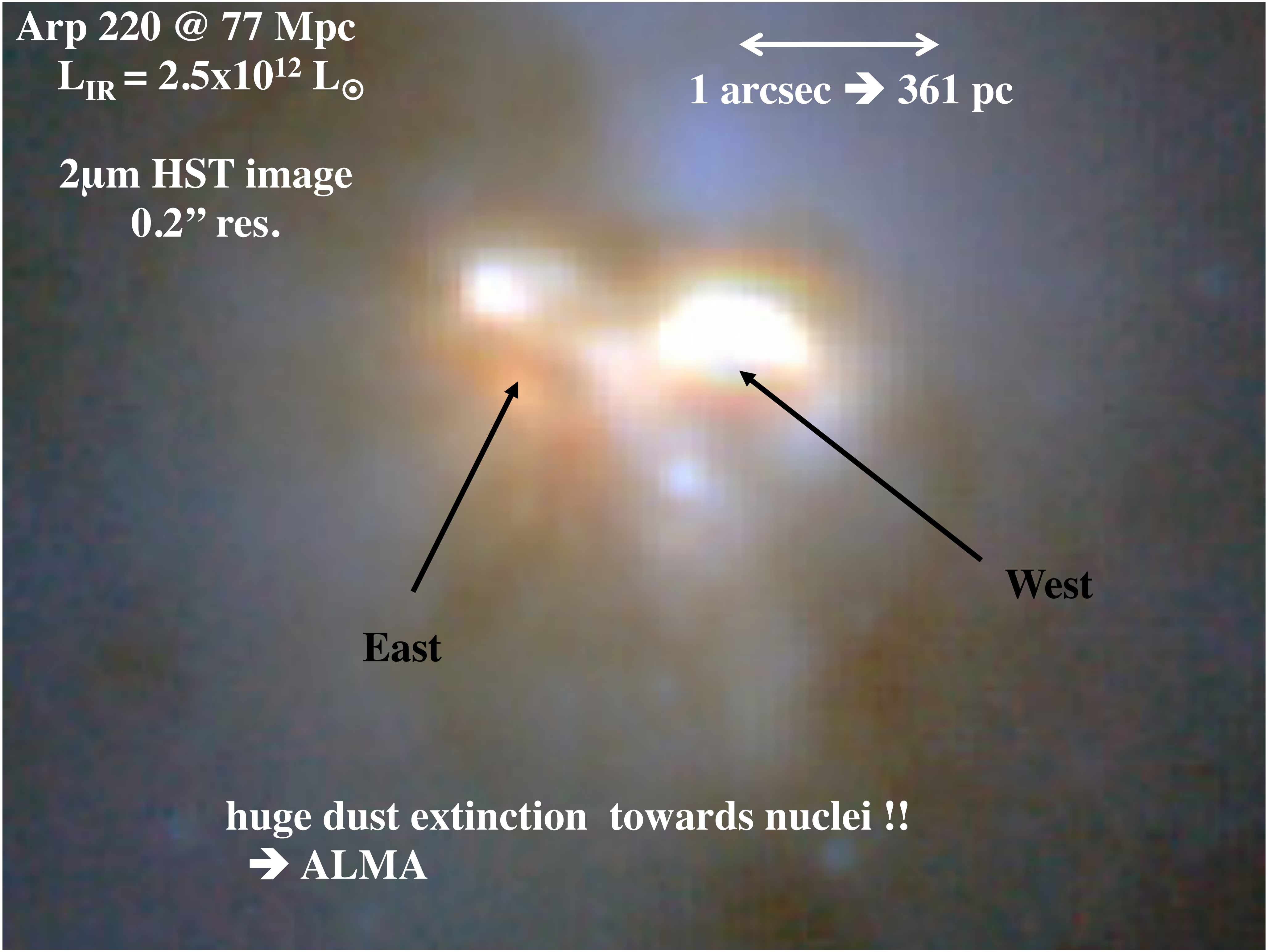
==> lower at high $M_{stellar}$

Arp 220 -- double nuclei (separation ➔ 412 pc)

11 km baselines !! ➔ 90 mas resolution ➔ 35 pc

➔ resolves nuclear disks !!

w/ Murchikova, Walter, Koda, Vanden Bout, Vlahakis, Barnes, Armus, Yun, Sheth, Sanders, Cox, Zschaechner, Tacconi, Torrey, Hayward, Thompson, Genzel, Robertson, Hernquist, Hopkins, van der Werf, Decarli

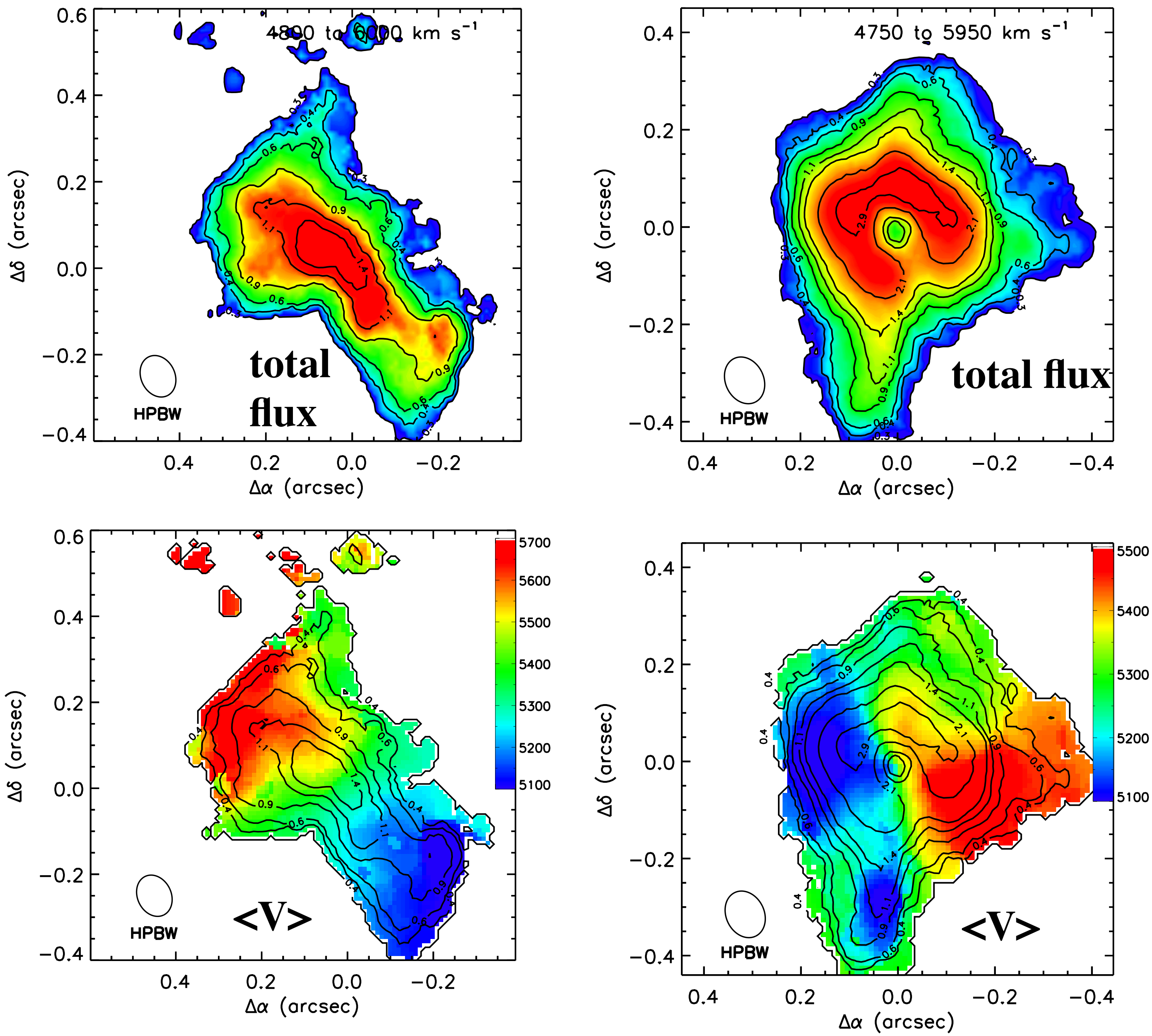

Arp 220 @ 77 Mpc
$L_{IR} = 2.5 \times 10^{12}\ L_{\odot}$
2µm HST image
0.2” res.
1 arcsec ➔ 361 pc
East
West
huge dust extinction towards nuclei !!
➔ ALMA

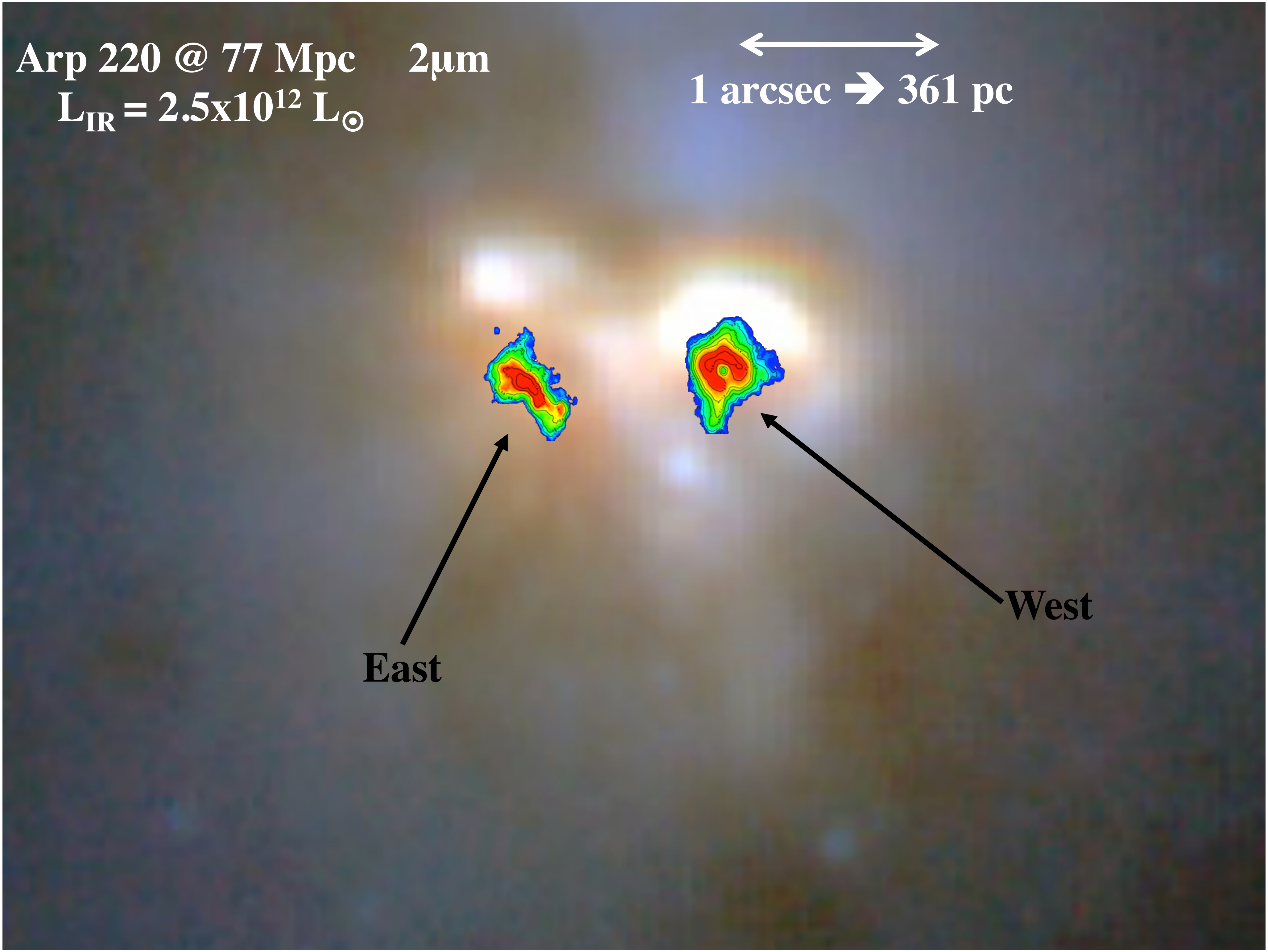
integrated CO line and <V> (0,0 = continuum peaks)

total emission ➔

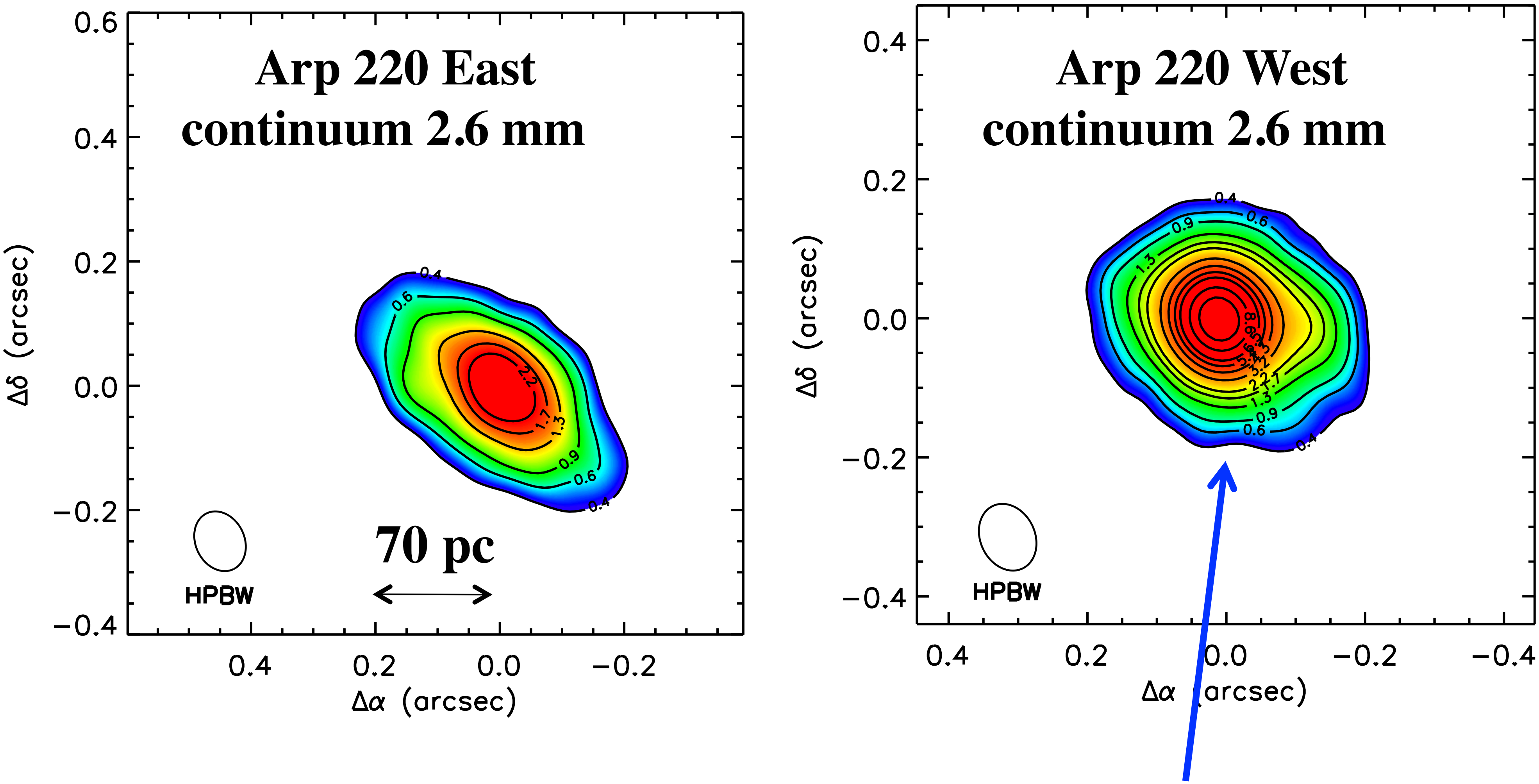
velocities ➔

Arp 220 East CO (1-0) Arp 220 West CO (1-0)



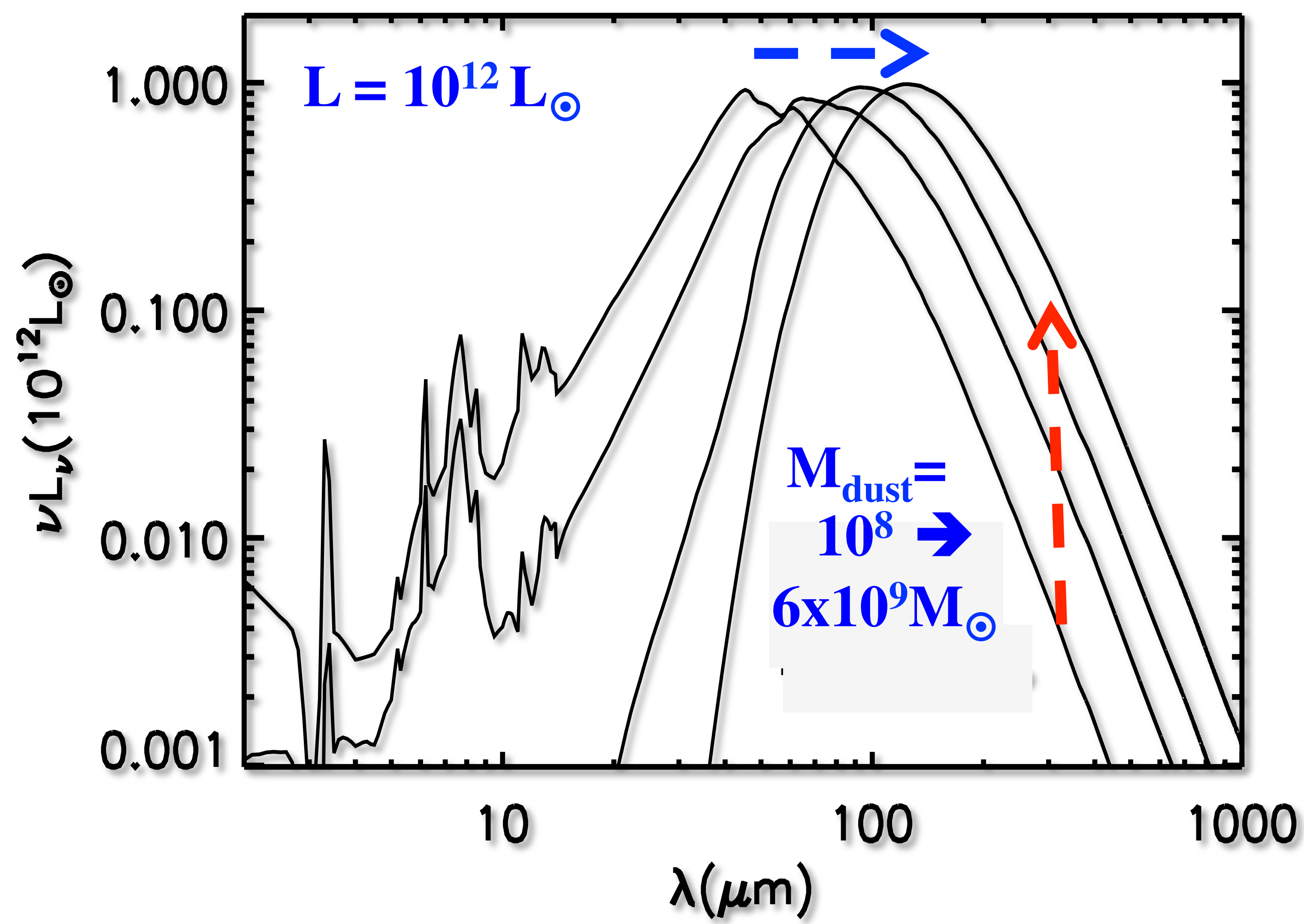

Arp 220 @ 77 Mpc
2µm
$L_{IR} = 2.5x10^{12}\ L_{\odot}$
1 arcsec → 361 pc
East
West

2.6 mm dust continuum



at 2.6 mm dust emission West $T_B = 120$ K ~ T_D
➔ optically thick

NB : $T_B \sim 200$ K ➔ $T_D > 200$ K , yet $T_{FIR} \sim 38$ K !!



peak shifts to longer λ for increased τ

at 2.6 mm dust emission West $T_B = 120$ K

(expect ~170 K for $10^{12} L_\odot$ $R \sim 15$ pc)

➔ <u>$\tau \sim 1$</u> at 2.6 mm !!

➔ $N_{H2} = 2x10^{26}$ cm^{-2} , $A_V = 10^5$ mags !!

M_{ISM} (west compact nucleus) ~ $2x10^9 M_\odot$ $R < 16$ pc

$n_{H2} \sim 10^6$ cm^{-3}

<u>dust column ➔ $A_V = 10^5$ mags</u> !!!!!!!!

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M_{ISM} (west compact nucleus) ~ $2\mathrm{x}10^9\ M_\odot$ $R < 16$ pc

$n_{H2} \sim 10^6\ \mathrm{cm}^{-3}$

dust column ➔ $A_V = 10^5$ mags !!!!!!!!

$= 200\ \mathrm{gr\ cm}^{-2}$

~ 1 ft thick wall of GOLD !!

summary :

measure ISM rapidly (2min) w/ RJ dust continuum

gas contents ~ 50% of mass, 'SB gal.' have more gas

SF law w/ dep. time ~ 500 Myr

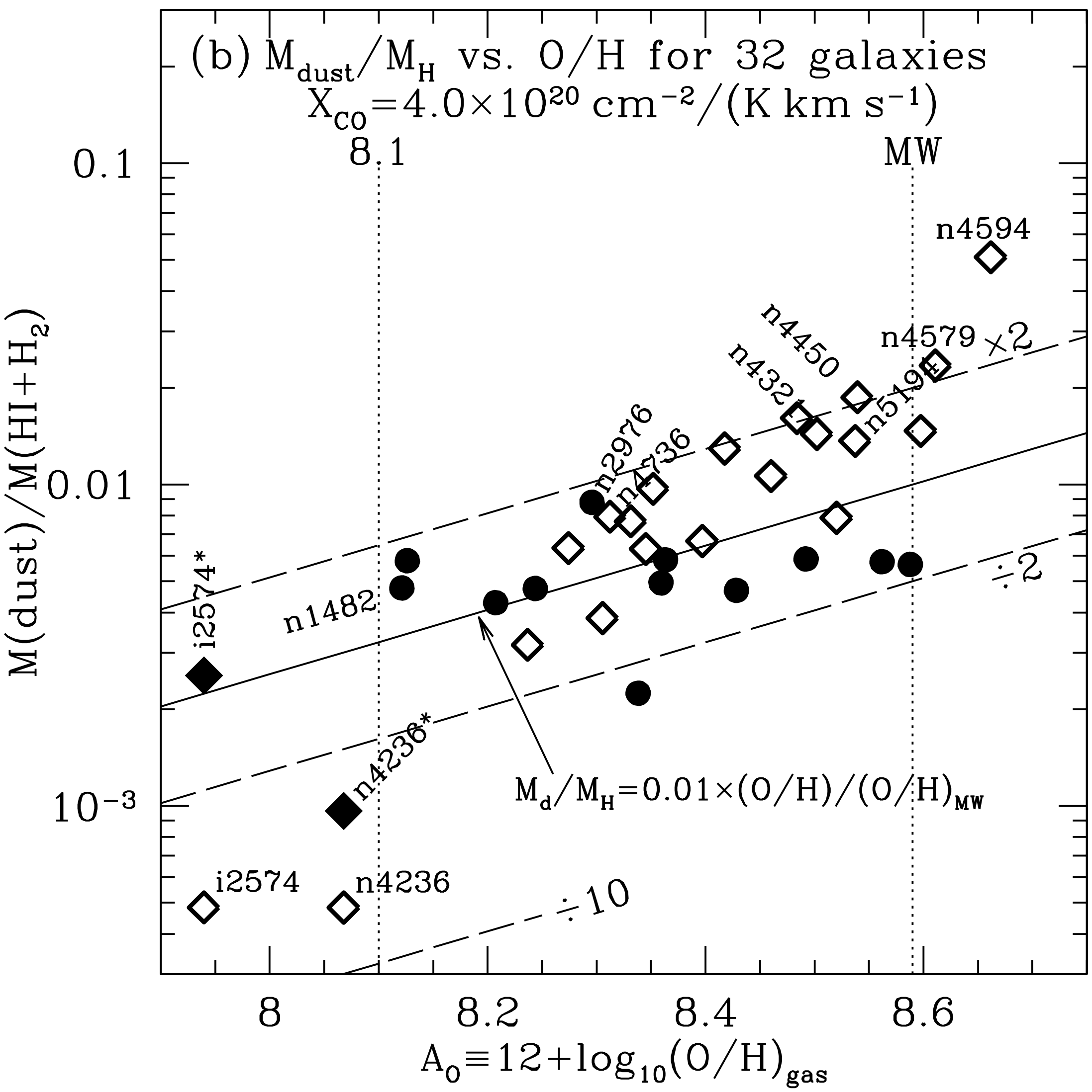
at high z and above MS

more gas and higher eff. (SF/M_{gas})

90 mas imaging of Arp 220 resolves nuclear disks

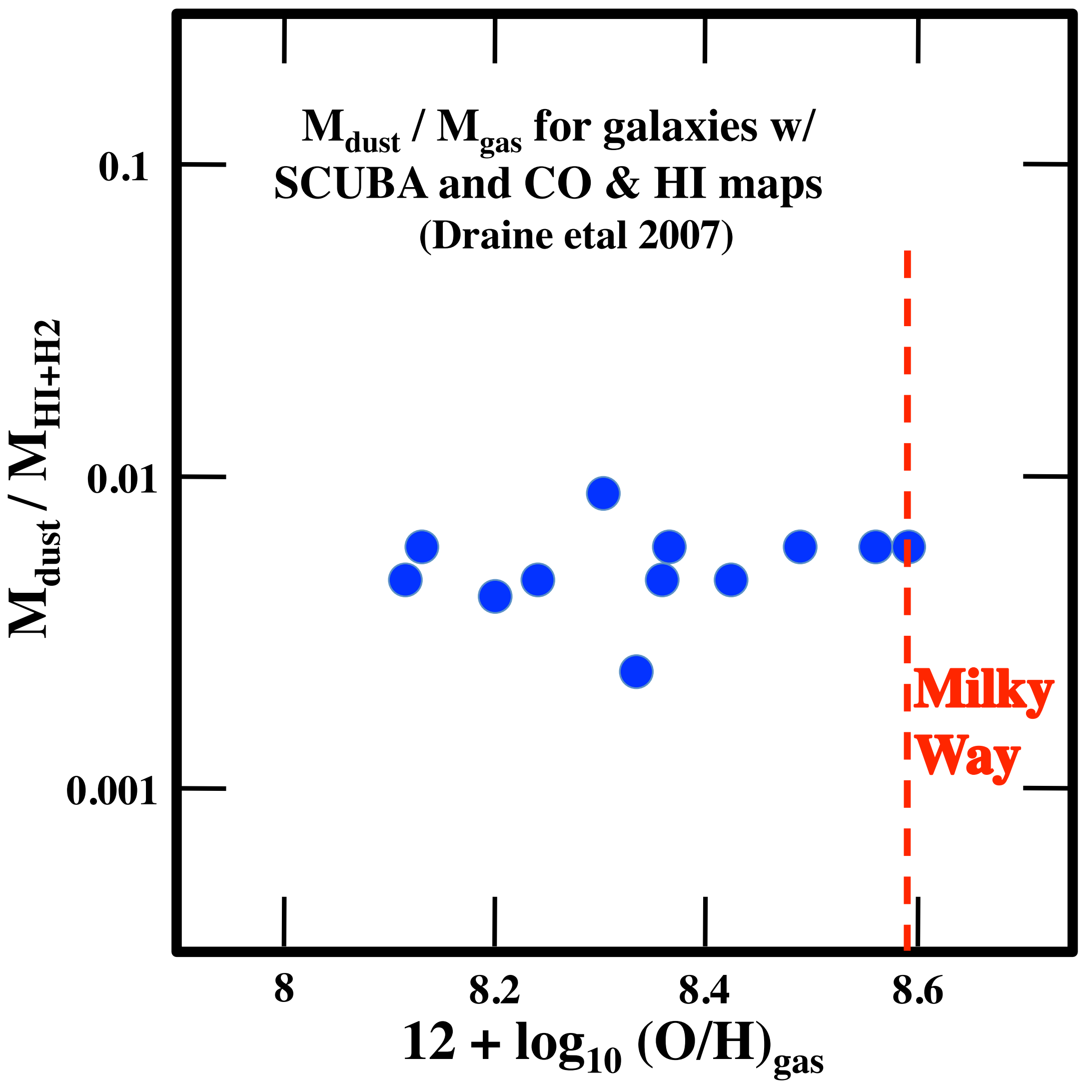
disk masses from dust cont., CO 1-0 & rotation curves
agree w/i factor 2-3
obscuration wall !!

dust/gas ratio (Draine etal '07)



solid points with good sub-mm and CO & HI

dust/gas ratio (Draine etal '07)
solid points with good sub-mm and CO & HI

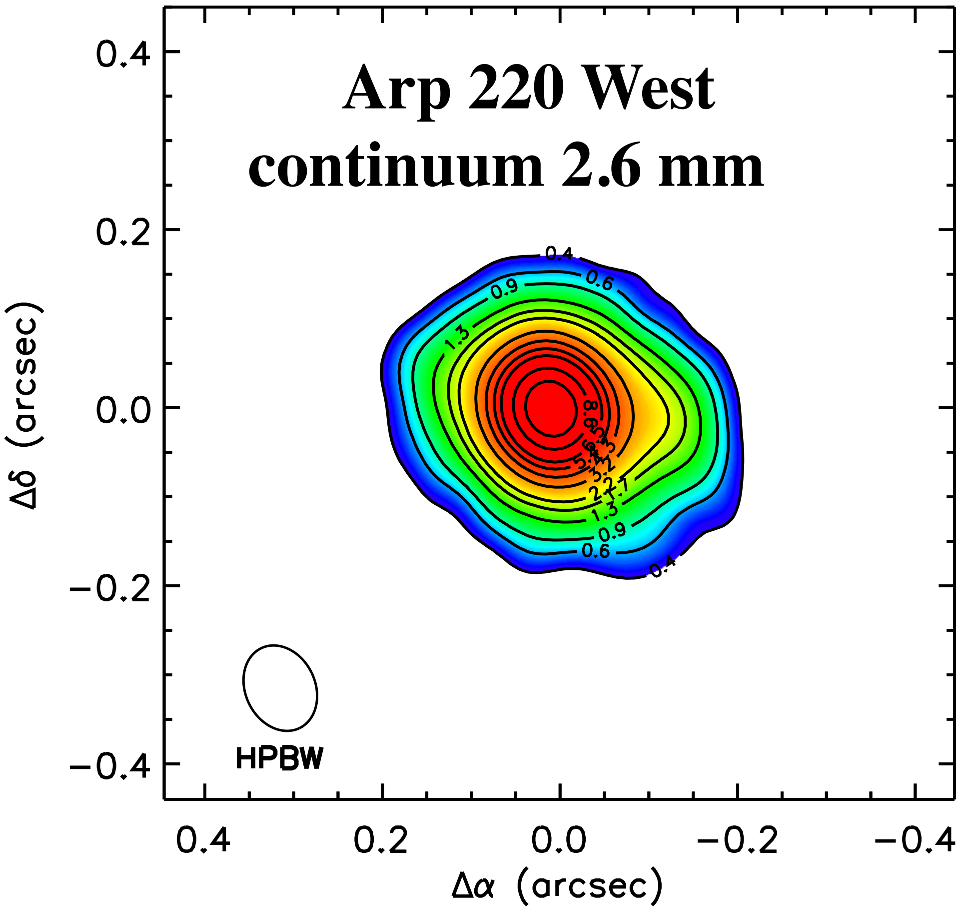


➔ ~constant ratio for $Z_\odot$ to $Z_\odot/3$

my ?? – a puzzle :

Arp 220 W – dust peak on nucleus , CO hole

why ? (1 £ !!)



Arp 220 West CO (1-0)