The Evolution of Galaxies: From the Local Group to the Epoch of Reionization

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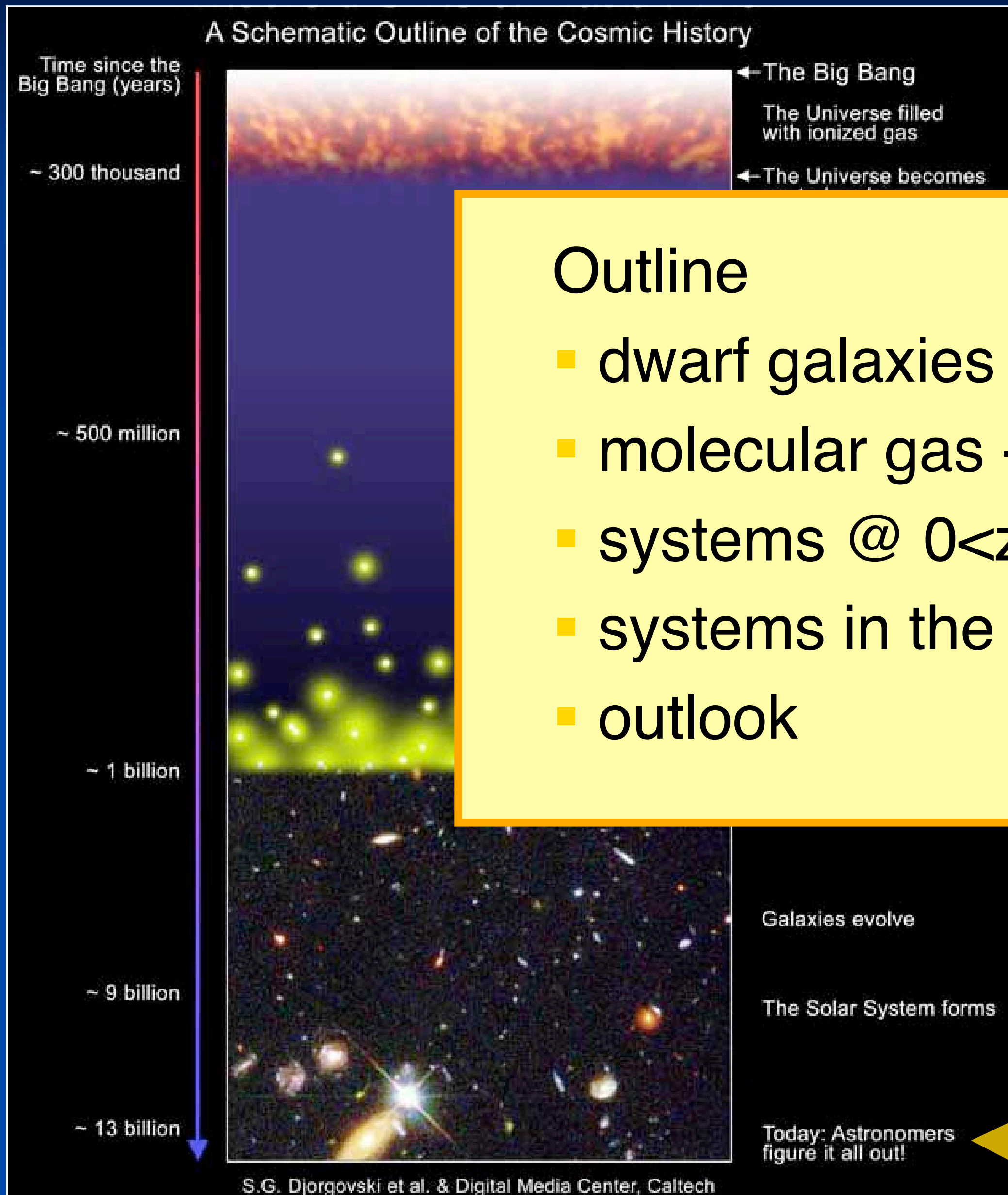
History of the Universe



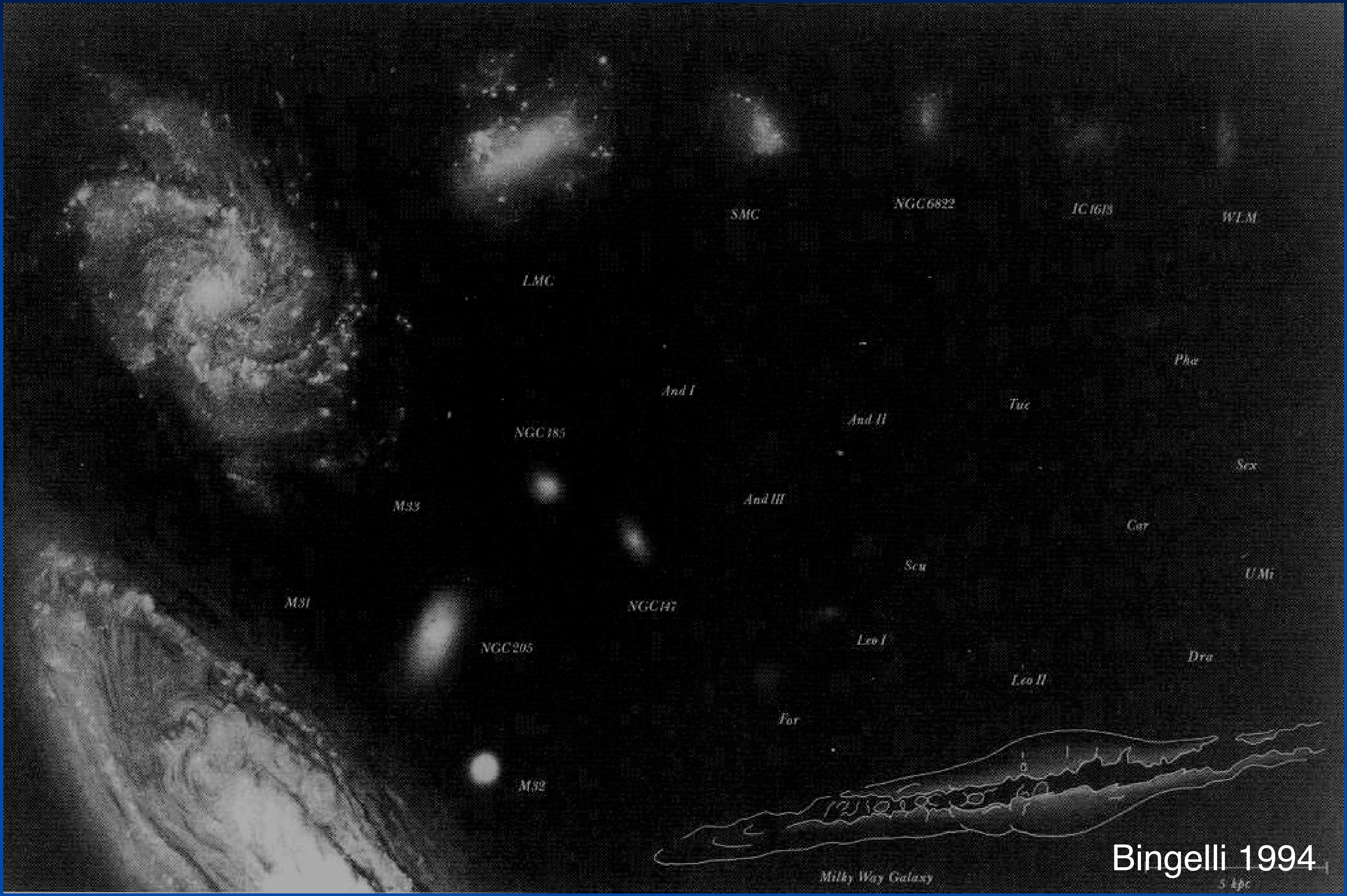
S.G. Djorgovski et al. & Digital Media Center, Caltech

Outline

- dwarf galaxies - building blocks?
- molecular gas - fuel for SF
- systems @ 0<z<5
- systems in the EoR: z>6
- outlook

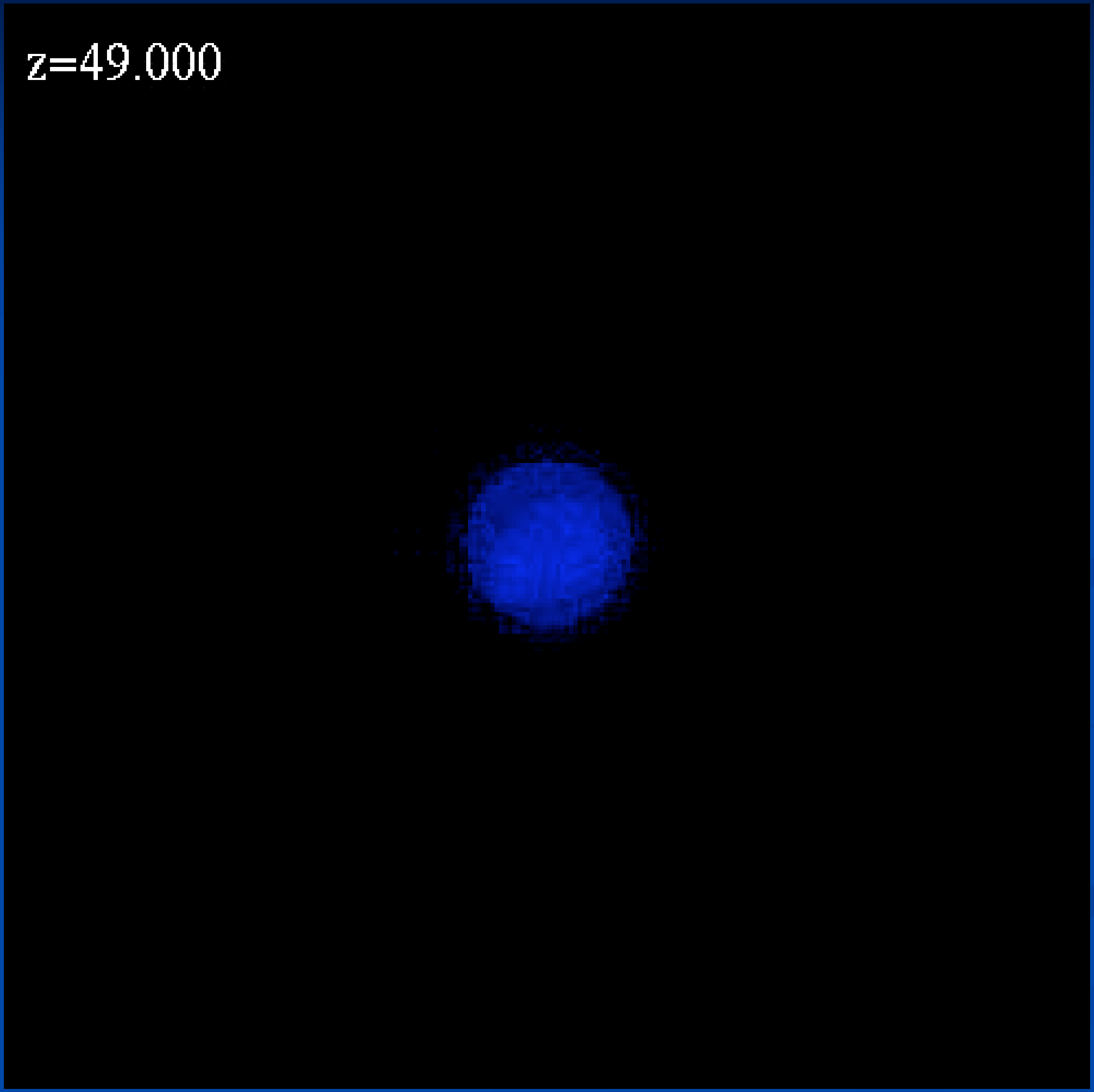
galaxies today

The Local Group



Dwarfs: most numbers type of galaxies + low metallicity

Structure Formation

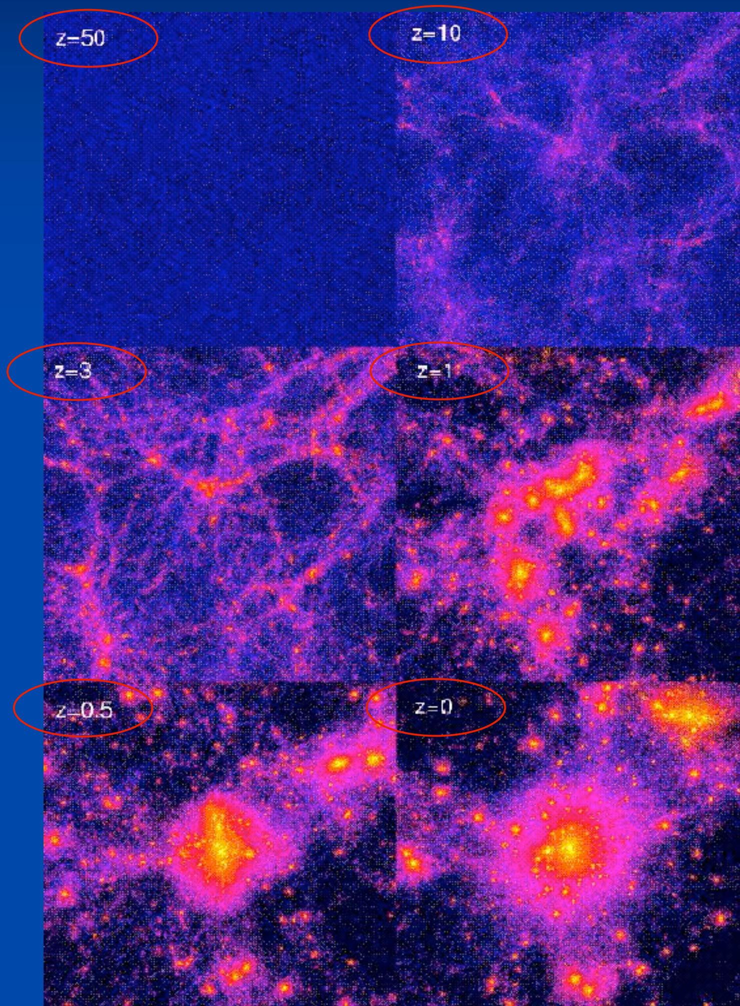


high-z:
small -> large structures
today:
still lots of low mass DM halos

Moore et al. 1999
Ghigna et al. 1998

CDM Models vs. Local Group

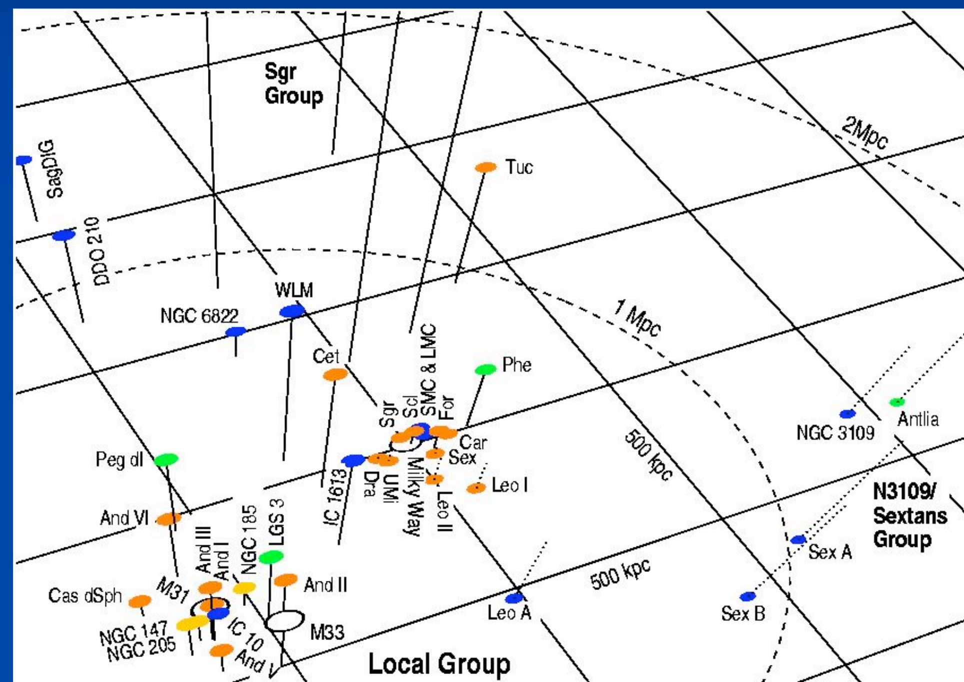
CDM simulations



Moore 1999

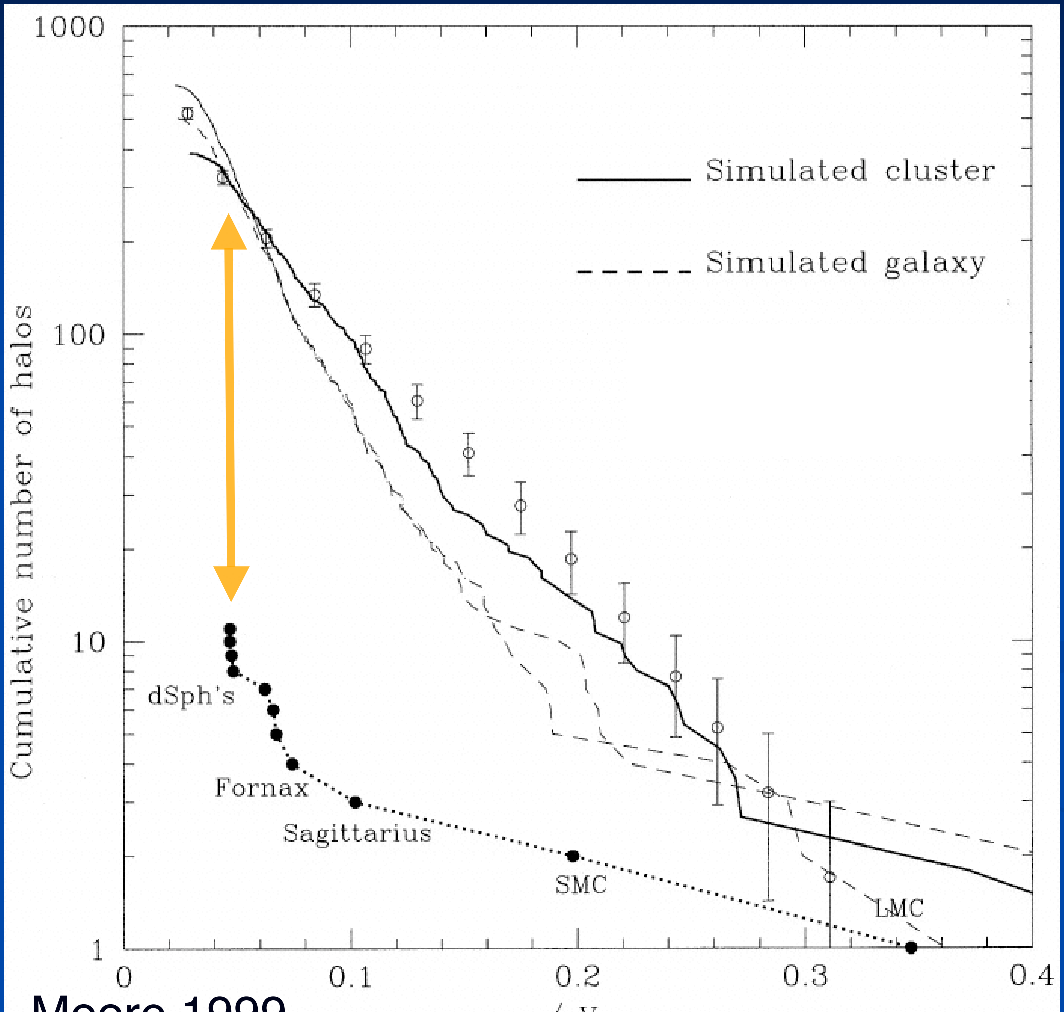
vs.

Structure of Local Group



Grebel 2002

CDM Models vs. Local Group

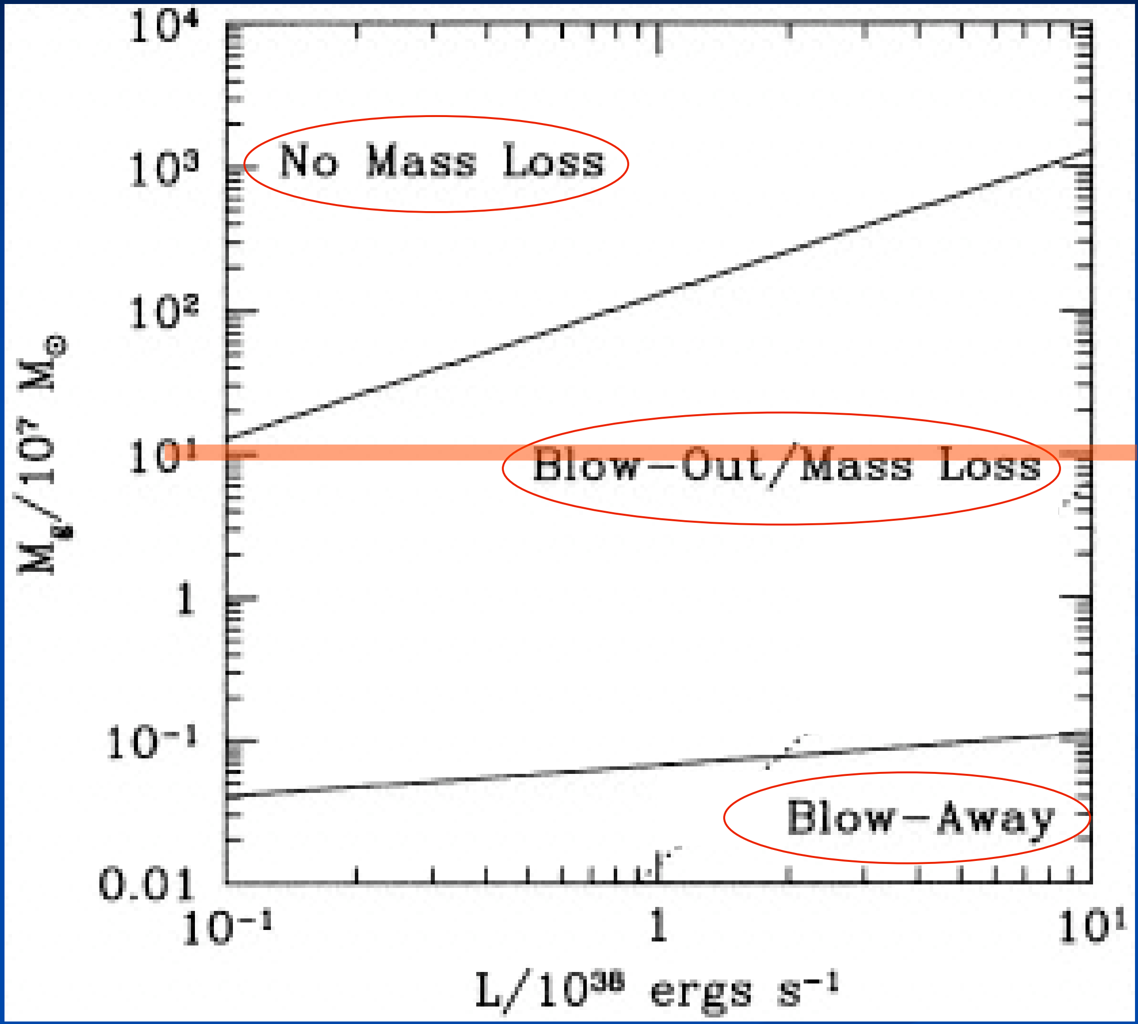


Moore 1999

'missing satellite problem'

-> challenge for both theoreticians and observers!
searches did not find missing population.

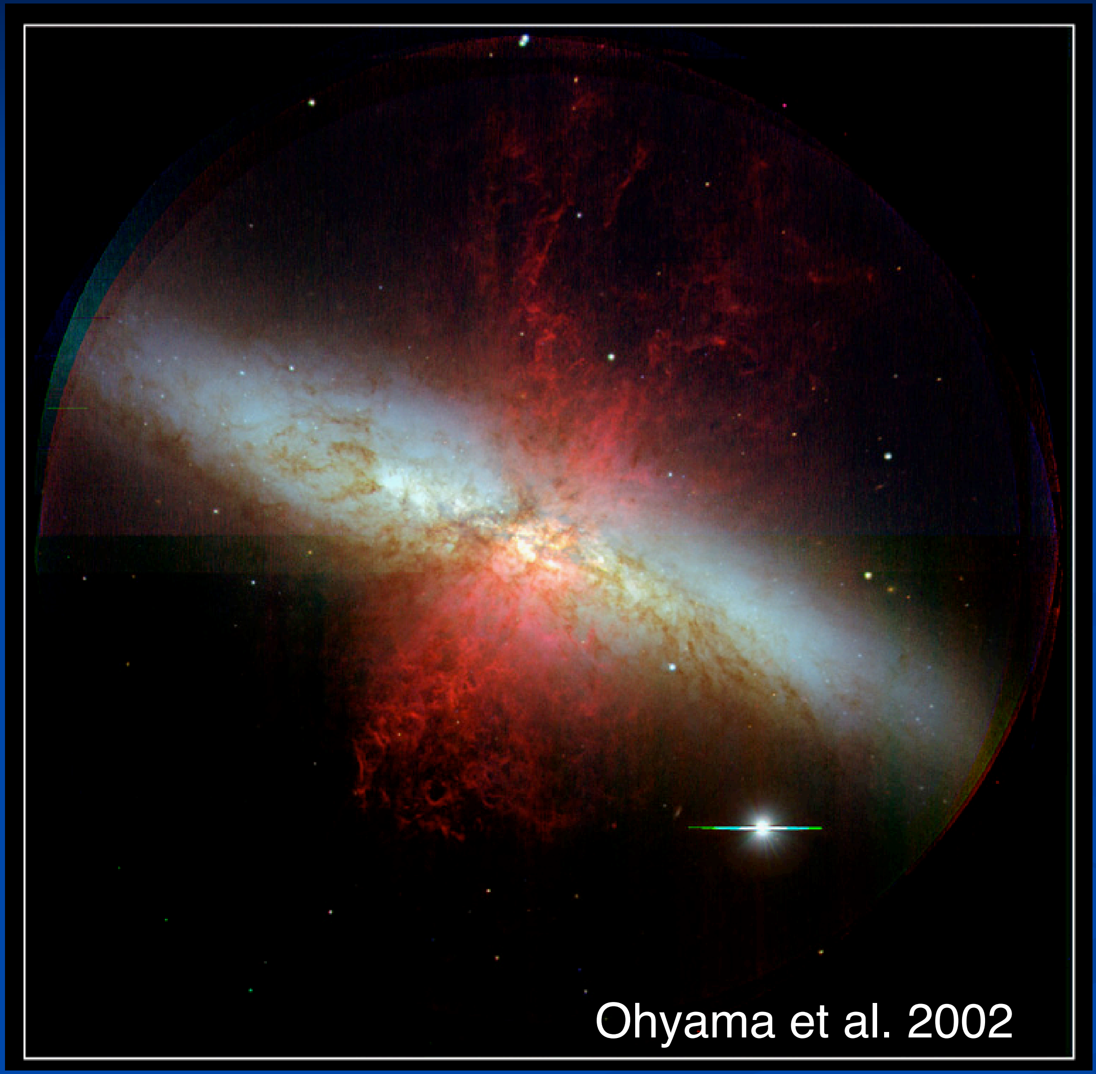
The Impact of SF



Mac Low & Ferrara 1999

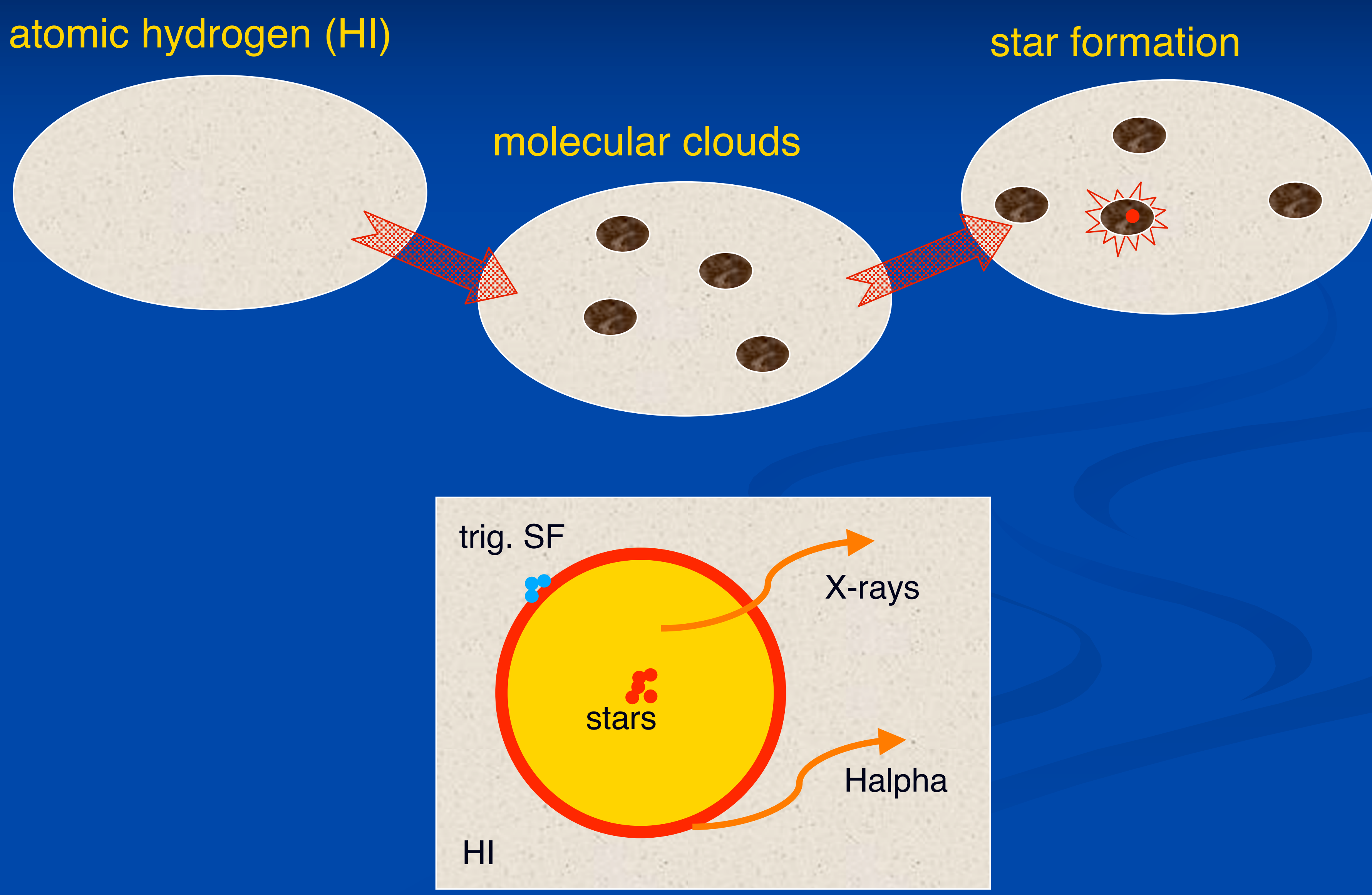
can blow-away explain 'missing satellite problem'?

The Impact of SF: M82


Ohyama et al. 2002

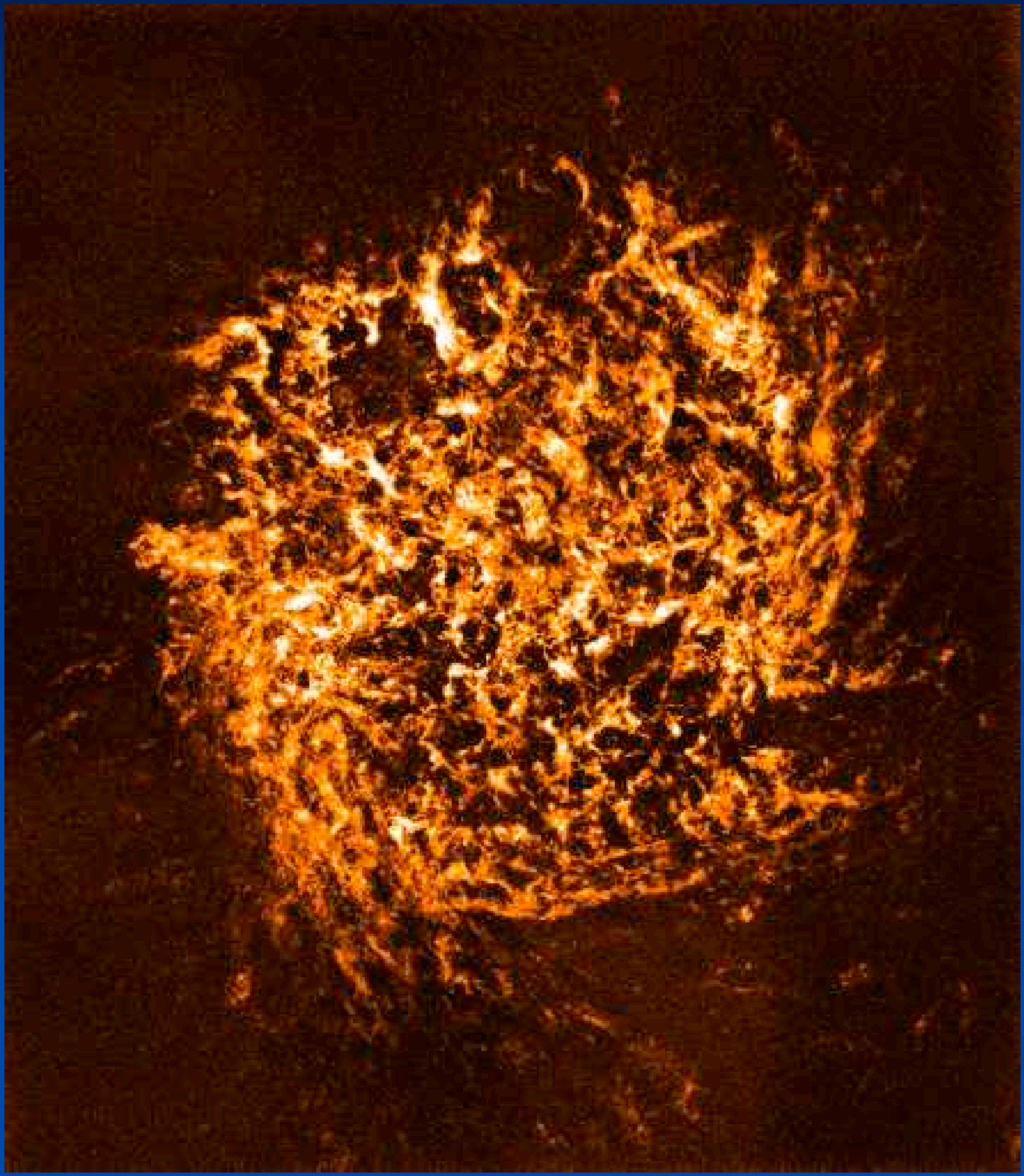
-> but can dwarf galaxies be ‘blown away’?

ISM <-> Star Formation



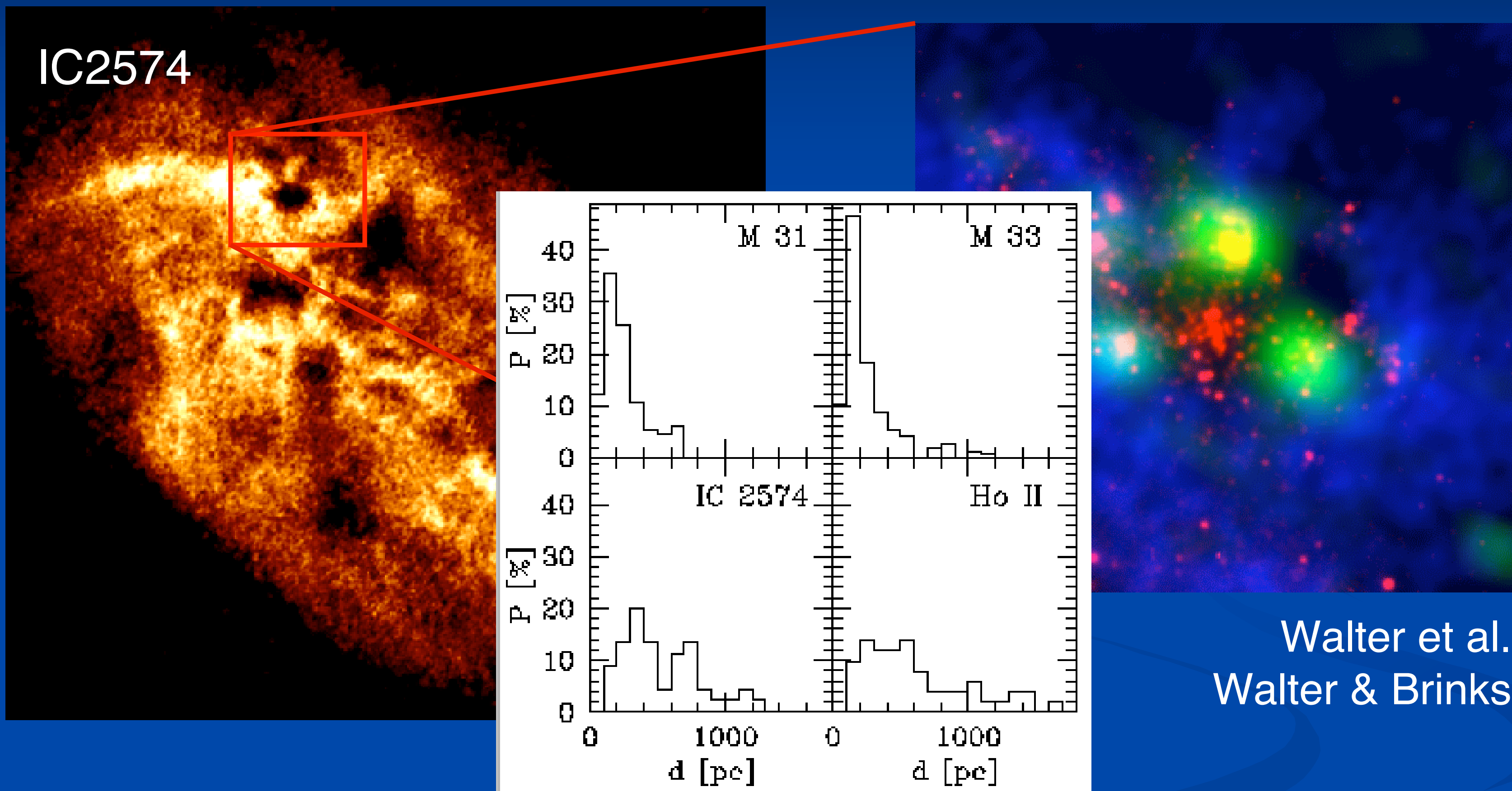
LMC

Atomic Hydrogen
in the LMC



Kim et al. 1998

The Impact of SF: IC2574



Walter et al. 1998
Walter & Brinks 1999

- v_{exp}=25 kms^{-1}, age: 15x10^{6} yr, E~10^{53} erg
  -> hole formed by central cluster (?)

trace SFH w/ HST ACS/WFC

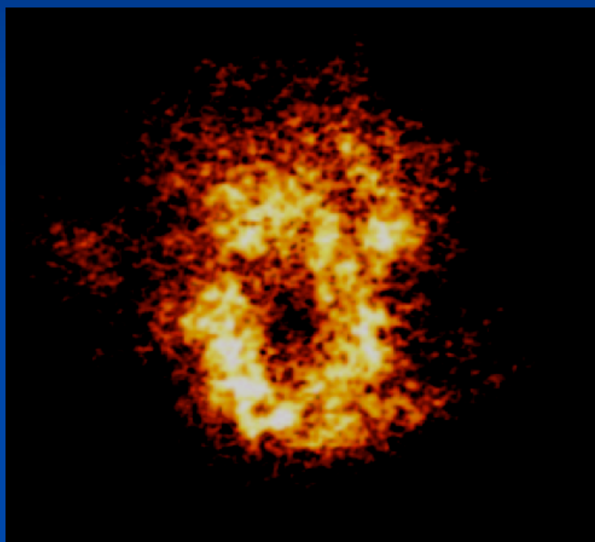
The Impact of SF: Lowest Mass

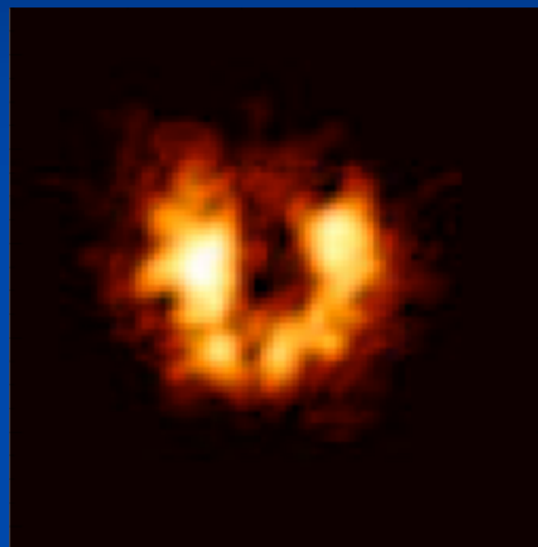
SFR~0.001 M_{sun} yr^{-1}

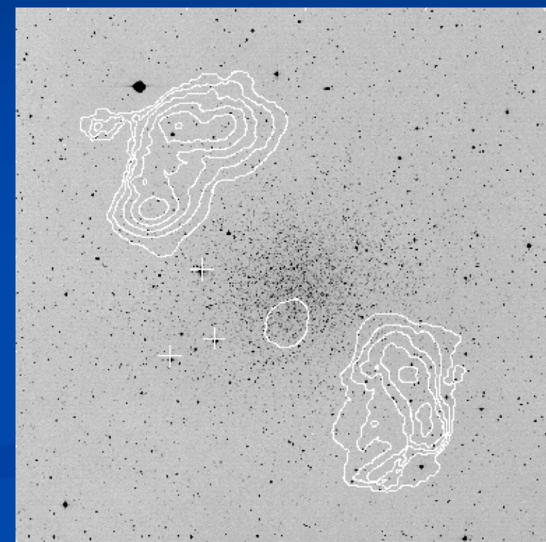
Holmberg I

M81 dwarf A

Sculptor







$M_{HI}=10^8\,M_{sun}$

$M_{HI}=10^7\,M_{sun}$

$M_{HI}\sim10^4\,M_{sun}$

Ott, Walter et al. 2001

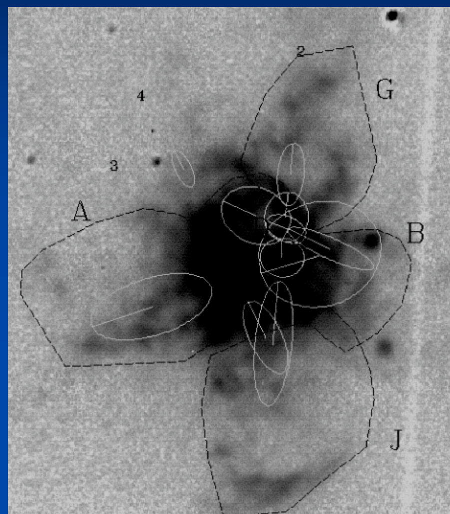
Carignan et al. 1998

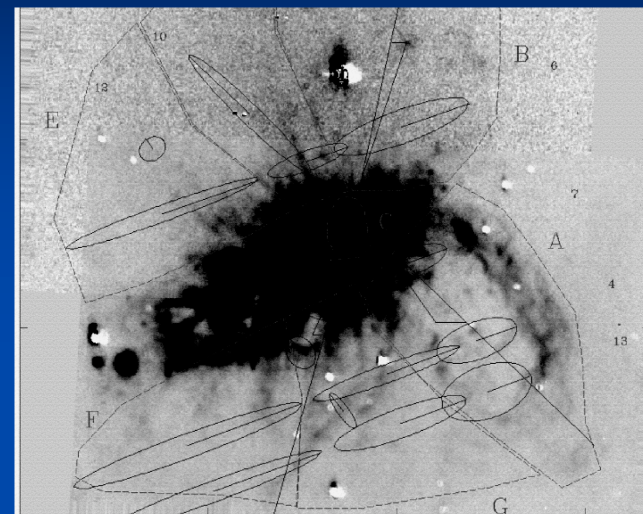
transition objects?
circumstantial evidence: SF pushes gas out
need observations of hot gas phase (X-rays)

The Impact of SF: Dwarf Starburst Galaxies

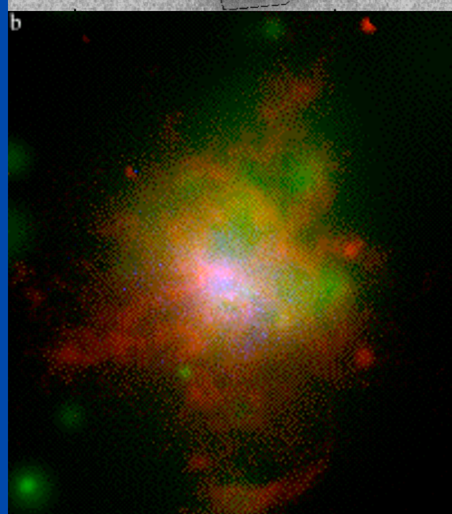
NGC 3077 | NGC 1569

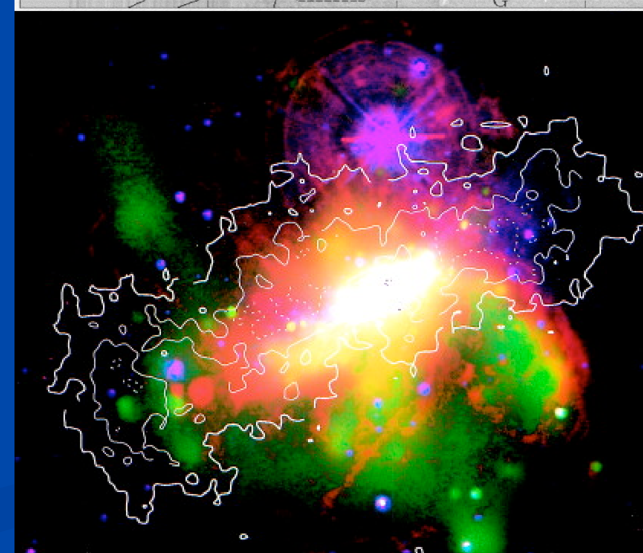
- Hα





- X-rays (Chandra)





$T \sim 3 \times 10^6$ K
$\rho \sim 0.1$ cm^{-3}
D=0.5-1.5 kpc

$SFR \sim 0.1\ M_{sun}\ yr^{-1}$

Ott, Martin & Walter 2003

Martin et al. 2002

Missing Satellites

Discrepancy w/ CDM model?

Some cases show ‘blow-out’...
...but ‘blow-away’ ?

still need to find transition objects
-> *deep* optical/Hα observations + spectroscopy
-> XMM-Newton follow-up

other ‘solutions’: problem w/ CDM simulations
low-mass dark matter halos DARK

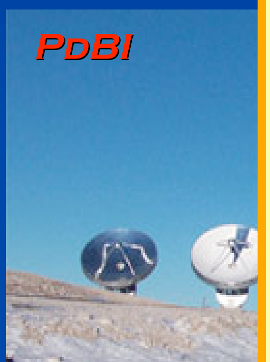
Mol. Gas & Millimeter Interferometers

- molecular gas: fuel for SF
- cold H_2 invisible -> use CO as tracer
- [C

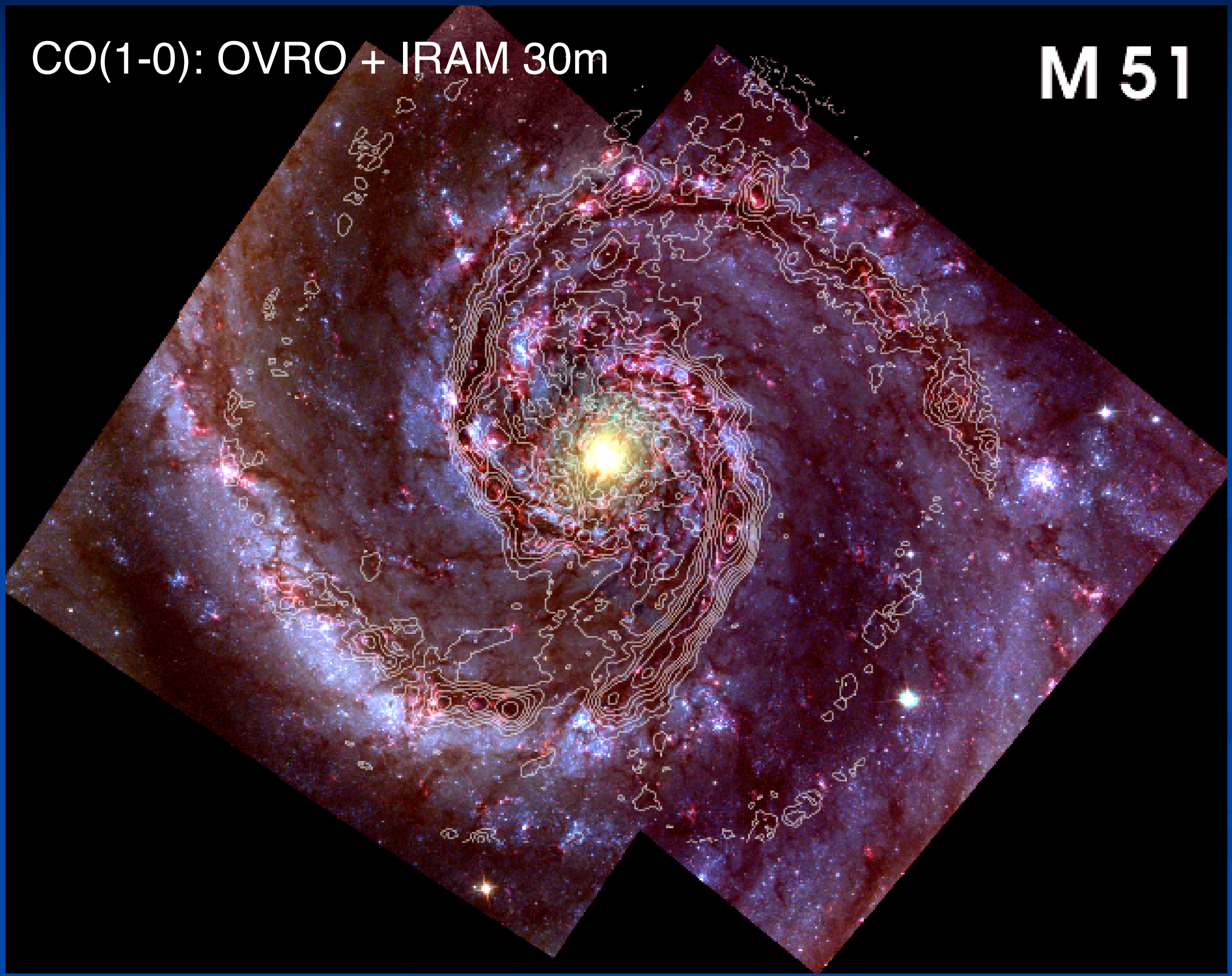
Fuel for SF in:

z=0
- spiral galaxies
- dwarf galaxies
- starburst galaxies
- mergers

high z
- sources @ 2<z<5
- sources in the EoR: z>6



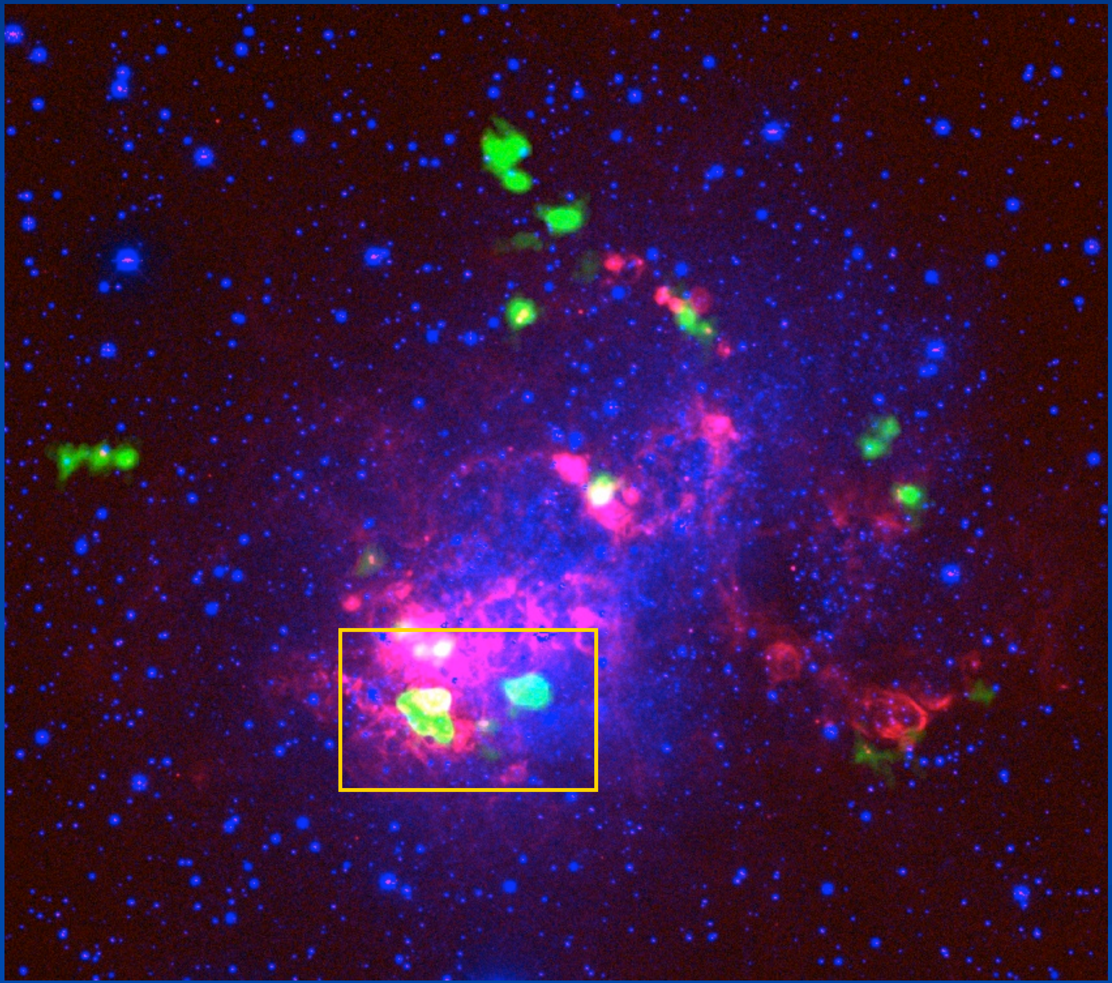
Spiral Galaxy: M51



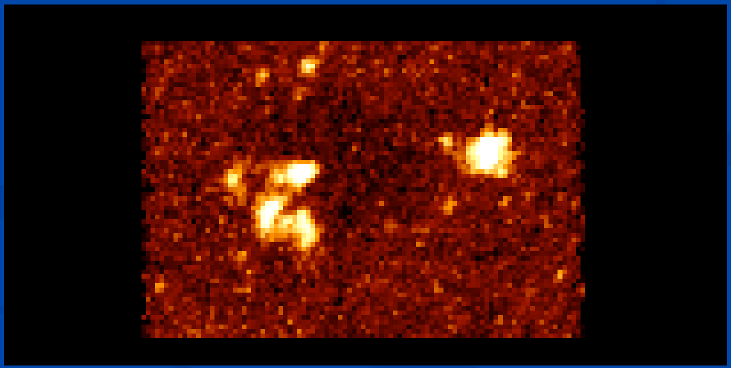
Scoville et al. 2002, Aalto et al. 2000, Schinnerer et al. 2004

Dwarf Galaxy: IC10

low-metallicity dwarf galaxy



CO(1-0): OVRO



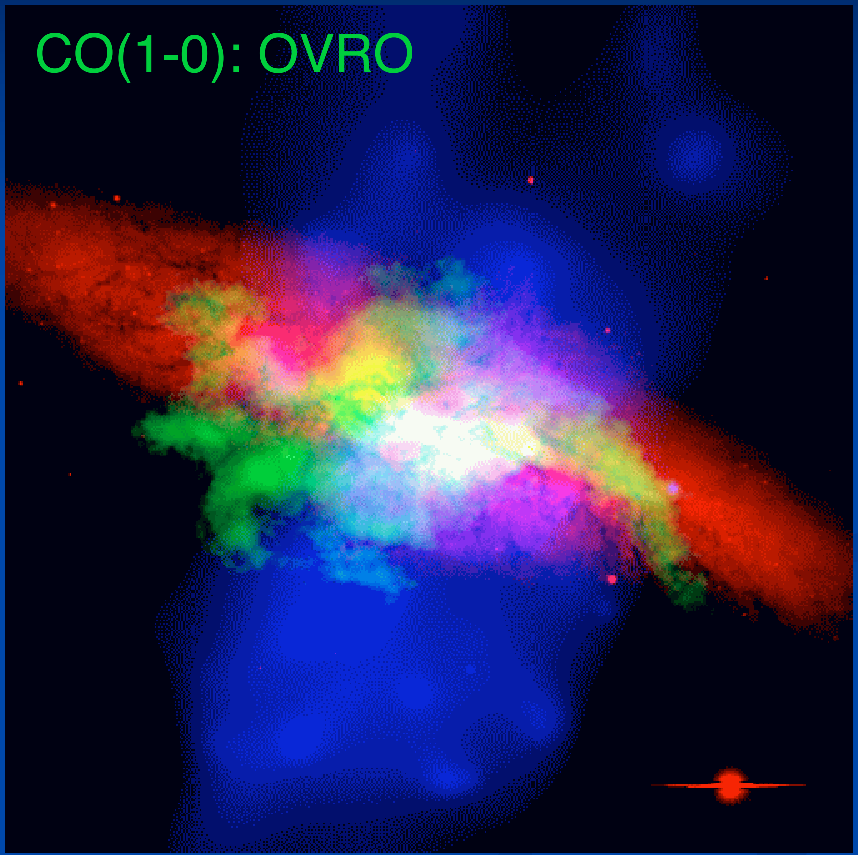
res.: 12 pc, 0.6 kms^{-1}

Walter et al. 2004

Starburst Galaxy: M82

D ~ 3.5 Mpc

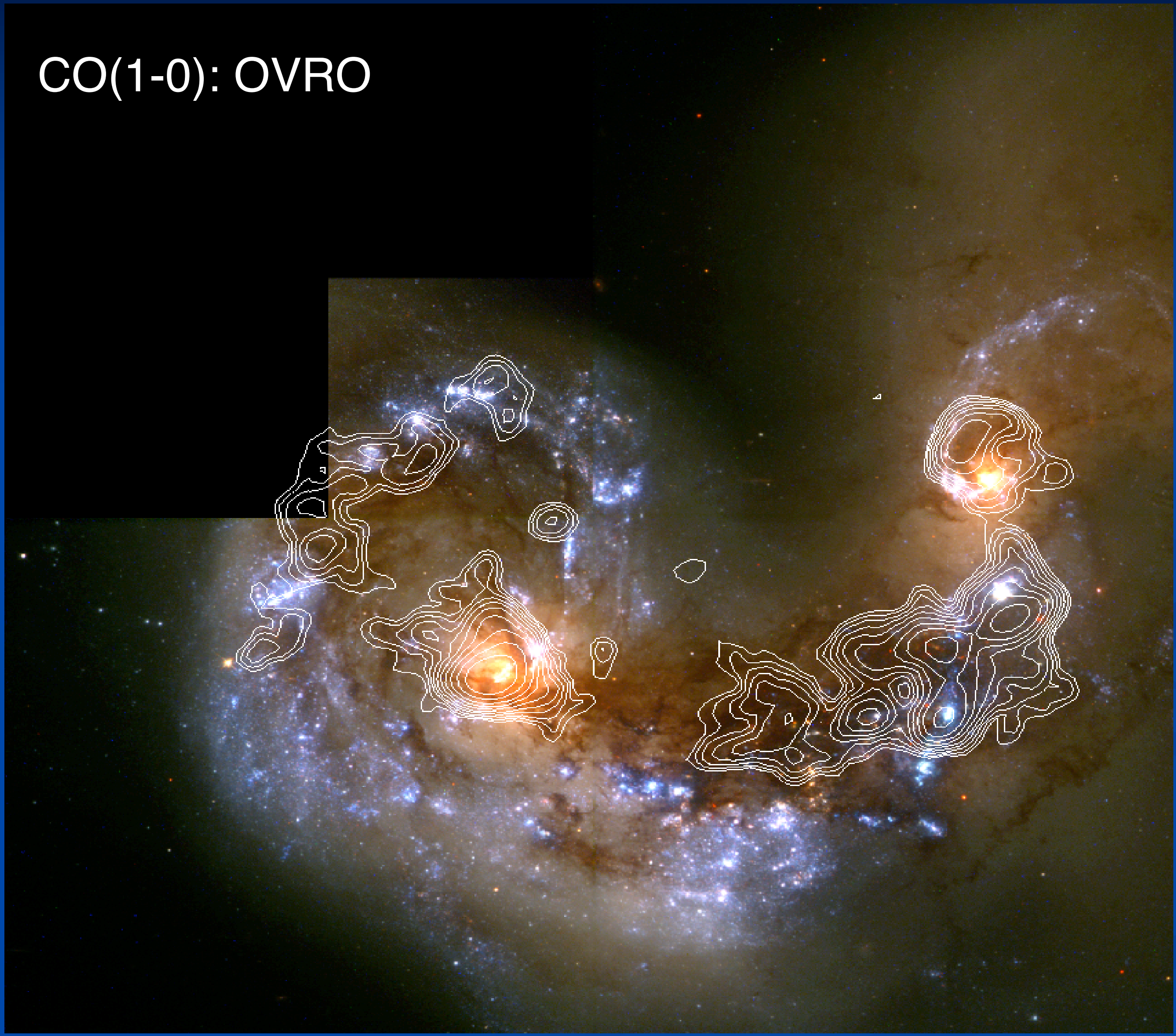
Ohyama et al. 2002



Walter, Weiss & Scoville 2002

- Streamers with no SF, M_{H2}~10^9 M_{sun}; M(disk:halo:streamers)=1:1:1
- Molecular Gas in Outflow/Halo (line splitting)

Merger: Antennae



$3 \times 10^9\ M_{sun}$

Whitmore et al. (1999)
Wilson et al. (2000)

Conversion CO -> H_2

- CO luminosities -> M_{H2}

  $X_{CO} = N(H_2)/I_{CO}$ -> $M(H_2)$

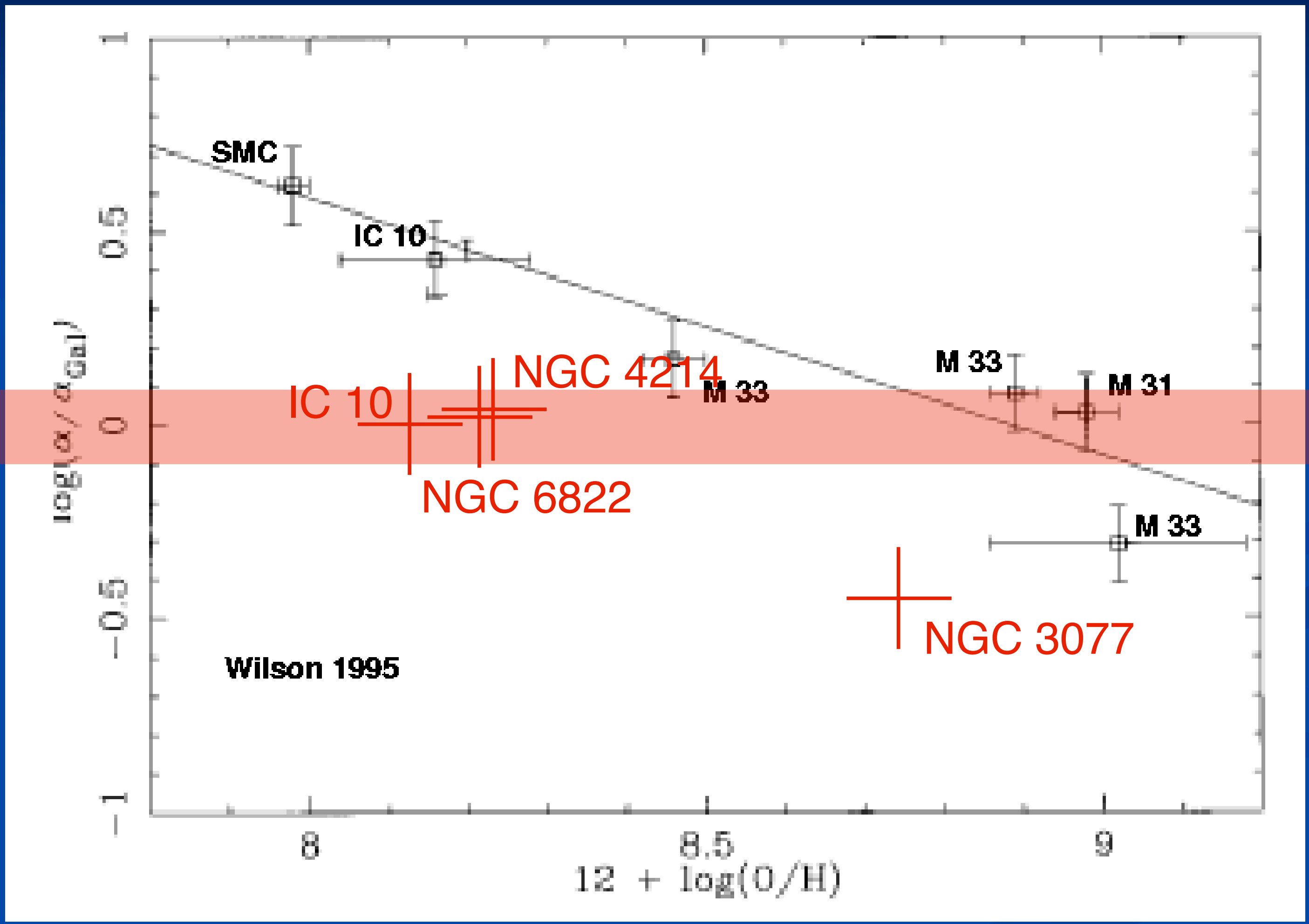
  $M_{vir} = M(H_2) \sim 240$ * r[pc] * □v^2[km/s]

- Galaxy: $X_{CO} = X_{gal} = 2.3 \times 10^{20}$ cm^{-2} $(K\ km\ s^{-1})^{-1}$
  (Strong et al. 1988)

- starburst galaxies/ULIRGs: $X_{CO} \sim 0.3\ X_{gal}$
  (Downes & Solomon 1998, Weiss et al. 2000)

- low-metallicity dwarfs: $X_{CO} = X_{gal}$
  (Walter et al. 2001, 2002; Bolatto et al. 2003)

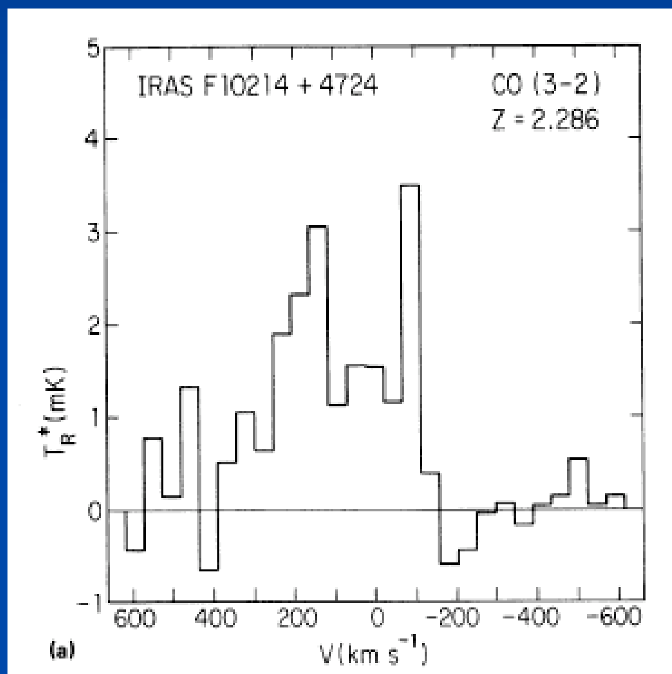
X_{CO} at low Metallicity ?



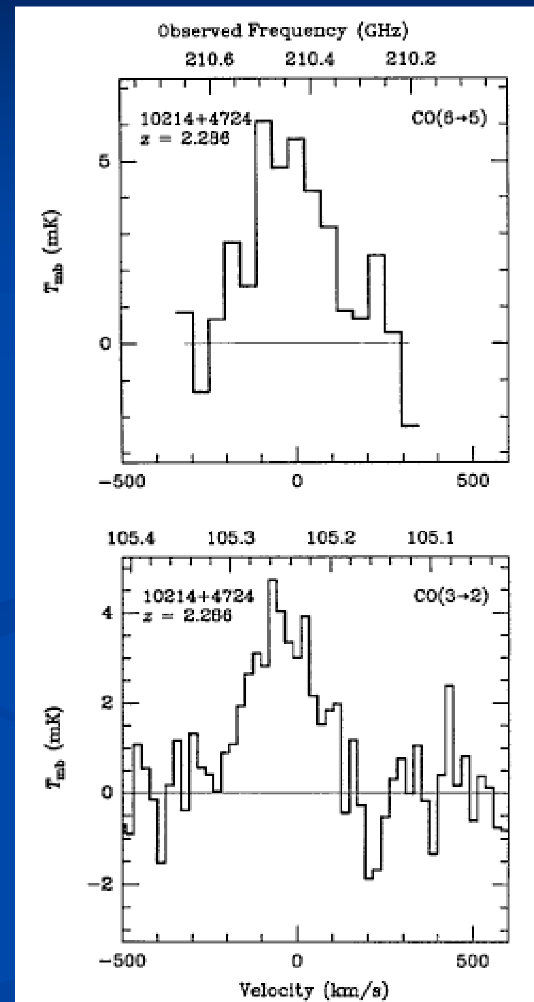
finding consistent with Bolatto et al., Rosolowsky et al. (2003)
X_{CO} dependent on metallicity + starburst environment?

CO @ z=2.29

IRAS 10214+4724 at z=2.286



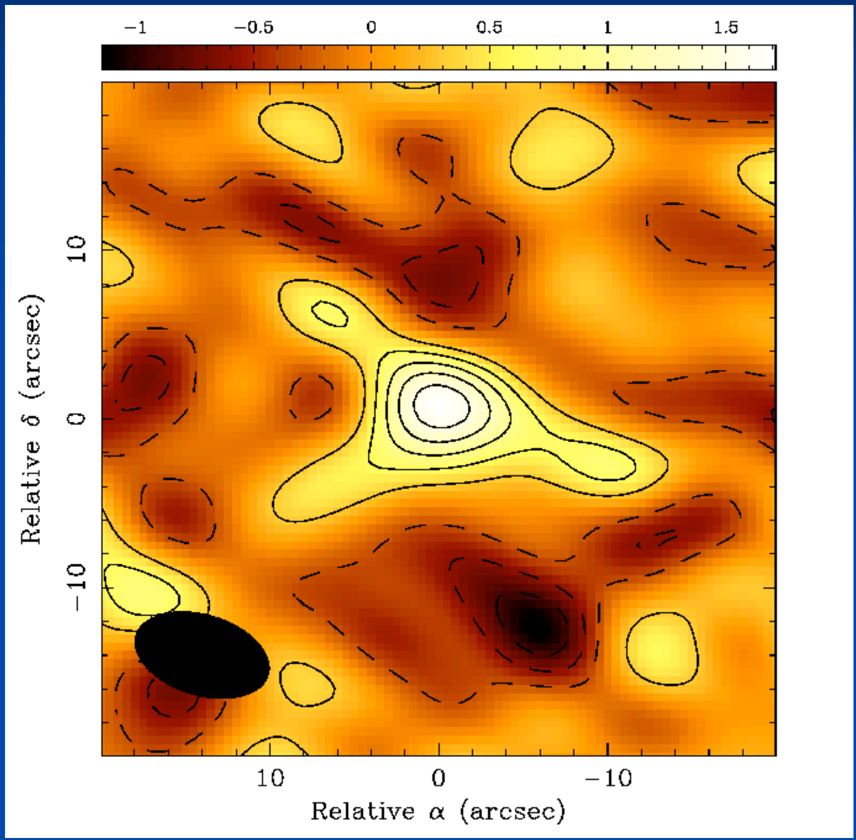
Brown & van den Bout 1991

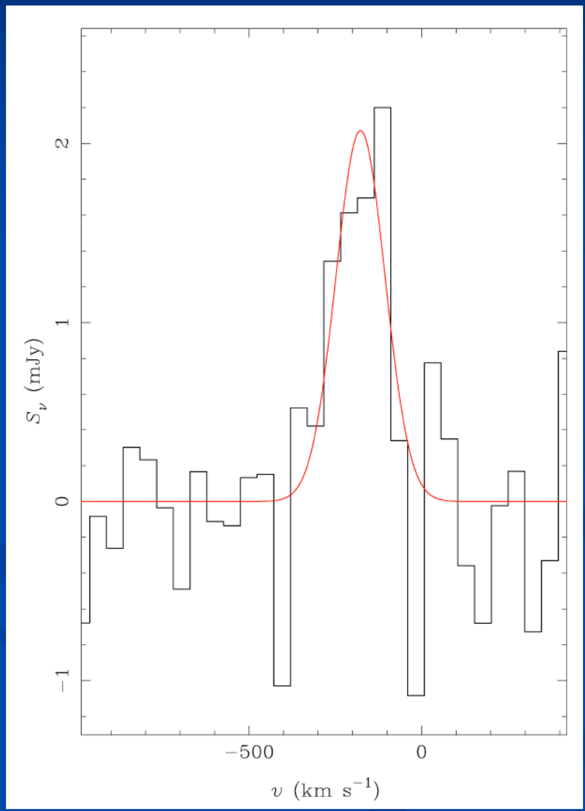


Solomon, Downes & Radford 1992

MS1512-cB58

Lyman Break galaxy at z=2.7





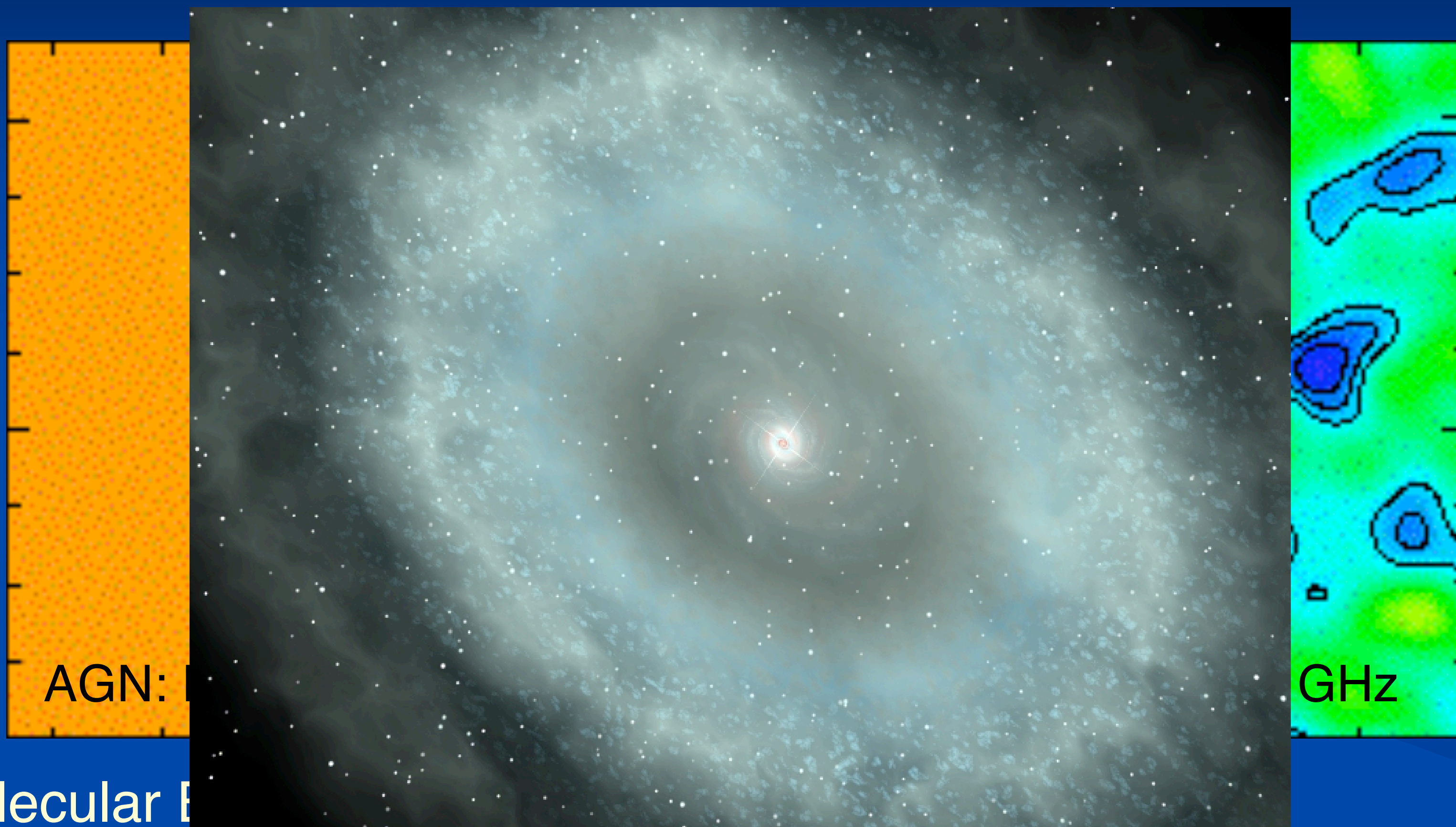
Baker et al. (2003)

lensing factor: 31.8

M_{gas}=6.6 10^9 M_{sun}; M_{dyn}=1.0 10^{10} M_{sun}

4kpc SF Disk Around QSO

J2322+1922: Lensed QSO at z=4.12



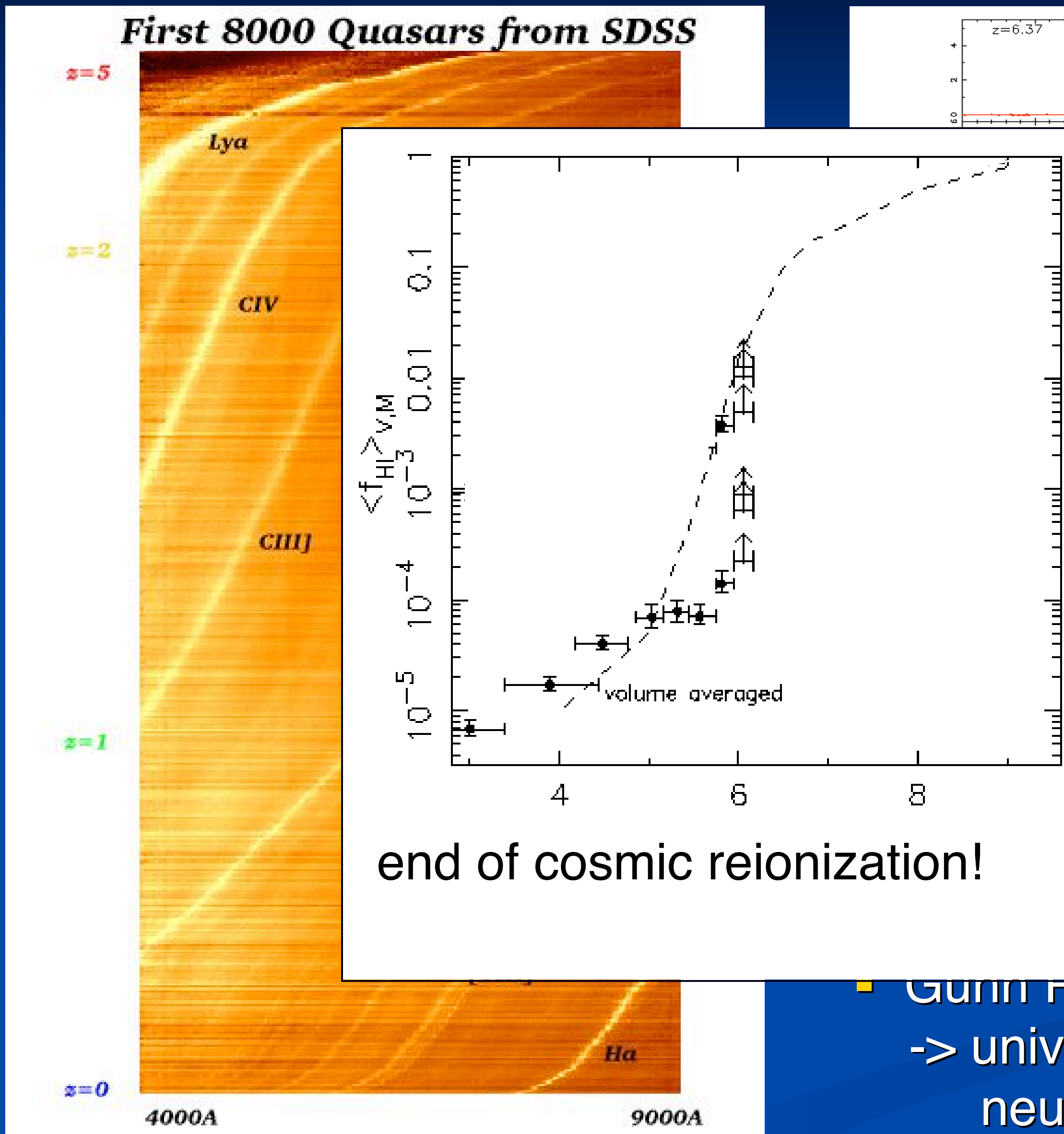
Carilli et al. (2003)

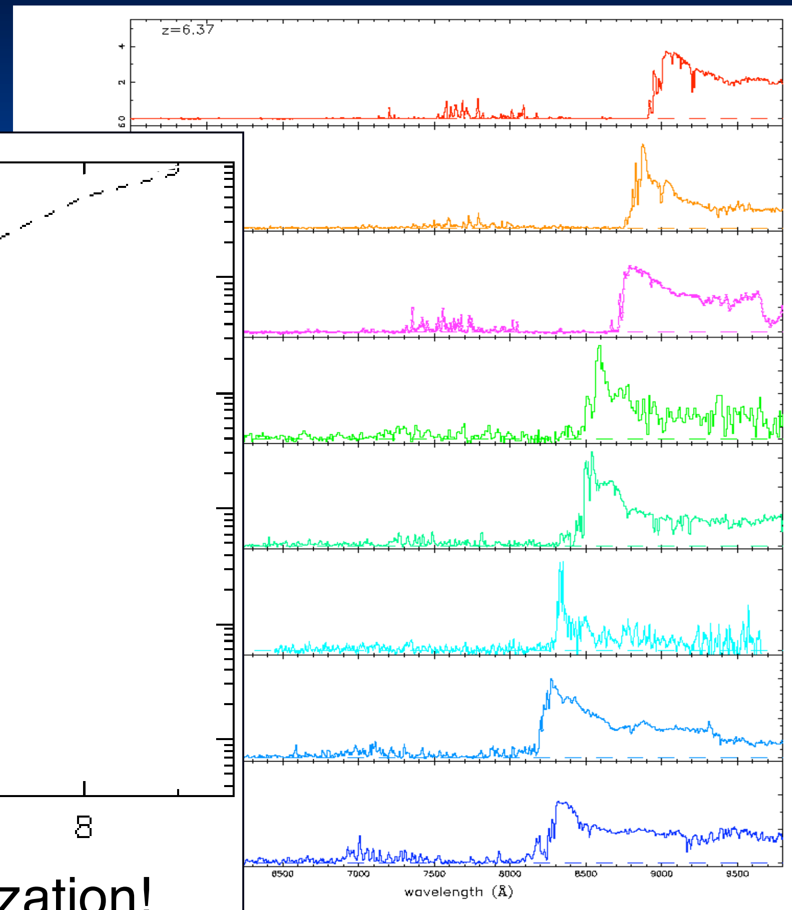
Molecular E

RC *cospatial* w/ Gas, not AGN, r ~ 2kpc

dust emission heated by SF *not* AGN, SFR~3000 $M_{sun}yr^{-1}$ (!)

SDSS Detection of High-z QSOs

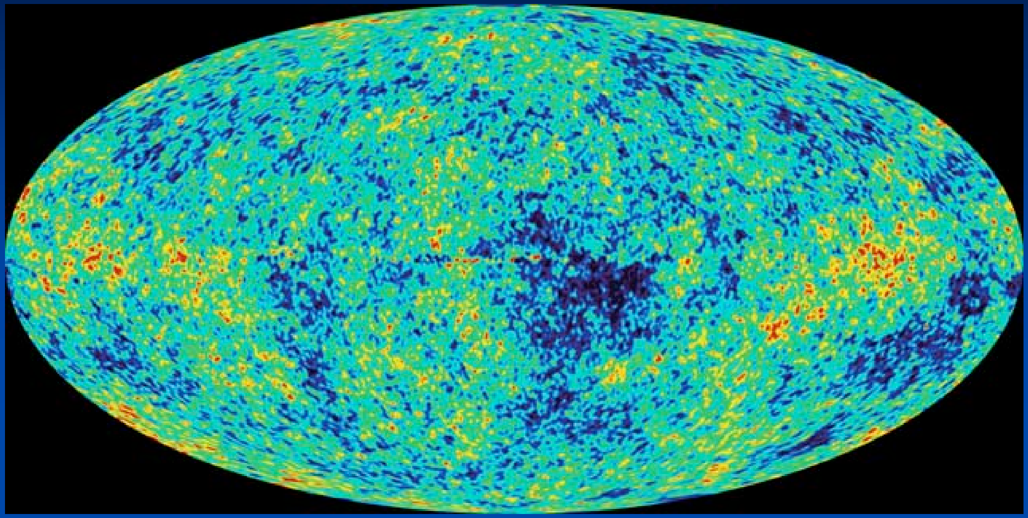


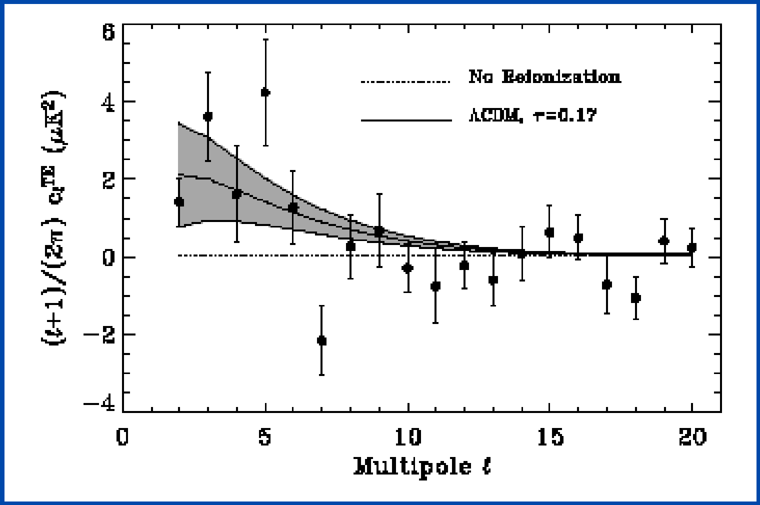


- Gunn Peterson effect:
  -> universe significantly (>1%)
  neutral at z>6

Fan et al. 2003

WMAP CMB Polarization





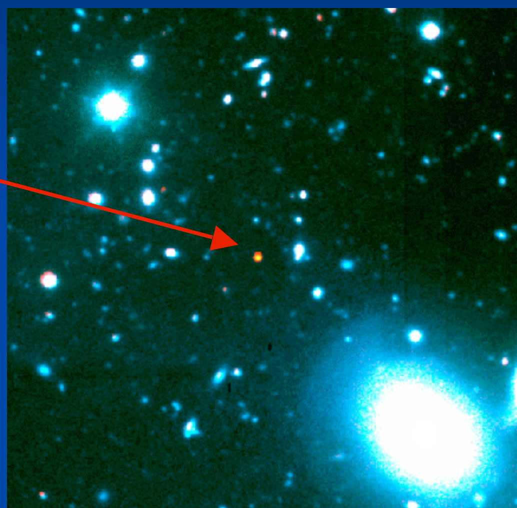
Kogut et al. 2003

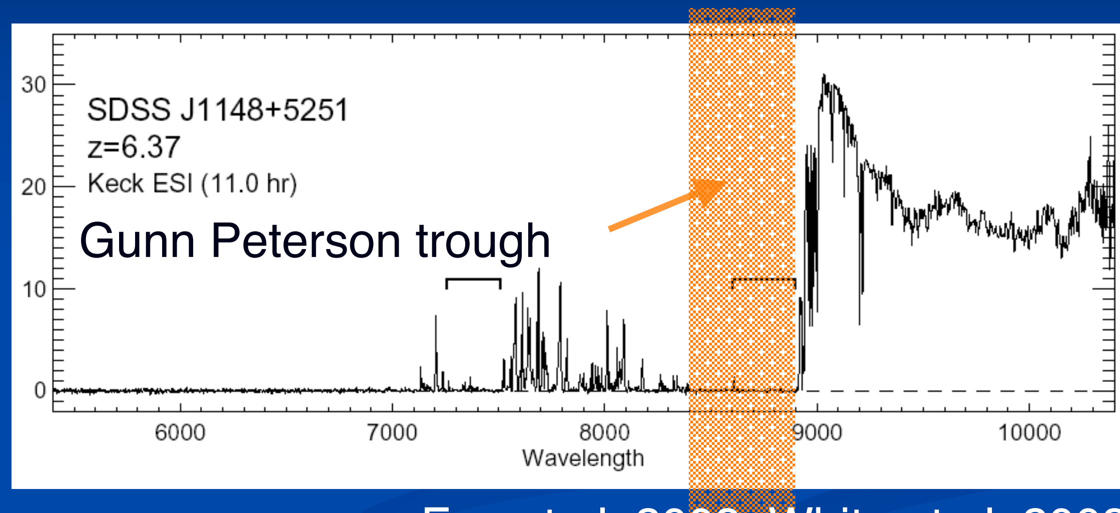
WMAP polarization: universe ~50% neutral at z=17+/-3

Reionization complex (z~20-6); not a phase transition

J1148+5251

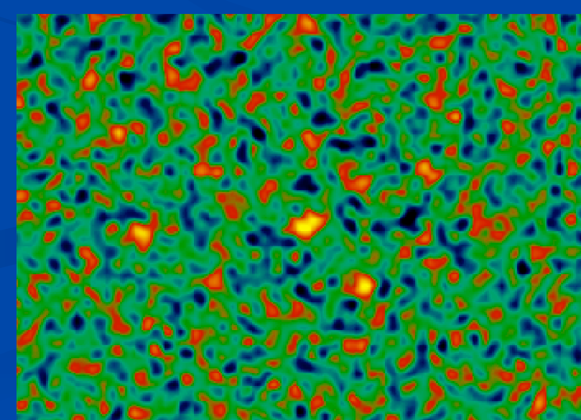
J1148+5251 at z=6.4 (@ end of EoR)



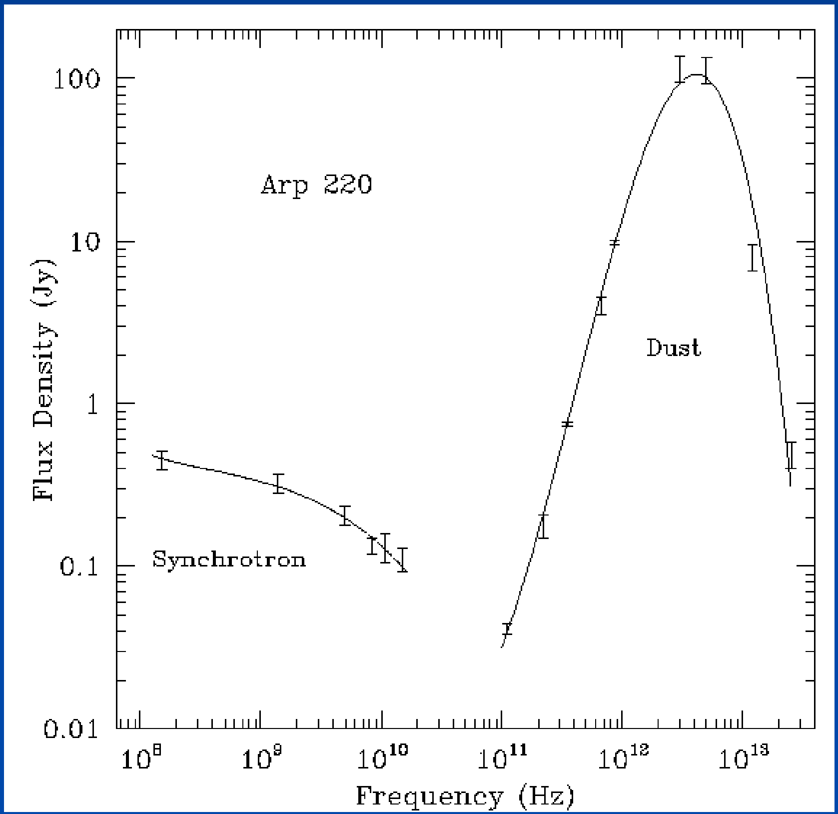


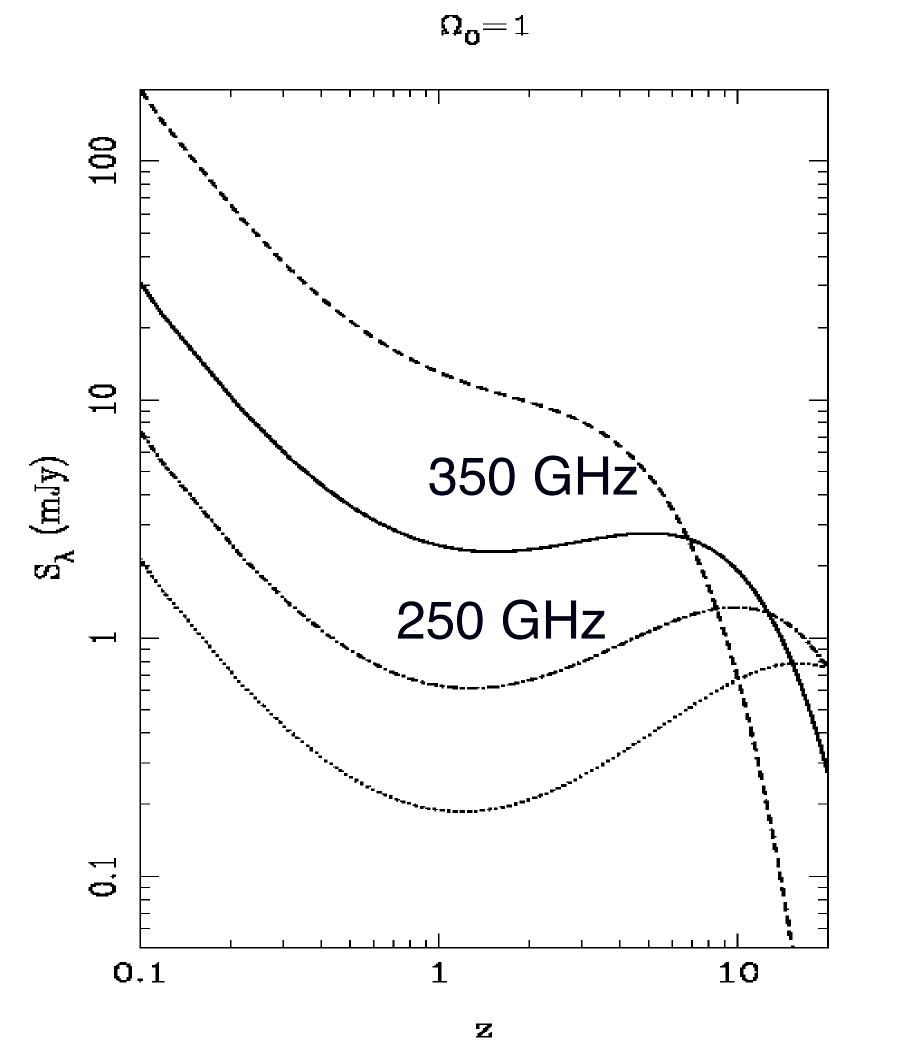
Fan et al. 2003, White et al. 2003

- z=6.42; age~870 Myr
- one of the first luminous sources
- M_{BH} ~ 1-5 x 10^9 M_{sun} (Willot et al. 2003)
- M_{dust} ~ 10^8 M_{sun} (Bertoldi et al. 2003)
- ~solar metallicity

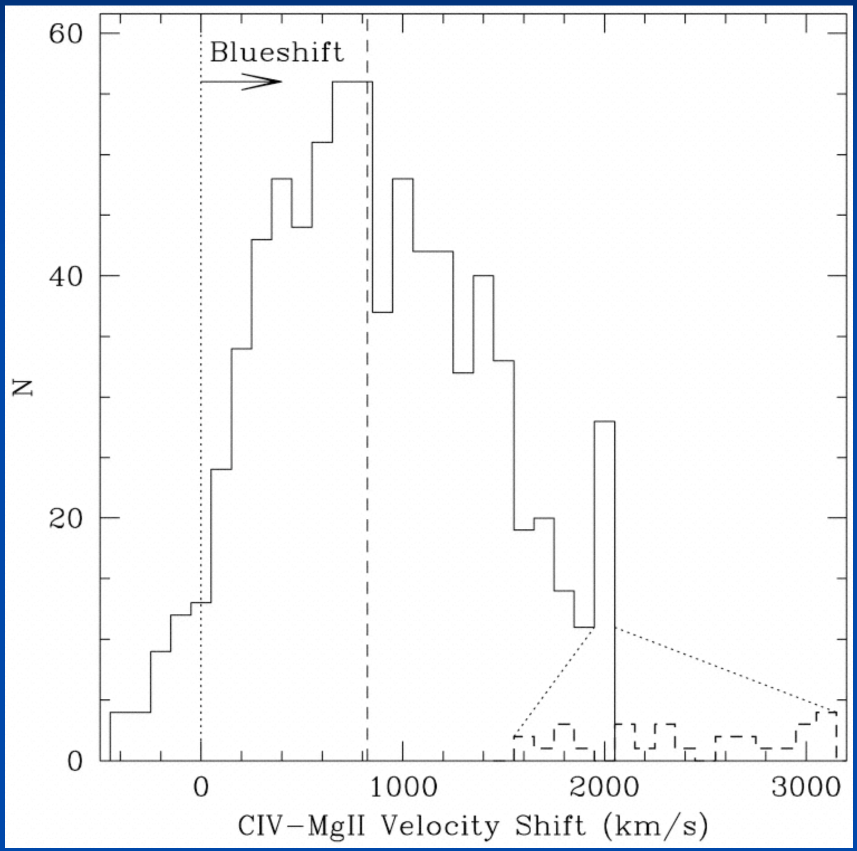


The ‘Magic’ of MM/SUBMM





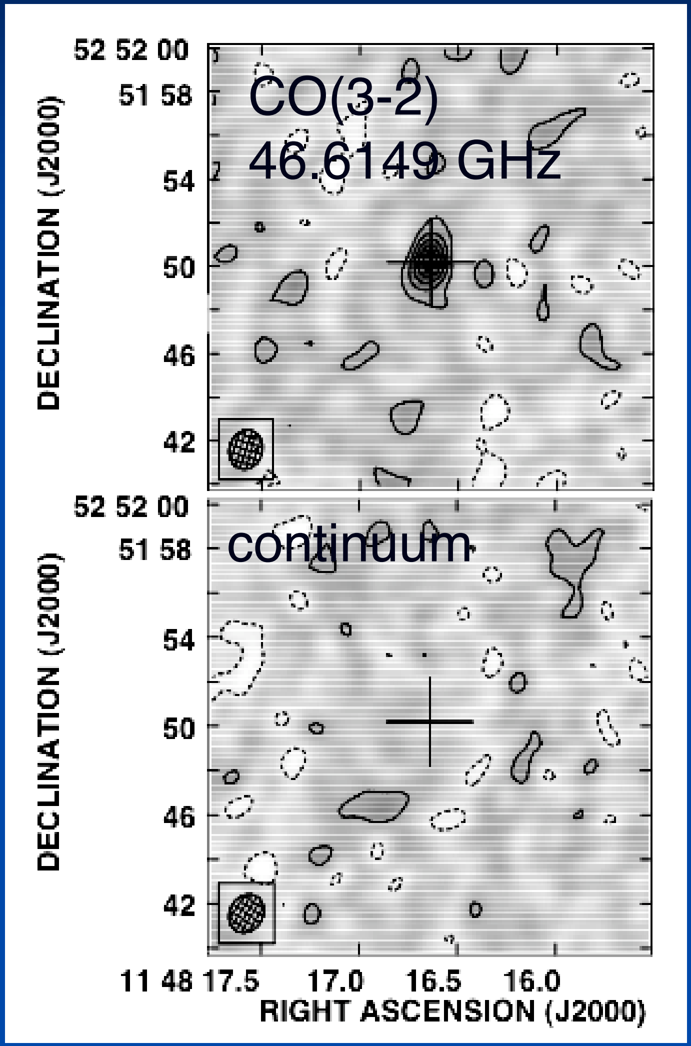
Redshift of Host Galaxy?



Richards et al. 2002

Problem for CO search:
e.g.: VLA
50 MHz = 300 km/s
$\Delta\nu/\nu$=0.001 (bad!)

Mol. Gas @ End of EoR



- host galaxy(!)
- molecular gas mass:
  $M_{H2} = 2 \times 10^{10}\ M_{sun}$
- diameter:
  0.2"<D<1.5"   (1"=5.6 kpc)
- mass in C and O: $\sim 3\times10^{7}\ M_{sun}$
  enrichment started at z>8
  (10^{7} [100 M_{sun}] Pop III stars)

Walter, Bertoldi, Carilli et al. 2003, Nature

Metals at z>6

- CO: C and O are abundant
- metallicities: (super)solar!

  e.g., Pentericci et al. 2002, based on NV/CIV ratio
- Fe/α ratios (α=Mg); no evolution of QSO metallicity

  e.g., Freudling et al. ‘03; Barth et al. ‘03;

  Maiolino et al. ‘03; Dietrich et al. ‘03

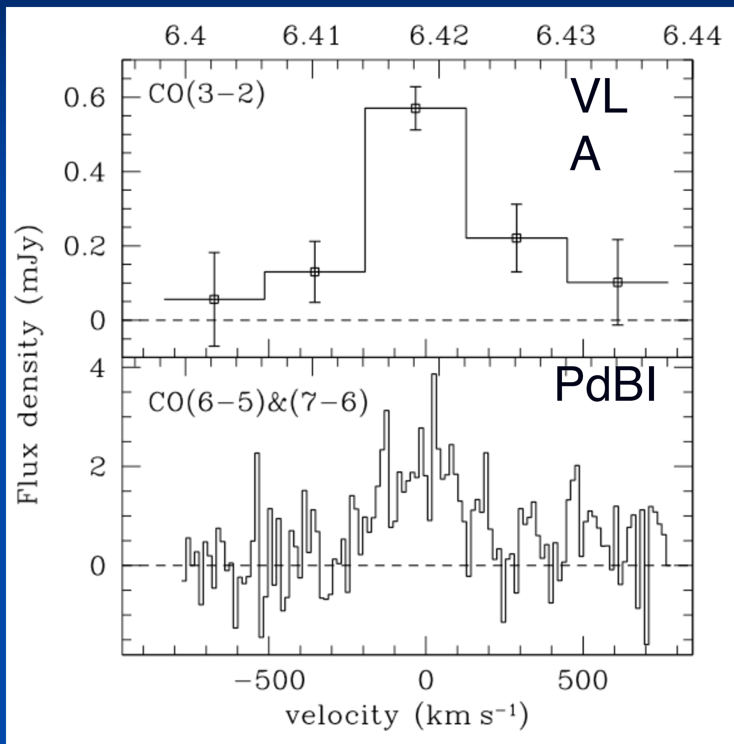
-> generations of stars must have formed at z>8

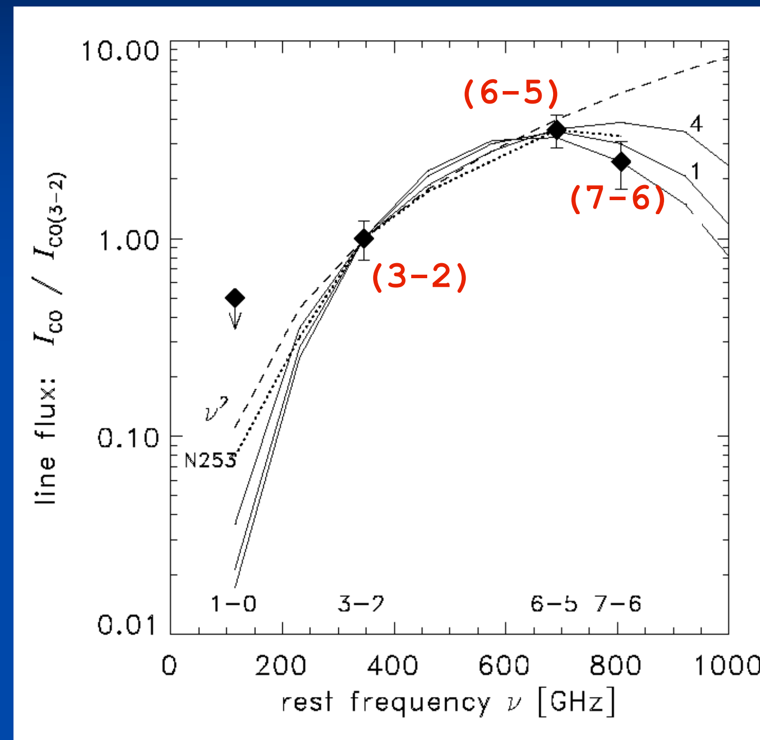
(SN Ia progenitors?, Pop III stars)

optical studies:

- give abundances but not masses!
- trace AGN region only

CO @ z=6.42

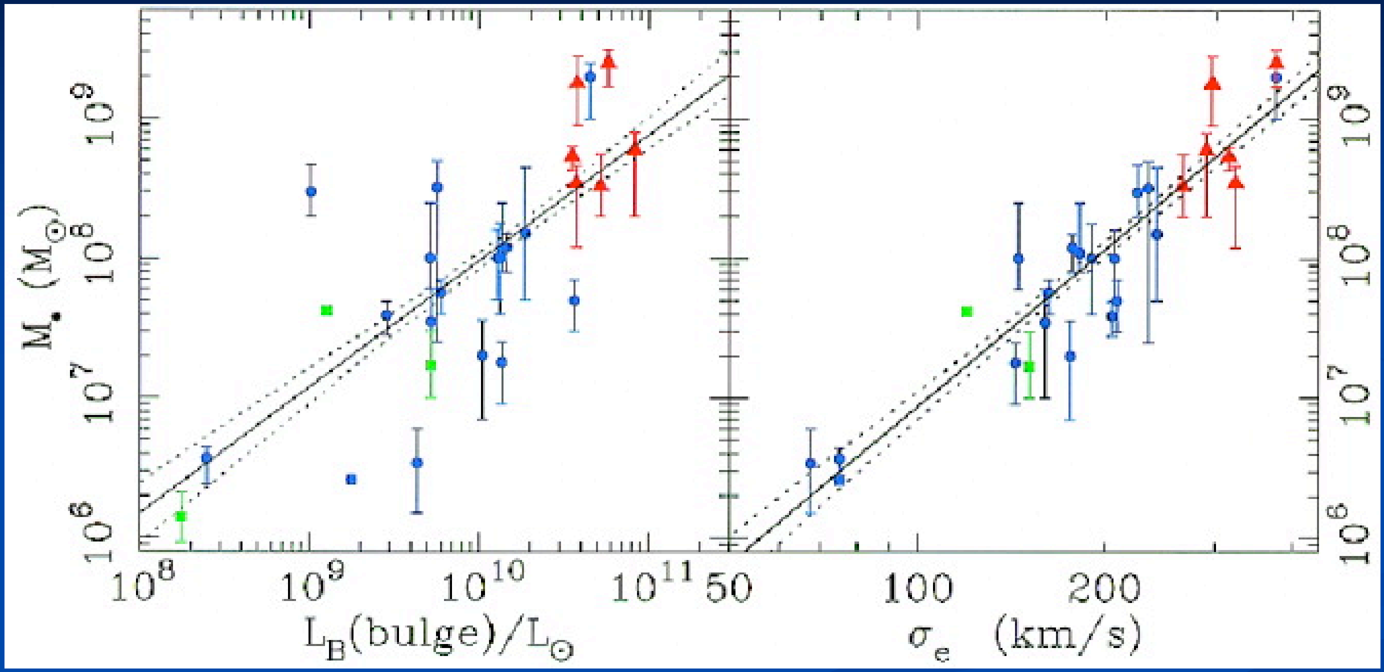




- M_{dyn} = 2x10^{10} M_{sun} (sin i)$^{-2}$; massive! (<-> CDM models, M-□)
- z=6.419 (precise)
- T_{kin}=100K, n_{H2}=10^5 cm^{-3}

Walter et al. 2003
Bertoldi et al. 2003

M_{BH}-σ Relation at highest z?



Gebhardt et al. 2000

Coevolution of BH and Bulge

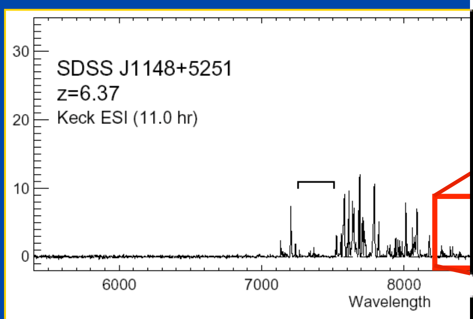
Shields, Gebhardt et al. 2003: M_{BH}-σ holds to z~3

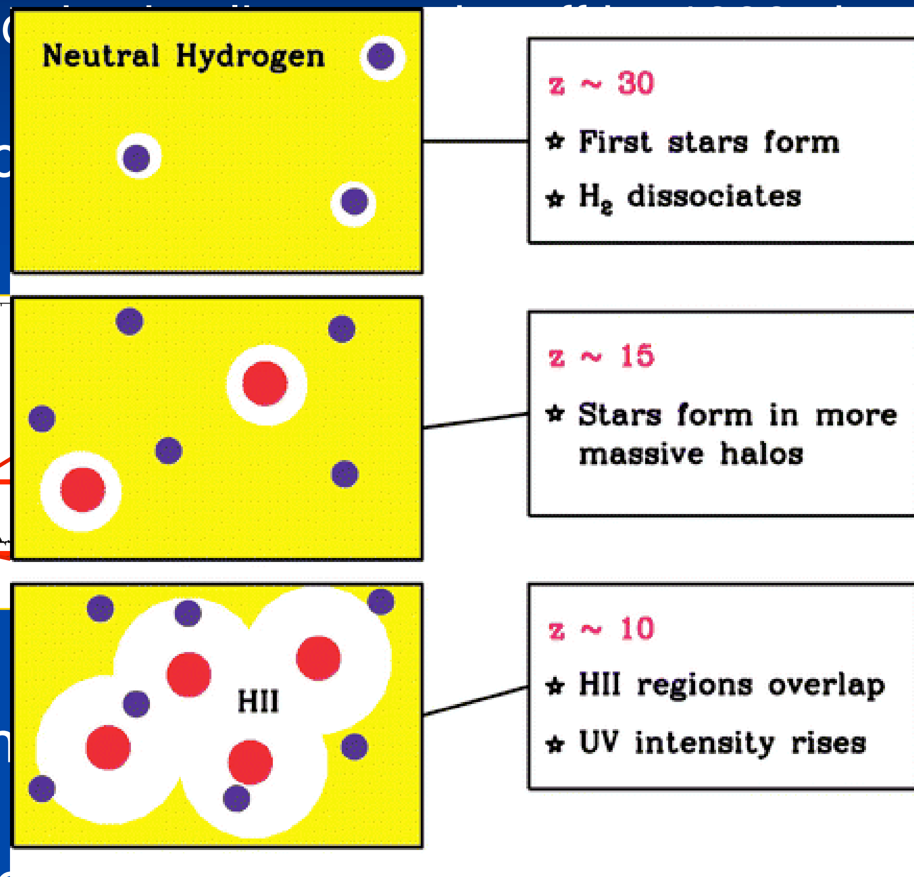
1148+5251: $M_{BH}=3x10^9$ M_{sun}
$M_{dyn}=M_b>2x10^{10}$ M_{sun}

ratio ~ 1:10 and not 1:1000 ? -> need to resolve disks (ALMA)

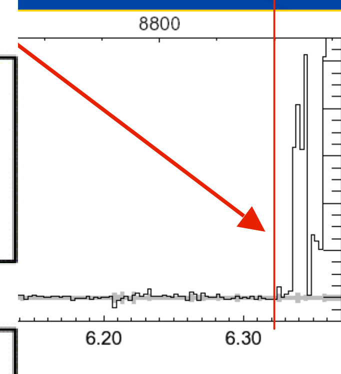
Cosmological Stromgren Sphere Around QSO

- CO: z=6.419
  (optical high i   s^{-1})
- proximity effec





Barkana & Loeb 2001

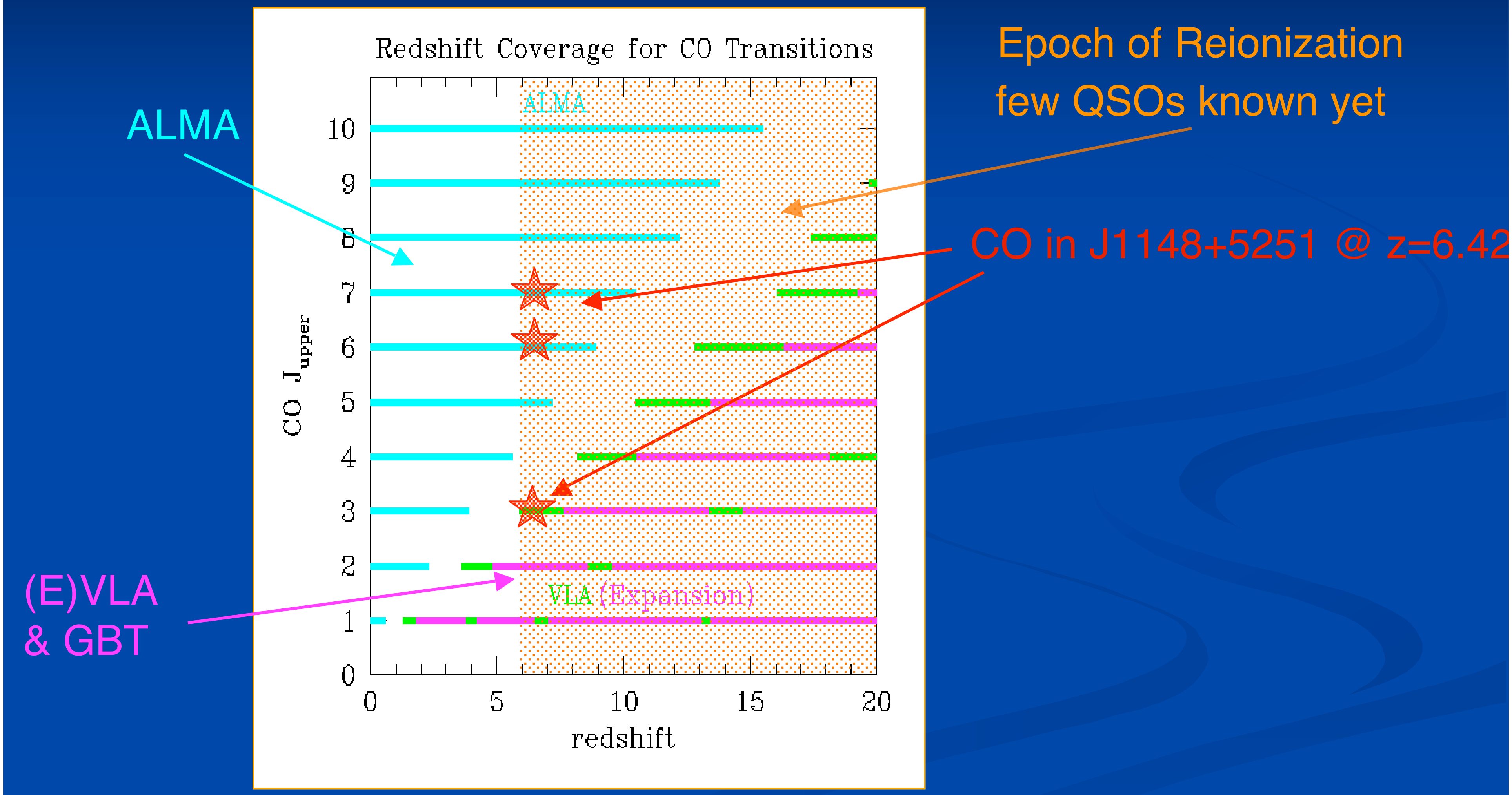


White et al. 2003

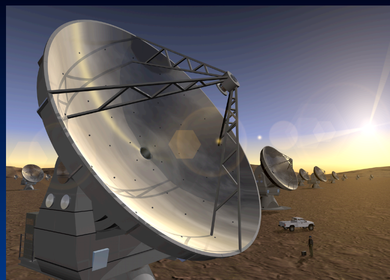
- ionized sph
- age of sphe
  similar to

Walter et al. 2003

ALMA/EVLA Redshift Coverage



ALMA



- early science OP: 2007
- 64 antennas, 4 bands @ >5000 m alt.

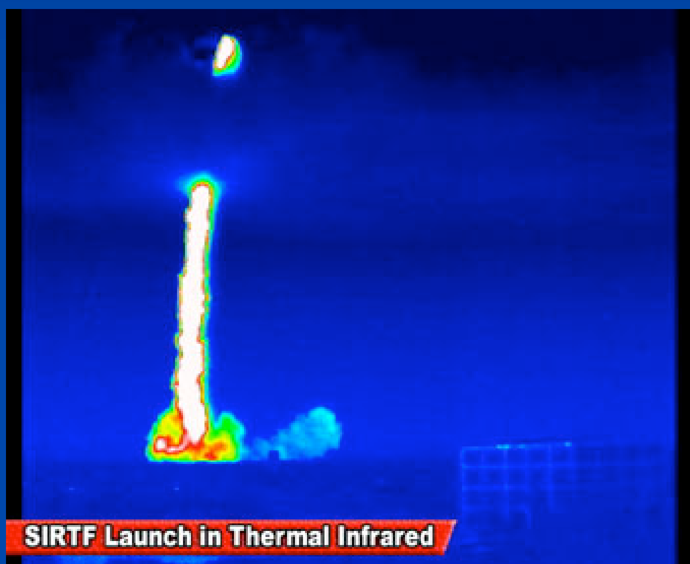
Future Challenges

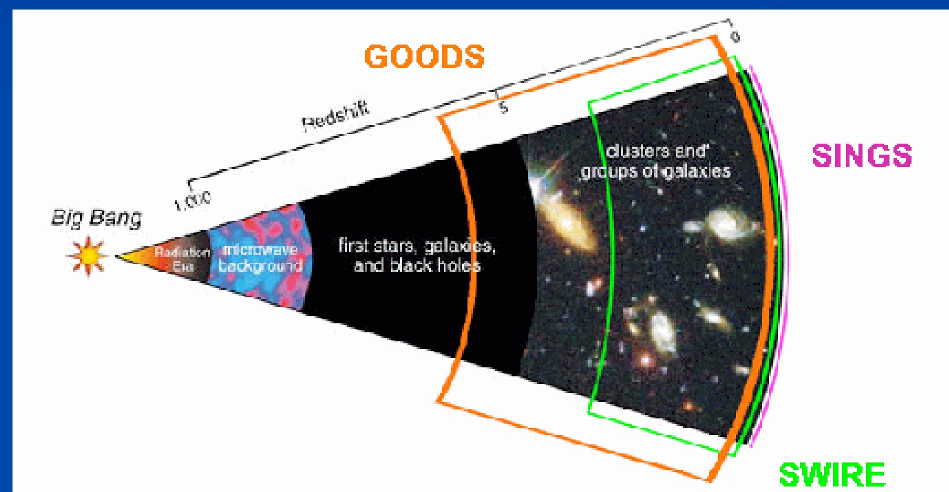
- find missing dwarf galaxies - blown away?
- EoR: find objects @ z>8
- are high masses in conflict w/ CDM models? M-□?
- rapid early metal production/enrichment?

SINGS: SIRTF Nearby Galaxy Survey

SIRTF: Space Infrared Telescope Facility

SINGS: 1 of 6 SIRTF ‘Legacy’ projects (512 hours), PI: R. Kennicutt



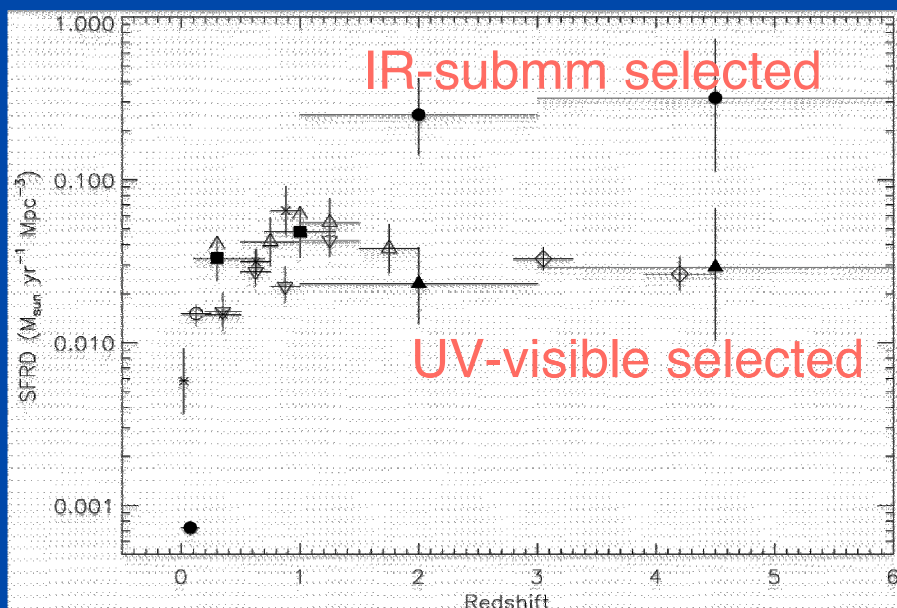


SINGS Science Core

- IR imaging and spectroscopy of 75 nearby galaxies of *all Hubble types,* resolution: ~100pc
- SED templates for high-z galaxies...

Star Formation History of the Universe

- SINGS major goal: ‘calibrate’ SFR
- SFR typically derived from UV and H measurements
- -> derive star formation history of the universe



z<1: decline

z>1: constant?

Barger et al. 2000

- surveys: GOODS, GEMS, COSMOS, UDF; highest z: SDSS

SINGS Multi-Wavelength Data

- *SIRTF: IR imaging* (3-180 μm), *IR spectroscopy* (5-40 μm)
- *visible/NIR imaging* (BVRIJHK, Hα)
- *visible spectra* (3600-7000 A)
- *HST Pa-α, H-band maps* (central arcmin^2)
- *radio continuum maps* (VLA, WSRT)
- *UV imaging* (GALEX 1500 A, 2500 A)
- *X-rays* (Chandra)
- *CO* (BIMA SONG)
- *HI imaging* (VLA, 6”, 2.5 kms^{-1})

http://sings.stsci.edu
Kennicutt et al. 2003

-> Nearby Galaxy Survey of the next decade!

The End