Physics 343 Lecture # 11: distant, dusty galaxies

Schedule for this week and next

Monday-Wednesday 4/14-16: second session for Lab # 5, in my office (Serin W309) for all sections

Monday 4/21: Lab # 5 due

Tuesday-Wednesday 4/22-23: Lab # 6 observations for those not going to WV (only Sections B/E/G/H will meet)

Friday 4/25: drive NJ → WV

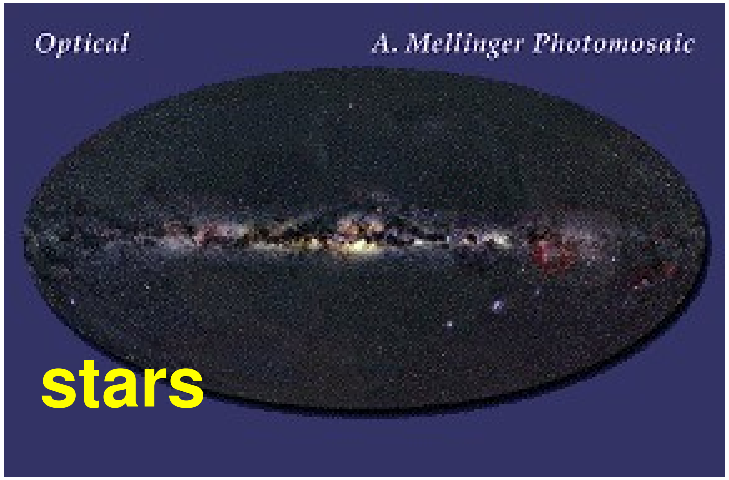
21 people + 6 cars to Green Bank

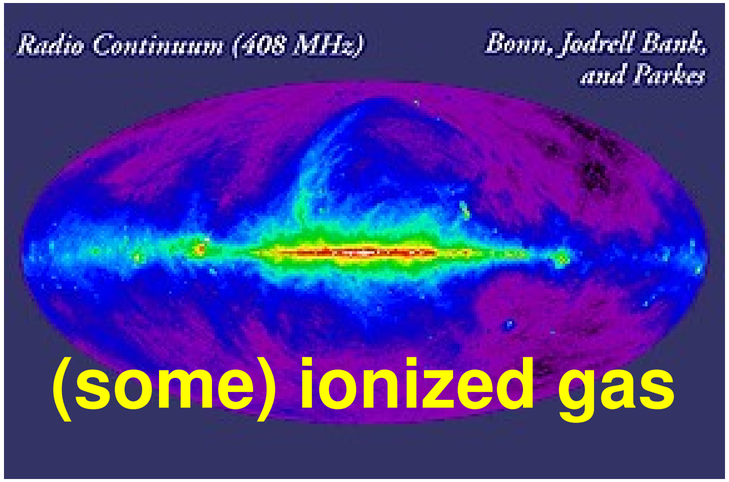
Departs	Driver	Passengers
12:30pm	Baker	Dobaria, Fekete, Wasserman
1:30pm	Perruzzo	Belfer, Brody, Kaufman
2:00pm	Leung	Trinker
2:30pm	Yolleck	Kammerer, King
3:00pm	Singh	Leong, Patel, Rice
4:00pm	Rivera	Fahy, Parikh, Porter

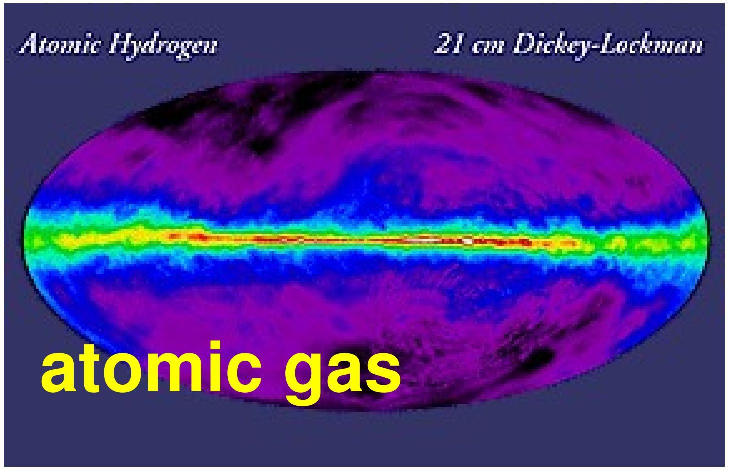
Return trip: passengers can be reshuffled if needed. One passenger cell phone number per car. Do NOT trust GPS once in West Virginia!

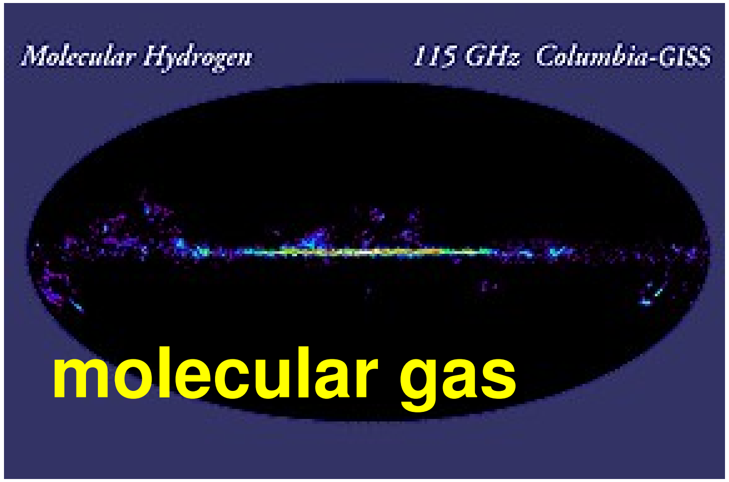
Interstellar gas in the Milky Way

All-sky images projected with center of Milky Way at (0,0).





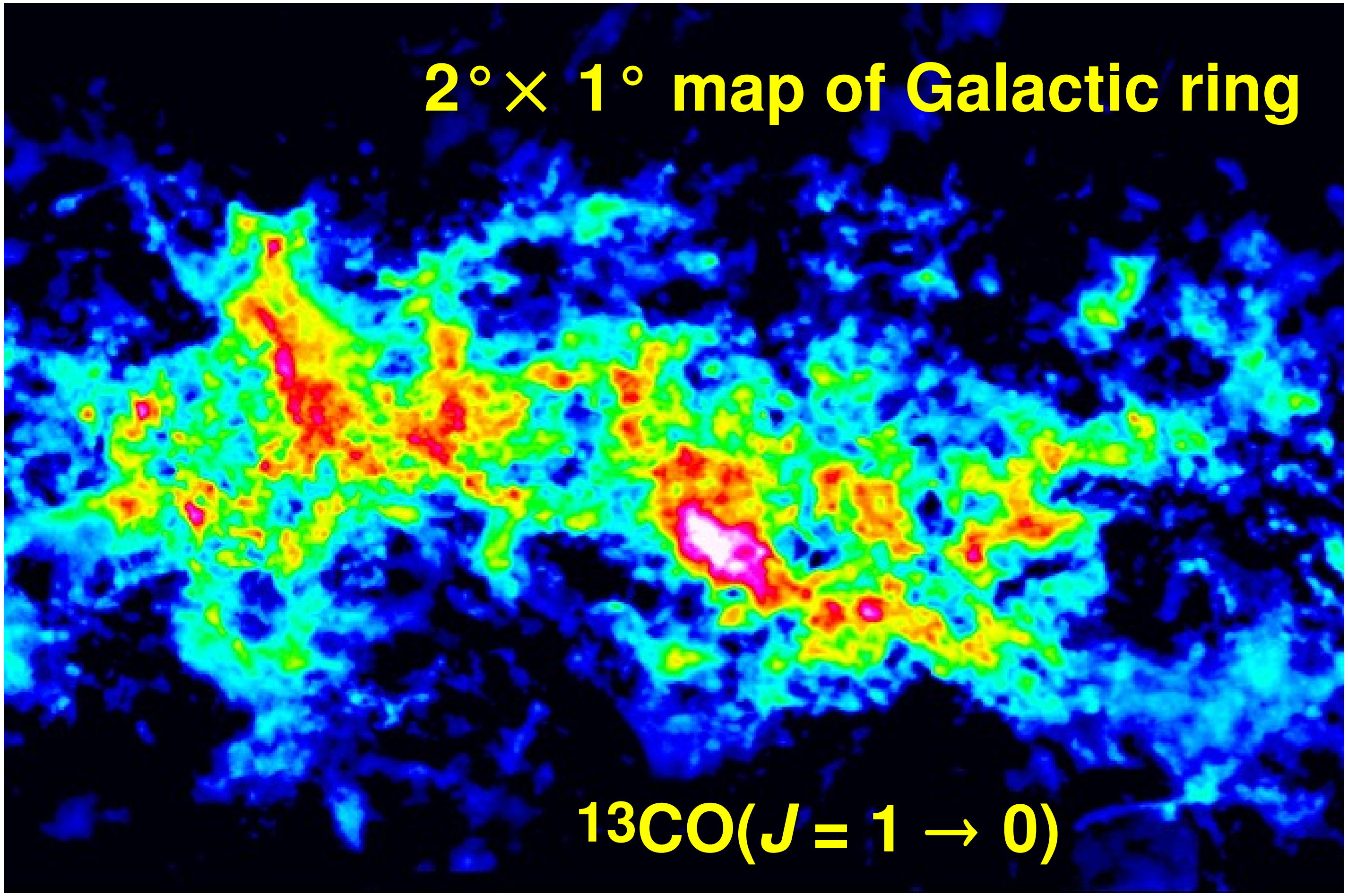




NASA/Multiwavelength Milky Way project

Molecular clouds

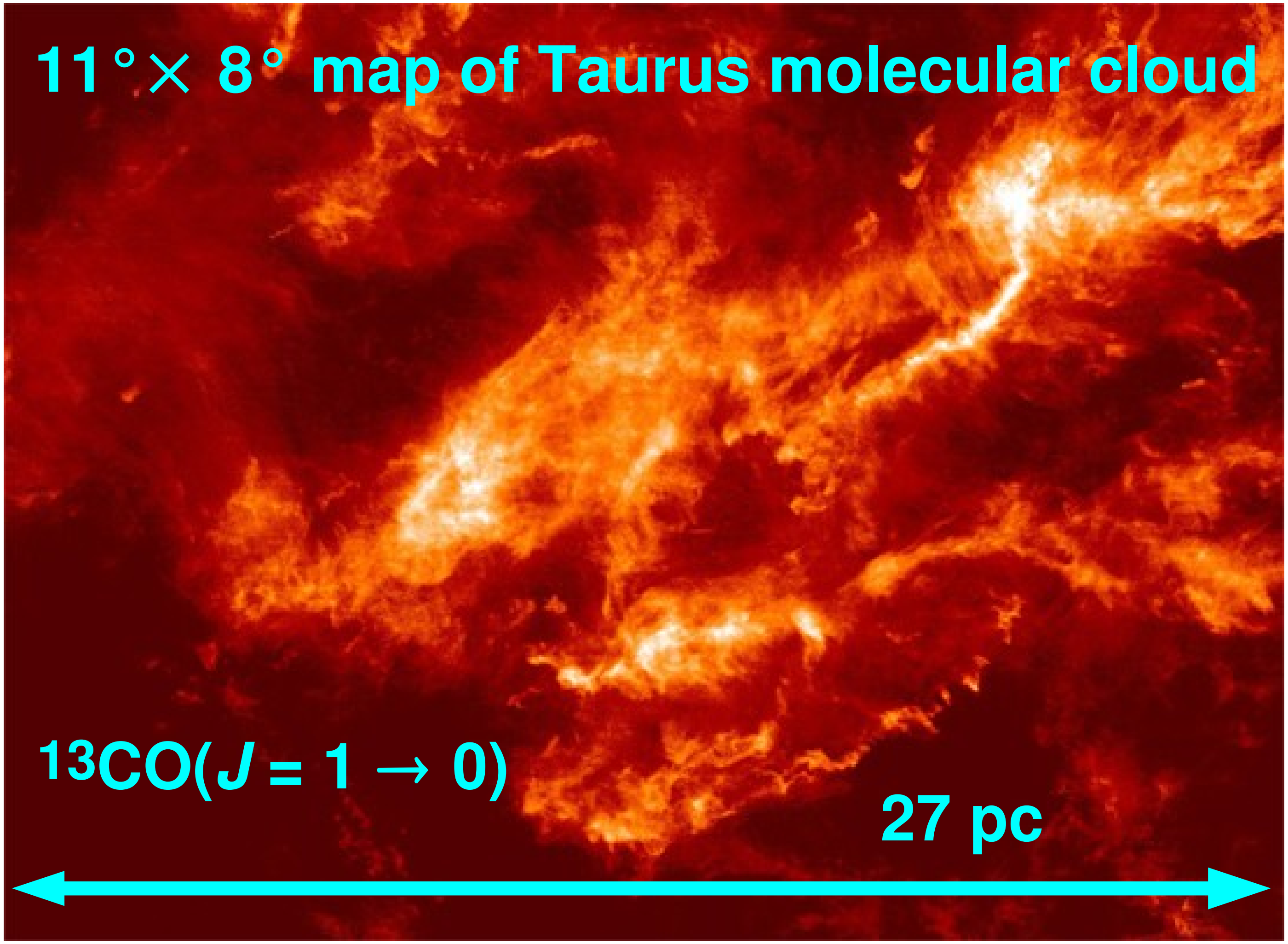
Molecular gas in the Milky Way is distributed in clumpy, filamentary clouds with masses $M \sim 10^4 - 10^6\ M_\odot$.



Jackson et al. (2006, ApJS, 163, 145)

Molecular cloud properties

Clouds gravitationally bound, exhibit supersonic turbulence.



Narayanan et al. (2008, ApJS, 177, 341)

Dense gas is elusive!

Molecular clouds are ~74% H_2 and ~25% He by mass.

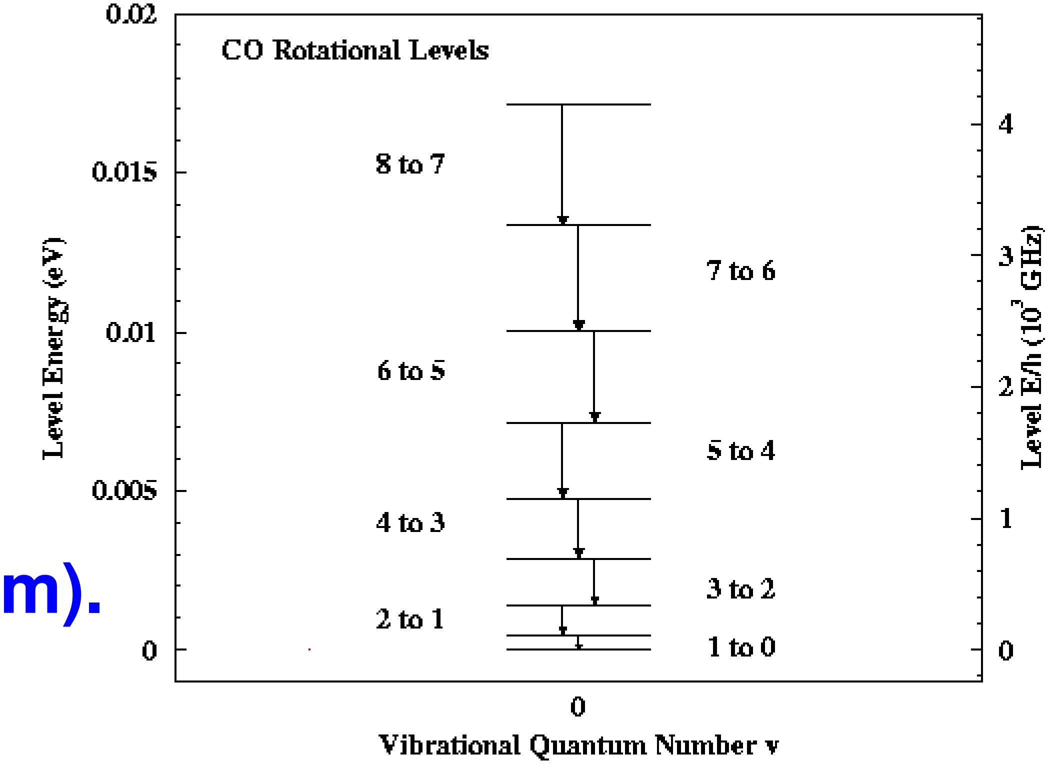
Excitation is determined by collisions with H_2 and He. However, at low temperatures (T_{kin} ~ 10–50 K), only excited rotational states will be populated.

H_2 does not deexcite radiatively because it has no permanent electric dipole moment. Thus, H_2 in molecular clouds produces almost no emission.

CO: a proxy for H_2

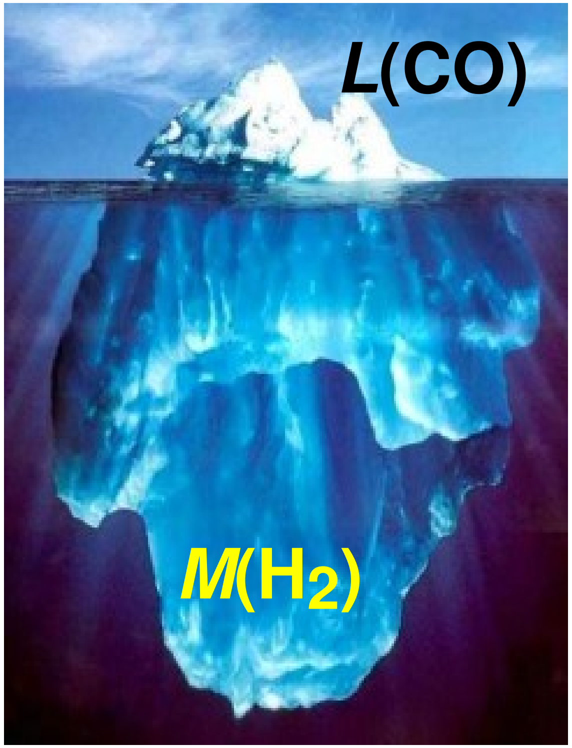
CO has only ~10^{-4} the abundance of H_2, but it does have a permanent electric dipole moment, and energy levels that are only $h\nu/k$ = 5.5 K, 17 K, ... above ground.

One rotational quantum number J with selection rule $\Delta J = \pm 1$ gives a set of rotational transitions with rest frequencies 115, 230, 345, ... GHz (λ_{rest} = 2.6, 1.3, 0.87, ... mm).

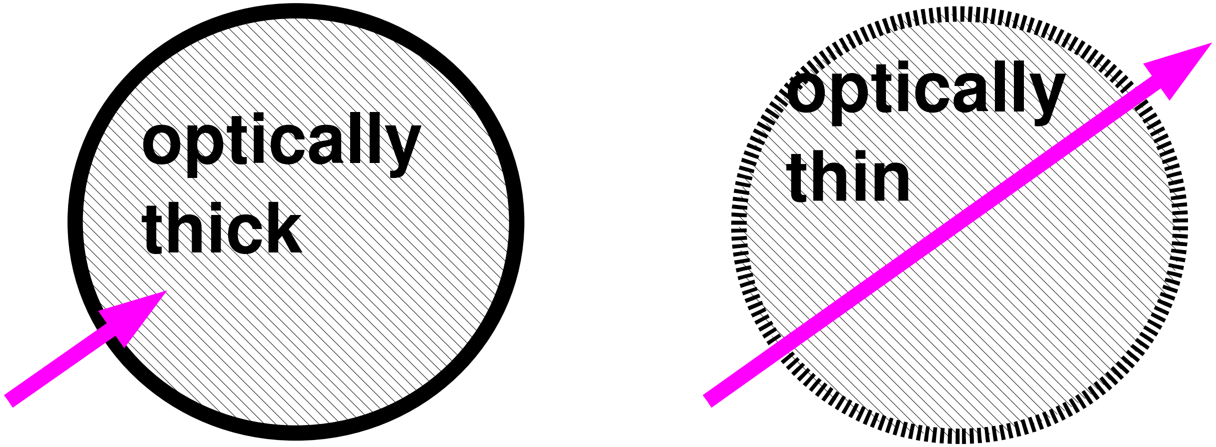


courtesy K. Volk

A CO-to-H_2 conversion factor



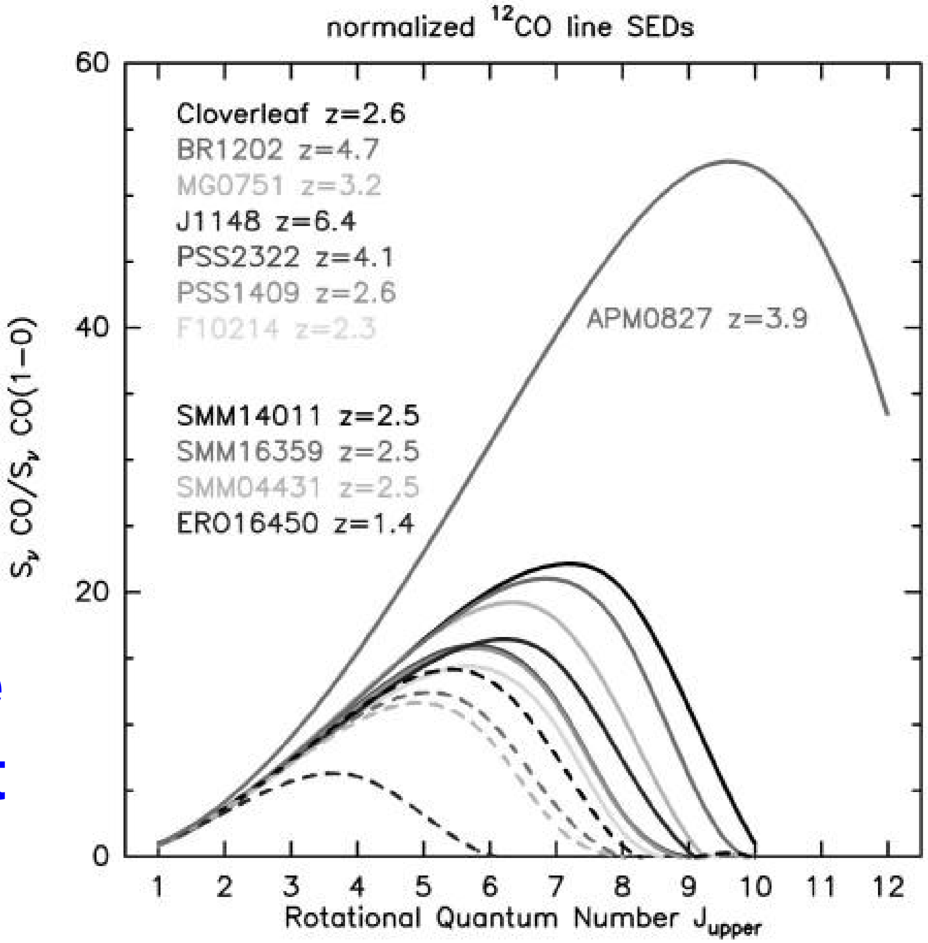
α_{CO} = H_2 mass/CO($J = 1 \rightarrow 0$) luminosity calibrated using Milky Way clouds.



CO($J = 1 \rightarrow 0$) is optically thick, so we don't "see" every CO molecule in a cloud. However, α_{CO} can still be used as long as clouds are roughly virialized.

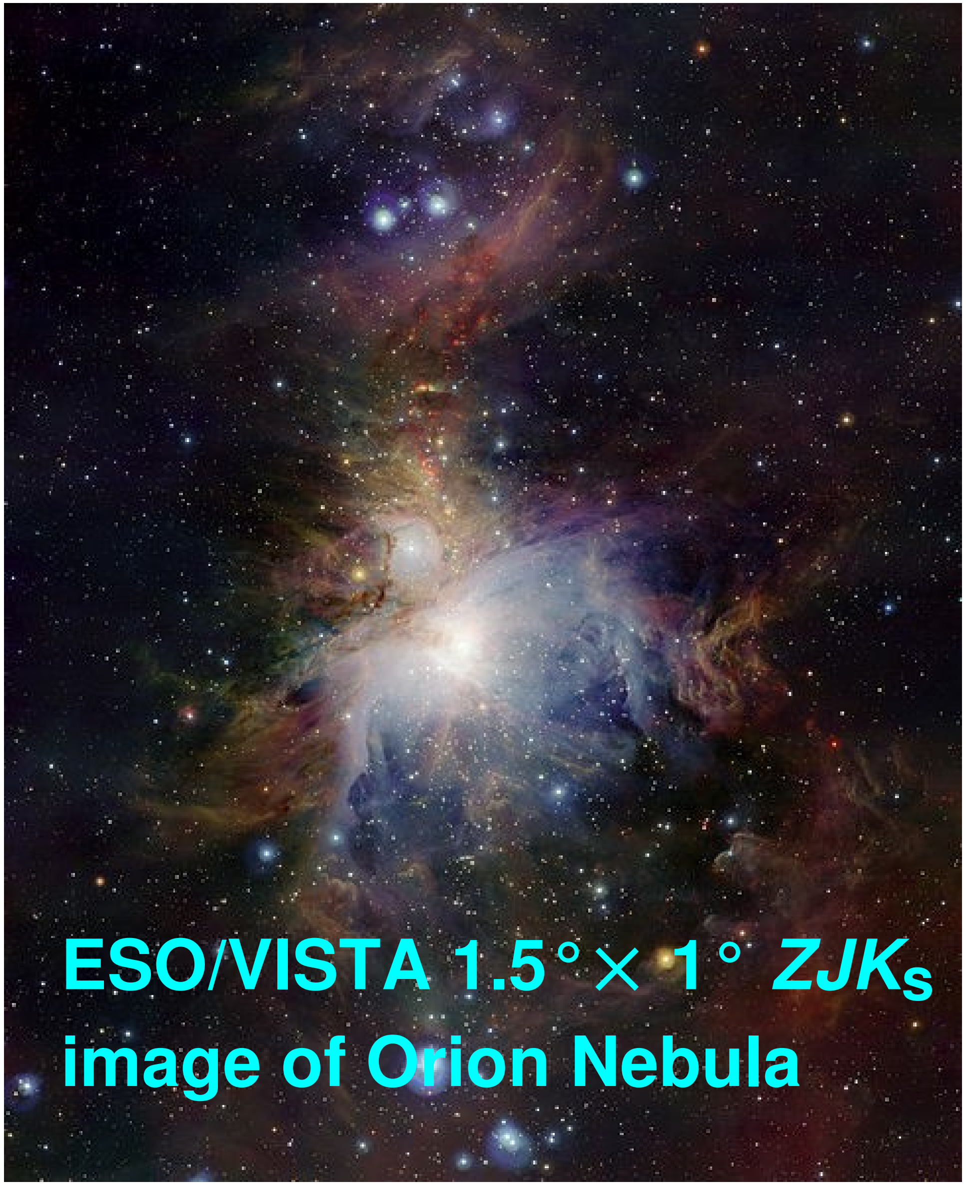
The value of CO SLEDs

CO Spectral Line Energy Distributions constrain a combination of T_{kin}, n_{H2}, and (if we include absorption and stimulated emission) fractional CO abundance per unit velocity gradient $X_{CO}/(dv/dr)$.

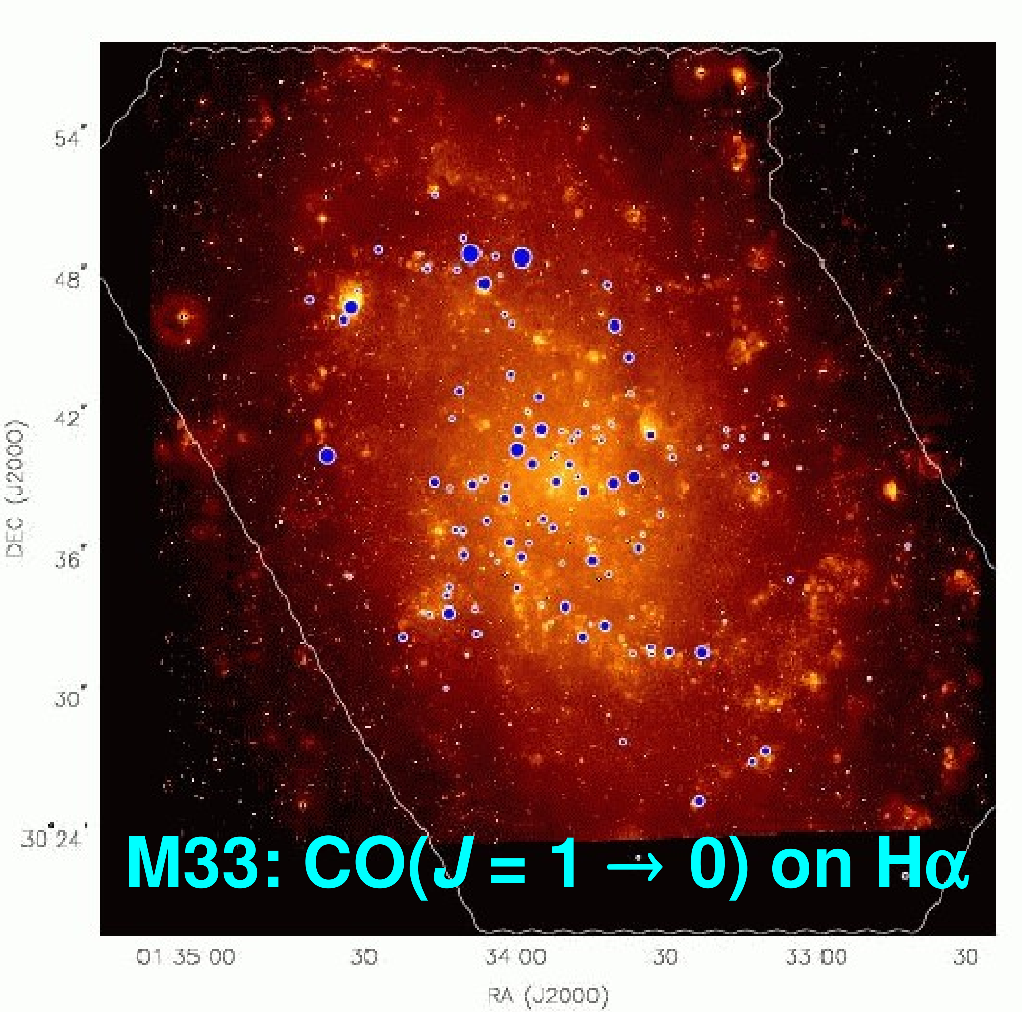


Weiss et al. (2007, ASPC, 375, 25)

Key fact: new stars form from H_2



ESO/VISTA 1.5°× 1° ZJK_s image of Orion Nebula

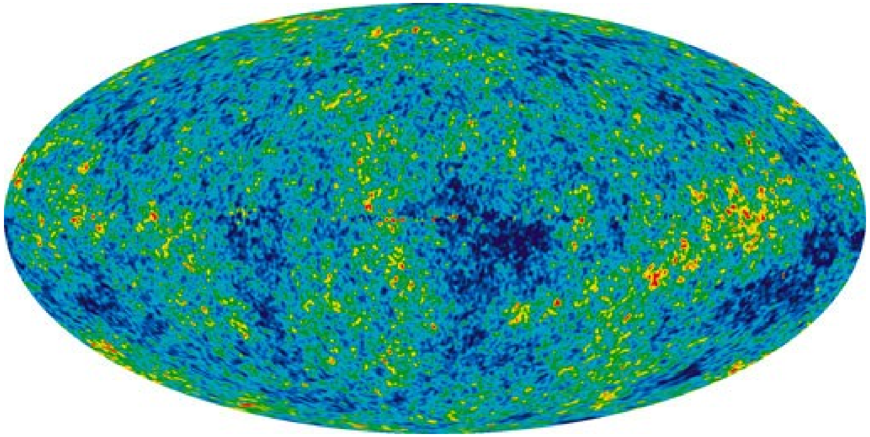


M33: CO($J = 1 \rightarrow 0$) on Hα

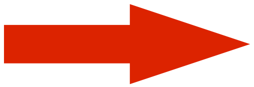
Engargiola et al.
(2003, ApJS, 149, 343)

Understanding galaxy evolution

cosmic microwave background:
smooth to 10^{-4} of mean $\langle T \rangle$

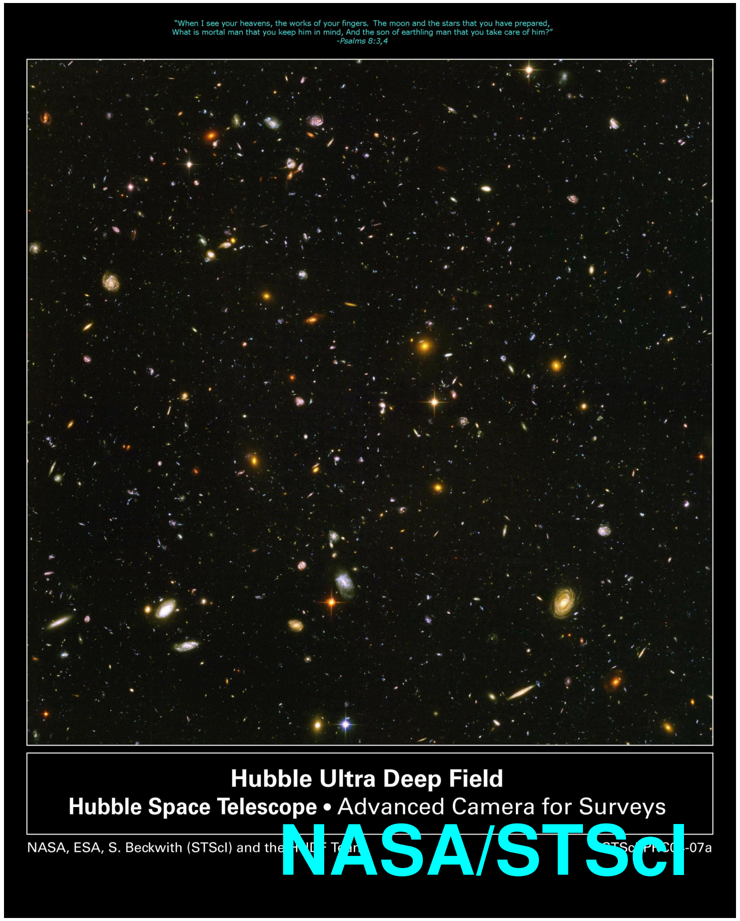


NASA/WMAP



?

local universe: lumpy,
with galaxies showing
"complex regularities"



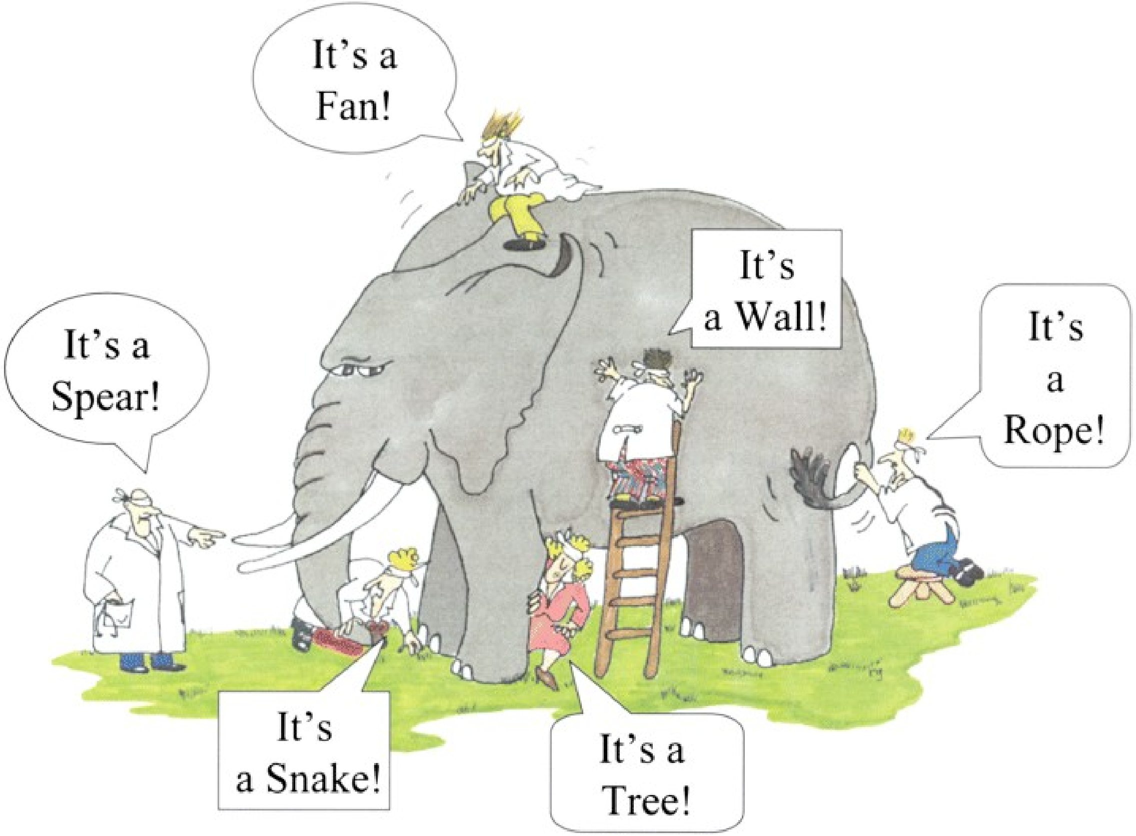
"When I see your heavens, the works of your fingers. The moon and the stars that you have prepared,
What is mortal man that you keep him in mind, And the son of earthling man that you take care of him?"
-Psalms 8:3,4

Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the [illegible] STScI-PRC0[illegible]-07a

NASA/STScI

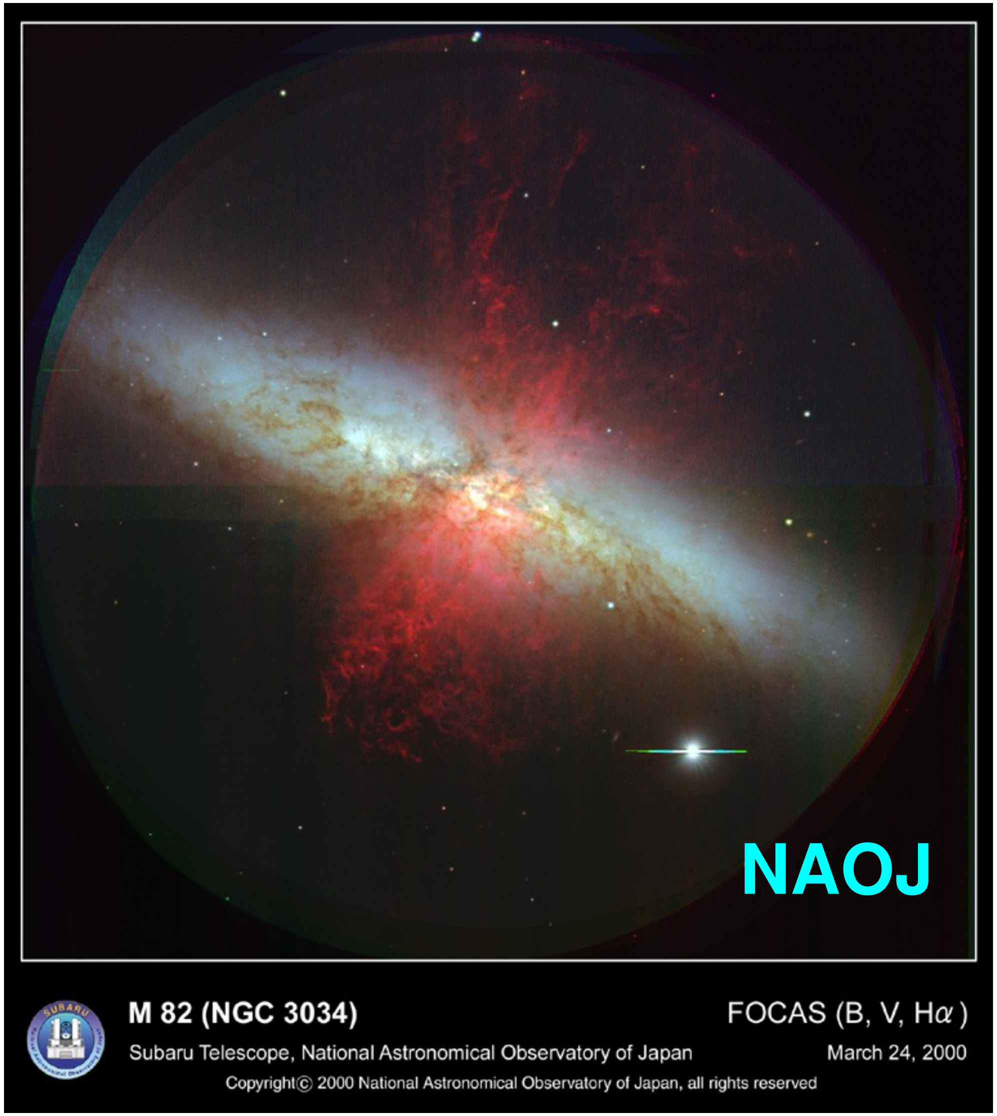
Finding distant galaxies



Identifying distant galaxies in formation ($1 + z = \lambda/\lambda_{rest}$) depends strongly on technique: tend to find different (but overlapping) samples in different ways.

Two local star-forming galaxies...

M82 (ordinary "starburst")

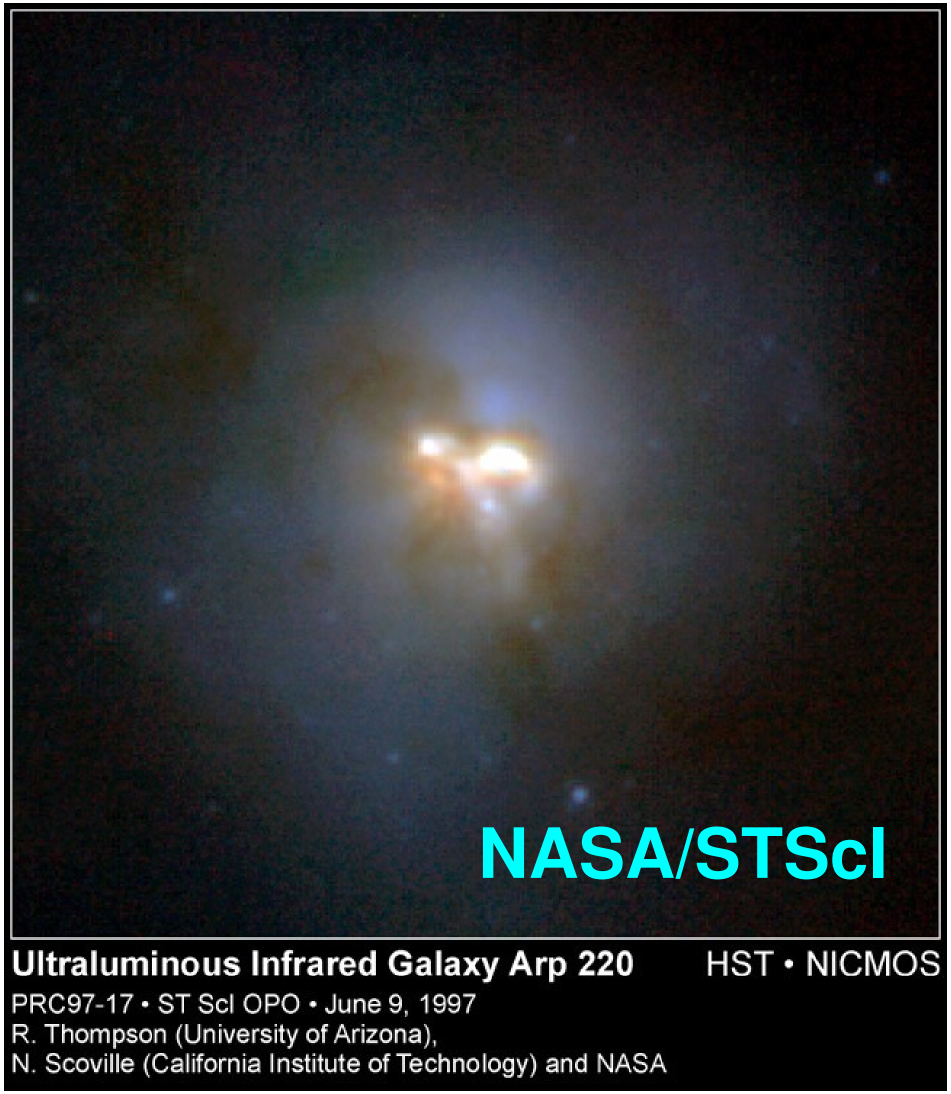


NAOJ

M 82 (NGC 3034) FOCAS (B, V, Hα)

Subaru Telescope, National Astronomical Observatory of Japan March 24, 2000

Arp 220 (messy merger)



NASA/STScI

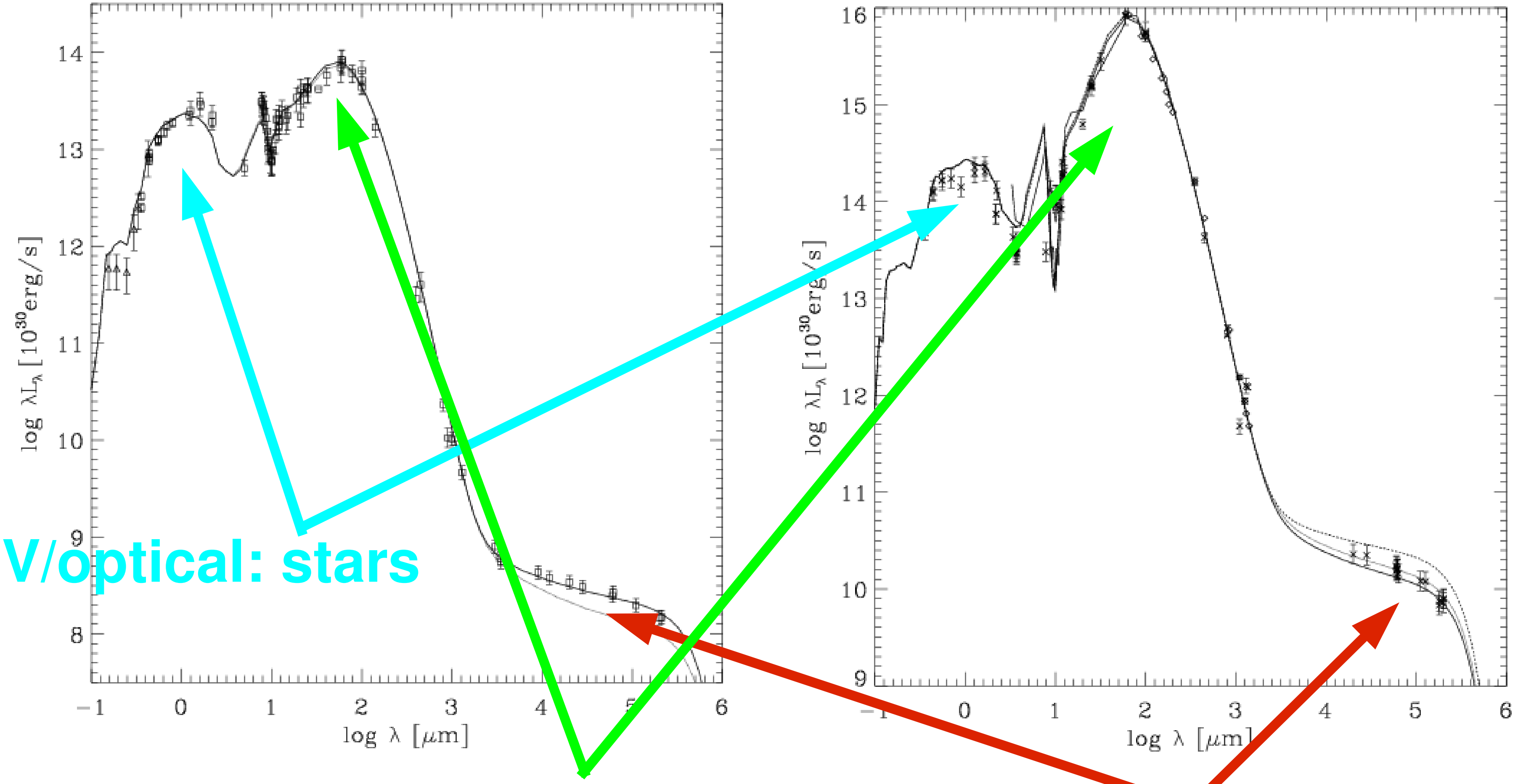
Ultraluminous Infrared Galaxy Arp 220 HST • NICMOS

PRC97-17 • ST ScI OPO • June 9, 1997
R. Thompson (University of Arizona),
N. Scoville (California Institute of Technology) and NASA

A multiwavelength view

M82 (ordinary "starburst")

Arp 220 (messy merger)



UV/optical: stars

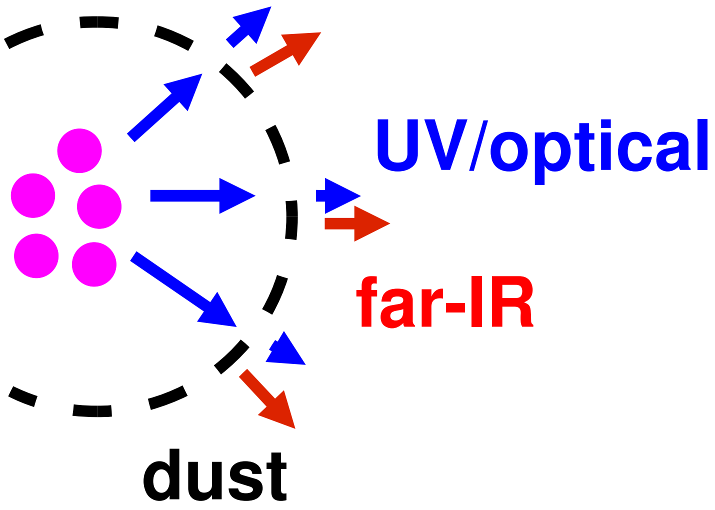
far-infrared: dust

radio: supernova renmants

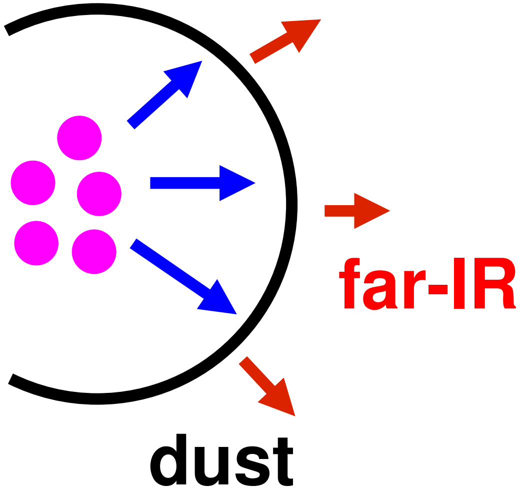
Bressan et al. (2002, A&A, 392, 377)

Messy mergers are dustier

M82 (ordinary “starburst”)

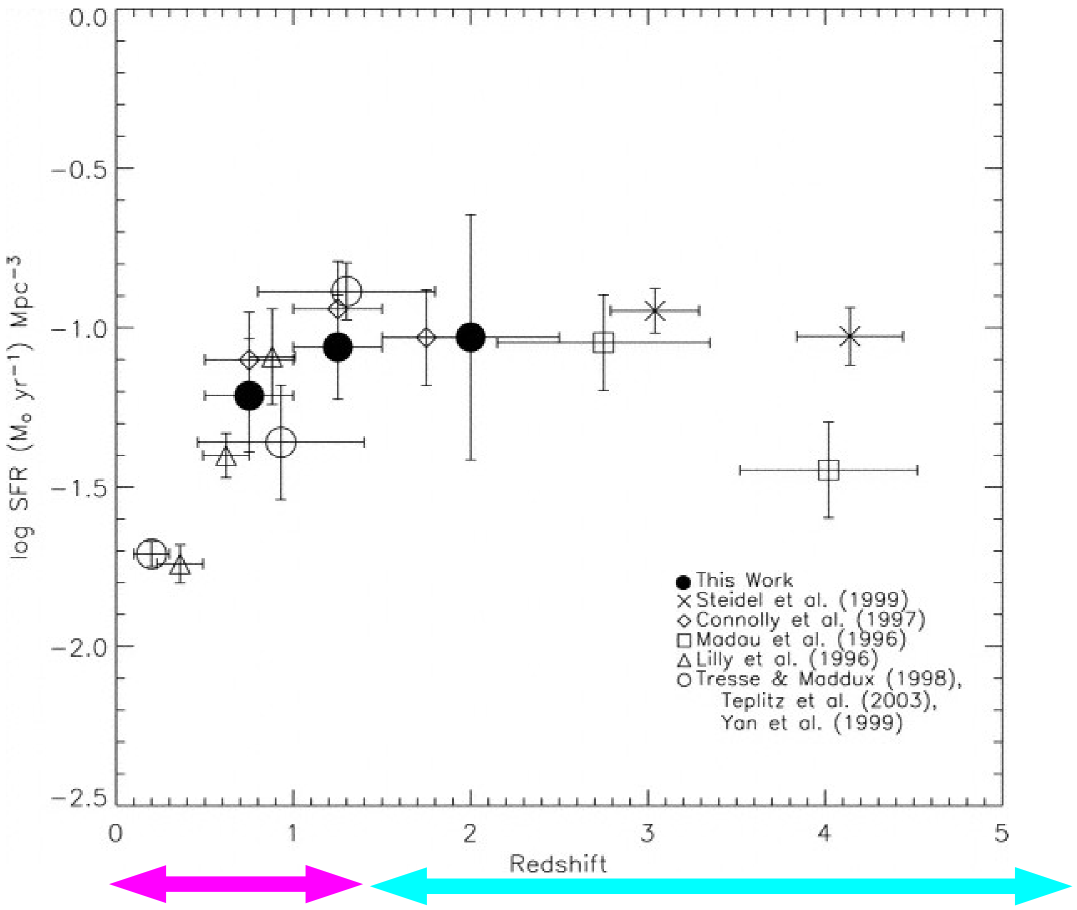


Arp 220 (messy merger)



In a merger, dense gas coalesces into center of mass of system and triggers an obscured “burst” of star formation.

Cosmic star formation rate vs. *z*



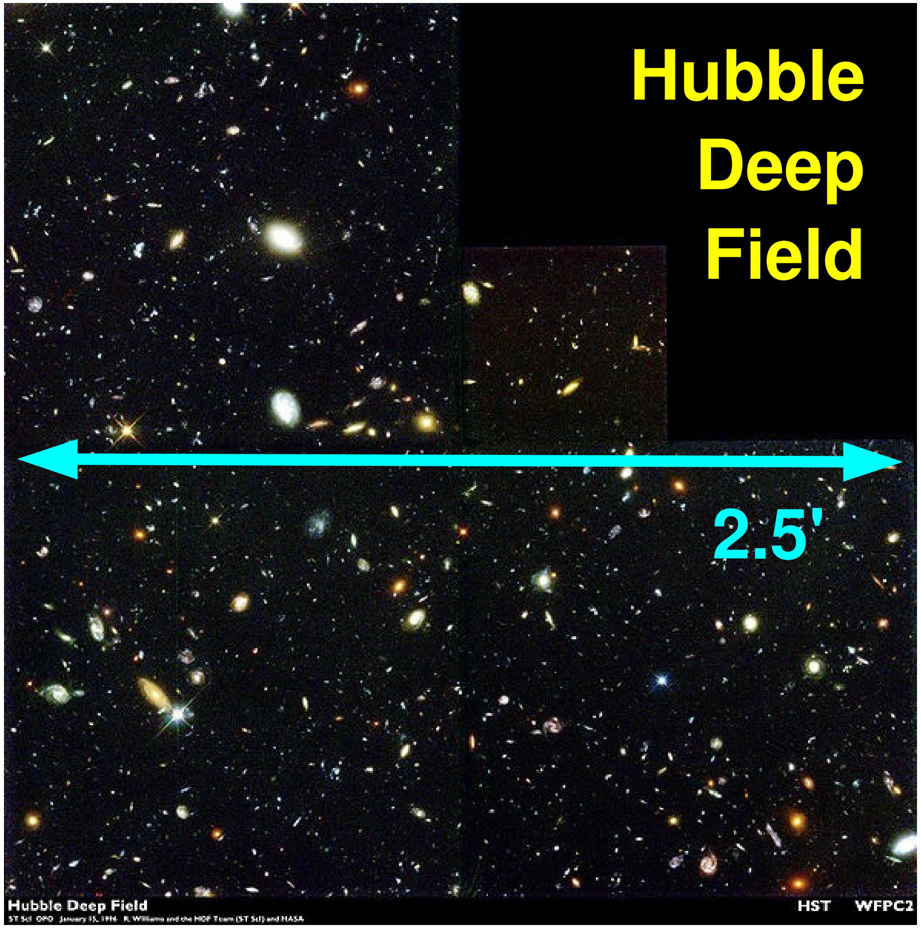
~9 Gyr

~4 Gyr

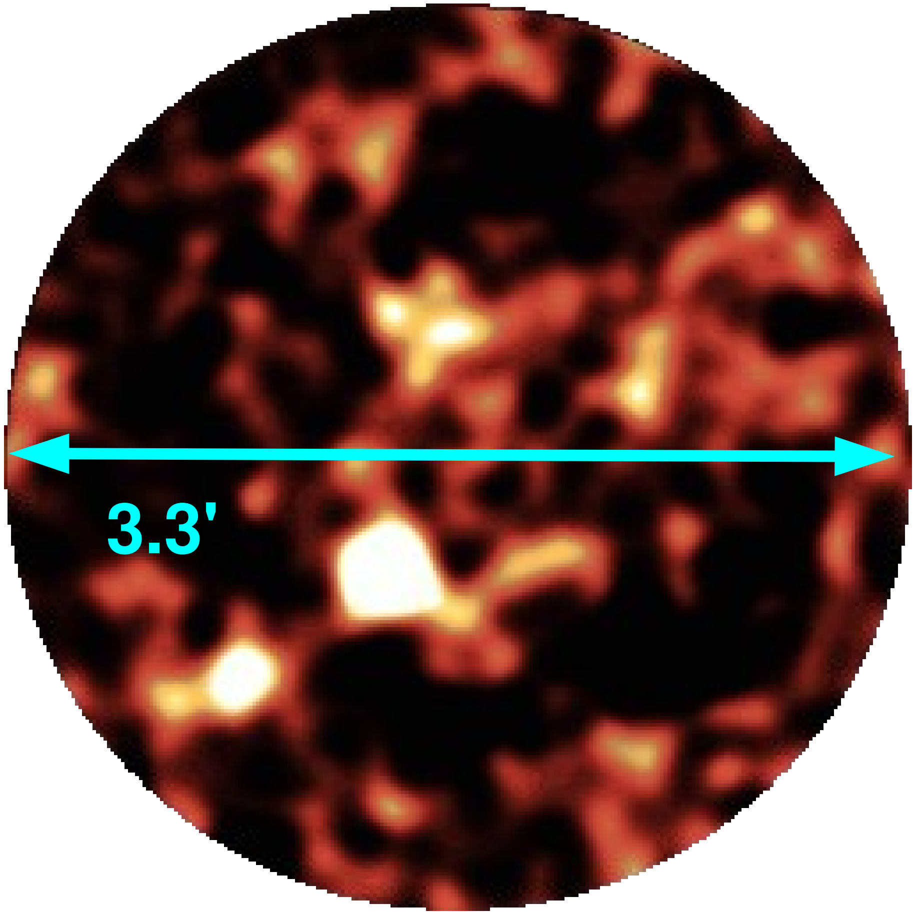
Colbert et al. (2006, ApJ, 648, 250): star formation rate per unit volume vs. redshift (for UV/optical samples)

Quantity of star formation dominated by $z < 1.5$.
Quality of star formation different at $z > 1.5$.

A mysterious dusty galaxy...

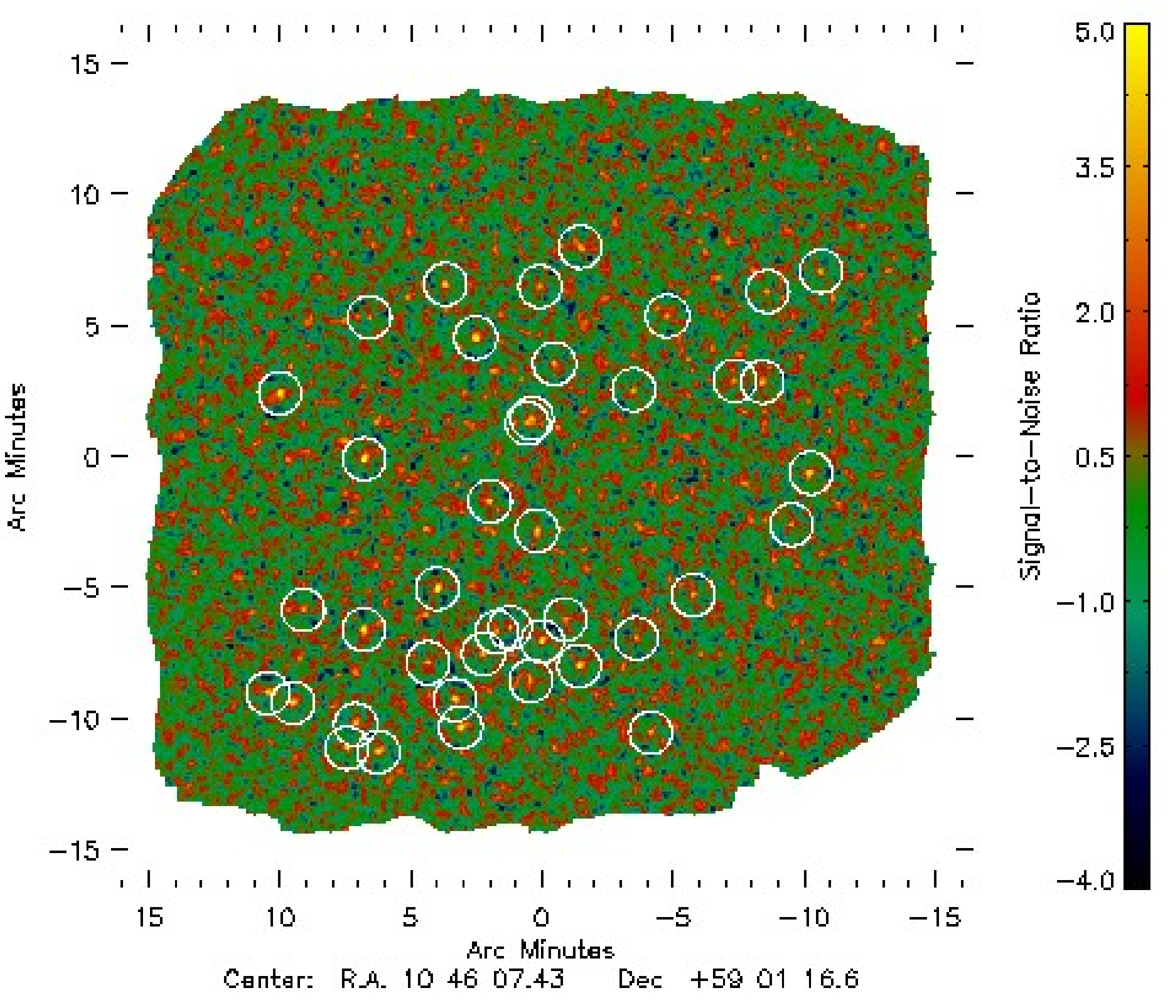


optical: Williams et al.
(1996, AJ, 112, 1335)



850 μm: Hughes et al.
(1998, Nature, 394, 241)

Dusty galaxies *ubiquitous* at high *z*

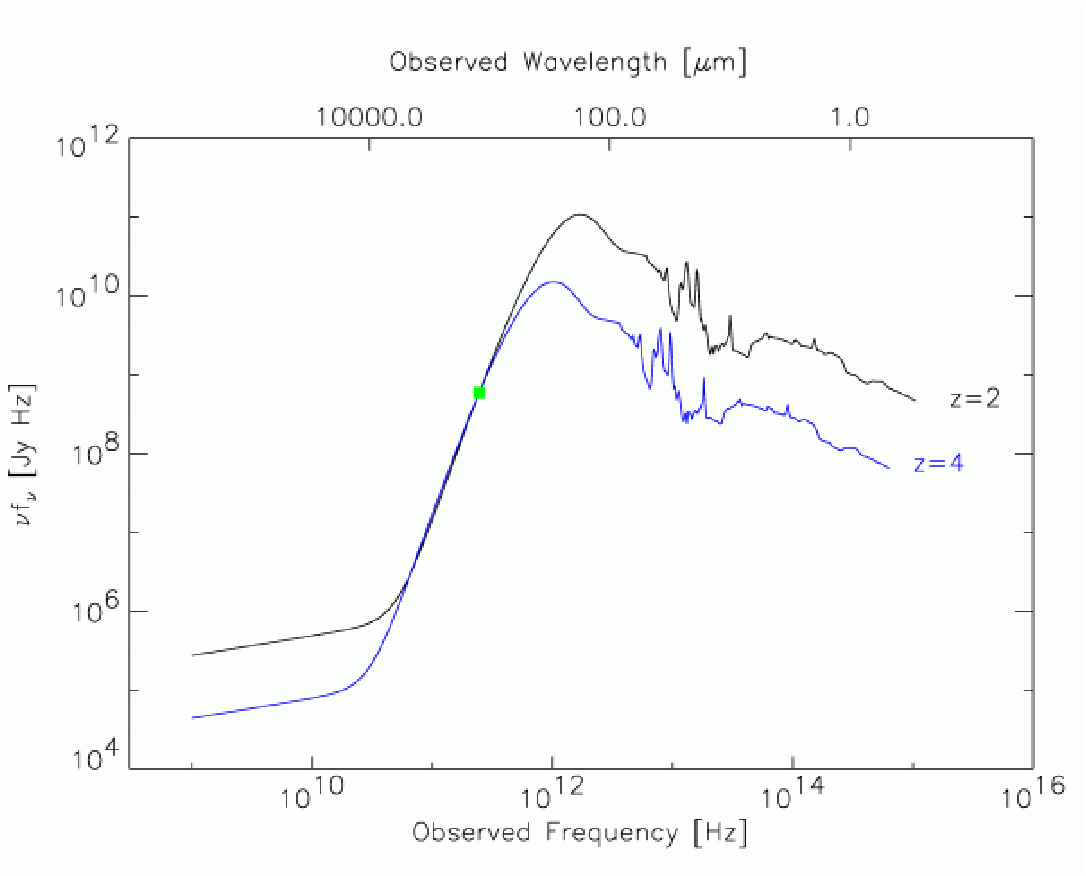


If we make a deep map of any region of the sky at far-IR to millimeter wavelengths, we'll find very dusty galaxies at a wide range of *z* > 1– and many more than in same volume at *z* = 0!

Lindner, Baker, et al. (2011, ApJ, 737, 83): <*z*> ~ 3.1

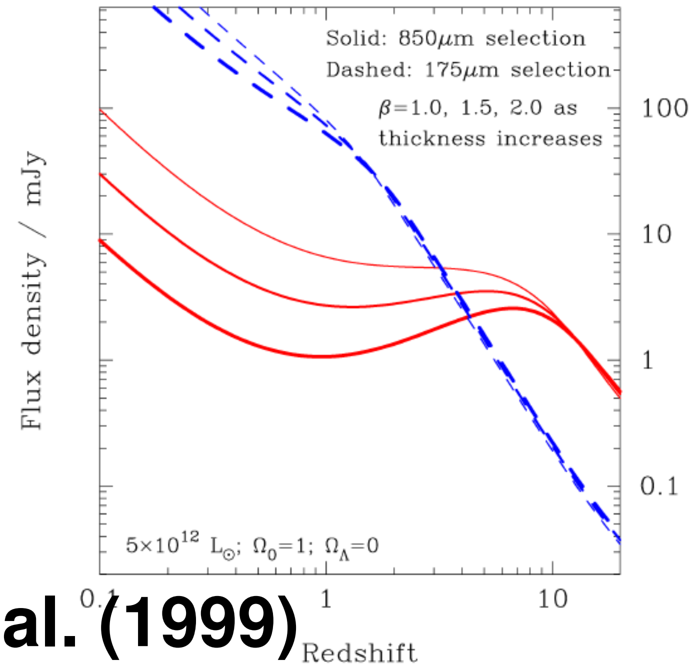
A surprising and helpful property

Surprise: more distant galaxies are not always fainter!



redshift

$1/D^2$



Blain et al. (1999)

Why dusty galaxies are important

We know that (per unit comoving volume):

(a) UV/optical-selected galaxies turn gas into stars at a higher integrated rate at higher *z*; and

(b) dust-selected star-forming galaxies (some entirely hidden in UV/optical!) are more abundant at higher *z*.

We also know that stars form from dense gas.

Conclusion: we must understand dense gas in distant galaxies to get a complete picture of galaxy evolution.

The threefold path to enlightenment

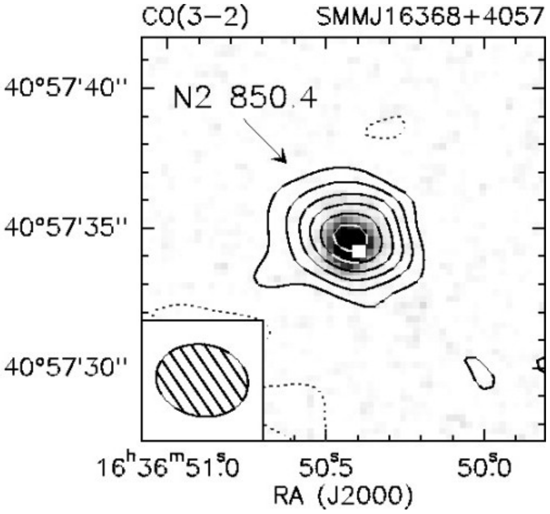
Leading redshift search strategy for dusty galaxies:

Step 1: Deep radio continuum mapping.

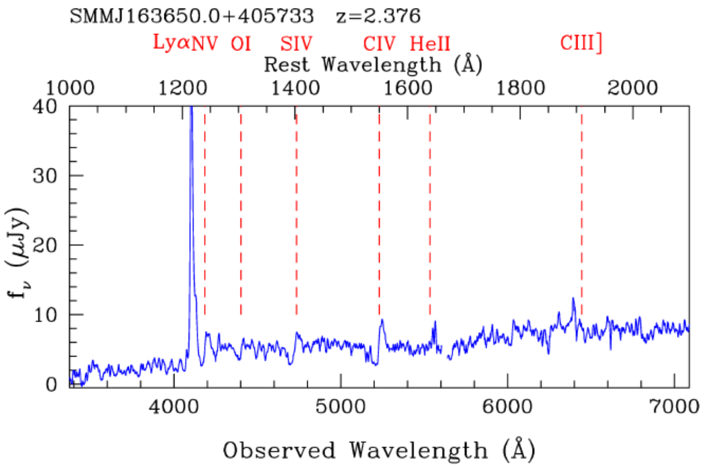
Step 2: Deep optical spectroscopy.

Step 3: CO line search at $z_{\rm opt}$.

Neri et al. (2003, ApJ, 597, L113)



Chapman et al. (2003, Nature, 422, 695)



Step 1 fails for ~30% (no counterpart).

Step 2 fails for ~25% (no $z_{\rm opt}$).

Step 3 fails for ~50% ($z_{\rm opt}$ is wrong?).

Two kinds of molecular line searches

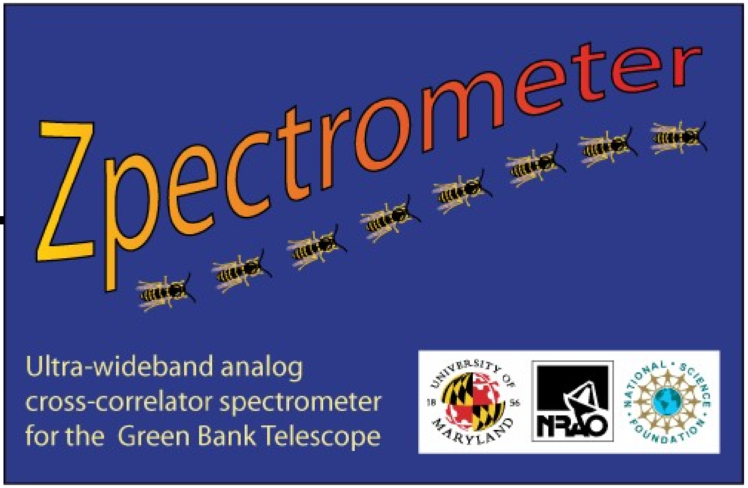
(1) Source has a known redshift, typically from optical spectrum or a molecular line measured elsewhere. Main challenge for (single-dish) CO spectroscopy: frequency structure in noise.

shooting fish in a barrel

(2) Source has no redshift, typically due to high dust obscuration in the UV/optical. Main challenges for spectroscopy: structured noise + bandwidth.

shooting fish in a lake

A better mousetrap: the Zpectrometer



Ultra-wideband analog
cross-correlator spectrometer
for the Green Bank Telescope

PI: A. Harris
(U Maryland)

Telescope: 100m Green Bank Telescope

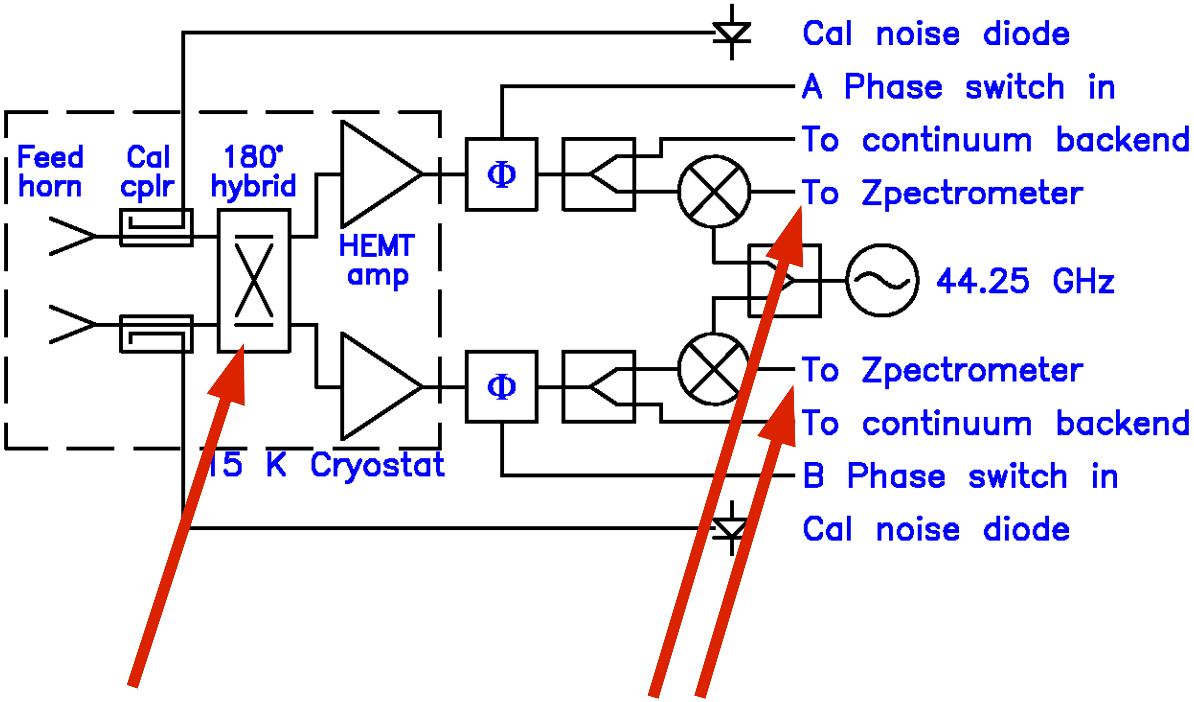
Frontend: 26–38 GHz receiver probes

CO at $2.0 < z < 3.4$ and $z > 5.0$

Backend: WASPs = Wideband Analog SPectrometers deliver 16.4 MHz ~ 150 km s^{-1} resolution over full Δz

Combine signals before amplifying

GBT frontend electronics



Source and sky signals combined before amplifier.

Amplifier outputs cross-correlated to defang fluctuations in system gain ⇒ noise integrates down with time.

Install on telescope

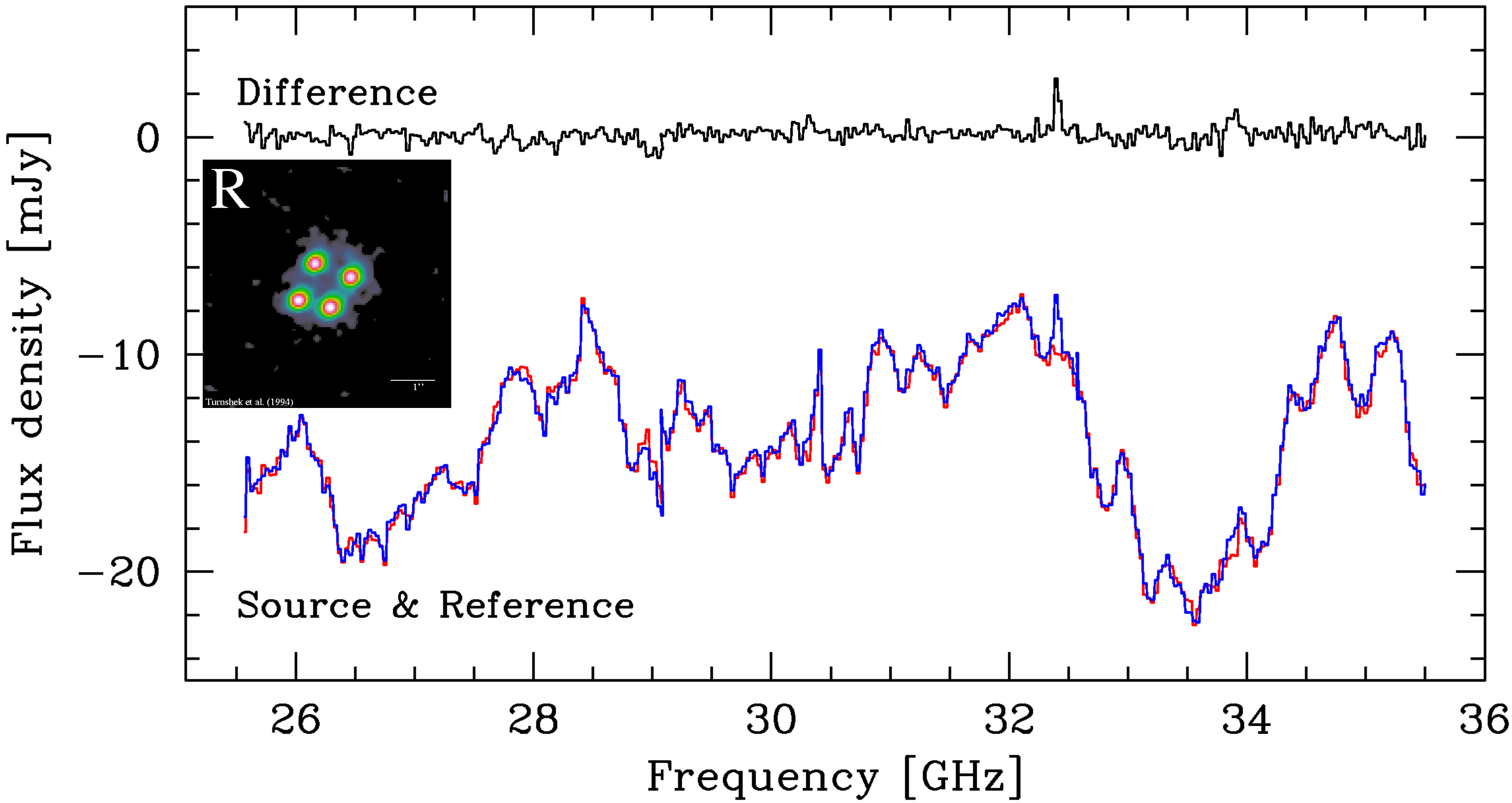
S. Zonak

Analog vs. digital backend:

- + less mass
- + less heat dissipation

⇒ can be directly hung from turret, reducing structured noise due to long cable or fiber runs

Eliminate stable noise structure

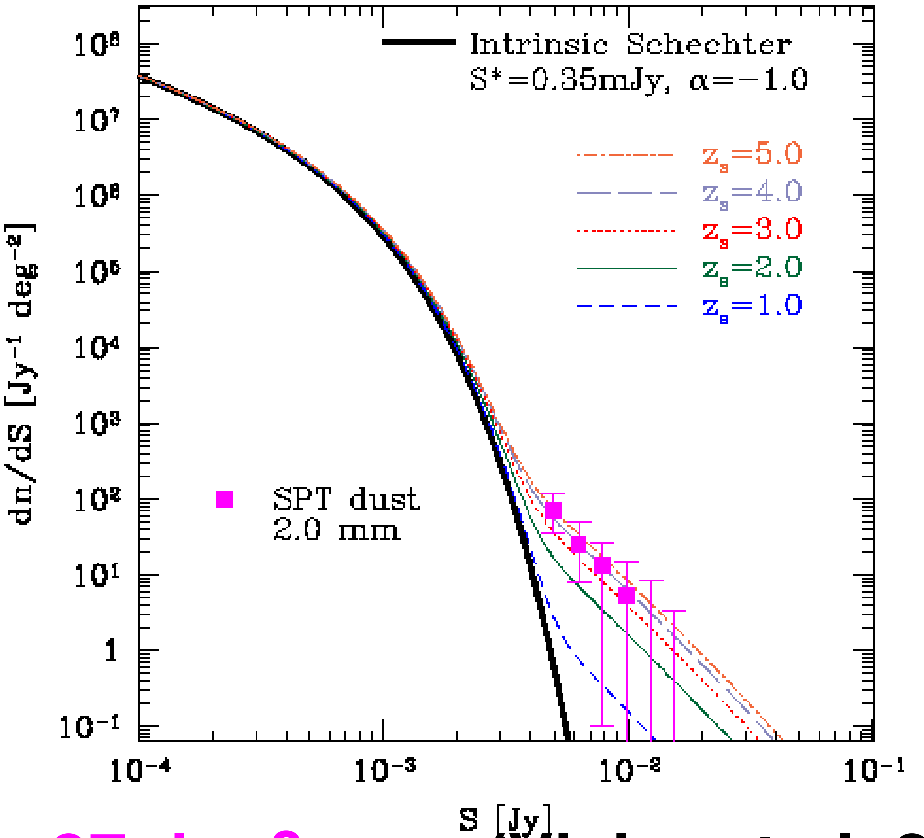


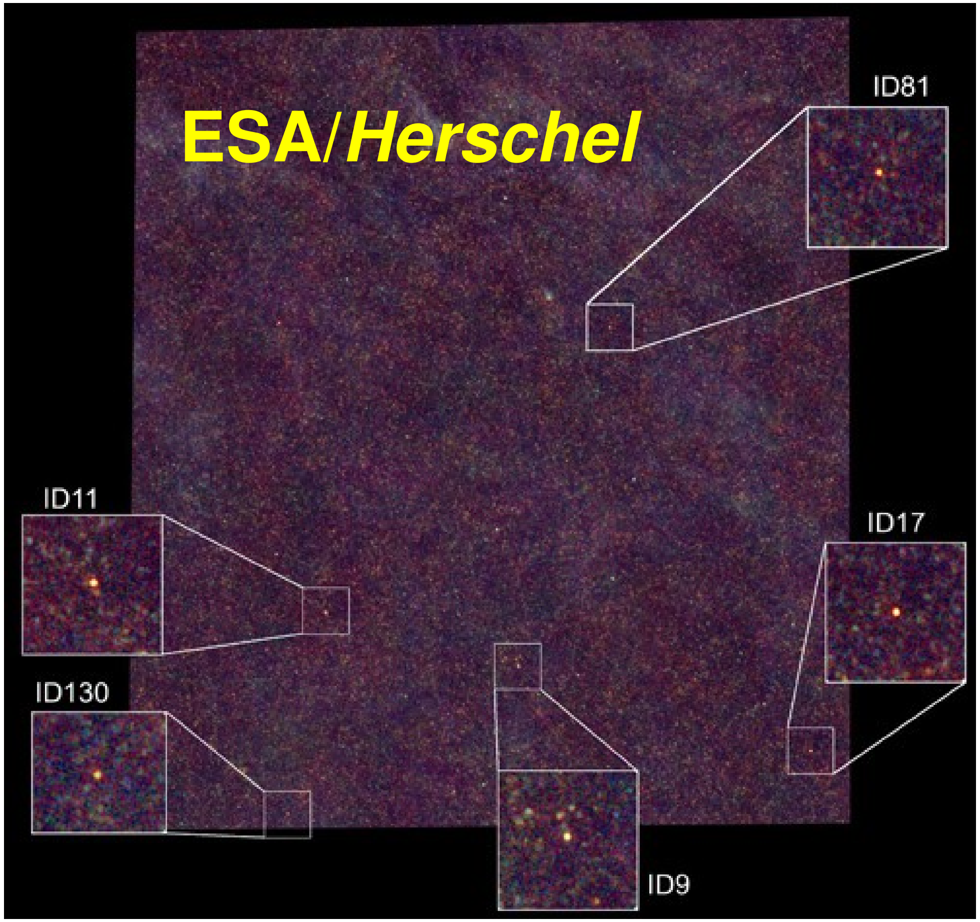
“Cloverleaf”: CO($J = 1 \rightarrow 0$) at $z = 2.56$, 1.9 hrs telescope time

Quiz

Determining redshifts

In the last few years, large-area surveys have detected new very rare populations of extremely bright dusty galaxies.



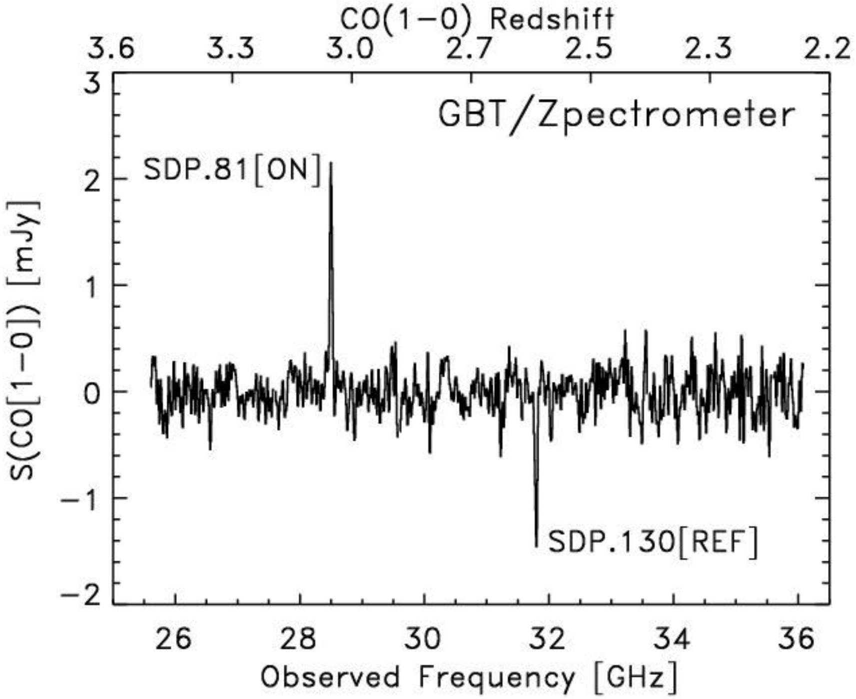


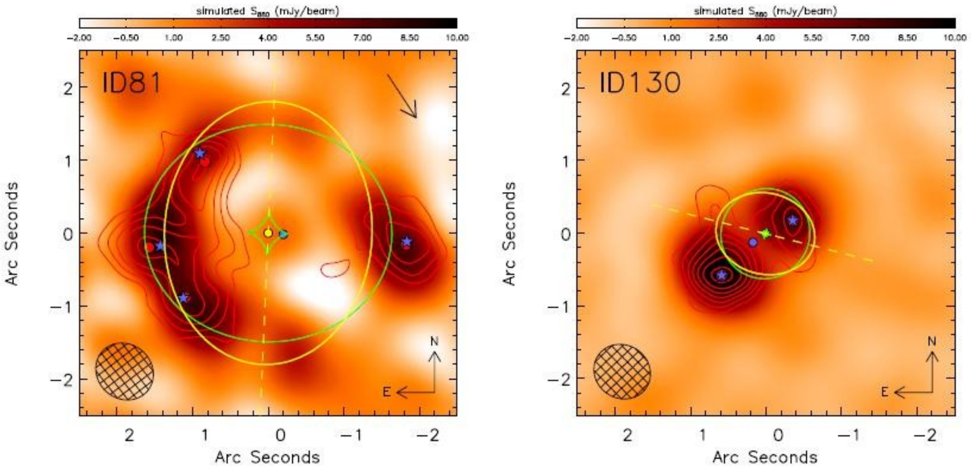
87 deg^2 map (Vieira et al. 2010, ApJ, 719, 763)

Discrepant optical/radio redshifts

Frayer et al. (2011, ApJ, 726, L22): use Zpectrometer to determine $z_{CO} > z_{opt}$ for two *Herschel* galaxies.

Gravitationally lensed!



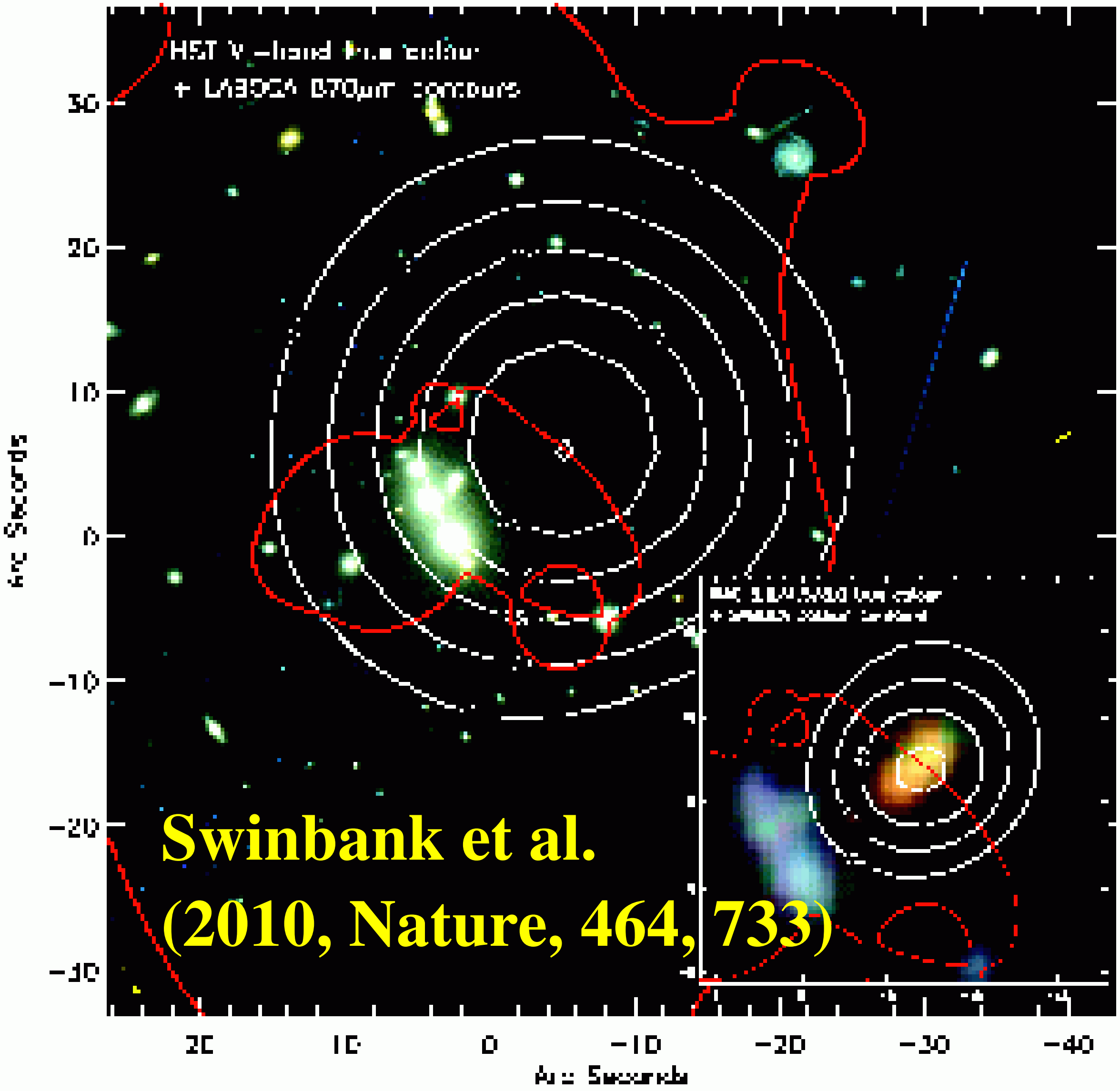


Supported by morphologies in dust continuum maps (Negrello et al. 2010, Science, 330, 800).

Brightest known dusty galaxy!

May 8, 2009:
Mark Swinbank and collaborators find a 106 mJy source in 870 μm imaging of MACS J2135–010217 (a *z* = 0.32 cluster).

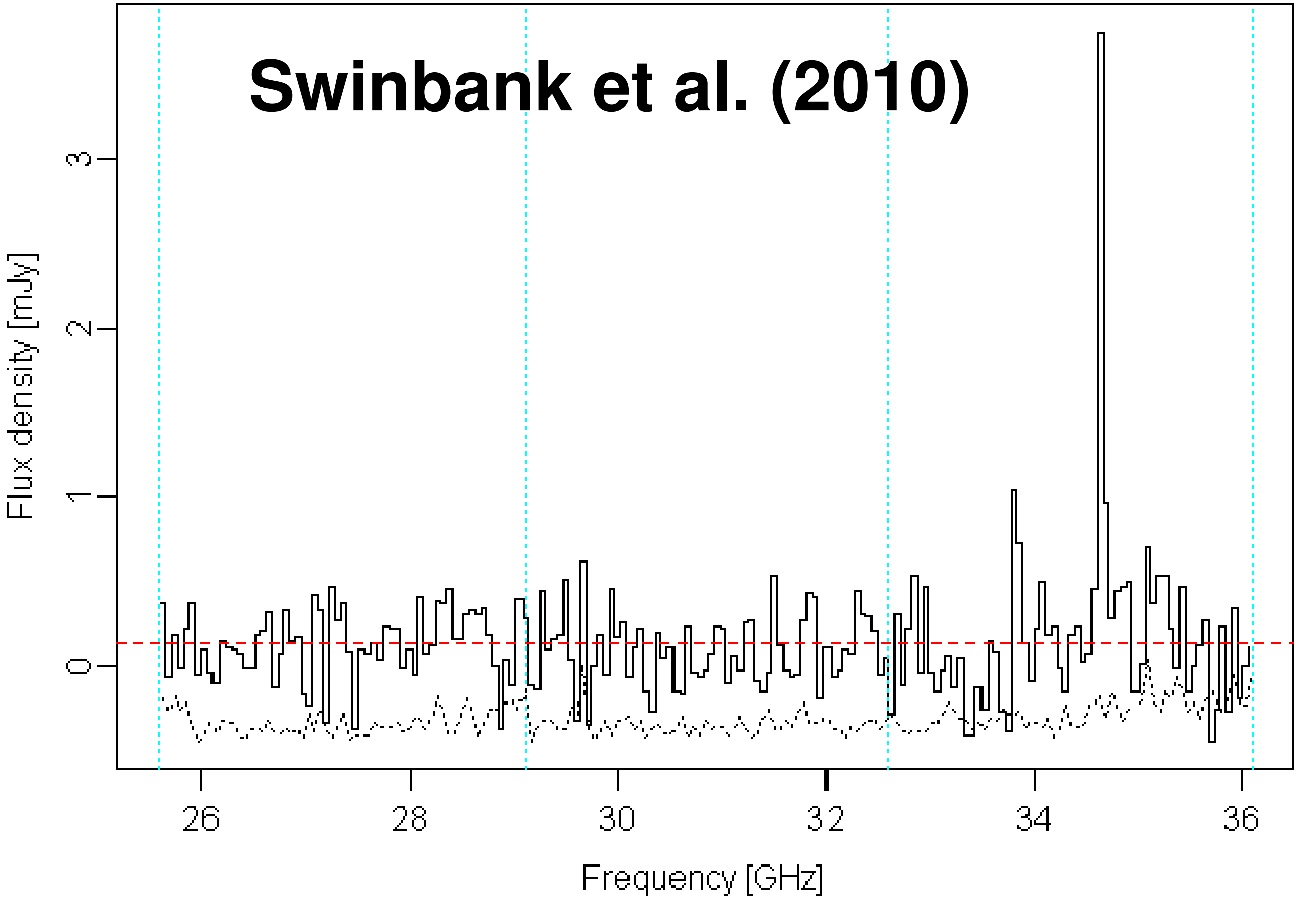
Optical counterpart is faint and red.



Swinbank et al. (2010, Nature, 464, 733)

Zpectrometer delivers quick redshift

May 19: Zpectrometer detects CO(1–0) line at *z* = 2.32, confirmed May 27 by detection of CO(3–2) with PdBI.

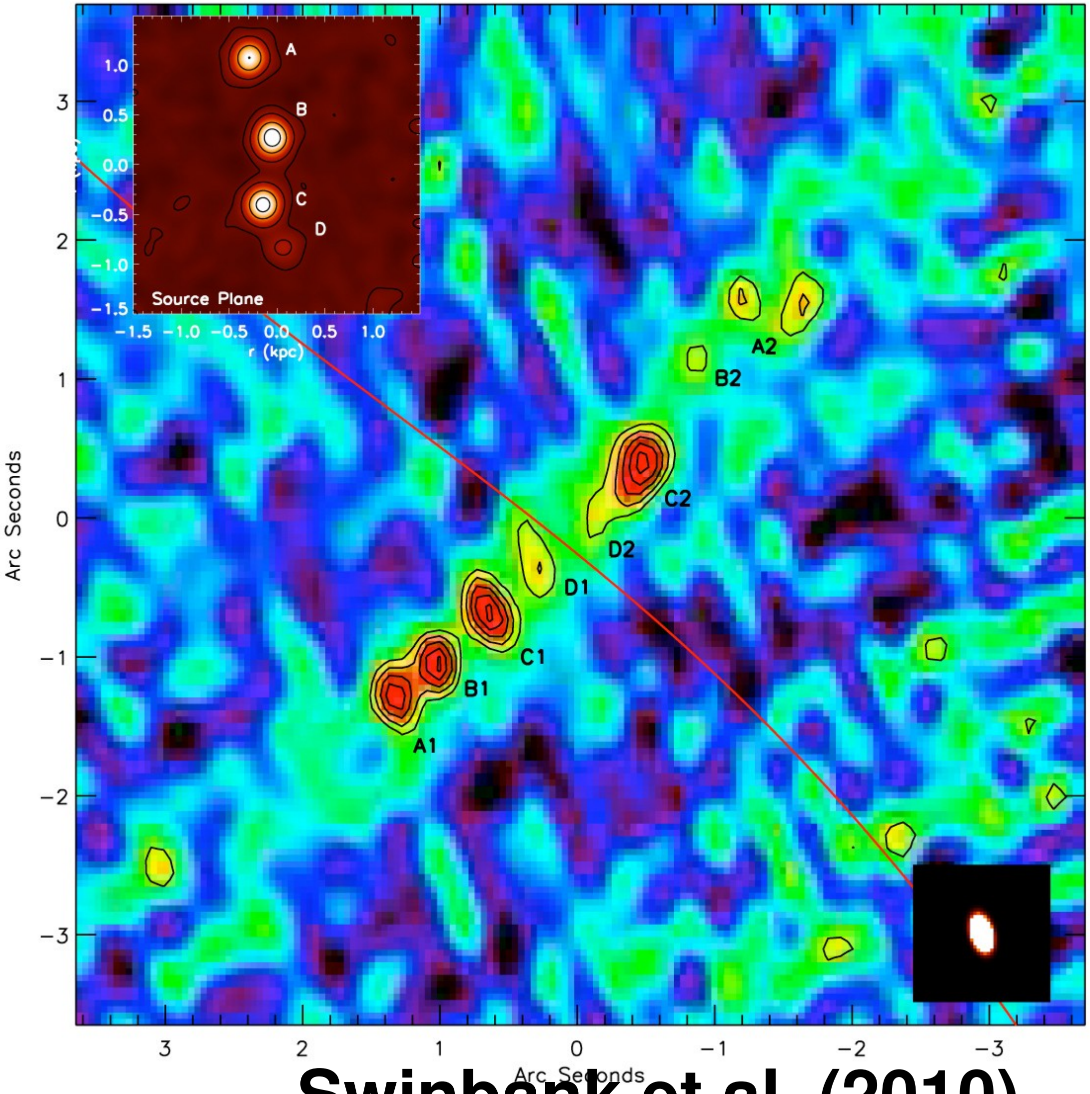


Lensed images are resolved

July 13:

High-resolution mapping at 345 GHz reveals four knots of (rest) 260 µm emission each doubly imaged.

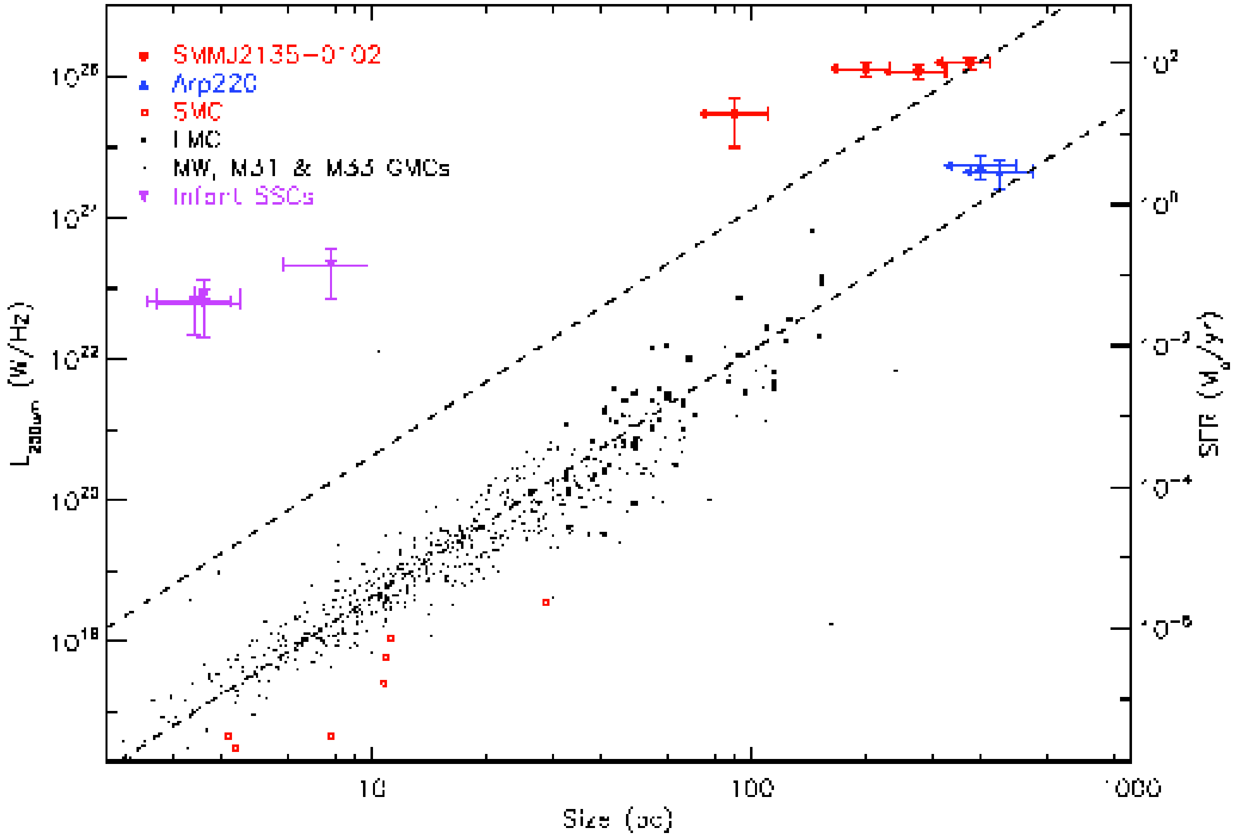
With source and lens redshifts in hand, can derive magnification: *M* = 2 × 16 = 32.



Swinbank et al. (2010)

Scaled-up nascent star clusters?

Star-forming knots in SMM J2135–0102 fall above the luminosity–size relation for Milky Way molecular clouds, but to the same degree as knots in two local starbursts.



Swinbank et al. (2010)

Summary

Dense molecular gas, the raw material from which galaxies form new stars, can be studied with multiple emission lines of CO and other species.

In the distant ($z > 1$) universe, such studies allow us to

+ measure dense gas masses
+ characterize dynamical states
+ determine redshifts (especially for dusty galaxies!)

which are important for understanding galaxy evolution.