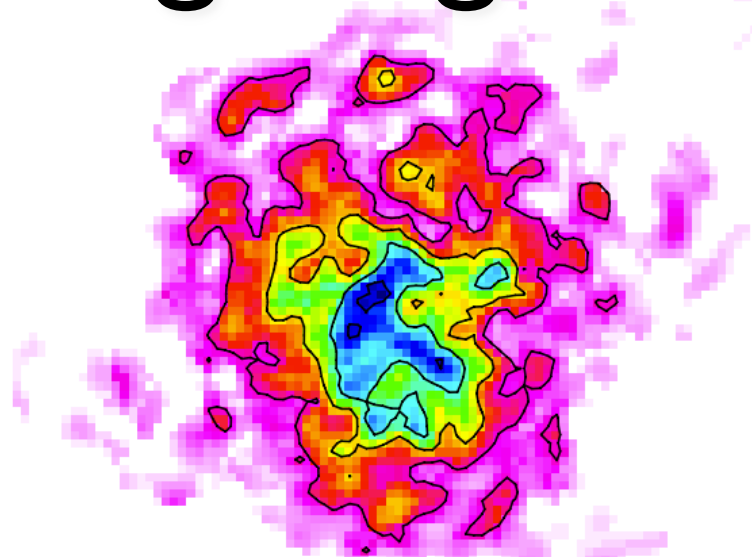# Resolved studies of gas in high-z galaxies



## Jacqueline Hodge

Jansky Fellow (NRAO)

With Fabian Walter (MPIA), Chris Carilli (NRAO), Erwin de Blok (ASTRON),

Dominik Riechers (Cornell), Emanuele Daddi (CEA)

3D2014 ESO Workshop

13 Mar 2014 – Garching, Germany

# Resolved studies of gas in high-z galaxies

submillimeter

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Jansky Fellow (NRAO)

With Fabian Walter (MPIA), Chris Carilli (NRAO), Erwin de Blok (ASTRON),

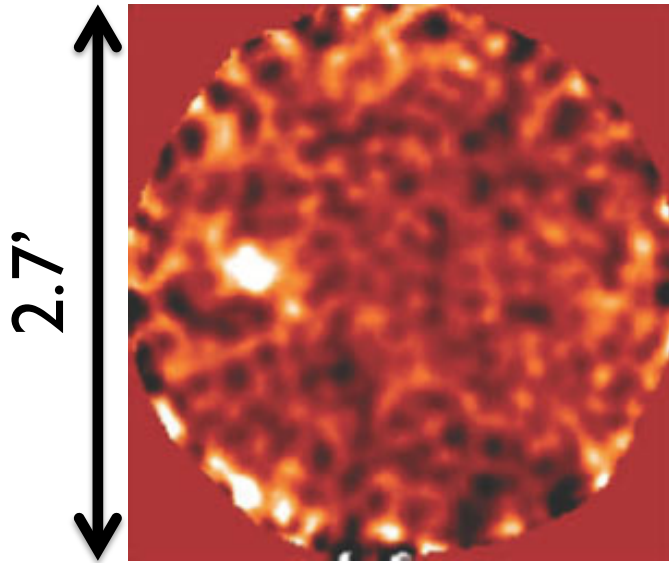Dominik Riechers (Cornell), Emanuele Daddi (CEA)

3D2014 ESO Workshop
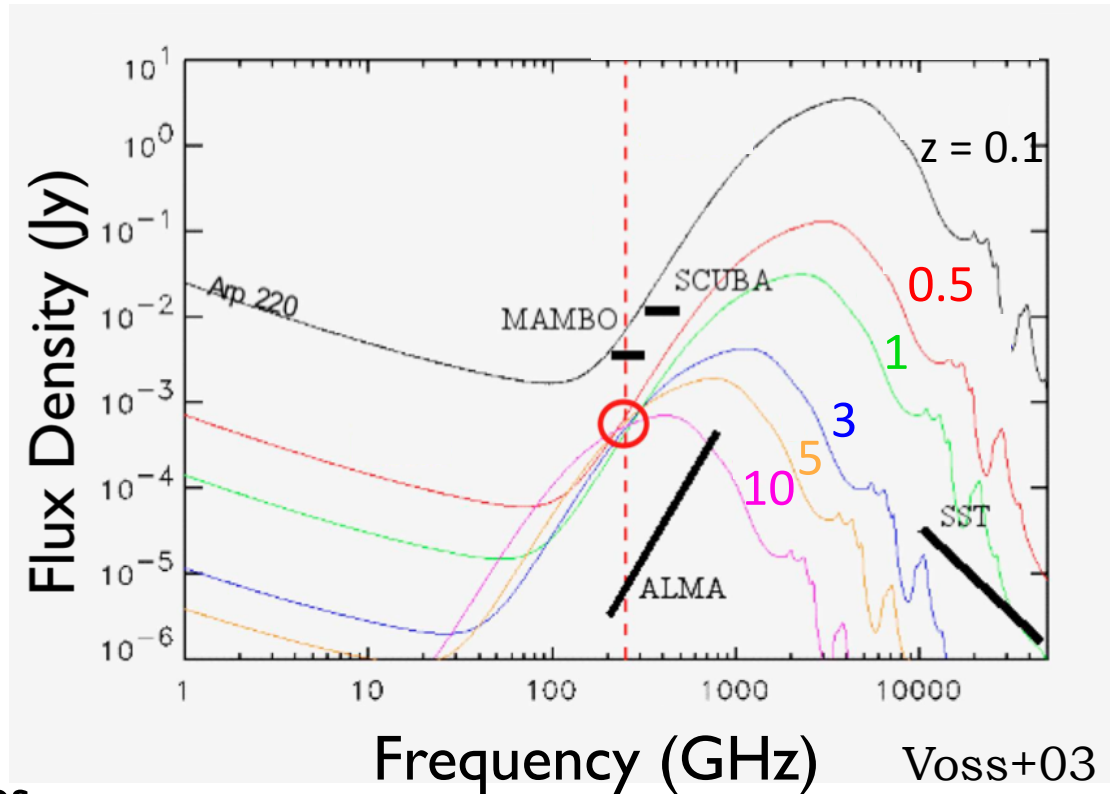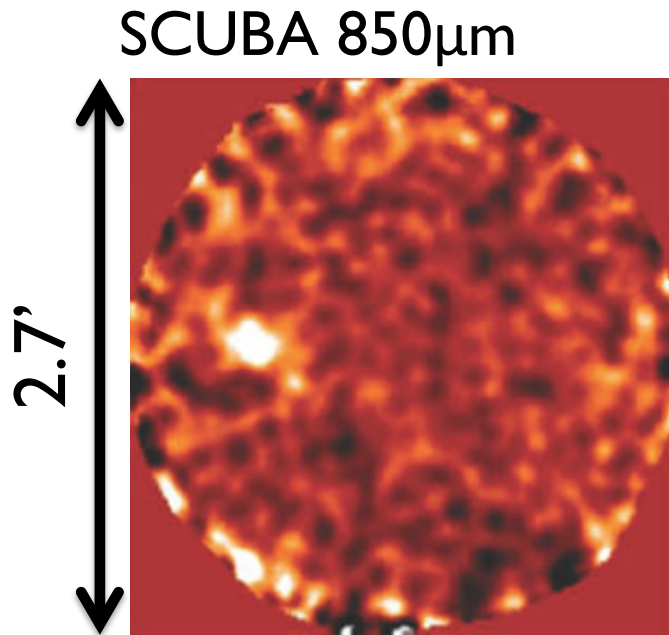
13 Mar 2014 – Garching, Germany

# Submillimeter Galaxies (SMGs)

SCUBA 850μm



2.7'

E.g., Barger+98, Smail+97; Hughes +98; Eales+99; Blain+99; Bertoldi +00; Greve+04; Scott+08
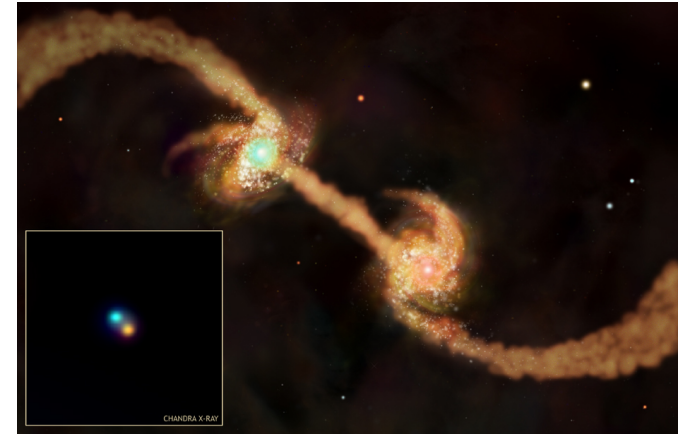
# Submillimeter Galaxies (SMGs)

SCUBA 850μm



E.g., Barger+98, Smail+97; Hughes
+98; Eales+99; Blain+99; Bertoldi
+00; Greve+04; Scott+08

# The Big Question
What is driving the intense star formation?

- Gas-rich major mergers
    - Induce nuclear starburst
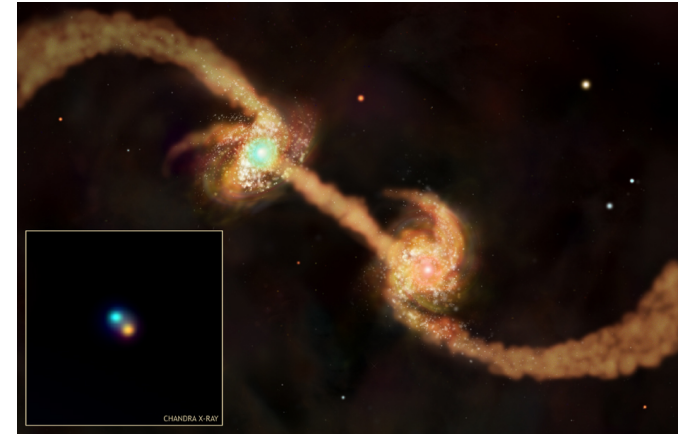    - High brightness temperature, concentrated emission



X-ray: NASA/CXC/IoA/D.Alexander et al.
Illustration: NASA/CXC/M.Weiss

OR

# The Big Question

What is driving the intense star formation?



X-ray: NASA/CXC/IoA/D.Alexander et al.
Illustration: NASA/CXC/M.Weiss

- Gas-rich major mergers
  - Induce nuclear starburst
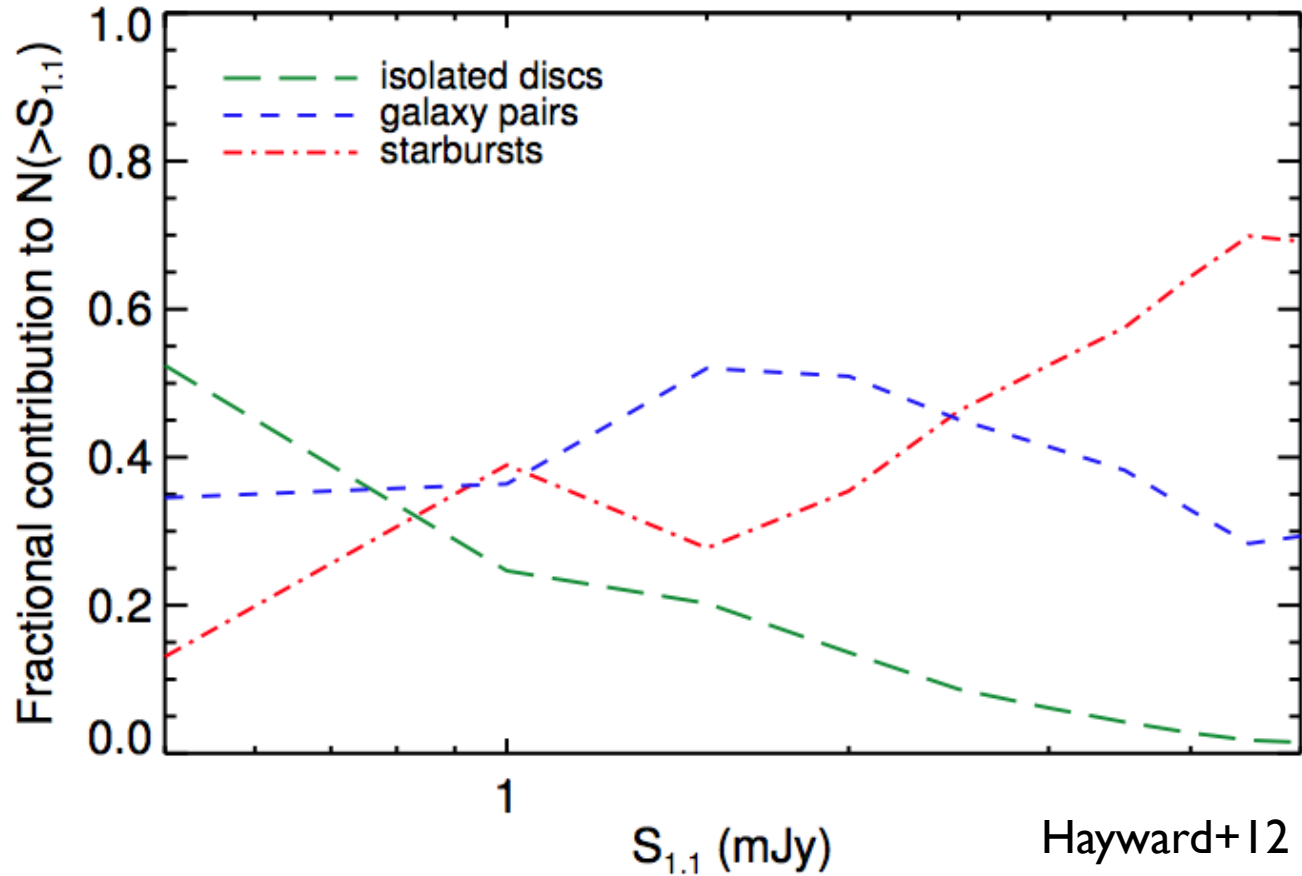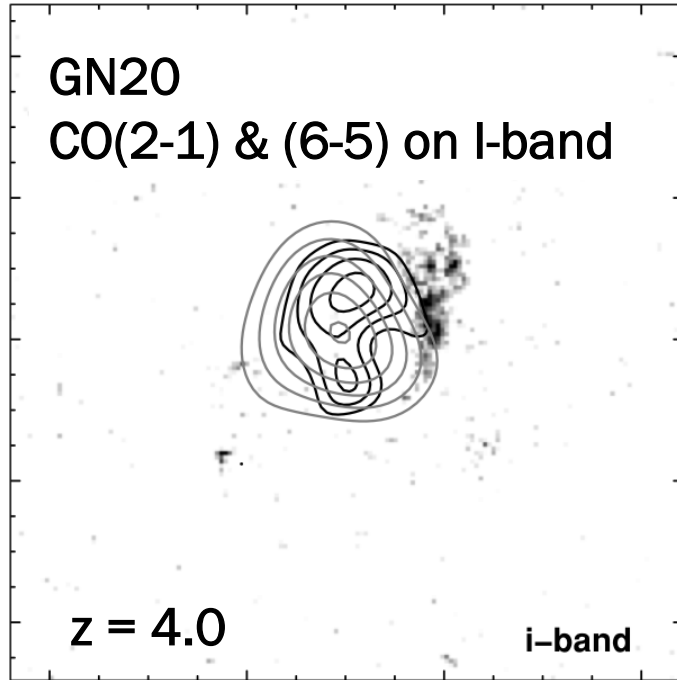  - High brightness temperature, concentrated emission

## OR



Cresci et al. 2010, Nature
Image credit: ESO/L.Calcada

- Cold-mode accretion (CMA)
  - Gas flows in from IGM
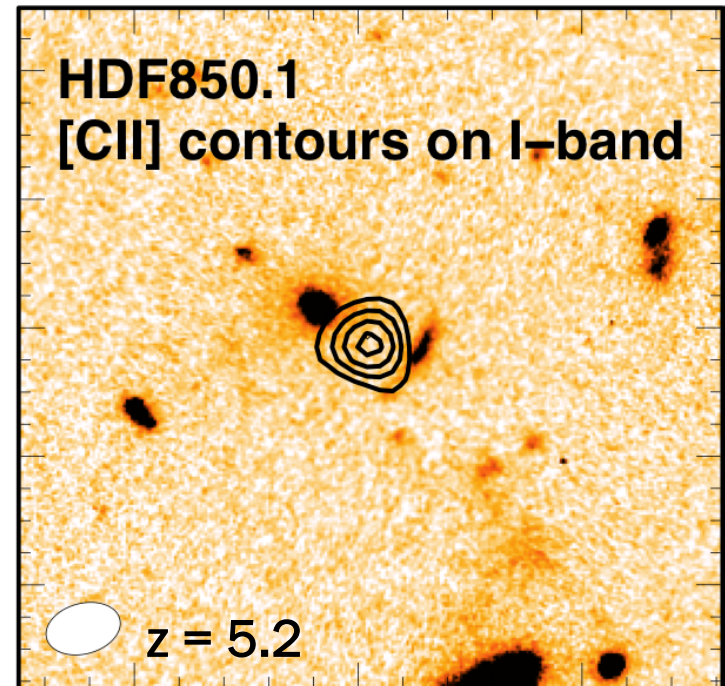  - Cools rapidly
  - Results in clumpy, star forming disk

# Likely a heterogeneous population

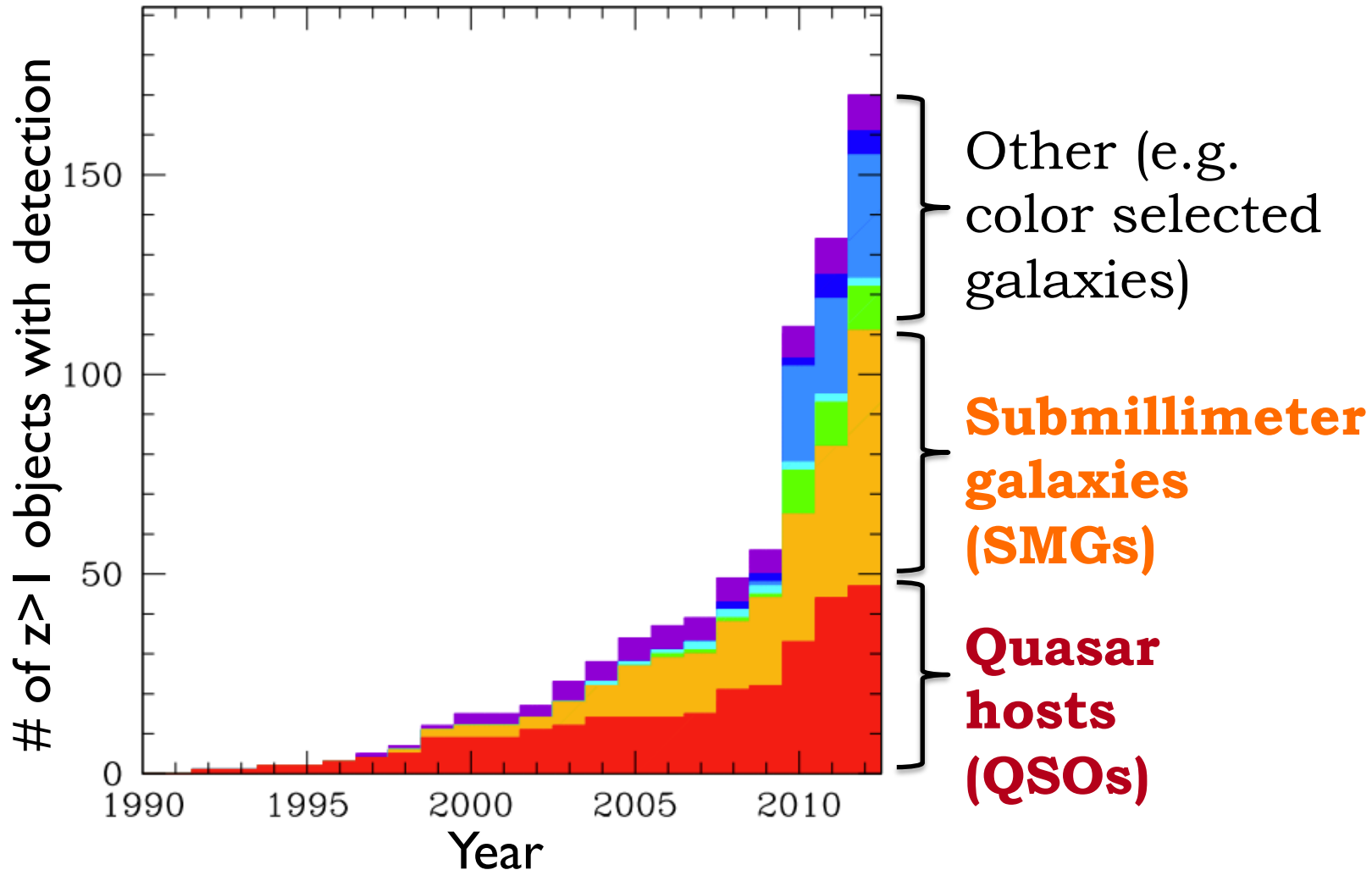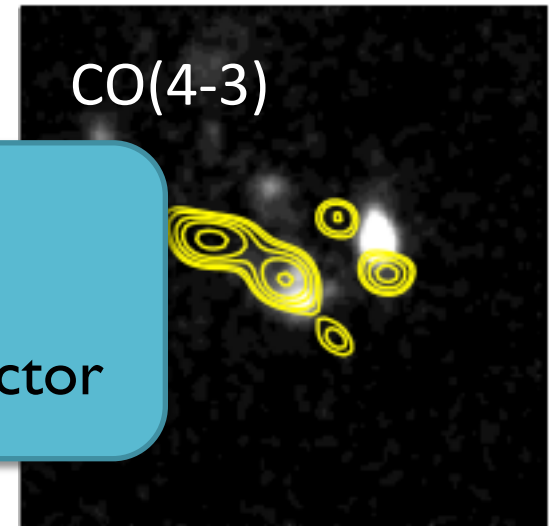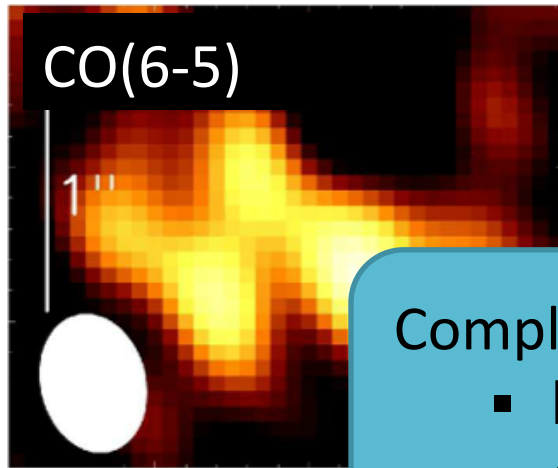# High-z galaxies can be highly obscured!



GN20
CO(2-1) & (6-5) on I-band

z = 4.0

i-band

Carilli+10



HDF850.1
[CII] contours on I–band

z = 5.2

Walter+12

# Gas at high (z>1) redshift



Other (e.g. color selected galaxies)

**Submillimeter galaxies (SMGs)**

**Quasar hosts (QSOs)**

# of z>1 objects with detection

Year

Carilli & Walter (2013)

# Previous studies of resolved gas in (unlensed) SMGs in one slide



CO(6-5)

1"

Engel+10



CO(3-2)

Tacconi+06



CO(4-3)

Bothwell+10



CO(6-5)

0.5"
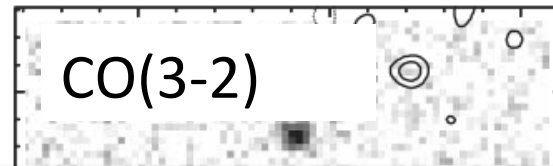
Tacconi+08

Complications with CO:
- Excitation
- CO-to-$H_2$ conversion factor
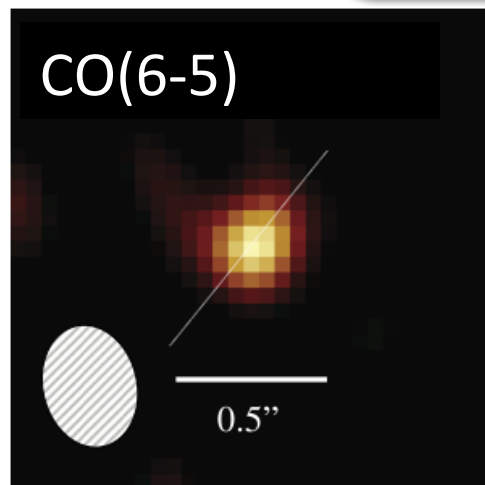
See e.g., Tacconi+06, 08; Bothwell+10; Engel+10; Ivison+10, 11; Riechers+11

# Complication: Excitation



Carilli & Walter (2013)

S(CO) / S(CO 1-0)

$J_{upper}$

Riechers, Hodge+2011

CO(1-0)

➡ low-J lines very important!
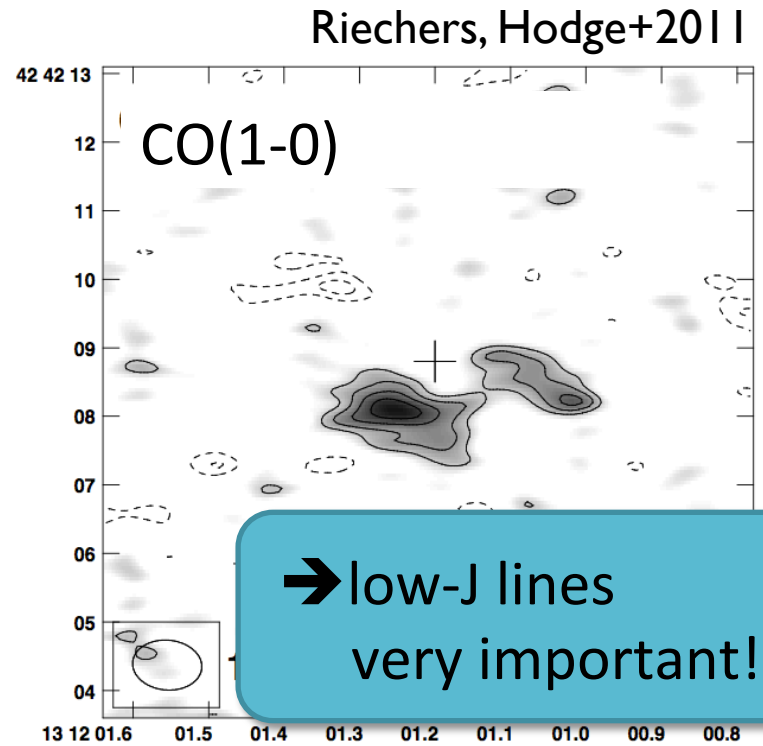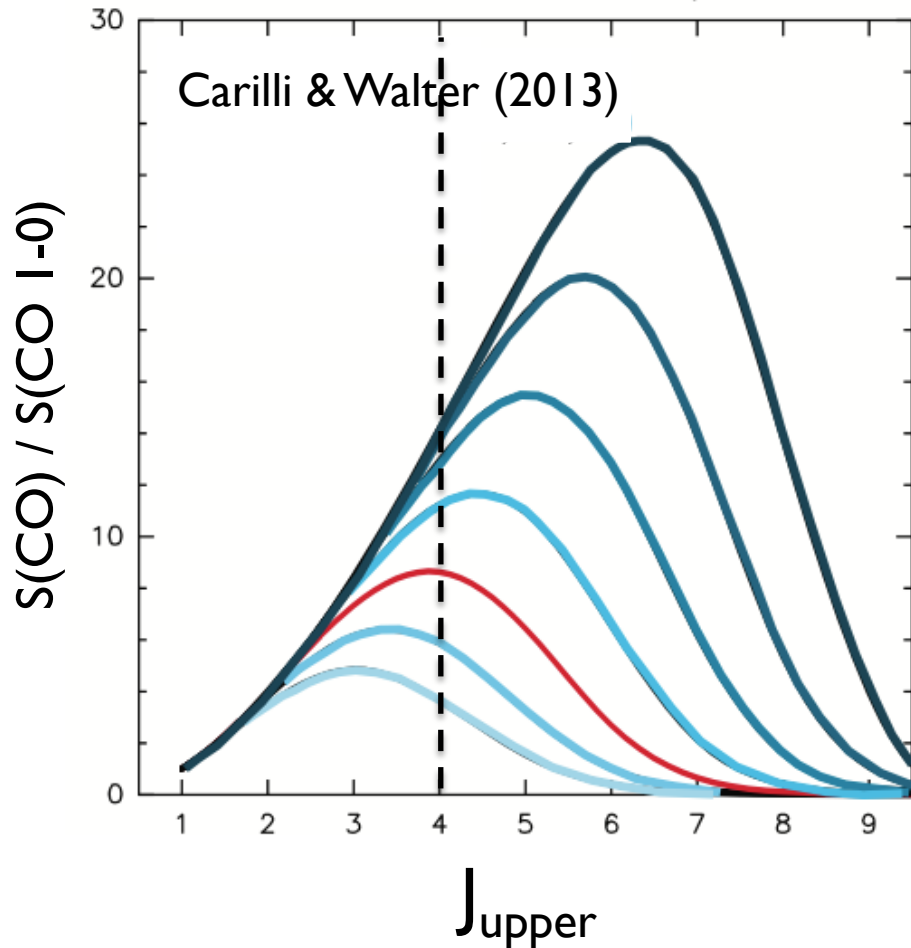
(See also Ivison+11)

# Complication: Conversion factor



VS

$$\alpha_{CO} \sim 4$$
$M_\odot$ (K km/s $pc^2$)$^{-1}$

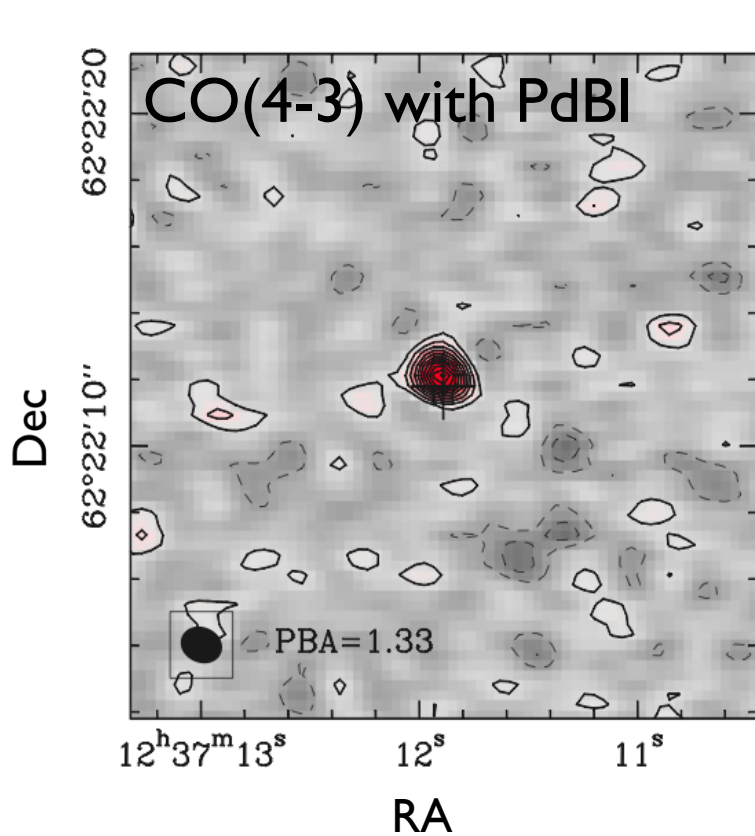$$\alpha_{CO} \sim 0.8$$
$M_\odot$ (K km/s $pc^2$)$^{-1}$
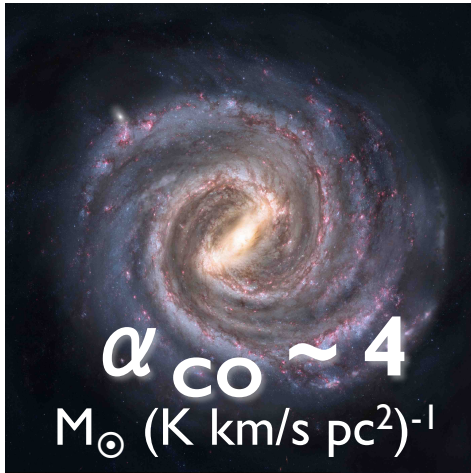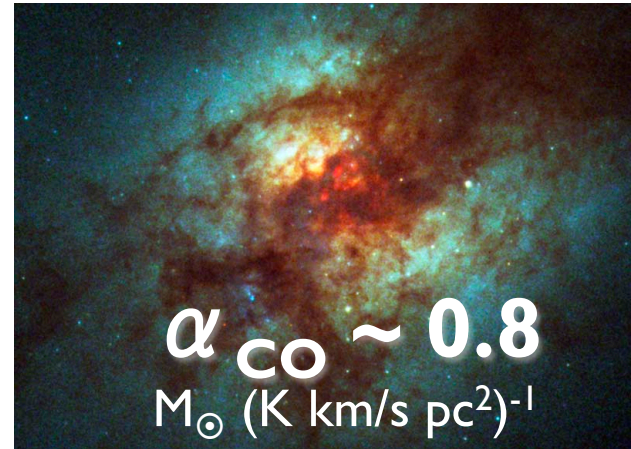
Varies with:
  → Density
  → Temperature
  → Metallicity

Locally, see (e.g.) Schruba+11; Leroy+11; Sandstrom+12, 13; Papadopoulos+12; Bolatto+13; etc  & talk by Karin Sandstrom

# Our target: the SMG GN20



CO(4-3) with PdBI

Dec

PBA=1.33

RA

Daddi+09

z = 4.05
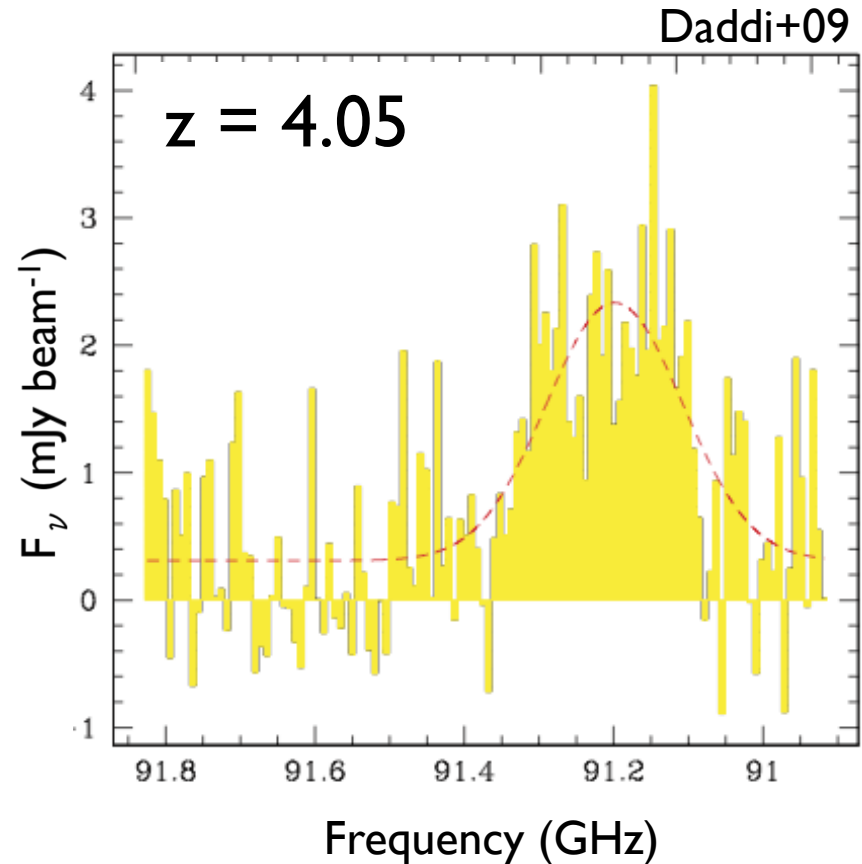
SFR ~ 3000 $M_\odot$ yr$^{-1}$

The GN20 Field

N
E

GN20

GN20.2a

GN20.2b
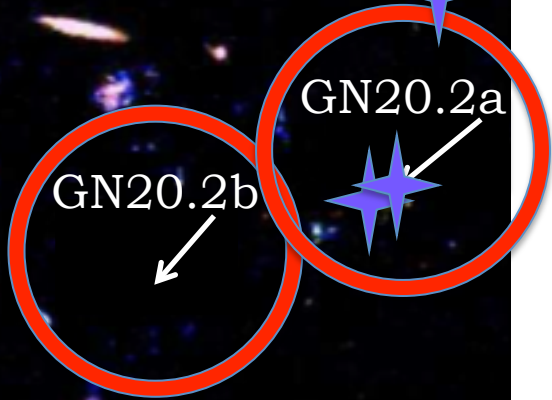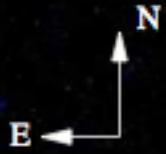
Daddi+09

J. Hodge (NRAO) - 13 Mar 2014

# Previous VLA Observations

CO(1-0) with VLA:



Carilli+10

GN20

GN20.2a

GN20.2b

Declination

Right Ascension



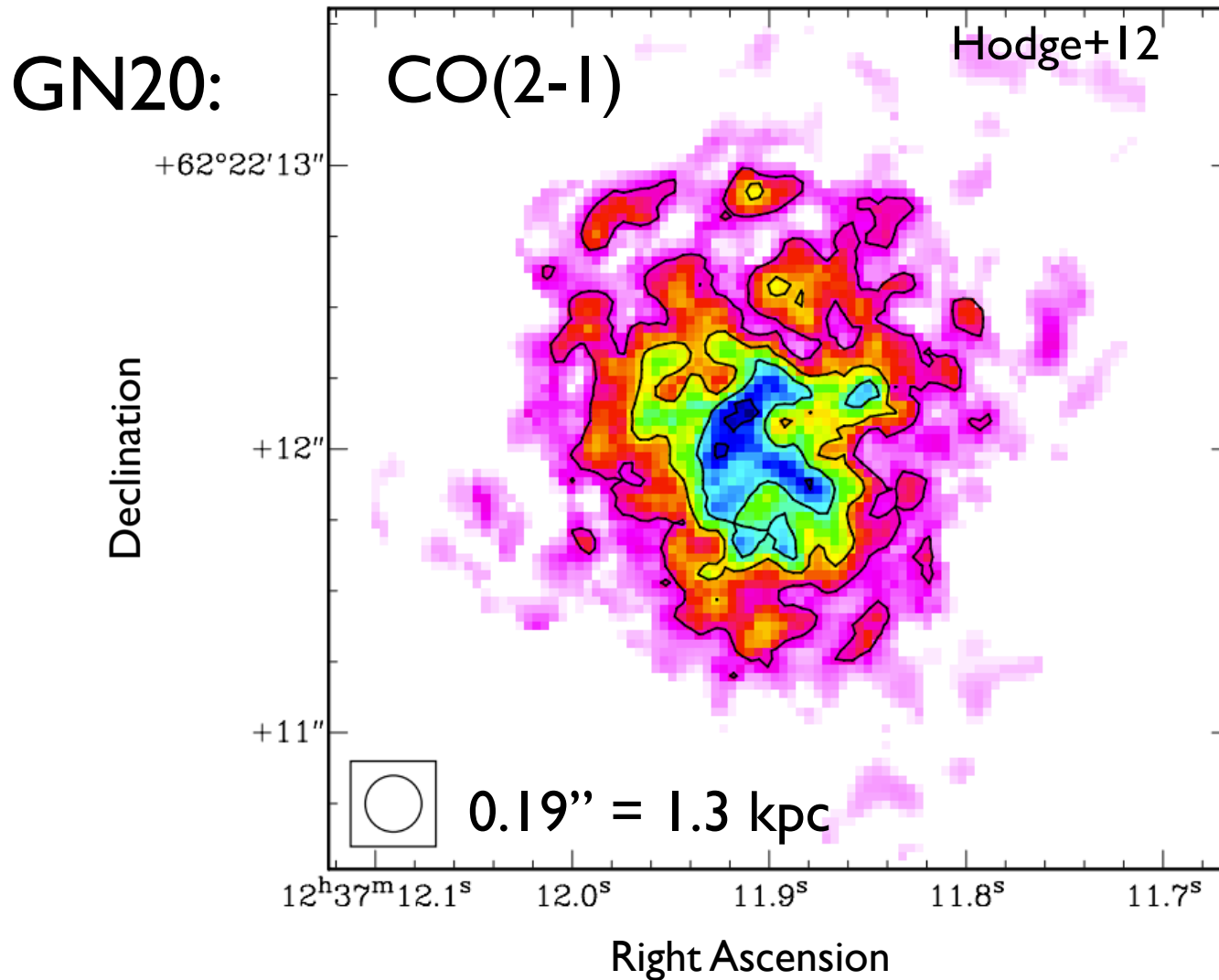CO(4-3) with PdBI

CO(1-0)   ≠ 3D!

Flux (mJy)

Velocity
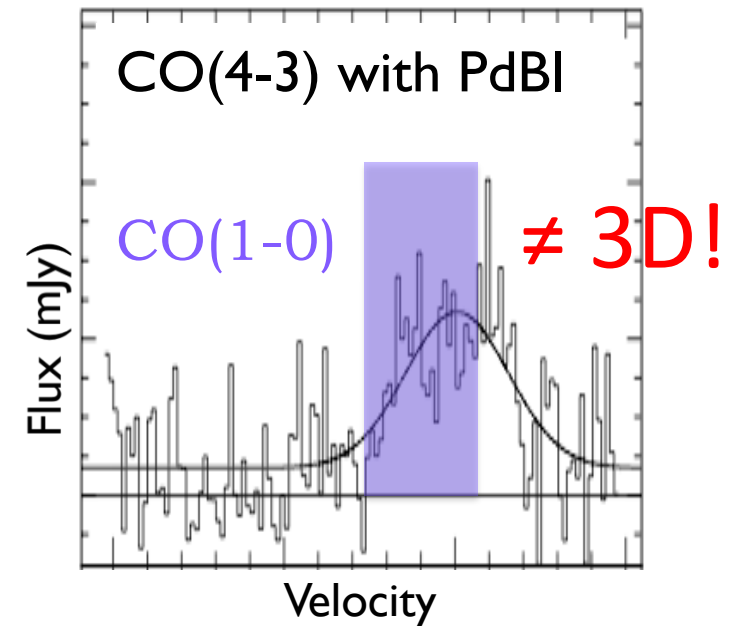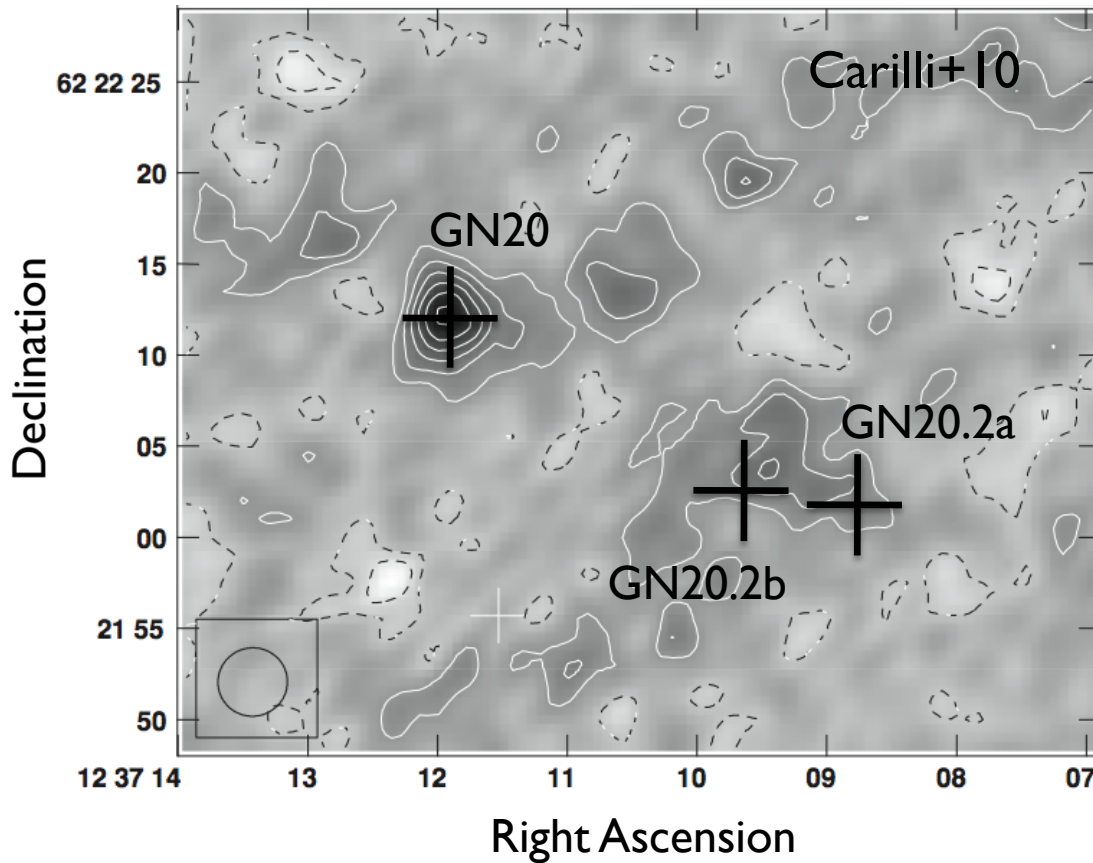
# Previous VLA Observations
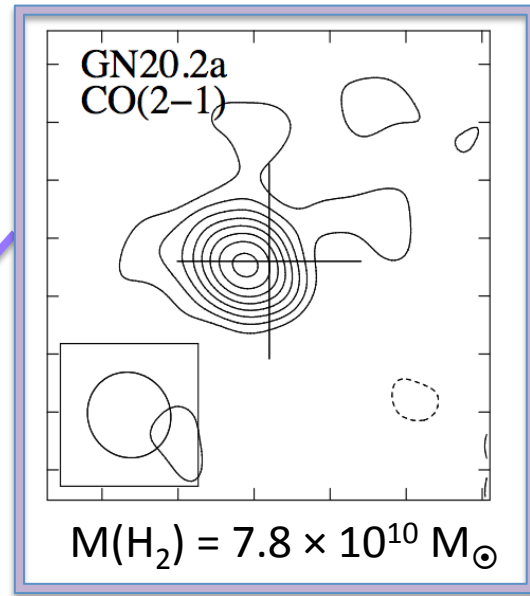
GN20: CO(2-1)
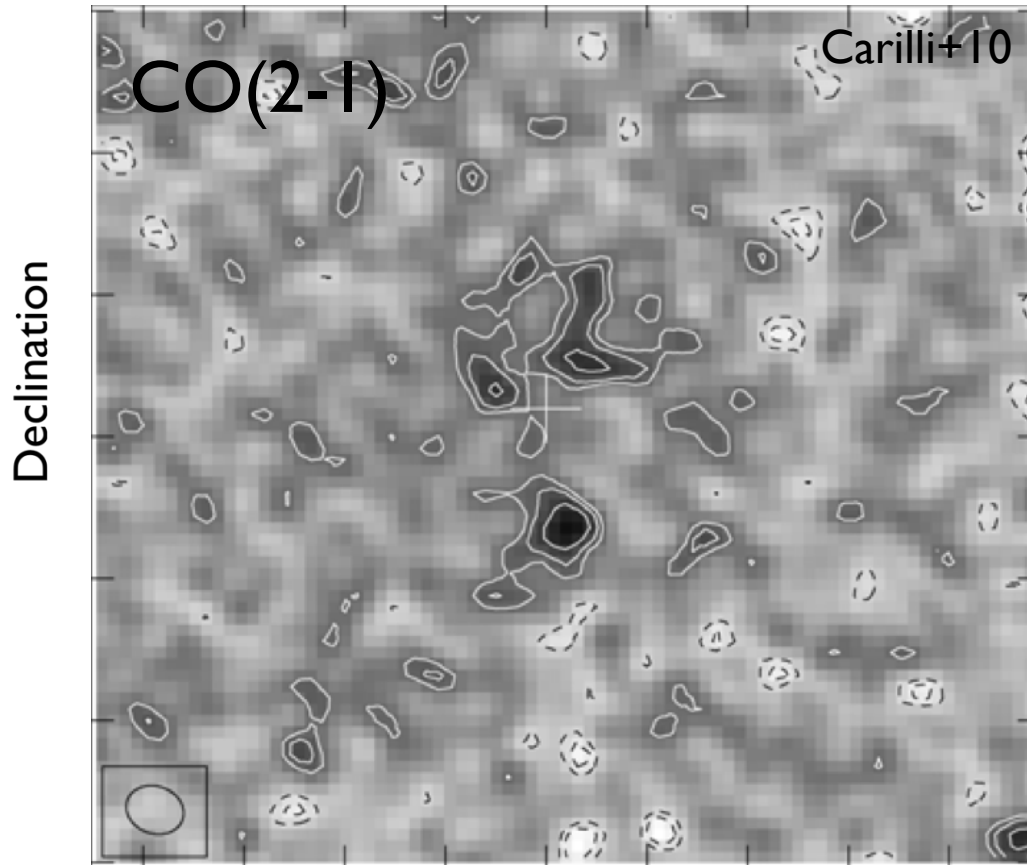


(Also not 3D!)

# The New (J)VLA Data



GN20:    CO(2-1)    Hodge+12

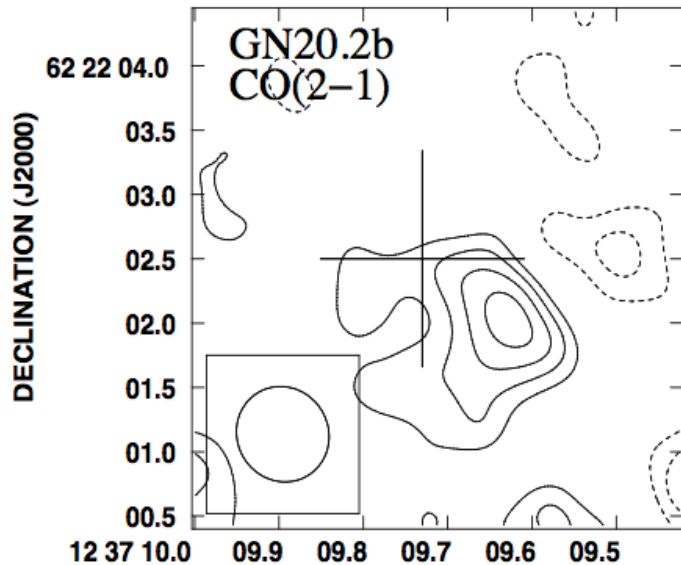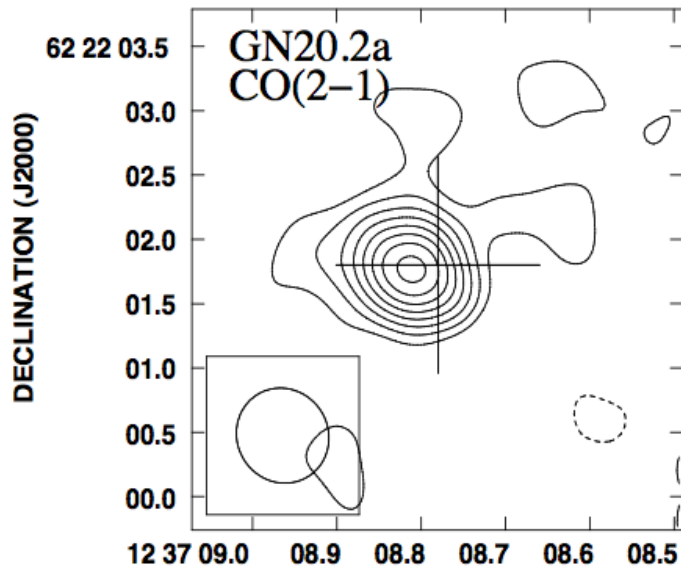0.19" = 1.3 kpc

# The New VLA Data



CO(2-1)

Hodge+12

0.19" = 1.3 kpc
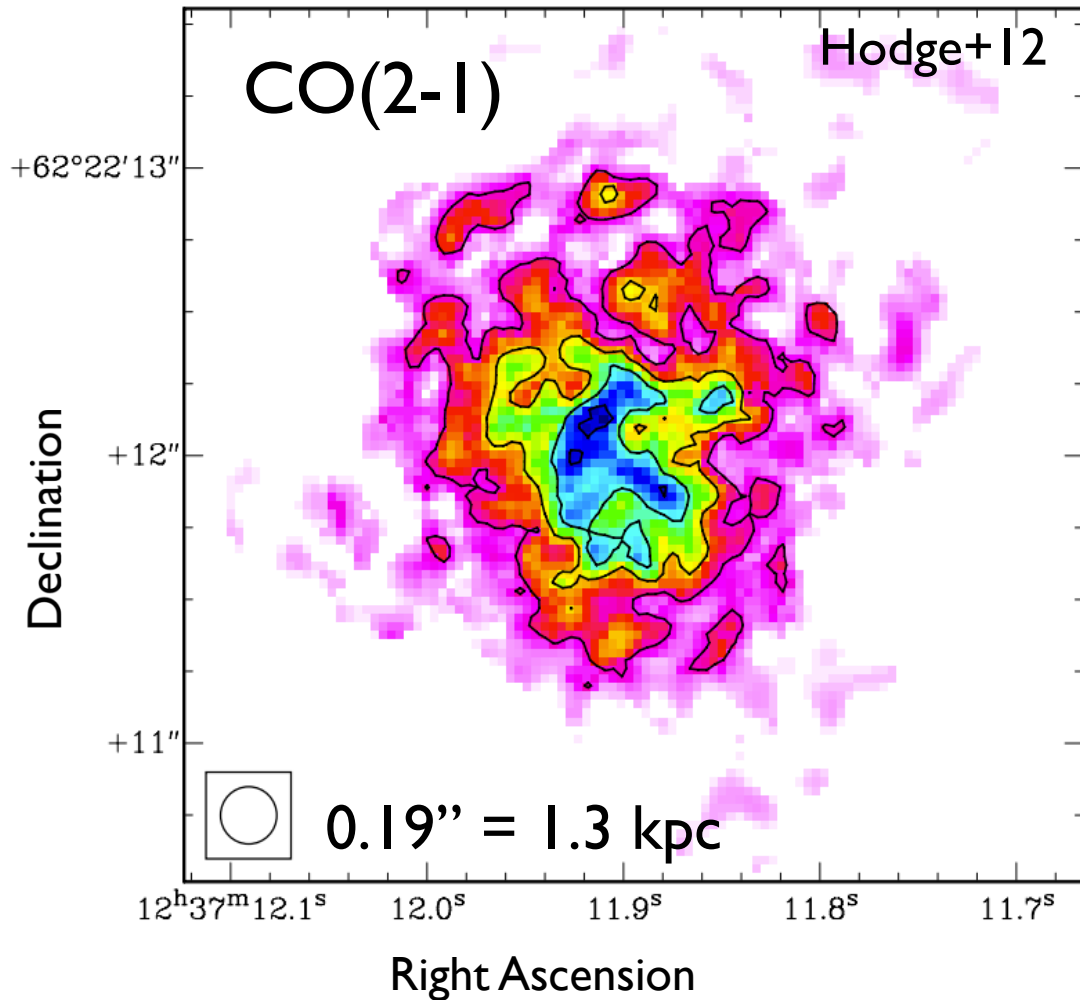
- $M(H_2) = 1.3 \times 10^{11} (\alpha_{CO}/0.8) M_\odot$

- Diameter = 14 kpc

# The New VLA Data

CO(1-0) with old VLA:



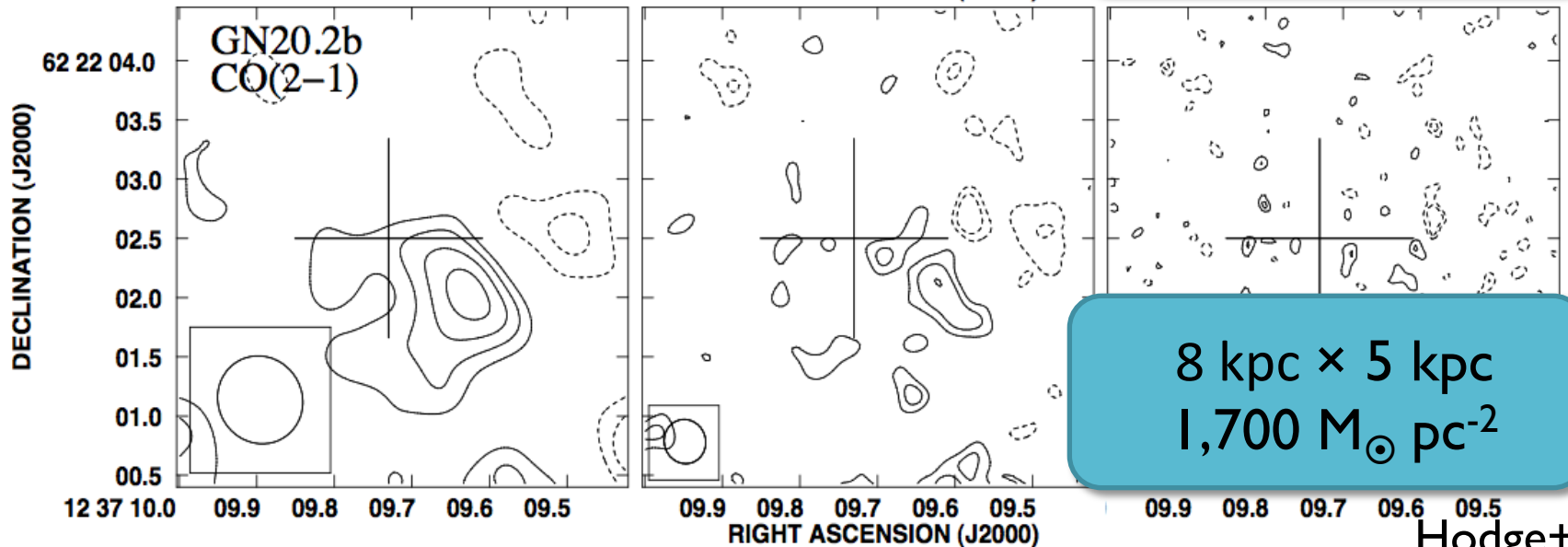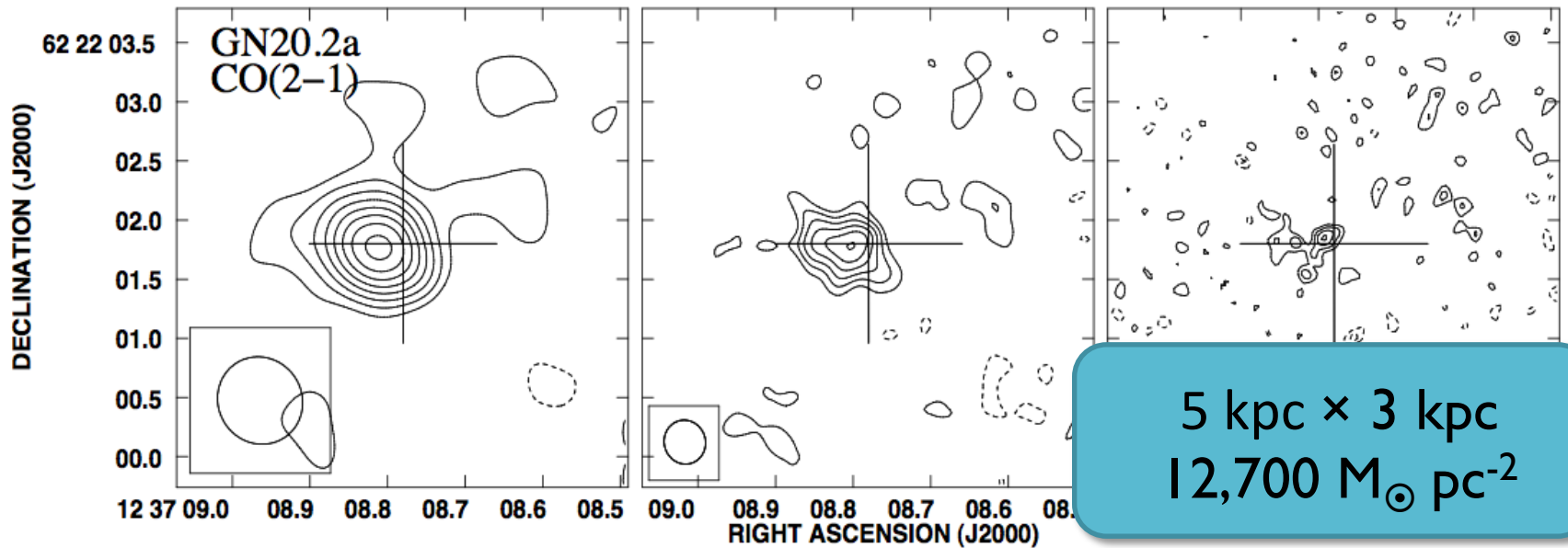M(H$_2$) = 7.8 × 10$^{10}$ M$_\odot$

M(H$_2$) = 3.4 × 10$^{10}$ M$_\odot$

Carilli+11;
Hodge+13c

# The New VLA Data

# The New VLA Data

# The New VLA Data



5 kpc × 3 kpc
12,700 $M_\odot$ pc$^{-2}$

8 kpc × 5 kpc
1,700 $M_\odot$ pc$^{-2}$

Hodge+13c

# Gas vs. Stars
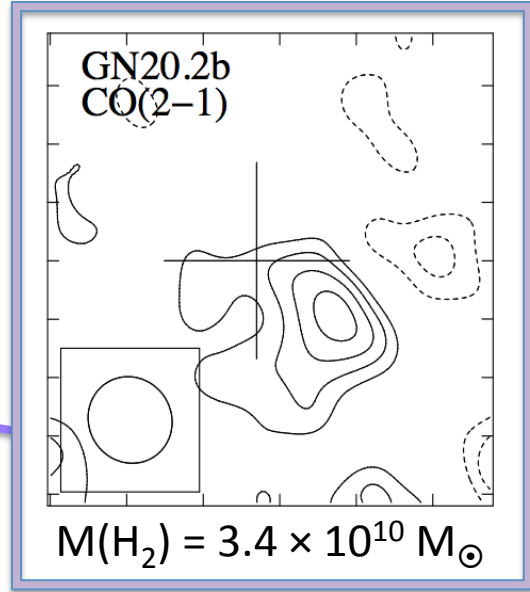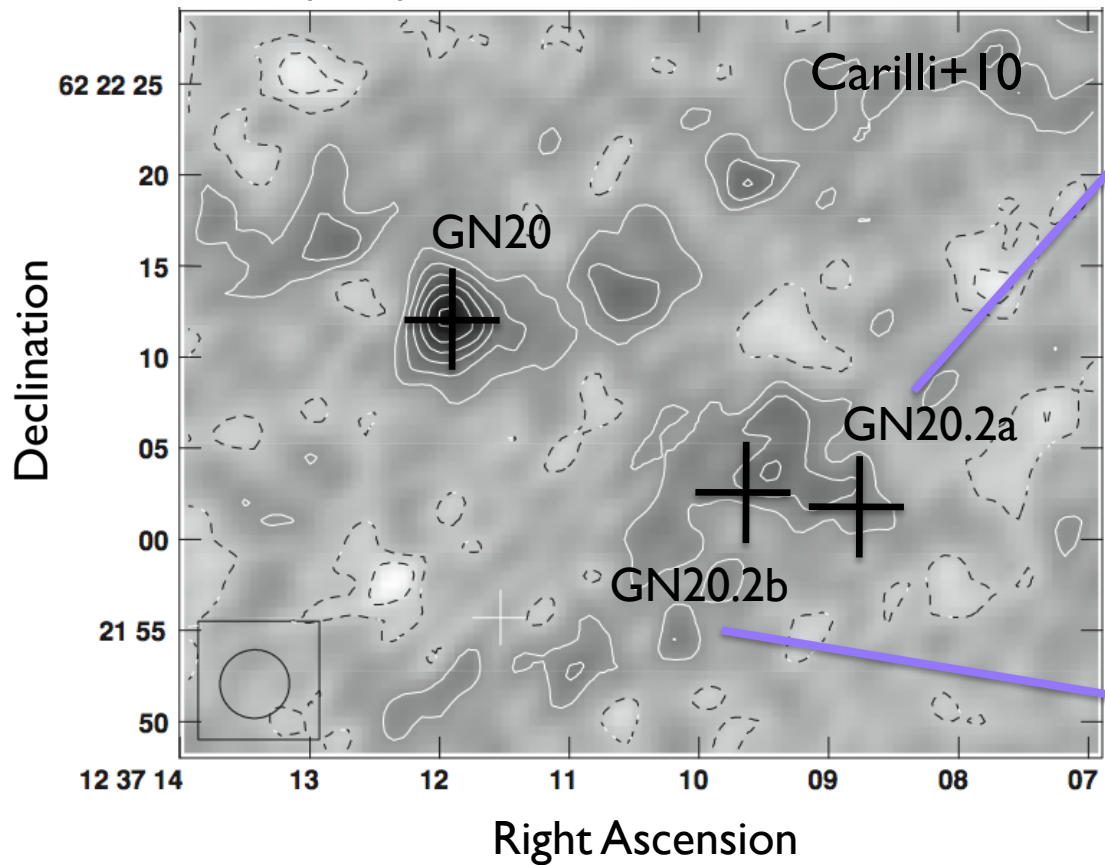


The GN20 Field

Hodge+12
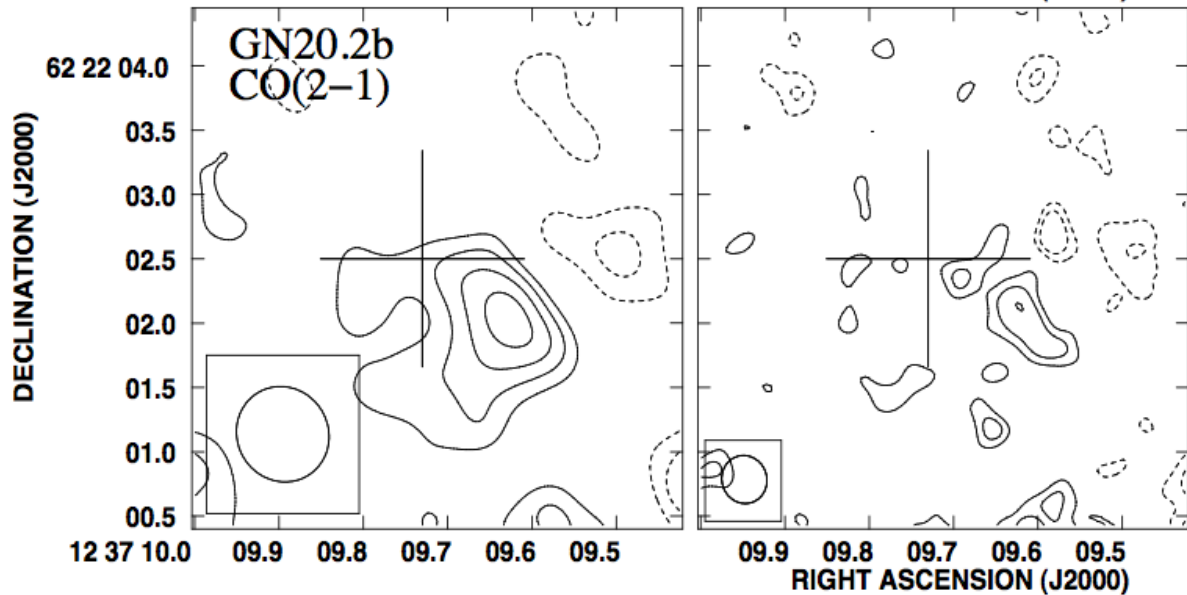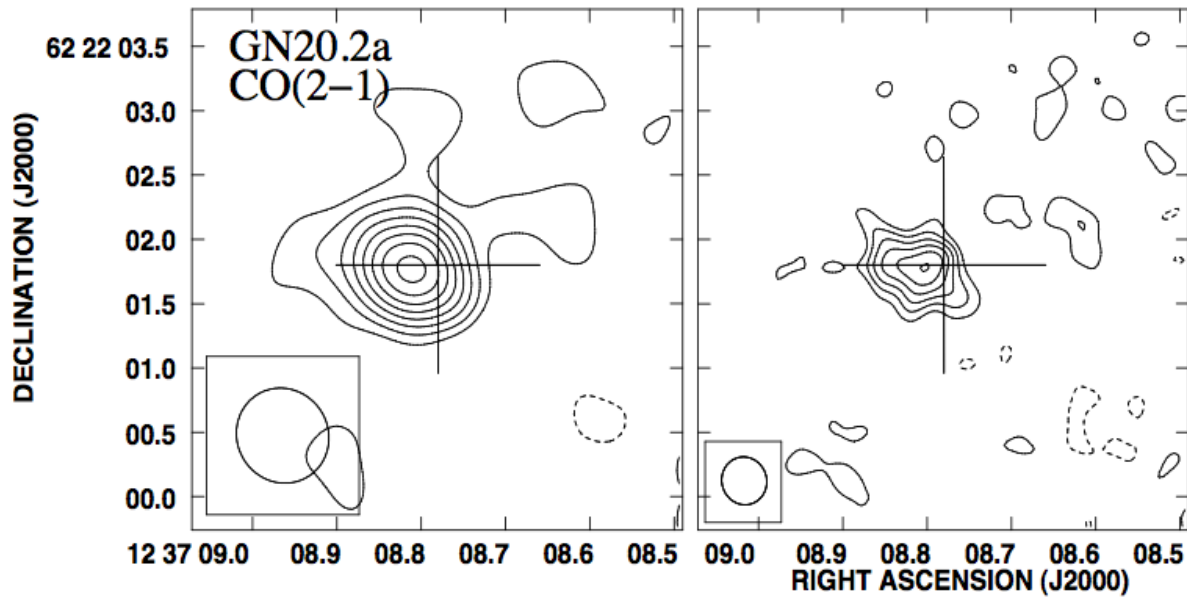
ACS 850z
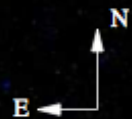
GN20

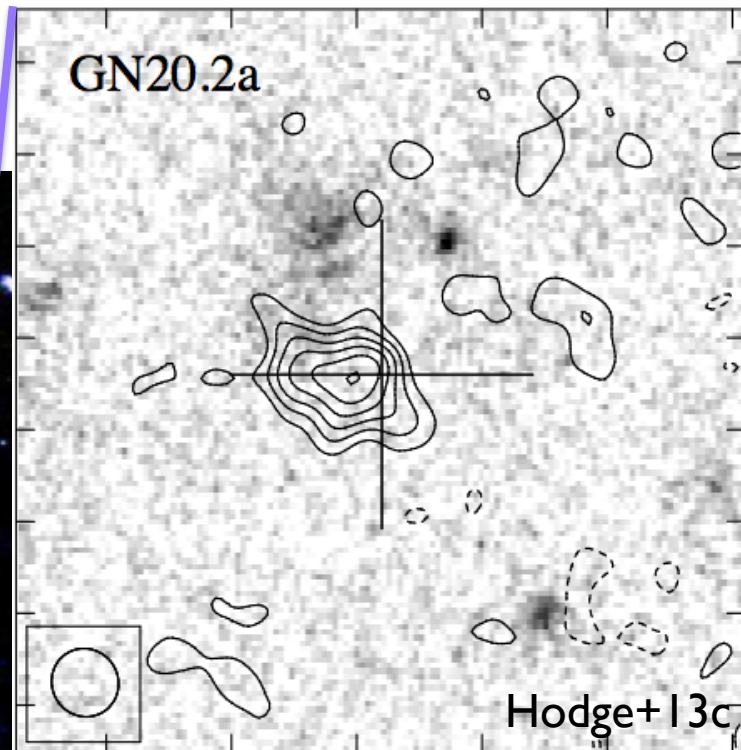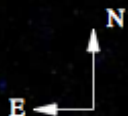Daddi+09

J. Hodge (NRAO) -

# Gas vs. Stars

The GN20 Field



GN20.2a

GN20.2a

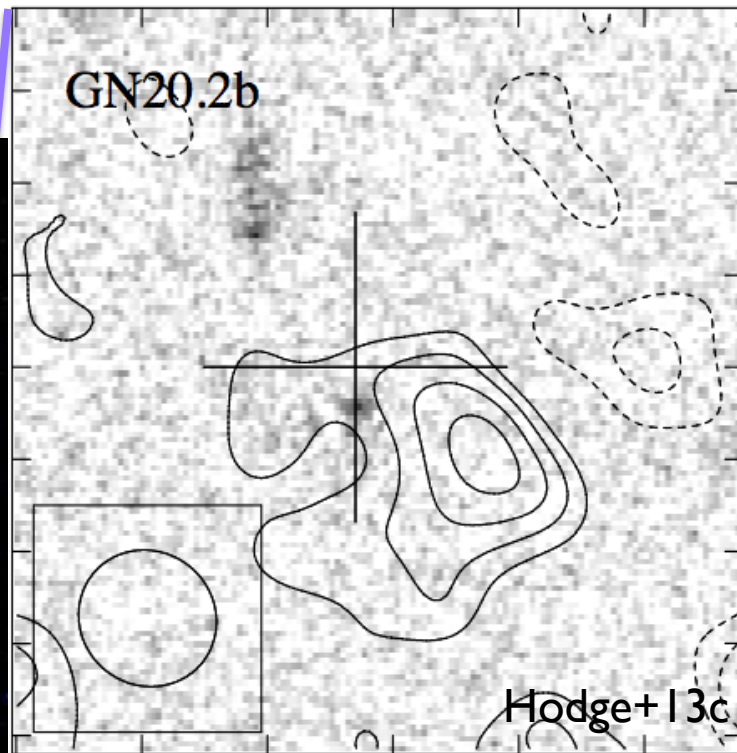Hodge+13c

Daddi+09

# Gas vs. Stars

The GN20



GN20.2b

GN20.2b

Hodge+13c

N

E
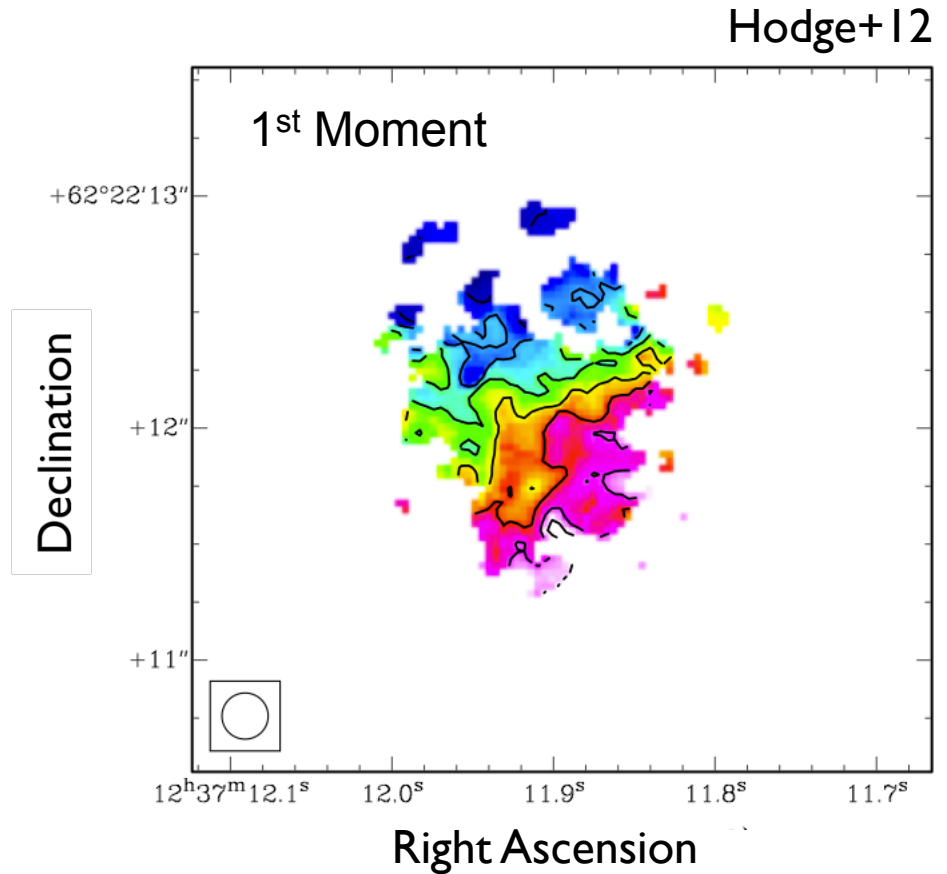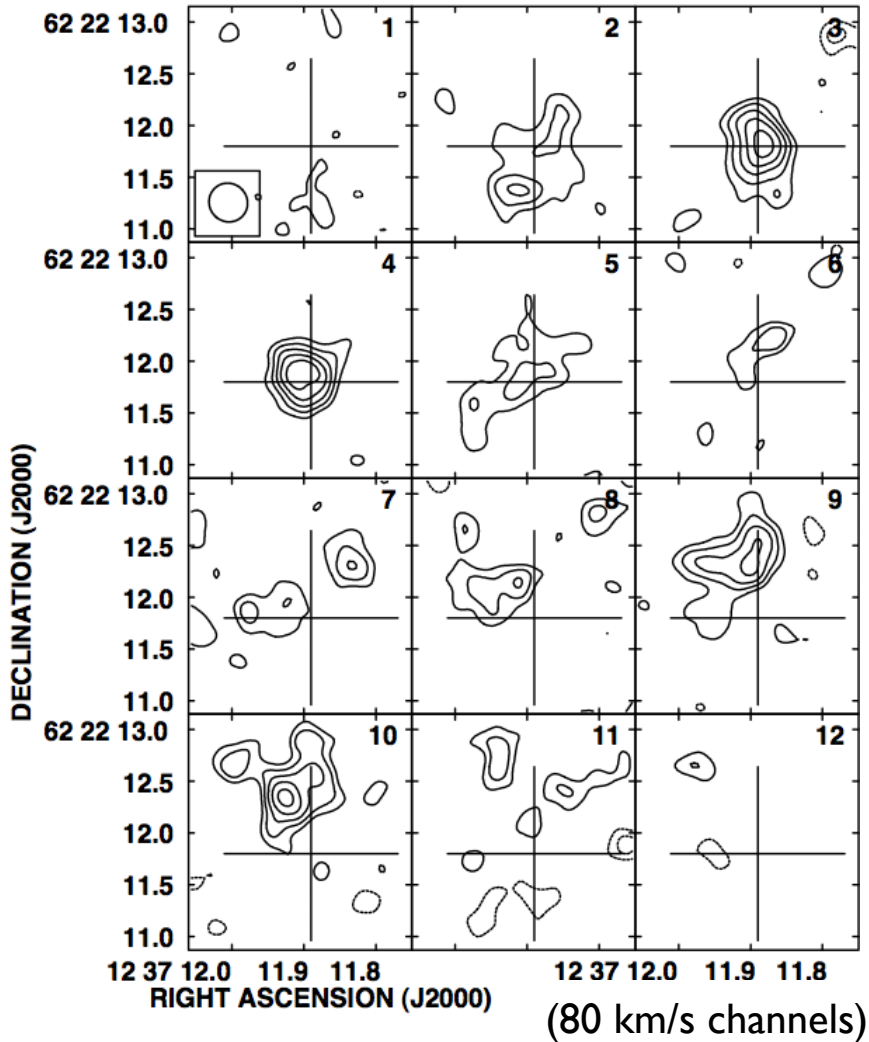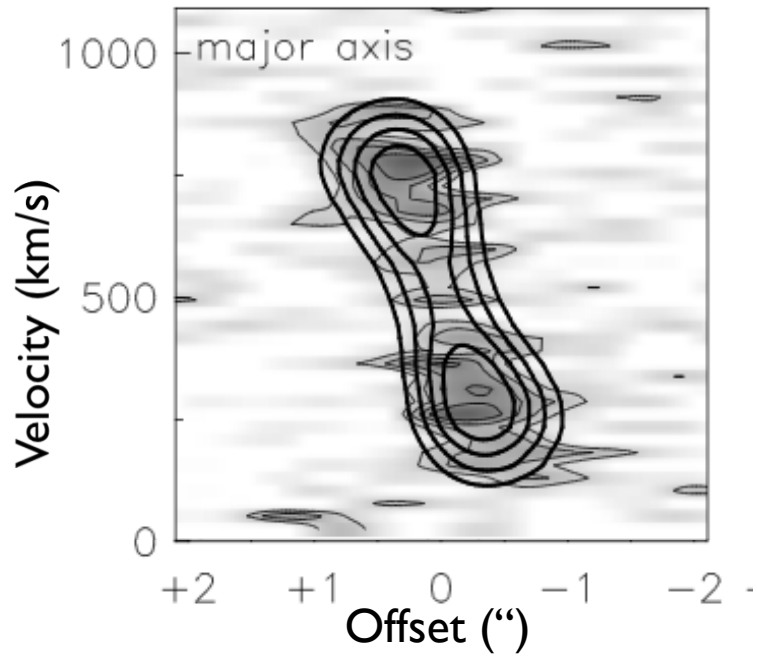
GN20.2b

# GN20: Gas Kinematics



Hodge+12

1st Moment

(80 km/s channels)

# Dynamical Modeling

# Dynamical Modeling



Flat

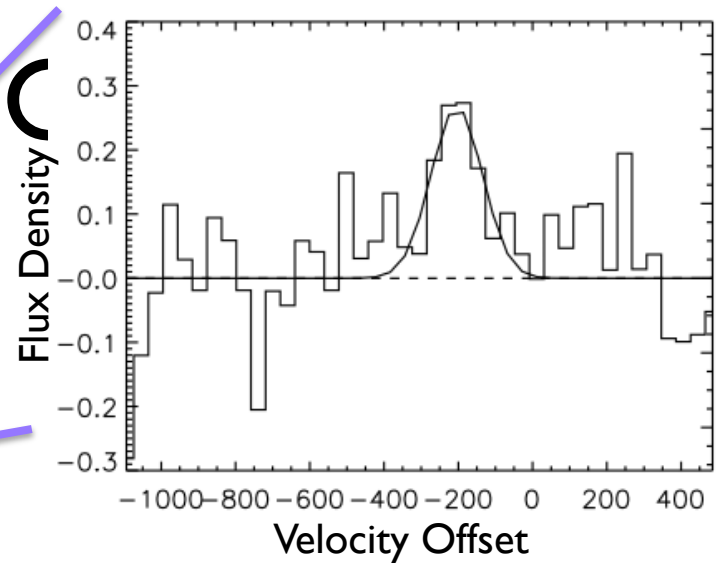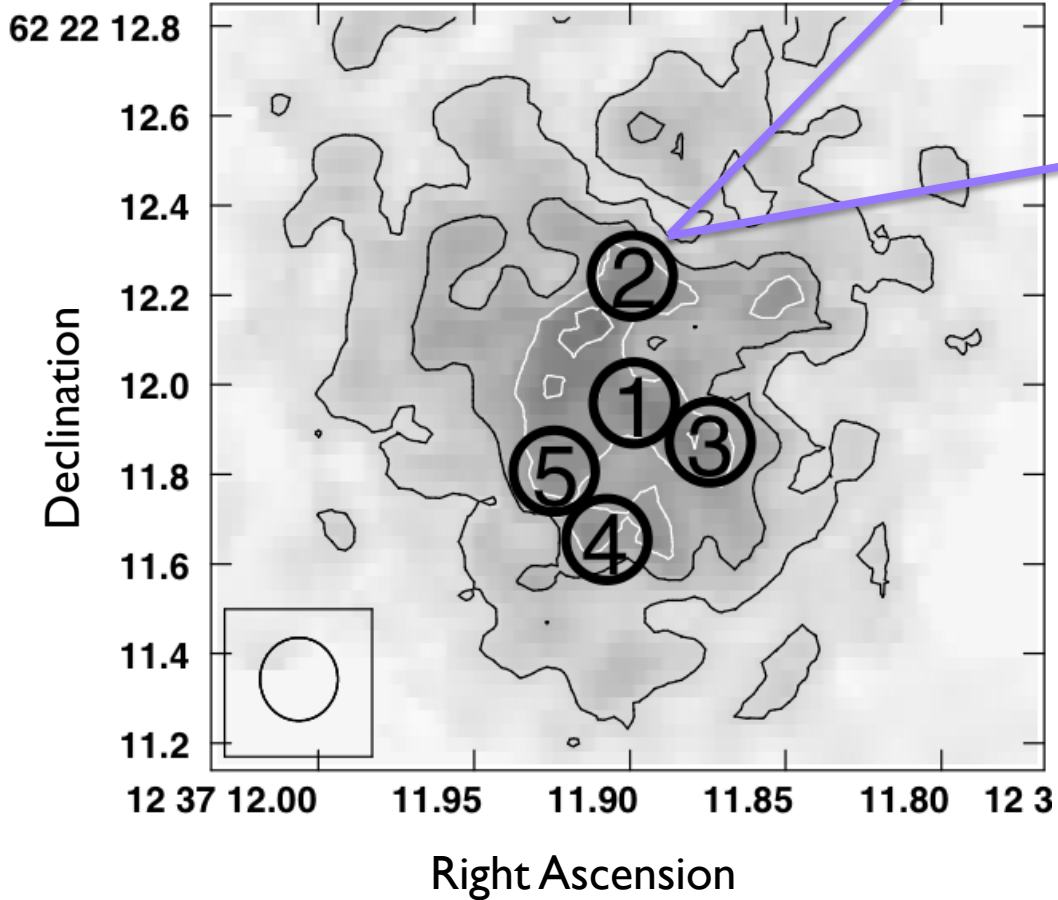Rising r<0.5", Flat

Rising r<1.0", Flat
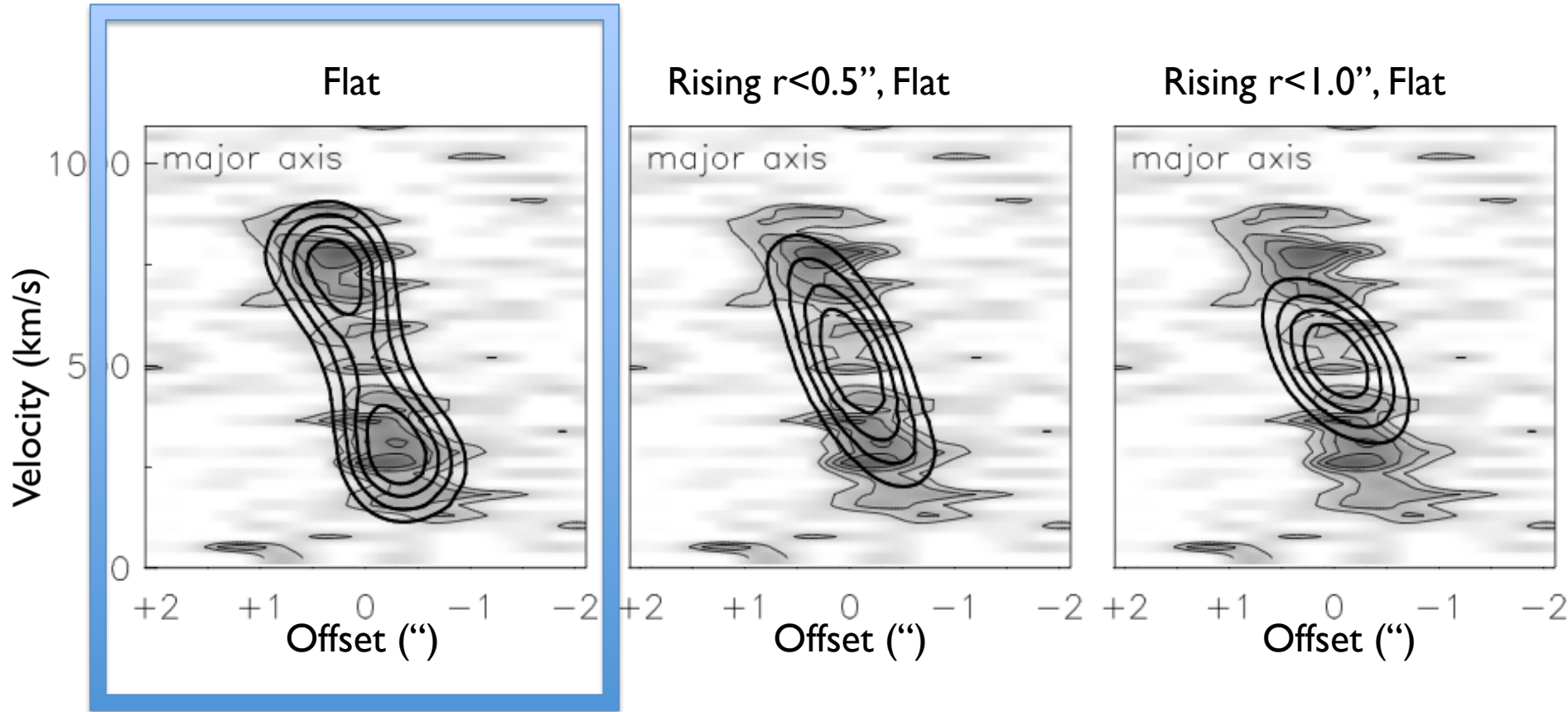
# Dynamical Modeling
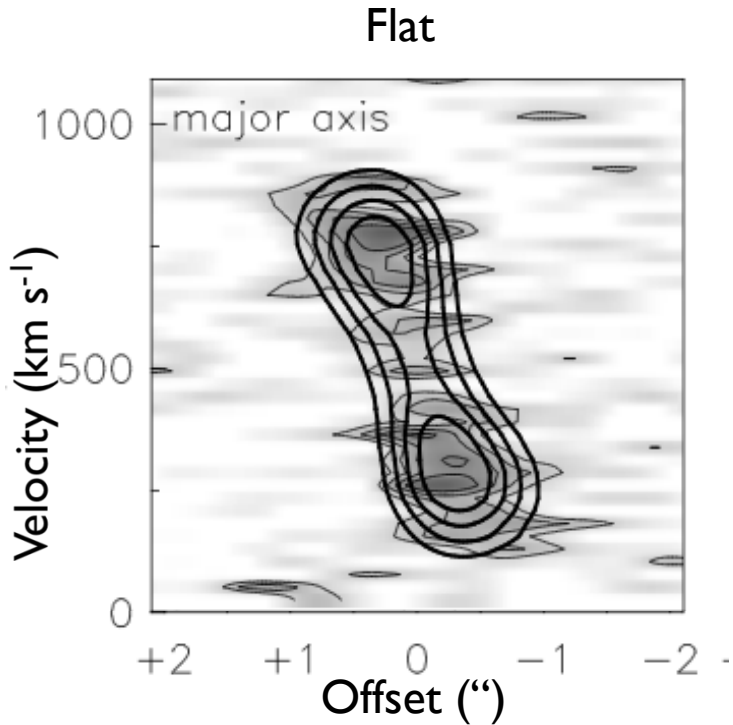


Flat

- Rotating disk with:
  - Flat rotation curve
  - Inclination: $30°$
  - $v_{max} = 575$ km s$^{-1}$
  - $\delta = 100$ km s$^{-1}$
- $M_{dyn} = 5.4 \times 10^{11}$ M$_{\odot}$
- $M_{*} = 2.3 \times 10^{11}$ M$_{\odot}$ (Daddi et al. 2009)

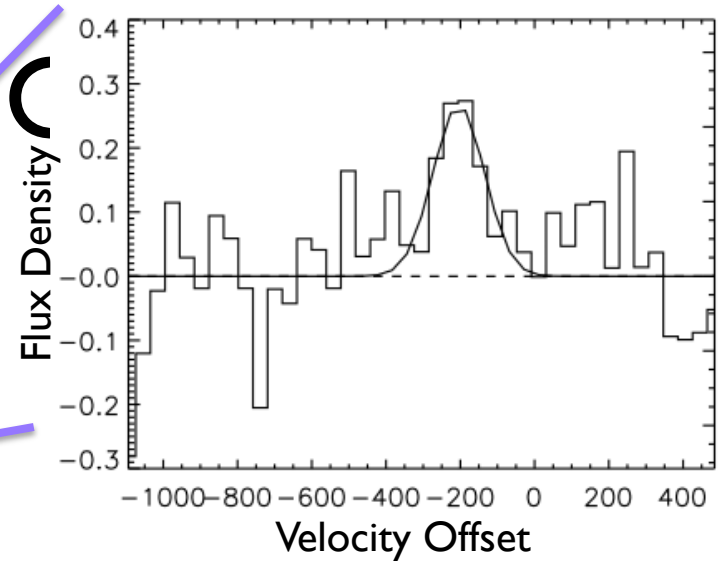➜ $\alpha_{CO} = 1.1 \pm 0.6$ M$_{\odot}$ (K km s$^{-1}$ pc$^2$)$^{-1}$

# Molecular Gas C



Hodge+12

# Molecular Gas C



Hodge+12
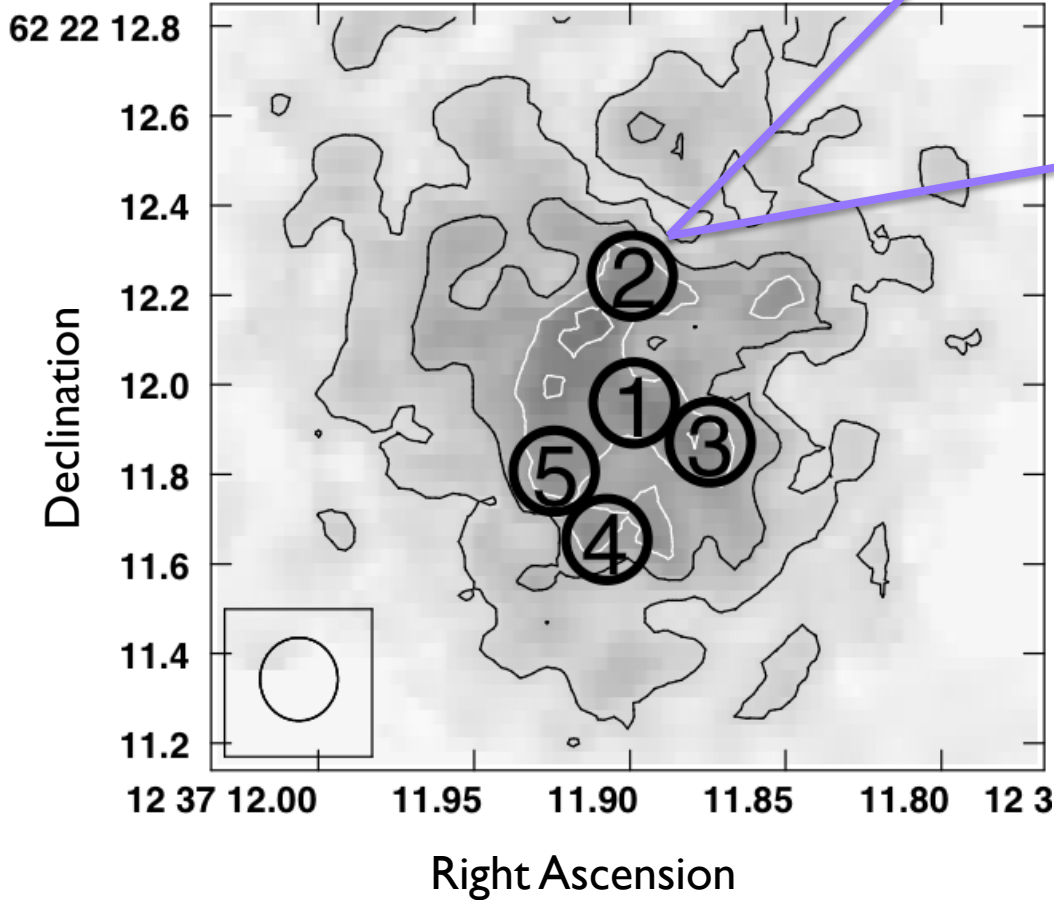
- $T_B$ = 16-32 K ~$T_{dust}$
- Size ~ 1 kpc
- Mass ~ $10^9$ M$_\odot$
- Self-gravitating
- 50% M$_{tot}$
- Densities ~ 100 cm$^{-3}$

# Looking ahead: resolved high-z Kennicutt-Schmidt relation

- PdBI program to resolve the dust continuum emission on the same scales as the molecular gas

  → Resolved KS relation (e.g. Decarli+12; Freundlich+13; Genzel+13) at z~4



$$\Sigma_{SFR} \sim \Sigma_{gas}^n$$
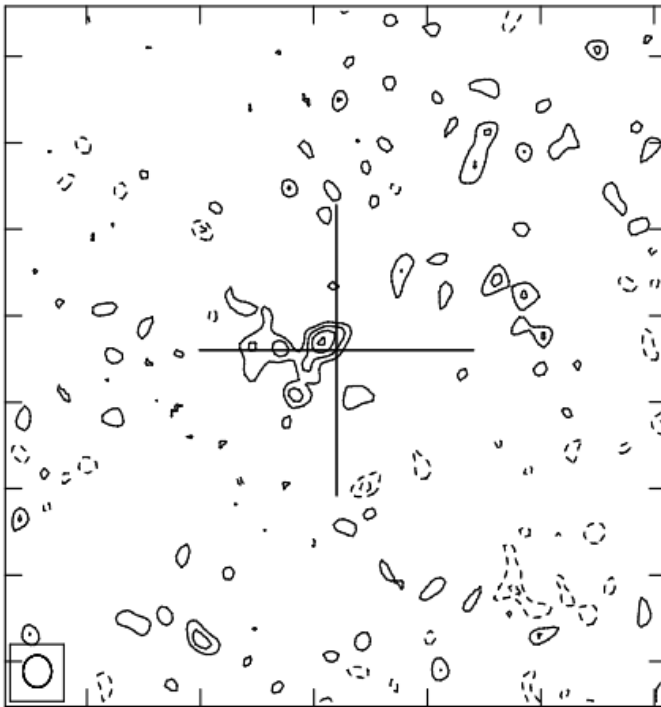
Dust

CO(2-1)

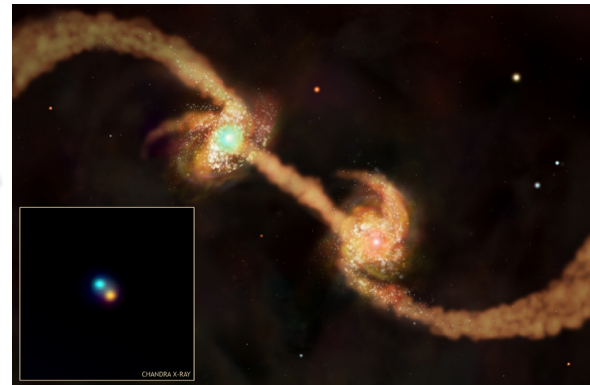PI: Hodge
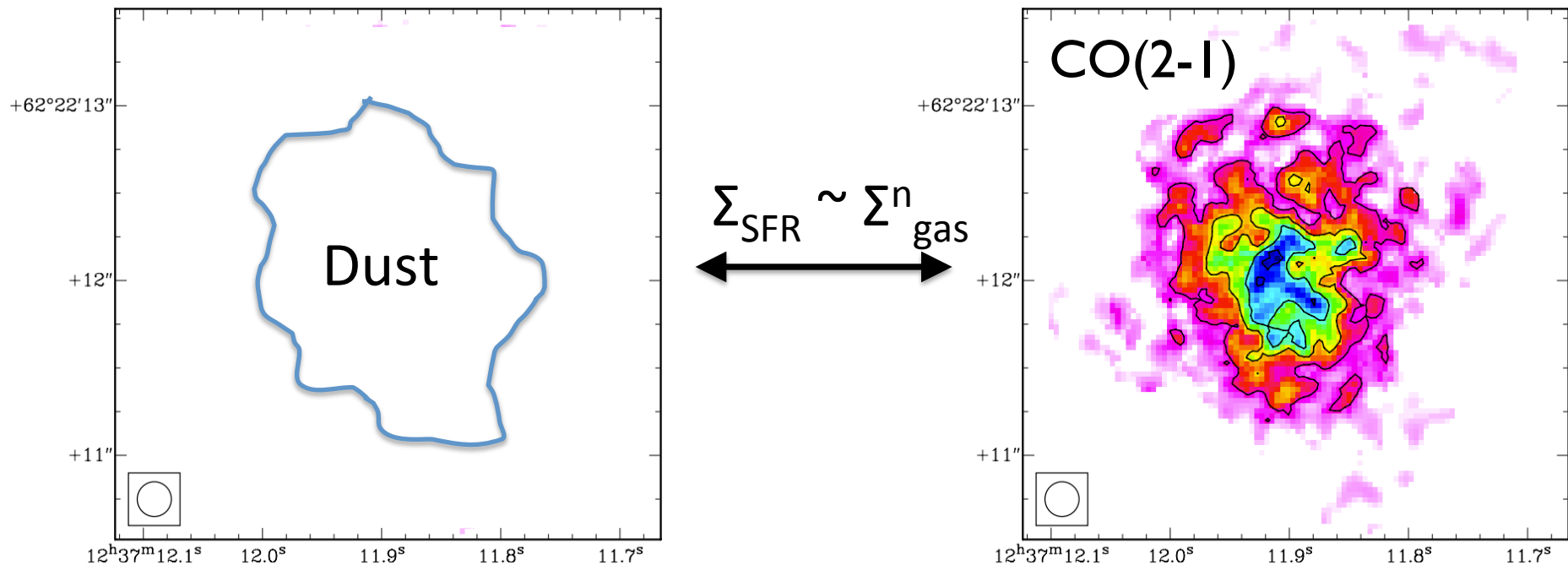
# What is fueling the starbursts?
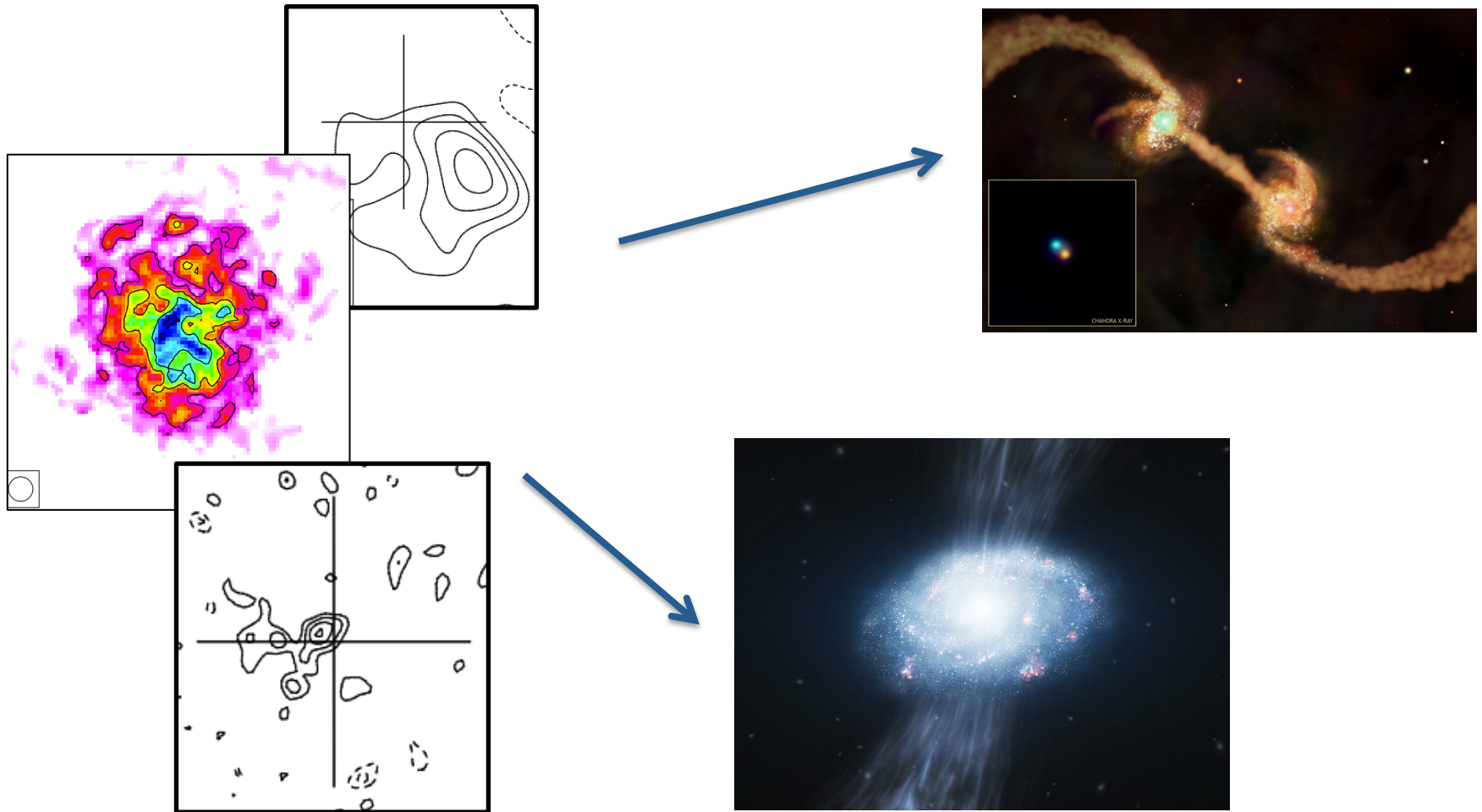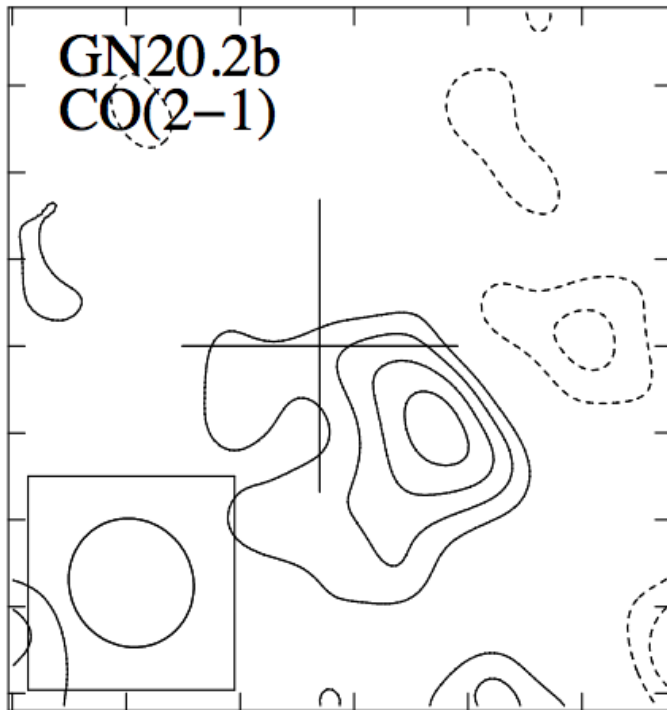
# What is fueling the starbursts?

GN20.2a:



- ▸ Compact molecular gas reservoir

- ▸ Very high surface density
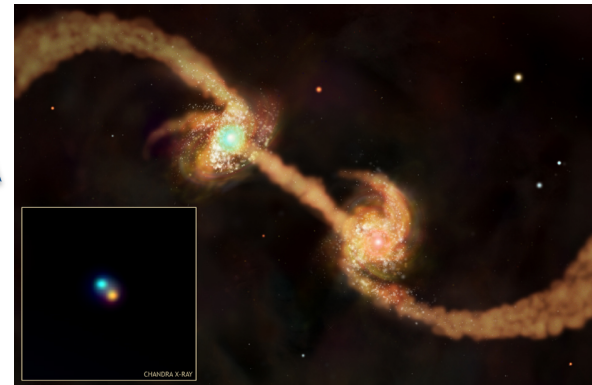
- ▸ Multiple optical counterparts

# What is fueling the starbursts?
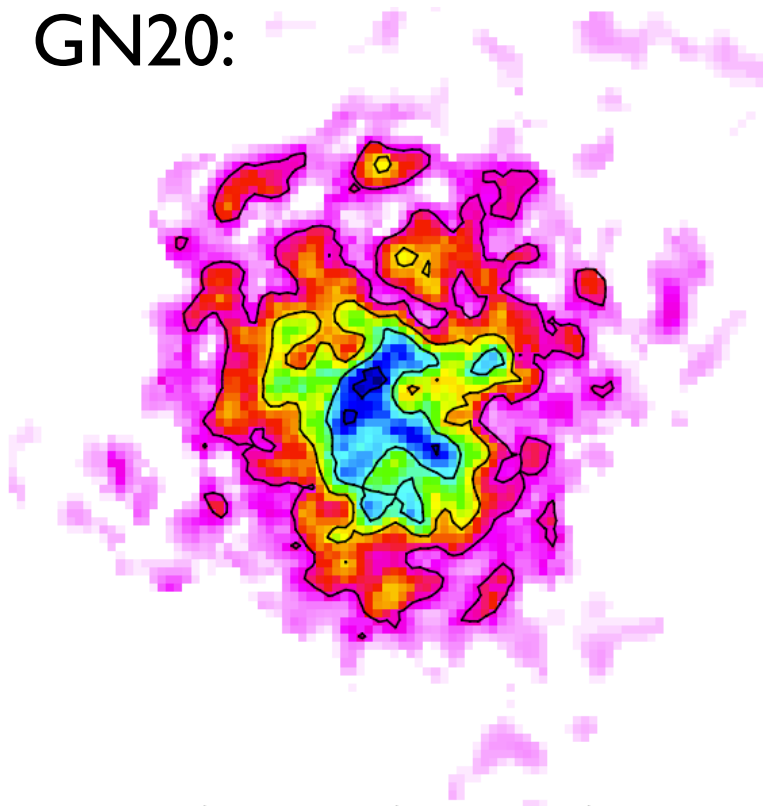
GN20.2b:



- ▶ Slightly more extended, diffuse emission

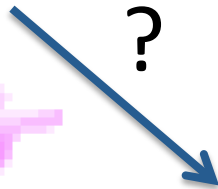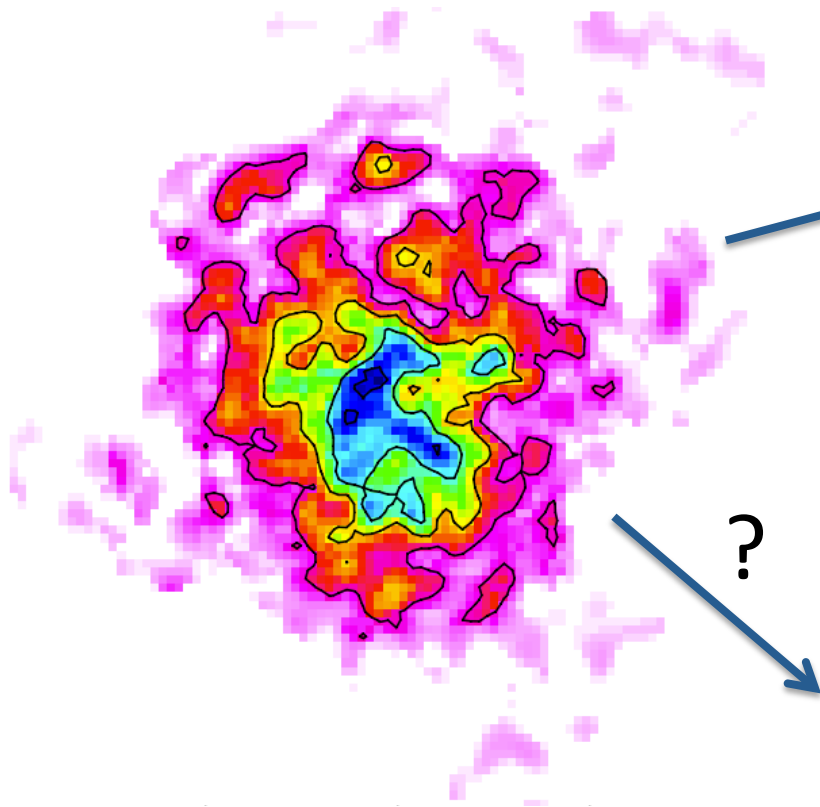- ▶ Lower (but still high!) surface density

?
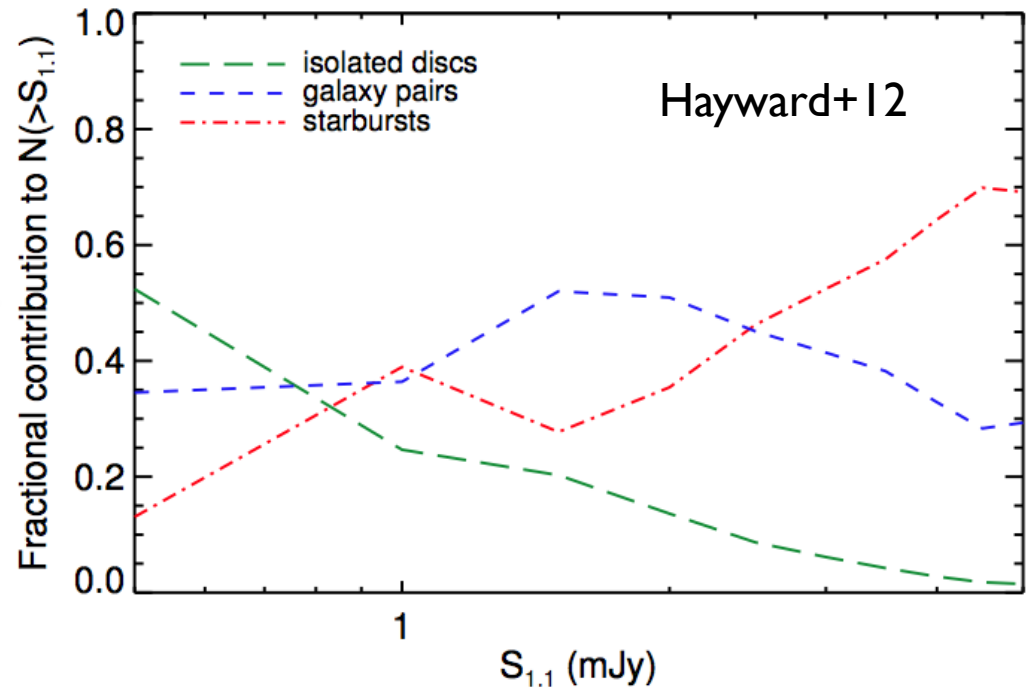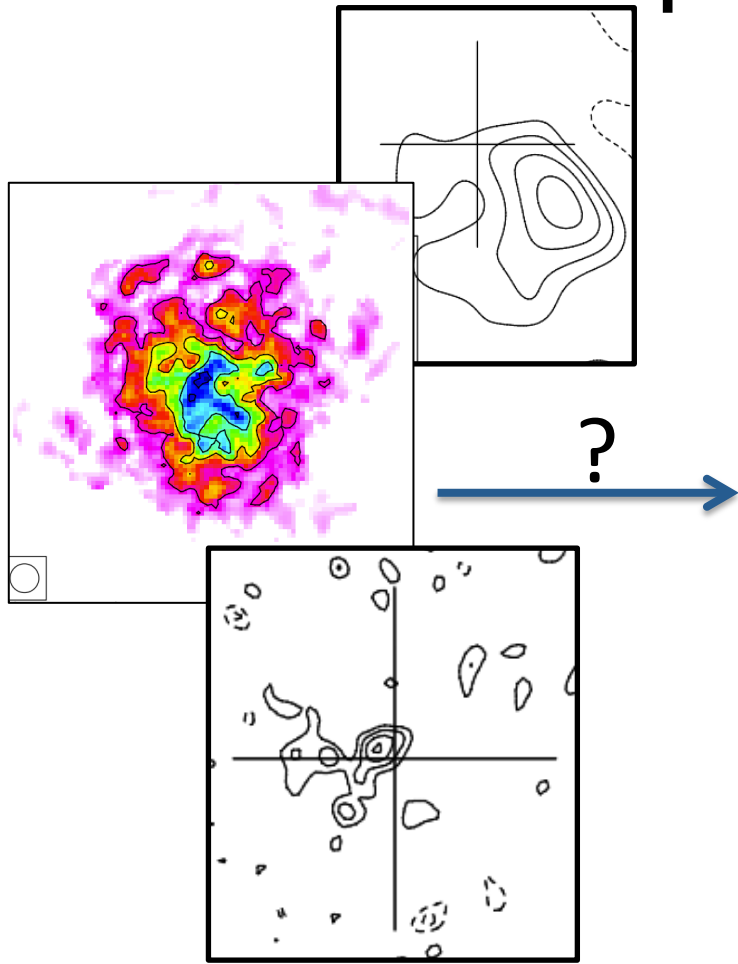
# What is fueling the starbursts?

GN20:



- ▶ Extended gas reservoir
- ▶ Multiple gas clumps
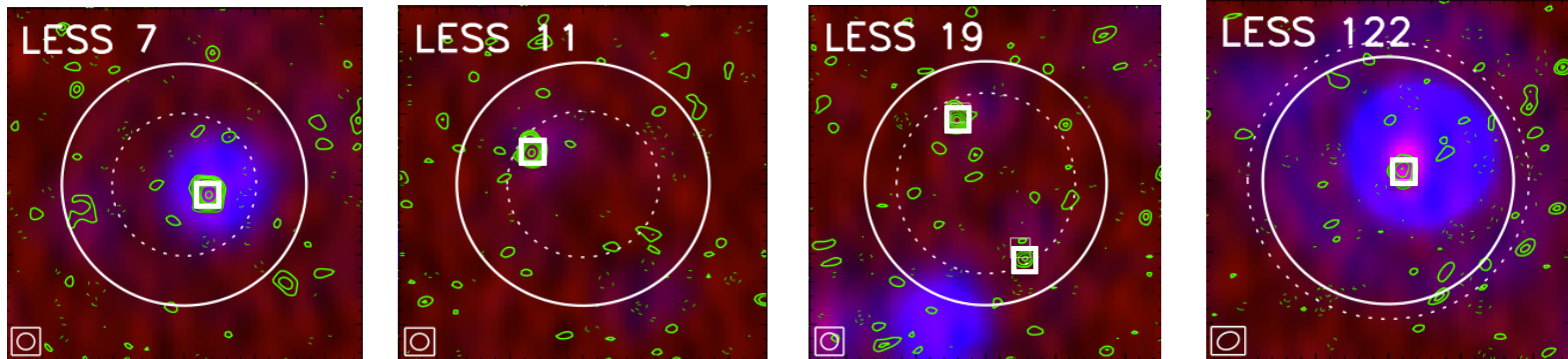- ▶ Rotating disk

# What is fueling the starbursts?



?

?

# Take away: Currently see range of gas properties



Hayward+12

isolated discs
galaxy pairs
starbursts

Fractional contribution to $N(>S_{1.1})$

$S_{1.1}$ (mJy)

# Looking further ahead: ALESS

- Used ALMA to map >100 SMGs at 870μm to 1.5" (ALESS; PI Smail)



Hodge et al. (2013a)

- Cycle 1 program to resolve continuum to 0.15"/1 kpc (PI Hodge)



ALMA Cycle 1 simulations