# The star formation law in Tidal Dwarf Galaxies

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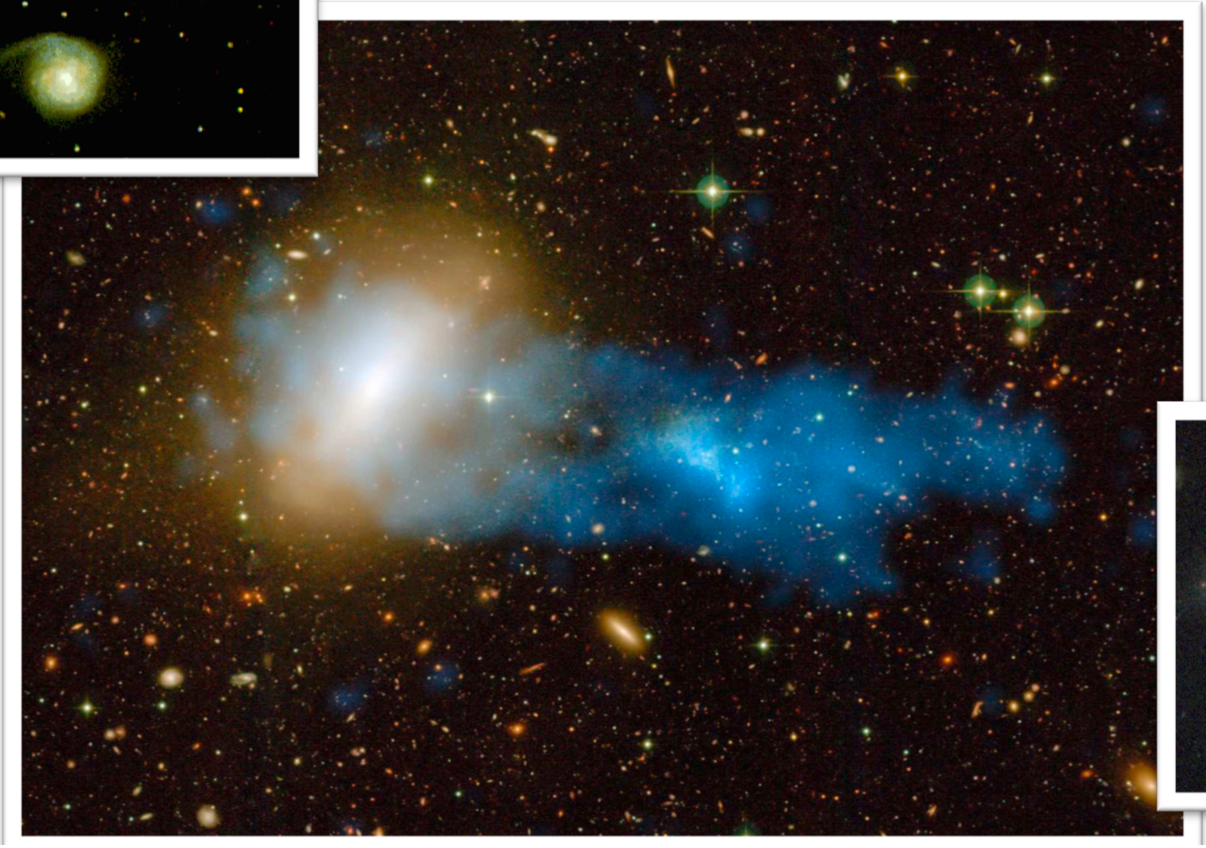
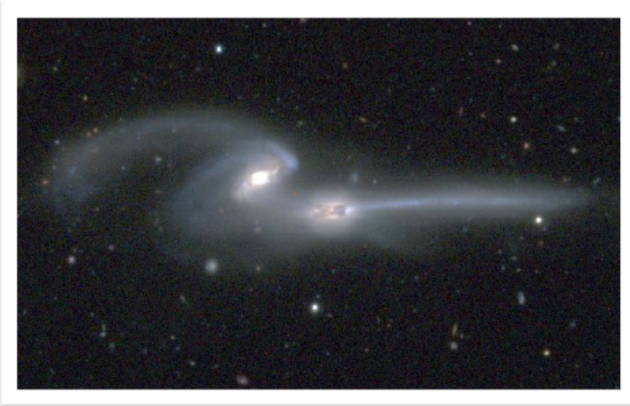




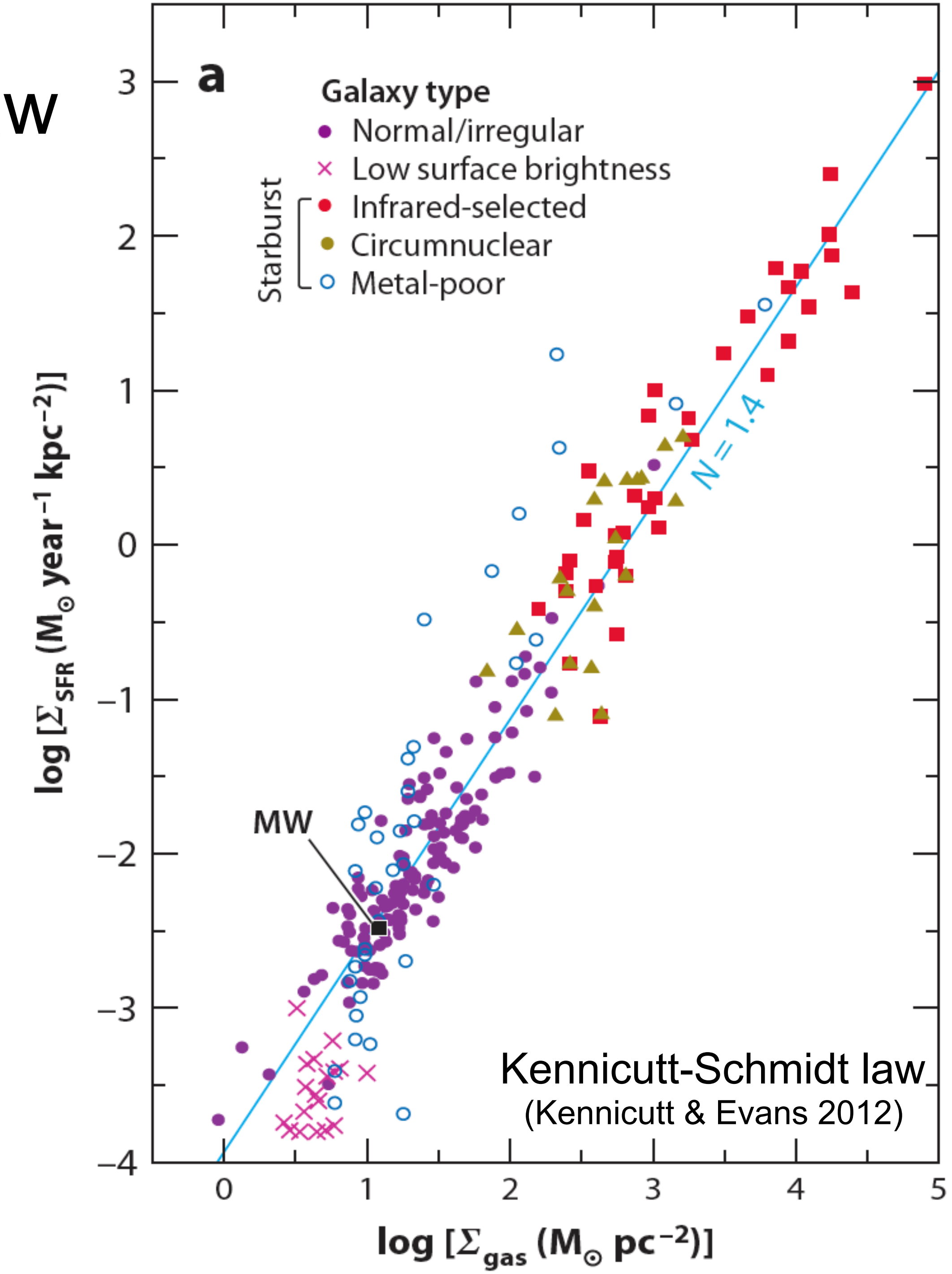
# The star formation law

- How do stars form from gas?
  ➔Compare (molecular) gas mass and star formation rate.
- For spirals, the molecular gas depletion time (=$M_{H2}$/SFR = $SFE^{-1}$) is ≈ 2 Gyr (Leroy+08, Bigiel +08,11), shorter for starbursts (e.g. Genzel+10,Daddi10).

- <u>What is the physical cause of this relation?</u>

➢ Study diverse objects/ environments

➢ Search for deviations from "normal" KS-law



Kennicutt-Schmidt law
(Kennicutt & Evans 2012)

# The SF law on the faint end

- Low surface brightness galaxies (Wyder+09): Low SFR/MHI (but no CO detected) – most likely due to a low molecular gas fraction.
- Outer spirals disks (Schruba+11): SFR/$M_{HI}$ is low
  - Stacking CO ➔ $M_{H2}/M_{HI}$ is low
  - SFR/$M_{H2}$ is the same as in the inner disk
  - ➔Molecular gas formation is low at outer radii, but SF from molecular gas is normal
- Dwarf galaxies: Problem: $M_{H2}$ hard to measure because X-factor is not well known for low metallicity.

- Here we study Tidal Dwarf Galaxies (TDGs) for the following reasons…..

# Tidal Dwarf Galaxies

- Form out of gas and stellar debris at the end of tidal tails.
- Gaseous and stellar properties: similar to classical dwarf irregular and blue compact dwarfs, except …..

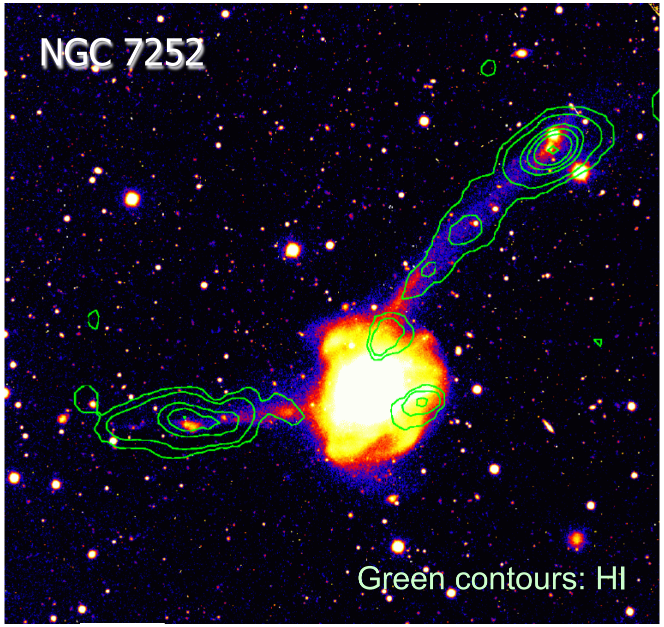
….their high metallicity

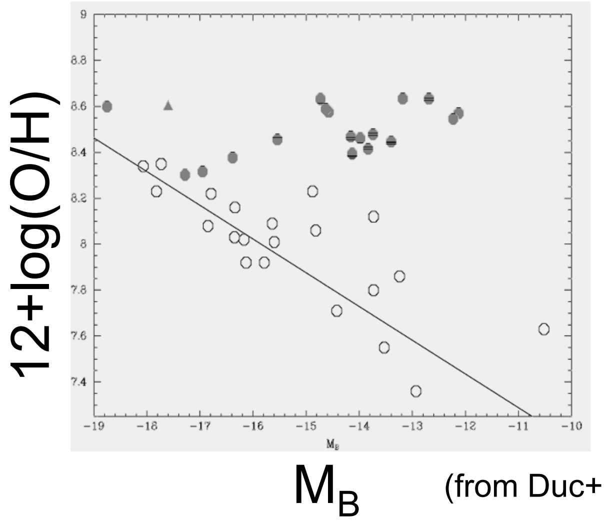
➔typical of outer regions of spiral galaxies: 12+log(O/H) ≈ 8.4-8.6

➔do not follow luminosity-metallicity relation

…. and their low dark matter content:

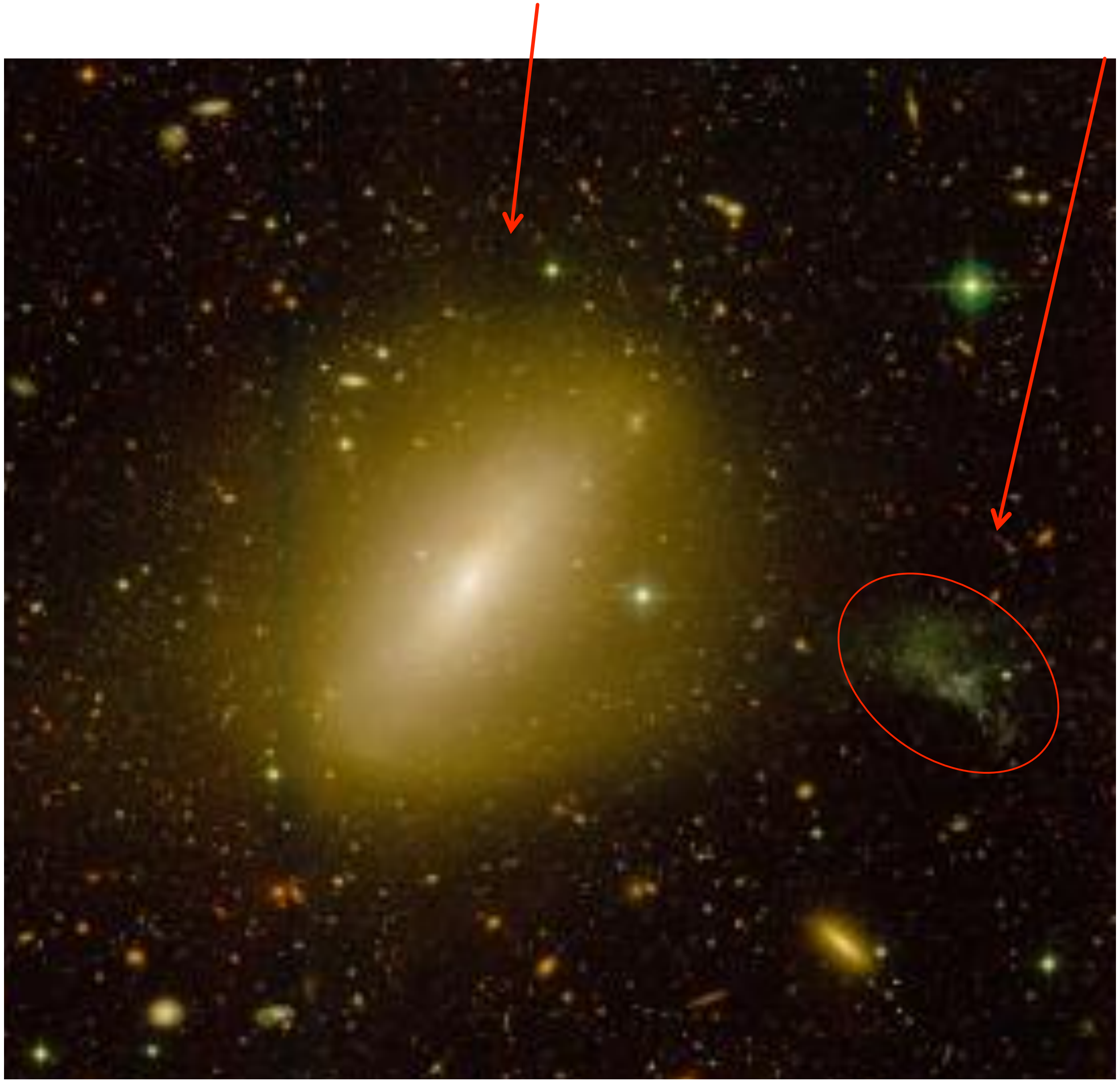
- Predicted from simulations (e.g. Barnes & Hernquist 1992)
- $M_{dyn}/M_{vis} \approx 1$ ( Bournaud et al. 2003, Lelli et al. 2015, in 6 TDGs in 3 systems)





(from Duc+00)

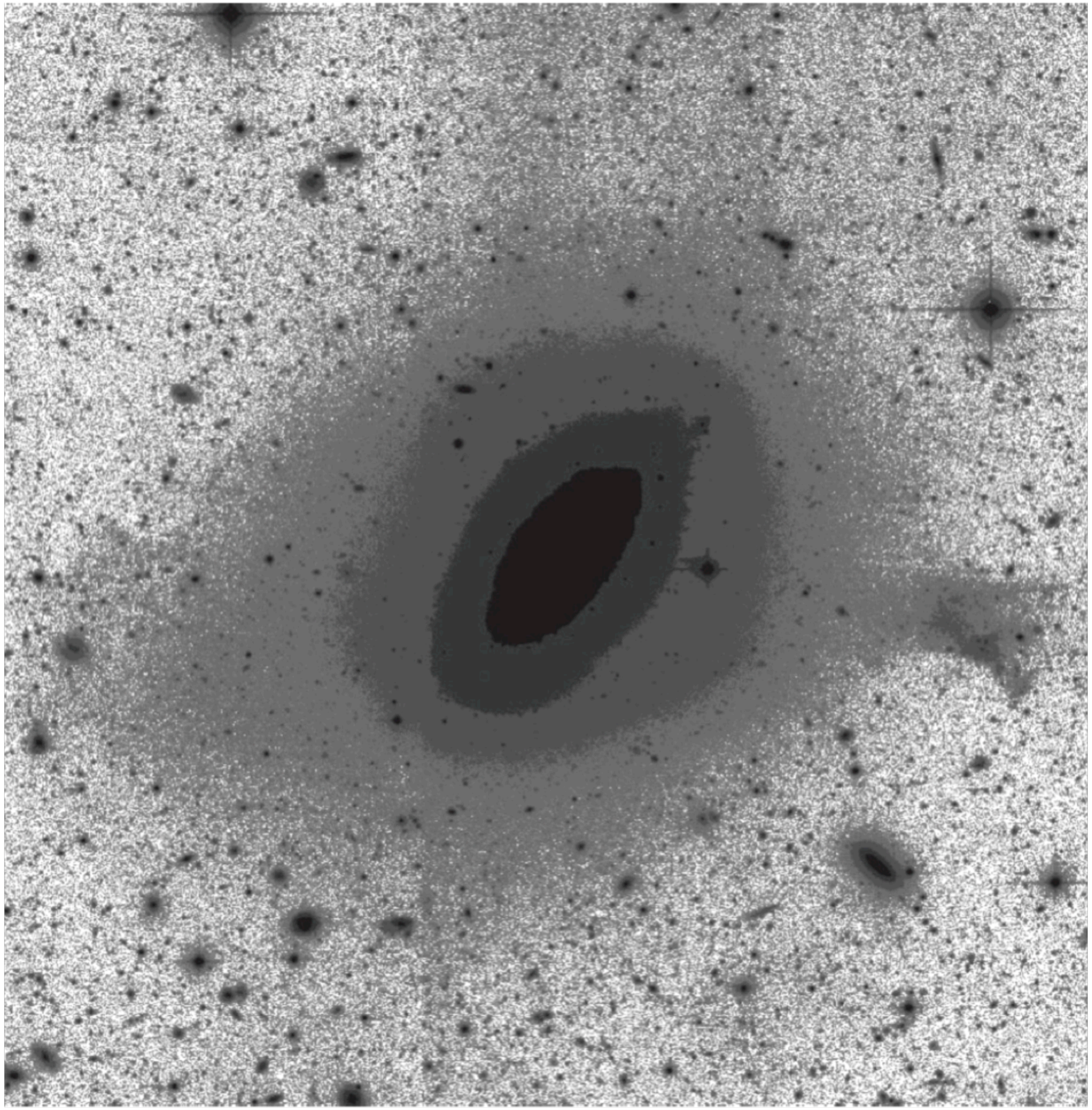
# NGC 4694 and VCC 2062



- Situated at the outskirts of the Virgo Cluster ➔ close-by (D = 17 Mpc)
- NGC 4694 and VCC 2062 have same recession velocity.
- NGC 4694: SB0 peculiar
- VCC 2062: very low surface brightness dwarf galaxy ($\mu_V$ = 25.5 mag/”$^2$)

Combined u,g,i image from the NGVS (Next Generaltion Virgo cluster Survey, Ferrarese et al. 2012)

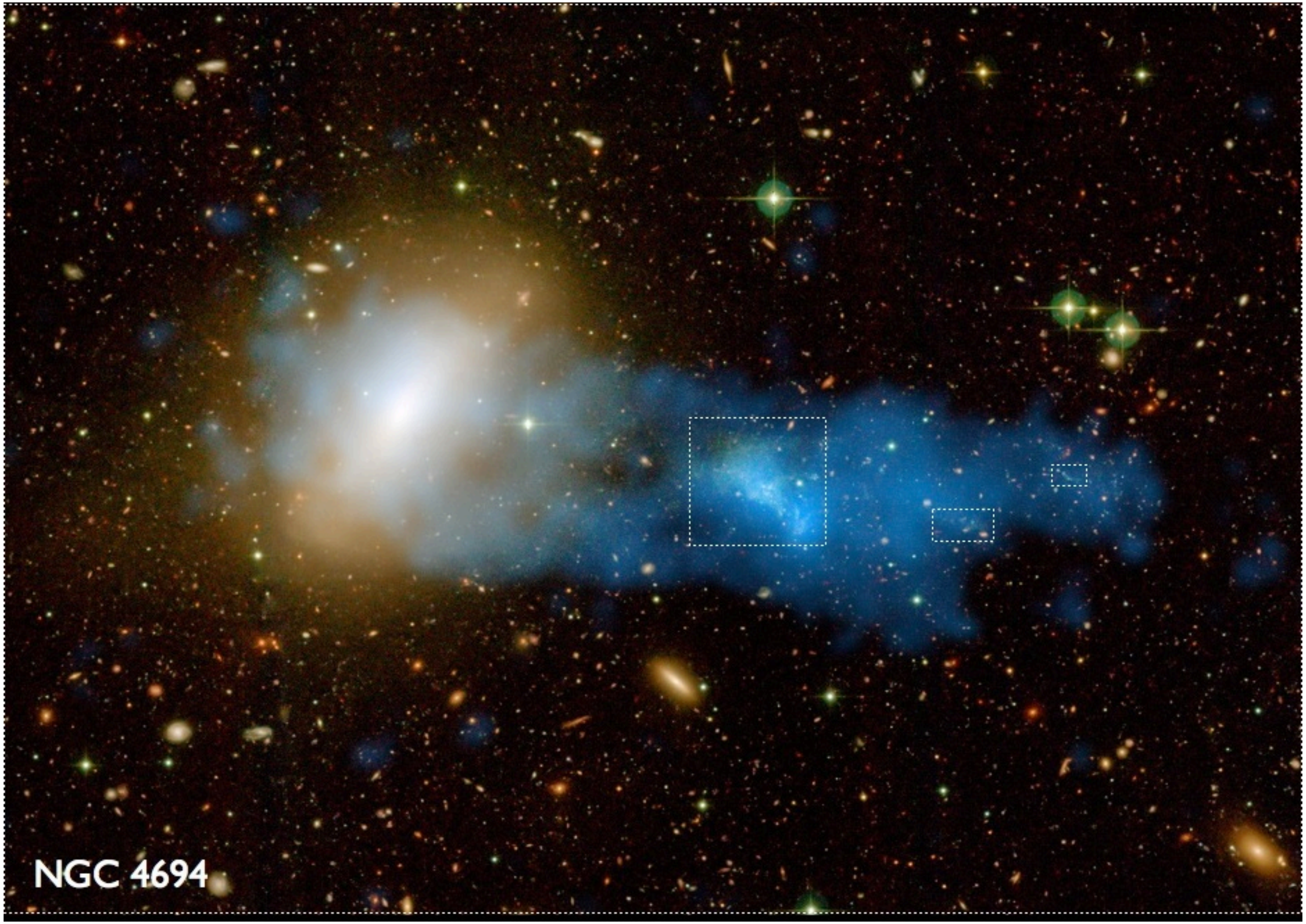
# NGC 4694 and VCC 2062



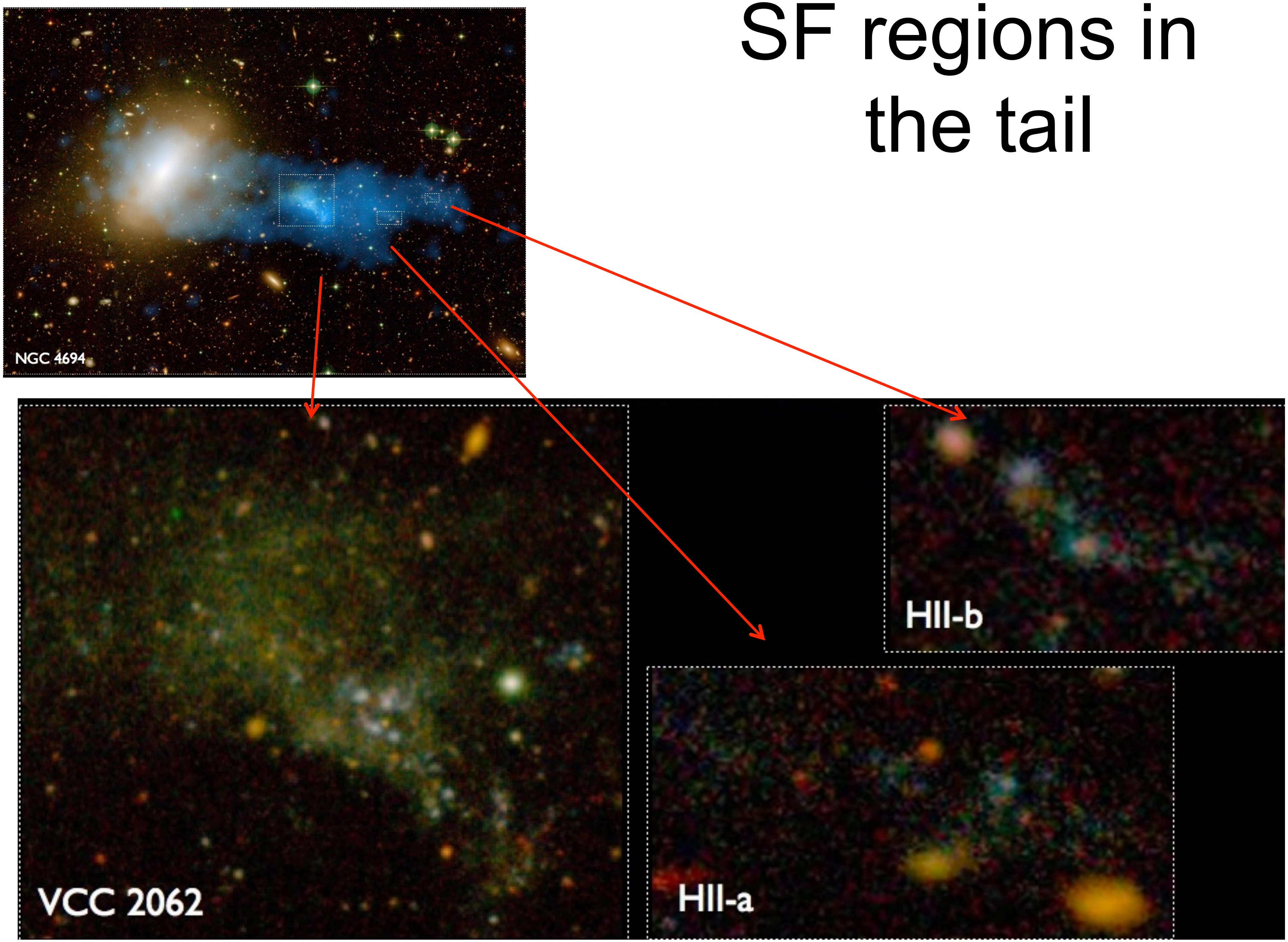
- Stellar bridge between both galaxies -> evidence that VCC 2062 is physically related to NGC 4694
- NGC 4694 is distorted and assymetric -> old merger

Deep g-band image from the NGVS (New Generation Virgo Survey, Ferrarese et al. 2012)

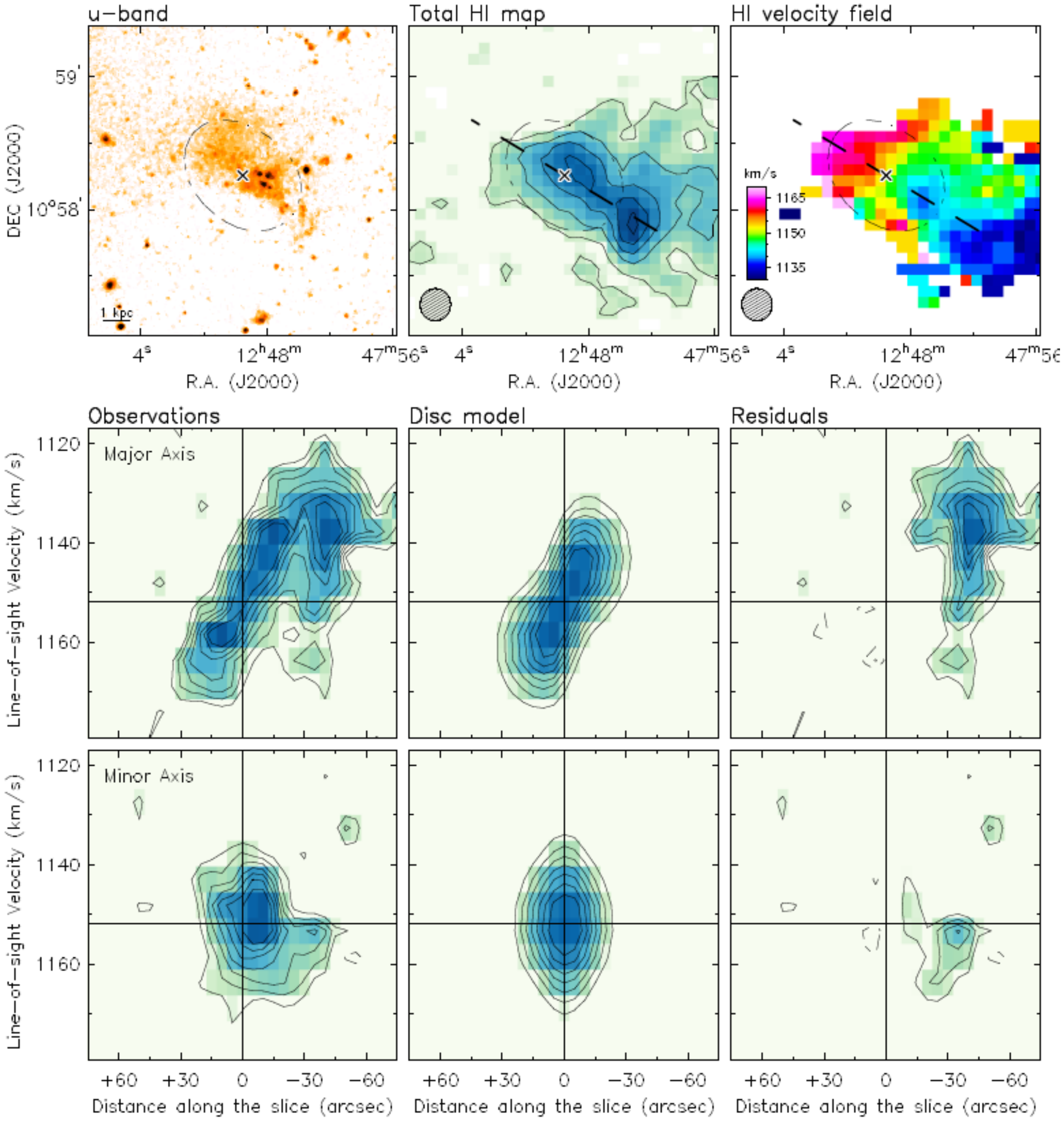
# Optical and HI (blue)



# SF regions in the tail



# Dynamical mass from HI kinematics



Analysis of the HI kinematics (Lelli et al. 2015)

VLA HI data (resolution 14.7''x14.3'')

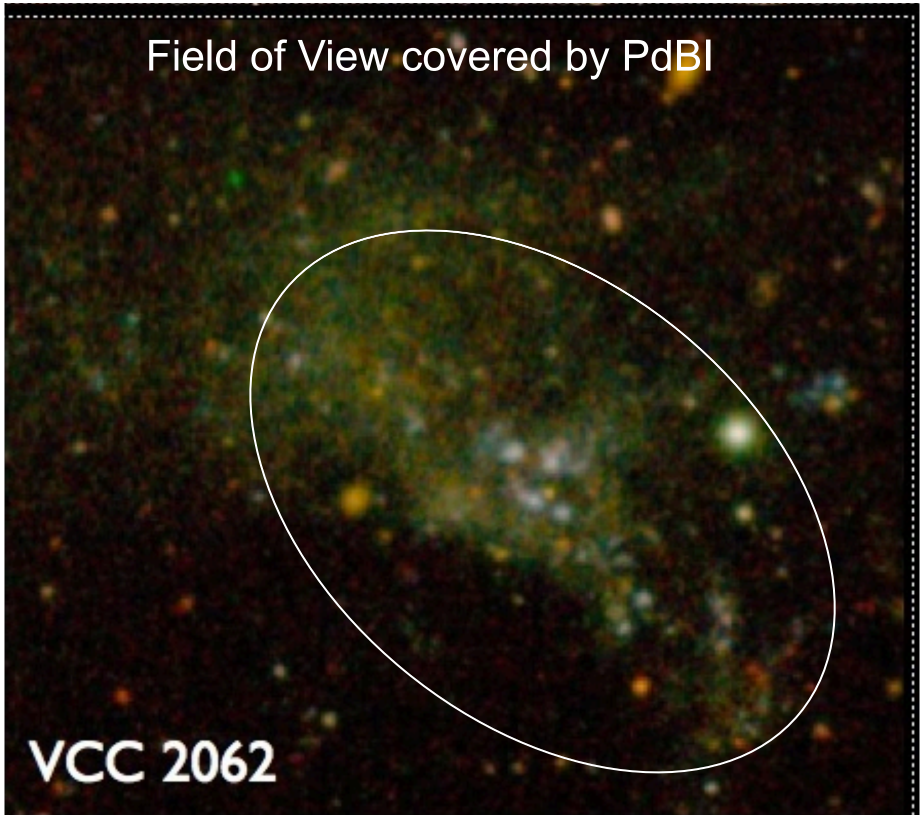
Model HI disk adopting PA, i , $v_{sys}$, flat rotation curve ($V_{rot}$, $R_{out}$) and fit to the HI data

Good fit, with residual HI (most likely tail material).

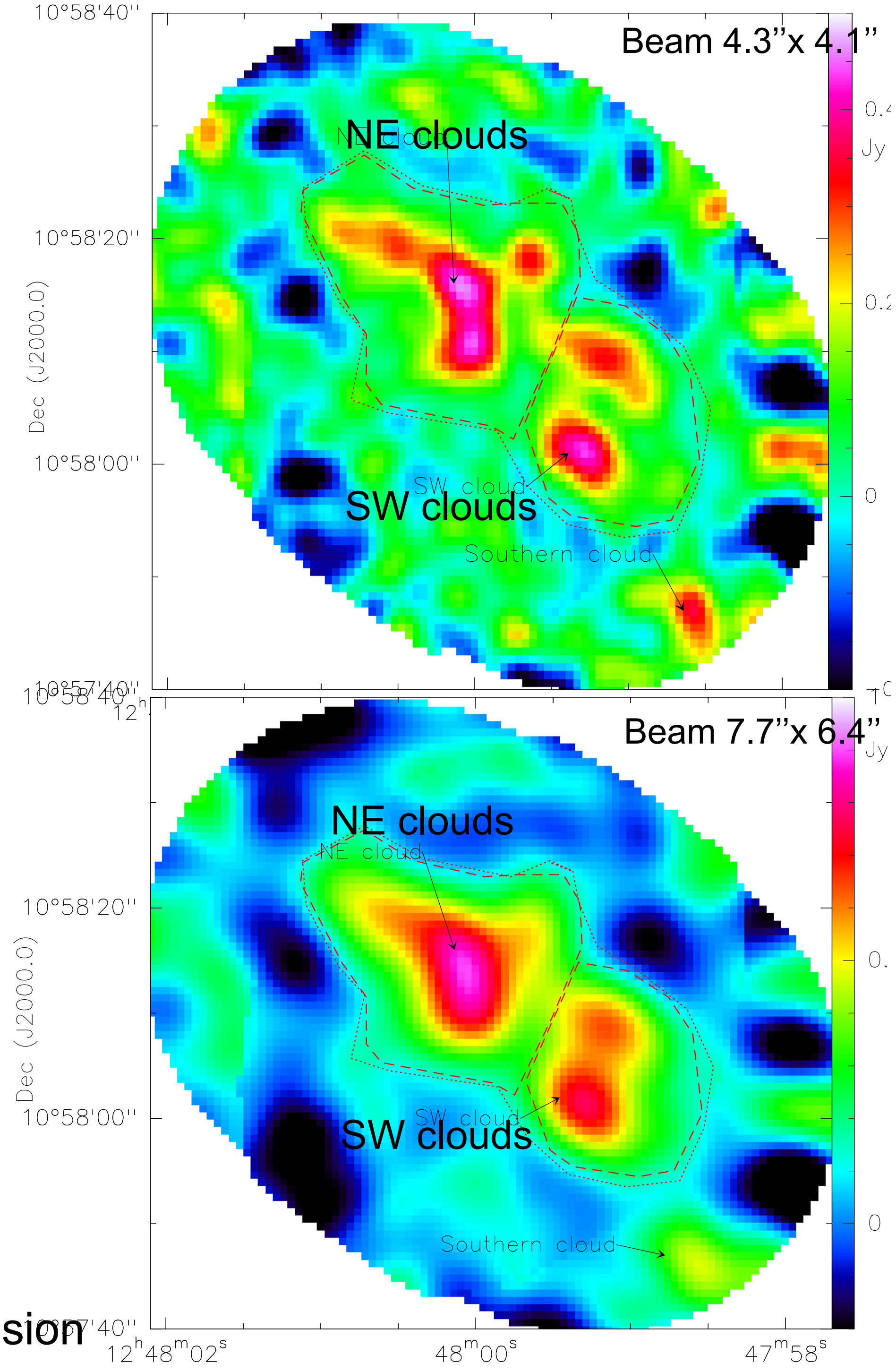
Derive dynamical mass, and compare to baryonic mass $M_{bar} = M_{gas}+M_{star}$

-> $M_{dyn}/M_{bar} = 1.0 \pm 0.9$
-> Consistent with no dark matter !!
-> Strong evidence that VCC 2062 is a TDG

# CO(1-0) observations with PdBI

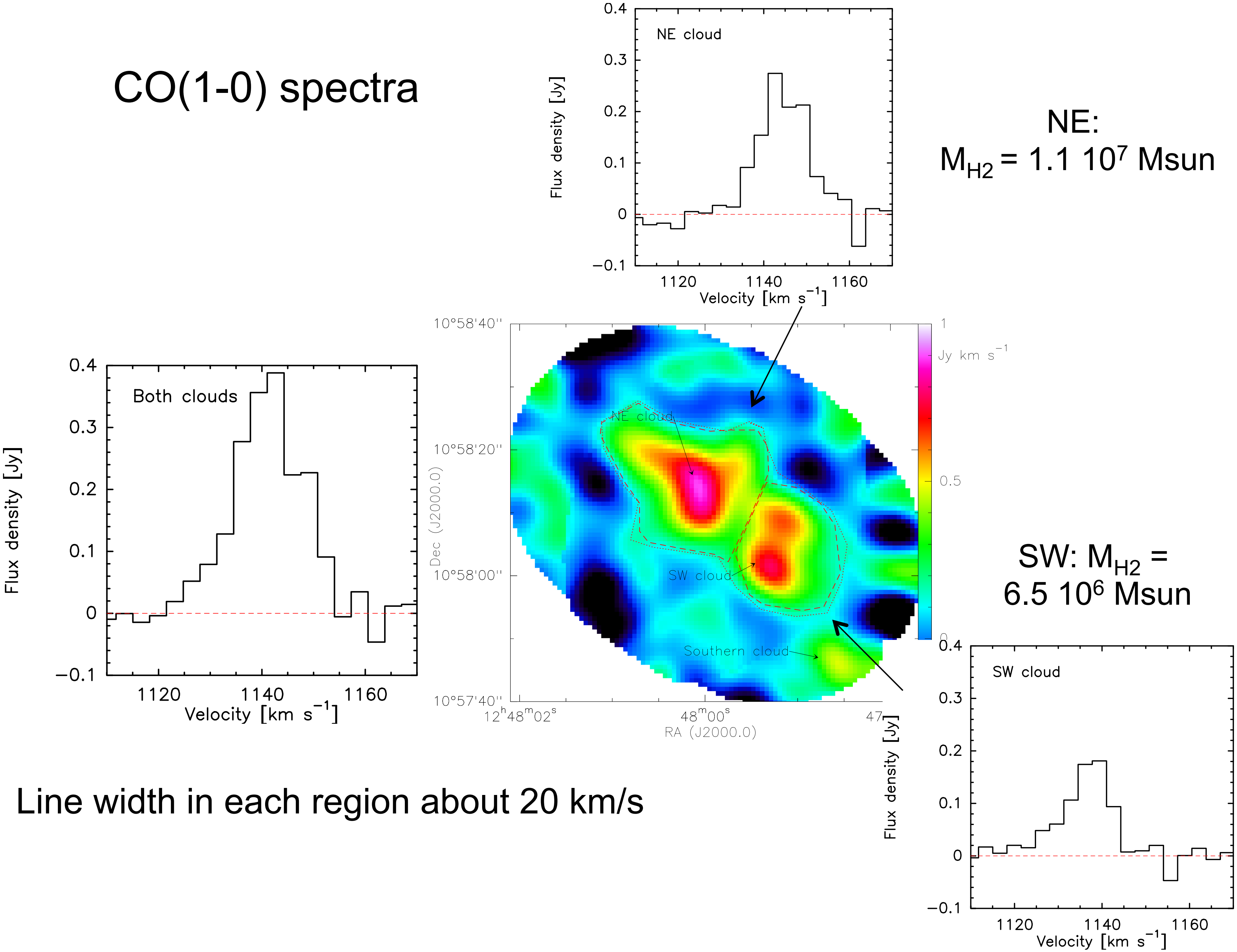


- Observations done in C and B conf.
- Original resolution 3.22''x 2.37'' (≈300pc)



Velocity integrated CO(1-0) emission

# CO(1-0) spectra



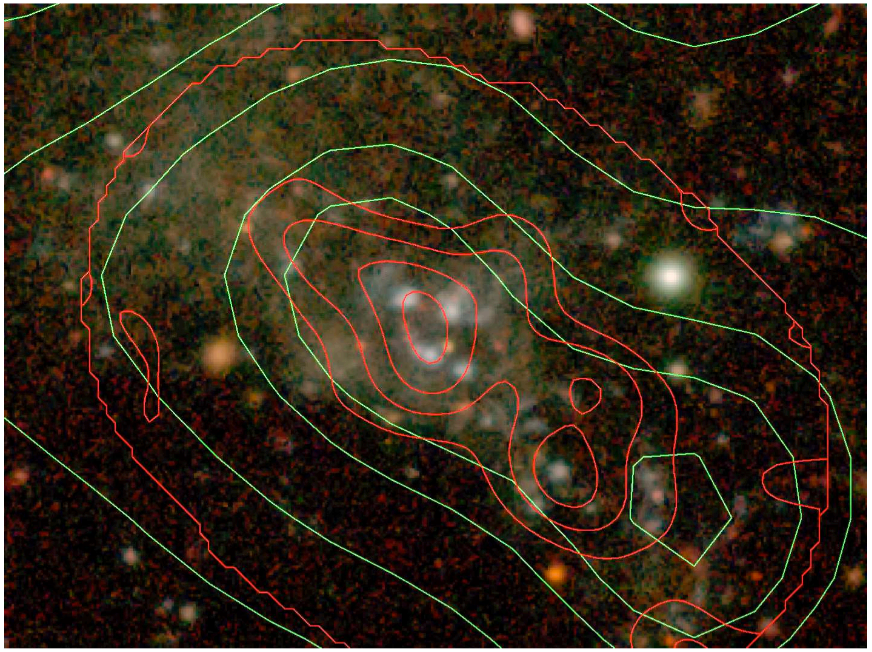
NE:
$M_{H2}$ = 1.1 $10^7$ Msun

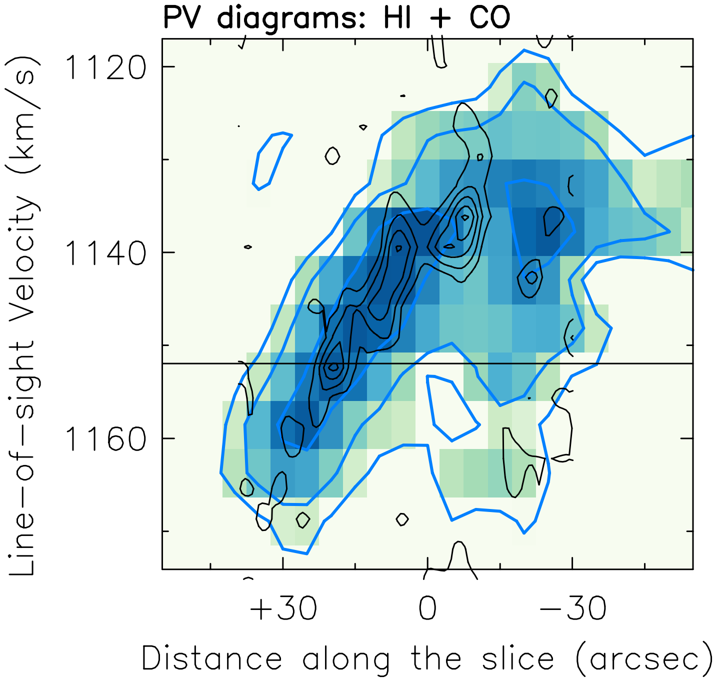
SW: $M_{H2}$ =
6.5 $10^6$ Msun

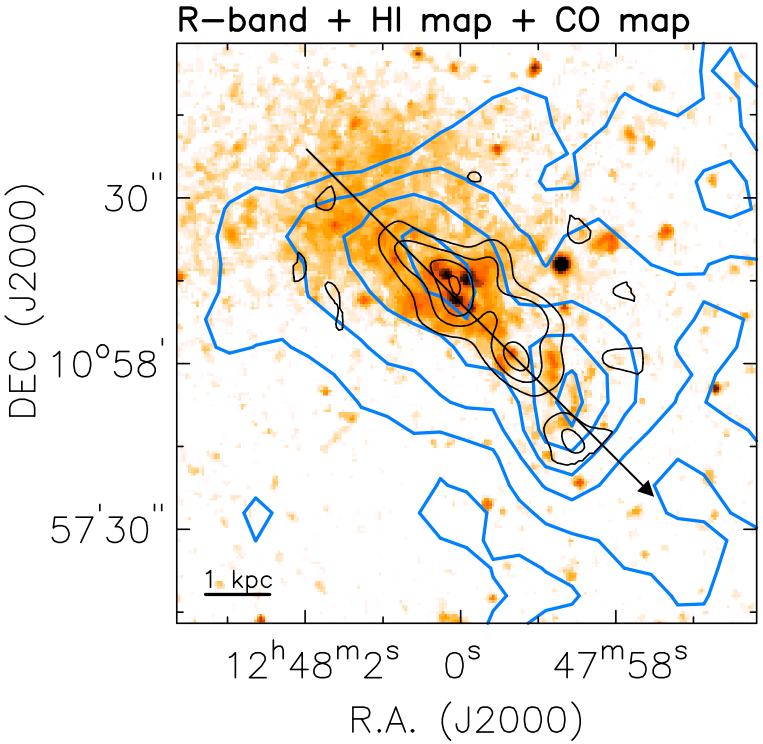
Line width in each region about 20 km/s

# Comparison to HI

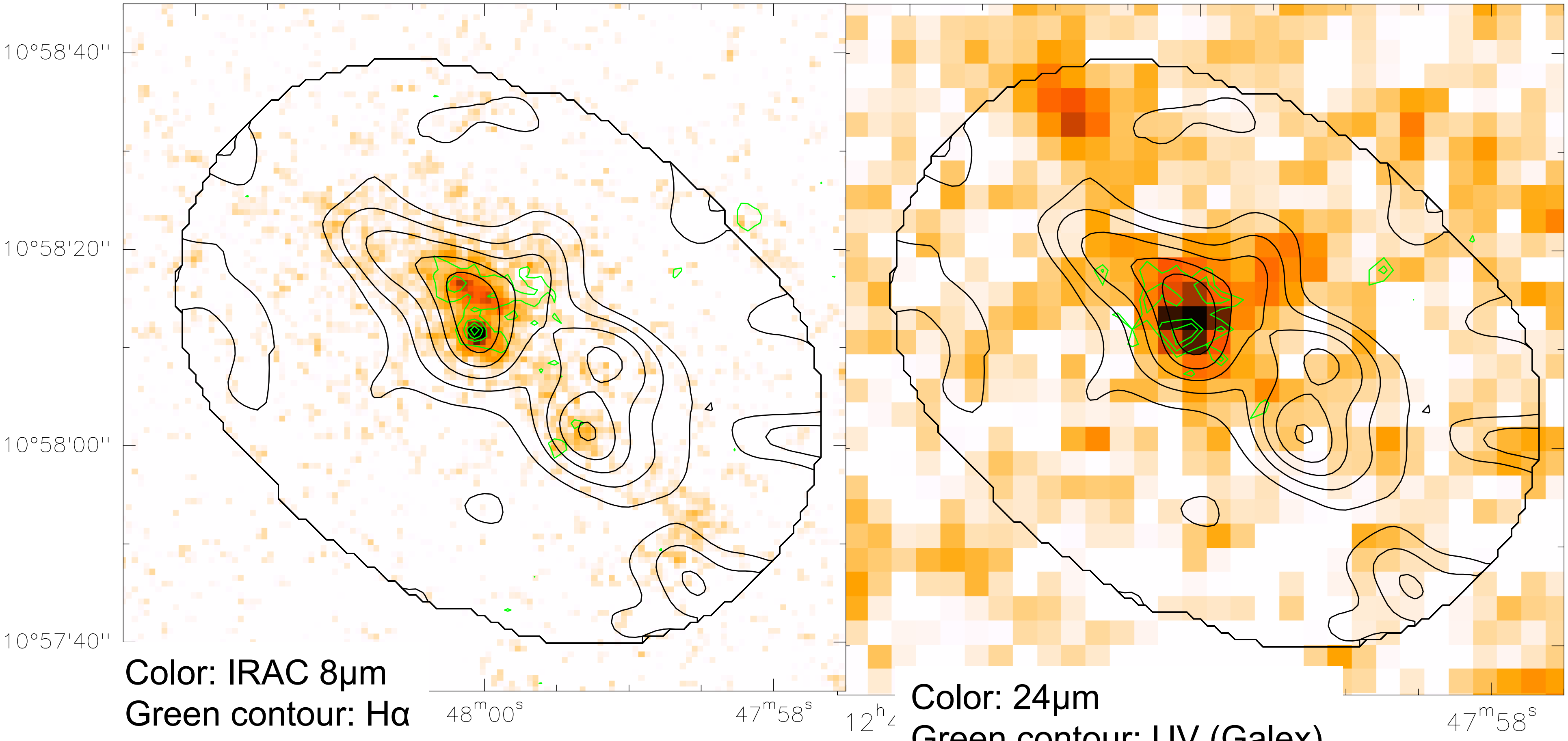
- NE clouds coincides with peak of HI
- SW cloud is between the two HI peaks
- CO is less extended than HI
- Kinematics of CO and HI agree where they overlay.







# Comparison to star formation



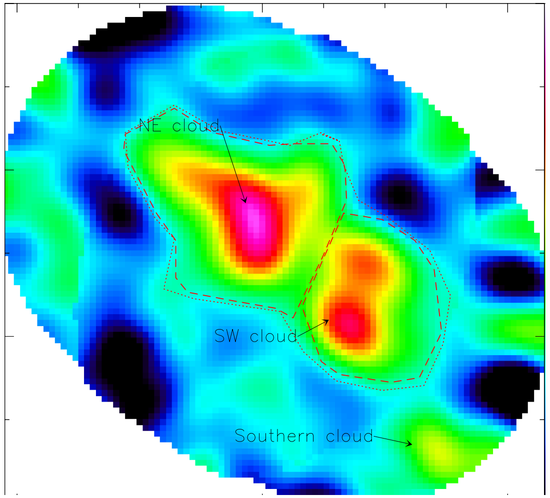
Color: IRAC 8µm
Green contour: Hα

Color: 24µm
Green contour: UV (Galex)

- Good coincidence between CO and SF tracers in NE region
- Weaker SF in SW region (but present, see 8µm)

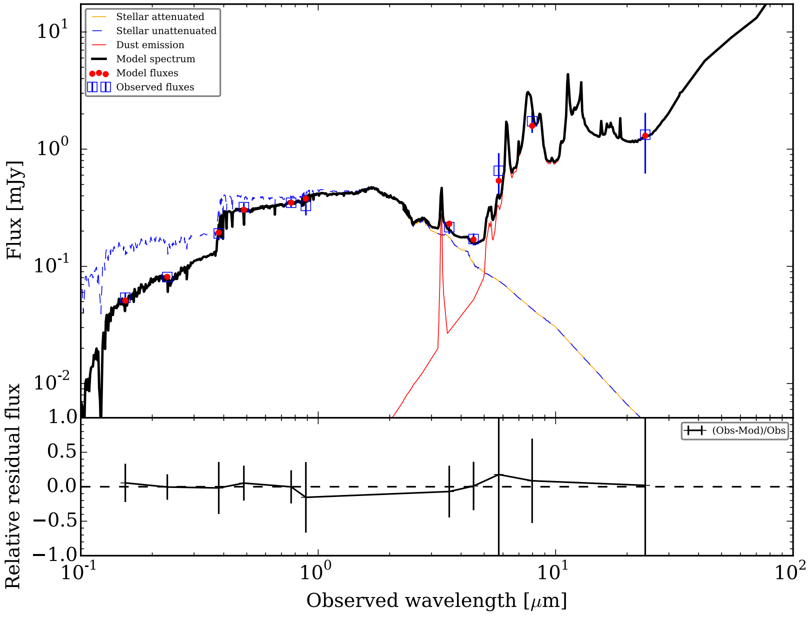
# Measure SFR

- Integrate SF tracers in the same apertures as CO
- Use different tracers (Hα, UV, 8/24µm, 8/24µm+ Hα/UV)
- Apply standard conversion from luminosities to SFR (Kennicut & Evans 2012)

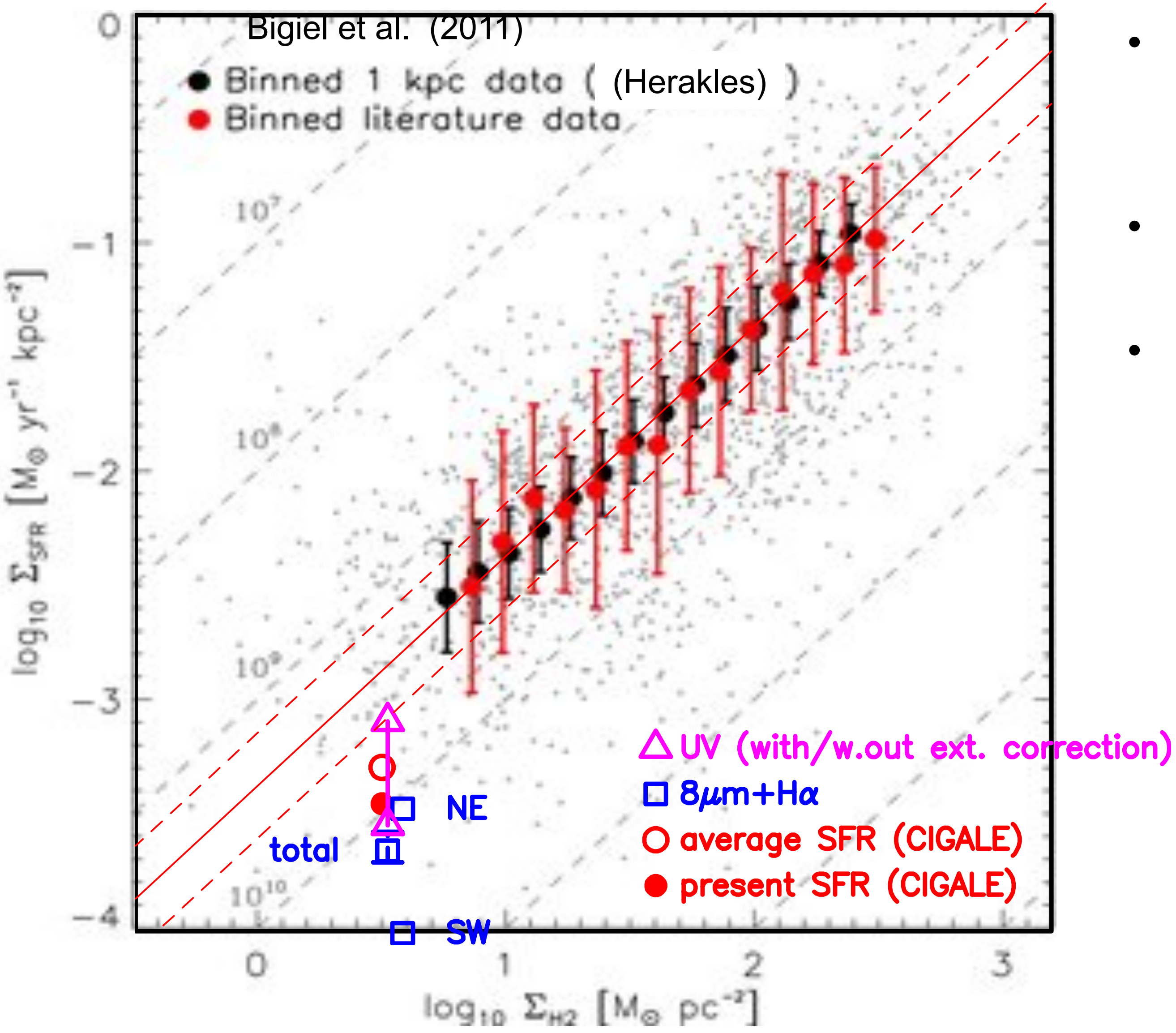


- Modelling of UV-optical-IR SED with CIGALE for the entire galaxy.
  - ➢ Present SFR =3 $10^{-3}$ Msun $yr^{-1}$
  - ➢ Averaged SFR (past $10^8$ yr) = 4.5 $10^{-3}$ Msun $yr^{-1}$
  - ➢ Total stellar mass = 7 $10^6$ Msun

UV/optical/NIR SED and CIGALE model



# Molecular gas and SF

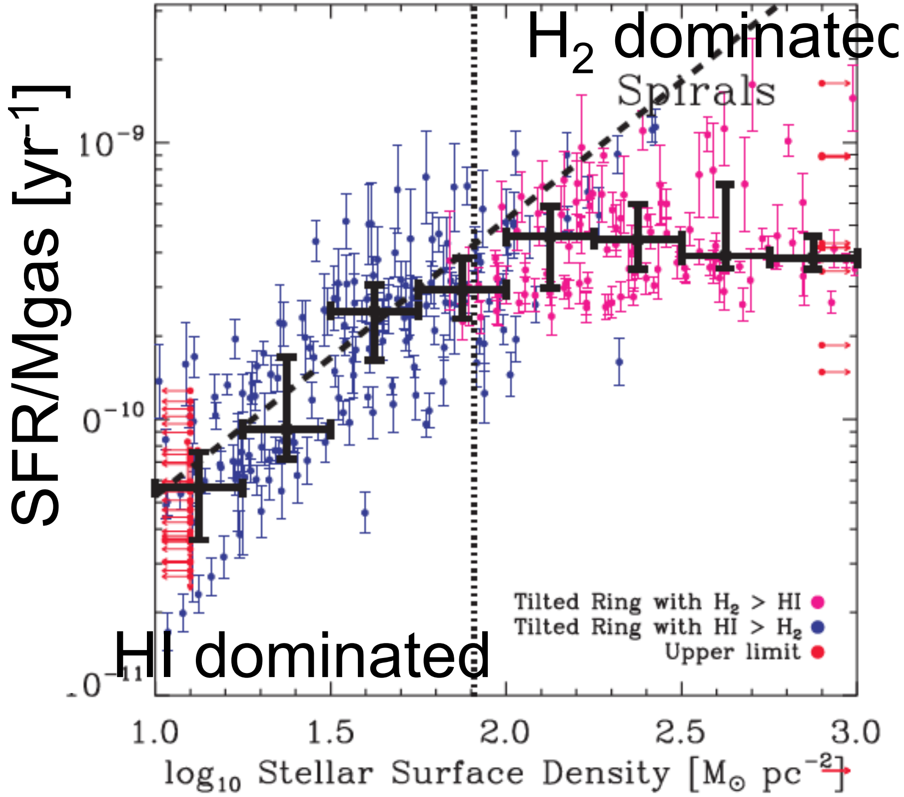


- Recent SF tracers (Hα, 8/24μm) give low $\Sigma_{SFR}$ compared to $\Sigma_{H2}$.
- Especially low in region SW
- Long term SF tracer are more in agreement with SFE of spiral galaxies.

# Why is SFE so low?

## Low gas surface density?

- VCC 2062 has:
  - low surface brightness: $\mu_v$=25.5 mag/’’$^2$)
  - low stellar mass surface density: 1 Msun pc$^{-2}$
  - low gas surface density: $\Sigma_{gas} \approx 6$ Msun pc$^{-2}$)
  - At these low surface densities, $\Sigma_{SFR}/\Sigma_{gas}$ decreases usually – but also $M_{H2}/M_{HI}$



Leroy+2008, SFE in THINGS galaxies

- VCC 2062 does have considerable molecular gas, with $M_{H2}/M_{gas} \approx 50\%$
  ➔ molecular gas to form stars is present.

# Why is SFE so low?

## Decreasing SFR:

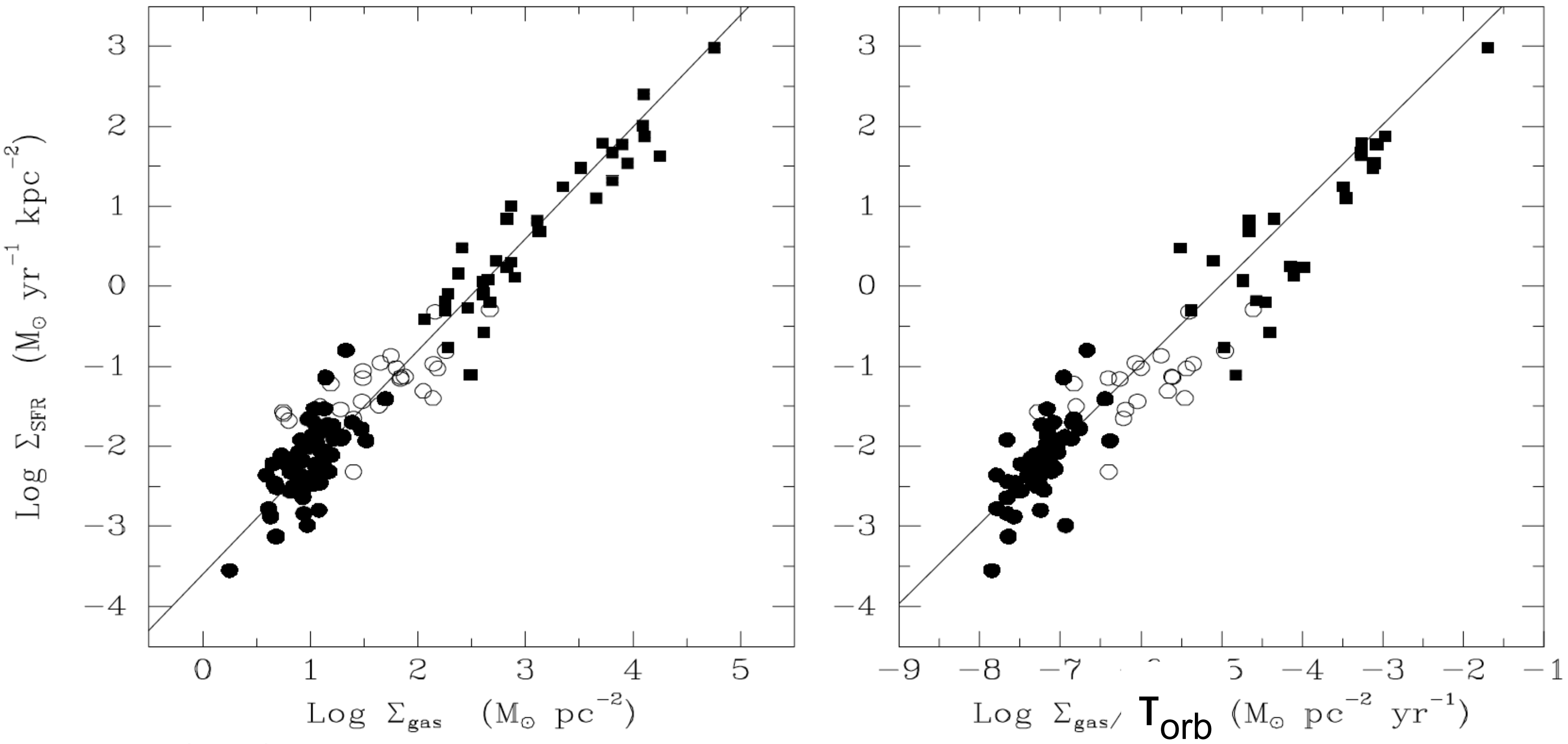
- CIGALE fitting: SFR(average $10^8$ yr) ≈ 1.5 x present SFR
- Consistent with low SFR(Hα)/SFR(UV)

➔ Non equilibrium situation; few massive stars compared to continuous SFR for which indicators are calibrated.

## Low SFR (≈$10^{-3}$ Msun $yr^{-1}$)

- Stochastic sampling of IMF ➔ few O stars are being formed
- Difference in expected L(Hα) can be factor of 2 for SFR < $10^{-3}$ Msun $yr^{-1}$ (Cerviño 2003, Cerviño & Luridiana 2004)

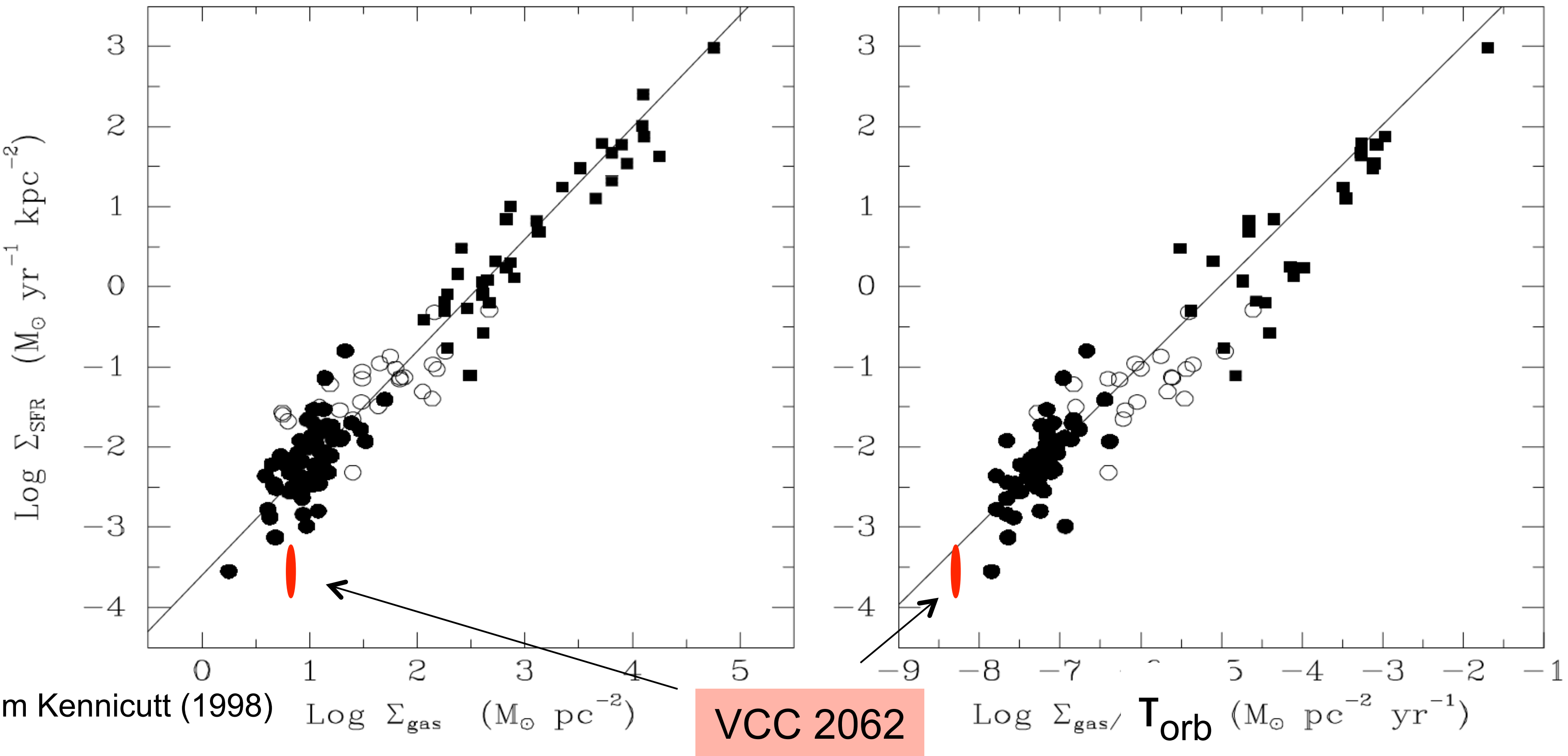
# Does orbital time play a role?



from Kennicutt (1998)

Gas consumption for star formation is about 10% per orbital time.

# Does orbital time play a role?



from Kennicutt (1998)

VCC 2062

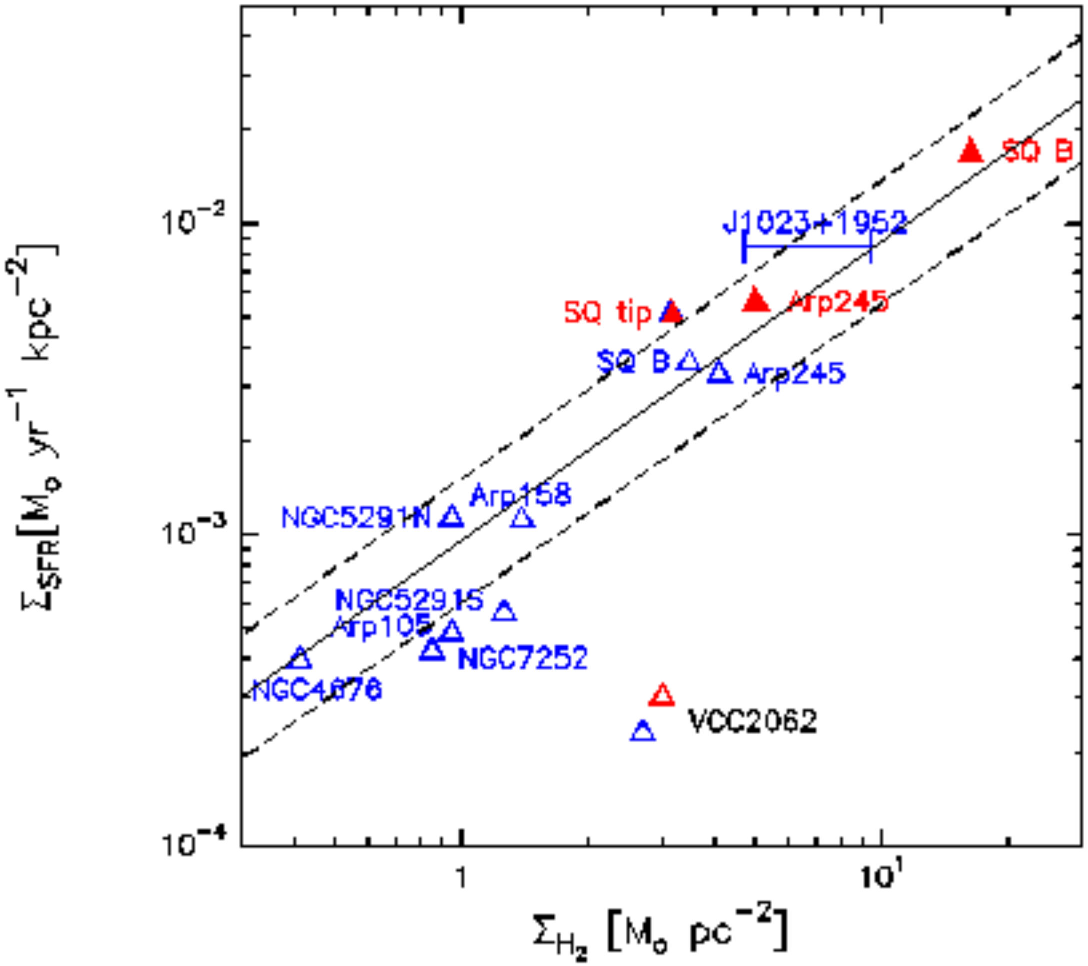
- VCC 2062 has a long $\tau_{orb}$ ($1.2 \times 10^9$ yr) due to lack of dark matter
- Gas consumption per orbit is ≈ 10%, as in spiral galaxies.

BUT: - What could be physical cause?

- VCC 2062 is different from other TDGs.

# How is the SF law in TDGs?

For most objects there is only single-dish data.



- Blue: single dish CO data.
- Red: Interferometric CO data

- Lines: Relation found by Bigiel (2008), and 0.2 dex scatter range (no helium fraction)

- SFR ($M_{o}\ yr^{-1}$)= $5.3\ 10^{-39}$ L(Ha) (erg $s^{-1}$) (Kennicutt 1998, adapted for Kroupa IMF)
- SFR for Arp 158 from FUV and 24 μm (Boquien et al. 2011)
- SFR for Arp 245 from 24 μm and Hα

→ In general (except of VCC 2062) reasonable agreement with relation found by Bigiel et al. (2008).

# Summary

- TDGs are interesting objects to study the SF law, because of:
  - High metallicity -> CO is a good tracer of the molecular gas
  - Low dark matter content -> different conditions
- VCC 2062 is an old, nearby TDG with a large data set
- Interferometric observations of the molecular gas together with the measurement of the SFR from different tracers a low SFE for VCC 2062. Possible reasons are:
  - **Decling SFR in the past**
  - Short orbital time
- For other TDGs with CO the SFE is similar to that in spiral galaxies.