#### **Cold Gas in Early-type Galaxies**

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Image credit: P.-A. Duc 2011 (c) CEA/CFHT

### **Context and Project Goals**



E and S0 galaxies move onto the red sequence by losing most of their cold gas, through

- consumption (star formation)
- feedback, AGN or stellar
- environmental effects, stripping

• ??

*Our Goal:* read the signatures of these processes in stellar kinematics, stellar populations, and gas of early-type galaxies.

# Atlas3D: complete volume-limited sample of ETGs







- **Optical spectroscopy** (SAURON on WHT)
  - Stellar kinematics, ionized gas distribution & kinematics, stellar populations
- **Deep optical imaging** (CFHT Large Programme)
- *HI maps* of 170 northern galaxies with WSRT
- Single-dish CO + some <sup>13</sup>CO, HCN, HCO+, CS (IRAM 30m)
- **CO maps** of 40 detections with CARMA, PdB, 5" resolution
- cosmological SAM simulations
- high-resolution merger simulations

#### Cold Gas

raw material for star formation
tracer of galaxy interactions
dust shows up in optical images, but without kinematic information.

HST image gallery; credit: NASA, ESA, R.M. Crockett et al.

## Basic cold gas (CO and HI) data

- CO (IRAM 30m) detection rate 22% +- 3%
  - $\rm H_2$  masses  $10^{7.1}$  to  $10^{9.3} \rm \ M_{\odot}$  or
  - Log M(H<sub>2</sub>)/M<sub> $\star$ </sub> = -3.5 to -1.1 (Young+ 2011)
- 40 CO detections mapped at 5" res. ~ 600 pc
  - Disks, rings, bars, irregular morphologies (Alatalo+ 2013)
- HI maps (WSRT) at ~ 35" resolution (Serra+ 2012), 40% detected
  - HI sensitivity ~ few  $10^{19}$  cm<sup>-2</sup> or  $10^6$  to  $10^8$  M<sub> $\odot$ </sub>
  - Disks (up to many 10s kpc), irregular morphologies, clouds
- Largest set of cold gas maps ever assembled for early-type galaxies



#### Cold gas in red sequence E and S0

• gas mass and detection rate do **not** depend on stellar mass

• CO content is higher in more disky galaxies (vs spherical/bulge dominated)

• reddening by dust doesn't affect colors much NUV-K

• the approach to the red sequence does **not** have to involve the loss of all cold gas. (or was it re-acquired?)



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Young et al (1312.6318)

#### Cold gas vs. stellar kinematics (assembly history)

merger sims by Bois et al 2010, 2011; Naab et al, 1311.0284



detected in CO (24  $\pm$  3%) and HI (31  $\pm$  5%)



Slow rotators (11% of ETGs) and spherical Non-rotators (3% of ETGs)

detected in HI (41  $\pm$  14%) but rarely in CO (6  $\pm$  4%)



### Kinematics; the origin of the cold gas

- stellar--gas kinematic misalignments are common, occurring in > 35% of fast rotators (oblate galaxies; Davis 2011; Sarzi 2006)
- > 50% of the  $H_2$  and HI is **not** recycled from internal stellar mass loss
  - $H_2$  misalignments are less common in high mass galaxies and cluster members



### Kinematics; the origin of the cold gas

• Question for simulators: can you reproduce this distribution of kinematic misalignments with accretion of gas? satellites? major mergers? ...?



### Gas Kinematics in Simulations



Lagos et al (1405.0016): reproduce HI and H2 contents w/gentle stripping of hot gas

Serra et al (1401.3180): difficult to reproduce large quantities of misaligned gas

Lagos et al (in prep): can reproduce misalignments with minor mergers AND cooling from hot halo gas which is misaligned w.r.t. stellar body

#### Star Formation Rates and Galaxy Dynamics



#### **Star Formation Rates and Galaxy Dynamics**



Gas depletion times are longer (star formation efficiency is lower) when most of the gas is in the rising part of the rotation curve.

## **Additional Fun Projects**

- gas-phase metallicity vs stellar metallicity; another indication of the origin of the cold gas
- star formation histories of individual galaxies, deconvolved from optical spectra and correlated with gas contents
- testing analytic models for the HI H2 transition
- molecular chemistry tracing shocks, XDR, enhanced cosmic ray populations
- spatially resolved measures of star formation efficiency

## Summary

- 1. There is more cold gas in early-type galaxies than most of us expected. ~ 50% have  $10^7$  to  $10^9 M_{\odot}$  of HI and/or H<sub>2</sub>.
- 2. The approach to the red sequence does not mean the loss of all cold gas. Or red sequence galaxies reacquire gas.
- 3. Much of the cold gas in ETGs is kinematically misaligned.
- 4. Cold gas contents and kinematics in these galaxies are sensitive probes of their evolution useful constraints on numerical simulations.
- 5. Diversity in the stellar kinematics, gas contents, & gas kinematics of early-type galaxies emphasizes diversity in their evolutionary paths.