Probing gas reservoirs in galaxies throughout the history of the Universe

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With Françoise Combes, Philippe Salomé, Isadora Bicalho, Linda Tacconi, Reinhard Genzel, Roberto Neri, Santiago Garcia-Burillo & the PHIBSS consortium

Outline

1. Introduction: gas and star formation in galaxies
2. Molecular gas reservoirs across cosmic time
3. Perspectives with SKA

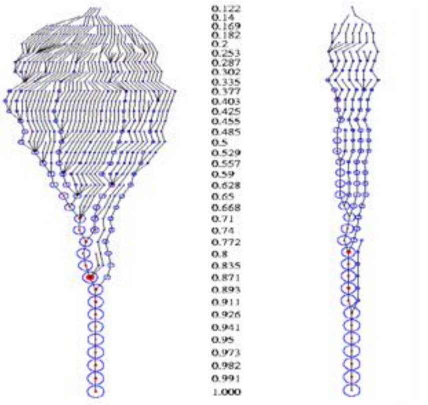
Outline

Star formation in the interstellar medium

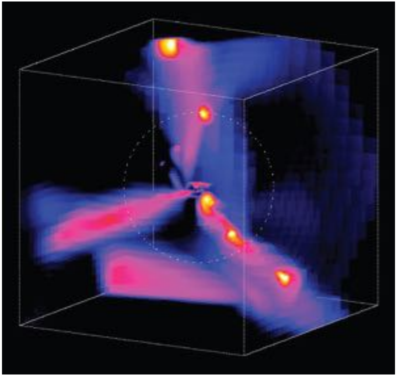

The Orion nebula, a stellar nursery (NASA)

How do galaxies get their gas?

Mergers vs. smooth accretion along the streams of the cosmic web.

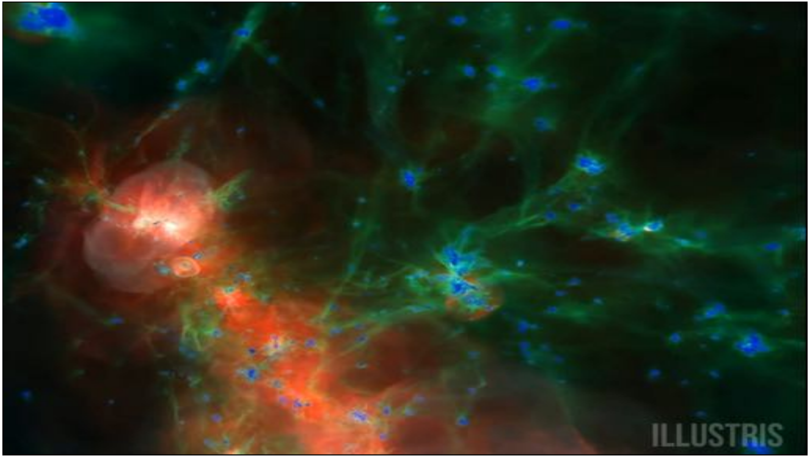


White (1996)



Dekel et al. (2009)

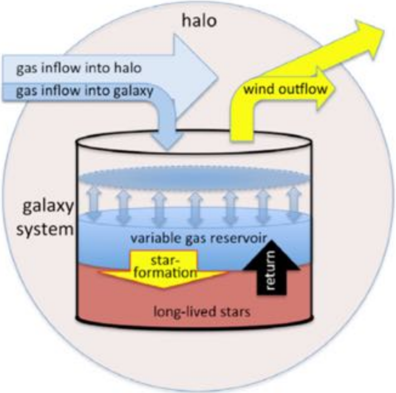
Feedback processes from stars and active galactic nuclei



Vogelsberger et al. (2014)

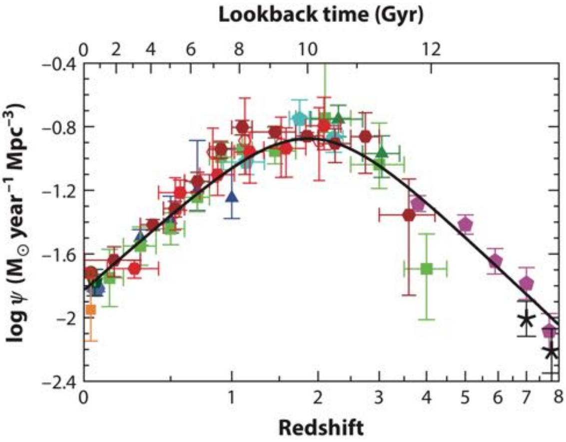
Galaxies as star factories

$$\underbrace{\dot{M}_{gas}}_{\text{gas reservoir}} = \underbrace{\dot{M}_{gas,in}}_{\text{inflows}} - \underbrace{\dot{M}_{stars}}_{\text{star formation}} - \underbrace{\eta \dot{M}_{stars}}_{\text{outflows}} + \underbrace{R\dot{M}_{stars}}_{\text{recycling}}$$



Lilly et al. (2013)

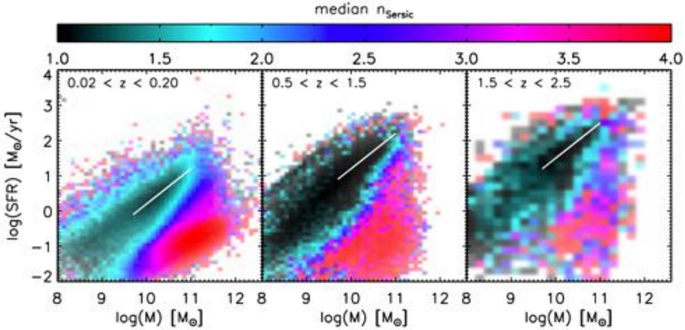
A star formation peak around z≃2-3



Madau & Dickinson (2014)

The Main Sequence of star-forming galaxies

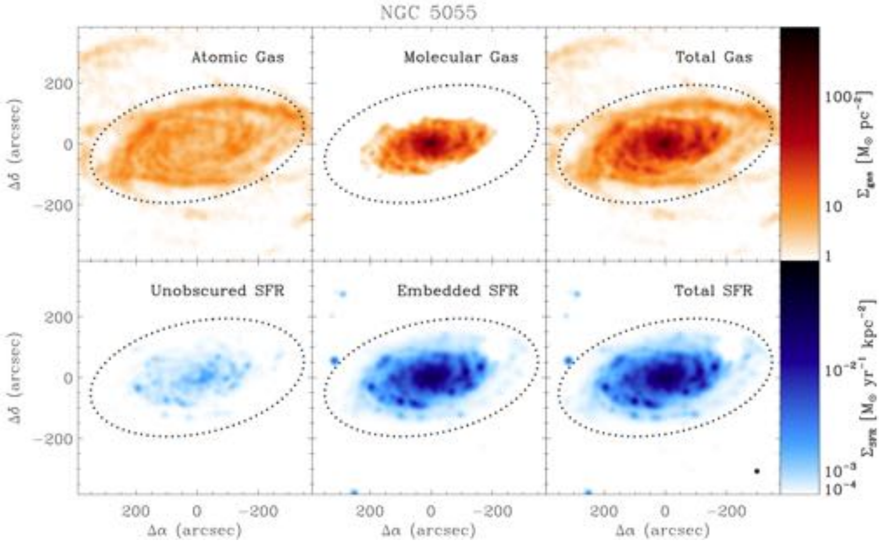
A galaxy bimodality: blue star-forming disks vs. red and passive (quenched) galaxies.



Wuyts et al. (2011)

- Sersic index: n = 1 exponential disks vs. n=4 de Vaucouleurs profiles (ellipticals)
- About 90% of the cosmic star formation history since $z \lesssim 2.5$ took place near the MS (Rodighiero et al. 2011, Sargent et al. 2012)
- At a given M_{star}, the SFR on the MS drops by a factor ~ 20 from $z \sim 2$ to the present time

Gas and star formation



Leroy et al. (2008)

The Kennicutt-Schmidt relation

Molecular gas and star formation are correlated on galactic scales and on local scales.

The **Kennicutt-Schmidt (KS) relation** reflects this correlation and characterizes the star formation efficiency

- **Schmidt (1959) :**
  $\rho_{SFR} \propto (\rho_{gas})^n$

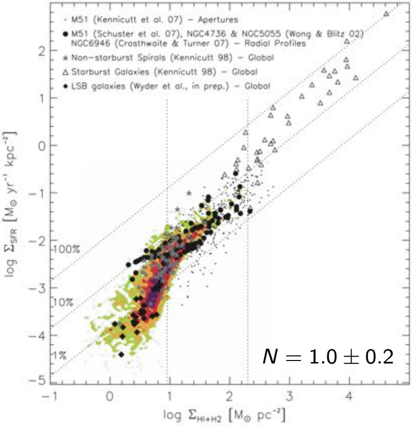
  $n \sim 2$ in our Galaxy

- **Kennicutt (1998) :**
  $\Sigma_{SFR} \propto (\Sigma_{gas})^N$

  $N = 1.40 \pm 0.15$ in a sample of 61 spiral galaxies and 36 starburst galaxies

A linear relation indicates a constant depletion time $\mathrm{t_{depl} = M_{gas}/SFR}$.

Atomic and molecular KS relations at sub-galactic scales (750 pc):



Bigiel et al. (2008)

Outline

The IRAM PHIBSS survey (2010-2013)

IRAM **P**lateau de Bure **HI**gh-z **B**lue **S**equence CO(3-2) **S**urvey
(PIs: Linda Tacconi & Françoise Combes)

- → a statistical sample of MS galaxies near the peak epoch of star formation
- → CO cold molecular gas observations
- → high-resolution follow-ups

Cf. Tacconi et al. 2010, 2013, Genzel et al. 2010, 2012, **2013**, **Freundlich et al. 2013**

IRAM Plateau de Bure interferometer

The PHIBSS2 Legacy Program (2013-2017)

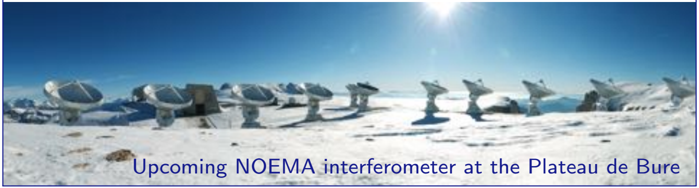
PIs: F. Combes, S. Garcia-Burillo, R. Neri, & L. Tacconi
Data reduction at IRAM: J. Boissier, C. Feruglio, & R. Neri

→ Covers the **build-up** ($z \sim 2.5 - 3$), the **peak** ($z = 1 - 2$) and the **winding-down** ($z < 1$) of massive galaxy formation

→ More than **120 targets**, including galaxies **on and below the MS**

→ Test the impact of AGNs, environment and morphology owing to a purely mass-selected sample

→ High-resolution follow-ups: spatially- resolved KS, rotation curves, velocity dispersion


Upcoming NOEMA interferometer at the Plateau de Bure

Cf. **Genzel et al. 2015**, **Tacconi et al. 2018**, **Freundlich et al. 2018**

Co-PI: Francoise Combes (Obs. Paris – France)
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Co-PI: Roberto Neri (IRAM – France)
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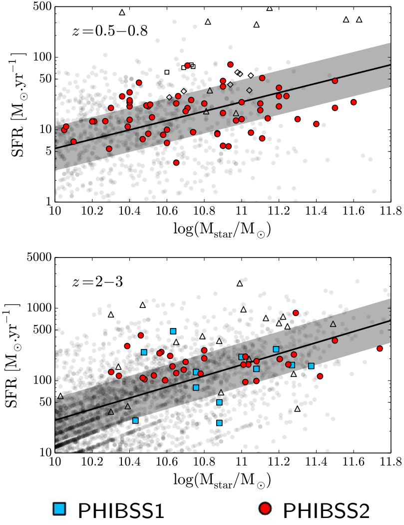
F. Bournaud (CEA – France)
A. Burkert (USM – Germany)
M. Carollo (ETH – Switzerland)
L. Colina (CSIC – Spain)
M. Cooper (UCI – US)
P. Cox (IRAM – France)
C. Feruglio (IRAM – France)
J. Freundlich (Obs.Paris – France)
N. Förster Schreiber (MPE – Germany)
S. Juneau (CEA – France)
K. Kovac (ETH – Switzerland)
M. Lippa (MPE – Germany)
D. Lutz (MPE – Germany)
T. Naab (MPA – Germany)
A. Omont (IAP – France)
A. Renzini (Univ.Padova – Italy)
A. Saintonge (MPE – Germany)
P. Salomé (Obs.Paris – France)
A. Sternberg (Univ.Tel Aviv – Israel)
F. Walter (MPIA – Germany)
B. Weiner (Steward Obs.Arizona – US)
A. Weiß (MPIfR – Germany)
S. Wuyts (MPE – Germany)

The PHIBSS/PHIBSS2 samples

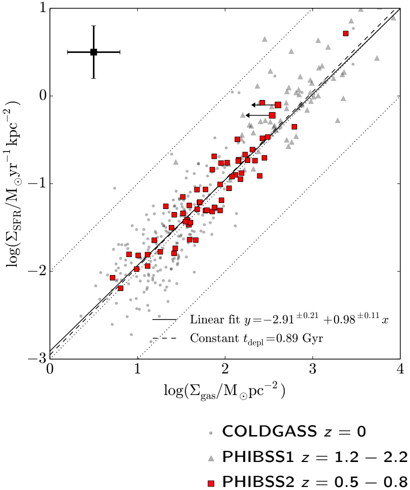


Sample selection:

- Cover the winding-down, peak and build-up of massive galaxy formation
- Well-understood parent samples (in the GOODS-N, COSMOS, AEGIS fields)
- Homogeneous coverage of the MS and its scatter
- No morphological selection

Star formation and molecular gas reservoirs

- Large molecular gas fractions at high redshift: $f_{\rm gas} = 30 - 50\%$ at $z \sim 1-2$ (Tacconi et al. 2013) compared to $\sim 8\%$ at z=0 (Saintonge et al. 2011)
- Near-linear galaxy-averaged molecular KS relation between $z = 1 - 3$.
- The evolution of the cosmic SFR is mainly driven by the available gas reservoirs.

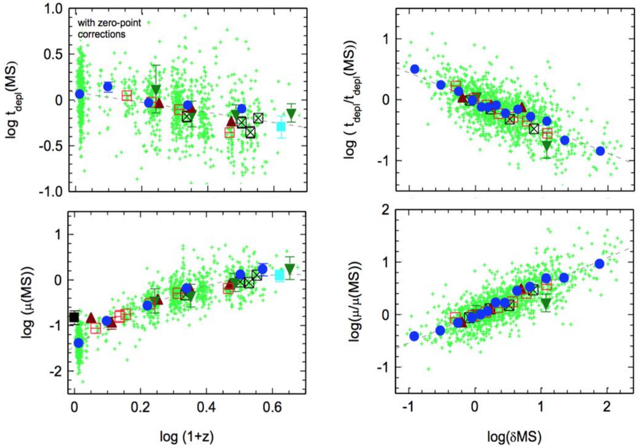


Freundlich et al. (2018), submitted

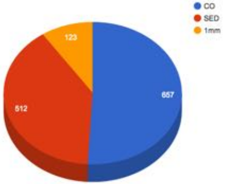
Scaling relations for $t_{\rm depl} = M_{\rm gas}/SFR$ and $\mu_{\rm gas} = M_{gas}/M_{\rm star}$

$$t_{\rm depl} \propto (1+z)^{-0.57} \left(\frac{SSFR}{SSFR_{\rm MS}}\right)^{-0.44} \left(\frac{M_{\rm star}}{5.10^{10} M_\odot}\right)^{+0.07} \left(\frac{R}{R_{\rm MS}}\right)^{+0.12}$$

$$\mu_{\rm gas} \propto (1+z)^{+2.60} \left(\frac{SSFR}{SSFR_{\rm MS}}\right)^{+0.54} \left(\frac{M_{\rm star}}{5.10^{10} M_\odot}\right)^{-0.33} \left(\frac{R}{R_{\rm MS}}\right)^{+0.09}$$



1428 measurements:
- 657 CO
- 512 dust SED
- 123 dust continuum

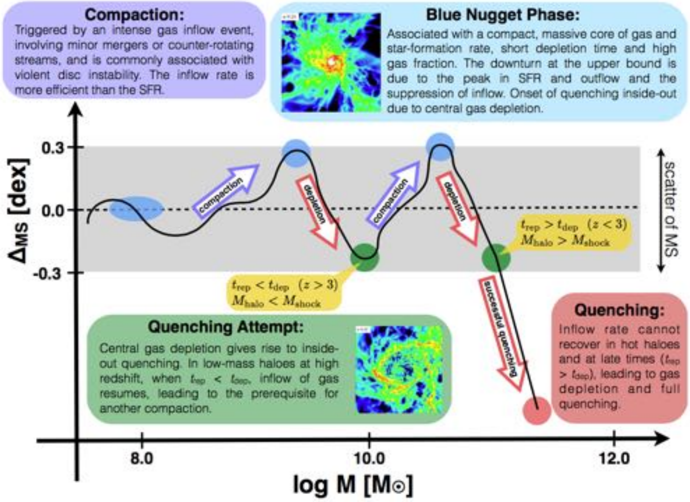


$z = 0 - 4.4$
$\log(M_{\rm star}/M_\odot) = 9 - 11.9$
$|\log(\delta MS)| \leq 2$

$\delta MS = SSFR/SSFR_{MS}$
$\delta MS = M_{star}/5.10^{10} M_\odot$

Genzel,...,**JF** et al. (2015), Tacconi,...,**JF** et al. (2018)

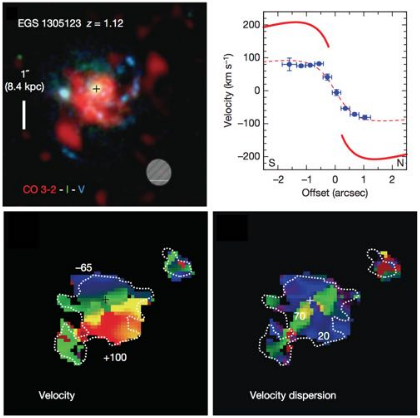
Interpretation of the δMS trend: compaction and replenishment



Tacchella et al. (2016)

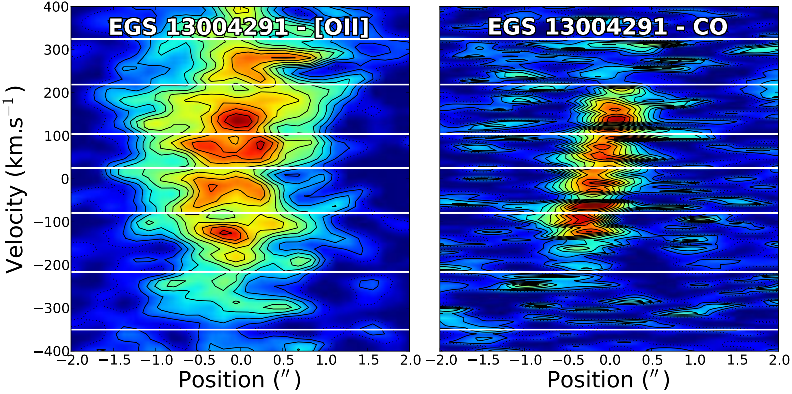
Rotating, turbulent disks at high redshift

- Rotationally-supported turbulent disks: $v_{\rm rot}/\sigma \sim 5-7$ at $z \sim 1-2$ compared to $\sim 10-20$ at $z=0$ (Dib et al. 2006)



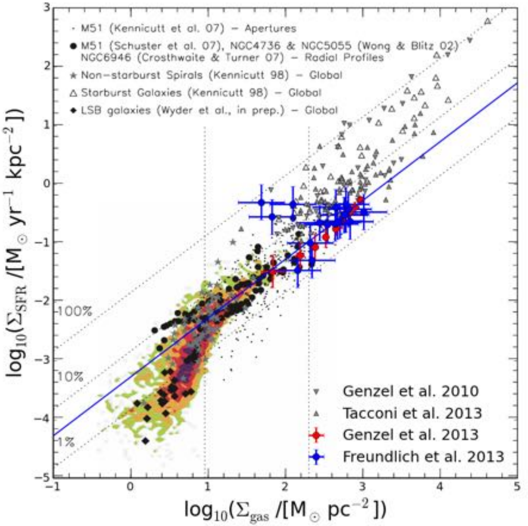
Tacconi et al. (2010, 2013)

Beating the resolution limit with the kinematics



Freundlich et al. (2013)

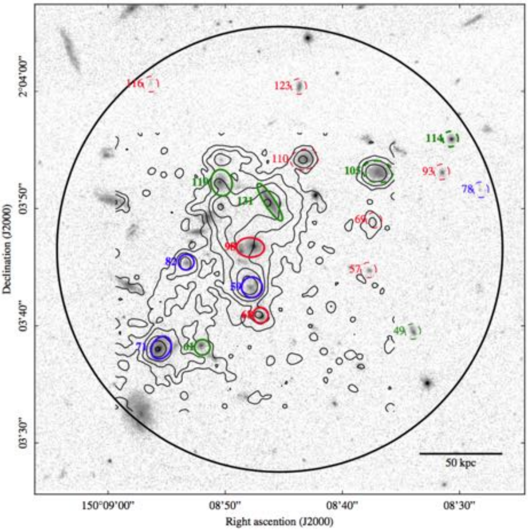
A resolved KS relation



Freundlich et al. (2014)

The role of environment

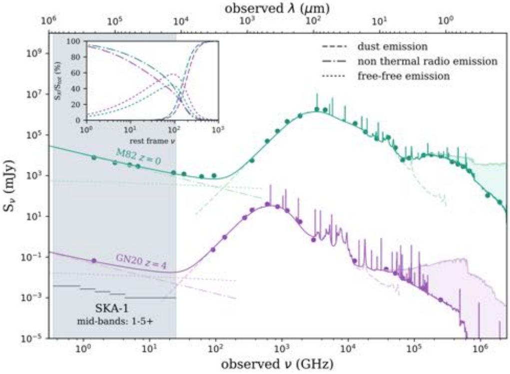
- Comparing different types of environment using NOEMA (PI: T. Contini): a galaxy group at $z = 0.7$ observed with MUSE, gas fraction and star formation efficiency, expelled gas.



Outline

Probing star formation up to $z = 10$

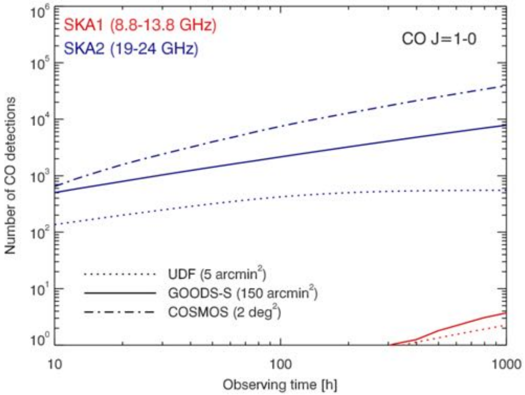
- **SKA-mid**: SFR down to a few $\mathrm{M}_\odot/\mathrm{yr}$ up to $z \sim 10$ (Mancuso et al. 2015)
- **Synchrotron emission** – related to the SFR but may be contaminated by other processes (relativistic electrons, magnetic fields, dust, AGN)
- **Free-free emission** from hot electrons ionized by young stars, optically thin and unaffected by dust – a more direct tracer of the the SFR than UV and IR luminosities



French SKA white book, 2017

Molecular gas at very high redshift

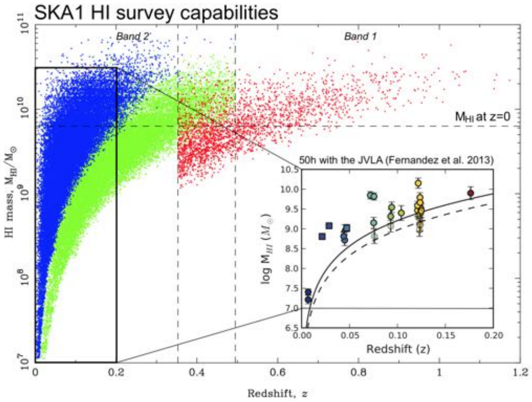
- Today, molecular gas surveys only reach $z \sim 3$
- **SKA1**: CO (1-0) at $z > 7.3$ for galaxies previously identified with ALMA (lensed galaxies for example) to calibrate the α_{CO} conversion factor and construct the CO SED
- **SKA2:** CO (1-0) at $z > 3.8$, possibility to make surveys
- **Dense gas tracers:** HCN, HCO^+, CS, etc.



French SKA white book, 2017

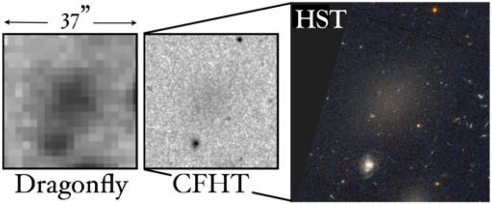
The missing component at high redshift: atomic gas

- Today, HI 21 cm emission is only detected up to $z \lesssim 0.2$
- **SKA 1**: will detect HI in galaxies up to $z \sim 1.7$ and do maps up to $z \lesssim 1$



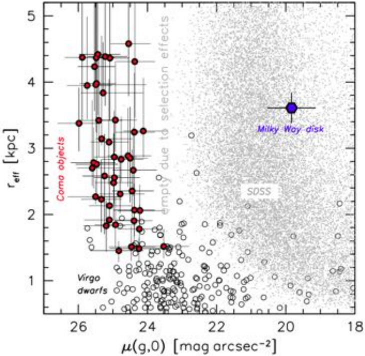
Staveley-Smith & Oosterloo (2015), Fernandez et al. (2013)

Low Surface Brightness & Ultra Diffuse Galaxies



Characteristics of UDGs:

- Stellar masses of dwarf galaxies
  $7 < \log(\mathrm{M_{star}}/\mathrm{M_\odot}) < 9$
- Effective radii of MW-sized objects
  $1 < \mathrm{r_{eff}}/\mathrm{kpc} < 5$
- Low central surface brightness
  $23.5 < \mu(\mathrm{g}, 0)/\mathrm{mag\ arcsec^{-2}} < 28$



Van Dokkum et al. 2015

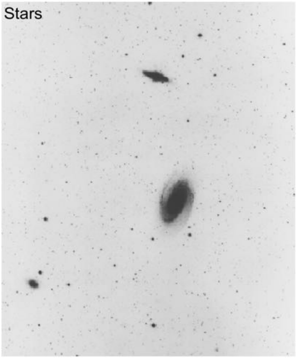
Possible formation scenarii:

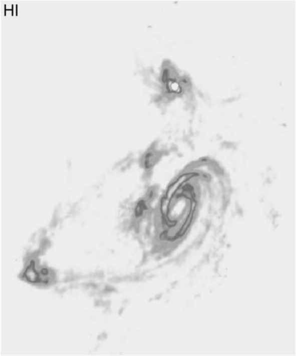
- **Failed MW-like galaxies** that lost their gas after forming their first stars (Van Dokkum et al. 2015)
- **High-spin tail** of the dwarf galaxy population (Amorisco & Loeb 2016)
- **Tidal debris** from mergers or tidally disrupted dwarfs (Greco et al. 2017)
- **Episodes of inflows and outflows from stellar feedback** (Di Cinto et al. 2017)

HI will help discriminate between these scenarii

Environmental effects on galaxies

- **Tidal stripping and ram pressure stripping:** atomic gas more extended and more loosely bound, hence more easily perturbed by the environment
- **Connection between galaxies and their surroundings:** cold streams from the cosmic web, environmental quenching by starvation
- **SKA1:** will map the HI line in clusters and proto-clusters up to $z \sim 1$

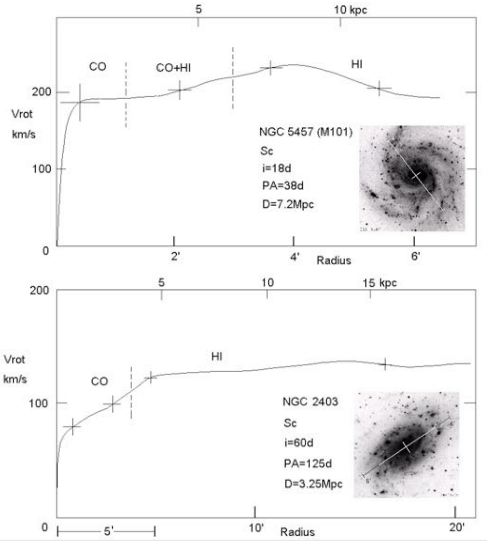




M81 galaxy group from Yun et al. (1994)

The dark matter content of galaxies

- HI gas reveals the rotation curves of galaxies outside the optical disk, where CO and Hα are confined
- Accurate determination of the dark matter content and of its evolution with redshift



Sofue (1997)

Thanks for your attention

Expected SKA-mid (SPDO/Swinburne Astronomy Productions)