Robust profile decomposition for large extragalactic spectral-line surveys

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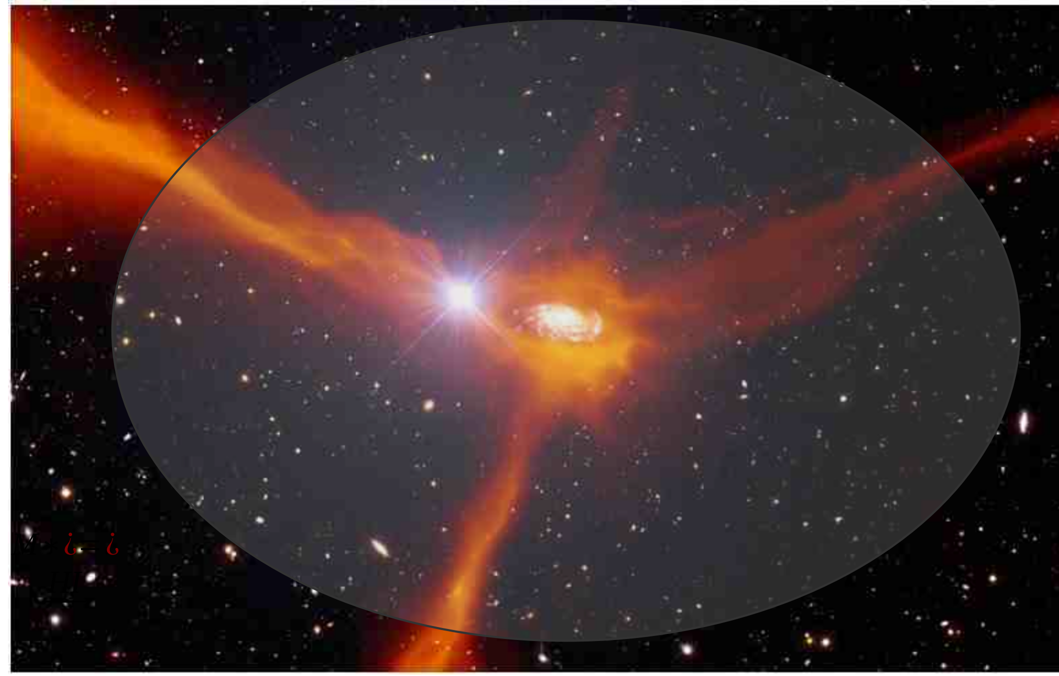
Outline

- The star formation threshold in galaxies
- Kinematically decoupled ISMs and their link to star formation
- A new gas profile decomposition
- Some practical applications to dwarfs (DDO 210, NGC 6822, LMC) in preparation for the SKA pathfinders

A fundamental view of galaxy formation and evolution (in gas perspective)

- **Key galaxy properties:**
  - ∑ SFR : # of stars forming / time or area
  - sSFR : SFR / M*
  - ∑ gas (HI + H2)
  - SFE : # of stars existing
  - colors (age, metallicity)
  - redshift
  - Mhalo
  - angular momentum
  - feedback (AGN, Sne, winds)
  - accretion / inflow / outflow
  - dust properties

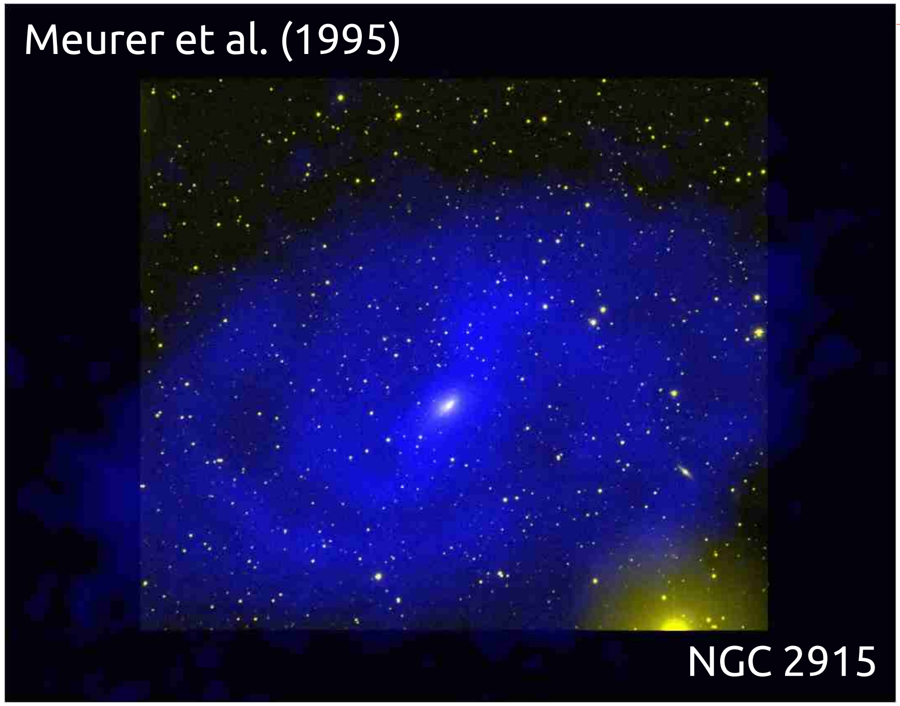


Gas reservoir **SF efficiency**

$$\frac{SFR}{M_*} = \frac{HI}{M_*} \times \frac{H_2}{HI} \times \frac{SFR}{H_2}$$

Specific Star Formation Rate **Molecular gas fraction**

Galaxy dynamics and its link to star formation in galaxies



High-resolution HI 21cm observations of nearby galaxies …

… allow us to study (but not limited to) the following:

- the dynamical mass and structure of galaxies
- scaling relations (e.g., Tully-Fisher relation)
- the distribution and evolution of angular momentum
- The distribution of dark and luminous matter …

The star formation threshold

- Toomre Q parameter (Toomre e tal. 1989, modified by Kennicutt 1989):

$$Q(r) = \frac{c_s k}{\pi G \Sigma_g}, \qquad k^2 = 2\left(\frac{V^2}{R^2} + \frac{V}{R}\frac{\mathrm{d}V}{\mathrm{d}R}\right) s^{-2},$$

→ Q < 1 : unstable against radial perturbations

→ one can define a critical gas density for star formation

→ Instability is expected if the surface density exceeds the critical value:

$$\Sigma_c = \alpha \frac{c_s \kappa}{\pi G}.$$

Gas velocity dispersion: σ sqrt(γ)

Epicycle frequency

~1.0 (dimensionless constant): to reconcile the model with observations

The star formation threshold

- Gas rich dIrr galaxies but little star formation!

  ← inefficient star formation or simply the gas density below the threshold?

- Previous studies

  - Kennicutt (1989) and Martin and Kennicutt (2001): CO/HI vs. H-alpha radial profiles

  → $\Sigma g/\Sigma c$ ~ 0.63 for spirals

  - Hunter et al. (1998): $\Sigma g/\Sigma c$ ~ 0.34 for dwarfs and irregulars

  - Bigiel et al. (2008): star formation laws of spirals and dwarfs

  → star formation rate density vs. molecular hydrogen surface density

  - Schaye et al. (2004): model calculation from hydrodynamic simulations

  → critical hydrogen surface density: log(NH)~20.75 ~ 4.5 solar_mass/pc^2

  → the star formation threshold is dependent on the velocity dispersion of gas

- But complex gas dynamics is common in galaxies:

  ← An increase in density in the warm phase leads to an onset of a cool phase, accompanied by a steep drop in velocity dispersion, resulting in a lower value of Q

  ← Regions with Q < 1 will form stars, diminishing the local gas density and increasing the gas velocity dispersion due to mechanical stirring and true heating

  → eventually quench star formation

  ← A new build-up of gas by nearby star formation can then restart the whole process

Complex kinematics structures of the ISM

- Turbulent random motions deviating from the underlying circular rotation of the gas disk

  ← driven by star formation or SNe (Hopkins et al. 2014; Fierlinger et al. 2016)

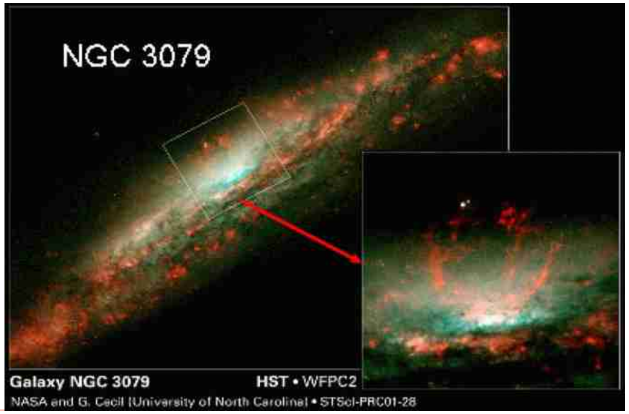
  → holes or local cavities often found in HI gas disk of galaxies (Bagetakos et al. 2011)

  → some gas clouds with substantial deviation up to several hundreds km/s above the projected velocities at their positions, the so-called high-velocity clouds (HVCs, Westmeier 2018)

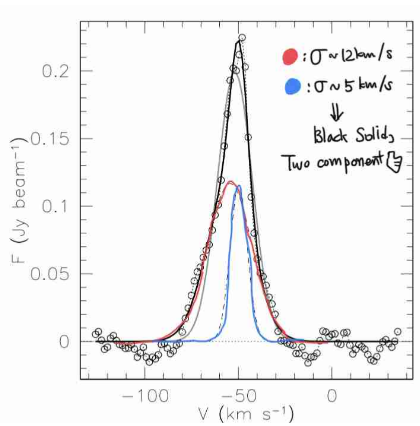
- This in turn allows us to investigate the interplay between bayronic feedback and the ISM (Bournaud et al. 2010)

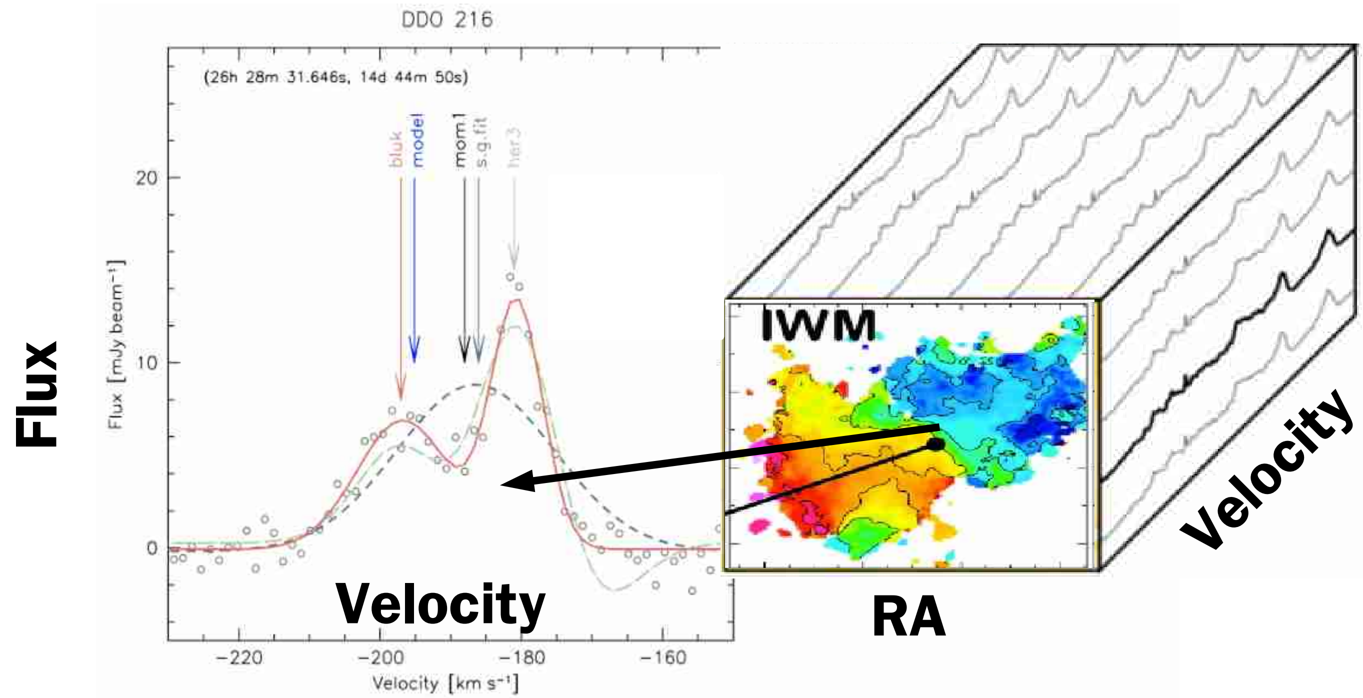
  → modelling of asymmetric and non-Gaussian ISM line profiles is not straightforward when classical moment analysis is applied

  → fits are often sensitive to initial estimates



Complex kinematics structures of the ISM





← gas displacement, heating and ionisation from outflows, SNe, shock fronts, and gravitational interactions

→ locally disturbed ISM driven by the deposition of energy (baryonic feedback), giving rise to complex gaseous structures, kinematics and multiple phases

→ a broadening or skewing of line-of-sight velocity profiles (Young & Lo 1997), after correcting for the projection effect

Robust profile decomposition for large extragalactic spectral-line surveys (Oh, Staveley-Smith & For 2019)

- **Bayesian Gaussian Decomposer (BAYGAUD)**

  - A new profile decomposition based on a Bayesian MCMC technique

  - A non-Gaussian velocity profile modelled as a set of multiple Gaussian components

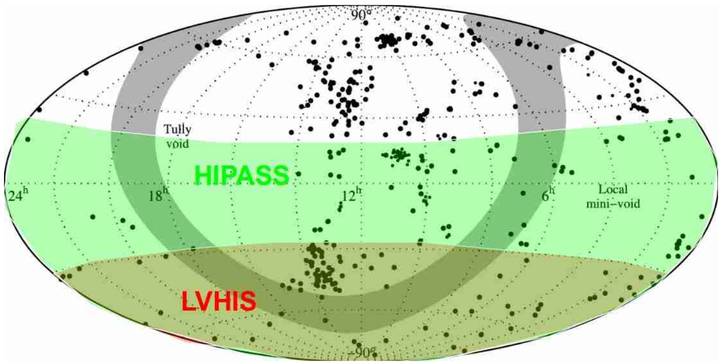
  - Model selection by Bayes factor statistics, giving the optimal number of Gaussian components

  - a standalone code written in C + MPI (parallelised)

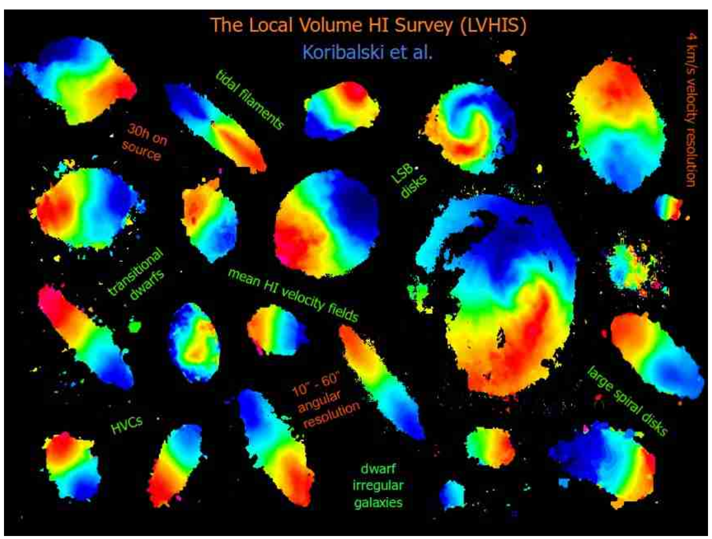
$$G(x) = \sum_{i=1}^{m} \frac{a_i}{\sqrt{2\pi}\sigma_i} \exp\left(\frac{-(x-\mu_i)^2}{2\sigma_i^2}\right) + \sum_{j=0}^{n} b_j x^j$$

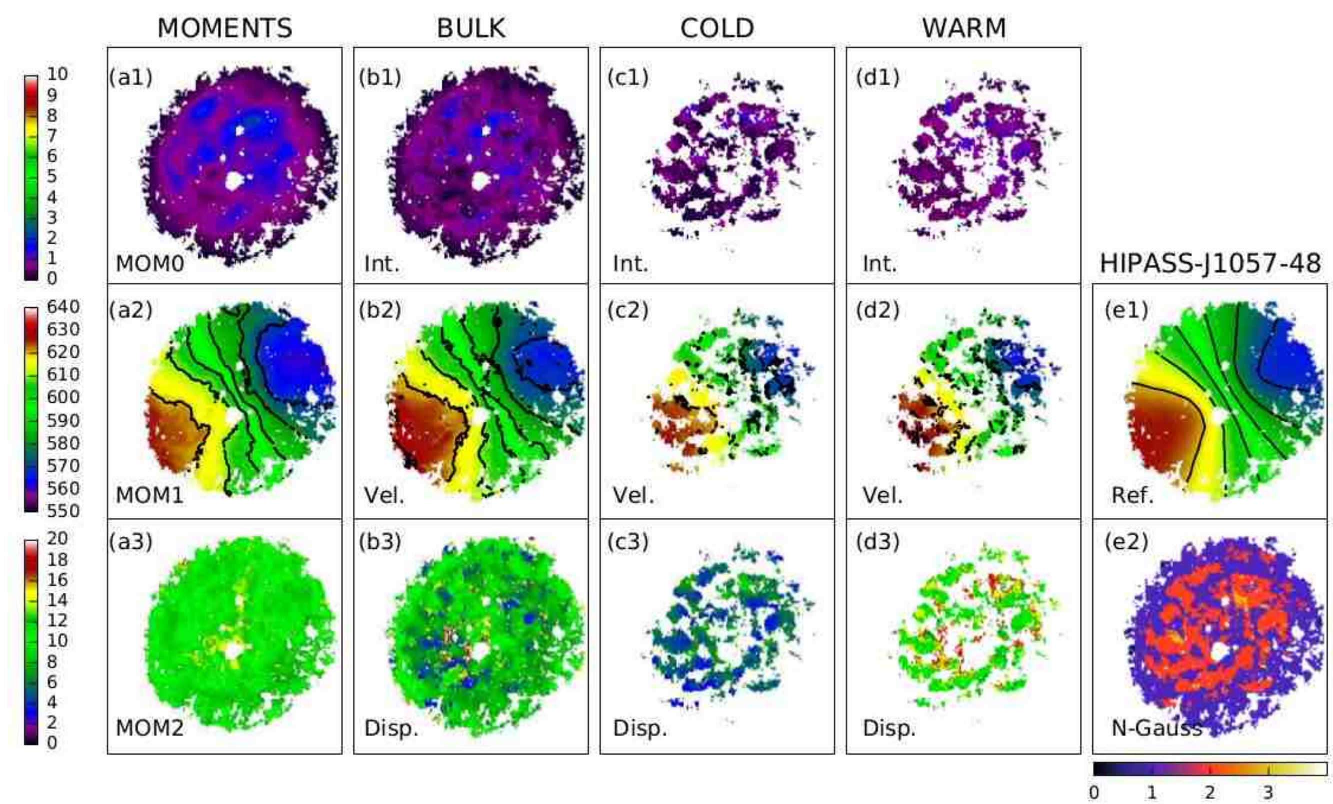
$$\frac{\textit{Likelihood of data given } \mathrm{H1}}{\textit{Likelihood of data given } \mathrm{H0}} = \frac{P(D|H1)}{P(D|H0)}$$

e.g., BAYGAUD application to sample galaxies from Local Volume HI Survey (LVHIS)



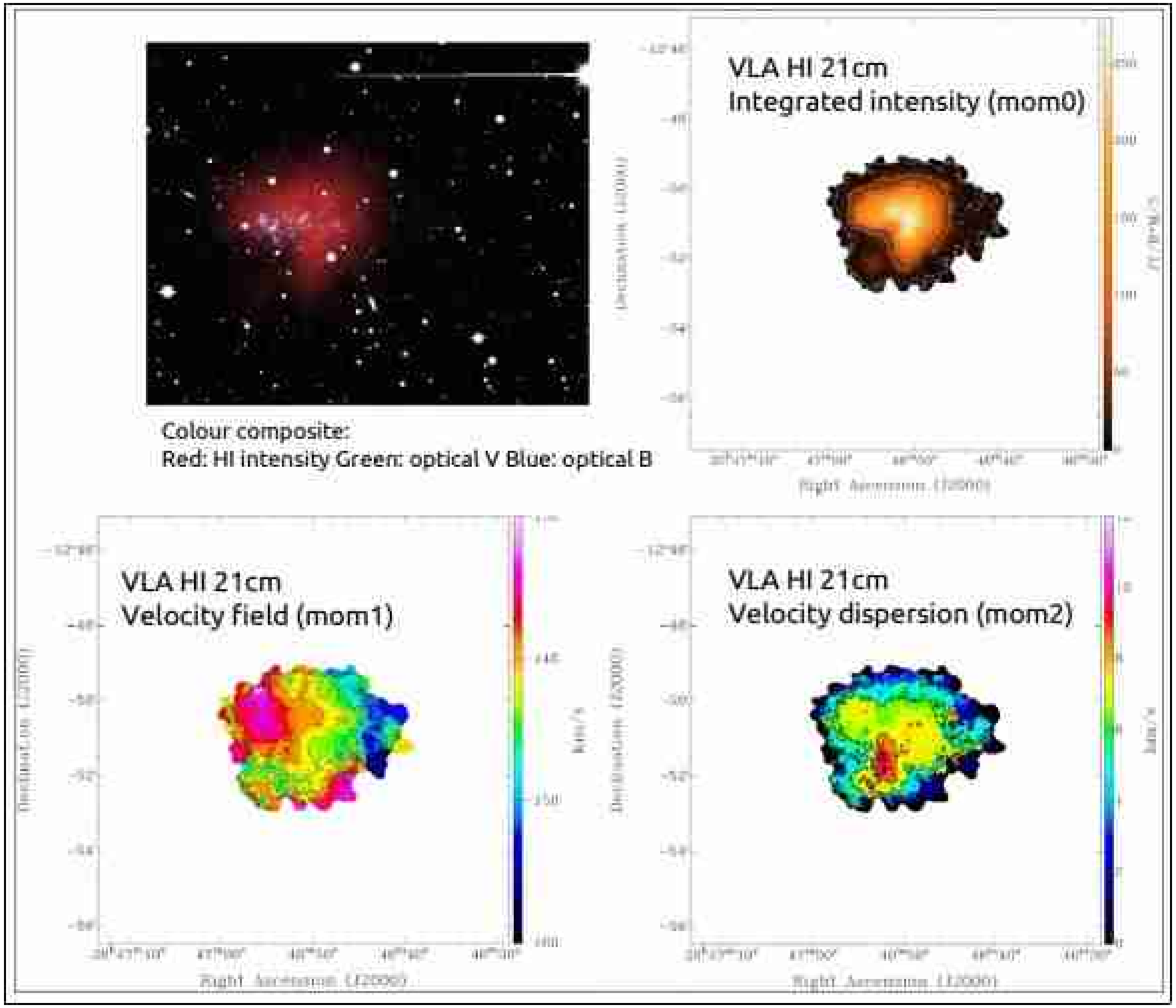
82 nearby galaxies within 10 Mpc in Southern sky



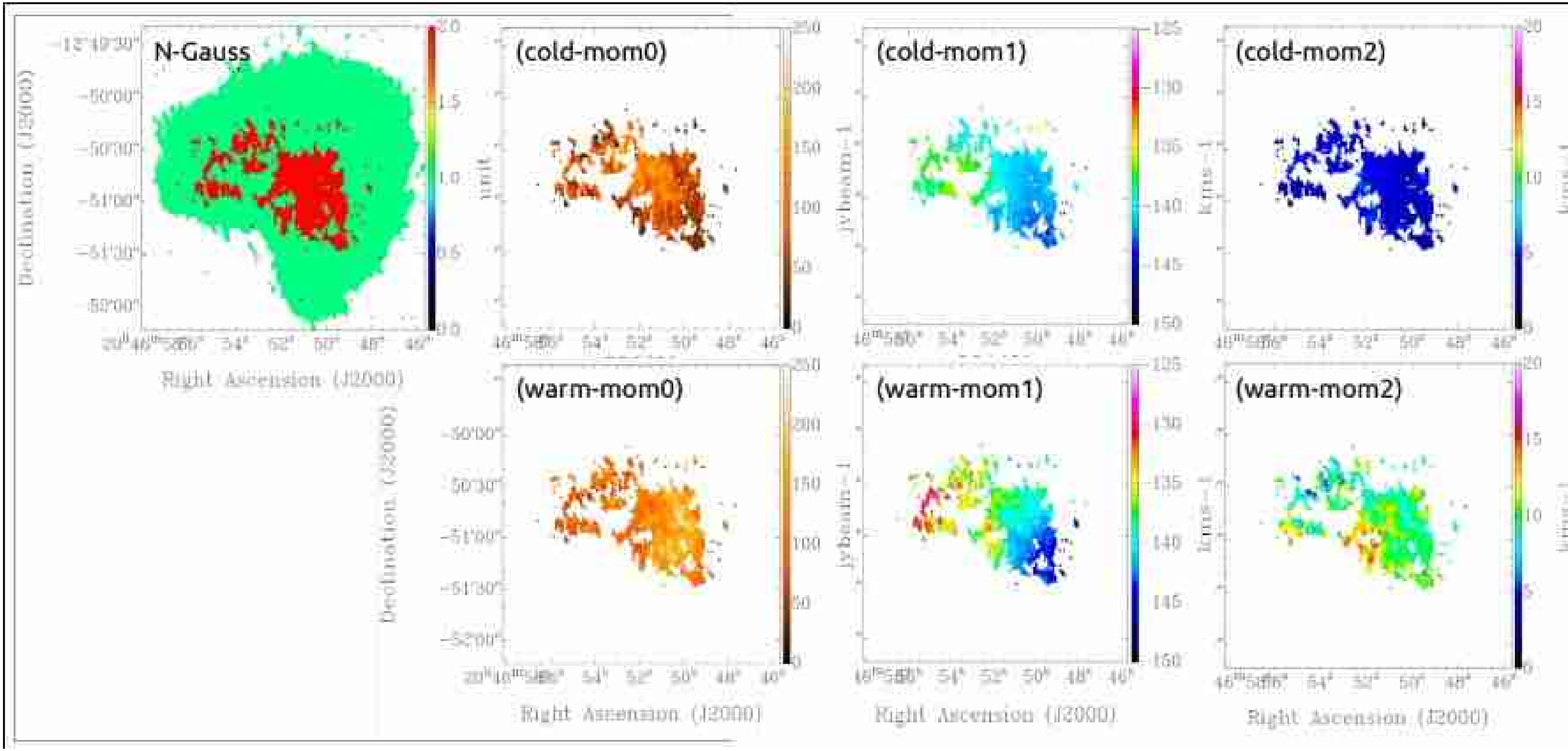


Oh et al. (in prep)

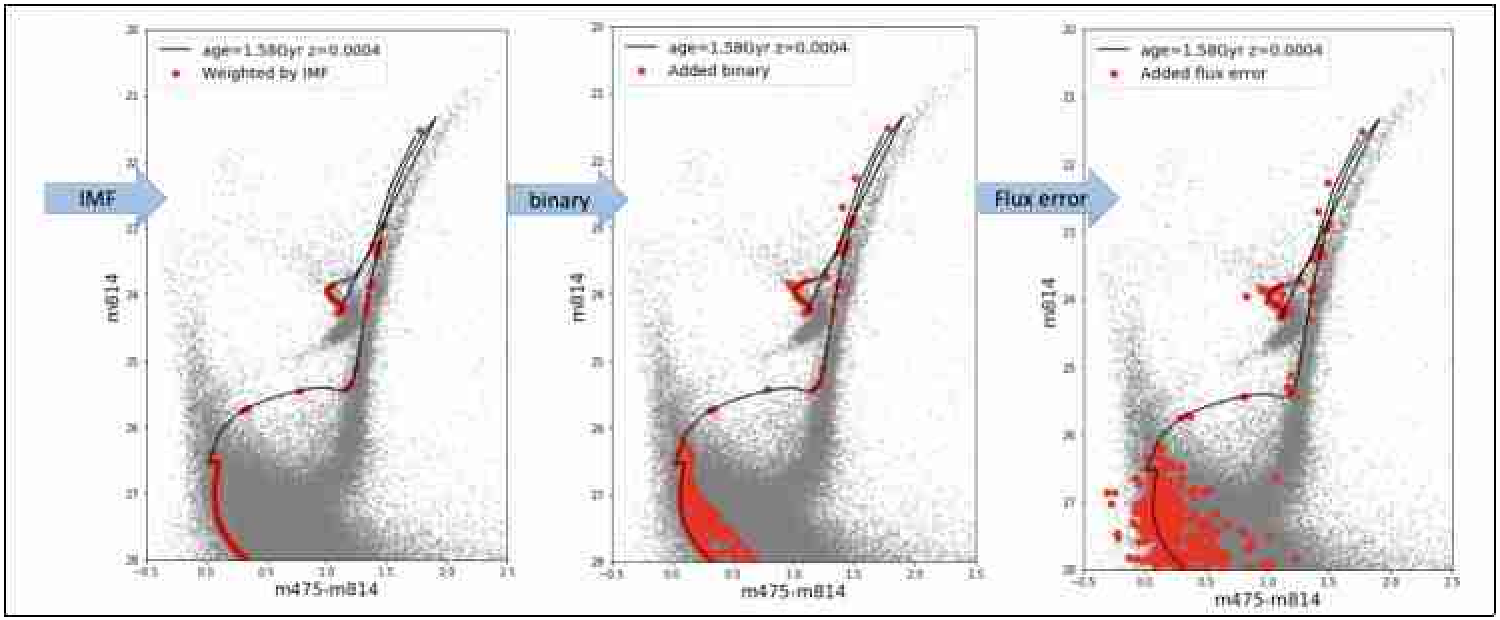
Some practical applications: dIIr DDO 210

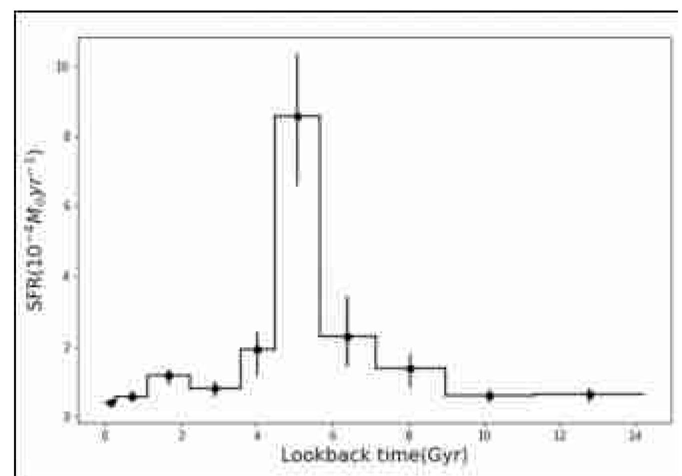


Gas dynamics and star formation in dwarfs: DDO 210



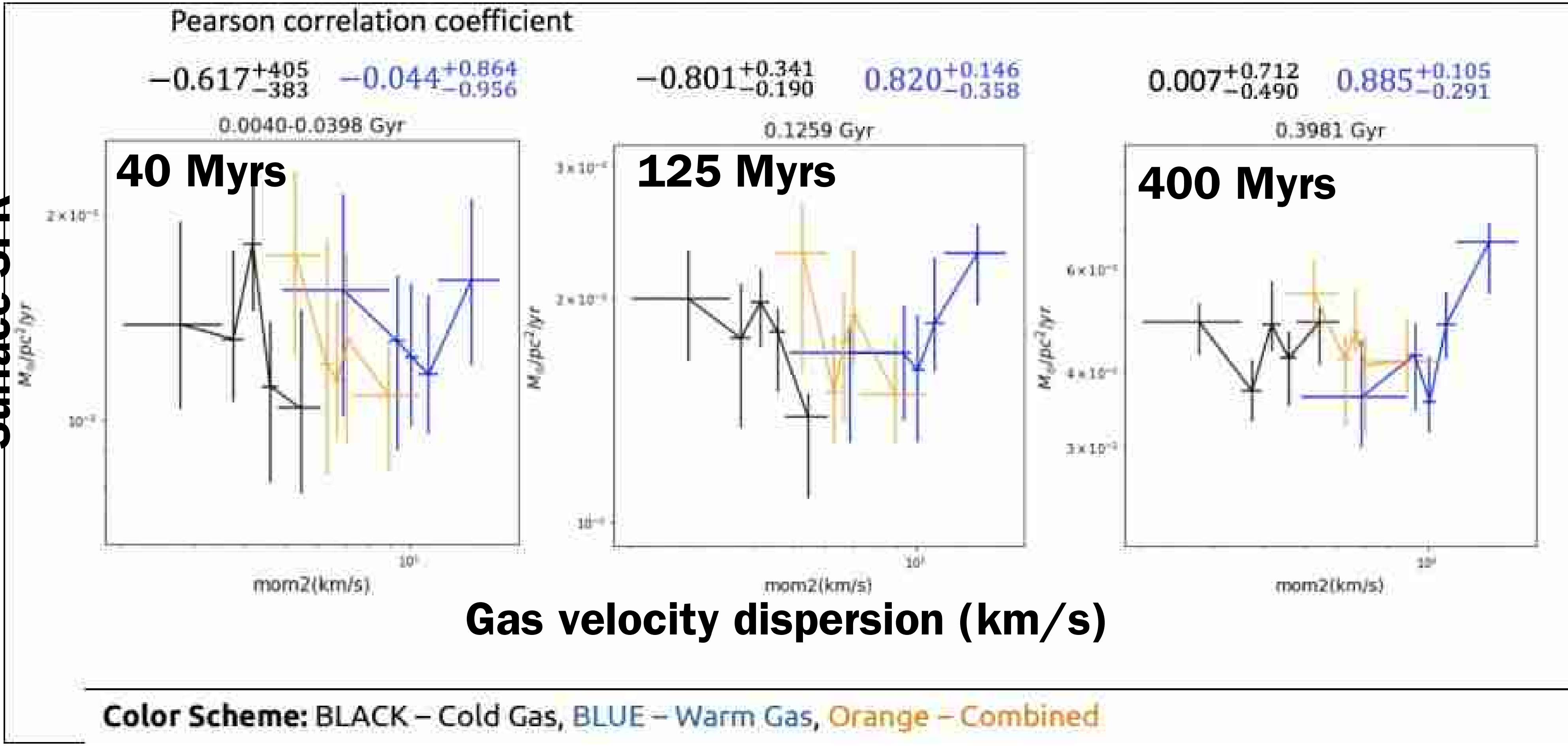
Gas dynamics and star formation in dwarfs: DDO 210





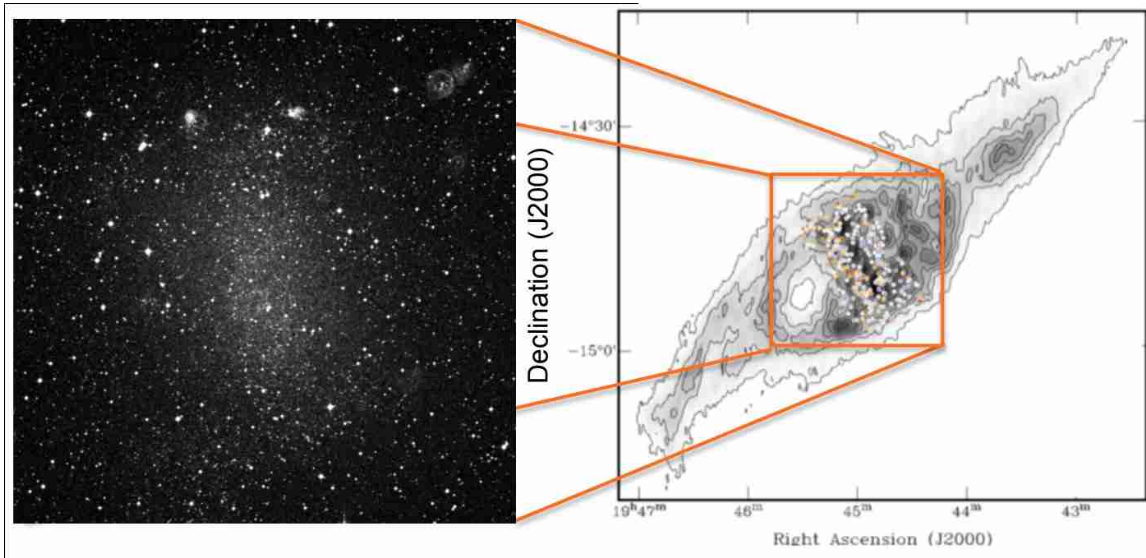
Gas dynamics and star formation in dwarfs: DDO 210

(Yun et al. in prep. at PhD project at Peking Univ.)

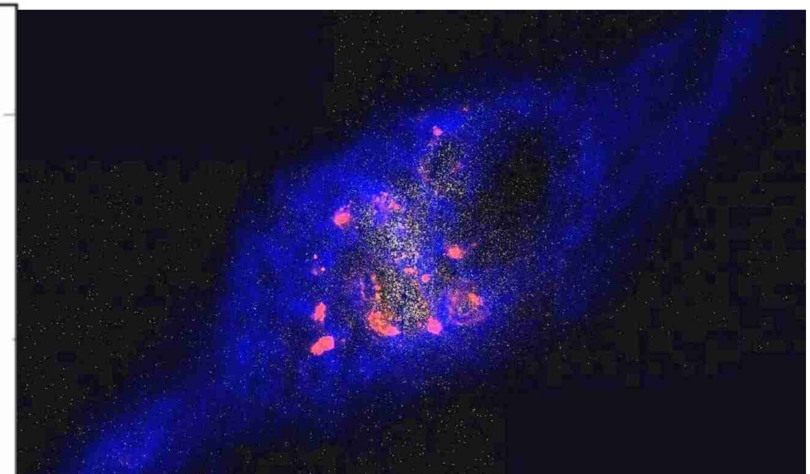


Gas dynamics and star formation in dwarfs: NGC 6822

(Park et al. in prep., MSc project at Sejong)



(de Blok & Walter 2000)

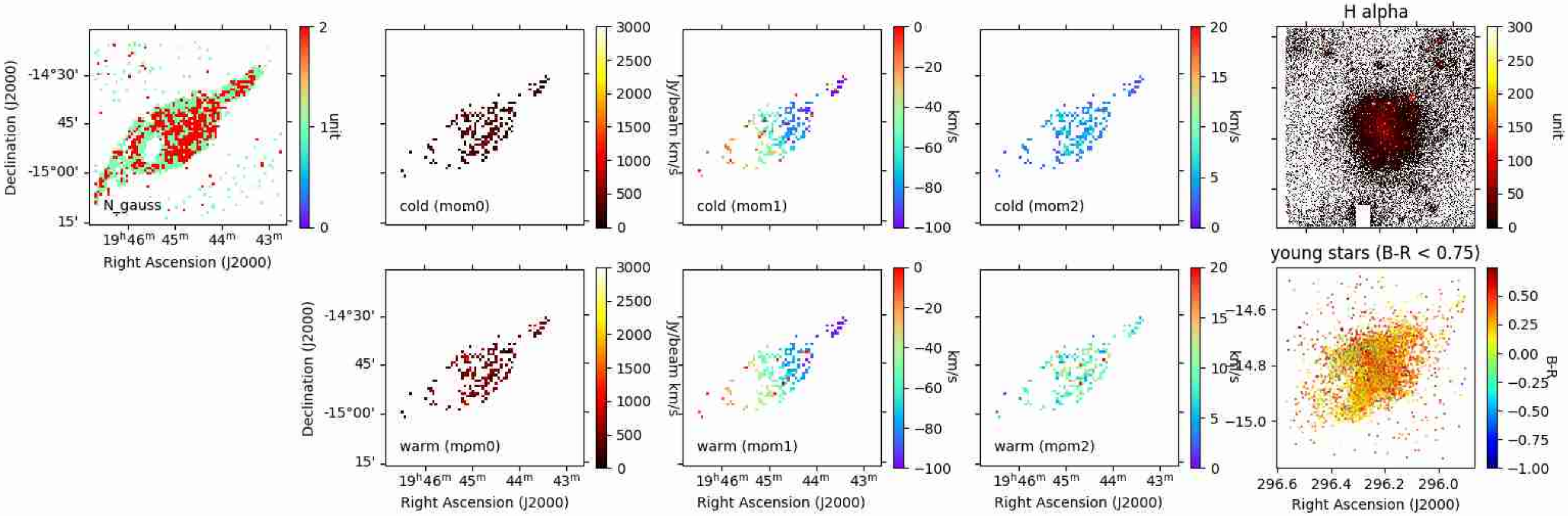


- A dIrr in the local Group at a distance of ~490 kpc
- HI 21cm: 8 pointings mosaic with the ATCA (42” x 12”: ~100 pc GMC scale, 1.6 km/s, de Blok et al. 2002)

  → Hanning smoothed and regridded to 48” to minimize the galactic contamination and ensure every spaxel contains an independent profile
- Optical and H-alpha: Subaru 8m + Issac Newton telescopes (de Blok et al. 2006)
- + HST optical data

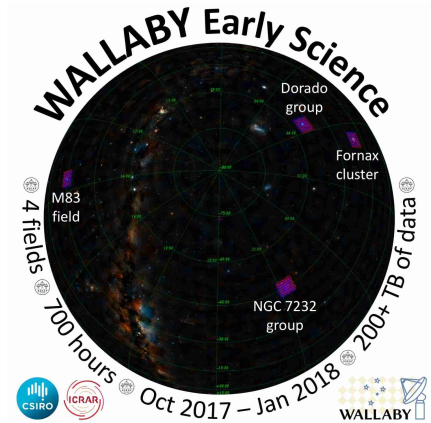
Gas dynamics and star formation in dwarfs: NGC 6822

(Park et al. in prep., MSc project at Sejong)



SKA data already in hand:

ASKAP Early Science Observations → Now, pilot observations underway!



- ~100 hours of full-ASKAP time assigned to the Pilot survey phase
- 3 high priority fields: Hydra cluster, NGC 4636 group, Norma cluster
- The square 6x6 tiles ~ 5.4 x 5.4 deg^2 FOV
- 1152 ~ 1440 MHz (288 MHz bandwidth)
- 30”x30” beams, 4 km/s, Tsys~70 K, ~16 hours of on-source integration, ~1.7 mJy/beam

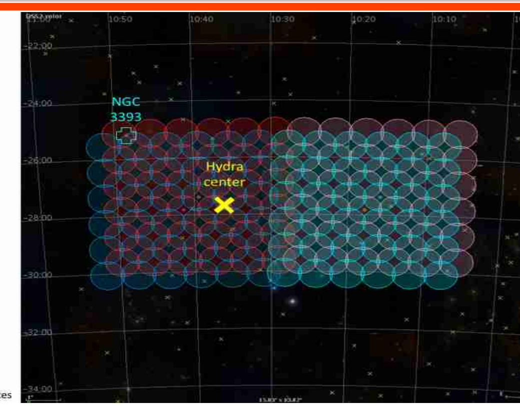
Hydra Cluster

WALLABY_1013-26
WALLABY_1037-26
(tiles 447 & 448)

footprint A
10:15:47.844, -27:22:27.66
rotation: -0.004 deg
10:39:24.238, -27:22:27.66
rotation: -0.004 deg

footprint B
10:17:49.958, -27:49:24.30
rotation: -0.24 deg
10:41:26.352, -27:49:24.30
rotation: -0.24 deg

green x's = HIPASS sources



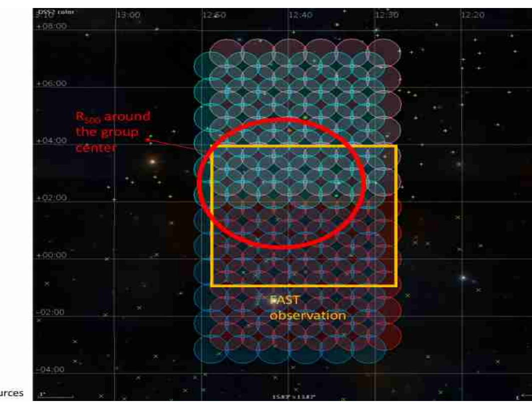
NGC4636 group

WALLABY_1236-00
WALLABY_1236+05
(tiles 714 & 781)
with 4 arcsec RA shift

footprint A
12:38:02.328, -00:26:59.95
rotation: 0 deg
12:38:02.729, 04:56:58.64
rotation: +0.001 deg

footprint B
12:39:50.337, -00:53:59.85
rotation: -0.01 deg
12:39:51.059, 04:29:58.13
rotation: +0.04 deg

green x's = HIPASS sources



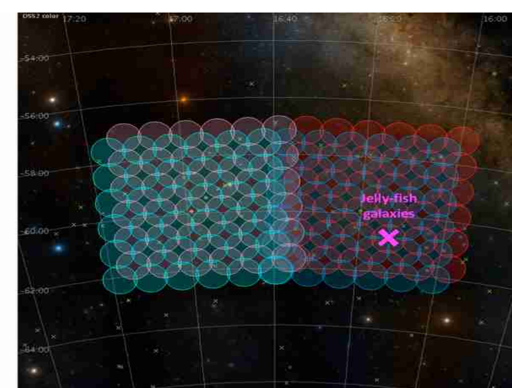
Norma Cluster

WALLABY_1612-59
WALLABY_1651-59
(tiles 107 & 108)

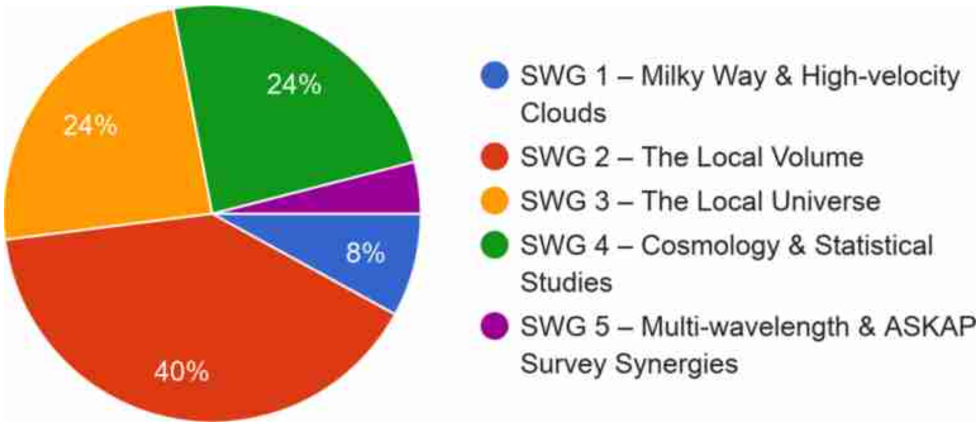
footprint A
16:16:30.928, -59:27:41.88
rotation: -0.013deg
16:55:26.063, -59:27:41.88
rotation: -0.013deg

footprint B
16:20:06.332, -59:54:30.90
rotation: -0.77 deg
16:59:01.467, -59:54:30.90
rotation: -0.77 deg

green x's = HIPASS sources



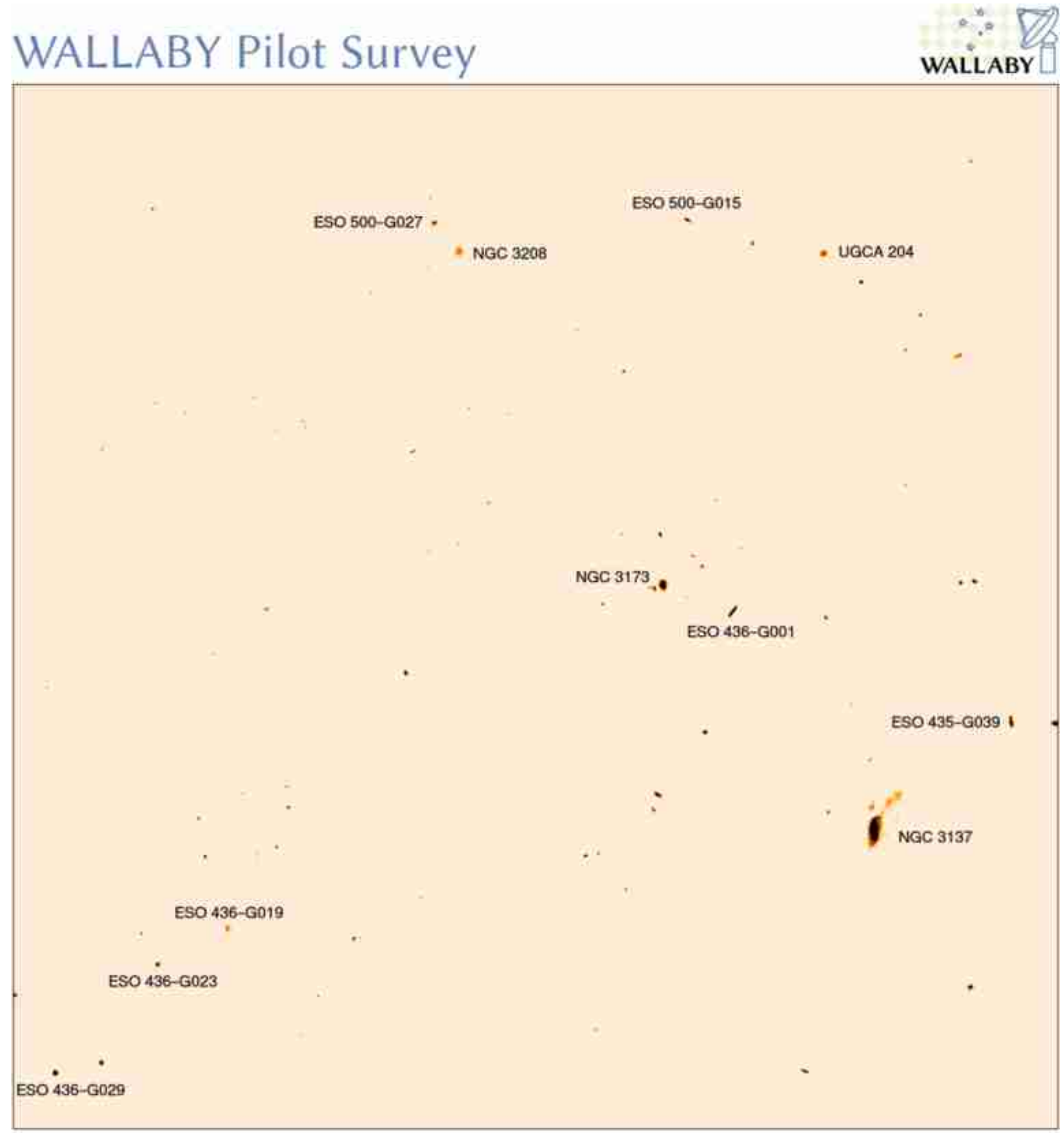
WALLABY (ASKAP HI all-sky galaxy survey) pilot survey



- 23 paper proposals for WALLABY pilot observations (SWG1 ~ 5)

  → HI properties of galaxy pairs in cluster and group environment via profile decomposition (Oh et al.)

  : to see how the cold/warm/hot gas are affected by the merging process and global cluster environment



Neutral hydrogen emission from the Hydra cluster