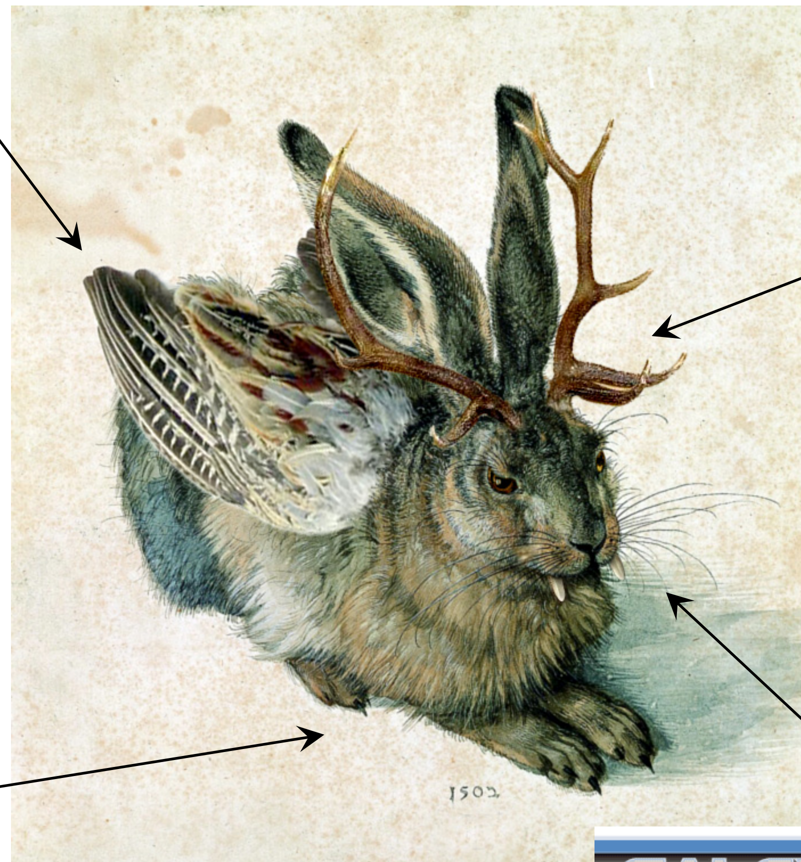
Massive Star Formation in THINGS++

THINGS
The HI Nearby Galaxy Survey



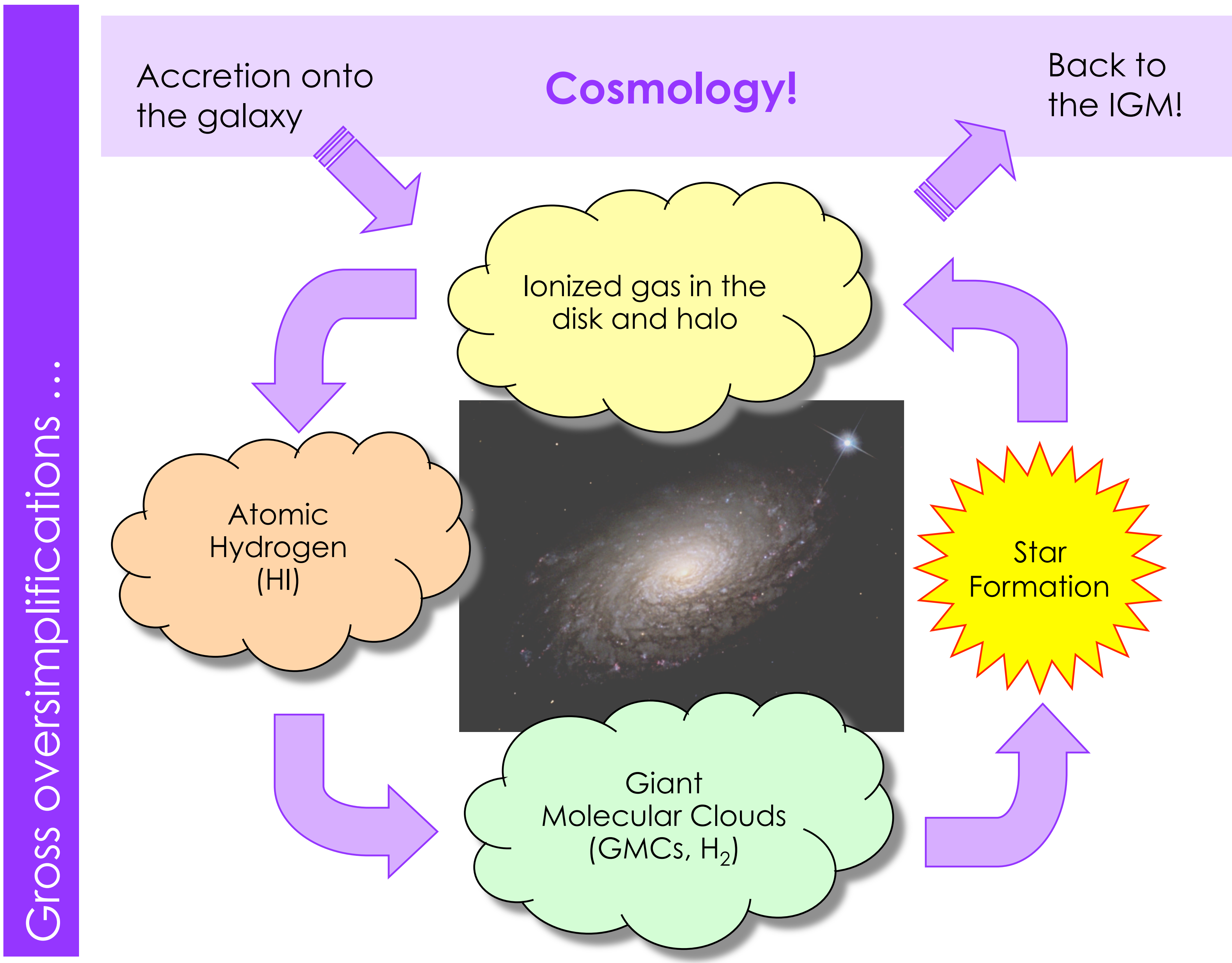
Pretty much just the sum of its parts…

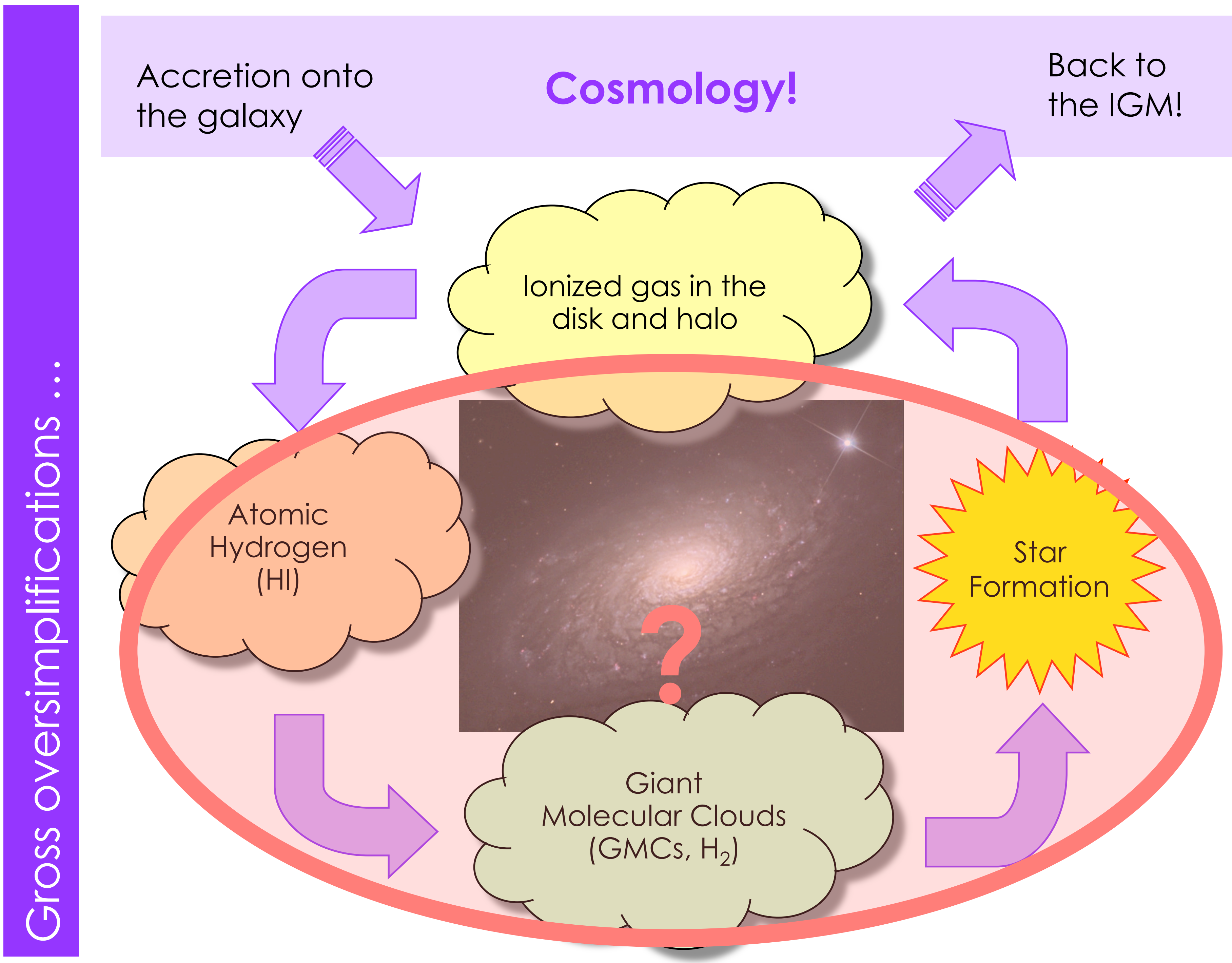
SINGS - SPITZER INFRARED NEARBY GALAXIES SURVEY

HERACLES

GALEX Galaxy Evolution Explorer

Adam Leroy
Fabian Walter (THINGS PI) & Frank Bigiel (Thesis)
Max Planck Institute for Astronomy, Heidelberg


Gross oversimplifications …
Accretion onto the galaxy
Cosmology!
Back to the IGM!
Ionized gas in the disk and halo
Atomic Hydrogen (HI)
Star Formation
Giant Molecular Clouds ($GMCs$, H_2)



Gross oversimplifications . . .
Accretion onto the galaxy
Cosmology!
Back to the IGM!
Ionized gas in the disk and halo
Atomic Hydrogen (HI)
Star Formation
?
Giant Molecular Clouds (GMCs, H_2)

Star Formation **Laws** & **Thresholds** ...

Review: McKee & Ostriker '07

Atomic Hydrogen

Large-scale collapse is possible gravity > kinetic energy & Coriolis forces (e.g. Toomre '64, Kennicutt '89, Martin & Kennicutt '01, Rafikov '01, Yang+ 07)

Instabilities aided by B-fields, grow into GMCs **before shear disperses them** (e.g. Elmegreen '93, Hunter '98, Kim & Ostriker '01)

Where a **cold ISM phase** is abundant high density fluctuations have little kinetic support (e.g. Elmegreen & Parravano '94, Schaye '04, de Blok & Walter '06)

Giant Molecular Clouds

Thresholds: Where?

Giant Molecular Clouds

unstable gas collapses directly to form stars over a **disk free-fall time** (i.e. a "Kennicutt-Schmidt law")

Properties of Individual GMCs e.g., cloud free fall time/density (e.g. Krumholz & McKee '05)

balance between ISM phase set by **pressure**, limits SFR (e.g. Elmegreen & Parravano '94, Wolfire '03 Wong & Blitz '02, Blitz & Rosolowsky '04,'06)

Rate of collisions between bound clouds (e.g. Wyse & Silk '87, Tan '00)

Star Formation

"Laws": How fast?

Method/Madness…

1. Formulate star formation recipes from the literature as predictions of **star formation efficiency** (SFE)

$$\mathrm{SFE} = \frac{\Sigma_{\mathrm{SFR}}}{\Sigma_{\mathrm{Gas}}}$$

Star formation rate normalized by gas.

How effective is a given parcel of ISM at turning itself into stars?

Convolves timescale and true efficiency.

or H_2-to-HI ratio:

$$R_{\mathrm{mol}} = \frac{\Sigma_{\mathrm{H2}}}{\Sigma_{\mathrm{HI}}}$$

Measures the phase of the ISM.

In simplified equilibrium between phases: ratio of H_2 creation to destruction.

2. Measure the SFE…

3. Measure the quantities that drive the predictions…

This will be on the test.

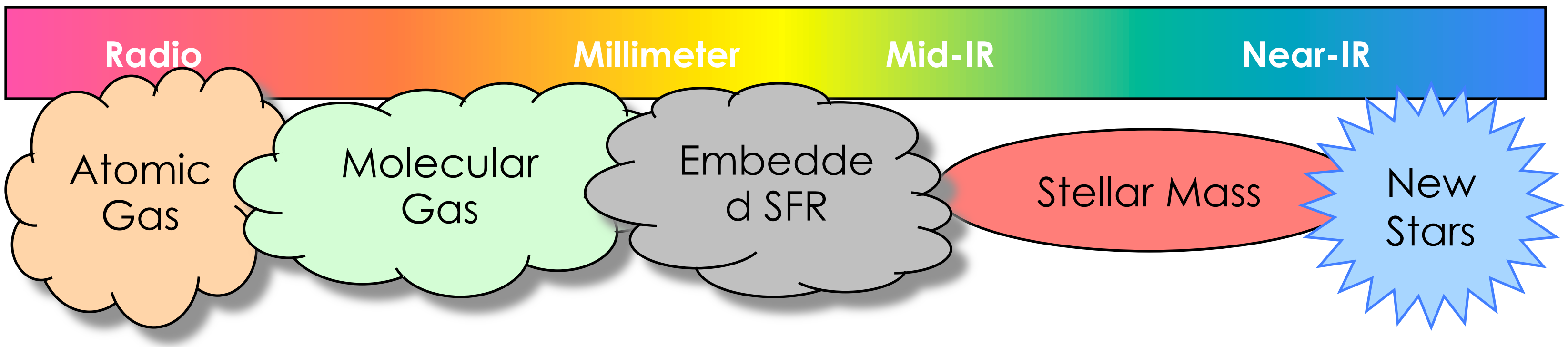
Predictions for SFE and R_{mol}

Theory	Form	Observables
Star Formation Laws		
Disk free–fall time		
. . . fixed scale height	$SFE \propto \Sigma_{gas}^{0.5}$	Σ_{gas}
. . . variable scale height	SFE or $R_{mol} \propto \frac{\Sigma_{gas}}{\sigma_g} \left(1 + \frac{\Sigma_*}{\Sigma_{gas}} \frac{\sigma_g}{\sigma_*}\right)^{0.5}$	$\Sigma_{gas}, \Sigma_*, \sigma_g, \sigma_*$
fixed GMC efficiency	$SFE = SFE\,(H_2) \frac{R_{mol}}{R_{mol}+1}$	Σ_{H2}
orbital timescale	SFE or $R_{mol} \propto \tau_{orb}^{-1} = \frac{v(r_{gal}}{2\pi r_{gal}}$	$v(r_{gal})$
cloud-cloud collisions	$SFE \propto \tau_{Dyn}^{-1}\ Q_{gas}^{-1}\ (1 - 0.7\ \beta)$	$v(r_{gal})$
Equilibrium H_2-to-H I	$R_{mol} \propto \left(\Sigma_{gas}\ \left(\Sigma_{gas} + \frac{\sigma_g}{\sigma_*}\Sigma_*\right)\ P_0^{-1}\right)^{1.1}$	$\Sigma_{gas}, \Sigma_*, \sigma_g, \sigma_*$
Star Formation Thresholds		
gravitational instability		
. . . in the gas disk	$Q_{gas} = \left(\frac{\sigma_g\ \kappa}{\pi\ G\ \Sigma_{gas}}\right) < 1$	$\Sigma_{gas}, \sigma_g, v(r_{gal})$
. . . in a two component disk	$Q_{stars+gas} = \left(\frac{2}{Q_{stars}} \frac{q}{1+q^2} + \frac{2}{Q_{gas}}\ R\ \frac{q}{1+q^2R^2}\right)^{-1} < 1$	$\Sigma_{gas}, \Sigma_*, \sigma_g, \sigma_*, v(r_{gal})$
competition with shear	$\Sigma_{gas} > \frac{2.5\ A\ \sigma_g}{\pi\ G}$	$\Sigma_{gas}, \sigma_g, v(r_{gal})$
thermal instability		
. . . critical column density	$\Sigma_{gas} \gtrsim 10\ M_\odot\ pc^{-2}$	Σ_{gas}
. . . Schaye (2004) model	$\Sigma_{gas} > 6.1\ M_\odot\ pc^{-2}\ f_g^{0.3}\ Z^{-0.3}\ I^{0.23}$	$\Sigma_{gas}, \Sigma_*, Z, I$

THINGS we want.

What we need to do this…

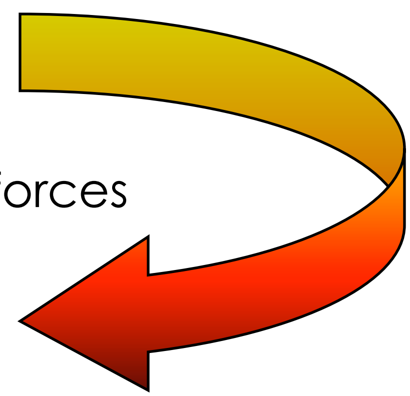
- Data at a wide variety of wavelengths:



- Kinematic information:

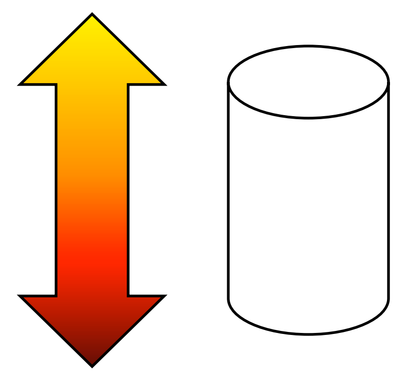
Rotation:

- Coriolis forces
- Shear

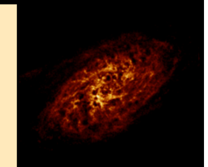
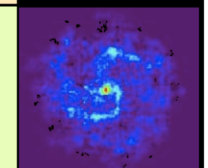
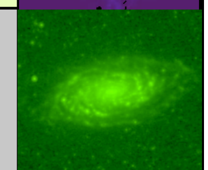
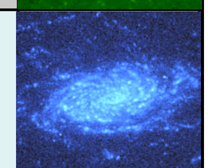
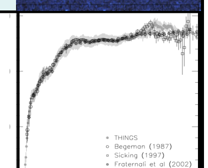
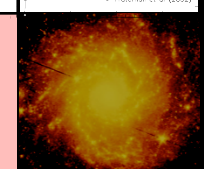


Dispersions:

- Map column into local conditions.
- Support against collapse.



EveryTHINGS we have…

Physical Quantity	Source	Data Set	
Atomic Gas	VLA 21cm line maps	THINGS Walter+ '08	
Molecular Gas	HERACLES CO 2-1 maps	HERA Atlas Leroy+ '08	
New Stars: Obscured by Dust	*Spitzer* 24 μm maps	SINGS Kennicutt+ '03	
New Stars: Unobscured	GALEX FUV maps	GALEX NGS Gil de Paz+ '07	
Kinematics	VLA 21cm line cubes	THINGS rot. curves de Blok+ '08	
Stellar Disk	*Spitzer* 3.6 μm maps	SINGS Kennicutt+ '03	

THINGS & HERACLES

The HI Nearby Galaxy Survey

www.mpia.de/THINGS

Walter et al. (2008)

- NRAO large program ('03-'06) to map 21cm emission
- high resolution, sensitive VLA maps of 34 mostly SINGS galaxies
- Cubes and maps publicly available on the web!

F. Walter (MPIA)
R. Kennicutt (Cambridge)
E. Brinks (Hertfordshire)
M. Thornley (Bucknell)
E. de Blok (Cape Town)
F. Bigiel (MPIA)

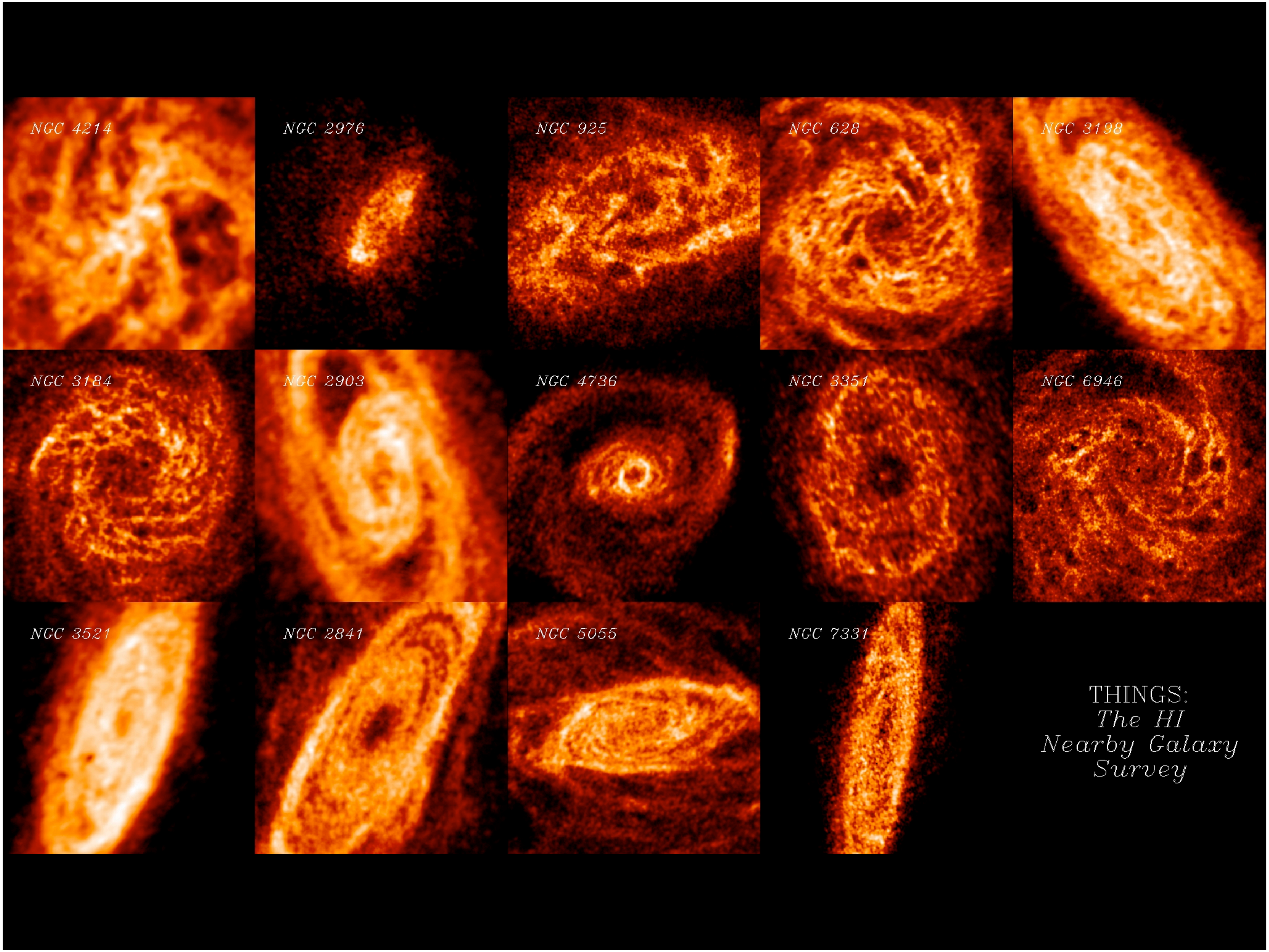
The HERA CO-Line Extragalactic Survey

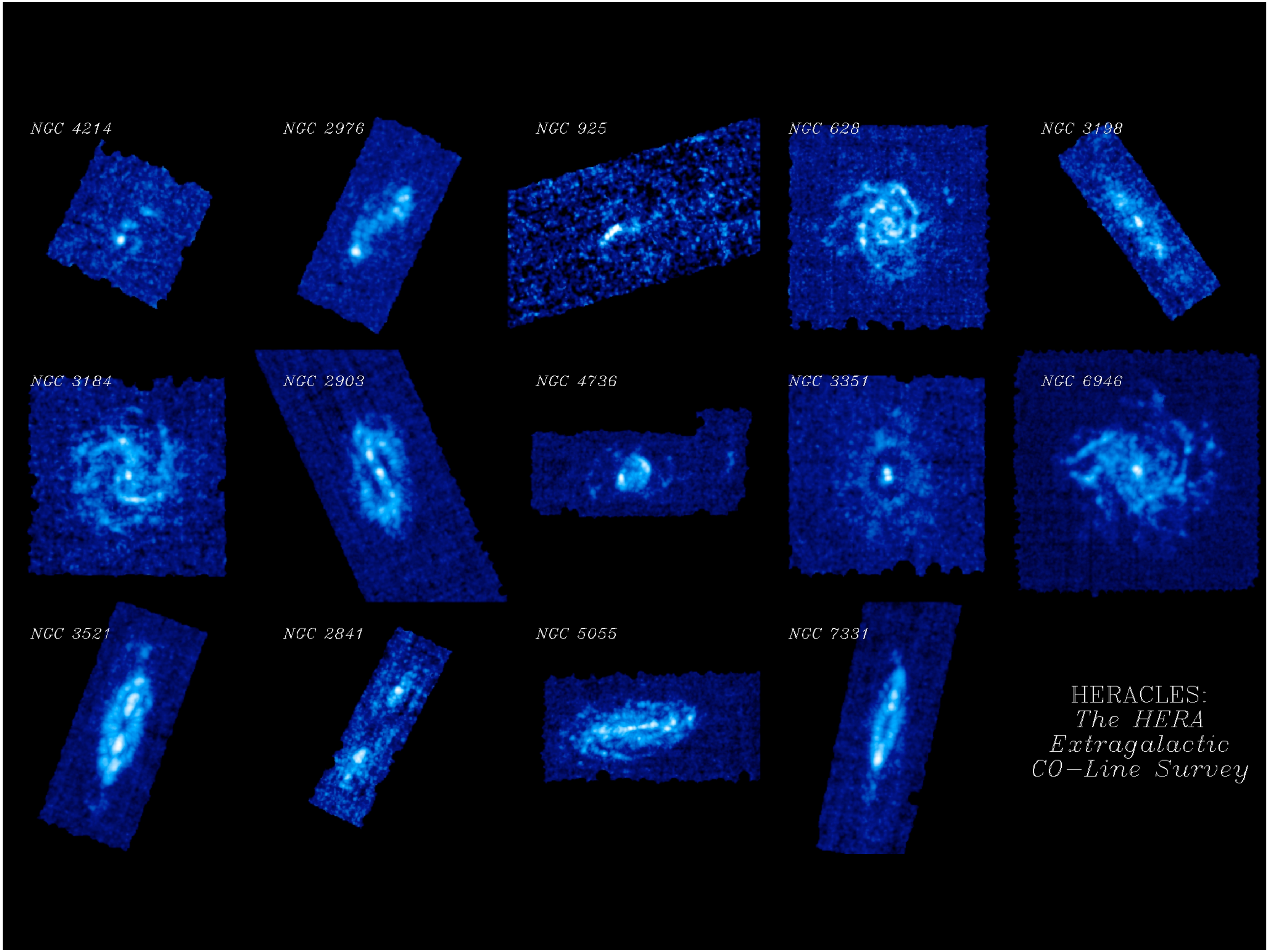
HERACLES

Leroy et al. (2008)

- ~250h using the IRAM 30m to map CO J = 2→1
- 11", wide-field (~ r_{25}), sensitive maps of 18 THINGS galaxies.
- HERA (Schuster+ '04): 9-pixel, 2-polarization receiver array.

THINGS + A. Usero Hertfordshire
C. Kramer (IRAM)
A. Weiss(MPIfR)
H. Wiesemeyer (IRAM)
K. Schuster (IRAM)
H. Roussel (IAP)


NGC 4214
NGC 2976
NGC 925
NGC 628
NGC 3198
NGC 3184
NGC 2903
NGC 4736
NGC 3351
NGC 6946
NGC 3521
NGC 2841
NGC 5055
NGC 7331
THINGS:
The HI
Nearby Galaxy
Survey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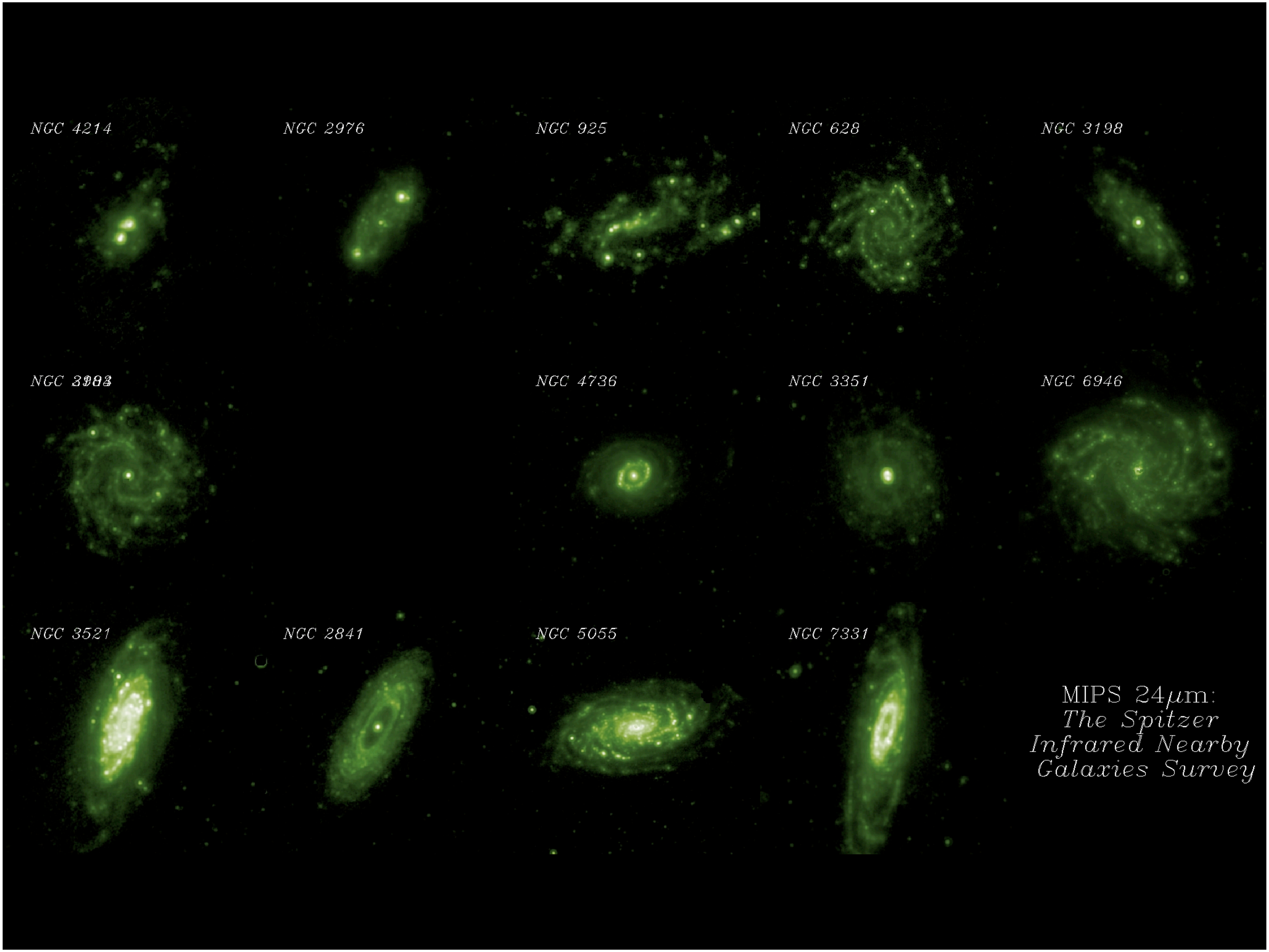

NGC 4214
NGC 2976
NGC 925
NGC 628
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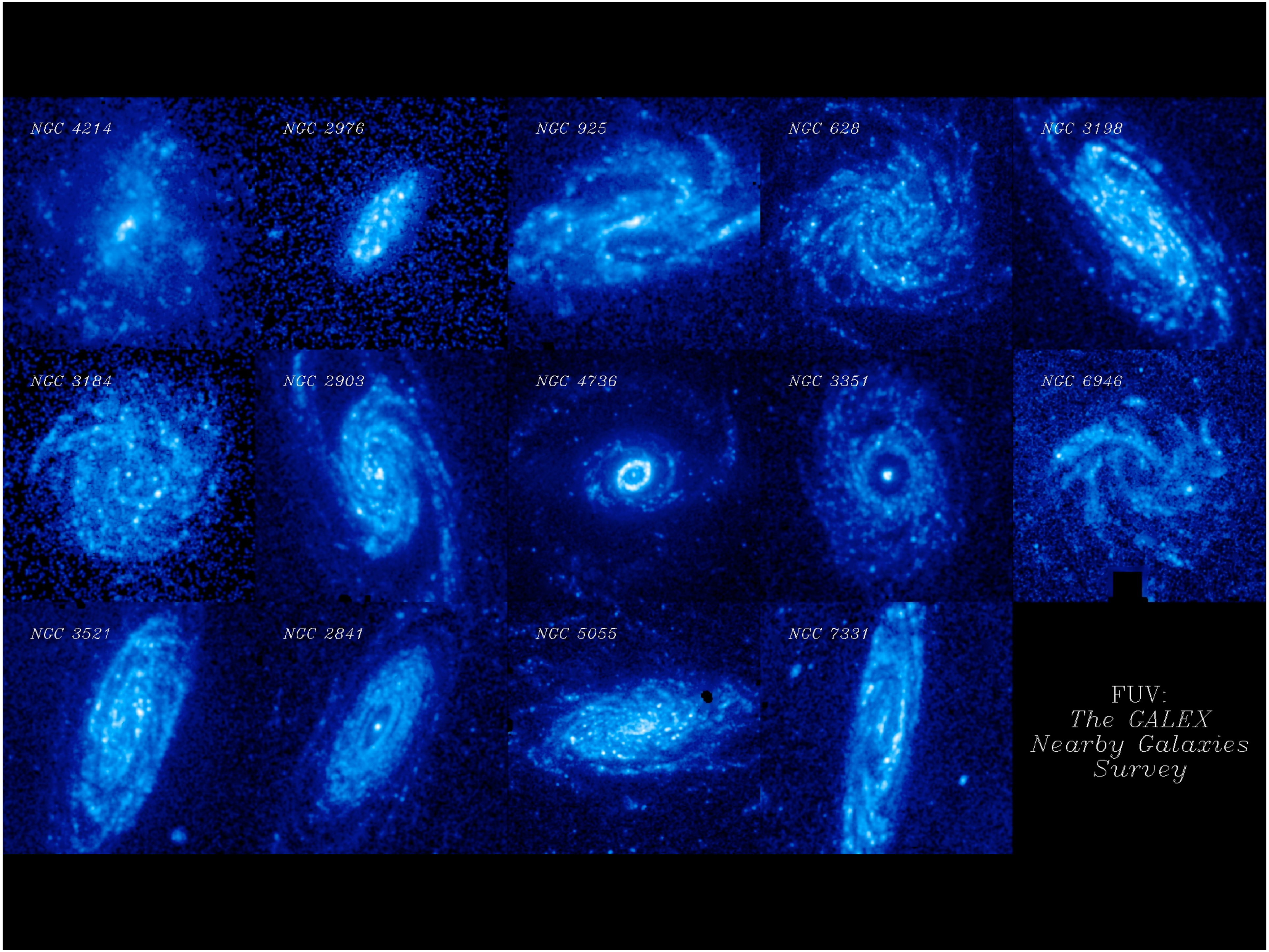
NGC 3351
NGC 6946
NGC 3521
NGC 2841
NGC 5055
NGC 7331
MIPS 24μm:
The Spitzer
Infrared Nearby
Galaxies Survey


NGC 4214
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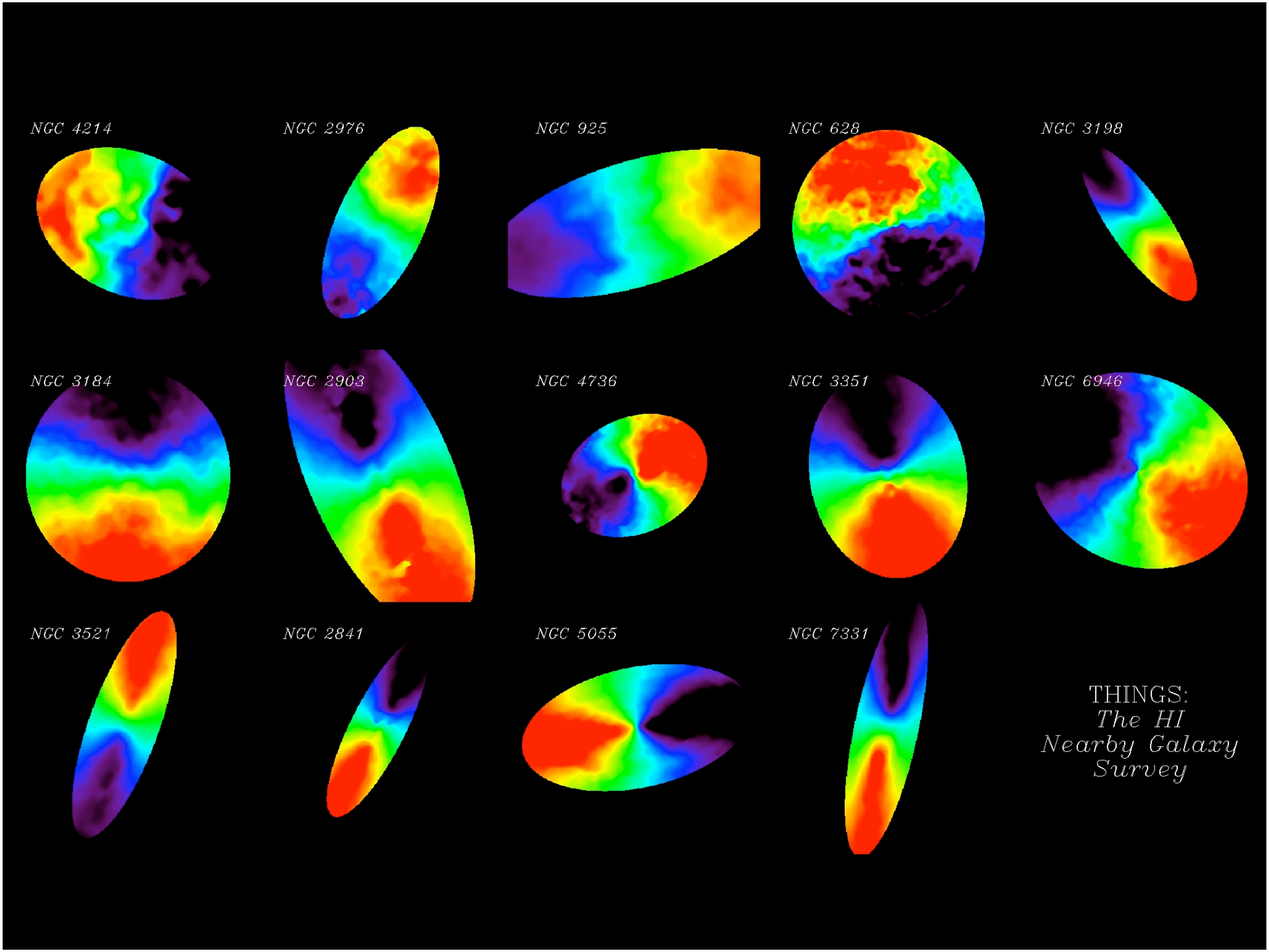
NGC 2903
NGC 4736
NGC 3351
NGC 6946
NGC 3521
NGC 2841
NGC 5055
NGC 7331
FUV:
The GALEX
Nearby Galaxies
Survey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THINGS:
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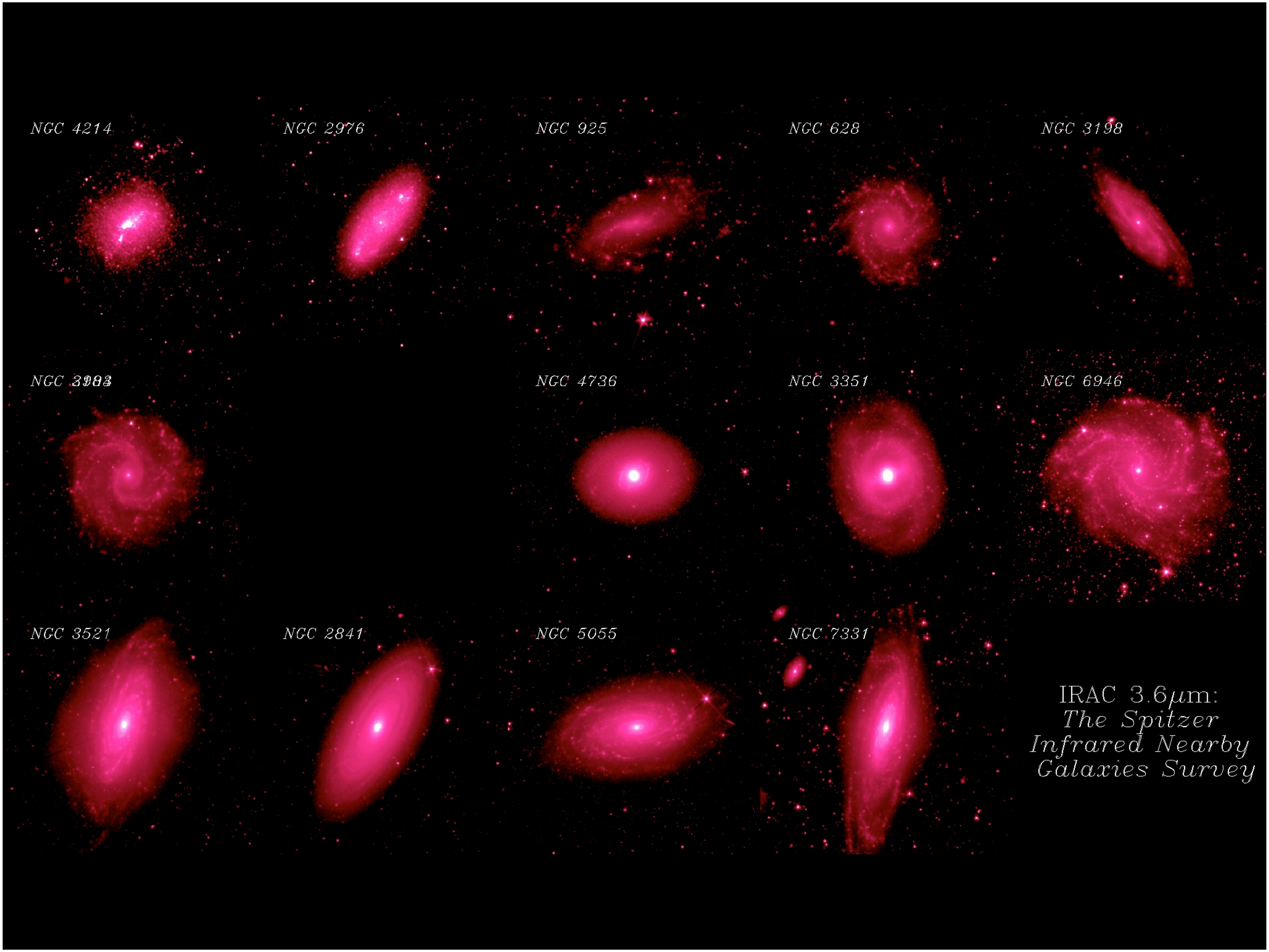
Survey


NGC 4214
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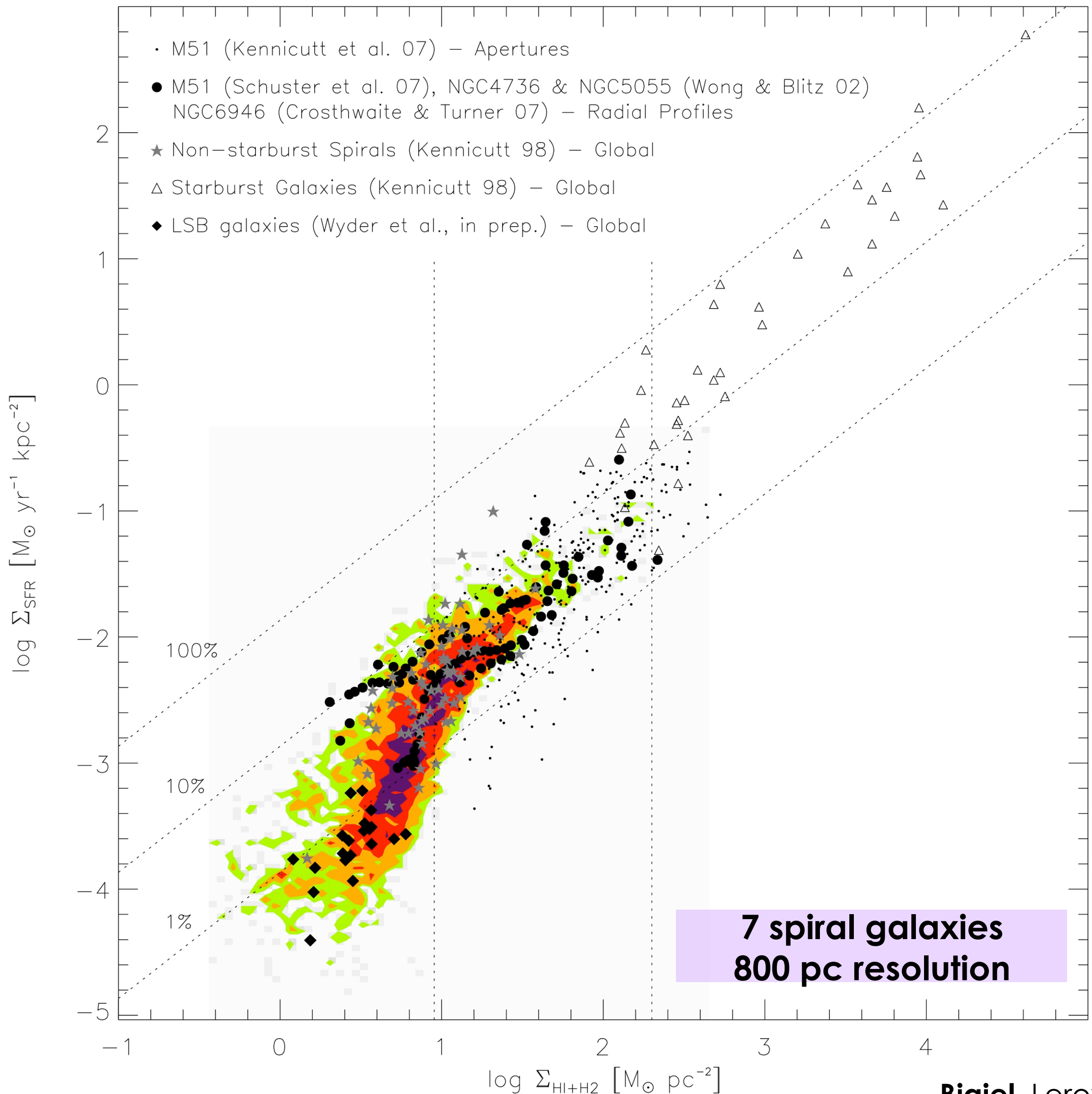
NGC 3351
NGC 6946
NGC 3521
NGC 2841
NGC 5055
NGC 7331
IRAC 3.6μm:
The Spitzer
Infrared Nearby
Galaxies Survey

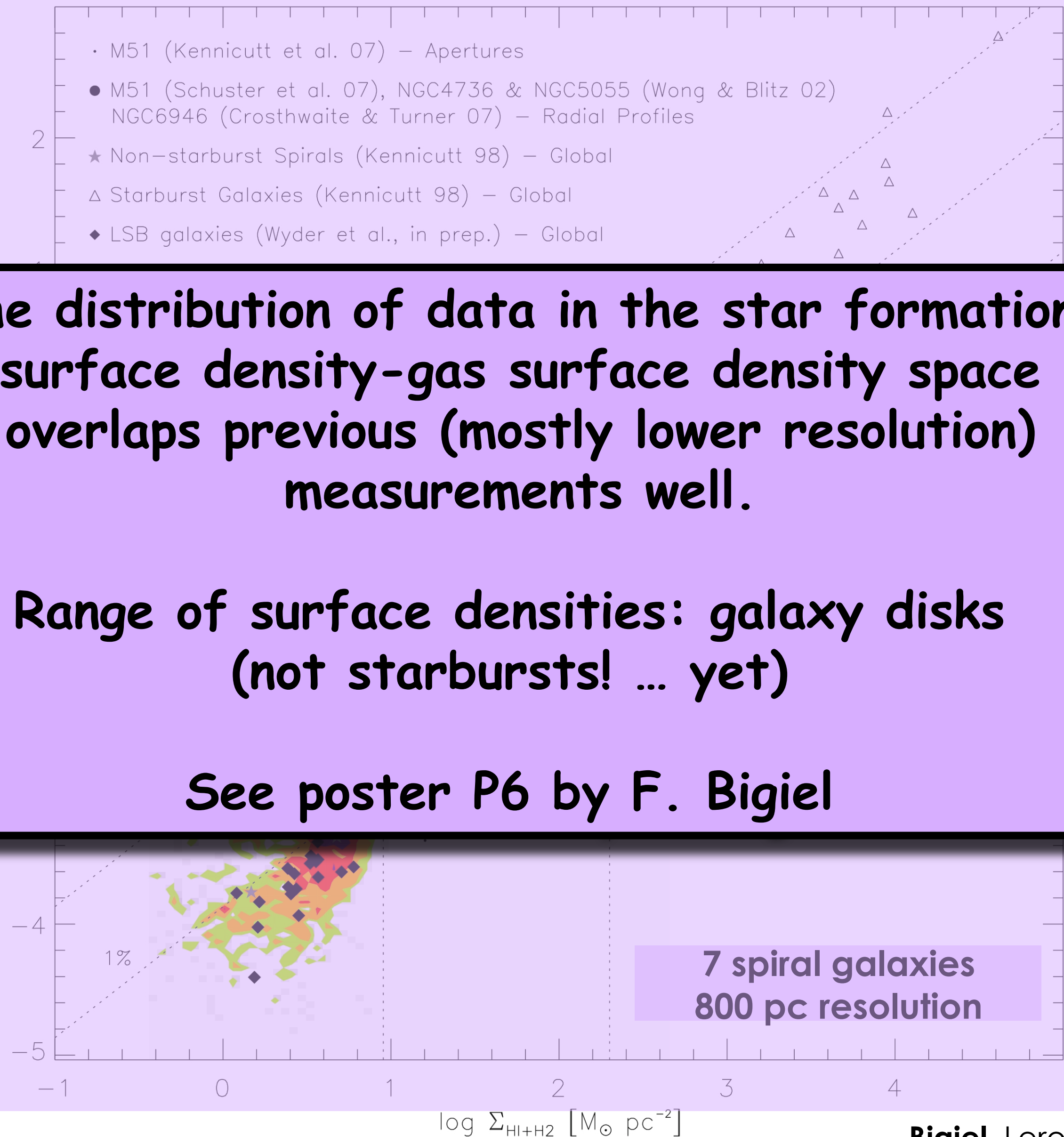
First THINGS first.

The Basic Plot: SFR vs. Gas



Bigiel, Leroy, Walter, et al. 2008

The Basic Plot: SFR vs. Gas



The distribution of data in the star formation surface density-gas surface density space overlaps previous (mostly lower resolution) measurements well.

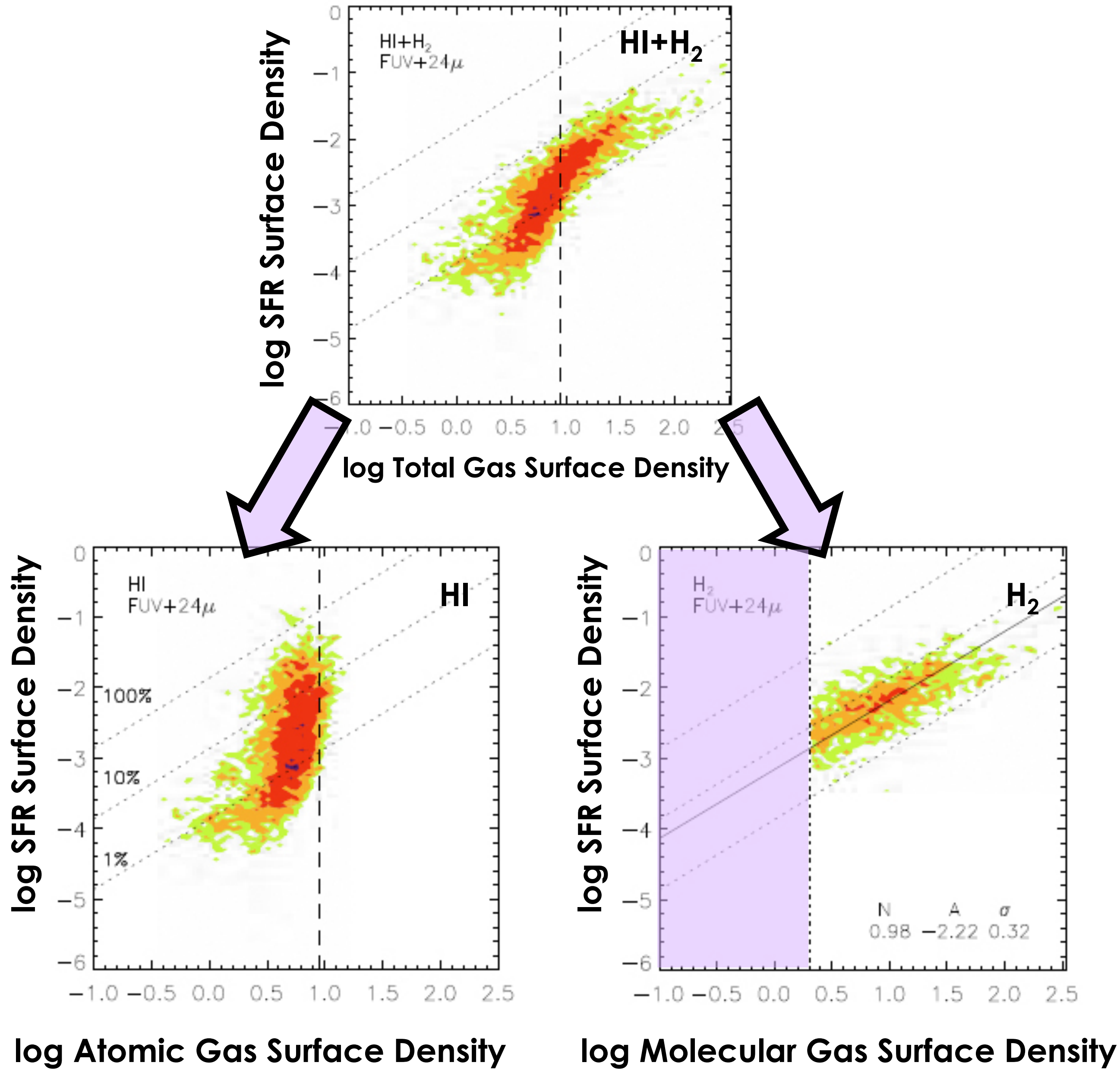
Range of surface densities: galaxy disks (not starbursts! … yet)

See poster P6 by F. Bigiel

Bigiel, Leroy, Walter, et al. 2008

First THINGS first.

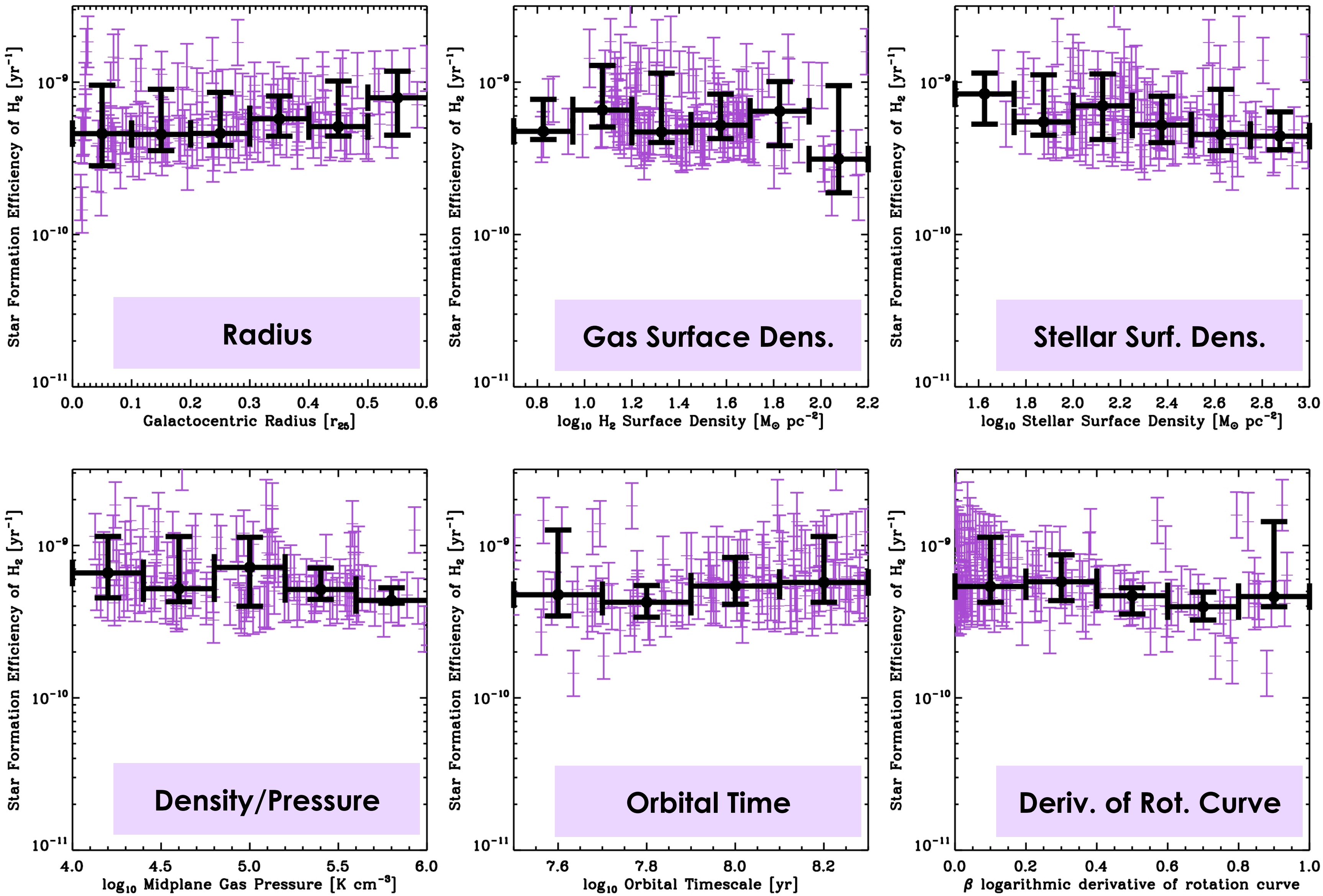
These two THINGS aren't the same.



Bigiel, Leroy, Walter et al. 2008

SFE (H_2) vs. Environment

SFE (H_2) is *constant* as a function of …

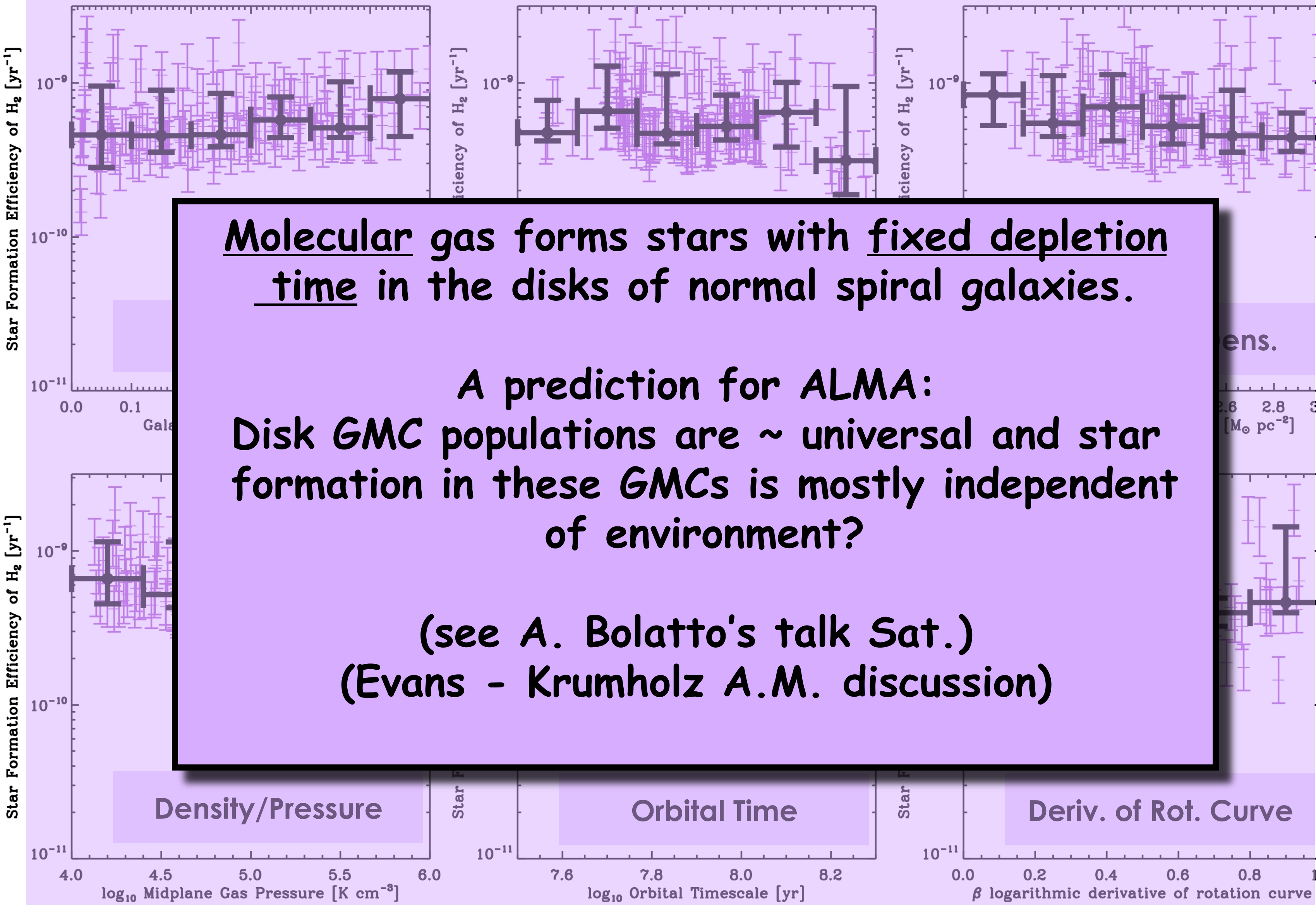


12 spiral galaxies : data points = 10" tilted rings

Leroy, Walter et al. 2008

SFE (H_2) vs. Environment

SFE (H_2) is *constant* as a function of …



Molecular gas forms stars with fixed depletion time in the disks of normal spiral galaxies.

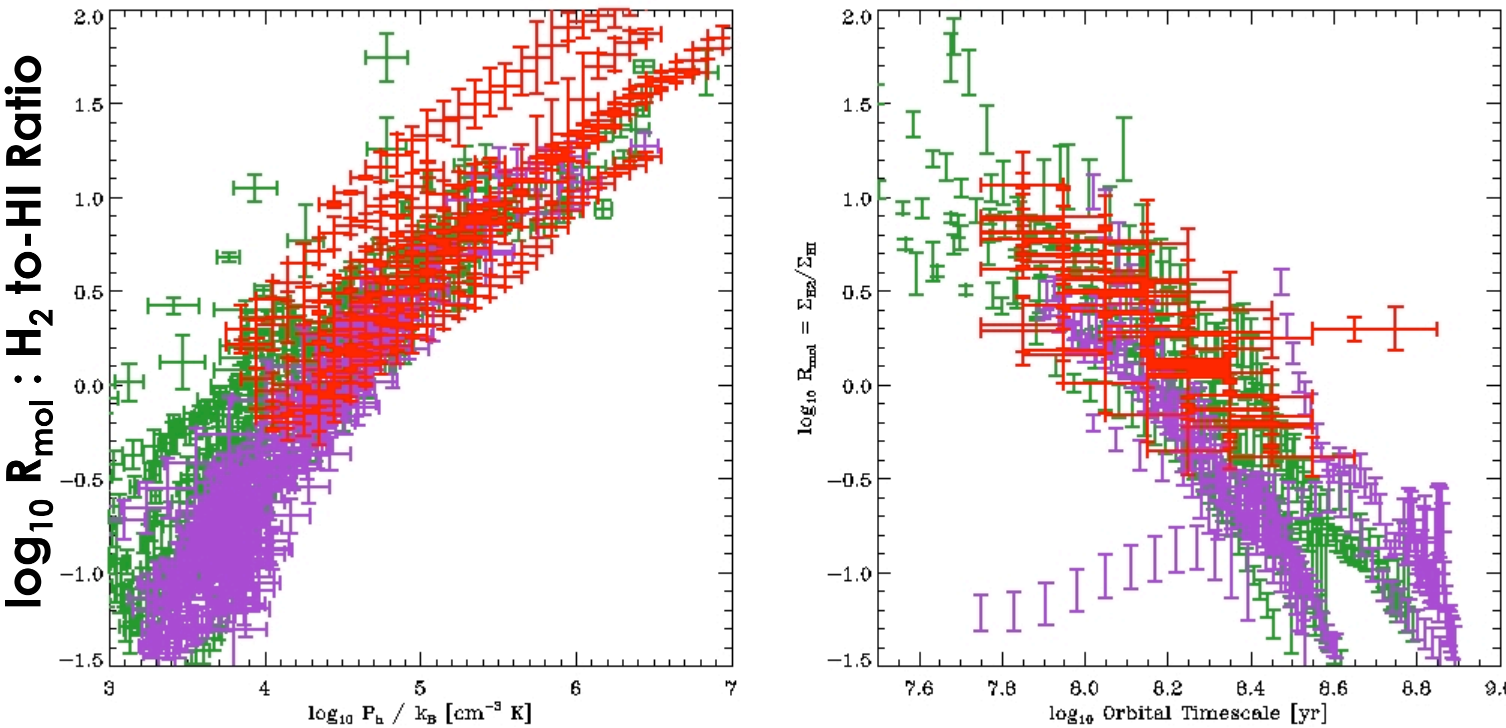
A prediction for ALMA:
Disk GMC populations are ~ universal and star formation in these GMCs is mostly independent of environment?

(see A. Bolatto's talk Sat.)
(Evans - Krumholz A.M. discussion)

12 spiral galaxies : data points = 10" tilted rings

R_{mol} vs. Environment

R_{mol} (H_2/HI) vs. Environment



Pressure, Density, Disk Free Fall Time

Orbital Time

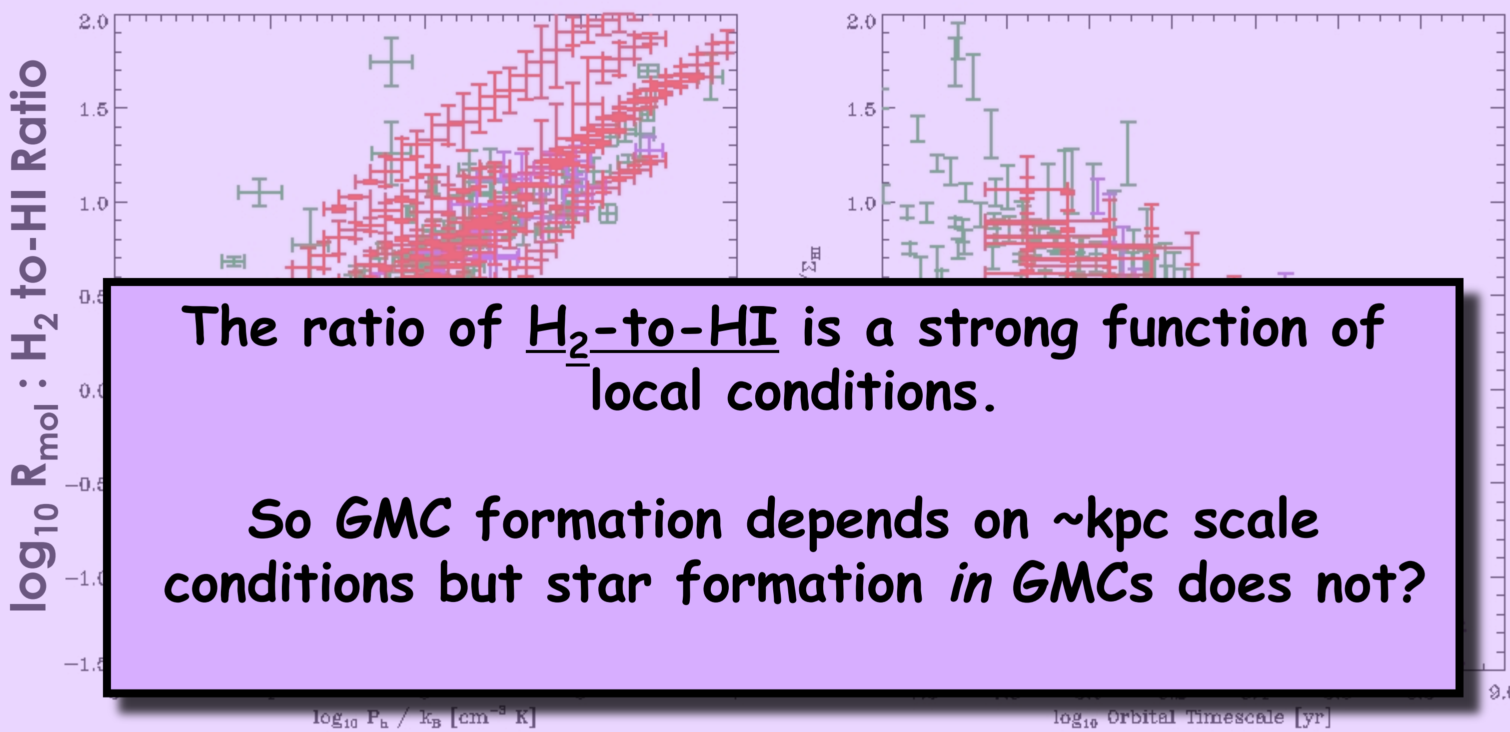
Spirals: binned pixel-by-pixel data
Spirals: tilted rings - R_{mol} from SFR/HI
Dwarfs: tilted rings - R_{mol} from SFR/HI

q.v., Wong & Blitz ‘02
Blitz & Rosolowsky ‘06

12 spiral galaxies

Leroy, Walter et al. 2008

R_{mol} (H_2/HI) vs. Environment



The ratio of <u>H_2-to-HI</u> is a strong function of local conditions.

So GMC formation depends on ~kpc scale conditions but star formation *in* GMCs does not?

Pressure, Density, Disk Free Fall Time

Orbital Time

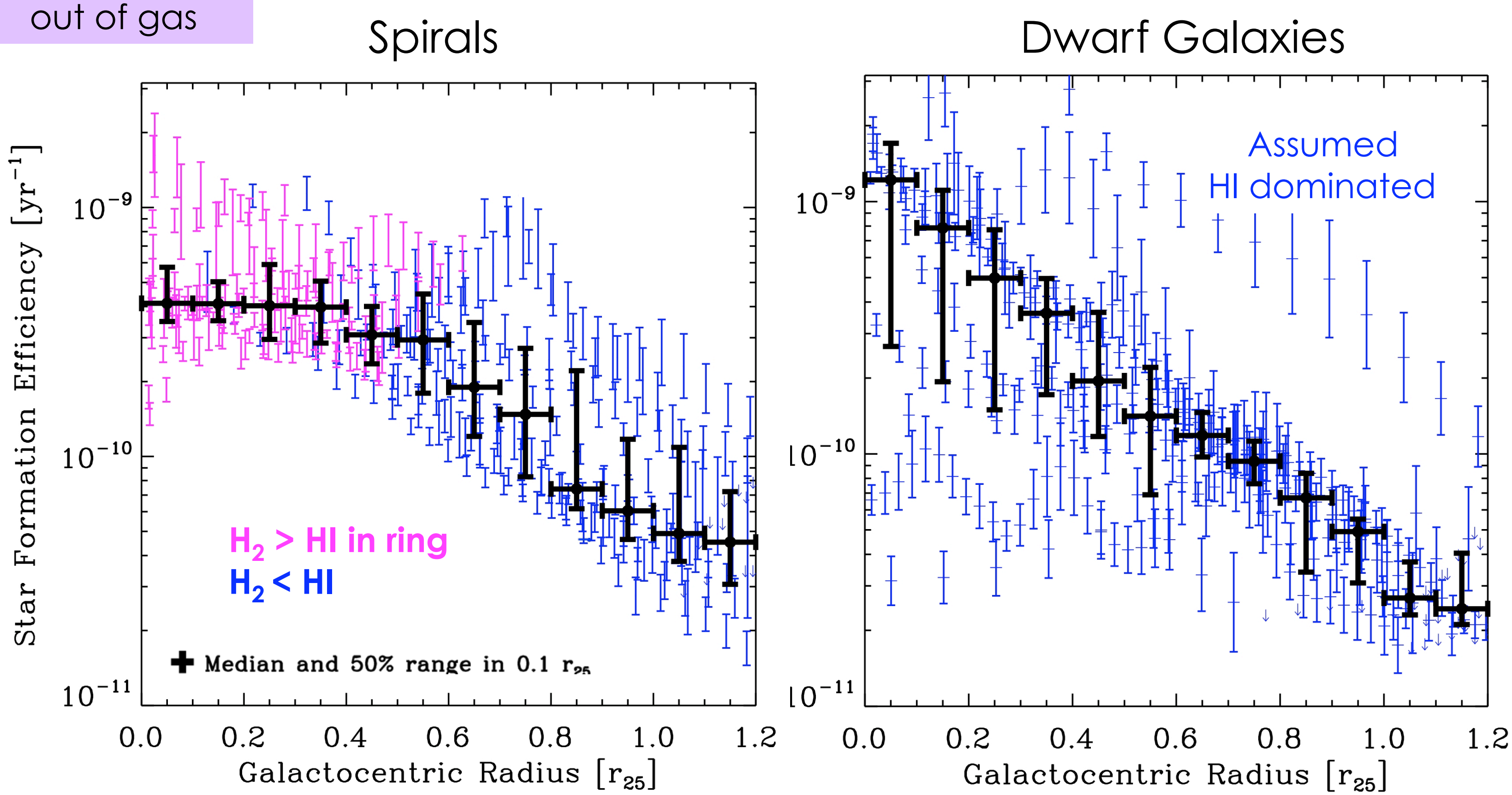
Spirals: binned pixel-by-pixel data
Spirals: tilted rings - R_{mol} from SFR/HI
Dwarfs: tilted rings - R_{mol} from SFR/HI

Leroy, Walter et al. 2008

Combined: the SFE vs. Radius

SFE ($\Sigma_{SFR}/\Sigma_{gas}$) vs. Radius

Good at forming stars out of gas



Bad at forming stars out of gas

… each point: a 10" (~400/200 pc) wide tilted ring.

Note: drop even more dramatic if missing H_2

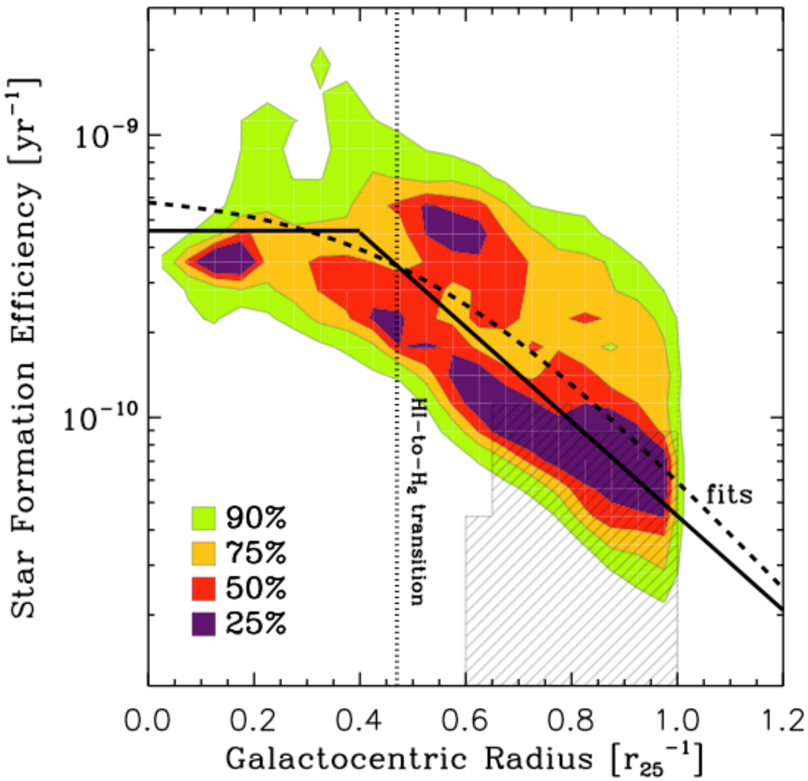
Leroy, Walter et al. 2008

Combined: the SFE vs. Radius

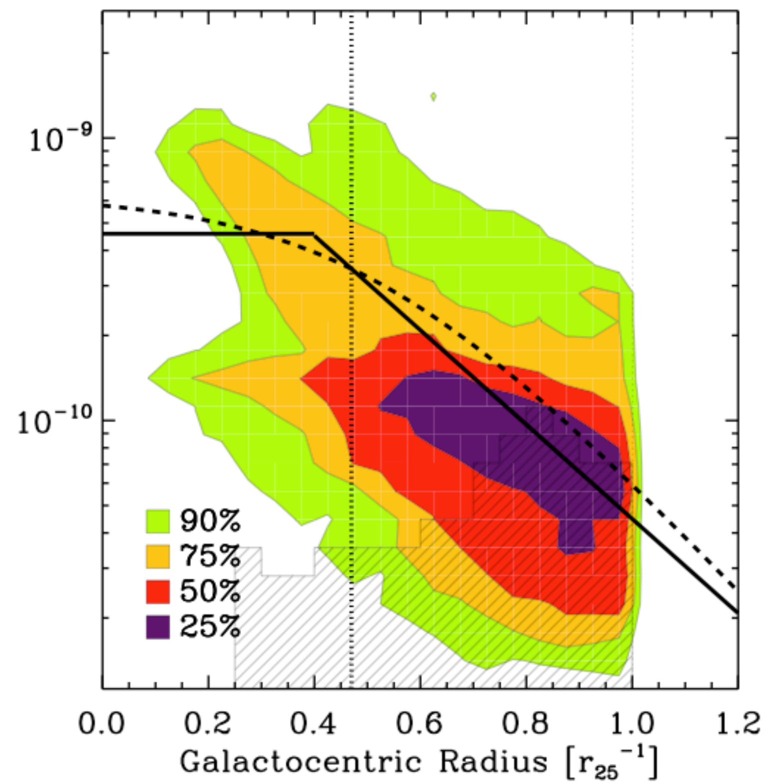
SFE ($\Sigma_{SFR}/\Sigma_{gas}$) vs. Radius

Good at forming stars out of gas

Spirals



Dwarf Galaxies



Bad at forming stars out of gas

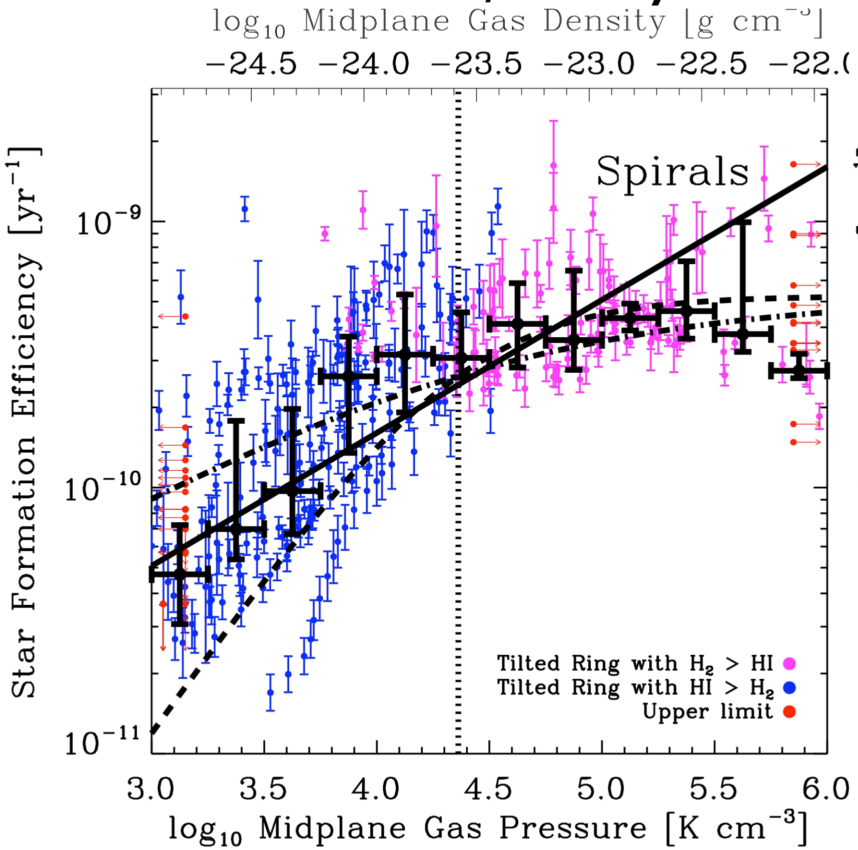
Same result when using pixel-by-pixel analysis

Large Scale Instability or Microphysics?

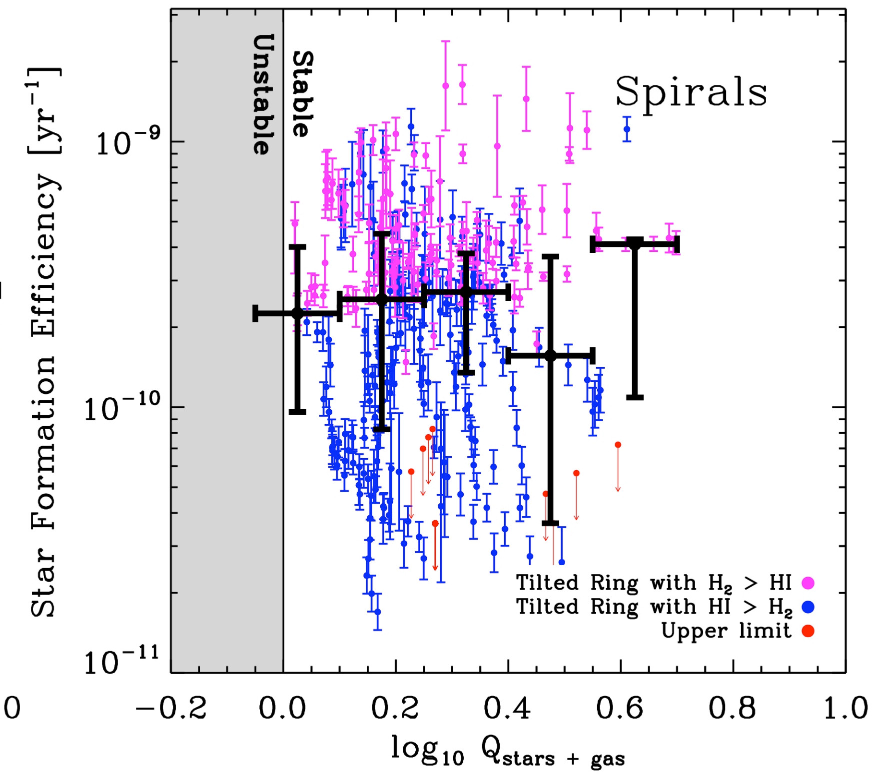
SFE drivers?

Good at forming stars out of gas

Pressure/Density



Gravitational Instability

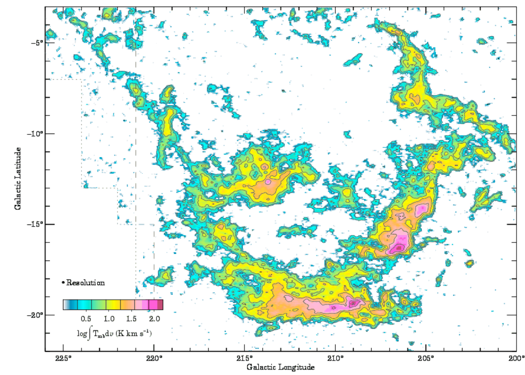


Bad at forming stars out of gas

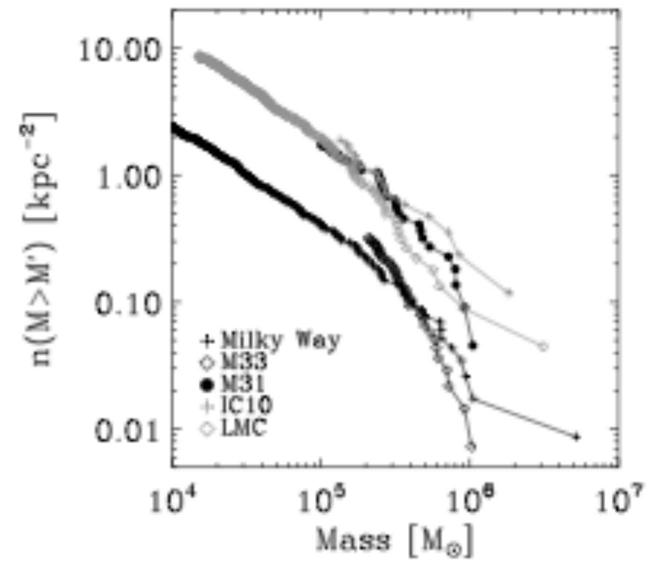
ALMA = GMCs in Other Galaxies

THINGS ALMA can do.

- Massive environmental database will be in place when ALMA comes online.
- GMCs : regulating structures for SF
- ALMA : can resolve GMCs at extragalactic distances
- this is really hard right now! Mostly confined to the LG. (Talk by A. Bolatto)
- How do mass function, "Larson" scaling relations vary?
- How does SFE of individual GMCs depend on environment?



Orion in CO (Wilson+ 05)



Local Group GMC Mass Functions (Blitz+ 07, Rosolowsky 05)

THINGS to take away…

- THINGS++ :
  High quality, multi-λ database to study star formation
- HERACLES:
  Wide-field, sensitive CO maps of THINGS galaxies.
- SFR per H_2 strikingly constant in the disks of spirals.
- H_2-to-HI ratio a strong function of environment: P_h, τ_{ff}, τ_{orb}
- Clear radial behavior of in SFE = SFR/gas.
- GMC/star formation dependent more on microphysics than large-scale instability?
- ALMA: GMCs in other galaxies…

THINGS AJ Special Issue later this year:
Walter et al. "THINGS: The HI Nearby Galaxy Survey"
Leroy et al. "HERACLES: The HERA CO-Line Extragalactic Survey"
Bigiel et al. "The Star Formation Law on sub-Kiloparsec Scales"
Leroy et al. "The Star Formation Efficiency in Nearby Galaxies"

www.mpia.de/THINGS