Structure of Nearby Galaxies

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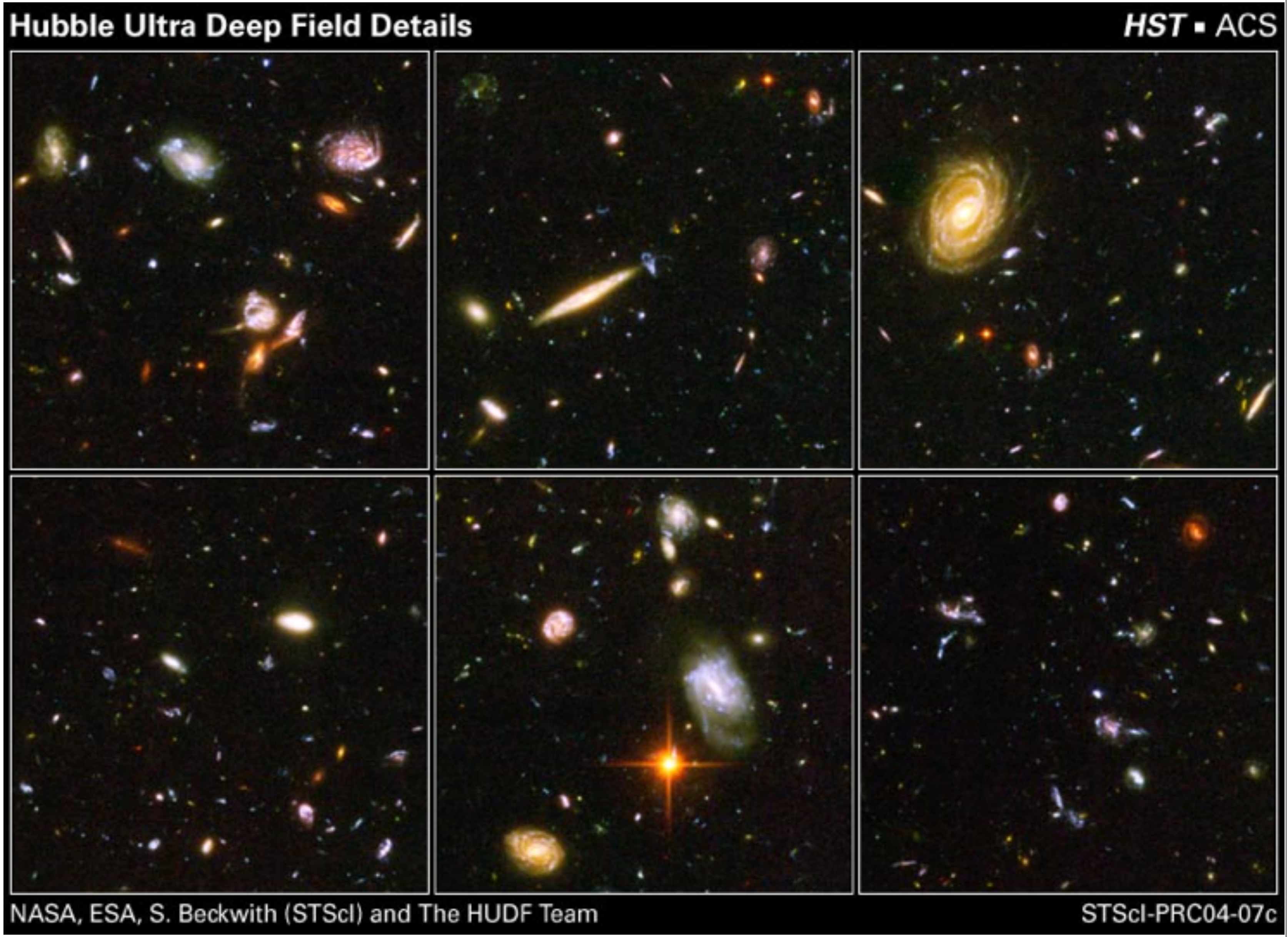
Imaging HI in Galaxies

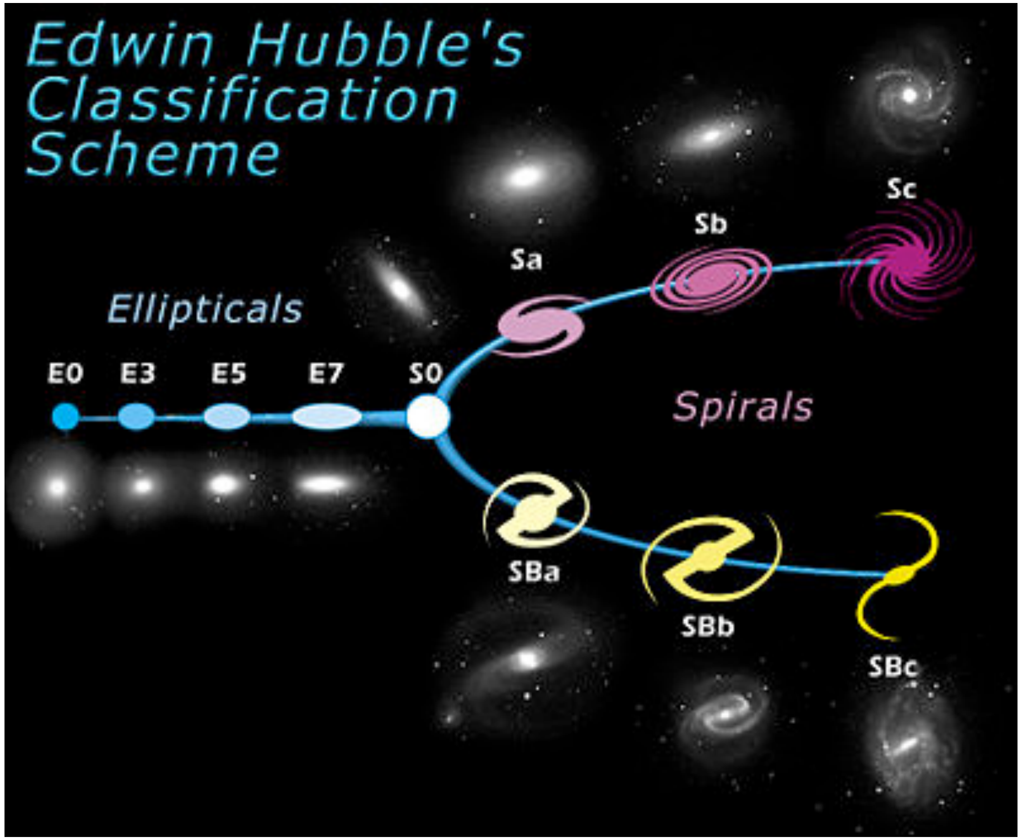
Content

- Some basics
- THINGS - The HI Nearby Galaxy Survey
  - overview and PR material
  - rotation curves and Dark Matter
  - Star Formation thresholds and SF Law
  - the Violent Interstellar Medium
  - where is the edge?
- Future


Hubble Ultra Deep Field
HST ▪ ACS
NASA, ESA, S. Beckwith (STScI) and The HUDF Team
STScI-PRC04-07a


Hubble Ultra Deep Field Details
HST ▪ ACS
NASA, ESA, S. Beckwith (STScI) and The HUDF Team
STScI-PRC04-07c

Galaxy classification



Related talks by: Dave Alexander
Malcolm Bremer
Judith Croston

Imaging HI in Galaxies

Galaxy Morphologies

ESO 325-G004

The Spindle Galaxy (NGC5866)

M 101/NGC 5457

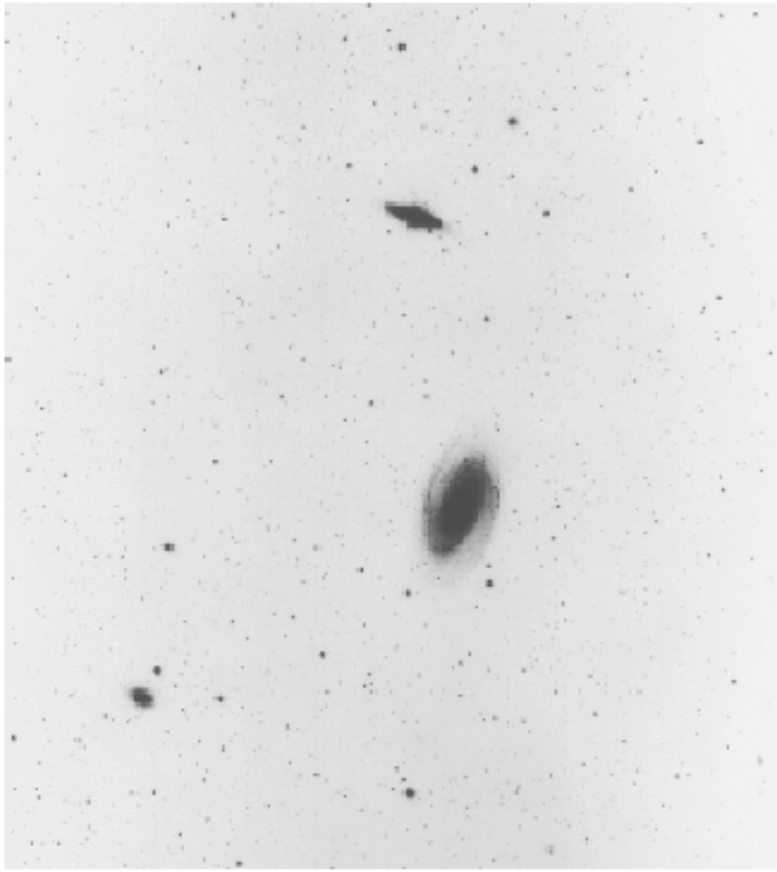
LMC

NGC 1300

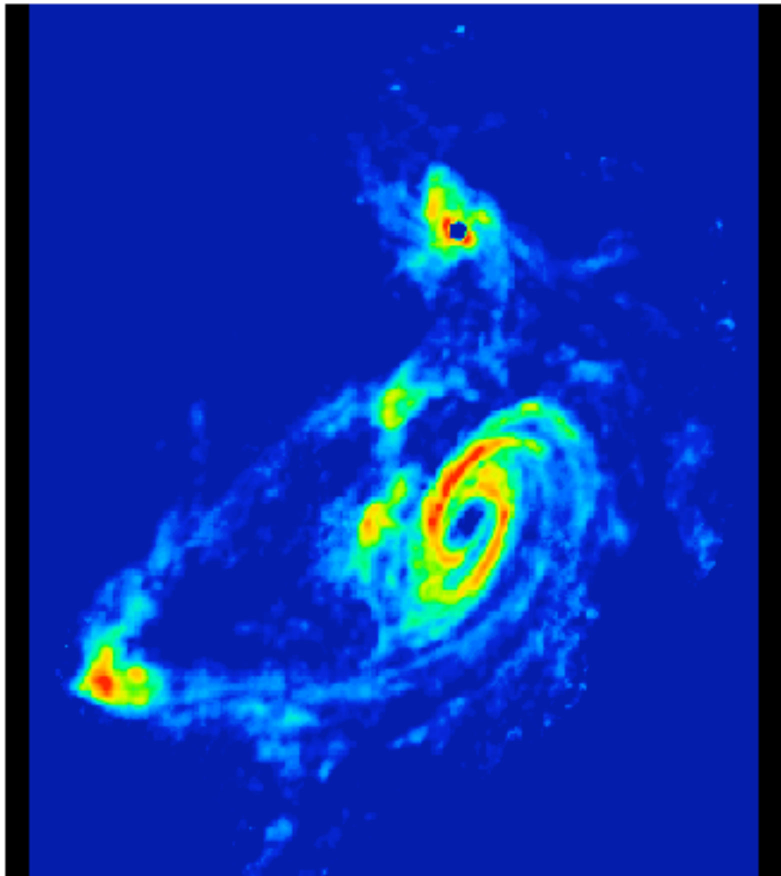
Why imaging HI?

Tidal Interactions in the M81 Group

Stellar Light Distribution



21-cm HI Distribution



Imaging HI in Galaxies

Advantages of HI

- one obtains morphology *and* velocity information
- it extends well beyond R_{25} so it traces the mass distribution out to larger radii than any other tracer
- HI in the outskirts is loosely bound ---> is sensitive to (past) tidal interactions
- HI is the reservoir for future star formation

But...

- it is a weak line

Some Basics

Current deepest HI emission line maps are from clusters at: **z ~ 0.2**

HI is terribly weak!!! Here is why...

HI is thermal line emission (mainly collisionally excited)

- T_B = const. $T_S \times \tau$ where $T_S \approx 5000$ K and $\tau \approx 0.01$, so $T_B \approx 50$ - 150 K
- and for optically thick clouds, $T_B = T_S \approx 50$ K
- sensitivities of interferometers are given usually in Jy beam^{-1}; e.g the VLA in D-array (45" resolution) in a 10 km s^{-1} has a sensitivity in a few hours of 0.6 mJy beam^{-1}. The sensitivity in A-array (1.5" resolution) will be the same, 0.6 mJy beam^{-1} for the same observing time.

$$\Delta S = \frac{k_B T_a}{\eta_a A \sqrt{N(N-1)\Delta t \Delta \nu}}$$

Some Basics

- from the conversion from Jy beam^{-1} to Kelvin it follows that for VLA D-array (45") 0.6 mJy beam^{-1} corresponds to ~2 K (for emission filling the beam, that is). However, for A-array (1.5") this corresponds to ~180 K, i.e. HI becomes hard to detect.

- Deep HI surveys exist only for nearby objects at modest resolution

- Conversely, at high z, where you need high angular resolution to resolve your targets, sensitivity is insufficient with state of the art telescopes.

$$\Delta S = \frac{k_B T_a}{\eta_a A \sqrt{N(N-1)\Delta t \Delta \nu}}$$

Hence, the need for vastly increased collecting area, i.e. the Square Kilometre Array or SKA

On a historical note, the original specifications for the SKA leading to its target size were that it should allow detailed HI studies of spiral galaxies like M 51 at a redshift of z = 1.0

Some Basics

It therefore won't be surprising that most deep (i.e. high-z) studies, or ultra-high angular resolution work (VLBI) probe non-thermal continuum (e.g., synchrotron) emission or, in the case of spectral lines, masers.

There is a lot more that can be said about all this. For example, I haven't at all mentioned the possibility of detecting HI in absorption at high z, in which case the intensity of the background rather than the intervening HI sets the detection threshold.


THINGS
The HI Nearby
Galaxy Survey

The THINGS Team

- Front: **F. Walter** (PI), *D. Tamburro*, A. Usero, *I. Bagetakos*, *V. Buenrostro-Leiter*, *A. Portas*
- Back: *F. Bigiel*, A. Leroy, R. Kennicutt, *J. Rich*, *S-H. Oh*, M. Zwaan, **W. J.G. de Blok** (Co-I), **E. Brinks** (Co-I), *C. Trachternach* Michele Thornley (not pictured)

The HI Nearby Galaxy Survey

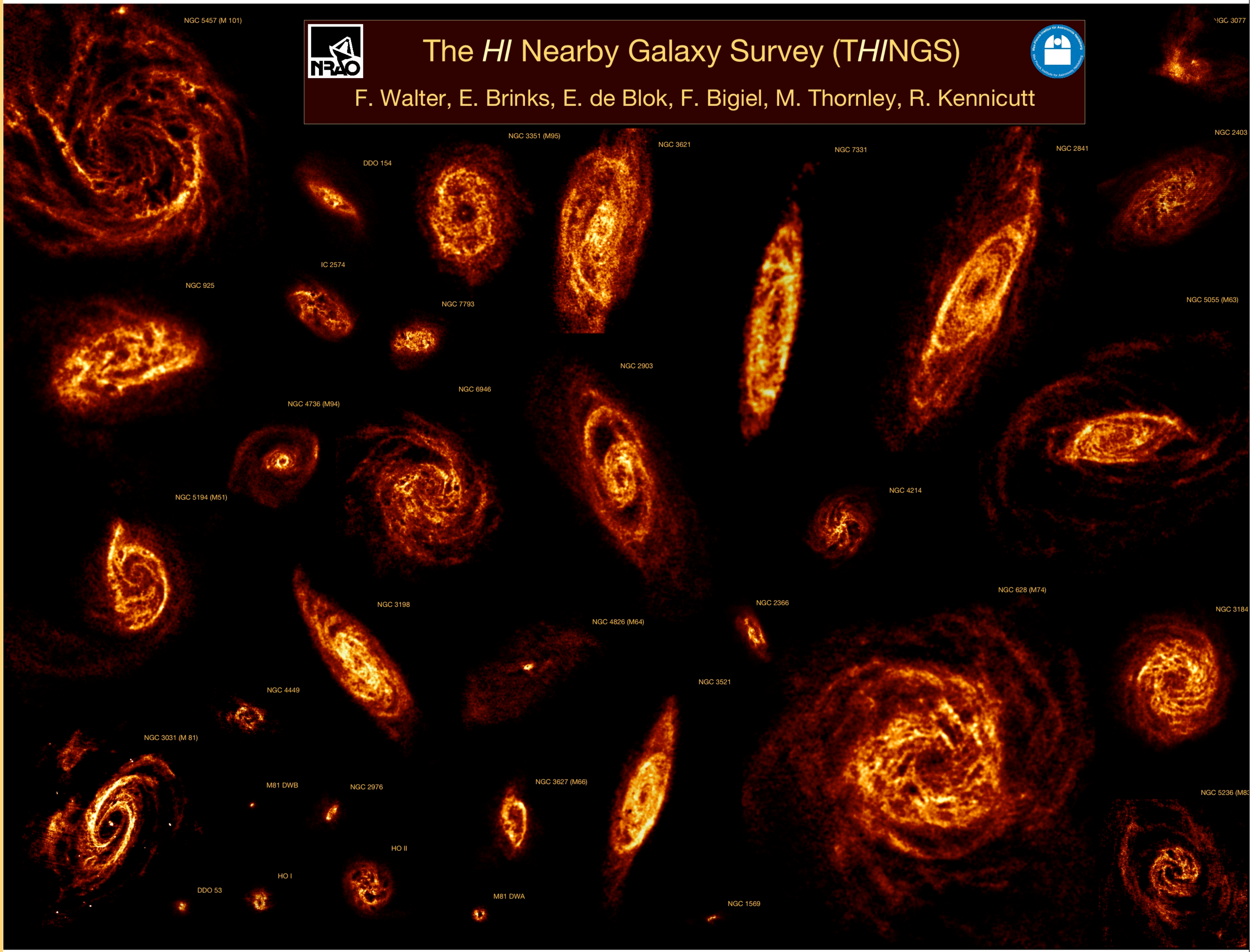
What is THINGS?

- ~500 hours: B, C & D arrays -- Large NRAO VLA program (2003-2006)
- 34 galaxies: Sa - Irr
- Resolution ~ 6" (100-300 pc)
- Velocity Resolution ~ 5 km s^{-1}
- Sensitivity ~ 5 x 10^{19} cm^{-2}
- total: 1 Tbyte
- Targets complement SINGS, the *Spitzer* Infrared Nearby Galaxies Survey, a Legacy Survey, and the *GALEX* Nearby Galaxies Survey (NGS)

Which THINGS?

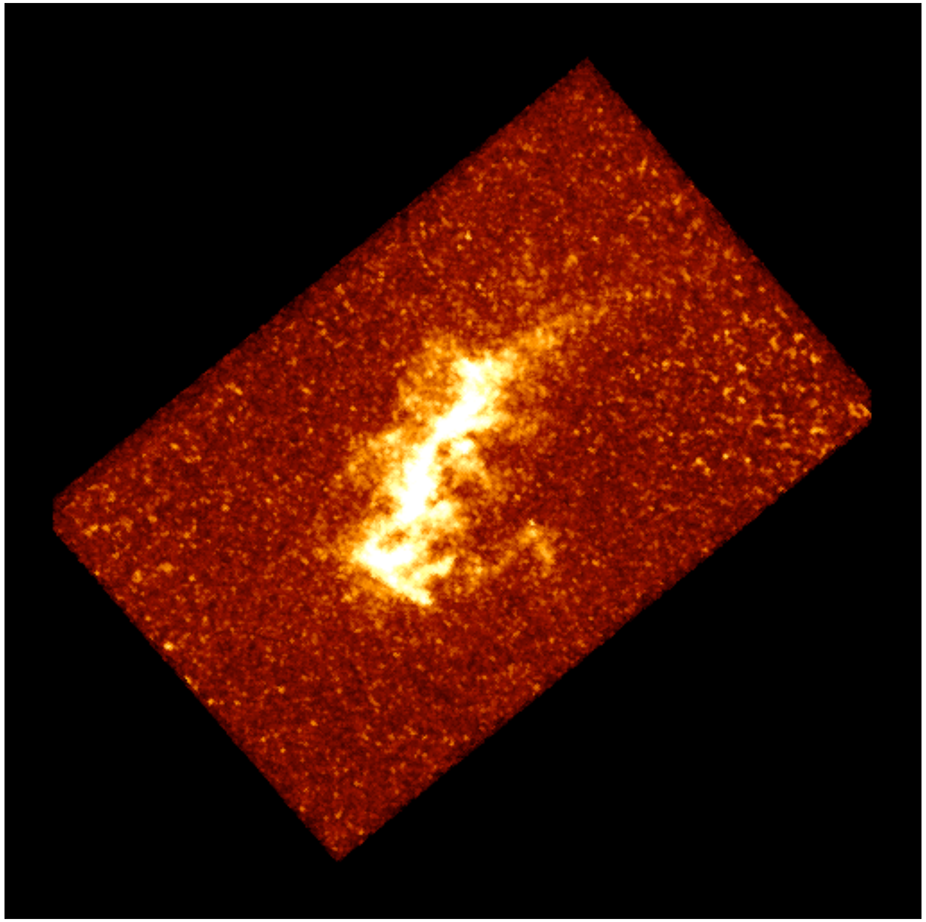
Name	Alias	Type	RA	dec	V_{rad}	W_{20}	size	incl
			h m s.s	° ′ ″	km s^{-1}	km s^{-1}	′×′	°
NGC628	M74	Sc	01 36 41.7	+15 46 59	656	77	10.5 × 9.5	35
NGC925		SBcd	02 27 16.9	+33 34 45	553	217	10.5 × 5.9	61
NGC1569		IBm	04 30 49.0	+64 50 53	−90	83	3.6 × 1.8	68
NGC2366		Irr	07 28 47.6	+69 11 39	99	114	8.1 × 3.3	90
NGC2403		SBc	07 36 51.4	+65 36 09	130	241	21.9 × 12.3	60
HolmbergII	UGC4305	Irr	08 19 04.0	+70 43 09	157	72	7.9 × 6.3	47
M81dwA	PGC23521	Irr	08 23 56.0	+71 01 45	113	33	1.3 × 0.7	–
DDO53	UGC4459	Irr	08 34 07.2	+66 10 54	19		1.5 × 1.3	45
NGC2841		Sb	09 22 02.6	+50 58 35	638	607	8.1 × 3.5	68
NGC2903		SBbc	09 32 10.1	+21 30 04	555	384	12.6 × 6.0	56
HolmbergI	UGC5139	Irr	09 40 32.3	+71 10 56	137	44	3.6 × 3.0	37
NGC2976		Sc	09 47 15.3	+67 55 00	3	135	5.9 × 2.7	61
NGC3031	M81	Sab	09 55 33.2	+69 03 55	−35	442	26.9 × 14.1	59
NGC3077		Sd	10 03 20.6	+68 44 04	13	90	5.4 × 4.5	41
M81dwB	UGC5423	Irr	10 05 30.6	+70 21 52	343	61	0.9 × 0.6	67
NGC3184		SBc	10 18 16.9	+41 25 28	591	151	7.4 × 6.9	24
NGC3198		SBc	10 19 54.9	+45 32 59	662	321	8.5 × 3.3	70
IC2574	UGC5666	SBm	10 28 21.2	+68 24 43	48	109	13.2 × 5.4	75
NGC3351	M95	SBb	10 43 57.8	+11 42 14	778	280	7.4 × 5.0	42
NGC3521		SBbc	11 05 48.6	−00 02 09	809	462	11.0 × 5.1	66
NGC3621		SBcd	11 18 16.0	−32 48 42	726	278	12.3 × 7.1	66
NGC3627	M66	SBb	11 20 15.0	+12 59 30	726	377	9.1 × 4.2	57
NGC4214		Irr	12 15 38.9	+36 19 40	290	86	8.5 × 6.6	42
NGC4449		Irr	12 28 11.2	+44 05 36	202	143	6.2 × 4.4	56
NGC4736	M94	Sab	12 50 53.0	+41 07 14	309	232	11.2 × 9.1	35
DDO154		Irr	12 54 05.2	+27 08 55	373	93	3.0 × 2.2	44
NGC4826	M64	Sab	12 56 43.7	+21 40 52	406	315	10.0 × 5.4	60
NGC5055	M63	Sbc	13 15 49.2	+42 01 49	502	400	12.6 × 7.2	56
NGC5194	M51a	Sbc	13 29 52.7	+47 11 43	463	199	11.2 × 6.9	30
NGC5236	M83	SBc	13 37 00.8	−29 51 59	515	281	12.9 × 11.5	46
NGC5457	M101	SBc	14 03 12.5	+54 20 55	241	188	28.8 × 26.9	22
NGC6946		SBc	20 34 52.3	+60 09 14	51	235	11.5 × 9.8	31
NGC7331		SAb	22 37 04.1	+34 24 56	816	520	10.5 × 3.7	71
NGC7793		Scd	23 57 49.7	−32 35 30	229	192	9.3 × 6.3	53

THINGS Showcase



THINGS Showcase

NGC1569



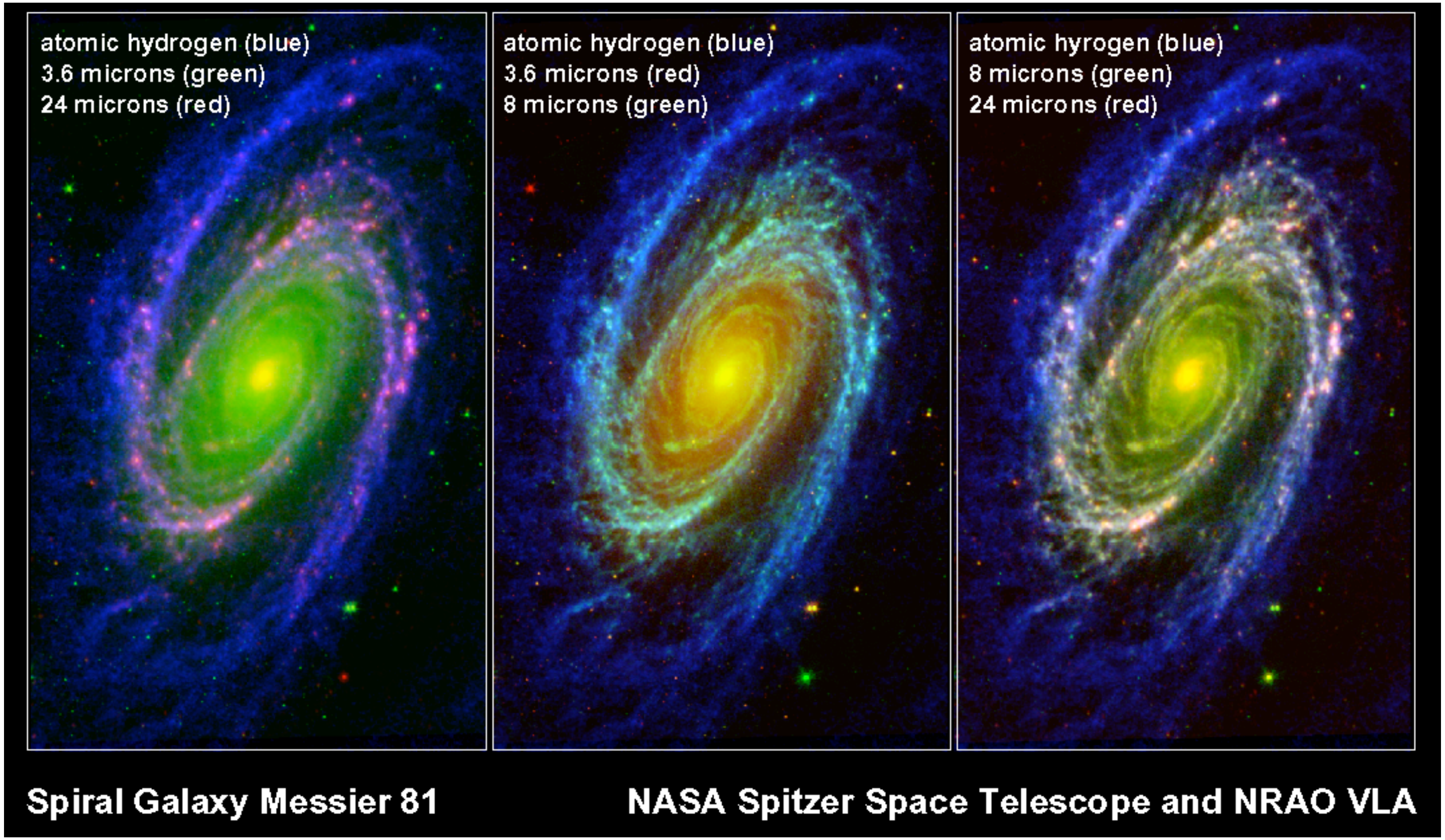
Data form 3-D cubes with axes: α, δ, V

Image cube size (typically): 1024 x 1024 x 100

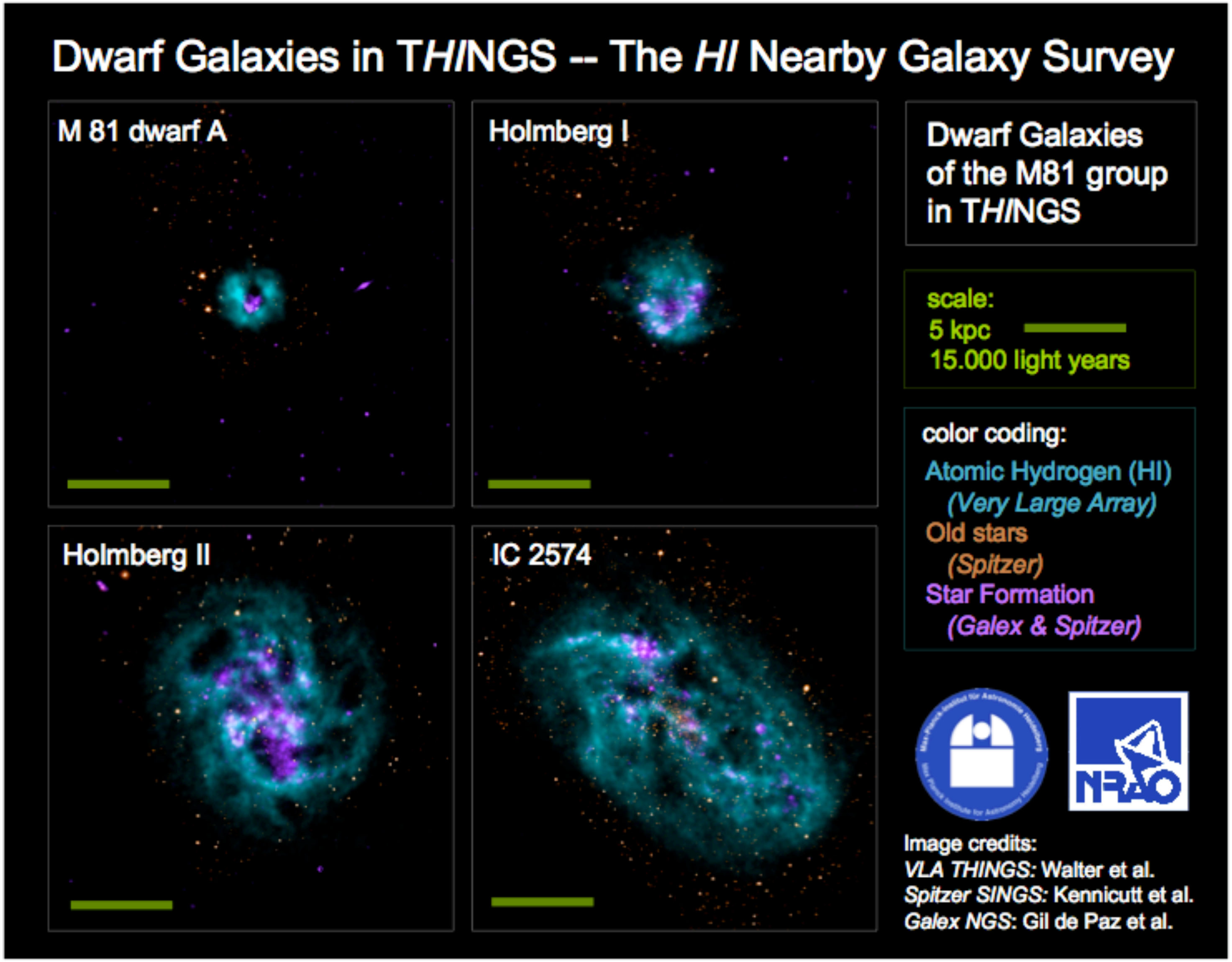
Walter et THNGS, 2008

Multi-λ Database

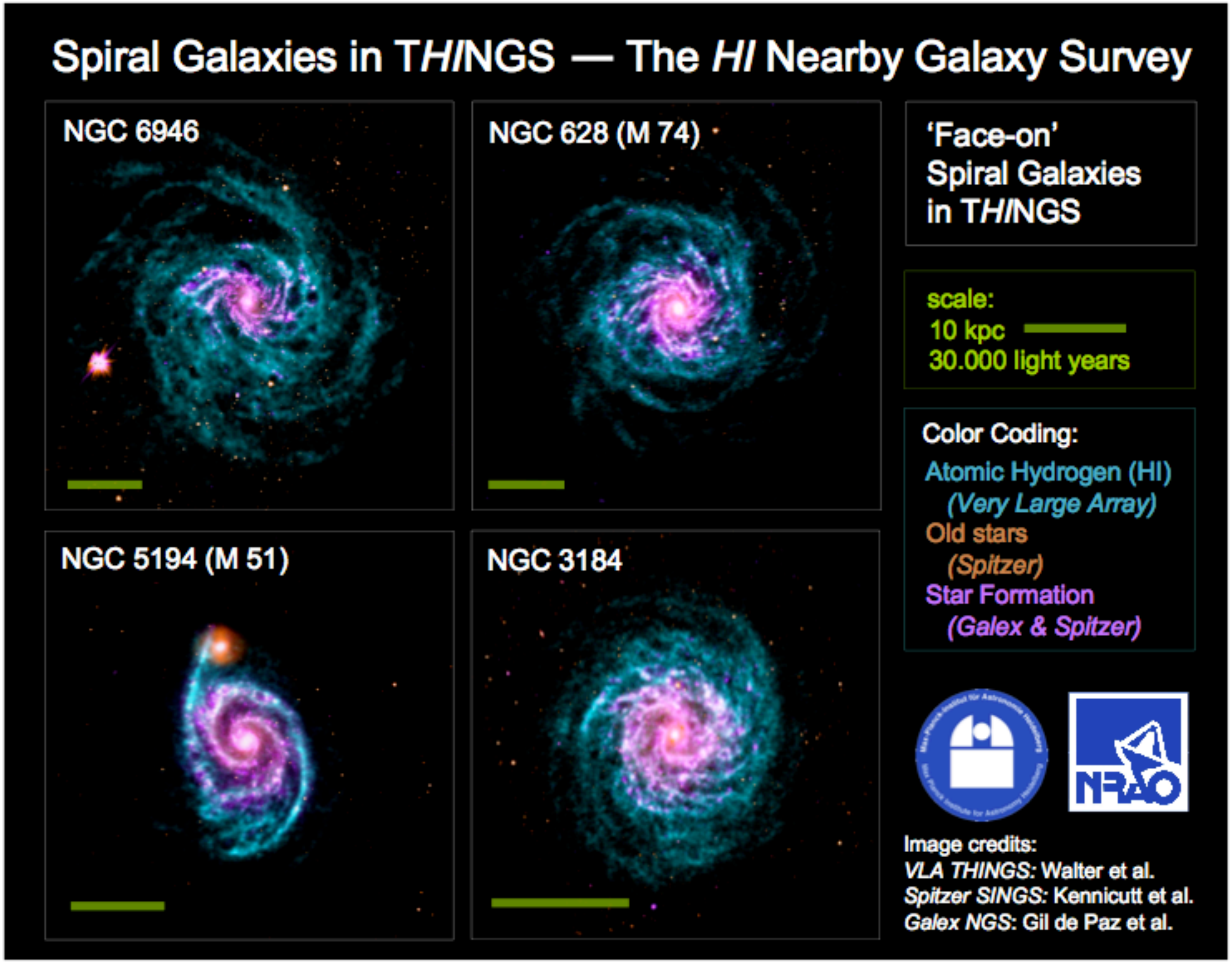
- multi-wavelength data from SINGS (Kennicutt et al. 2003)
- and GALEX Nearby Galaxy Survey (Gil de Paz et al. 2007)



THINGS Showcase



THINGS Showcase



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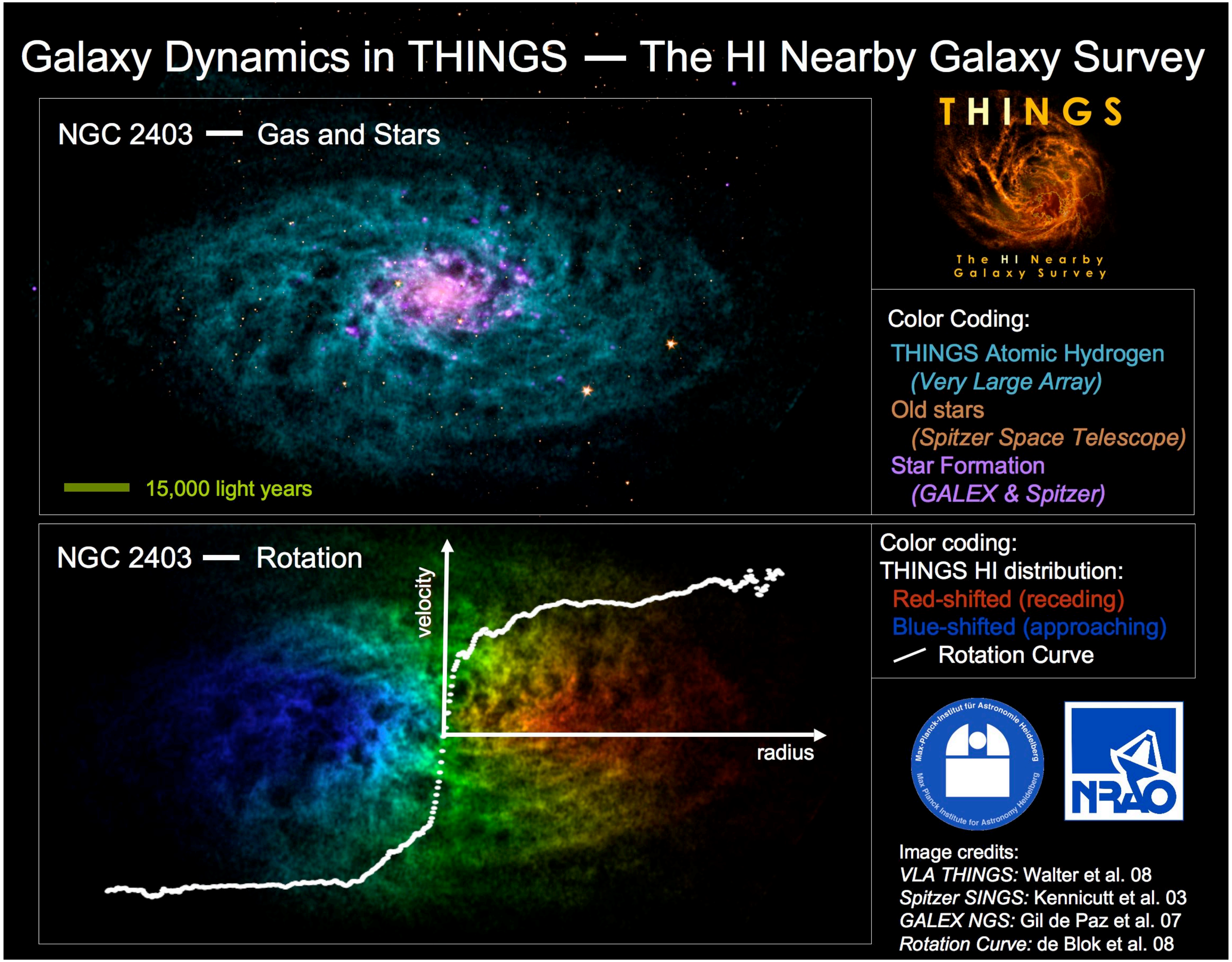
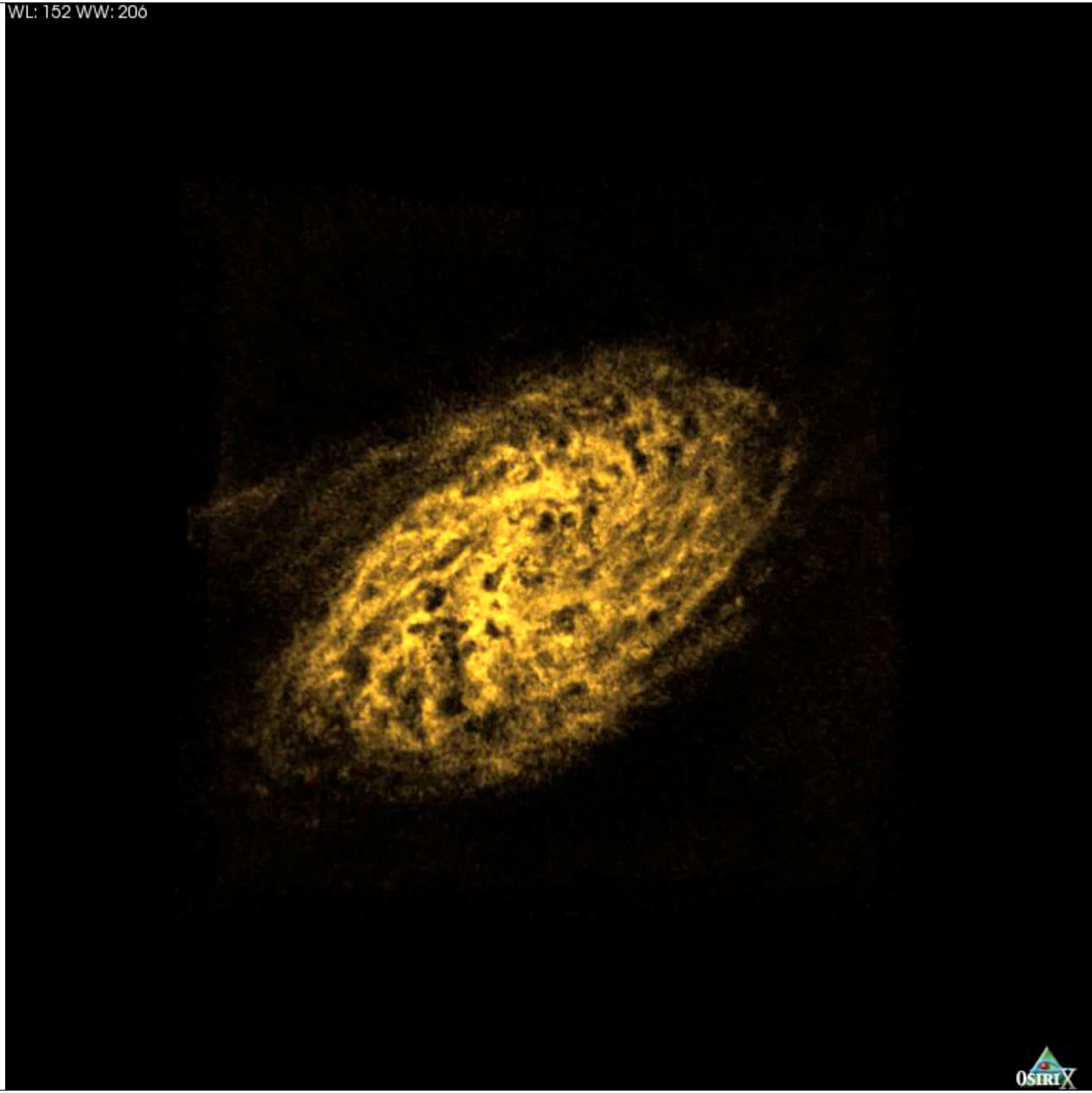


THINGS Showcase



First Science With THINGS

Fabian Walter … Max Planck Institute for Astronomy

Frank Bigiel, Adam Leroy, Domenico Tamburro

- What is the lag between spiral arms seen in the HI and in SF tracers?
- Does the Schmidt Law hold at 500 pc? Does it vary with galaxy or scale?
- How do proposed SF recipes perform in THINGS?

Erwin de Blok … Cape Town/Mount Stromlo Observatory

Se-Heon Oh, Joshua Rich, Clemens Trachternach (Bochum)

- Rotation curves, mass-modeling and testing whether CDM profiles hold.
- Measuring non-circular motions and their effect on mass-models.
- Testing the multi-scale clean algorithm and its effect on structure measures.

Elias Brinks … University of Hertfordshire

Ioannis Bagetakos, Valeria Buenrostro Leiter, António Portas, Antonio Usero

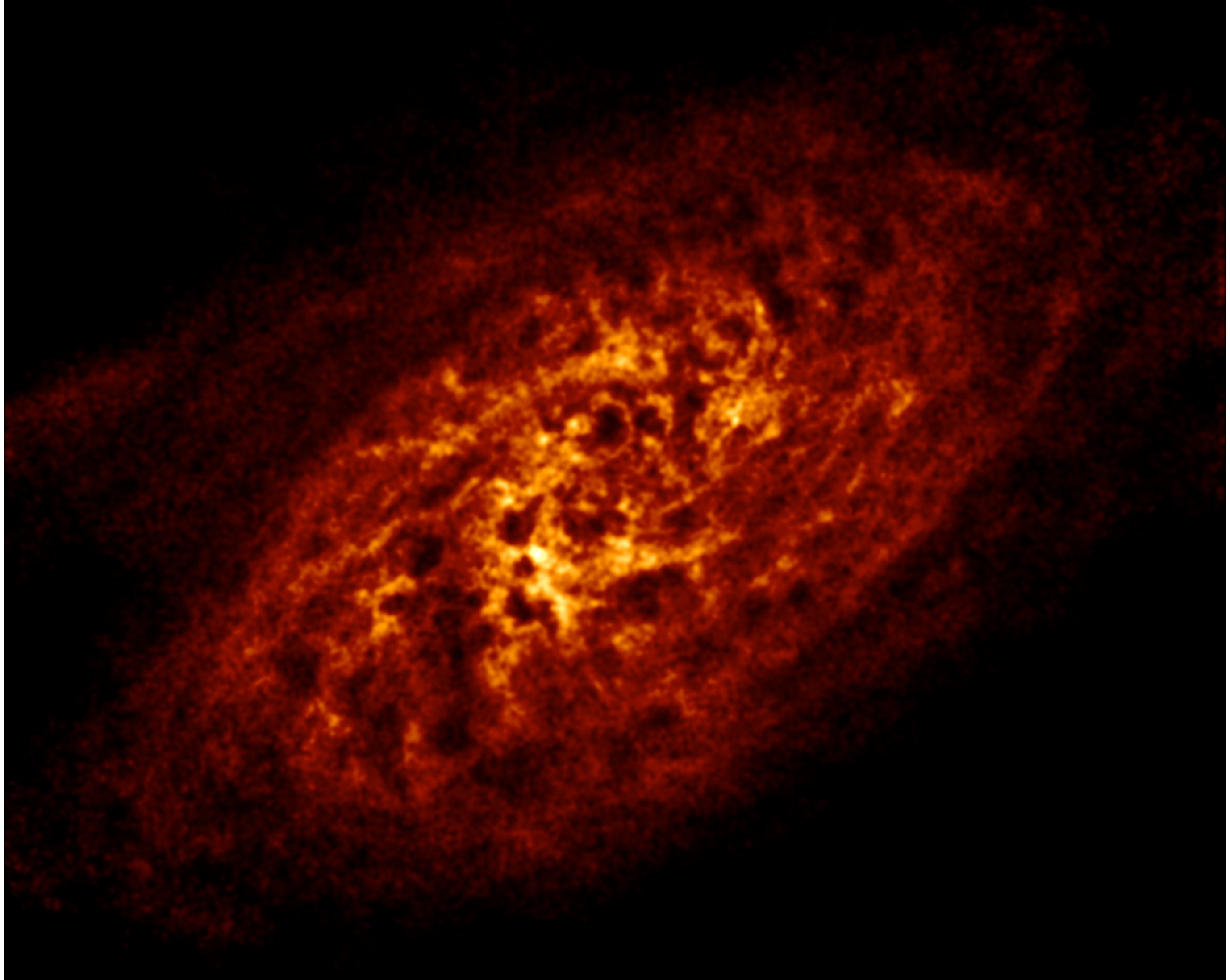
- What are the distribution and energetics of HI holes?
- Where are the edges of HI disks? Are they sharp?
- How does the warm/cold HI breakdown vary with environment?

Martin Zwaan (ESO)

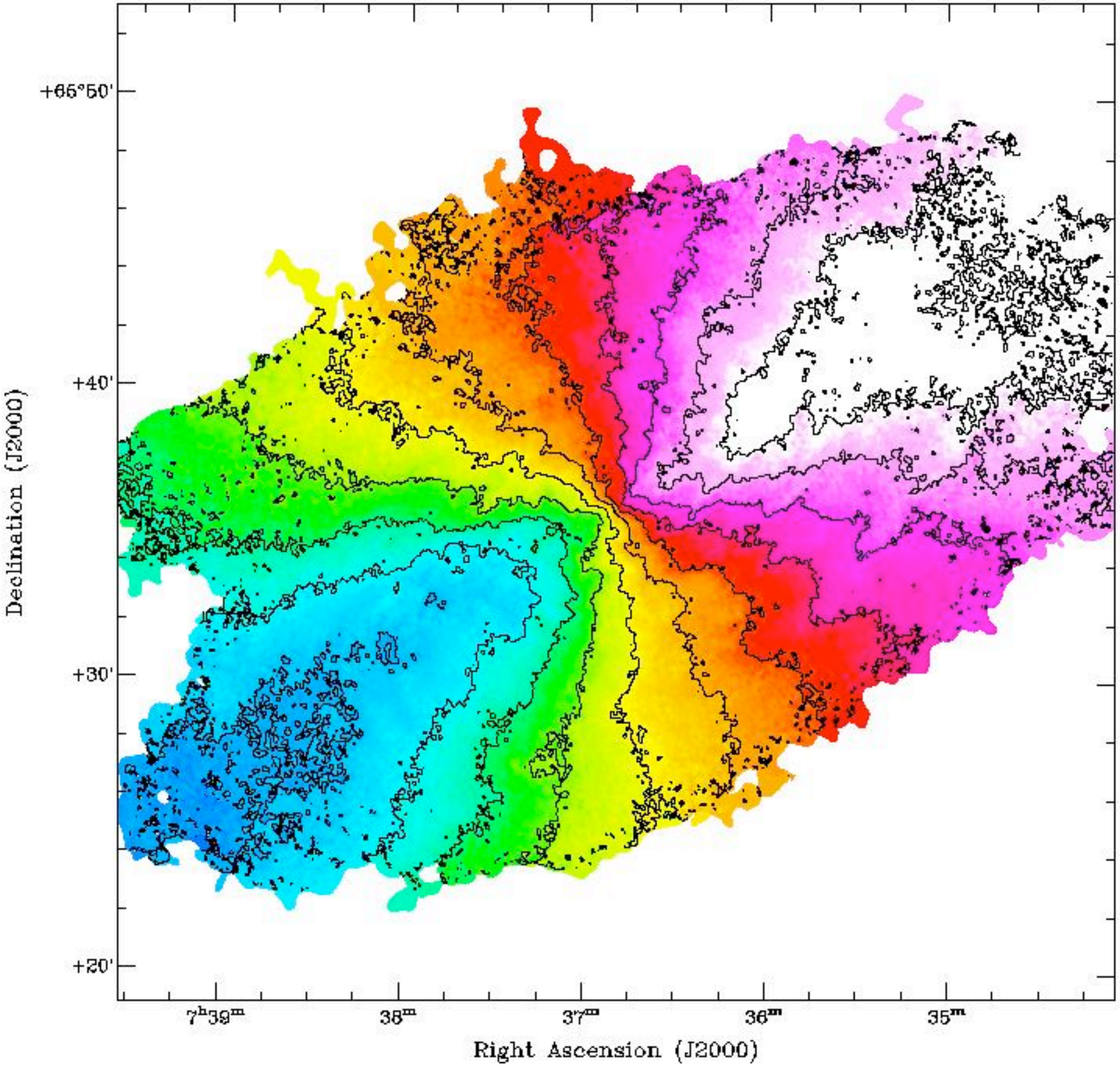
- How does THINGS compare to observations of DLAs?

THINGS Data: Integrated HI

Example: NGC 2403

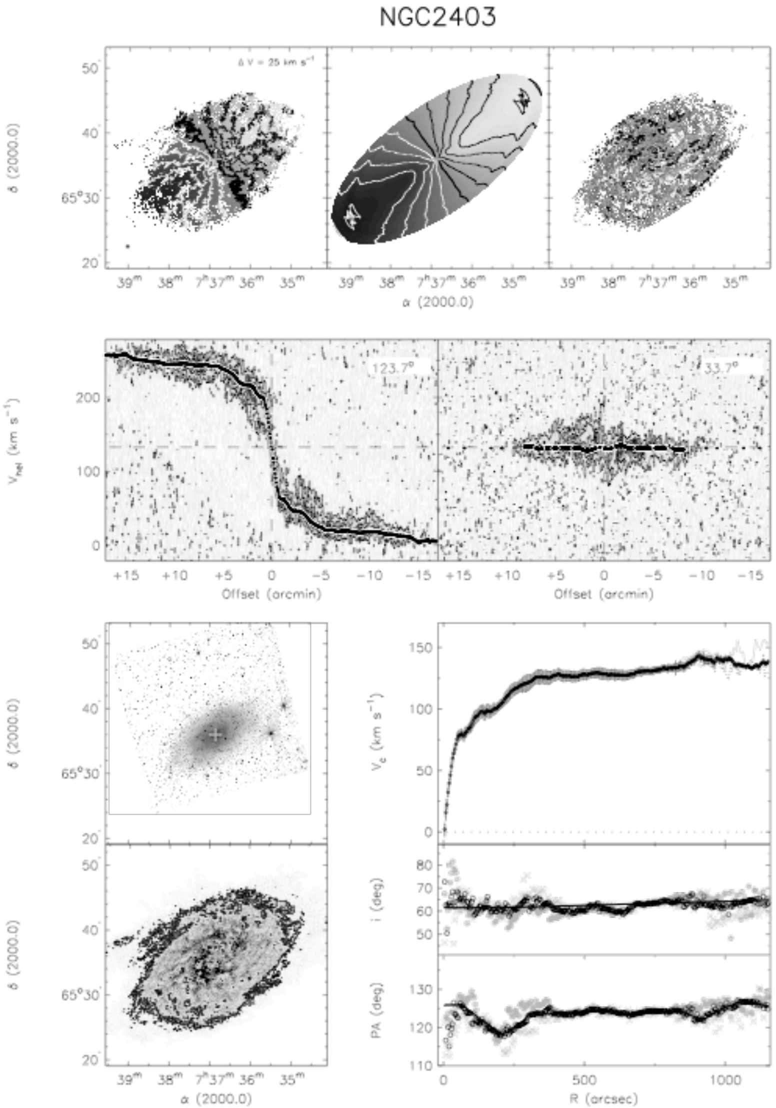


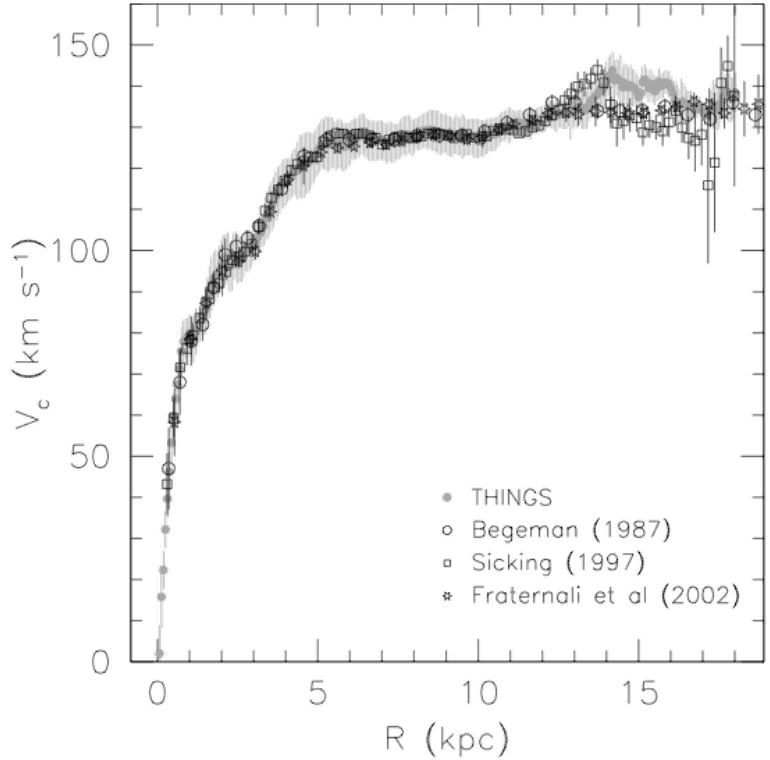
THINGS Data: Velocity Field



Rotating THINGS

Kinematics: NGC 2403



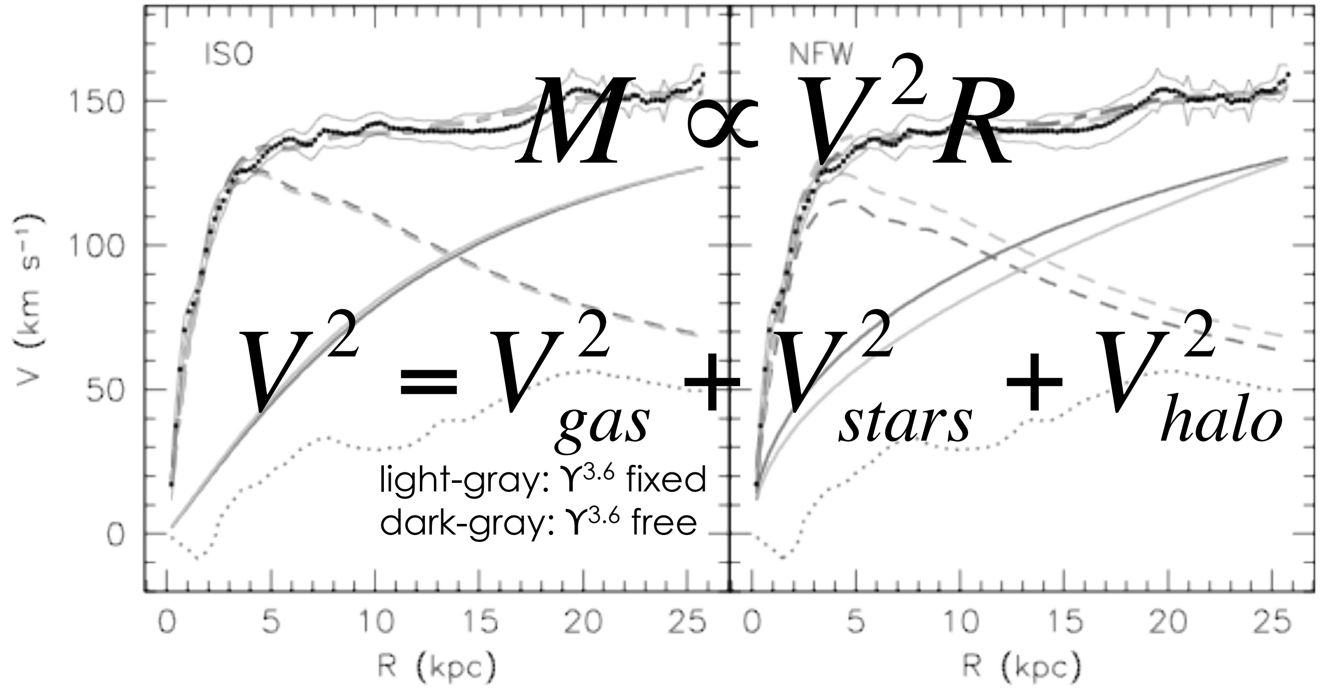


This information is available for all THINGS galaxies

de Blok et THINGS

Rotating THINGS

Mass models example



- $M = (1.4)M_{HI} + \Upsilon^{3.6} L_{disk} + M_{halo}$
- For every galaxy produce models with $\Upsilon^{3.6}$ fixed to predicted value based on IRAC 3.6 μm and with $\Upsilon^{3.6}$ free

Rotating THINGS

NFW model

$$\rho_{\mathrm{NFW}}(R) = \frac{\rho_i}{(R/R_s)\,(1+R/R_s)^2}$$

$$V(R) = V_{200}\left[\frac{\ln(1+cx) - cx/(1+cx)}{x[\ln(1+c) - c/(1+c)]}\right]^{1/2}$$

With $x = R/R_{200}$ and $c = R_{200}/R_s$

Isothermal sphere

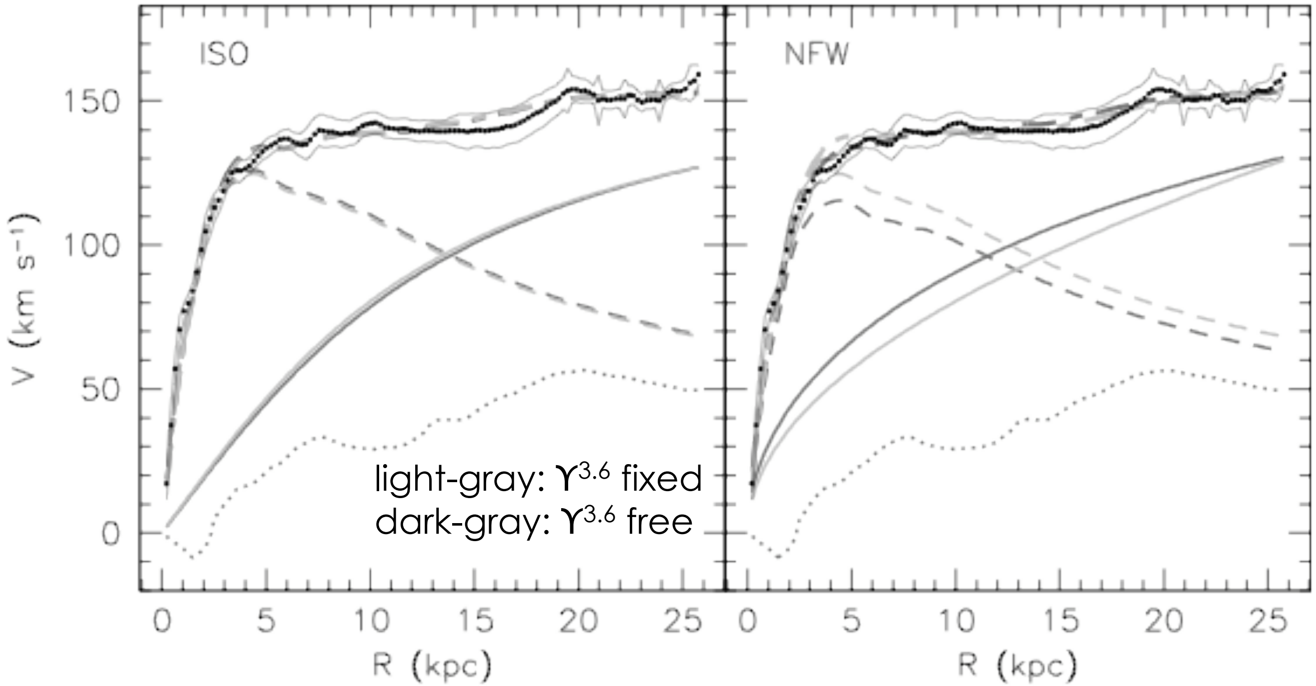
$$\rho_{\mathrm{ISO}}(R) = \rho_0\left[1 + \left(\frac{R}{R_C}\right)^2\right]^{-1}$$

$$V(R) = \sqrt{4\pi G\rho_0 R_C^2\left[1 - \frac{R_C}{R}\arctan\left(\frac{R}{R_C}\right)\right]}.$$

$$V_\infty = \sqrt{4\pi G\rho_0 R_C^2}.$$

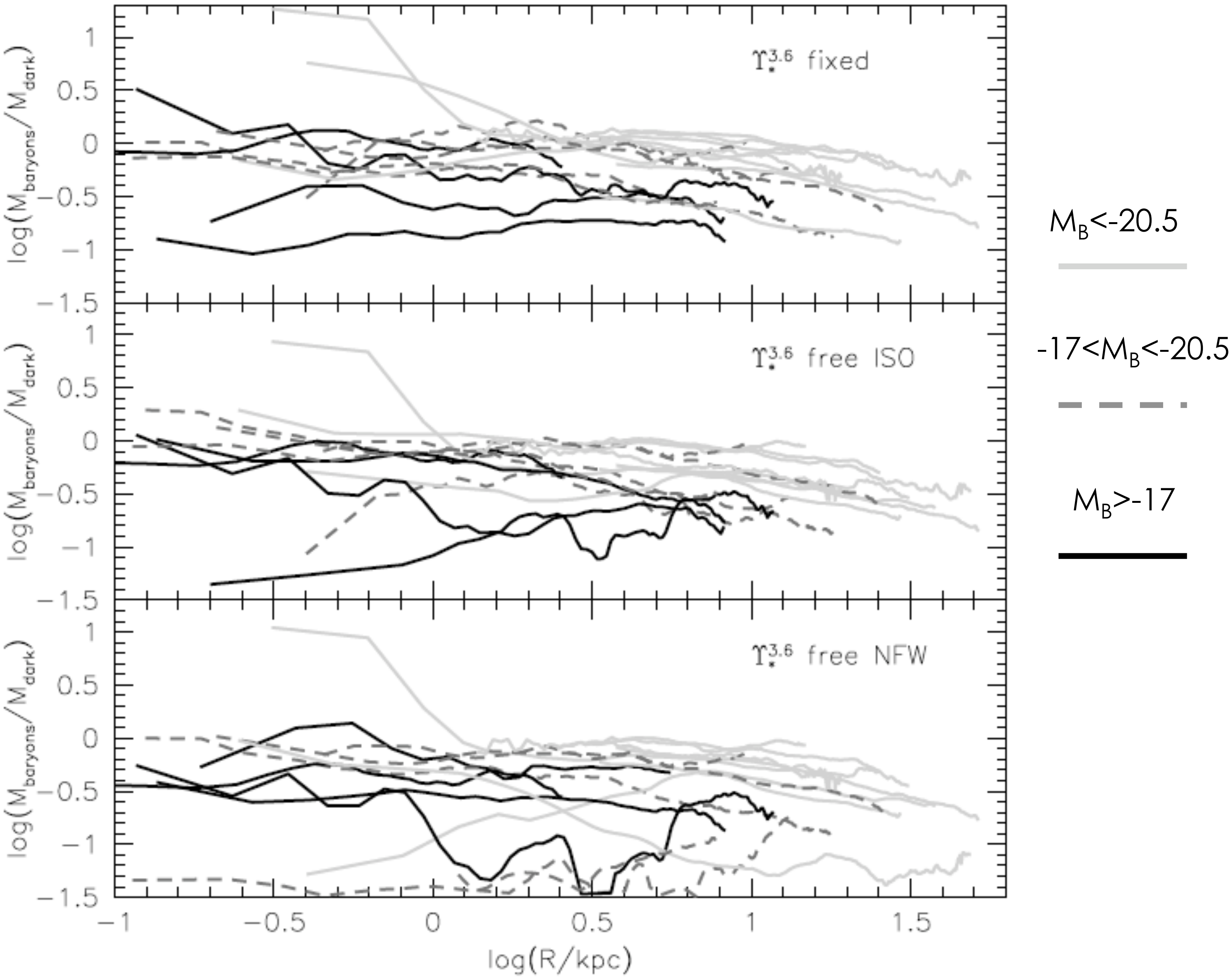
Rotating THINGS

Mass models example



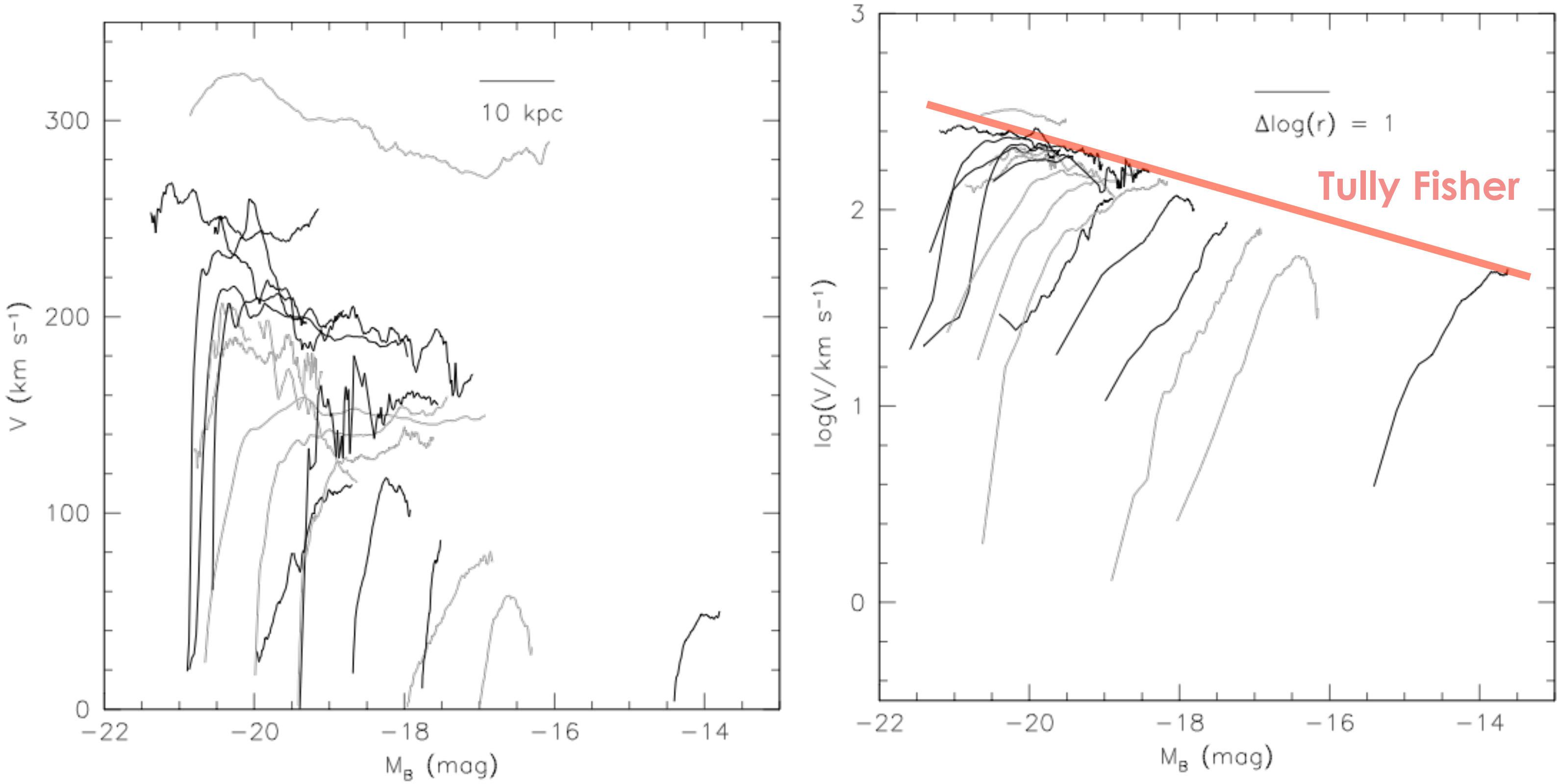
- $M = (1.4)M_{HI} + \Upsilon^{3.6} L_{disk} + M_{halo}$
- For every galaxy produce models with $\Upsilon^{3.6}$ fixed to predicted value based on IRAC 3.6 μm and with $\Upsilon^{3.6}$ free

Rotating THINGS



Rotating THINGS

All THINGS rotation curves together...



Rotating THINGS

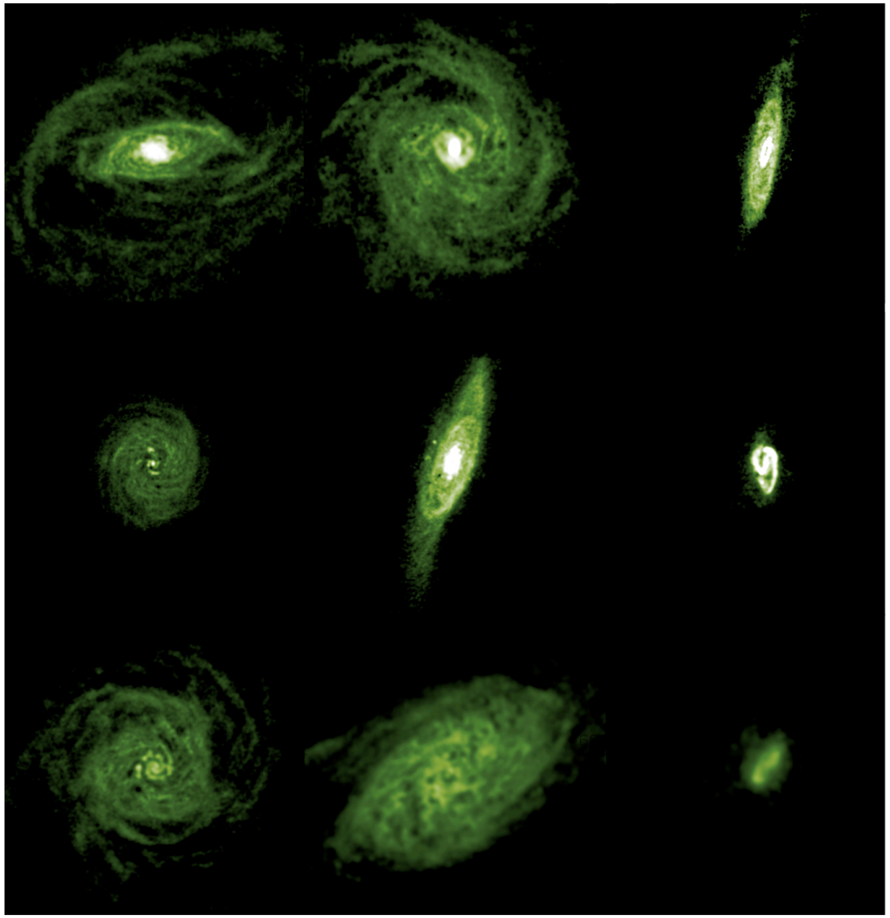
Results from Rotation Curves

- Stellar mass-to-light ratios derived using population synthesis and Spitzer data agree very well with "best fit" values
- No need for minimum/maximum disk assumptions
- NFW and ISO models fit bright galaxies equally well, but beware of M/L trade-offs
- Faint galaxies prefer ISO
- Non-circular motions are $< 2\%$ of V_{max}
- Elongation estimator of Dark Matter potential is compatible with **no** elongation

Star Formation Recipes in THINGS

How do SF Recipes Perform in THINGS?

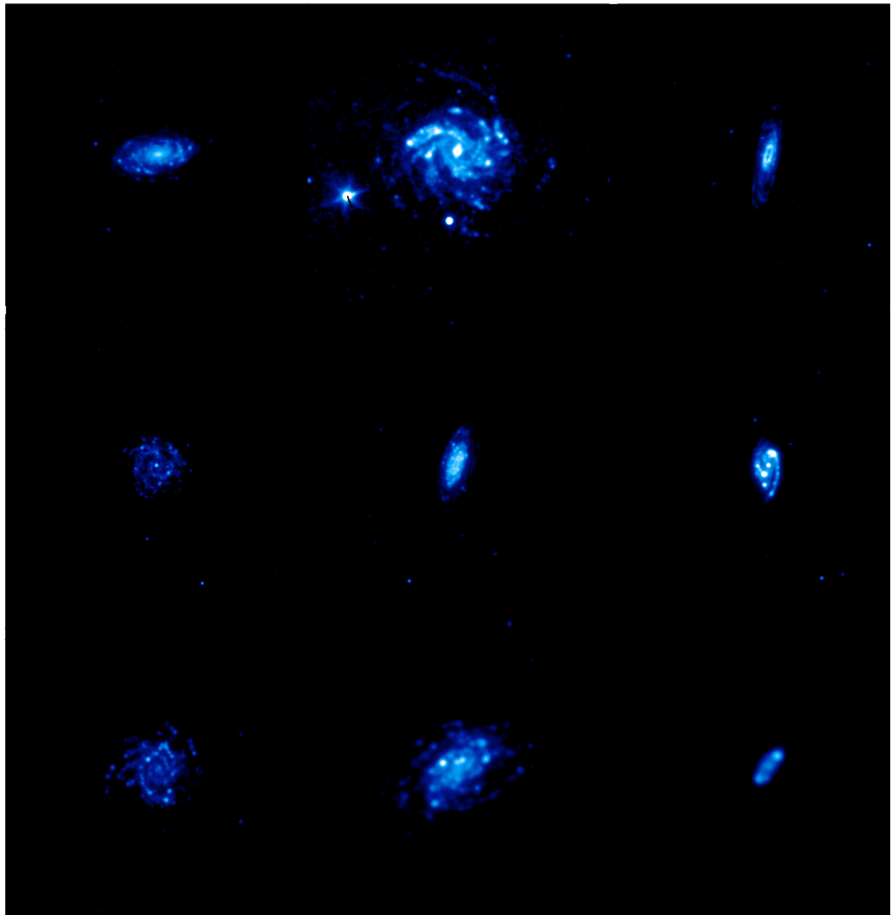
- Can we turn this…



Gas distributions from THINGS + IRAM 30-m HERA or BIMA SONG

How do SF Recipes Perform in THINGS?

- … into this?

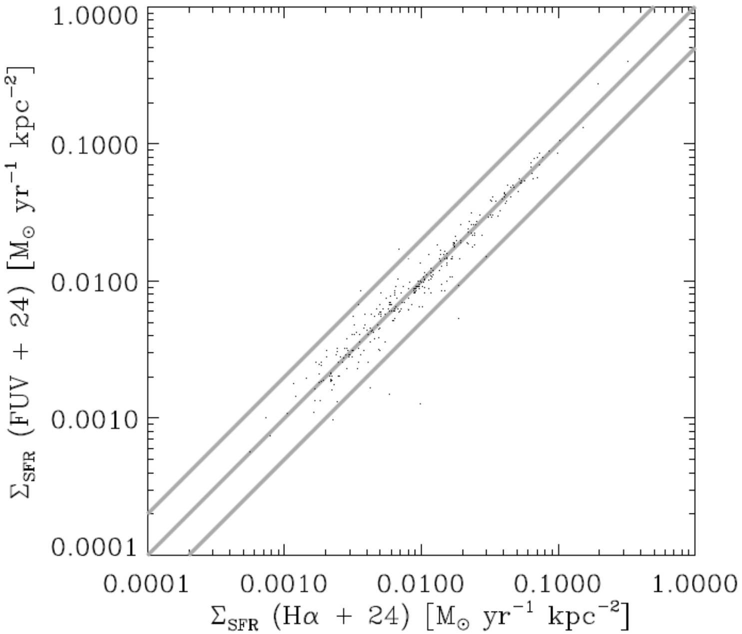


SFR distributions from GALEX + SINGS

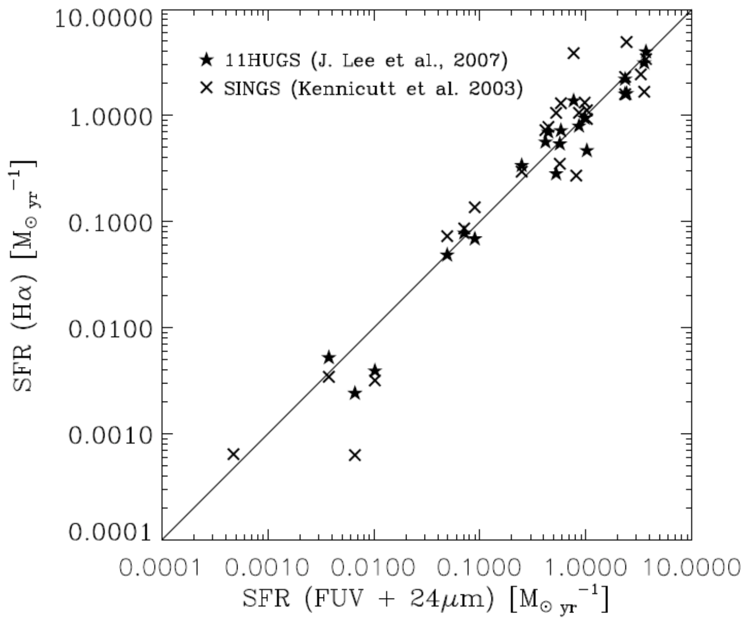
Star Formation Rate Maps

- use combination of UV and 24 μm [obscured and unobscured SF]
- Q: why not Hα? A: Availabilty and FOV; sensitivity at large R

$$\frac{SFR_{\rm Total}}{\rm M_{\odot}\ yr^{-1}} = 0.68 \times 10^{-28}\ \frac{L_{\nu}\,({\rm FUV})}{\rm erg s^{-1}\ Hz^{-1}} + 2.38 \times 10^{-42}\ \frac{L\,(24\mu{\rm m})}{\rm erg s^{-1}}$$



Hα + 24μm Calibrated by
Calzetti et al. 2007

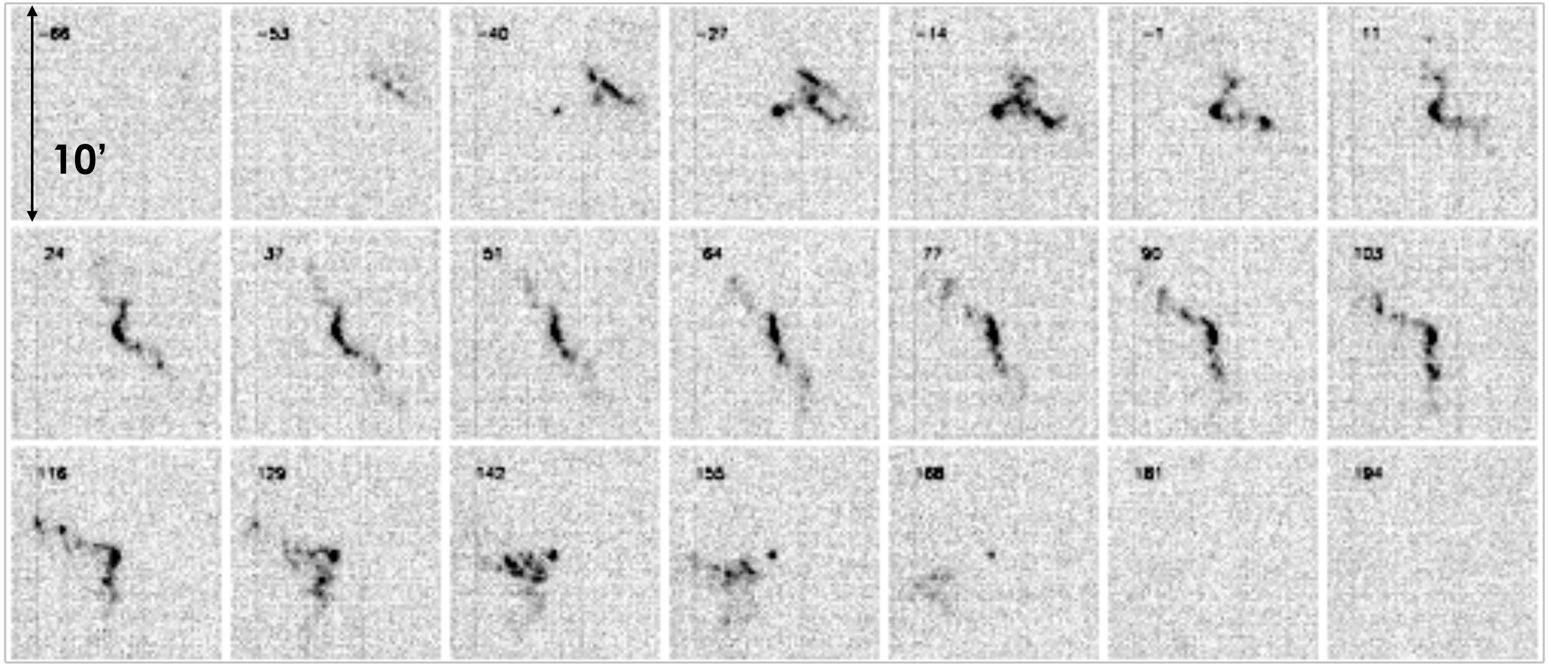


Leroy, Bigiel et THINGS

The missing piece: Molecular Gas

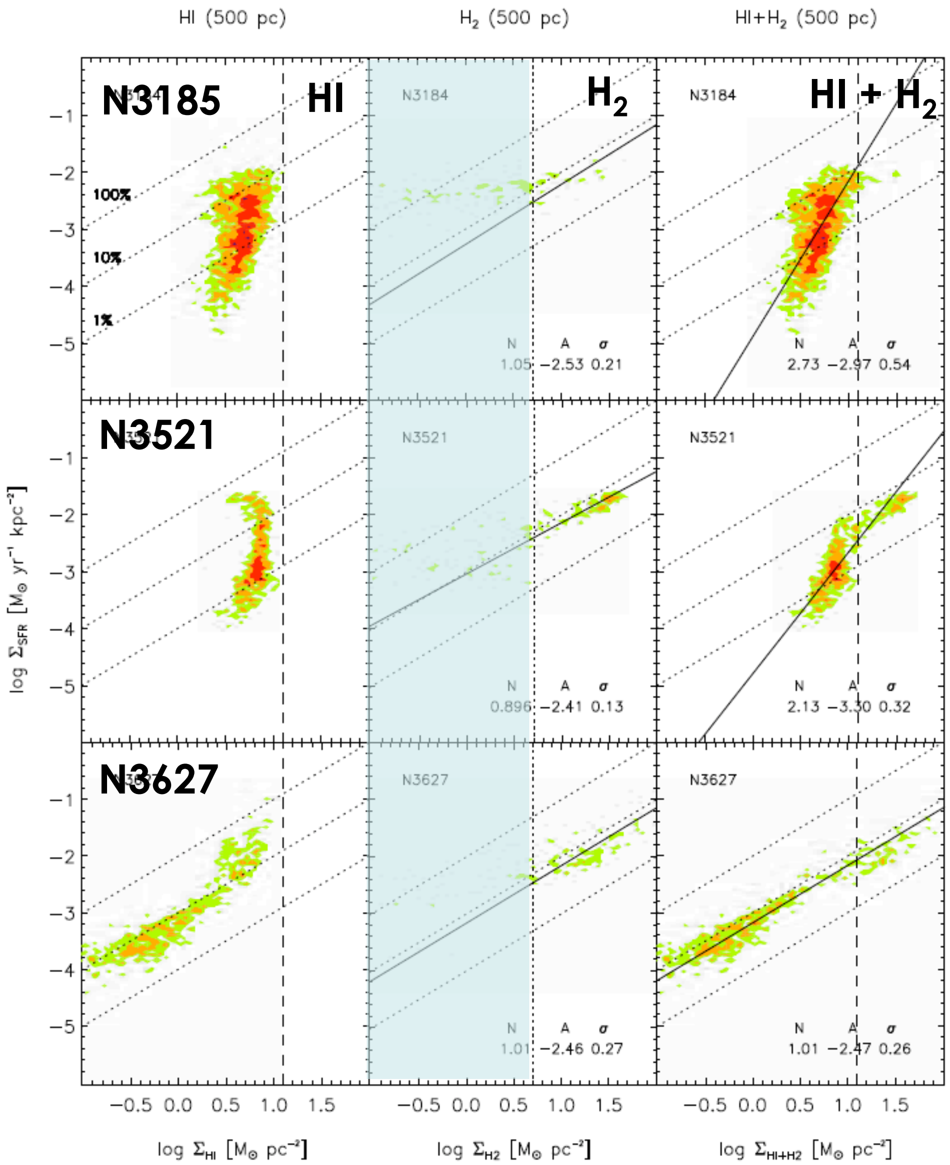
THINGS CO survey

Ongoing CO survey at IRAM 30-m telescope using HERA array:
Example: CO(2-1) channel maps in NGC 6946
Proposal approved to map ~15 THINGS galaxies



Schmidt-Kennicutt Law in THINGS

SFR vs. Gas Density - Pixel by Pixel



Testing
Schmidt-Kennicutt Law
on 500 pc scales

$SFR \sim \Sigma^{N}_{gas}$

H_2: N~1

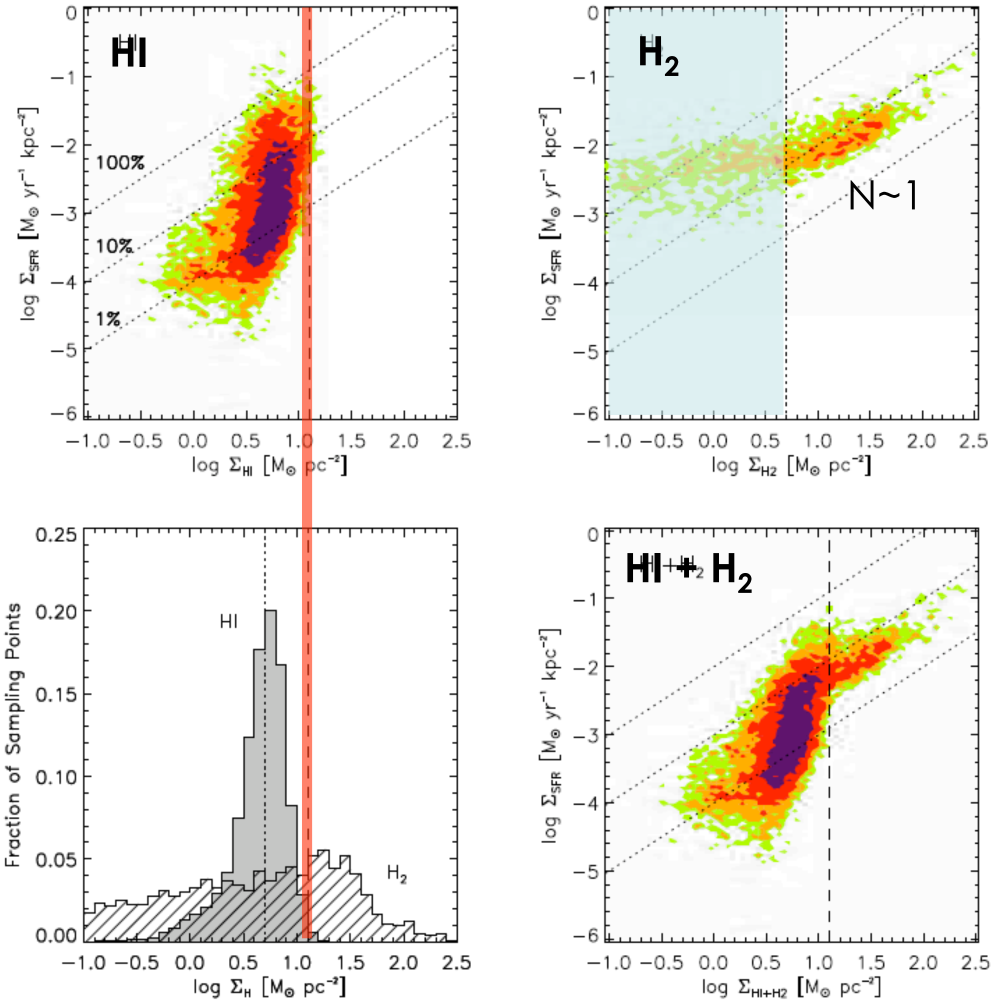
HI: N>1
but: slope driven by
radial dependence
…

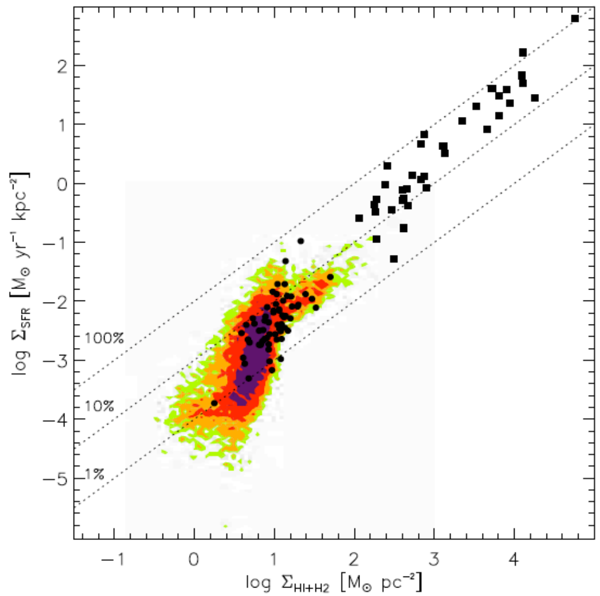
Bigiel et THINGS, 2008

Schmidt-Kennicutt law in THINGS

SFR vs. Gas Density - all THINGS spirals

all THINGS galaxies



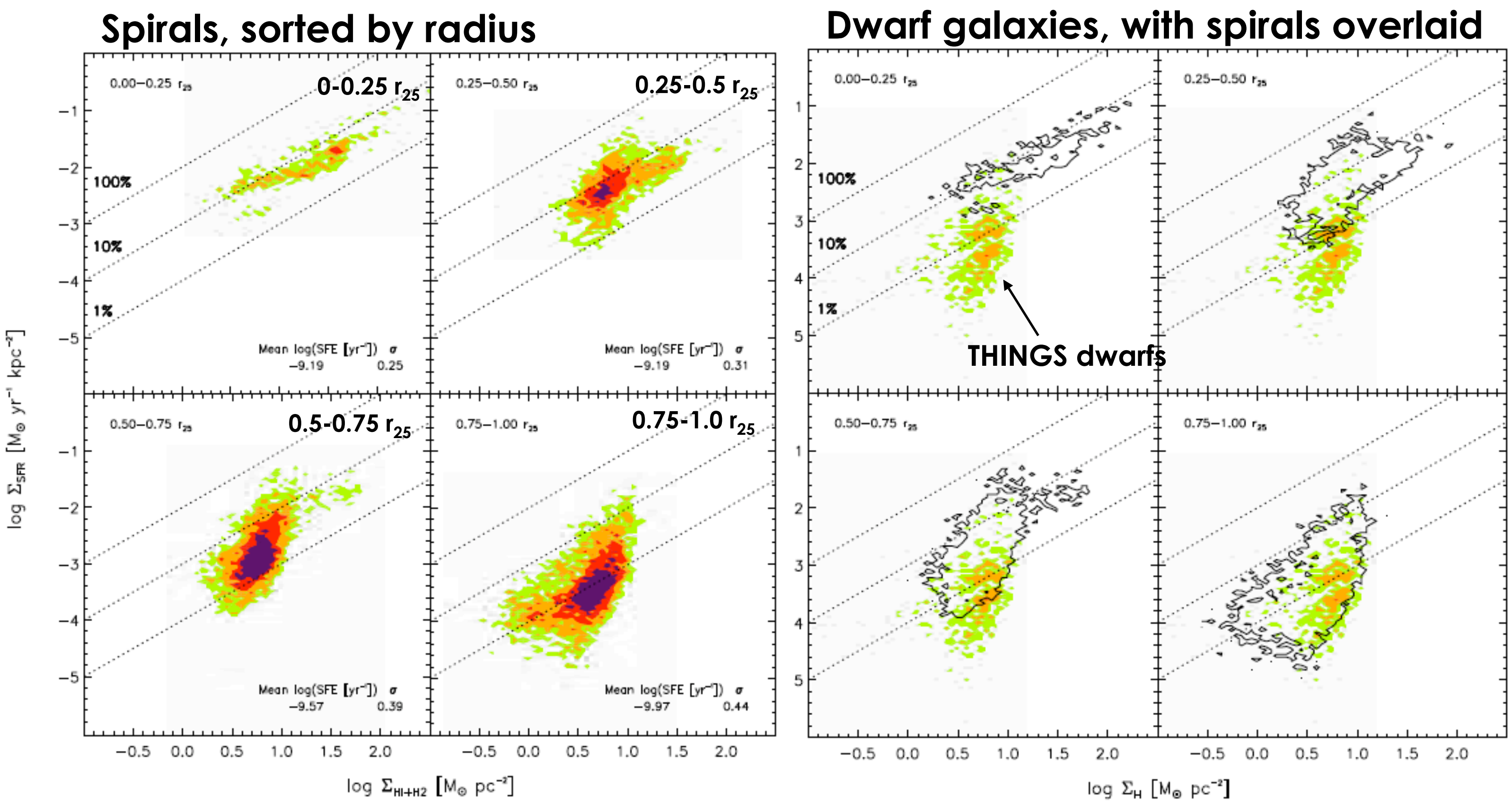


Colour contours: THINGS
Black points: Kennicutt '98

Bigiel et THINGS

Schmidt-Kennicutt law in THINGS

Radial dependence of SFR vs Σ_{gas}

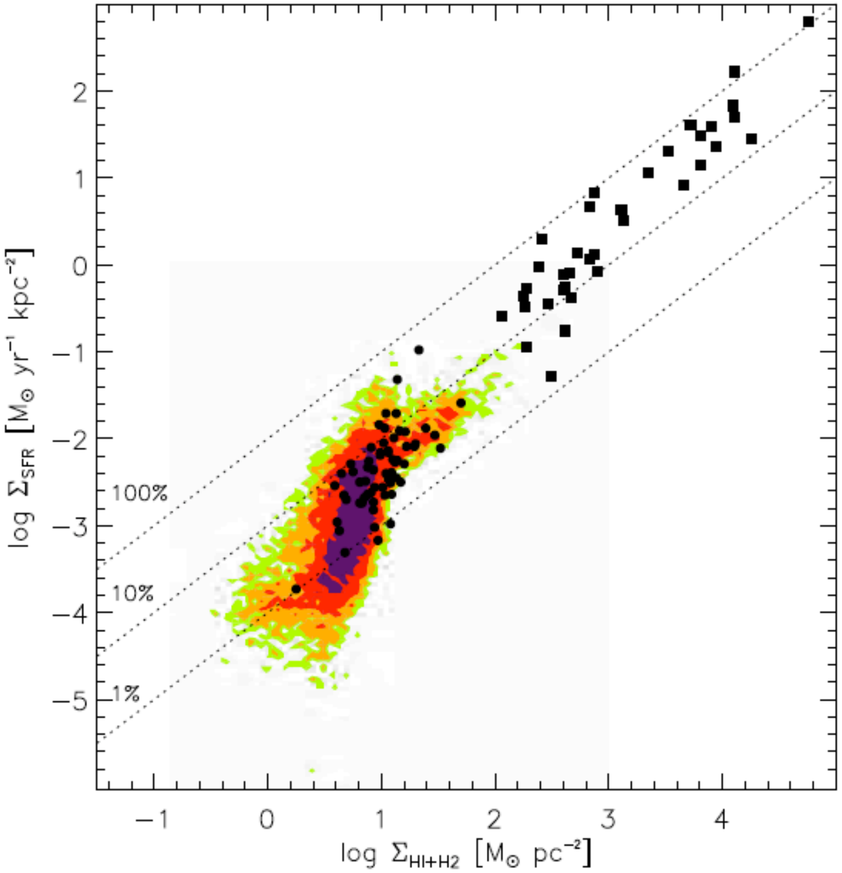


Clear radial dependence
SFR drops as f(radius)

->Dwarf galaxies resemble outer regions of galaxies [shear can not be reason why!]

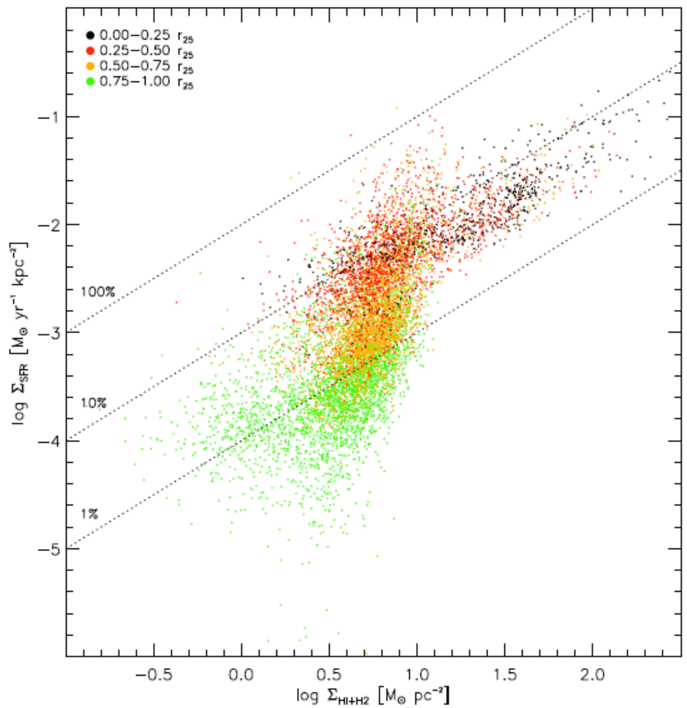
Schmidt-Kennicutt law in THINGS

Radial dependence of SFR vs Σ_{gas}



Colour contours: THINGS
Black points: Kennicutt 1998

Radial dependence of SFR



Bigiel et THINGS

Results on SF law

- HI turns almost completely molecular above 9 $M_{\odot}$ pc^{-2} (12 $M_{\odot}$ pc^{-2} when including He)

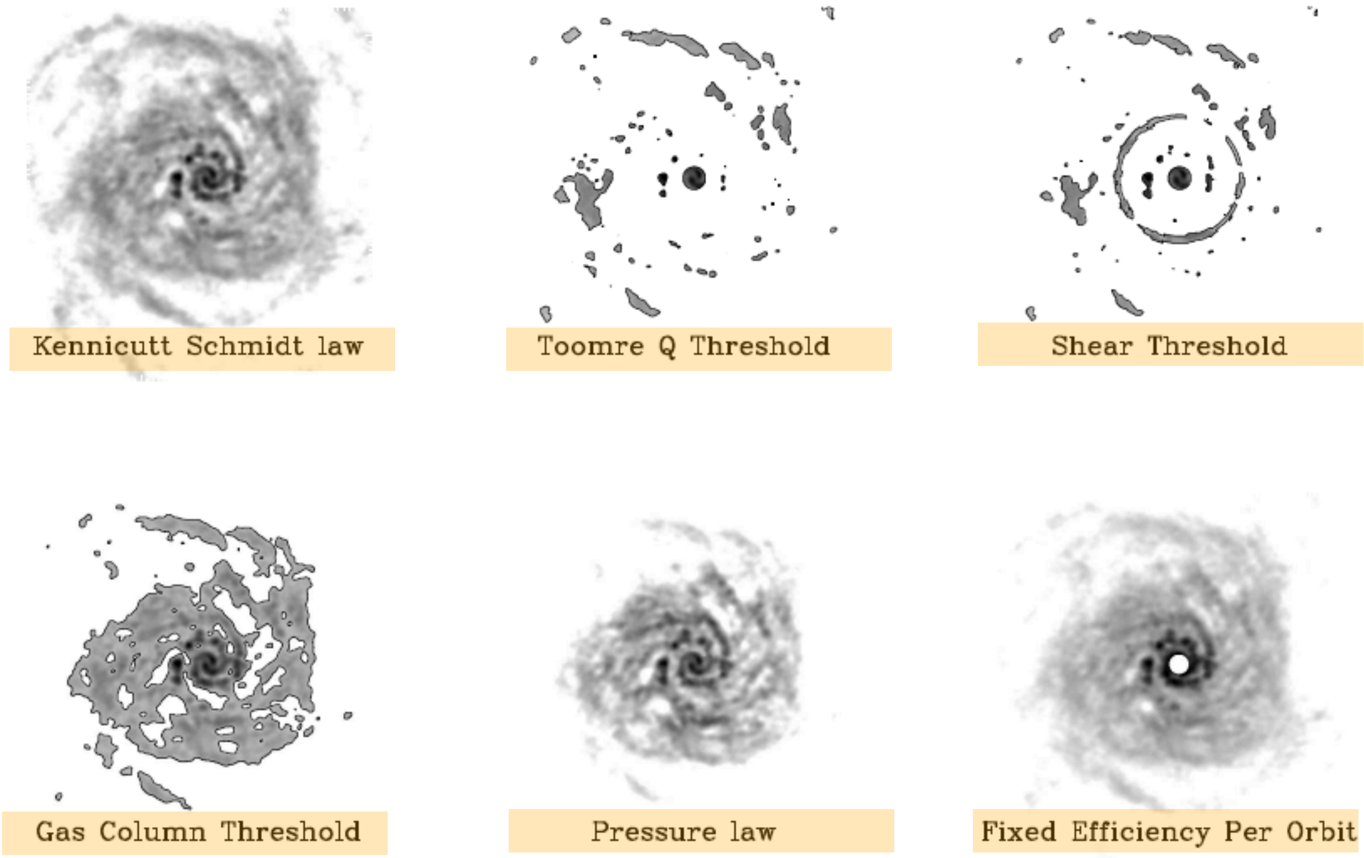
- Where gas is predominantly molecular, the Schmidt-Kennicutt law has a powerlaw index N = 1.05±0.20

- In this regime the SFE is constant; the gas depletion time corresponds to 1.8 x 10^9 yr

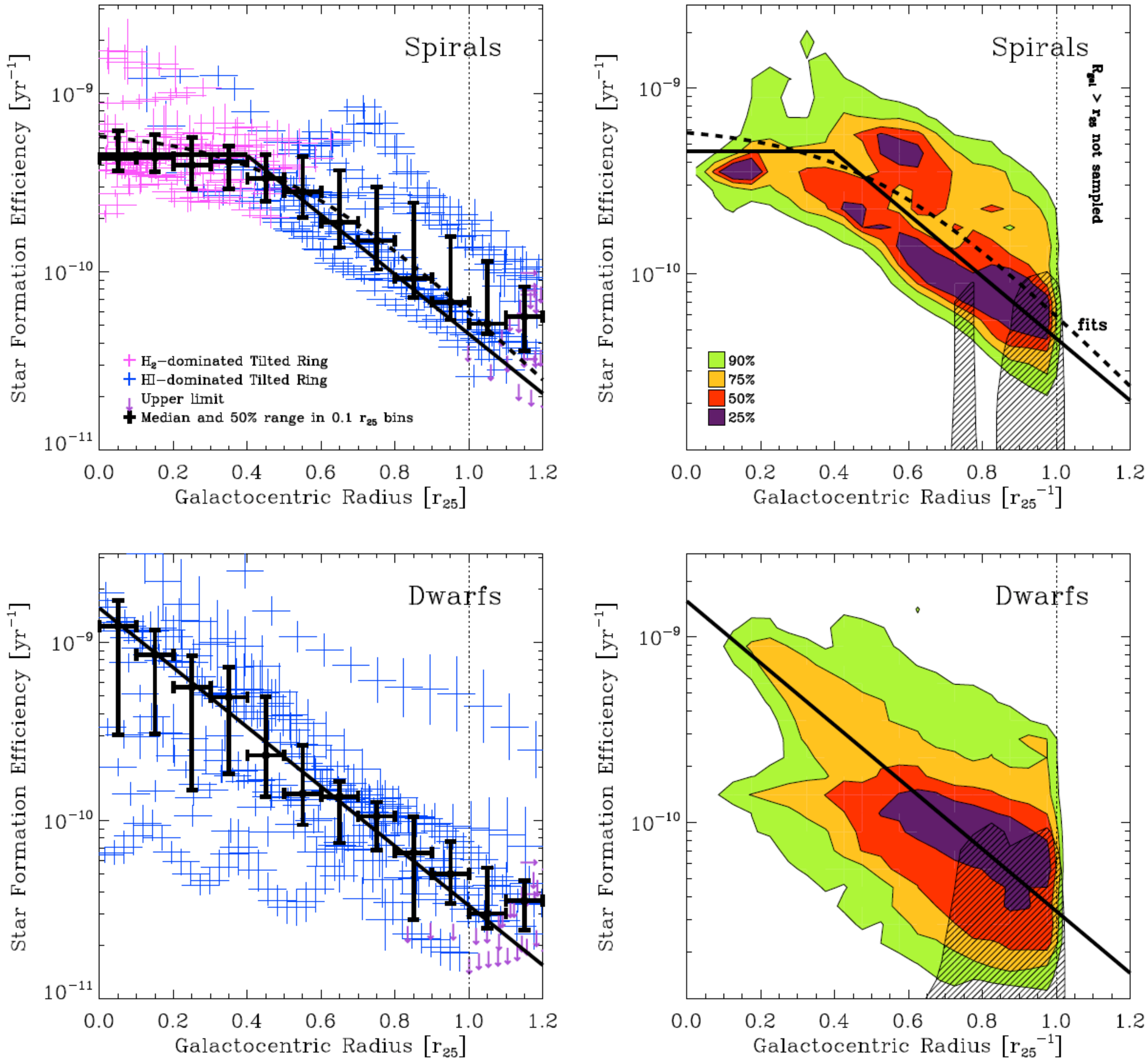
- Where HI dominates, SF is less efficient, the efficiency decreasing monotonically with radius

Prediction Maps - NGC 628

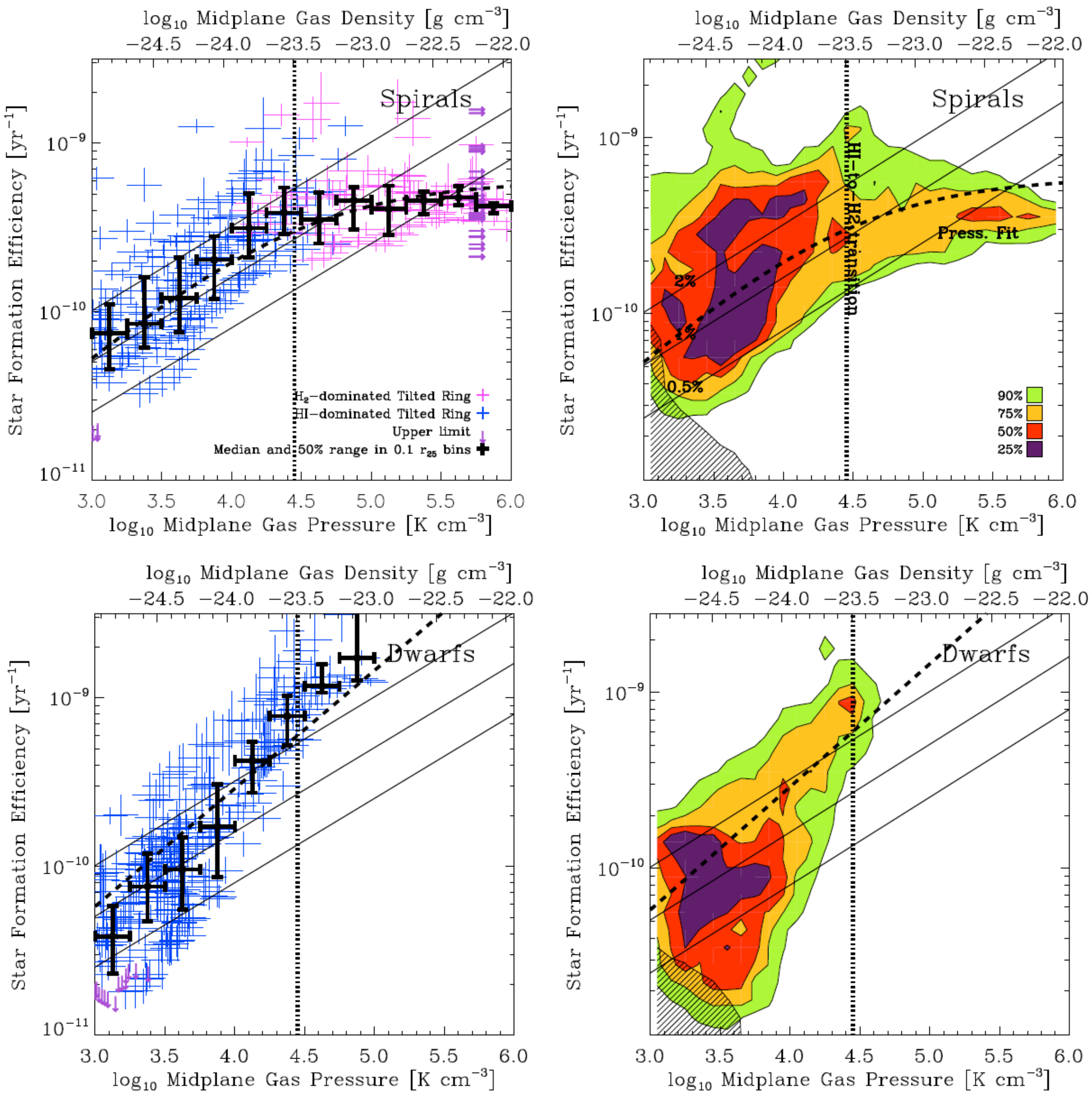
- "Prediction maps" for various SF recipes: example: NGC628



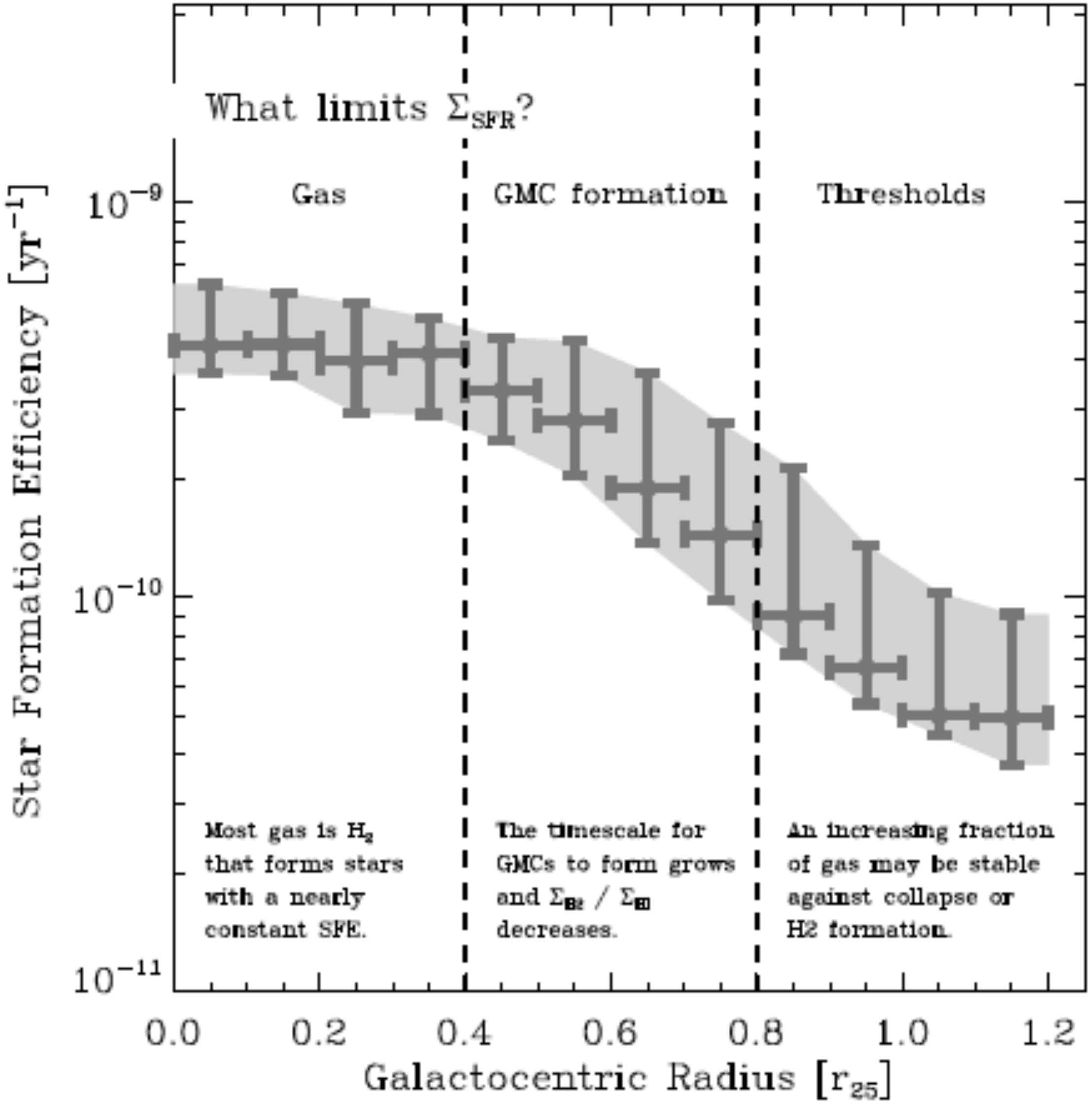
Star Formation Recipes in THINGS



Star Formation Recipes in THINGS



Star Formation Recipes in THINGS



Leroy et THINGS, 2008

More results on SF law

- Where gas is predominantly molecular, the SFE is constant; the gas depletion time corresponds to 1.8 x 10^9 yr. There is no dependence on radius, gas or stellar surface densities, mid-plane pressure, Toomre-Q, etc.

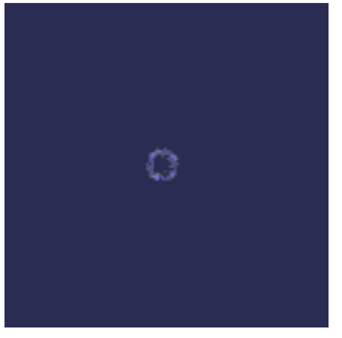
- Where HI dominates, SF is less efficient, the efficiency decreasing monotonically with radius. SFE is set by the ratio of H_2/HI gas surface densities

- Below a set HI surface density, gas might be stable against GMC formation and SF dies out

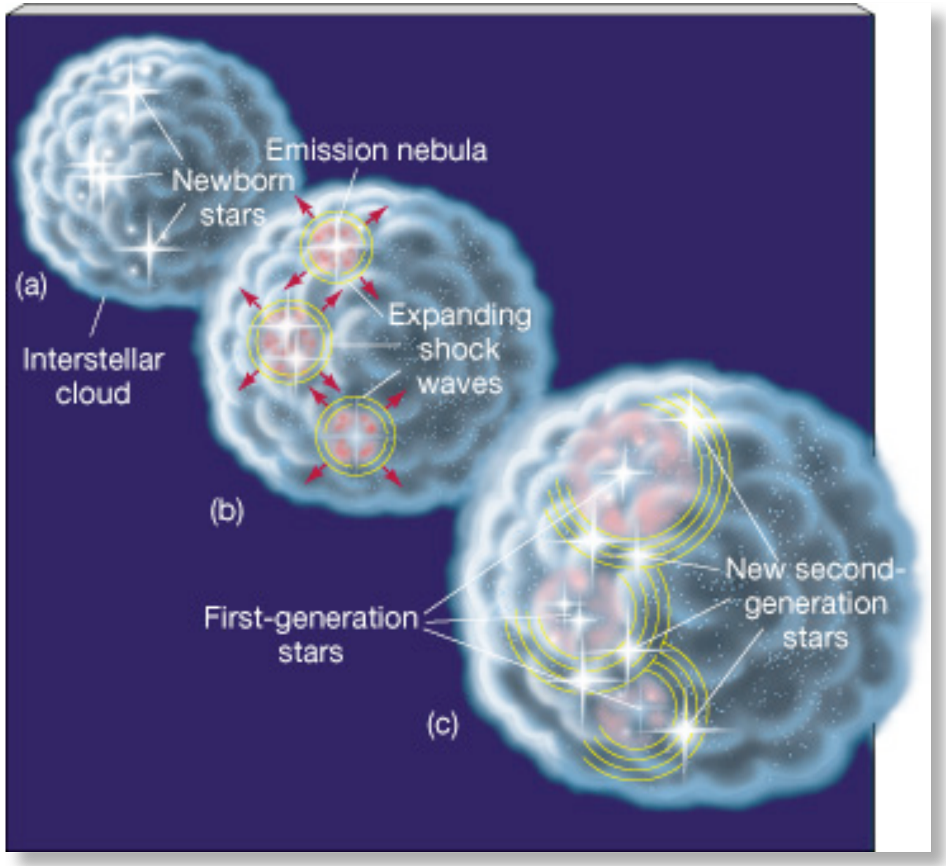
- Basically, GMC formation is set by mid-plane pressure which in turn depends most directly on stellar surface density

- Toomre-Q is not a good predictor for a SF threshold

The Violent Interstellar Medium in Nearby Galaxies



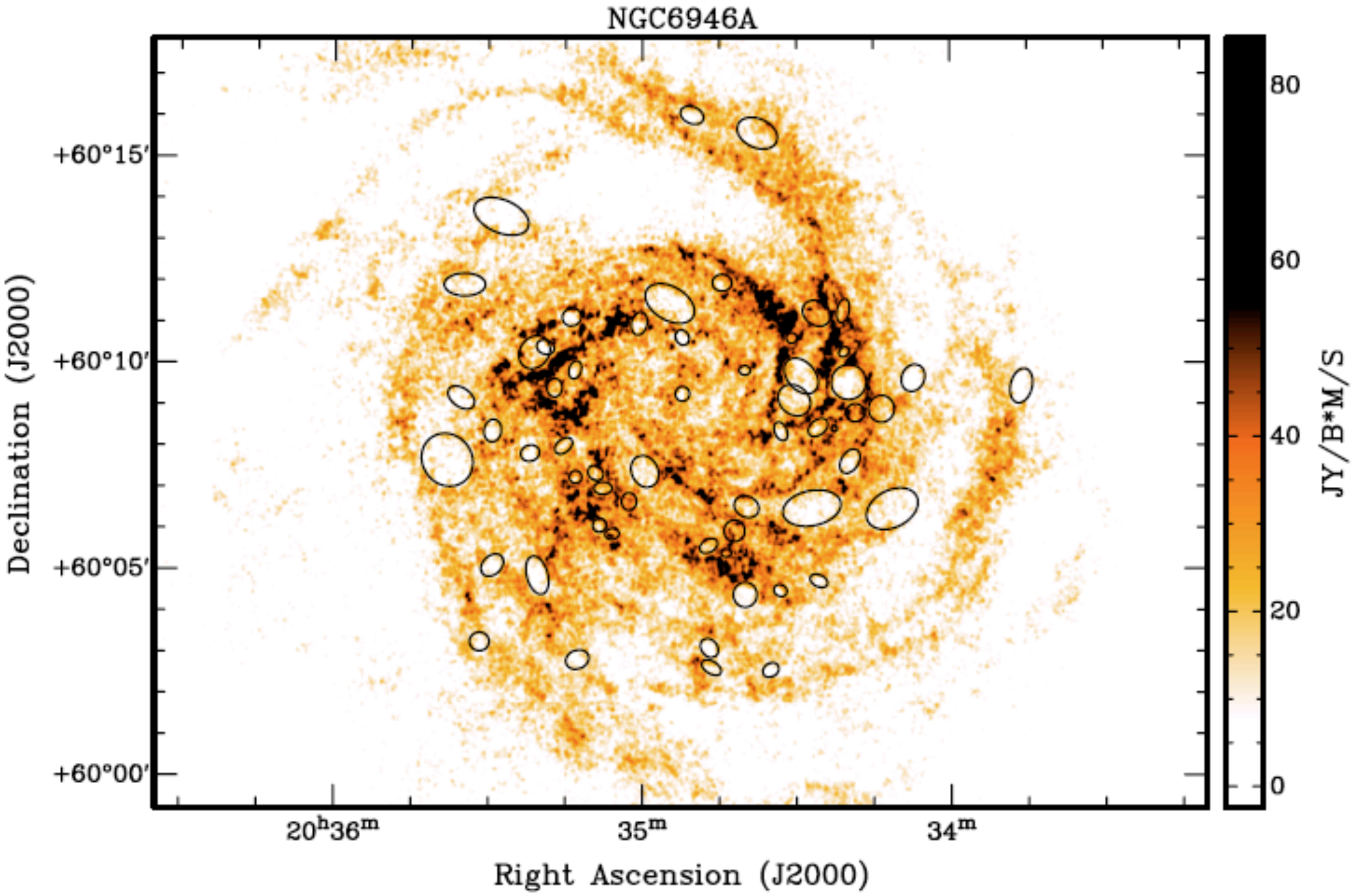
HI holes in THINGS



Up to several hundred SNe explode within a small (few tens of pc) volume and within a short (<50 Myr) time, creating ~100pc to 1-2 kpc large cavities.

HI holes in THINGS

Structure of the ISM (Holes and Shells)



Bagetakos et THINGS

HI holes in THINGS

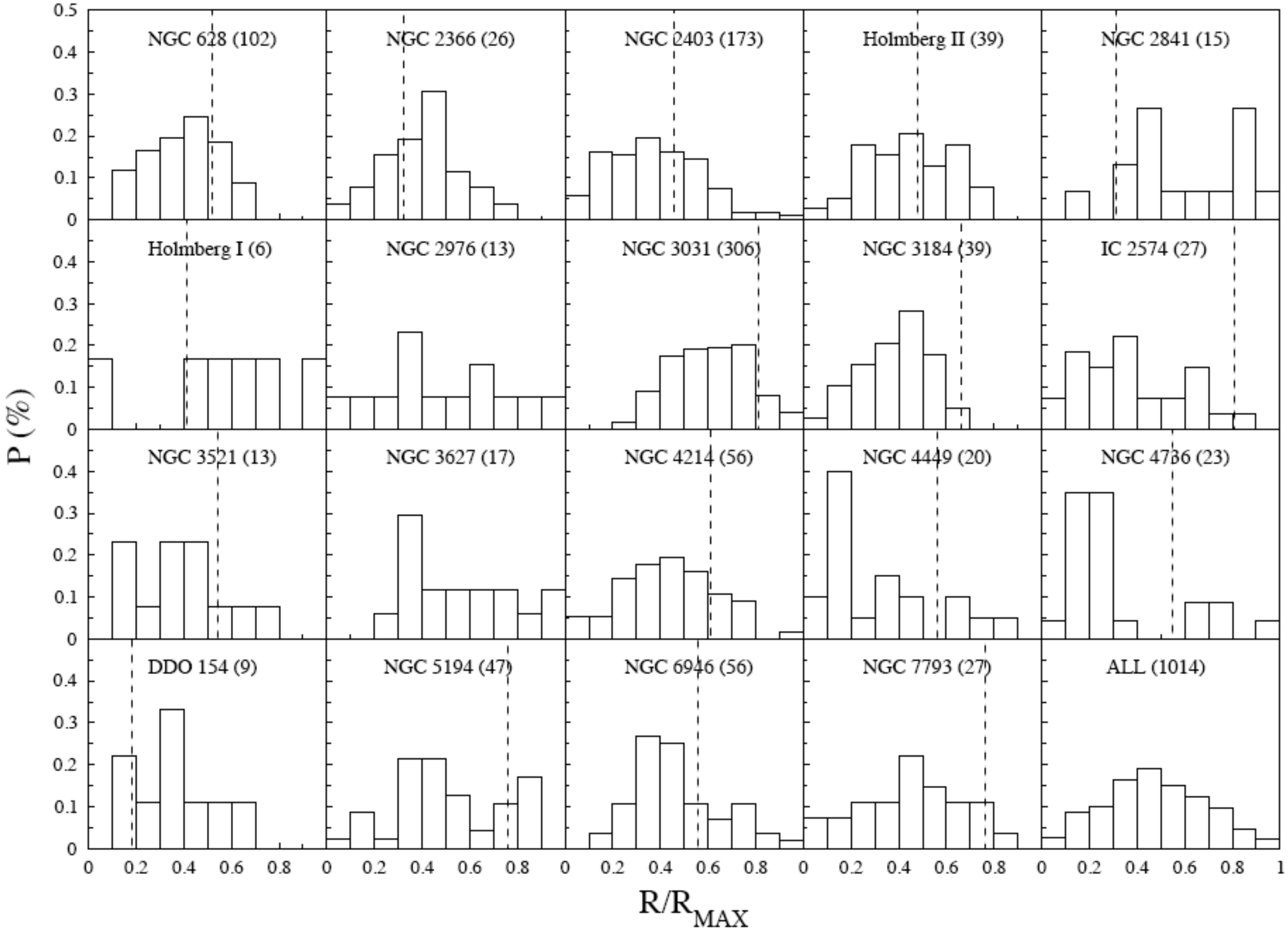
Observational evidence for SN origin:

- expanding Hα shells
- OB associations or remnant cluster
- associated coronal gas (X-rays)
- associated UV (GALEX NGS)
- CO and HII regions coinciding with HI rims

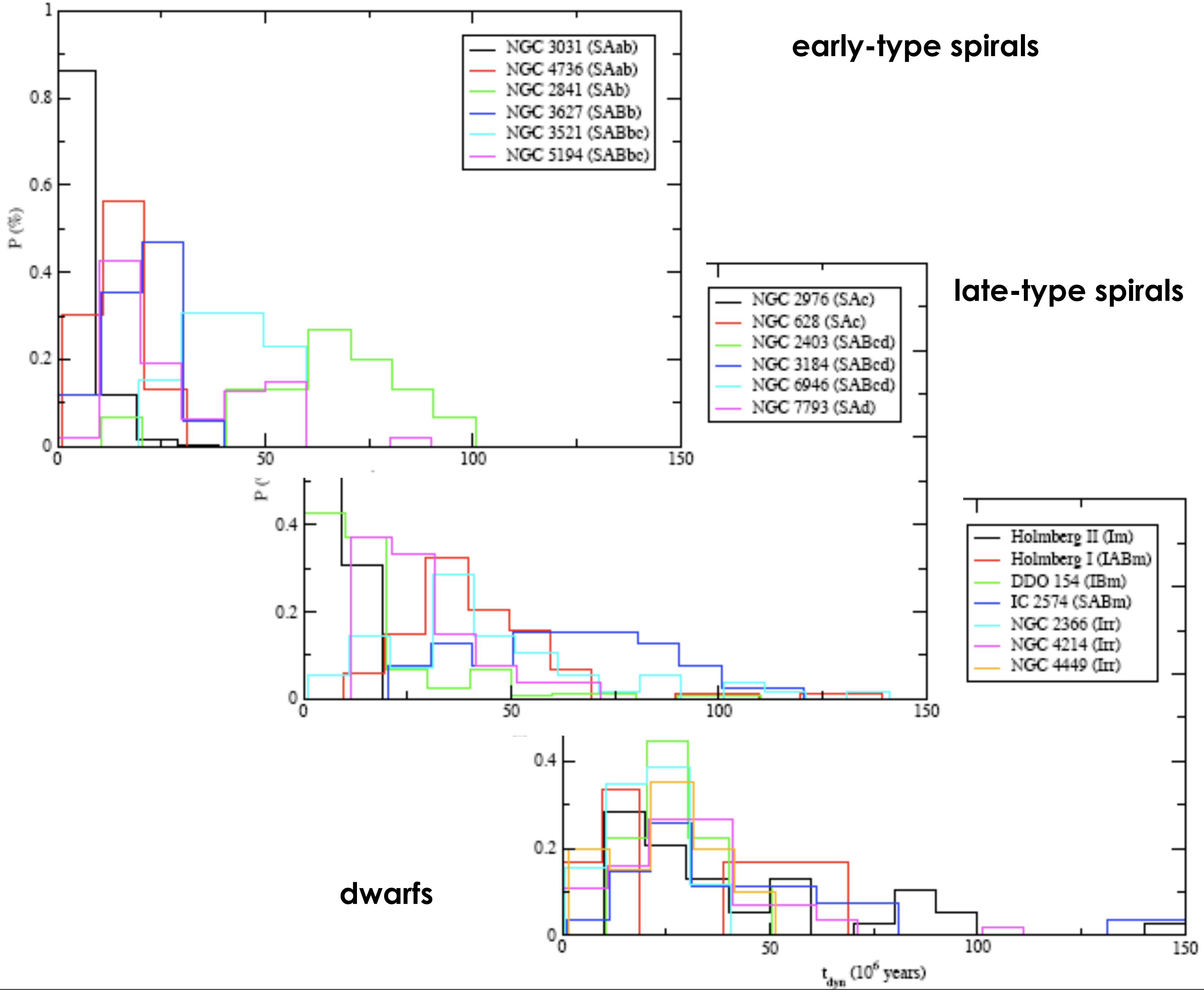
From theory:

- energetics commensurate with SN origin
- hydrodynamical and MHD simulations can explain SN-powered shells
- Superbubble size distribution fits prediction from HII region luminosity function

HI holes in THINGS



HI holes in THINGS



Results on HI holes

- ~1000 holes identified in 20 galaxies

- Relations with Hubble Type
  - Holes in dwarfs are larger then in spirals
  - Holes in dwarfs are older than in spirals

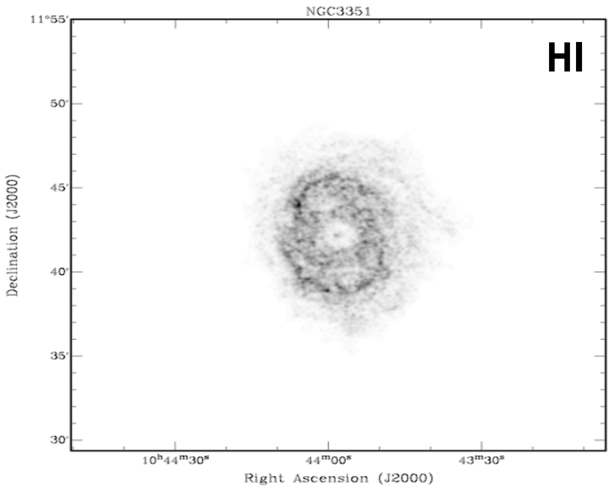
- Energy input in ISM is independent of Hubble type

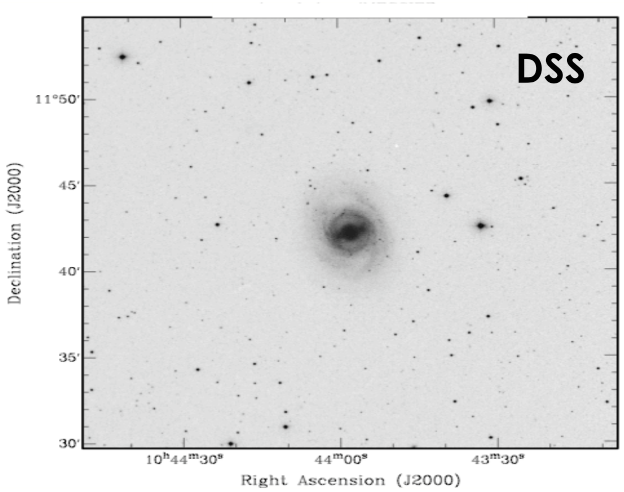
- Can be used as a measure for SN rate and SFR

- Determine the 2-D and 3-D porosity of the ISM

The Edges of THINGS

Where do galaxies end?



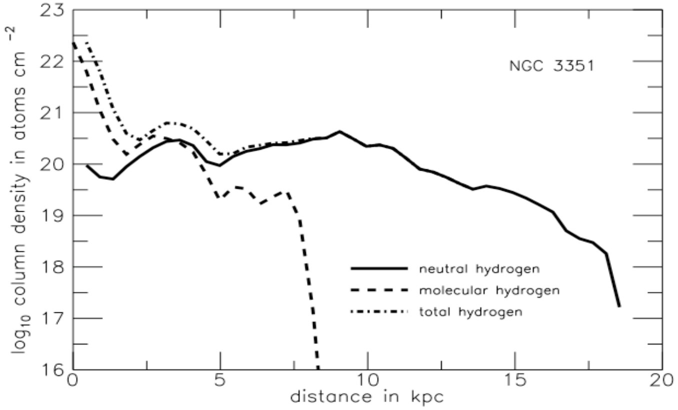


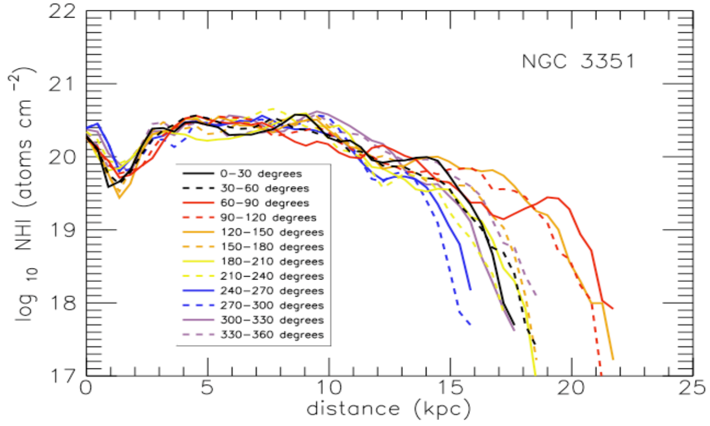
NGC 3351

Portas et THINGS

The Edges of THINGS

Radial gas column density profiles





Azimuthally averaged, radial HI profiles

HI: solid line

H_2: dashed line

HI+H_2: dot-dash line

HI radial profiles in 30° sectors

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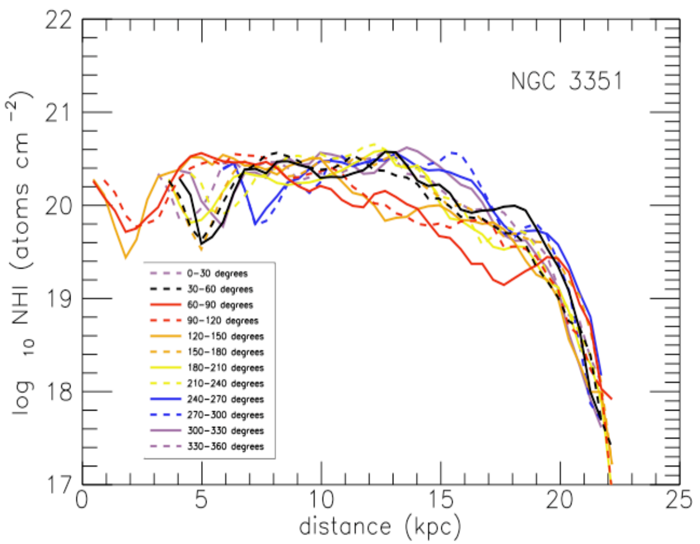
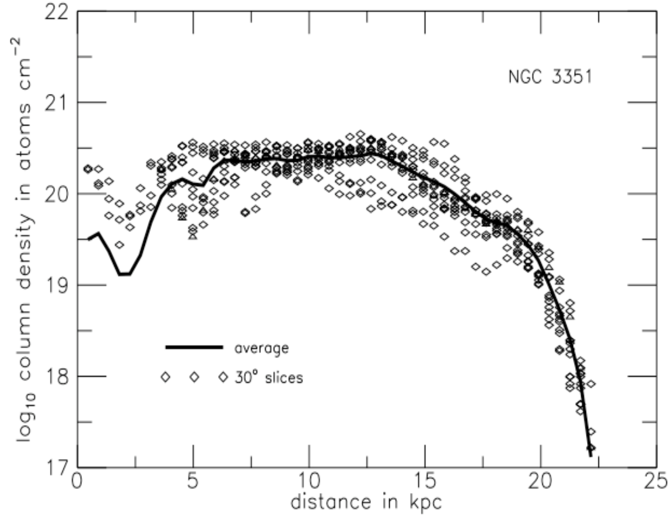
Radial gas column density profiles



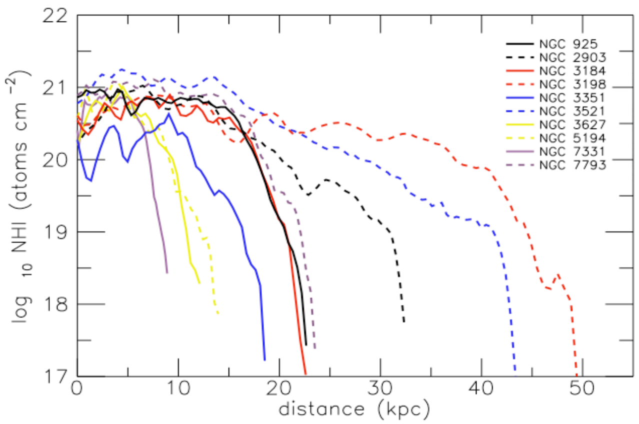
Radial profiles in sectors, shifted so as to align their edges.



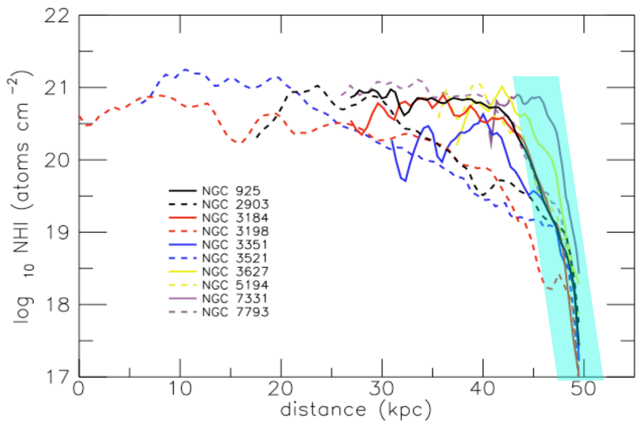
Same as left panel; the drawn line is the average of all segments.

Portas et THINGS

Ionisation by the Extragalactic Radiation Field?



Azimuthally averaged radial profiles of all targets based on a 30° sector along the major axis.



Same as left panel, but shifted so as to align their outer edges.

Portas et THINGS

Results on HI edges

- HI disks have a well-defined edge
- Edge of the disk within a galaxy is dependent on azimuth within a galaxy
- Edges of individual galaxies are similar
- HI edge can be parameterised by a Sersic-type $r^{1/n}$ profile
- Ionisation by an extragalactic radiation field doesn't seem a plausible explanation as the edge "sets in" at too high a column density value (few x 10^{20} atom cm^{-2} versus few x 10^{19} atom cm^{-2} for ionisation)

THINGS Summary

Summary

- THINGS: HI survey providing data of uniform quality

- High-quality rotation curves:
  - no declining curves
  - non-circular motions small; no DM halo elongation
  - ISO halos preferred over NFW for low-mass galaxies

- Improved understanding about SF
  - Schmidt-Kennicutt Law --> N=1.05+/-0.2 for $R < 0.4r_{25}$
  - SFR/E drops dramatically for larger R
  - mid-plane pressure drives H_2/HI and hence GMC formation
  - SFE fixed where H_2 dominates

- HI holes compatible with SN origin --> SN and SF rate

- HI edges are sharp …but not due to ionisation by the extragalactic radiation field

Future

- Data release: imminent!

- THINGS-South in progress

- Future VLA HI surveys @ same resolution/sensitivity:

  2 large VLA NRAO programs (2007 -):

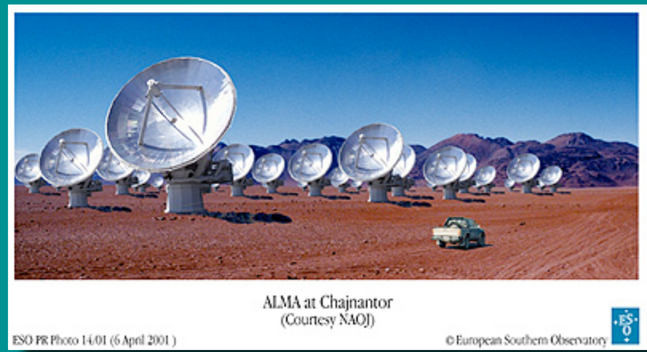
  - Little THINGS (PI: D. Hunter): dwarf sample
  - VLA-ANGST (PI: J. Ott): D < 4 Mpc

  Soon of order ~1500 hours at VLA, ~120 galaxies at 6'' resolution / high sensitivity available. This is at the limit of what is possible with state of the art instruments (VLA, WSRT, GMRT, ATCA)

--> **next major leap: SKA**

Expanded VLA

Low Frequency Array



ALMA

Combined Array for Millimeter Astronomy

Allen Array

e-MERLIN

What is the value of THINGS?

THINGS a benchmark for the SKA

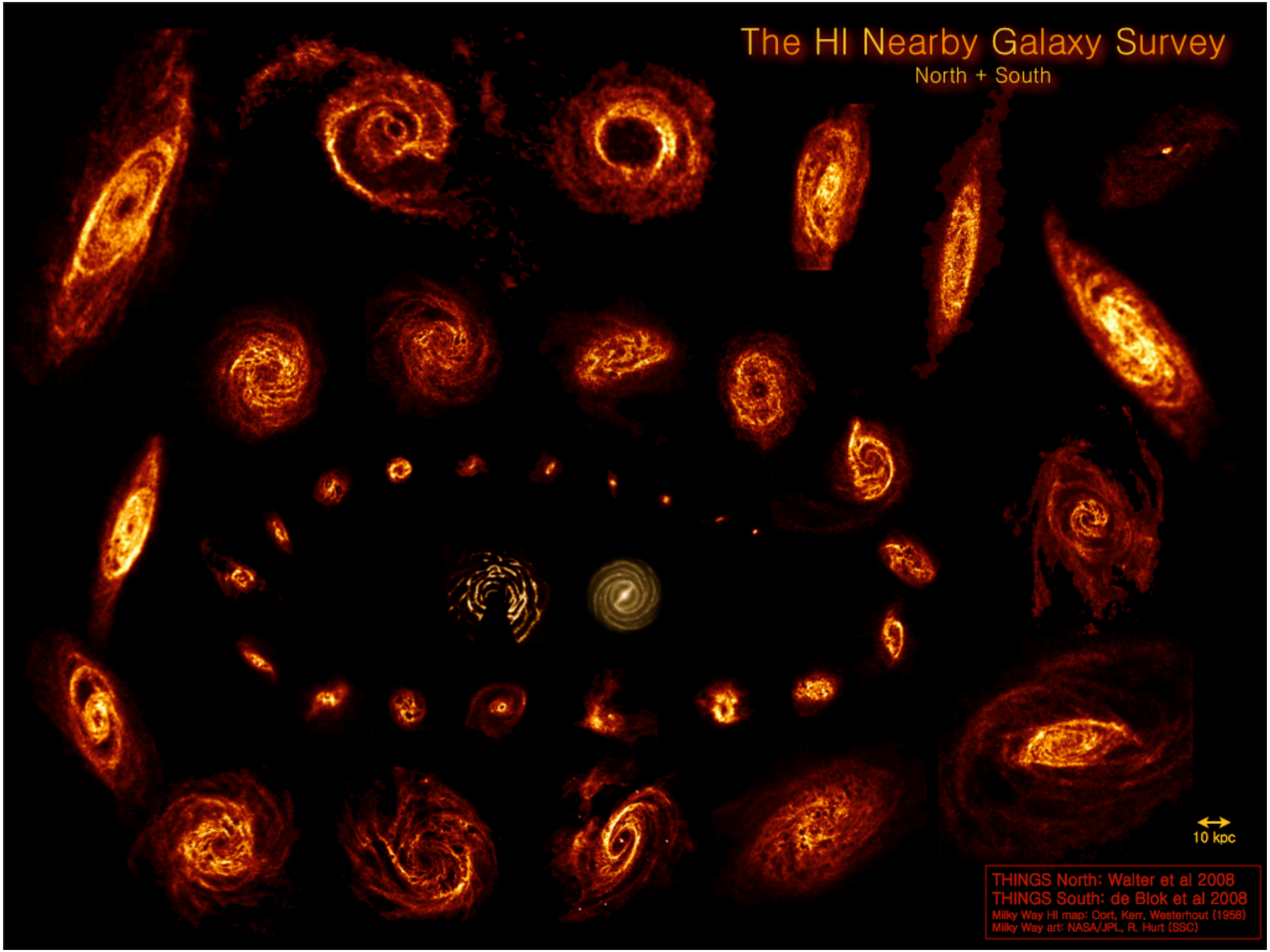
THINGS represents the ultimate of what is possible with current instruments and provides a *window* on what will become possible routinely with an SKA in the Local Universe, *and* across a vastly increased volume of the Universe out to where evolutionary effects become evident. An SKA will allow us to:

- in 24hr achieve the same sensitivity as THINGS at 1" and 10 km s^{-1} out to Coma (~100 Mpc)

- do resolved, few kpc, studies out to z = 0.2 - 0.5 (2.4 - 5 Gyr look-back time) at 0.5-0.6" or 1.7 to 4 kpc resolution; HI mass limit 6-8 10^8 $M_\odot$ (or 1/10th MW)

- push down to 4 x 10^{17} at cm^{-2} --> cosmic web

- search for extra-planar HI (galactic fountain, HVC, etc.)


The HI Nearby Galaxy Survey
North + South
10 kpc
THINGS North: Walter et al 2008
THINGS South: de Blok et al 2008
Milky Way HI map: Oort, Kerr, Westerhout (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)

The End