The Neutral Atomic Interstellar Medium in the Nearby Universe

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THINGS

LITTLE THINGS

VLA-ANGST

LVHIS

SHIELD

FIGGS

SPARC

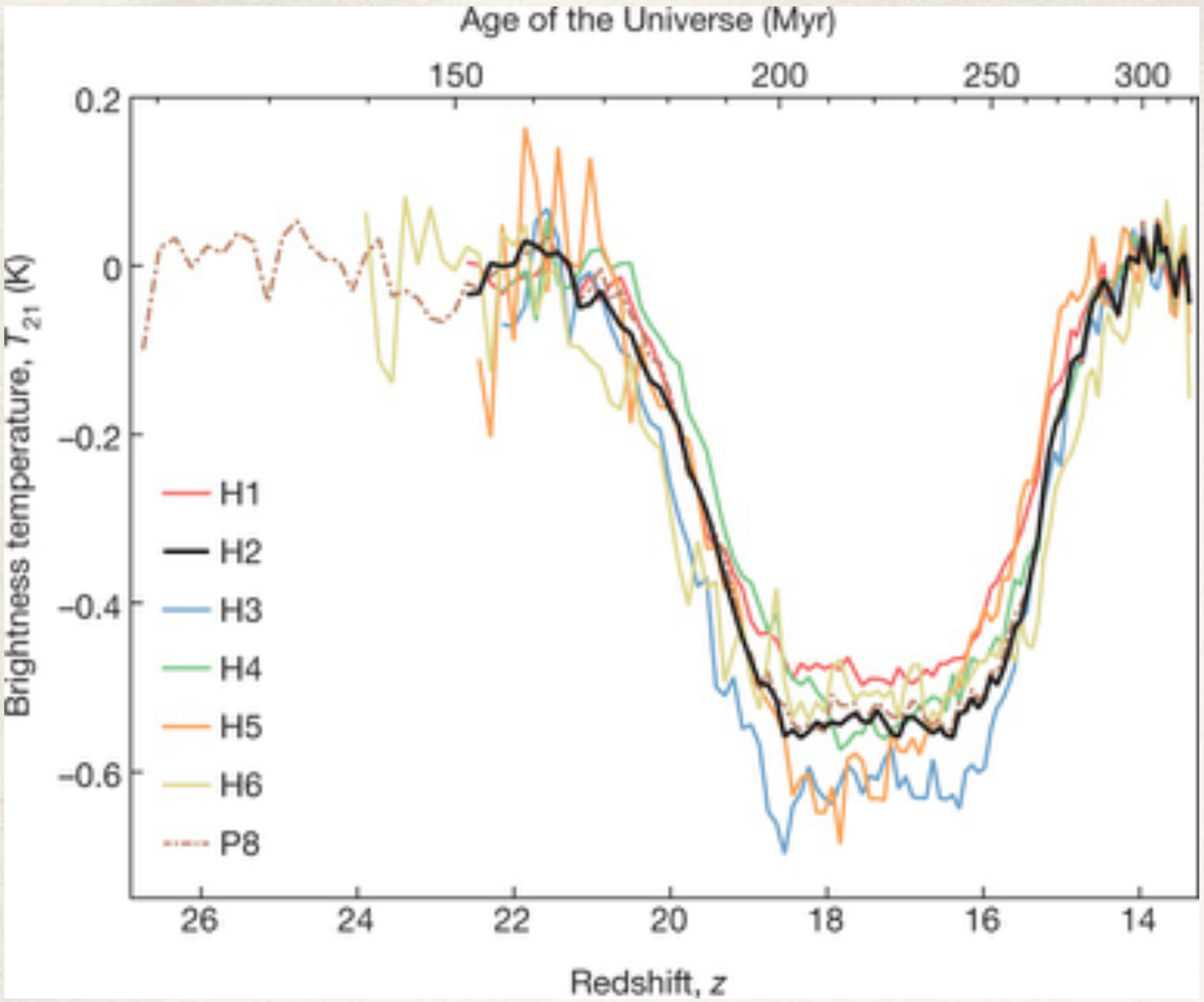
VIVA

HALOGAS

CHILES

WALLABY

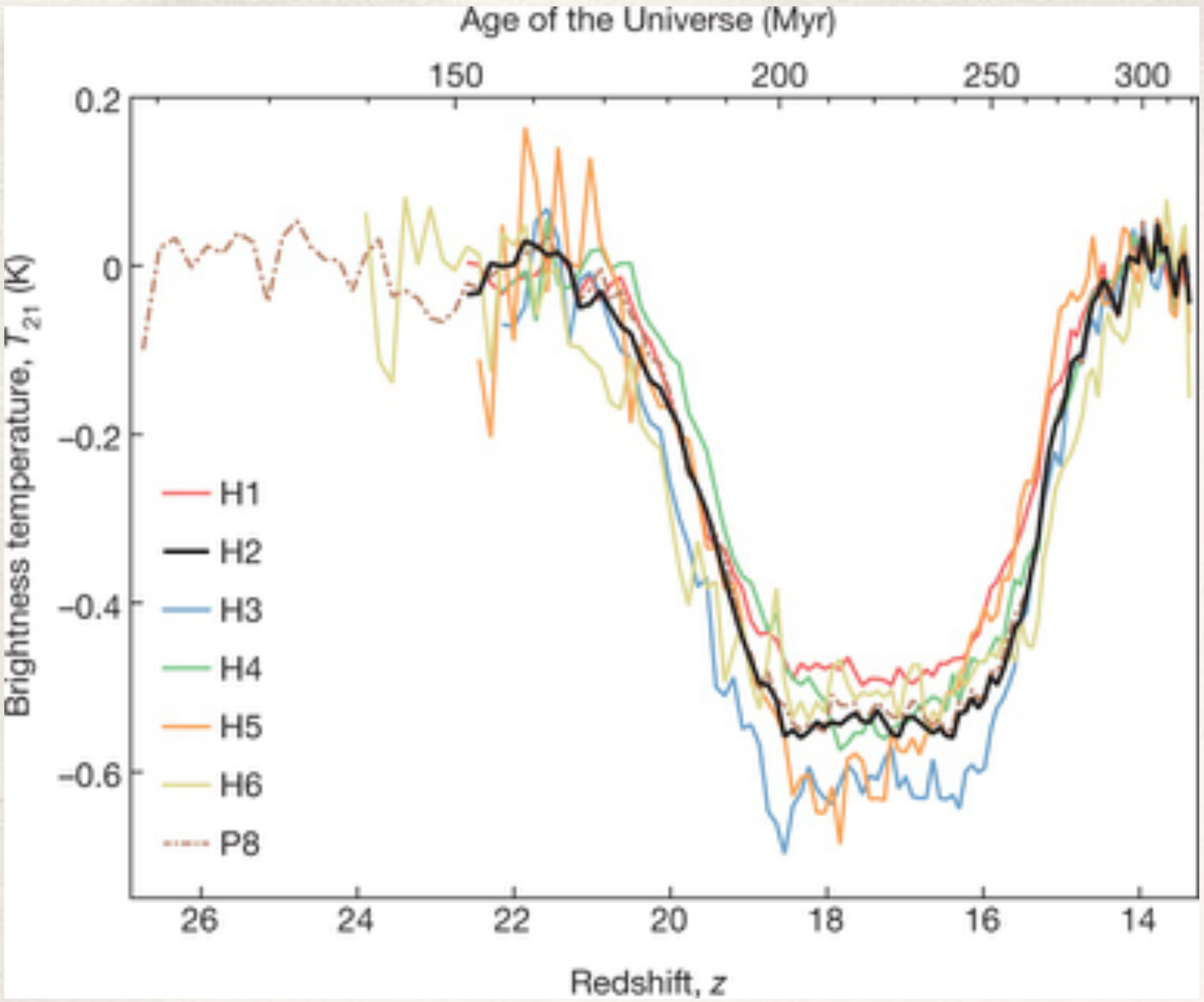
MHONGOOSE



Cosmic dawn?

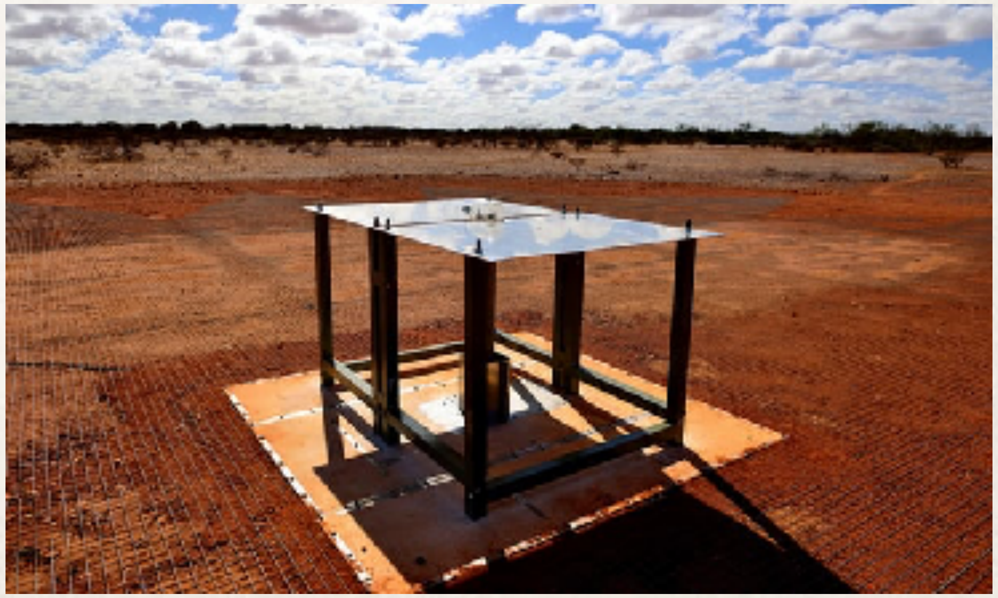
Bowman et al. **Nature** 555, 67–70 (2018)

Cosmic dawn?

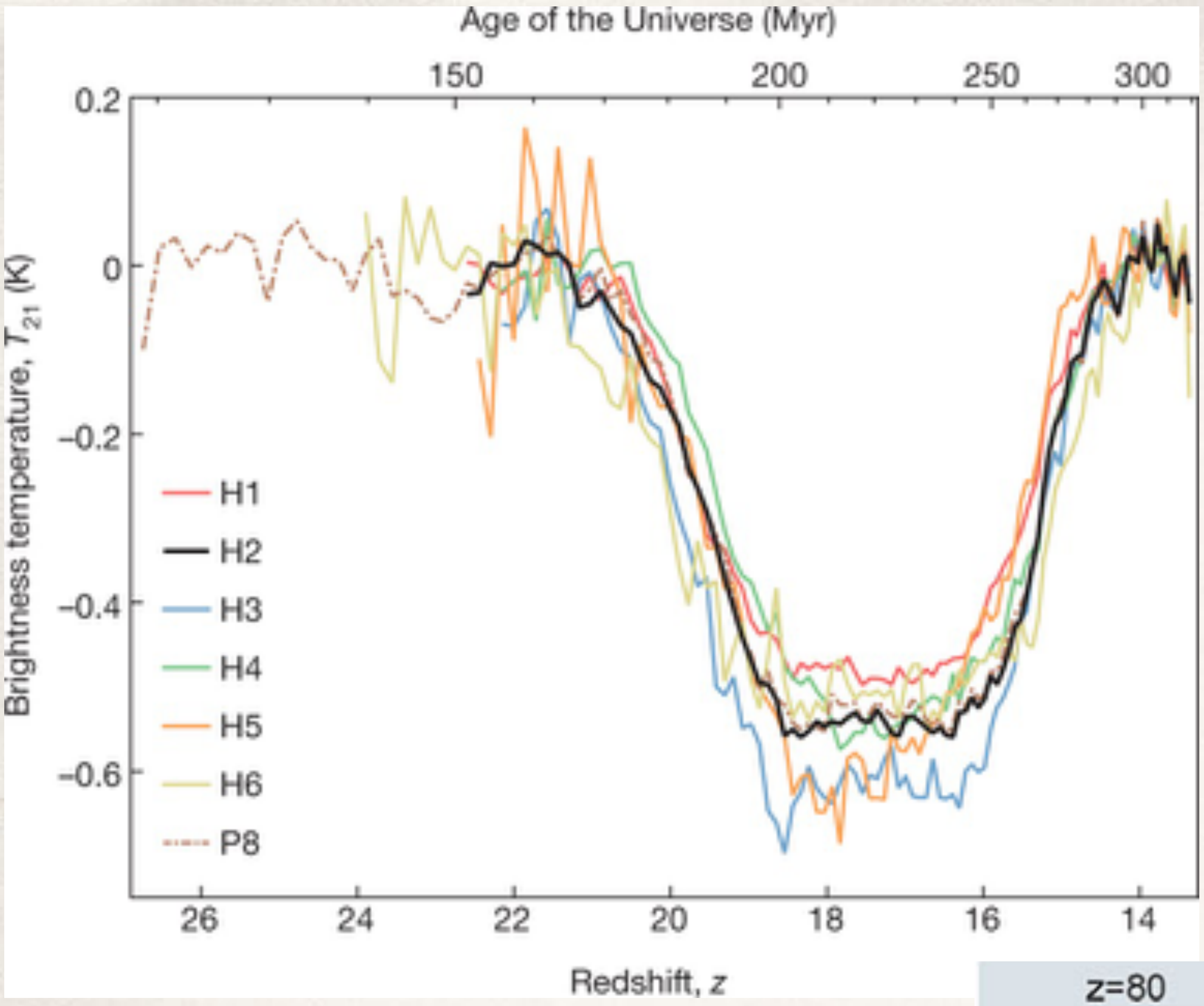


Bowman et al. **Nature** 555, 67–70 (2018)

The “telescope”



Cosmic dawn?

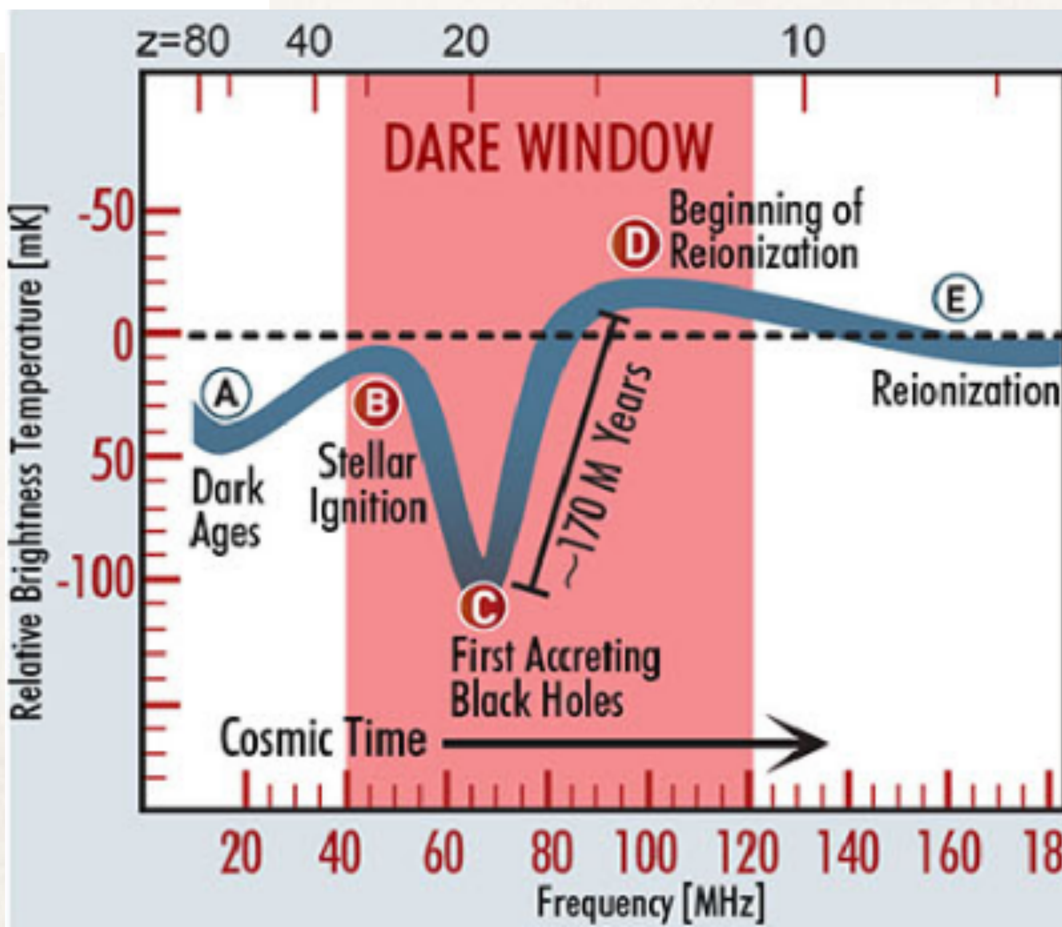


Bowman et al. **Nature** 555, 67–70 (2018)

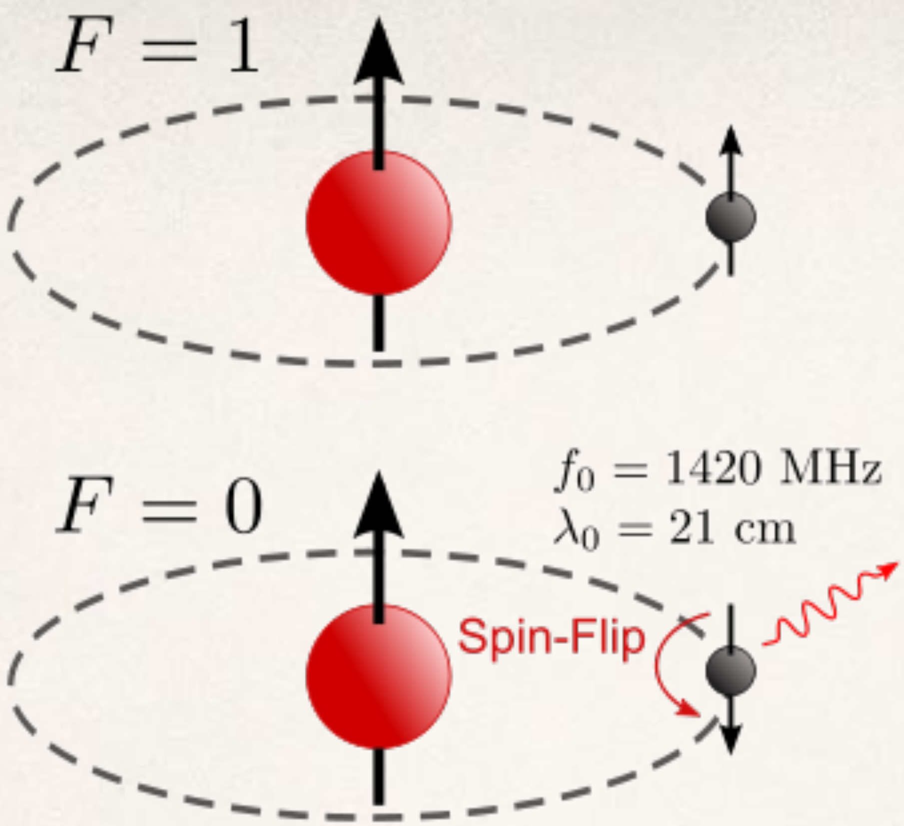
At z ~ 20 - 15, before first stars T_S is coupled to T_R at 57 - 44 K; T_G is at 5 - 10 K, decoupled from T_R

Lyα from first stars recouple T_S and T_G, giving rise to the observed absorption.

X-ray radiation from accretion disks around black hole remnants of the first stars heats the gas and the absorption disappears. First galaxies form and EoR starts



DARE measures the global 21-cm spectrum (left) including the frequencies (redshifts) of the extrema within Regions B, C, and D to determine the onset of star/galaxy formation and their characteristics.



HI transition

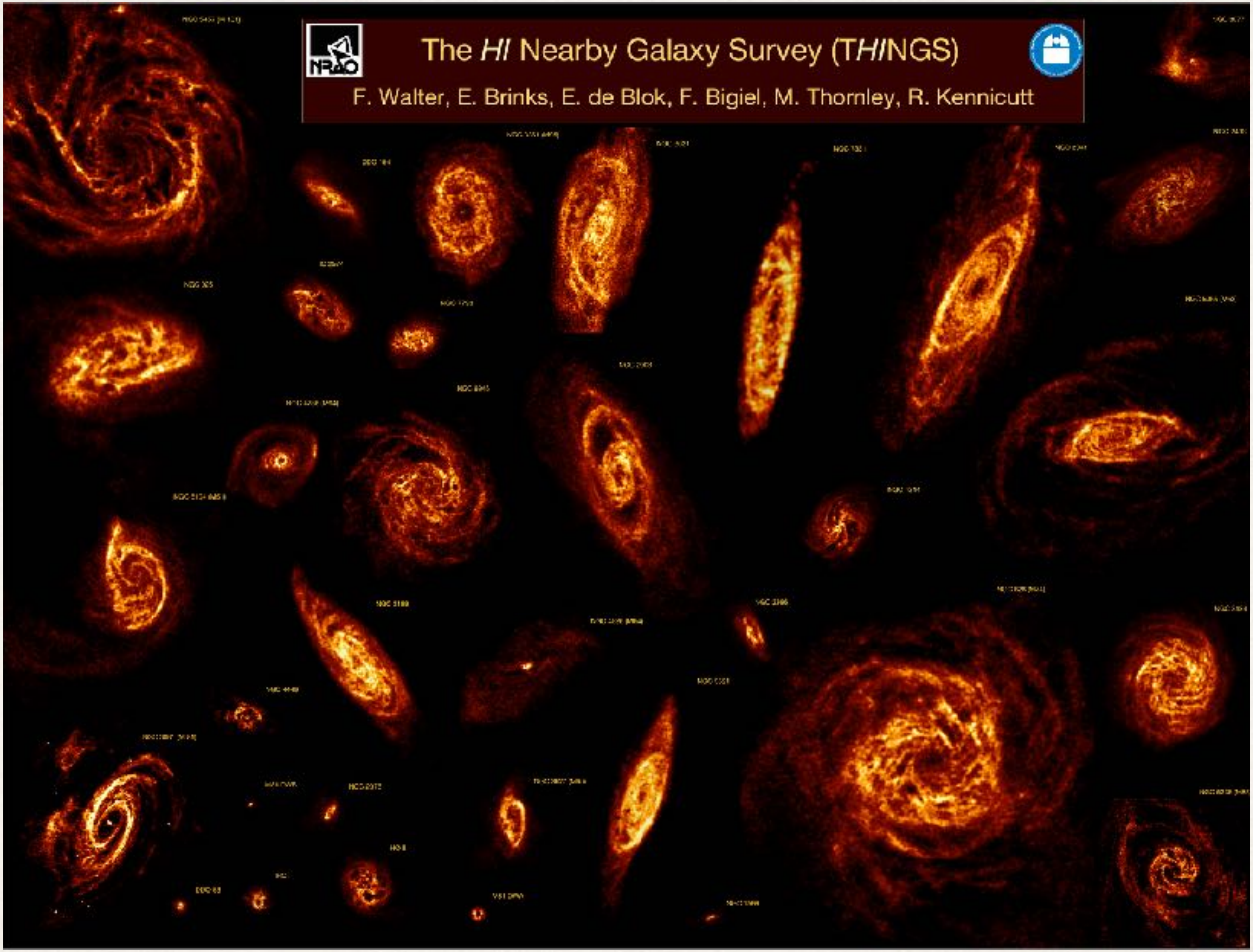
Predicted by van de Hulst (1944)
detected by Ewen and Purcell (1951)

very low transition rate: 2.9×10^{-15} s^{-1}
—> 10^7 yr lifetime and consequently narrow intrinsic line width
—> excellent for probing velocity structure (and dispersion)

line is optically thin (mostly) —> column density tracer

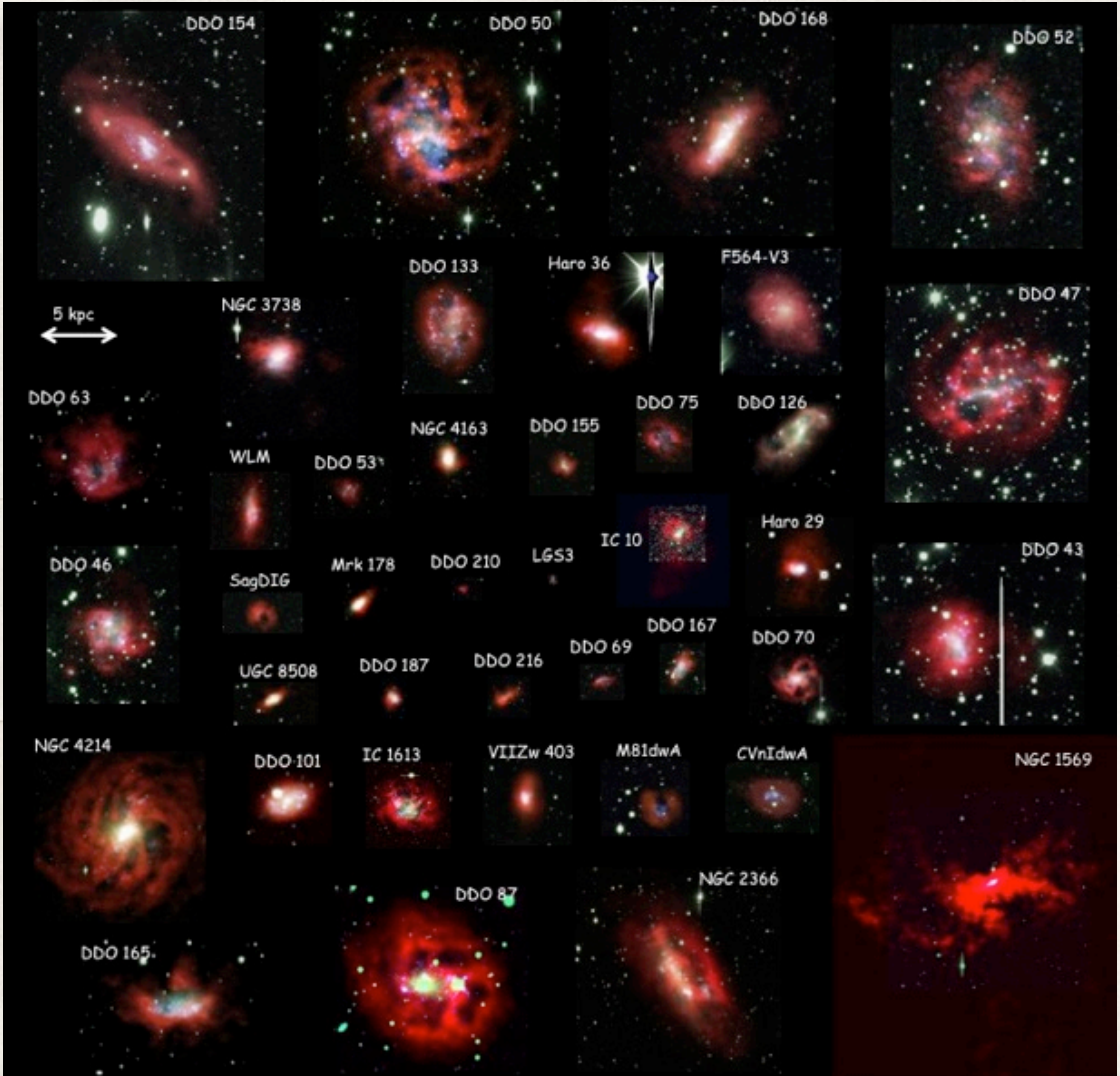
but: low brightness temperature —> faint —> out to z~0.2

HI and dust are well mixed; **B**-field frozen in

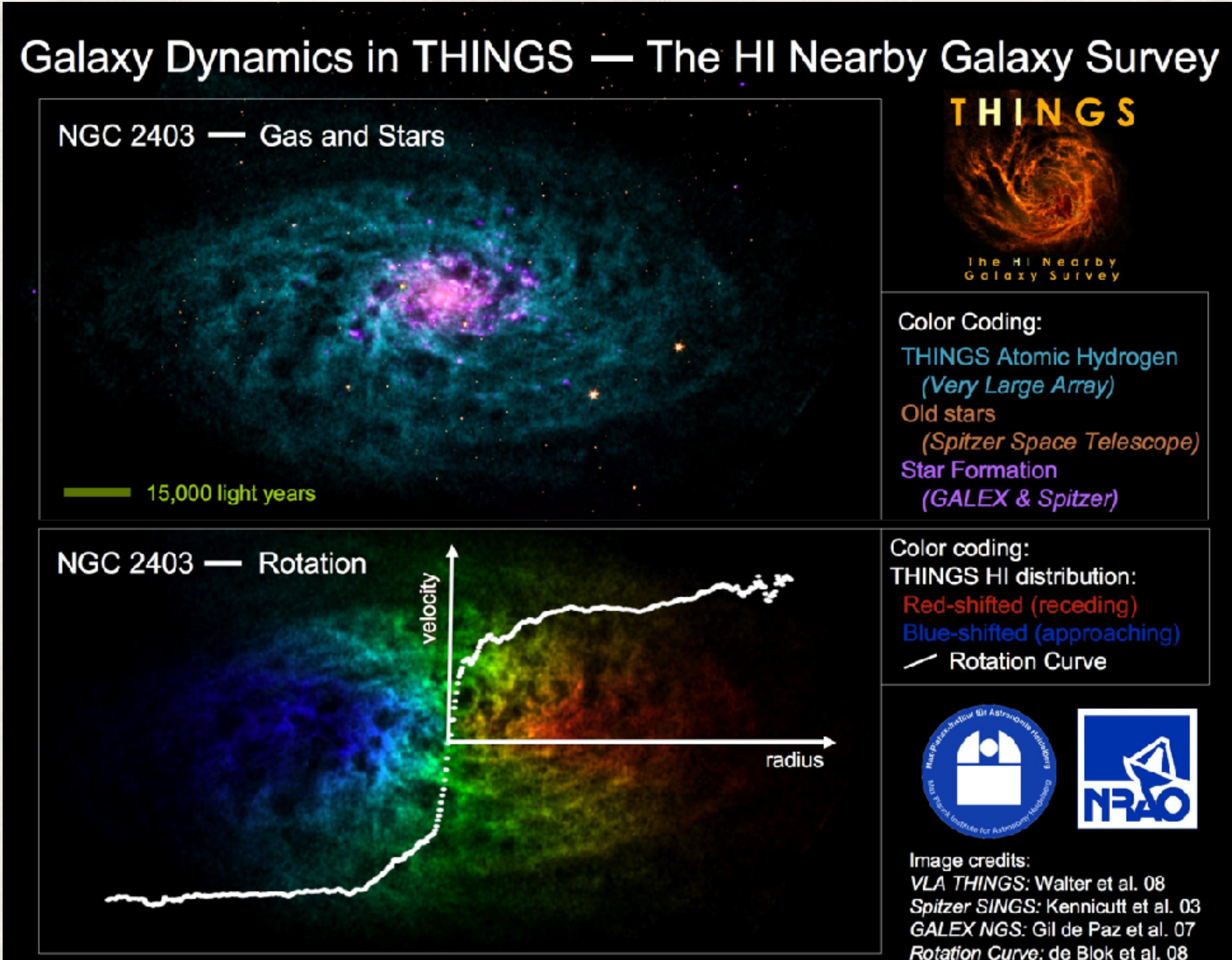


Walter et al. (2008) AJ 136, 2563

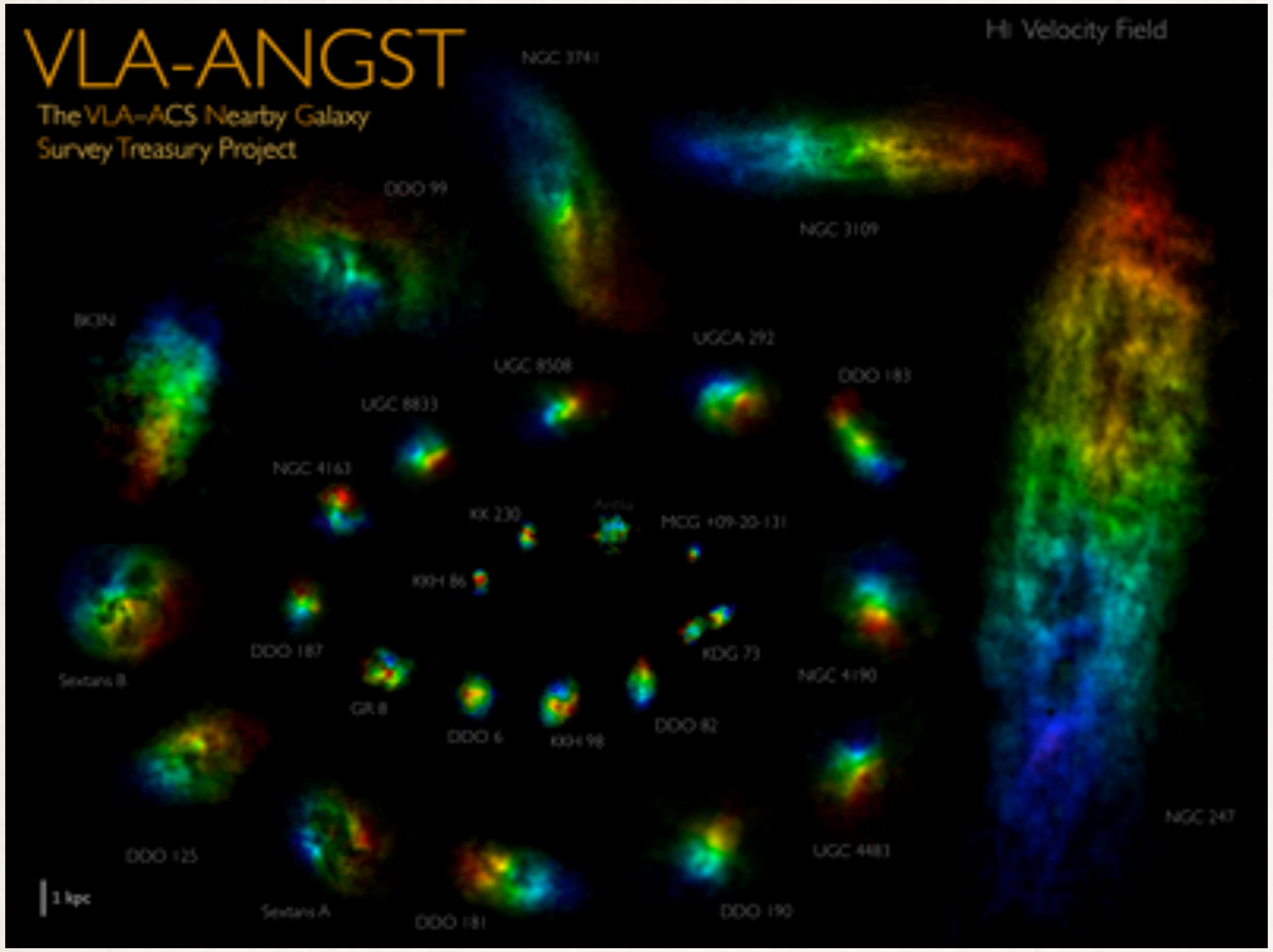
LITTLE THINGS



Hunter et al. (2012) AJ 144, 134


Galaxy Dynamics in THINGS — The HI Nearby Galaxy Survey
NGC 2403 — Gas and Stars
15,000 light years
THINGS
The HI Nearby Galaxy Survey
Color Coding:
THINGS Atomic Hydrogen (Very Large Array)
Old stars (Spitzer Space Telescope)
Star Formation (GALEX & Spitzer)
NGC 2403 — Rotation
velocity
radius
Color coding:
THINGS HI distribution:
Red-shifted (receding)
Blue-shifted (approaching)
Rotation Curve
NRAO
Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07
Rotation Curve: de Blok et al. 08

Very Large Array - ACS Nearby Galaxy Survey Treasury



Ott et al. (2012), AJ, 144, 123

Common characteristics of the (LITTLE) THINGS, VLA-ANGST and SHIELDS surveys resulting in observations of >100 nearby galaxies (< 10 Mpc)

- VLA B+C+D configuration HI observations at 1.3, 2.6, or 5.2 km s^{-1} velocity resolution tracing low density (~10^{19} cm^{-2}) HI
- 6” angular resolution (110 pc at 3.7 Mpc, the typical distance of the galaxies)
- *GALEX*, *Spitzer*, and UBVJHK plus Hα ancillary data gives snapshot of star formation process on 3 timescales

Scope

- concentrate on what we can learn about the (atomic) ISM by studying (nearby) extragalactic systems (excluding gas-poor Early-Type systems)
- Milky Way will be covered in the following talks
- HI global distribution, velocity dispersion, vertical distribution, ISM porosity
- HI in the SKA era

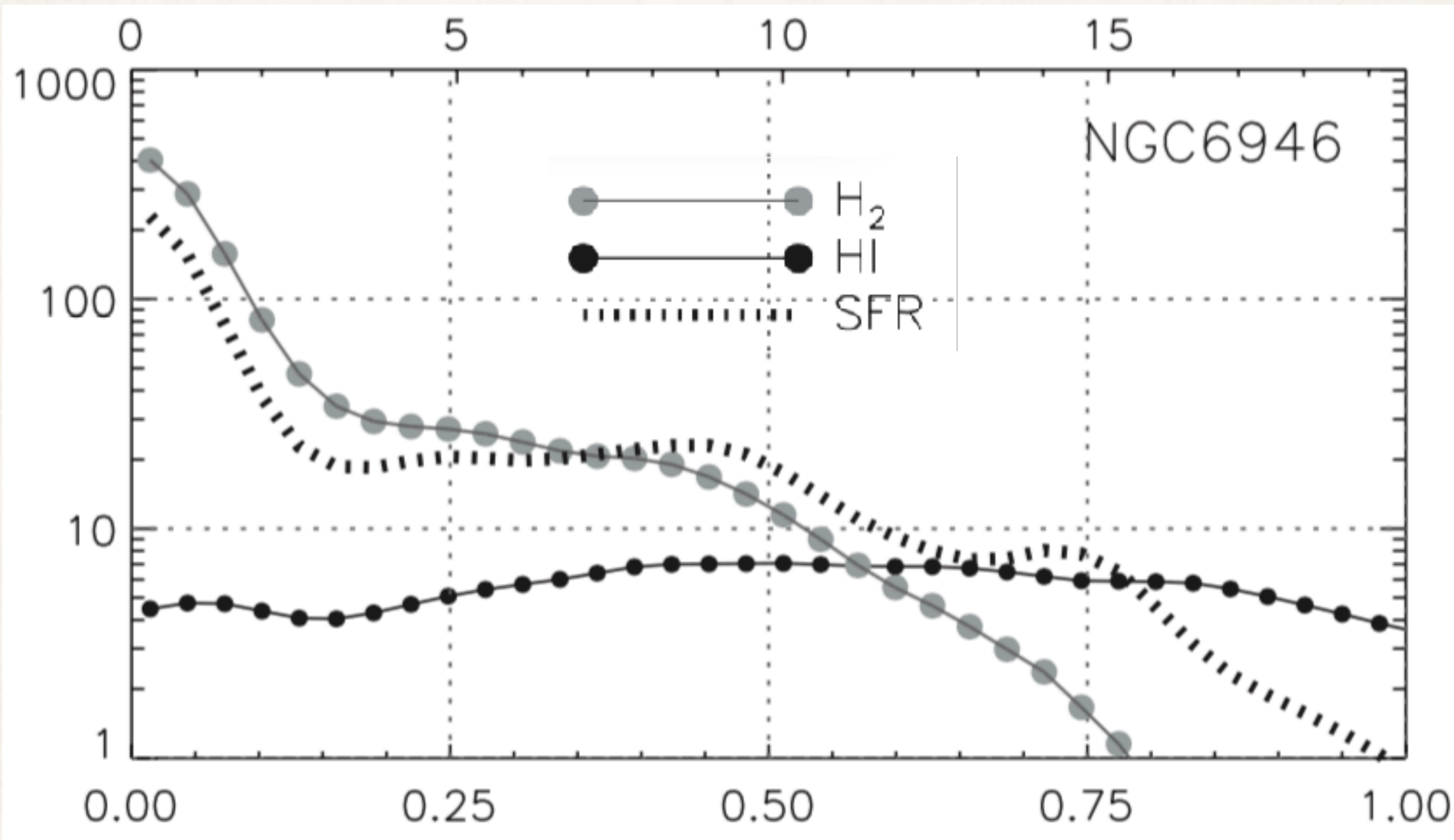
The phases of the ISM

Table 1: Components of the interstellar medium[3]

Component	Fractional volume	Scale height (pc)	Temperature (K)	Density (particles/cm^3)	State of hydrogen	Primary observational techniques
Molecular clouds	< 1%	80	10–20	10^2–10^6	molecular	Radio and infrared molecular emission and absorption lines
Cold Neutral Medium (CNM)	1–5%	100–300	50–100	20–50	neutral atomic	H I 21 cm line absorption
Warm Neutral Medium (WNM)	10–20%	300–400	6000–10000	0.2–0.5	neutral atomic	H I 21 cm line emission
Warm Ionized Medium (WIM)	20–50%	1000	8000	0.2–0.5	ionized	Hα emission and pulsar dispersion
H II regions	< 1%	70	8000	10^2–10^4	ionized	Hα emission and pulsar dispersion
Coronal gas Hot Ionized Medium (HIM)	30–70%	1000–3000	10^6–10^7	10^{-4}–10^{-2}	ionized (metals also highly ionized)	X-ray emission; absorption lines of highly ionized metals, primarily in the ultraviolet

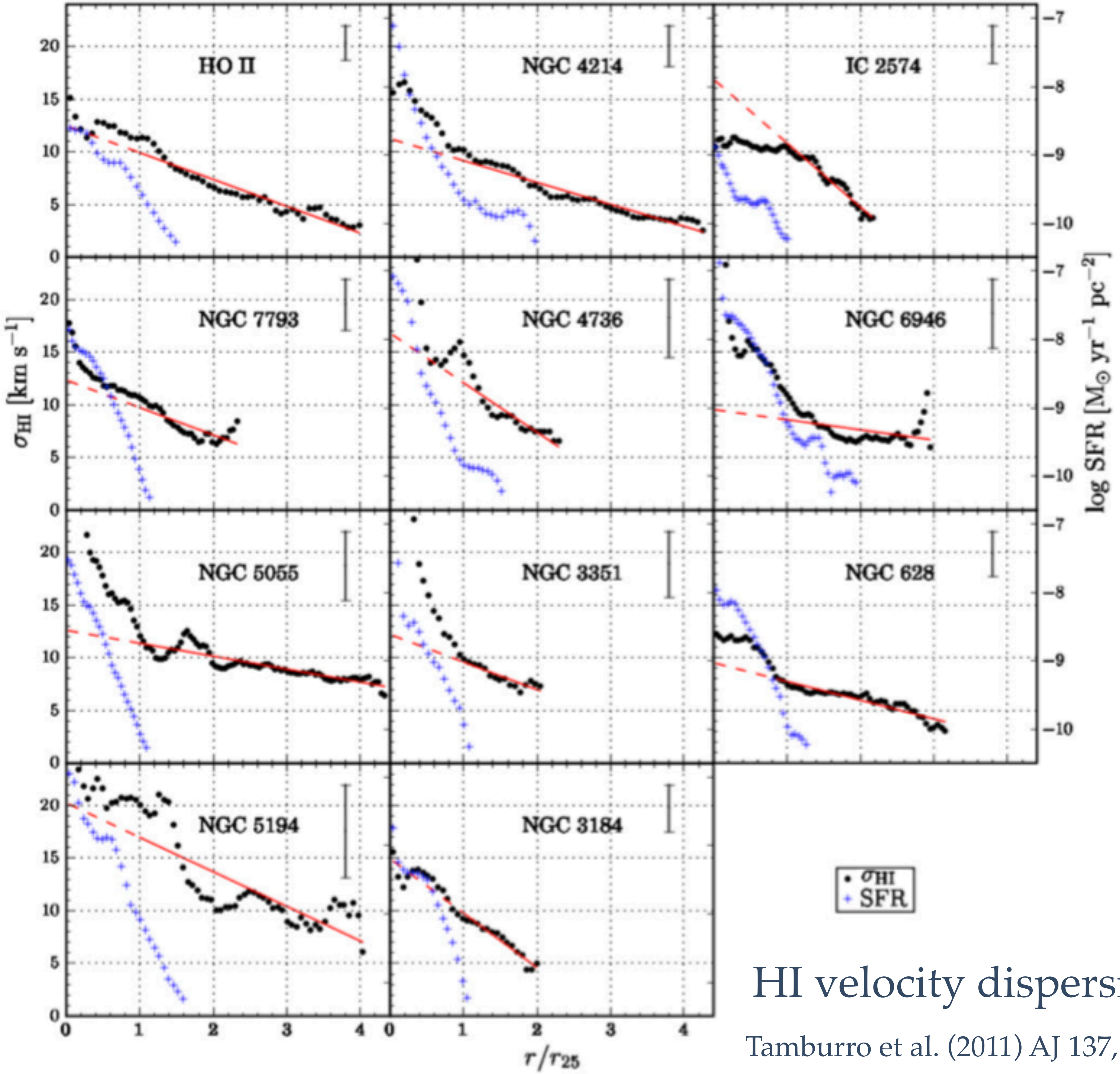
Gas surface density in $M_\odot\ pc^{-2}$ for HI and H_2
and SFR density in units of $10^{-3}\ M_\odot\ yr^{-1}\ kpc^{-2}$

surface density



normalised radius r / r_{25}

Bigiel et al. (2008) AJ 136, 2872



HI velocity dispersion

Tamburro et al. (2011) AJ 137, 4424

Recap

HI surface density is largely flat at ~10^{21} cm^{-2} (9 $M_\odot$ pc^{-2})

SFR follows H_2 distribution

velocity dispersion decreases monotonically from ~15 km s^{-1} to 6 km s^{-1}

velocity dispersion within the disk can be accounted for entirely as a result of SF (i.e., SN) driven turbulence

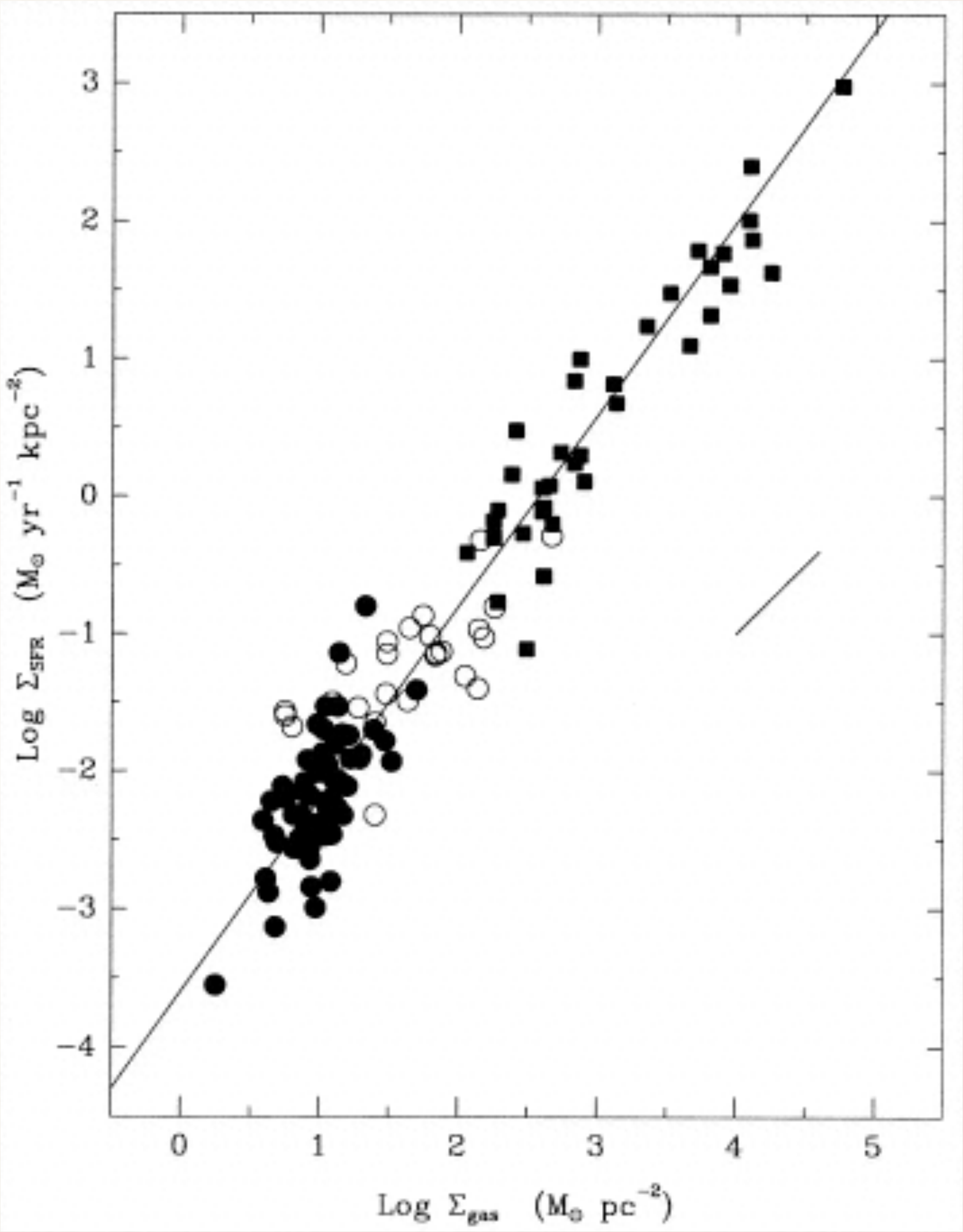
beyond the optical disk, another mechanism is needed to maintain a flat, 6 km s^{-1}, level: magneto-rotational instability

Schmidt - Kennicutt relation

A relation connecting Σ_{SFR} to Σ_{gas}:

$$\Sigma_{SFR} = A \cdot (\Sigma_{gas})^N$$

(going back to Schmidt 1959)



Kennicutt (1998) AJ 498, 541

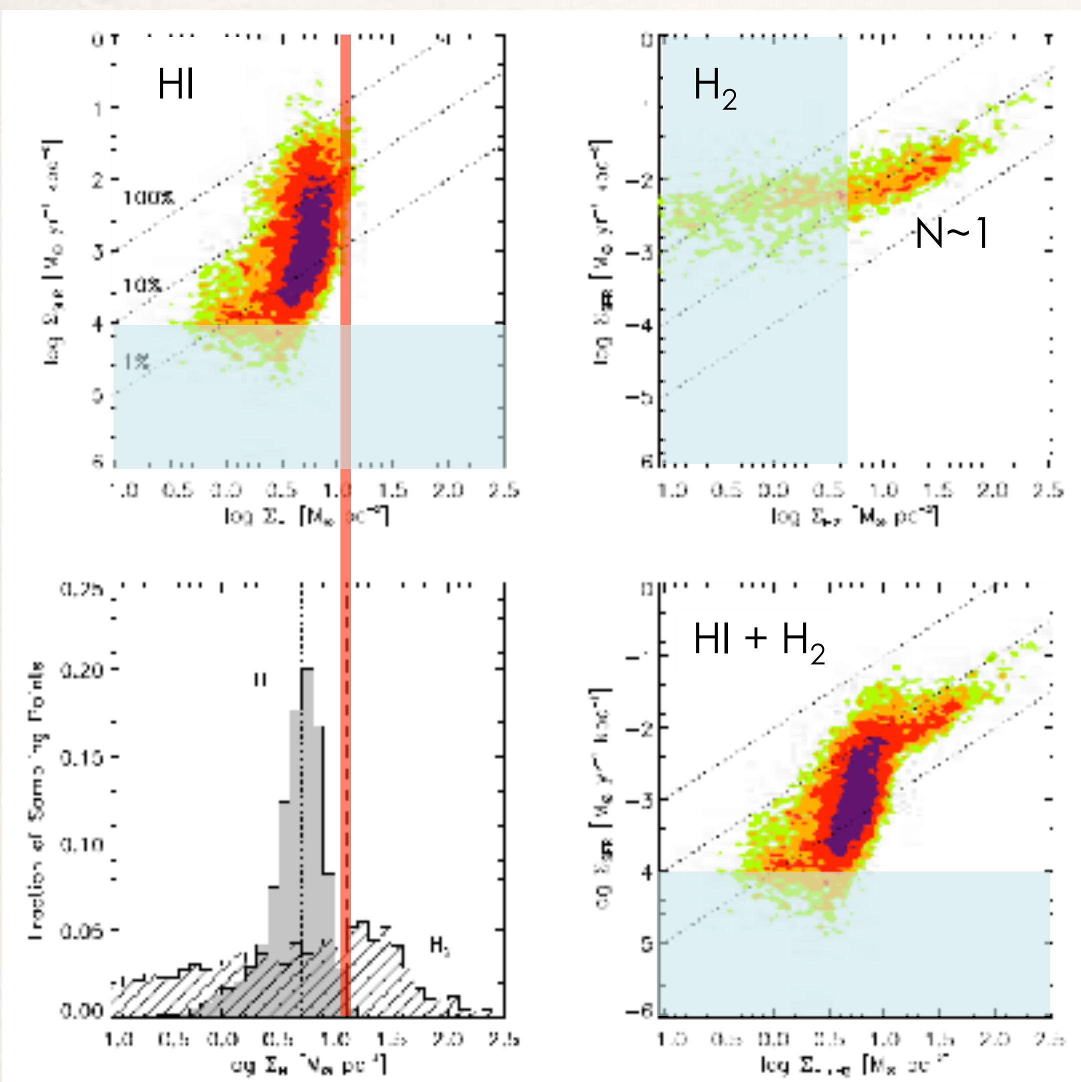
Schmidt - Kennicutt relation

Previous studies include, e.g.,

- Schmidt (1959): N≈2 (Milky Way)
- Kennicutt (1989,1998): N≈1.4 (sample of ~90 nearby galaxies)
- Wong & Blitz (2002): N=1.2-2.1 (6 nearby spiral galaxies)
- Boissier et al. (2003), Heyer et al. (2004): N≈2 (16 galaxies) and N≈3.3 (M33)

SF from THINGS

all THINGS galaxies



Bigiel et al. (2008) AJ 136, 2872

Schmidt-Kennicutt: $\Sigma_{SFR} \sim (\Sigma_{gas})^N$

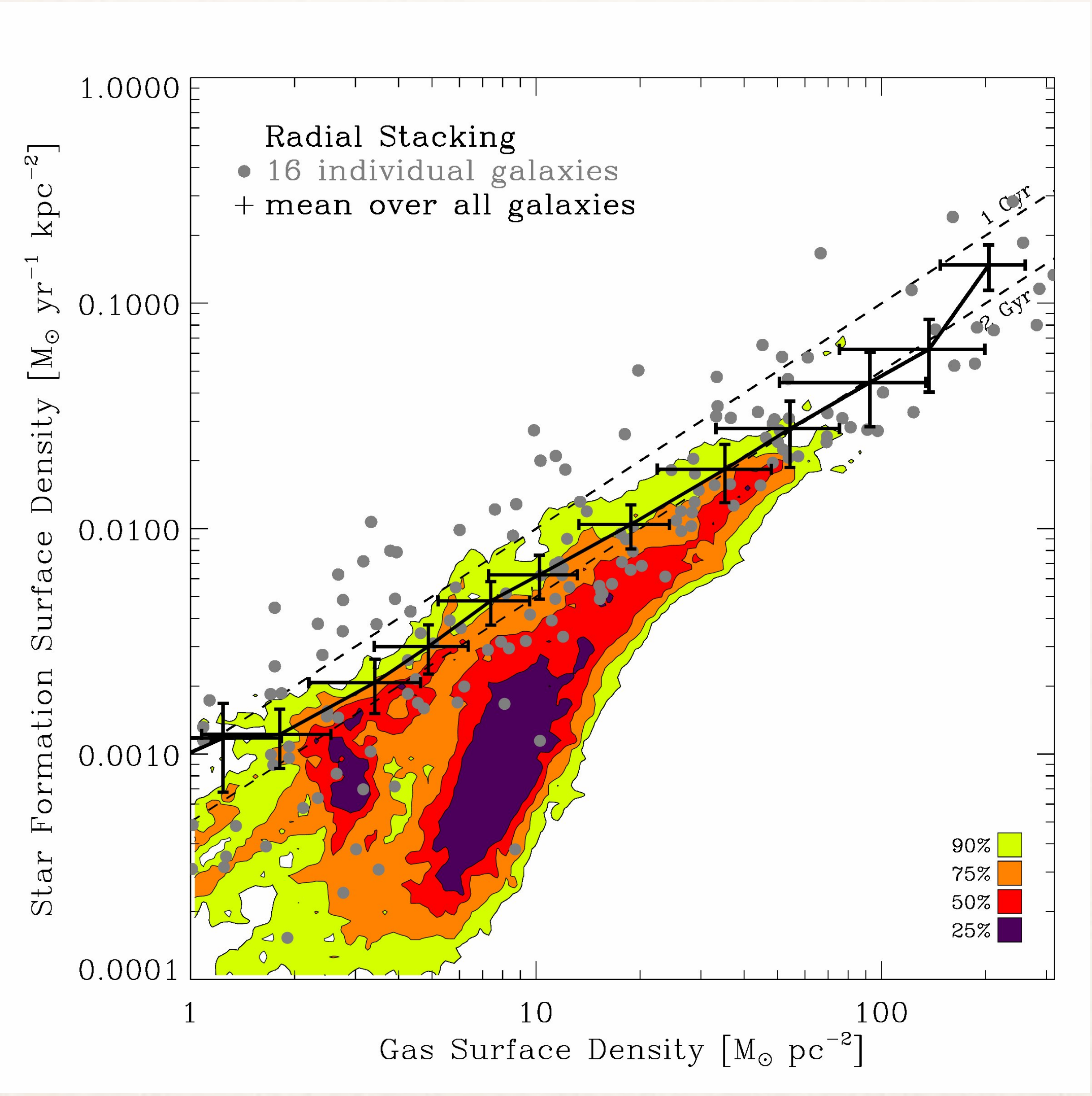
- Σ_{H2} is tightly correlated with Σ_{SFR} ($N_{H2} = 1.0 \pm 0.2$), 0.3 dex spread (uncertainty mainly in SFR proxies)
- Data are compatible with a molecular gas SK-relation, and a constant SFE ($\tau \sim 2 \times 10^9$ yr)
- Σ_{HI} saturates at ~ 10 $M_\odot$ pc^{-2}

Summary on Star Formation

in "normal" galaxies: gas surface densities ~1 - 200 $M_\odot pc^{-2}$

- 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 relation has a power-law with index N = 1.0 ± 0.2
- In this regime the SFE is constant; the gas depletion time corresponds to 2 x 10^9 yr, independent of environment
- Where HI dominates, SF efficiency decreases monotonically with the ratio H_2/HI; this in turn scales with mid-plane hydrostatic pressure (and also dust-to-gas ratio), i.e. scales with stellar light.
- SF primarily depends on H_2 (i.e., cold, dense ISM) , not total gas (HI + H_2)
- relation holds in the outskirts where ISM is HI dominated

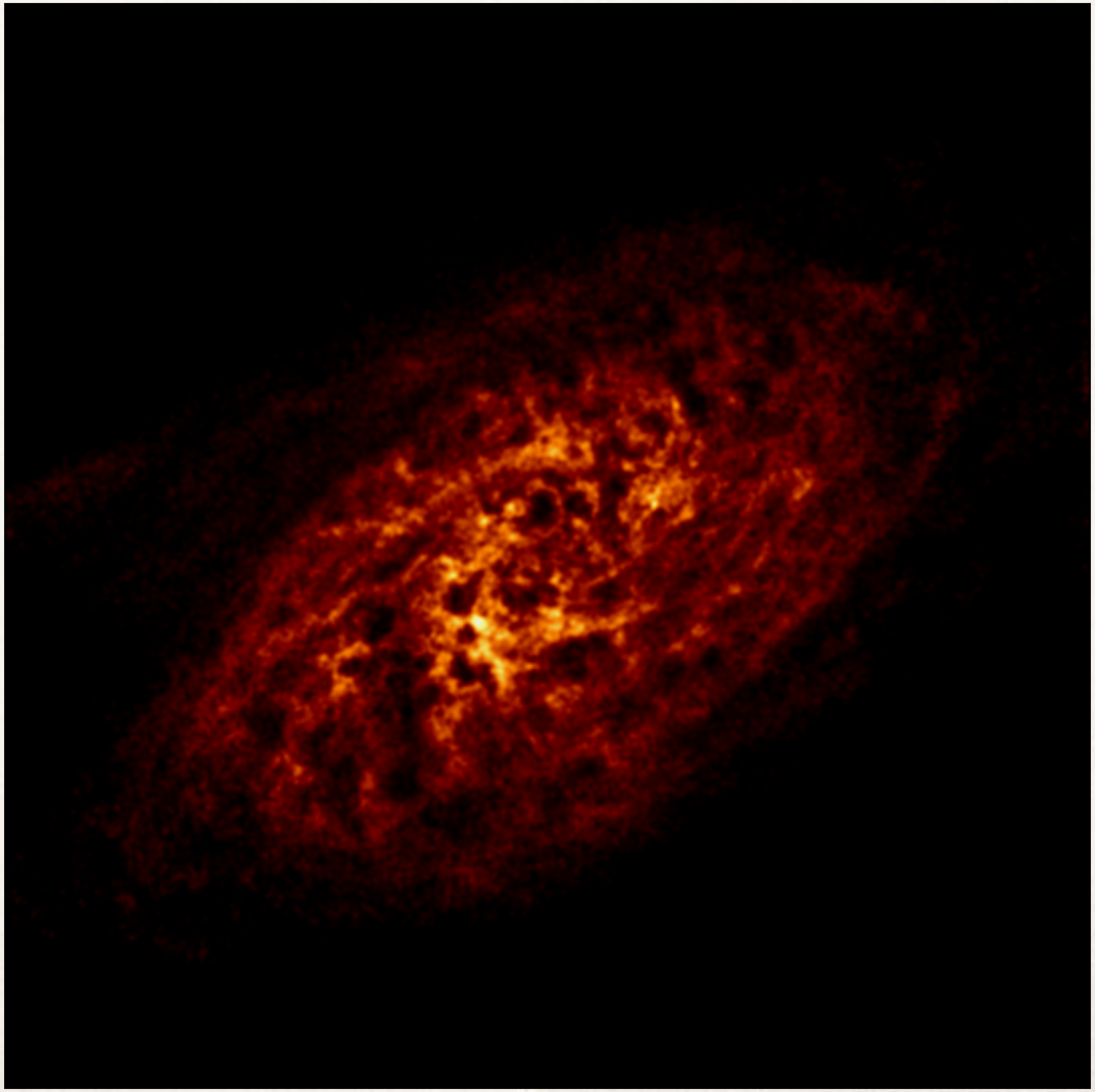
SF in spiral outskirts



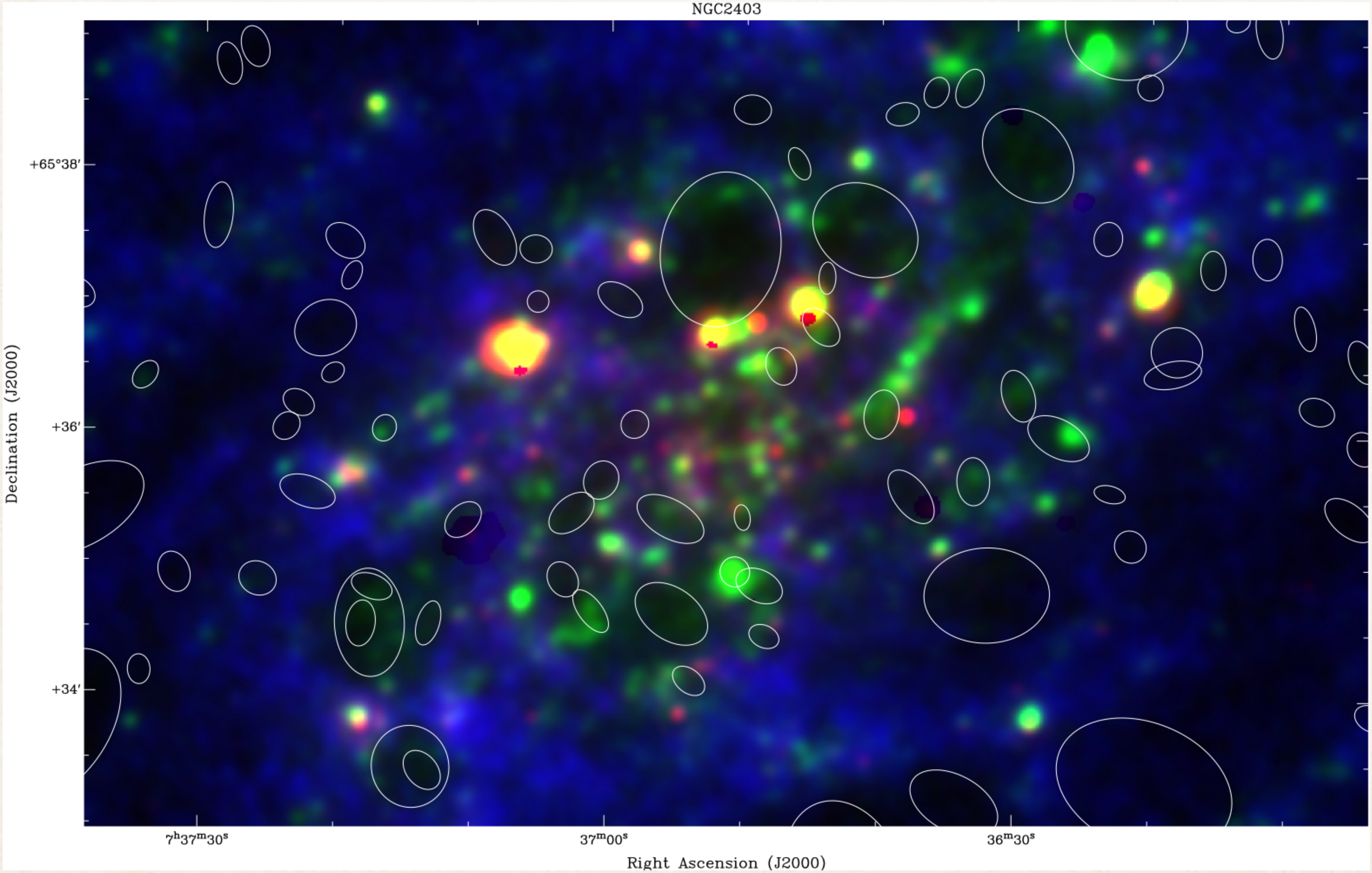
Schruba et al. (2011), AJ, 142, 37

CO stacking by Andreas Schruba brings out low surface brightness CO in spirals in their outskirts

The porous ISM: NGC2403



The porous ISM: NGC2403



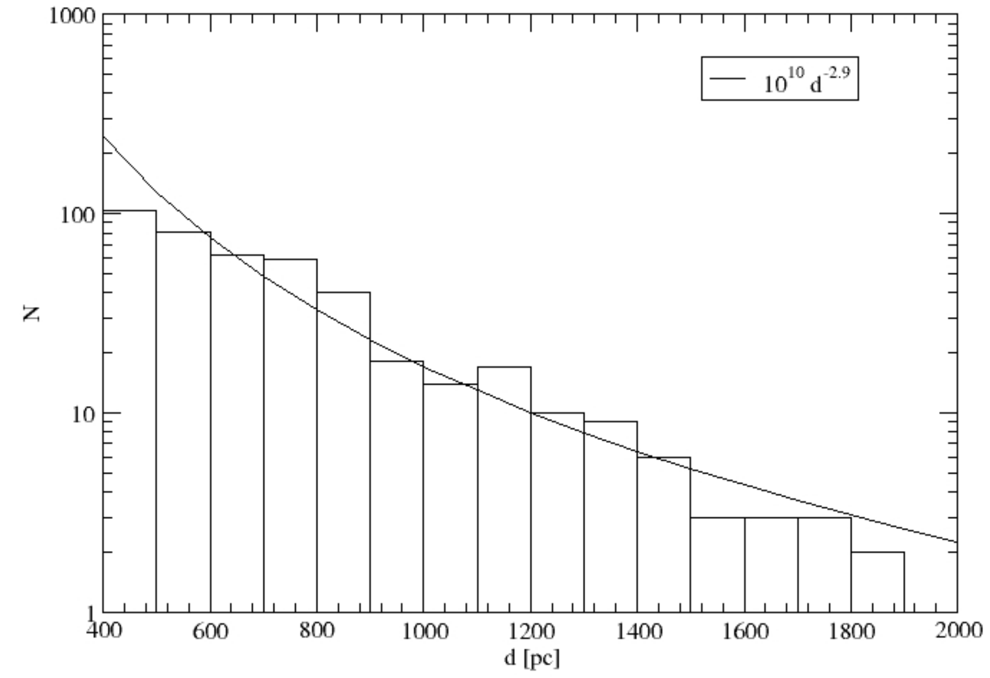
blue: HI
green: FUV
red: Hα

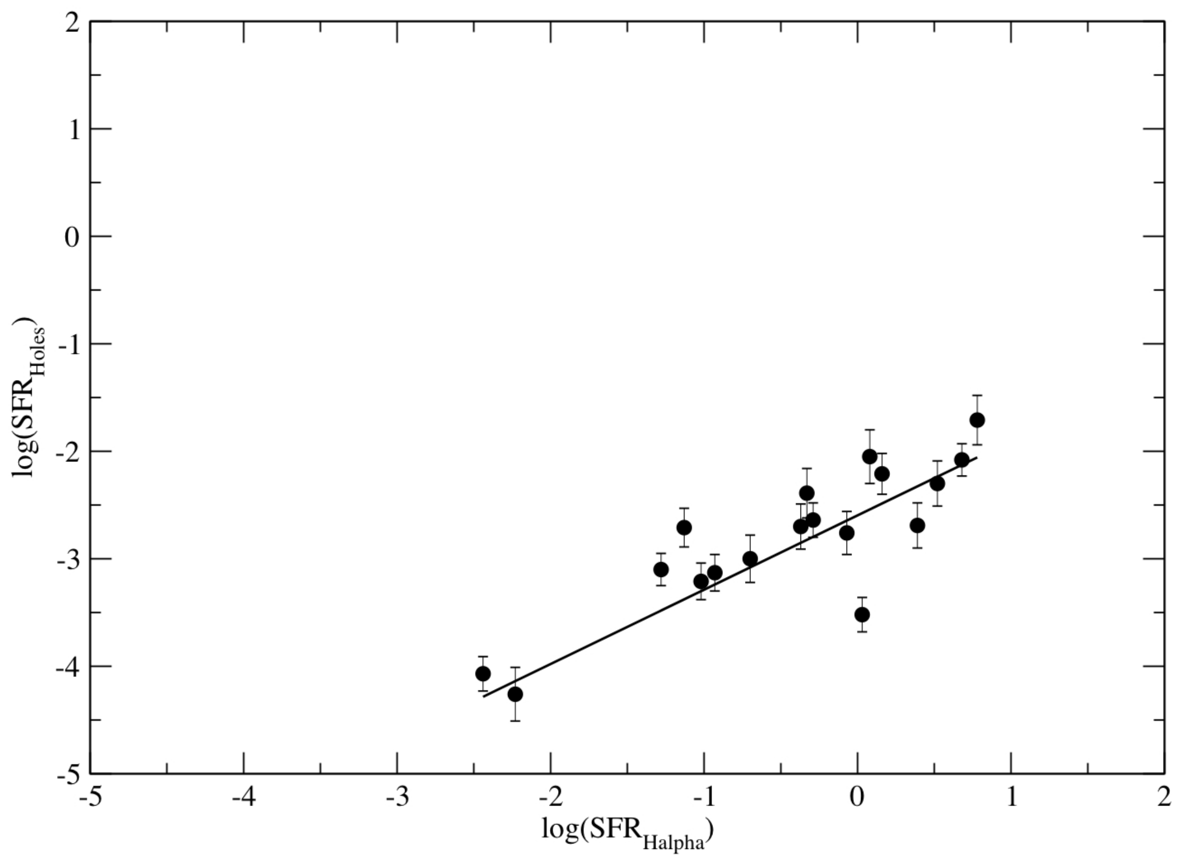
Bagetakos et al. (2011) AJ 141, 23

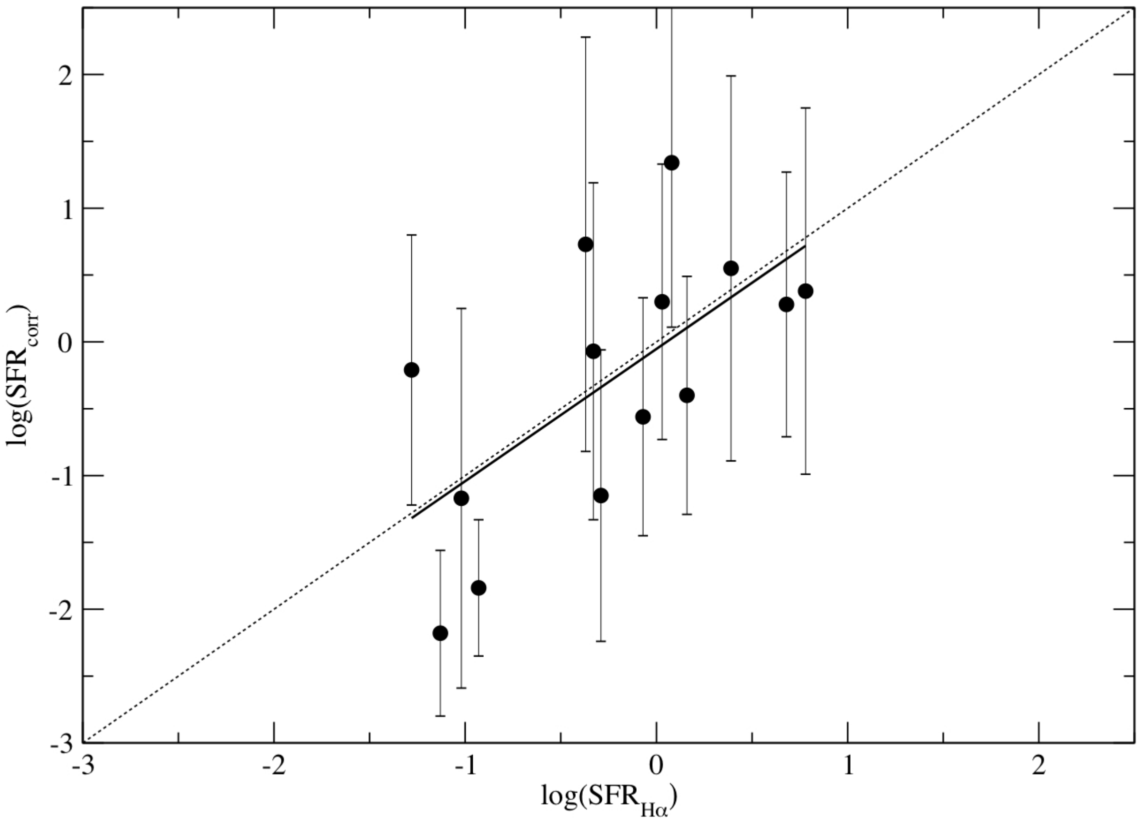
Porosity of the ISM

- ~1000 HI holes in 20 THINGS spirals, ranging from ~100 pc (resolution limit) to ~1 kpc
- expansion velocities: 4 - 36 km s^{-1}
- HI hole lifetime limited by shear
- HI holes are compatible with SF origin
- ISM 2D and 3D porosity is higher in later type spirals and dIrr

HI Holes and SF

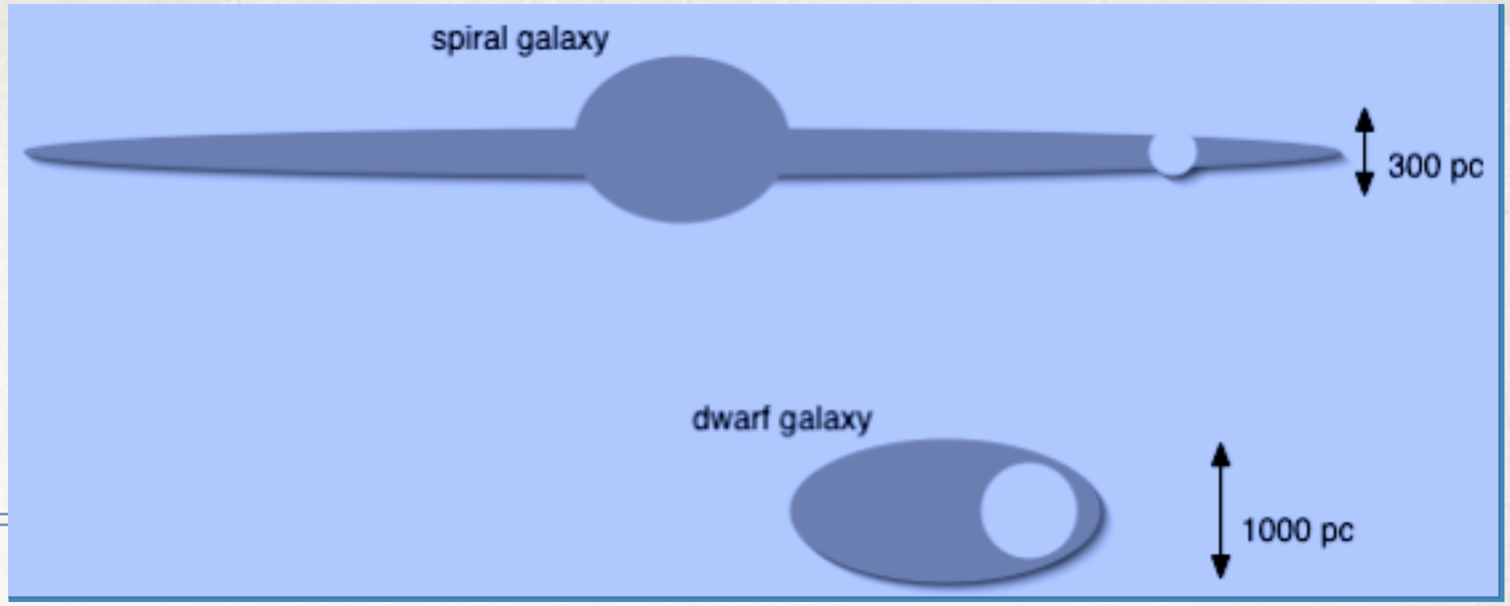




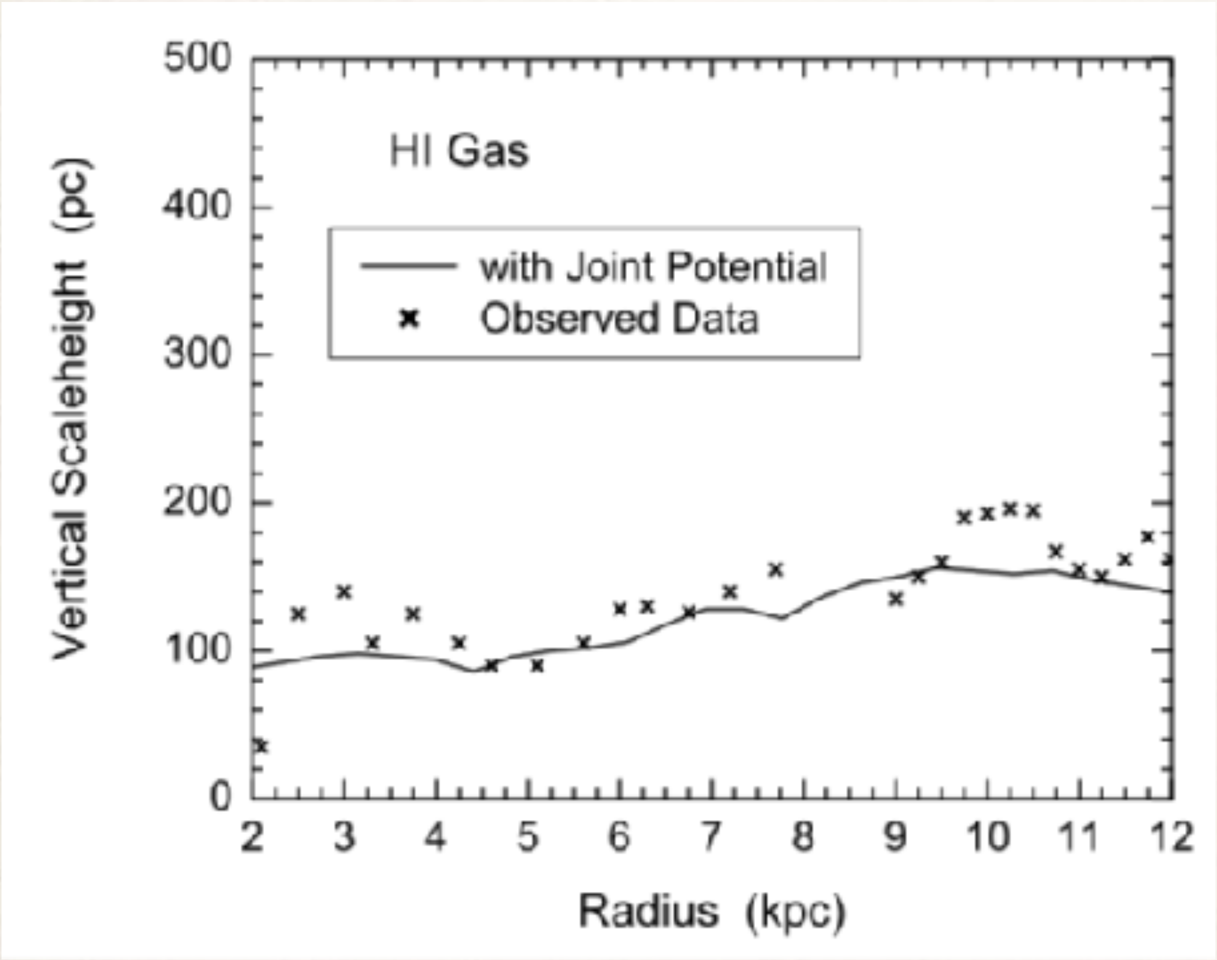


Bagetakos et al. (2011) AJ 141, 23

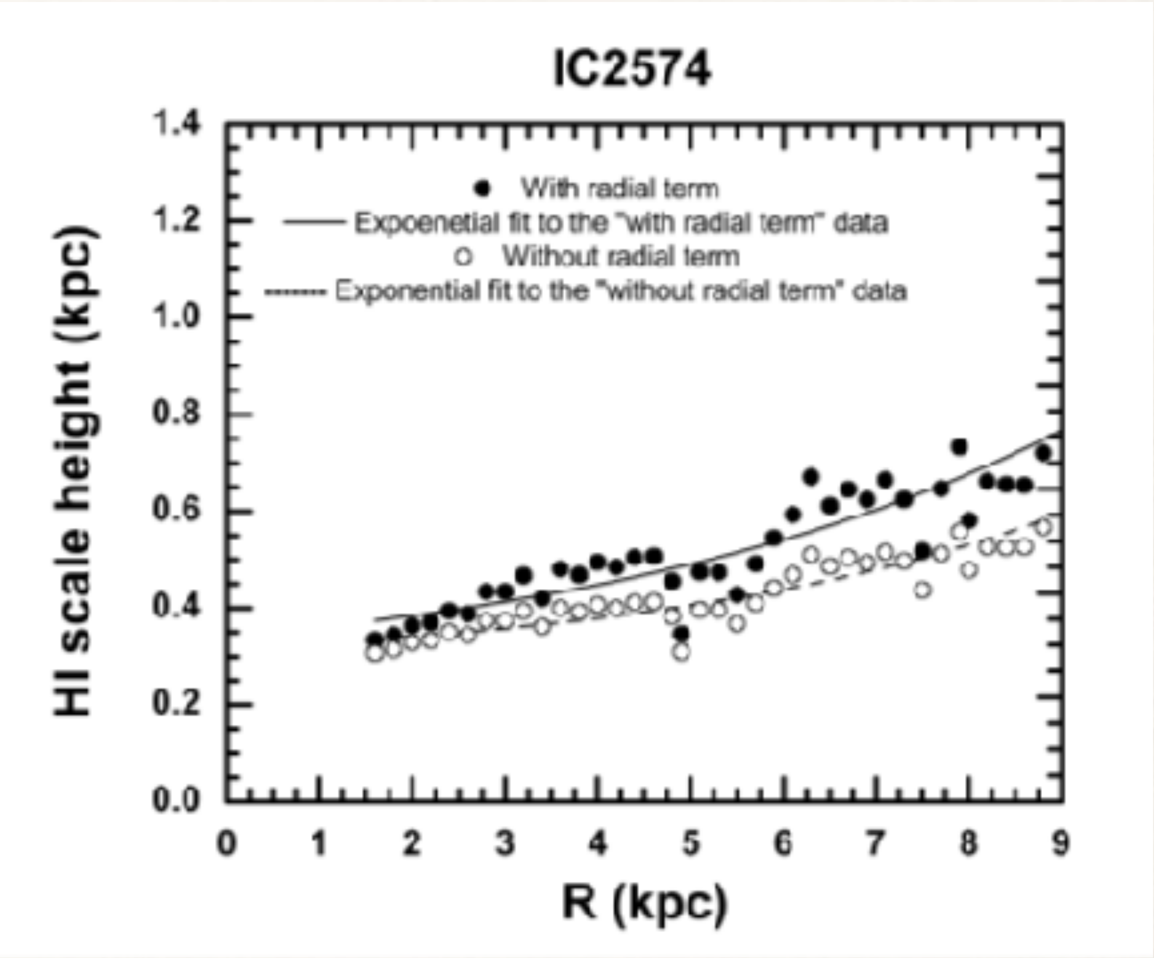
HI scaleheight



spiral

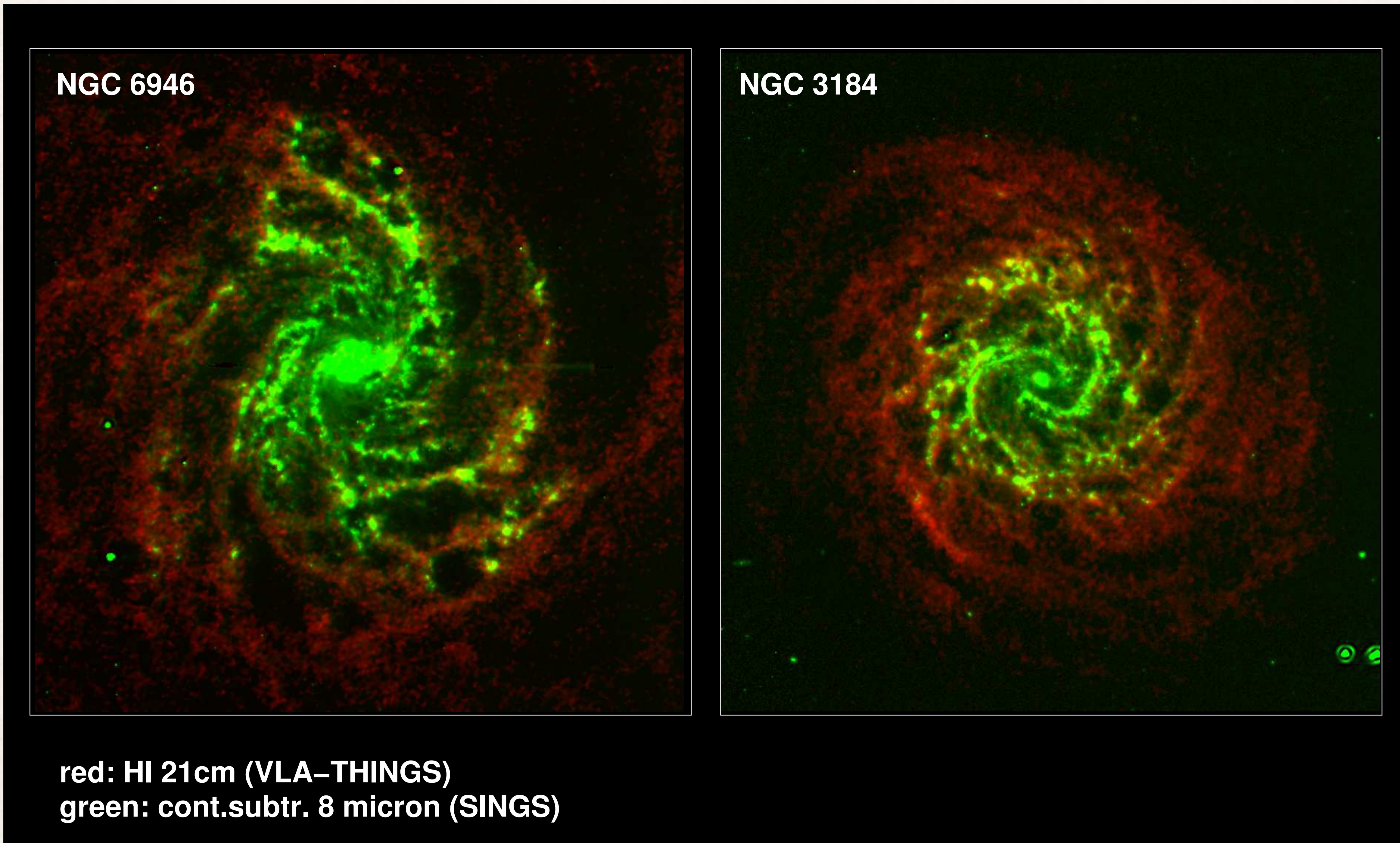


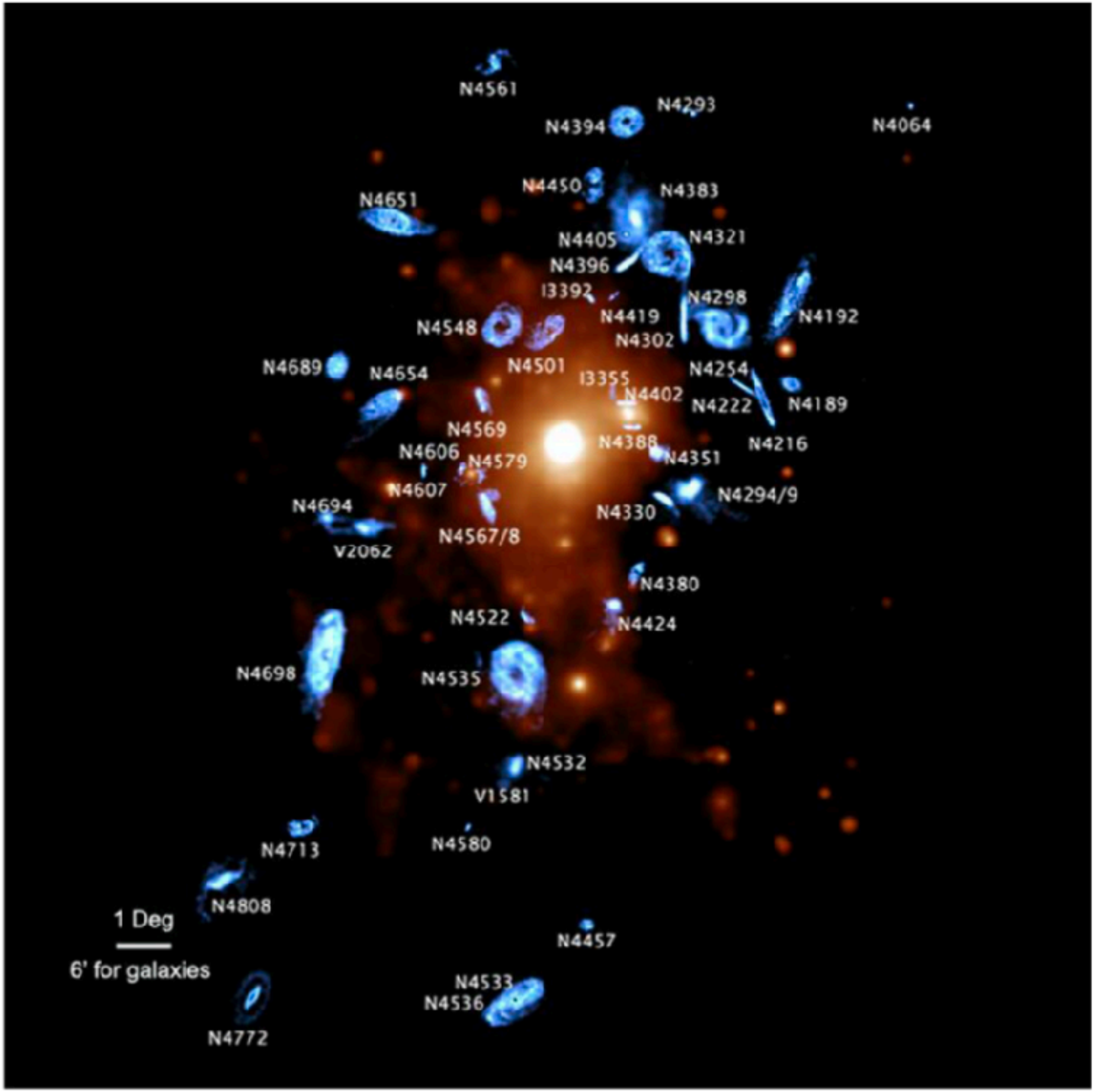
dwarf



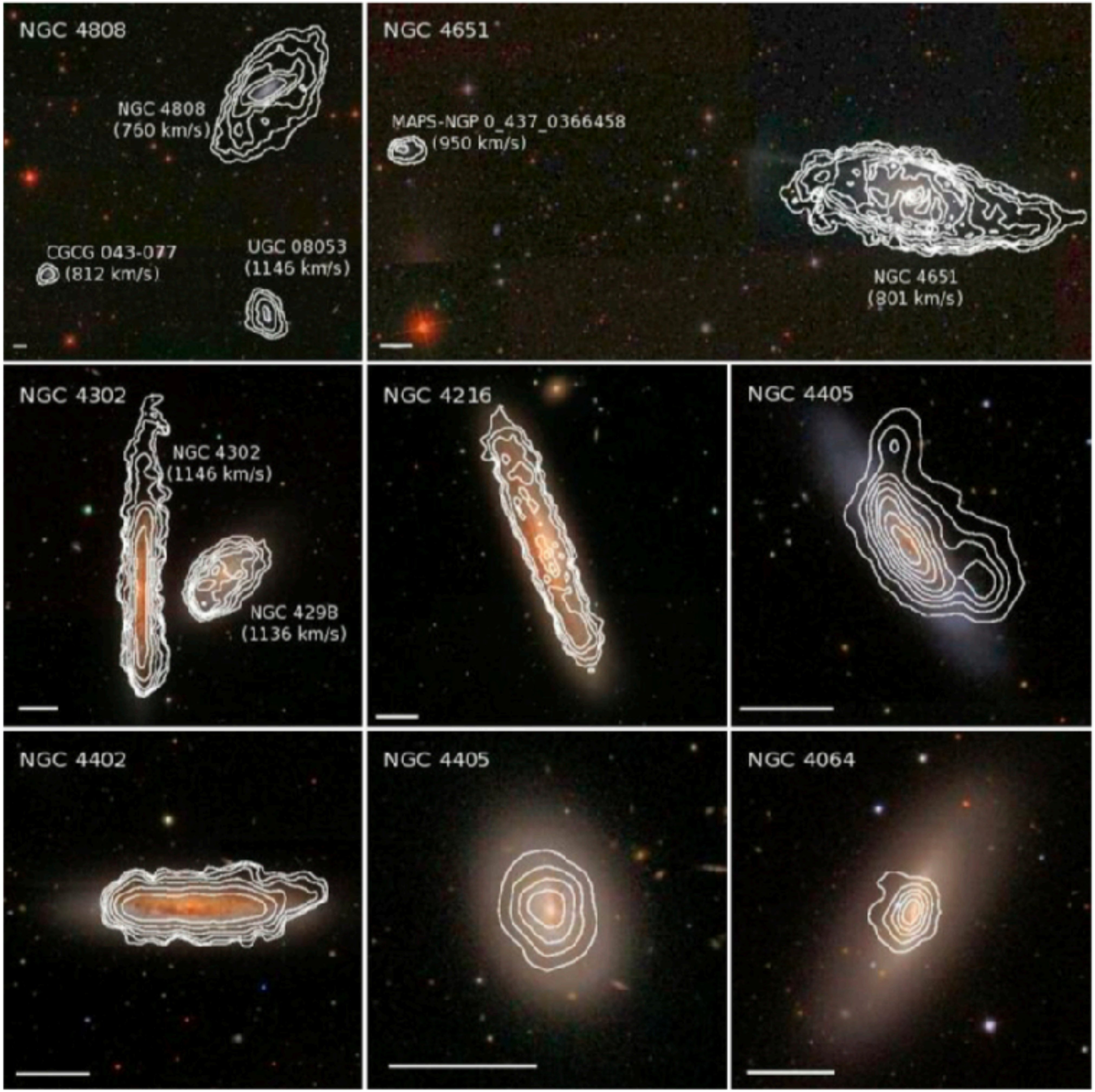
for details on HI scaleheights, see Banerjee et al. (2011) MNRAS 415, 687 and references therein.

Gas and dust: well mixed



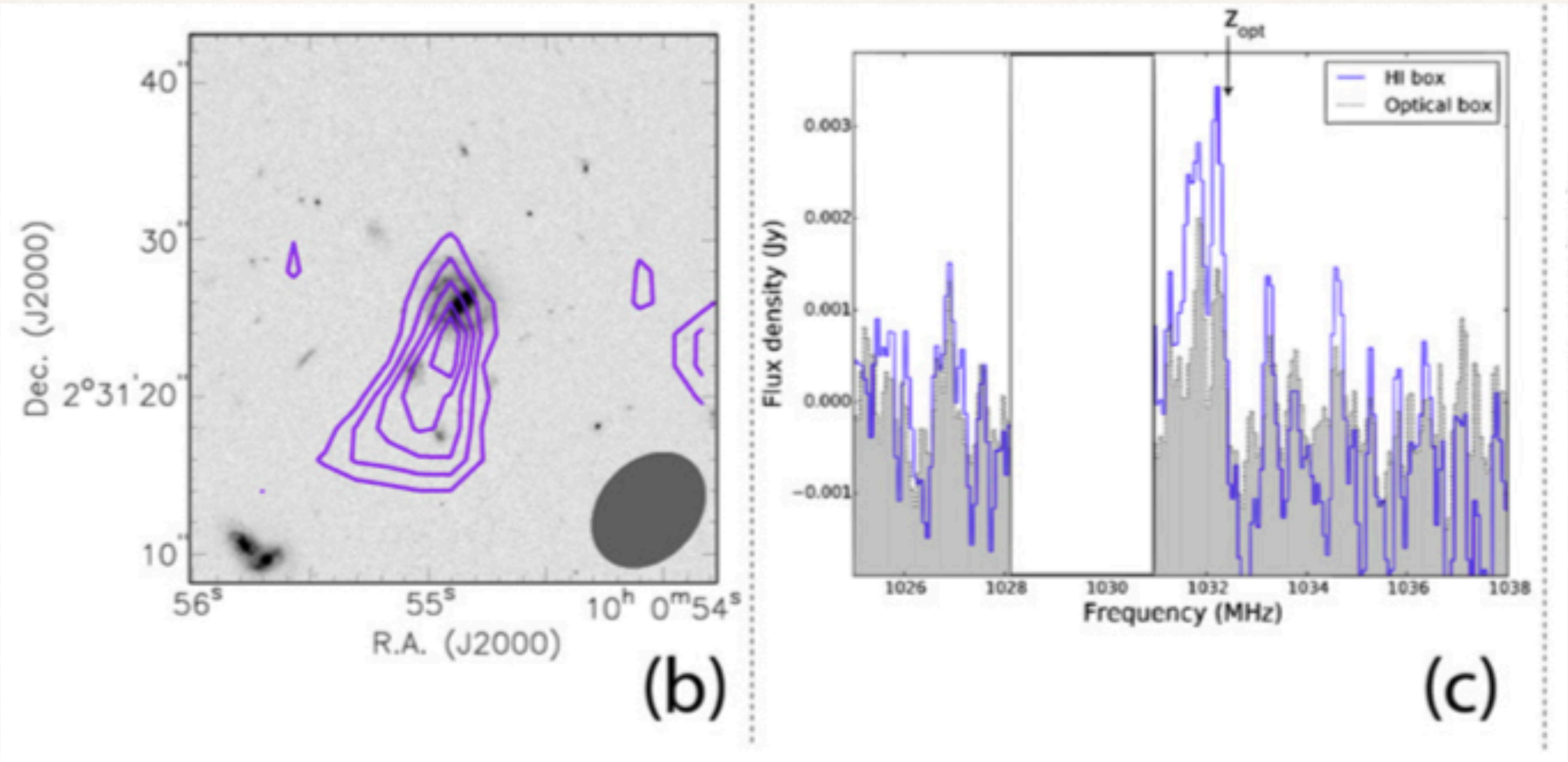

N4561
N4293
N4394
N4064
N4450
N4383
N4651
N4405
N4321
N4396
I3392
N4298
N4419
N4192
N4548
N4302
N4689
N4654
N4501
I3355
N4254
N4402
N4222
N4189
N4569
N4388
N4216
N4606
N4579
N4351
N4607
N4294/9
N4694
N4330
N4567/8
V2062
N4380
N4522
N4424
N4698
N4535
N4532
V1581
N4713
N4580
N4808
1 Deg
N4457
6' for galaxies
N4533
N4536
N4772

VIVA survey



Chung et al. (2009)
AJ 138, 1741

Highest HI in emission detected



CHILES survey HI detection of J100054 at $z = 0.376$
(Fernández et al. 2016, ApJL 824, L1)

The Future: SKA

- next generation All-Sky (i.e., Southern hemisphere) HI surveys will be done with SKA Precursors: MeerKAT (MHONGOOSE) and ASKAP (WALLABY).
- MeerKAT will map 1000s of nearby galaxies (à la THINGS); WALLABY will target 500000 galaxies out to $z \sim 0.5$, but at lower resolution.
- current instruments can either provide high resolution, or high surface brightness sensitivity, but not both; also, their sensitivity limits observations to modest redshift.
- Only the full SKA will provide both the sensitivity and resolution to map galaxies at sub-kpc resolution out to $z \sim 1$

SKA projected sensitivity

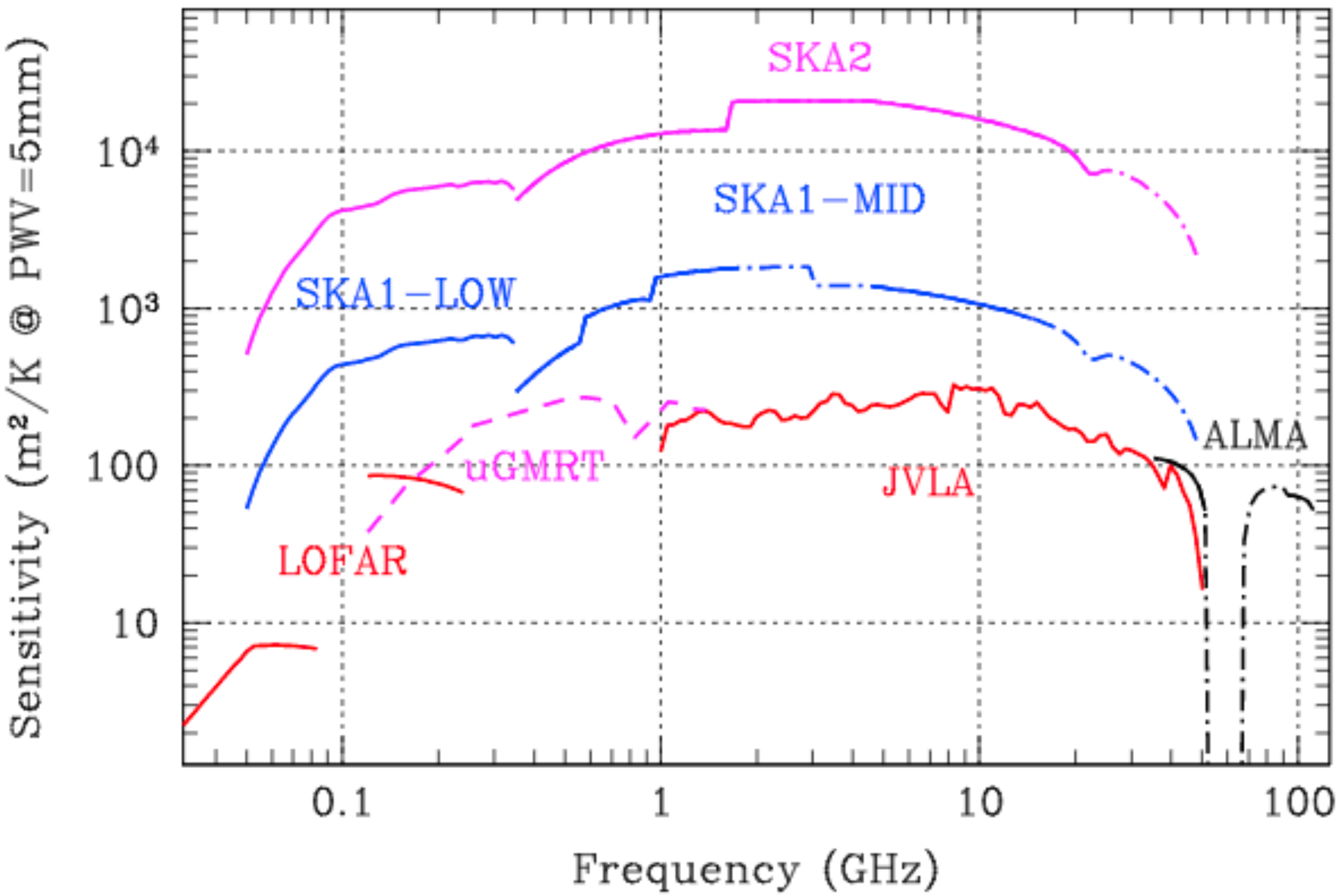


Figure 7. Sensitivity comparison of some existing and planned facilities. For SKA, the feed systems that are not yet planned for deployment are indicated by the dot-dashed line. Dry conditions (PWV ≈ 5mm) are assumed for the SKA and VLA sites while the same PWV = 5mm corresponds to poor conditions for the ALMA site.

The End