The Kennicutt-Schmidt relation in the HI dominated regime

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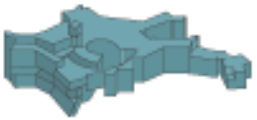

collaborators:
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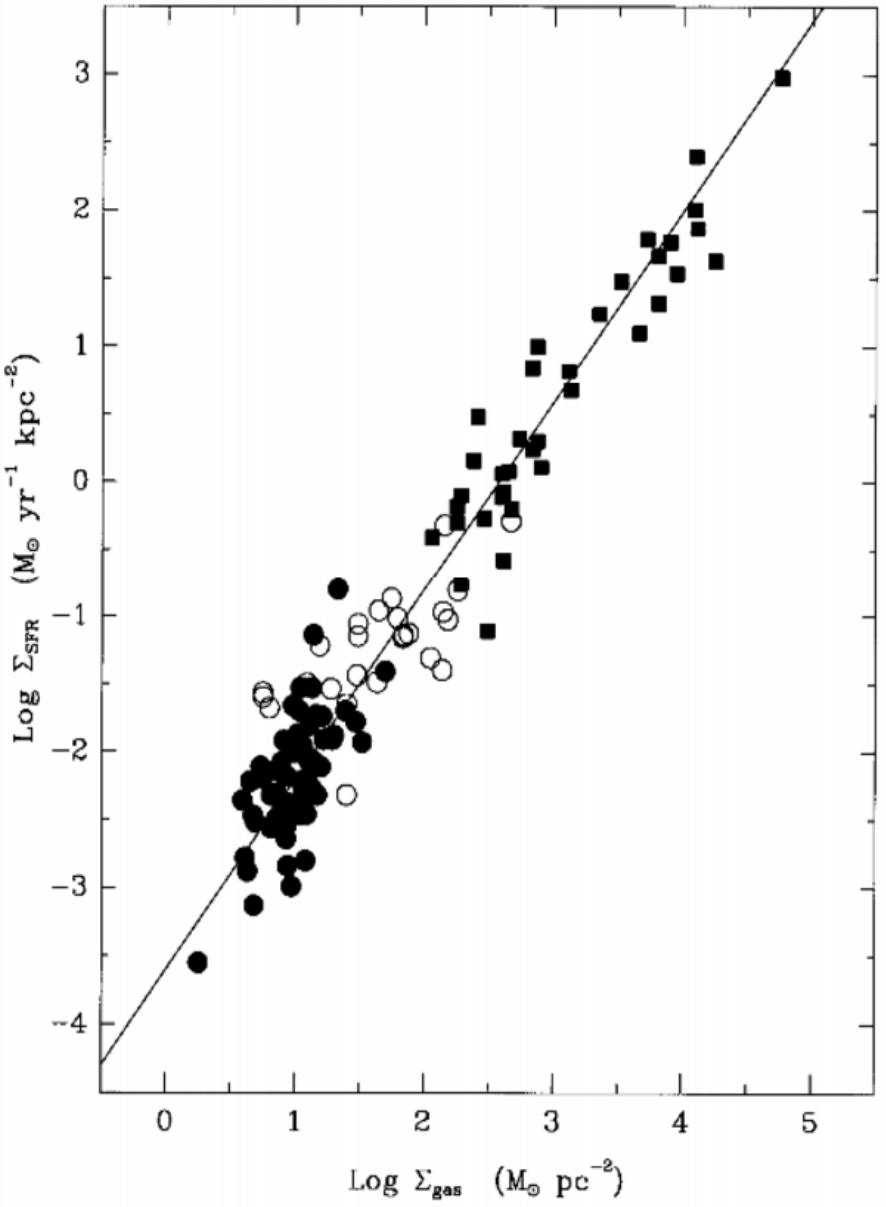
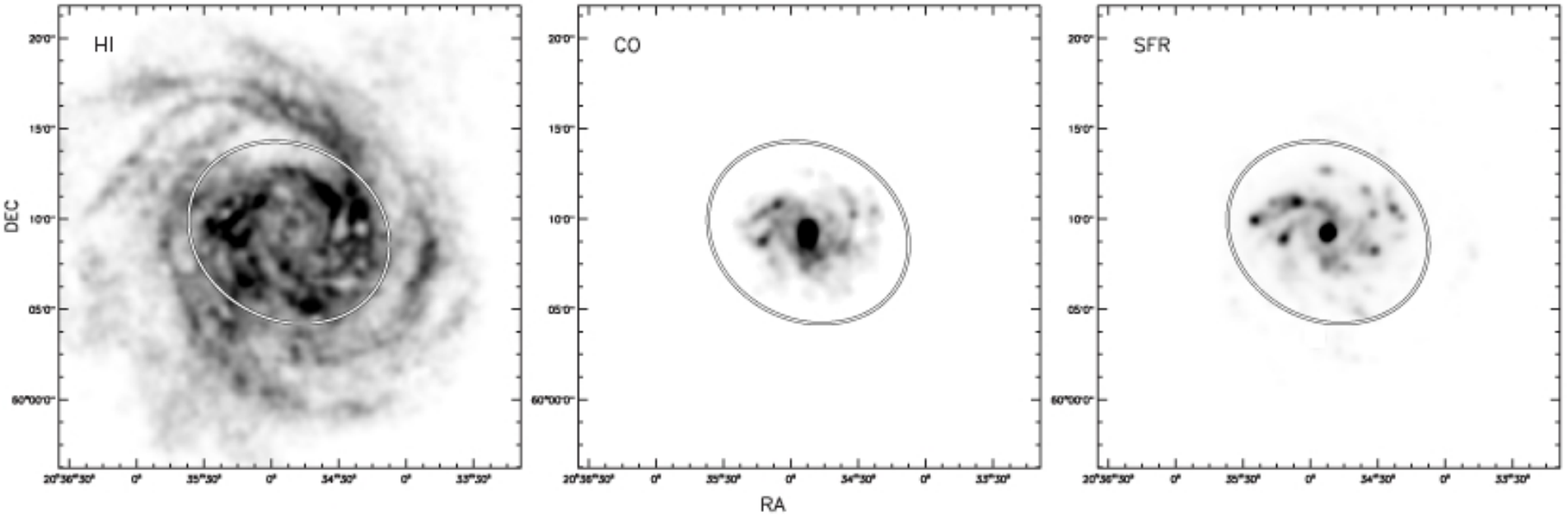
Jayaram Chengalur (NCRA-TIFR), Jing Wang (ATNF),
Igor Karachentsev (SAO-RAS)

"In what is seen, there should be just the seen ..." - *Sutta Nipata* (Buddhist scripture)

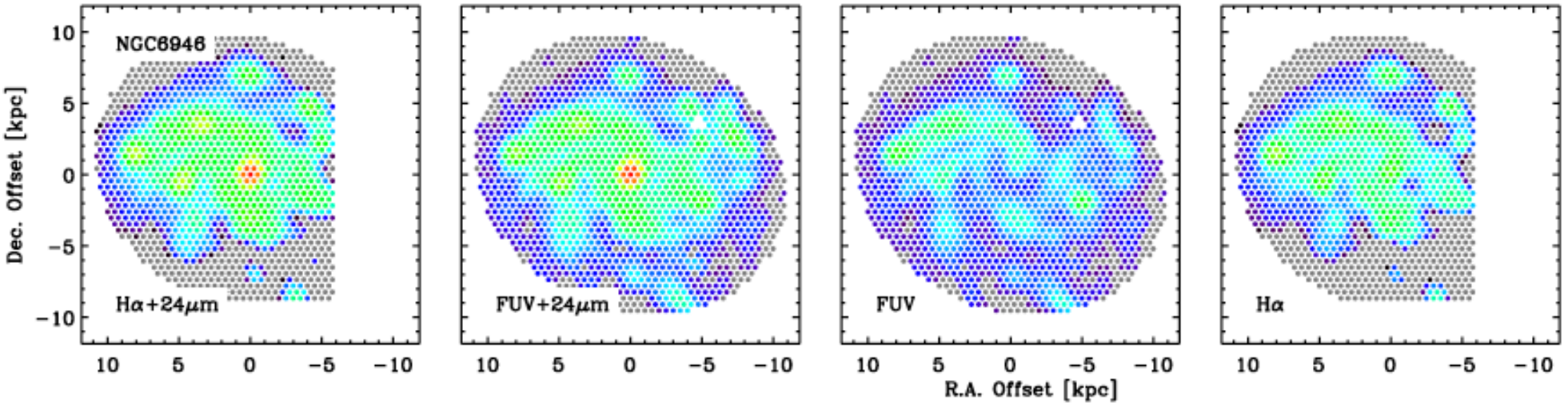
Kennicutt-Schmidt relation

- "It is assumed that the rate of star formation ... varies with a power *n* of the density of interstellar gas ..."
- Surface densities of gas and star formation related as:
  $\Sigma_{SFR} = A\,\Sigma_{gas}^{N}$ (Schmidt 1959)
- From disc-averaged values for large spirals and starbursts →
  N = 1.4 (Kennicutt 1998)



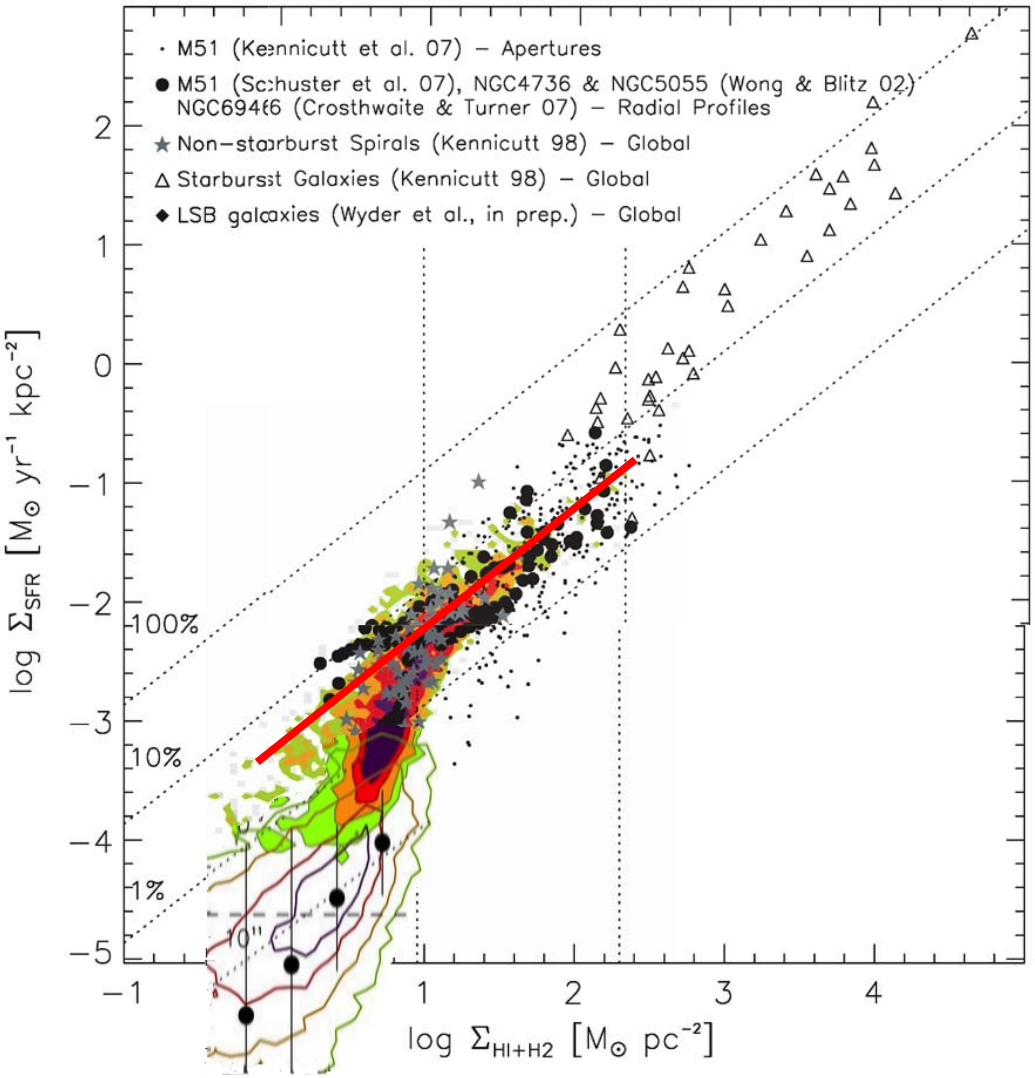


Bigiel et al. 2008



Leroy et al. 2012

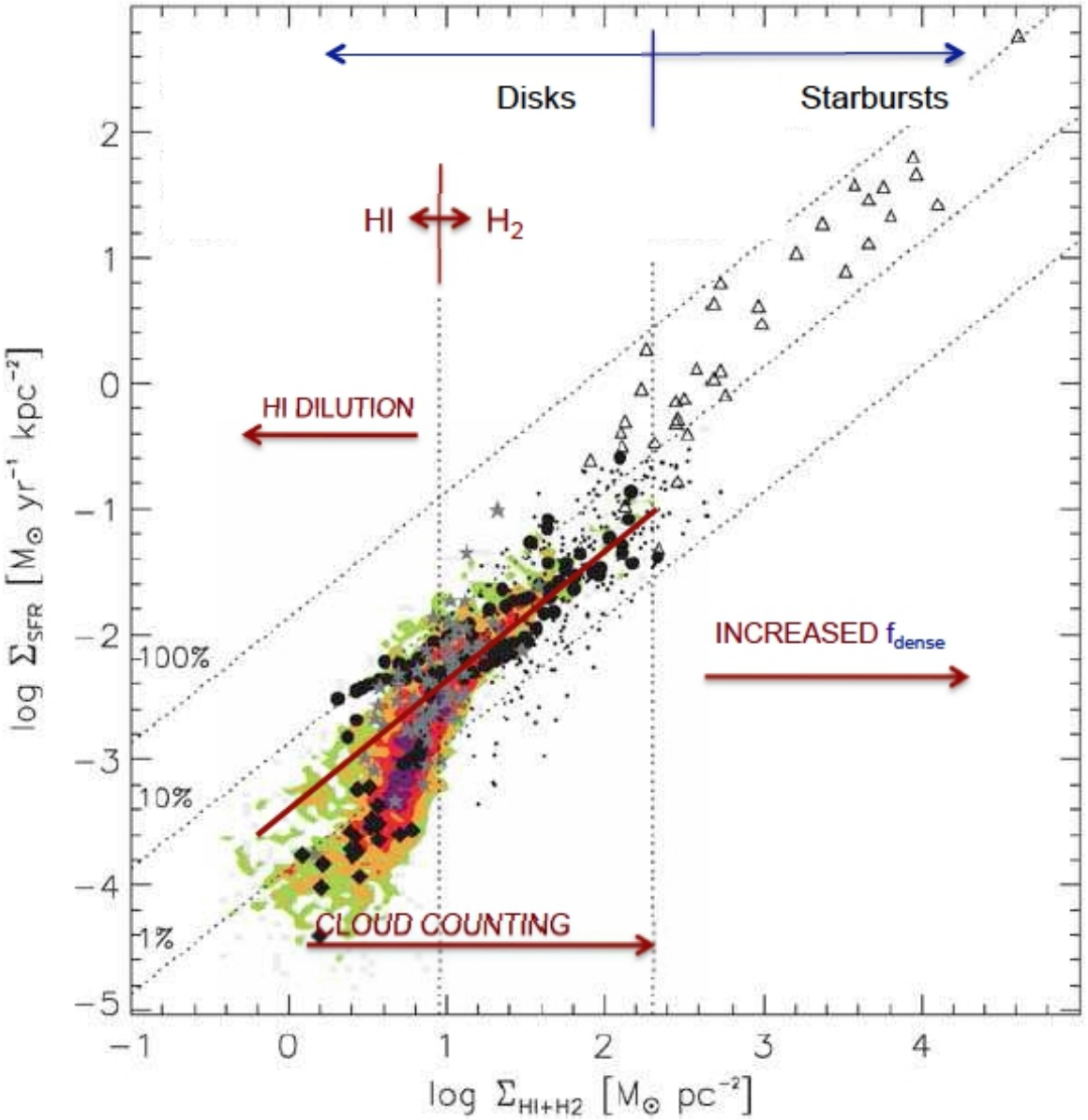
Kennicutt-Schmidt relation



Bigiel et al. 2008, 2010a; Schruba et al. 2012; Leroy et al. 2013

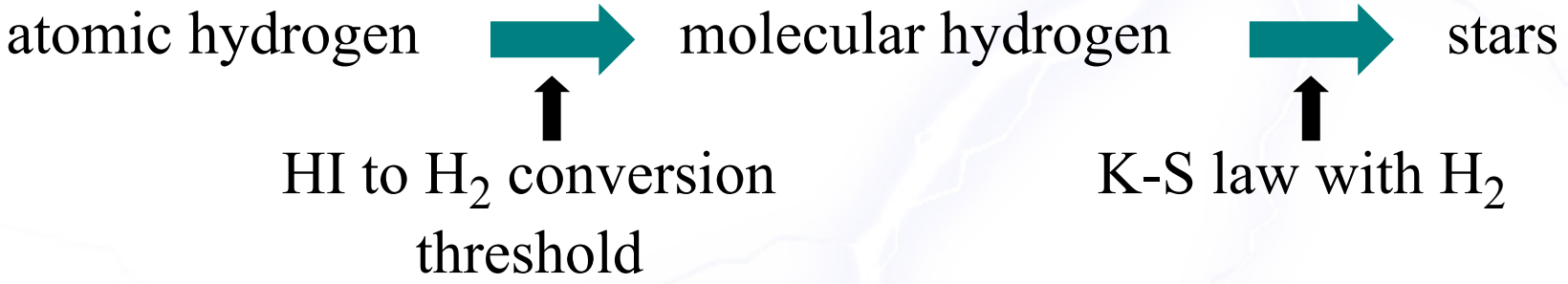
But R. Shetty's talk yesterday ...

Kennicutt-Schmidt relation



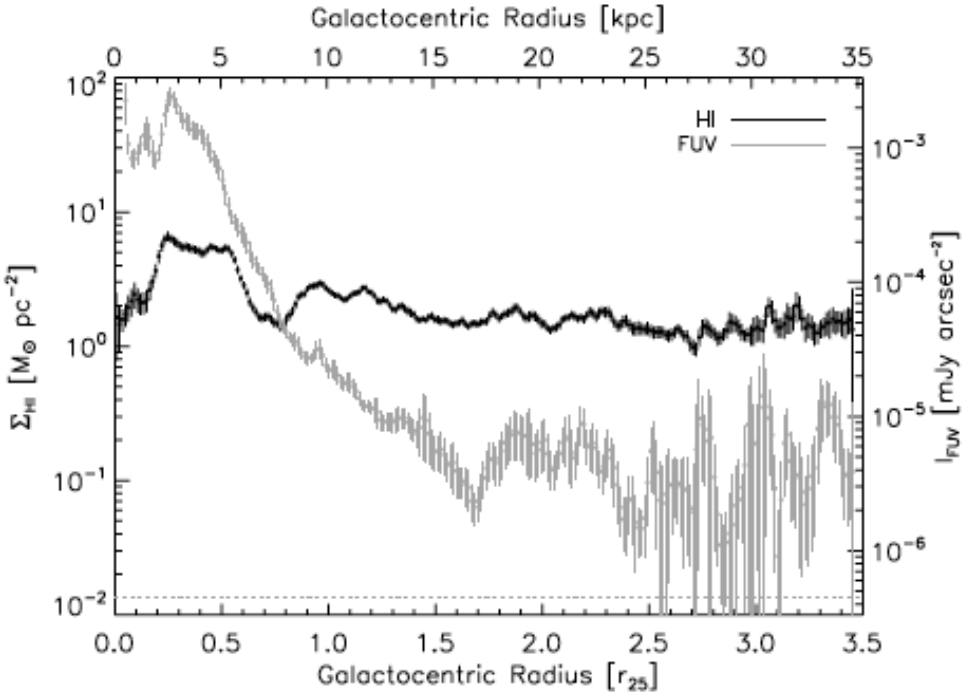
Lada 2014

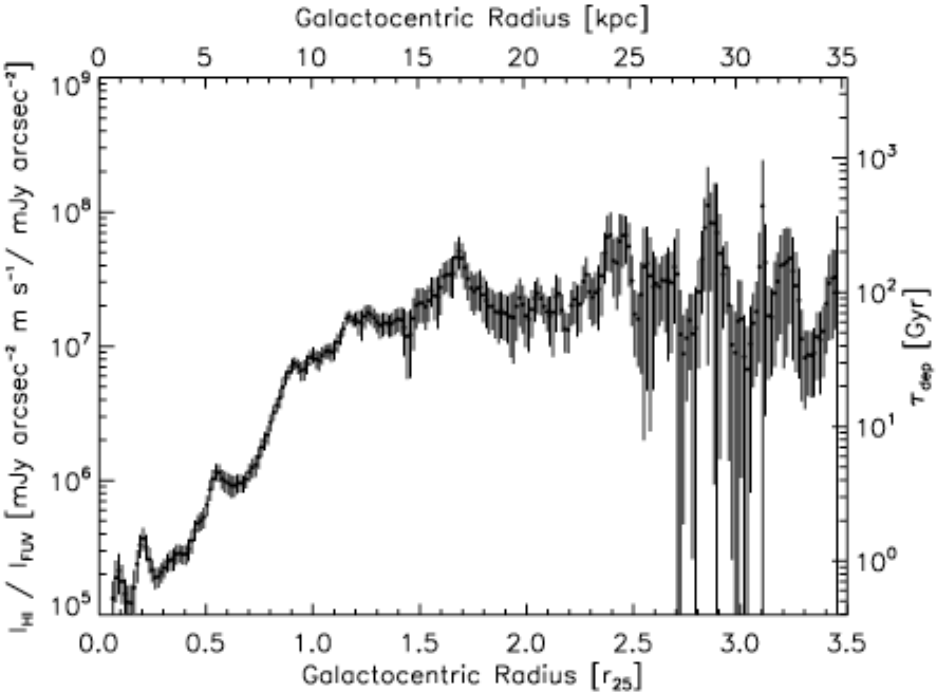
- Observations indicate two-step process for star formation:



- Physically motivated models to explain what is observed:
  - Krumholz, McKee & Tumlinson (2009, KMT); Krumholz 2013 (low Z)
    - SFR surface density = total gas surface density (fuel)
      x fraction of molecular gas
      x fraction of H_2 in GMCs transformed to stars per free-fall time.
  - Ostriker, McKee & Leroy (2010, OML)
    - Vertical dynamical equilibrium and thermal equilibrium in two-phase diffuse gas with Gravitationally Bound Clouds.

Outer disk of massive spiral





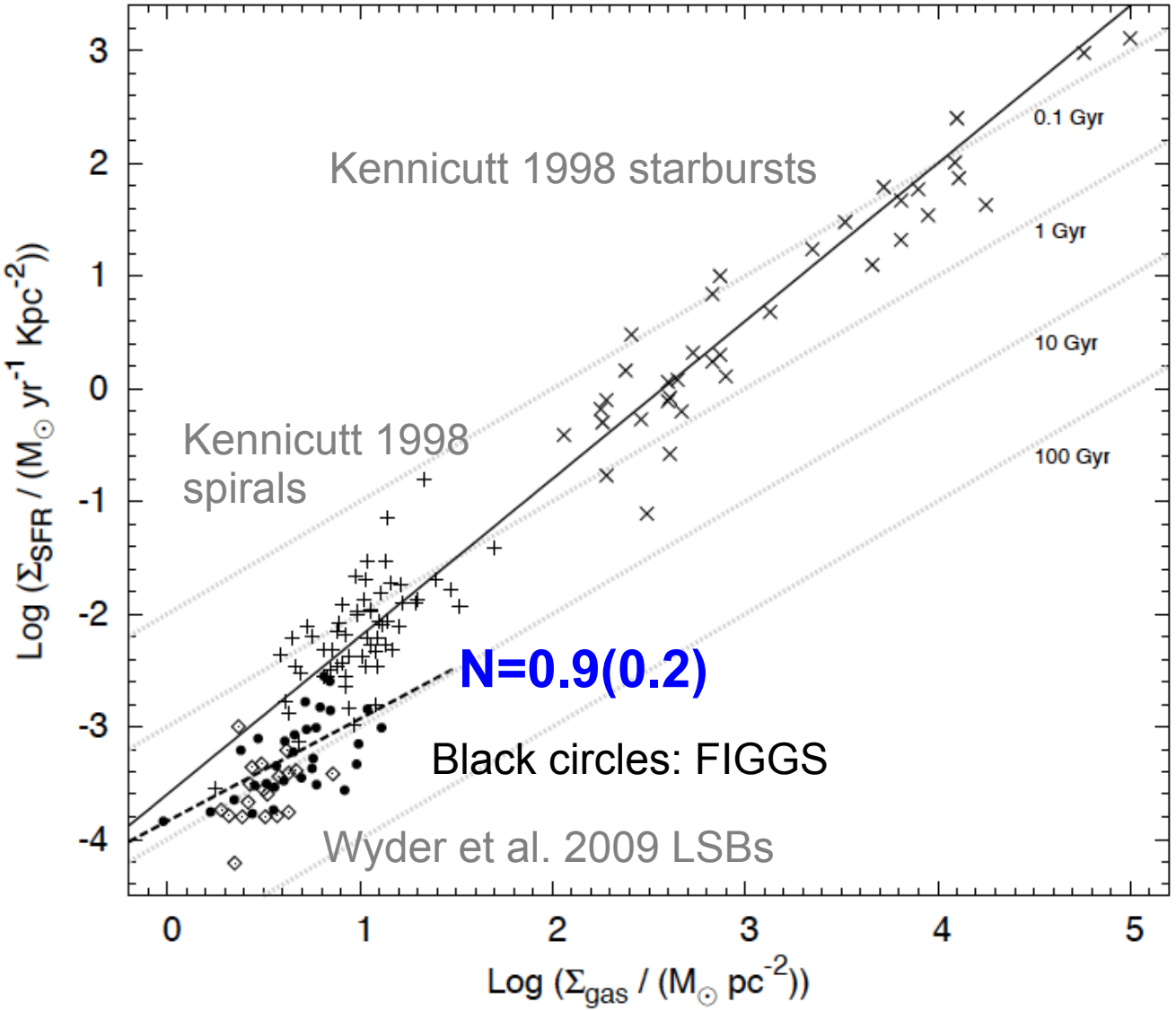
- Tight correlation between HI and FUV fluxes out to 4 effective radii in M83 (Bigiel et al. 2010b)
- After 1.5 effective radii, depletion time constant around 100 Gyr

Faint Irregular Galaxy GMRT Survey

- For 62 (→ 73) galaxies HI 21 cm emission observed, largest such sample
- Sample properties (Begum et al., 2008):

  $M_B > -14.5$, $\langle M_B \rangle \sim -13$, $\langle D \rangle \sim 4$ Mpc, $\langle M_{HI} \rangle \sim 3 \times 10^7 M_\odot$
- Fraction of gas in baryonic mass, <fgas> ~ 0.7
- Metallicity < 0.2 solar
- Molecular hydrogen assumed to be negligible (no detected CO emission)
- Star Formation Rate: **FUV** from *GALEX*
- Effect of dust inside the galaxies : **24 μm** *Spitzer* data (Dale et al. 2009)
  → very little dust in general.
- Corrections applied due to account for: varying emergent fluxes from stars in low metallicity ISM, using Raiter et al. (2010) values.
- 'Composite' calibration from Hao et al. (2011)
- Average surface densities over 'optical-disk' of each galaxy ...

Disk-averaged relation for faint dwarfs



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- Questions:

  - In empirical determinations of the Kennicutt-Schmidt relation on sub-kpc scales, especially in regions dominated by HI, does the HI only act as a diluting factor?

  - We empirically check for HI dominated regions, and for all of the HI.

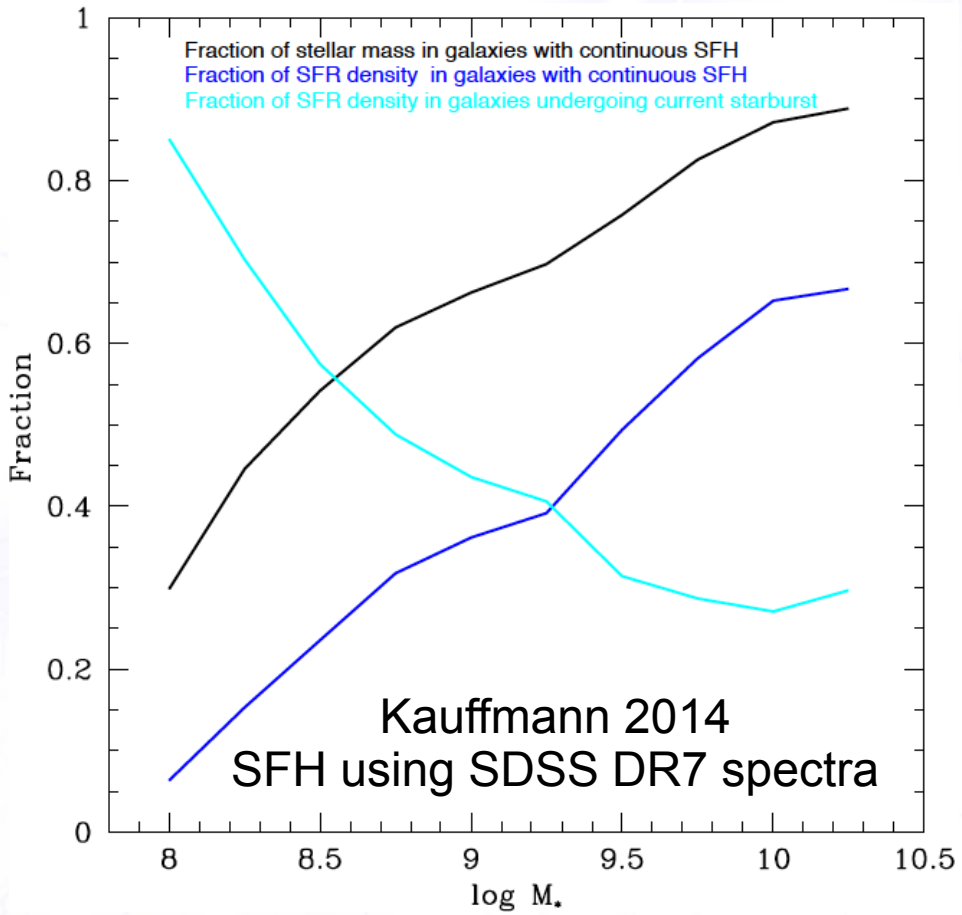
  - In the HI-dominated regime, is what we measure a direct relation between the amount of gas and the corresponding rate of star formation, or there are other processes which determine the form of the relation as we see it?

Measuring SFRs in HI dominated regime

- SFRs are intrinsically low in this regime.
- 'Resolved' studies with small regions brings measured SFR down further.
- Dwarf galaxies have 'bursty' star formation history.
- 'Resolved' regions in spirals will also be affected by local variations of SFH.

Assumptions in SFR calibrations

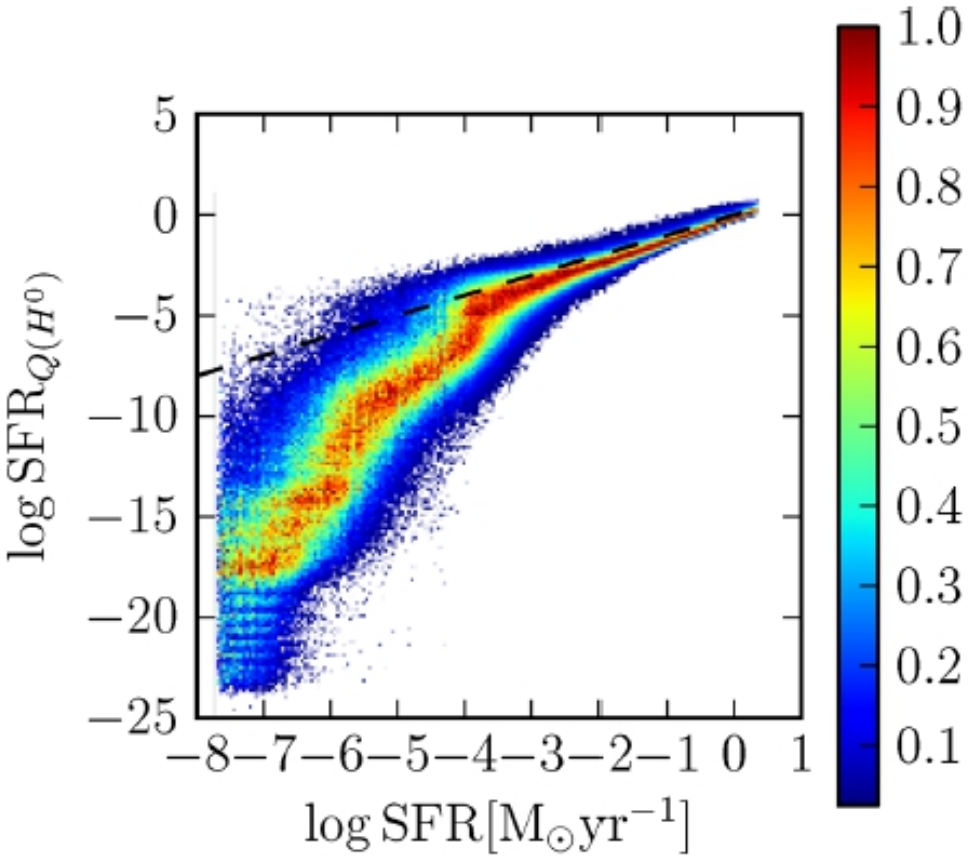
- SFR calibrations assume continuous star formation for the last ~ 100 Myr

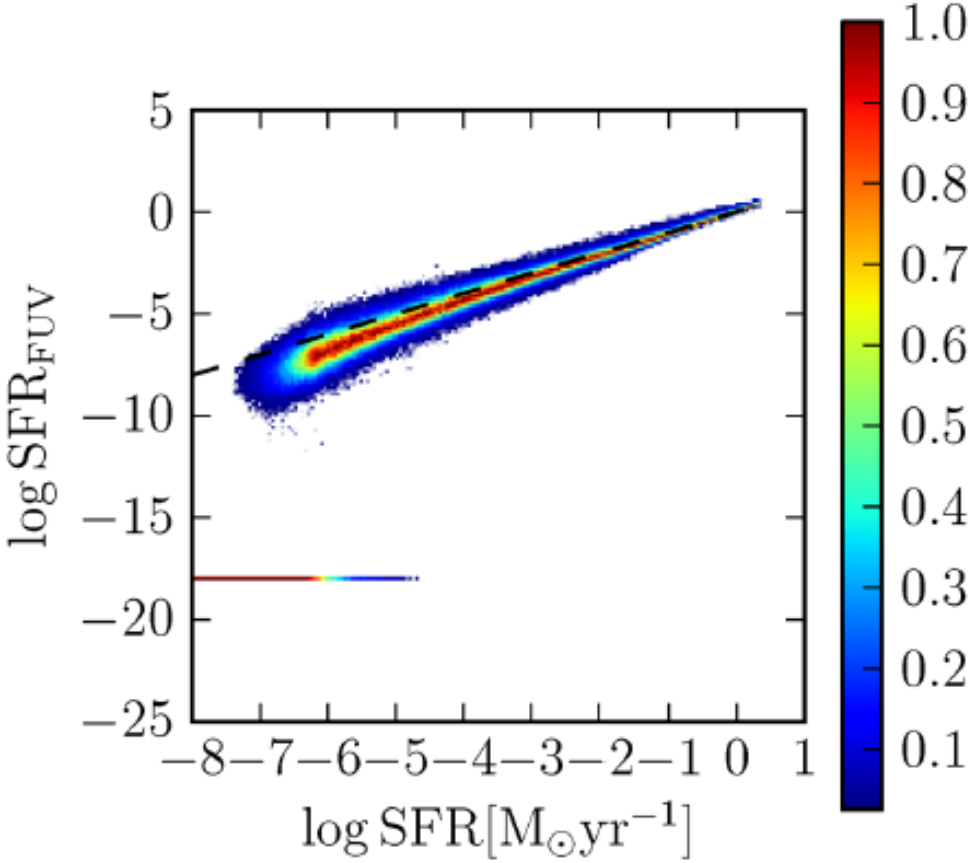


- Calibrations assume IMF, low SFRs → stochastic sampling of high mass end

Estimating the effect of bursty SF

- Stochastically Lighting Up Galaxies (SLUG) code (da Silva et al. 2012, 2014):
- Monte Carlo realizations of photometric properties given SFH, IMF, ICMF
- Increasing bias (median of estimated SFR lower) and scatter at low SFRs





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- Resolution (for now):
- Use FUV as the tracer of star formation

  (we also use mid-IR fluxes to correct for internal dust extinction by using 'composite' SFR calibrations)
- Average over large enough area to reduce local variations in SFH

  Method therefore not sensitive to the intrinsic scatter in SFR

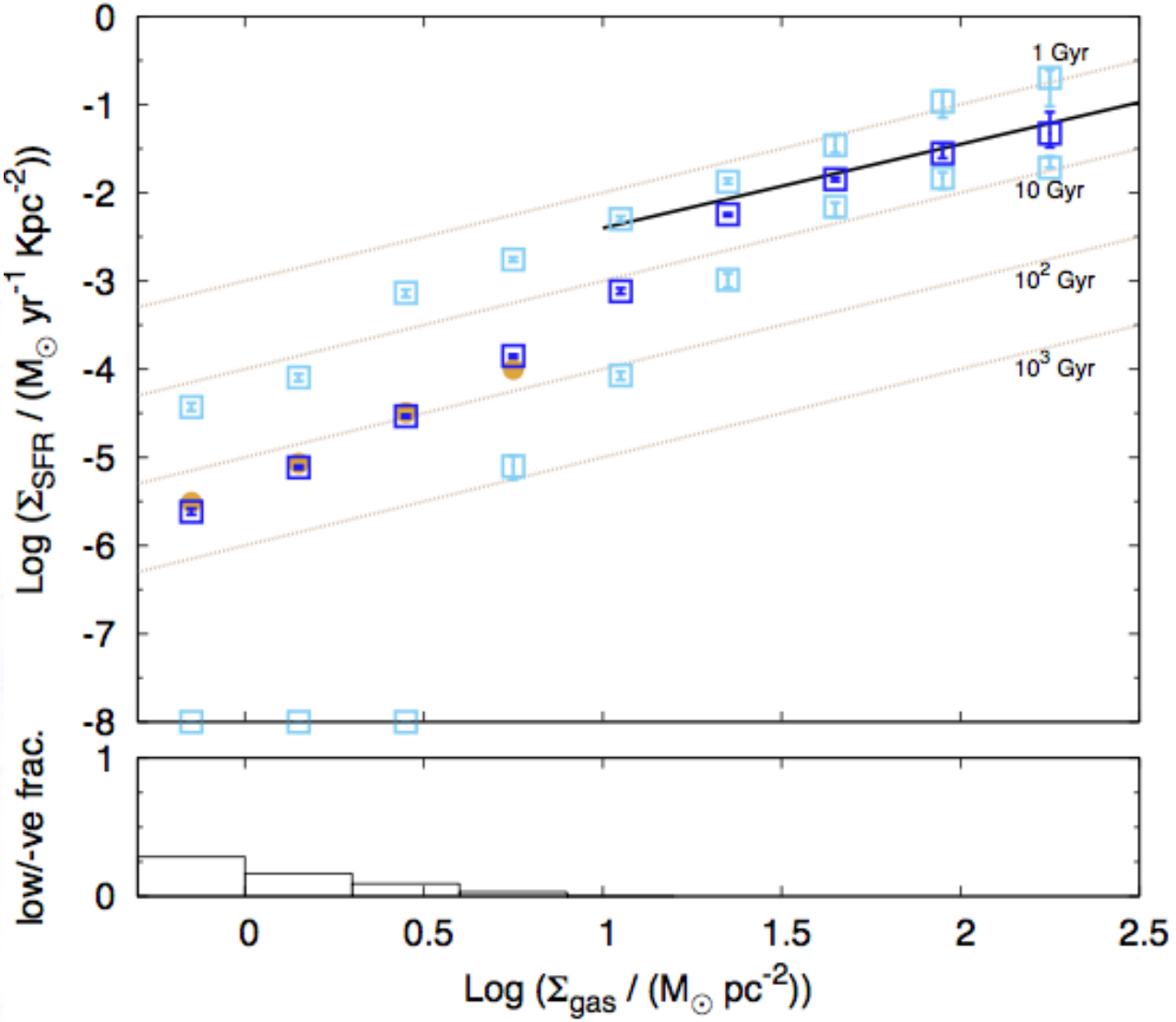
The spatially resolved relation - nearby spirals

- Tracers
  - Atomic gas: **HI** from **T**he **HI** **N**earby **G**alaxy **S**urvey (Walter et al. 2008)
  - Molecular hydrogen: **CO** from HERACLES survey (Leroy et al. 2009)
  - Star Formation Rate: **FUV** from *GALEX*

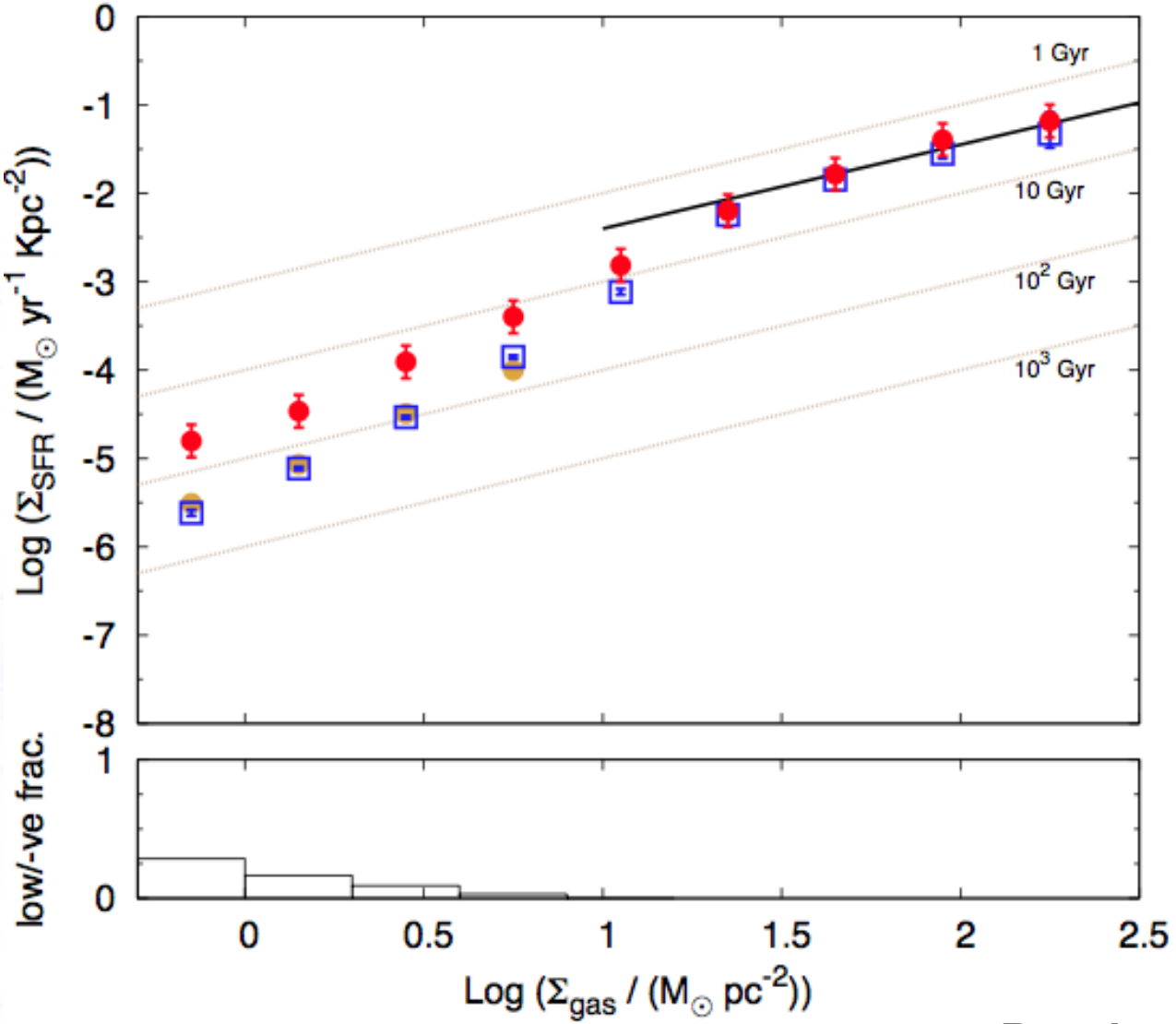
    To account for internal dust: **24 μm** fluxes from *Spitzer*

    'Composite' calibration from Hao et al. (2011)
- 12 spirals from the sample used in Bigiel et al. (2010) → 1kpc size regions
- 7 spirals : 400 pc regions (native HI resolution)
- HI dominated regions are those without detected CO emission

THINGS galaxies ~ 1 kpc scales



THINGS galaxies ~ 1 kpc scales



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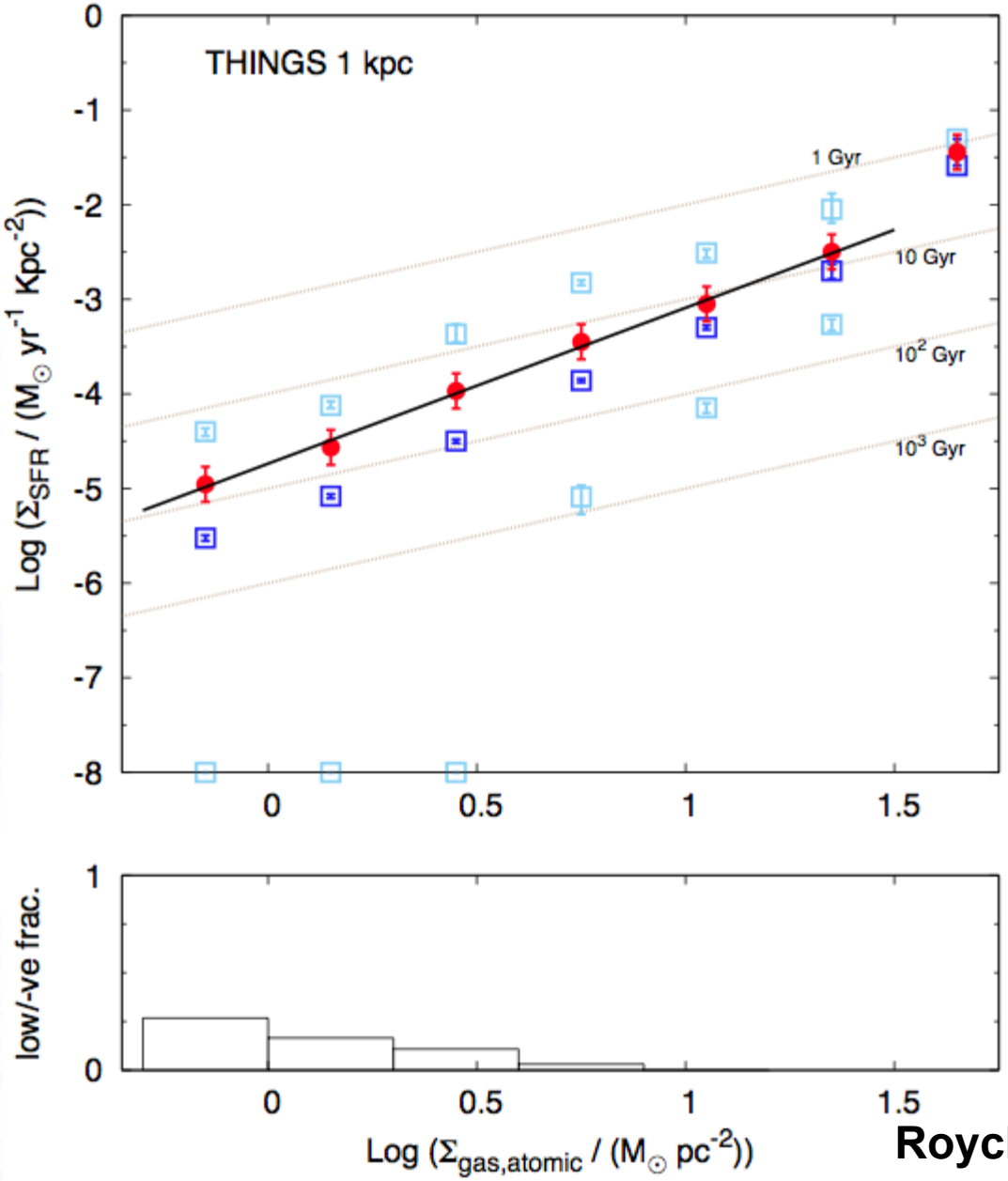

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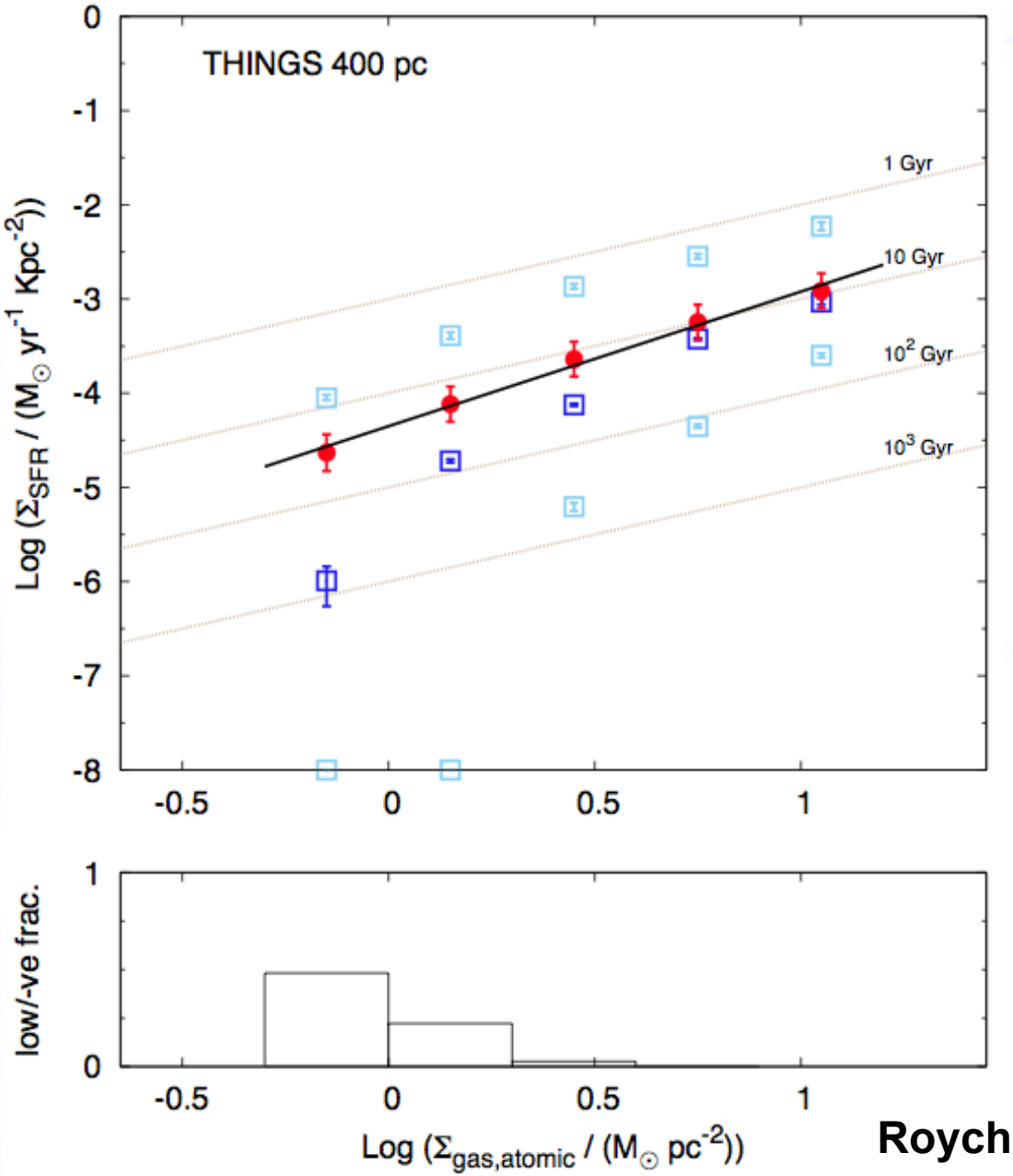
THINGS galaxies ~ 400 pc scales



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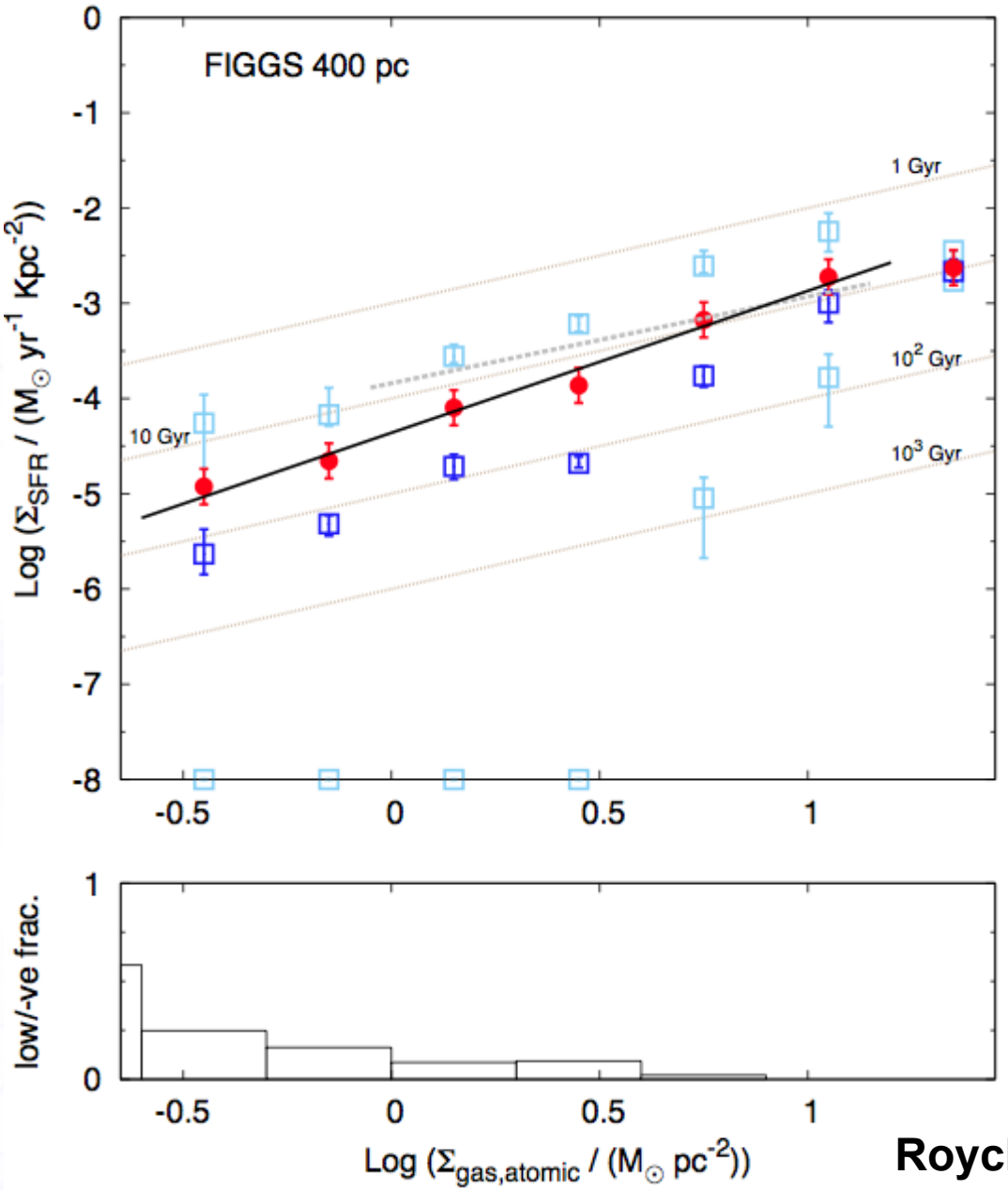
FIGGS galaxies ~ 400 pc scales



22 galaxies

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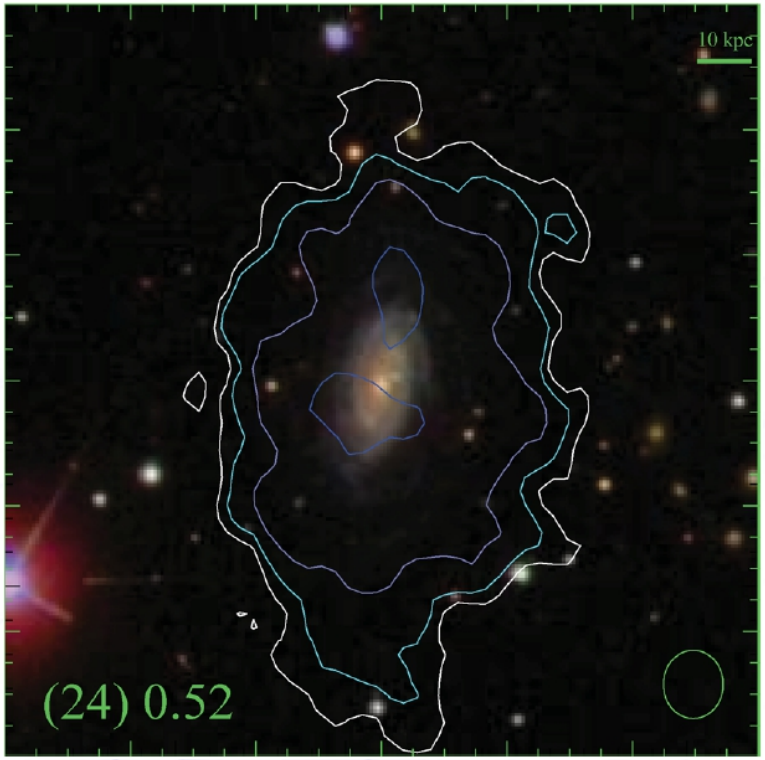
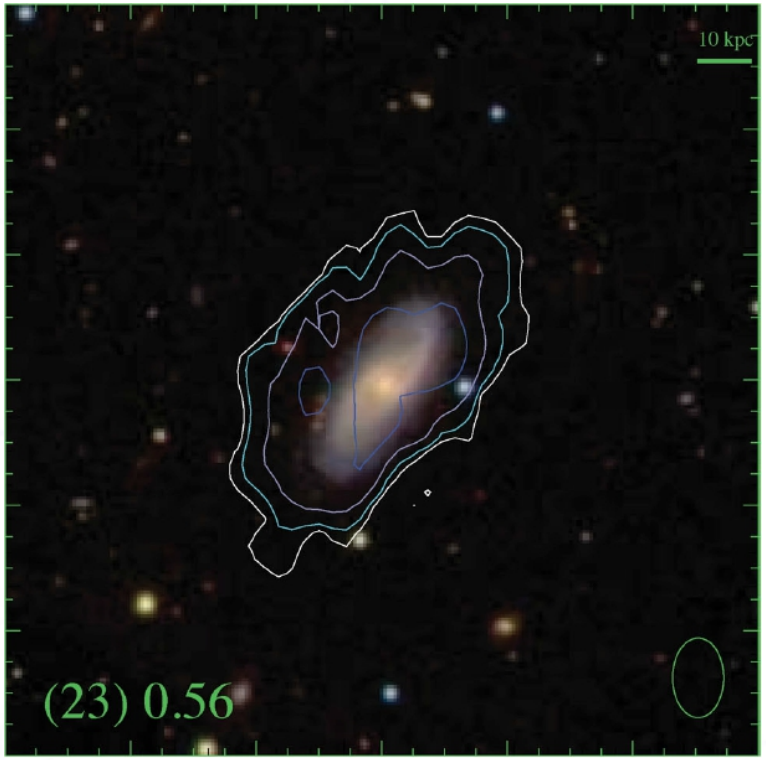
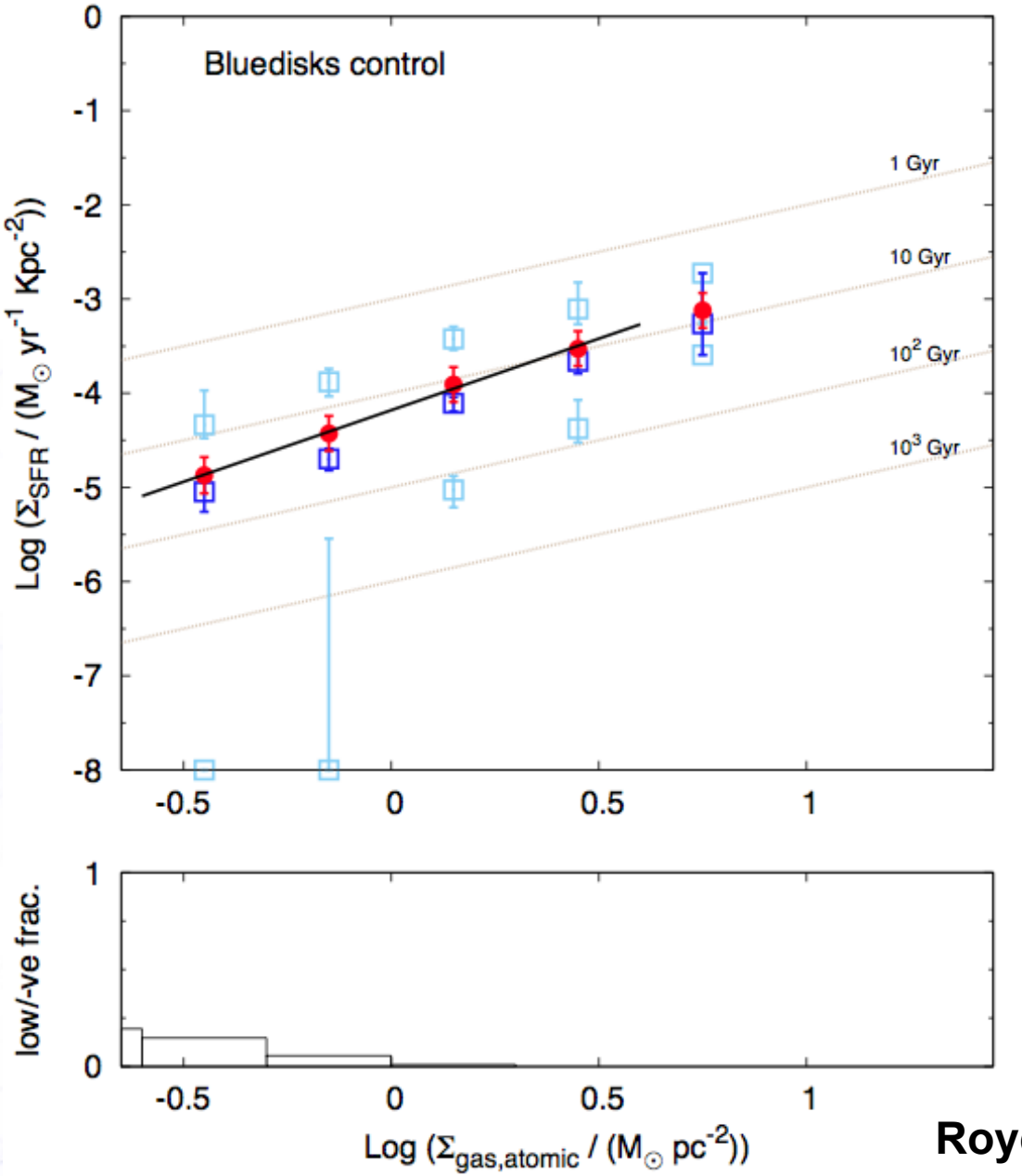
'Bluedisks' survey ~ 10 kpc scales

- **HI** survey of massive ($M_* > 10^{10}\ M_\odot$) very HI rich galaxies (23) and control galaxies (19) at z ~ 0.01, with optical disks tens of kpc across using the WSRT
- CO observations not yet available → outside R25 assumed HI-dominated
- Star Formation Rate: **FUV** from *GALEX*
- To account for internal dust: **22 μm** fluxes from *WISE*
- 'Composite' calibration from Hao et al. (2011)





'Bluedisk' control galaxies ~ 10 kpc scales



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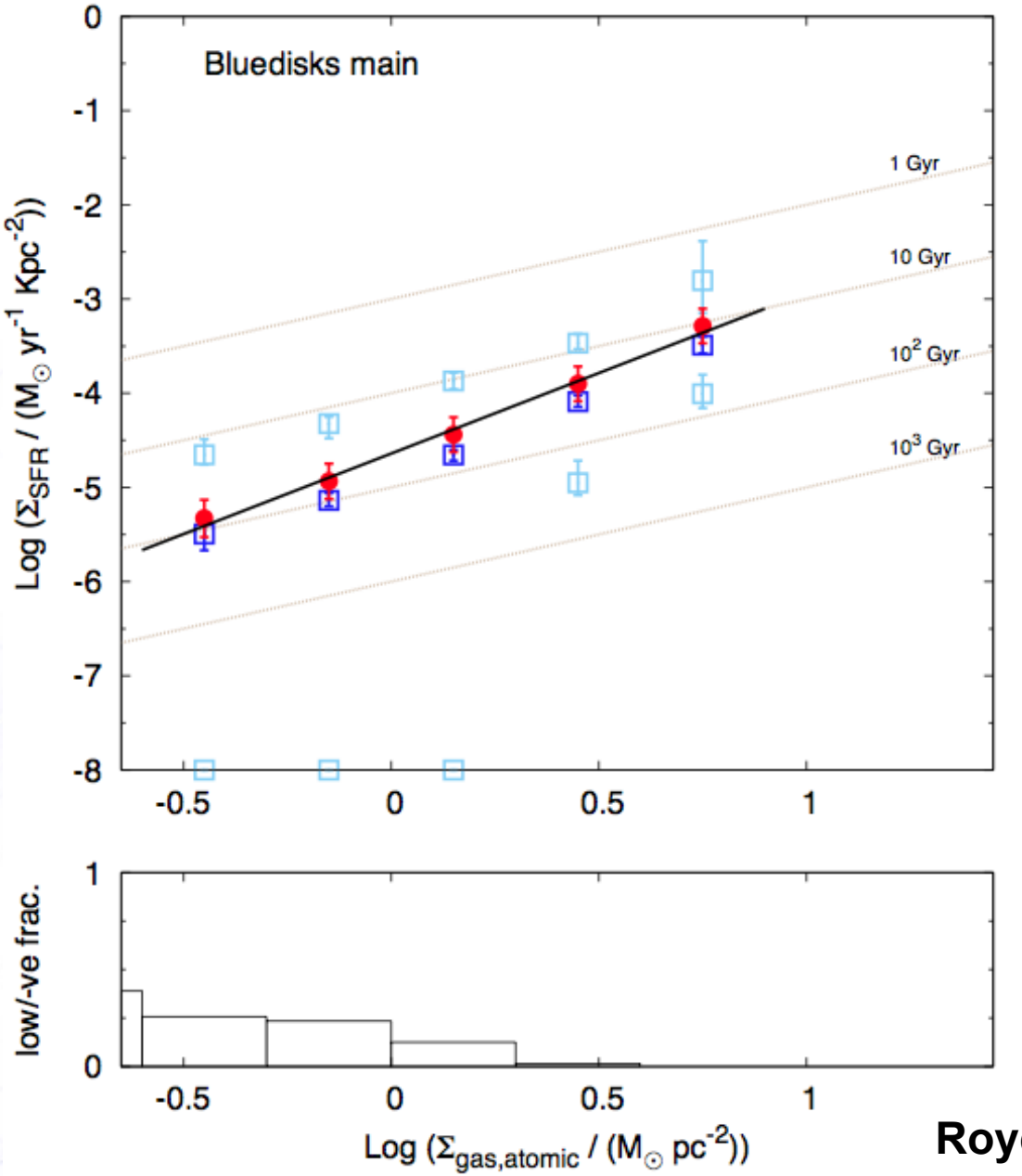
'Bluedisk' main sample ~ 10 kpc scales



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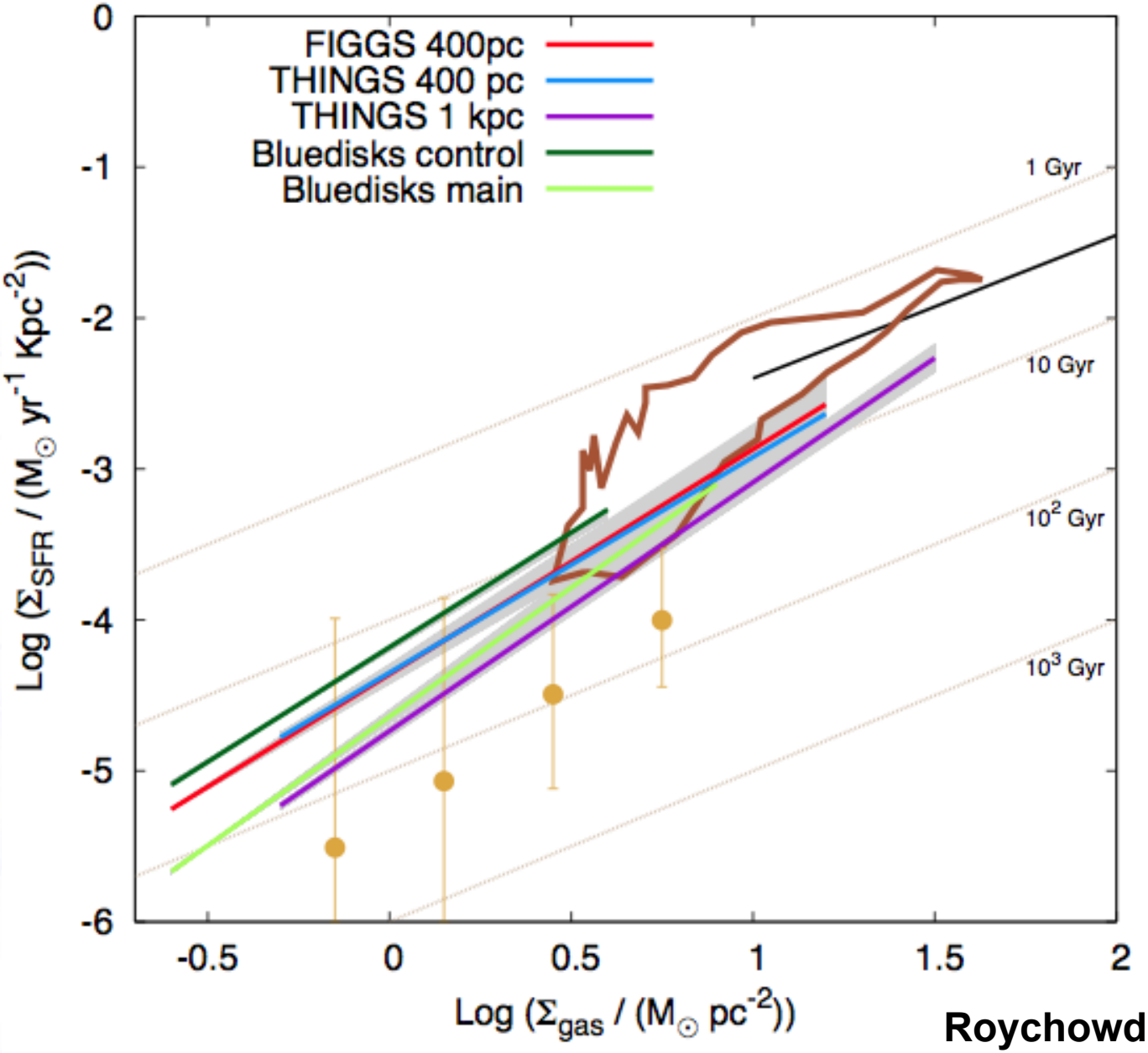
K-S relation in the HI dominated regime



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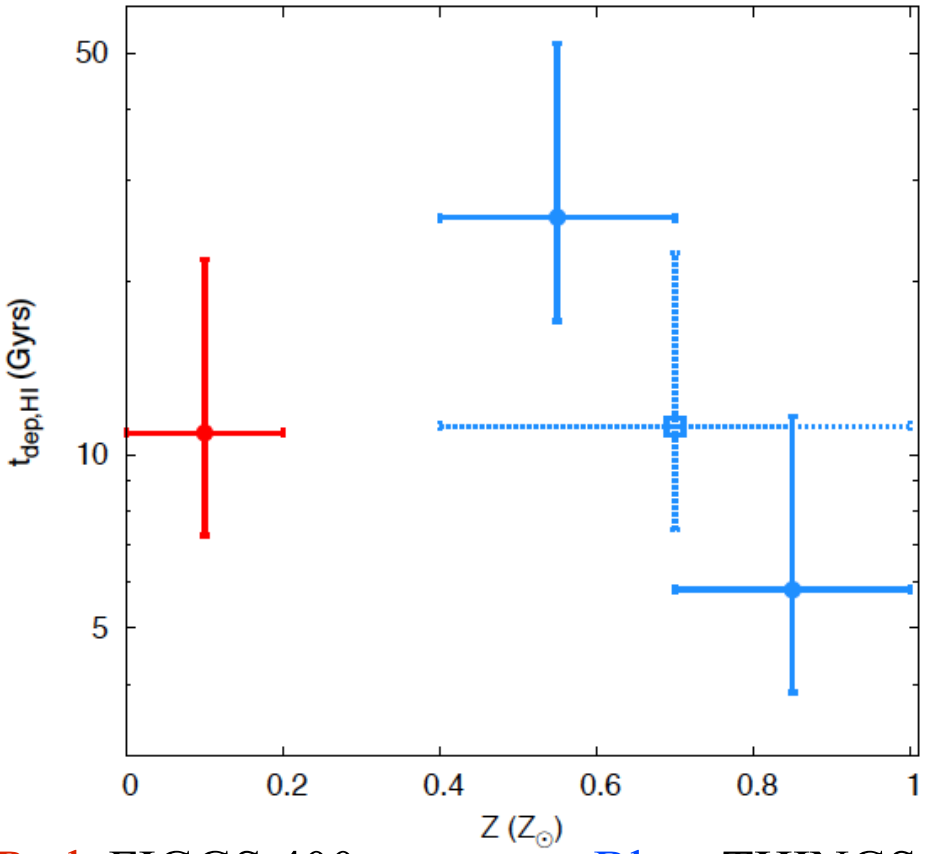
Comparing diverse environments



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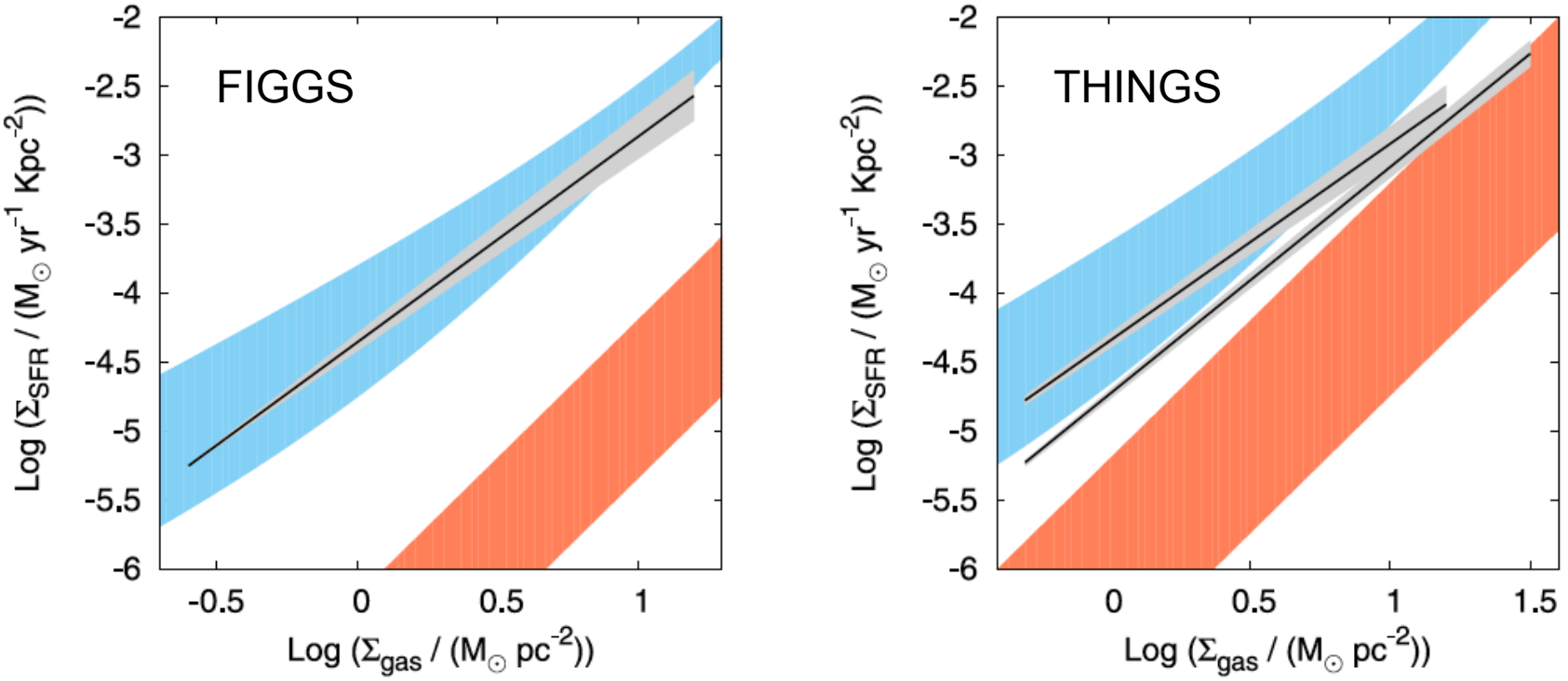
Red: FIGGS 400 pc Blue: THINGS 400 pc

- The amount of dust in the ISM scales with the measured metallicity
- (i) The rate of H_2 formation, (ii) the shielding of UV radiation enabling H_2 formation – both proportional to the amount of dust in the ISM

Comparison with models



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- Blue: OML10 model for outer disks
- Red: KMT+ model
- Metallicity: 0.1 $Z_\odot$ for FIGGS, varied between 0.4 and 1 $Z_\odot$ for spirals
- Density of gas and stars varied between 0.003 to 0.03 $M_\odot$ pc^{-3}
- Clumping factor for HI: 1.3 (400 pc & 1 kpc, Leroy et al. 2013)

Summary

- Is there a Kennicutt-Schmidt relation involving HI, or is it just a diluting factor on the 'true' relation involving the molecular phase?
- We look at HI dominated regions of very nearby galaxies
- In dwarf Irregulars and outer regions of spirals with low SFRs, one has to be very careful and account for the limit below which SFR calibrations become highly uncertain
- HI gets converted to gas inefficiently compared to molecular hydrogen, but not as inefficiently as previously believed
- An average Kennicutt-Schmidt relation (N~1.5) exists between HI and SFR surface densities in the HI dominated regime, gas consumption timescale ~ few times 10 Gyr, for dwarf and spiral galaxies across different scales
- The depletion times for atomic gas in the HI dominated ISM of these nearby galaxies do not show any obvious dependence on metallicity
- OML10 model gives a better fit to the result - simulations suggest thermal pressure set by turbulence driven by stellar and supernova feedback