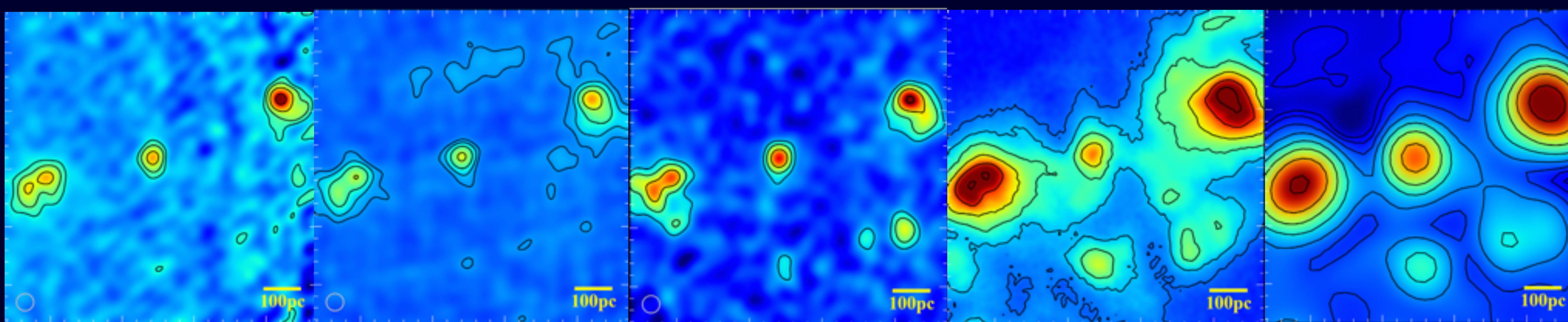
The Star Formation in Radio Survey:

Comparing the 3-33 GHz radio continuum with Hα and 24μm emission in SINGS galaxies

NGC 2403 Extra-nuclear region 2



VLA 3 GHz | VLA 15 GHz | VLA 33 GHz | Archival Hα | Spitzer 24μm

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The challenge:

To best approximate a "gold standard" star formation rate measure

What might we want in a "gold standard" ?

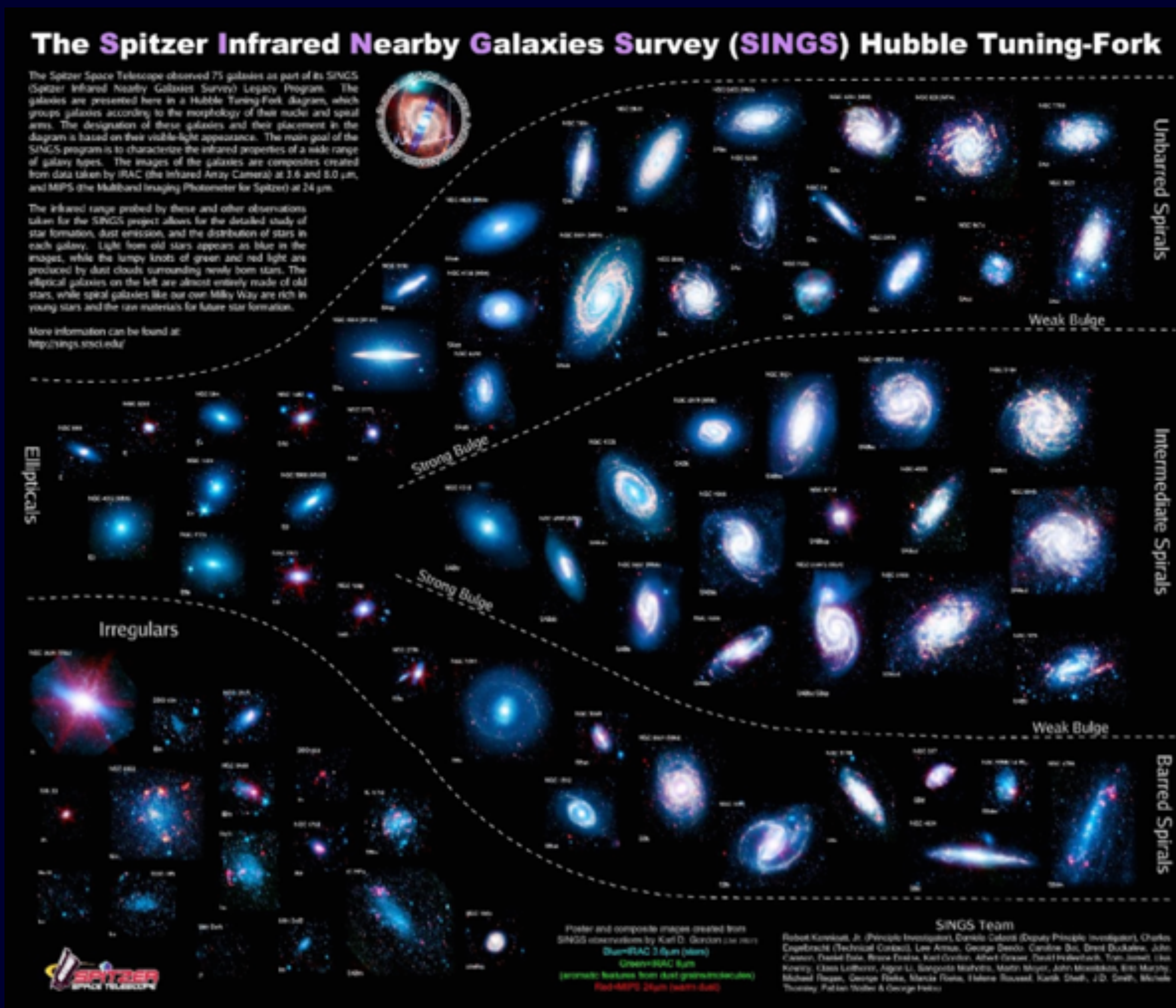
1. Controlled measurement systematics

   - Dust
   - Contamination (cirrus, galactic synchrotron, anomalous microwave emission, etc.)

2. Well calibrated physical systematics

   - Environment (metallicity, etc.)
   - Luminosity scale (how does the tracer scale with SFR?)
   - Size scale (resolved vs integrated SF)
   - Direct tracer (less model / environment dependent)

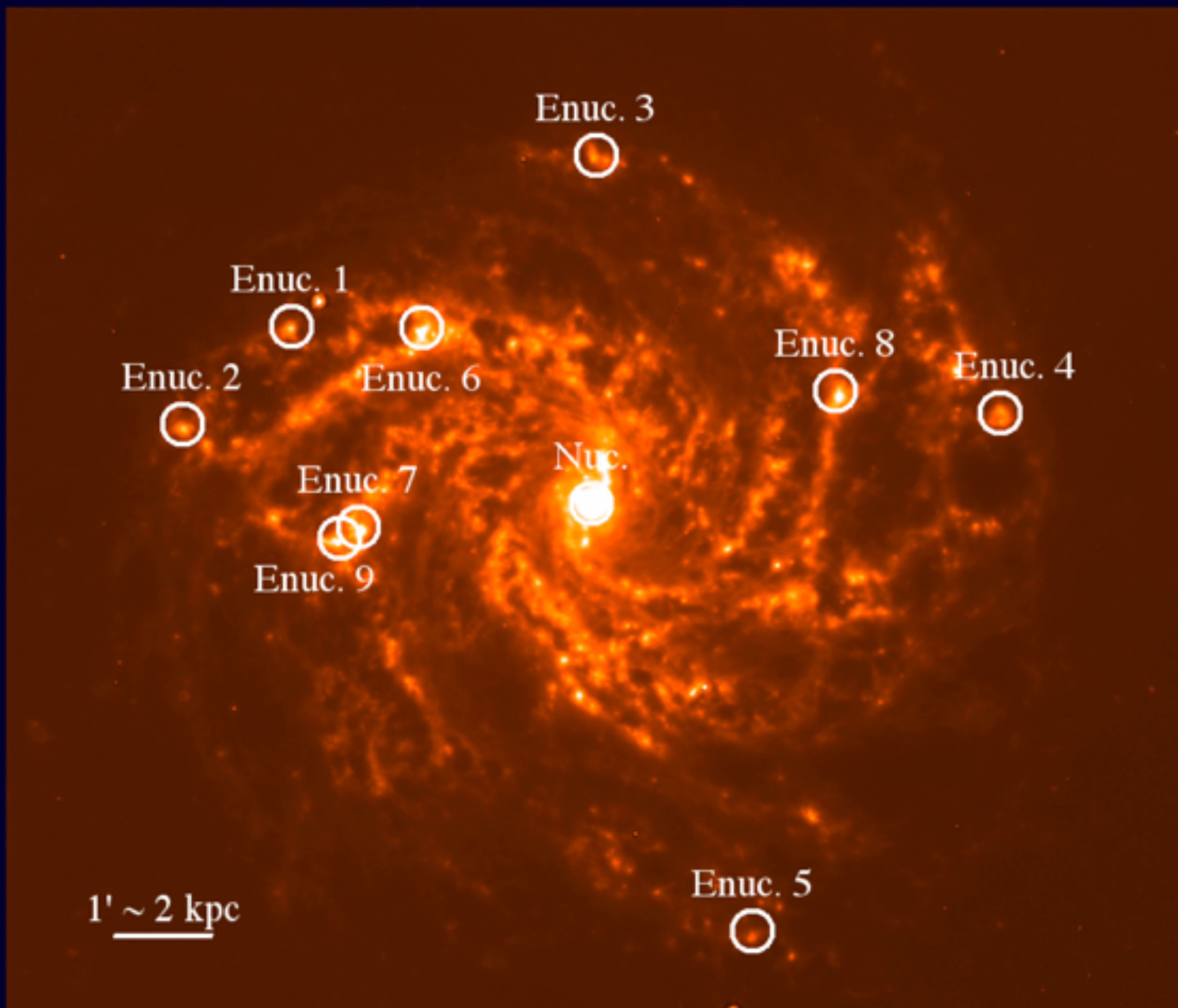
Our progenitor survey: SINGS



- Spitzer Legacy project, followed up with Herschel KINGFISH Legacy project
- 75 nearby galaxies fully covered in IR and optical
- Representative sample of ISM and SF properties in nearby galaxies, covering:
  - All morphologies
  - Range of ~10^5 in L_{TIR}
  - Range of ~10^4 in SFR
  - Range of ~10^3 in L_{IR} / L_{opt}

Kennicutt+2003

GBT pilot for the Star Formation in Radio Survey (SFRS)

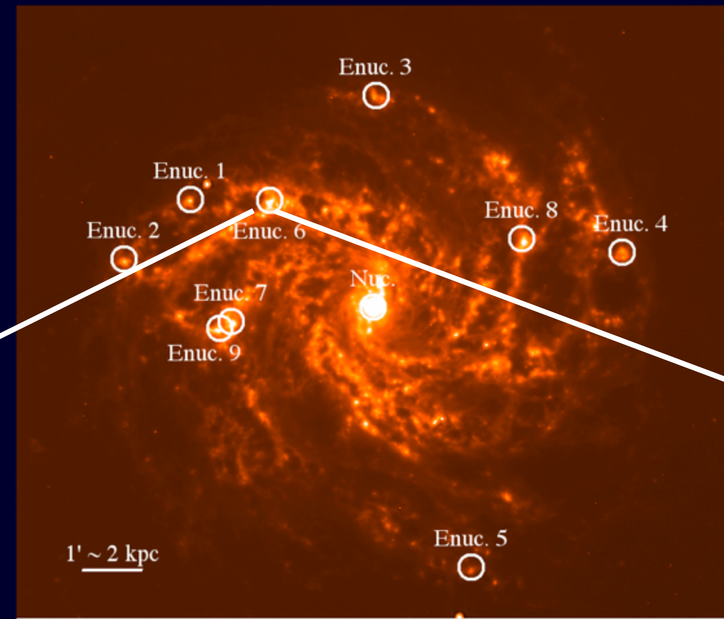


30'' circles on a 24um image of NGC 6946

- 56 nearby (d < 30Mpc) galaxies from SINGS / KINGFISH sample
- Optical / IR selection of targets within these galaxies
- 118 total observations of galaxy nuclei, HII regions
- 26-40 GHz coverage with a 25'' FWHM

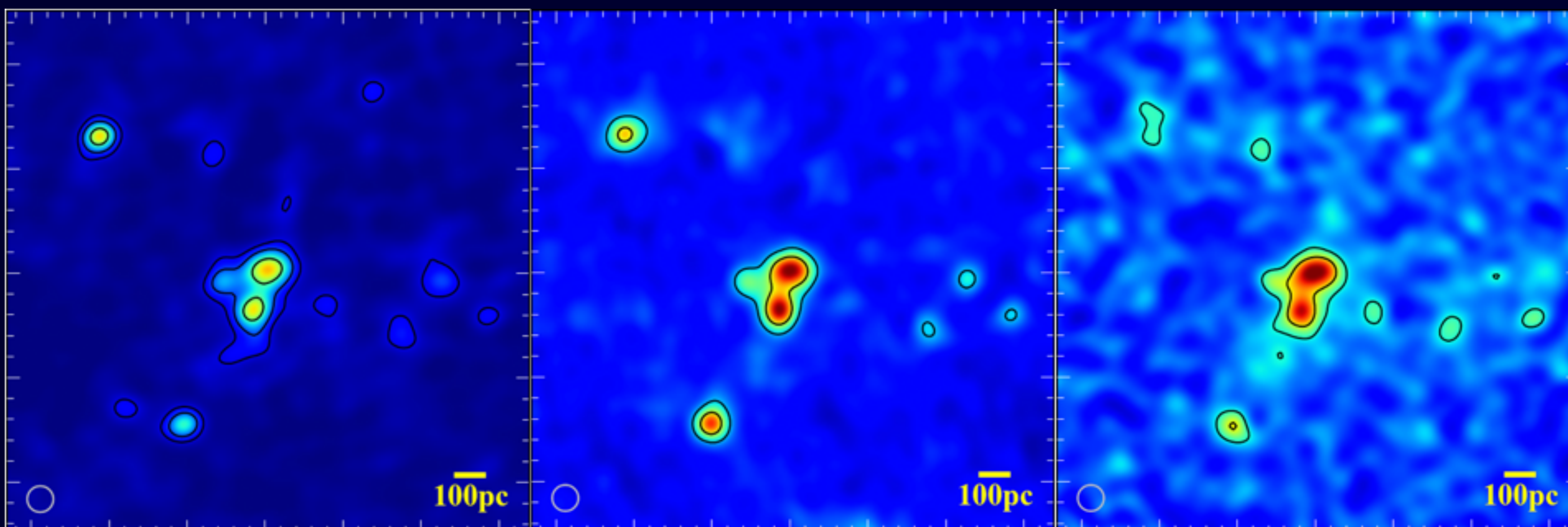
Murphy+2012

VLA component of the Star Formation in Radio Survey (SFRS)



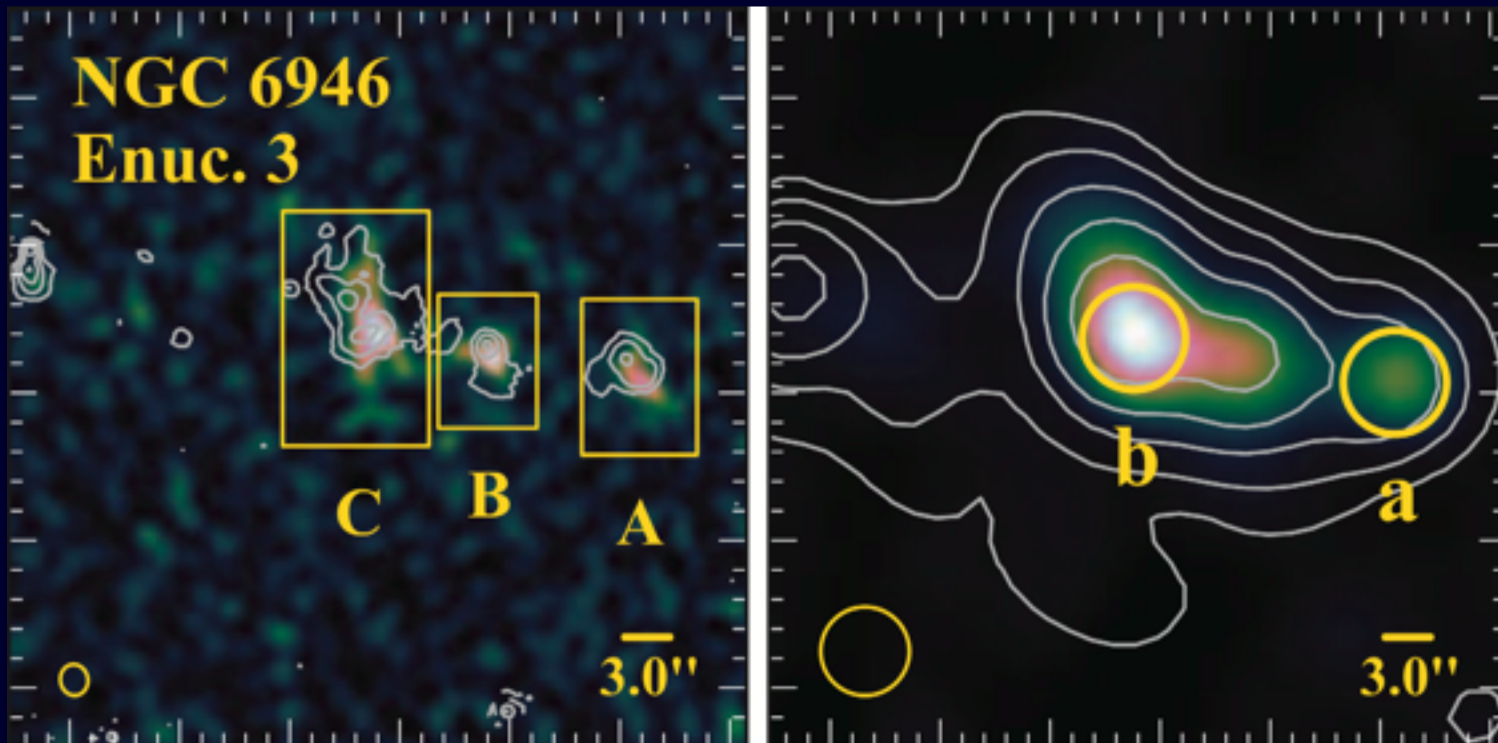
NGC 6946 extra-nuclear region 6

2-4 GHz (S) | 12-18 GHz (Ku) | 29-37 GHz (Ka)



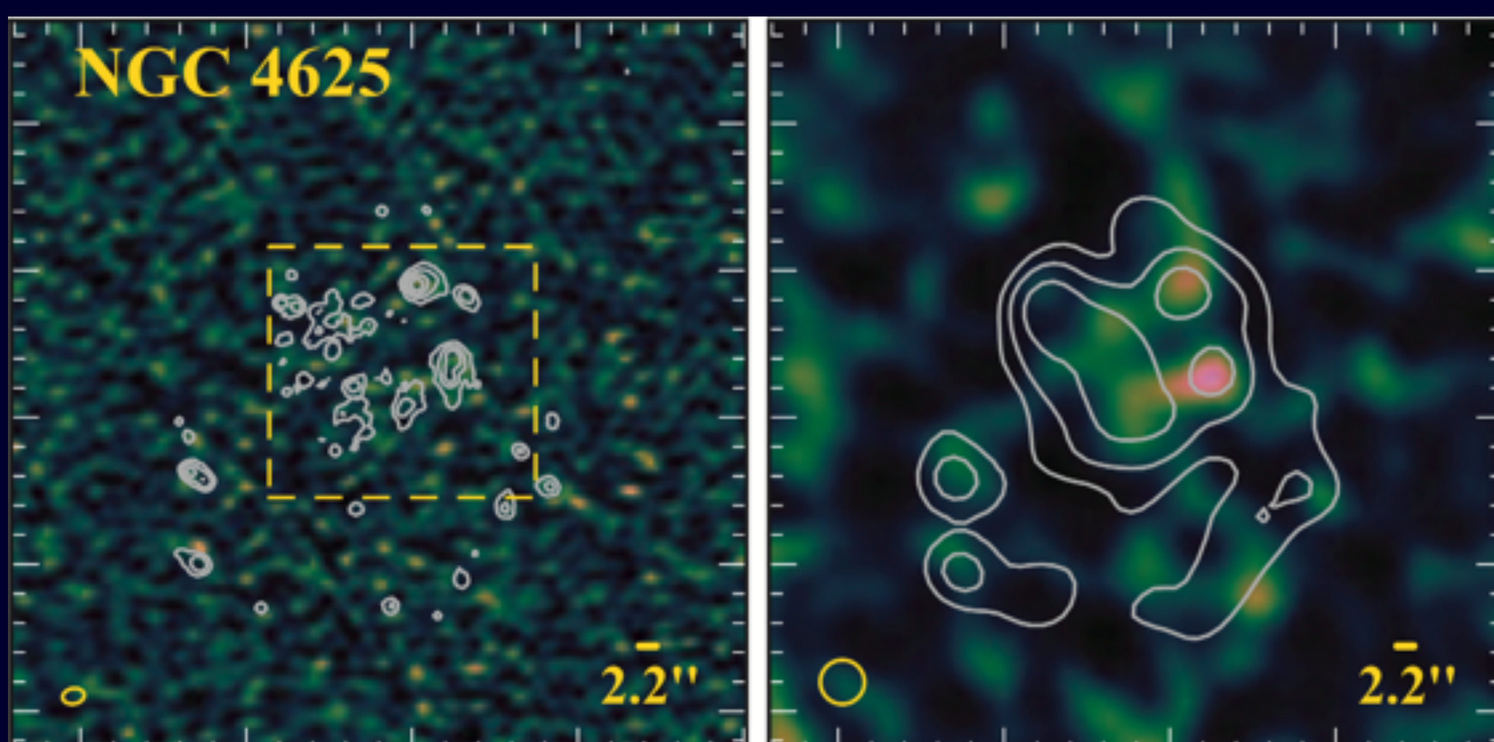
- S, Ku, Ka wideband VLA coverage of all 118 GBT pointings
- ~2'' resolution (Briggs, robust = 0.5)
- ~15μJy/beam noise (corresponding to ~12 min on source time)

33 GHz morphology
nearly identical to Hα (~2'' FWHM), 24μm (~6'' FWHM)



33GHz native resolution image
Hα contours

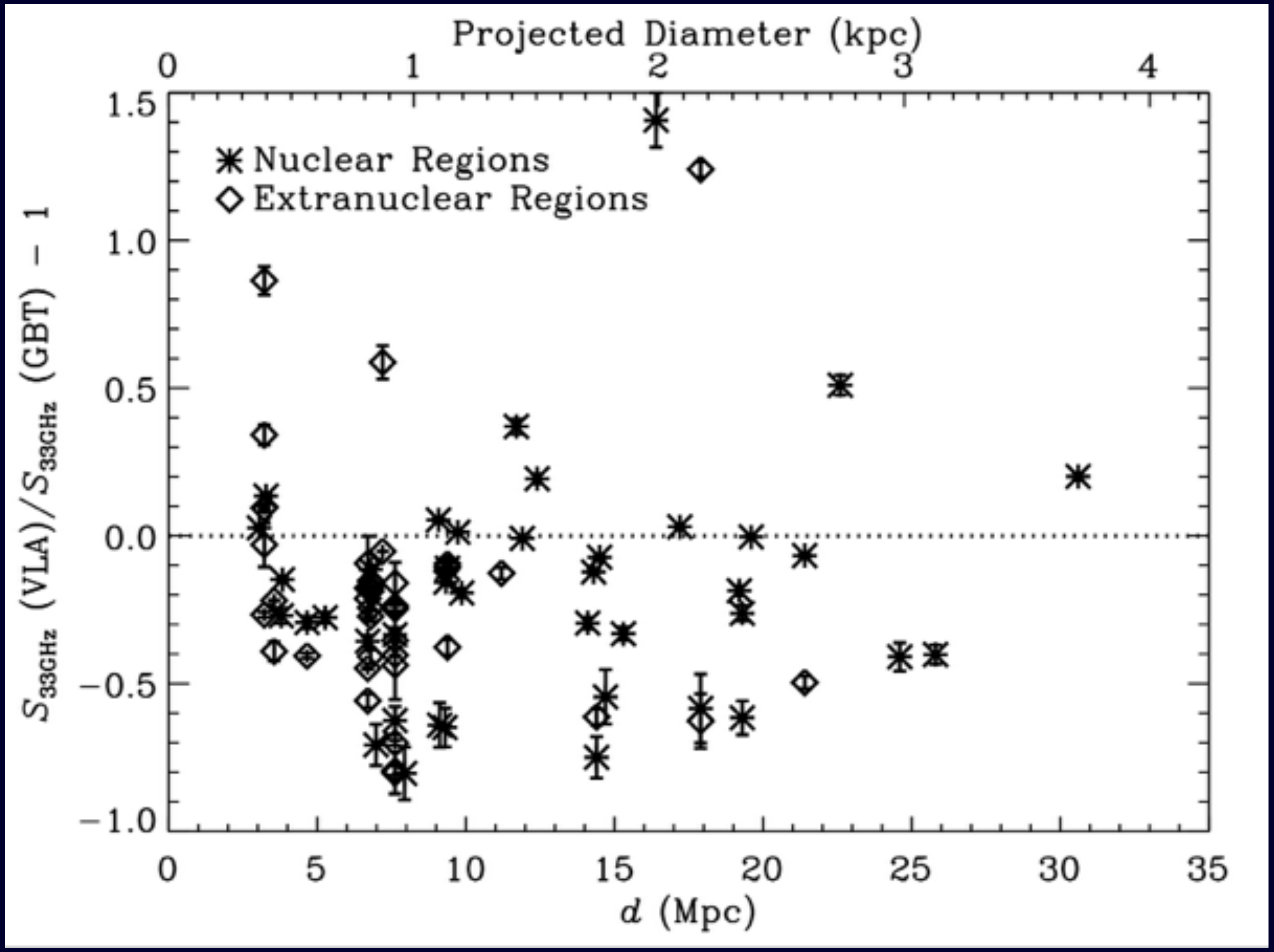
33GHz smoothed image
24μm contours



Murphy, Dong, Linden et al. 2017 (in prep)

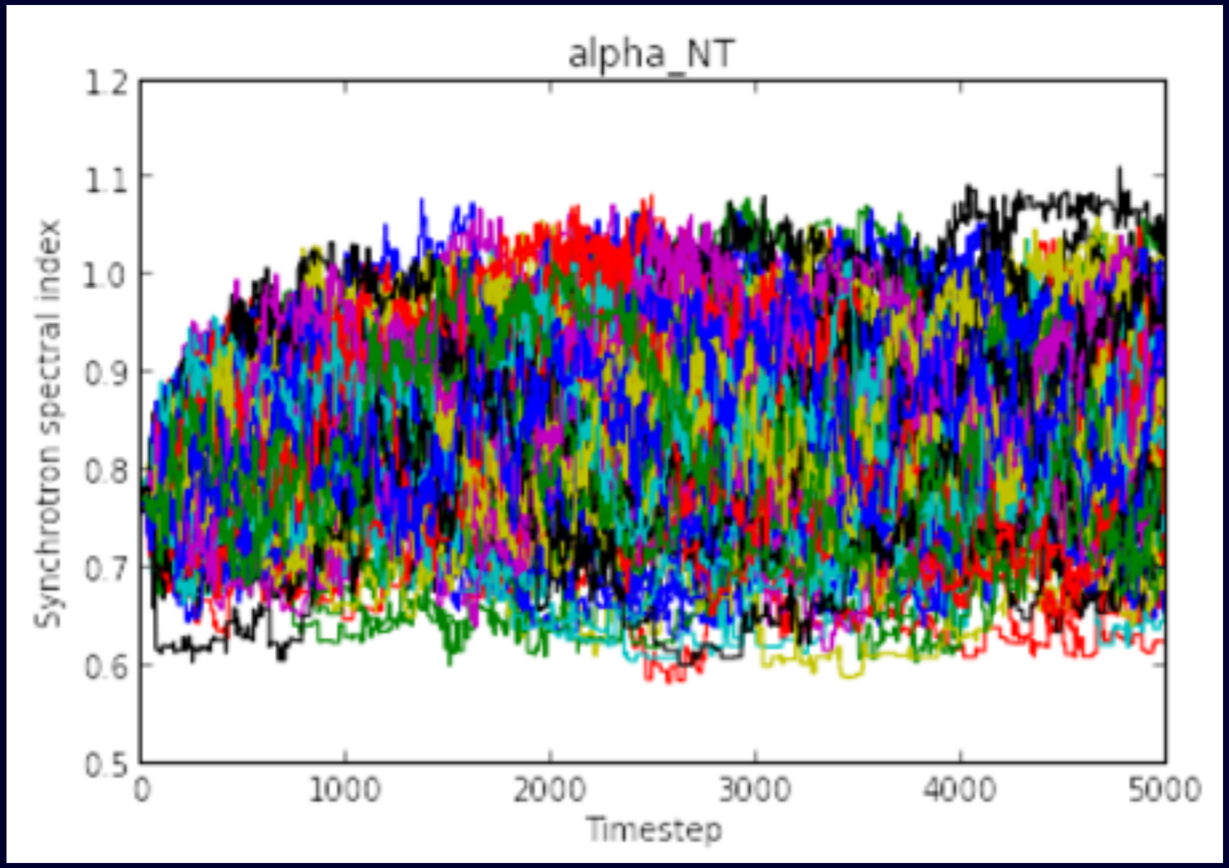
- 99% of 33GHz sources have *both* Hα and 24μm counterparts (Prescott +2007 find 95% agreement between Hα and 24μm at 500kpc scales in 1800 regions in SINGS galaxies)
- 33 GHz emission comes from the same physical structures on ~100pc scales as Hα
- Suggests free-free dominance at 33GHz

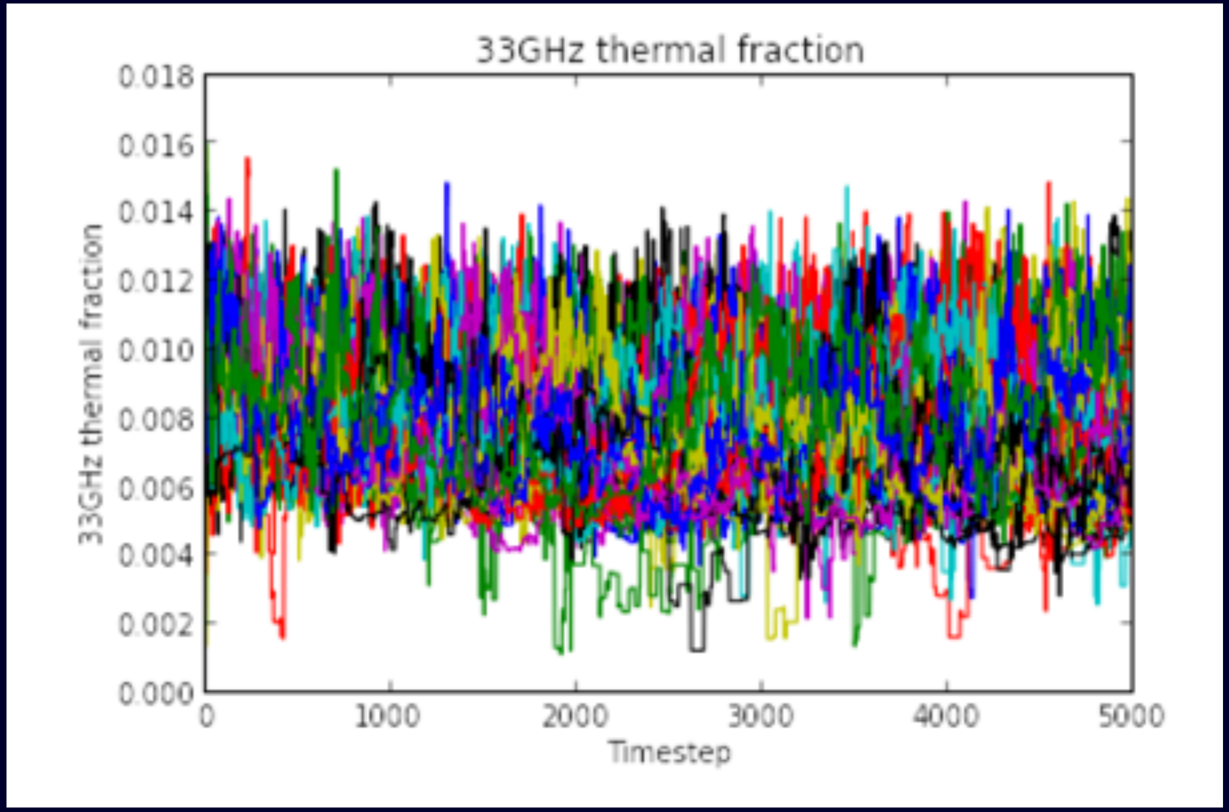
VLA vs GBT flux comparison



- Median VLA/GBT 33 GHz flux ratio ~ 0.78 ± 0.04
- Compare to the 25'' thermal fraction of ~70% found by Murphy+2012
- We resolve out large scale synchrotron emission

Estimating thermal fractions directly



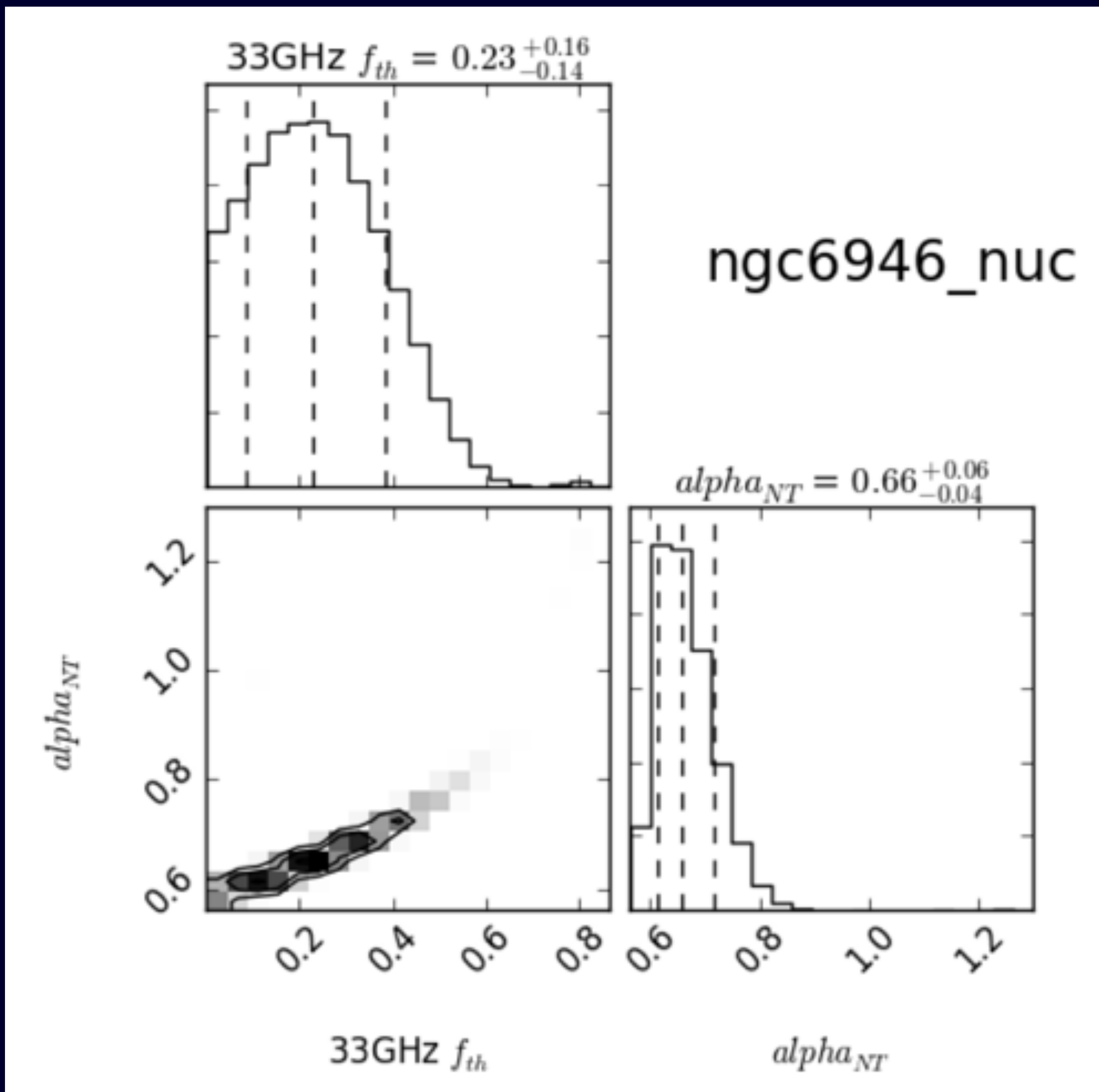


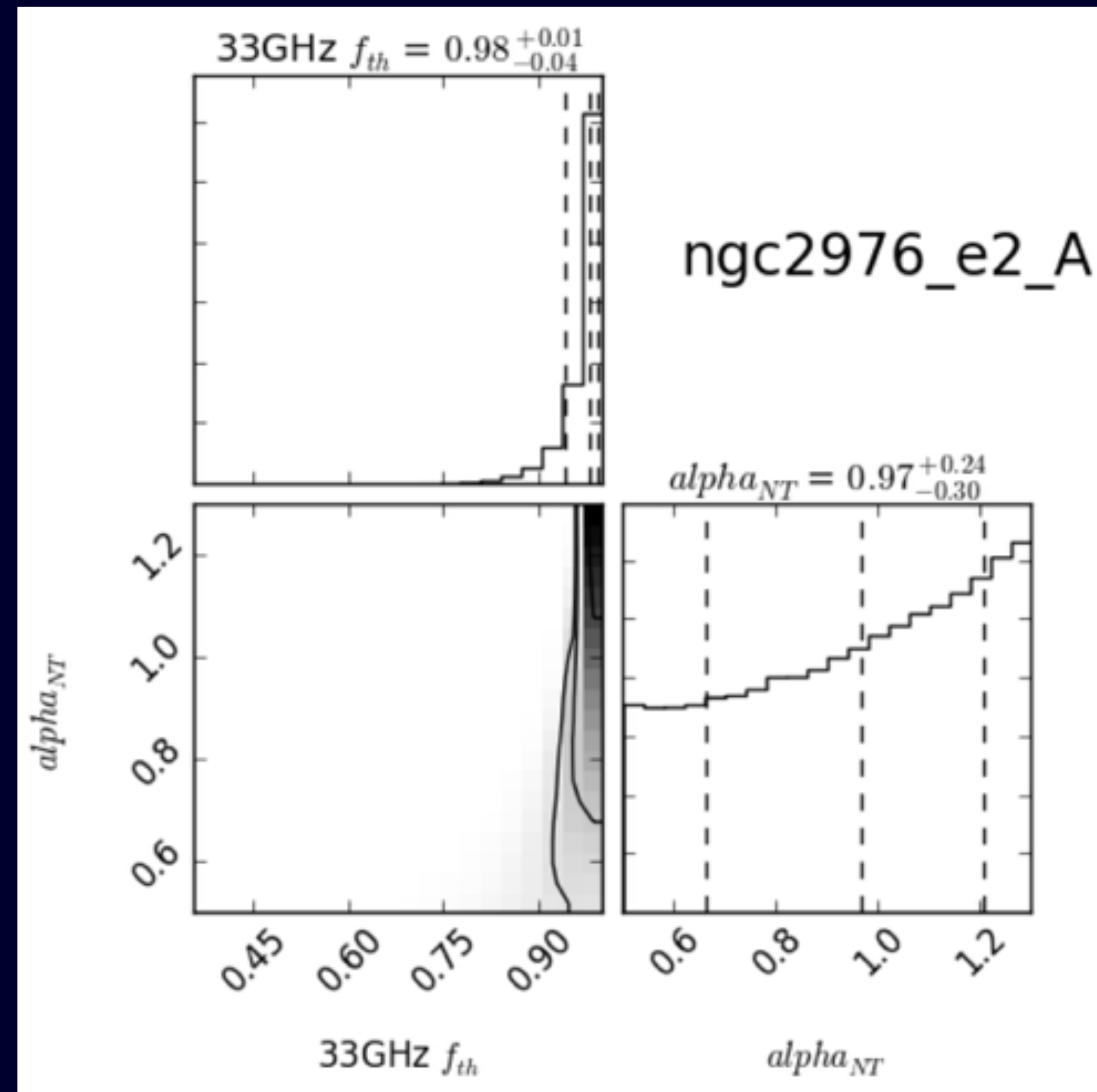
$S_\nu = A\nu^{-\alpha} + B\nu^{-0.1}$

Synchrotron + Free-free

- Using *emcee* "the MCMC hammer" (Foreman-Mackey+2012)
- Evolve 500 'walkers' through parameter space from max likelihood initial conditions
- Uniform priors
- Produces *distribution* of reasonable model parameters, constraining degeneracies

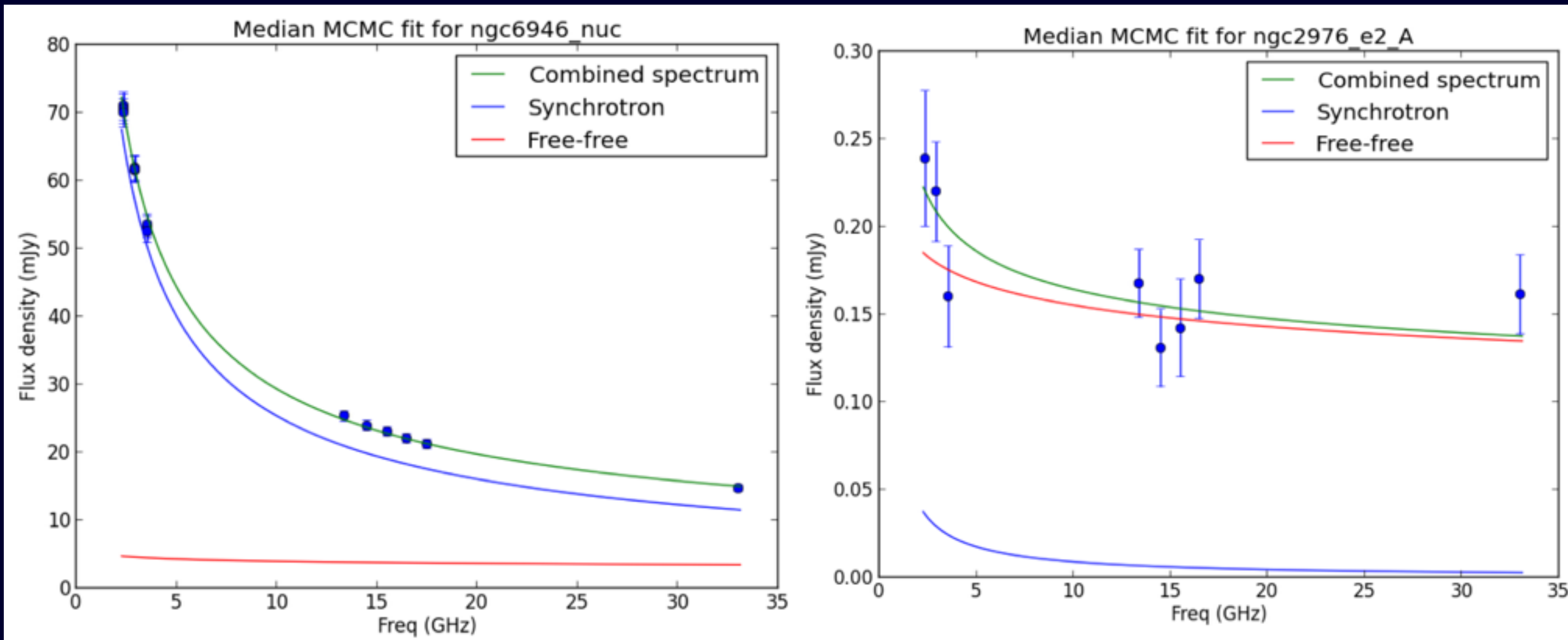
Thermal fraction vs synchrotron spectral index for two example sources





- Could get tighter errors with more sub-band images
- Synchrotron spectral index unconstrained for this HII region because it is ~100% thermal

Modeling the thermal fraction

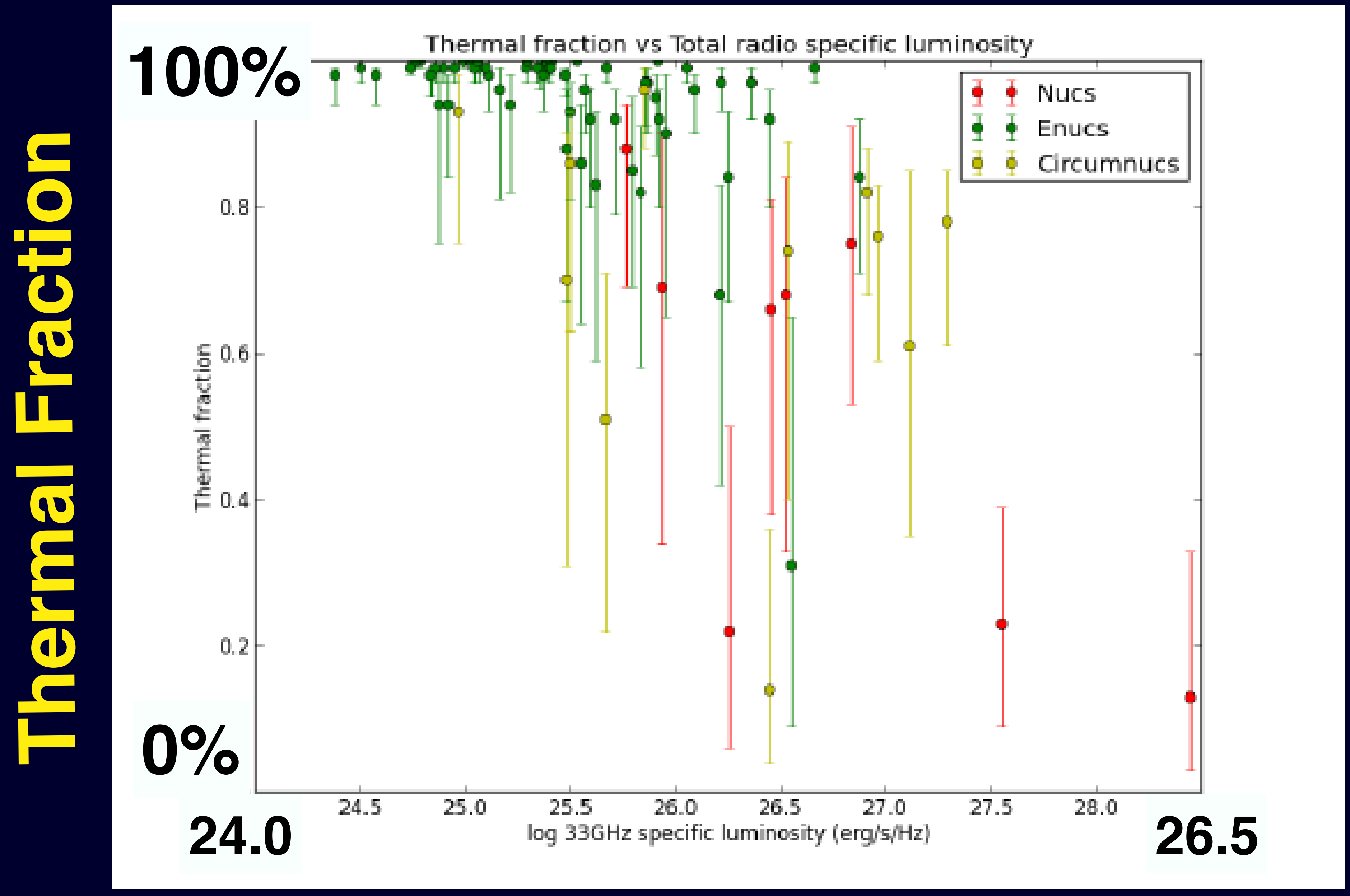


$$S_\nu = A\nu^{-\alpha} + B\nu^{-0.1}$$

Synchrotron+ Free-free

(Data points from sub-band imaging)

(Preliminary) MCMC thermal fractions from a SFRS subsample

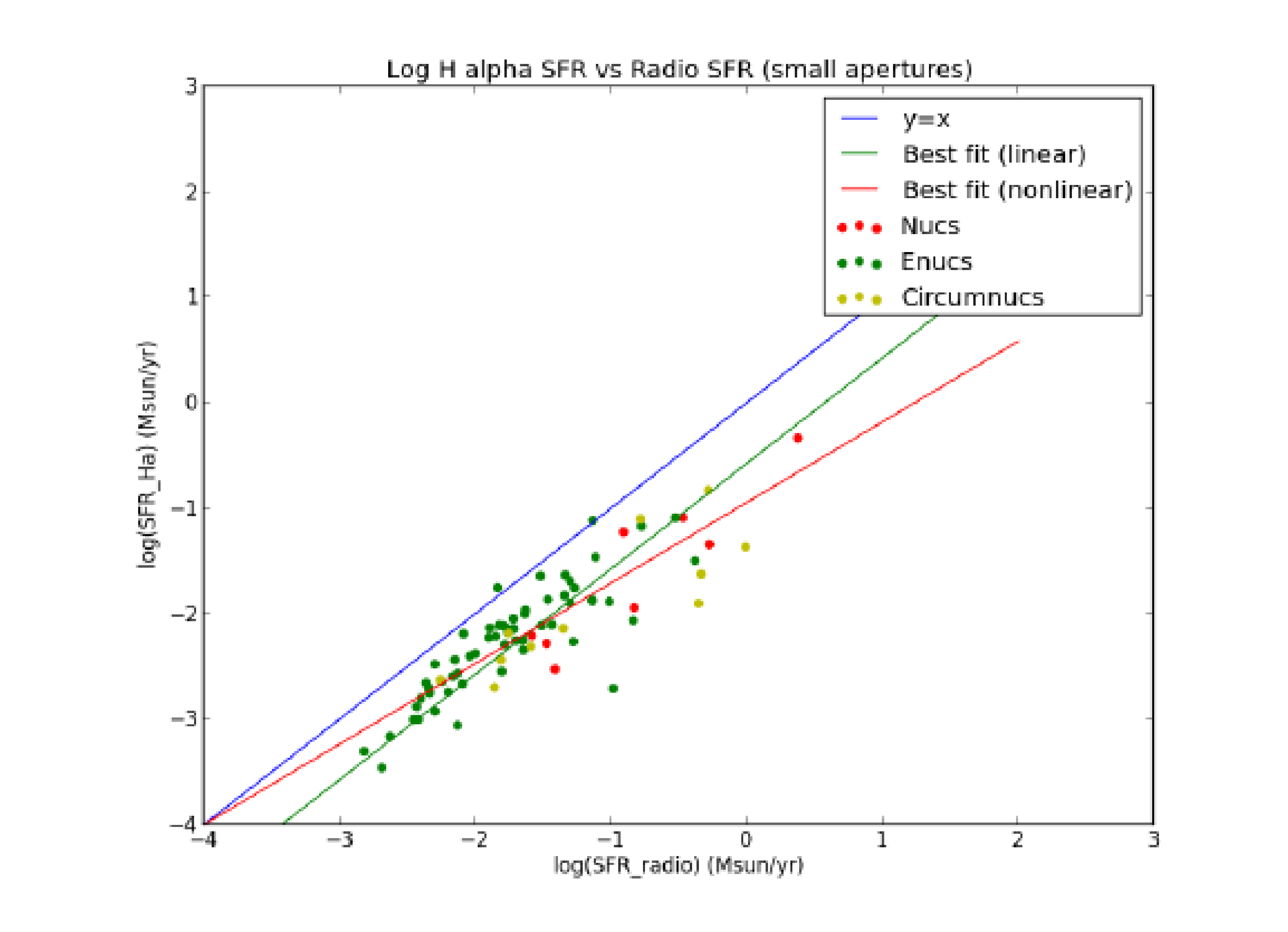


- HII regions far from nucleus have thermal fractions ≳ 90%
- Regions closer to nucleus and nuclei have thermal fractions all over
- Brighter -> more synchrotron

Dong et al. in prep

(Preliminary)

Comparison of Thermal fraction corrected 33GHz vs Hα SFRs



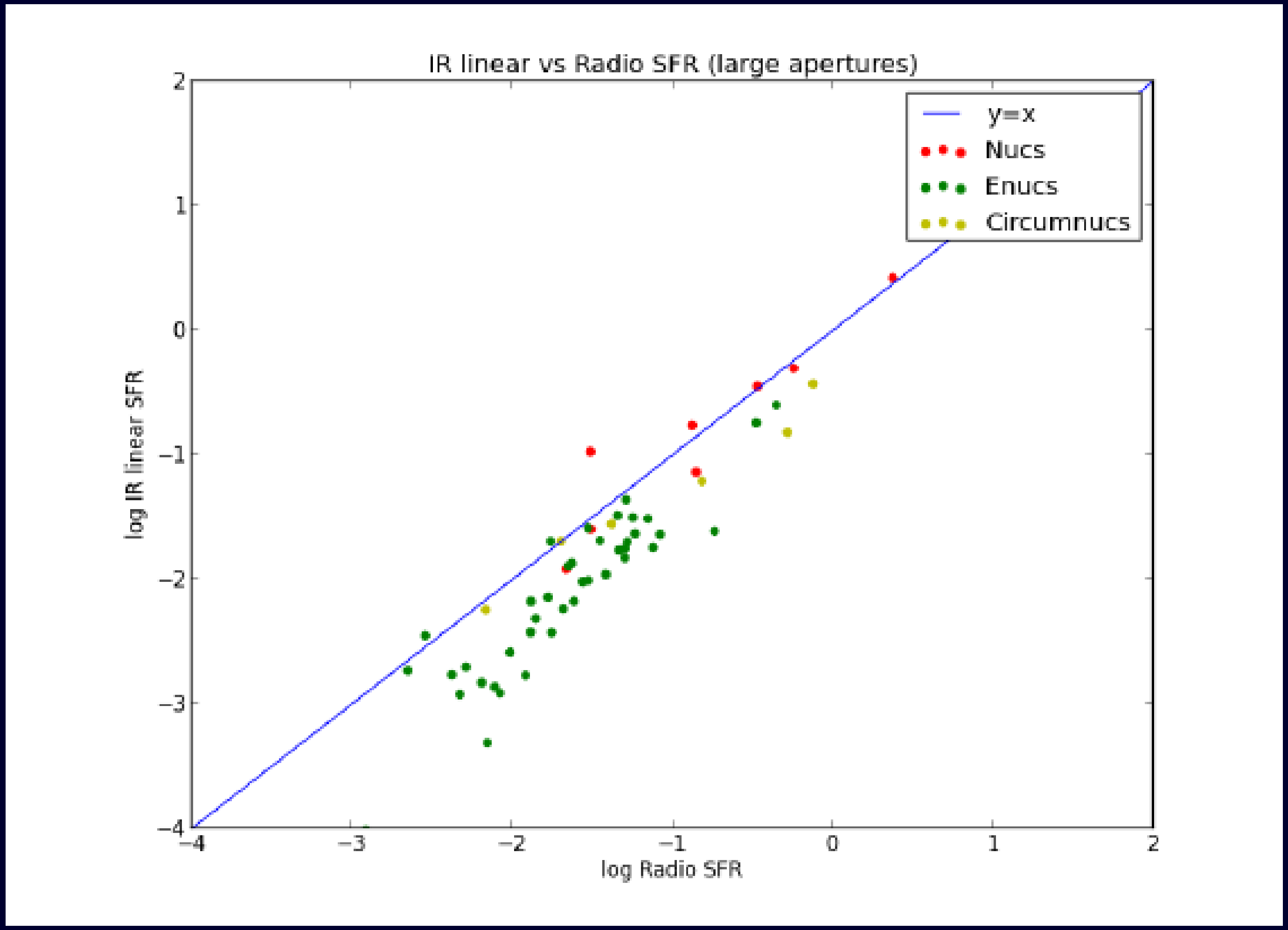
- Median Hα extinction of 1.07 mag
- Hα scales ~linearly with free-free for HII regions, but not for nuclei
- Nuclei more heavily obscured

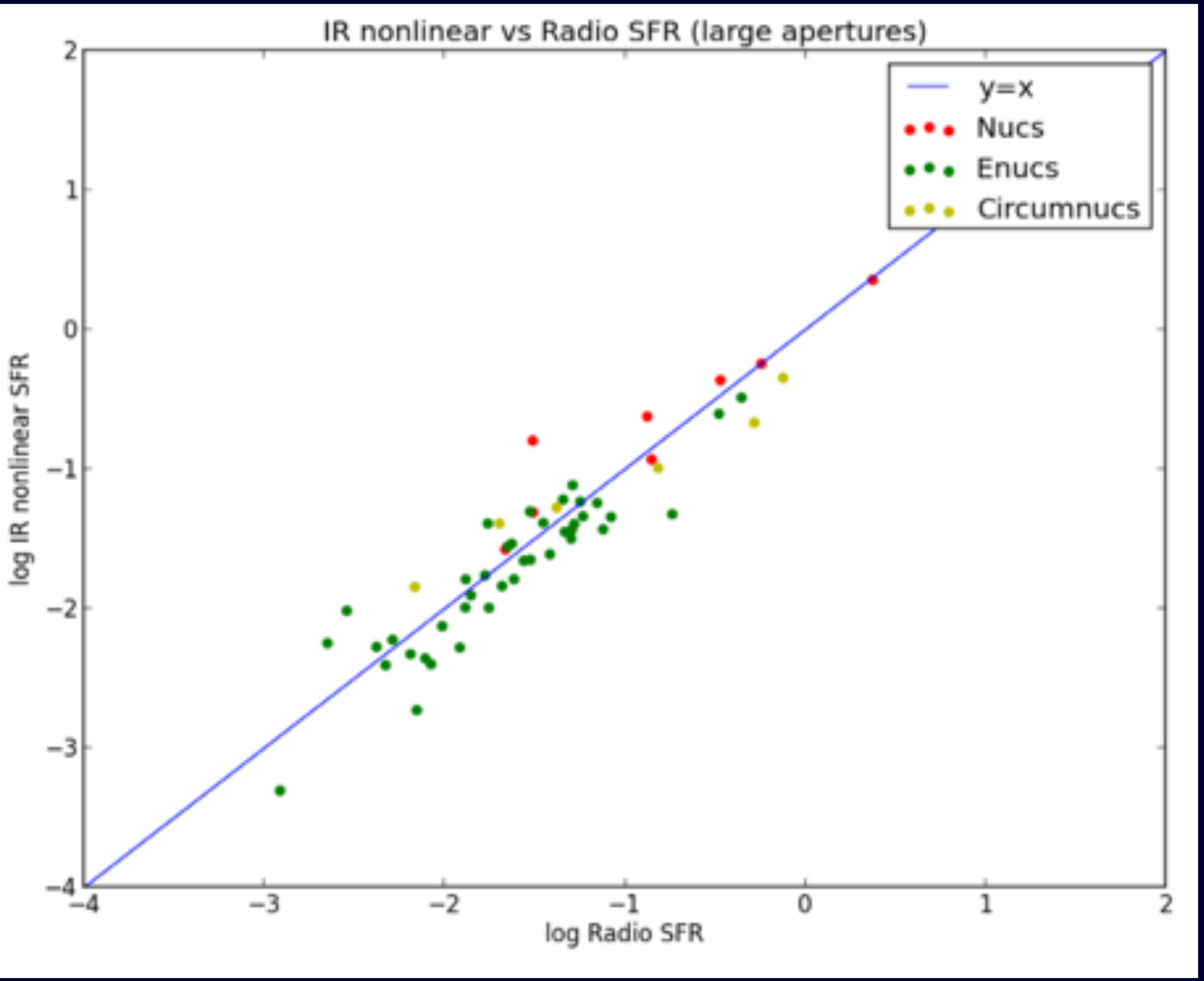
(Using Murphy+2011 Hα & 33GHz calibrations)

Dong et al. in prep

(Preliminary) 24μm vs 33 GHz

- 24μm linear calibration (Rieke+2007) predicts lower SFRs than 33 GHz
- 24μm nonlinear calibration (Relaño+2007) agrees well with 33 GHz



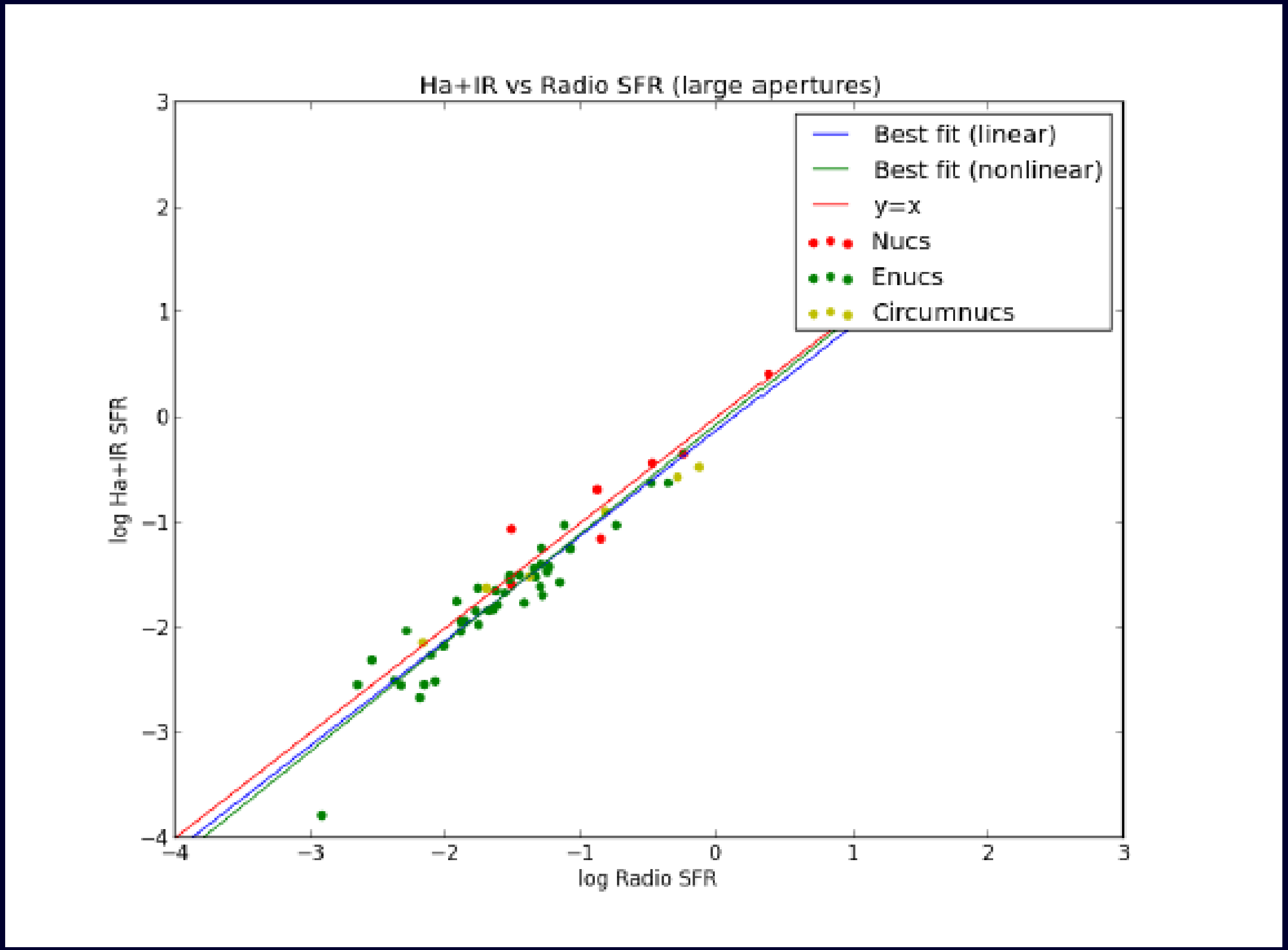


Dong et al. in prep

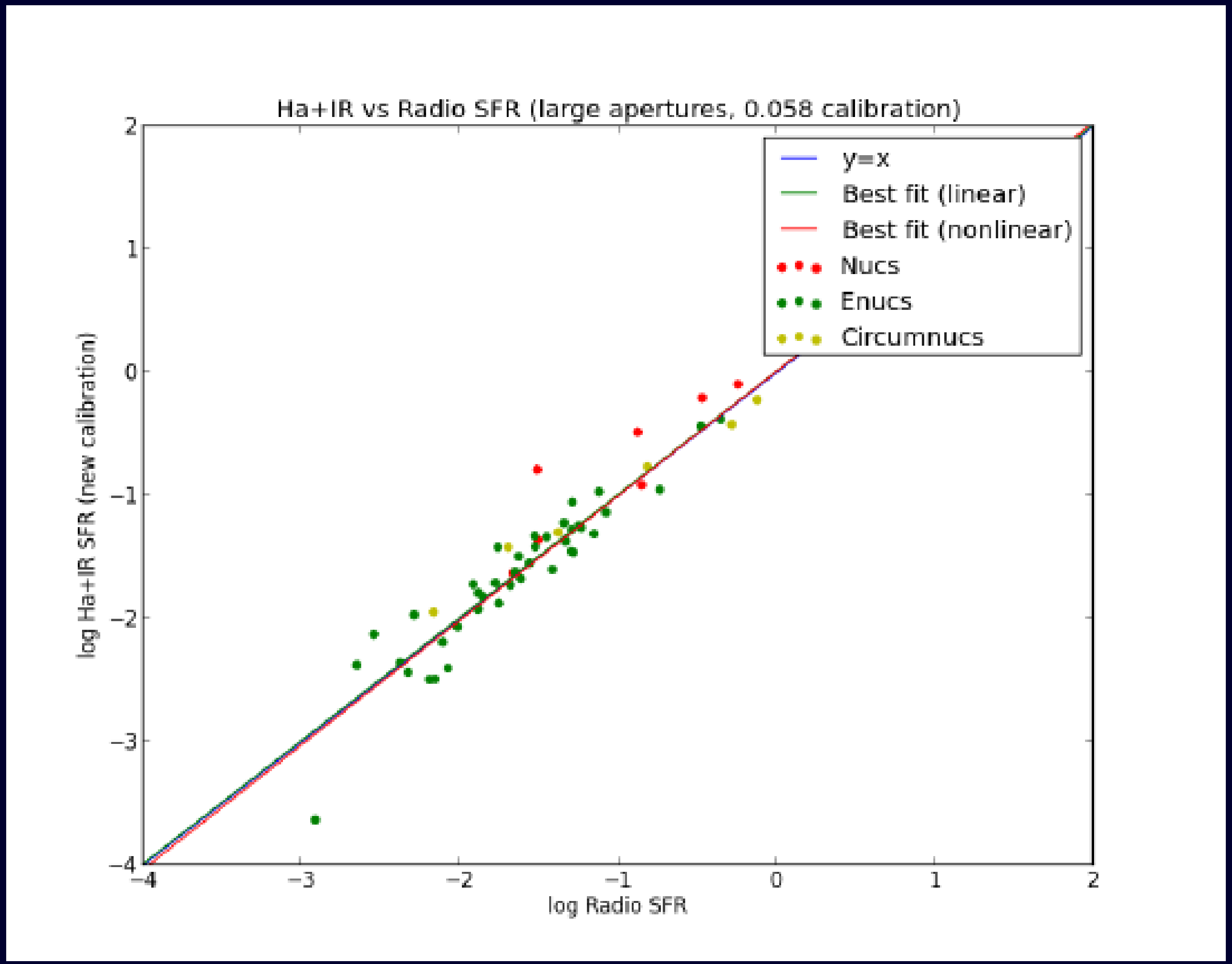
(Preliminary)

Hα+24μm vs 33GHz

Beautiful *linear* agreement with Calzetti+2007 calibration with a slight zero point offset



Pα zeropoint (Calzetti+2007, Kennicutt+2007)



33GHz zeropoint

Dong et al. in prep

High frequency radio as a “gold standard” candidate

1. Measurement systematics

- Dust — Dust free

- Contamination — Low synchrotron contamination at high freq, Appears to be little AME.
  - need sensitivity & frequency coverage to do SED modeling
  - resolution helps (most galactic synchrotron resolved out)

2. Physical systematics

- Environment — SFRS sample covers a range of environments (future targeted studies required to isolate e.g. metallicity)

- Luminosity scale — We detect bright HII regions (≳ several Orions) (deeper obs needed to detect Orion in nearby galaxies)

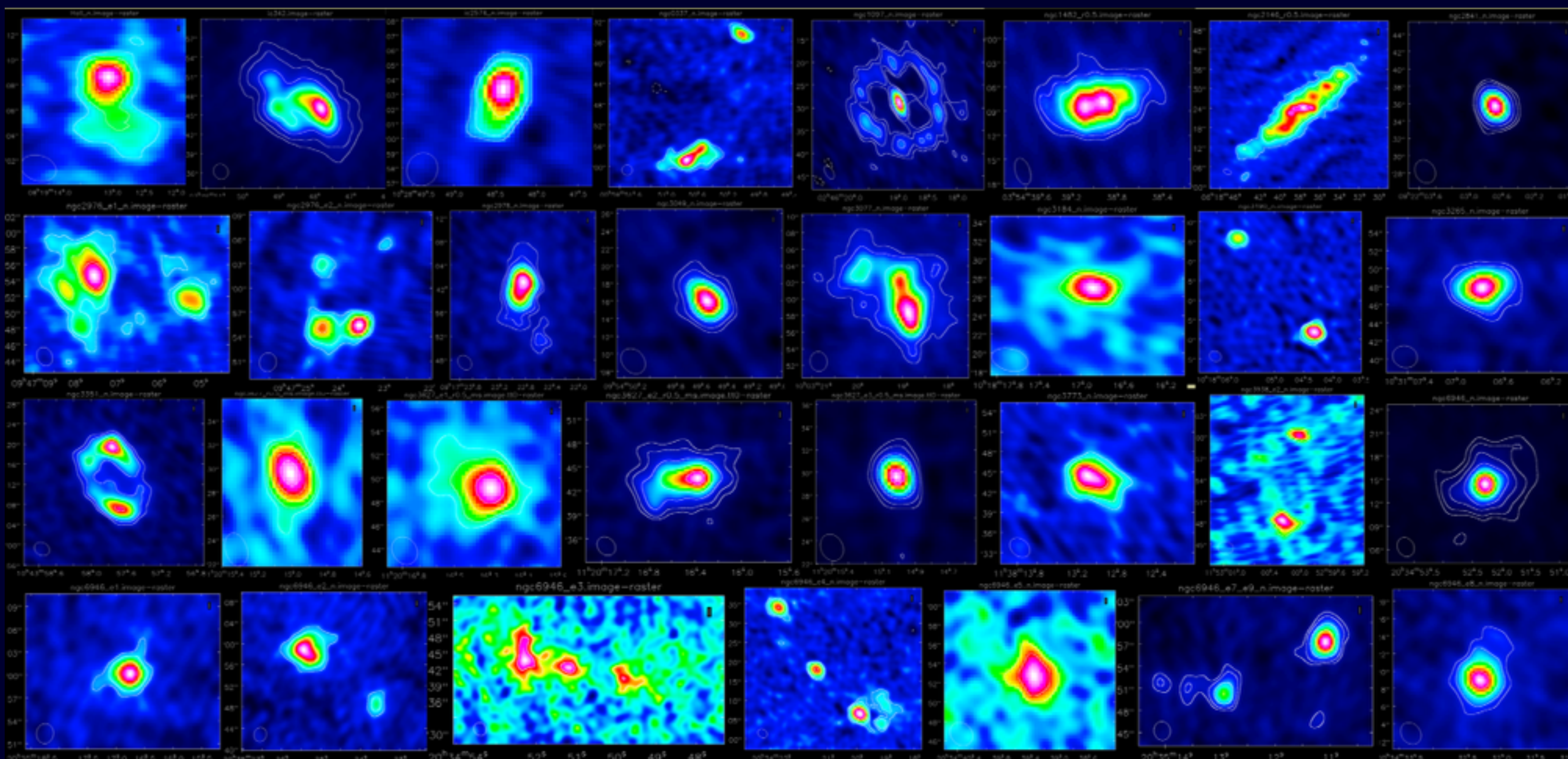
- Size scale — Our study is for resolved HII regions (deeper obs needed to detect low surface brightness emission)

- Direct measure — One of the least model dependent extinction-free tracers

Future work

- Improve MCMC thermal fraction decomposition (starting from visibilities?)
- Investigate synchrotron diffusion around HII regions & nuclei
- Search for AME
- Follow up on interesting single targets
- Better understand the gap between resolved & integrated measurements (using Hα images as a guide?)
- Investigate metallicity dependence?
- Develop SFR calibrations for high z surveys

Questions?



Example 33 GHz images from the SFRS