AME in Extragalactic Sources:
The GBT Star Formation in Radio Survey (SFRS)

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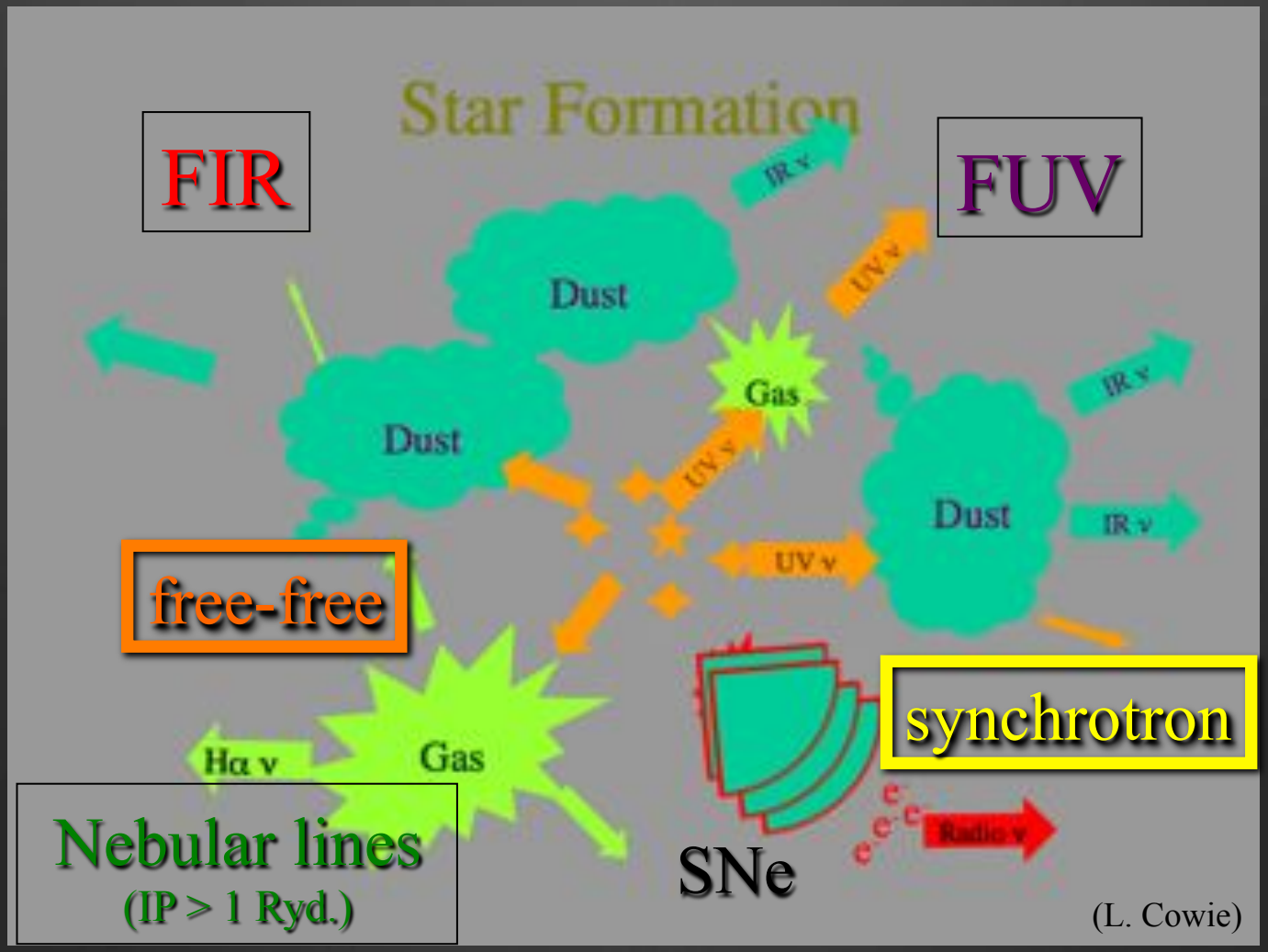
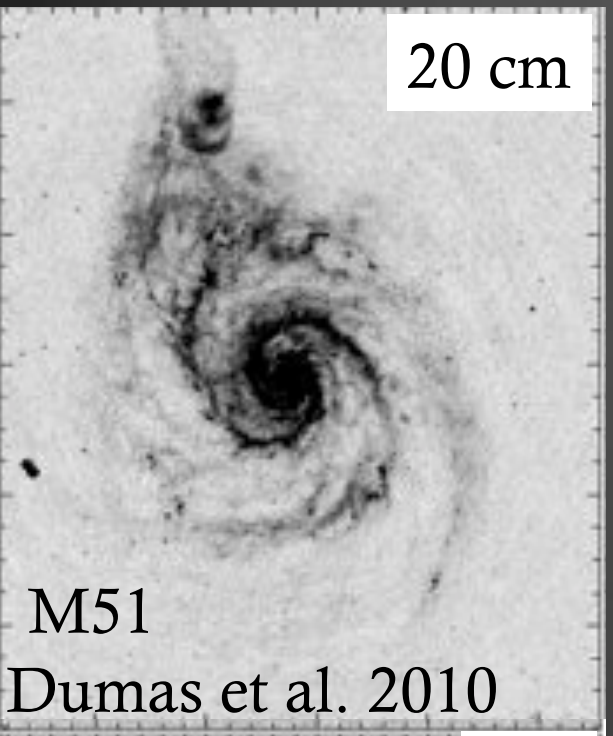
How I got dragged into this…

- The Star Formation in Radio (SFR) Survey:
  - High frequency radio continuum as a SFR diagnostic
  - >100 Star-forming complexes spanning a large range in parameters
  - Galaxy Sample from: **SINGS/KINGFISH/GOALS**
    - 3.6 – 500 μm imaging of 61+ nearby galaxies borne from SINGS
    - *Spitzer*/IRS + *Herschel*/PACS spec-mapping for 118 Nucs (56) + enucs (62)
    - Additional ~100 Local LIRGs/ULIRGs

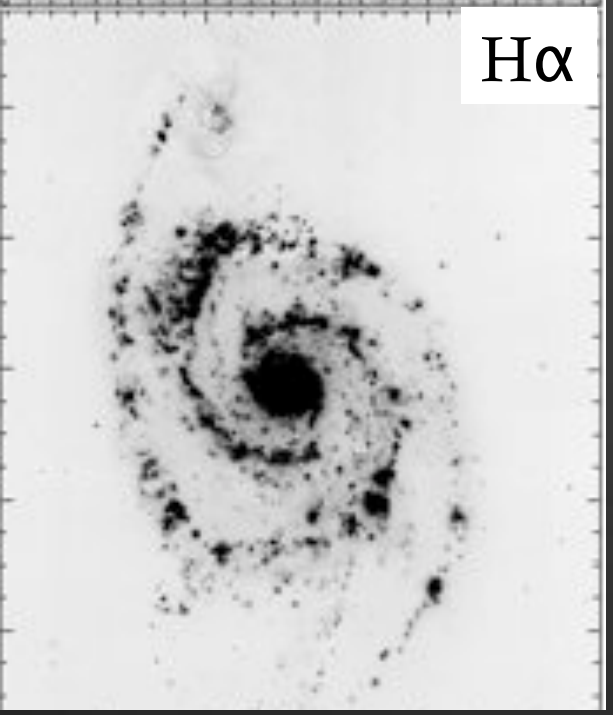
- New GBT Ka-band observations of NGC 6946
  - A reference SFR diagnostic to critically assess other "extinction-free" SFR diagnostics
  - *First extragalactic detection of anomalous dust emission*

Common Star Formation Diagnostics





M51
Dumas et al. 2010



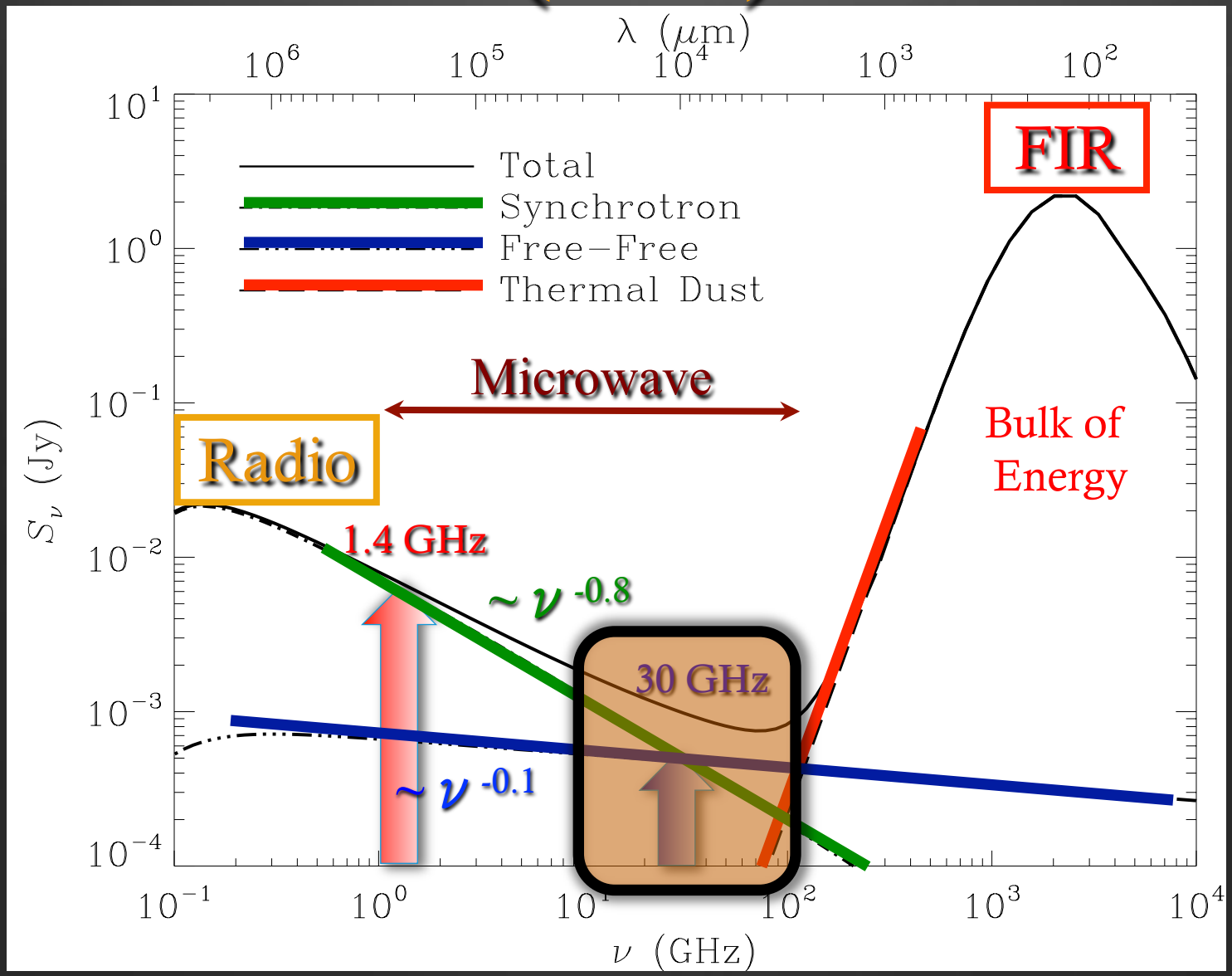
Radio Emission from Galaxies

- Combination of thermal and non-thermal radiation
  - Both arise from massive star formation

- 20 cm (globally ~90% non-thermal)
  - Synchrotron radiation from accelerated CR electrons by SNe
  - Discrete star-forming regions + SNRs on top of *diffuse disk.*

- 3.6 cm (globally ~30% thermal)
  - Bremsstrahlung (free-free) radiation from star-forming regions
  - Less of a diffuse component

FIR to Radio Spectral Energy Distribution (SED) of a Galaxy

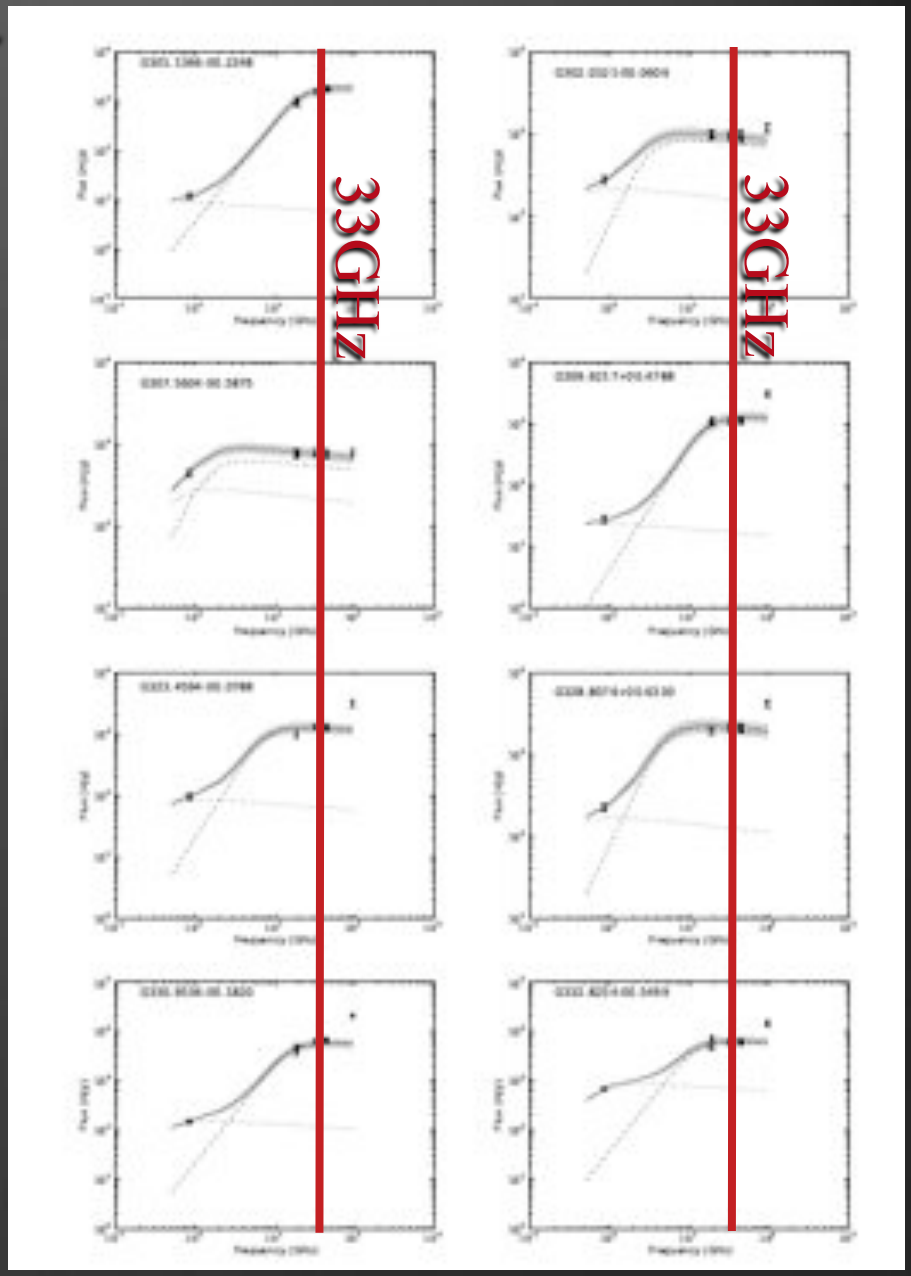


Flux Density

Why ~30 GHz? Optically-Thick Free-Free Emission

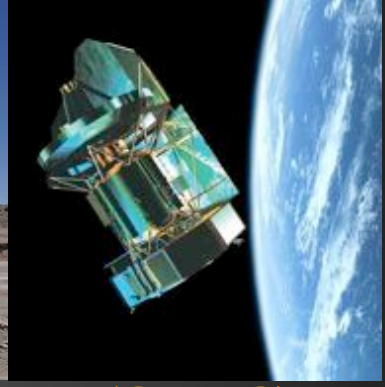
- By observing at such a high-frequency, we largely avoid being misled by optically-thick free-free emission.

- Past VLA work has rarely gone higher than 15GHz (e.g., Turner & Ho 1994; Turner & Beck 2004)



H/UCHII Regions (Murphy et al. 2010)

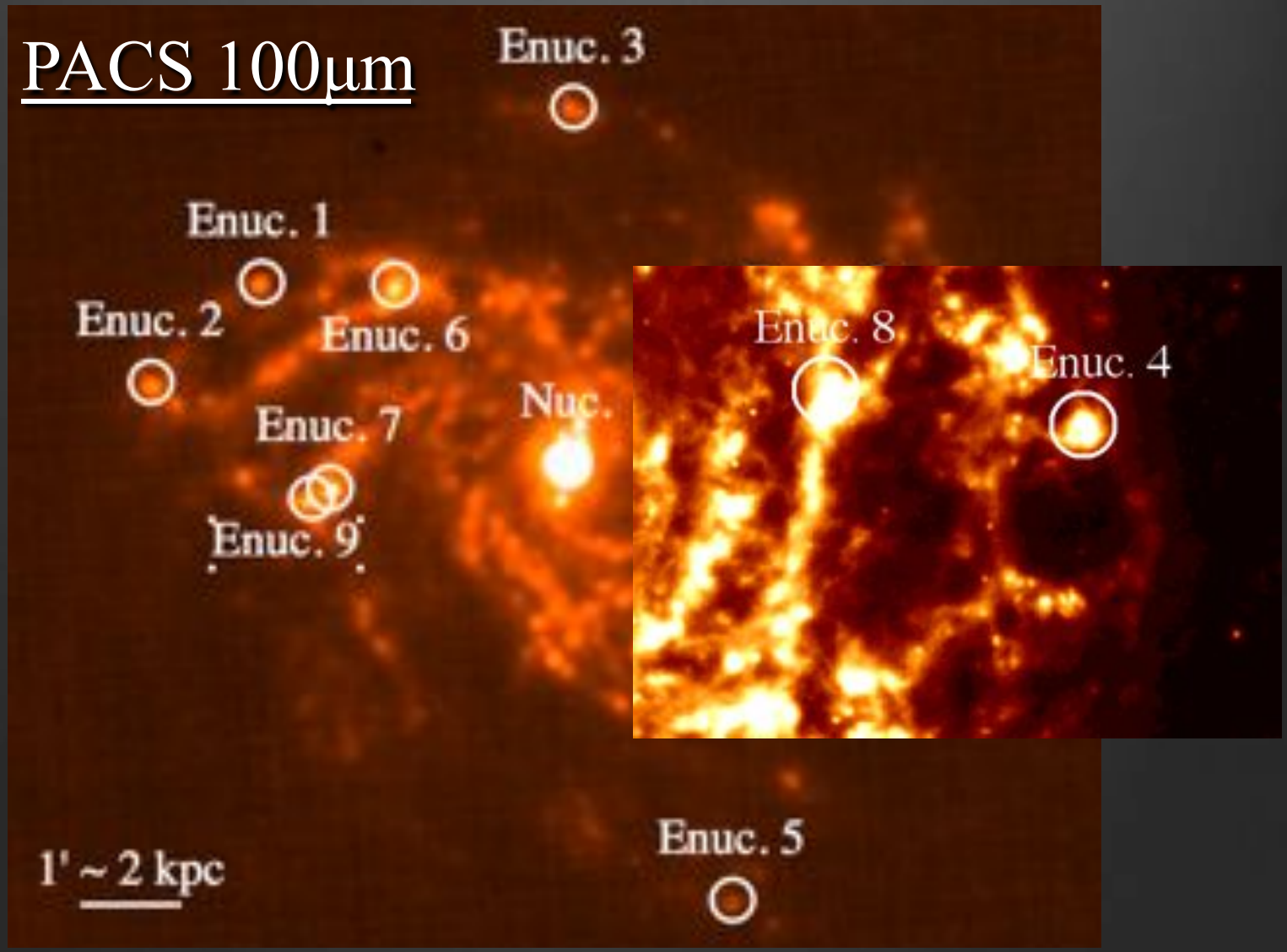


The Star Formation in Radio Survey (SFRS)

- **GBT/EVLA/ATCA/ALMA**
  - ***GBT/EVLA*** Ka-band data of >~100 SINGS/KINGFISH SF regions.
  - ***ALMA*** for dense gas tracers (e.g., HCN, HNC, CS) for resolved SF Law work
- **Status of Nearby Galaxy Observations:**
  - ✓ GBT: *completed* (~103 regions, 2+yrs – help from B. Mason & J. Condon)
    - ✓ *Pilot GBT (N6946) (EJM+ 2010, 2011b, 2012)*
    - ✓ 46 nuclei & 57 enucs
  - ATCA: 6 Southern sources
    - ✓ First 7mm; taken July 2011
  - EVLA: under way
    - ✓ ECSO taken (N6946/IC342)
    - ➢ Imaging of SF-regions started Oct. 2011
  - ALMA Early Science (<~50 regions)
    - ➢ 20 sources - Band 3 Cont. approved (in filler queue)

The Pilot Project: NGC 6946



SINGS+KINGFISH e-nucs

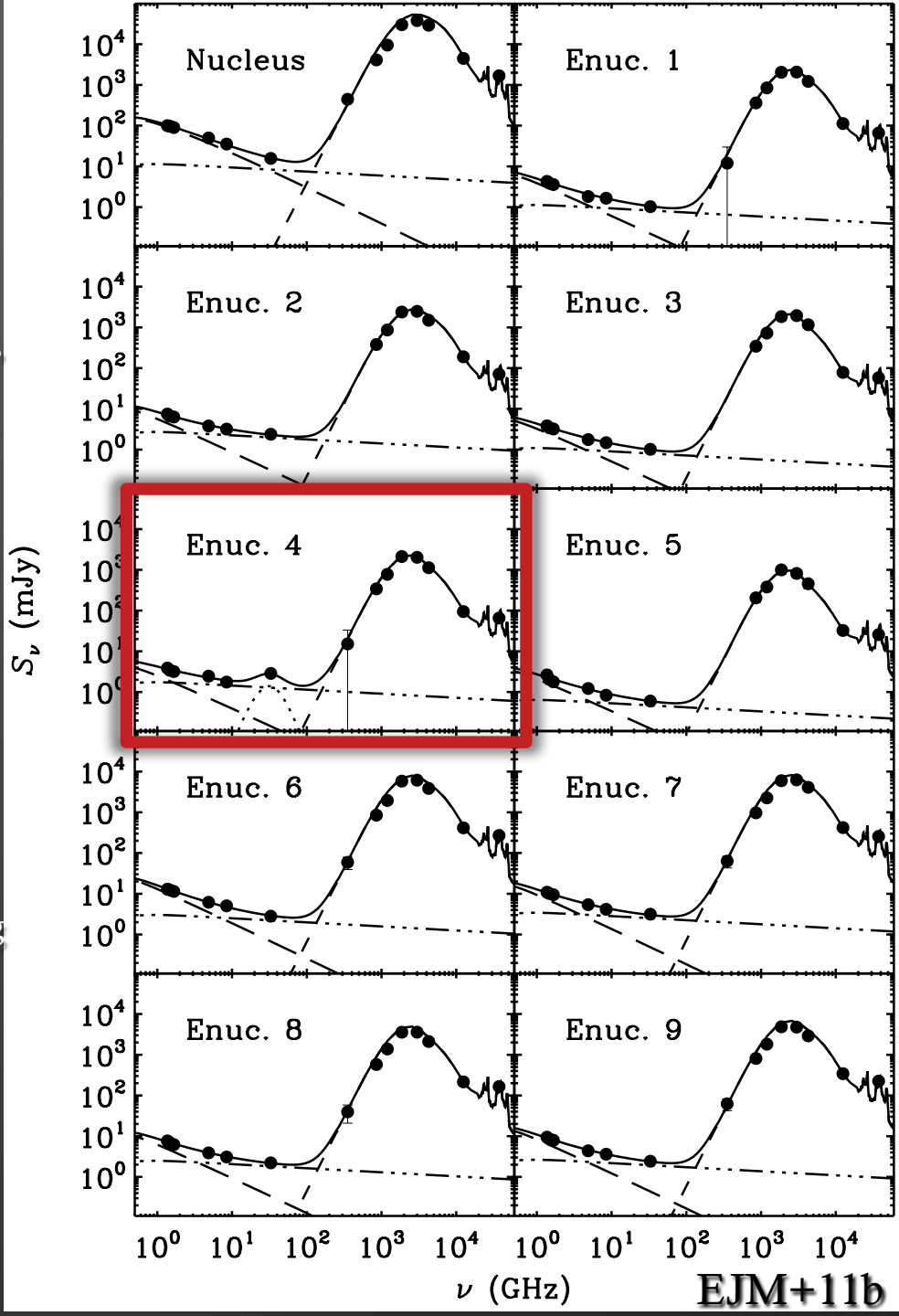
Radio-FIR Spectra
(NGC 6946)

- No local backgrounds removed.

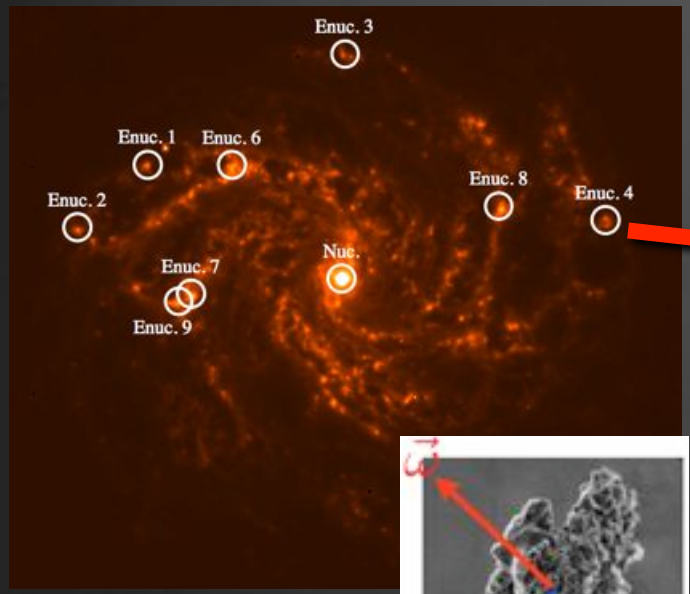
- Infrared Photometry:
  - Spitzer (8, 24), Herschel (70, 100, 160, 250, 350), SCUBA 850 μ m
  - Fit with Dale & Helou 2002 SEDs

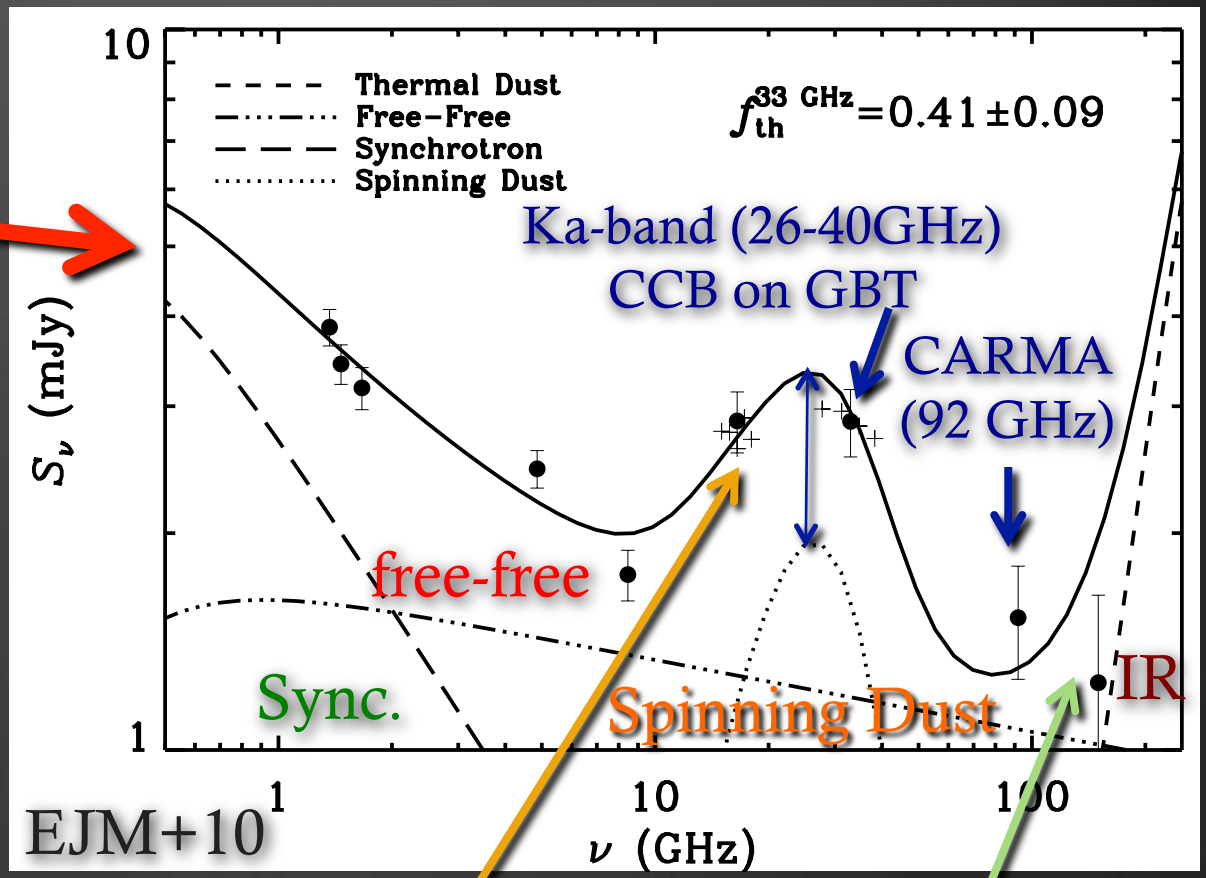
- Radio Photometry:
  - WSRT (1.4, 1.7), VLA (1.5, 4.9, 8.5), Effelsberg (4.9, 8.5), GBT (33 GHz)
  - Fit with combination of thermal & non-thermal emission.
    - NT emission includes all CR electron cooling terms (e.g., Murphy 2009).
    - One Exception (Enuc. 4): fit with spinning dust component (Ali-Haimoud+ 2009).

✧ $\langle f_T^{33GHz} \rangle \sim 80\%$; $\langle \alpha^{NT} \rangle \sim -0.8$



Quick Aside/Caveat: First Extragalactic Detection of Anomalous Dust Emission





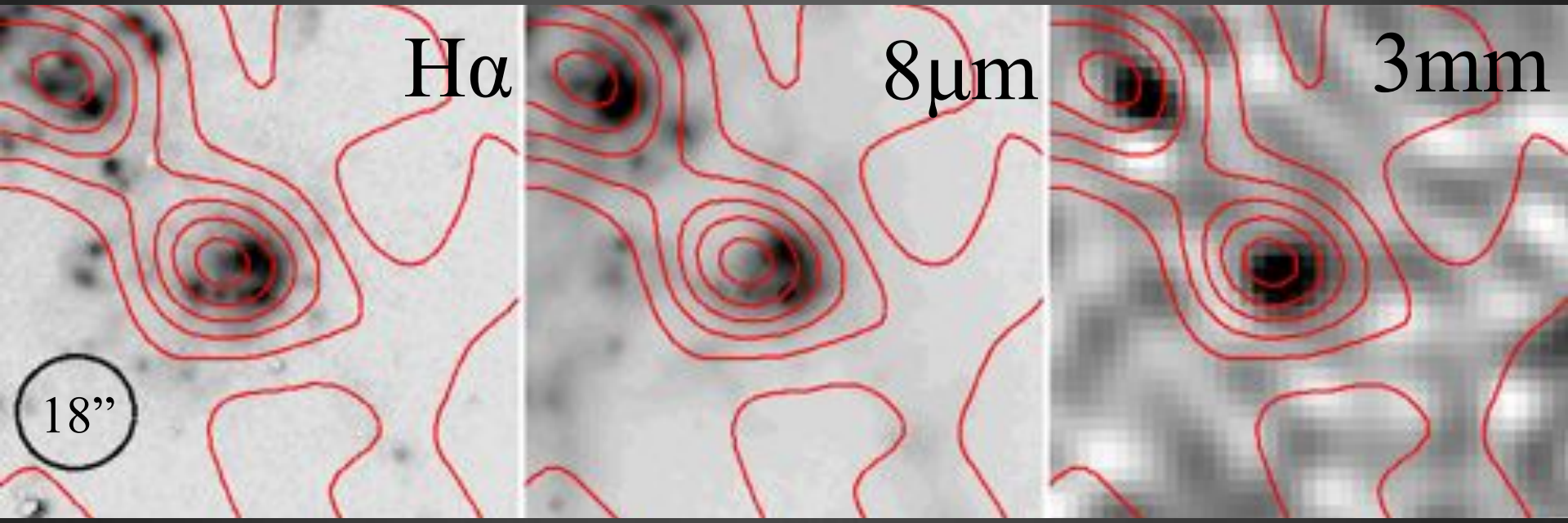
AMI (16.5 GHz)
(Scaife et al. 2010)

GISMO
(150 GHz)

Enuc 4:

- 50% excess emission
- 7.3σ significance
- Well fit by spinning dust
  - *Erickson (1957)*
  - Drain & Lazarian (1998)
  - Ali-Haimoud, et al. (2009)
- <10% excess from total 33GHz

CARMA 1cm & 3mm Imaging



1cm contour peak offset from HII regions in Hα and 8μm

Brandon Hensley (Princeton): First Year Observing Project

- Reduced CARMA DDT imaging (tentative new detections)
- Modeling candidates (magnetic + electric dipole – Bruce Draine)

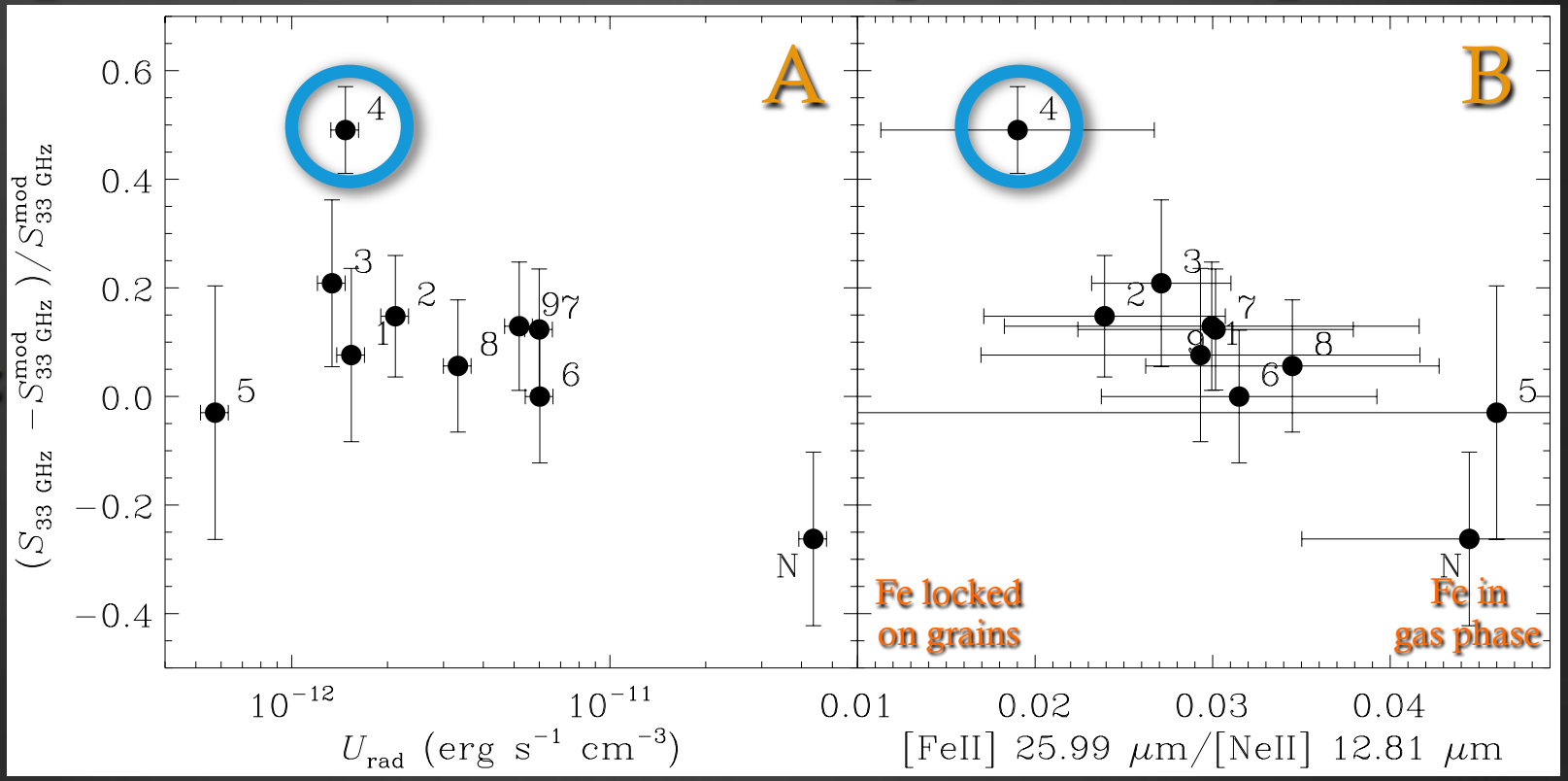
Continuing Follow-up:

- GBT/MUSTANG 3mm imaging (this Winter)
- EVLA 33GHz imaging (being reduced)
- HST/COS mapping of extinction curve to get size distribution (failed!)

Variations in Grain Distribution?

Importance of MIR/FIR Spectral Maps

Strength of 33 GHz Excess

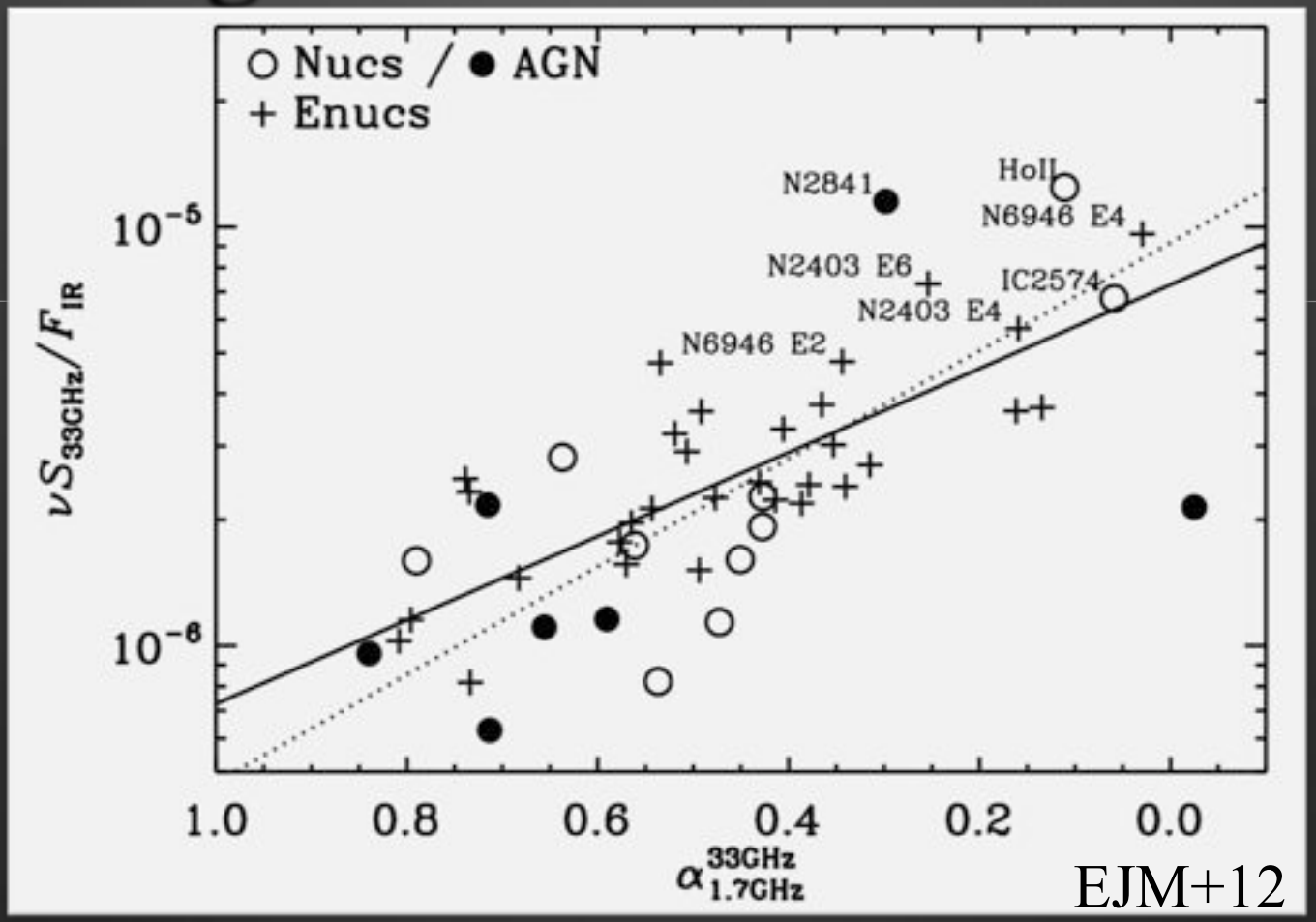


A. Exposed to a near-average radiation field.

B. Much less gas phase Fe^+ (IP~7.9eV) relative to Ne^+ (IP~21.9eV)

- Fe locked up on grains that have not been processed by shocks?
  - *Abundance of small grains ($a < 10^{-7}$cm) present contributing to anomalous emission?*
  - More work to be done, like high resolution EVLA imaging…

Searching for AME in Other Sources



- Trend consistent with constant NT/IR ratio and increase in thermal fraction
  - Max scatter in $\alpha^{NT} \sim 0.13$ among star-forming sources
- N6946 E4 falls right on expected trend
  - *Really need x2 or finer spectral sampling to identify sources*

What is next?

- How can we identify extragalactic candidates?
  - Need better than x2 sampling in frequency
  - Observations tracing small grain emission?
  - …
- Higher resolution imaging.
- Look for spectral signatures in radio data
  - Yacine's suggestion to look for spacings in AME spectra