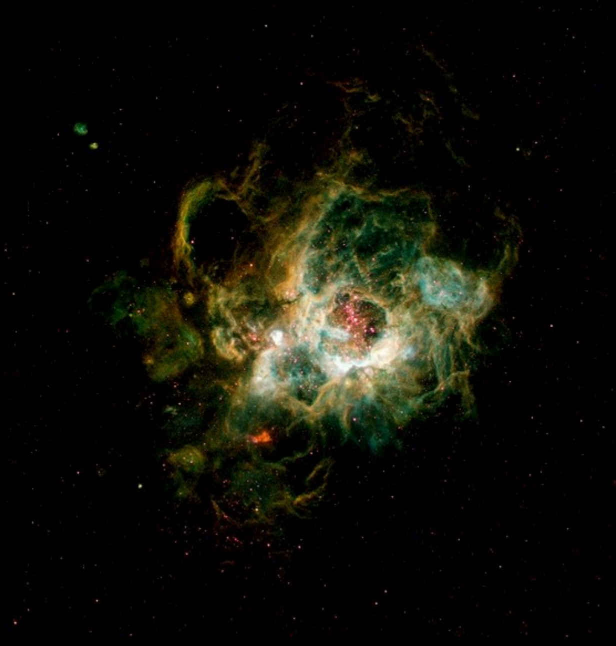
Extragalactic Hydrogen Radio Recombination Lines as a Tracer of Star Formation

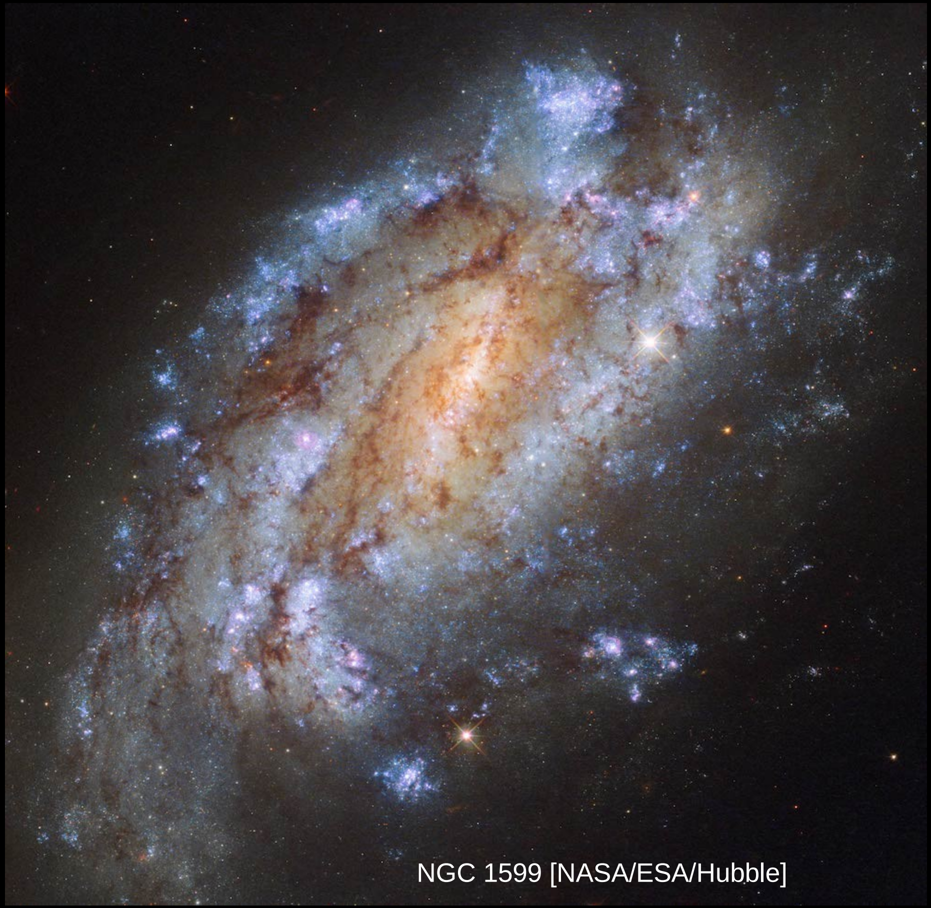


12.05.2021
Argelander Institut für Astronomie

Toma Bădescu
Prof. Frank Bertoldi
Dr. Benjamin Magnelli

Overview

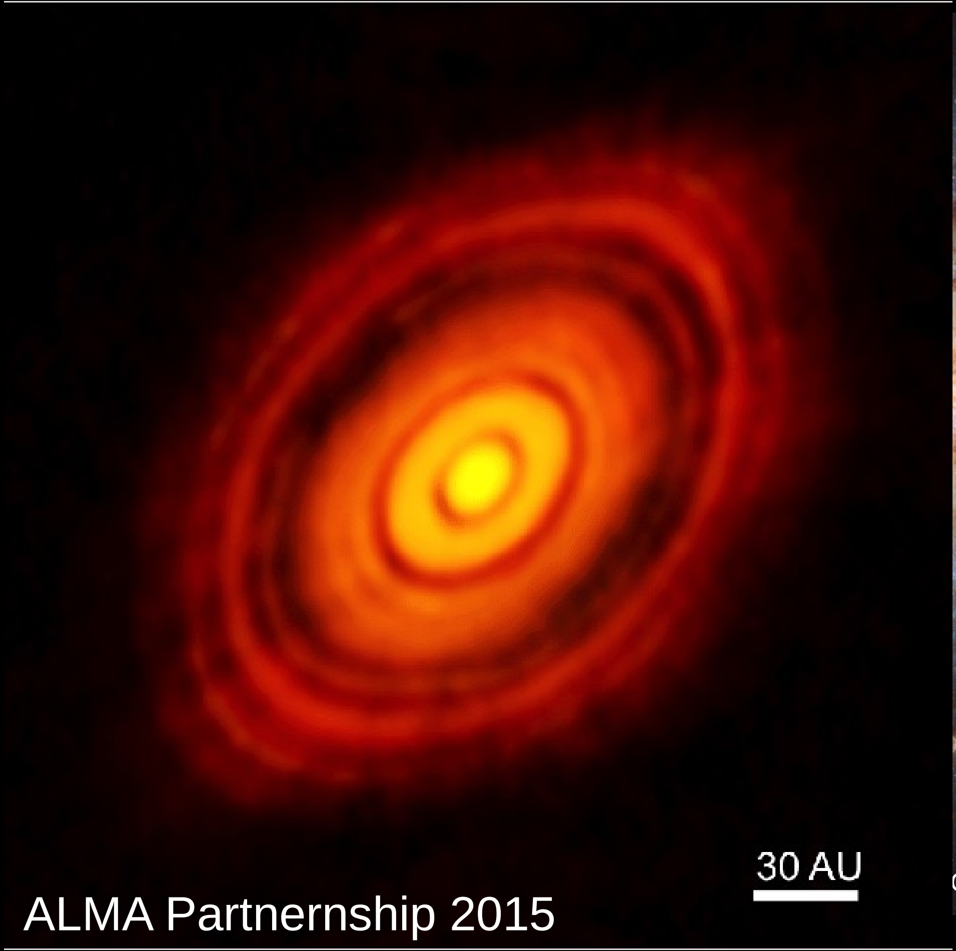
- star formation rate tracers
- massive star formation
- hydrogen recombination lines



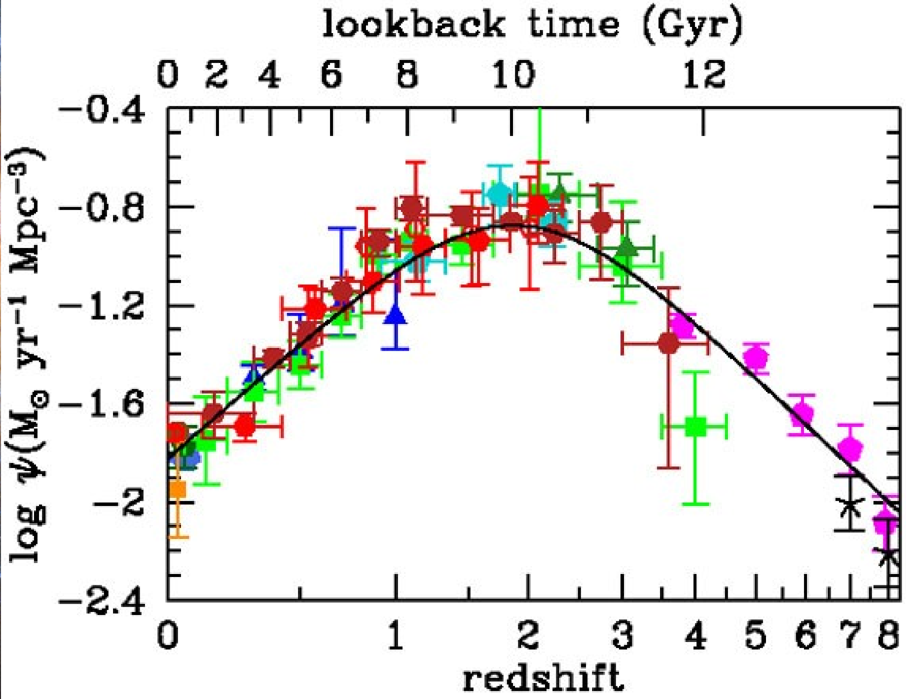
NGC 1599 [NASA/ESA/Hubble]

- sample and data
- results
- summary

Overview of Star Formation



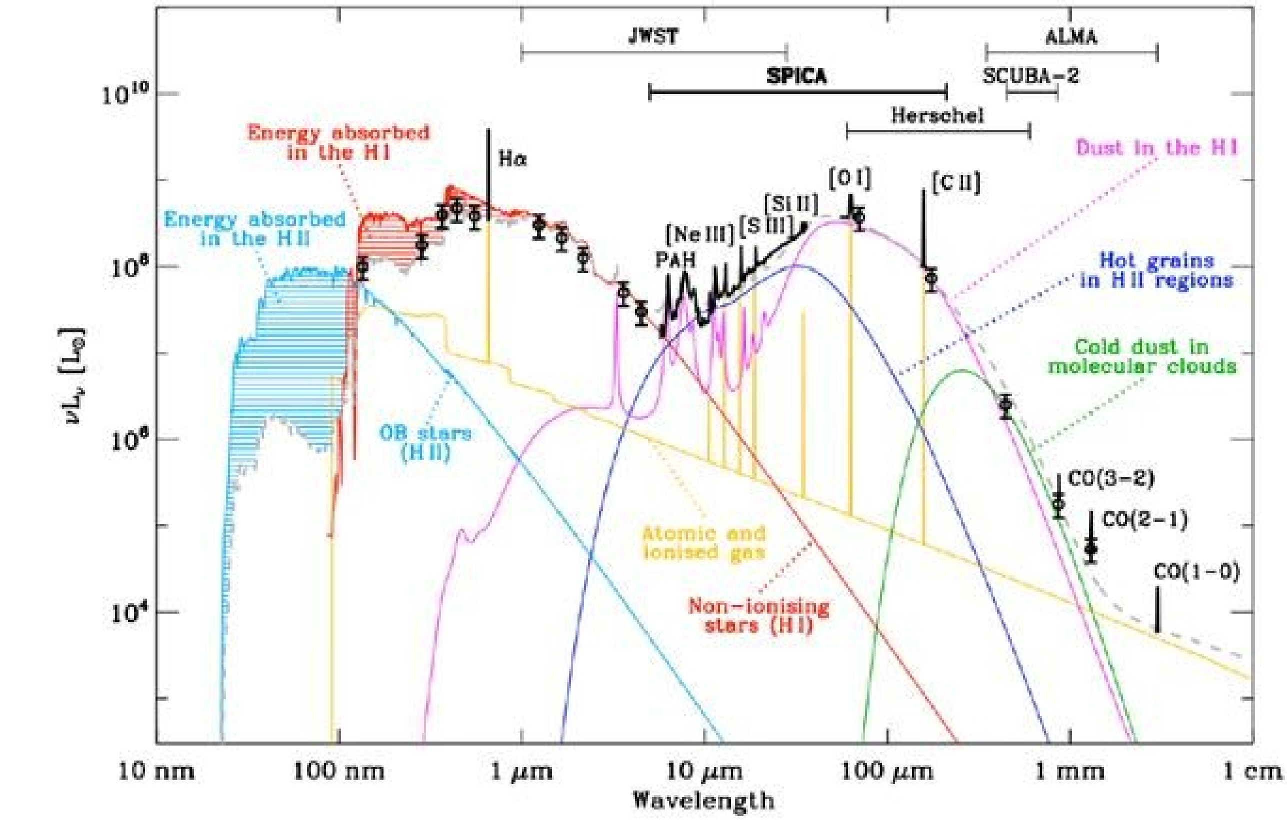
ALMA Partnernship 2015



Madau+2014

Massive Star Formation Tracers

- spectral energy distribution (SED)
- direct starlight - UV/vis
- dust continuum - FIR
- recombination lines
- free-free emission – mm
- other, indirect methods

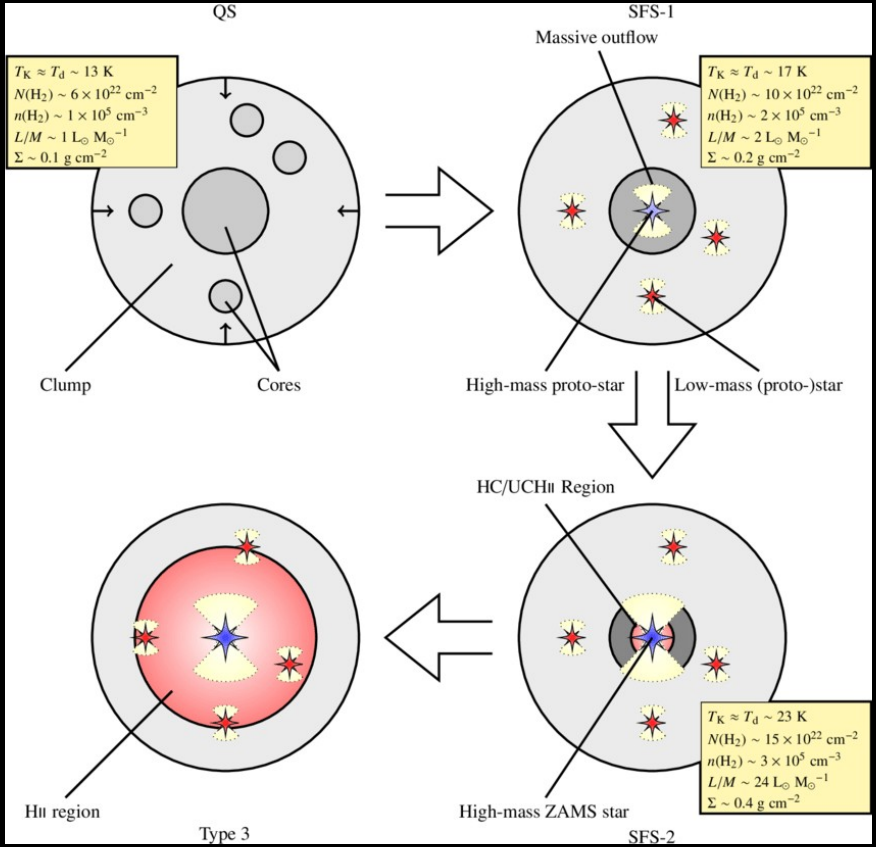


Galliano+2008

(Massive) Star Formation

- cold gas/dust collapse
- proto-star forms
- evolution through outflows/accretion
- young star emerges

Why massive stars?
- luminous (3×10^4 - 10^6 $L_\odot$)
- high impact on the interstellar medium (ISM) through outflows, radiation, supernovae (SN)



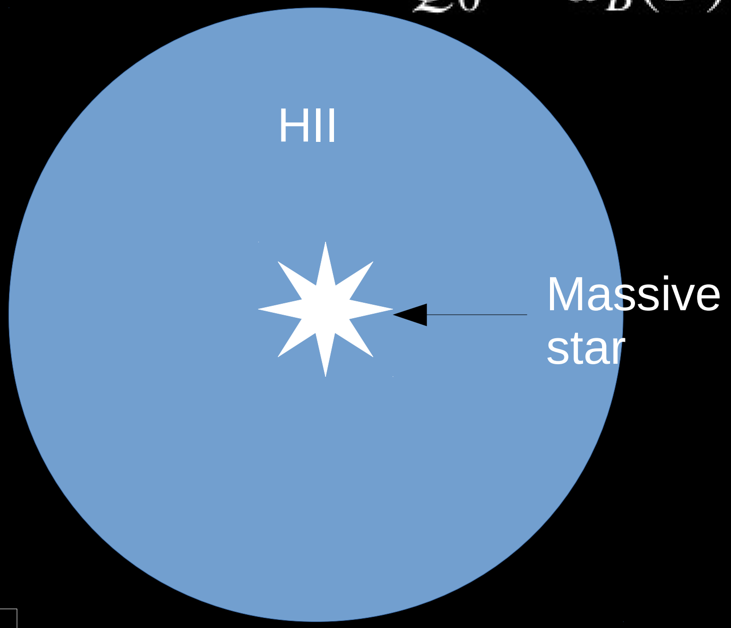
Giannetti+2013

Massive Stars

$$Q_0 = \alpha_B(T)\,\mathrm{EM}_V$$

Why massive stars?
- luminous (3×10^4 - $10^6\ L_\odot$)
- high impact on the interstellar medium (ISM) through outflows, radiation, supernovae (SN)

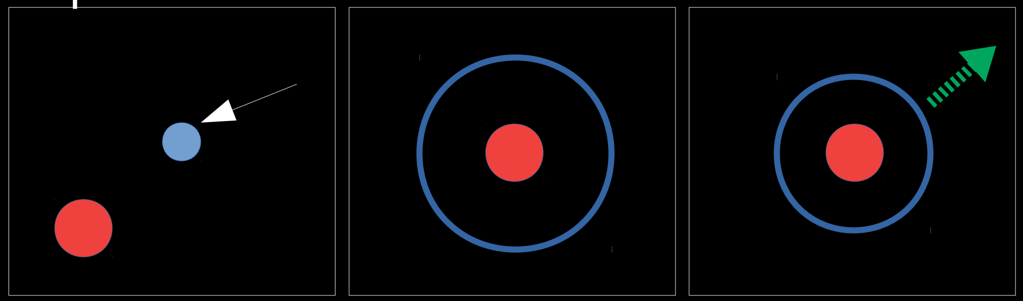
Massive Stars:
- short life ($\sim10^7$ yr)
- ionizing radiation -> bubble of ionized gas



Electron Capture

Excited Atom

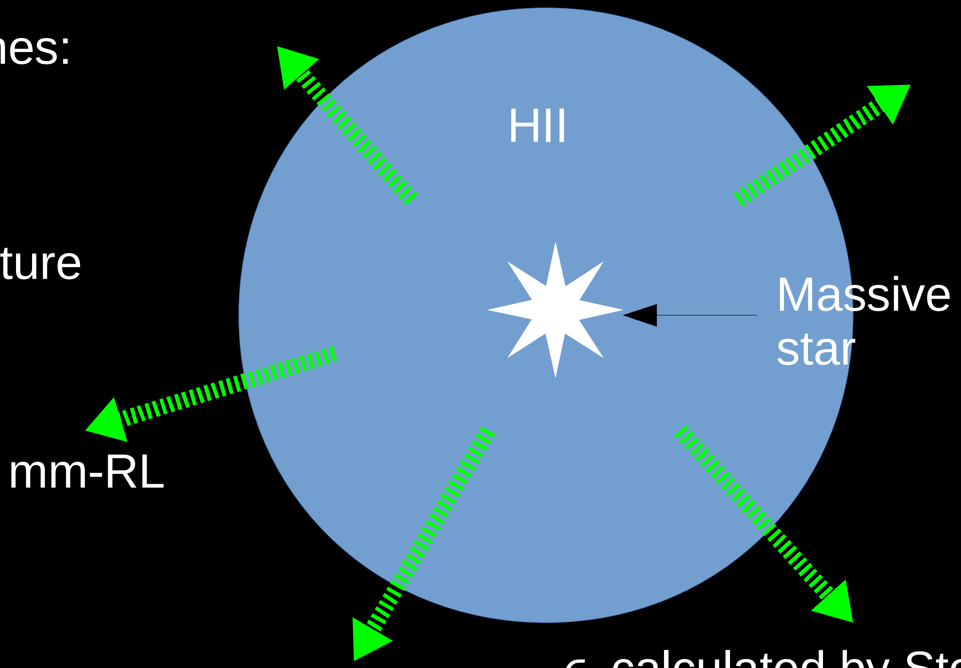
Transition



Hydrogen (Radio) Recombination Lines:
- high-n transition of Hydrogen
- wavelengths from mm to cm

Hydrogen Recombination Lines

Hydrogen (Radio) Recombination Lines:
- high-n transition of Hydrogen
- wavelengths from mm to cm
- originate in HII regions
- line/free-free continuum -> temperature



Line:

$$I_{n\alpha} = \frac{\epsilon_V \, \mathrm{EM}_V}{4\pi D^2}$$

ϵ_V calculated by Storey+95

$$\mathrm{EM}_V \equiv \int_V n_e n_p \, dV,$$

Free-free continuum:

$$\frac{F_{\nu,\mathrm{ff}}}{\mathrm{Jy}} = 0.057 \left[\frac{g_{\mathrm{ff}}(\nu, T_e)}{3.4}\right]\left[\frac{\mathrm{EM}_V}{10^9\ \mathrm{cm}^{-6}\ \mathrm{pc}^3}\right] T_4^{-0.5} D_{\mathrm{Mpc}}^2$$

Hydrogen Recombination Lines

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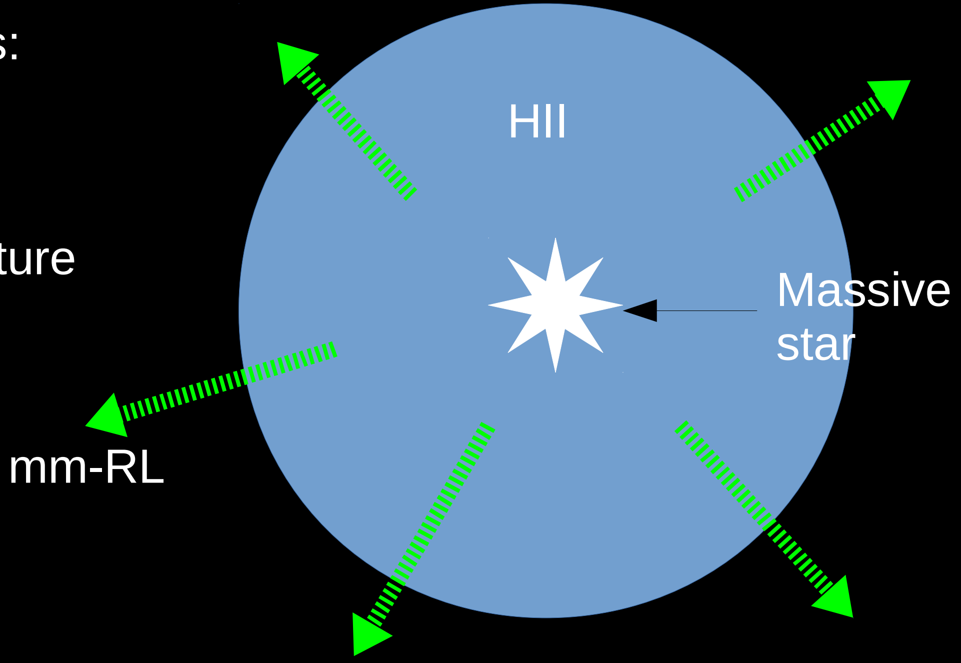


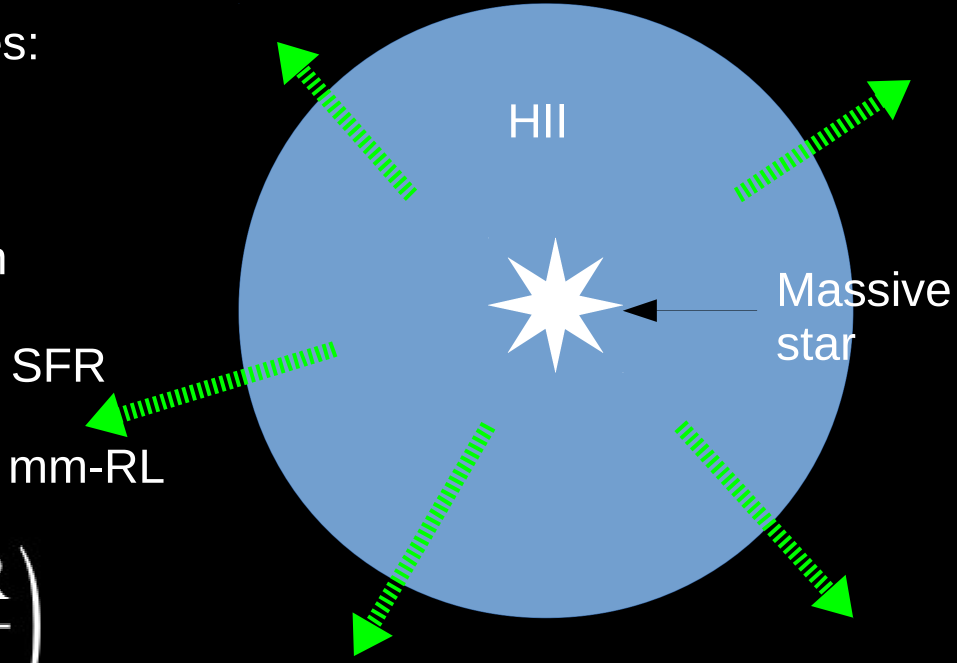
$$\frac{T_e}{10^4\ \mathrm{K}} = \left\{ \frac{g_{\mathrm{ff}}(\nu, T_e)}{3.4} \left[\frac{I_{\mathrm{n}\alpha}/F_{\nu,\mathrm{ff}}}{27\ \mathrm{Jy\ km\ s^{-1}\ Jy^{-1}}} \right] \left[\frac{\epsilon_{n\alpha,4}}{\epsilon_{40\alpha,4}} \right]^{-1} \left[\frac{\nu_9}{99.02} \right] \right\}^{-1.294}$$

Hydrogen Recombination Lines

Hydrogen Radio Recombination Lines:
- high-n transition of Hydrogen
- wavelengths from mm to cm
- originate in HII regions
- line/free-free continuum -> electron temperature
- intensity proportional to Q -> traces SFR

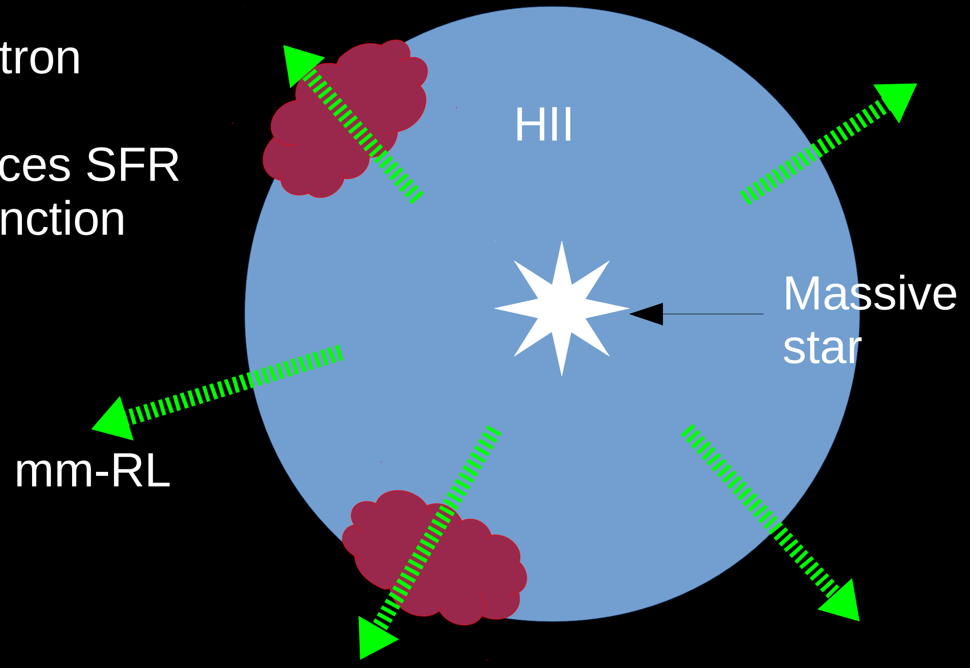
$$Q_0 = \alpha_B(T)\,\mathrm{EM}_V$$

$$\mathrm{SFR}_{\mathrm{n}\alpha} = 4\pi D^2 I_{\mathrm{n}\alpha}\,\frac{\alpha_B}{\epsilon_V}\left(\frac{\mathrm{SFR}}{Q}\right)_{B15}$$



Hydrogen Recombination Lines

Hydrogen Radio Recombination Lines:
- high-n transition of Hydrogen
- wavelengths from mm to cm
- originate in HII regions
- line/free-free continuum -> electron temperature
- intensity proportional to Q -> traces SFR
- mm-RL not affected by dust extinction
- instantaneous SFR (~10 Myr)

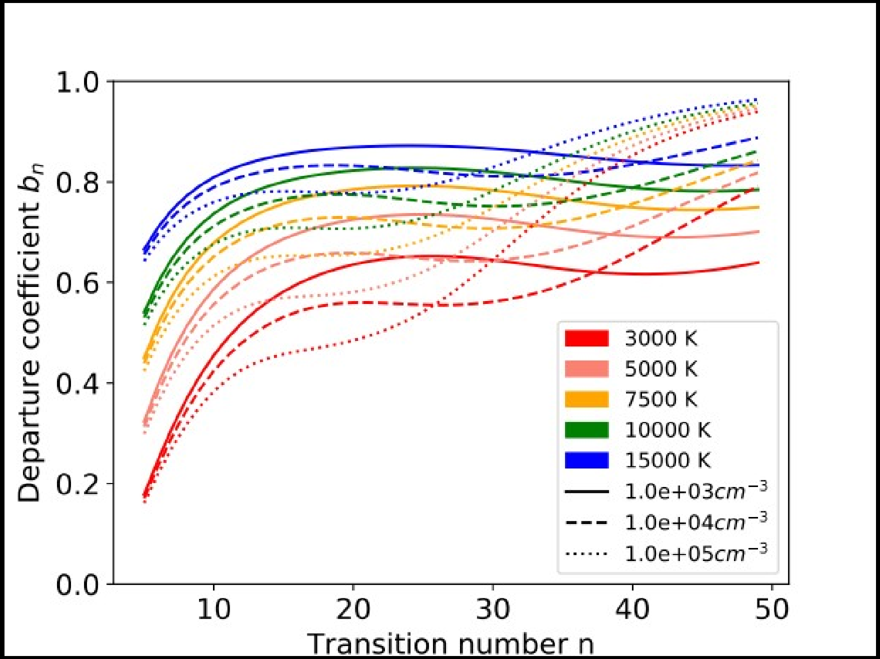


Hydrogen Recombination Lines: Opacity

- Non LTE conditions can affect cm and mm-RL
- low opacity (optically thin) negates most of these effects
- high opacity (optically thick): amplification or attenuation
- This would influence SFR calculations

$$F_{\nu,\mathrm{n}\alpha} = B_\nu(T_e)\eta\left(1 - e^{-\tau_{\mathrm{n}\alpha}-\tau_C}\right) - B_\nu(T_e)\left(1 - e^{-\tau_C}\right)$$

$$\eta = \frac{1 + b_{n+1}(\kappa^*_{\mathrm{n}\alpha}/\kappa_C)}{1 + b_n(\kappa^*_{\mathrm{n}\alpha}/\kappa_C)\gamma_n}$$



b_n data from Storey+95

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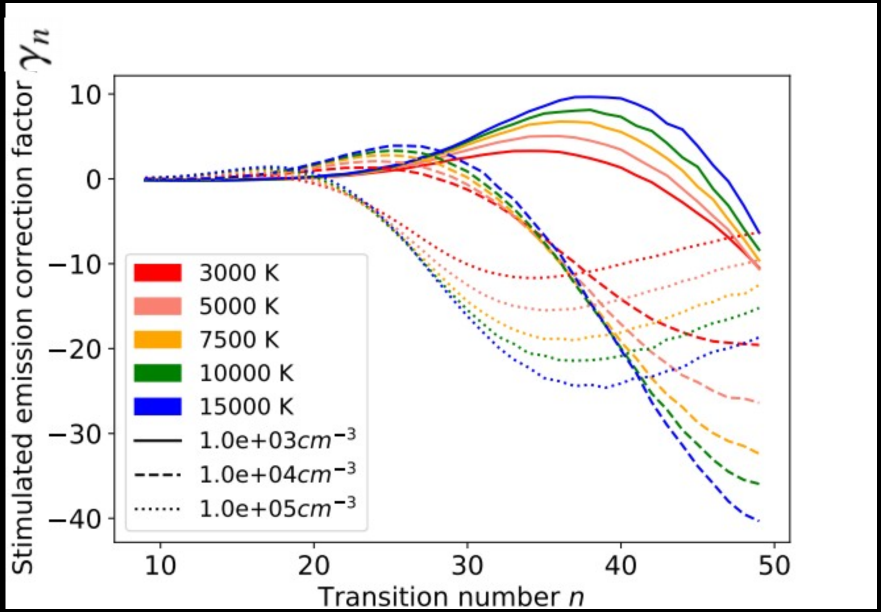
$$\tau \propto \mathrm{EM_{LOS}} \propto \int_L n_e^2 \, \mathrm{d}l \gamma_n$$

$$\gamma_n = \frac{1-(b_{n+1}/b_n)e^{-h\nu/kT_e}}{1-e^{-h\nu/kT_e}}$$



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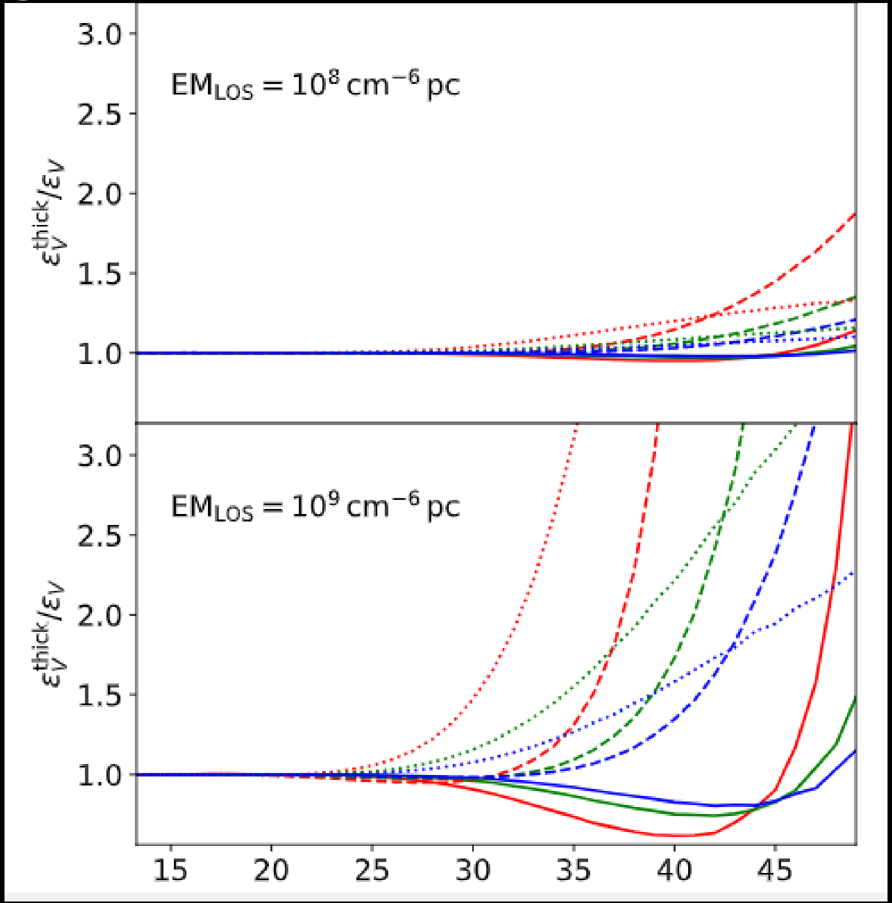
$$\frac{\epsilon_V^{\rm od}}{\epsilon_V} = \frac{I_{{\rm n}\alpha}^{\rm od}}{I_{{\rm n}\alpha}} \times \left[\frac{1\,{\rm cm^{-6}\,pc}}{\rm EM_{LOS}}\right]$$



Data: ALMA Archive Mining

Using python module astroquery:
- get all galaxies with redshifted mm-RL emission covered by an ALMA project
- select top 20 brightest galaxies at 100 μm (IRAS-RBGS Sanders+2004)
- pick deepest observations

With CASA:
- visually inspect for mm-RL emission
- archive products/re-reduced products used

Final Sample


NGC4945


NGC253


M83


NGC5128


NGC1068


NGC0055


NGC1365


NGC1808


NGC3627


NGC2903


Arp220


NGC3256


NGC3628


NGC1097


NGC6822


NGC4038


NGC7582


NGC5253


NGC4418


NGC1614

Detections of mm-RL


NGC4945


NGC253


M83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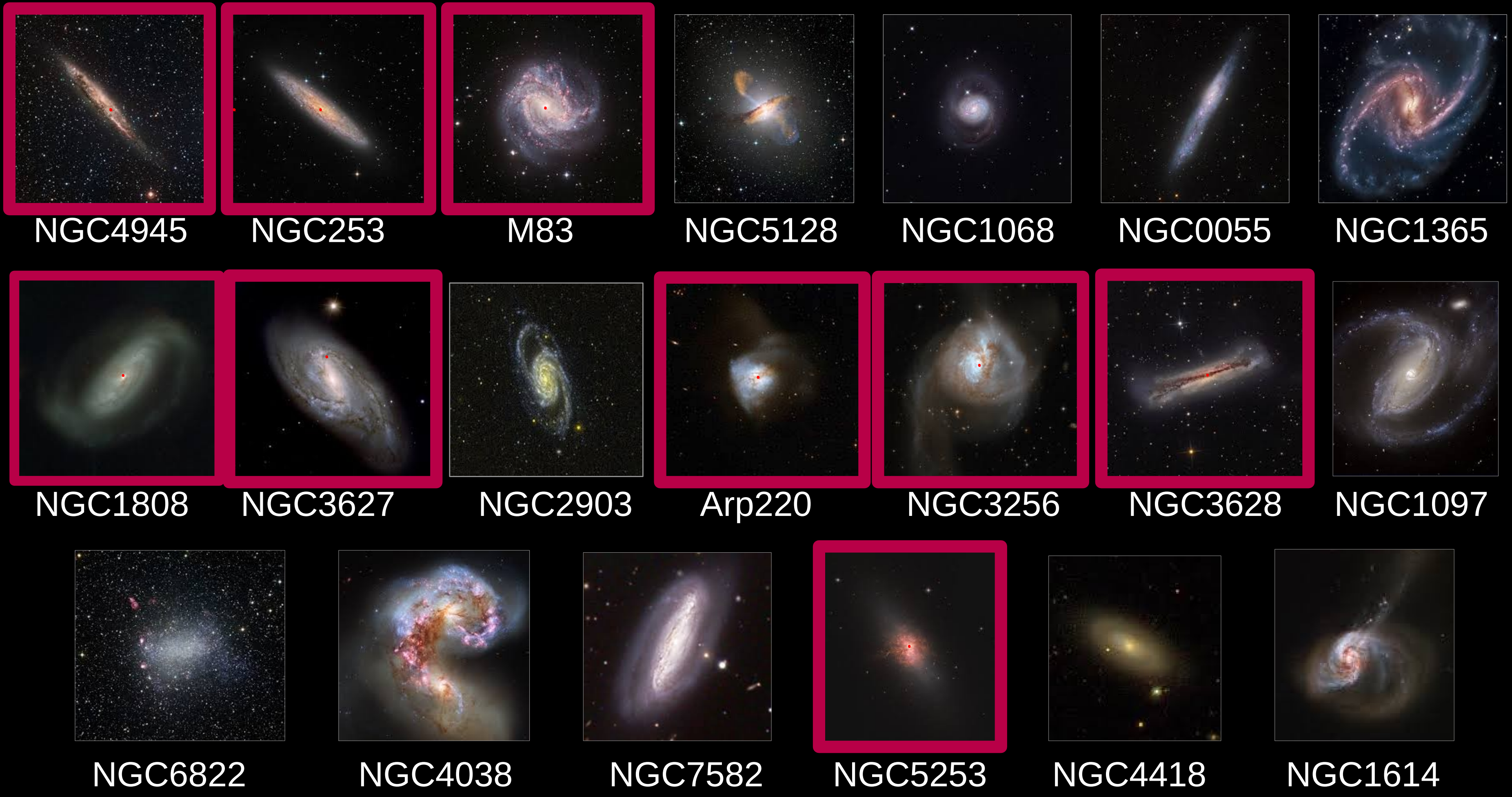
Detections of mm-RL



Results: Detections of H-RL

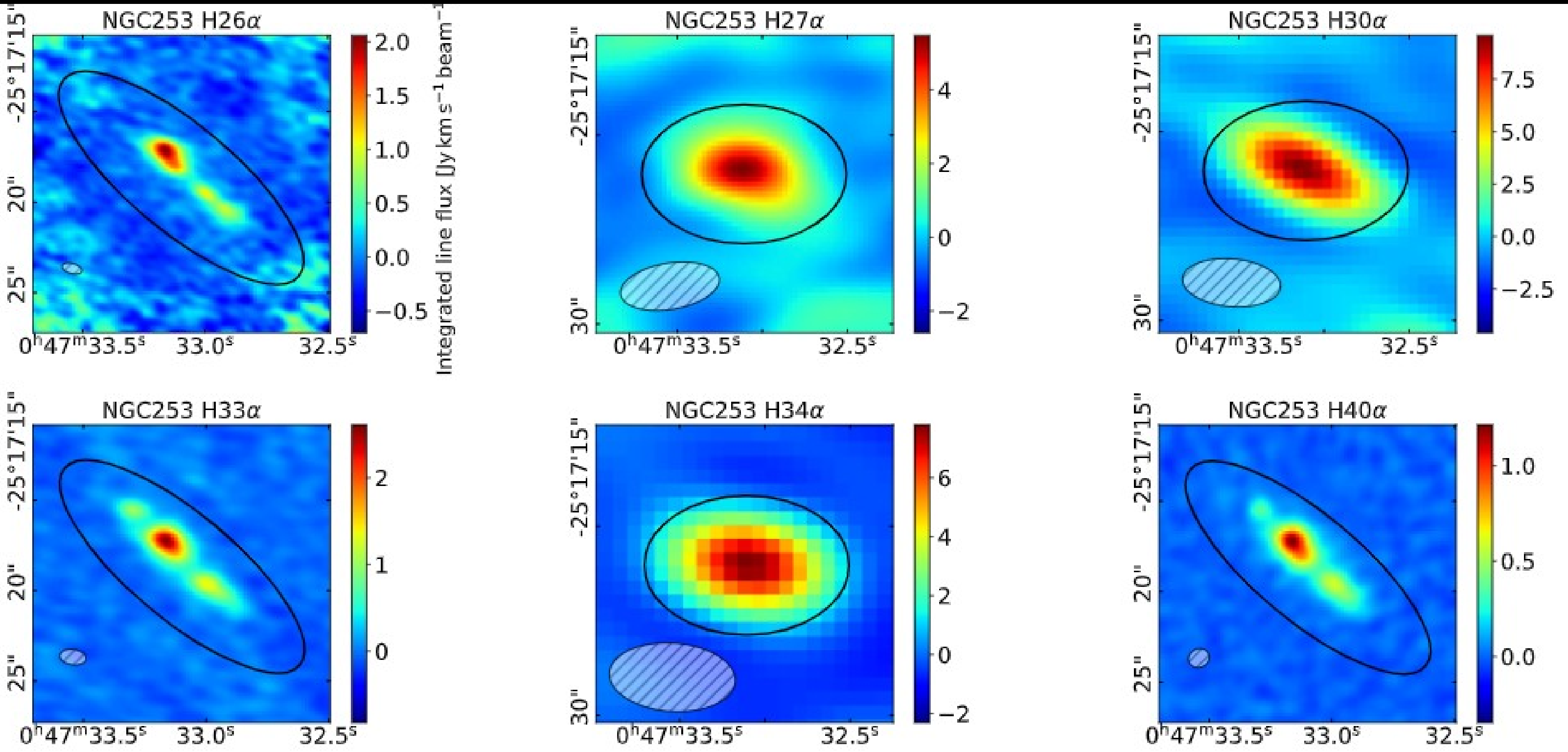


Fig. 3. ALMA moment zero maps of the H-RL detected in NGC253. The H27α, H30α, and H34α lines were detected with the ACA and are shown in the top, top right, and bottom middle panel, respectively. The H26α, H33α and H40α lines were detected with the ALMA main array and are shown in the top left, bottom left and bottom right panels, respectively. The aperture used to extract the fluxes of all the lines is outlined in black. The telescope beam is shown in the lower left corner of each panel.

Detections of H-RL

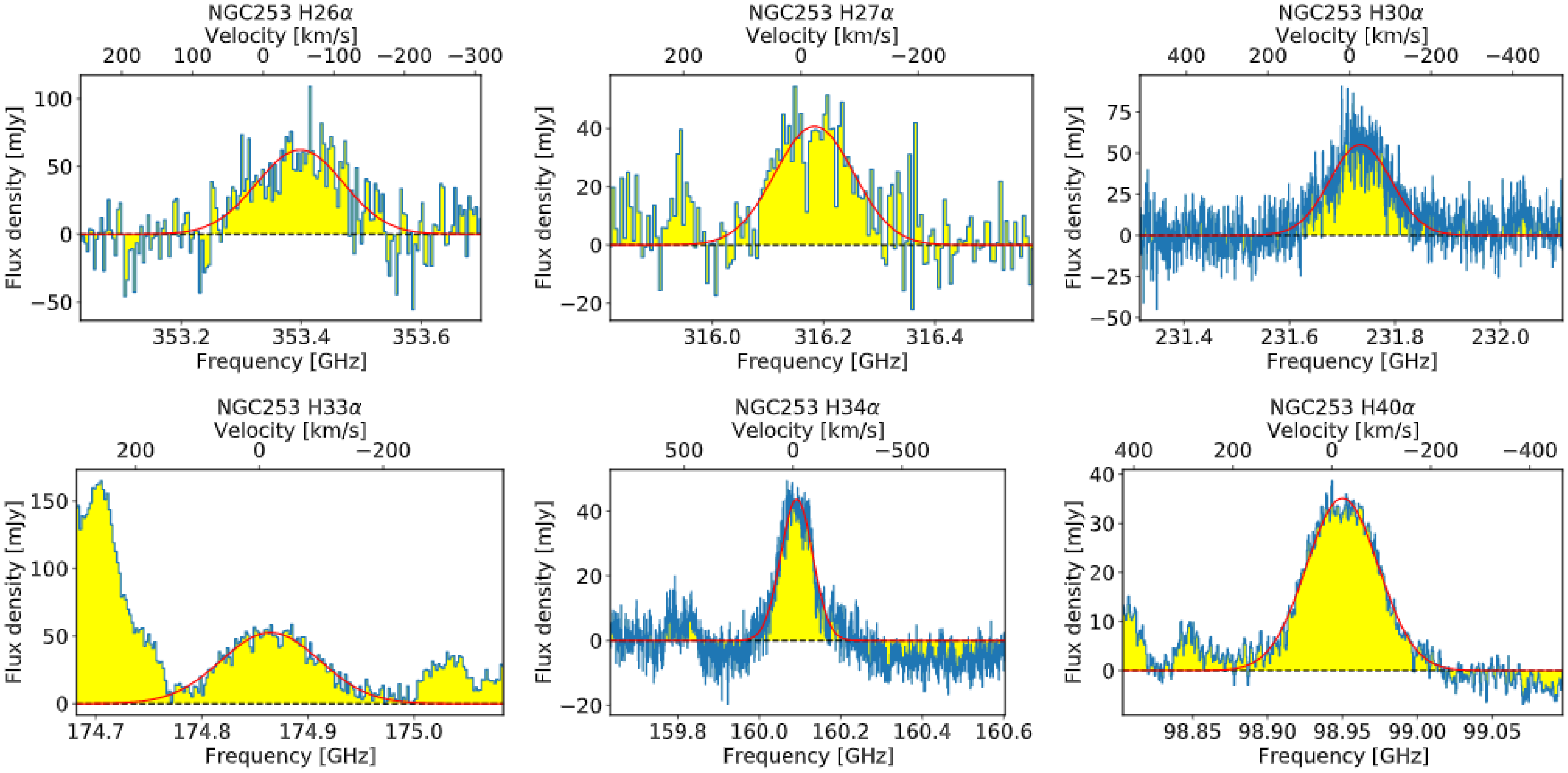
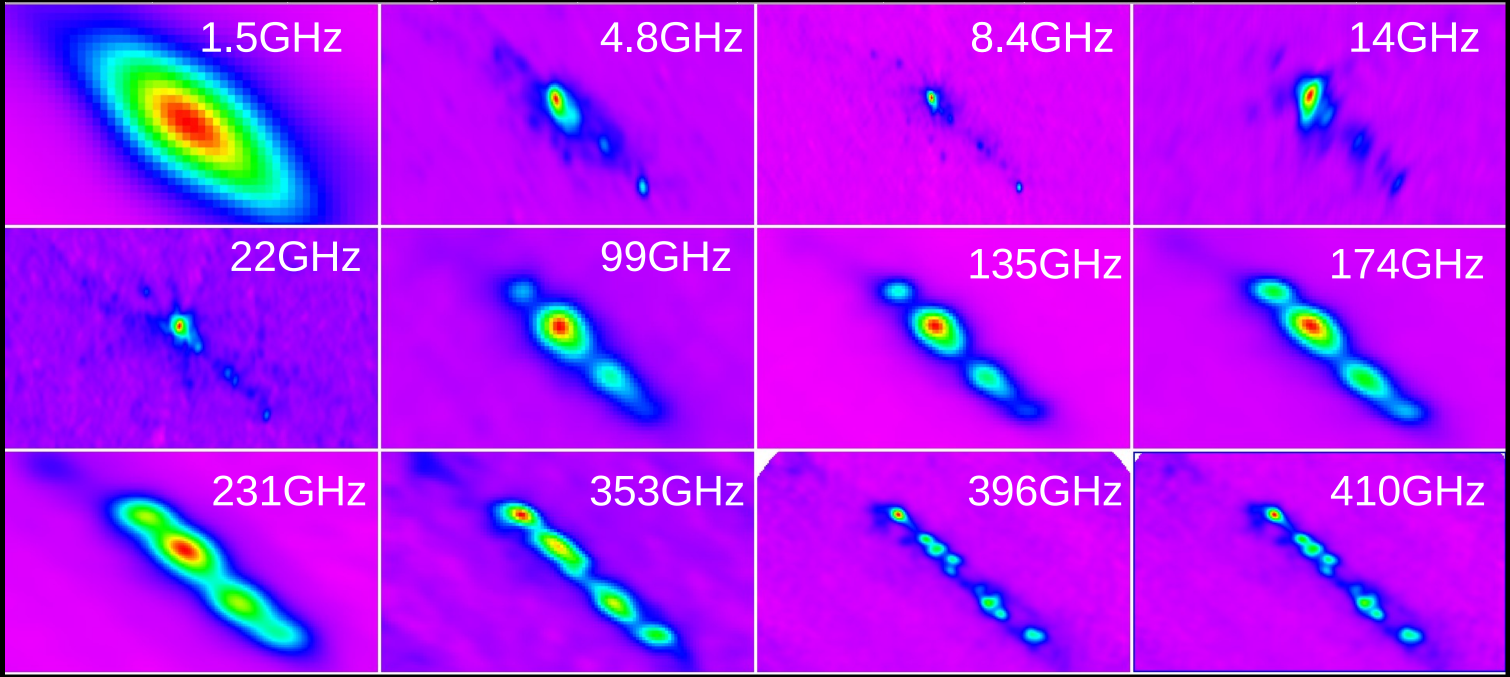


Fig. A.8. Spectra of detected mm-RL in NGC253

SED fits

Goal: obtain the free-free fraction of the continuum
Continuum data from:
- archival images from VLA, ALMA
- literature data from ATCA, SMA etc.

Wavelength coverage:
- 1.5~400 GHz
- matched aperture



SED fits

With emcee package from python:
- Fit three component SED

$$F_\nu = F_\nu^{\mathrm{sync}} + F_\nu^{\mathrm{ff}} + F_\nu^{dust} = a_1\nu^\alpha + a_2 g_{\mathrm{ff}} + a_3 B_\nu(T_{\mathrm{dust}})\nu^\beta$$

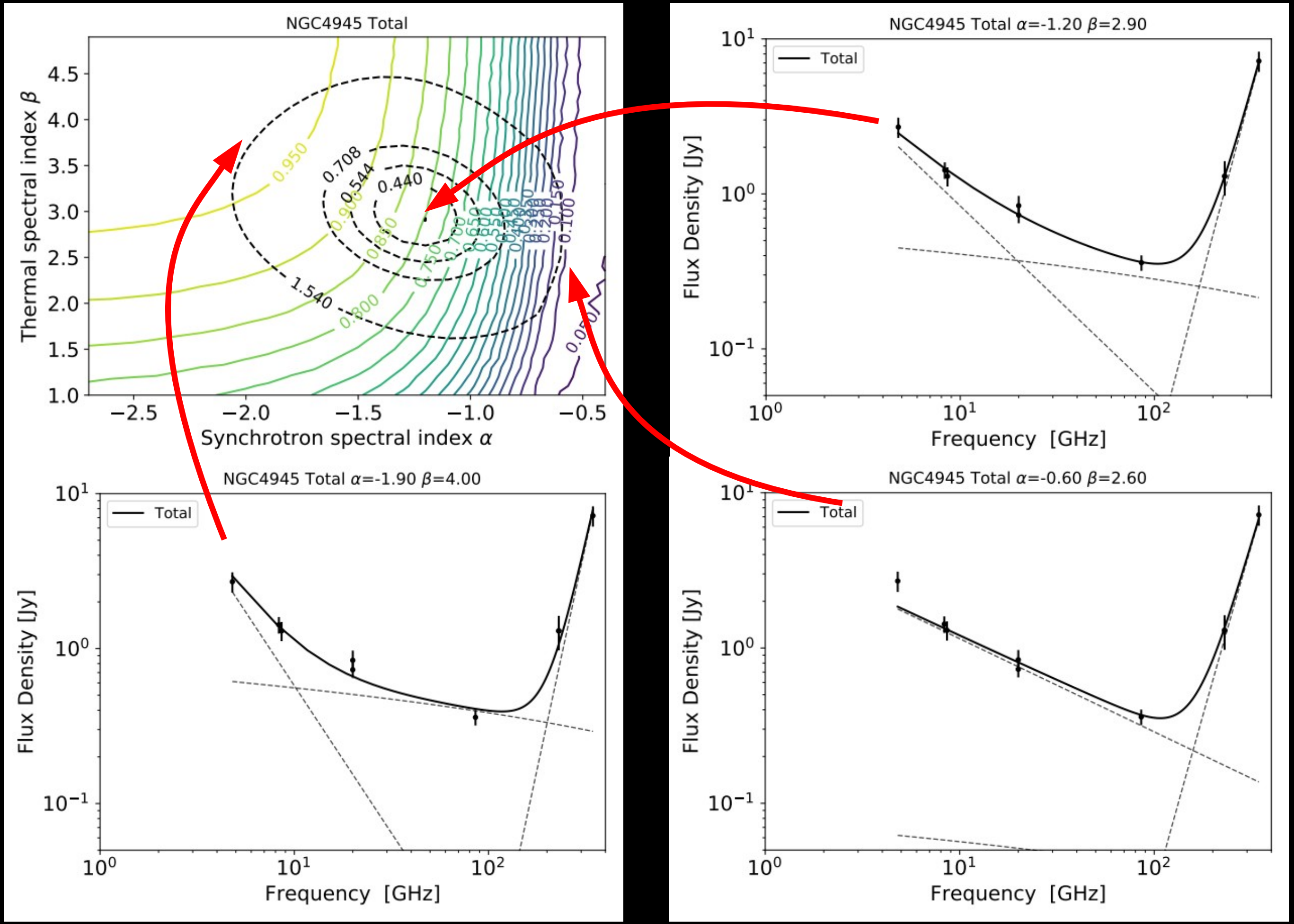
$$g_{\mathrm{ff}} = 0.5525 \ln\left[\left(\frac{T_e}{\mathrm{K}}\right)^{1.5}\left(\frac{\nu}{\mathrm{GHz}}\right)^{-1} Z^{-1}\right] - 1.682,$$

- Scaling parameters free, T_{dust} = 30K for mbb, T_e = 5000K for g_{ff}
- Synchrotron and dust emissivity index varied over a grid of values
- Get reduced χ^2 for each pair of α and β
- Values that minimize the reduced χ^2 are adopted, resulting uncertainties from that SED fit are statistical uncertainties
- Values which correspond to the 68% confidence level in the reduced χ^2 values are systematic uncertainties

SED fits

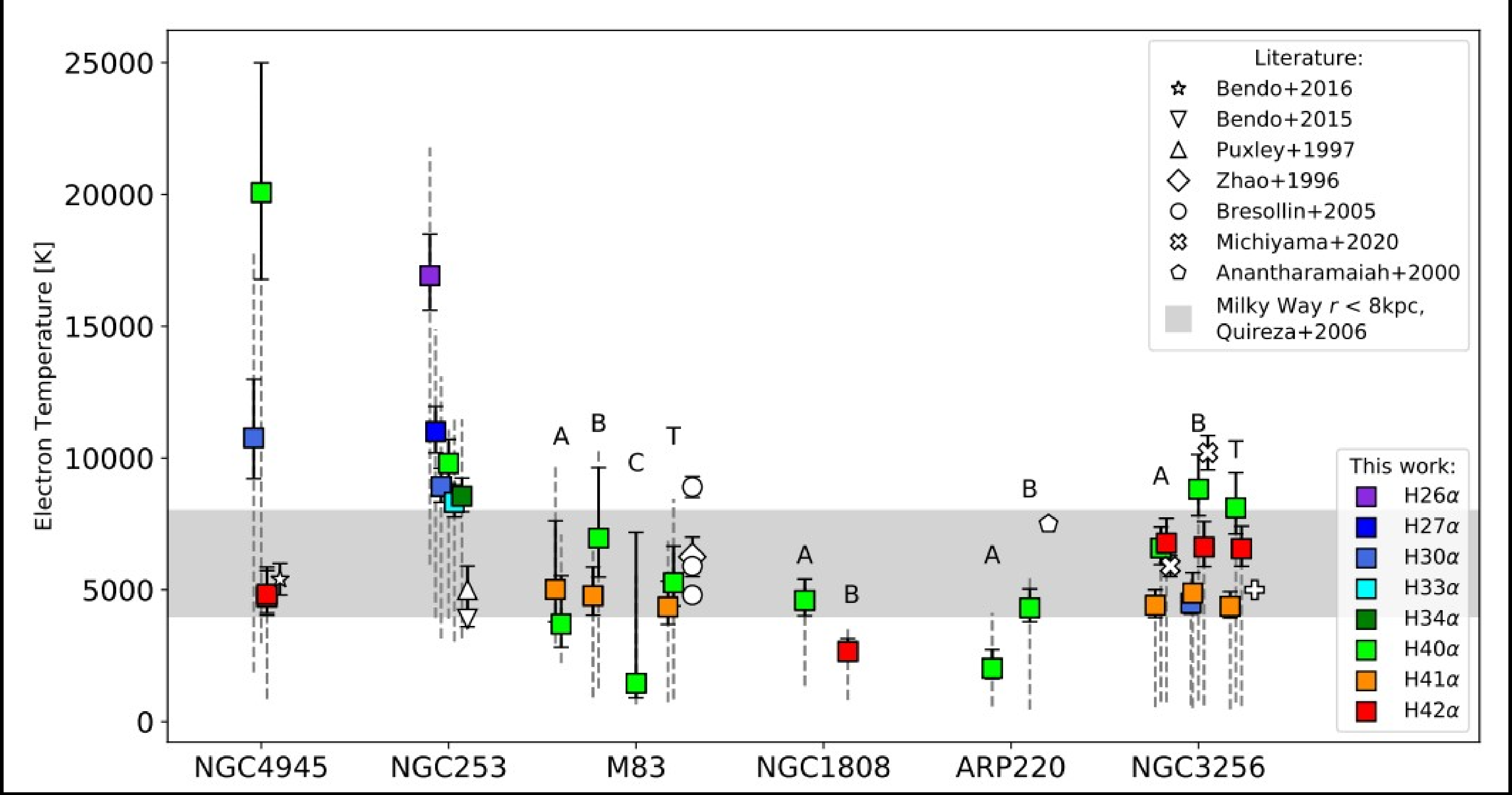
Reduced χ^2 values over a grid of α and β values for NGC4945

- Photometric uncertainties: errors from fitting middle point
- “Systematic” uncetainties: values corresponding to extremes on 68% confidence level contour
- conclusion: free-free continuum level uncertain

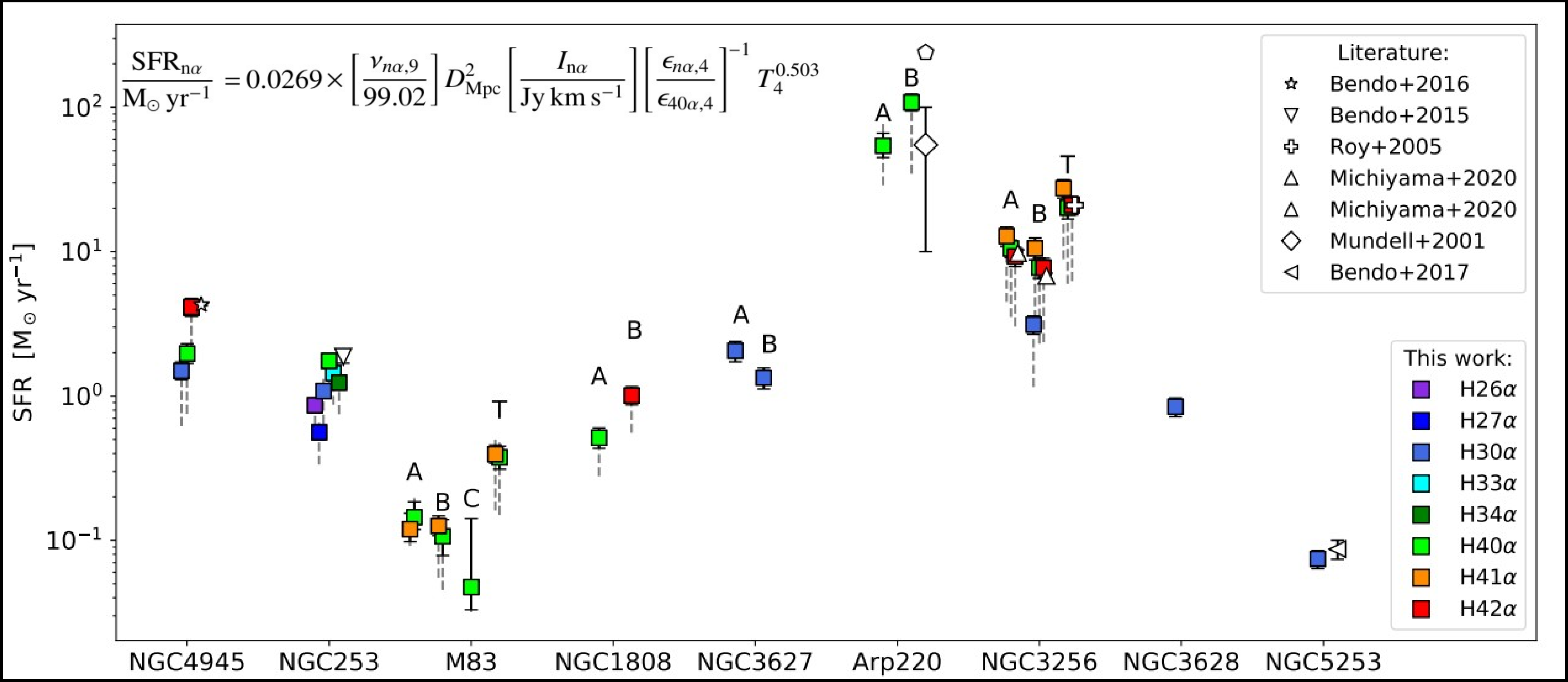


Electron Temperature

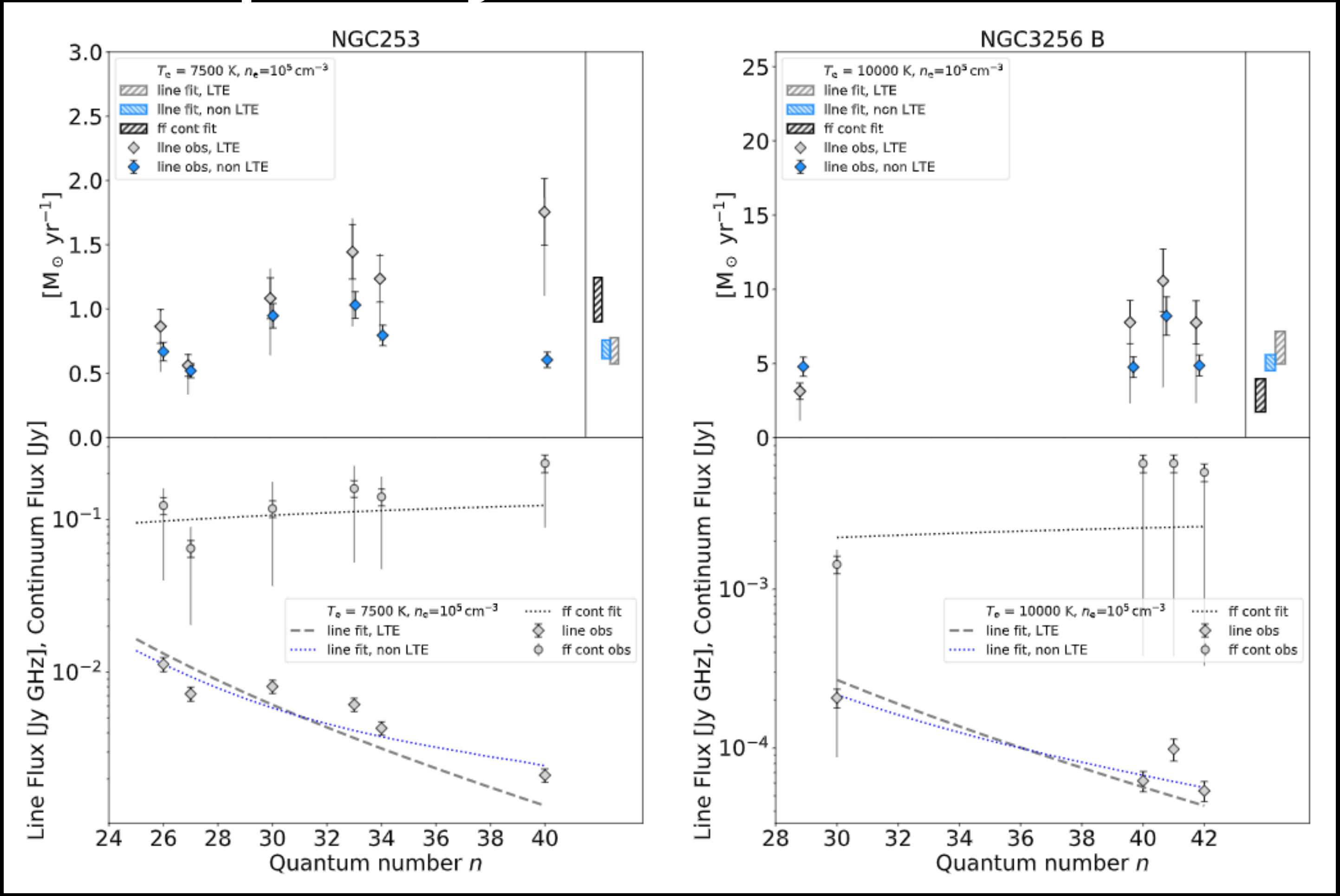
T_e determined using line/free-free continuum ratio



Star Formation Rates



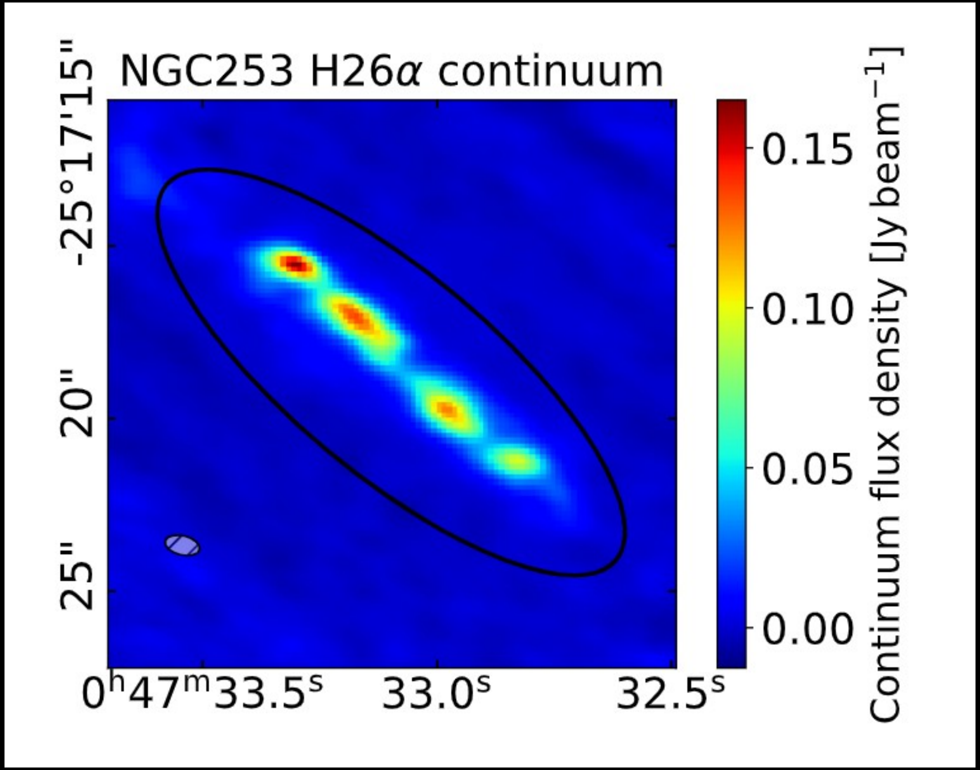
Opacity corrected SFR



Comparison to FIR

- FIR based SFR requires coverage of the FIR spectrum
- Herschel resolution: ~7” to 36”
- ALMA resolution: ~1” or less
- Solution? Use ALMA high frequency data and MBB fit:

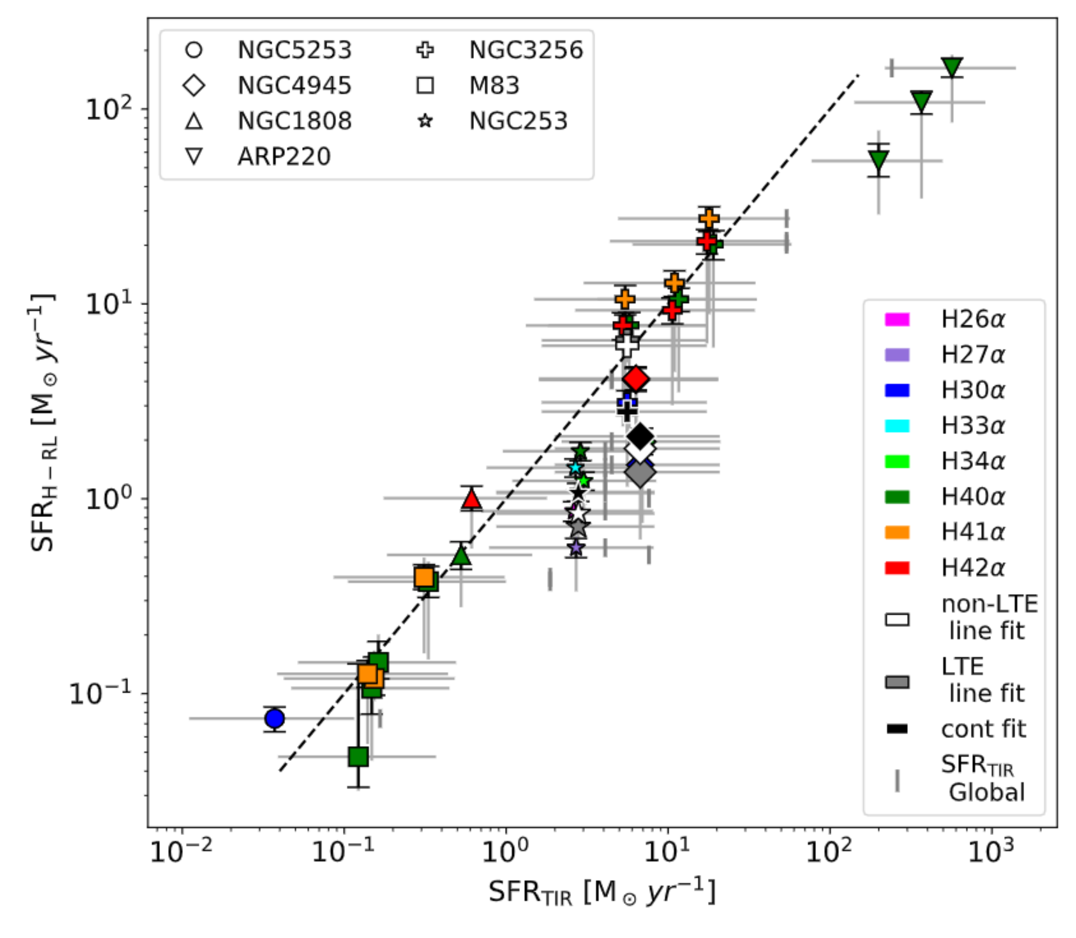
$$F_\nu \propto \nu^\beta B_\nu(T)$$



- Murphy+2011:

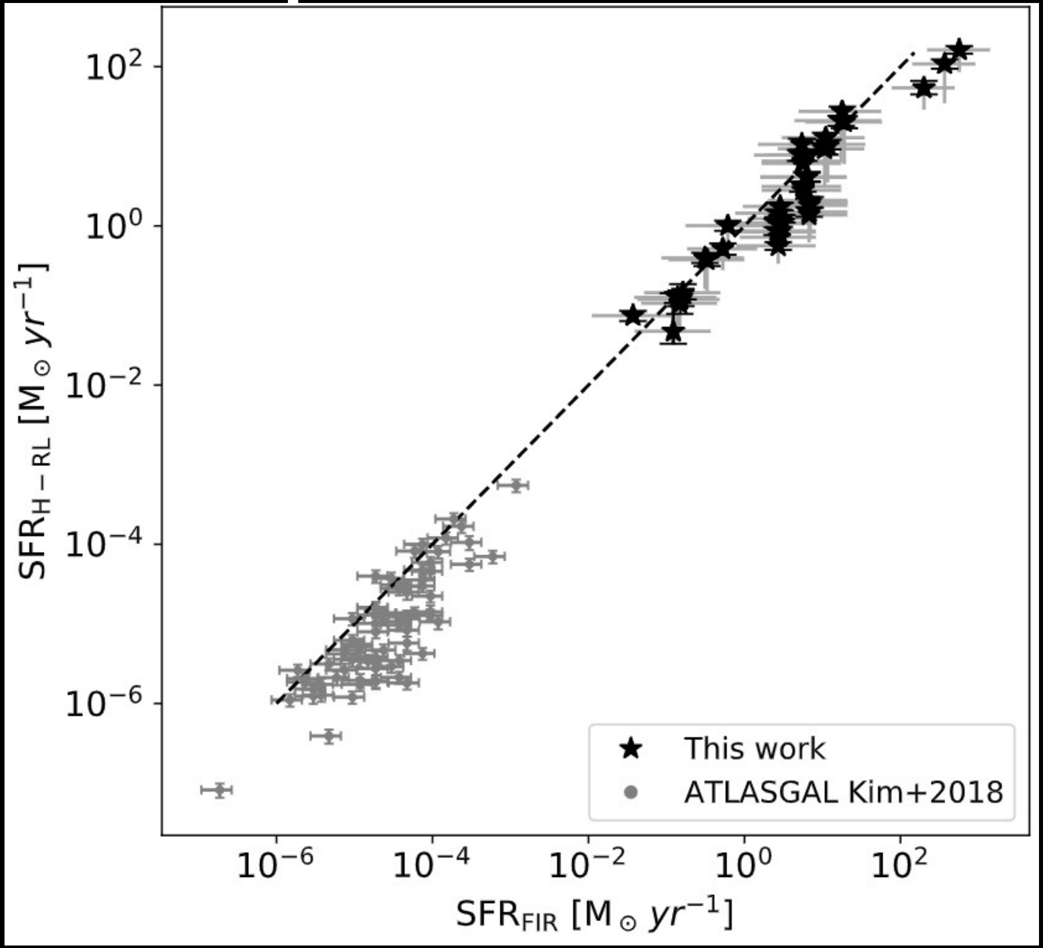
$$\mathrm{SFR_{TIR}}\ [\mathrm{M_\odot\ yr^{-1}}] = 1.49 \times 10^{-10}\ (L_{\mathrm{TIR}}/L_\odot)$$

Comparison to FIR



- β = 1.5-2
- T_d=35-45 K

Comparison to FIR



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- T_d=35-45 K

Summary

- 9 out of 20 brightest galaxies at 100 microns show H-RL emission
- free-free continuum and electron temperature are poorly constrained using SED fitting
- opacity and non-LTE effects apparent in 2 out of 3 galaxies where this analysis was possible
- SFR from H-RL and FIR are in agreement
- at ALMA resolutions, FIR data cannot be used to trace SFR directly, leaving H-RL as a possible best tracer of SFR
- Correlation between FIR- and H-RL-based SFR extends to galactic regions, over 8 orders of magnitude in SFR.

Thank you!