Rising from Obscurity:
Optical Signatures of Outflows & Interactions in CONs & Related LIRGs

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CON-quest: Susanne Aalto, Niklas Falstad, Sabine König, Youichi Ohyama, George Privon, Kazuchi Sakamoto…

Katey Alatolo & crew

(NICMOS HST Pioneers include Alonso-Herrero, Scoville)

Curtain of Dust III – Sexten, Italy

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Wisconsin→ Minnesota
Dust opacity modles

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Juniata College
GALFIT modeling & galaxy structures

Eowyn Yangyang Liu
Wisconsin
CMZs, bars & star formation

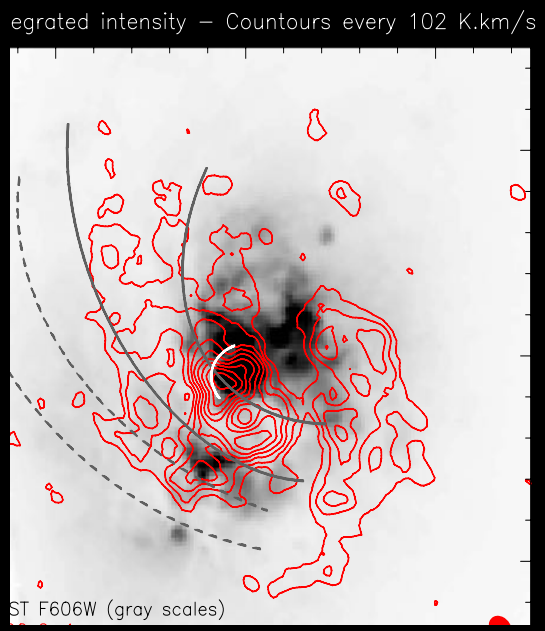
Jalyn Krause
Wisconsin
Dust opacity & gas masses

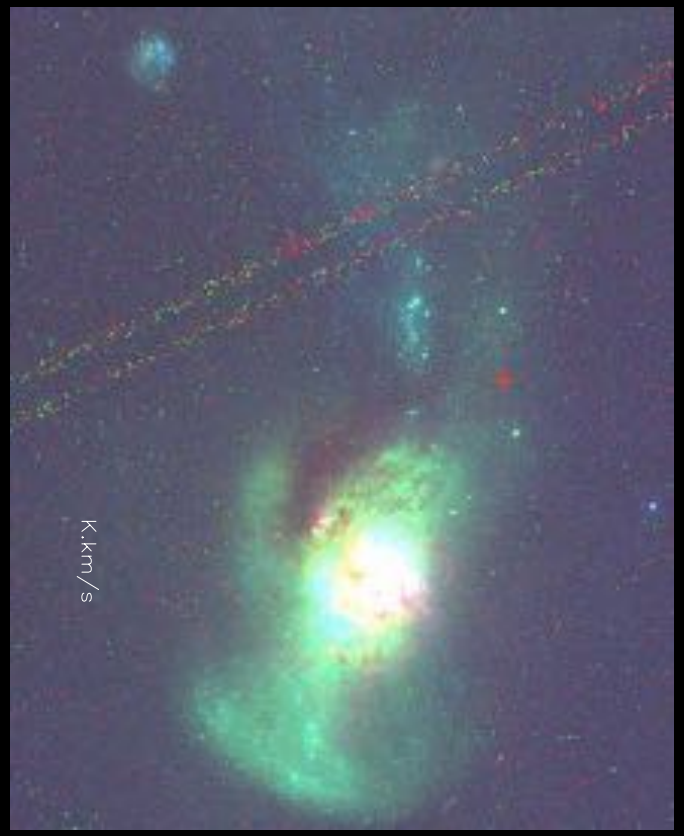
Project Goals

- Explore connections between obscured nuclei and larger scale structures
  - Stellar substructures—indication of interactions
    - $t_{dynamical} \sim V/R \propto 1/R$ – outer regions retain dynamical record
    - Asymmetric structures generally last few $t_{dynamical}$
  - Features due to dust obscuration
    - Dust absorption -- $\tau \cong \kappa(\mathrm{dust})\rho(gas)\left(\frac{dust}{gas}\right)L$ -→ N(H+H_2)
    - Locations & gas column densities—mass cycling process
    - Connect kinematics (multi-$\boldsymbol{\lambda}$ spectra) to structures.

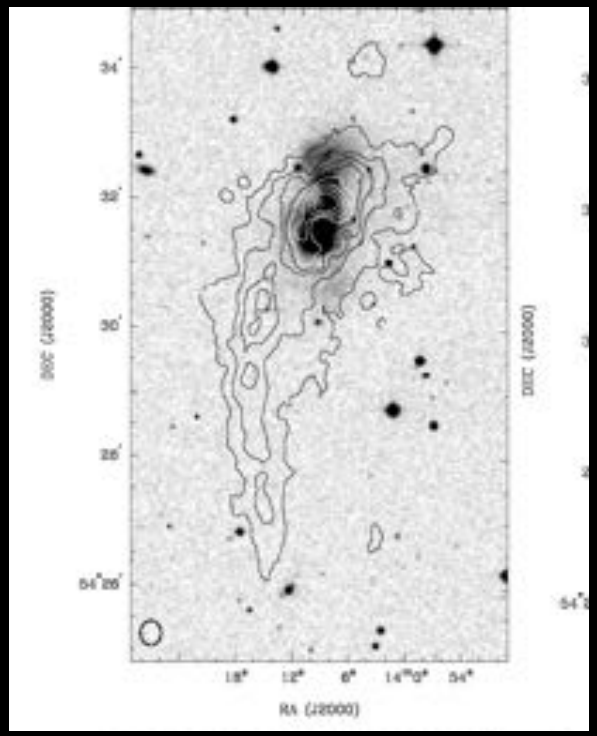
Minor Mergers: A Path to Obscured Nuclei

HI tails
Outer stellar tidal debris
Growth in central gas concentration





Medusa—see S. König Talk

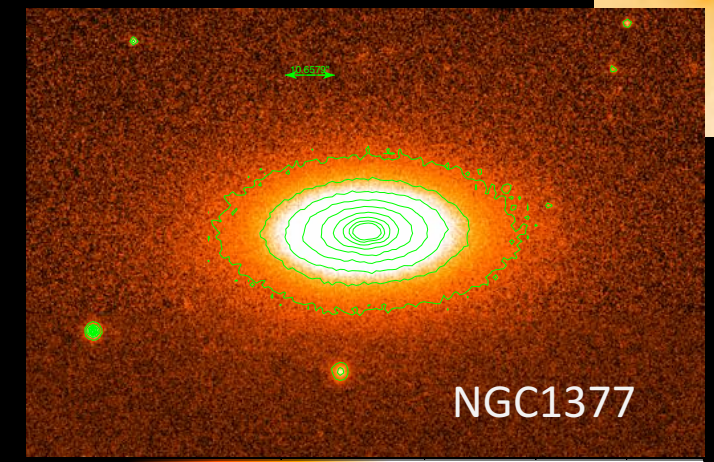


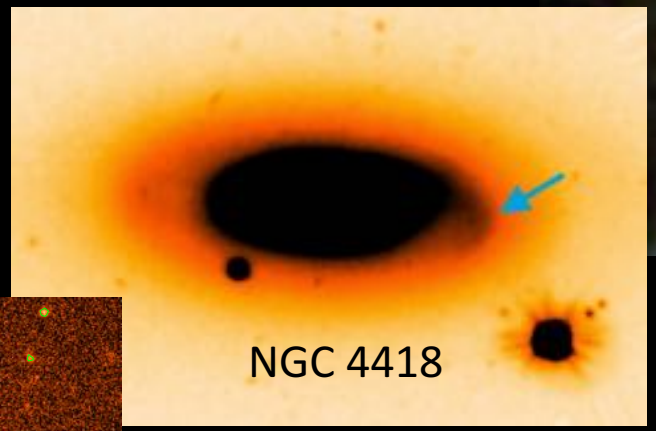
Optical Diagnostics

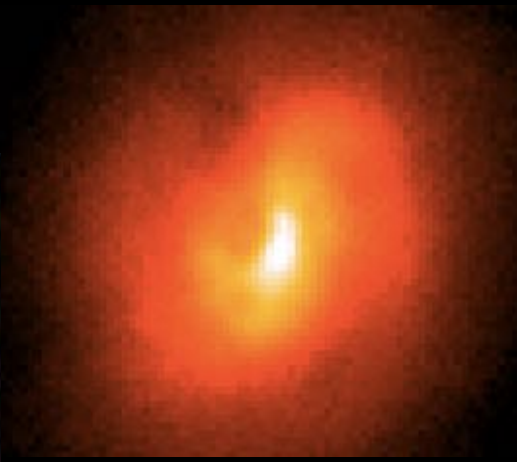
- IMAGING – Early Structural Class Galaxies (Simplicity?):
  - *Stellar features—bars, arms, tidal debris*
    - *Colors & stellar populations*
  - *Dust structures—ISM concentrations*
    - *Polar vs. disk components orbiting gas from geometry*
    - *Outflows—unique linear strucures*
    - *Optical depths—gas mass/phase estimates*
    - *Ionized gas—star forming sites, AGN, …*

Low resolution: range of host structures

Possible sequence in terms outer structural disturbances





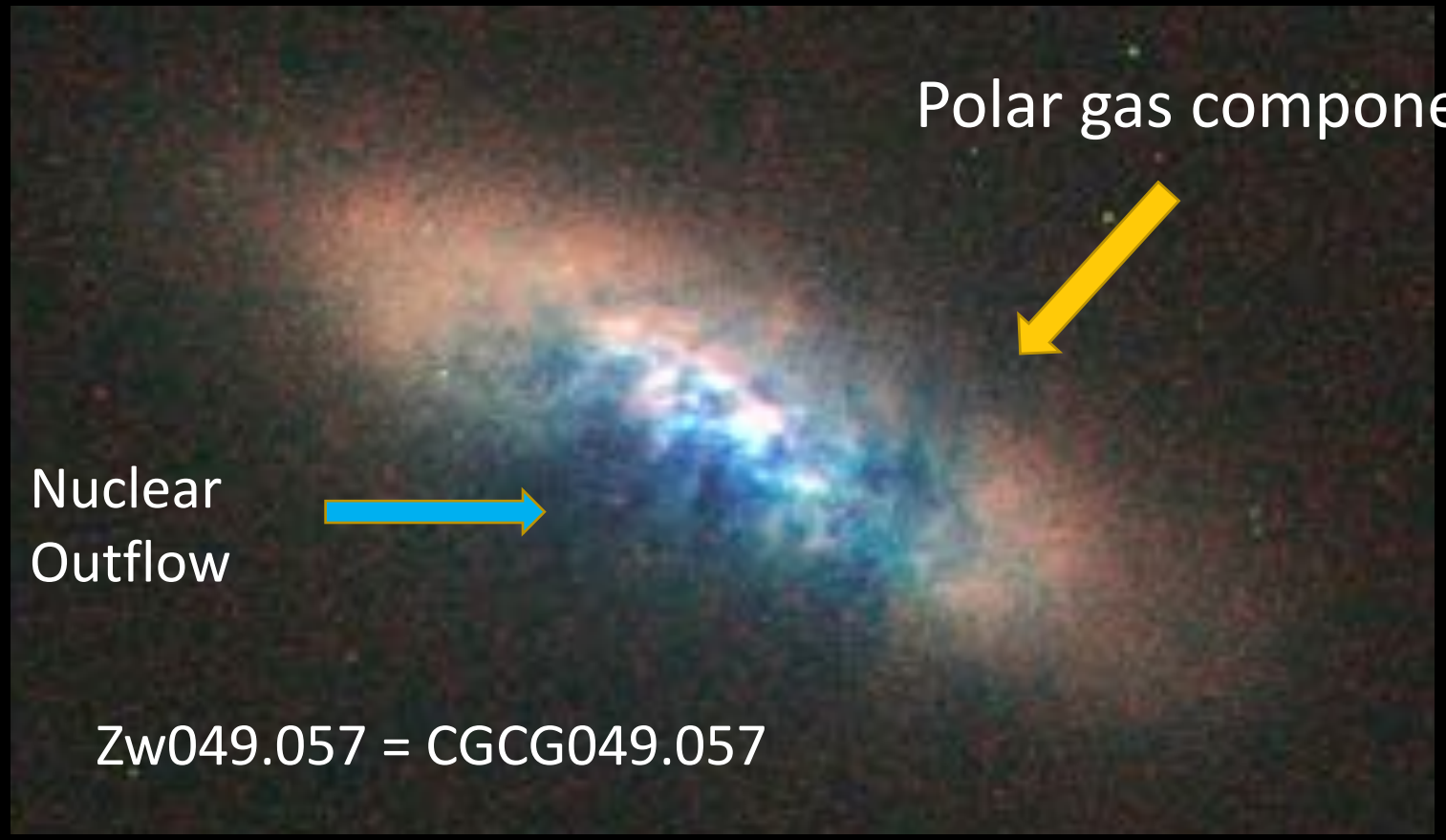


More Disturbance
TIME SINCE INTERACTION?
NATURE OF TRIGGER?
DISK INSTABILITIES?

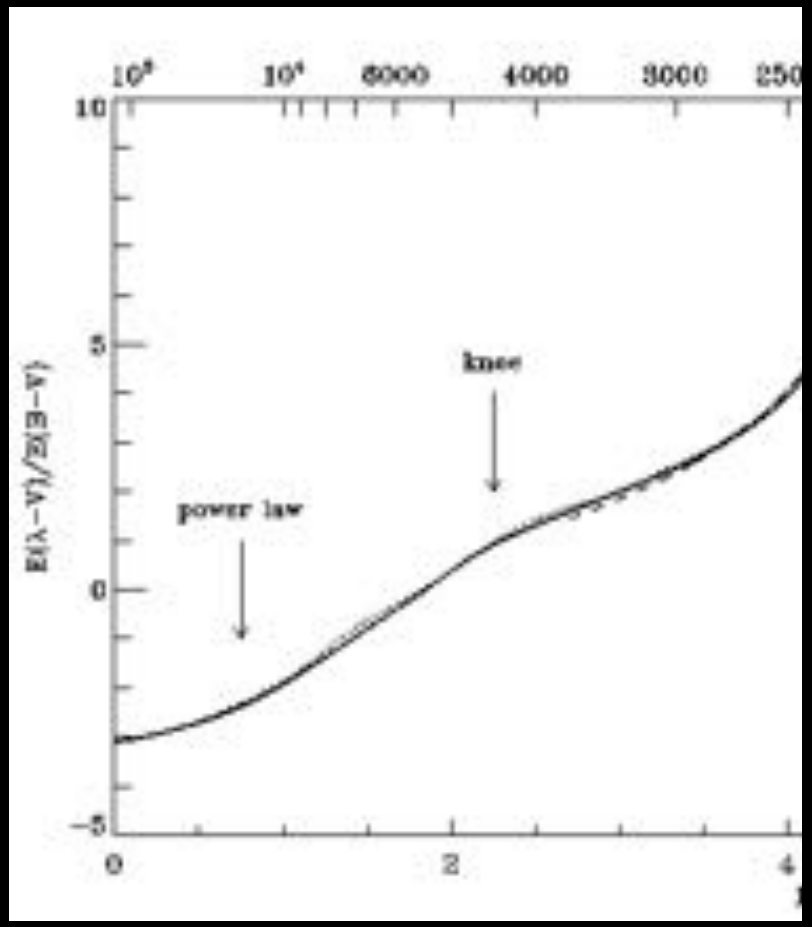
HST (JSG+ & ATALOLO+ GO): More details

- Multiple—bands: optical depth of dust obscuration & locations of younger stars.

Analysis needs to deal with presence of dust



Interstellar Obscuration vs. Wavelength



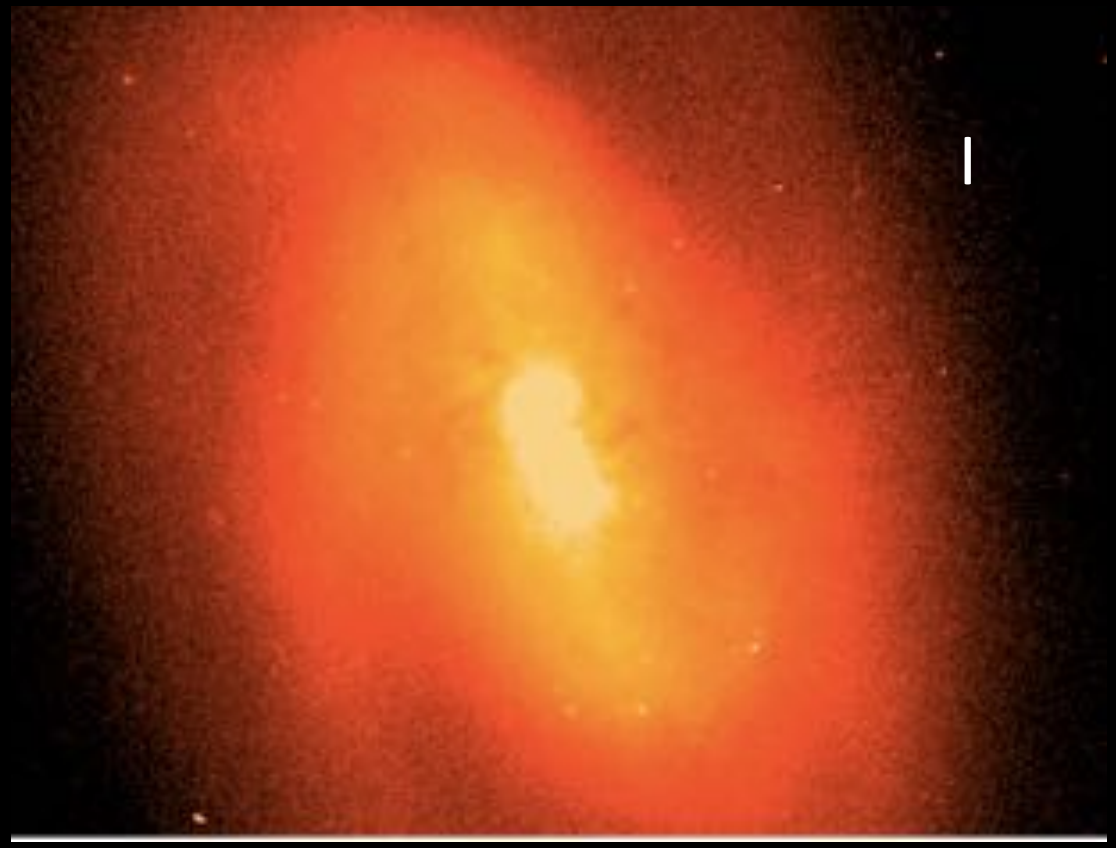
$(\tau(\lambda) - \tau(V))/(\tau(B) - \tau(V))$

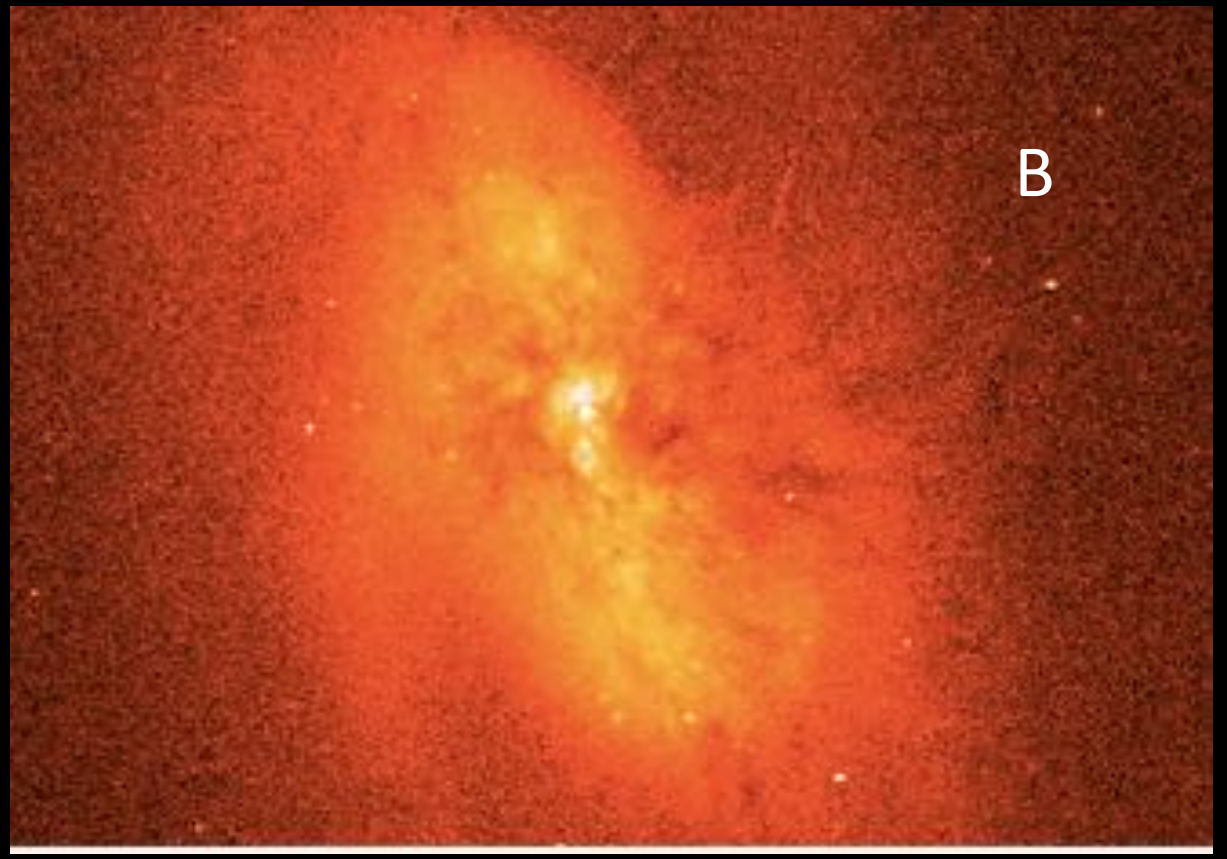
1. $\boldsymbol{\tau}(\lambda)/\boldsymbol{\tau}$(V) fixed by obscuration model
2. $\boldsymbol{\tau}(\lambda)/\boldsymbol{\tau}$(V) decreases as $\boldsymbol{\lambda}$ increases

Longer wavelengths: More transparency & probe higher column density gas

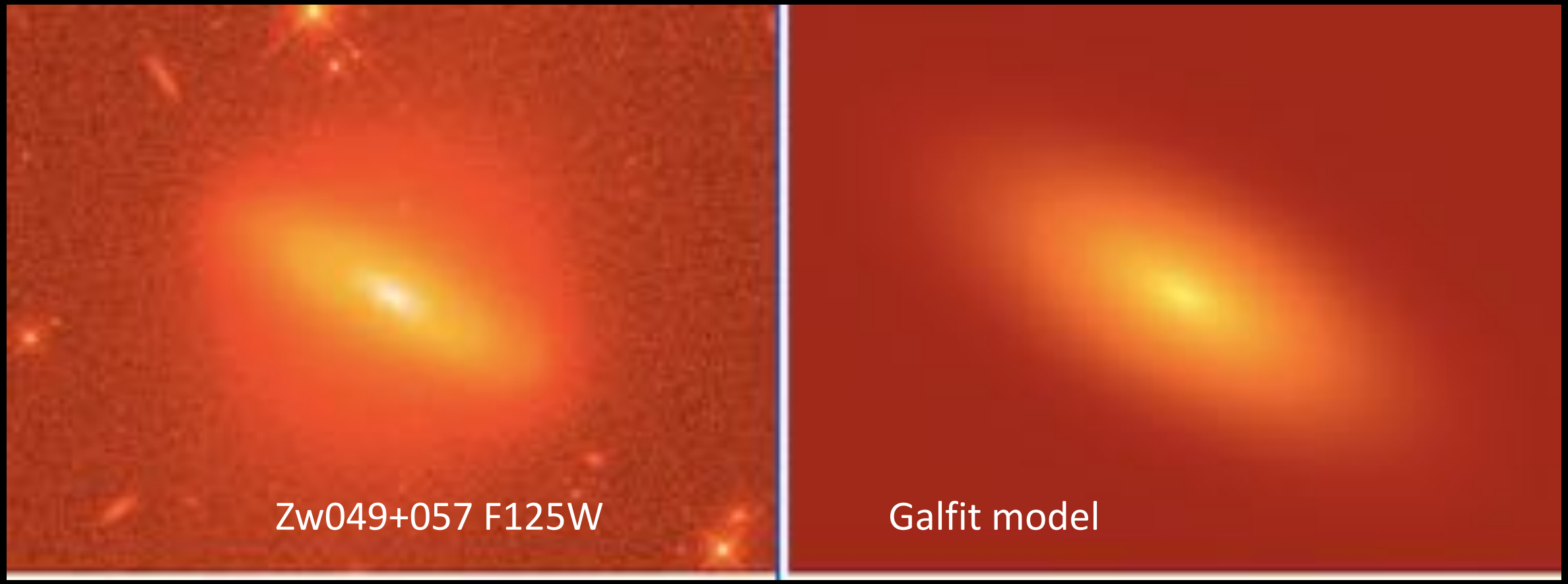
Example: IC860 HST (K. Alatolo)

HST “B-band” traces lower column dust—extent of outflow

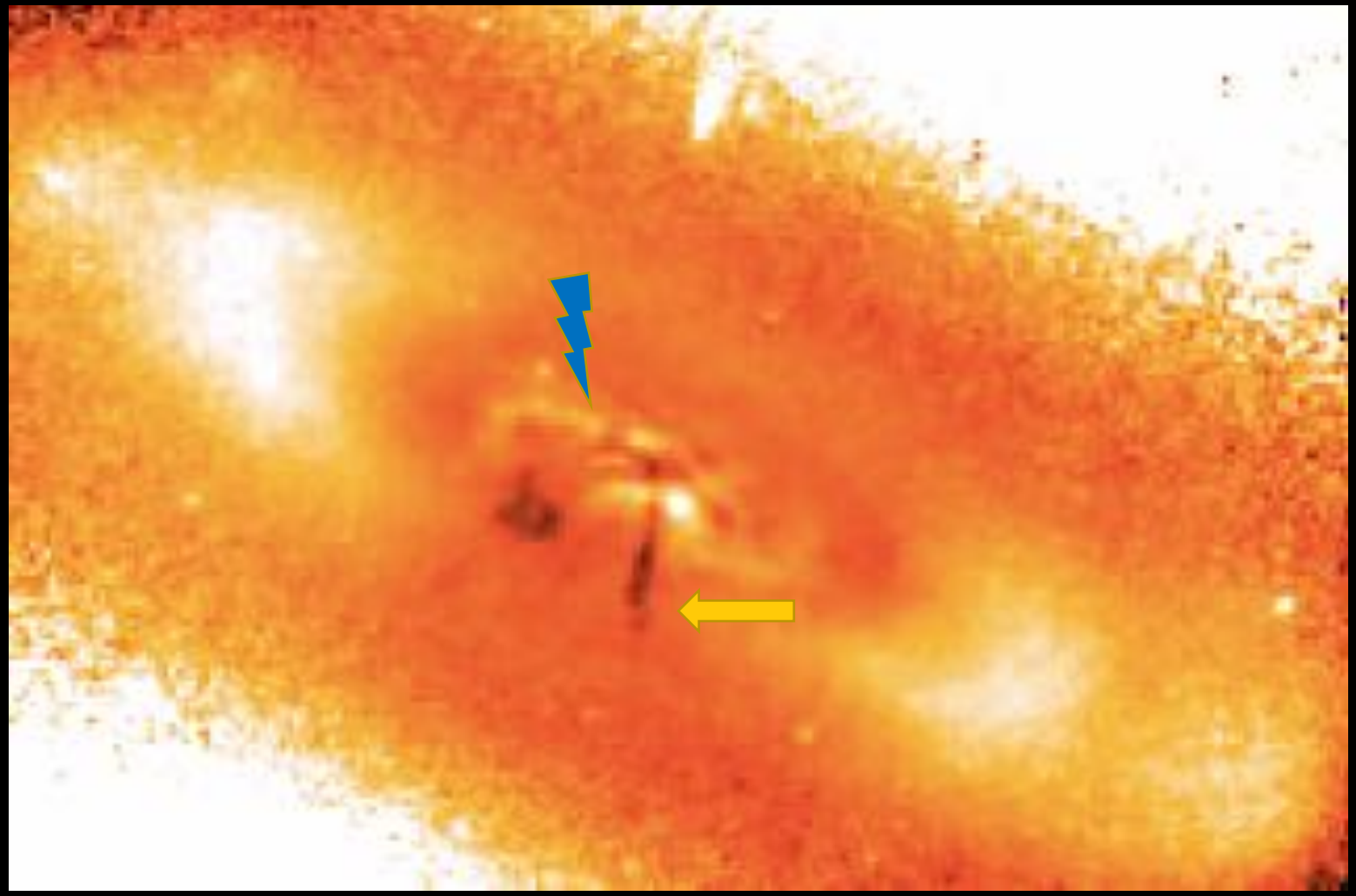




Model NIR HST images via simple GALFIT solution: approximate smooth light distributions



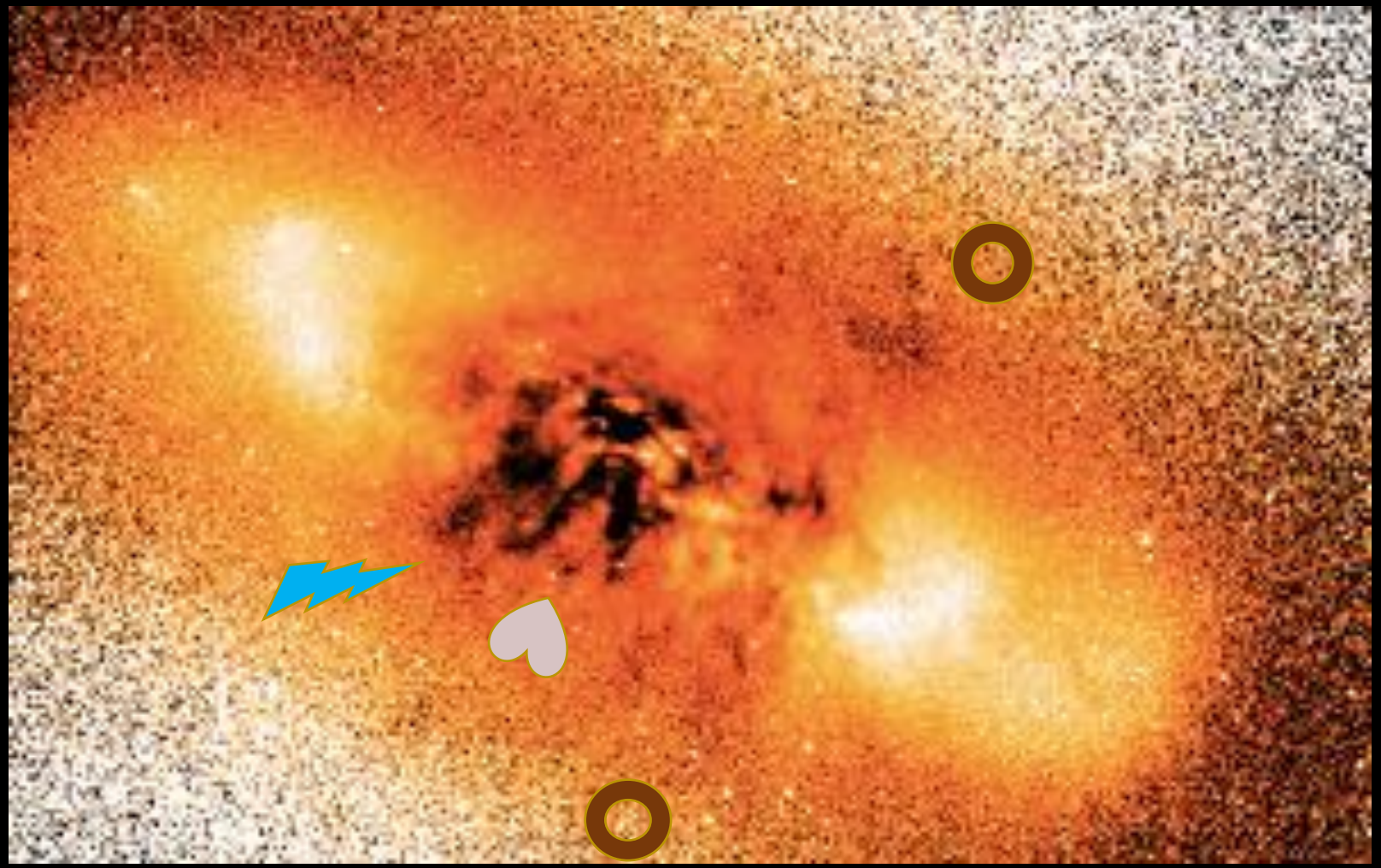
Ratio of model to observed image reveals small scale structures (& errors since the models aren't perfect!).



F125W Ratio Image: Tourist Guide

- "Nick's pillar" (arrow)
- High opacity regions, $N \gtrsim 10^{23}$ cm^2
- Inner arms (SF Lightning strike))
- Smooth disk

Zw049 F555W Ratio model [τ(V) ≈ 4.5 τ(F125W)]

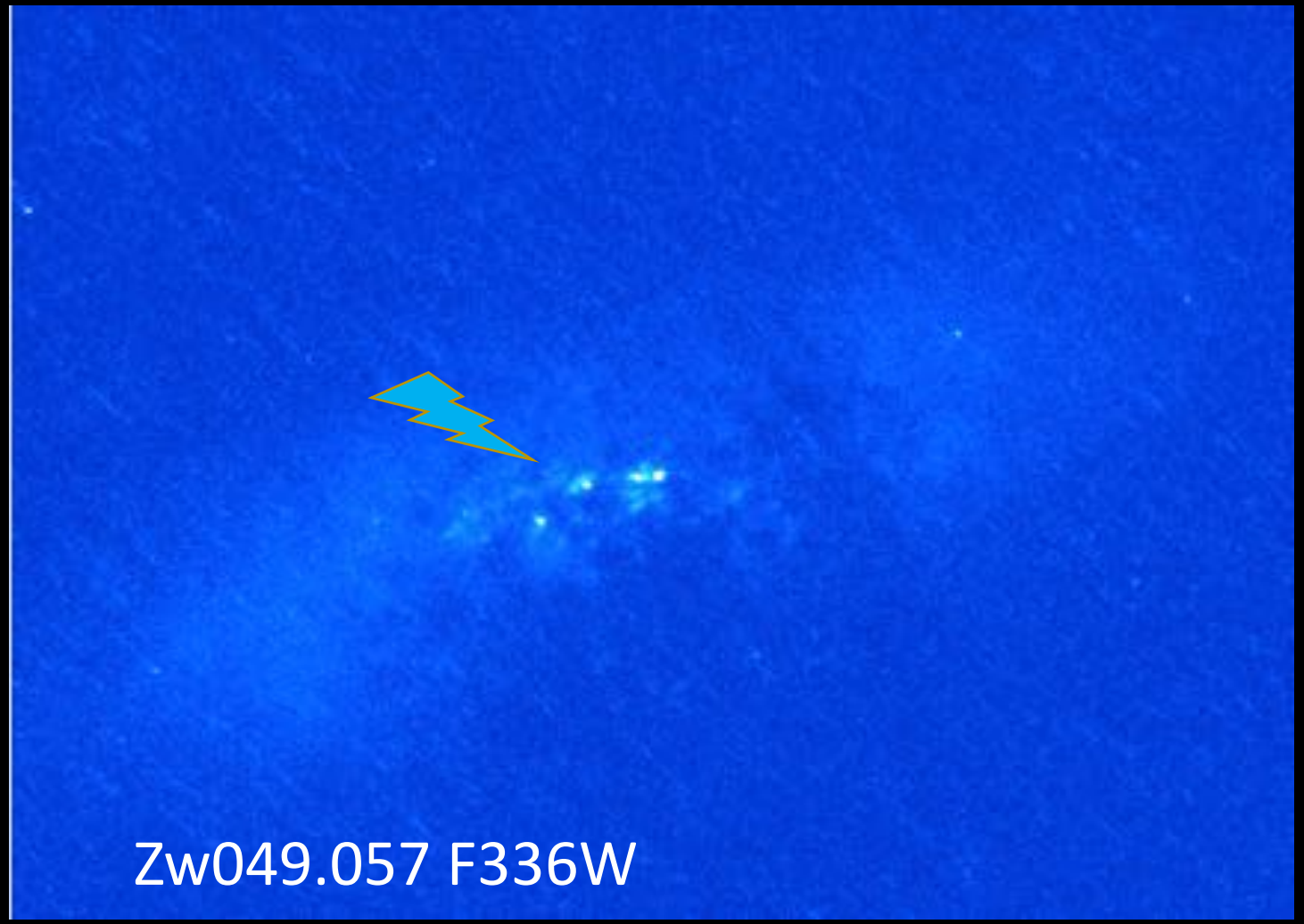


Polar gas disk

Outflow cone or dust jets?

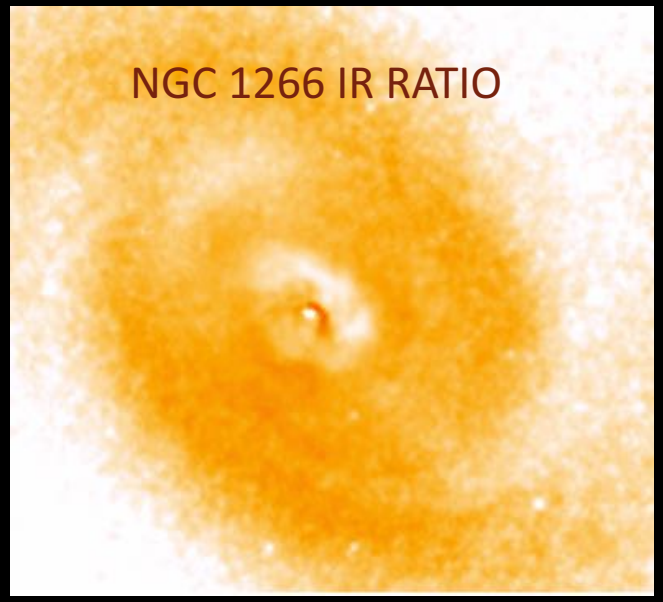
Starburst wind?

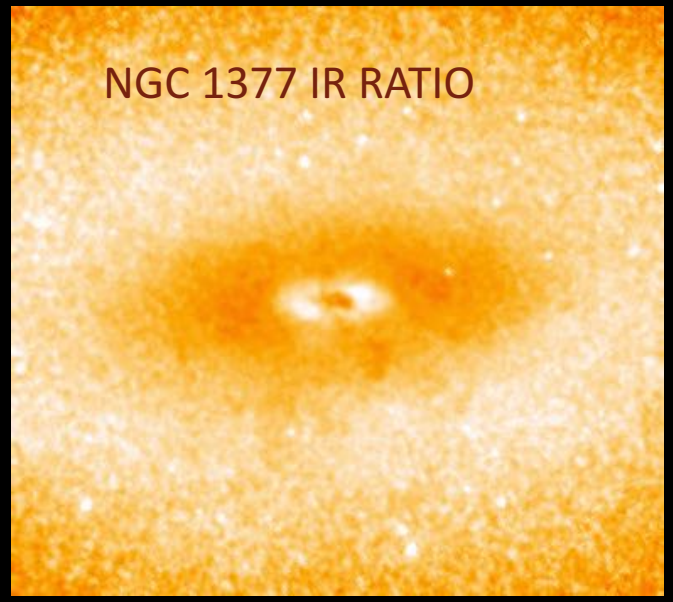
Young(ish) stellar populations exist

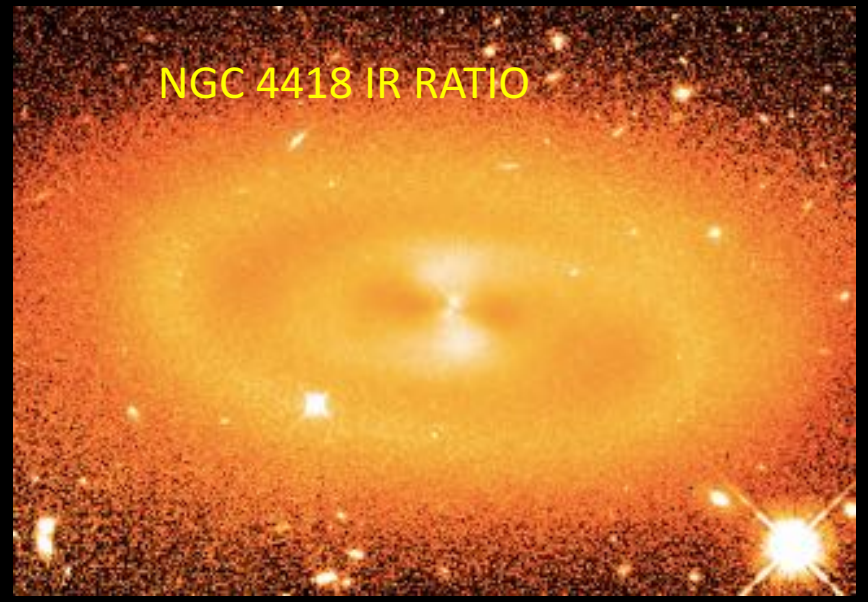


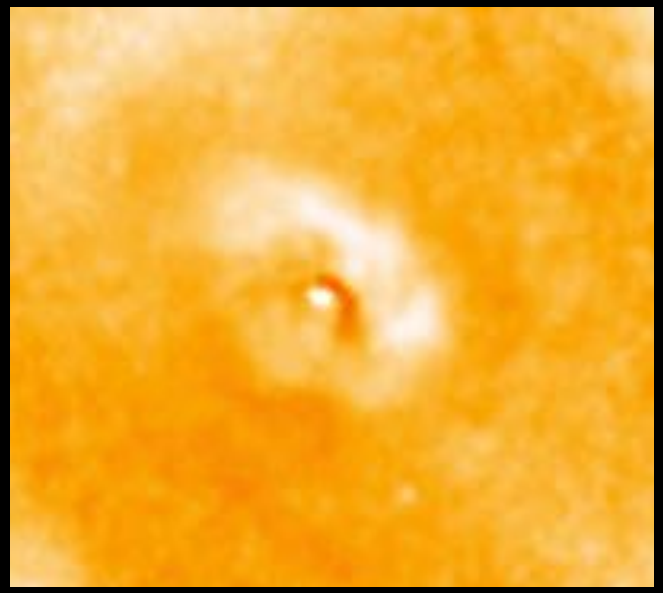
Characterizing the Core S0/a Group

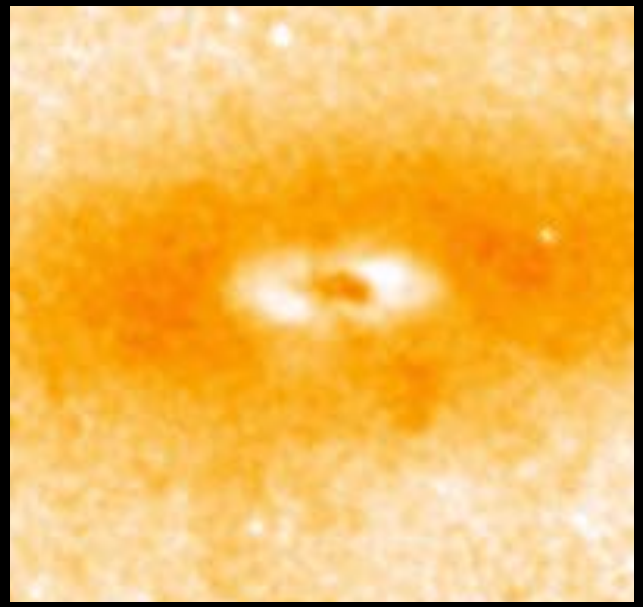
- HST GO Imaging JSG+ (NGC1377, NGC4418, Zw049.057), *Katy Atalolo+ (NGC1266, IC860).*
- "Wisconsin" team: JSG; Scientists: Tova Yoast-Hull (now CITA), Ralf Kotulla; Undergraduates Lauren Laufman (to U. Minnesota), Emily Geist (Juaniata College), Eowyn Yangyang Liu
- Structures: stellar substructures; dust absorption levels
  - Symmetric model light distributions to detect substructures—GALFIT models. NGC 1377 & Zw049.057

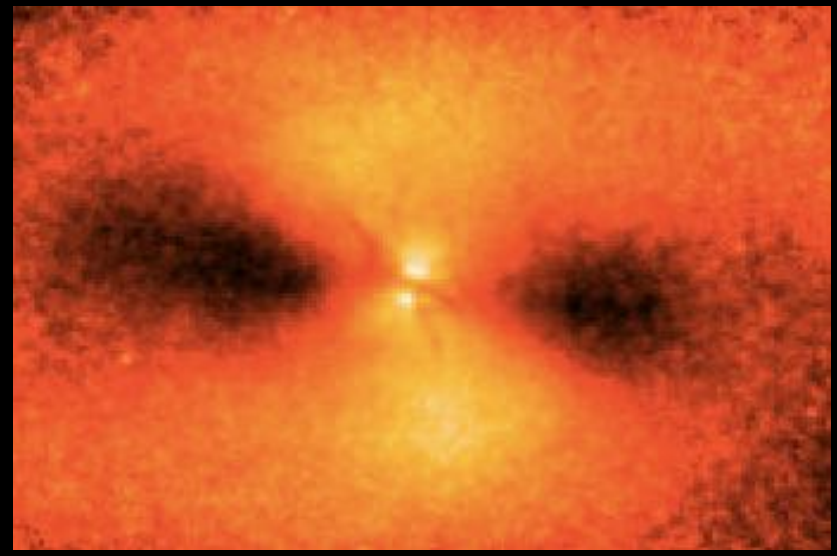

NGC 1266 IR RATIO


NGC 1377 IR RATIO

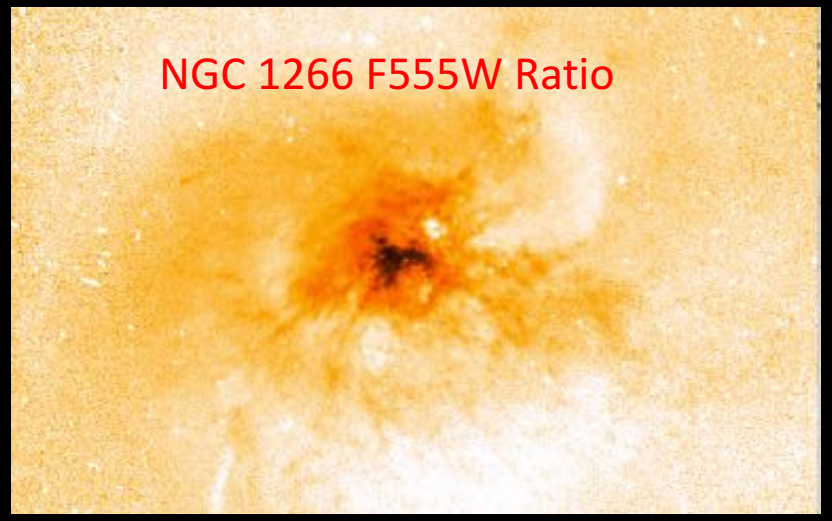

NGC 4418 IR RATIO



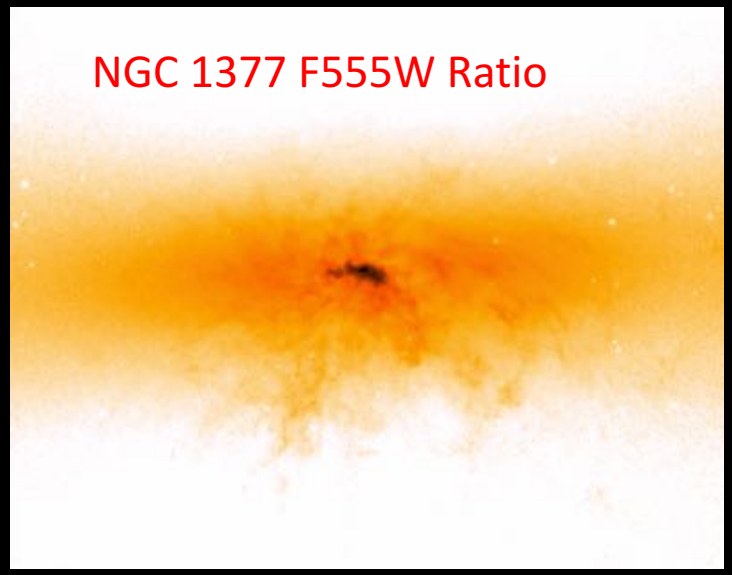




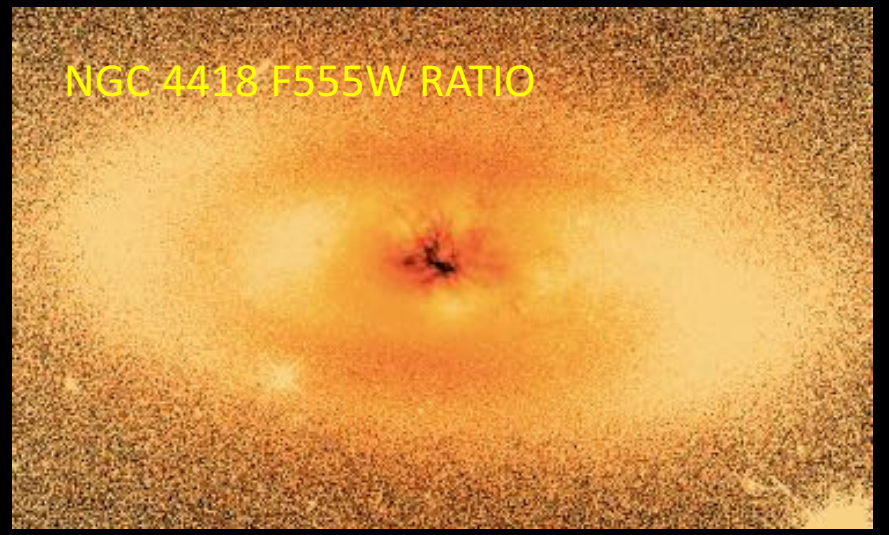
NGC 1266 F555W Ratio

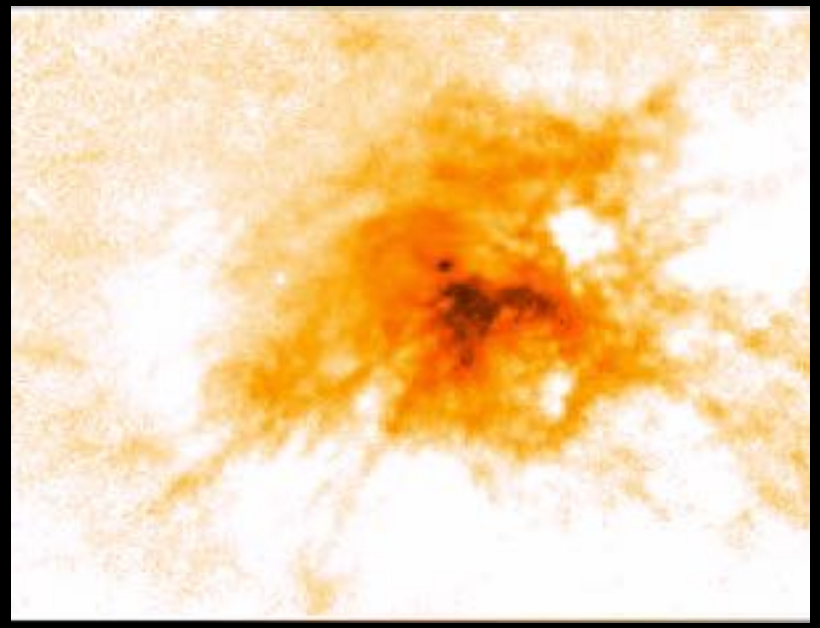


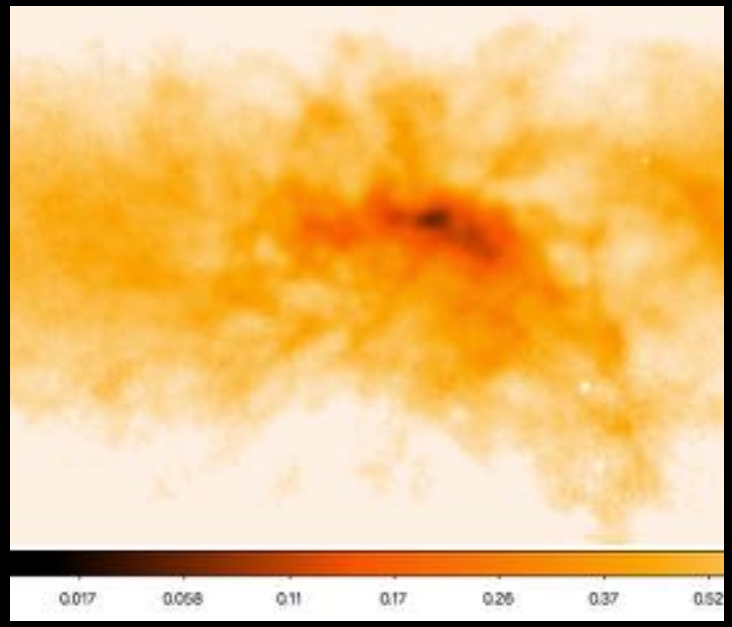
NGC 1377 F555W Ratio

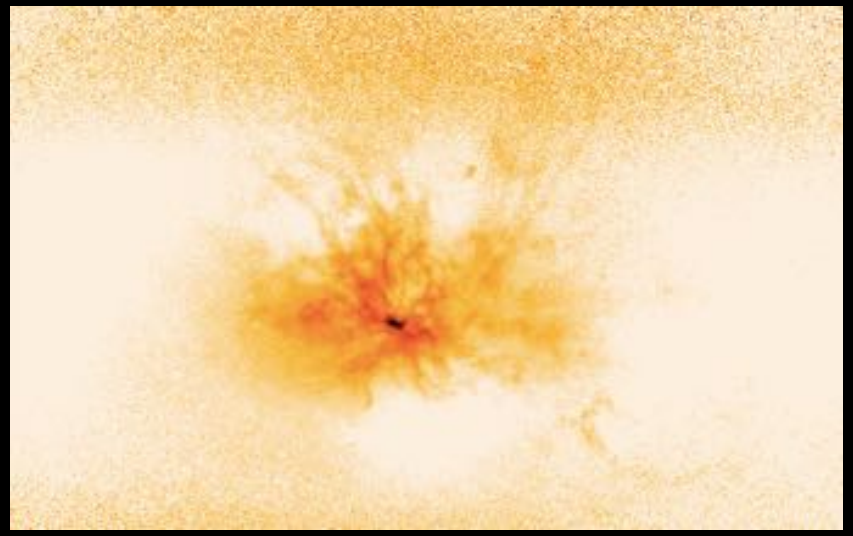


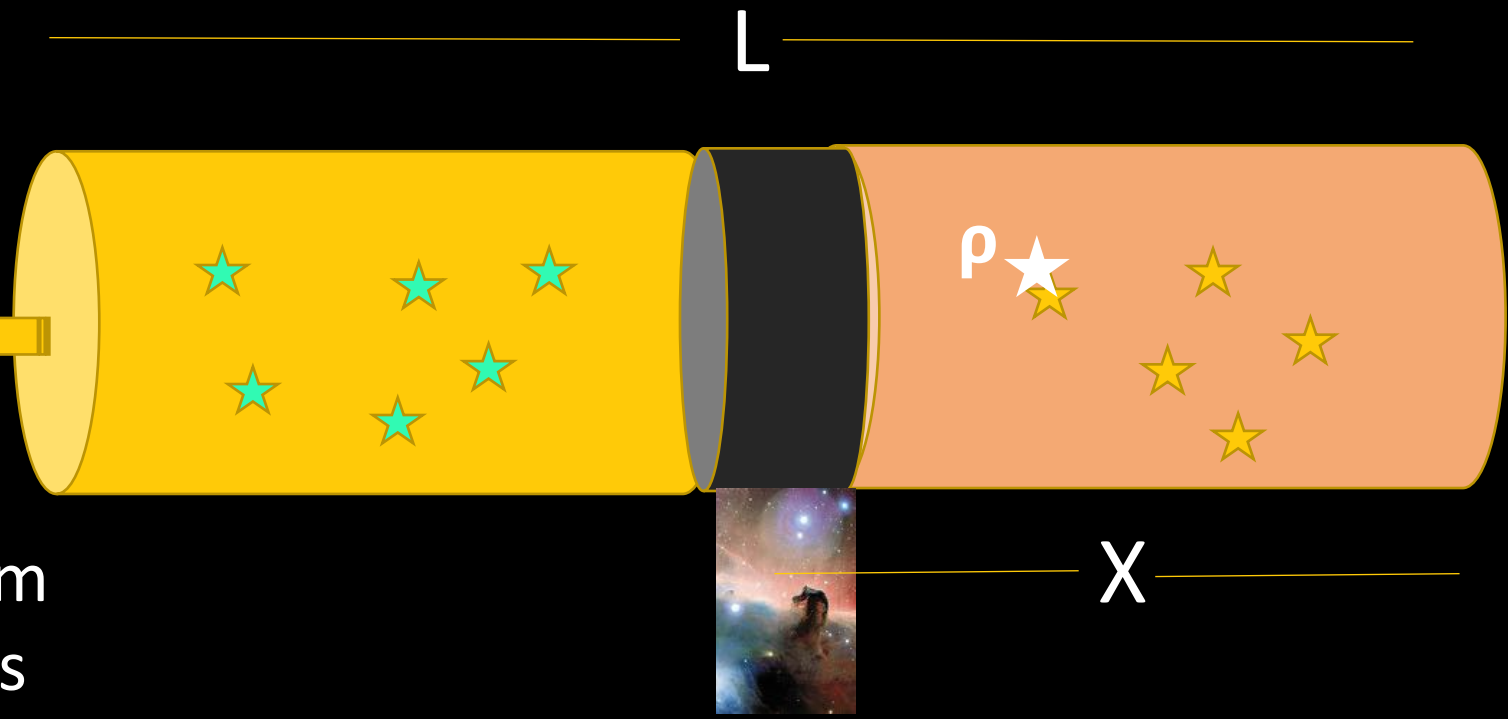
NGC 4418 F555W RATIO









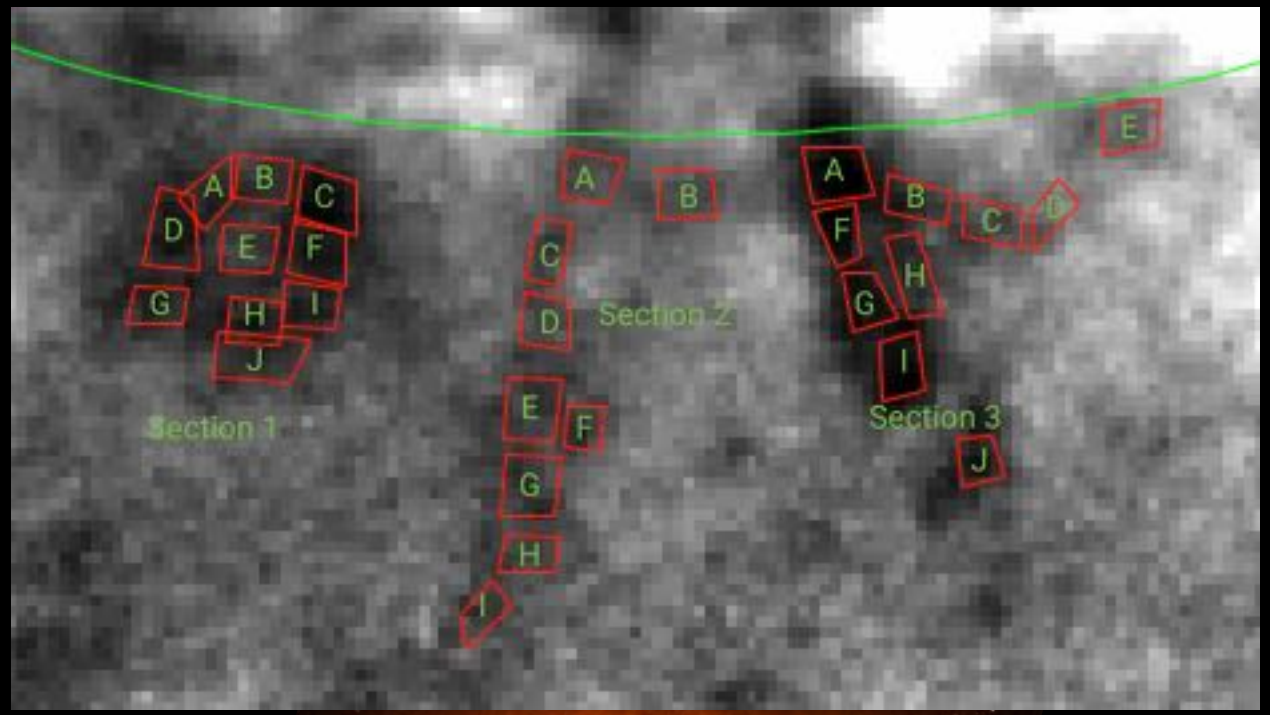


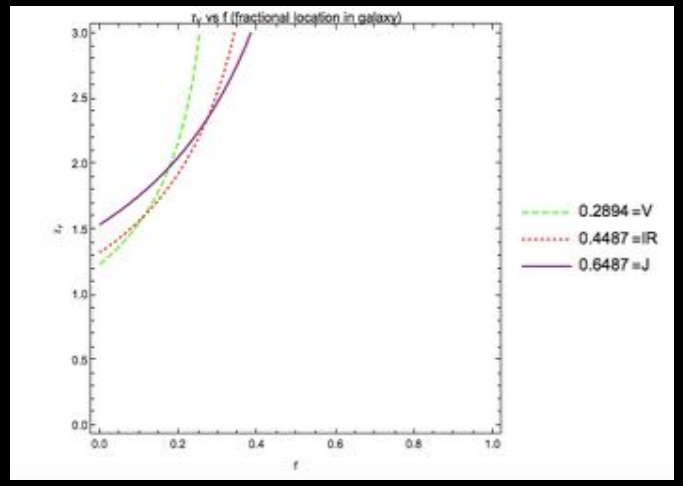
Ratio of $\tau(\lambda)$ from extinction curves

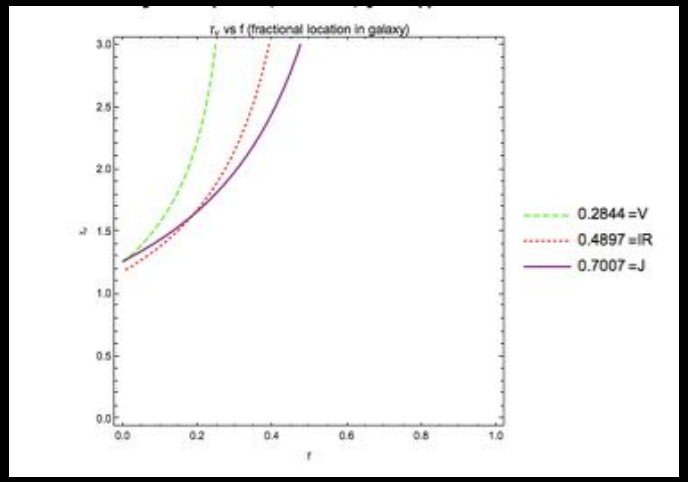
Multiple wavelengths solve for x and $\tau(V)$
→ N_{gas}

$$I_{obs\ \lambda} = S_{\star\ \lambda}(L\text{-}X) + (S_{\star\ \lambda}\ X)e^{-\tau(\lambda)}$$

Example: Zw049 (Gallagher, (Laufman)+ in prep)





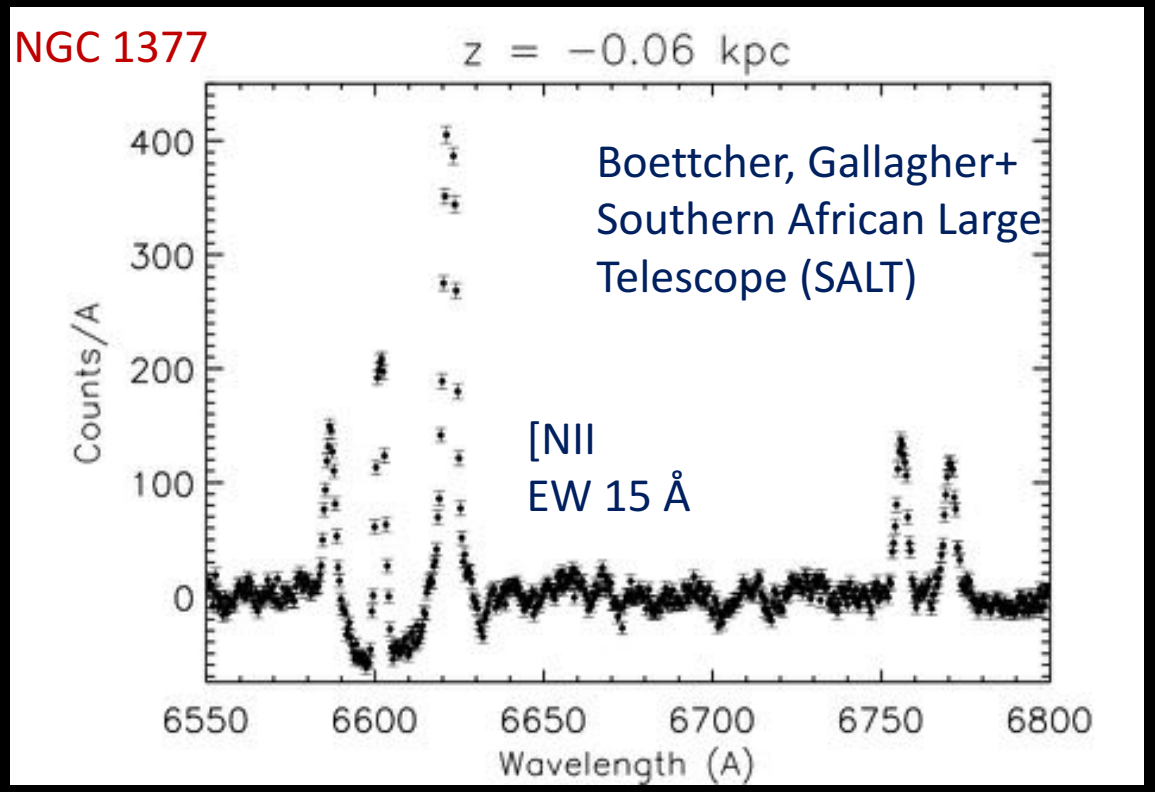


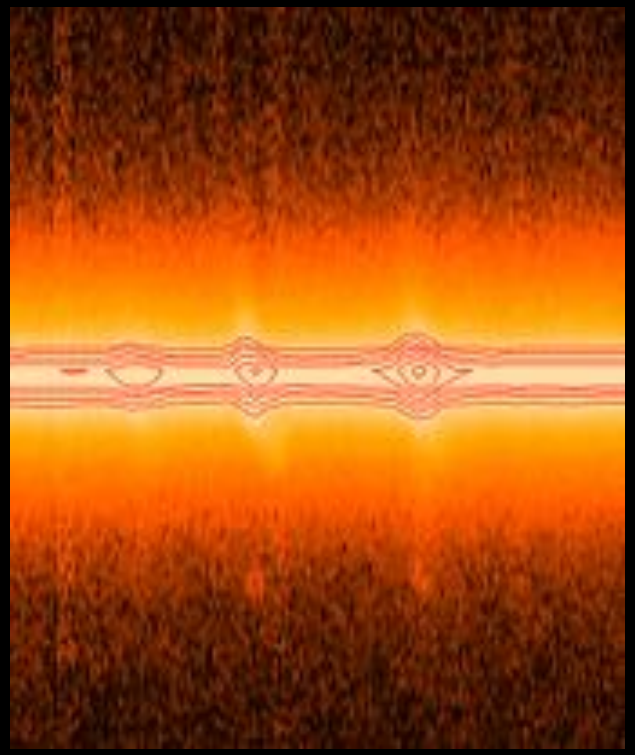
Results

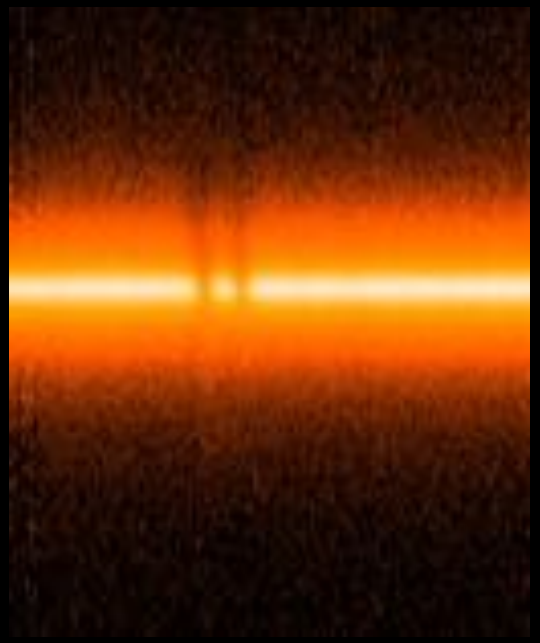
- $N(H \cong \tau(V)(2E21)$ cm^{-2} Low density Galactic. Better Choice?

- Depth of feature = projected size (spherical cow approximation)
- Results likely underestimates—only dense gas, model ignores scattering, etc.
- Nick's column in Zw049 $M_{gas} \geq$ 2-10E6 Msun
- Dust columns contain substantial mass, but likely ~10% of inner molecular mass in discreet features
- Total masses in outflows difficult to estimate

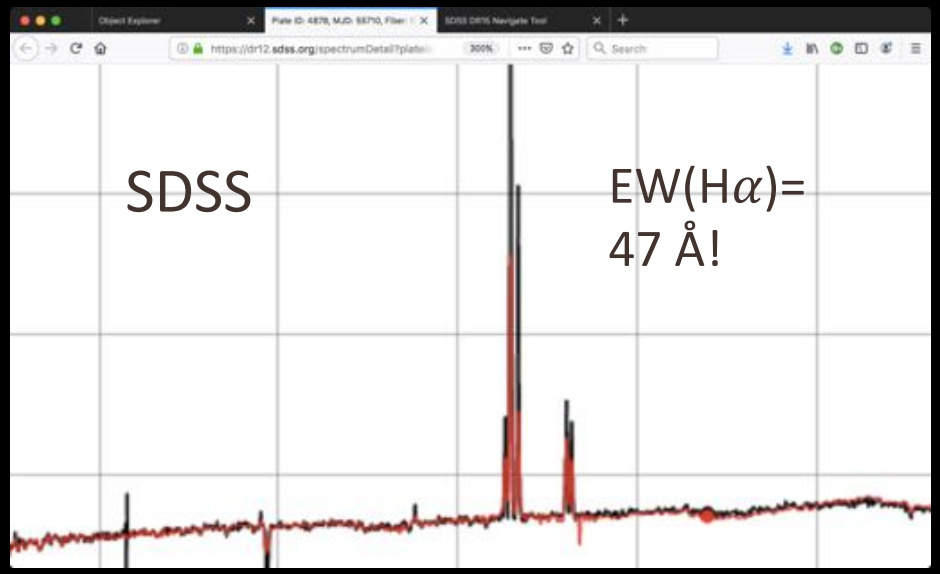
Spectra & Evolutionary Phases







Spectra & Evolutionary Phase: Zw049.057



Starburst CMZ?

Preliminary Results

- Early--type hosts of obscured nuclei show evidence for past interactions in terms of structures and in some cases post-starburst spectra. → ~Gyr time scales.
- Bipolar dusty winds appear to correlate with presence of obscured nuclei. These features are rare in early-type galaxies → important phase of rapid evolution. Possibly in systems where star formation was previously dying?
- Winds appear to be multi-phase but cool (NaD absorption, HII emission) and slow (see also excellent spectrscopic study of NGC 4418 by Ohyama+ 2019, ApJ
- Outflows may contain few-10% of central molecular mass in the form of dense gas; total mass likely substantially higher.
- Structures suggest both starburst and AGN wind components could be present.
- NEXT steps: Zw049 pilot paper in prep; analysis of HST imaging sample under way; SALT spectra obtained for NGC 1377 & Zw049, ….

NGC 1266 & NGC 4418 HST