The Mystery of Dust in Early-Type Galaxies

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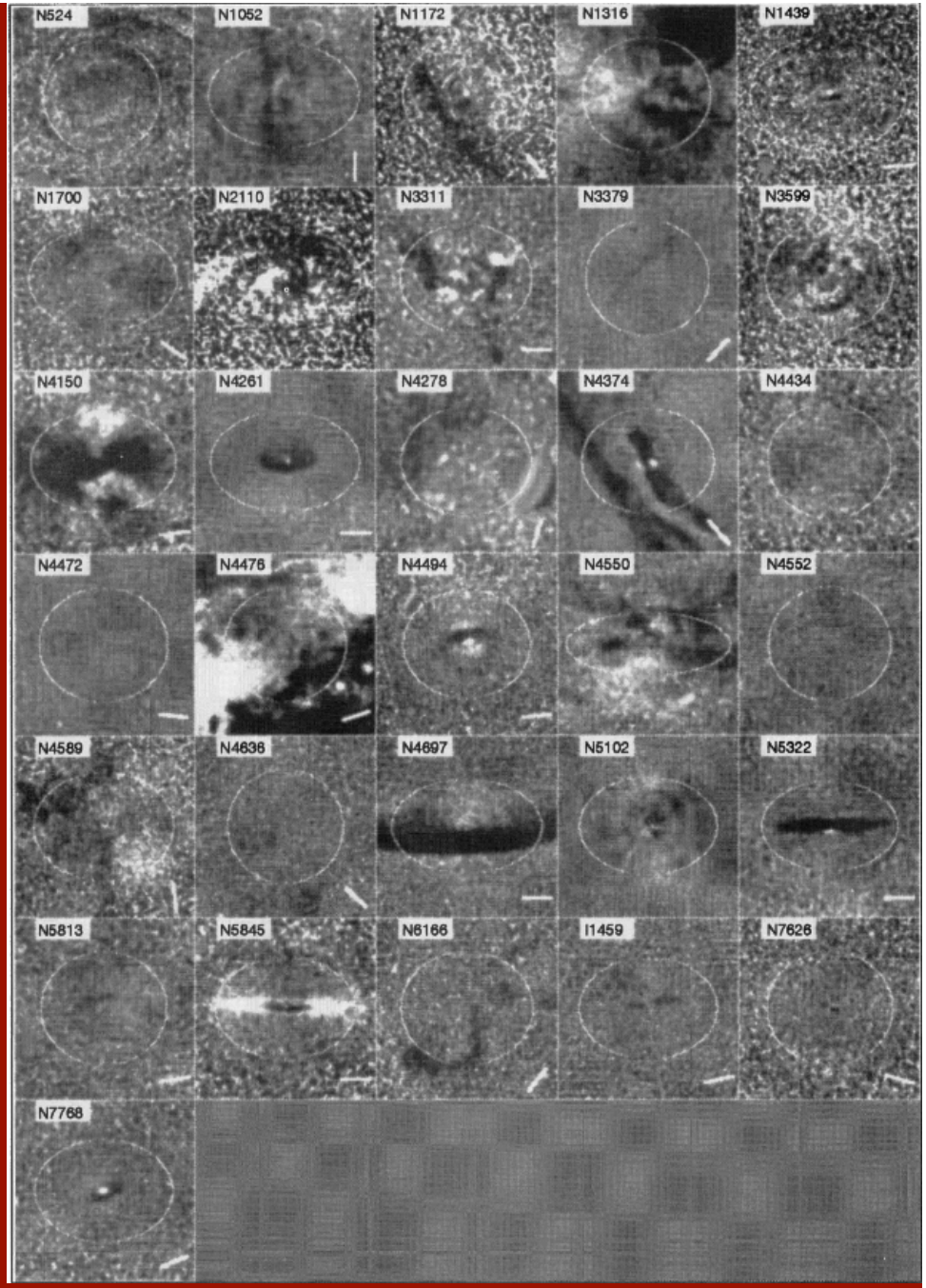
Discovery

- A few, spectacular examples were well known
- Dust quite common in HST images (~50%)
- Dusty ellipticals also tended to be AGN



van Dokkum & Franx (1995)

Creation and Destruction

Creation/Growth:

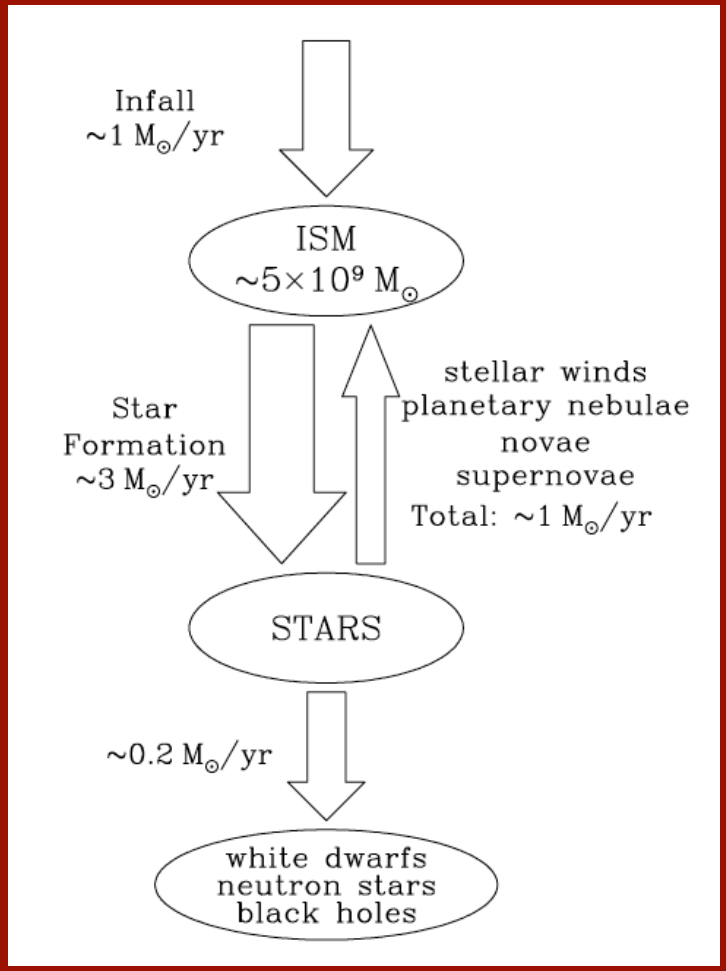
- Evolved stars
- Supernovae
- Cold, neutral ISM

Destruction:

- Supernovae
- Sputtering
- Grain-grain collisions

(τ_{dust} ~ 0.4 Gyr)

Baryon Budget for our Galaxy



Draine (2009)

Dust in Early Types

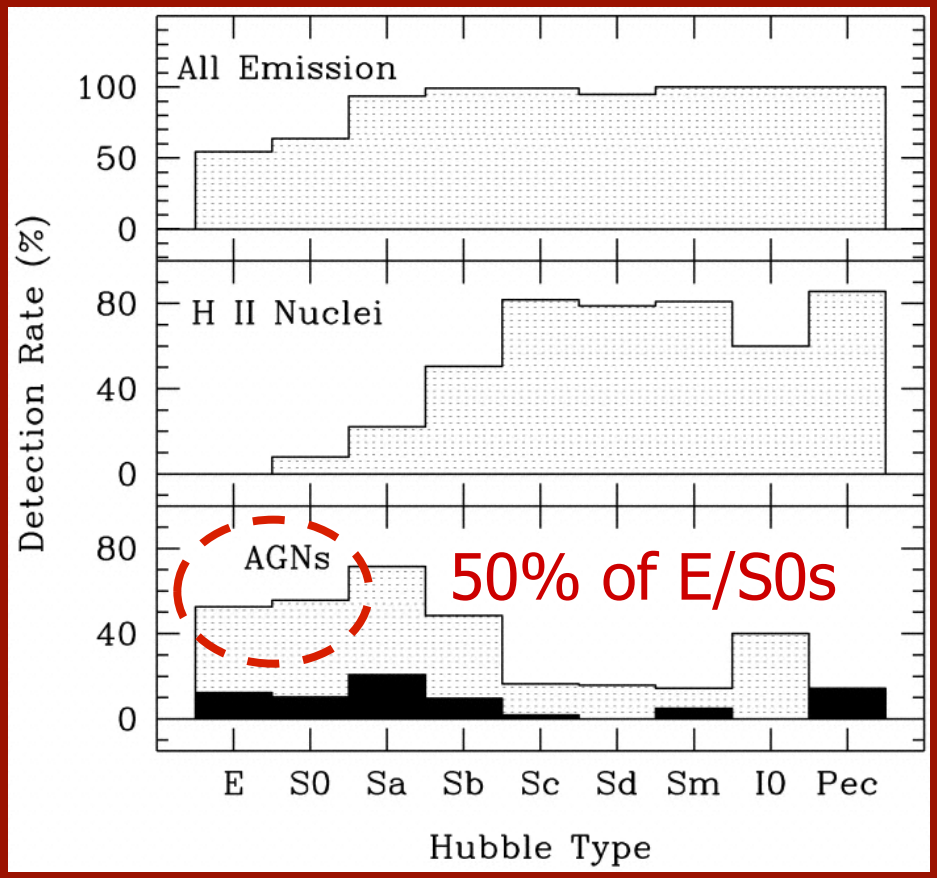
Creation/Growth

- Dust formation in stellar winds
- Supernovae (mostly Type Ia)?
- Not much (or no) cold, neutral medium
- External accretion of gas-rich satellites

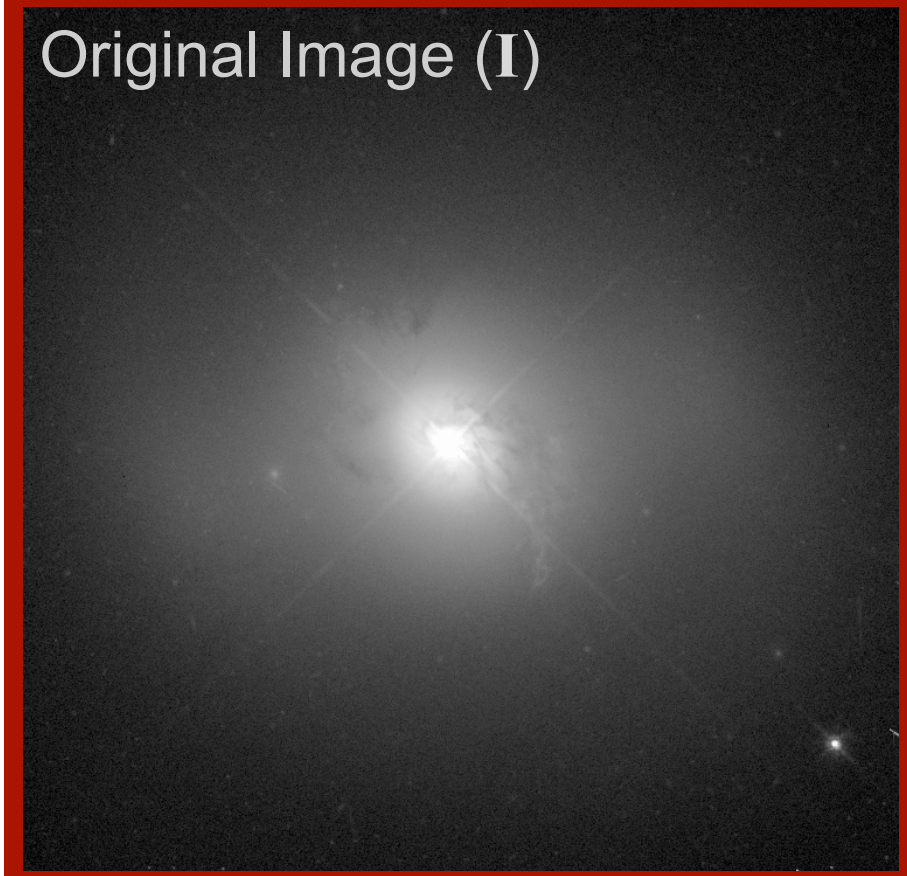
Destruction

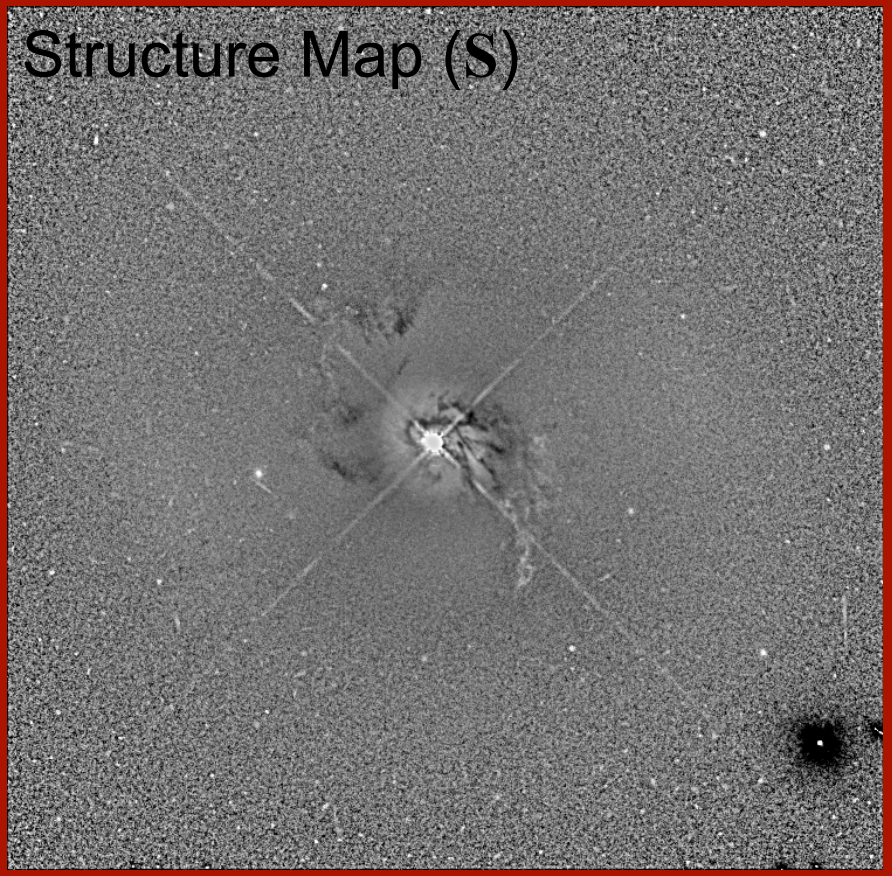
- Sputtering

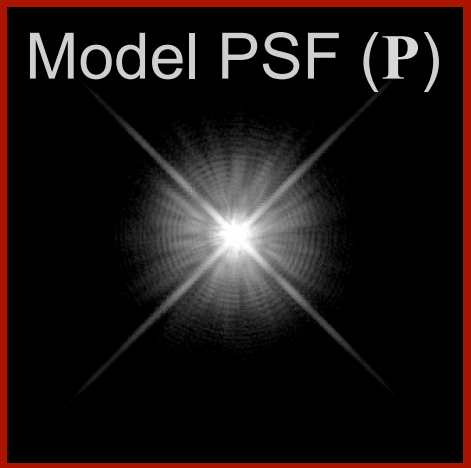
Demographics



Ho et al. (1997)



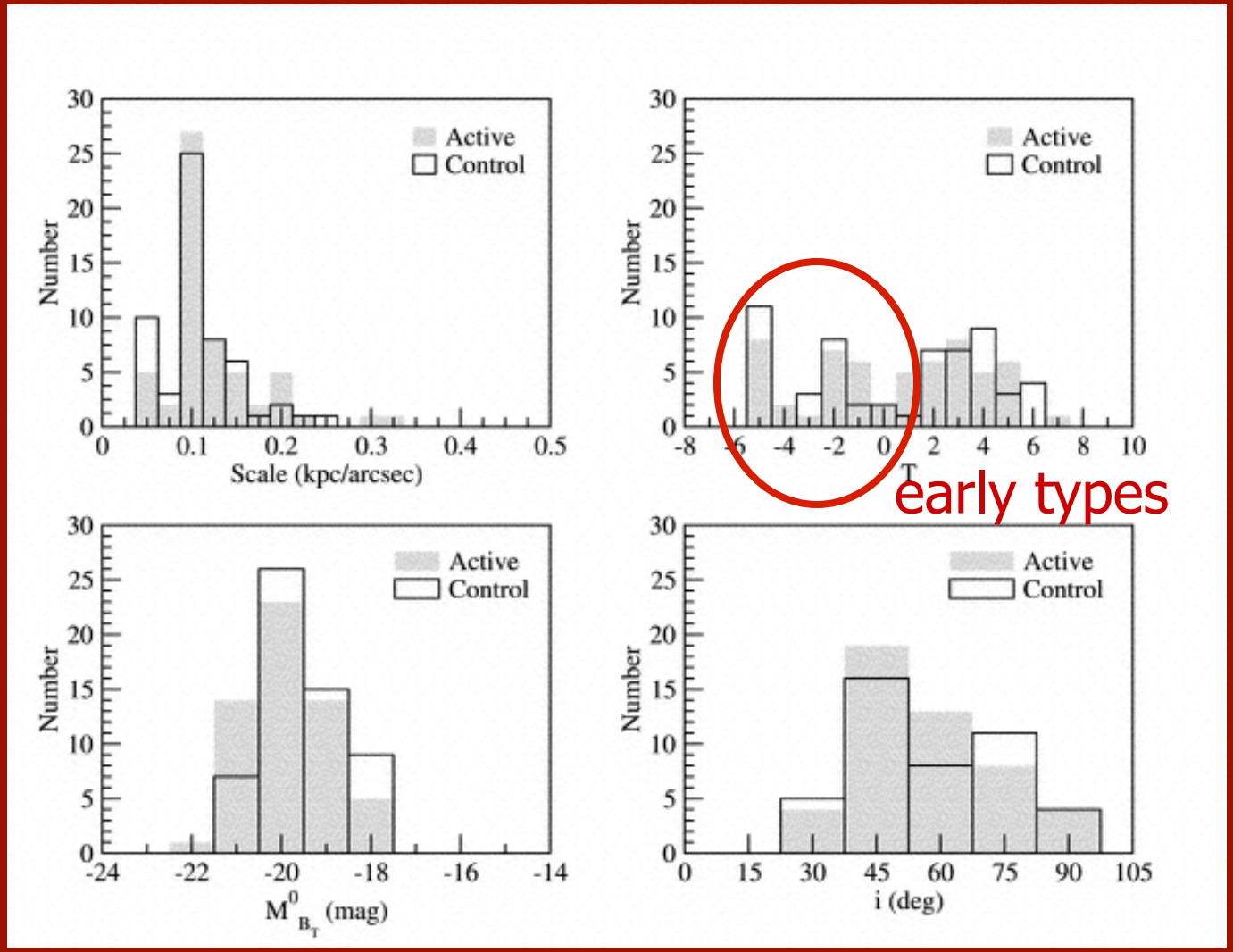




$$S = \left[\frac{I}{I \otimes P} \right] \otimes P^t$$

Pogge & Martini (2002)

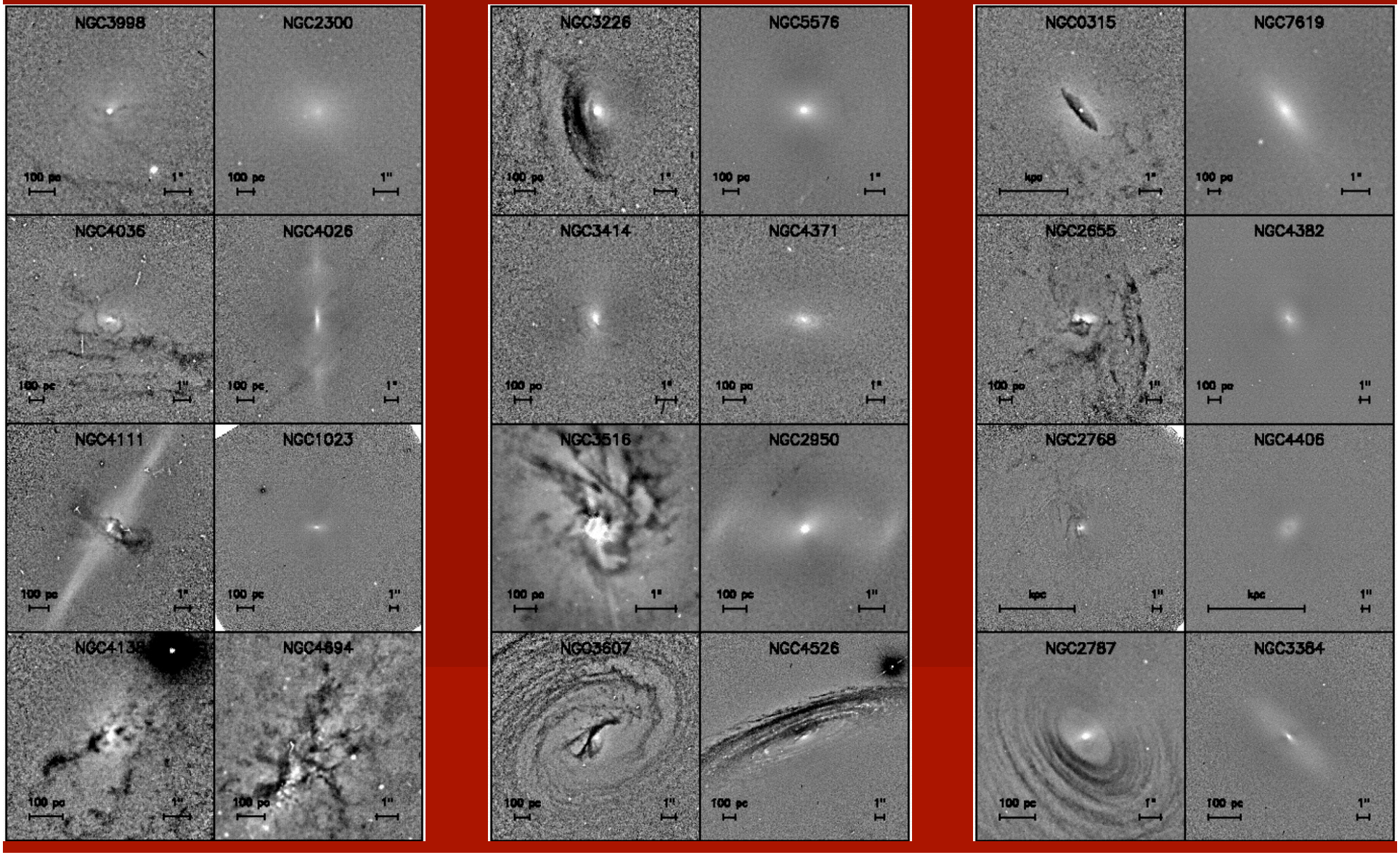
HST Observations



Simões Lopes et al. (2007)

12 of 34 pairs

active	inactive	active	inactive	active	inactive
NGC3998	NGC2300	NGC3226	NGC5576	NGC0315	NGC7619
NGC4036	NGC4026	NGC3414	NGC4371	NGC2655	NGC4382
NGC4111	NGC1023	NGC3516	NGC2950	NGC2768	NGC4406
NGC4138	NGC4694	NGC3607	NGC4526	NGC2787	NGC3384



HST Results

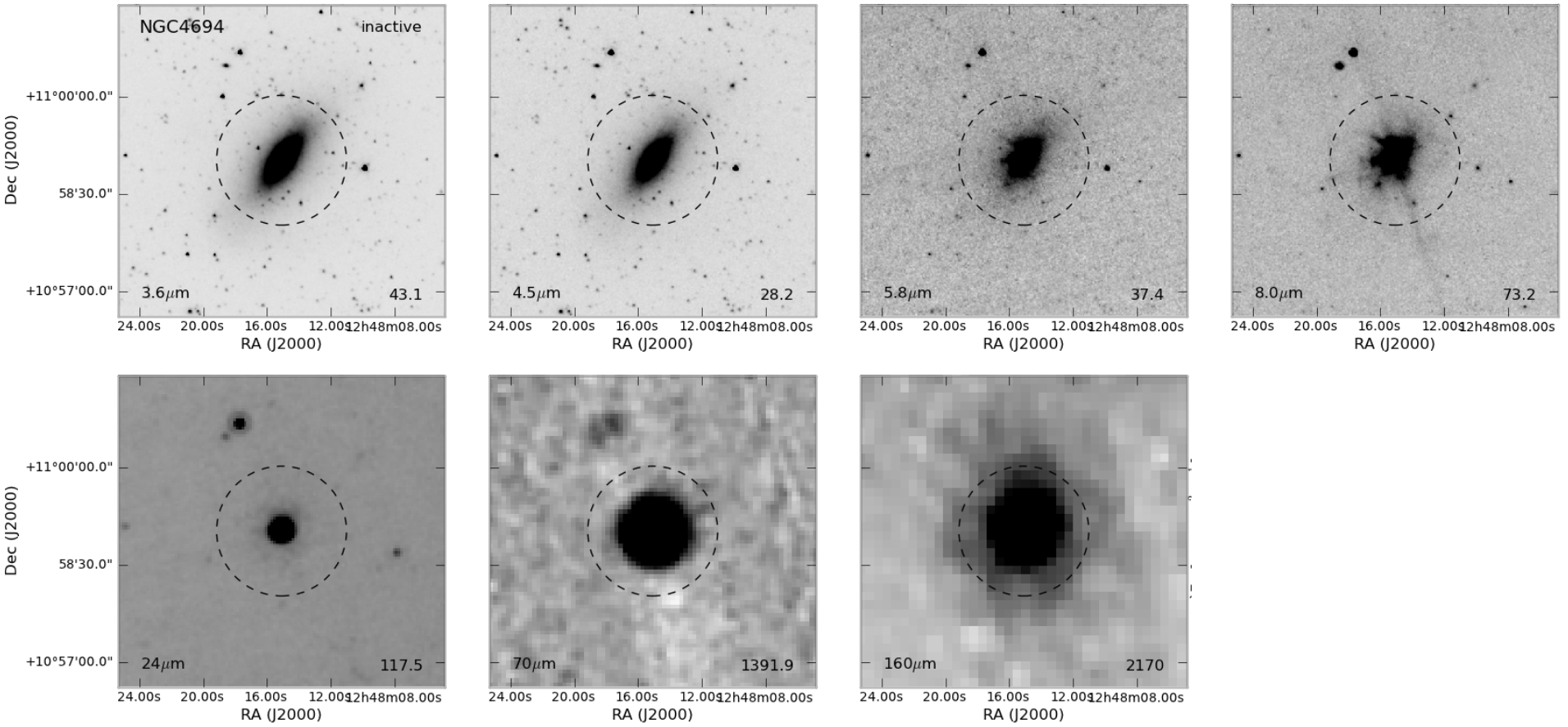
Observations of early-types show:

- 100% (34) of LINERs and Seyferts have circumnuclear dust
- 26% (9) of inactive galaxies have dust
- LINERs and Seyferts constitute ~50% of all early-type galaxies, so ~60% of early-type galaxies have circumnuclear dust

Where did this dust originate?
Is the presence of nuclear activity important?

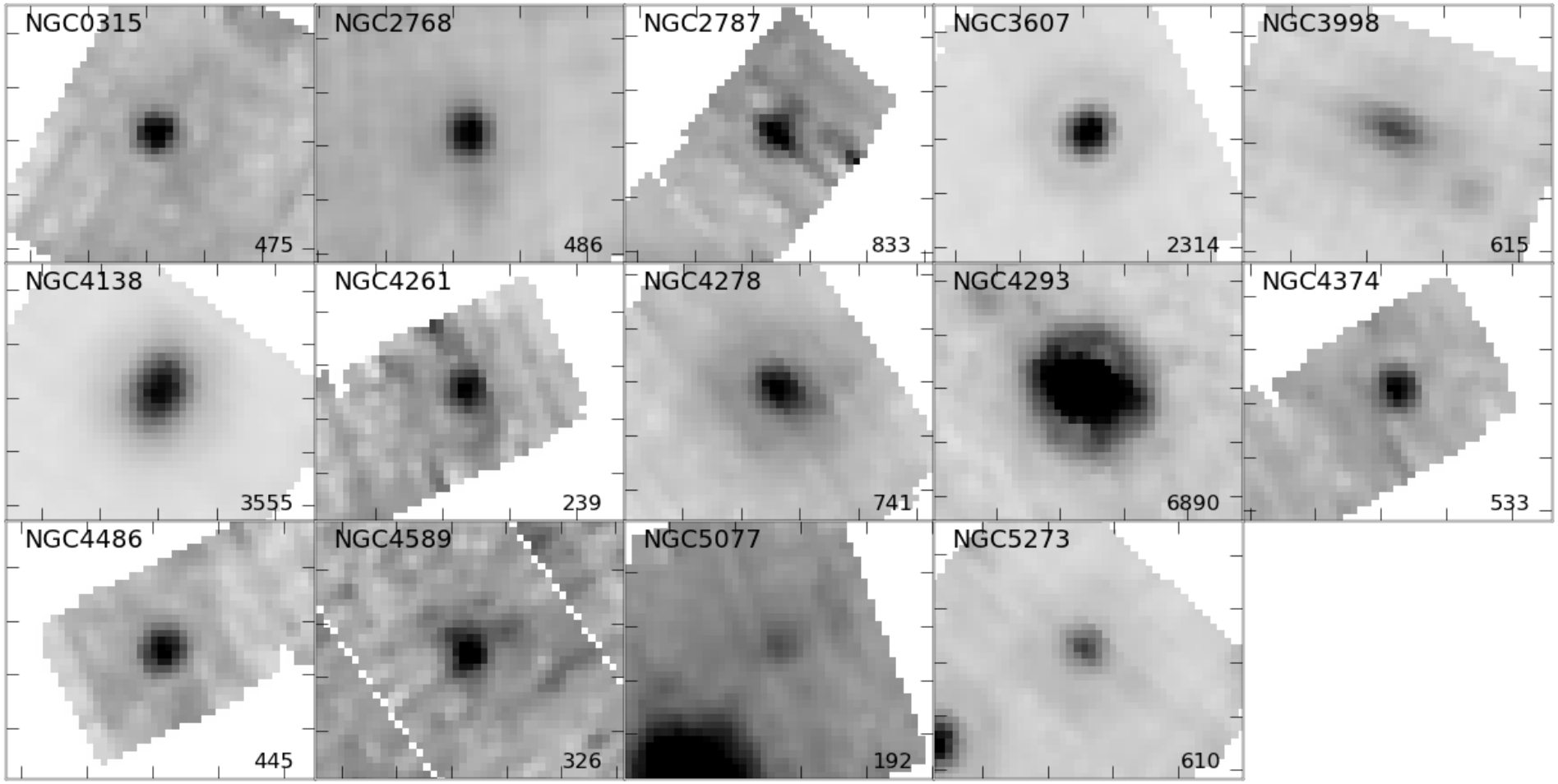
Spitzer Observations

3.6 μm 4.5 μm 5.8 μm 8.0 μm



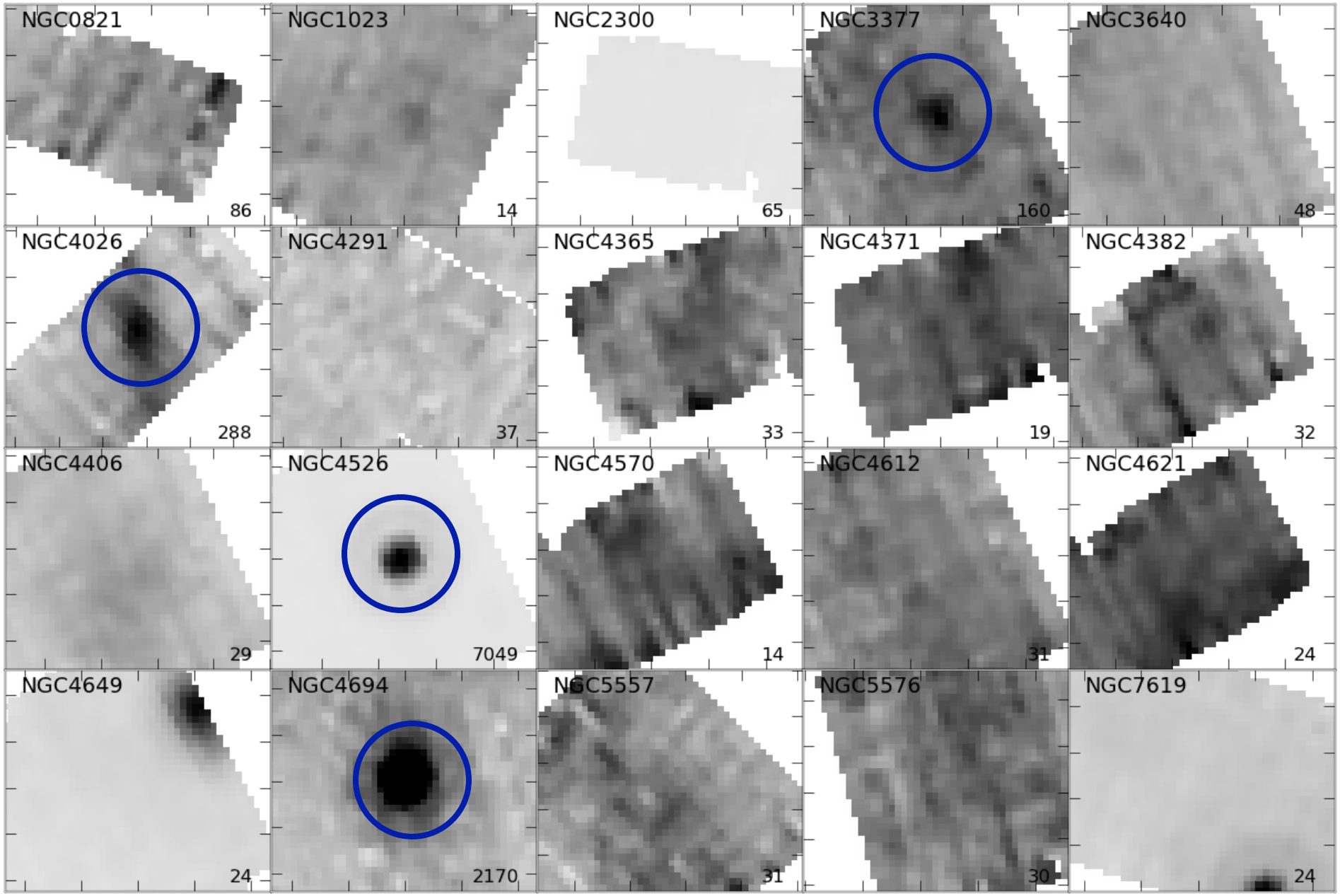
24 μm 70 μm 160 μm

Active Early-Type Galaxies at 160μm

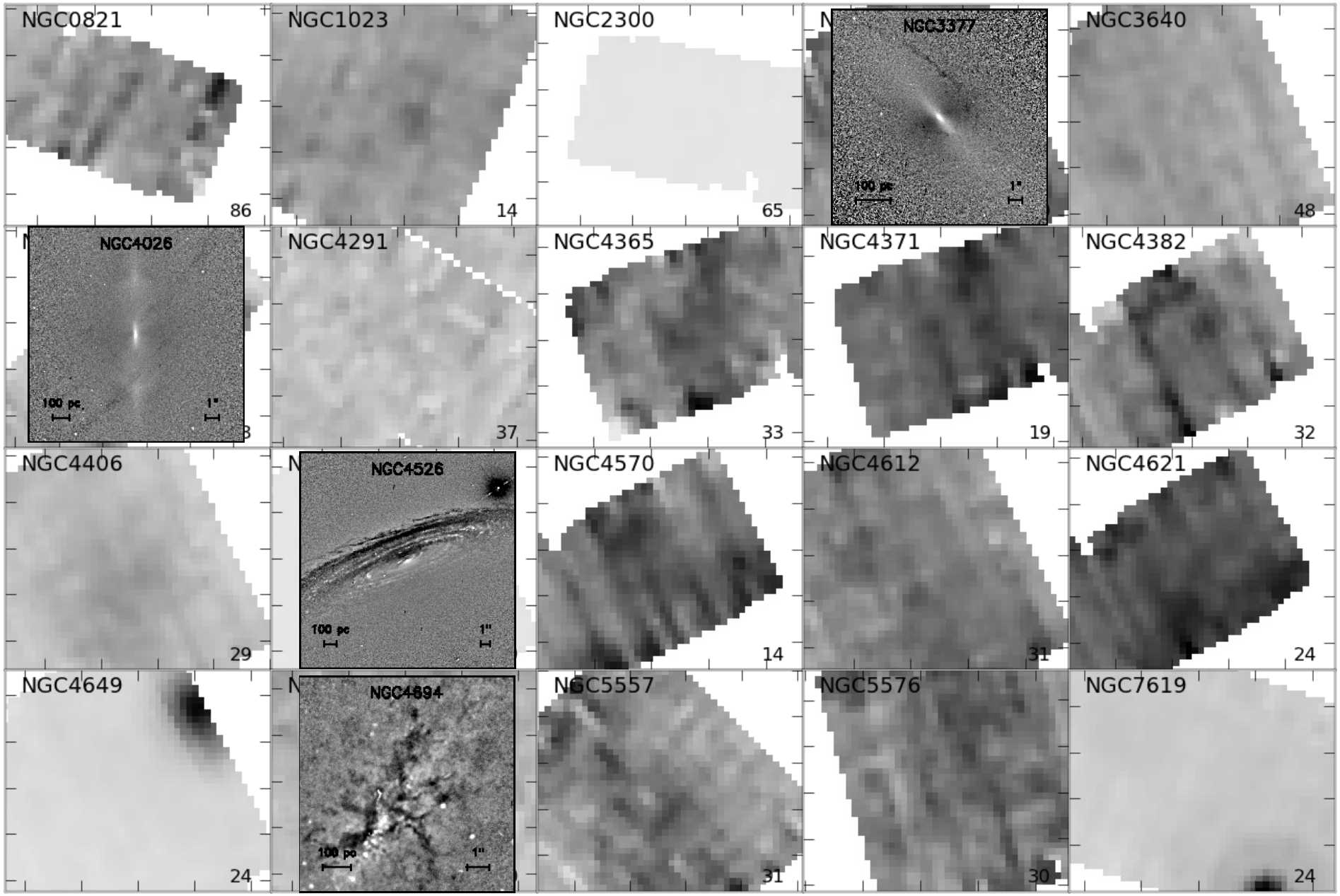


Martini et al. (2012)

Inactive Early-Type Galaxies at 160μm



Inactive Early-Type Galaxies



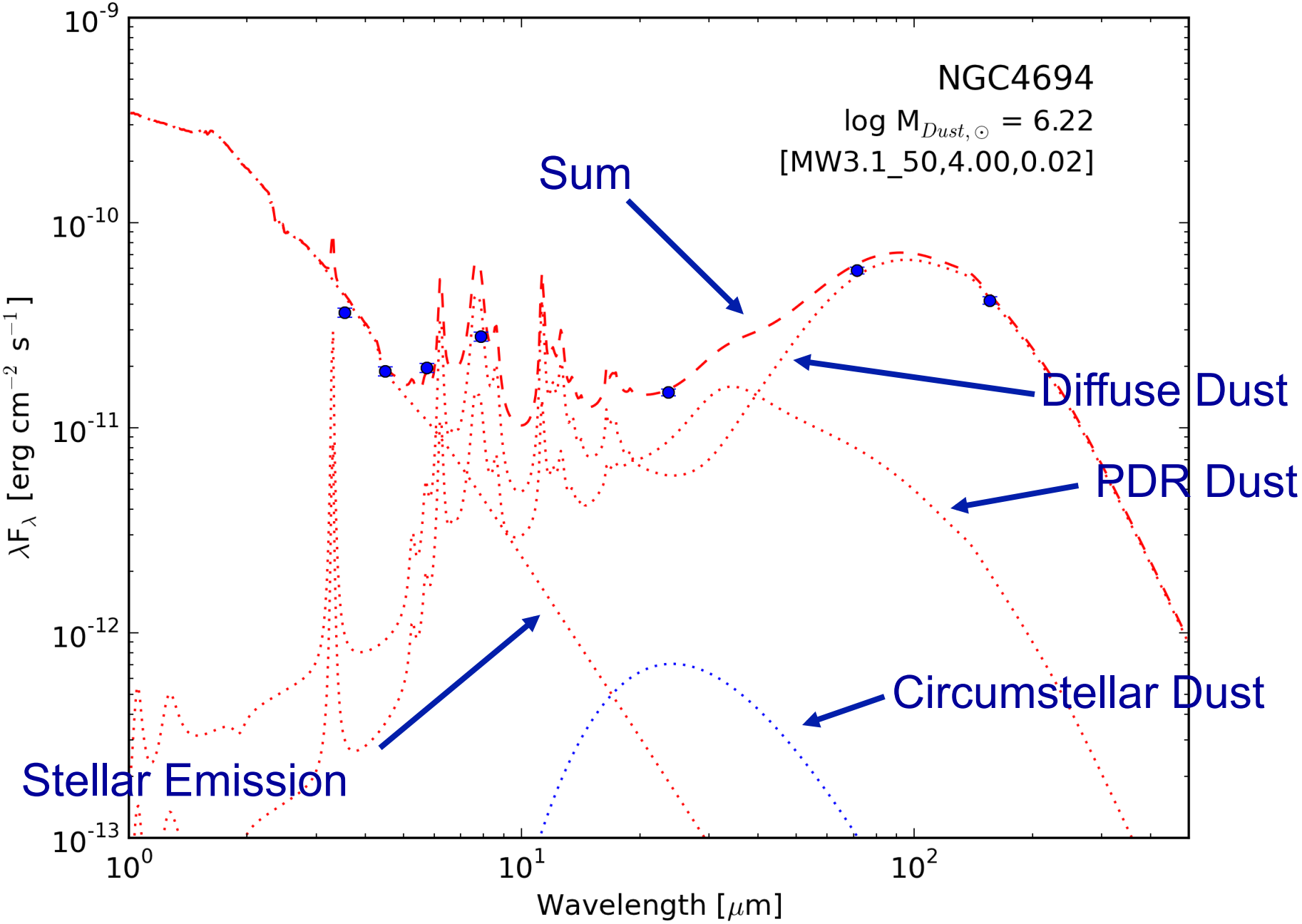
Dust Model

Parameters are:

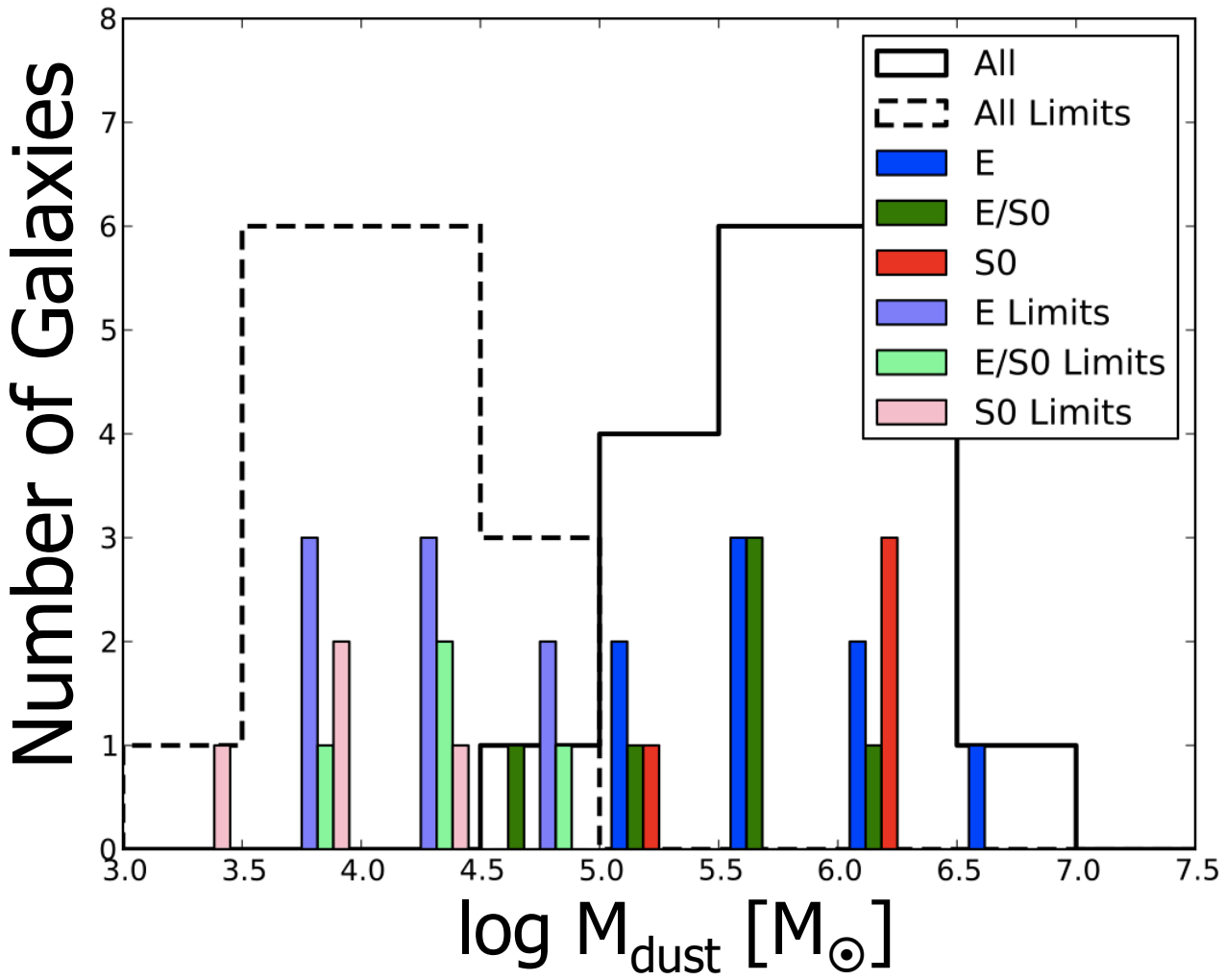
- U_{min} ISRF for diffuse component
- γ fraction exposed to higher ISRF
- q_{PAH} PAH fraction

$$M_{\rm dust} = \frac{\Psi}{\langle U \rangle} \left(\langle \nu F_\nu \rangle_{24} + \langle \nu F_\nu \rangle_{71} + \langle \nu F_\nu \rangle_{160} \right) D^2 .$$

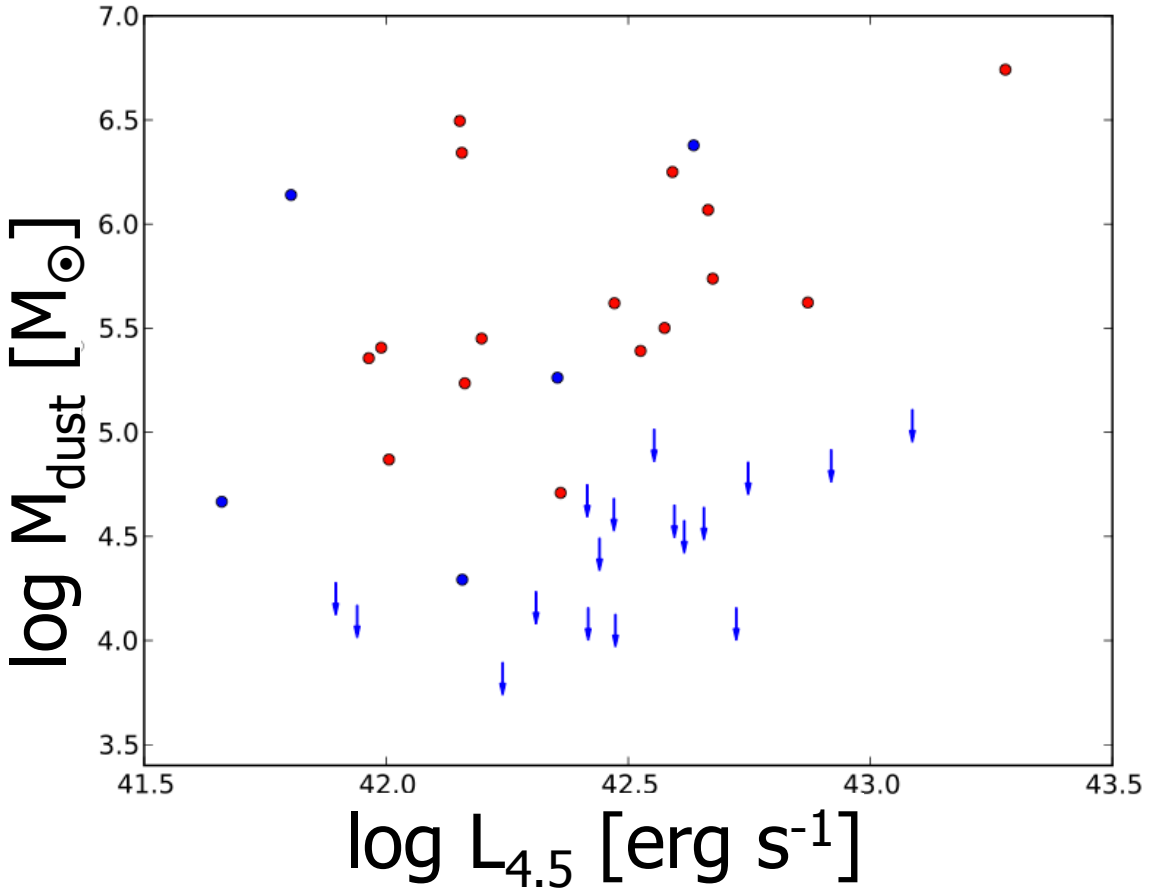
Draine & Li (2007)


NGC4694
log $M_{Dust,\odot}$ = 6.22
[MW3.1_50,4.00,0.02]
Sum
Diffuse Dust
PDR Dust
Circumstellar Dust
Stellar Emission
λF_λ [erg cm^{-2} s^{-1}]
Wavelength [μm]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{0}
10^{1}
10^{2}

Dust Mass Distribution

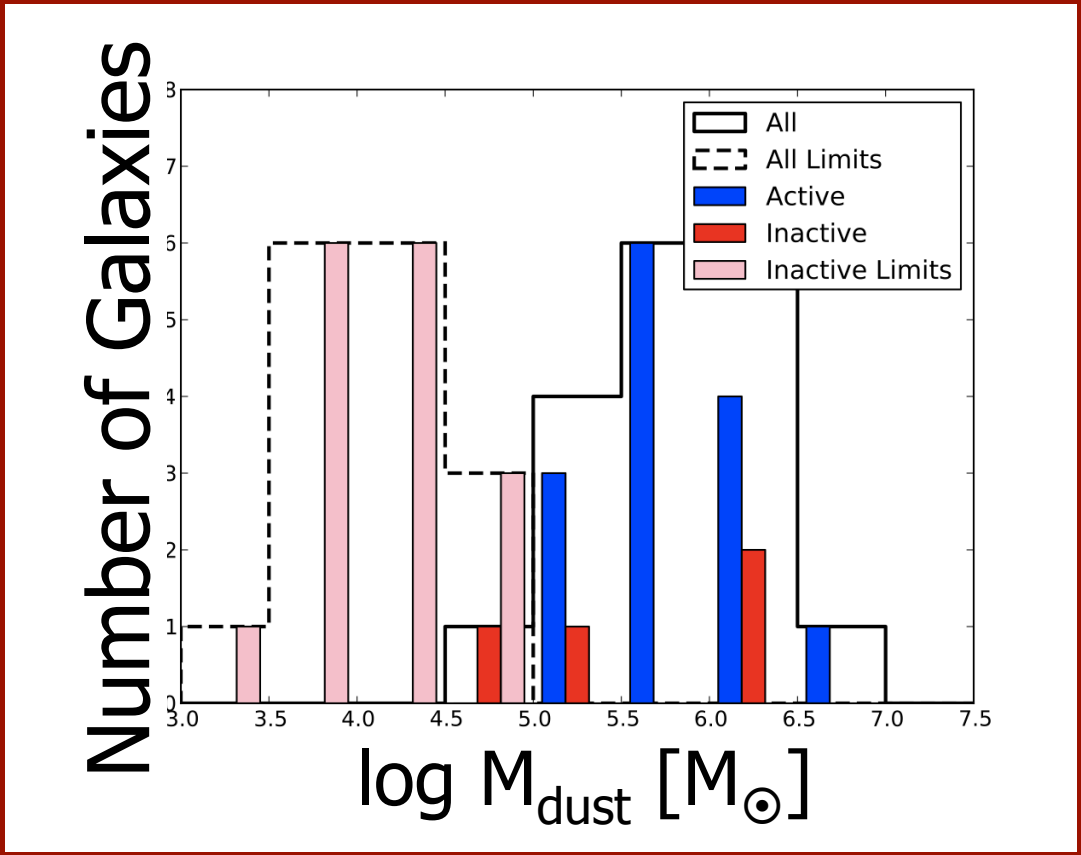


Dust Destruction Time



$$\tau_{\rm dust} < 2\times10^{7}\left(\frac{M_{\rm dust,lim}}{10^{4}}\right)\left(\frac{0.1}{\dot{M}_{\rm gas}}\right)\left(\frac{0.005}{\varepsilon_{dg}}\right)\rm yr$$

Dust and Activity



Strong correlation between dust and activity

Are AGN responsible?

No, because:

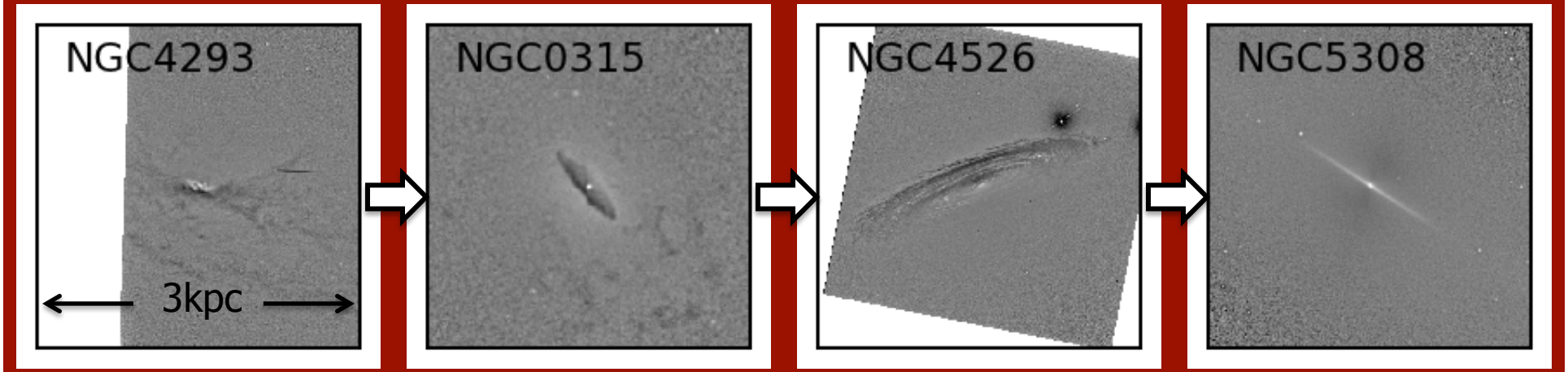
- Many LINERs are *primarily* powered by old stellar populations, rather than AGN
- While all early-type AGN hosts have dust, many others with dust are consistent with other types of emission-line galaxies

Emission lines and activity are likely by-products of dust (and gas), rather than the cause

Is the origin all internal?

Potential Dust Settling Sequence:

Filamentary dust	Dust filaments + small-scale disk	Well-ordered dust disk	Stellar disk (no dust)

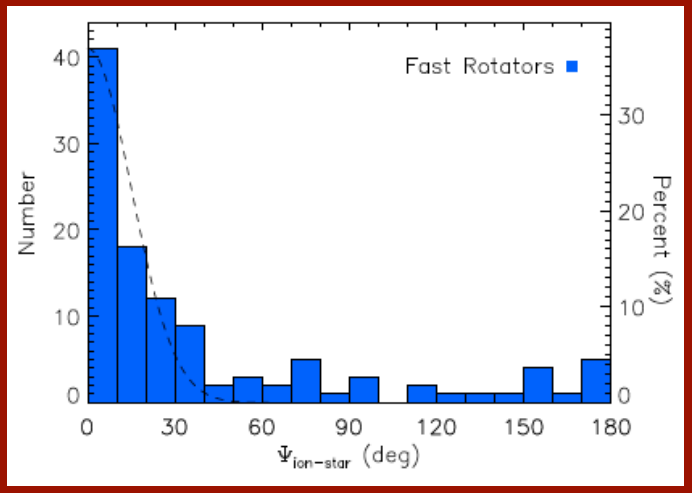


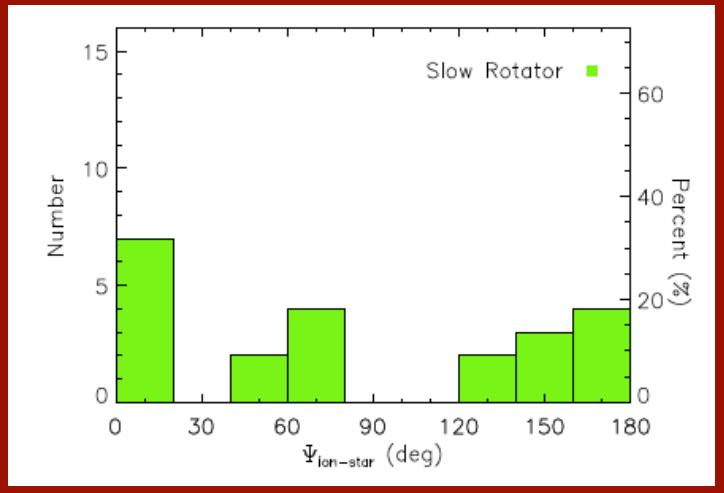
Proposed by Tran et al. (2001), Verdoes Kleijn & de Zeeuw (2005)

Is the origin all internal?

No, because:

- There are order of magnitude differences in dust mass between otherwise identical galaxies
- Gas and stellar kinematics are misaligned
- Dust morphology





Davis et al. (2012)

Is the origin all external?

We need to determine:

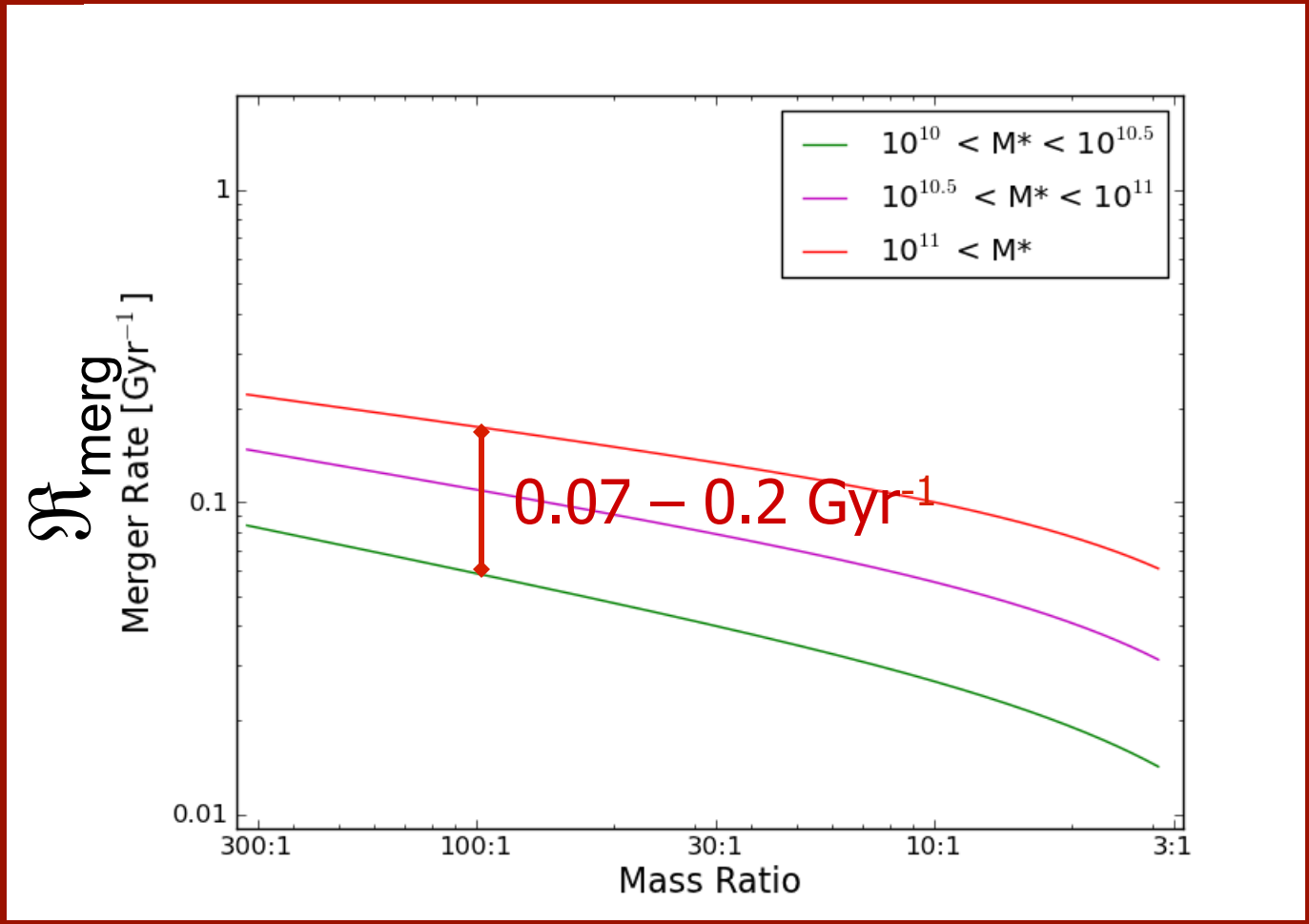
- What 'donors' have enough dust?
- What is their merger rate?

Our constraint is that 60% of early-type galaxies have dust:

$$f_{dust} = \Re_{merg}\, \tau_{dust} = 0.6$$

where $\tau_{dust} < 2 \times 10^7$ yr

Theoretical Merger Rates



Based on Stewart et al. (2009)

Is the origin all external?

No, because:

- Dusty fraction is predicted to be:

  $f_{dust} = \Re_{merg} \tau_{dust} =$

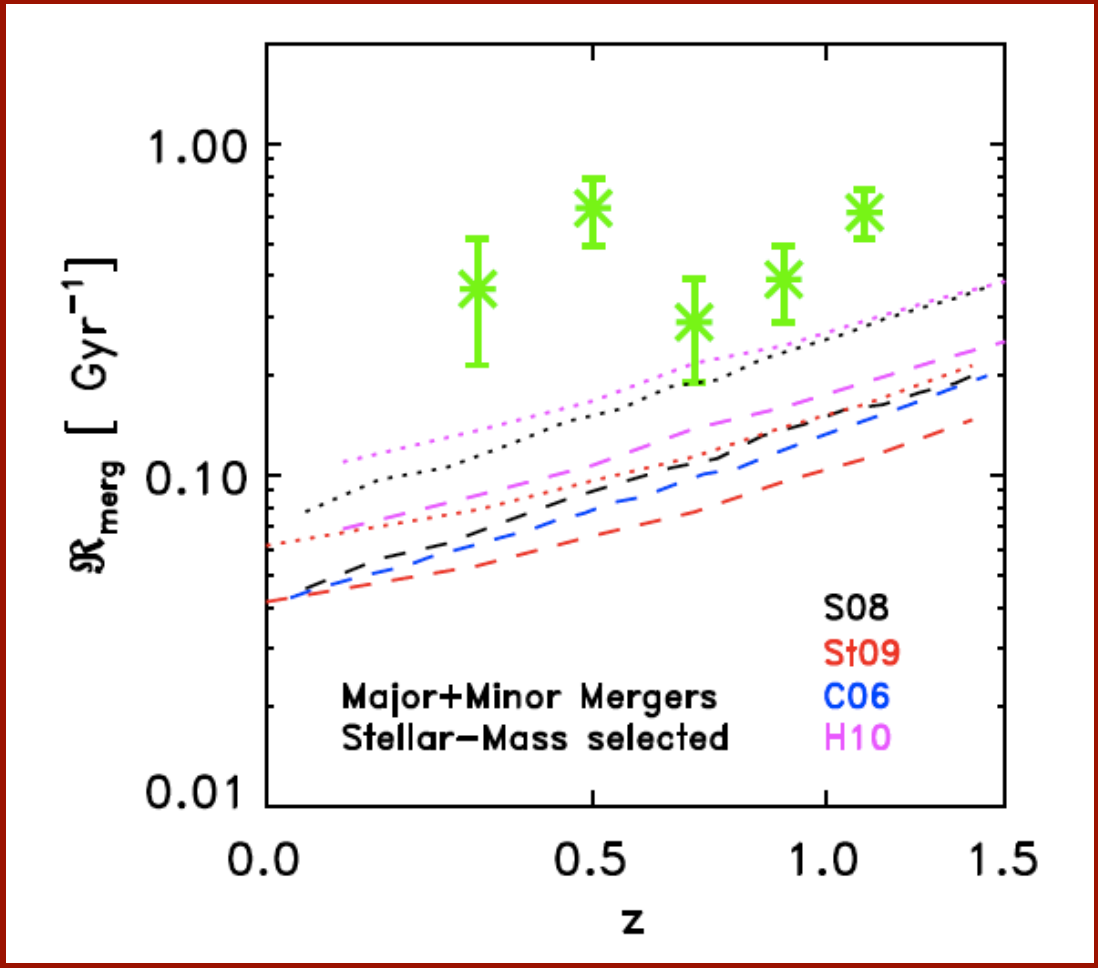
  $(0.07 – 0.2)\ 0.02 = 0.0014 - 0.004$

- Compare to the observed dusty fraction:

  $f_{dust} = 0.6$

Dust destruction timescale would need to be at 150-430x longer to explain observations

Observed Merger Rates



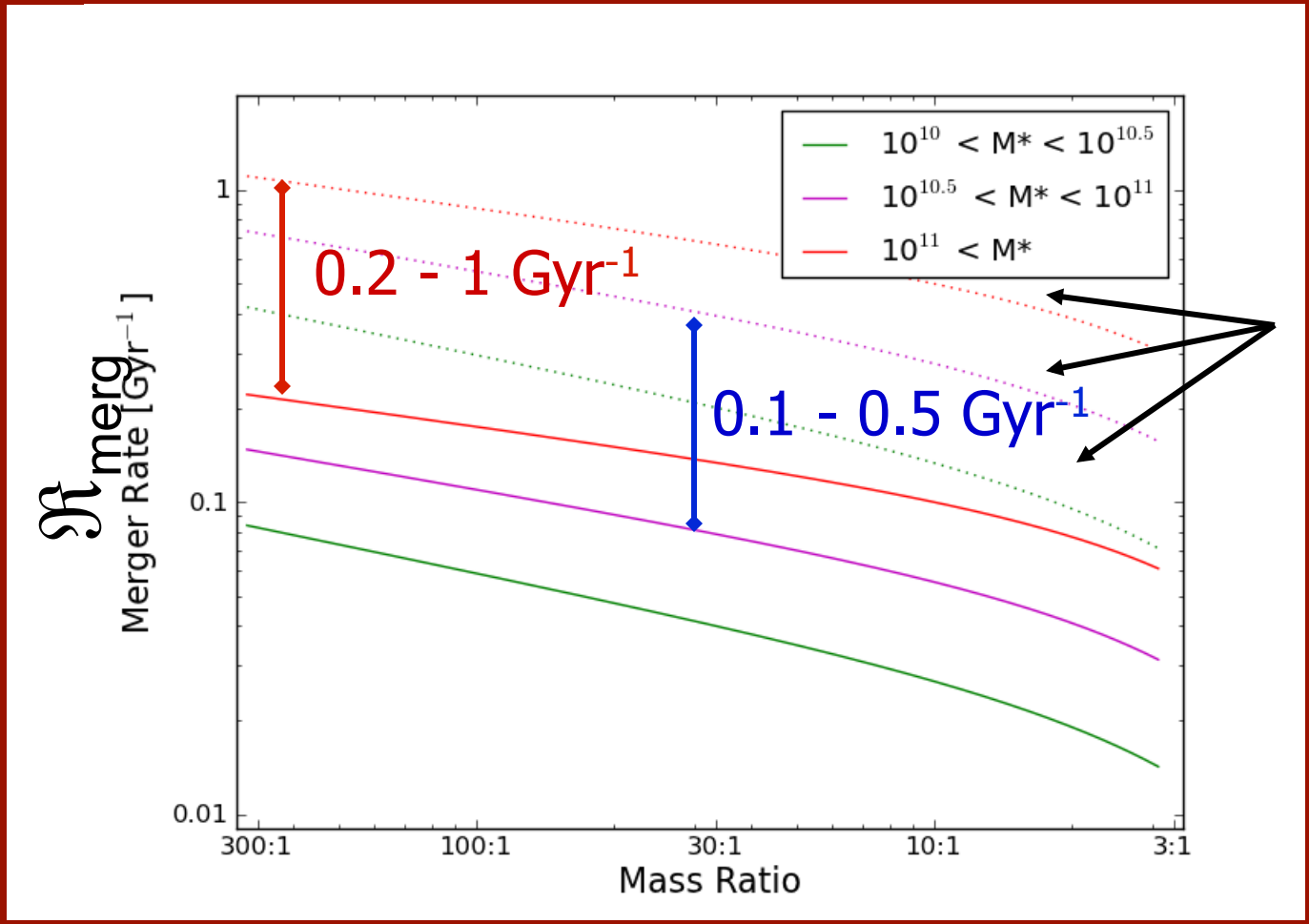
..... 1:1→30:1

- - - - - - 1:1→10:1

5x discrepancy

Lotz et al. (2011)

Theoretical Merger Rates



5x Higher

Based on Stewart et al. (2009)

Destruction Time?

Milky Way value is much higher

τ_{dust} = 0.4 Gyr (5x higher)

Early-type galaxies have lower SN rates

Plausibly within a factor of a few for the highest predicted merger rates

Hybrid Solution

Milky Way appears to produce most (~90%) of its dust in the cold, neutral ISM

If the entire dust mass were produced in the cold ISM, then the steady-state value is:

$$M_{dust} = \varepsilon_{dg} M_{gas}$$

Typical ETGs have $10^{7\text{-}8}$ $M_\odot$ of neutral gas, consistent with satellite accretion

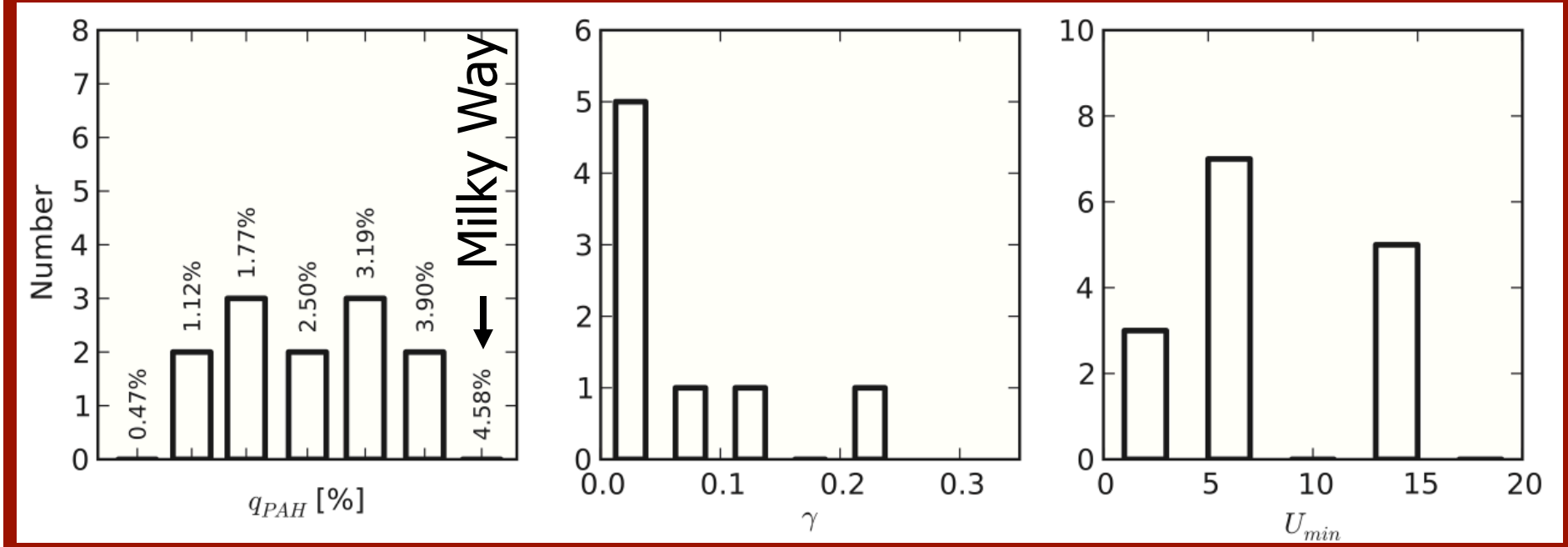
They should have a steady-state $M_{dust} = 10^{5\text{-}6}$ $M_\odot$, in agreement with observations

The neutral gas is exhausted on ~Gyr timescales due to star formation and/or evaporation

Summary

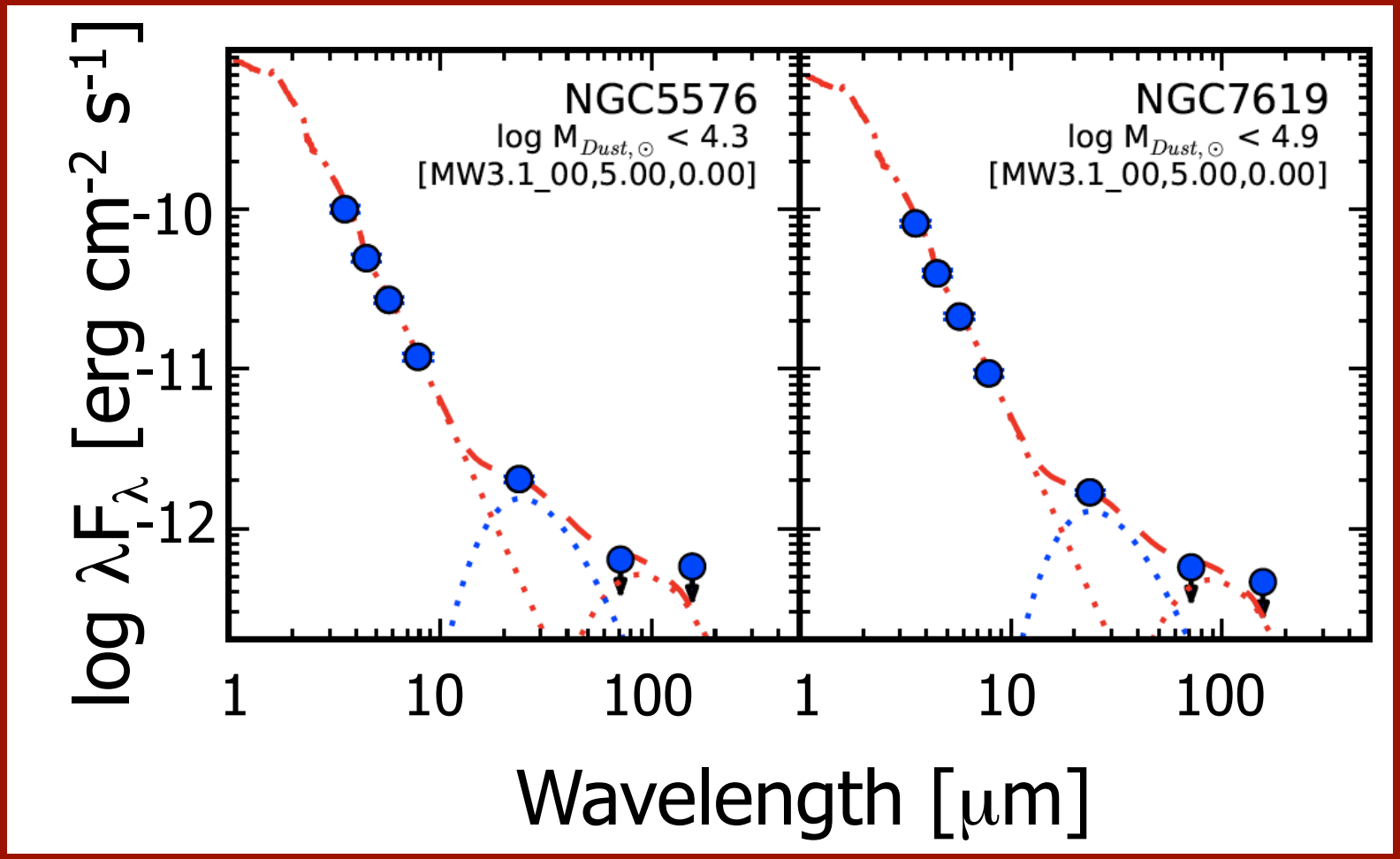
- The majority (~60%) of early-type galaxies have at least 10^5 $M_\odot$ of dust
- The remainder have at least an order of magnitude less
- The dust mass distribution rules out a purely internal origin, while the dust destruction timescale, mass, and merger rate rule out a purely external origin
- Continued dust production in the (accreted) cold, neutral ISM could resolve the discrepancy
- The ‘active’ lifetime would be similarly long-lived, namely several Gyr

Dust Properties

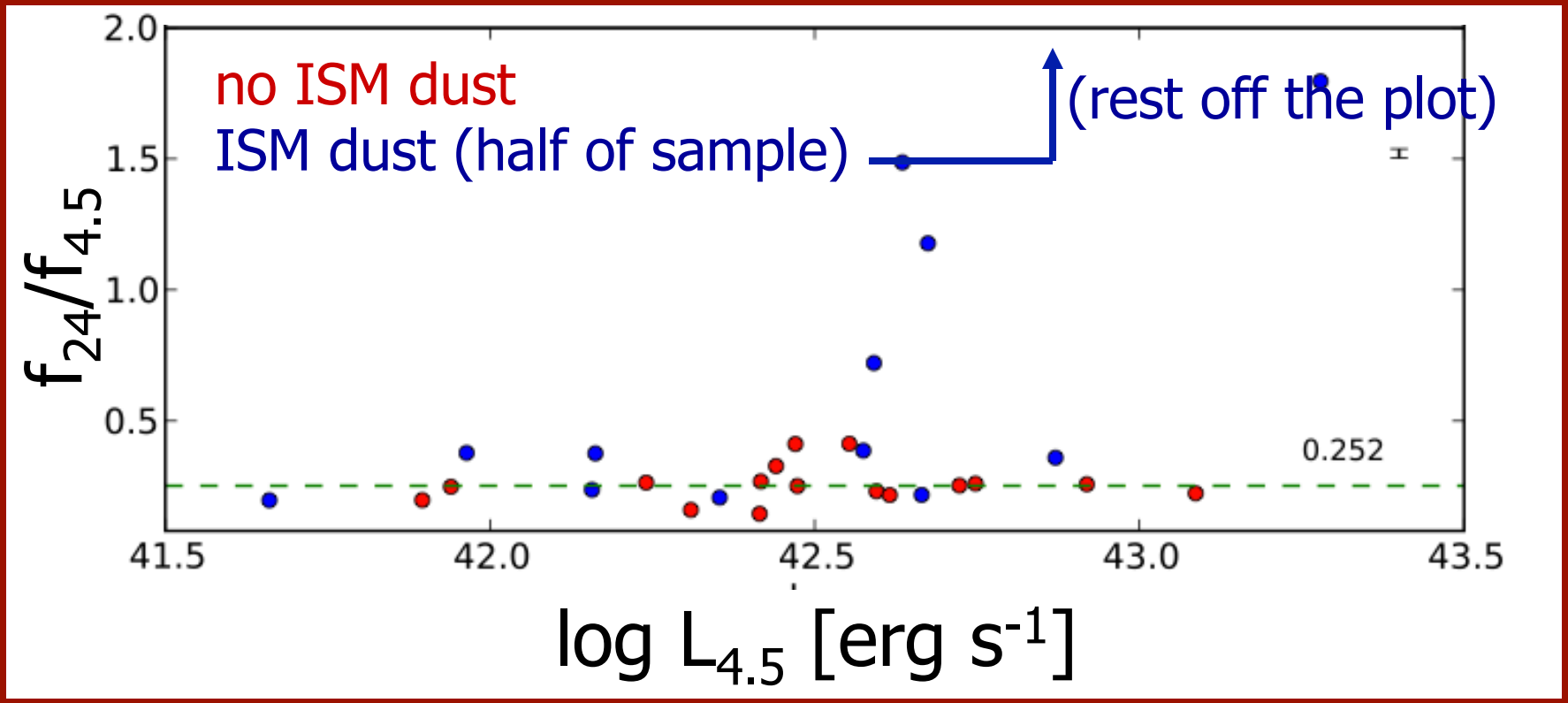


Low PAH fractions relative to the Milky Way
Very little hot dust due to star formation/AGN
More intense average radiation fields

Circumstellar Dust



Circumstellar Dust



Circumstellar dust is always present