Sunrise:

Panchromatic SED Models of Simulated Galaxies

Lecture 4:

Dust emission & Sunrise science

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Lecture outline

- Lecture 1: Why Sunrise? What does it do? Example science. How to use the outputs? Projects?
- Lecture 2: Sunrise work flow. Parameters, convergence, other subtleties.
- Lecture 3: Radiation transfer theory. Monte Carlo. Polychromatic MC.
- Lecture 4: Dust emission, dust self-absorption. Sunrise on GPUs. Sunrise science.

Dust models

- Models of dust try to match observations with a physical description of the grains
- Typically composed of
  - Silicate grains (amorphous SiO_2)
  - Carbonaceous grains (graphite)
  - Polycyclic aromatic hydrocarbons (PAHs)
- with a distribution of sizes
- Cross sections calculated from material constants and geometry (spheres)
- See review by Draine (2003)

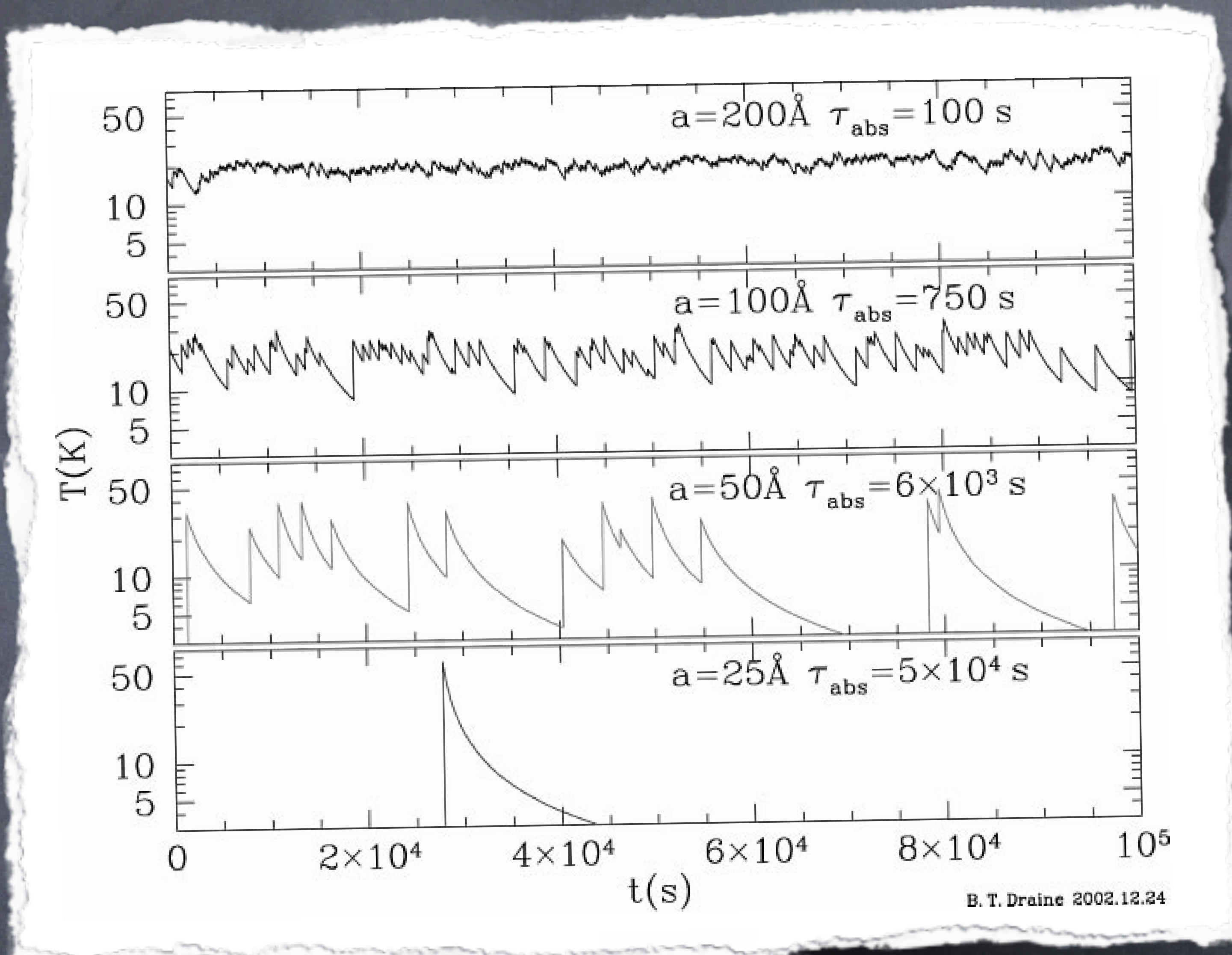
Dust emission

- For **large grains** (many hundreds of Å) emission can be calculated as a modified blackbody

$$L_h = \int \sigma_a(\lambda) B(\lambda, T_e)\, \mathrm{d}\lambda = 2hc^2 \int \frac{\sigma_a(\lambda)}{(e^{hc/(k\lambda T_e)} - 1)\lambda^5}\, \mathrm{d}\lambda$$

- But very small grains have such low heat capacity they are heated by single-photon absorptions
  - fluctuate in temperature
  - thermal equilibrium not a good approx.

Very small grain emission

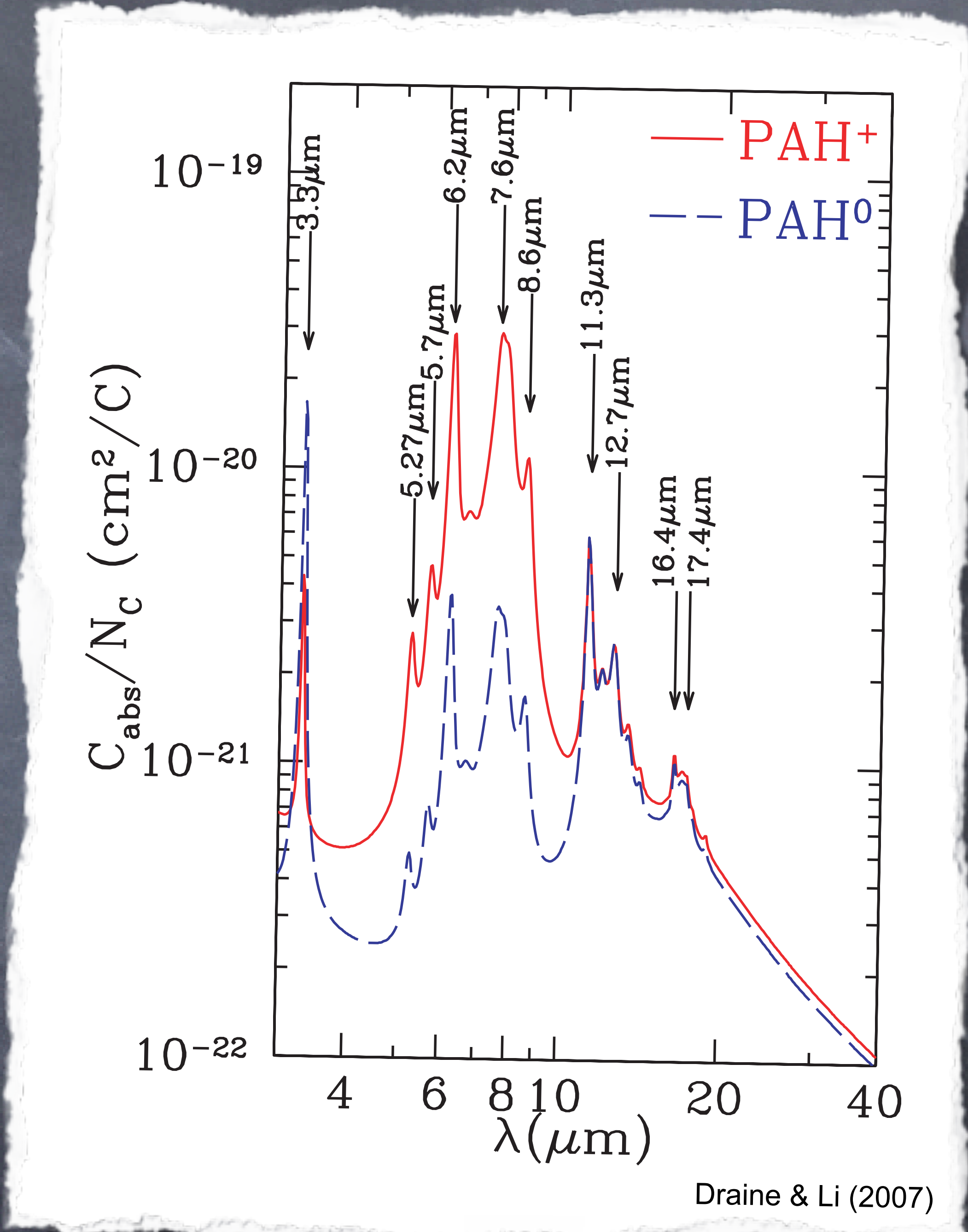


grains are both hotter **and** colder than one might guess

Emission is broader than if thermal equilibrium is assumed

BUT much harder to calculate

PAH emission

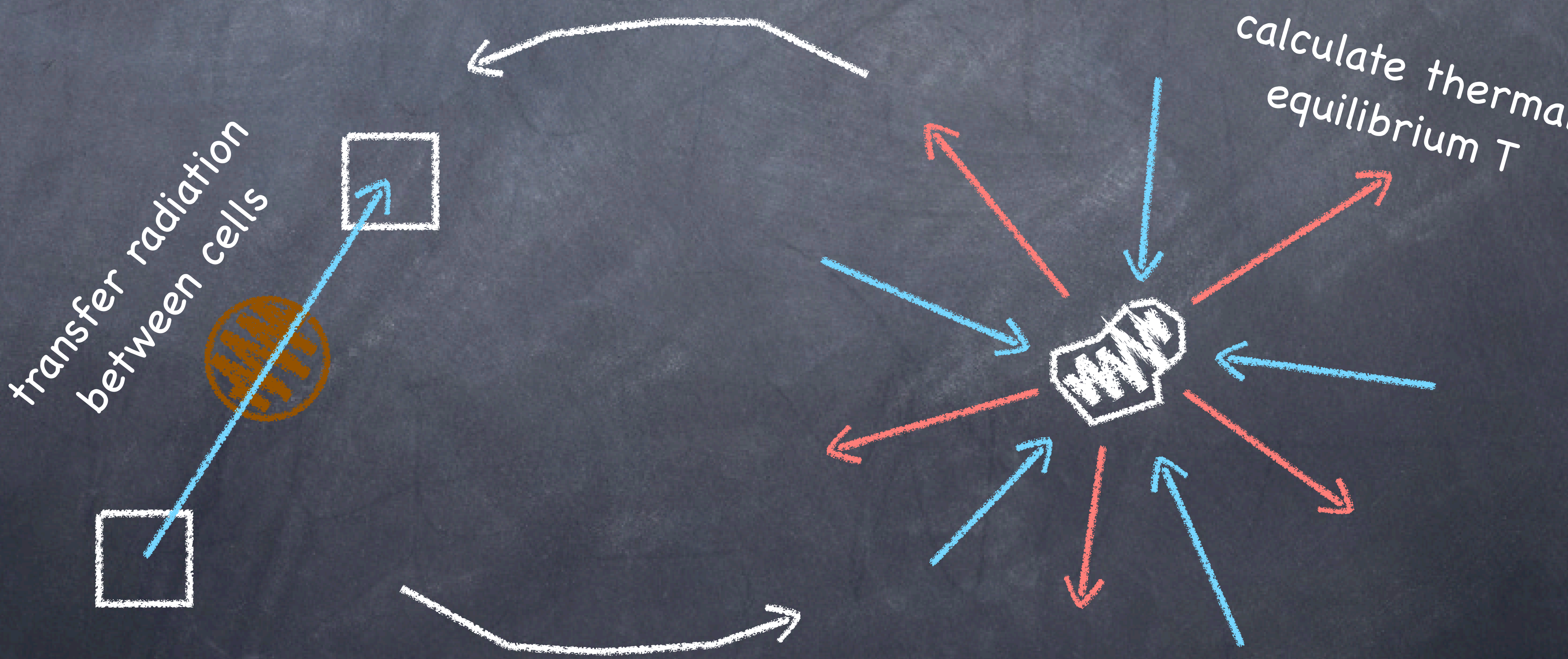


currently only modeled as a fixed fingerprint in Sunrise

A series of narrow features between 5-20 μm

Dust self-absorption

- Would be straightforward if dust was only heated by starlight
  - but it's not - dust absorbs its own emission
  - need to iterate:

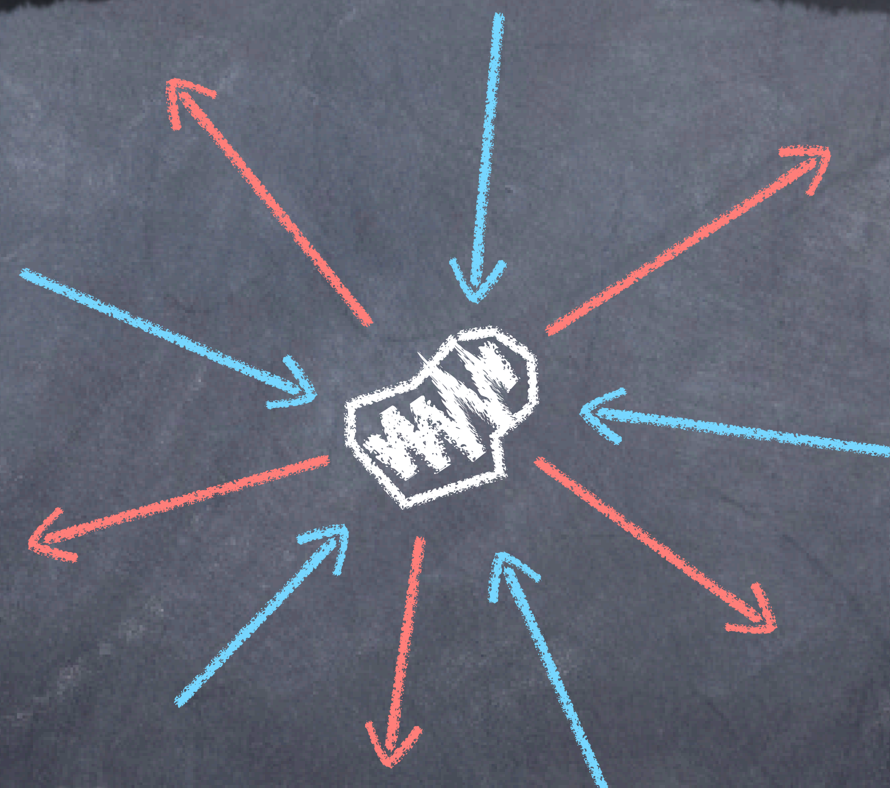


Dust self-absorption: step 1

Calculate the equilibrium temperature of the dust grains

$$L_{h;c,s} = \int I_c(\lambda)\sigma_{a;s}(\lambda)\,\mathrm{d}\lambda$$

heating by absorption of radiation



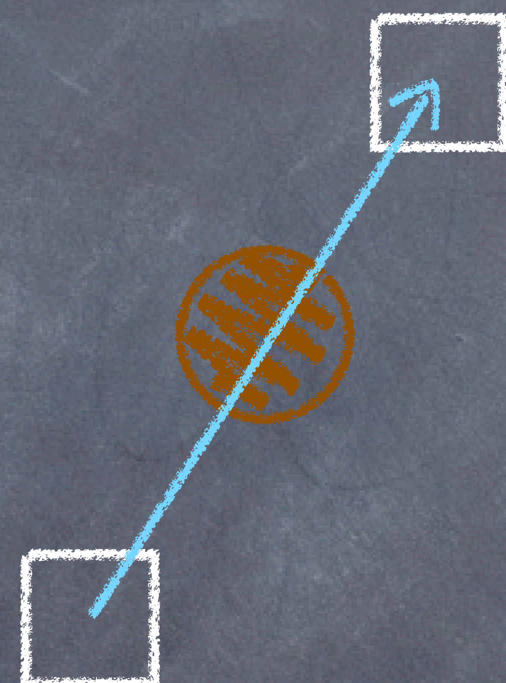
balances

$$L_{h;c,s} = 2hc^2 \int \frac{\sigma_{a;s}(\lambda)}{\left(e^{hc/(k\lambda T_{e;c,s})} - 1\right)\lambda^2}\,\mathrm{d}\lambda$$

cooling by emission of radiation

Dust self-absorption: step 2

Calculate how much dust emission in the cells contributes to radiation intensity in the other cells



This is like a normal Monte Carlo pass, only sources aren't stars but the dust

- and now go back and recalculate temperatures

More on dust self-absorption

Actually, it's a bit more complicated...

Let's look at this in more detail:

- The temperature calculation we just talked about can be viewed as a conversion from intensity to luminosity

$$L_\lambda = B_\lambda \left(I_{\lambda'} \right)$$

- And the transfer of radiation as a conversion from luminosity to intensity

$$I_{i,\lambda} = \sum_j L_{j,\lambda} T_{ij,\lambda}$$

T is known as the "lambda operator"

More on dust self-absorption

$$I_{i,\lambda} = \sum_j L_{j,\lambda} T_{ij,\lambda}$$

- Problem: we are recomputing the solution from the start each time
- Elements of T are subject to MC noise
  - The resulting intensities will always change within the MC error
  - Will **never** "converge", unless we use very many rays...
  - Difficult to judge when solution is stationary

Dust self-absorption: a better way

~~$$I_{i,\lambda}^{k+1} = \sum_j L_{j,\lambda}^{k} T_{ij,\lambda}$$~~

Instead: only transfer the **change** in L each MC pass, not the full luminosity

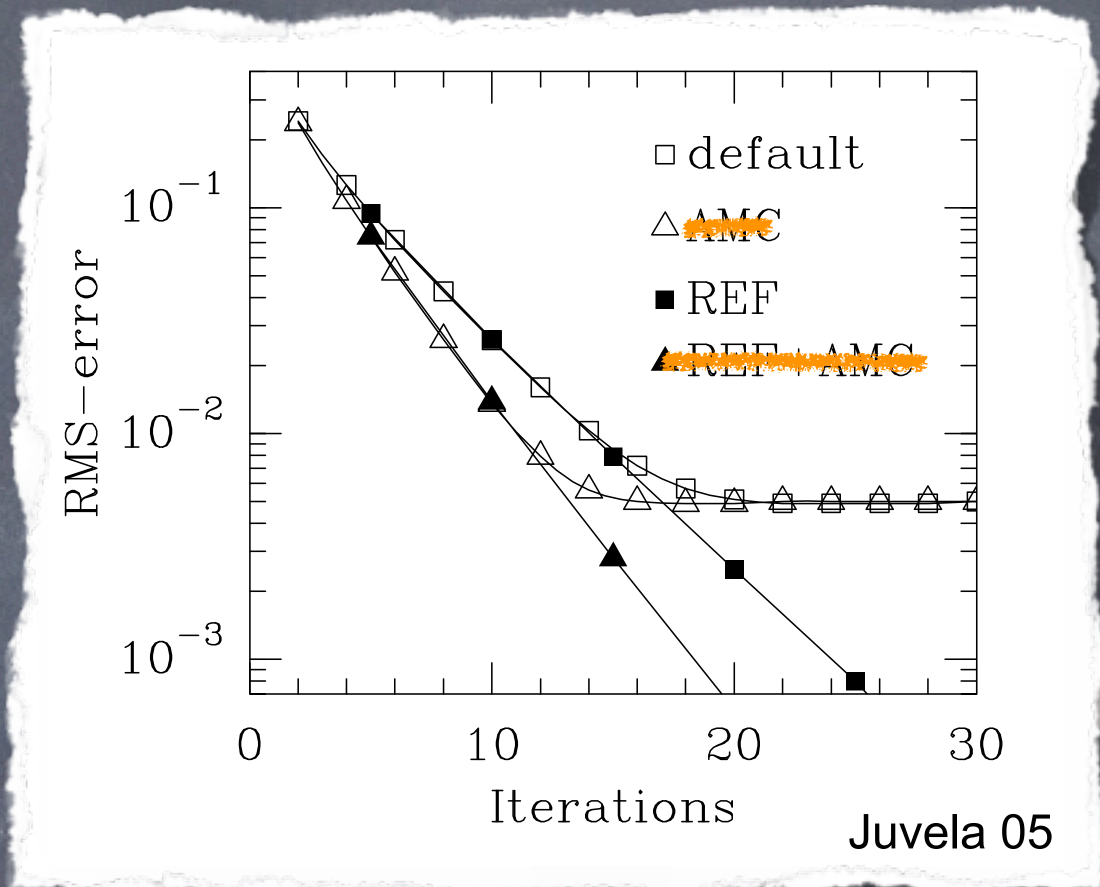
$$I_{i,\lambda}^{k+1} = I_{i,\lambda}^{k} + \sum_j \left(L_{j,\lambda}^{k} - L_{j,\lambda}^{k-1}\right) T_{ij,\lambda}$$

Signal being transferred is now **at most** as large as previous iteration

Eventually, all L must leave the box ⇒ scheme must converge

Dust self-absorption: a better way

Works quite well

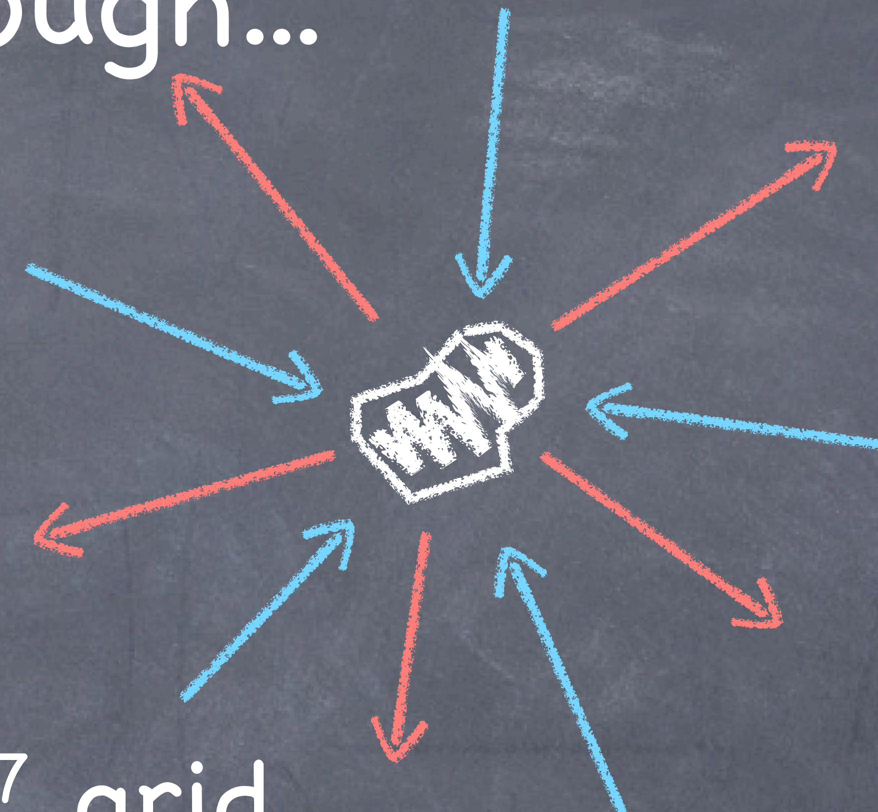


Really interesting paper

The convergence criterion now: less than a specified fraction of the original luminosity left in the grid

This is expensive, though...

$$L_{h;c,s} \quad = \quad 2hc^2 \int \frac{\sigma_{a;s}(\lambda)}{\left(e^{hc/(k\lambda T_{e;c,s})} - 1\right)\lambda^2}\, \mathrm{d}\lambda$$



Need to do this for 10^6 – 10^7 grid cells and 100 wavelengths, for about 10 iterations, for **each** pass

= Evaluating A LOT of exponentials

temperature calculation actually takes much longer than the ray tracing...

(Yes, you can make a table... bear with me!)

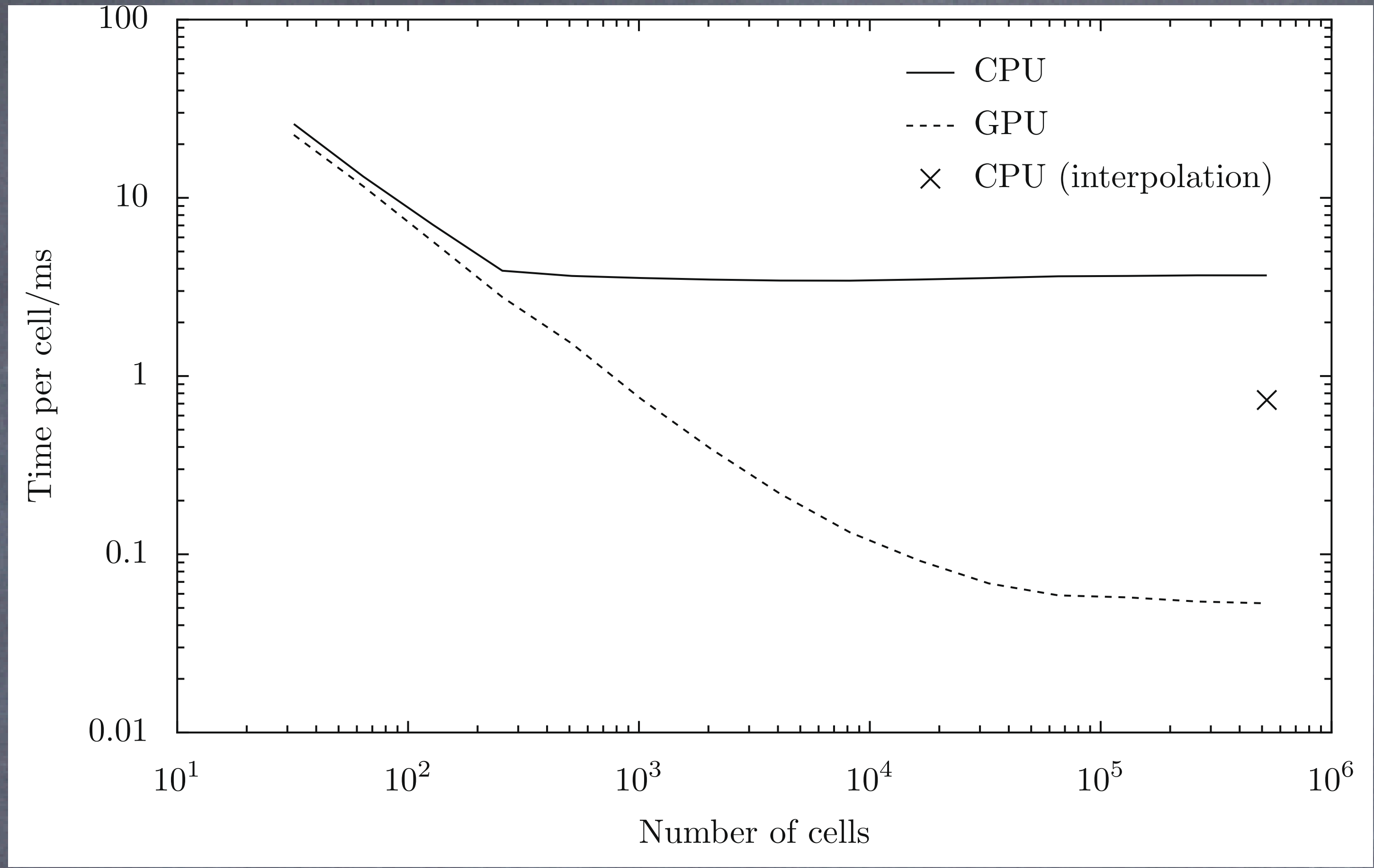
…use a GPU to speed it up

- Graphics processors are now fully programmable, massively data-parallel machines
- Raw floating-point performance is many times larger than that of CPUs
- But small or non-existent cache - sensitive to memory layout
- double-precision performance << single
- Can be programmed in a C-like language (CUDA/OpenCL)

$$L_{h;c,s} = 2hc^2 \sum_l \frac{\sigma_{a;s,l}\,\Delta\lambda_l}{\left(e^{hc/(k\lambda_l T_{e;c,s})} - 1\right)\lambda_l^5}$$

- Temperature calculation is **perfect** for a GPU
- Massively parallel, floating-point intensive
- Has been ported to run on Nvidia GPUs with CUDA (Jonsson & Primack 2010)
- Each core will calculate the temperature for one specific cell and dust species

It's FAST!



GPU (Tesla C1060) is **69x** faster than 8 Xeon cores!

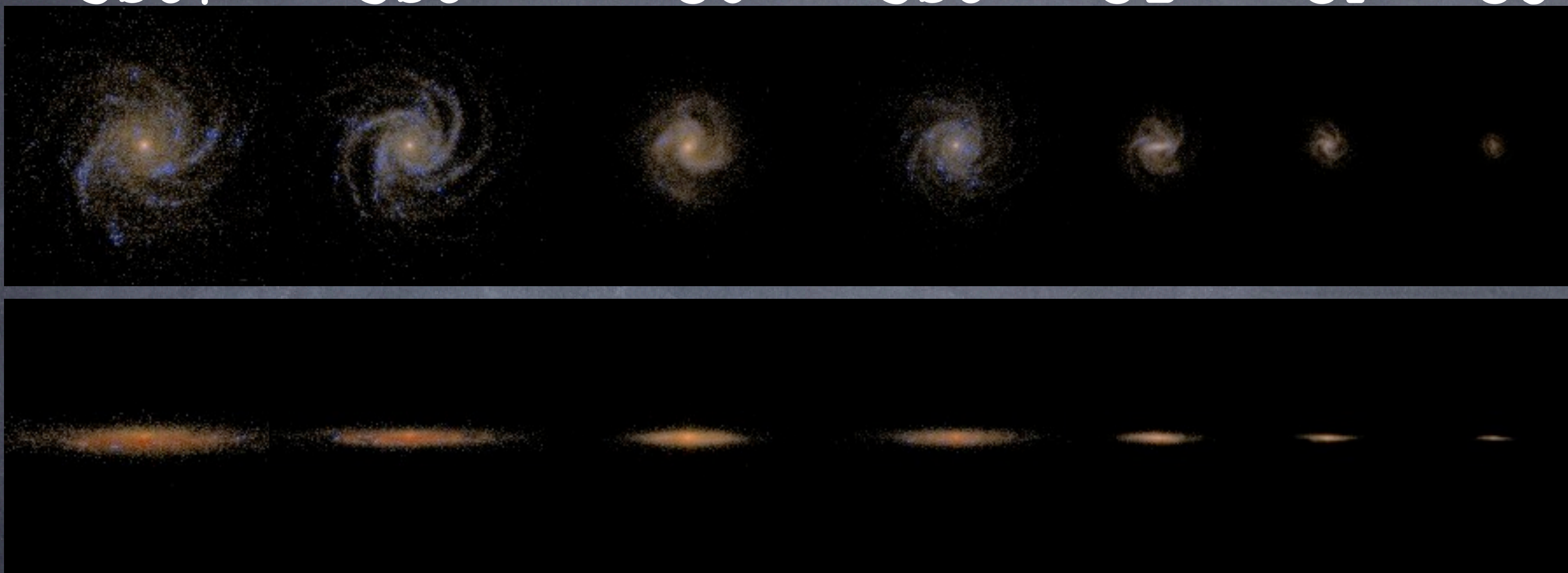
The GPU is even **16x** faster than the CPU doing **interpolation**!

Sunrise results

do these galaxies actually look real?

Remember these guys?

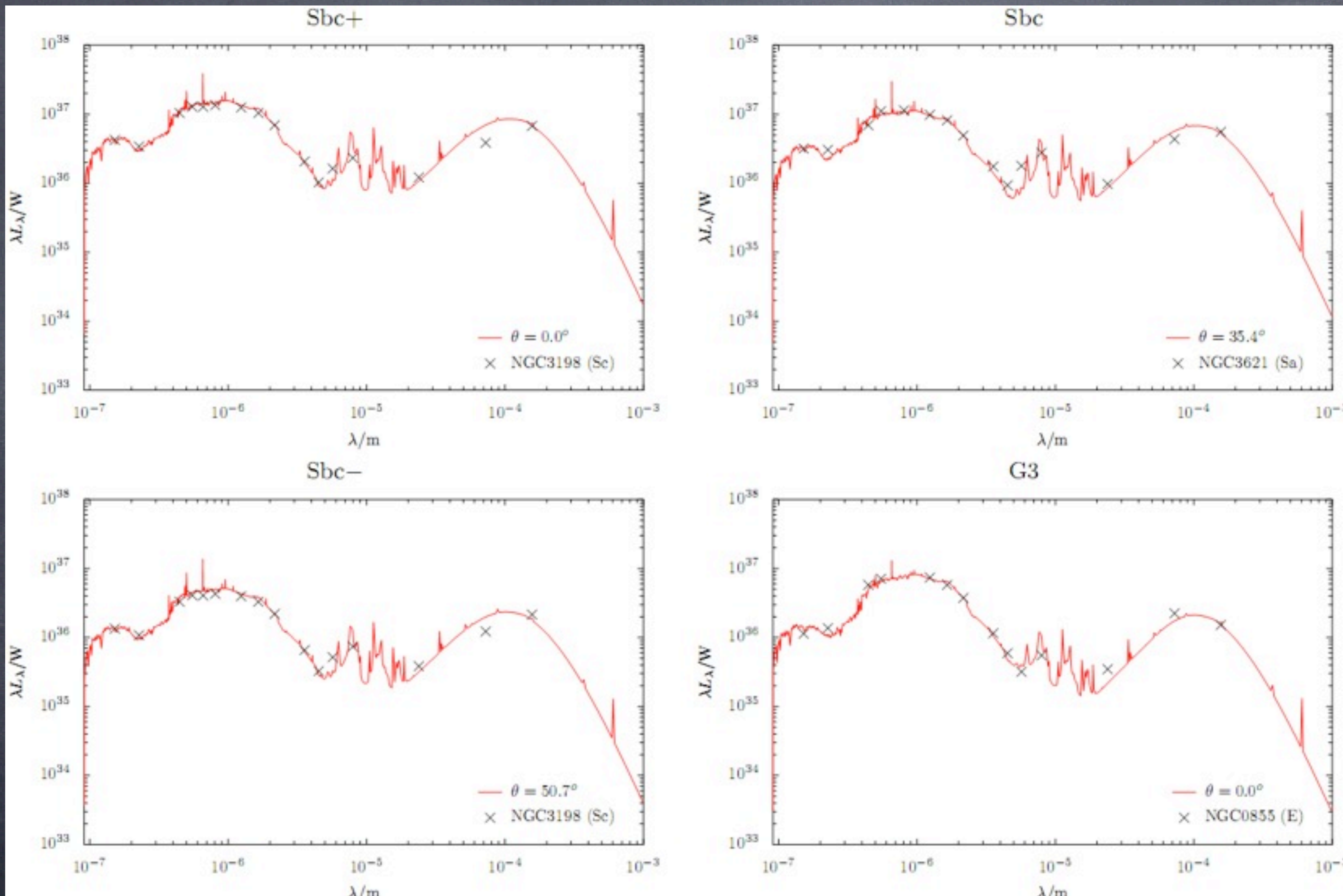
Sbc+ Sbc G3 Sbc- G2 G1 G0



Simulated these in isolation for 1 Gyr,
observed from many inclinations and bands

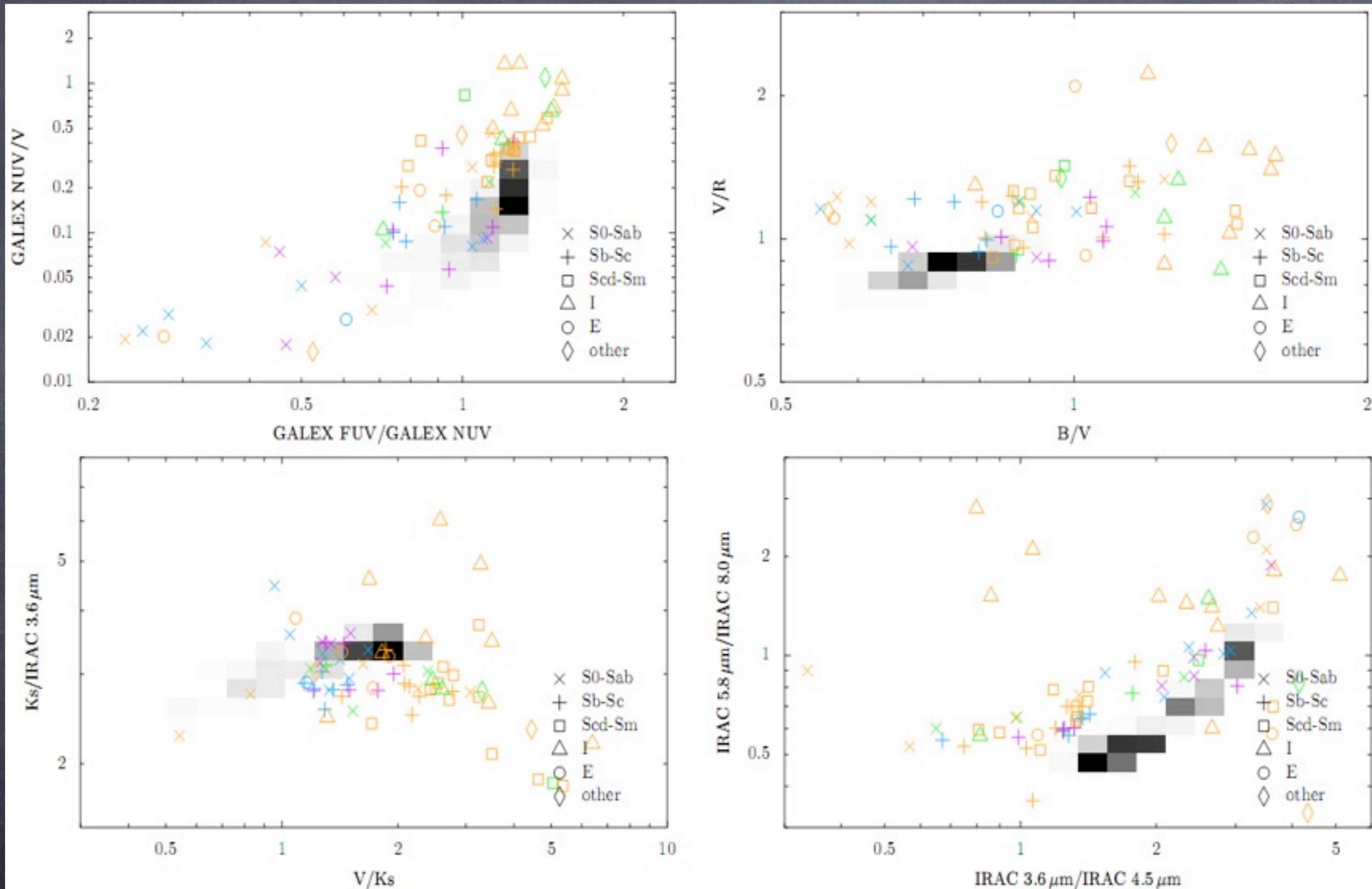
Now let's compare them to the SINGS sample

Matching SEDs with SINGS galaxies



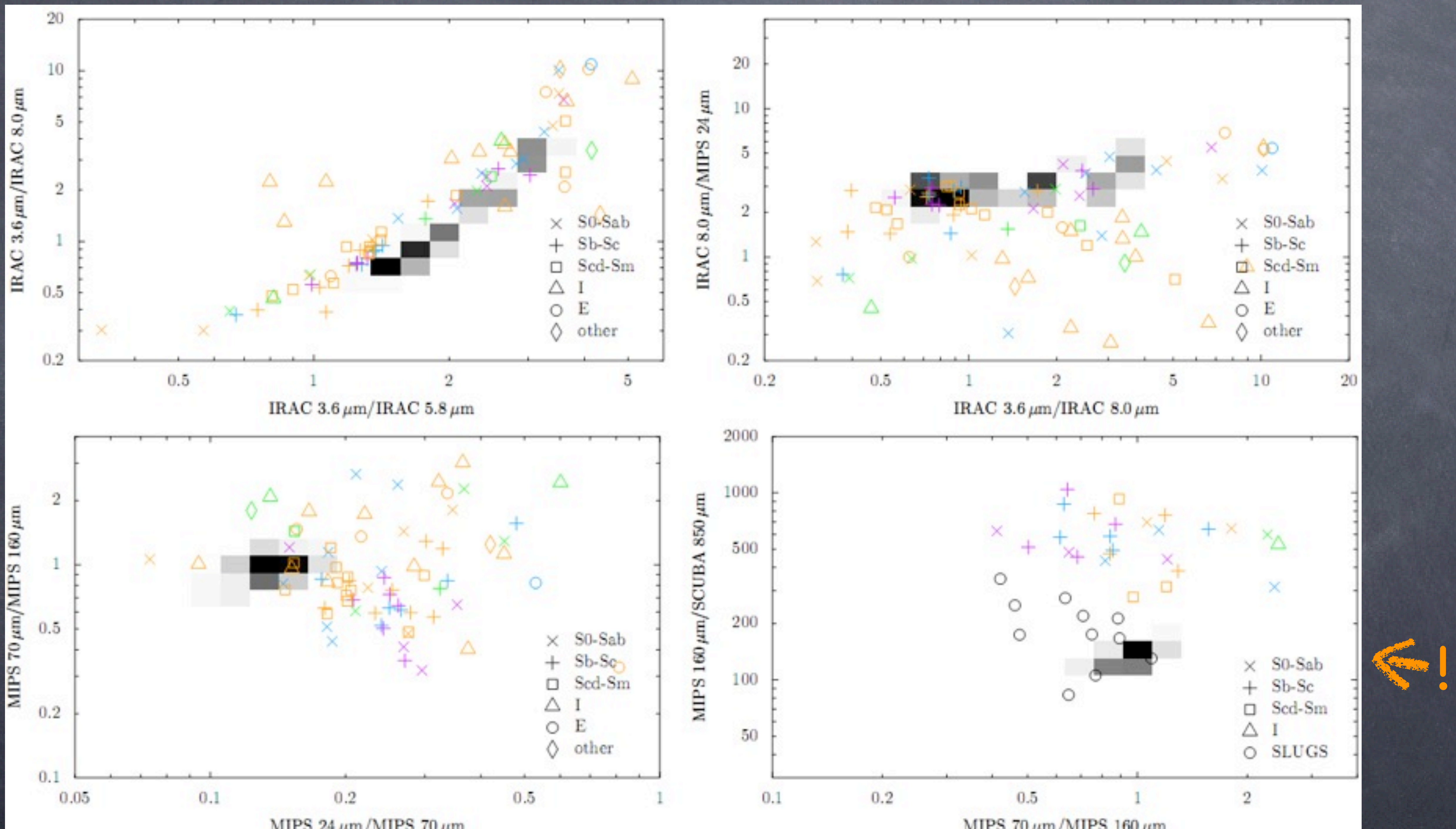
SINGS data from Dale et al 07

Comparing to SINGS: UV-NIR



color indicates nuclear type (orange: SB; green: LINER; blue: Sy; purple: n/a)

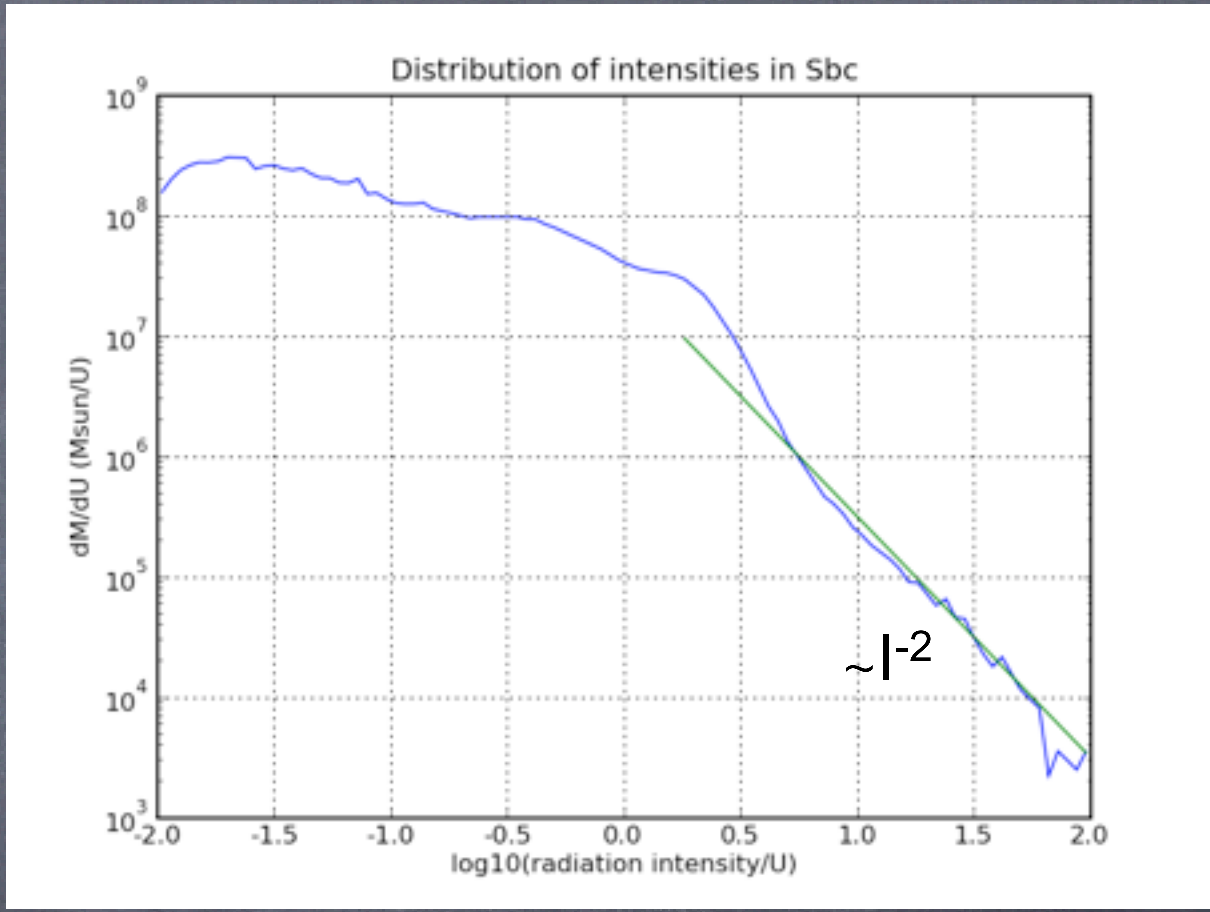
Comparing to SINGS: NIR-FIR



SLUGS from Willmer et al 09.

Origin of 850μm mismatch?

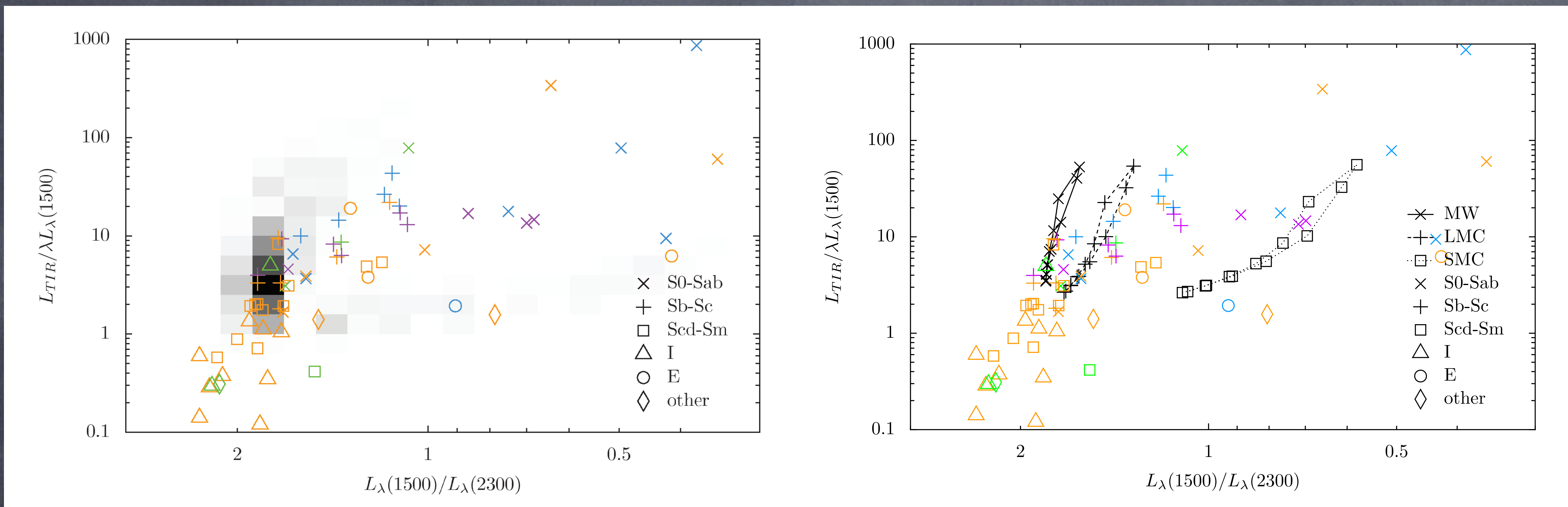
- Draine et al finds NO dust at <1U in any of the SINGS galaxies
- Sbc galaxy has 60%
- Setting an intensity floor of 5U decreases discrepancy
- But how do you get a galaxy with no dust at low radiation intensities?



Origin of 850μm mismatch?

- Dale & Helou (2002) find same mismatch with ISO/IRAS/SCUBA in their (much simpler) models
- Solve this by assuming a different cross section at long wavelengths
  - instead of $\kappa \sim \lambda^{-2}$
  - they use $\kappa \sim \lambda^{2.5-0.4 \log U}$
  - dust properties change with environment
- But what about the SLUGS galaxies?
  - they might be missing galaxies with less cold dust due to 850μm flux limit
  - The small sample size of SINGS might not have picked up this population with more cold dust

Comparing to SINGS: IRX-β



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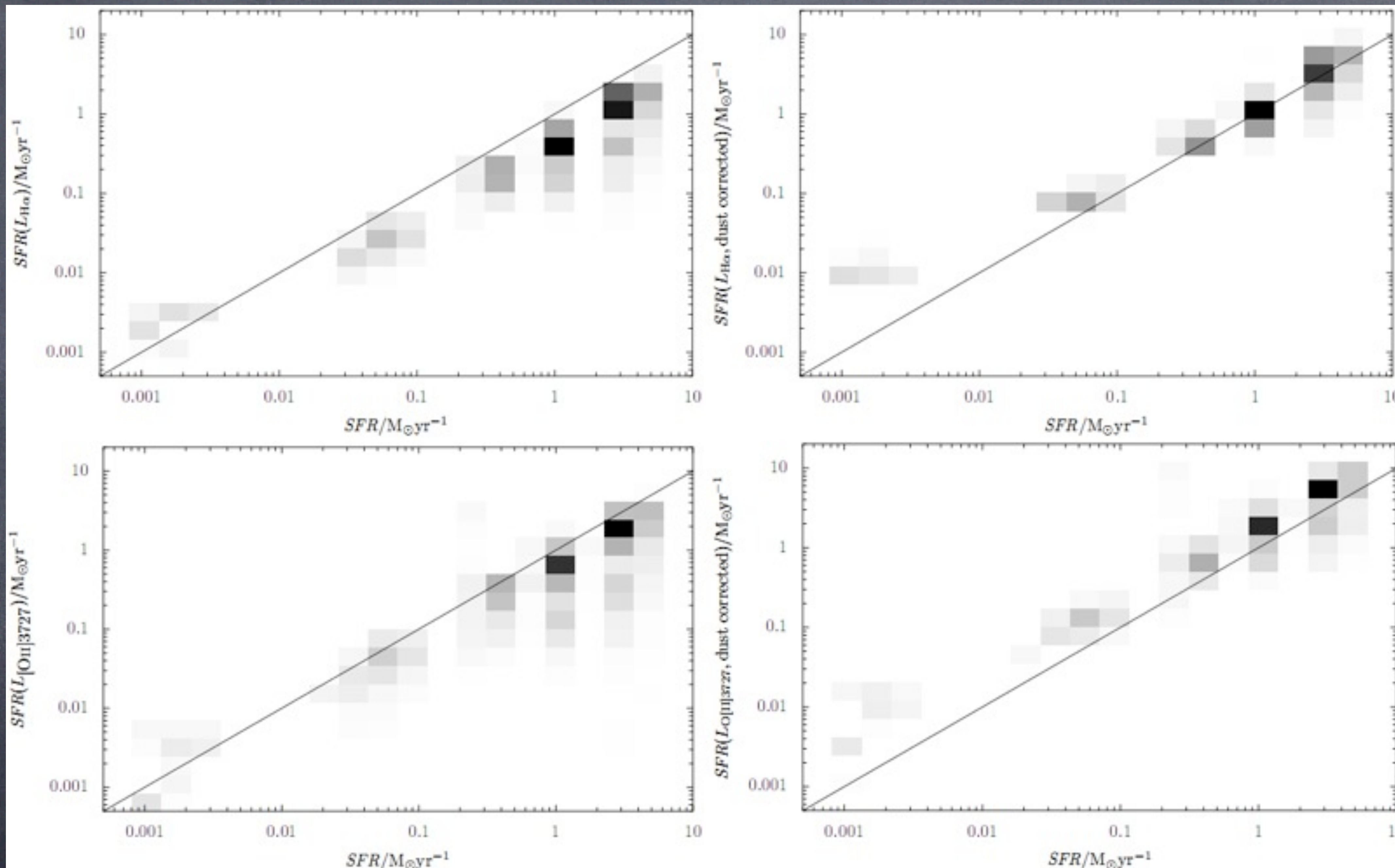
Star-Formation Rate indicators

Uncorrected | Corrected

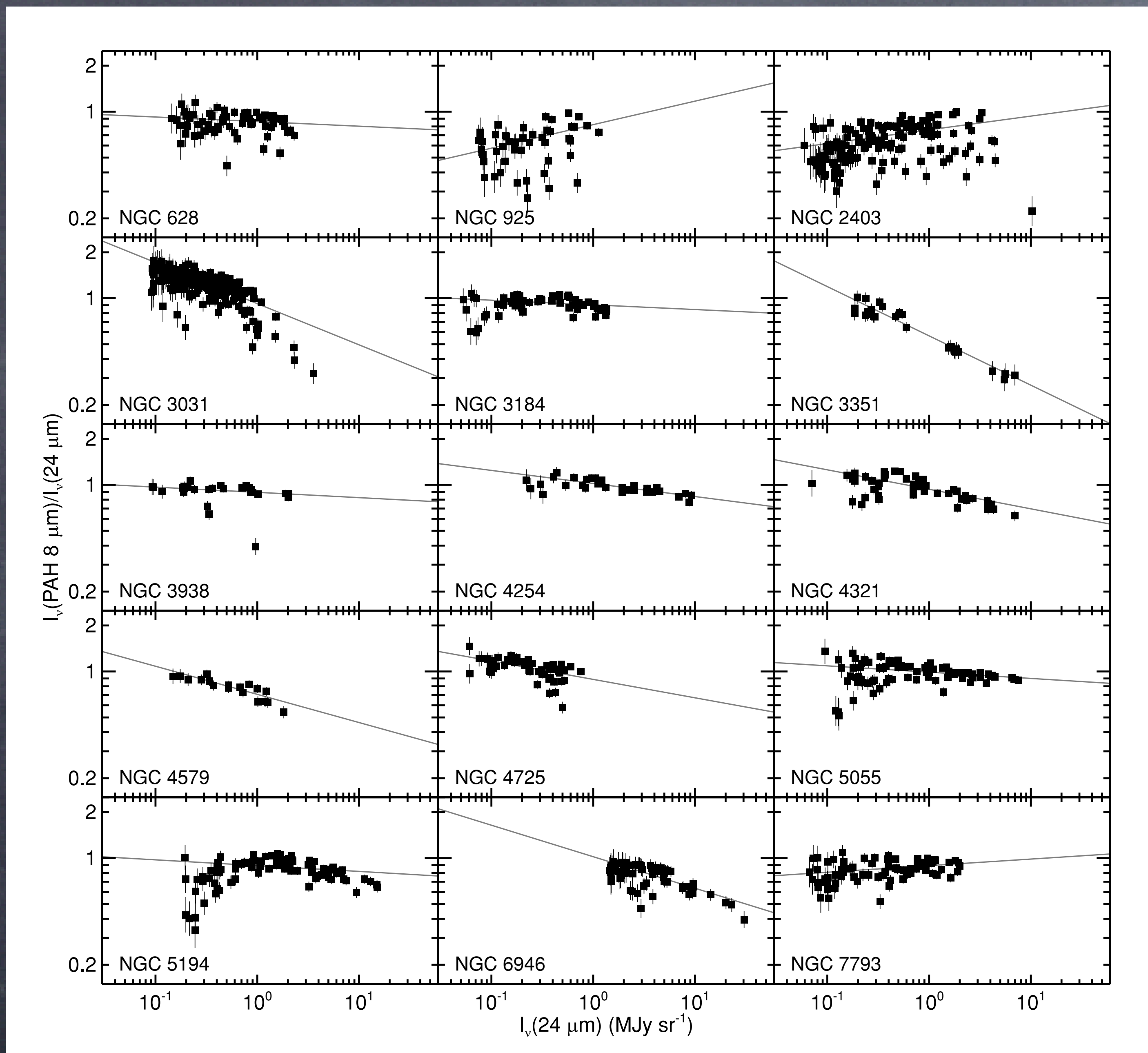
Hα

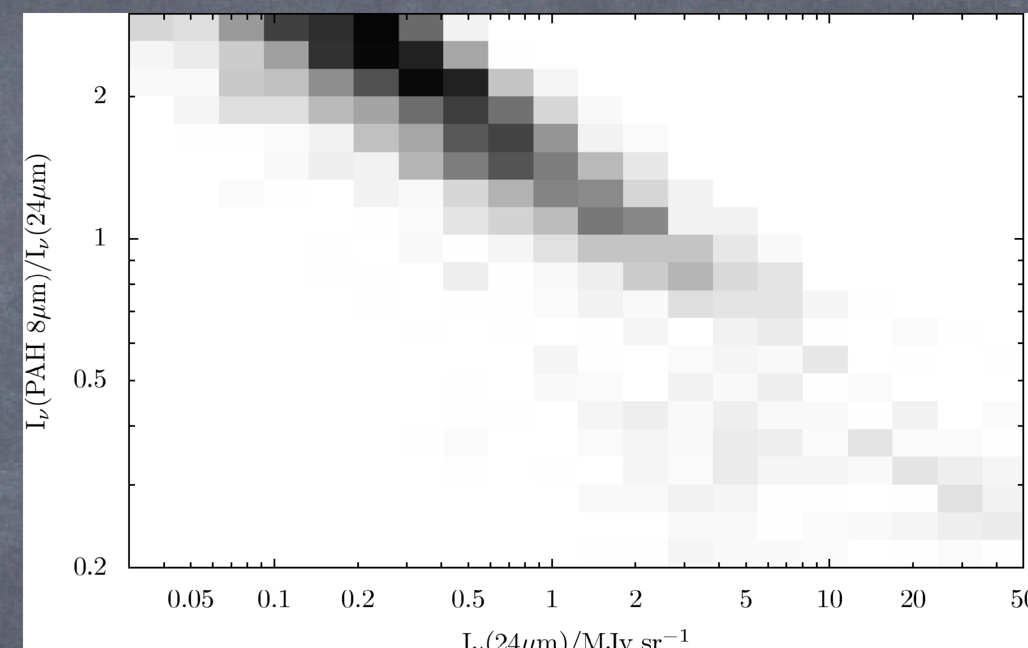
[OII] 3727



Using SFR calibrations of Kennicutt (1998)

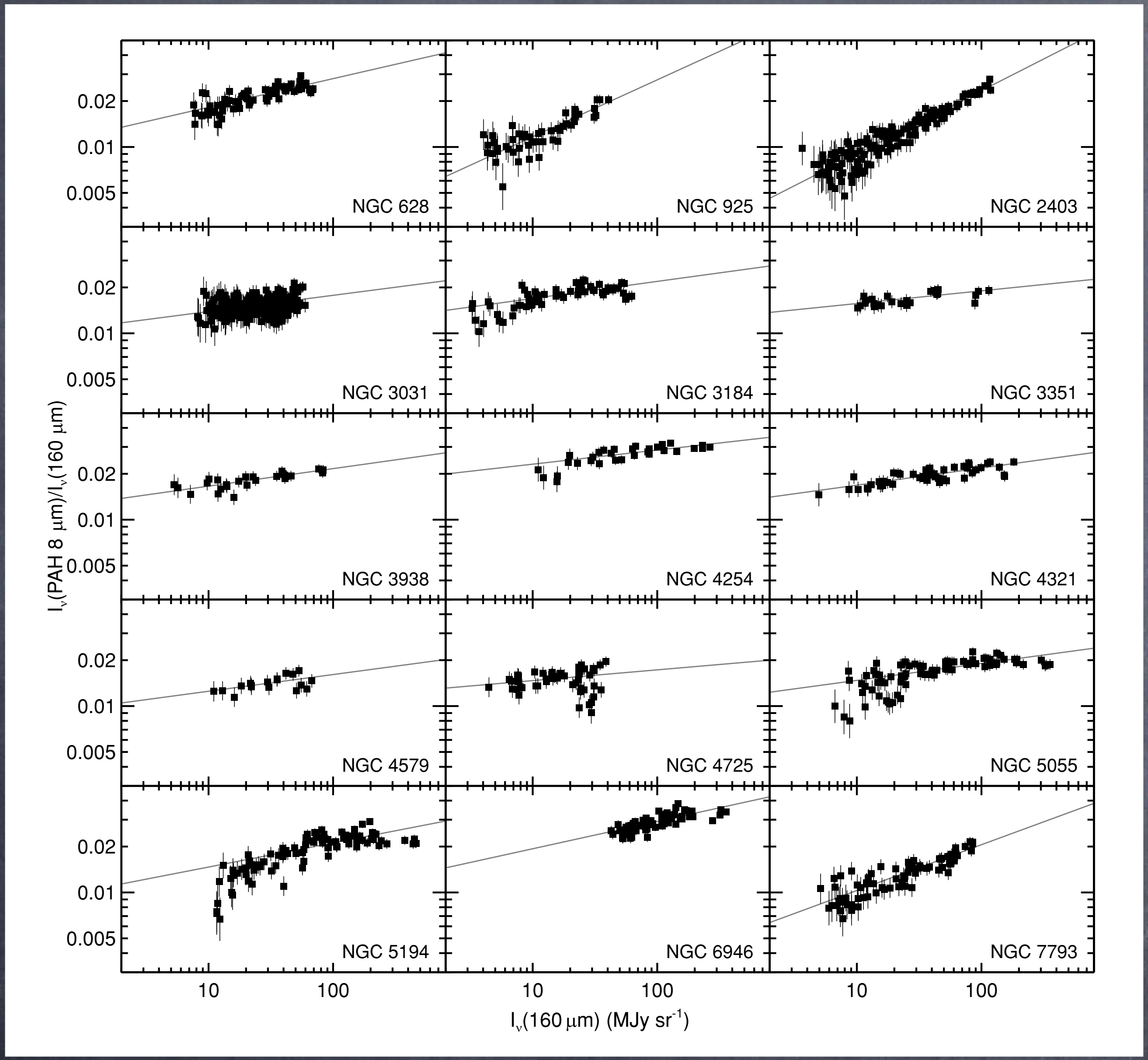
Spatially resolved colors: 8/24



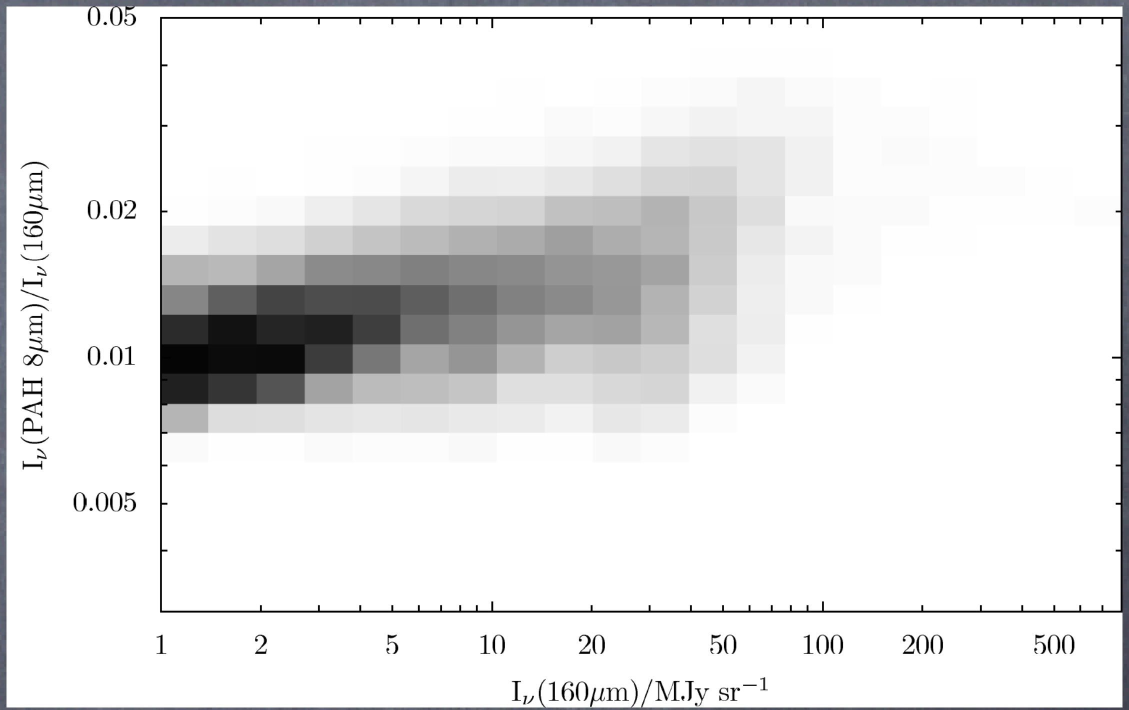


Bendo et al. 2008

Spatially resolved colors: 8/160



Bendo et al. 2008

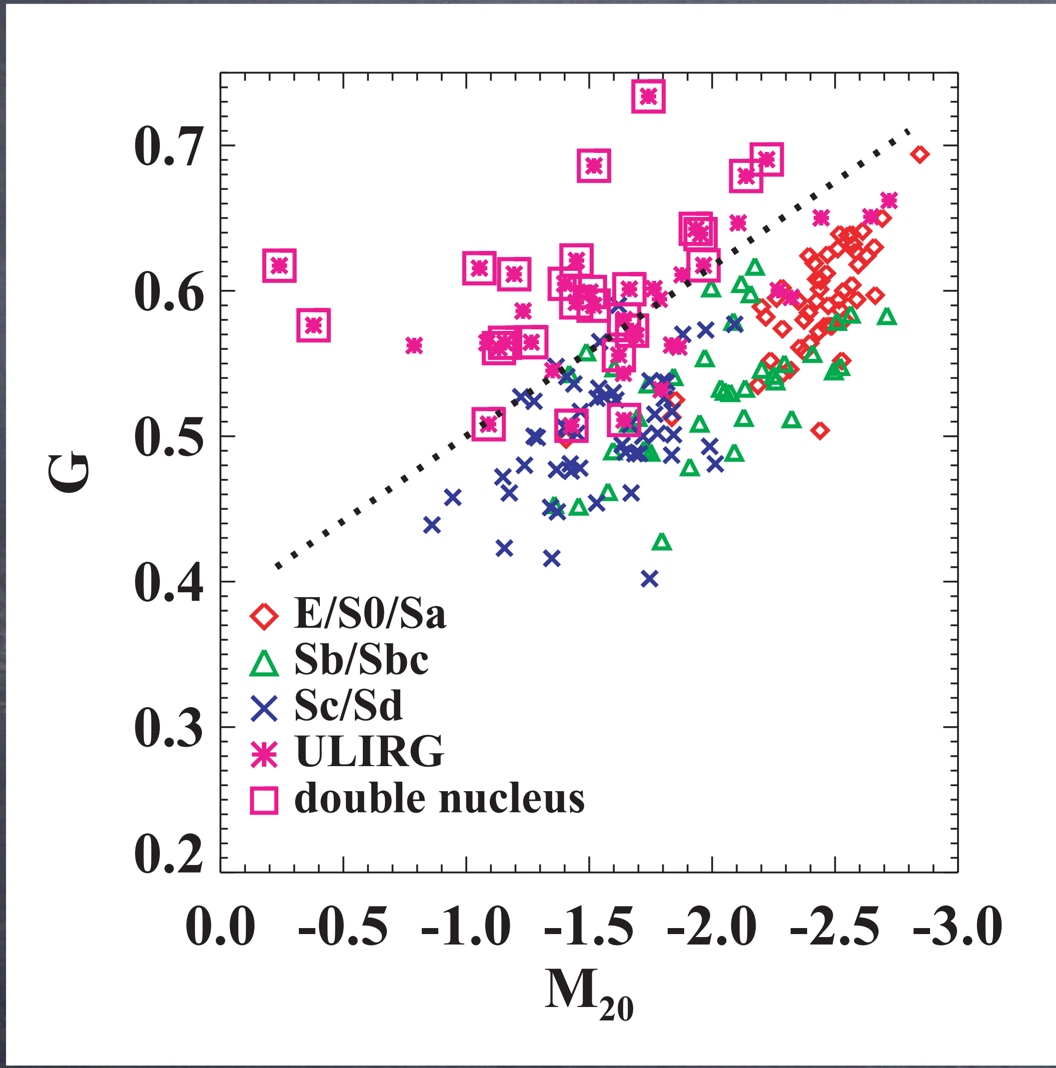


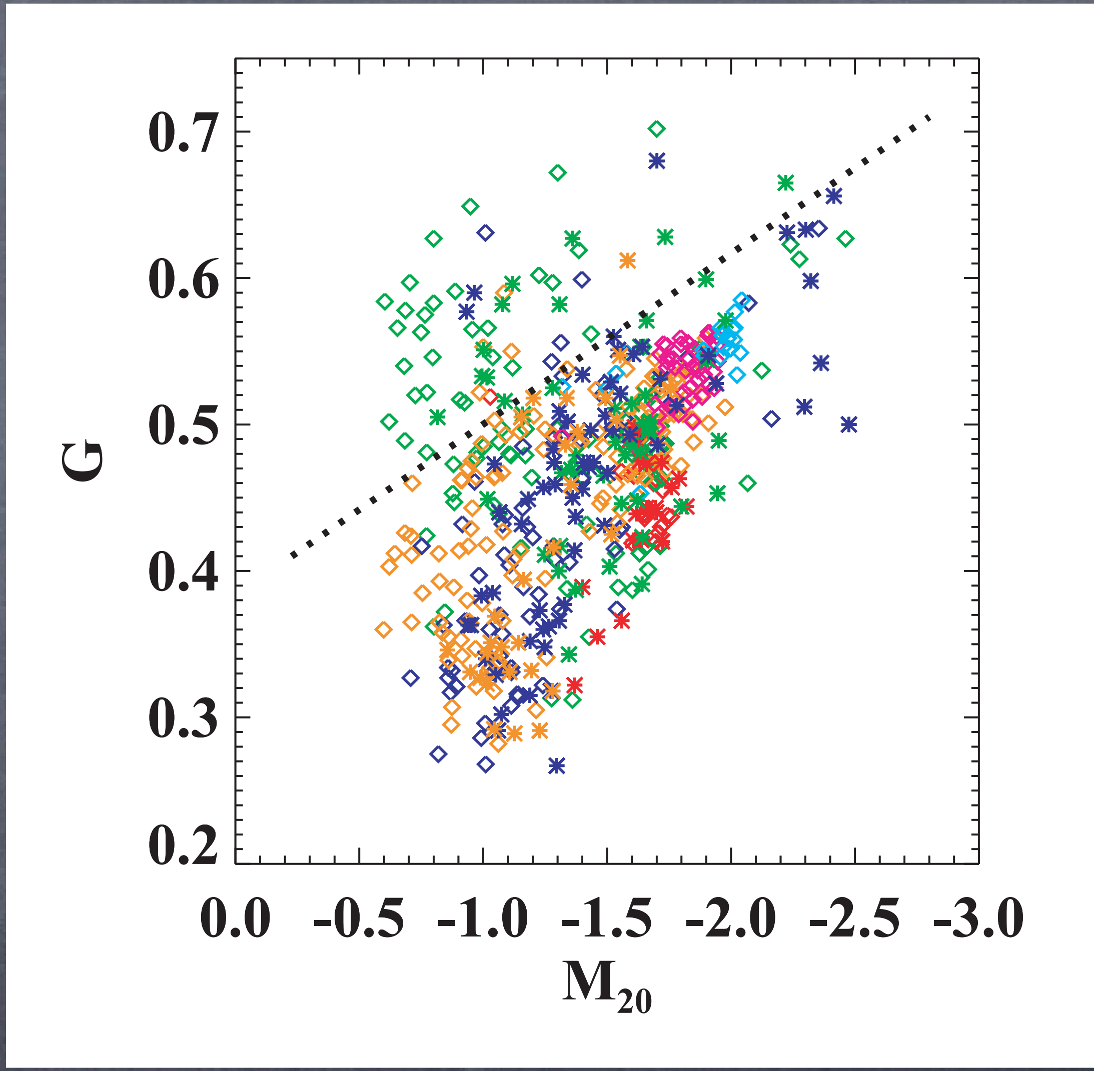
Sunrise applications

just a few examples

Merger identification calibration

Can measure sensitivity of merger detection methods on simulations

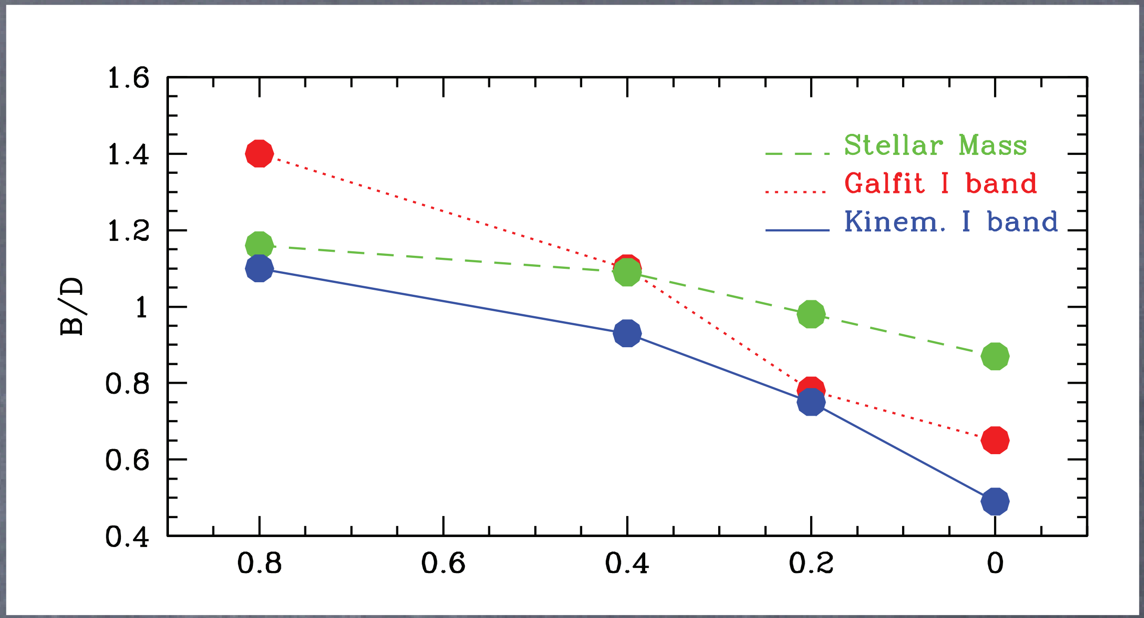


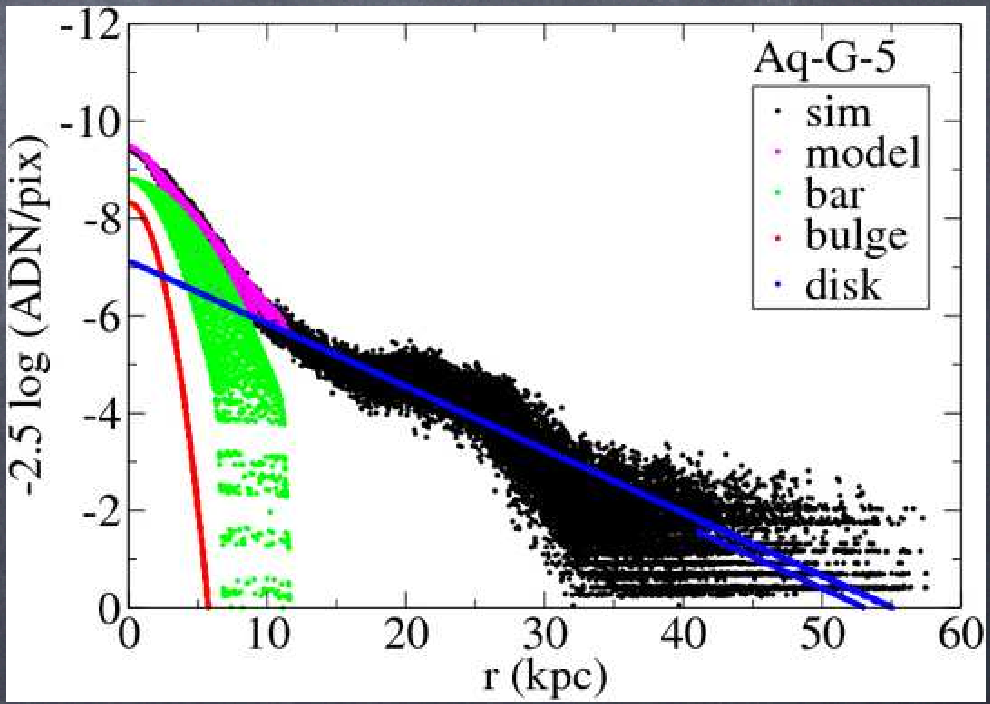


Lotz et al. (08, 10a, 10b)

Bulge/disk decompositions

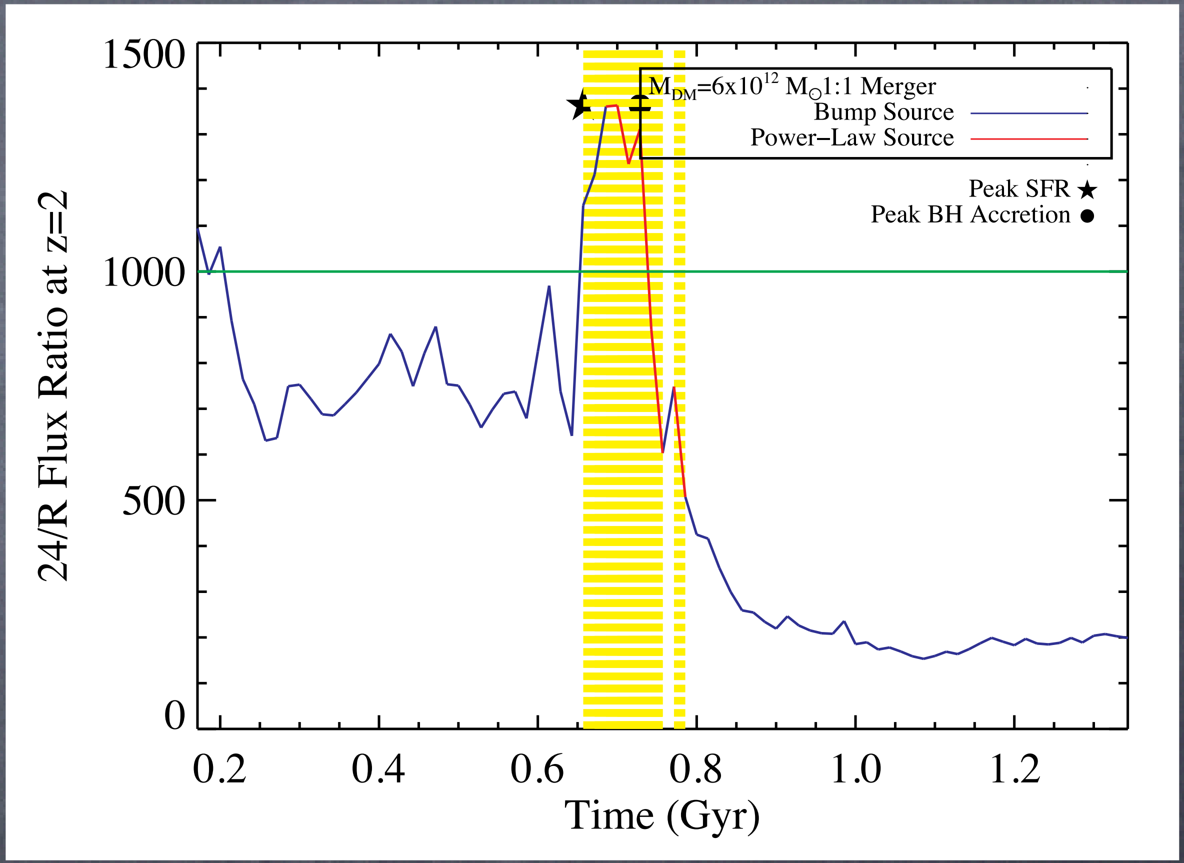
- Compare kinematic bulge/disk decomposition (as done in simulations) to photometric (as done in observations)
  - Governato et al (09)
  - Scannapieco et al (10)
- Conclusions unclear at this point





Identifying high-redshift populations

- Test if simulated merging galaxies would be selected as DOGs (Dust Obscured Galaxies) or SMGs (Submillimeter Galaxies)



Narayanan et al. (09, 10)

Summary

- Sunrise is a useful tool for making observational predictions from simulated galaxies
- Outputs match properties of observed galaxies well, but some discrepancies exist
- Real galaxies make up a more diverse set than the simulations
  - Simulated galaxy population or dust properties?
- I hope you now have a good grasp of what Sunrise is capable of and how to use it