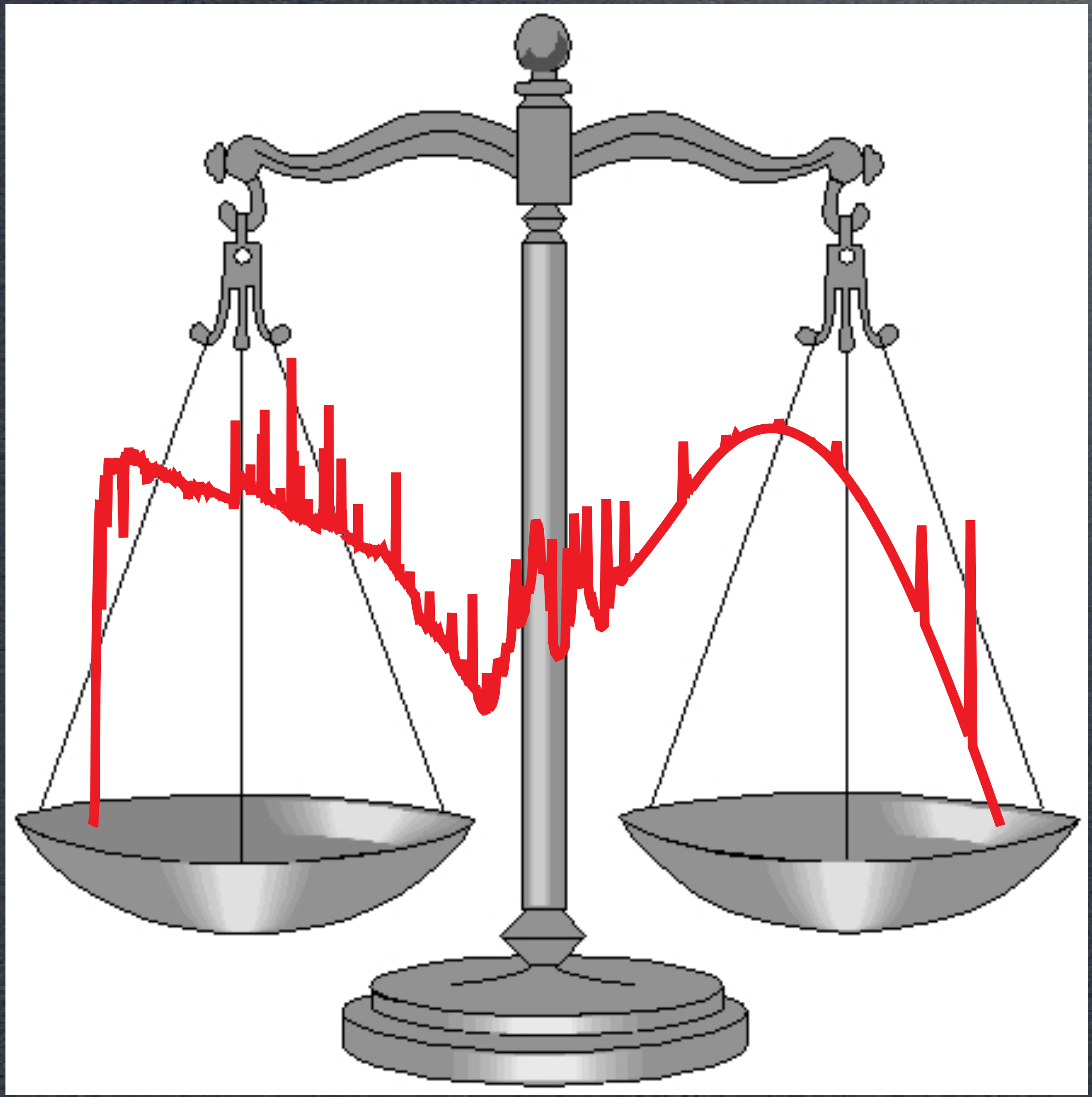
Balancing the Budget:
Energy Budgets and SEDs in Galaxies



Brent Groves
(Max Planck Institute for Astronomy)

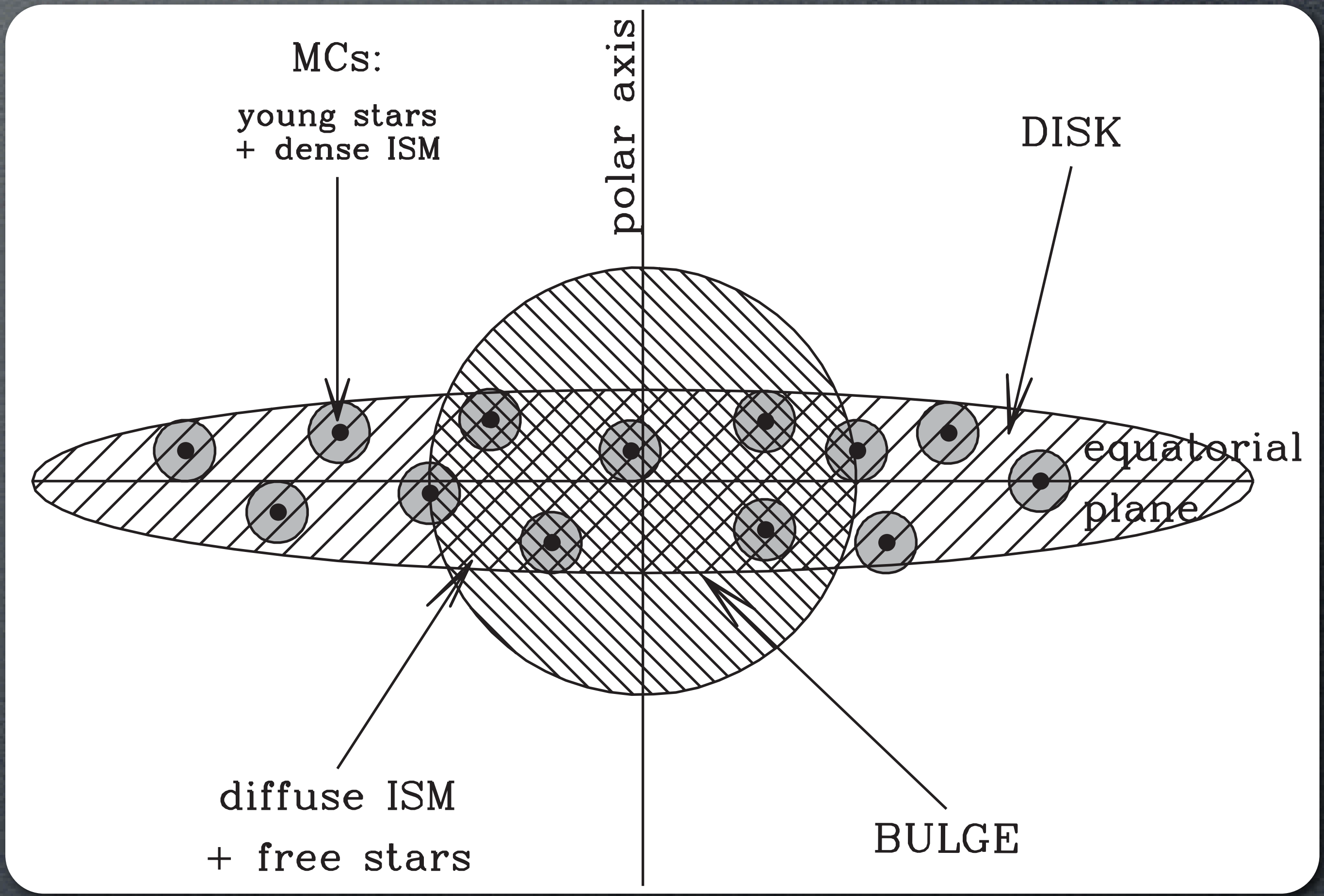
From Dust to Galaxies
1 July 2011
IAP, Paris

SED by numbers

- Thanks go to...
  - Stéphane Charlot
  - Oliver Krause
  - Eva Schinnerer
  - Michael Dopita
  - Elisabete da Cunha
  - Patrik Jonsson
  - Stefano Zibetti
  - and many more...

Making a Galaxy (UV-IR) SED

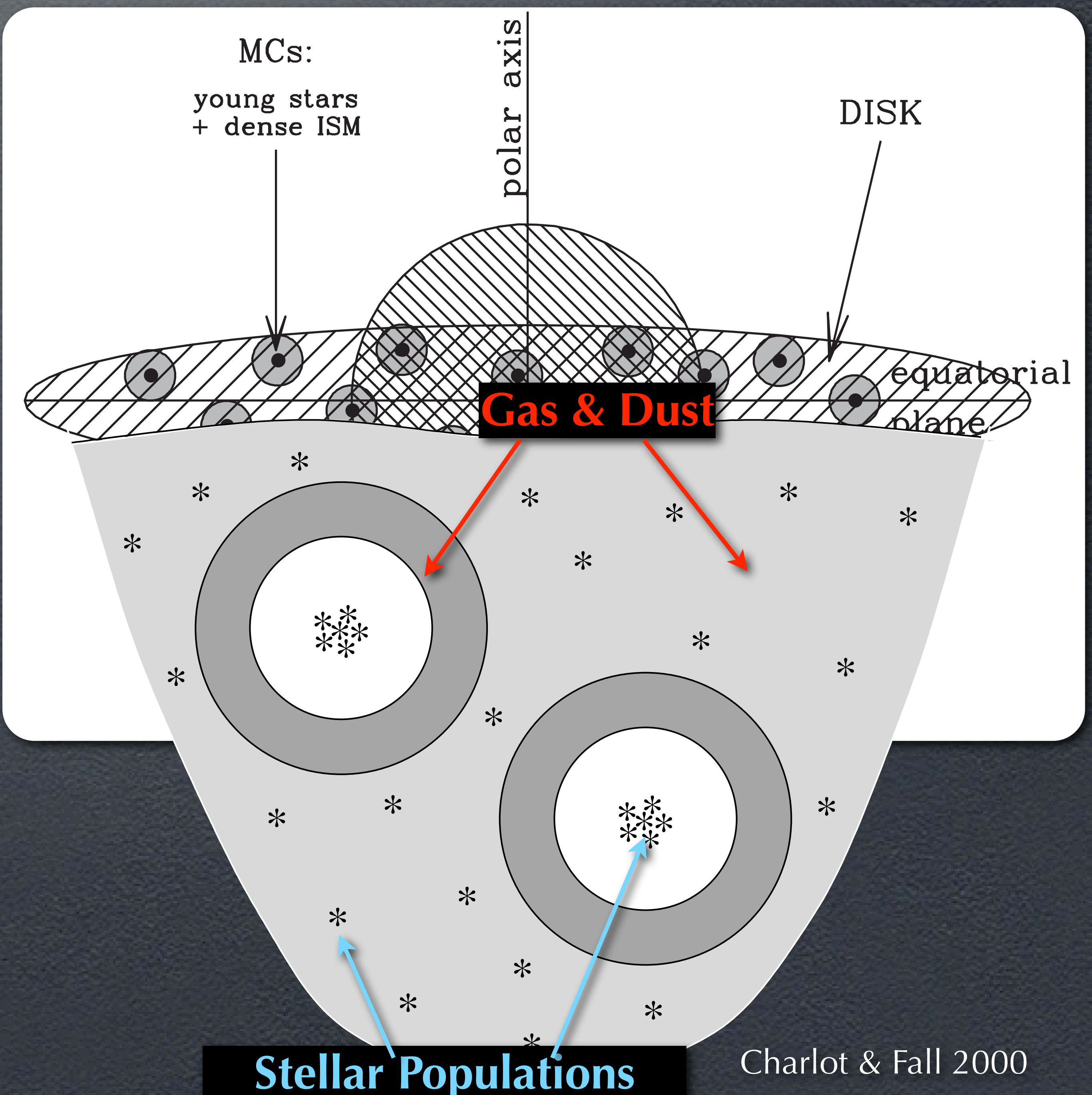
- Basically -
  - account for stars through combination of Simple Stellar Populations (SSPs)
  - Account for dust (& gas) extinction of stars
  - Account for dust (& gas) emission
- But the true trick is LINKING these together
- Do you want a DESCRIPTIVE model or INTERPRETIVE?



Granato et al. (2000)

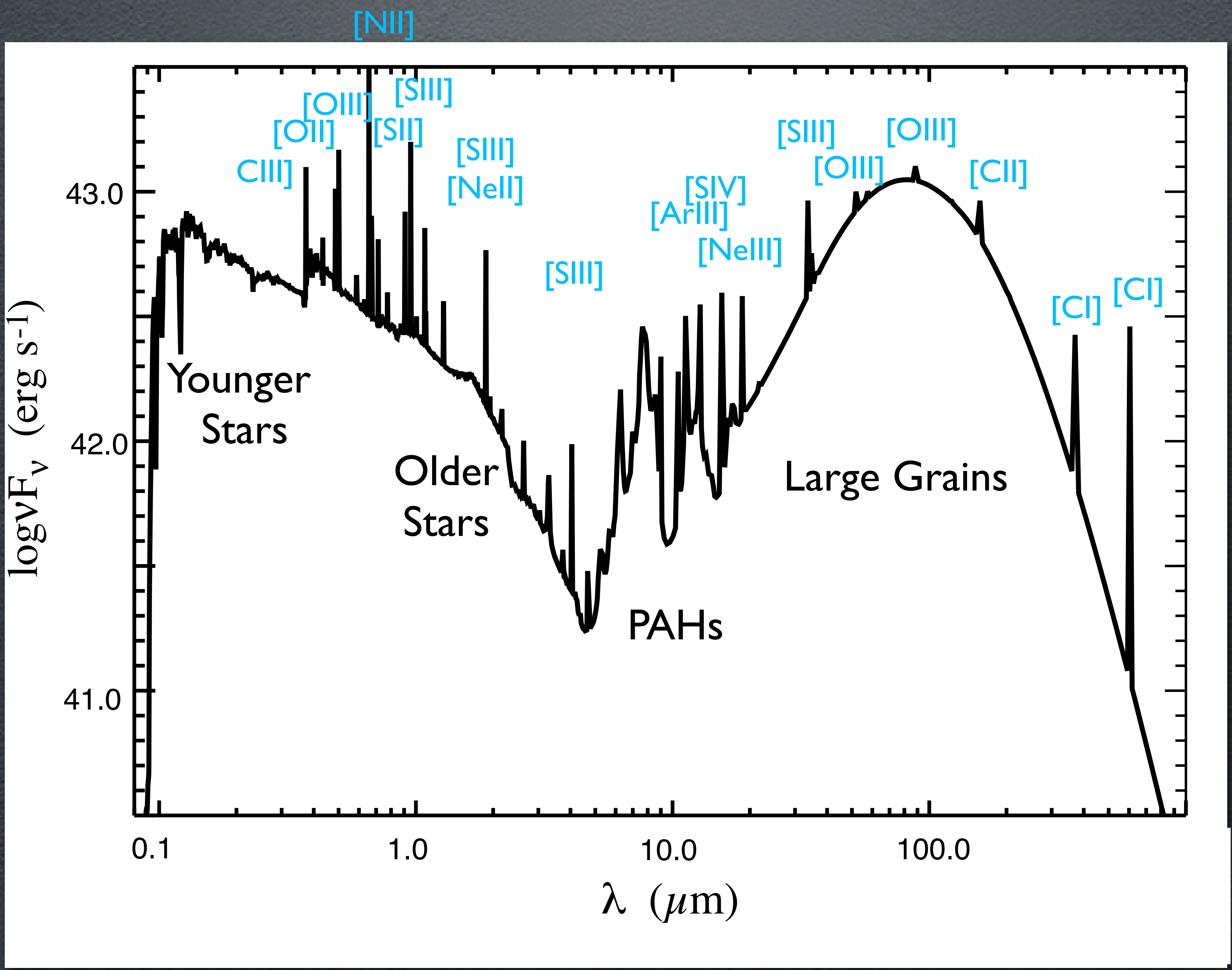
Making a Galaxy (UV-IR) SED

- Basically -
  - account for stars through combination of Simple Stellar Populations (SSPs)
  - Account for dust (& gas) extinction of stars
  - Account for dust (& gas) emission
- But the true trick is LINKING these together
- Do you want a DESCRIPTIVE model or INTERPRETIVE?



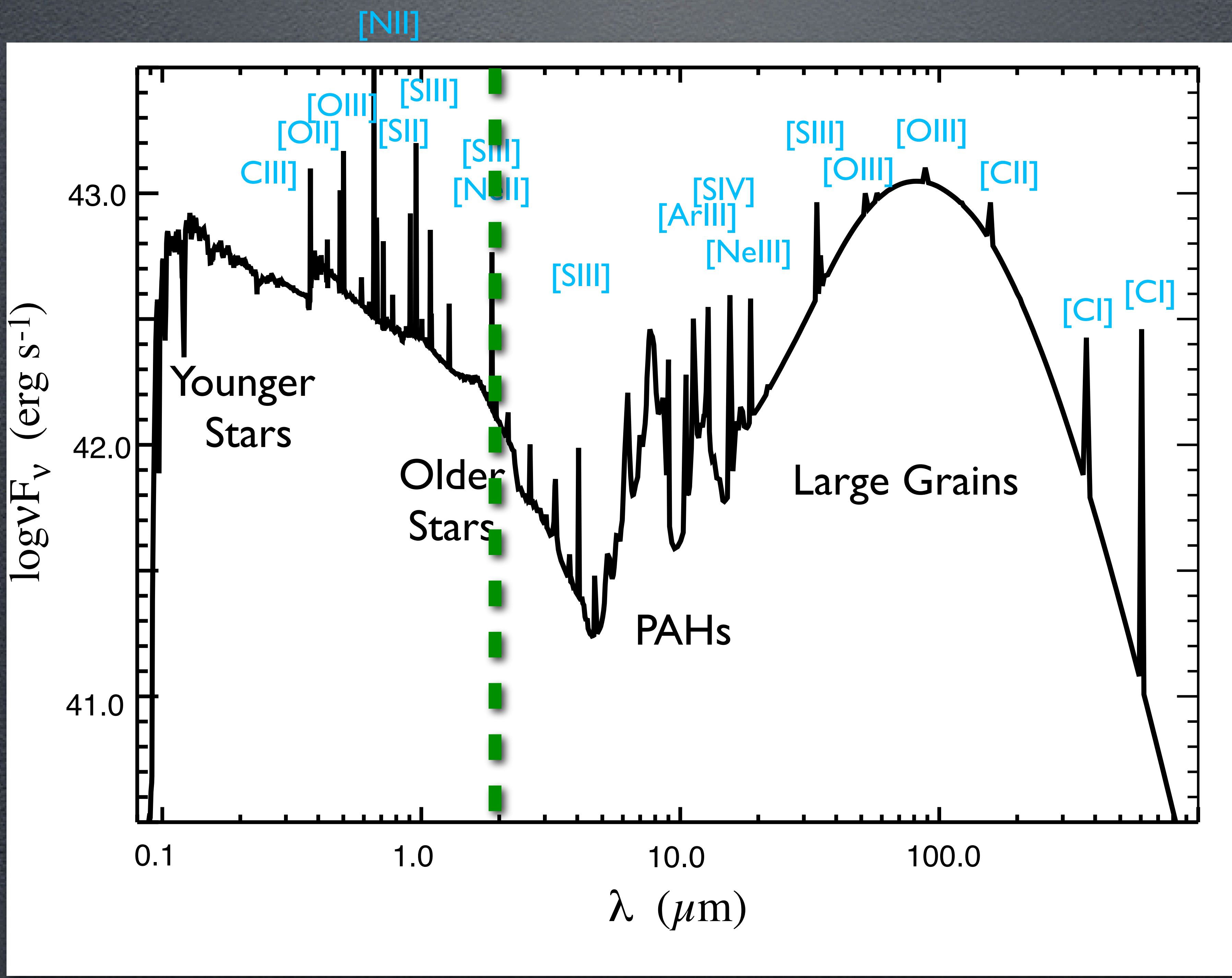
Charlot & Fall 2000

Making a Galaxy (UV-IR) SED



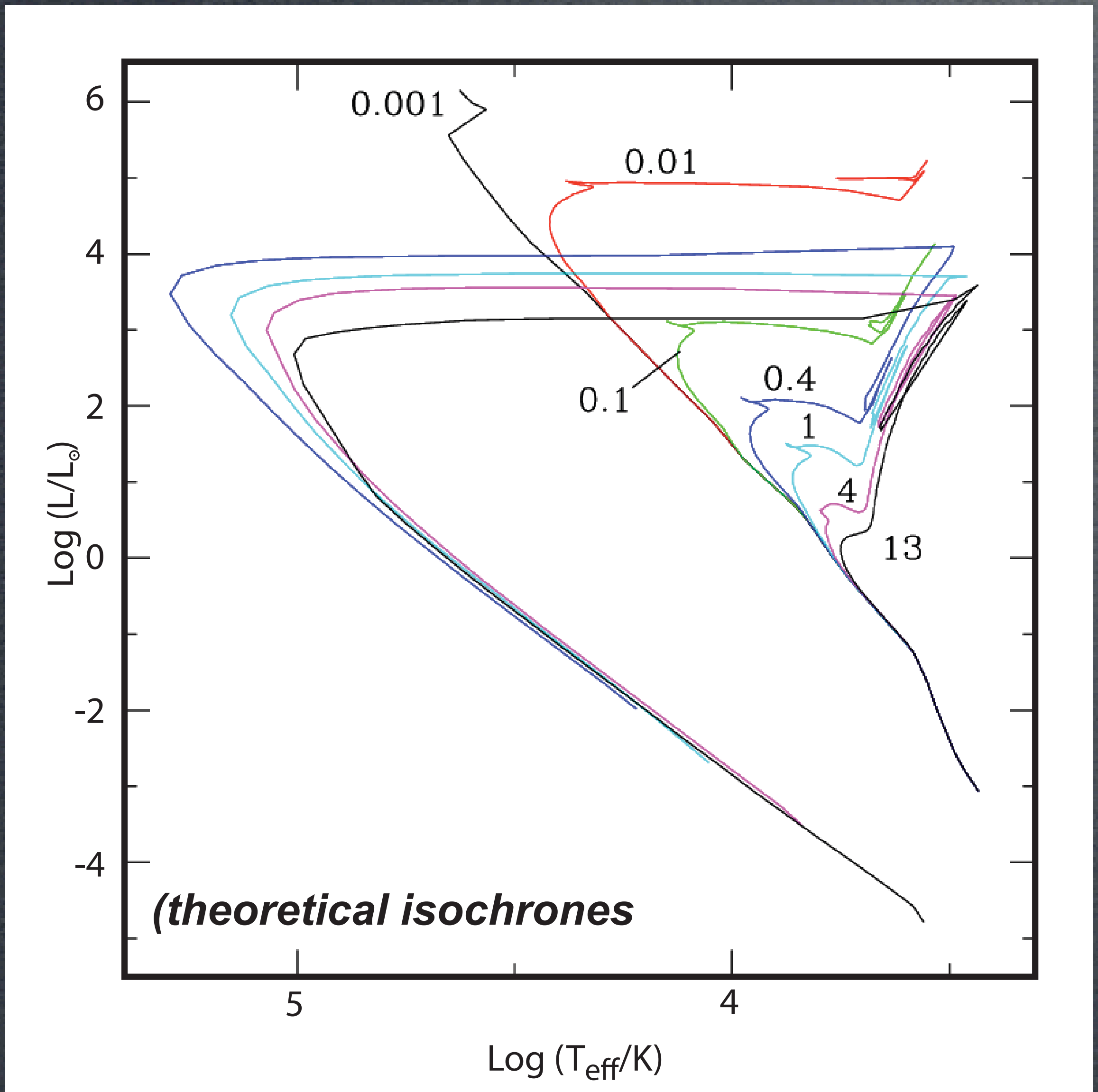
models by Groves et al. 2008 ApJS

Making a Galaxy (UV-IR) SED



models by Groves et al. 2008 ApJS

SSPs are simple!

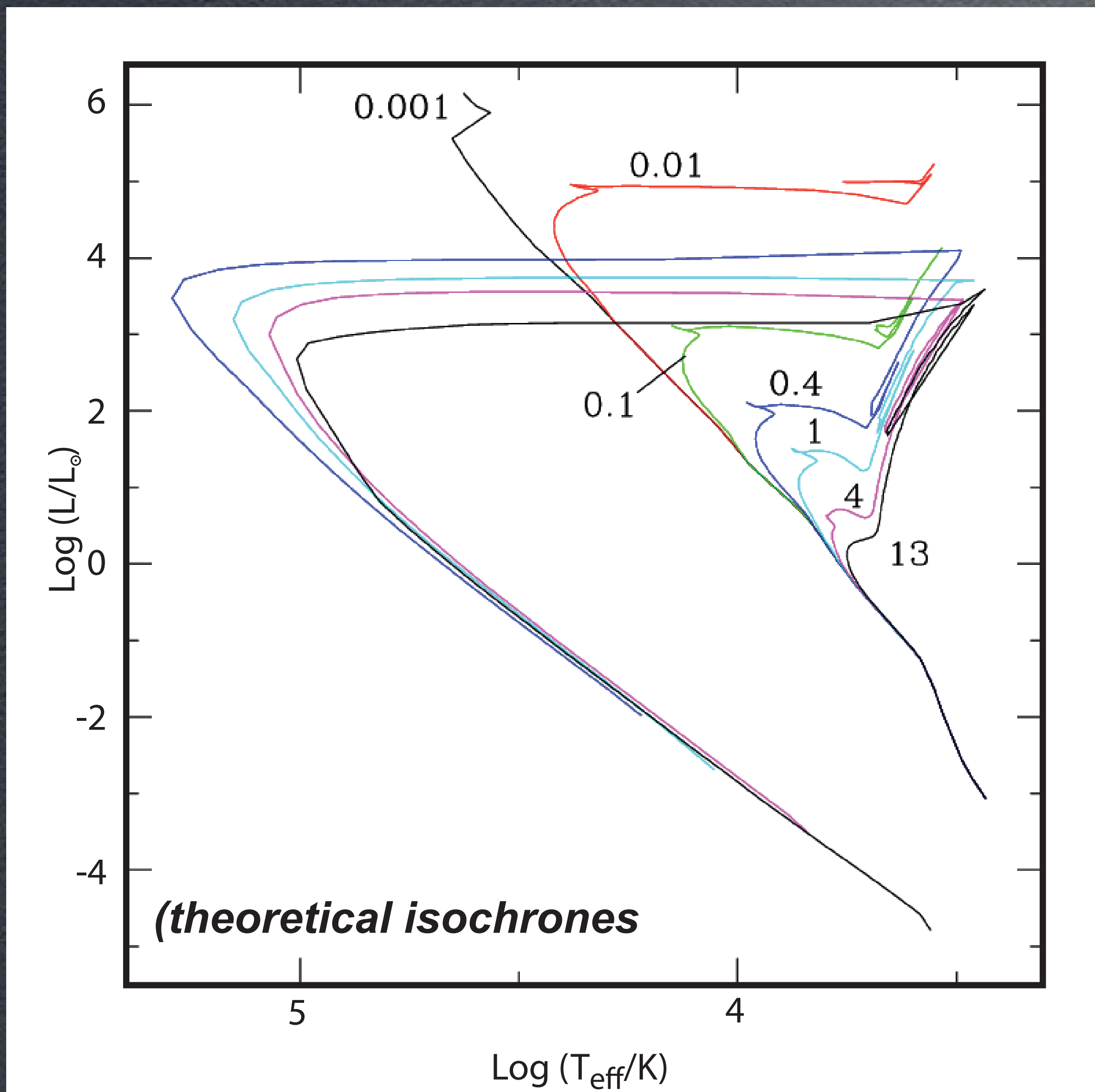


- Stellar population synthesis models give stellar spectra for a given:
  - Age
  - Metallicity
  - IMF (Kroupa, Salpeter)
  - Other params: (binarity, α/Fe, etc)

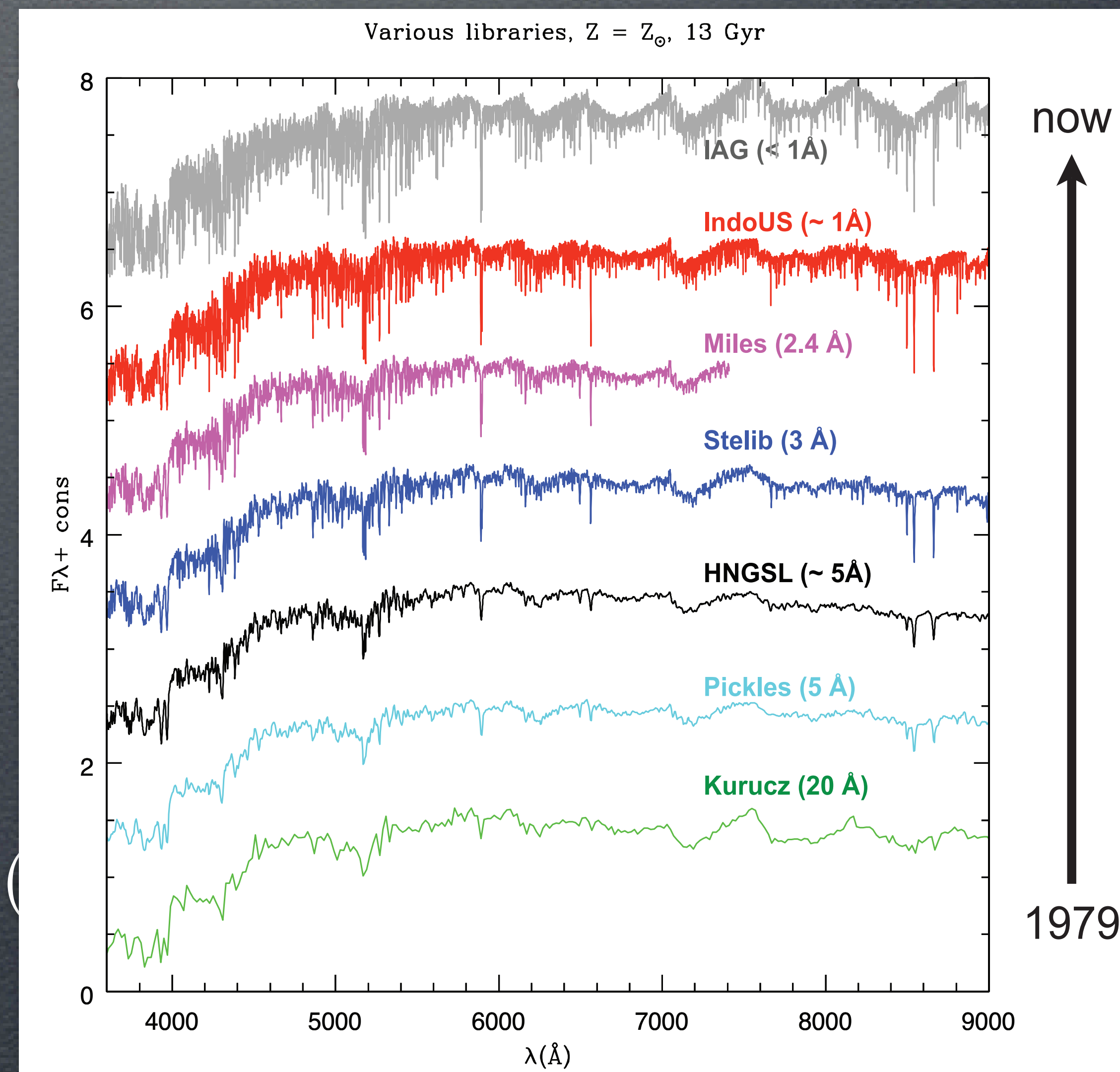
Stellar Tacks
(Padova, Geneva, etc)

Stellar Lib
(MILES,Stelib,IndoUS)

SSPs are simple!



- Stellar population synthesis models give stellar spectra for a

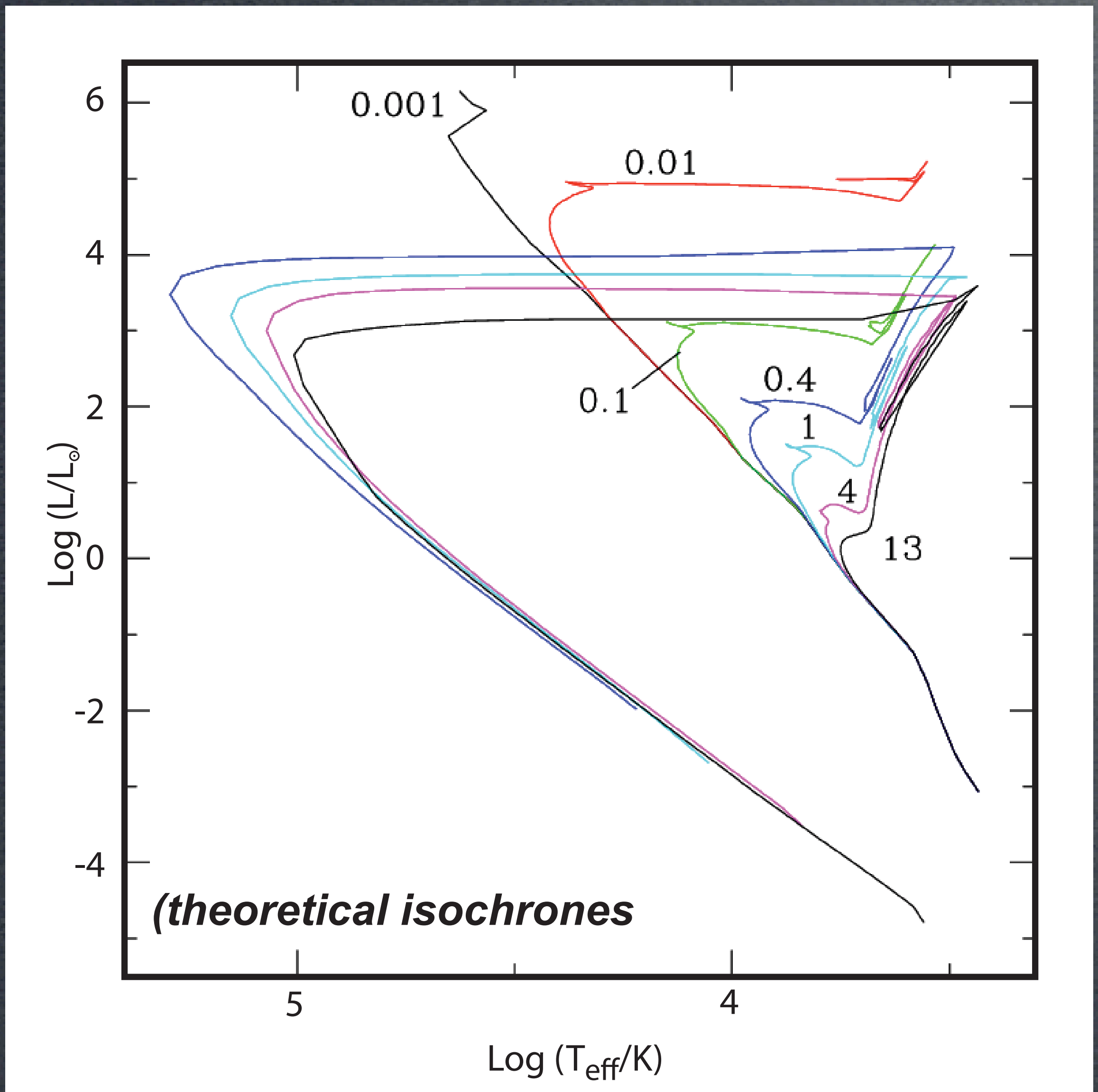


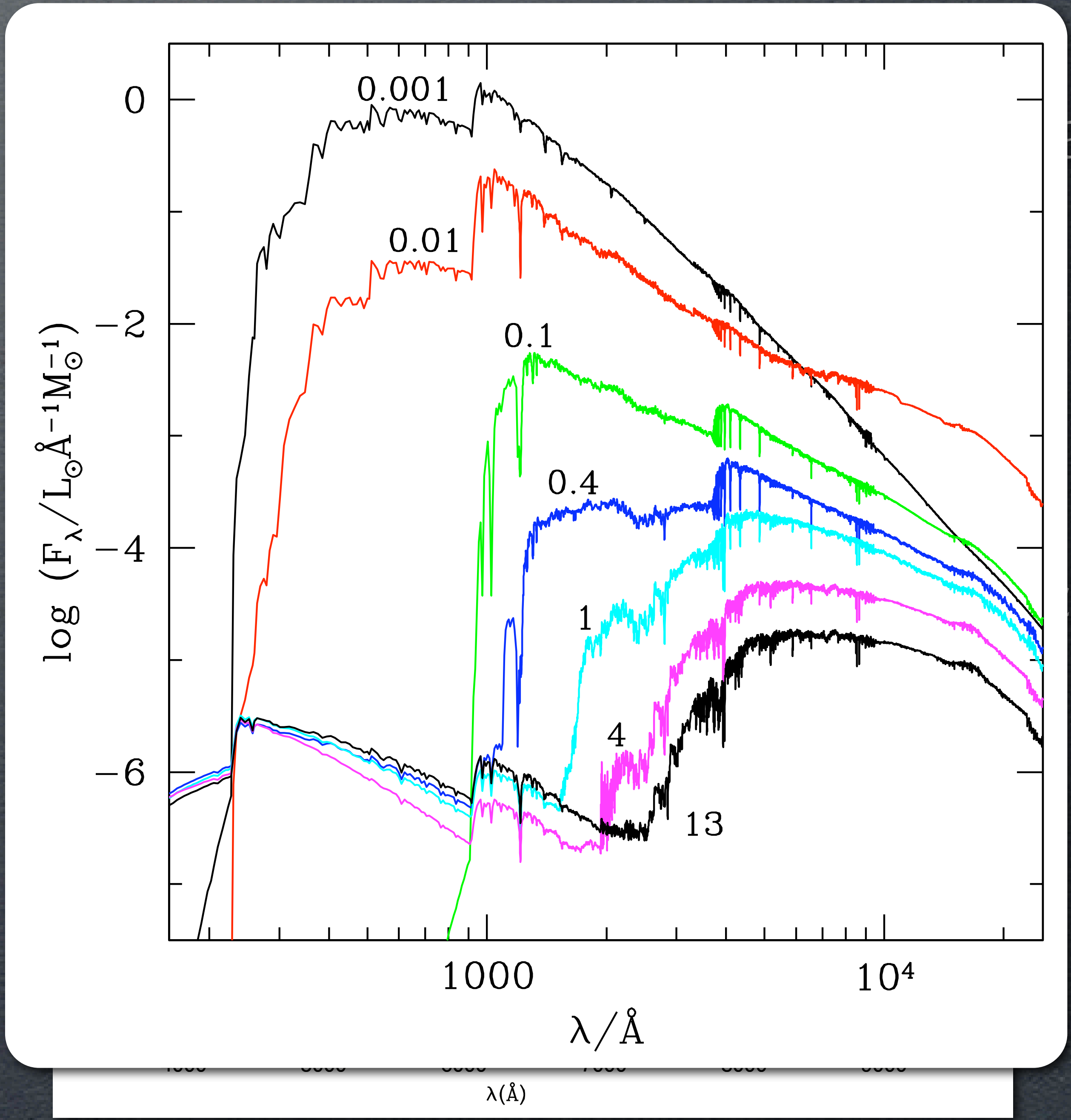
tc)

(

Stellar Lib
(MILES,Stelib,IndoUS)

SSPs are simple!

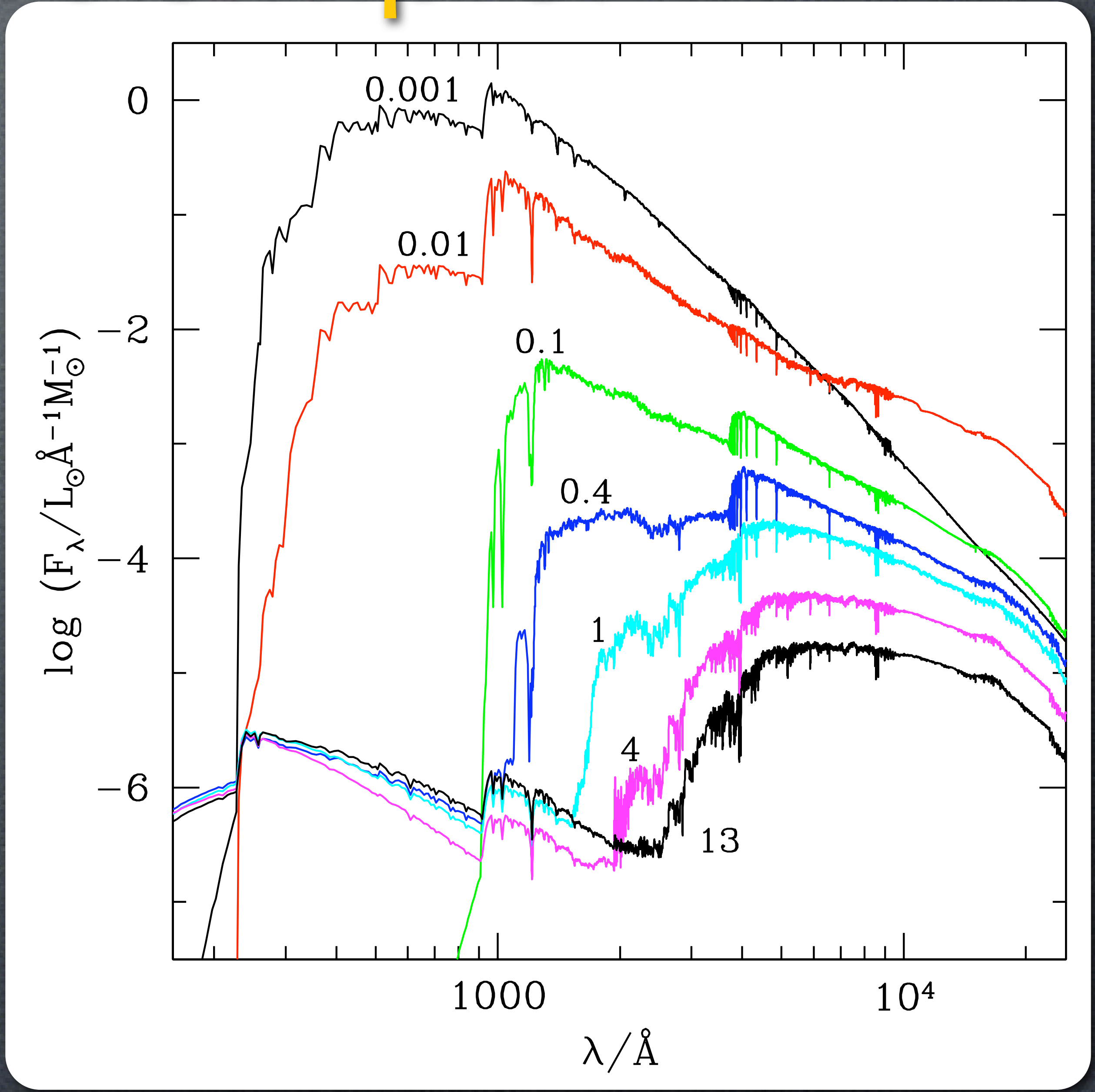




Stellar Lib
(MILES,Stelib,IndoUS)

SSPs are simple!

- Have well matched, high resolution (1-3Å) SSP spectra
- For several metallicities, even abundance variations (eg α/Fe, Coelho et al. (2008))
- Several codes exist for the creation of these:
  - eg BC03, Maraston05, Starburst99, PEGASE, etc



models from Bruzual & Charlot (2003)

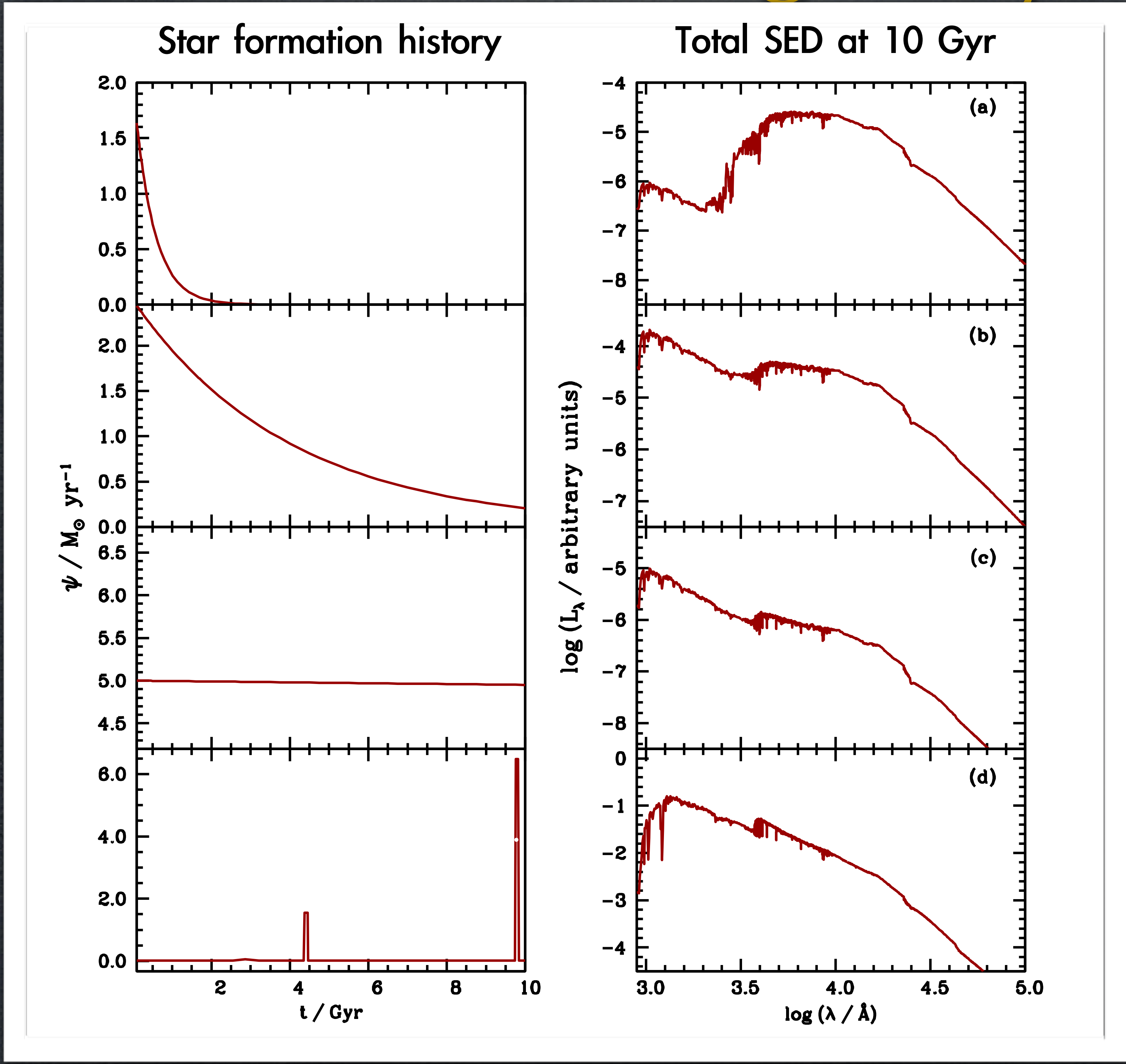
A star is born...

- Basic idea: Every galaxy is a sum of simple stellar populations (SSPs)

$$L_*(\lambda, t) = \int_0^t f_{\rm SSP}(\lambda, \tau, Z, \ldots)\mathrm{SFR}(t-\tau)d\tau$$

- SFR(t-τ) is the star formation rate (mass per unit time) at age (t-τ)
- $f_{\rm SSP}$ is the luminosity (per mass) of a stellar population of age τ and metallicity Z, created:
  - assuming an IMF (#stars per mass)
  - an isochrone: distribution of stars of Mass M with $T_{\rm eff}$ - gravity
  - stellar templates: spectral shape given $T_{\rm eff}$ and g

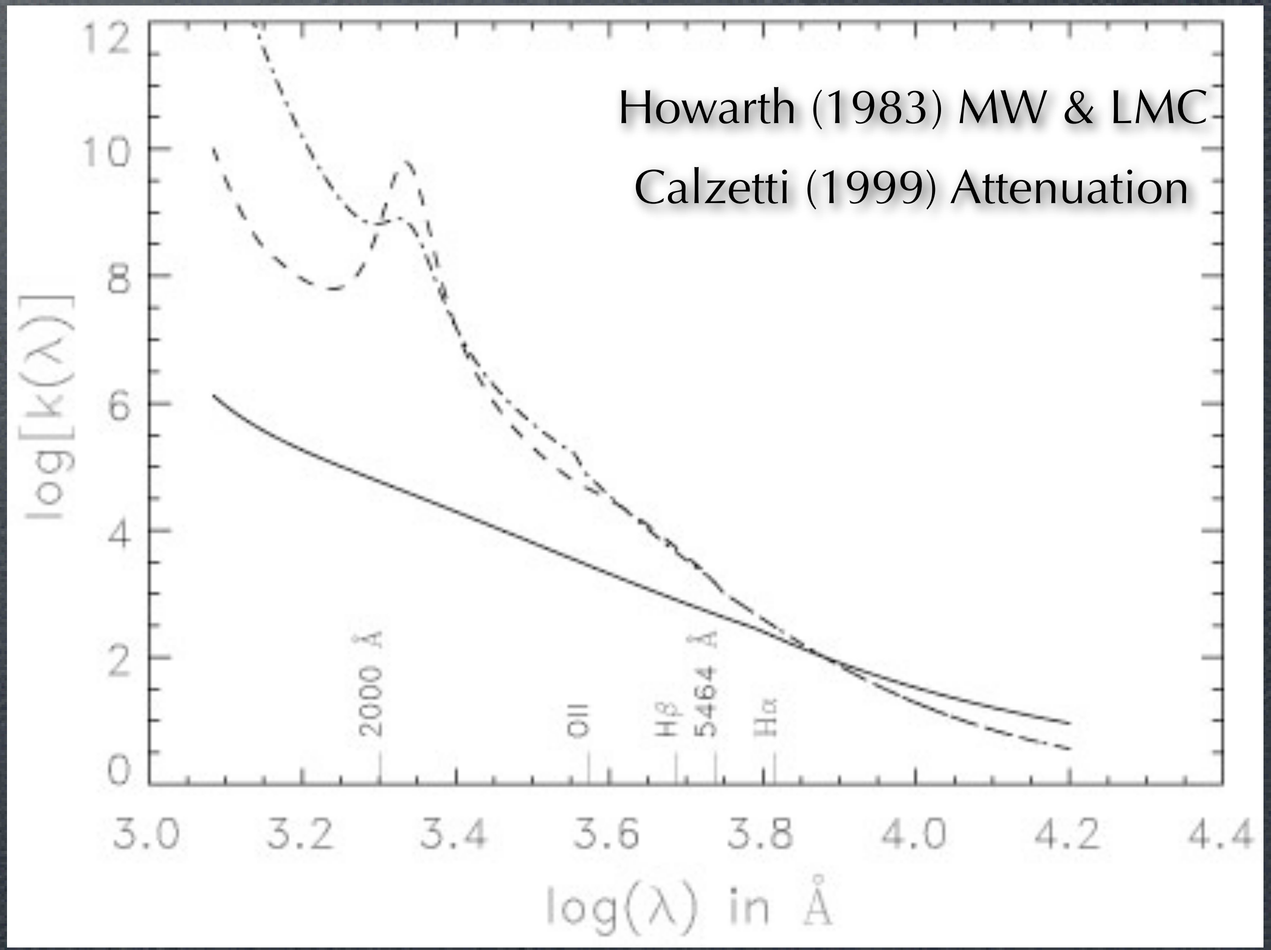
...and makes a galaxy?



Brent Groves

Not a clear picture

- Of course the stars are obscured by gas & dust
- Can use simple screen/ mixed extinction law



Rosa-González et al. 2002

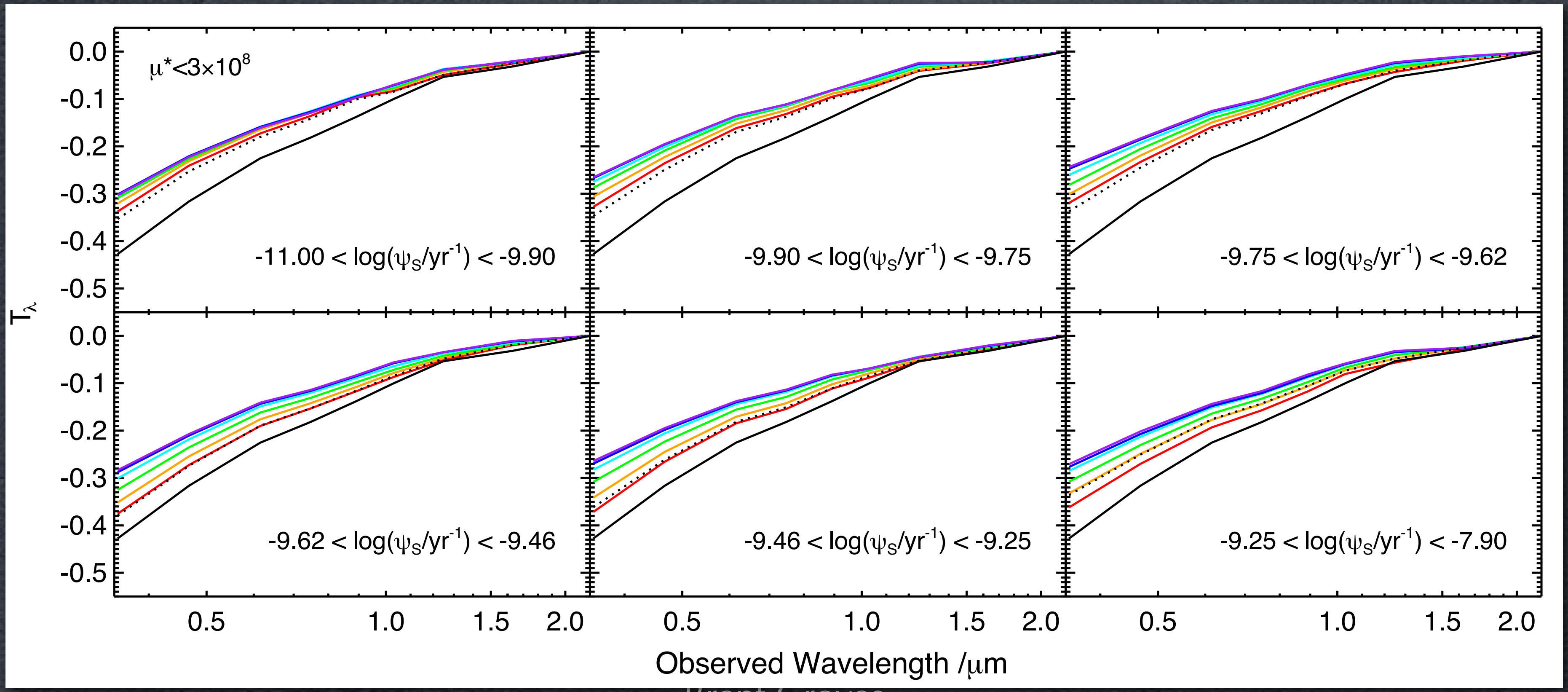
Not a clear picture

- Of course the stars are obscured by gas & dust
- Can use simple screen/mixed extinction law
- Use a more complex attenuation law (i.e scattering)

Not a clear picture

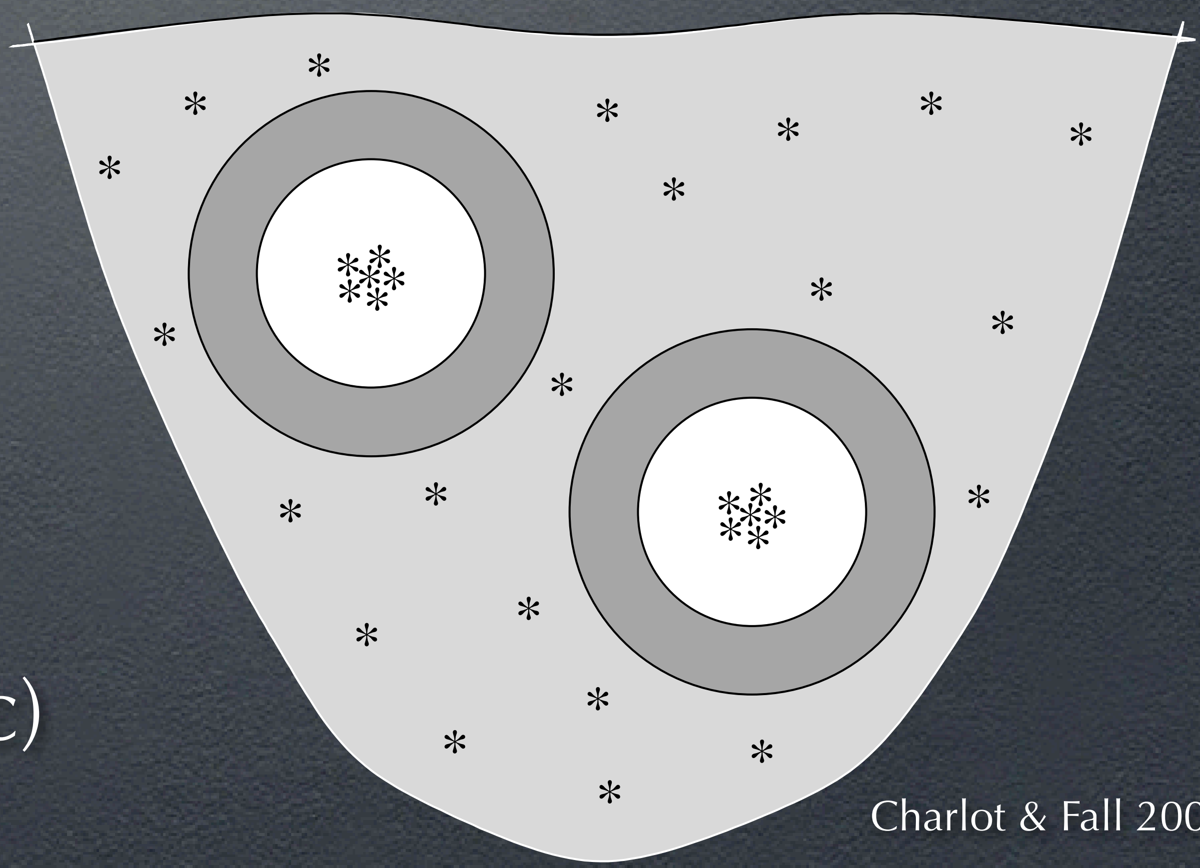
- Of course the stars are obscured by gas & dust
- Can use simple screen/mixed extinction law
- Use a more complex attenuation law (i.e scattering)

Wild et al. (2011)



Not a clear picture

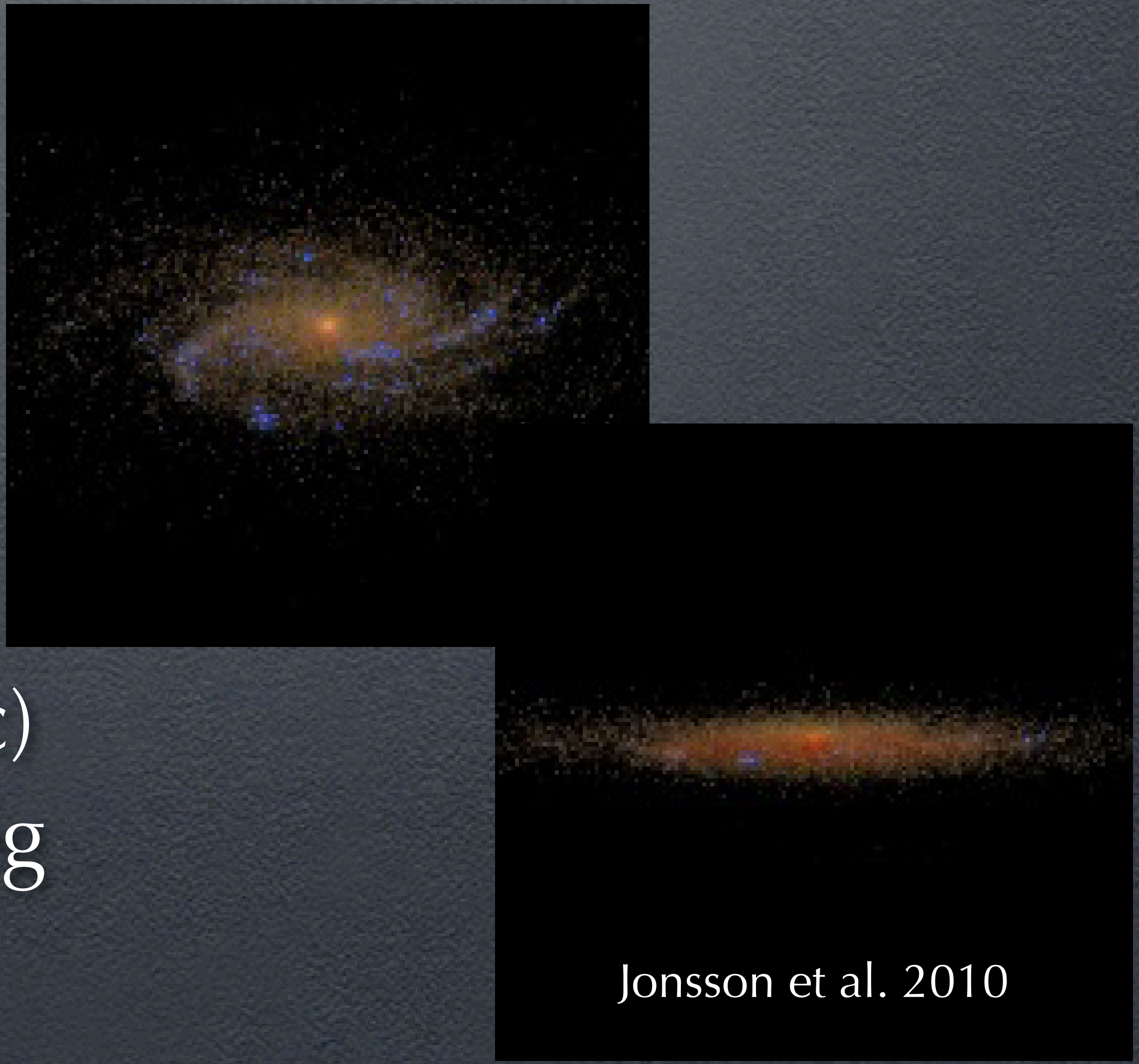
- Of course the stars are obscured by gas & dust
- Can use simple screen/ mixed extinction law
- Use a more complex attenuation law (i.e scattering)
- Use two (or more) phase attenuation (young & old star, disk & bulge/halo, etc)



Charlot & Fall 2000

Not a clear picture

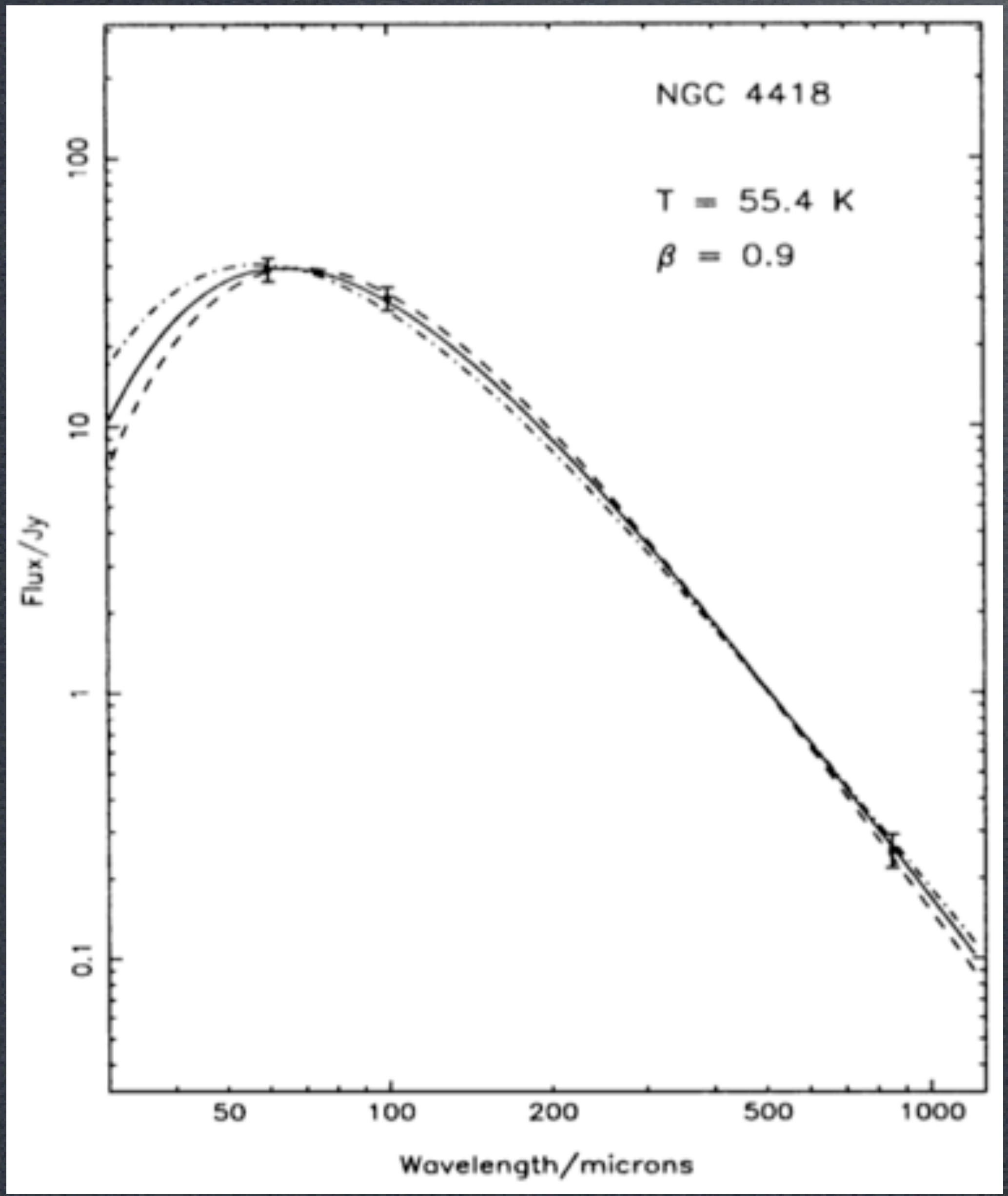
- Of course the stars are obscured by gas & dust
- Can use simple screen/ mixed extinction law
- Use a more complex attenuation law (i.e scattering)
- Use two (or more) phase attenuation (young & old star, disk & bulge/halo, etc)
- Or full radiative transfer (eg SUNRISE, DIRTY, etc)



Jonsson et al. 2010

Feeling the Heat

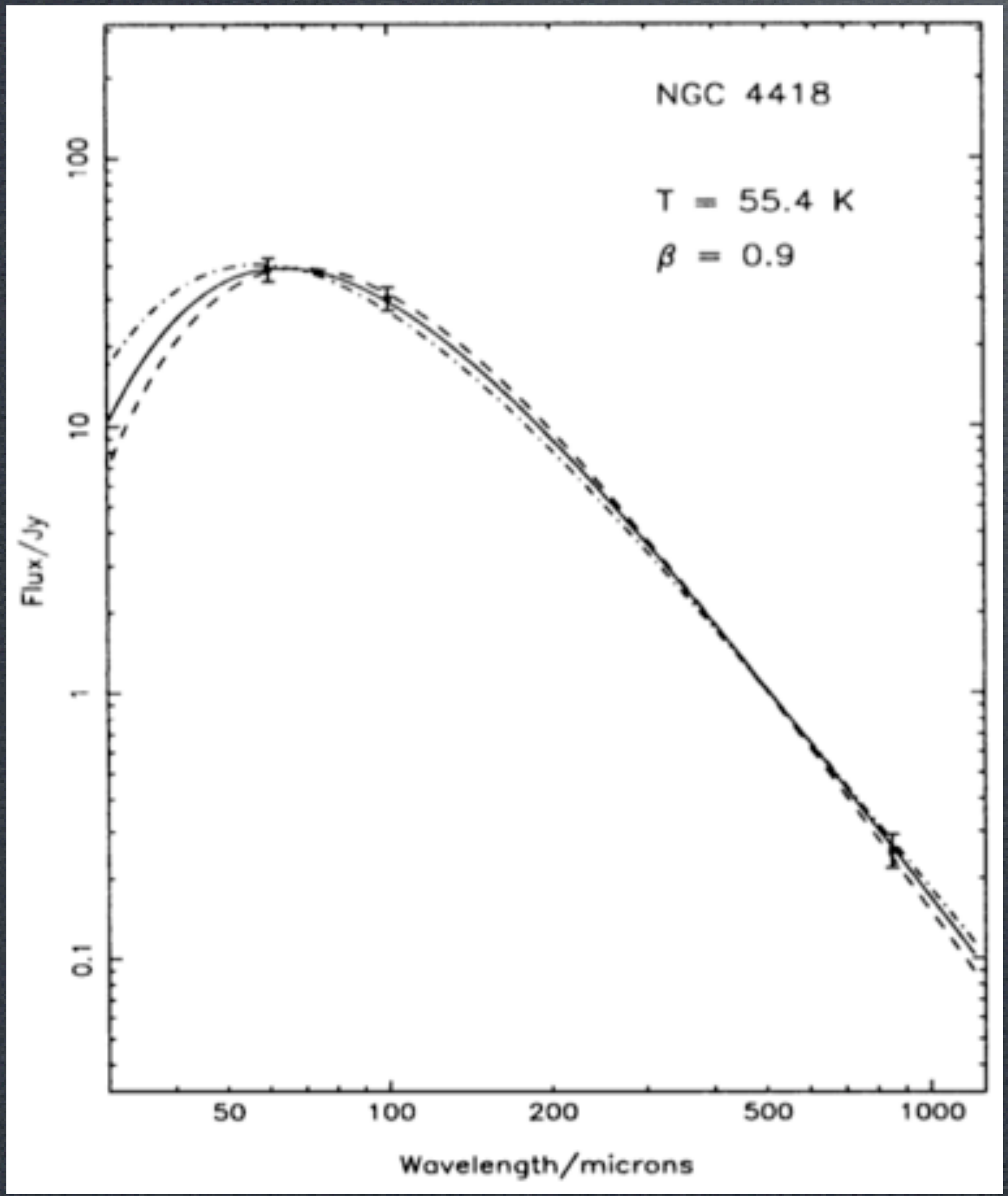
- In most modelling treatments, IR emission is 'simply' a sum of emmisivity modified blackbodies



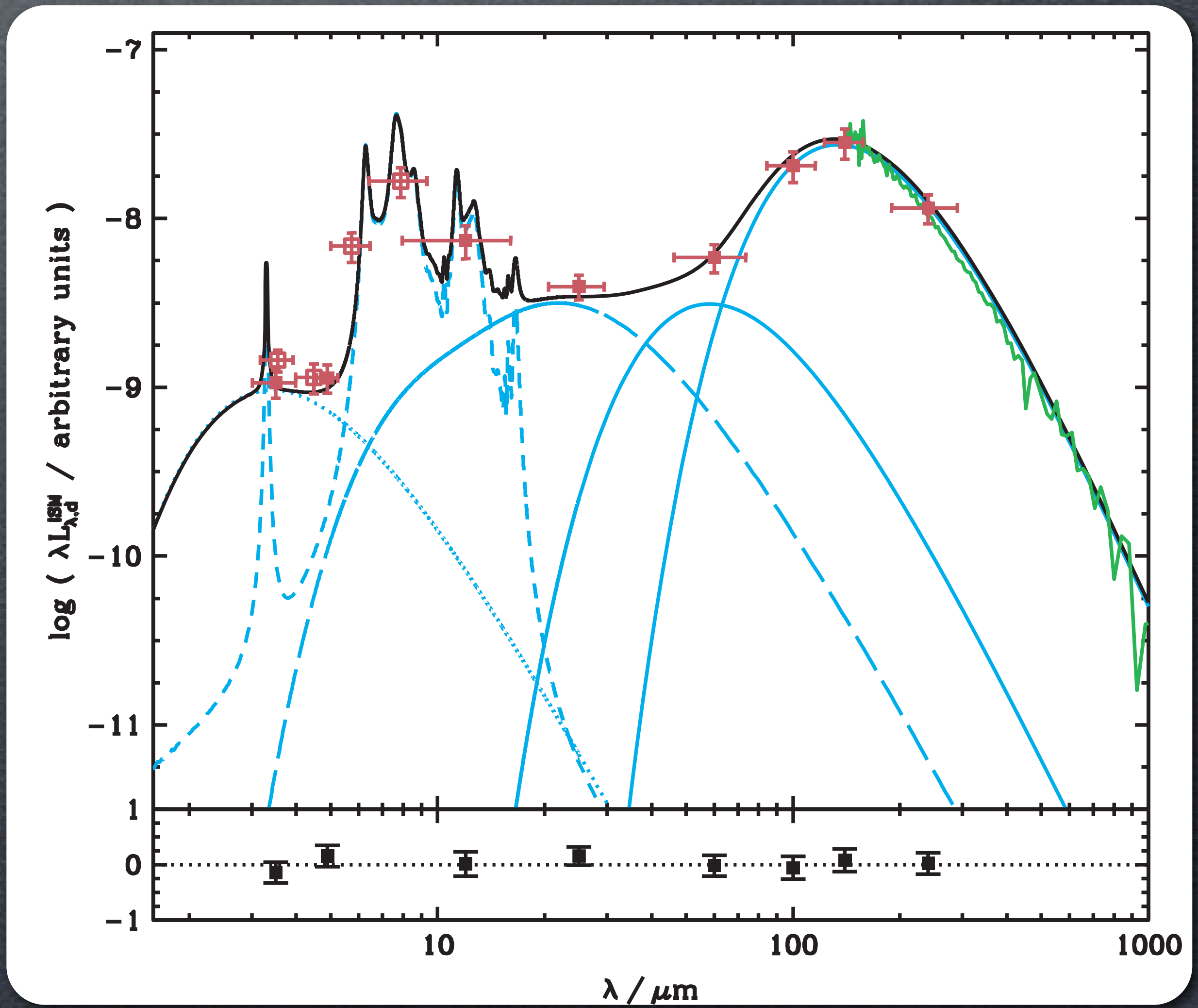
Dunne et al. 2000

Feeling the Heat

- In most modelling treatments, IR emission is ‘simply’ a sum of emmisivity modified blackbodies



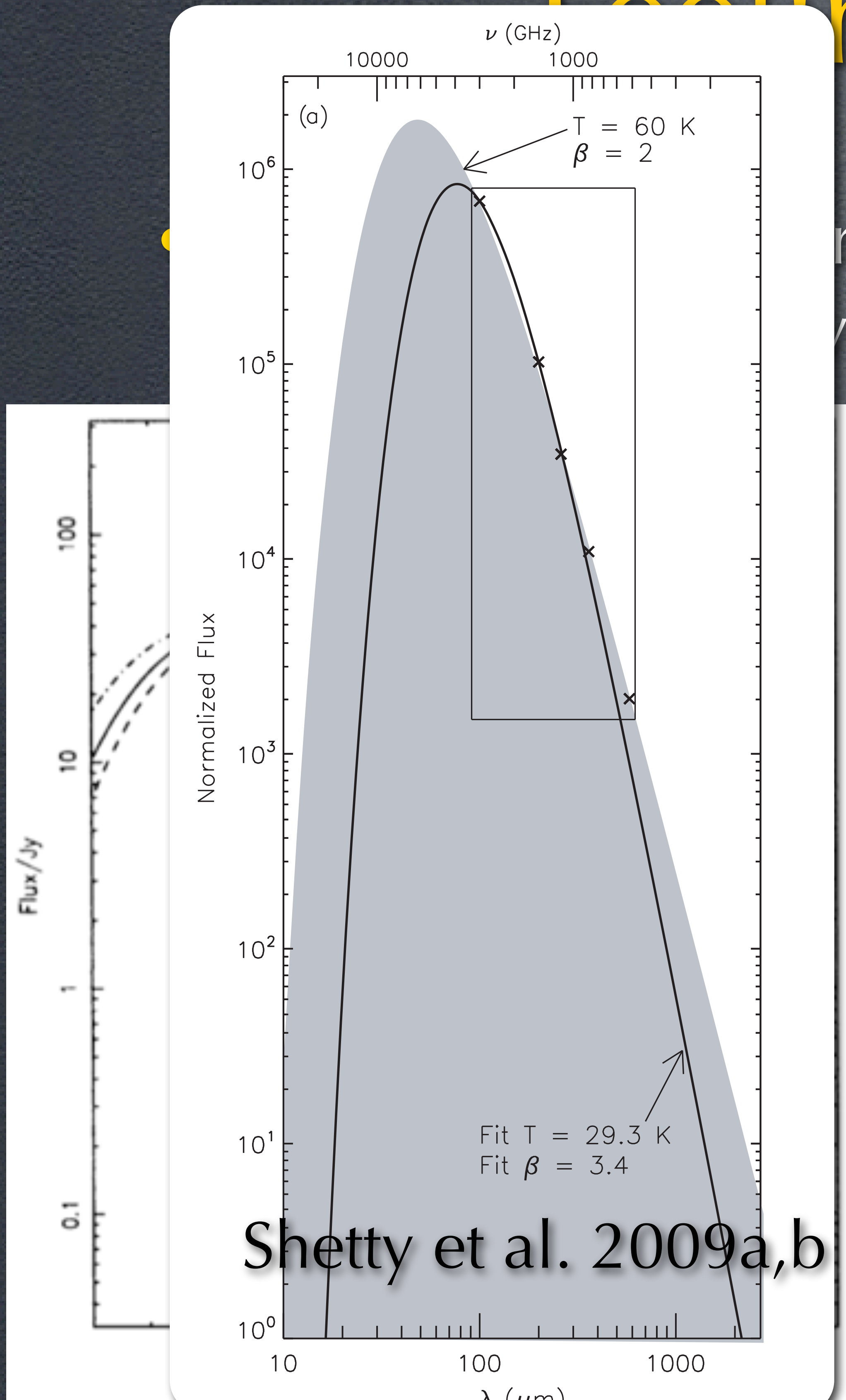
Dunne et al. 2000



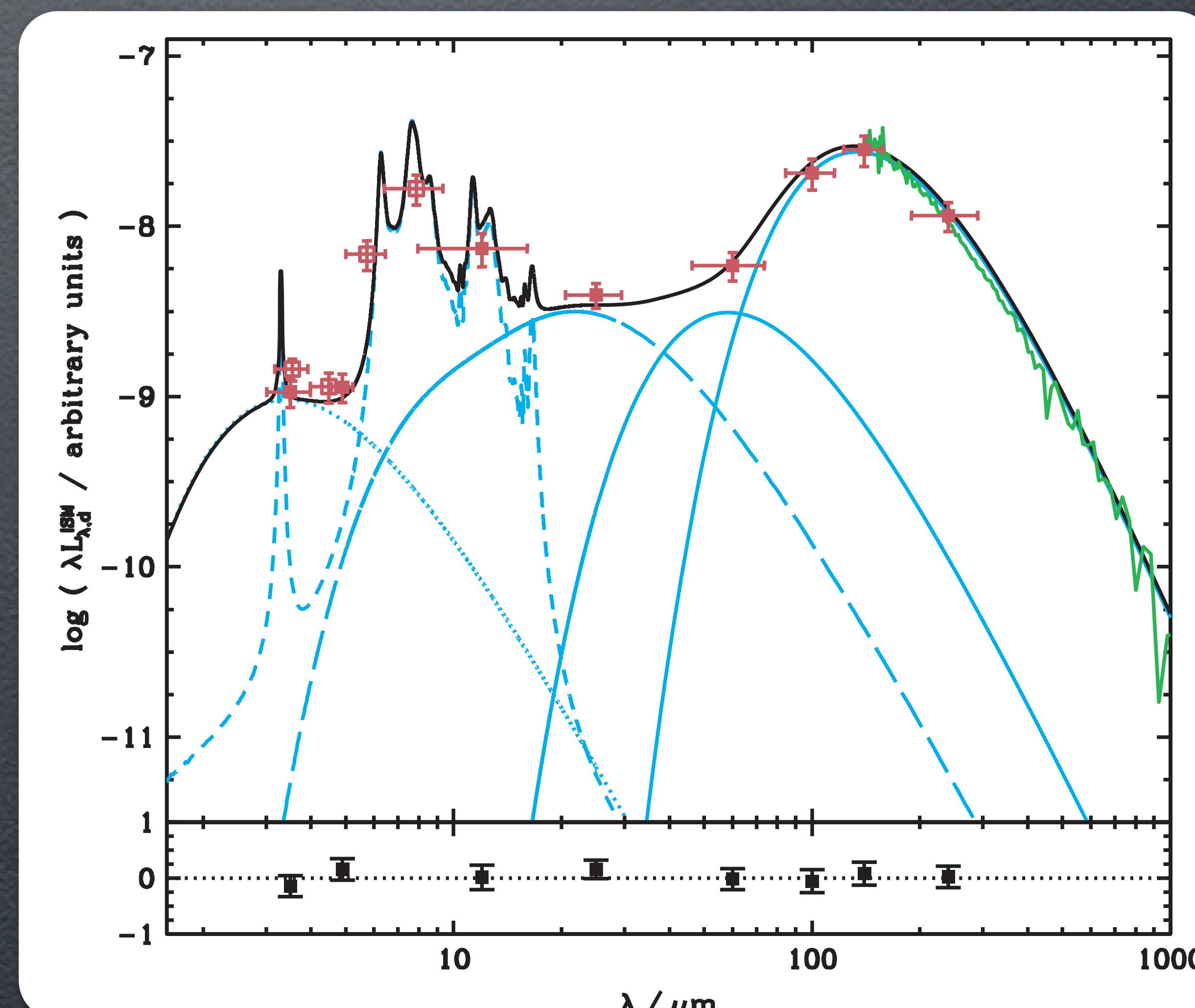
da Cunha et al. 2008

Feeling the Heat

- ...reatments, IR emission is 'simply' ... modified blackbodies



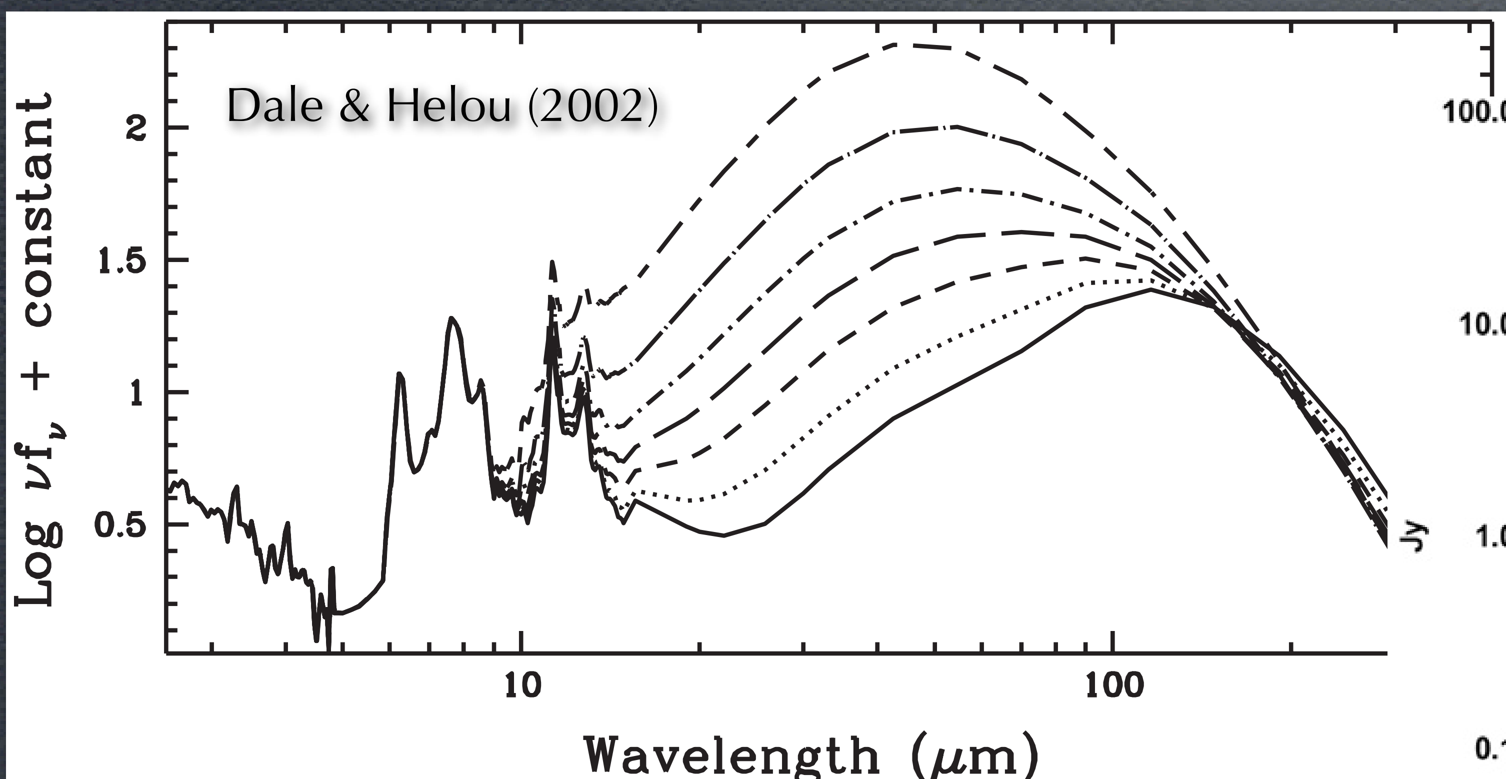
Dunne et al. 2000

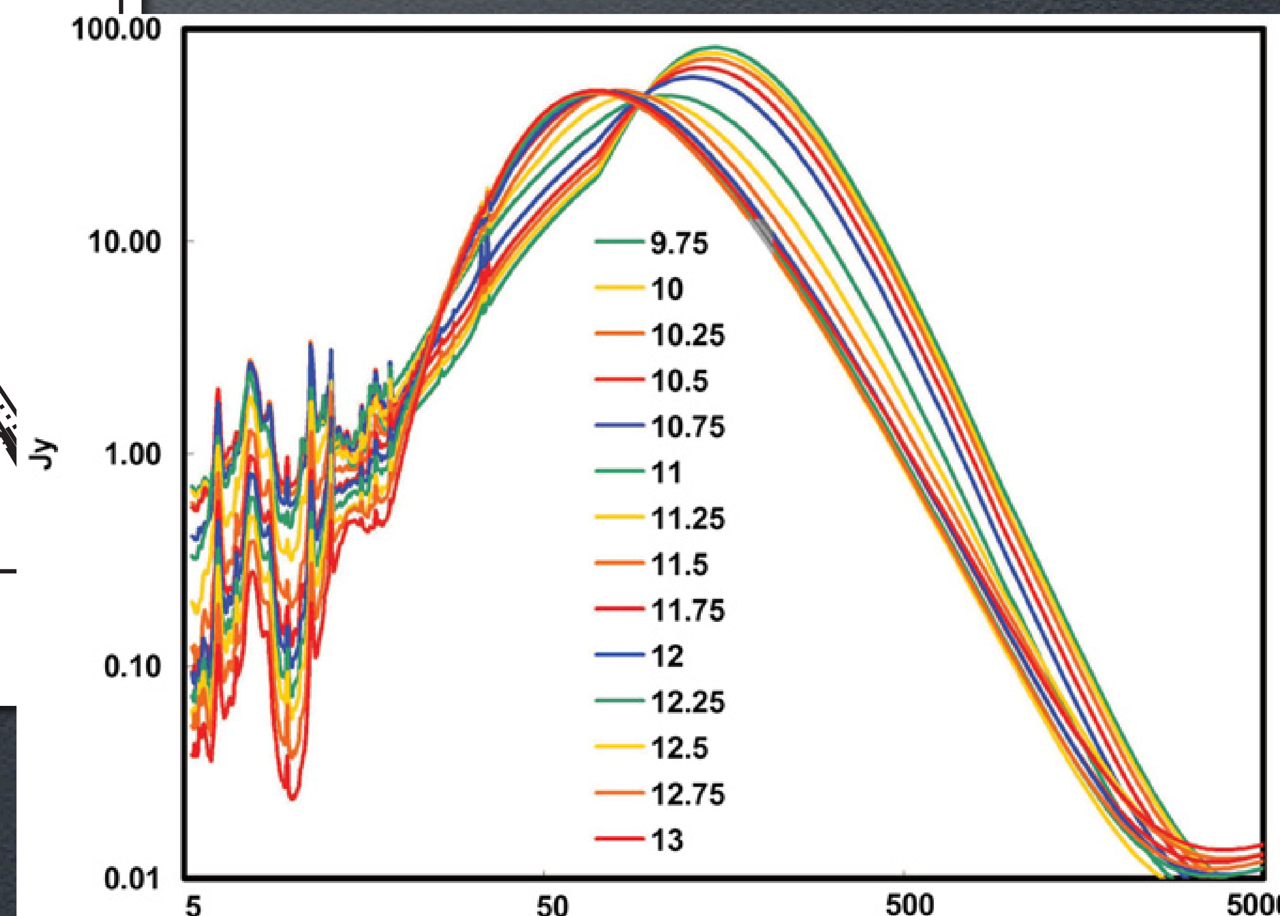


da Cunha et al. 2008

Feeling the Heat

- In most modelling treatments, IR emission is 'simply' a sum of emmisivity modified blackbodies
- Extended to semi-empirical parameterized by Luminosity or Heating intensity



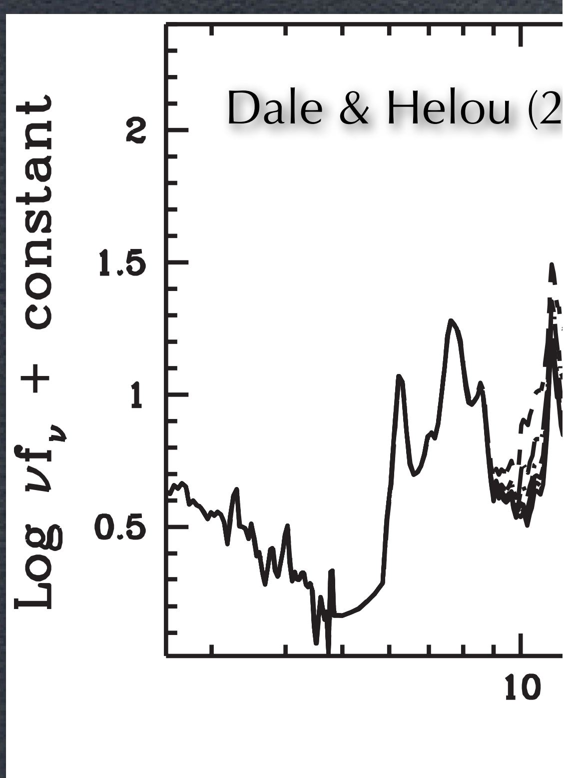


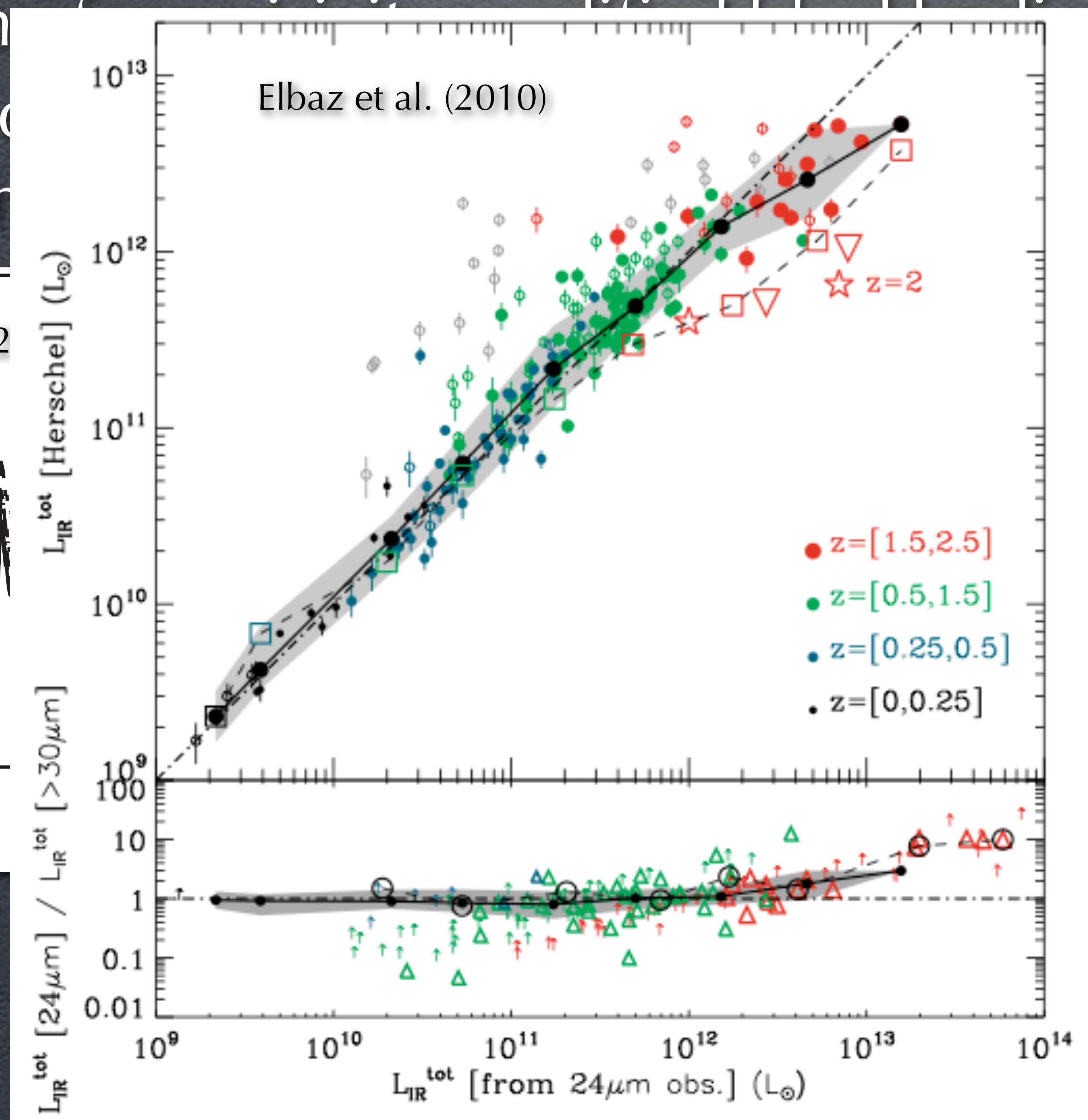
Rieke et al. (2009)

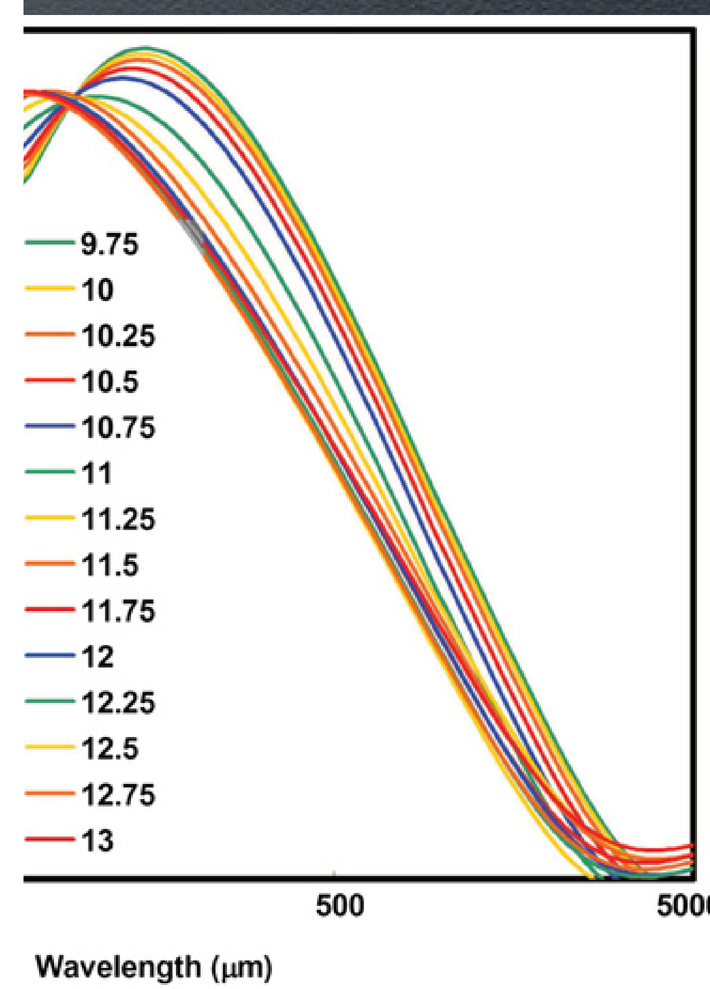
Brent Groves

Feeling the Heat

- In most modelling treatments, IR emission is ‘simply’ a sum … s
- Extend … d by Lumin …

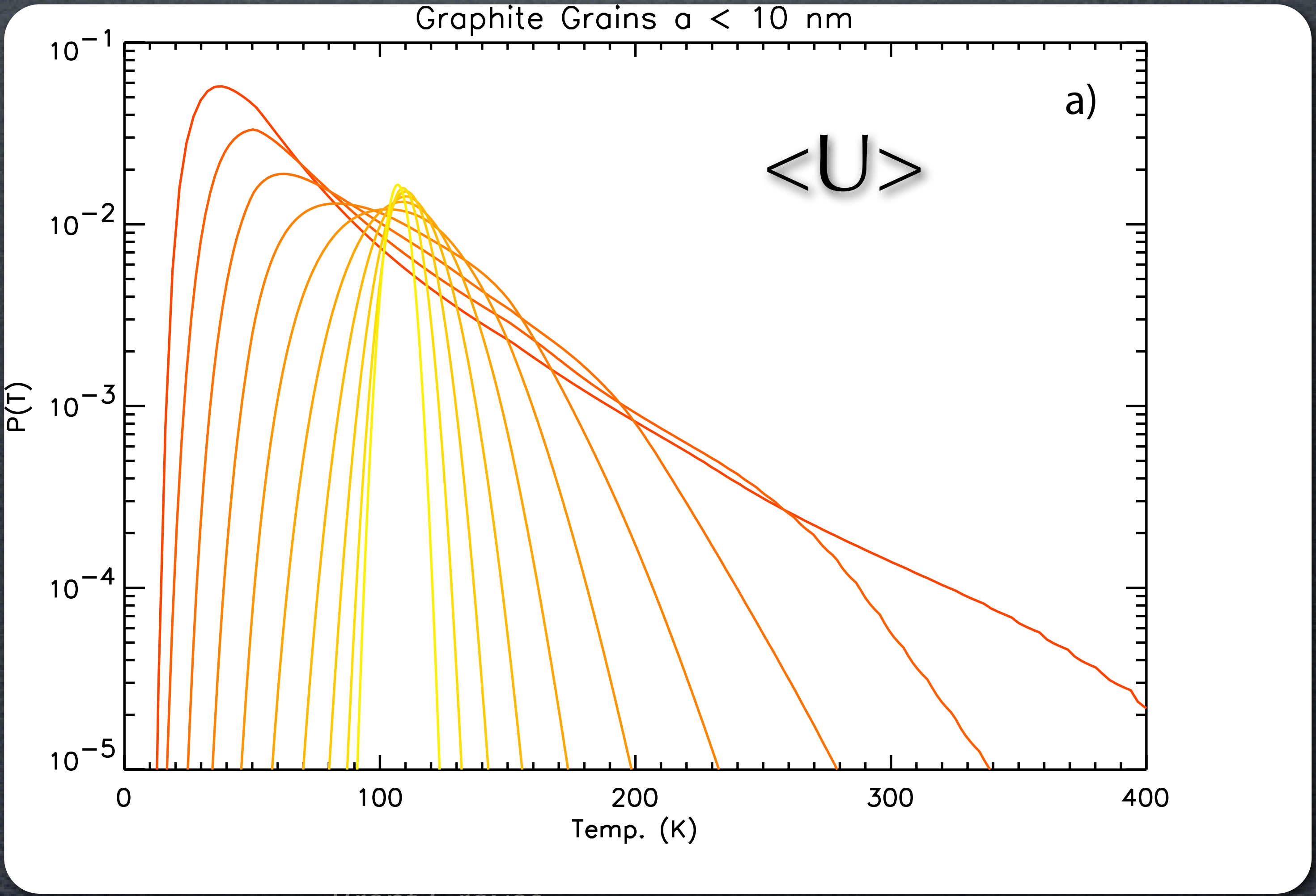






Feeling the Heat

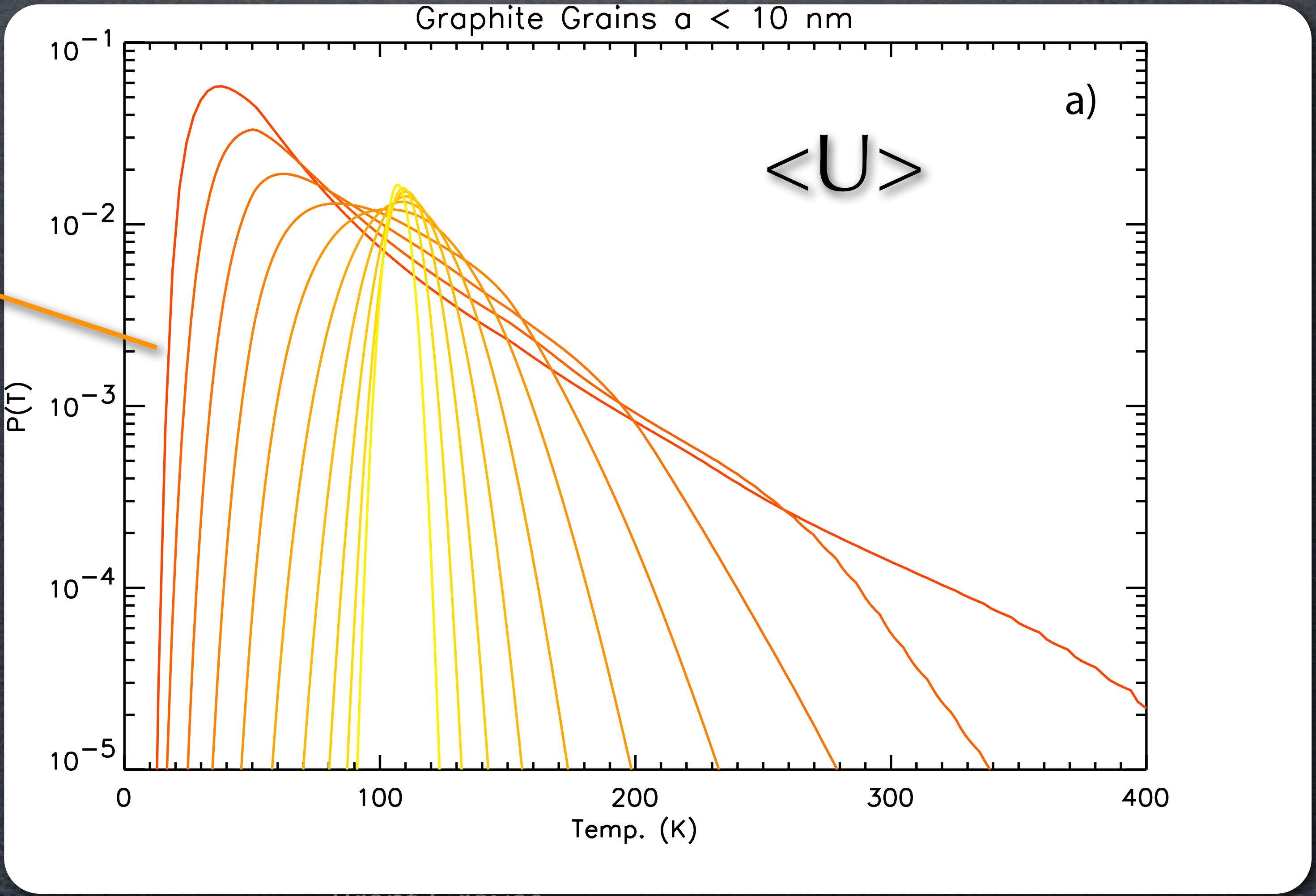
- In most modelling treatments, IR emission is ‘simply’ a sum of emmisivity modified blackbodies
- Extended to semi-empirical parameterized by Luminosity or Heating intensity
- Or use all available information to calculate full dust spectrum



Feeling the Heat

- In most modelling treatments, IR emission is 'simply' a sum of emmisivity modified blackbodies
- Extended to semi-empirical parameterized by Luminosity or Heating intensity
- Or use all available information to calculate full dust spectrum

Blackbody(λ,T)



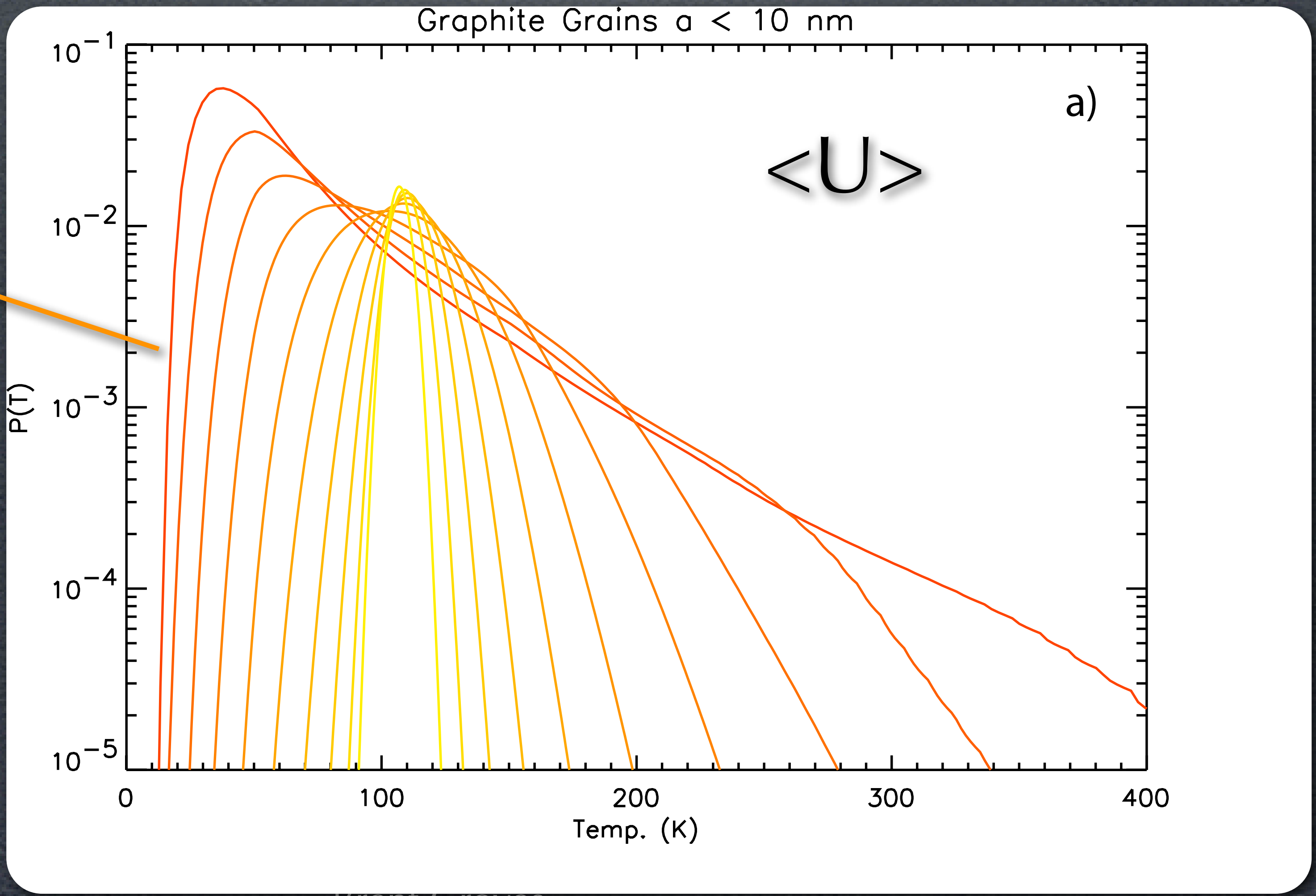
Brent Groves

Feeling the Heat

- In most modelling treatments, IR emission is ‘simply’ a sum of emmisivity modified blackbodies
- Extended to semi-empirical parameterized by Luminosity or Heating intensity
- Or use all available information to calculate full dust spectrum

Blackbody(λ,T)

κ(λ,Dust)



Brent Groves

Feeling the Heat

- In most modelling treatments, IR emission is ‘simply’ a sum of emmisivity modified blackbodies
- Extended to semi-empirical parameterized by Luminosity or Heating intensity
- Or use all available information to calculate full dust spectrum

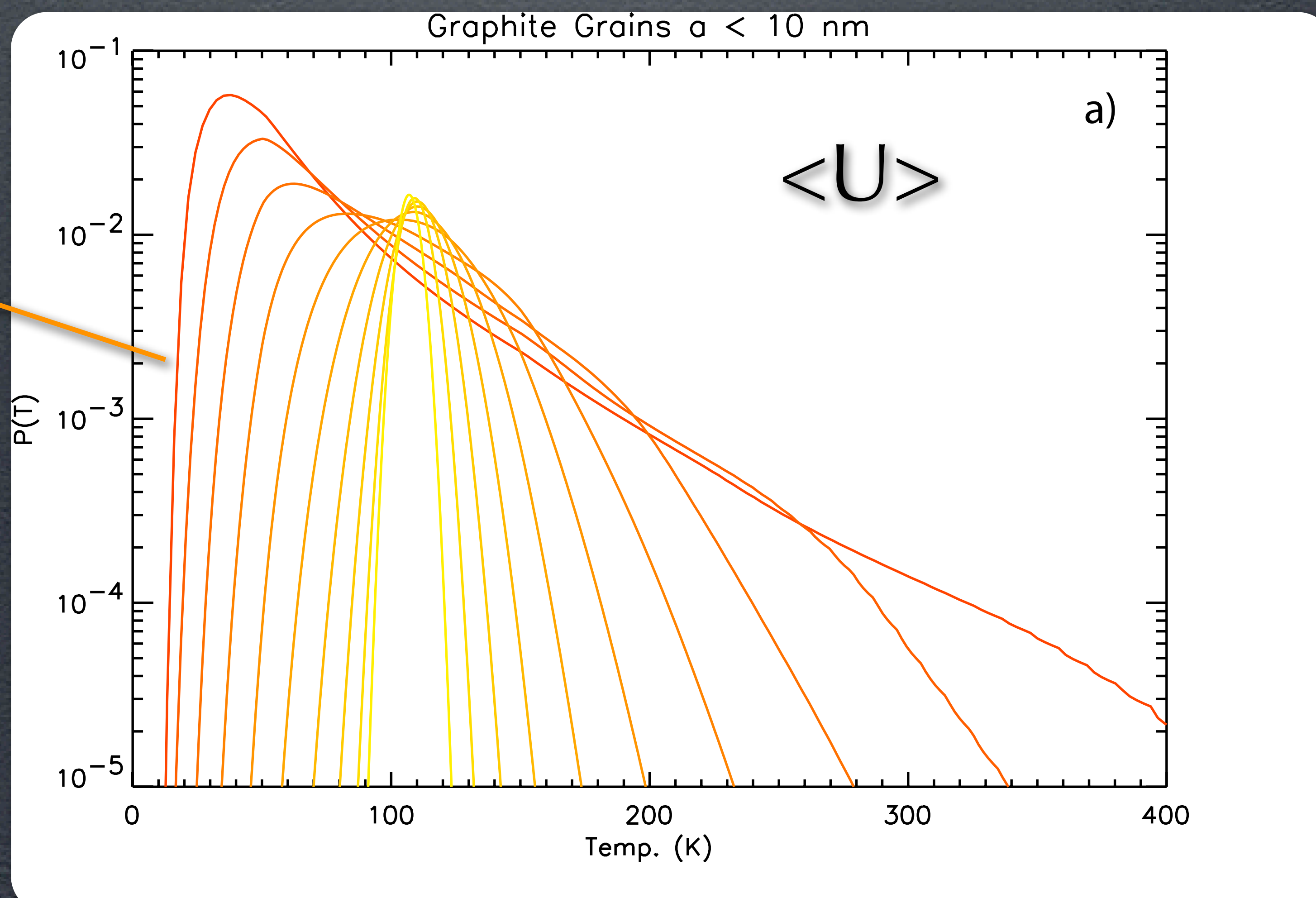
Blackbody(λ,T)

↓

κ(λ,Dust)

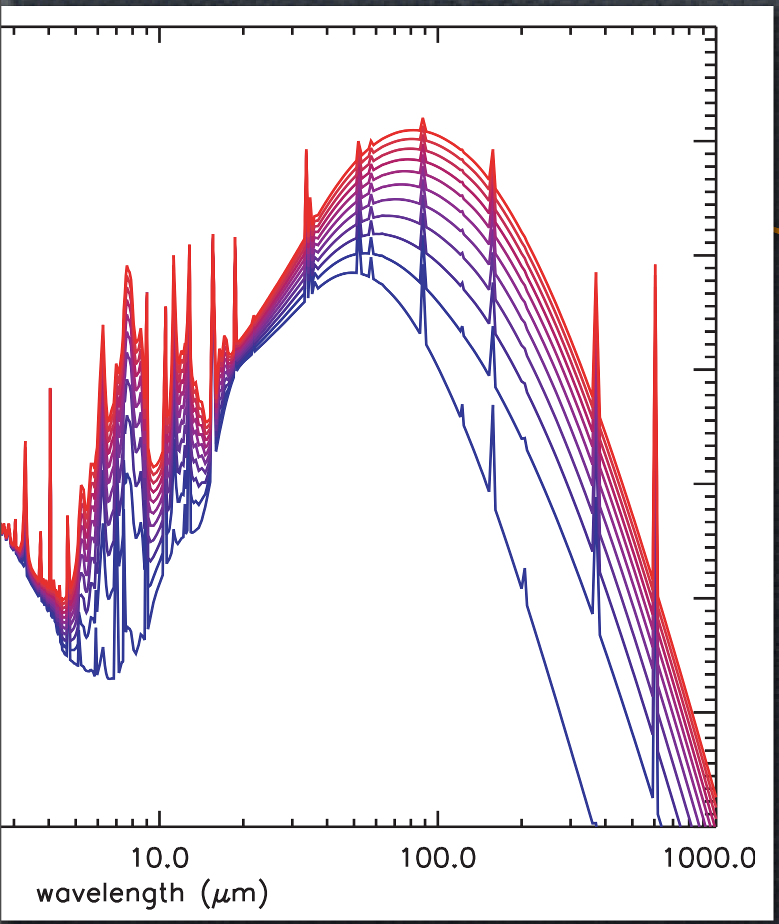
↓

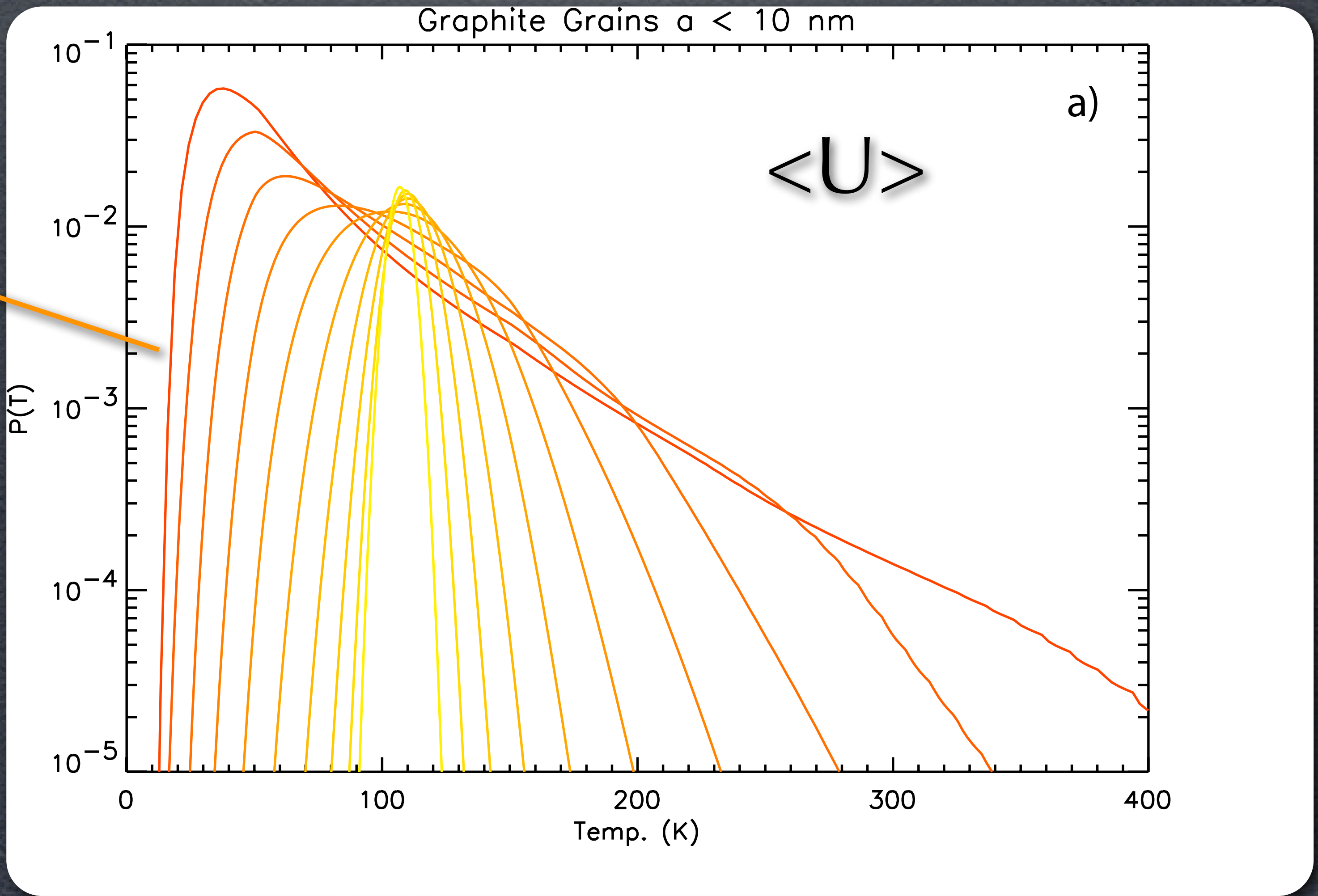
Dust Distribution



Feeling the Heat

- In most modelling treatments, IR emission is 'simply' a sum of emmisivity modified blackbodies
- Extended to semi-empirical parameterized by Luminosity or Heating intensity
- Or use all available information to calculate full dust spectrum



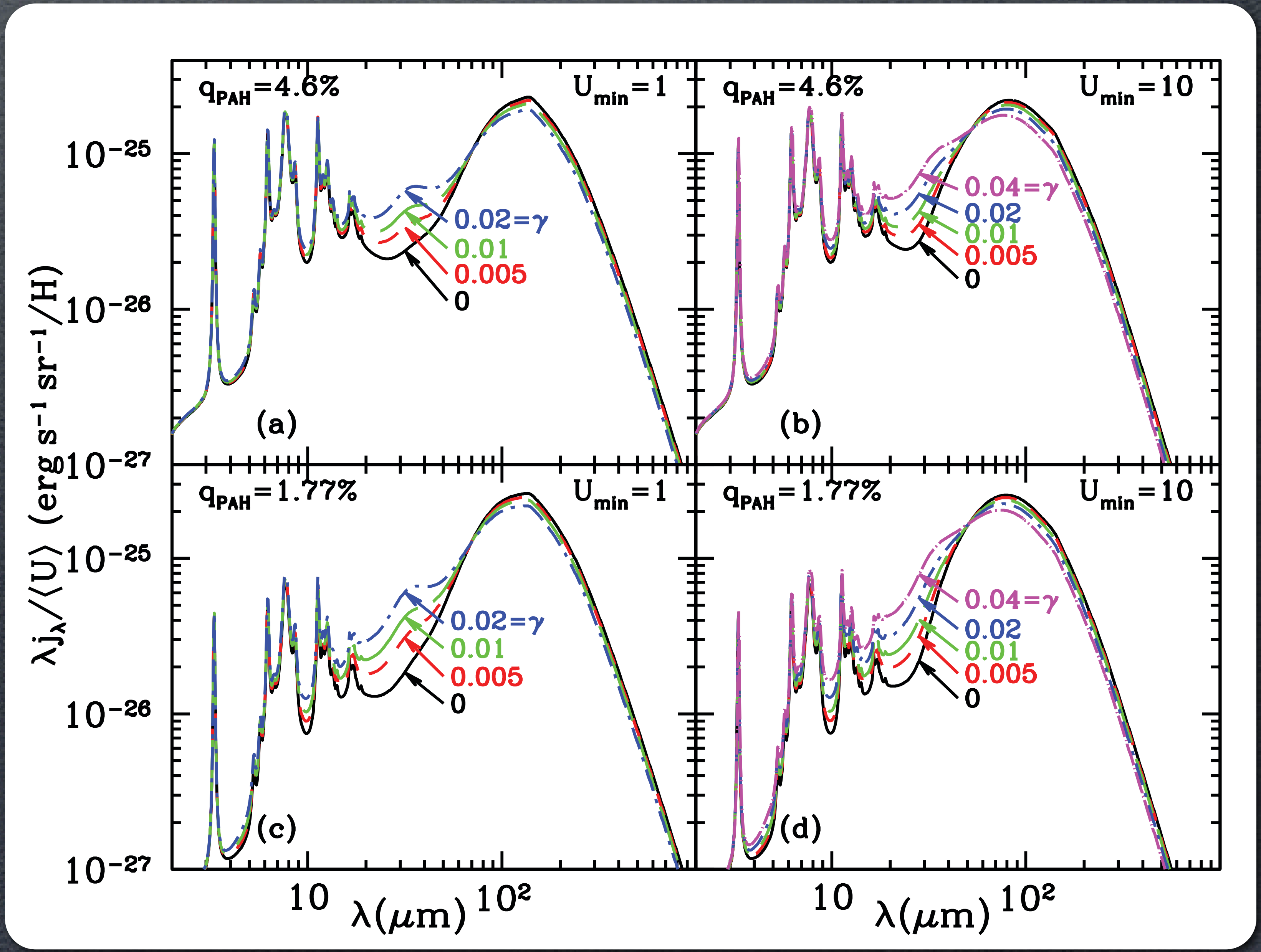


Brent Groves

Feeling the Heat

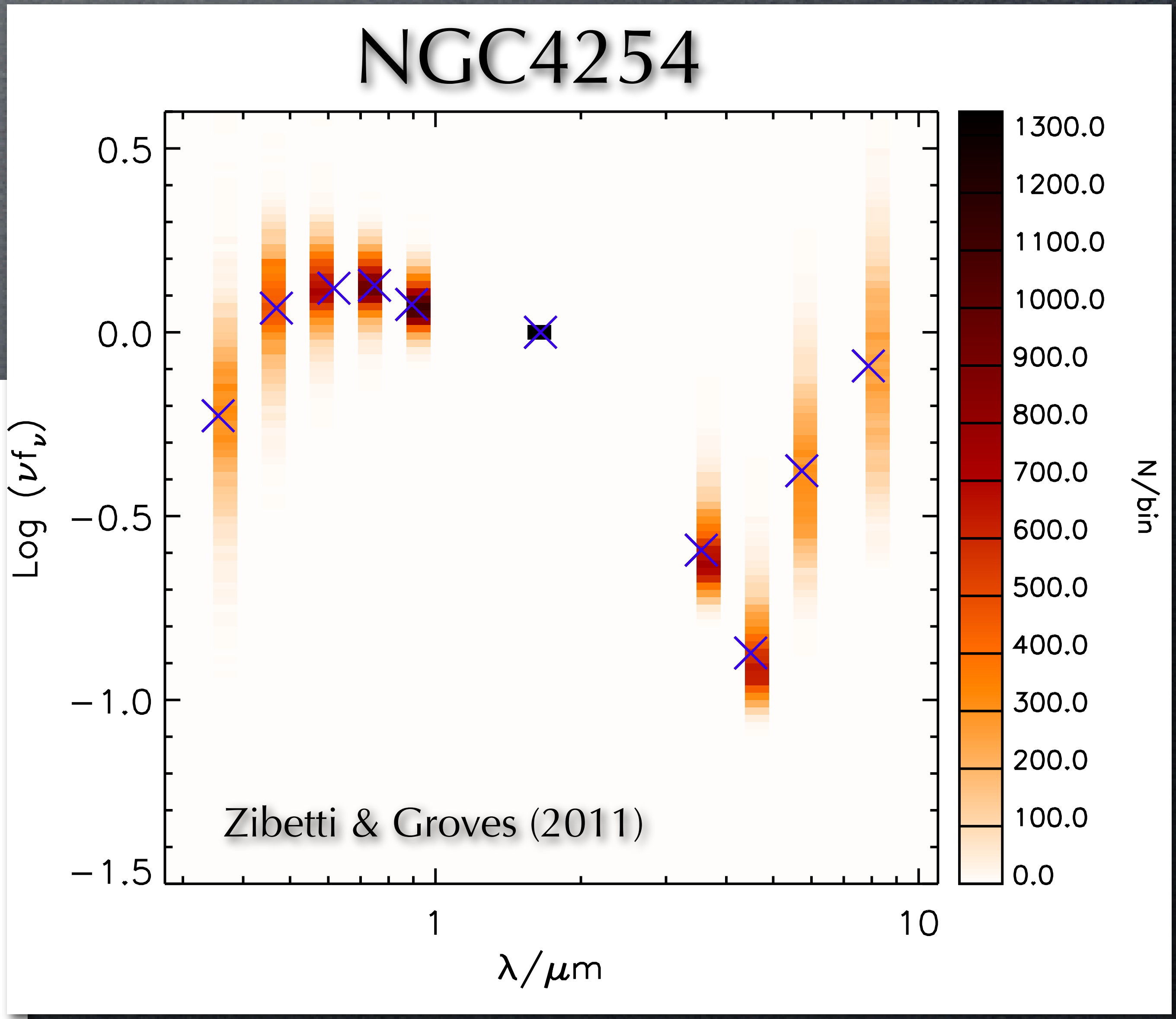
- Talks by F. Galliano, B. Draine, J-P. Bernard, A. Tielens, K. Gordon, (and basically every talk so far!)
- "Use them as far as you trust them" - unknown source

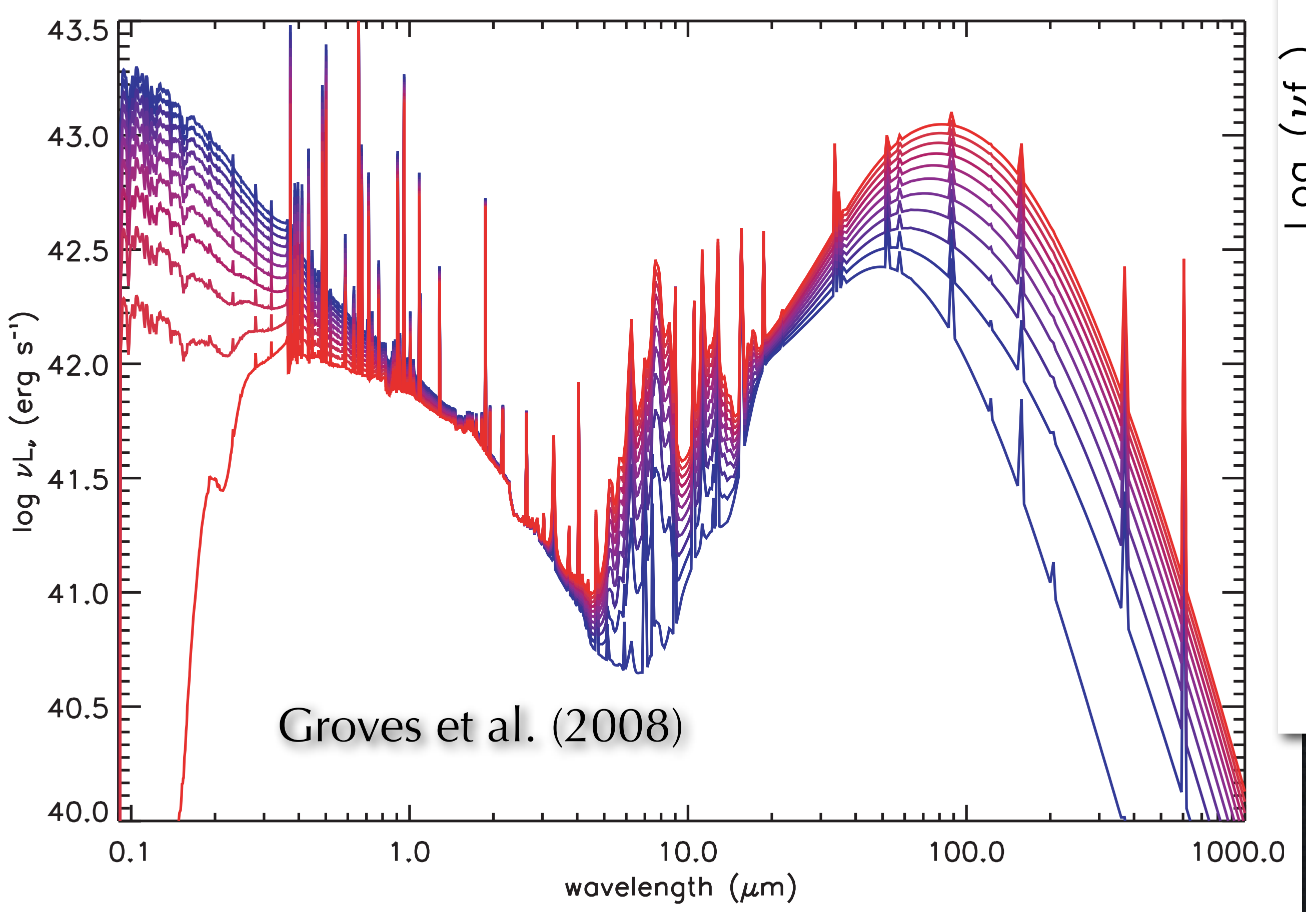
- Draine & Li (2007)
- Radiation Field
  - Minimum/Diffuse (U_{min})
  - U_{max}
  - distribution of U ($dM/dU \propto U^{-\alpha}$)
  - PDR (γ)
- PAH fraction
- Metallicity/ dust composition
- Total Dust Mass/ Surface Dens.



Should I cut it here in the middle?

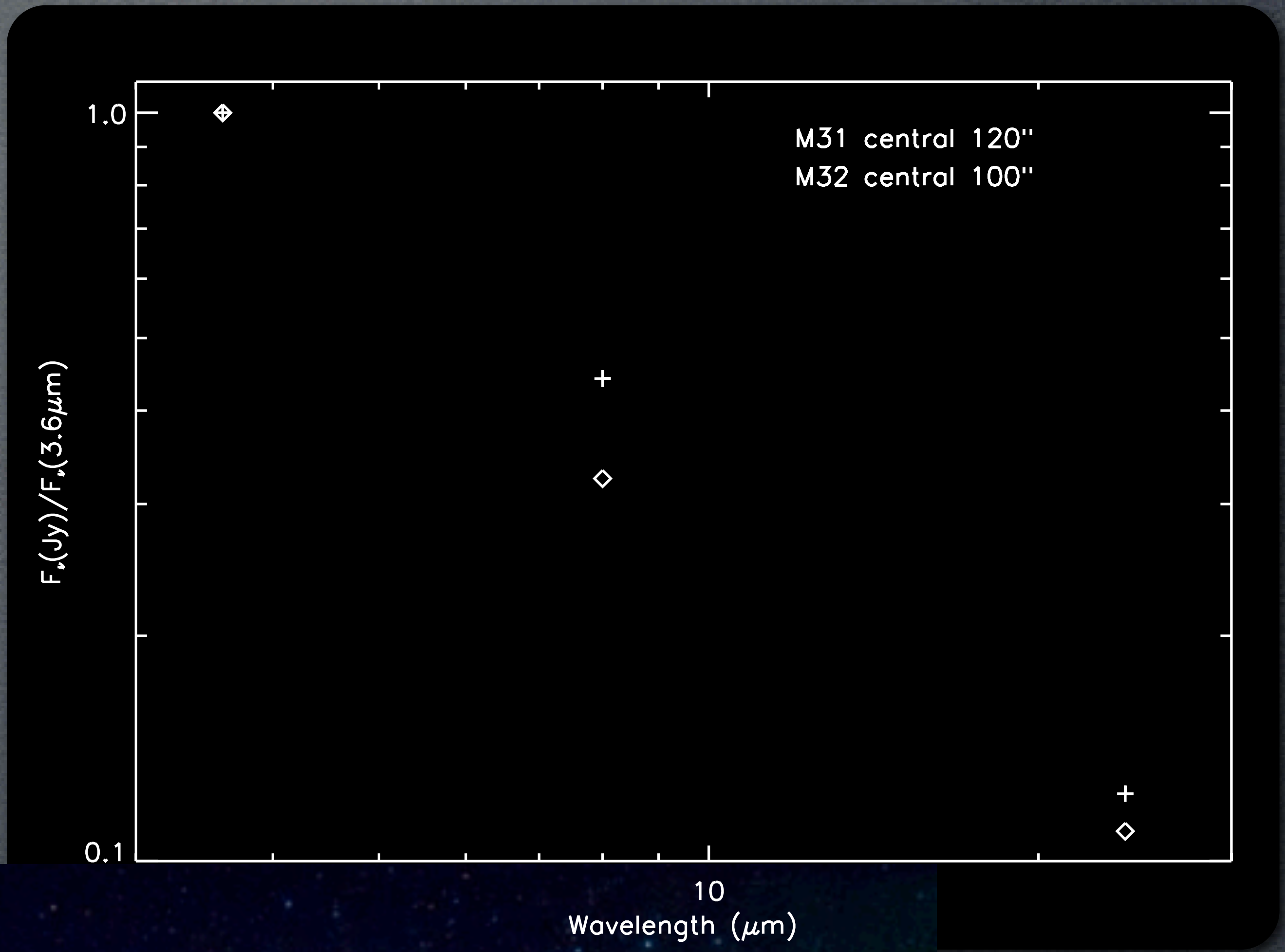
- Minimum between stellar and dust emission in near IR





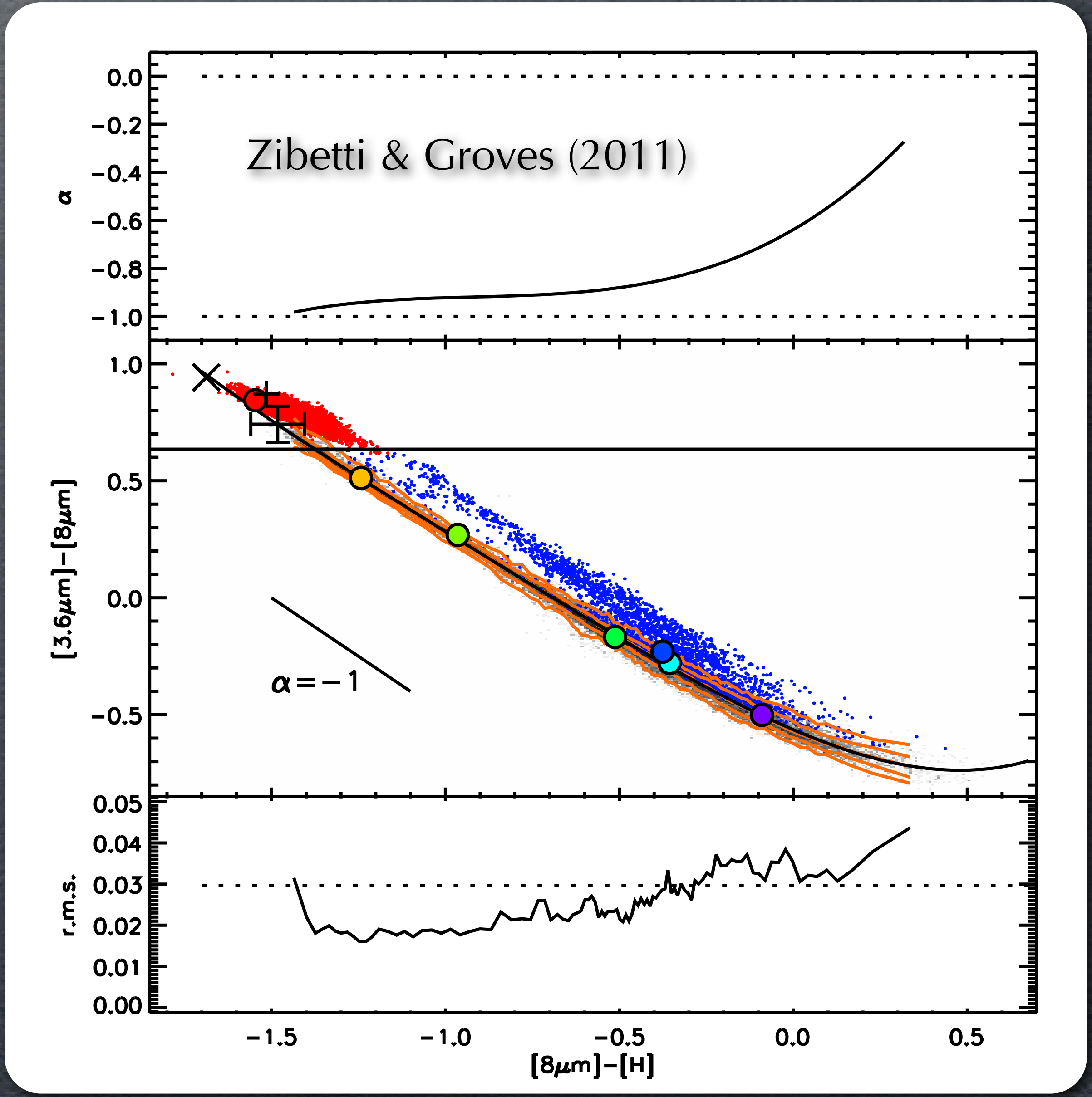
Should I cut it here in the middle?

- Minimum between stellar and dust emission in near/mid-IR
- Even at 8 & 24 `stellar' contribution exists



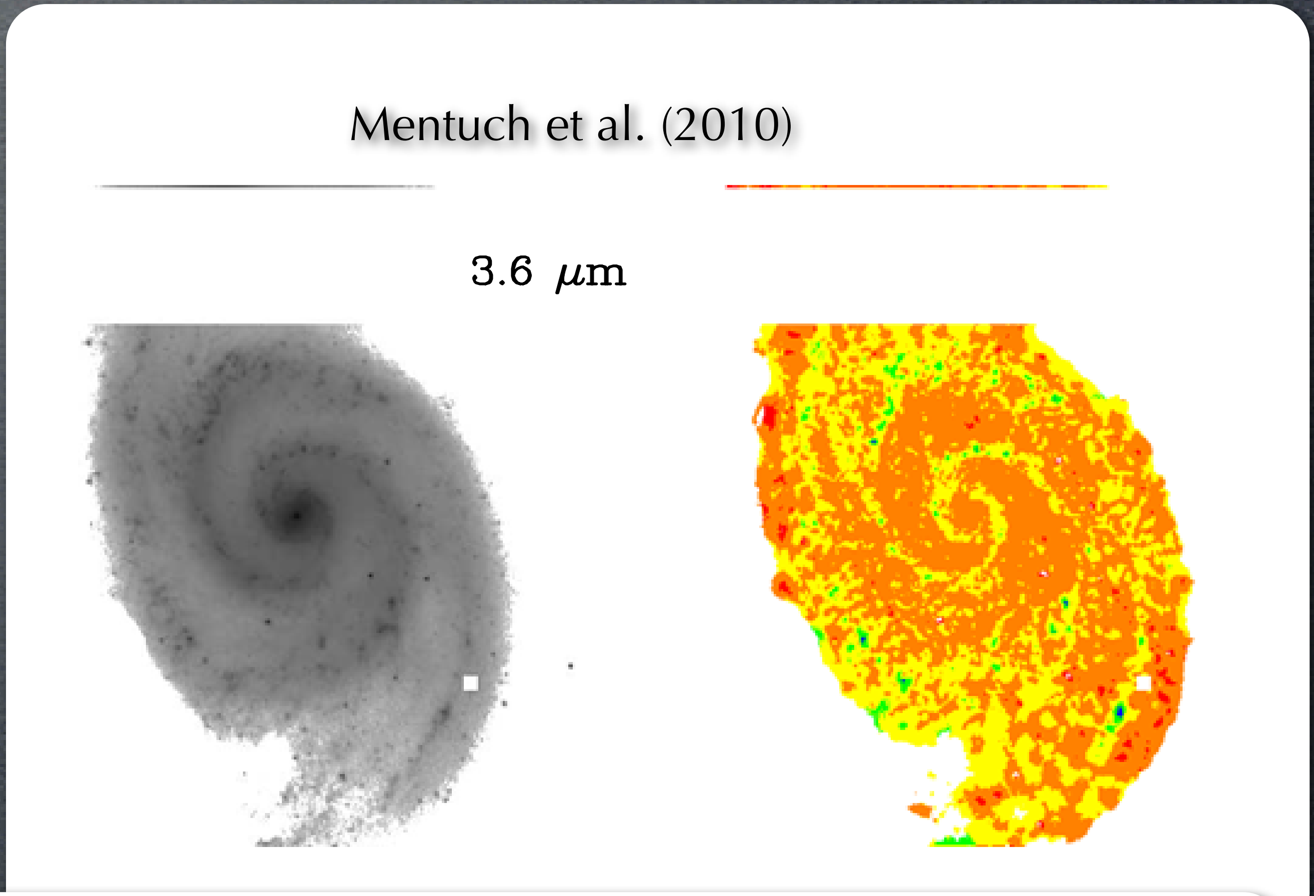
Should I cut it here in the middle?

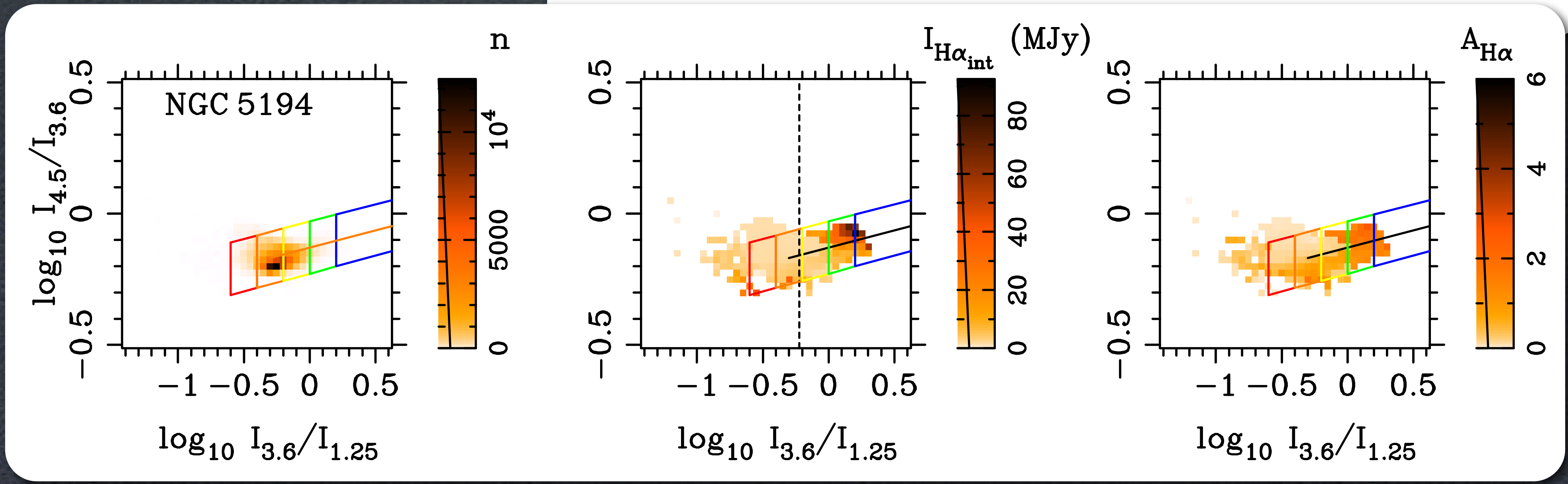
- Minimum between stellar and dust emission in near/mid-IR
- Even at 8 & 24 `stellar' contribution exists
- But even *H*-band can suffer attenuation
- and dust at 3.6μm
- Colours can separate these:
  - Stars
  - Hot Dust
  - PAH



Should I cut it here in the middle?

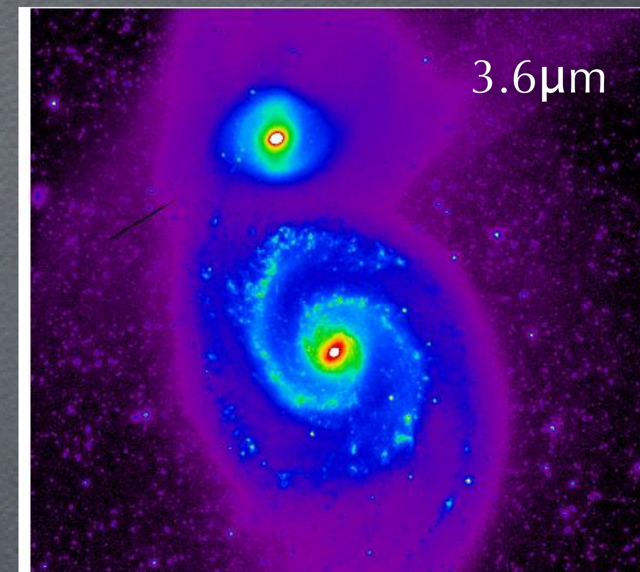
- Minimum between stellar and dust emission in near/mid-IR
- Even at 8 & 24 `stellar' contribution exists
- But even *H*-band can suffer attenuation
- Colours can separate these:
  - Stars
  - Hot Dust
  - PAH



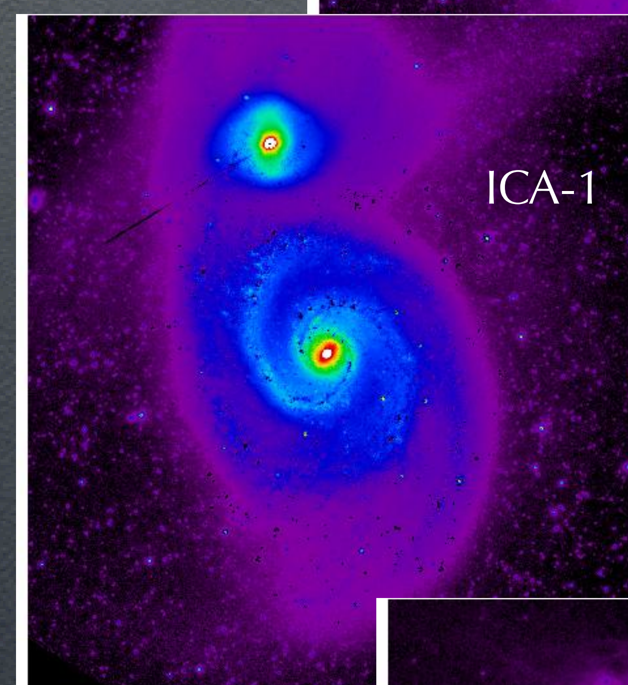


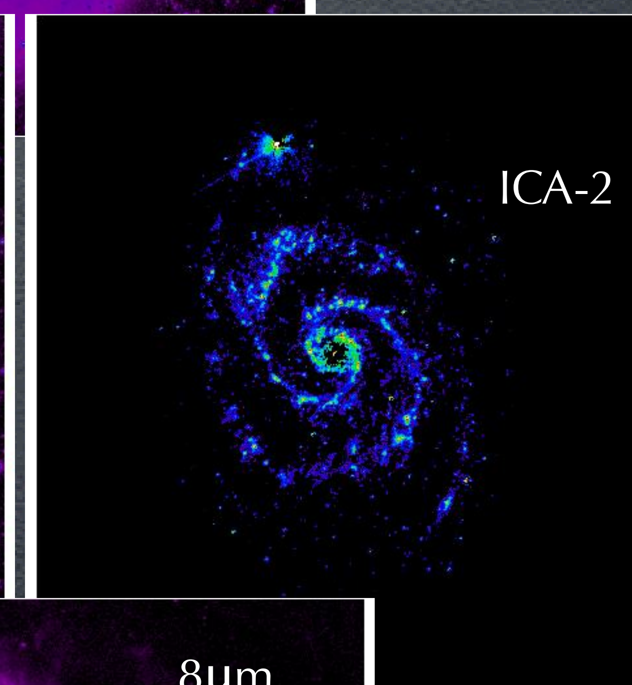
Should I cut it here in the middle?

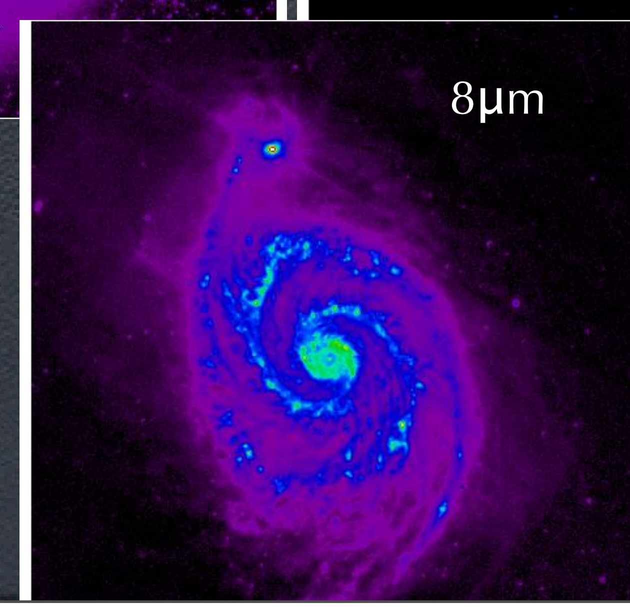
- Minimum between stellar and dust emission in near/mid-IR
- Even at 8 & 24 `stellar' contribution exists
- But even *H*-band can suffer attenuation
- Colours can separate these:
  - Stars
  - Hot Dust
  - PAH



NGC 5194



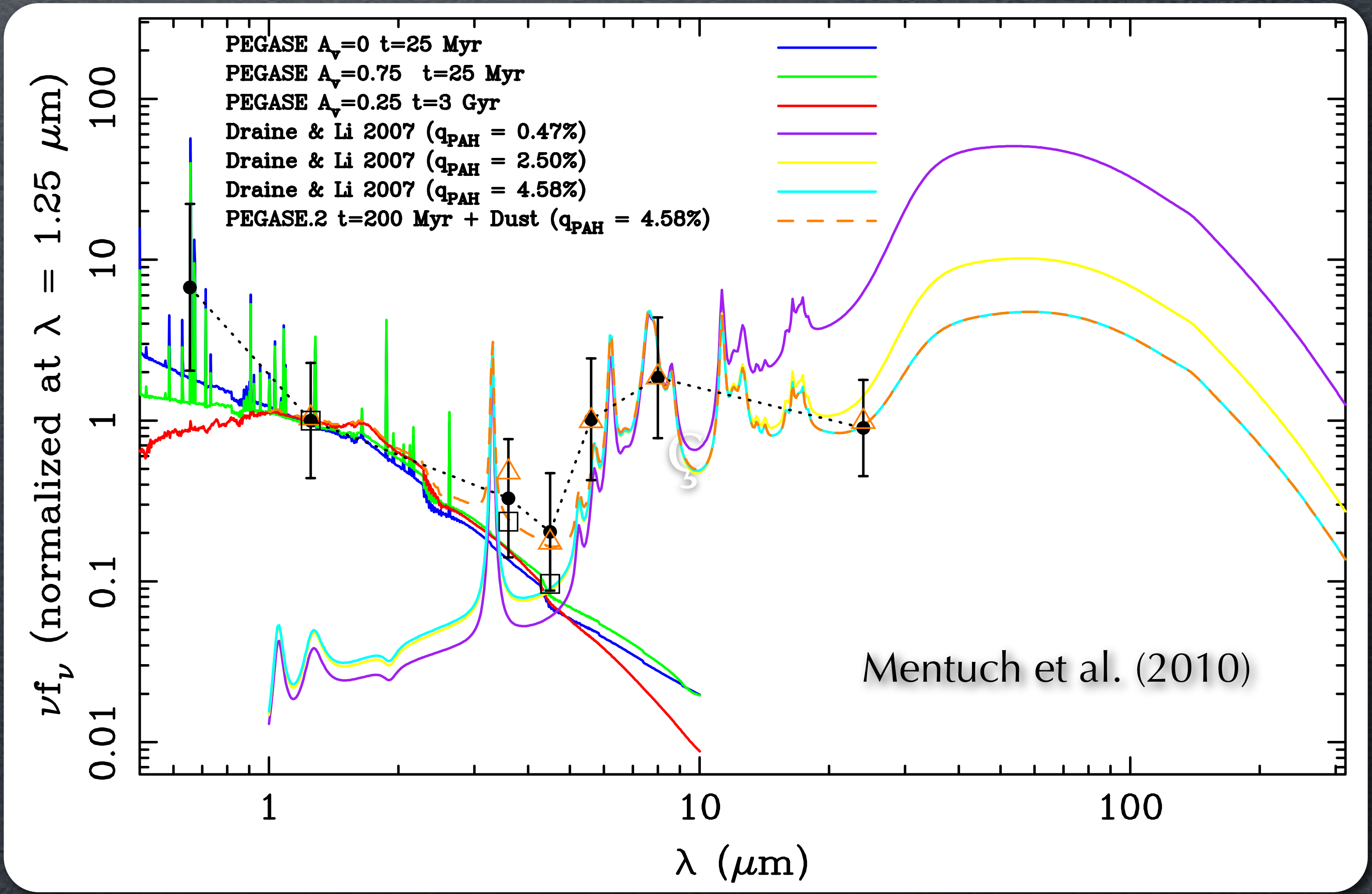




Meidt et al. (accepted)

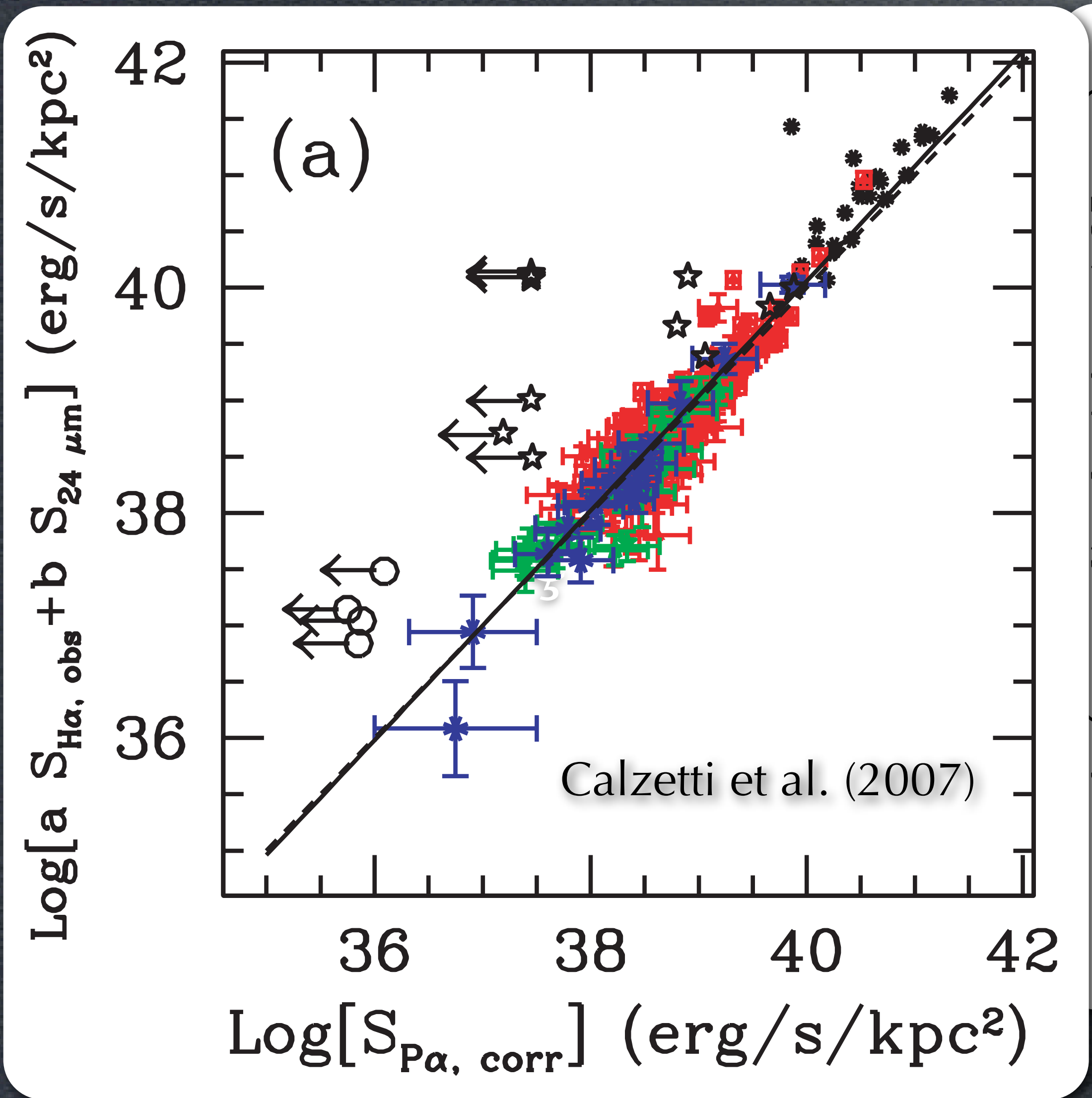
How do I stick it together again?

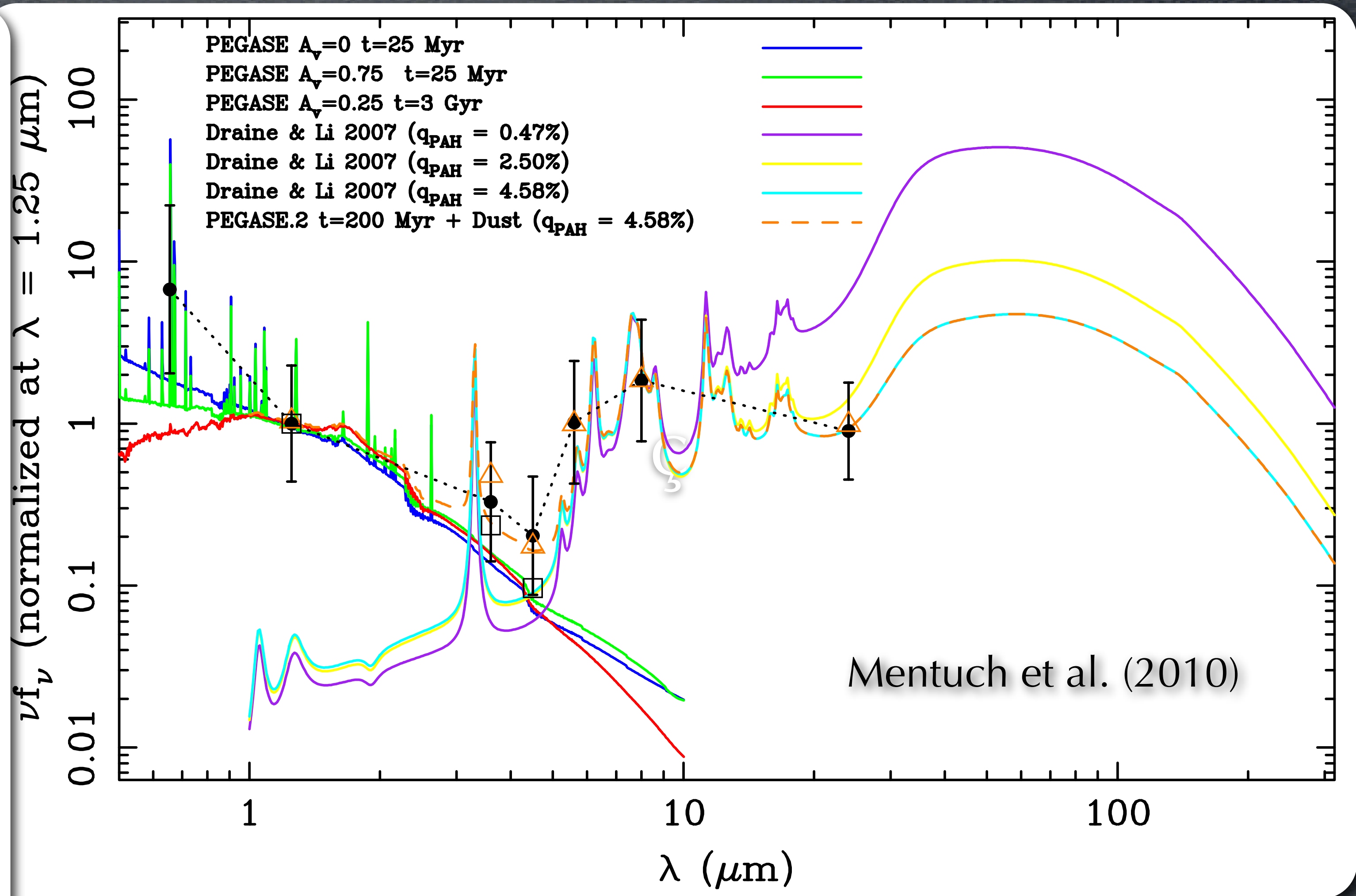
- While each can be treated distinctly (optical vs IR)...
- These ARE related via heating and absorption
- Simultaneous fitting/modelling provides constraints on both
- How do we link these?



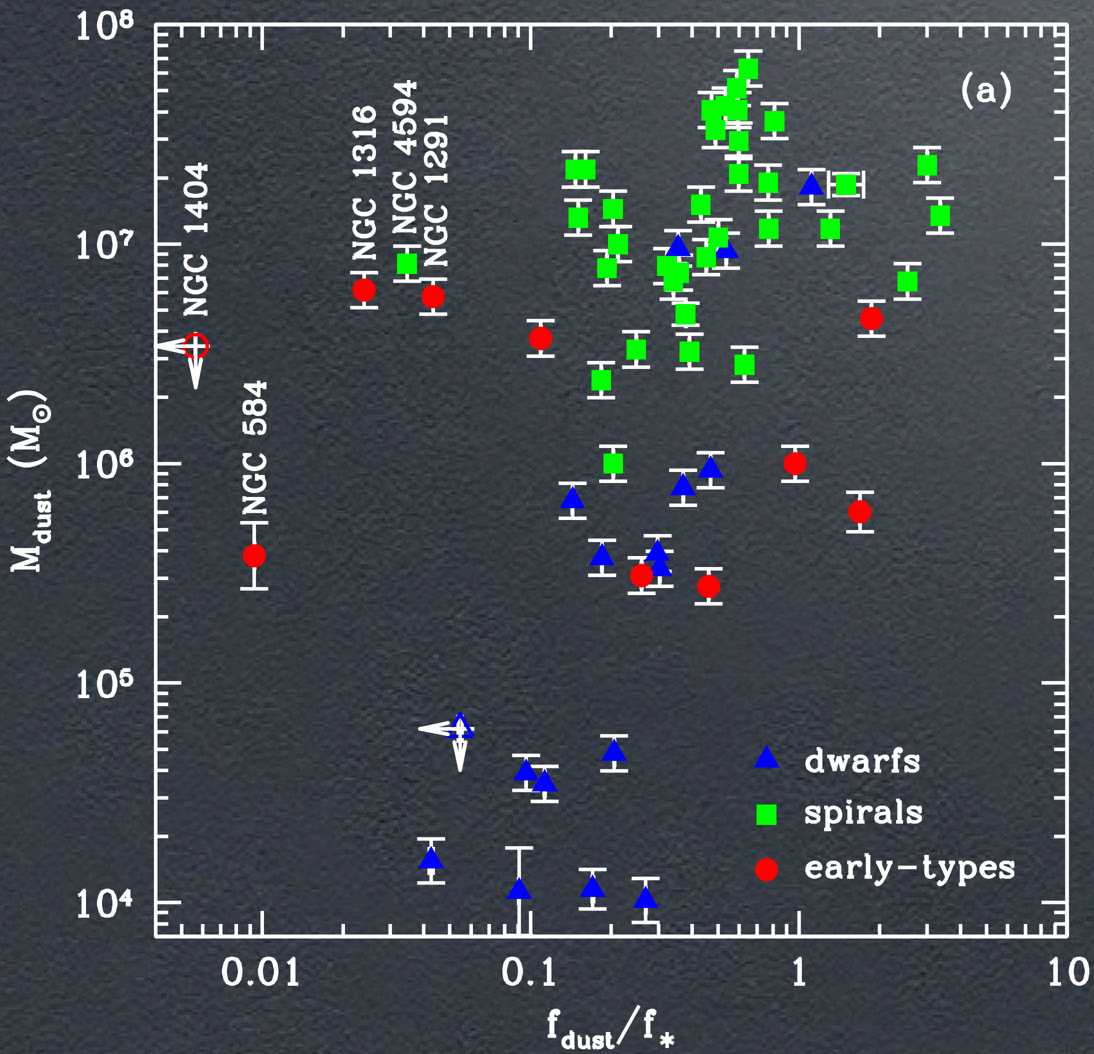
How do I stick it together again?

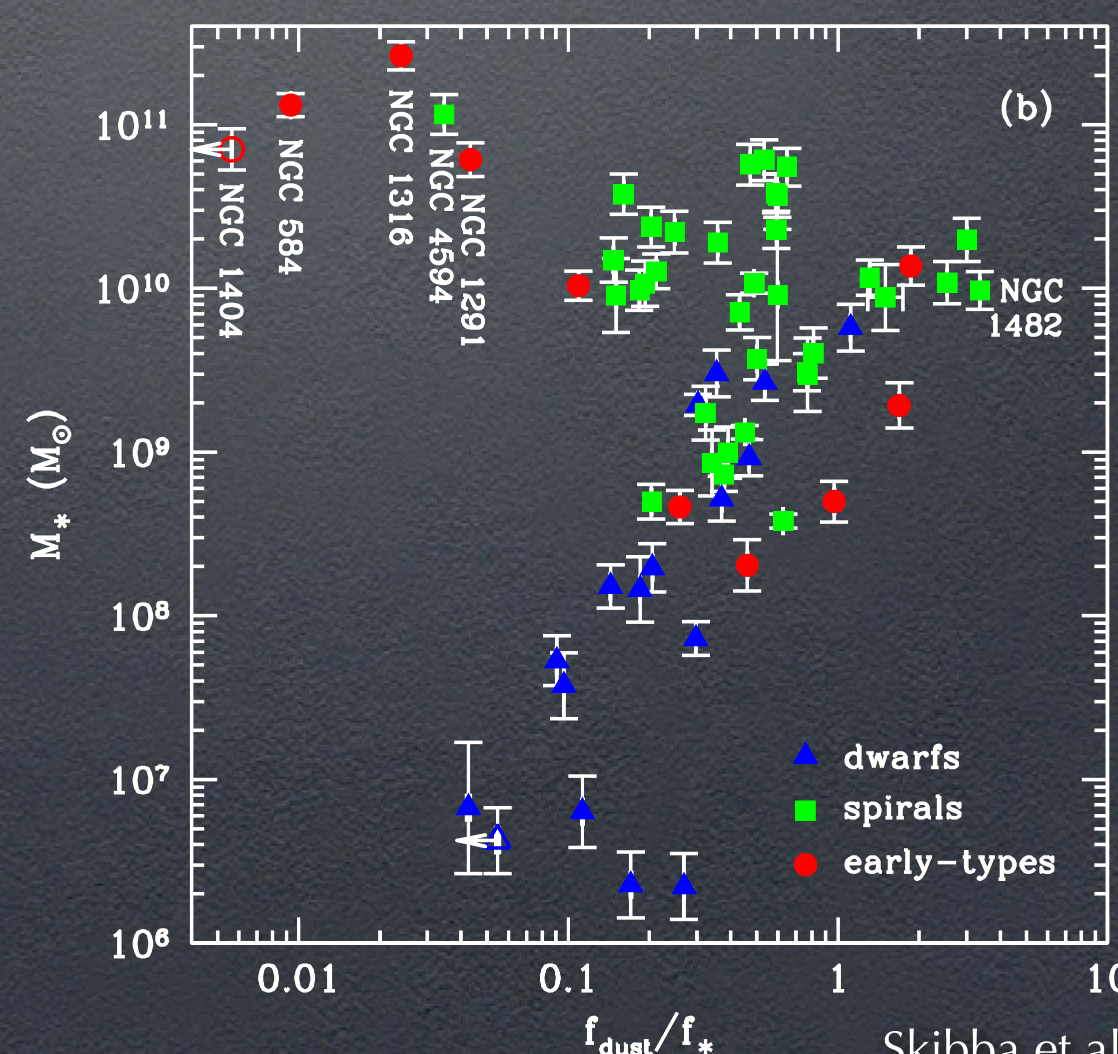
- While each can be treated distinctly (optical vs IR)...
- These ARE related via heating and absorption
- Simultaneous fitting/modelling provides constraints on both
- How do we link these?





Stars and dust are unbalanced?

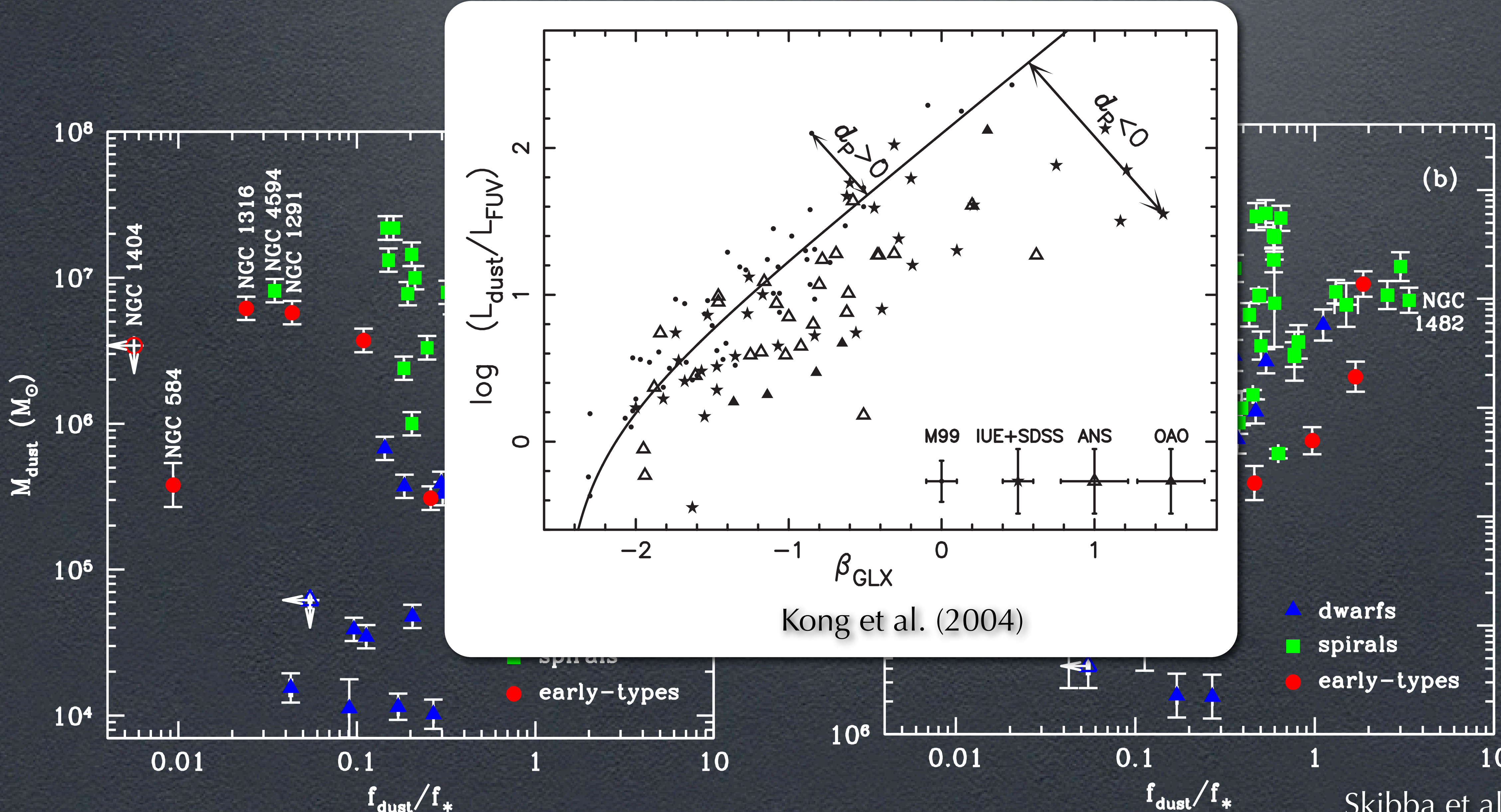




Skibba et al. (2011)

Brent Groves

Stars and dust are unbalanced?

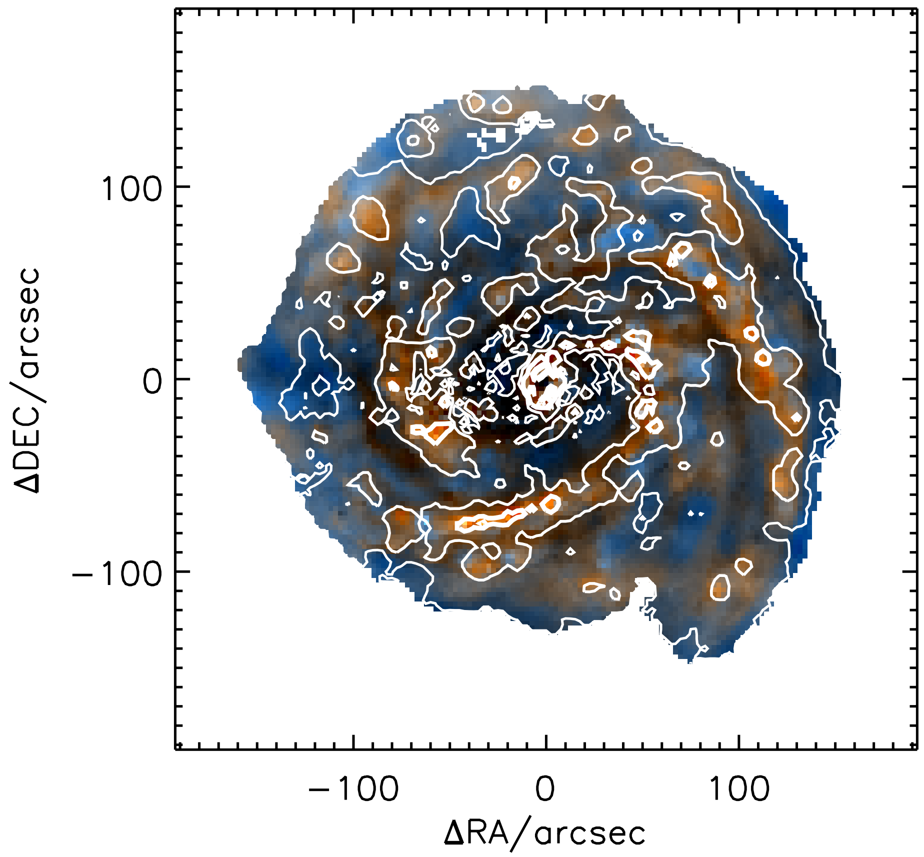


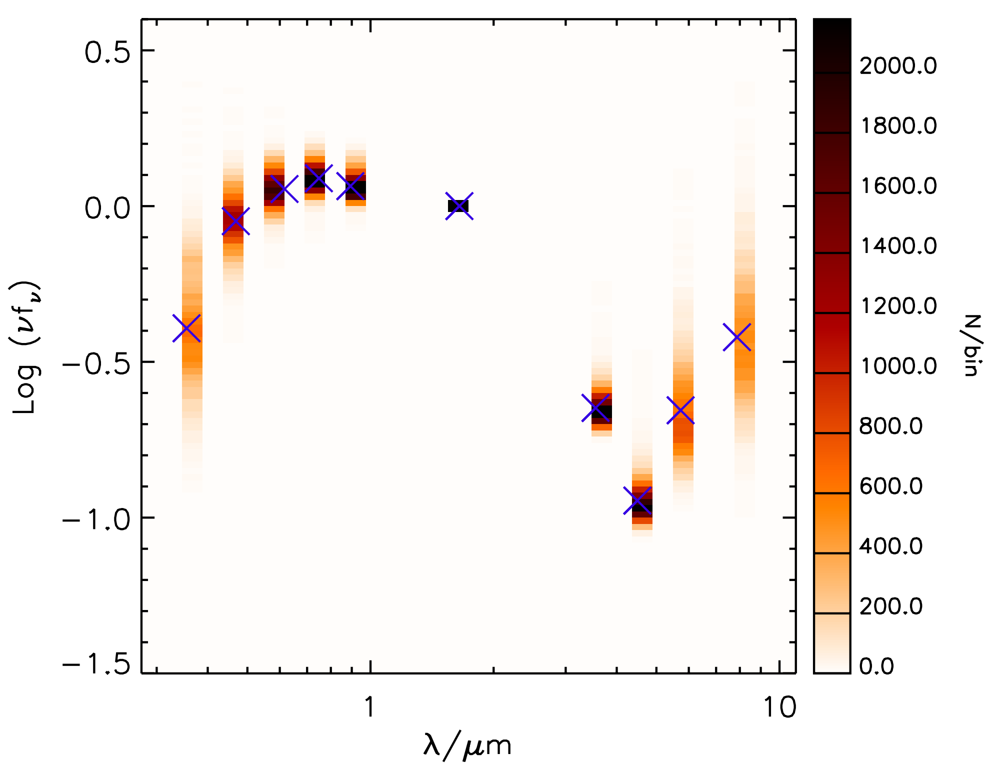
Kong et al. (2004)

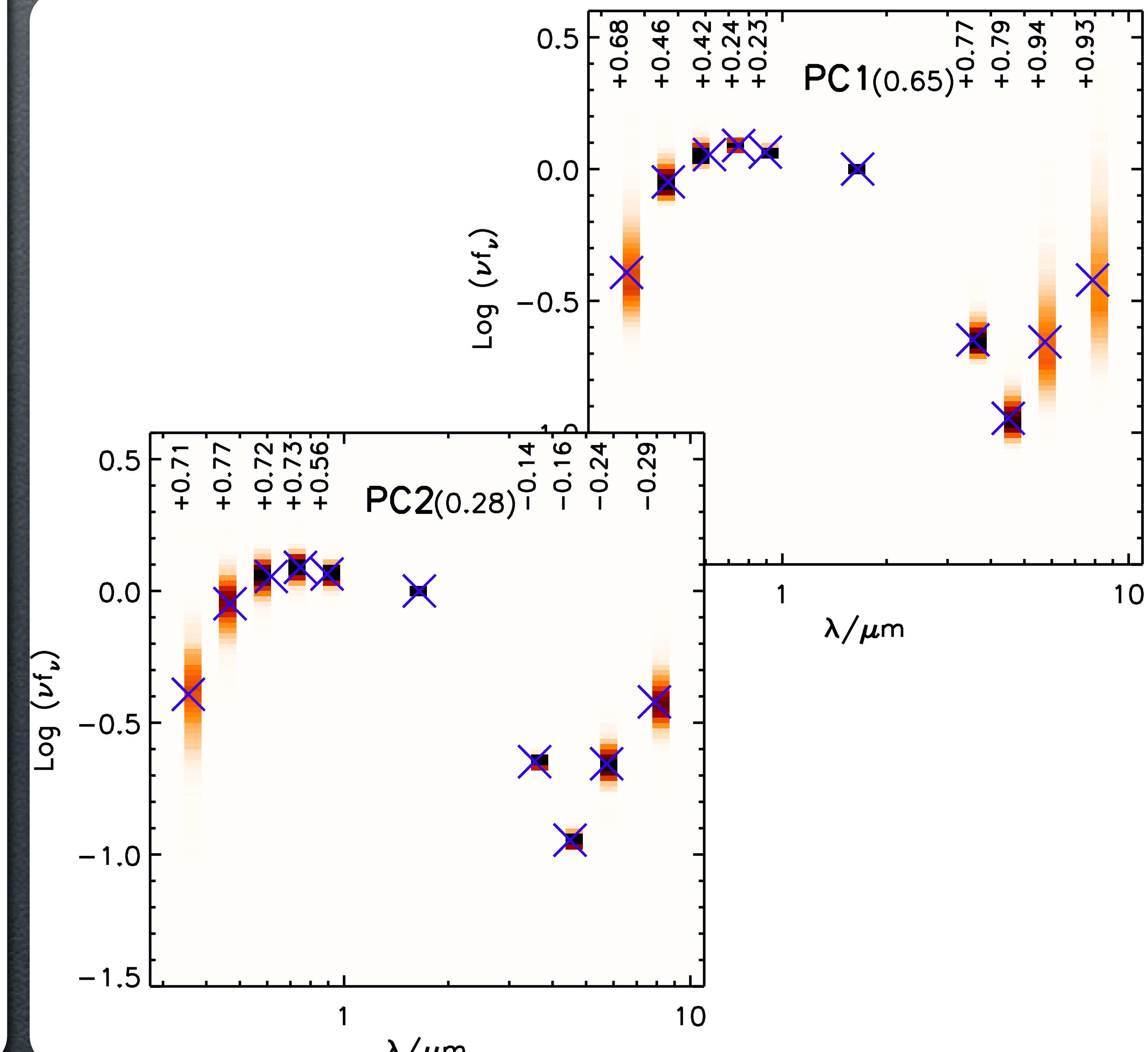
Skibba et al. (2011)

How do I stick it together again?

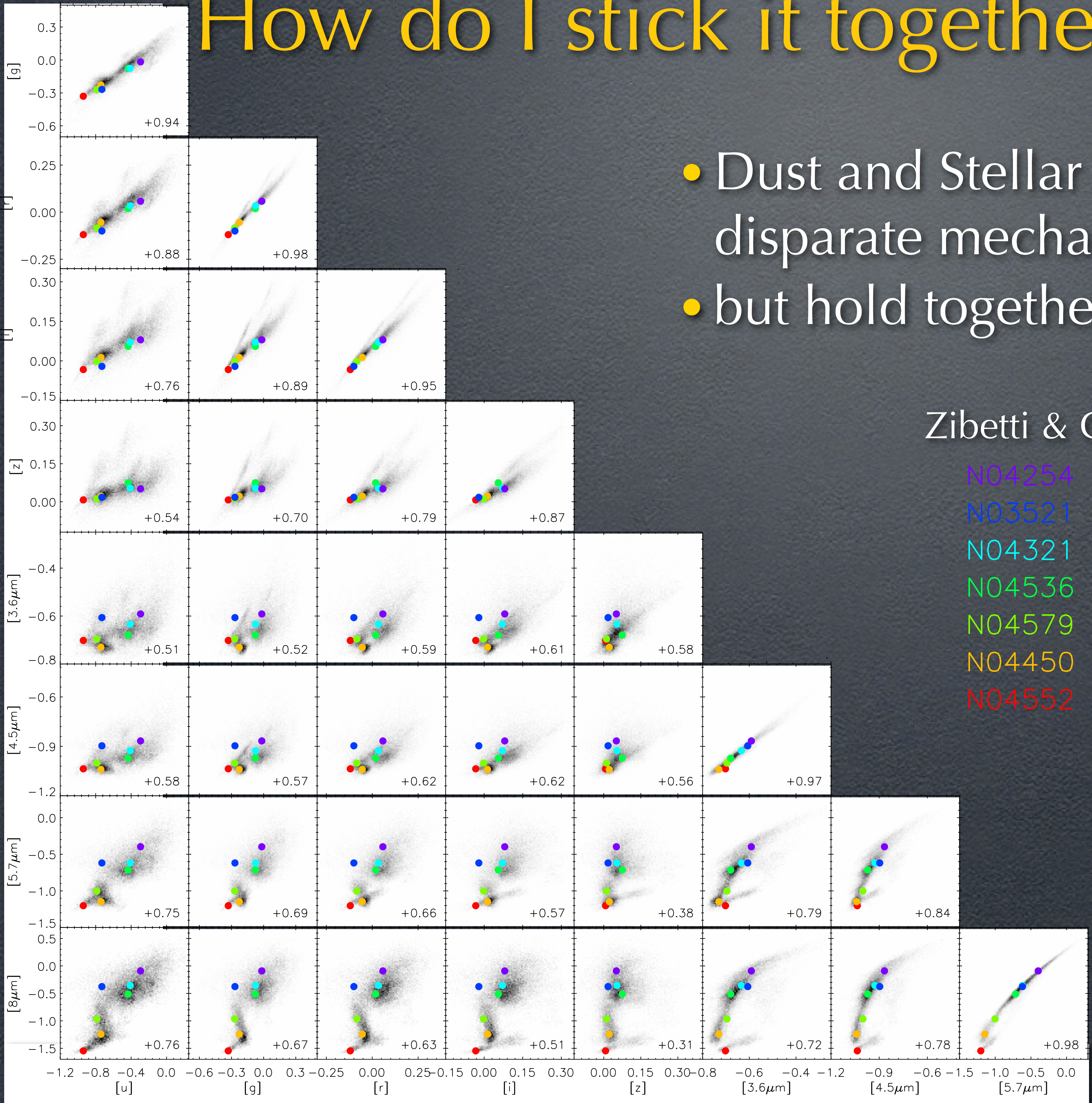
- Dust and Stellar emission disparate mechanisms







How do I stick it together again?

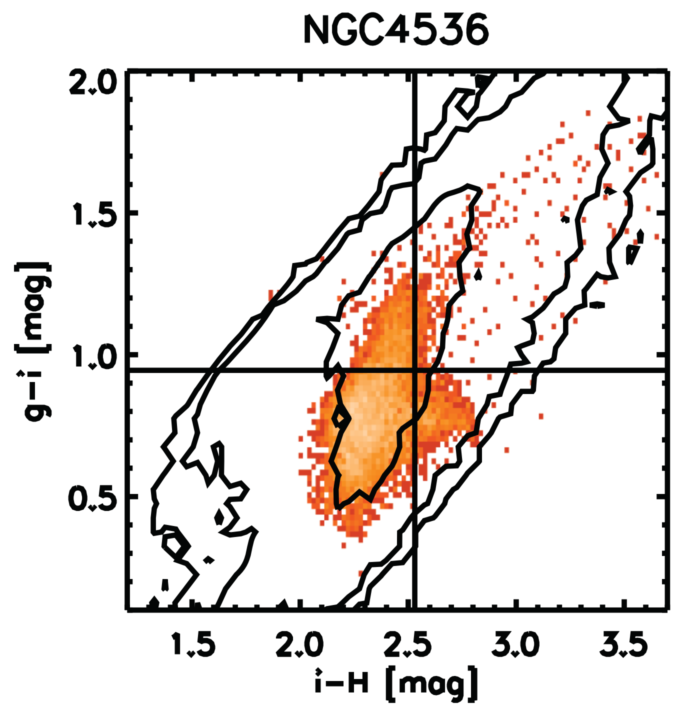


- Dust and Stellar emission disparate mechanisms
- but hold together globally

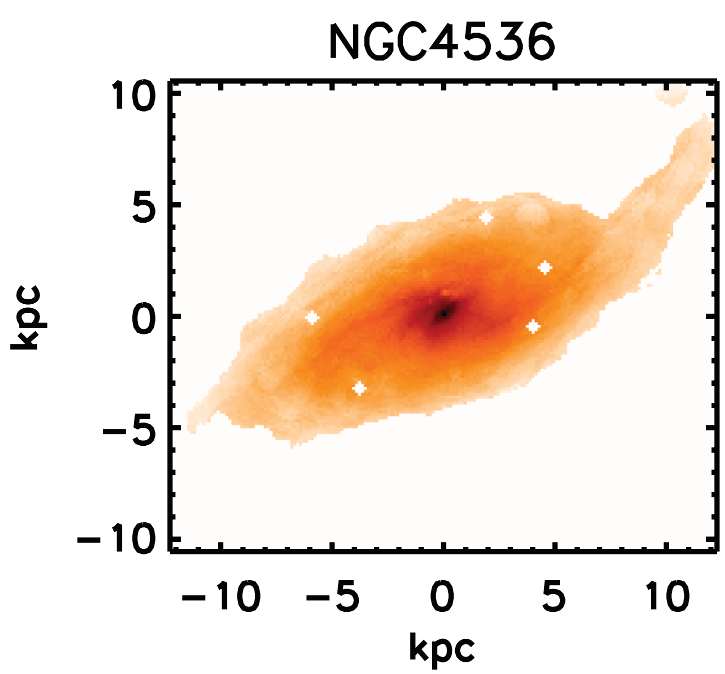
Zibetti & Groves (2011)

N04254 – SAc
N03521 – SABbc
N04321 – SABbc
N04536 – SABbc
N04579 – SABb
N04450 – SAab
N04552 – E

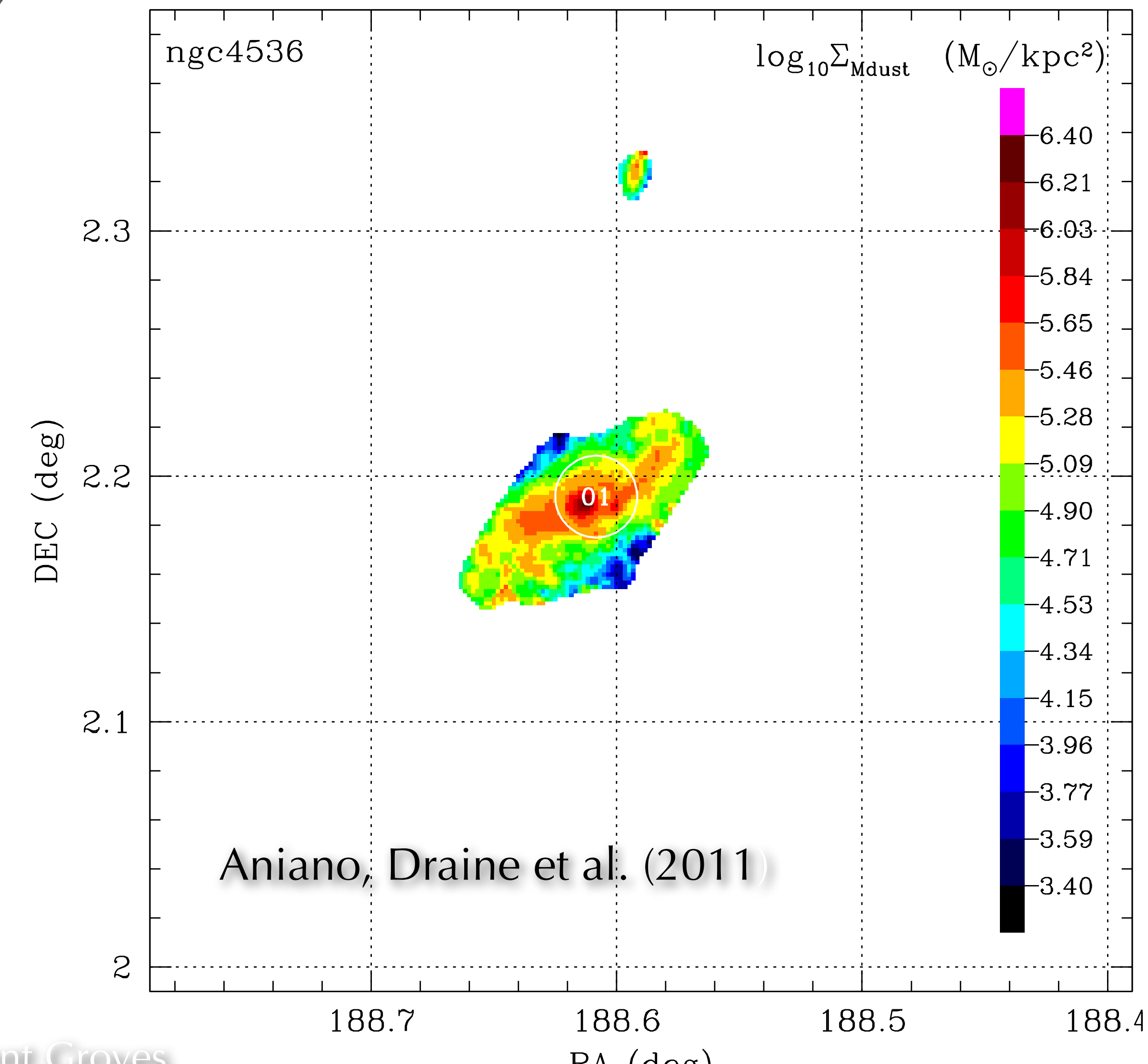
How do I stick it together again?



Zibetti, Charlot, & Rix (2010)



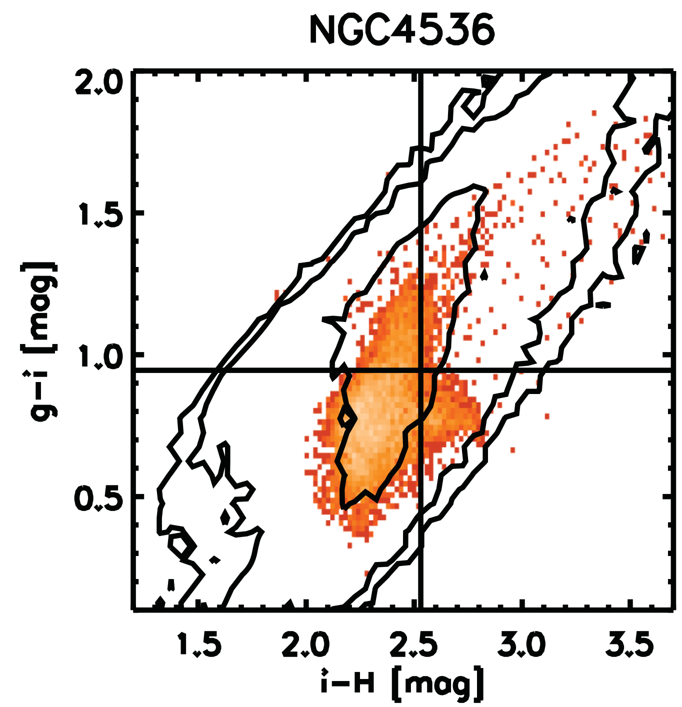
- Dust and Stellar emission disparate mechanisms
- but hold together globally
- So we can treat them separately...



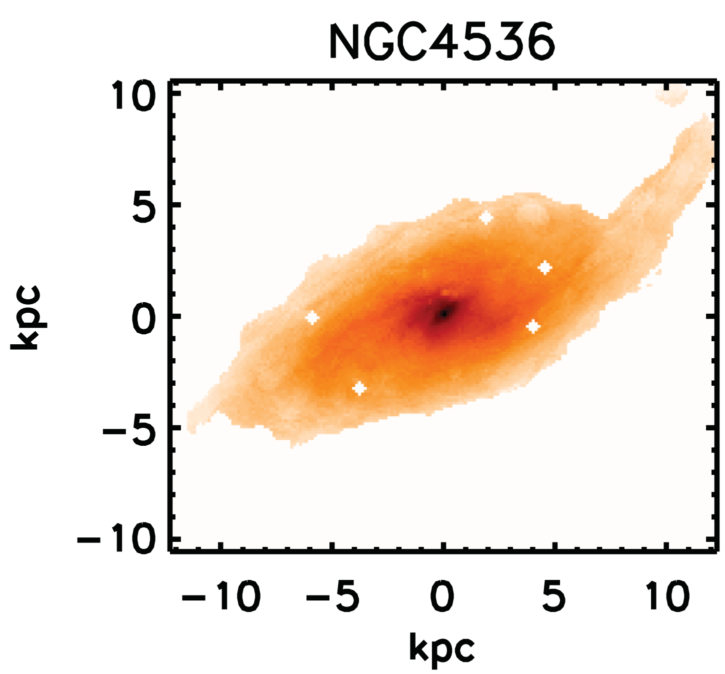
Aniano, Draine et al. (2011)

Brent Groves

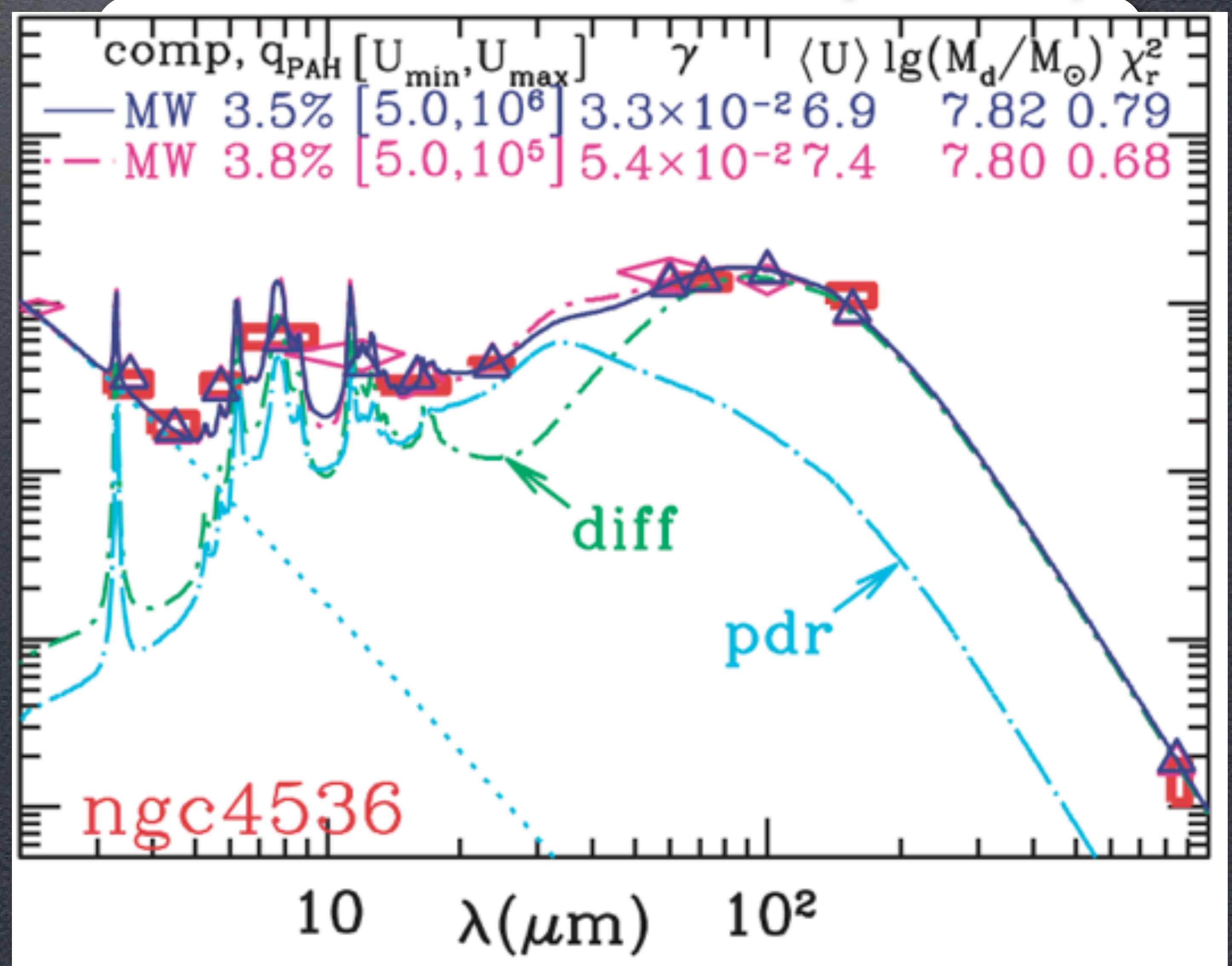
How do I stick it together again?



Zibetti, Charlot, & Rix (2010)



- Dust and Stellar emission disparate mechanisms
- but hold together globally
- So we can treat them separately...

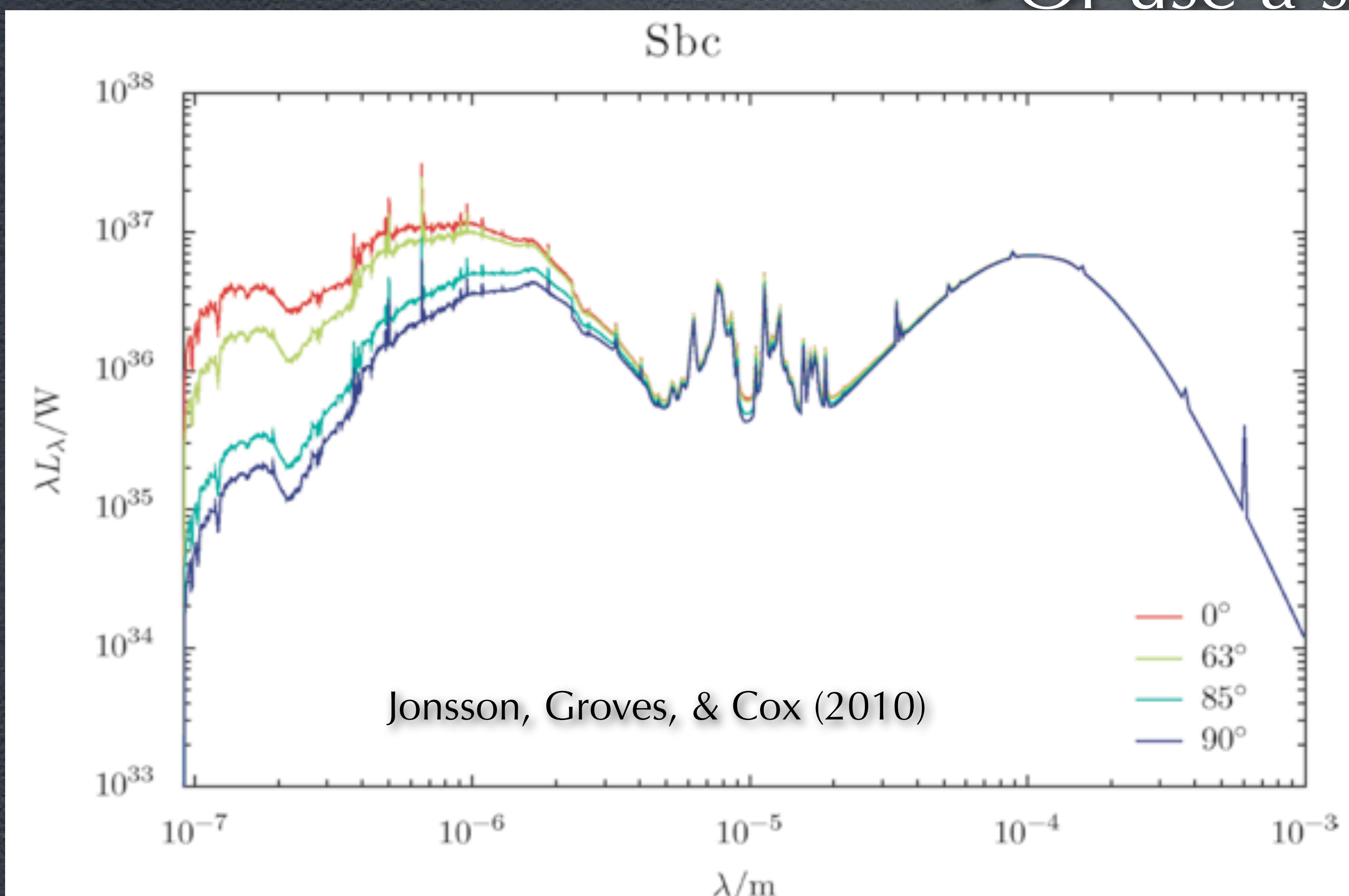


How do I stick it together again?

- Dust and Stellar emission disparate mechanisms
- but hold together globally
- So we can treat them separately...
- Or use a simple energy balance (ie Absorbed=Emitted)

How do I stick it together again?

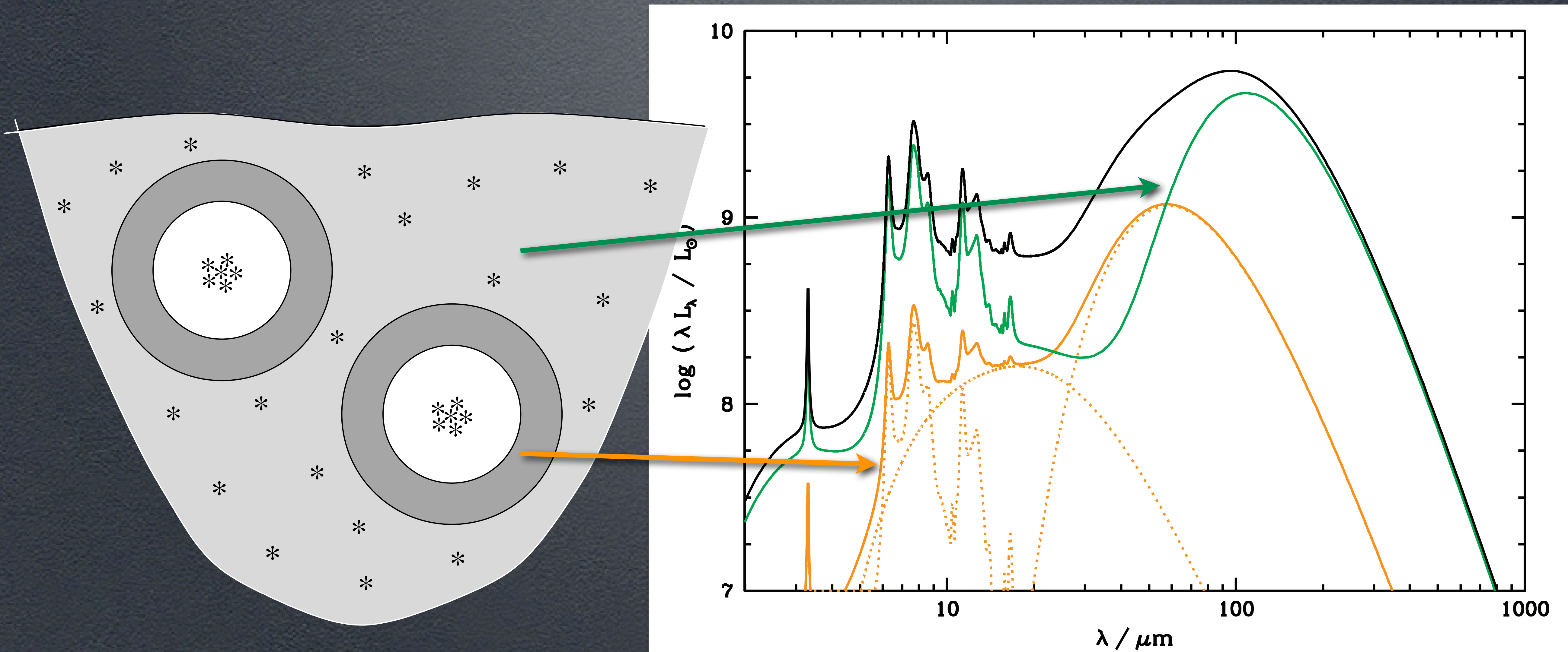
- Dust and Stellar emission disparate mechanisms
- but hold together globally
- So we can treat them separately...
- Or use a simple energy balance
ed=Emitted)



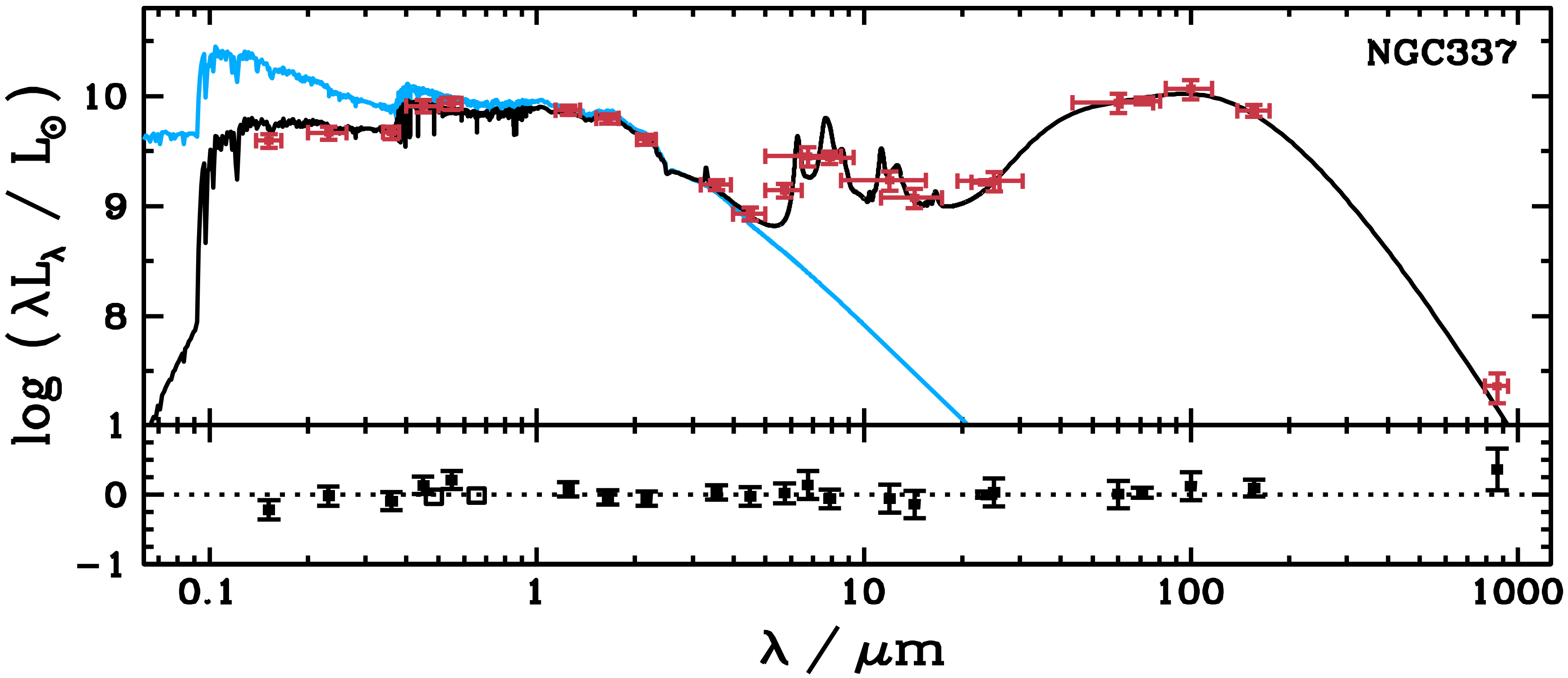
Jonsson, Groves, & Cox (2010)

- But allow for inclination/spatial variation!

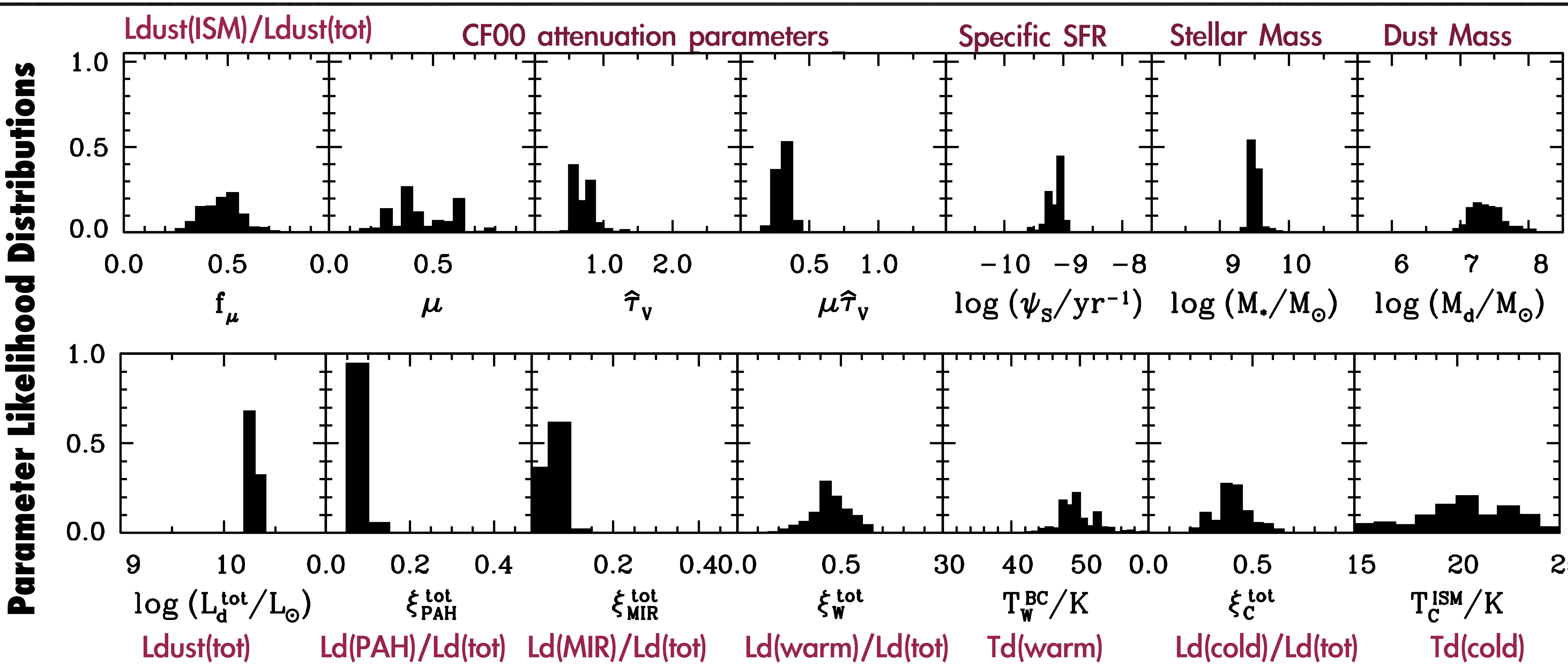
Hot & Cold Flushes



- Associate with Hot and Cold dust ie Star forming regions vs diffuse
- Allow 15% for spatial variation between absorbed and emitted E
- Allows for interpretations of full SED with statistical constraints
- But only weakly predictive (da Cunha et al. (2008))



da Cunha, Charlot, & Elbaz (2008)

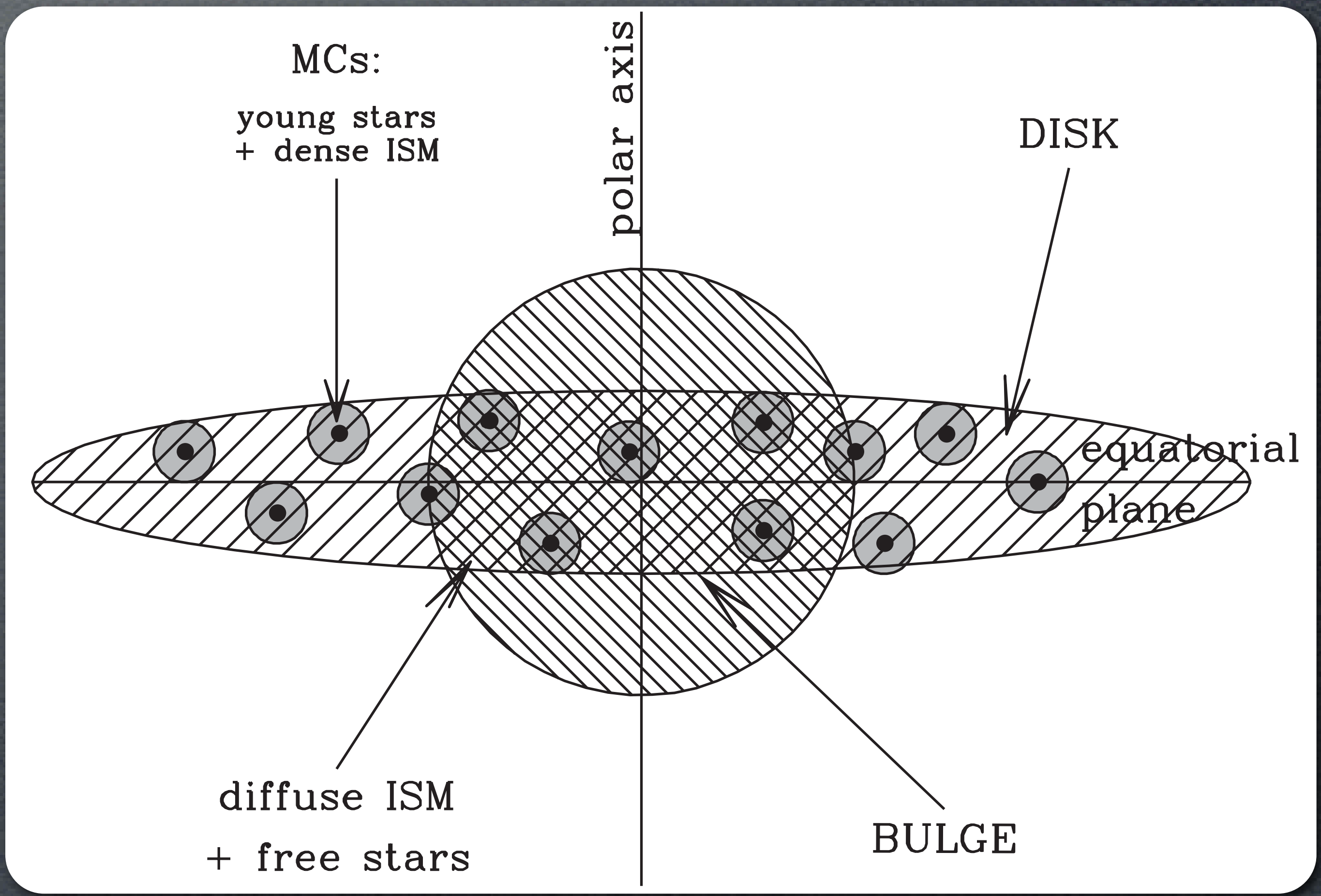


How do I stick it together again?

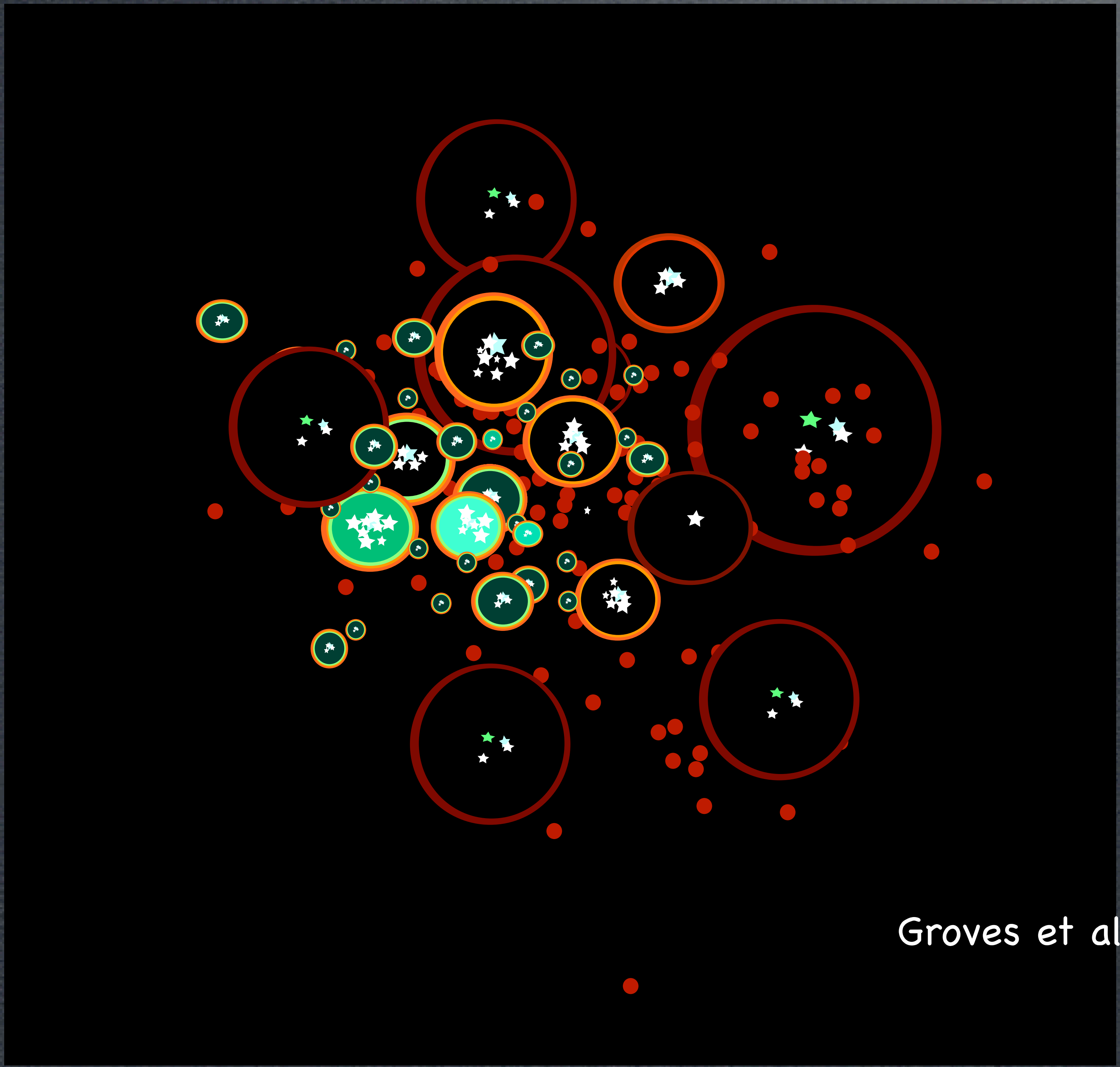
- Dust and Stellar emission disparate mechanisms
- but hold together globally
- So we can treat them separately...
- Or use a simple energy balance (ie Absorbed=Emitted)
- OR something more complex...

Geometry Lessons

- GRASIL (Silva et al. (1998)
- Improve geometry
- closer to full galaxy
- BUT.. lose on some of the details



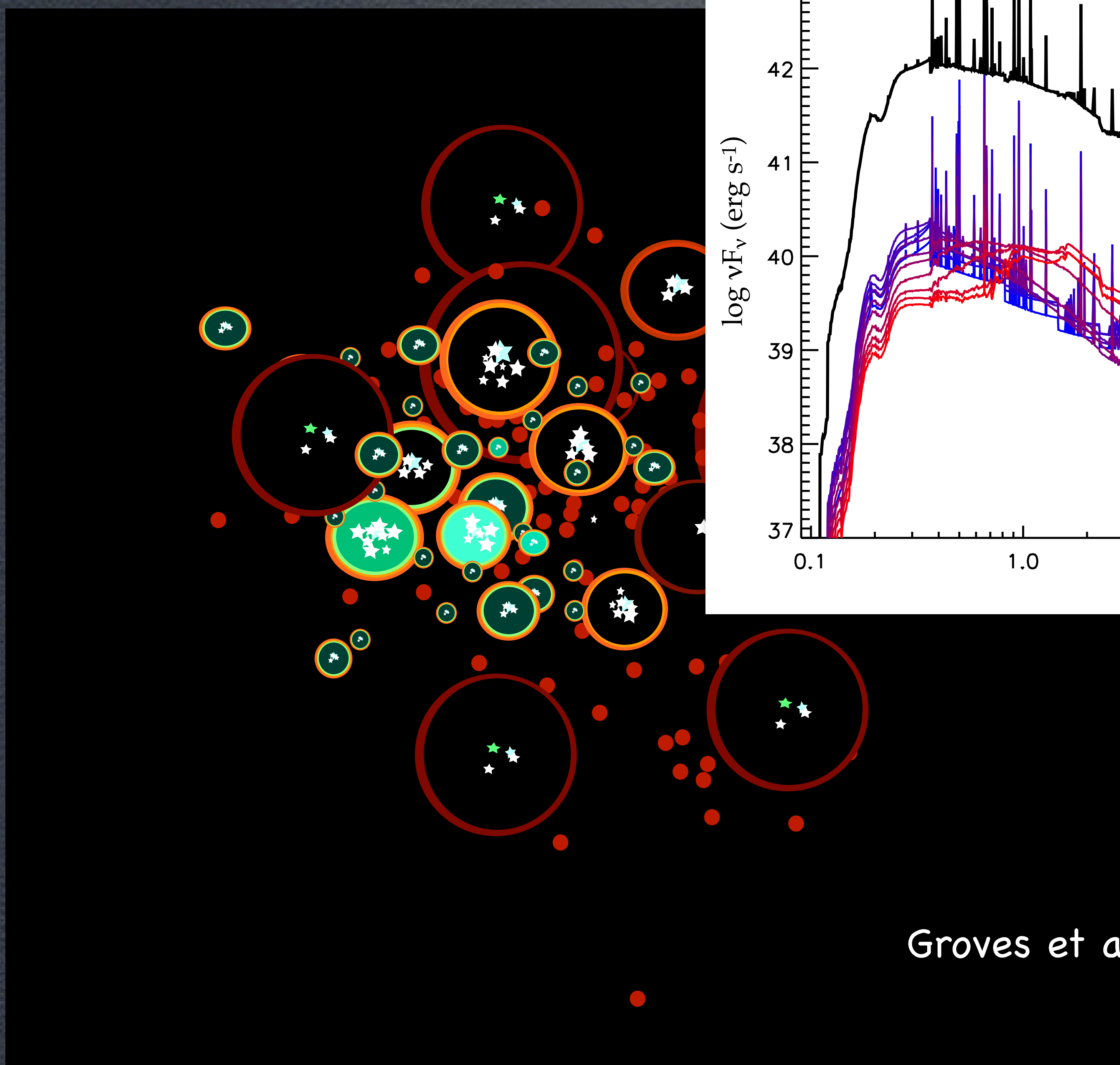
Bubble, bubble

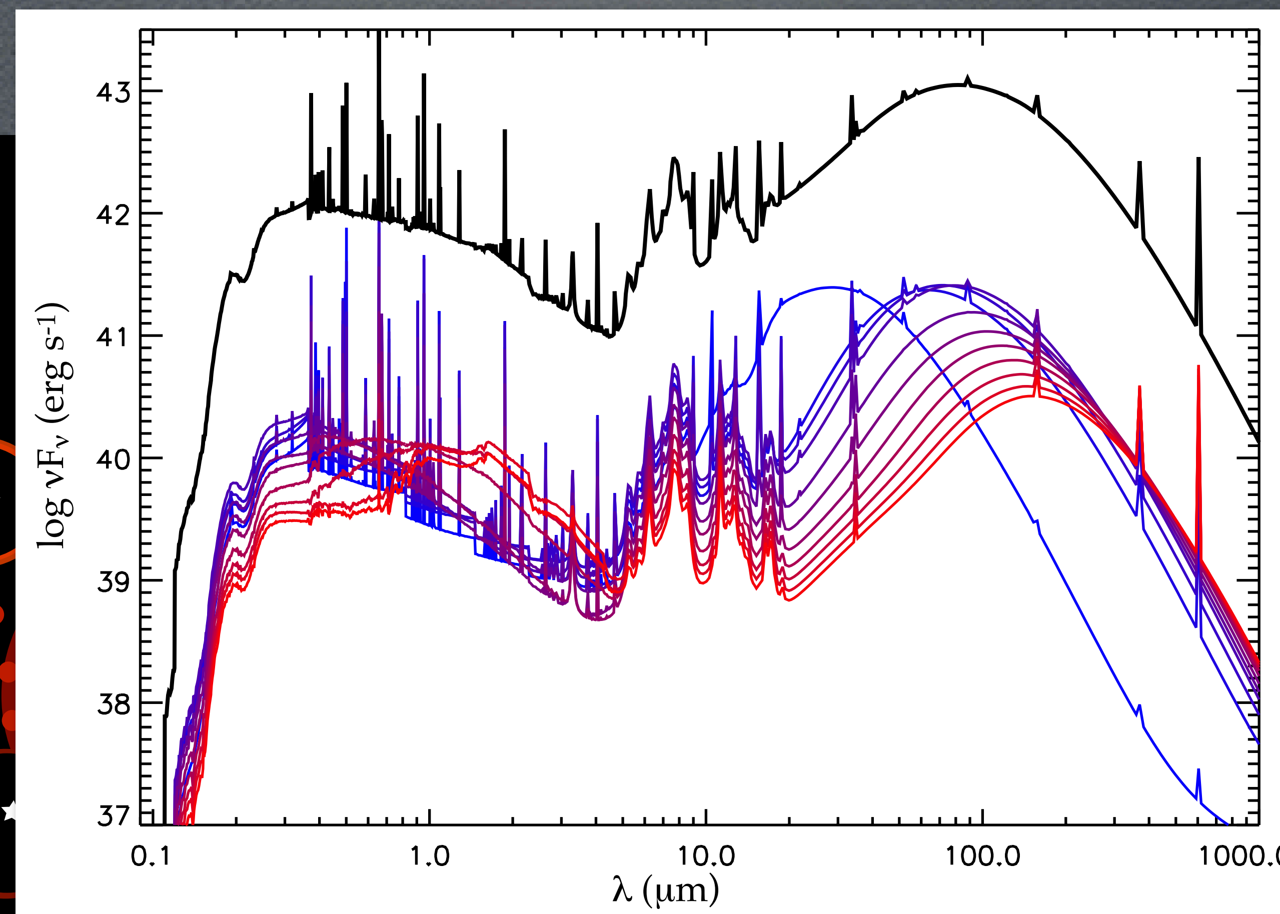


- Star forming regions expand over time
- Clear away "birth clouds" of gas and dust - link SF, emission lines and IR
- Full Radiative transfer
- Predictive and somewhat descriptive
- Simple geometry means only for starburst galaxies

Groves et al. (2008)

Bubble, bubble





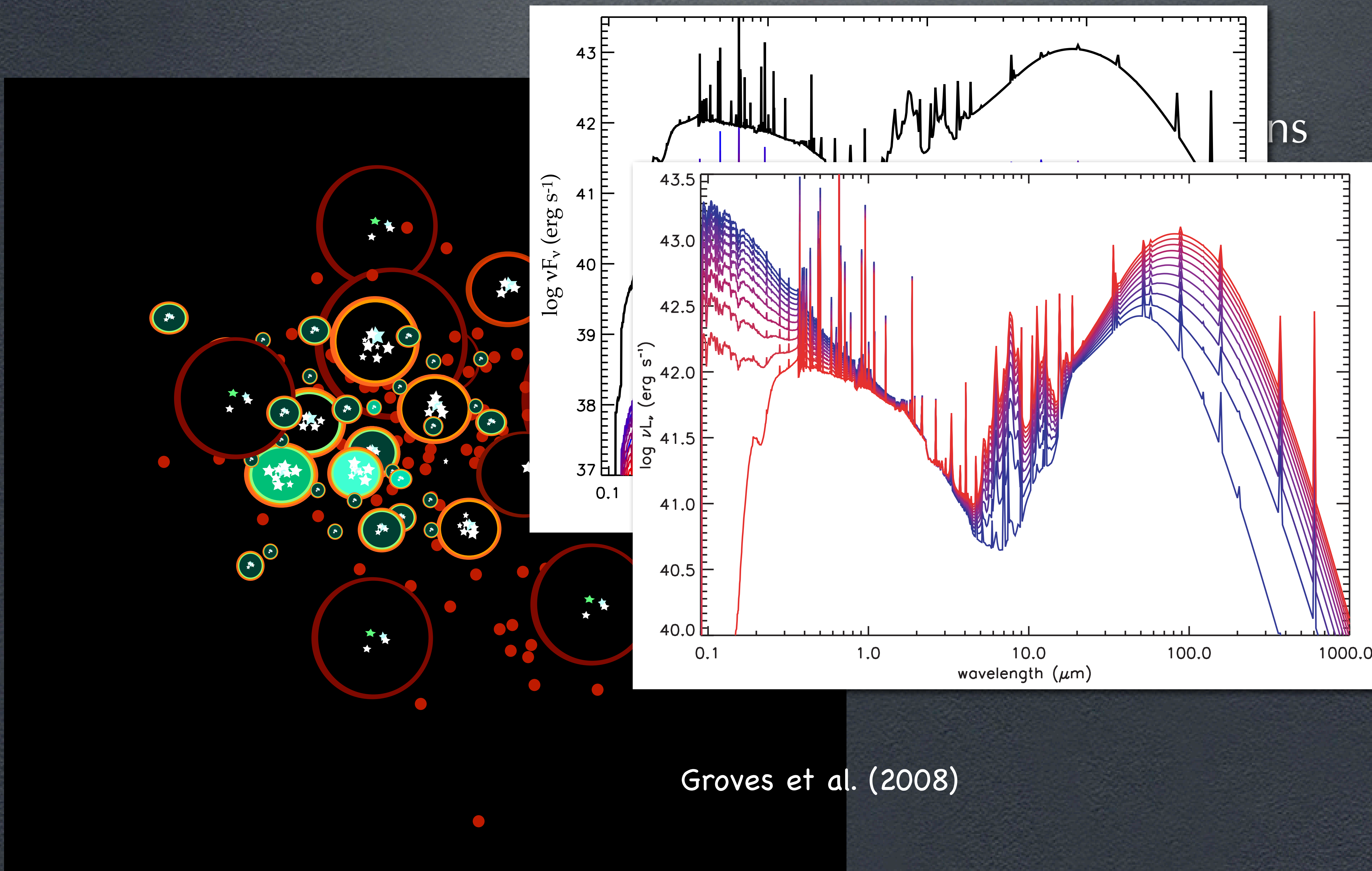
ns

clouds”
ink SF,
l IR
sfer
newhat
descriptive

- Simple geometry means only for starburst galaxies

Groves et al. (2008)

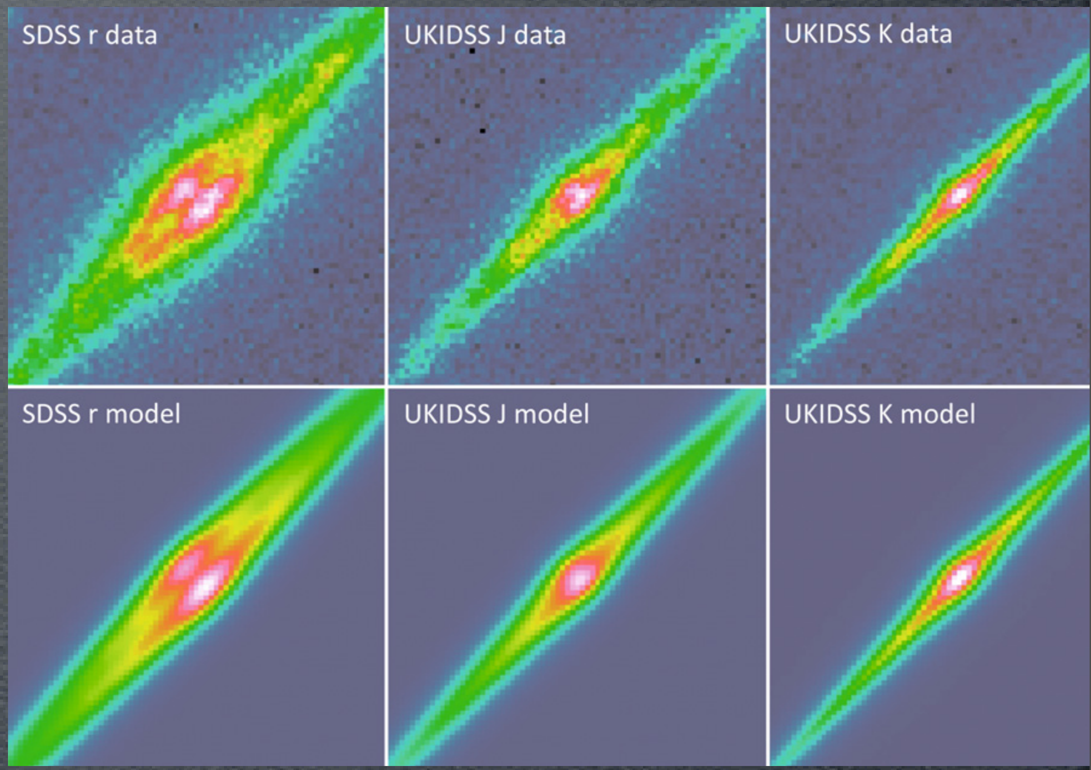
Bubble, bubble



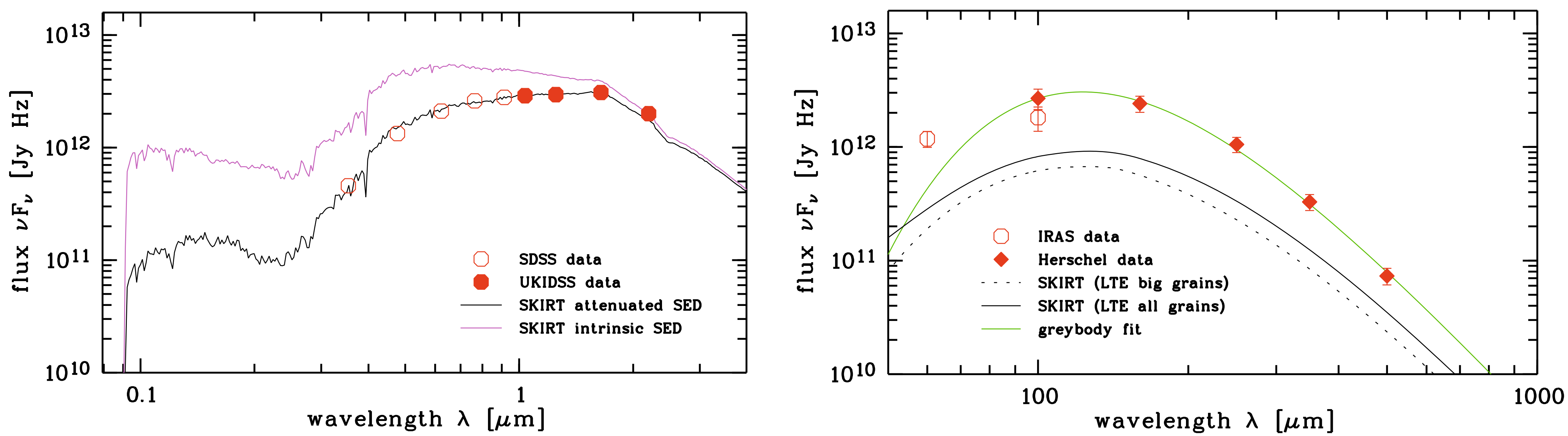
Groves et al. (2008)

Tracing the lines

- Radiative transfer gives both direct absorption, scattering, and radiation field heating dust
- Importantly, gives 2D images, 3D picture
- eg SKIRT(Baes et al. (2005)),
- eg Popescu, Tuffs, Kylafis



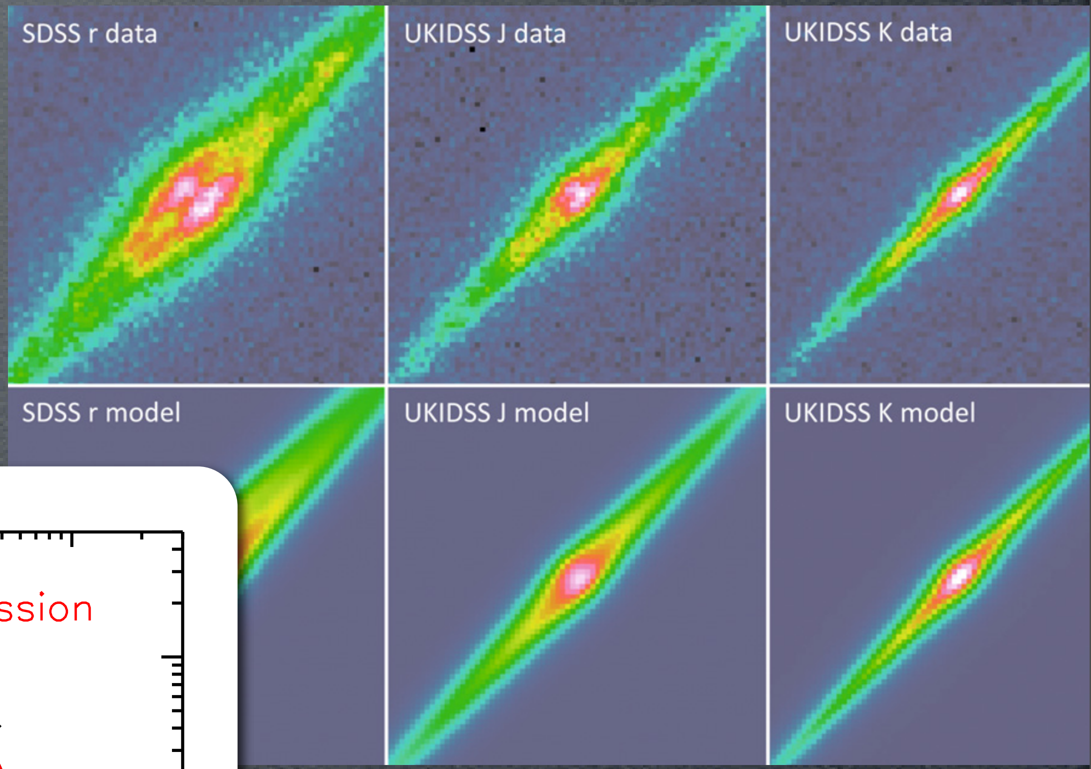
Baes et al. (2010)



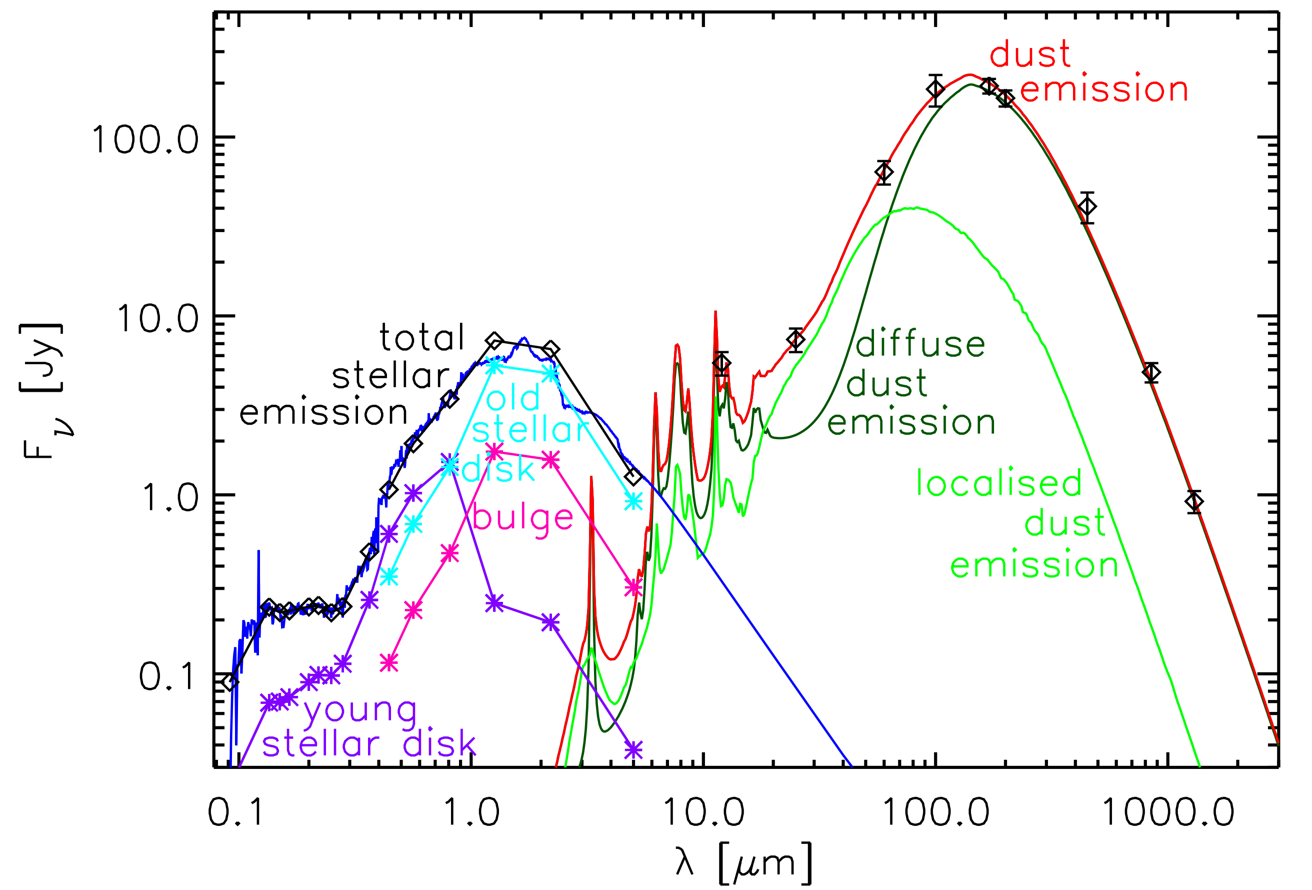
UGC 4754

Tracing the lines

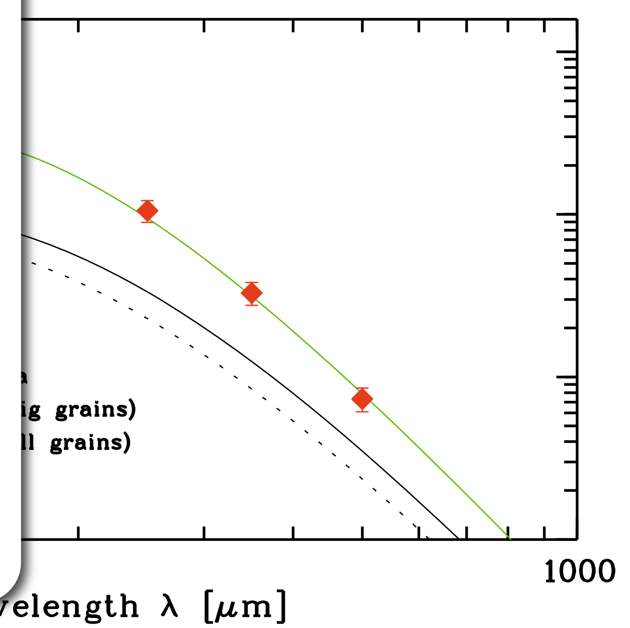
- Radiative transfer gives both direct absorption, scattering, and radiation field heating dust
- Importantly, gives 2D images, 3D picture
- eg SKIRT(Baes et al. (2005)),
- eg Popescu



aes et al. (2010)



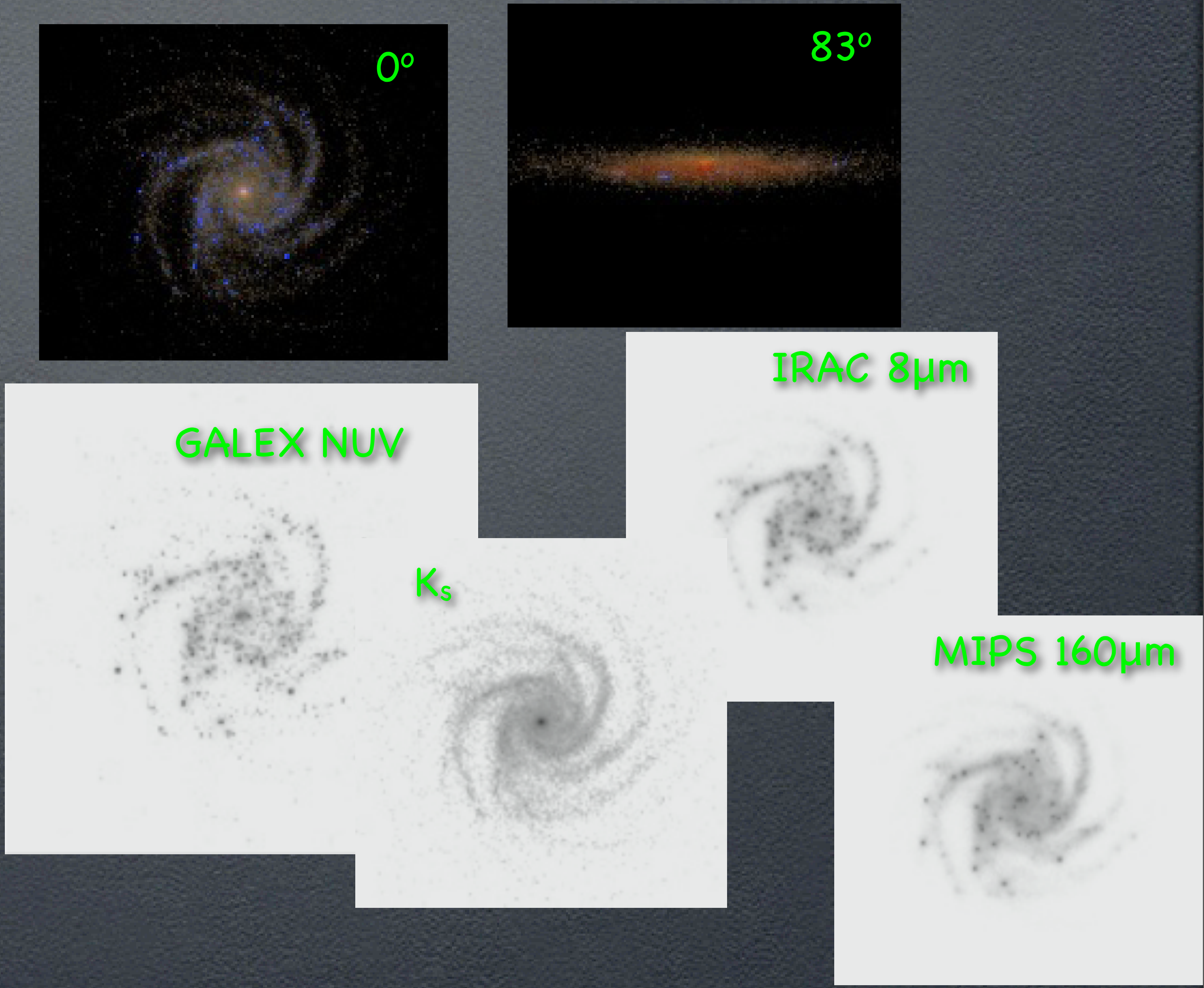
Popescu, Tuffs, et al. (2010)



UGC 4754

Random but Colourful

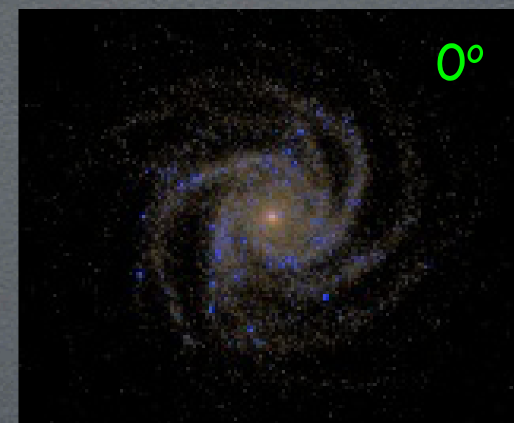
- Monte-Carlo gives full 3D geometry
- but computationally most expensive
- Polychromatic rays help...
- MAPPINGS + SUNRISE for hot (Stochastic) & cold (diffuse)
- Totally predictive, not descriptive

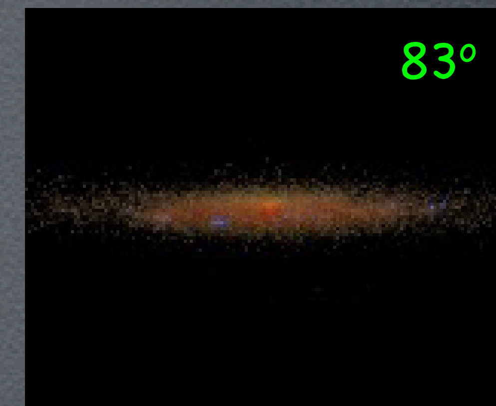


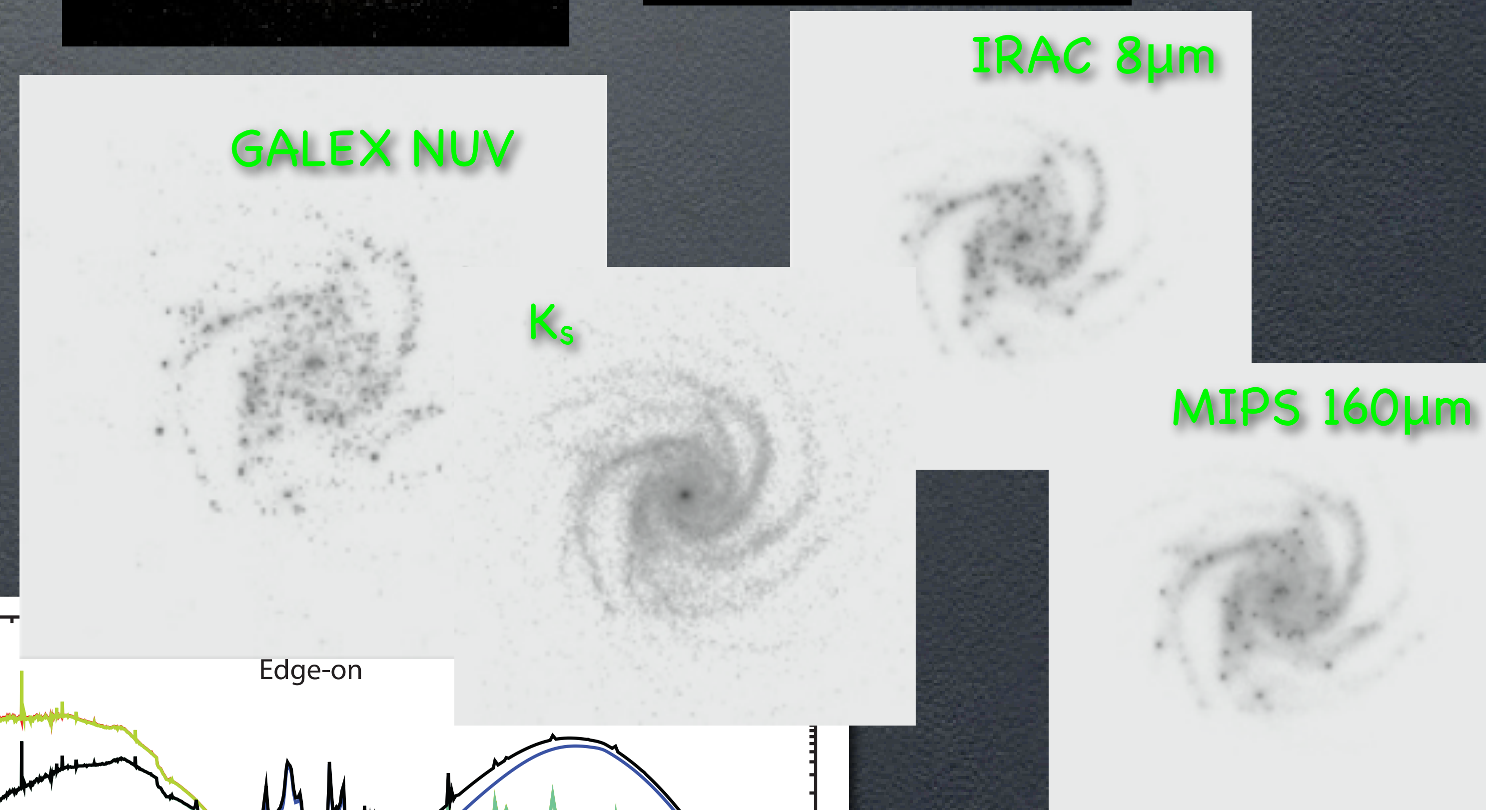
Jonsson, Groves & Cox (2009)

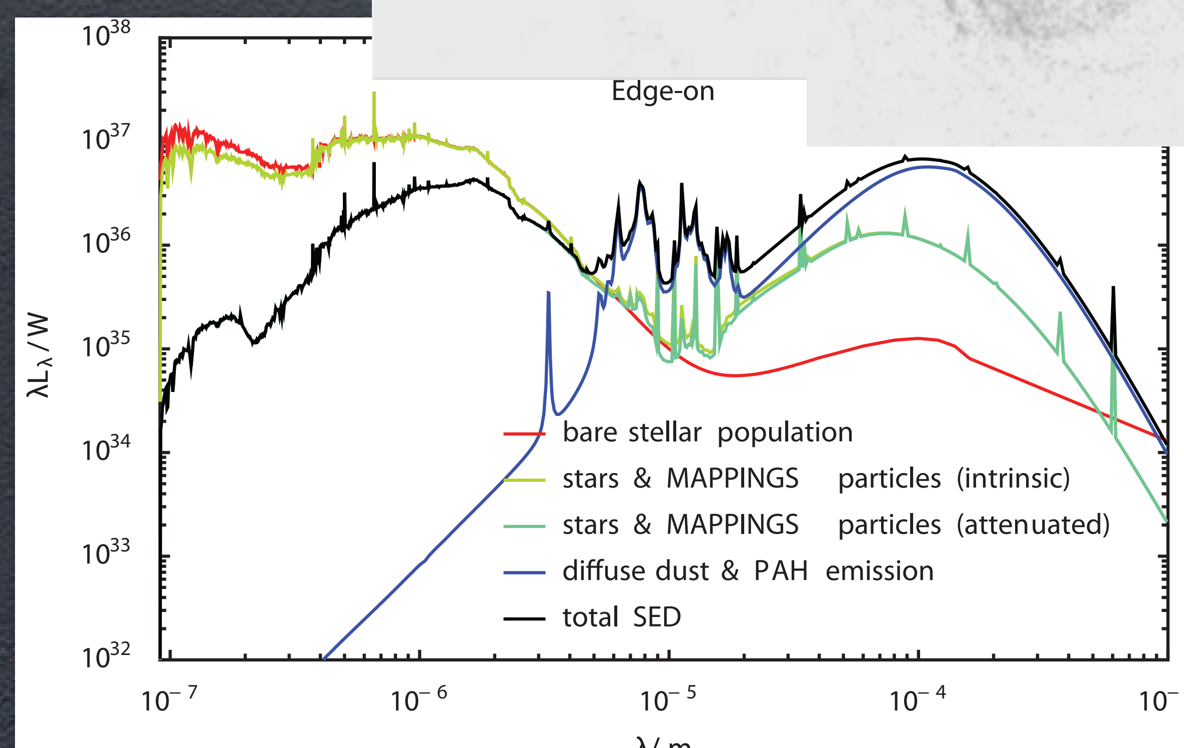
Random but Colourful

- Monte-Carlo gives full 3D geometry
- but computationally most expensive
- Polychromatic rays help...
- MAPPINGS + SUNRISE for hot (Stochastic) & cold (diffuse)
- Totally predictive, not descriptive









Jonsson, Groves & Cox (2009)

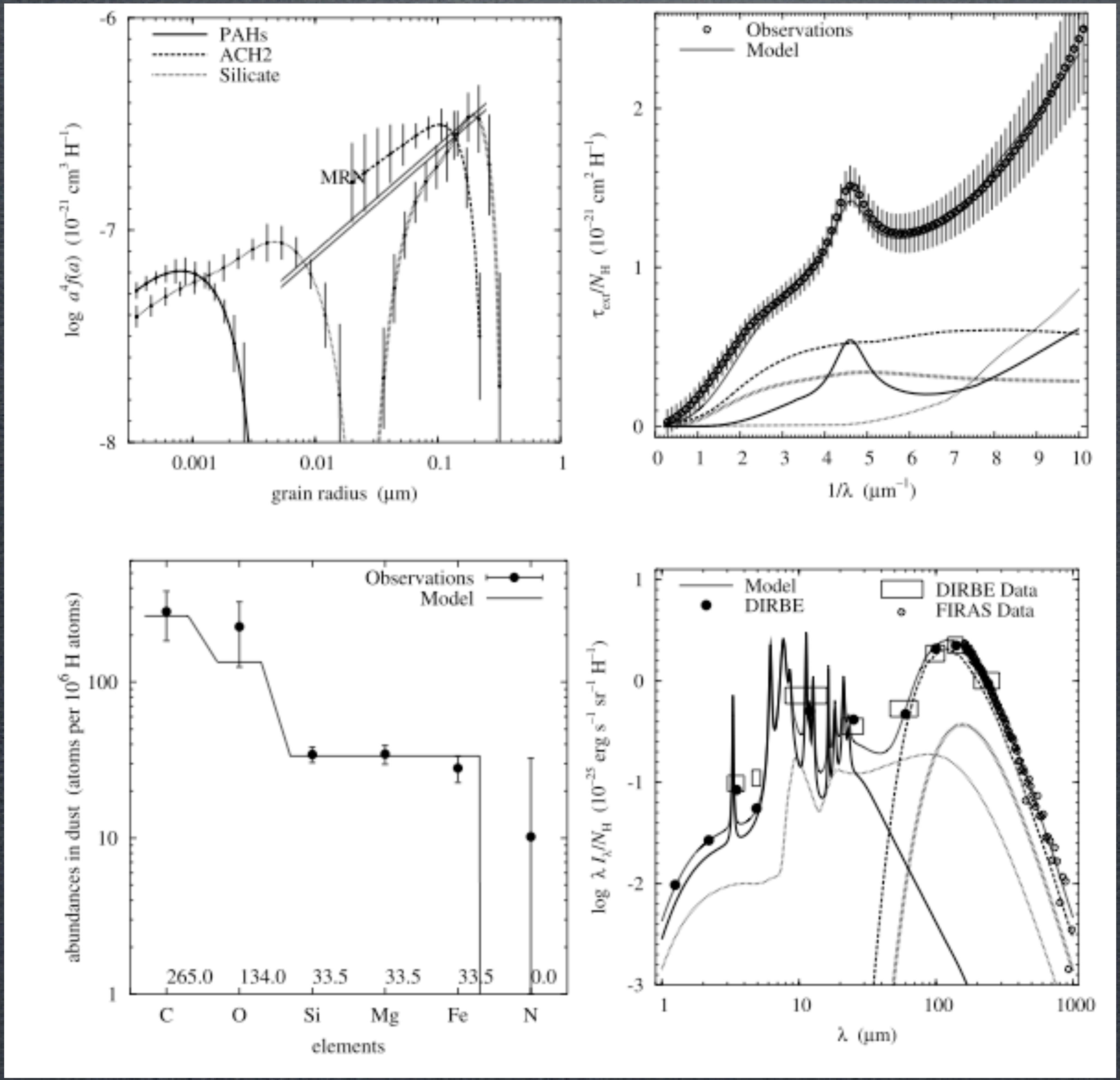
The List Goes on

- www.SEDfitting.org
  - Rowan-Robinson et al.
  - Dopita, Groves et al.
  - Siebenmorgen & Krugel
  - Arimato & Hanami
  - Gordon, Misselt et al.
  - da Cunha, Charlot, & Elbaz
  - Granato & Silva
  - Burgarella et al.
  - Ercolano et al.
  - and many more (who I apoligise to!)

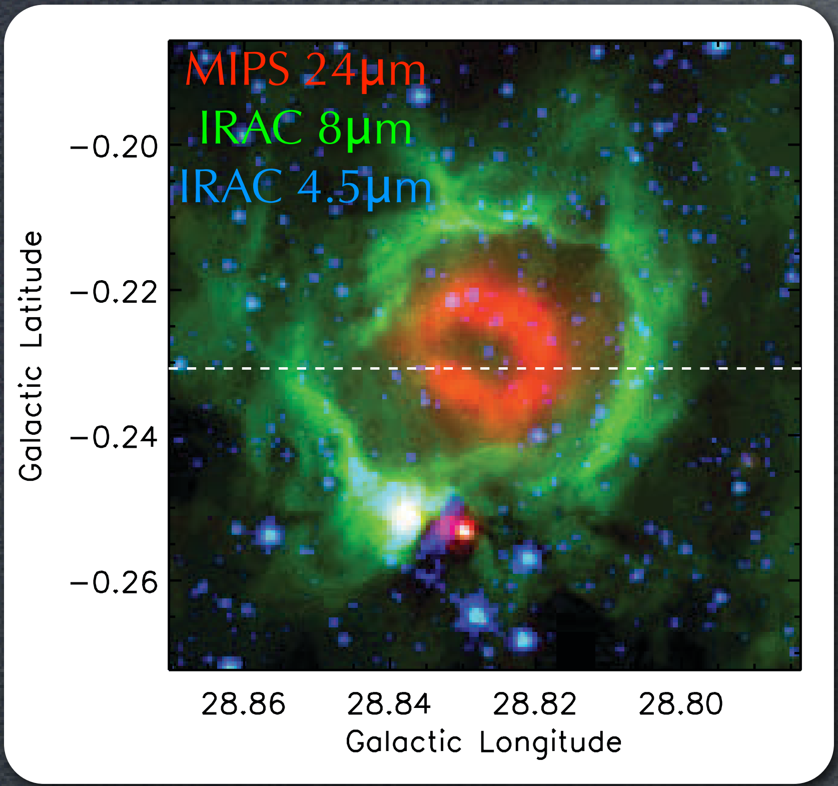
Glue all the pieces together?

- Dust and stars are linked in more than energy:
  - Metallicity?
  - Metal depletion?
  - Dust destruction?
  - Dust Creation?
  - and what about gas (ie emission lines)?

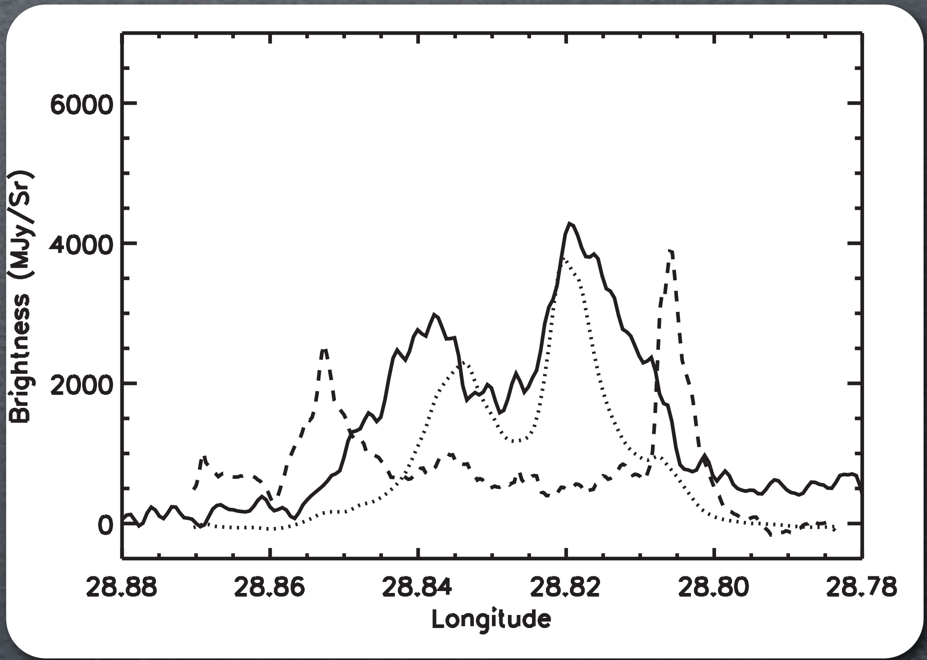
Fitting altogether?



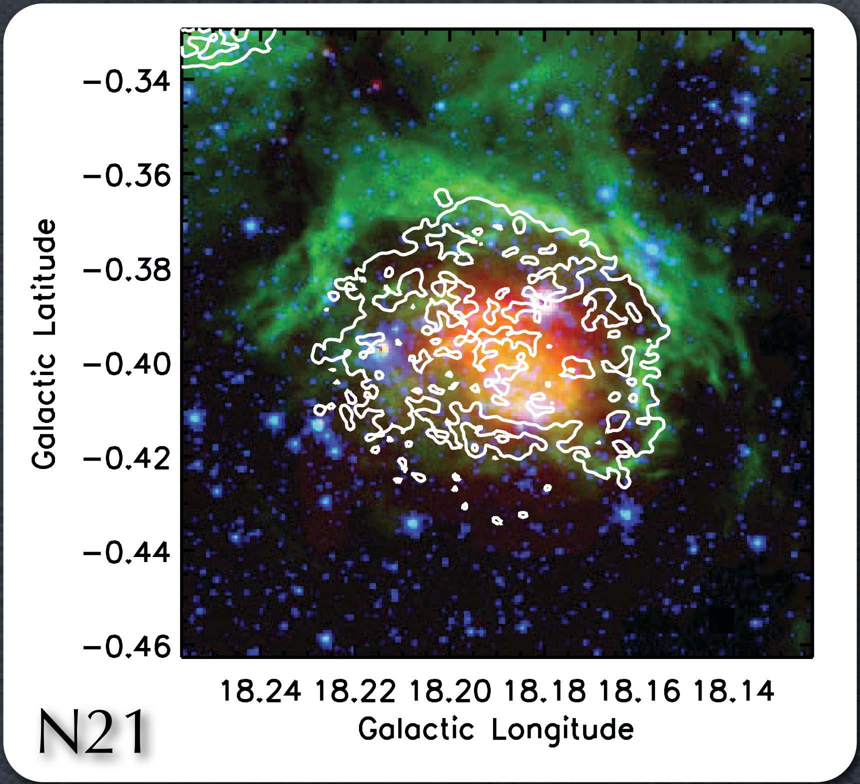
Hot Bubbles



N49



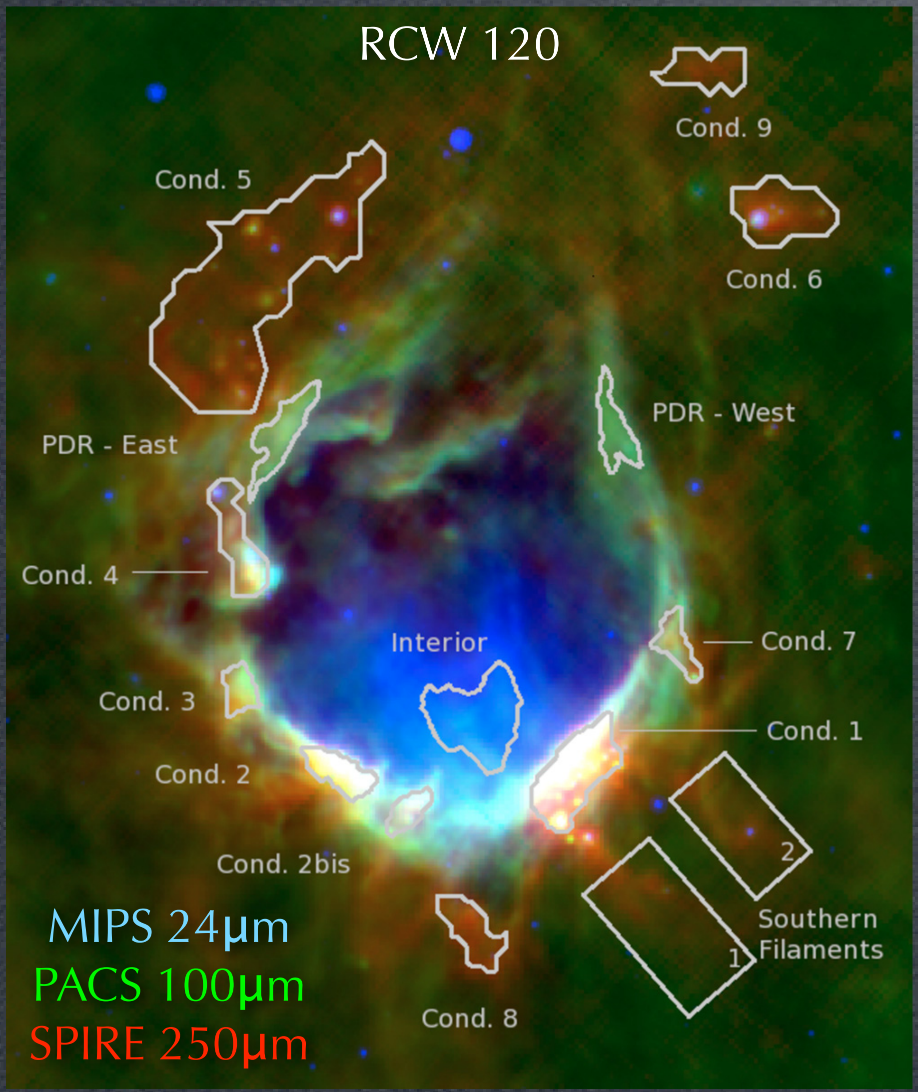
Watson et al. (2008)

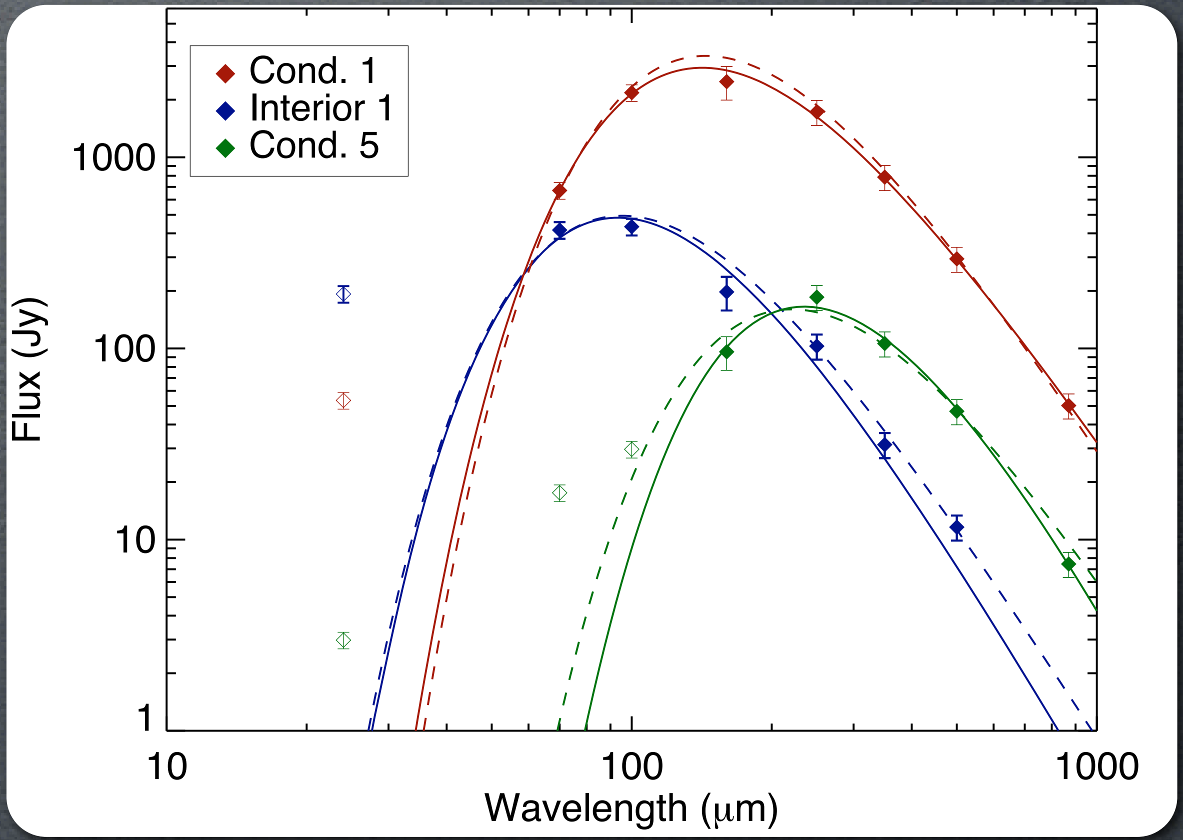


N21

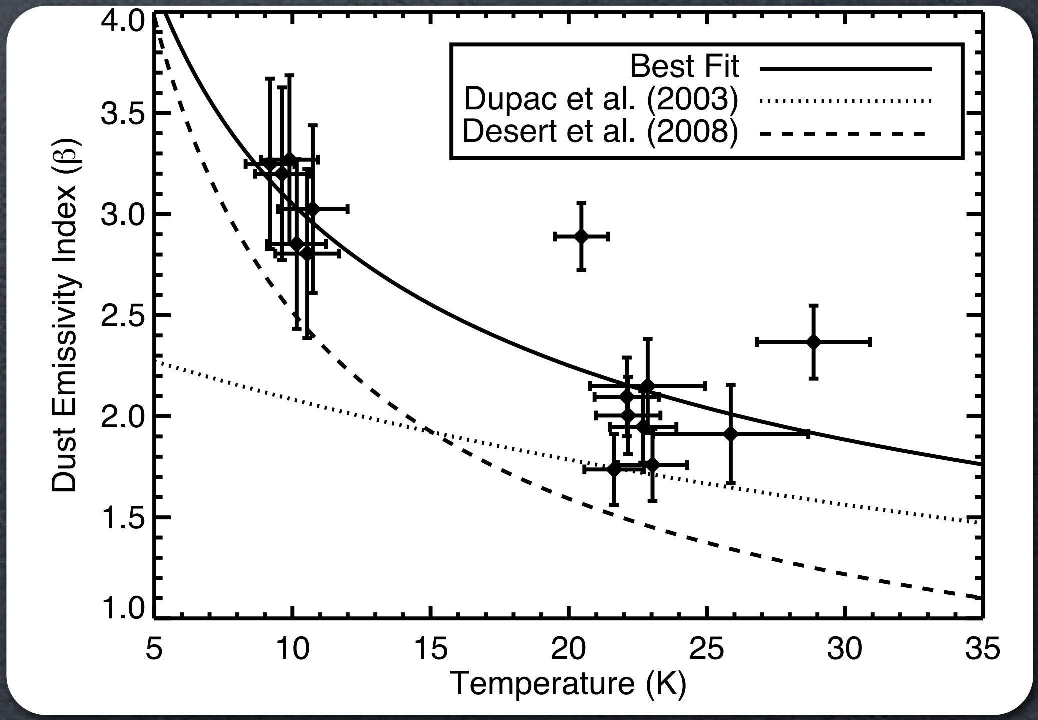
- Strong correlation of hot dust (24μm) with ionized gas (20 cm continuum)
- 8μm found outside HII region the PDR/PAH envelope

Blue but Bubbly



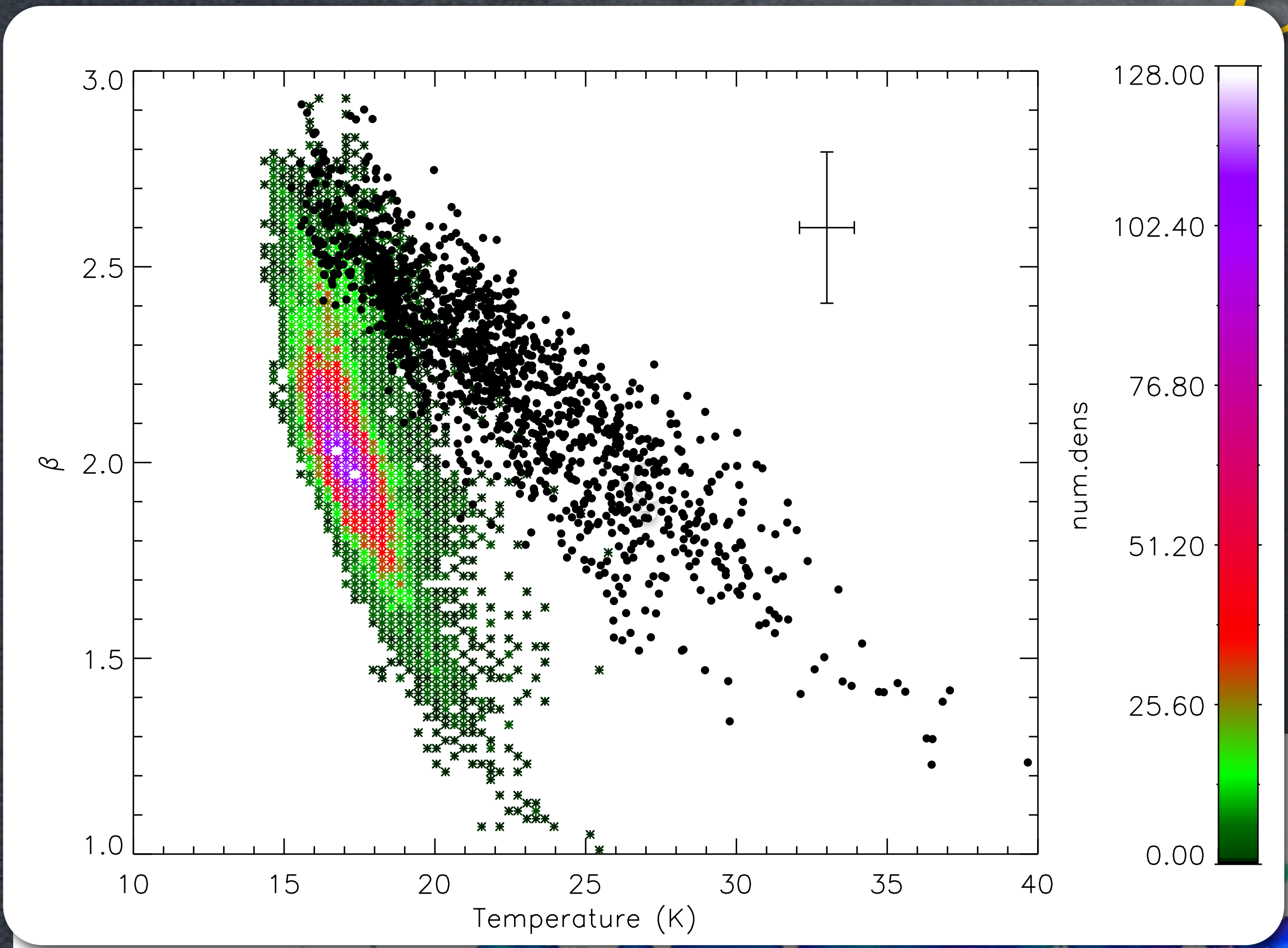


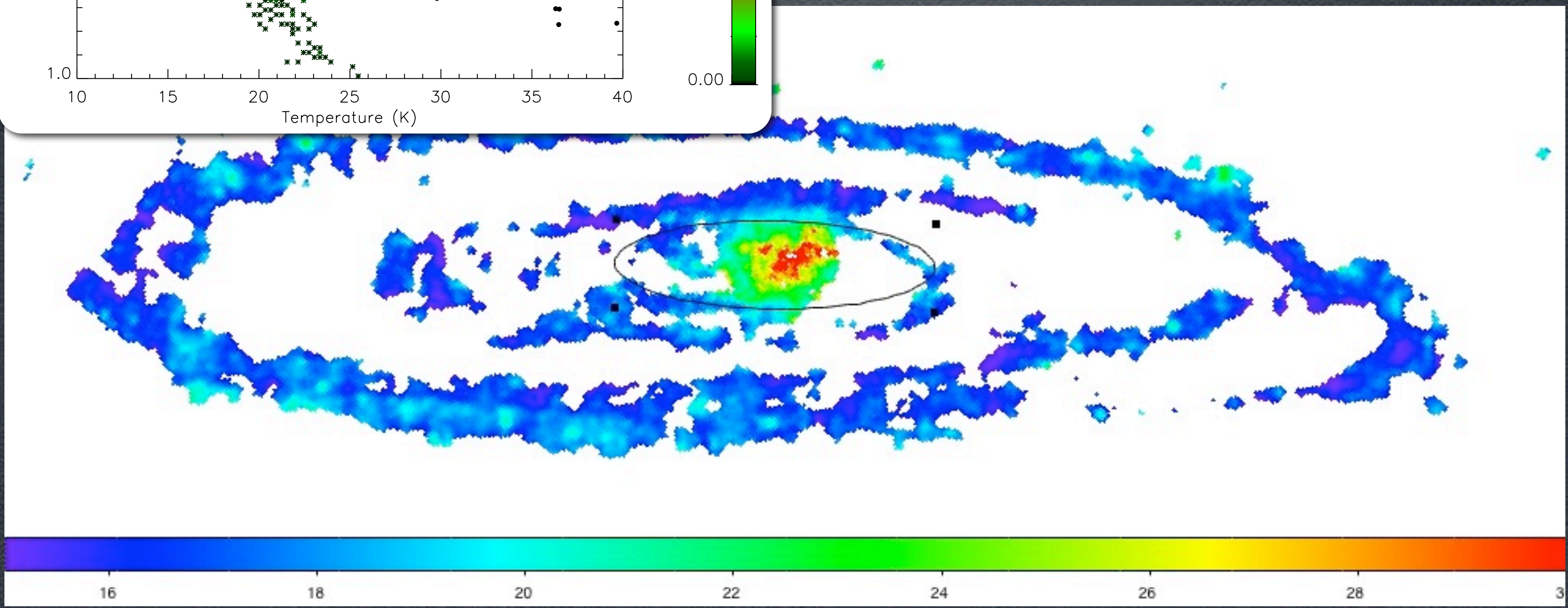
Anderson et al. (2010)



- HII regions hot but diffuse
- PDR luminous and dense
- Condensations cold and dense

Even on bigger scales...





So in balance...

- The Modelling of the Optical and IR SEDs are well advanced
- Yet caution is needed in the use of INTERPRETIVE versus PREDICTIVE models
(and how you interpret them!)
- Linking of these two regimes is limited, but by using optical, line, IR, and radio data additional constraints on parameters in all regimes can be gained