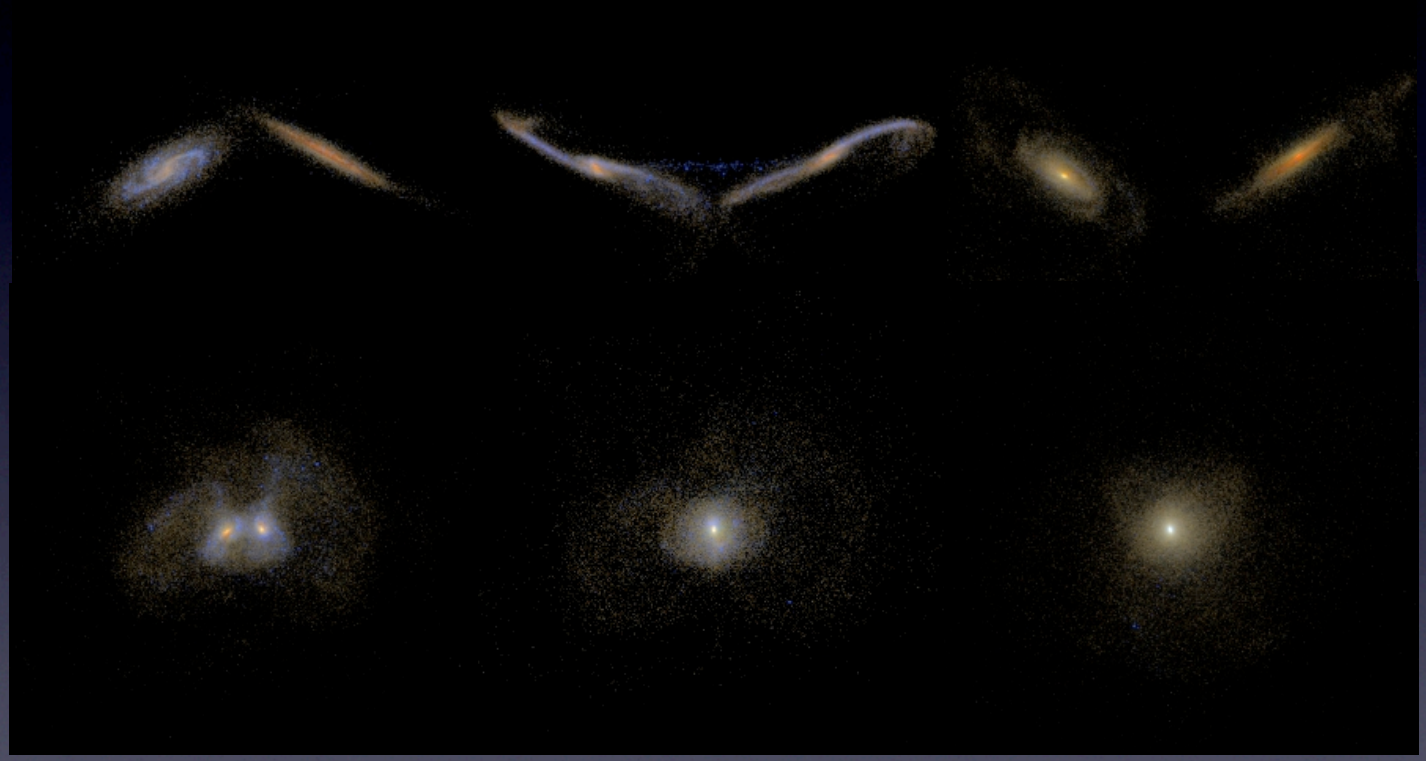
Calibrating & testing star formation rate indicators using simulations



Chris Hayward, Harvard-Smithsonian CfA

7 July 2009

SFR@50: Filling the Cosmos with Stars

Collaborators

- Kai Noeske, Stijn Wuyts, T.J. Cox, Desika Narayanan, Lars Hernquist (CfA)

- Patrik Jonsson (UCSC)

- Brent Groves (Leiden)

SFR indicators

- UV continuum (e.g., Madau+98, Salim+07)
- Recombination & forbidden lines (e.g., Hα, [OII]) (e.g., Kennicutt 98, Kewley+02)
- $L_{3\text{-}1000}$ (Kennicutt 98)
- Monochromatic IR (e.g., 24 μm: Calzetti+07, Kennicutt +07)
- UV & optical require dust corrections (e.g., Calzetti +94,00, Meurer+99, Bell & Kennicutt 01)

SFR indicators

3 questions:

1. How well do indicators trace SFR?
2. How well can we correct for dust?
3. How well can we infer $L_{3\text{-}1000}$ using templates (e.g. Dale & Helou 02, Chary & Elbaz 01)?

SFR indicator calibration

- SFR indicators typically calibrated using simple SFH (e.g., single burst or constant) + IMF + SPS models
- Correct for dust using simple analytic model (e.g., foreground screen)
- We apply SFR indicators to simulations and ask, "How well do they recover the SFR?"
- Benefits of our approach: more realistic SFH, inclusion of AGN, complex source & dust geometry

➡ We can provide more sophisticated calibrations

Testing SFR indicators

- Isolate effects of:
  - Star formation history
  - Source & dust geometry
  - Viewing angle
  - AGN & old star contamination
  - IMF
  - Stellar population synthesis model
  - Dust model
- Identify potential biases due to, e.g., correlation of dust obscuration with galaxy properties

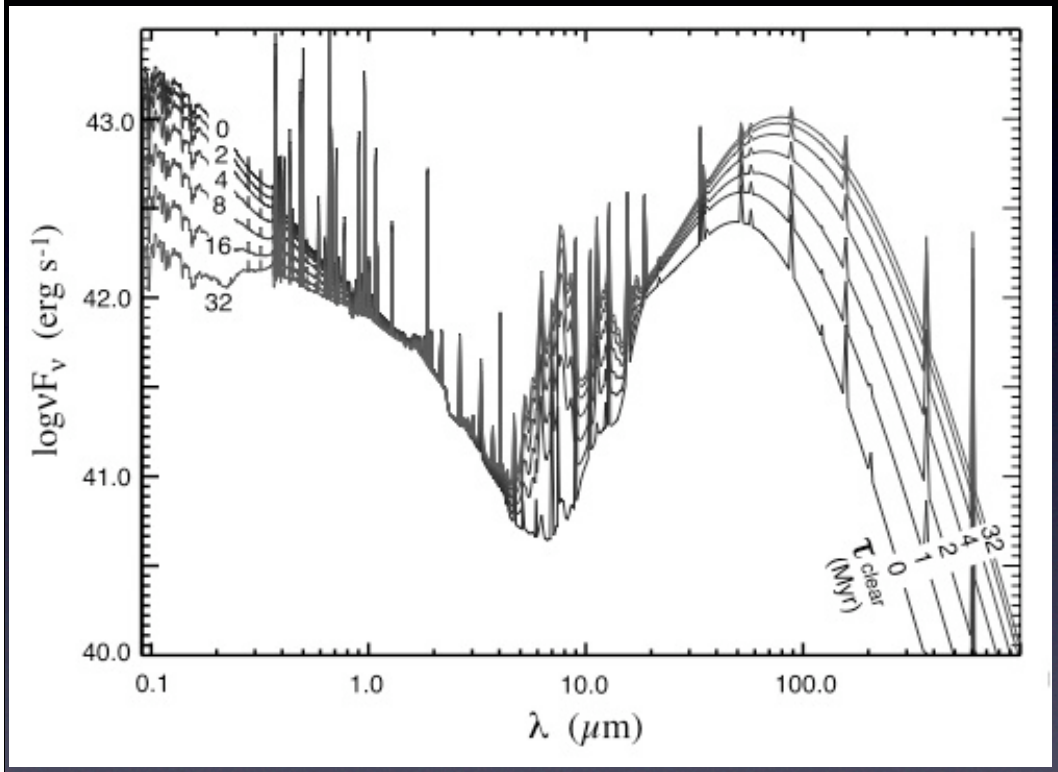
Merger simulations

- Large suite of major mergers, some minor & re-mergers (described in detail in Cox+06)
- GADGET-2 N-body/SPH (Springel 05)
- Schmidt-Kennicutt SF recipe (Schmidt 59, Kennicutt 98)
- Two-phase ISM of Springel & Hernquist (03)
- Radiative heating & cooling (Katz+96)
- BH growth & feedback (Springel+05)

Sunrise radiative transfer code

- We utilize the 3-D adaptive grid polychromatic Monte Carlo RT code *Sunrise*, developed by Patrik Jonsson, UC Santa Cruz
- Publicly available: http://www.ucolick.org/~patrik/sunrise
- 3-D adaptive grid → can resolve complex density structure present in simulations
- Polychromatic → study spectral lines
- Stellar SEDs from *Starburst99* (Leitherer+99)
- Kroupa IMF (future work will vary)
- WD01 + DL07 MW dust model, dust-to-metals = 0.4 (can vary)
- Self-consistent treatment of dust re-emission, including self-absorption

Sunrise: HII regions & PDRs



Groves+08

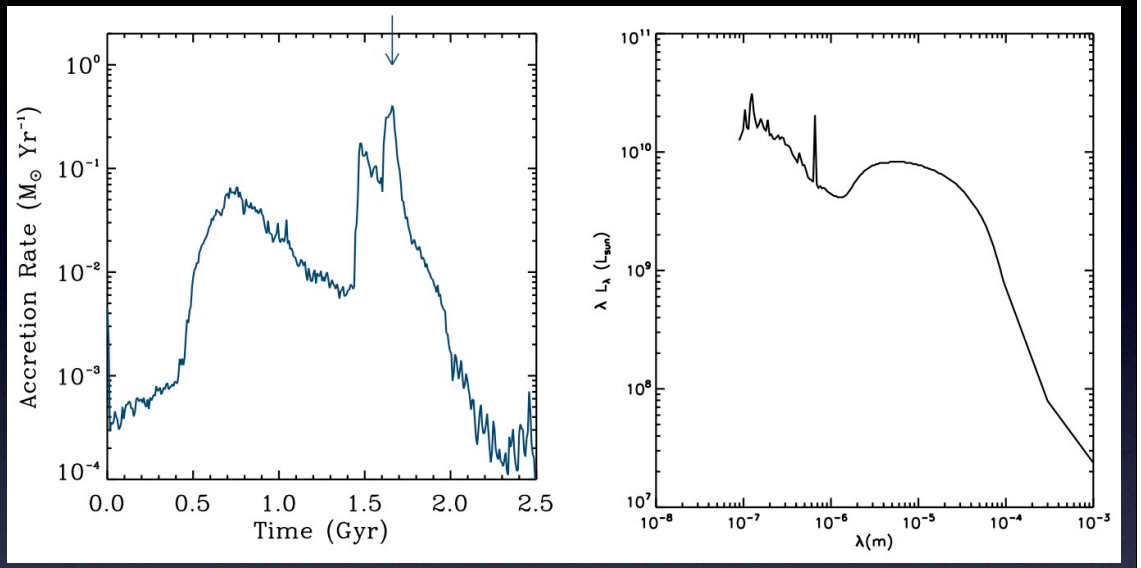
- Use Groves+08 SED templates for clusters < 10 Myr old, which include effects of HII regions & PDRs

➡ Self-consistent calculation of nebular recombination lines

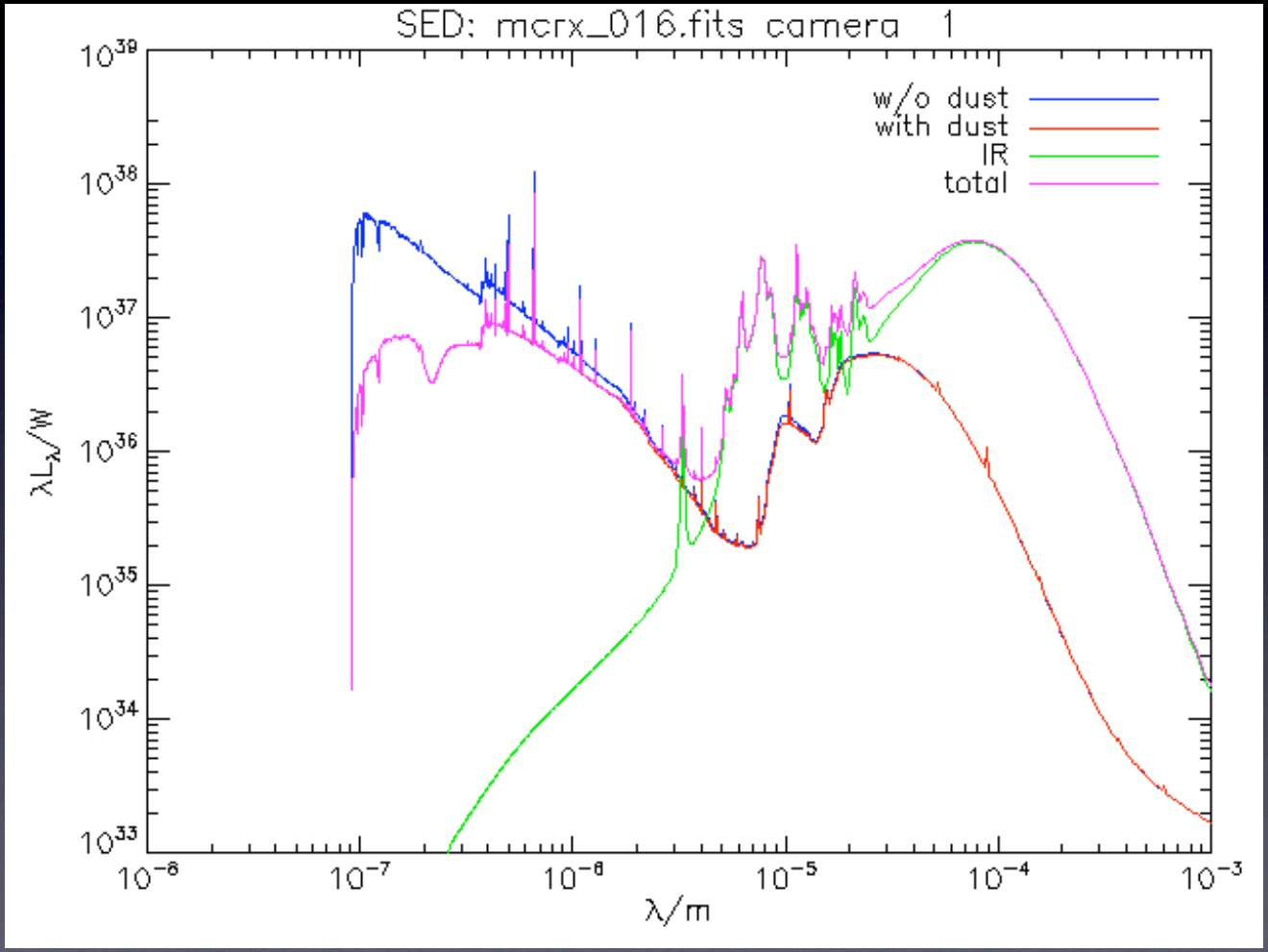
➡ Young clusters more heavily obscured, as is observed (e.g., Calzetti +94)

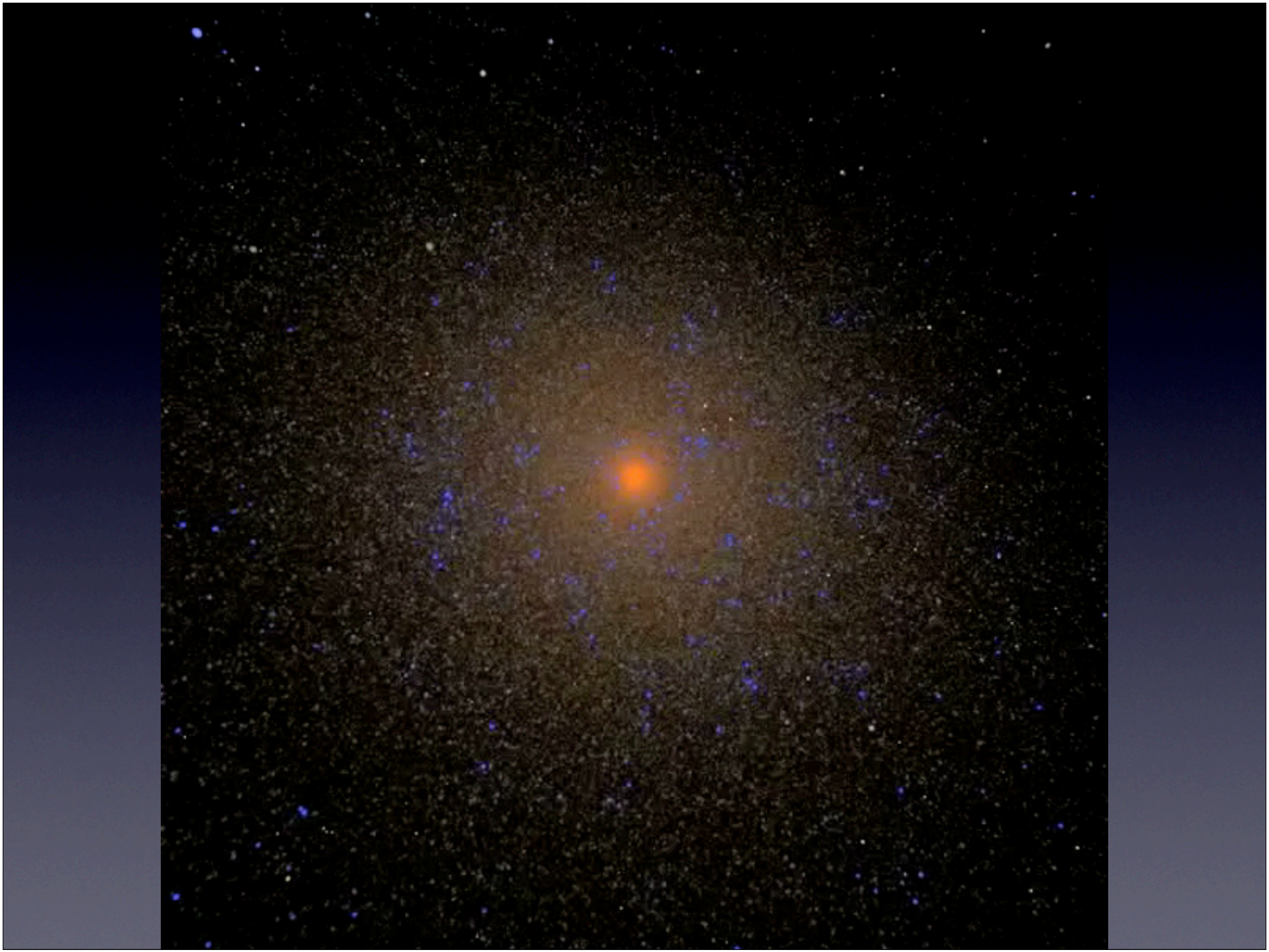
Sunrise: AGN

- Our version of Sunrise includes AGN emission
- Luminosity-dependent template of Hopkins +07
- $L = \epsilon c^2 (dm/dt)$, where $\epsilon = 0.1$ & dm/dt is taken from simulation (assuming Bondi-Hoyle accretion)

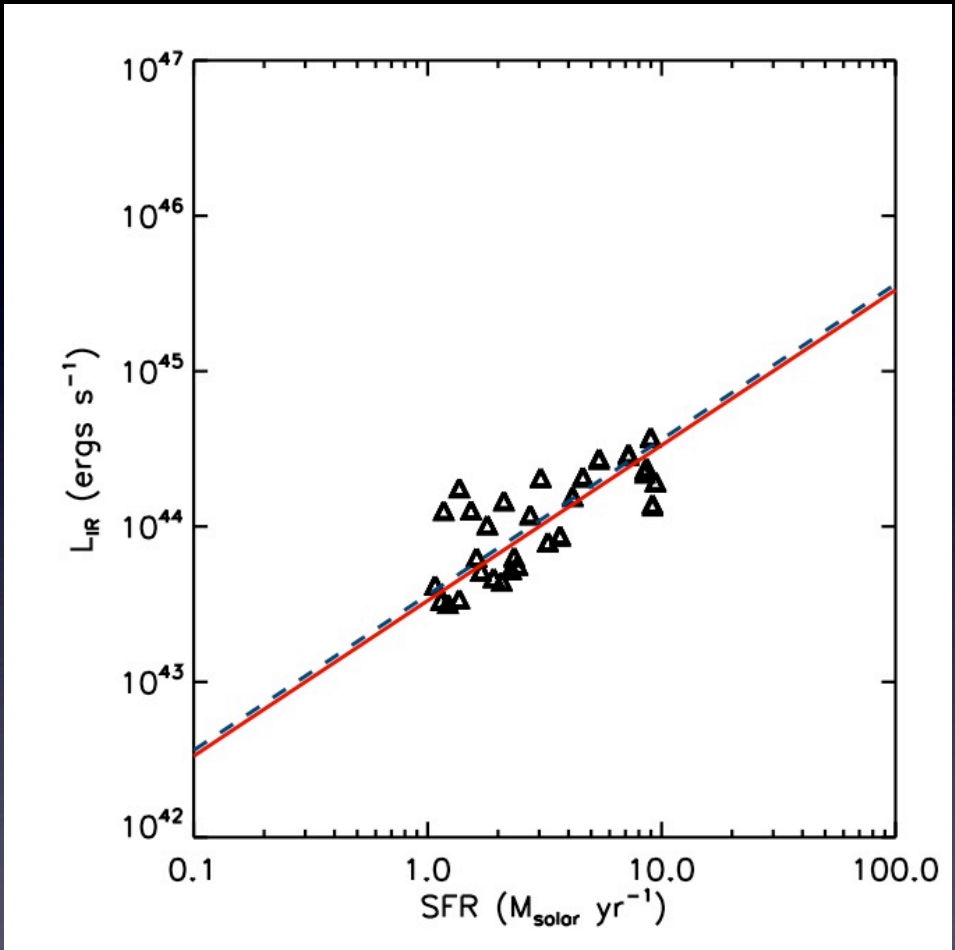


Example SED


SED: mcrx_016.fits camera 1
w/o dust
with dust
IR
total
λL_λ/W
10^{39}
10^{38}
10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
λ/m

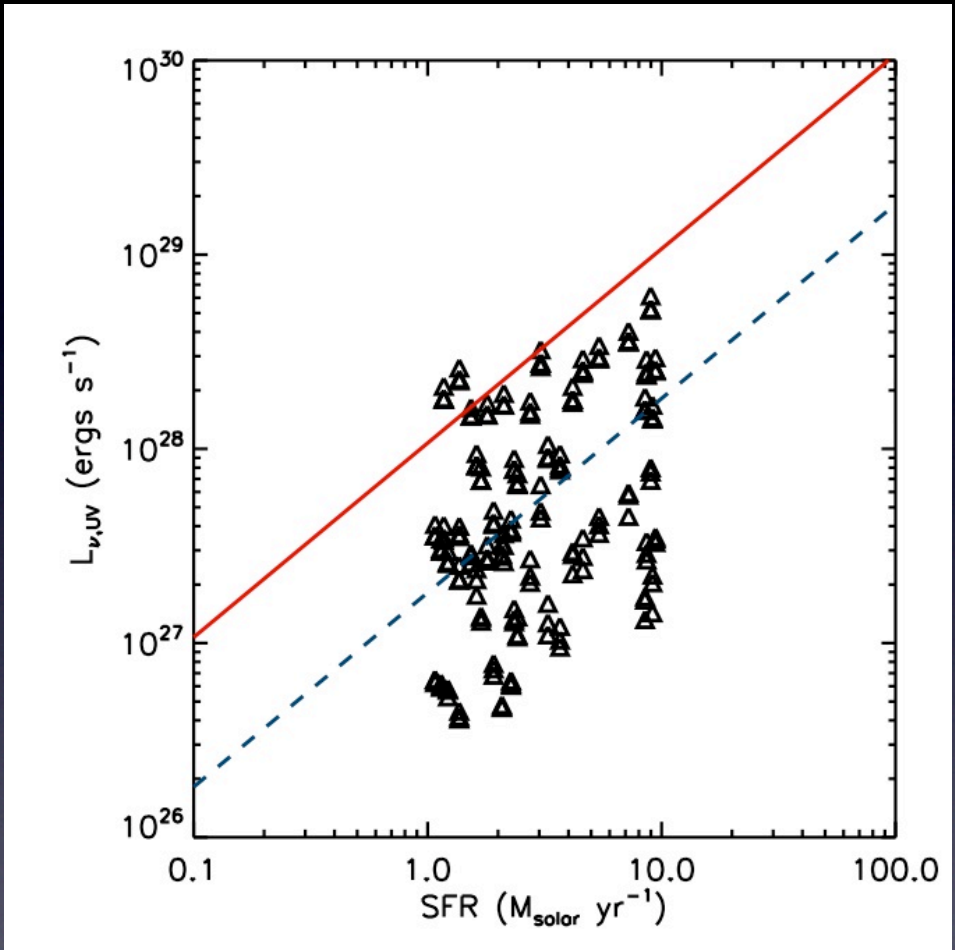


Isolated disks



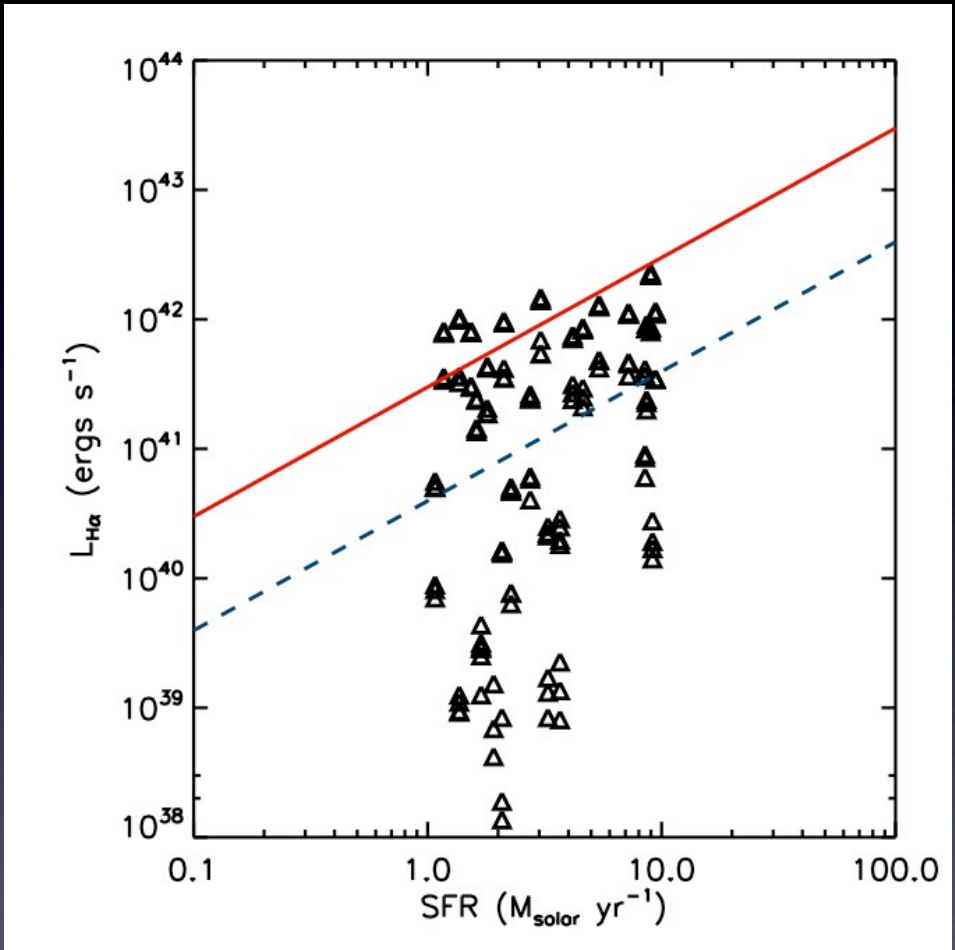
Indicator	K98/1.5	Best fit	Best fit/ (K98/1.6)
IR	2.8e-44	2.8e-44	1
UV	8.8e-29	5.5e-28	6.3
Hα	4.9e-42	2.5e-41	5.1
Hα, corr	4.9e-42	7.7e-42	1.5

Isolated disks



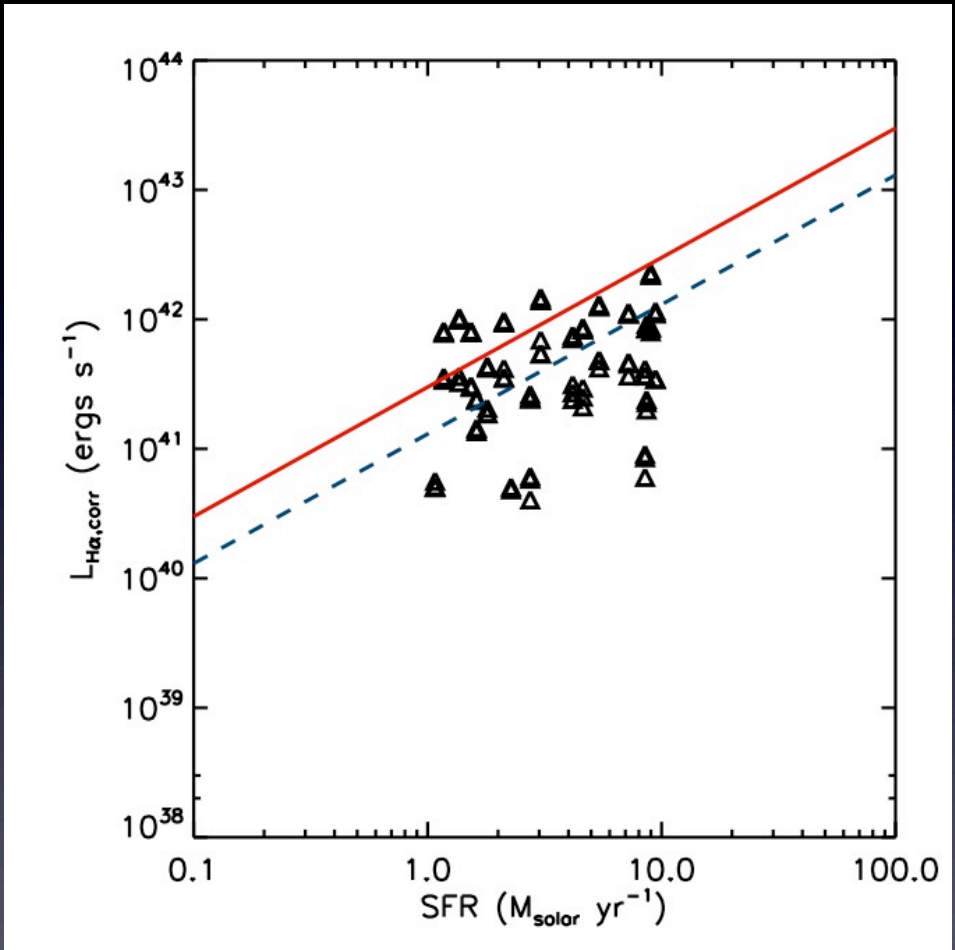
Indicator	K98/1.5	Best fit	Best fit/ (K98/1.6)
IR	2.8e-44	2.8e-44	1
UV	8.8e-29	5.5e-28	6.3
Hα	4.9e-42	2.5e-41	5.1
Hα, corr	4.9e-42	7.7e-42	1.5

Isolated disks



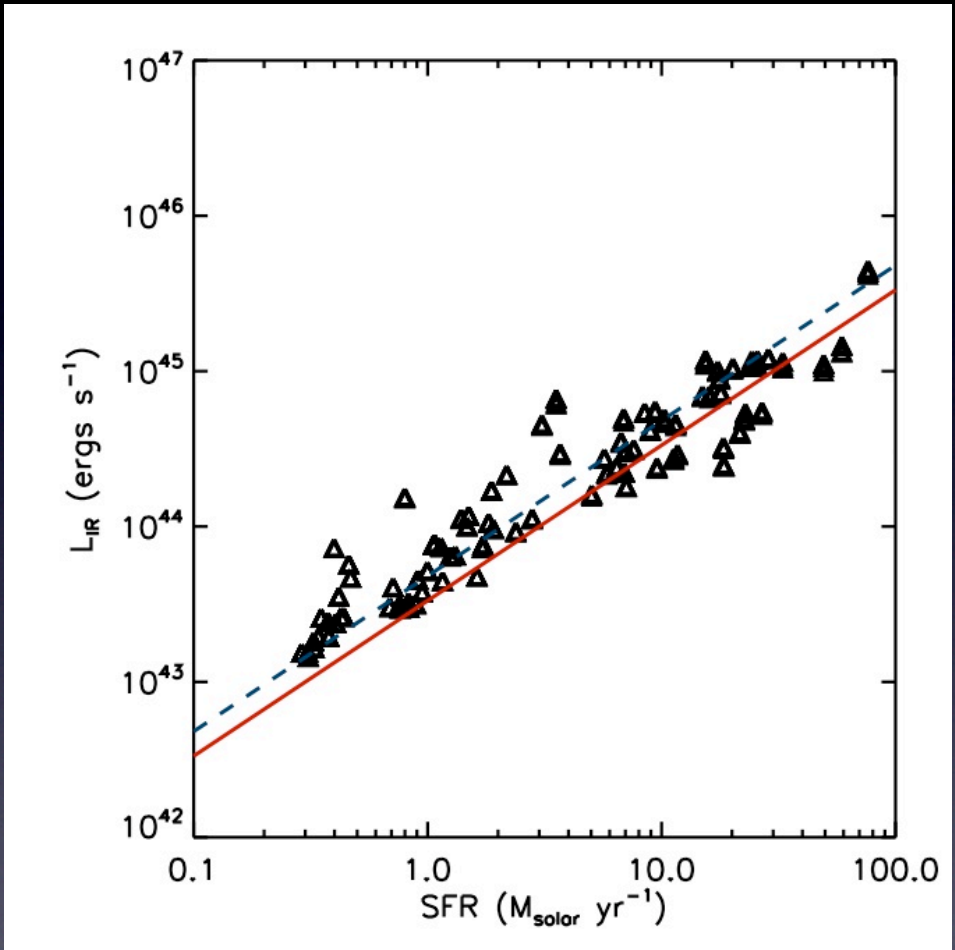
Indicator	K98/1.5	Best fit	Best fit/ (K98/1.6)
IR	2.8e-44	2.8e-44	1
UV	8.8e-29	5.5e-28	6.3
Hα	4.9e-42	2.5e-41	5.1
Hα, corr	4.9e-42	7.7e-42	1.5

Isolated disks



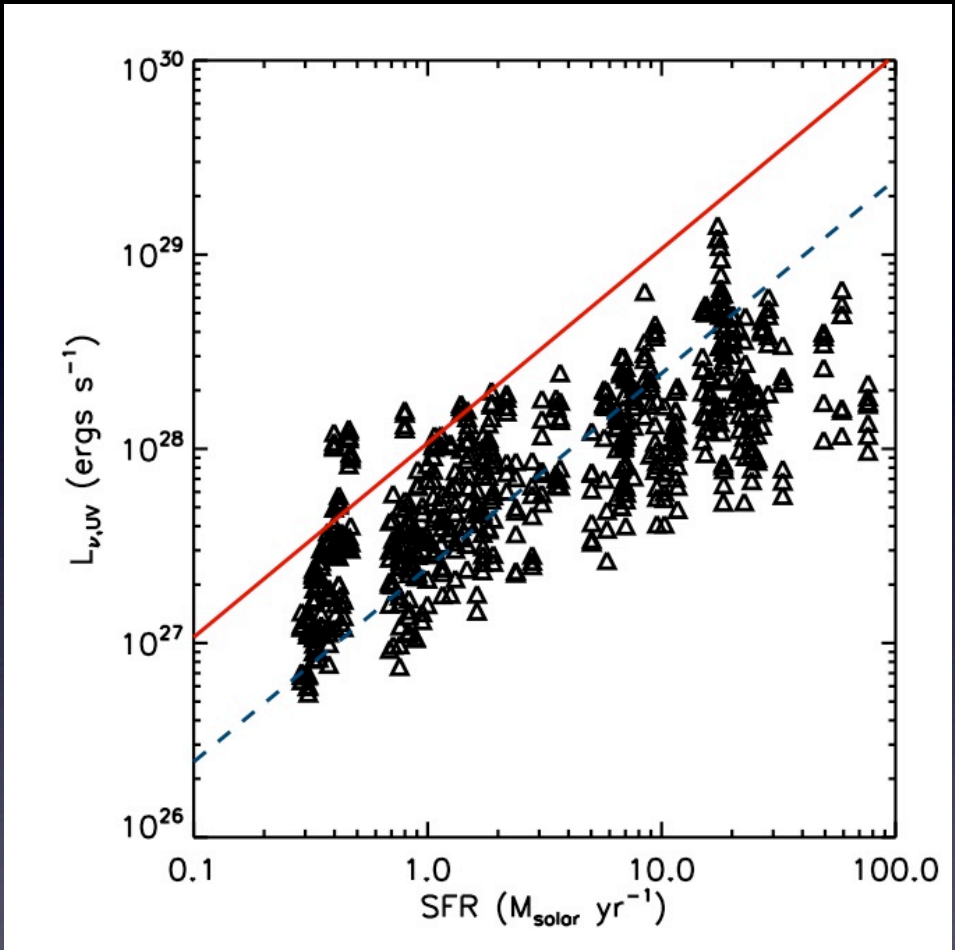
Indicator	K98/1.5	Best fit	Best fit/ (K98/1.6)
IR	2.8e-44	2.8e-44	1
UV	8.8e-29	5.5e-28	6.3
Hα	4.9e-42	2.5e-41	5.1
Hα, corr	4.9e-42	7.7e-42	1.5

Major mergers



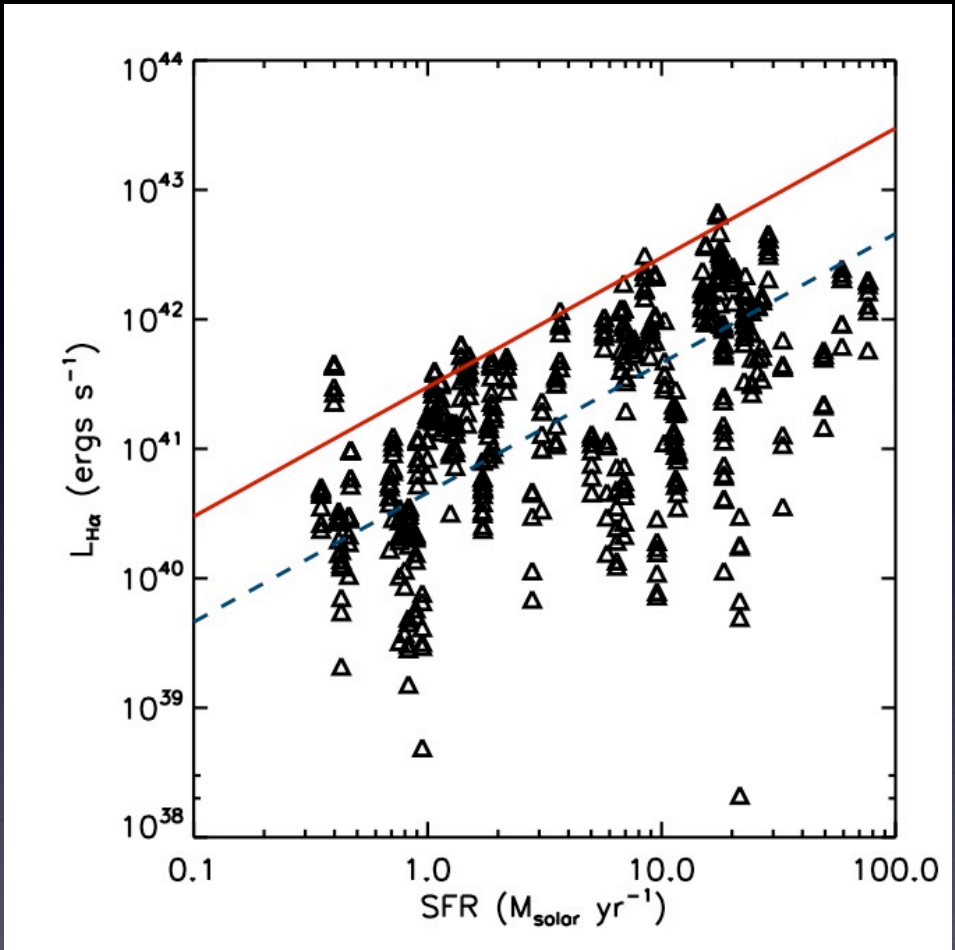
Indicator	K98/1.5	Best fit	Best fit/ (K98/1.6)
IR	2.8e-44	2.1e-44	0.75
UV	8.8e-29	4.1e-28	4.7
Hα	4.9e-42	2.2e-41	4.5
Hα, corr	4.9e-42	1.6e-41	3.3

Major mergers



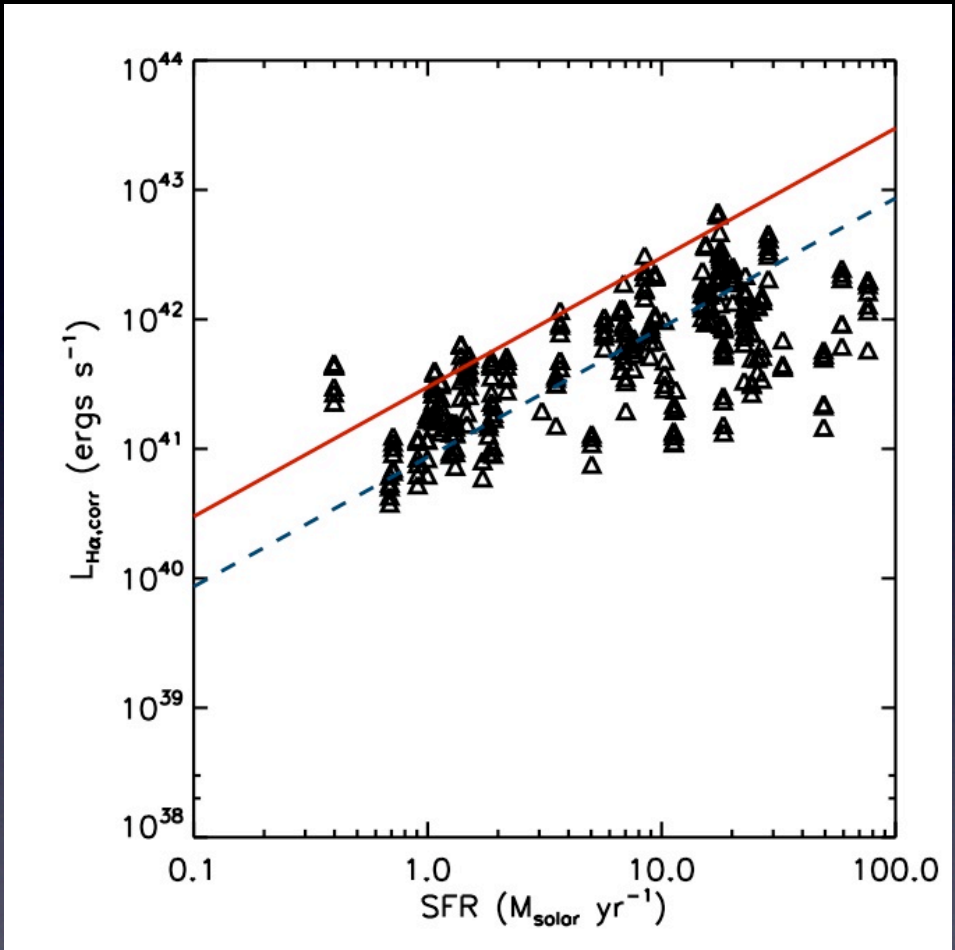
Indicator	K98/1.5	Best fit	Best fit/ (K98/1.6)
IR	2.8e-44	2.1e-44	0.75
UV	8.8e-29	4.1e-28	4.7
Hα	4.9e-42	2.2e-41	4.5
Hα, corr	4.9e-42	1.6e-41	3.3

Major mergers



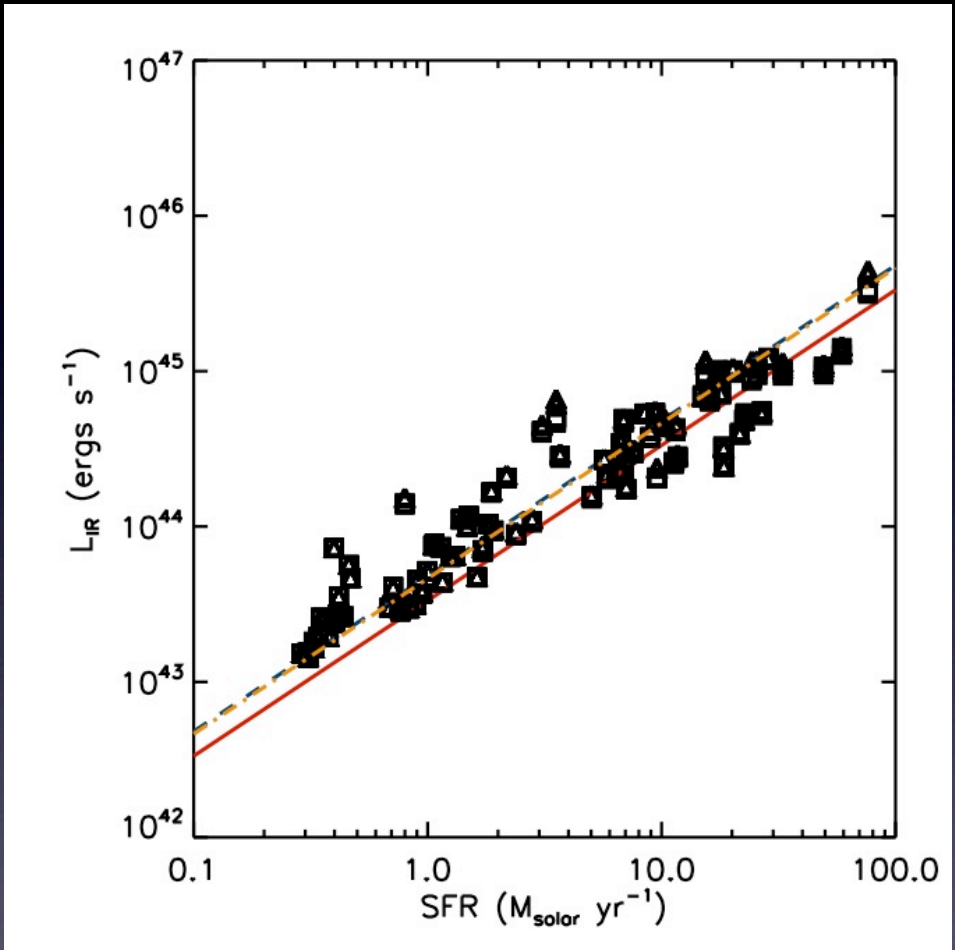
Indicator	K98/1.5	Best fit	Best fit/ (K98/1.6)
IR	2.8e-44	2.1e-44	0.75
UV	8.8e-29	4.1e-28	4.7
Hα	4.9e-42	2.2e-41	4.5
Hα, corr	4.9e-42	1.6e-41	3.3

Major mergers



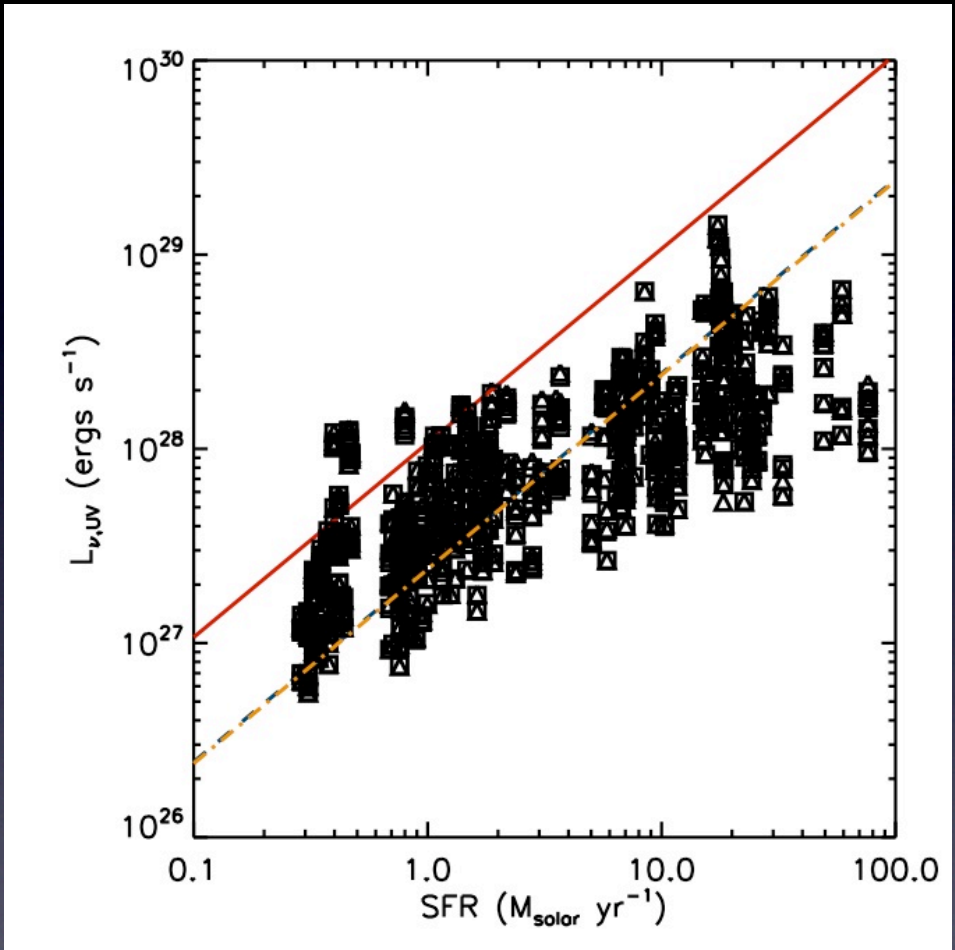
Indicator	K98/1.5	Best fit	Best fit/ (K98/1.6)
IR	2.8e-44	2.1e-44	0.75
UV	8.8e-29	4.1e-28	4.7
Hα	4.9e-42	2.2e-41	4.5
Hα, corr	4.9e-42	1.6e-41	3.3

Effect of AGN



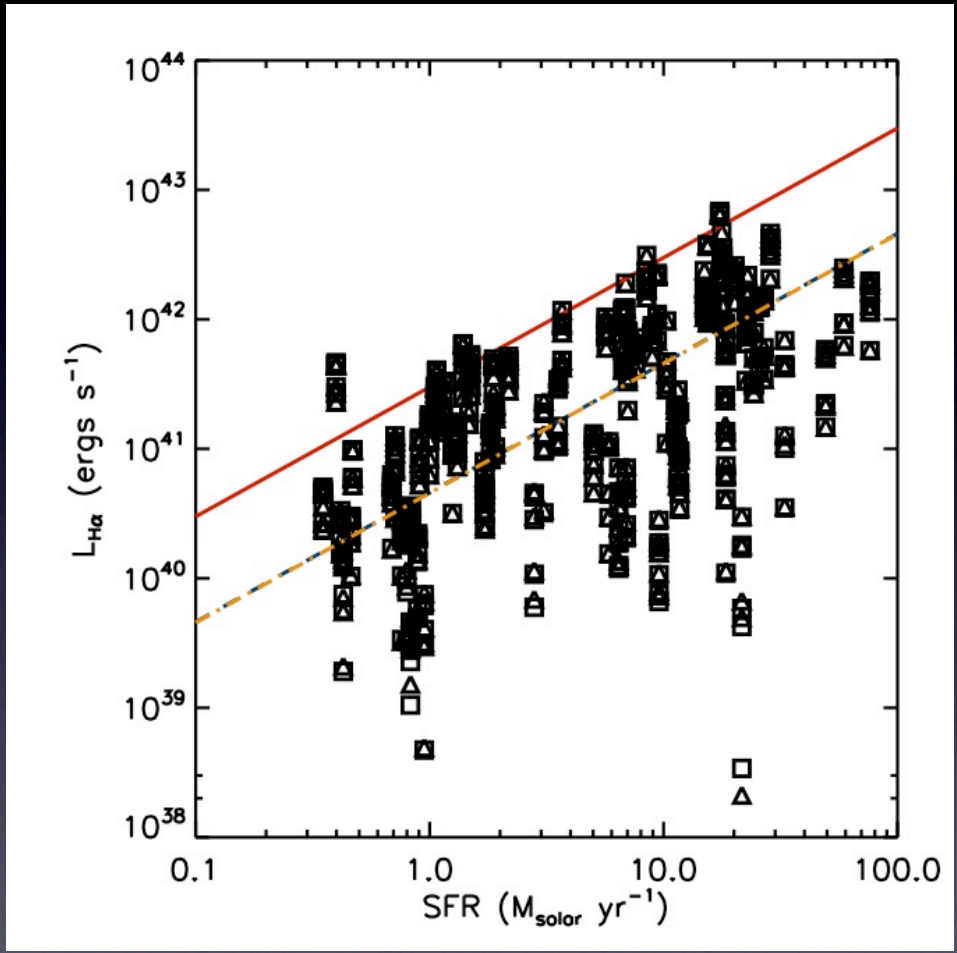
Indicator	K98/1.5	Best fit	Best fit/ (K98/1.6)
IR	2.8e-44	2.2e-44	0.79
UV	8.8e-29	4.2e-28	4.8
Hα	4.9e-42	2.2e-41	4.5
Hα, corr	4.9e-42	1.2e-41	2.4

Effect of AGN



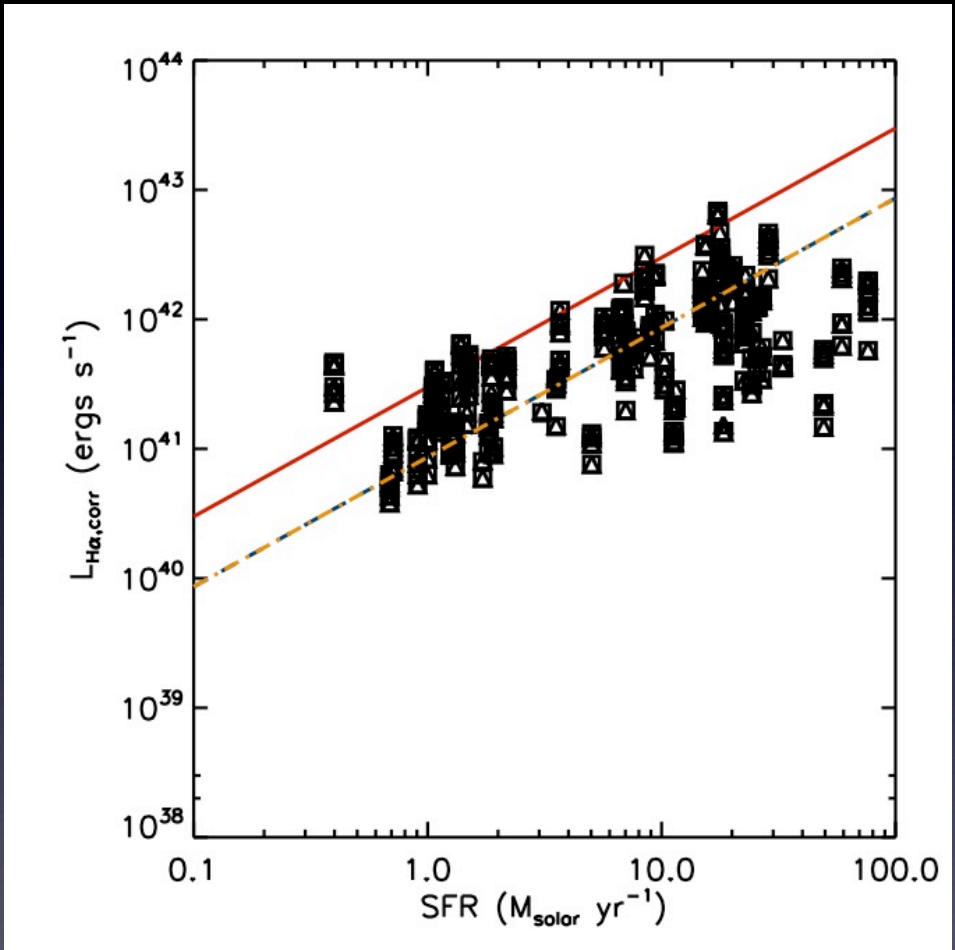
Indicator	K98/1.5	Best fit	Best fit/ (K98/1.6)
IR	2.8e-44	2.2e-44	0.79
UV	8.8e-29	4.2e-28	4.8
Hα	4.9e-42	2.2e-41	4.5
Hα, corr	4.9e-42	1.2e-41	2.4

Effect of AGN



Indicator	K98/1.5	Best fit	Best fit/ (K98/1.6)
IR	2.8e-44	2.2e-44	0.79
UV	8.8e-29	4.2e-28	4.8
Hα	4.9e-42	2.2e-41	4.5
Hα, corr	4.9e-42	1.2e-41	2.4

Effect of AGN



Indicator	K98/1.5	Best fit	Best fit/ (K98/1.6)
IR	2.8e-44	2.2e-44	0.79
UV	8.8e-29	4.2e-28	4.8
Hα	4.9e-42	2.2e-41	4.5
Hα, corr	4.9e-42	1.2e-41	2.4

Summary

- Simulations can be a useful tool to calibrate & test SFR indicators
- Some preliminary results:

  1. Standard IR cal works well; AGN can affect by ~5%

  2. Corrected Hα works well for isolated disks, but not for SFR > 10-20 M_{solar} yr^{-1}

- Future work:
  - Explore additional SFR indicators & dust corrections; find "empirical way" to correct for dust at higher SFR?
  - Apply to full suite of simulations, including high-z (see Narayanan, Hayward+09 for application to SMGs)
  - Study templates used to infer bolometric L_{IR}