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YUNNAN OBSERVATORIES,CHINESE ACADEMY OF SCIENCES

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Group of Binary Population Synthesis

Bayesian interpretation of the spectral energy distribution of galaxies with BayeSED

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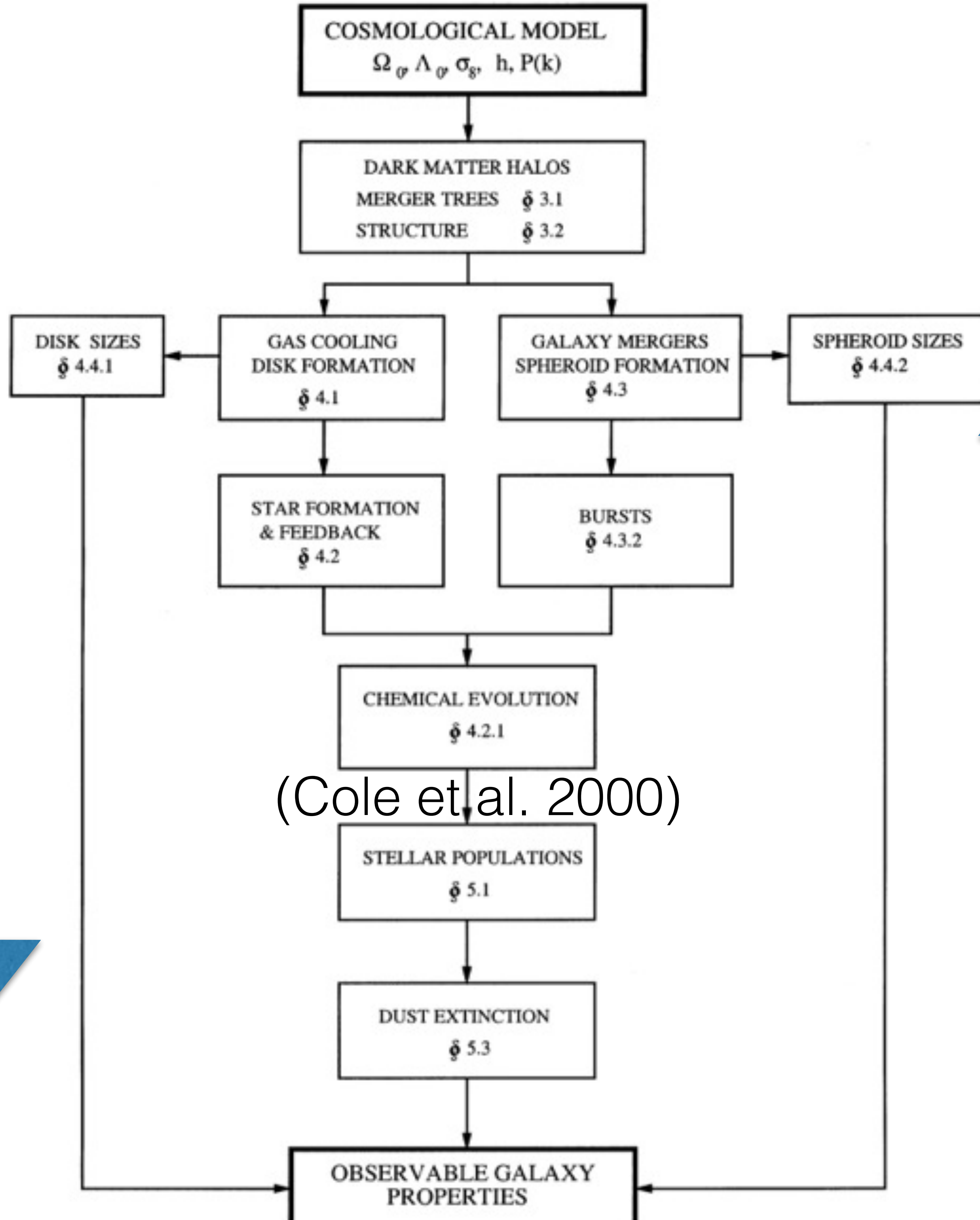
Modeling and interpreting the observable properties of galaxies

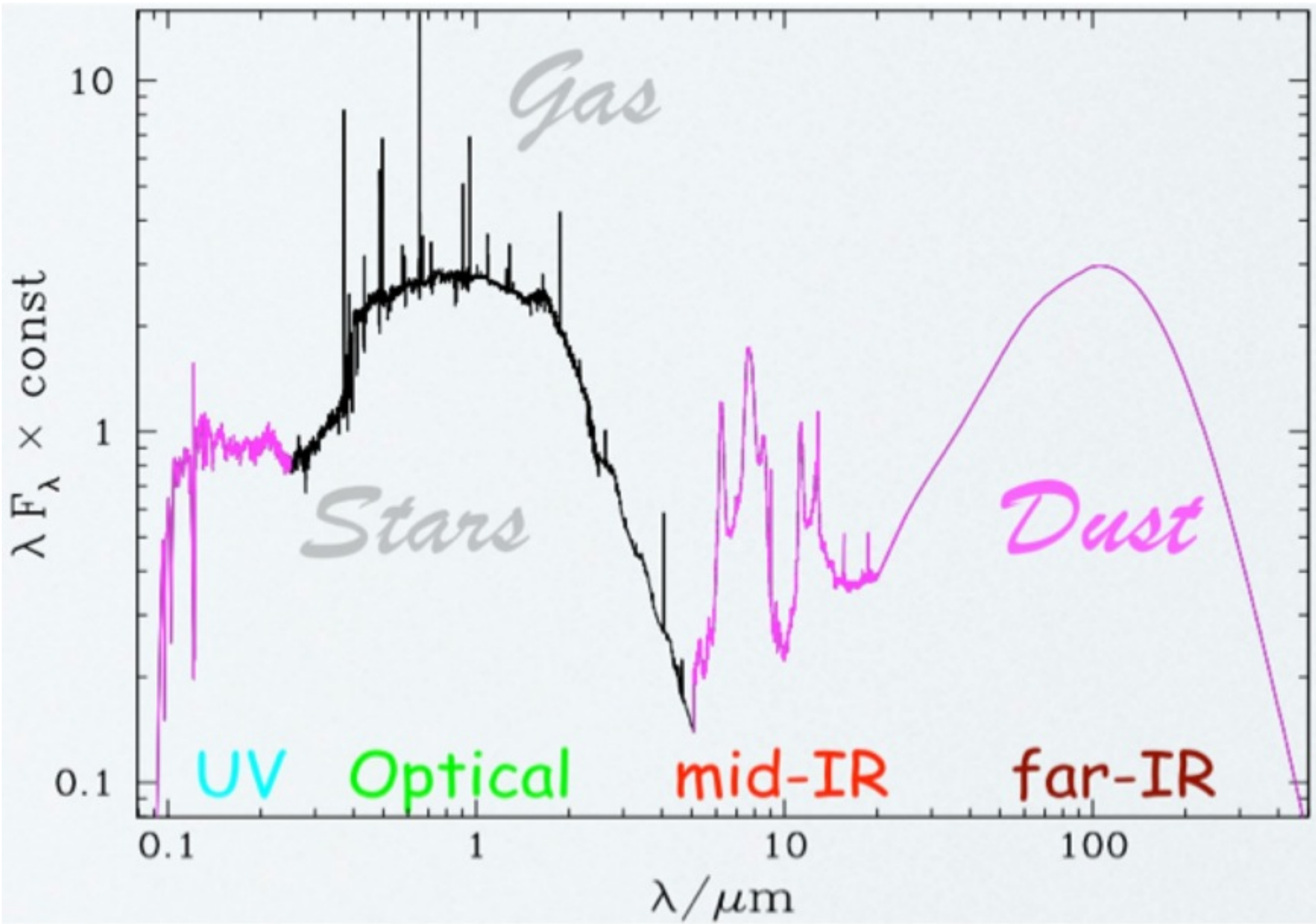
Modeling the observable properties of galaxies



(Cole et al. 2000)

Interpreting the observable properties of galaxies

The multi-wavelength SED of galaxies



Bayesian methods

(see, e.g., Trotta 2008, Bayes in the sky)

Bayes' Theorem:

$$P(A|B) = \frac{P(B|A)\,P(A)}{P(B)}$$

or

$$\text{posterior} = \frac{\text{prior} \times \text{likelihood}}{\text{evidence}}$$

(The rule of updating our state of knowledge in the light of new data)

If we can model a observable property forward somehow,
then
we can interpret it backward with the help of Bayes' Theorem

Parameter estimation:

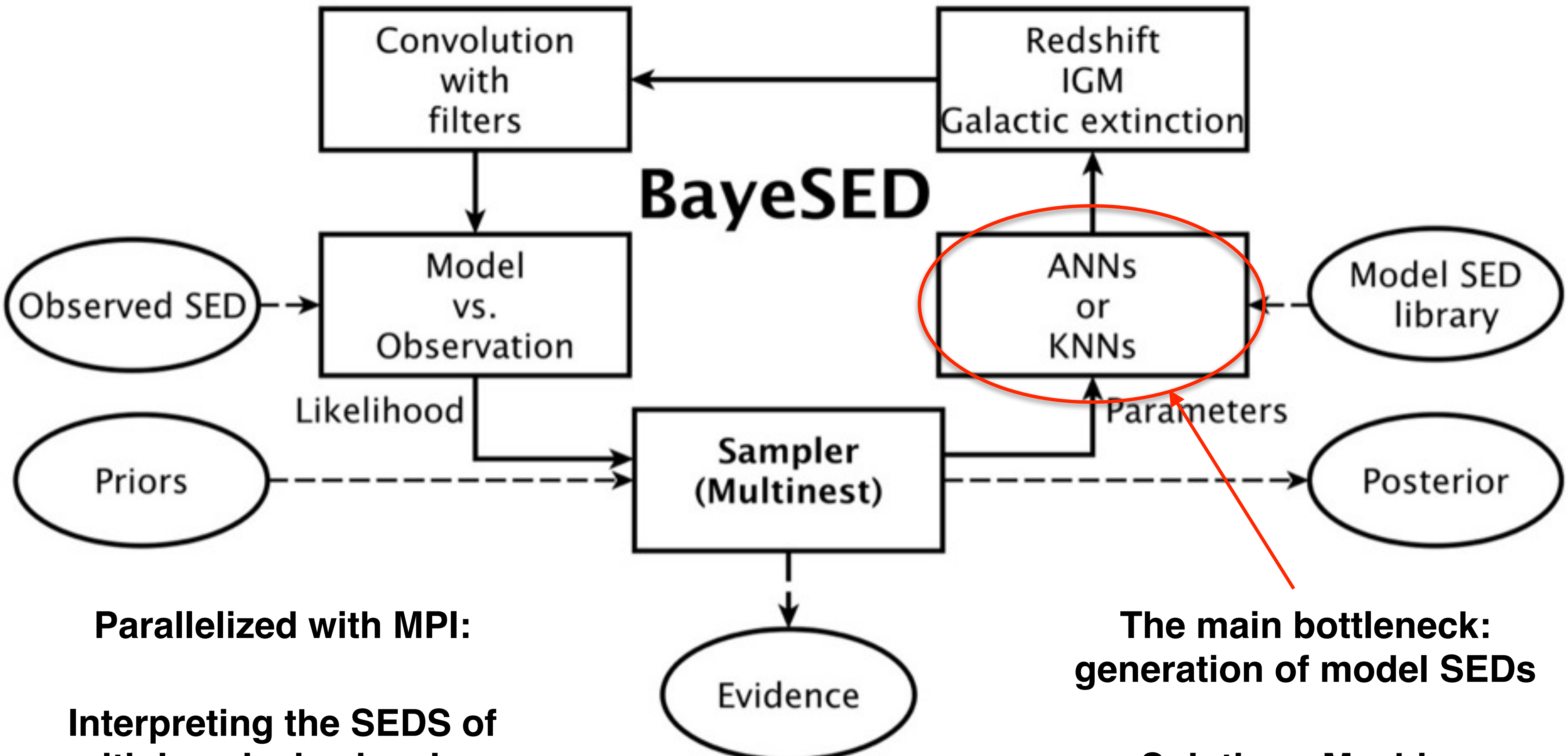
$$p(\theta \mid D, M_i) = \frac{p(D \mid \theta, M_i)\,p(\theta \mid M_i)}{p(D \mid M_i)}$$

Model comparison:

$$p(M_i|D,I) = \frac{p(M_i|I)\,p(D|M_i,I)}{p(D|I)}$$

Interpreting the SEDS of galaxies With BayeSED

(Han & Han 2014, ApJS,251,2)



Parallelized with MPI:

Interpreting the SEDS of multiple galaxies in a large sample simultaneously

The main bottleneck: generation of model SEDs

Solution: Machine learning techniques

The probability distribution functions of parameters as the results of a Bayesian interpretation of SED

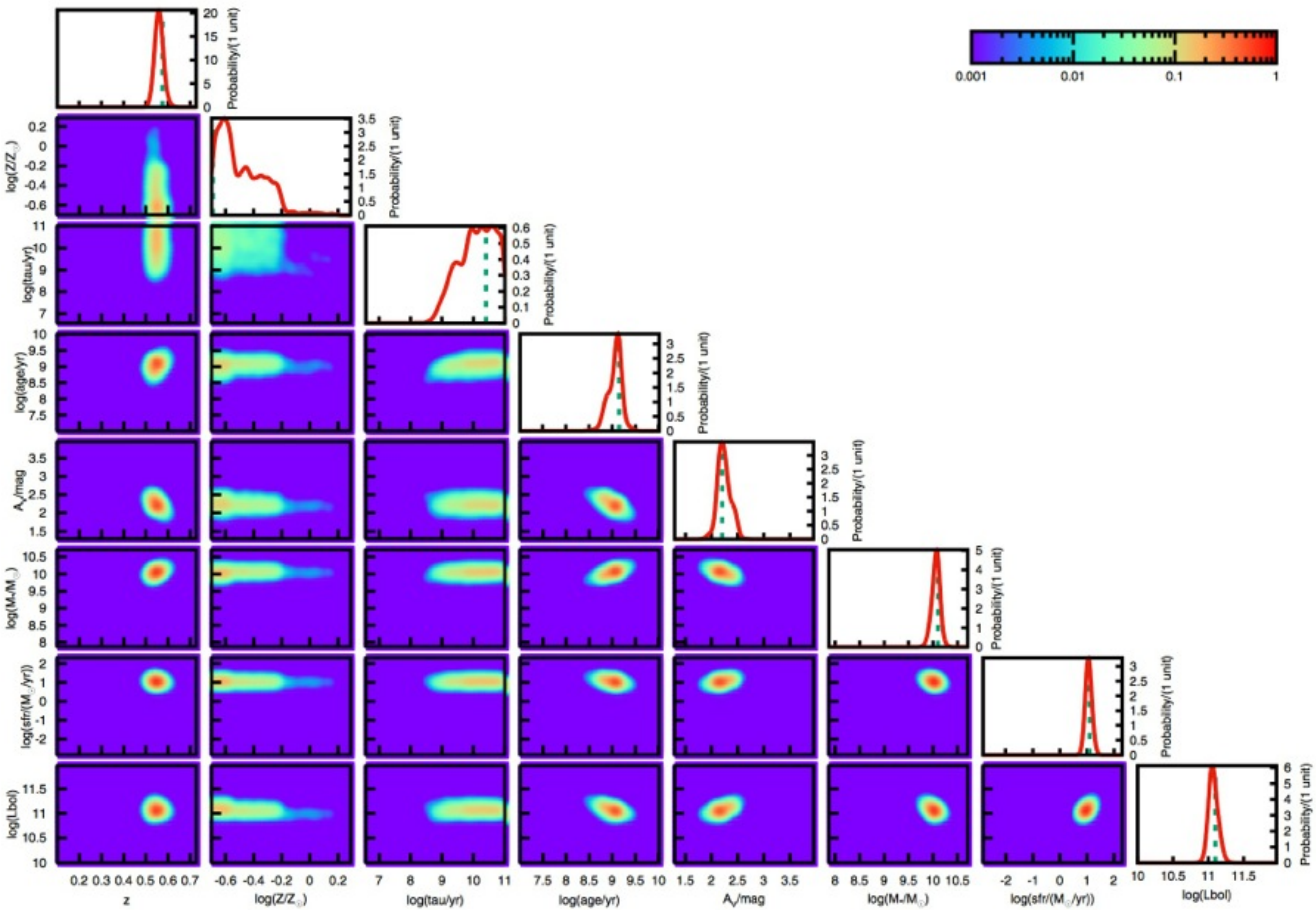


Photo-Z and M*-SFR relation obtained with BayeSED

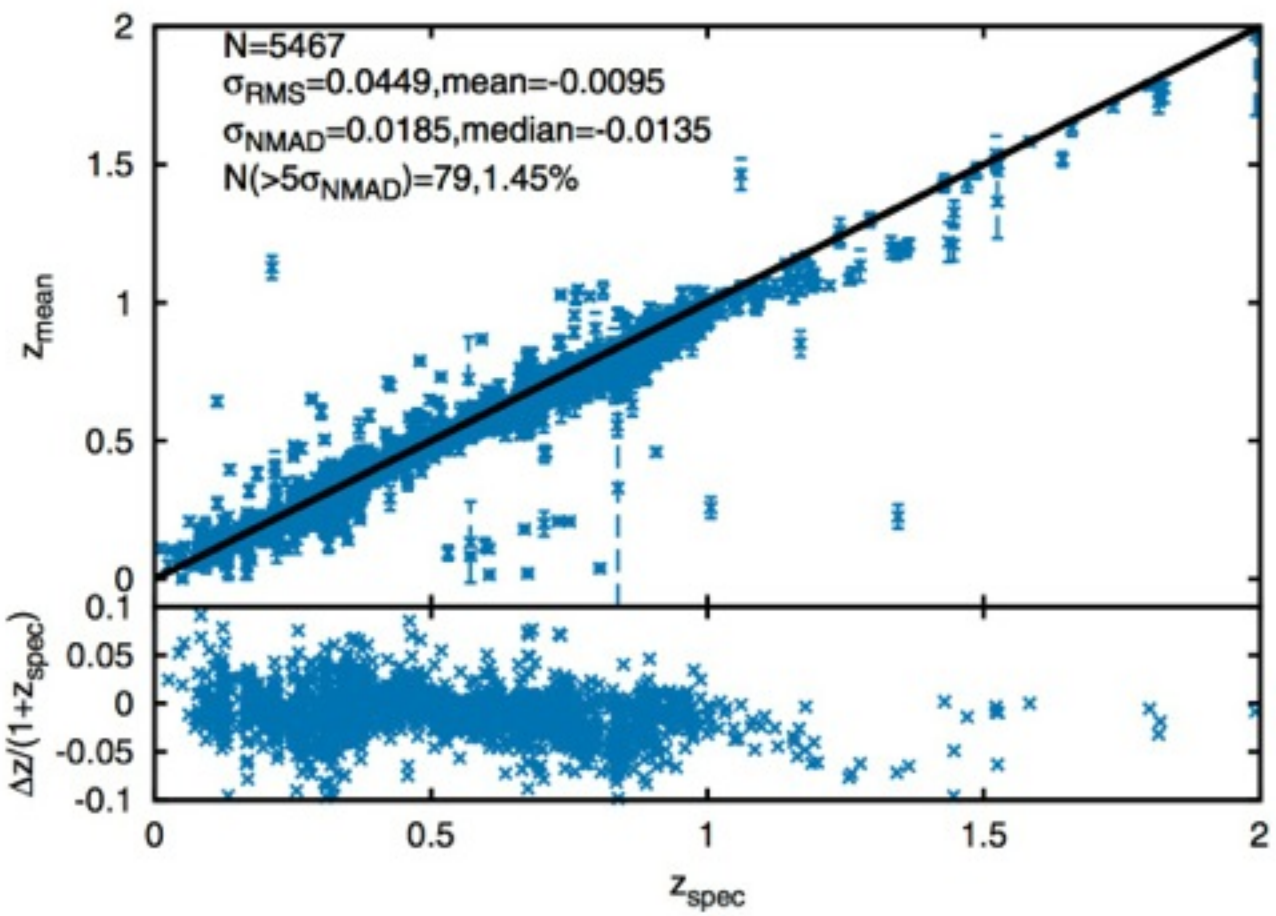


Figure 36. Photometric redshifts vs. spectroscopic redshifts for galaxies in our sample. By using BayeSED, it is now possible to obtain the photometric redshift

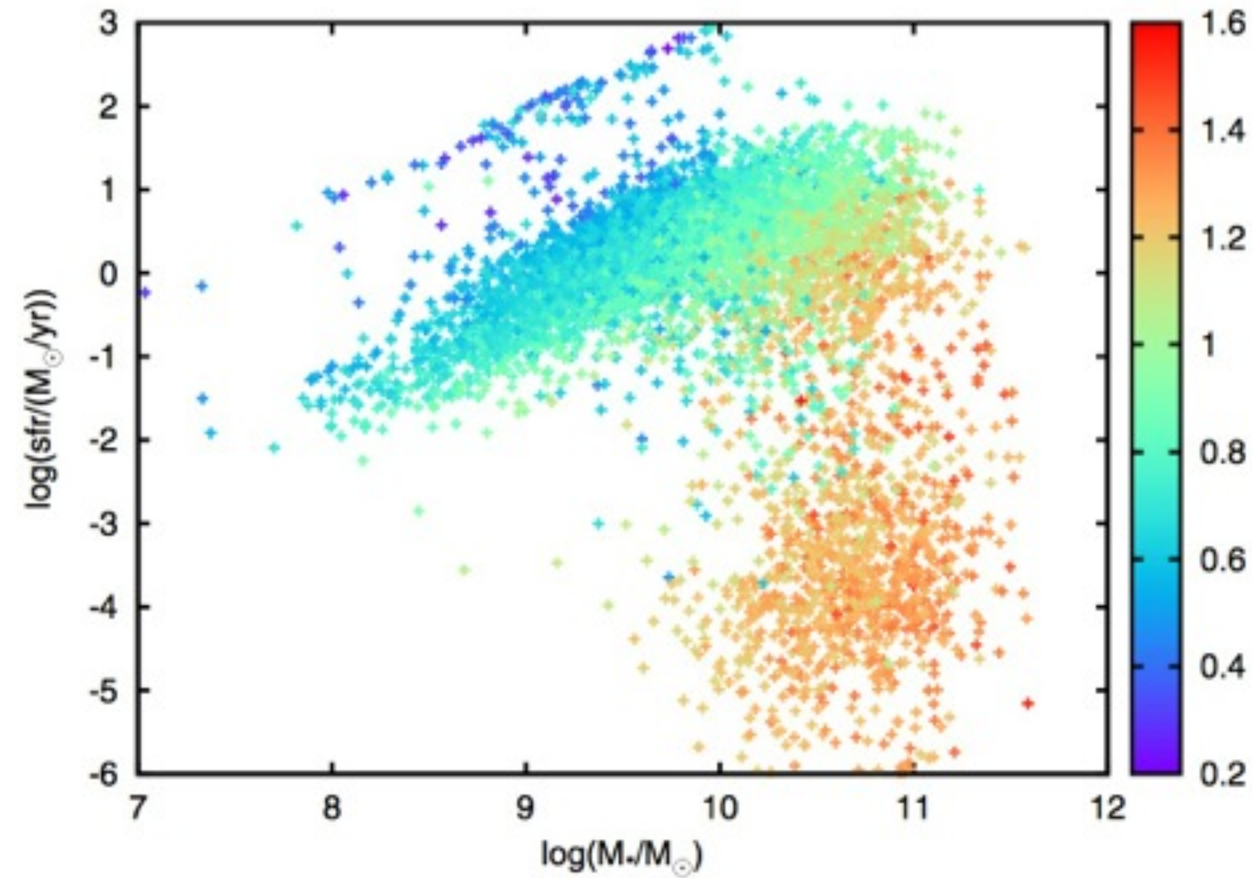
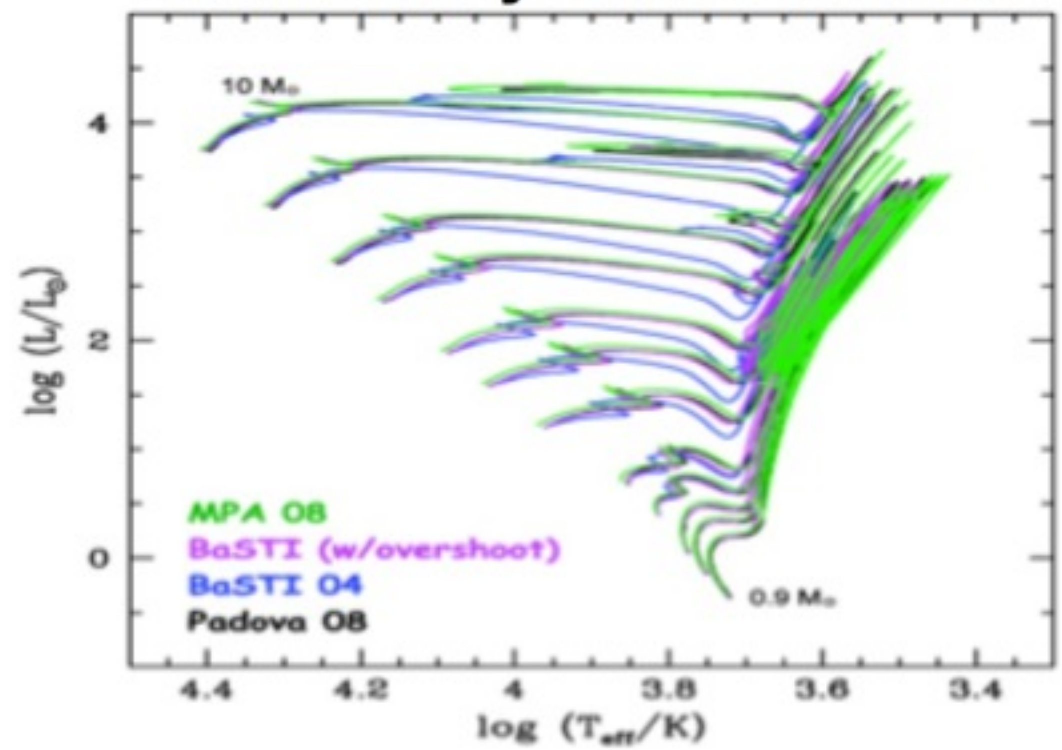


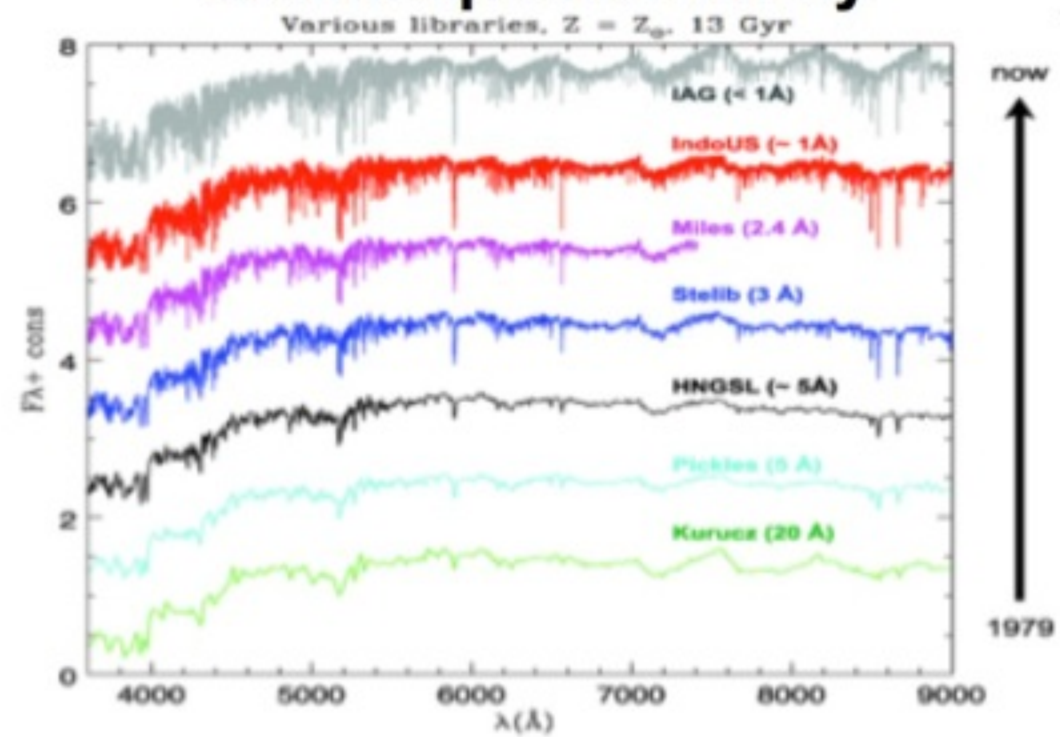
Figure 38. Distribution of rest-frame $U-B$ colors in the M_*–SFR diagram. (A color version of this figure is available in the online journal.)

Evolutionary population synthesis model

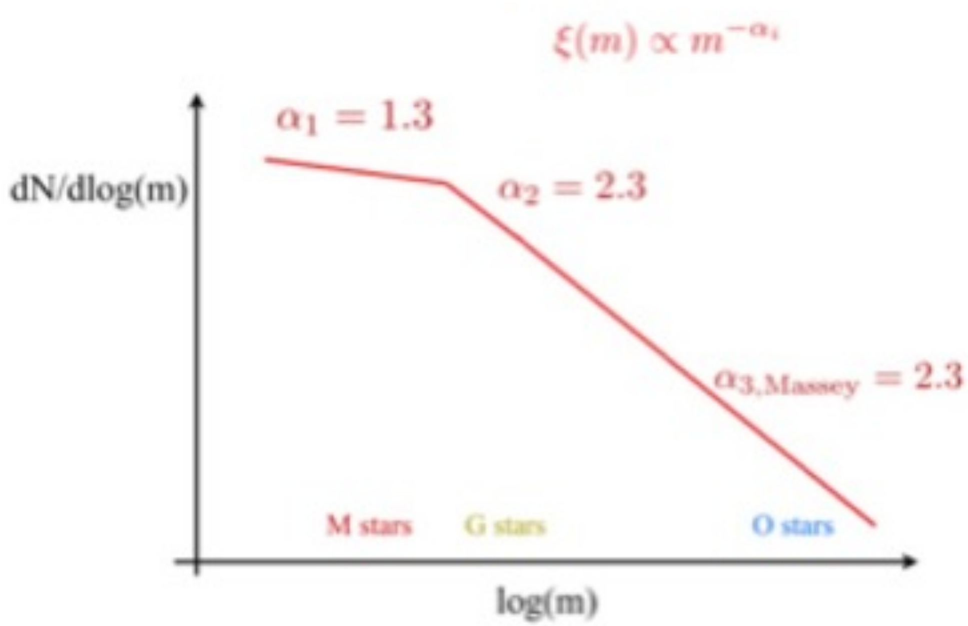
Evolutionary tracks of stars



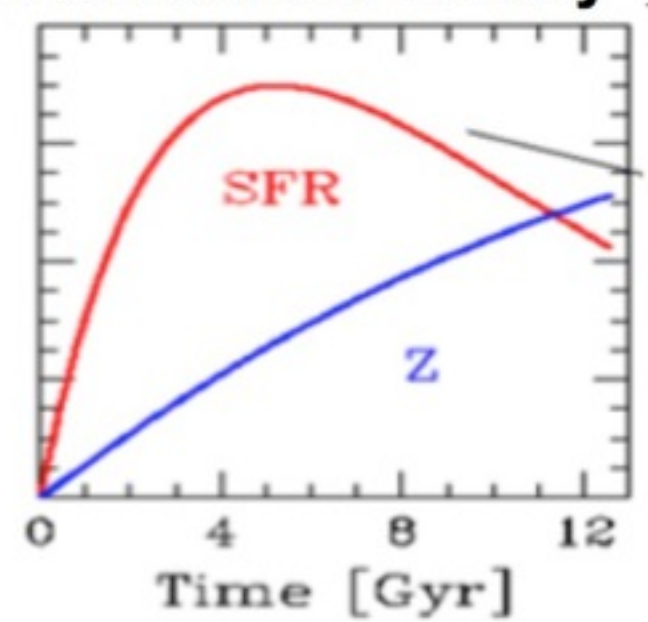
Stellar spectra library



IMF



SF and metallicity enhancement history



Diversity of stellar population models

BASTI
A bag of Stellar Tracks and Isochrones

BPASS
Binary Population and Spectral Synthesis

Buzzoni
SSPs, Template Galaxy Models and more

Coelho
Spectral models for Solar scaled and α-enhanced stellar popula

FSPS
Flexible Stellar Population Synthesis by Conroy et al.

Galadriel
The Padova GALaxies AnD single stellaR populatIon modELs

Galaxev
The Bruzual and Charlot Stellar Population Synthesis models

Galev
GALaxy EVolutionary Synthesis models by Kotulla et al., includes the spectral and chemical evolution of galaxies

Gonzalez Delgado
Models for both evolution of Balmer Absorption lines, and high spectral resolution stellar libraries

Lee, Worthey et al.
Lick indices with individual element abundance variations

Maraston
The Maraston et al. 'fuel-consumption' stellar population synthesis

MILES
The stellar population synthesis models for old and intermediate age stellar populations by Vazdekis et al.

Pegase
"Projet d'Etude des GALaxies par Synthese Evolutive" code by Rocca-Volmerange et al., includes high-res SSPs based on ELODIE

PopStar
Evolutionary Synthesis Models by Garcia-Vargas, Bressan, Molla

SLUG
Stochastically Lighting Up Galaxies

SPoT
Stellar Population Tools

Starburst99
Stellar population code designed to model spectrophotometric and related properties of young galaxies

Yggdrasil
Spectral models for the first galaxies, including nebular continuum and emission lines

http://www.sedfitting.org/SED08/Models.html

What kind of model is better?

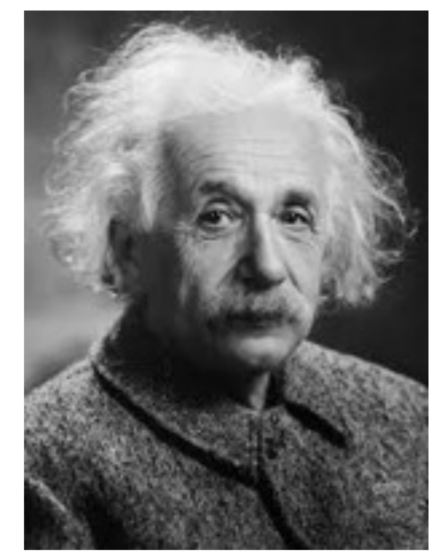
With four parameters I can fit an elephant,

and with five I can make him wiggle his trunk.

(John von Neumann)

Everything should be made as simple as possible,
but not simpler.

(Albert Einstein)

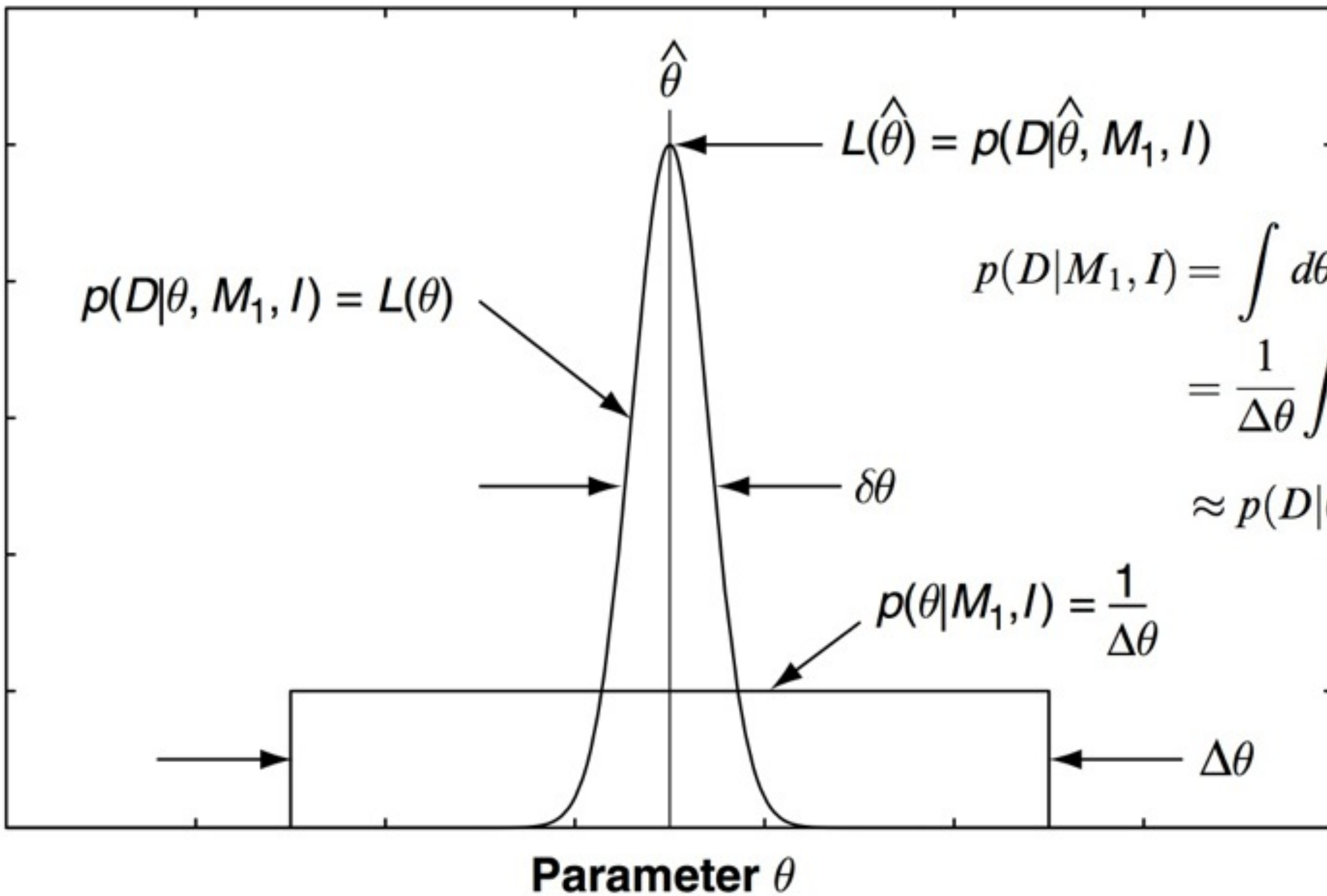


Entities should not be multiplied beyond necessity.

(William of Ockham)

Bayesian evidence as quantified Occam's razor

(Gregory,2005,Bayesian Logical Data Analysis for the Physical Sciences)



$$p(D|M_1, I) = \int d\theta\ p(\theta|M_1, I)p(D|\theta, M_1, I) = \mathcal{L}(M_1)$$

$$= \frac{1}{\Delta\theta}\int d\theta\ p(D|\theta, M_1, I)$$

$$\approx p(D|\hat{\theta}, M_1, I)\frac{\delta\theta}{\Delta\theta}$$

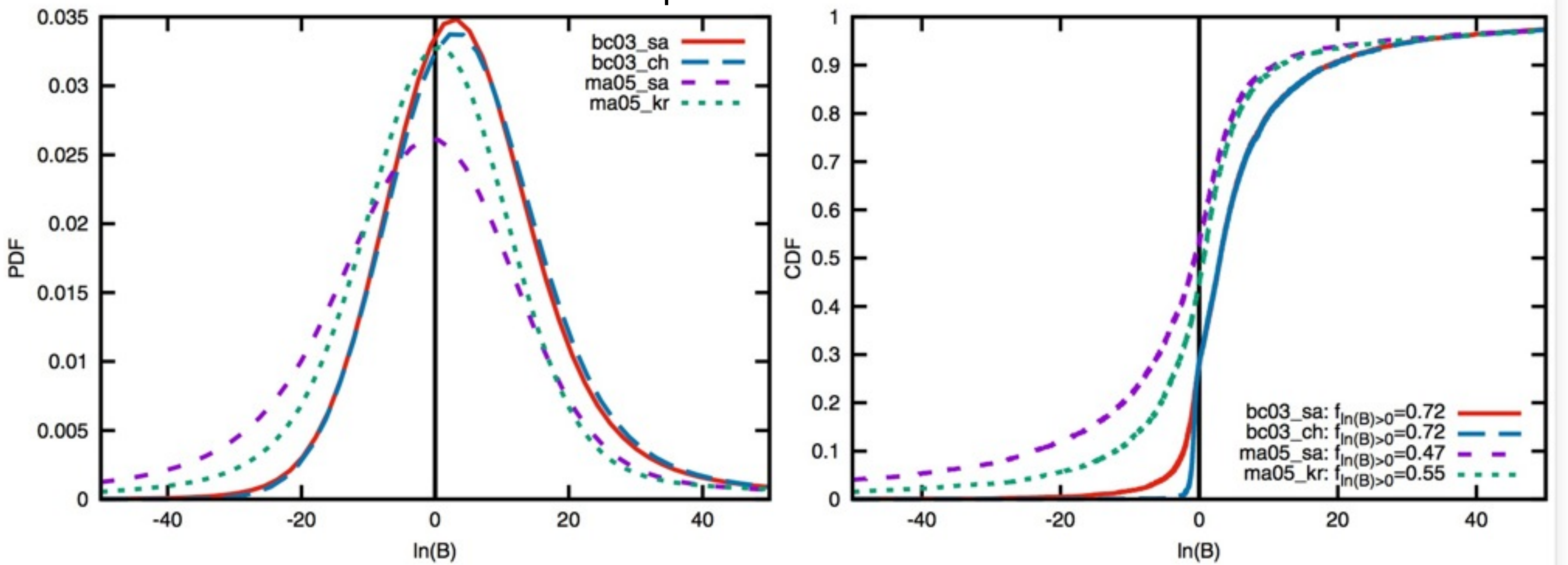
Ockham factor

By **penalizing the complicated model for any "wasted" parameter space** that gets ruled out by the data, the Bayes evidence will thus favor the more complicated model only if the likelihood is large enough to overcome this penalty

The first Bayesian model comparison of stellar population synthesis models

(Han & Han, 2014,ApJS,251,2)

with a Ks-selected sample in the COSMOS/UltraVISTA Field



PDF and CDF of the Bayes factors ln(B) for 5467 galaxies in the Ks-selected sample with spectroscopic redshift.

$$\frac{P(M_2|\boldsymbol{d})}{P(M_1|\boldsymbol{d})} = \frac{P(\boldsymbol{d}|M_2)P(M_2)}{P(\boldsymbol{d}|M_1)P(M_1)}, \quad B_{2,1} \equiv \frac{P(\boldsymbol{d}|M_2)}{P(\boldsymbol{d}|M_1)}$$

The Bruzual & Charlot (2003) model with a Chabrier (2003) IMF and solar metallicity

Bayesian SED model comparison of hyperluminous infrared galaxies(HLIRGs)

(Han & Han,2012,ApJ,749,123)

Table 1
The Bayesian Evidences of the "SB," "AGN," and "SB+AGN" Models for Galaxies in the Classes A and B of the Ruiz et al. (2007) HLIRG Sample

Source	$\ln(ev_{SB})$	$\ln(ev_{AGN})$	$\ln(ev_{SB+AGN})$
Class A HLIRG			
PG1206+459	$-12.65^{+0.09}_{-0.09}$	$-15.08^{+0.08}_{-0.08}$	$-9.39^{+0.08}_{-0.08}$
PG1247+267	$-11.45^{+0.09}_{-0.09}$	$-8.02^{+0.08}_{-0.08}$	$-7.71^{+0.08}_{-0.08}$
IRASF12509+3122	$-9.78^{+0.09}_{-0.09}$	$-7.81^{+0.07}_{-0.07}$	$-7.38^{+0.07}_{-0.07}$
IRAS14026+4341	$-54.16^{+0.13}_{-0.13}$	$-21.64^{+0.12}_{-0.12}$	$-19.27^{+0.12}_{-0.12}$
IRASF14218+3845	$-5.91^{+0.06}_{-0.06}$	$-6.36^{+0.06}_{-0.06}$	$-5.59^{+0.06}_{-0.06}$
IRAS16347+7037	$-35.98^{+0.12}_{-0.12}$	$-23.48^{+0.12}_{-0.12}$	$-18.10^{+0.12}_{-0.12}$
IRAS18216+6418	$-172.25^{+0.14}_{-0.14}$	$-72.53^{+0.14}_{-0.14}$	$-26.36^{+0.14}_{-0.14}$
Class B HLIRG			
IRASF00235+1024	$-11.15^{+0.09}_{-0.09}$	$-38.92^{+0.09}_{-0.09}$	$-11.09^{+0.09}_{-0.09}$
IRAS07380−2342	$-159.50^{+0.12}_{-0.12}$	$-179.24^{+0.15}_{-0.15}$	$-76.36^{+0.17}_{-0.17}$
IRAS00182−7112	$-22.09^{+0.10}_{-0.10}$	$-57.88^{+0.14}_{-0.14}$	$-19.10^{+0.12}_{-0.12}$
IRAS09104+4109	$-31.31^{+0.11}_{-0.11}$	$-71.56^{+0.15}_{-0.15}$	$-29.62^{+0.13}_{-0.13}$
IRAS12514+1027	$-63.33^{+0.10}_{-0.10}$	$-62.12^{+0.13}_{-0.13}$	$-30.01^{+0.14}_{-0.14}$
IRASF15307+3252	$-12.64^{+0.10}_{-0.10}$	$-51.24^{+0.14}_{-0.14}$	$-11.97^{+0.10}_{-0.10}$

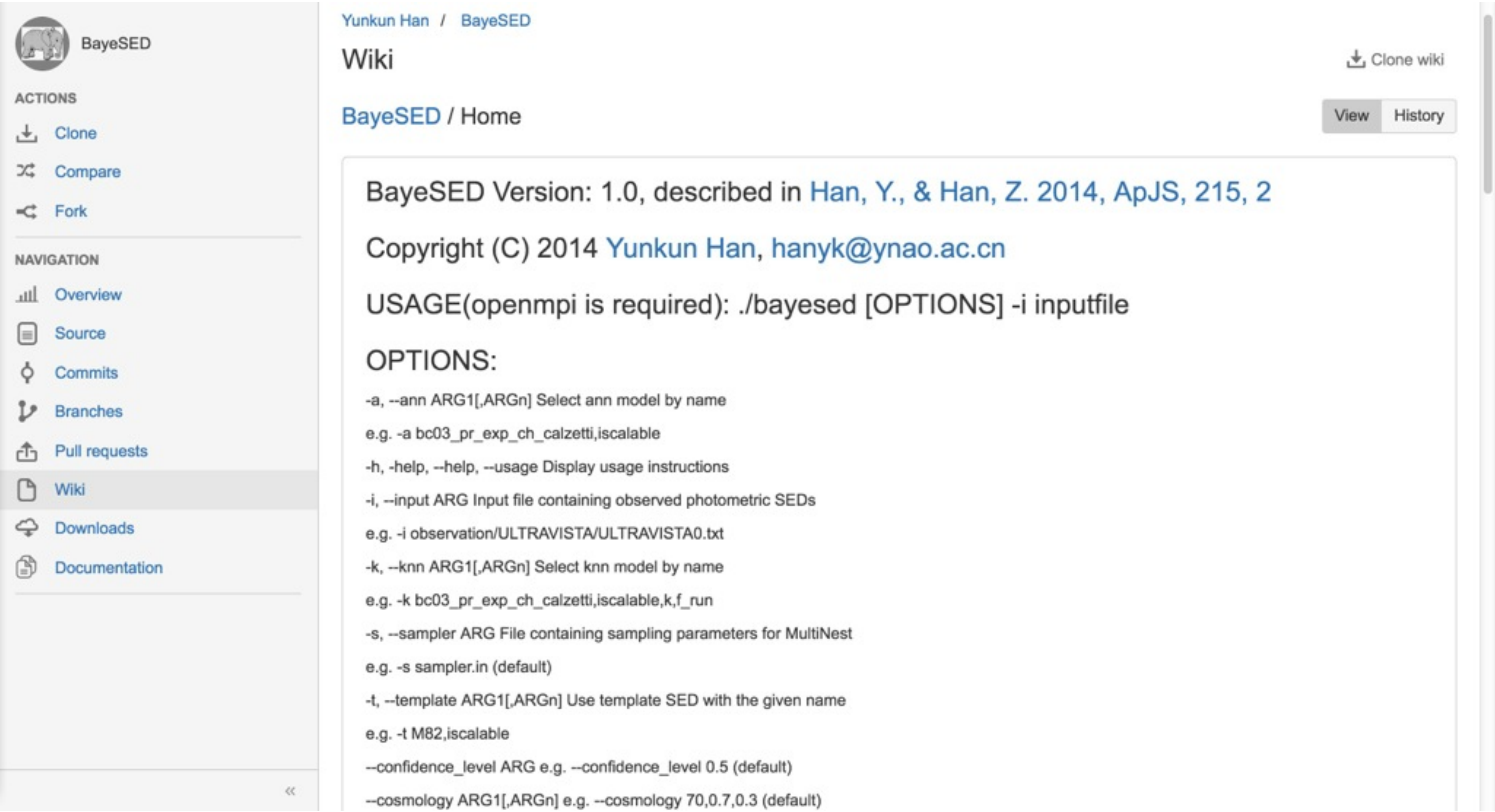
Bayesian SED model comparison of hot dust-obscured galaxies(Hot DOGs)

(Fan,L.,Han, Y., et al.,2016,ApJ,823,107)

Table 4
The Bayesian Evidence of the "TORUS" and "TORUS+GB" Models

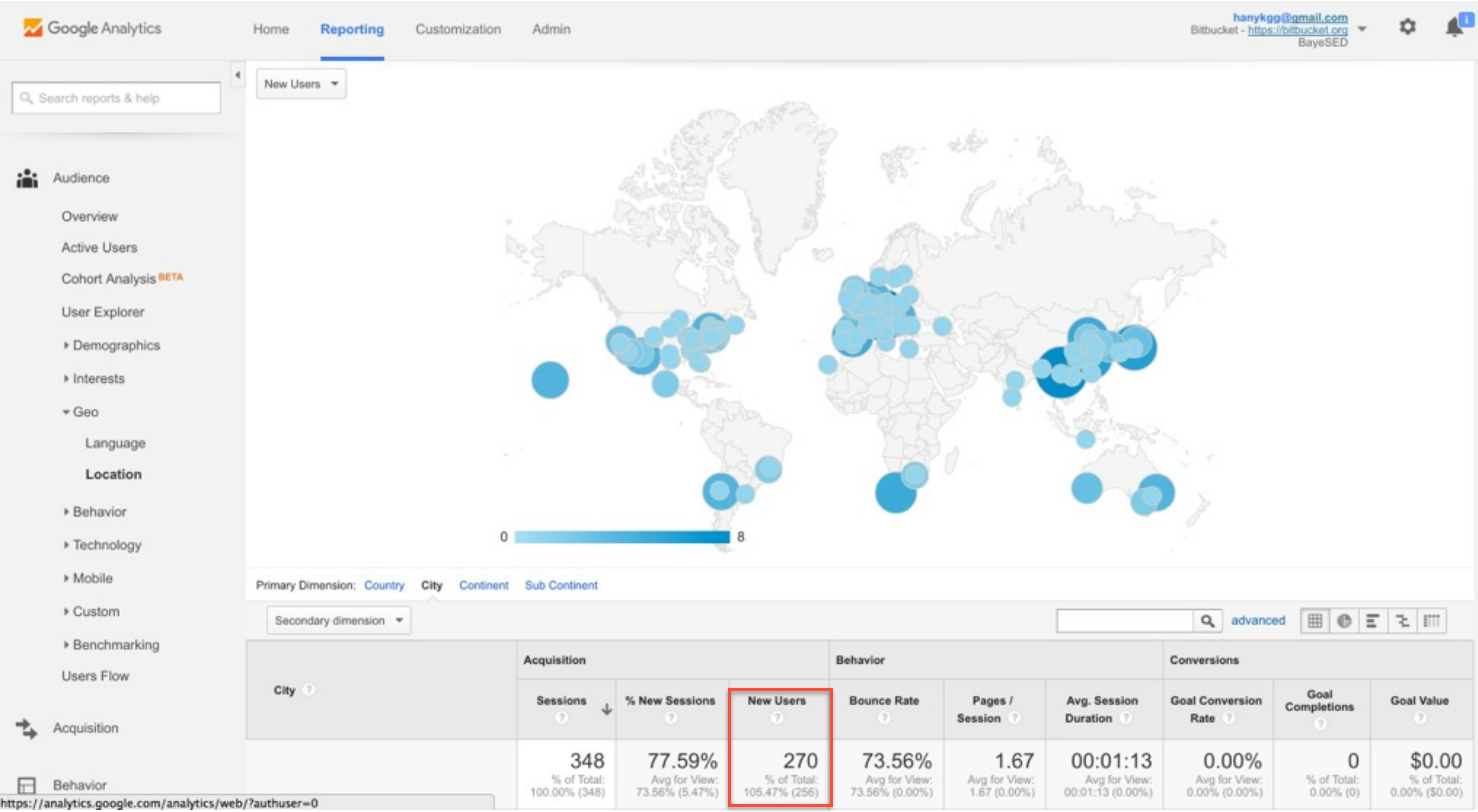
Source	$\ln(ev_{TORUS})$	$\ln(ev_{TORUS+GB})$	$\ln\left(\frac{ev_{TORUS+GB}}{ev_{TORUS}}\right)$
W0126−0529	−158.38 ± 0.18	−71.88 ± 0.23	86.50 ± 0.41
W0134−2922	−62.42 ± 0.13	−15.26 ± 0.14	47.16 ± 0.28
W0149+2350	−34.56 ± 0.14	−9.15 ± 0.12	25.41 ± 0.26
W0220+0137	−49.31 ± 0.17	−9.25 ± 0.13	40.06 ± 0.30
W0248+2705	−34.11 ± 0.13	−9.43 ± 0.12	24.68 ± 0.24
W0410−0913	−49.89 ± 0.17	−12.51 ± 0.14	37.37 ± 0.31
W0533−3401	−28.80 ± 0.14	−7.65 ± 0.12	21.15 ± 0.26
W0615−5716	−28.50 ± 0.16	−11.74 ± 0.15	16.76 ± 0.31
W0757+5113	−42.14 ± 0.12	−7.73 ± 0.12	34.41 ± 0.24
W0859+4823	−68.60 ± 0.16	−9.93 ± 0.13	58.68 ± 0.29
W1136+4236	−39.94 ± 0.15	−19.71 ± 0.10	20.23 ± 0.25
W1248−2154	−34.39 ± 0.17	−7.84 ± 0.13	26.55 ± 0.29
W1603+2745	−59.20 ± 0.18	−10.33 ± 0.13	48.87 ± 0.30
W1814+3412	−62.11 ± 0.15	−9.49 ± 0.14	52.62 ± 0.29
W1835+4355	−191.90 ± 0.19	−13.28 ± 0.15	178.62 ± 0.34
W2054+0207	−53.24 ± 0.14	−15.48 ± 0.11	37.77 ± 0.25
W2201+0226	−60.11 ± 0.18	−14.92 ± 0.15	45.19 ± 0.33
W2210−3507	−112.54 ± 0.16	−18.67 ± 0.14	93.87 ± 0.31
W2216+0723	−25.41 ± 0.14	−7.15 ± 0.11	18.25 ± 0.26
W2238+2653	−90.39 ± 0.16	−11.86 ± 0.14	78.52 ± 0.30
W2246−0526	−32.61 ± 0.14	−22.29 ± 0.16	10.32 ± 0.30
W2305−0039	−128.15 ± 0.17	−43.15 ± 0.20	85.01 ± 0.36

https://bitbucket.org/hanyk/bayesed/



git clone https://bitbucket.org/hanyk/bayesed.git

Users (or just visitors) of BayeSED



BayeSED 2.0
(Han at el.,2016,in prep.)

What's New

1. Build-in Composite Stellar Population synthesis modeling with freely changeable SSP (BC03, CB07, M05, GALEV, FSPS, Yunnan-II) and SFH (Constant, Exponentially declining,increasing, delayed,Linearly declining,increasing, truncated …)

2. Build-in dust extinction laws (MW, LMC, SMC, Calzetti2000, Noll +2009)

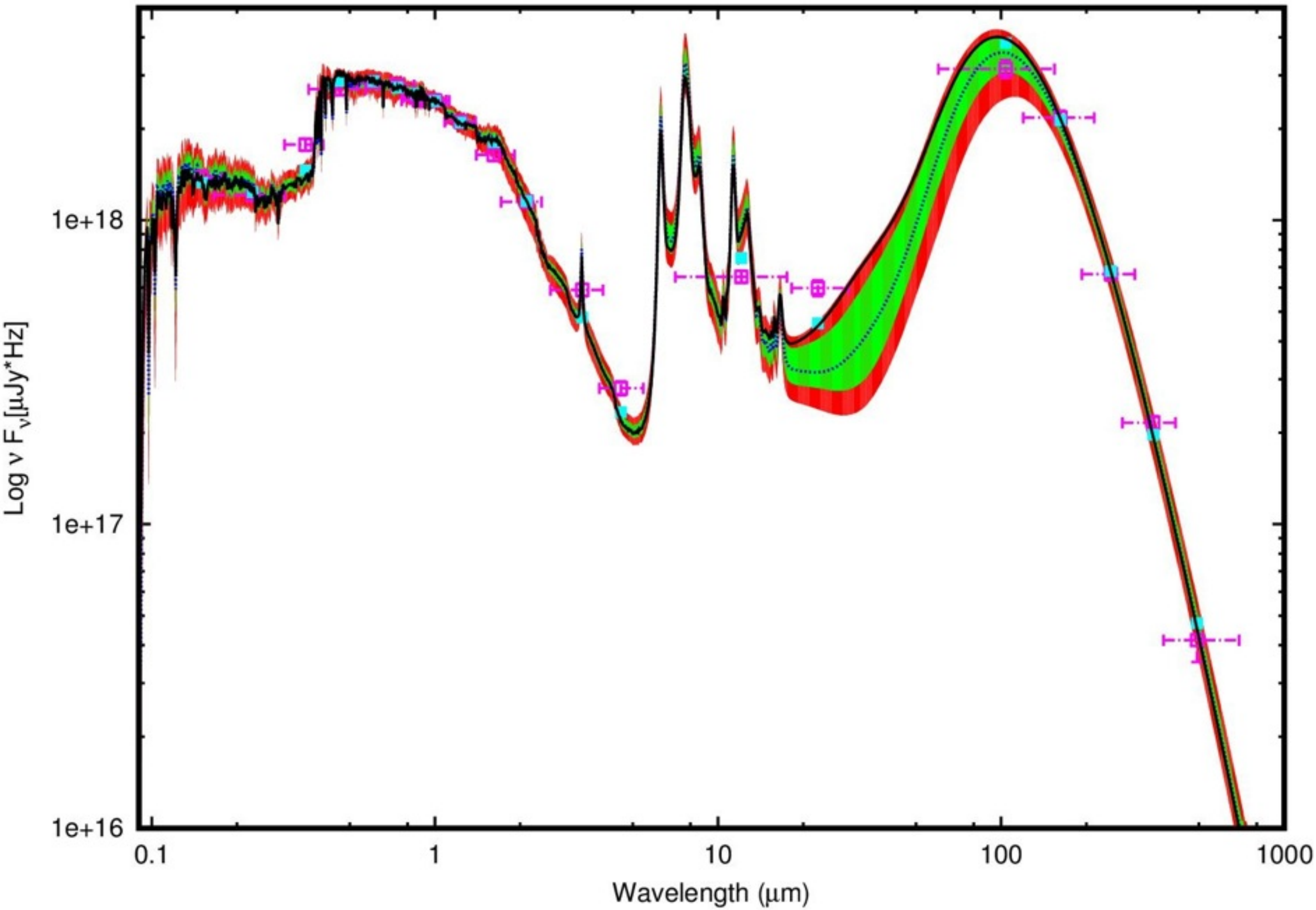
3. A Consistent UV-Optical to FIR connection based on a simple energy balance argument (as MAGPHYS and CIGALE)

4. More free form of Priors (based on KDE)

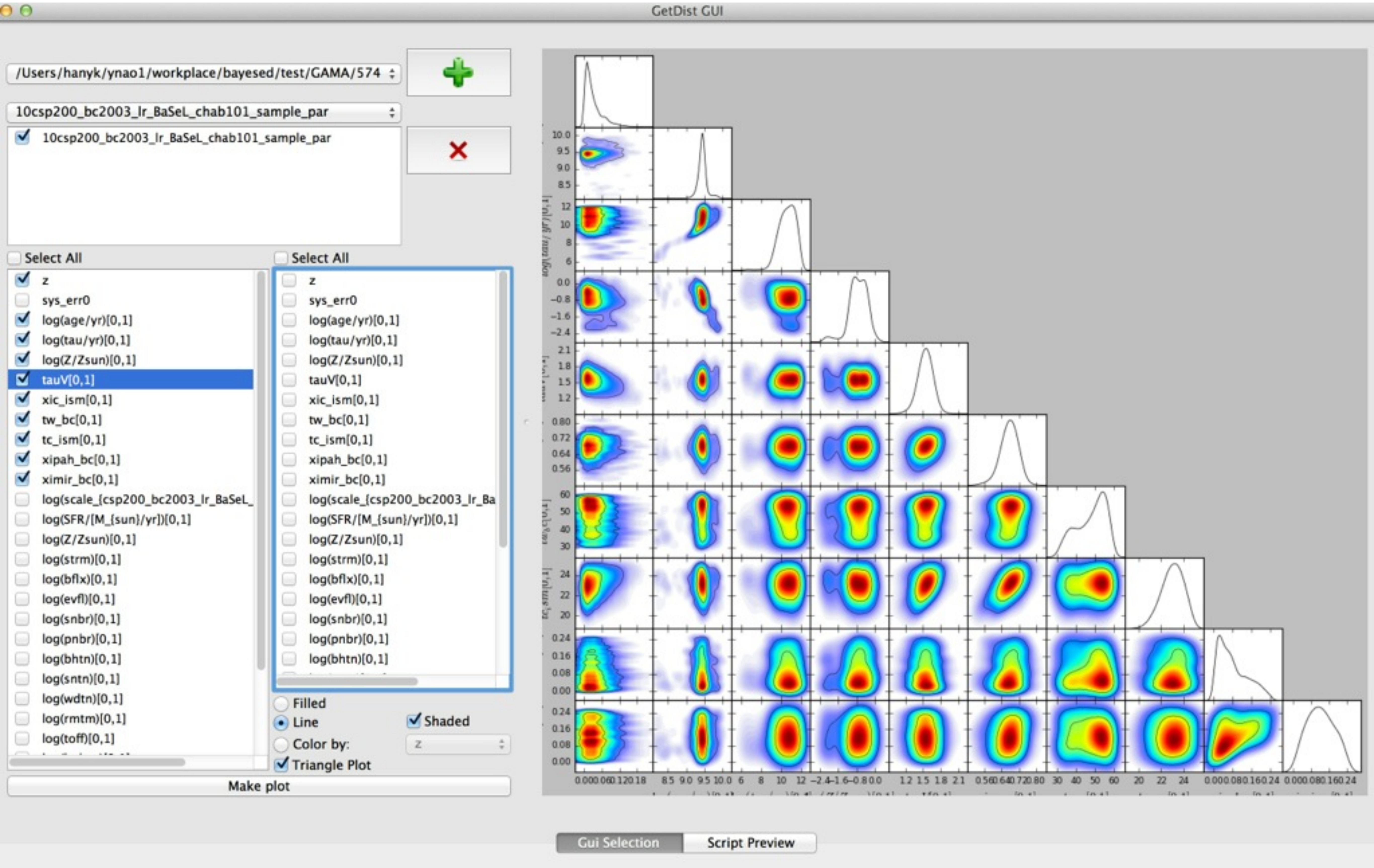
An Example

```
mpirun -np 160 ./bayesed

-i observation/Lambdar/test.txt

 --filters observation/Lambdar/filters.txt

--filters_selected observation/Lambdar/filters_selected.txt

 --csp 0,bc2003_lr_BaSeL_chab,1,3,1,0,0,1,0,1

 --sfh 0,2,0,0

--outdir test

--sys_err_obs 0,1

--select_sample 21,0,10

--save_bestfit

--save_sample_par

--save_pos_spec
```

Result for GAMA object G574689



Postprocessing with GetDist GUI



Summary

- Modeling and interpreting the multi-wavelength SED of galaxies are complicated by many uncertainties
- Bayesian statistical inference provides a consistent conceptual basis for handling these uncertainties
- BayeSED could be a convenient and reliable tool for a full Bayesian interpretation of the SEDs of galaxies
- Enjoy it!

Thank You