Co-funded by the
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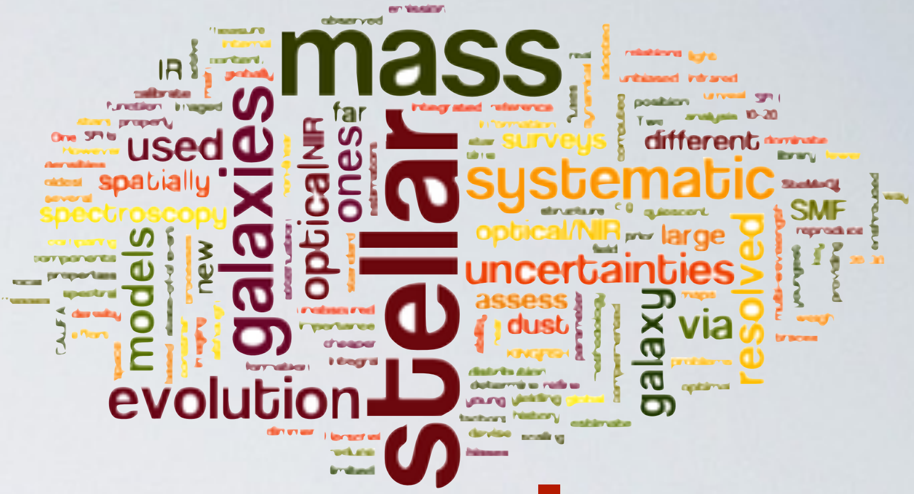
via FP7 Career Integration Grant
SteMaGE

PEOPLE



(How) do we understand stellar masses?

SteMaGE

a systematic effort to chart the **Ste**llar **Ma**ss in galaxies
and understand its role in **G**alaxy **E**volution

Stefano Zibetti - INAF-OAArcetri
In *collaboration* with Anna Gallazzi, Stéphane Charlot,
Elena Tundo and the CALIFA collaboration

ISTITUTO NAZIONALE DI ASTROFISICA INAF

INAF - Arcetri

14.1.2015 - Osservatorio Astronomico di Trieste

M*, Morphology, Colors

Astron. Astrophys. 312, L29–L32 (1996)

ASTRONOMY AND ASTROPHYSICS

The birth of "downsizing" (™Cowie+1996)

Letter to the Editor

The mass dependence of the star formation history of disk galaxies

Giuseppe Gavazzi[1,2] **and Marco Scodeggio**[3]

[1] Università degli Studi di Milano, Via Celoria 16, I-20133 Milano, Italy
[2] Osservatorio Astronomico di Brera, Via Brera 28, I-20121 Milano, Italy
[2] Department of Astronomy and National Astronomy and Ionosphere Center, Cornell University, Ithaca, NY 14853, USA

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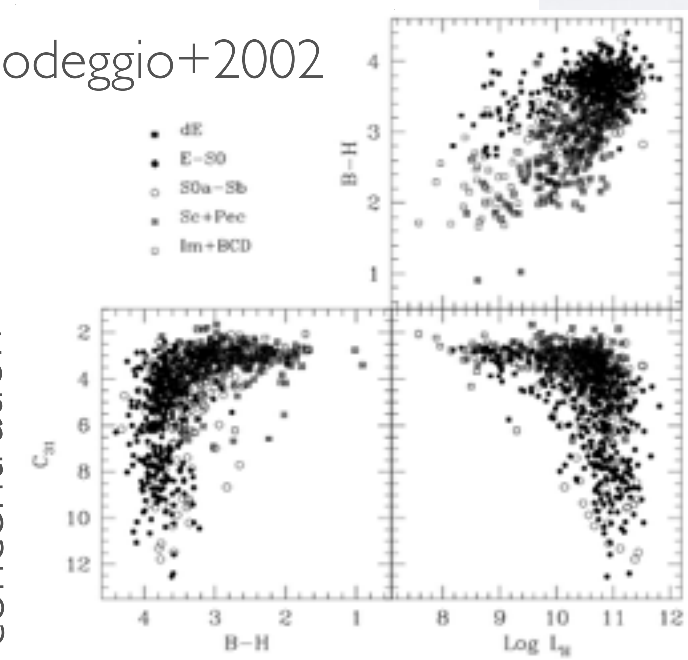
Abstract. Visible (U,B,V), Near Infrared (H) and UV (λ 2000 Å) photometric measurements of a complete sample of 928 nearby (z<0.03) late-type (spiral and irregular) galaxies are analyzed. The four sets of color indices UV-V, B-H, B-V, U-B are found tightly correlated with the galaxy H band luminosity (which is a reliable mass indicator). The synthesis population model of Bruzual & Charlot (1993) characterized by a Salpeter IMF and an exponential star formation history predict color indices consistent with the observed ones, under the assumption that galaxies of different luminosity all have similar ages (about 10 GYrs). The observed correlation of color indices with H luminosity is reproduced by the model assuming that the exponential SFR decay time (τ) is as short as 0.5 GYrs (quasi istantaneous burst) for giant disk galaxies ($L_H = 10^{11}$ $L_\odot$) and >5 GYrs (quasi constant SFR) for dwarf galaxies. The galaxy mass could be the most important factor in the regulation of the star formation history of late-type galaxies.

Scodeggio+2002

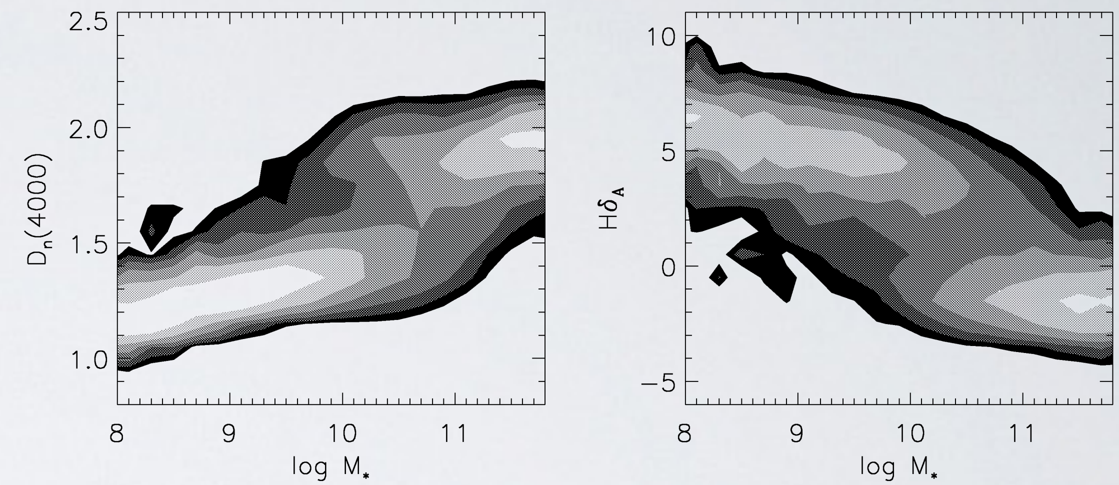


concentration

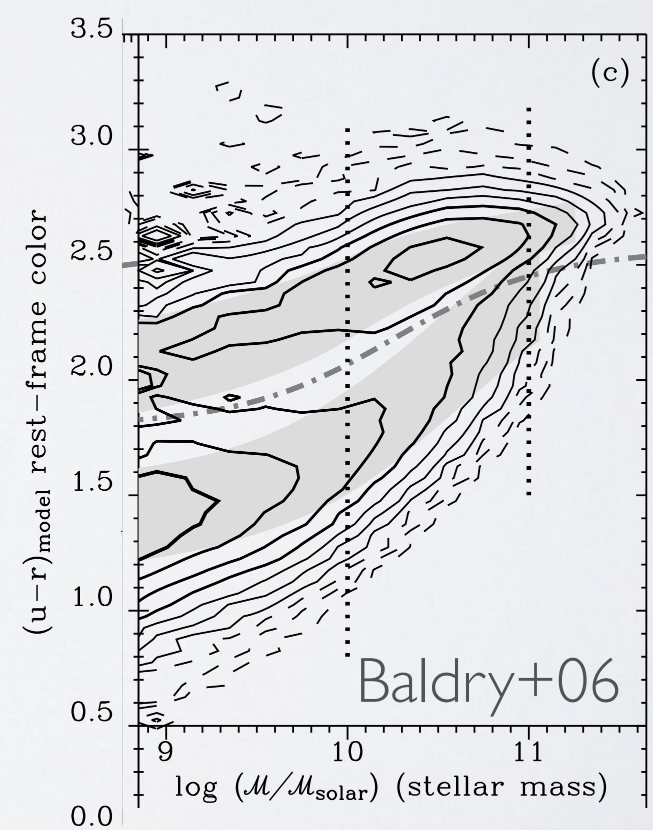
color

L_H~M*

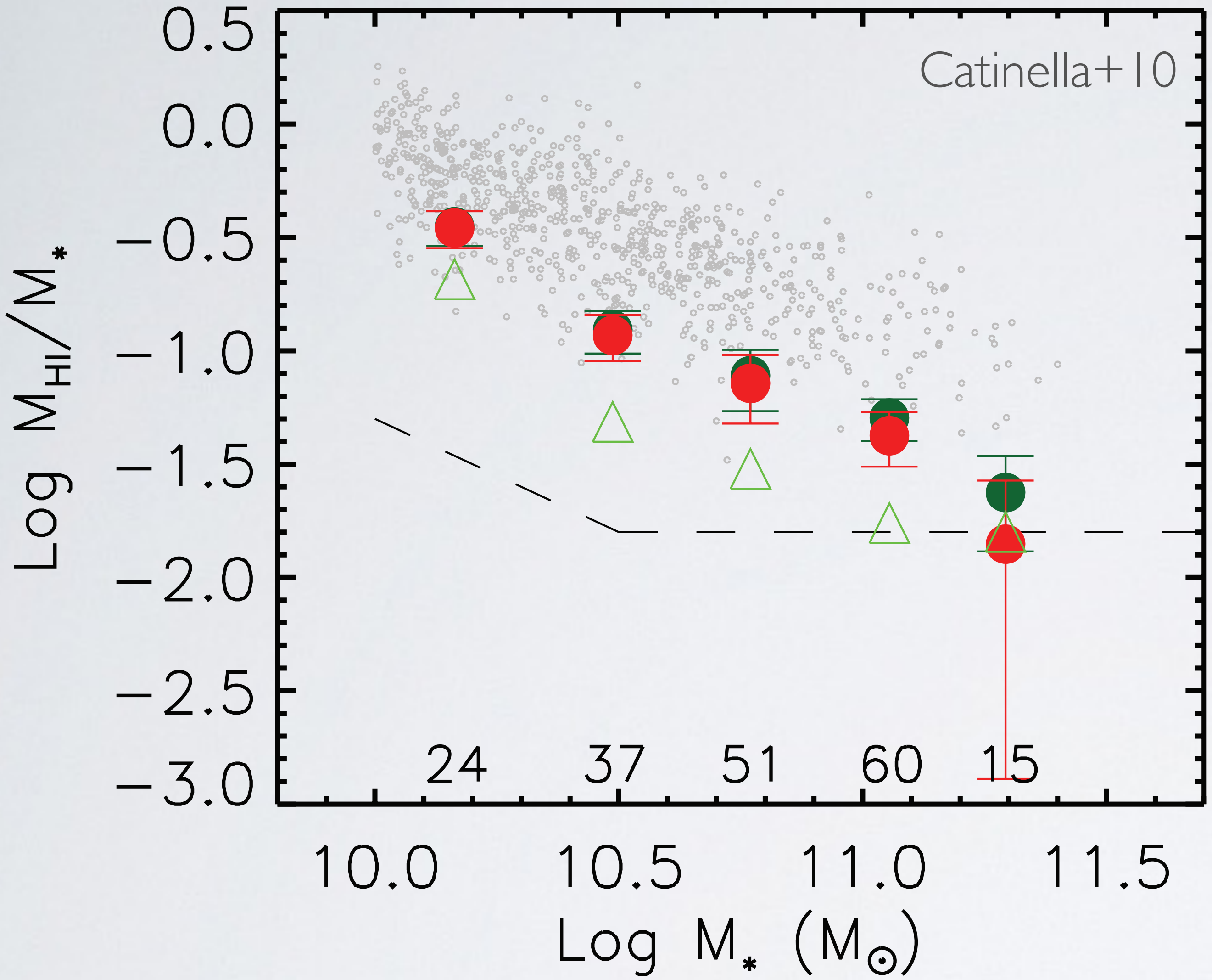
The birth of "transition mass" (Kauffmann+03)

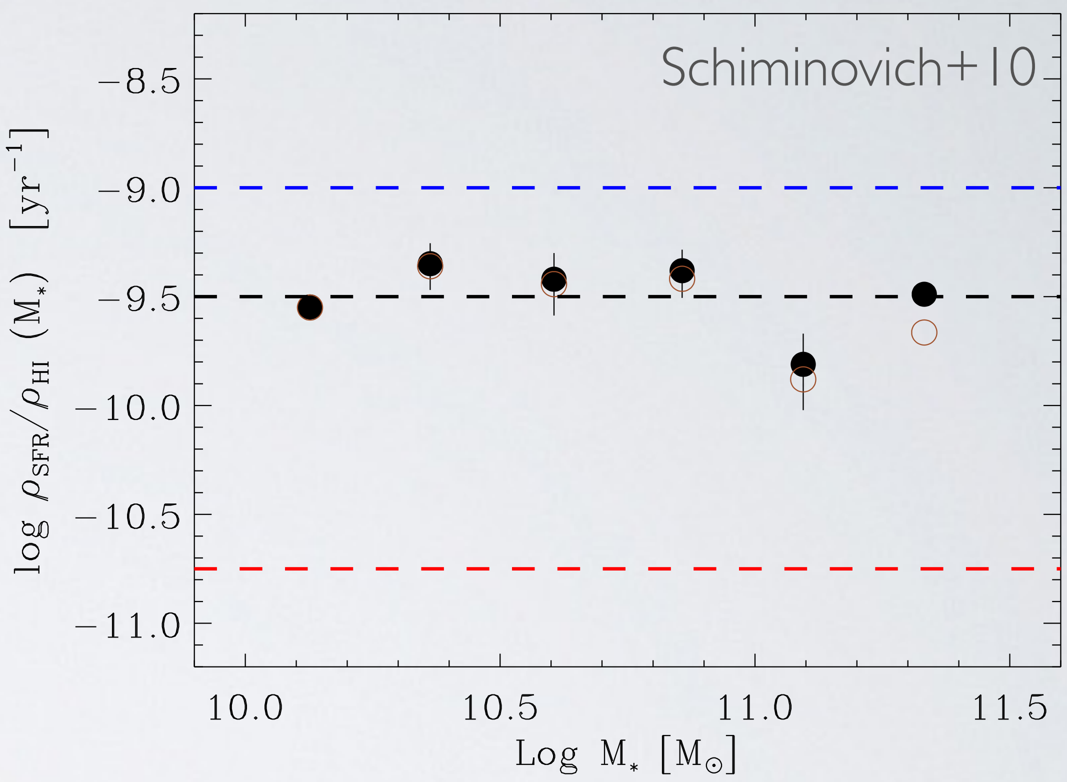


Color bimodality



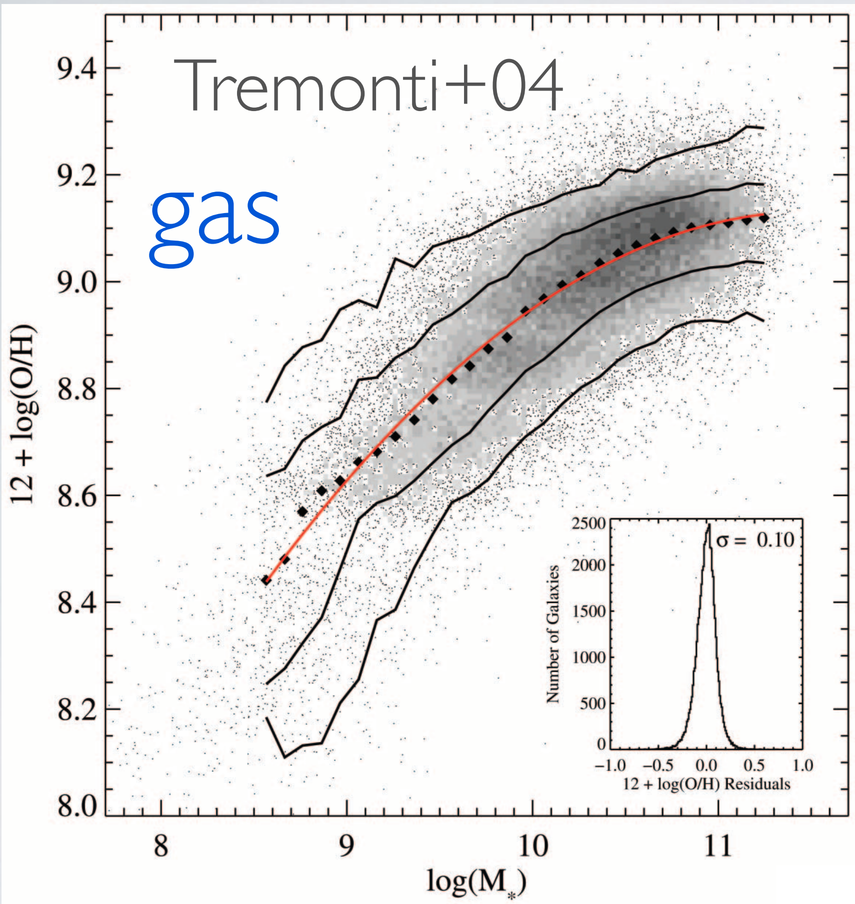
M* vs gas



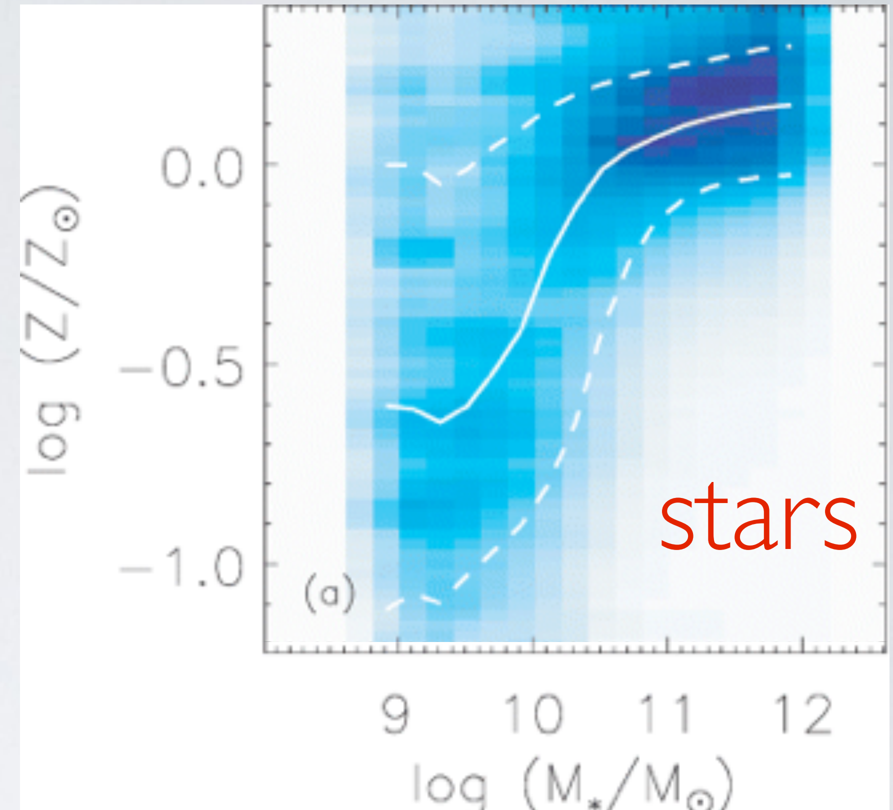


- M* is strongly related with gas fraction: just a consumption argument?
- SFE (or SF time-scale) appears largely independent of M*

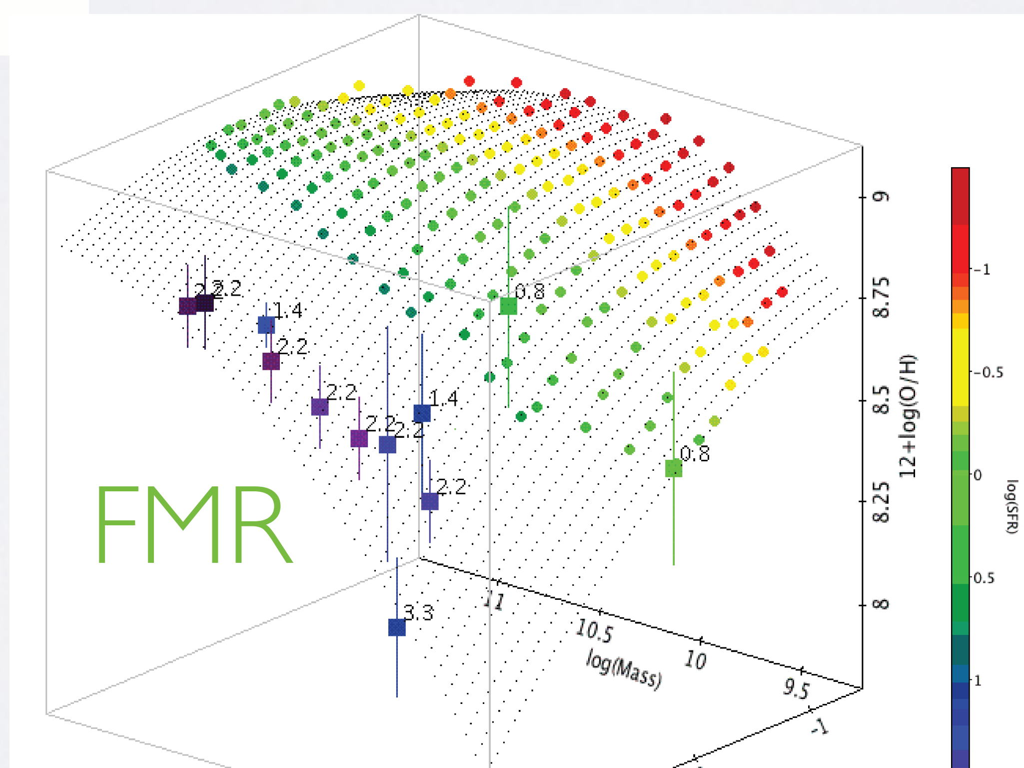
Mass-Metallicity Relations



Stellar mass is clearly linked to the chemical evolution via SFH, feedback, inflows



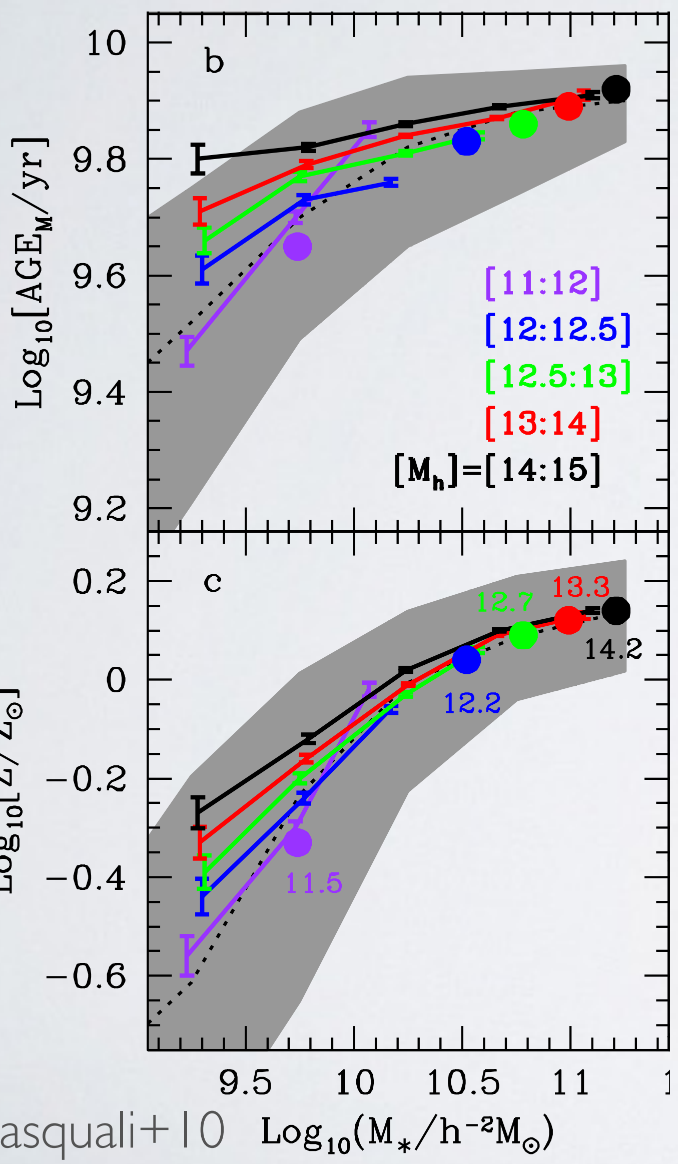
Gallazzi+05



Mannucci+10

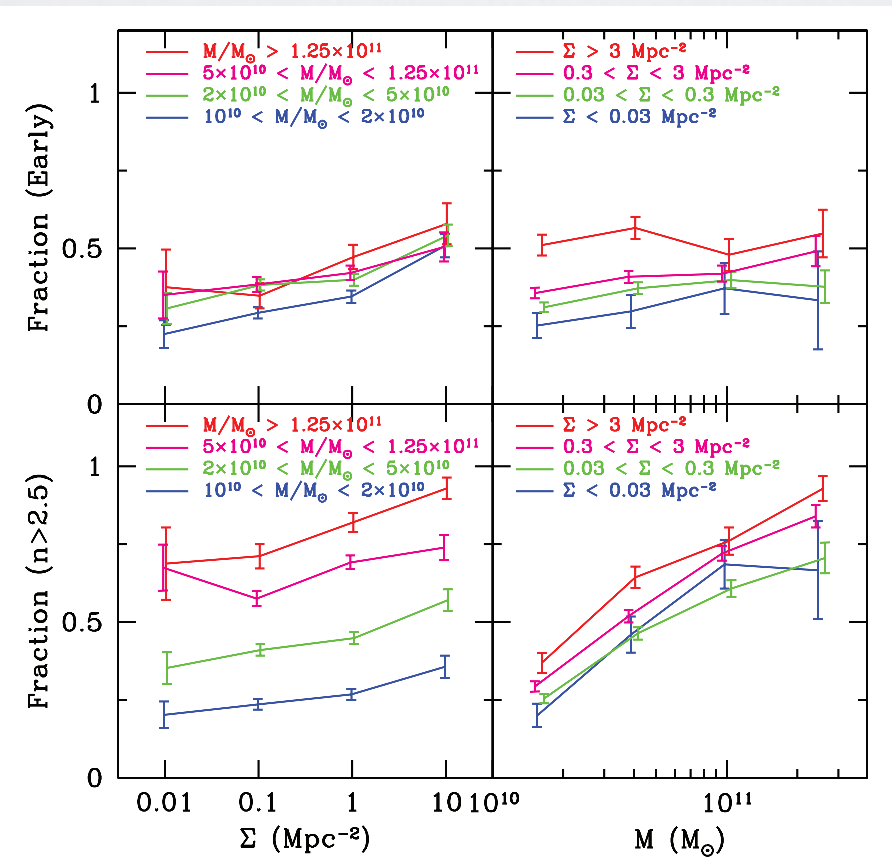
Mass vs Environment And Nature vs Nurture

Age and Z



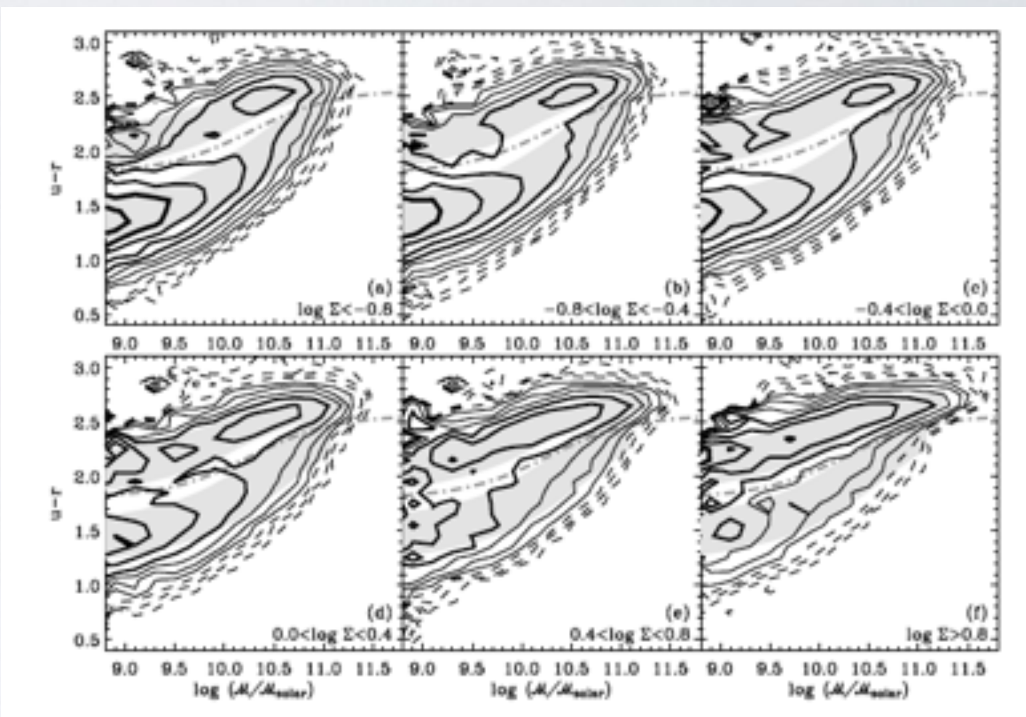
Pasquali+10

Morphology



Van der Wel (2008)

Bimodality



Baldry+2006

- **Stellar mass** sets the trends, **environment** is a secondary parameter

MASS IS KING

(cit. Darren Croton, Kuala Lumpur, Malaysia, 2009)

Key Question: What's Behind All This?

- M*-age-Z-sSFR relations suggest that there is **limited choice for SFH** of a galaxy and the "end-product" normalisation (=M*) plays a key role
  - stars belonging to massive galaxies formed early, in a quickly enriched ISM and with a fast consumption of the gas
  - less massive galaxies are allowed to have much more extended SFH
- ***Transition mass***, "red"/early above $\sim 3 \cdot 10^{10}$, "blue"/late below
  - evolution in z (Pannella+09) or not (Bell+07)? which "**downsizing**"?
  - why? feedback? transition in gas accretion/SF mode?
- **Secular evolution and Dynamics**: key role of stellar mass in determining secular bulge growth, bars, redistribution of angular momentum and matter, stability of the gaseous disk

Measuring M* Across Cosmic Time And Galaxy Types

- Stellar mass, arrow of time
- **Accuracy** is crucial! (i.e. a factor ~2 is not good, not anymore)
  - Evolution of scaling relations
  - Blue to red transition: requires unbiased knowledge of stellar mass for different populations
  - The mystery of the non-evolving massive end
    - lack of accretion or diffusion of stars?
  - Mapping stellar mass to analyse internal galaxy dynamics

How (Well) Do We Estimate Stellar Masses?

- "Stellar mass is just a luminosity corrected by a color term" (anonymous astronomer, Kuala Lumpur, Malaysia, March 2009)
- ...if you ***just*** knew this term!
- SED interpretation/fitting: SED→M*/L
    - derive SF and chemical enrichment history via inversion of SSP linear combination... tough and degenerate!
    - Monte Carlo / bayesian approach, based on large comprehensive libraries:
        - multivariate likelihood function marginalisation, required to take degeneracies into account

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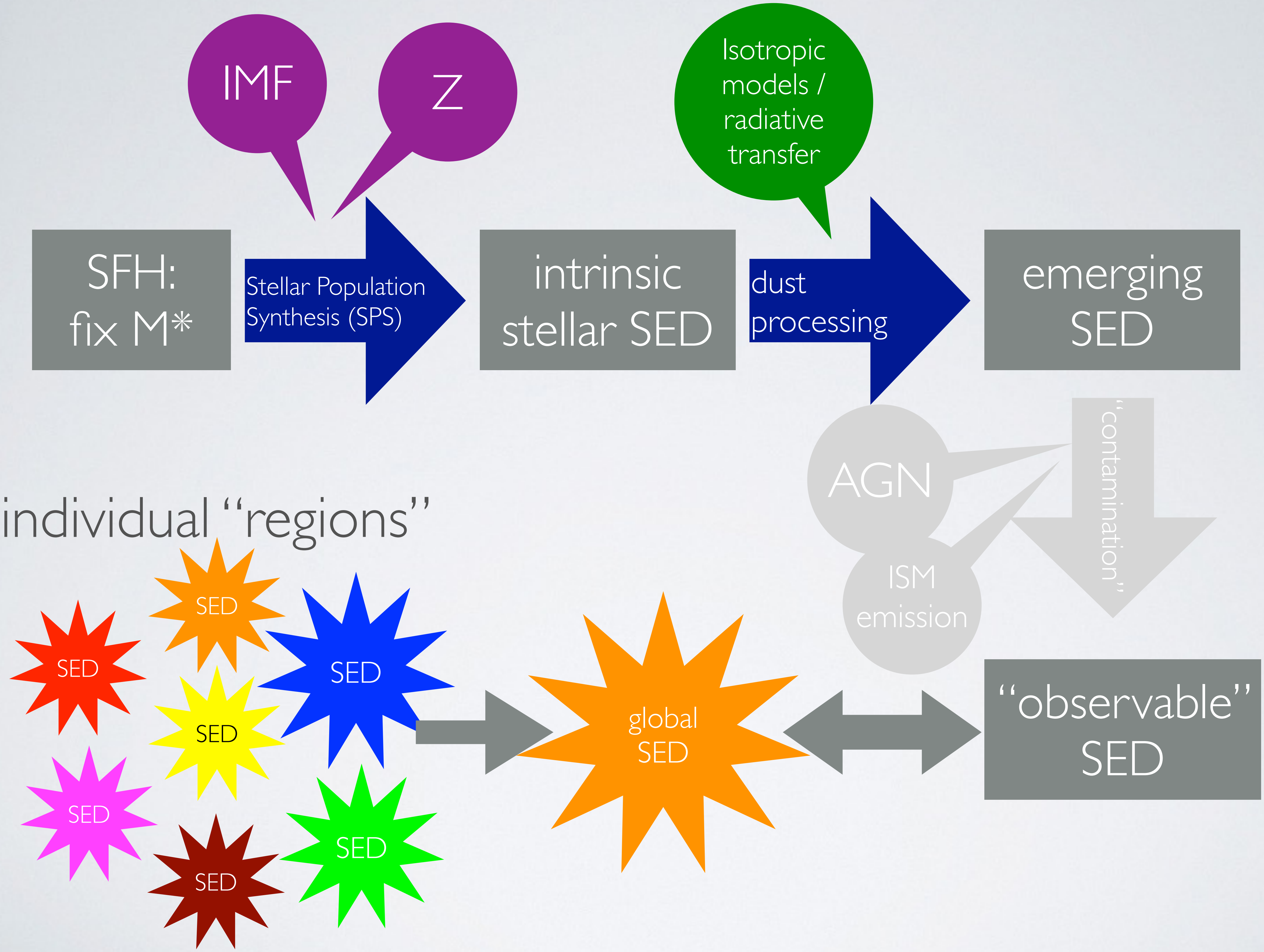
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Uncertainties In All Steps...

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  - exponentially declining
    - w/ or w/out bursts (Kauffmann, Samir, Gallazzi, DaCunha, Bell...)
  - delayed exponential (Sandage)
  - inverse tau, aka raising SFR (Maraston)
  - from semi-analytic models (Pacifici+12)
  - which t_0?

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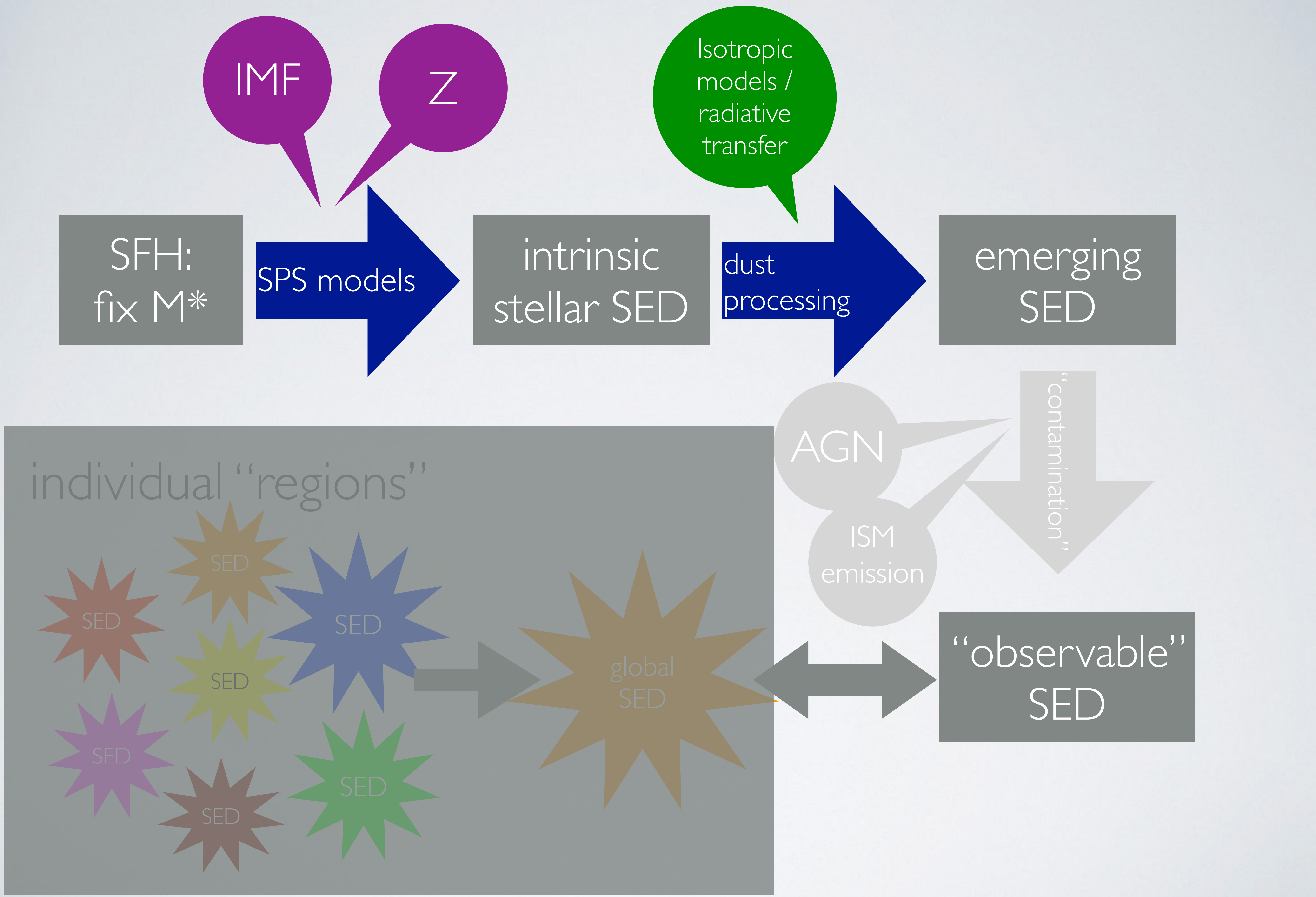
- **Structure bias**: some regions outshine the rest

EXPERIMENTS
AND
THINGS WE'VE LEARNT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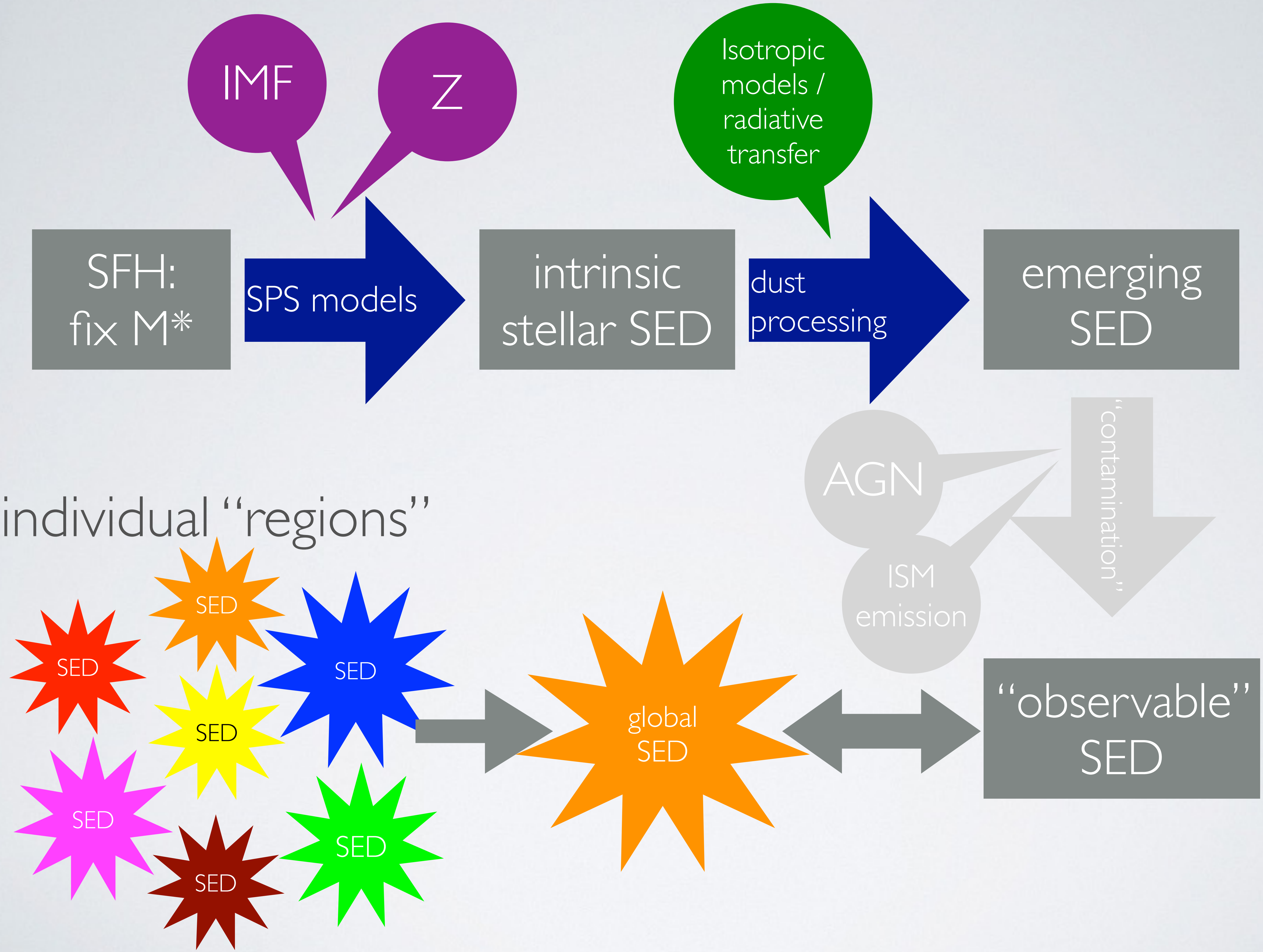
- **Everything can (must) be improved!**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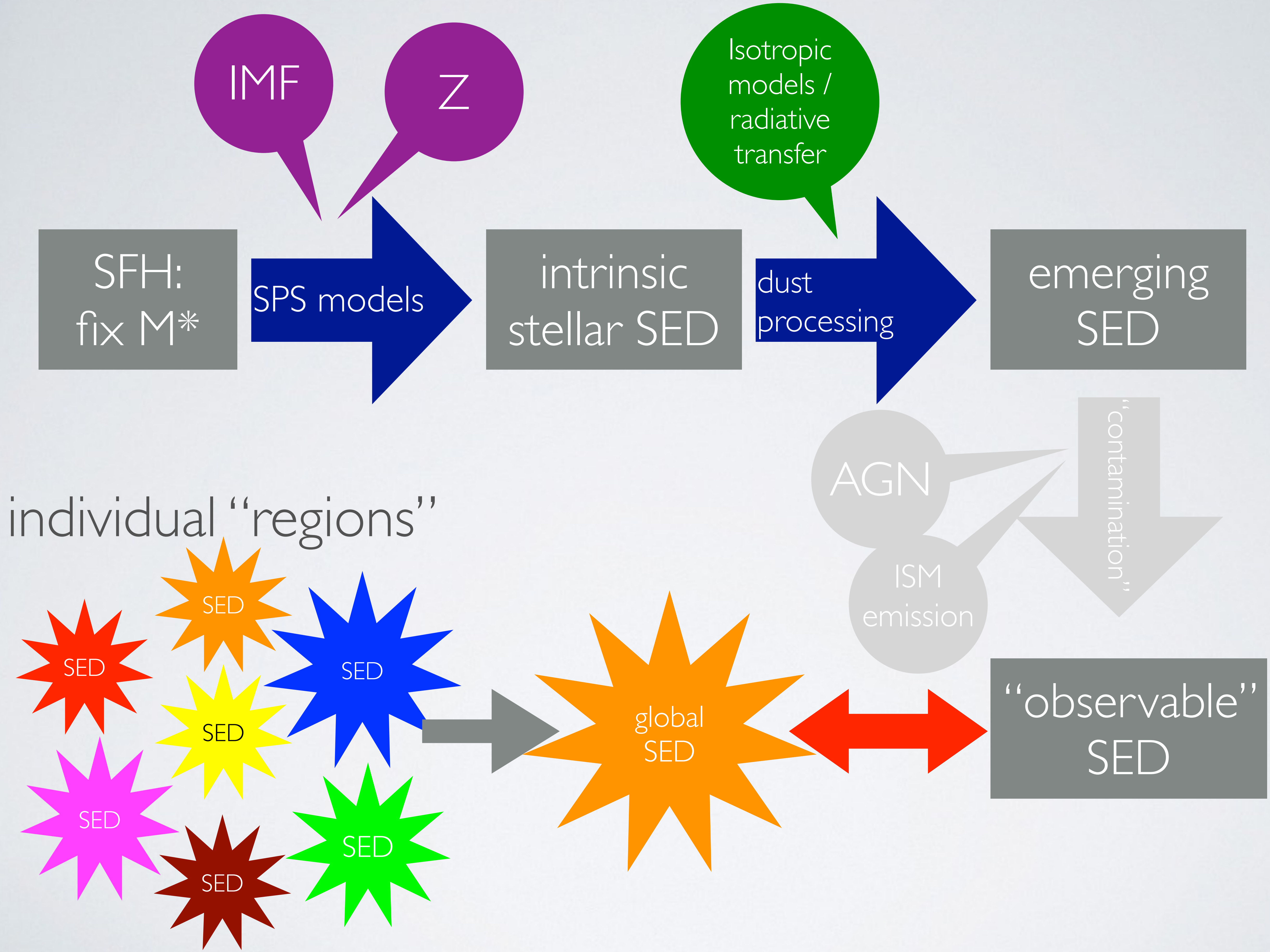

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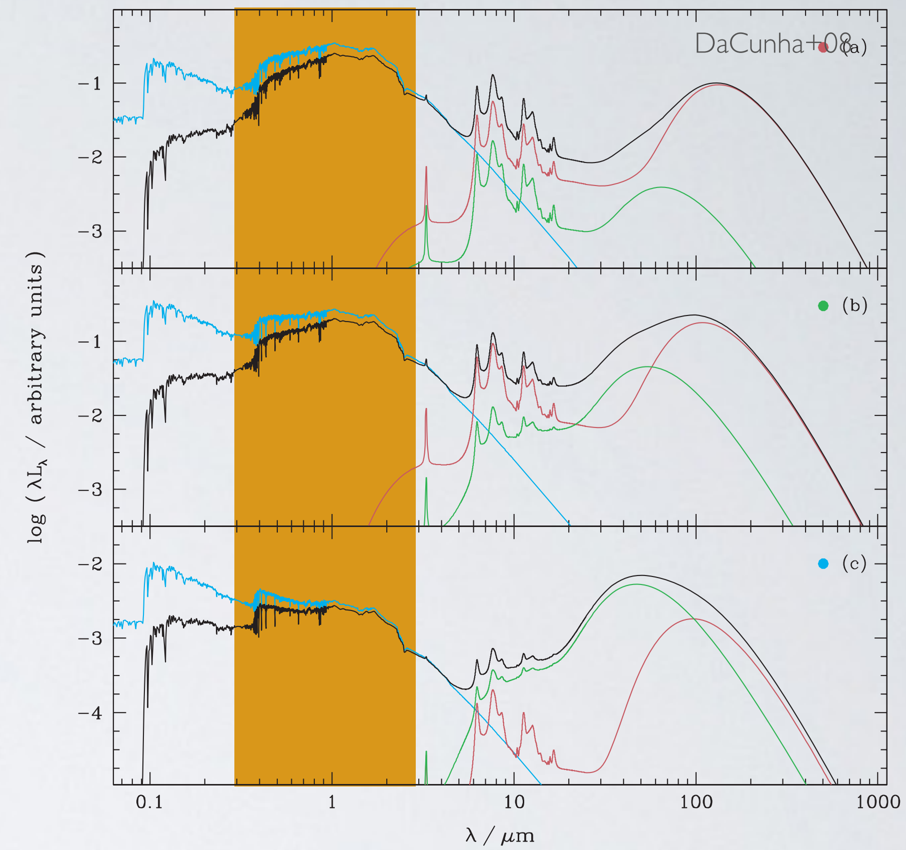
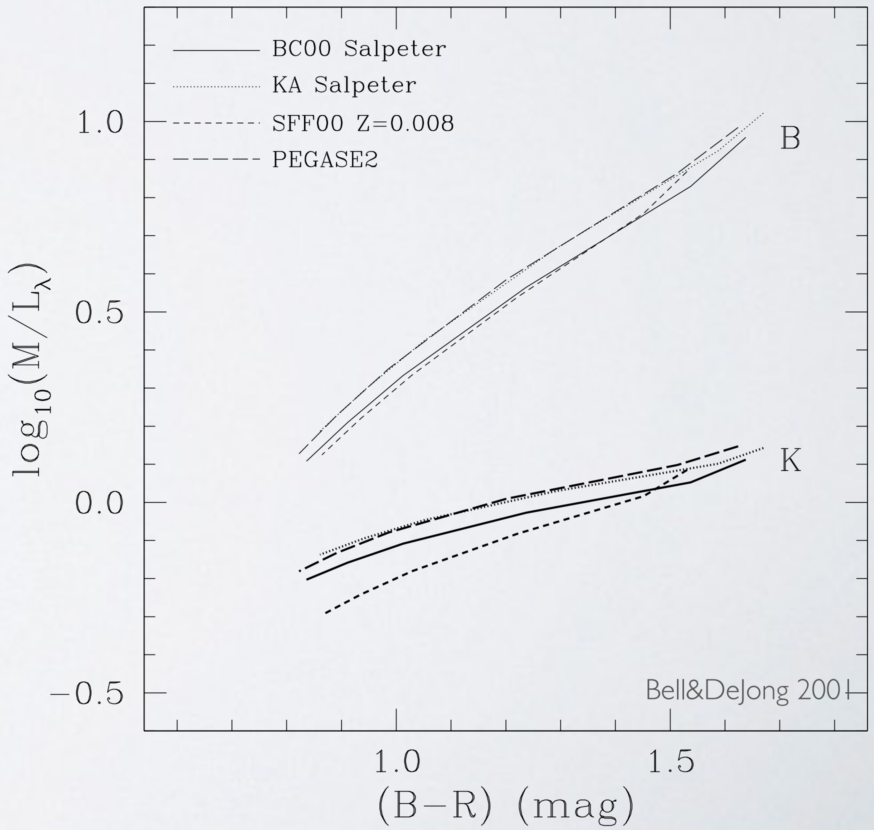
SED Diagnostics

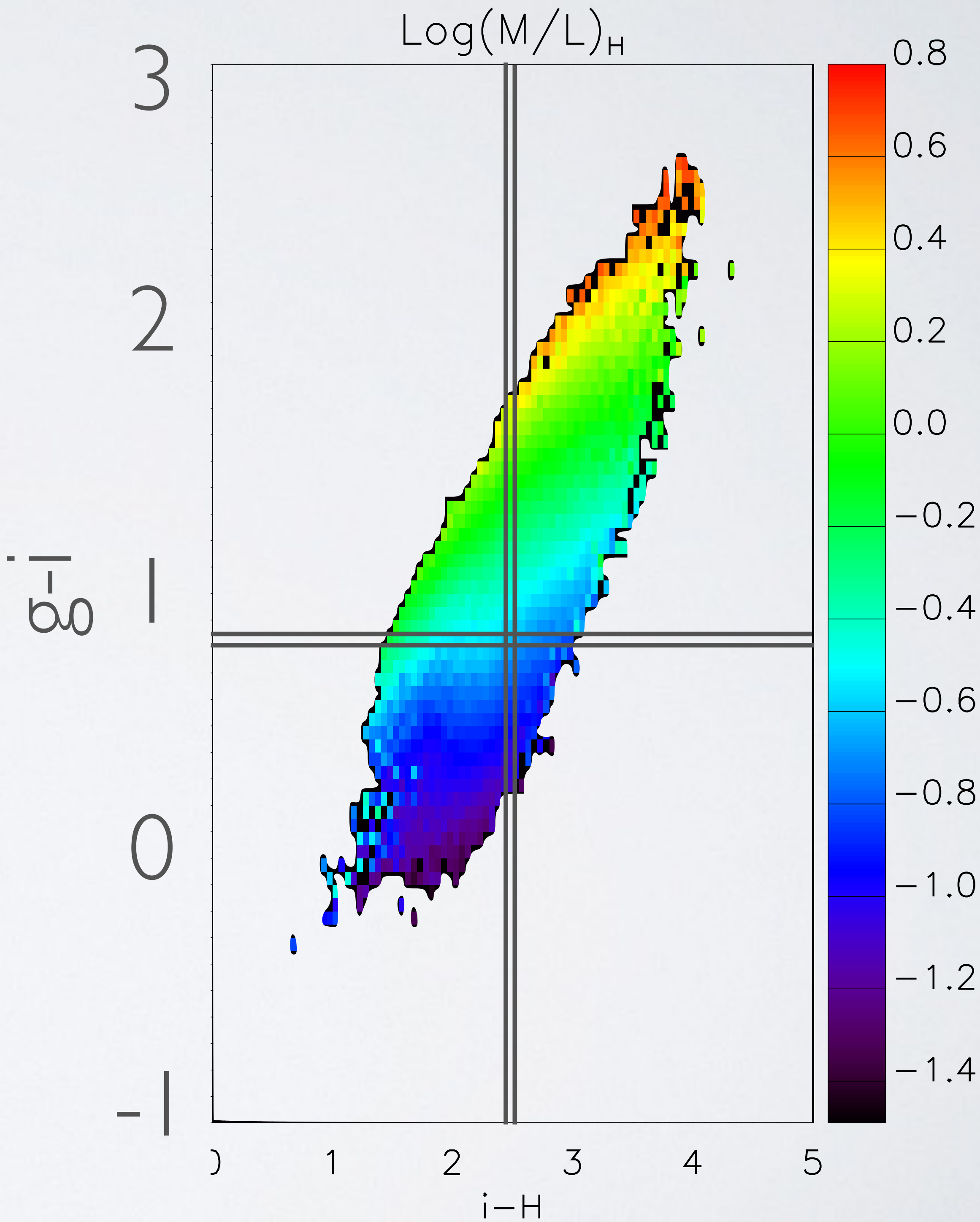
- Look for bands that are maximally sensitive to the bulk of M*
  - minimize M/L variation: **NIR**?
- Broad band **colors**, esp. UV-opt-NIR
  - well known age-Z-dust degenerate effect on M/L vs color relation (e.g. Bell&deJong 2001)
- **Optical spectra**
  - stellar absorption features: lift age-Z degeneracy, need colors to recover dust
- More constraints from **other wavelengths** (e.g. FIR on dust)





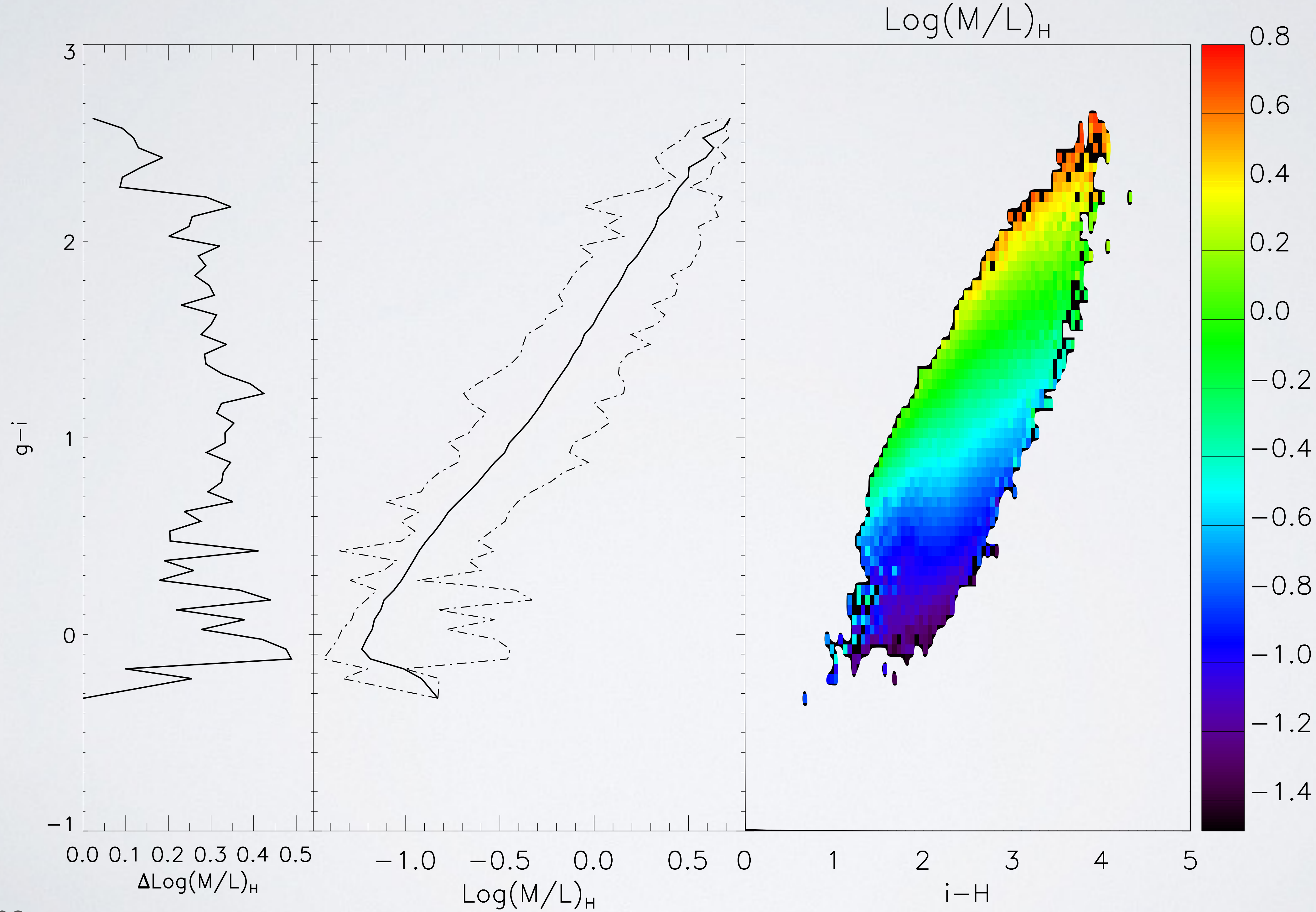
Let's Build A Simple M* Estimator

- 50 000 models
- Optimal/minimal SED diagnostic set:
  - 1 opt-opt color (g-i)
  - 1 opt-NIR color (i-H)
- Marginalise $(M/L)_H$ over the 2D (g-i,i-H) parameter space ⇒ median estimate



SZ, Charlot & Rix (2009, ZCR09)

PRECISION



ZCR09

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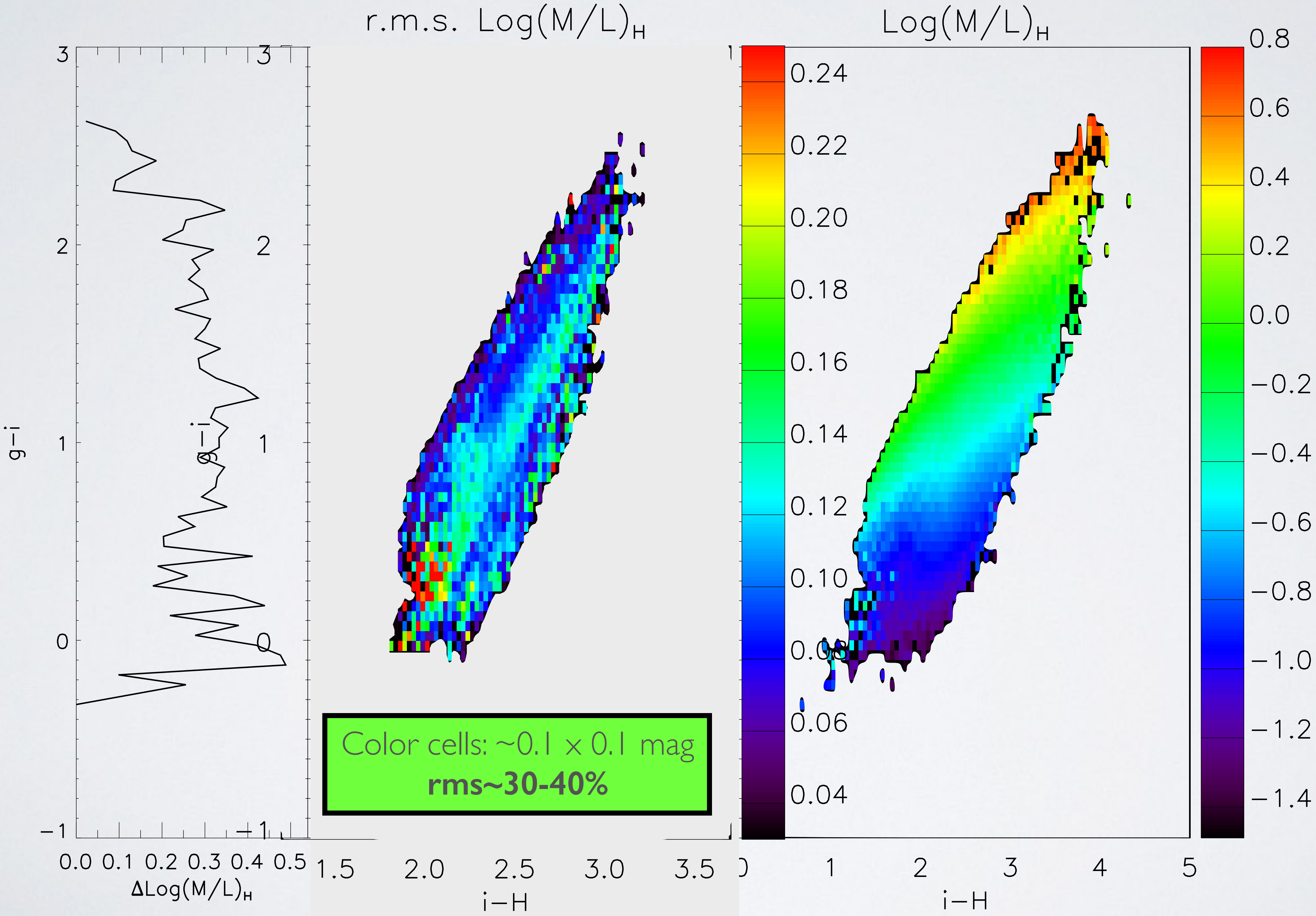
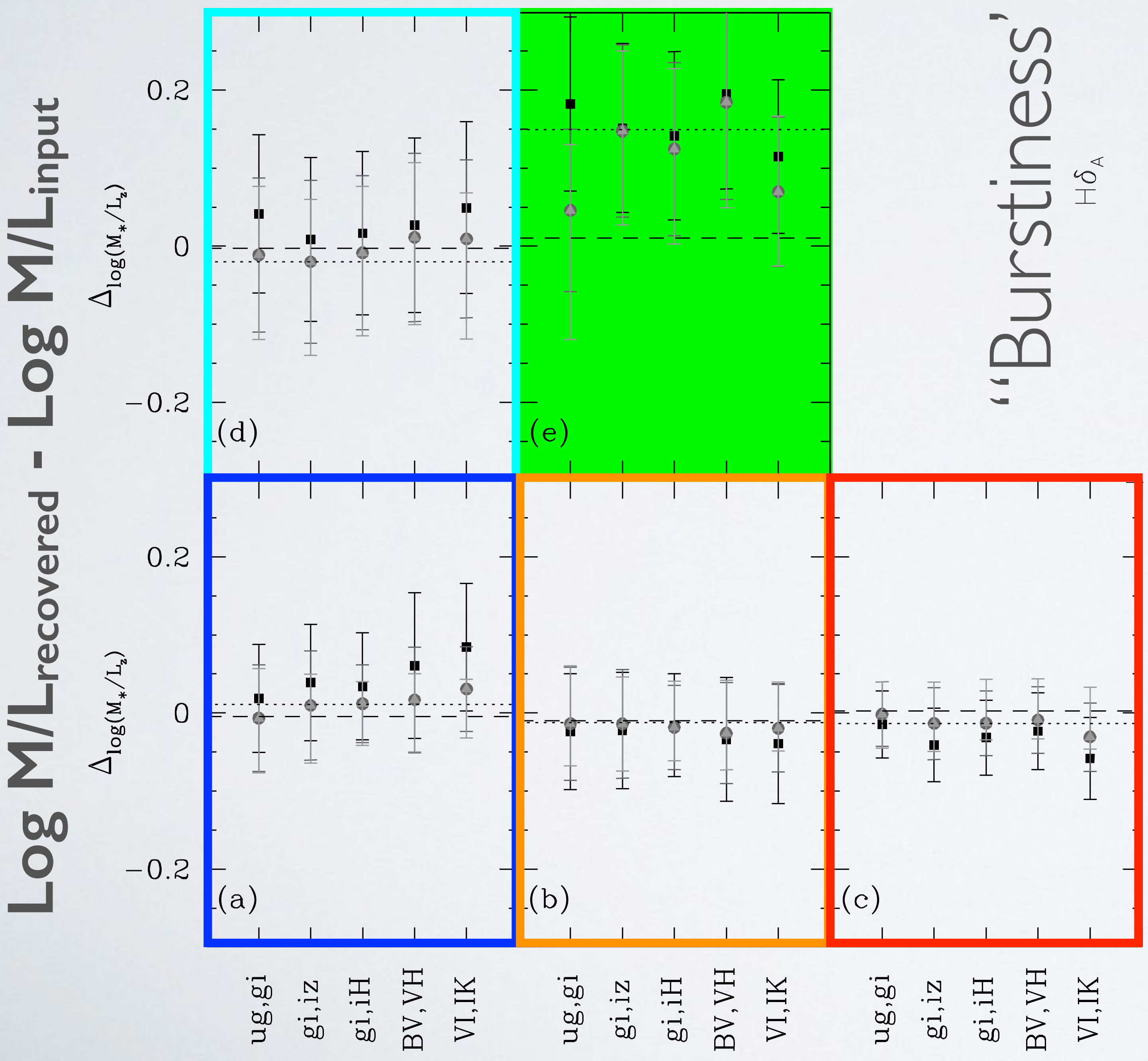


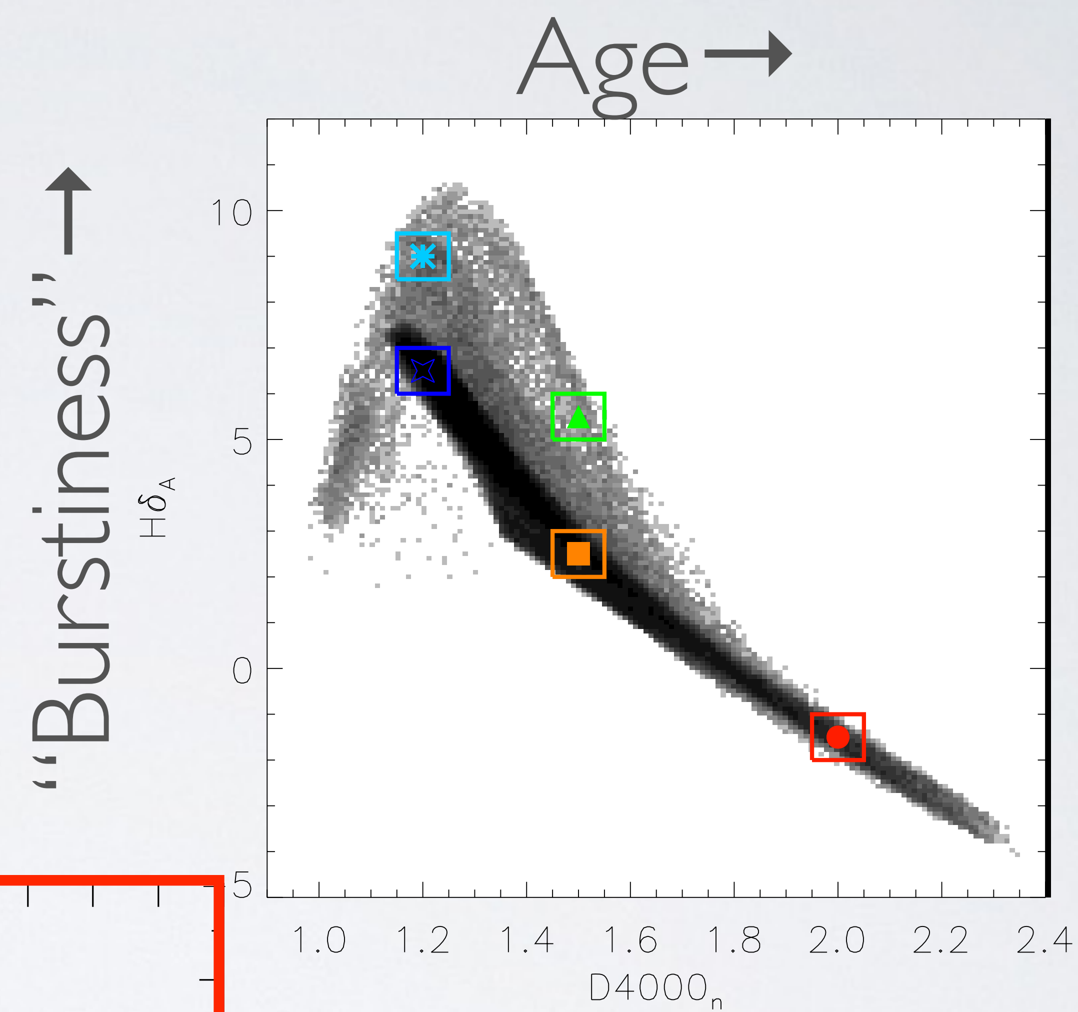
Color cells: ~0.1 × 0.1 mag
rms~30-40%

ZCR09

ACCURACY

- Different SFH
- No dust





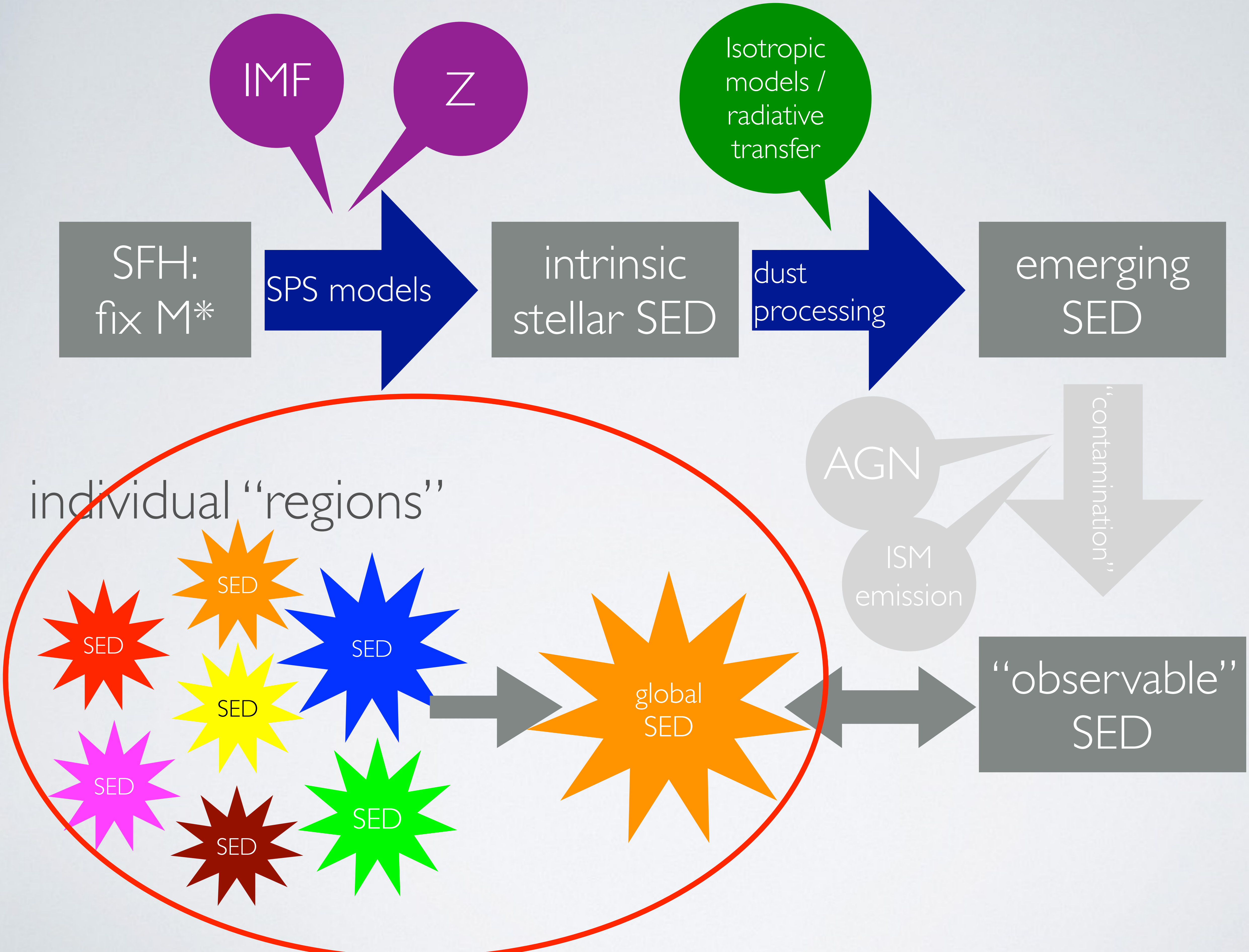
Gallazzi & Bell (2009)

- Colors tend to miss underlying old stellar populations
- But spectral absorptions are insensitive to dust!

LESSON #1

- Best results from joining broad band photometry and spectral absorption features: the latter can resolve the SFH much better, the former help a lot with dust attenuation

LET'S PLAY WITH COLORS…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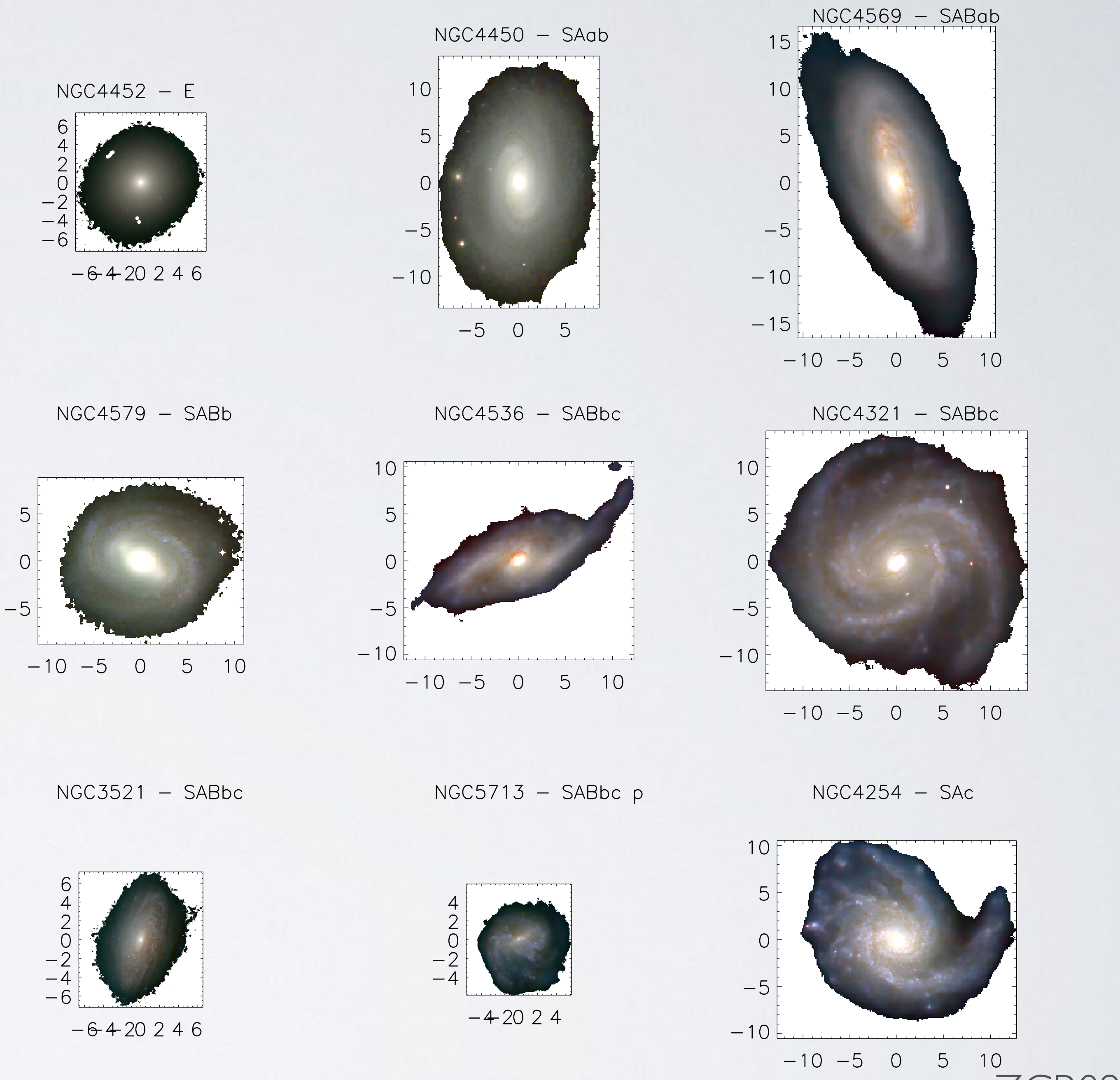
Resolving Galaxies' Structure

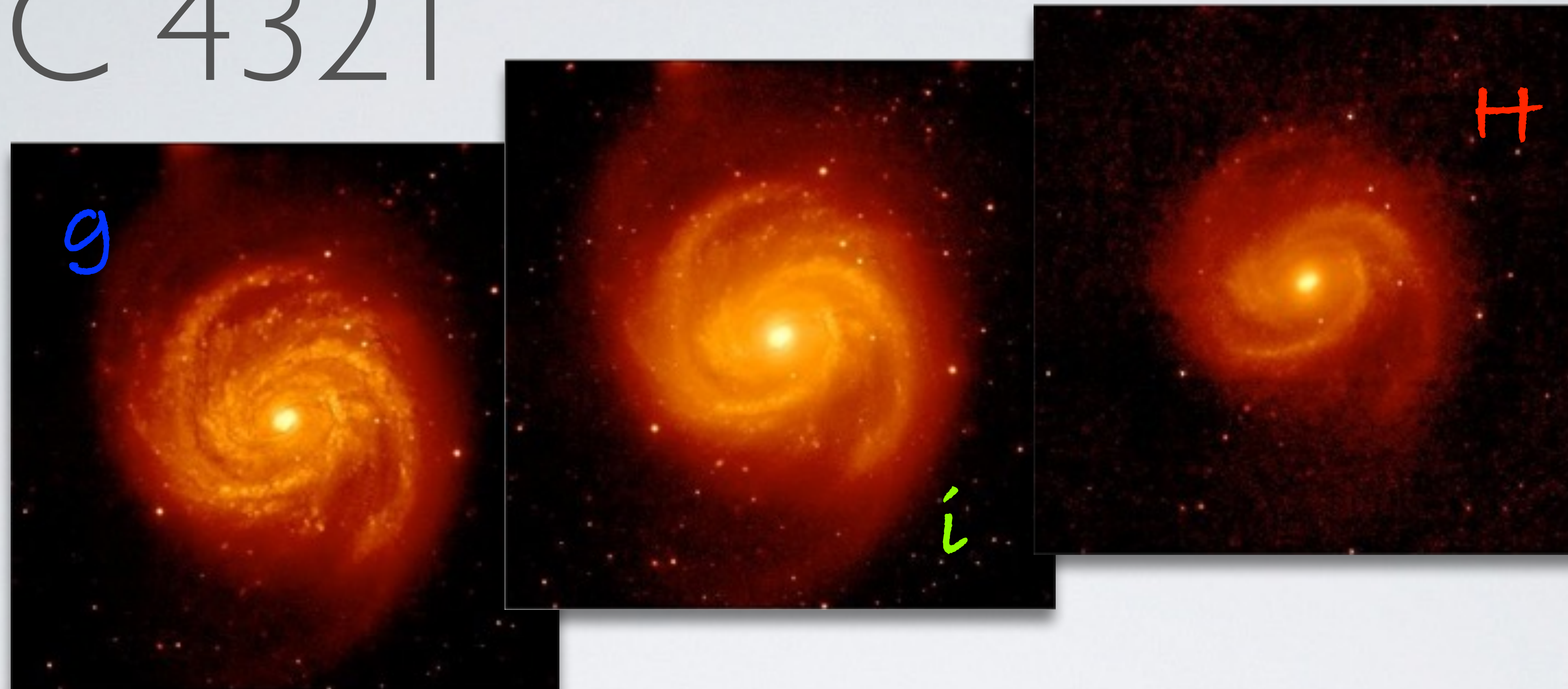
- Colors are very handy to work with in imaging!
- Derive M/L and M* pixel by pixel from opt-NIR imaging
- Pilot study with a small sample of nearby galaxies
- ~100 pc resolution



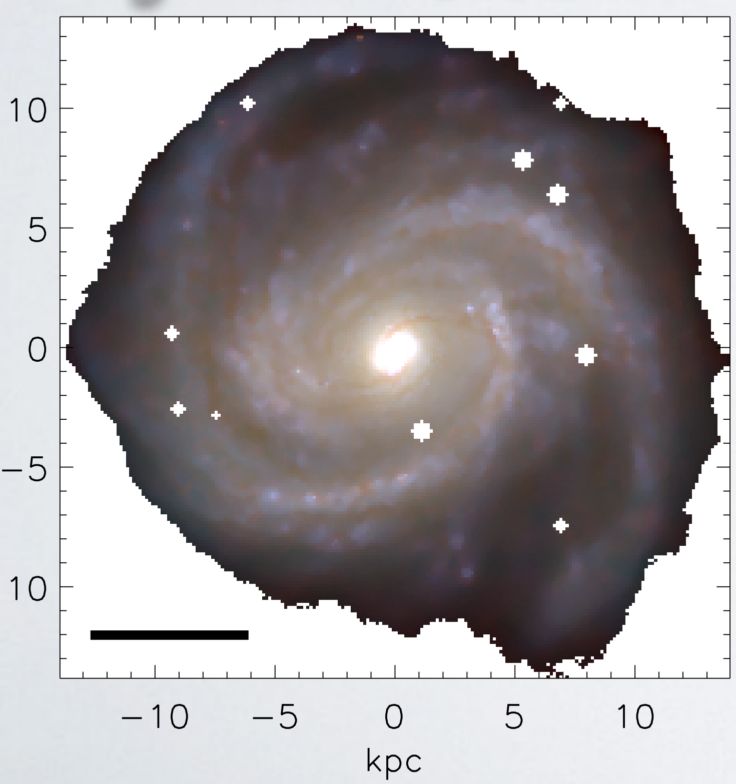
ZCR09

- Drawn from SINGS (Kennicutt et al. 2003)
- SDSS
- NIR imaging in at least 1 band (H or K) ➔ GOLD Mine or UKIDSS
- Initially only SDSS+NIR

NGC 4321



g-i-H "true colour"



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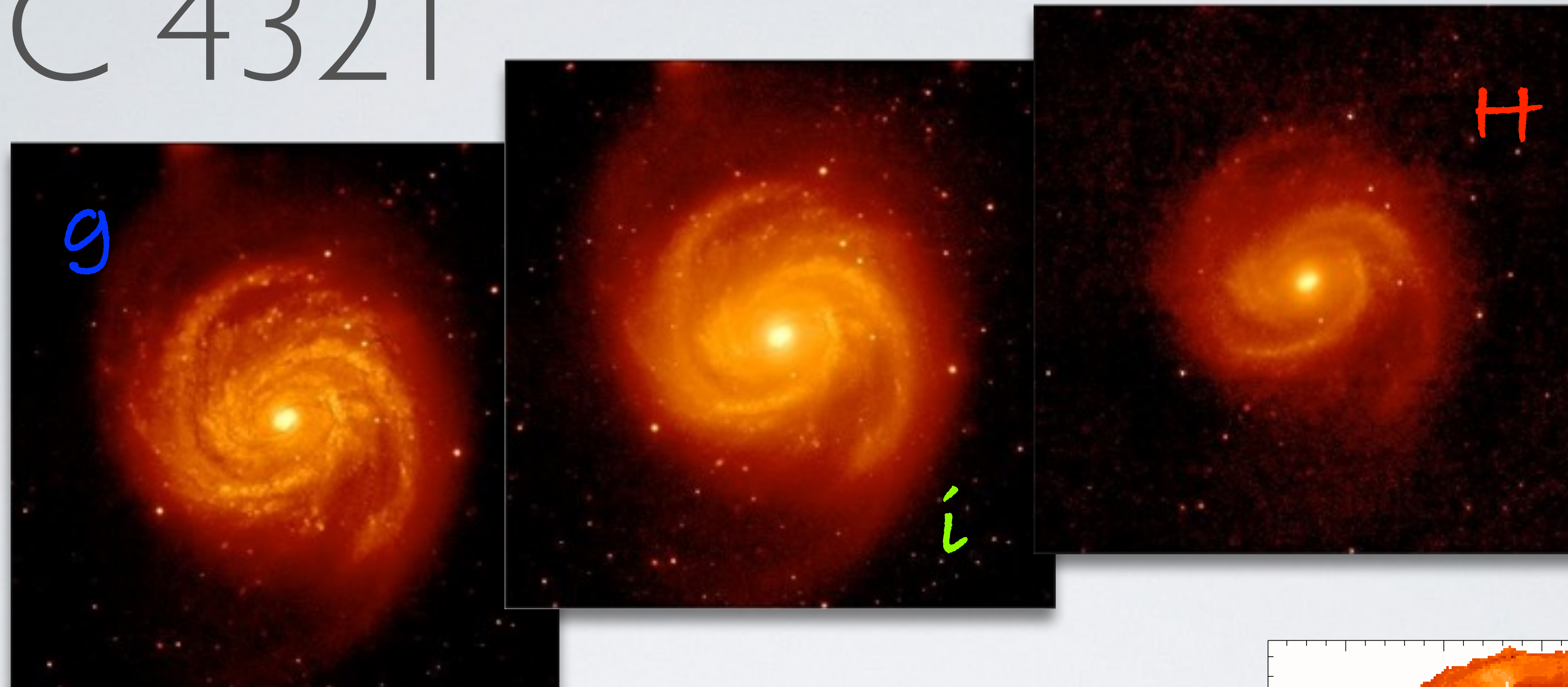
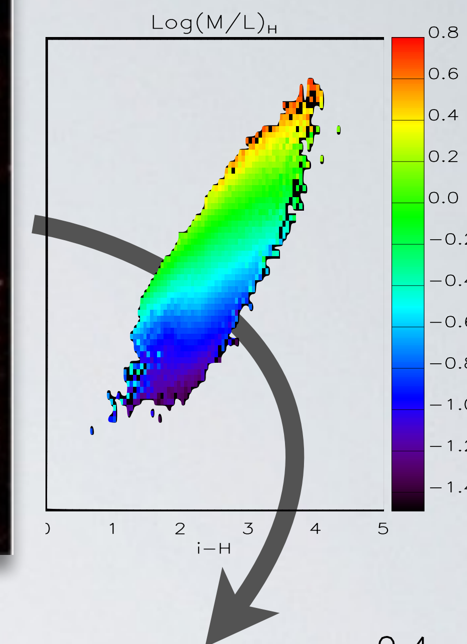
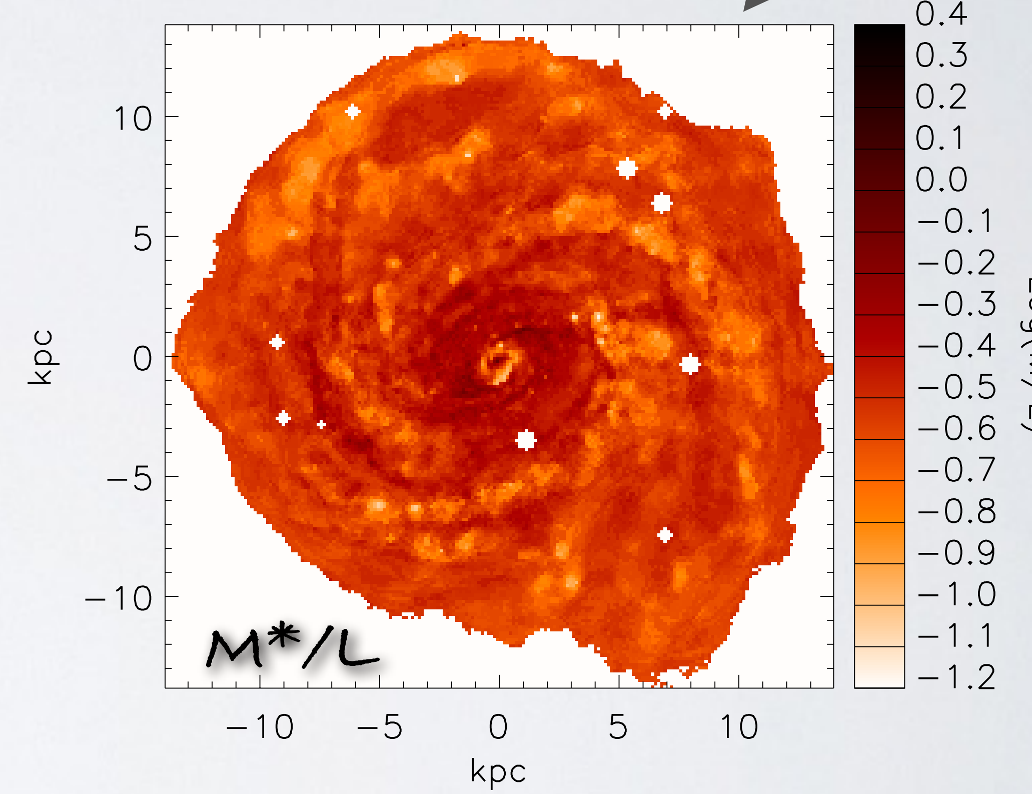
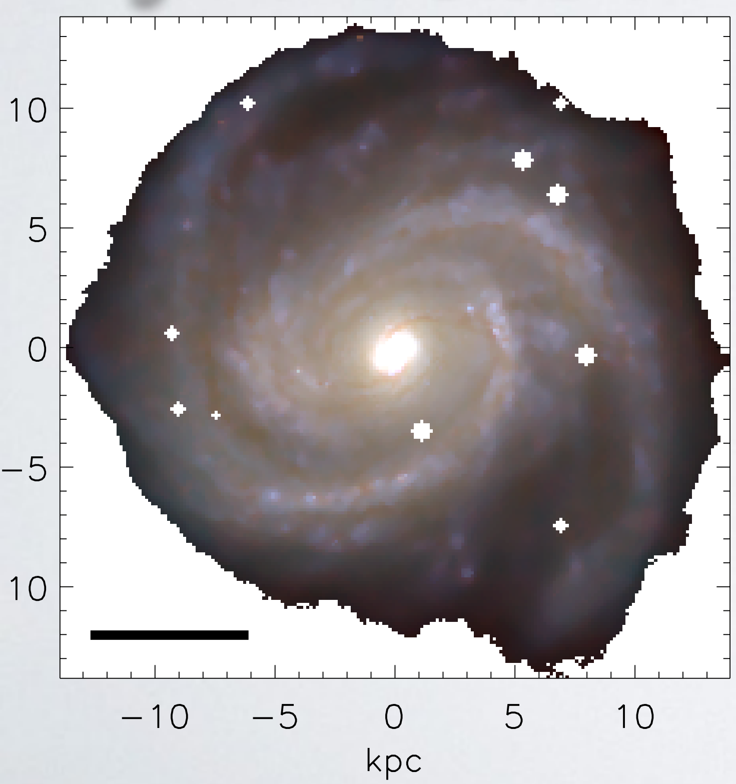


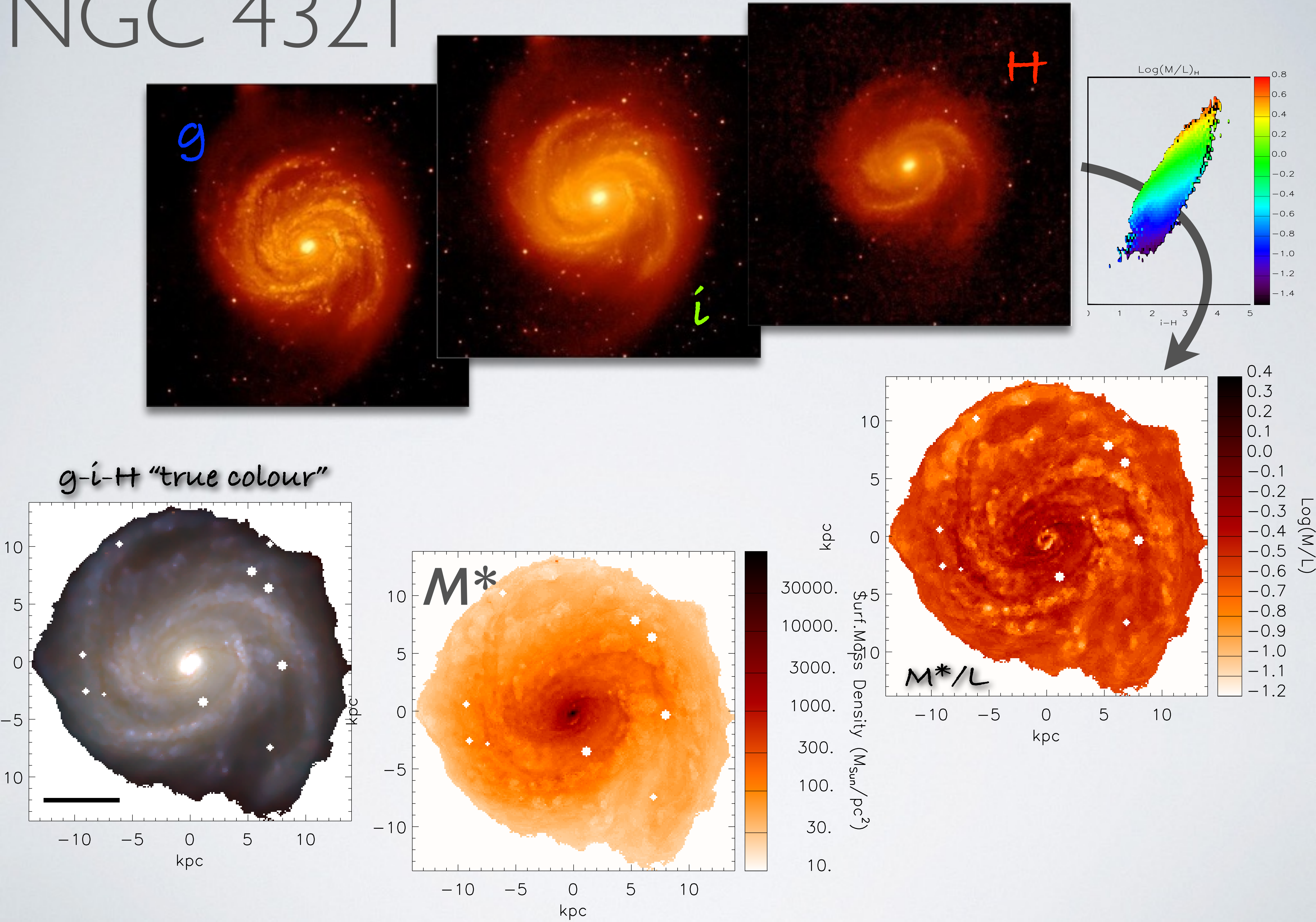




g-i-H "true colour"

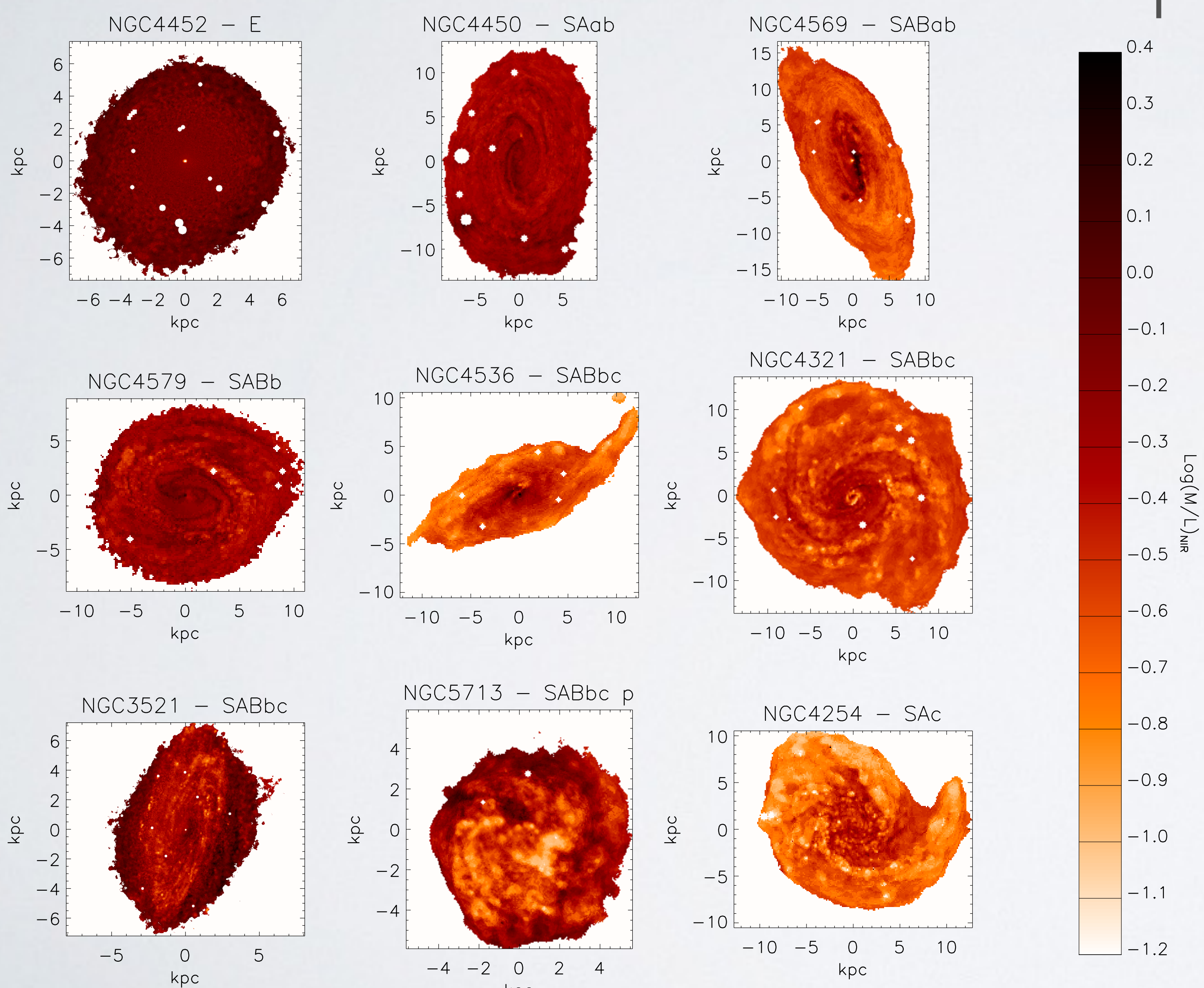


NGC 4321


g
i
H
Log(M/L)H
i−H
g-i-H "true colour"
M*
Surf.Mass Density (M_{sun}/pc^2)
M*/L
Log(M/L)
kpc

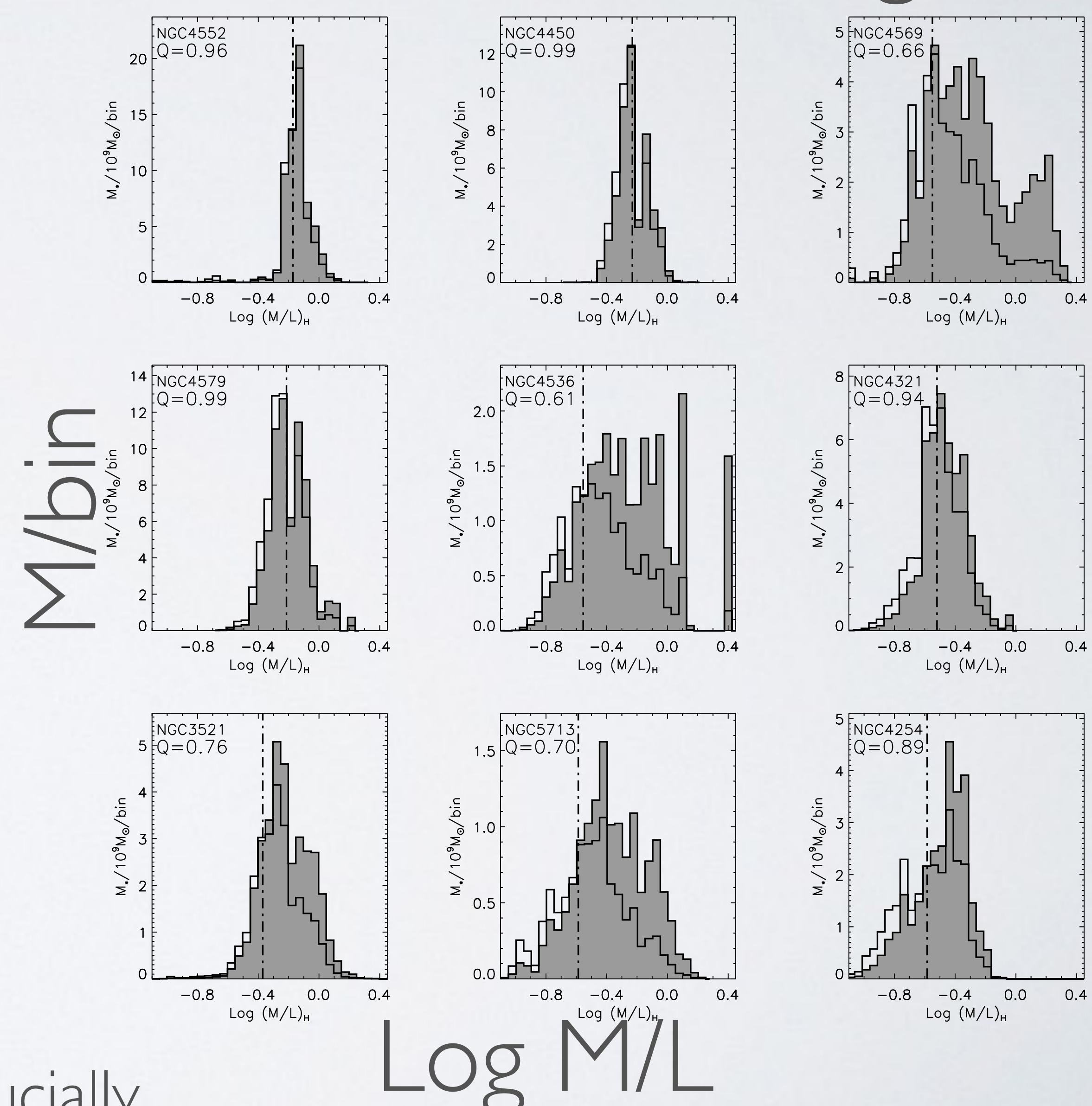
MASS IS LIGHT-WEIGHTED!

M*/L: maps



M* contribution by M*/L

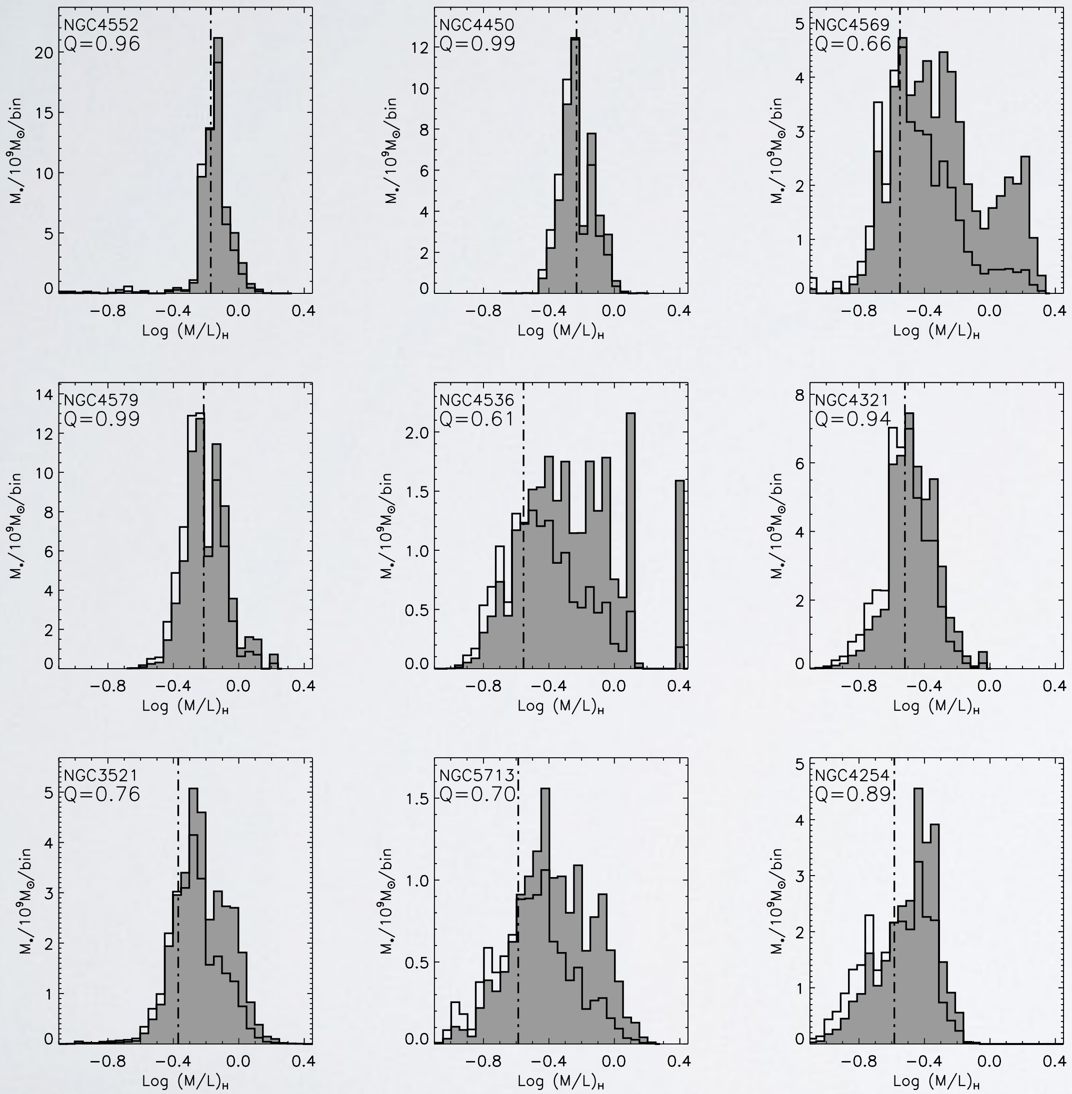
M_{tot} = Area under histograms

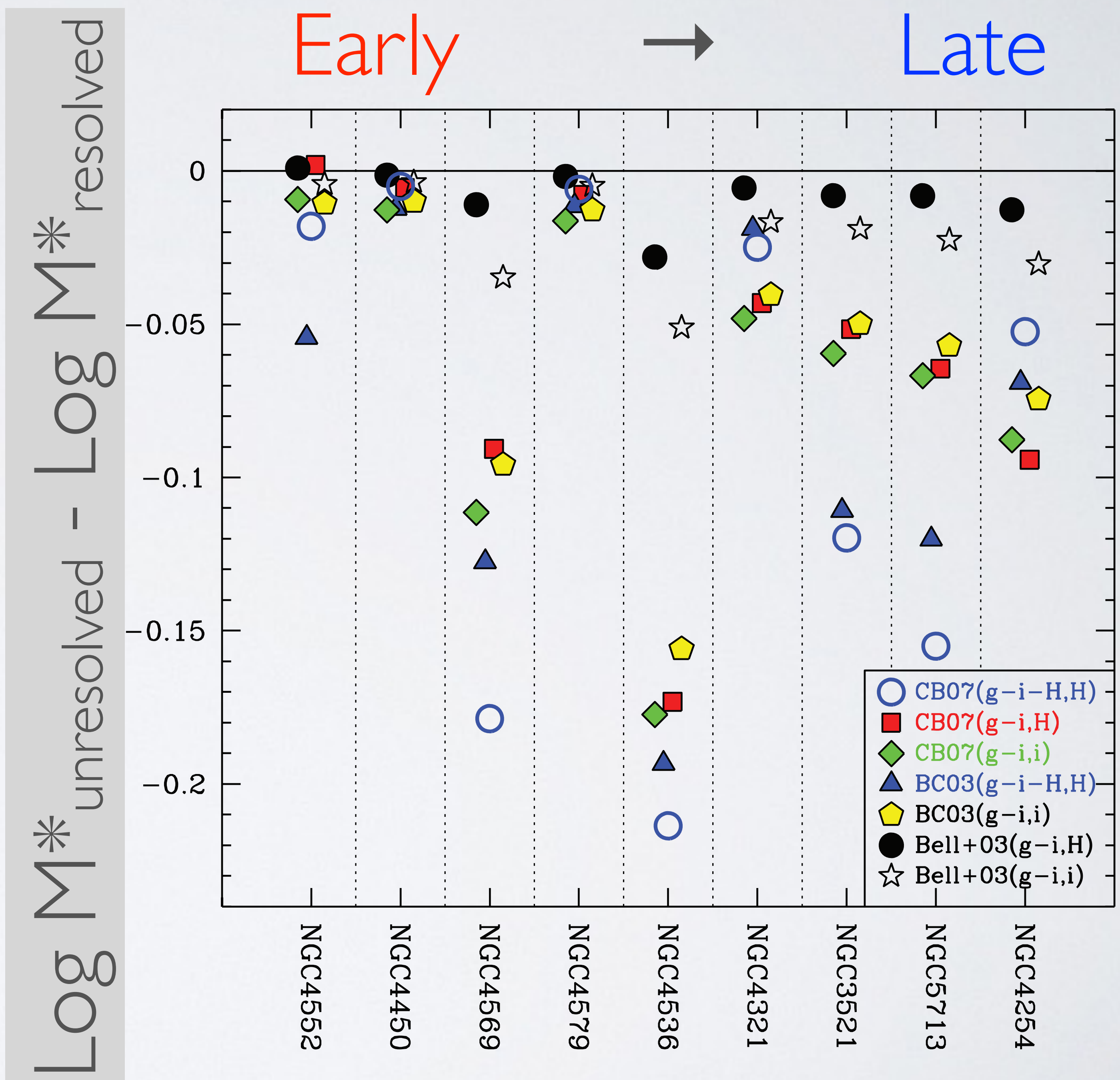


Caveat: the amplitude of this effect may depend crucially on the slope of M/L vs color relations!

ZCR09

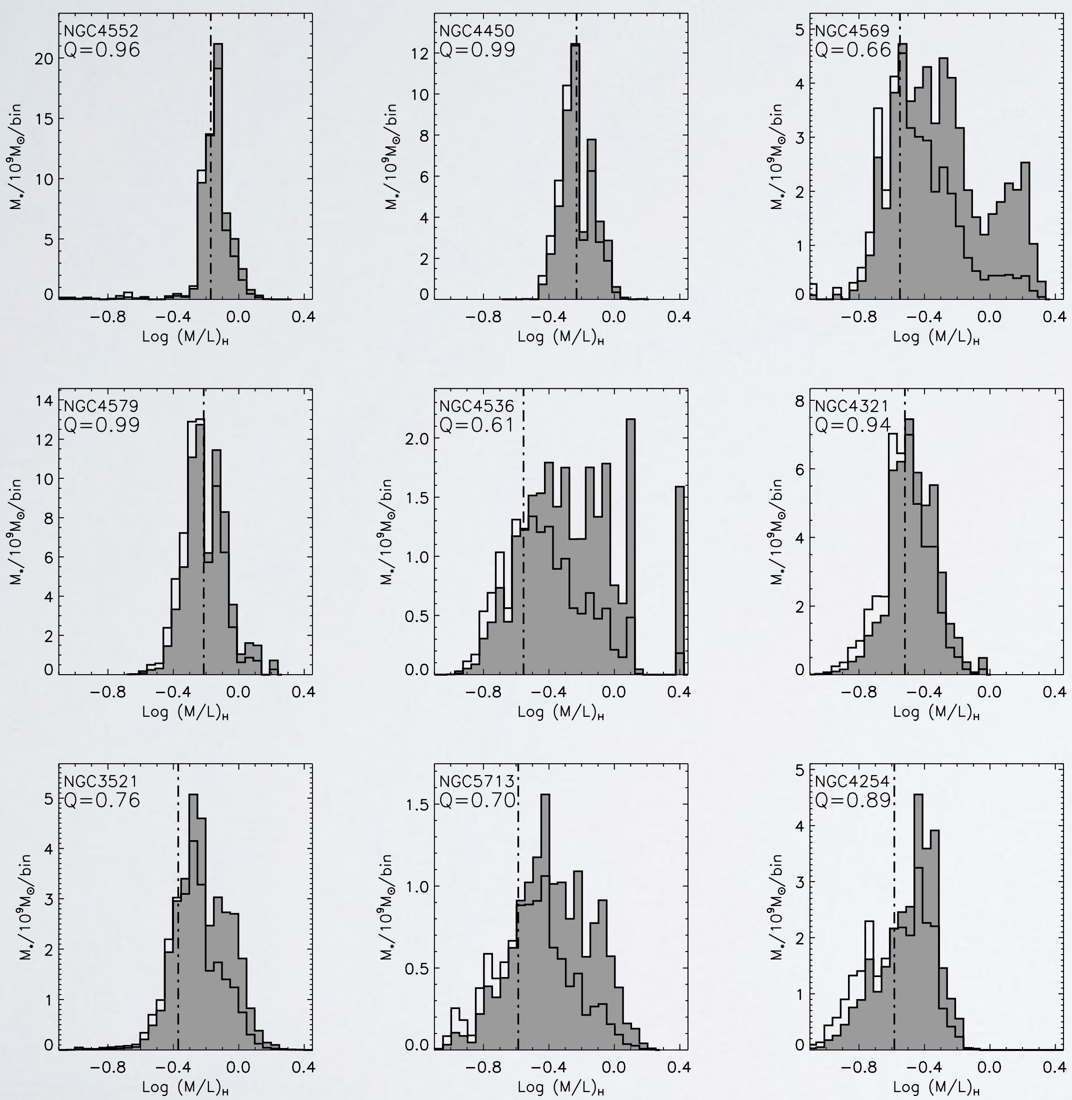
STRUCTURE/BRIGHTNESS BIAS

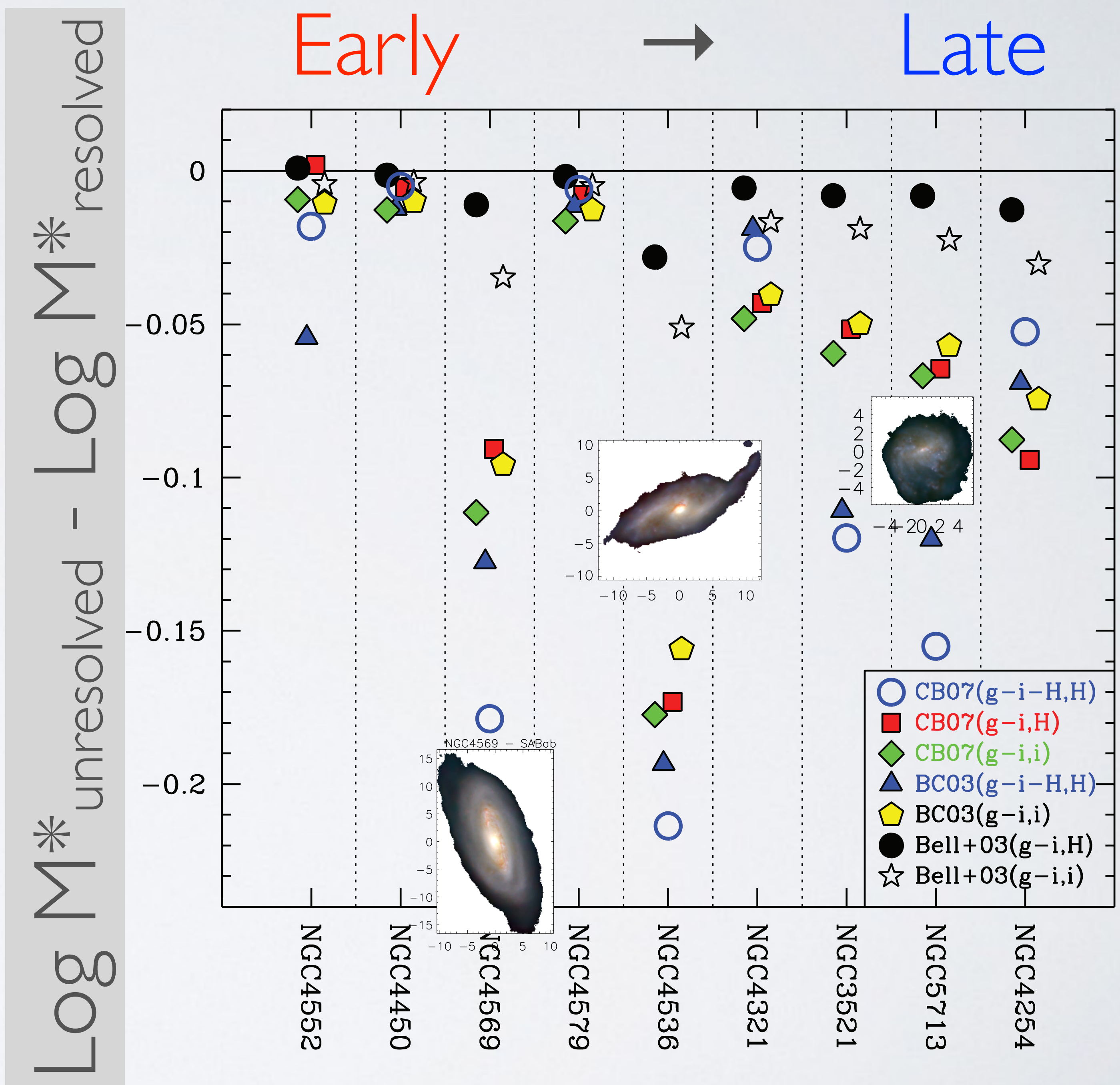




ZCR09

STRUCTURE/BRIGHTNESS BIAS





ZCR09

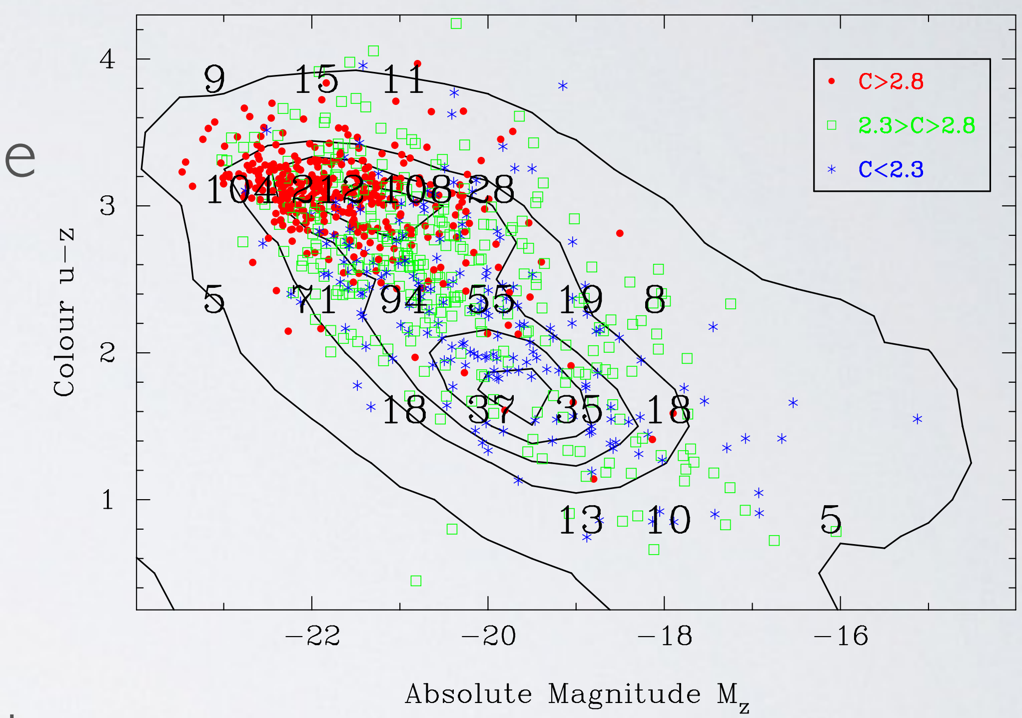
LESSON #2

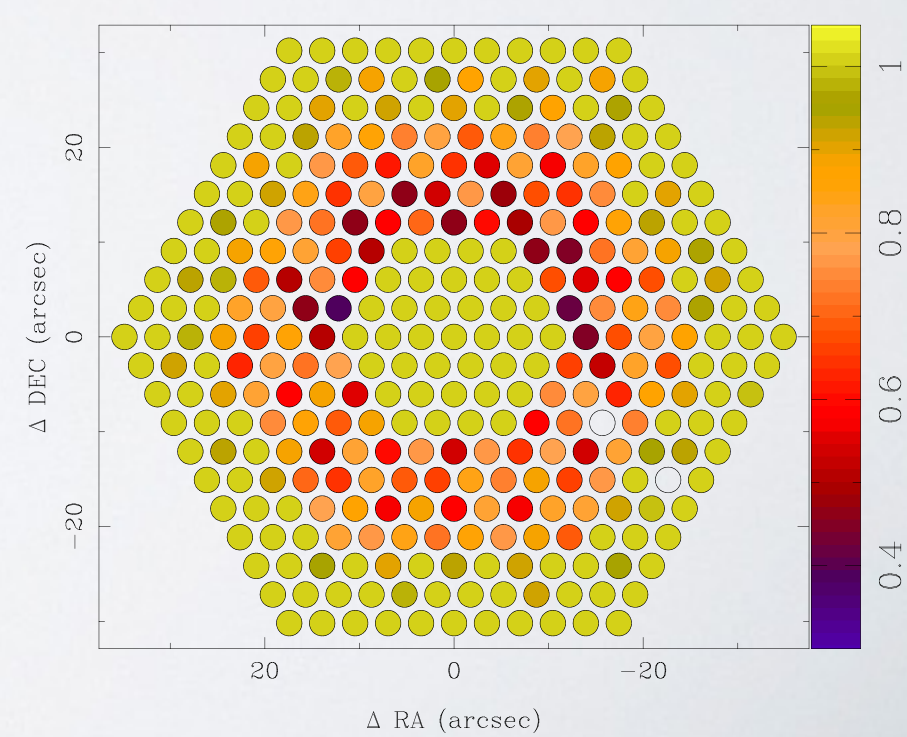
- Need to resolve galaxy structure
  - Obscured regions are "missed" in stellar mass budget when not resolved
  - Young stars tend to outshine the rest and bias M/L low
- High obscuration regime must be treated carefully
- Not always feasible: provide calibration for large surveys

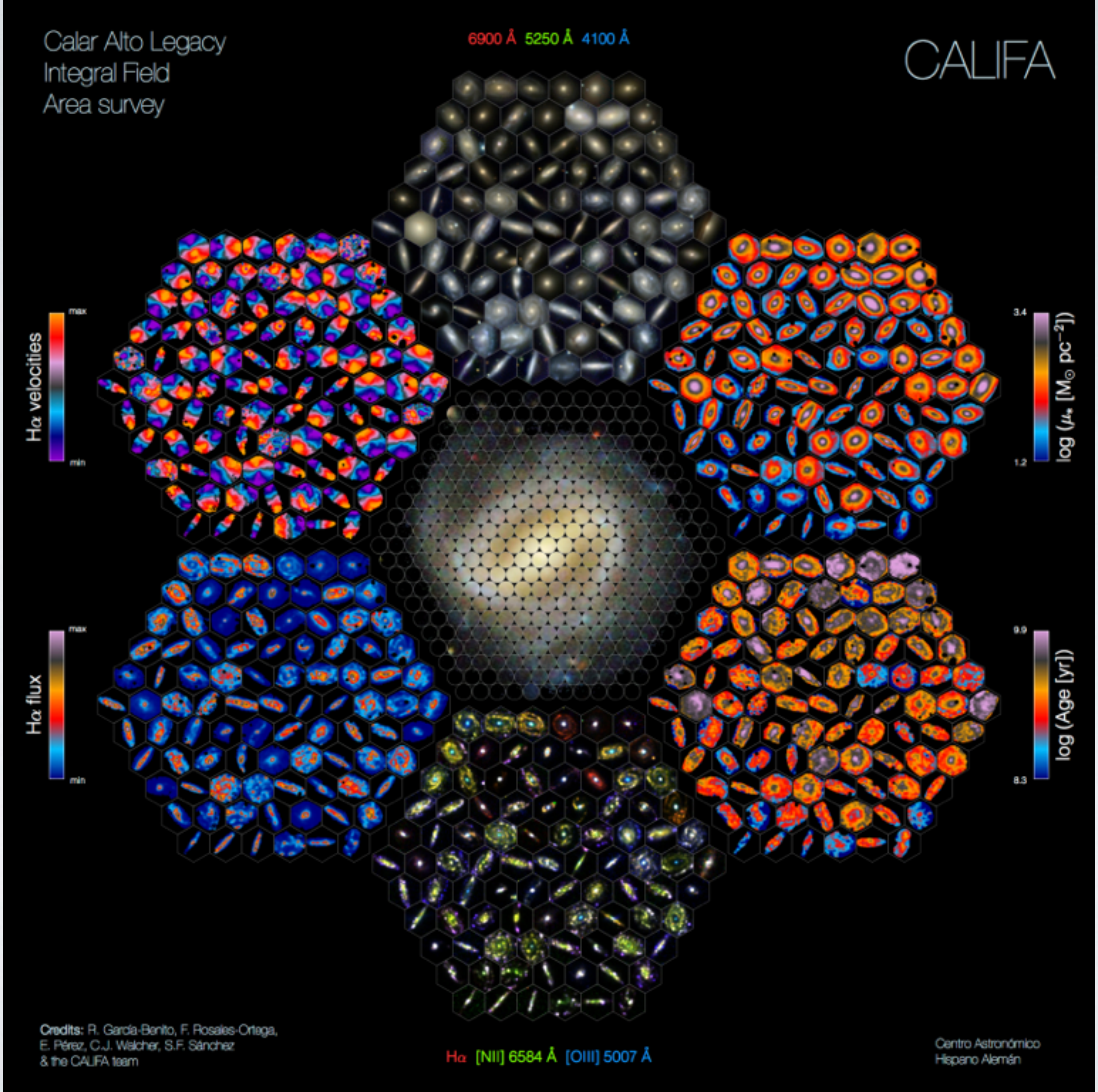
LET'S GET SERIOUS…

DEVELOPMENTS: CALIFA

- CALIFA, the **Calar Alto Legacy Integral Field Area survey** (Sánchez et al. 2012, DR2 w/200 galaxies available - García-Benito+2014)
  - **spatially resolved spectroscopic information** of a *diameter selected sample* of ~**600** galaxies in the *Local Universe* (0.005 < z < 0.03).
  - 2D maps of
    - **stellar populations**: ages and metallicities
    - **ionized gas**: distribution, excitation mechanism and chemical abundances
    - **kinematic** properties, both from stellar and ionized gas components.
  - PPAK integral field unit (IFU), with a hexagonal field-of-view of ~1.3 sqarcmin.
  - 3700 to 7000 Å, two overlapping setups (V500 and V1200), R~850 and R~1650.

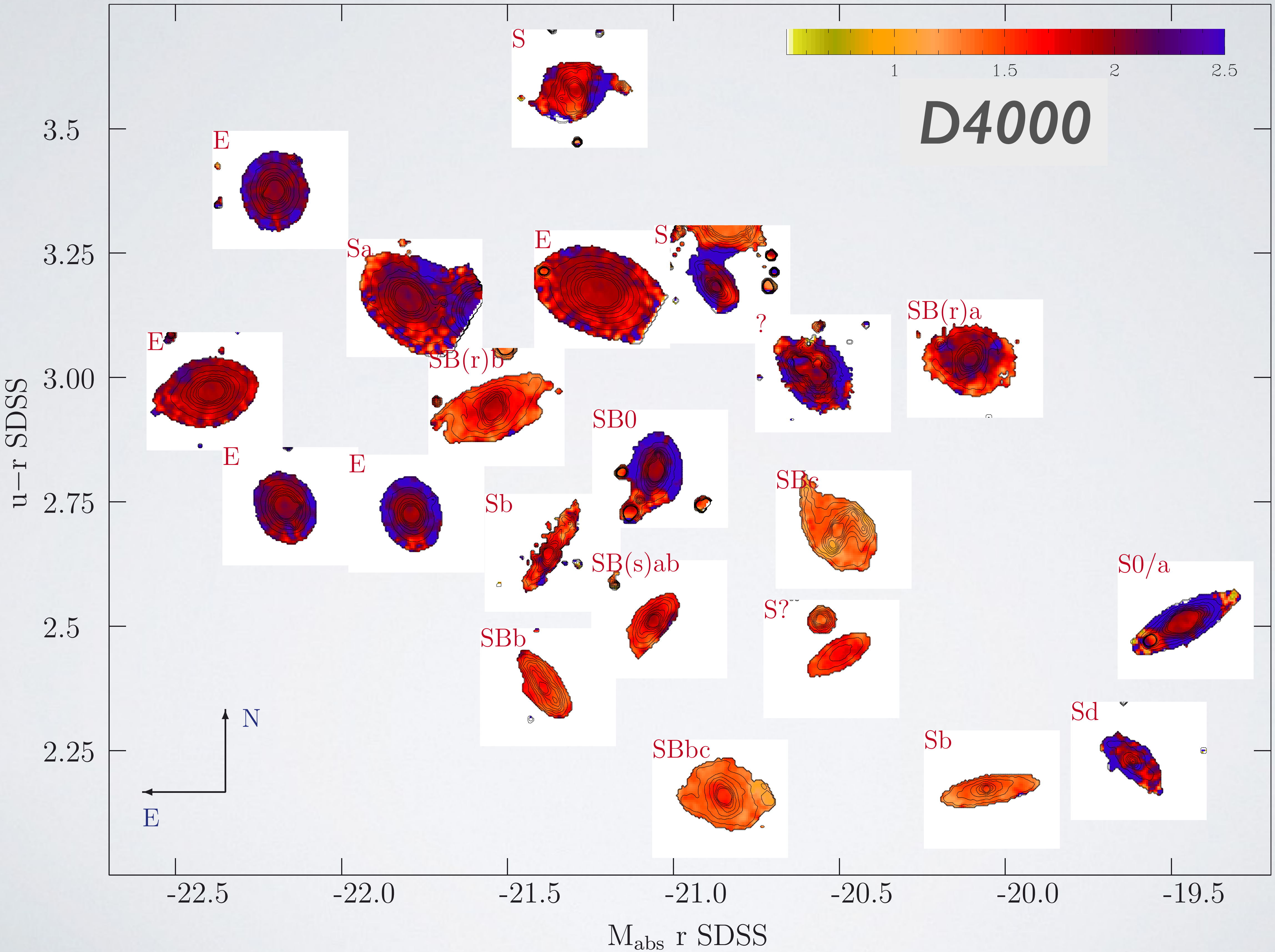






Calar Alto Legacy
Integral Field
Area survey
6900 Å 5250 Å 4100 Å
CALIFA
Hα velocities
max
min
log (μ* [M⊙ pc⁻²])
3.4
1.2
Hα flux
max
min
log (Age [yr])
9.9
8.3
Credits: R. García-Benito, F. Rosales-Ortega,
E. Pérez, C.J. Walcher, S.F. Sánchez
& the CALIFA team
Hα [NII] 6584 Å [OIII] 5007 Å
Centro Astronómico
Hispano Alemán

DEVELOPMENTS: CALIFA



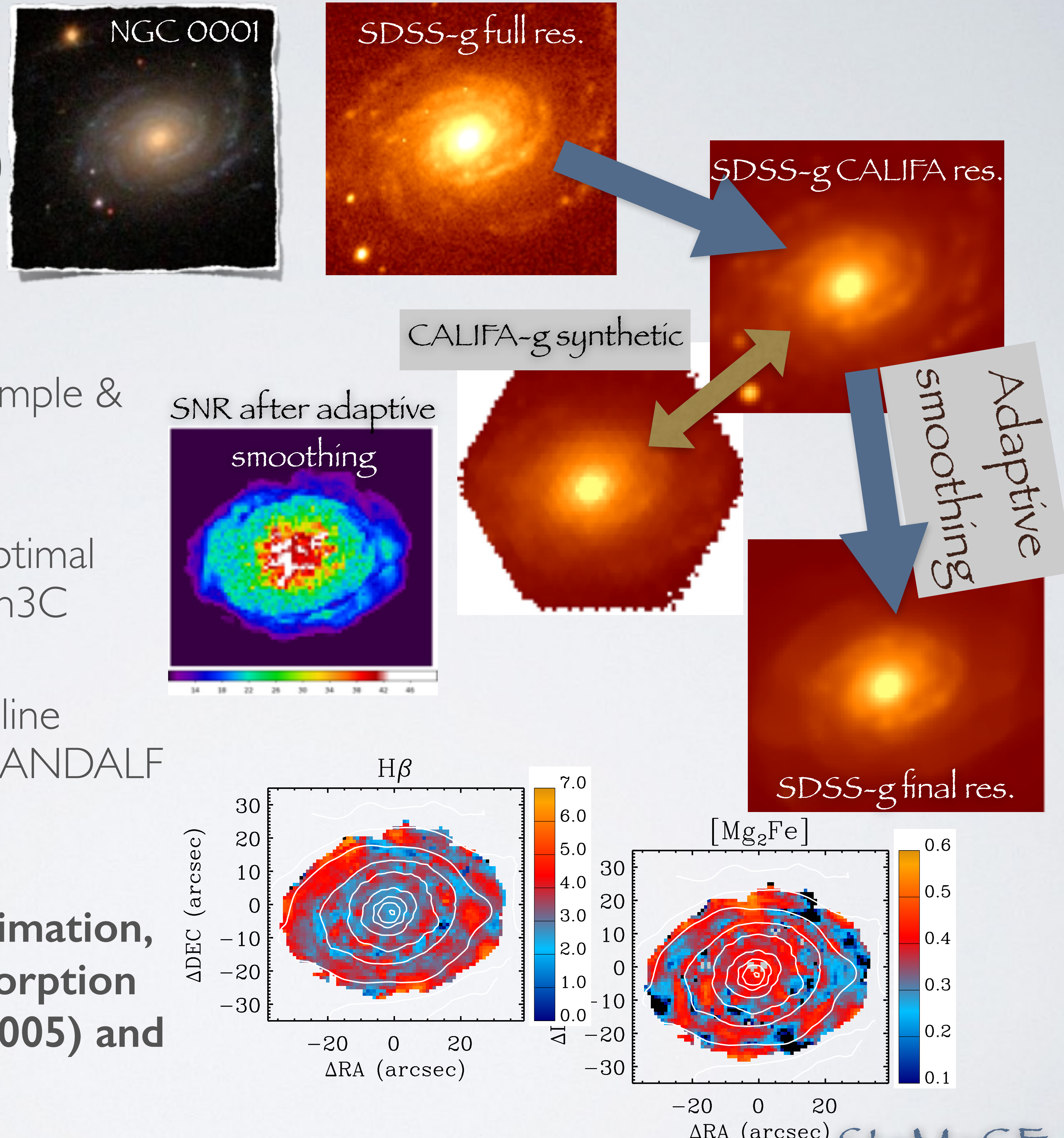
DEVELOPMENTS: CALIFA

- Join resolved photometry gi[H] (SDSS, [UKIDSS]) and spectroscopy (CALIFA)
  - develop matched adaptive smoothing in 3D
- New stellar mass determinations from **re-calibrated estimators**
- Compare with previous determinations and estimate bias as a function of different properties
  - stellar populations from spectral stellar absorption
  - resolved vs unresolved
- Stellar mass functions in the local Universe

CALIFA + SDSS IMAGING: FIRST RESULTS

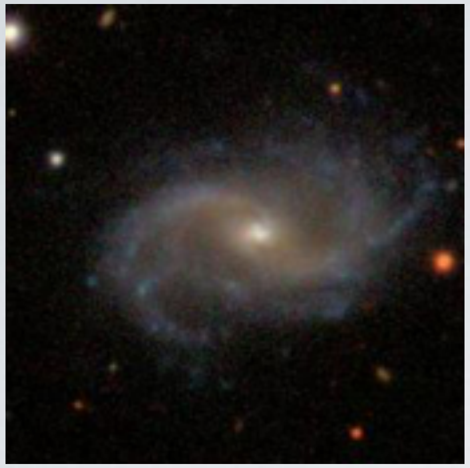
METHOD

- CALIFA-SDSS match: resample & PSF match
- Adaptive smoothing for optimal SNR>20 [10]/pix: azmooth3C
- Stellar continuum-nebular line decoupling (customized GANDALF +pPXF) spaxel by spaxel
- **Bayesian parameter estimation, based on 5 spectral absorption indices (Gallazzi et al. 2005) and color[s]**



SteMaGE

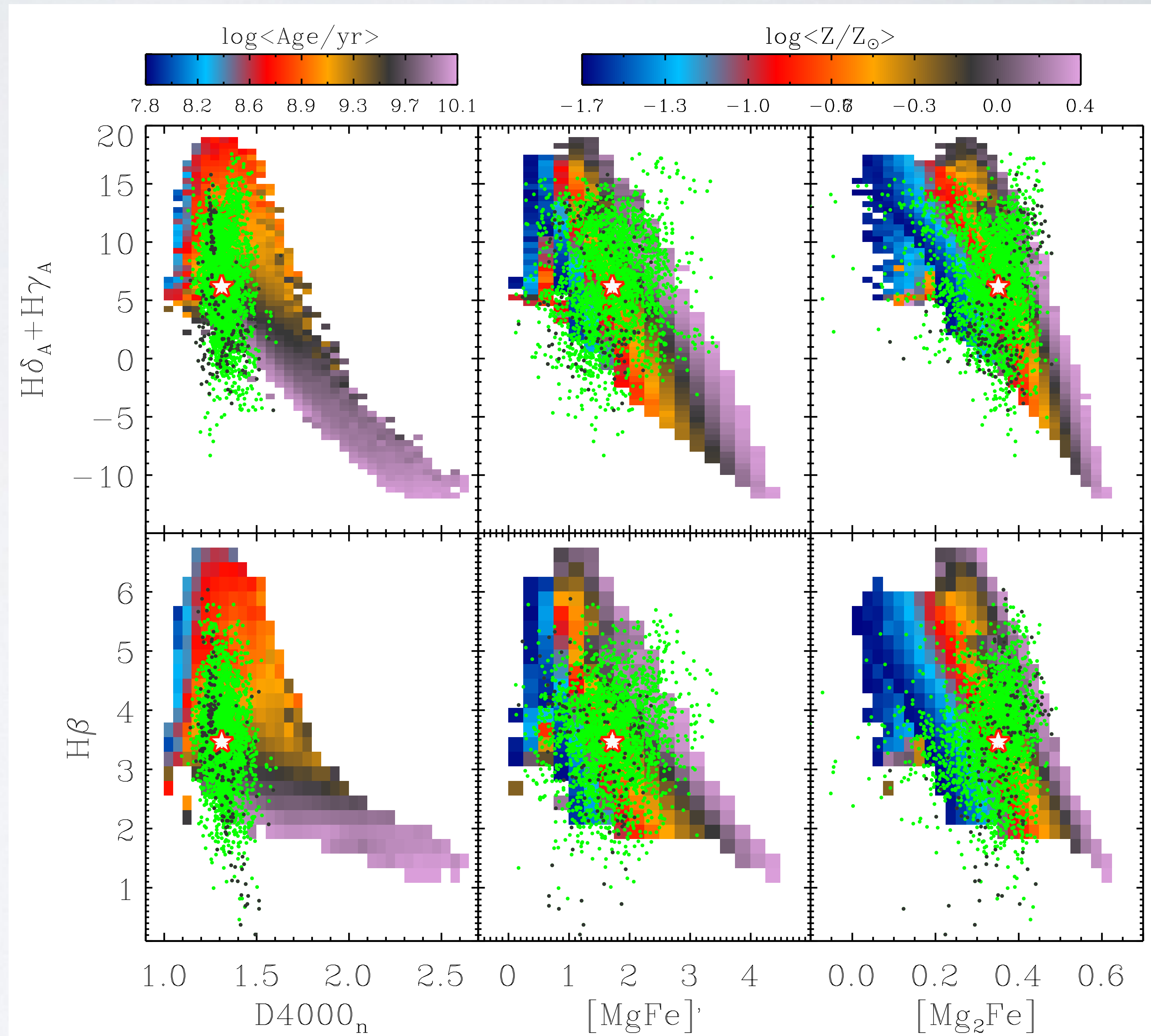
AGE- AND METALLICITY-SENSITIVE ABSORPTION FEATURES
SDSS 5-BAND PHOTOMETRY



One galaxy e.g.(NGC 7819):

- diversity of regions (each dot is a spaxel!), spread over a large extent of the index-index planes ⇒

  diversity of physical properties!
- compare with the integrated value (star)



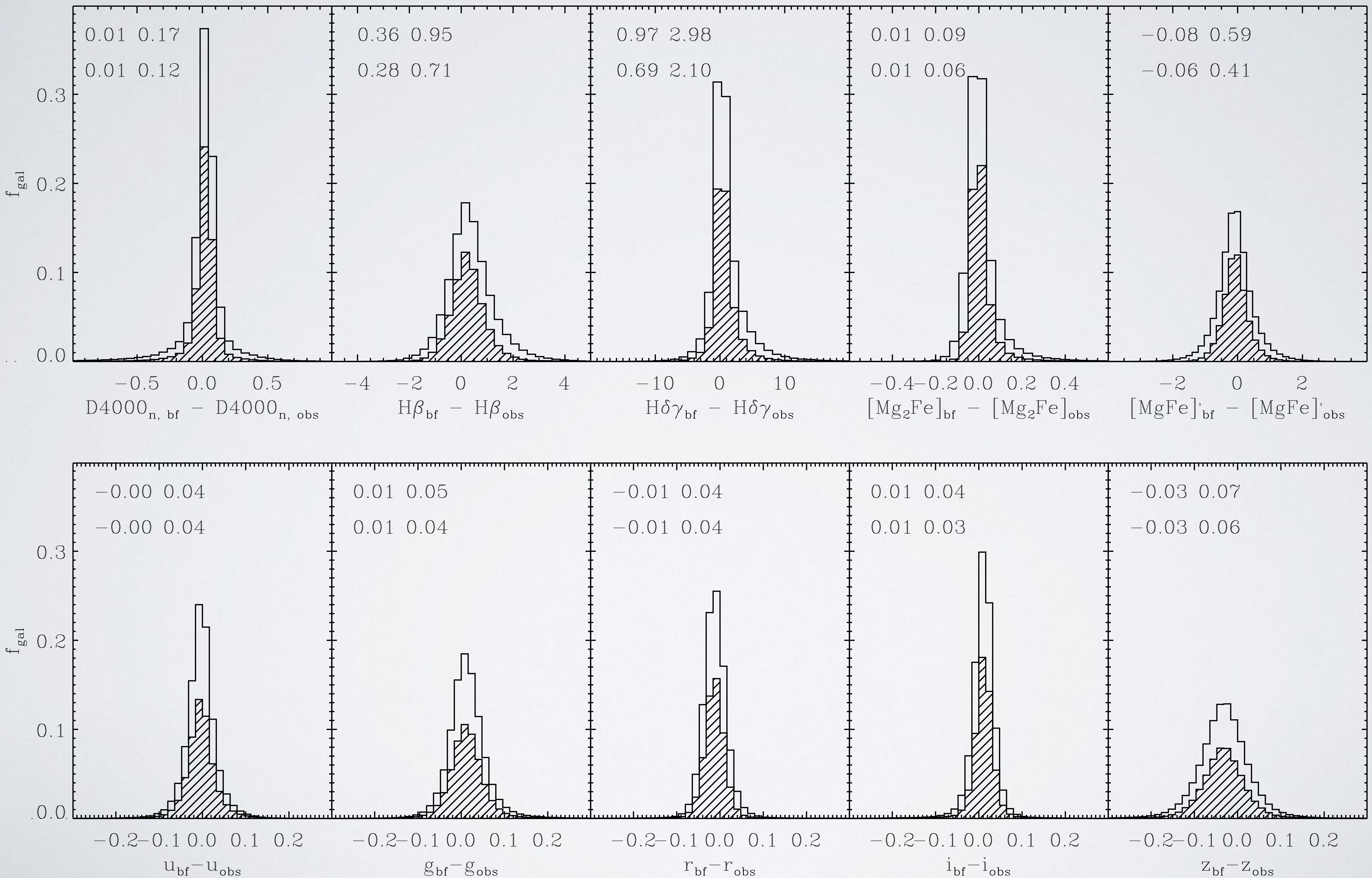
METHOD: BAYESIAN LIKELIHOOD MARGINALISATION

- Precomputed library of models with attached physical parameters (the unknowns in real galaxies) and synthetic observables
  - The density distribution of models in the space of physical parameters gives the **prior probability distribution**
- For each model we define the **likelihood function** (="probability of the data given a model") via comparison between its synthetic observable and real data observables (typically $P \propto \exp(-\chi^2)$)
- The **posterior probability distribution** (="probability of a model parameter given the data") is then proportional to "prior probability distribution" times the "likelihood function"
- Not all parameters are of interest (certainly not all simultaneously!) so one has to collapse the multi-dimensional space of physical parameters and retain only the interesting dimension(s), i.e. one has to **marginalise**
- Analyse the marginalised posterior probability **function**!
  - Quantiles provide **uncertainties**
- *Goal*: make likelihood dominate over prior, i.e. let data decide - high quality dataset and optimal diagnostics
- **Advantages** over best fit approach:
  - robust against **degeneracies**!
  - hard to estimate uncertainties in the frequentist approach

MODELS

- 150,000 with varying SFH, metallicity and dust (following Gallazzi+2005, daCunha+2008)
- Base SSP from revised BC03 (“CB12”): fixed some problems with returned mass fraction and minor “bugs”, improved treatment of (TP)AGB
  - Note: different from CB07 used in the SZ+2009 paper and Maraston(2005) especially for TP-AGB
- Dust prescription a la Charlot&Fall (ISM+birth cloud)

DO MODELS FIT?



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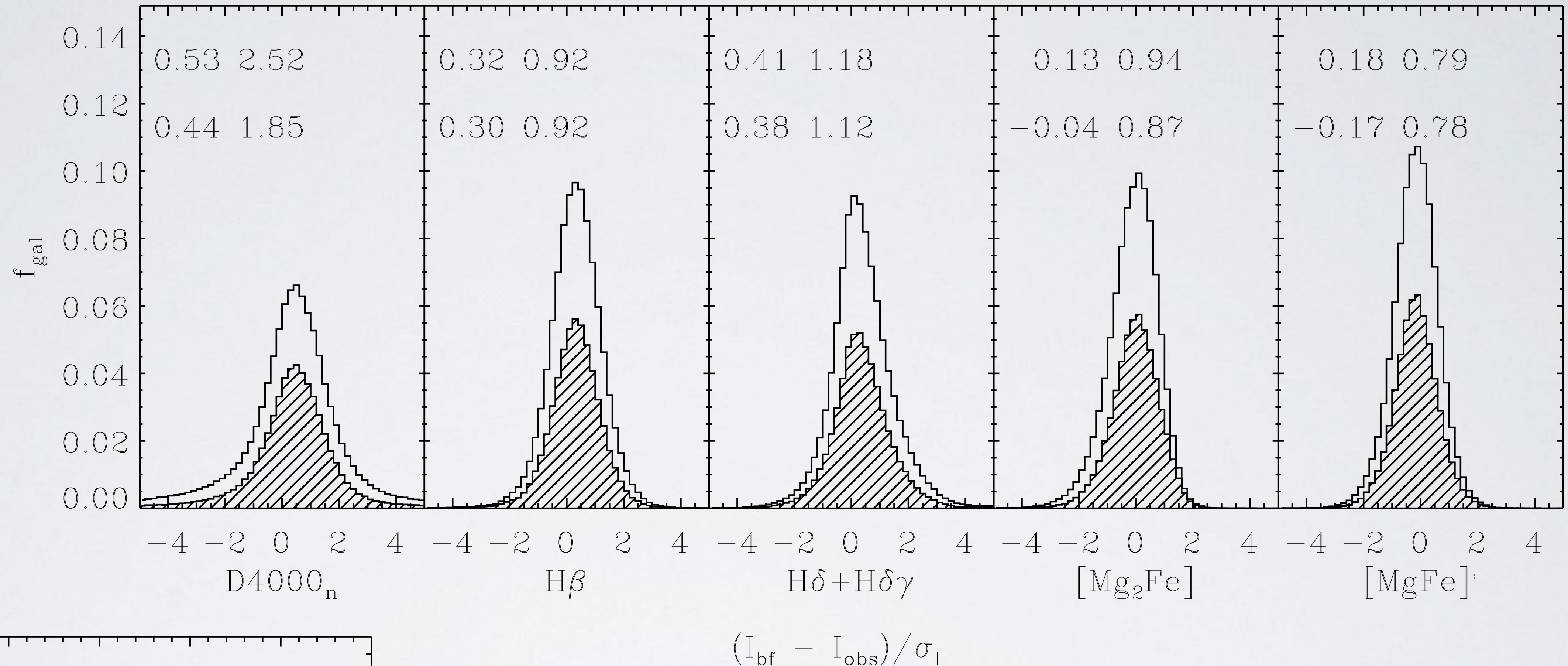
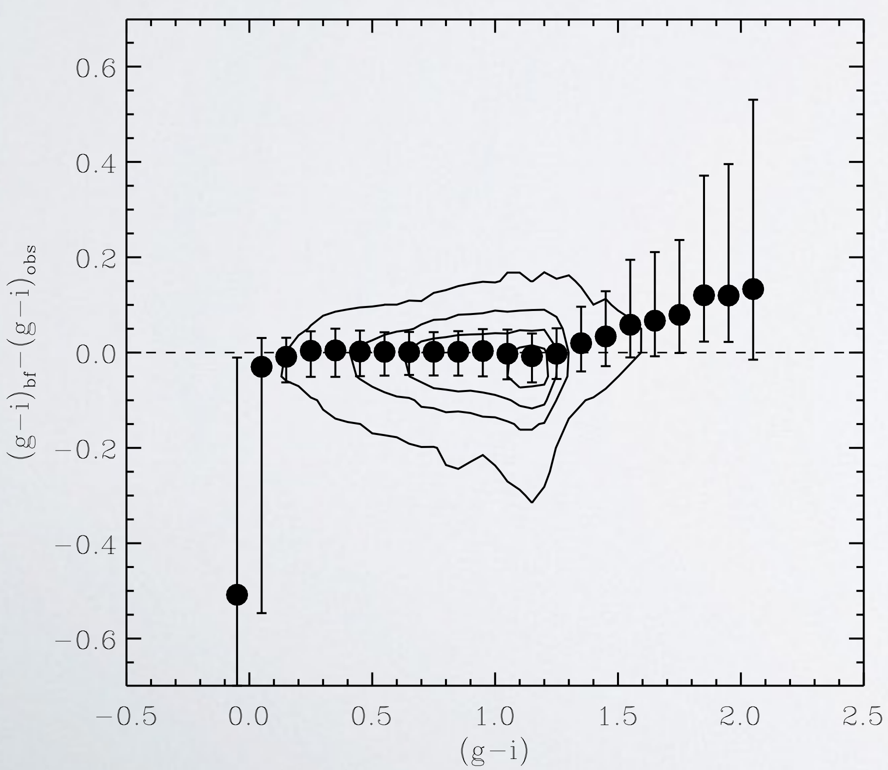
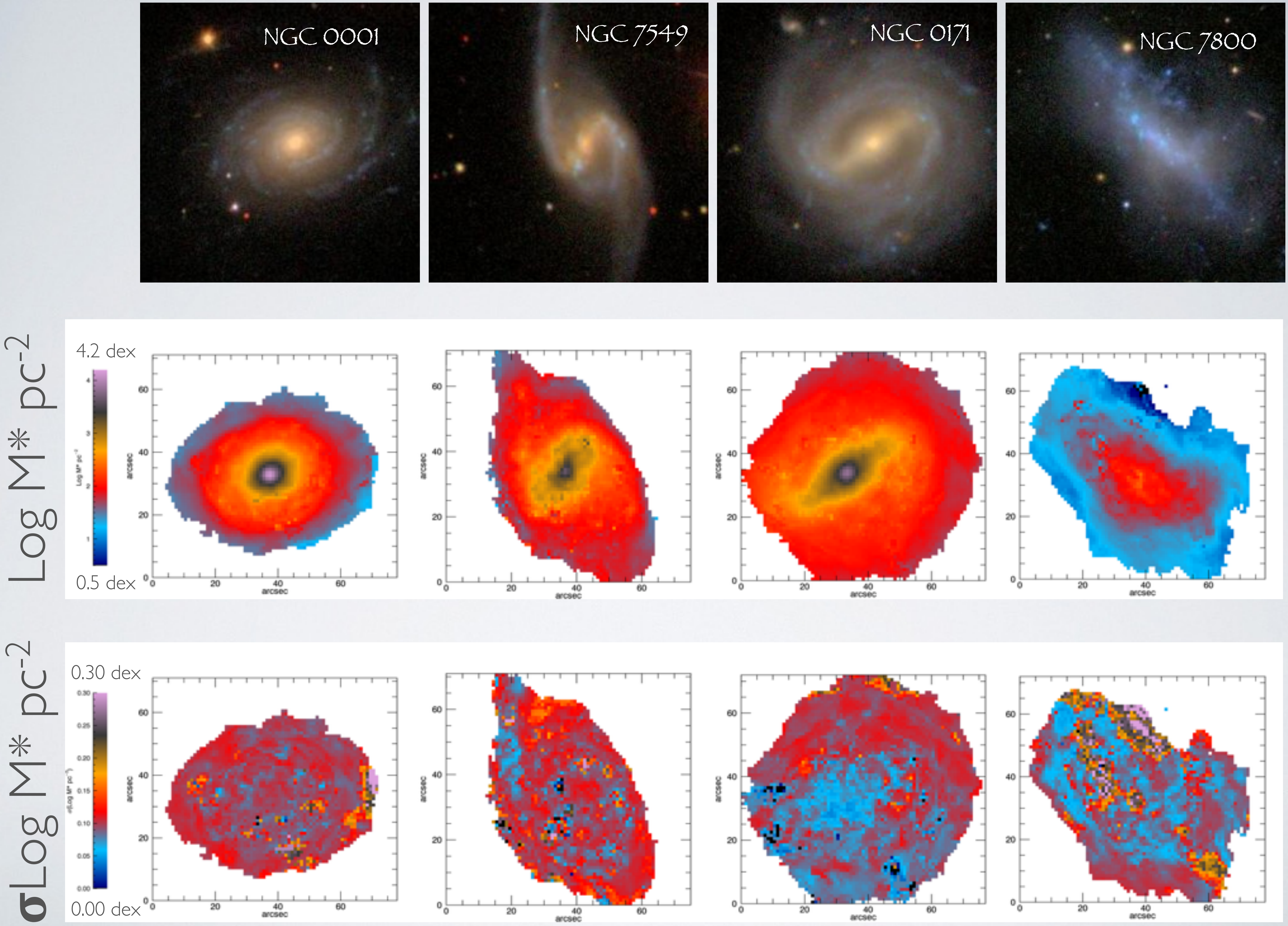




BACK TO MASSES…

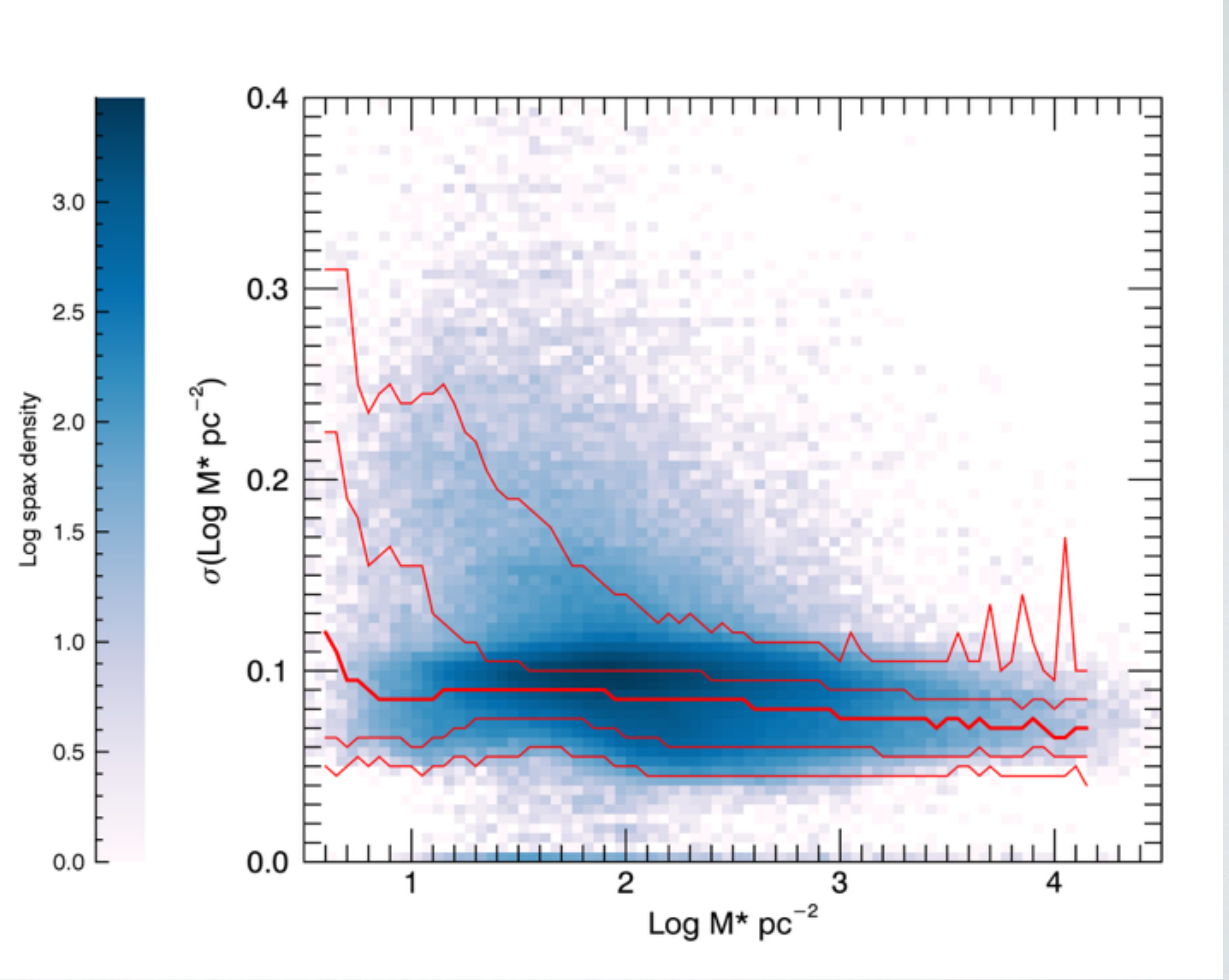
- Our physical parameter of interest is stellar mass (or the luminosity-normalized equivalent, i.e. M/L)
- Observables are 5 spectral indexes and 5 SDSS photometric fluxes
- Posterior:
    - median is the fiducial estimate
    - 16-84% interquantile half-range gives the uncertainty



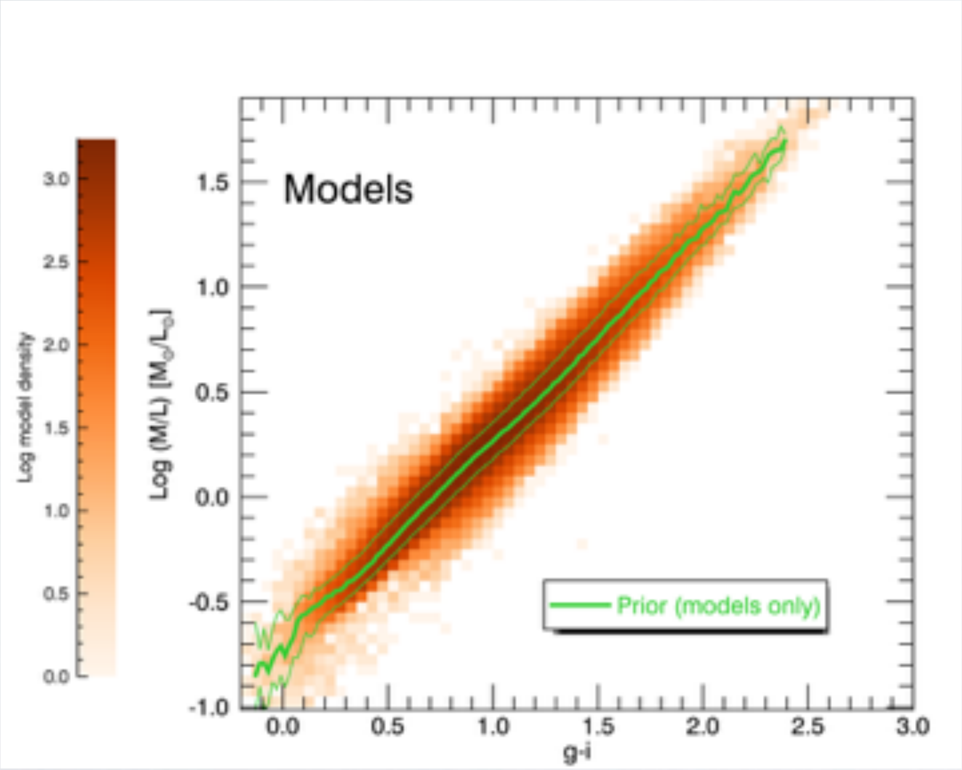
NGC 0001
NGC 7549
NGC 0171
NGC 7800
Log M* pc-2
4.2 dex
0.5 dex
σLog M* pc-2
0.30 dex
0.00 dex
arcsec

IS THE METHOD PRECISE?

- Error on mass <~0.1 dex (25%) for most spaxels
- 84% of spaxels have <0.1 dex at >50 M_{Sun} pc^{-2}
- Approx a factor 2 better than colors alone in percentage



WHAT'S NEW? ACCURACY!



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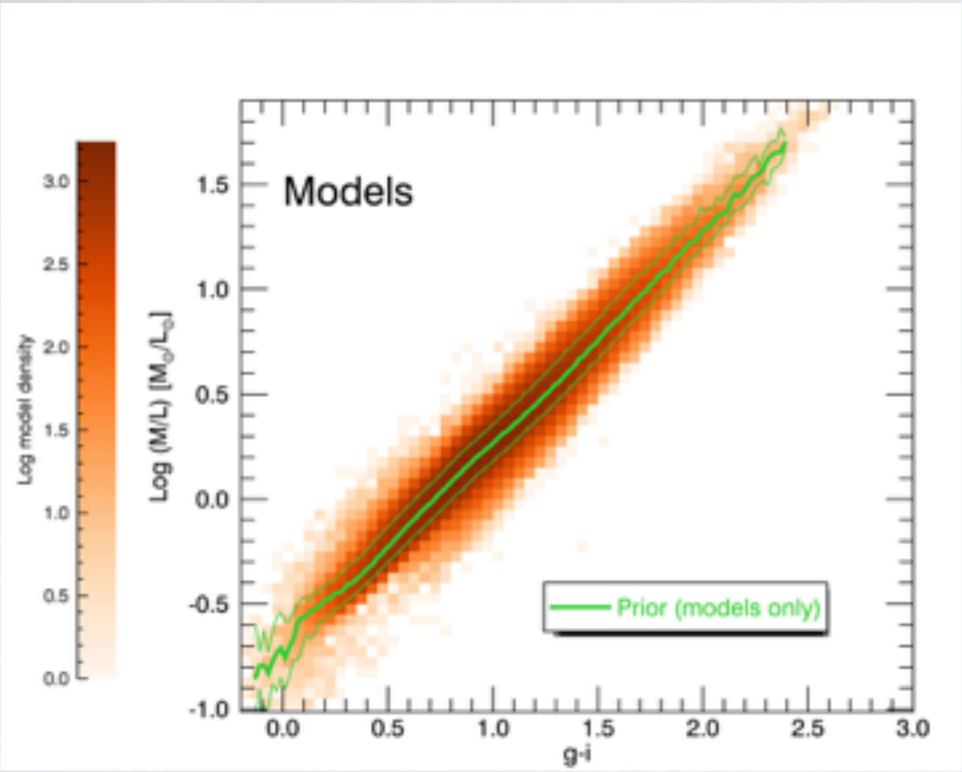

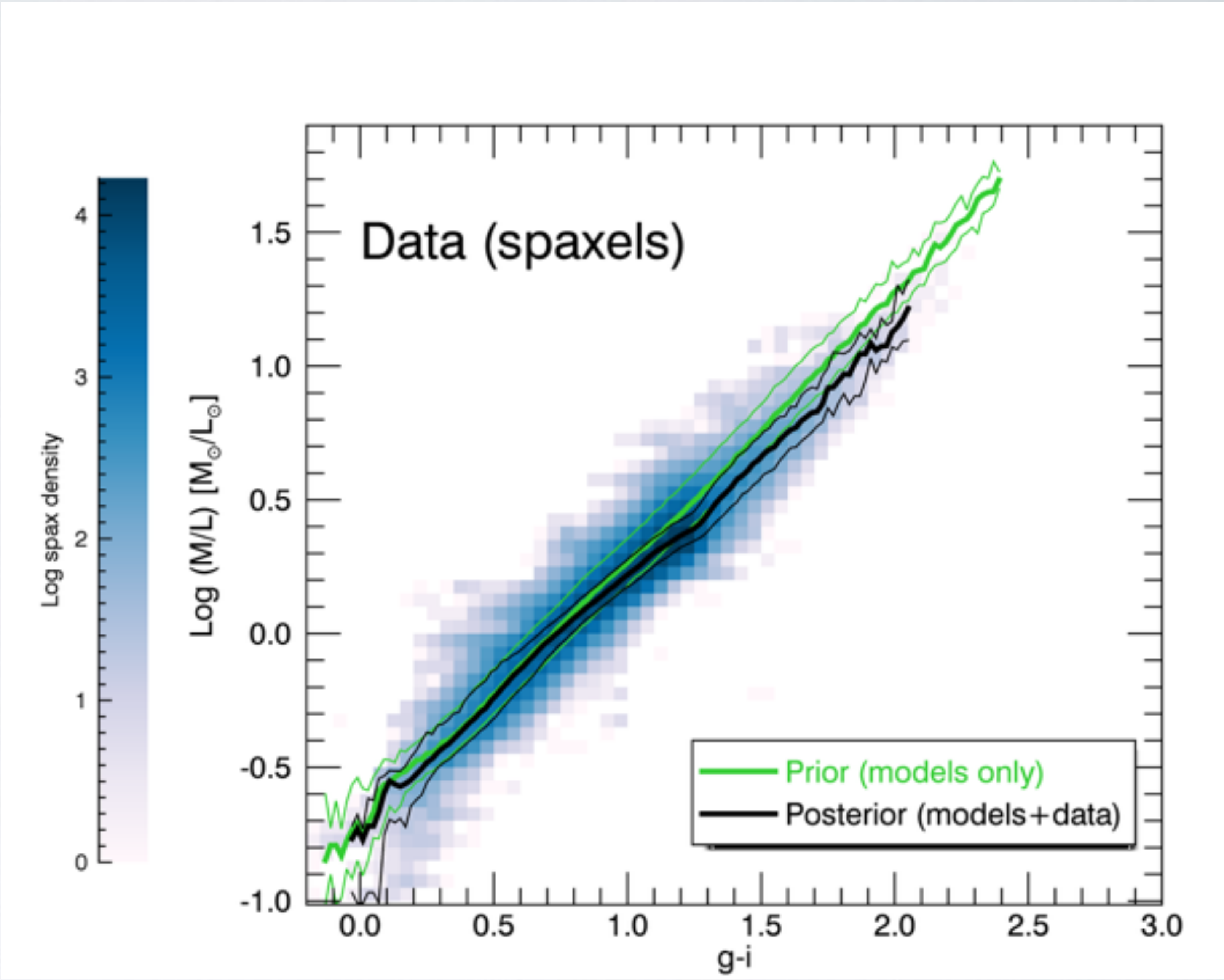

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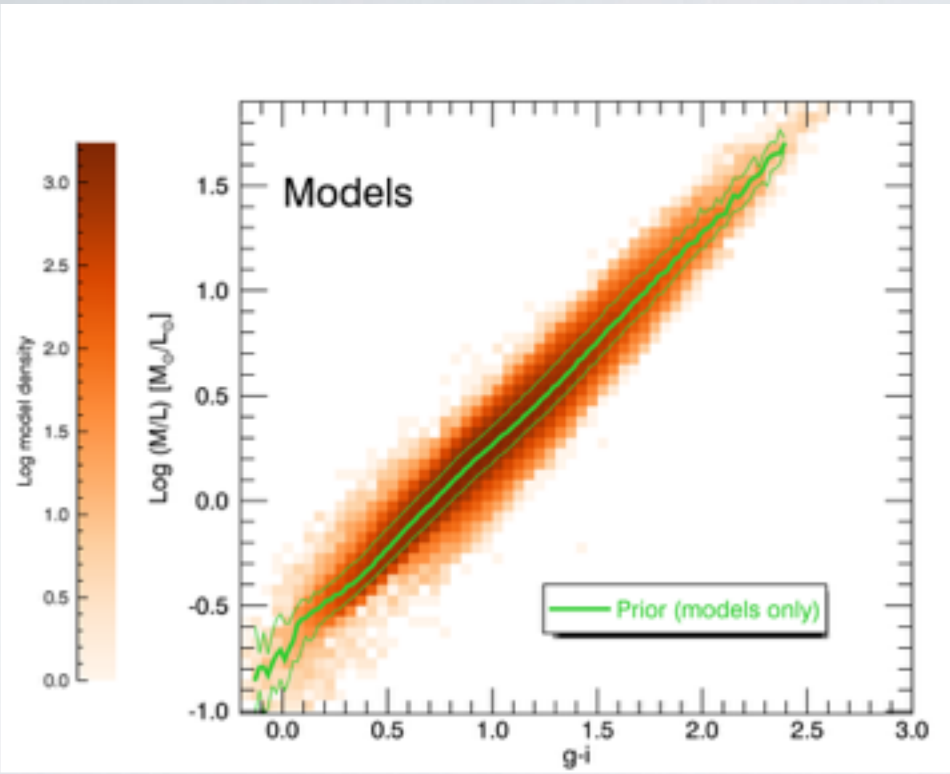

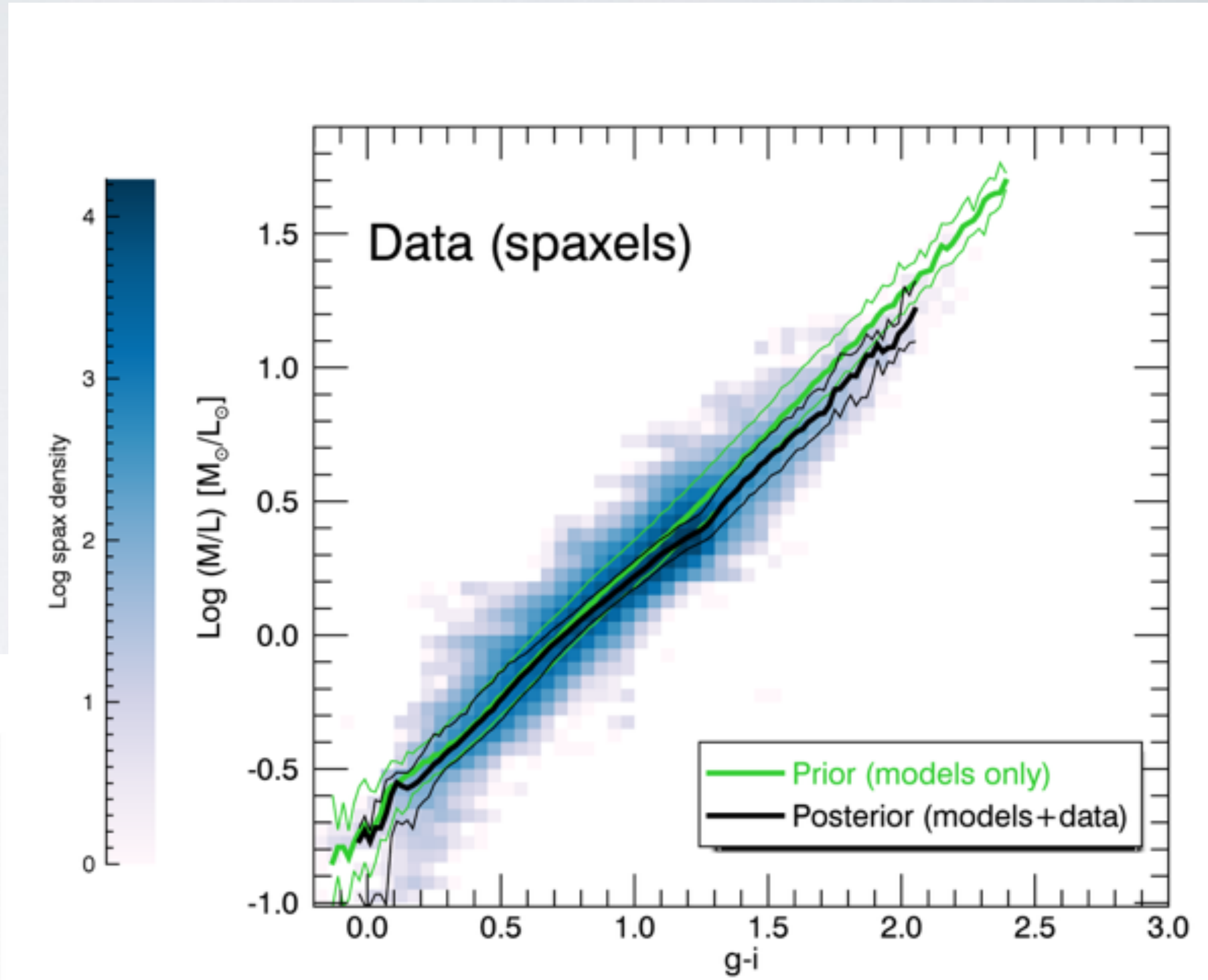

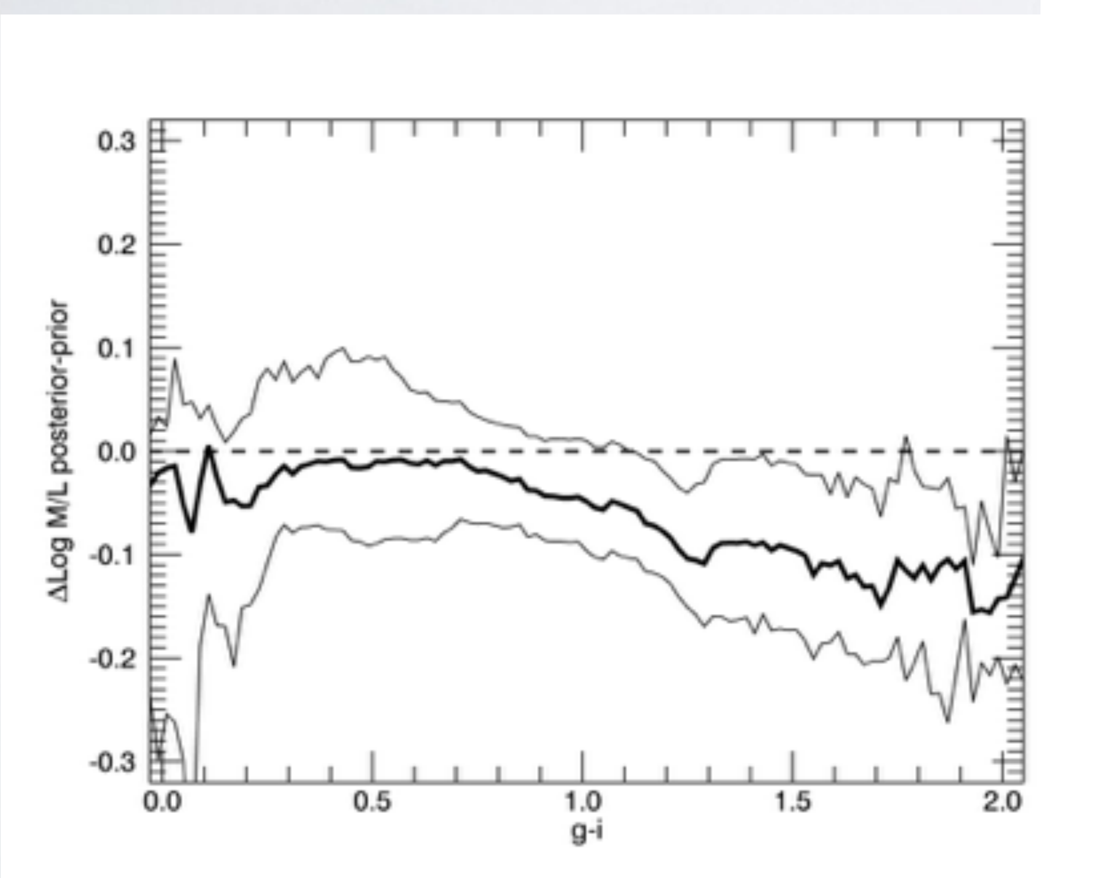

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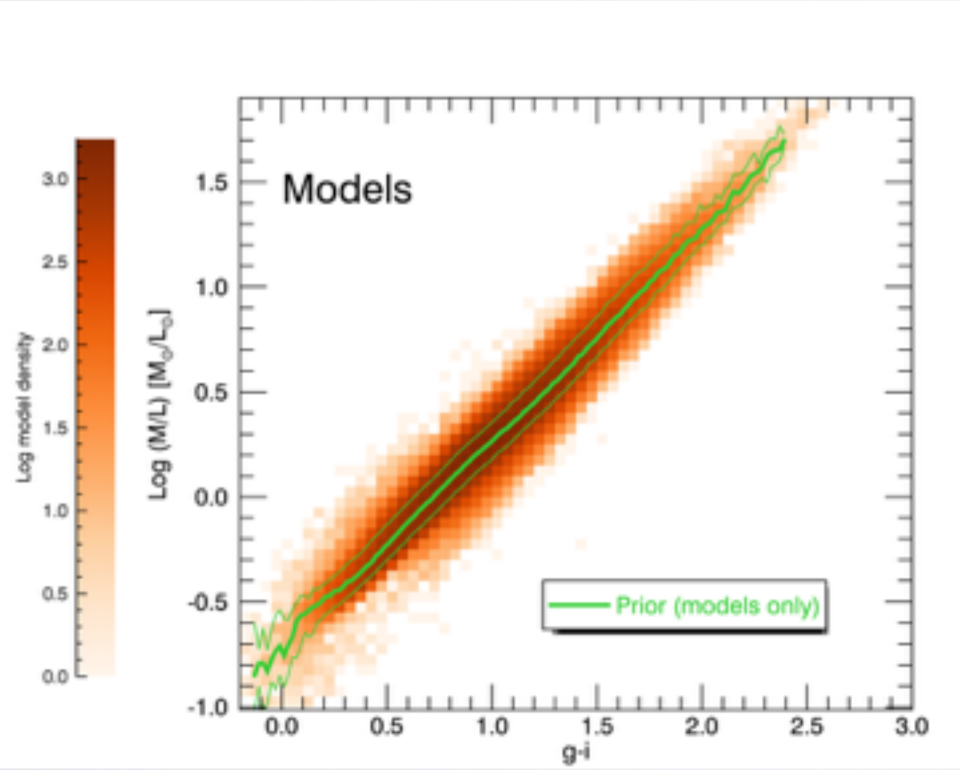
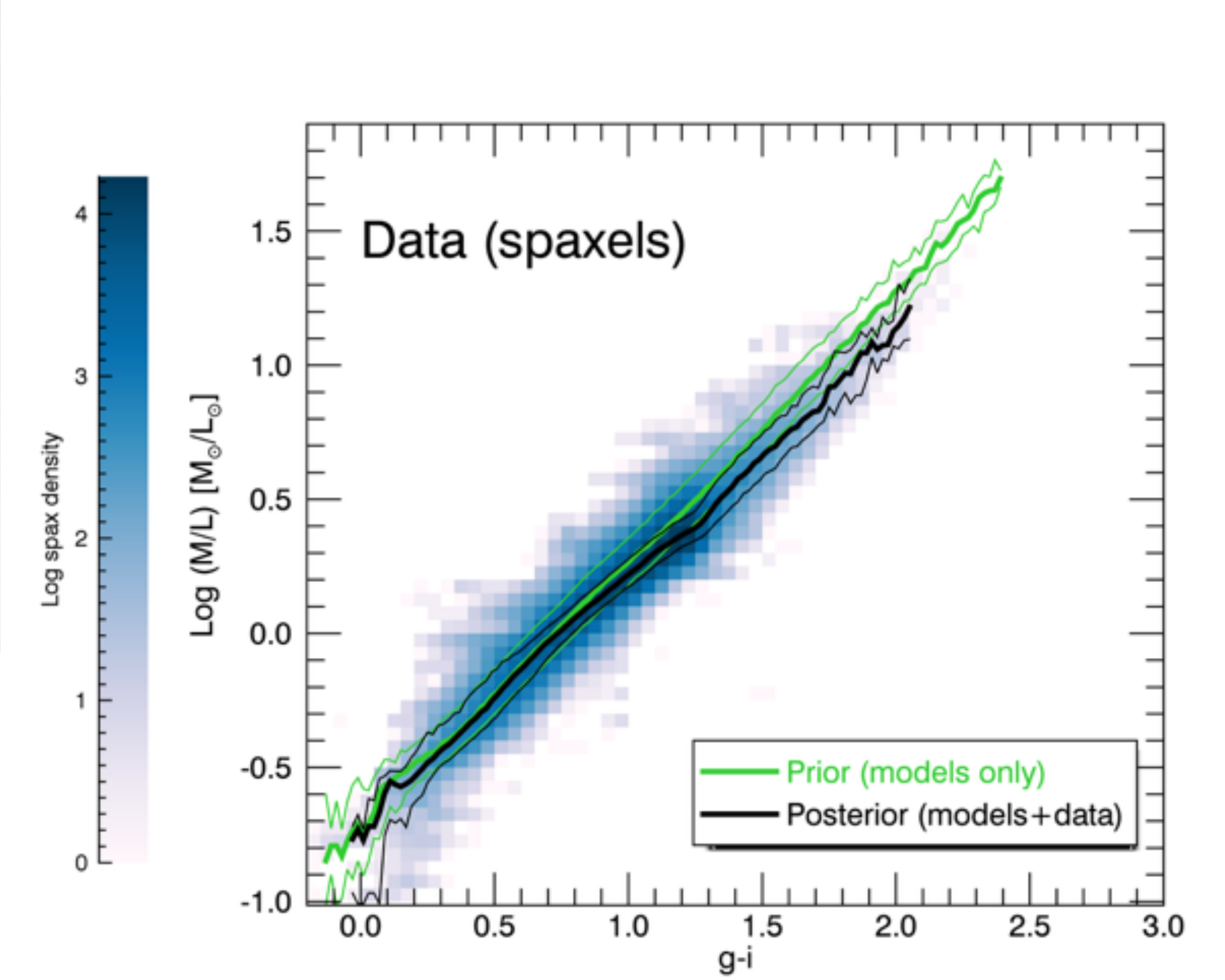
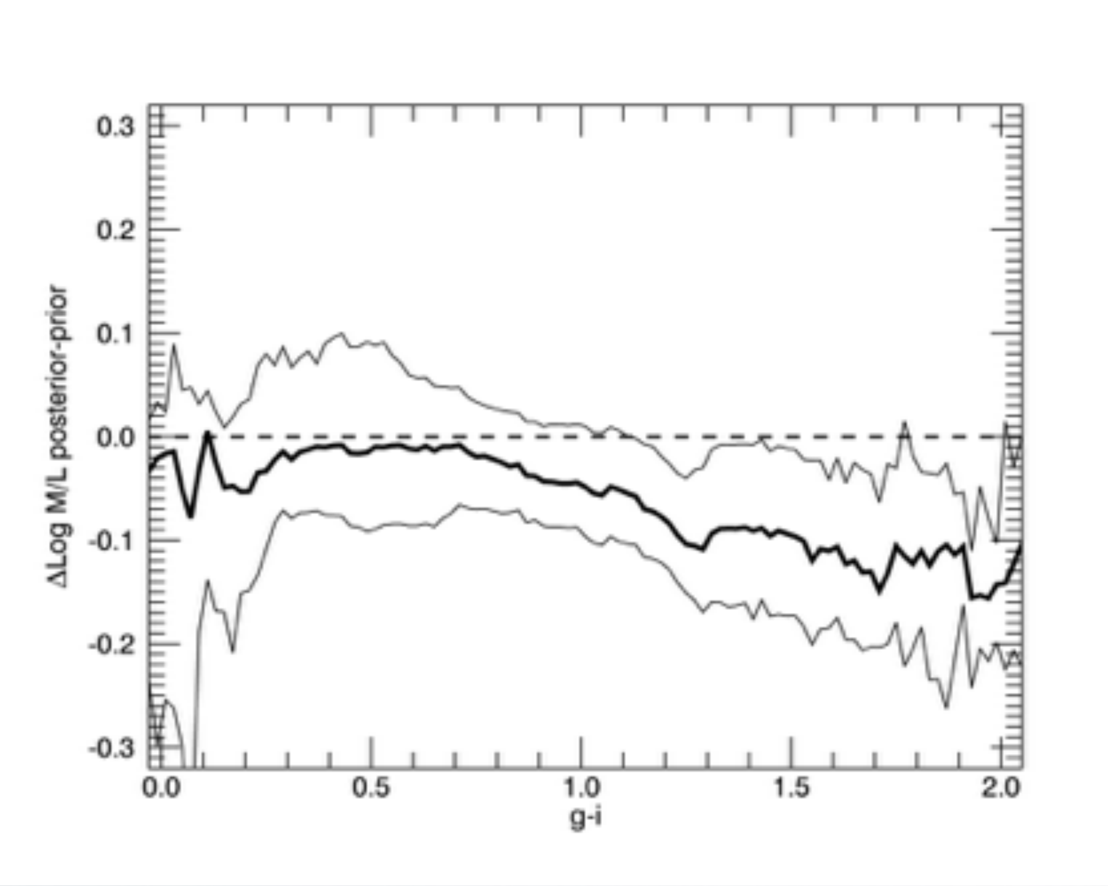
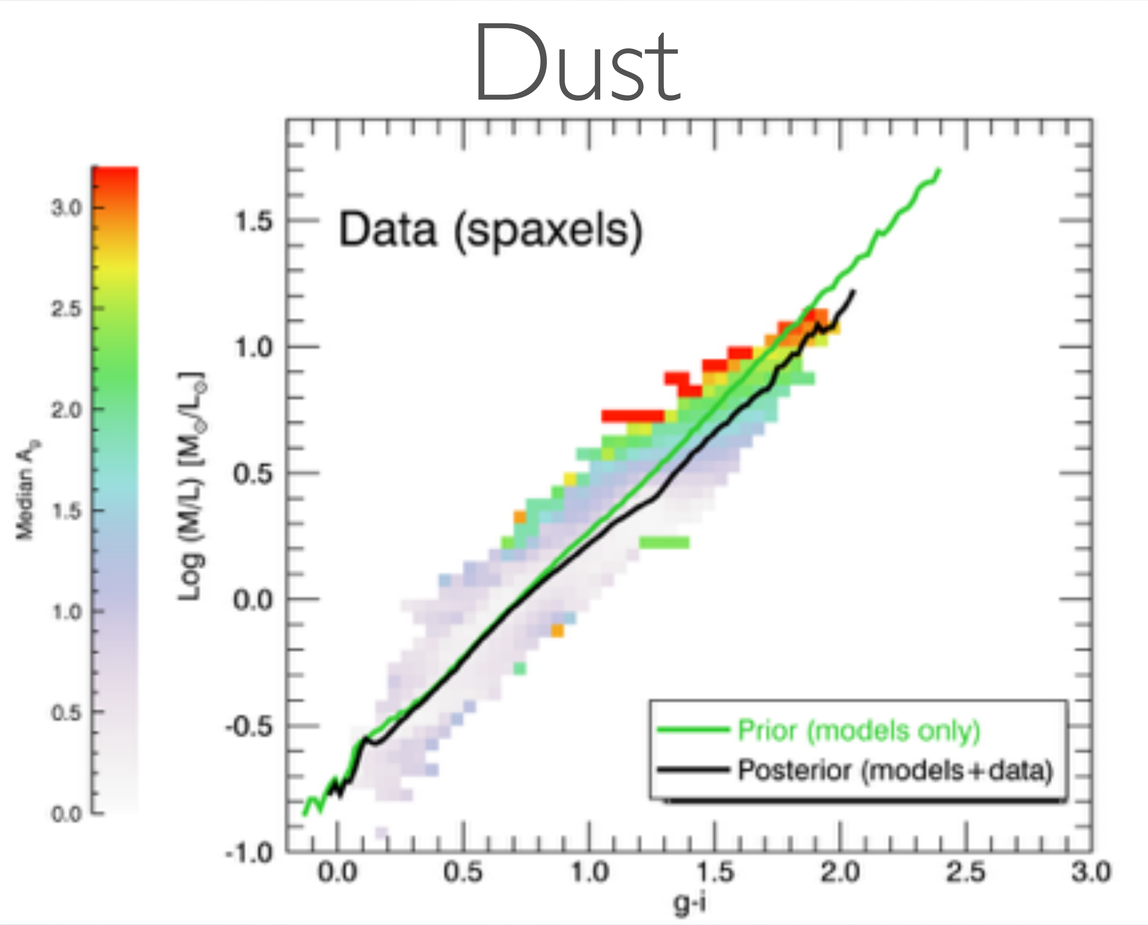


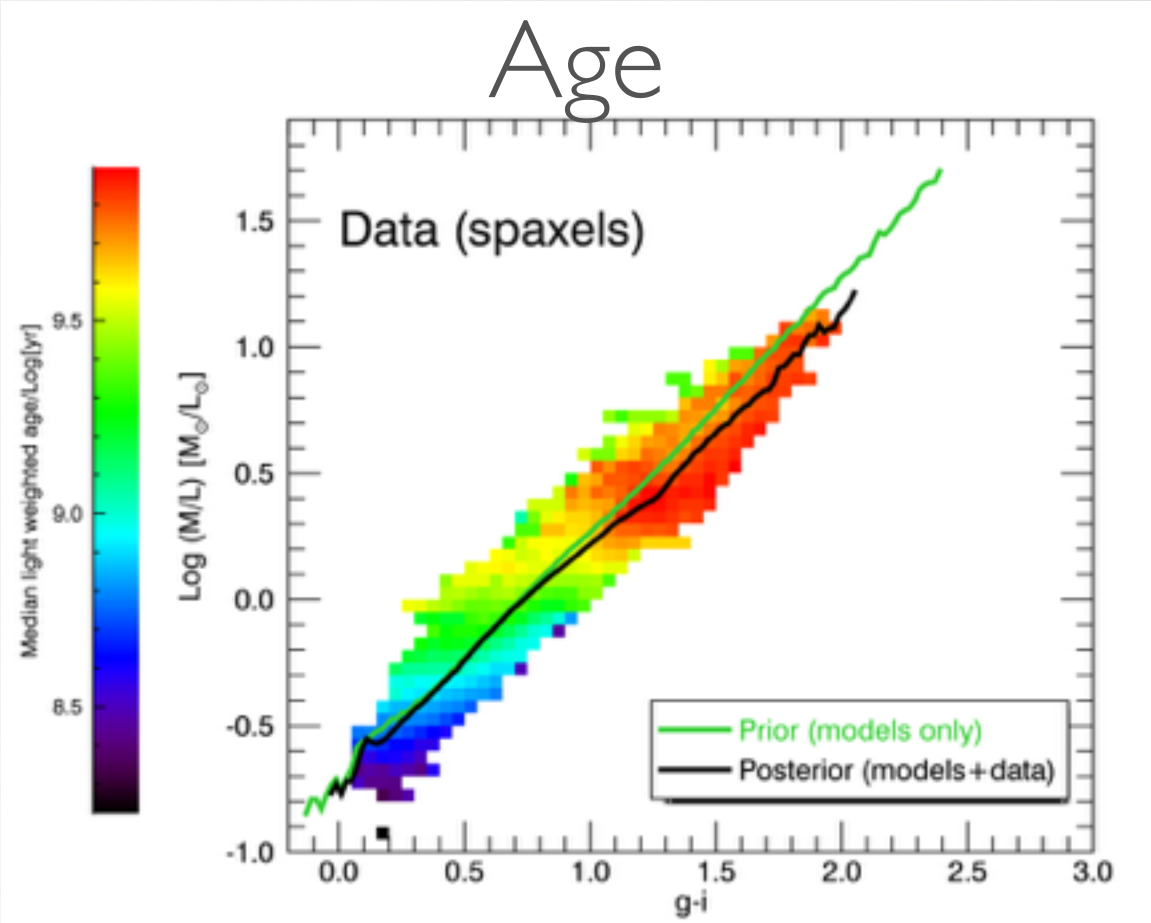




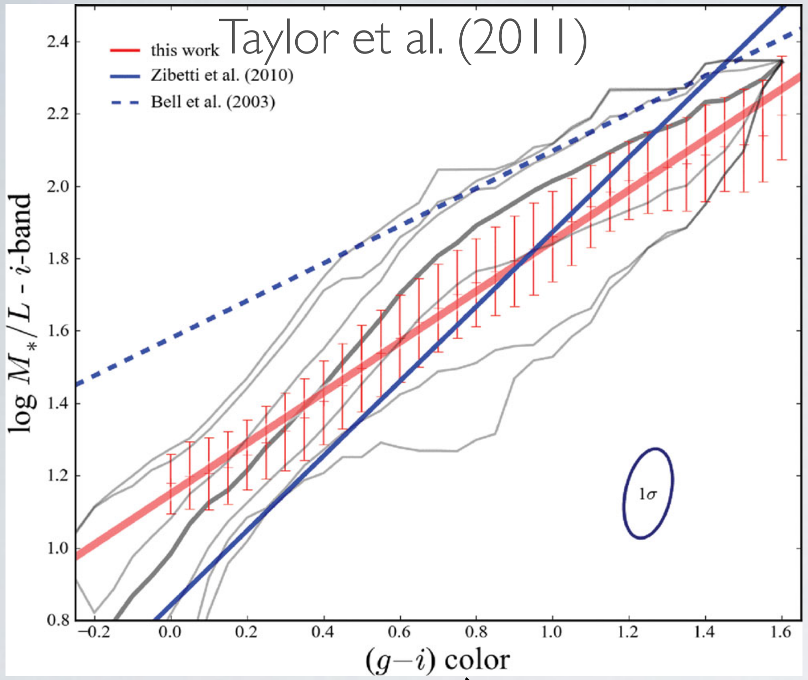
This is exactly what we had in mind when we talked about RECALIBRATION

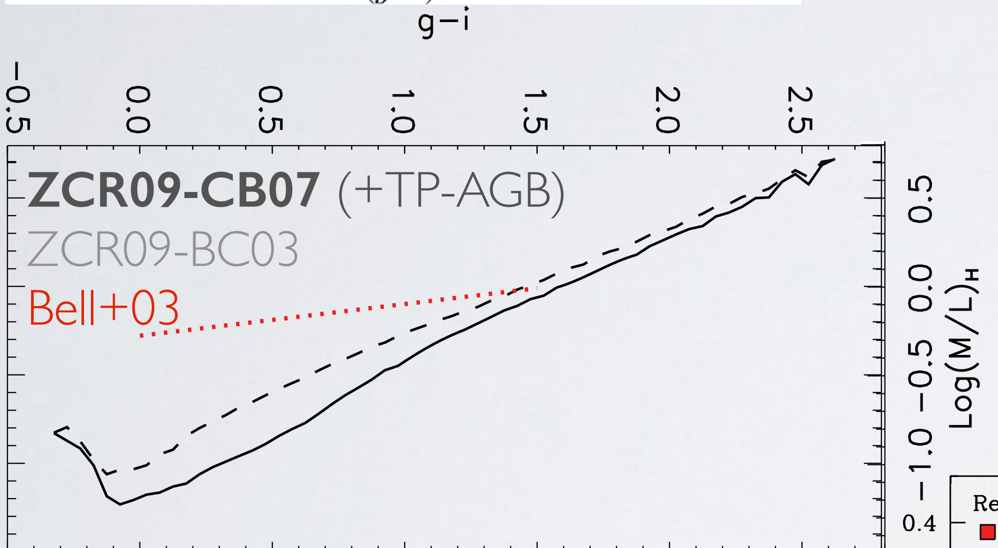
WHAT'S WRONG WITH COLORS?





- The effects of population ageing and dust reddening are not completely degenerate in M/L and color
- Only spectroscopy can help disentangle in *individual* regions, but a re-calibrated color-M/L relation can work *statistically*

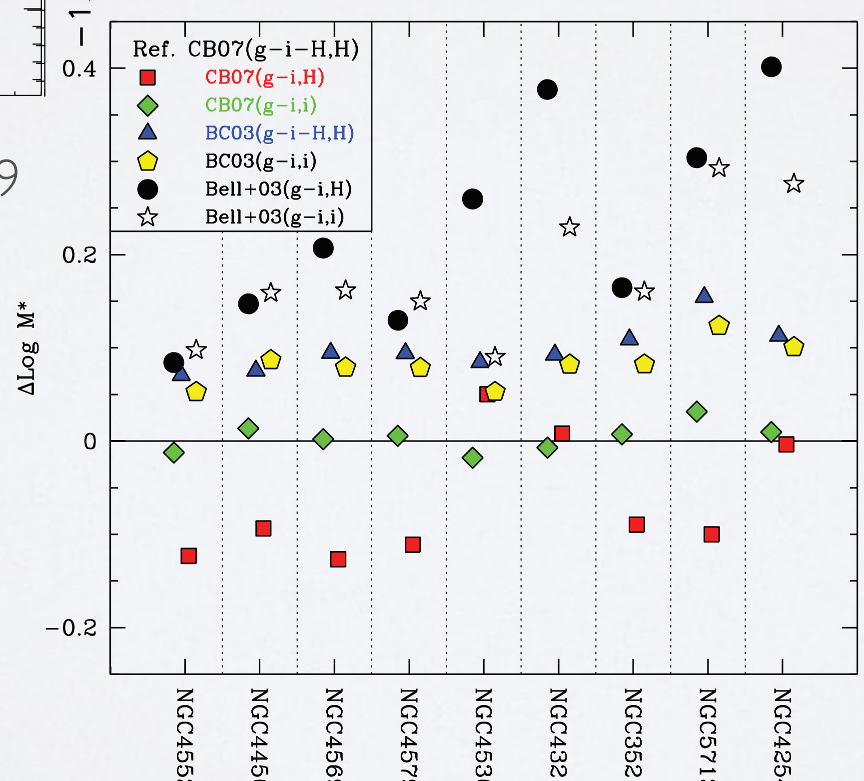


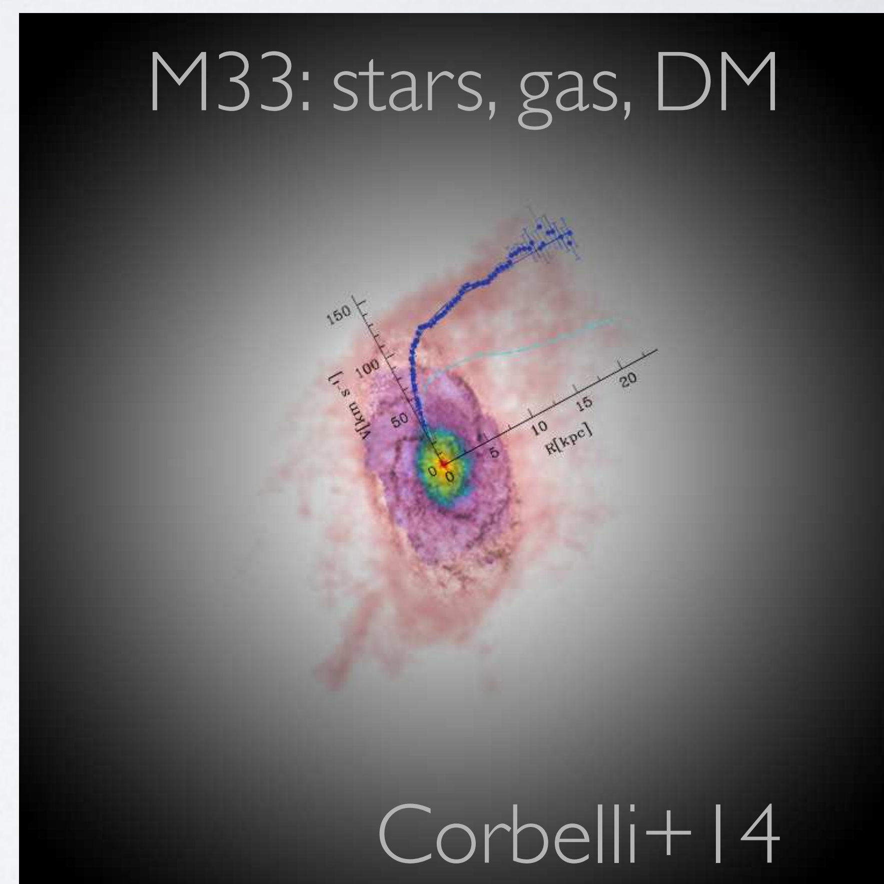


ZCR09

BIAS BIAS BIAS

- **Choice of SFH** is crucial: old stars hide behind young ones
  - factor ~2 for blue galaxies
  - can this spectrophotometric analysis help out?
- **SPS models** (base SSP!) are crucial especially for some phases
- **Dust treatment** and effective attenuation curves (see Chevallard et al. 2013)
- **IMF** (!)

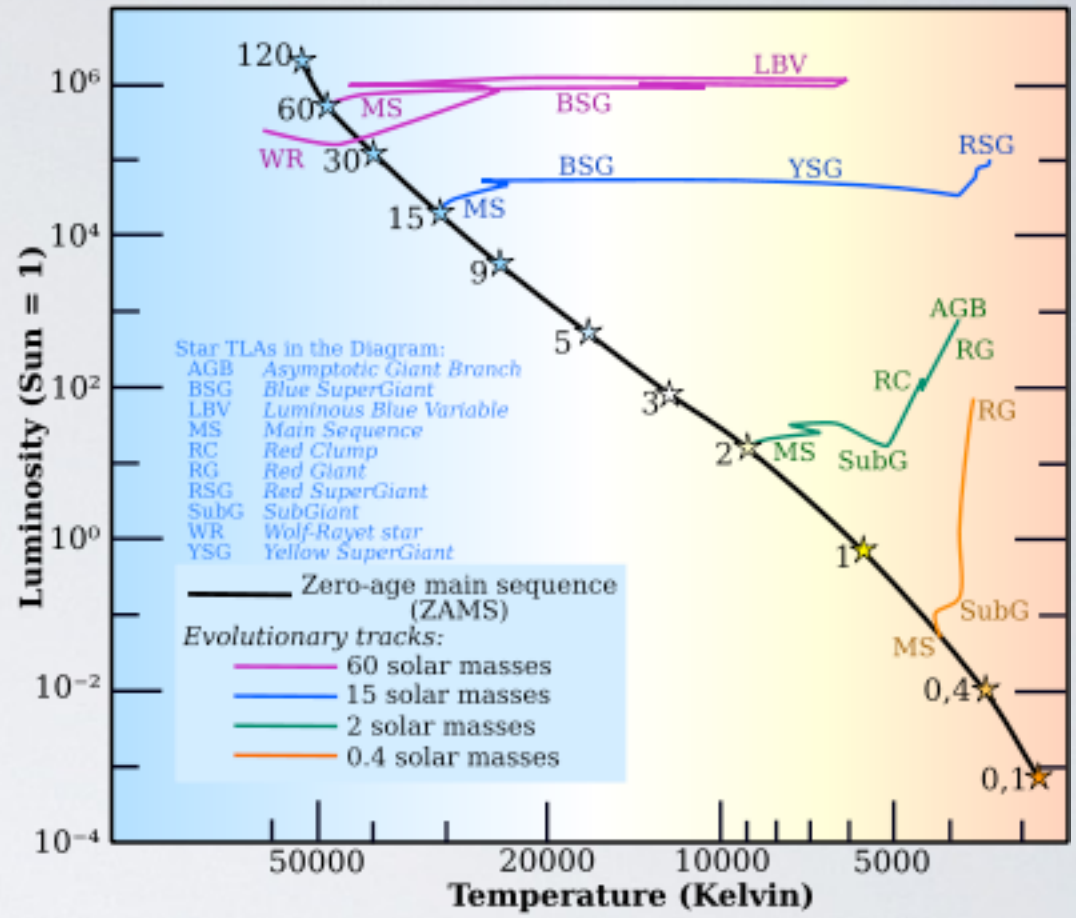


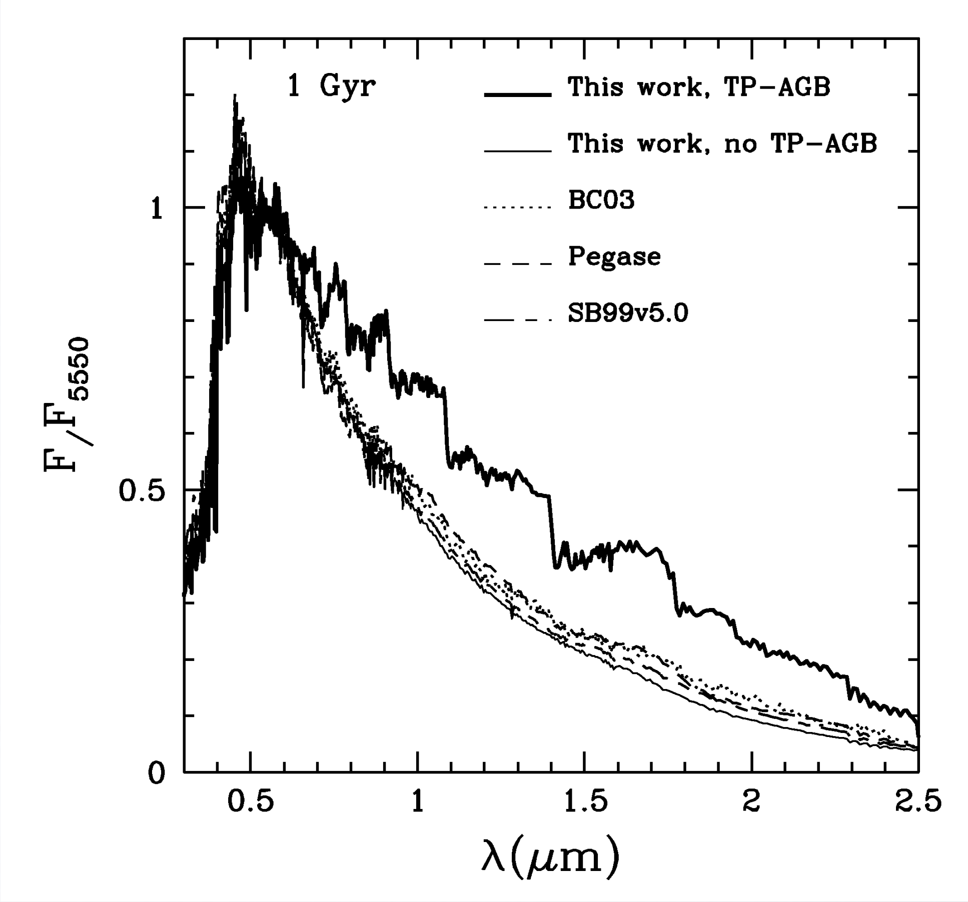


MY 5CENTS
ON THE TP-AGB DISPUTE

THE TP-AGB DISPUTE

- TP-AGB stars are already included in Bruzual&Charlot (2003)! Certainly not perfect, but still not missing...
- Maraston (2005) revised the recipe for TP-AGB stars based on the "fuel consumption theorem" and template spectra of O and C stars (Lançon&Mouchine, 2000)
  - calibration based on MCs globular clusters *photometry*
- Huge effect on colors, luminosity, M/L of 0.5-1.5 Gyr stellar populations, potentially affecting M* by factor >2
- Claim on high-z galaxies by Maraston et al. (2006), although based on exclusion of dust (!)





Maraston (2005)

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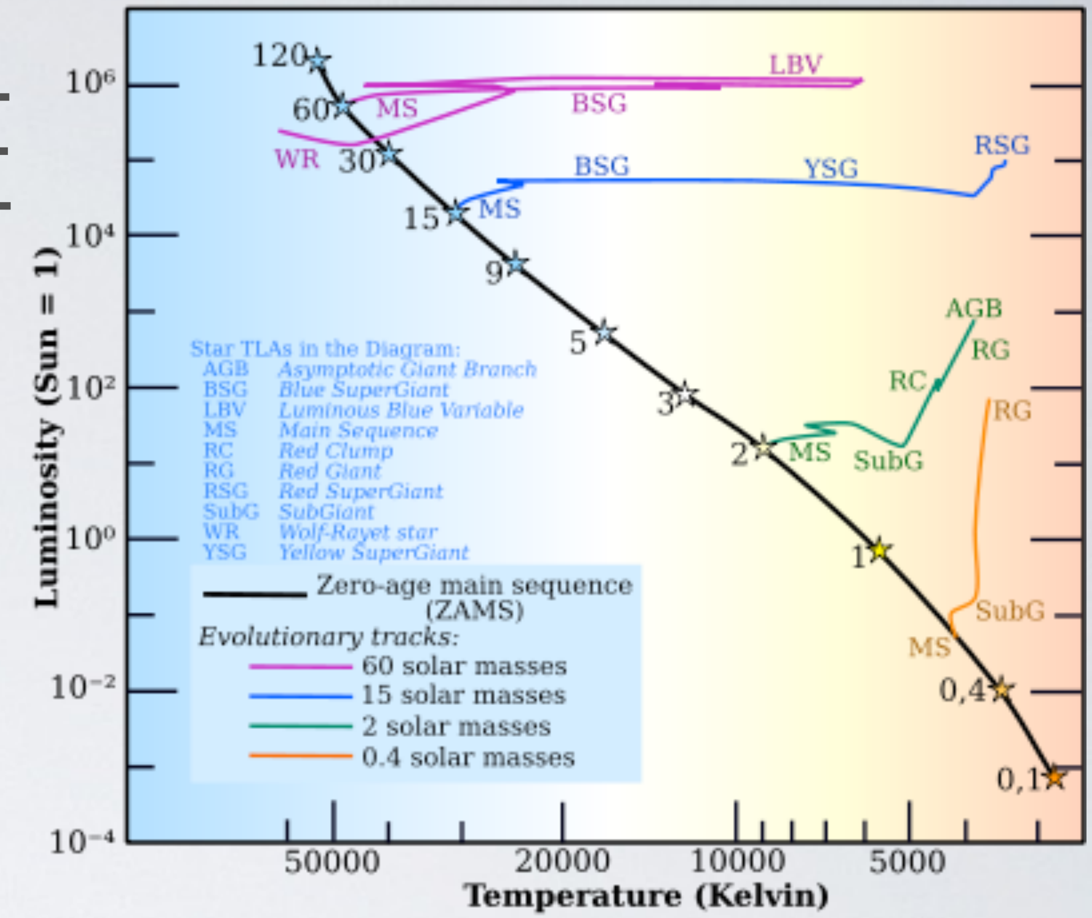
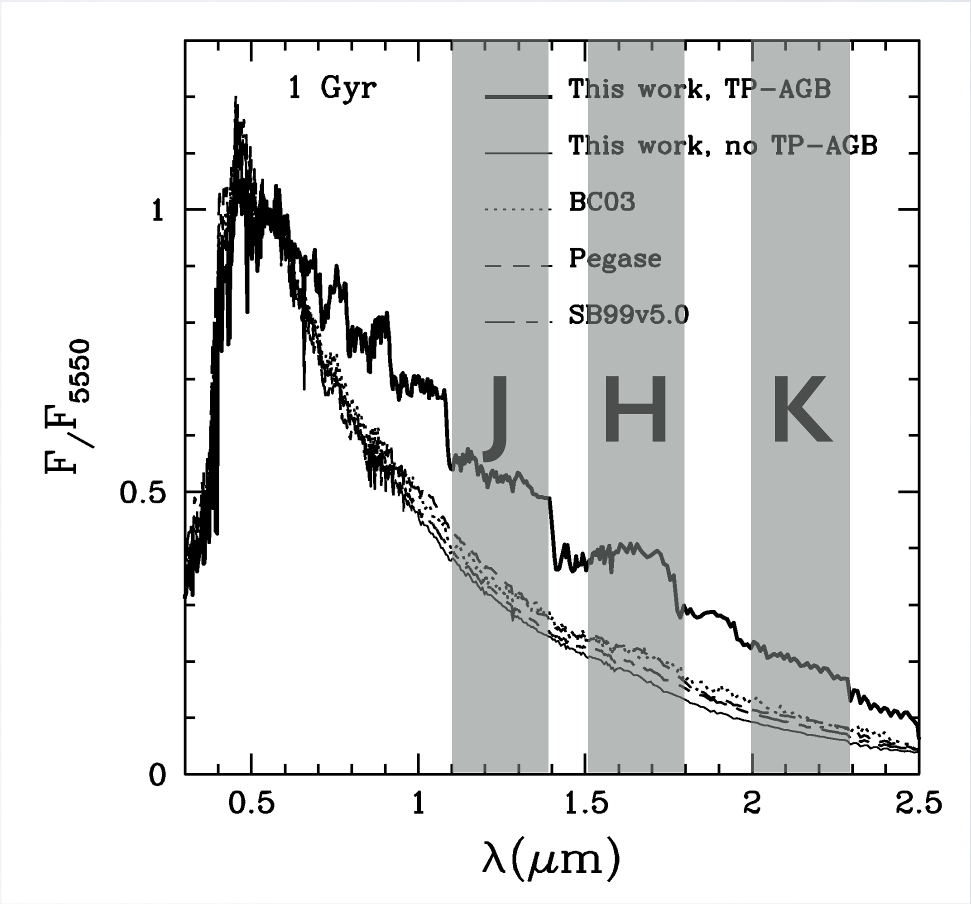
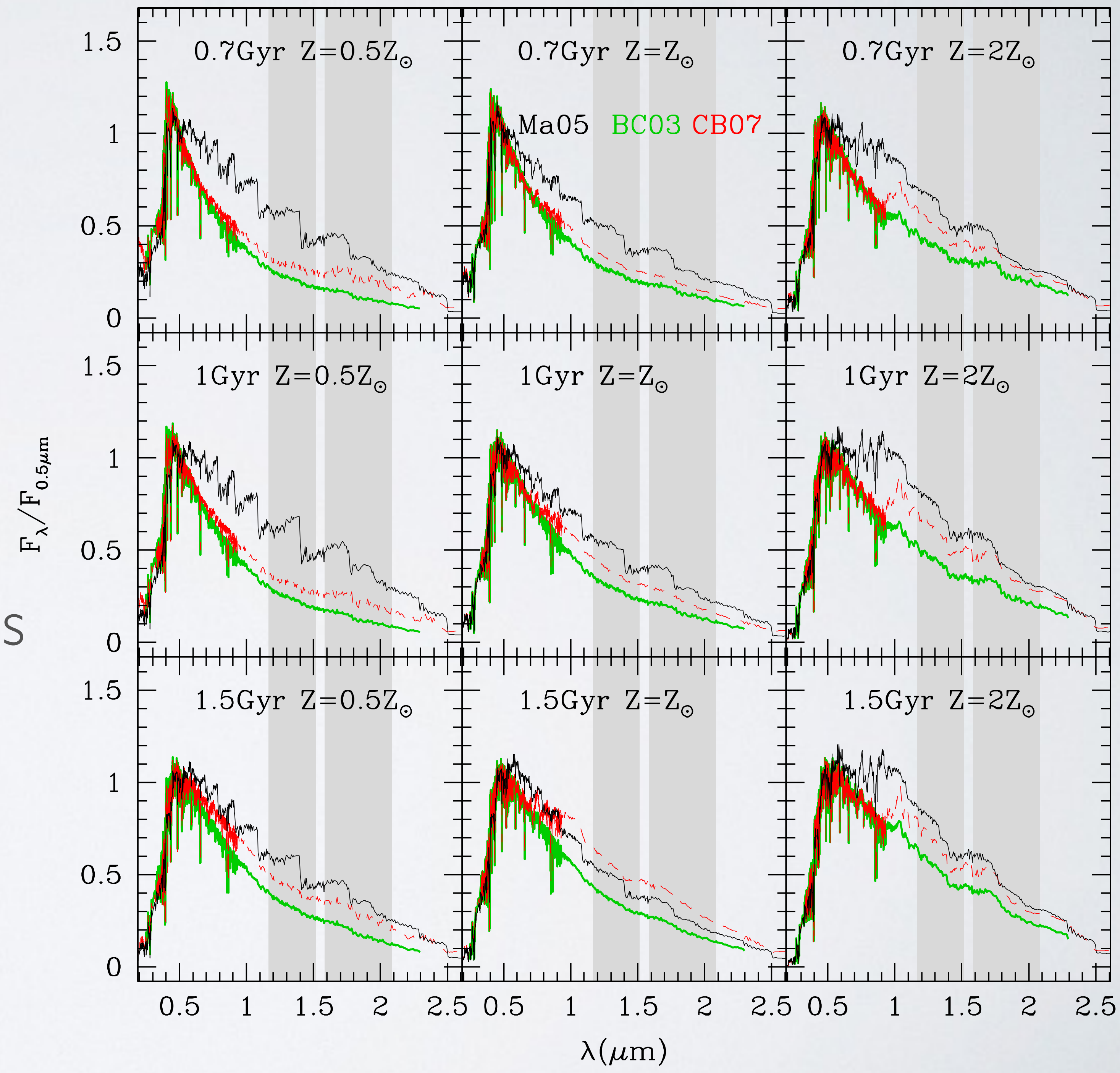




Maraston (2005)

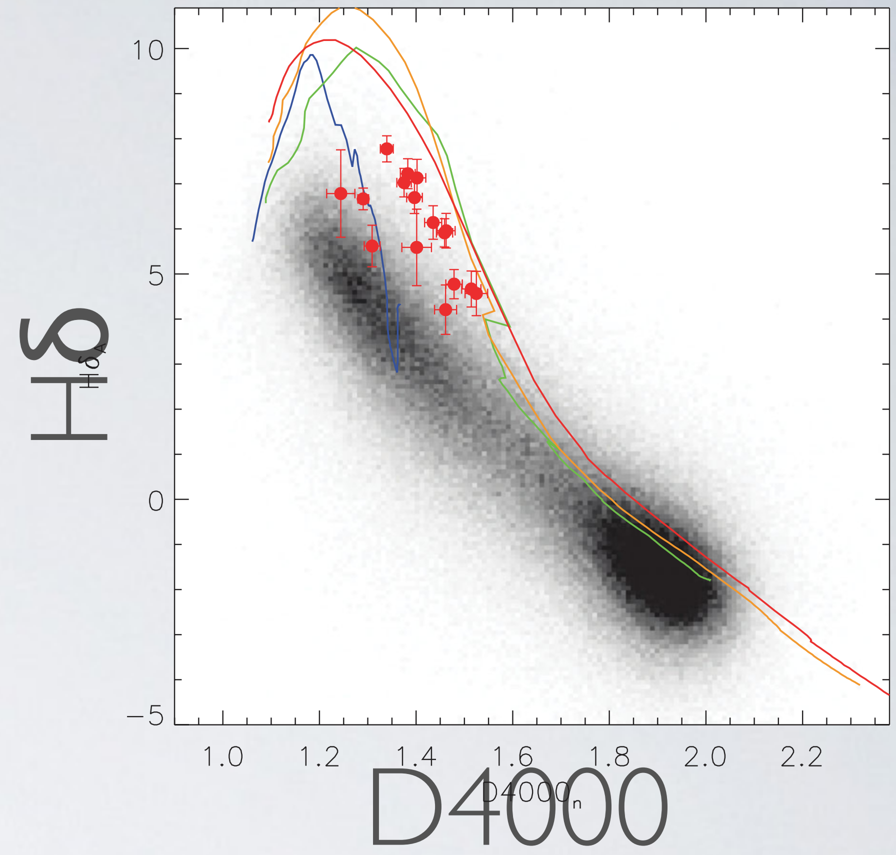
IMPACT OF TP-AGB STARS ON GALAXY SEDS

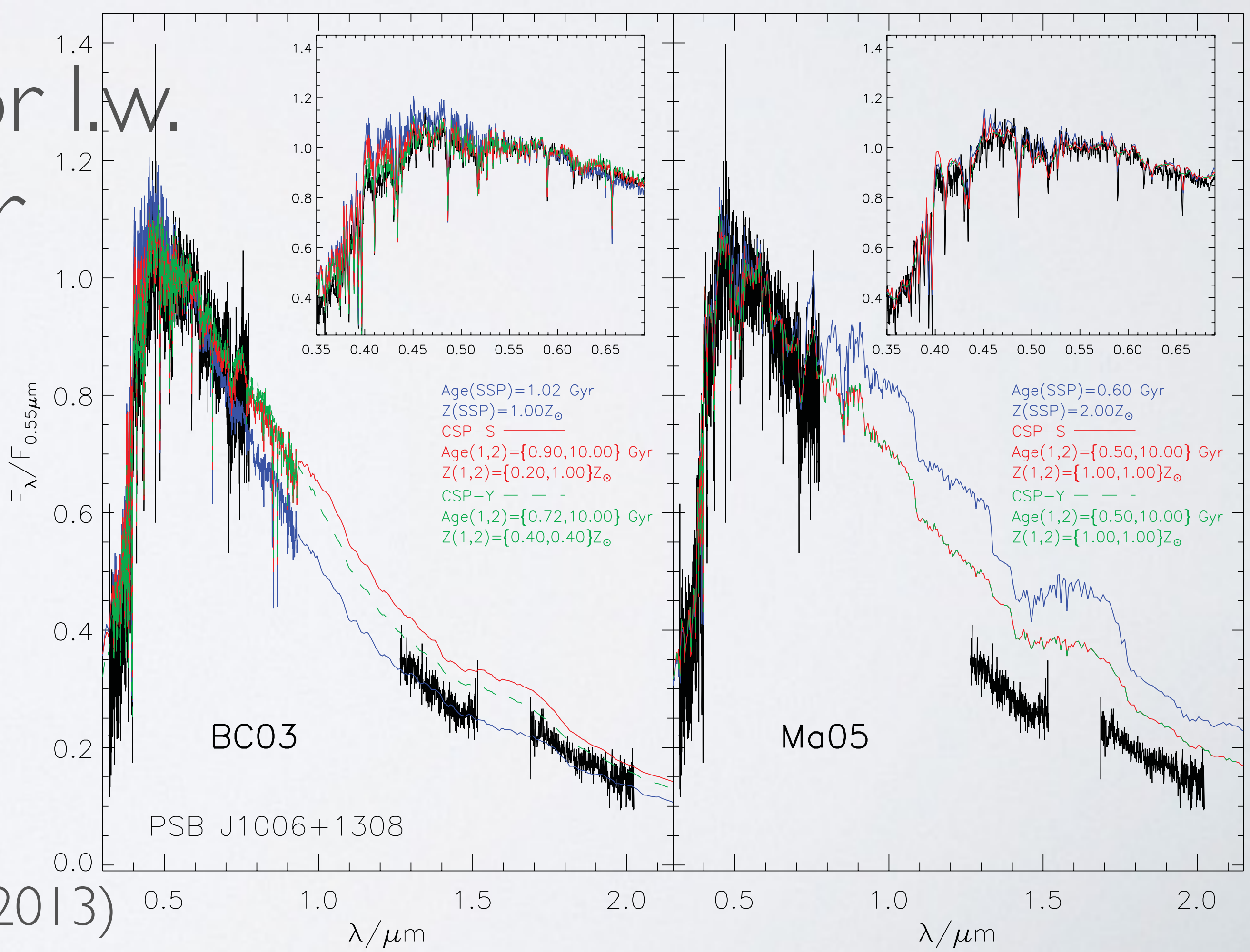
- Open problems:
  - stellar evolutionary tracks
  - mixture of different types (O and C stars)
  - dust cocoons and self-absorption
  - Stellar templates
- Yet modellers have made choices and make clear predictions!
- Use **NIR spectroscopy** and move the features out of the atmospheric gaps: observe at **z=0.2** !



OBSERVATIONAL CONSTRAINTS FROM POST-STARBURST GALAXIES AT Z~0.2

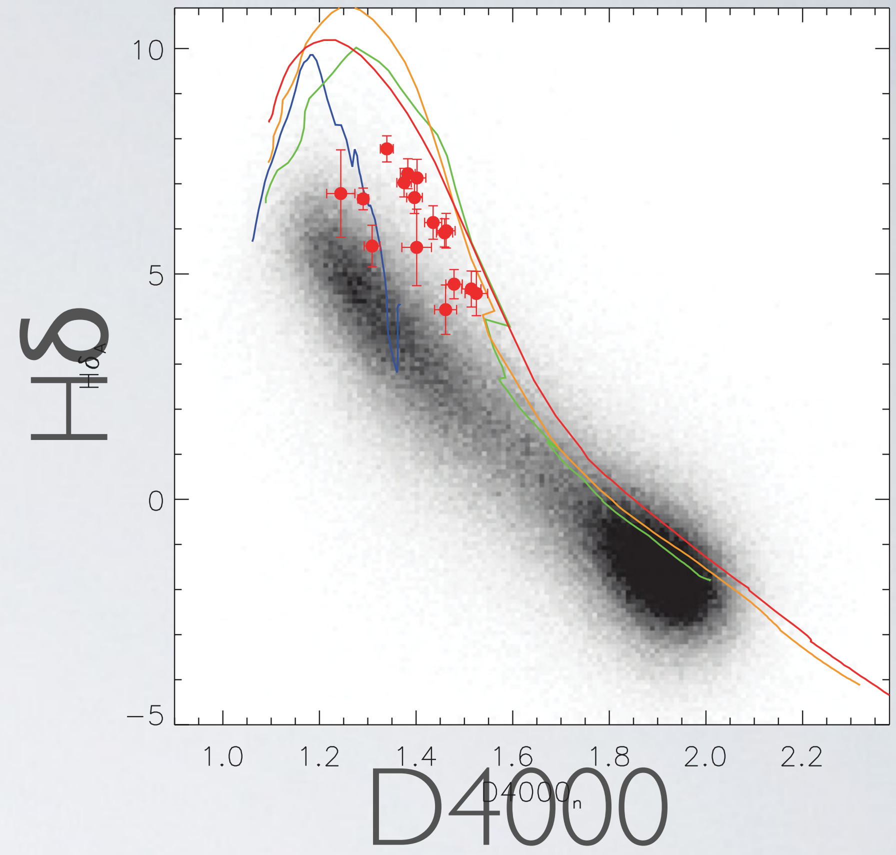
- 16 galaxies in post-starburst phase, hence at the peak of TP-AGB contribution:
  - age-selected in the optical for l.w. age between 0.8 and 1.5 Gyr
- ISAAC NIR spec in H and K, looking for
  - C-features
  - NIR boost





Zibetti et al. (2013)

OBSERVATIONAL CONSTRAINTS FROM POST-STARBURST GALAXIES AT Z~0.2



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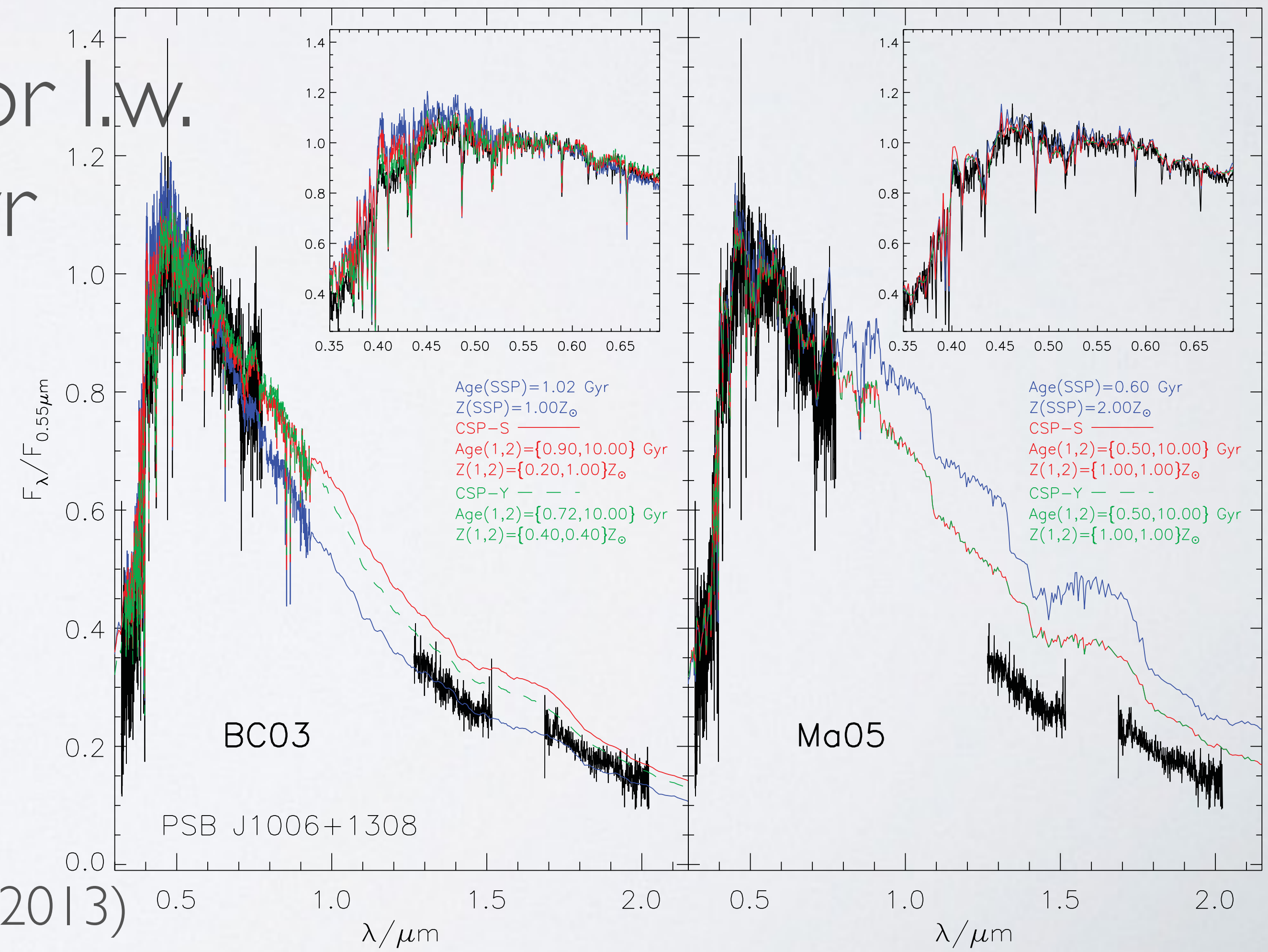
NONE!



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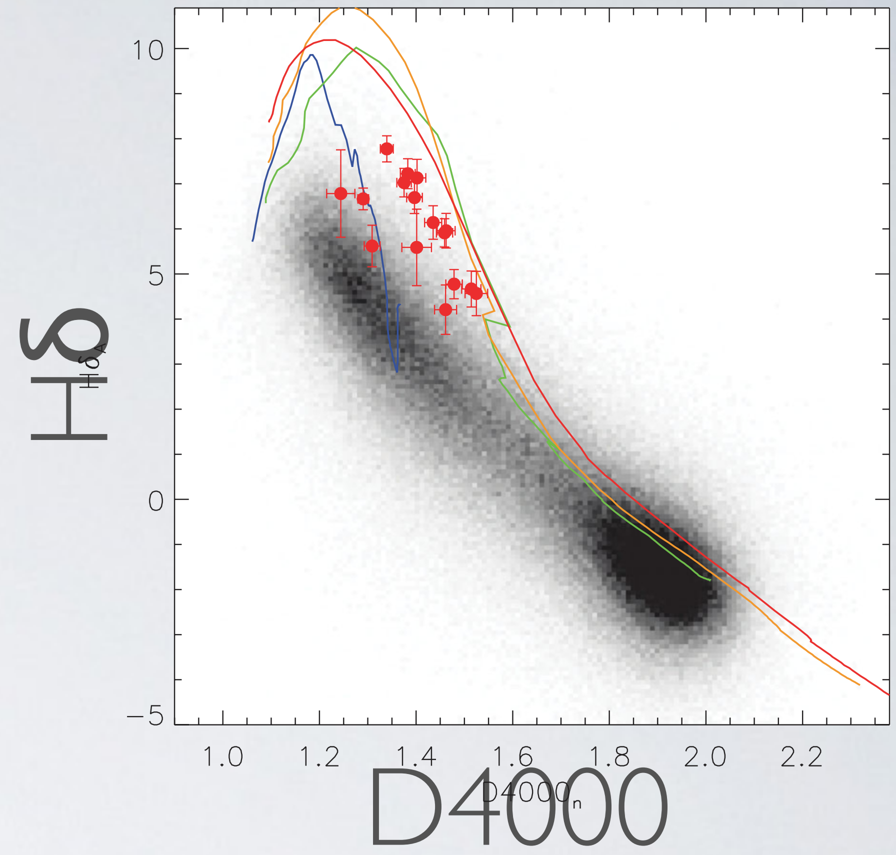

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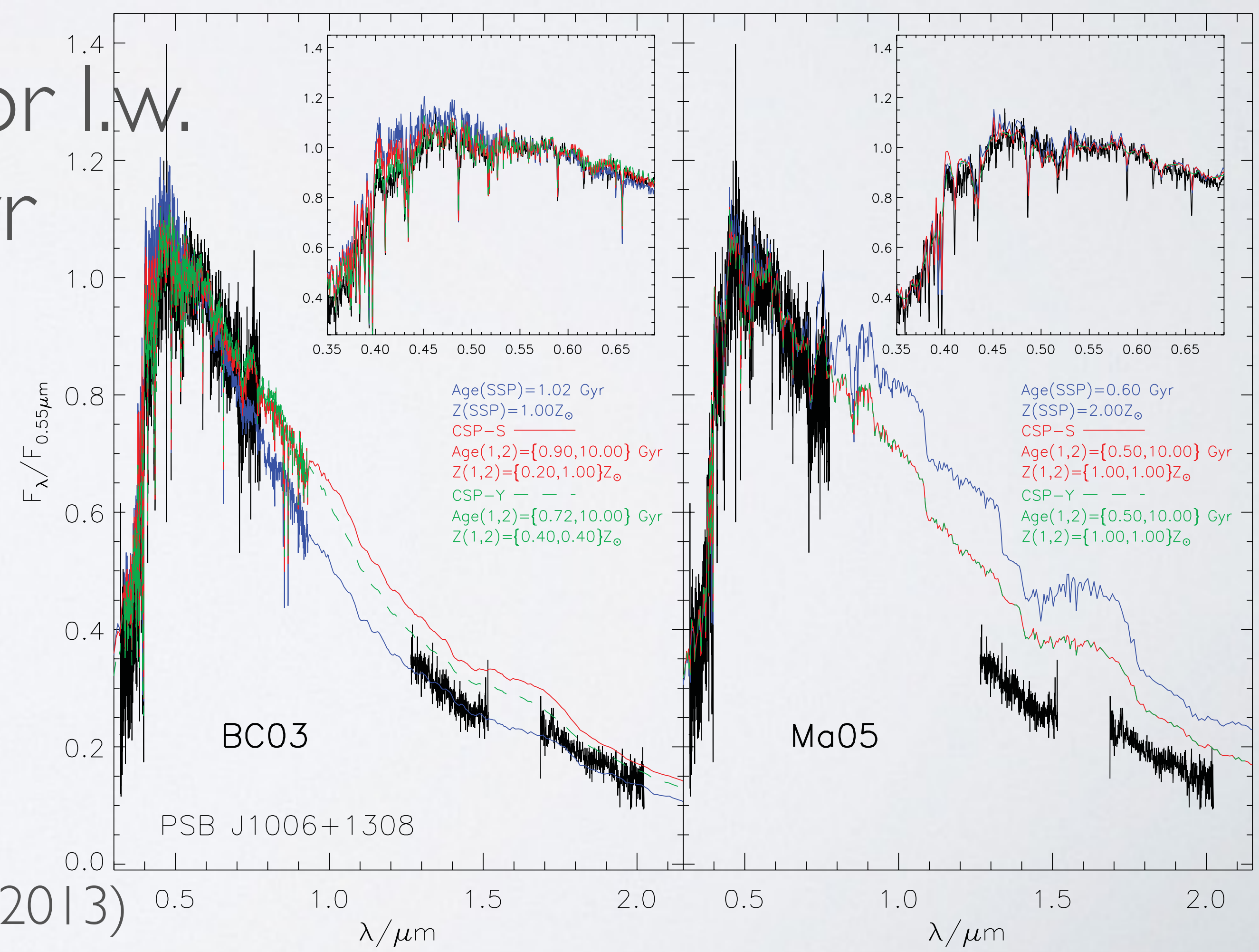
NONE!

NONE!

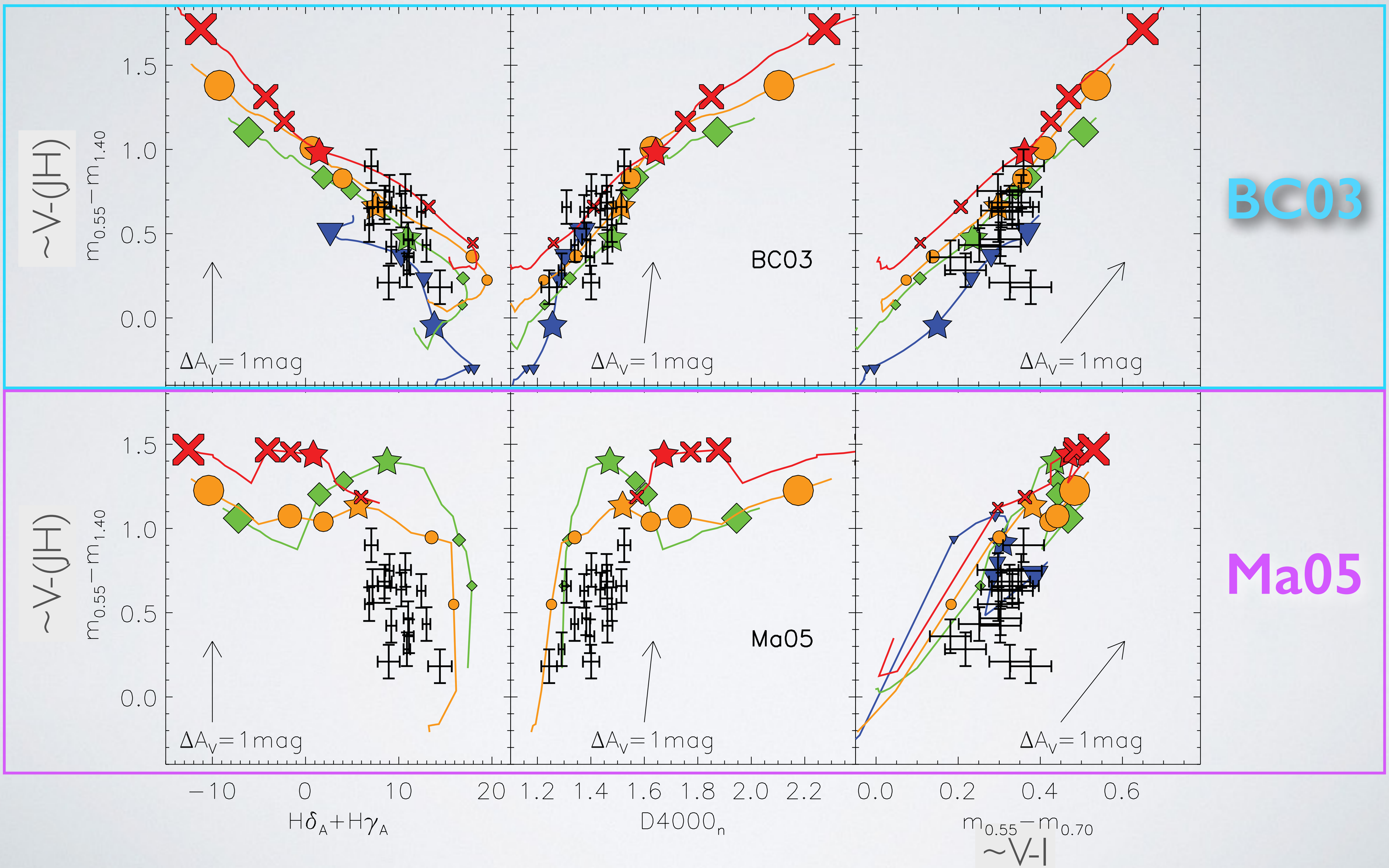
BC03 **Ma05**



Zibetti et al. (2013)

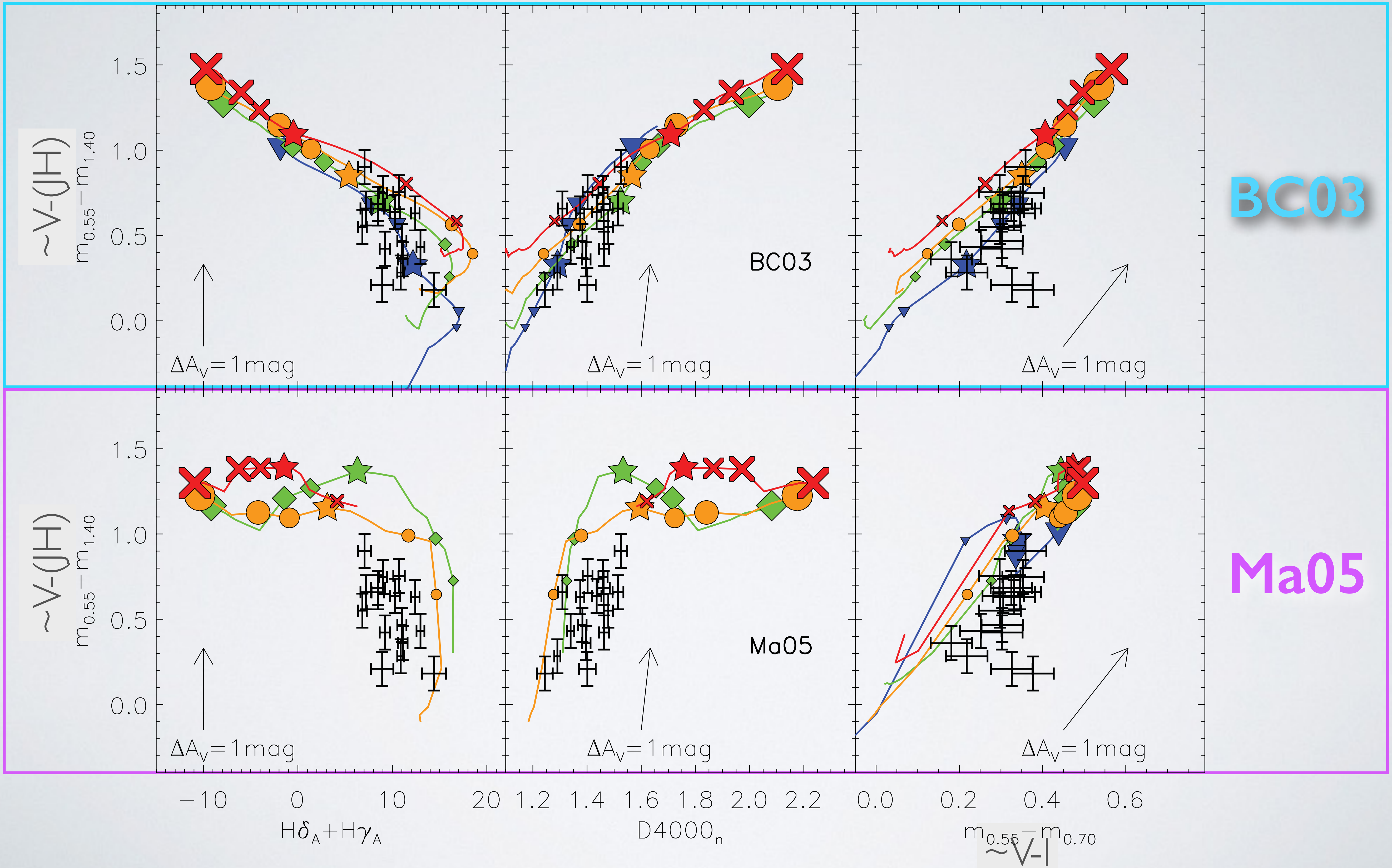
SZ+13

OPTICAL VS NIR: SSP



SZ+13

OPTICAL VS NIR: CSP



“CONCLUSIONS” ON TP-AGB STARS

(Zibetti et al. 2013)

- No evidence for highly boosted NIR emission from intermediate-age stellar population (TP-AGB stars)
- No evidence for sharp C features in the NIR
- Consistent with stacked intermediate-band photometry at z~0.7-2 (Kriek+2010), recent results by Melnick & DePropris (2014)
- Much more work to be done to develop and test models! but at least we have a benchmark now

LESSON #3

- Don’t trust stellar population synthesis models and SED fitting codes blindly: they are much more uncertain than (some) modellers claim!

SUMMARY & OUTLOOK

- Still a lot of **uncertainties**
  - SFH: up to ~2x
  - dust: up to ~2x
  - structure/brightness bias: ~50%
  - lack of spectroscopy: ~30-40%
  - IMF: 2x
- Too much for **“precision” galaxy formation & evolution**:
  - Stellar mass function, its evolution, split for galaxy types
  - Scaling relations
  - Baryon fraction in galaxies and groups
- Too much for **precise dynamical modelling**
- Require huge **calibration** work, but **we have** the **data** and the **tools** now: this is what ***SteMaGE*** is about!
- First results highlight the **complexity** but also the **feasibility** of this task