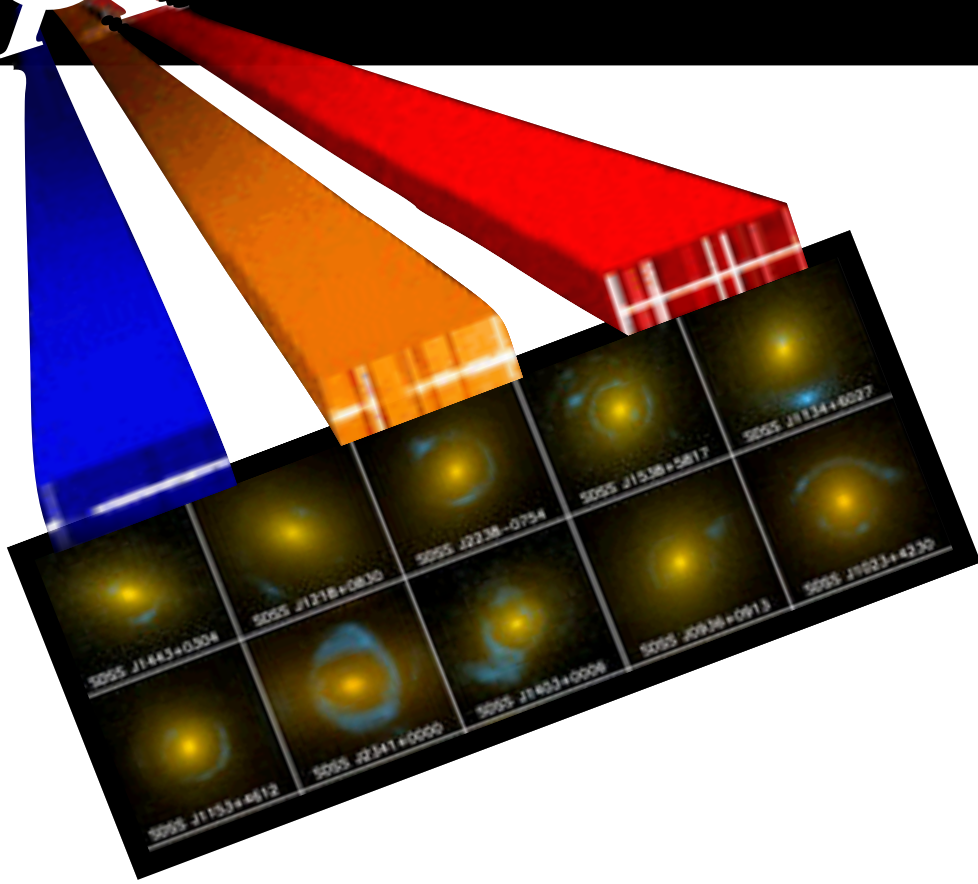
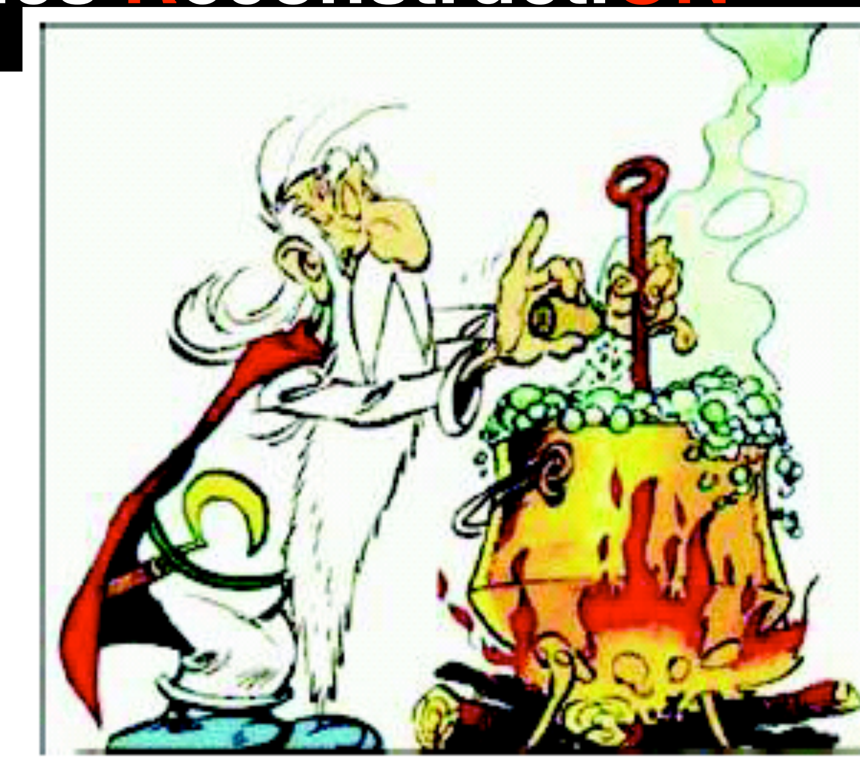
Combined Algorithm for Unified Lensing and Dynamics ReconstructiON





Strong lensing & Dynamics + Stellar population

Constraining the Initial Mass Function and its lower cutoff mass

Chiara Spiniello

Kapteyn Astronomical Institute
University of Groningen (NL)

M. Barnabè, L.V.E. Koopmans, S.C.Trager, T.Treu, O.Czoske

Spiniello et al. 2011

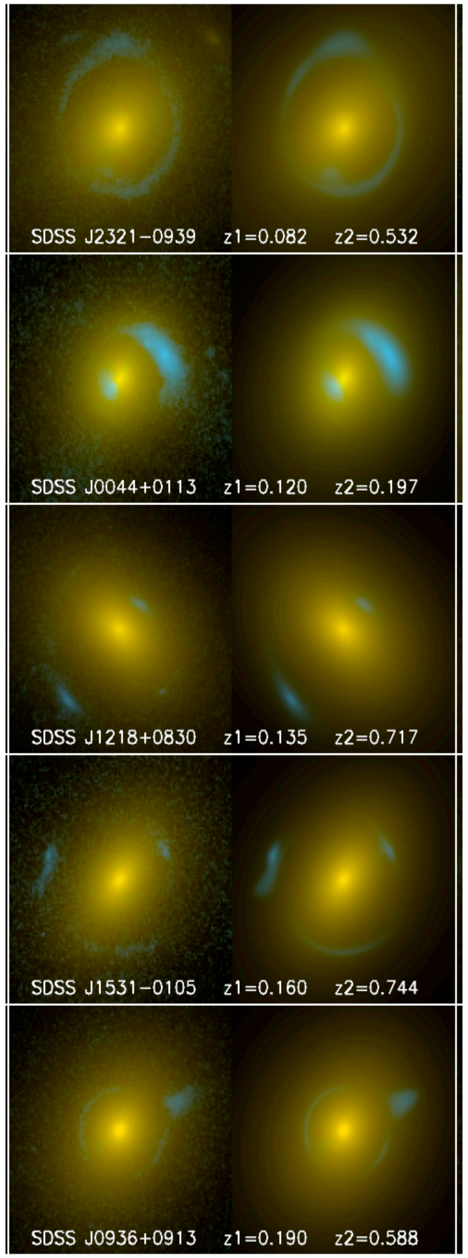
The X-Shooter Lens Survey

SCIENCE GOALS

Barnabè et al. 2012

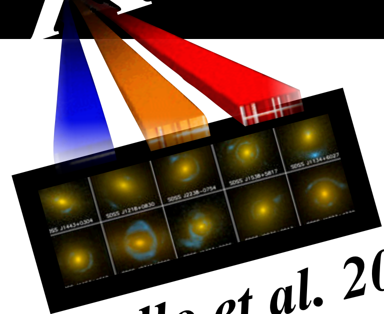
WHAT?

- ETGs z~[0.1-0.4] , σ_* > 250 km/s
- Strong gravitational lensing+ dynamics (CAULDRON) + spatially resolved kinematics (XSH)
- Stellar population analysis (SSP modelling, line-strengths)



SCIENTIFIC GOALS:

- Disentangle stellar and dark-matter content
- Mass distrubution as function of galaxy mass and redshift
- Slope and <u>lower cutoff mass</u> of the Initial Mass Function (IMF) directly from spectra



Spiniello et al. 2011

THE METHOD

Barnabè et al. 2012

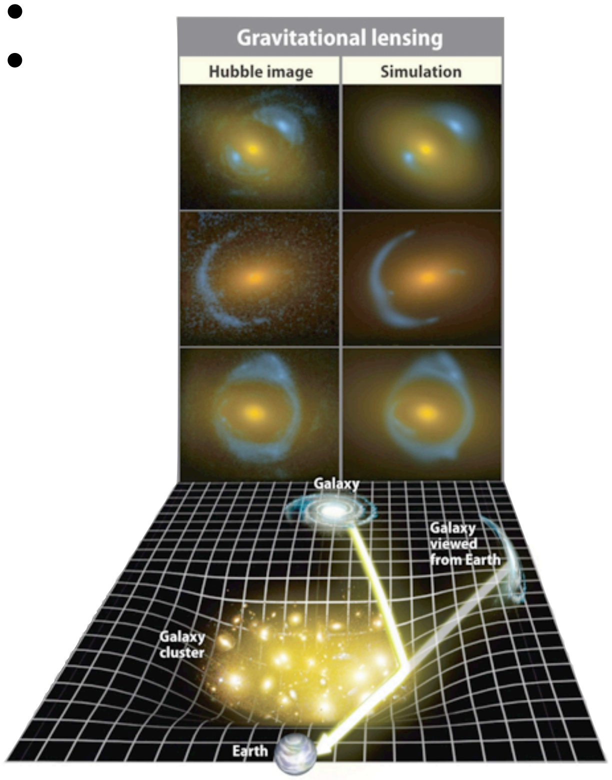
We infer stellar masses from two **independent methods**:

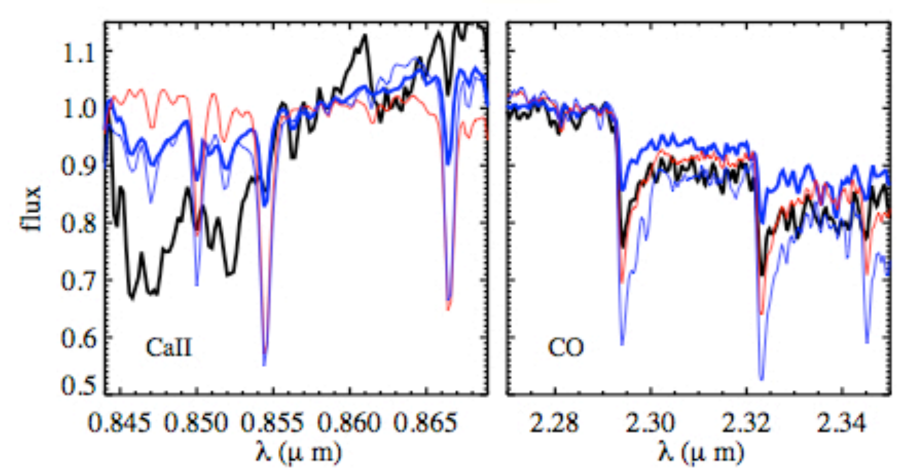
1. Joint self-consistent lensing + dynamics analysis *Barnabè et al. 2012*

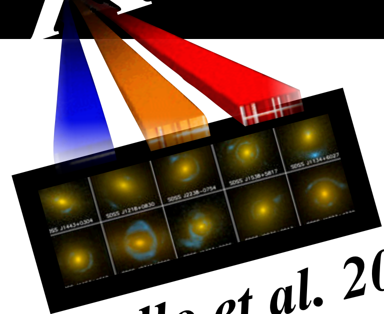
   Tracing the mass

2. Spectroscopic Simple Stellar Population study *Spiniello et al. 2013*

   Tracing the light







Spiniello et al. 2011

THE METHOD 1.

CAULDRON: COMBINED LENSING AND DYNAMICS ANALYSIS

Barnabè et al. 2012

Barnabè et al. 2012

axisymmetric density distribution

↓

gravitational potential

↓

LENSING MODEL
pixelated source reconstruction method

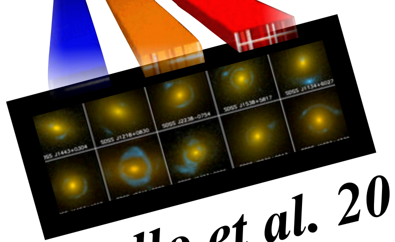
DYNAMICAL MODEL
anisotropic Jeans eqs.

↓

joint posterior prob. (w/ Bayesian statistics) → (back to axisymmetric density distribution)

⇩

inferences on the posterior PDF of parameters



Spiniello et al. 2011

THE METHOD 1.

CAULDRON:Combined lensing and dynamics analysis

Barnabè et al. 2012

Barnabè et al. 2012

DARK MATTER : Axisimmetric generalized NFW profile

$$\rho_{\rm DM}(m) = \frac{\delta_c\, \rho_{\rm crit}}{(m/r_{\rm s})^{\gamma}\, (1 + m/r_{\rm s})^{3-\gamma}}$$

$$m^2 \equiv R^2 + \frac{z^2}{{q_{\rm h}}^2} \qquad \delta_c = \frac{200}{3}\,\frac{c^3}{\zeta(c, \gamma, 1)}$$

- **Free parameters [#1-4]: inner slope γ, three-dimensional axial ratio q_h, concentration c_{-2}, virial velocity v_{vir}**

LUMINOUS MATTER : Decompose and de-project the galaxy high-res image in K-band using the *multi-Gaussian expansion (MGE) technique*

(by Emsellem et al. 99, Cappellari 2002)

- Luminous mass distribution is self-gravitating, *not just a tracer*
- Free parameter [#5]: baryonic mass M_{bar}

Spiniello et al. 2011

THE METHOD 2.
STELLAR POPULATION ANALYSIS: LINE-INDEX MEASUREMENTS

Spiniello et al. 2013

Barnabè et al. 2012

We Measure <u>indices</u>:

that are more or less sensitive to different stellar population parameters (age, α/Fe, gravity, effective Temperature of RGB)

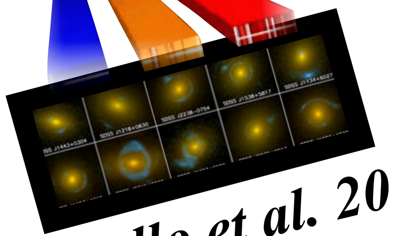
1. in the <u>XLENS</u> Galaxy Spectra

Current sample:12 systems z~[0.1-0.5] , $\sigma_* > 250$ km/s
Pilot program : the most massive and the least massive XLENS galaxies

2a. in single spectra from the <u>MILES</u> Stellar Library

995 stars spectra ,
Wavelegth Range: 3525-7500Å
Resolution: 2.50Å (FWHM)

Sánchez-Blázquez, et al 2006



Spiniello et al. 2011

THE METHOD 2.
STELLAR POPULATION ANALYSIS:
LINE-INDEX MEASUREMENTS

Spiniello et al. 2013

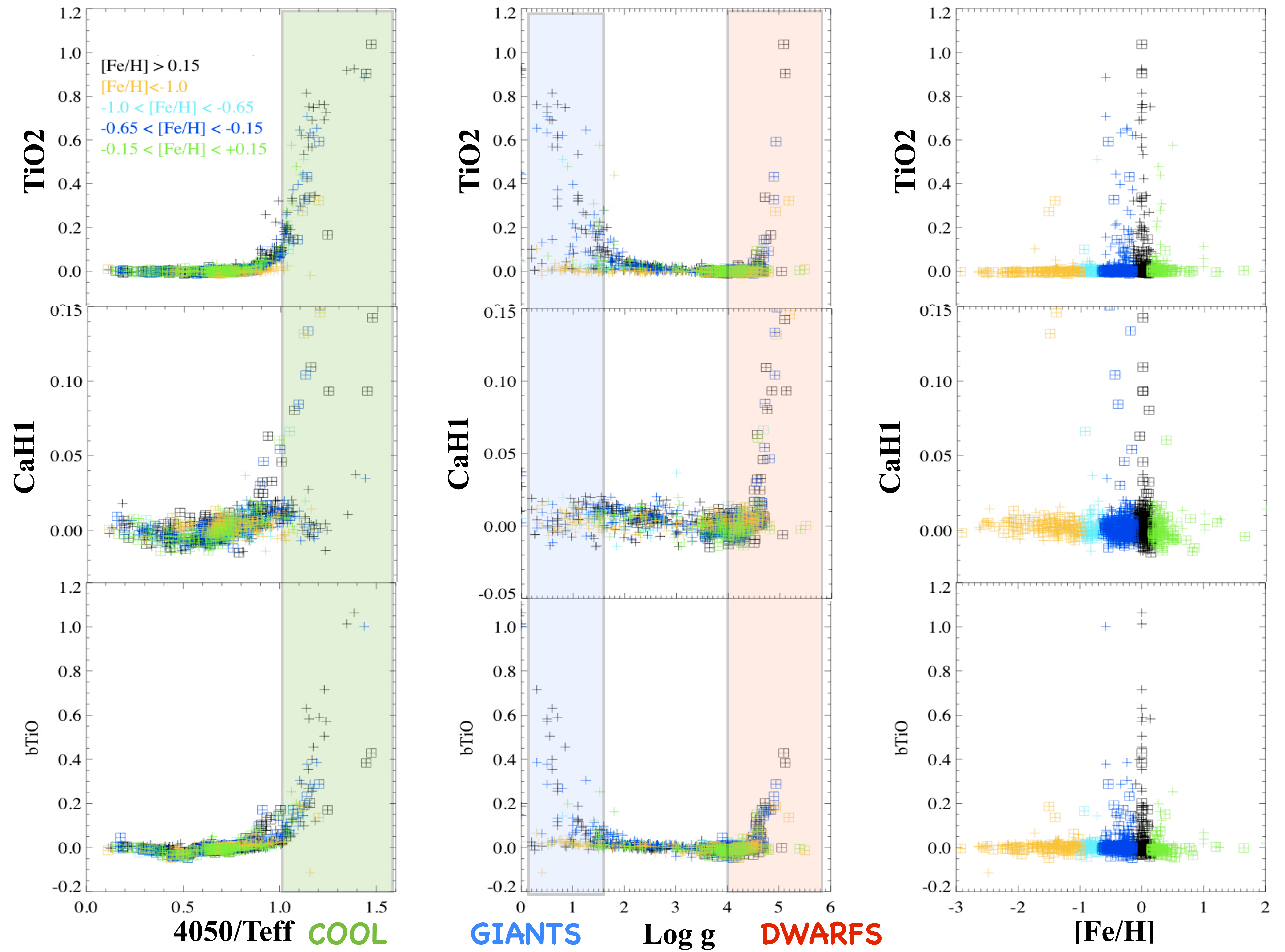
Barnabè et al. 2012

Searching for (new) M-dwarfs indicators in the optical

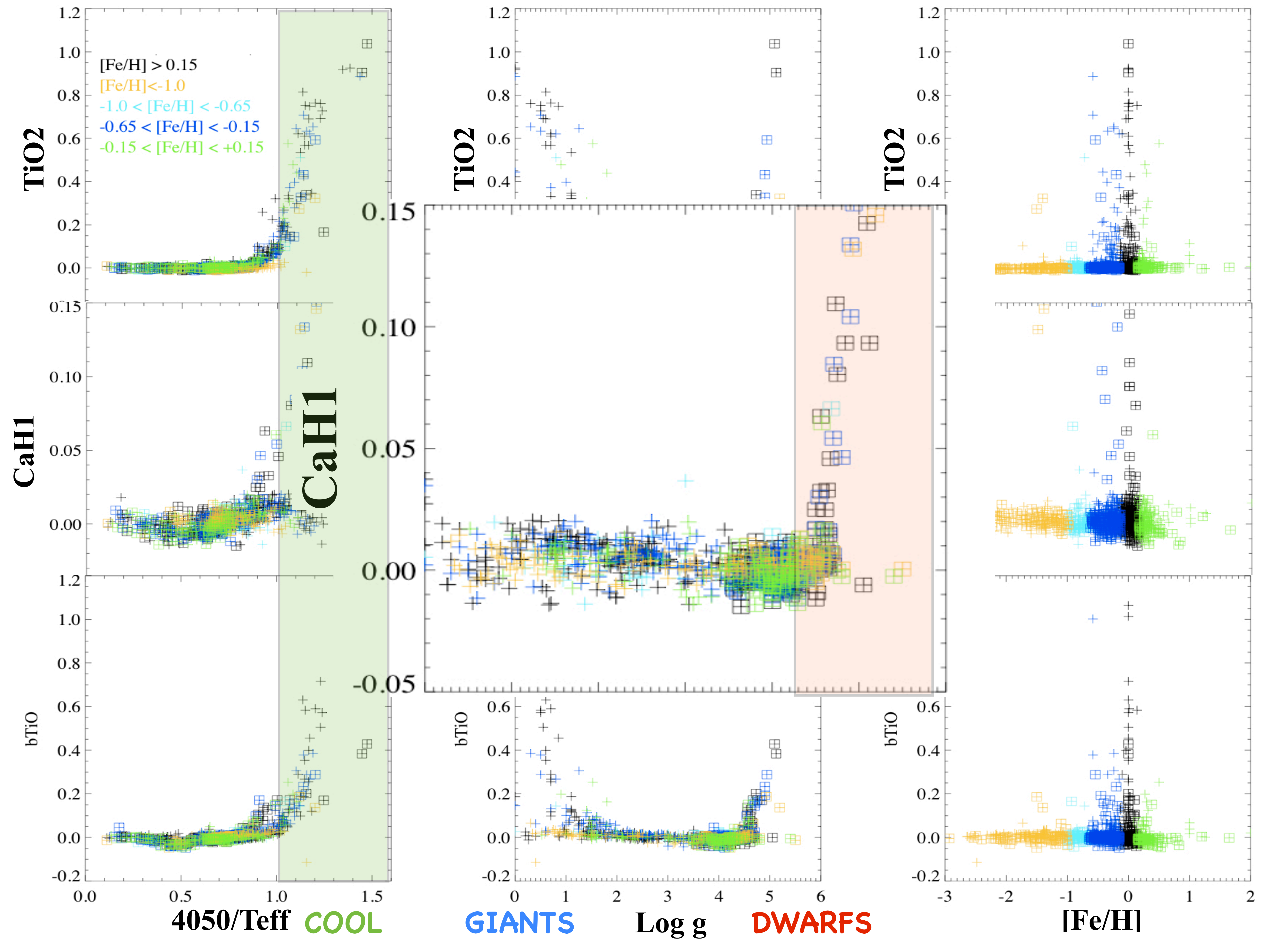
Searching for indicators that :

- are strong in COOL STARS
- are GRAVITY-SENSITIVE
- do not depend strongly on metallicity and age

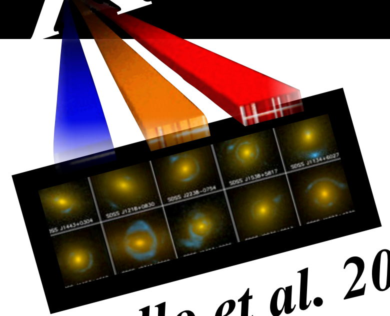
(at least for population older than 7Gyr)



[Fe/H] > 0.15
[Fe/H]<-1.0
-1.0 < [Fe/H] < -0.65
-0.65 < [Fe/H] < -0.15
-0.15 < [Fe/H] < +0.15
TiO2
CaH1
bTiO
4050/Teff
COOL
GIANTS
Log g
DWARFS
[Fe/H]



[Fe/H] > 0.15
[Fe/H]<-1.0
-1.0 < [Fe/H] < -0.65
-0.65 < [Fe/H] < -0.15
-0.15 < [Fe/H] < +0.15
TiO2
CaH1
bTiO
4050/Teff
COOL
GIANTS
Log g
DWARFS
[Fe/H]



Spiniello et al. 2011

THE METHOD 2.
STELLAR POPULATION ANALYSIS: LINE-INDEX MEASUREMENTS

Spiniello et al. 2013

Barnabè et al. 2012

We Measure <u>indices</u>:

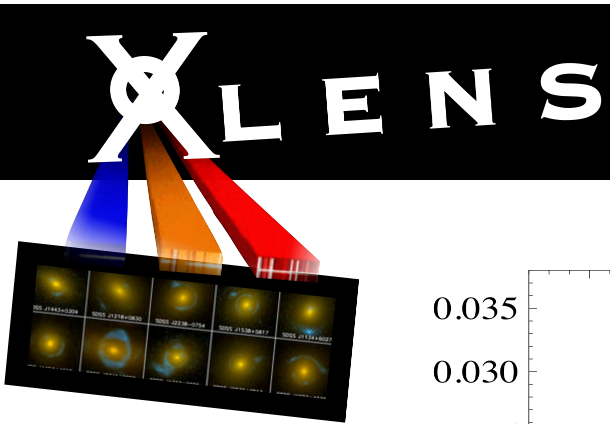
that are more or less sensitive to different stellar population parameters (age, α/Fe, gravity, effective Temperature of RGB)

1. in the <u>XLENS</u> Galaxy Spectra

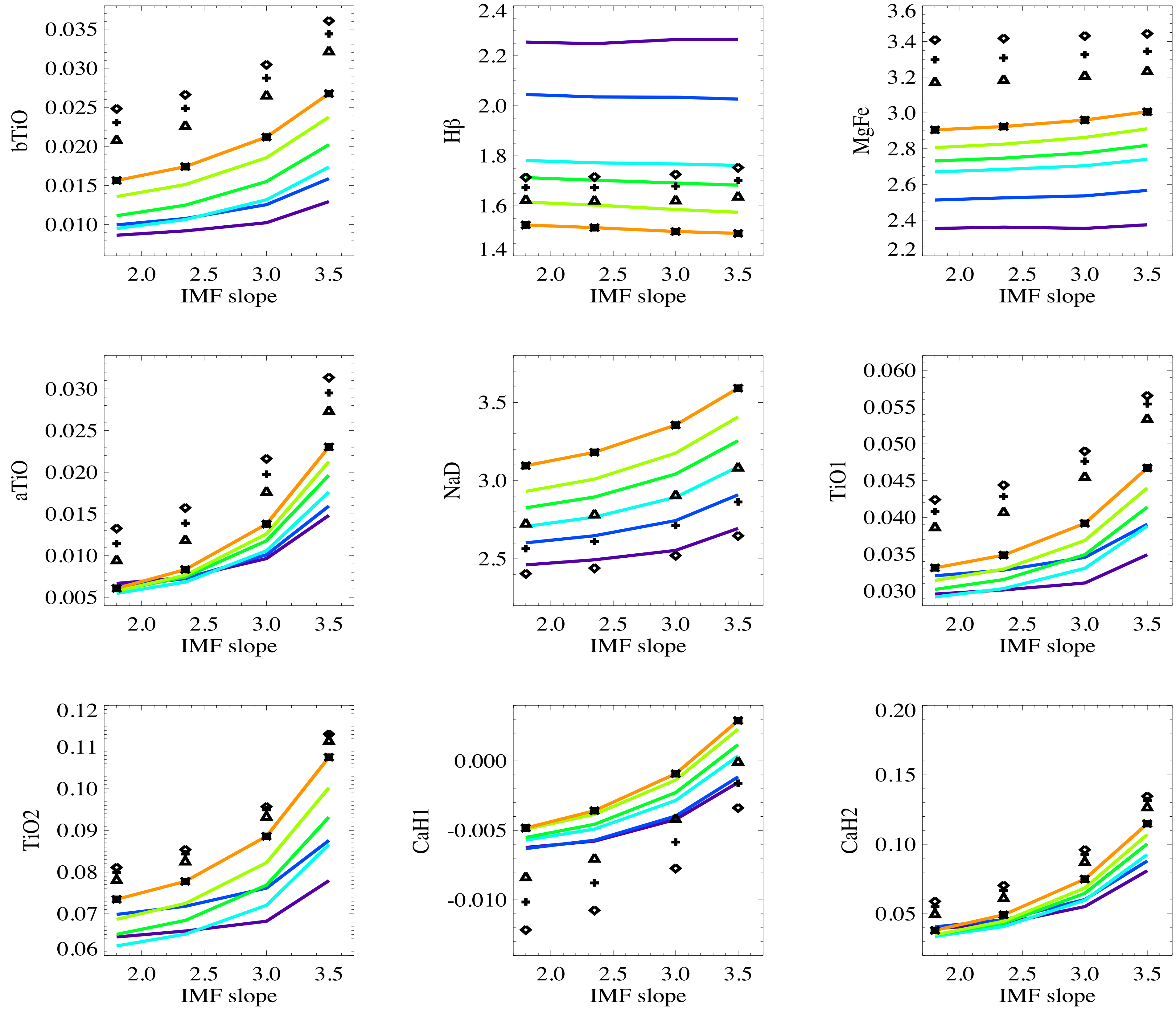
Current sample:12 systems z~[0.1-0.5] , $\sigma_* > 250$ km/s
Pilot program : the most massive and the least massive XLENS galaxies

2b. in the <u>CvD+12</u> Simple Stellar Population Models

Ages: {3-13.5}Gyr ,
[α/Fe] : {-0.2 - 0.4},
IMF slopes: {1.8 - 3.5} (Salp=2.35)



+ Combined Algorithm for Unified Lensing and Dynamics ReconstructiON

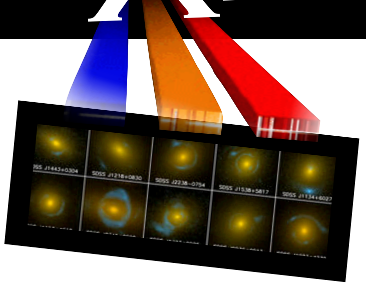


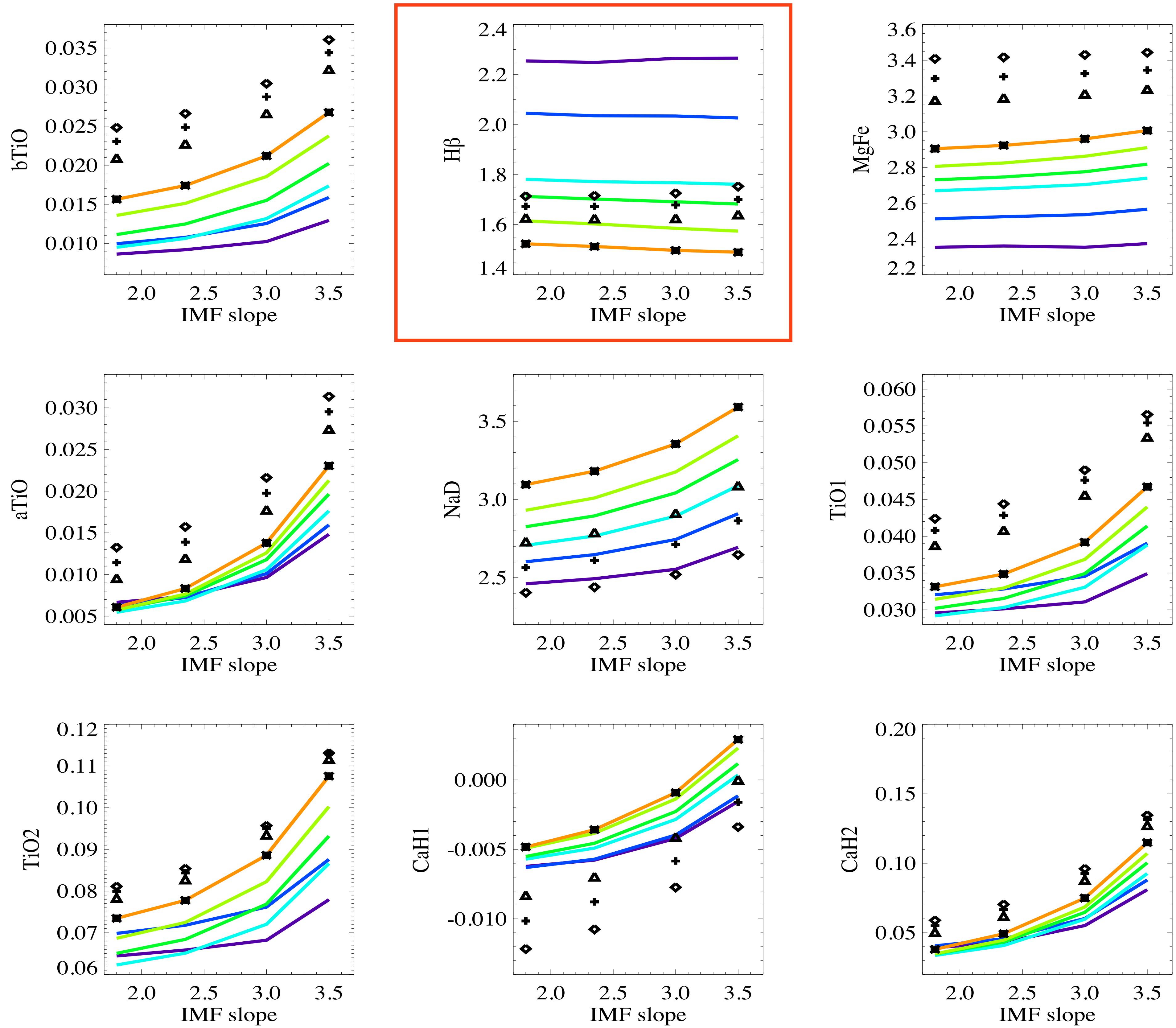
Ages
3.00000
5.00000
7.00000
9.00000
11.0000
13.5000

[α /Fe]
+0.0
+0.2
+0.3
+0.4

Spiniello et al. 2013

XLENS + **C**ombined **A**lgorithm for **U**nified **L**ensing and **D**ynamics **R**econstructi**ON**



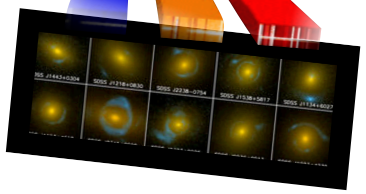


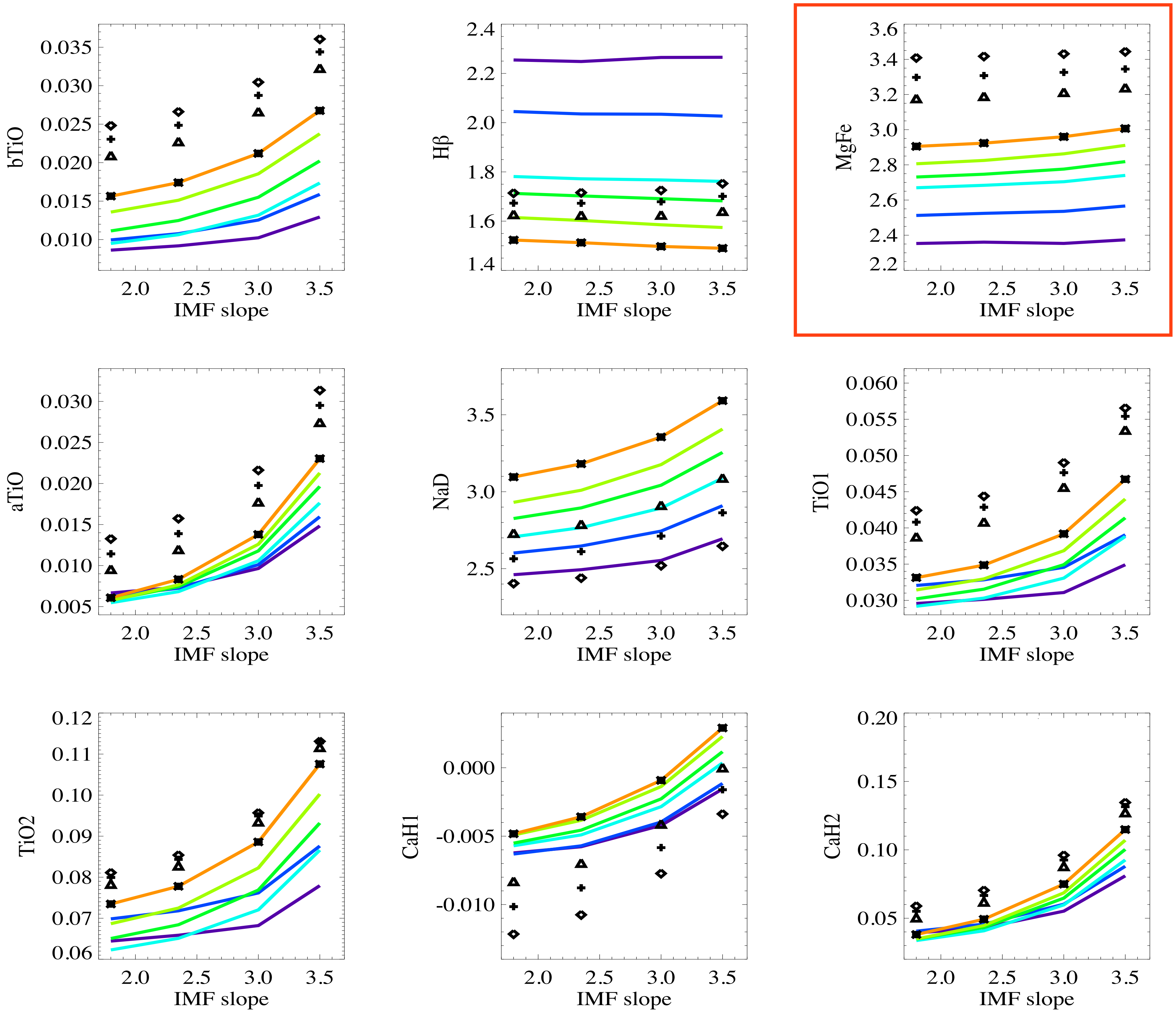
Ages
3.00000
5.00000
7.00000
9.00000
11.0000
13.5000

[α /Fe]
+0.0
+0.2
+0.3
+0.4

Spiniello et al. 2013

XLENS + **C**ombined **A**lgorithm for **U**nified **L**ensing and **D**ynamics **R**econstructi**ON**



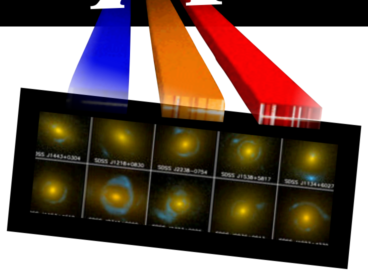


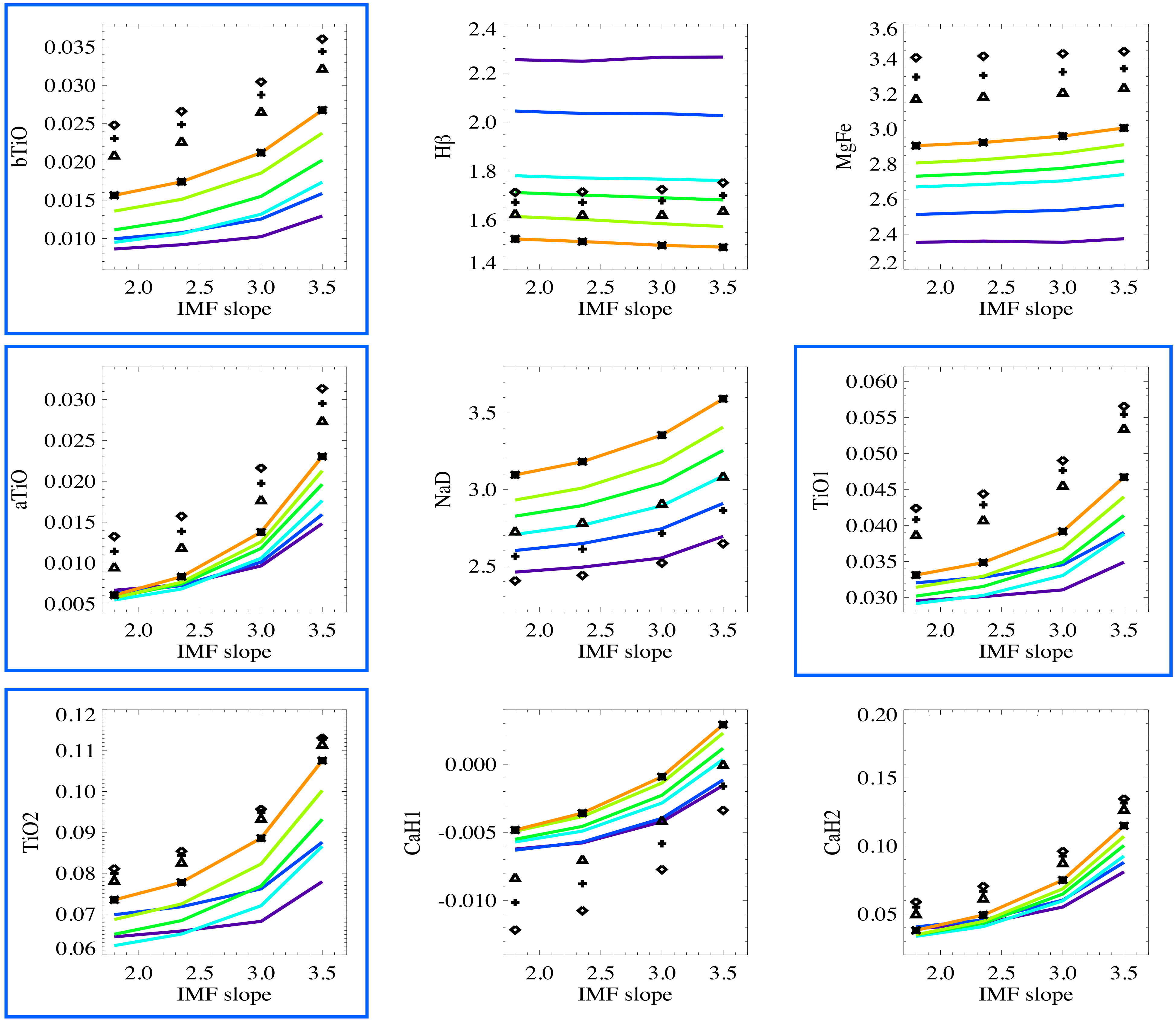
Ages
3.00000
5.00000
7.00000
9.00000
11.0000
13.5000

[α /Fe]
+0.0
+0.2
+0.3
+0.4

Spiniello et al. 2013

XLENS + Combined Algorithm for Unified Lensing and Dynamics ReconstructiON



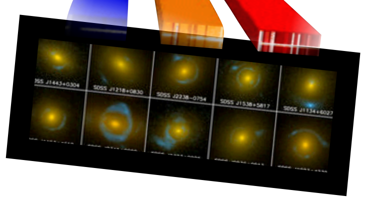


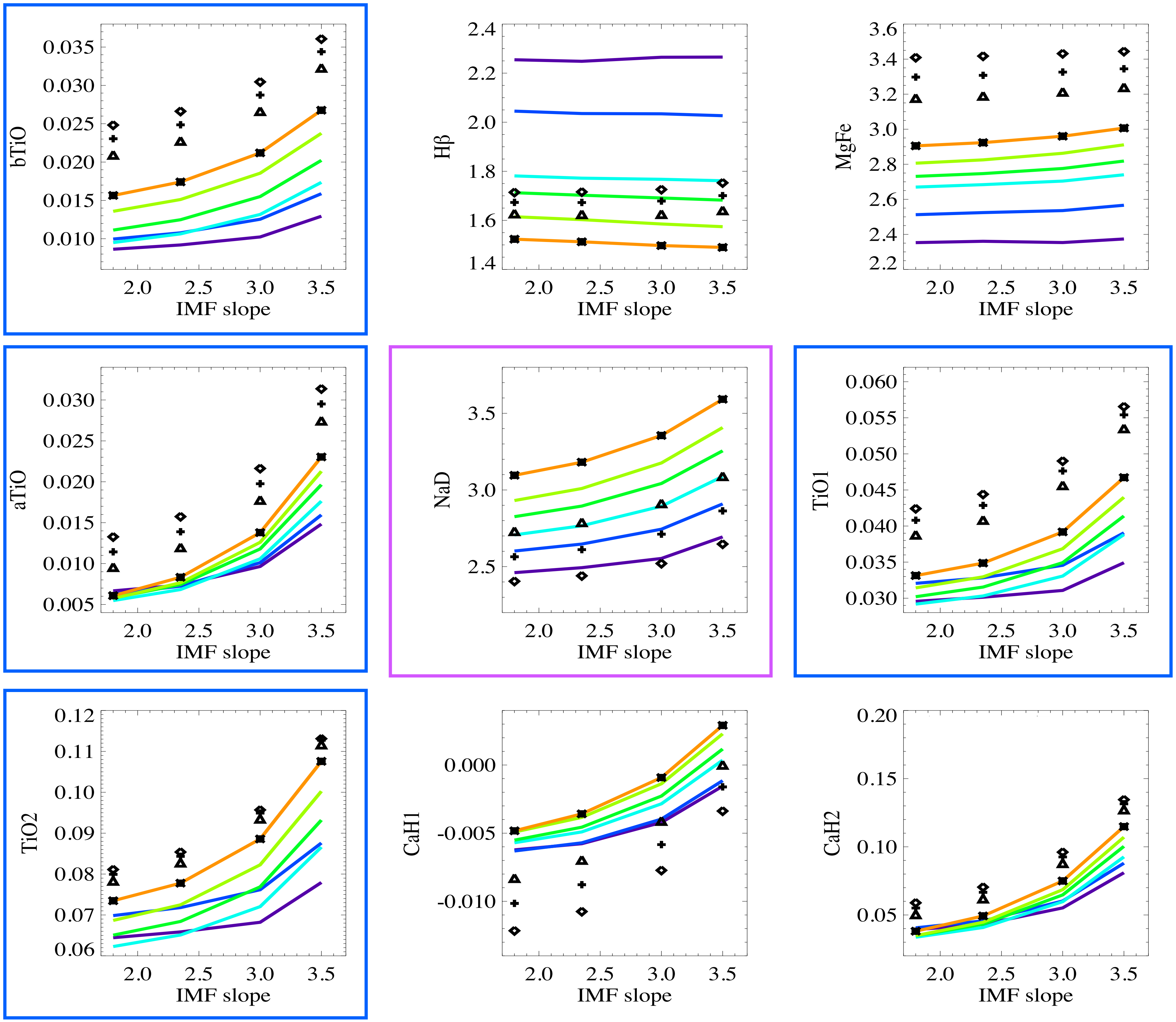
Ages
3.00000
5.00000
7.00000
9.00000
11.0000
13.5000

[α /Fe]
+0.0
+0.2
+0.3
+0.4

Spiniello et al. 2013

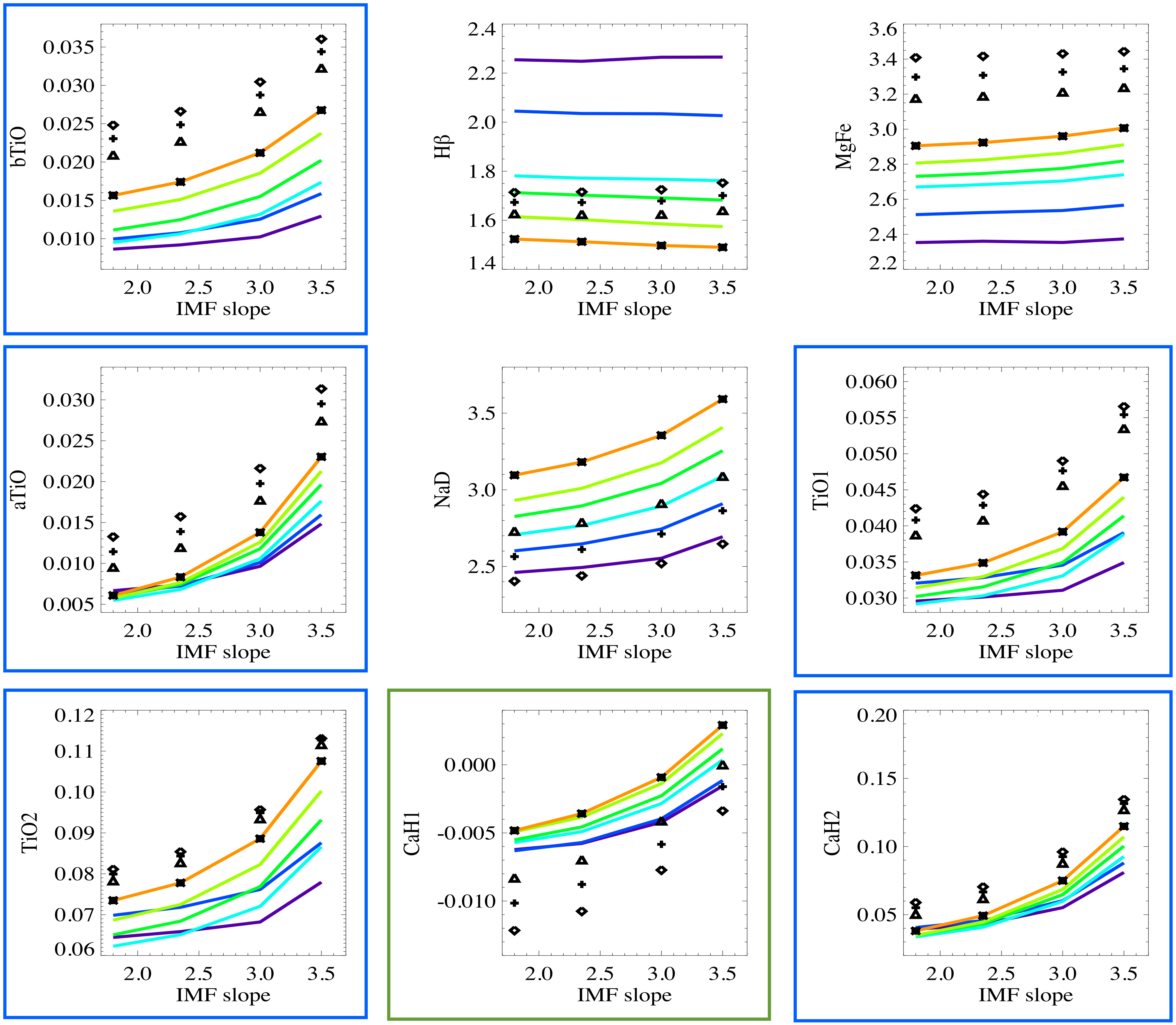
XLENS + Combined Algorithm for Unified Lensing and Dynamics ReconstructiON





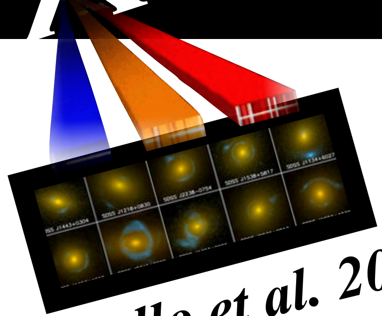
Spiniello et al. 2013

XLENS + **C**ombined **A**lgorithm for **U**nified **L**ensing and **D**ynamics **R**econstructi**ON**



Ages
3.00000
5.00000
7.00000
9.00000
11.0000
13.5000
[α /Fe]
+0.0
+0.2
+0.3
+0.4

Spiniello et al. 2013



Spiniello et al. 2011

THE METHOD 2.
STELLAR POPULATION ANALYSIS: LINE-INDEX MEASUREMENTS

Spiniello et al. 2013

Barnabè et al. 2012

We measure EWs of several indices :

Hβ, Mgb, Fe5270, Fe5335, bTiO, aTiO, TiO1, TiO2, CaH1,CaH2, (and NaD)

We compare each galaxy spectrum with grids of SSPs models

8 log(t){0.5 - 1.15Gyr} × 13 [α/Fe]{-0.2,+0.4} × 18 IMF{1.8,3.5} × 9 $T_{eff,RGB}$ {-200K, 200K}

Probability density function (PDF) via the Likelihood function :

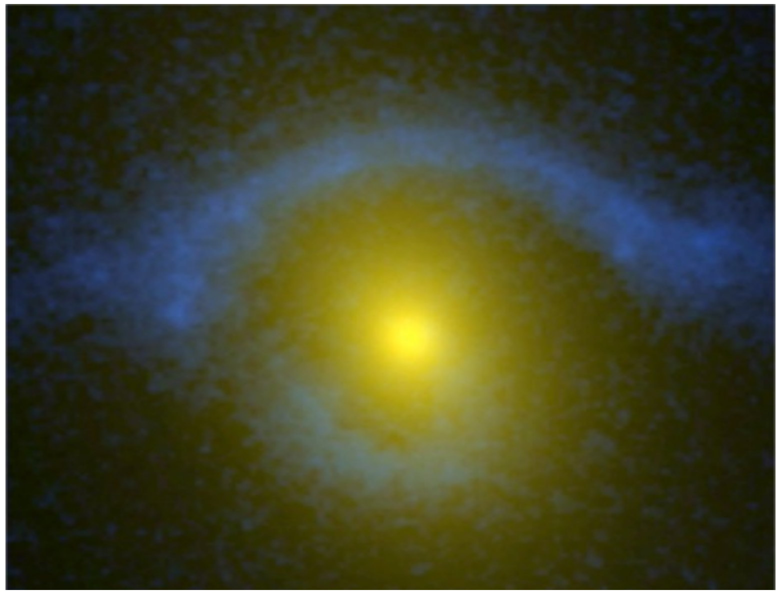
$$L \propto \exp(-\chi^2/2)$$

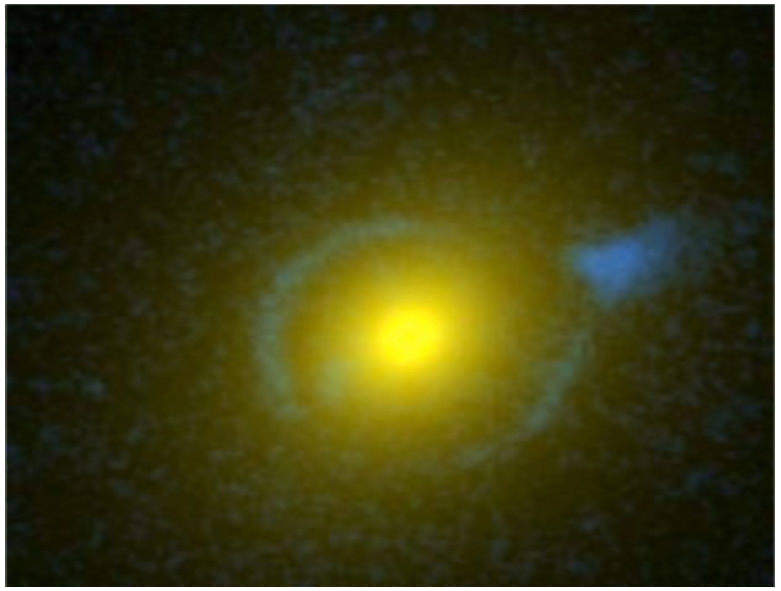
$$\chi^2_n = \sum_{ind=1}^{10} \chi^2_{ind,n} = \sum_{ind=1}^{10} \frac{(EW_{ind} - EW_n)^2}{\sigma^2_{EW_{ind}}}$$

FIRST RESULTS: A PILOT PROGRAM ON TWO MASSIVE XLENS GALAXIES

Barnabè, Spiniello et al. 2013

The most massive:	The least massive:
SDSSJ0912	**SDSSJ0936**



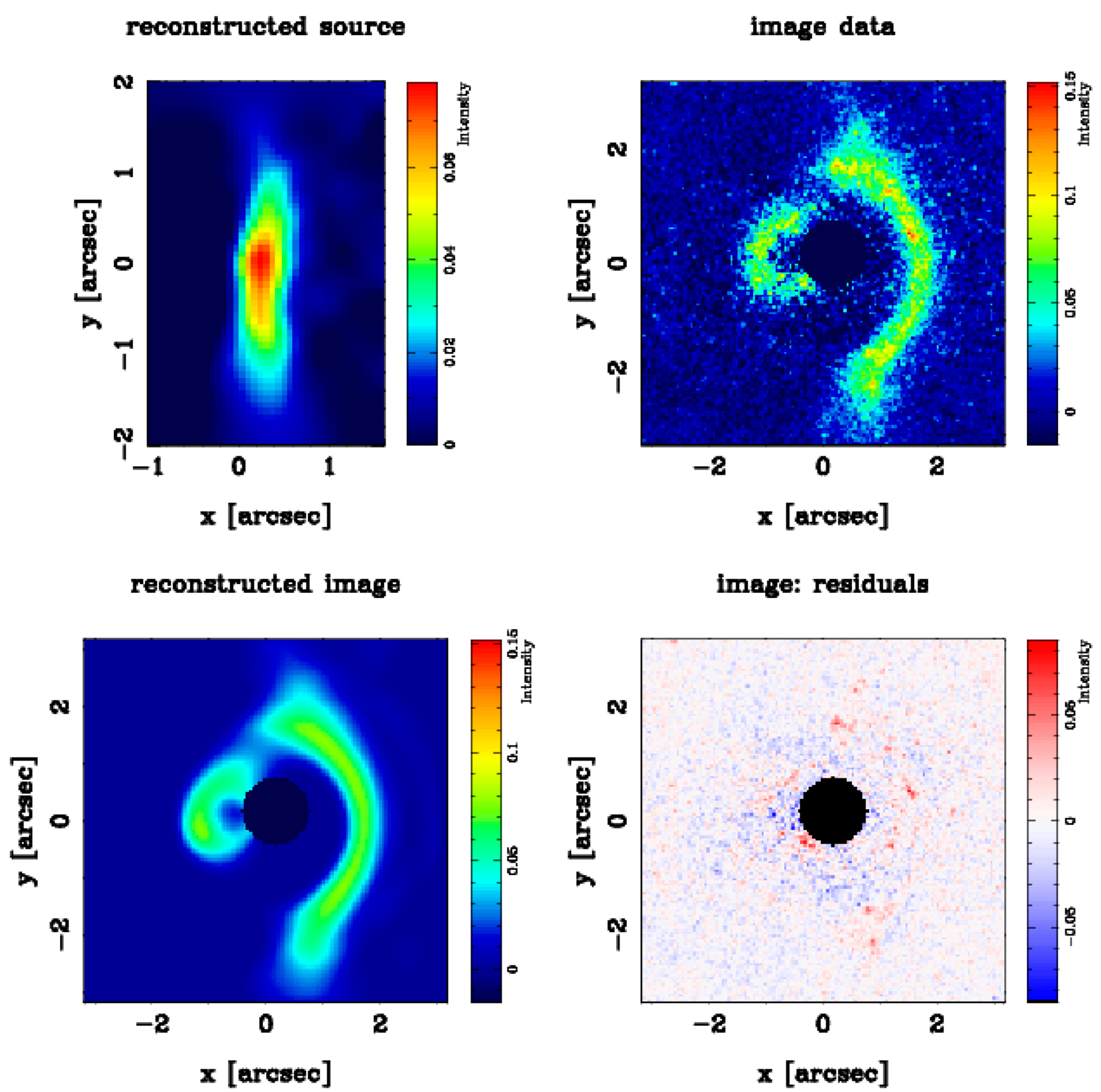


$\sigma \sim 330$km/s	$\sigma \sim 250$km/s

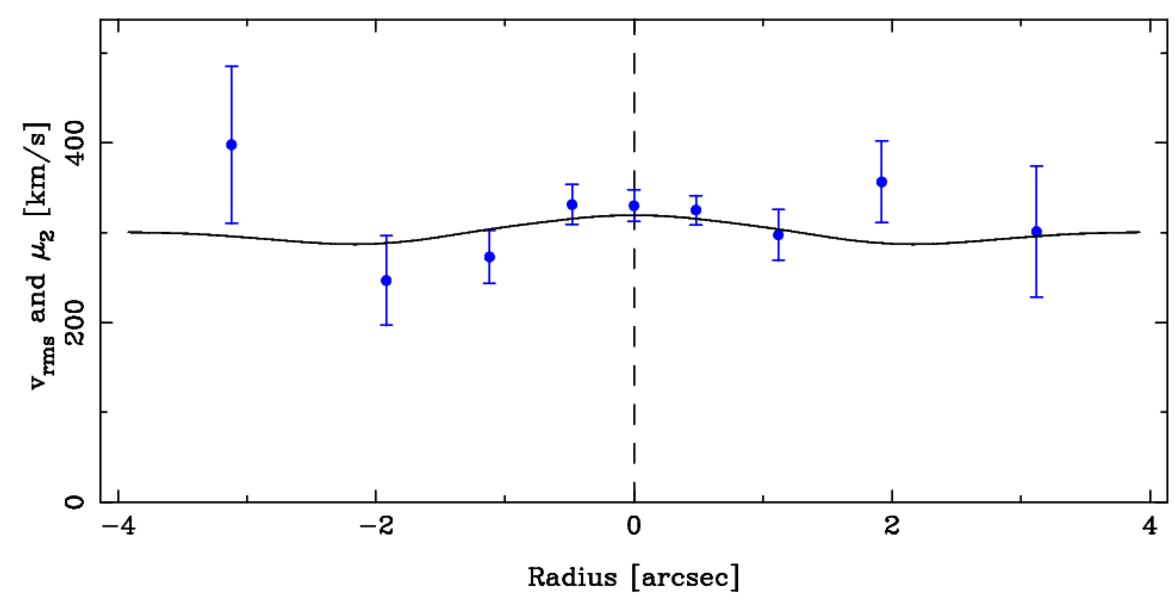
X LENS + Combined Algorithm for Unified Lensing and Dynamics ReconstructiON

SDSSJ0912

GRAVITATIONAL LENSING



STELLAR KINEMATICS



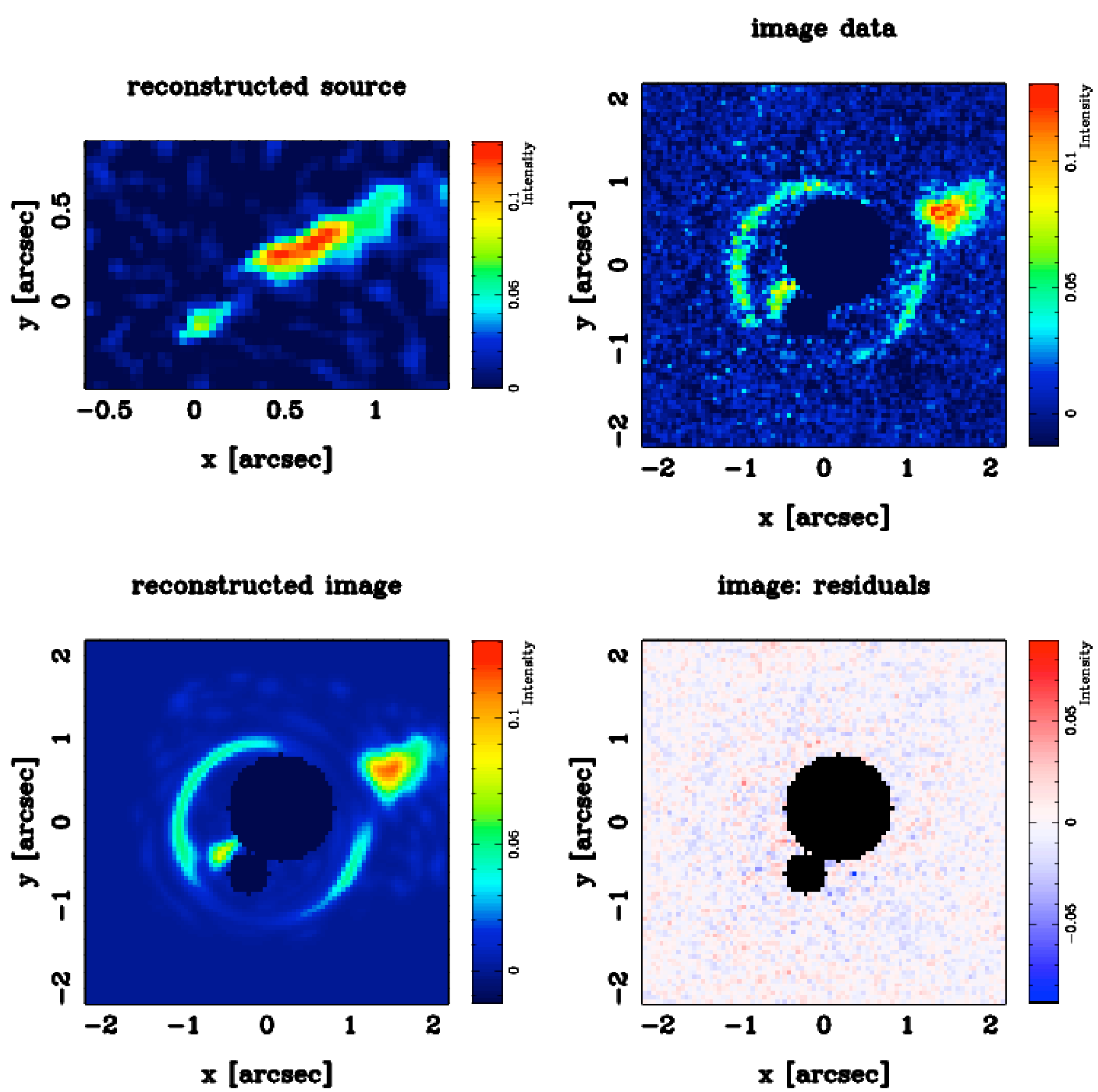
z_{lens}	z_{BG}	R_{eff}(kpc)	R_{Ein} (kpc)	M_V (mag)
0.1642	0.3239	10.8	4.58	16.56

$$\sigma_* = 326 \pm 13 \text{ km/s}$$

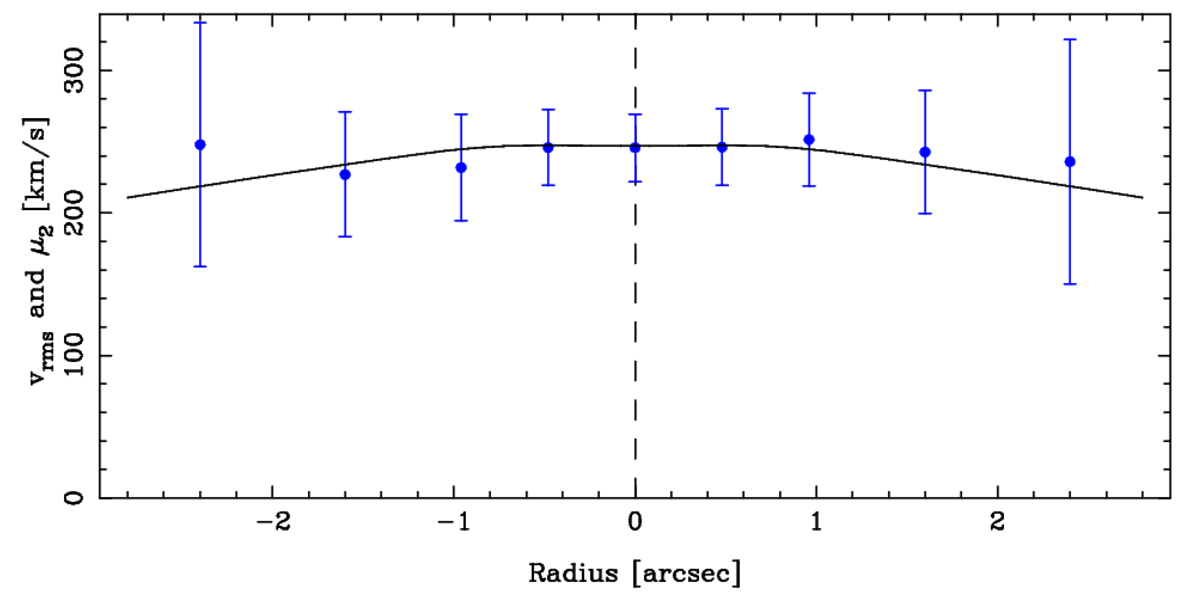
$$f_{DM} (1 R_{eff}) = 0.20 \pm 0.08$$

SDSSJ0936

GRAVITATIONAL LENSING



STELLAR KINEMATICS



z_{lens}	z_{BG}	R_{eff}(kpc)	R_{Ein} (kpc)	M_V (mag)
0.1897	0.5880	6.61	3.45	17.12

$\sigma_* = 326 \pm 13$ km/s

f_{DM} (1 R_{eff}) = 0.04±0.03

COMPLETELY BLIND ANALYSIS

Dark Cosmology Centre

Kapteyn Astronomical Institute
University of Groningen (NL)

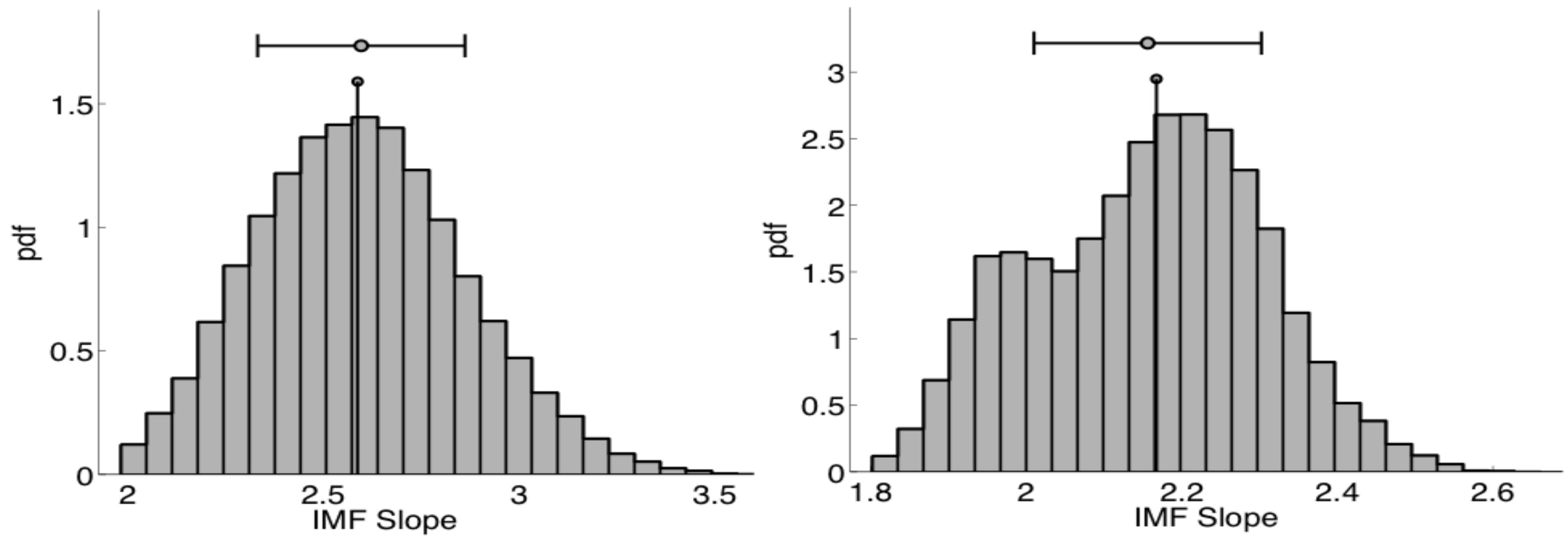
COMPLETELY BLIND ANALYSIS

1. Lensing & Dynamics

parameter	prior J0936	posterior J0936	prior J0912	posterior J0912
$v_{\rm vir}/{\rm km\,s}^{-1}$	U(0, 650)	49^{+64}_{-32}	U(0, 650)	385^{+115}_{-83}
γ	U(0, 2)	$1.04^{+0.64}_{-0.67}$	U(0, 2)	$0.53^{+0.50}_{-0.37}$
c_{-2}	U(0, 50)	18^{+17}_{-14}	U(0, 50)	$9.1^{+4.5}_{-3.5}$
$q_{\rm h}$	$L\mathcal{N}(1, 0.3)$	$0.94^{+0.29}_{-0.21}$	$L\mathcal{N}(1, 0.3)$	$0.54^{+0.09}_{-0.07}$
$M_\star/10^{11}M_\odot$	U(0, 10)	$3.41^{+0.09}_{-0.20}$	U(0, 35)	$10.12^{+0.67}_{-0.70}$
b	U(0, 5)	$0.88^{+0.34}_{-0.34}$	U(0, 5)	$1.94^{+0.21}_{-0.24}$

COMPLETELY BLIND ANALYSIS

2. Spectroscopy & SSP modeling

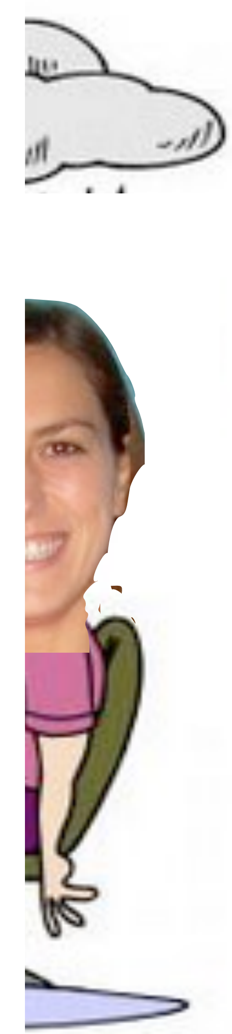


System	Log(Age) (Gyr)	[α/Fe]	IMF slope	$M^*_{M_{\rm low}=0.115}$ ($\times 10^{11} M_\odot$)
J0912+0029	1.1 ± 0.05	0.1 ± 0.03	2.6 ± 0.3	12.8 ± 0.4
J0936+0913	0.9 ± 0.05	0.05 ± 0.02	2.1 ± 0.15	3.01 ± 0.03

COMPLETELY BLIND ANALYSIS

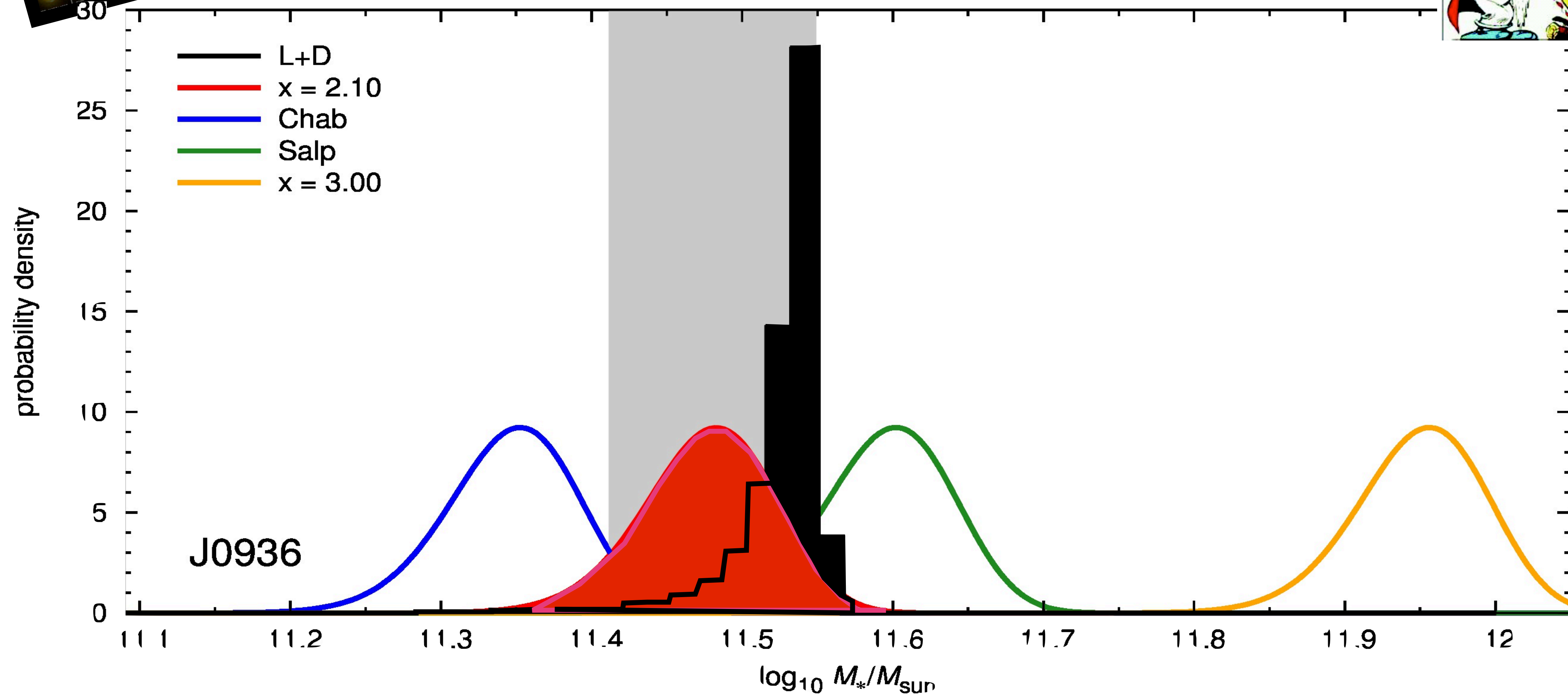
Dark Cosmology Centre

Kapteyn Astronomical Institute
University of Groningen (NL)



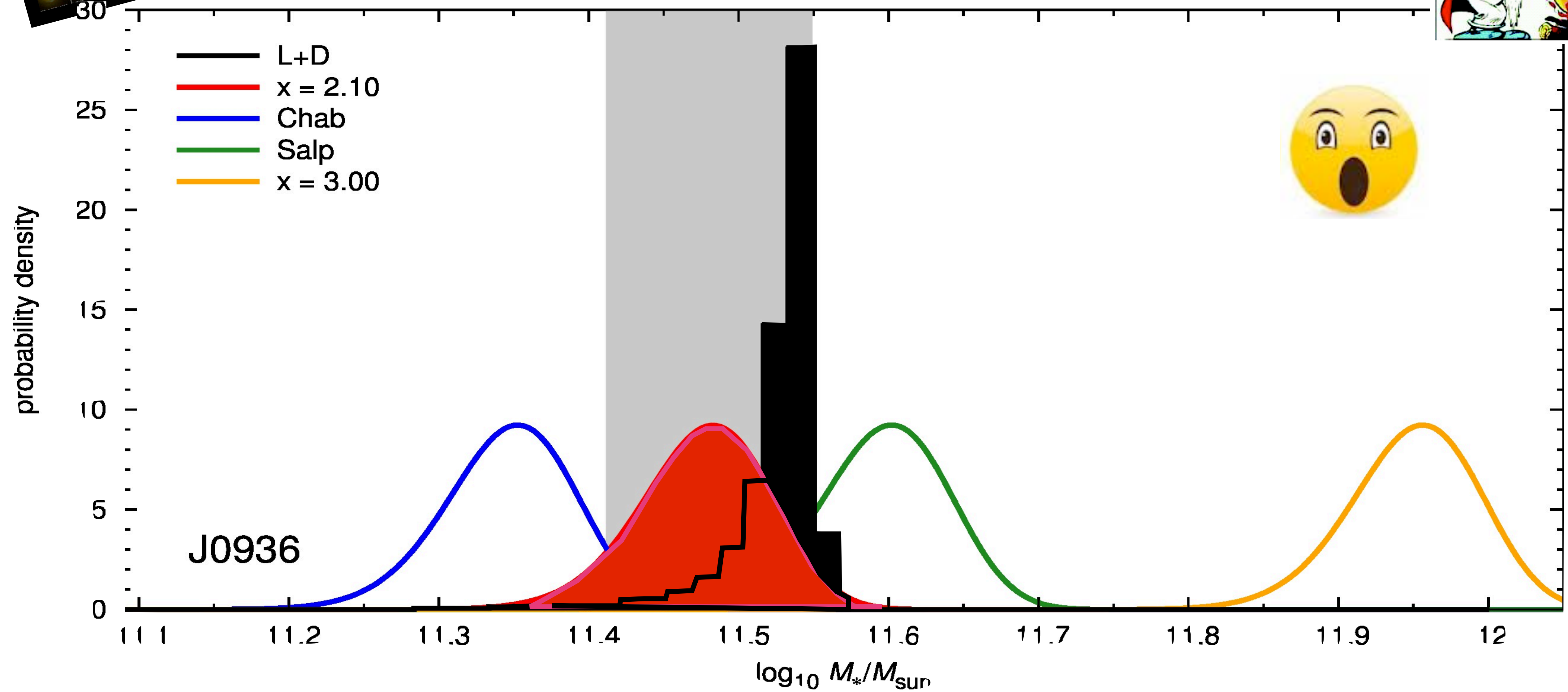
ical Institute
ingen (NL)

SDSSJ0936



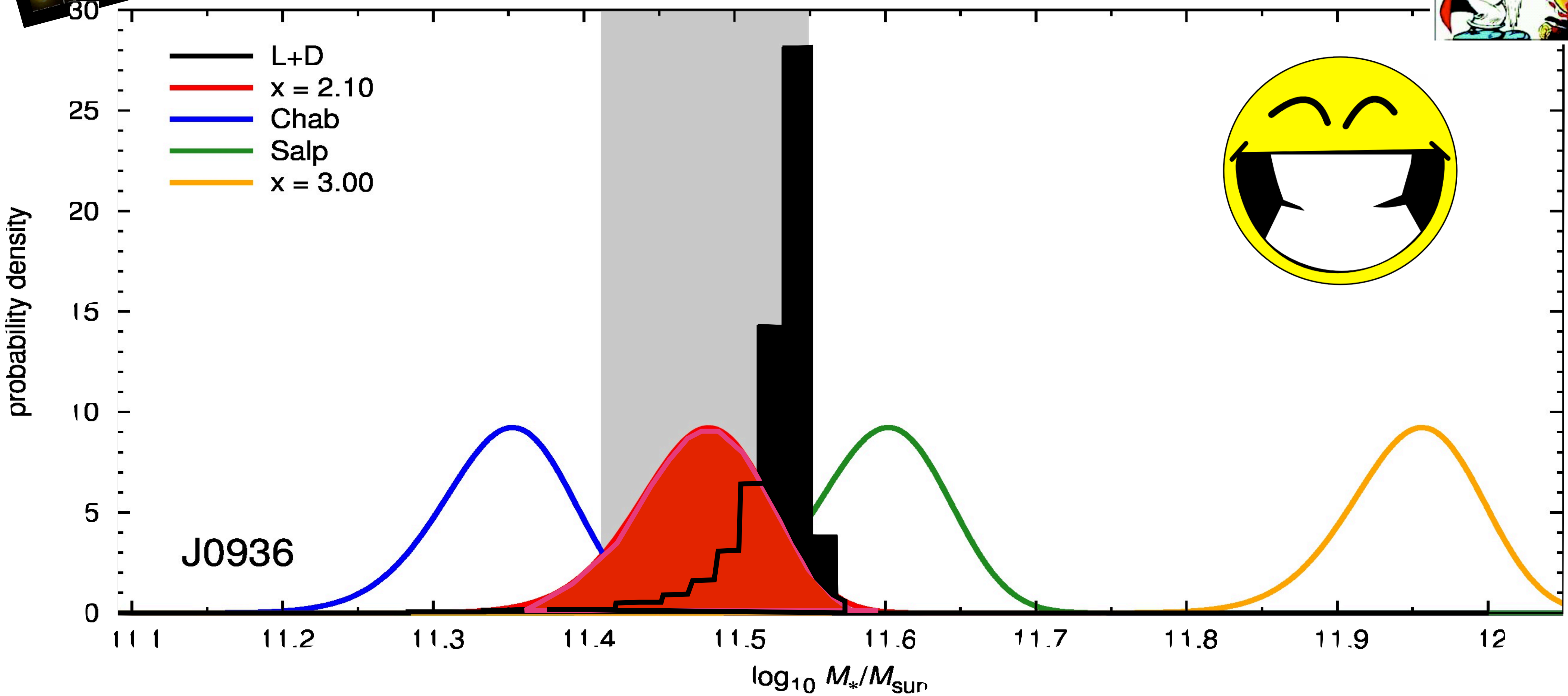
- The stellar masses inferred from the spectroscopic single stellar population (SSP) modelling based on line-strength indices is fully consistent with the *independent* inferences from the combined lensing and dynamics study (which makes no assumptions on the IMF)

SDSSJ0936



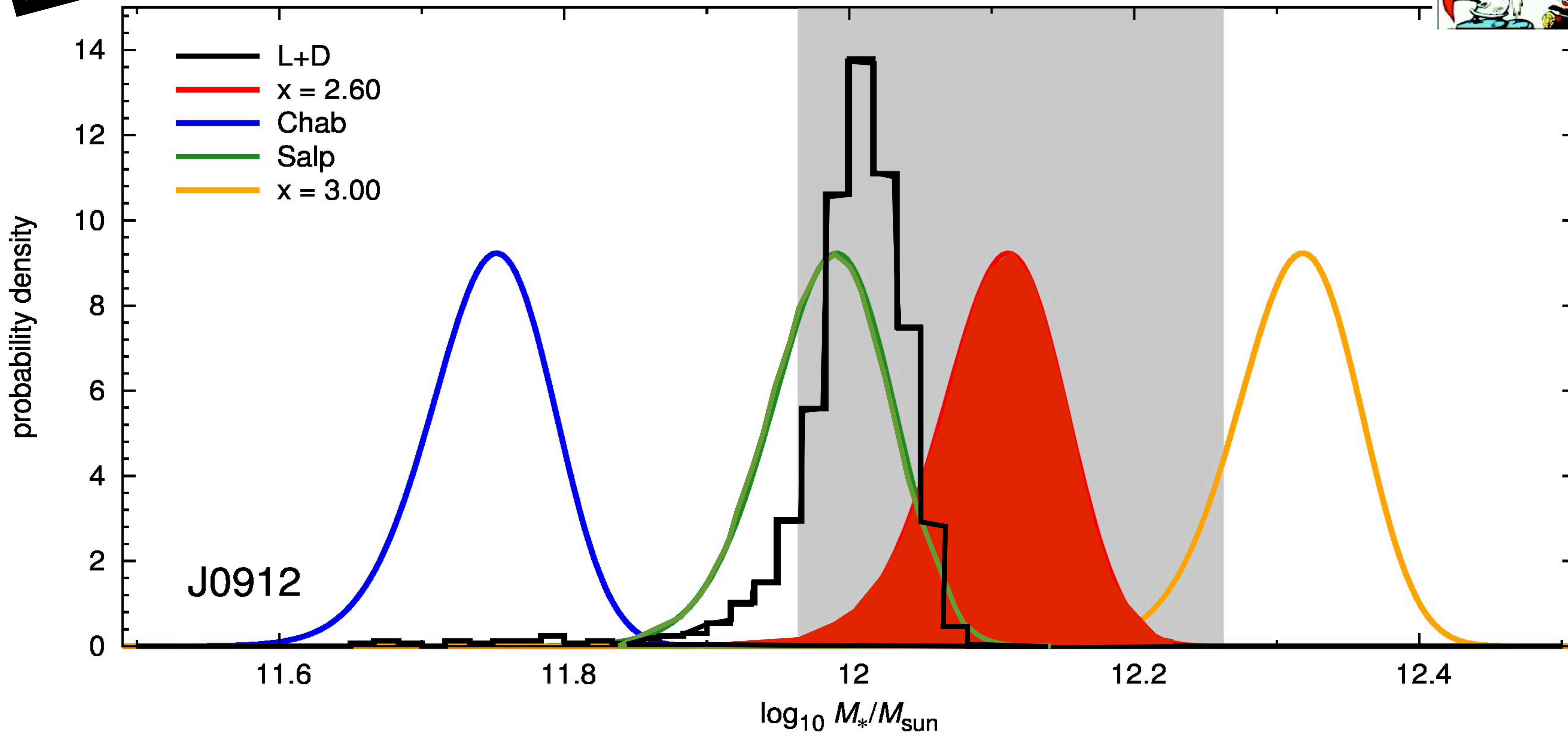
- The stellar masses inferred from the spectroscopic single stellar population (SSP) modelling based on line-strength indices is fully consistent with the *independent* inferences from the combined lensing and dynamics study (which makes no assumptions on the IMF)

SDSSJ0936



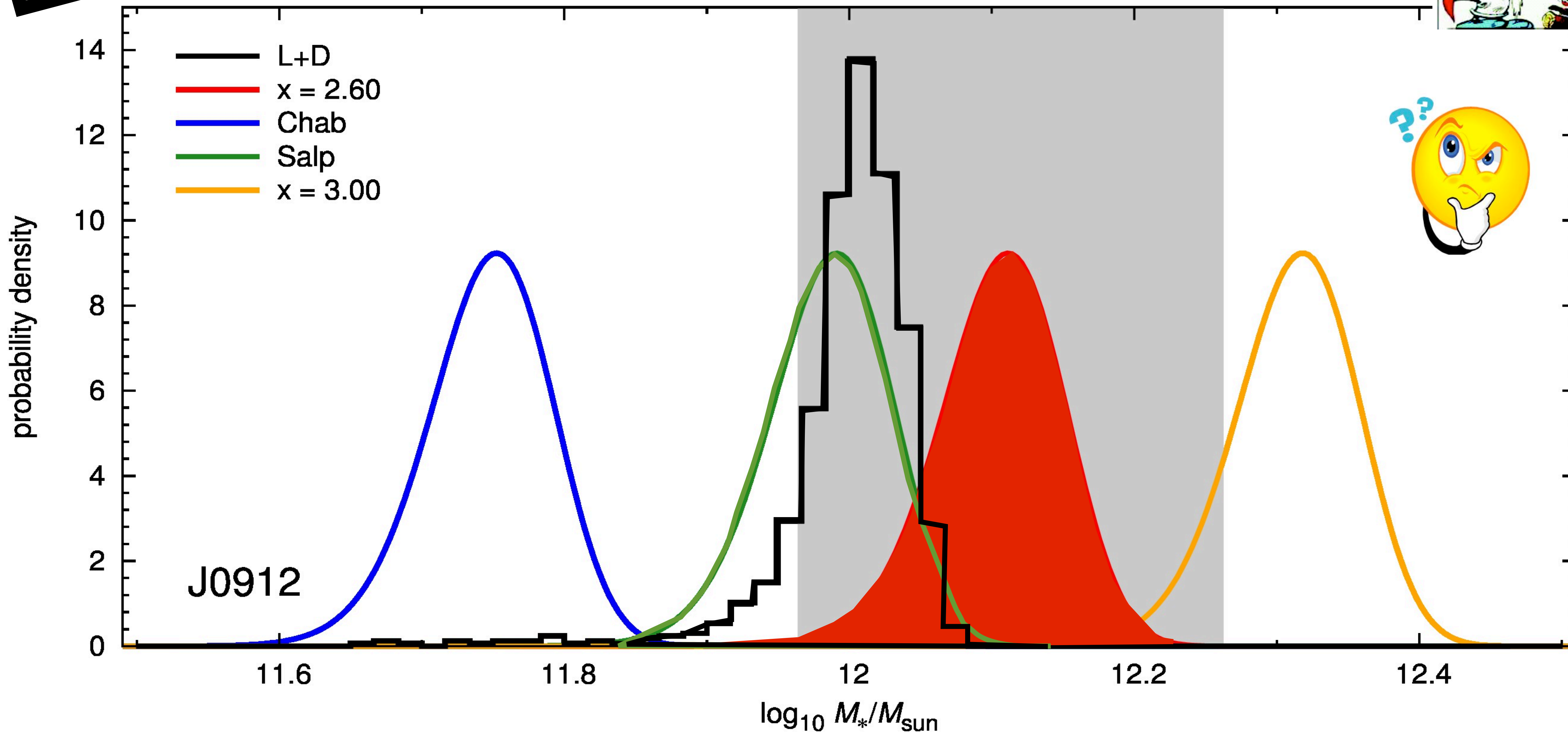
- The stellar masses inferred from the spectroscopic single stellar population (SSP) modelling based on line-strength indices is fully consistent with the *independent* inferences from the combined lensing and dynamics study (which makes no assumptions on the IMF)

SDSSJ0912

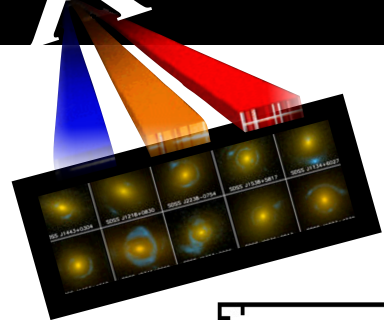


- Line-index-based stellar mass higher than the L&D one
- **IMFs significantly steeper than Salpeter (“bottom-heavy”, x ≥ 3.0) are ruled out with decisive evidence: Bayes factor *B* > 1000**

SDSSJ0912



- Line-index-based stellar mass higher than the L&D one **WHY?**
- **IMFs significantly steeper than Salpeter ("bottom-heavy", x ≥ 3.0) are ruled out with decisive evidence: Bayes factor *B* > 1000**



SDSSJ0912

- Line-in ... &D one **WHY?**
- **IMFs signif... y", x ≥ 3.0) are ruled out with decisive evidence: Bayes factor *B* > 1000**

THE LOW CUTOFF MASS

Using a (or more) set of isochrones and stellar libraries stellar population synthesis models construct the integrated light spectra:

$$f(\lambda) = \int_{m_l}^{m_h(t)} s(\lambda, m)\,\phi(m)\,dm$$

where φ(m) is the <u>IMF</u>:

$$\Phi(m) = \frac{dN}{dM} = M^{-x}$$

THE LOW CUTOFF MASS

Using a (or more) set of isochrones and stellar libraries stellar population synthesis models construct the integrated light spectra:

$$f(\lambda) = \int_{m_l}^{m_h(t)} s(\lambda, m)\,\phi(m)\,dm$$

where φ(m) is the <u>IMF</u>:

$$\Phi(m) = \frac{dN}{dM} = M^{-x}$$

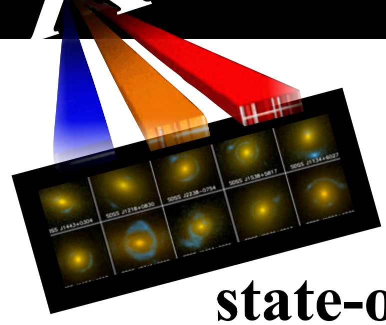
LOWER-MASS LIMIT

Until now fully unconstrained parameter, despite critical to determine stellar M/L.

<u>Different codes -> different assumptions !!!</u>

<u>Impossible to determine Mlow from spectroscopic studies alone</u>

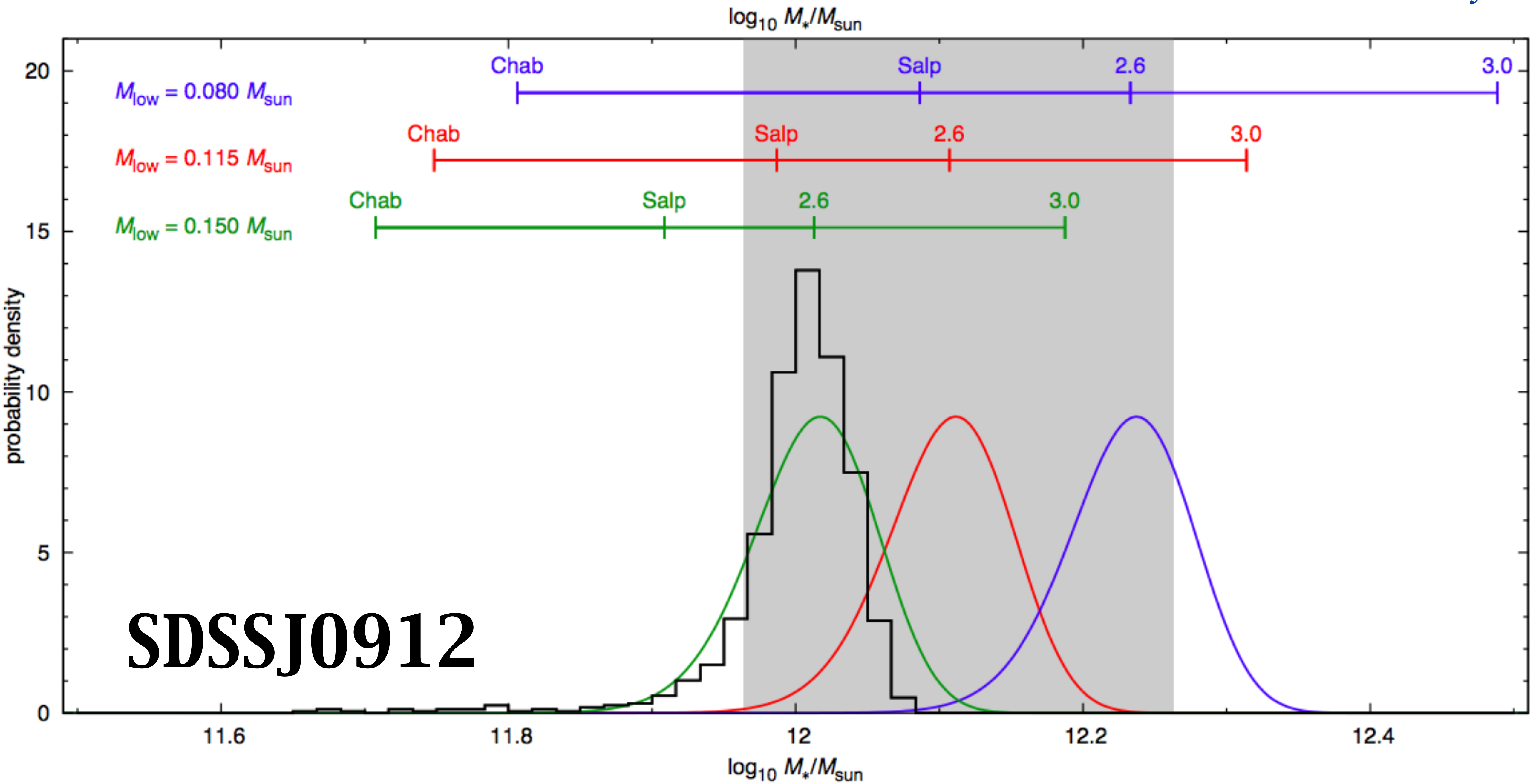
Stars with masses below ~ $0.15 M_{\odot}$ have no effect on the spectral lines for any assumed IMF slope (*CvD12*)...but they give a non-negligible contribution to the total mass budget of the system (*Worthey 1994*).



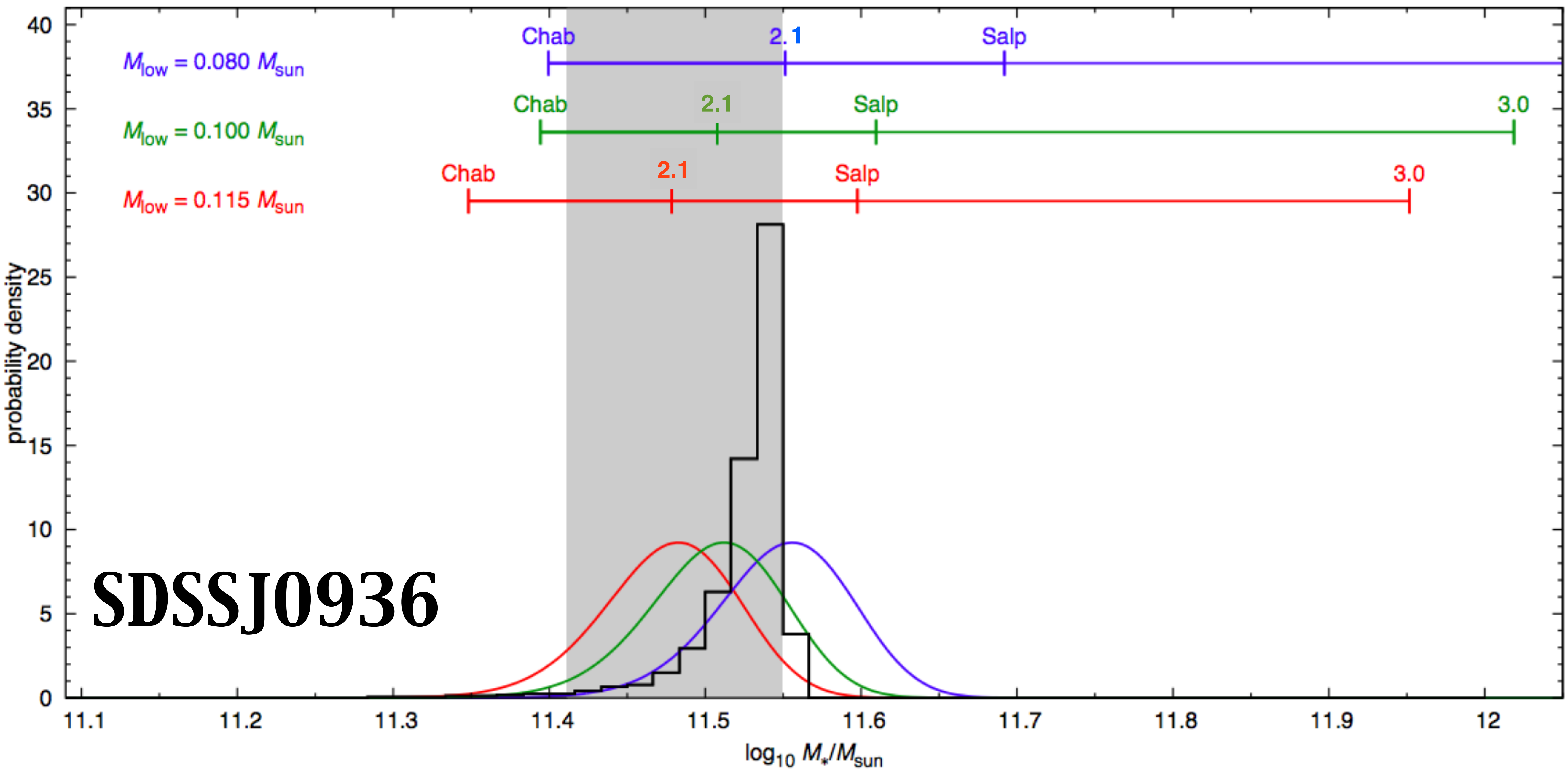
THE LOW CUTOFF MASS

We calculate (M/L)* using the isochrones at solar [Fe/H] from the state-of-the-art stellar evolution code Dartmouth Stellar Evolution Program selecting IMF slope, age, and [α/Fe] inferred from the line-strength analysis

DSEP, Chaboyer+01



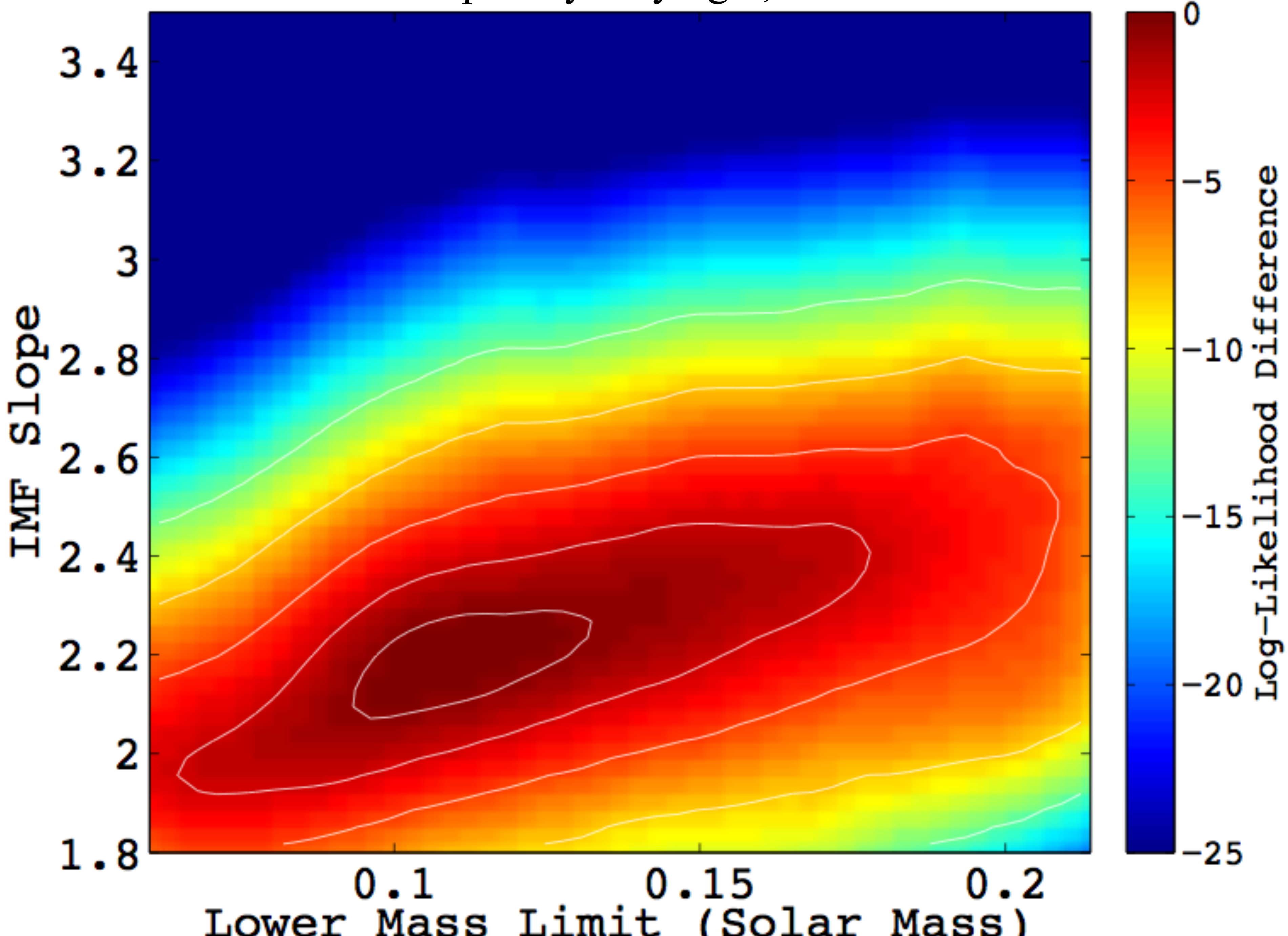
THE LOW CUTOFF MASS



FINAL JOINT PDF

MCMC to sample the joint lensing, dynamics and SSP posterior.

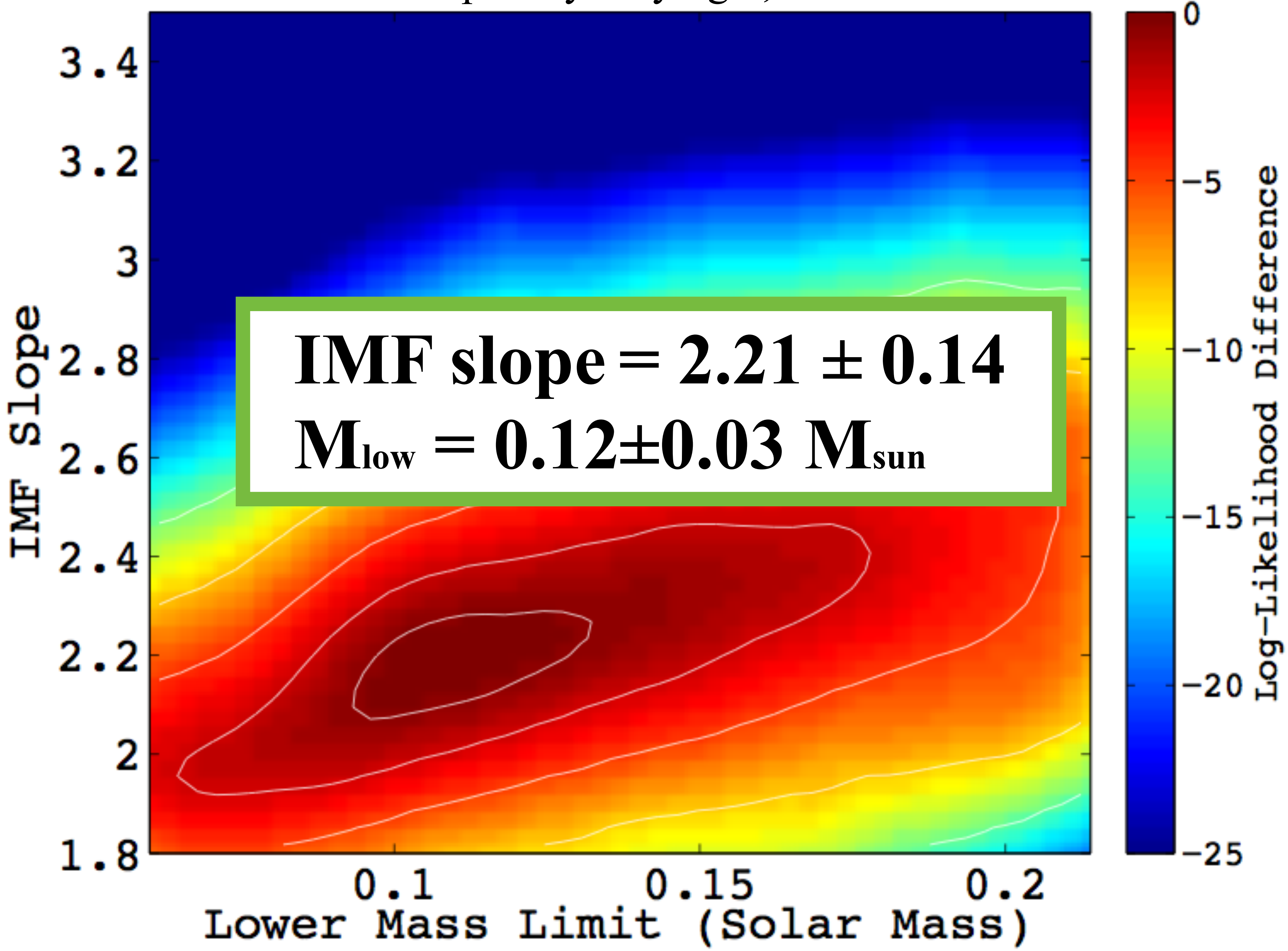
- 100000 samples by varying **x, Mlow and LV** -



FINAL JOINT PDF

MCMC to sample the joint lensing, dynamics and SSP posterior.

- 100000 samples by varying **x, Mlow and LV** -



CONCLUSION

- The inferences on stellar masses from two independent methods are consistent
- SSP modeling suggests a steepening of the IMF slope with mass (more data are coming!)
- First constraint on low-mass cutoff of the IMF

  $M_{low} = 0.12 \pm 0.03\ M_{sun}$
- The joint inference on the

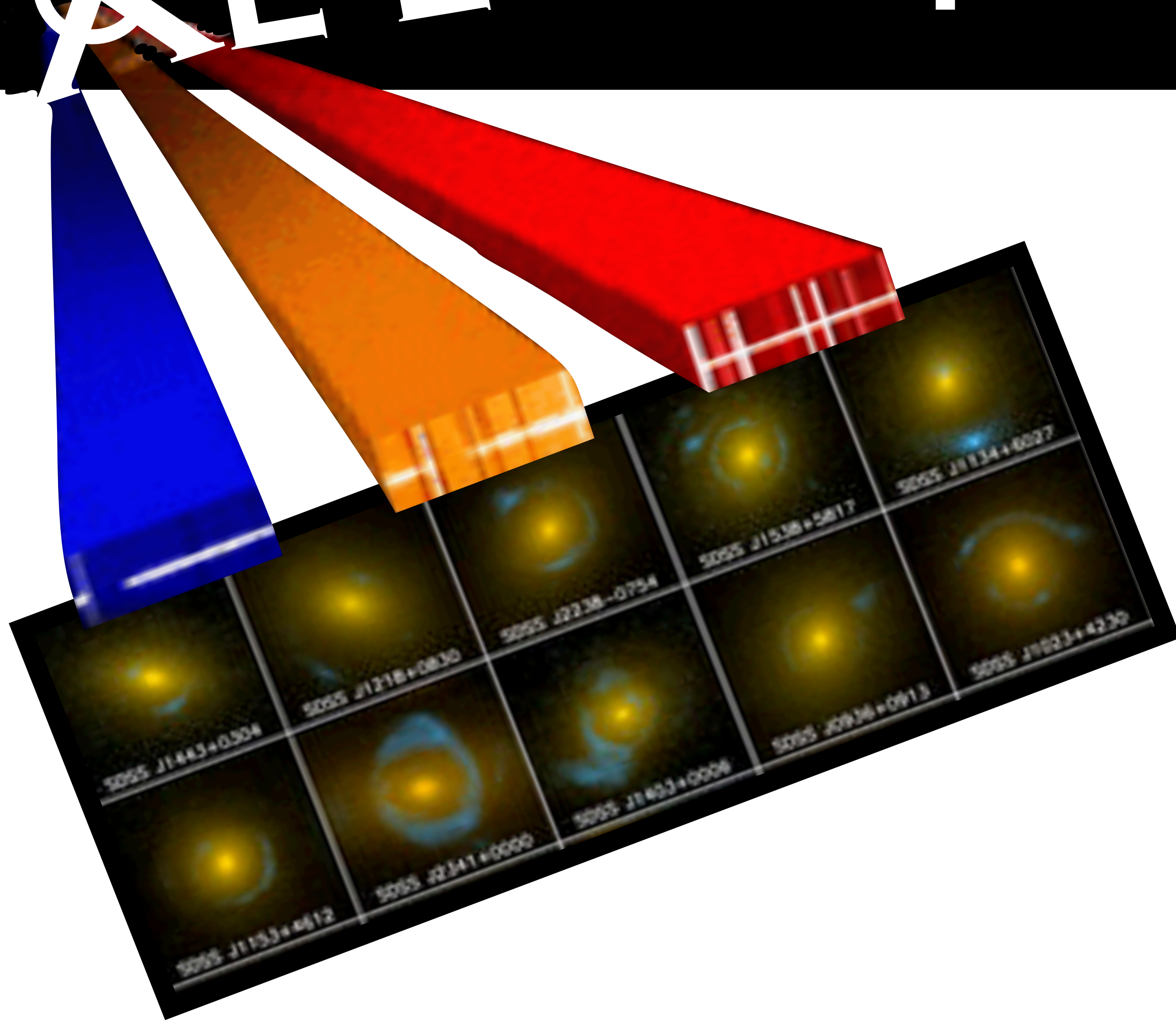
  IMF slope = 2.21 ± 0.14

  is consistent with Salpeter

A special thank to Matteo Barnabè

LENS +

Combined Algorithm for Unified Lensing and Dynamics ReconstructiON



THE END