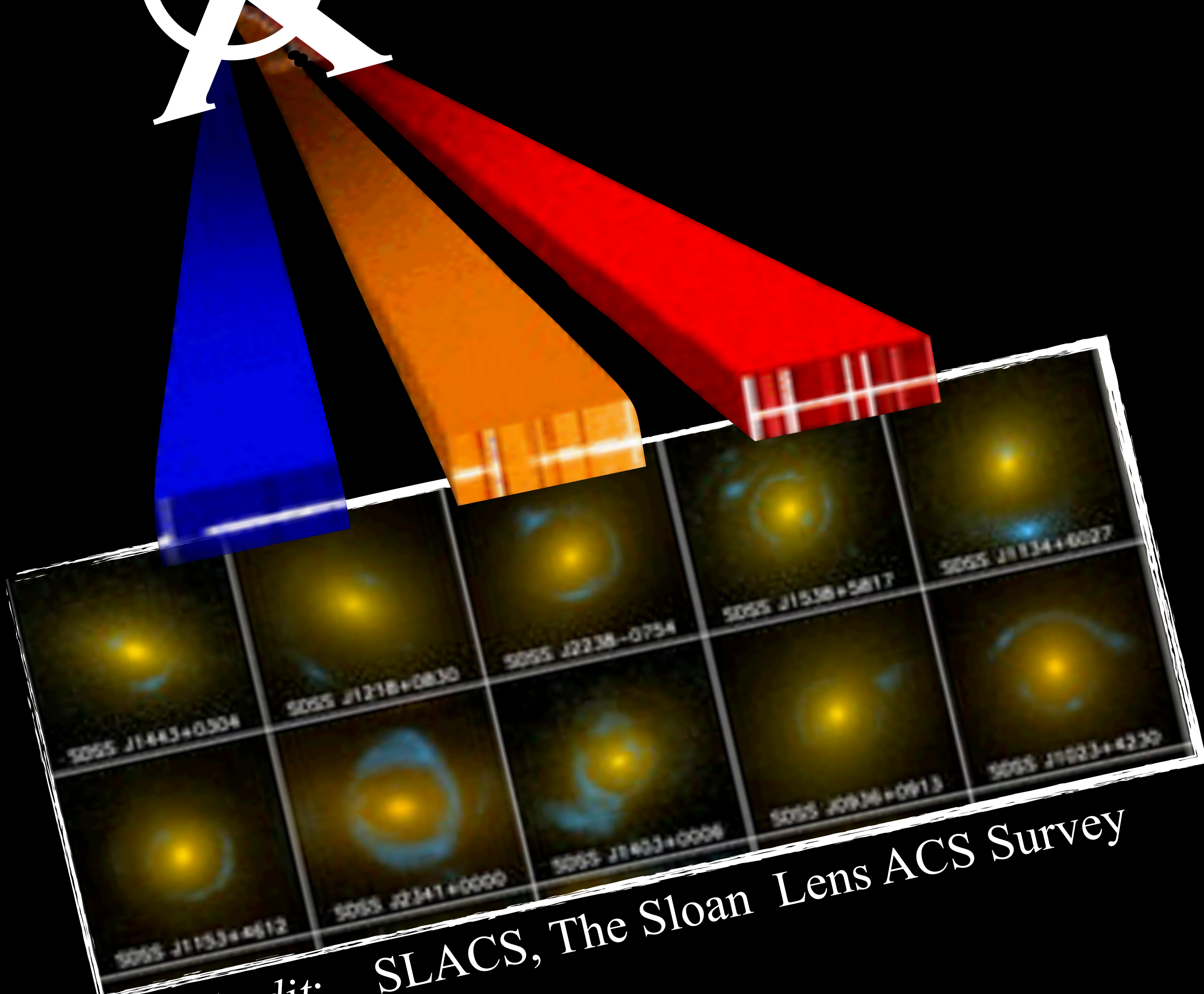
The X-Shooter Lens Survey

XLENS



Credit: SLACS, The Sloan Lens ACS Survey

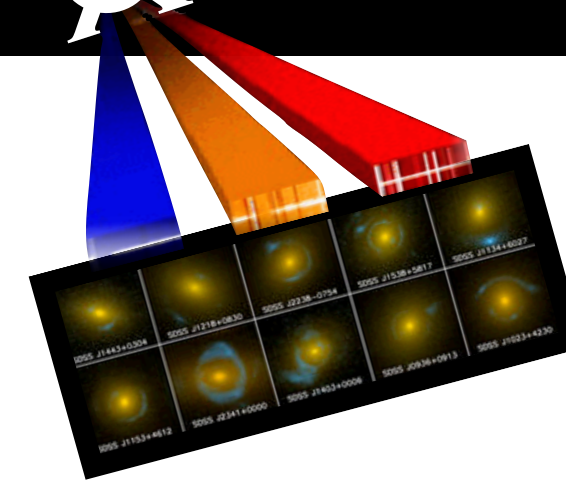
Chiara Spiniello

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

Kapteyn Astronomical Institute
University of Groningen (NL)

OVERVIEW

XLENS



1. Science goals and strategies

2. The method:

   Strong lensing + Dynamics + Stellar population

3. The goal

   Disentangle luminous from dark in internal region of massive ETGs

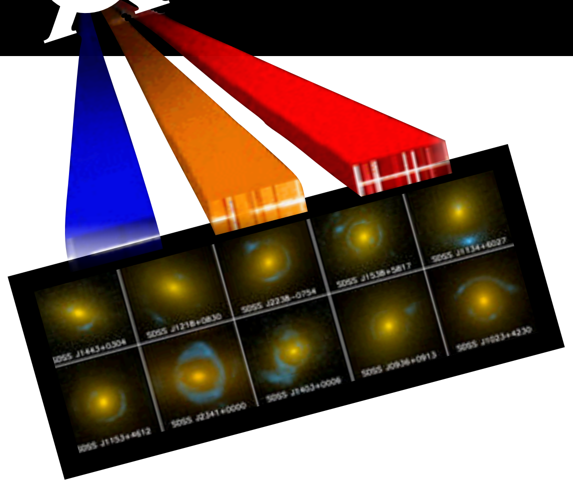
4. Results:

   Constraining the Initial Mass Function directly from galaxy spectra

5. Conclusions & Future works

OVERVIEW

XLENS



Spiniello et al. 2011, 2012, 2014b (in prep)

WHAT?

- Spectroscopically observe a sample of well studied massive lens ETGs ($z \approx 0.1 - 0.4$ and $\sigma_* > 250$ km/s), with multi-color HST data.
- Combine strong gravitational lensing with dynamics and stellar population.

SCIENTIFIC GOALS:

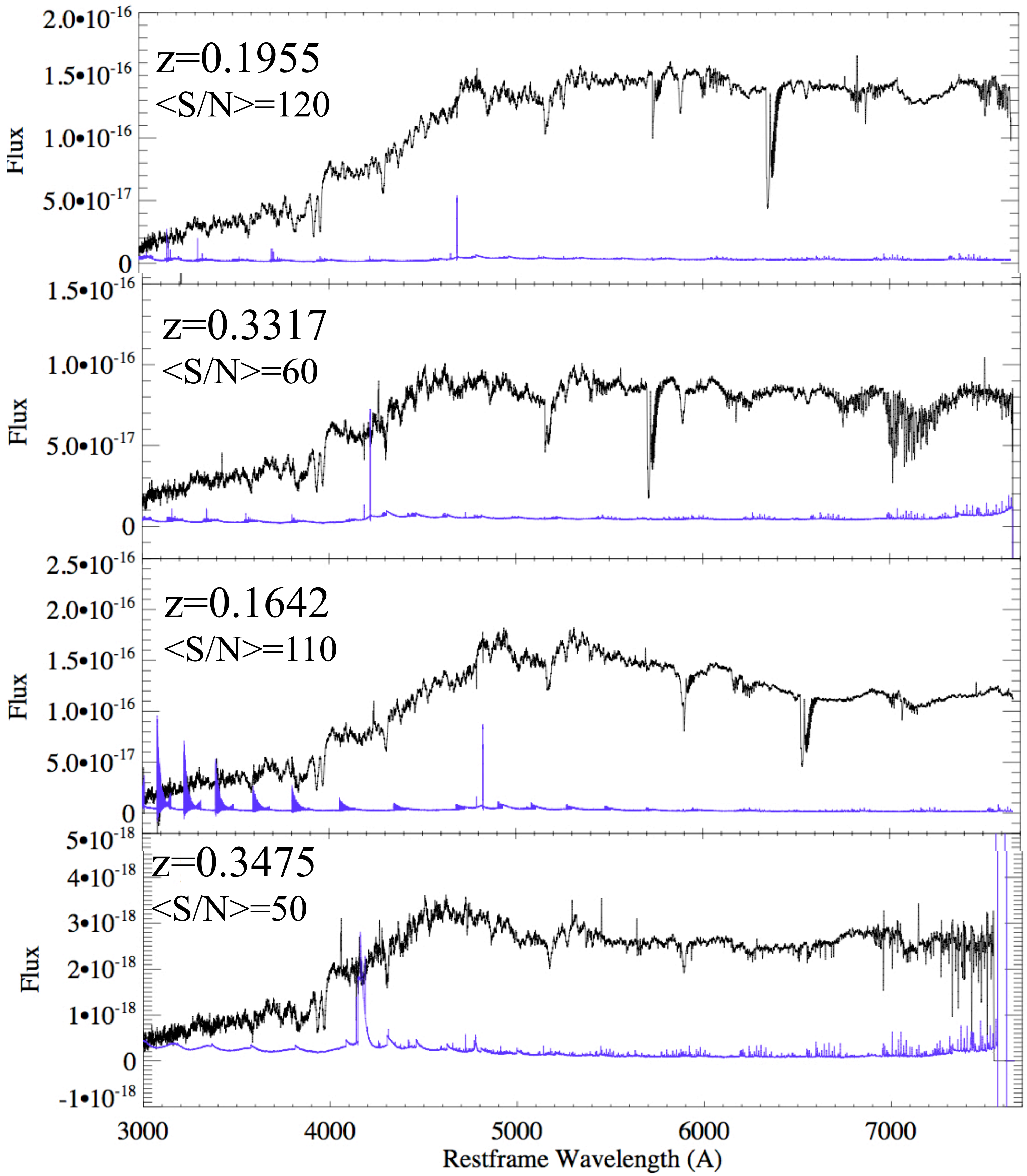
- Spatially resolved kinematics
- Disentangle stellar and dark-matter content
- Mass distrubution as function of galaxy mass and redshift
- Slope of the Initial Mass Function (IMF) ⟶ directly from spectra

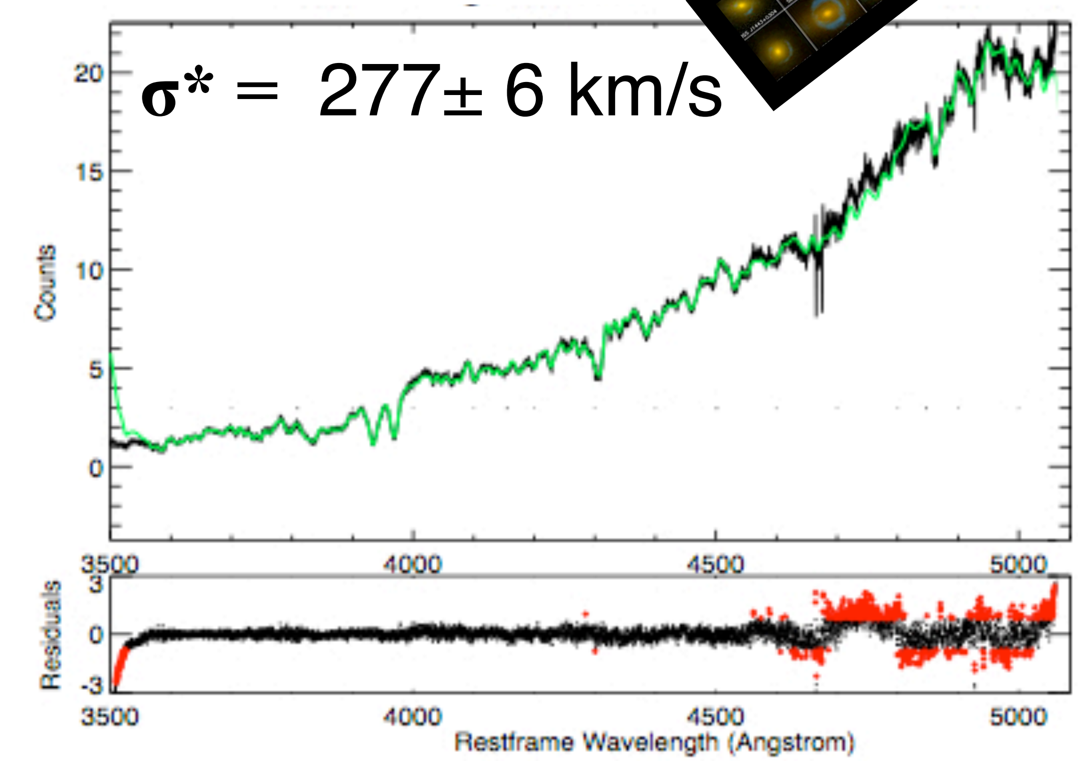
(Talk @ Special Session 12 "A fresh look at the stellar IMF")

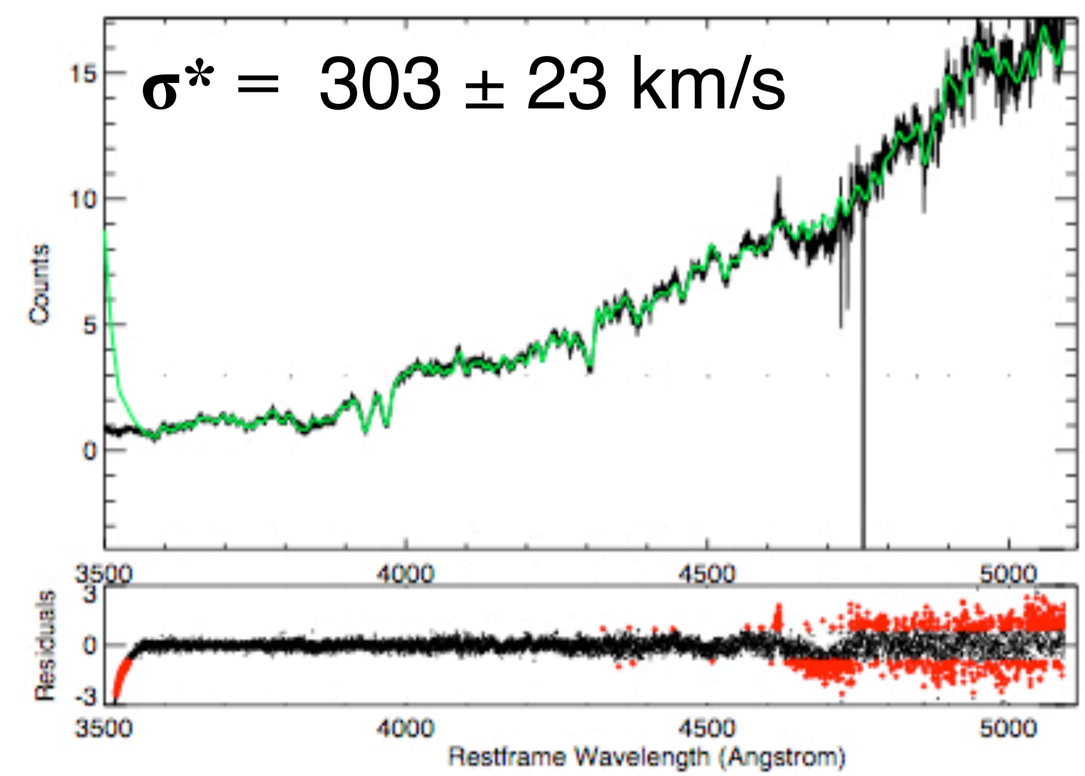
THE CURRENT SAMPLE I

SLACS System	z_{lens}	z_{BG}	R_{eff}(kpc)	R_{Ein} (kpc)	M_V (mag)	$\langle\sigma_{XSH}\rangle$ (km s^{-1})
Completed						
SDSSJ0037-0942	0.1955	0.6322	7.03	4.95	16.90	277 ± 6
SDSSJ0044+0113	0.1196	0.1965	5.56	1.72	16.32	260 ± 8
SDSSJ0216-0813	0.3317	0.5235	12.6	5.53	18.36	327 ± 19
SDSSJ0912+0029	0.1642	0.3239	10.8	4.58	16.56	325 ± 10
SDSSJ0935-0003	0.3475	0.4670	20.7	4.26	17.71	380 ± 22
SDSSJ0936+0913	0.1897	0.5880	6.61	3.45	17.12	256 ± 18
SDSSJ0946+1006	0.2219	0.6085	8.33	4.95	17.78	300 ± 22
SDSSJ1143-0144	0.1060	0.4019	9.21	3.27	15.83	287 ± 18
SDSSJ1627-0053	0.2076	0.5241	6.66	...	16.91	303 ± 23
SDSSJ2343-0030	0.1810	0.4630	8.27	4.62	17.17	298 ± 21
On-going						
SDSSJ1112+0826	0.2730	0.6295	6.20	6.19	17.97	
SDSSJ020+1122	0.2822	0.5530	6.73	5.12	18.12	
XLENS-Pilot Program						
SDSSJ1148+1930	0.4440	2.3815	12.5	29.0	20.02	352±26

THE CURRENT SAMPLE I





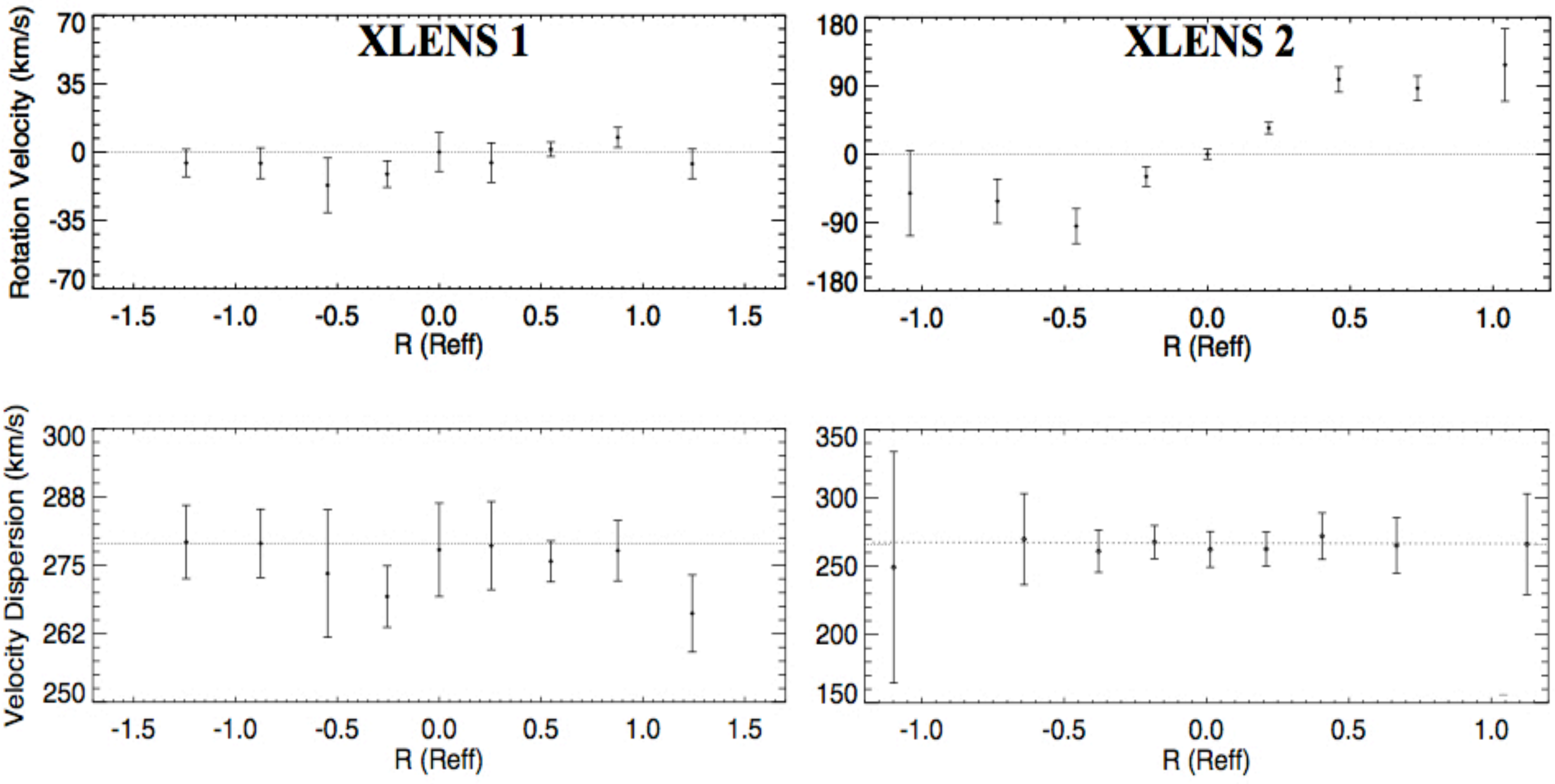


pPXF by *Cappellari & Emsellem 2004.*

THE CURRENT SAMPLE II

Spatially resolved kinematics profiles up to R_{eff}

Spiniello et al.2014b (in prep)



THE GOAL

Breaking the stellar mass - dark matter degeneracy

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Breaking the stellar mass - dark matter degeneracy

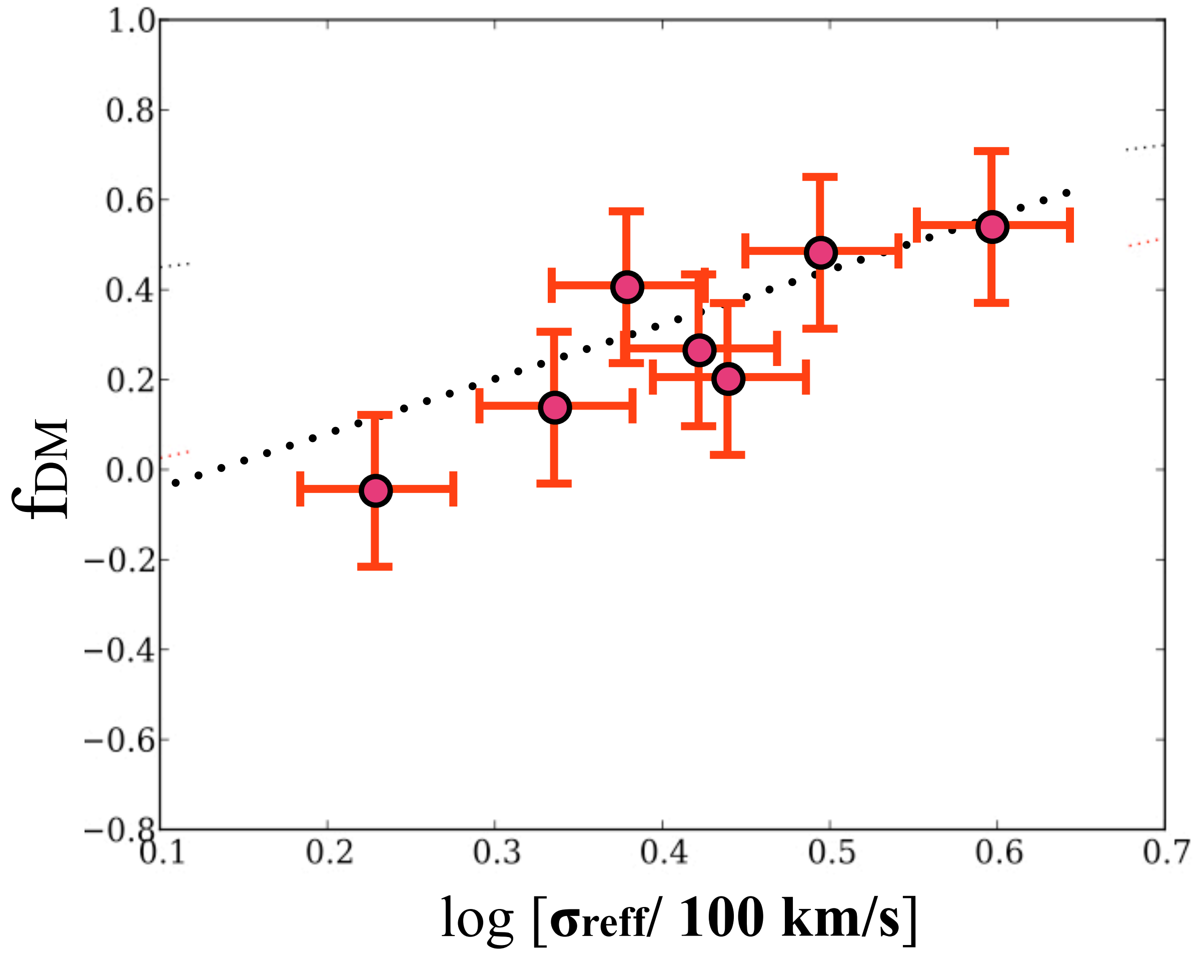
Is dark-matter in massive ETGs really dark or just invisible?

THE 1000000$ QUESTION

Do more massive Early-Type galaxies have...

More internal Dark Matter?

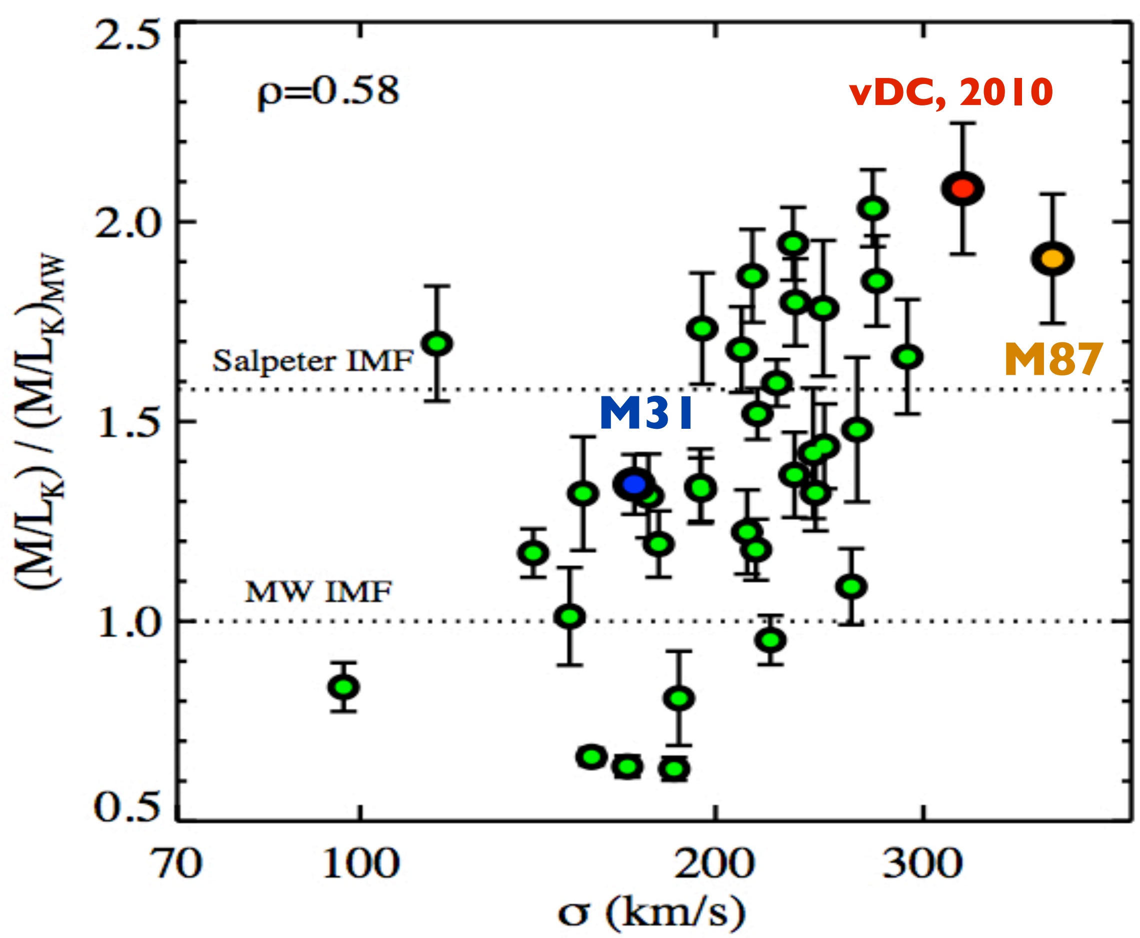
From lensing and dynamics + colors



Cappellari et al. 2006,
Auger et al. 2010

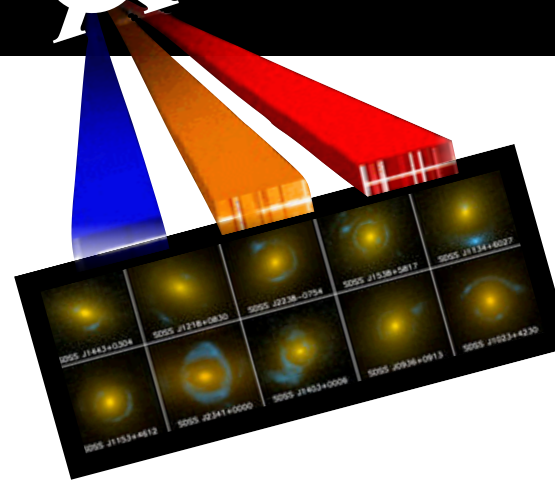
More stars with M < 0.3M☉ ?

NaI doublet and FeH Wing-Ford:



van Dokkum & Conroy 2010,
Conroy & van Dokkum 2012

THE METHOD I



Gravitational Lensing

GOOD

- Total mass within R_{Ein}
- Only gravity dependent

BAD

- Imposible to disentagle luminous from dark
- Mass-sheet degeneracy

Stellar Kinematics

GOOD

-Detailed analysis of the internal structure (Spatially resolved)

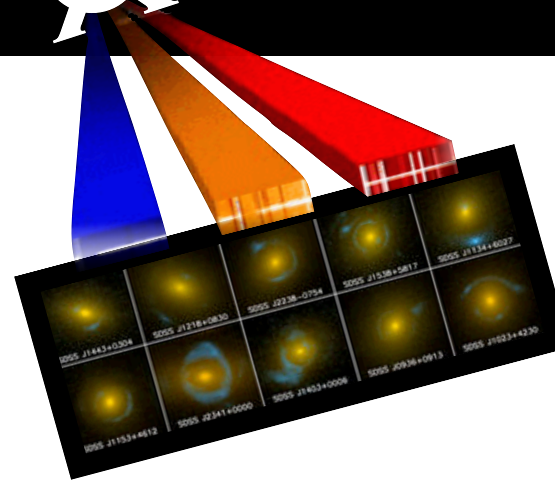
BAD

- Mass-anisotropy degeneracy
- Harder at higher redshift

TOTAL MASS

THE METHOD I

XLENS



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TOTAL MASS

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Stellar Population Analysis

GOOD
- Precise stellar mass
- Age and Z
- Accurate M/L

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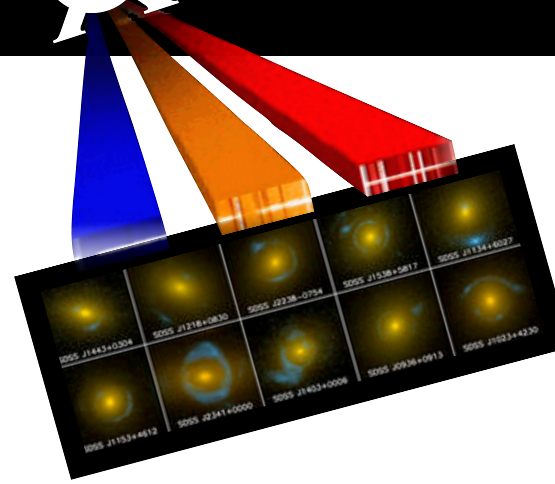
- High S/N spectra required (~75 Ang)
- Bad model in NIR

STELLAR MASS

THE METHOD I

XLENS



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TOTAL MASS - **STELLAR MASS**

DISENTANGLE LUMINOUS FROM DARK MATTER

THE METHOD II

SPATIALLY RESOLVED STELLAR KINEMATICS (X-Shooter)

+

STRONG GRAVITATIONAL LENSING

+

STELLAR POPULATION ANALYSIS

THE METHOD II

SPATIALLY RESOLVED STELLAR KINEMATICS (X-Shooter)
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STRONG GRAVITATIONAL LENSING

→ Precise total mass: upper limit on fraction of stellar mass inside R_{ein}
(no more than 100% in stars!)

→ With assumed luminosity profile

Upper limit on M/L

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STELLAR POPULATION ANALYSIS

→ With
assumed IMF

→ **Accurate stellar M/L**

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STELLAR POPULATION ANALYSIS

→ With assumed IMF → **Accurate stellar M/L**

<u>More BOTTOM-HEAVY IMF = higher M/L</u>
Low mass stars contribute > 60% on the stellar mass but only few % on the stellar light

THE METHOD II

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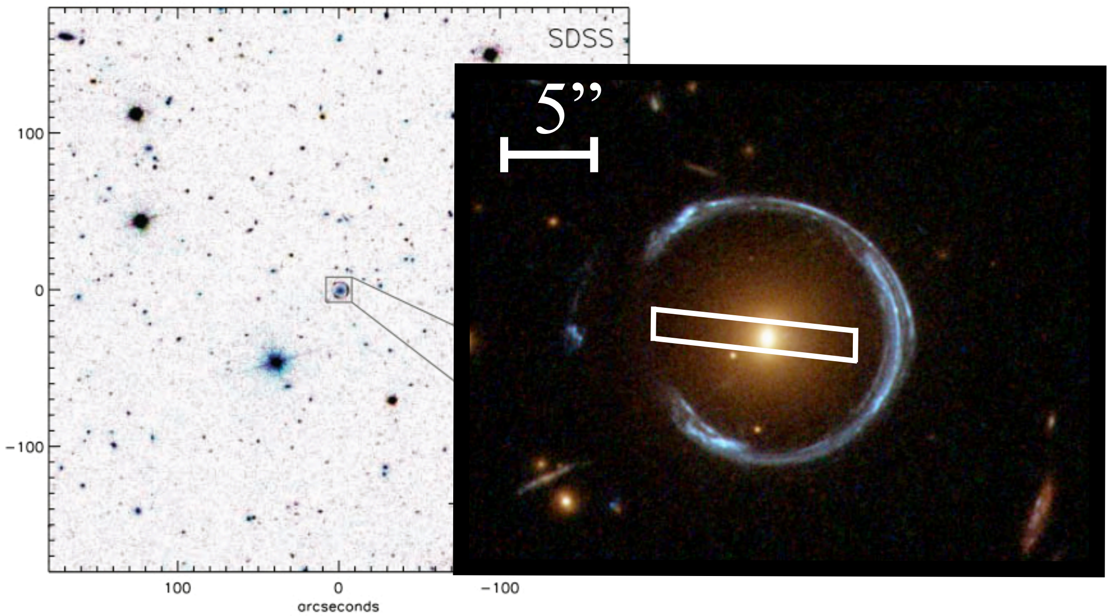
CONSTRAIN THE IMF SLOPE DIRECTLY FROM SPECTRA

RESULTS I

Spiniello et al. 2011

The Cosmic Horseshoe

SDSS 1148+1930



discovered by Belokurov+07

R_{eff} = 2.2" M_{ein} = $5.02 \times 10^{12} M_\odot$

R_{Ein} = 5.2" z_{lens} = 0.444

Stellar mass fraction within R_{Ein}

1. **From XSH spectra AND Lens mass model** $f^{*}_{\rm HQ} = 0.19^{+0.04}_{-0.09}$

RESULTS I

Spiniello et al. 2011

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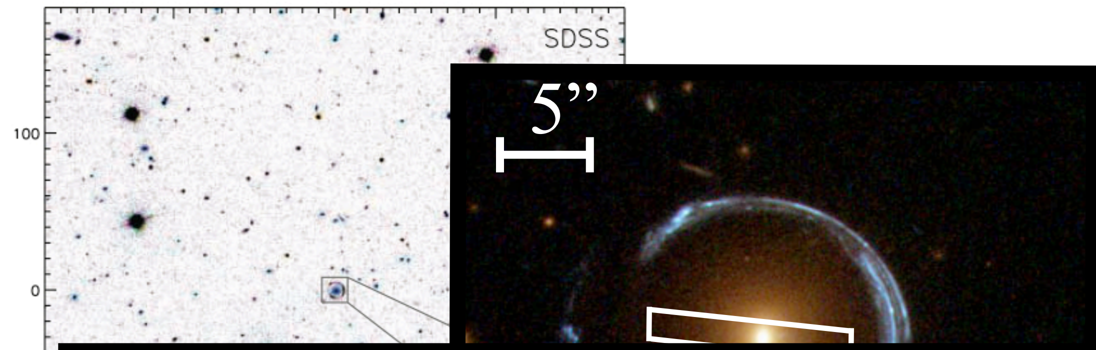

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Already Dark-Matter dominated within the Reff

$$f_{DM}(< R_{eff}) = 0.60^{+0.15}_{-0.06} \pm 0.1$$

Dark-matter fraction inside the effective radius

$R_{Ein} = 5.2”$ $z_{lens} = 0.444$

RESULTS I

Spiniello et al. 2011

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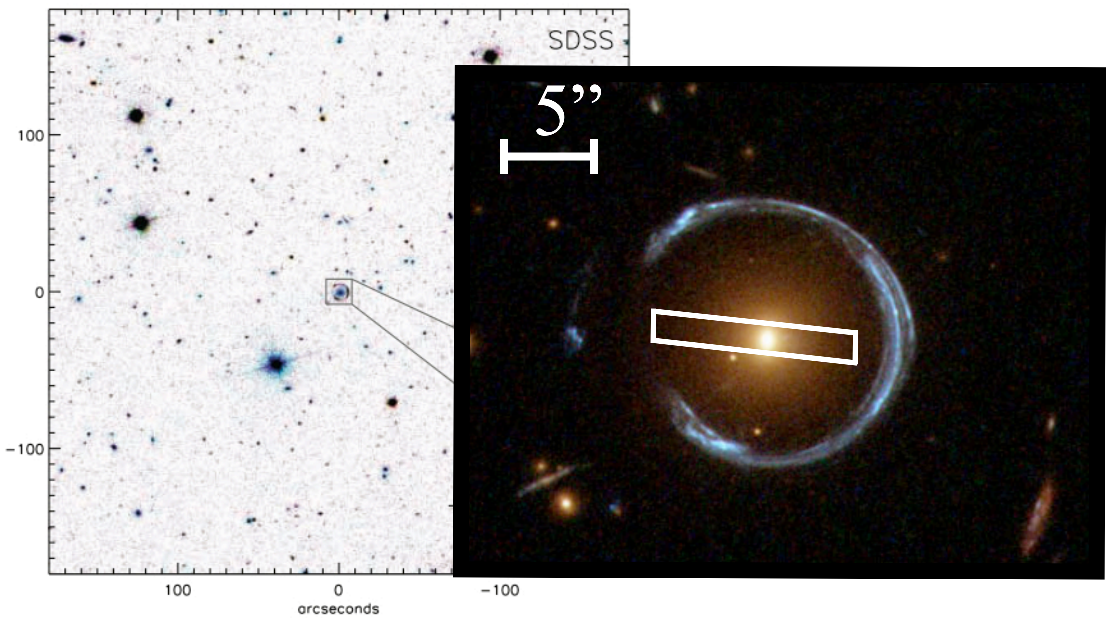

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$$f^{*}_{Chabrier} = M^{*}_{tot}/M^{Ein}_{tot} = 0.07 \pm 0.02$$

$$f^{*}_{Salpeter} = M^{*}_{tot}/M^{Ein}_{tot} = 0.17 \pm 0.06$$

$$f^{*}_{x=-3.0} = M^{*}_{tot}/M^{Ein}_{tot} = 0.30 \pm 0.11$$

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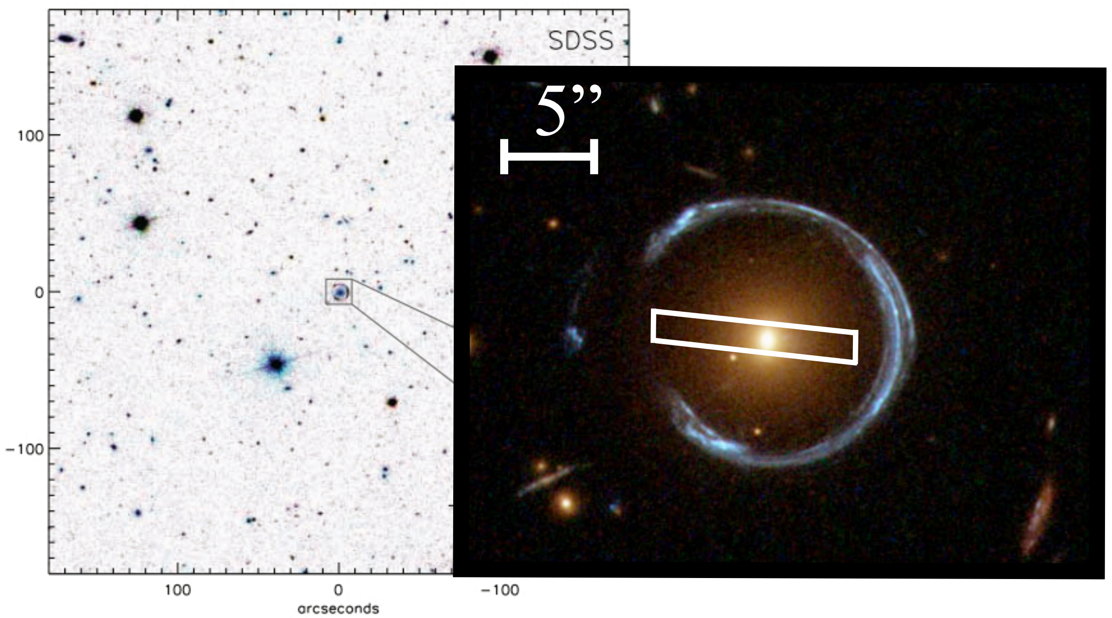

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➡ **Bottom-light IMF = too little mass in stars**
➡ **Bottom-heavy IMF = too much mass in stars** ⟶ **excluded at 90%CL** (consistent with ***Treu et al.,2010***)

RESULTS I

Spiniello et al. 2011

The Cosmic Horseshoe

SDSS 1148+1930

Stellar mass fraction within R_{Ein}

For a range in dynamical and stellar mass models,

<u>Salpeter IMF is fully consistent with all data.</u>

but this is just one galaxy...and we only used colors...

- ➡ **Bottom-light IMF = too little mass in stars**
- ➡ **Bottom-heavy IMF = too much mass in stars**

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(consistent with ***Treu et al.,2010***)

RESULTS II

Evidence for a mild steepening and bottom-heavy IMF in massive ETGs from Sodium and Titanium-Oxide indicators

Spiniello et al. 2012

DATA

SDSSJ0912+0029

$\langle\sigma\rangle$ = 312±12 km/s z = 0.1642

R_{Ein} = 3.87kpc

SDSS Data

1. Red and dead galaxies with different velocity dispersions (150 - 310 km/s)
2. Stacked sample of ~50 giant ETGs with σ > 300 km/s

SDSSJ0041-0914

Single galaxy from the LRG sample with a very strong NaI doublet absorption

SSP MODELS:

(Conroy & van Dokkum, 2012)

Empirical (MILES, IRTF)
+
Synthetic Libraries

- Ages: 7 - 13.5 Gyr
- [α/Fe] = 0 - 0.4
- IMFs : Chabrier , Salpeter (α= -2.35), α= -3.0, and α= -3.5

RESULTS II

Stellar mass fraction within R_{Ein} for different IMF slope

IMF slope ($dN/dm = M^{x}$)	f_B^* $(L_{\rm Ein}/M_{\rm Ein}) \times (M/L)_B^*$	f_V^* $(L_{\rm Ein}/M_{\rm Ein}) \times (M/L)_V^*$
- 2.35	0.75 ± 0.2	0.59 ± 0.18
- 3.00	1.6 ± 0.5	1.4 ± 0.4
- 3.50	2.4 ± 0.8	2.4 ± 0.7

Stellar mass fraction from LINE INDEX MEASUREMENTS

INDEX = Equivalent width normalized over a continuum

$$EW = \frac{(\lambda_{red} - \lambda_{blue})}{(1 - F_I/F_C)}$$

- Lick indices : Hβ, Mgb, Fe5270, Fe5335, NaD and TiO2 (by *Trager, 1998*)
- Commonly used $[\mathrm{MgFe}] = \sqrt{(\mathrm{Fe5270} + \mathrm{Fe5335})/2 \times \mathrm{Mg}b}$, *(by González, 1993)*
- New NaI doublet (8183, 8195 A) index (by *Spiniello et al., 2012)*

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More than 100% in stars!!!

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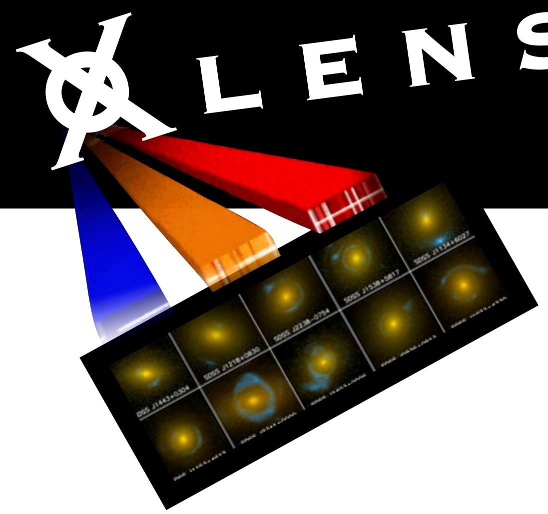
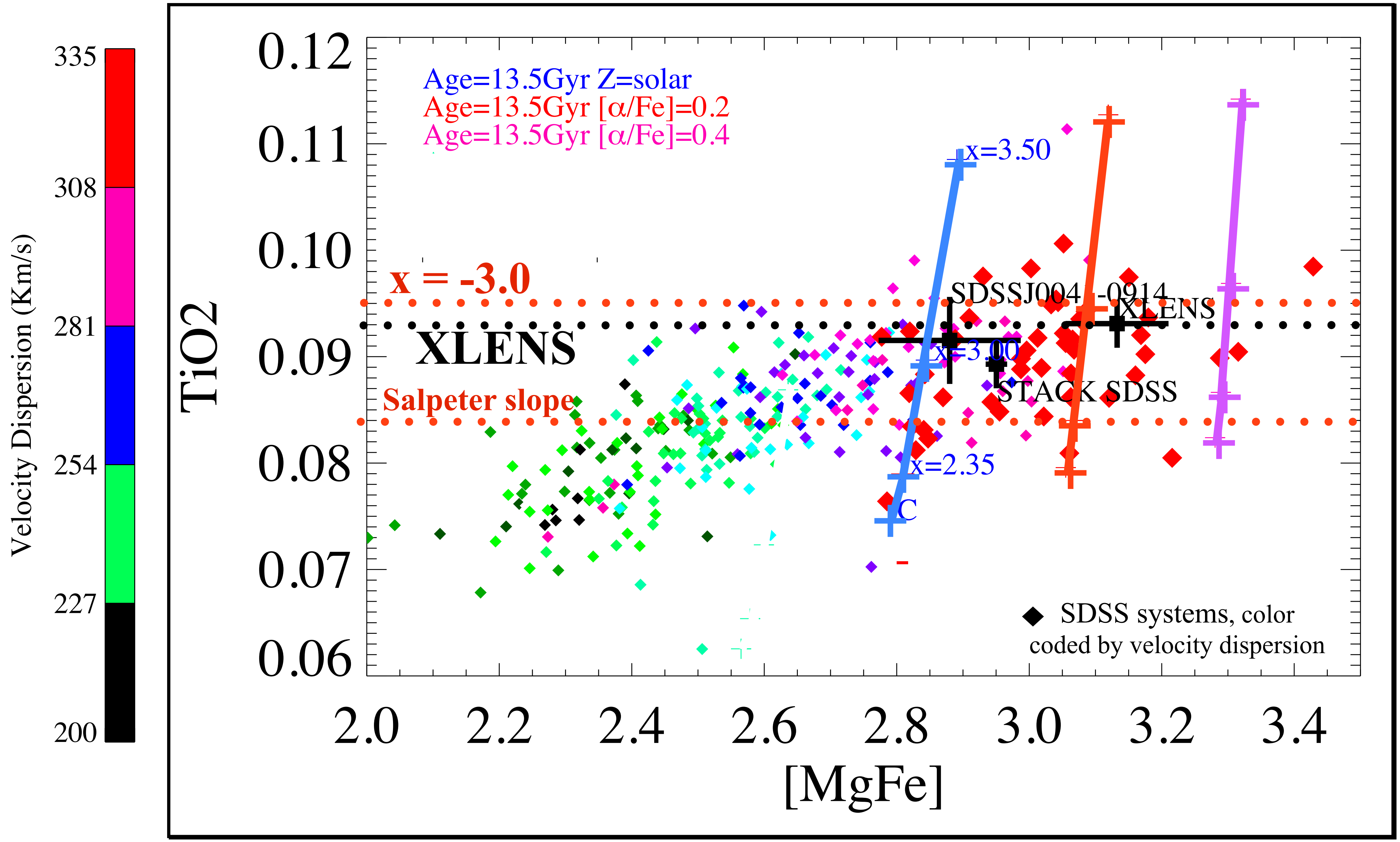
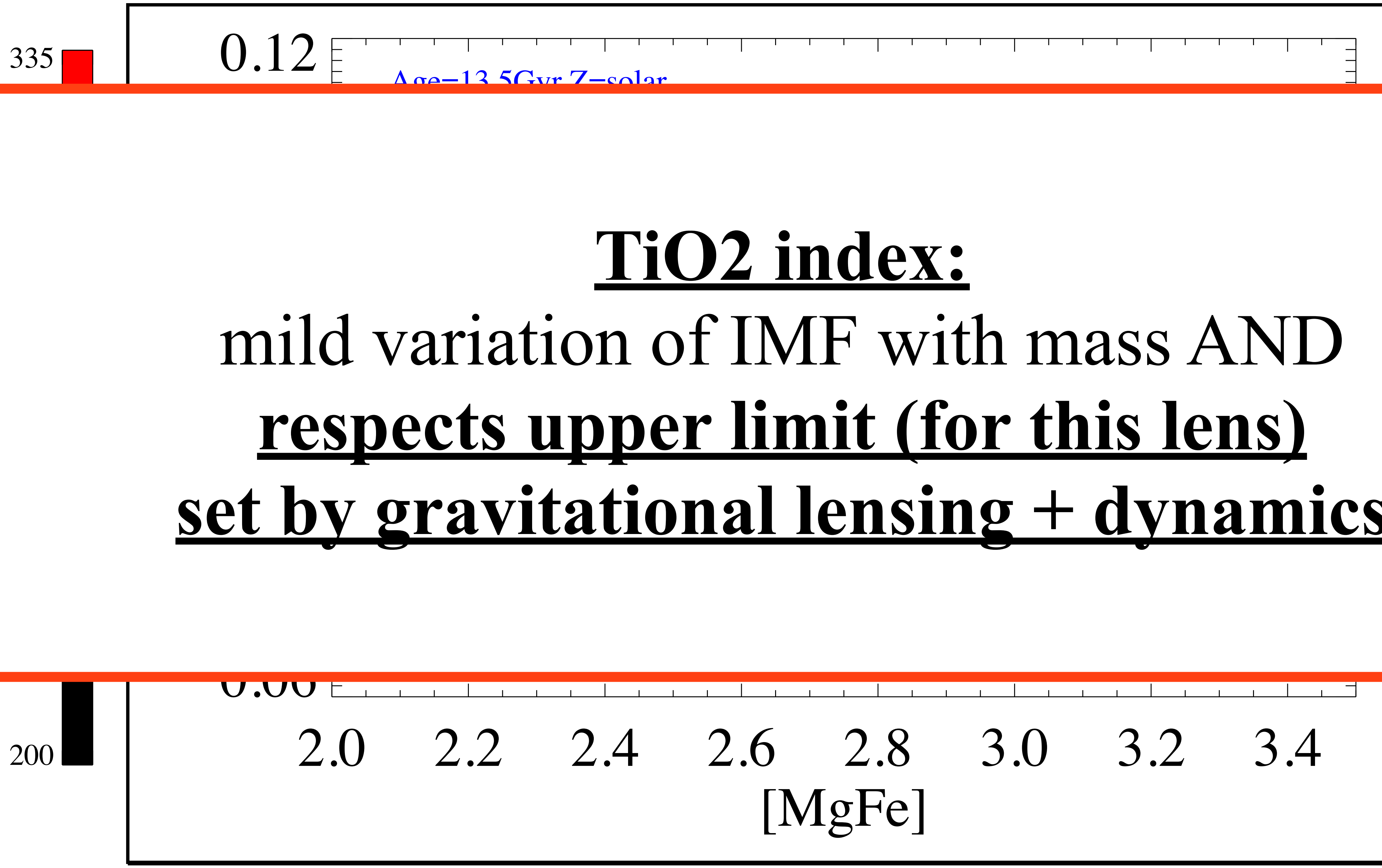




Velocity Dispersion (Km/s)
335
308
281
254
227
200
TiO2
[MgFe]
Age=13.5Gyr Z=solar
Age=13.5Gyr [α/Fe]=0.2
Age=13.5Gyr [α/Fe]=0.4
x = -3.0
XLENS
Salpeter slope
x=3.50
x=3.00
x=2.35
SDSSJ004 -0914
XLENS
STACK SDSS
SDSS systems, color coded by velocity dispersion

RESULTS II



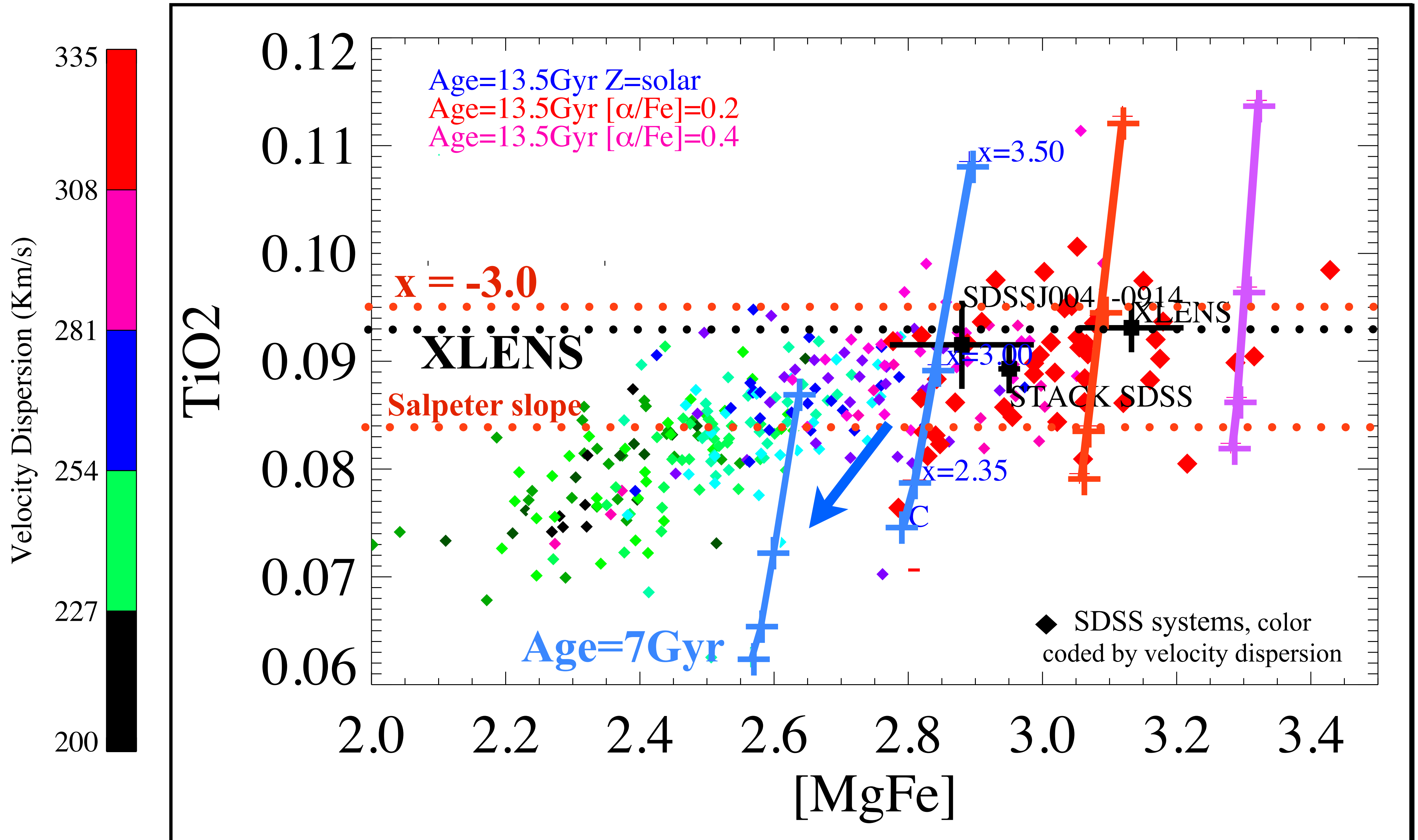
<u>TiO2 index:</u>

mild variation of IMF with mass AND

<u>respects upper limit (for this lens)</u>

<u>set by gravitational lensing + dynamics</u>

RESULTS II



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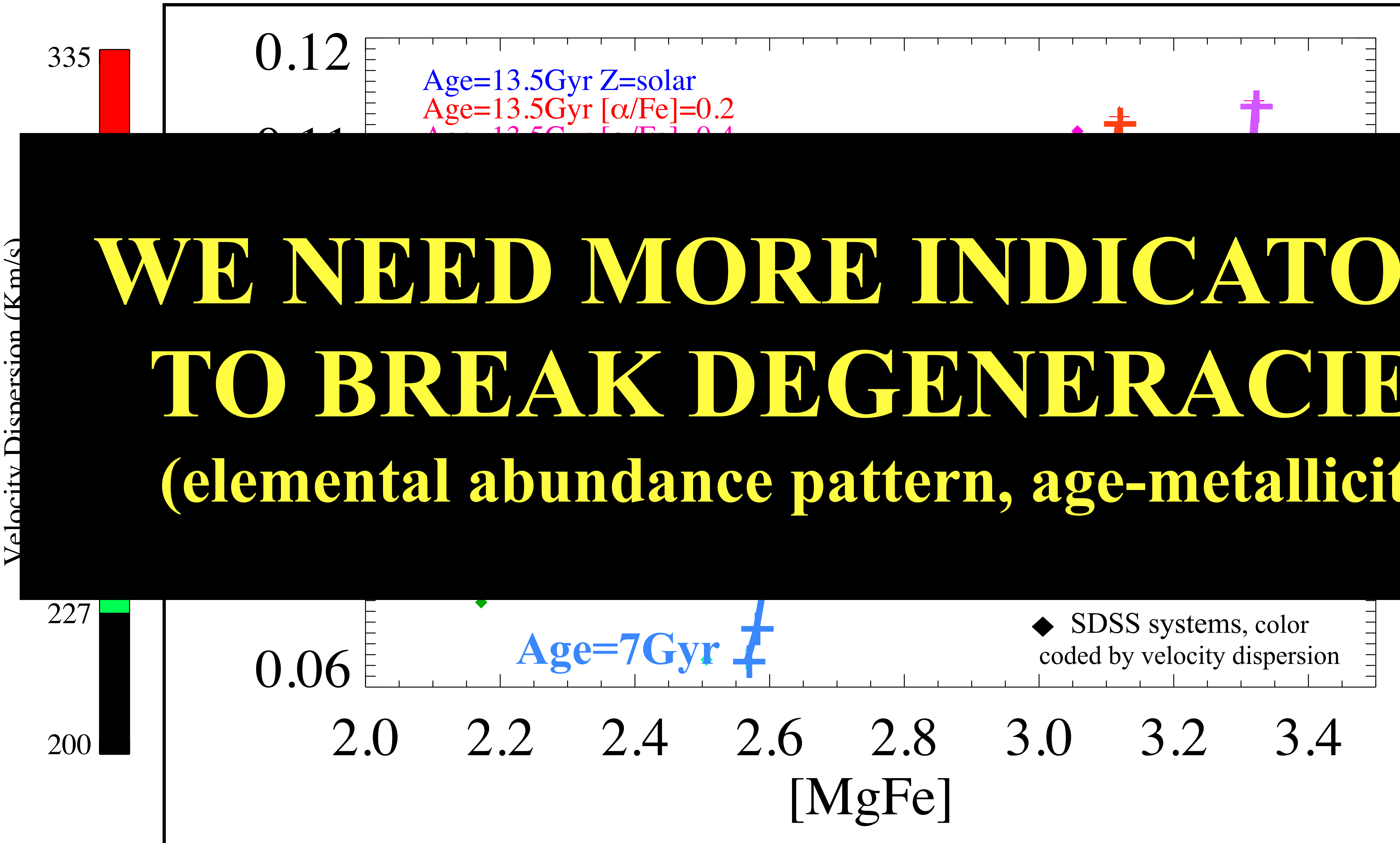
SDSSJ004 -0914
XLENS
STACK SDSS
Age=7Gyr
SDSS systems, color coded by velocity dispersion

RESULTS II



WE NEED MORE INDICATORS TO BREAK DEGENERACIES

(elemental abundance pattern, age-metallicity)

RESULTS III

Searching for new M-dwarfs indicators in the optical spectrum

Spiniello et al. 2013

First in single stars from MILES stellar library

Sánchez-Blázquez, et al 2006,

then **in the CvD+12 Simple Stellar Population Models**

Conroy & van Dokkum et al 2012

Empirical libraries:
- MILES [3500–7400]A
- IRTF [8100–24000]A

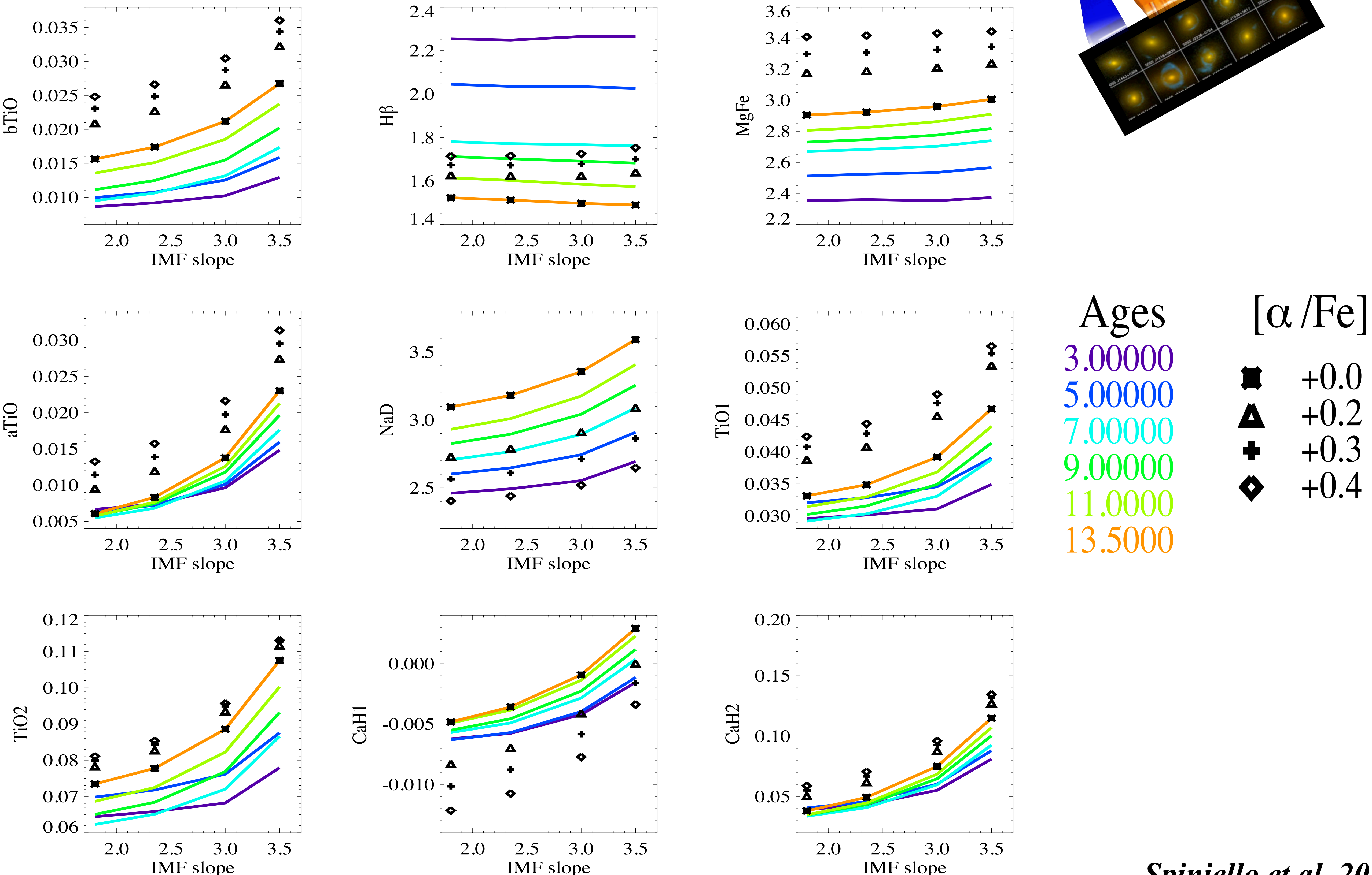
+

Synthetic spectra to:
- cover the gap in wavelength
- investigate changes in the overall Z and in individual elements abundances (at fixed [Fe/H])

- **Ages: {3 , 13.5}Gyr**
- **[α/Fe] : {-0.2 , 0.4}**
- **IMF slopes: {1.8 , 3.5}**
  (Salpeter=2.35)
- **Effective Temperature RGB stars: {-200K, 200K}**

The X-Shooter Lens Survey

RESULTS III



Spiniello et al. 2013

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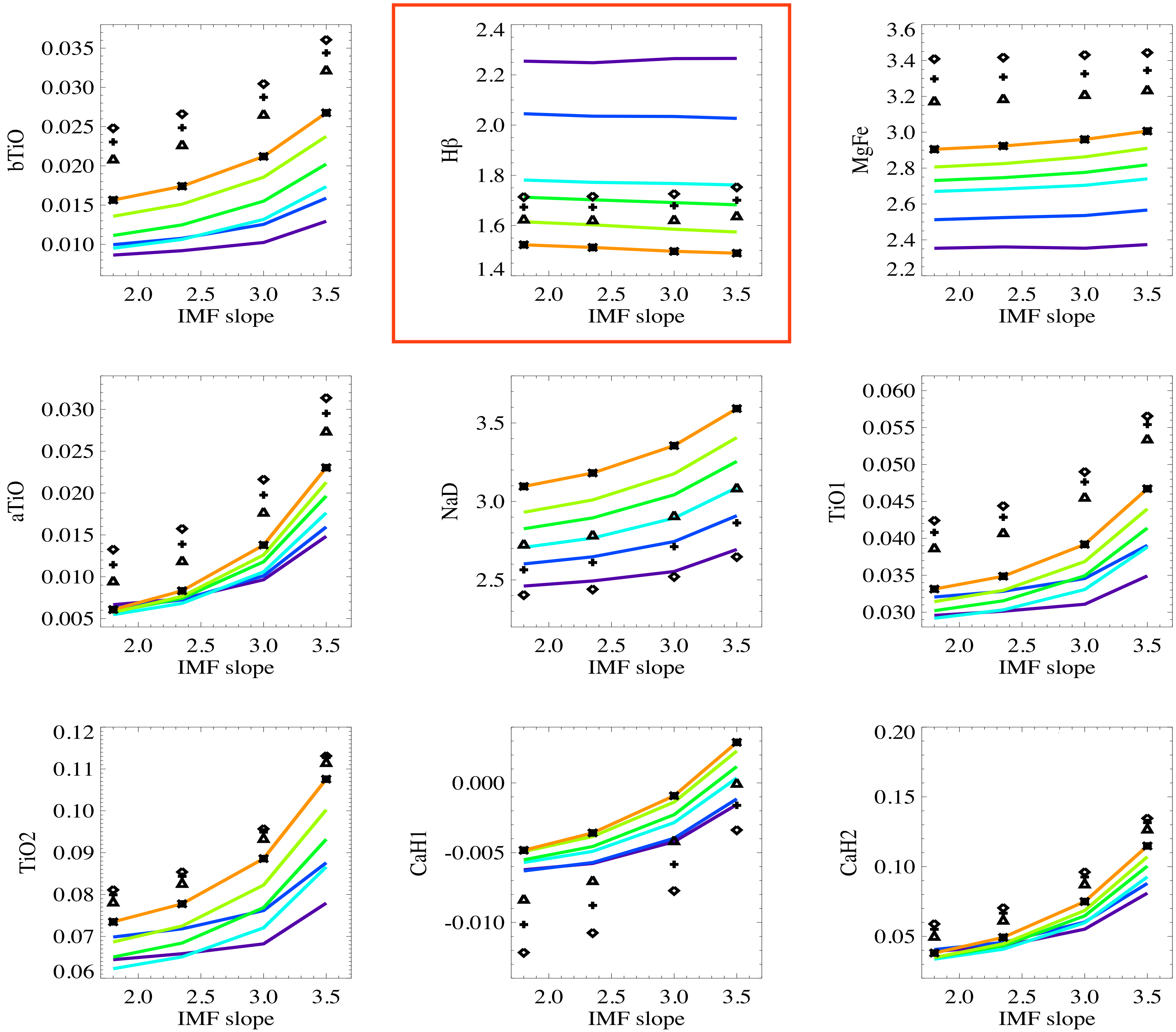
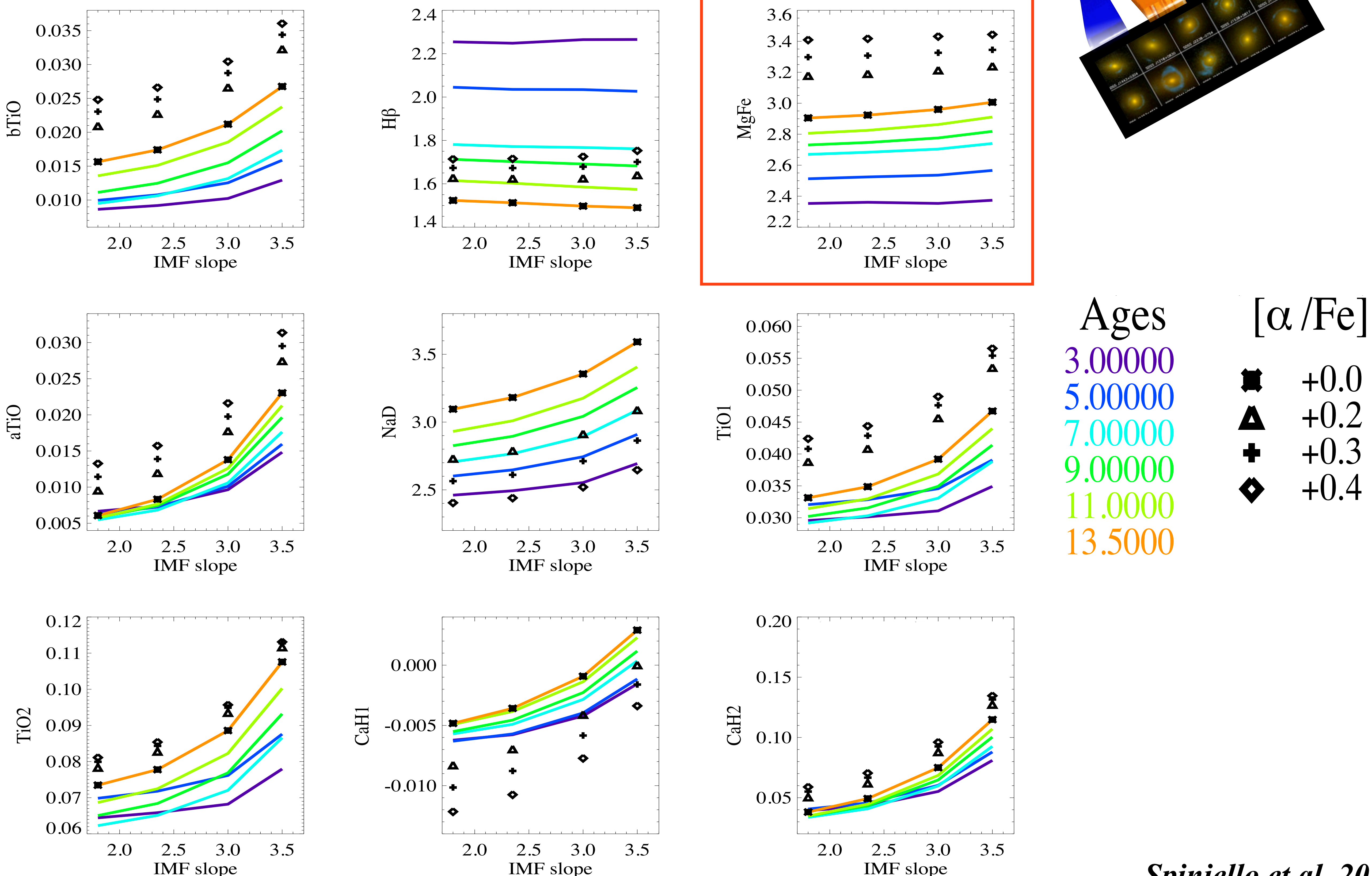


Ages
3.00000
5.00000
7.00000
9.00000
11.0000
13.5000

[α /Fe]
+0.0
+0.2
+0.3
+0.4

Spiniello et al. 2013

RESULTS III



Spiniello et al. 2013

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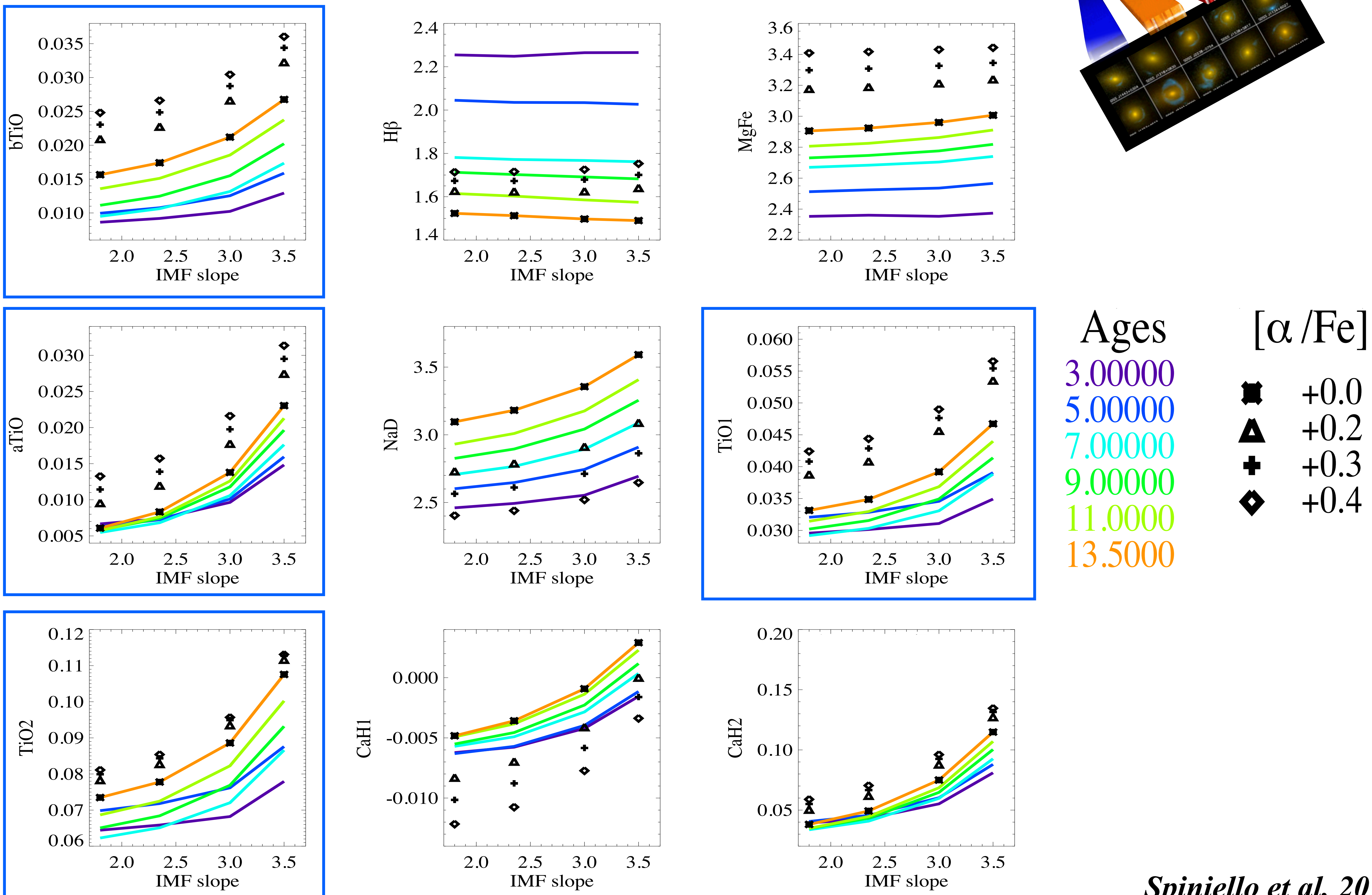

Spiniello et al. 2013

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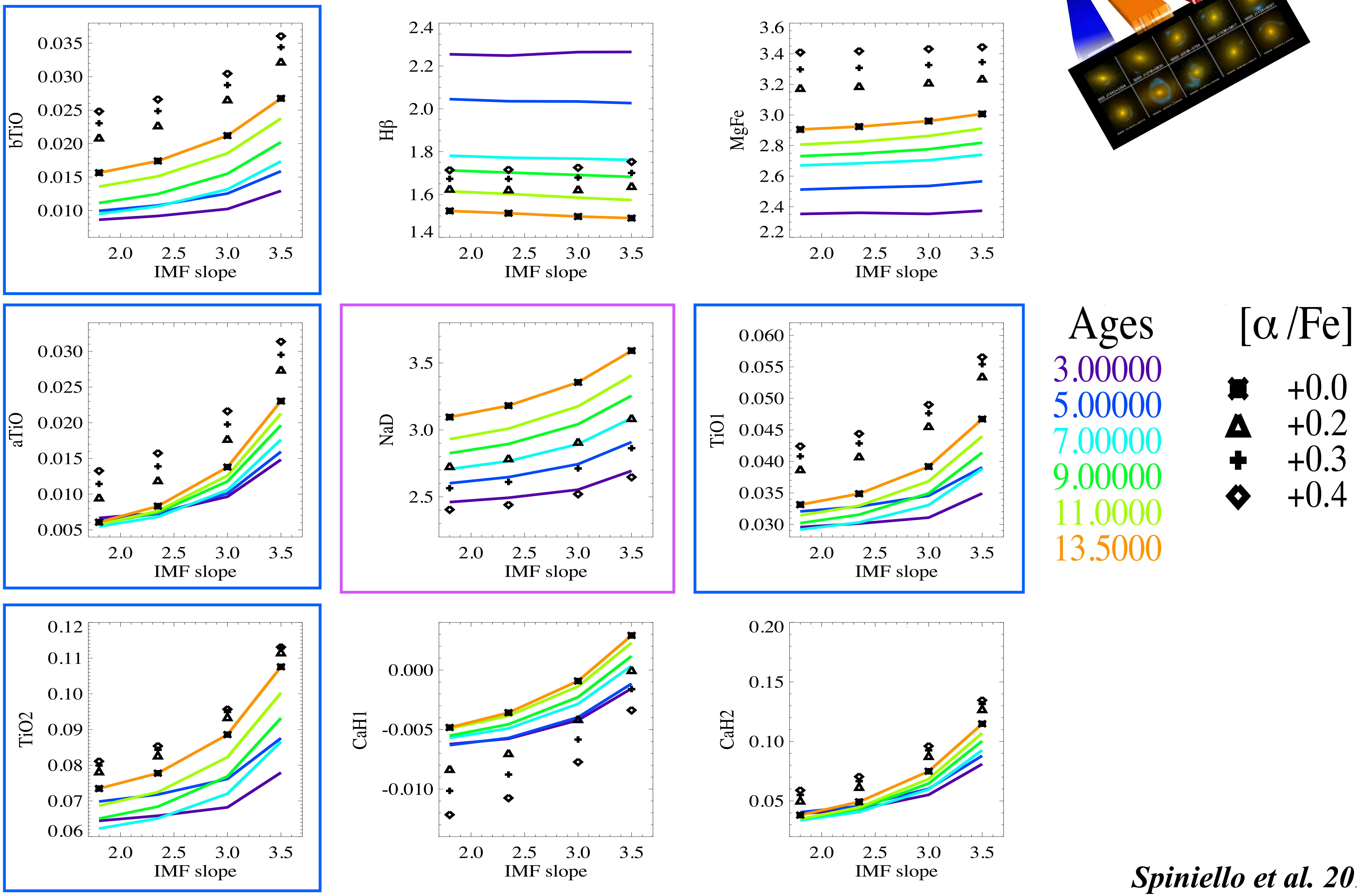

Spiniello et al. 2013

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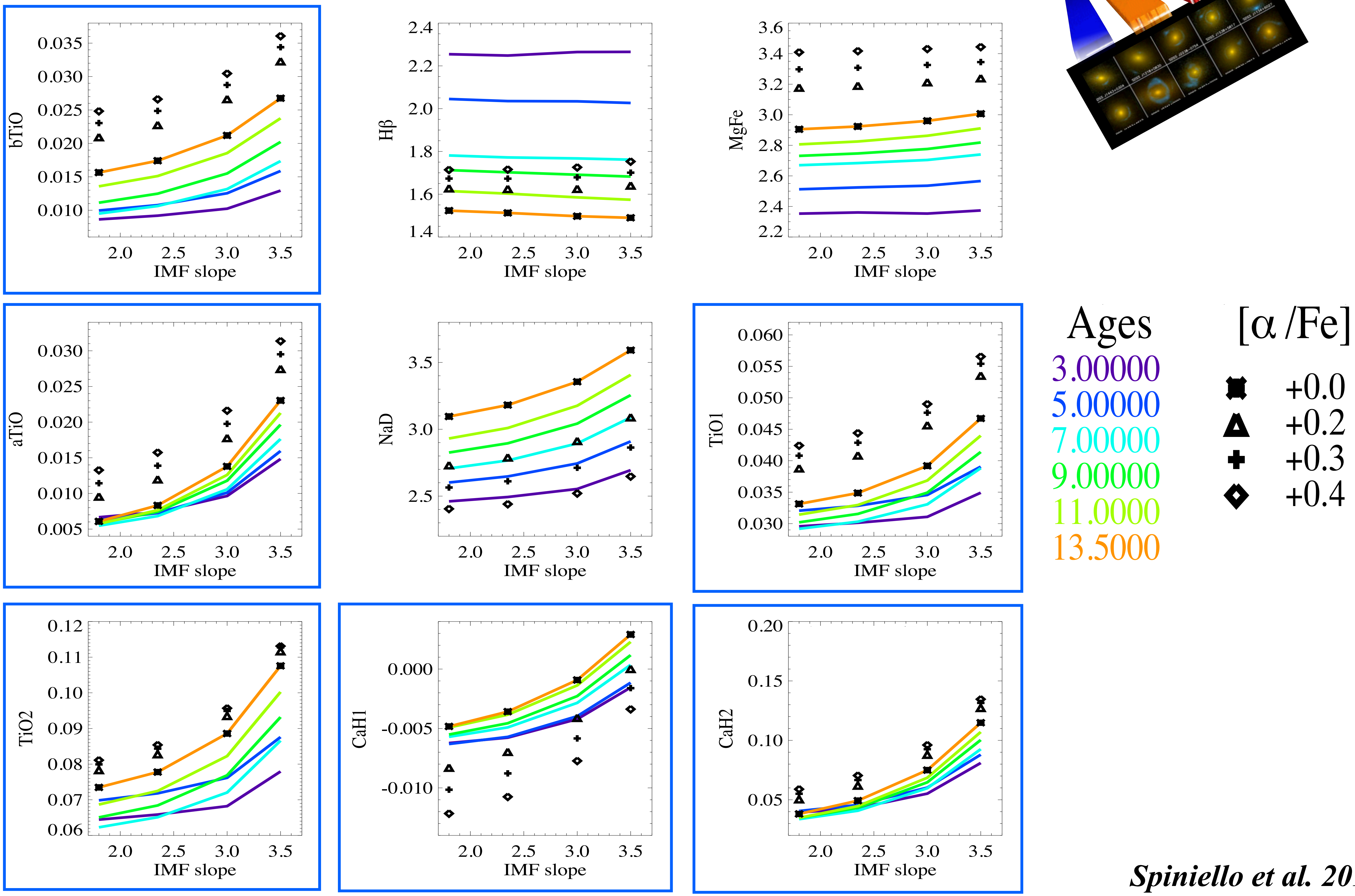

Spiniello et al. 2013

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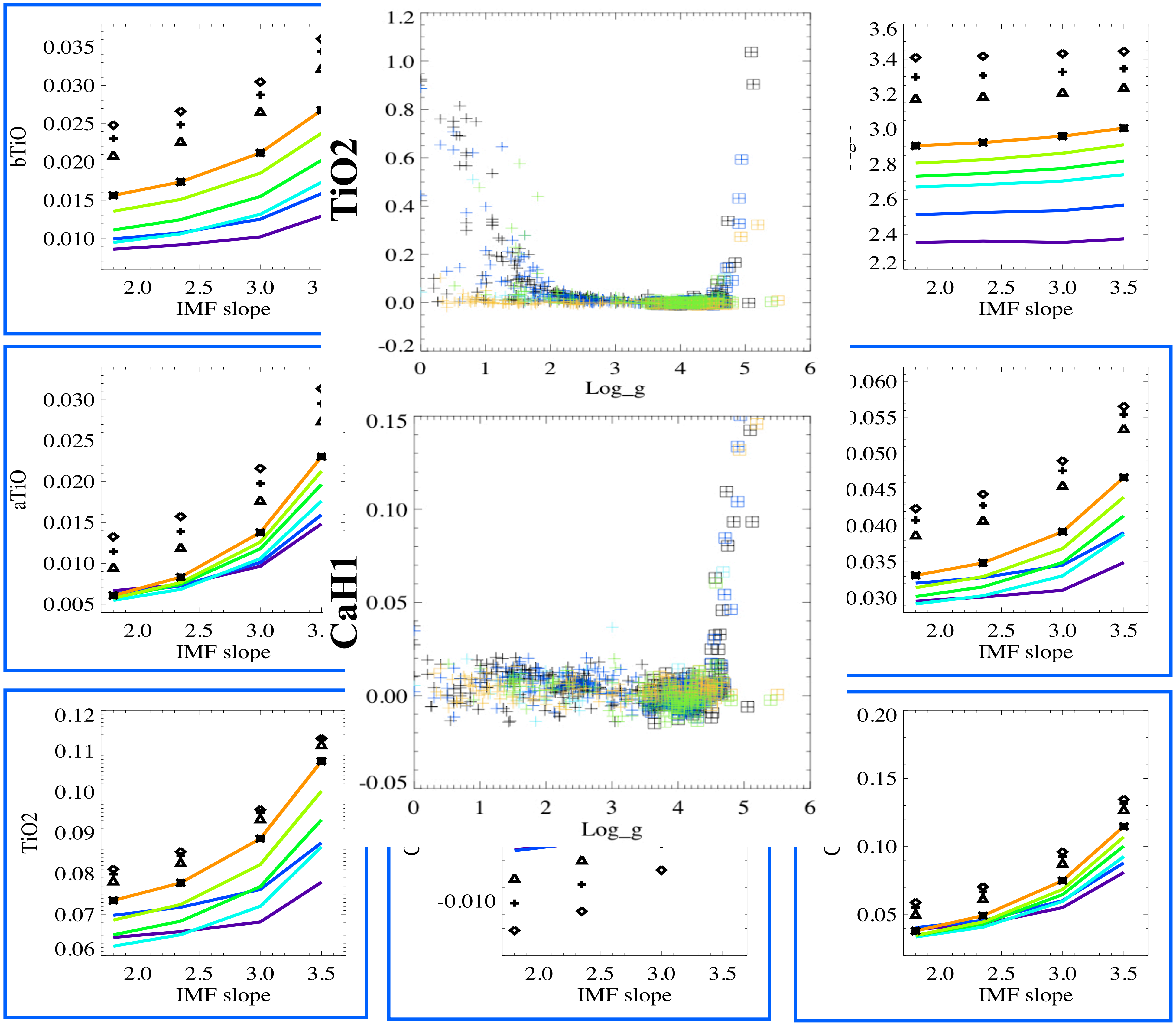

Ages
3.00000
5.00000
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[α /Fe]
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+0.2
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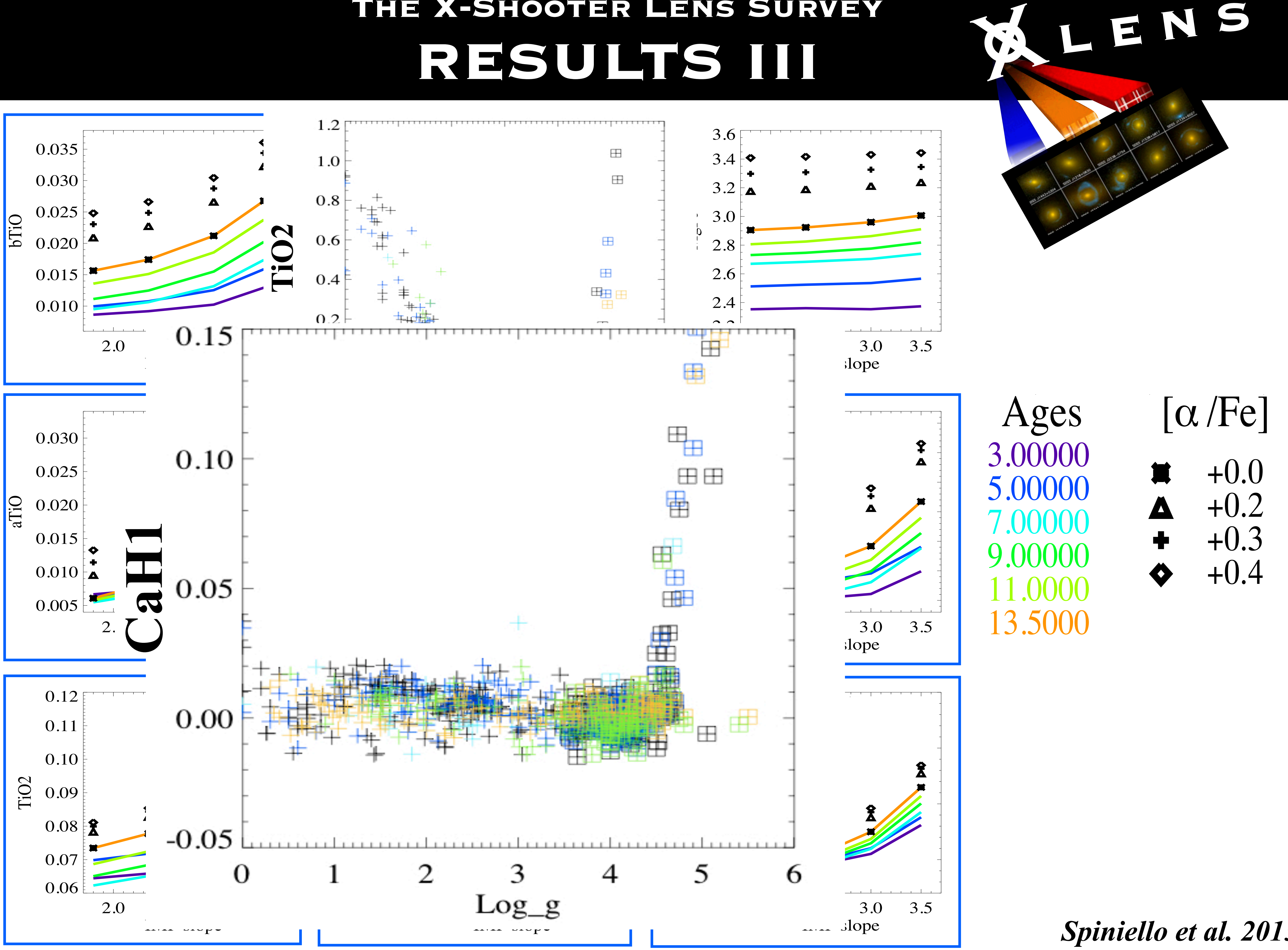
+0.4

Spiniello et al. 2013

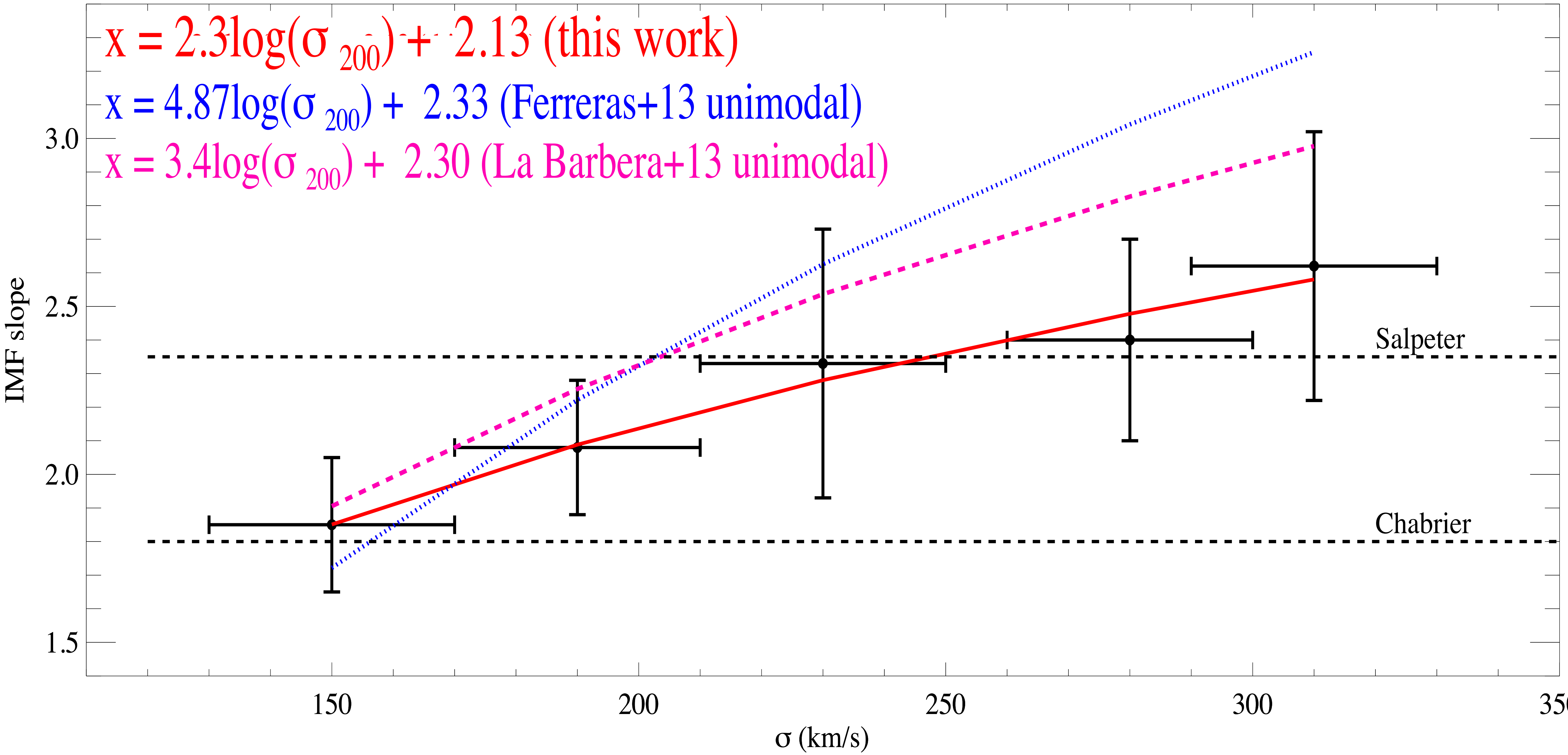
RESULTS III



Spiniello et al. 2013

Comparison with data and other results

Spiniello et al. 2013

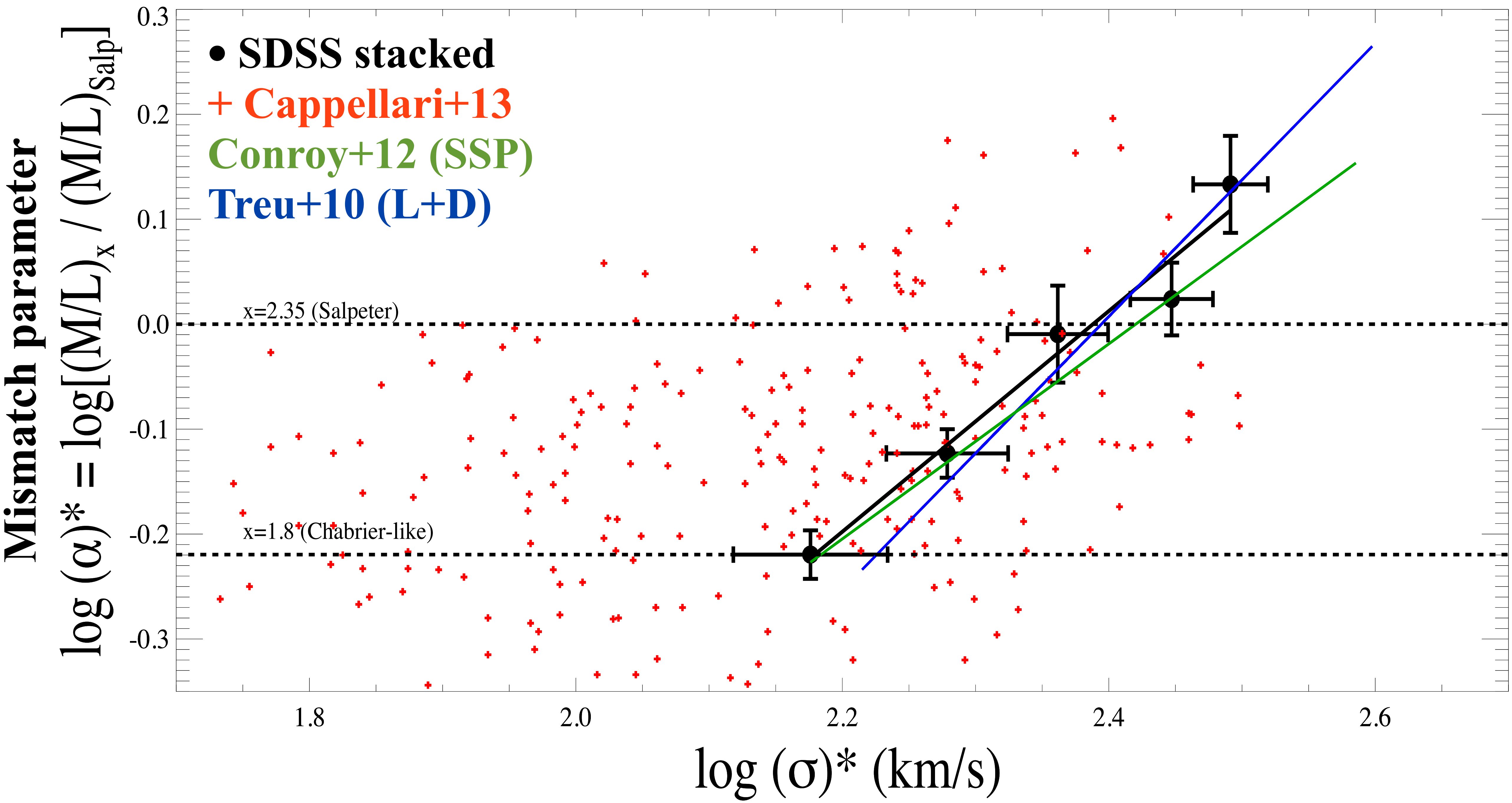


RESULTS IV

XLENS

Comparison with data and other results

Spiniello et al. 2013



RESULTS IV

X LENS

Comparison with data and other results

Spiniello et al. 2013

0.3

these independent studies all suggest that

<u>THE IMF IS NOT UNIVERSAL</u>

The low-mass end of the IMF slope (x) steepens with stellar velocity dispersion

$$\text{IMF slope} = (2.3 \pm 0.1)\ \log \sigma_{200} + (2.13 \pm 0.15)$$

Mismatch parameter

1.8 2.0 2.2 2.4 2.6

log (σ)* (km/s)

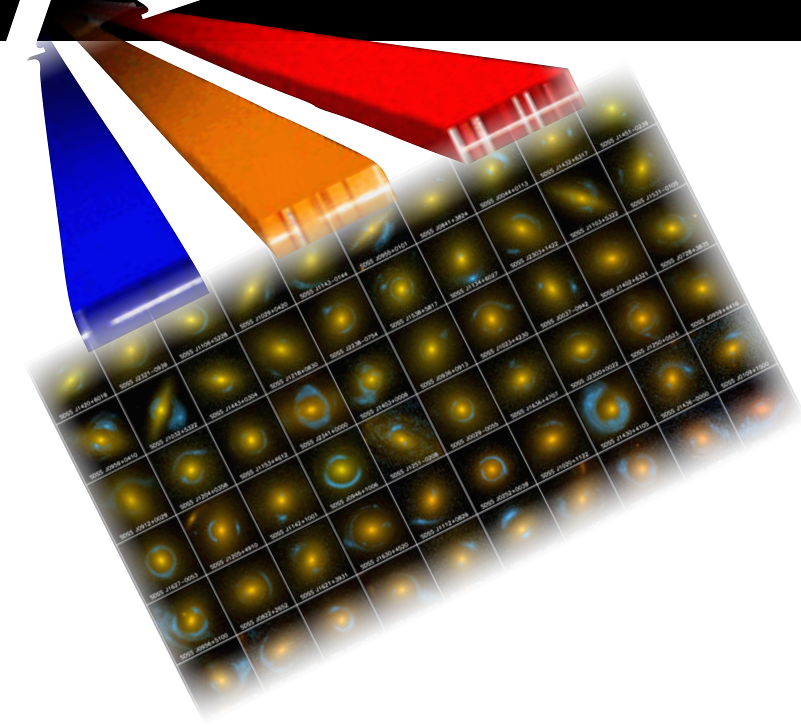
CONCLUSIONS

1. **The XLENS Survey**:
Lensing + Dynamics + Stellar Population Analysis
to separate the luminous from the dark matter in the internal region of massive ETGs

2. Constrain the low-mass end of the IMF
A lot of indicators (both in the optical and the NIR) are needed to break degeneracies and constrain age, abundance pattern *and* IMF slope in ETGs from SSP analysis

3. More and more evidences confirm that
the low-mass end of the IMF slope is NOT UNIVERSAL.
More massive ETGs require a Salpeter (or steeper) IMF slope.

FUTURE WORKS



1. DIFFERENT SSP MODELS :

Different models = different answers ???

2. L&D + SSP : CAULDRON + XLENS

Constraining the IMF cutoff Mass

(Barnabè+07,+12, Barnabè, Spiniello+13)

3. SPATIALLY-RESOLVED IMF

If mergers and accretion of galaxies with pre-enriched gas play an important role in the evolution of the most massive ETGs (Hopkins et al. 2007), IMF could be steeper in the center and flatter in the outer region. → **VIMOS (IFU) Data** (with Dr. O. Czoske) **CALIFA (IFU) Data** (with G.Mensinga)

4. NIR spectra from X-shooter

CaT (λ8600), Wing Ford Band (λ9916), CaI (λ19800), CO (λ 23000)

THANKS

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THE END