Cornering the *Hubble tension* by studying systematics and reconstructing the local Universe with supernovae

HOSTFLOWS (PID2020-115253GA-I00)

Lluís Galbany, RYC fellow, ICE-CSIC (Barcelona)

Institute of Space Sciences
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Consejo Superior de Investigaciones Científicas
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Outline of the talk

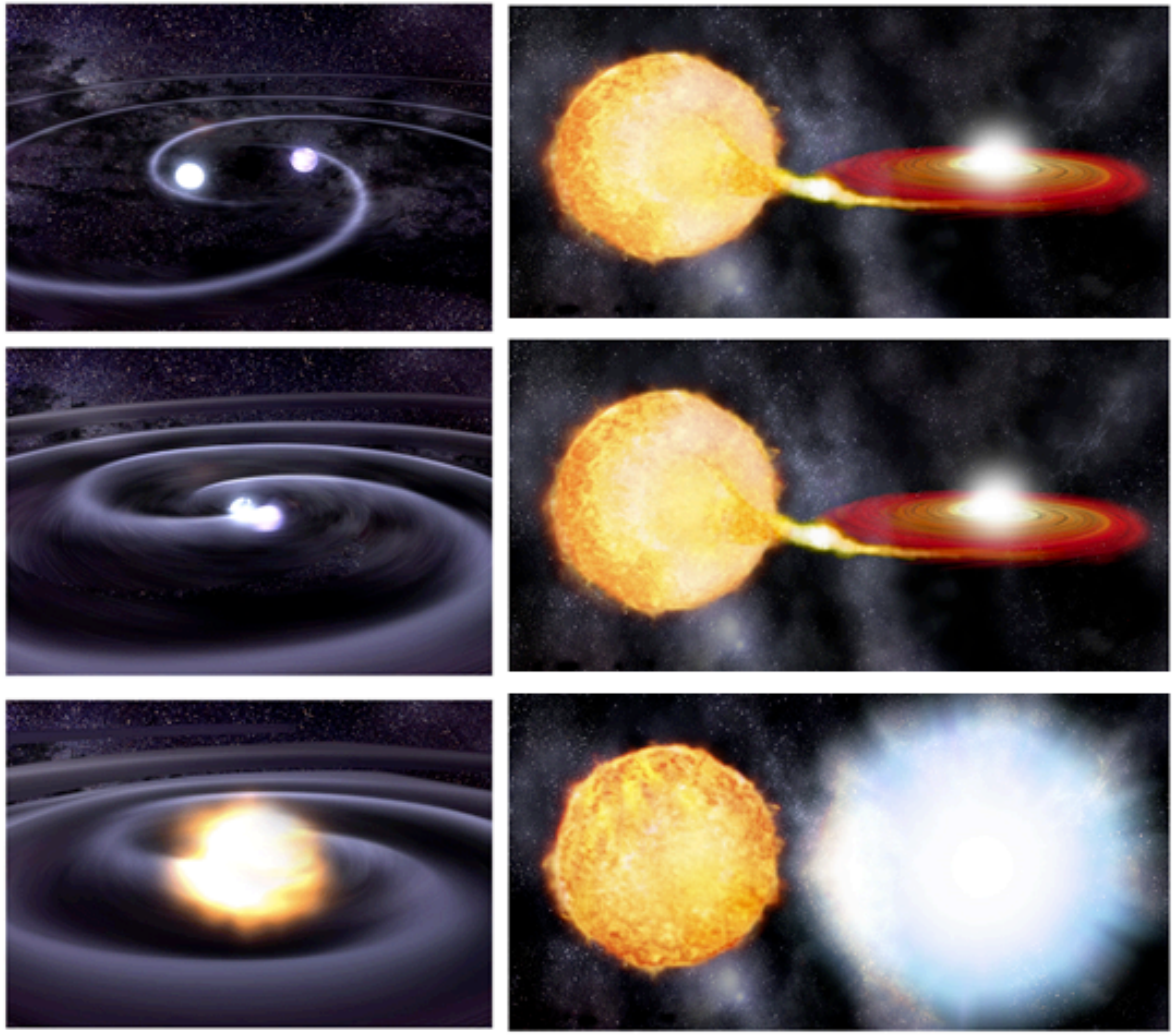
- Intro on SNIa cosmology *(~10 min)*

Only PhD students

Full audience

- Problem *(~5 min)*
- Approach A *(~15 min)*
- Current work on A *(~10 min)*
- Approach B *(~5 min)*
- Current work on B *(~10 min)*

Type Ia supernovae



What is exploding?

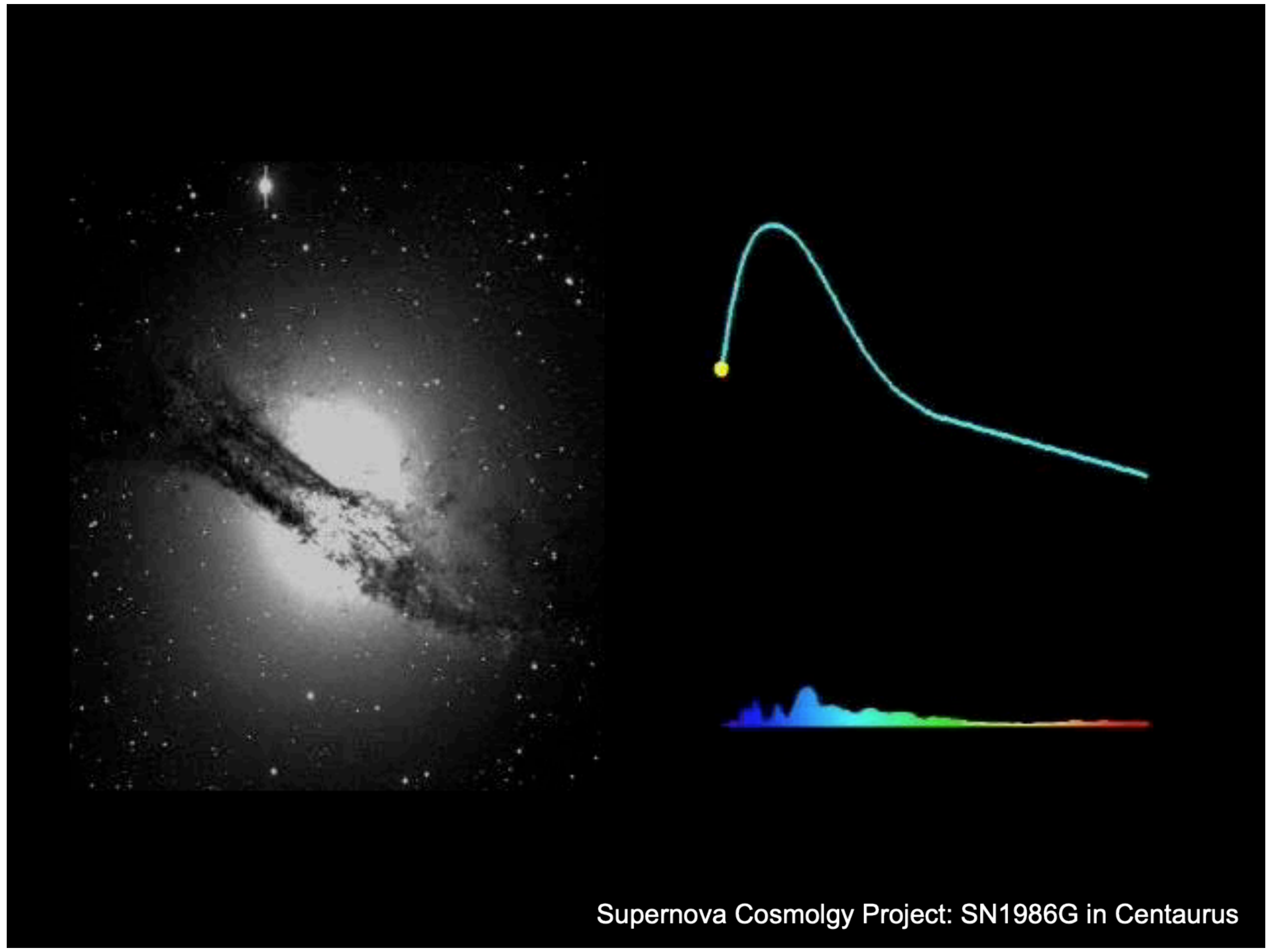
CO white dwarf (WD) in a binary system
single/double degenerate

How is it exploding?

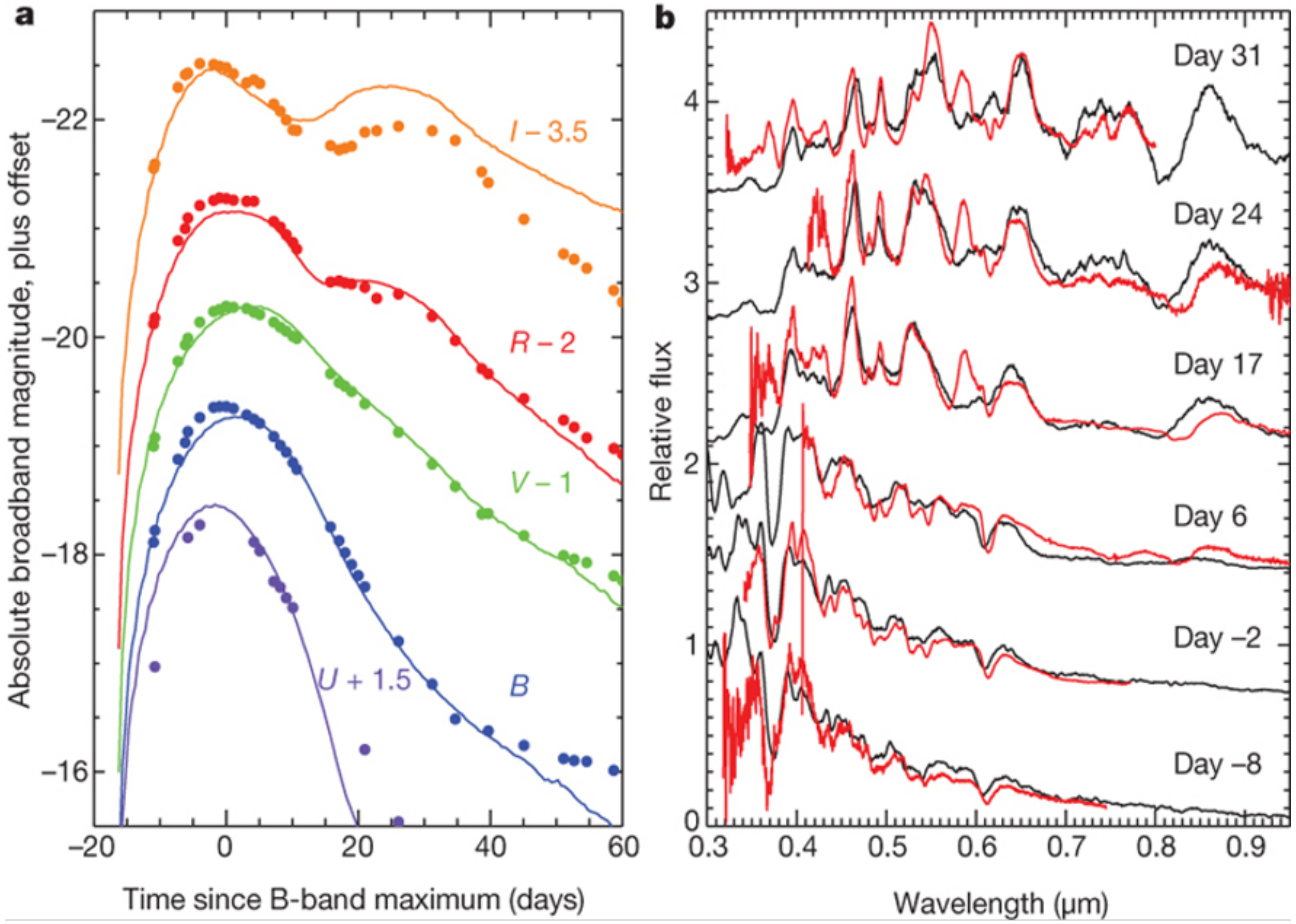
Merging/compression/He layer burn/collision
Detonation/deflagration/double-detonation
Chandrasekhar/sub-Chandrasekhar mass

Most probably a mixture of scenarios and explosion mechanisms

Type Ia supernovae



Supernova Cosmolgy Project: SN1986G in Centaurus



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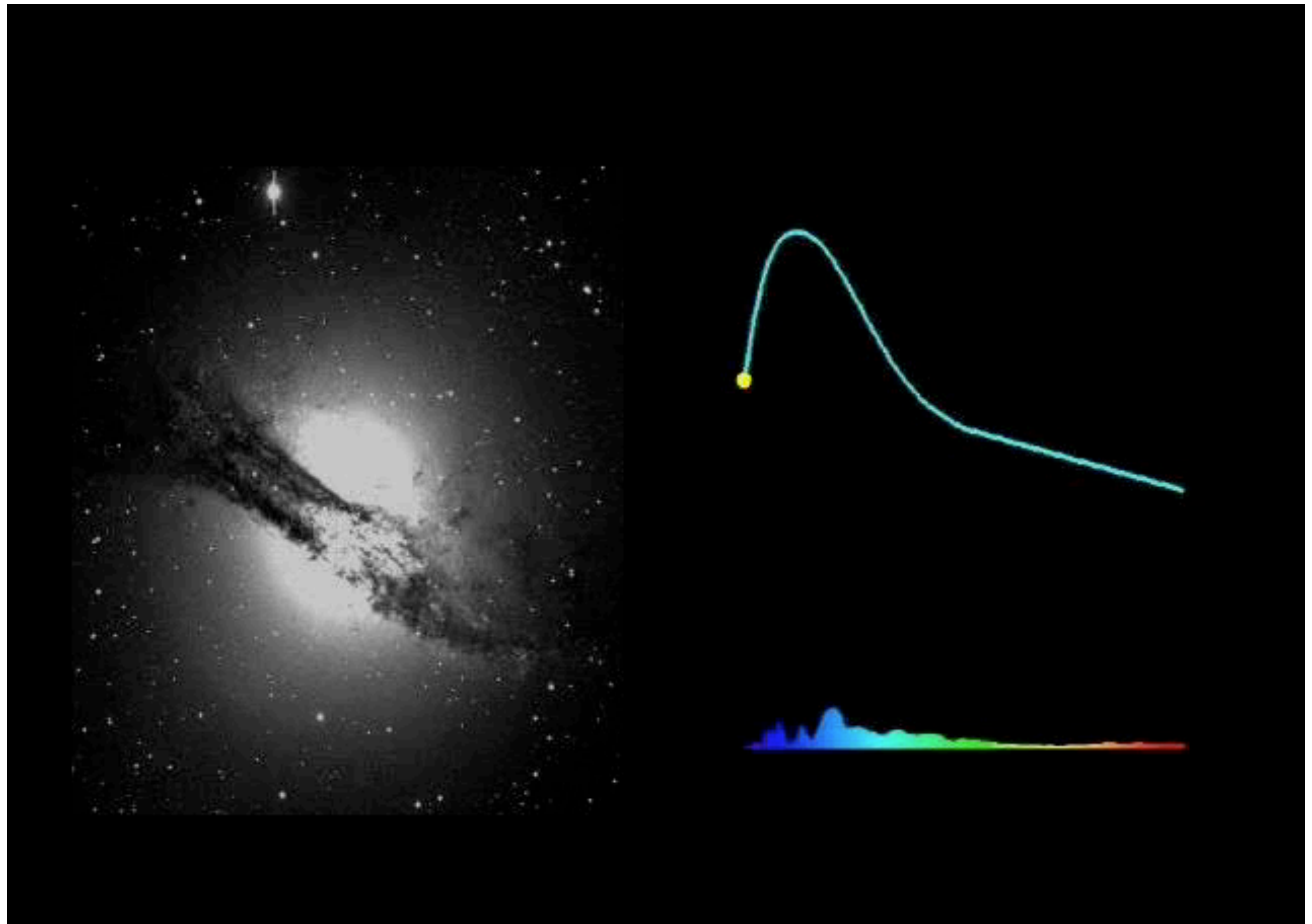
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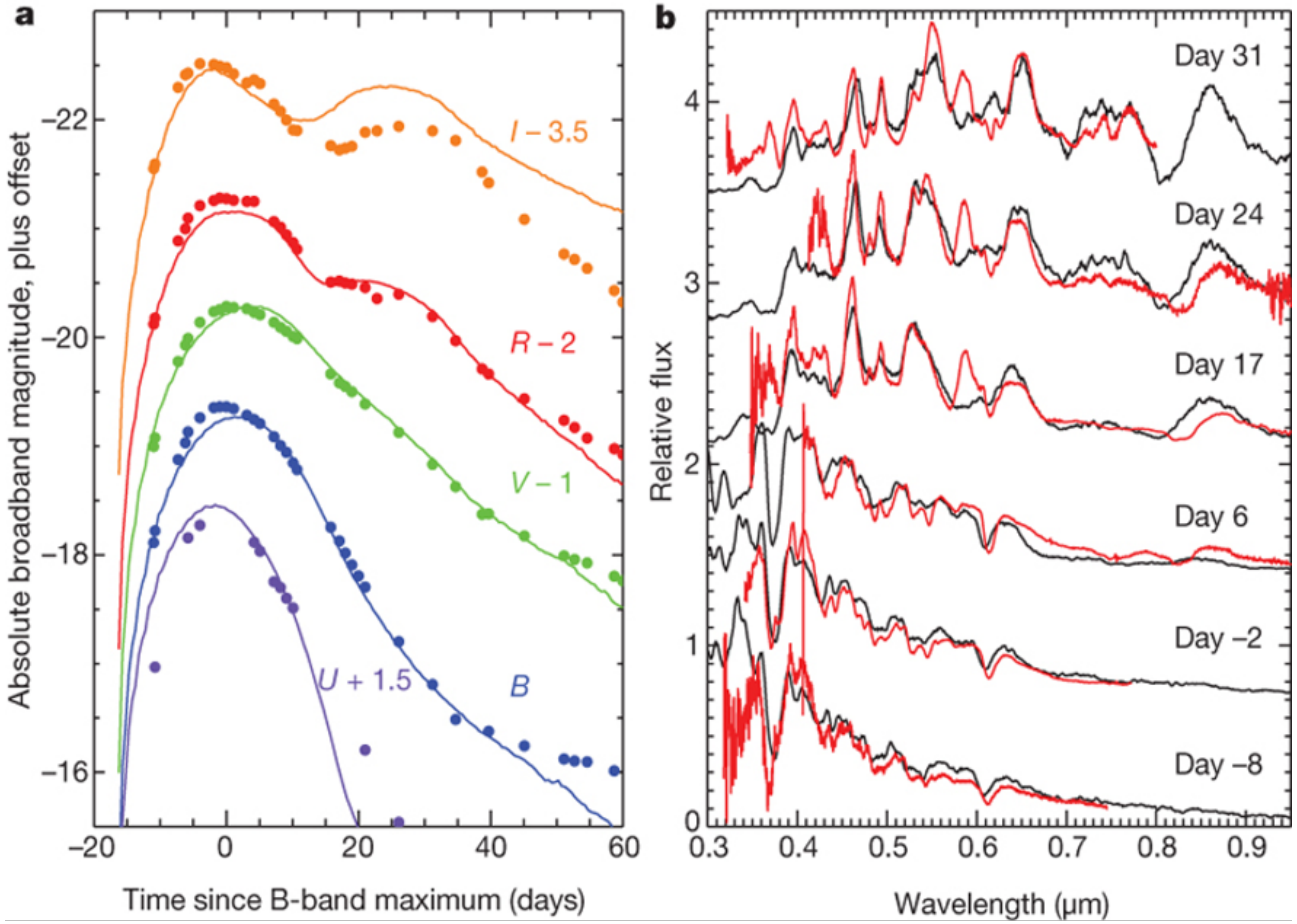

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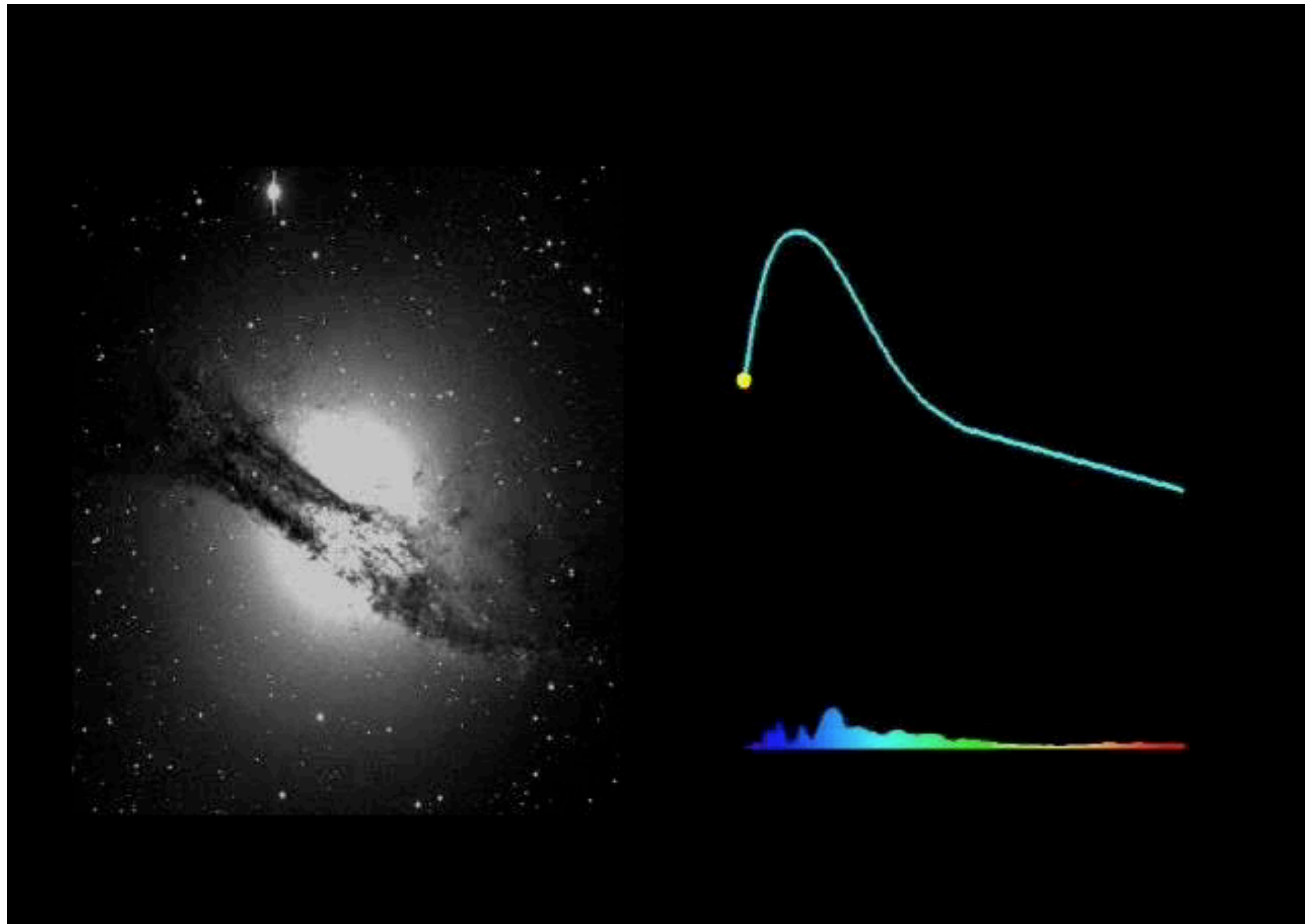

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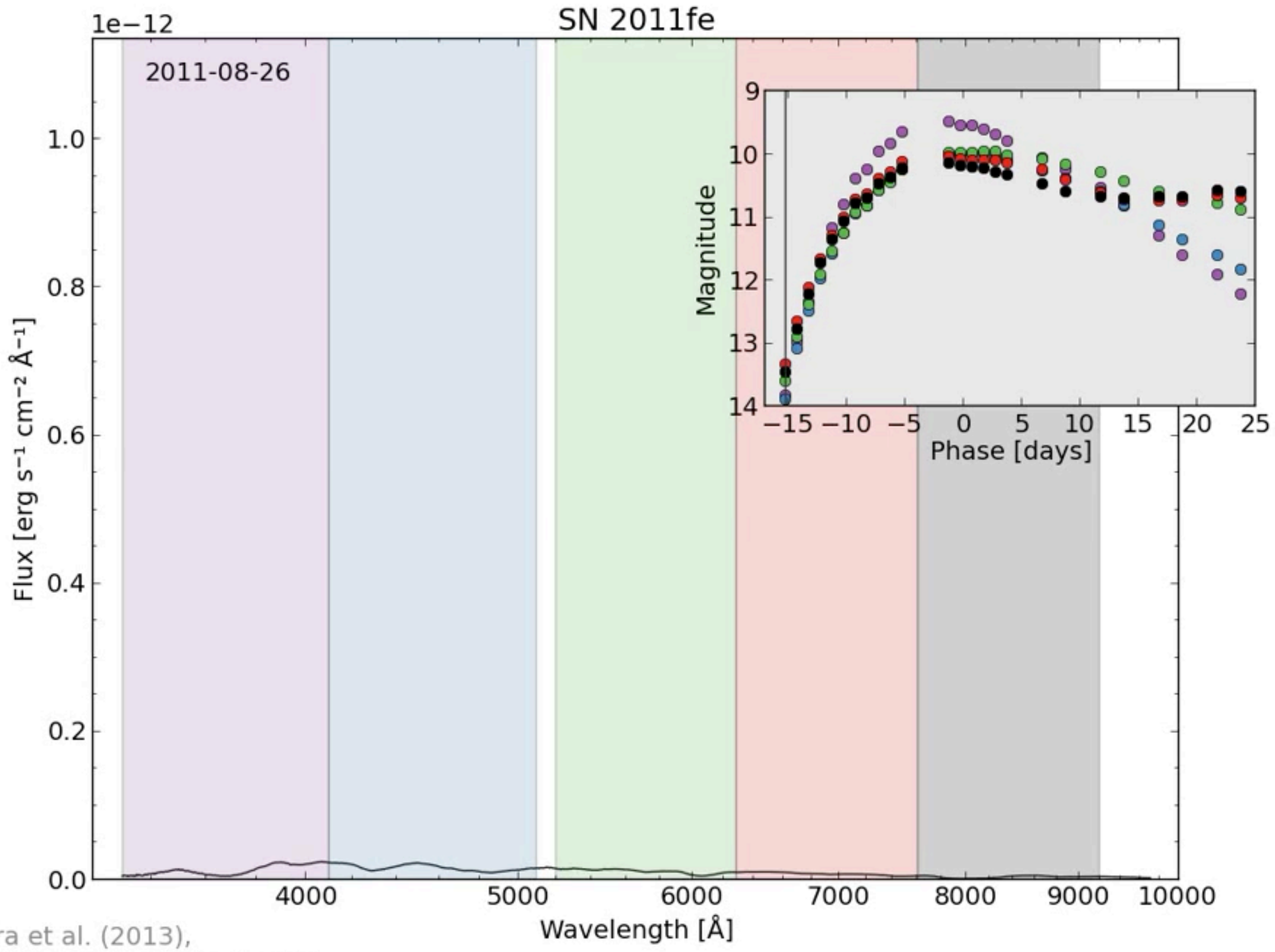


Pereira et al. (2013),
The Nearby Supernova Factory

SNIa cosmology

SNIa are the most precise extragalactic distance indicators (uncert. 5%)

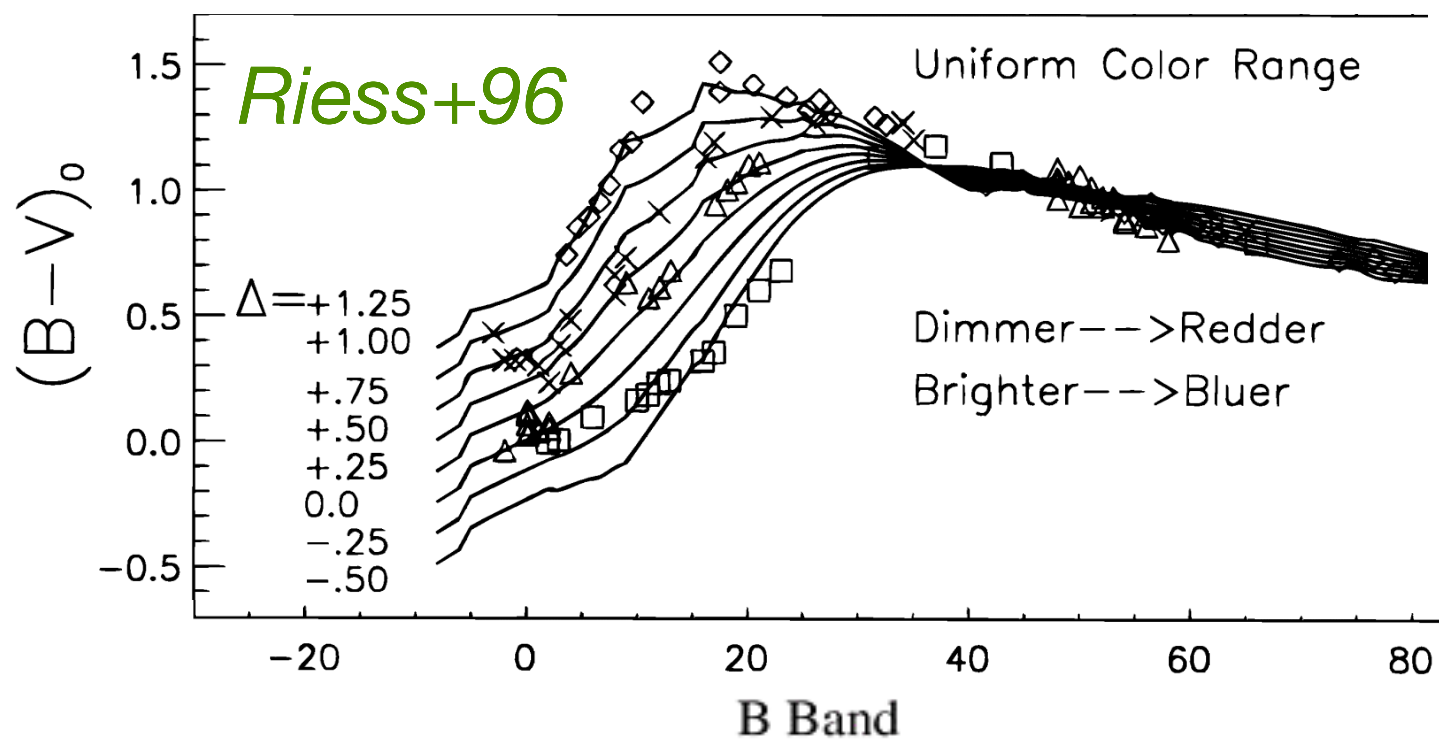
Two empirical correlations:

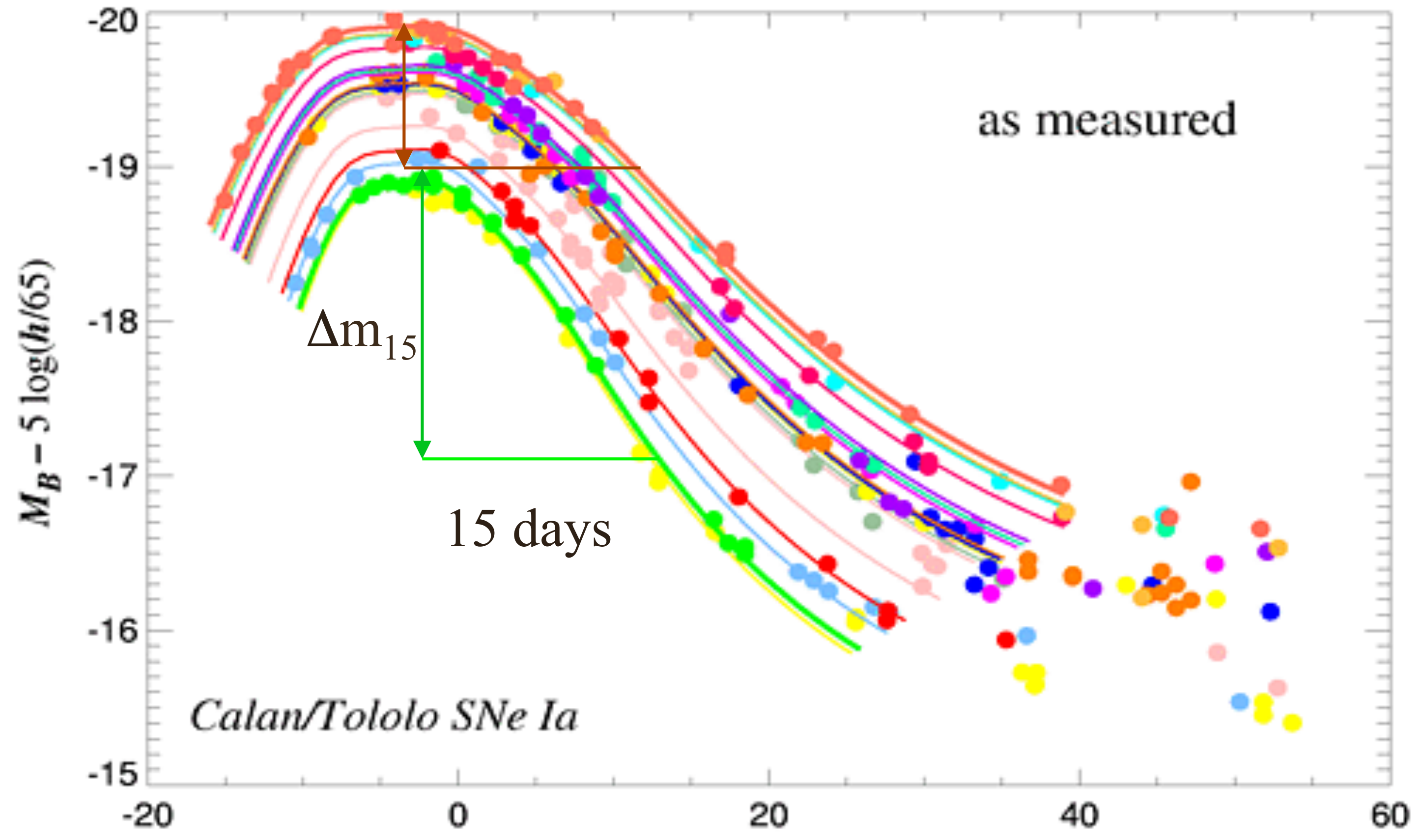
peak brightness vs brightness decay
peak brightness vs color

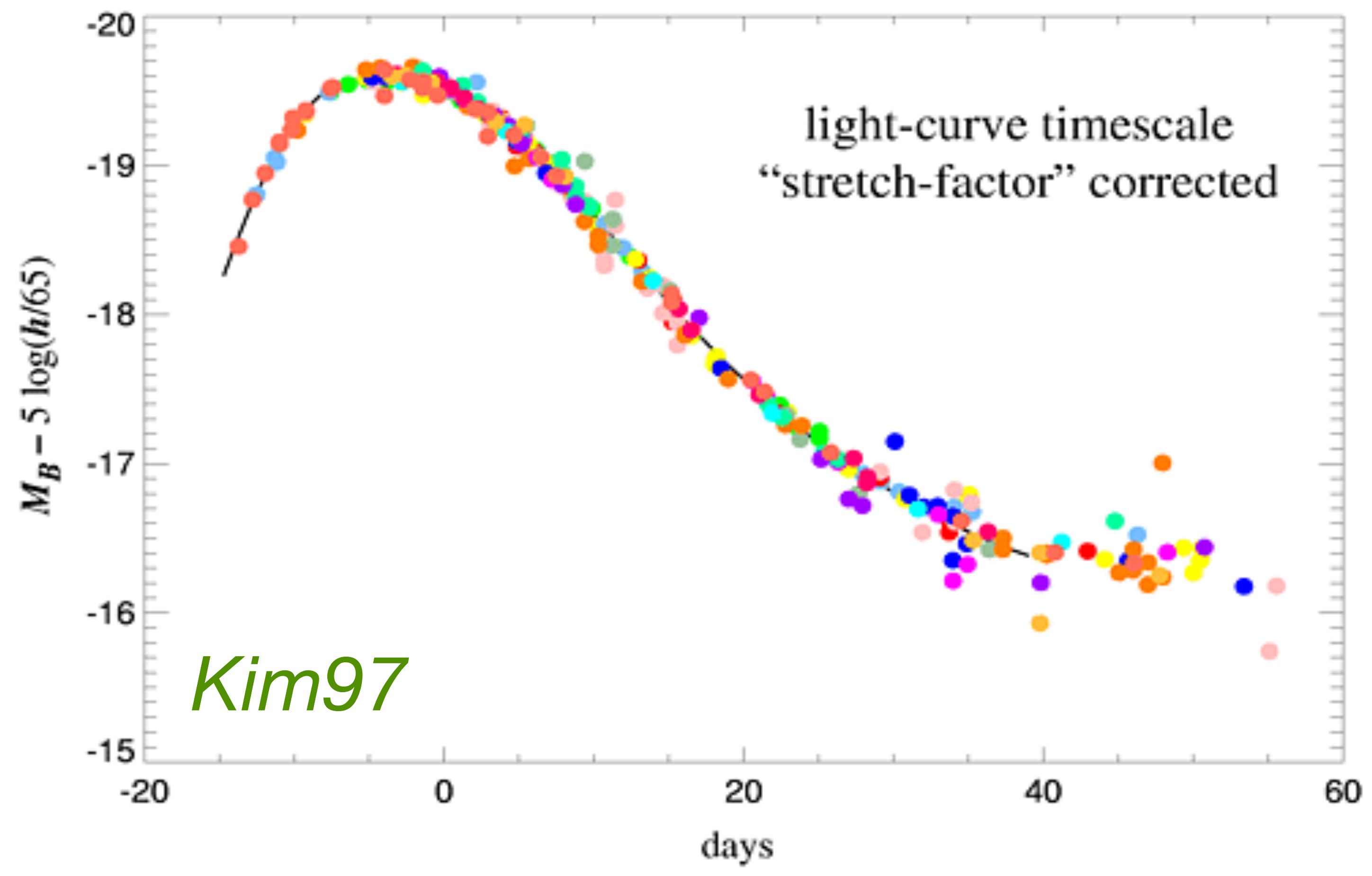
Standardized peak brightness

$$\mu(z)_{\rm SN} = m(z) - M = (m_{\rm obs} {\color{red}+\alpha x1} {\color{blue}-\beta c} - A_{\rm MW} + K_{x,y}) - M$$

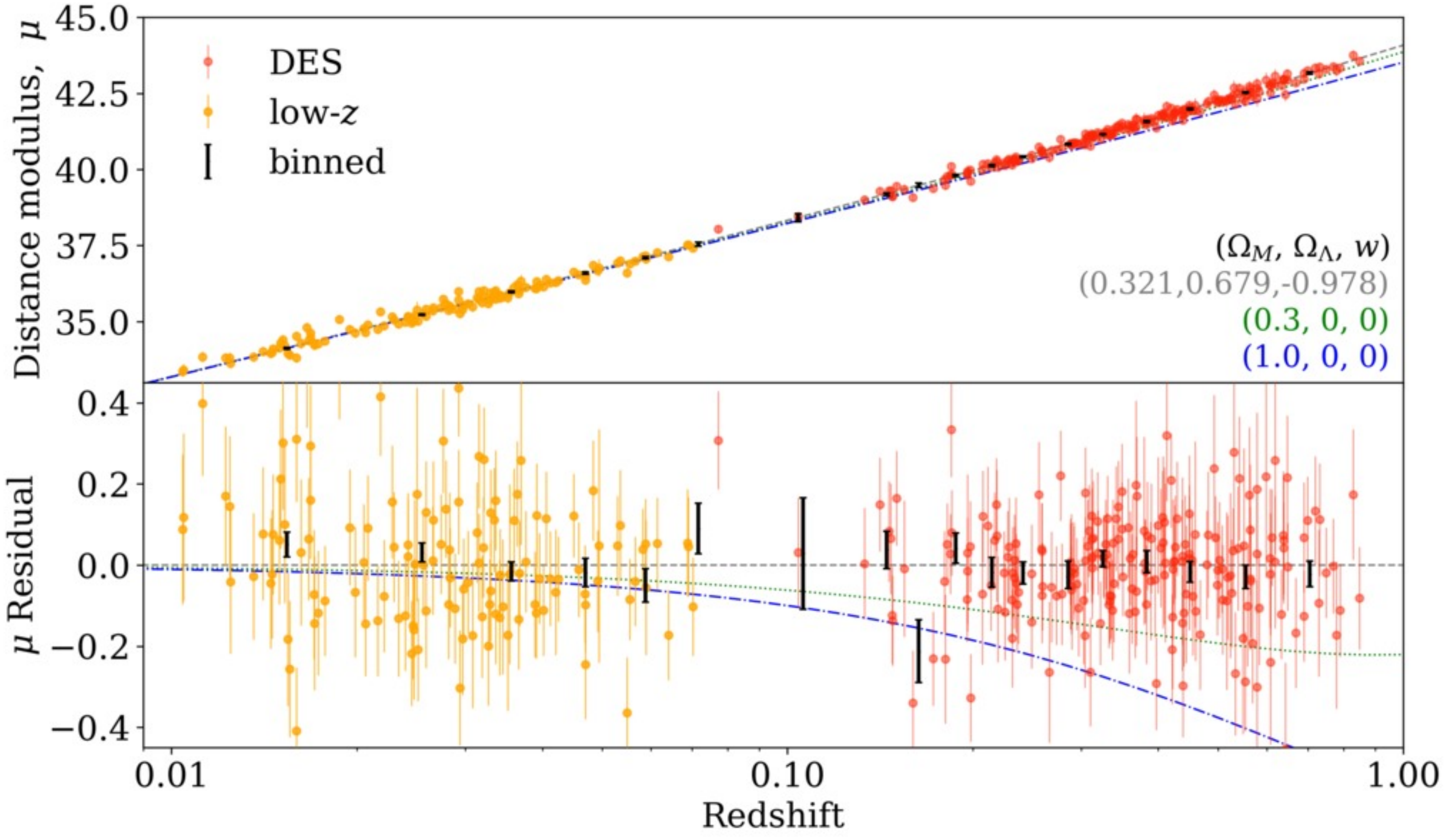
$$\mu(z)_{\rm model} = 5\log_{10}(d_L/10pc) \qquad d_L(z) = (1+z)\frac{c}{H_0}\int_0^z \frac{dz}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda(a+z)^{3(1+w)}}}$$







SNIa cosmology



Brout+19

$$HR = \mu(z)_{\rm SN} - \mu(z)_{\rm model}$$

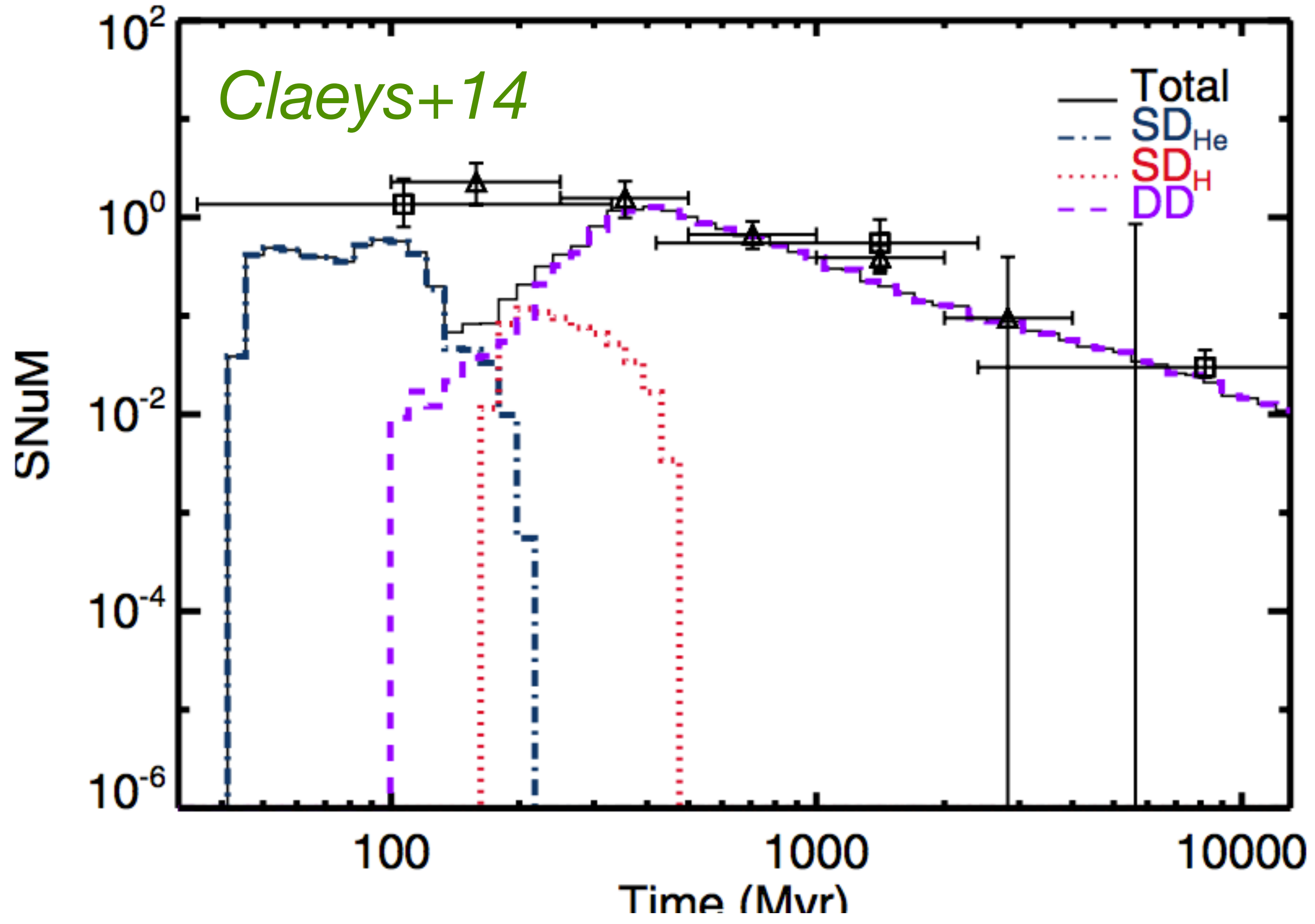
Recent (>2010) cosmological analysis found a dependence between the *Hubble residual and properties of the SN host galaxy**

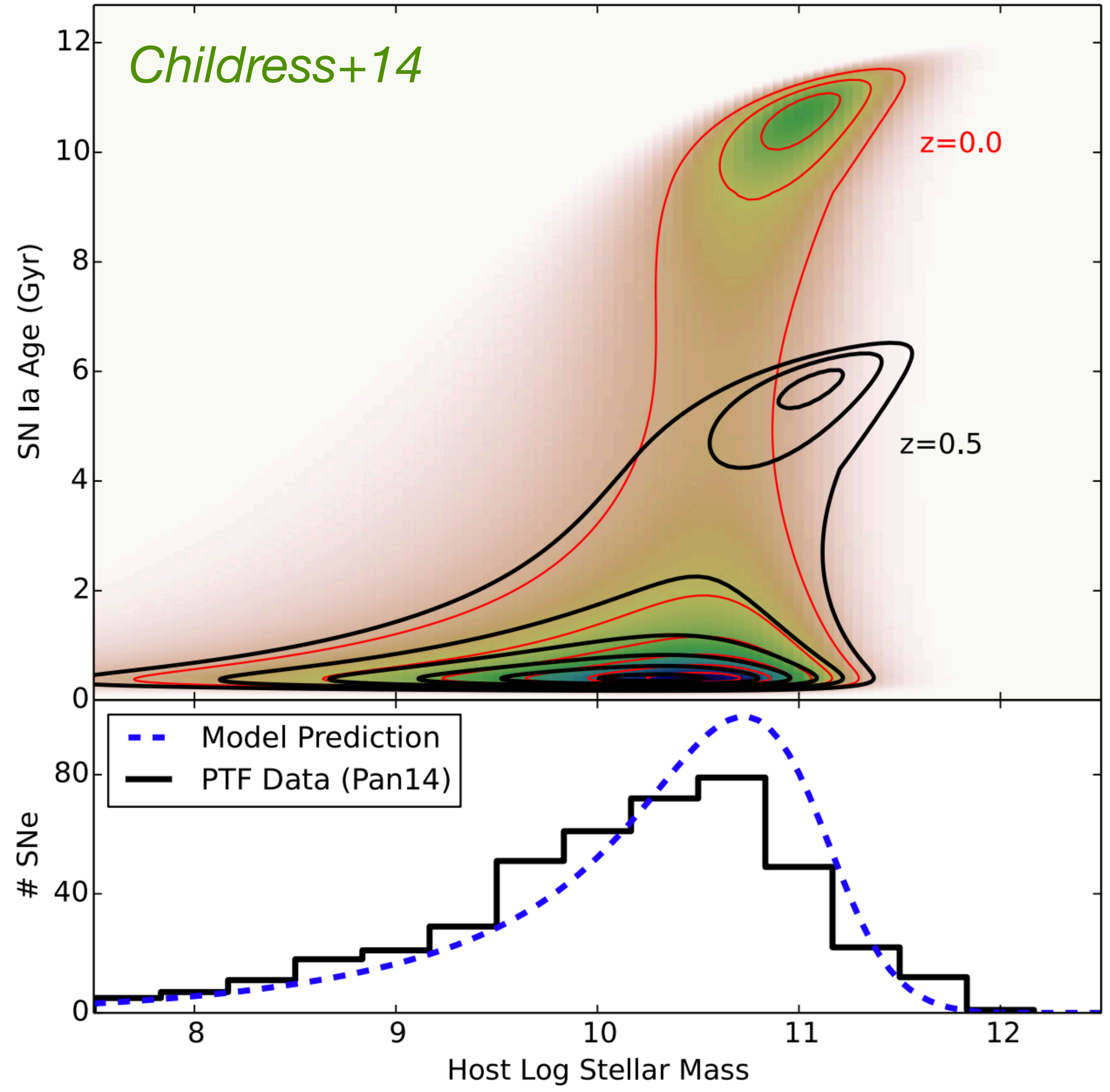
*deviation between the distance from the best cosmological model and the SN distance

Evidence for two populations?

SNIa rates and delay time distribution (DTD) models are consistent with two populations: prompt/delayed.

Continuous, though.

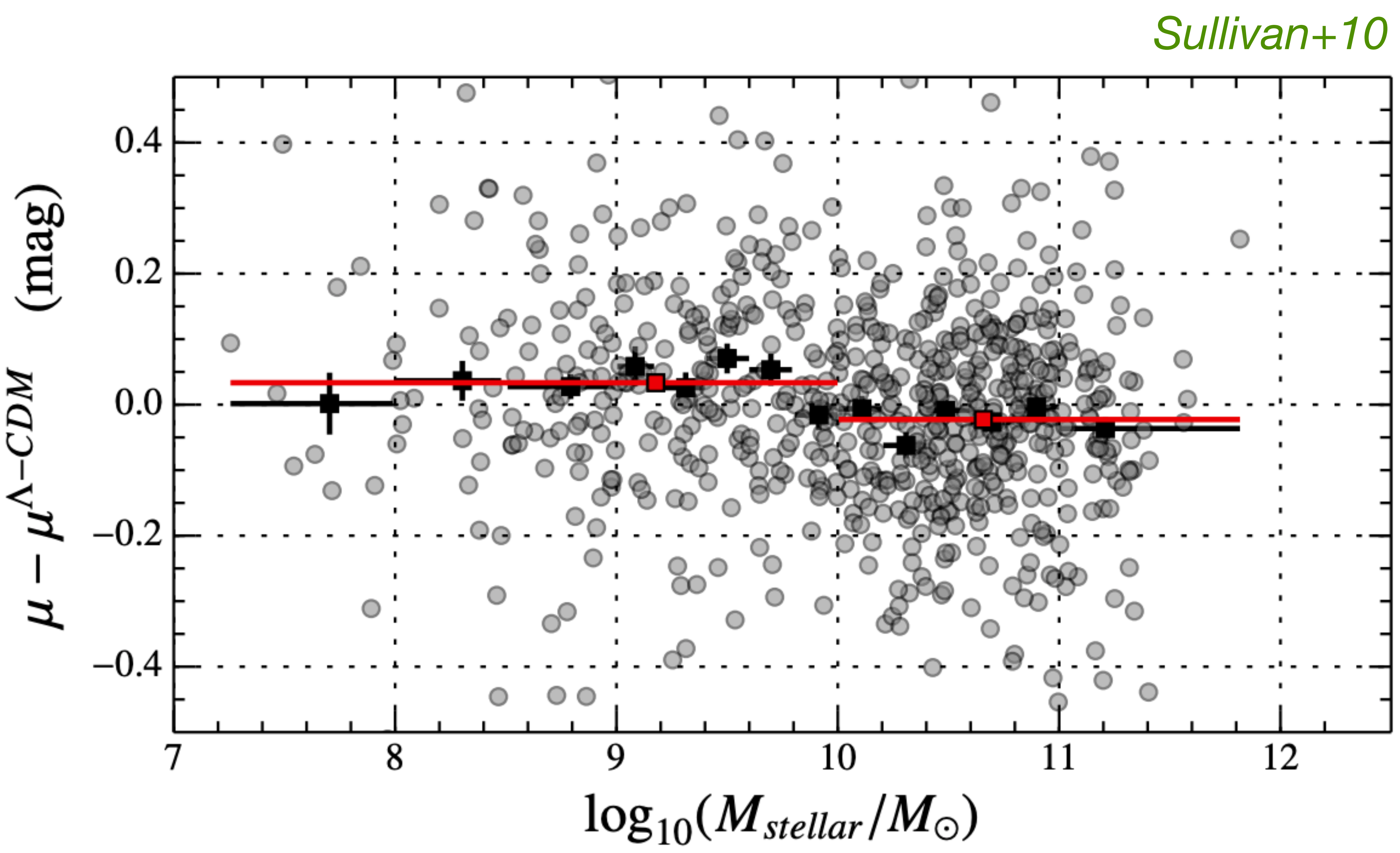


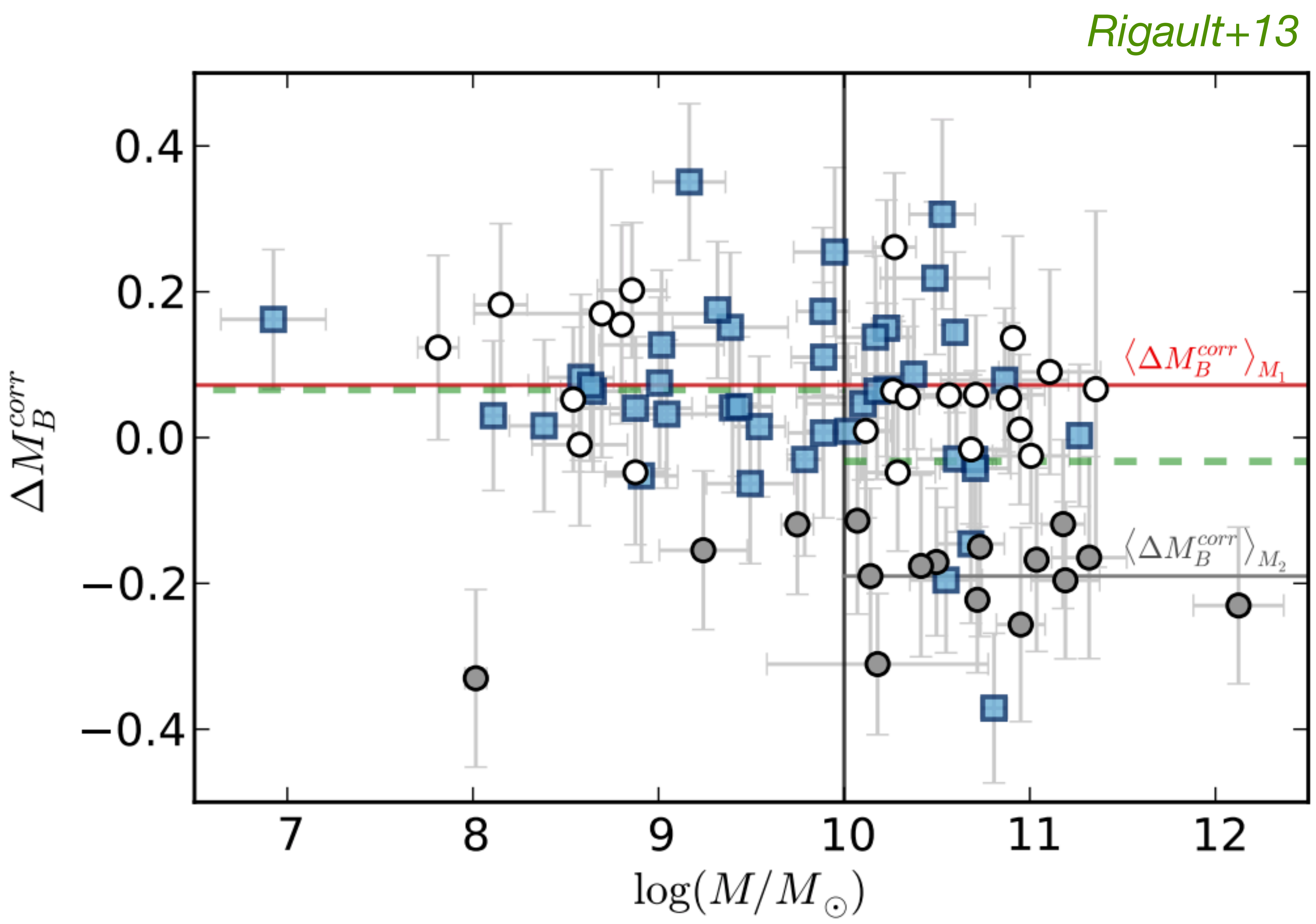


This is consistent with a young (~1 Gyr) and an old distinct SNIa populations.

Their ratio would evolve with redshift

SNIa environment

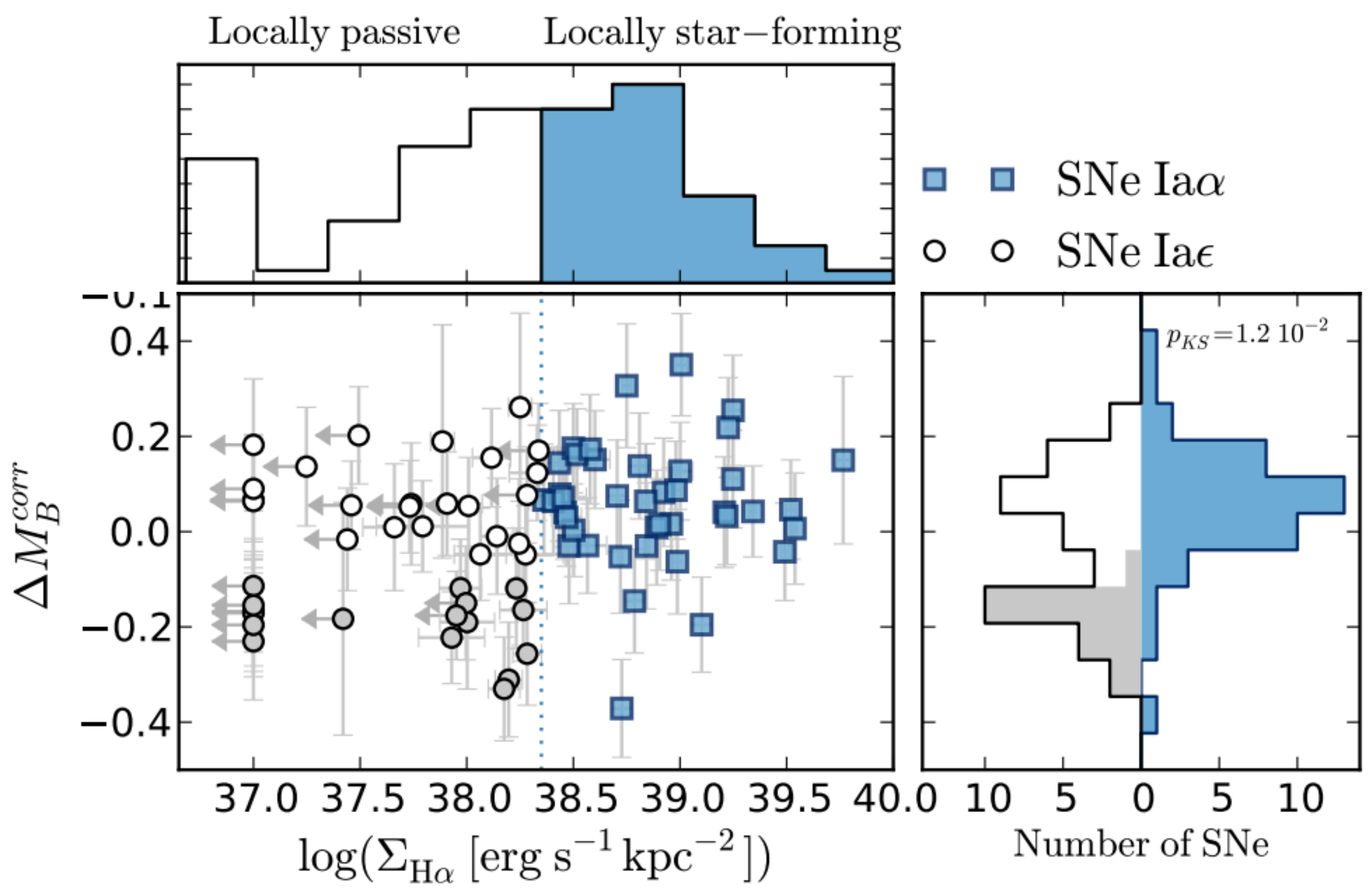




Two different populations, one associated to young and other to old populations, that evolve with z!

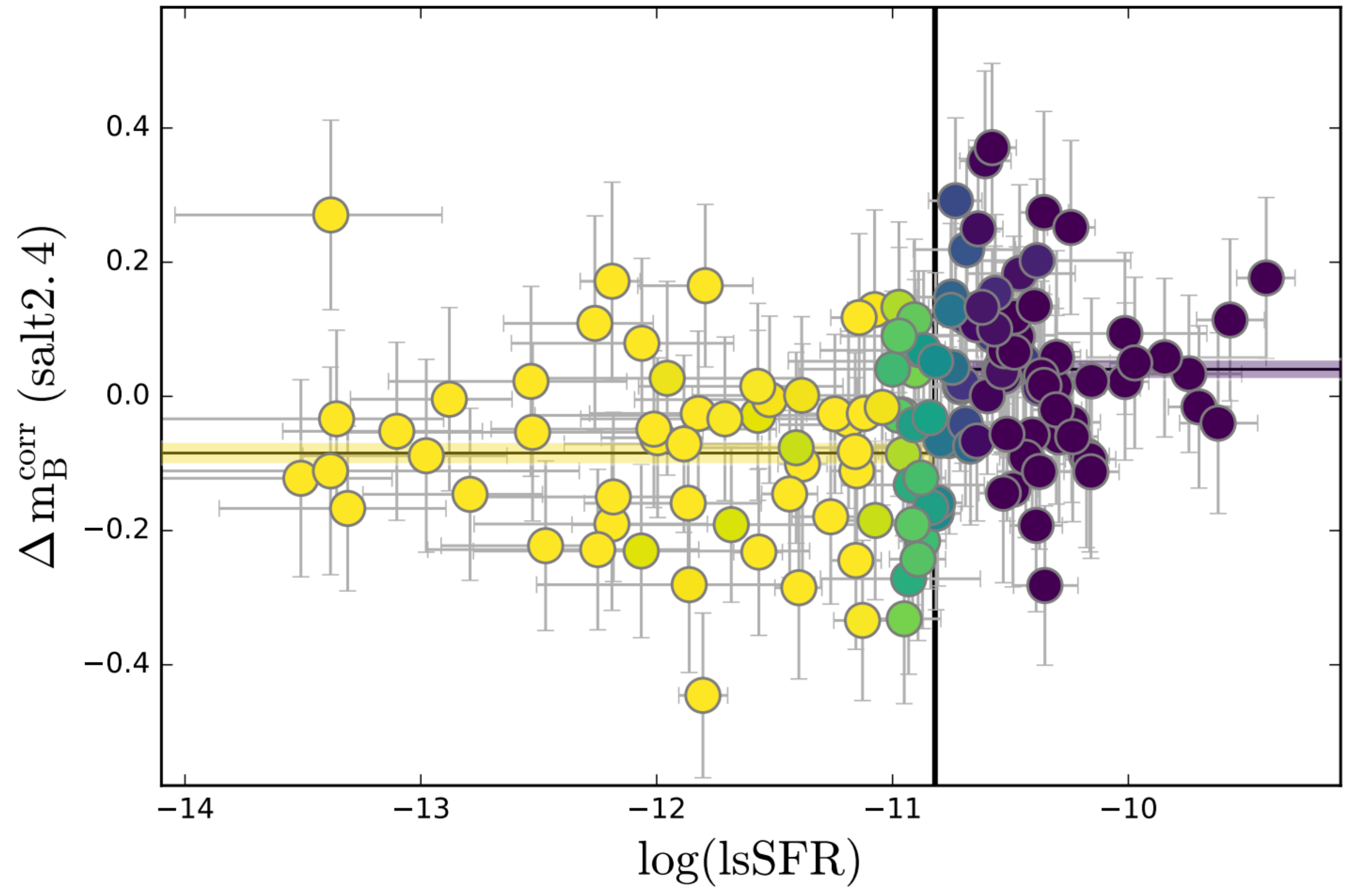
But mass should be just a proxy for another other parameter…

Local SNIa environment



SFR *Rigault et al. 2013*

IFS ~1kpc

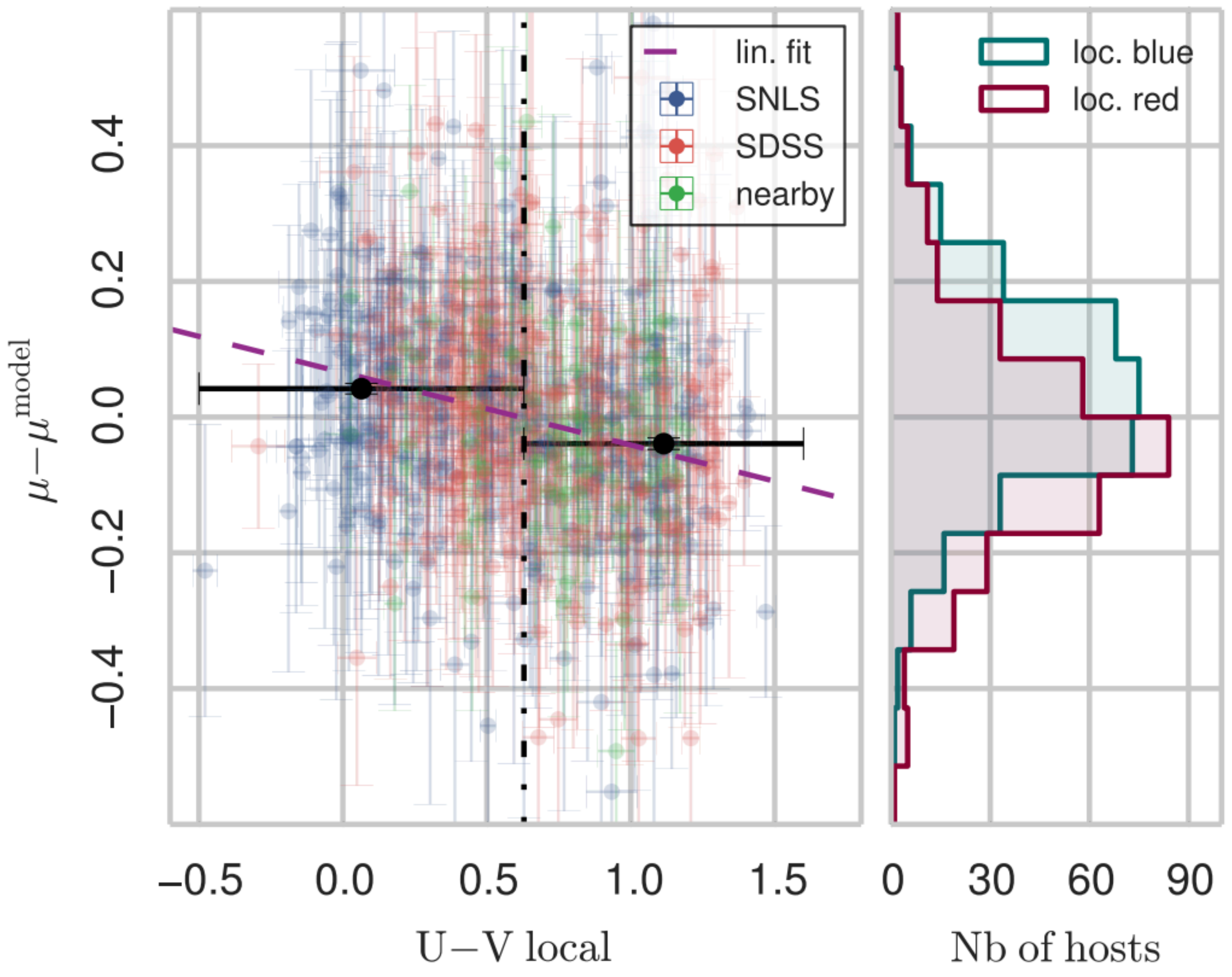


lsSFR *Rigault et al. 2018*

Phot ~1.5kpc

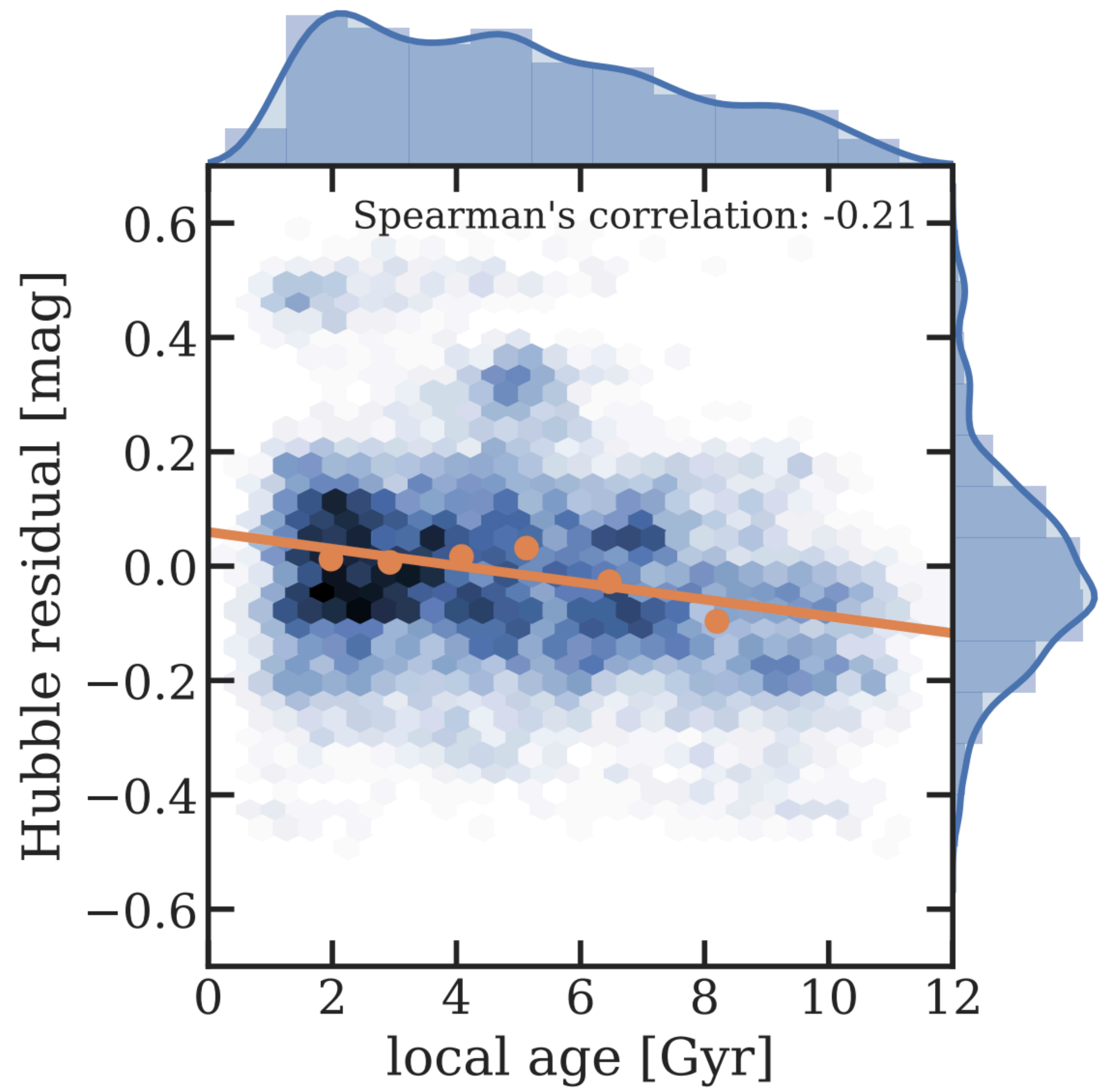
U-V *Roman et al. 2017*

Phot ~3kpc

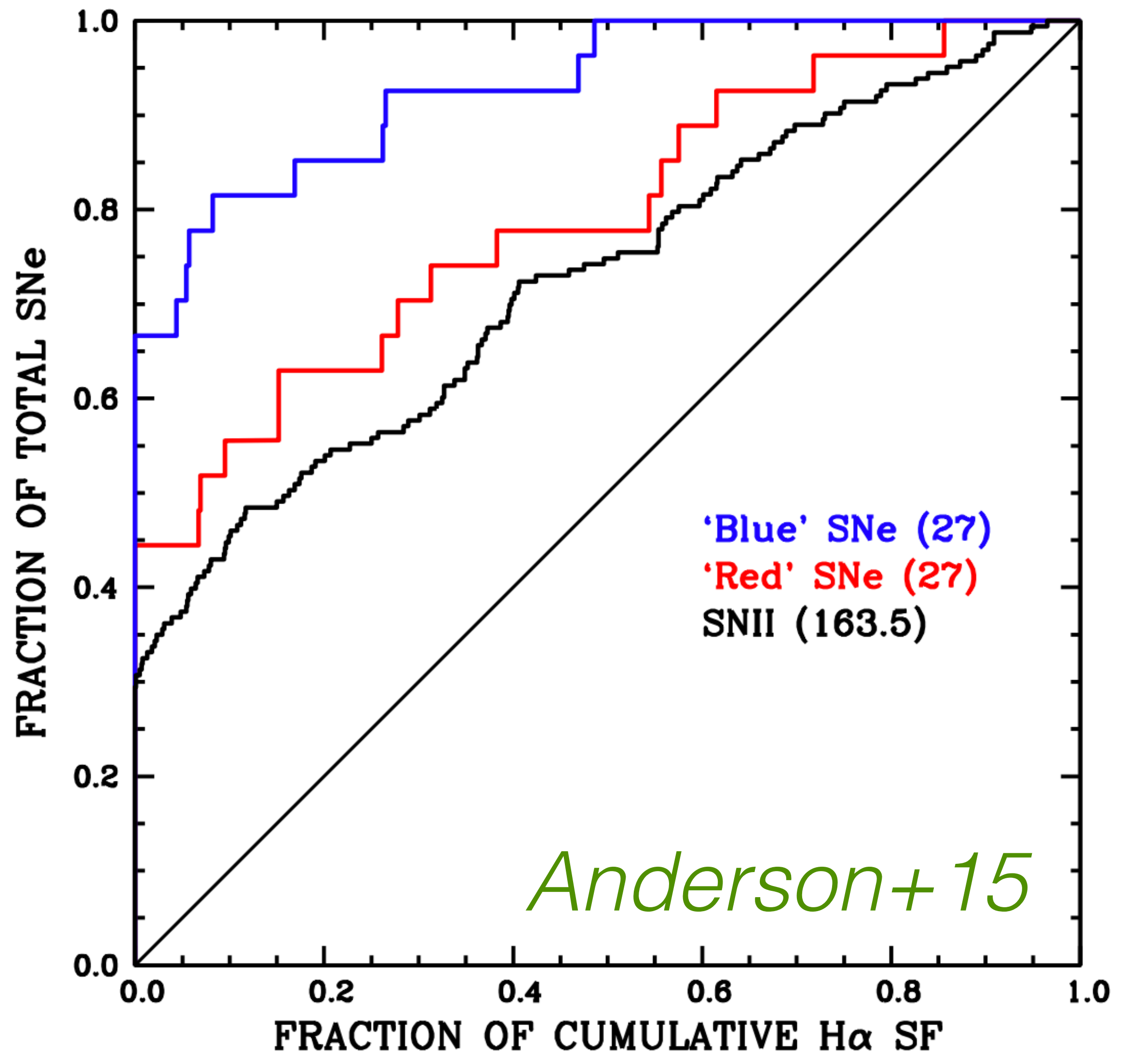


Age *Rose et al 2019*

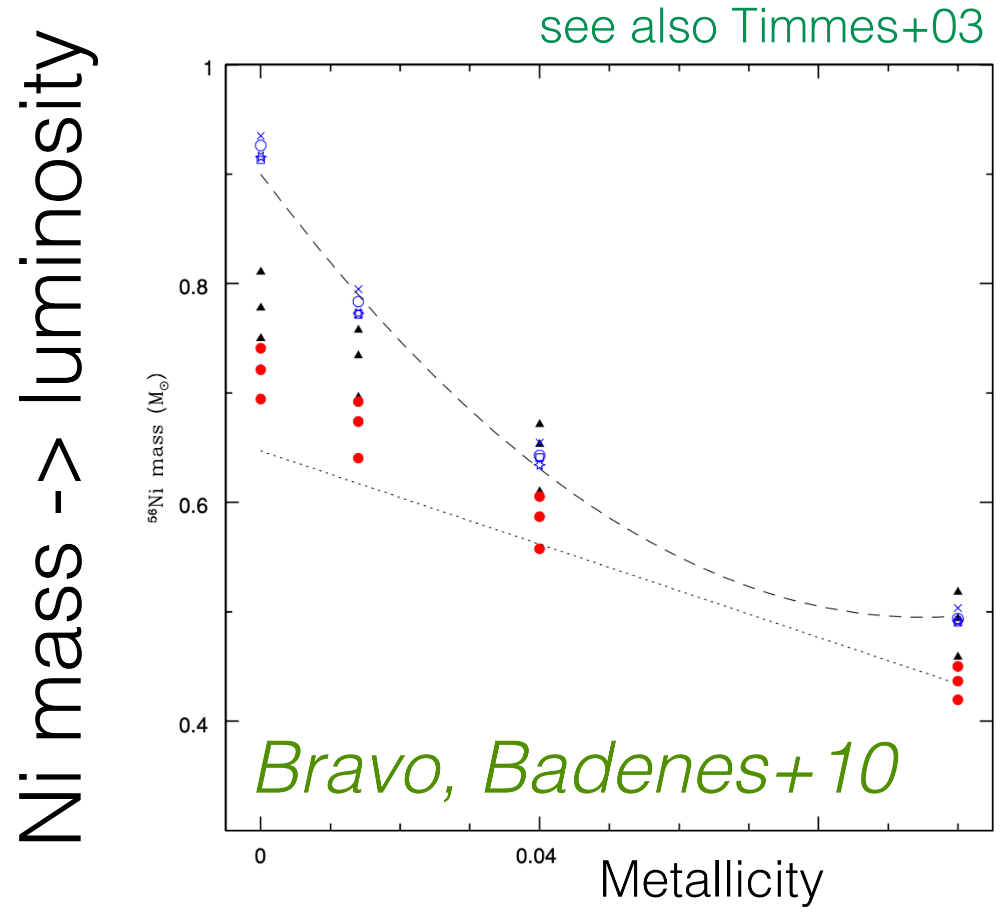
Phot ~5arcsec



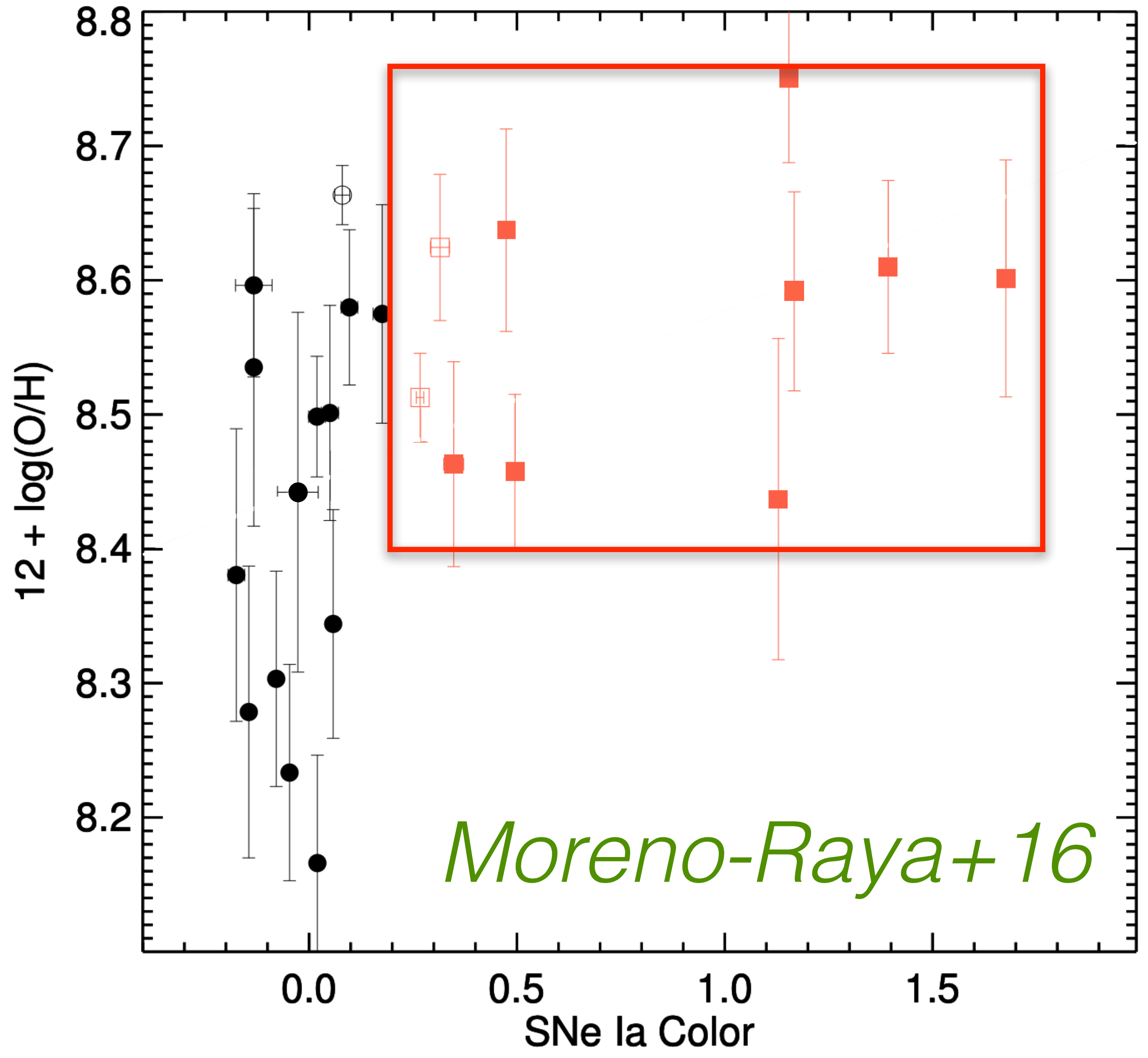
(Non-cosmological) local SNIa environment



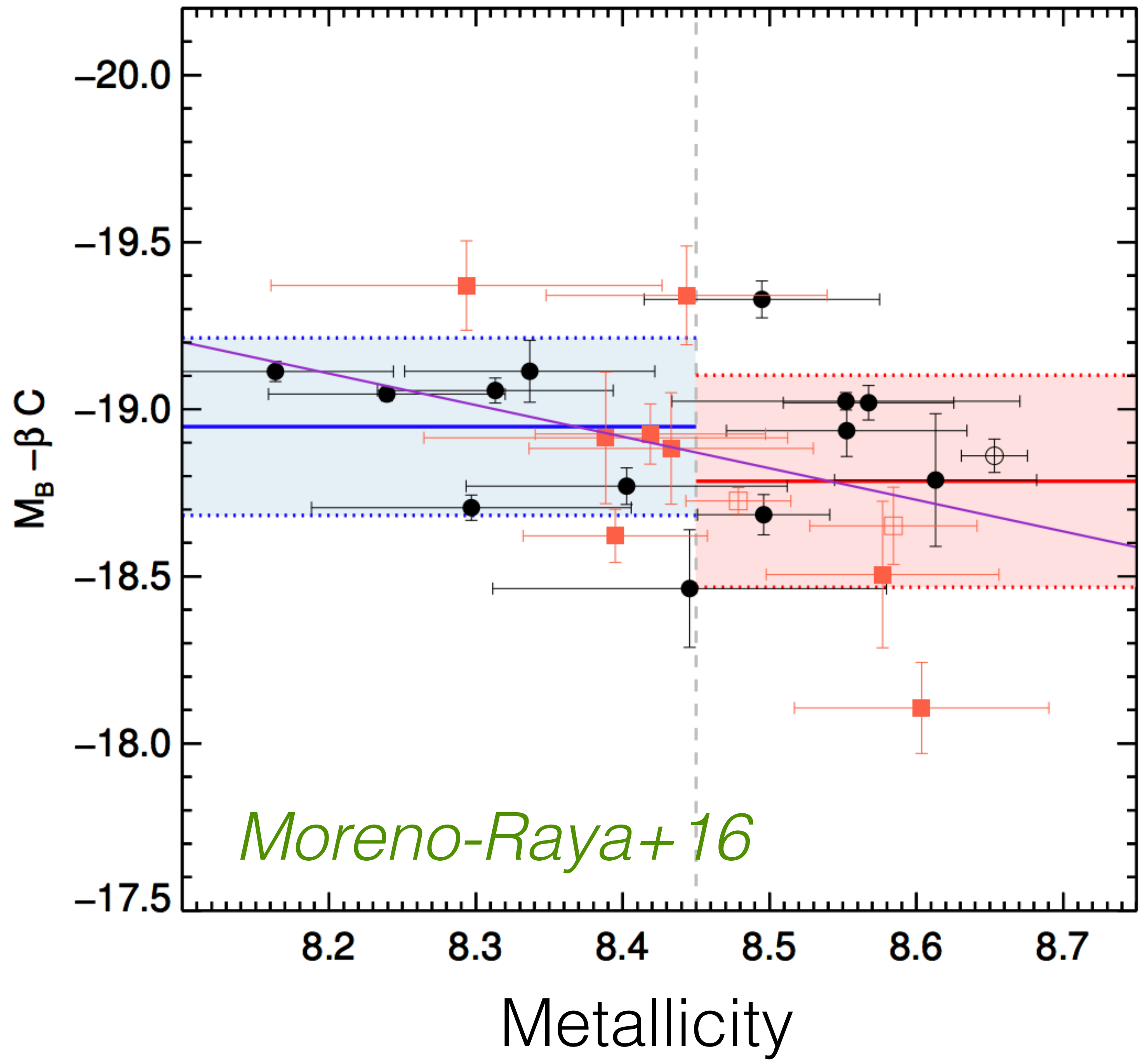
Redder SNIa more associated to HII regions
And found more centrally within hosts



Color corrected magnitudes depend on local metallicity



Red SNe in metal-rich environments



End of the 1st part

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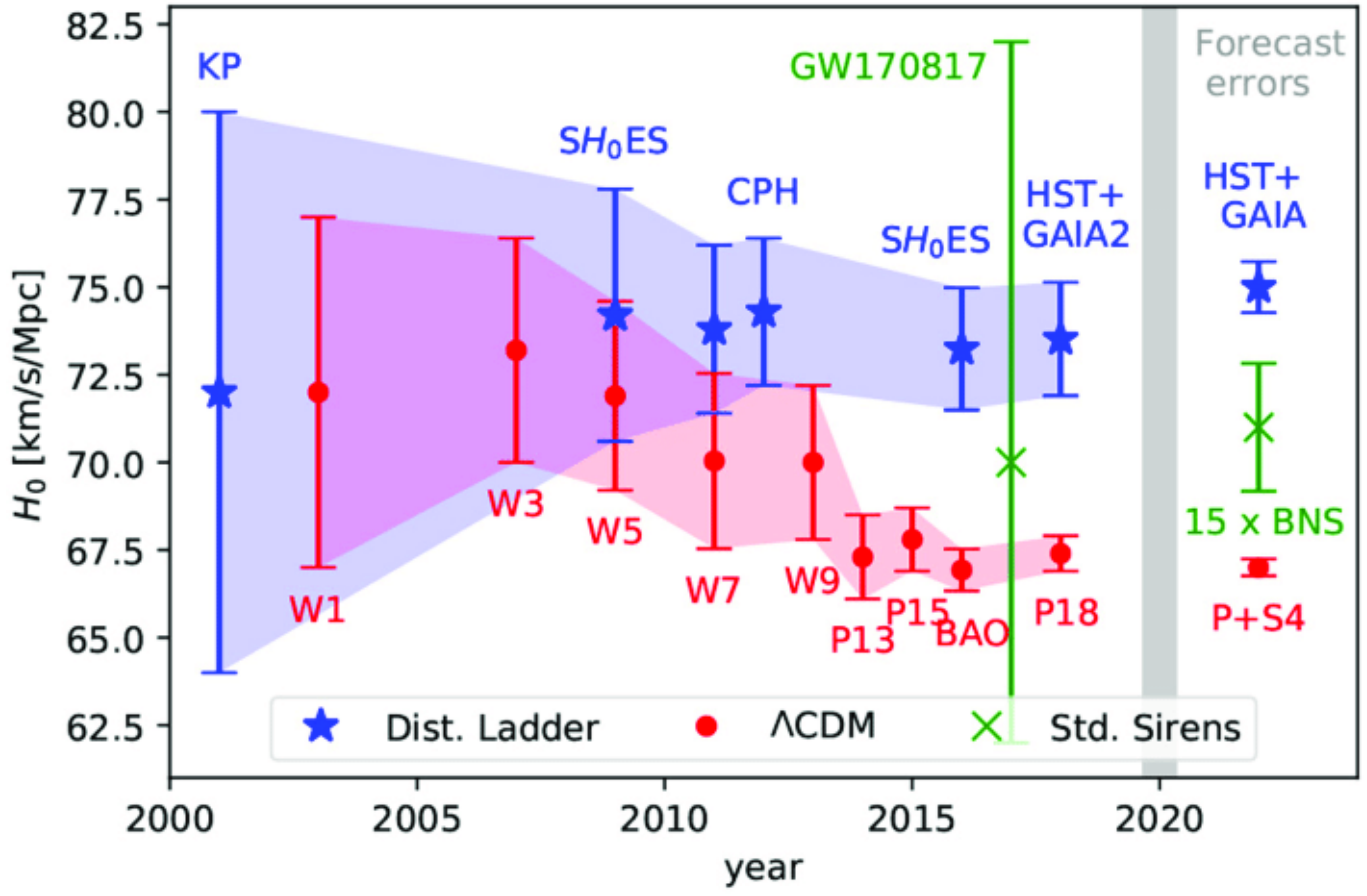
Problem

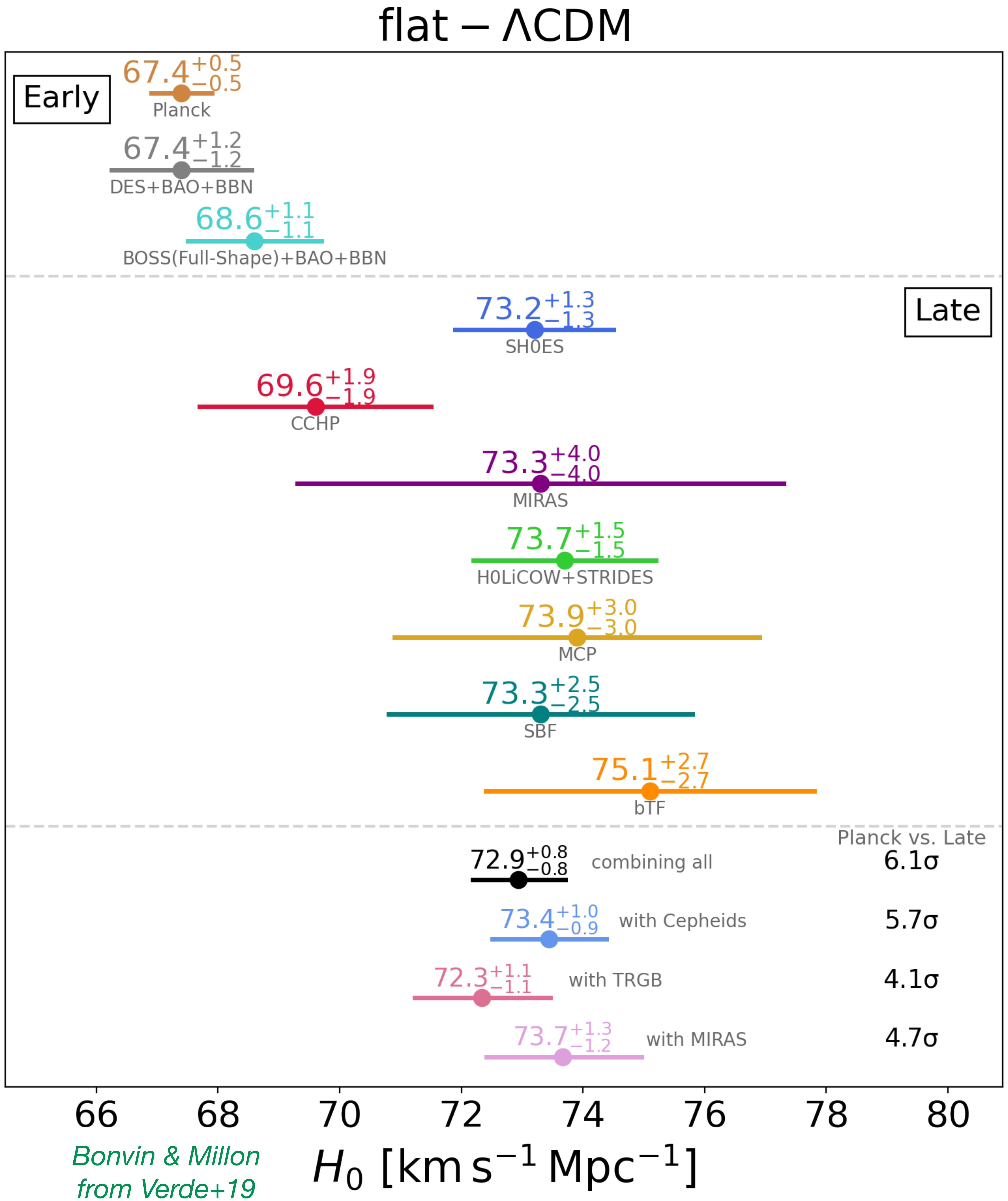
Hubble tension

Ezquiaga & Zumalacárregui 2018



$H_{0\ \text{Planck},\Lambda\text{CDM}}$ = (67.4 ± 0.5) km s^{-1} Mpc^{-1}

$H_{0\ \text{SHOES}}$ = (73.2 ± 1.3) km s^{-1} Mpc^{-1}



Bonvin & Millon from Verde+19

Problem

Hubble tension

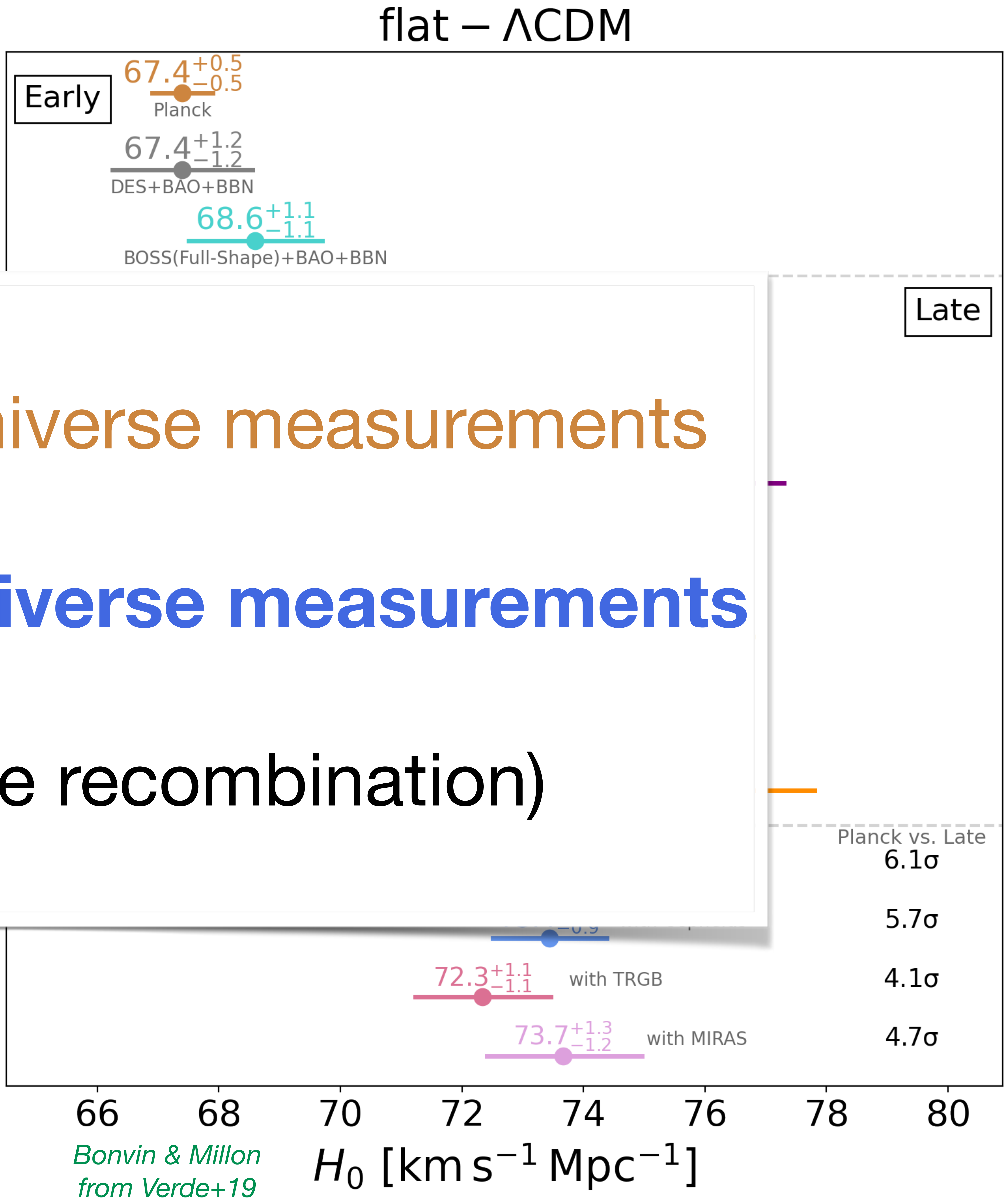
Systematics on Early Universe measurements

Systematics on Late Universe measurements

New physics (before recombination)

$H_{0\ \mathrm{Planck},\Lambda\mathrm{CDM}} = (67.4 \pm 0.5)\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$

$H_{0\ \mathrm{SHOES}} = (73.2 \pm 1.3)\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$



Bonvin & Millon from Verde+19

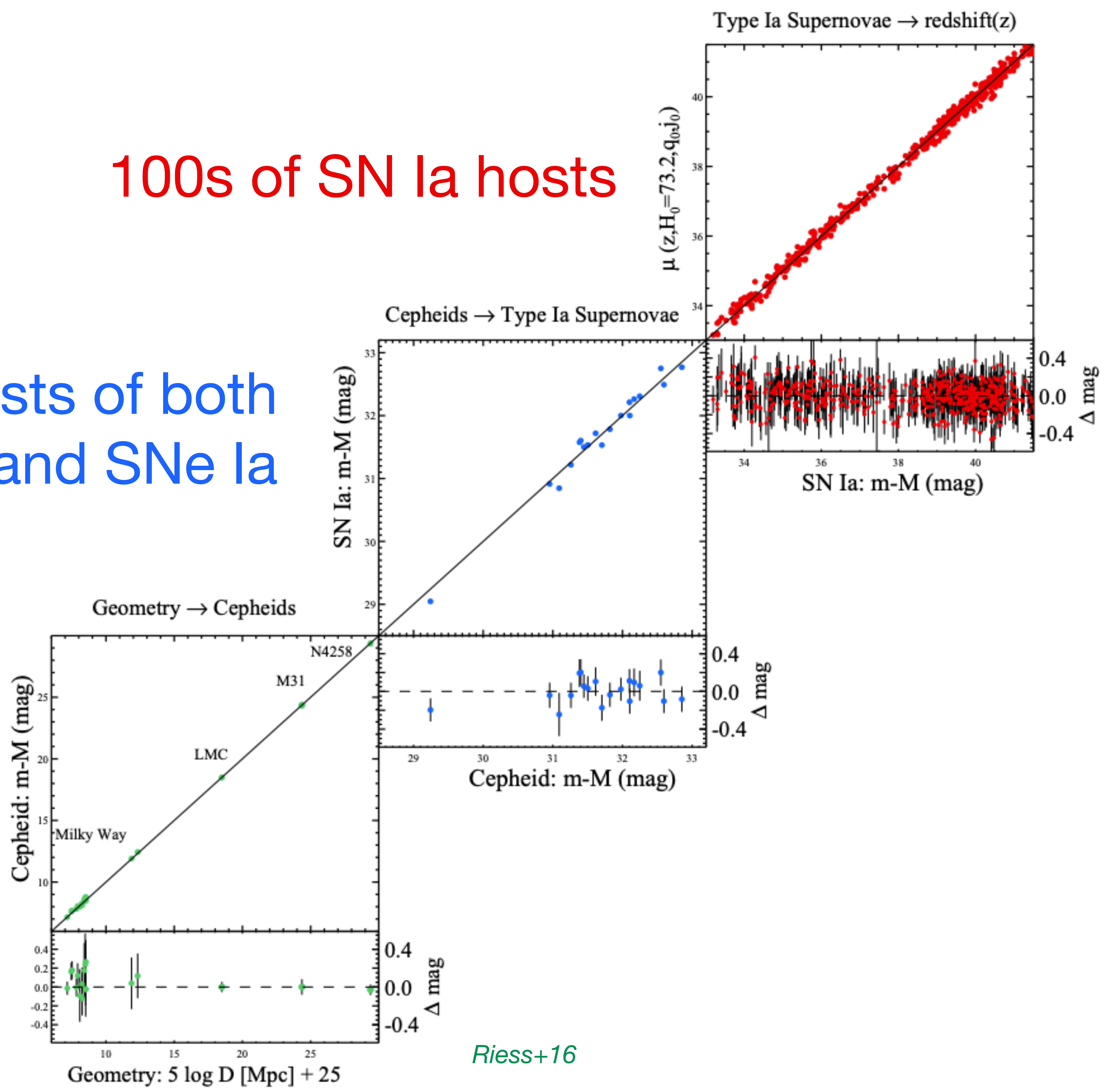
Distance ladder

100s of SN Ia hosts

19 hosts of both Cepheids and SNe Ia

Geometric distances to calibrate Cepheids

MW paralaxes
LMC DEBs
M31 DEBs
NGC4258 maser



Riess+16

Systematics (Cepheids)

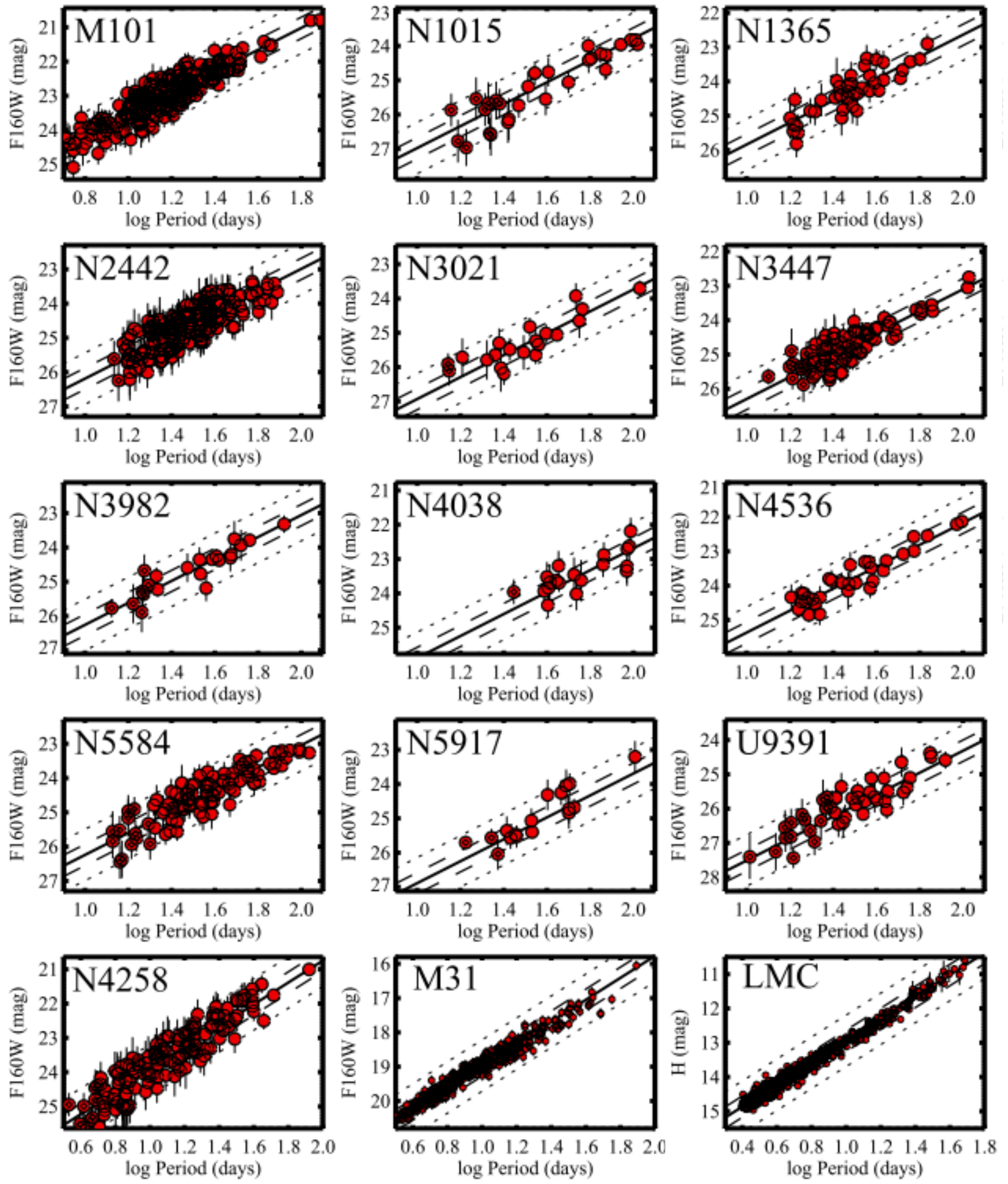
Wesenheit magnitudes measured as

$$m^W_{X,i,j} = m_{X,i,j} - R\ (V_{i,j} - I_{i,j}) \qquad R = A_X/(A_V - A_I)$$

And modeled as:

$$m^W_{X,i,j} = \mu_i + M^W_X + b_W \log_{10} P_{i,j} + Z_W \Delta \log(M/H)_{i,j}$$

Riess+16



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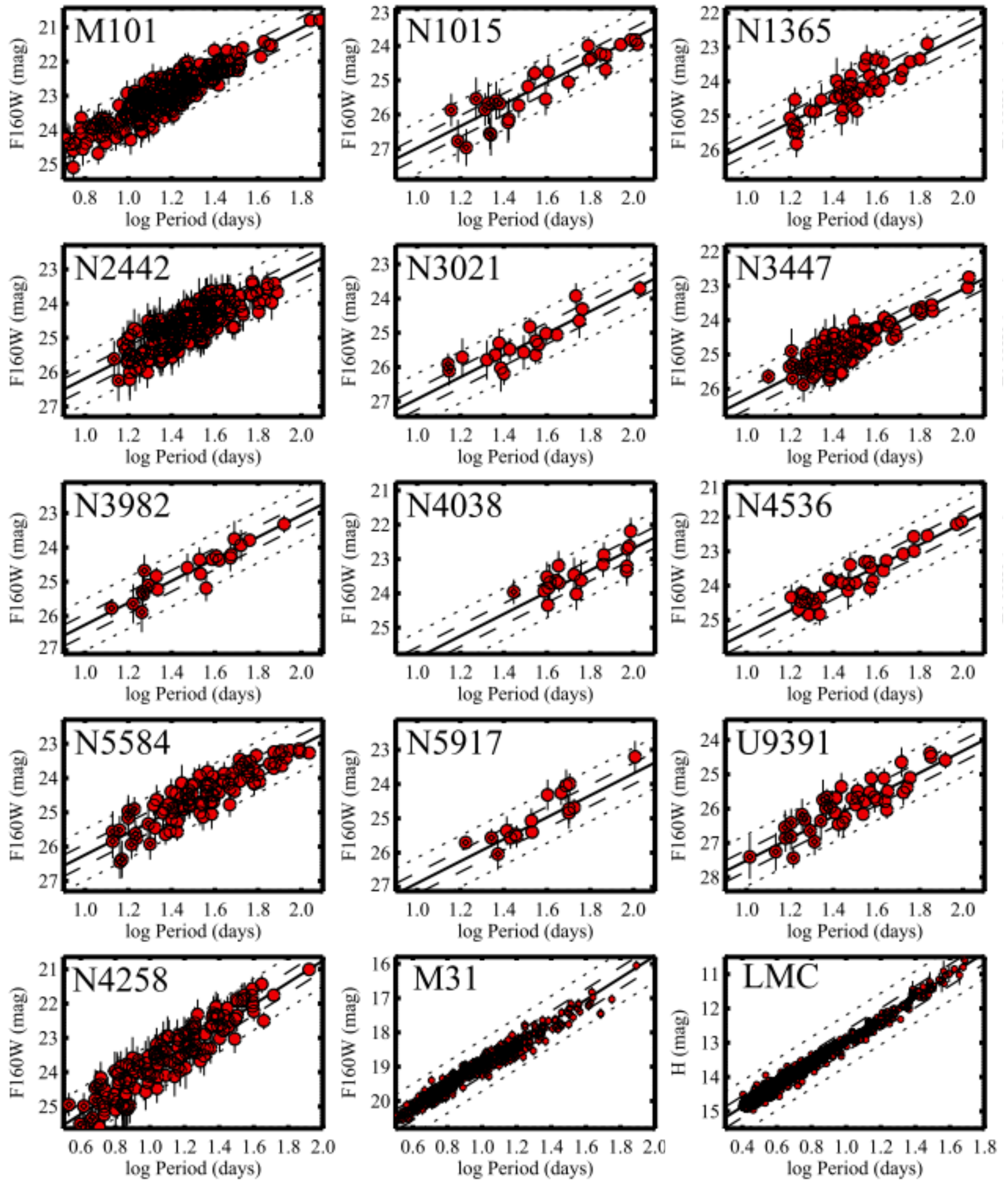

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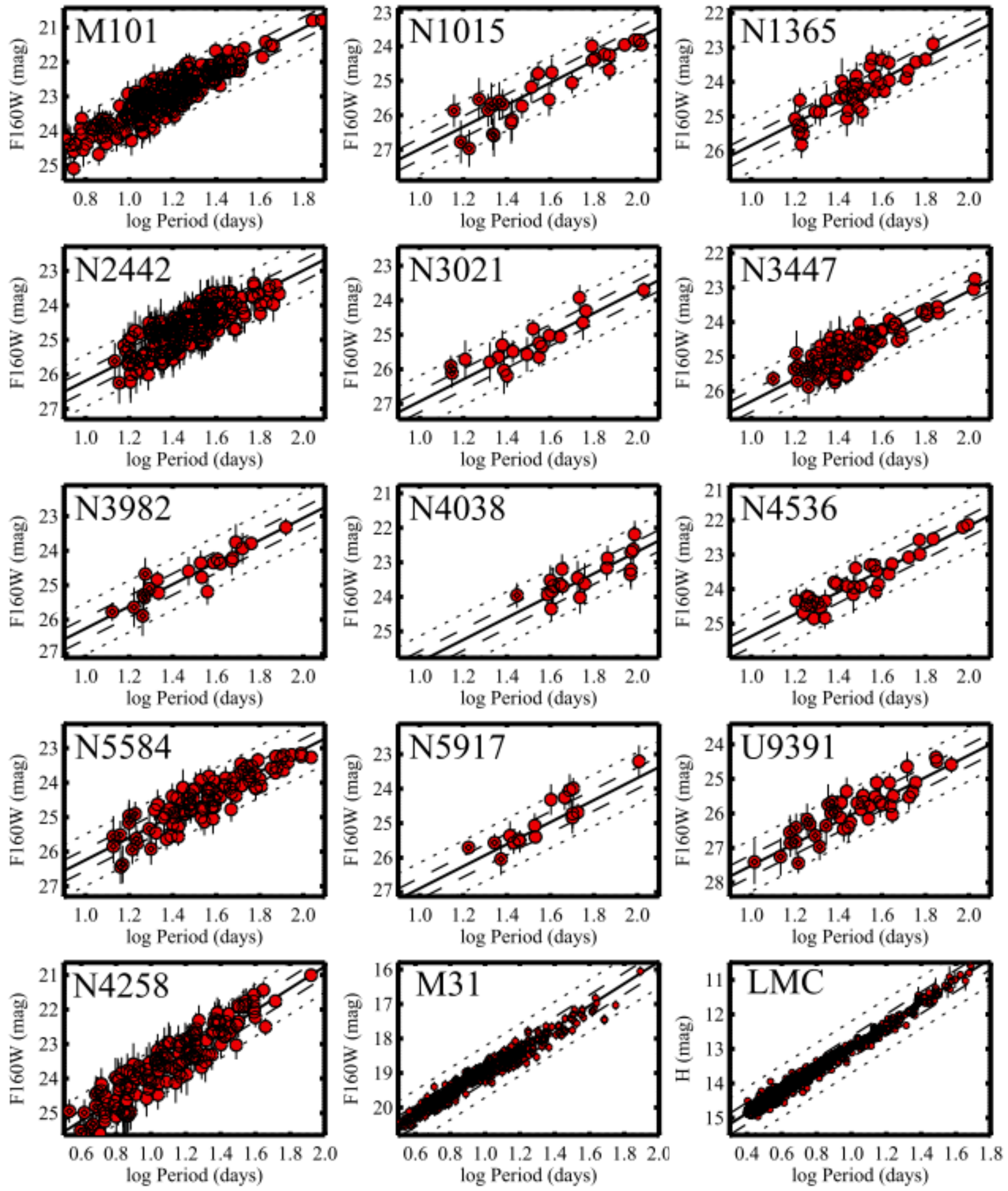

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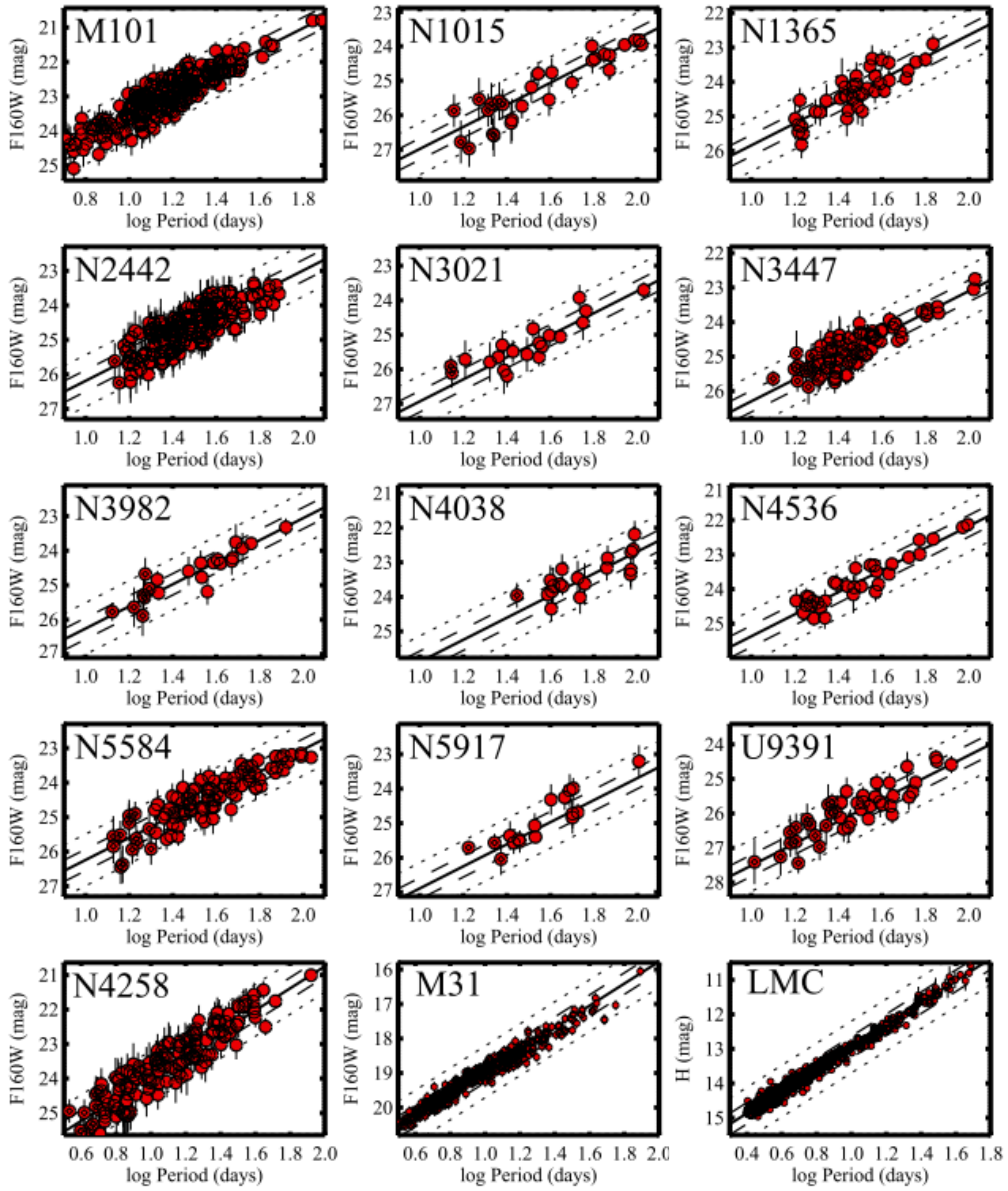

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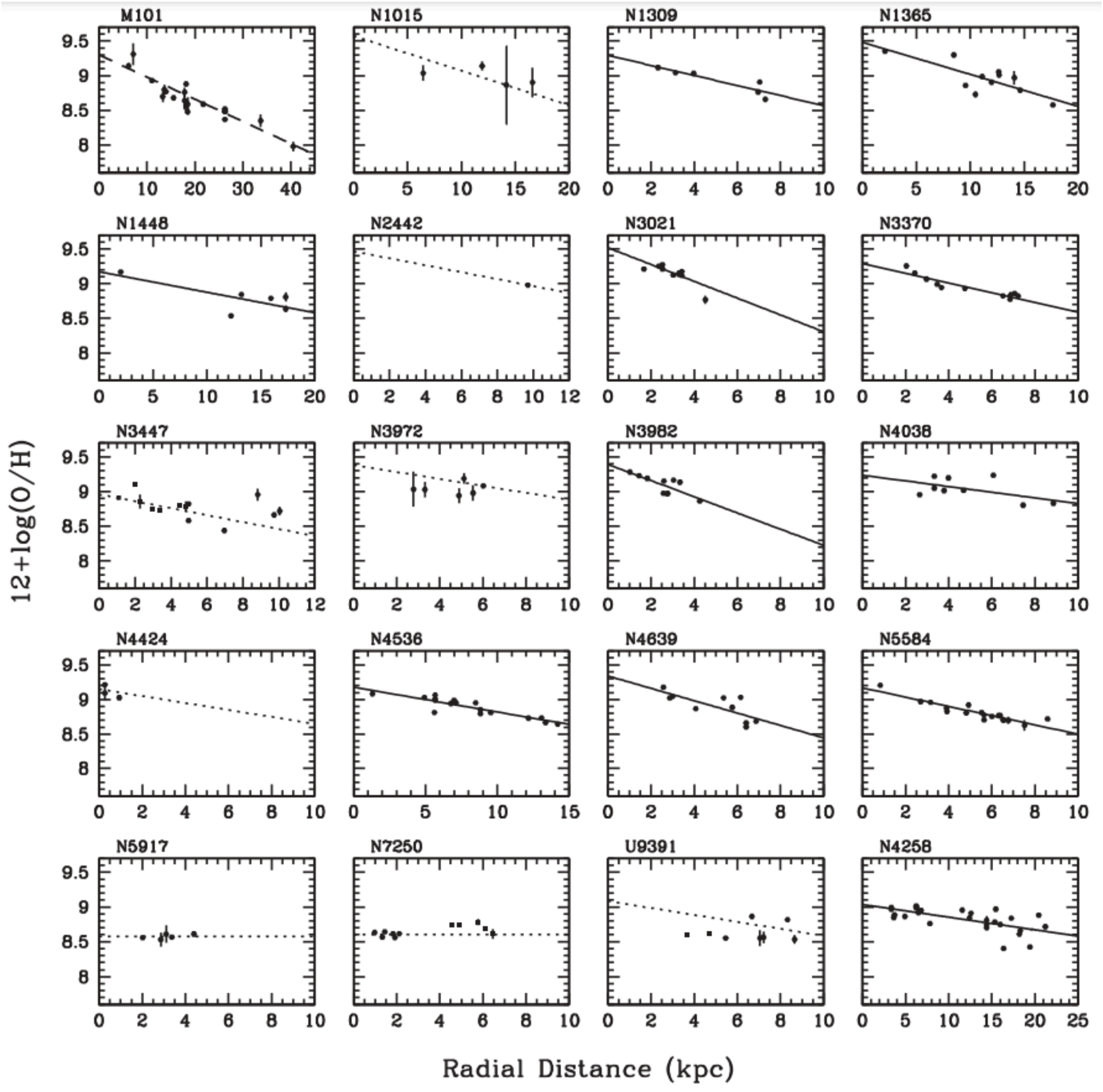
R dust/intrinsic -> 2,n R (see e.g. Mörtsell+21)

$P - L$ fast/slow -> 2 b_W

$\log(M/H)$ estimate, and global Z_W

Systematics (Cepheids)

Hoffman+16



Systematics (Cepheids)

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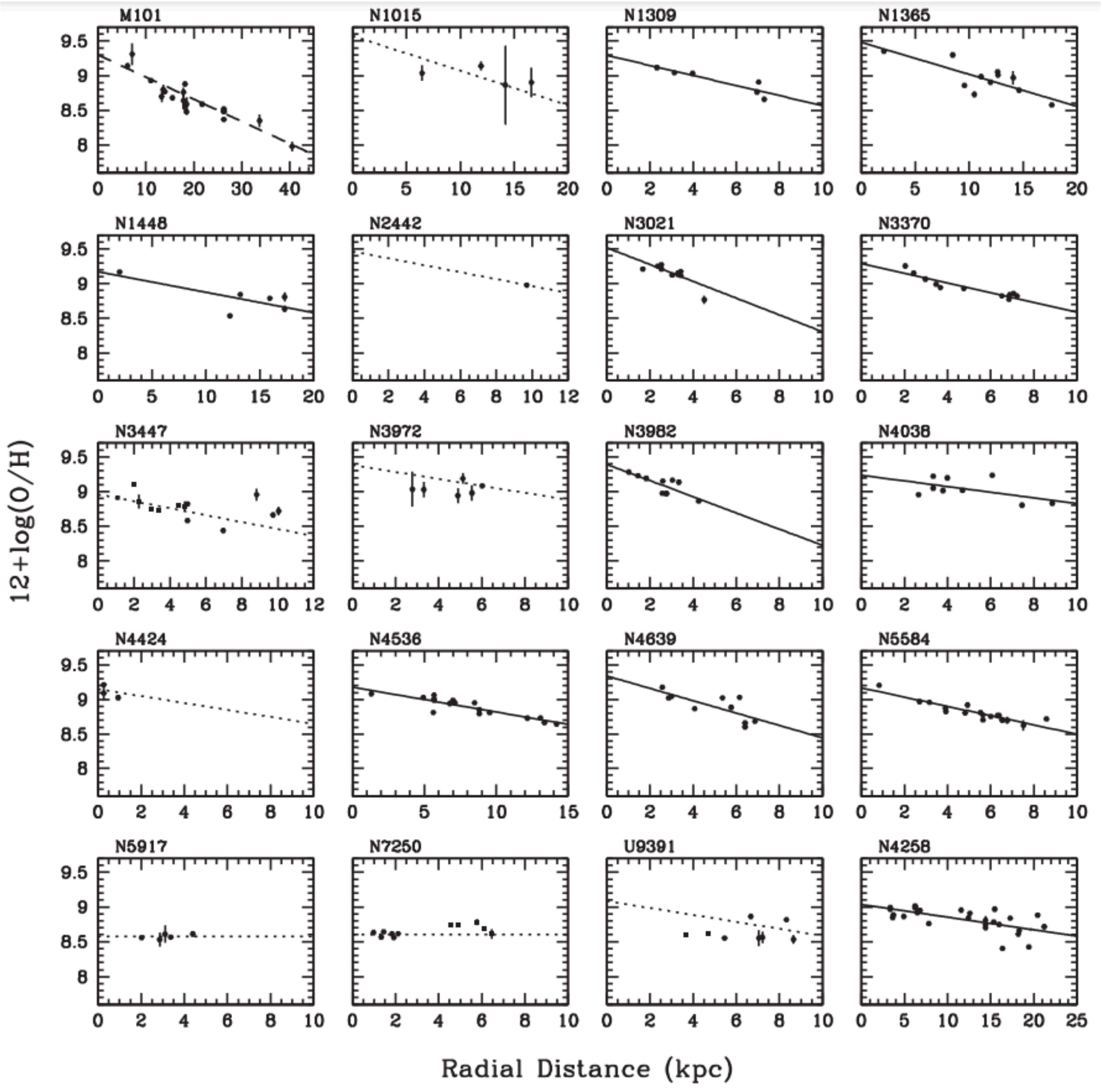
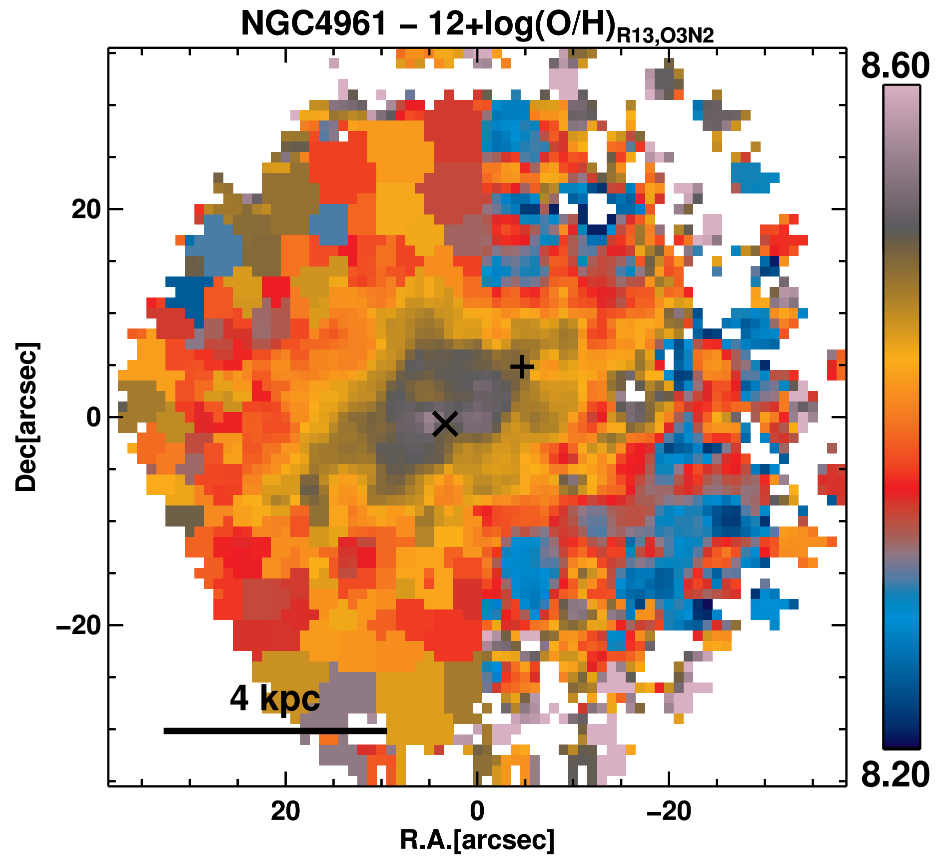
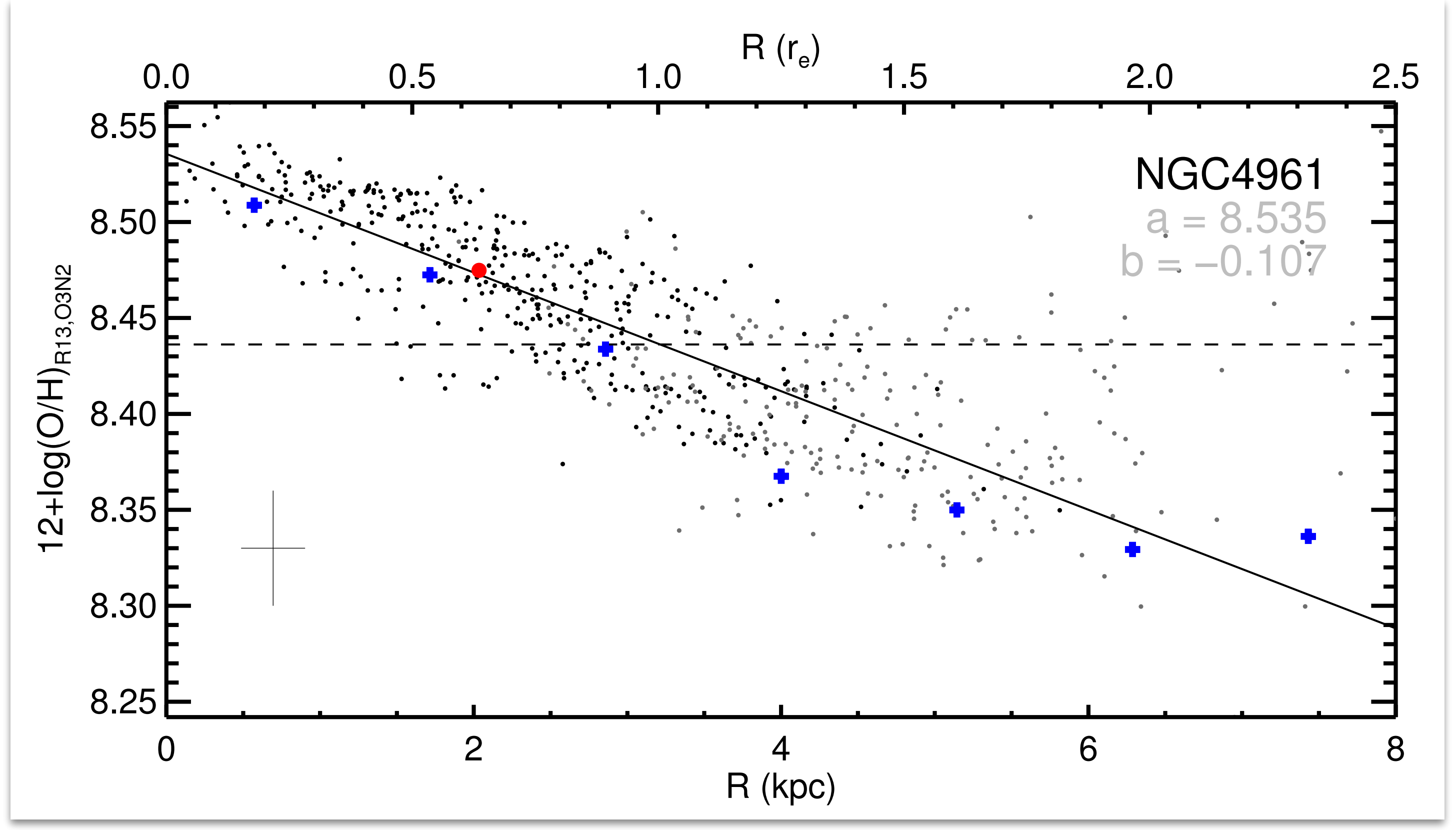
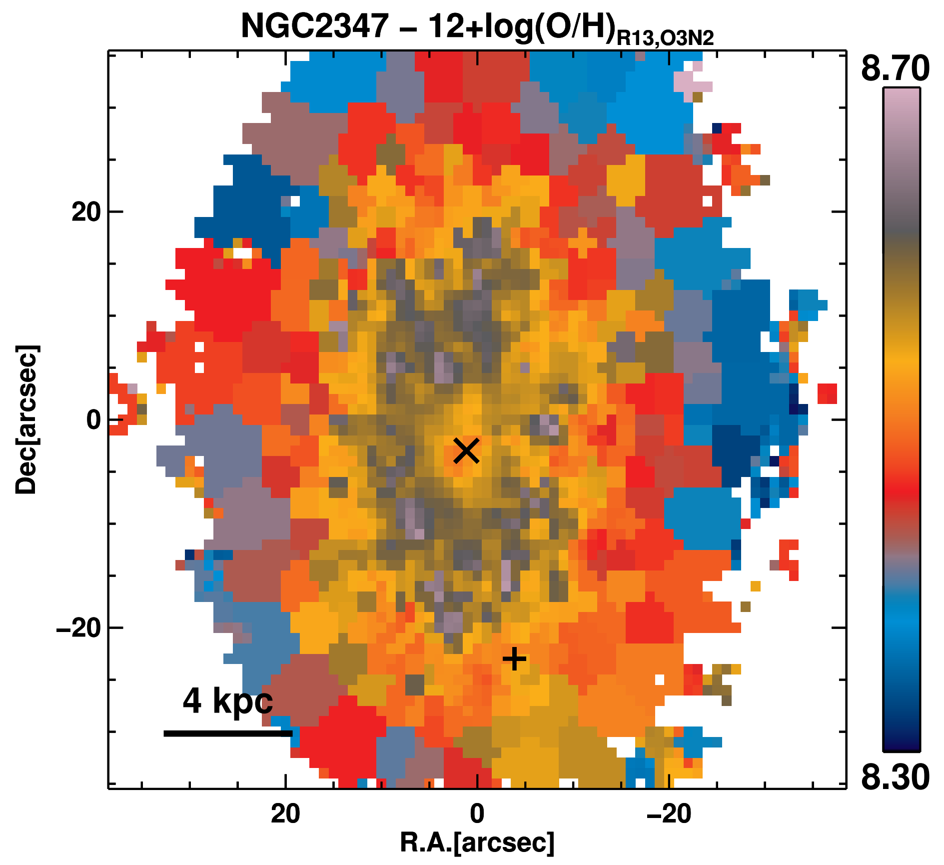
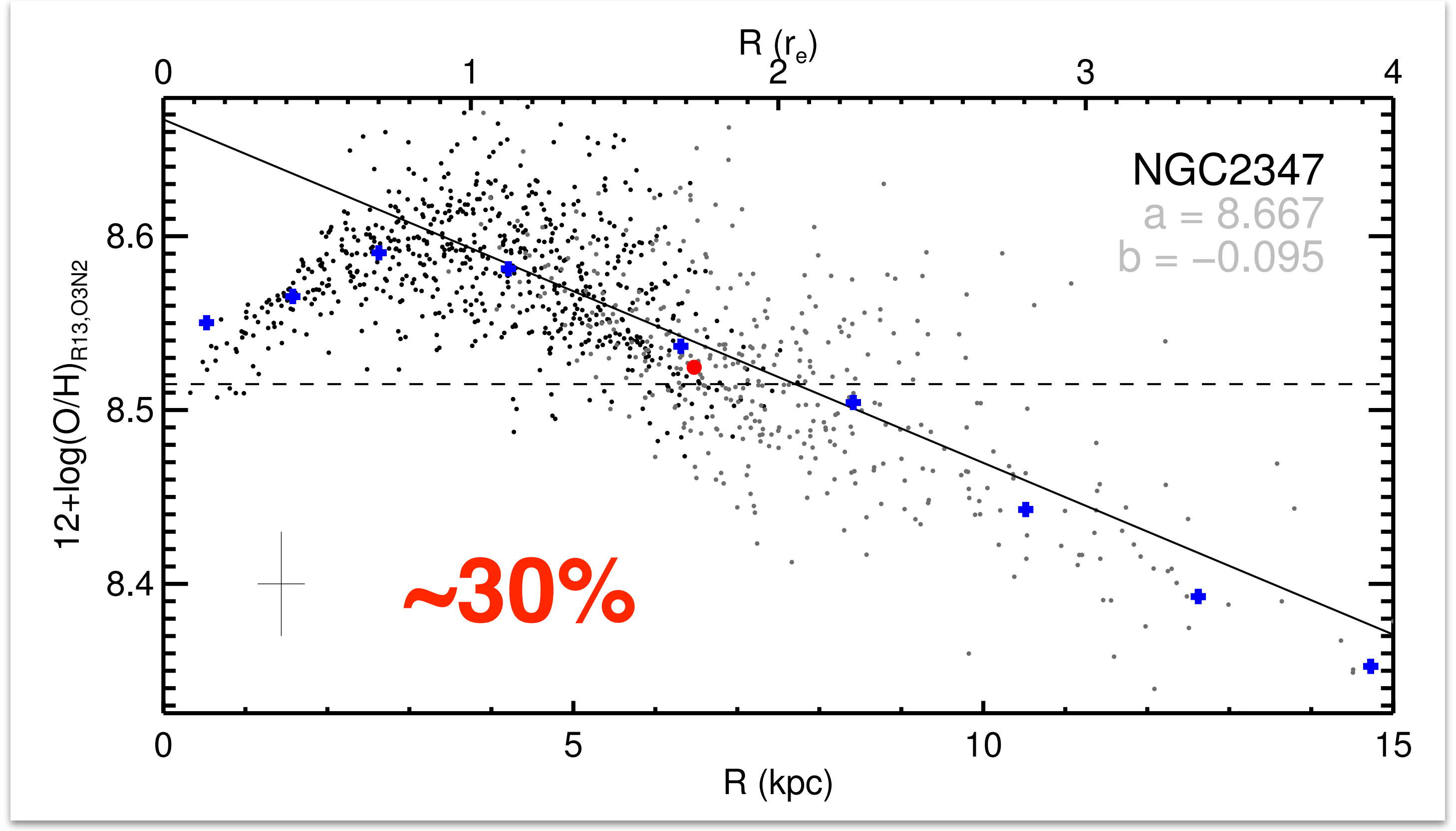


Galbany+16









Systematics (SNe Ia)

$$m_{X,i,j}^{corr} = m_{X,i,j} + \alpha x_1 - \beta c + \gamma(\mathrm{M}_{\mathrm{host}})$$

$$m_{X,i,j}^{corr} = M_X + 5\log_{10}(d_L/10pc)$$

$$d_L(z) = (1+z)\frac{c}{H_0}\int_0^z \frac{dz}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda(a+z)^{3(1+w)}}}$$

(see e.g. Brout+21)

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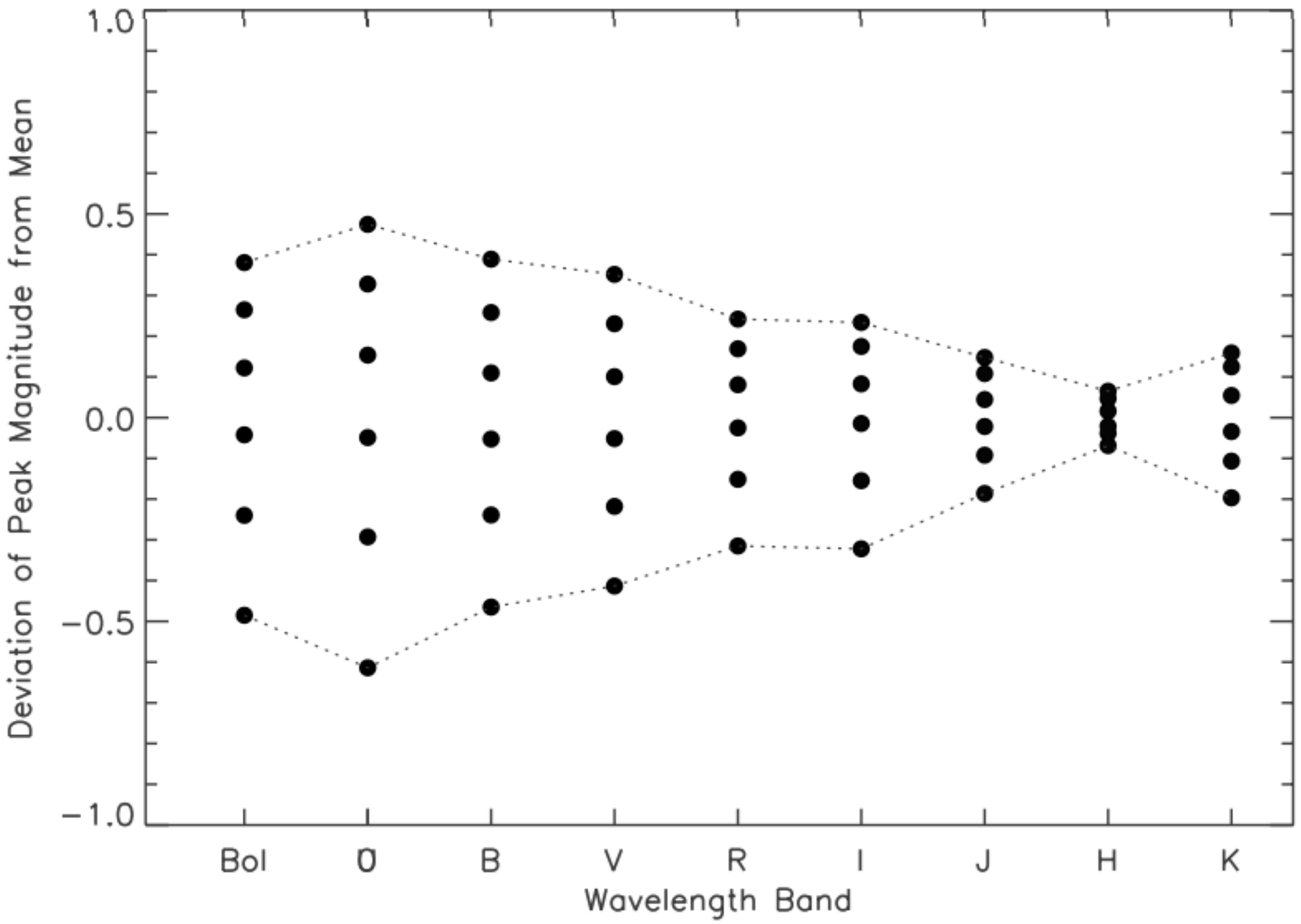
β dust/intrinsic -> 2,n β *(see e.g. Brout+21)*

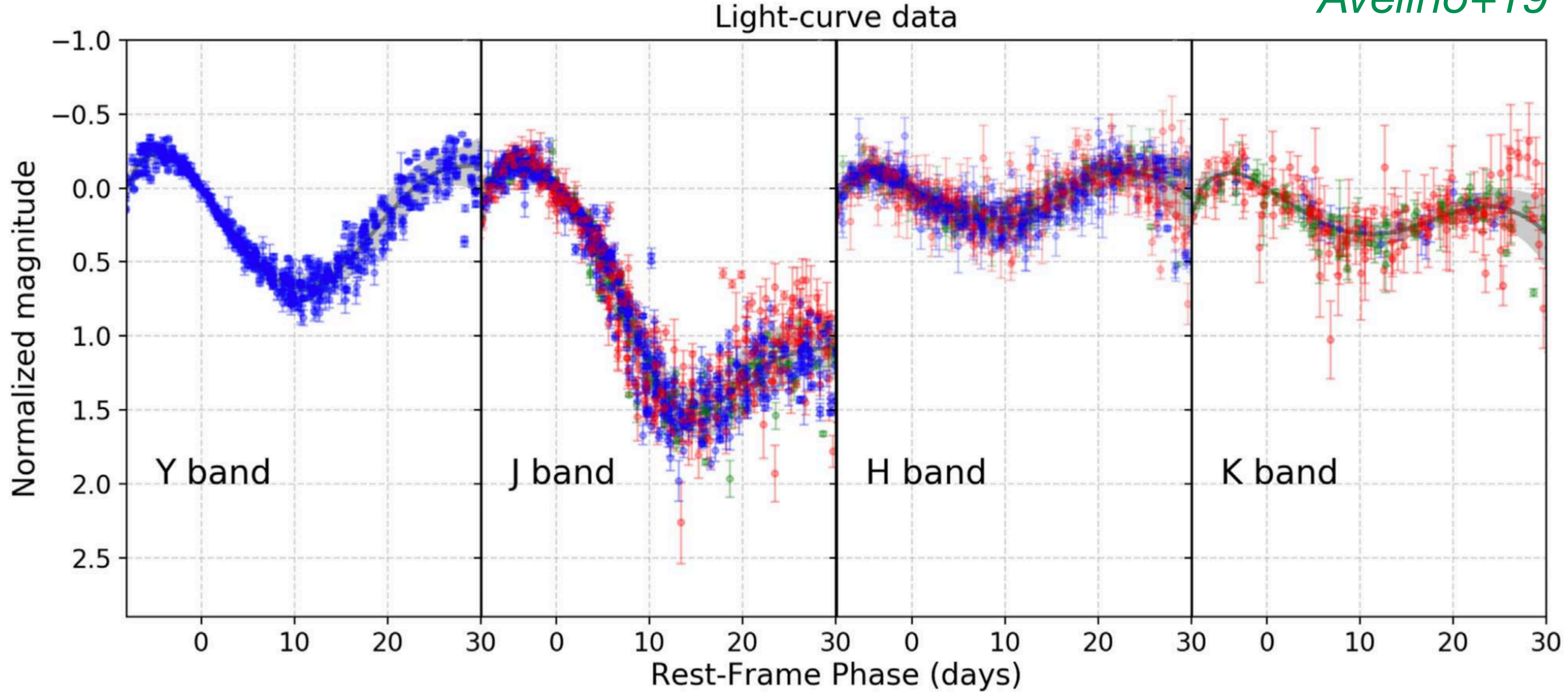
γ environment/physics

Natural NIR standard candles

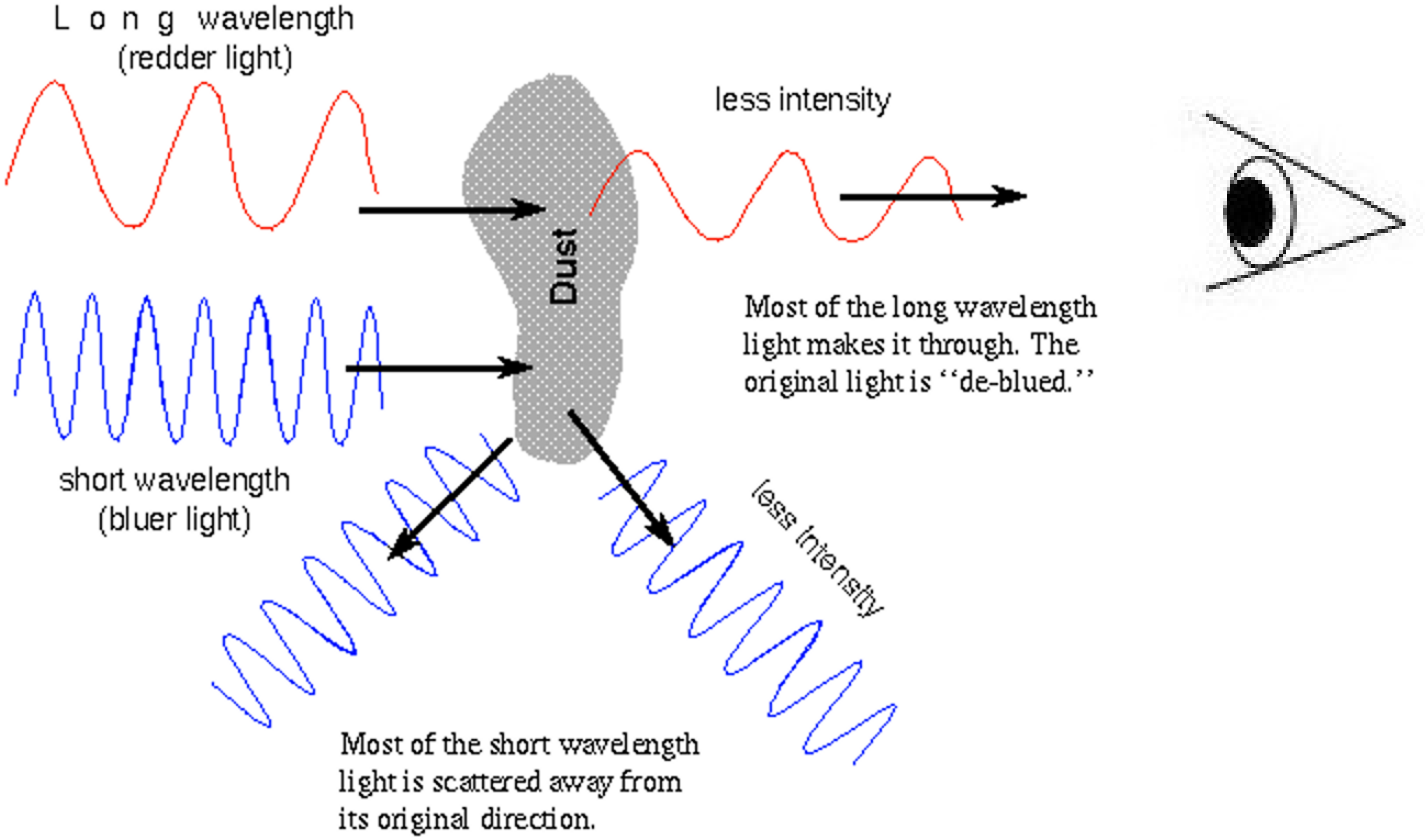
Kasen06



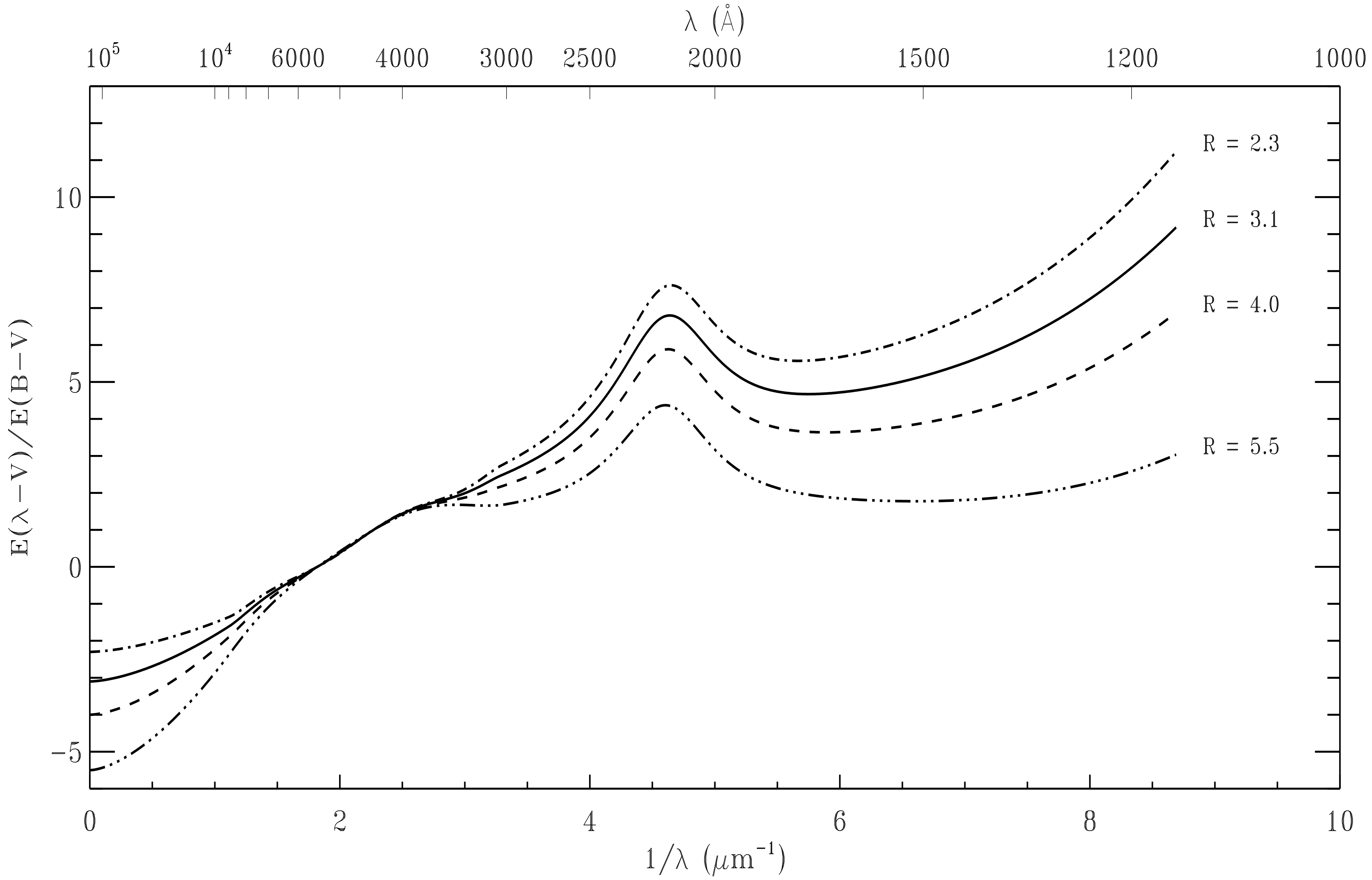
Avelino+19

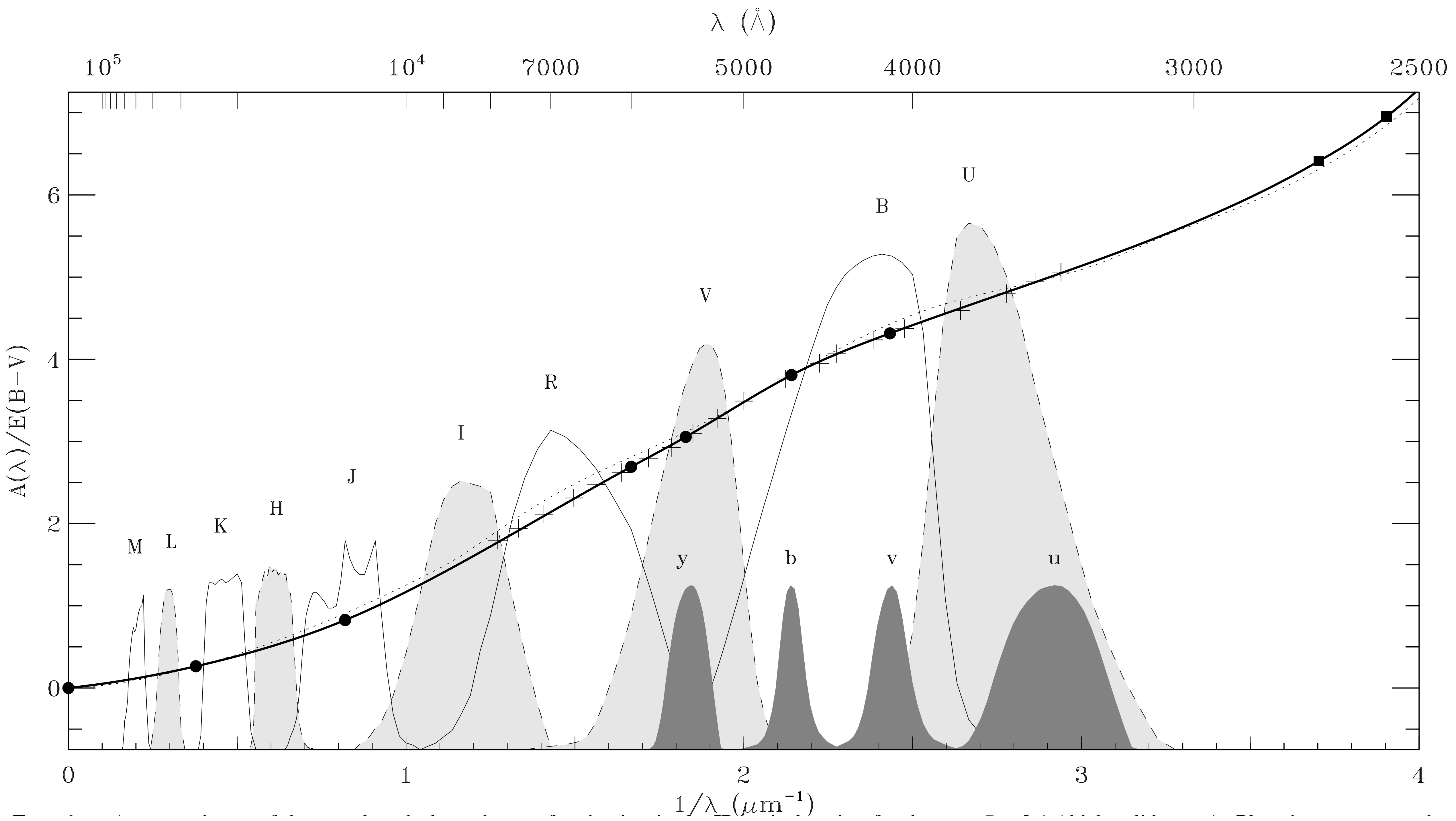


Reddening and extinction



Extinction/reddening law





$$R \equiv A(V)/E(B-V)$$

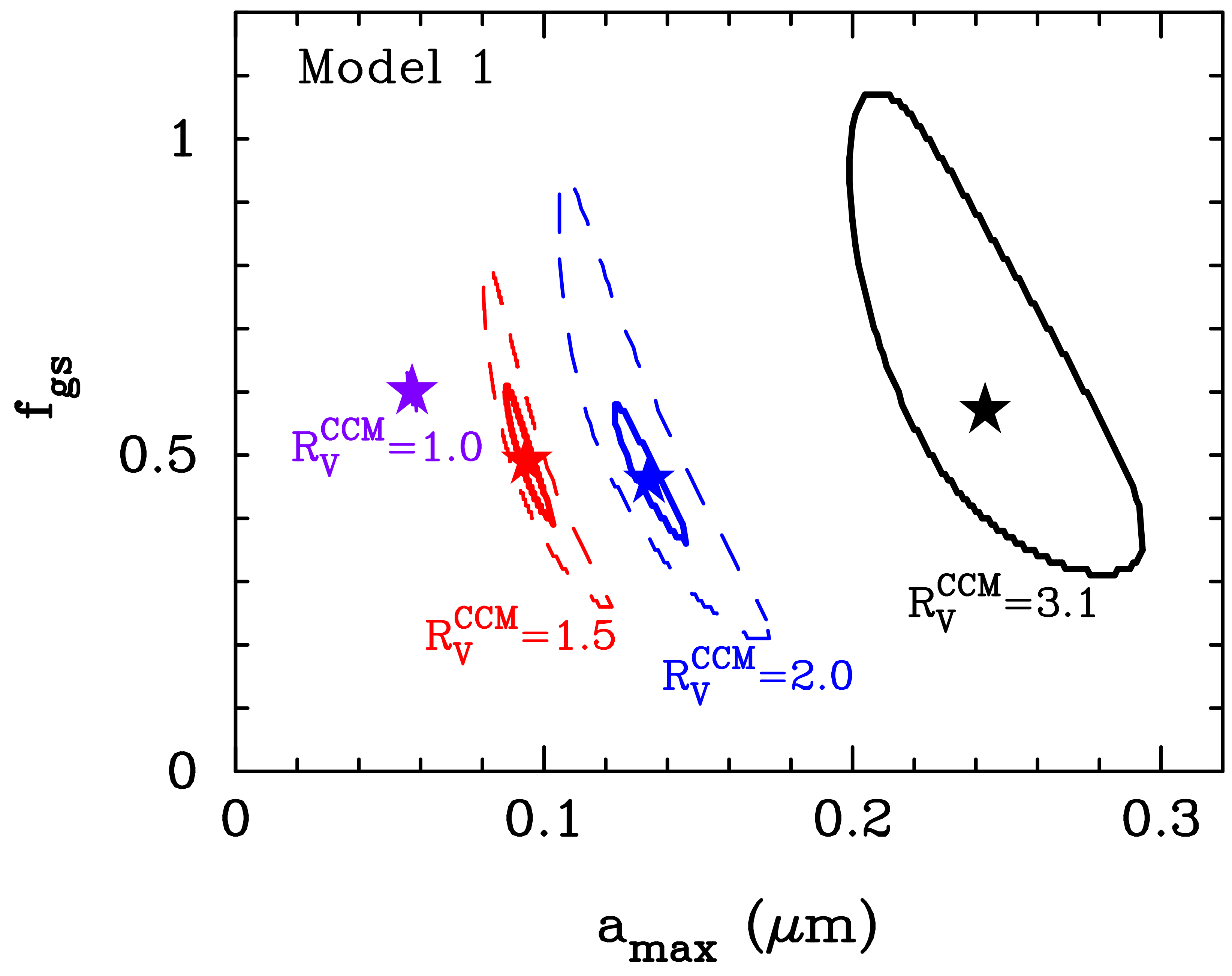
Several parametrizations:
Cardelli & O'Donnell (CCM), Fitzpatrick, etc.

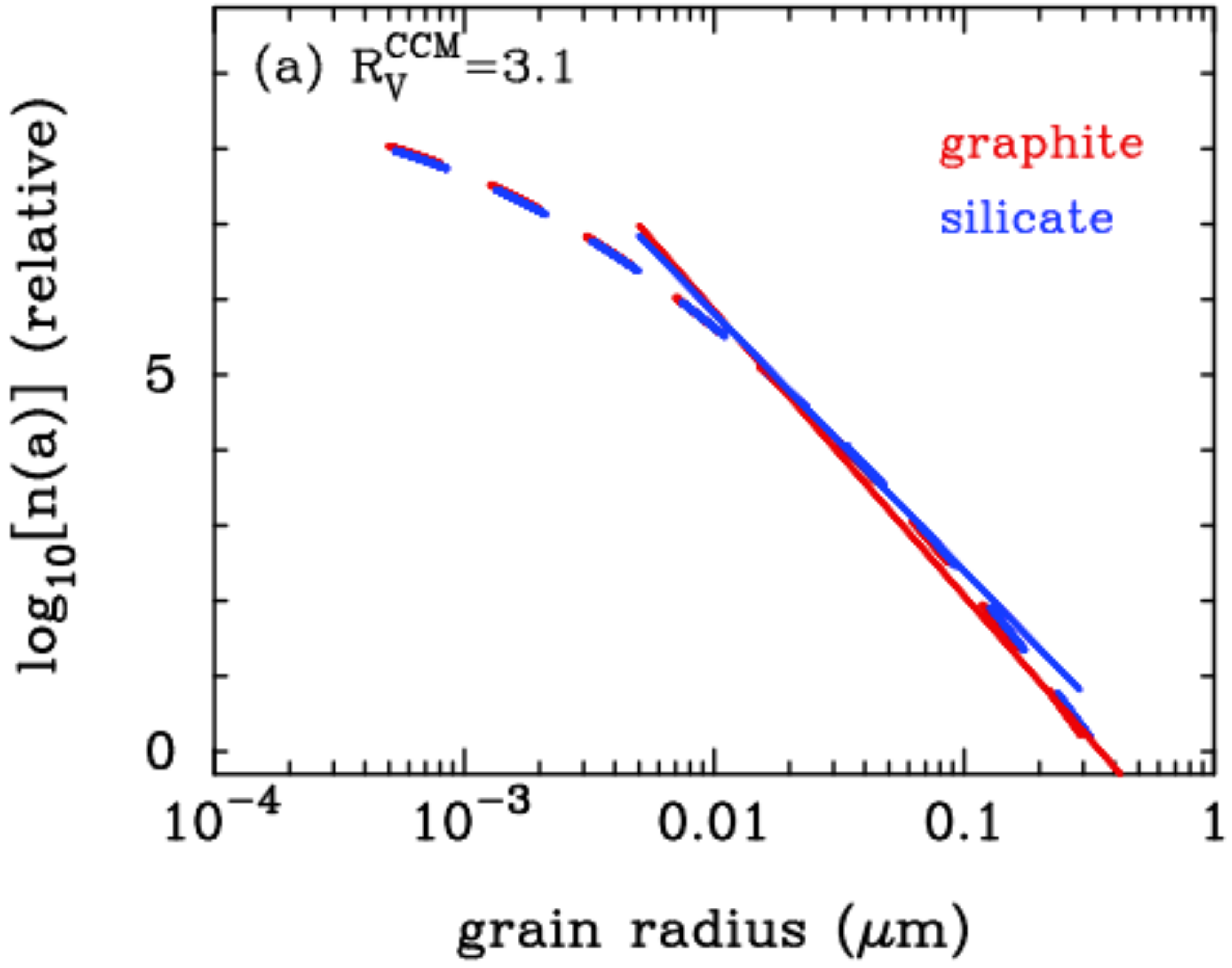
In the MW the average CCM measured from our position to other stars is
R=3.1 (2.5-5.5)
This value is generally assumed for other environments and galaxies.

Extinction/reddening law

The extinction law is determined by physical properties like composition (graphite and silicate grains) and size distribution

Nozawa+16





Smaller Rv is associated with smaller grain size!

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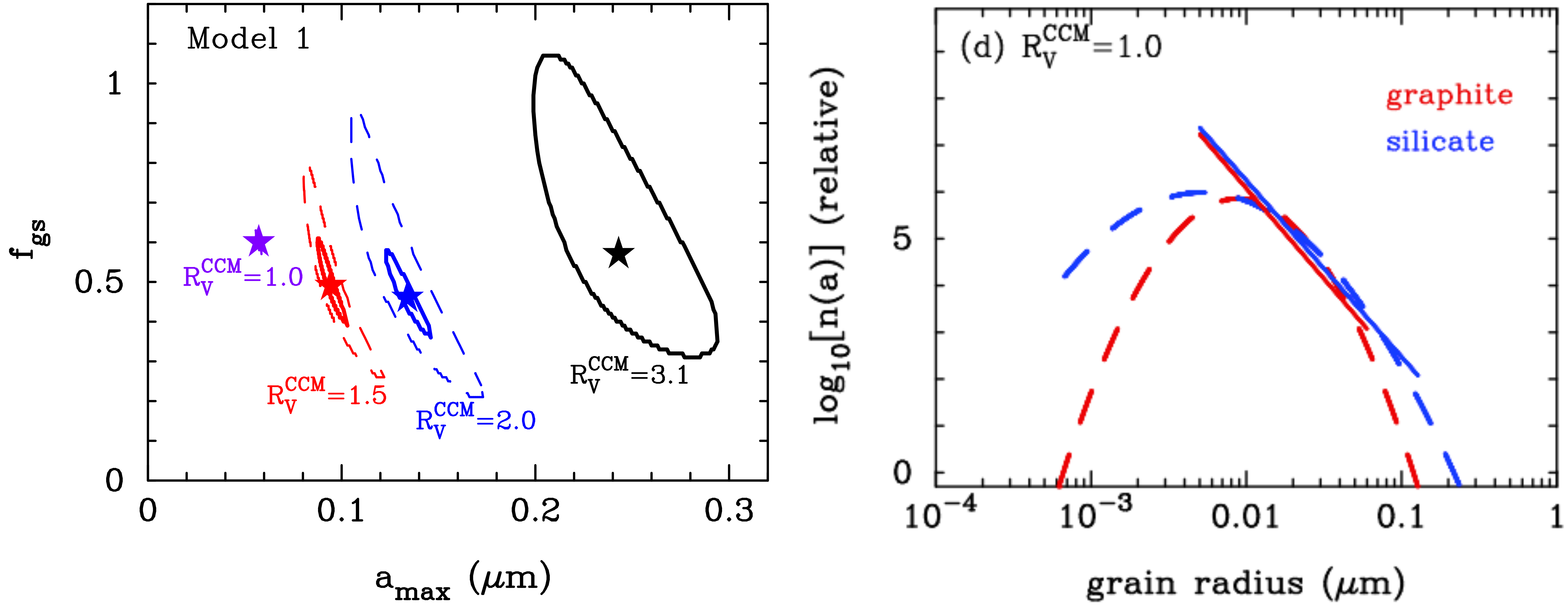


Smaller Rv is associated with smaller grain size!

Common SNIa color laws

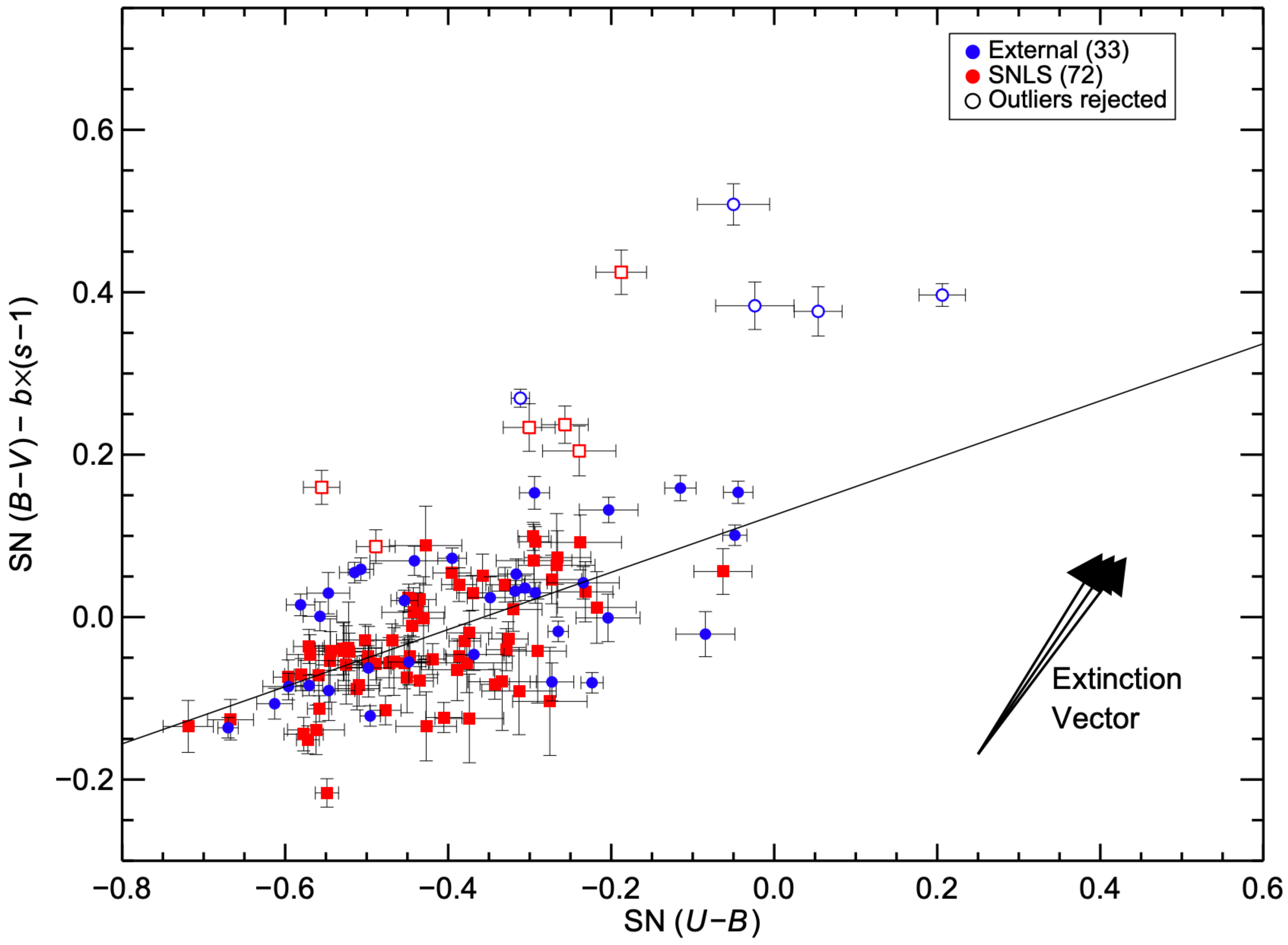
$$\mu(z)_{\rm SN} = m(z) - M = (m_{\rm obs} + \alpha x1 - \beta c - A_{\rm MW} + K_{x,y}) - M$$

If β is assumed to be a general description of the reddening law, then the inferred extinction law is not common: *R*~2

The magnitude-color relation of SNe in reality comes probably from two effects:

1. intrinsic (temperature, ionization evolution)
2. extrinsic (dust in the ISM)

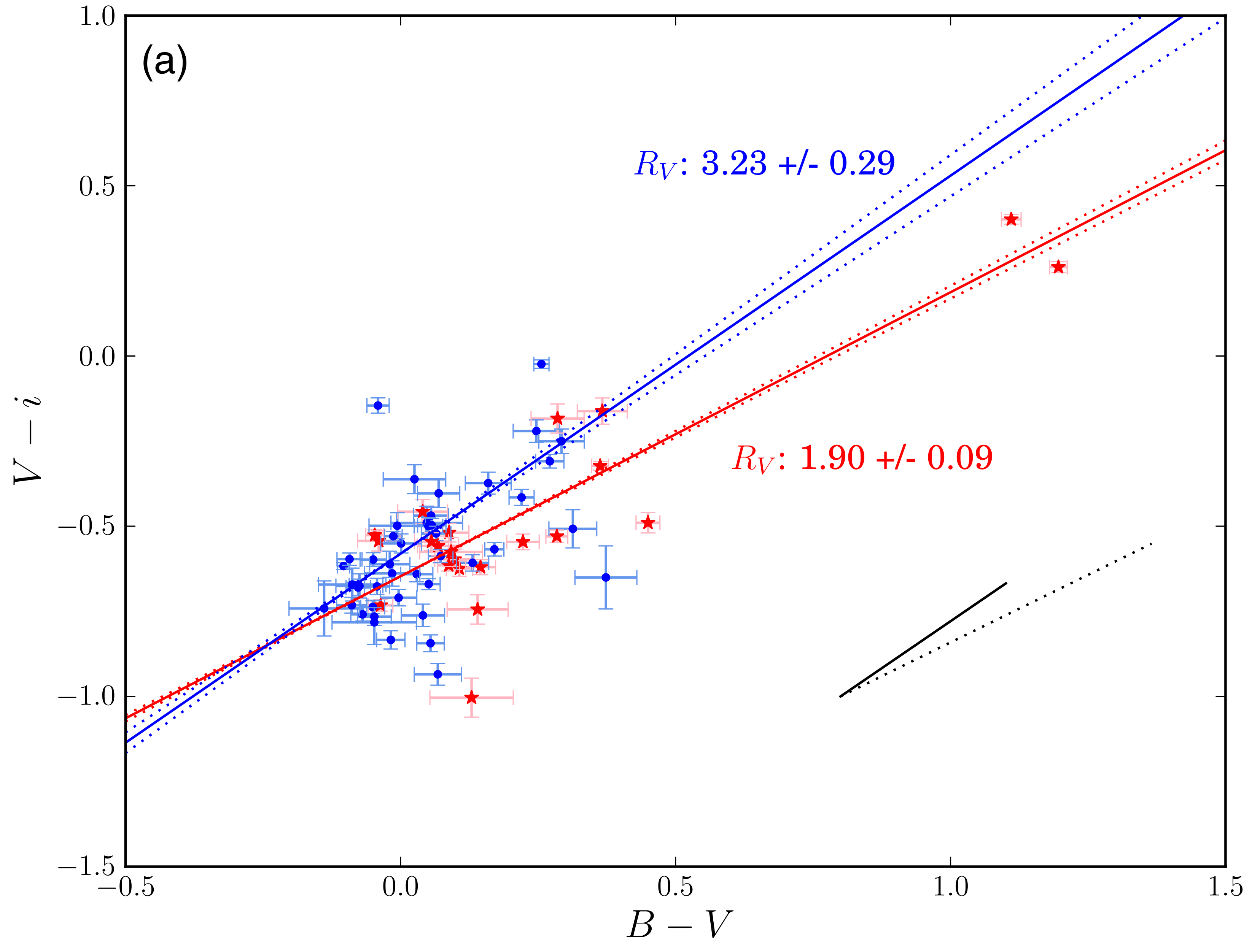
Conley+08



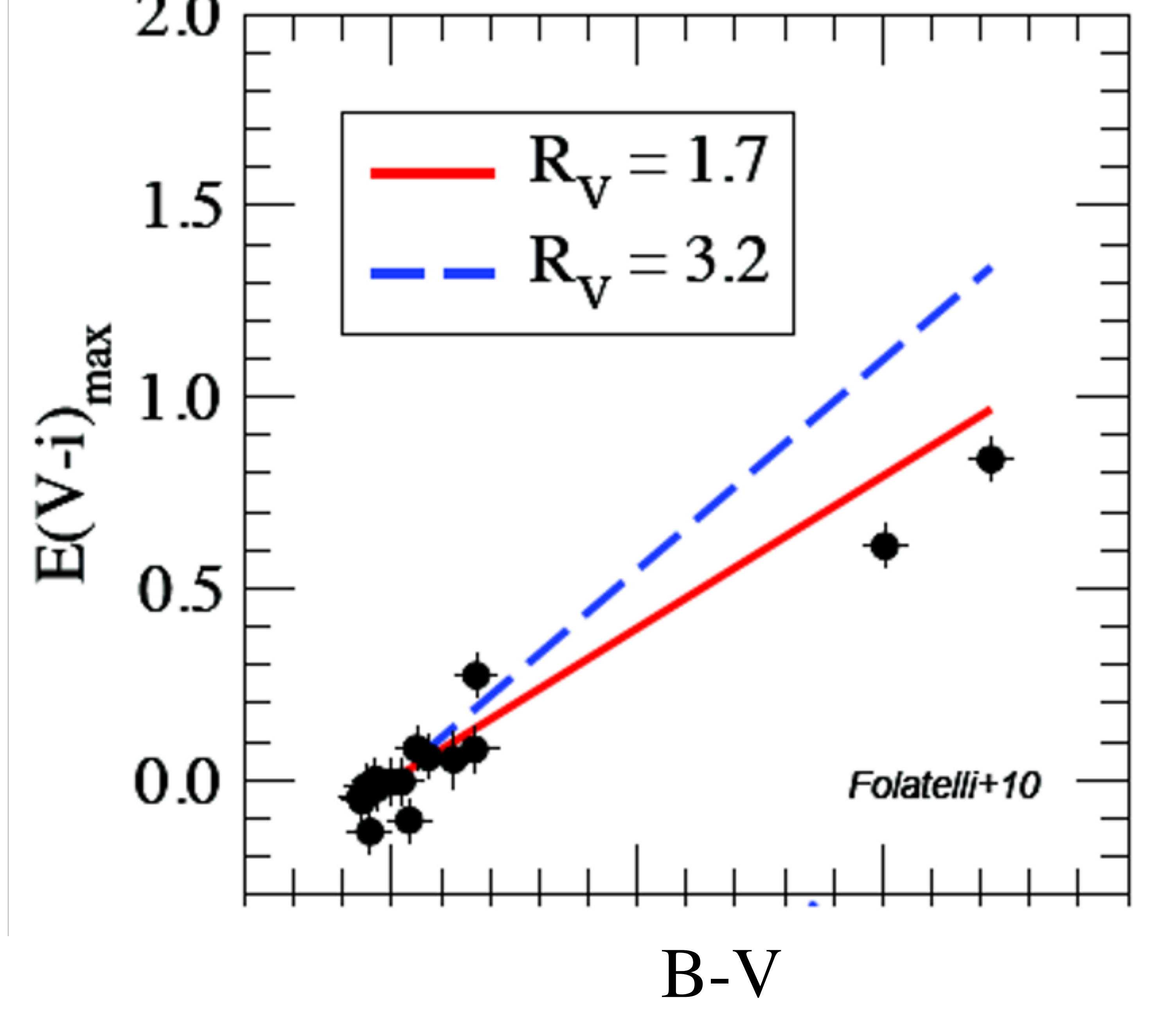
Multiple SNIa color laws

Although properly modeling colors reveals that most SNe are consistent with a normal Rv=3.1 reddening law (Chotard+11,Scolnic+14), there is diversity in SNe with different brightness-color relations.

Forster+13

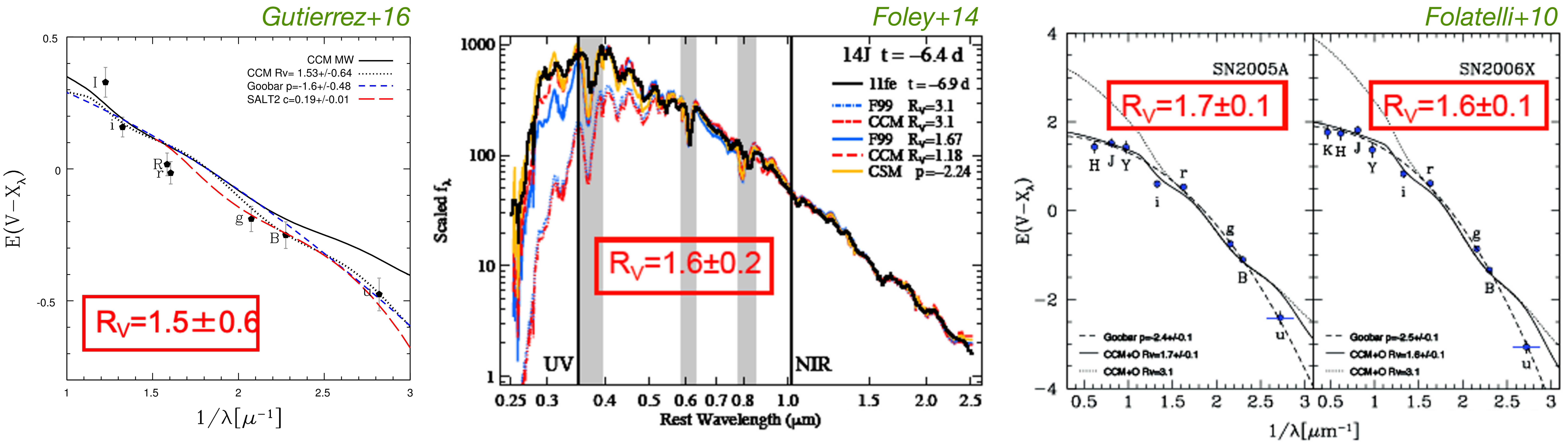


Folatelli+10



«Either SN intrinsic colors are more complicated that can be described with a single light-curve shape parameter or dust around SN is very unusual» ***Conley+07***

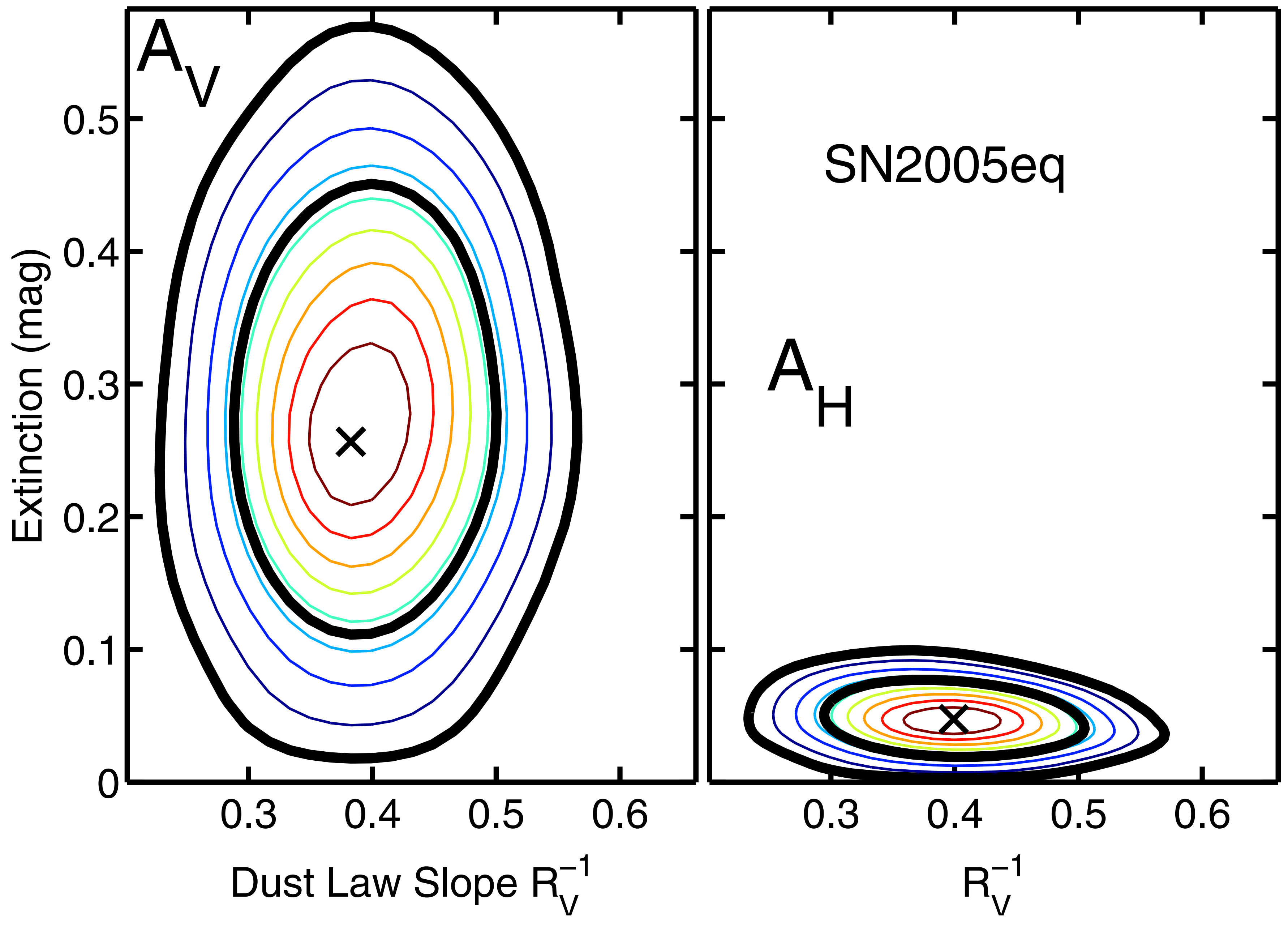
Individual SNIa color laws



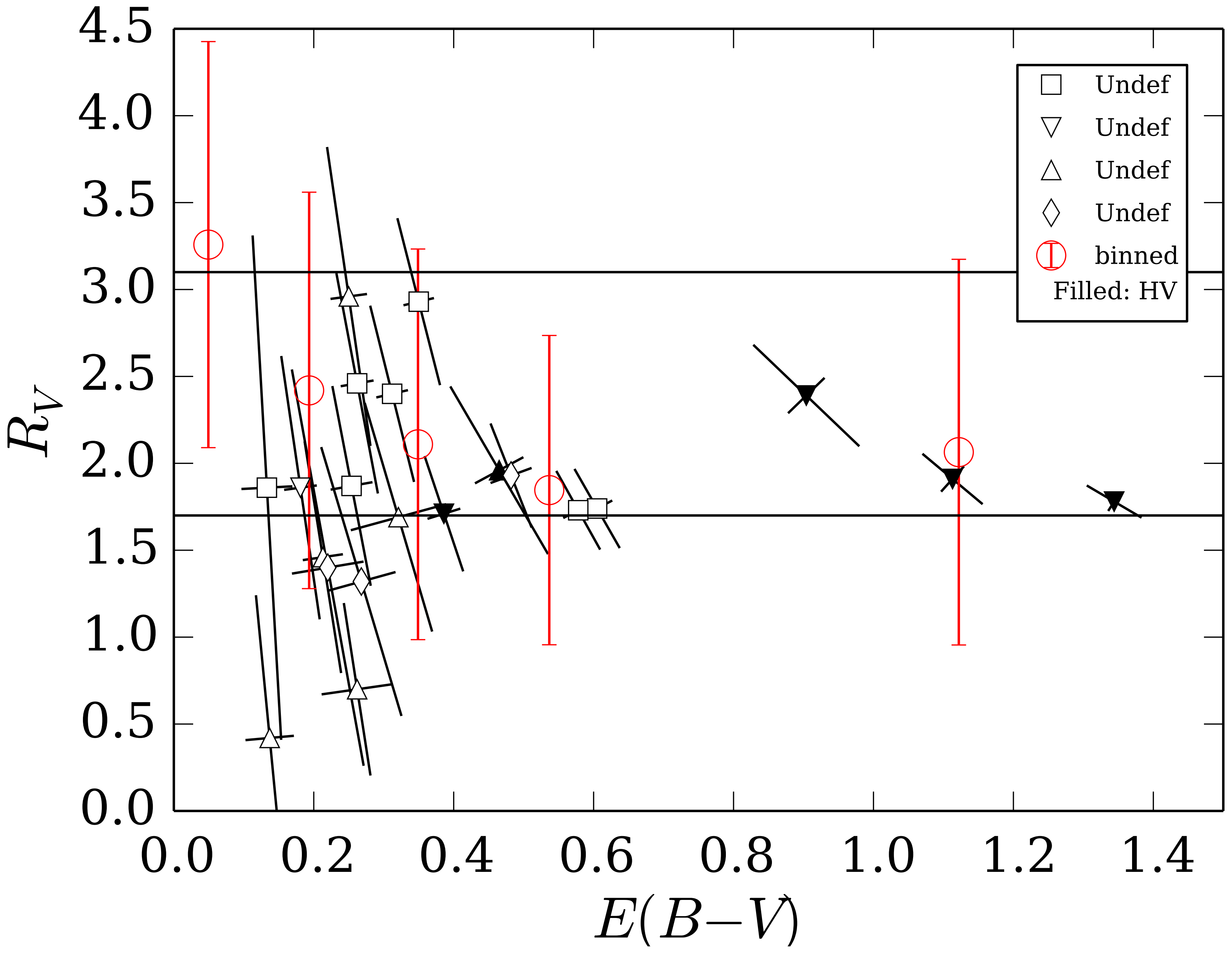
Extremely peculiar extinction laws found towards some SNe!

Individual SNIa color laws

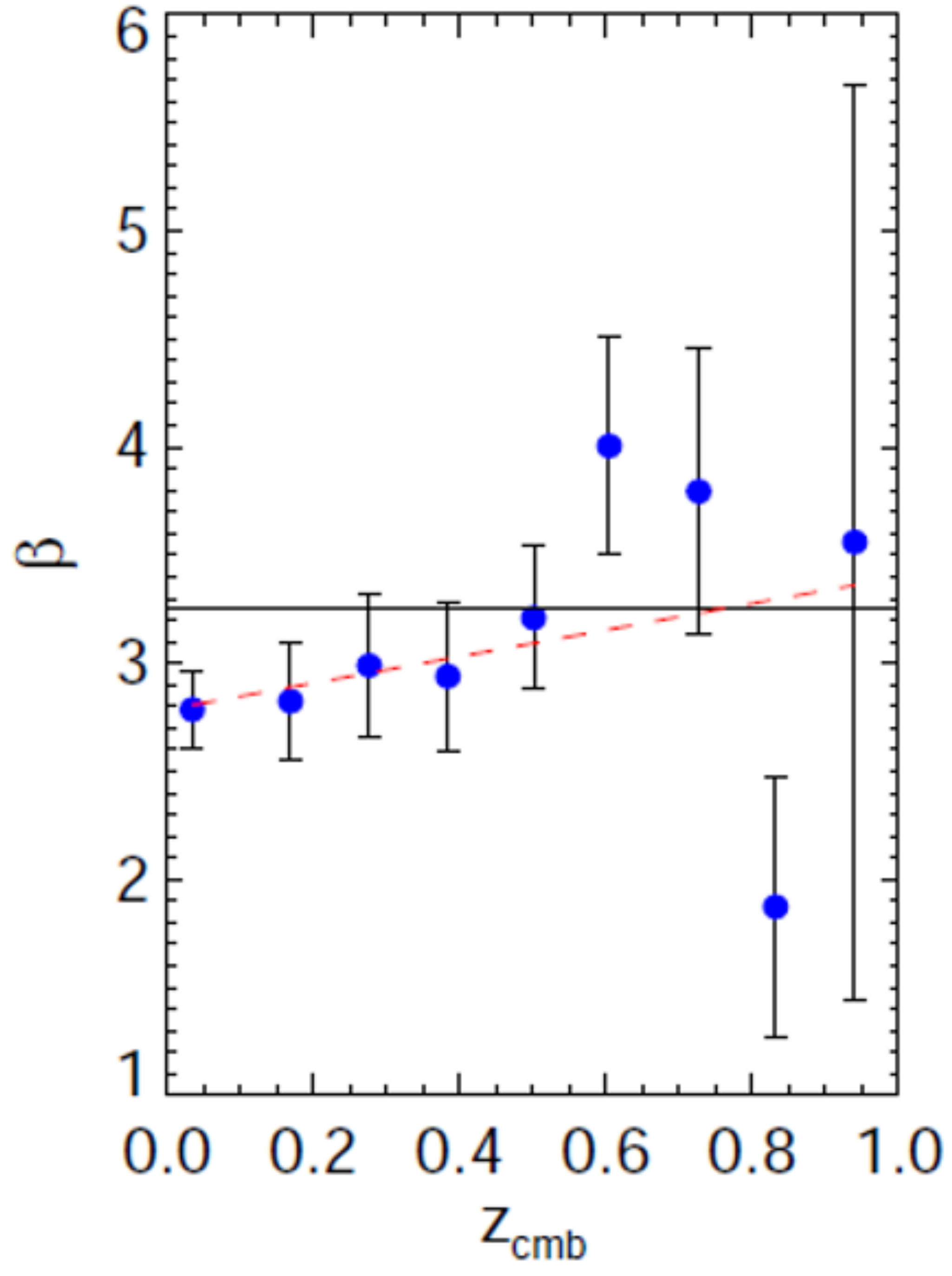
Mandel+11



Burns+14



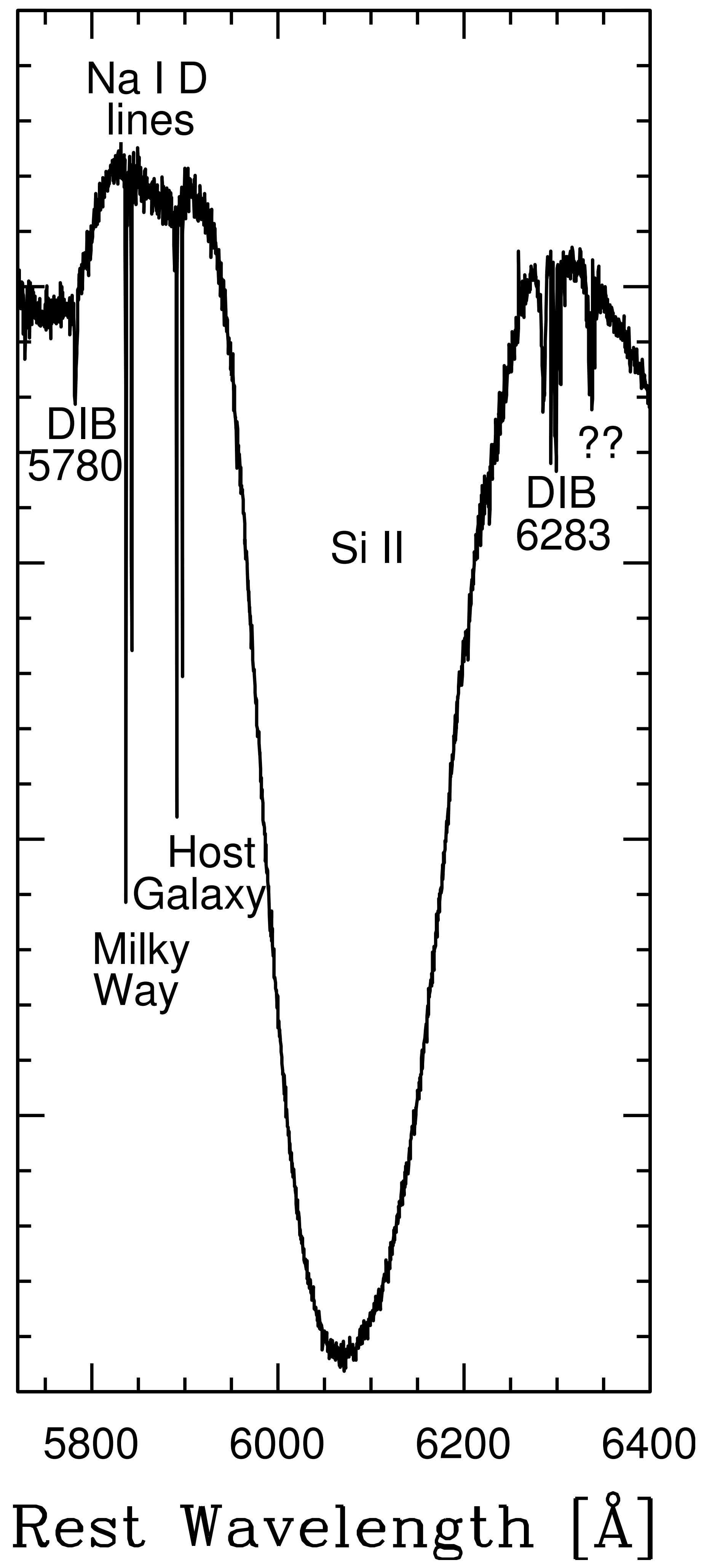
Conley+11



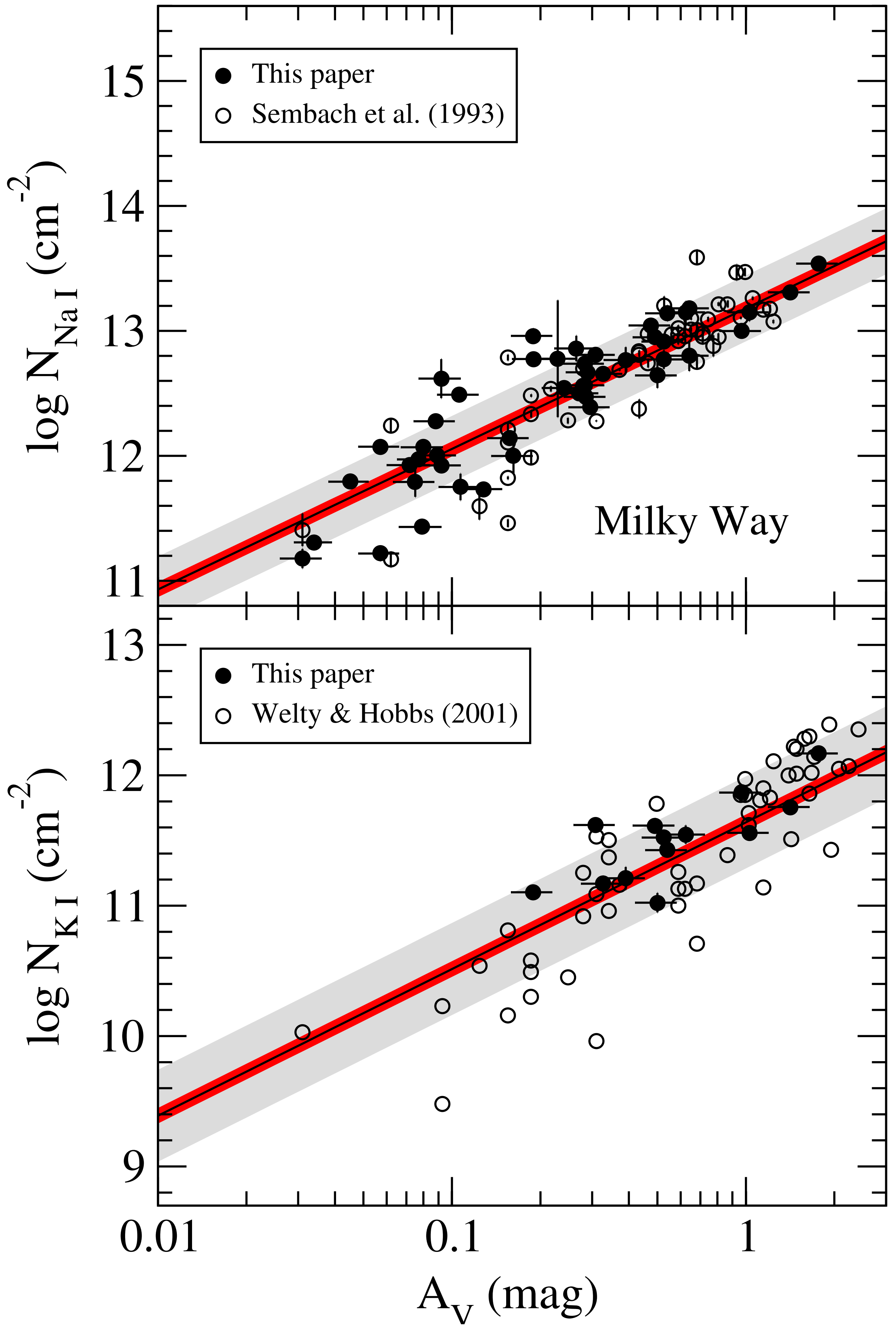
Light-curve fitters with individual color-law, but No Hubble diagrams with individual color-laws!

Other dust indicators

Gutierrez+16



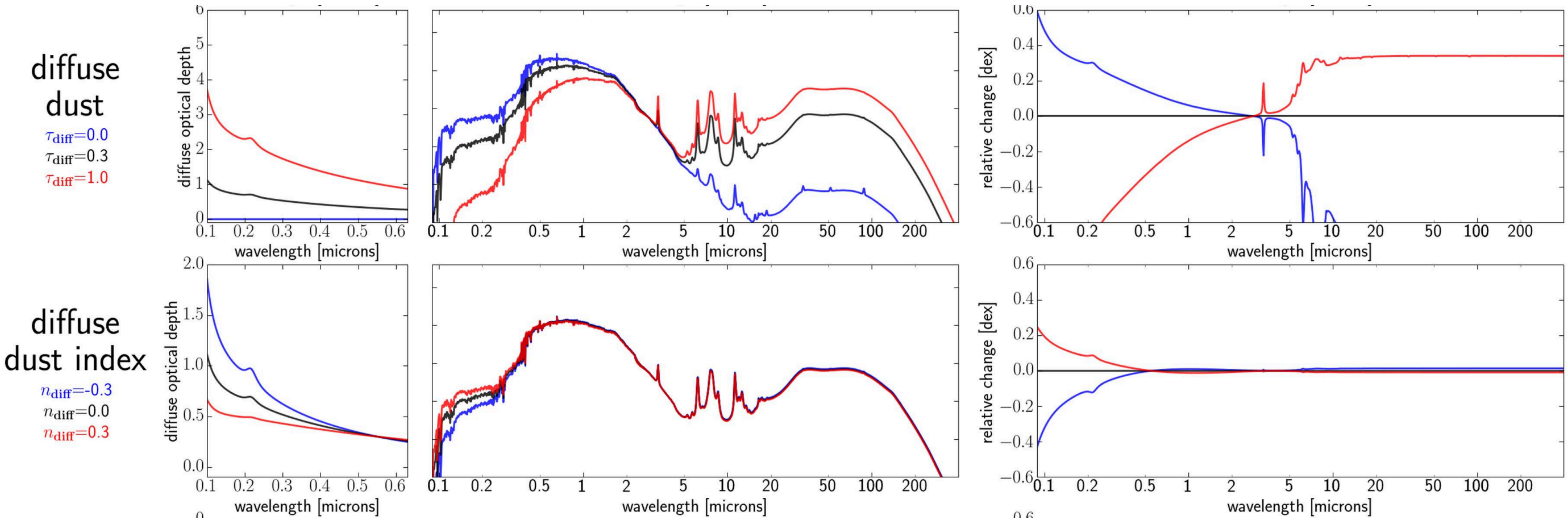
Phillips+13



Other spectroscopic indicators of cold gas arise when the SN ionizes neutral atoms (like Na I D, Ca II H&K, DIBs) which later recombines and narrow absorption lines are seen.

Host galaxy reddening

Leja+17



Current Bayesian SSP fitters allow for the treatment of different extinction laws

$$\hat{\tau}_{\lambda,2} = \frac{\hat{\tau}_2}{4.05}\,[k'(\lambda) + D(\lambda)]\left(\frac{\lambda}{\lambda_V}\right)^n$$

(Past) Approach

Correcting Reddening Intelligently for SN cosmological probes

4-year Portuguese nationally funded project (PI: A. M. Mourão)

PTDC/FIS-AST/31546/2017
1/09/2018 - 31/08/2022


Ana Mourão


Alberto Krone-Martins


Santiago González


Ana Sofia Afonso


Lluis Galbany


Antonia Morales


Claudia Gutiérrez


Thomas de Jaeg

(Current) Approach
The HOSTFLOWS project

https://github.com/HOSTFLOWS

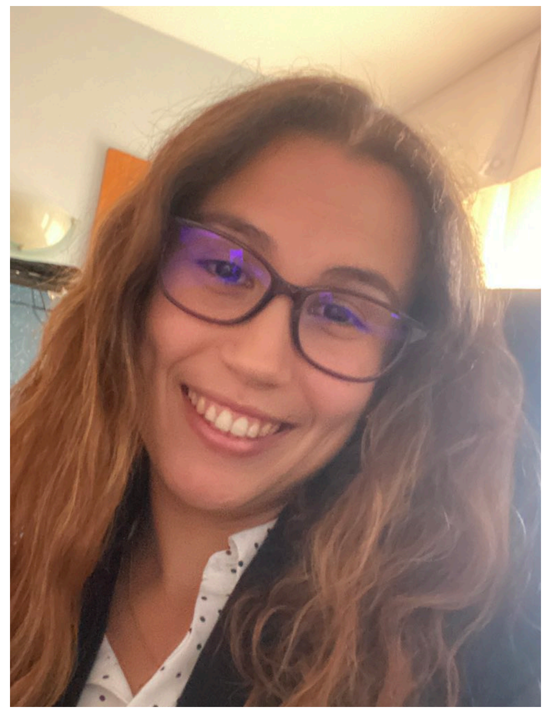
https://hostflows.github.io/

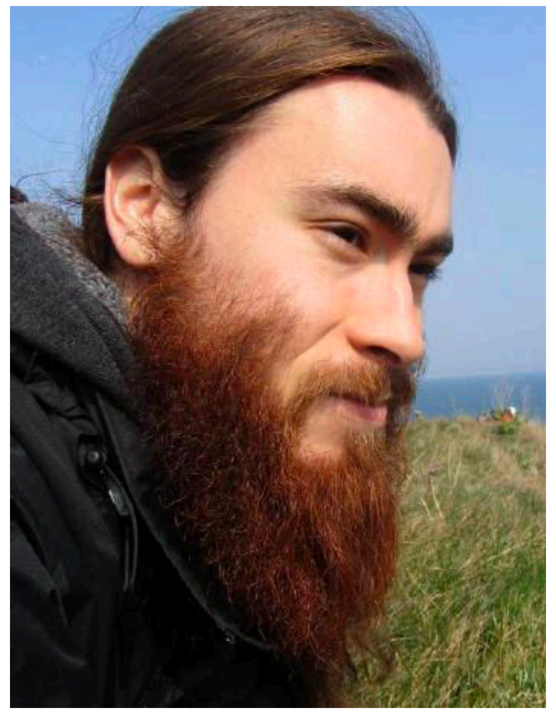
3-year Spanish nationally funded project (PI Galbany; PID2020-115253GA-I00)

1/09/2021 - 31/08/2024

- **A- H0 systematics:** SN/Cepheid phot/spec/pol and host galaxy IFU/pol to study extinction, environment and improve standardization.
- **B- Cosmography of Laniakea:** NIR SNIa survey to measure peculiar velocities and map dark matter in our supercluster

Cristina Jiménez
PhD student





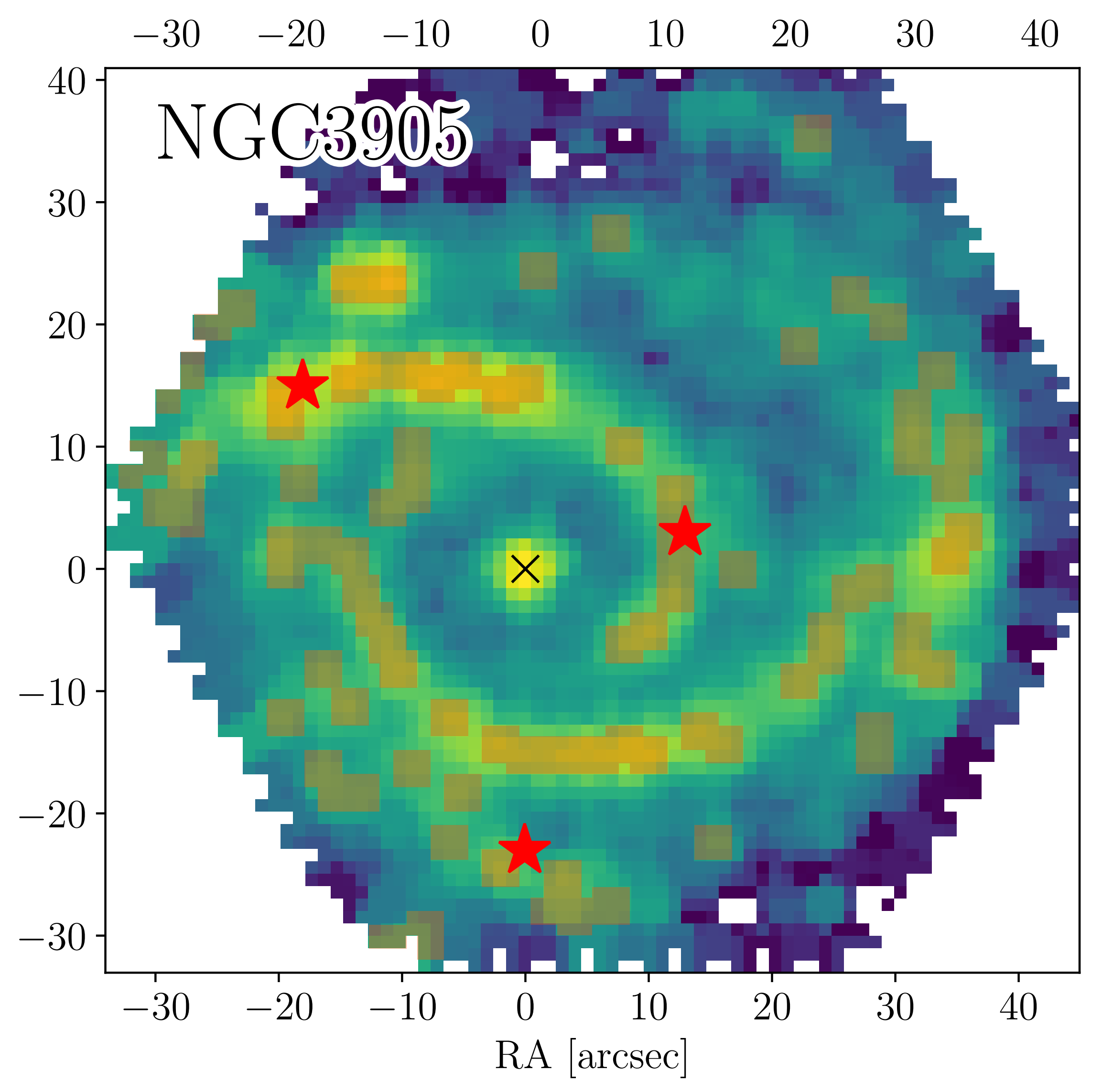
Tomás Müller
Postdoc

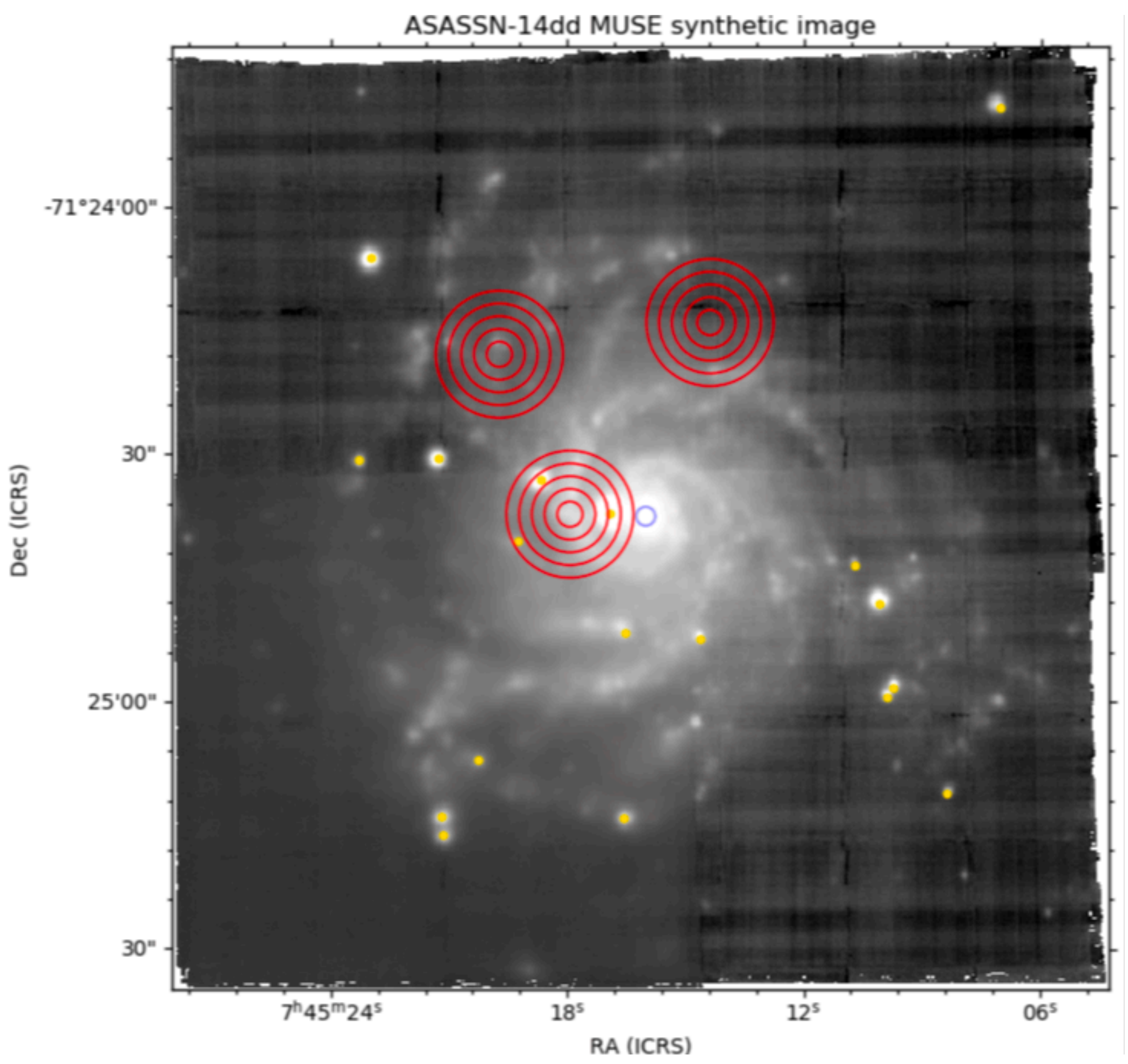
(Current) Approach

The HOSTFLOWS project

A- H0 systematics

IFS data of SN/Cph host galaxies

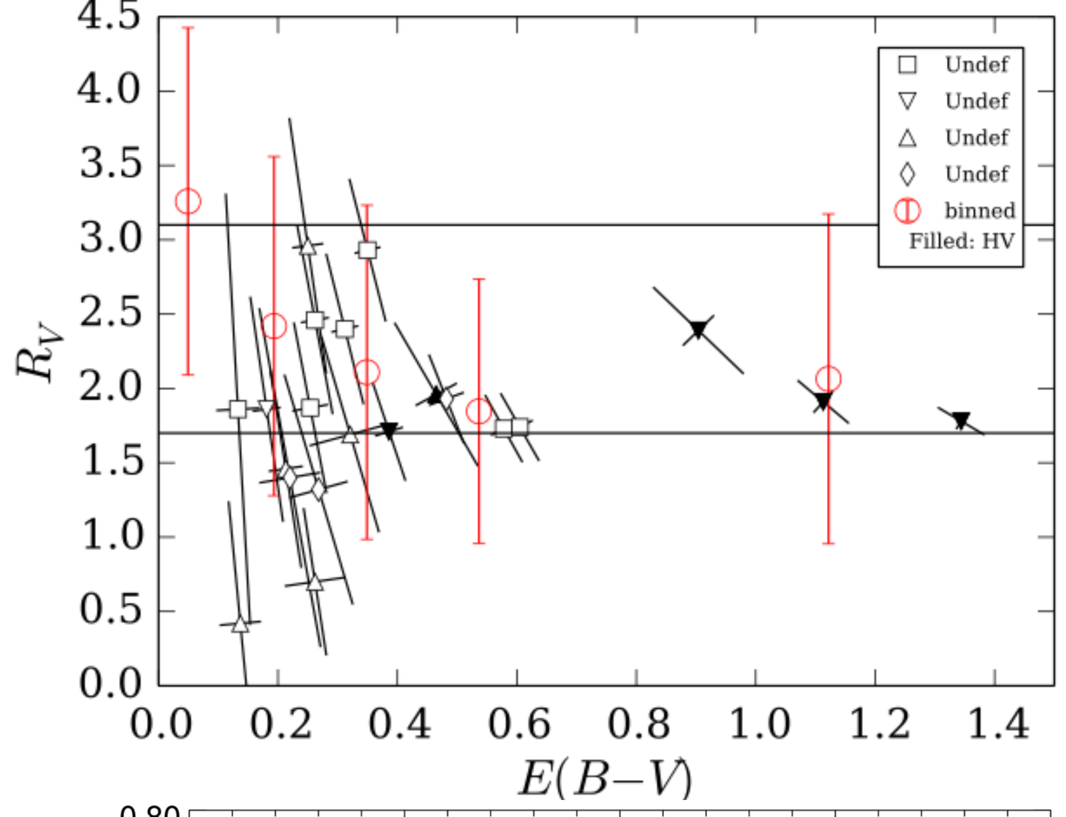


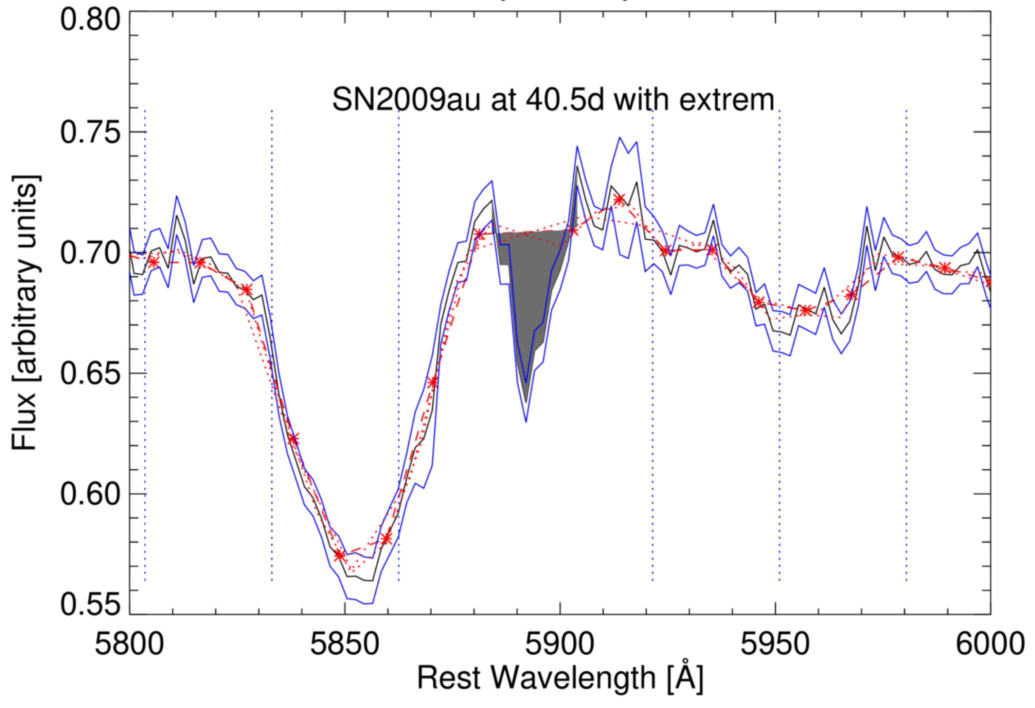


PISCO, *LG et al. 2018*   AMUSING, *LG et al. 2016*

phot/spec

Burns+14

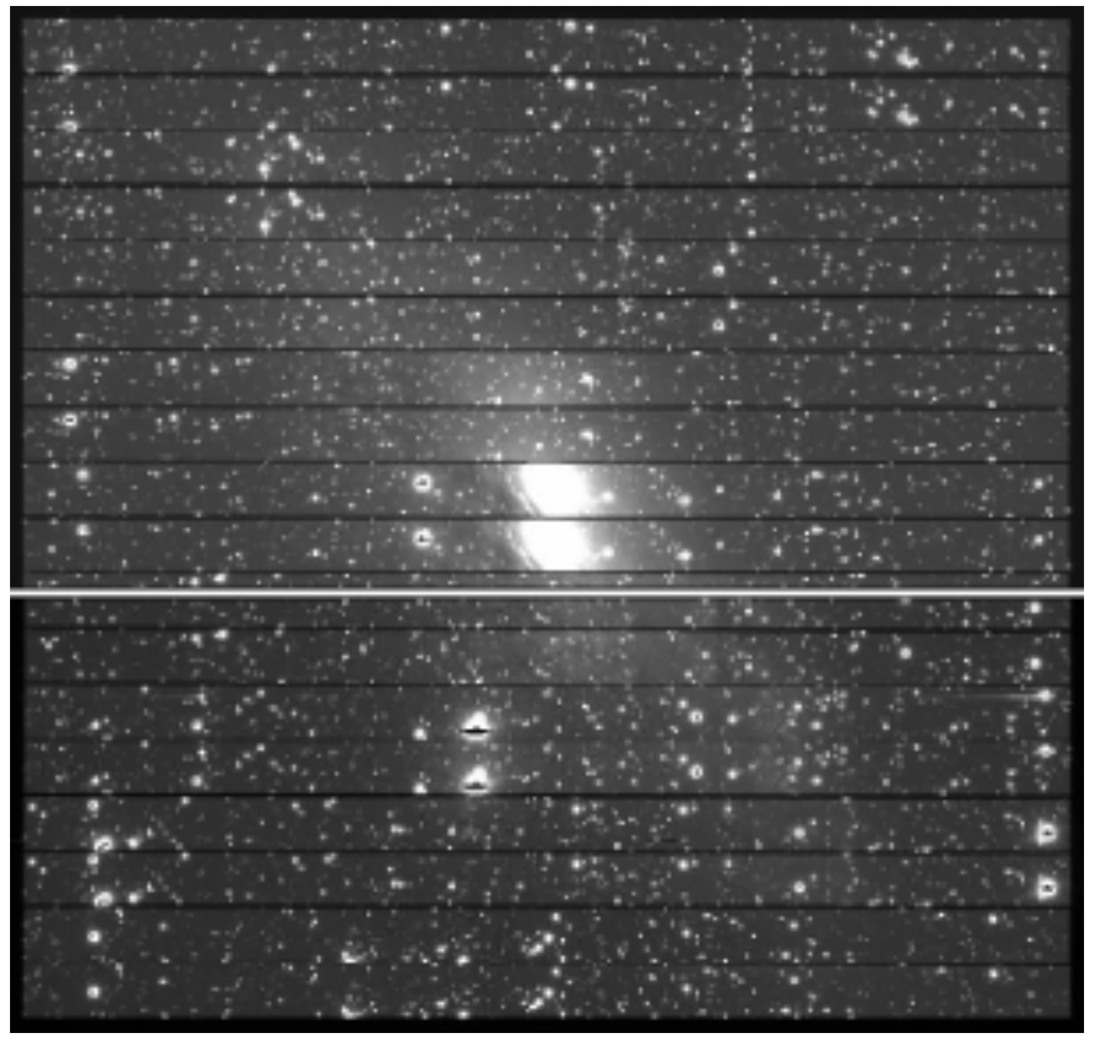




CPG+in prep.

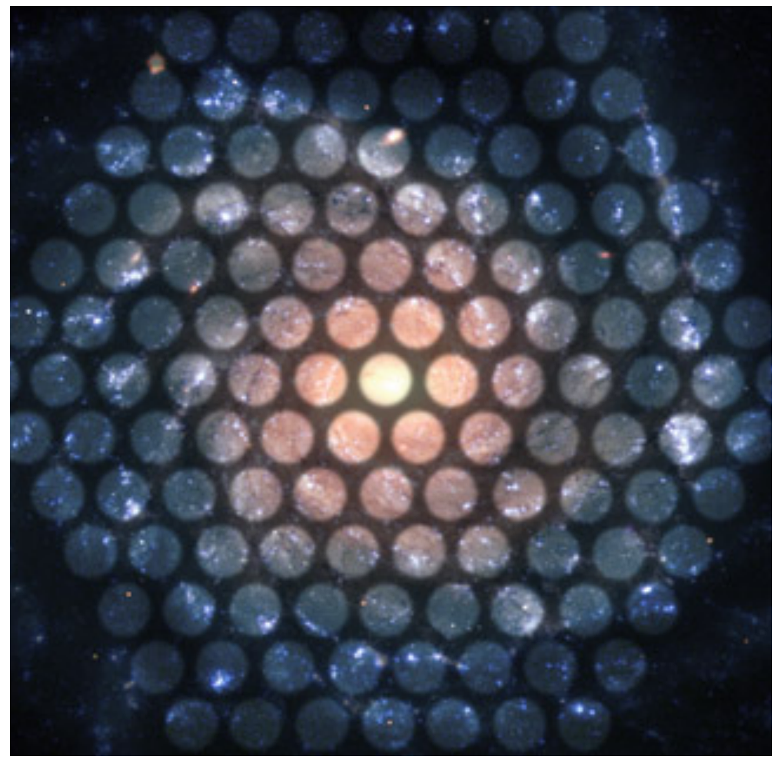
Host polarimetry

SGG+20

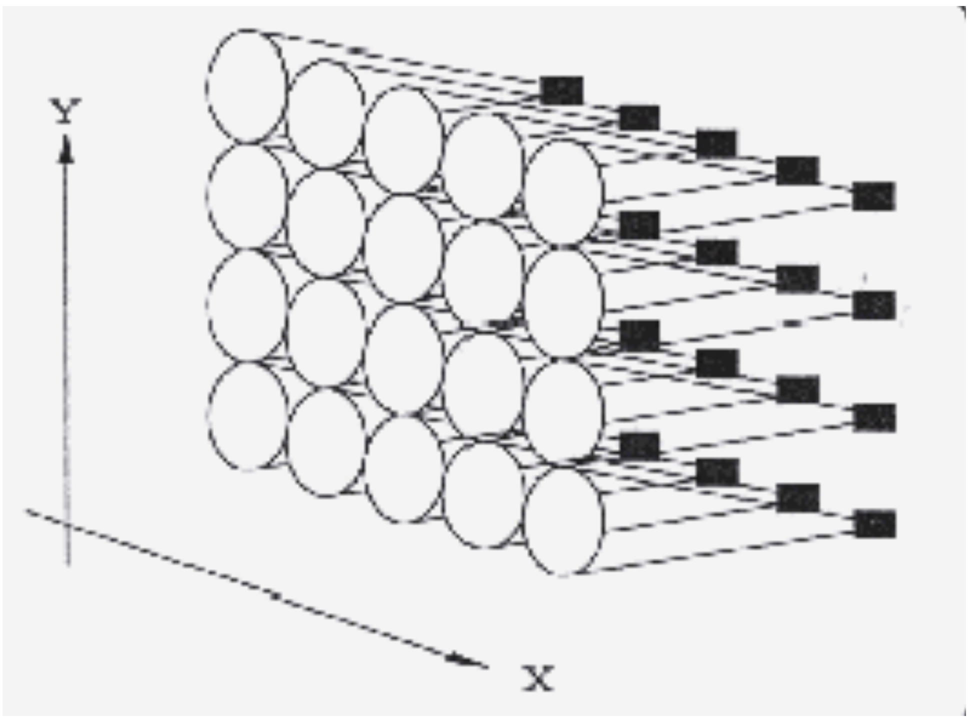


CAFOS/VLT

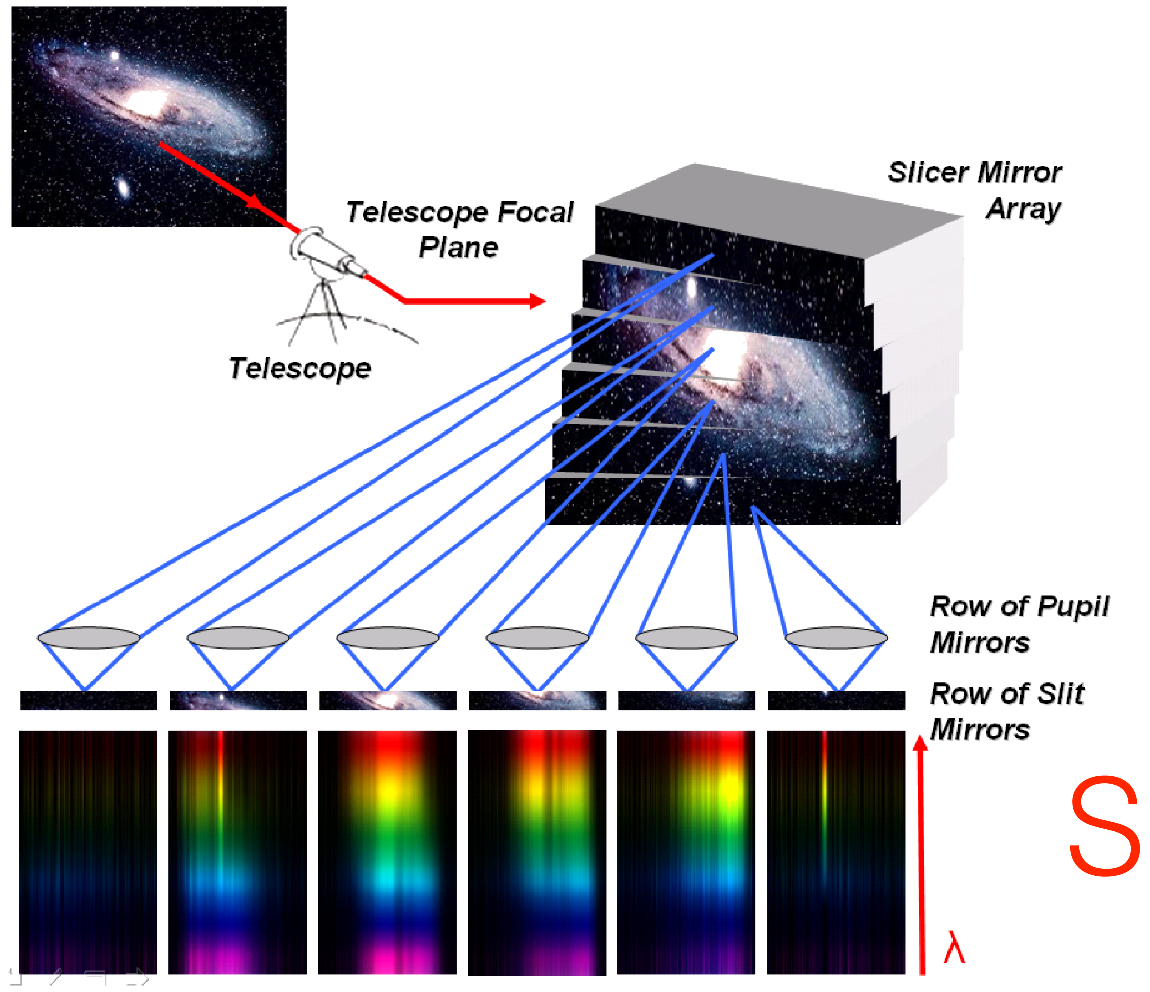
Integral Field Spectroscopy



Fiber bundle

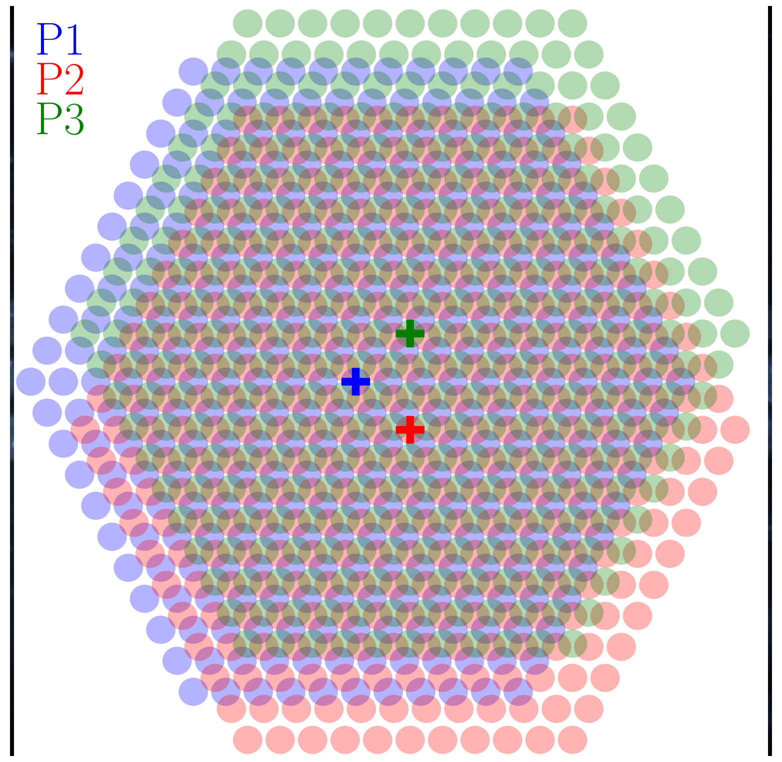


Lenslet



Slicer

Integral Field Spectroscopy



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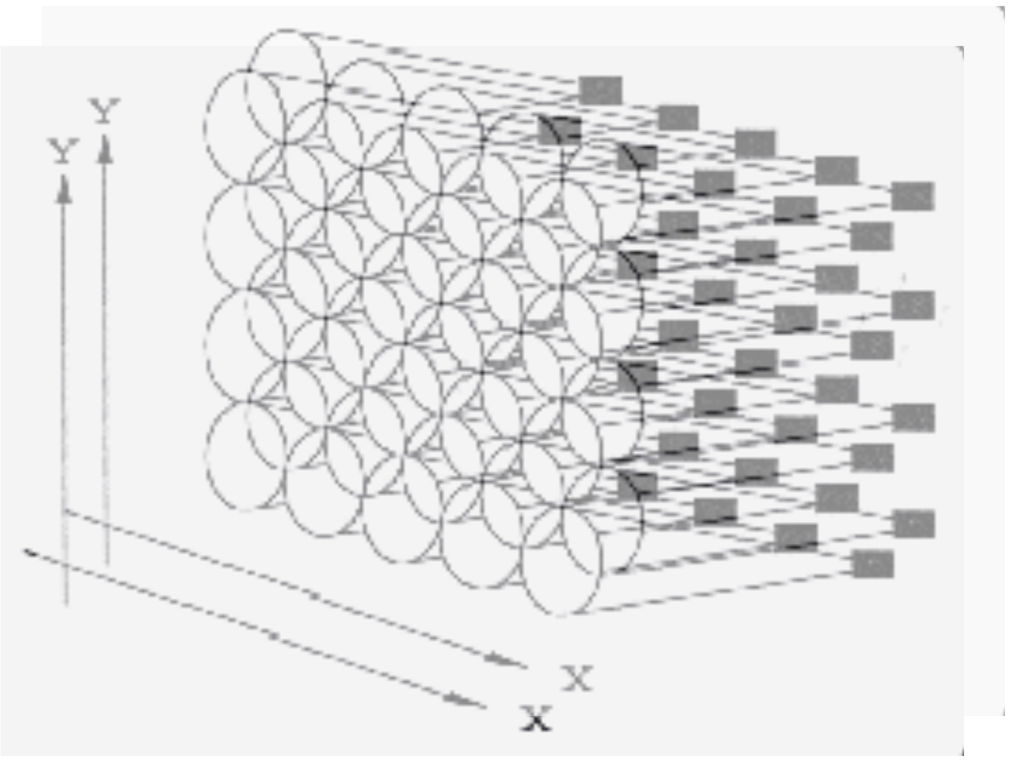
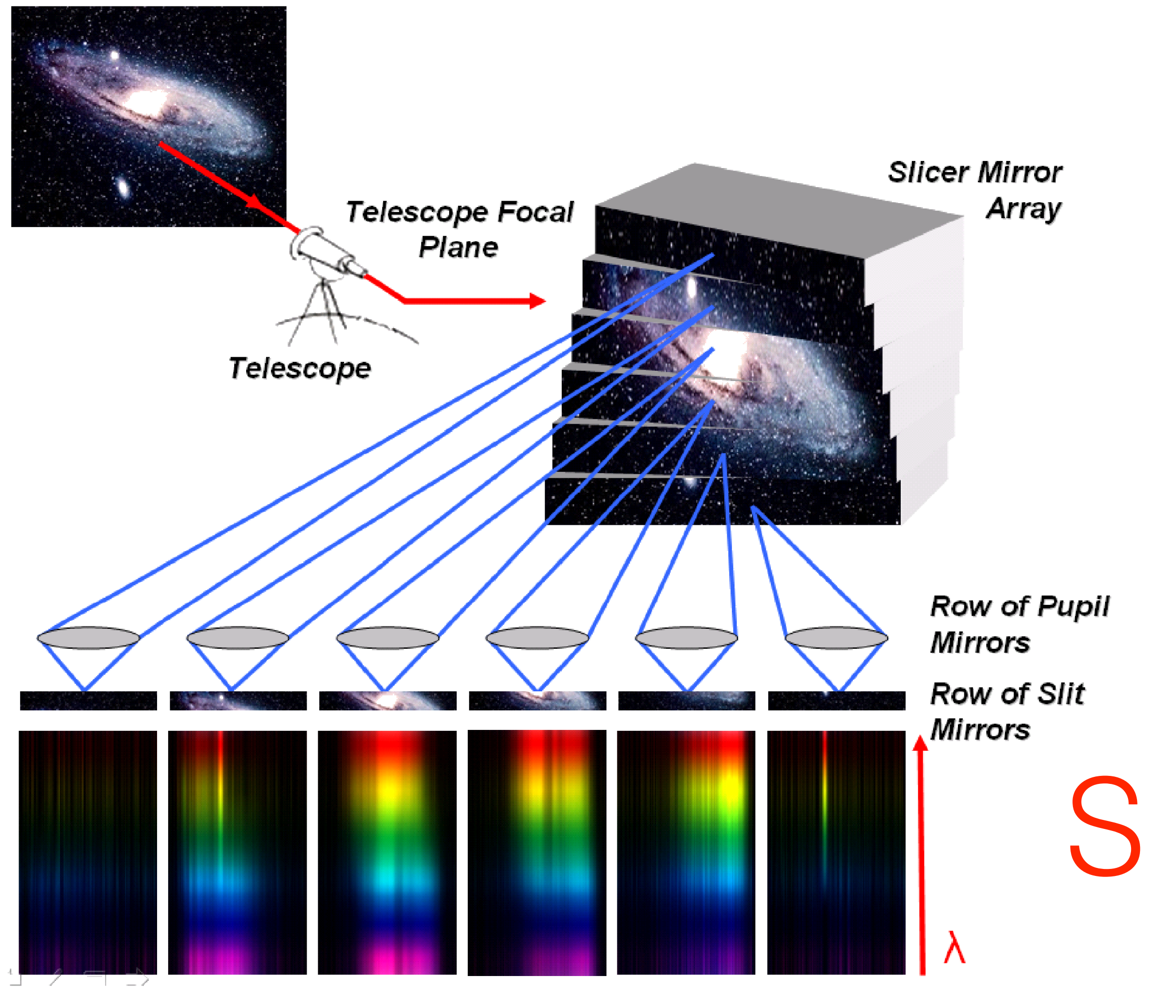


Lenslet



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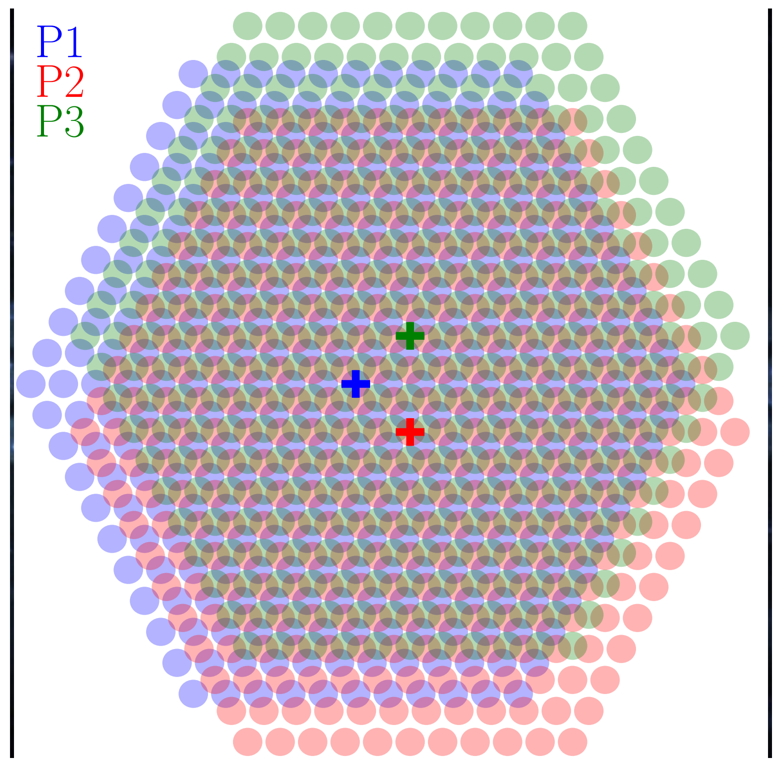

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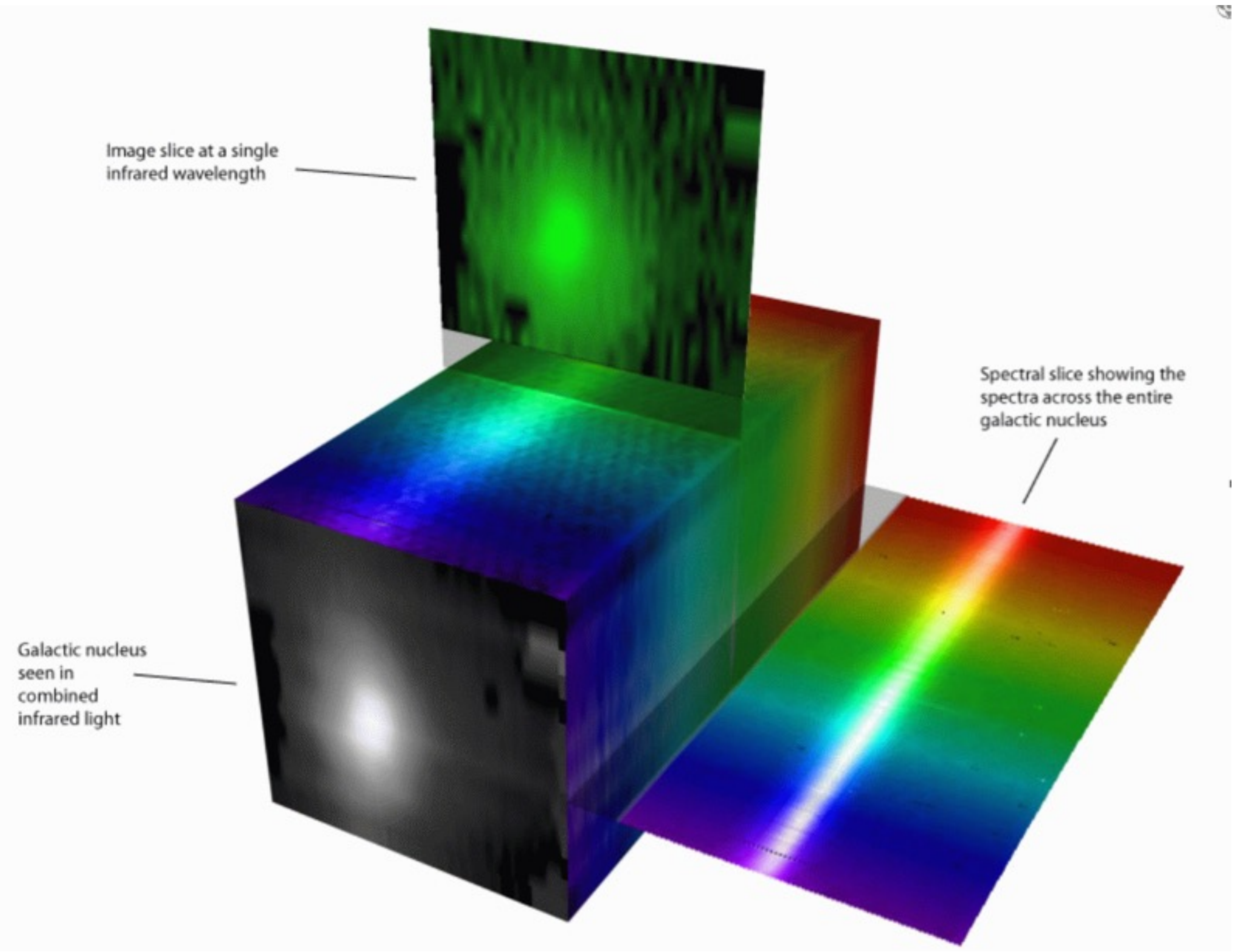

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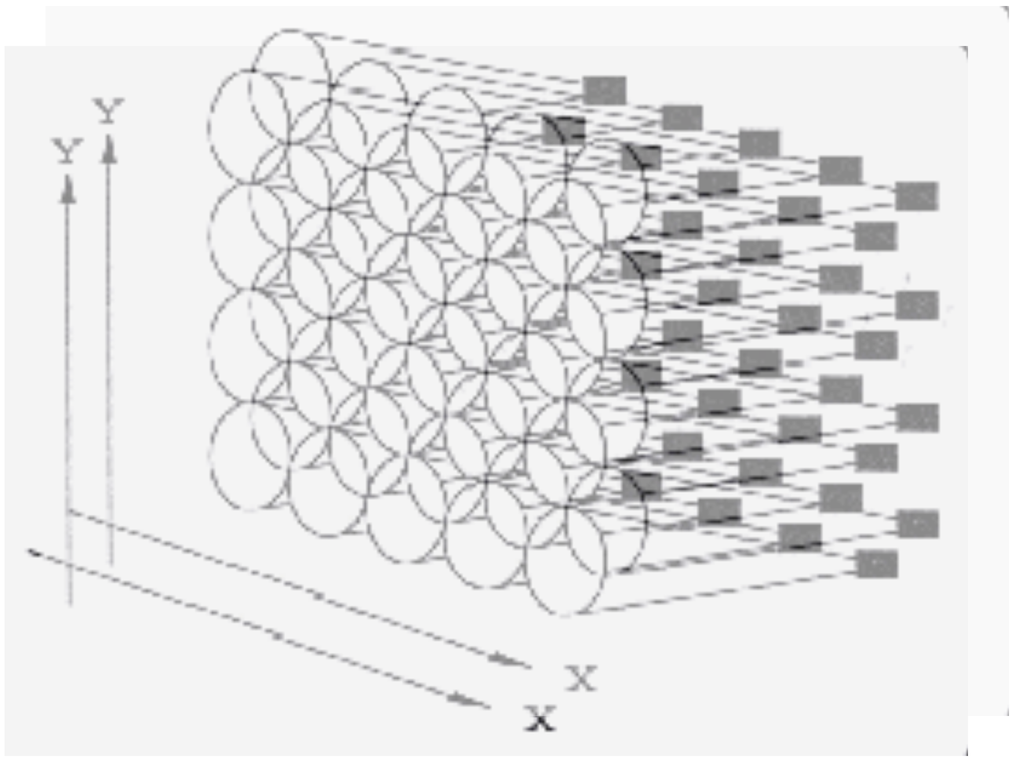
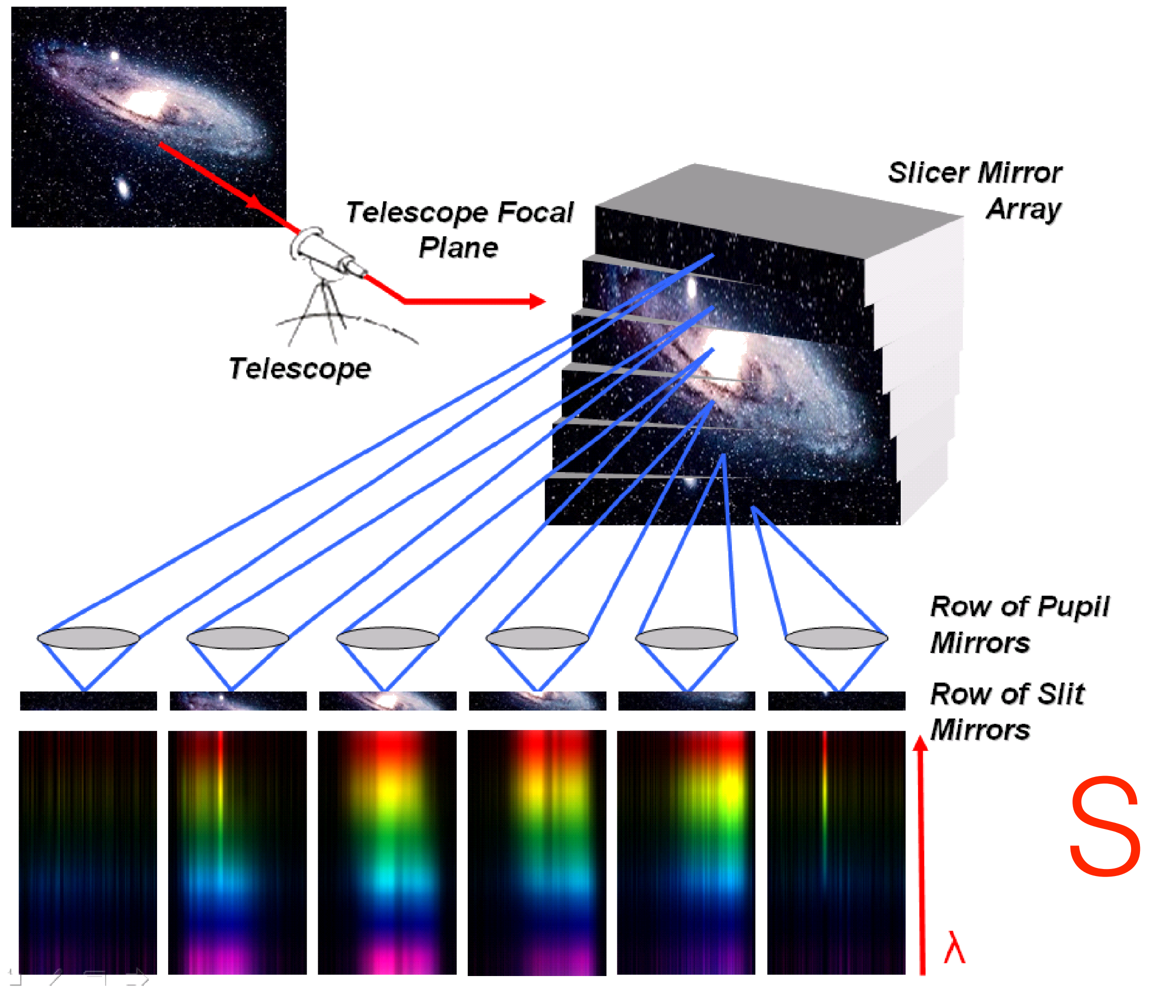
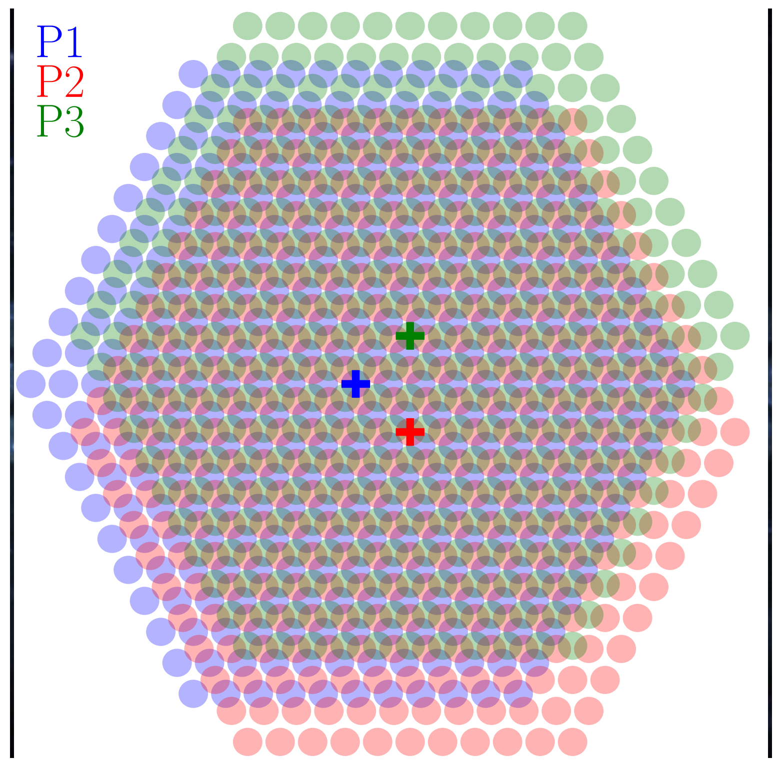




Slicer

Integral Field Spectroscopy



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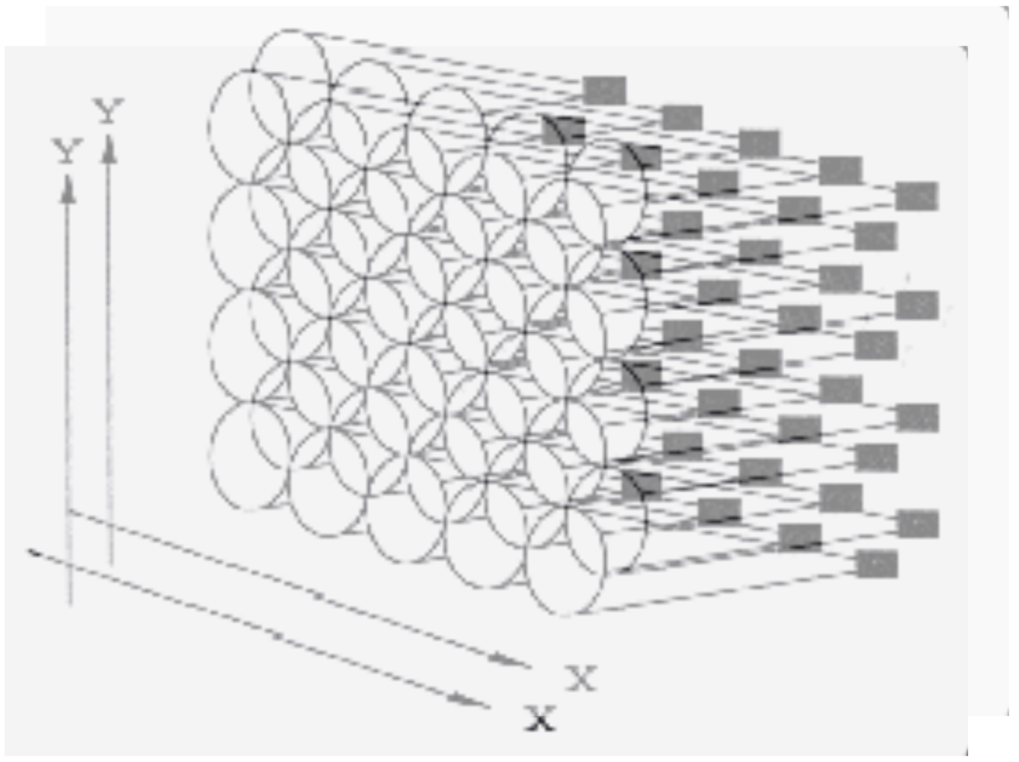

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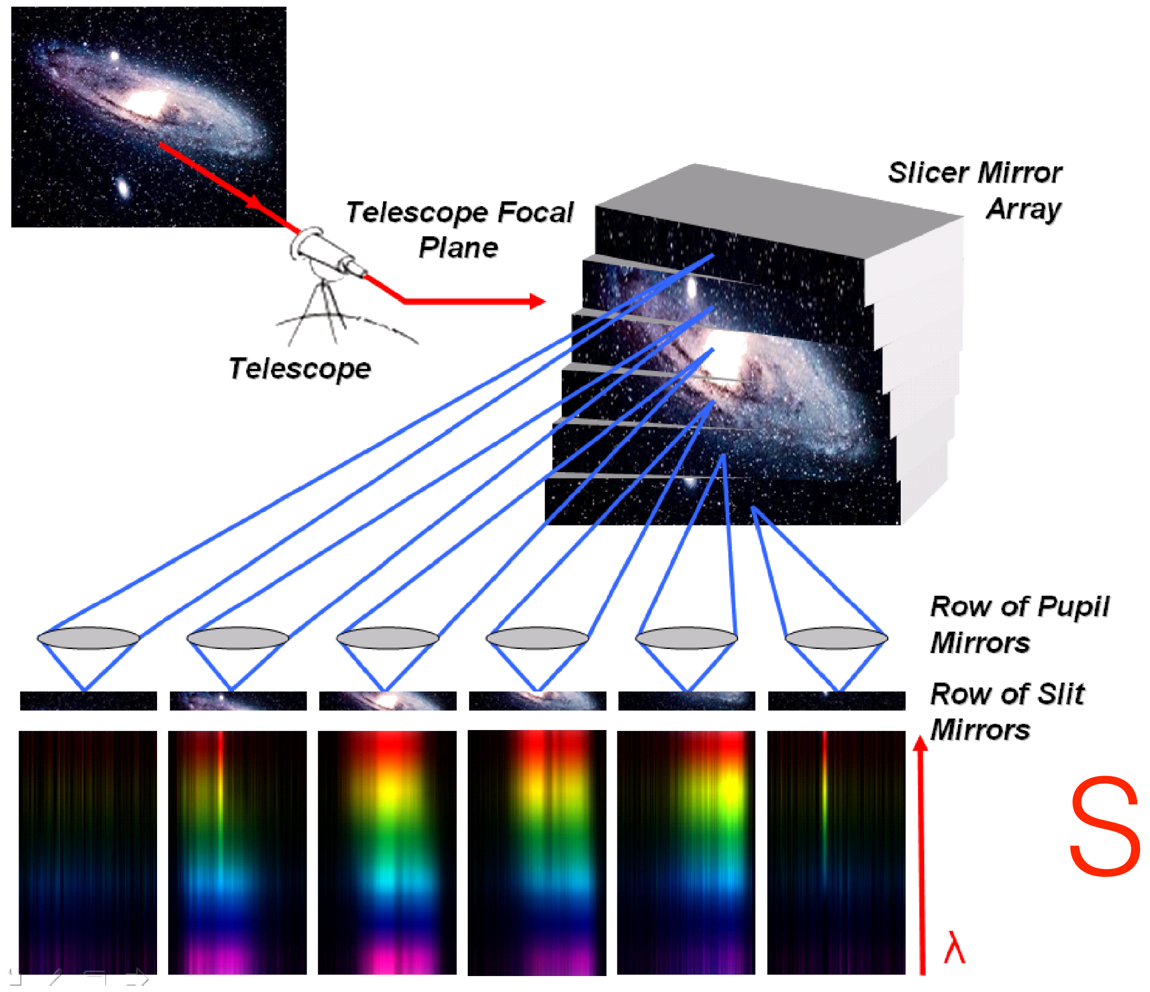
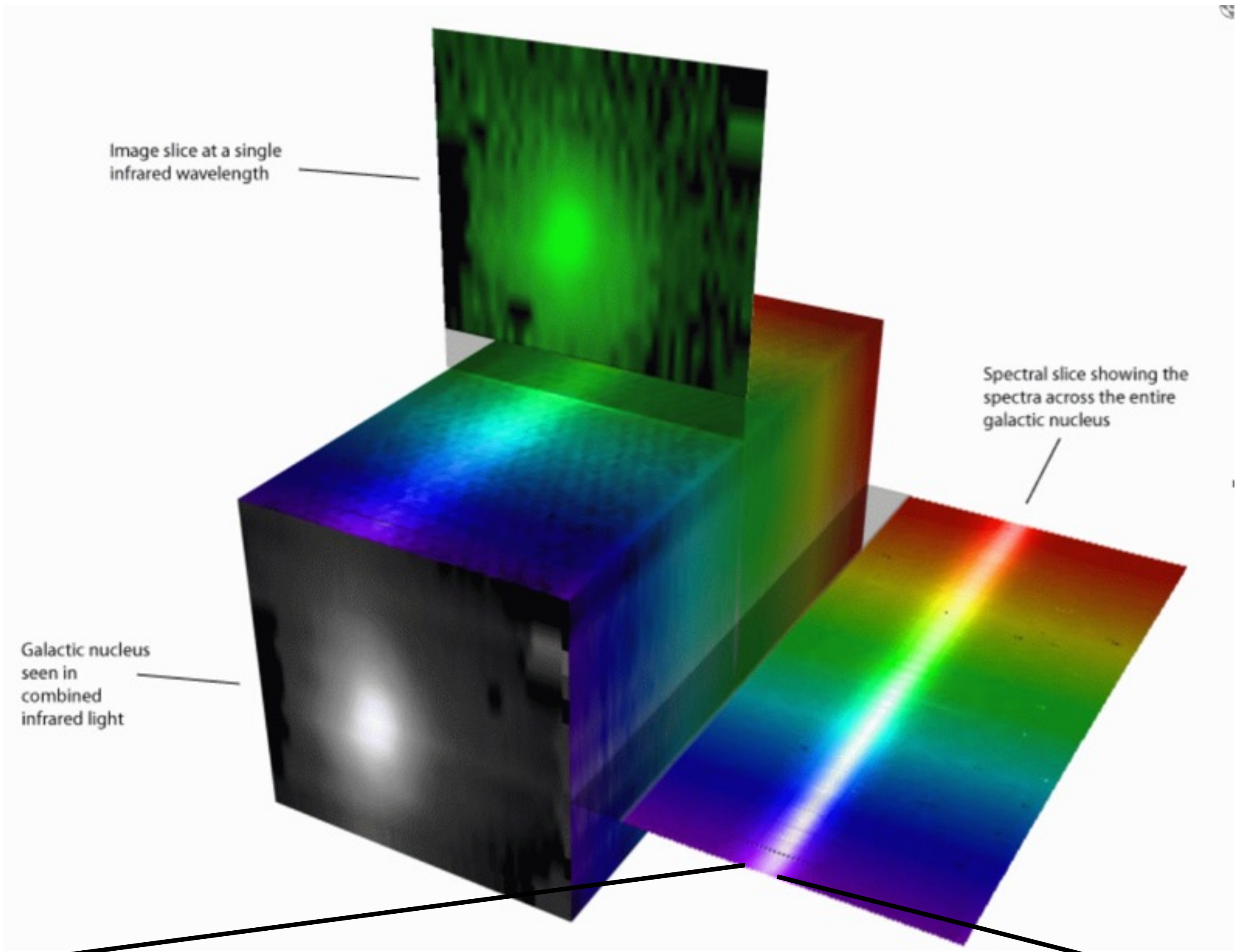
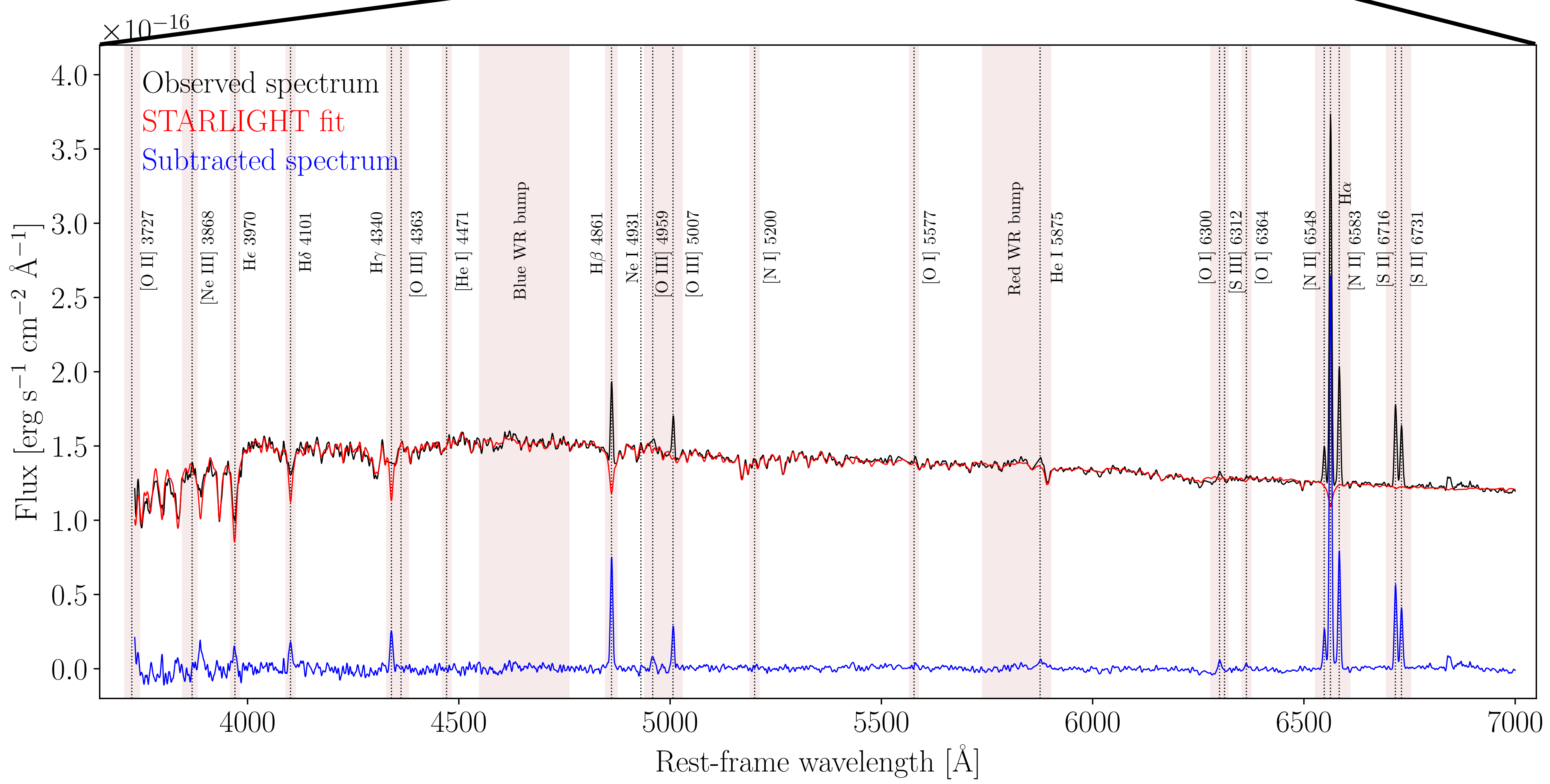
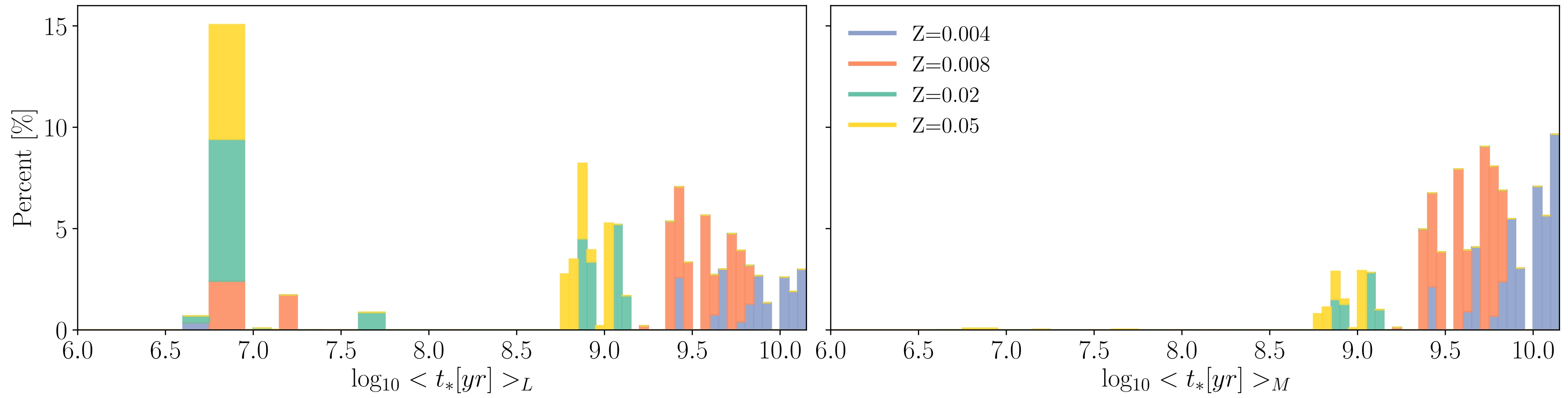


Slicer

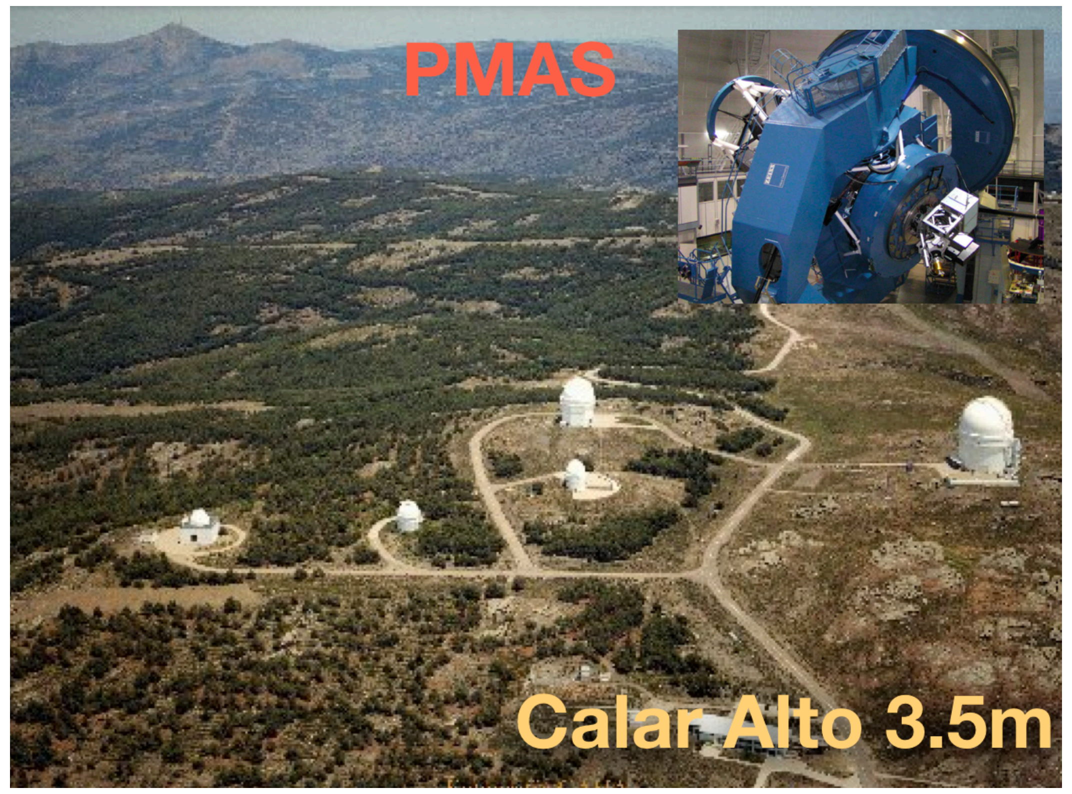


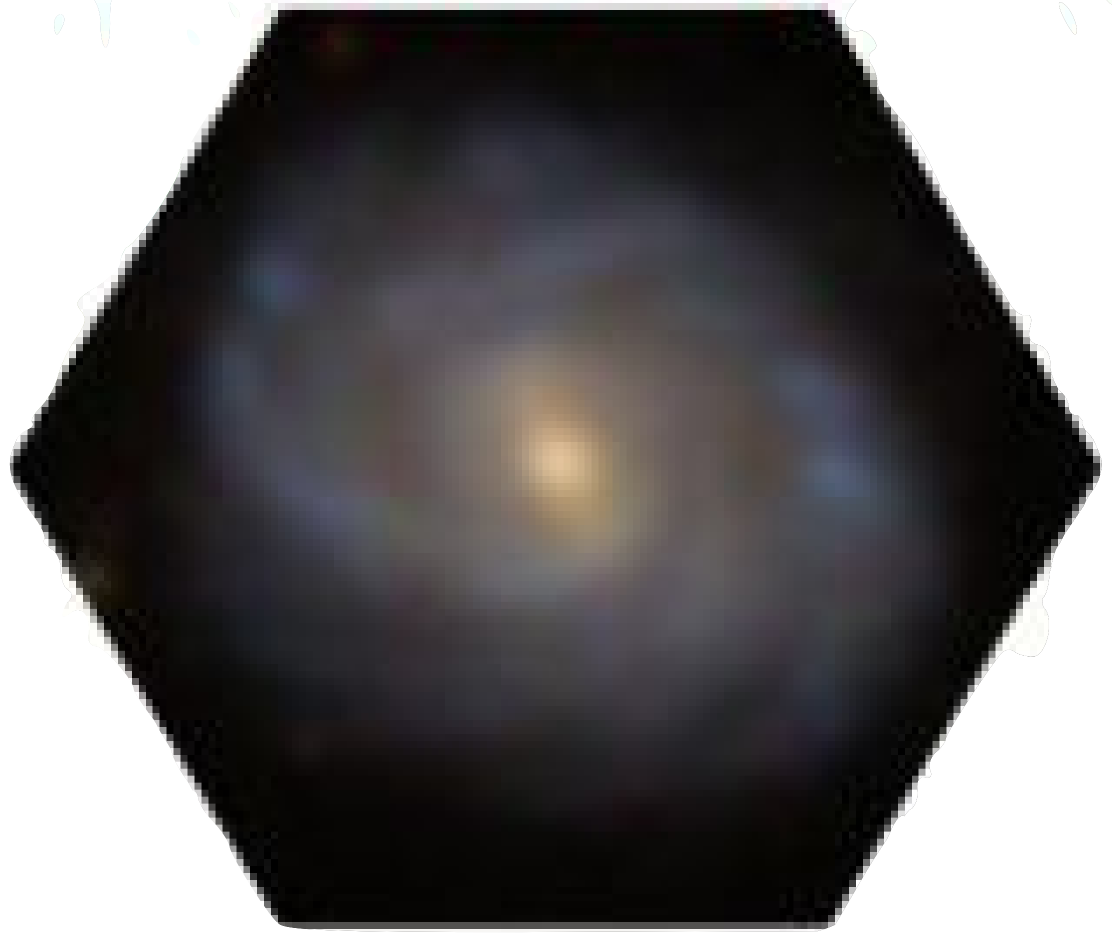


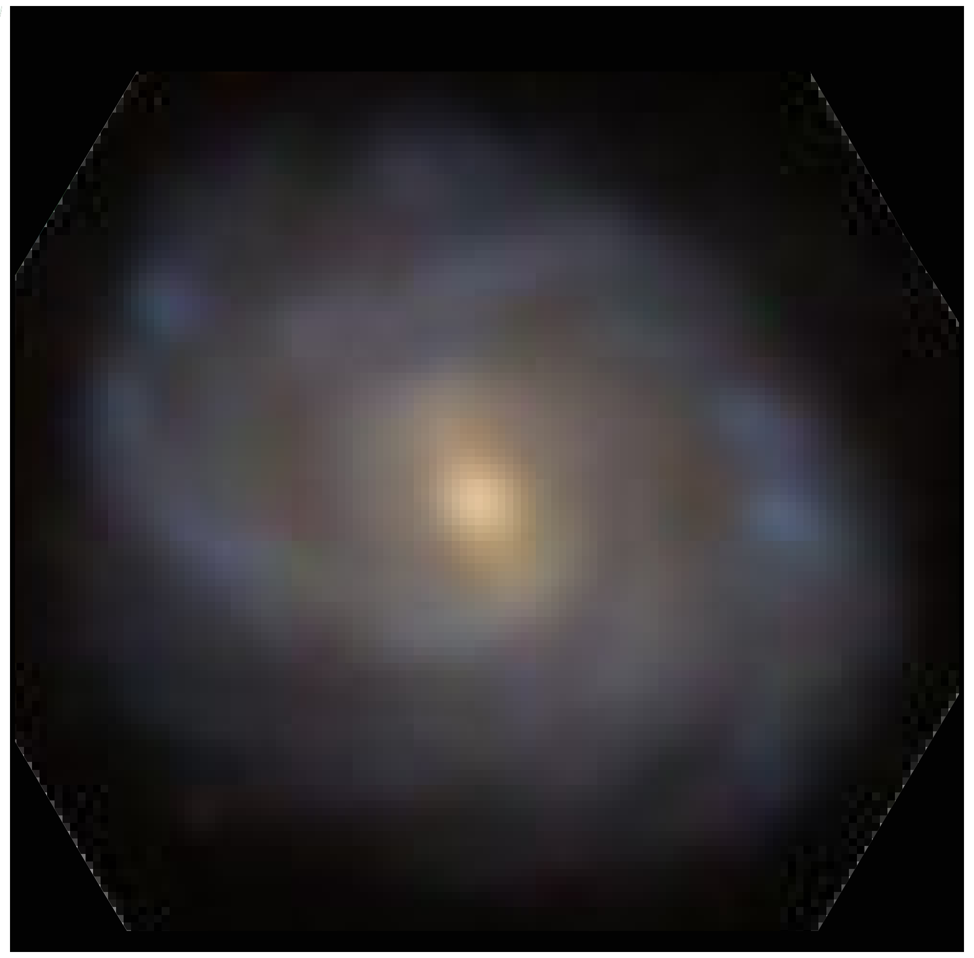


Integral Field Spectroscopy data

	PMAS	MUSE
Field of view	70”x70”	60”x60”
Spectral Resolution	R~500-1200	R~1700-3500
Number of spectra	~5,000 sp	~90,000 sp
Spatial Resolution	1”/spaxel	0.2”/spaxel
Wavelength coverage	3700-7500	4650-9300







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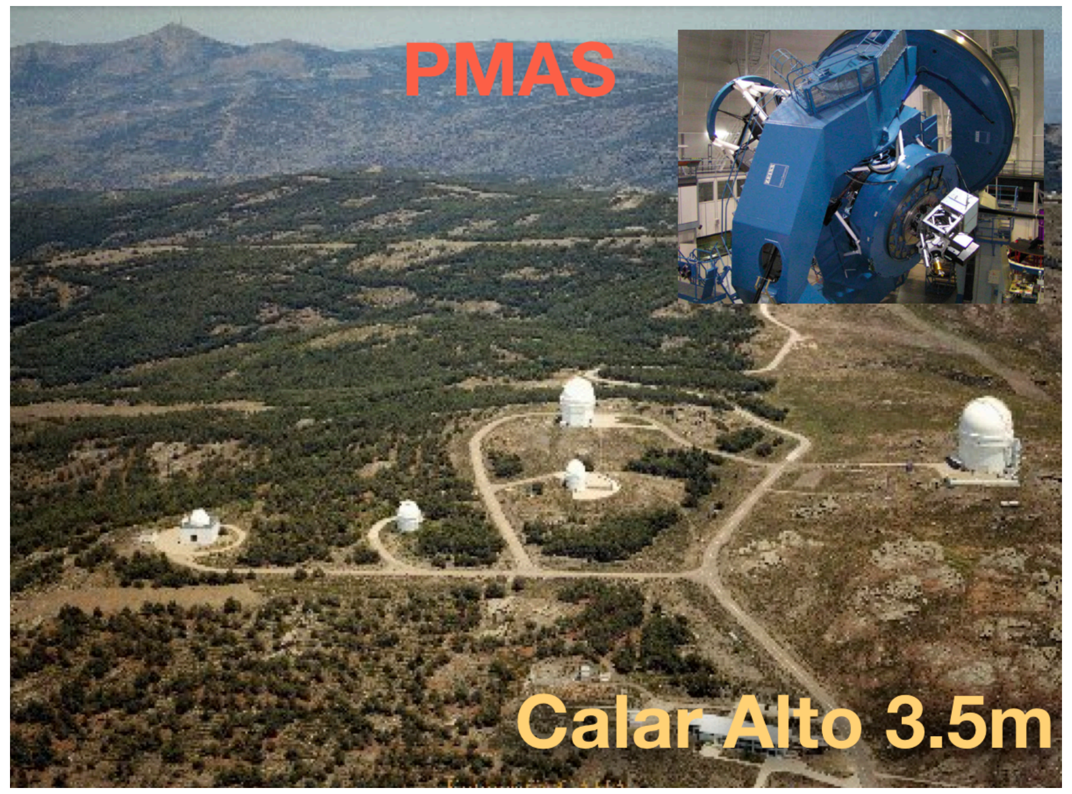
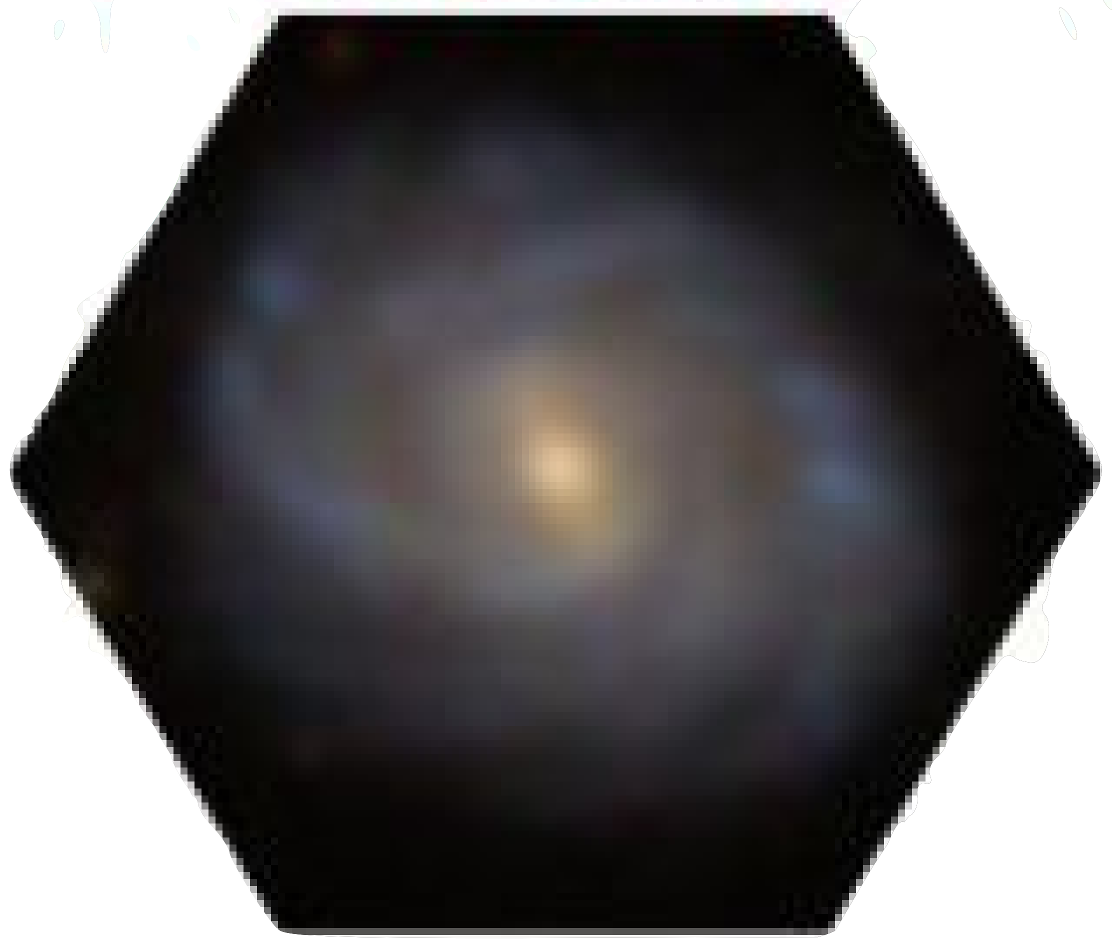
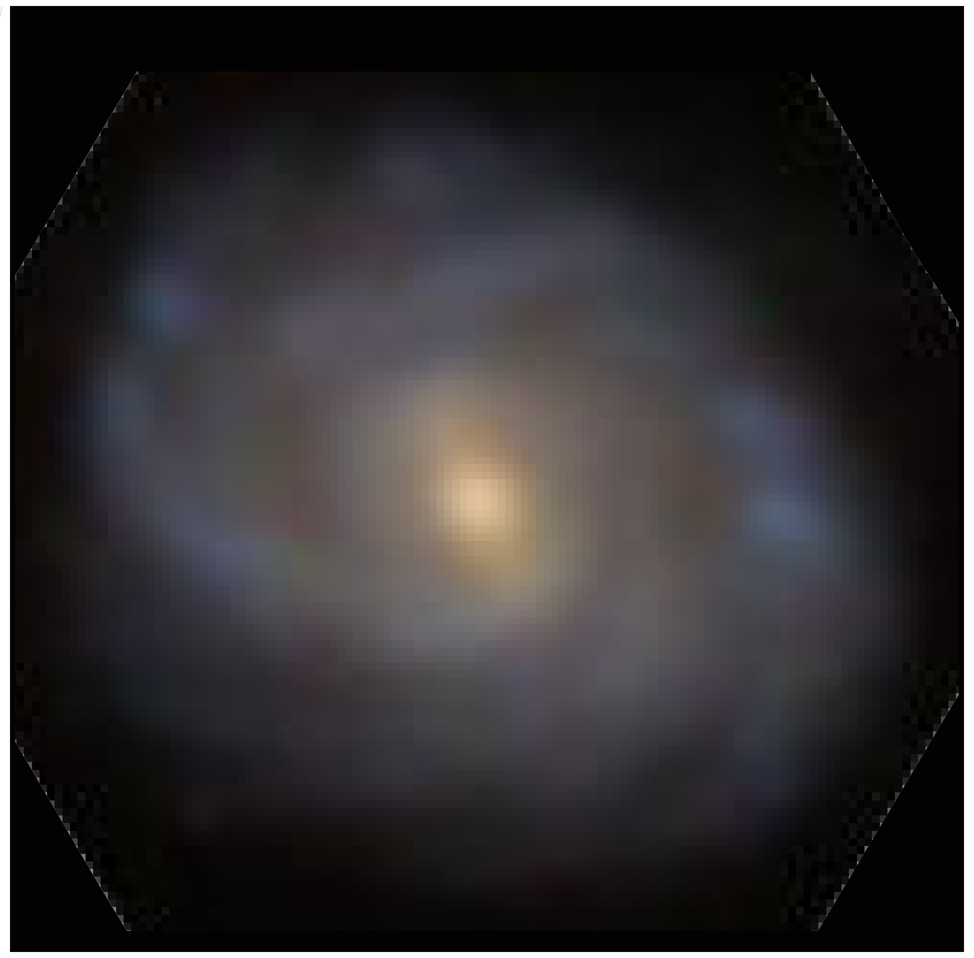
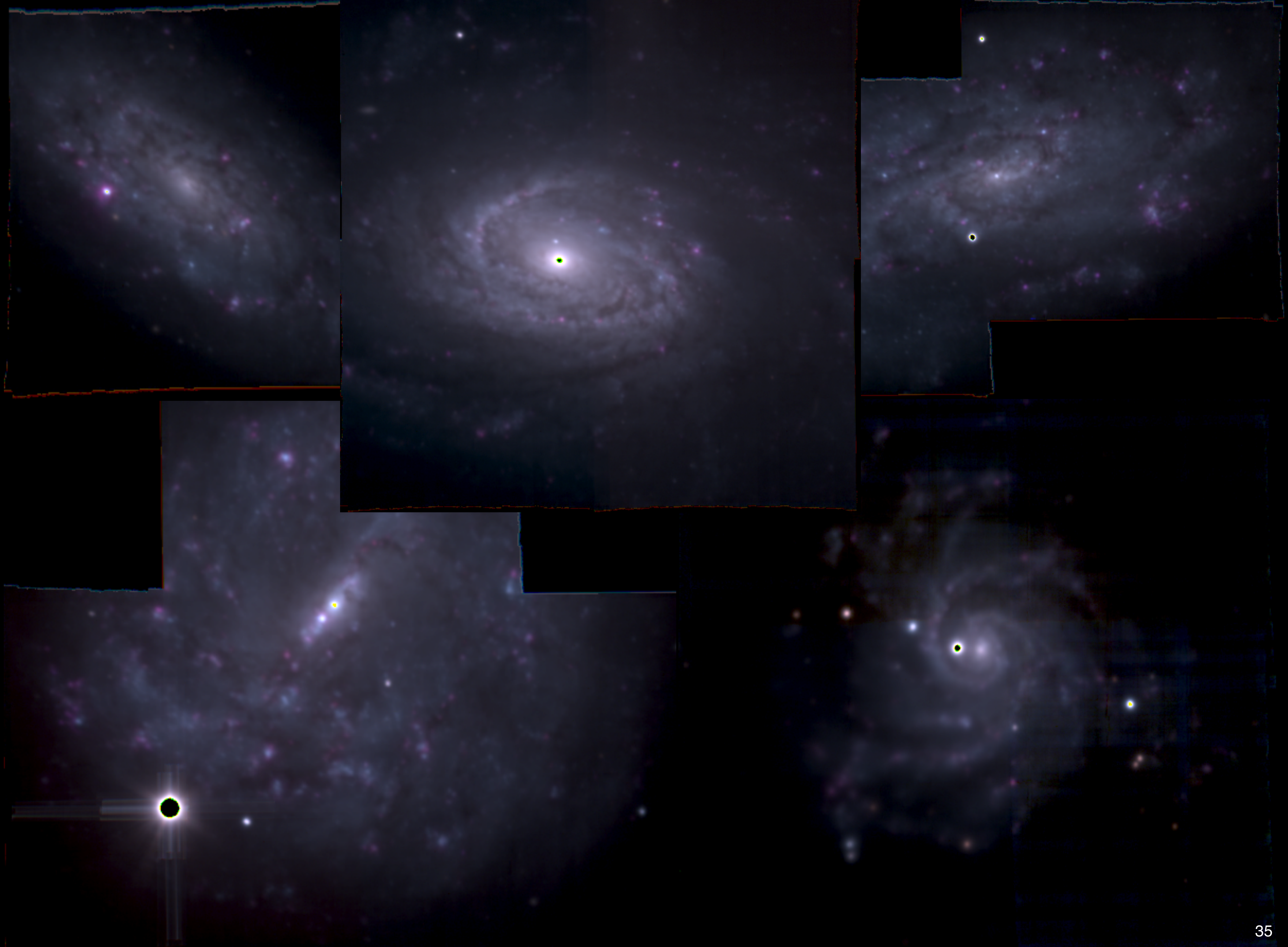
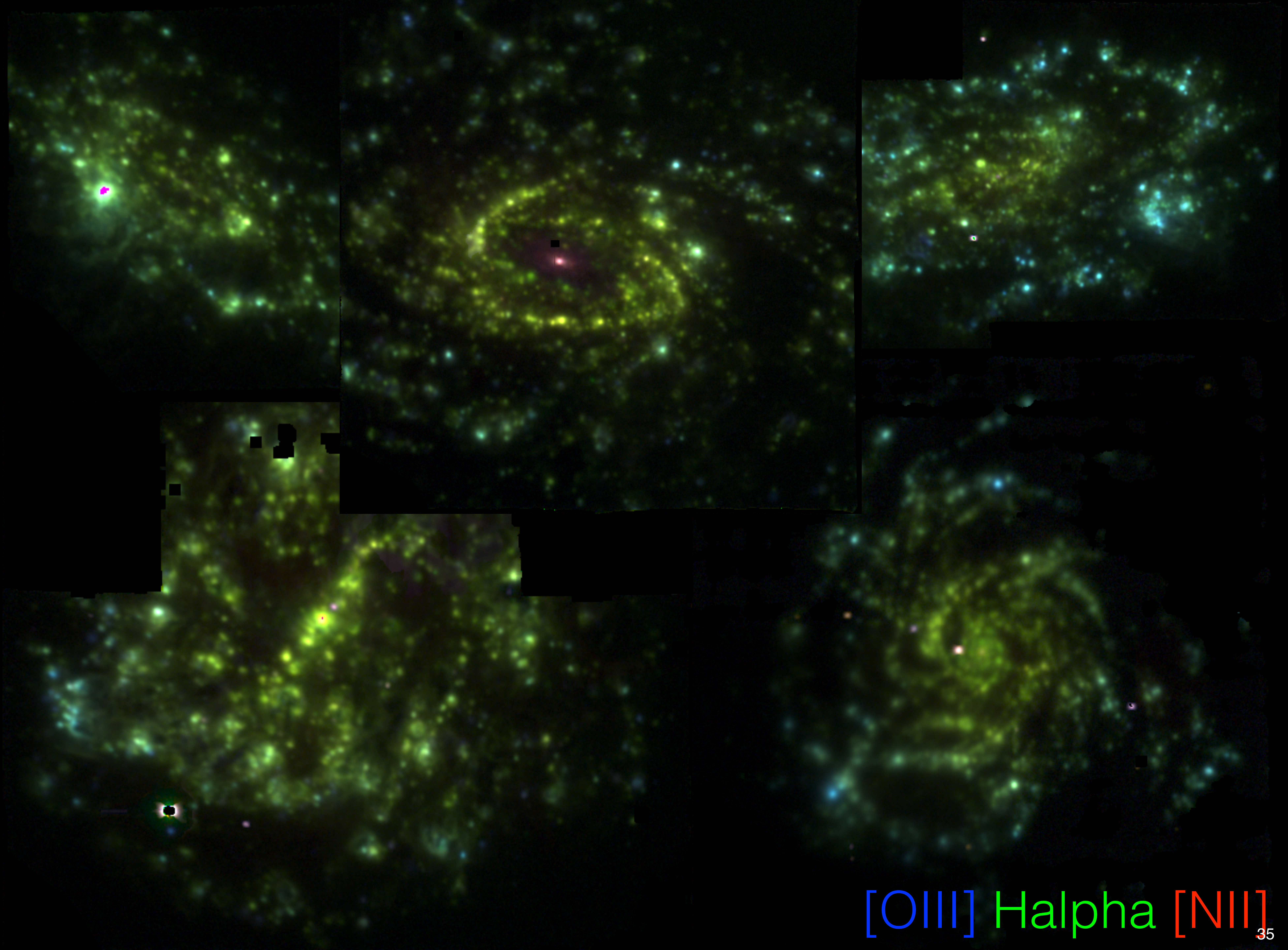
More than 1000 SNIa host galaxies available





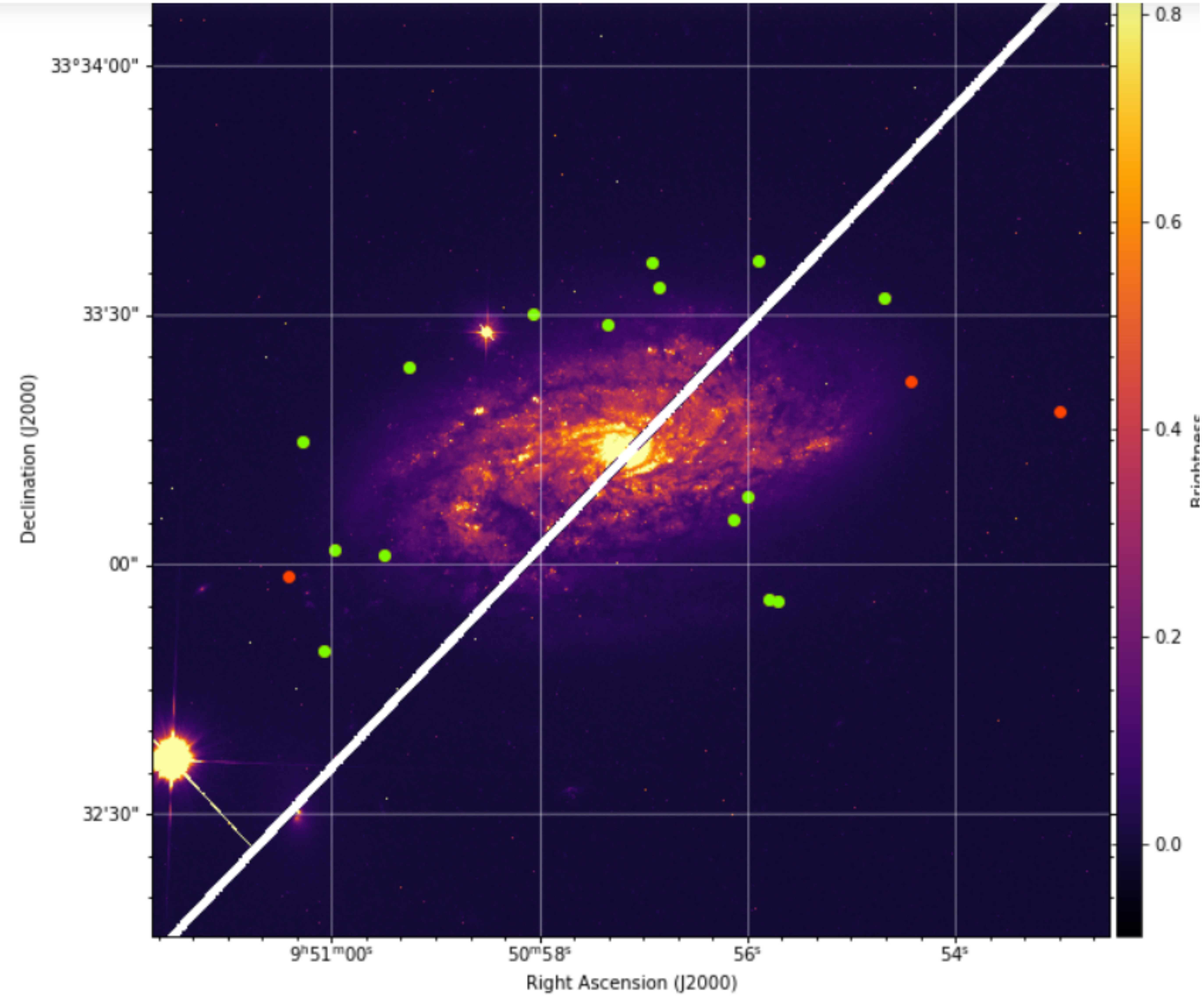





[OIII] Halpha [NII]

Cepheids calibration

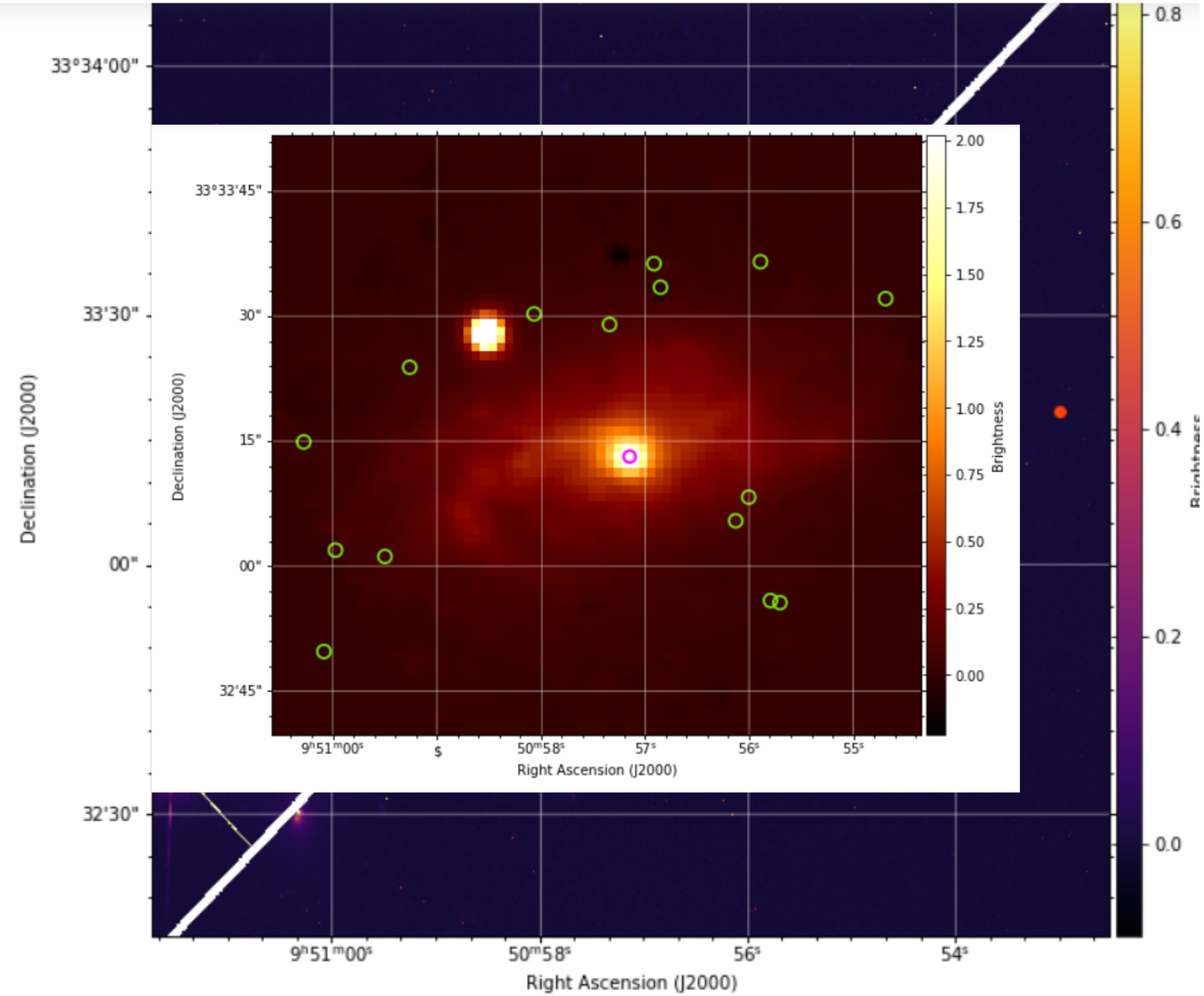
Sara Muñoz-Torres in prep.



Cepheids calibration

Sara Muñoz-Torres in prep.

IFS data of all 19 SHOES hosts



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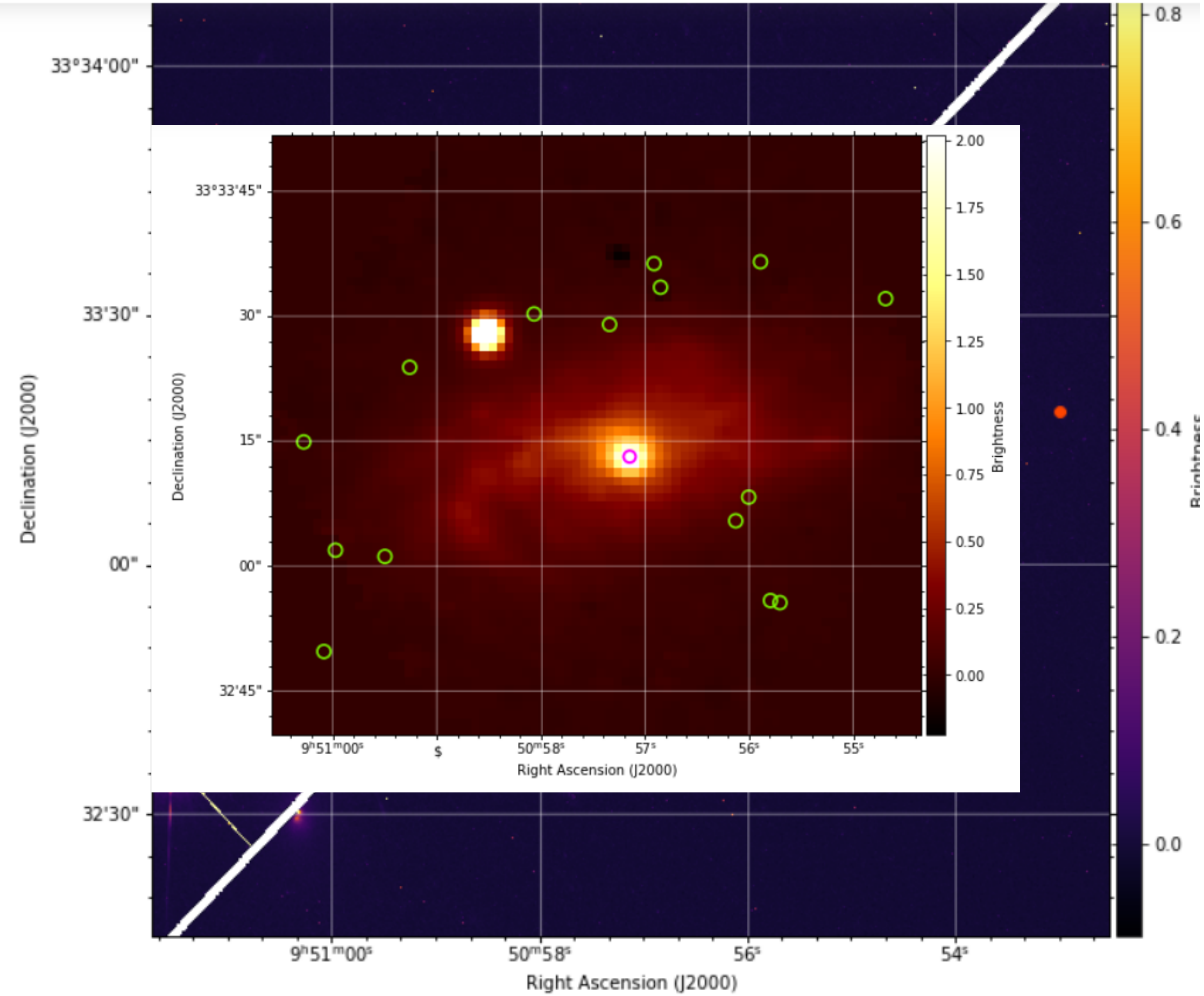
Sara Muñoz-Torres in prep.

IFS data of all 19 SHOES hosts

Measuring O abundance
at Cepheids location



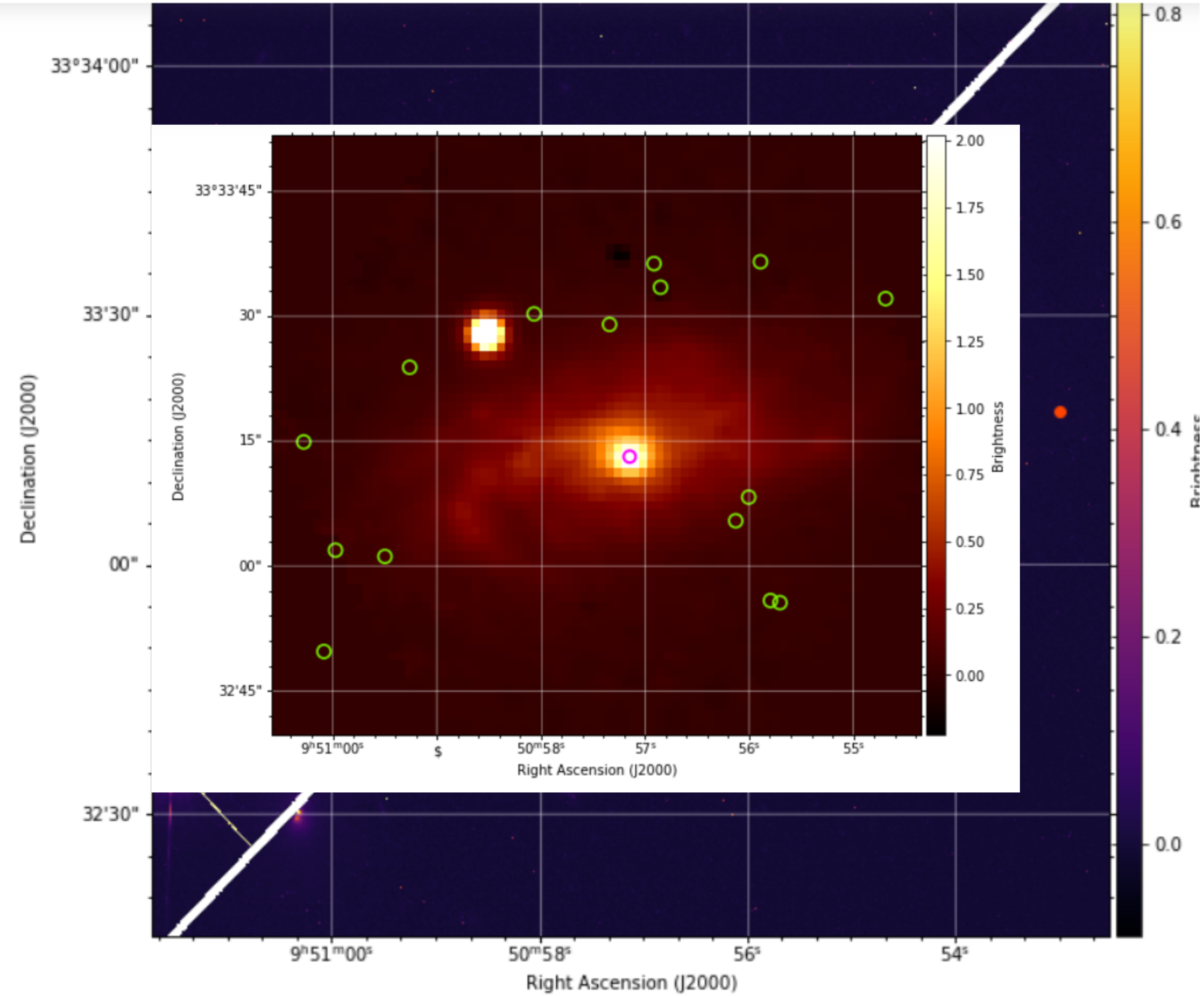
Cepheids calibration

Sara Muñoz-Torres in prep.

IFS data of all 19 SHOES hosts

Measuring O abundance at Cepheids location

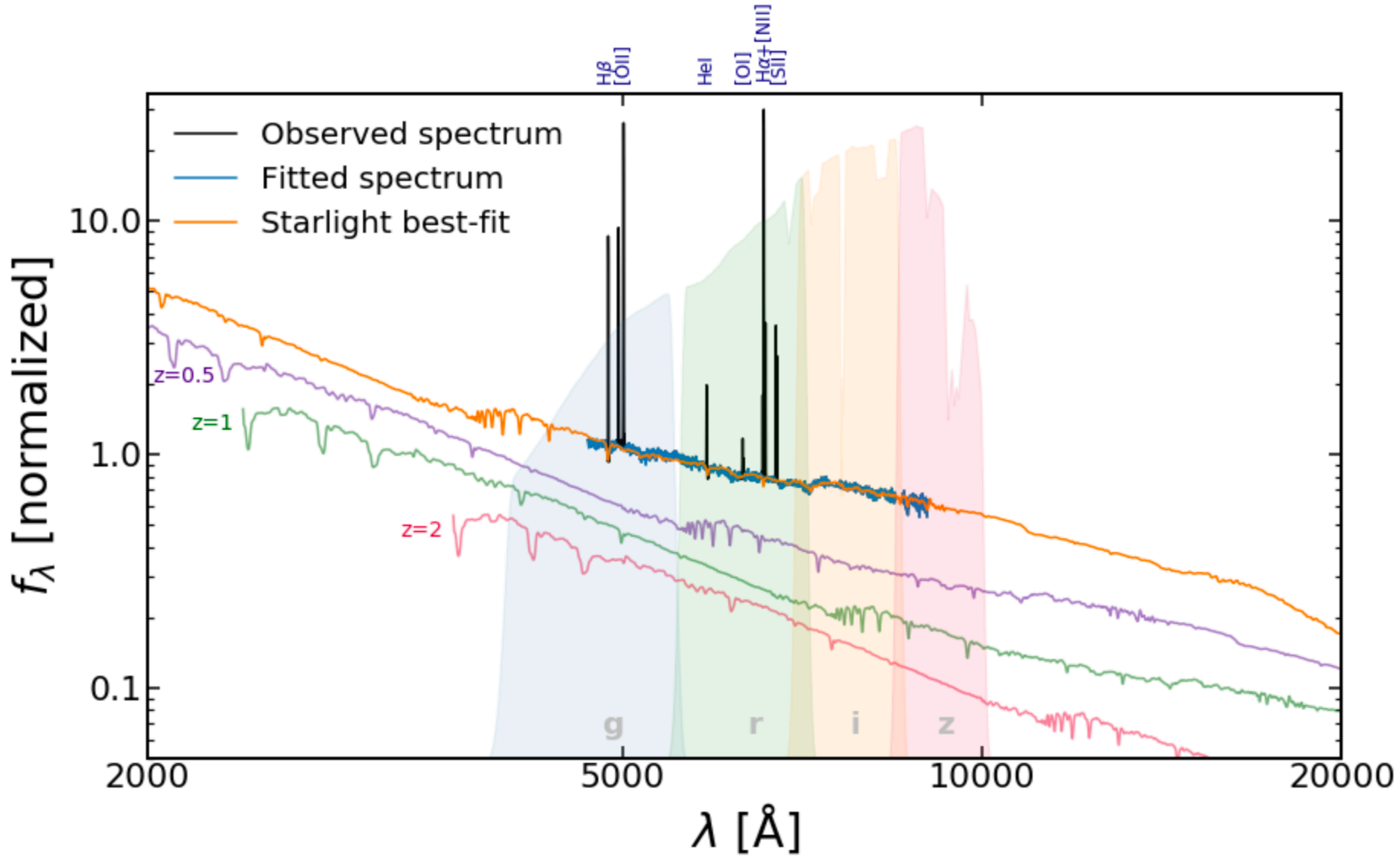
Local Rv from stellar and gas-phase extinction (non-universal)



Mass systematics

A.S.Afonso+21

SSP synthesis on
low-z MUSE cubes

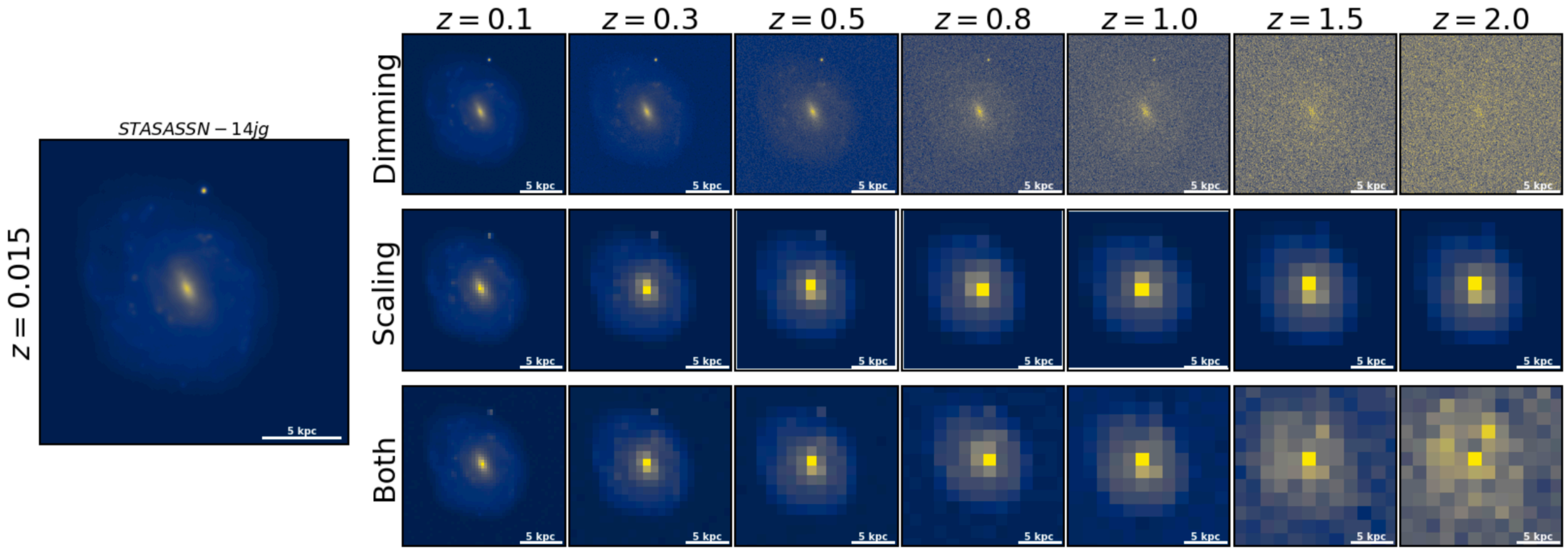


Mass systematics

A.S.Afonso+21

SSP synthesis on low-z MUSE cubes

Best fits used for constructing artificial high-z galaxies



Mass systematics

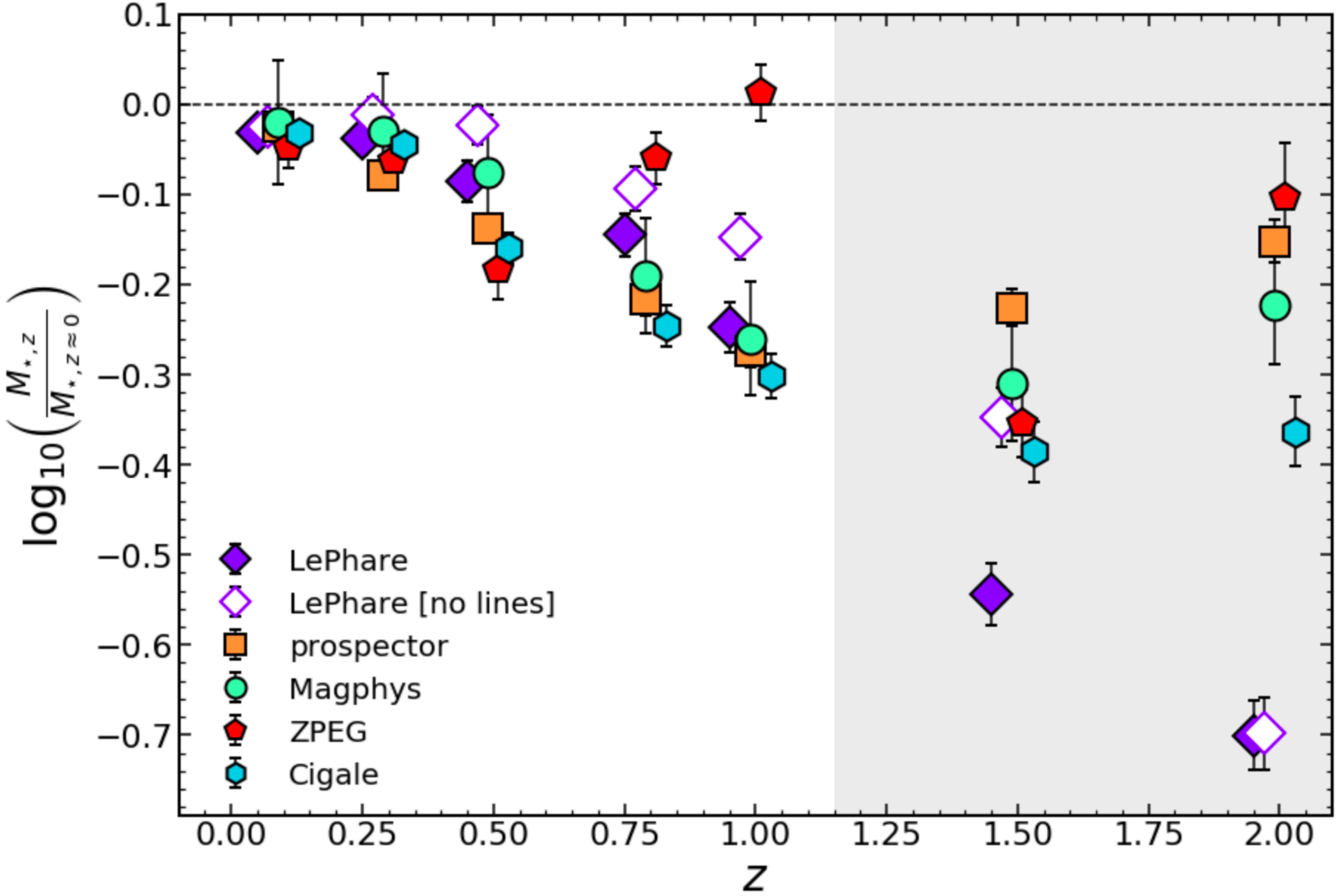
SSP synthesis on low-z MUSE cubes

Best fits used for constructing artificial high-z galaxies

Remeasure mass and look for biases

Effect: -0.6% in w
+0.6% in Ω_M

A.S.Afonso+21



Mass systematics

Ongoing study of dust

A.S.Afonso+21

SSP synthesis on
low-z MUSE cubes

Best fits used for
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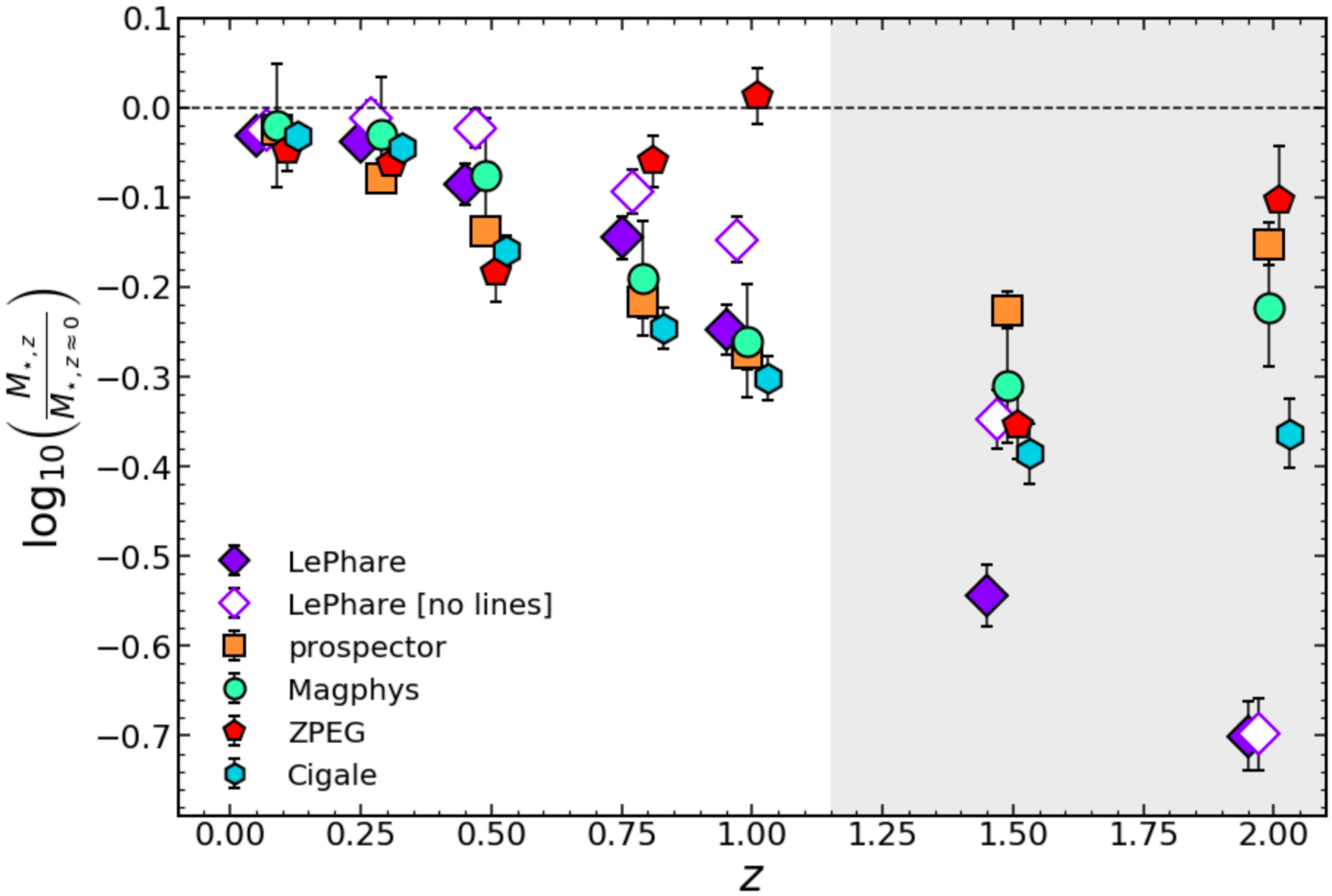
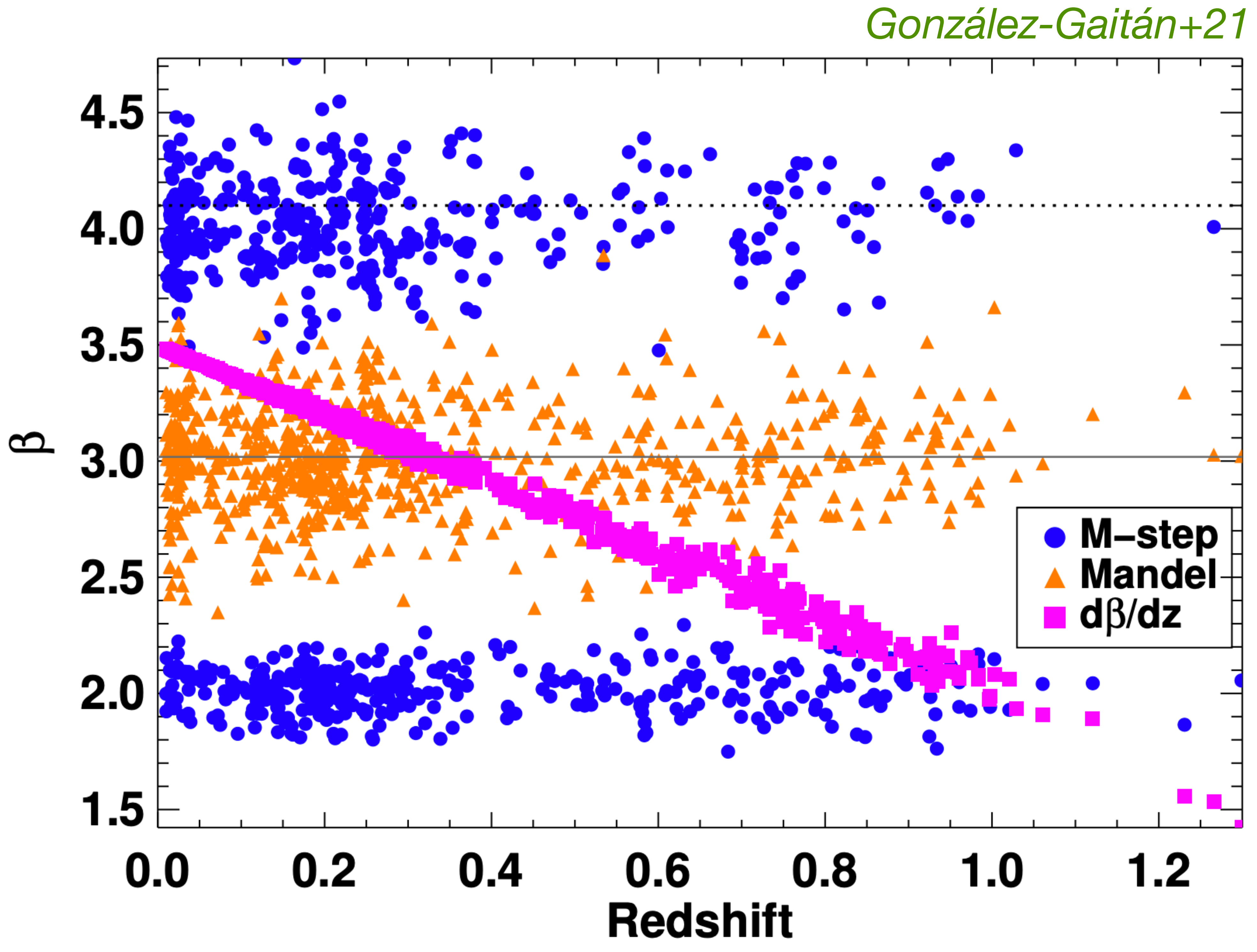


Multiple SN luminosity - color relations



Test cosmological fits with varying beta

232 mock distributions:

AB-model (Perrett+12 rates)

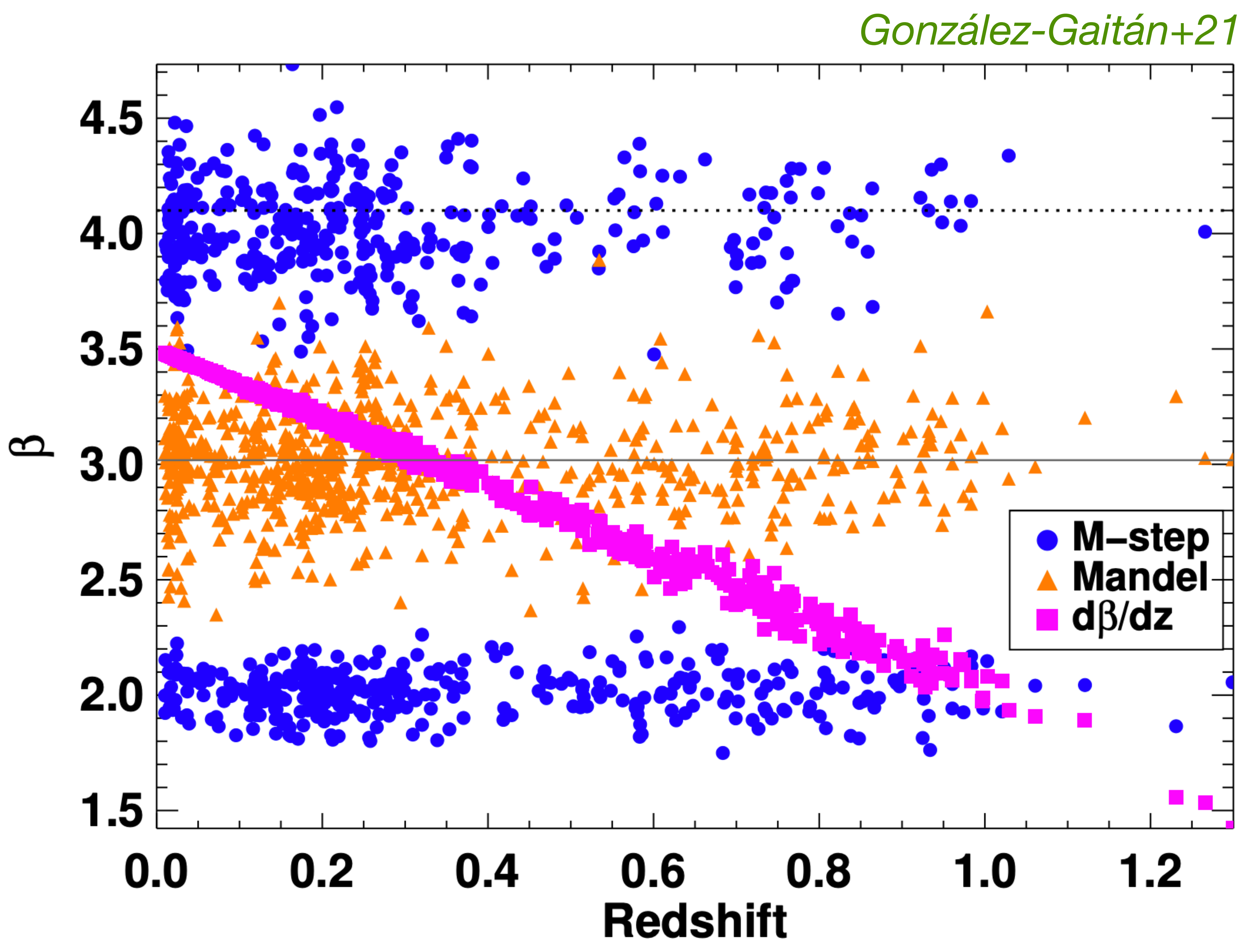
Mass step model

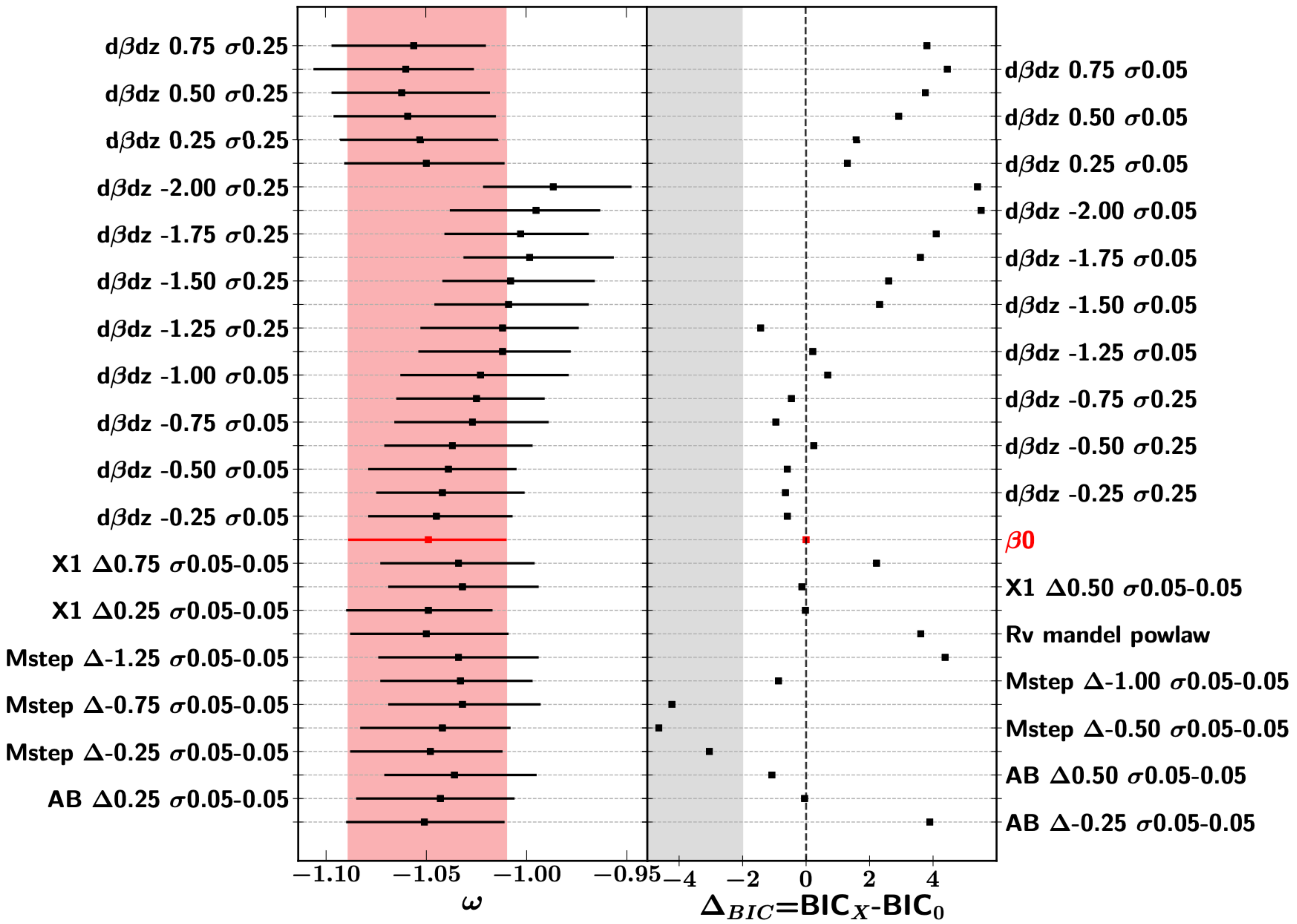
Stretch (X) model

Burns/Mandel model

z-model

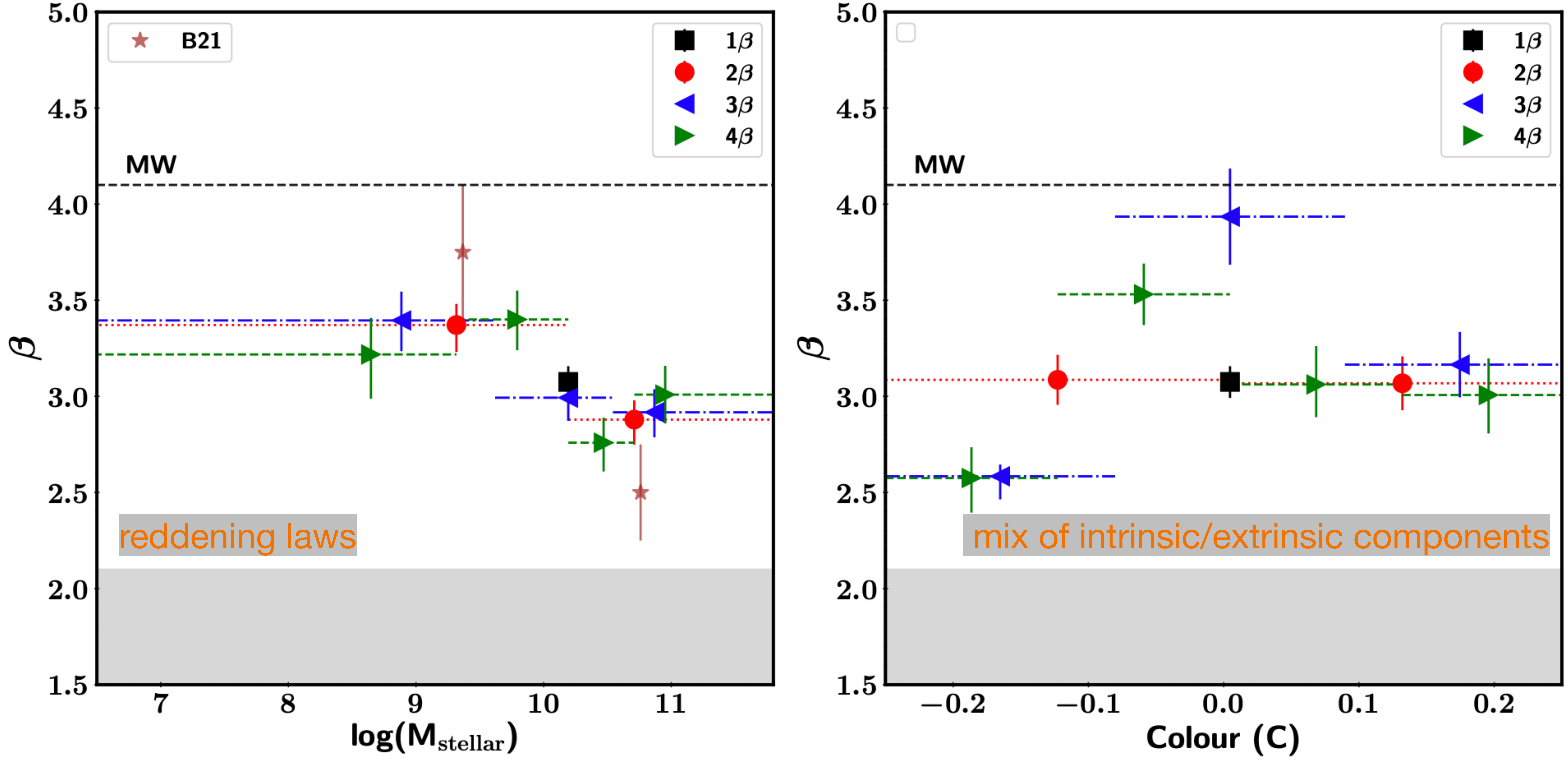
Multiple SN luminosity - color relations





Multiple SN luminosity - color relations

González-Gaitán+21



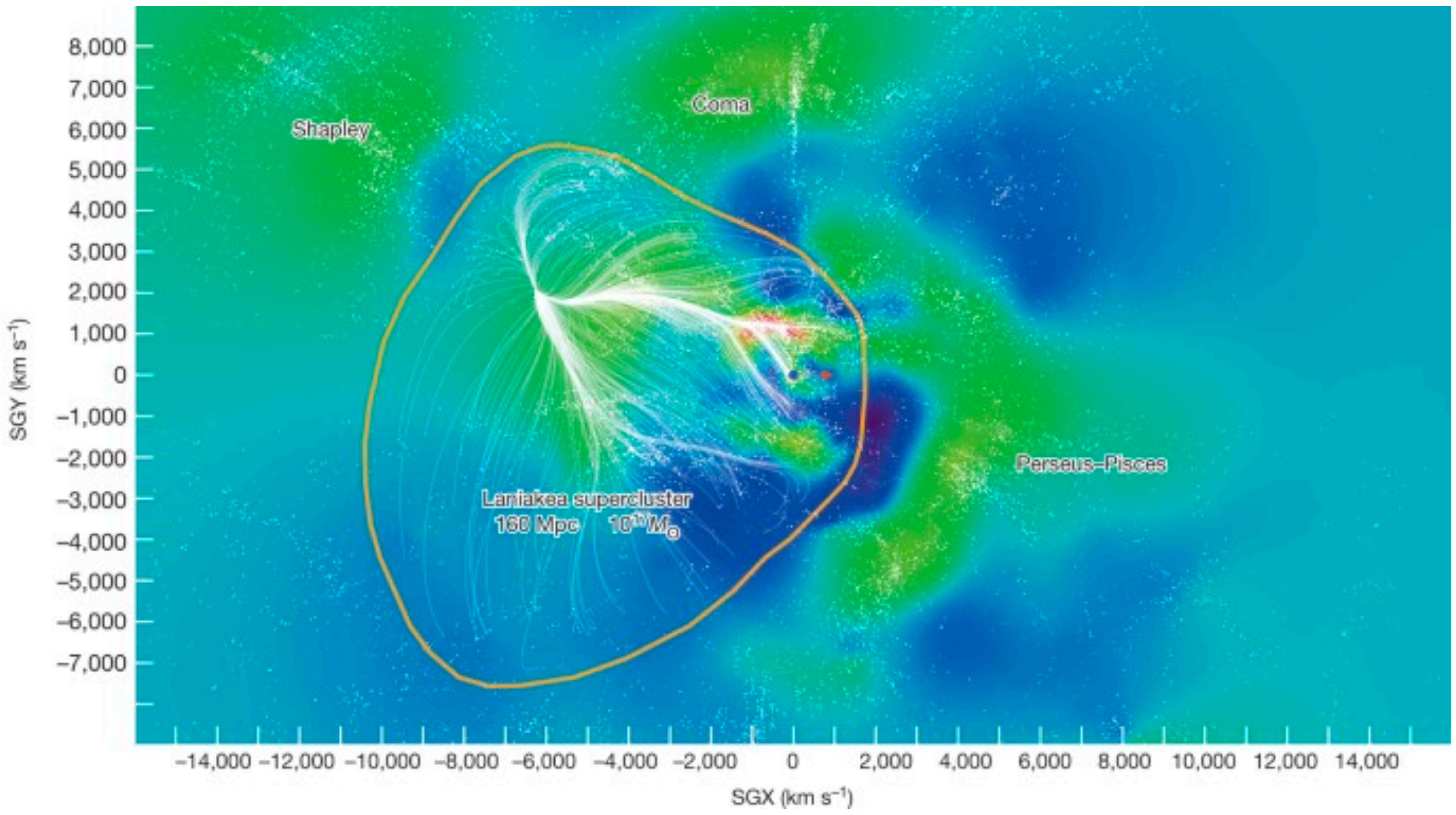
Cosmological fit with 1-4 beta, in bins of mass and color

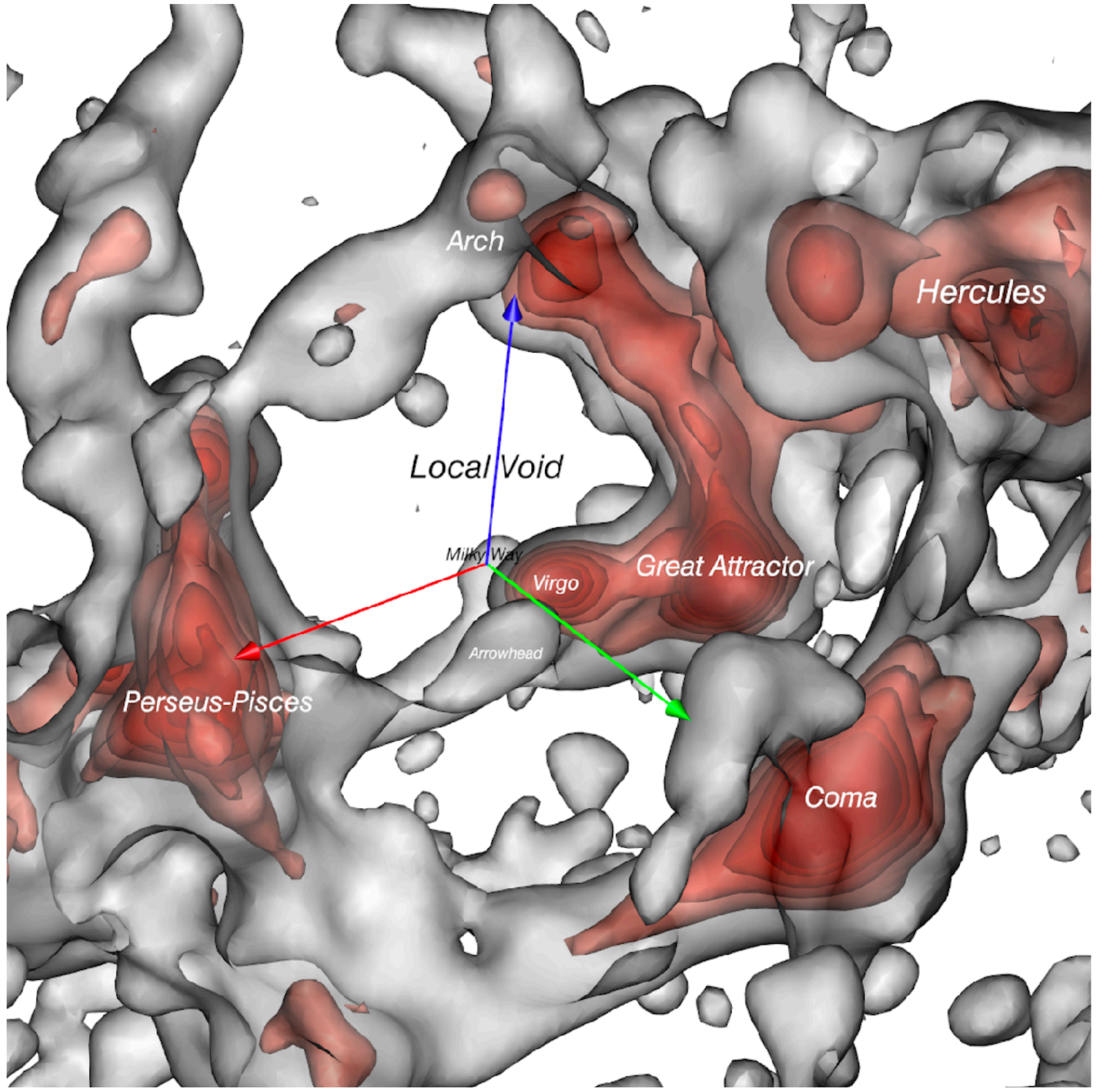
(Current) Approach

The HOSTFLOWS project

B- Cosmography of Laniakea

Tully+14





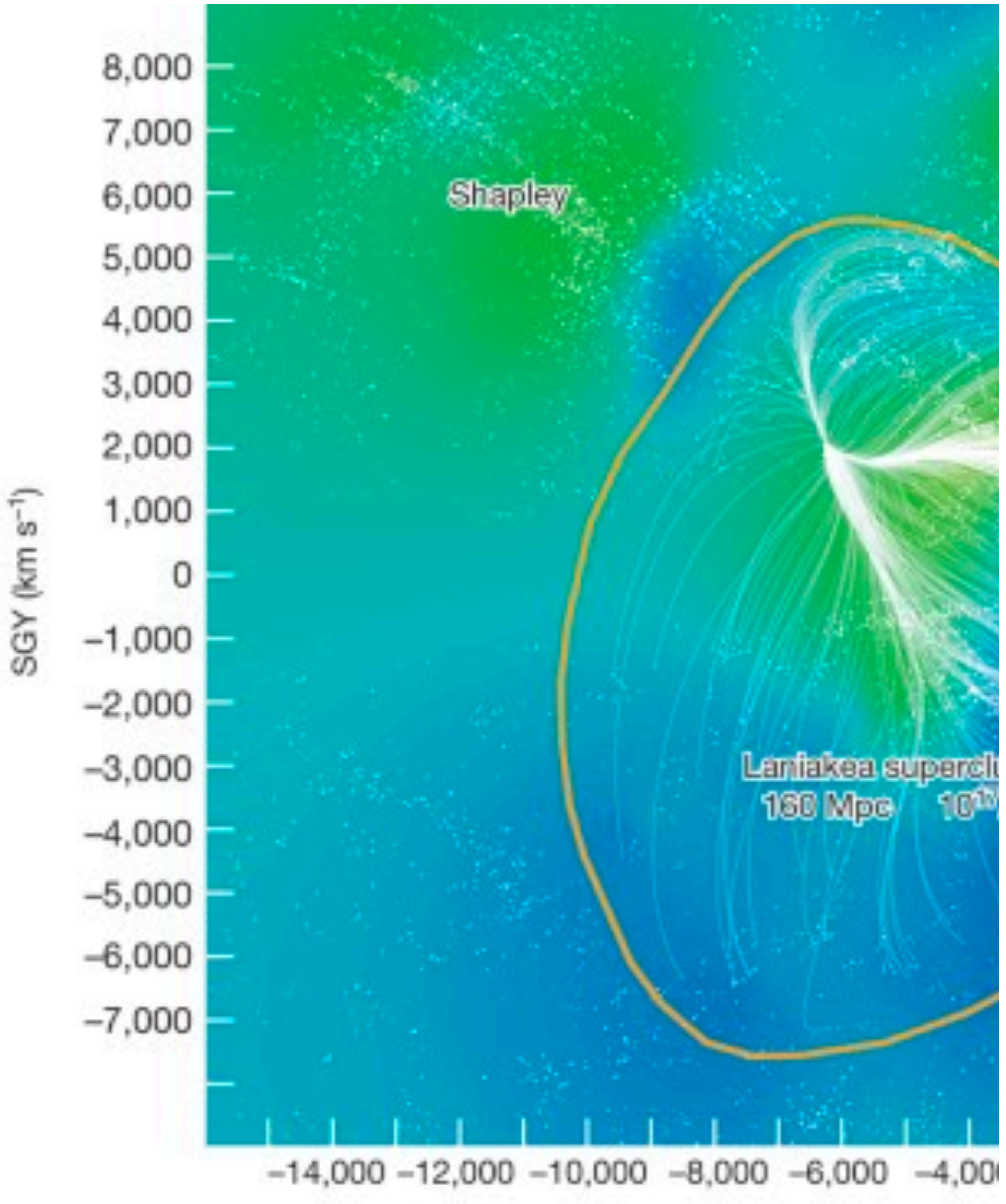
Tully+19

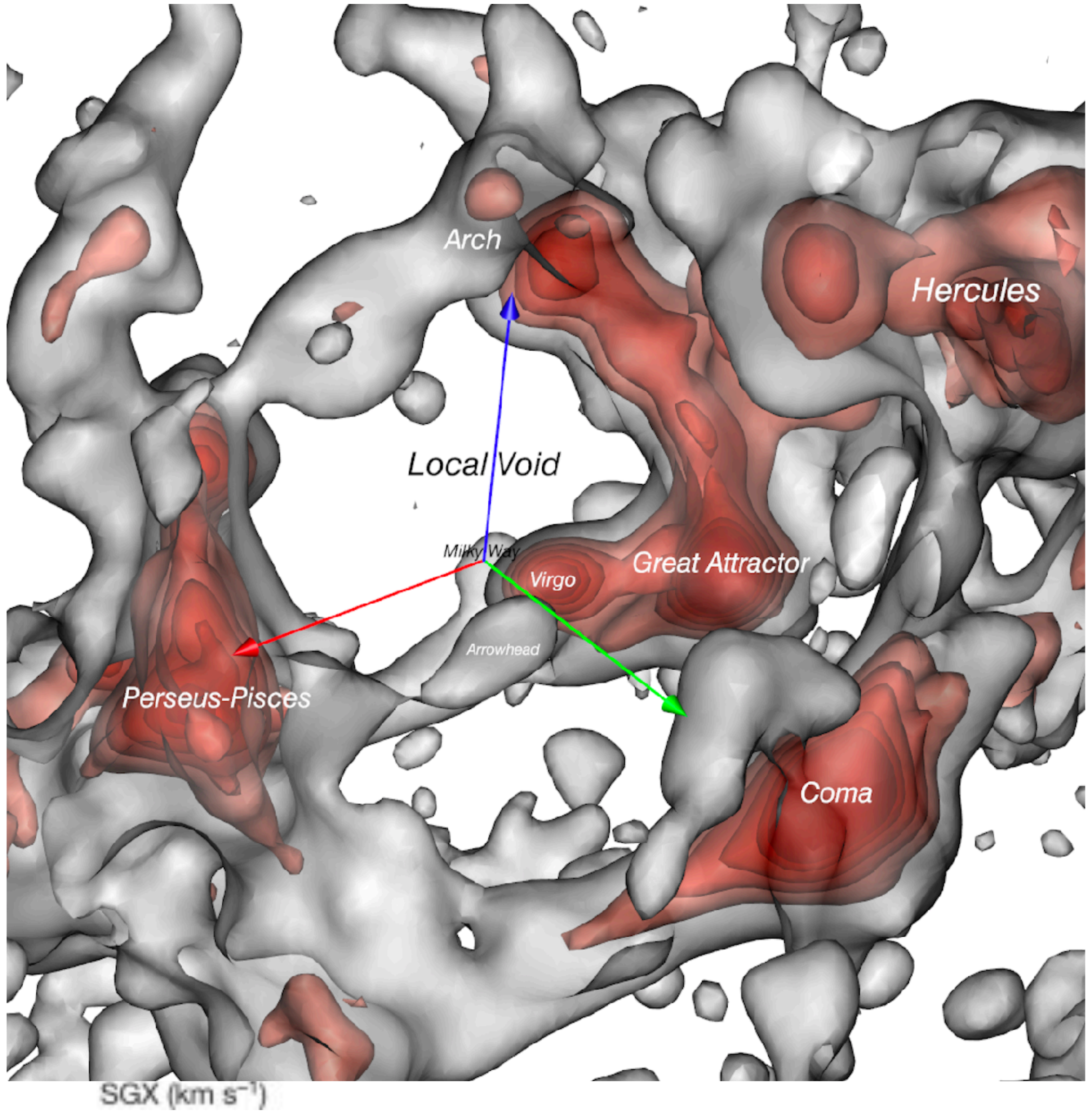
(Current) Approach

The HOSTFLOWS project

B- Cosmography of Laniakea

Tully+14





Tully+19

Construct a NIR SNIa sample to:

1. Infer the peculiar velocity field within Laniakea [$v_p = cz - H_0 D$]
2. Reconstruct the DM distribution on intermediate scales
3. Infer cosmological parameters related to the amplitude of the fluctuations of the early universe (σ_8) and the growth rate of structure (*fD*)
4. Test gravity models via measurements of the growth index γ

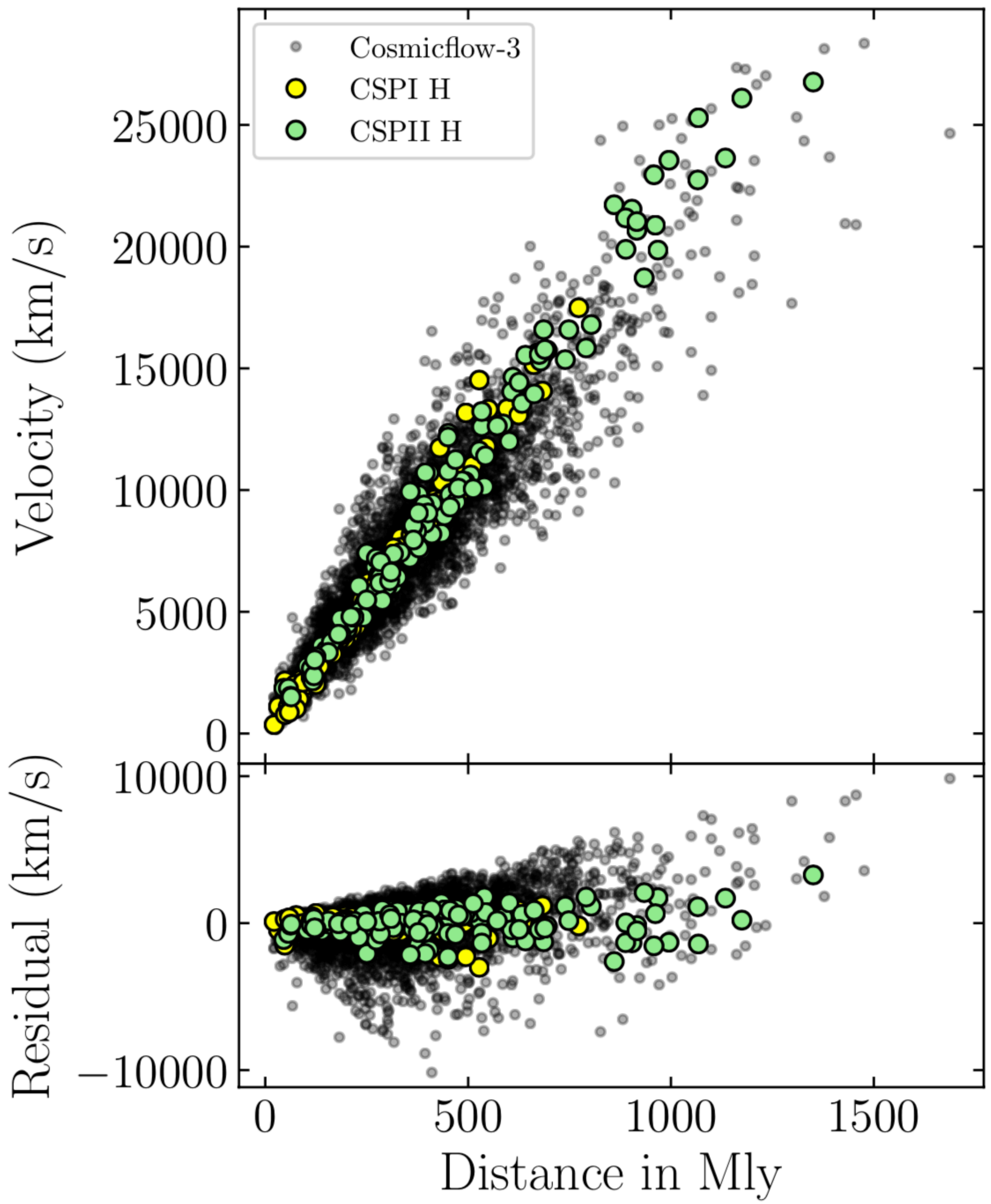
Why SNIa over TF/FP

Tully-Fischer (TF) and Fundamental Plane (FP) method distances are not precise beyond z=0.03 (~400 Mly)

SN Ia Systematics are minimized compared to TF and FP

Goal: Achieve a peculiar velocity measurement of 300 km/s w.r.t. the Hubble Flow at 1200 Mly (i.e. 3% in distance) by observing a few 1000 SN Ia & making use of 1/sqrt(N)

Burns et al in prep.

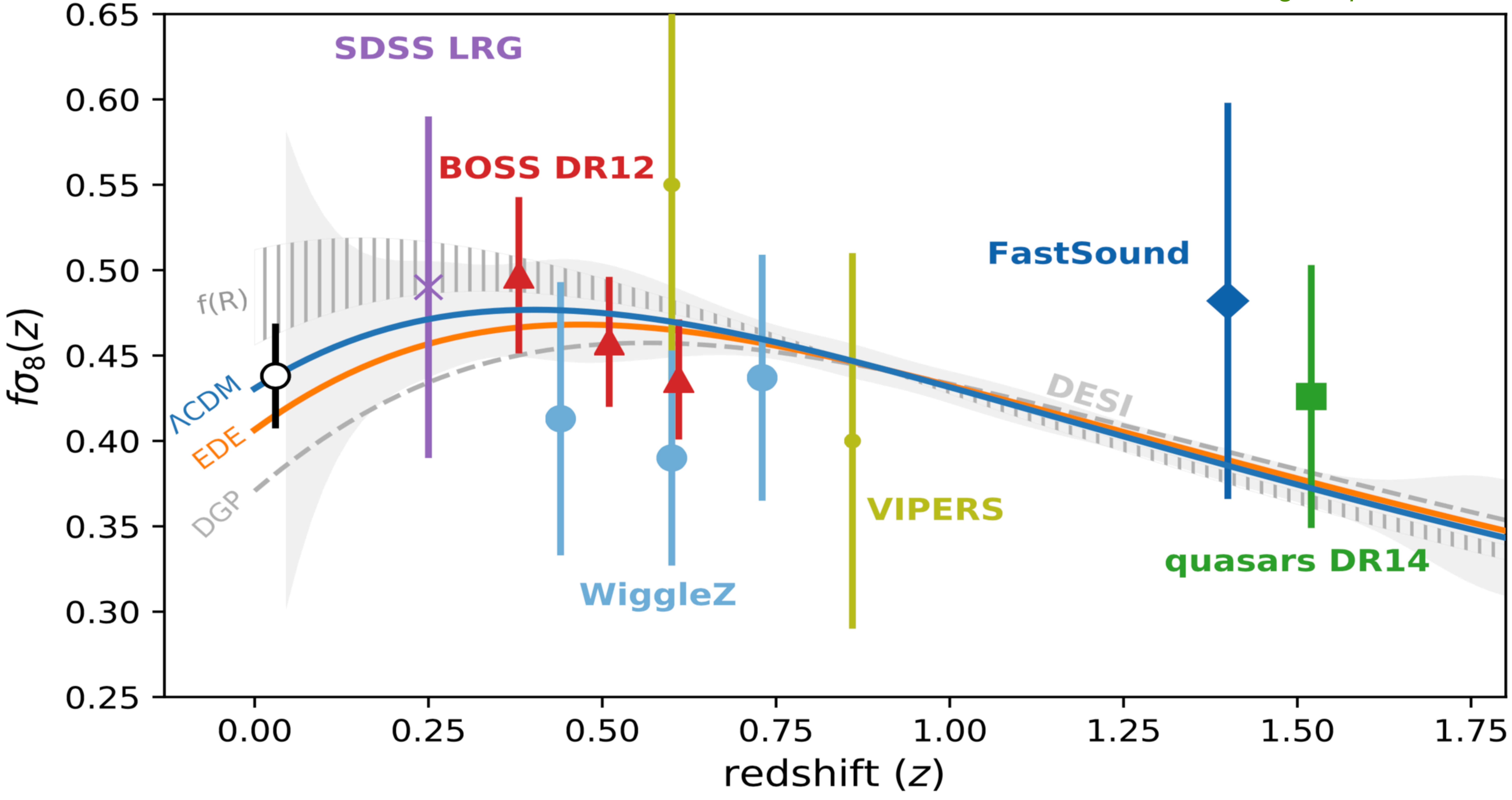


Approach

The HOSTFLOWS project

B- Cosmography of Laniakea

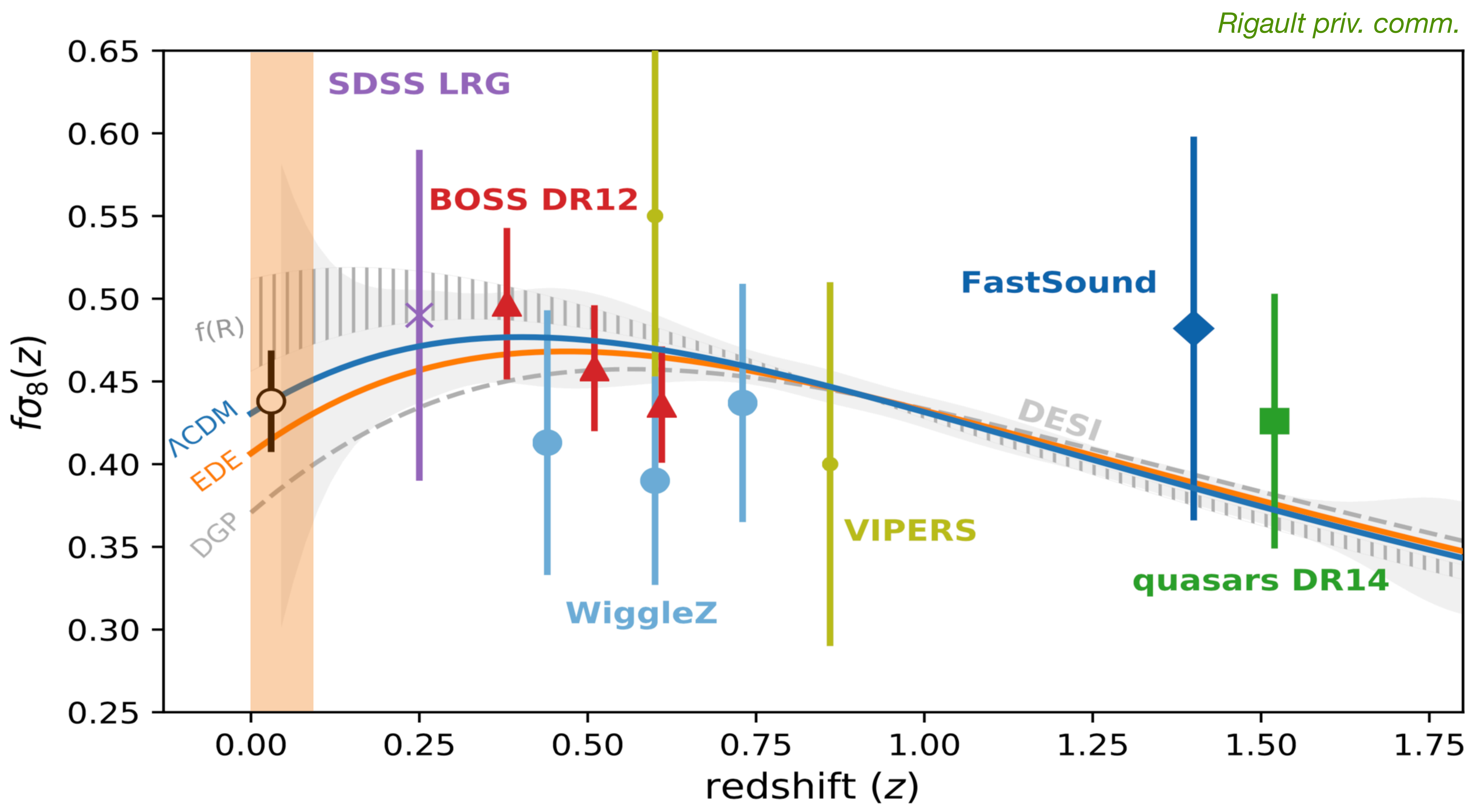
Rigault priv. comm.



Approach

The HOSTFLOWS project

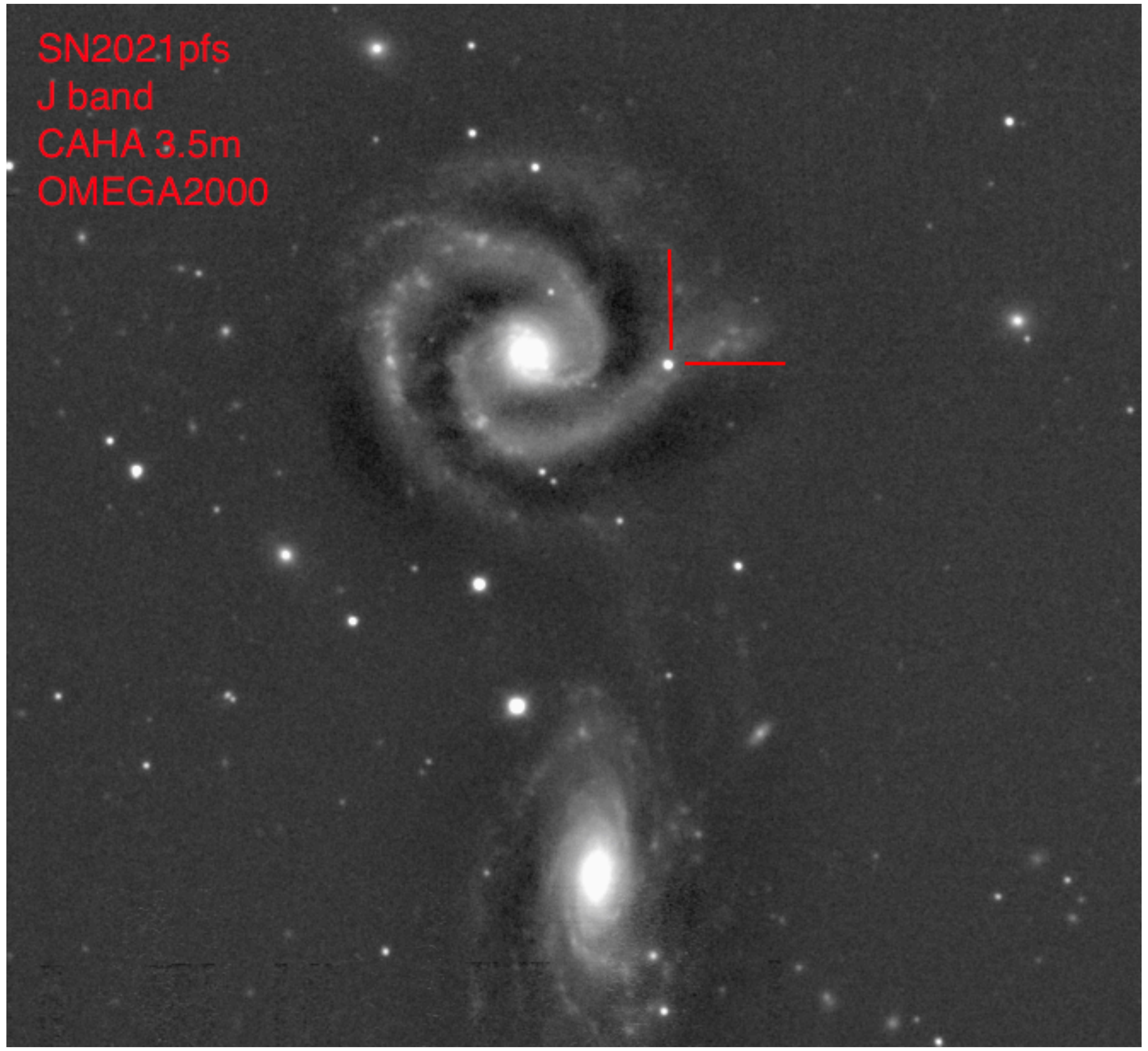
B- Cosmography of Laniakea



(Current) Approach

The HOSTFLOWS project

B- Cosmography of Laniakea



NIR SNIa survey

gr light-curves from ZTF

+ single JH epoch

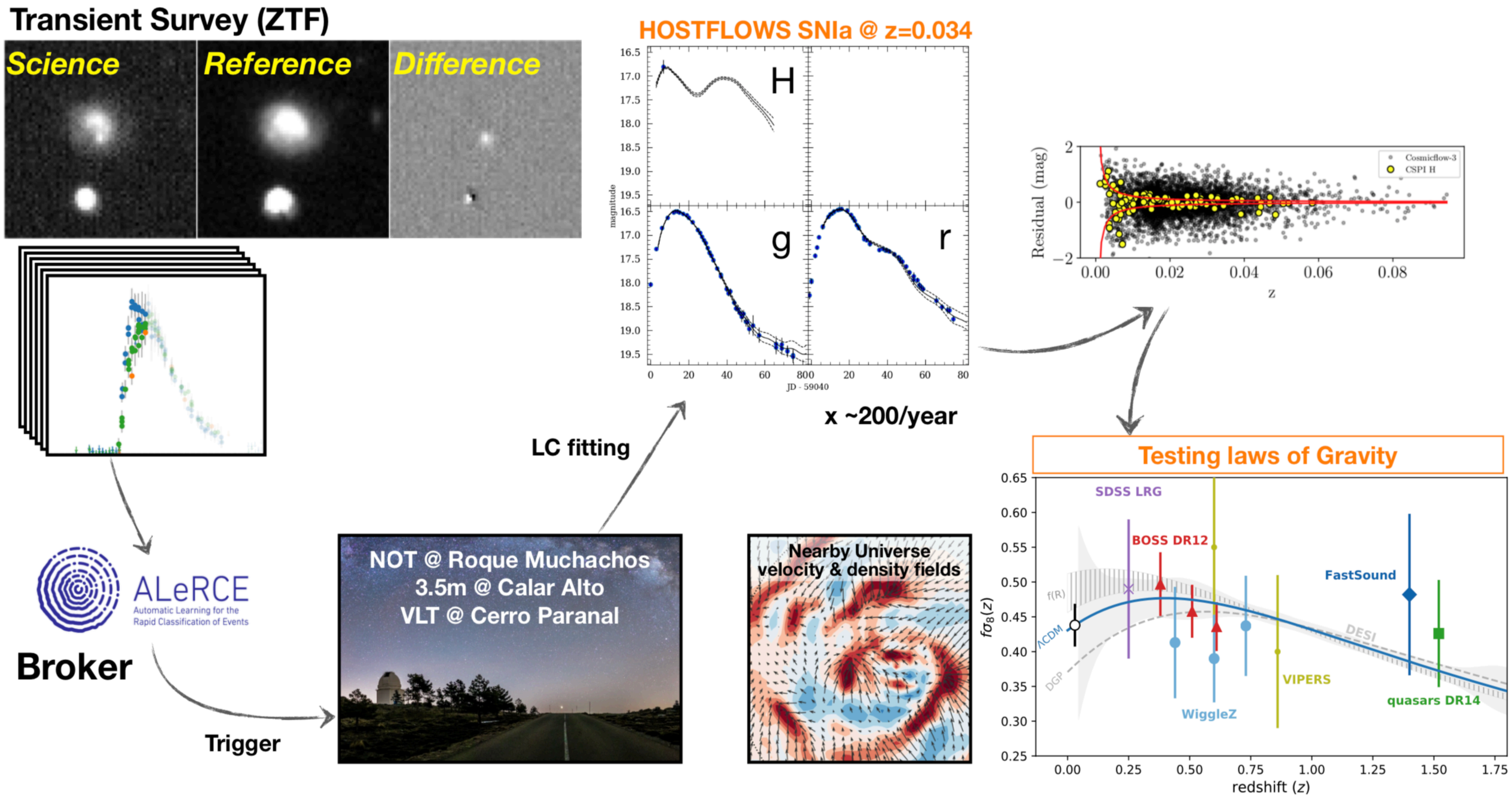
NOT-2.5m NOTCam
CAHA-3.5m Omega2000
NTT-3.5m SOFI
CMO-2.5m NIRCam
VLT-8.1m HAWKI

~400 SNe already observed (*goal 1000)*

Approach

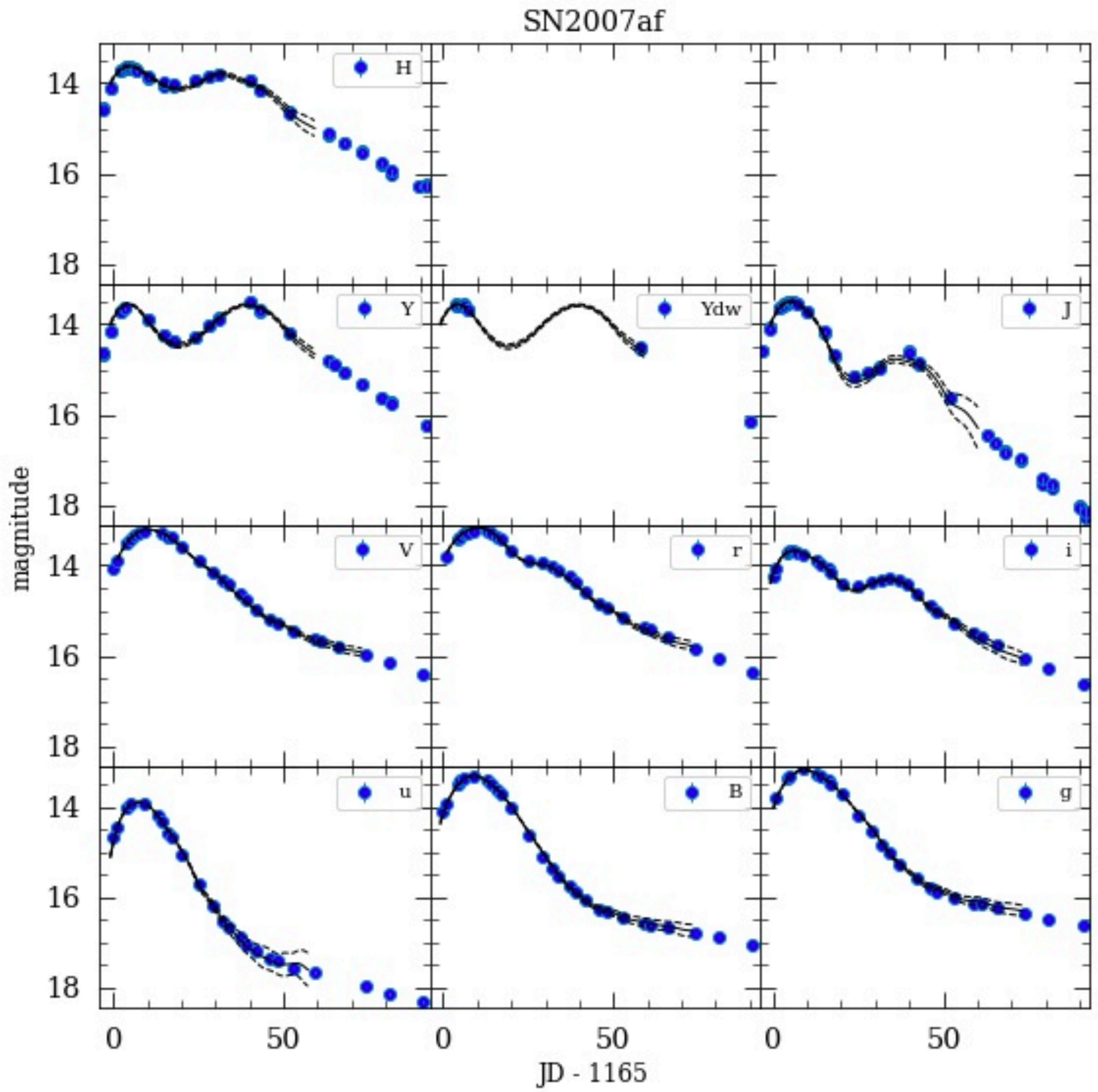
The HOSTFLOWS project

B- Cosmography of Laniakea



FLOWS simulation with CSP

Tomás Müller et al. in prep.



Fit to all bands

FLOWS simulation with CSP

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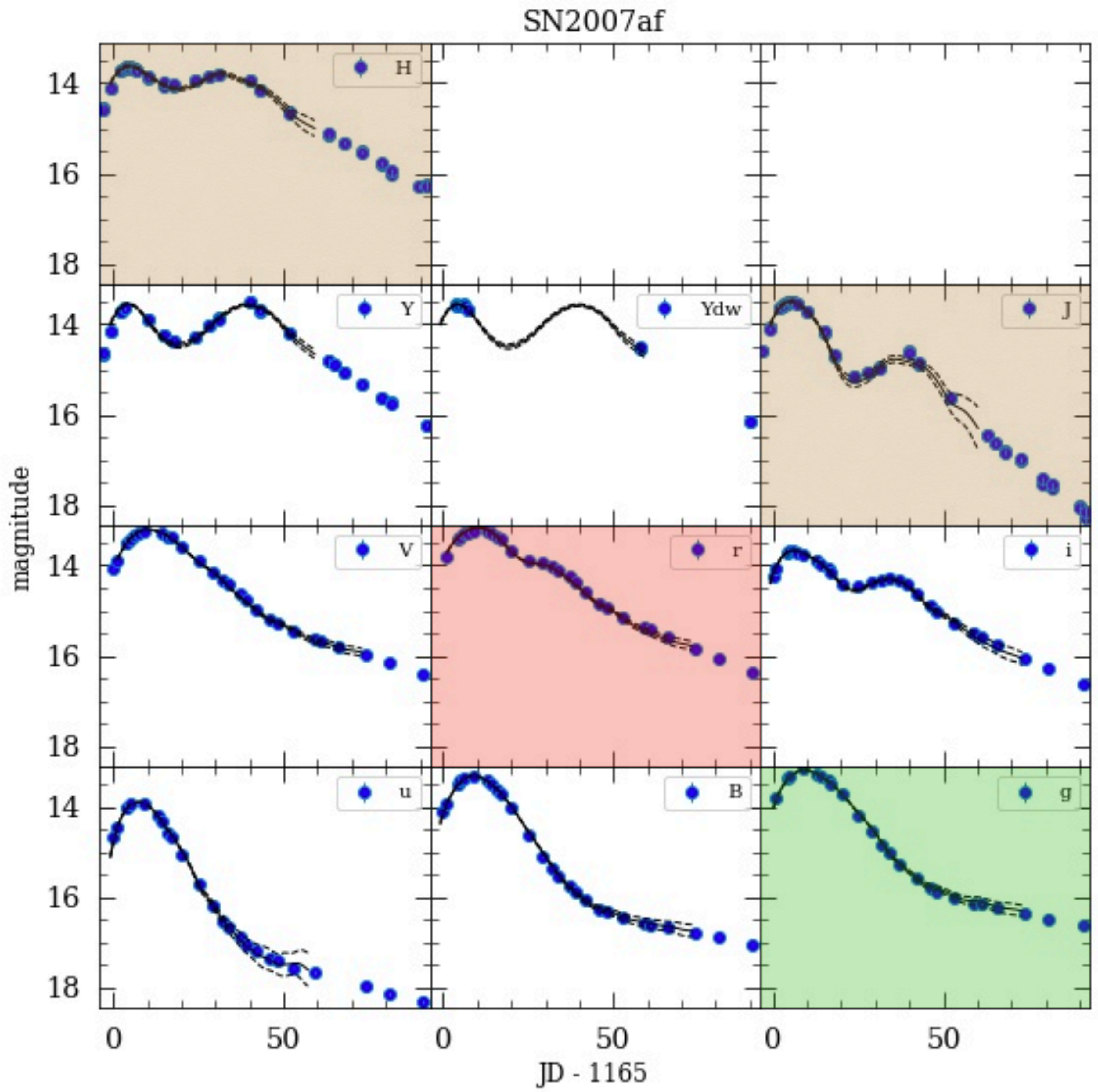

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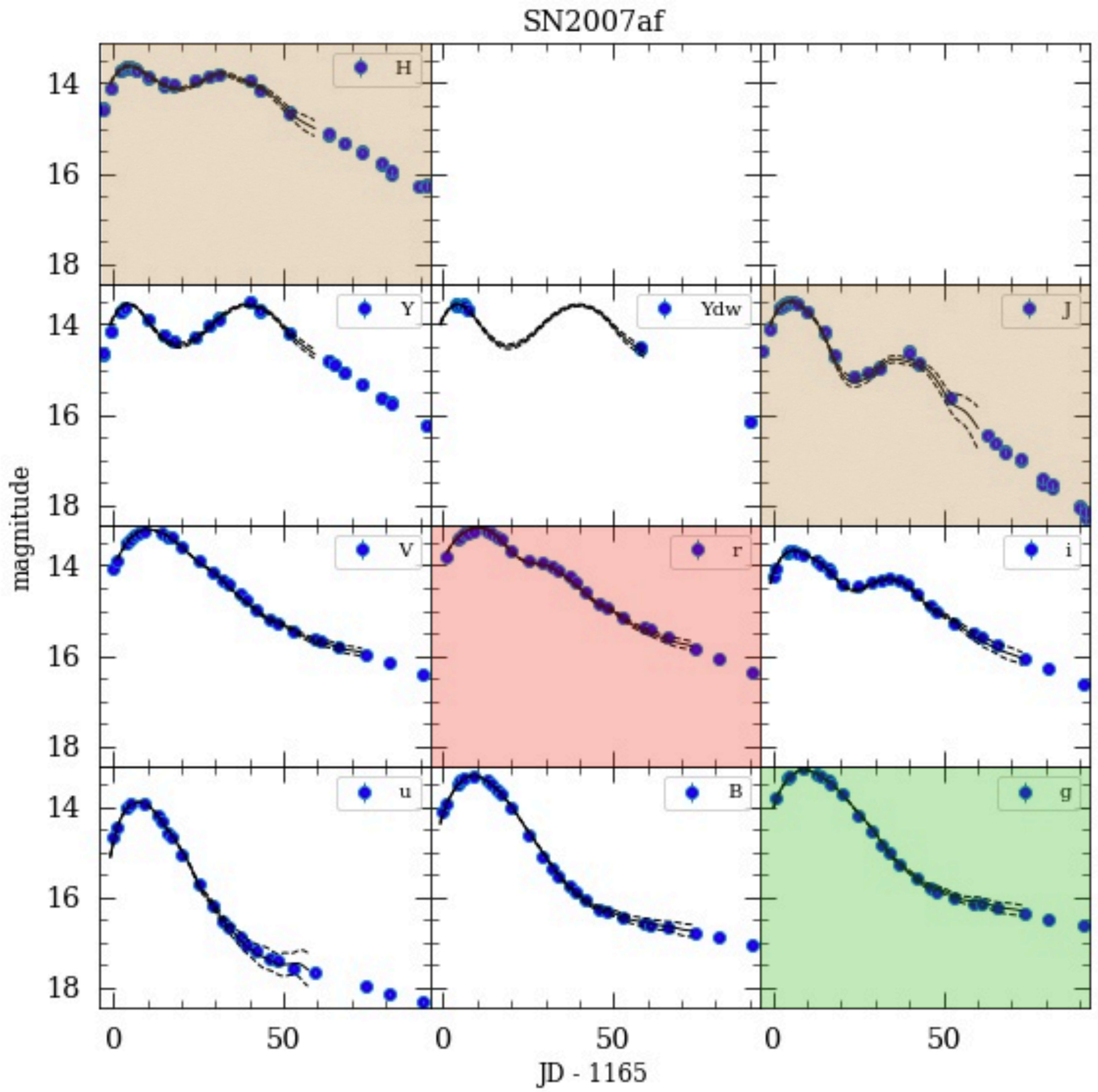
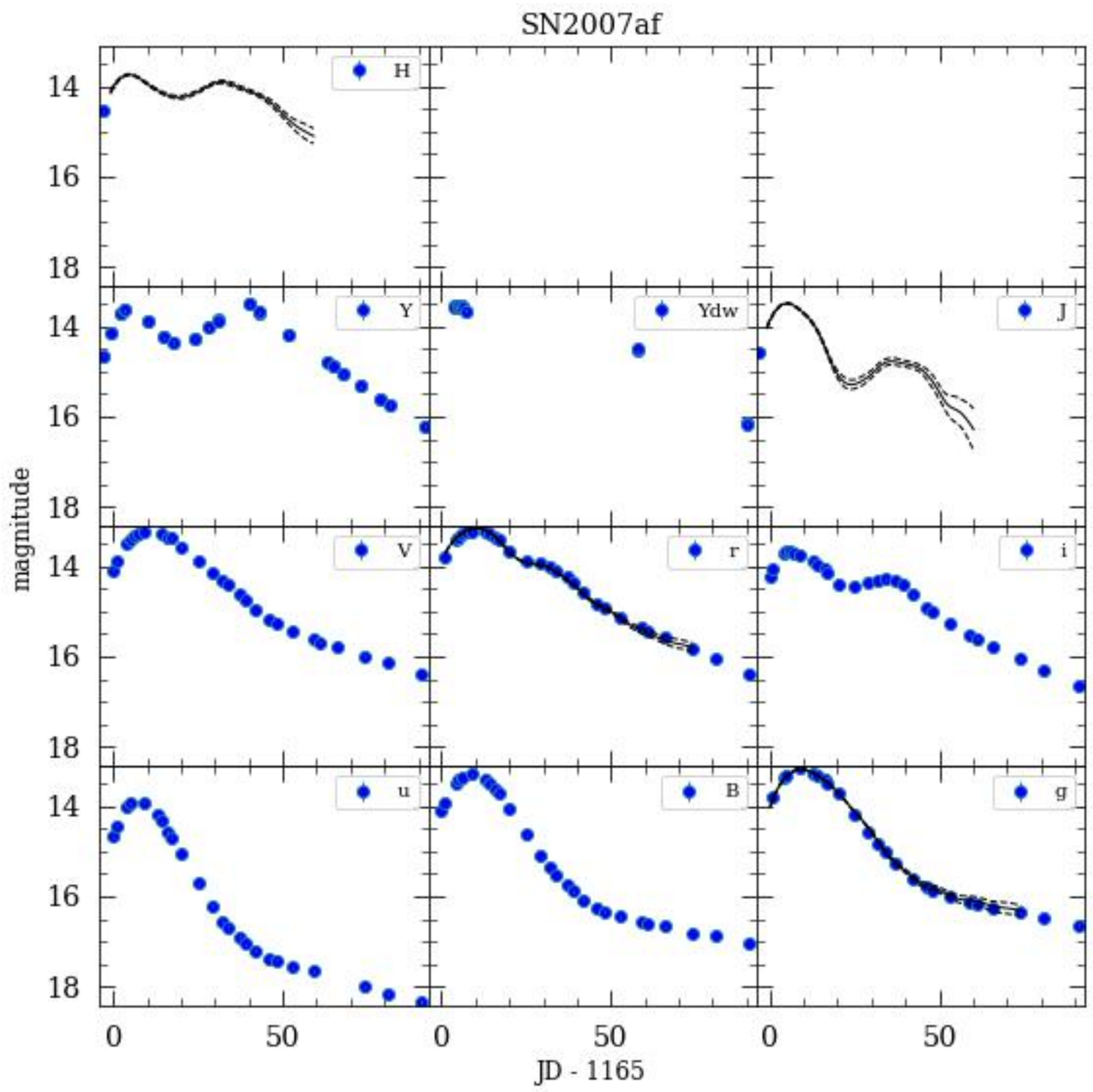


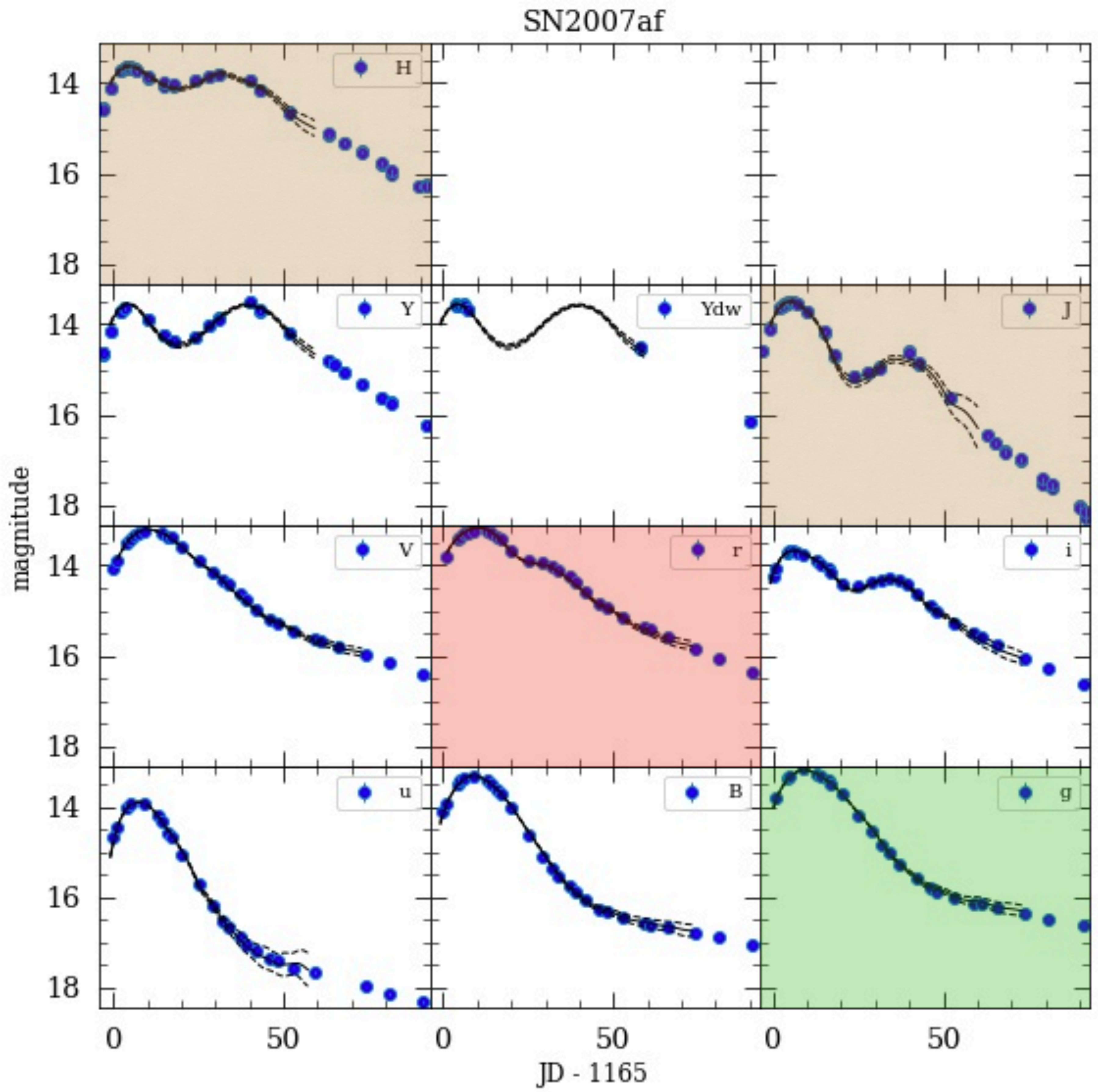
Fit to all bands



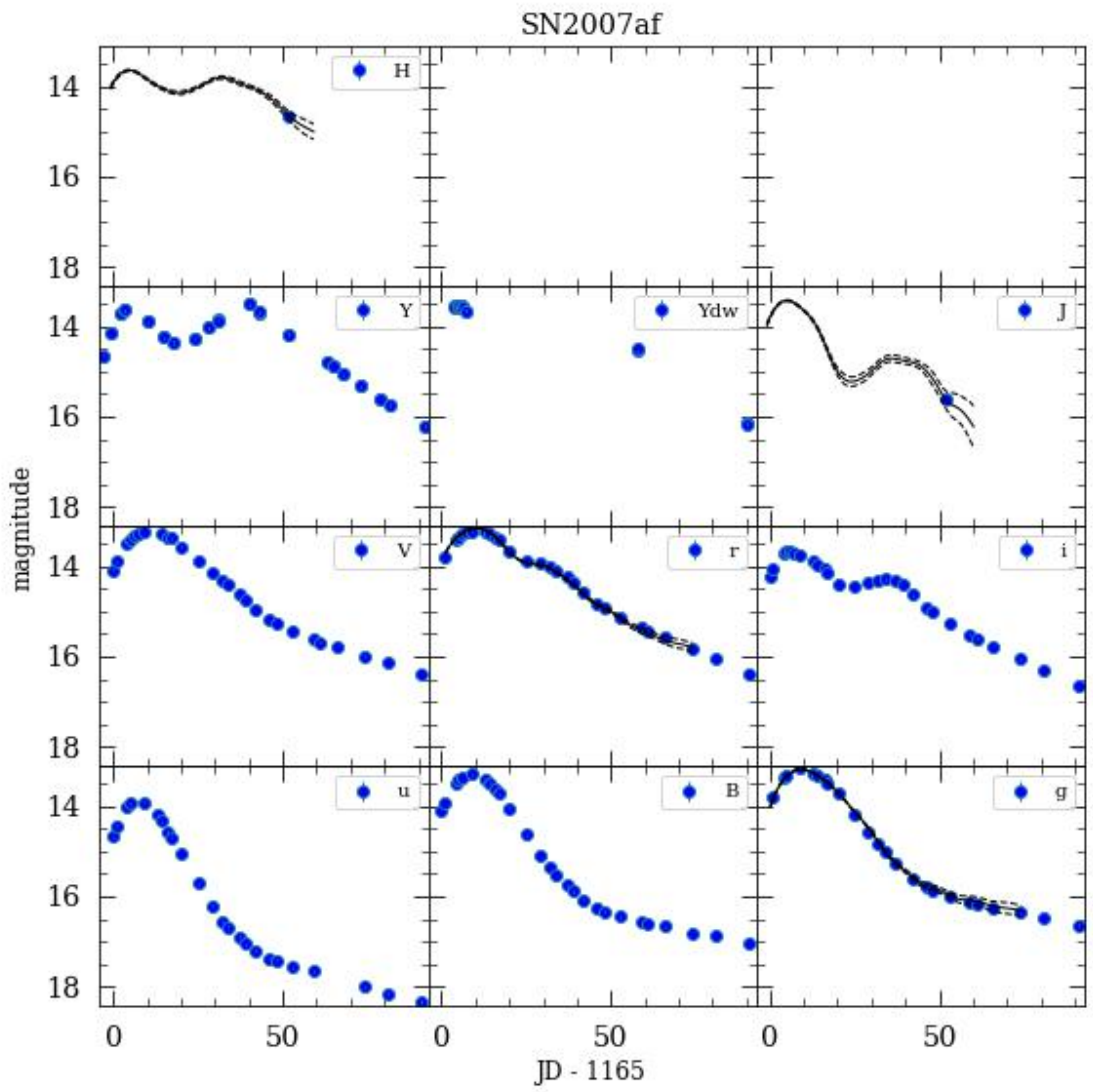
Fit to gr + 1 JH epoch

FLOWS simulation with CSP

Tomás Müller et al. in prep.



Fit to all bands



Fit to gr + 1 JH epoch

FLOWS simulation with CSP

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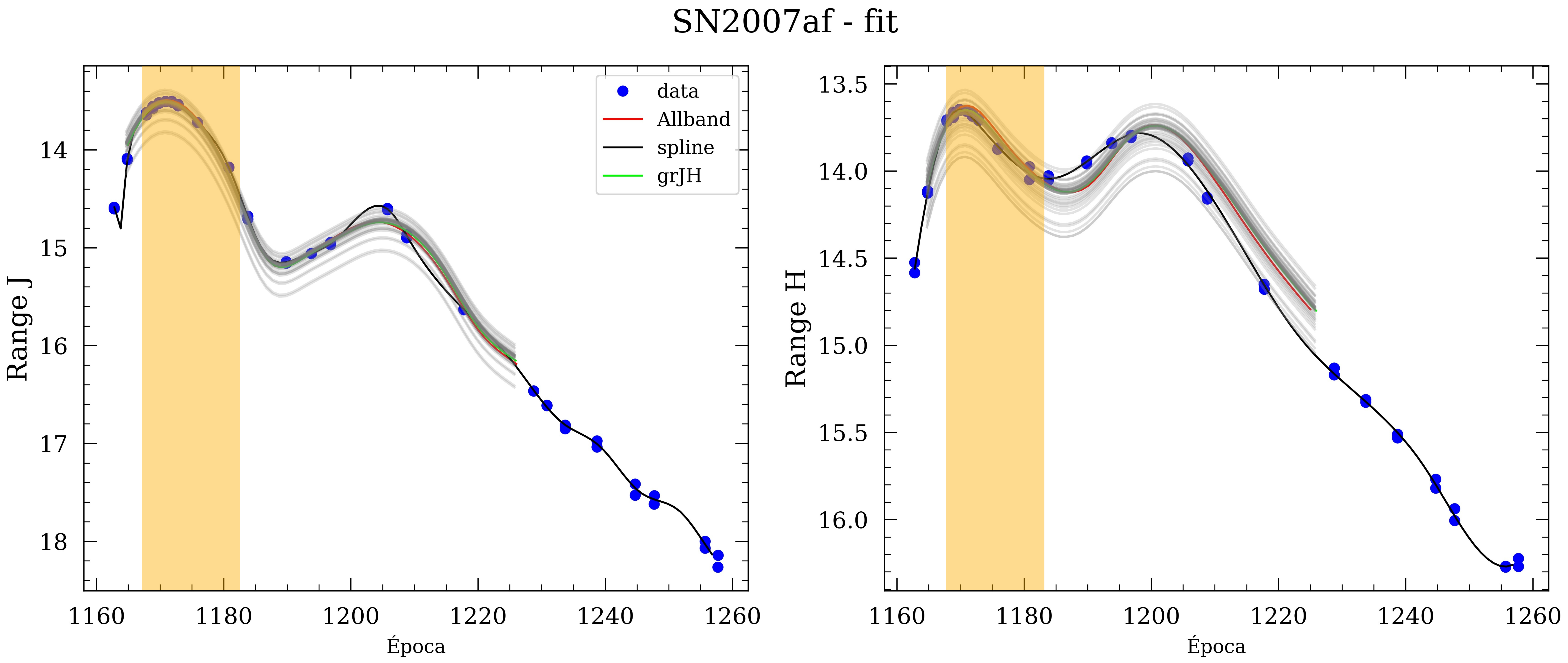
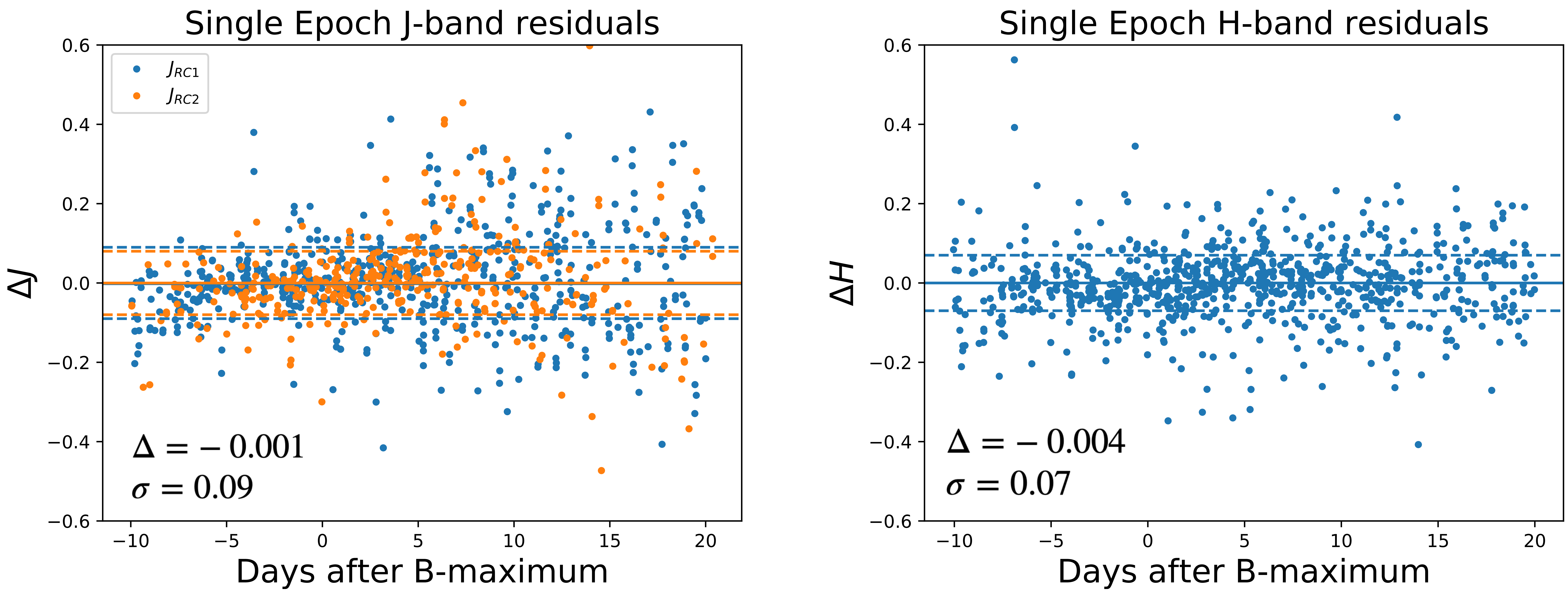
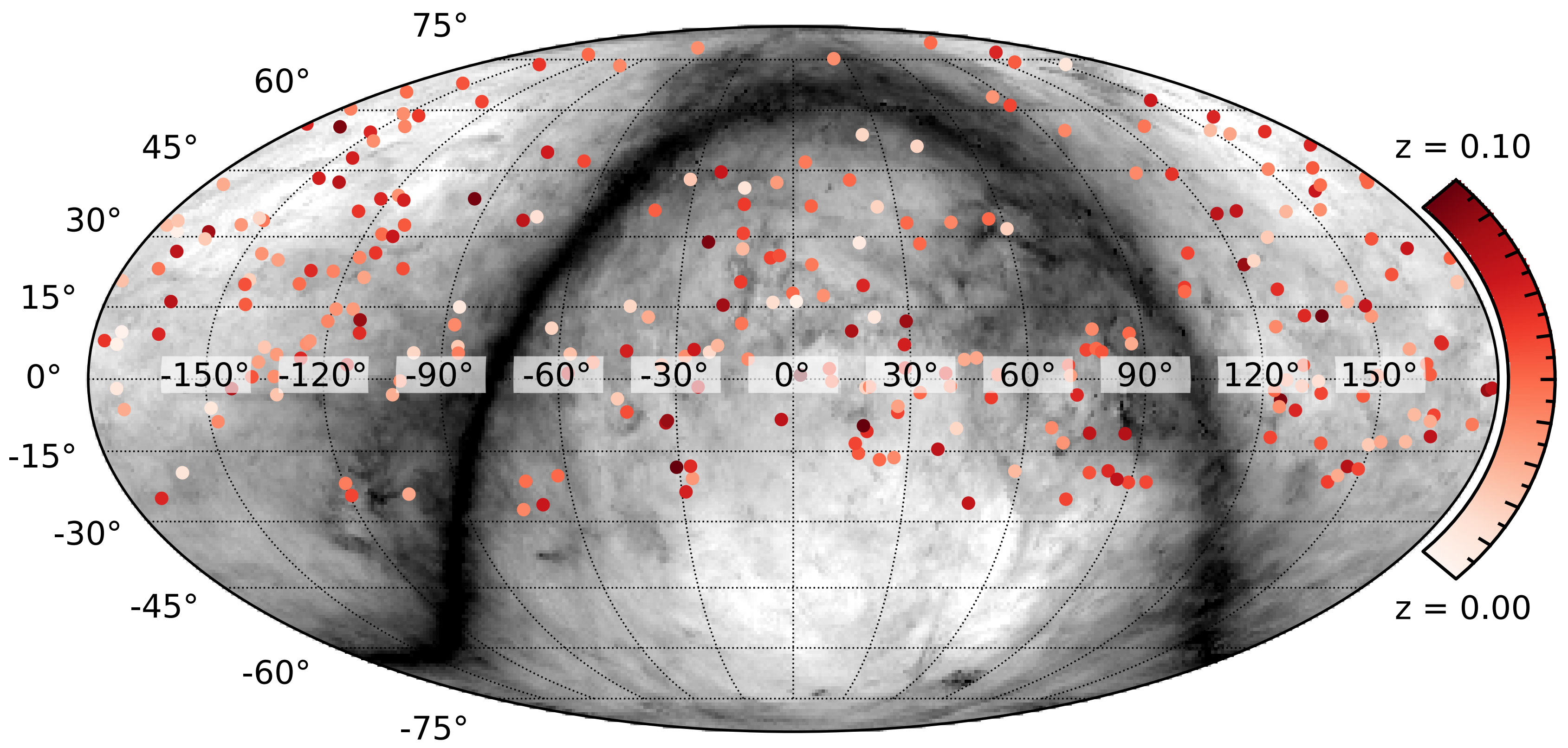


FLOWS simulation with CSP



Pipeline and webpage

Name	ZTF	RA (hours)	Dec	Redshift	Discovery date	Quicklook	Actions
2021acvk	ZTF21acjxsrf	09:12:41.0	+16:07:59.1	0.089	2021-10-22 11:55		Promote Reject
2021abzi	ZTF21acipmgw	08:28:51.7	+12:32:18.2	0.067155	2021-10-22 11:28		Promote Reject
2021acmy	ZTF21acjotbf	10:20:49.6	+51:43:34.9	0.07391	2021-10-22 11:21		Promote Reject
2021accl	ZTF21aciouwz	08:07:07.2	-00:05:42.5	0.055	2021-10-22 10:40		Promote Reject
2021abzu	ZTF21acidhhs	09:59:44.0	+49:19:41.8	0.076916	2021-10-22 10:27		Promote Reject



More than 400 objects already available

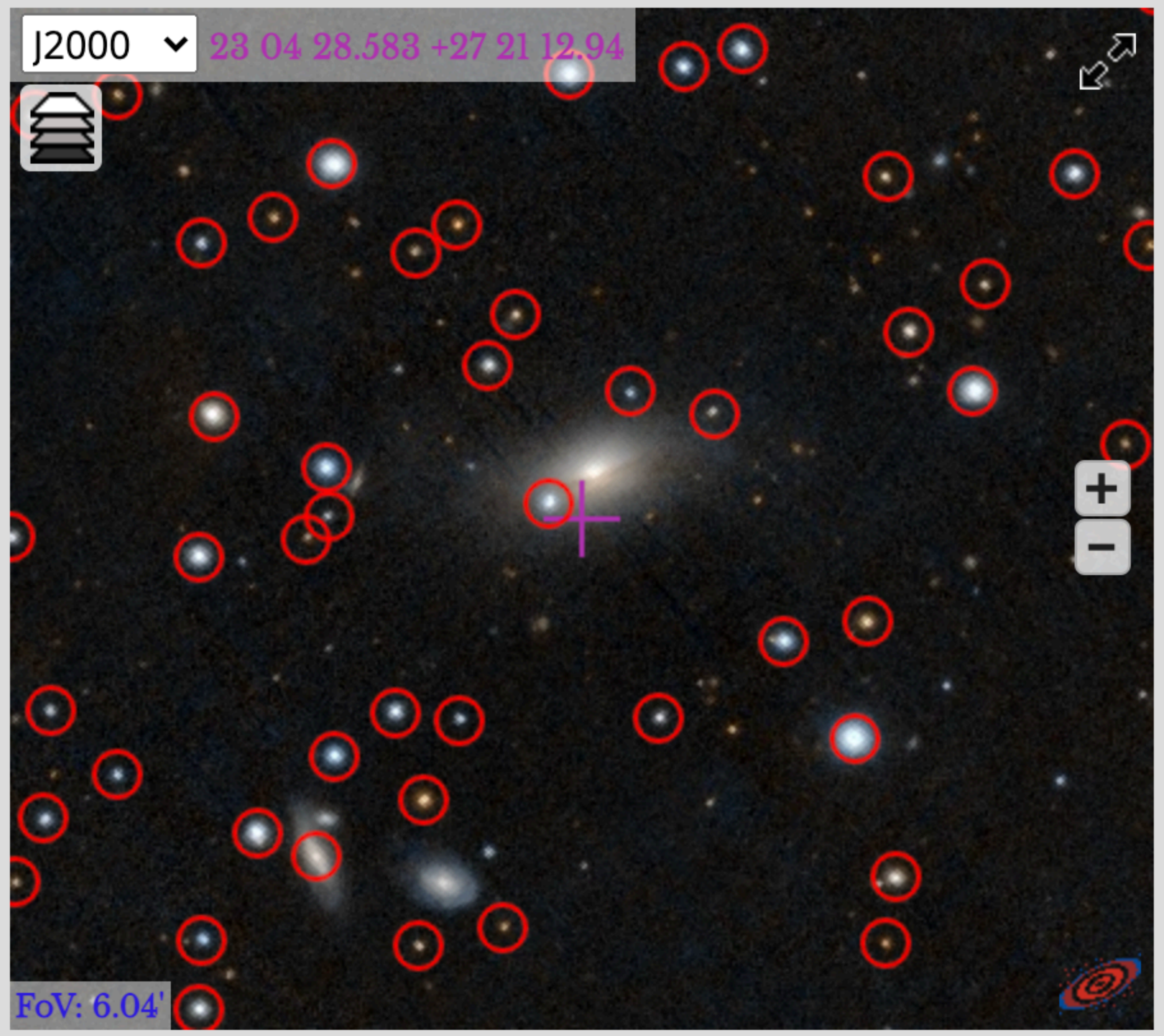
Target Catalog: 2021tmf

Flows | Active | NUTS/CSP | Andicam | ZTF-Ia | Search

Target

Target ID	1261
Discovery magnitude	19.94
Right Ascension	346.11909402 23:04:28.583
Declination	27.35359514 +27:21:12.943
Redshift	0.02566
Discovery	2021-07-16 09:40:12
Inserted	2021-07-23 22:04:28
Host galaxy	
ZTF ID	ZTF21abmjivk

Edit target



Processing

Catalog downloaded?	✔

Reference stars

ID	Distance (″)	Gaia mag	Gaia Bp	Gaia Rp	B	V	u	g	r	i	z	H	J	K
140823461221866436	10.9	14.985	15.306	14.478	15.632	14.964	16.628	15.331	14.97	14.83	14.79	13.597	13.882	13.545
140833461140798125	42.9	18.526	18.895	17.846			19.3119	18.654	18.191	17.948	17.962	16.228	17.248	15.958
140833461057975915	53.9	18.709	19.423	17.758			22.5877	19.769	18.699	18.175	17.878	15.822	16.593	15.892
140843461282490950	56.4	16.81	17.393	16.059	18.531	17.275	19.9475	17.548	16.784	16.441	16.271	14.618	15.141	14.463
140843461256186260	67.5	18.379	19.464	17.315			22.9173	19.892	18.605	17.733	17.309	15.342	15.834	15.075
140803461112563655	68.4	17.707	18.261	16.994			20.4665	18.37	17.656	17.368	17.231	15.696	16.122	15.21

Pipeline and webpage

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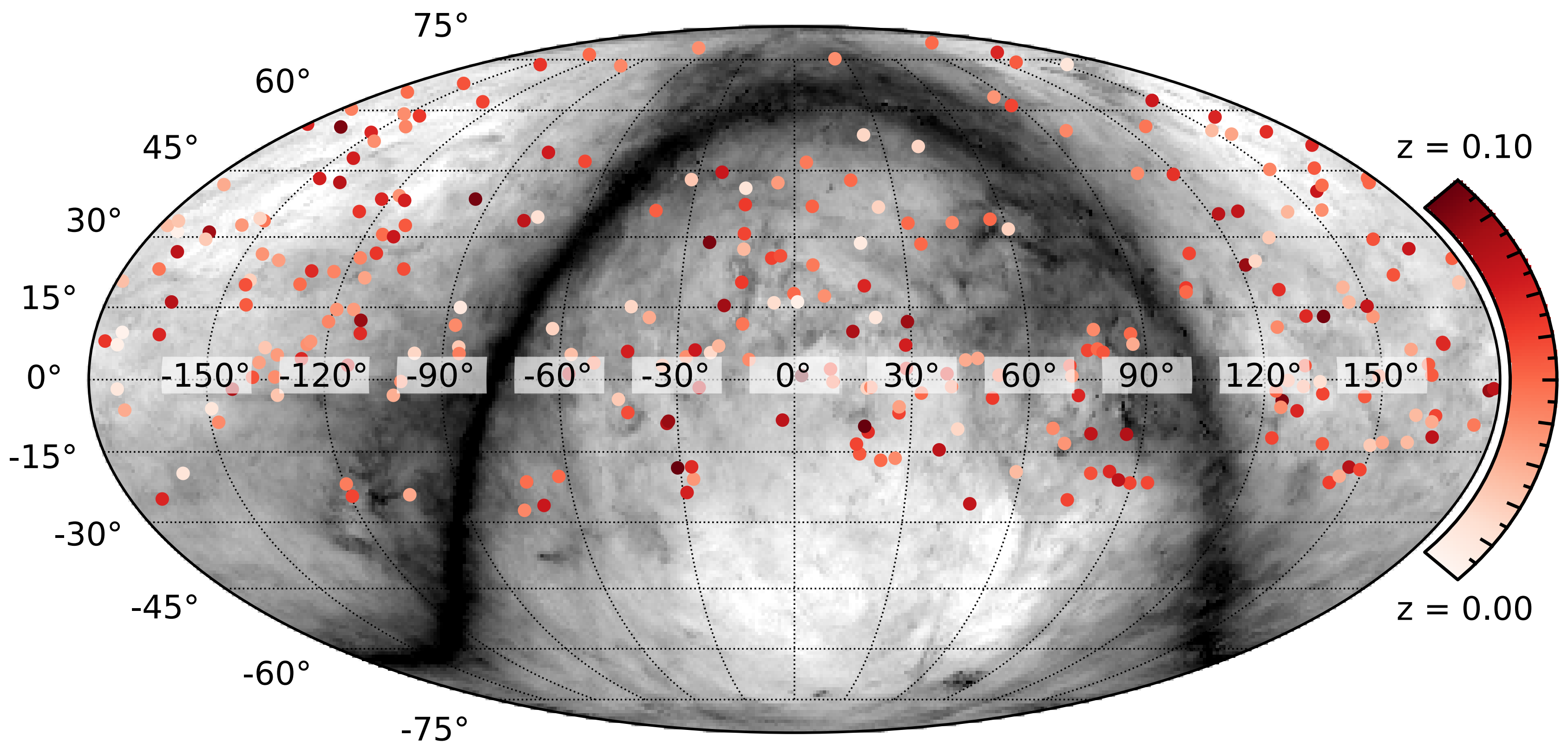
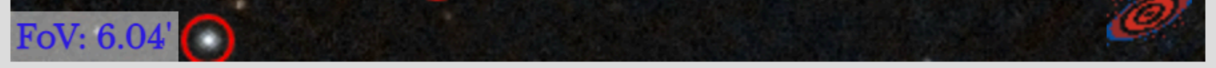


More than 400 objects already available

Catalog downloaded?	✔



Reference stars

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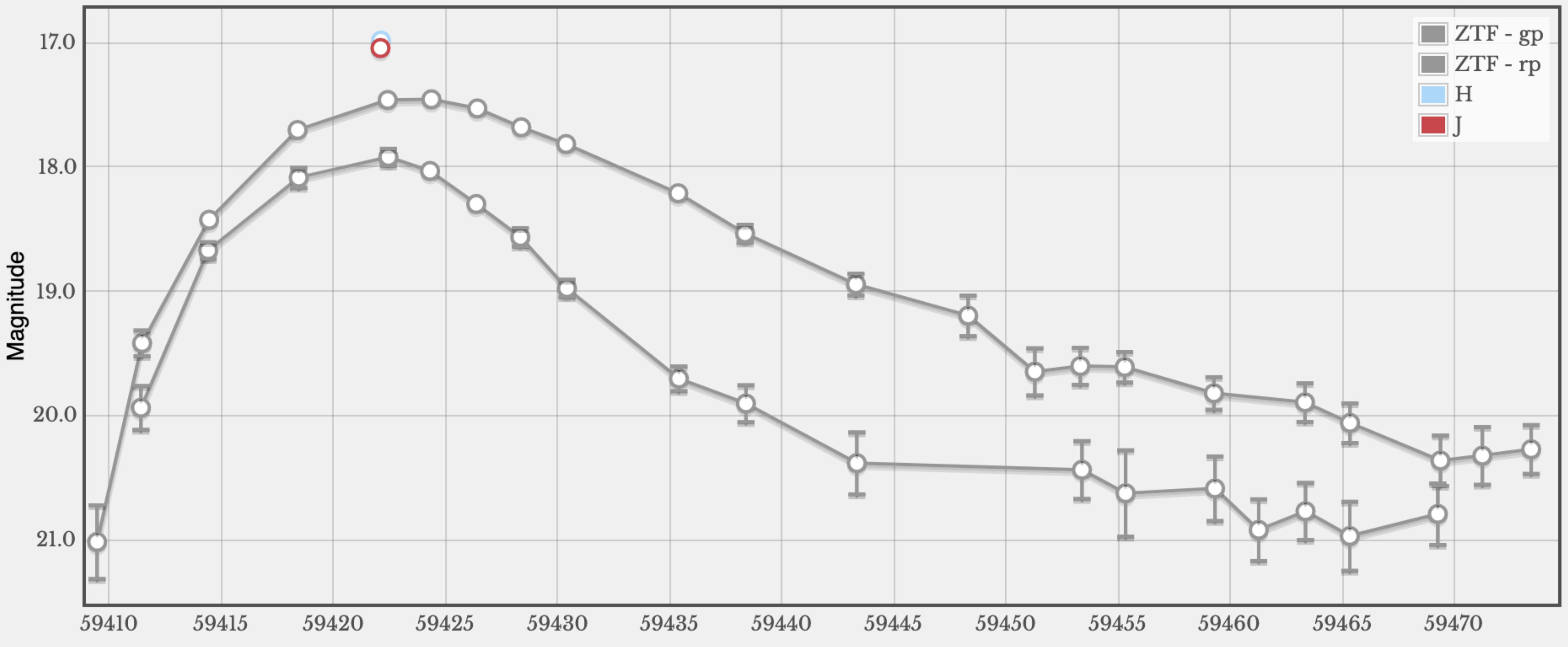
140833461140798125	42.9	18.526	18.895	17.846			19.3119	18.654	18.191	17.948	17.962	16.228	17.248	15.958
140833461057975915	53.9	18.709	19.423	17.758			22.5877	19.769	18.699	18.175	17.878	15.822	16.593	15.892
140843461282490950	56.4	16.81	17.393	16.059	18.531	17.275	19.9475	17.548	16.784	16.441	16.271	14.618	15.141	14.463
140843461256186260	67.5	18.379	19.464	17.315			22.9173	19.892	18.605	17.733	17.309	15.342	15.834	15.075
140803461112563655	68.4	17.707	18.261	16.994			20.4665	18.37	17.656	17.368	17.231	15.696	16.122	15.21
140803461311553442	75.0	18.264	18.683	17.664			20.5347	18.743	18.22	18.031	17.956	16.081	16.814	15.985
140813460990301697	75.4	15.635	15.975	15.118	16.501	15.786	17.2664	16.013	15.621	15.473	15.418	14.154	14.52	14.091
140823461441634955	80.2	18.579	19.158	17.829			21.0792	19.286	18.545	18.202	18.037	16.305	16.725	17.147
140833461442670061	82.0	15.453	15.731	15.016	16.164	15.617	16.9519	15.73	15.443	15.374	15.359	14.272	14.564	14.196

Observations

Raw: ☑ ZTF - gp ☑ ZTF - rp ☑ H ☑ J

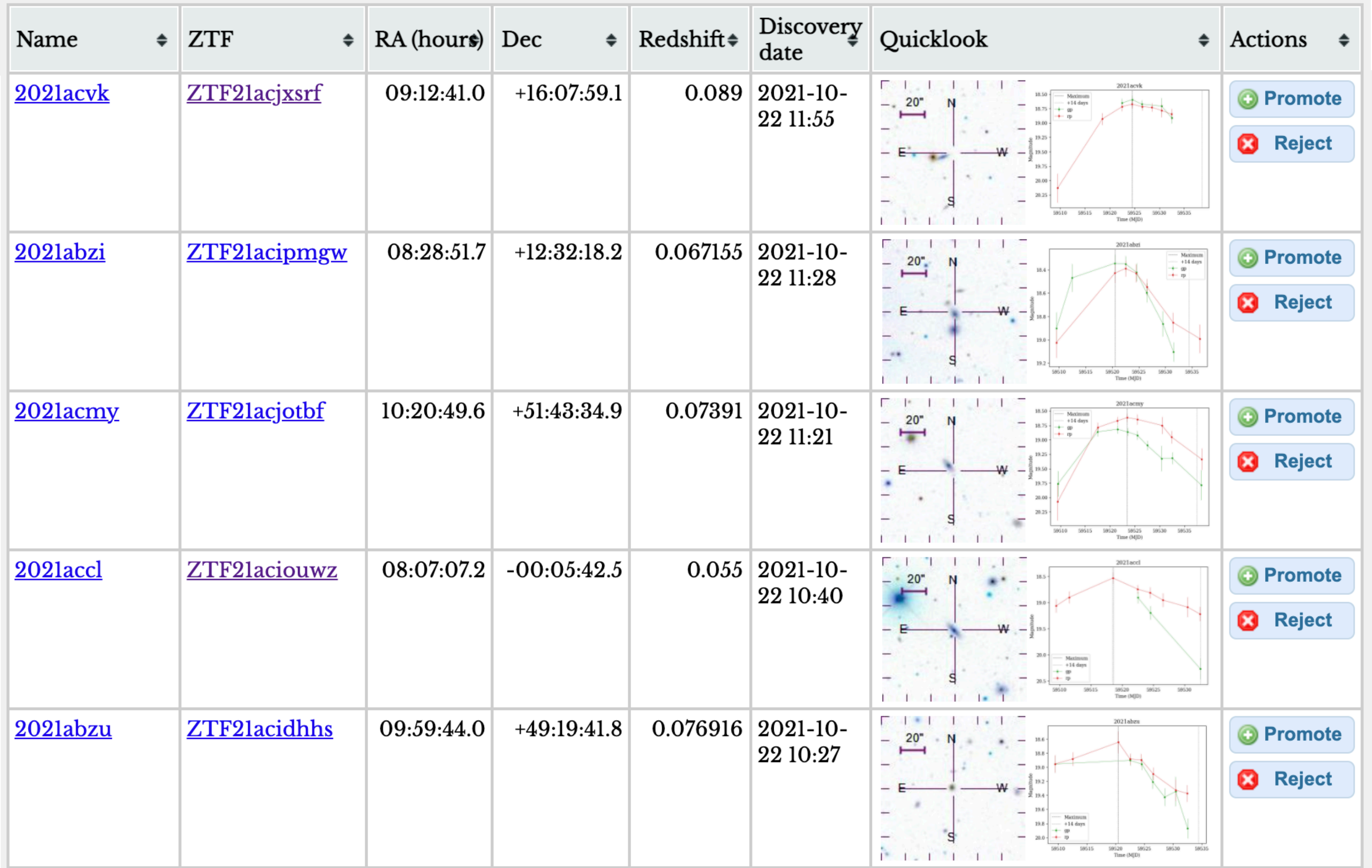
Subtracted:



Download lightcurve | Download ZTF lightcurve

ID	File name	Site	Obs. time	Filter	Image	Sub.	Photometry
10699	SN2021tmf_J_20210726	Calar Alto, 3.5m	59422.08484	J			Done
10700	SN2021tmf_H_20210726	Calar Alto, 3.5m	59422.10695	H			Done

Pipeline and webpage



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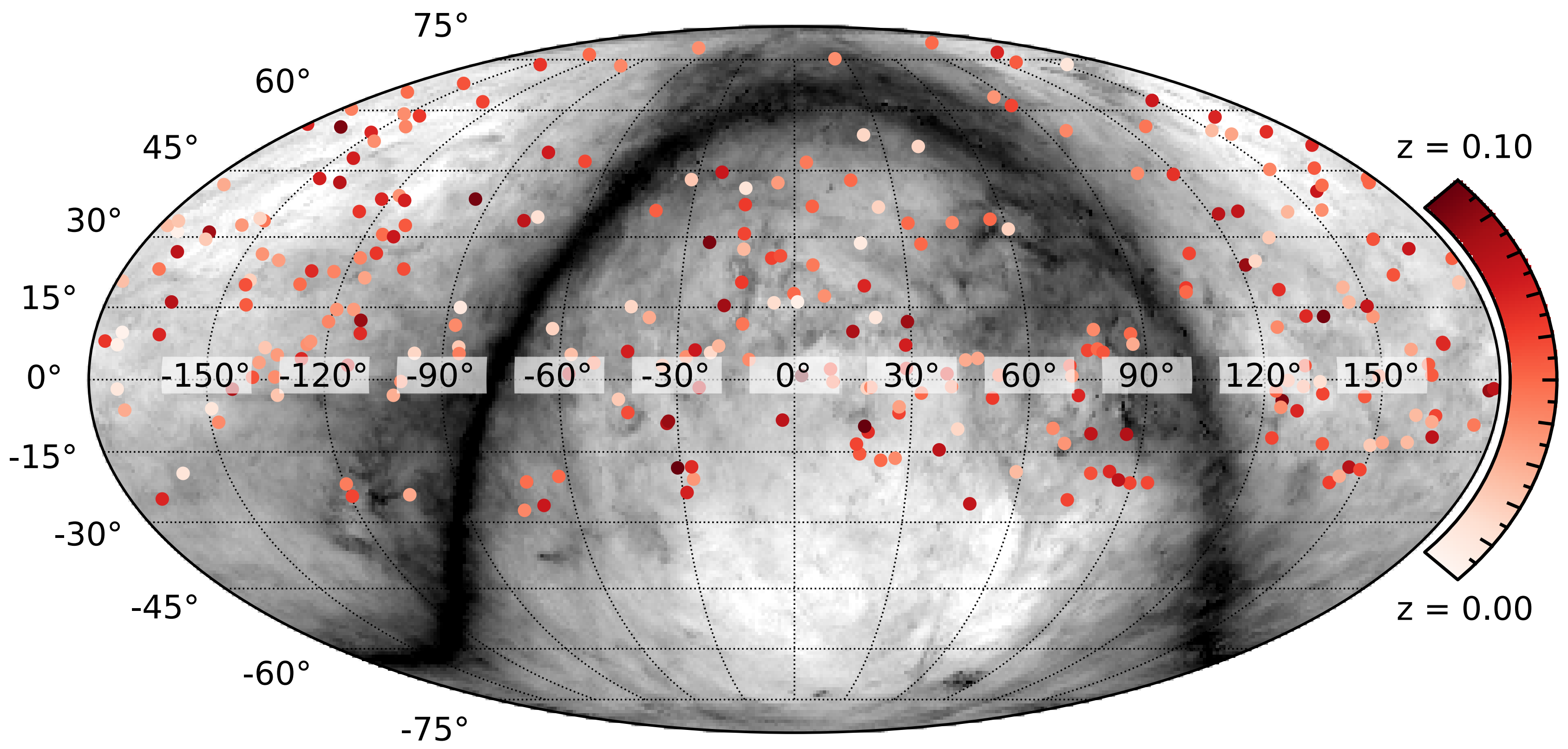

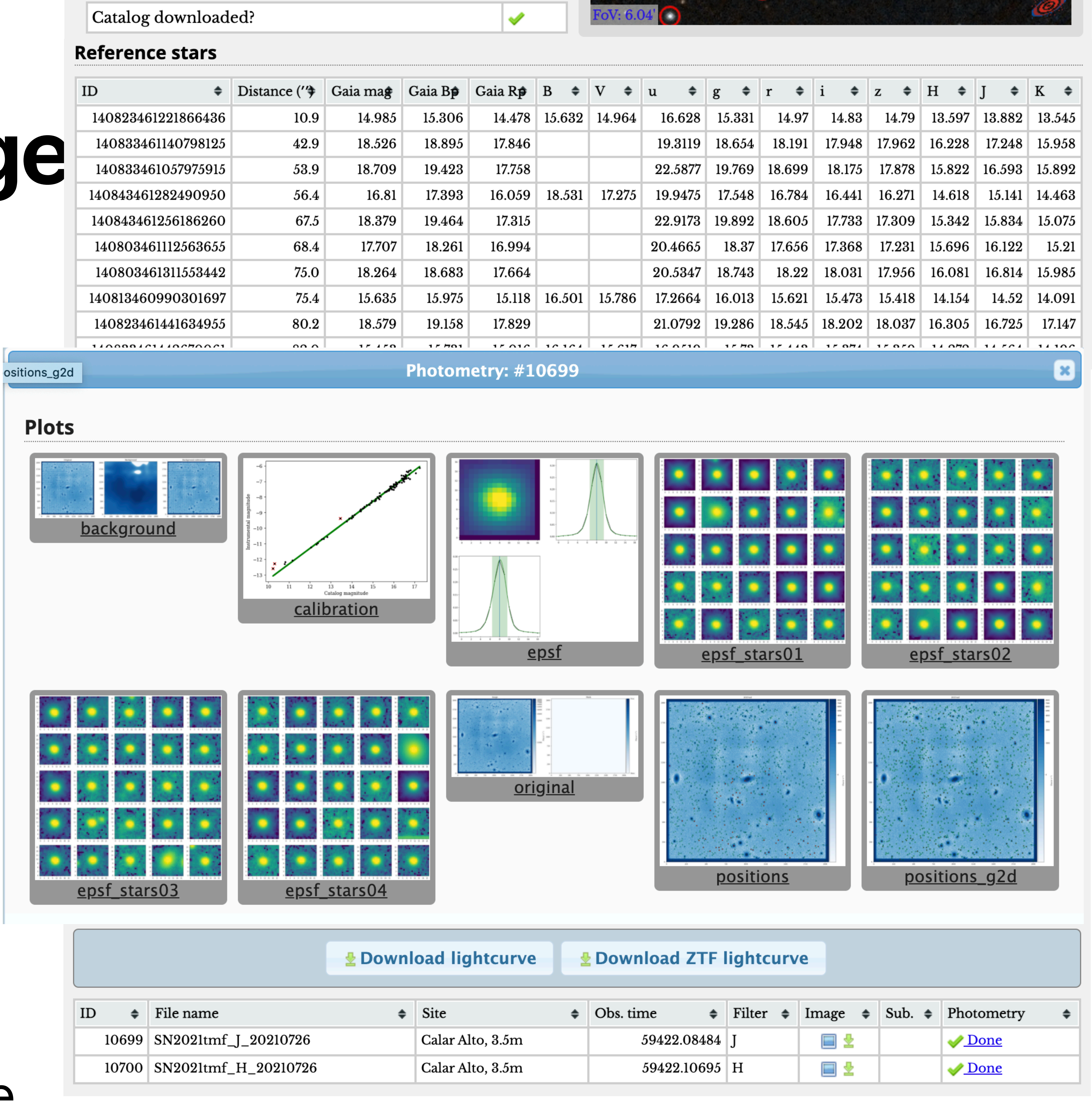

Catalog downloaded?

FoV: 6.04'

Reference stars

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140823461221866436	10.9	14.985	15.306	14.478	15.632	14.964	16.628	15.331	14.97	14.83	14.79	13.597	13.882	13.545
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ositions_g2d

Photometry: #10699

Plots

background

calibration

epsf

epsf_stars01

epsf_stars02

epsf_stars03

epsf_stars04

original

positions

positions_g2d

Download lightcurve

Download ZTF lightcurve

ID	File name	Site	Obs. time	Filter	Image	Sub.	Photometry
10699	SN2021tmf_J_20210726	Calar Alto, 3.5m	59422.08484	J			Done
10700	SN2021tmf_H_20210726	Calar Alto, 3.5m	59422.10695	H			Done

More than 400 objects already available

Summary and conclusions

- Tension in H0 could be due to either new physics or systematics (Early/Late)
- SNIa and Cepheid calibrations can be improved with current data (IFS/pol) and current (and new) methods
- CRISP studied the extinction towards SNe Ia from different approaches
- HOSTFLOWS aims to continue this effort, extend to Cepheids, and focus on determining H0 with improved standardisation
- In addition, a new survey of SNIa in the NIR will map the DM. In the local supercluster and provide an independent estimation of H0 and σ_8

Outreach

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Musician

joangarriga.cat

Esteve Plantada

Poet

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Thanks for your attention