Observations of White Dwarf Supernovae

Saurabh W. Jha

NOAO 4m image of SN 2011fe in M101 (T.A. Rector, H. Schweiker & S. Pakzad)

SN 2014J in M82 (Marco Burali, Osservatorio MTM Pistoia)

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Observational properties of thermonuclear supernovae

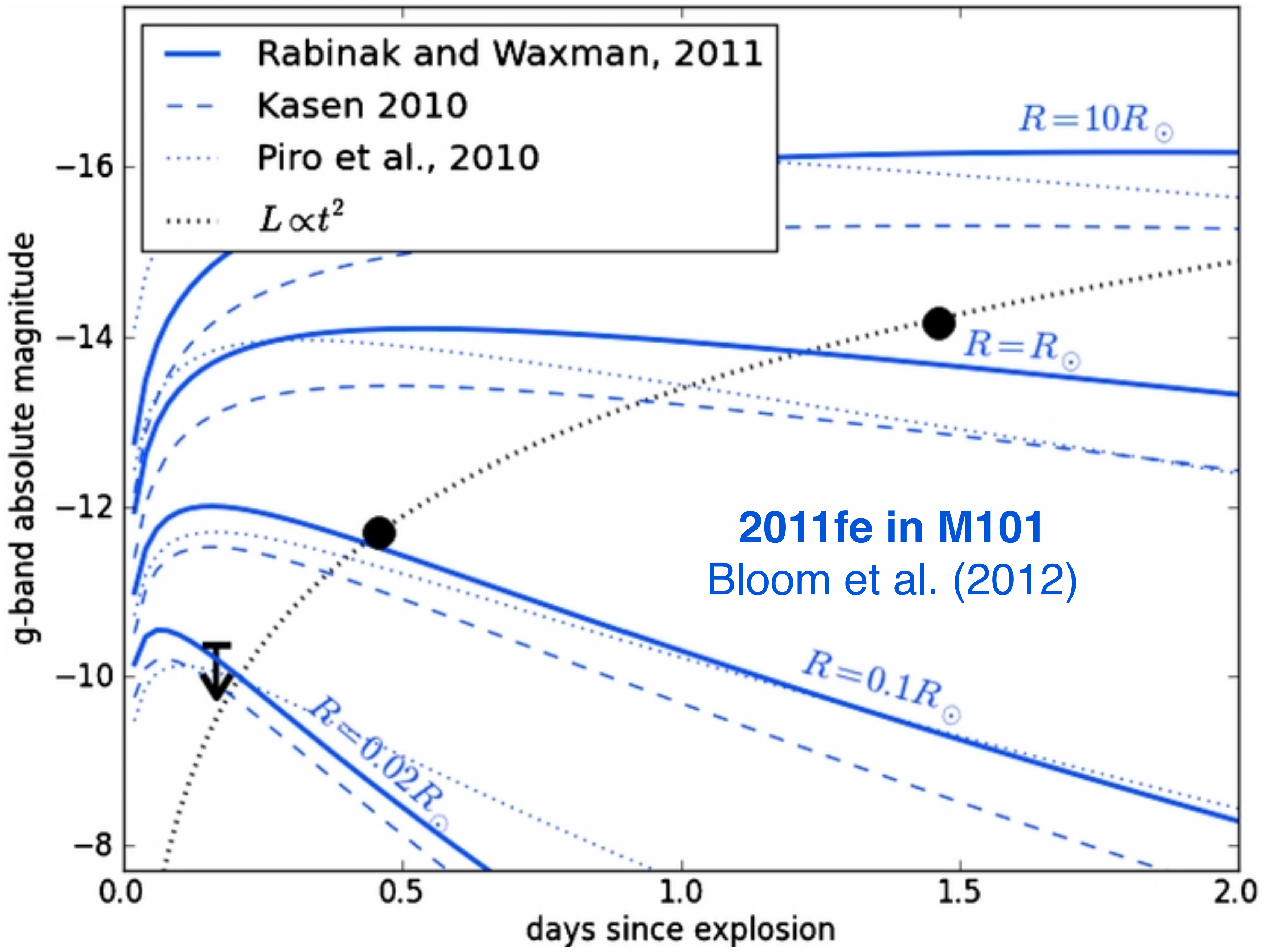
Saurabh W. Jha[1,2]*, Kate Maguire[3,4] and Mark Sullivan[5]

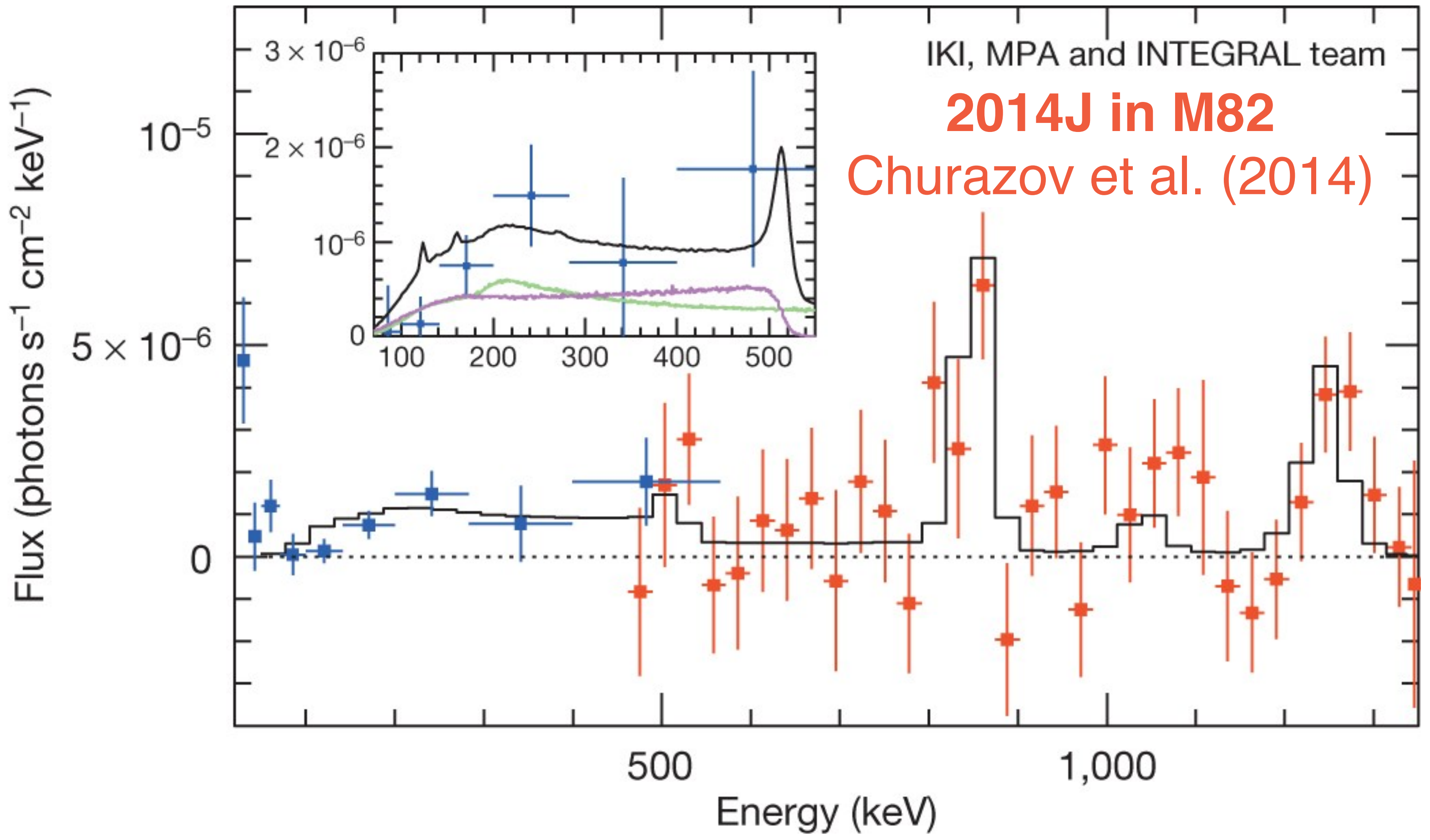
The explosive death of a star as a supernova is one of the most dramatic events in the Universe. Supernovae have an outsized impact on many areas of astrophysics: they are major contributors to the chemical enrichment of the cosmos and significantly influence the formation of subsequent generations of stars and the evolution of galaxies. Here we review the observational properties of thermonuclear supernovae—exploding white dwarf stars resulting from the stellar evolution of low-mass stars in close binary systems. The best known objects in this class are type-Ia supernovae (SNe Ia), astrophysically important in their application as standardizable candles to measure cosmological distances and the primary source of iron group elements in the Universe. Surprisingly, given their prominent role, SN Ia progenitor systems and explosion mechanisms are not fully understood; the observations we describe here provide constraints on models, not always in consistent ways. Recent advances in supernova discovery and follow-up have shown that the class of thermonuclear supernovae includes more than just SNe Ia, and we characterize that diversity in this review.

https://arxiv.org/abs/1908.02303

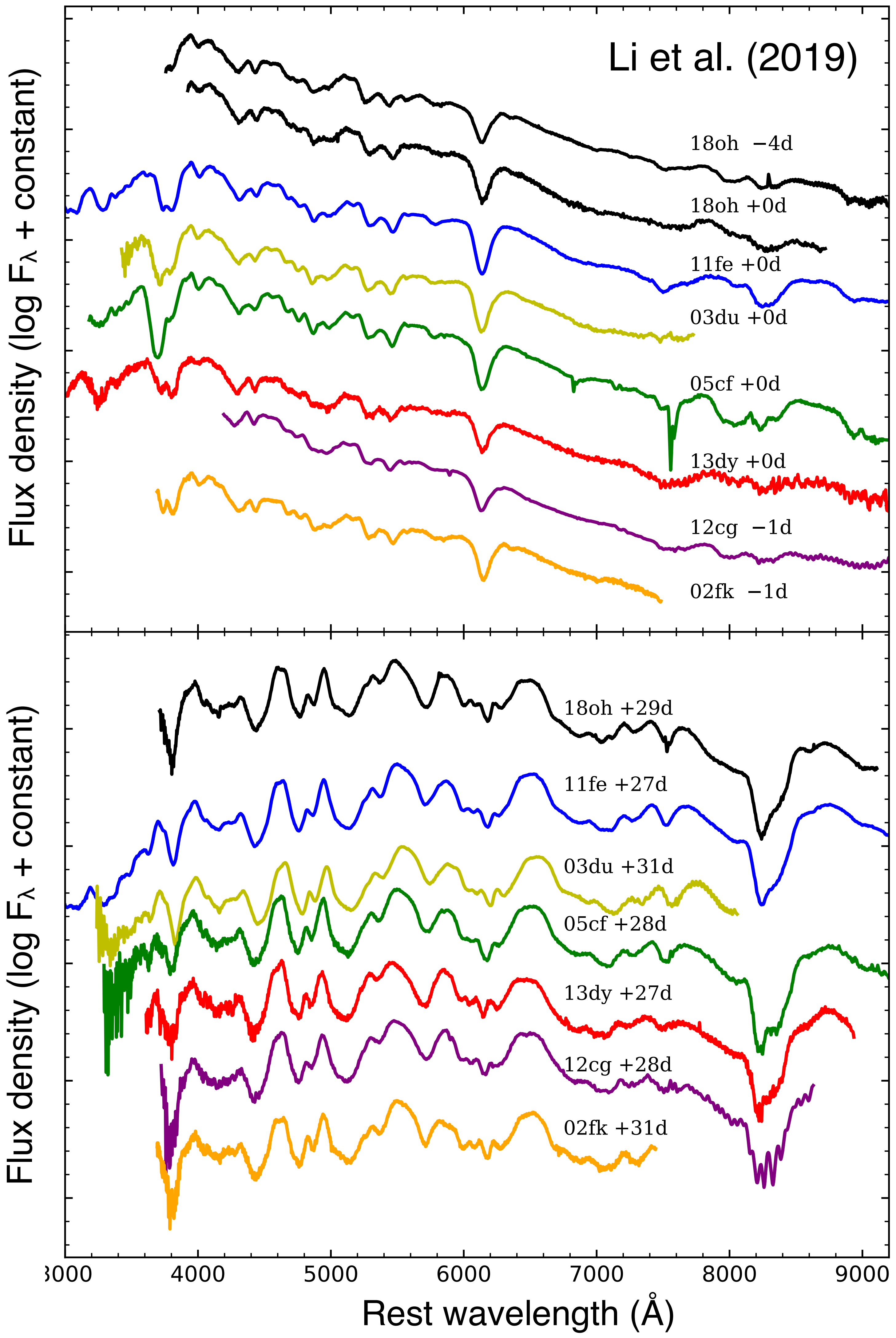
white dwarf/thermonuclear supernovae

limited *direct* evidence
for exploding white dwarfs





significant ***indirect*** evidence:

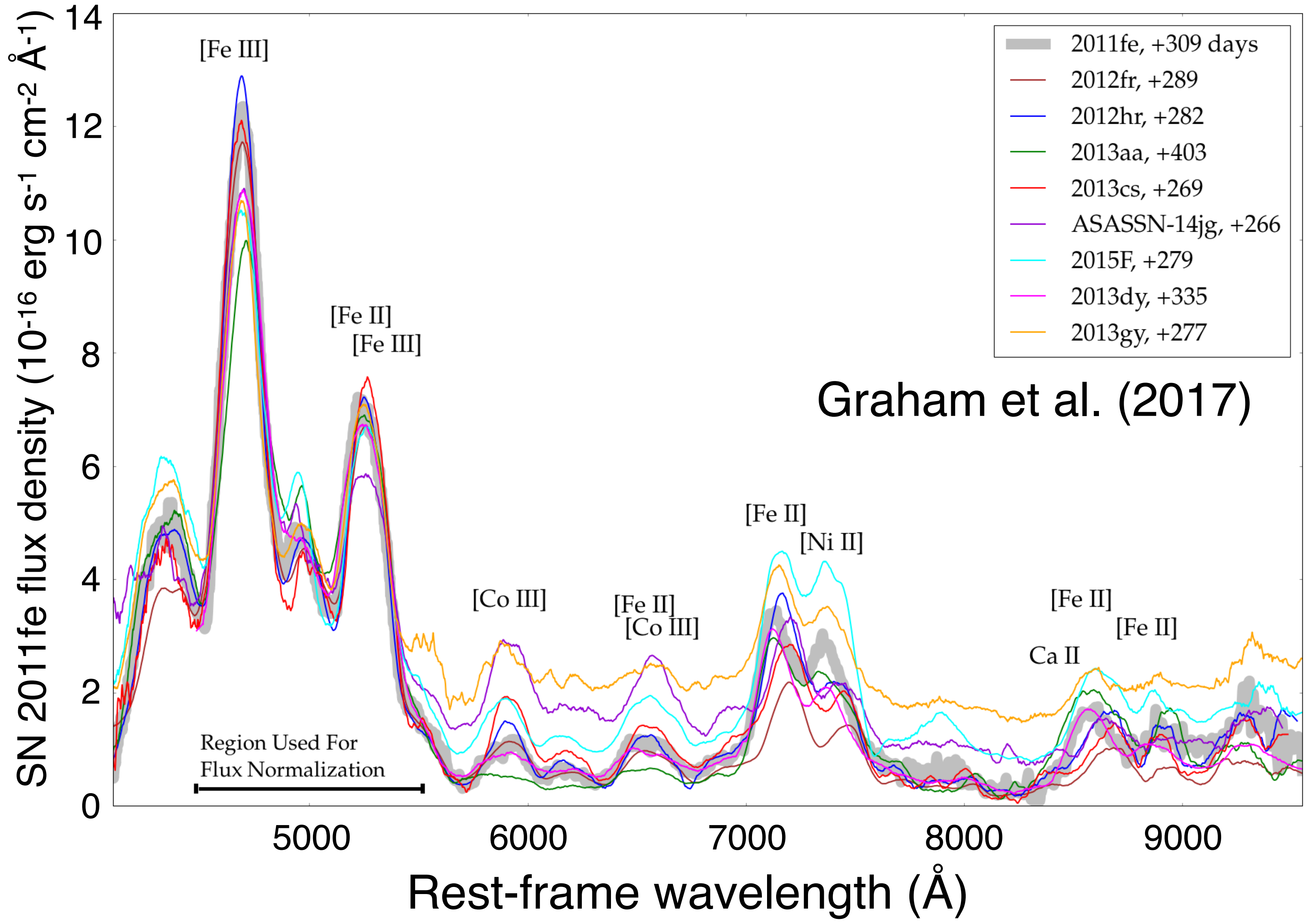


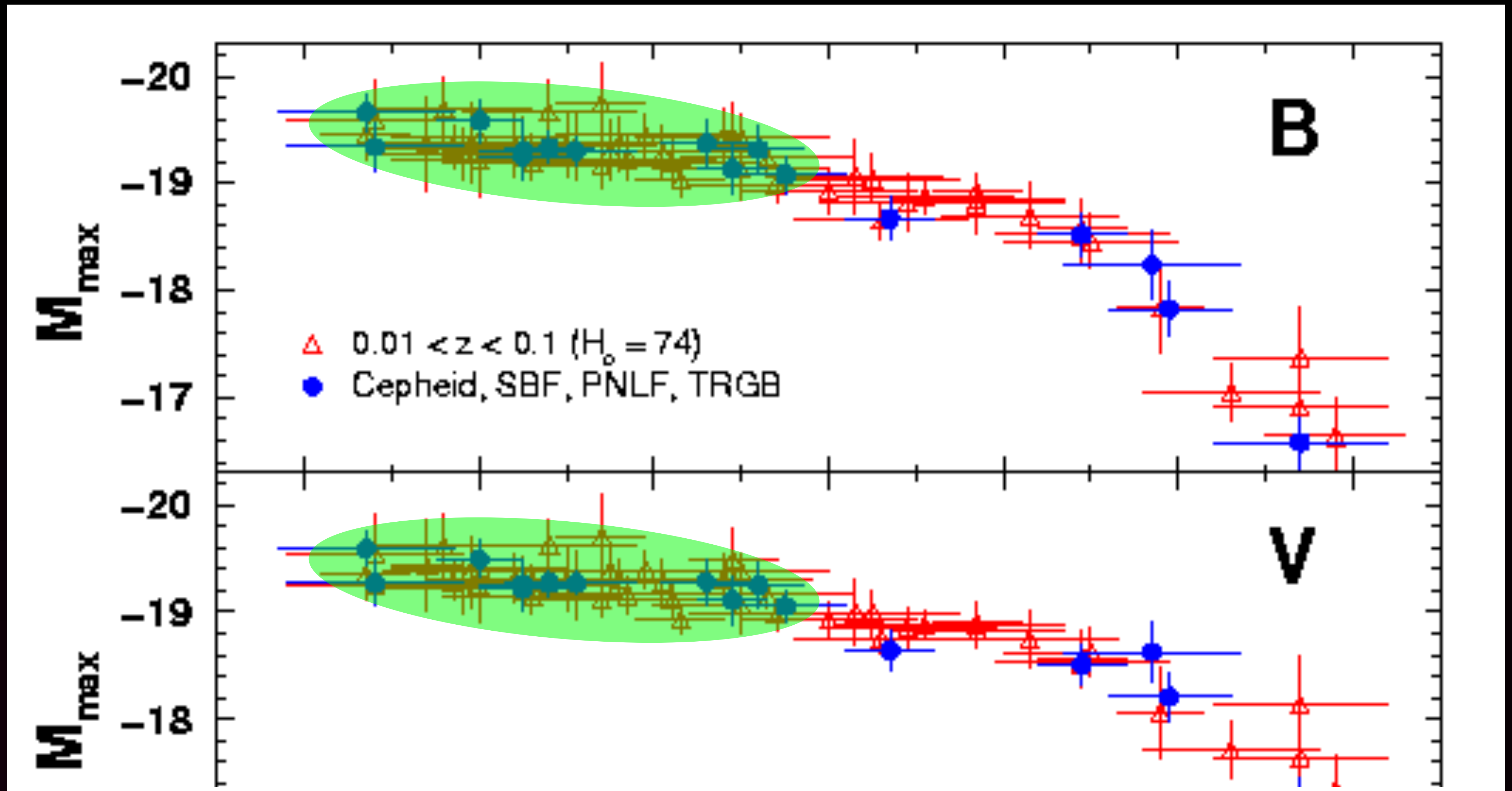
homogeneous spectra with
degenerate C/O fusion products

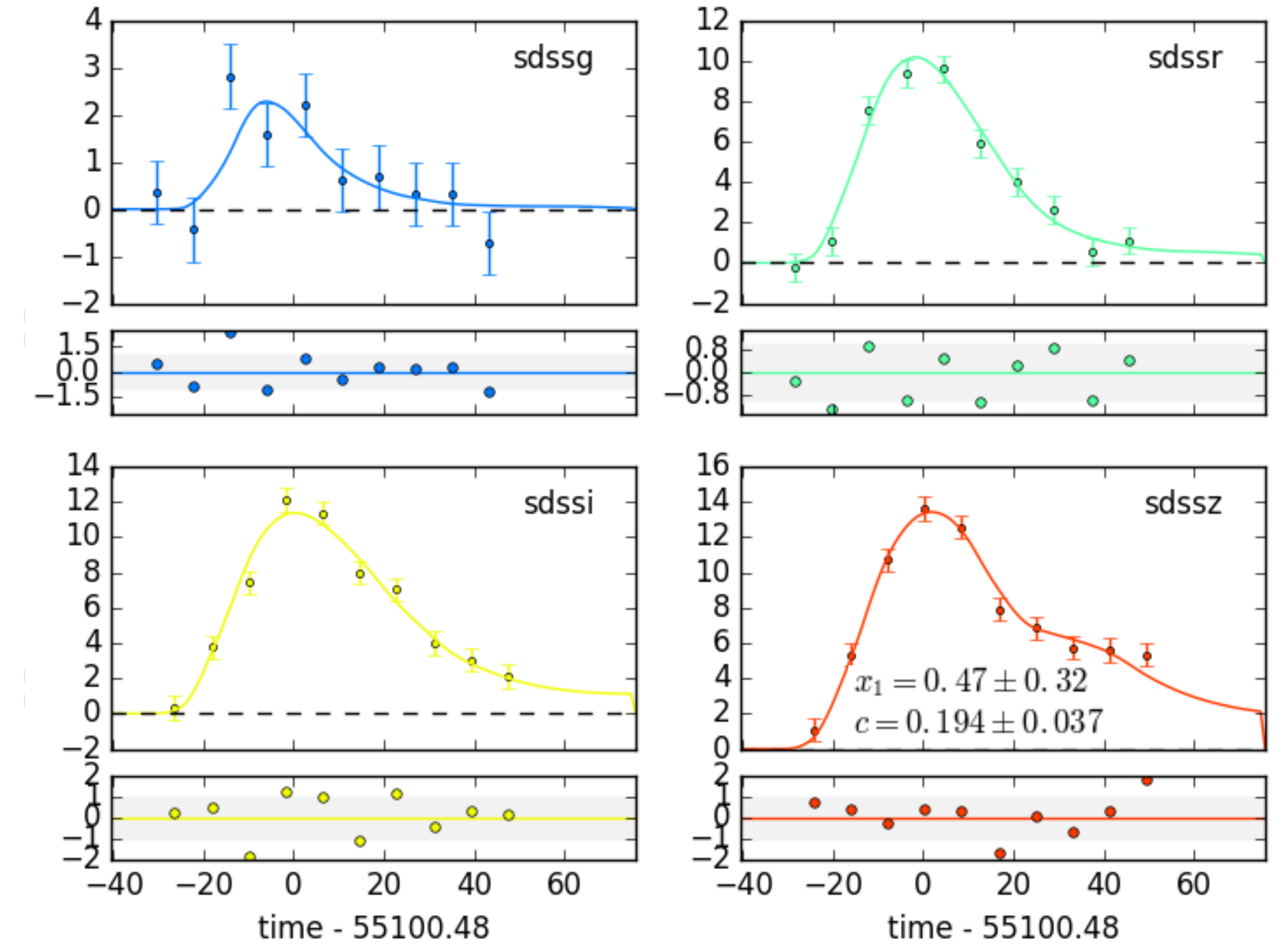
bolometric light curves
follow ^{56}Ni decay (Pankey 1962)

no massive star progenitor
no compact object in WDSNR

occur in old or non-star-forming
stellar populations







Krisciunas et al. (2006)

sncosmo (Barbary et al. 2016)

SN Ia are *standardizable* candles:

luminosity correlated with light-curve decline rate
(Phillips 1993; Hamuy et al. 1996)

colors constrain dust
(e.g., Riess et al. 1996; Jha, Riess, & Kirshner 2007)

SALT2 model (Guy et al. 2007)
with Tripp (1998) standardization

$$m_B + \alpha x_1 - \beta c$$

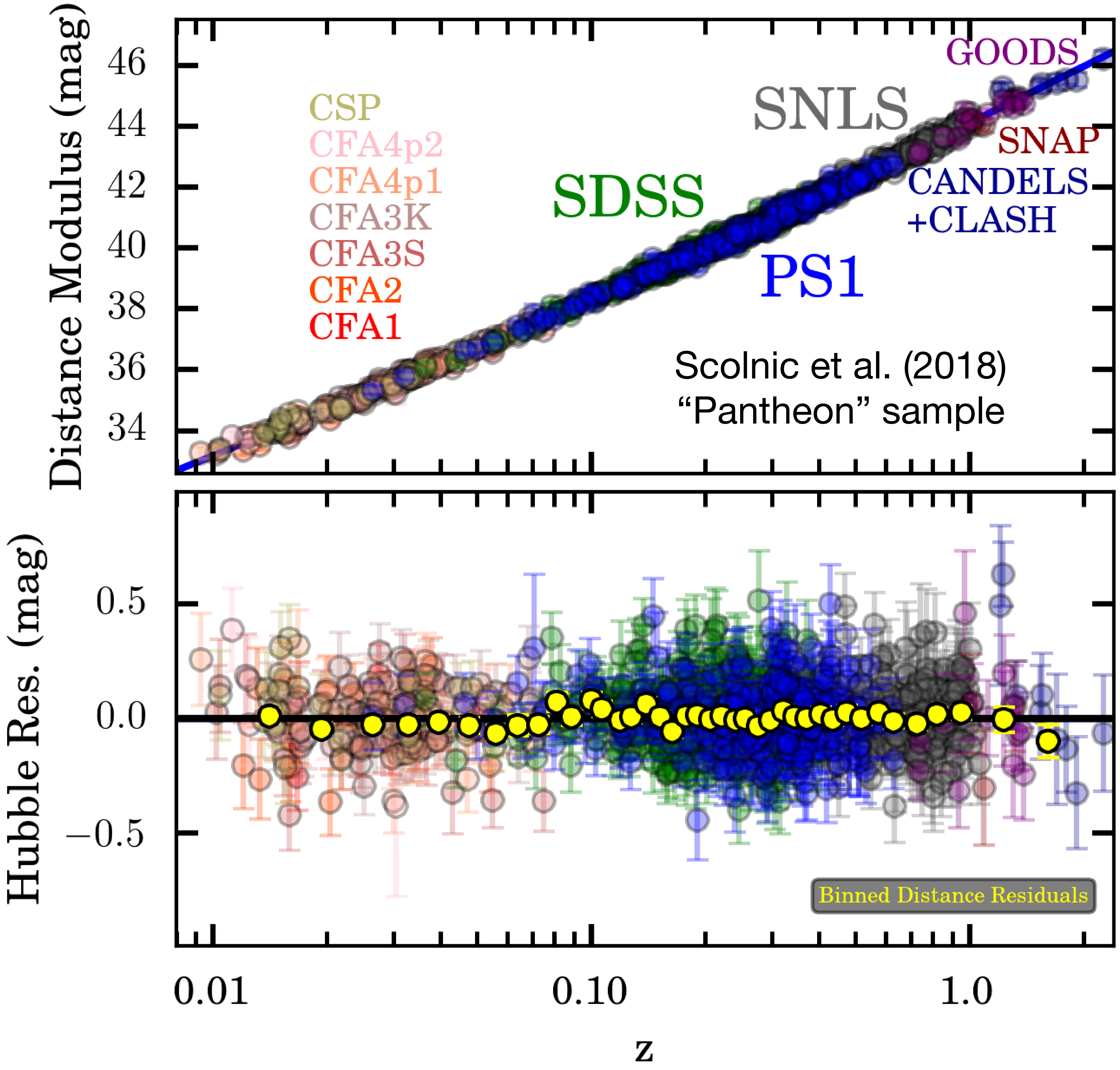
peak magnitude   light-curve shape   color

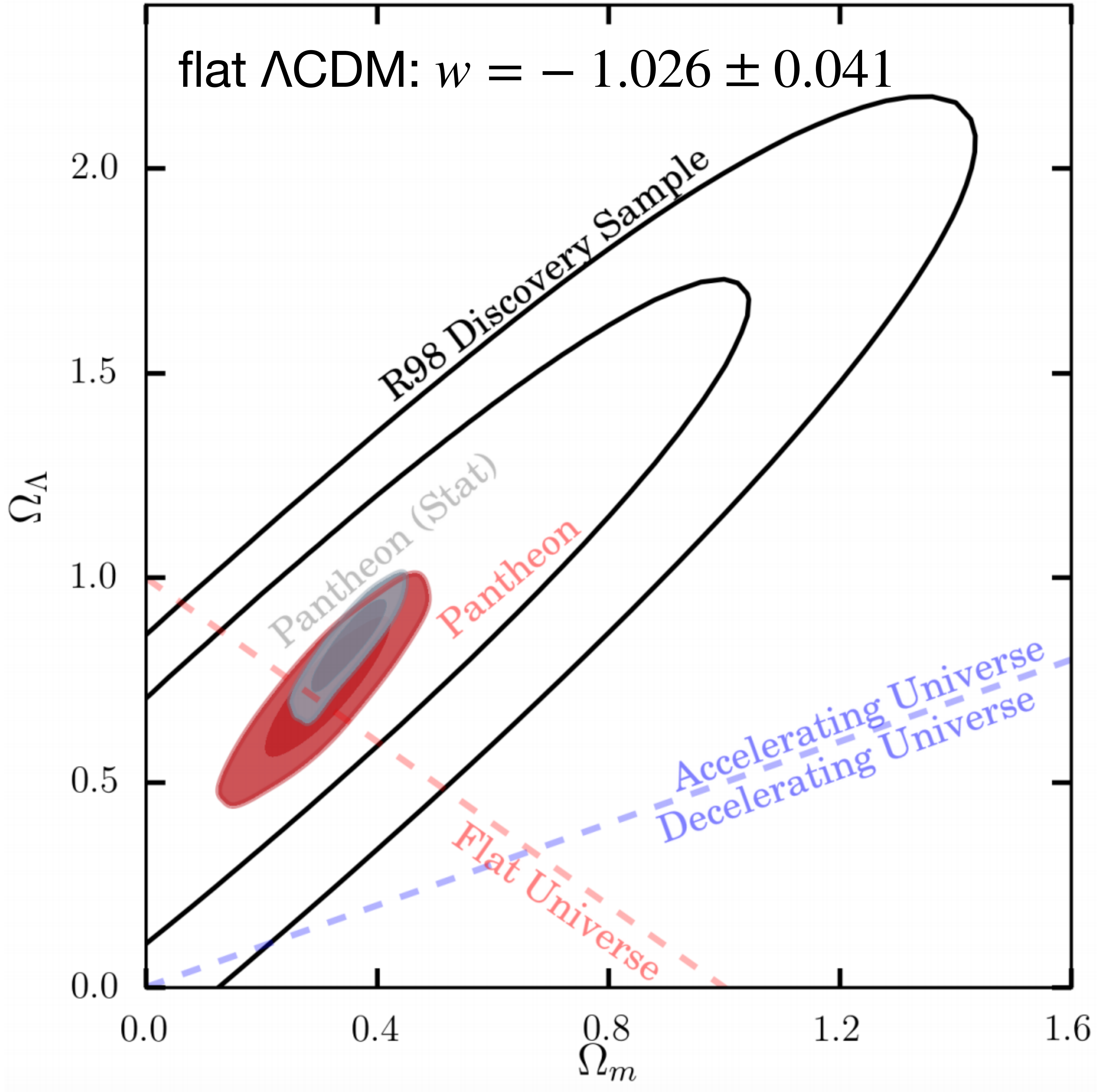
$\alpha \approx 0.14 \quad x_1 \in [-2,2] \;\Rightarrow\; -0.28 \leq \alpha x_1 \leq +0.28\,\mathrm{mag}$

$\beta \approx 3.1 \quad c \in [-0.1,0.3] \;\Rightarrow\; -0.31 \leq \beta c \leq +0.93\,\mathrm{mag}$

color gives the largest correction for
supernova cosmology analysis

applications: dark energy





a *differential* measurement between Hubble-flow and high-redshift SN Ia

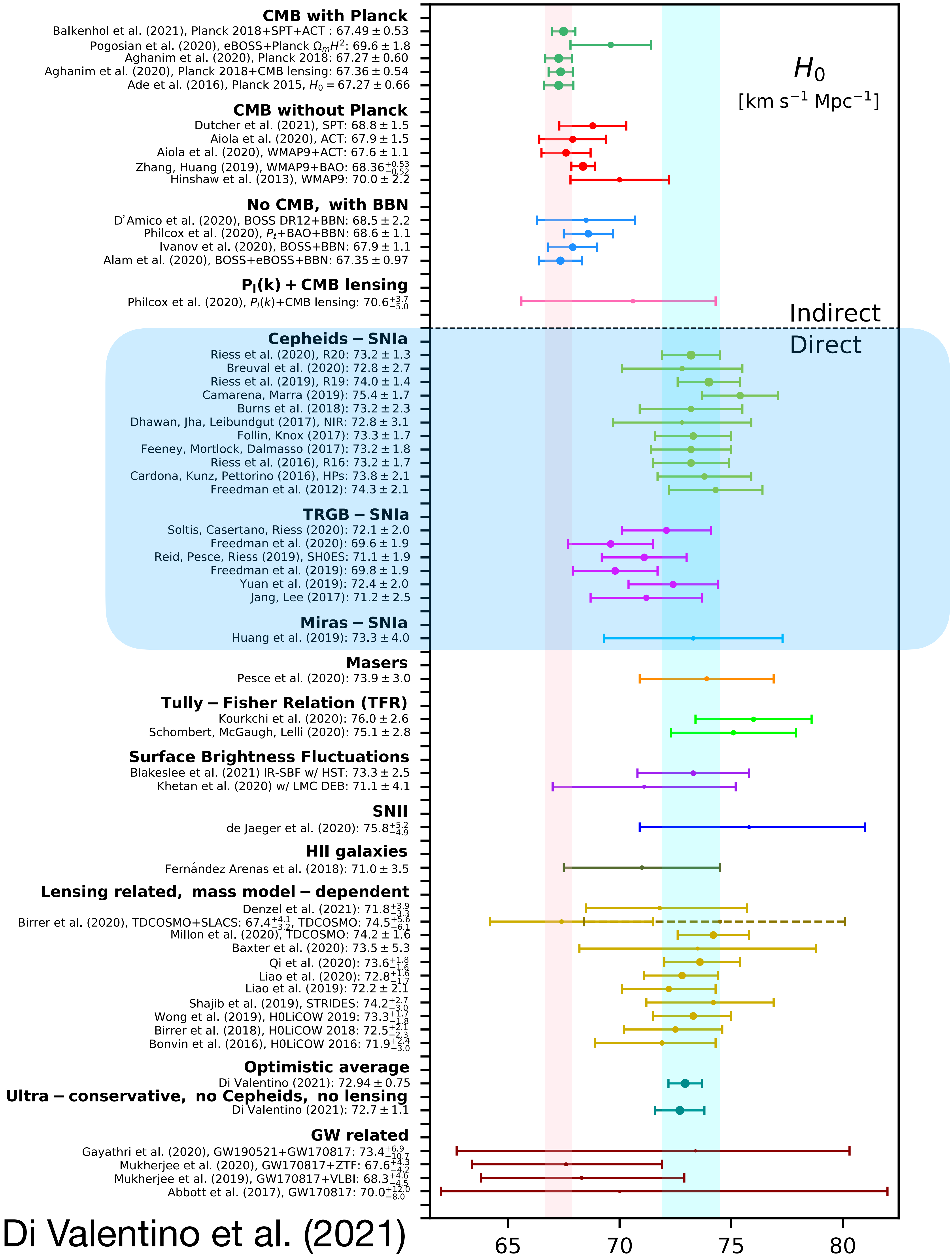
Hubble trouble

Geometric anchors + Cepheids + SN Ia show
~9% H_0 tension with Planck CMB + ΛCDM

a *differential* measurement between
Hubble-flow and local calibrator SN Ia

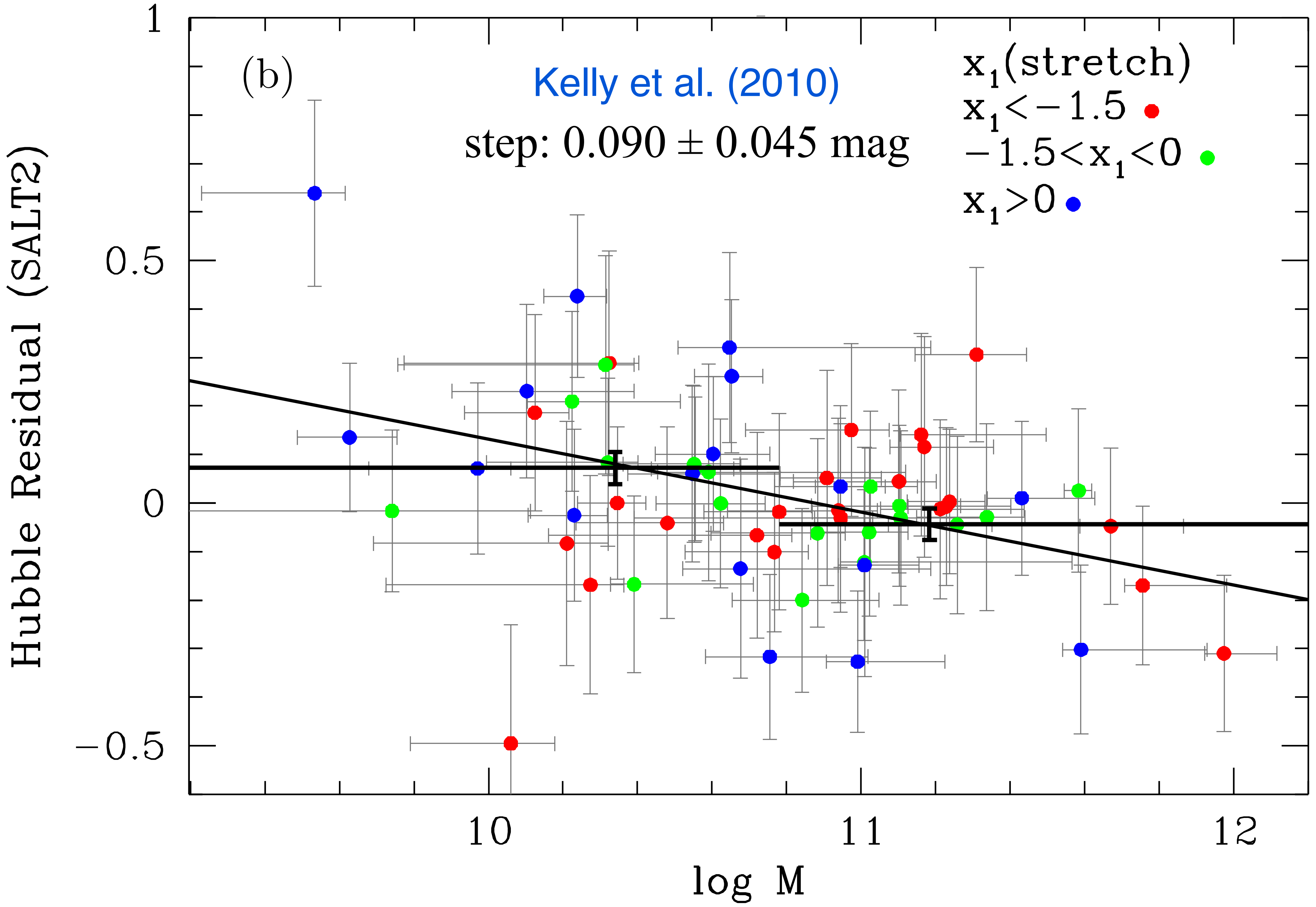
Calibrated SN Ia	Hubble-flow SN Ia
$d \sim 25\,\mathrm{Mpc},\ z \sim 0.006$	$d \sim 200\,\mathrm{Mpc},\ z \sim 0.05$
$\mu = m - M \sim 32$	$\mu = m - M \sim 36.5$
lookback $t \sim 80\,\mathrm{Myr}$	lookback $t \sim 650\,\mathrm{Myr}$

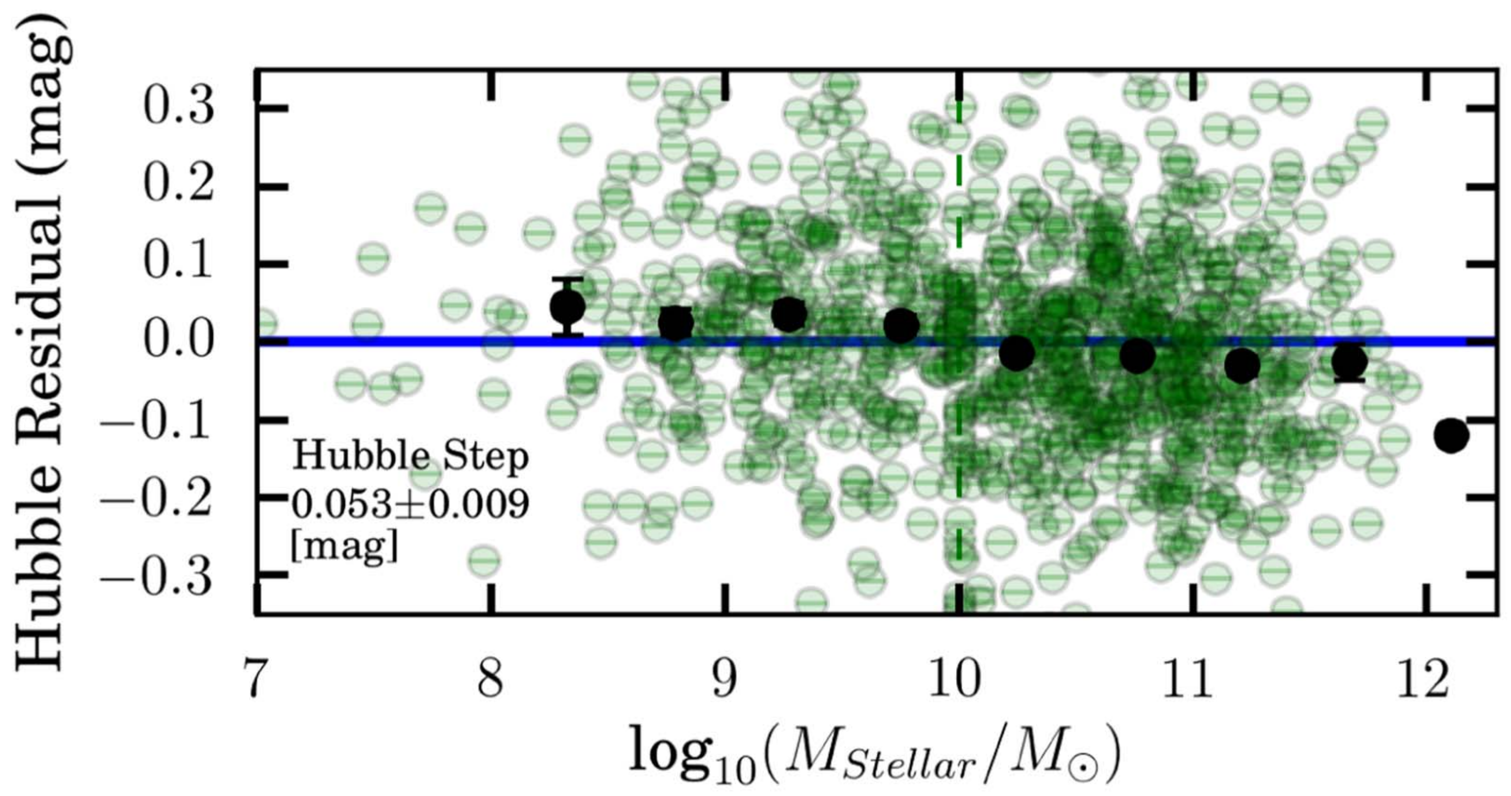
As long as these SN Ia samples are similar on average, there is no large SN Ia systematic. The Hubble flow SN Ia sample itself spans a wider range in distance, redshift, or lookback time than the difference with the calibrators, and it shows no evidence for large systematics.

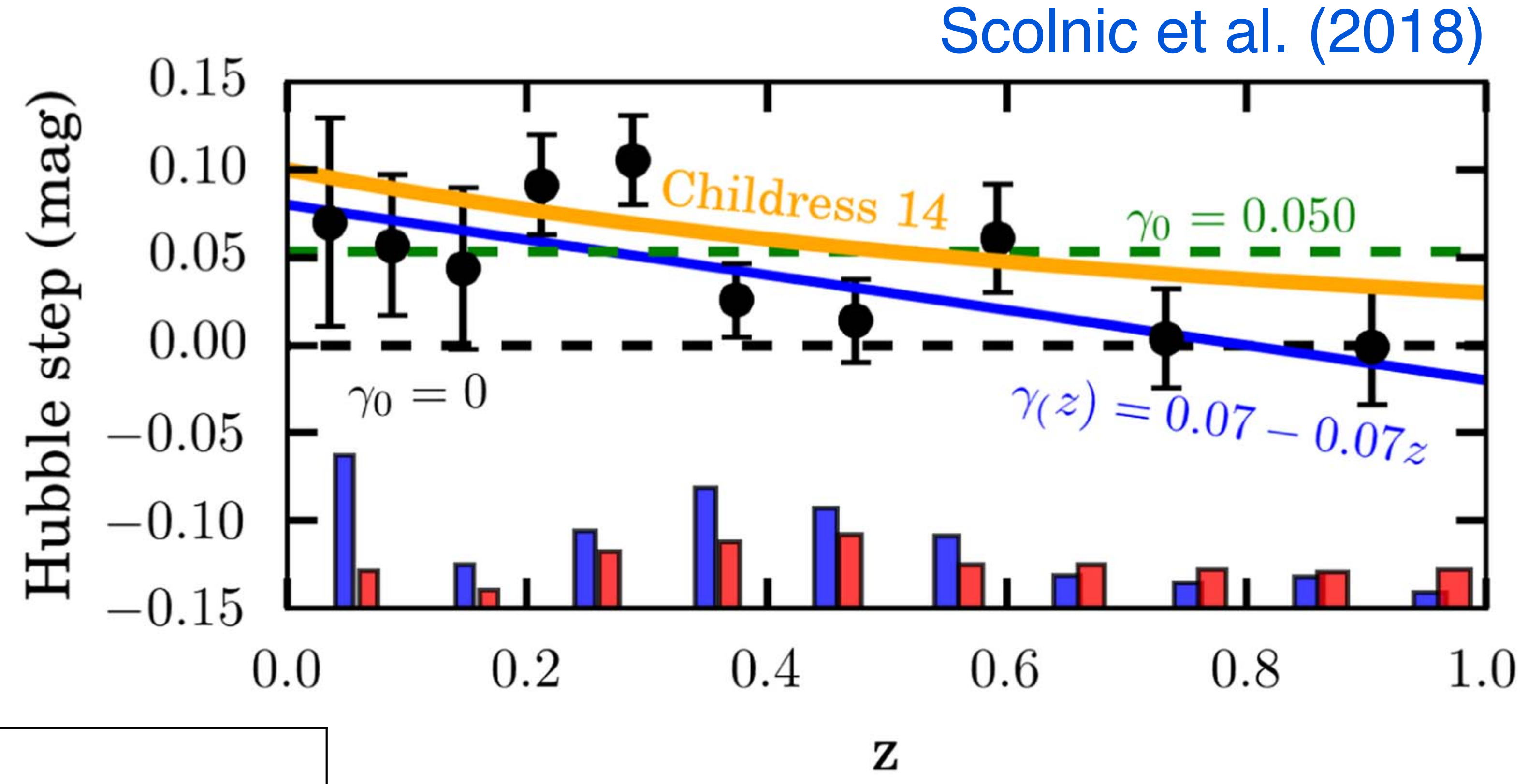


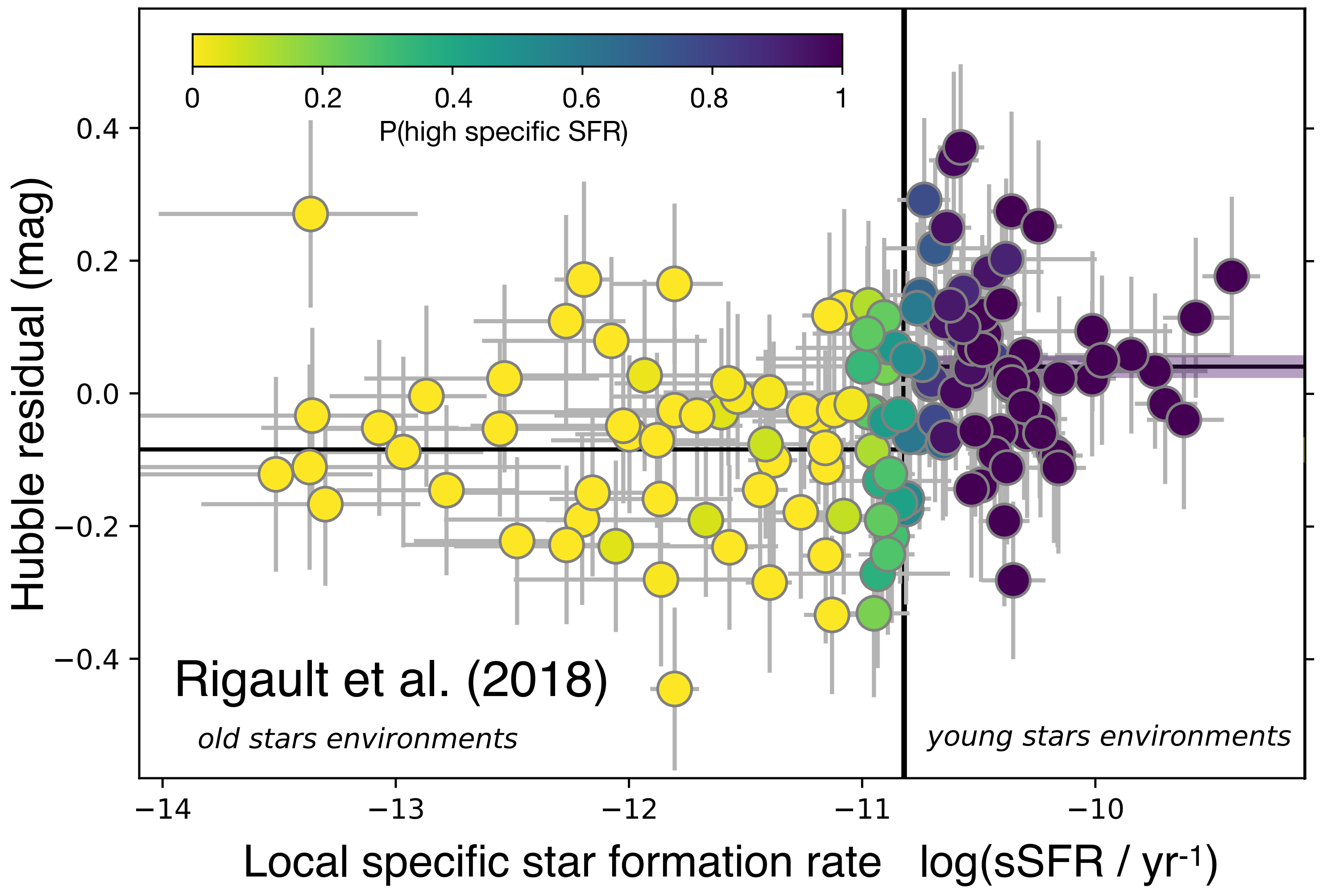
Di Valentino et al. (2021)

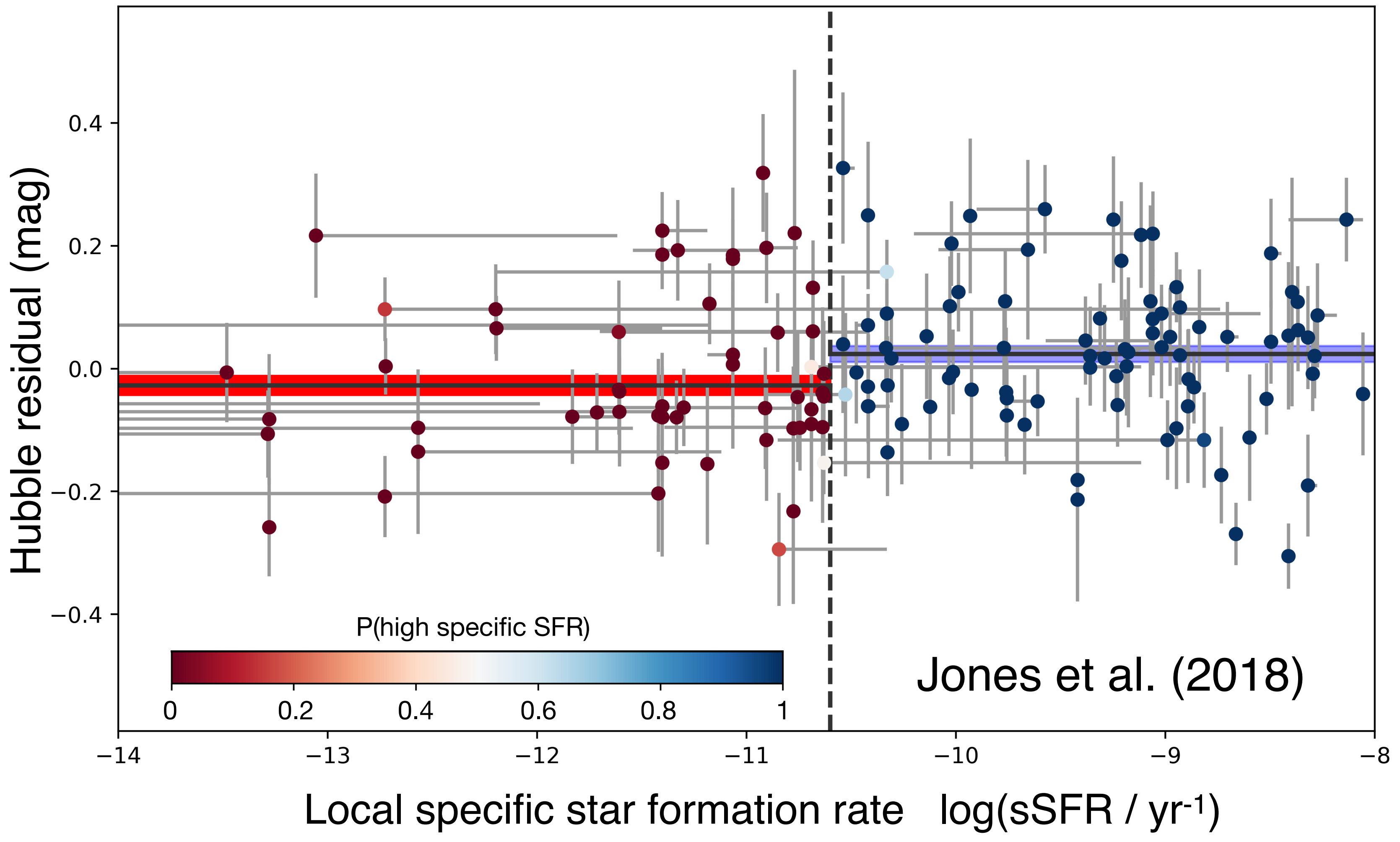
astrophysics: SN Ia standardized luminosity & environment







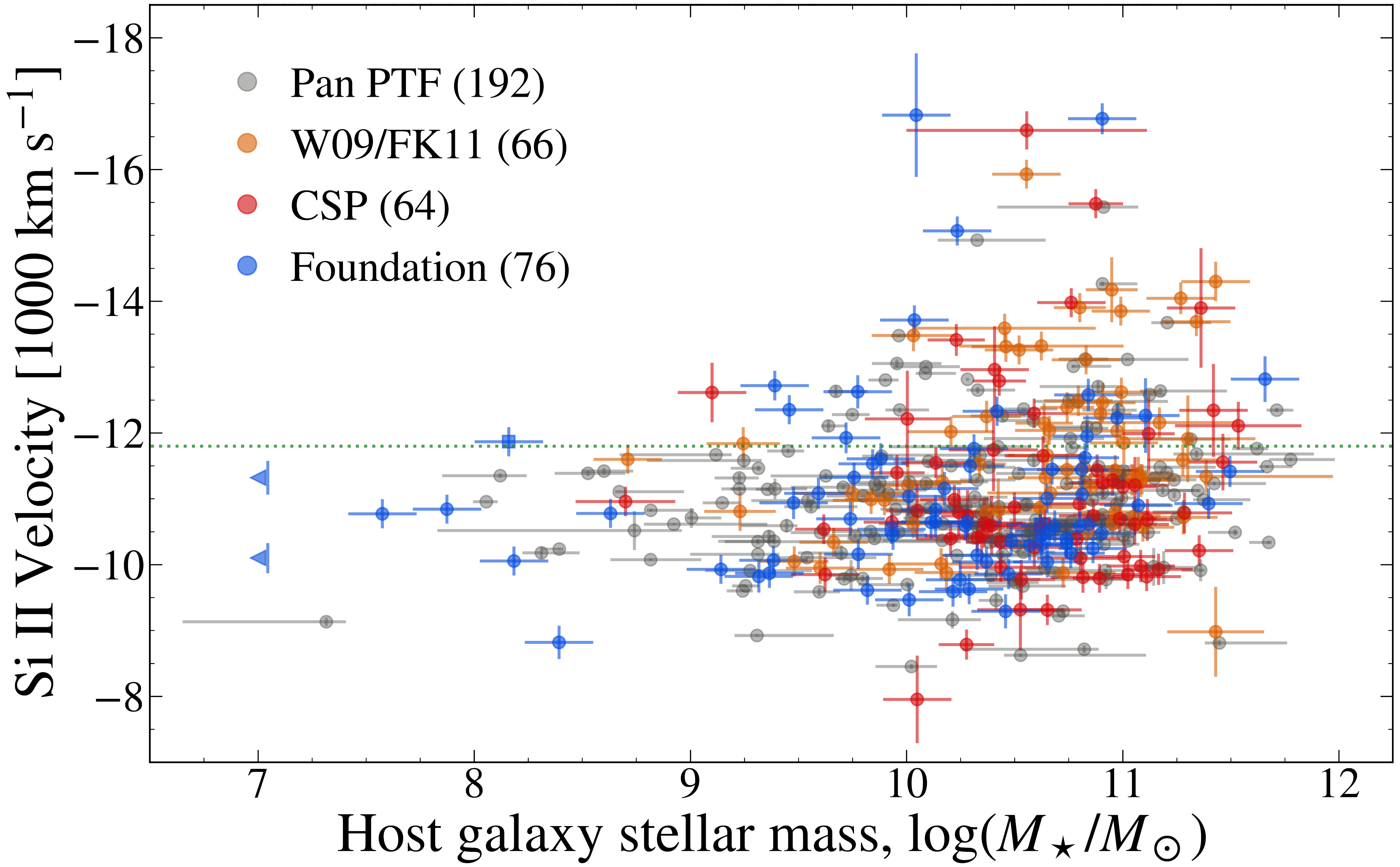




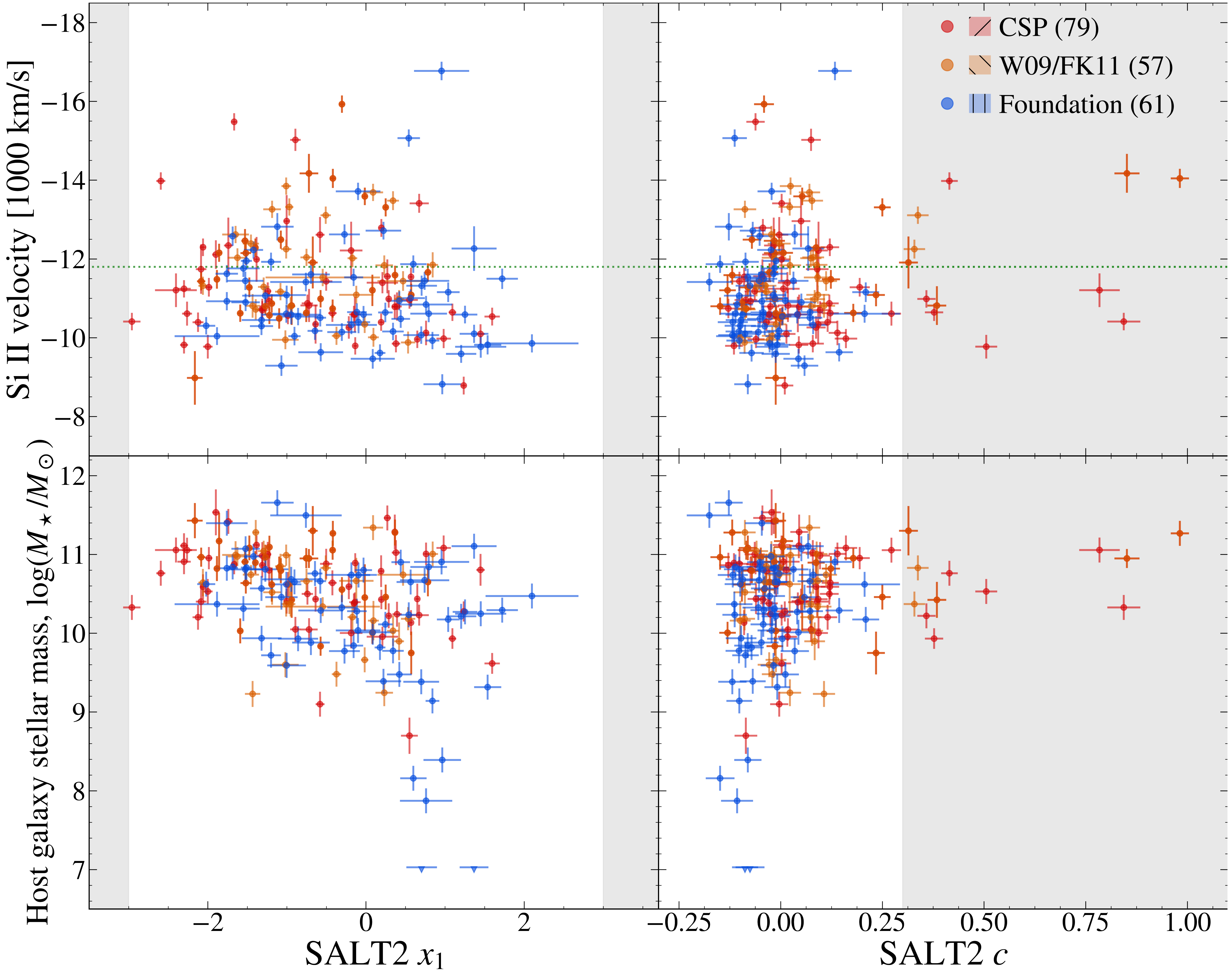
other analyses with, e.g., stellar ages:
Childress et al. 2014, Graur et al. 2015
Kang et al. 2016, 2020
Rose et al. 2019, 2020
Zhang et al. 2021

hard to make a large impact on H_0,
but could be bigger issue for dark energy parameter constraints

astrophysics: SN Ia properties & environment



Dettman et al. (2021)

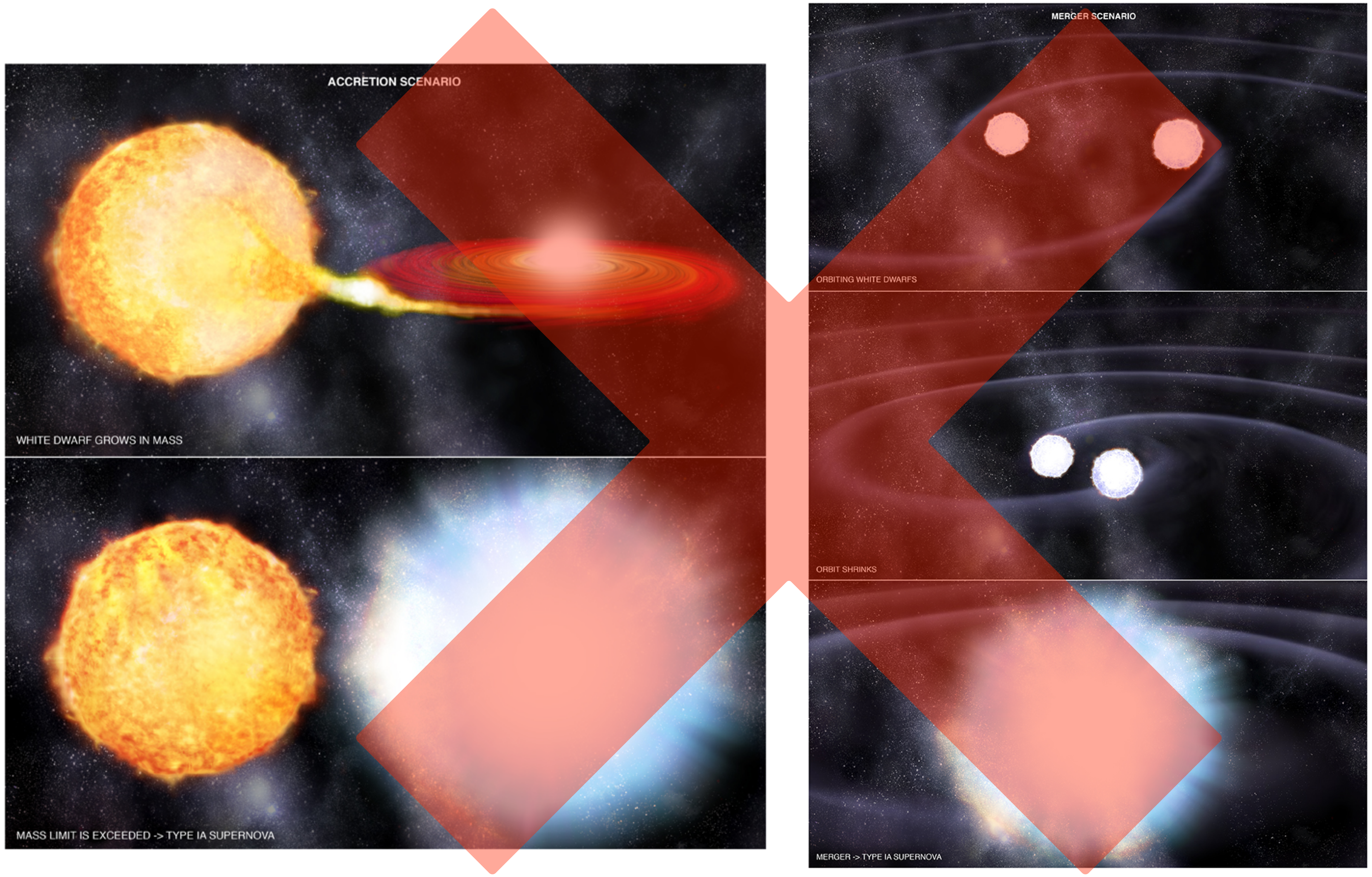


even before standardization
SN Ia show strong correlations between
supernova and environment properties
Branch et al. 1996, Hamuy et al. 2000, etc.

need to understand how these relationships
arise from the progenitor WD and binary system

SN Ia progenitors

more questions than just whether single or double degenerate!



what we know (probably):

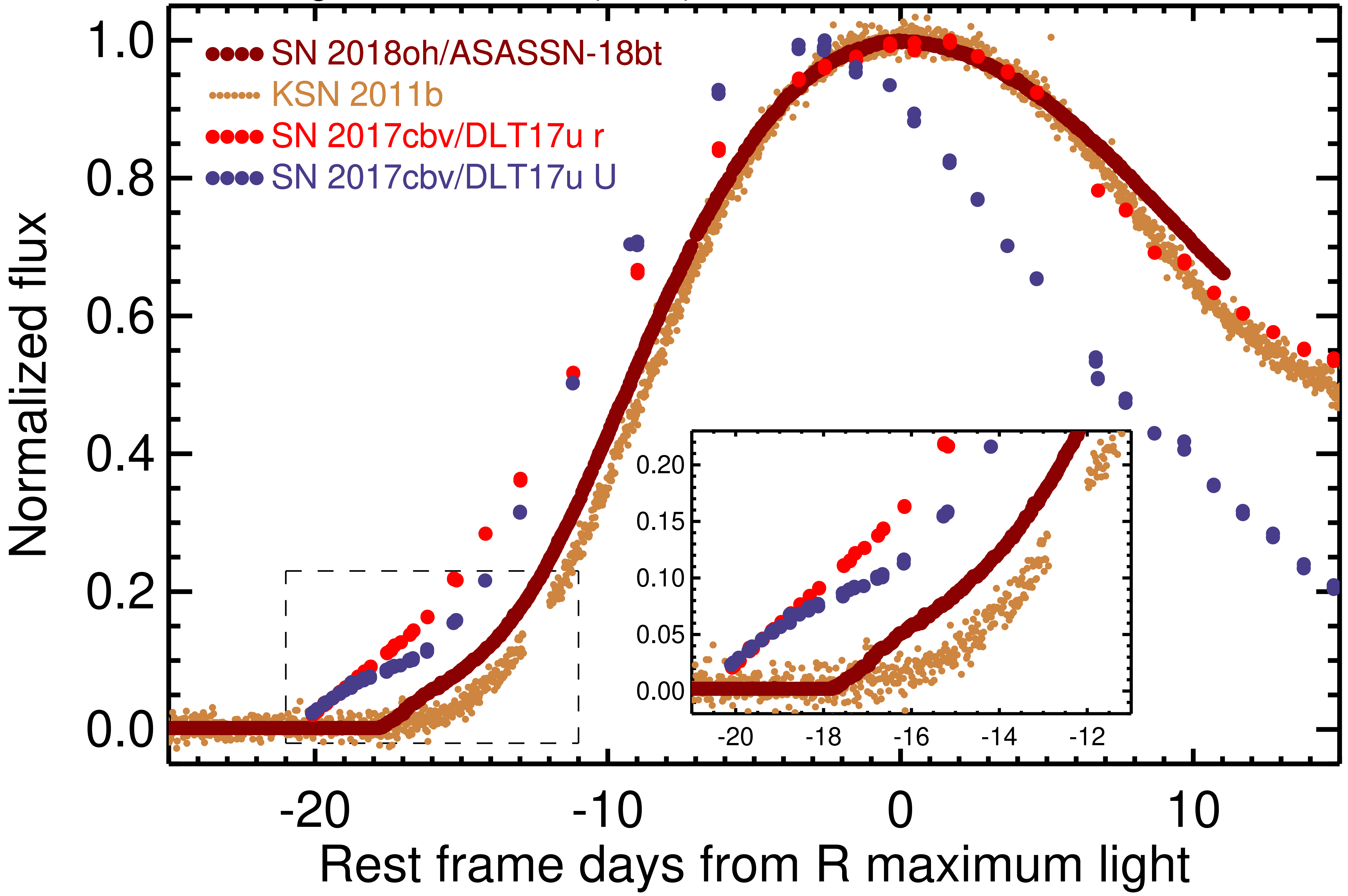
C/O WD explodes

what we don’t know:

at what mass? with what companion? with what accreted material?
how does explosion proceed? any interaction signature? what is left behind?

SN Ia bumps and wiggles

Jha, Maguire, & Sullivan (2019)



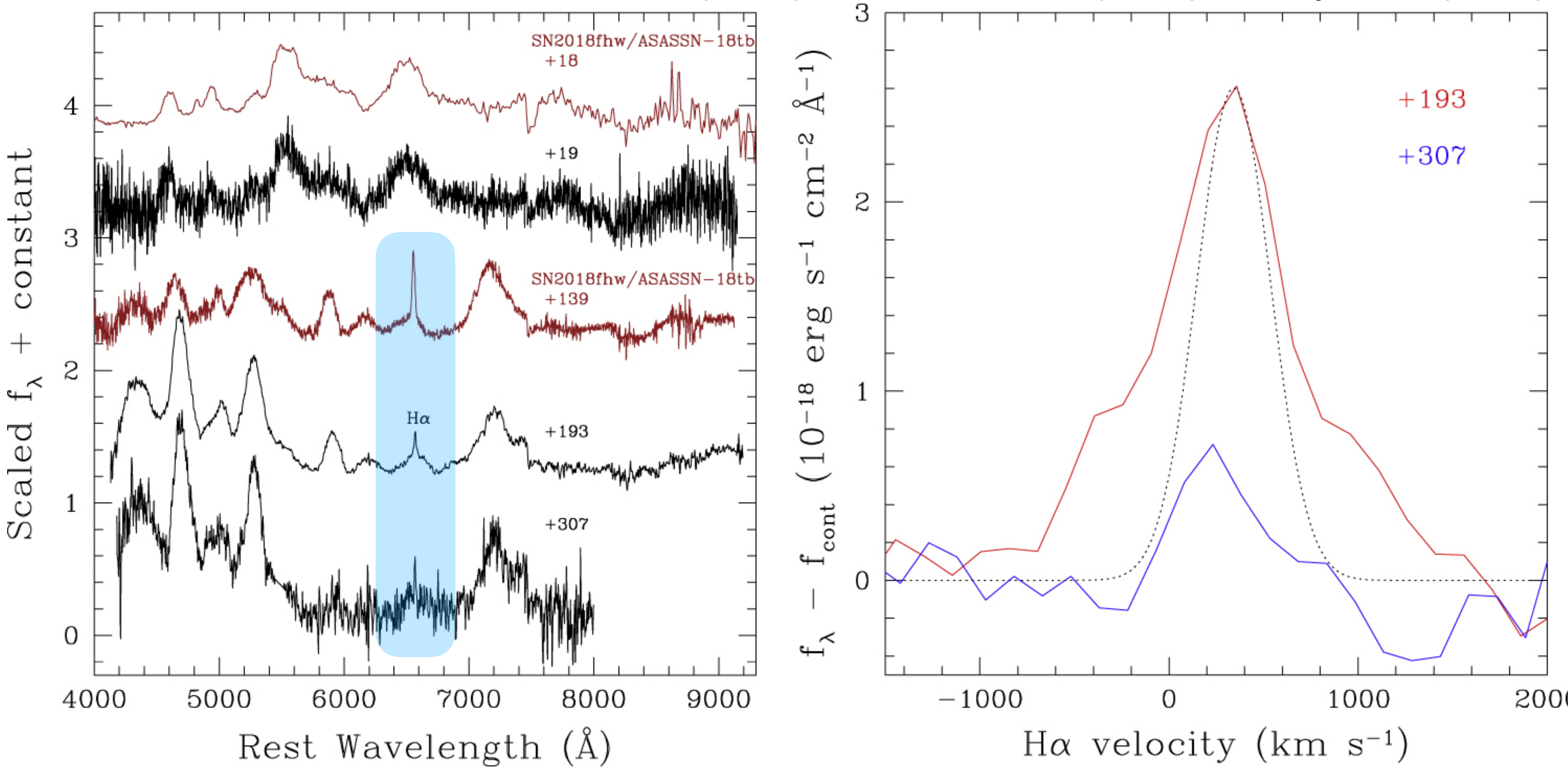
Dimitriadis et al. (2019)
Shappee et al. (2019)

Olling et al. (2015)

Hosseinzadeh et al. (2017)

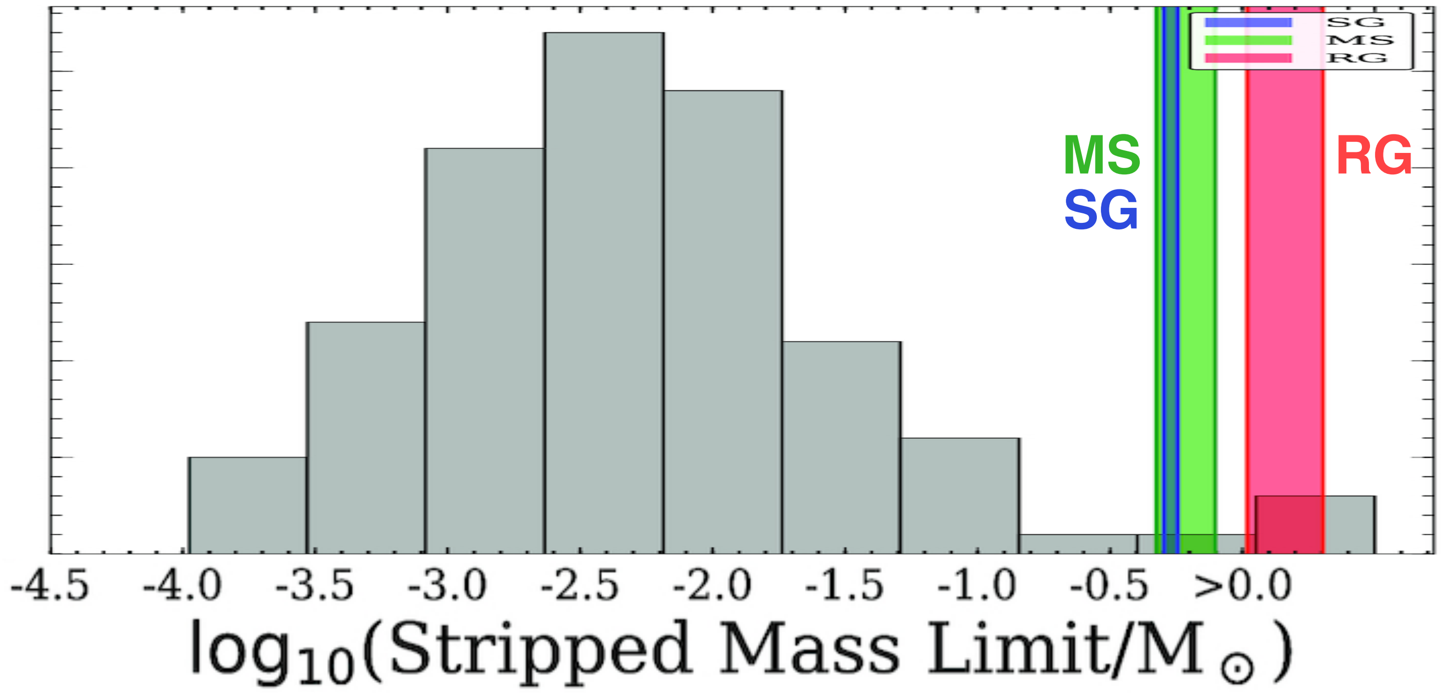
early-time bumps in light curves:
interaction with a companion? (Kasen 2010)
or radioactive material in outer layers?

Prieto et al. (2020), Kollmeier et al. (2019), Vallely et al. (2019)



late-time stripped or circumstellar hydrogen?

Tucker et al. (2020), Sand et al. (2019)



few examples (+ "Ia-CSM")
but they are rare

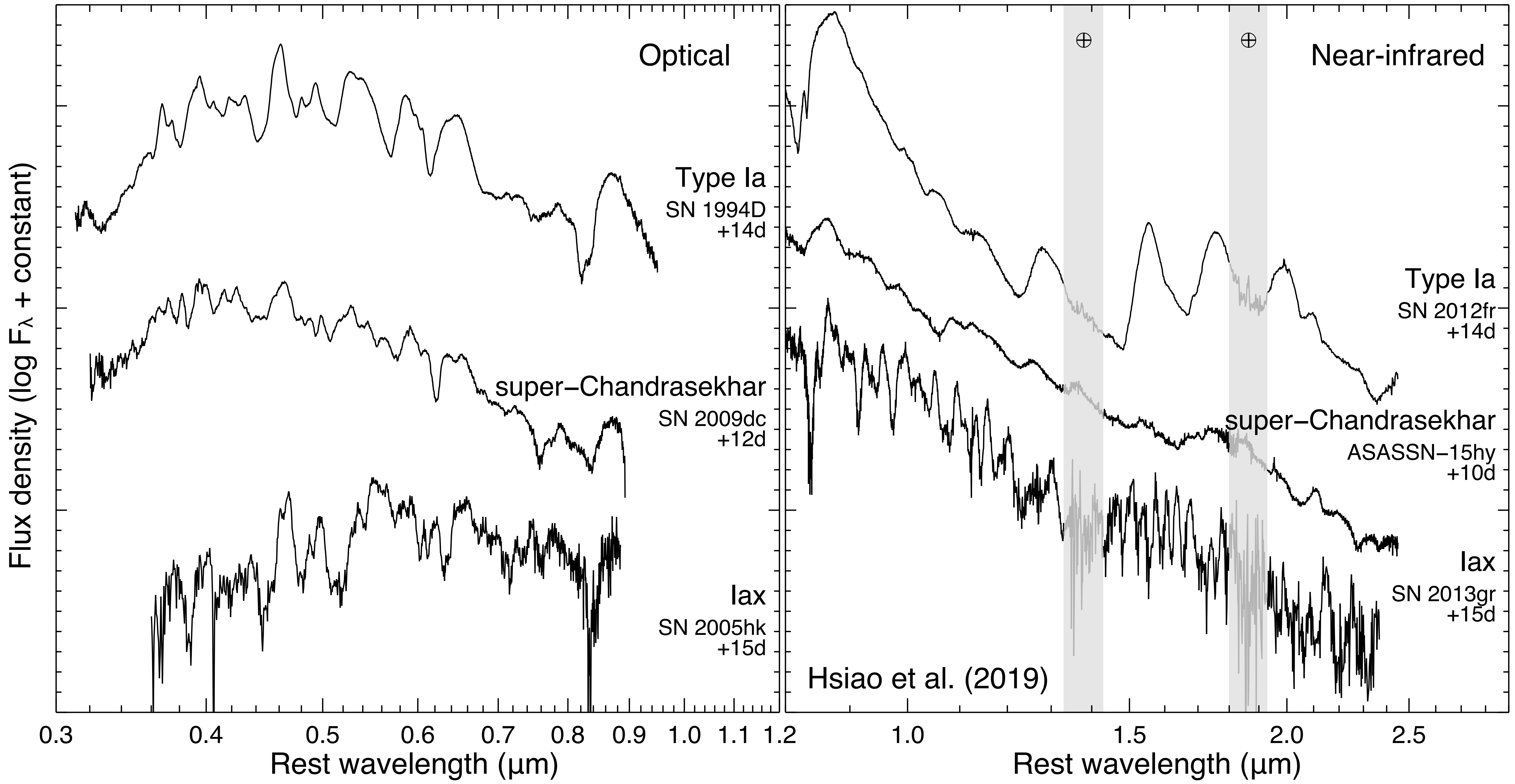
no radio or X-ray detections

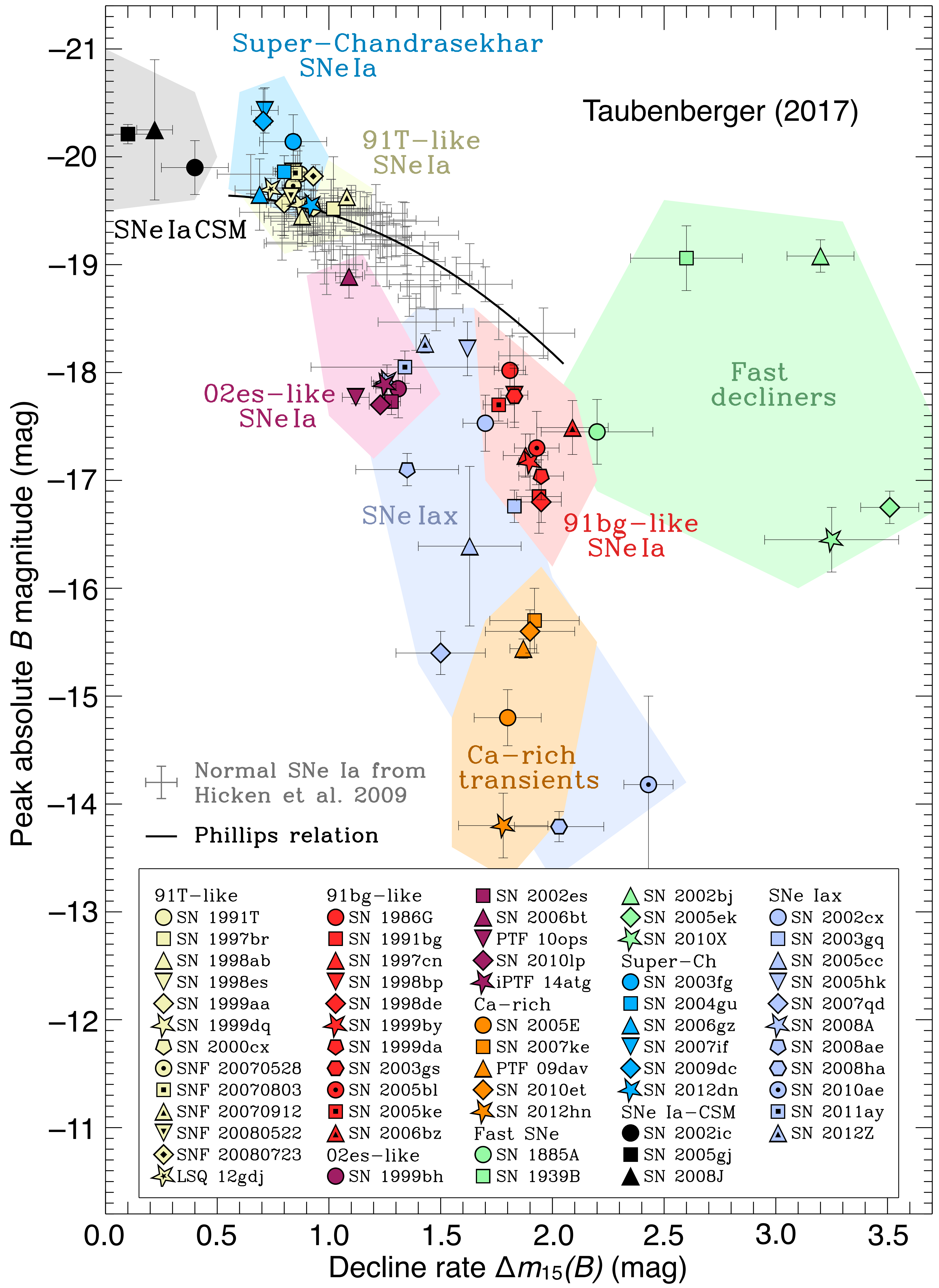
Chomiuk et al. 2016
Margutti et al. 2014
Horesh et al. 2012

the thermonuclear supernova zoo

exploding white dwarfs:
much more than just normal SN Ia!

what can the weirdos teach us?

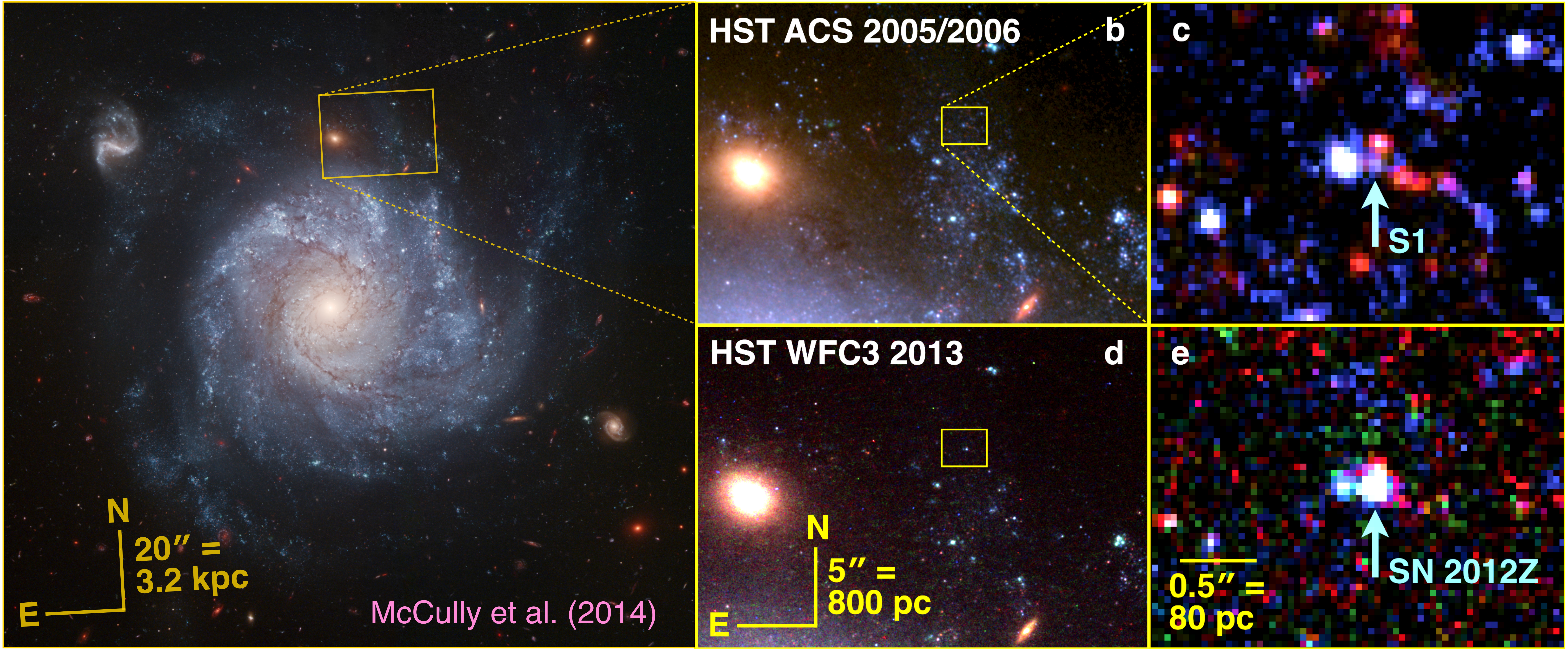




type Iax supernovae

A luminous, blue progenitor system for the type Iax supernova 2012Z

the only WDSN with a detected progenitor system

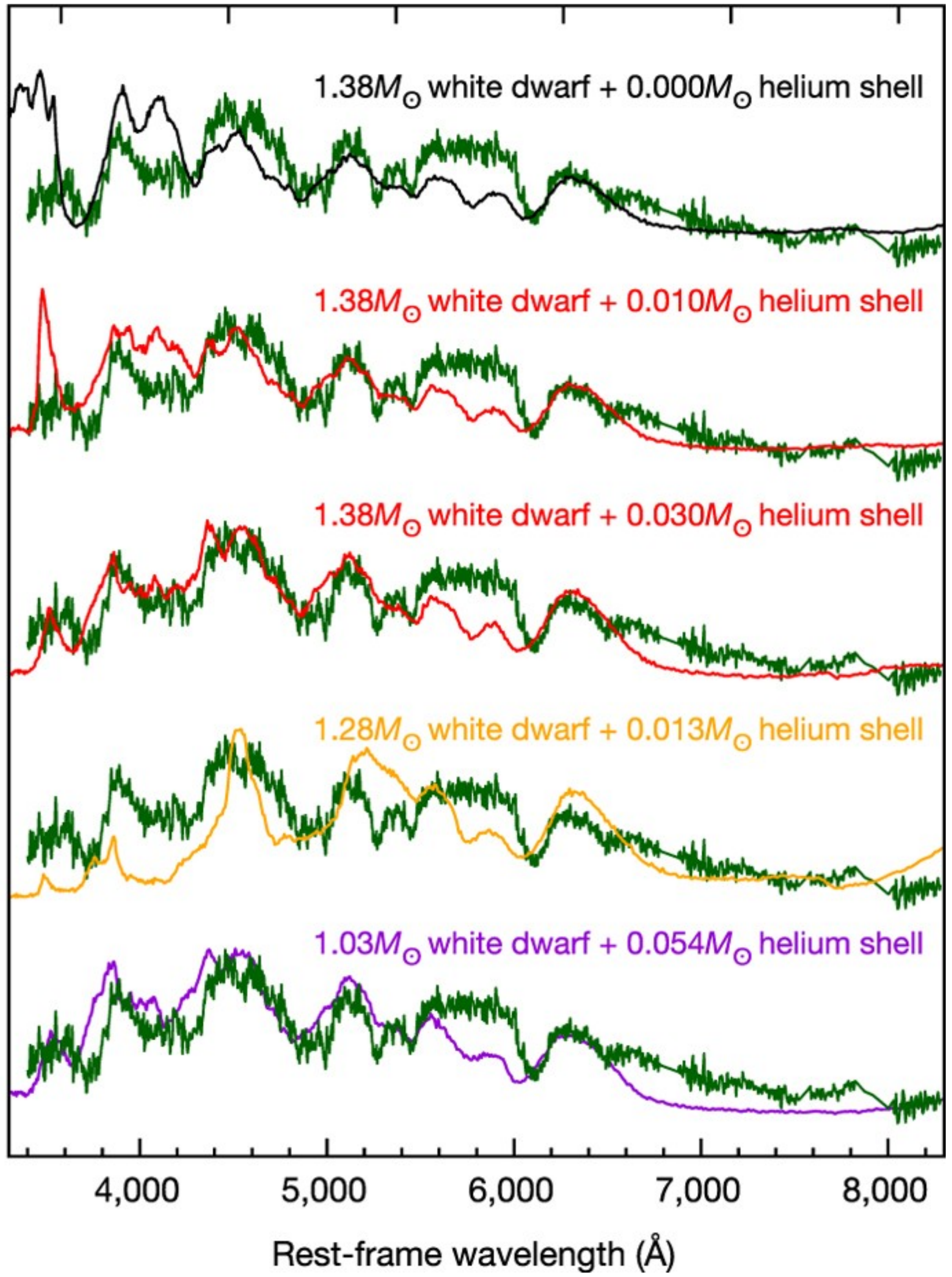


C/O WD + He star system deflagration explosion that does not unbind the WD?

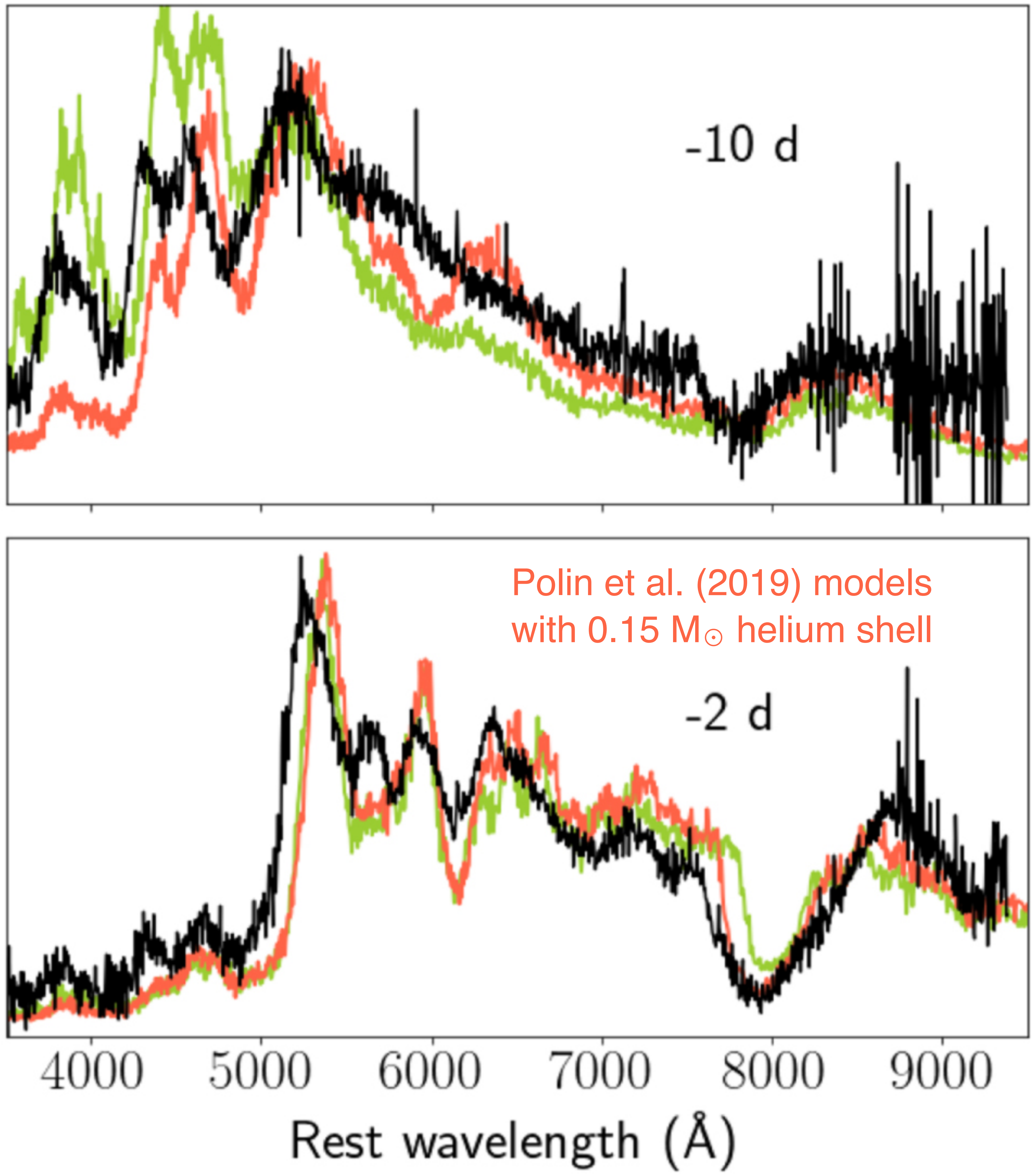
Foley et al. 2013, Jha 2017,
Stritzinger et al. 2015,
White et al. 2015,
Tomasella et al. 2016, 2020,
Foley et al. 2016,
Magee et al. 2017,
Lyman et al. 2018,
Singh et al. 2018,
Li et al. 2018,
Barna et al. 2018, 2021,
Kawabata et al. 2018,
Takaro et al. 2020,
Srivastav et al. 2020,
Stauffer et al. 2021,
+ many papers with models!

shell detonations observed?

Jiang et al. (2017)



De et al. (2019)



spectral matches to double-detonation models with helium shells

Shen et al. 2010, 2014, 2018

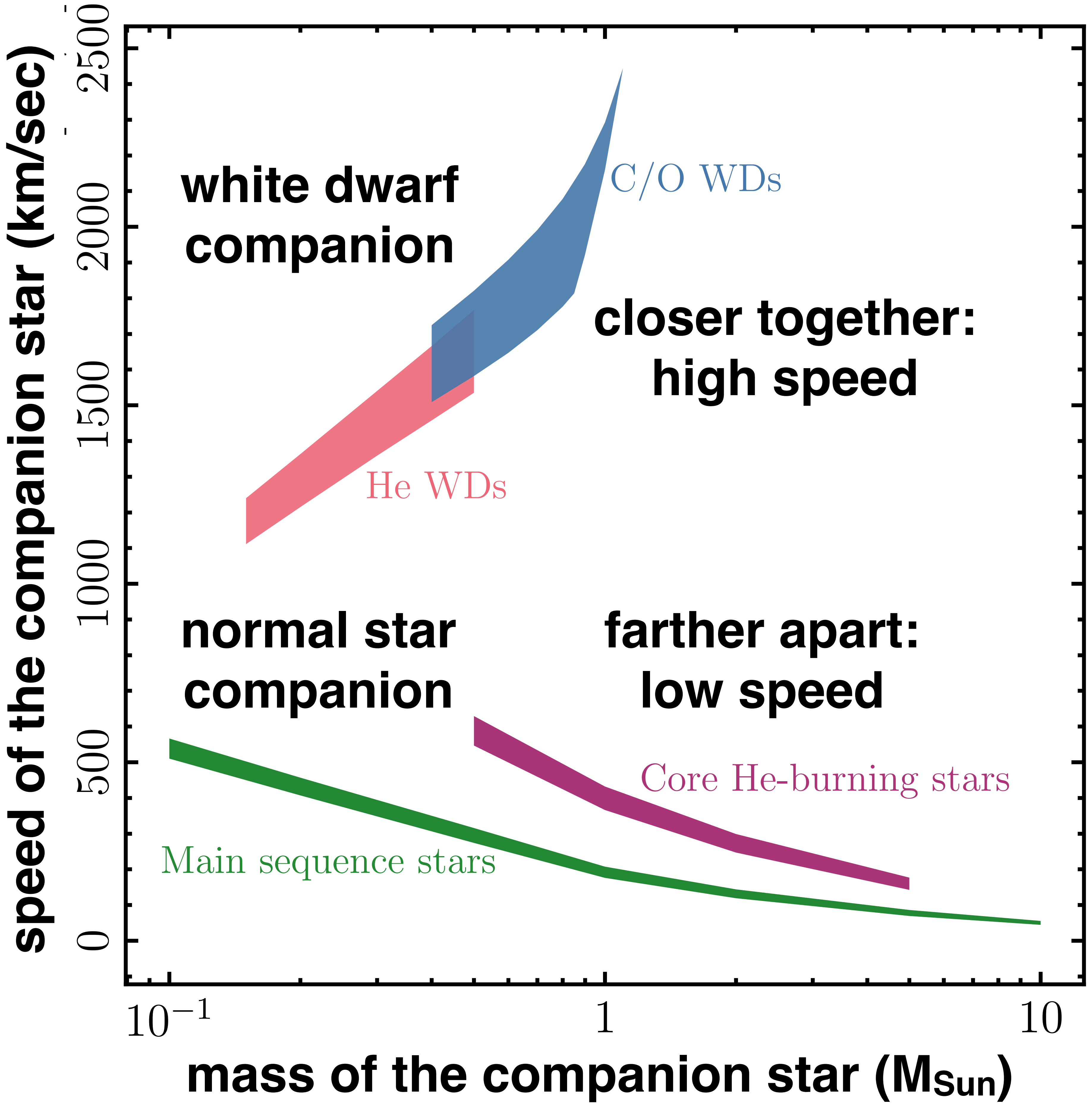
Polin et al. 2019

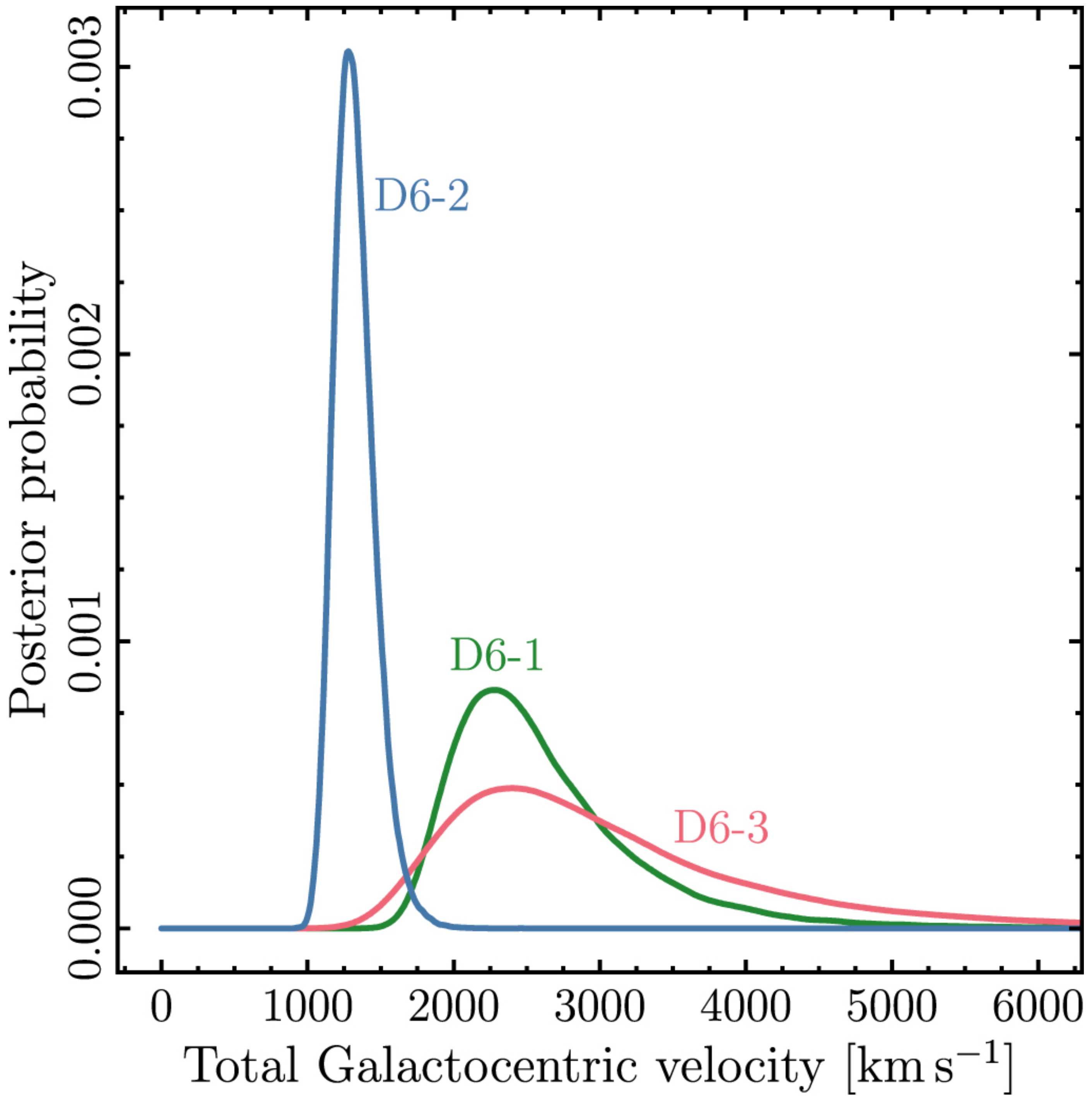
but signatures are rare

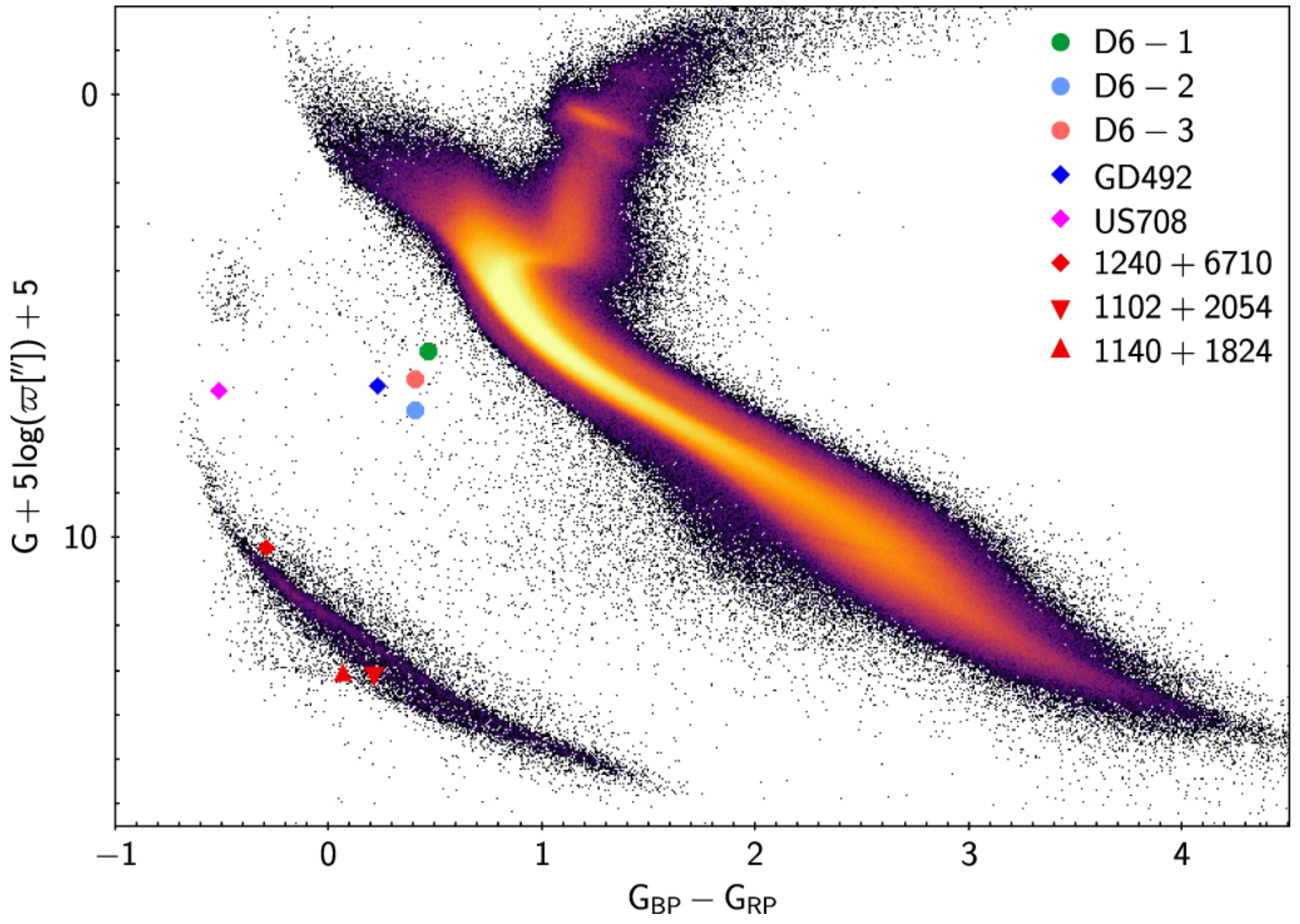
e.g., Siebert et al. 2020

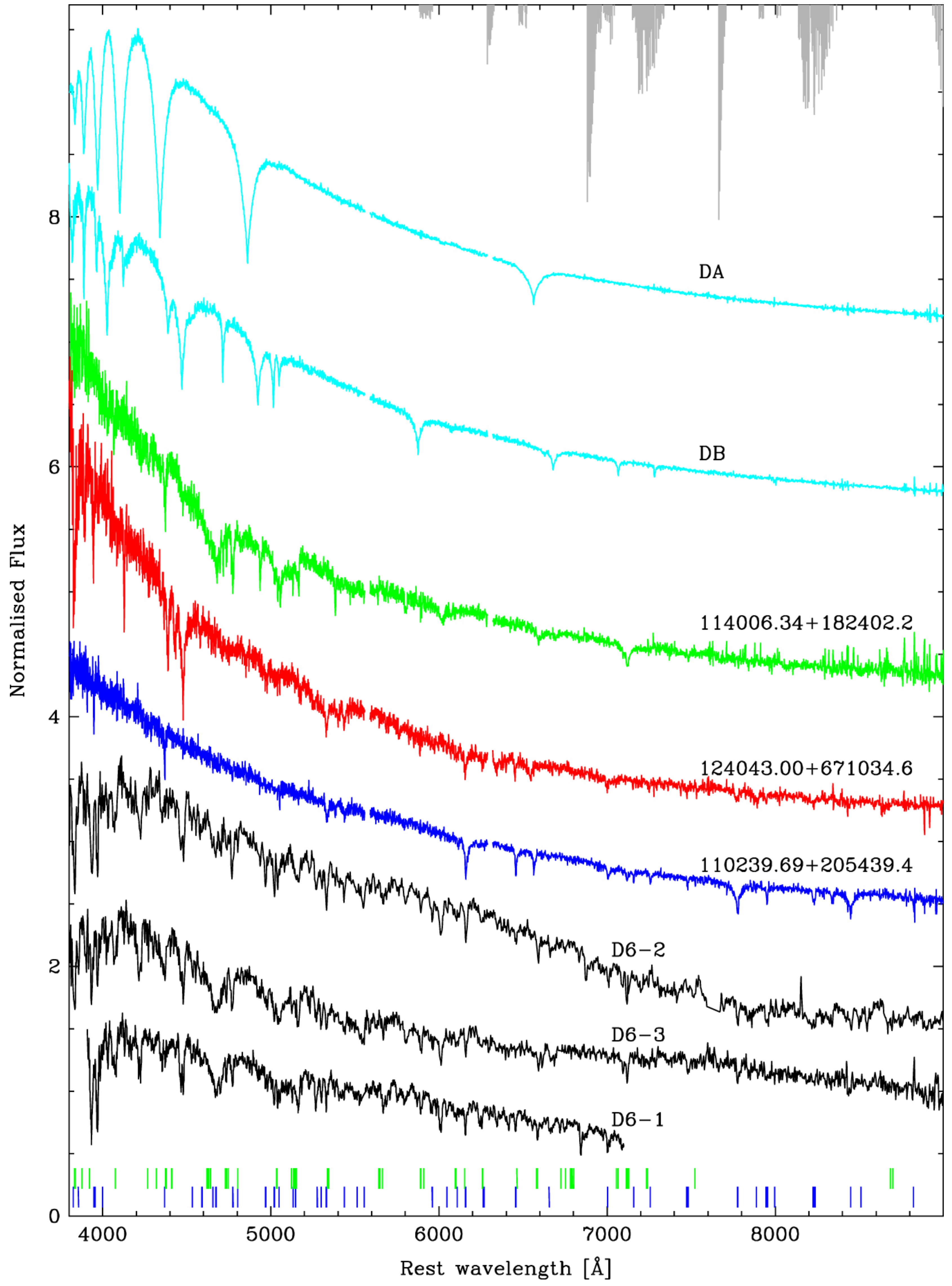
surviving companions: fugitive stars

Shen et al. (2018)





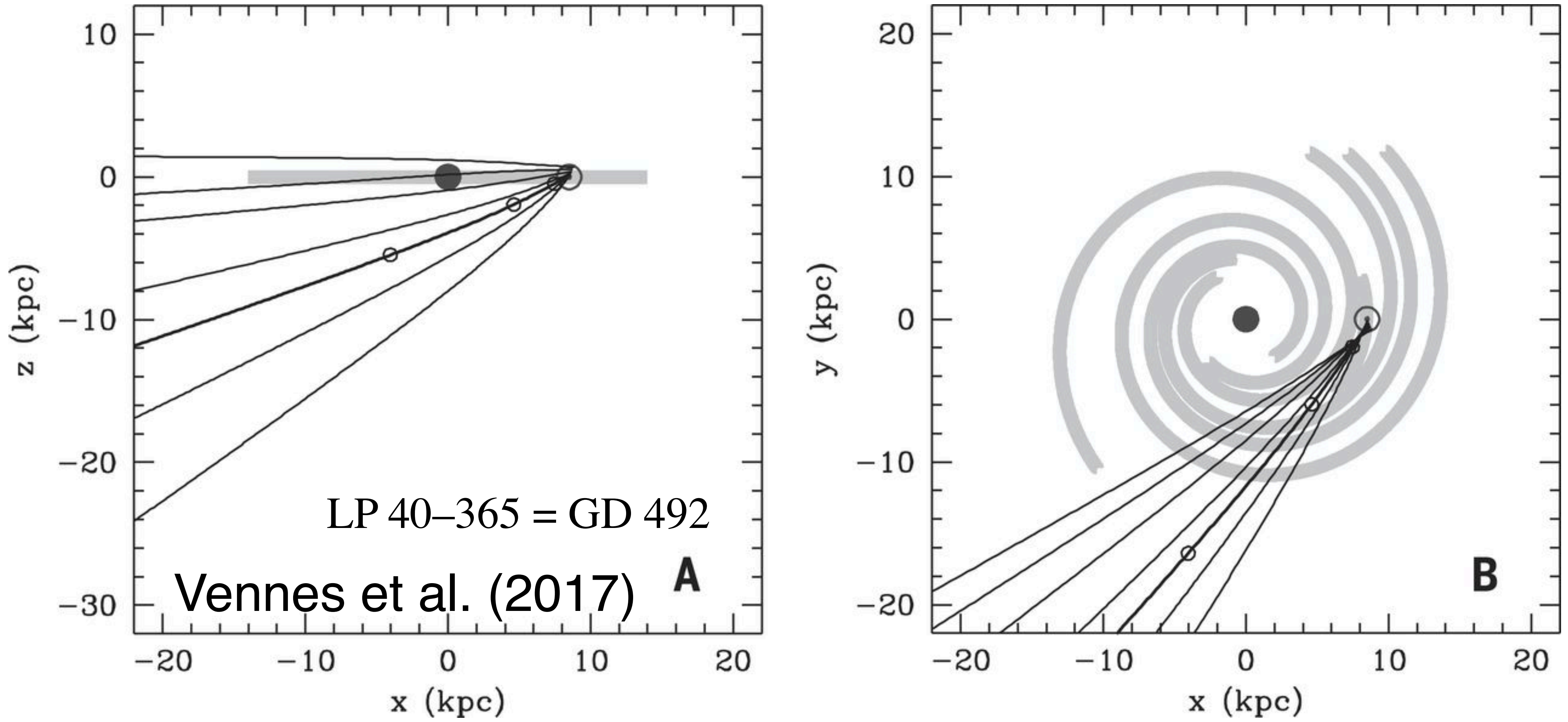


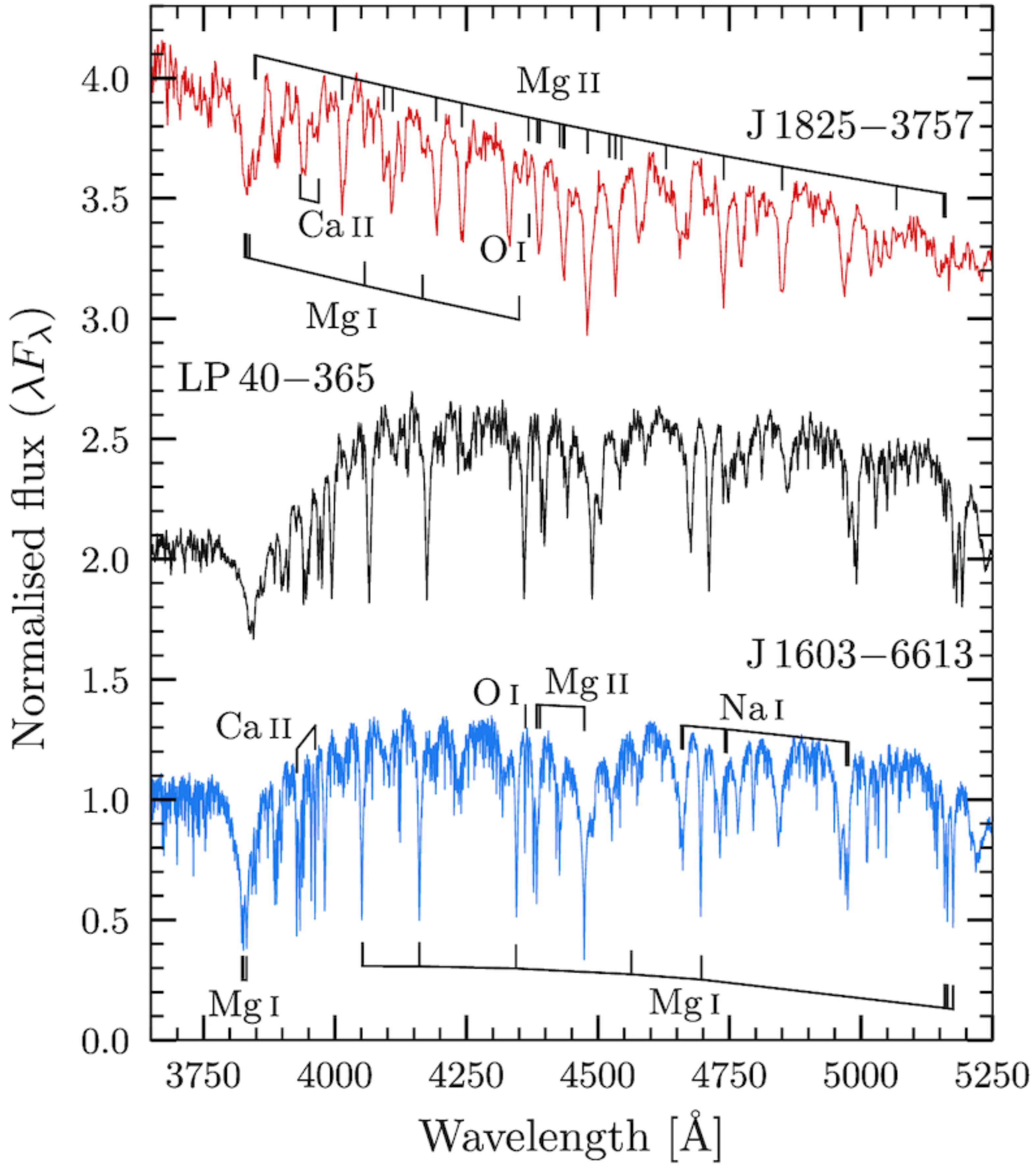


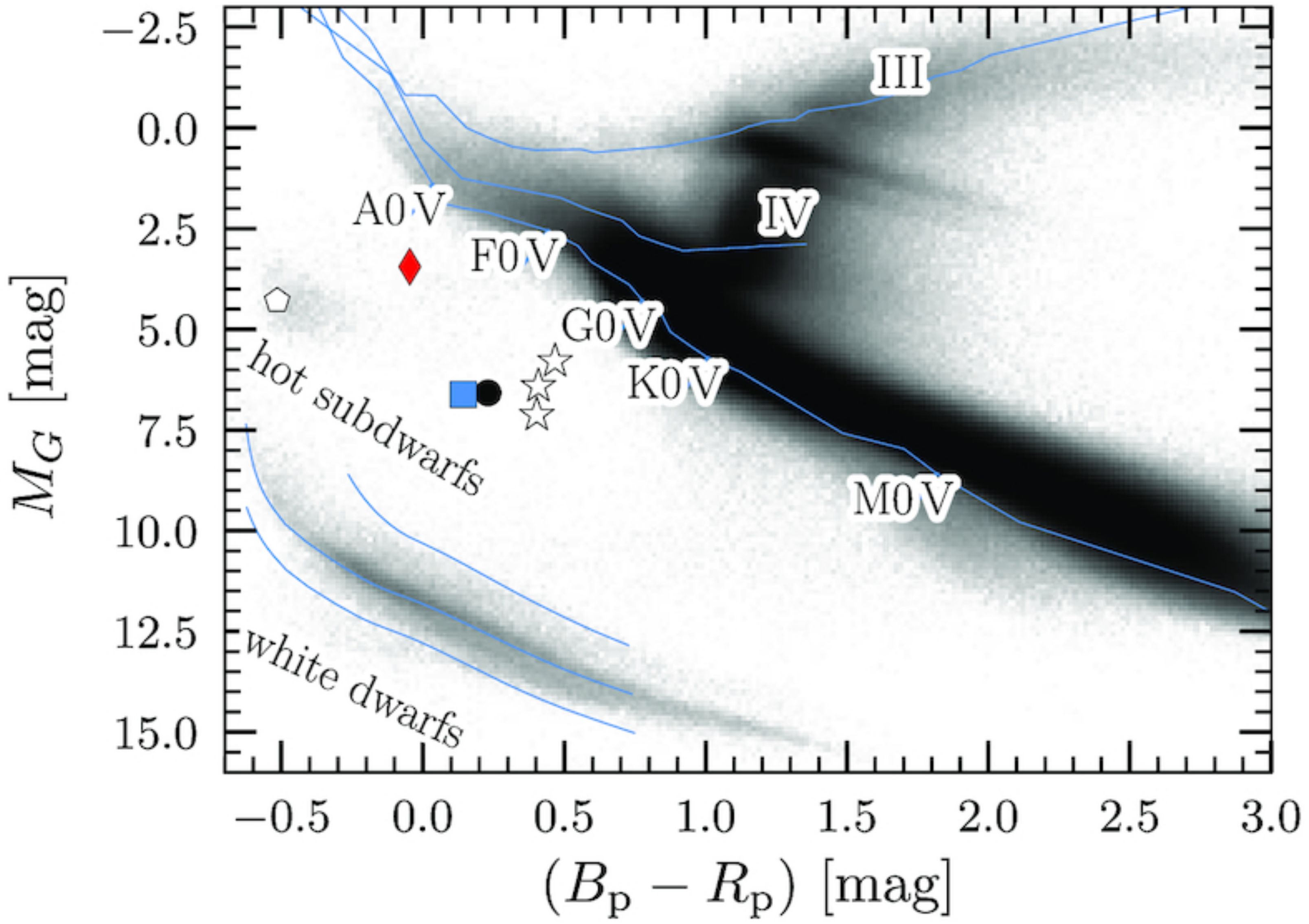
fastest unbound stars in the Galaxy
fleeing the scene of their crime
see also Geier et al. (2015)

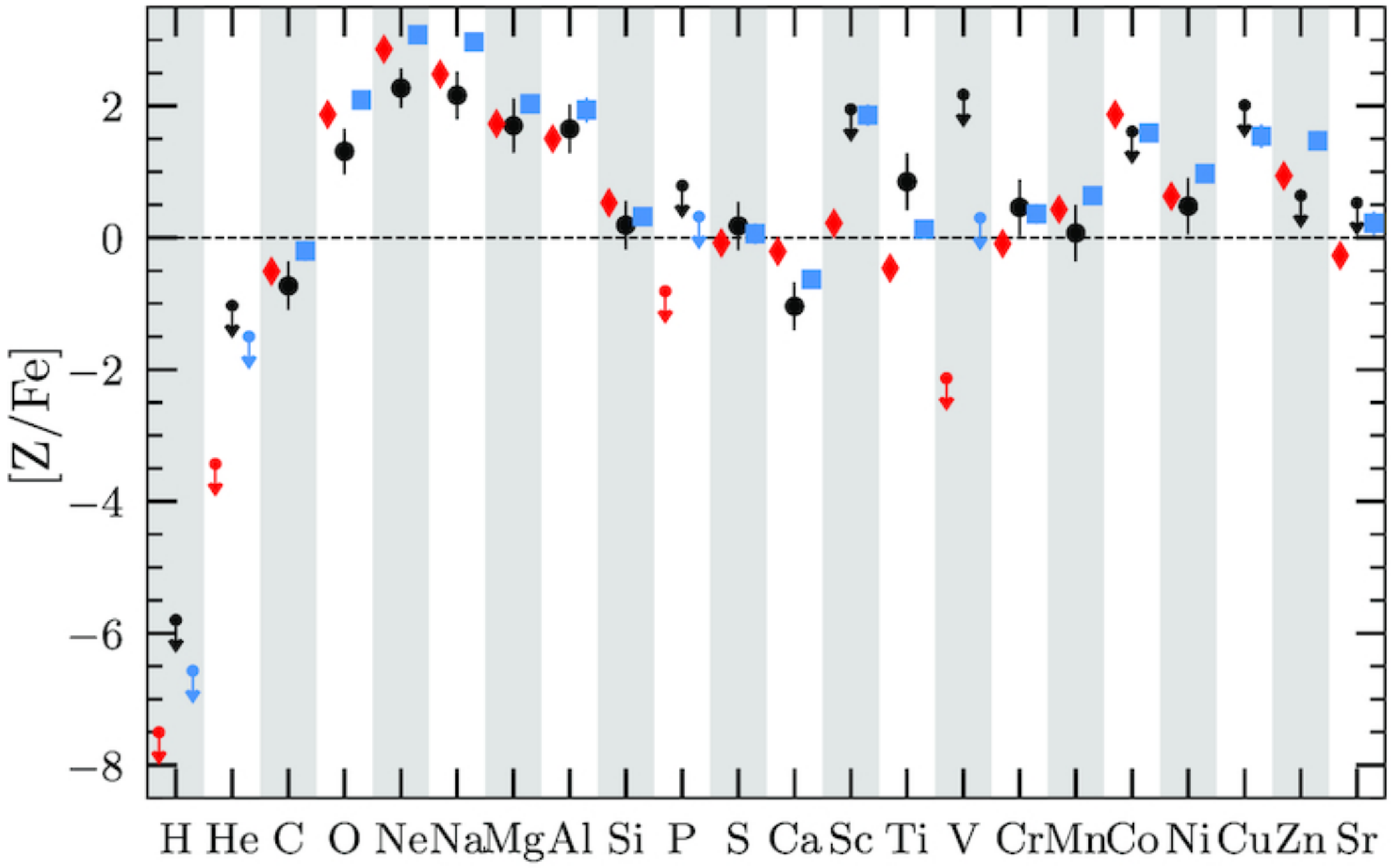
not dead yet: surviving the explosion?

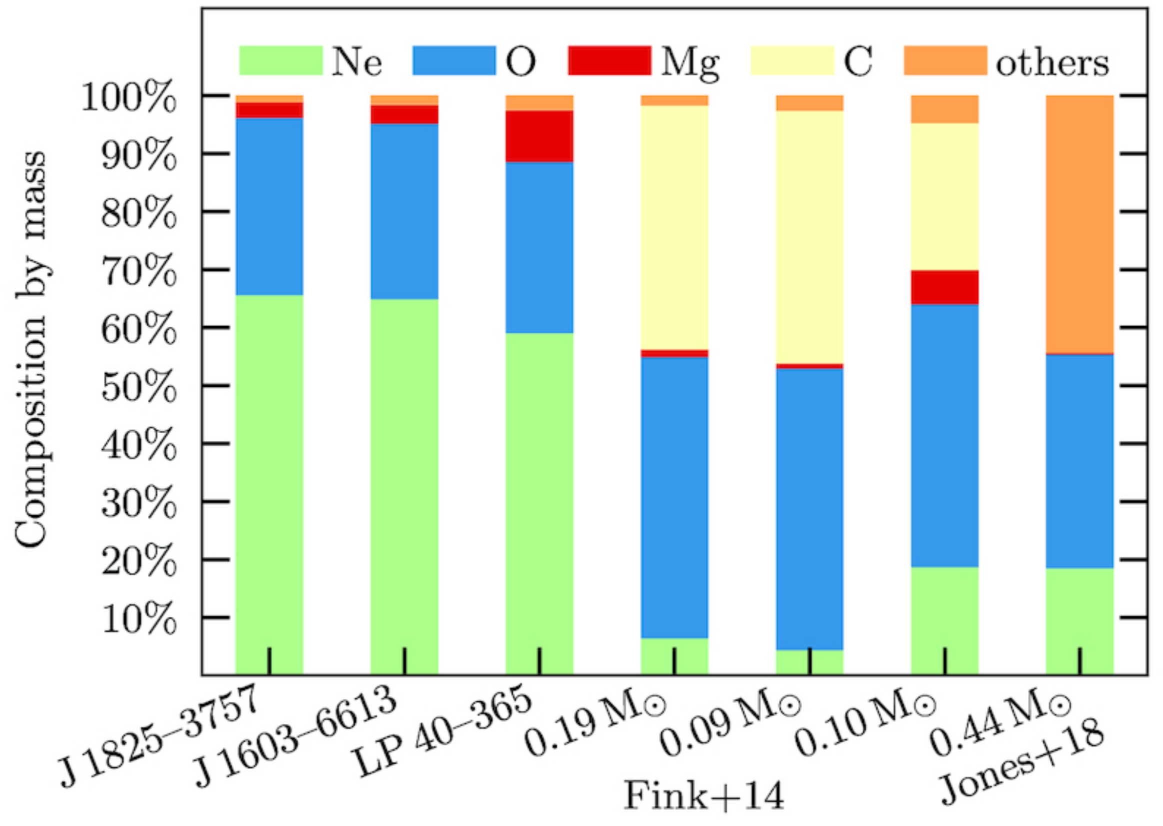
Raddi et al. (2018, 2019)











runaway partially-burnt remnants of WDSN (lax?)

predicted by Jordan et al. (2012)

other cases? Ruffini & Casey 2019, Oskinova et al. 2020

more observational constraints on progenitors and explosions

SN Ia rates
delay-time distribution
rates in different environments

nucleosynthesis
cosmic abundances
stable Fe-group isotopes (M_{Ch})

high-velocity features
nebular line shifts
stratification/tomography

supernova remnants
composition/abundances/structure
search for companion stars
light echos

circumstellar/interstellar absorption

signatures of unburned material

polarization

ultraviolet
near-infrared
mid-infrared (soon JWST!!)

very late-time decay
infrared plateau

deep, rich connections between
white dwarf astrophysics ⟷ supernova astrophysics ⟷ SN Ia distances & cosmology