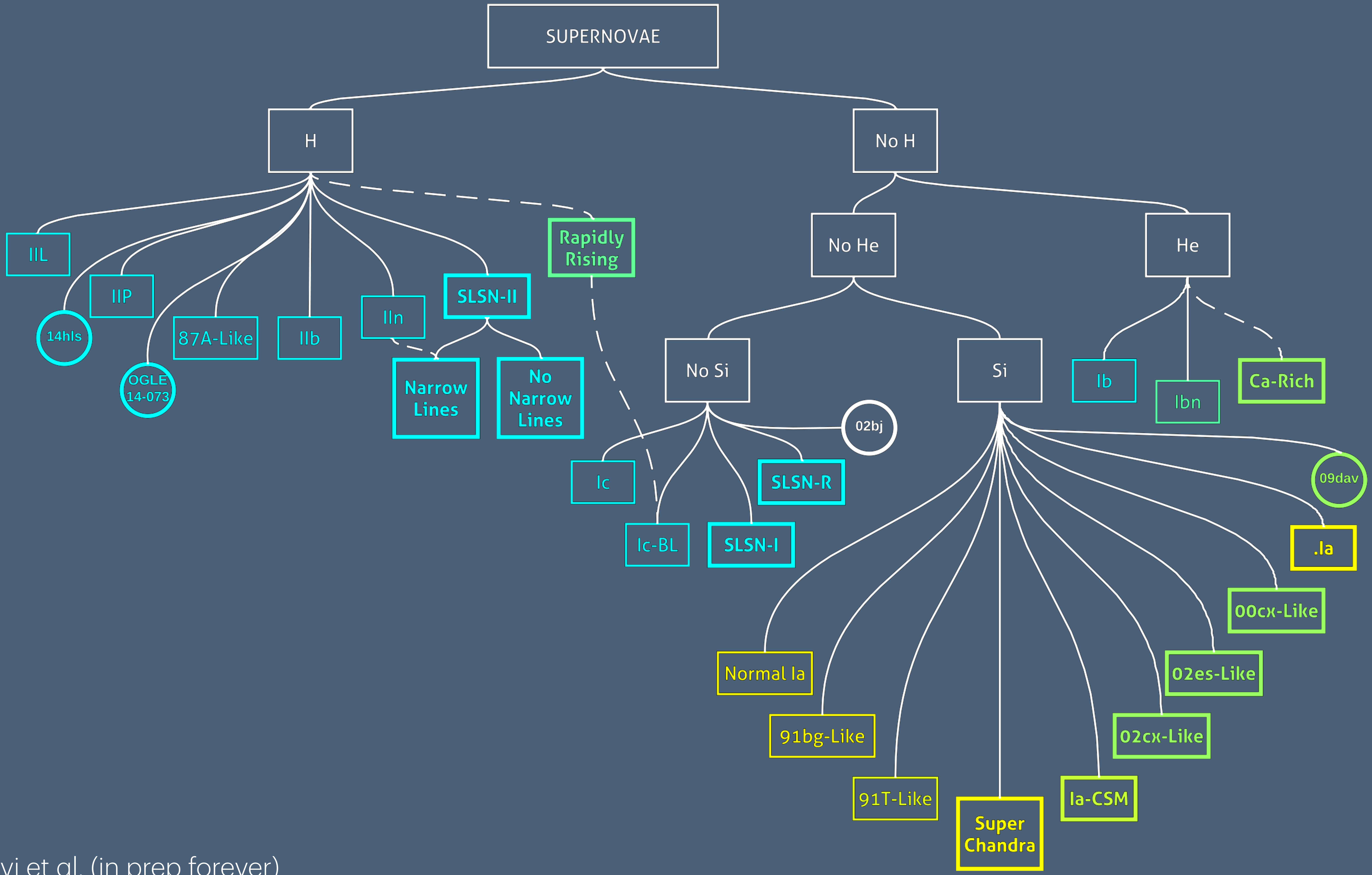
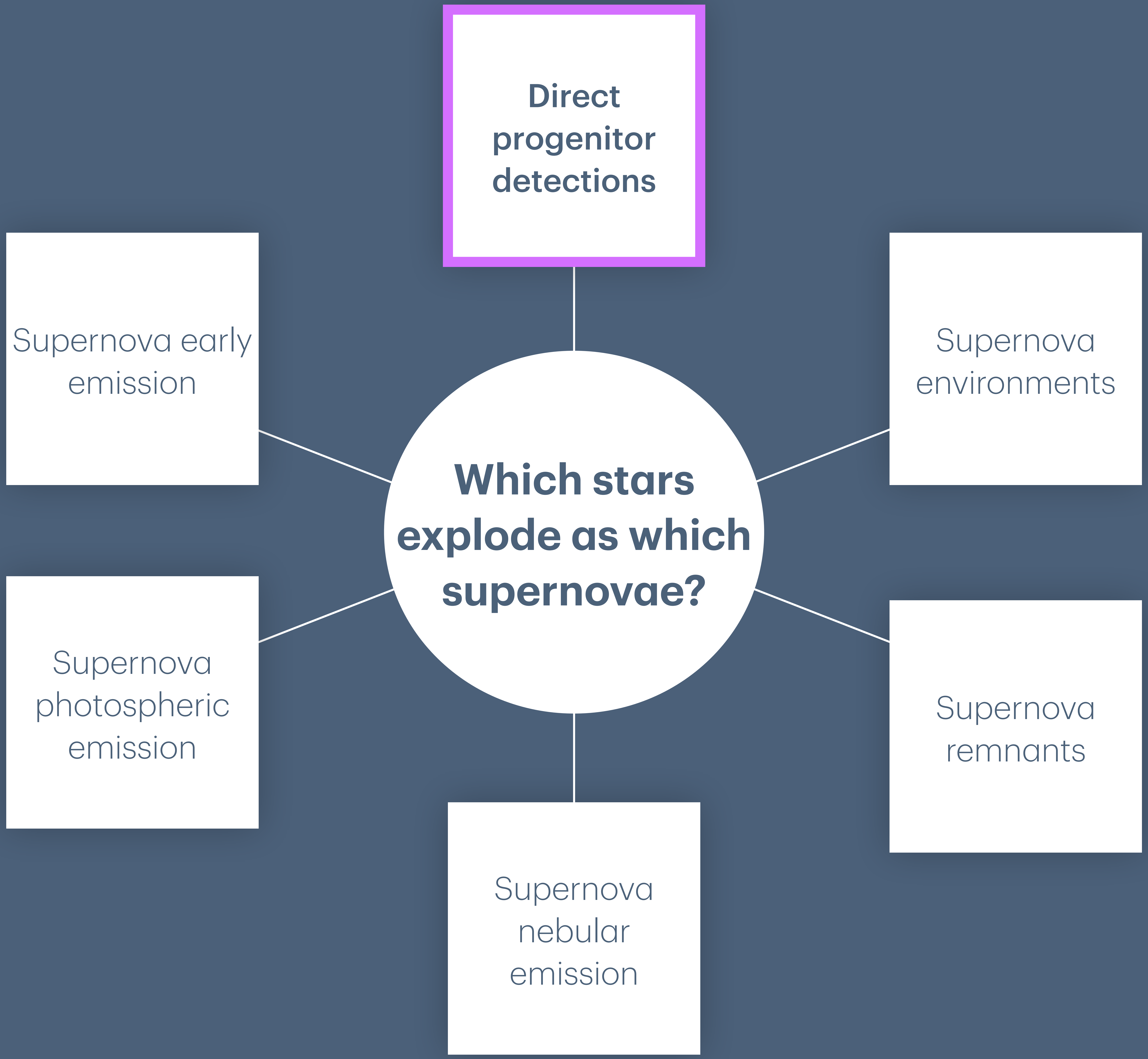
Supernova Progenitor & Explosion Parameters from Observations

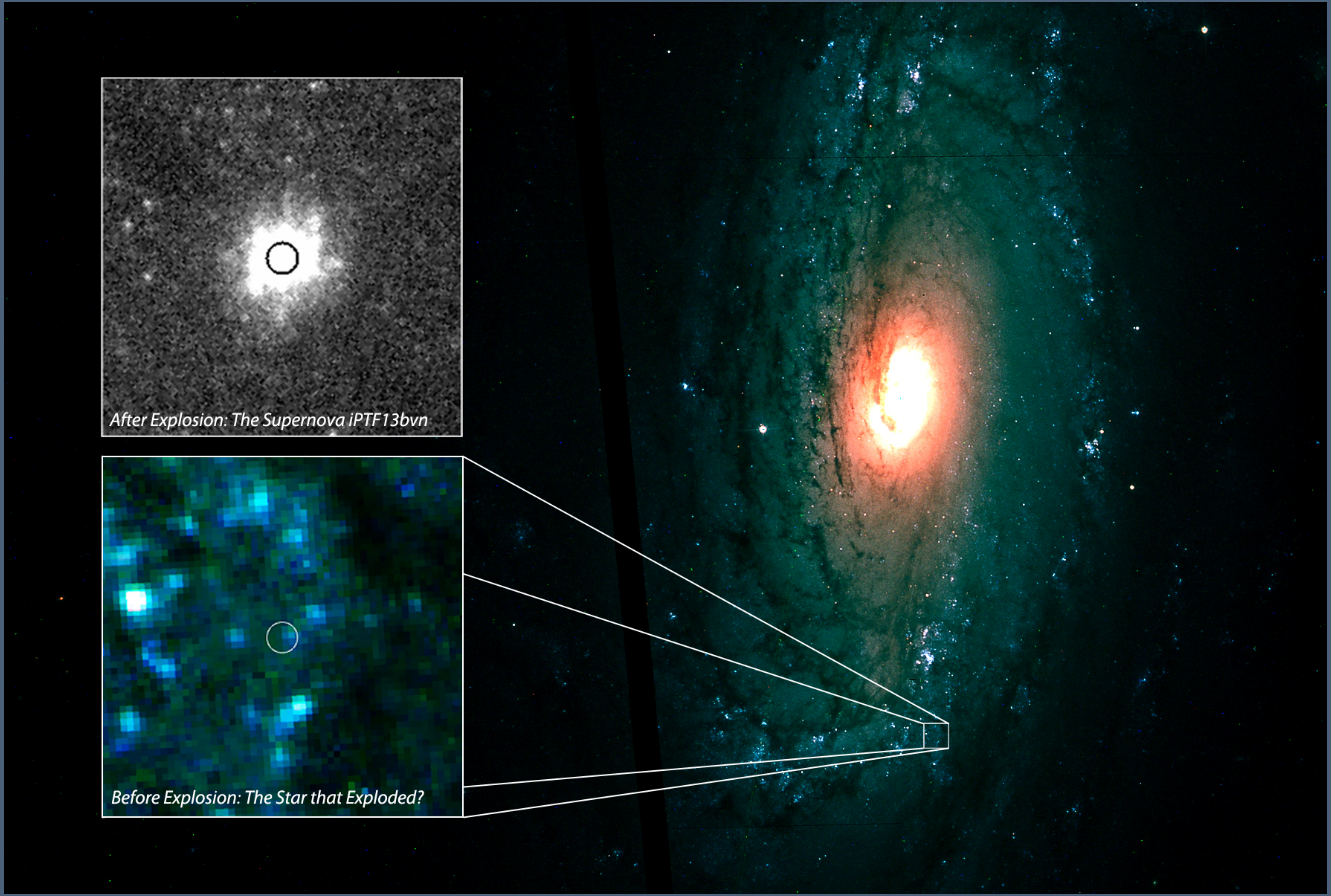
Iair (“ya-eer”) Arcavi, Tel Aviv University



Arcavi et al. (in prep forever)

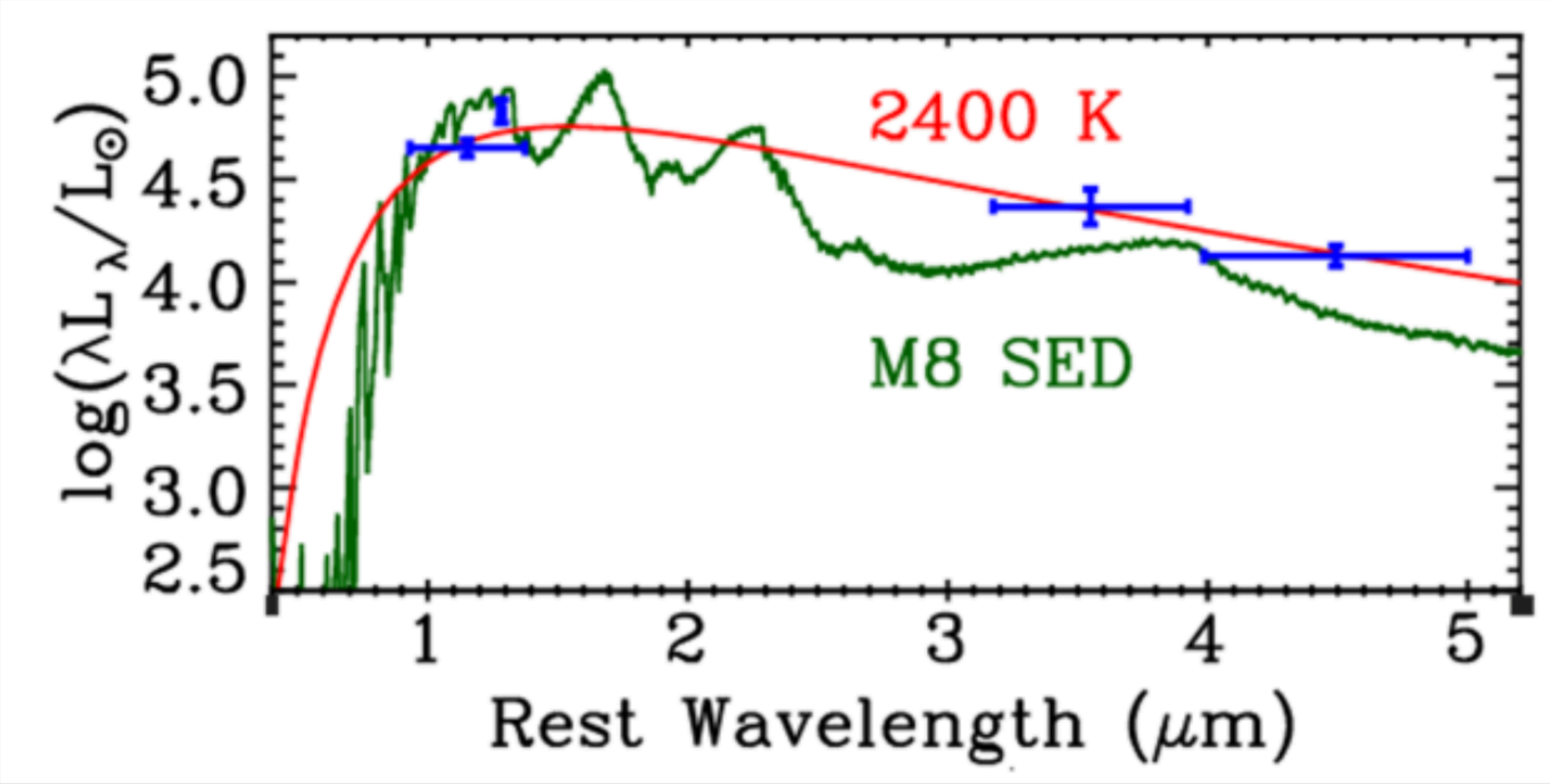

Direct progenitor detections
Supernova early emission
Supernova environments
Which stars explode as which supernovae?
Supernova photospheric emission
Supernova remnants
Supernova nebular emission

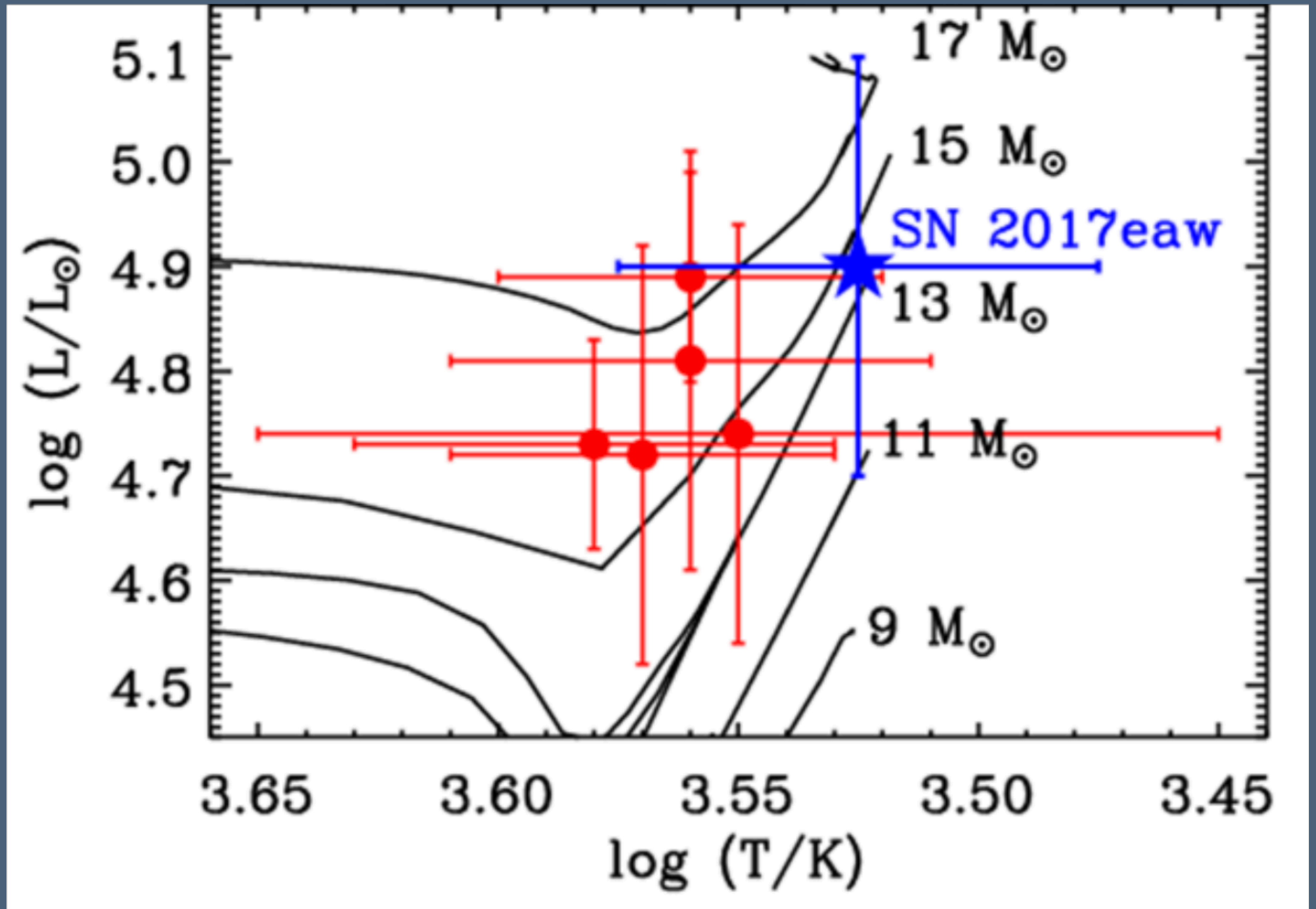
Direct progenitor detection

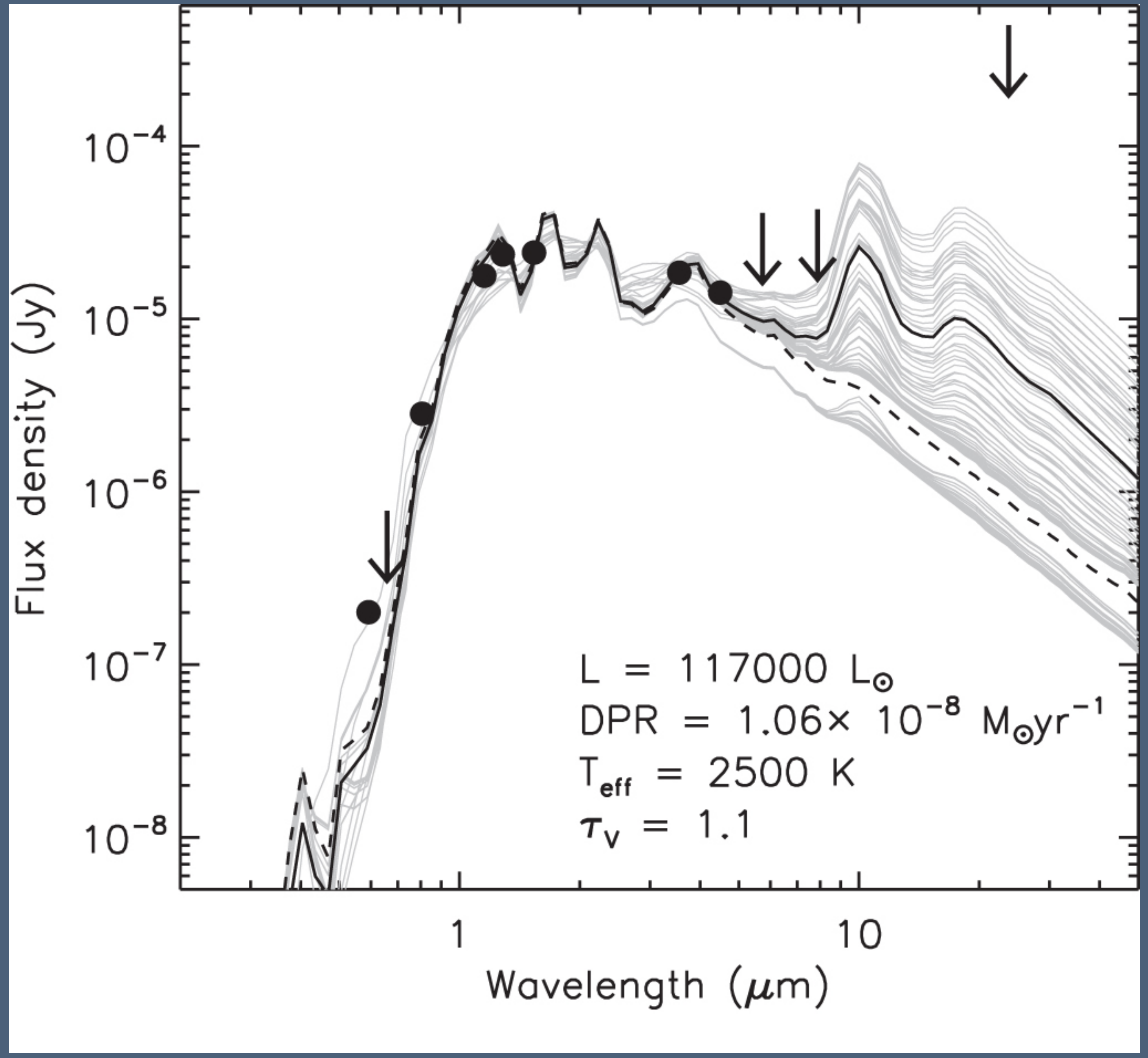


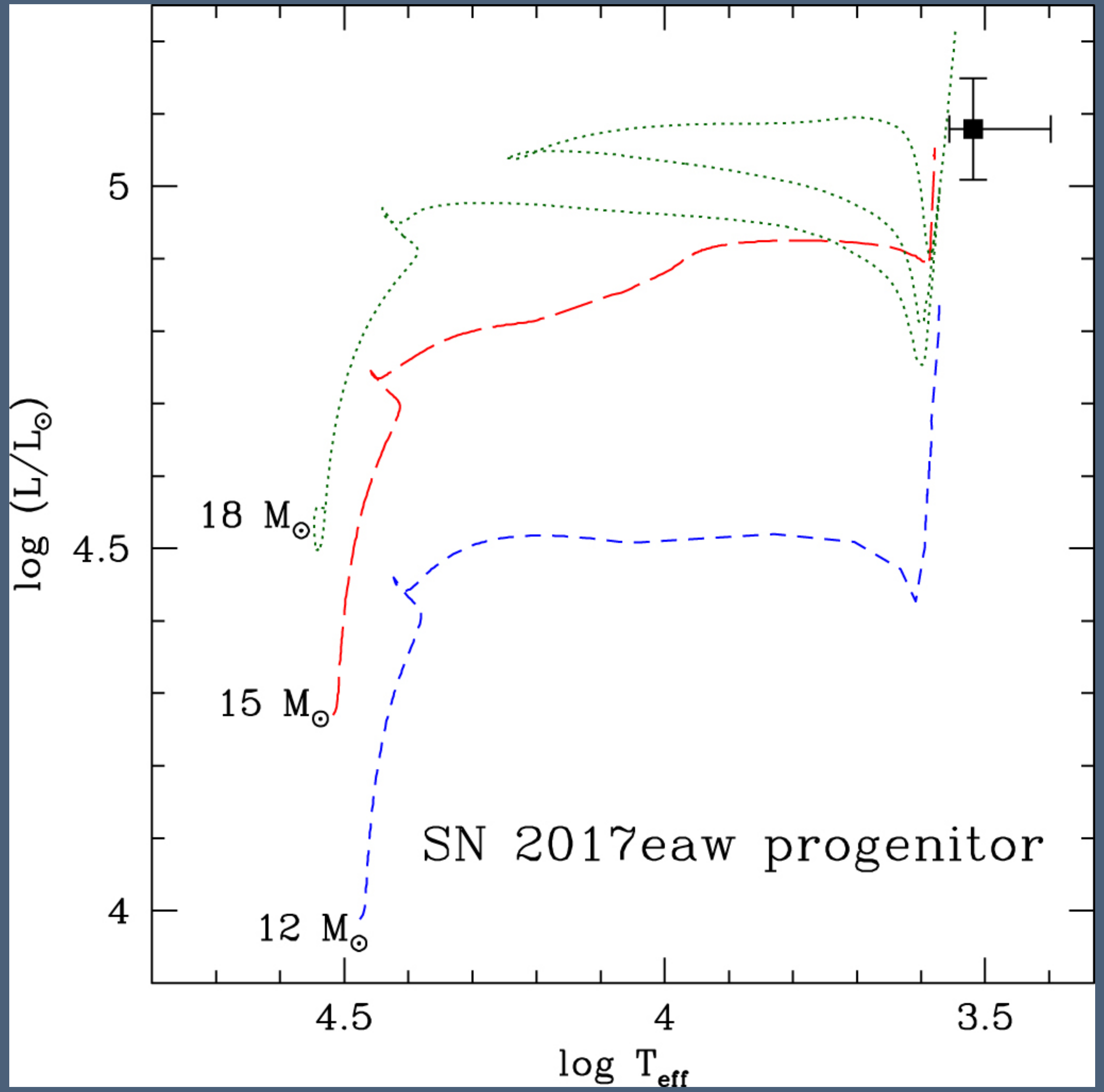
Cao, Kasliwal, Arcavi et al. (2013)

Typically: find **a** stellar model that reproduces the star





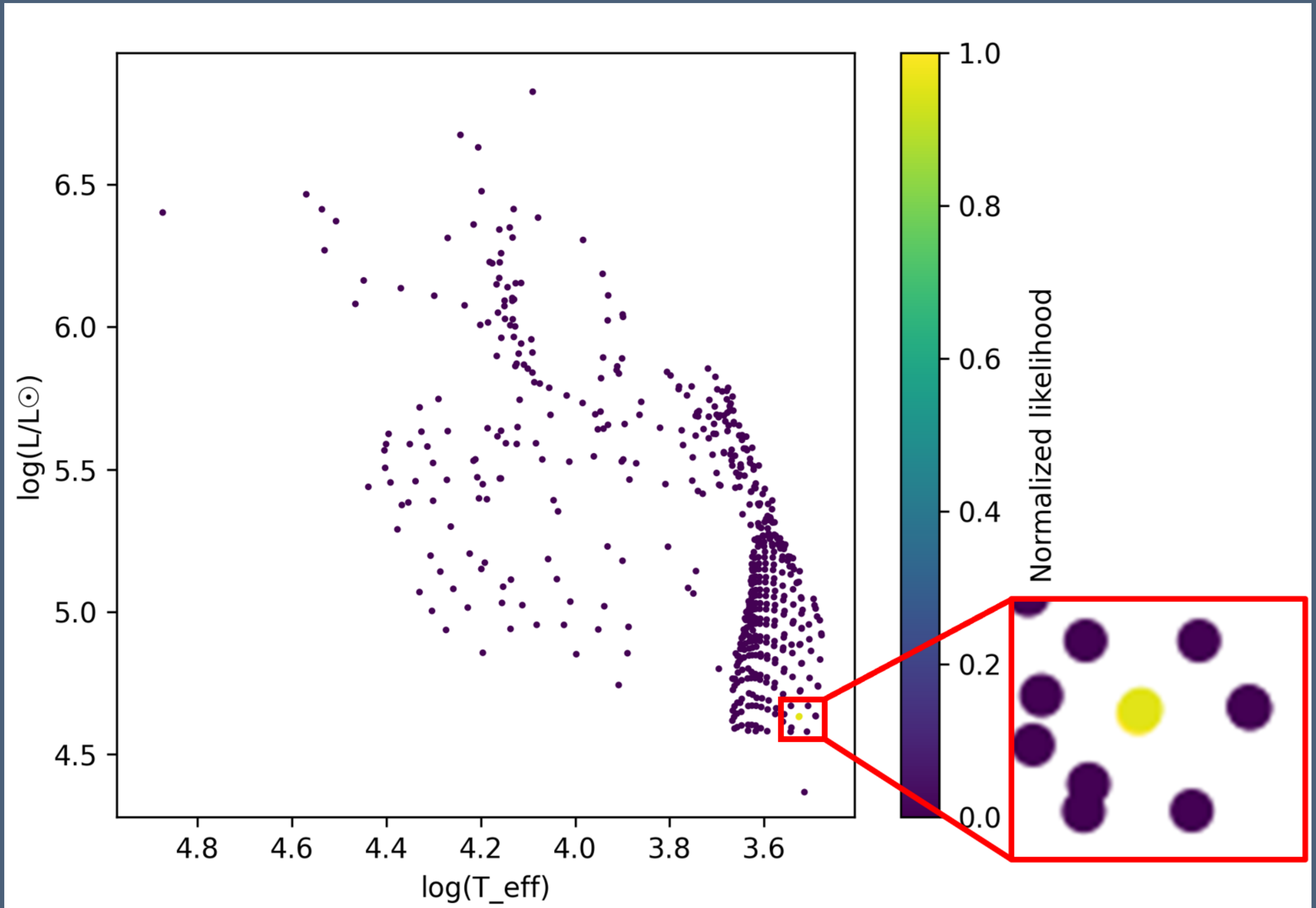




Van Dyk et al. (2018)

Kilpatrick & Foley (2018)

ProgenIt: Fit to grid of models with priors

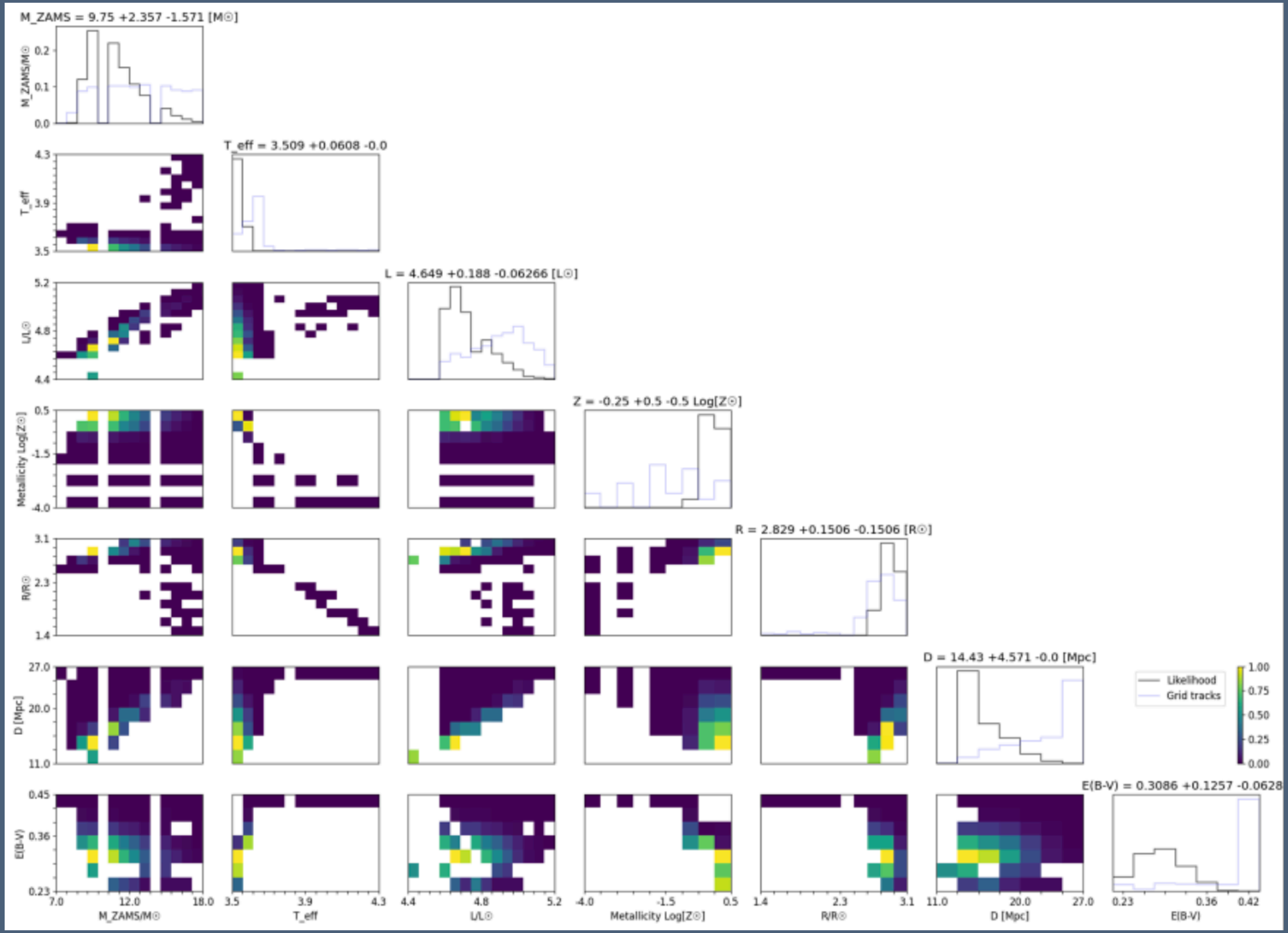


Katz & Arcavi (in prep)

Tomer Katz

MIST grid of MESA models
(Choi et al. 2016)

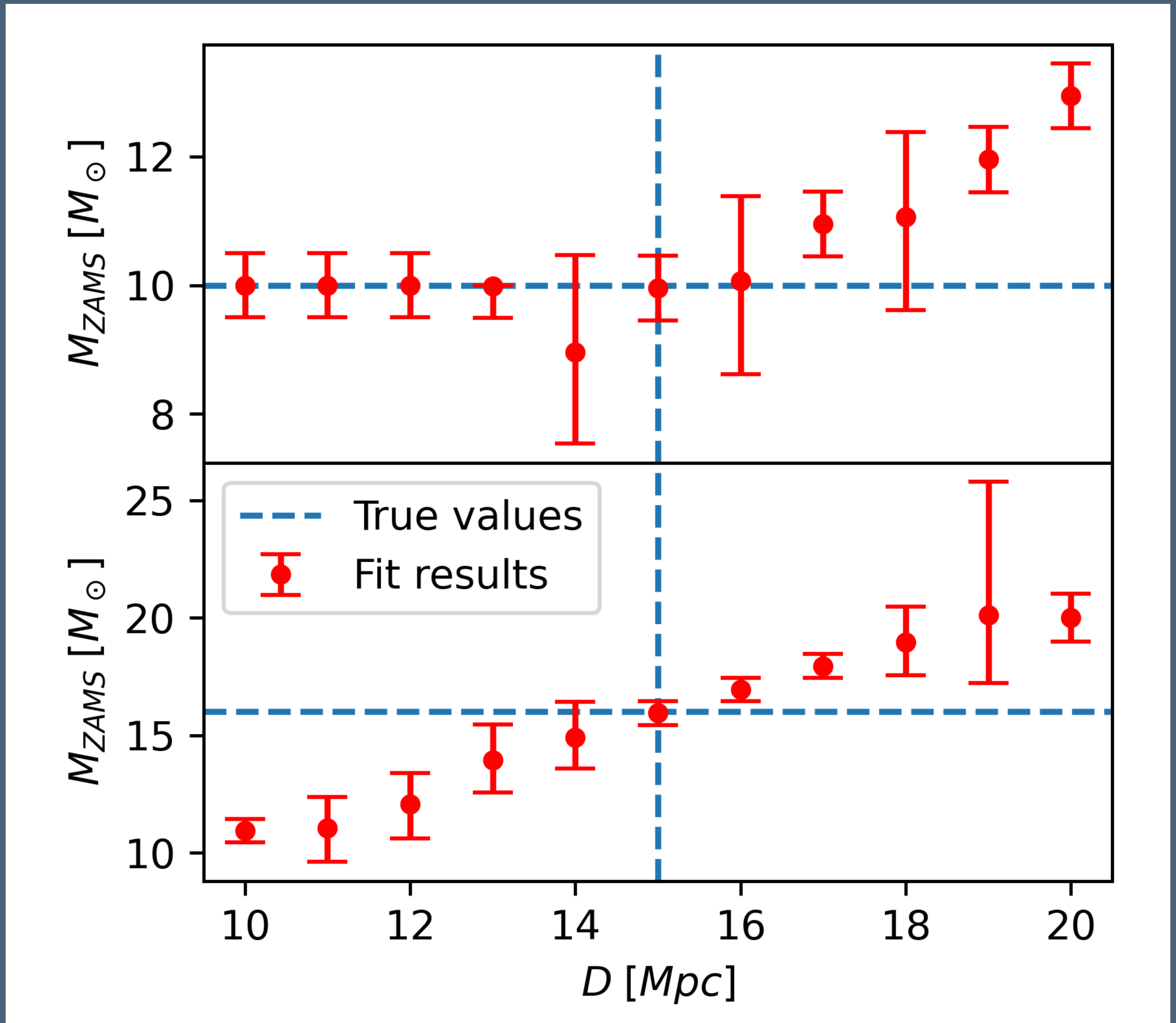
ProgenIt: Get posteriors, see degeneracies



Katz & Arcavi (in prep)

ProgenIt: Quantify sensitivity to assumptions

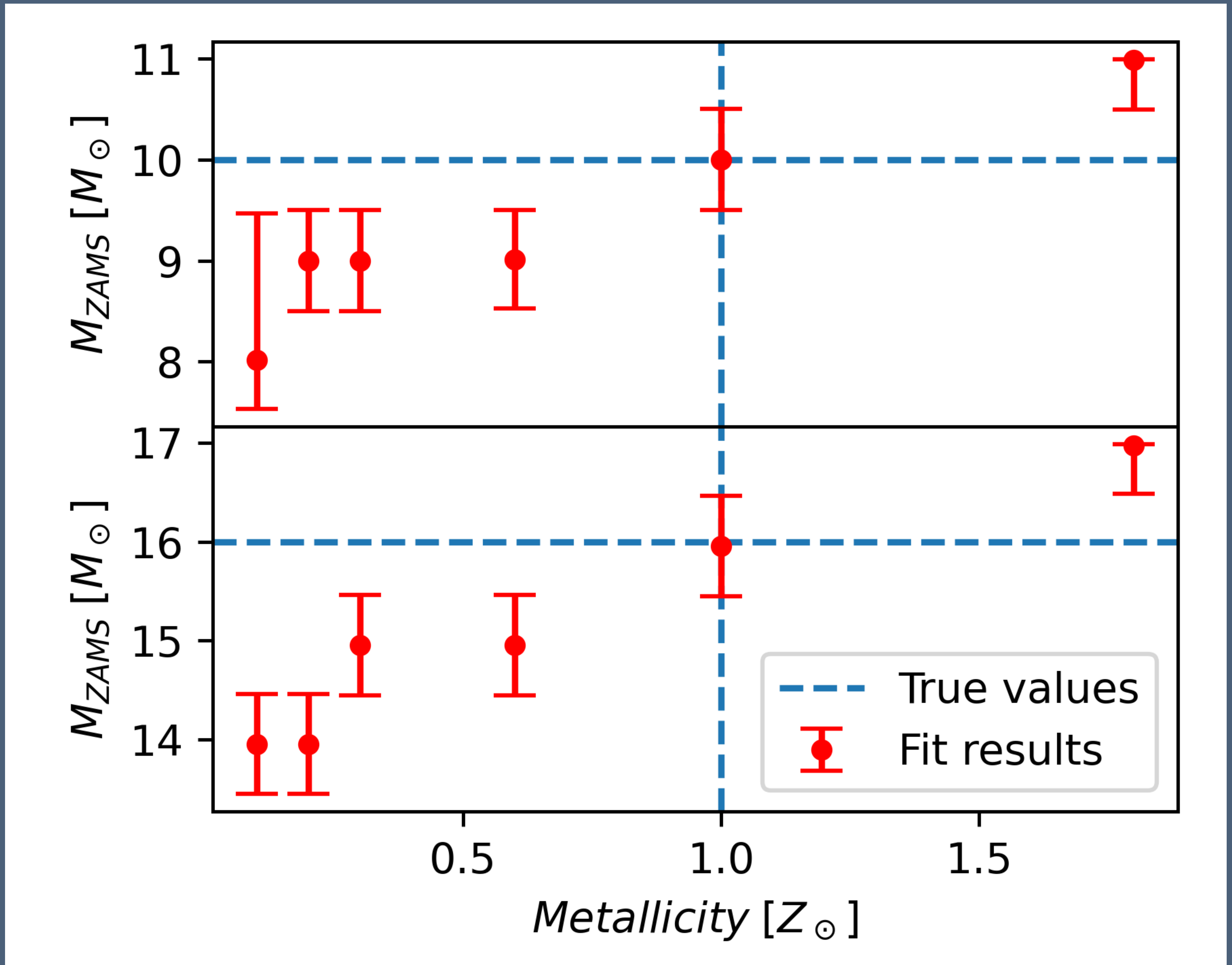
Quantify sensitivity to: assumed distance



Katz & Arcavi (in prep)

ProgenIt: Quantify sensitivity to assumptions

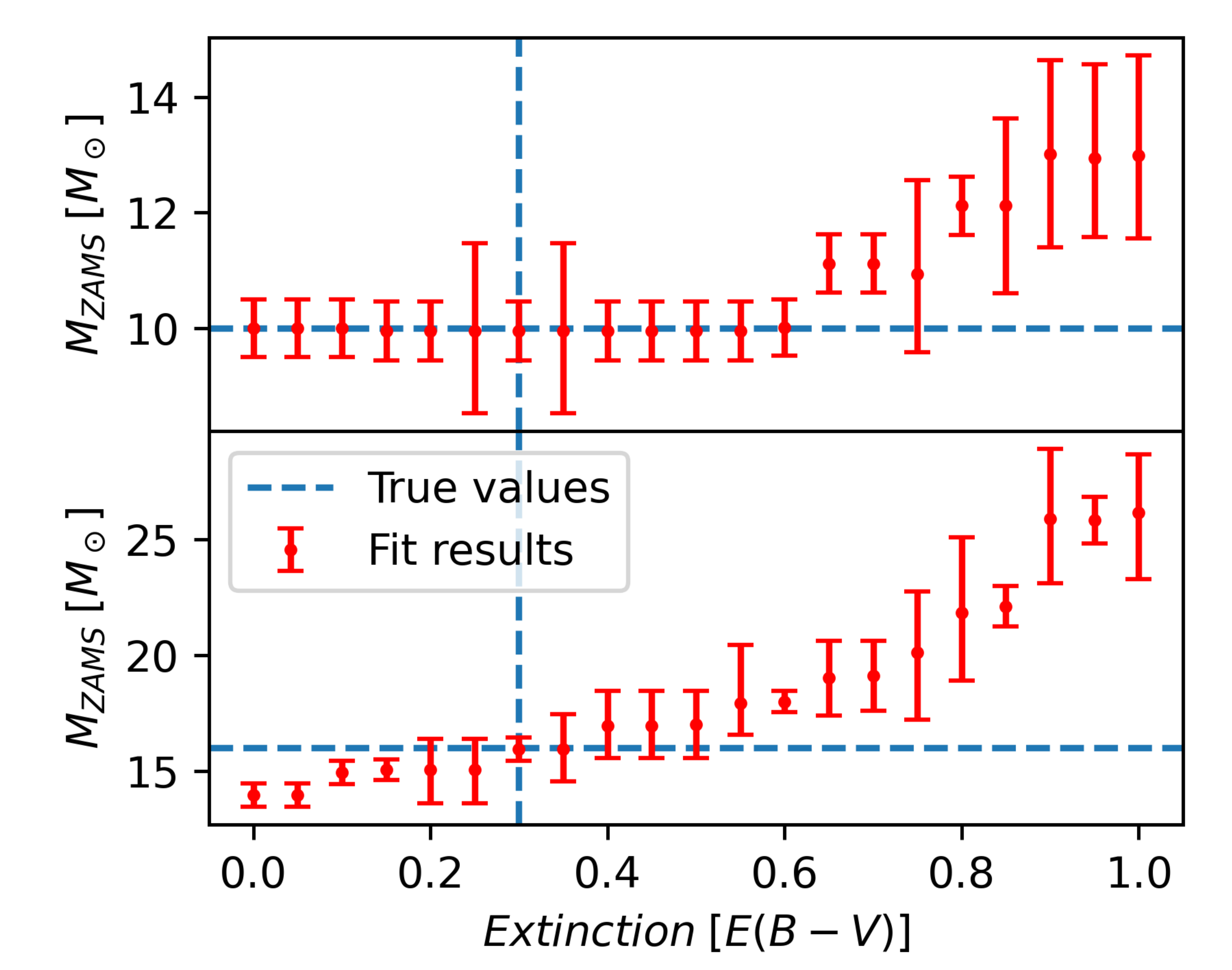
Quantify sensitivity to: assumed metallicity



Katz & Arcavi (in prep)

ProgenIt: Quantify sensitivity to assumptions

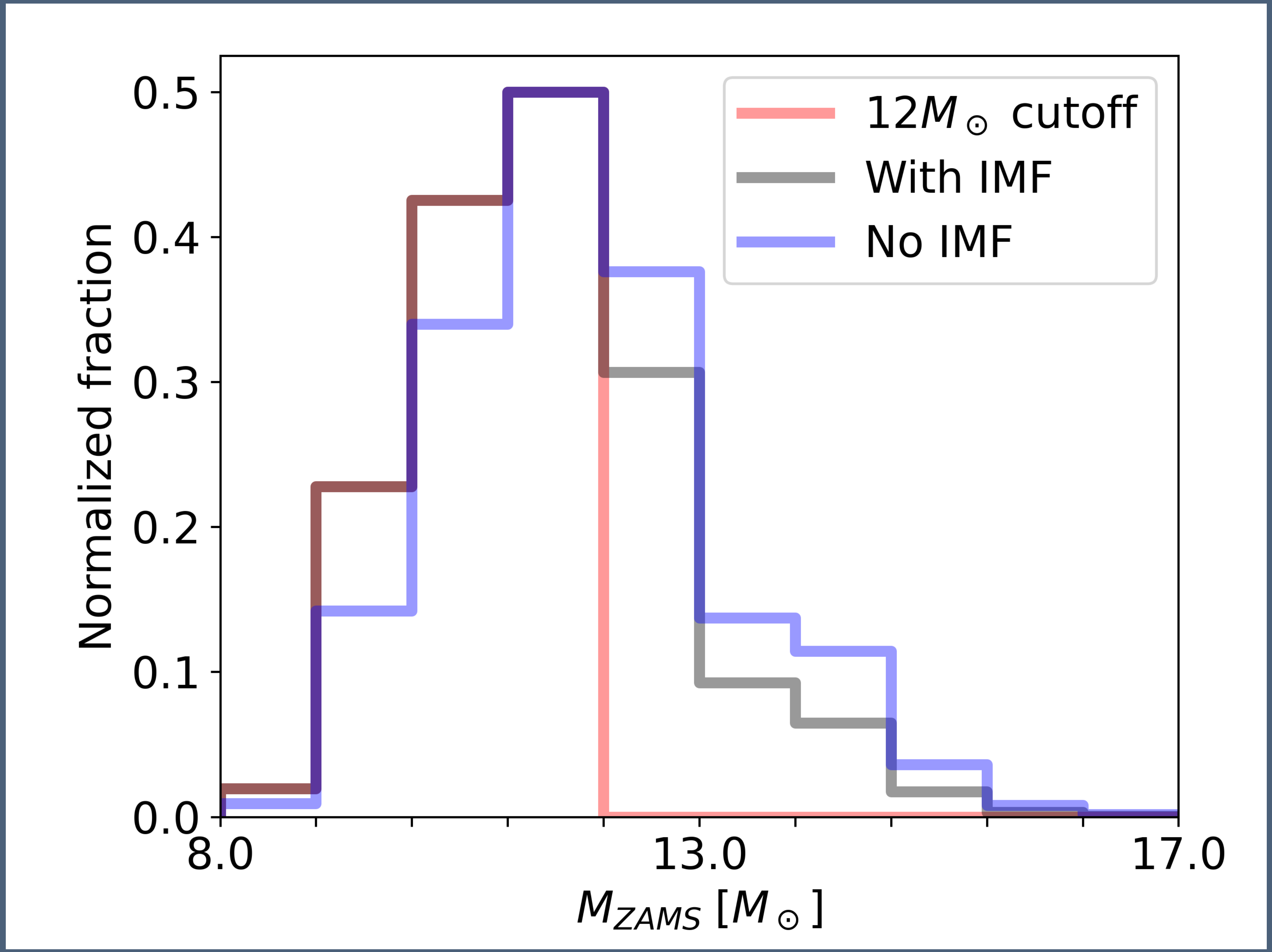
Quantify sensitivity to: assumed extinction



Katz & Arcavi (in prep)

ProgenIt: Quantify sensitivity to assumptions

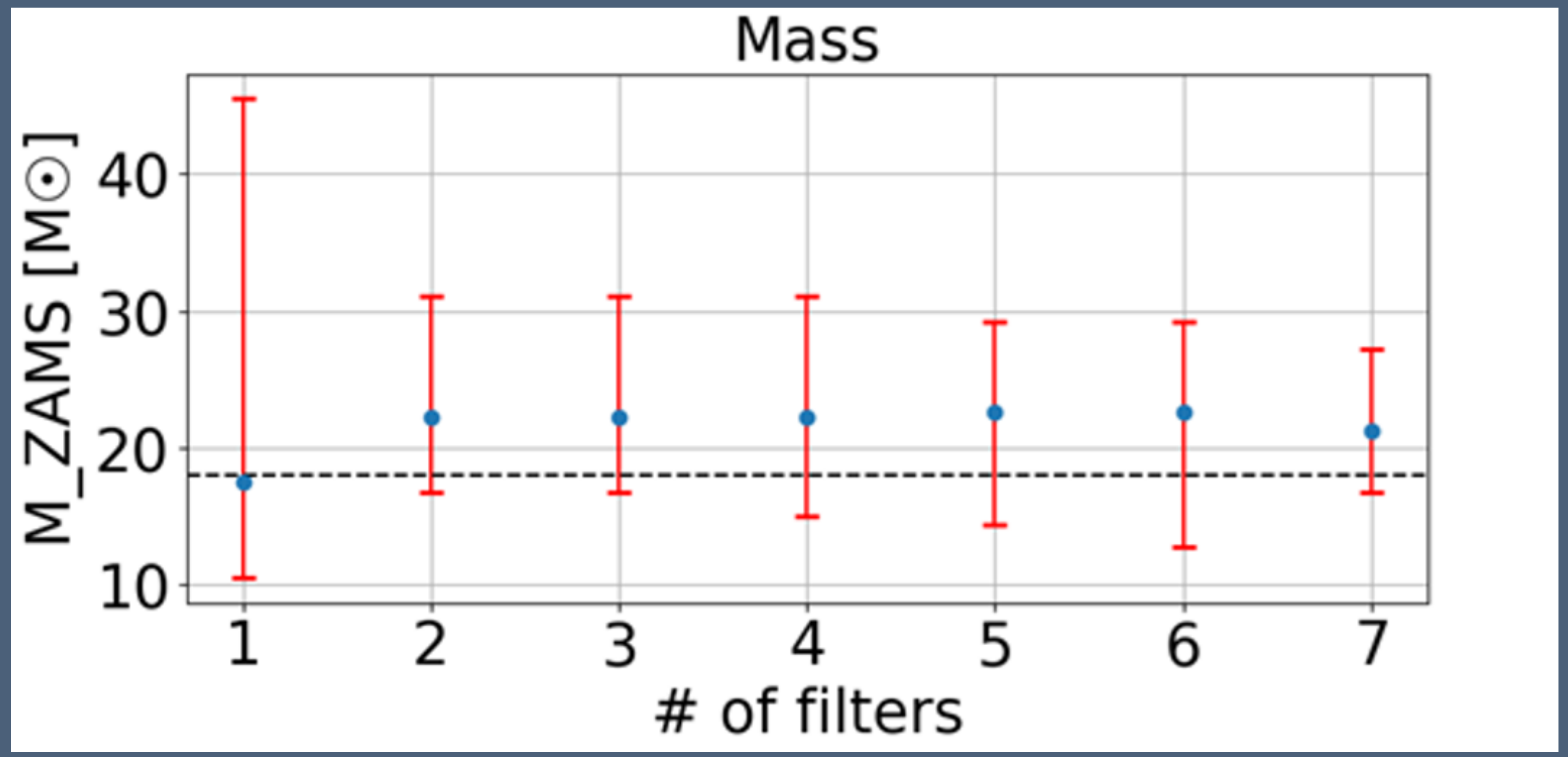
Quantify sensitivity to: mass prior

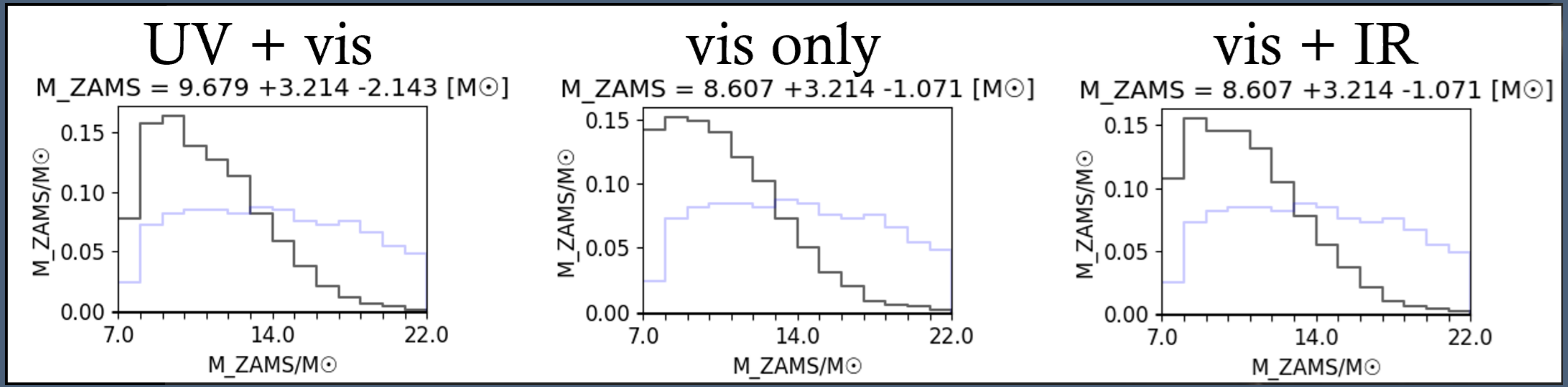


Katz & Arcavi (in prep)

ProgenIt: Quantify sensitivity to assumptions

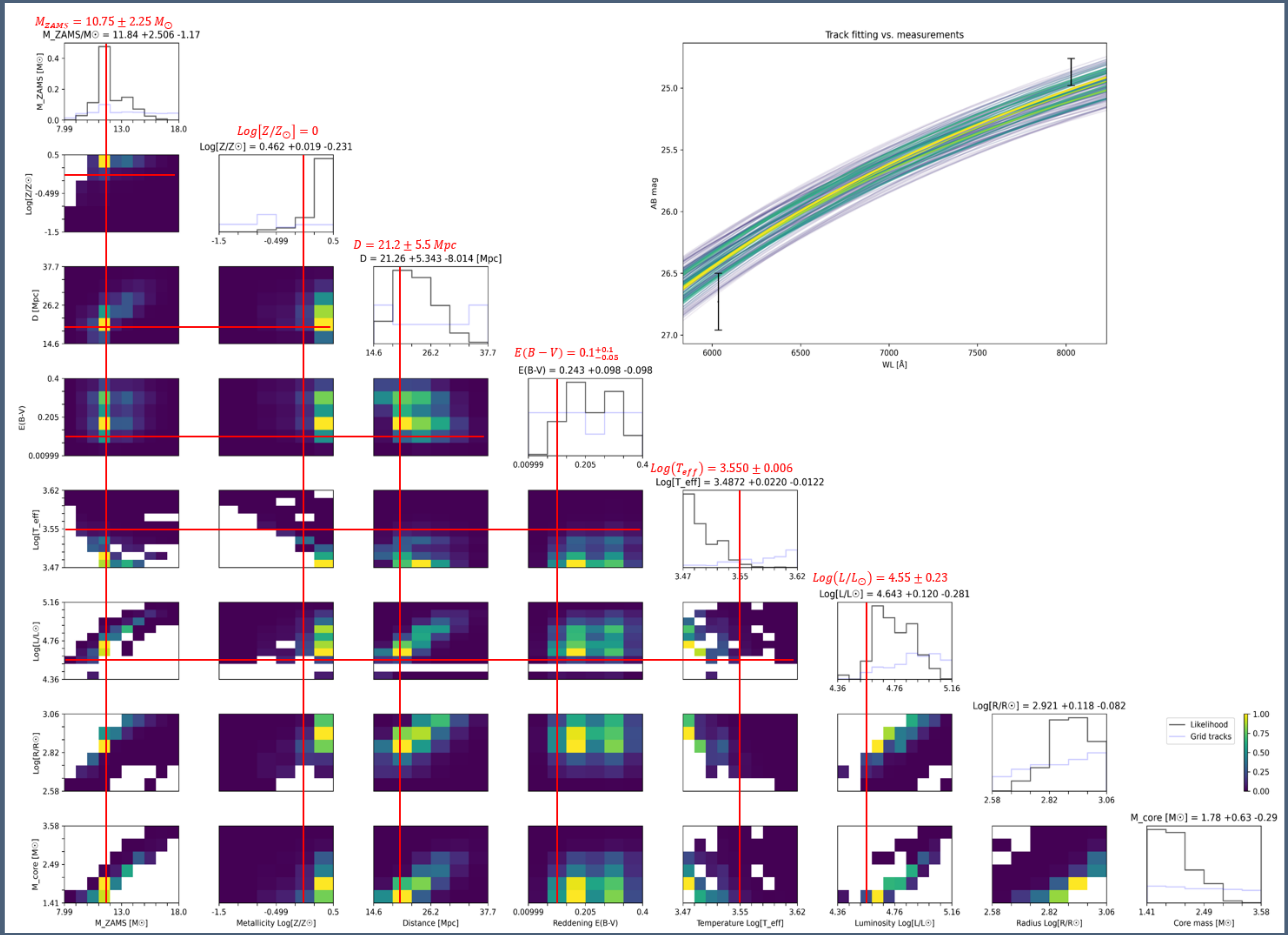
Quantify sensitivity to: observed filters





Katz & Arcavi (in prep)

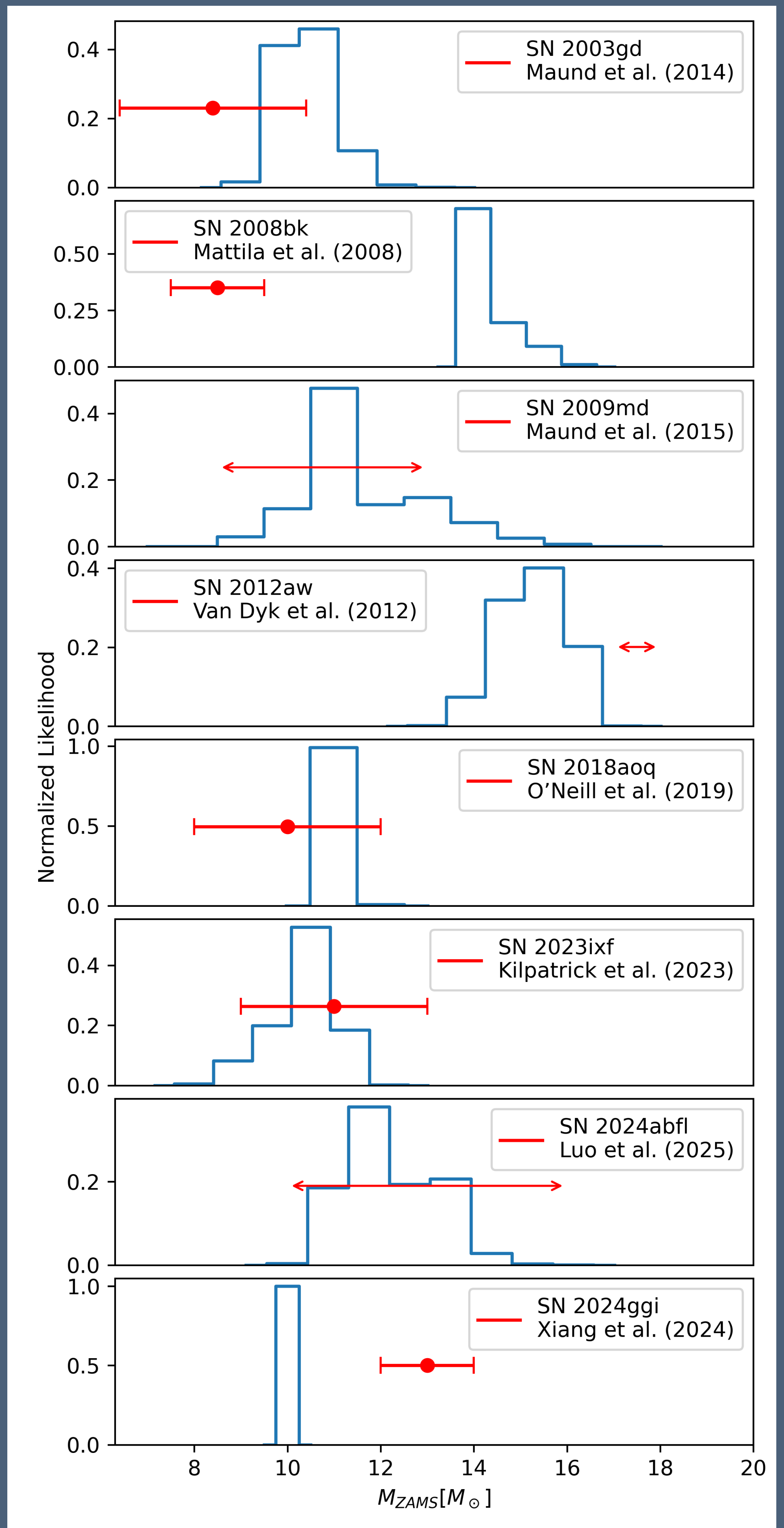
ProgenIt: Get posteriors, see degeneracies

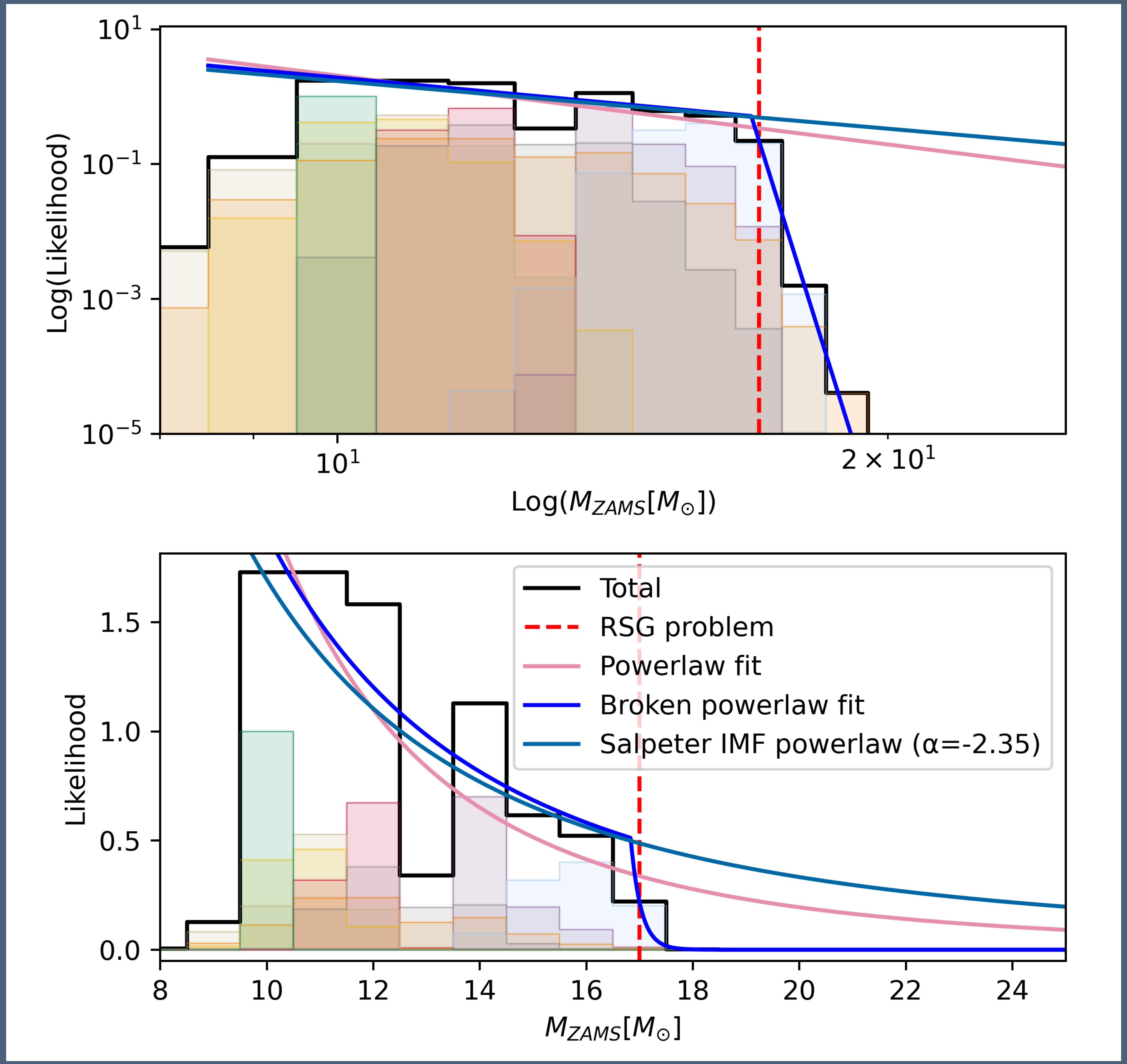


Reproduce published values but now with posterior distributions and degeneracies (and can run with any metallicity, distance, extinction priors)

Katz & Arcavi (in prep)
data from Maund et al. (2015)

Example use: population studies

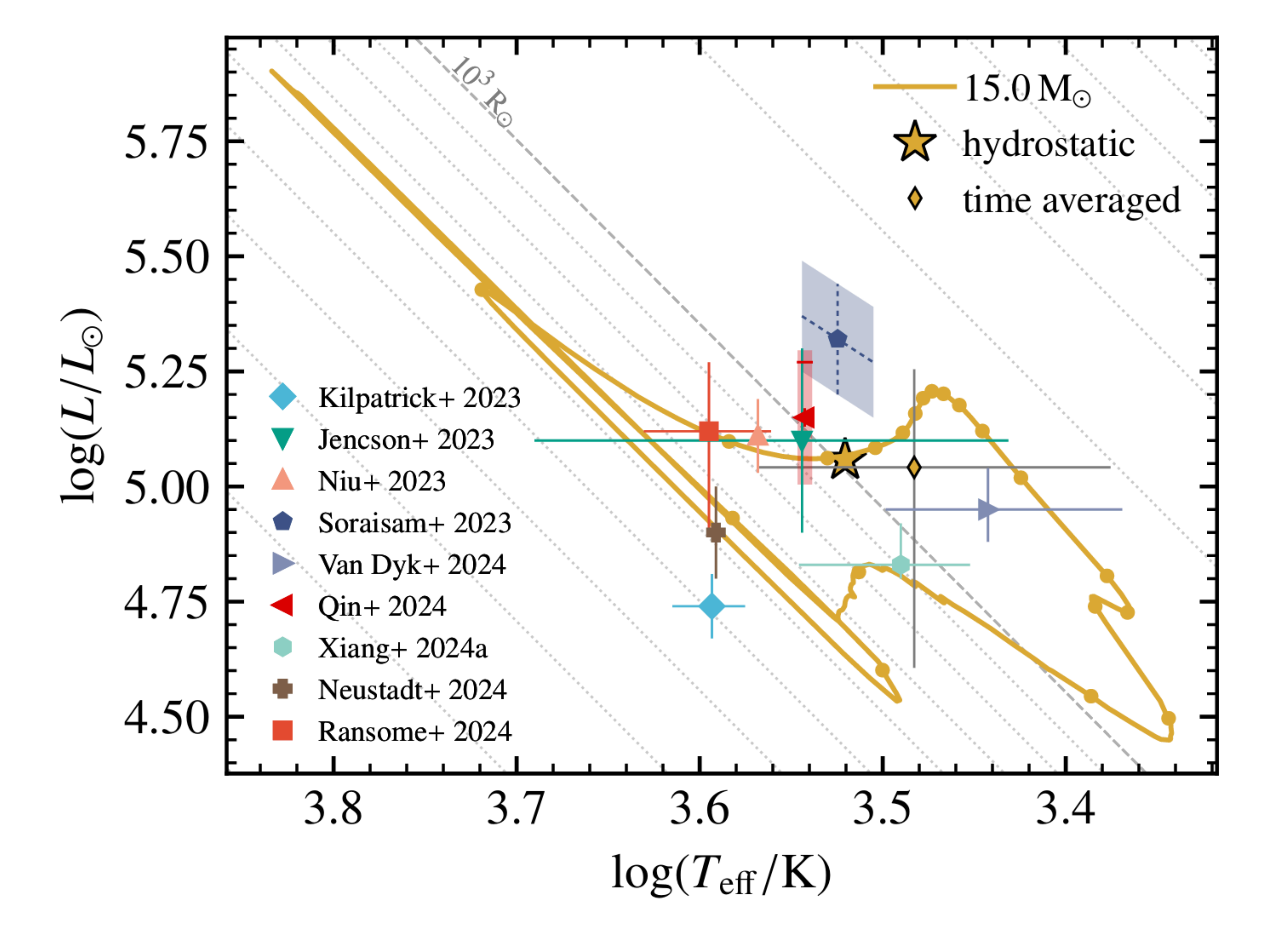




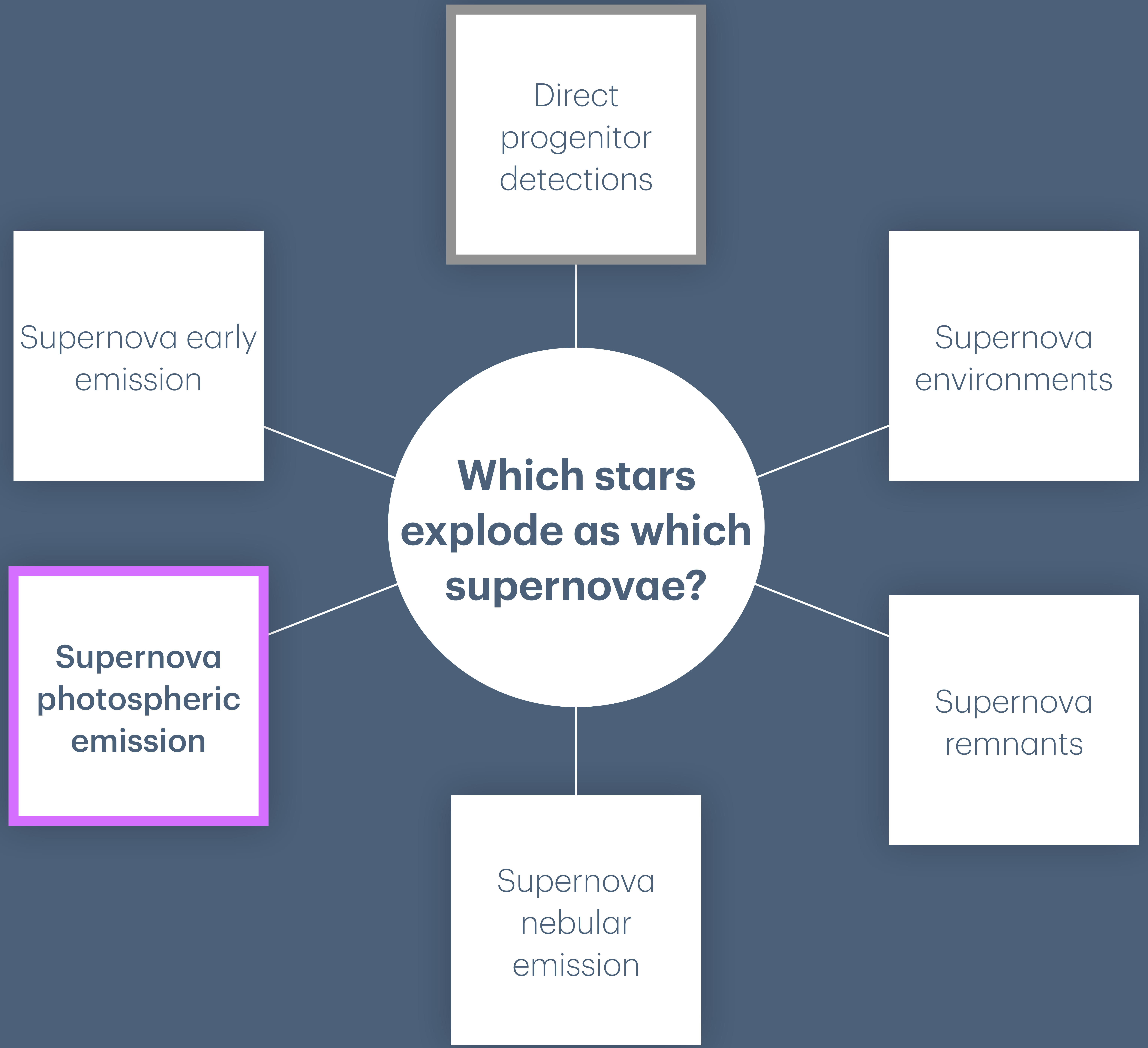
Katz & Arcavi (in prep)

New problem: pre-explosion RSGs don't sit still

(can be incorporated into the Progenit framework)



Laplace et al. (2025)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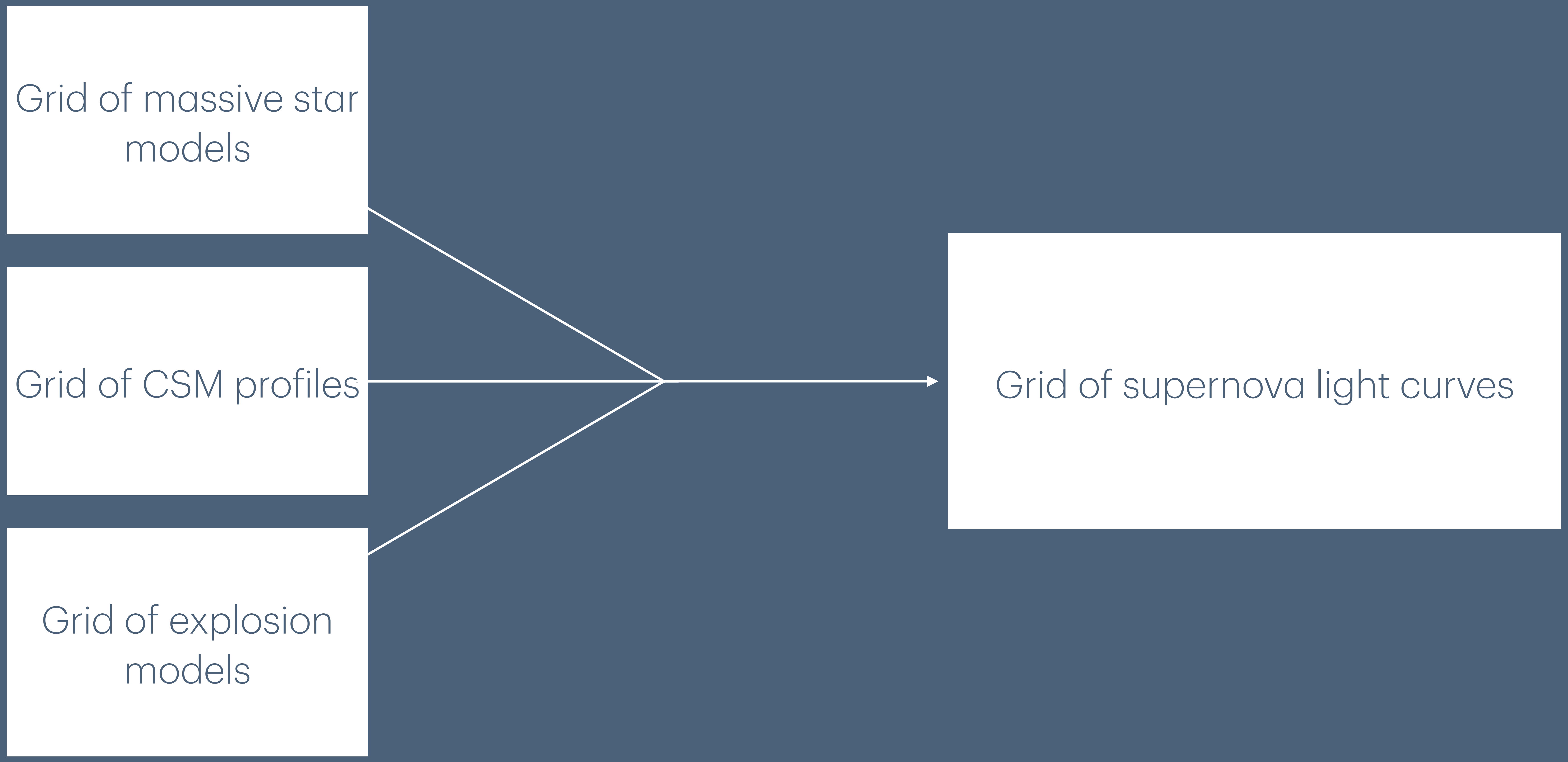
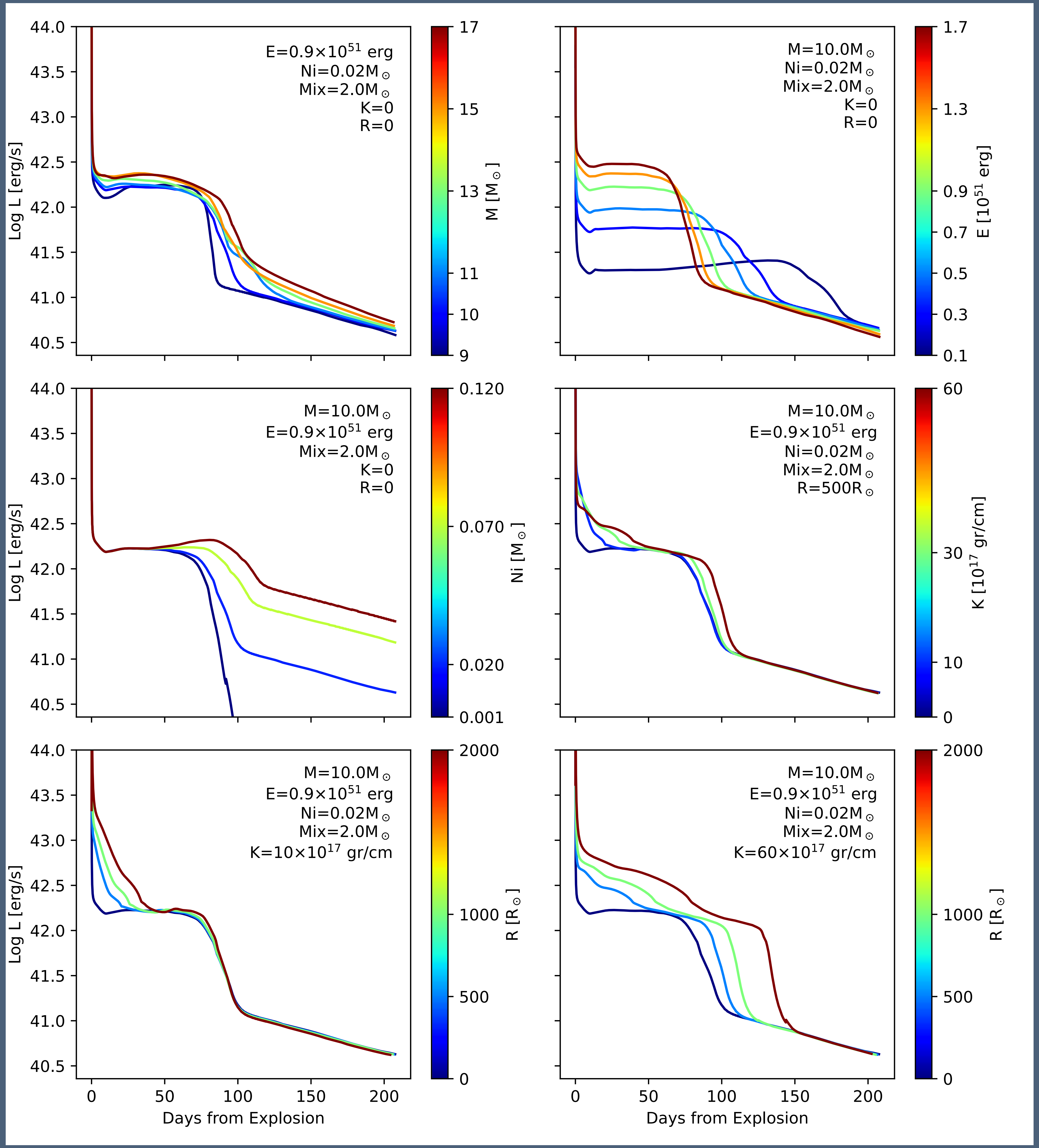
Fit supernova light curve

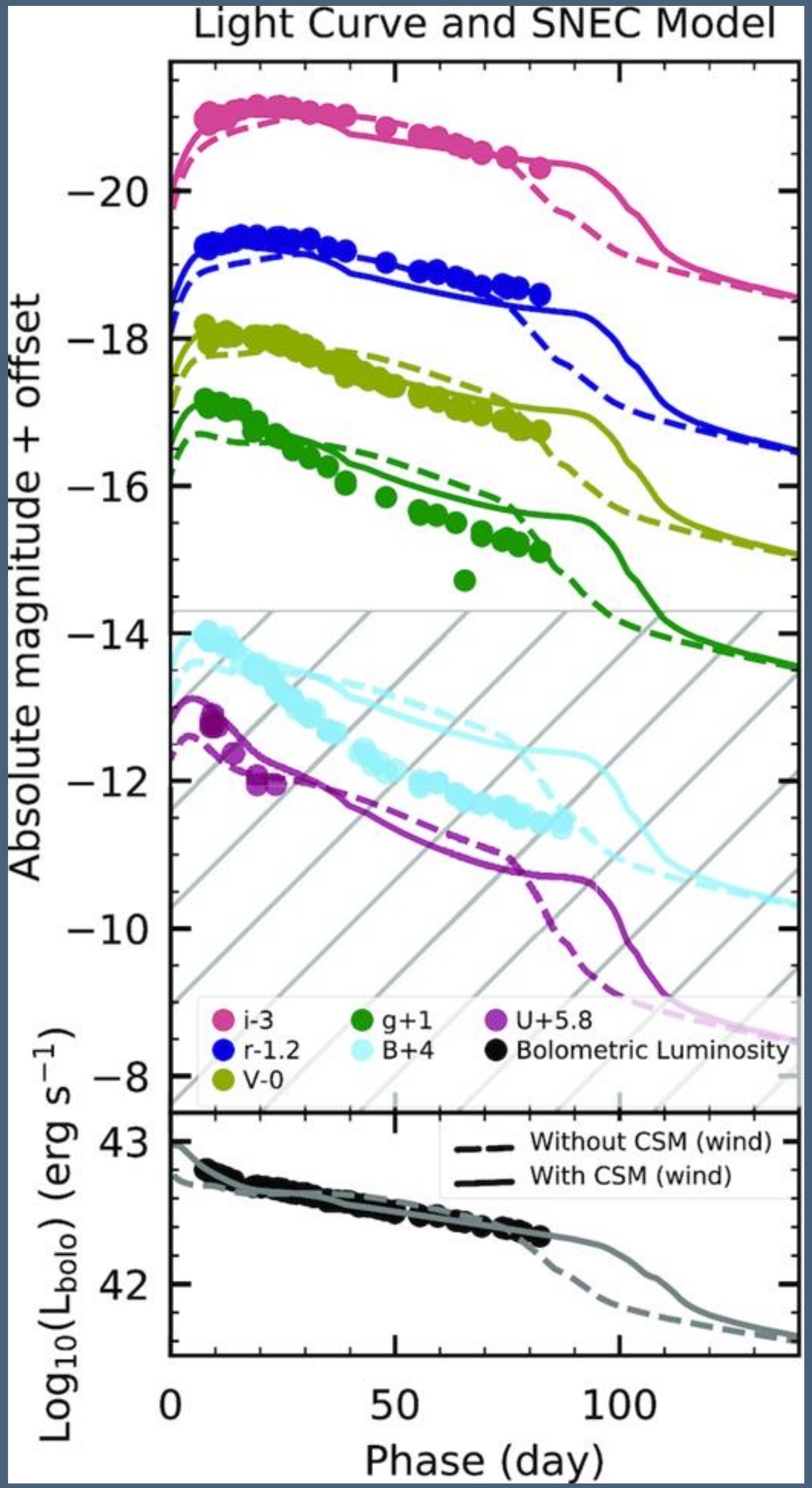


Fit supernova light curve



Mohsen, Bracha, Shitrit & Arcavi (in prep)

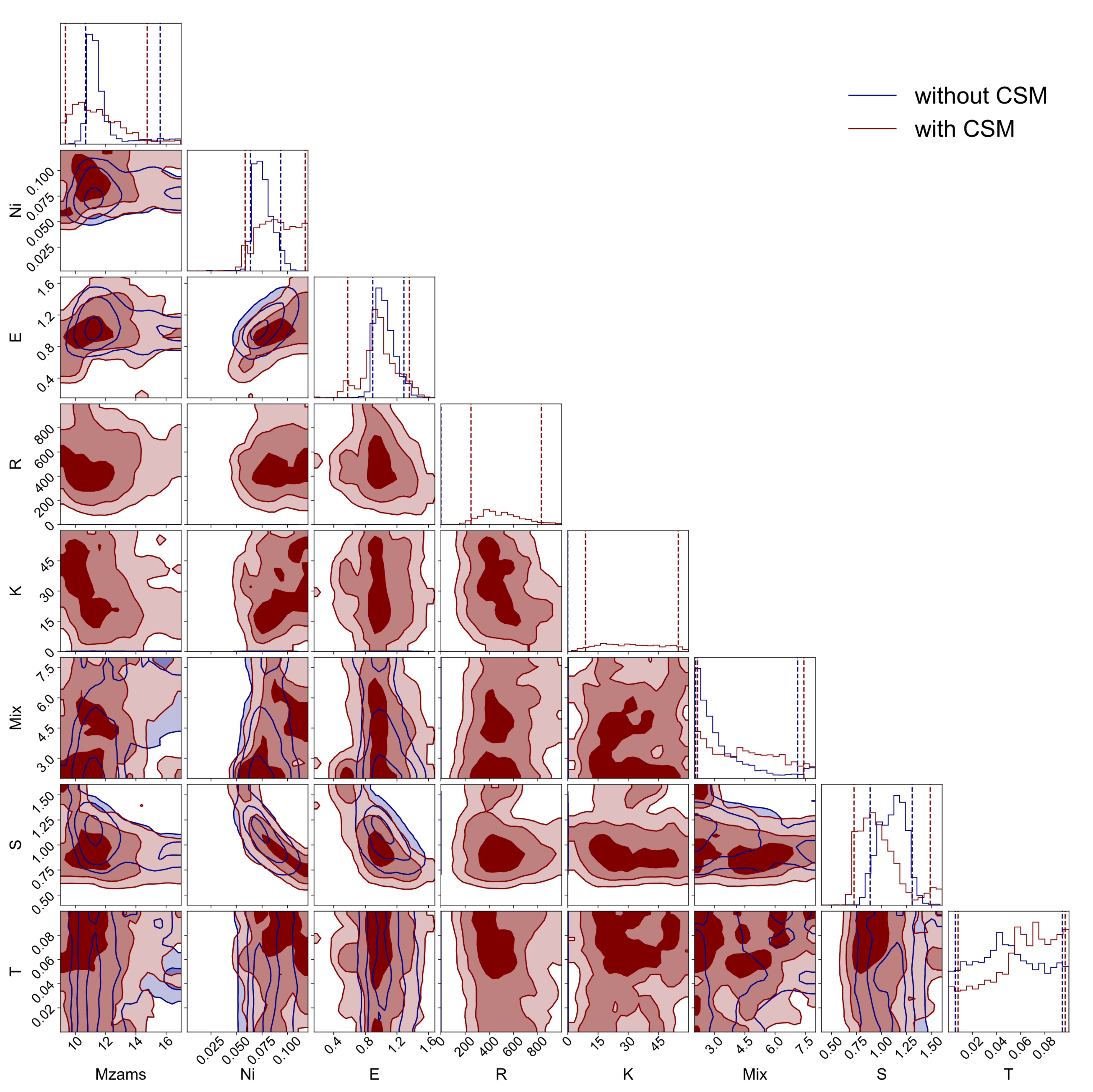
Typically: find **a** model that reproduces the supernova



Parameter	Values
Progenitor ZAMS mass ($M_{\rm ZAMS}$; $M_\odot$)	11, 13, 14, 16, **17**, 18, 21
Final pre-SN mass ($M_\odot$)	10.688, 11.567, 12.079, 13.145, **14.301**, 14.936, 16.119
Pre-SN radius (100 $R_\odot$)	5.7, 7.0, 7.8, 8.9, **9.1**, 9.7, 11.2
Explosion energy ($E_{\rm exp}$; 10^{51} erg)	0.5, 0.8, 1.1, **1.4**, 1.7, 2.0
CSM density (K; 10^{17} $\rm g\,cm^{-1}$)	0, 10, 20, 30, 35, **40**, 50, 60
CSM extent ($R_{\rm ext}$; 100 $R_\odot$)	0, 15, **18**, 21, 24, 27, 30, 33
Ni mass ($M_\odot$)	**0.08**, 0.09, 0.11

Bostroem et al. (2019)

SNemcee: Interpolate grid for MCMC



Mohsen, Bracha, Shitrit & Arcavi (in prep)

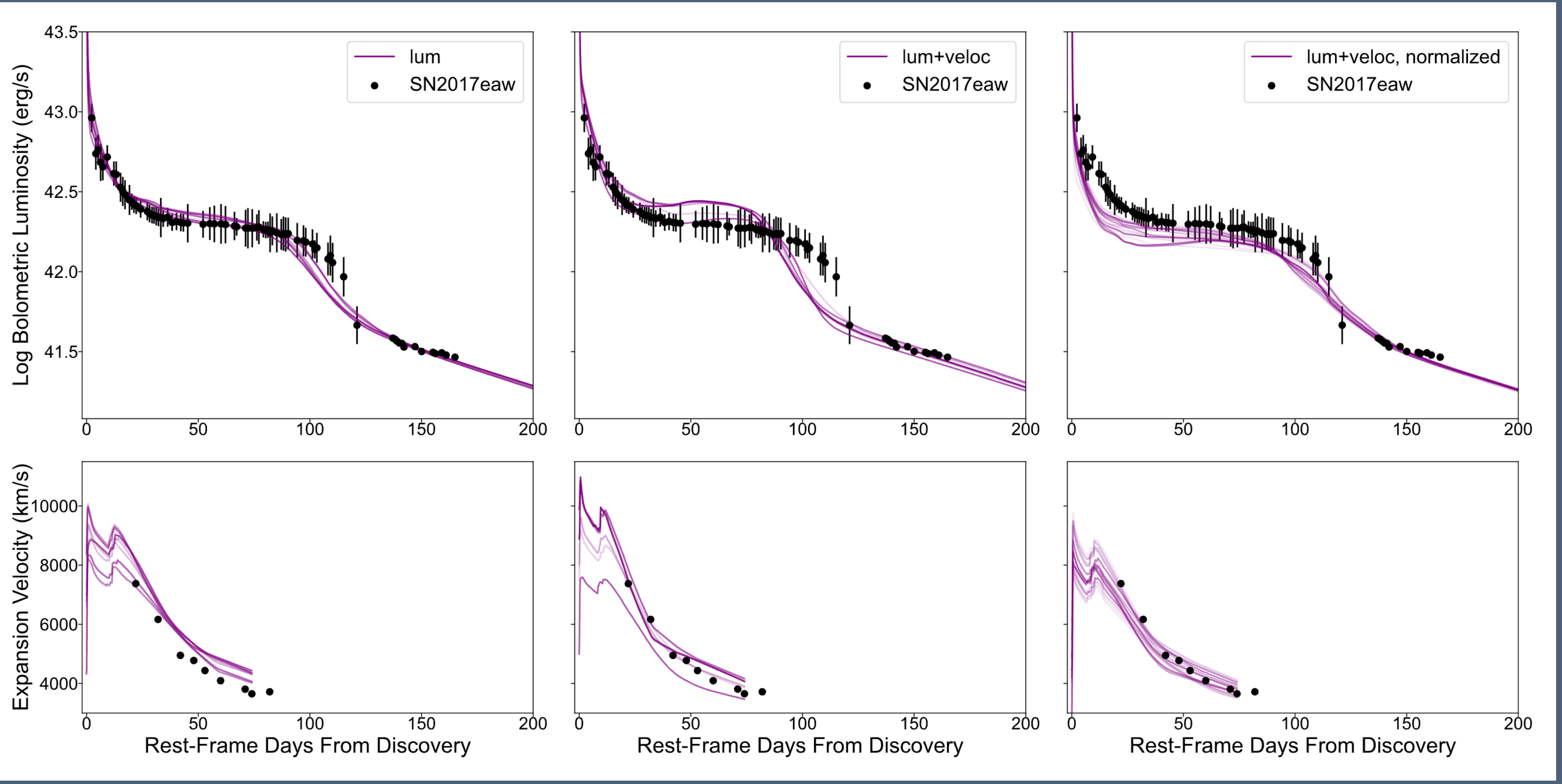
Sondos Mohsen

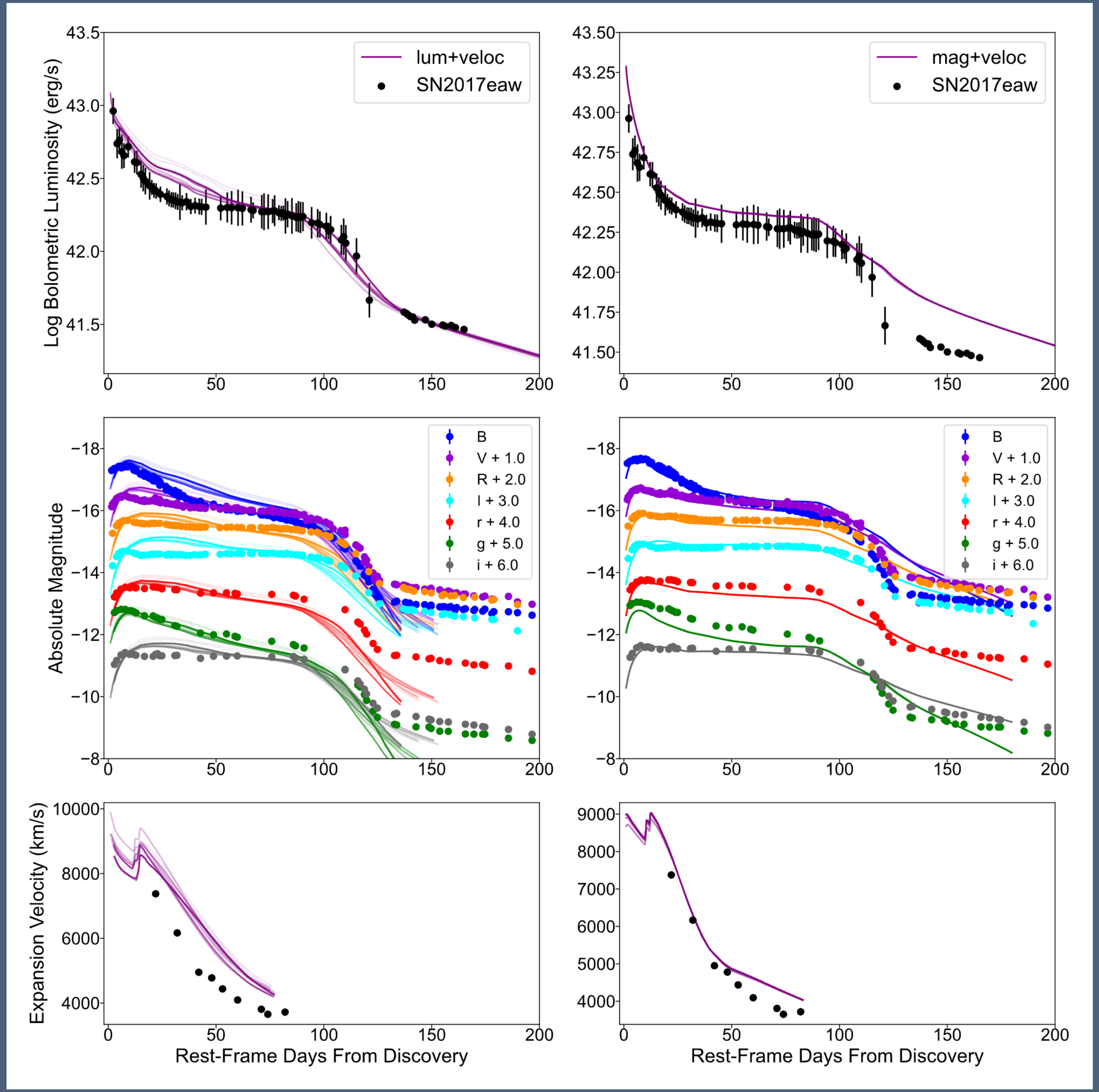
Noi Shitrit

Shahar Bracha

Sukhbold et al. (2016) KEPLER grid of H-rich massive stars, exploded with SNEC (Morozova et al. 2018)

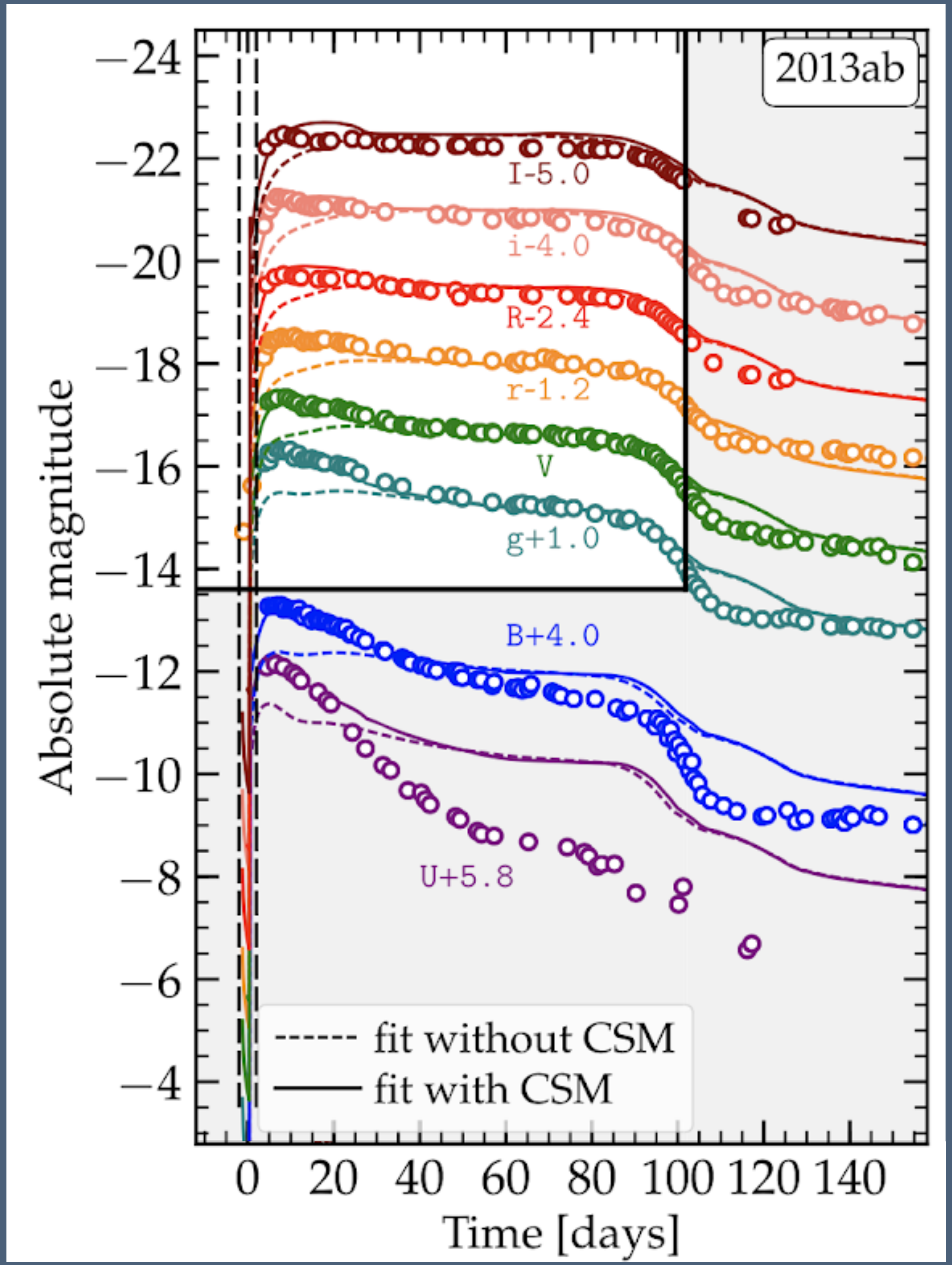
SNemcee: Fit bolometric / magnitudes / velocities



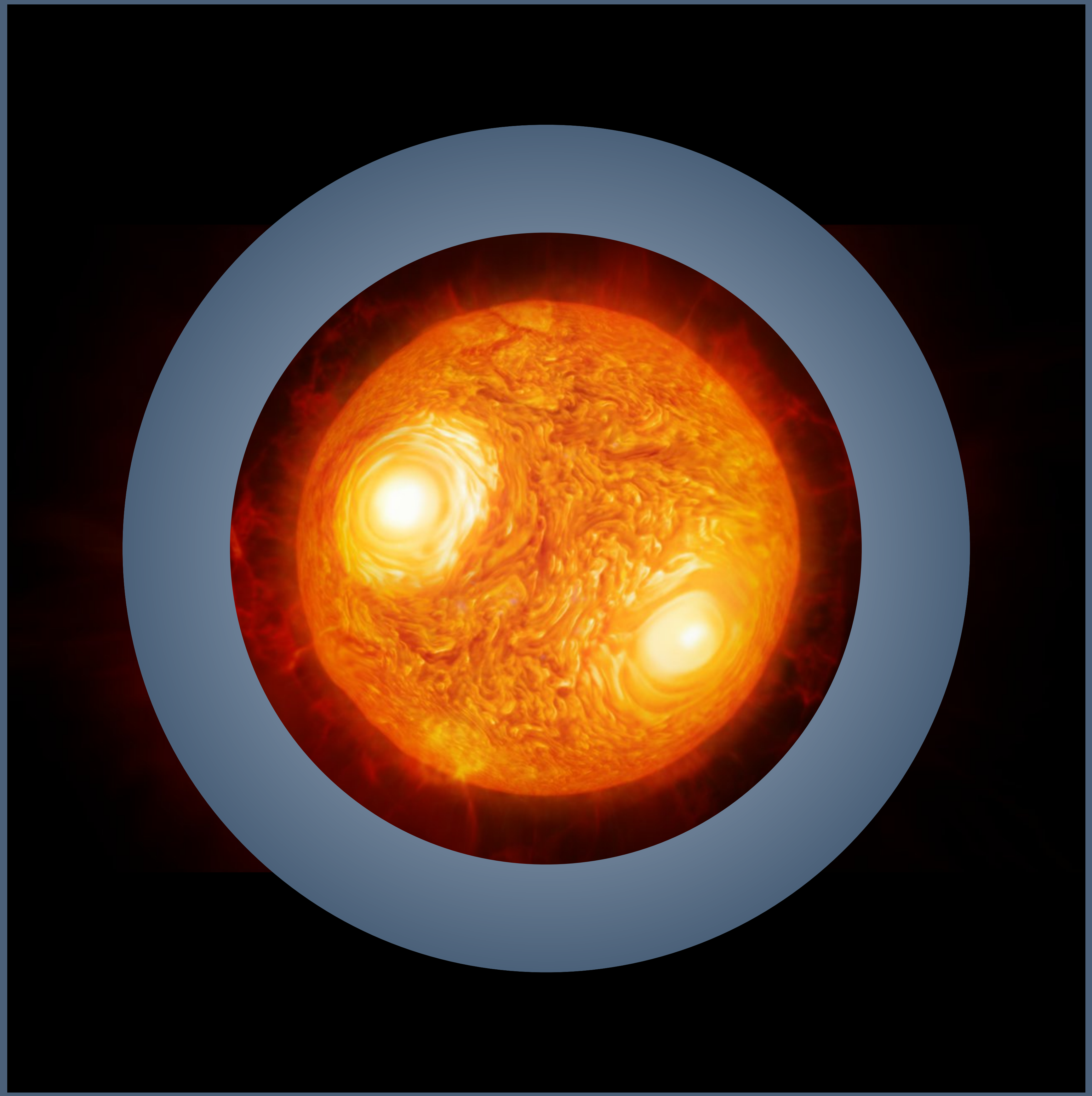


Mohsen, Bracha, Shitrit & Arcavi (in prep)

Example use: CSM around pre-explosion RSGs

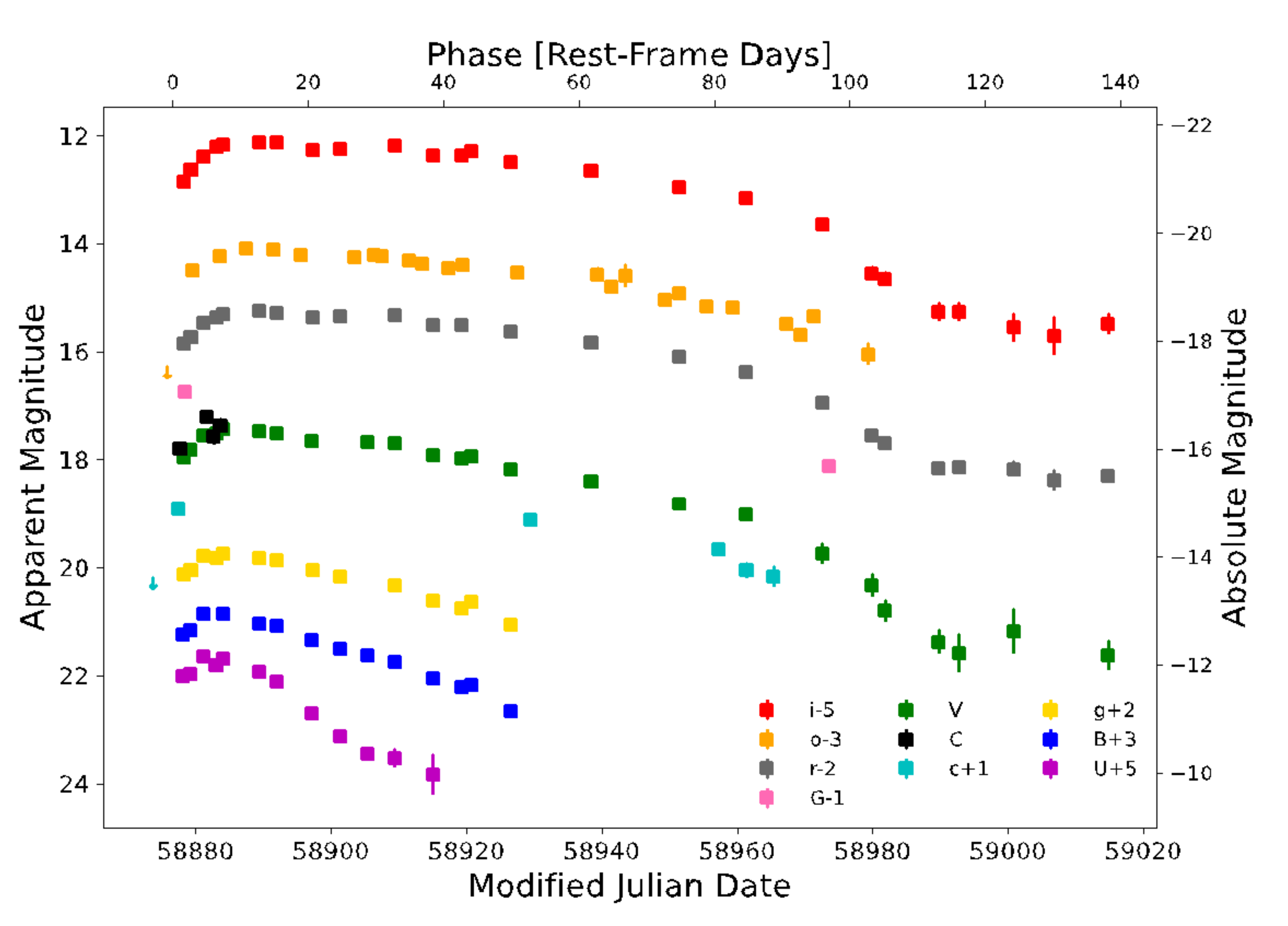


Morozova et al. (2018)



Credit: ESO/M. Kornmesser

SN 2020bij - A SN IIP with a slow rise: no CSM?

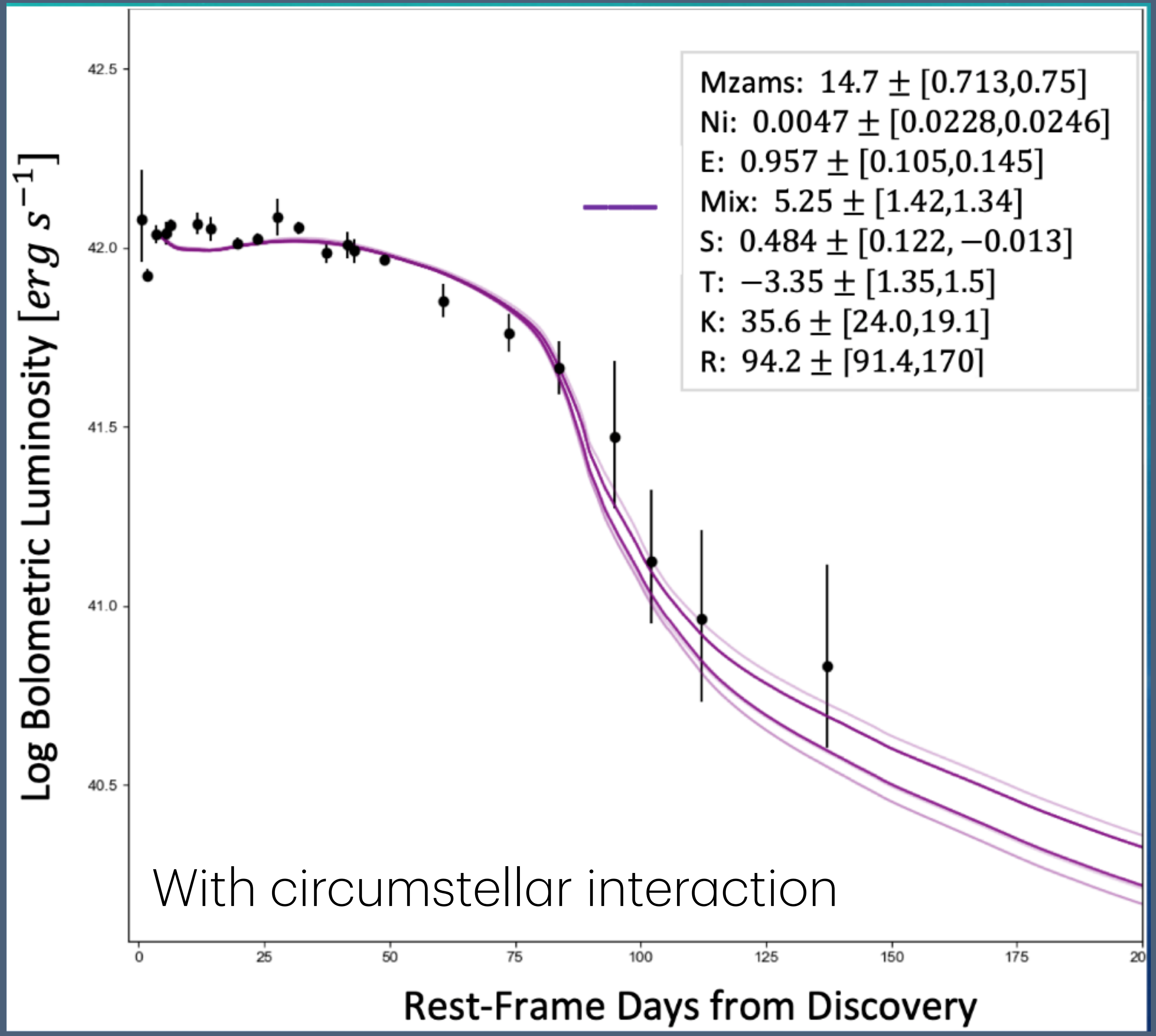


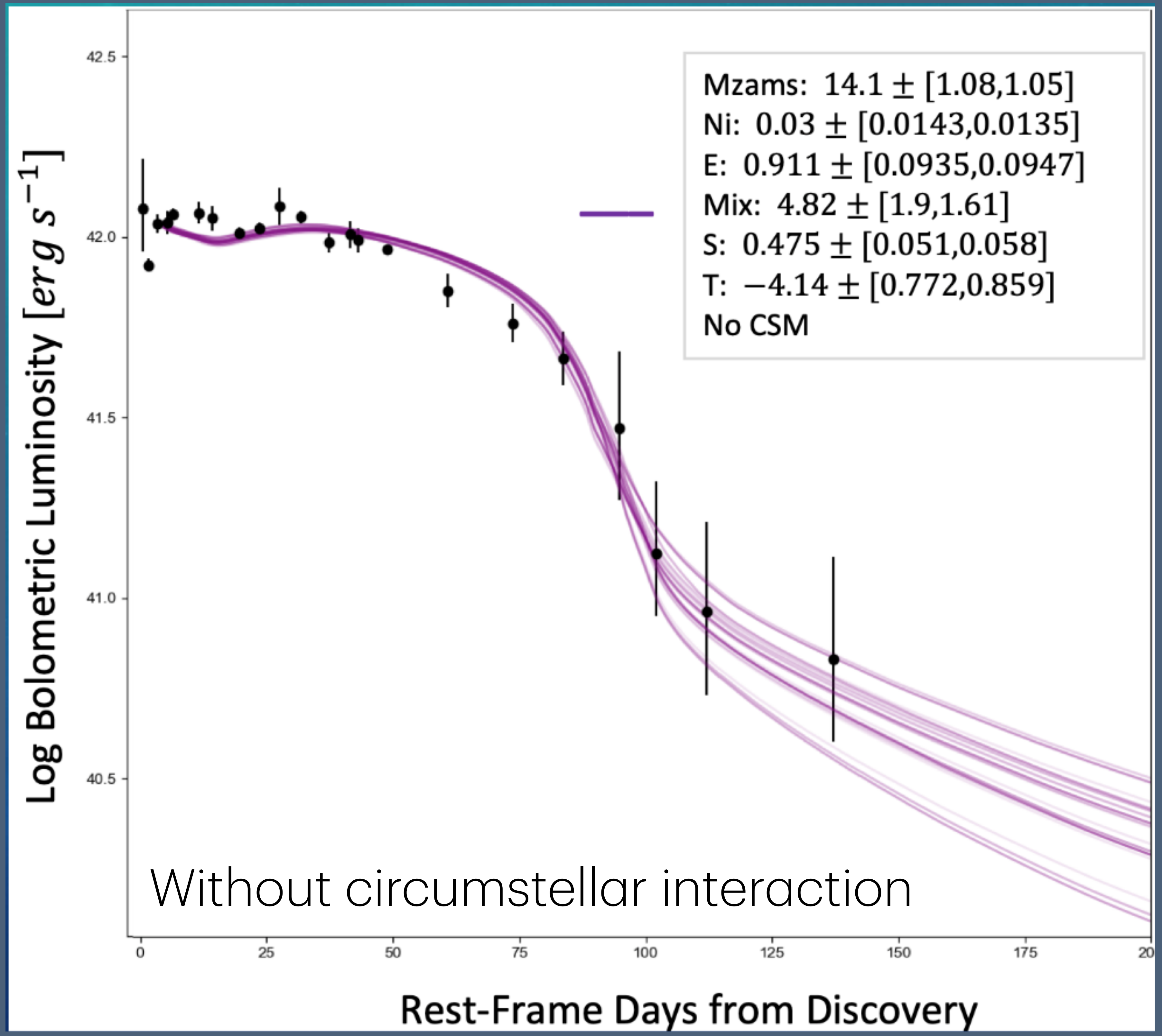
Sondos Mohsen

Mohsen, Arcavi et al. (in prep)

SN 2020bij - Models prefer little circumstellar interaction

Even when the model is given the freedom to add it





Mohsen, Arcavi et al. (in prep)

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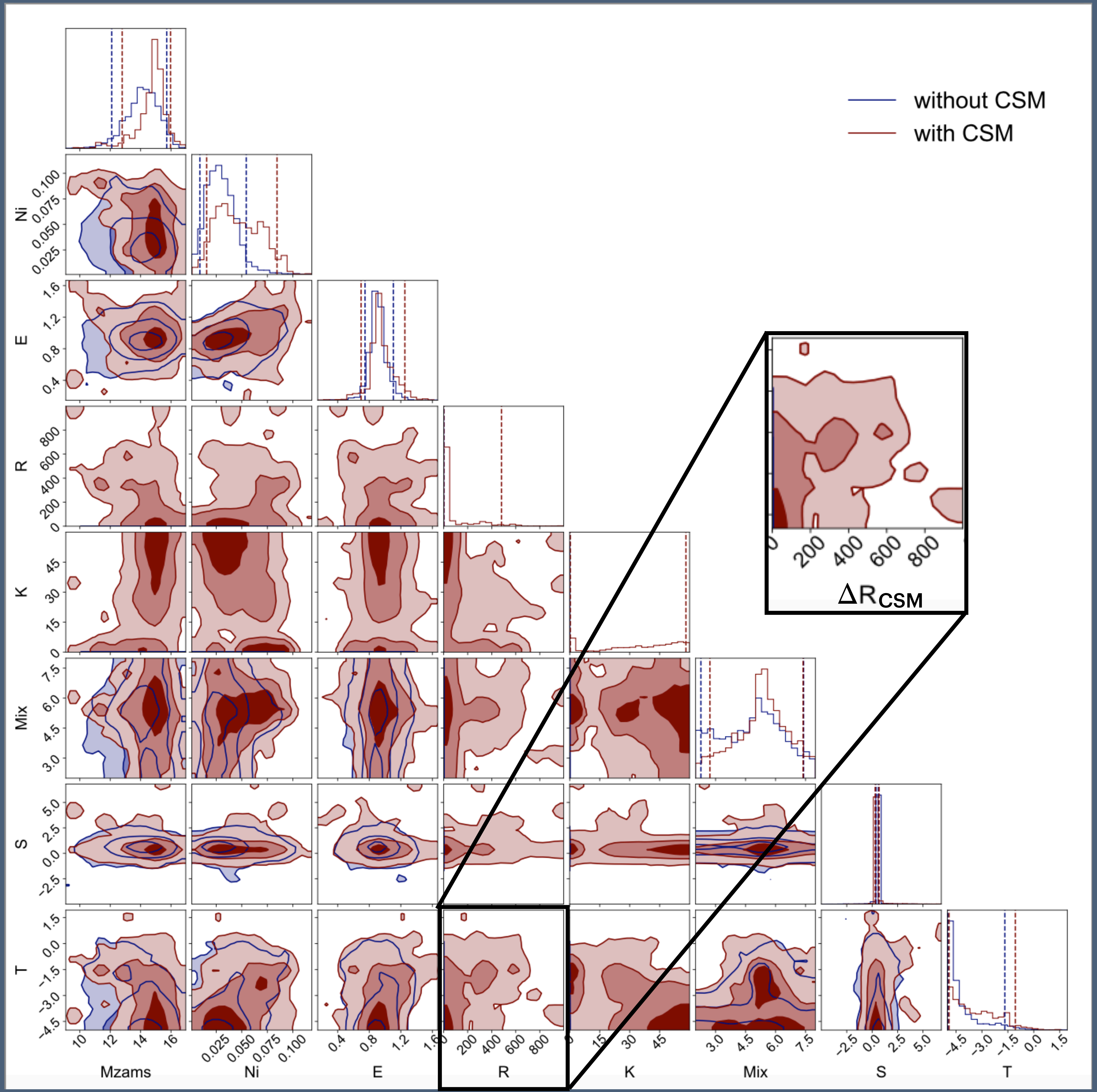
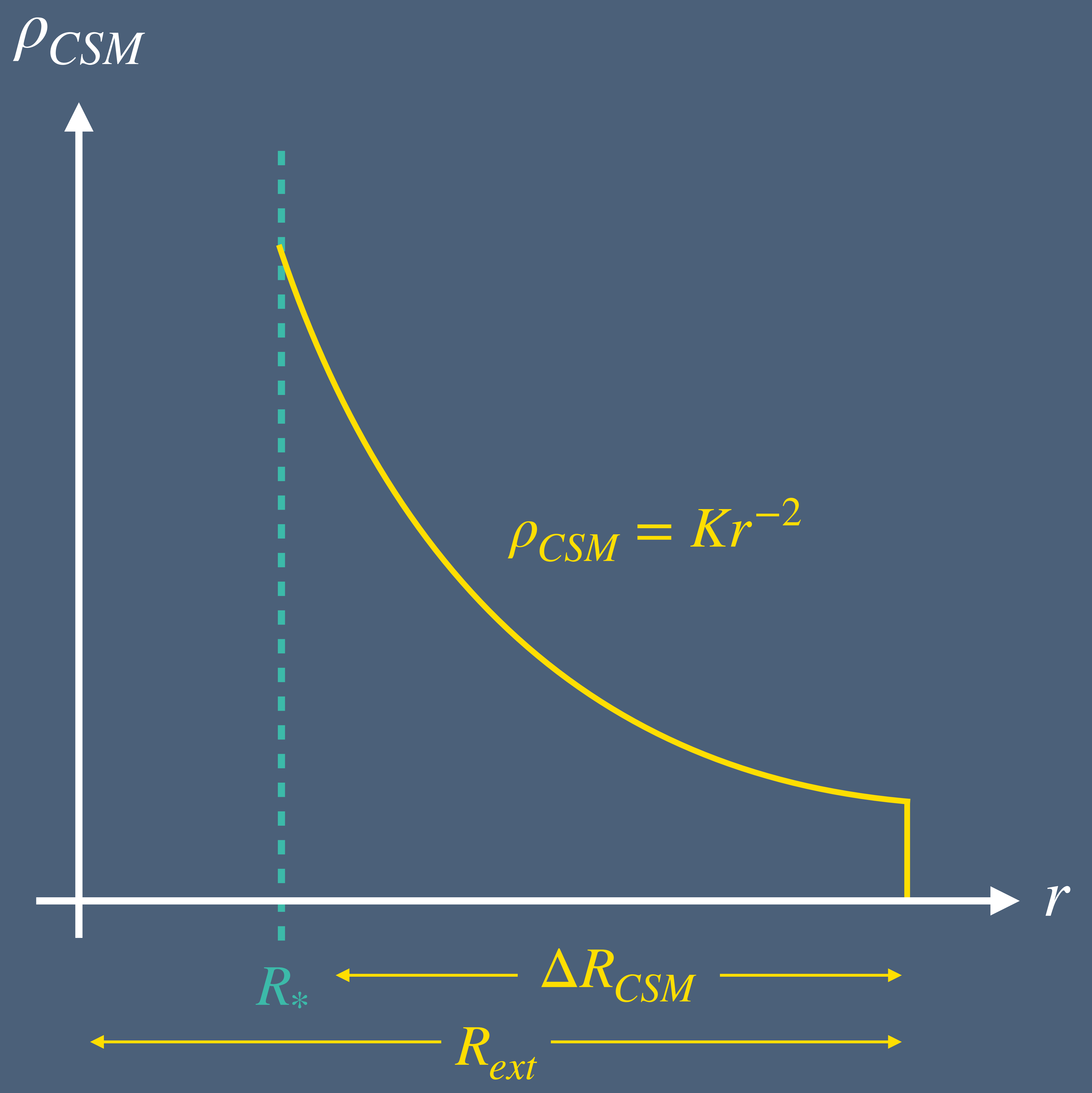
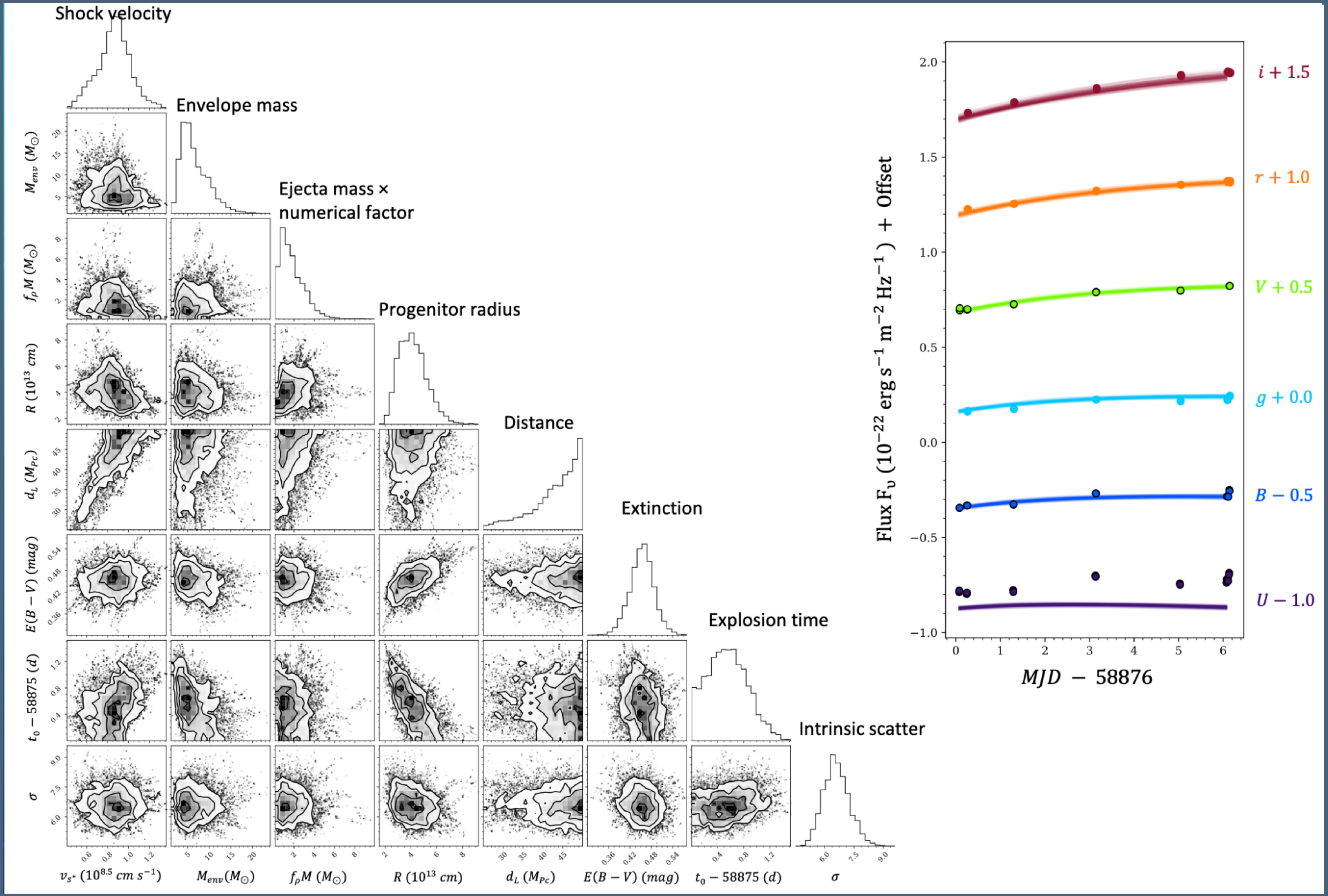




Mohsen, Arcavi et al. (in prep)

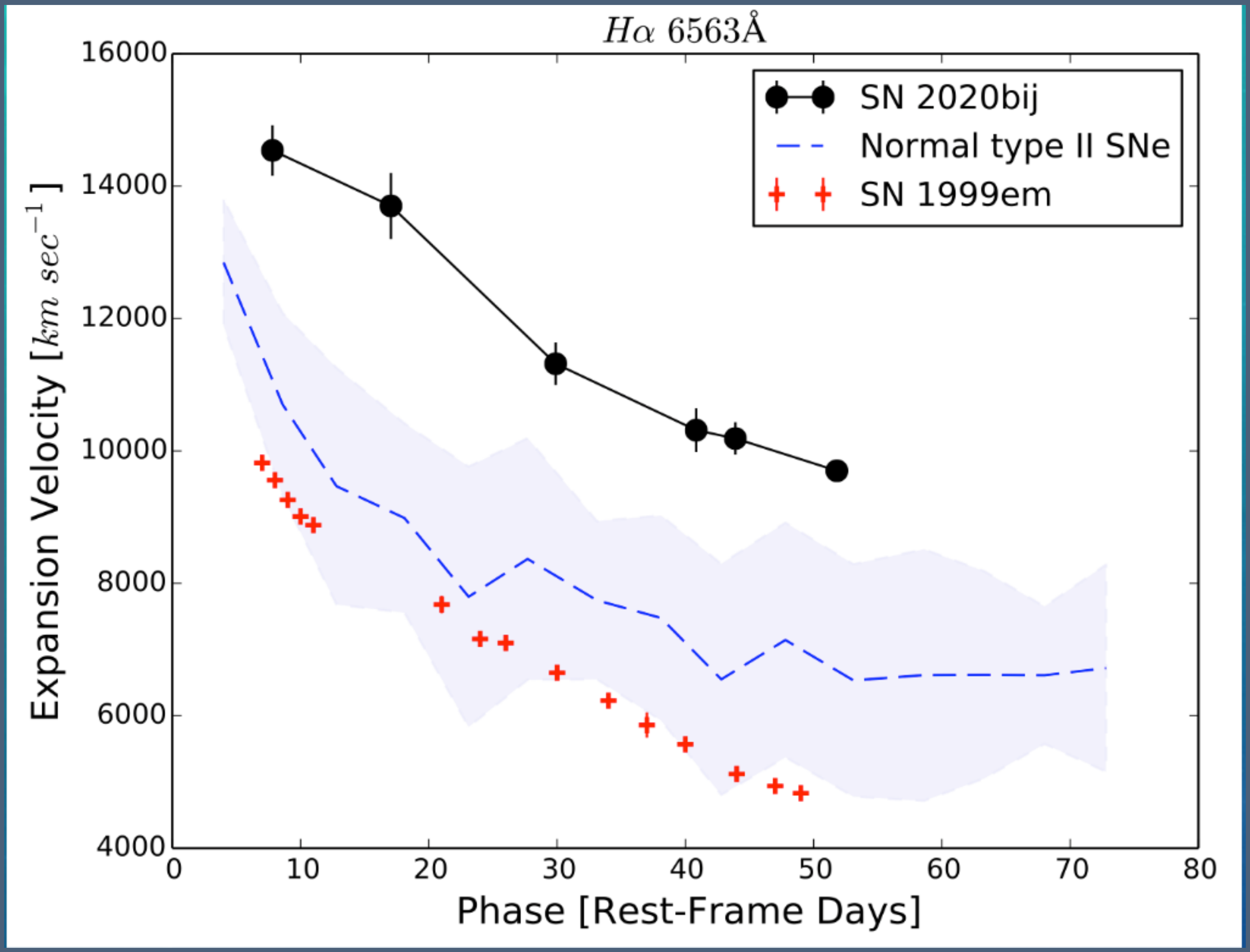
SN 2020bij - Can be explained with shock cooling alone

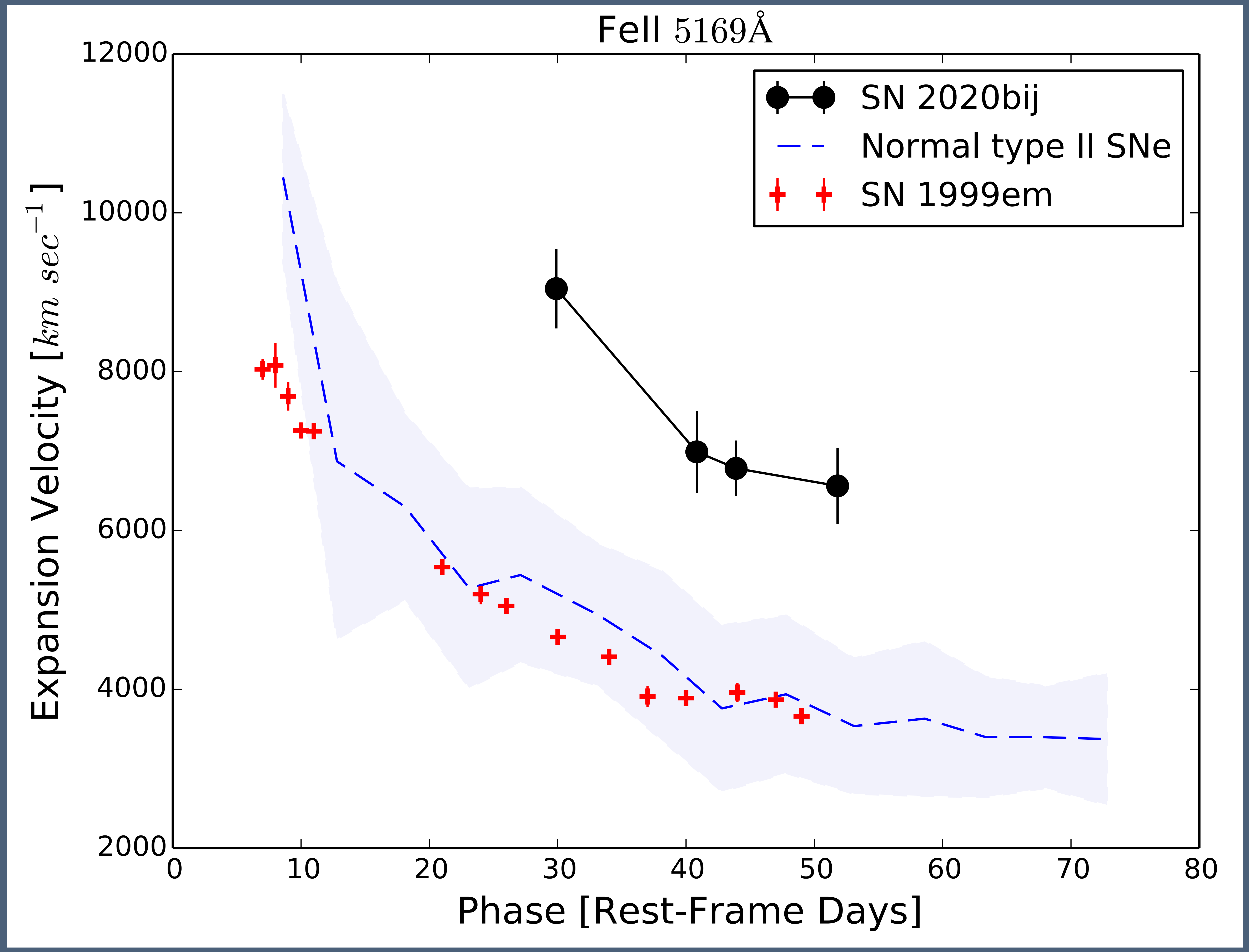
No need for circumstellar interaction like in most other IIP's



Mohsen, Arcavi et al. (in prep)

SN 2020bij - Highest velocity IIP ever seen?

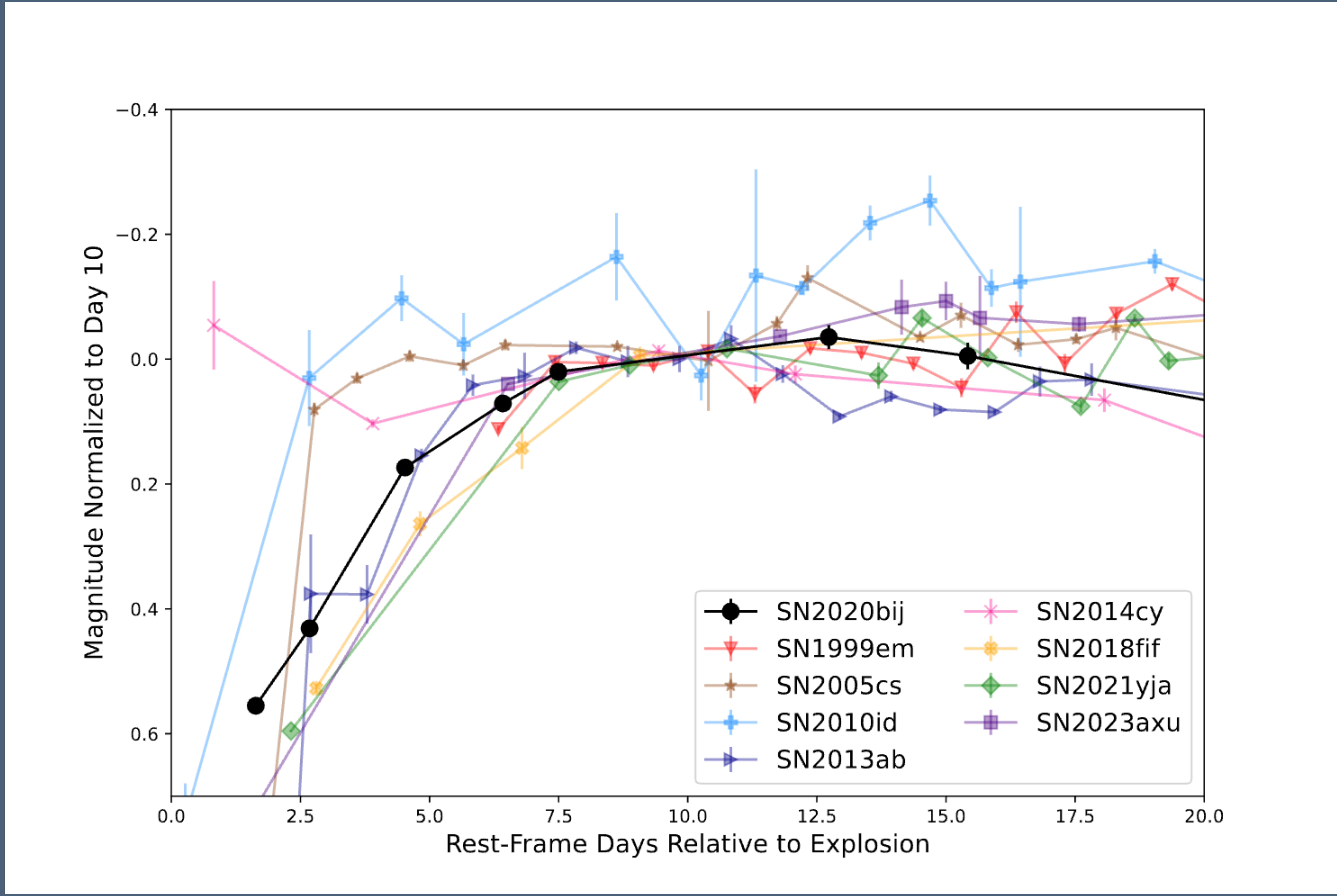




Mohsen, Arcavi et al. (in prep)

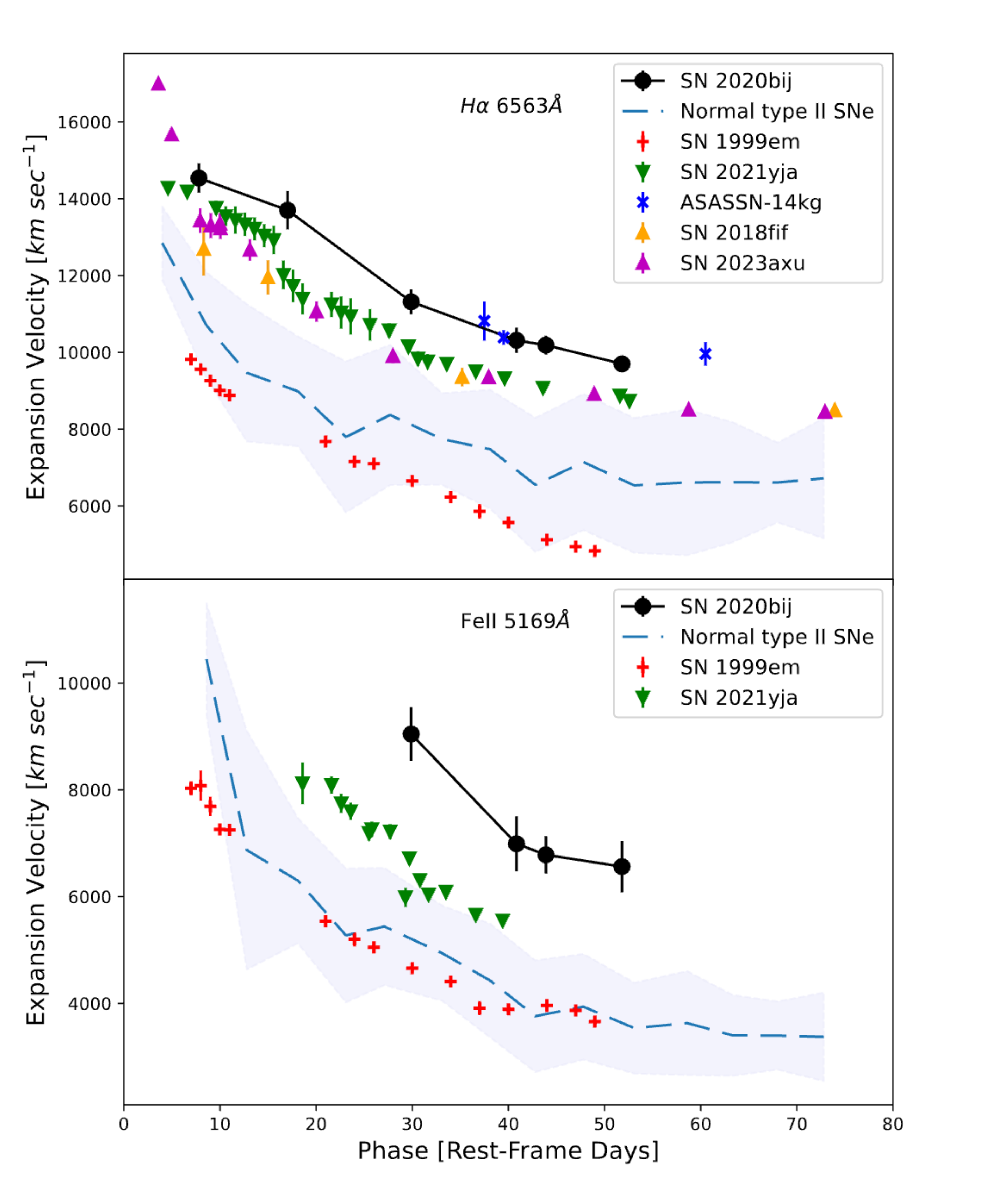
Comparison samples from Leonard et al. (2002) & Gutierrez et al. (2017)

Additional slowly-rising IIP SNe



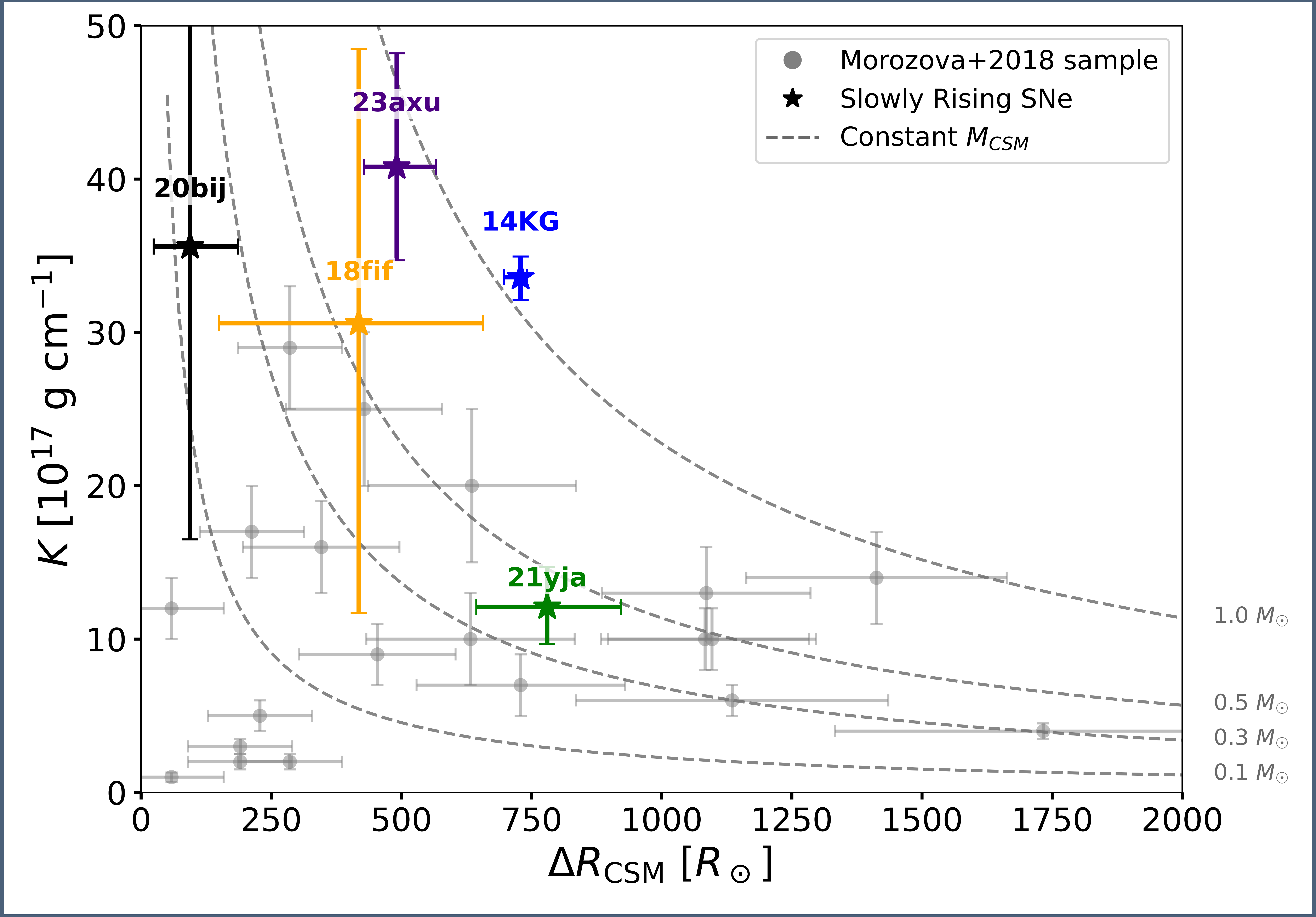
Mohsen, Arcavi et al. (in prep), Hamuy et al. (2001), Faran et al. (2014), Galbany et al. (2016), Soumagnac et al. (2020), Hosseinzadeh et al. (2022), Shrestha et al. (2023), Gal-Yam et al. (2011), Pastorello et al. (2009), Bose et al. (2015), Valenti et al. (2016)

All slow-rising events show extremely high velocities



Mohsen, Arcavi et al. (in prep)
Comparison sample from
Gutierrez et al. (2017)

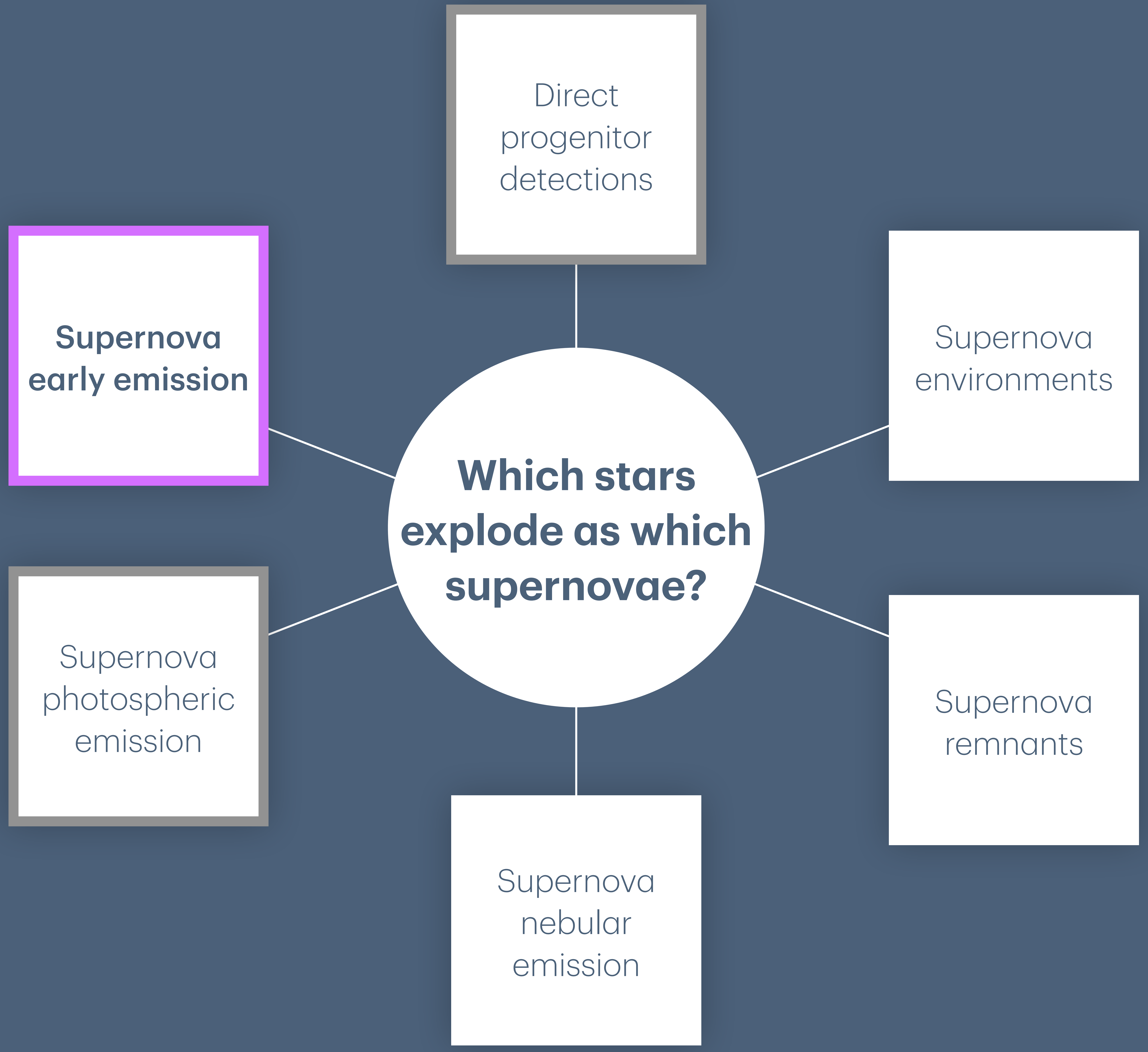
But not all slow-rising events have zero CSM



Mohsen, Arcavi et al. (in prep)

Class of slowly-rising high-velocity IIP's

Event	Slow rising	High Velocities	SNEmcee CSM Fits	Shock Cooling Model Fits
SN 2020bij	✓	✓	Very confined	✓
SN 2023axu	✓	✓	Confined	✓
SN 2021yja	✓	✓	Confined	✓
SN 2018fif	✓	✓	Confined	✓
ASASSN-14kg	✓	✓	Confined	Not enough early data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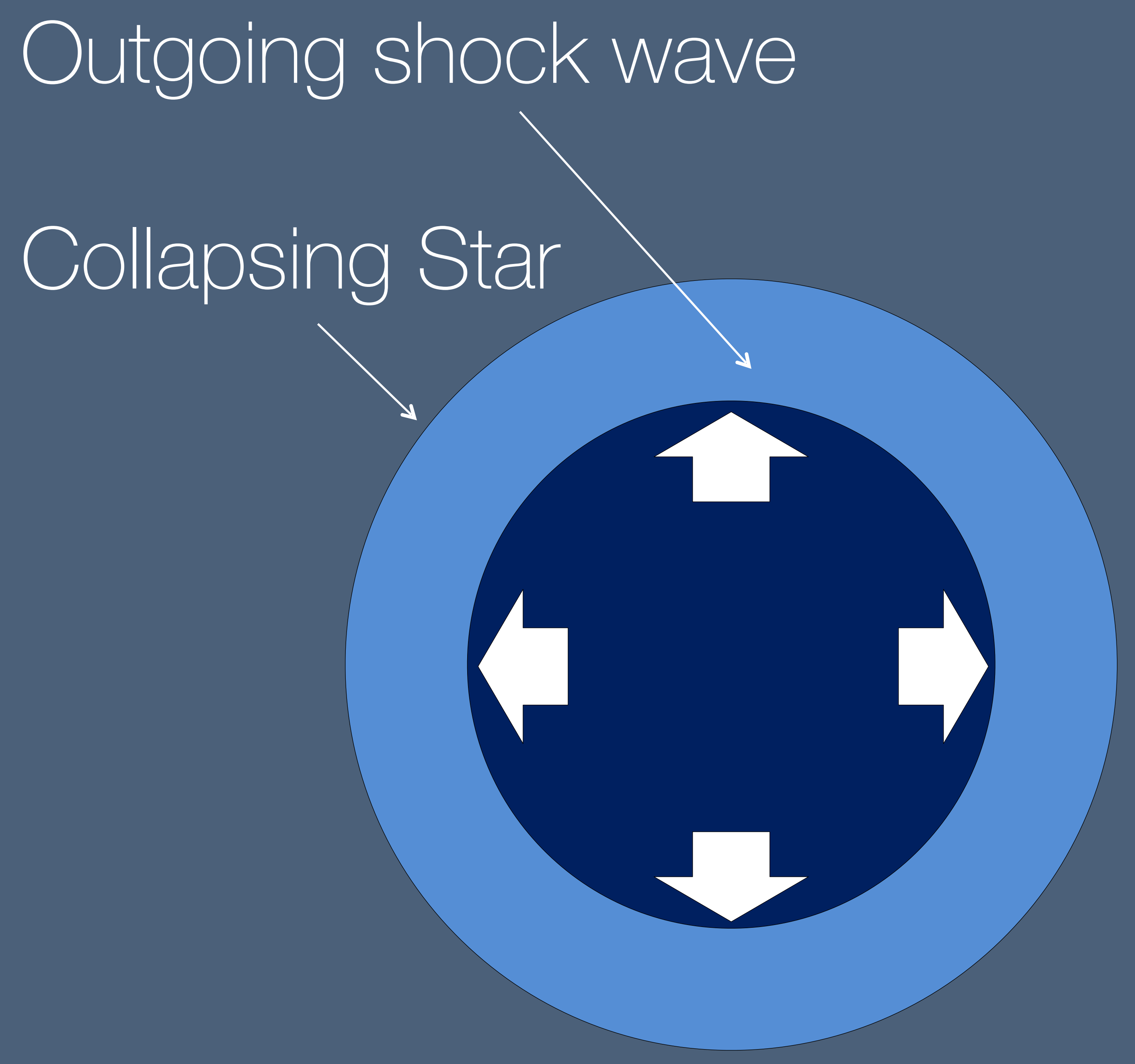
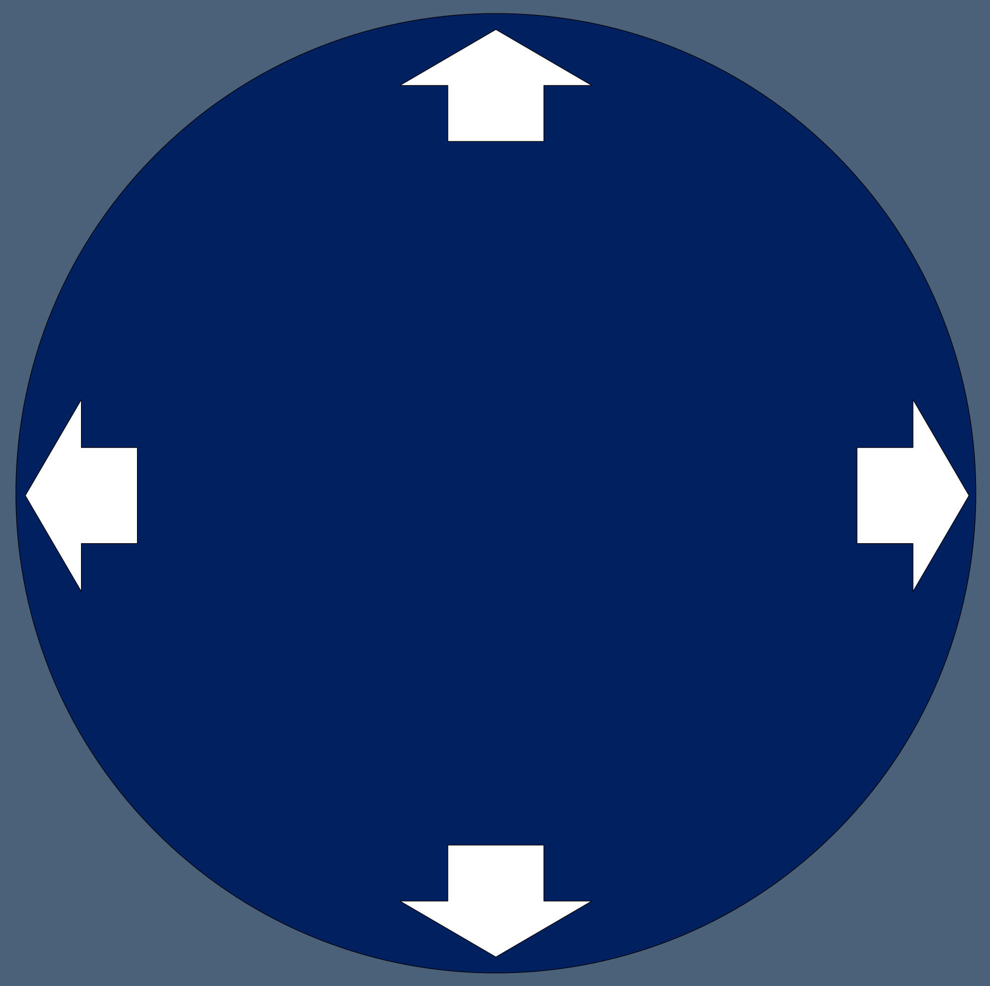
Early light from a SN remembers the star



Early light from a SN remembers the star



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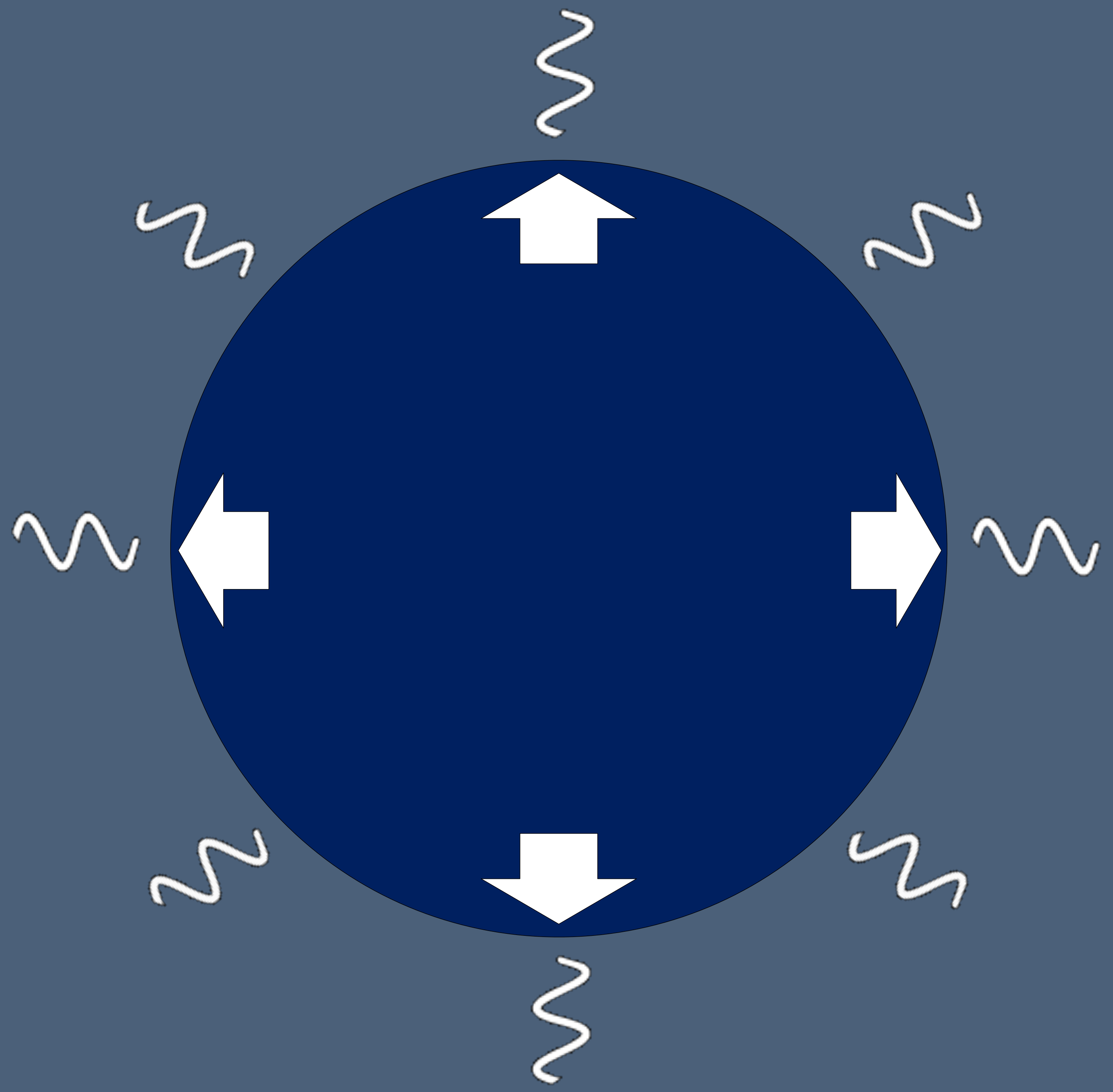
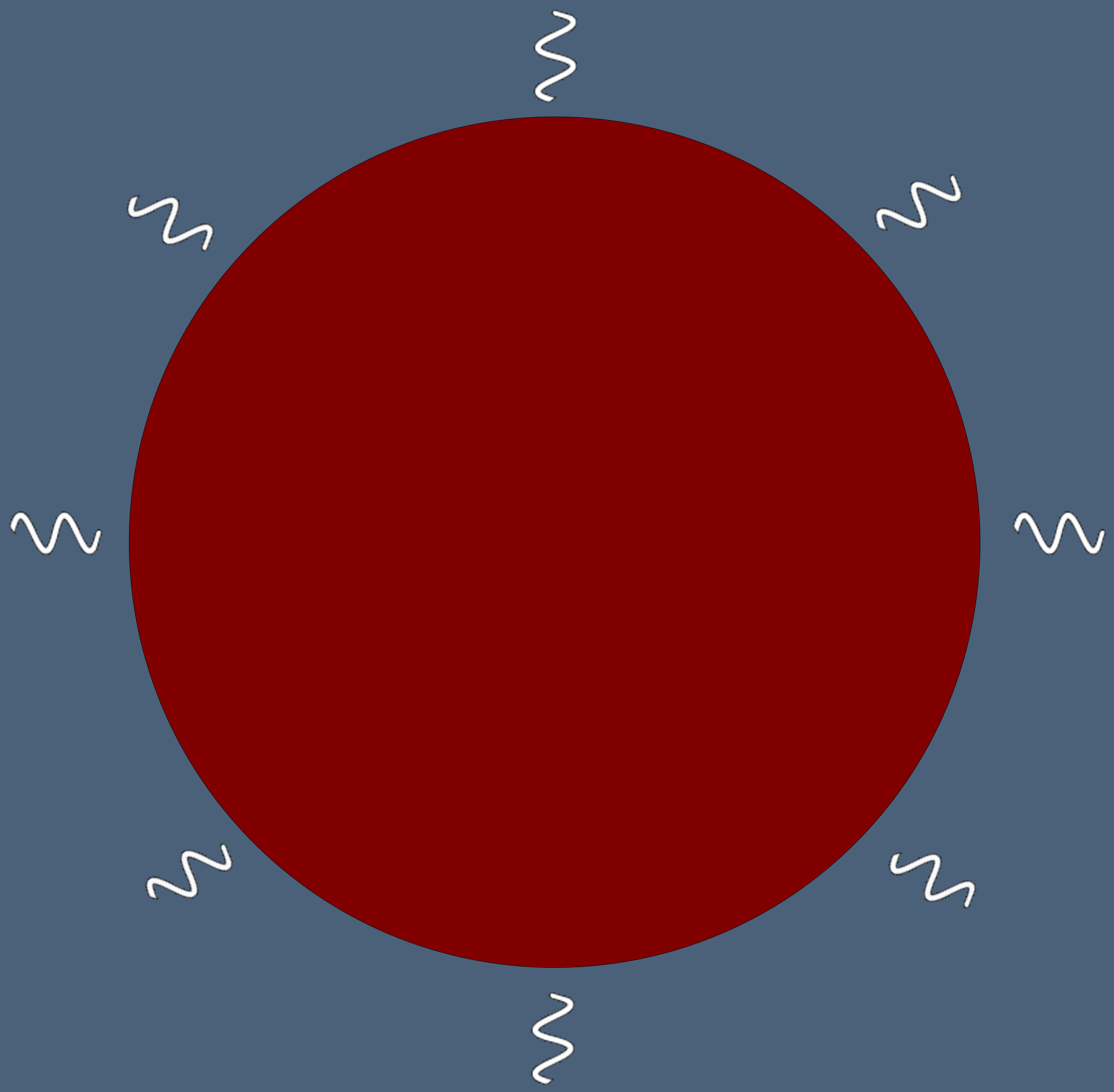


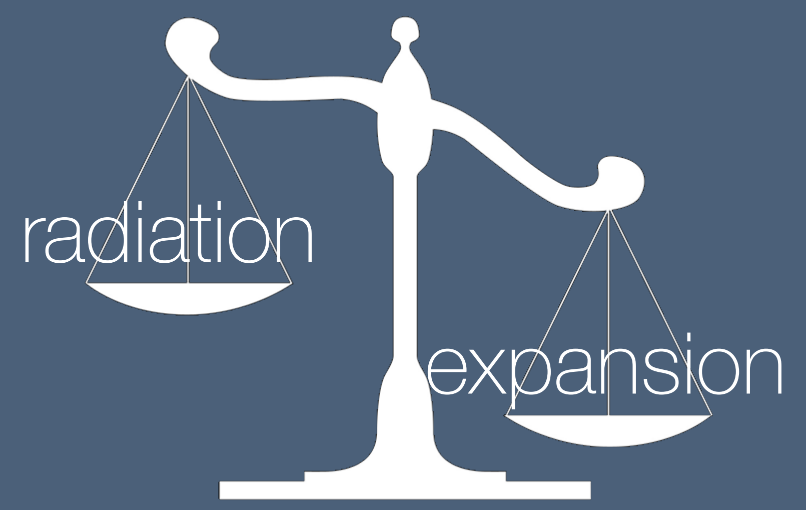
Shock breakout:
X-rays + UV, minutes to hours flash

Early light from a SN remembers the star

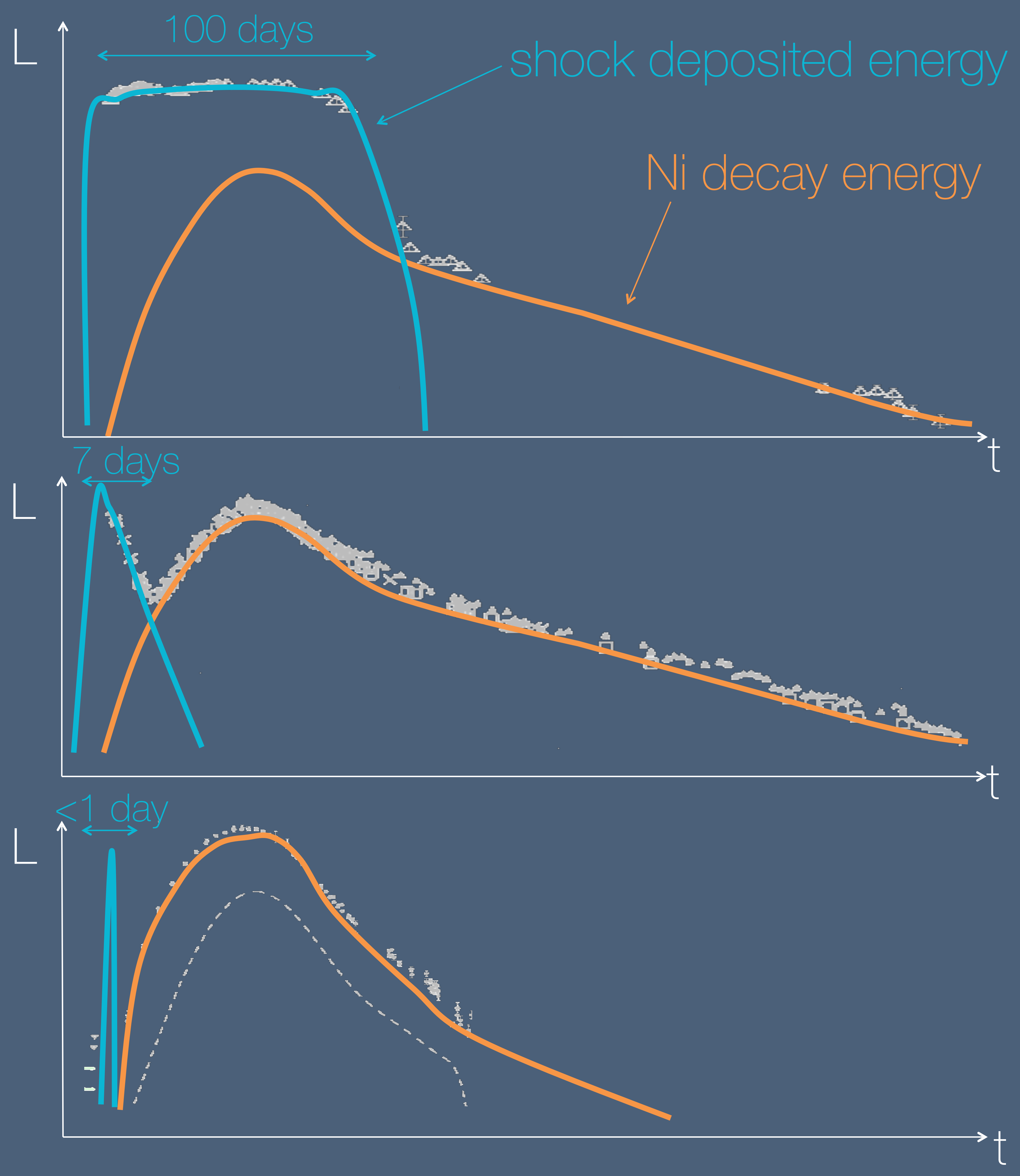


Shock breakout:
X-rays + UV, minutes to hours flash

Shock cooling:
Energy loss to expansion + radiation
UV → optical, hours to days to months



Shock cooling is sensitive to the progenitor radius

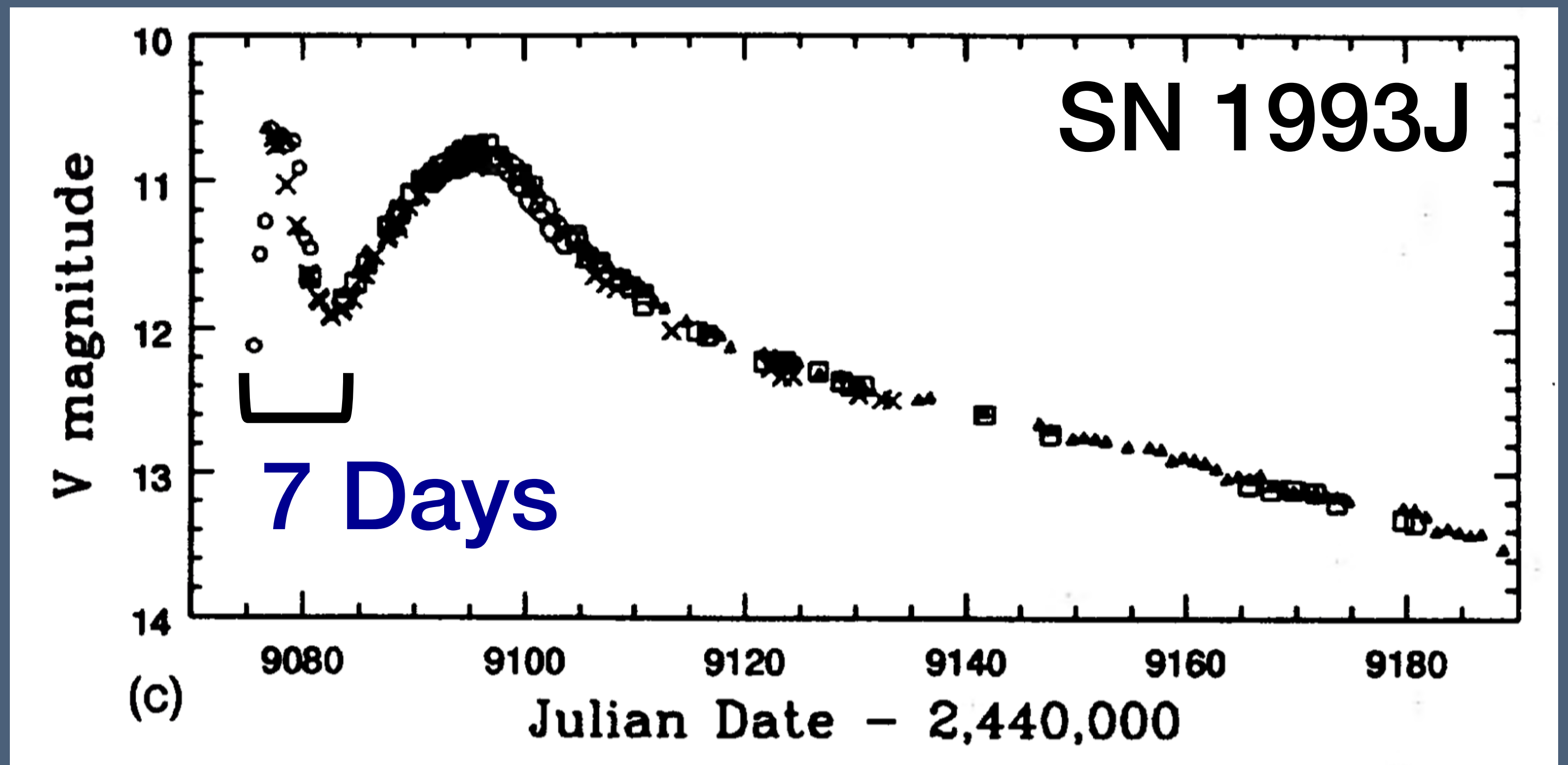


Large progenitor
(red super-giant)
SN1999em [Leonard et al. 2002]

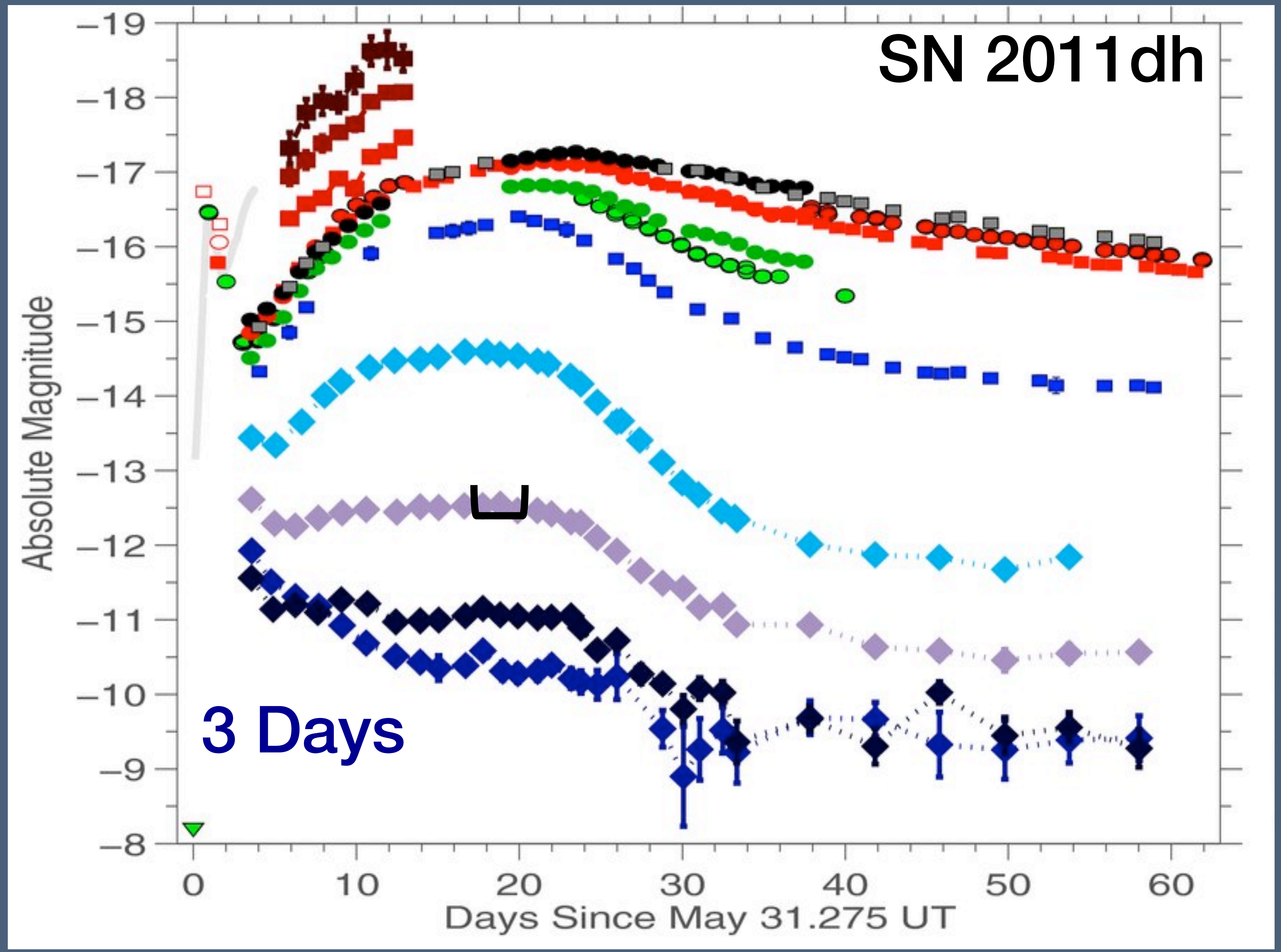
In-between progenitor
(partially stripped star)
SN1993J [Richmond et al. 1994]

Compact progenitor
(fully stripped star)
PTF10vgv [Corsi et al. 2012]

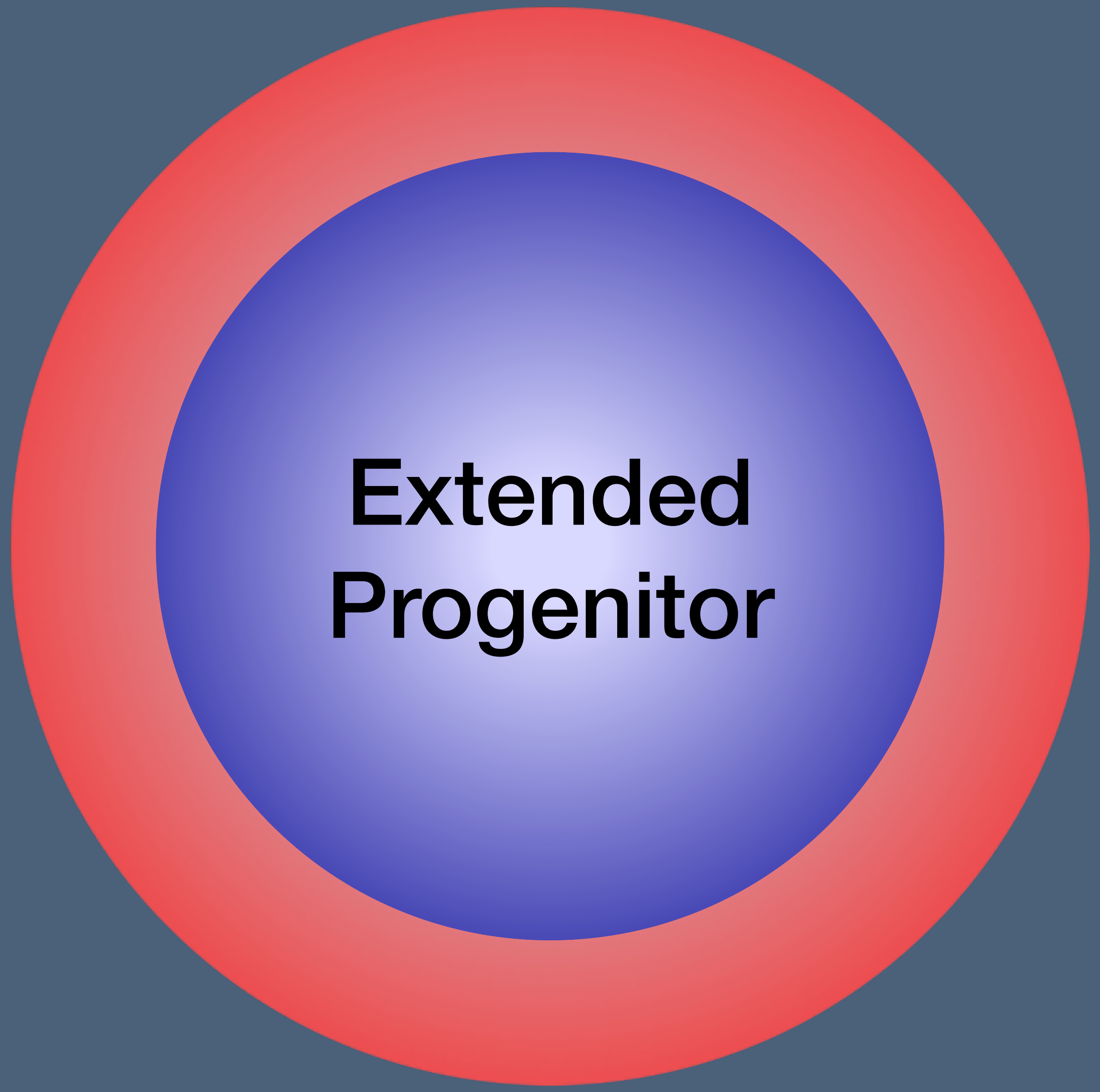
Diversity within partially stripped stars



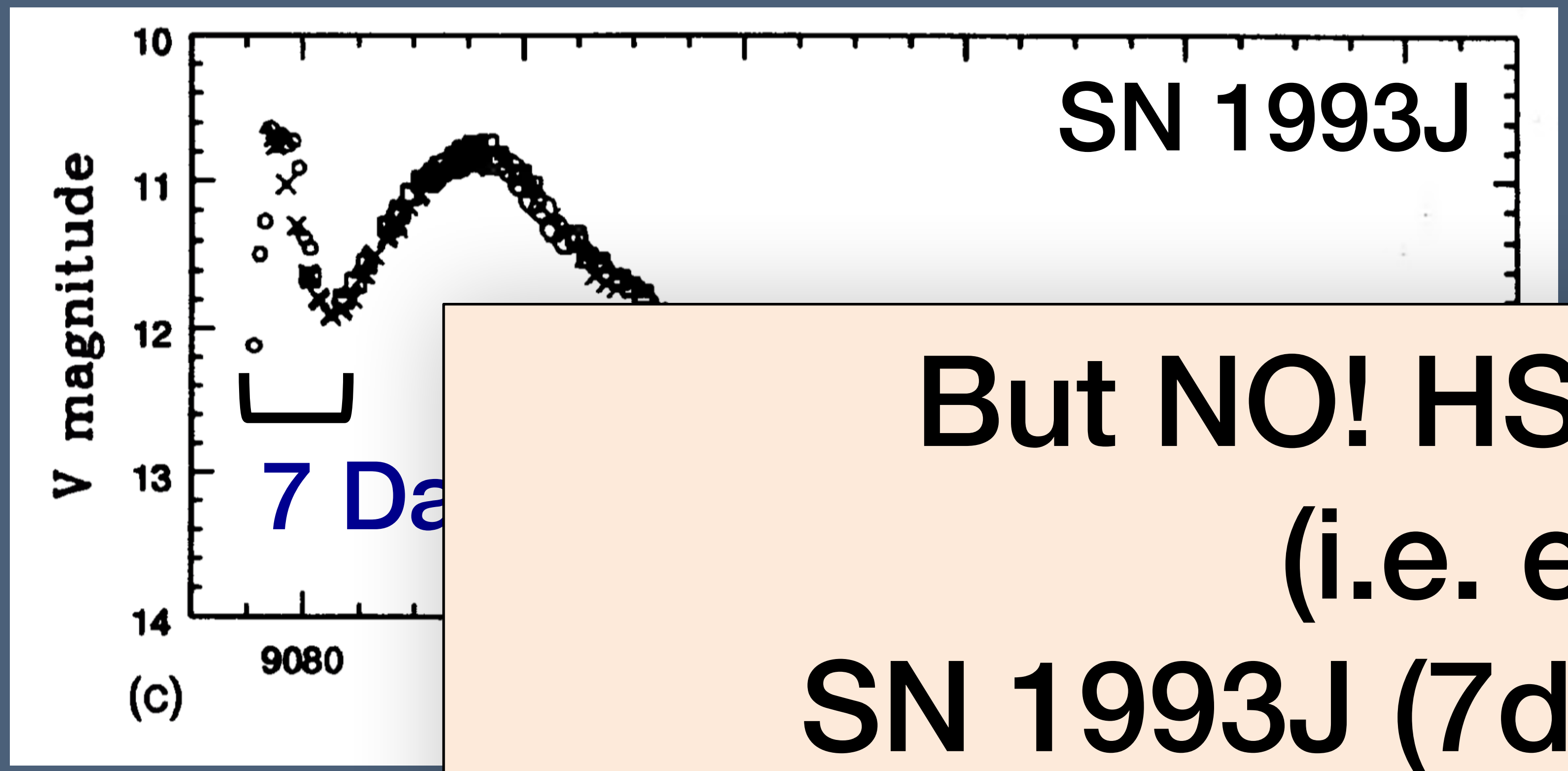
Richmond et al. 1994

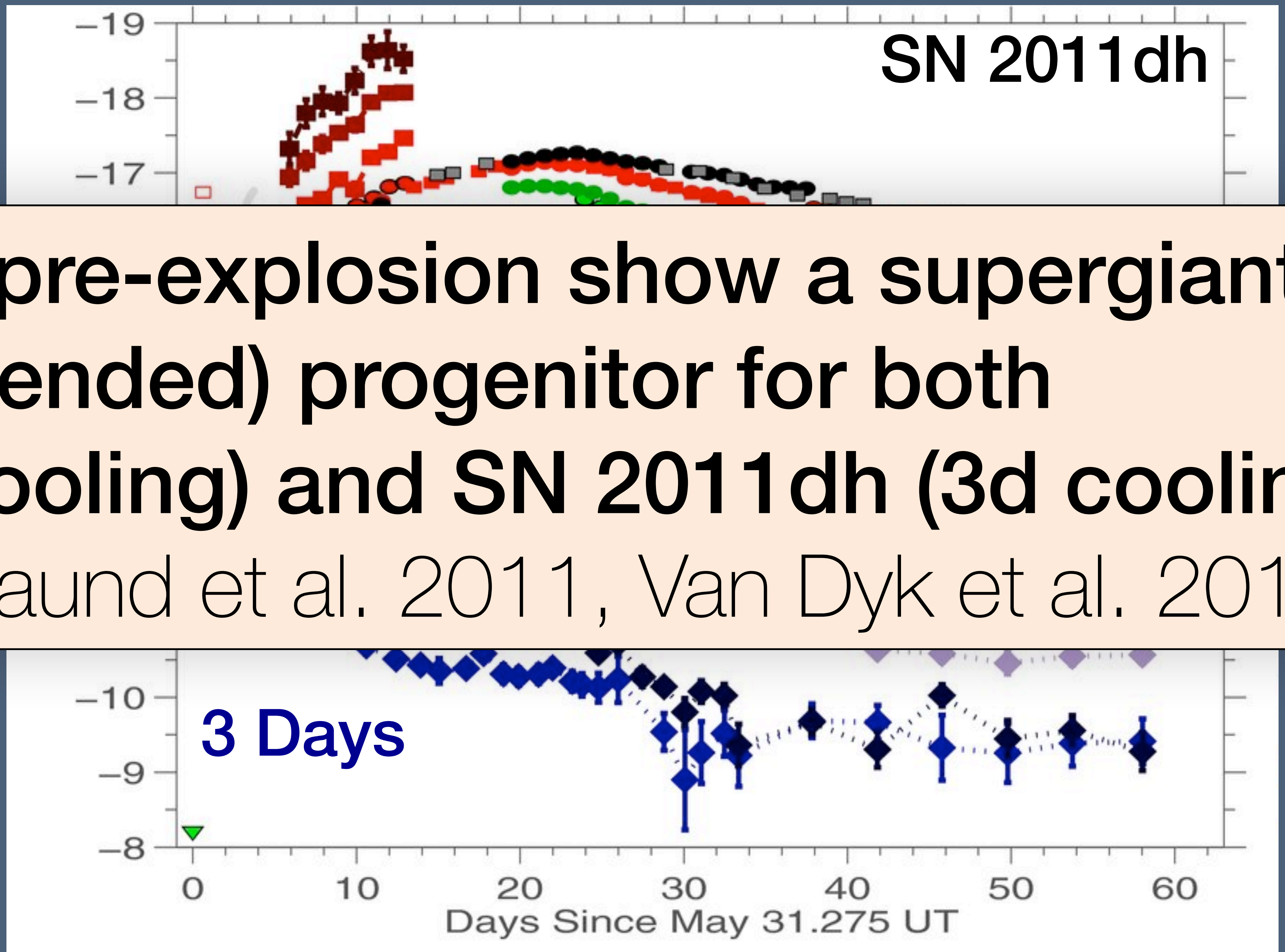


Arcavi et al. 2011



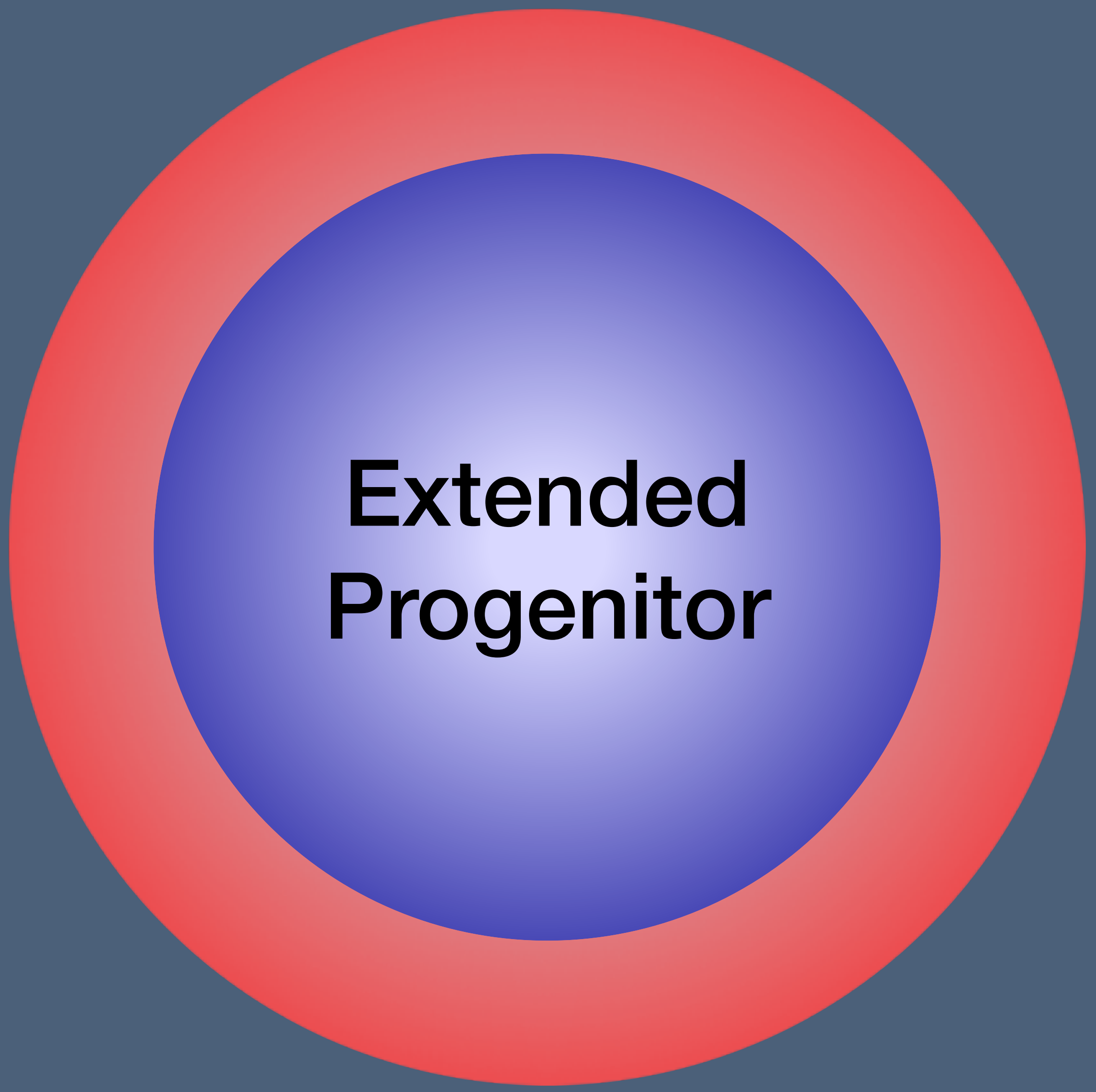
Diversity within partially stripped stars



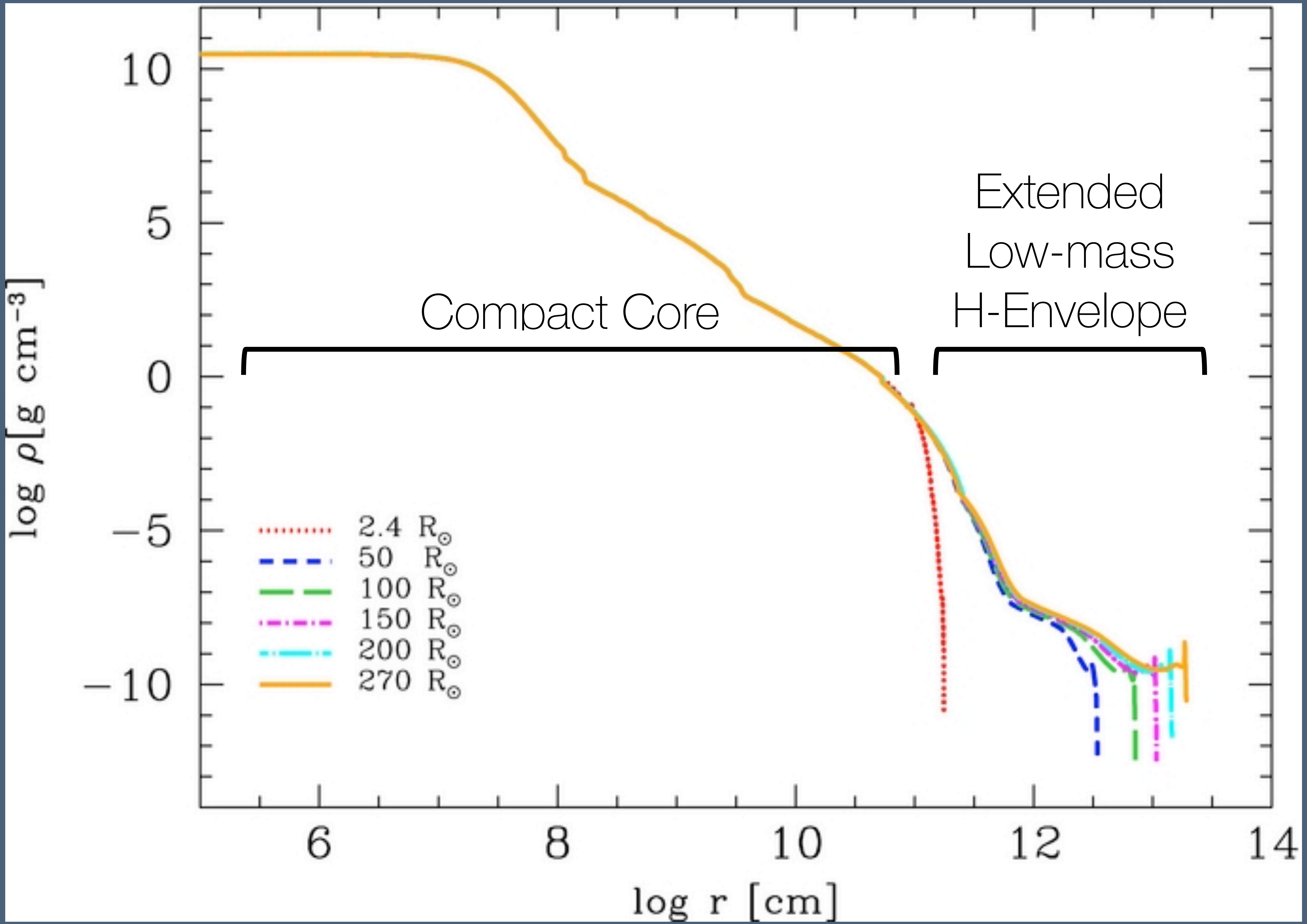


But NO! HST pre-explosion show a supergiant
(i.e. extended) progenitor for both
SN 1993J (7d cooling) and SN 2011dh (3d cooling)
Aldering et al. 1994, Maund et al. 2011, Van Dyk et al. 2011, 2014

Arcavi et al. 2011

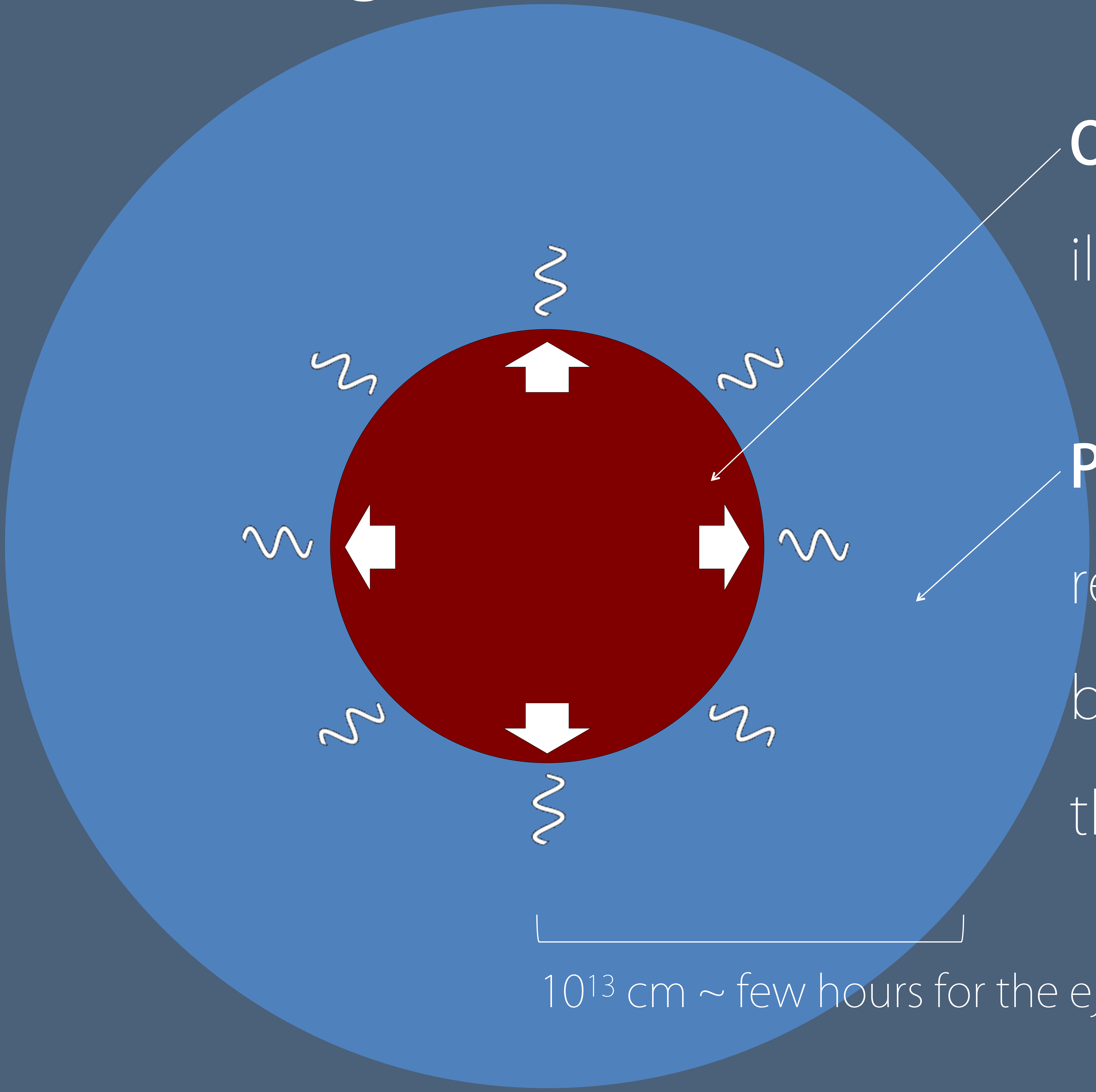


Shock cooling reveals peculiar progenitor structure



Bersten et al. 2012 (see also Hoflich et al. 1993; Woosley et al. 1994)

Flash ionizing the CSM with the shock breakout



Outflowing SN ejecta

illuminating the wind

Progenitor wind

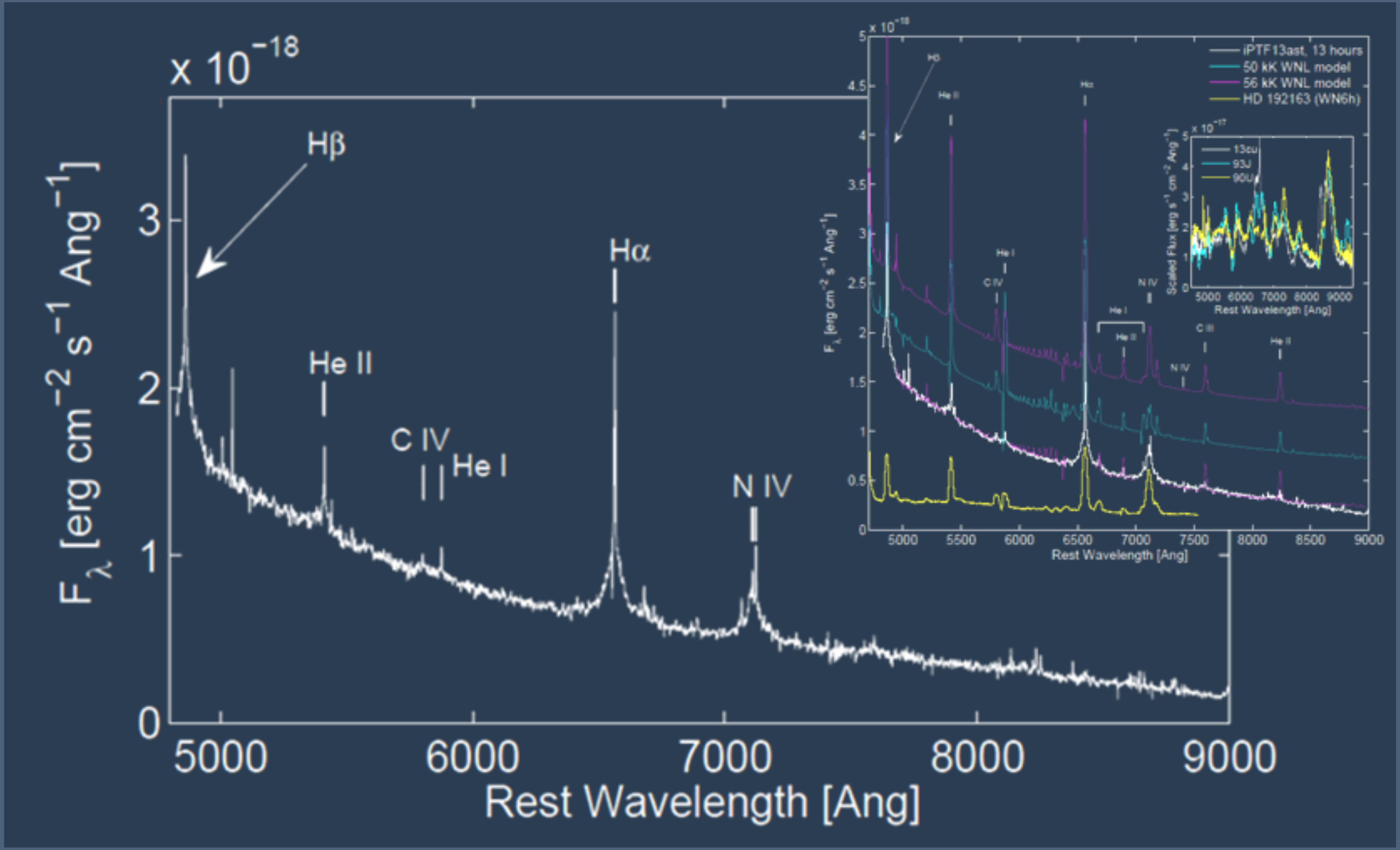
reacting to the SN flux

but not yet swept by

the ejecta

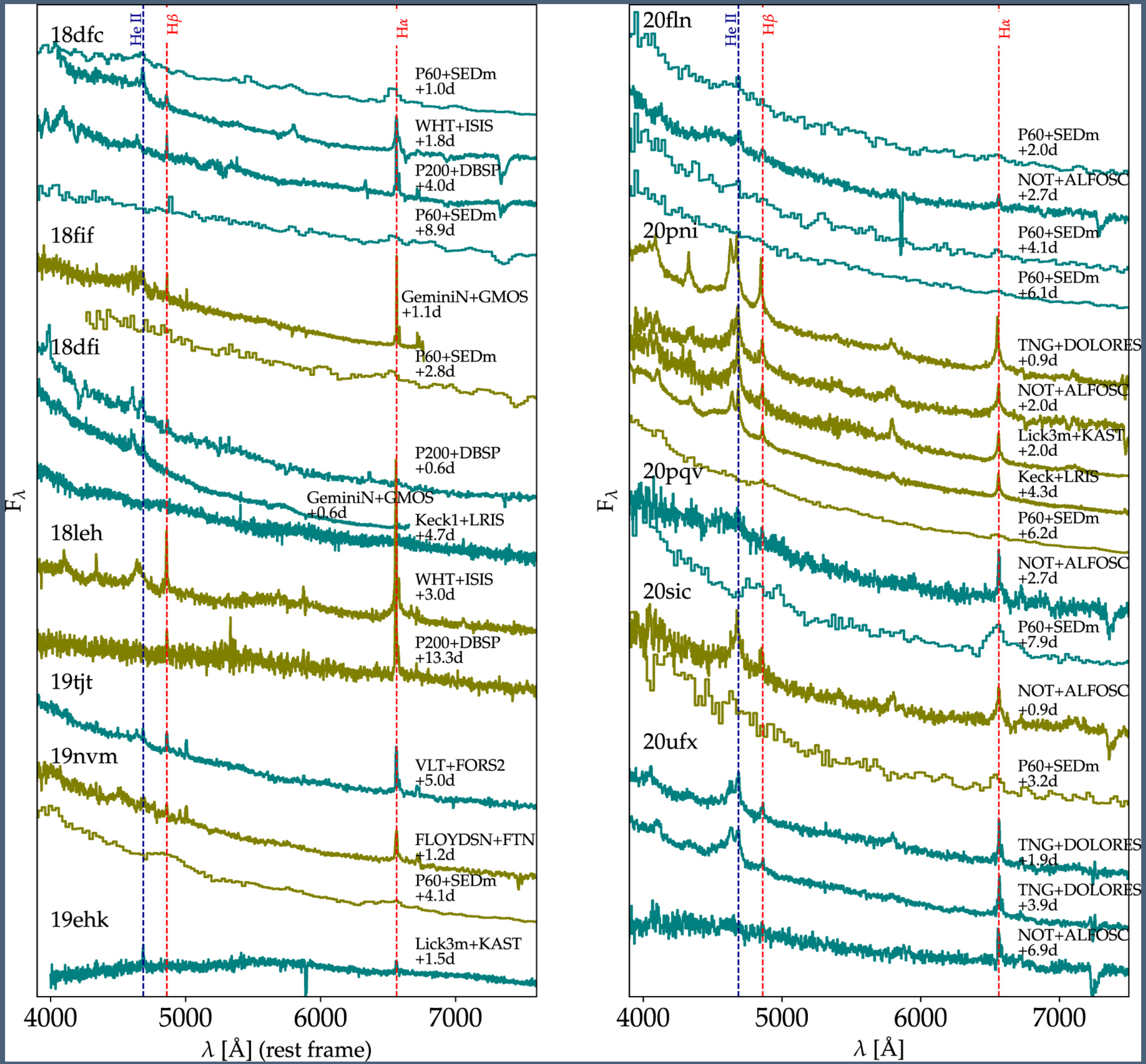
10^{13} cm ~ few hours for the ejecta to overtake

“Flash spectra” reveal confined CSM

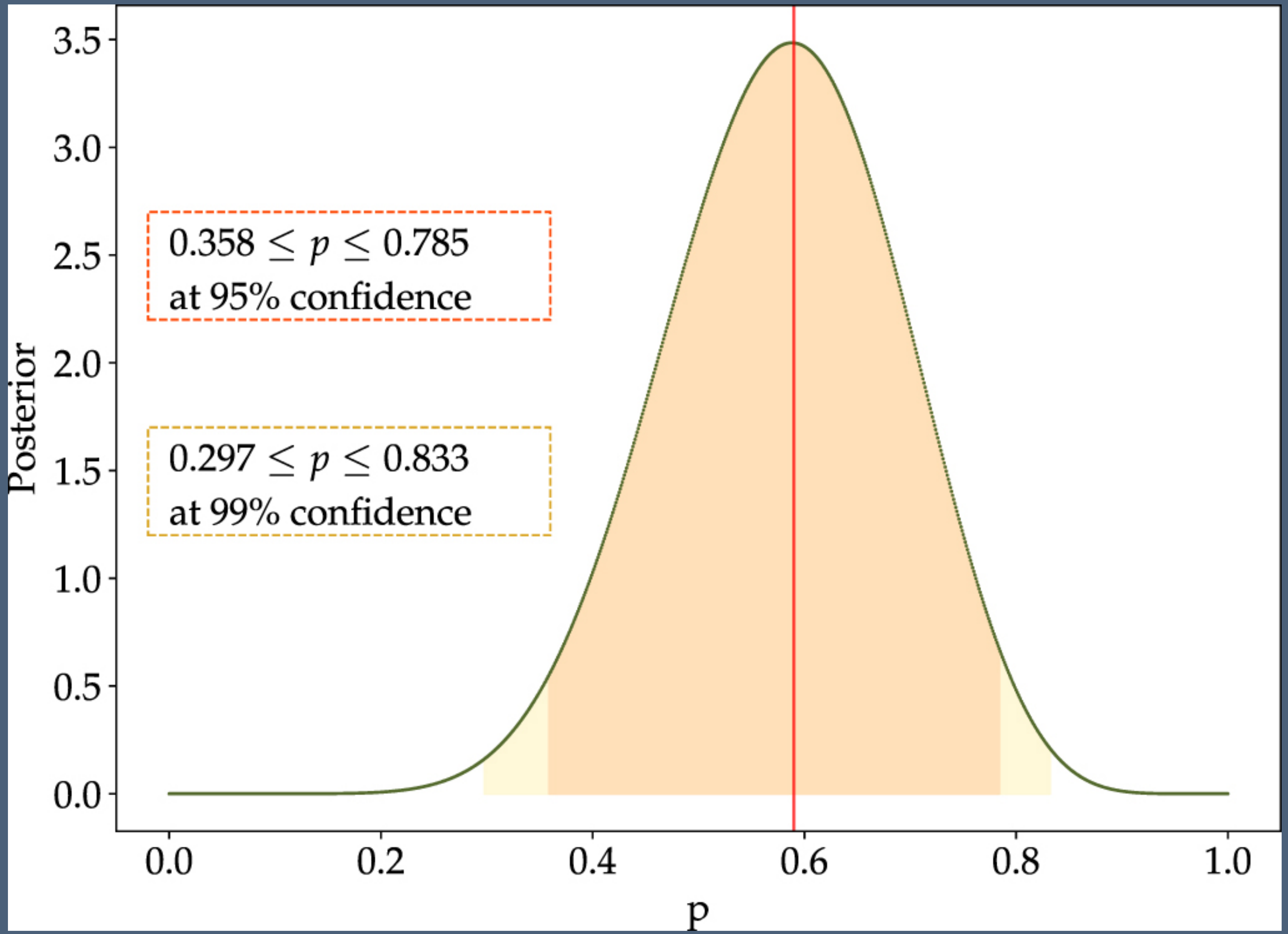


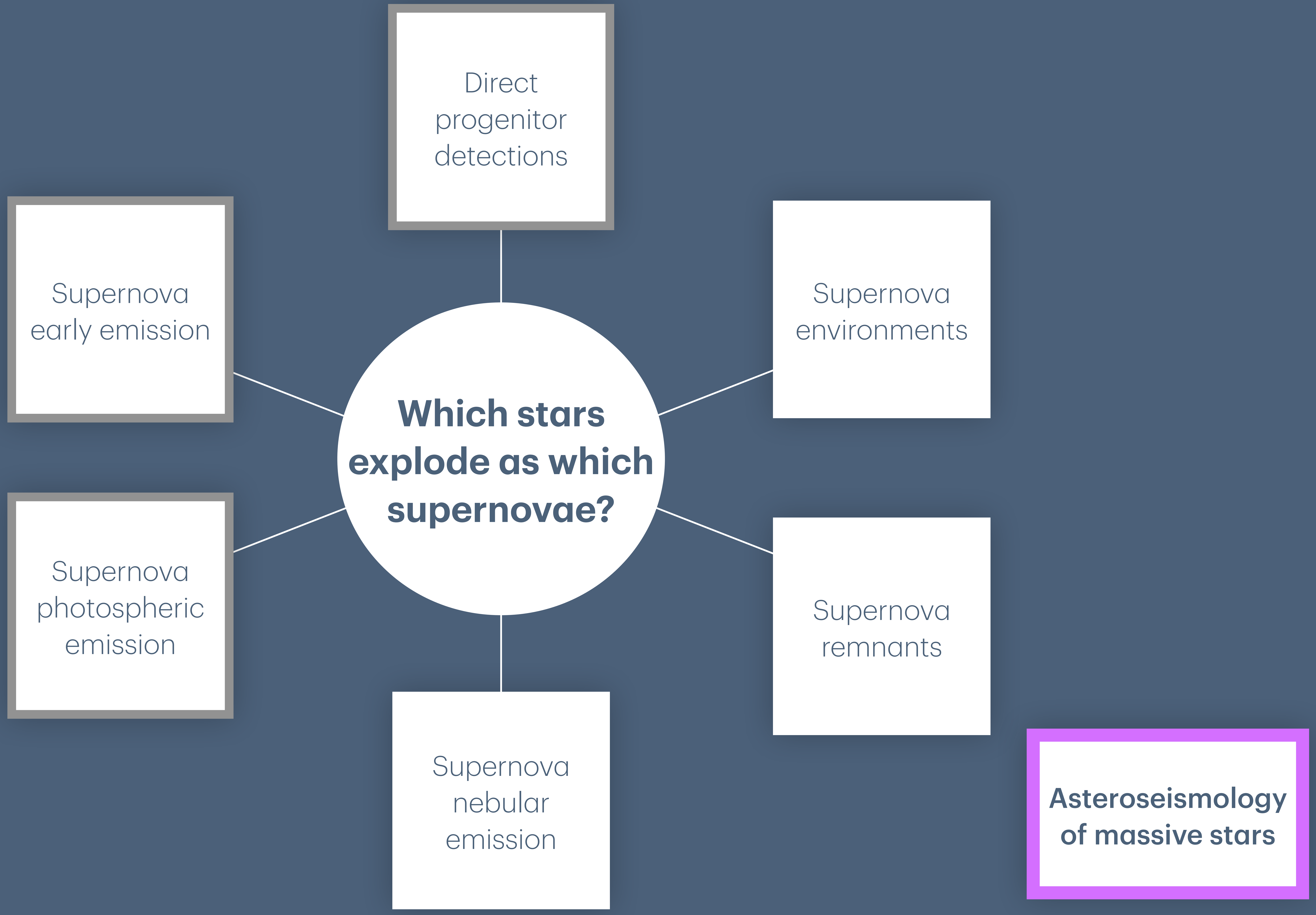
Gal-Yam, Arcavi et al. 2014

"Flash spectra" common in SNe II



Bruch et al. 2023

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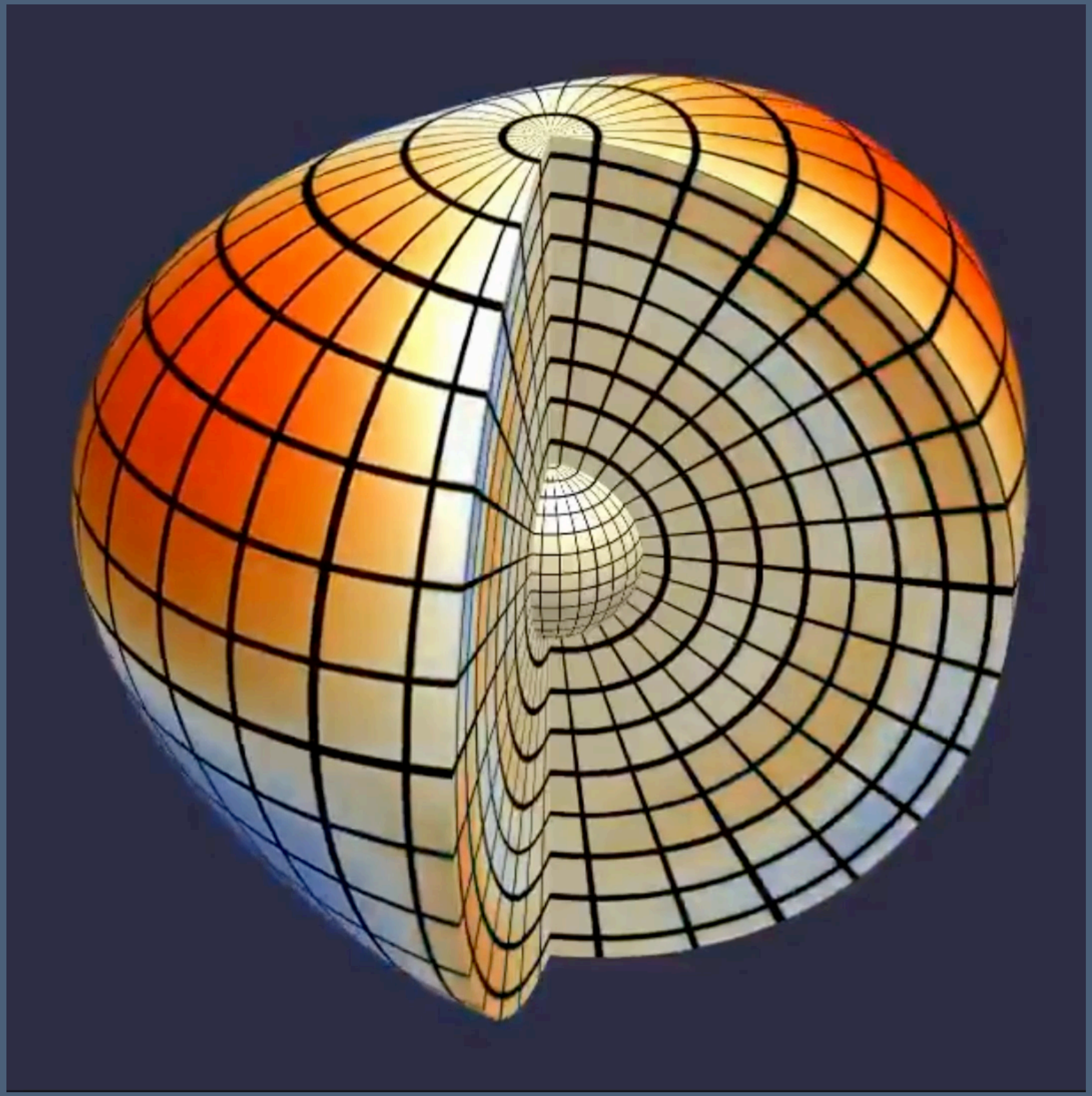
Asteroseismology of massive stars

Asteroseismology can probe stellar interiors

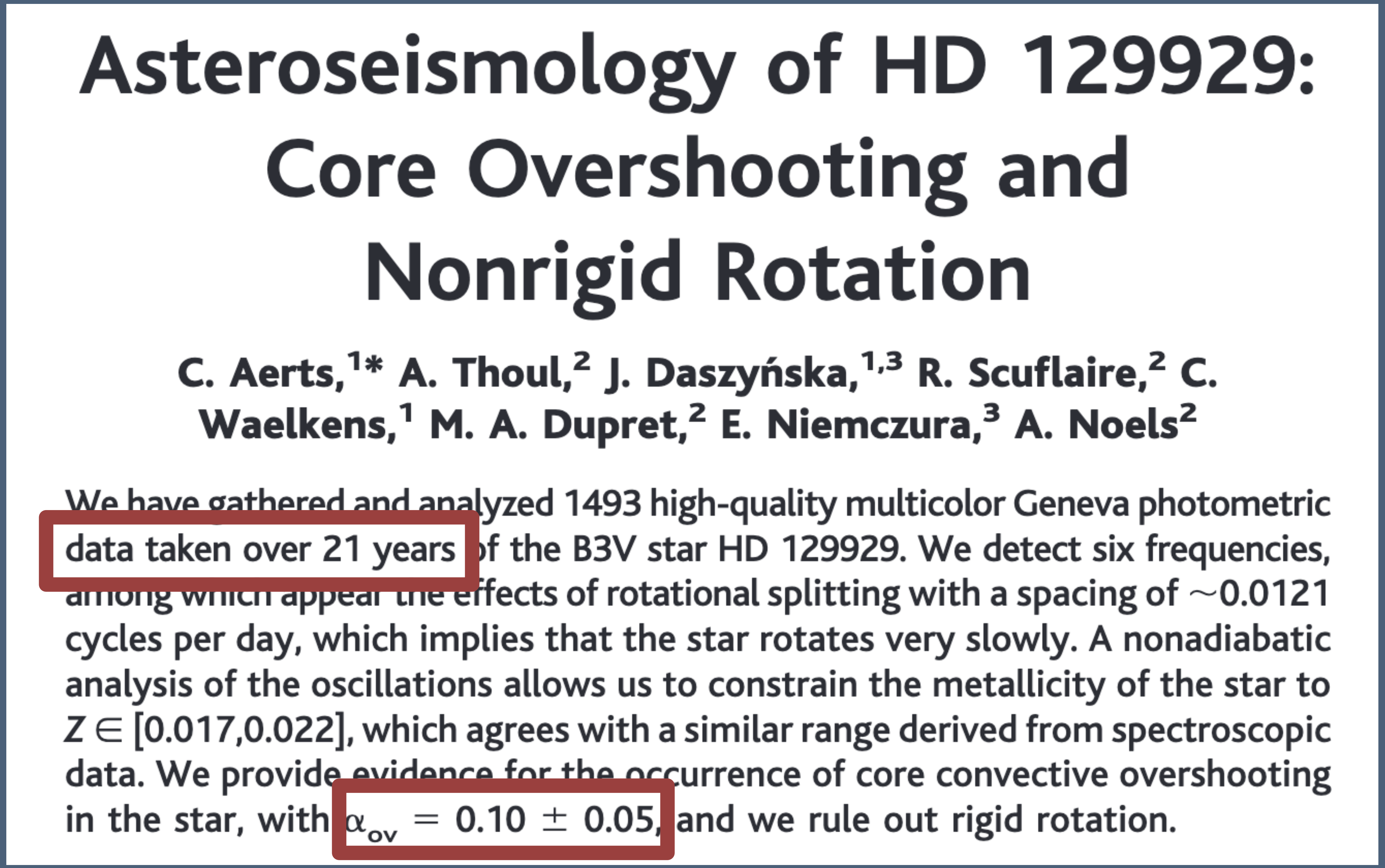


R. Townsend / UW-Madison

Stars oscillate.

These oscillations are influenced by the star's properties: **age, radius, mass, metallicity**, but also: **internal mixing** (i.e. core overshoot), **rotation, angular momentum transport** (i.e. differential rotation), **magnetic fields**...

Oscillation of massive stars are notoriously hard to discern

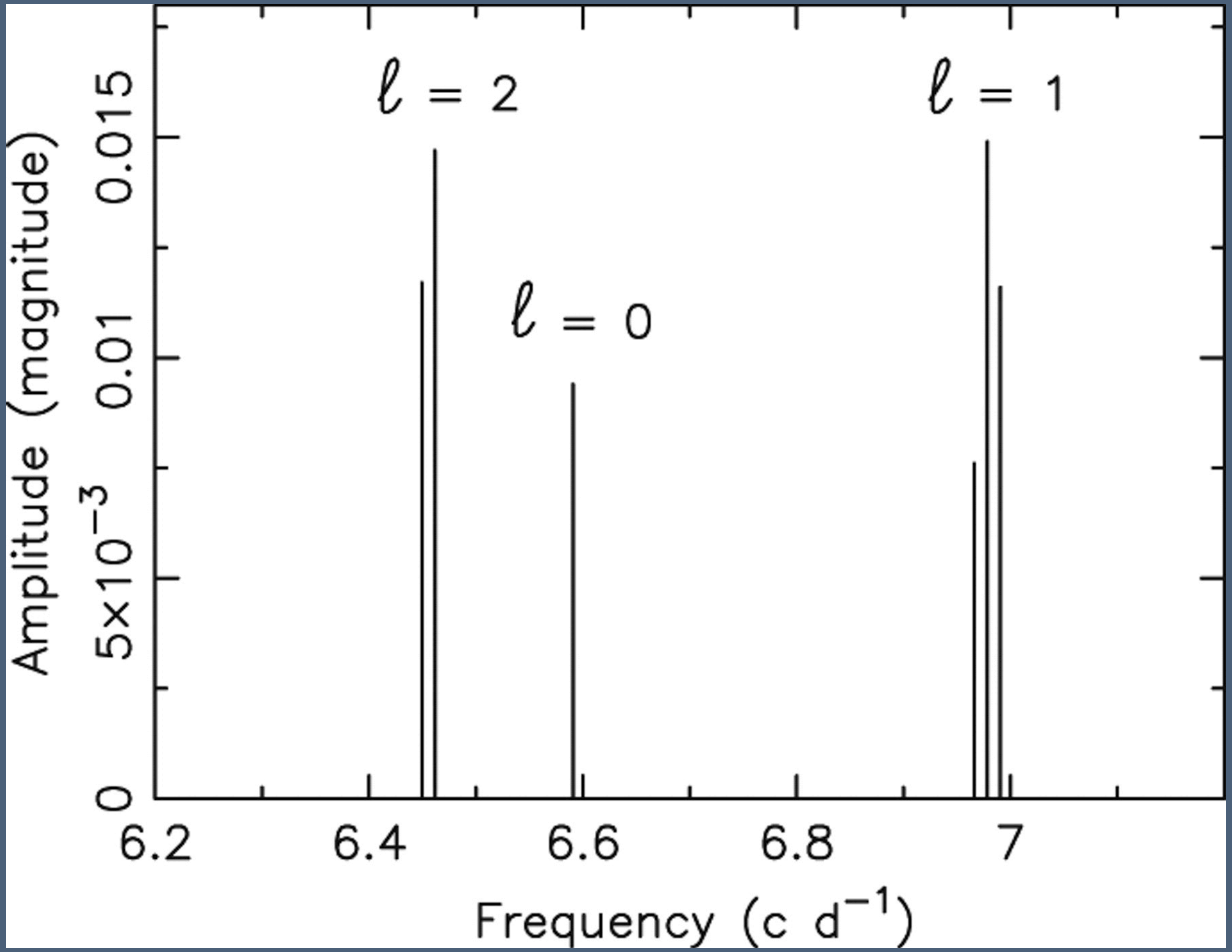


Asteroseismology of HD 129929: Core Overshooting and Nonrigid Rotation

C. Aerts,[1*] A. Thoul,[2] J. Daszyńska,[1,3] R. Scuflaire,[2] C. Waelkens,[1] M. A. Dupret,[2] E. Niemczura,[3] A. Noels[2]

We have gathered and analyzed 1493 high-quality multicolor Geneva photometric data taken over 21 years of the B3V star HD 129929. We detect six frequencies, among which appear the effects of rotational splitting with a spacing of ~0.0121 cycles per day, which implies that the star rotates very slowly. A nonadiabatic analysis of the oscillations allows us to constrain the metallicity of the star to $Z \in [0.017, 0.022]$, which agrees with a similar range derived from spectroscopic data. We provide evidence for the occurrence of core convective overshooting in the star, with $\alpha_{ov} = 0.10 \pm 0.05$, and we rule out rigid rotation.

Aerts et al. (2003)

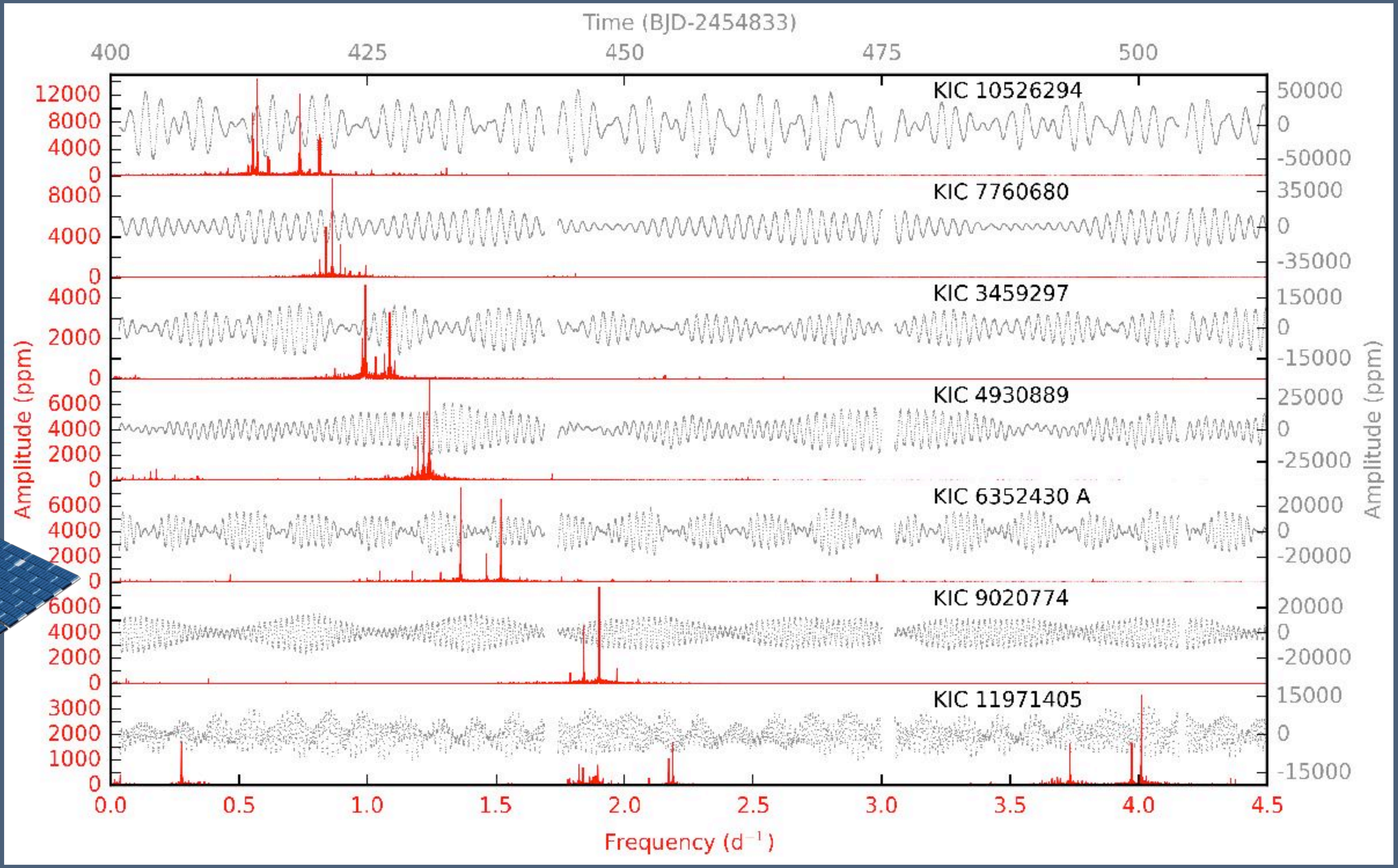


Informative, but hard to reproduce for a large sample

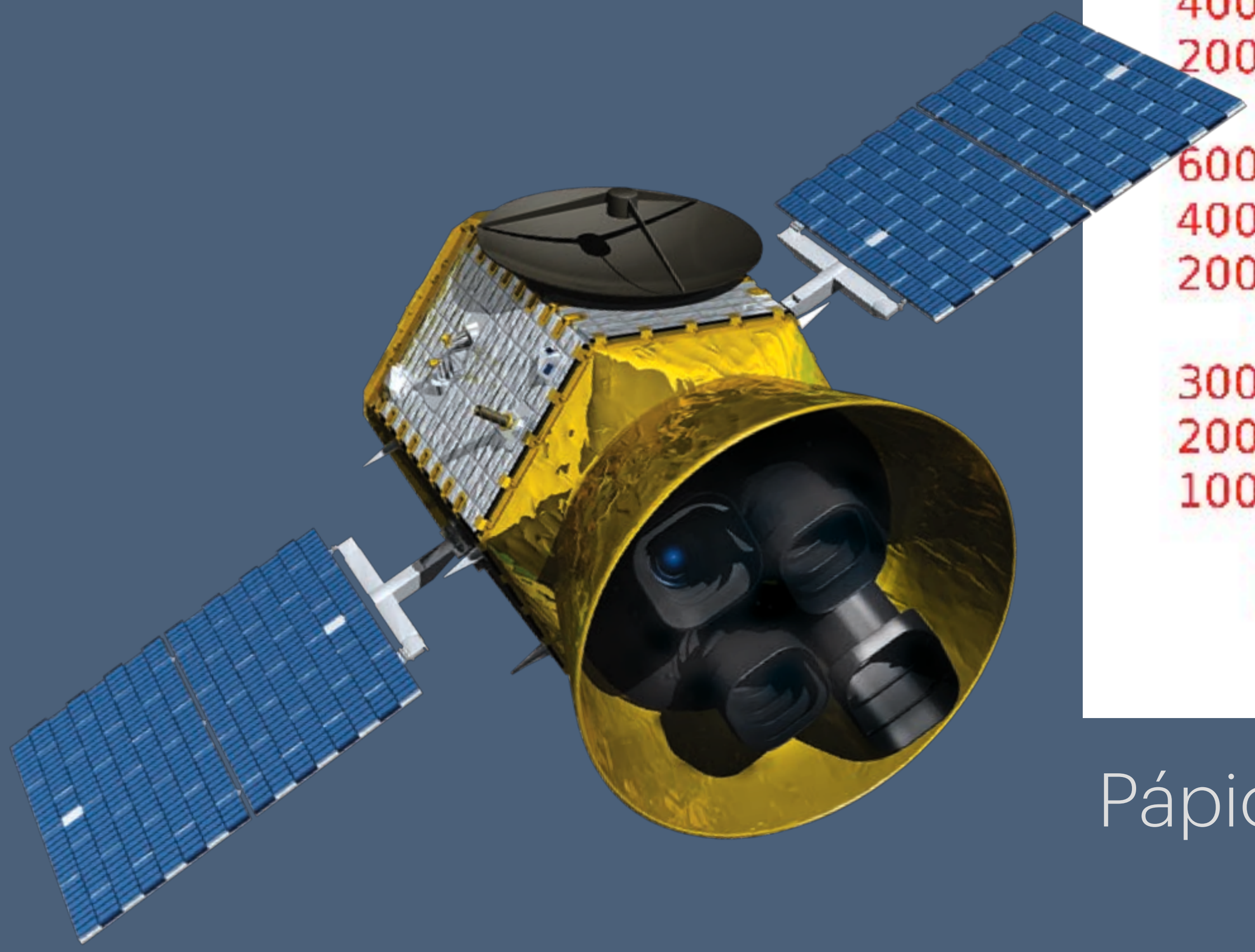
Full astroseismic studies have so far been performed **only on 9 massive stars**

Need long-term continuous coverage

The multiple frequencies can be mapped with **long continuous** light curves, as provided by space telescopes (CoRoT, Kepler, TESS, and others)



Pápics et al. (2017)



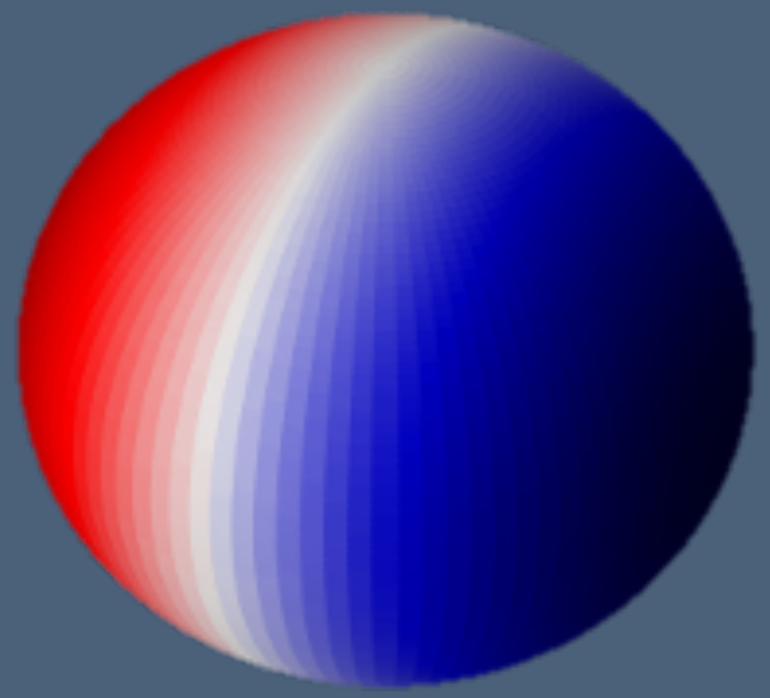
Need to identify the modes to constrain physics

Every oscillation mode is identified by its l, m and n.

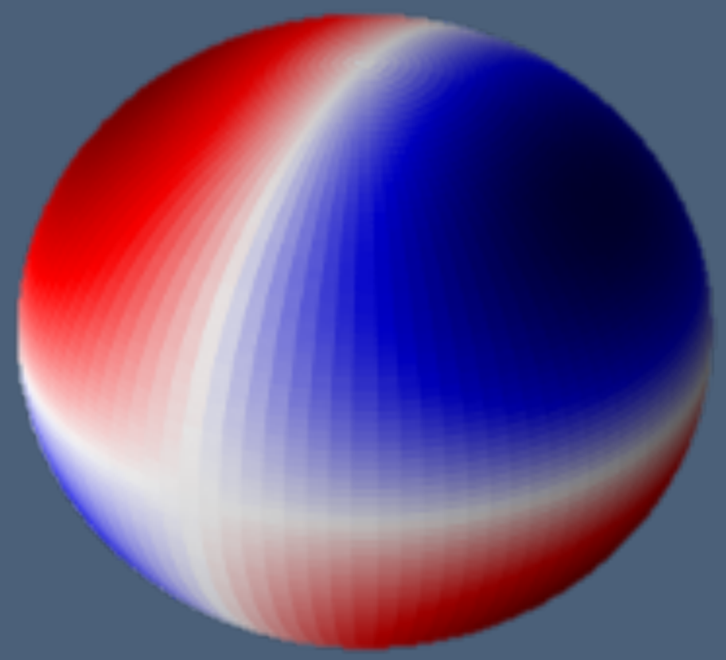
Full astroseismic analysis depends on:

1. **Measuring** the frequency, amplitude and relative phases of each mode.
2. **Associating** these modes with their respective l,m and n (“**mode identification**”) to lift model degeneracies.

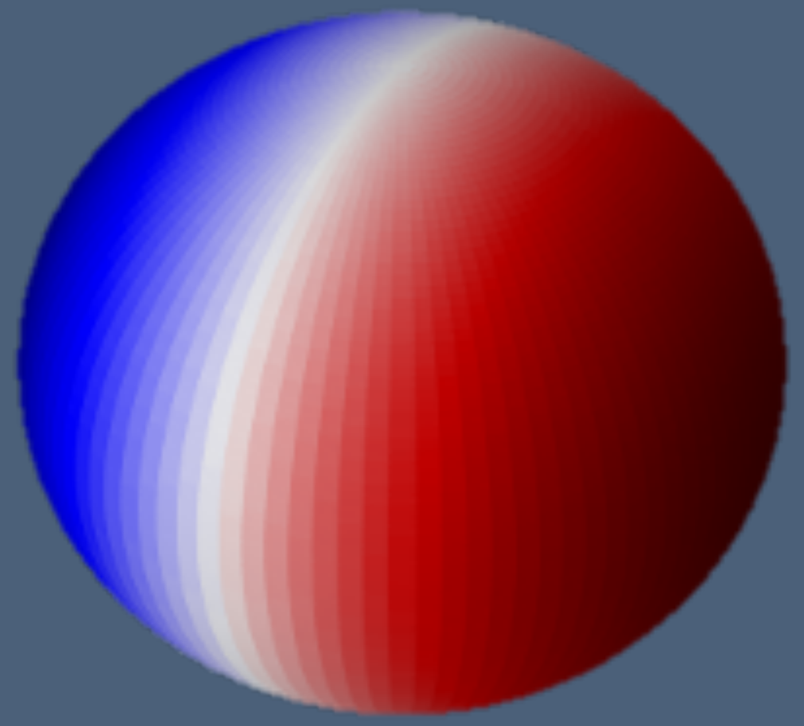
$l = 1, m = 1$



$l = 2, m = 1$



$l = 1, m = -1$

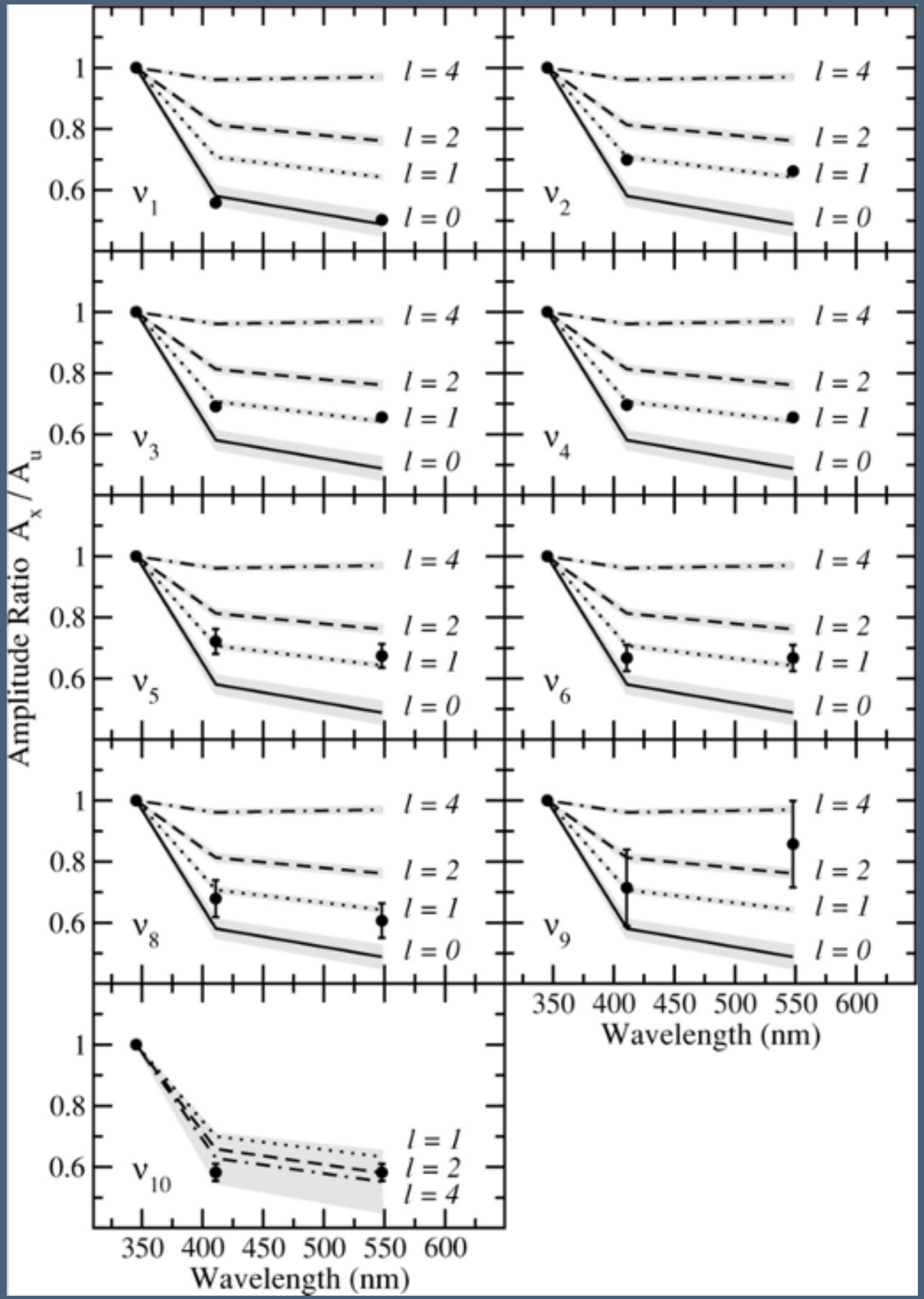


Need to identify the modes to constrain physics

Different modes produce different amplitude ratios across different bands.

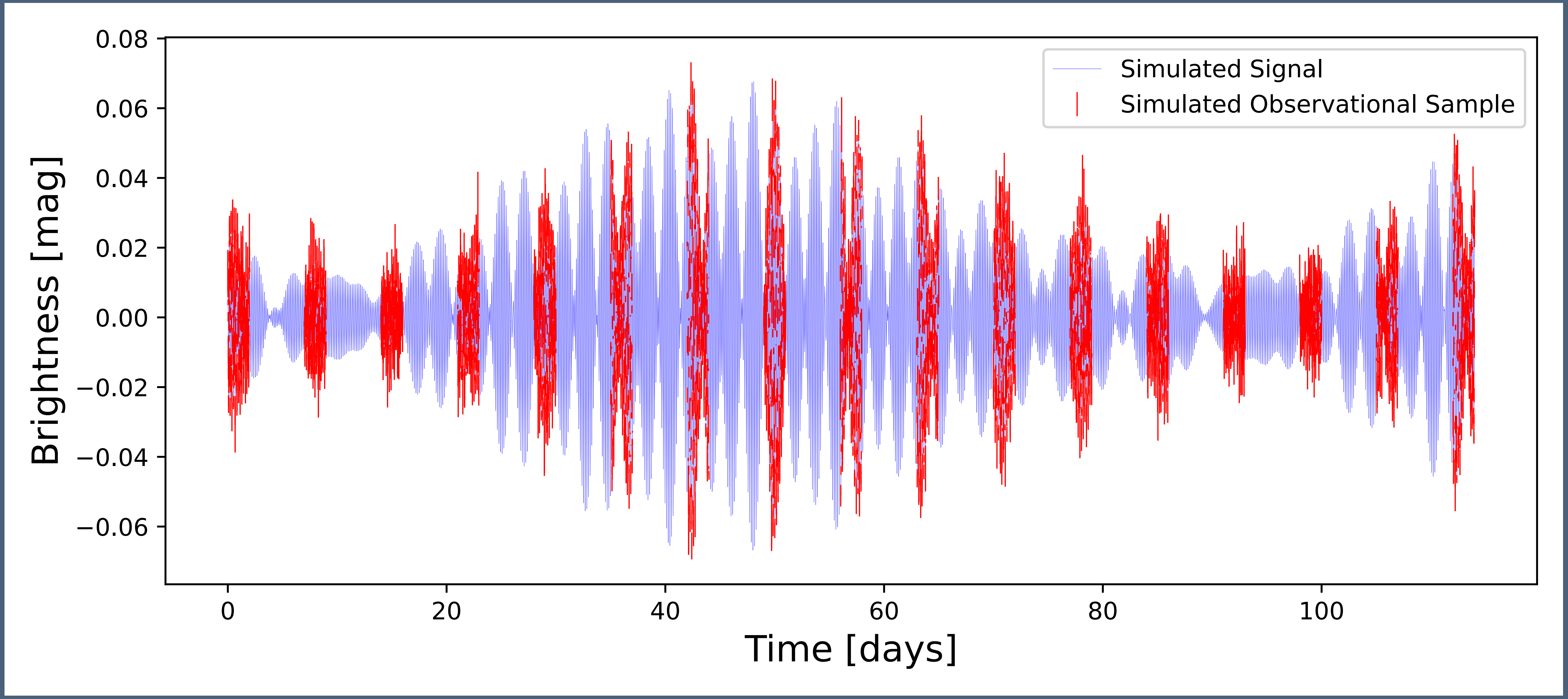
By comparing multi-band amplitude ratios to stellar models, the modes can be identified.

However, most space mission don't provide any color information.



De Ridder et al. (2004)

Reducing 21 years of observations to 4 months



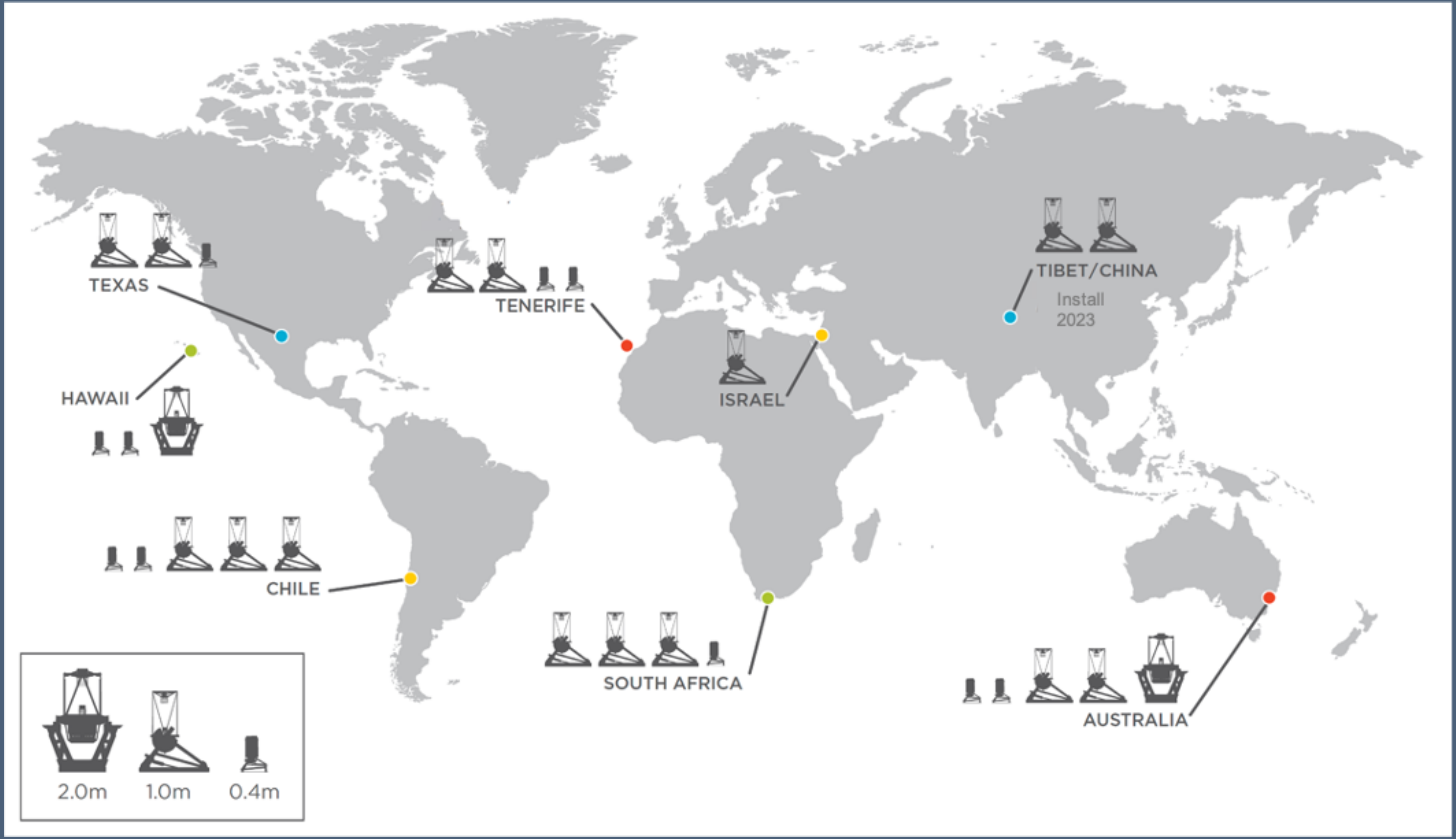
Shitrit & Arcavi (2024)

The same frequency spectrum that took Aerts et al. (2003) **21 years** to map, can be reproduced in **17 weeks** with weekly 48-hour runs.

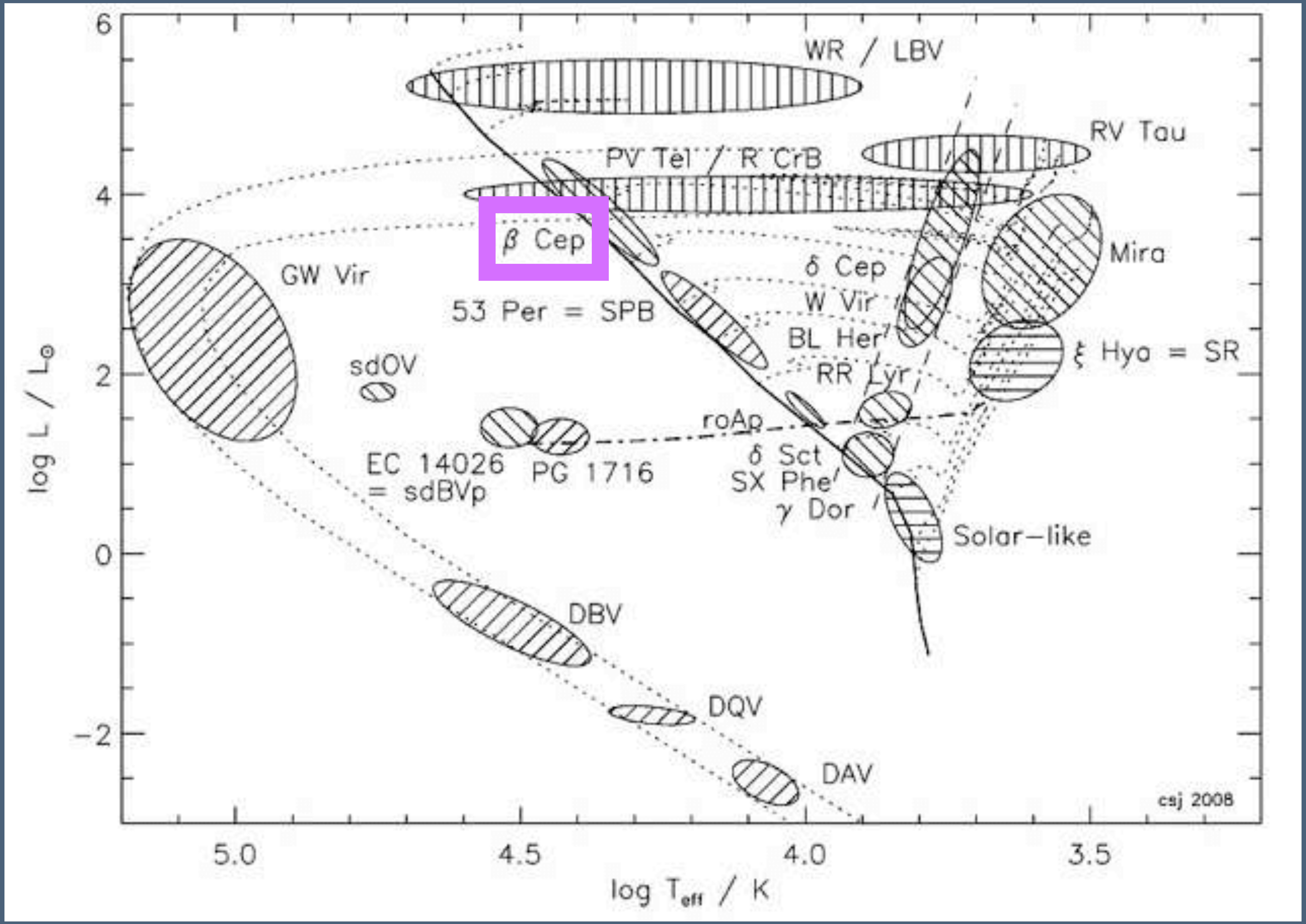
The Las Cumbres Observatory Global Network

Uniform

Robotic

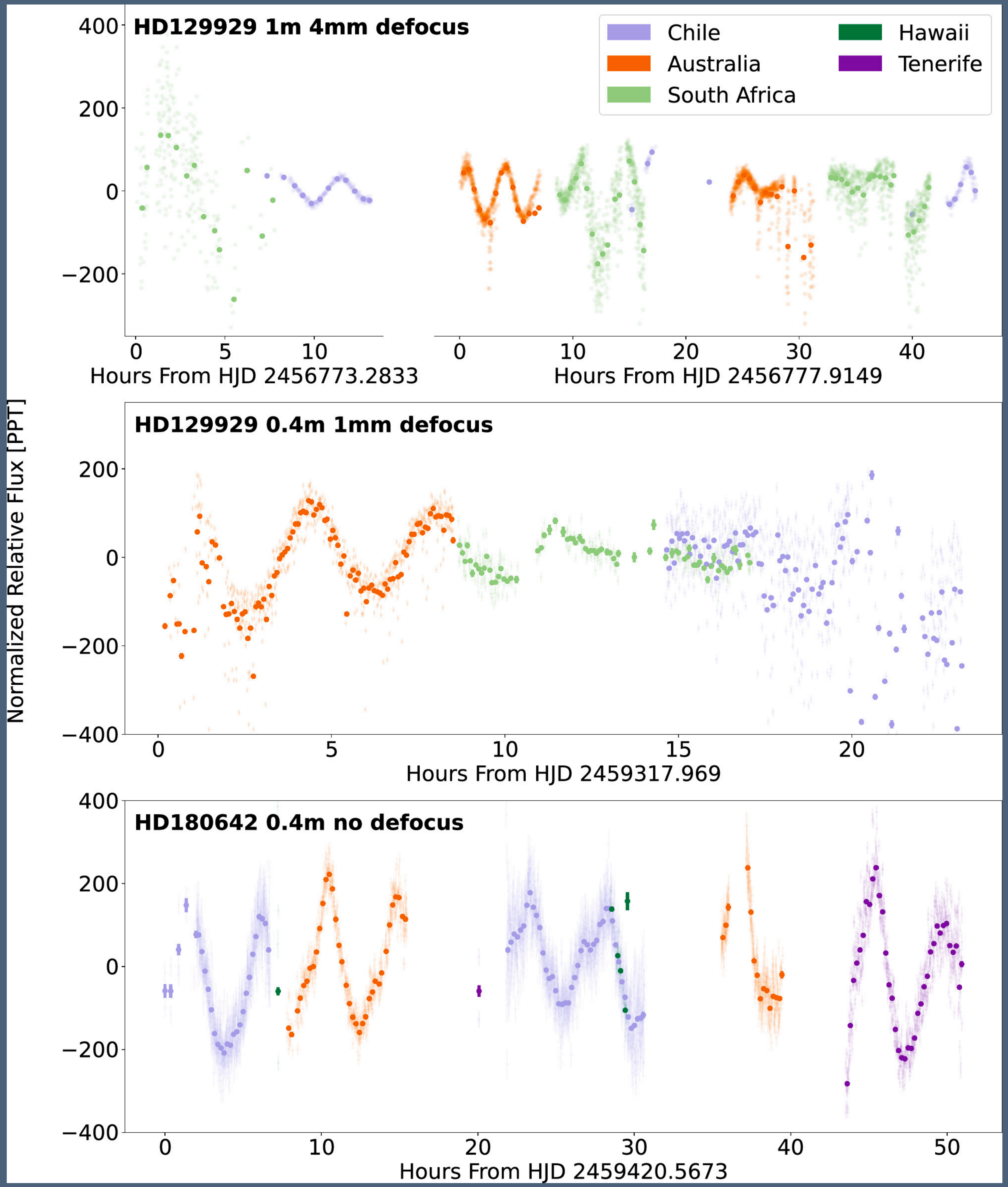


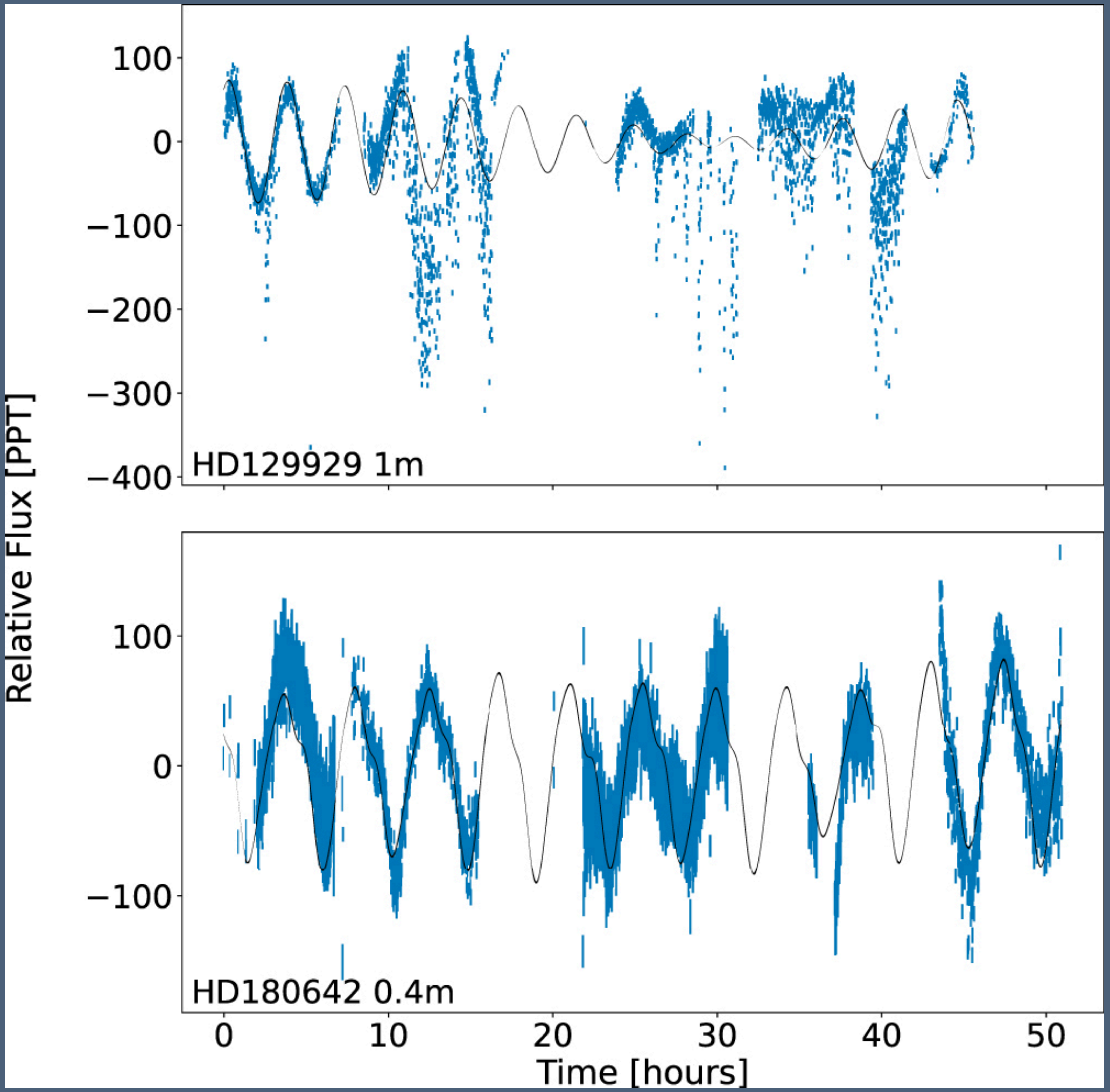
Pulsating main-sequence M > $8M_\odot$ = β-Cepheids



Jeffery (2008)

Proof-of-concept finds stable oscillations over decades

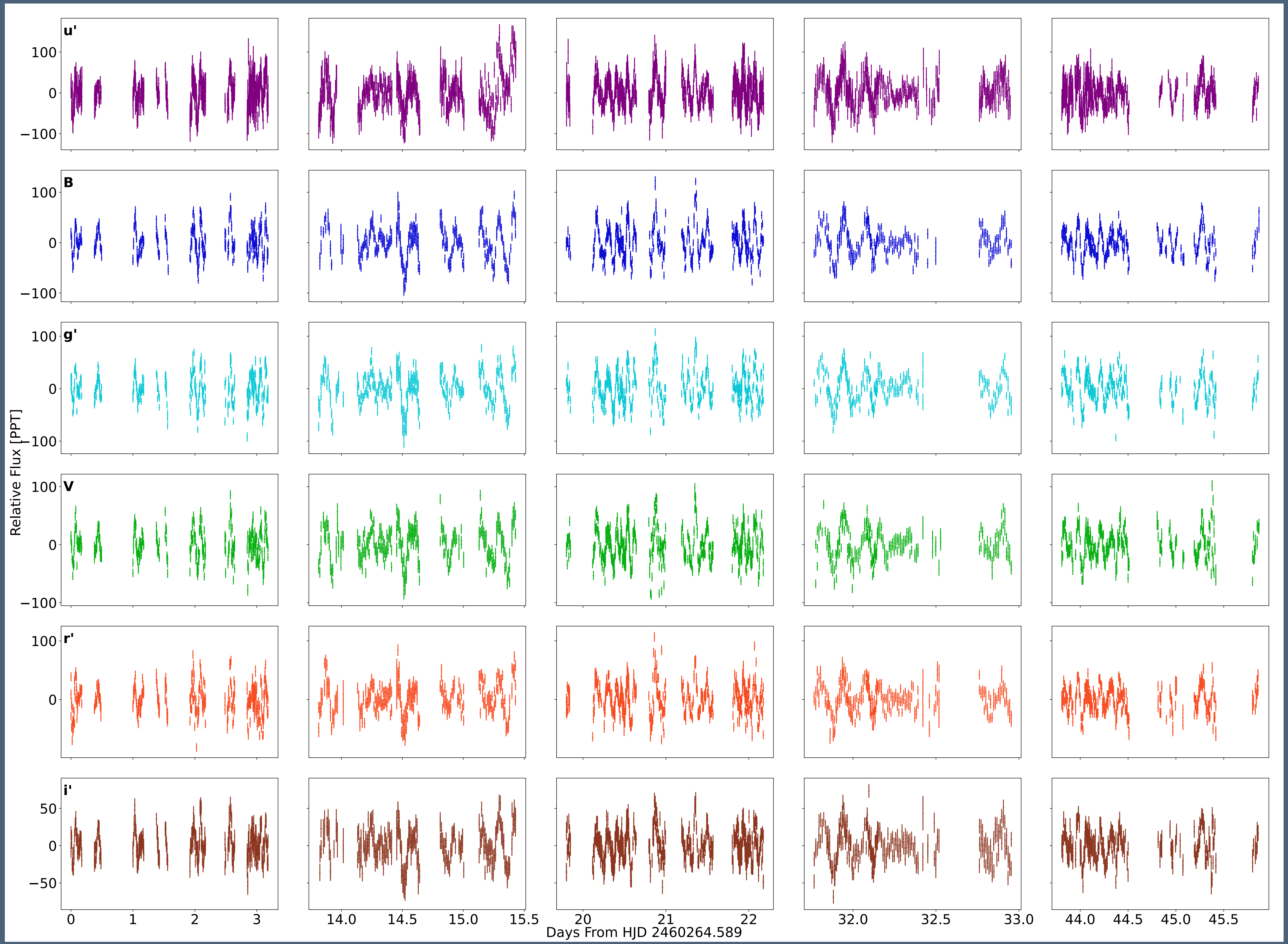




Shitrit & Arcavi (2024)

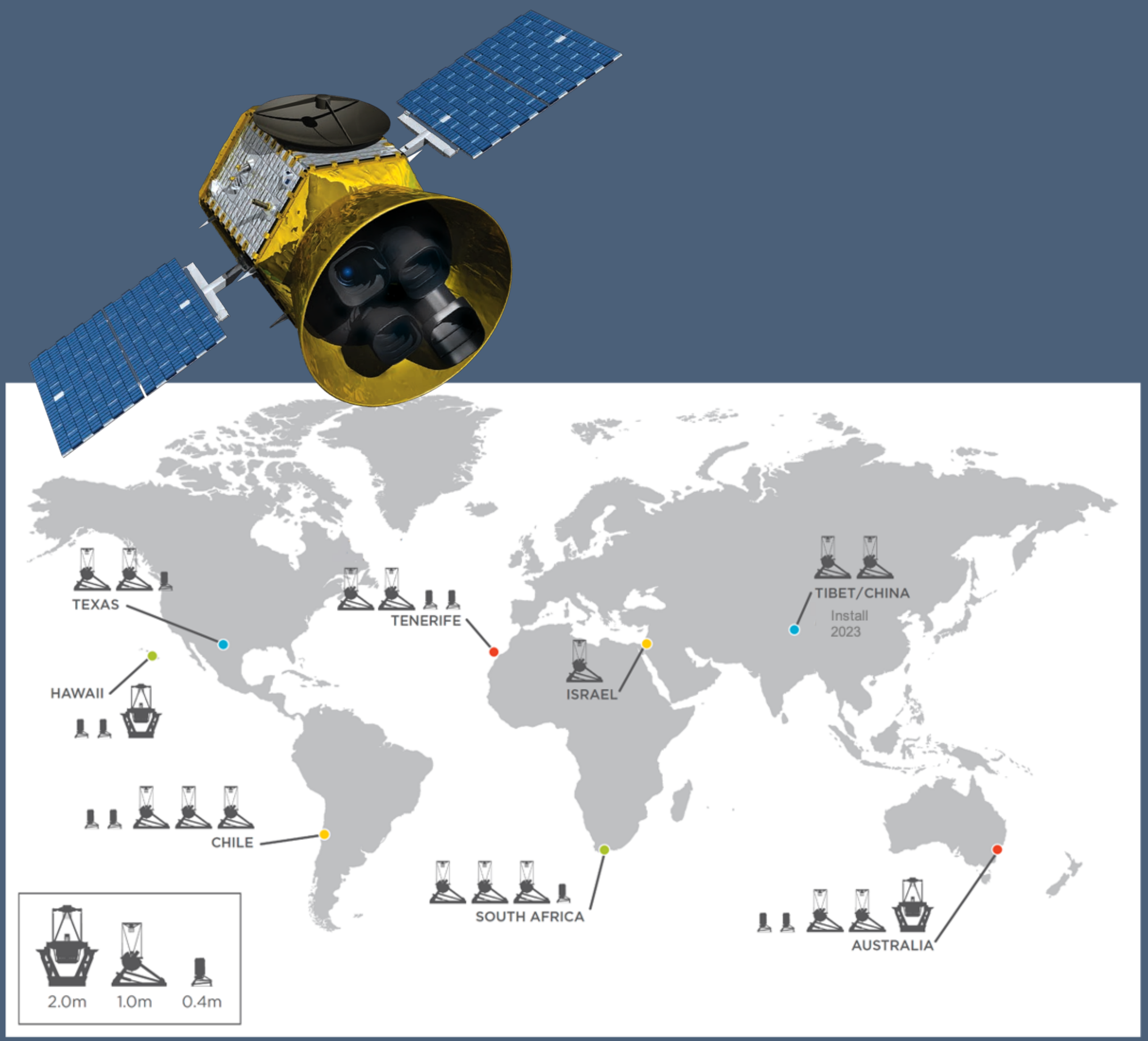
Tripling the sample

With: C. Aerts, D. Bowman, G. Handler, A. Gilkis, M. Lam and M. Pedersen



Adding color information for full mode identification

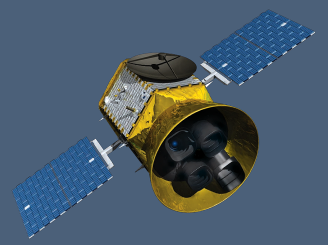
PI: Noi Shitrit

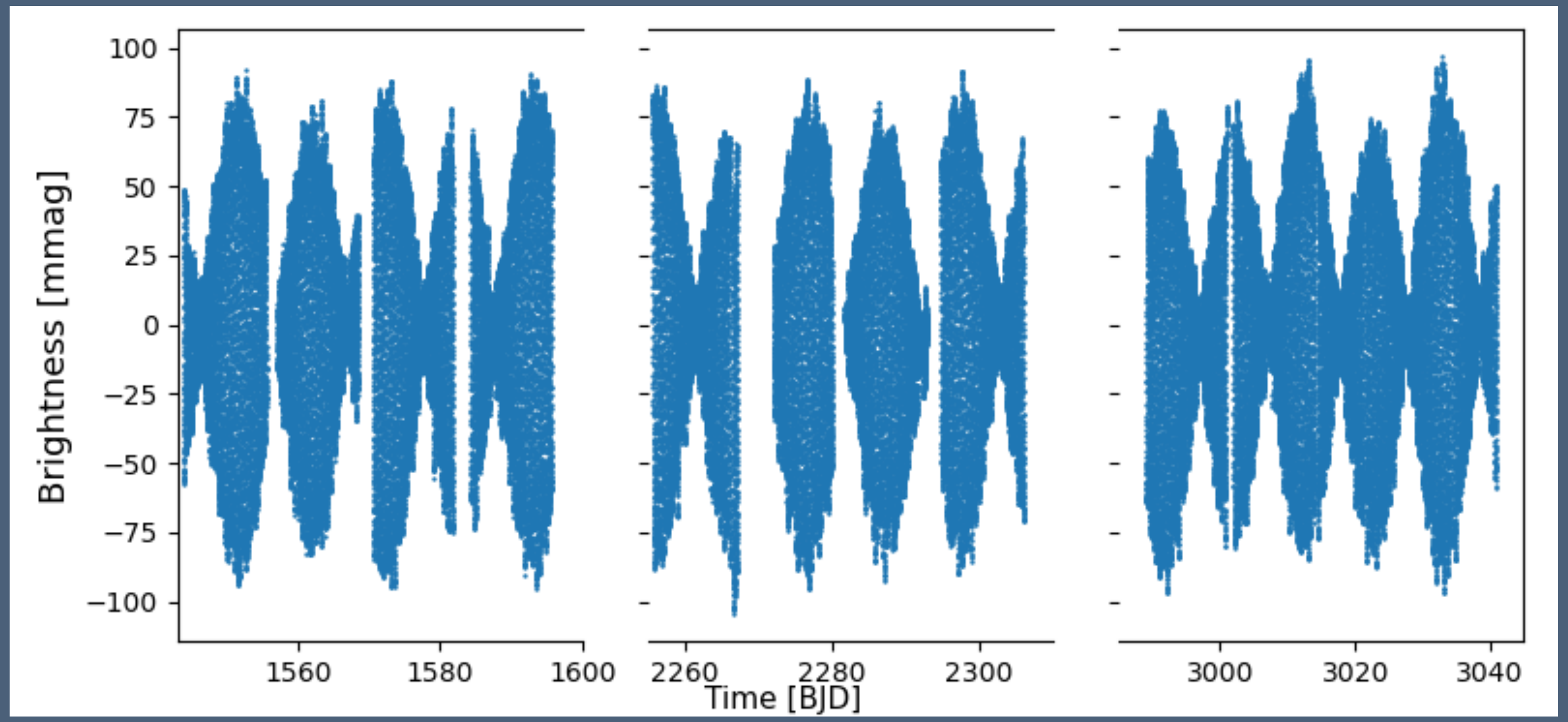


The Global Asteroseismology Project

With: C. Aerts, D. Bowman, G. Handler,
A. Gilkis, M. Lam and M. Pedersen

Pulsation Information

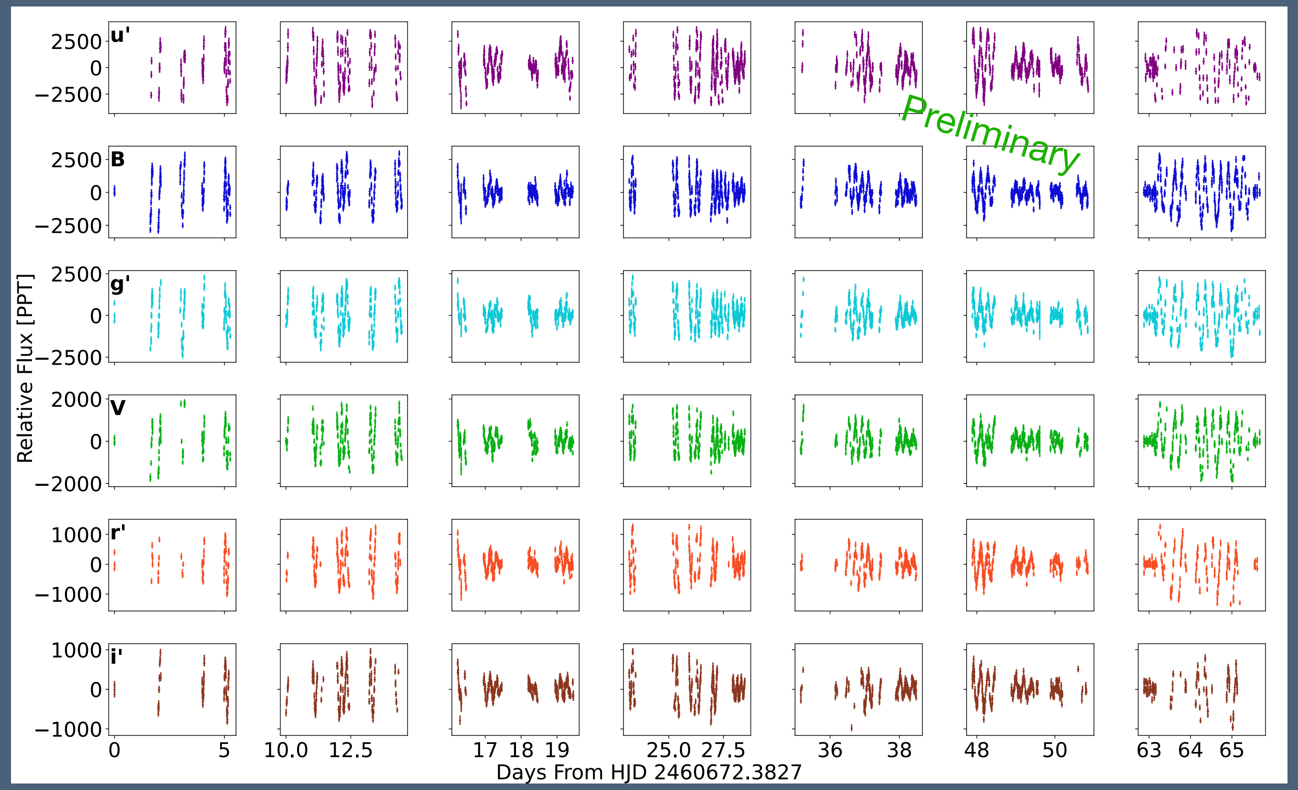




f, A, ϕ

Color information

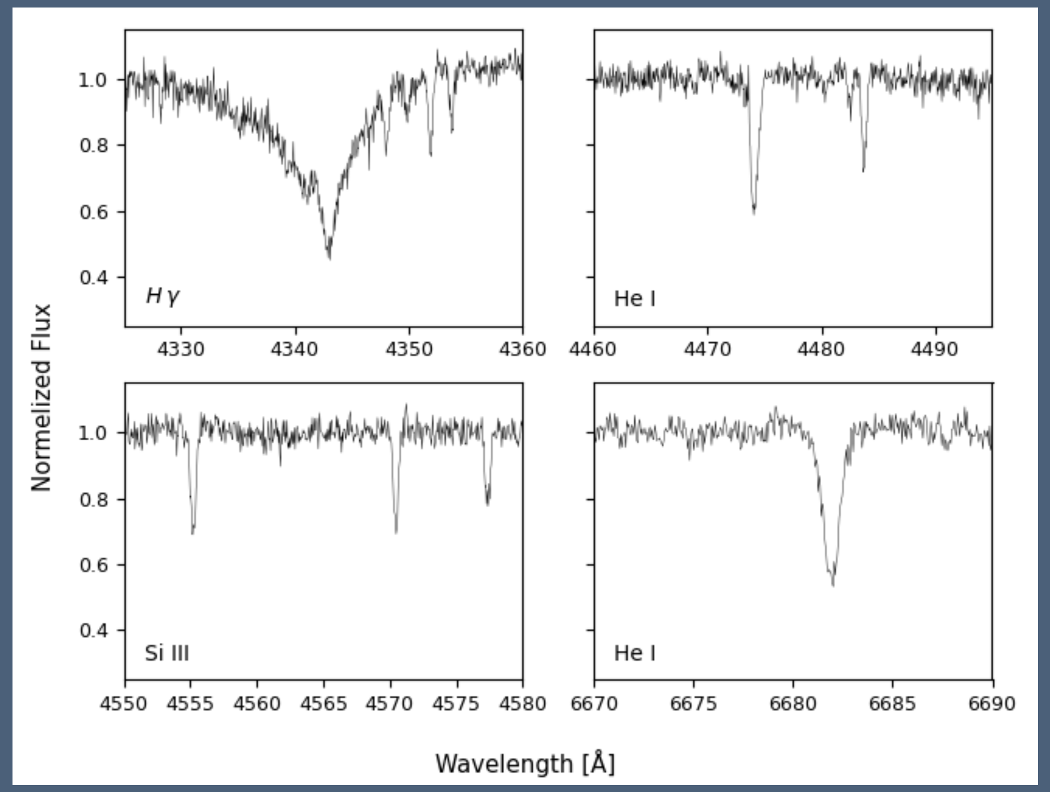
LCO
Las Cumbres Observatory



f, A, ϕ per band = Amplitude ratios

Stellar Properties

NRES



T_{eff}, $n(He)/n(H)$, $log(g)$

\+ Grid of MESA models + GYRE oscillations + atmospheric models

= Constraints on internal parameters of a sample of massive stars

Which stars explode as which supernovae?

Direct progenitor detections

ProgenIt: Fit progenitor photometry with variying extinction, distance, metallicity, mass priors. Produce posteriors, map degeneracies.
First science result: RSG problem persists.

Supernova early emission

Early Emission: Shock cooling can probe the progenitor structure; flash spectroscopy can reveal final stage mass loss history

Supernova photospheric emission

SNemcee: Fit supernova light curves and velocities with or without CSM.
First science result: Slow rising SN IIP class with confined CSM and high velocities.

Supernova nebular emission

Supernova environments

Supernova remnants

Asteroseismology of massive stars

The Global Asteroseismology Project: Using a global telescope network to triple the sample of massive stars with full asteroseismic analysis. **Stay tuned.**