



current status of type Ia supernova cosmology *(from scratch)*

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**Institute of
Space Sciences**

IEEC^R



CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS



Outline

- Type Ia supernovae: progenitors & explosion mechanisms
- Light curves & spectra: parameters and diversity
- Host galaxies, environments & explosion sites
- Standardization: from Phillips to the Tripp relation
- Distances & cosmology: dark energy, H_0 & growth of structure
- Systematic & open problems
- Future: LSST, Roman, and beyond

Why are Thermonuclear SNe important?

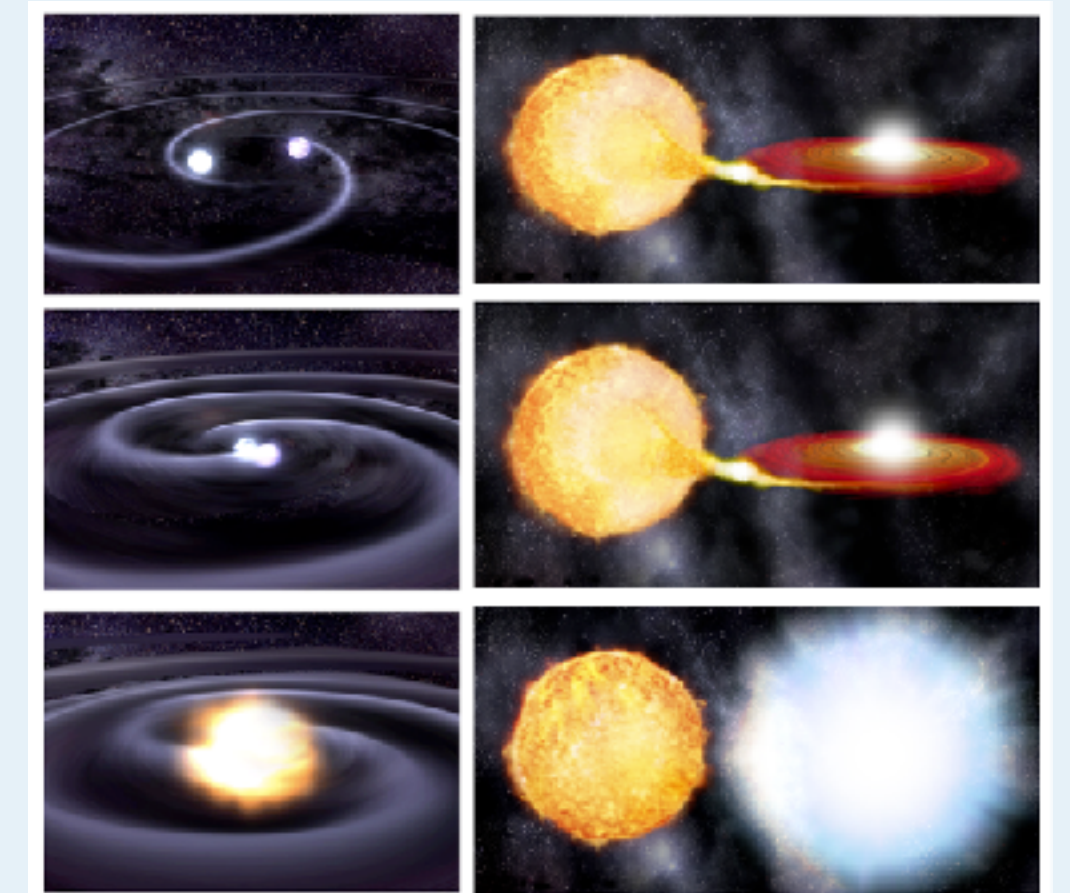
- Critical cosmological probes and distance indicators
- Produce large fraction of Fe group elements
- Kinematic E contribute to galaxy evolution
- After 60 years of research we embarrassingly don't know what their progenitors and explosions are!

What is exploding?

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

How is it exploding?

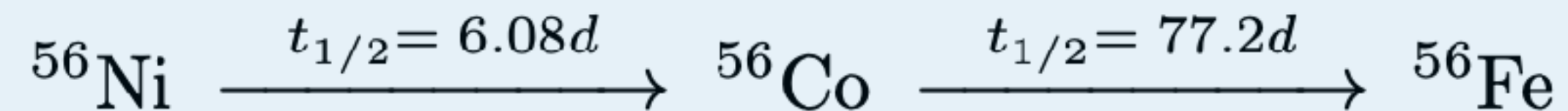
Merging/compression/He layer burn/collision
Detonation/deflagration/double-detonation
Chandrasekhar/sub-Chandrasekhar mass



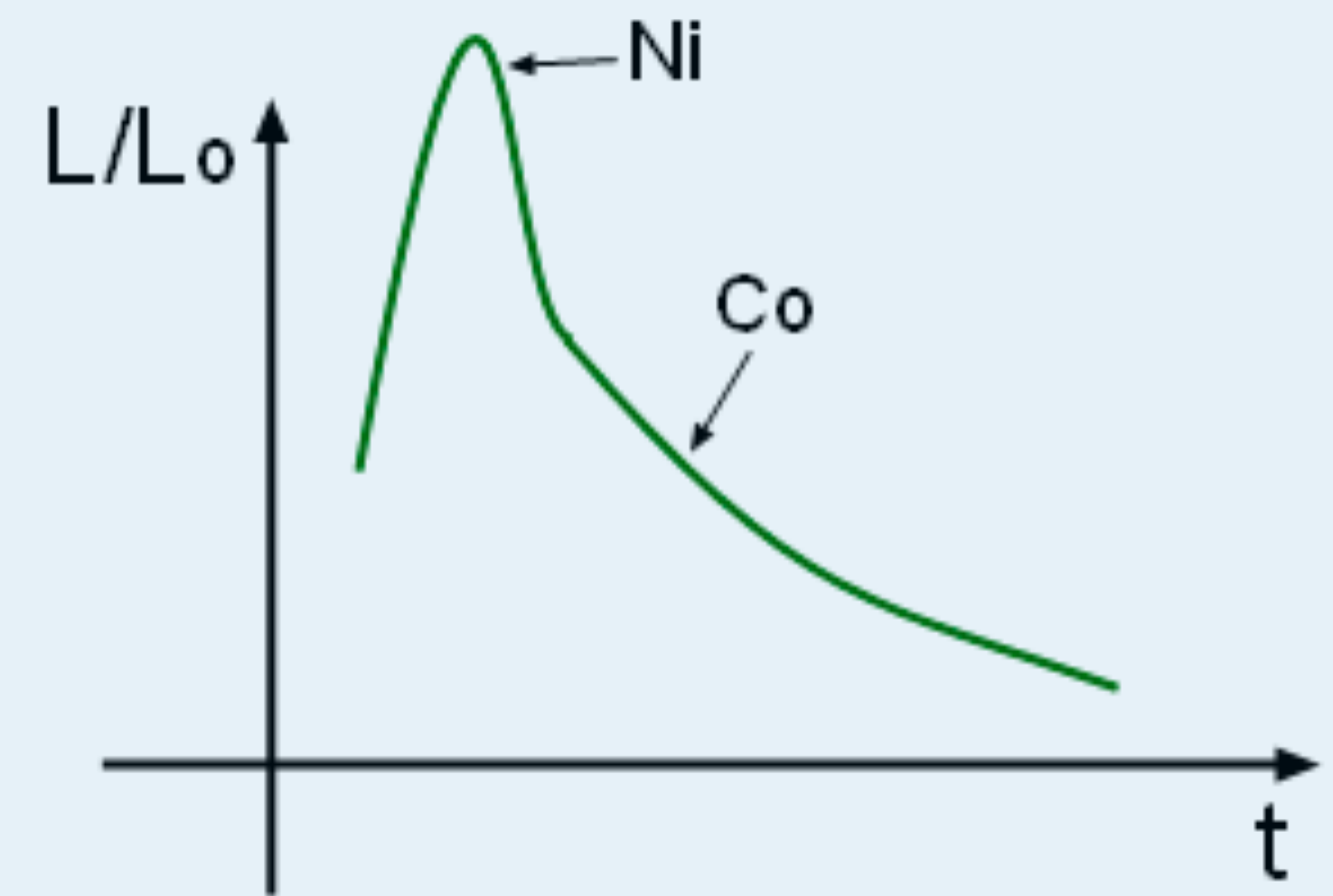
Most probably a mixture of scenarios and explosion mechanisms

(Simple) Explosion picture

- At Chandrasekhar Mass Limit (M_{Ch}): Gravity > Electron Degeneracy Pressure
- Nuclear fusion -> thermonuclear runaway
- Radioactive decay



$$L_{\text{peak}} \propto ^{56}\text{Ni mass (Arnett 1982)}$$



- Fusion drives the explosion, radioactivity makes it shine!

Type Ia SNe as standard candles

- The lack of understanding about SNe Ia progenitors and explosions could produce one of the largest systematics in cosmological experiments
- SNIa are the most precise extragalactic distance indicators (uncert. ~5%)

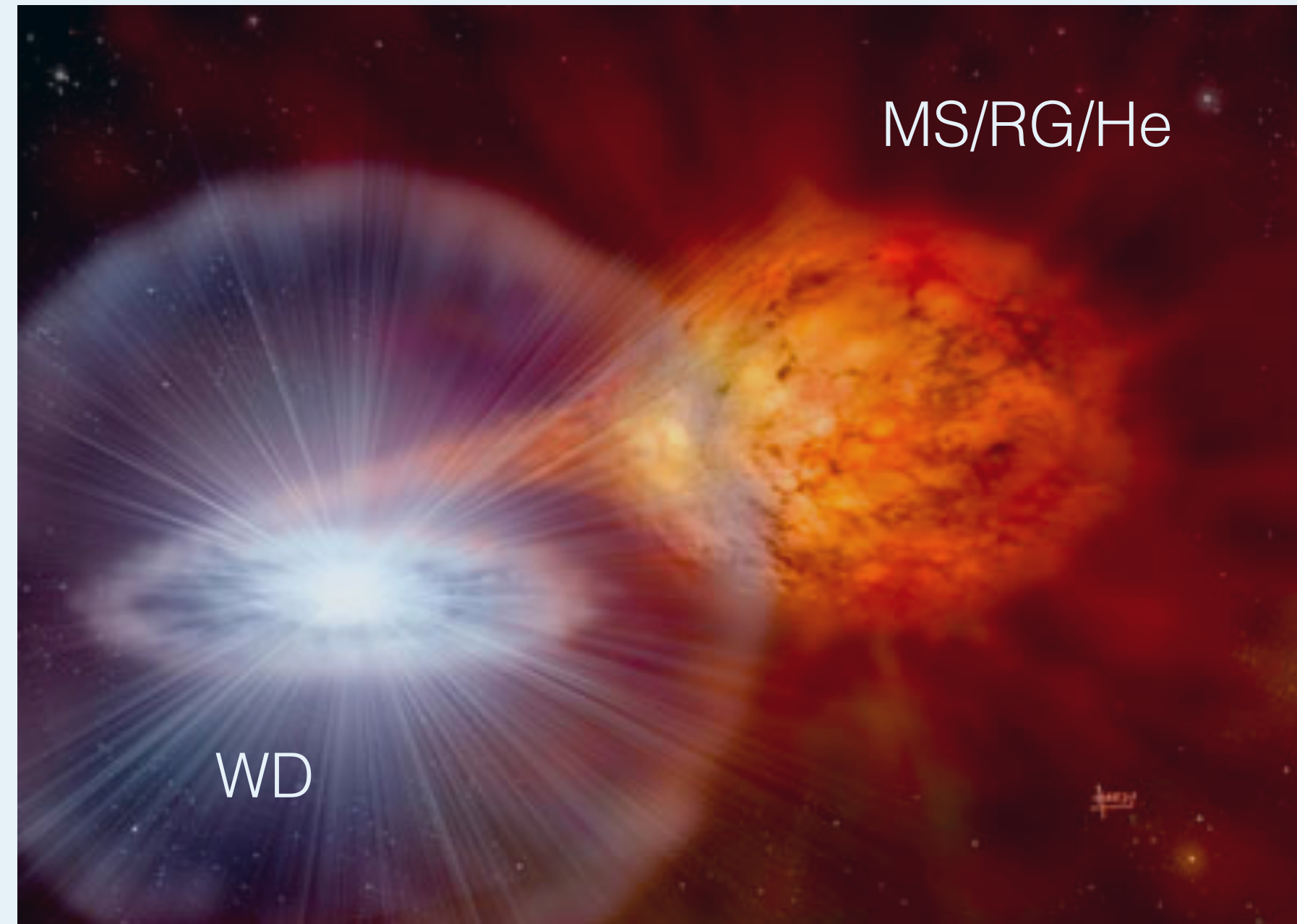
$$\mu(z) = m(z) - M$$

No evolution: $\text{SNIa}_{\text{low}} \sim \text{SNIa}_{\text{high}}$

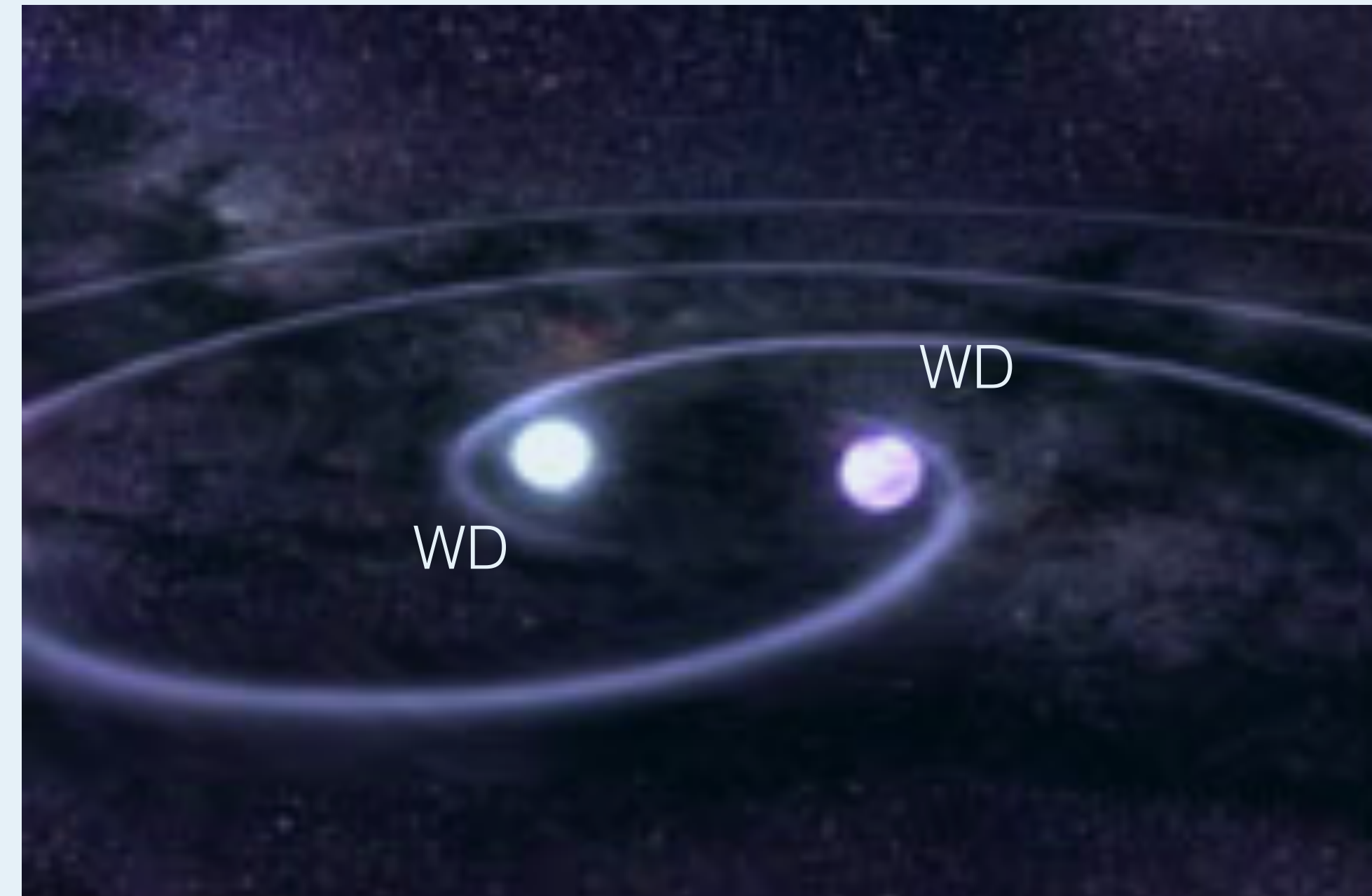
Same populations: $p(\text{SNIa}_{\text{low}}) \sim p(\text{SNIa}_{\text{high}})$

Progenitor scenarios

Single degenerate (SD)

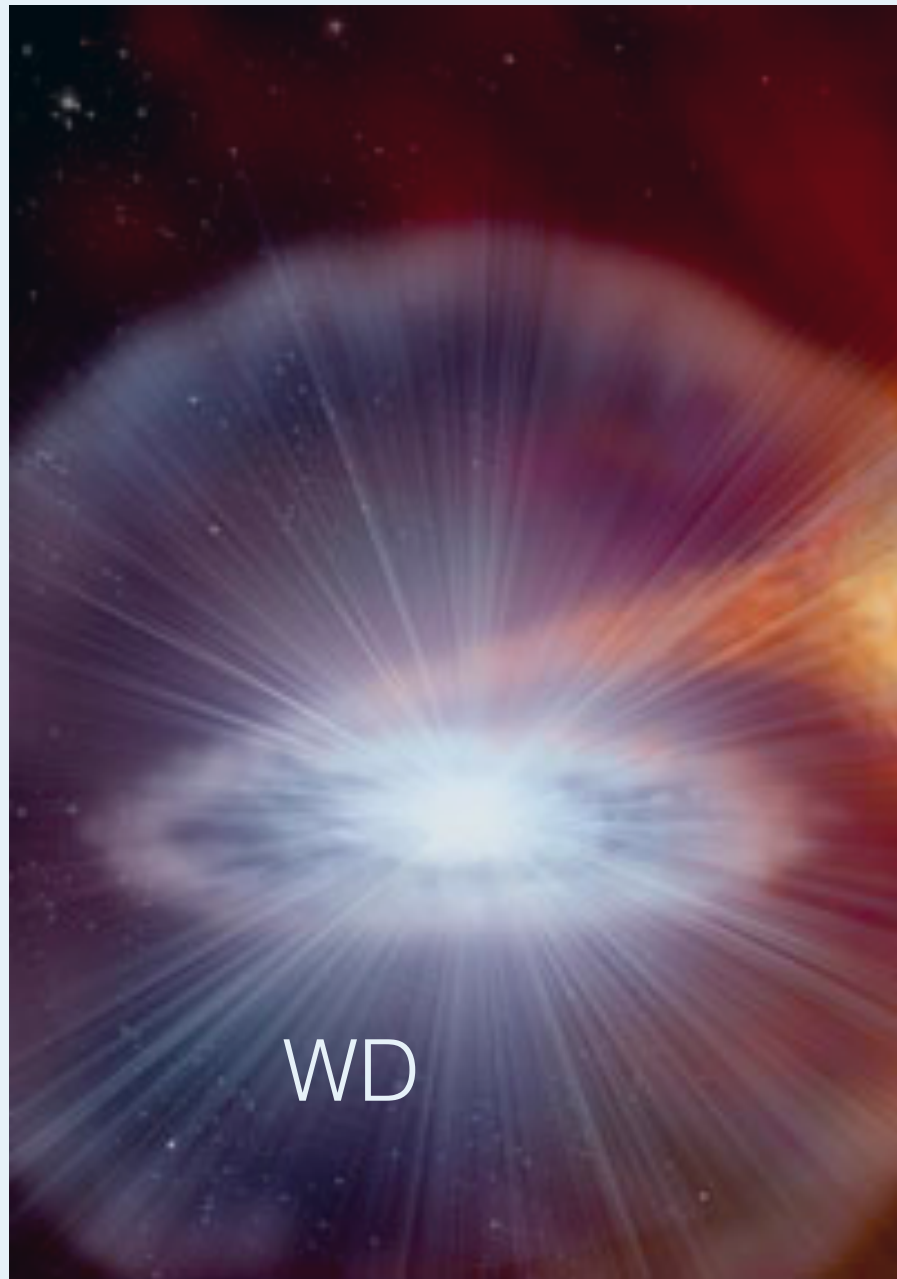


Double degenerate (DD)



Progenitor scenarios

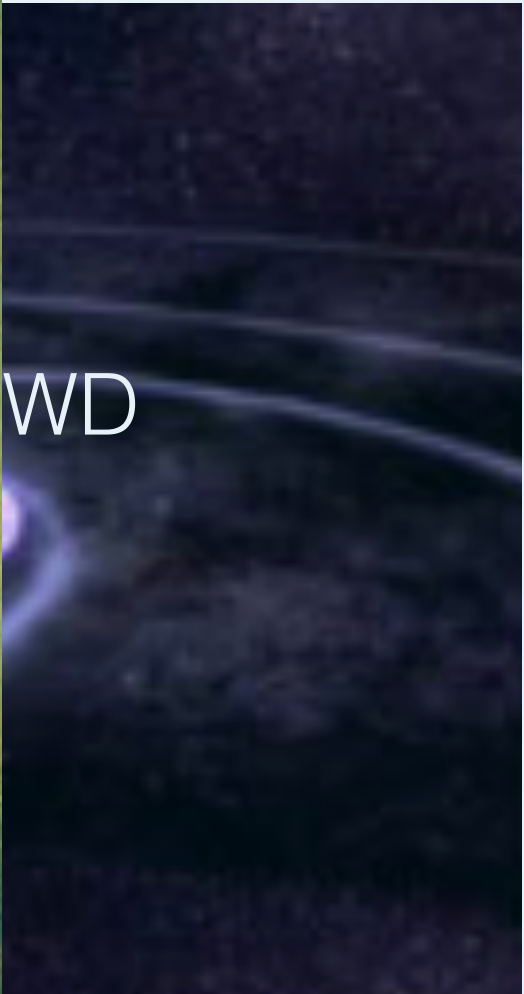
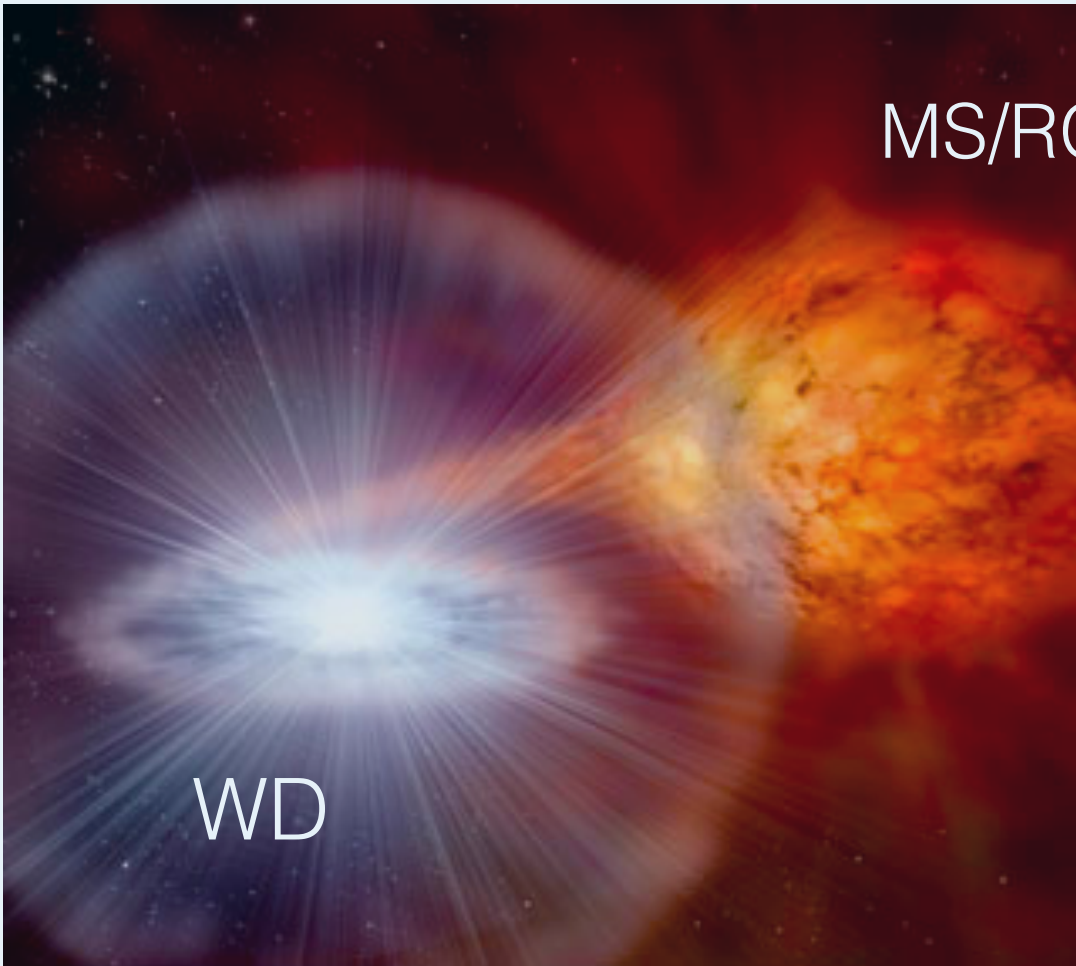
Single degenerate



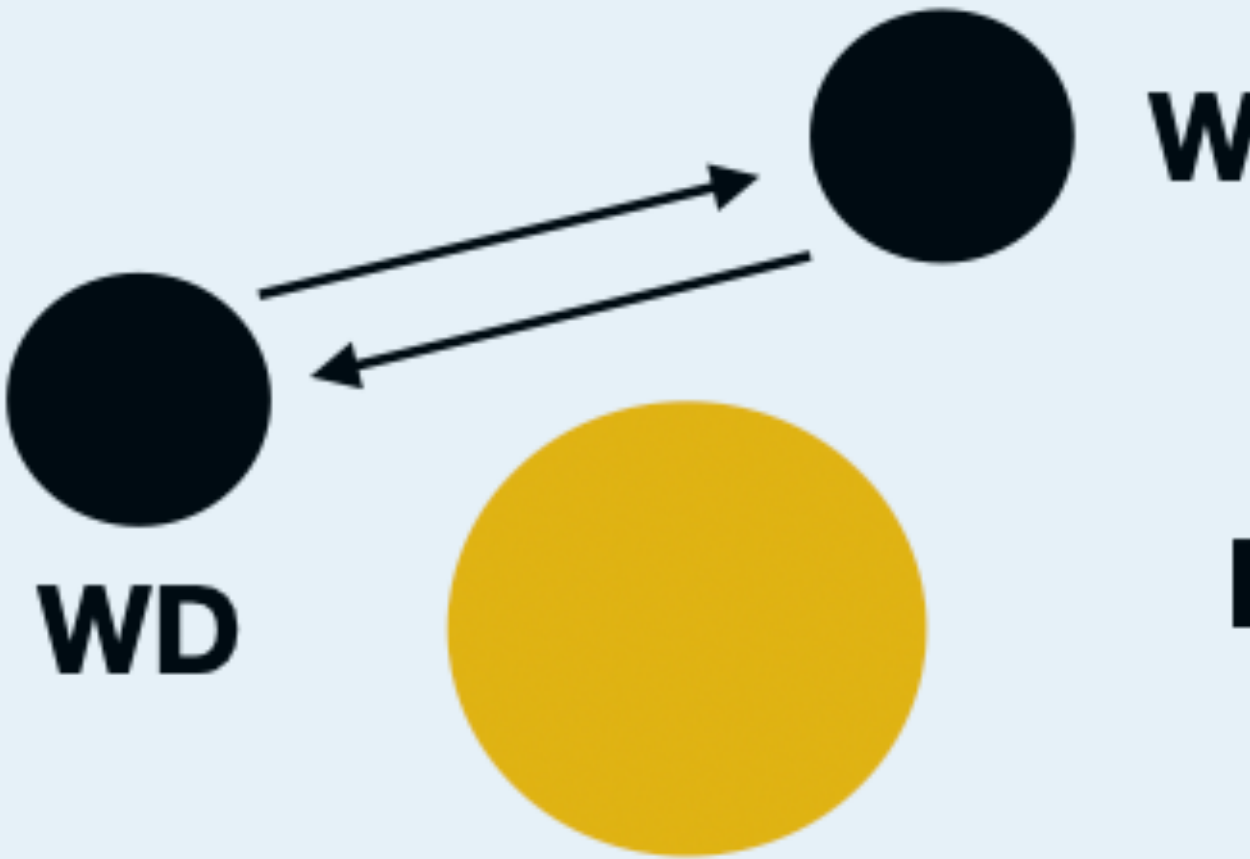
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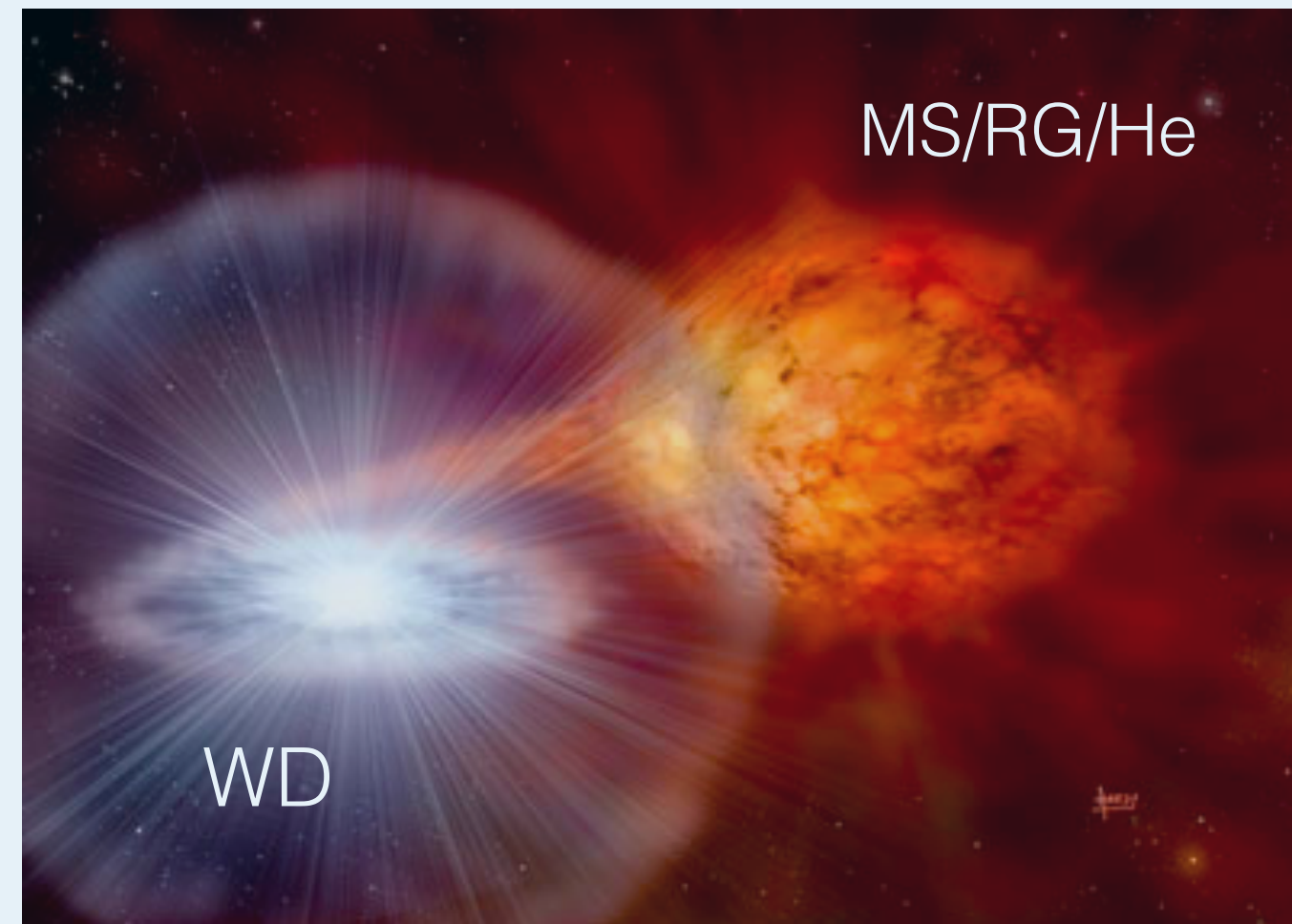


M_{ch}
sub- M_{ch}
super- M_{ch}



M_{ch}
super- M_{ch}

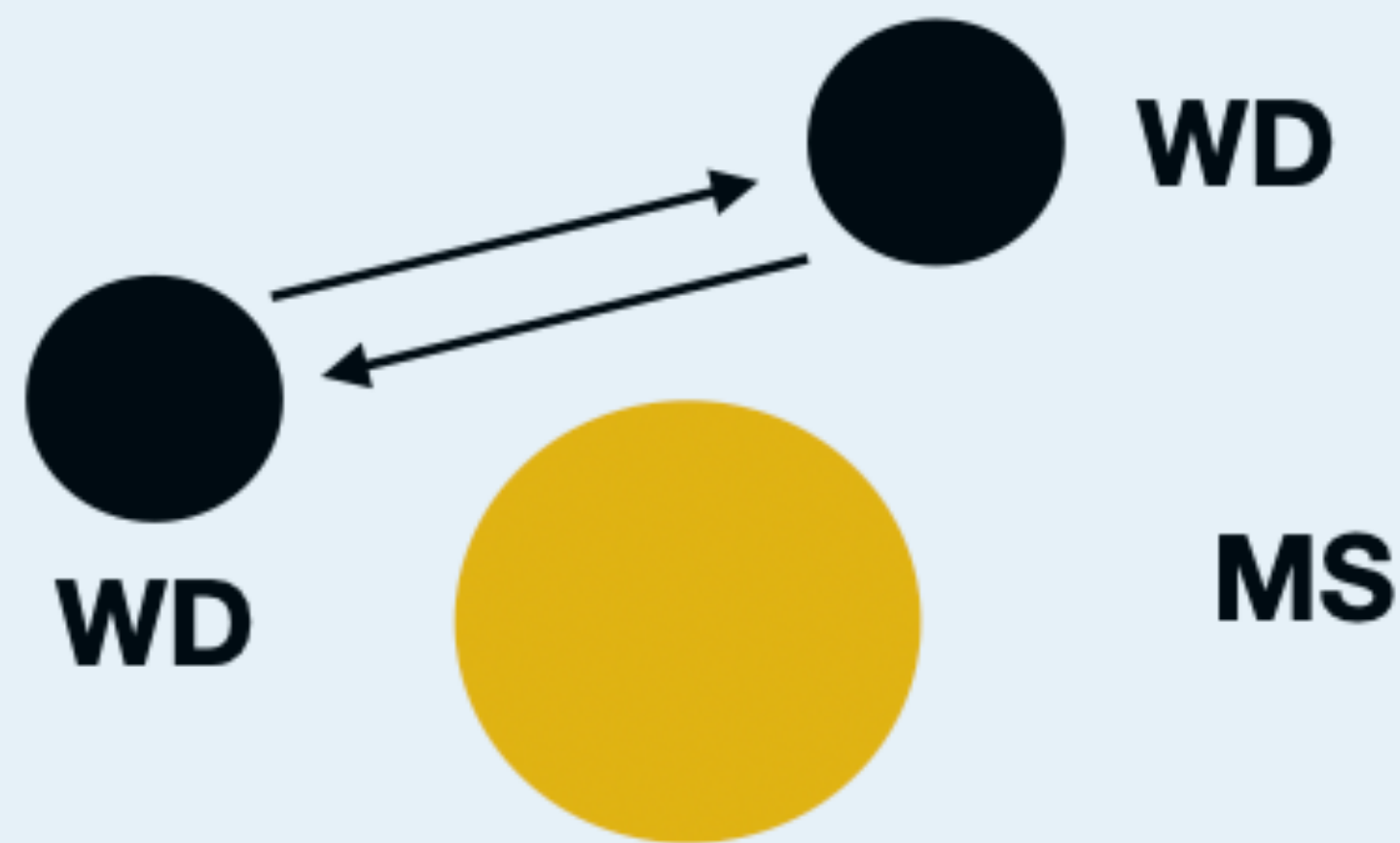
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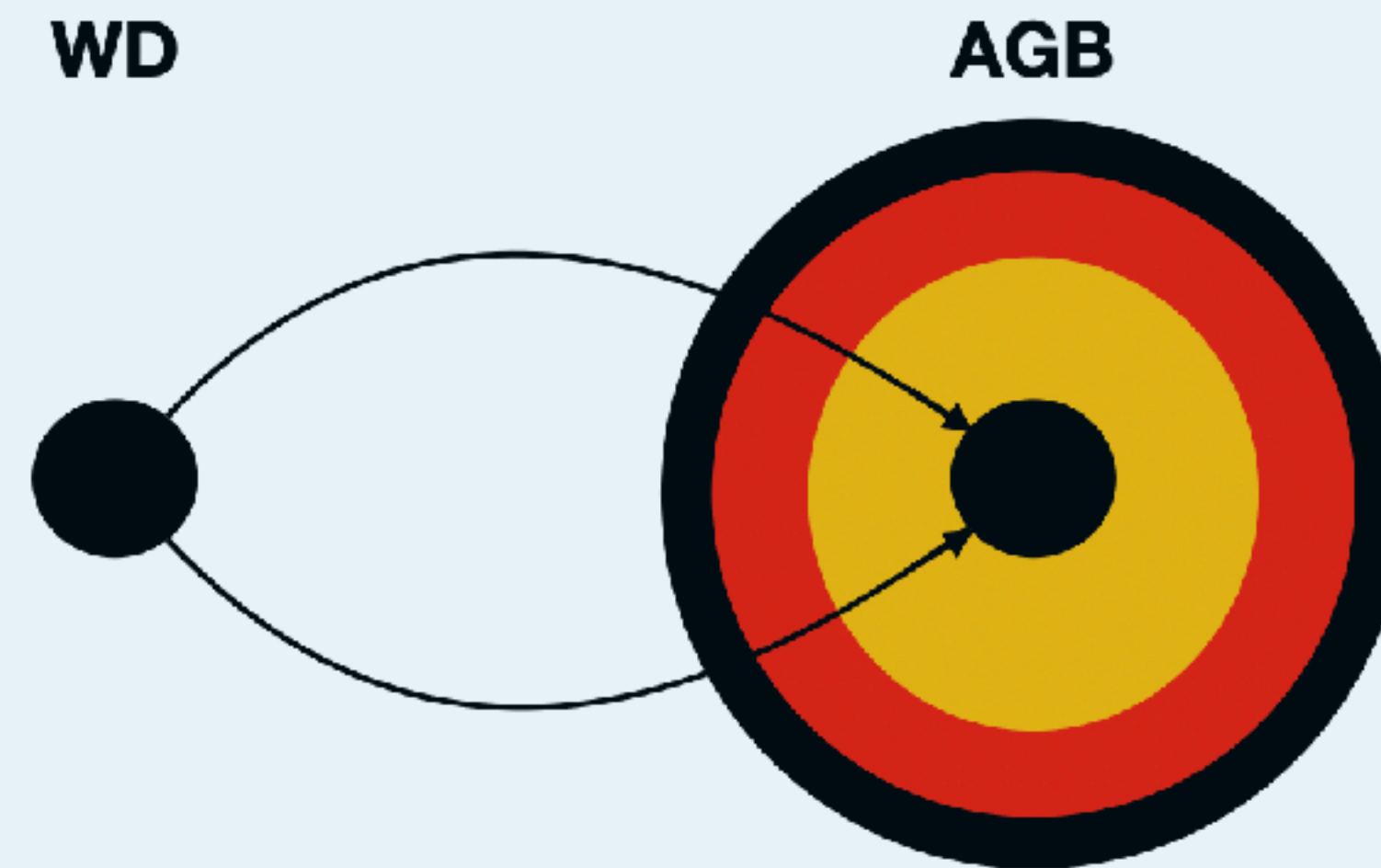
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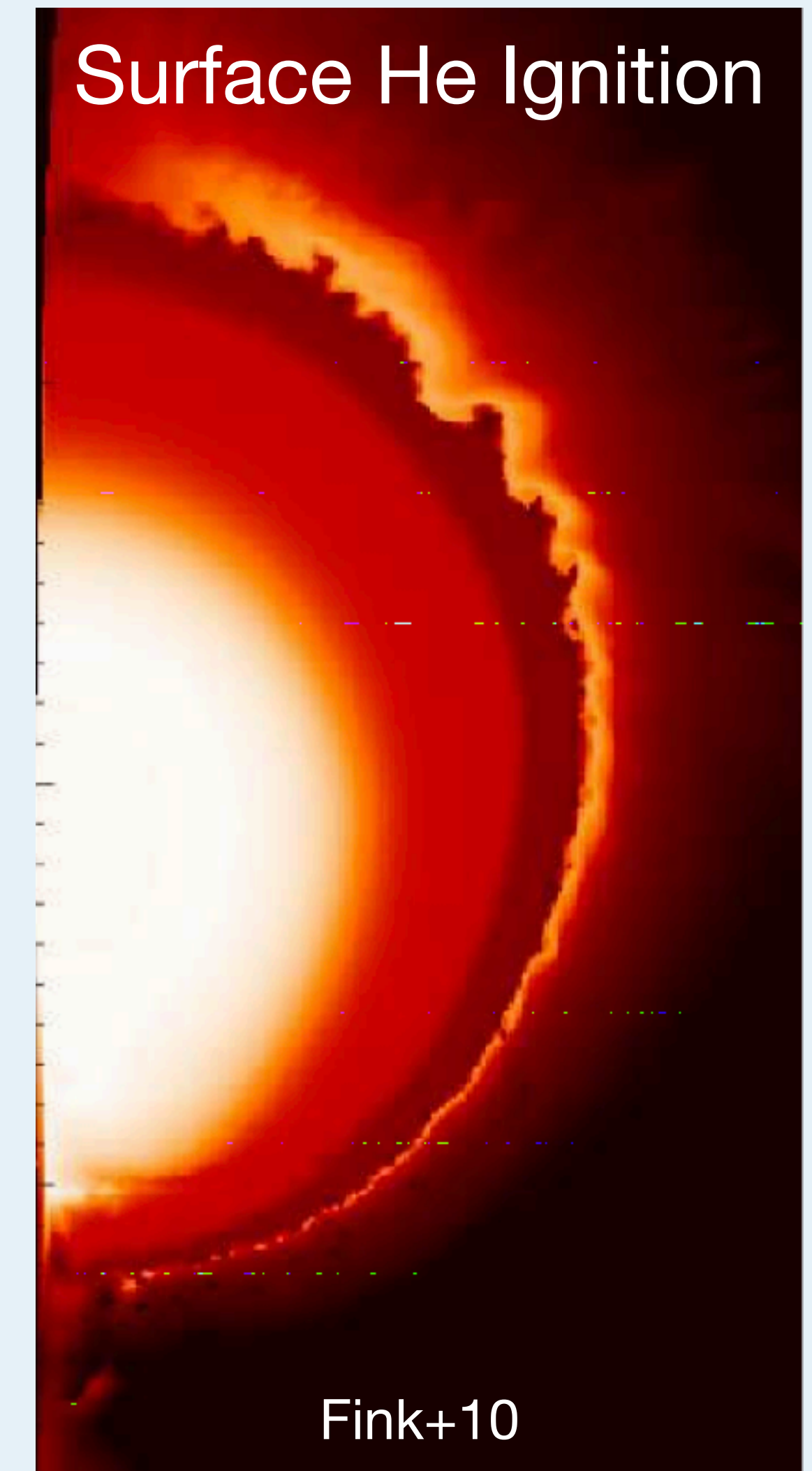
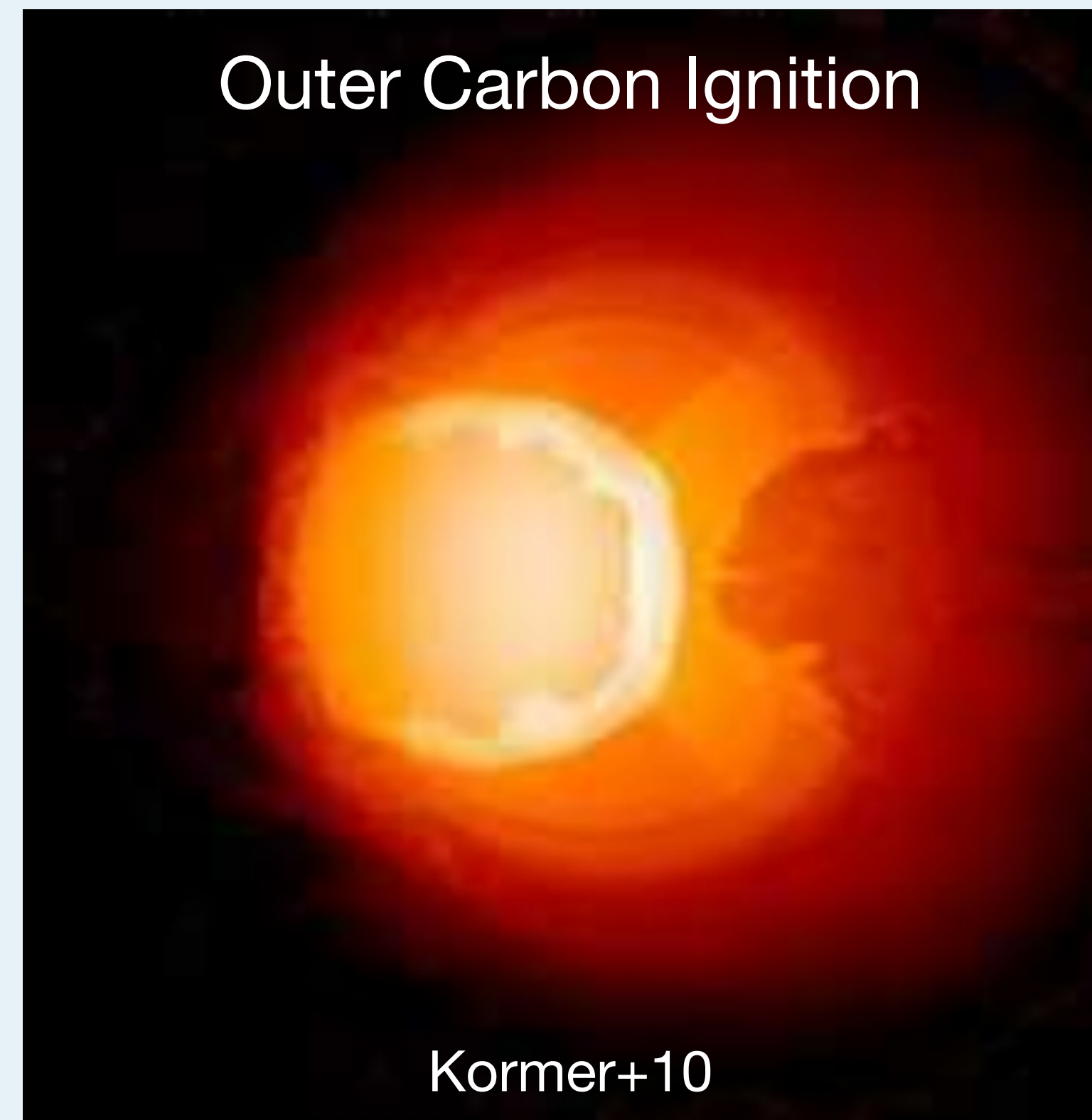
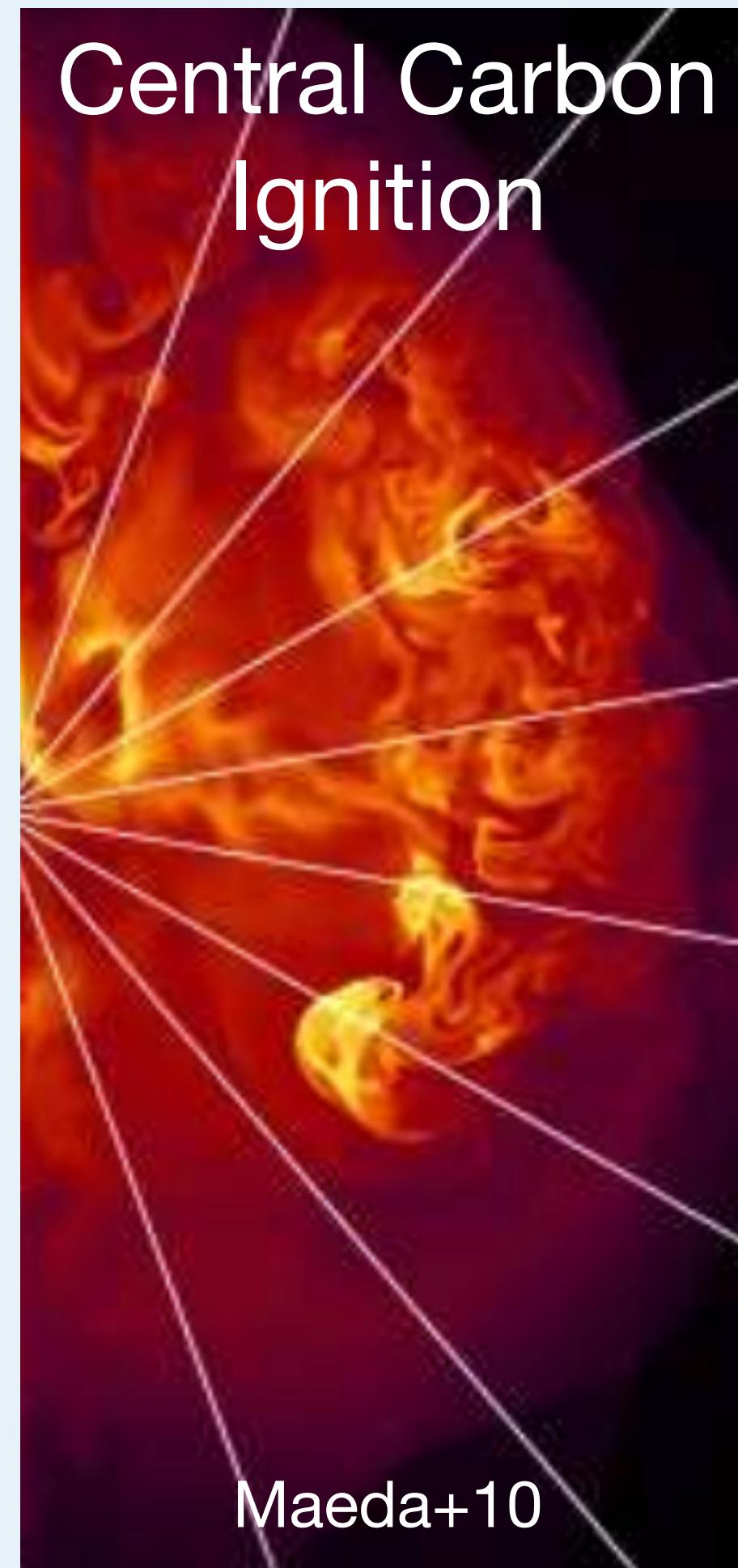


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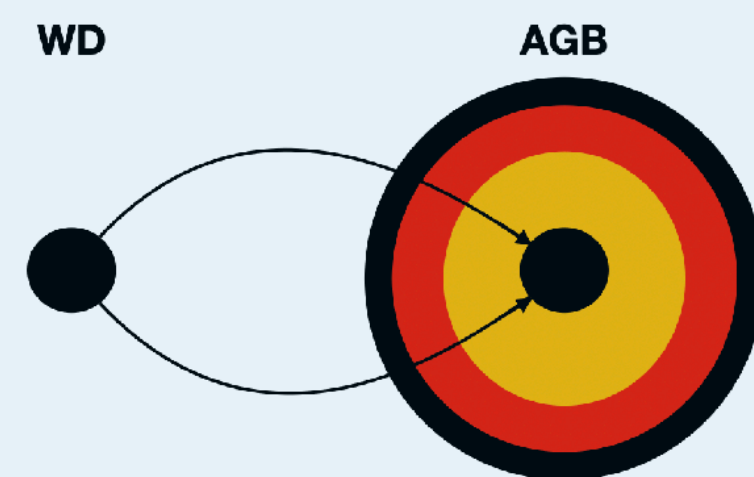
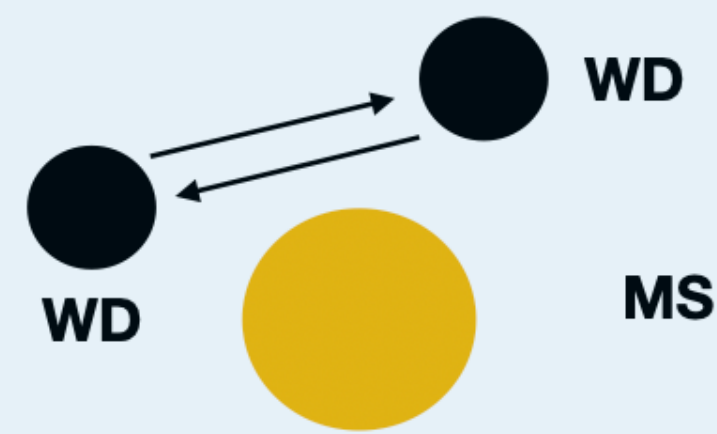
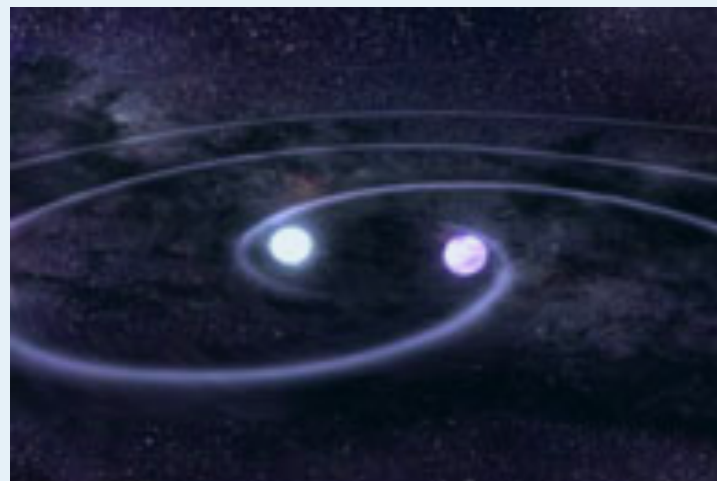
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Explosion mechanism

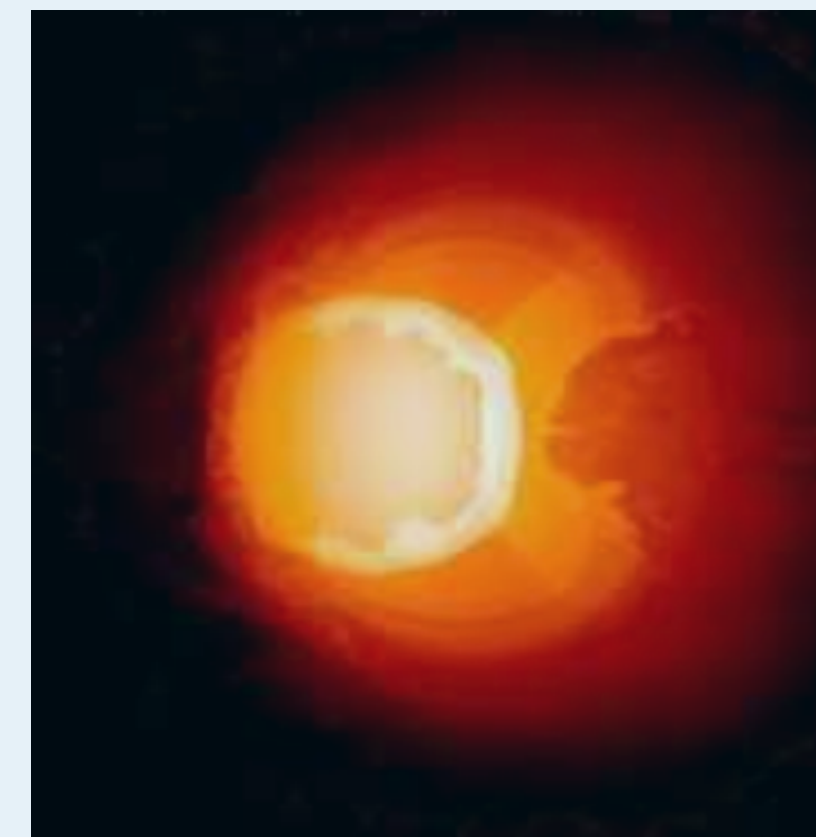
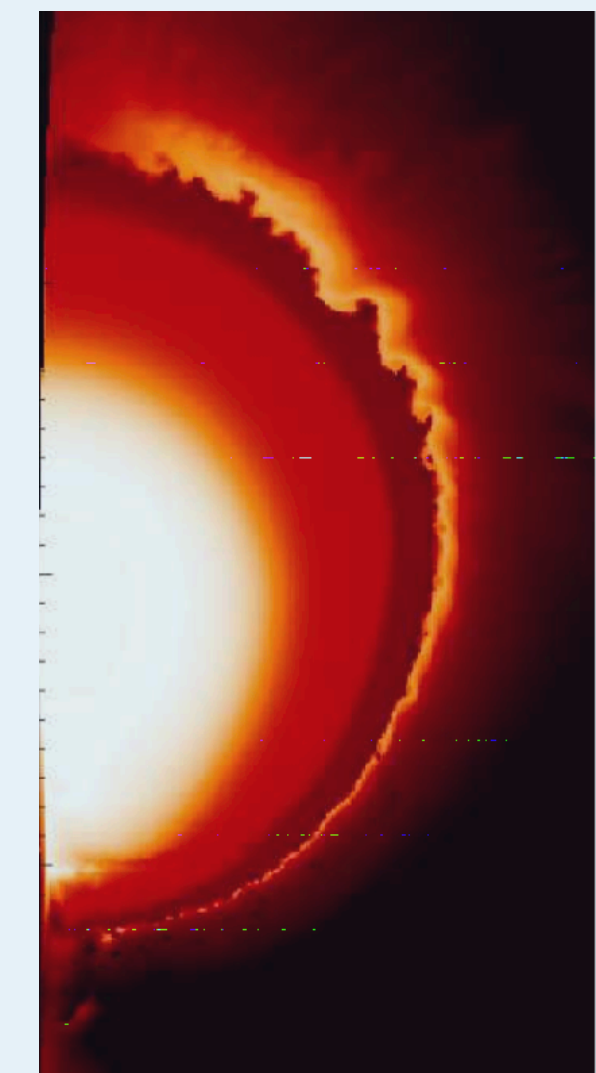
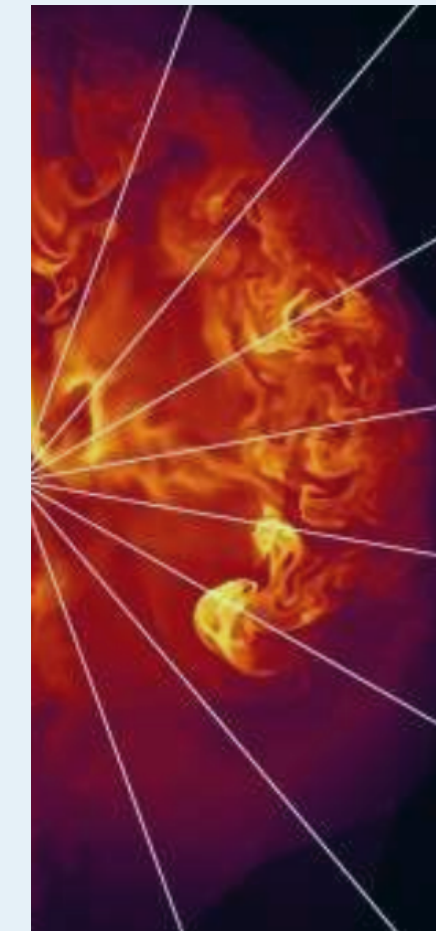


Flame propagation: Deflagration vs. Detonation

Progenitor Scenarios

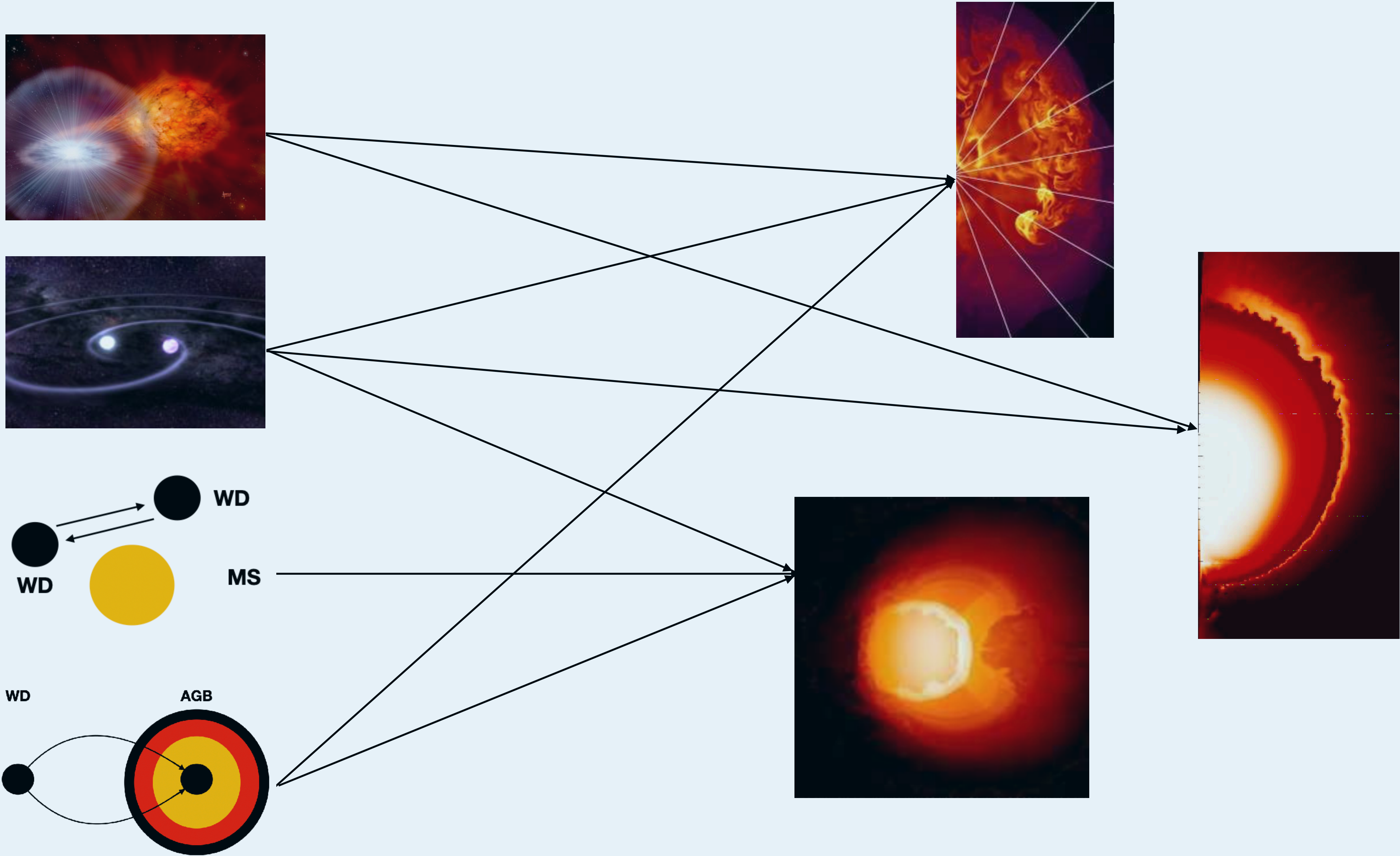
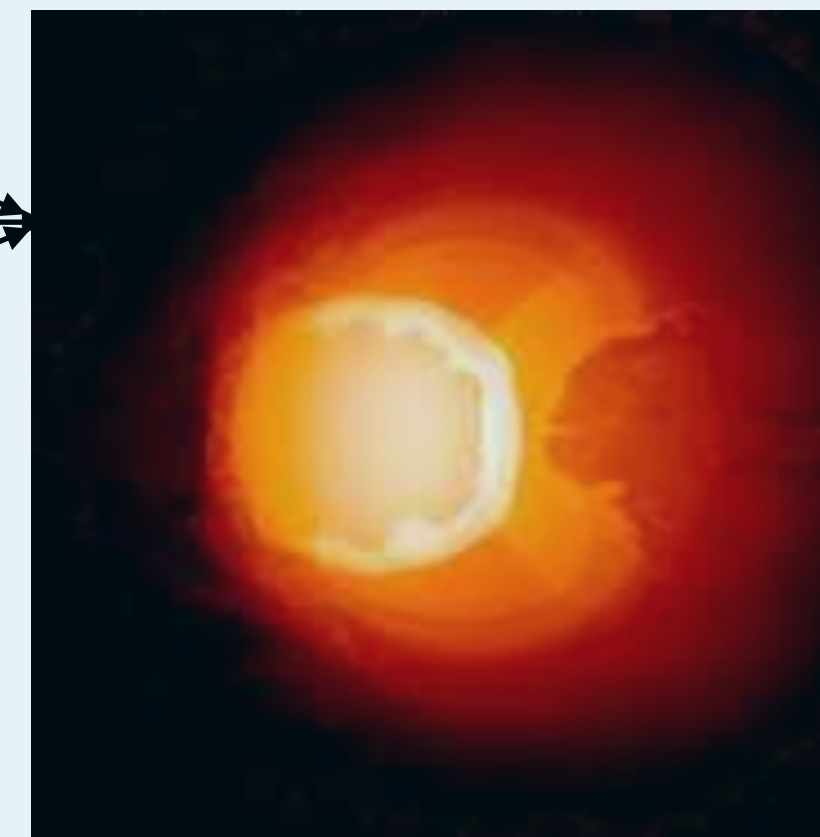
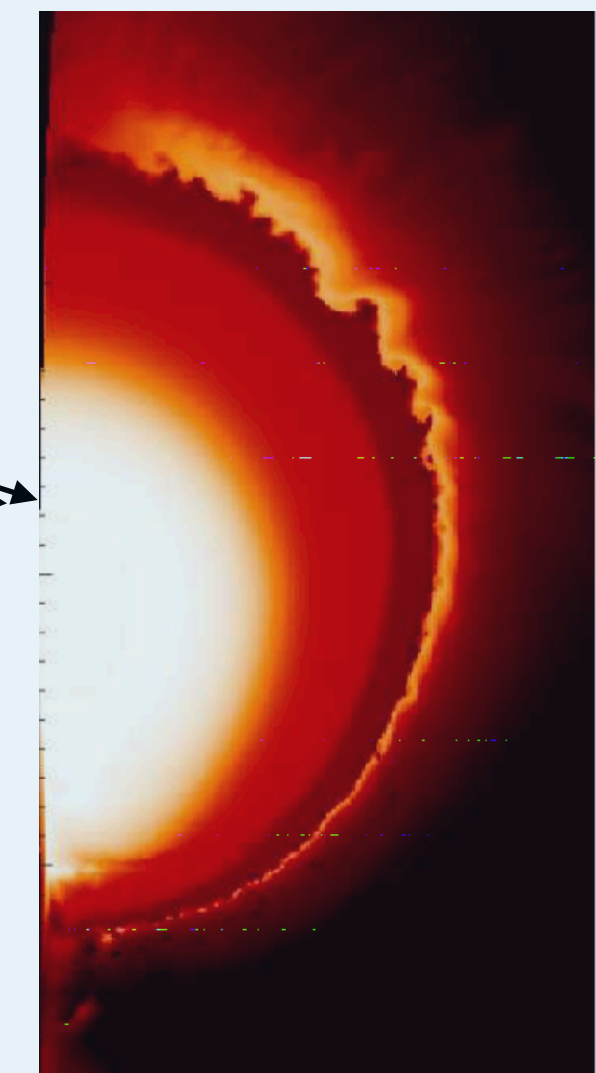
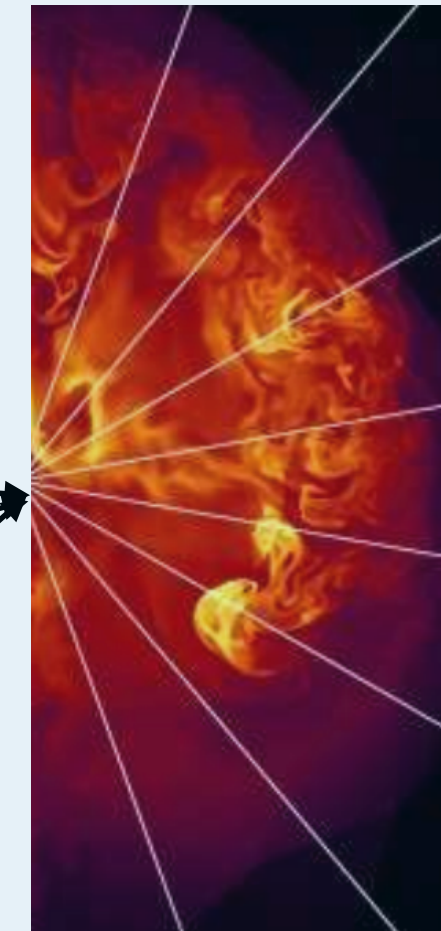
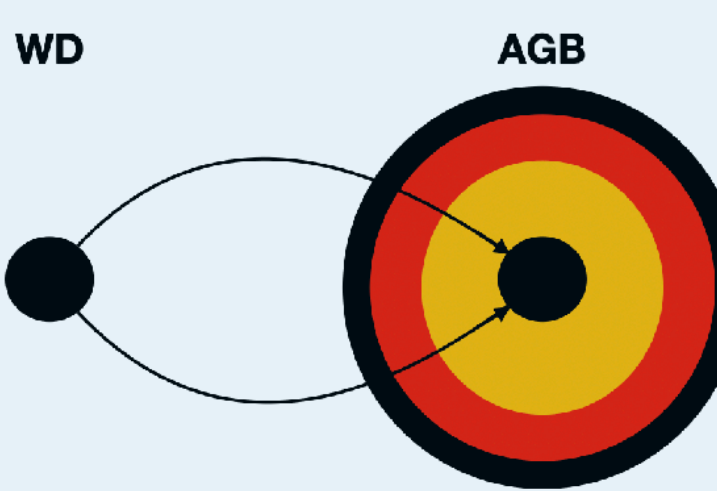
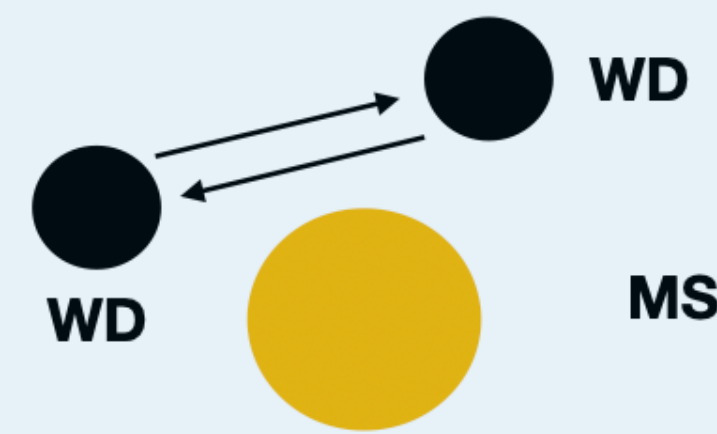
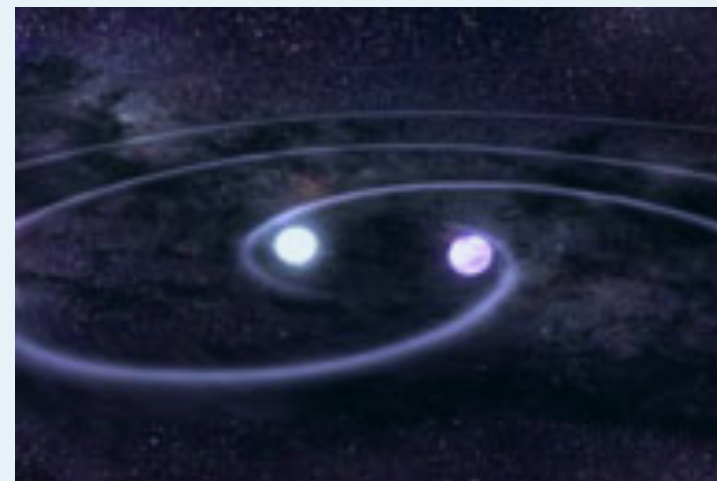


Explosion Mechanism



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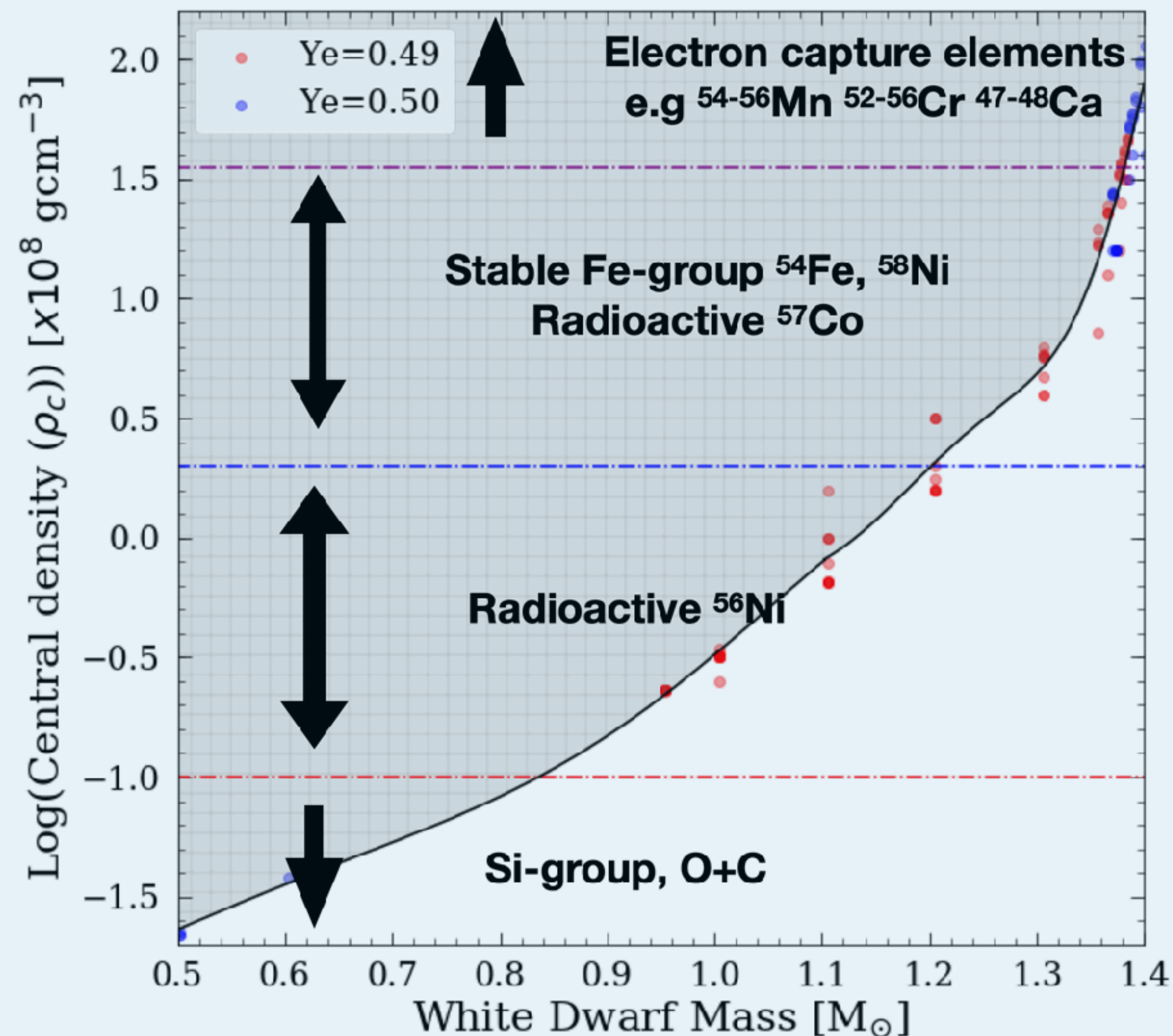
Explosion Mechanism



Observational support for scenarios

Single degenerate

- **Circumstellar Na I D absorption** (time-variable and blueshifted) implying outflows/CSM from a companion wind.
- **SNe Ia-CSM**, require a mass-donating companion (PTF11kx, Dilday+12; SN 2002ic, Hamuy+03)
- **Early blue/UV excess**, ejecta shocking a companion (SN 2017cbv, Hosseinzadeh+17; iPTF14atg, Cao+15)
- **Late-time H α from stripped companion material** (SN 2018fhw, Kollmeier+19, Vallely+19; SN 2015cp, Graham+19)
- **Possible surviving donor** and CSM in remnants: (Tycho G candidate, Ruiz-Lapuente+04)
- **Very neutron-rich isotopes (^{48}Ca , ^{50}Ti , ^{54}Cr)** requires high ρ_c reached only in **near-MCh** explosions



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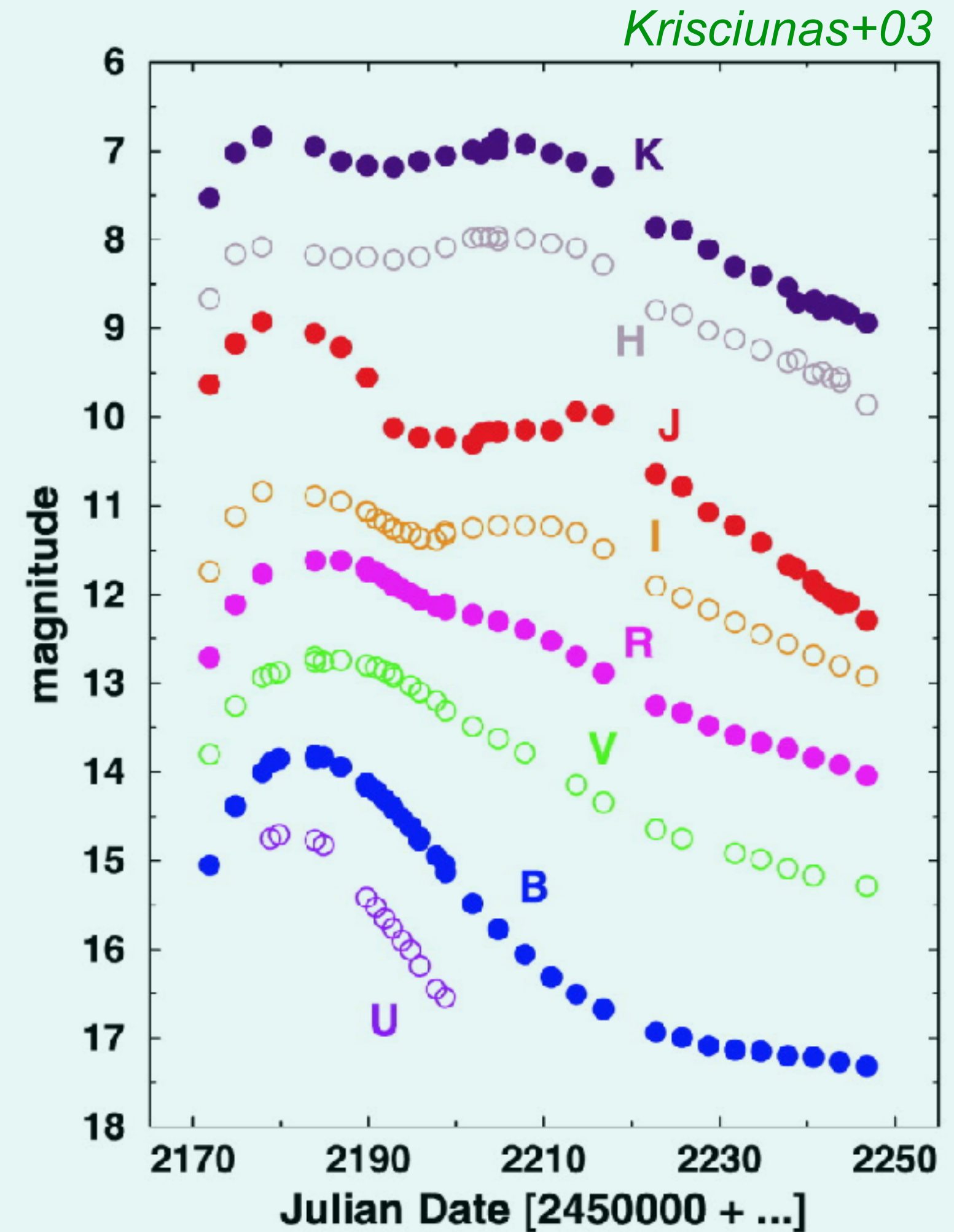
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Double degenerate

- **No surviving companion** in SNR: (SNR 0509-67.5, Schaefer+12; Tycho SNR Kerzendorf+09)
- **Pre-explosion imaging rules out luminous donors:** (SN 2011fe, Li+11, Nugent+11, Bloom+12).
- **No radio/X-ray from accretion winds or CSM** (Chomiuk+16, Margutti+14, Horesh+12)
- **Too few accreting, X-ray-bright pre-SN WDs** to supply the SN Ia rate (Gilfanov +10).
- **Delay-time distribution $\propto t^{-1}$** (Maoz+14, Totani et al. 2008).
- **Deep non-detections of hydrogen** in nebular spectra (Leonard+07, Maguire +16, Sand+19)
- **Hypervelocity surviving WDs** consistent with the D^6 (Shen+18).
- **Direct double-detonation "double shell"** in SNR 0509-67.5 (*sub-MCh*, Das+2025)
- **A confirmed super-Chandra DD progenitor binary** (WDJ181058.67+311940.94, Munday+25)

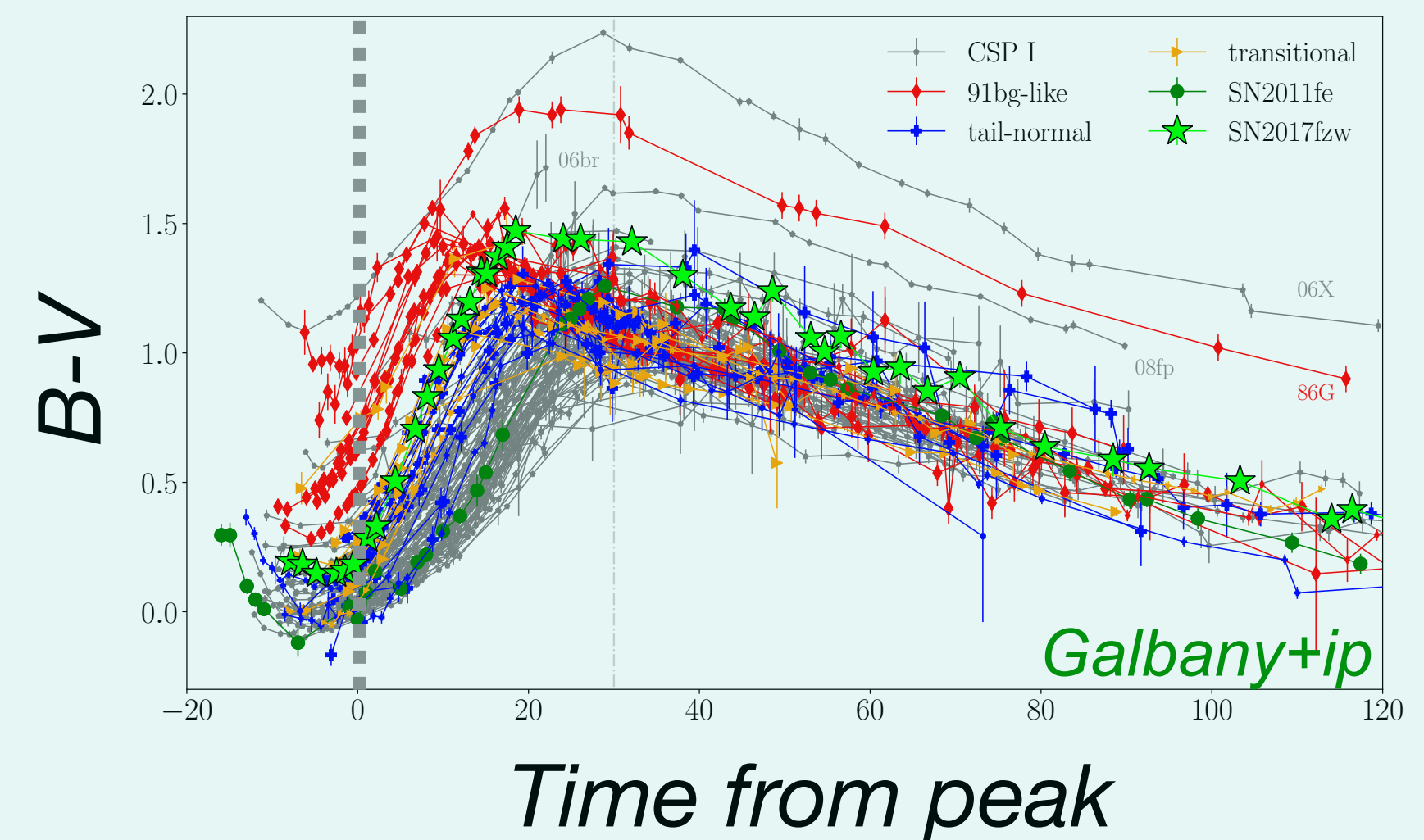
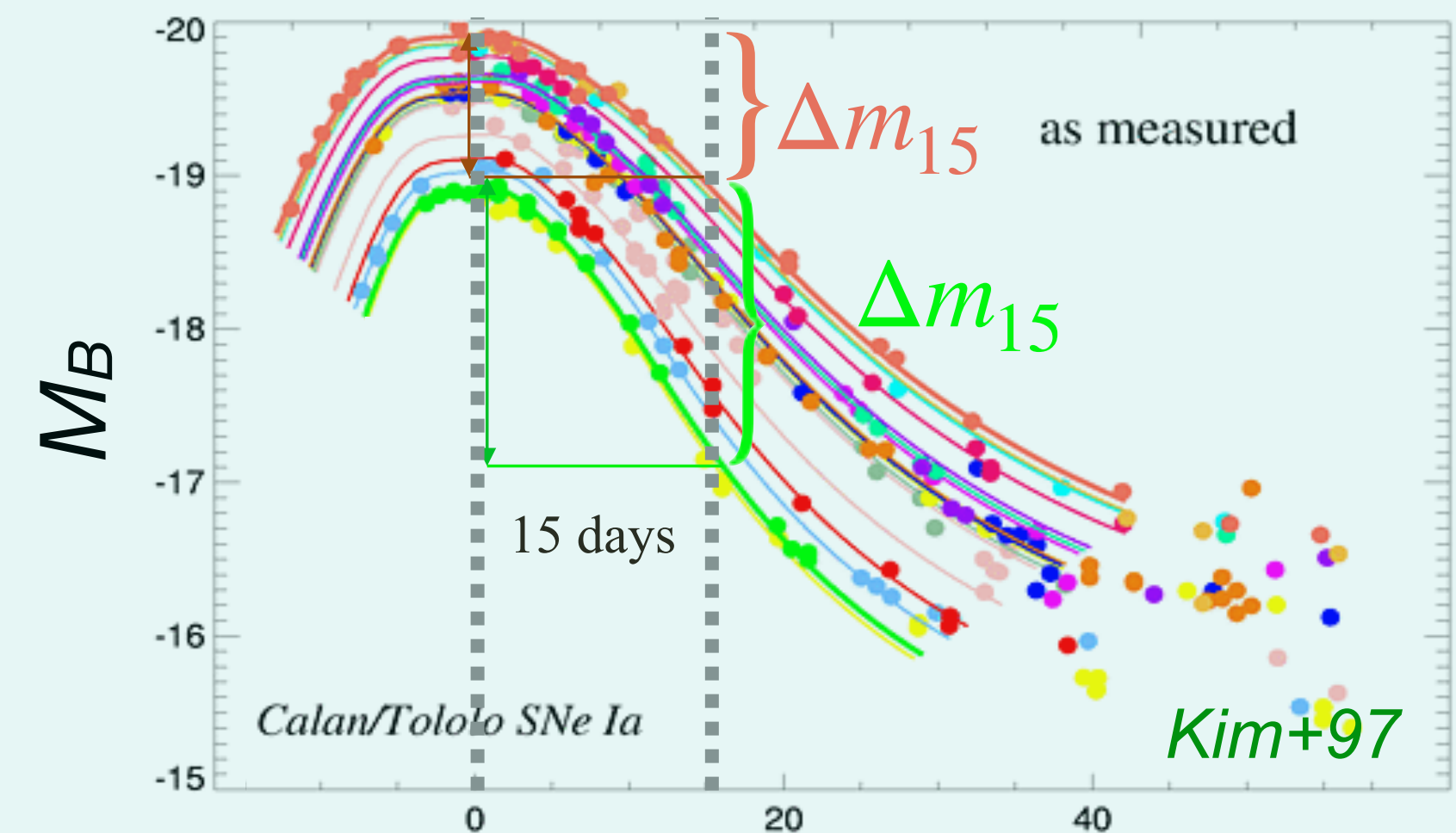
Type Ia supernovae: observations

- from Bolometric (Arnett) to multi-band photometry:
rise (~18 days) -> peak -> decline
- NIR secondary maximum due to Fe/Co recombination
- SNe Ia differ in three nearly separable ways: how **bright**, how **broad** and how **red** they are



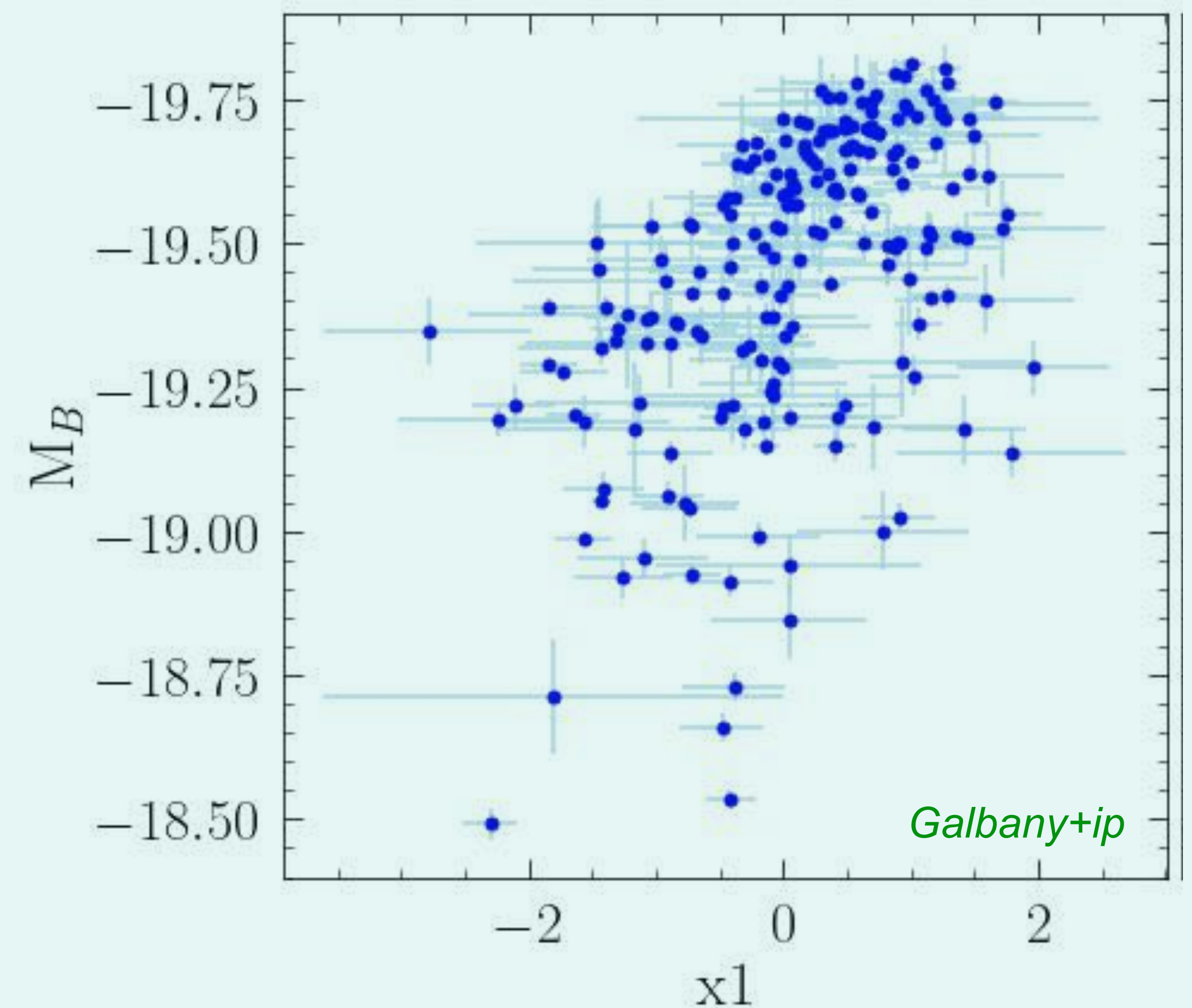
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Parameter 1: light-curve width

- Broader LC = brighter peak.
- *Arnett*: $L_{\text{peak}} \propto {}^{56}\text{Ni}$, and ${}^{56}\text{Ni}$ also sets the ejecta T/τ and hence the diffusion time.
- ${}^{56}\text{Ni}$ mass controls both peak brightness and light-curve width
- Width therefore traces explosion energetics and, via progenitor age, connects forward to hosts.



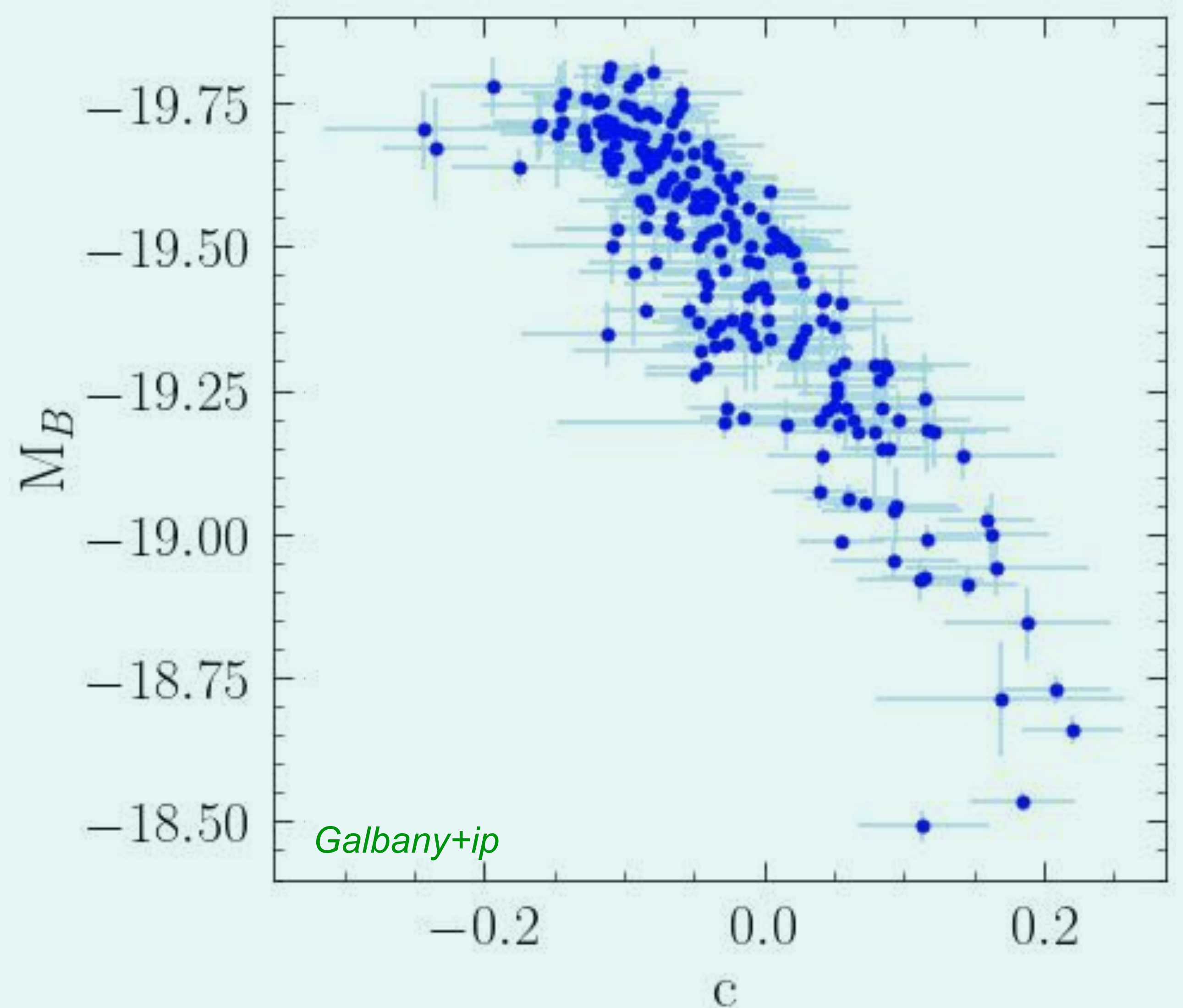
Parameter 2: color, intrinsic vs extrinsic

- The central problem.
Observed color has two origins:

intrinsic: brighter $\approx$ bluer,
Due to a temperature/ionization effect

extrinsic: dust reddening in the host.

• Disentangling them is one of the deepest issues in SN Ia physics.



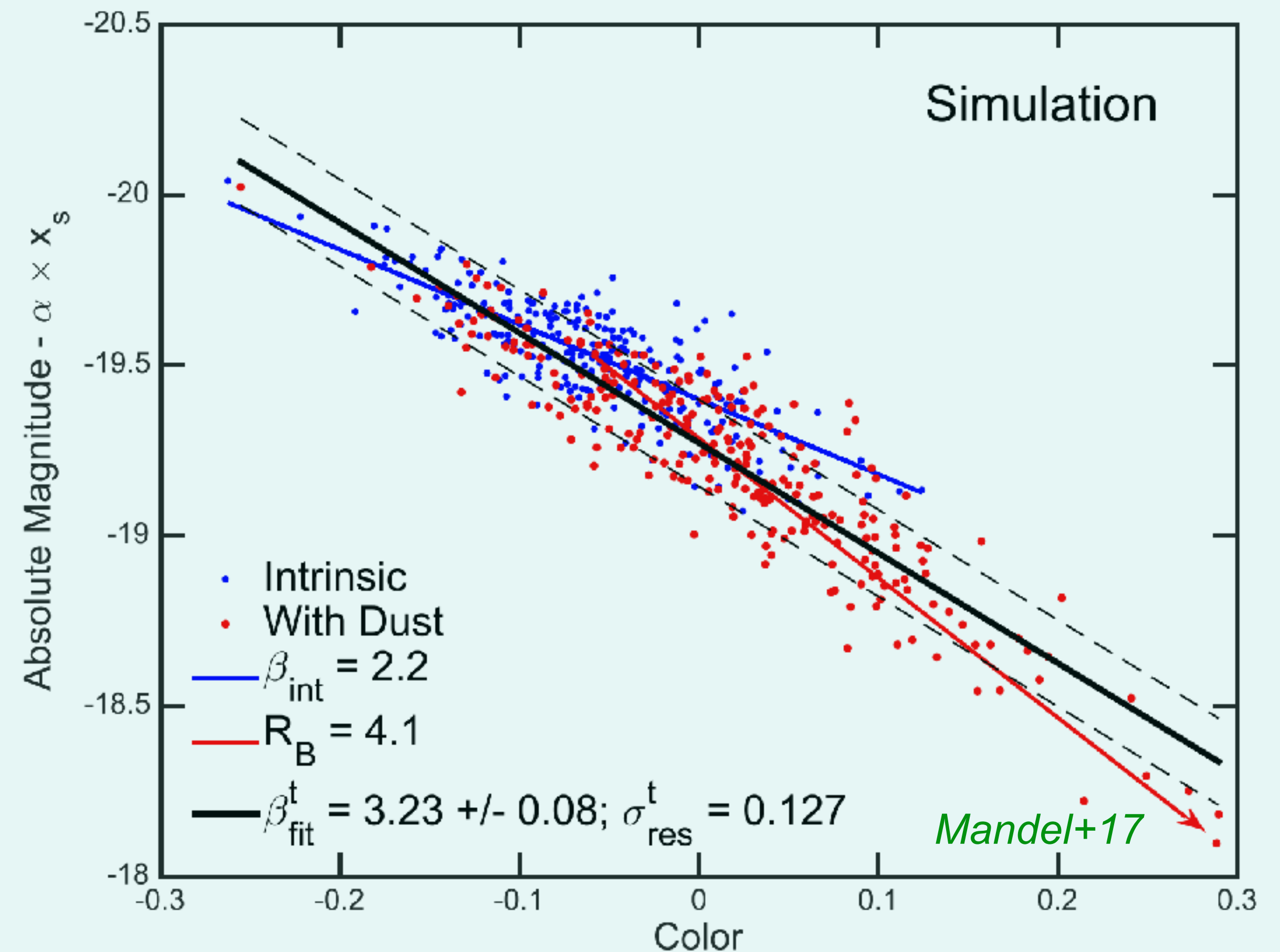
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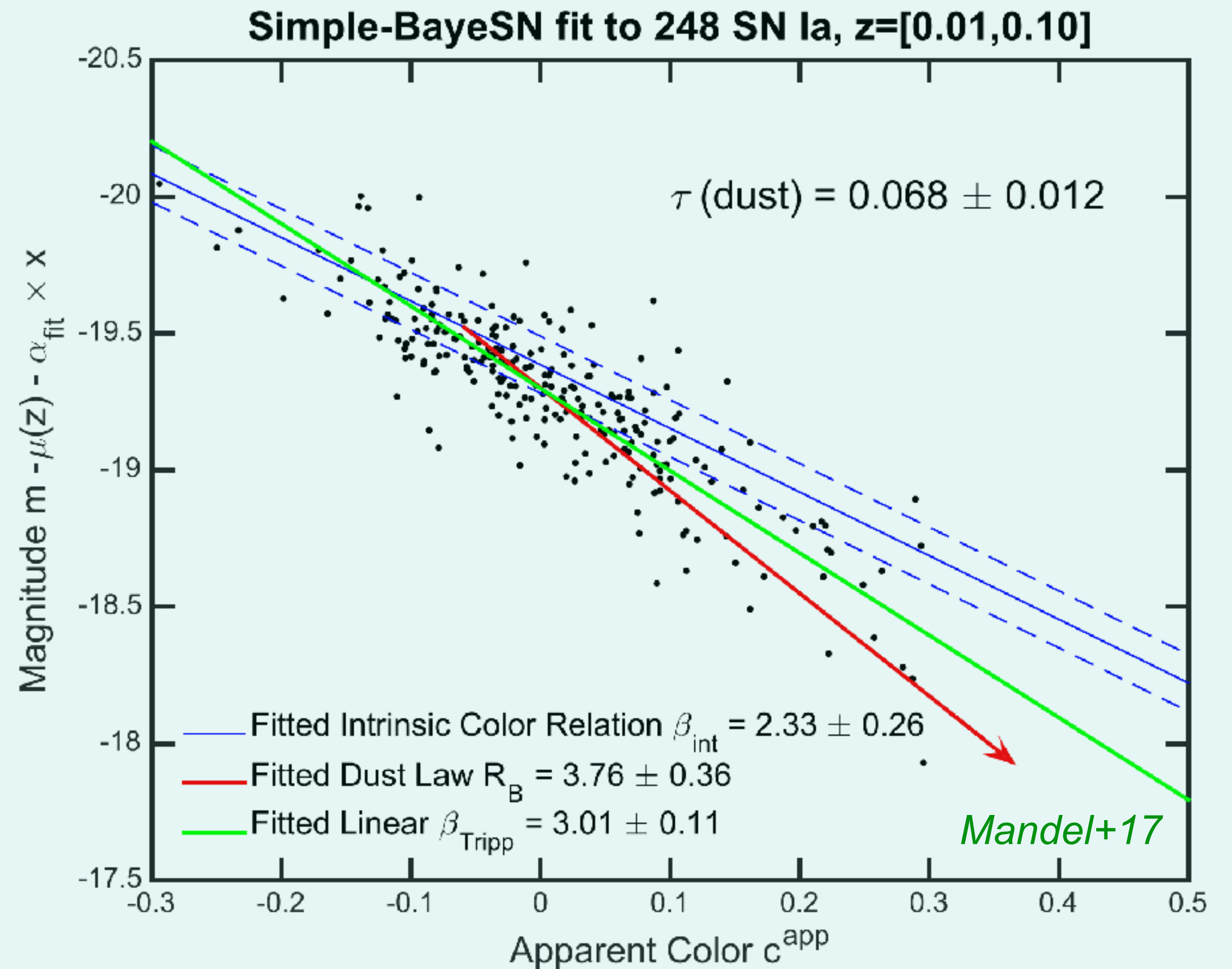
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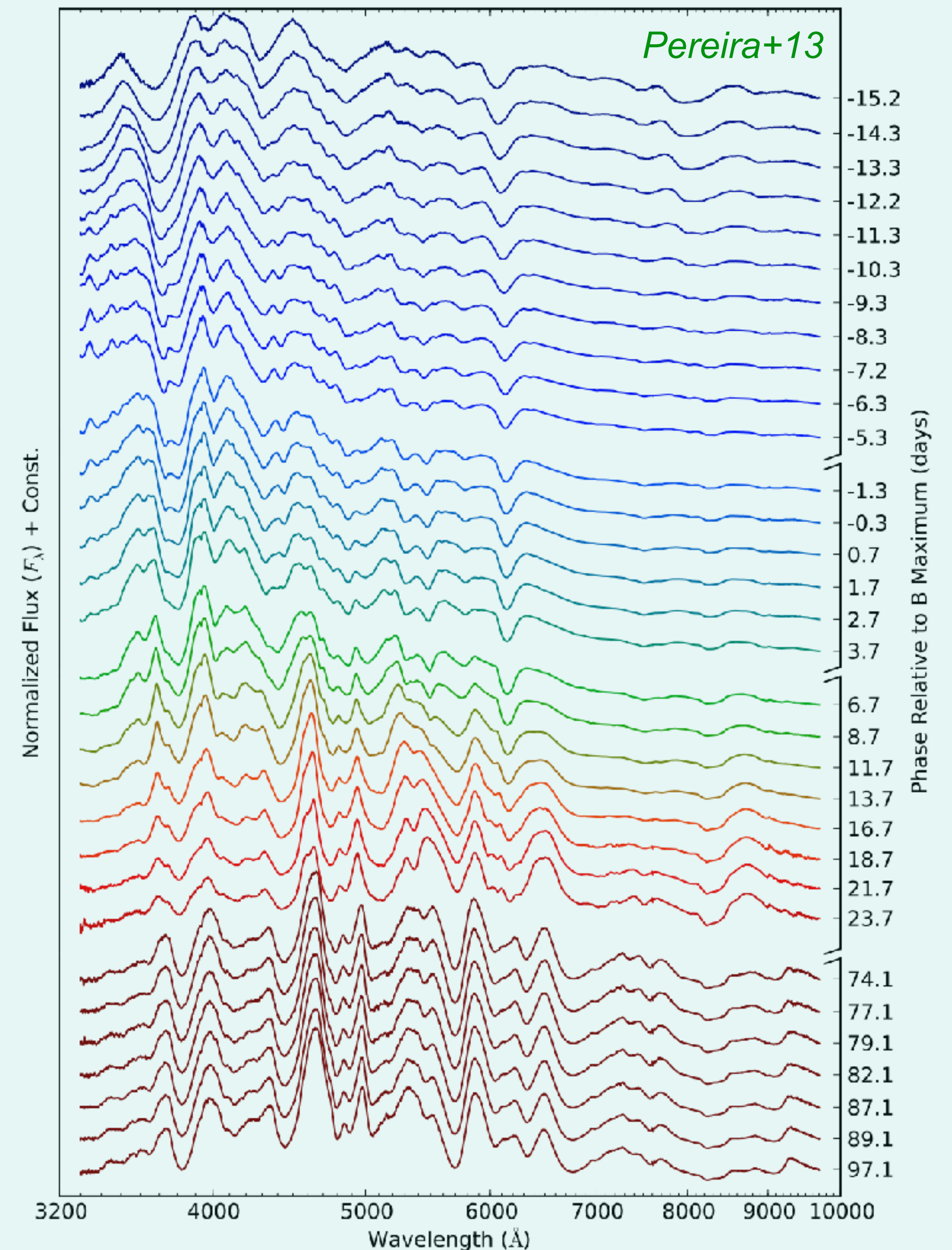
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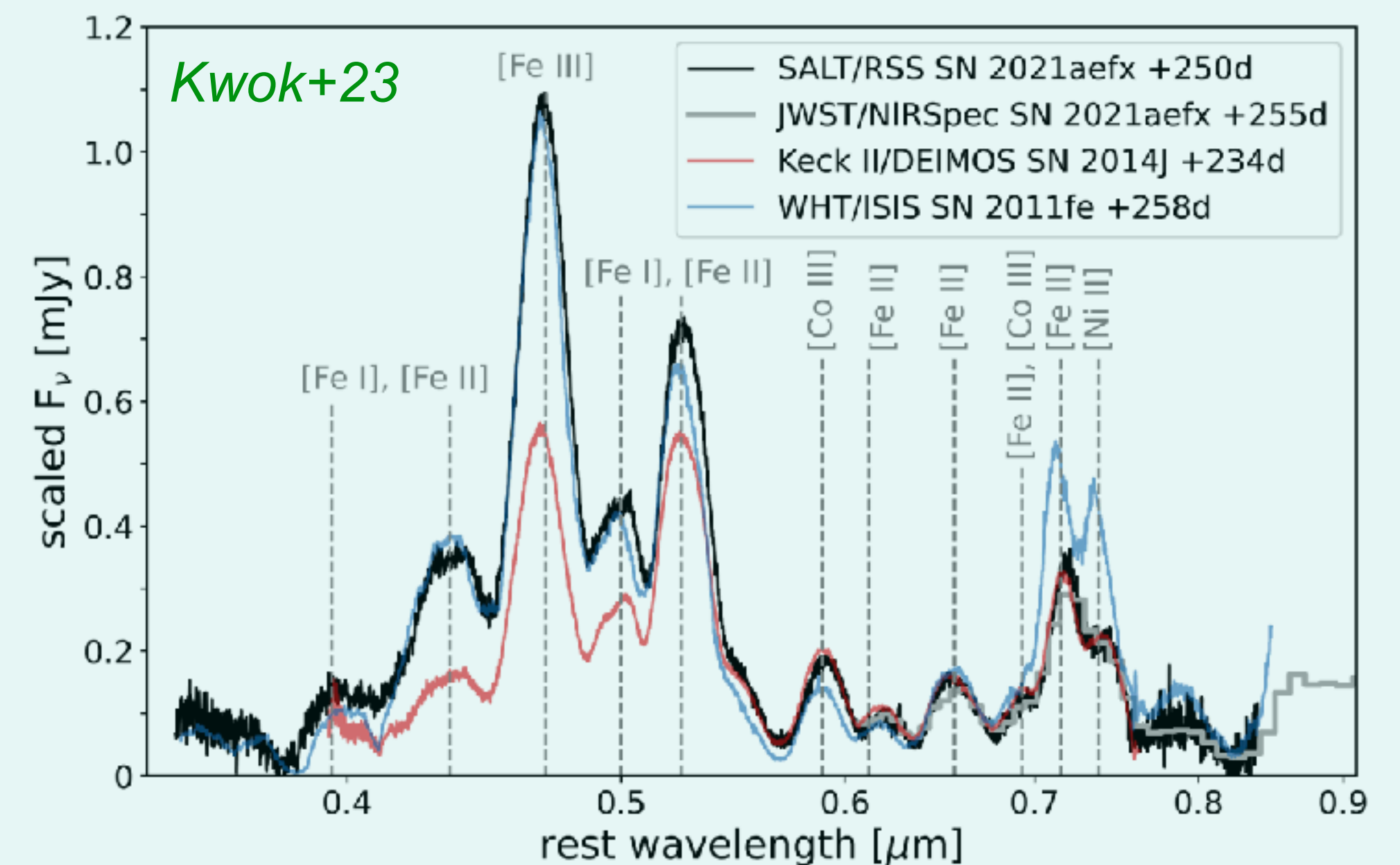
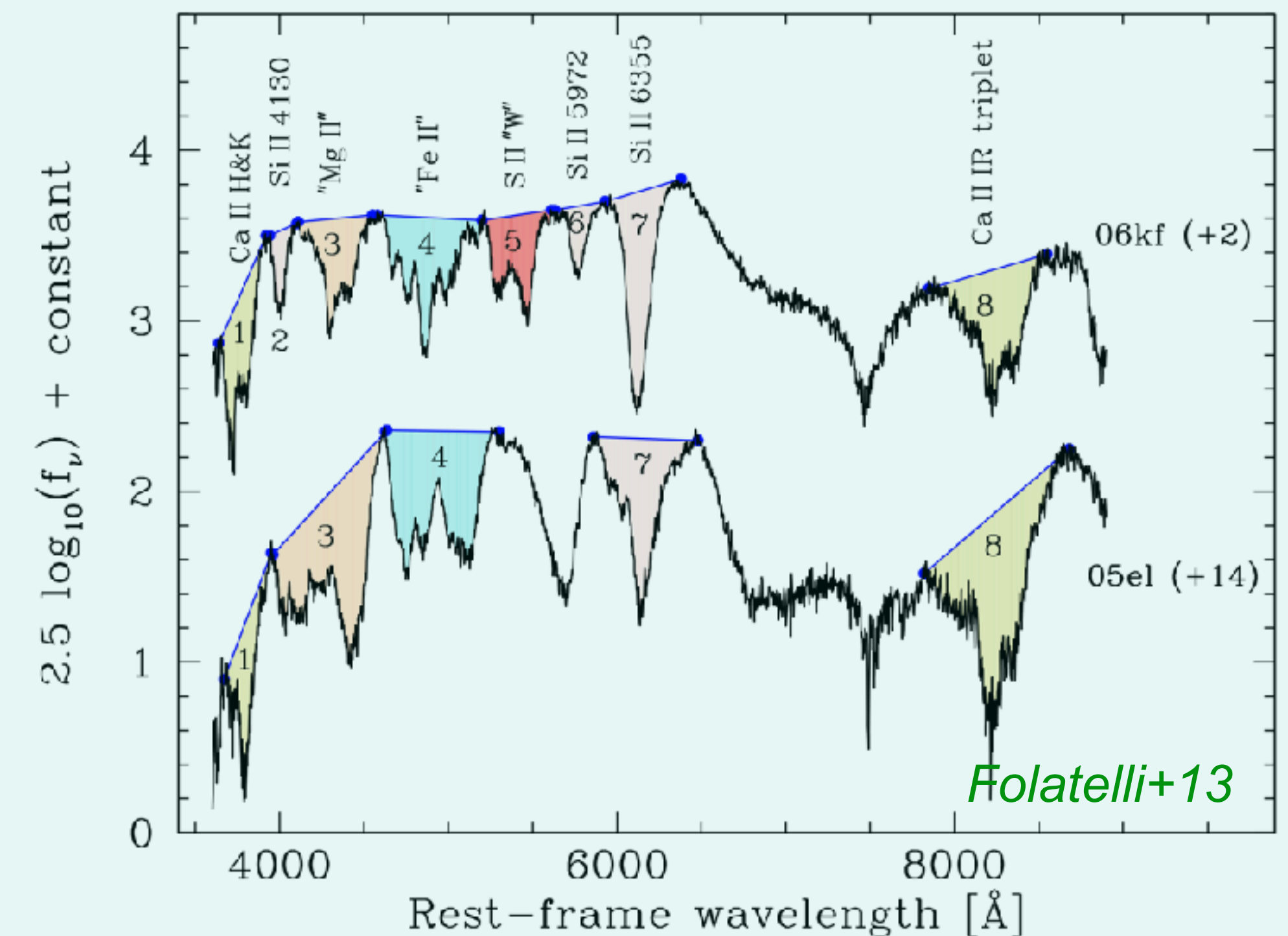
SN Ia spectra

- Defining features:
 - no H/He
 - strong Si, S, Ca, Fe-group abs.
 - evolution from photospheric (P-Cygni, ejecta velocities) to nebular (forbidden Fe/Co/Ni)
- Spectra are the basis for classification
- Add velocity/line-strength axes beyond width and color.



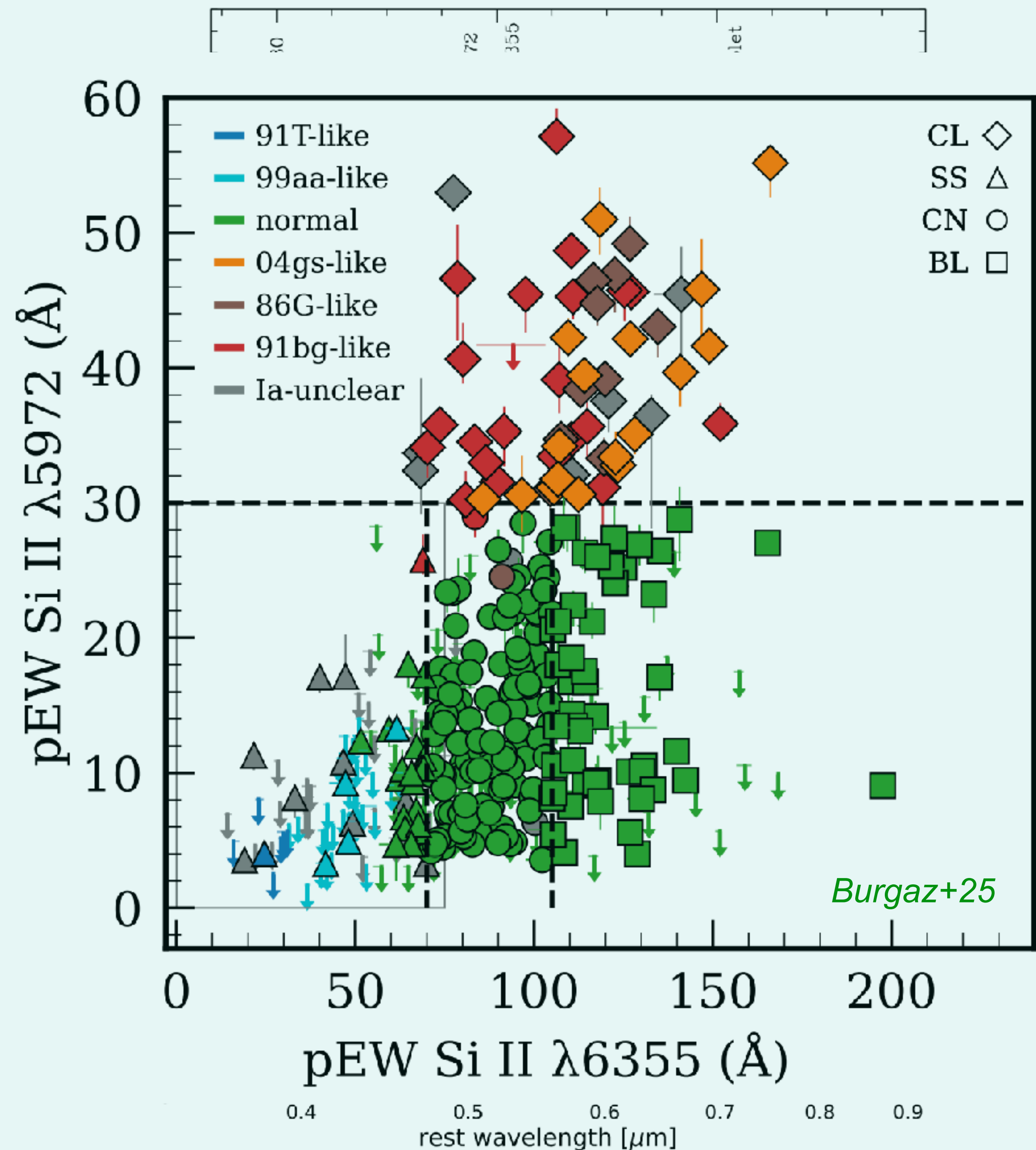
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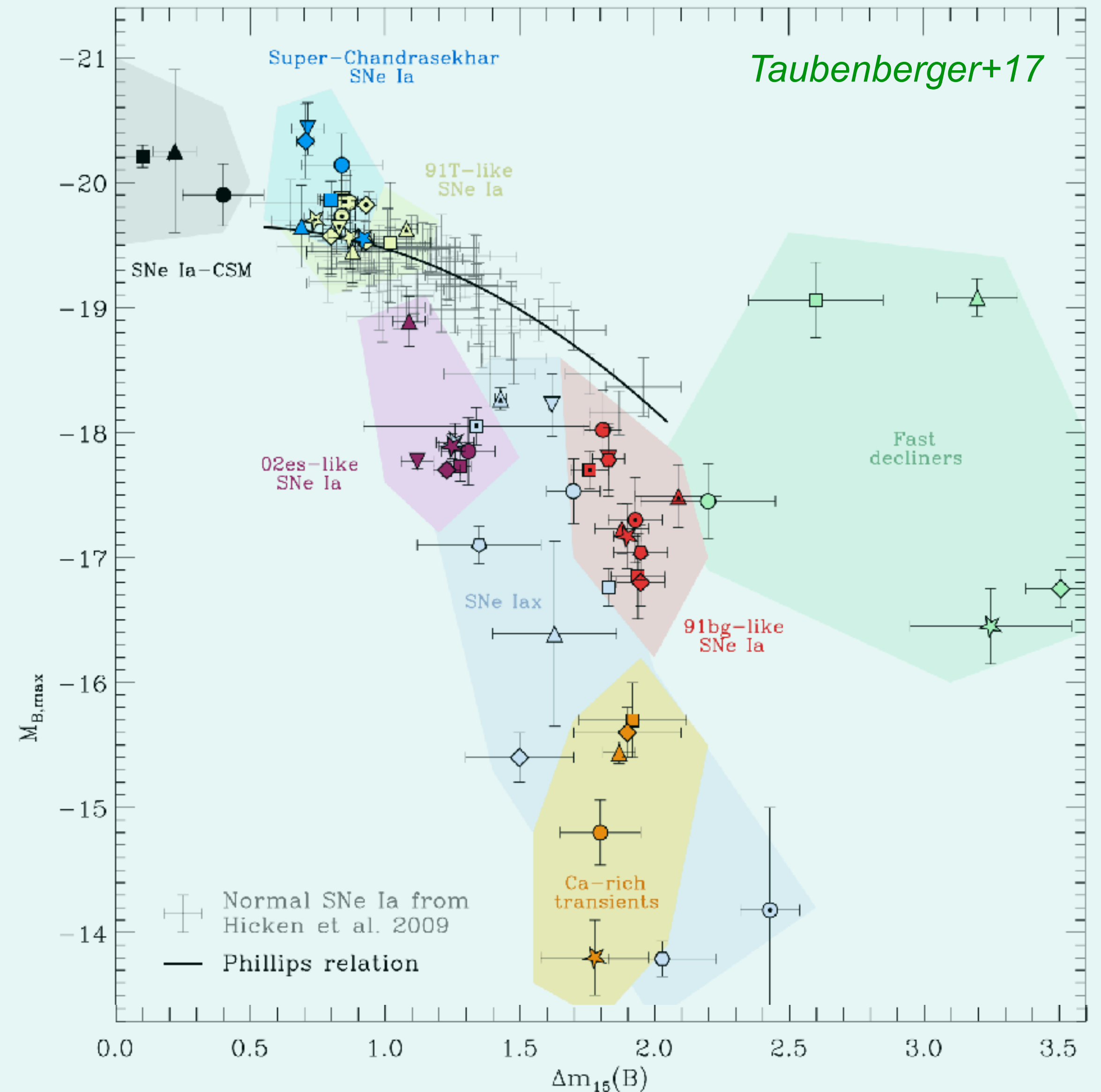
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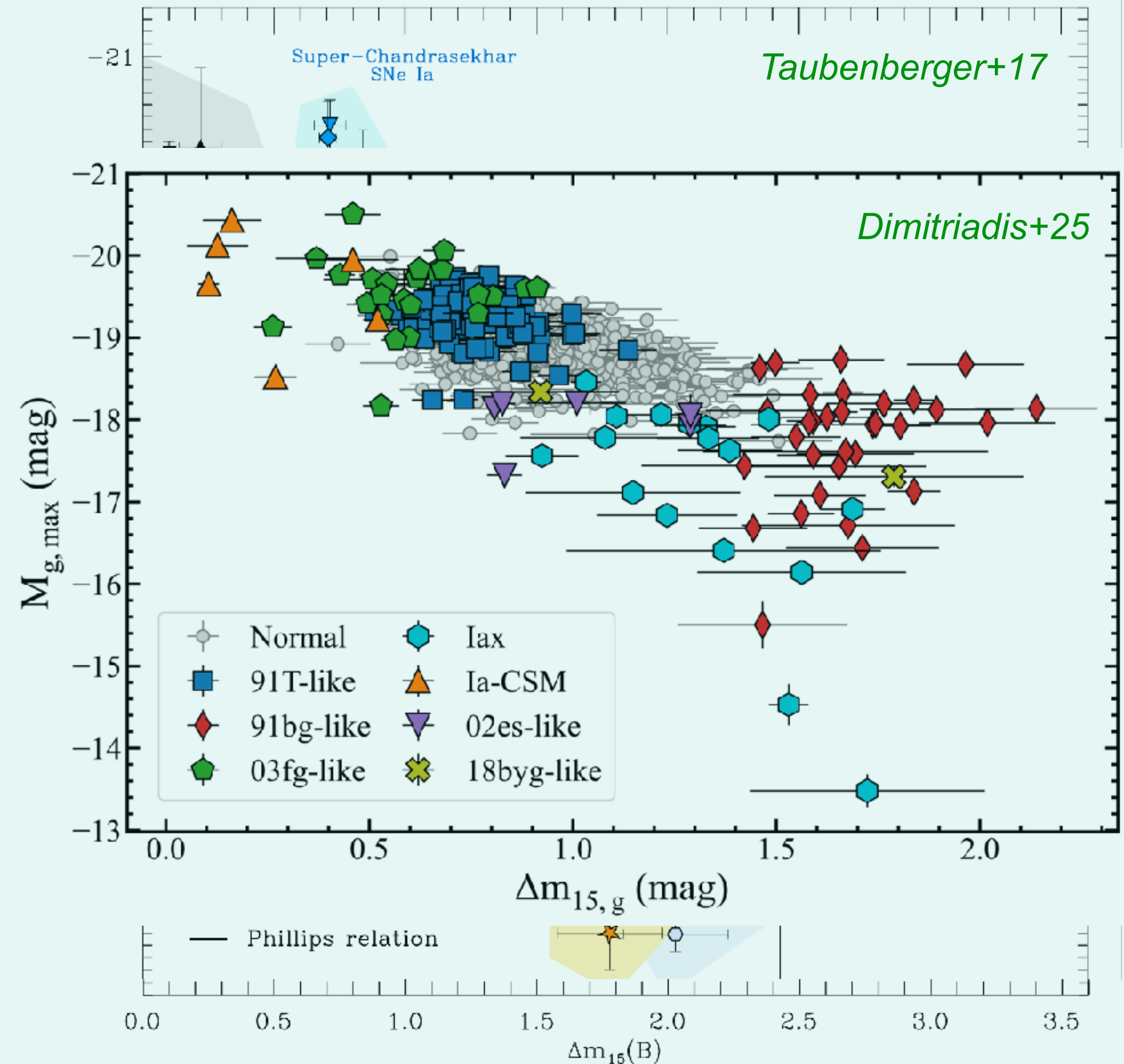
The SNIa subtype zoo

- Normal Ia dominate, but:
91T-like (luminous, weak Si),
91bg-like (subluminous, cool),
Iax (faint, low-velocity),
Ia-CSM (H-rich),
03fg-like (super-Ch)
- plus velocity subclasses (normal vs high-velocity).
- These link back to the scenario/mechanism diversity
(e.g., Ia-CSM $\rightarrow$ SD evidence;
sub-luminous $\rightarrow$ sub- M_{Ch})
and forward to environments.



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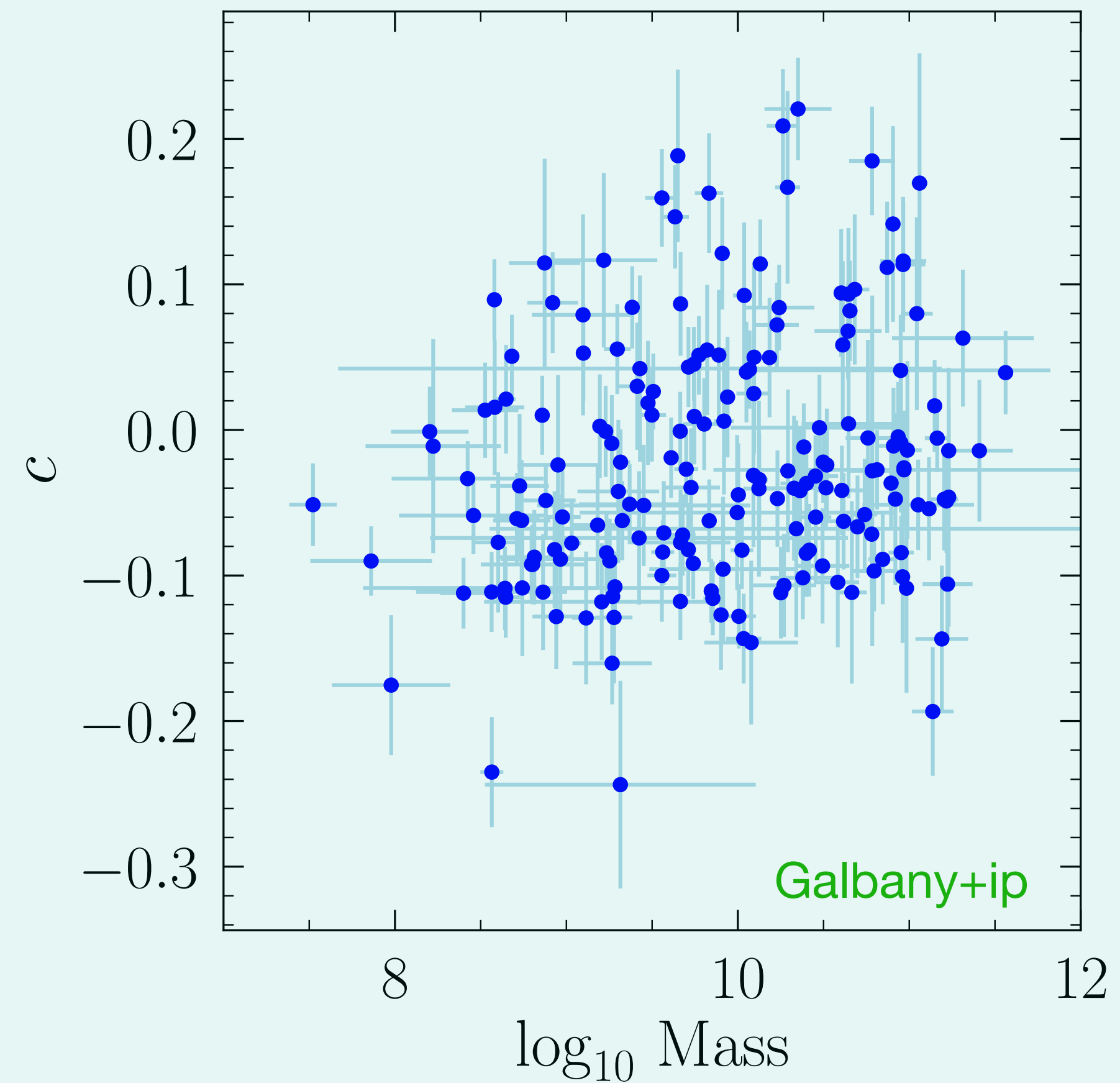
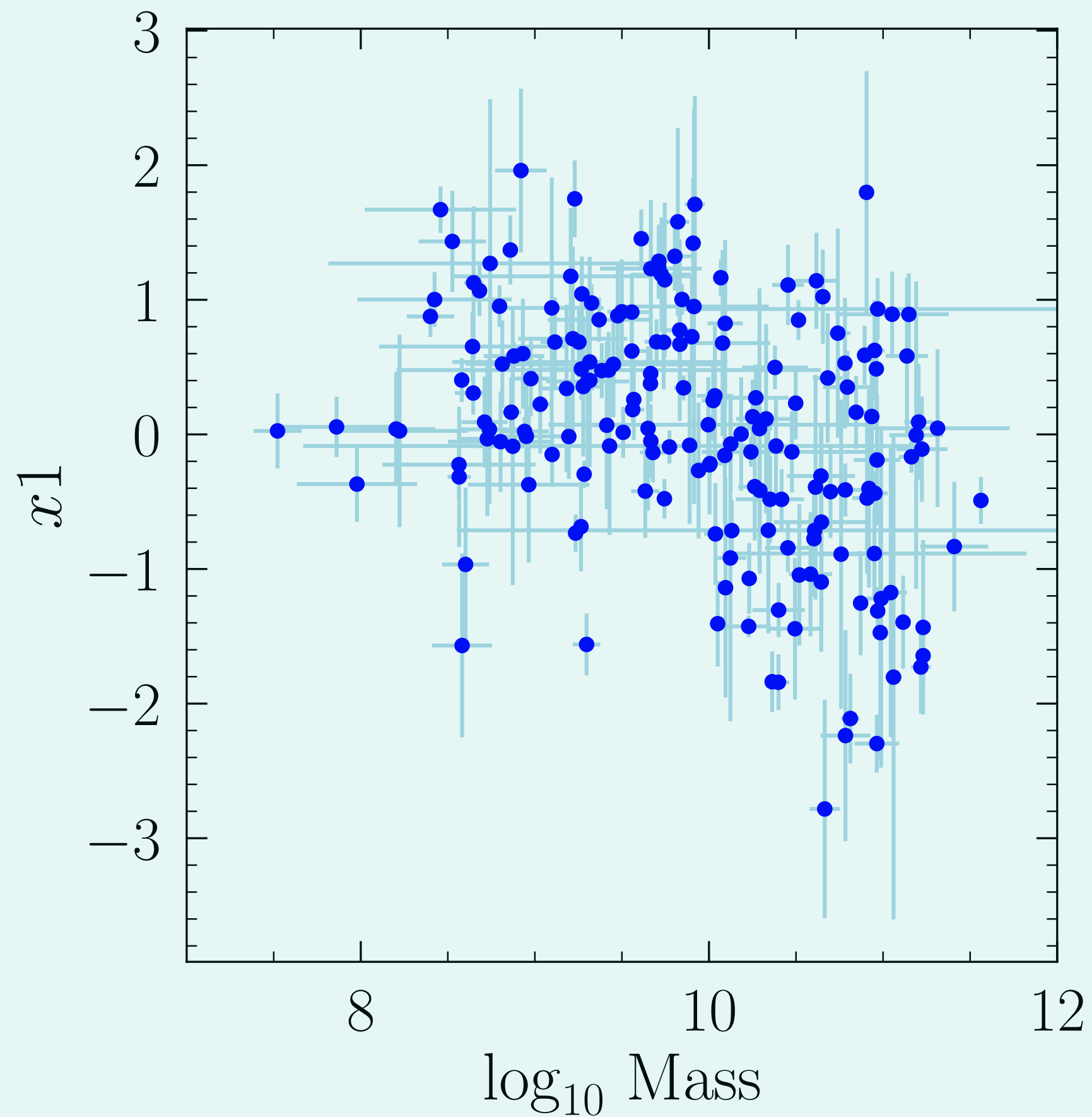


Bridge to hosts

- LC width, color, subtype, velocity, ... correlate with ***where*** the SN explodes.

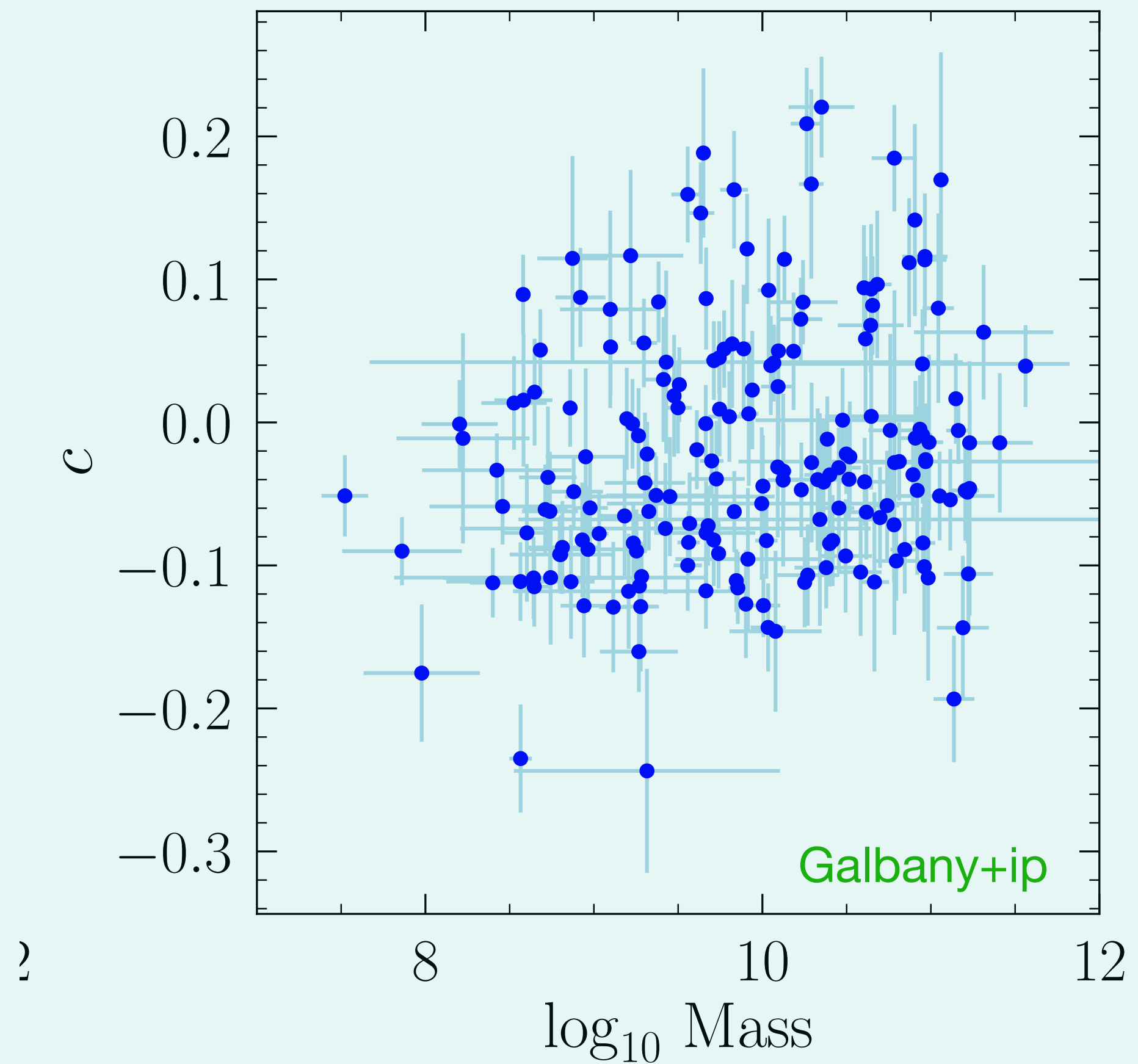
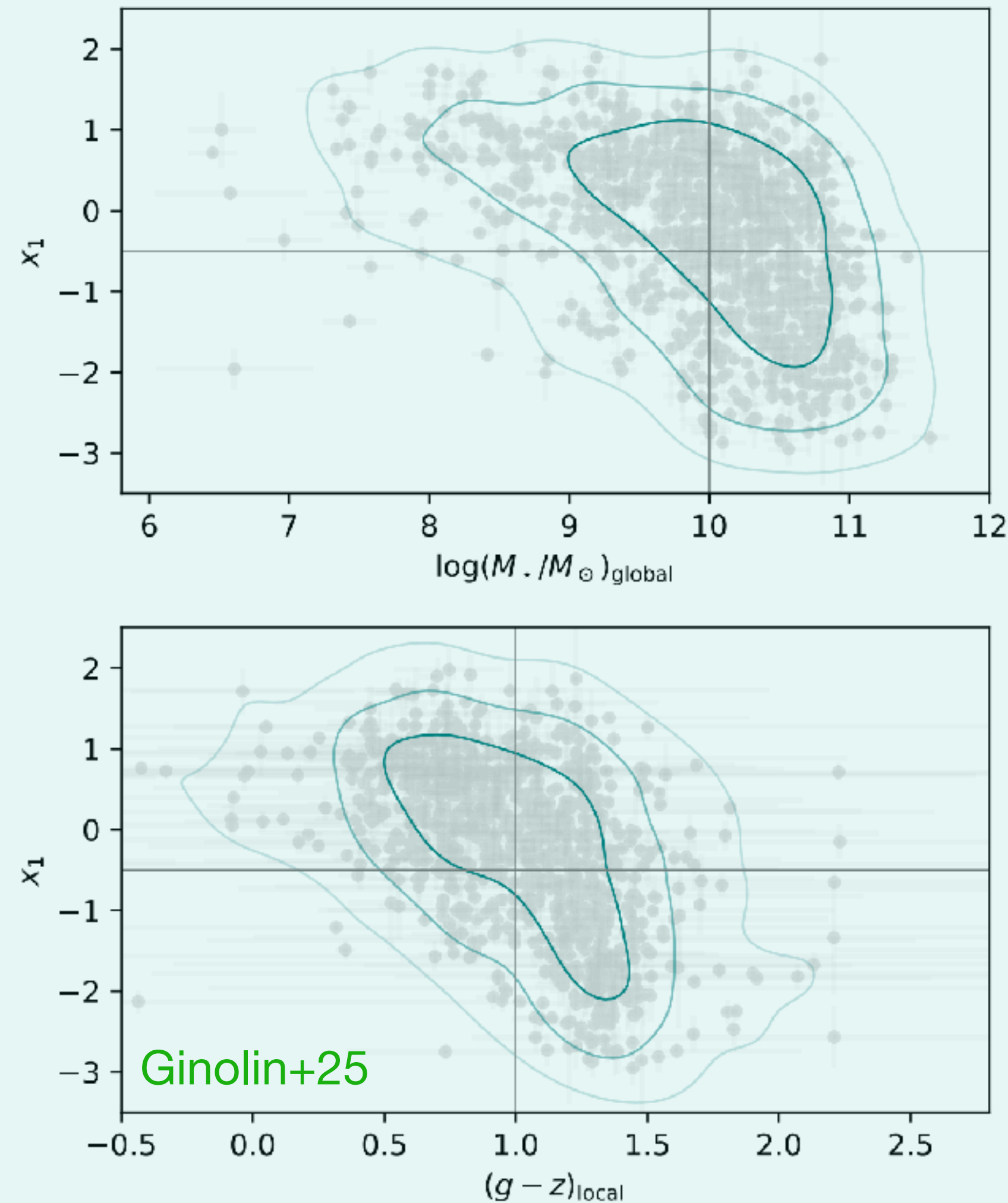
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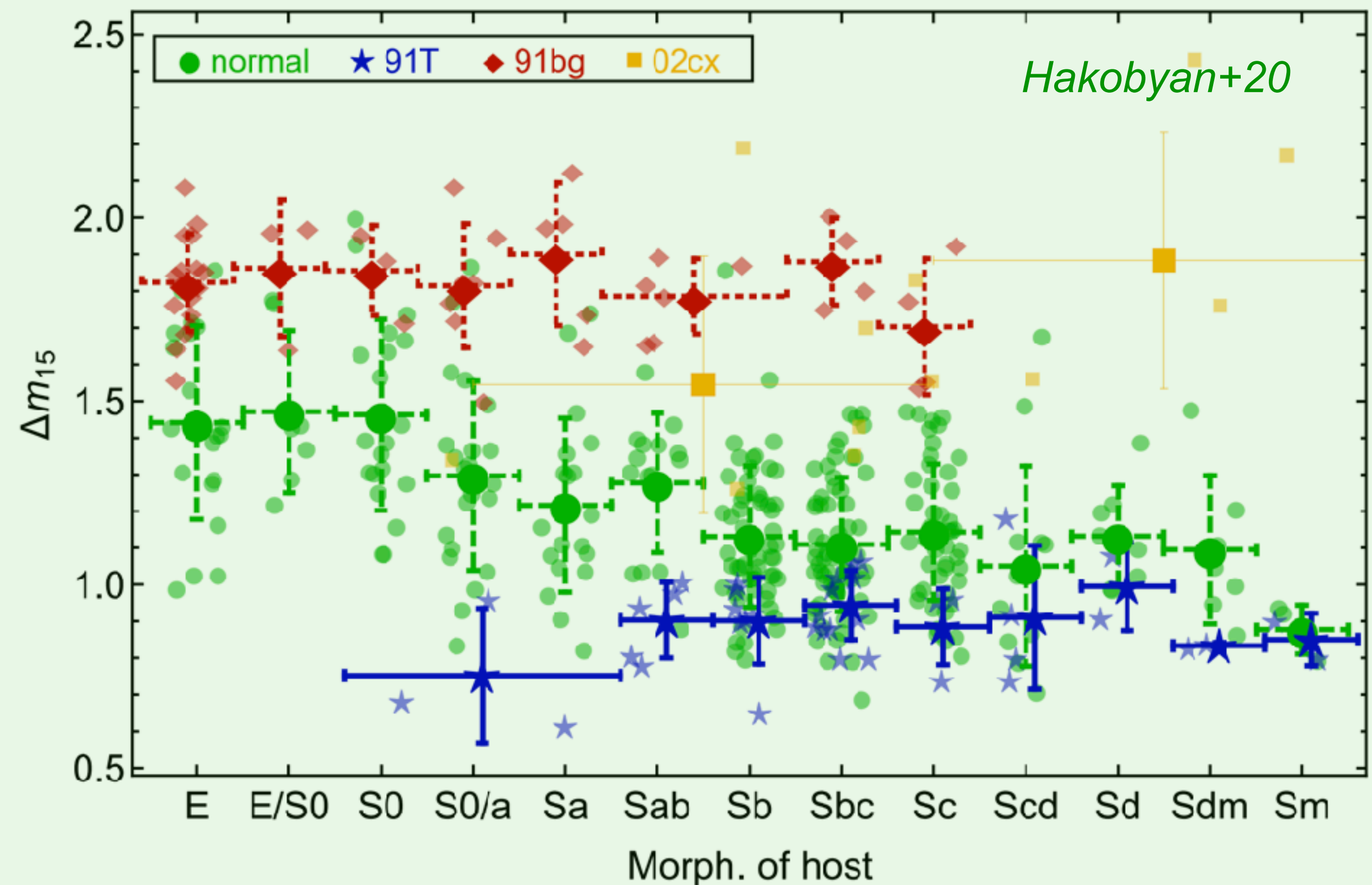
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Type Ia supernova host galaxies

- SNe Ia are found in both SF and passive galaxies.
- Progenitors span a wide range of stellar ages.
- The host is a fossil record of the progenitor



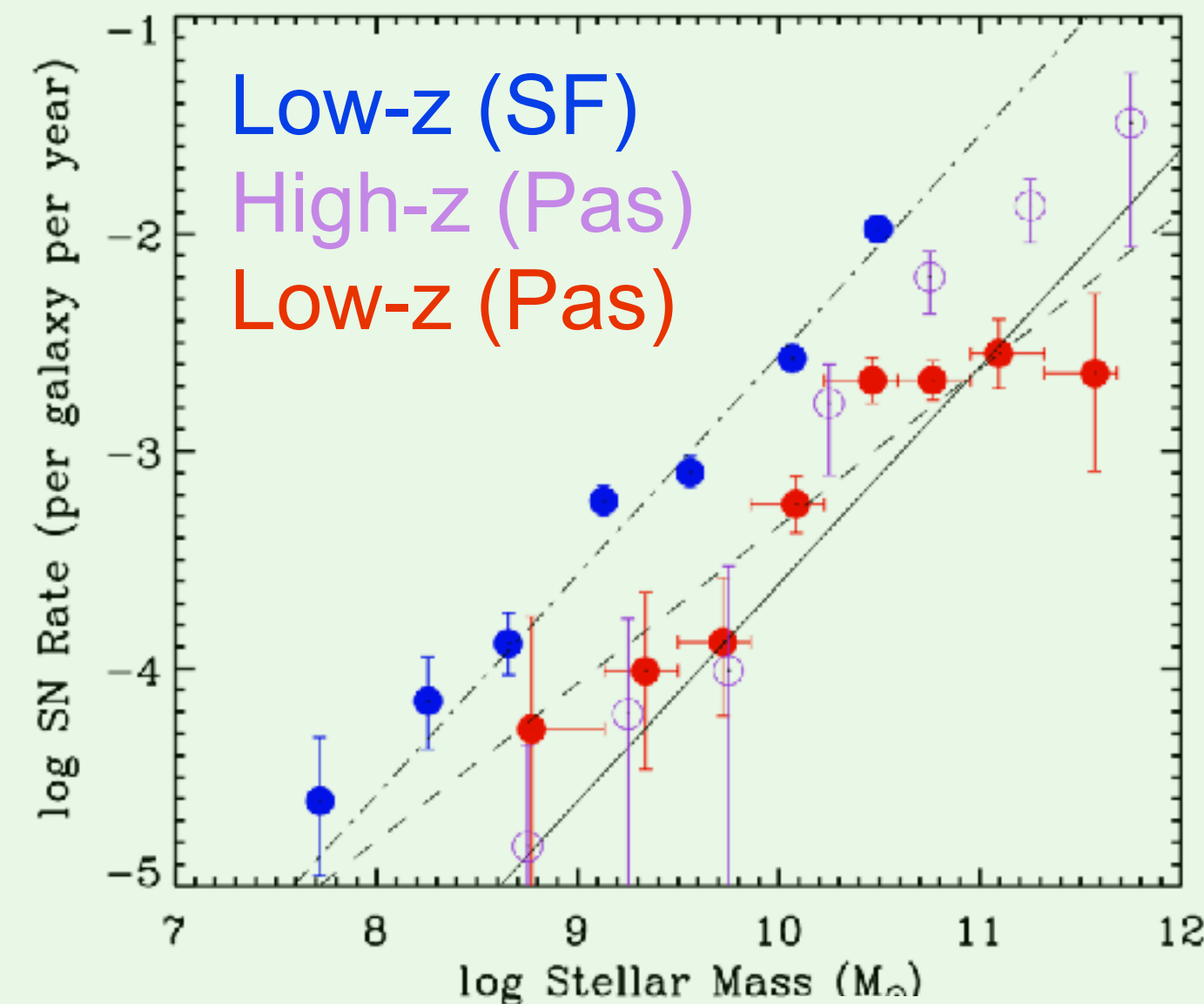
Hosts as a clock: Rates and delay-times

- SN Ia rate scales with stellar mass

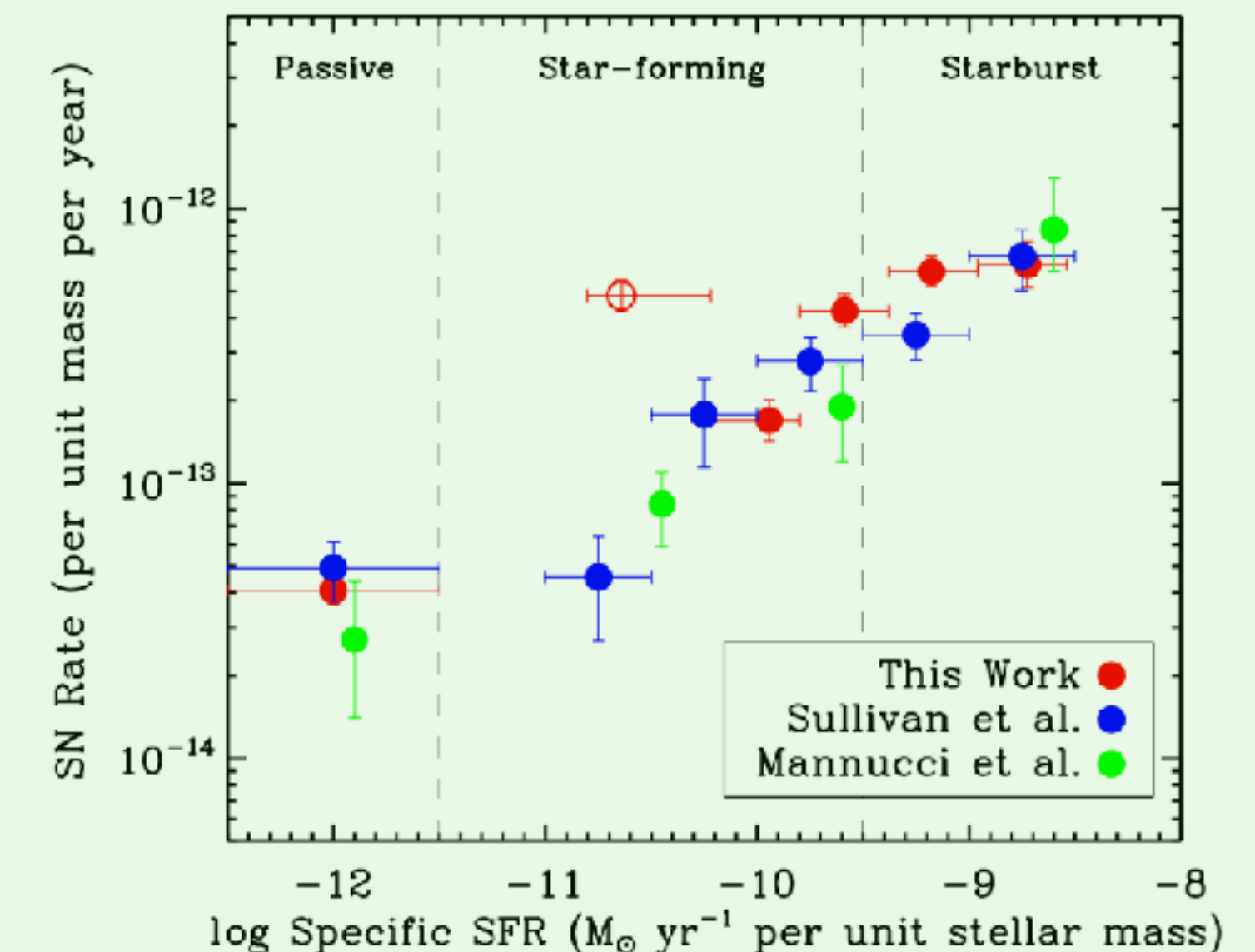
The relation has a different normalization and slope depending on morphology/color/SFR

- This tells us that the rate of SNe Ia depends on the **number (mass)** and **age** of stars in a galaxy...

...which sounds a lot like a SFH



Smith+12



Hosts as a clock: Rates and delay-times

- The SFH tells us when each of the stars were formed

For each epoch of SF, SNe do not explode instantaneously

Enter: the **delay time distribution** (DTD)

Time from SF to explosion

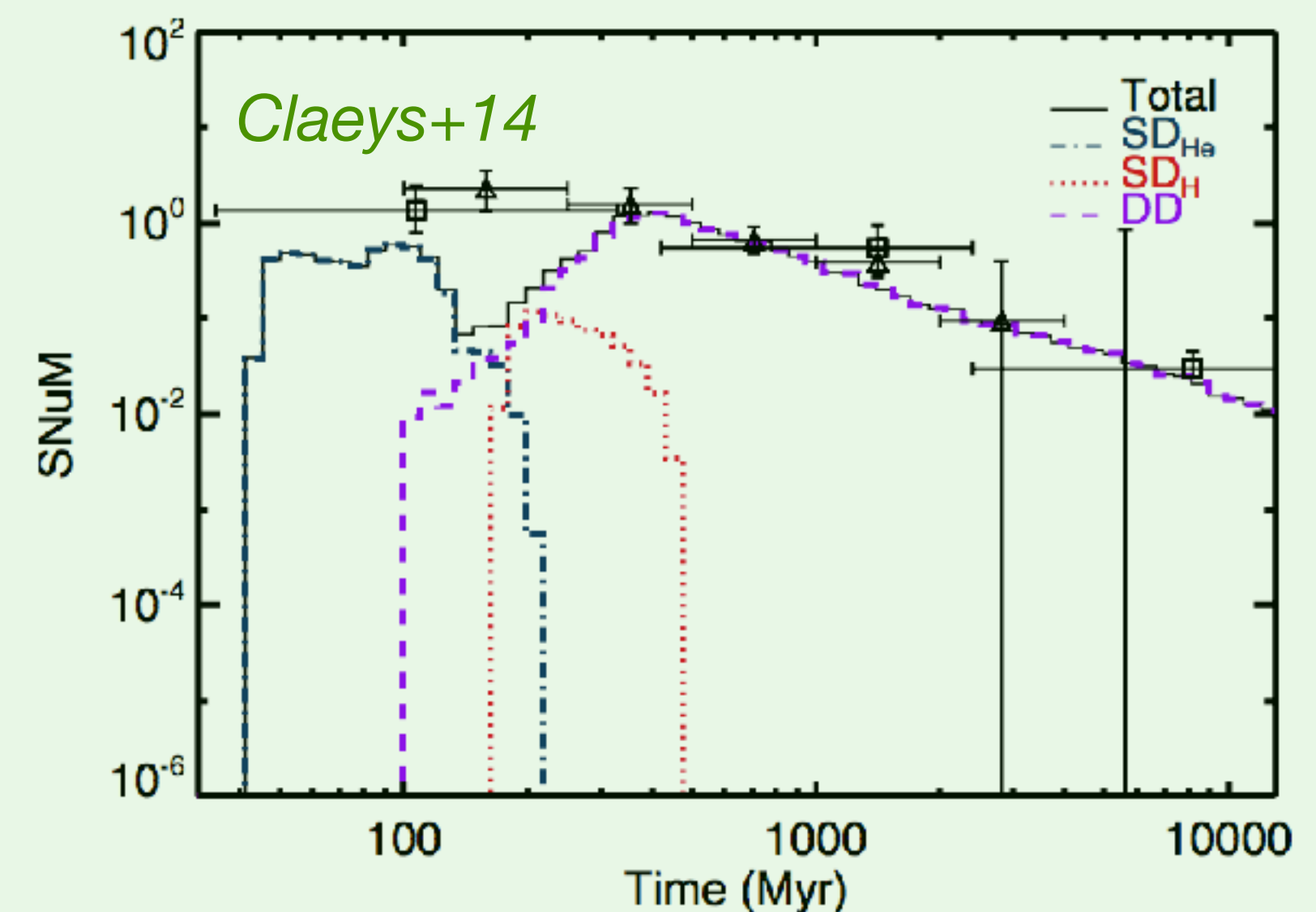
Statistical

- The measured DTD $\propto t^{-1}$

spans ~40 Myr to ~10 Gyr, telling us the progenitor channel produces both young and very old SNe Ia.

$$R_G = \int_{t_0}^{\infty} \underbrace{\psi(t_0 - \tau)}_{\substack{\text{SFH} \\ \text{how many stars} \\ \text{have age } \tau}} \underbrace{\Phi(\tau)}_{\substack{\text{DTD} \\ \text{What is the probability} \\ \text{of a star of age } t \\ \text{exploding a a SN?}}} d\tau$$

SN rate per galaxy



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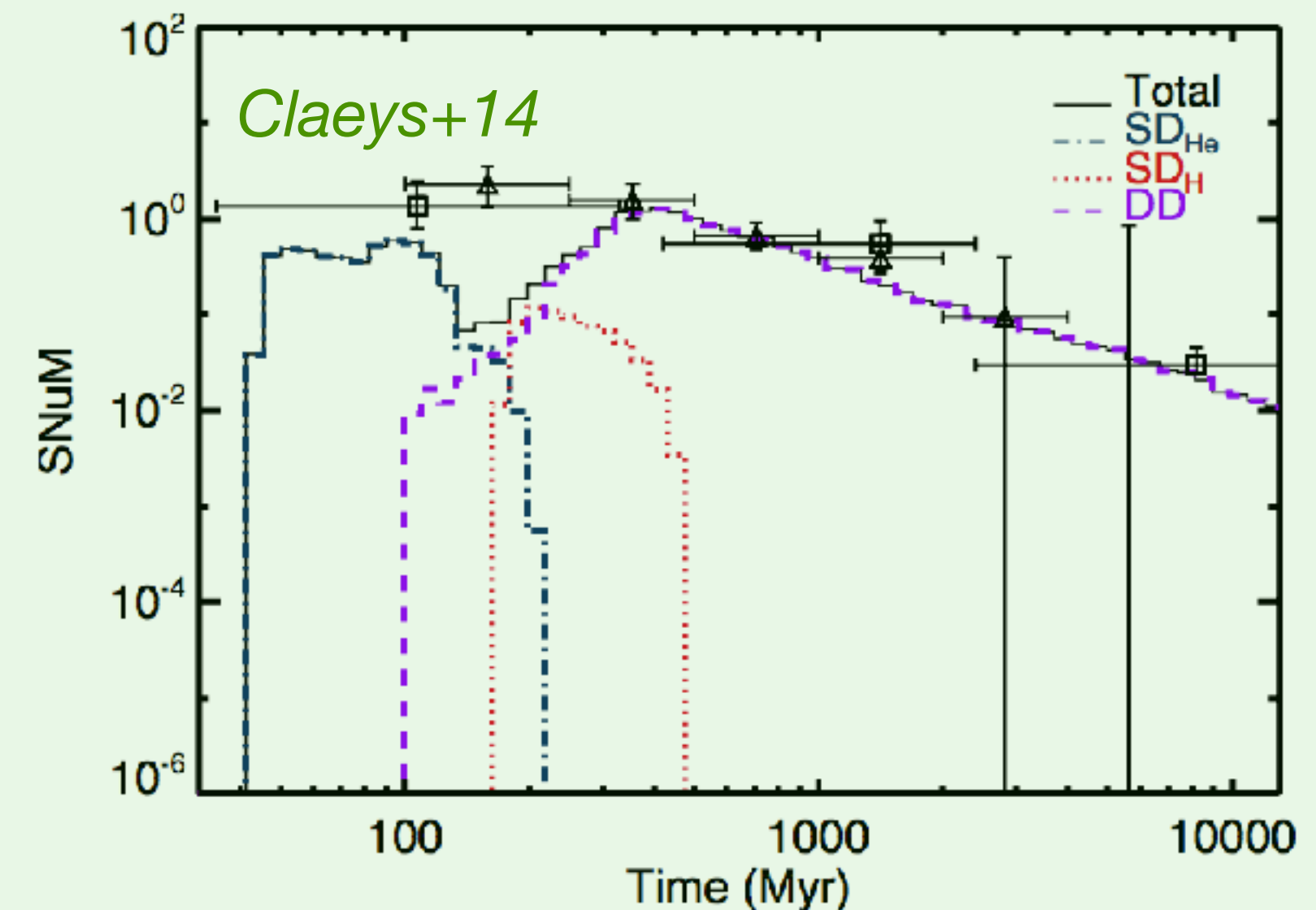
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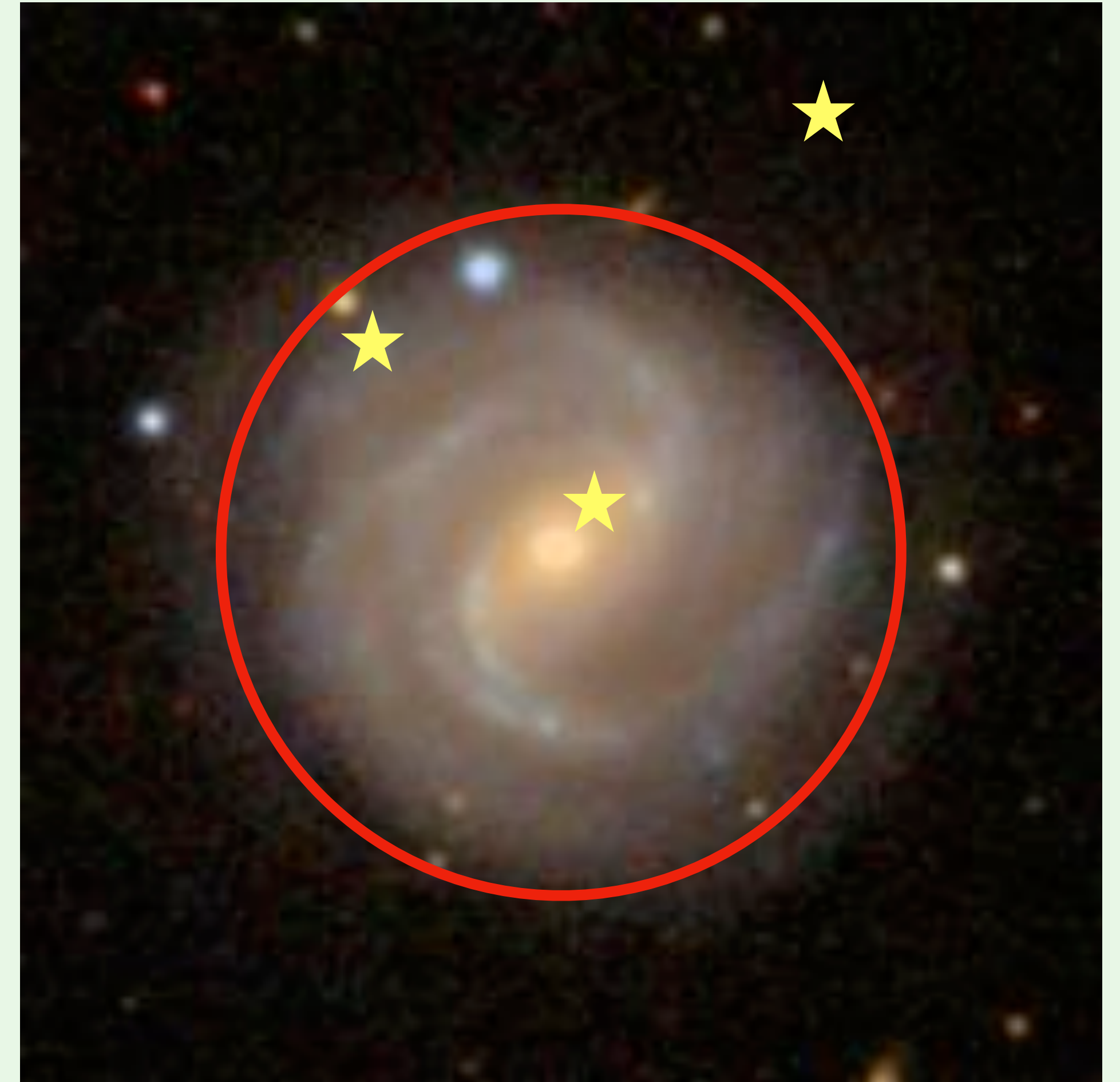
SN rate per galaxy



Global vs local environments

- Most of the correlations in the literature use global parameters (higher S/N), but average out all properties

e.g. Spiral arm $\neq$ Bulge
- The stellar population ***at the SN location*** is physically the right scale
- Local tracers (local sSFR, H α EW, color, surface brightness, O/H, metallicity...) isolate the progenitor's birth environment far better than integrated host properties.



e.g. *Rigault+13,20; Roman+18; Kelsey+21; Briday+22*

SN LC width correlates with environment: the age connection

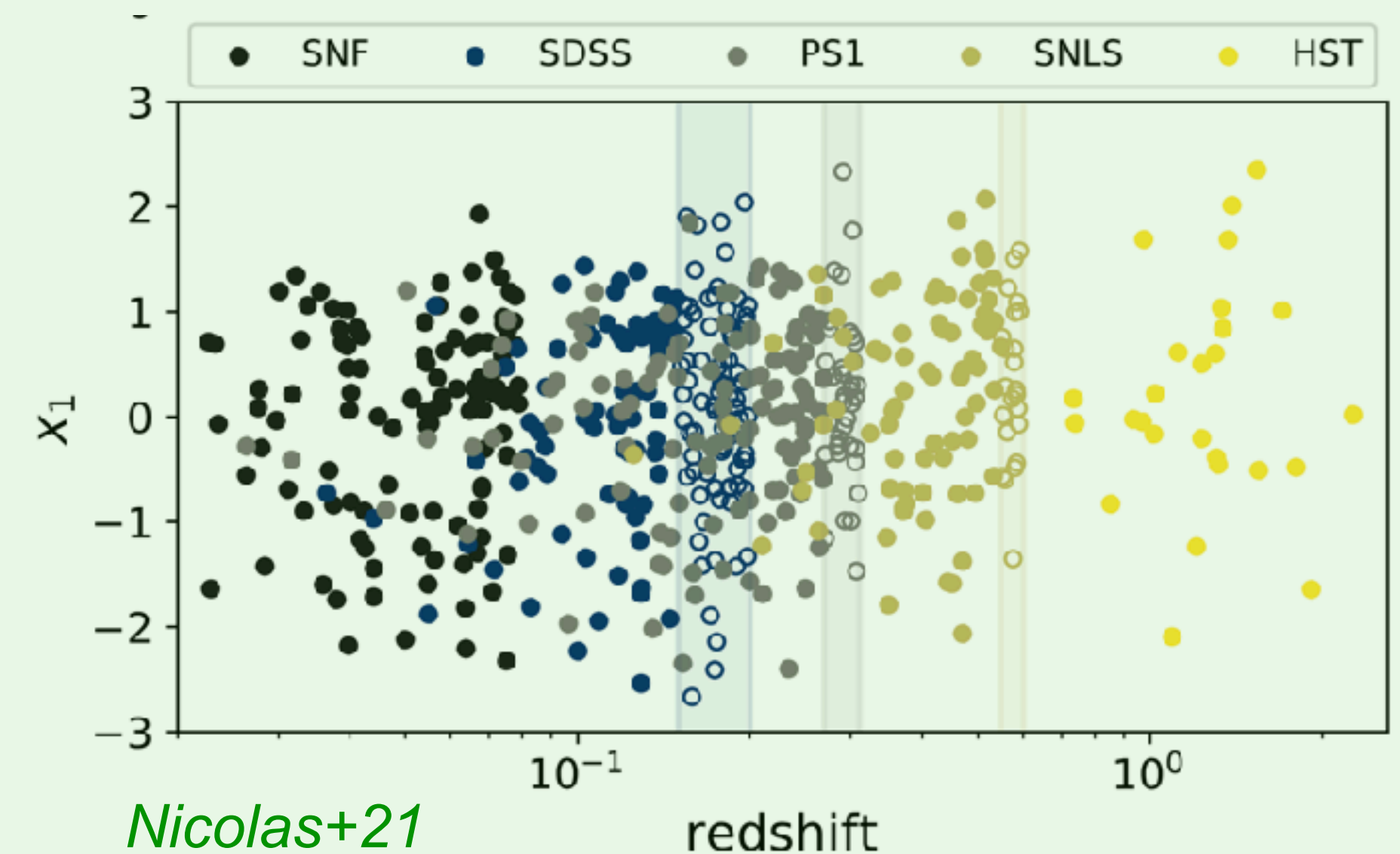
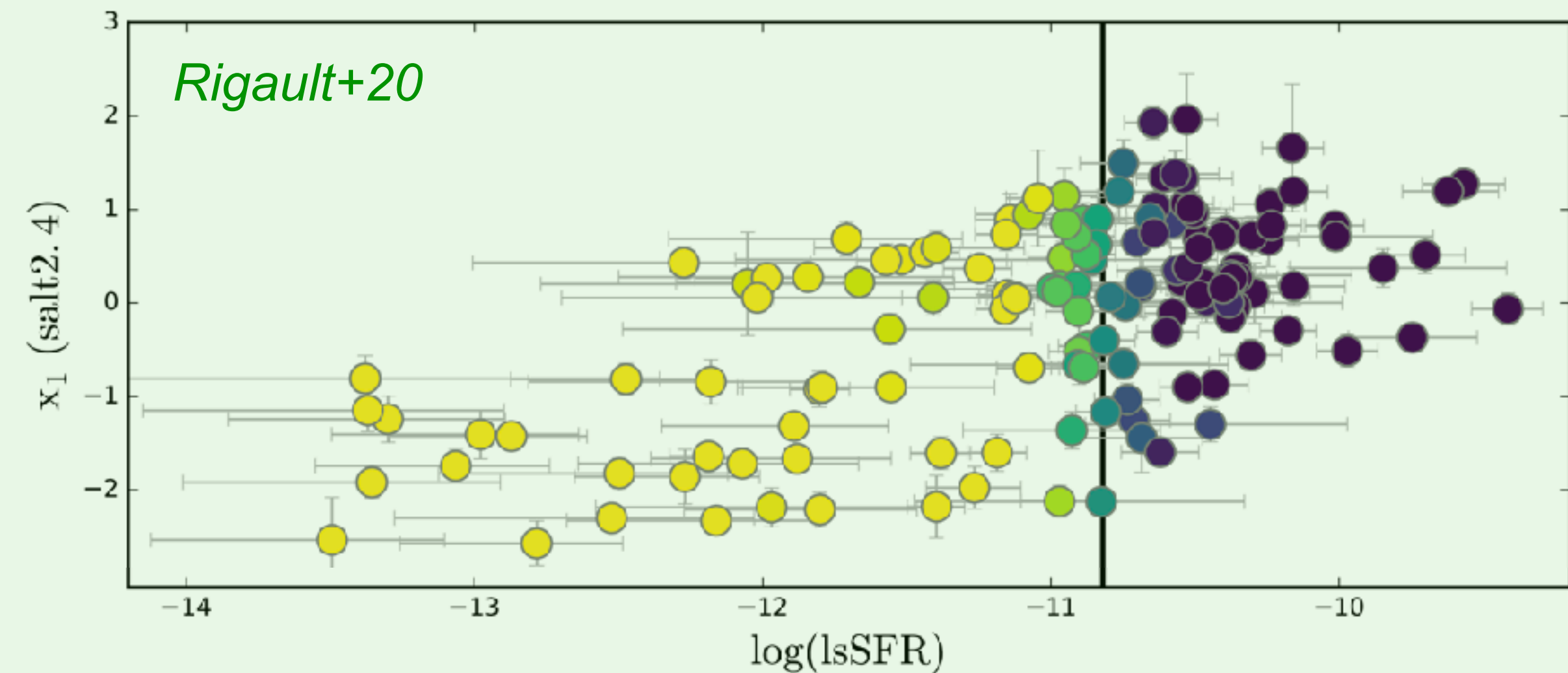
- Broad, **slow-declining SNe** preferentially occur in **young**, SF environments

Narrow, **fast-declining SNe** favor **old**, passive stellar populations.

The same light-curve width that encodes luminosity also encodes progenitor age.

- This is well described by the A+B model, with the observed distribution being the mix of the two.

Because the young fraction increases with redshift, the mean LC width of the population drifts with cosmic time



SN LC width correlates with environment: the age connection

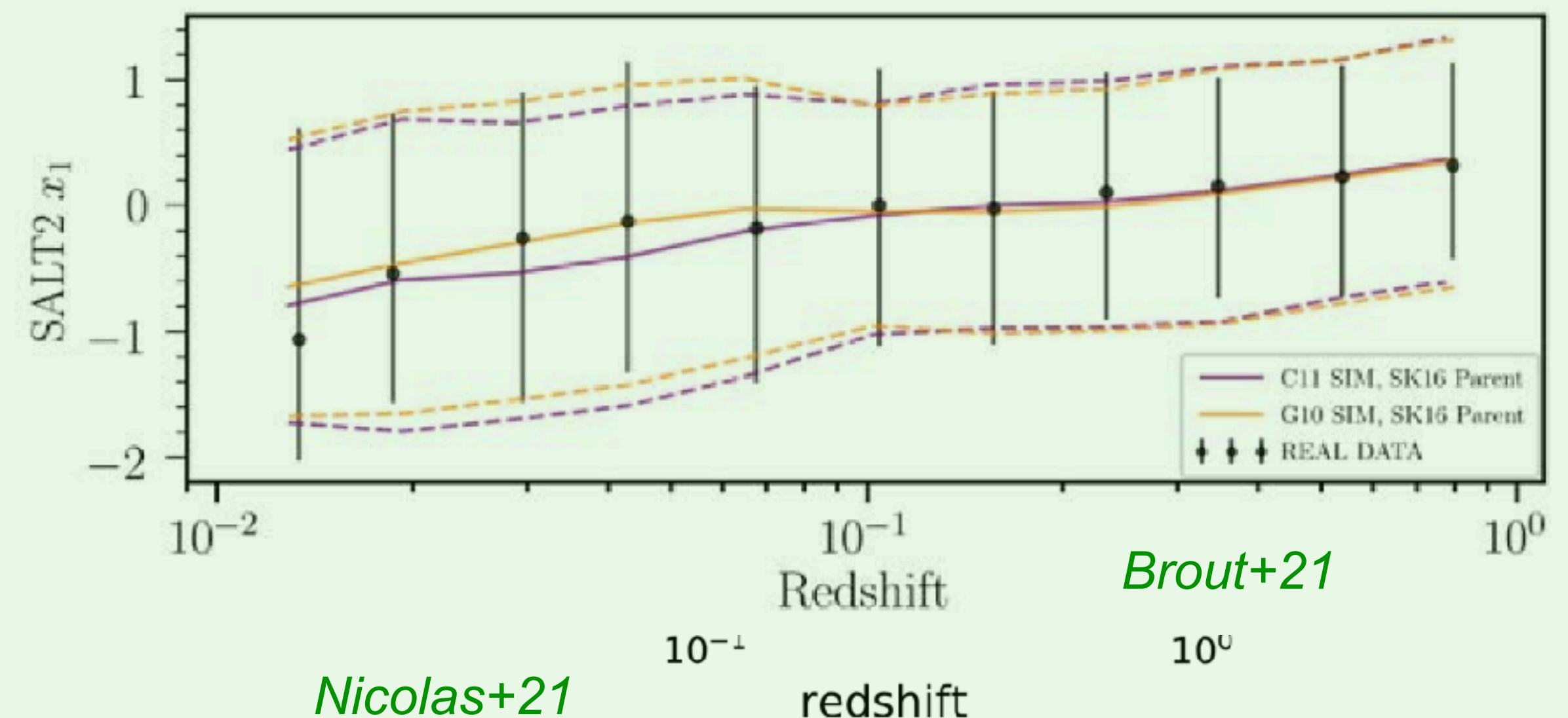
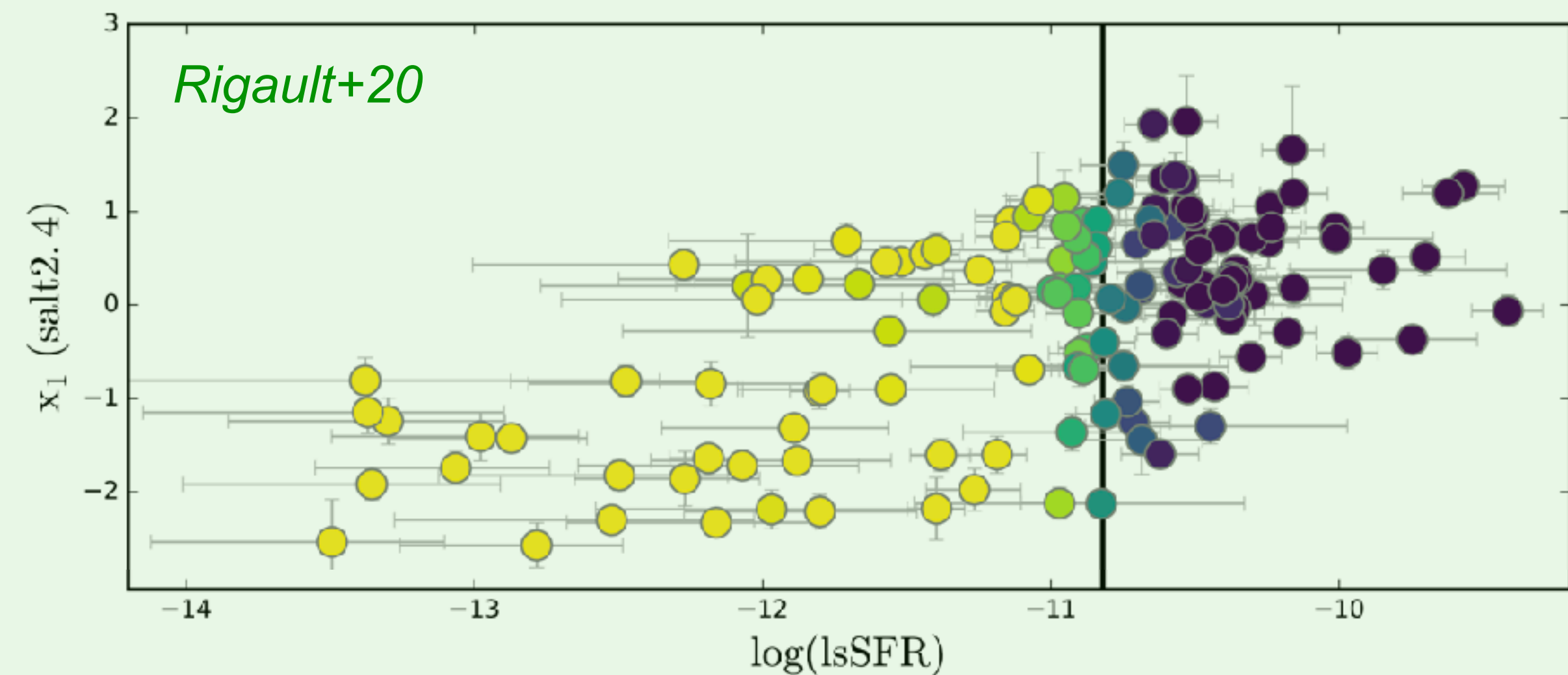
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Because the young fraction increases with redshift, the mean LC width of the population drifts with cosmic time



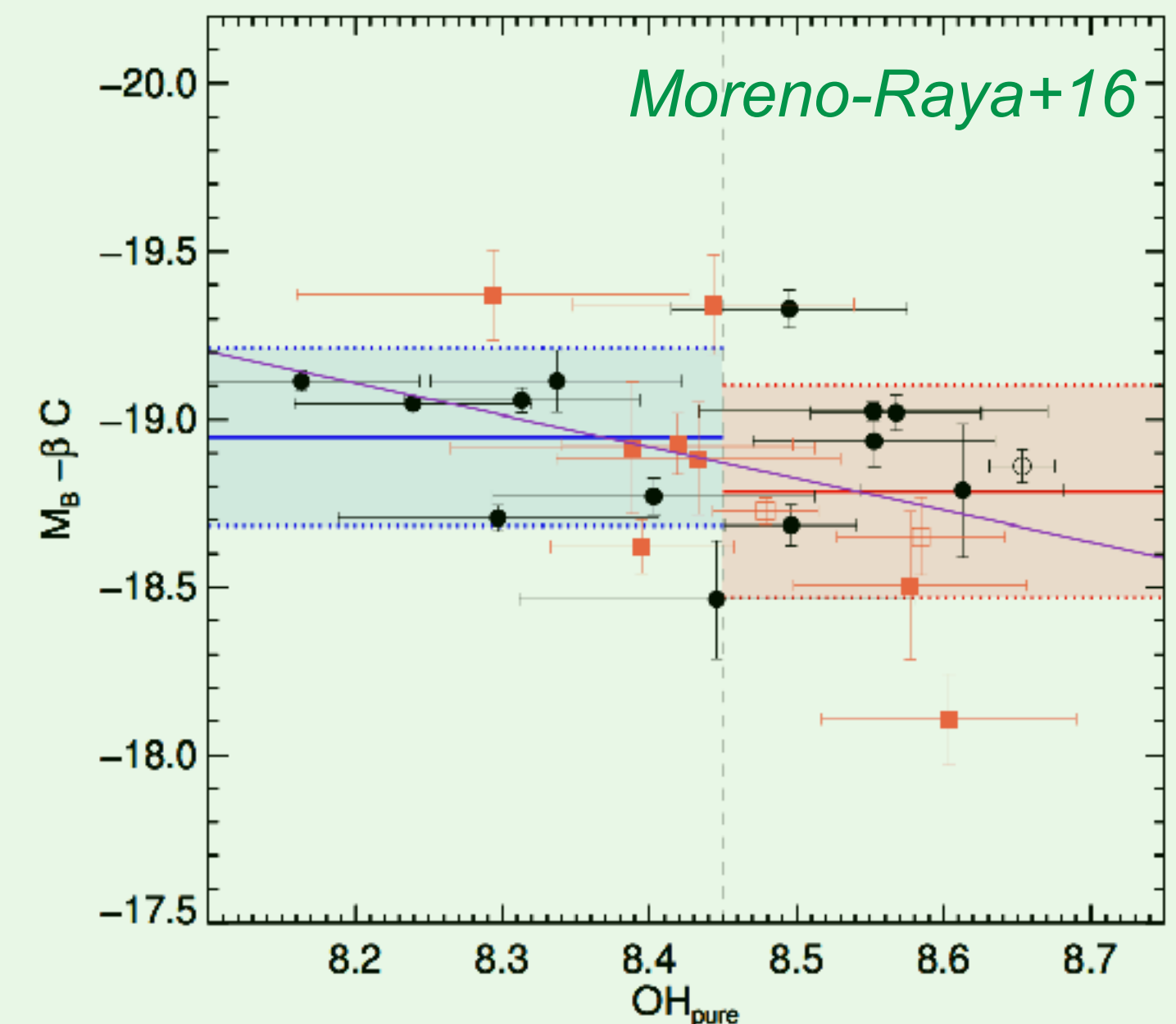
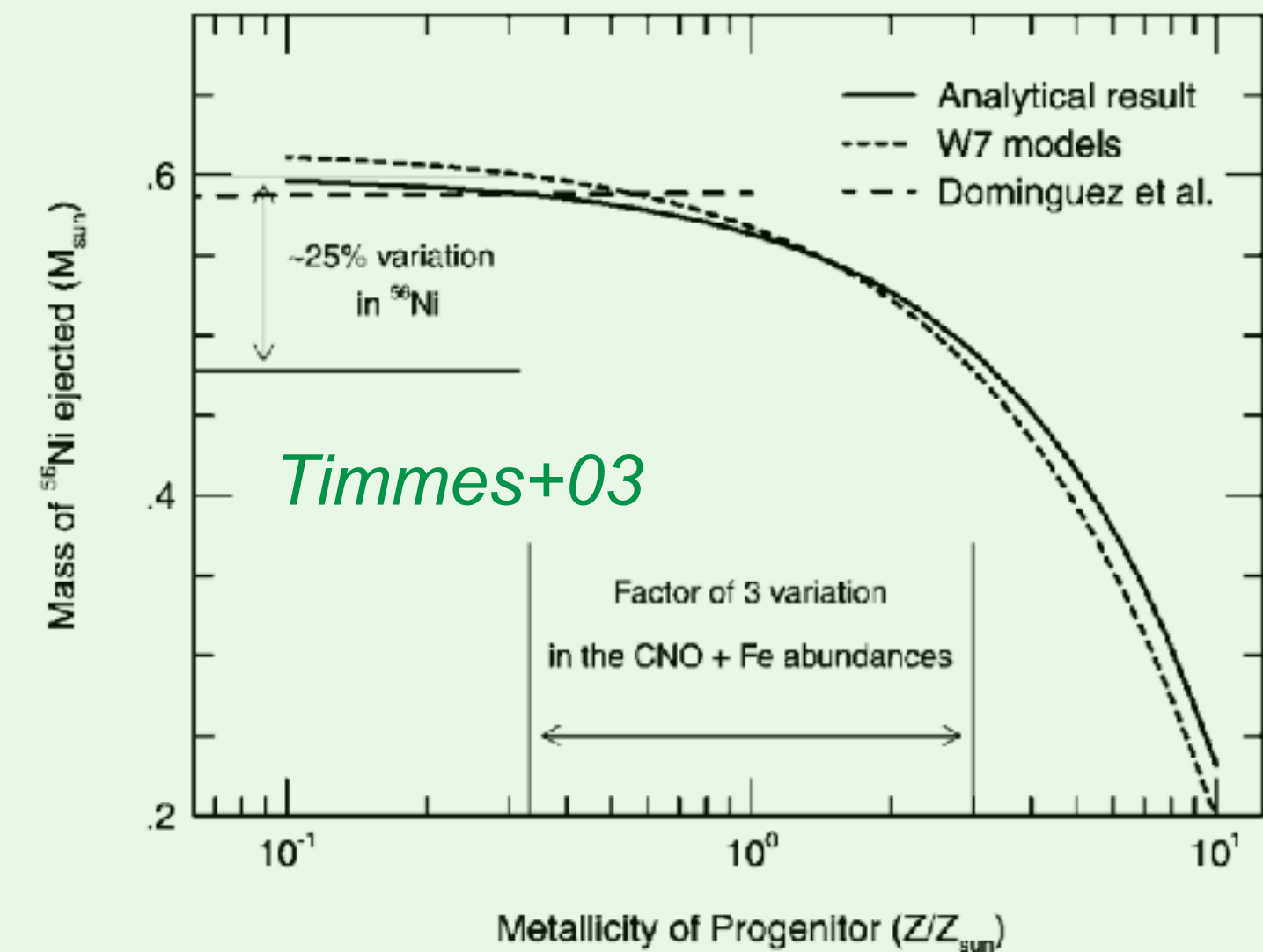
Environment shapes the physics of the explosion

- Progenitor metallicity and age plausibly shape the explosion itself

Metallicity sets the neutron excess and hence the ^{56}Ni yield (a luminosity lever)

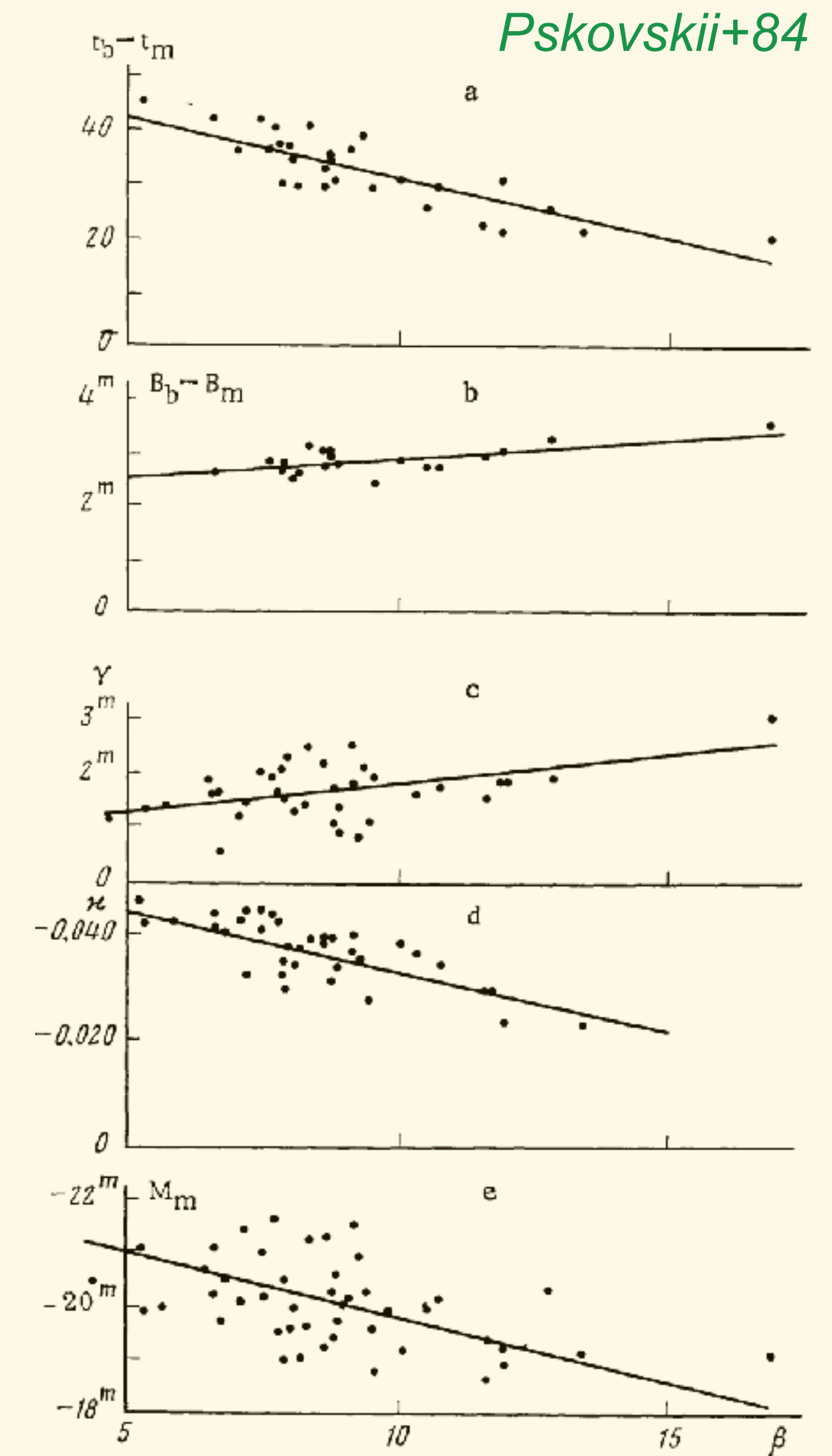
Age relates to WD mass at explosion

- Because these environmental dependences correlate with LC and luminosity, they may become an issue when ***standardizing*** brightness for measuring distances



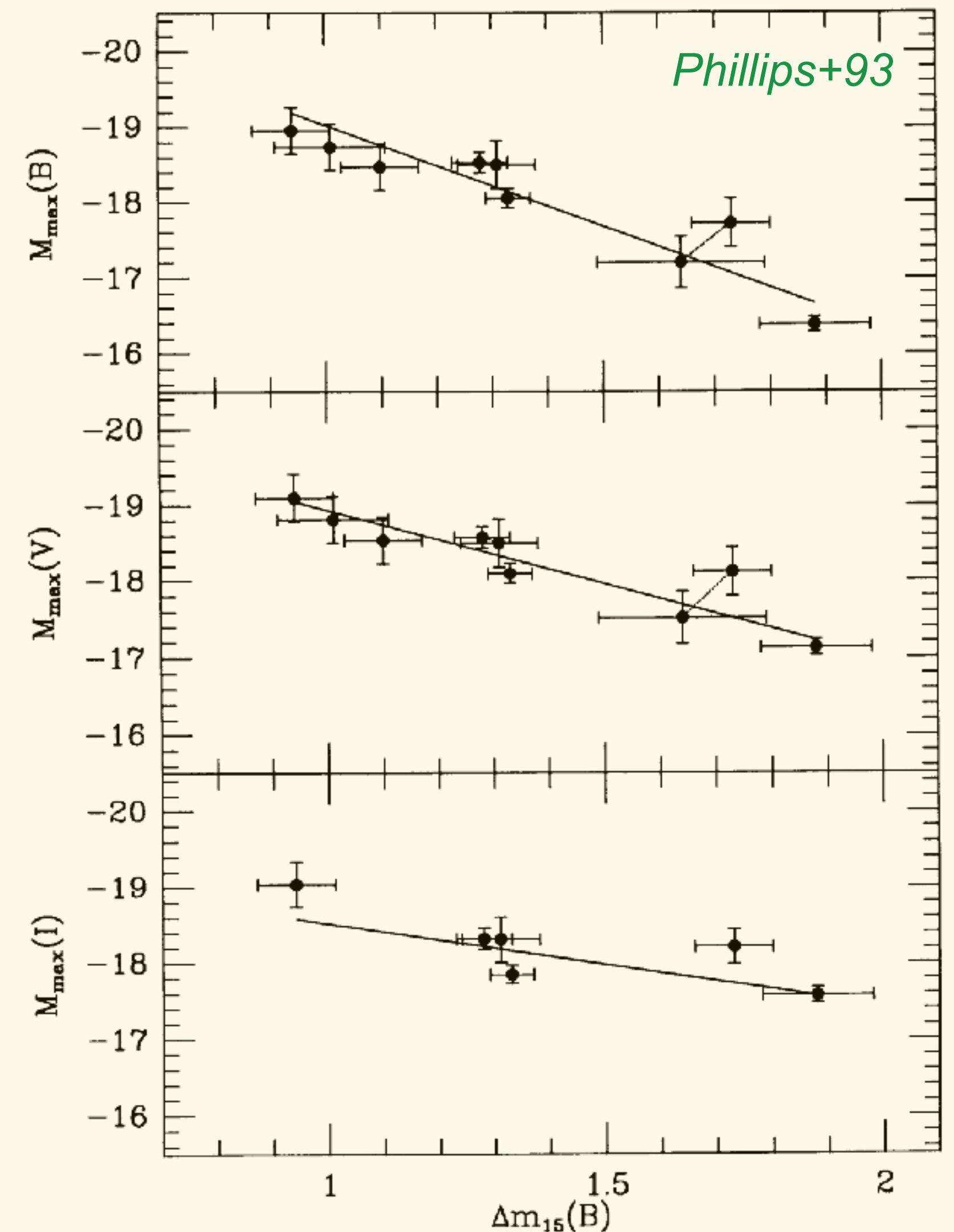
A brief history: from Pskovskii to Tripp

- Unfortunately, SNe Ia are not standard but **standardizable** candles.
 - *Pskovskii* (1977, 1984) first linked decline rate to luminosity
 - *Phillips* (1993) made it quantitative with $\Delta m_{15}(B)$
 - *Riess, Press & Kirshner* (1996) used the full multi-color light curve (MLCS) and added a color/extinction correction
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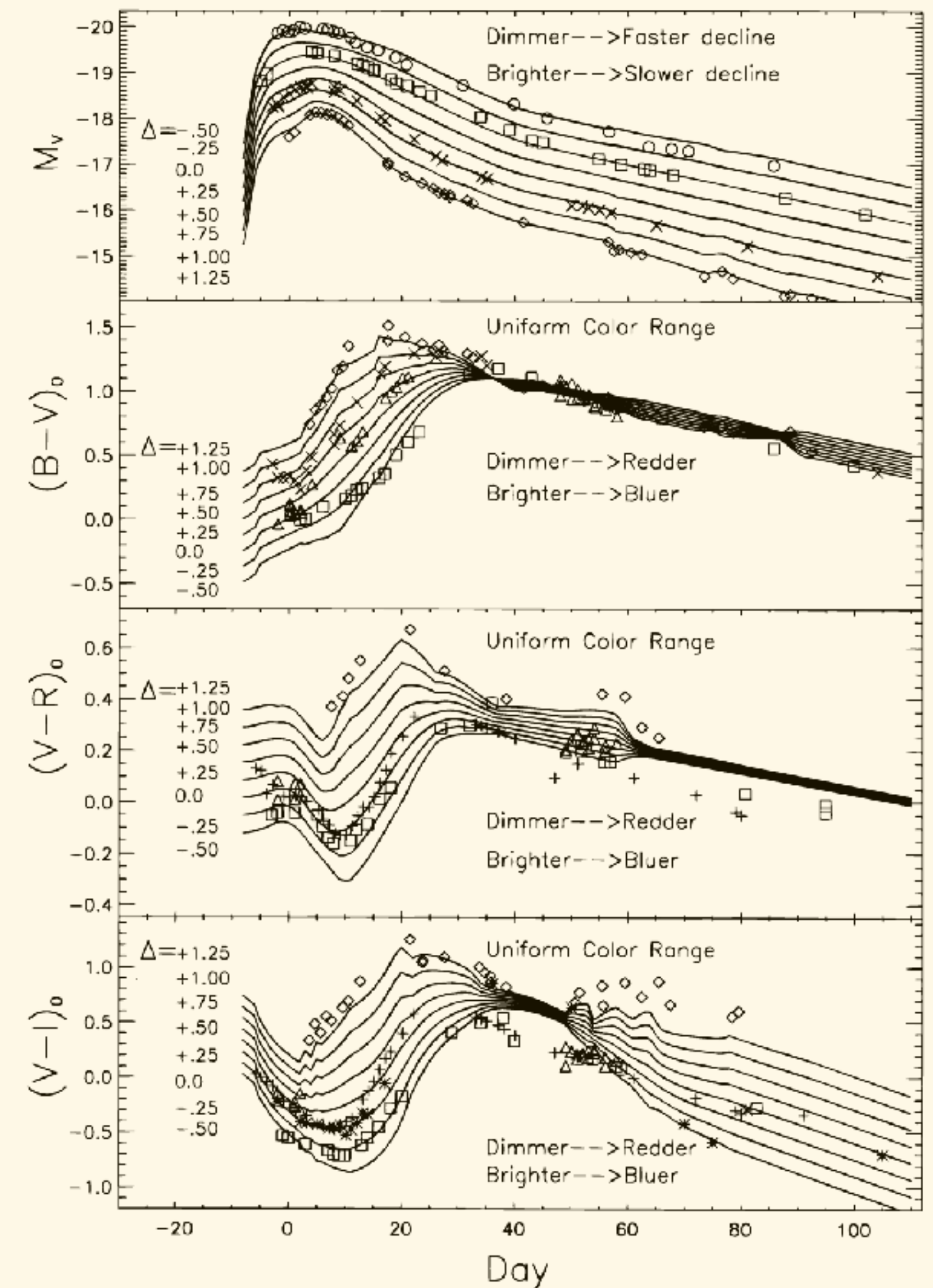
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A brief history: from Pskovskii to Tripp

Riess+96

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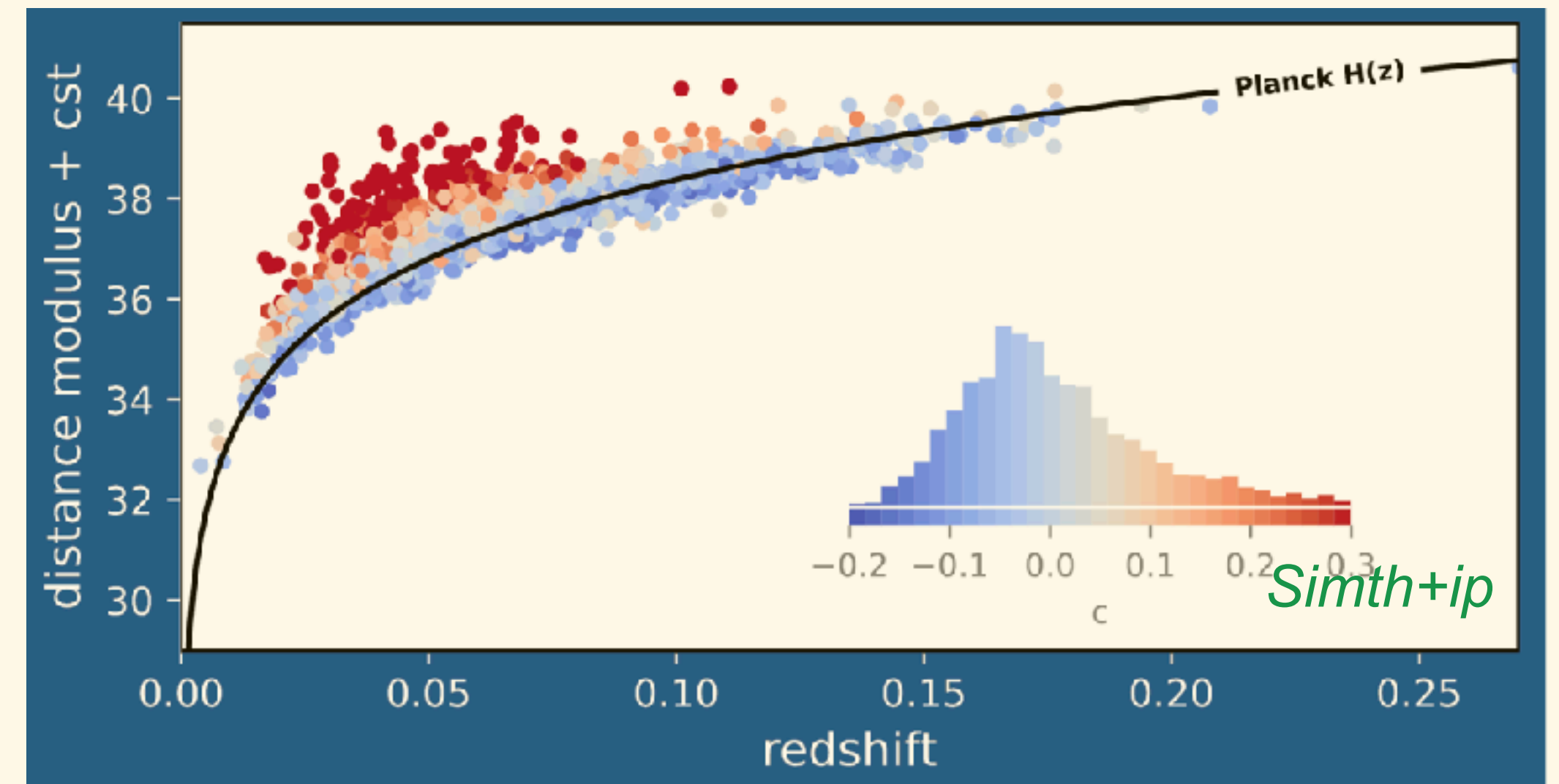
The distance modulus needs corrections

- Raw peak magnitudes scatter by ~ 0.4 mag.

To standardize we apply three corrections for light-curve **width**, for **color**, and for **environment** plus a **bias/selection** term for survey incompleteness

$$\mu = m - M + \alpha x_1 + \beta c + \gamma M_* + \mu_{bias}$$

- Standardized scatter shrinks from ~ 0.4 to ~ 0.15 mag.



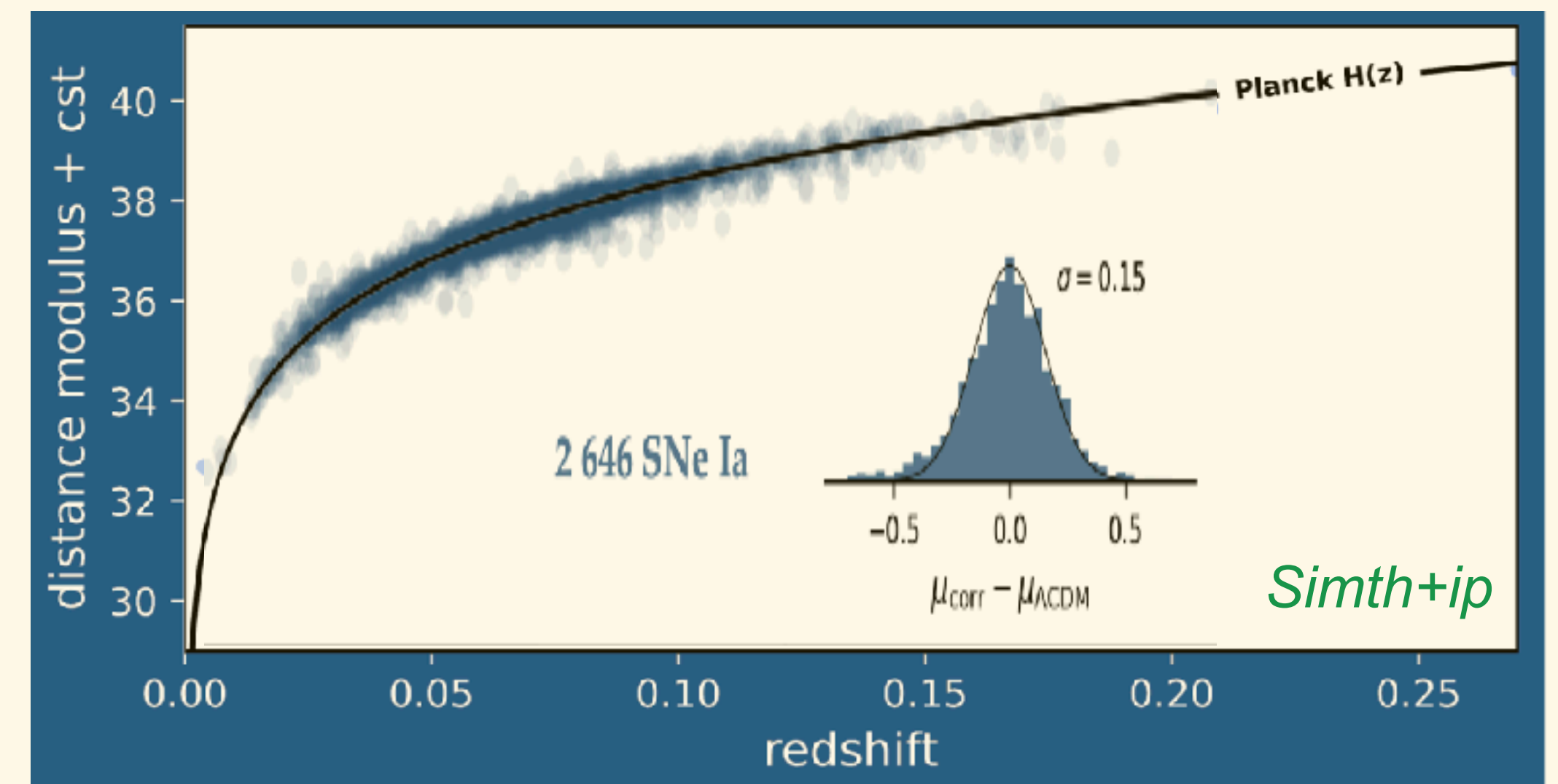
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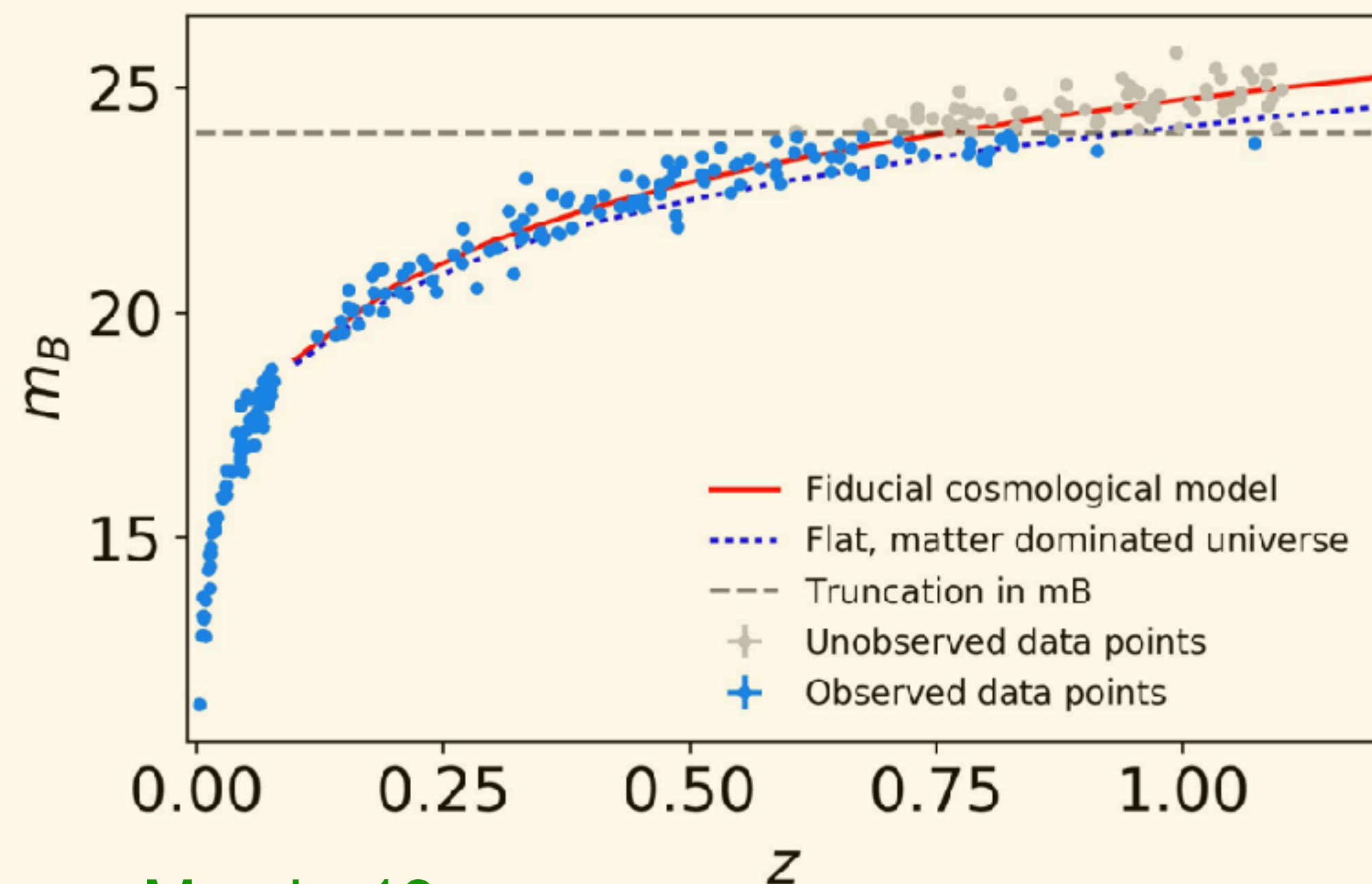
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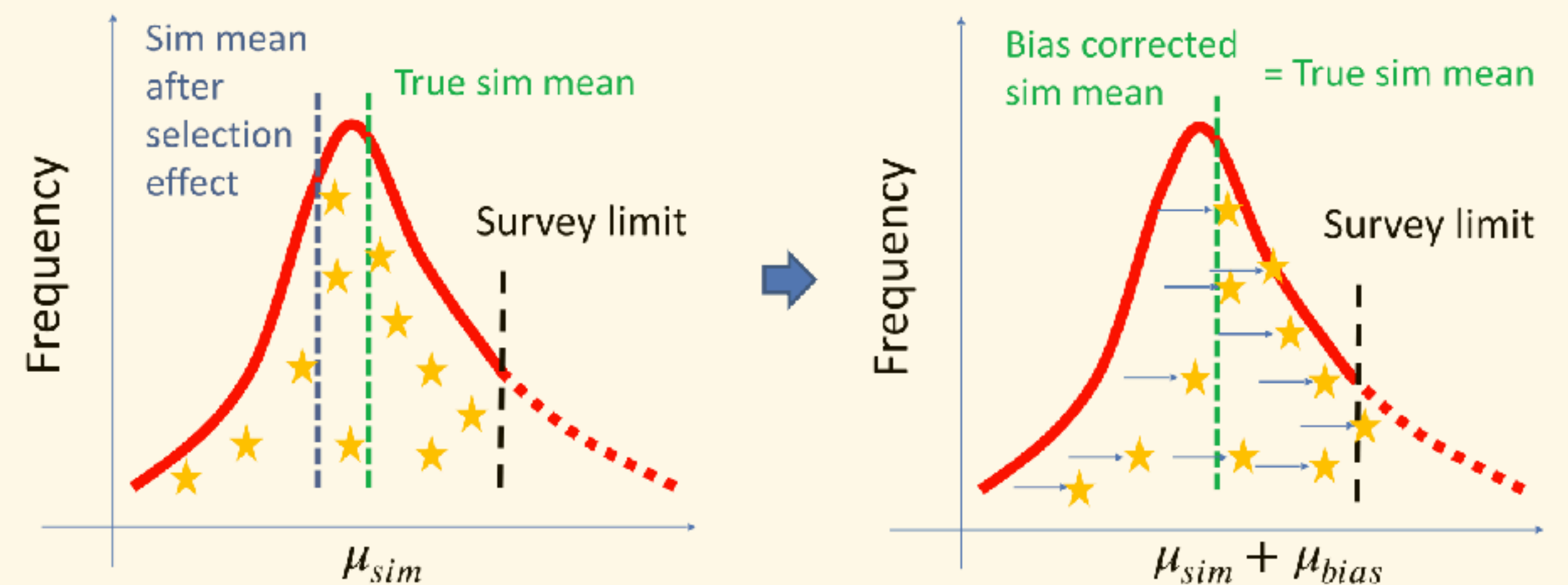
The bias correction

- Correction made to each SN to correct for both Malmquist-like selection effects and astrophysical effects introduced by the flux-limited nature of surveys
- BEAMS (P_{la} , *Kunz+07*) with Bias Corrections (BBC) includes modeling and selection effects
- It is calculated from simulations (*Kessler & Scolnic 2017*).



March+18

$$\Delta\mu_{\text{bias}} = m_x + \alpha^{\text{true}}x_1 - \beta^{\text{true}}c + \gamma^{\text{true}}G_{\text{host}} + \mathcal{M}_B^{\text{true}} - \mu^{\text{true}}$$



Vincenzi+25

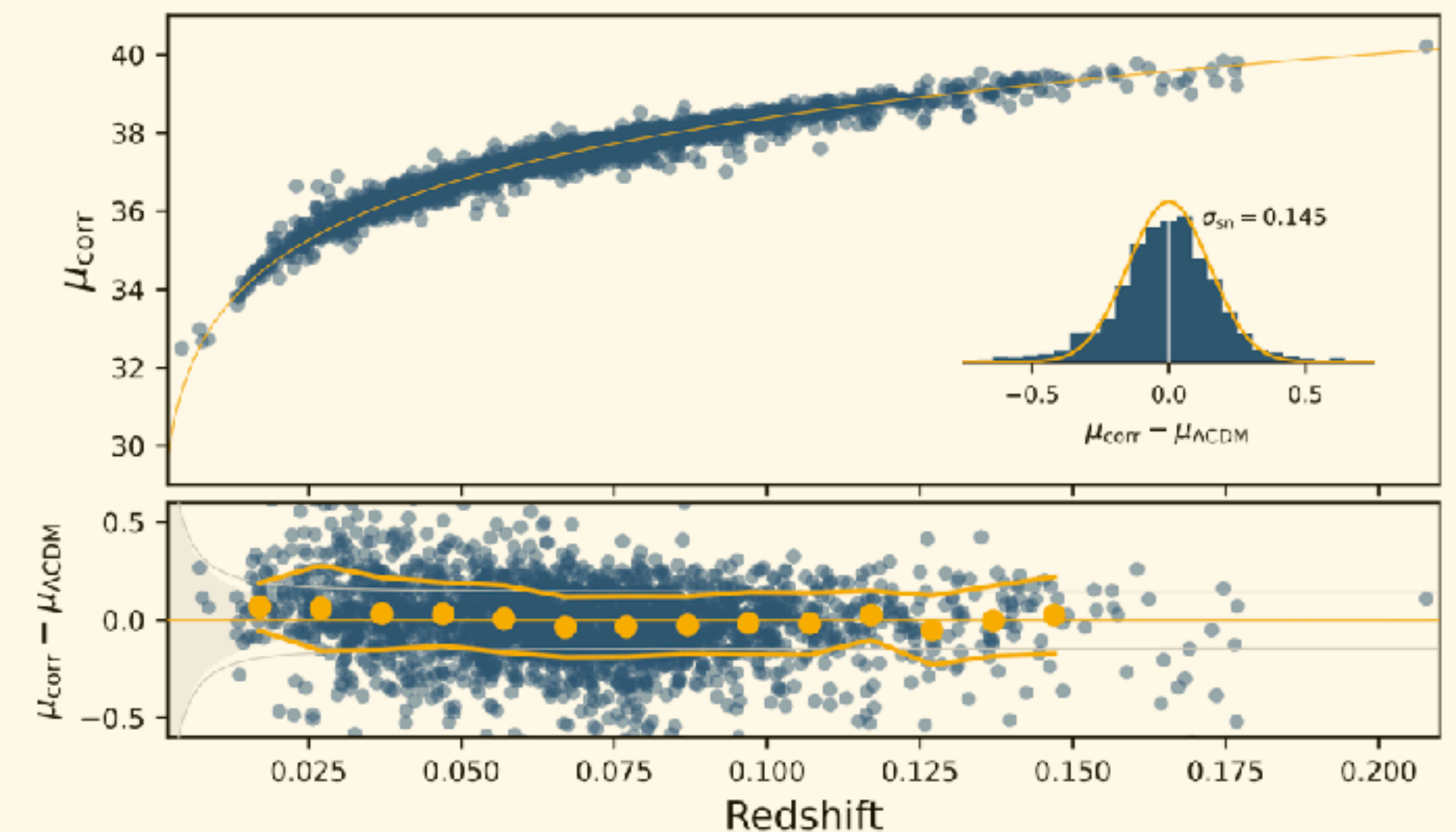
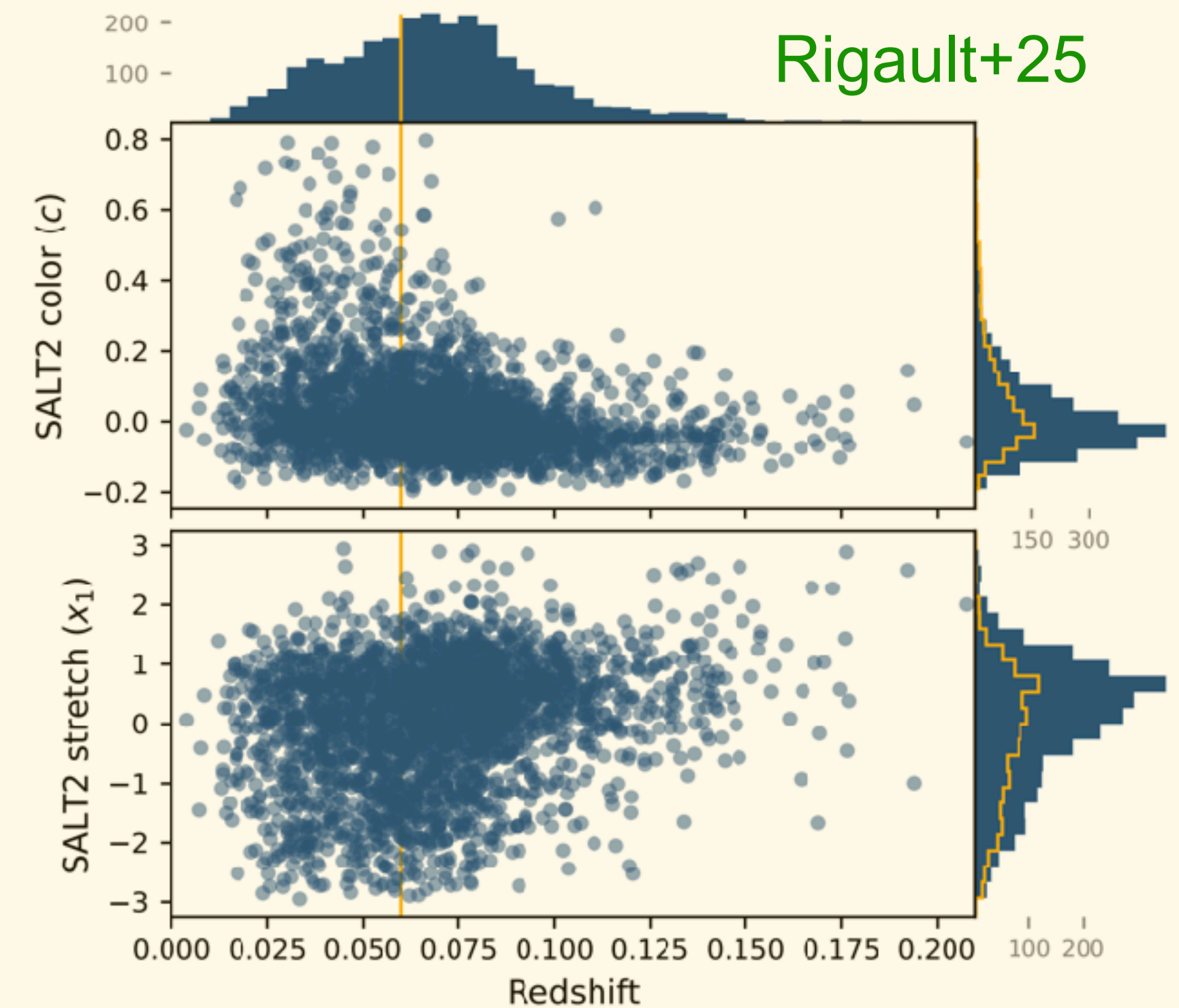
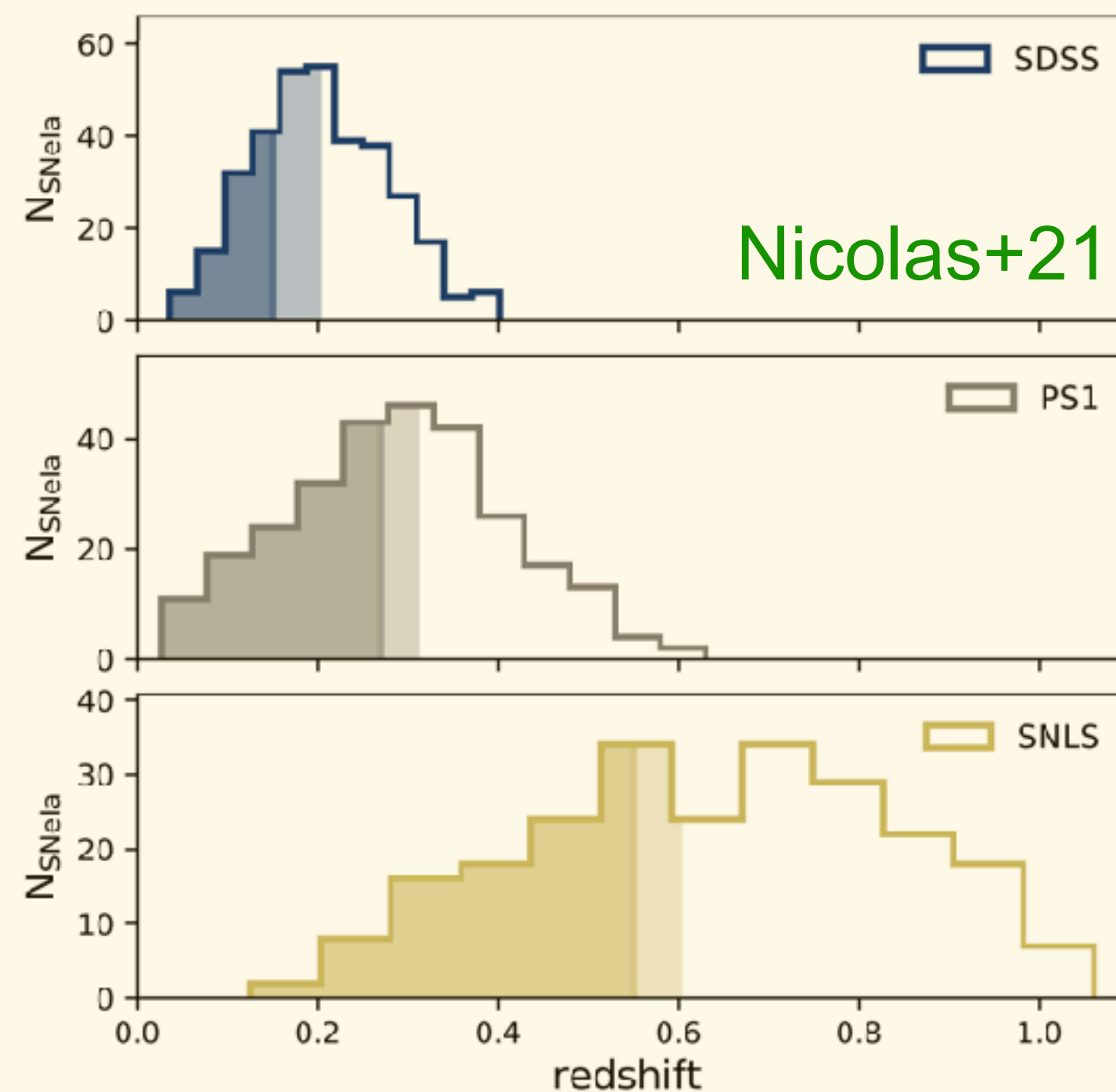
1D (z) - “Malmquist bias”
 4D (z, x_1 , c, M^*)
 5D (z, x_1 , c, α , β)

Alternative: completeness

To avoid bias (selection) corrections, we need samples that include the whole SN population.

Difficult for magnitude-limited surveys

e.g. ZTF: 3627 $\rightarrow$ 2667 $\rightarrow$ 994 ($z < 0.06$)



Implementation: light-curve models

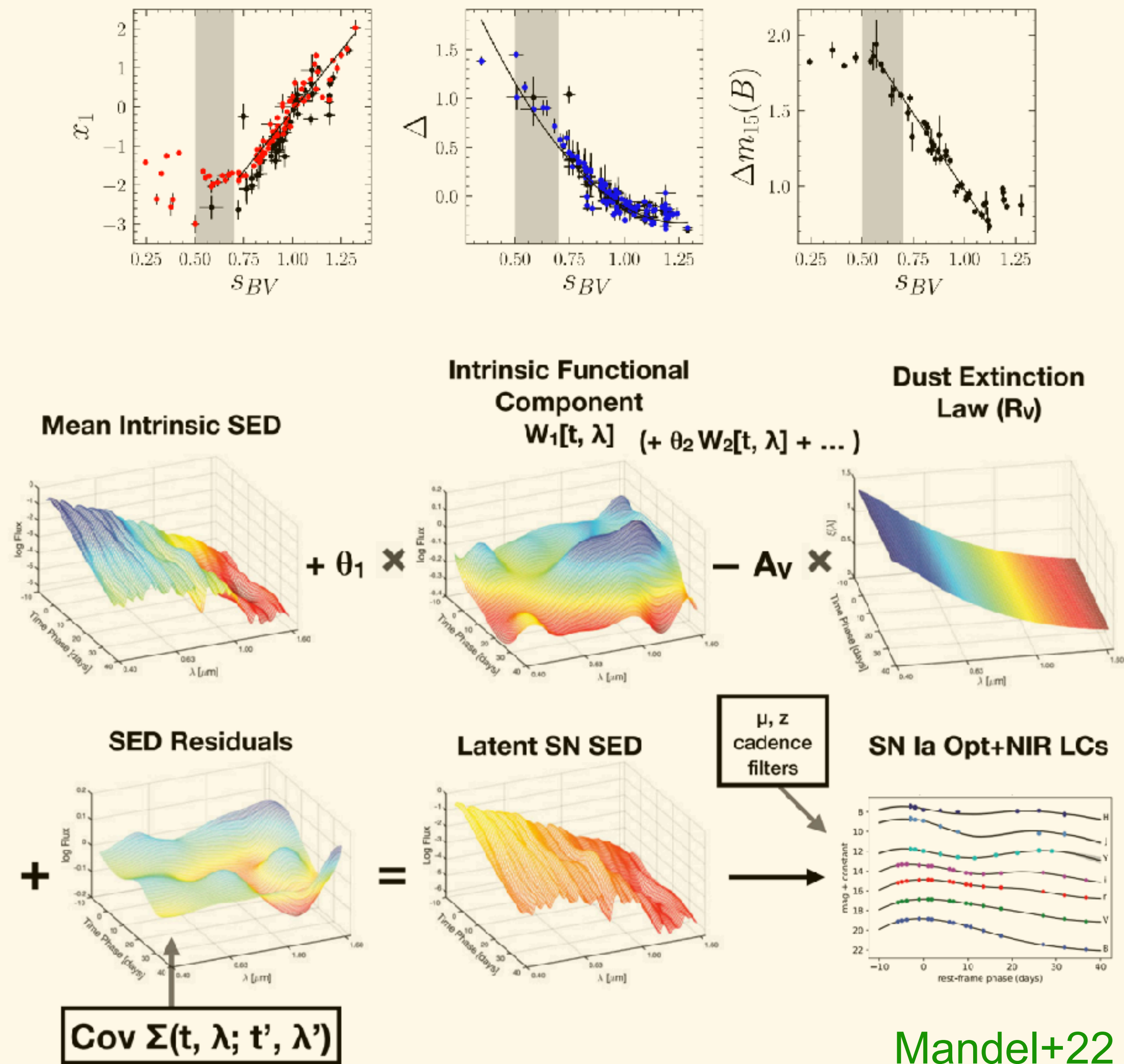
- How are the LC width and color measured?
Three main frameworks, each with its own parameters:

SALT2/SALT3: x_1 , c , m_B
(Guy 2007; Kenworthy 2021; Taylor 2023)

SNooPy — s_{BV} (color stretch), $E(B-V)_{\text{host}}$, R_V
(Burns 2011, 2014)

BayeSN — θ_1 (shape), A_V (host dust), R_V ,
plus intrinsic residual ε and μ .
hierarchical, *physically separates intrinsic from dust* (Mandel 2022; Grayling 2024)

Burns+18

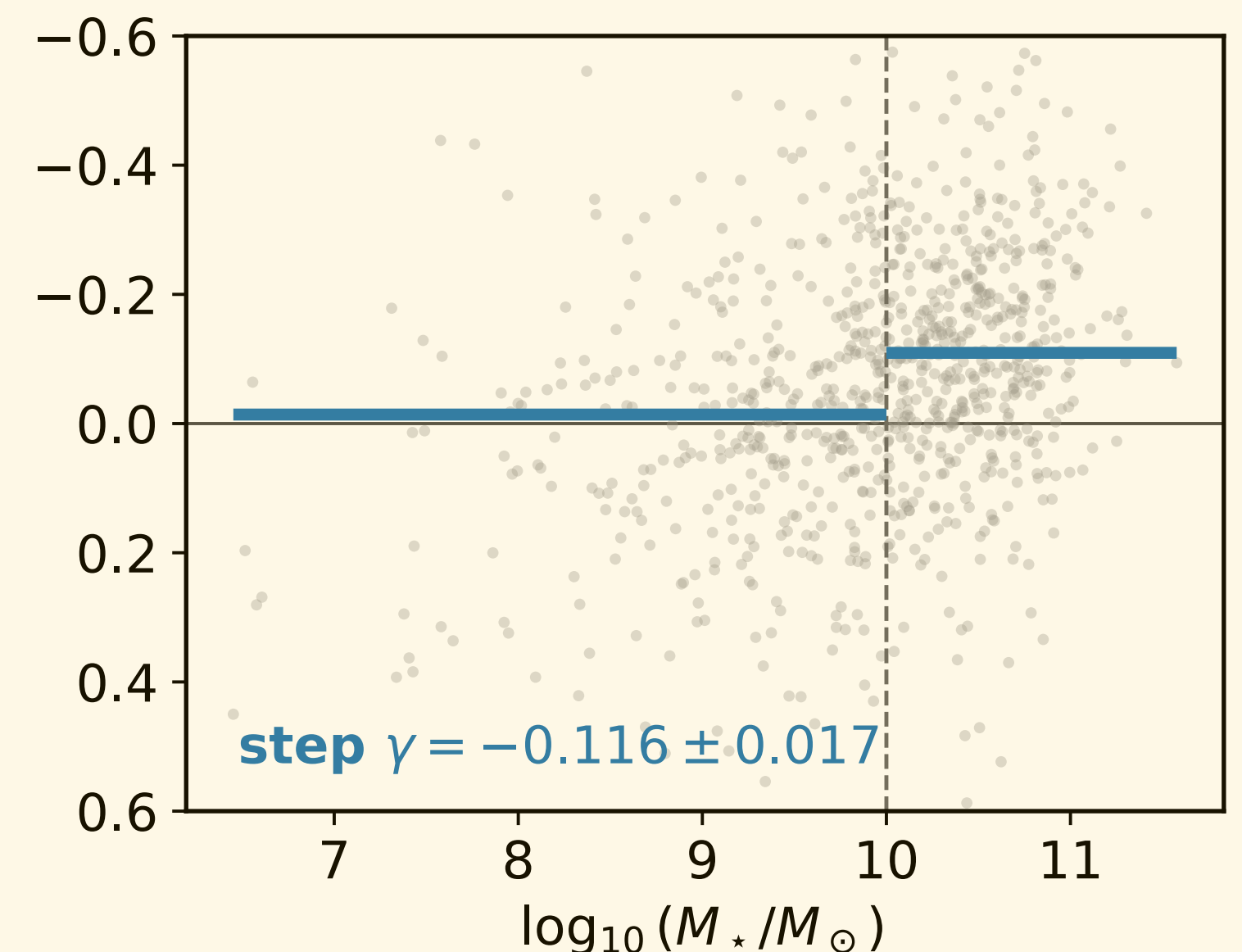
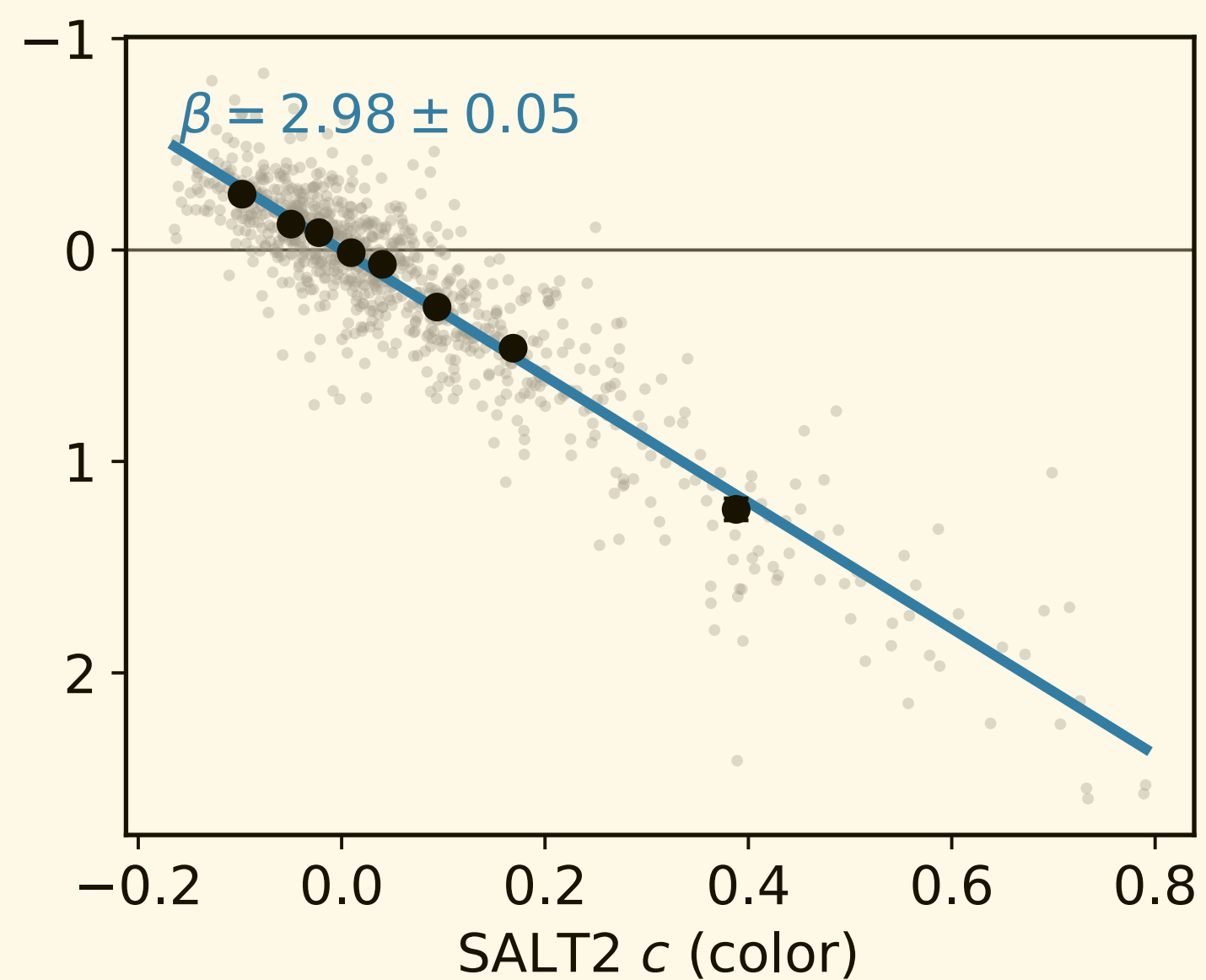
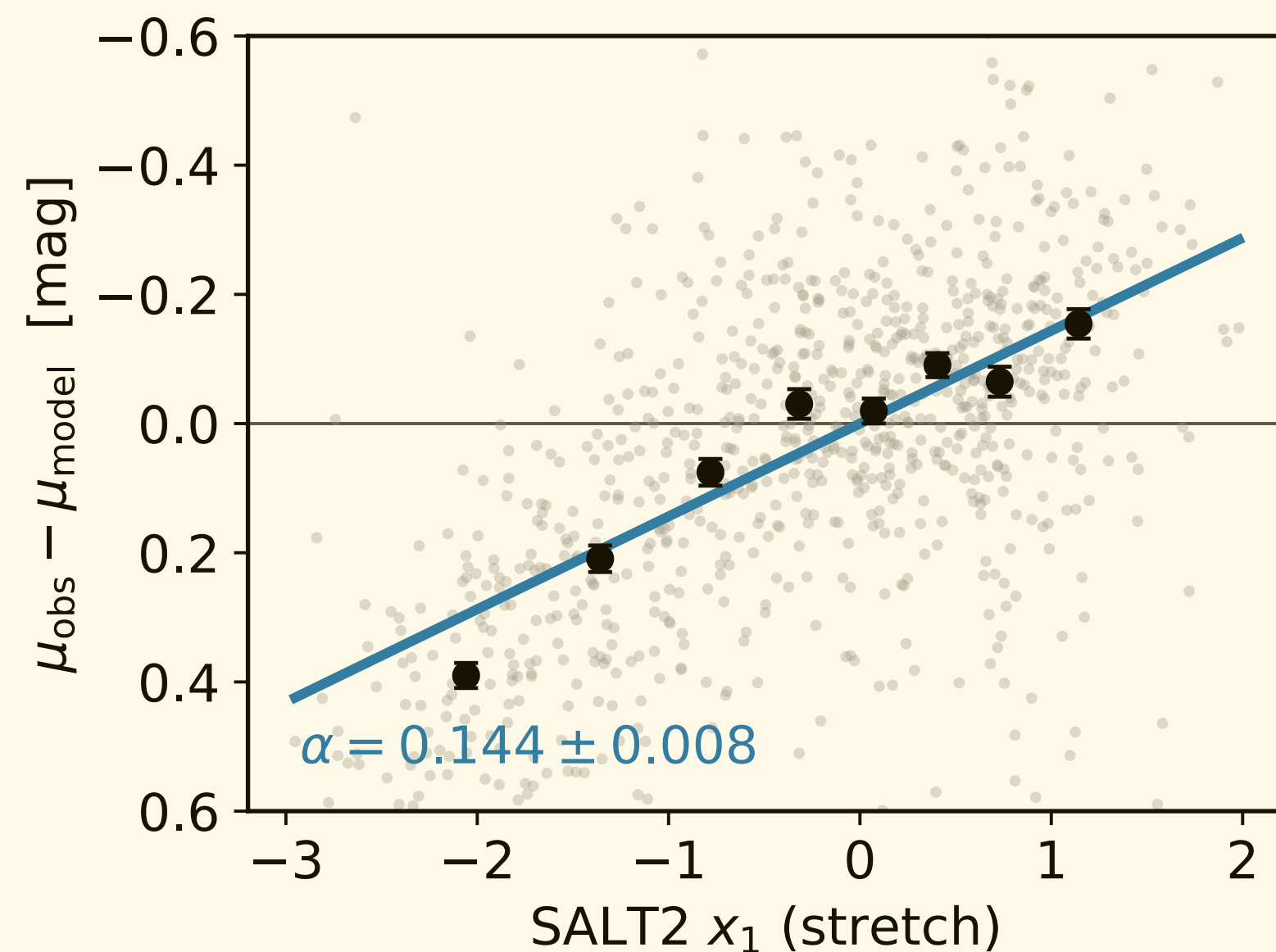


Mandel+22

The Tripp relation and its nuisance parameters

$$\mu = m - M + \alpha x_1 + \beta c + \gamma M_* + \mu_{bias}$$

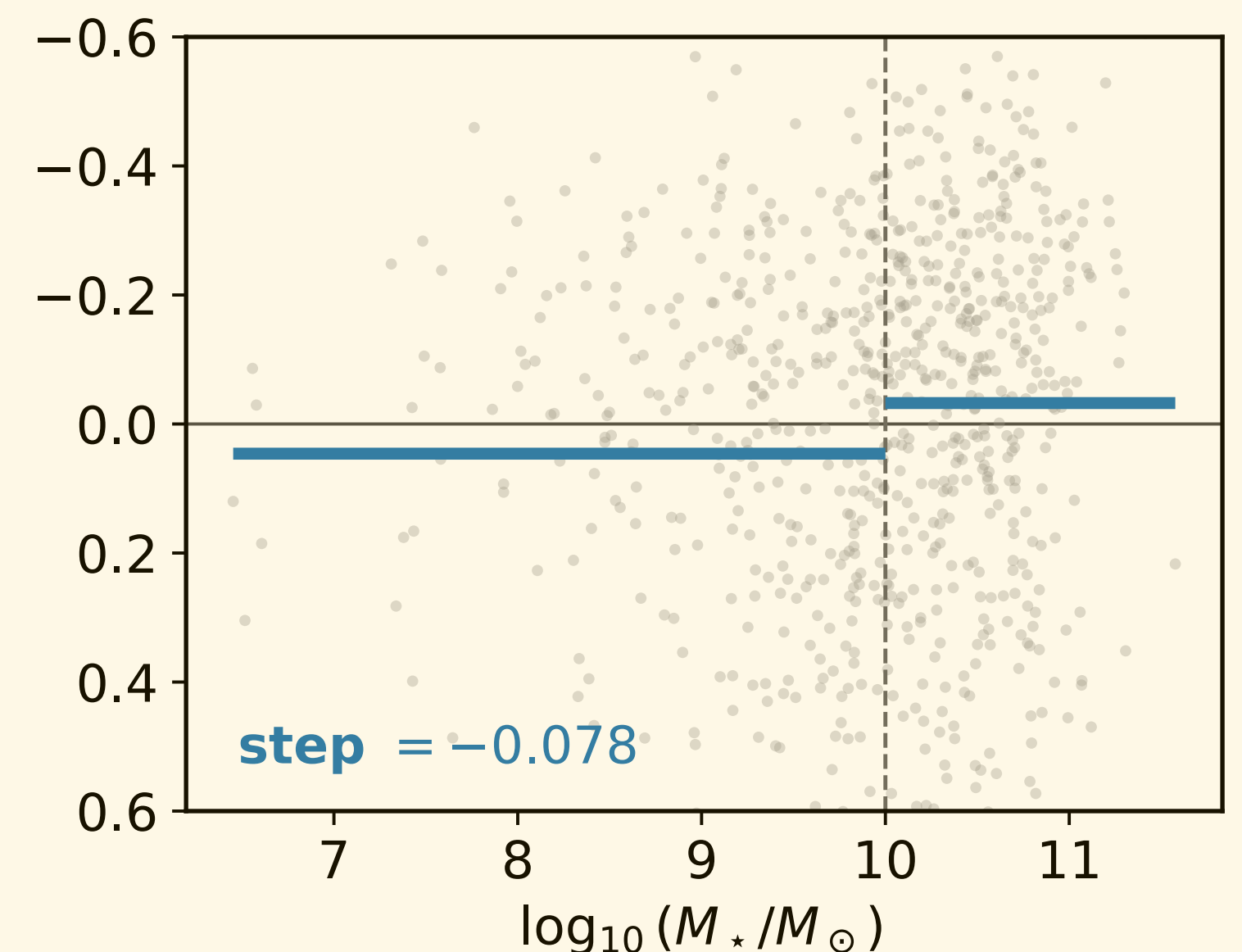
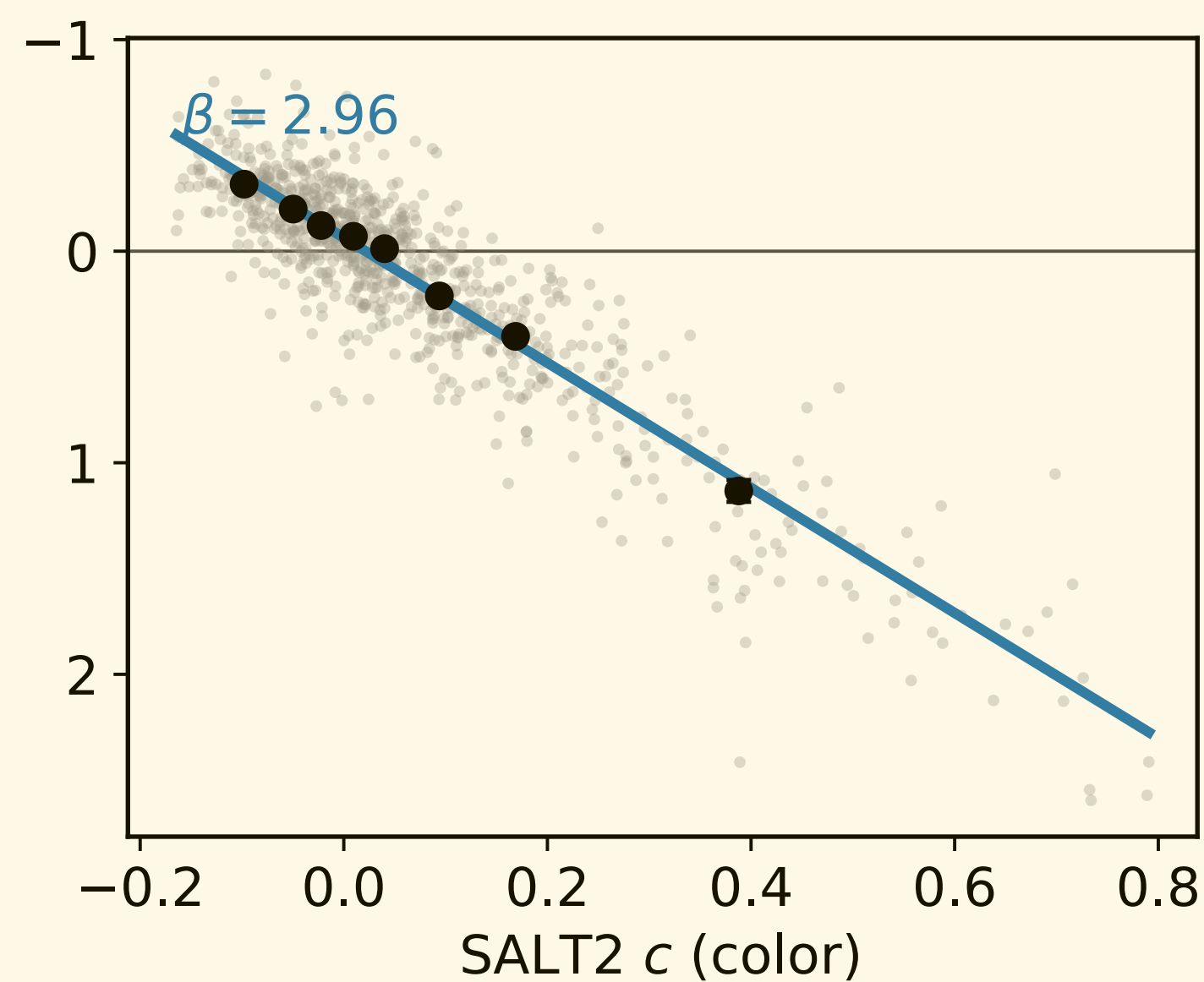
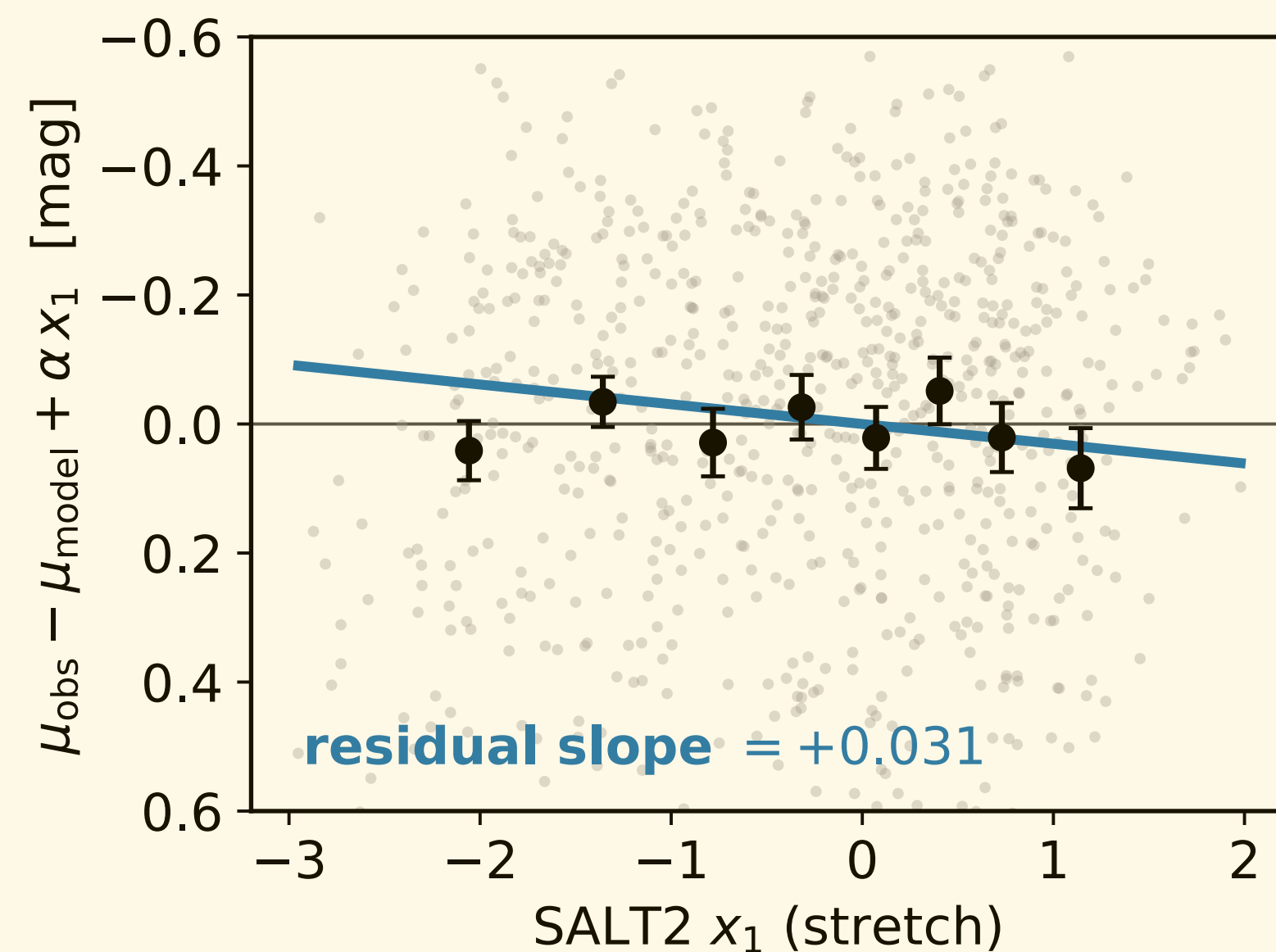
- The nuisance parameters α (width–luminosity), β (color–luminosity), γ (mass/environment step), M and the intrinsic scatter σ_{int} are fit globally



The Tripp relation and its nuisance parameters

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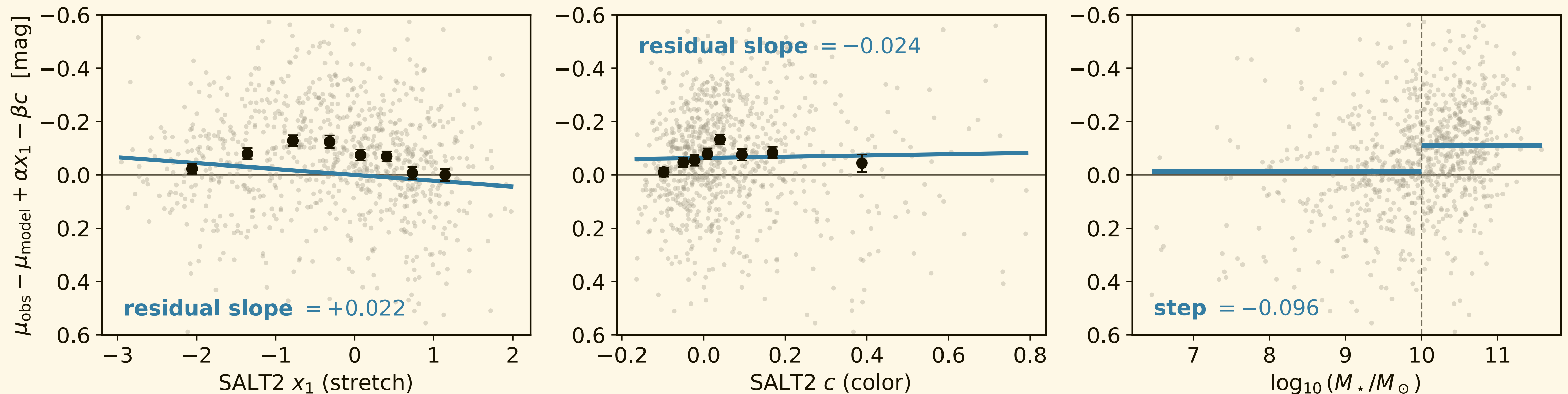
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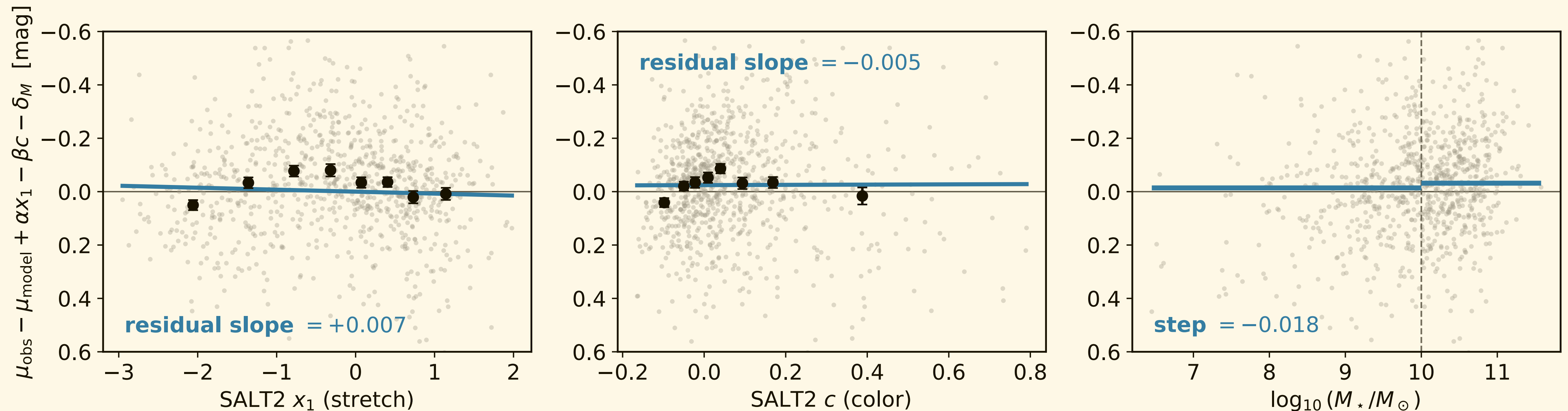
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ZTF DR2, $0.02 < z < 0.06$; Galbany+ip

Beyond linear: broken- α and subpopulations

- Tripp assumes **linear** + **universal** $\alpha, \beta \rightarrow$ both break
- **Non-linearity:** the stretch–lum. relation seems to be non-linear (broken- α)

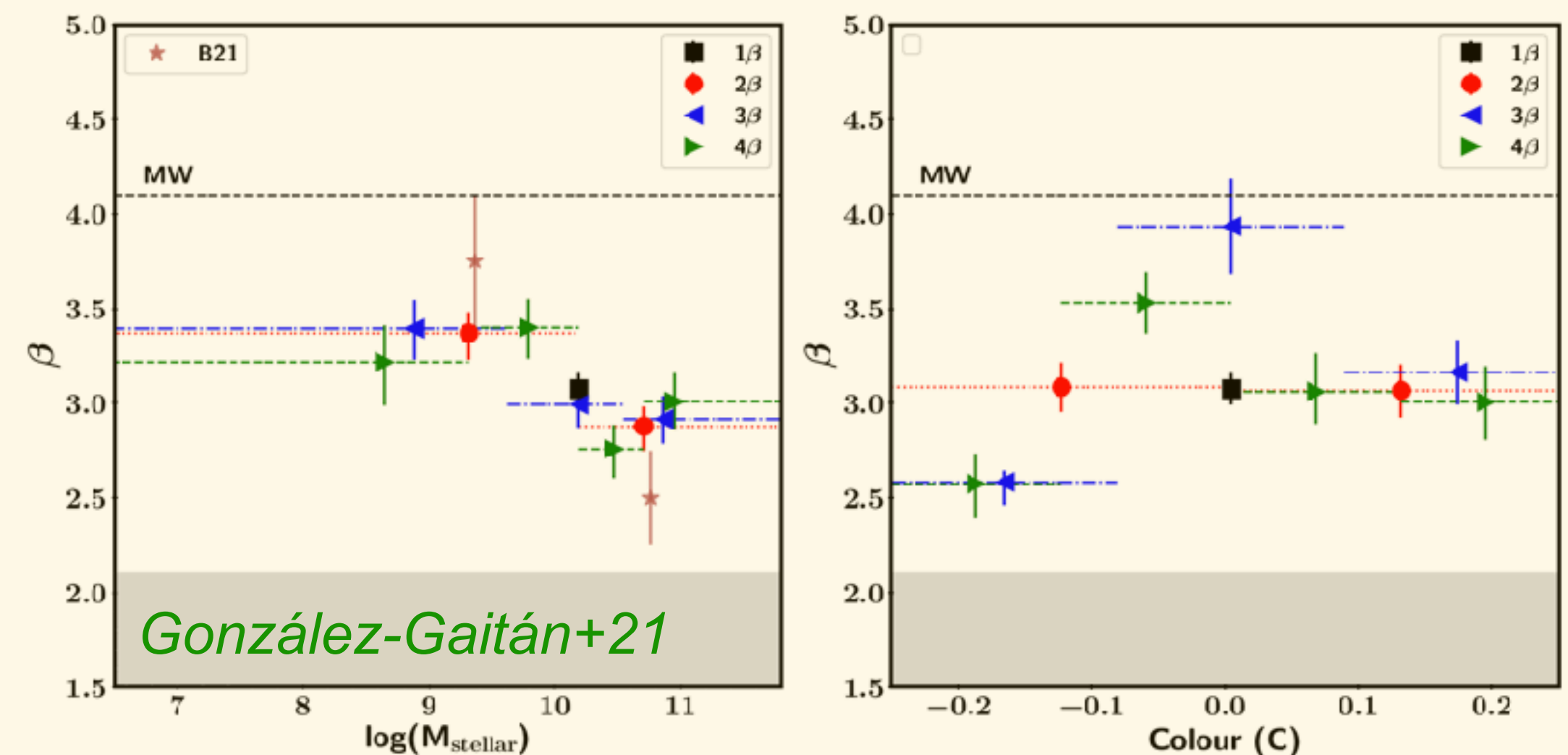
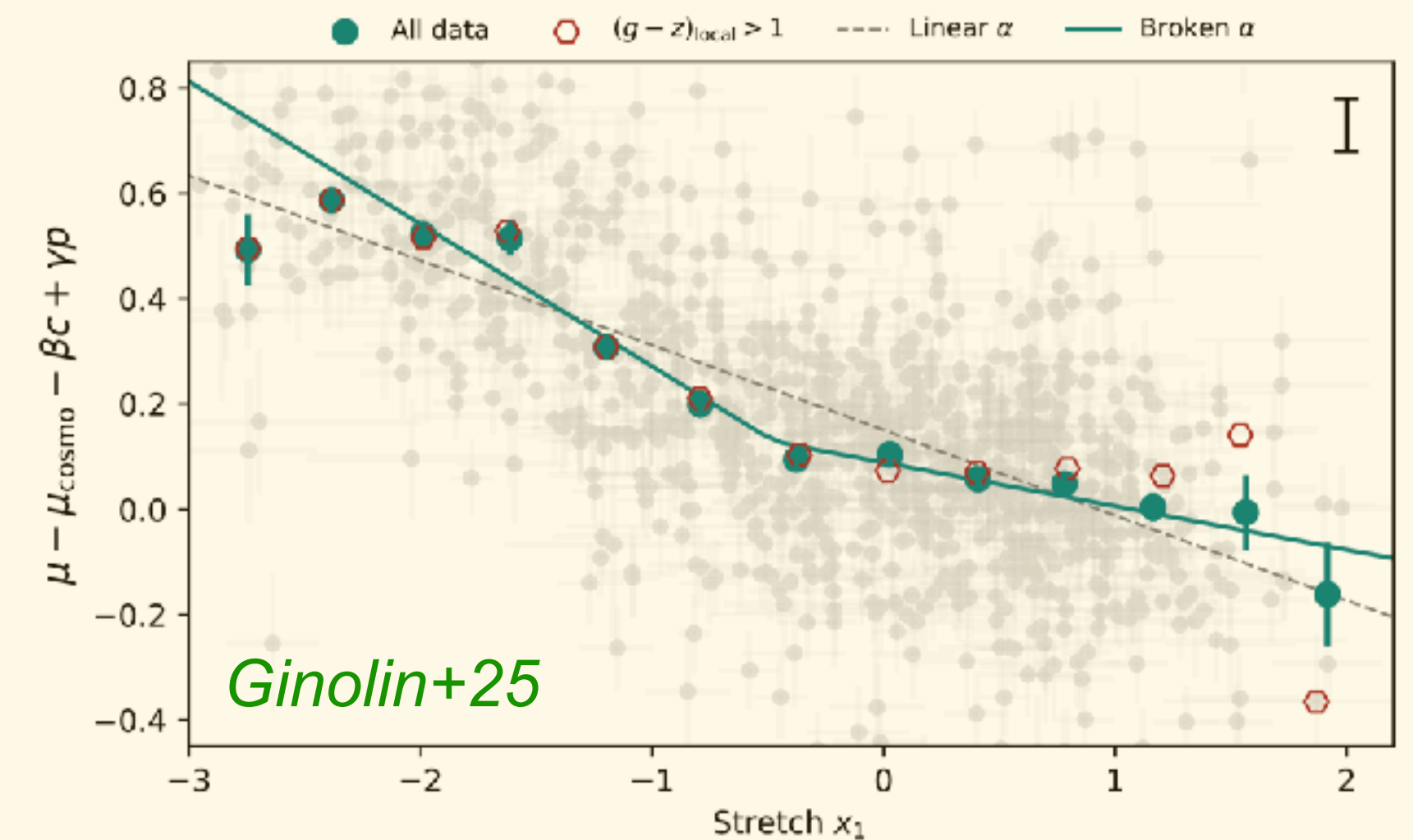
ZTF DR2 (Ginolin+25), also seen in Larison+24 (clusters/field) and Garnavich+23 (calibrators/HF)

- **Non-universality:** α, β and intrinsic properties depend on environment (subpopulations)

β varies with mass and color (β -step) explainable by different R_V or two intrinsic-color populations (González-Gaitán+21).

The mass step is largely **dust**: the R_V distribution differs with host mass, making β effectively host-dependent (Brout+21).

But **not all of it is dust**: hierarchical BayeSN finds an intrinsic mass step beyond R_V (Grayling+24; Thorp+22).



From standardized μ to cosmology

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

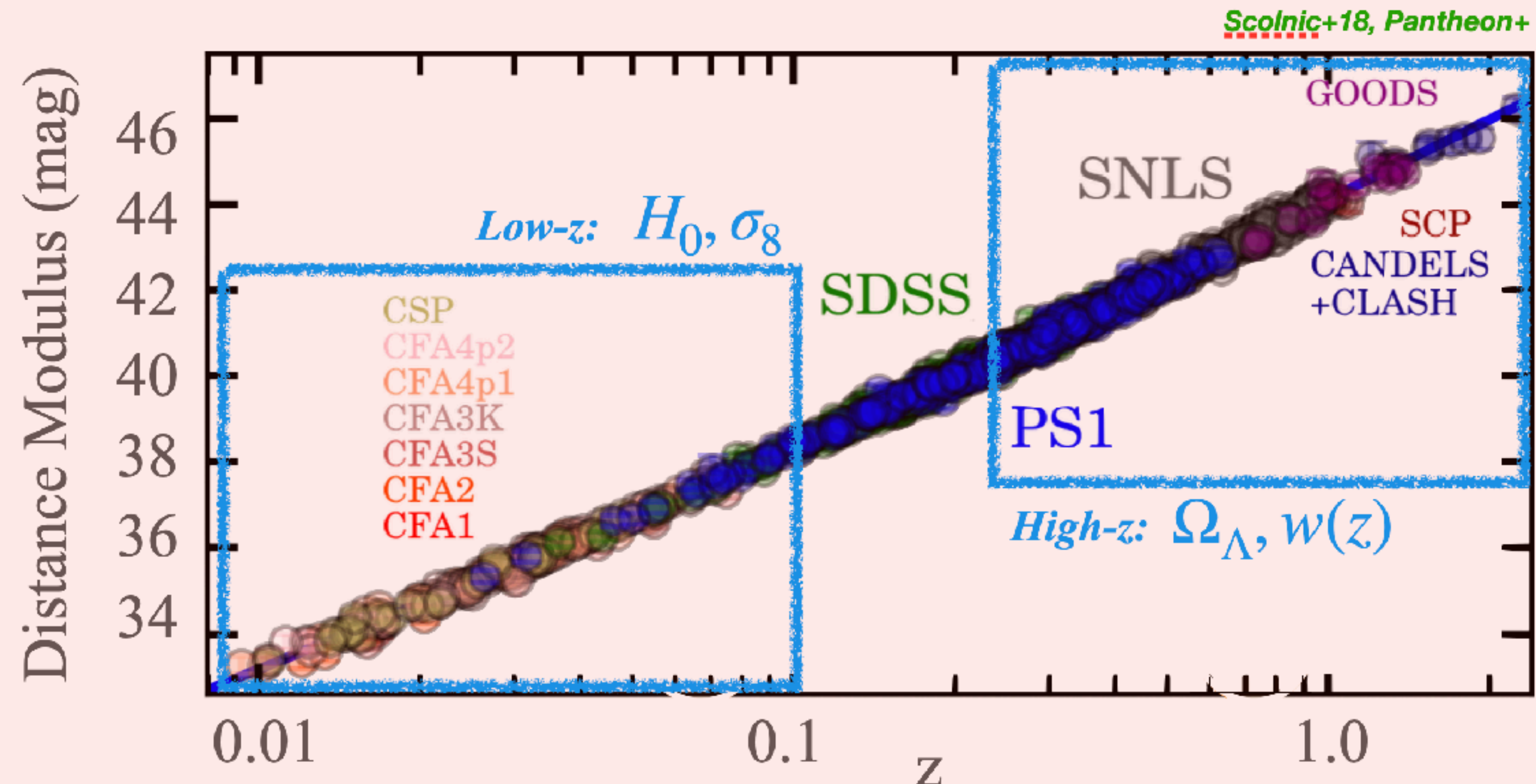
With standardized μ_{SN} , we compare to $\mu(z)_{\text{model}} = 5 \log_{10}(d_L/10\text{pc})$ to fit cosmology

EXTRAGALACTIC ASTROPHYSICS

SN progenitors
Environment

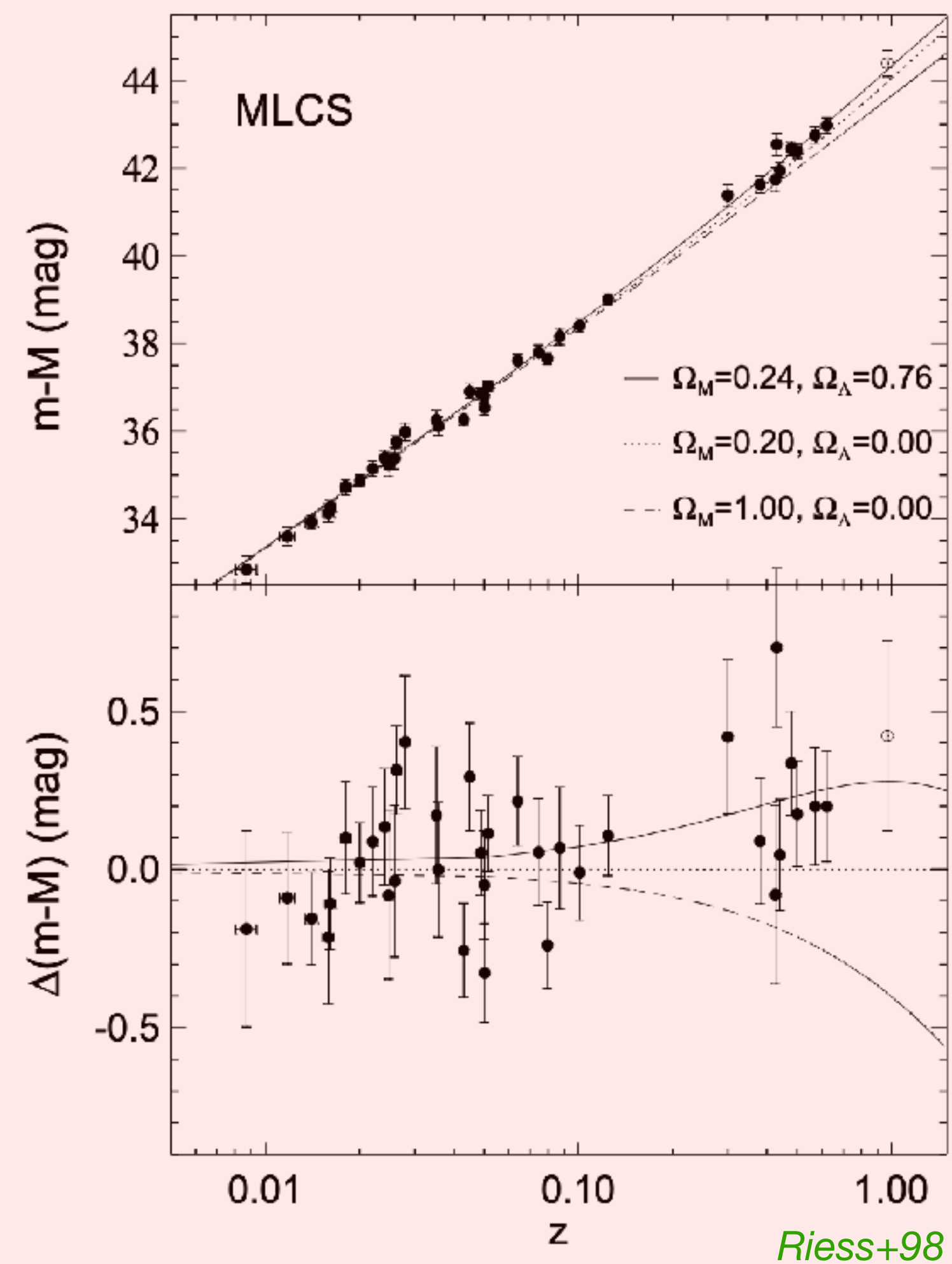
COSMOLOGY

$$\mu = m - M + \alpha x_1 + \beta c + \gamma M_* + \mu_{\text{bias}}$$

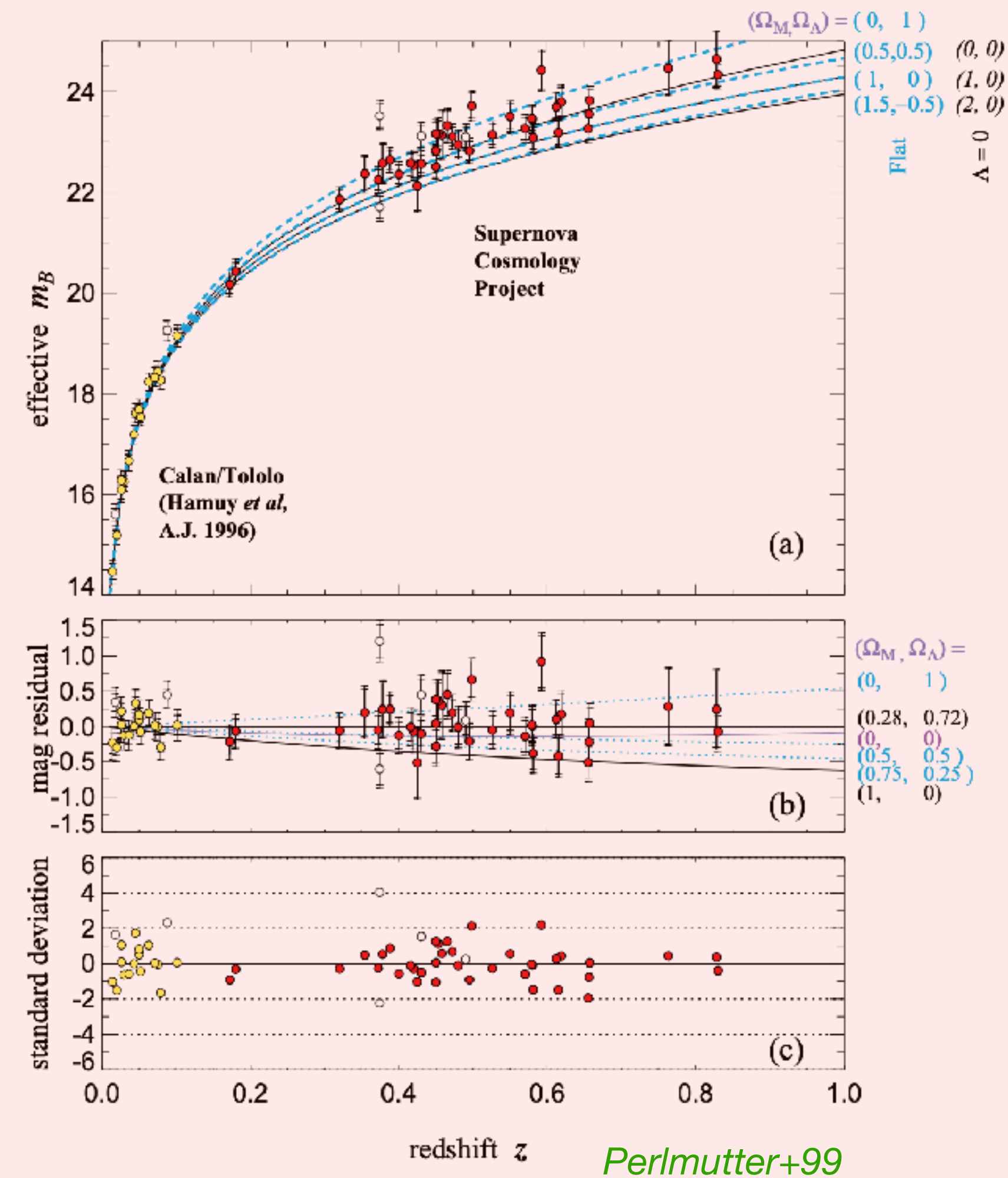


Ω_Λ : the discovery of DE

High-z SN Search

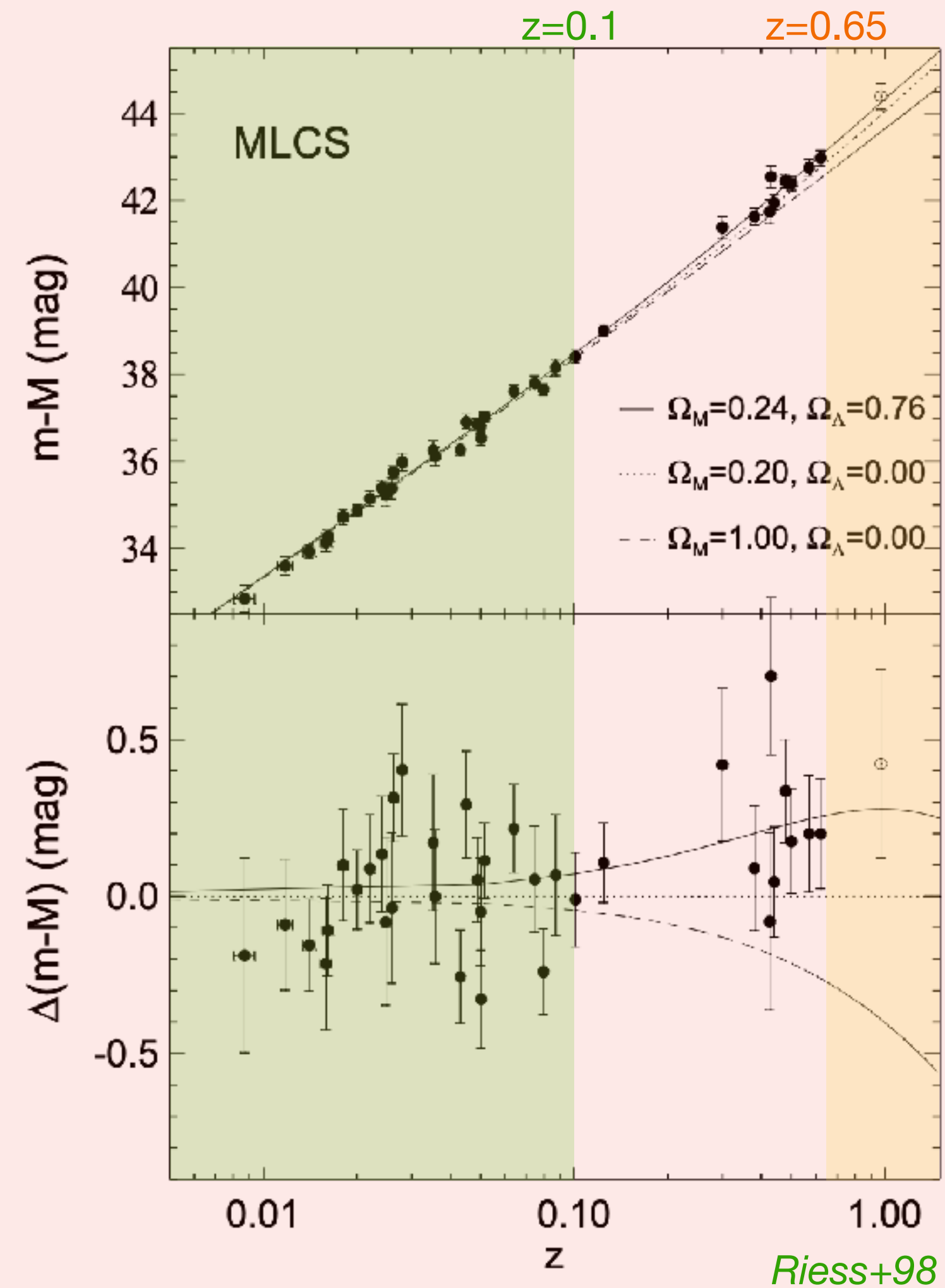


SN Cosmology Project



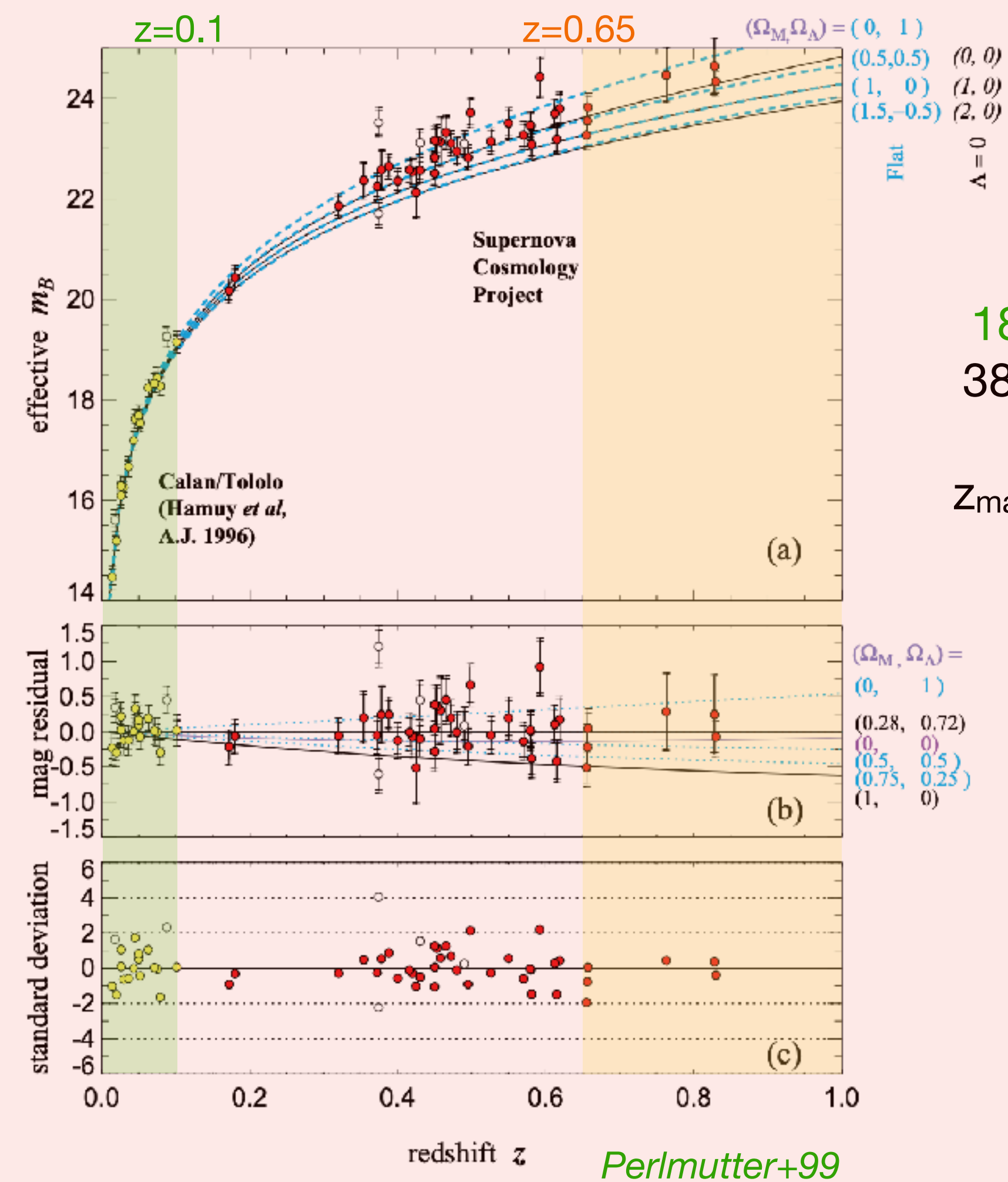
Ω_{Λ} : the discovery of DE

High-z SN Search



28 low-z
9 high-z
 $Z_{\text{max}} \sim 1.0$

SN Cosmology Project



18 low-z
38 high-z
 $Z_{\text{max}} \sim 0.85$

The rolling-survey era (SDSS, SNLS, PS1... P+)

- Dedicated multi-season surveys built statistically powerful, well-calibrated samples at intermediate z across *the redshift desert*.

SNLS ($0.3 < z < 1$)

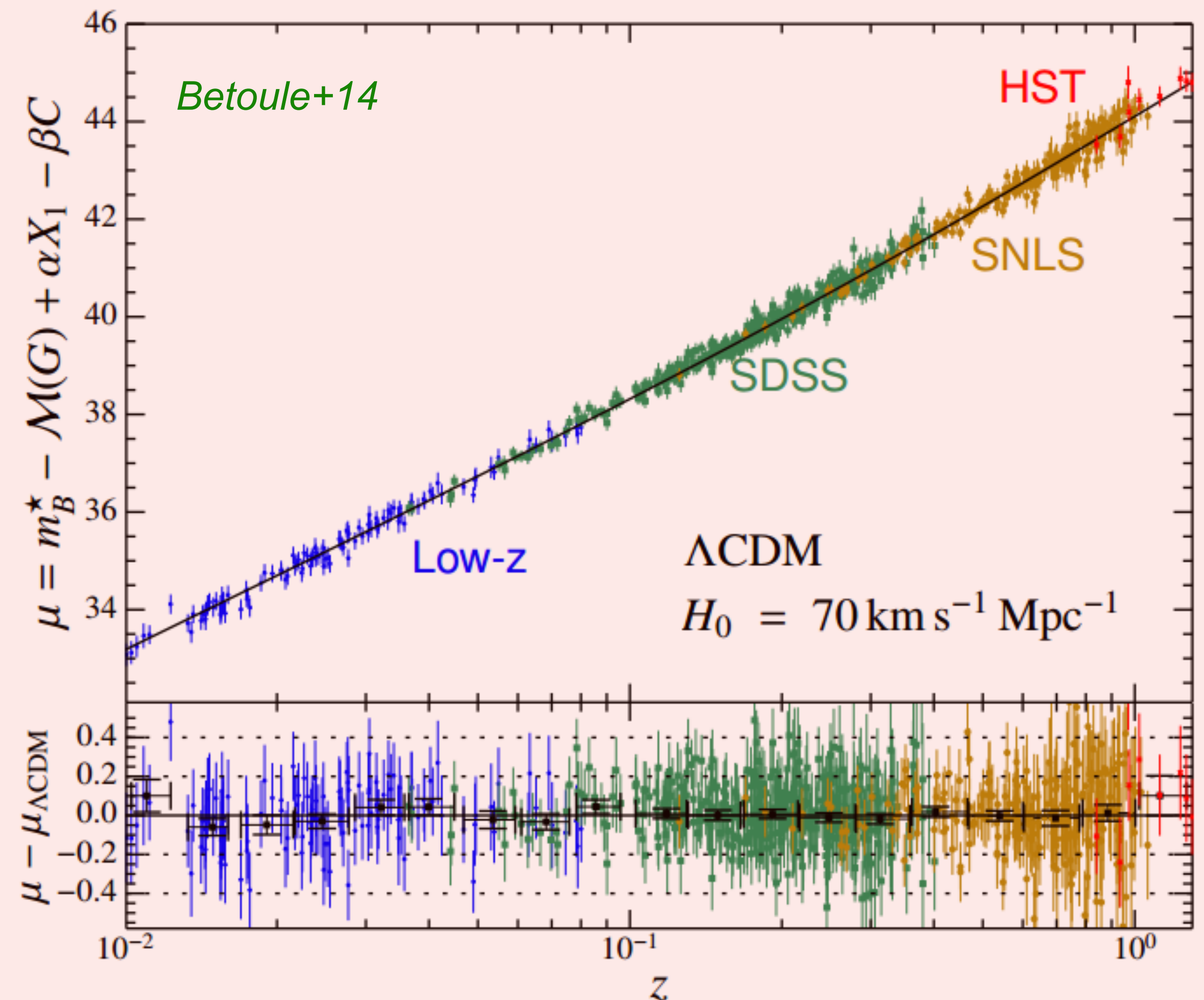
SDSS-II ($0.1 < z < 0.4$)

PS1 ($0.03 < z < 0.65$)

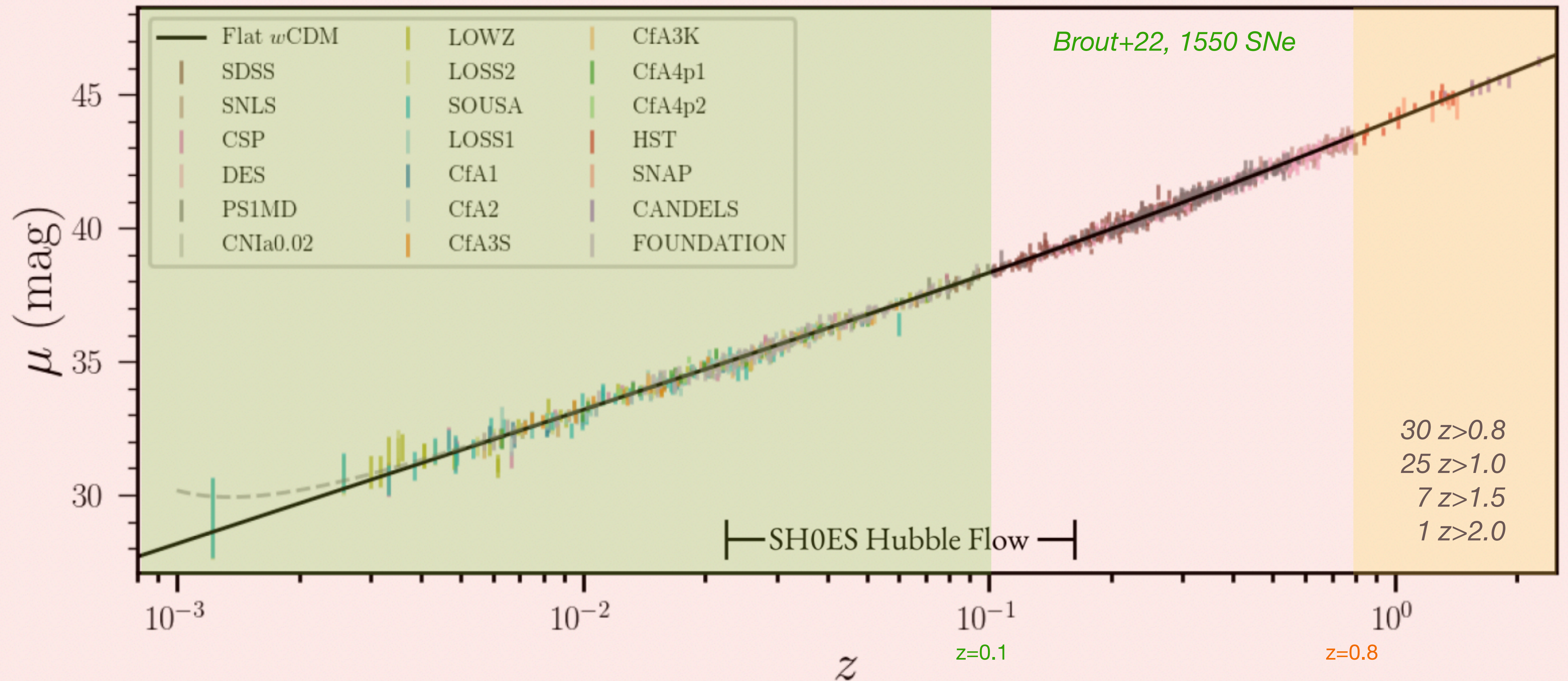
Shift from tens to hundreds of SNe with homogeneous photometry

- Pantheon** combined many past samples onto a common photometric system (cross-calibration supercalifragilistic).

Pantheon (2018) → Pantheon+ (2022),
~1550 SNe over $0.001 < z < 2.3$



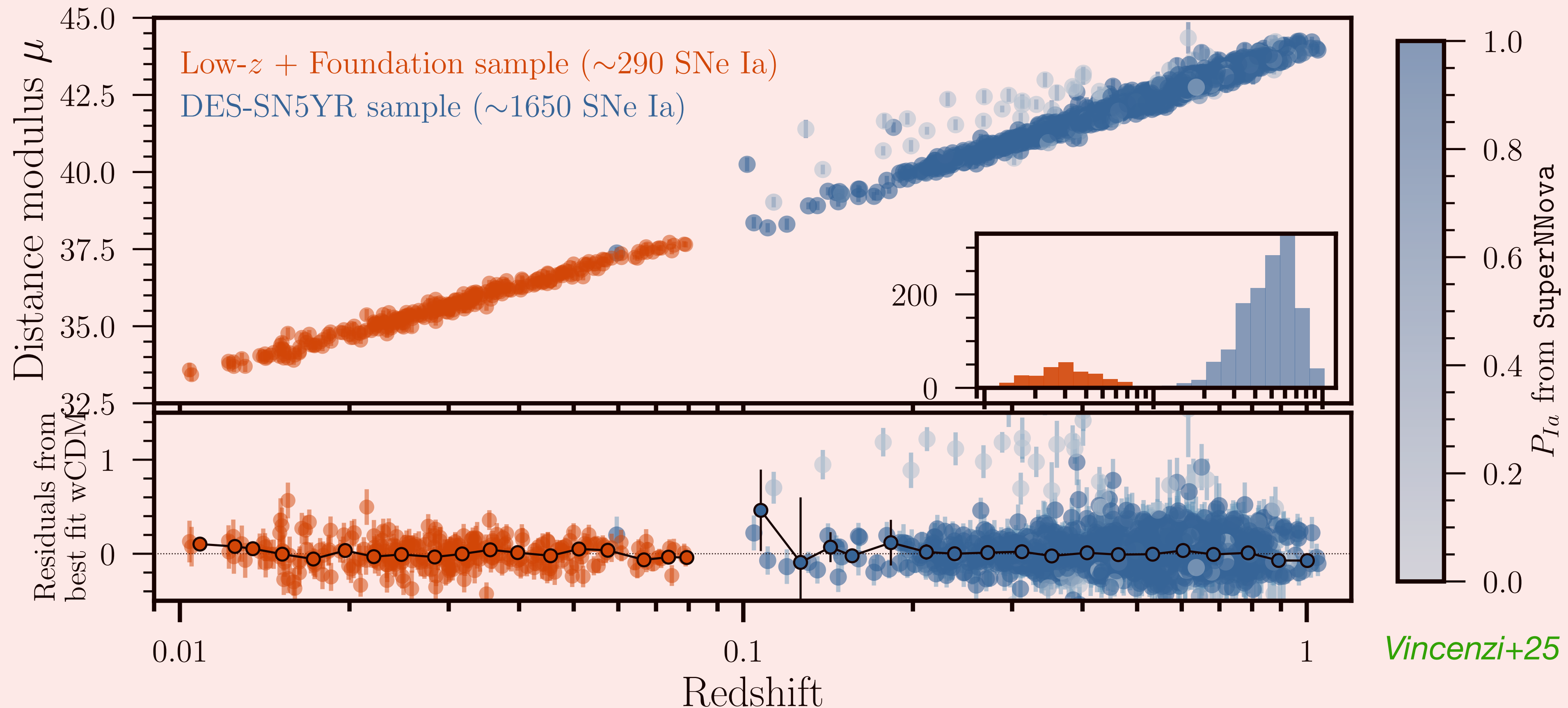
The rolling-survey era (SDSS, SNLS, PS1... P+)



DES: one instrument, external low-z anchor

- To overcome cross-calibration systematics, DES used a single, homogeneously-calibrated instrument (DECam) to observe ~ 1600 SNe to $z \sim 1.1$

Anchored by an external spec-low-z sample. DES high-z is photometrically selected.

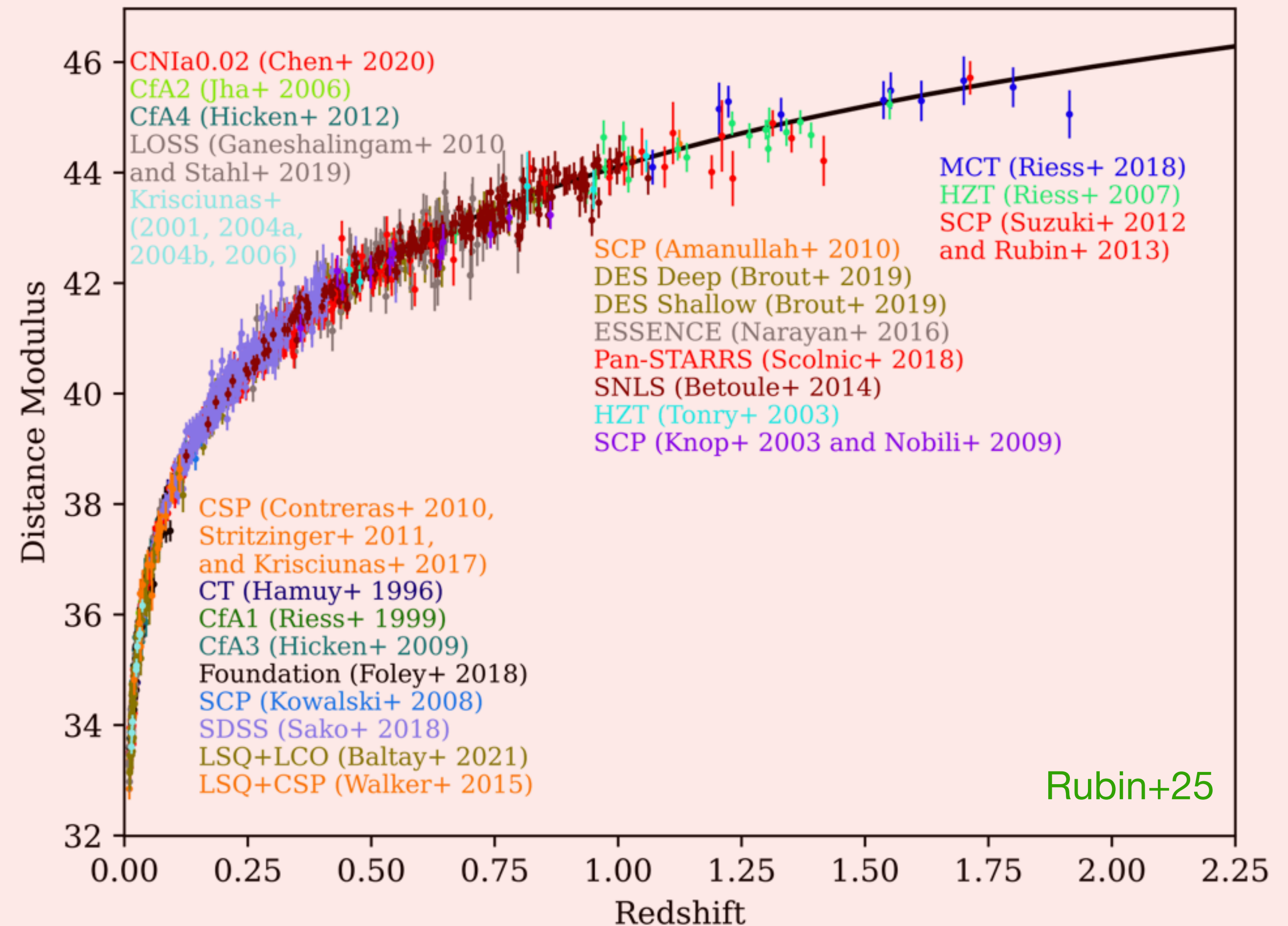


Union3: same data, different analysis

- Similarly to P+, Union3 uses a largely overlapping compilation (~2087 SNe)

As opposed to P+, Union3 analysis is based on a *Bayesian* framework (UNITY1.5) instead of SALT+BBC

different treatment of selection, outliers, and populations.



Evolving dark energy (DESI)

- Combining DESI BAO + CMB + SNe favors *time-varying* dark energy (w_0w_a CDM) over Λ CDM.

$$w(a) = w_0 + w_a(1 - a)$$

CPL: Chevallier–Polarski–Linder parametrization

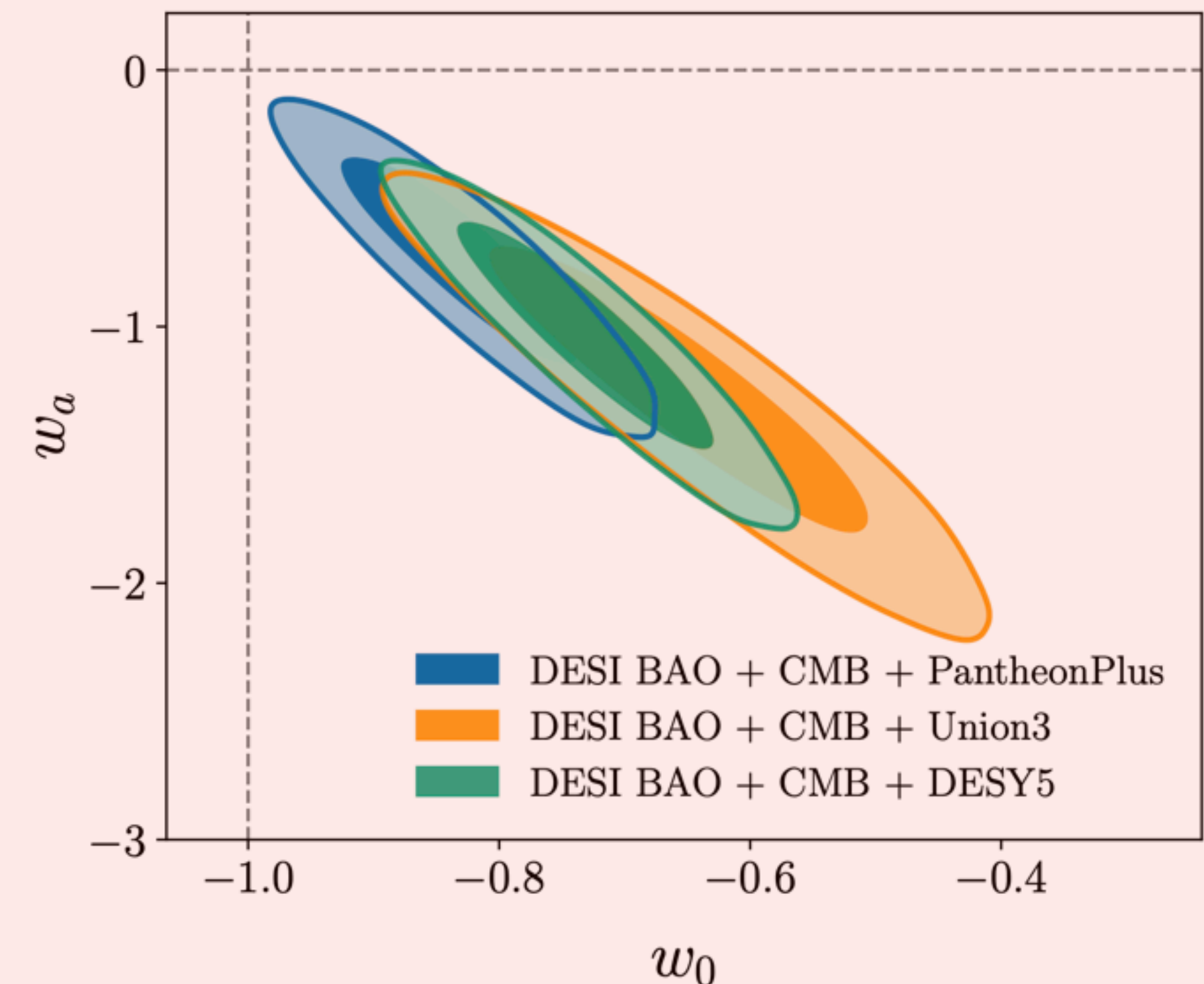
Significance depends on th SN sample used:

Pantheon+ ($2.5\sigma \rightarrow 2.8\sigma$)

DES-SN5YR ($3.9\sigma \rightarrow 4.2\sigma$)

Union3 ($3.5\sigma \rightarrow 3.8\sigma$)

DESI+24 (DR1)



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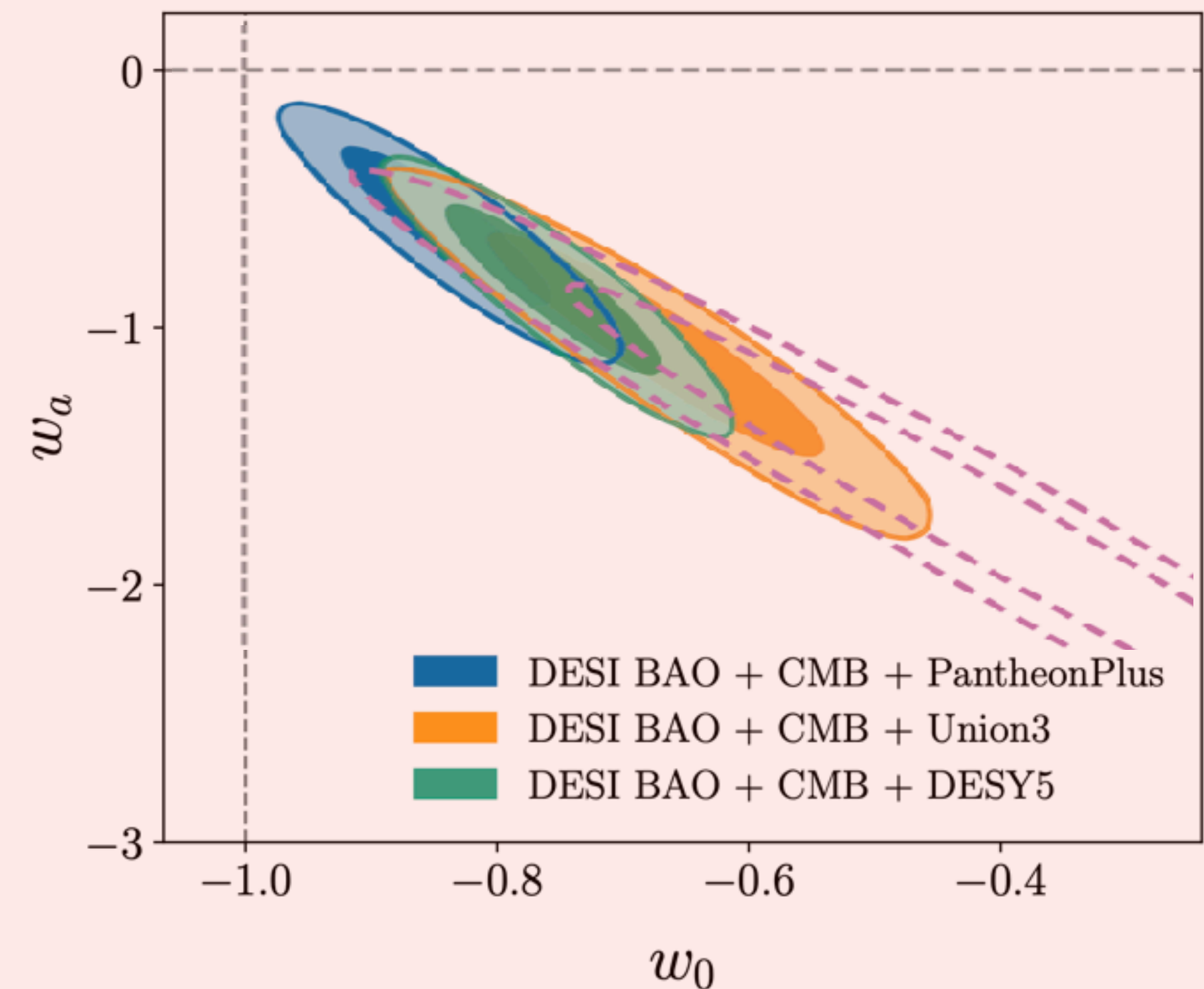
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DESI+25 (DR2)



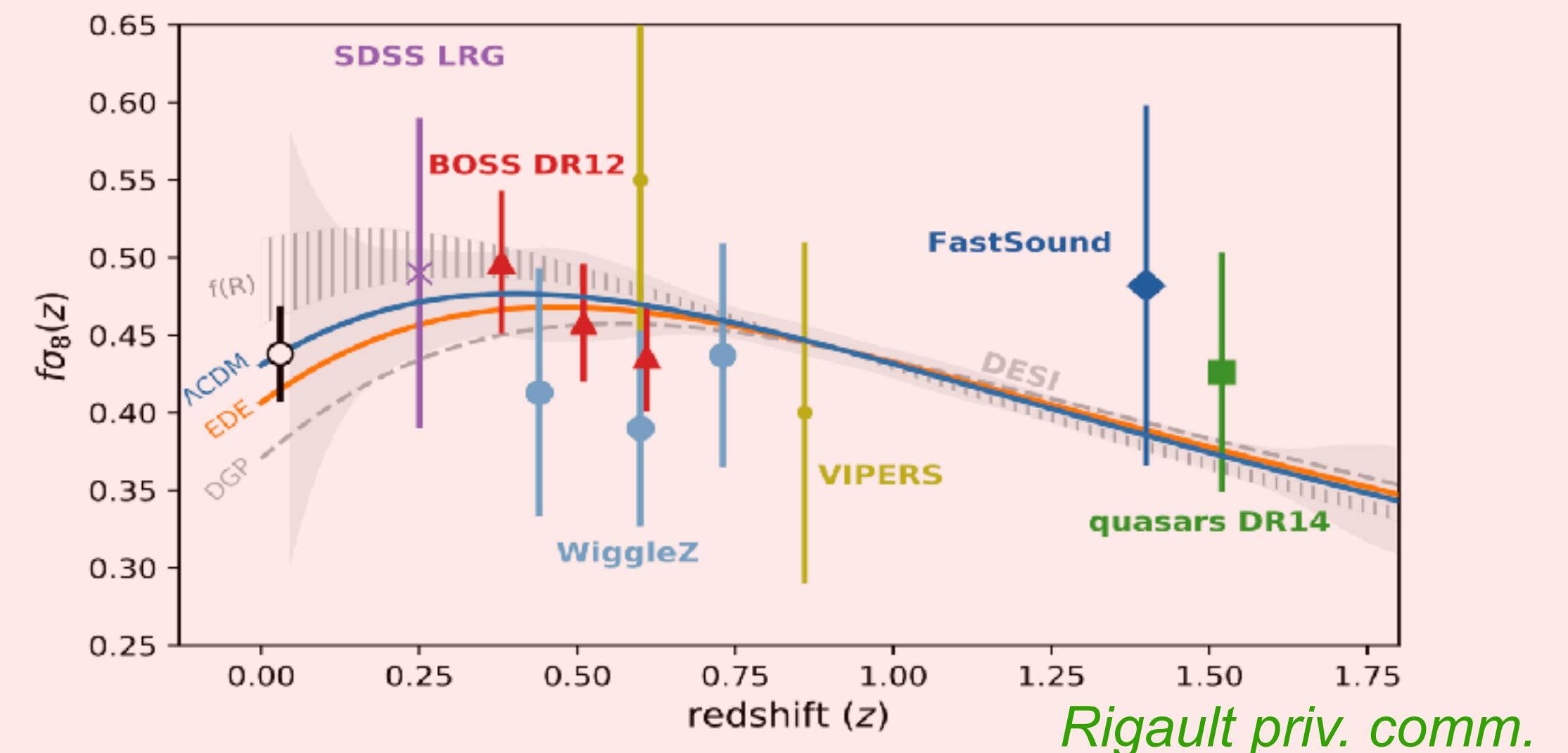
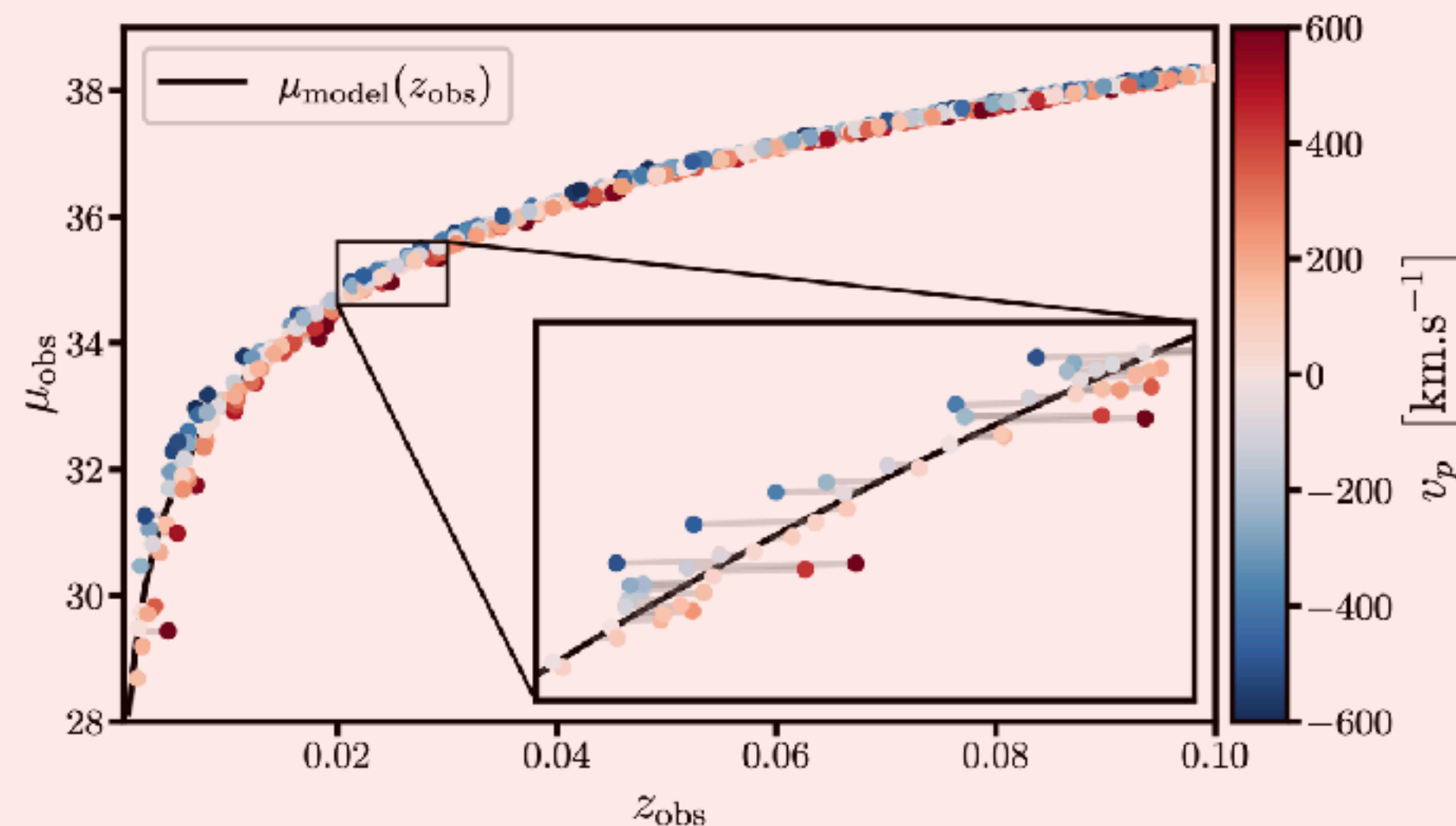
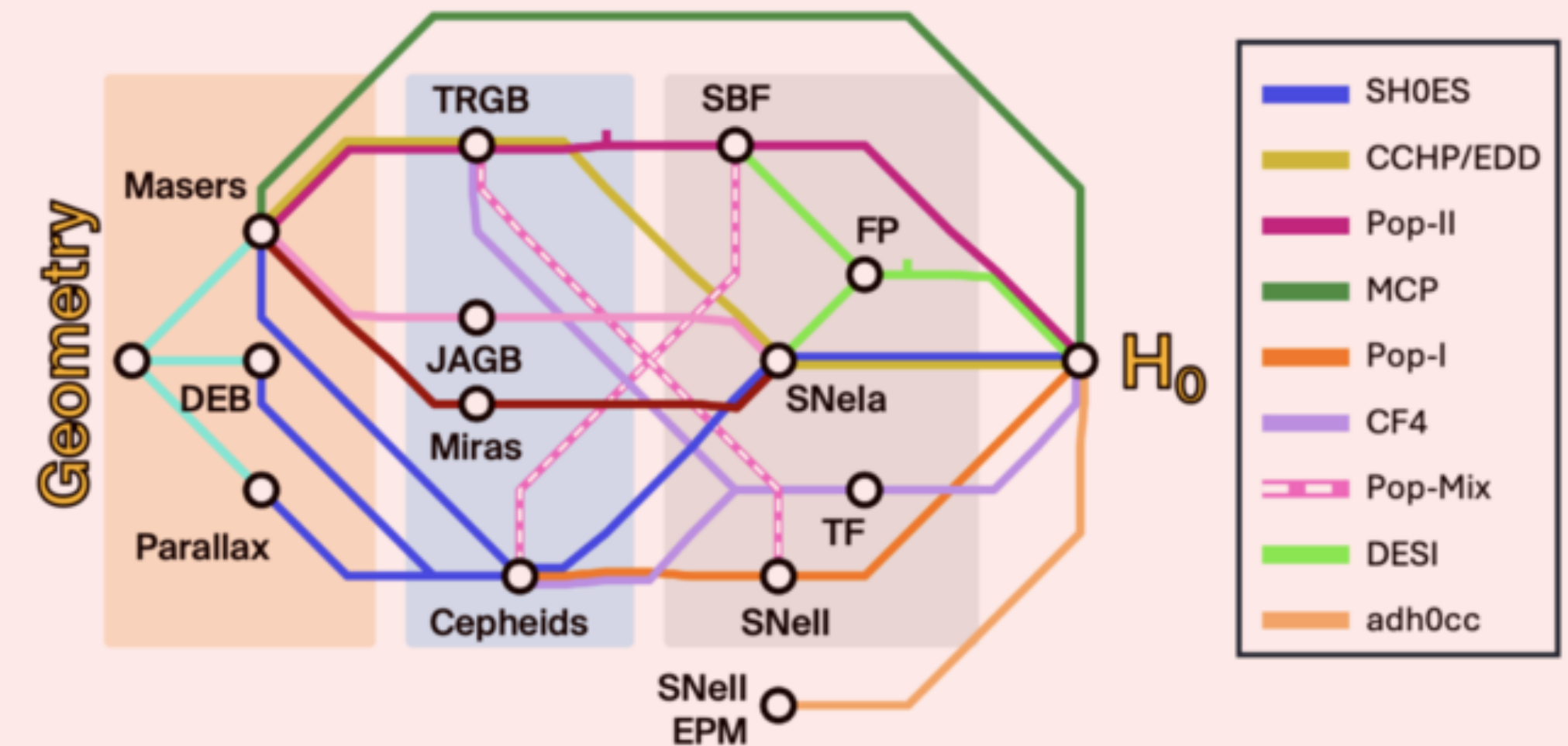
Beyond w : low- z uses (H_0 and growth)

SN distances aren't only for high- z Ω_Λ and w .

Two low- z applications:

(1) combined with objects with **calibrated distances** (Cph/TRGB), they set the local H_0

(2) their **peculiar velocities** trace the growth of structure constraining $f\sigma_8$ independent of the CMB

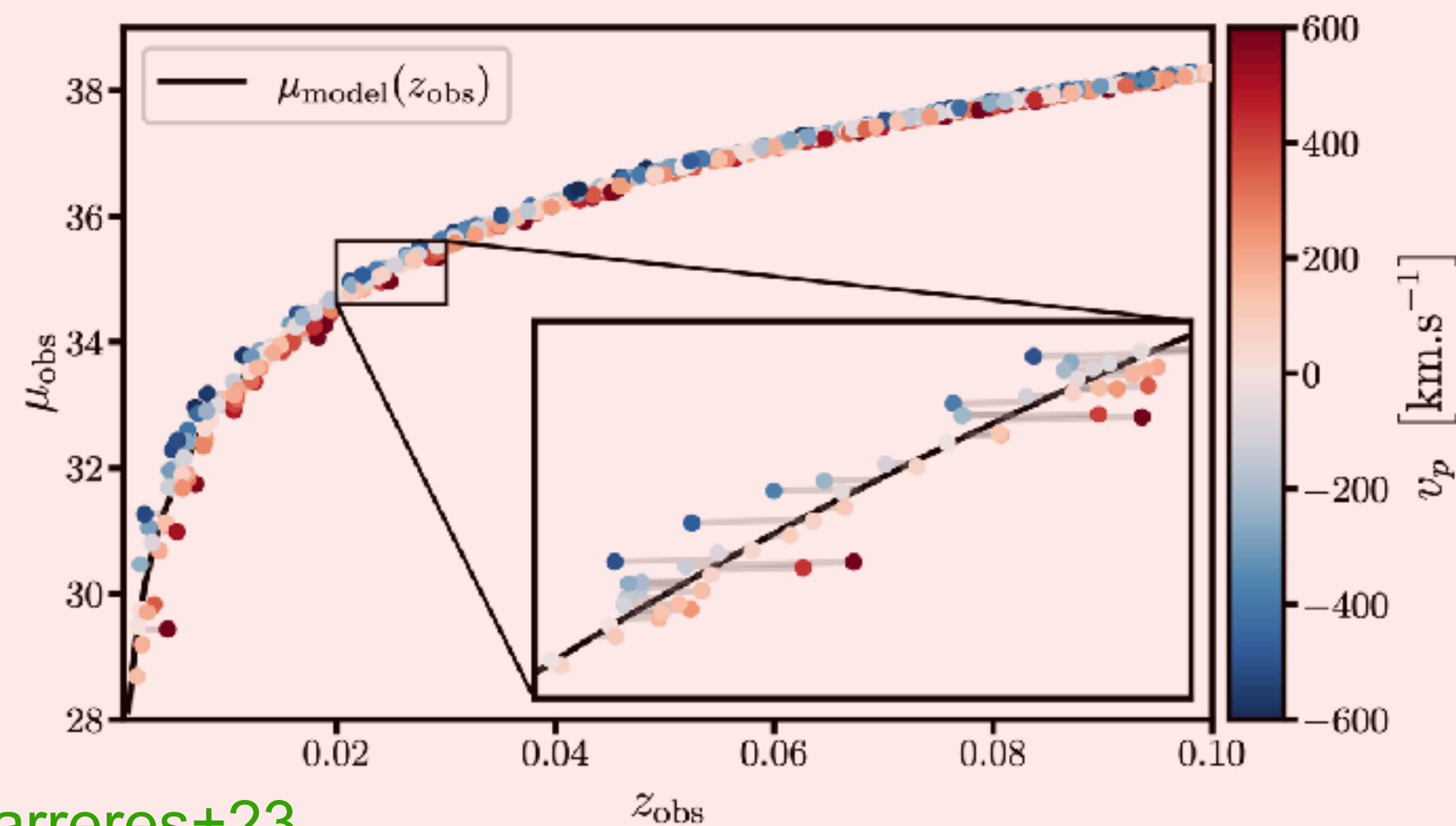
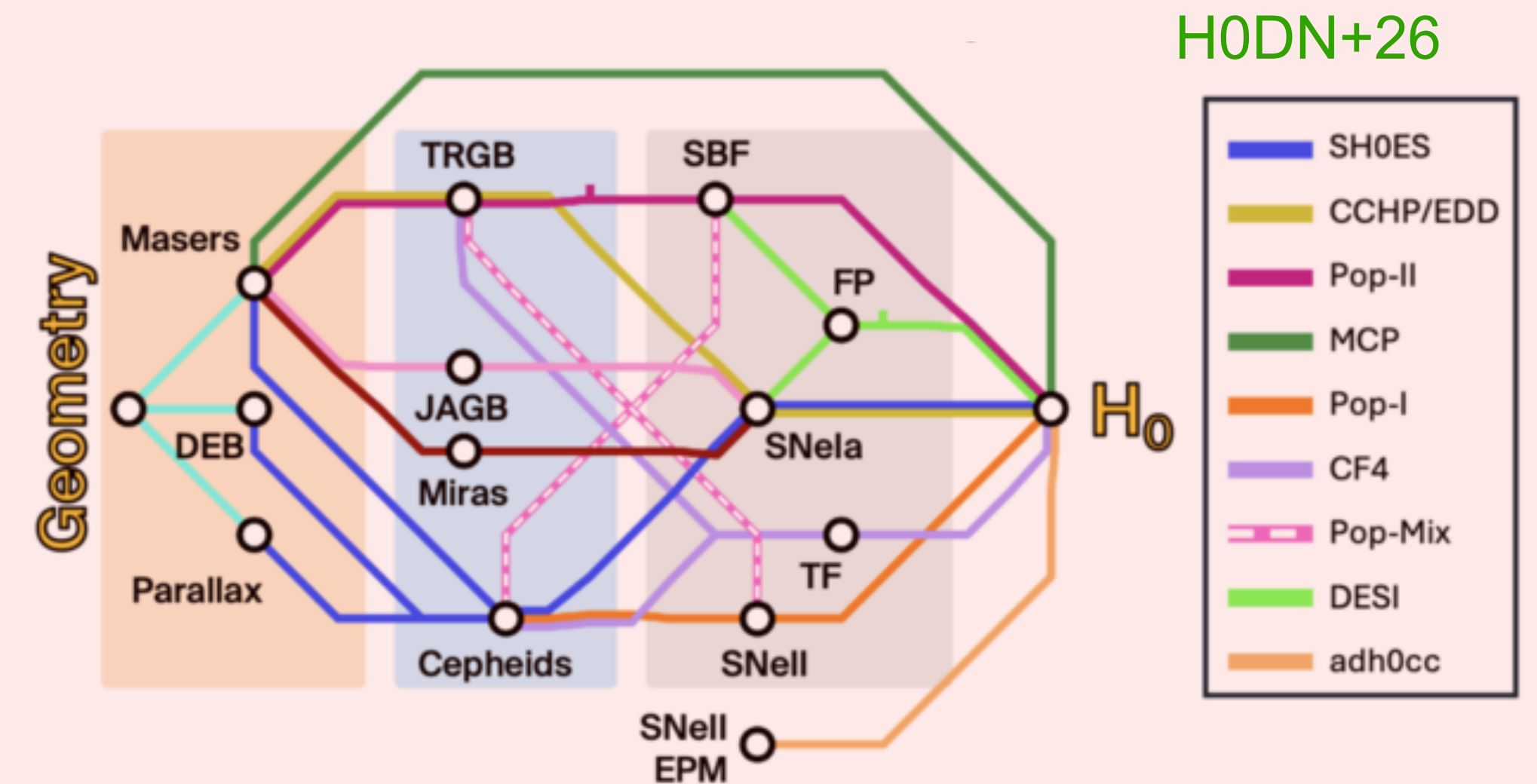


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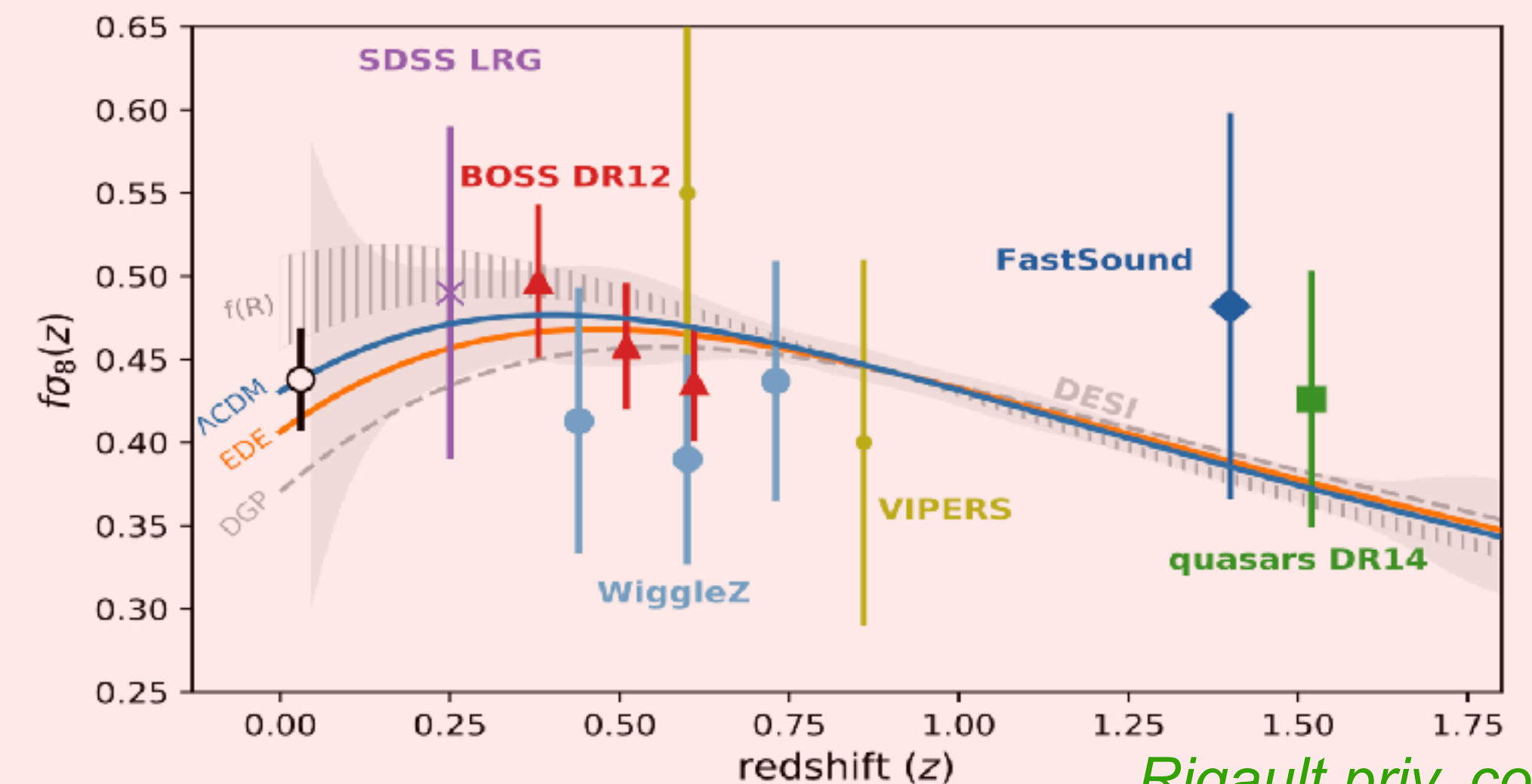
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Carreres+23



Rigault priv. comm.

The low-z problem: targeted vs untargeted

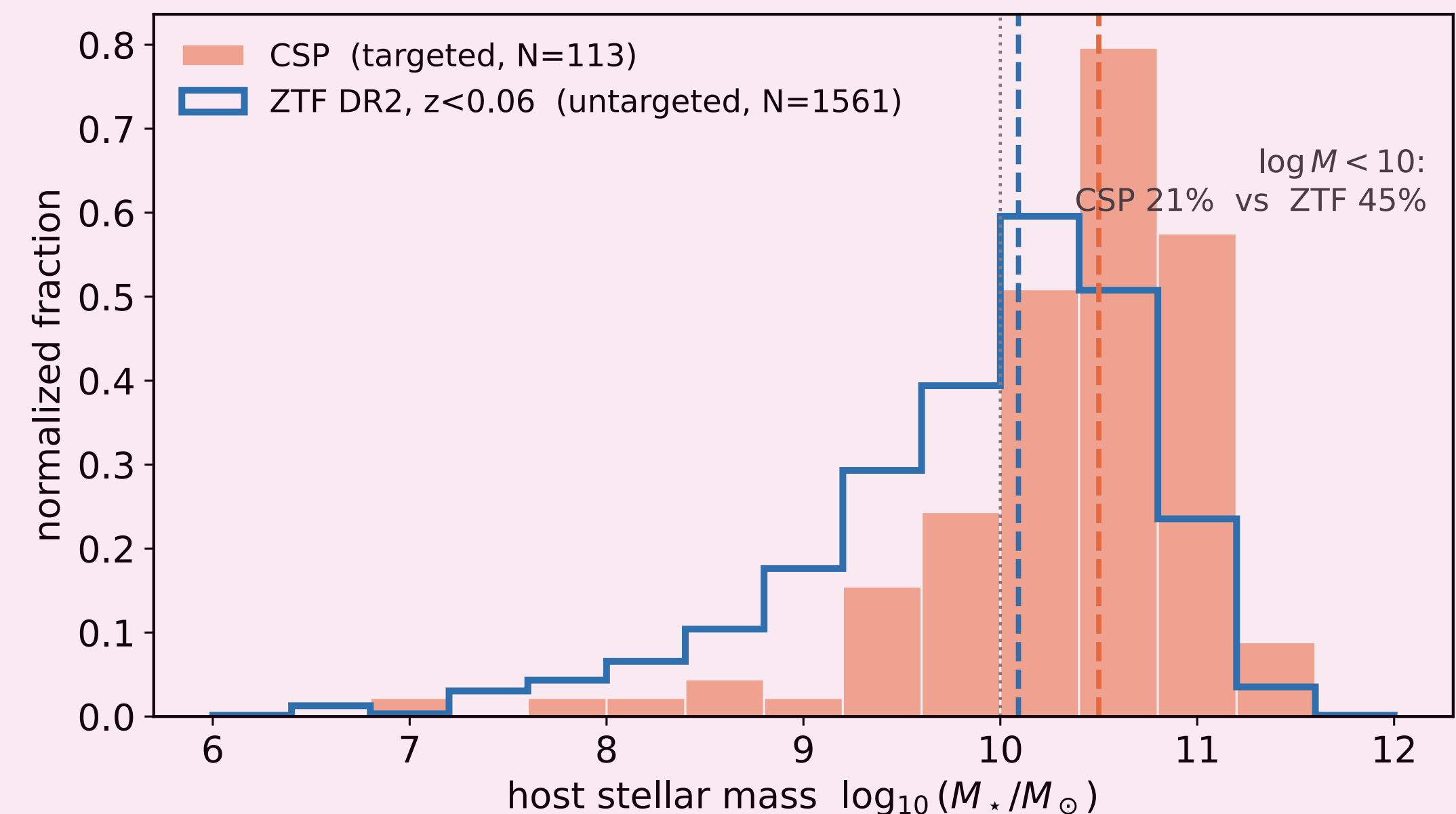
- Low-z is the anchor, provides large sky area, but small volume: fewer SN

Historically heterogeneous.

Calán/Tololo, CfA, CSP... were *targeted* follow-up of known galaxies

selection bias toward bright, massive, metal-rich hosts.

- Modern *untargeted* all-sky surveys (ZTF, ATLAS, ASAS-SN) remove that bias and deliver homogeneous, volume-limited samples.



Photometric calibration

- Calibration is the dominant systematic

small zeropoint errors amplify by up to $\sim \times 6$ in distances.

cross-calibrate our zeropoints across photometric systems:

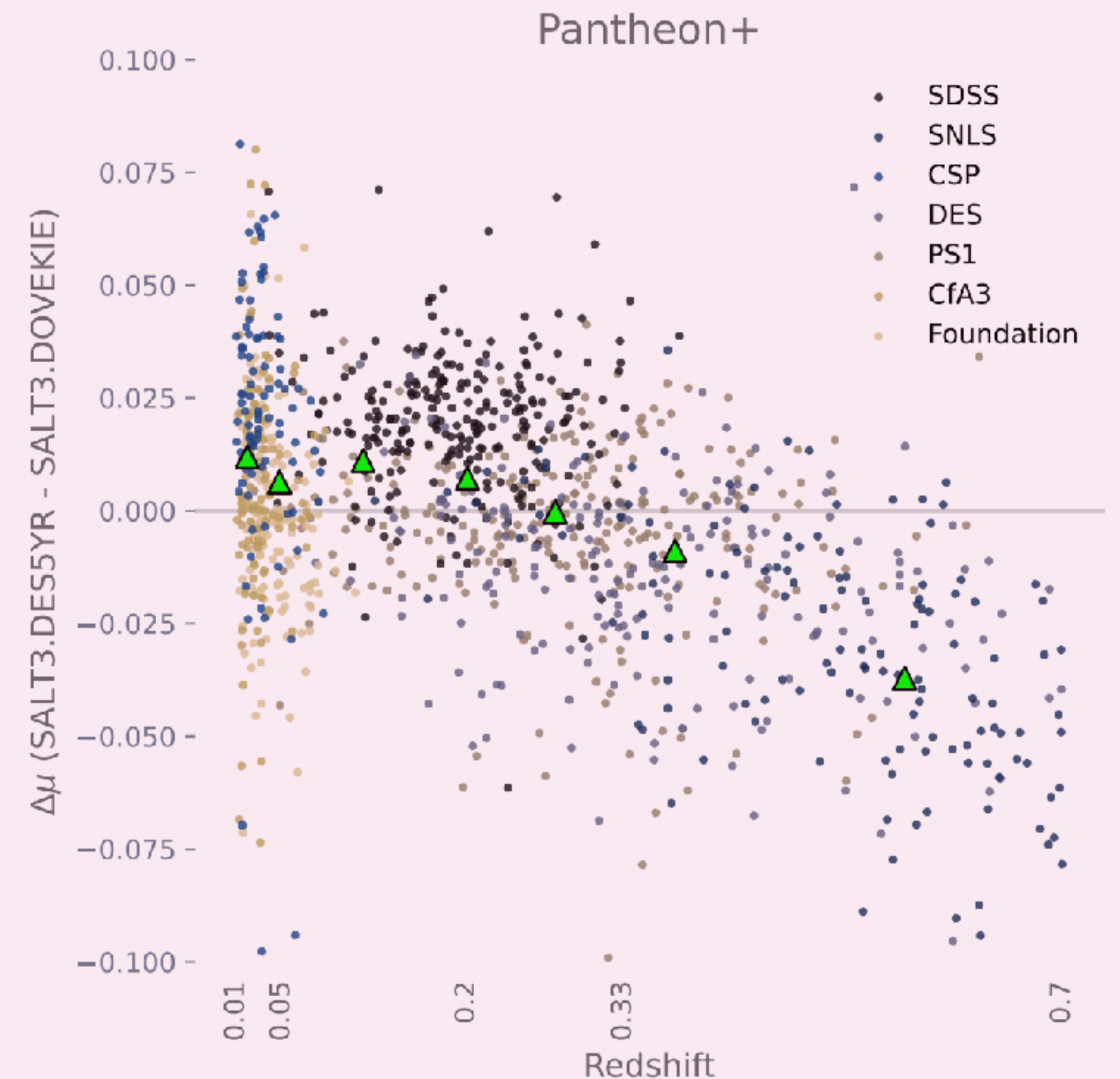
SuperCal $\rightarrow$ Supercal-Fragilistic $\rightarrow$ **Dovekie**
(new CALSPEC/DA-WD standards; Boyd et al. 2025).

fewer instruments = fewer cross-calibration steps.

Hence **DEBASS** (low-z on DECam) + DES-SN5YR

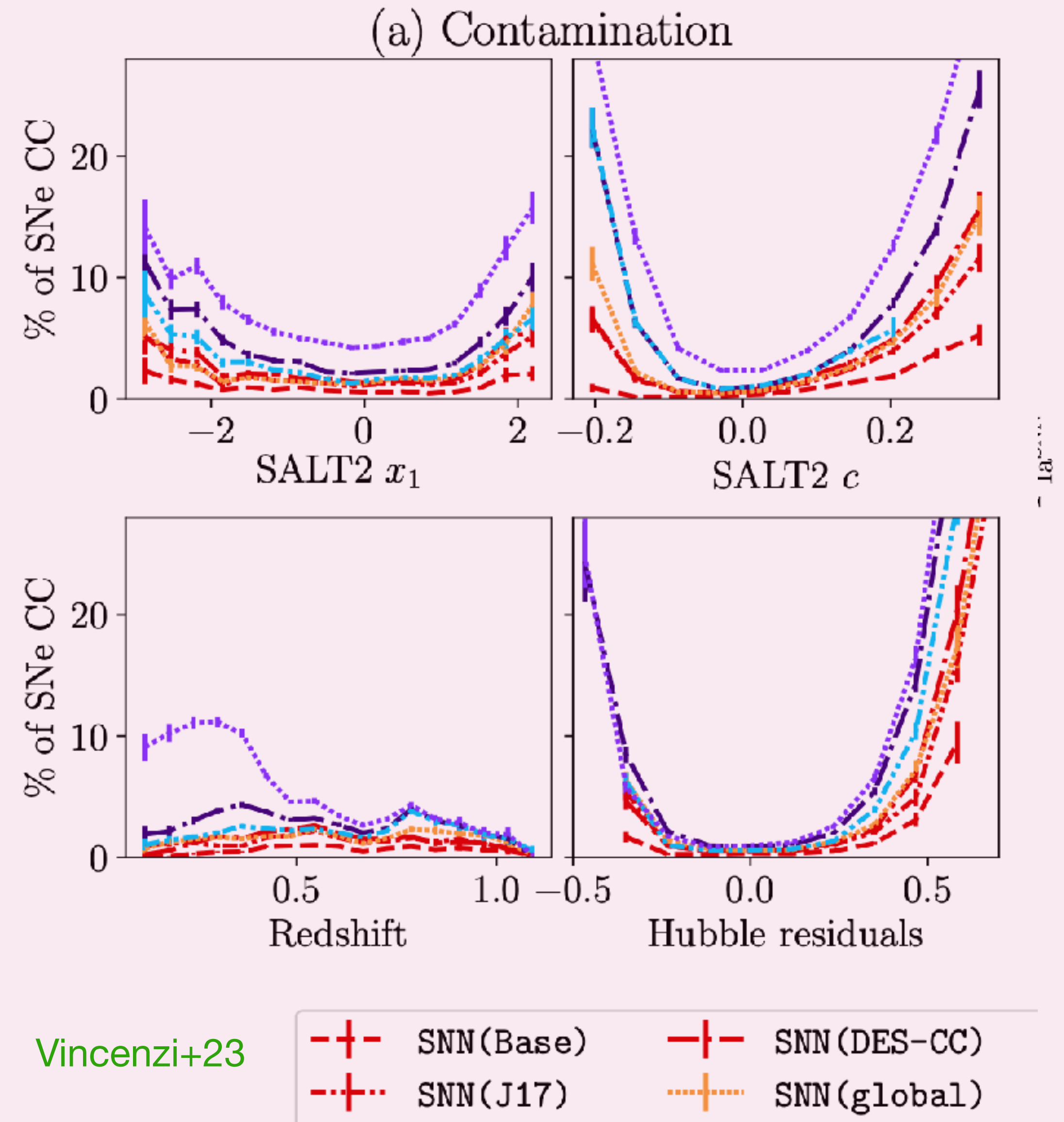
Lemaître (ZTF+SNLS+HSC), 3 well-characterized instruments

LS4+LSST starting now



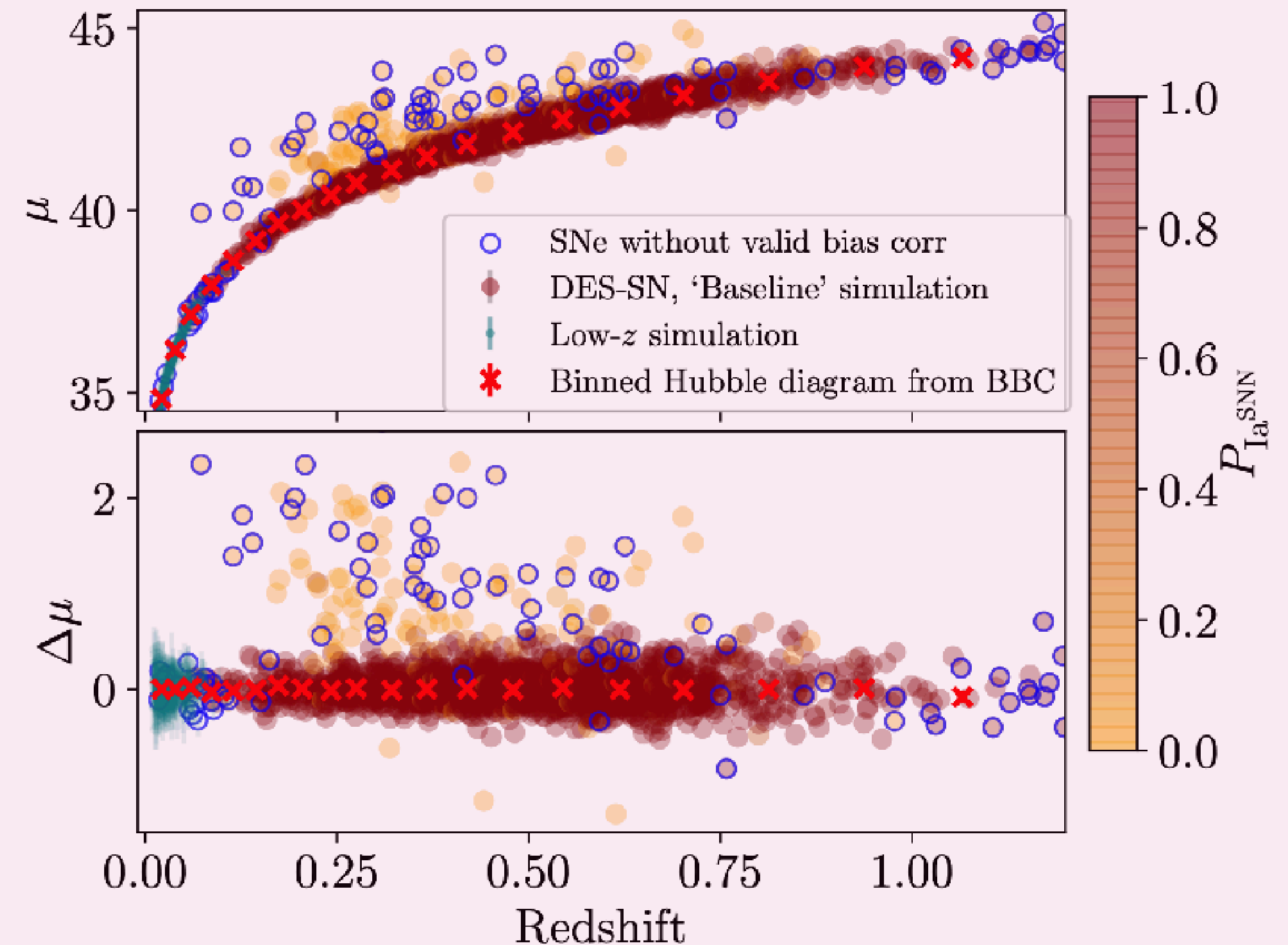
Classification: spectroscopic vs photometric

- Discovery now vastly outpaces spectroscopy
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- Cosmology therefore relies on photometric classification (SuperNNova, SCONE)
- Do we trust it, and how much non-Ia contamination leaks in?
- DES-SN5YR already runs fully photometric with contamination modeled in the likelihood.



Classification: spectroscopic vs photometric

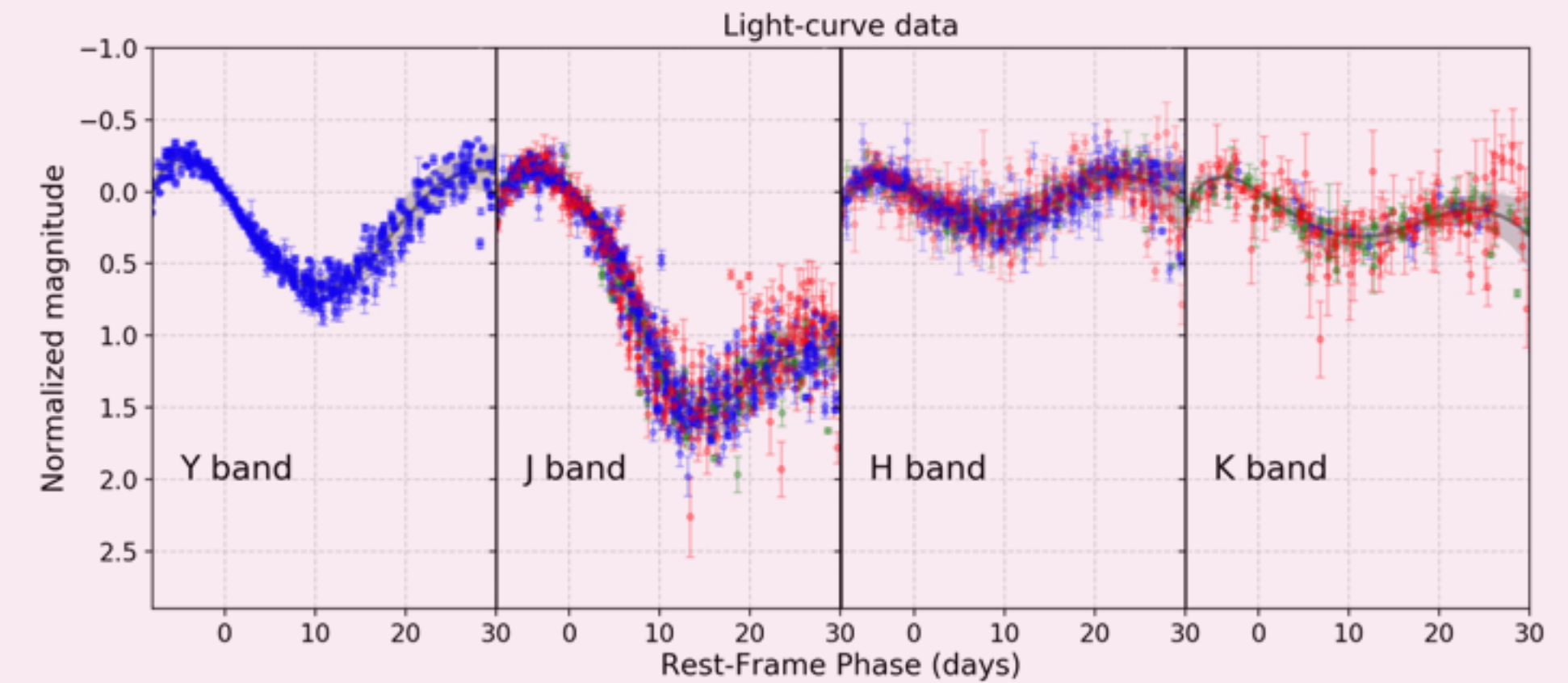
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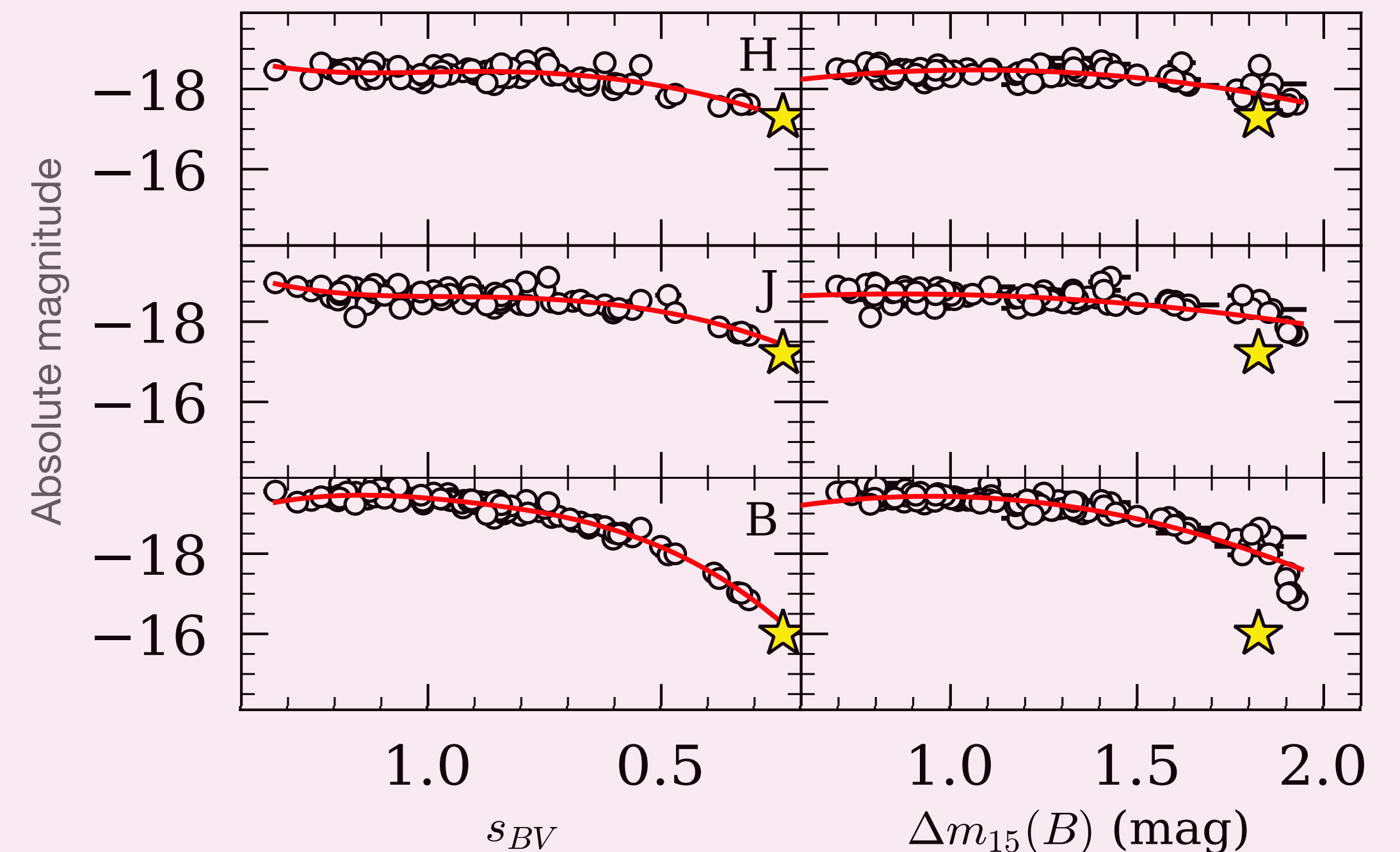
The promise of the NIR

- In the NIR, SNe Ia are **better** standard candles:
 - Less sensitive to host dust
 - Light-curve-width correction is much smaller
- But, fewer instruments, fewer observations, sparse templates, and mostly *targeted* surveys
- RAISIN at high- z (~ 0.4)
- Future: Roman brings NIR to high- z

Avelino+19

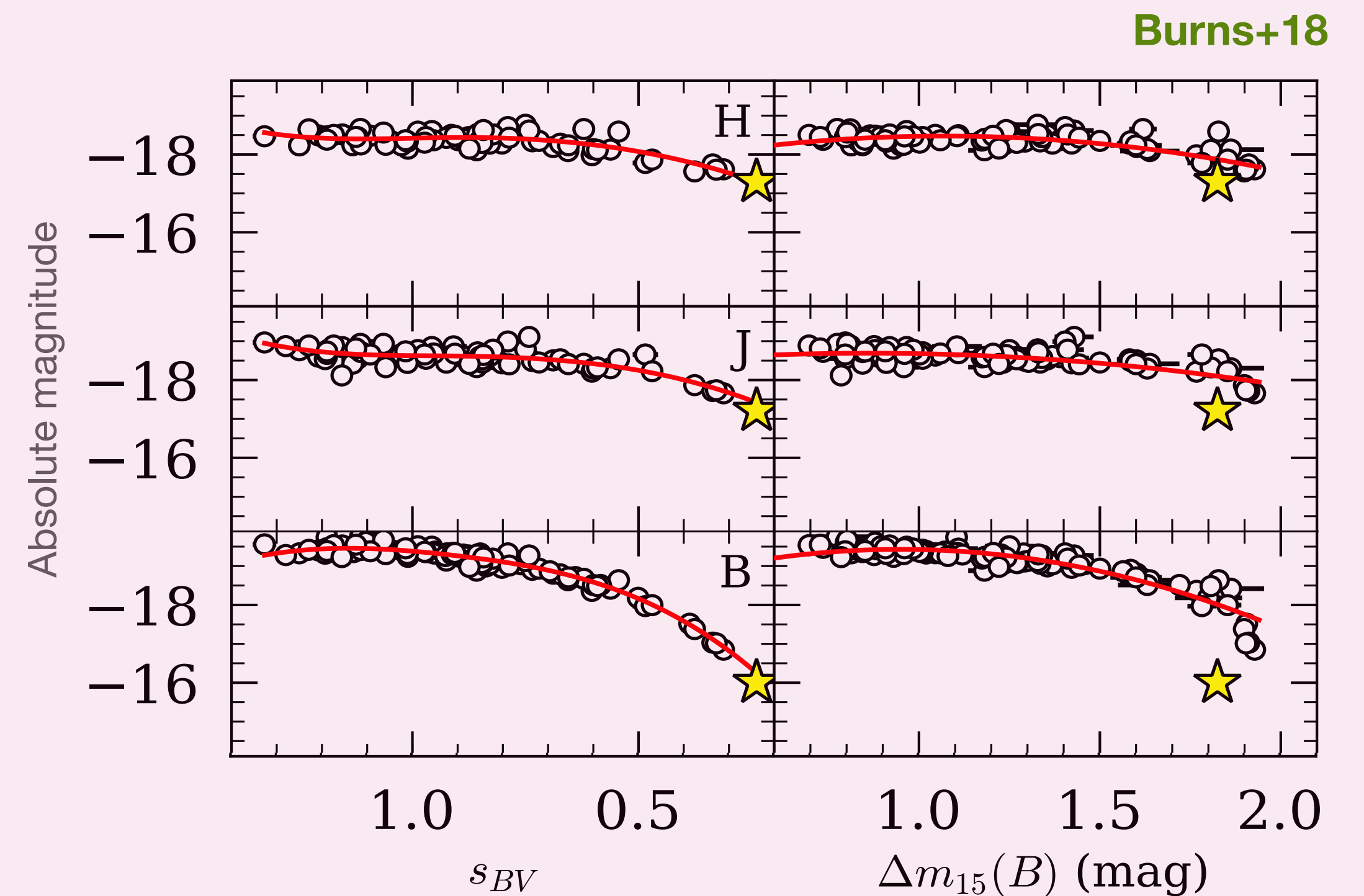
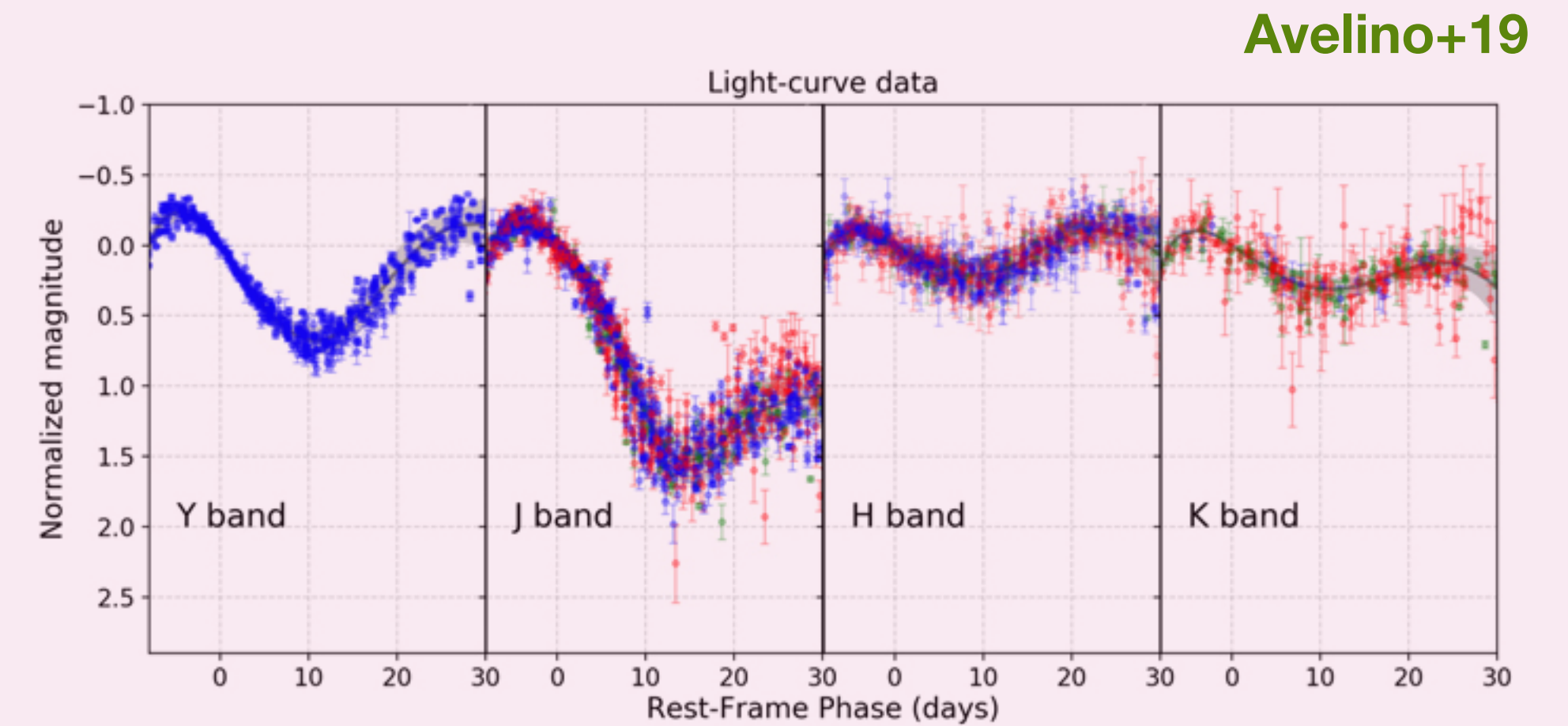
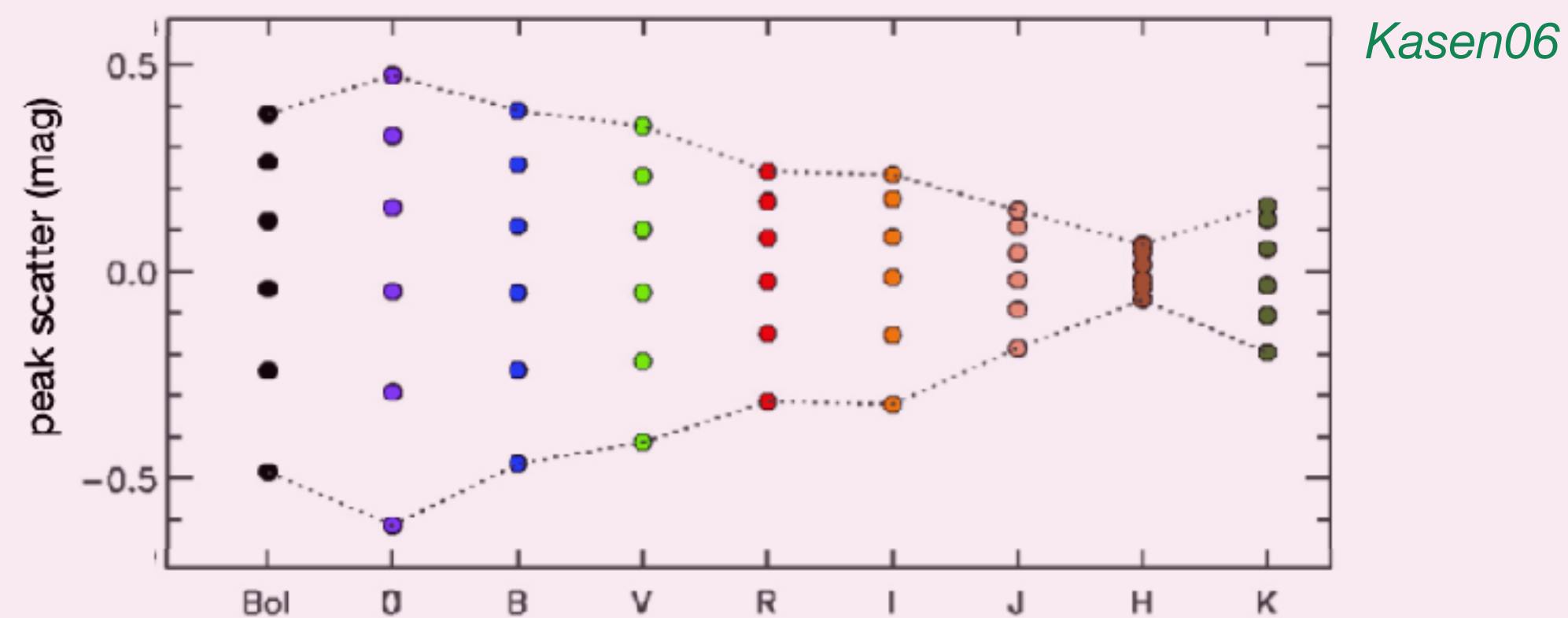


Burns+18



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The high- z future: Rubin/LSST + Roman

- Two complementary flagships.
- **Rubin/LSST** (started June 29 2026): *ugrizy* wide survey + deep-drilling fields

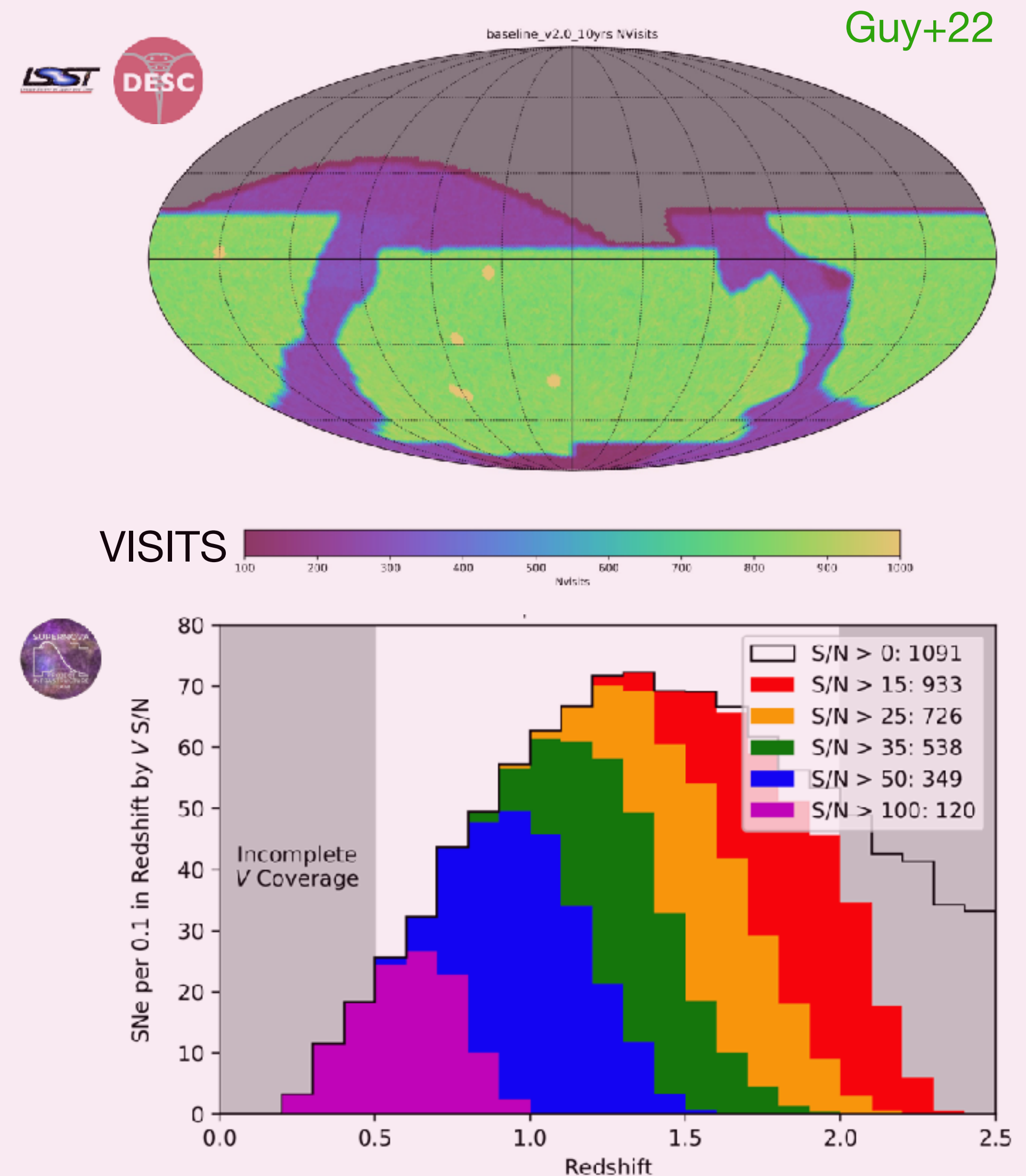
100,000s SNIa photometrically classified
With spec/phot redshifts up to $z < 1.2$

systematics- and calibration-limited, not statistics-limited.

- **Roman** (launch **Aug 30 2026**): space-based NIR High-Latitude Time-Domain Survey

10,000s SNIa from $z \sim 0.5$ to >2.5

rest-frame *optical* out to $z \sim 2.5$,
but rest-frame *NIR* only at $z \lesssim 1$.



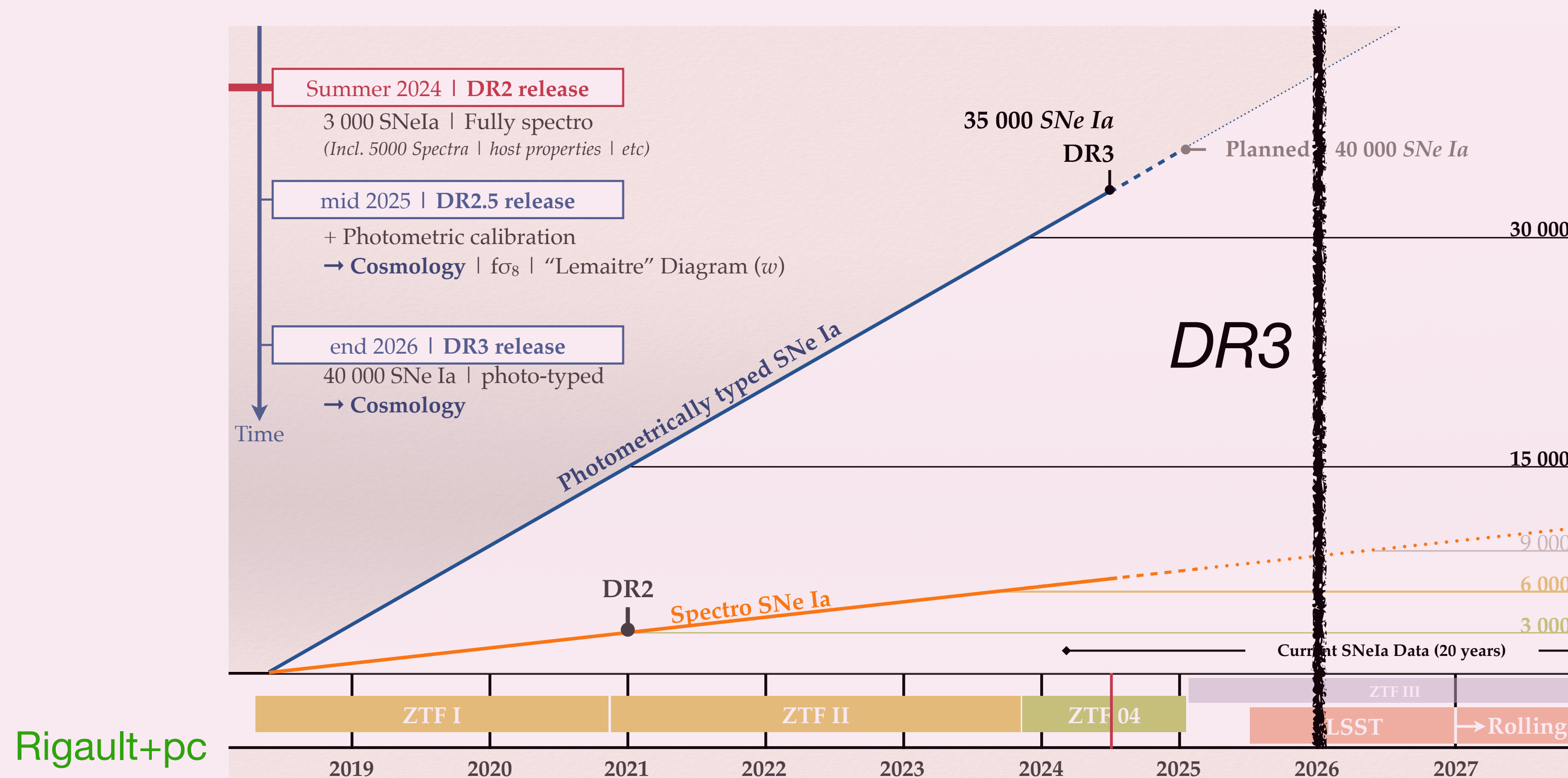
Rubin+22

The low- z future: untargeted all-sky anchors

 **ZTF DR3:** extending DR2 (3,628 SNe) toward ~**10,000 SNe Ia** at $z < 0.1$

- **TITAN:** recalibration of the ~5,000 **ATLAS** SNe Ia. Full-sky (N+S), untargeted coverage.

 **LS4** (La Silla Schmidt Southern Survey): starting in August 2026, southern all-sky, built to complement LSST at low z .



...DR4, 40k
photo-SNIa

Summary and conclusions

- SNe Ia are our premier cosmological distance indicators — yet we *still* don't know their progenitors: most likely a mix, with sub-M_{Ch} double detonations favored for the bulk
- Standardizable, not standard: width + color + **environment** corrections → ~0.14 mag; the mass/environment step is the astrophysical wildcard (progenitor age vs dust)
- They discovered dark energy (1998); today **DESI + SNe** hint at *evolving* dark energy (2025) — SNe are central to the result
- Progress is now **systematics-limited**: calibration, classification, selection, the low-z anchor — increasingly about survey *design*, not the SNe
- Not just w: SNe also set **H₀** (Hubble tension) and trace **growth** via peculiar velocities (σ_8)
- A golden era ahead: **LSST, Roman, Lazuli**, all-sky low-z (ZTF/ATLAS/LS4), and the **NIR**

Understanding the astrophysics — progenitors, explosions, and environments — is now a prerequisite for the next decade of precision cosmology.