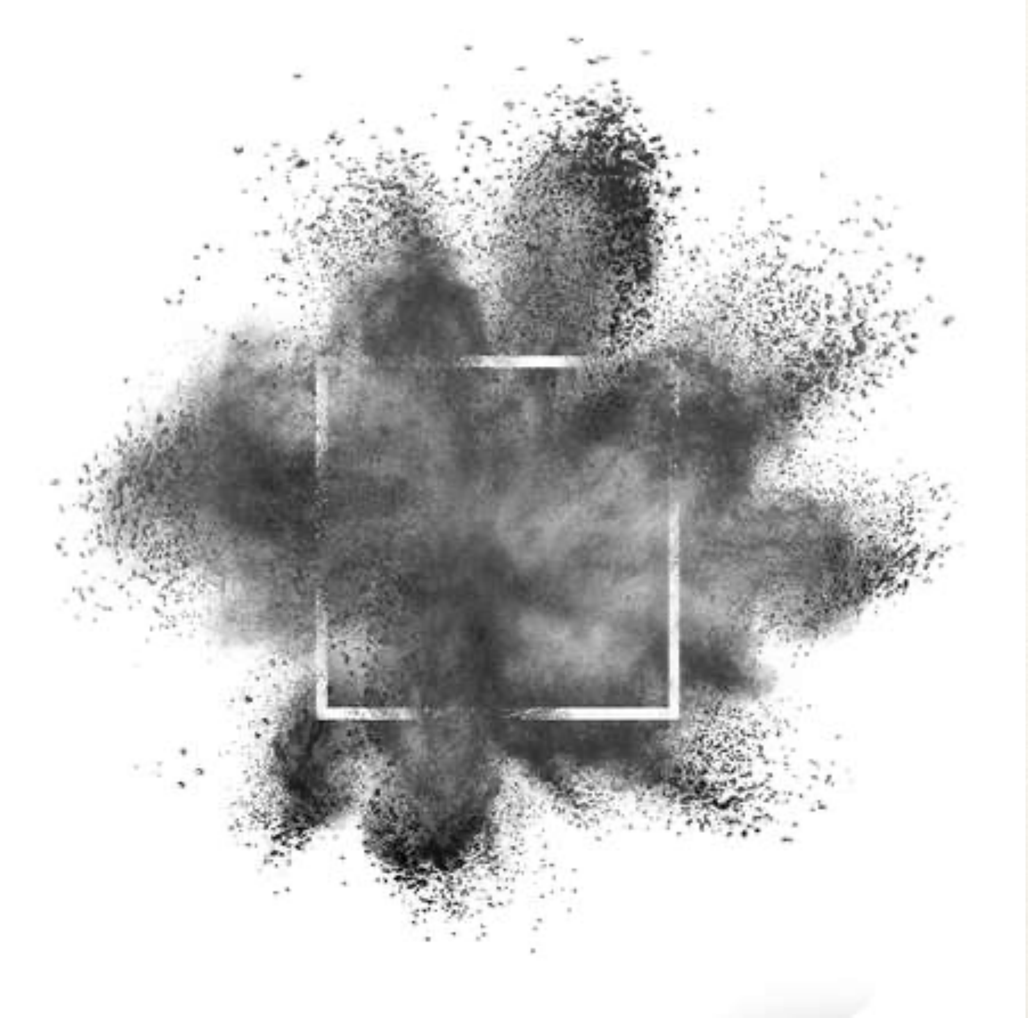
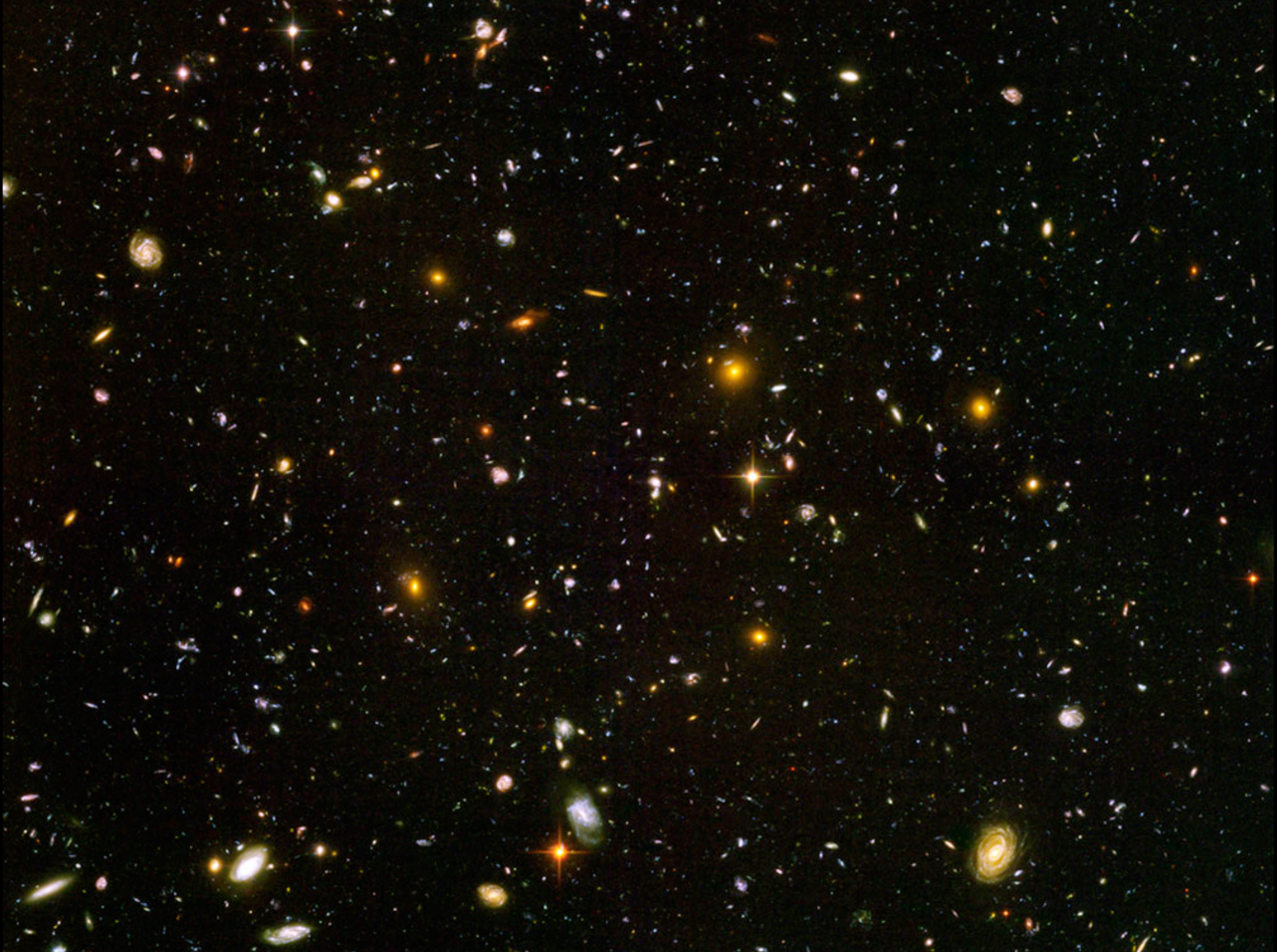


Supernova Cosmology

Part 1

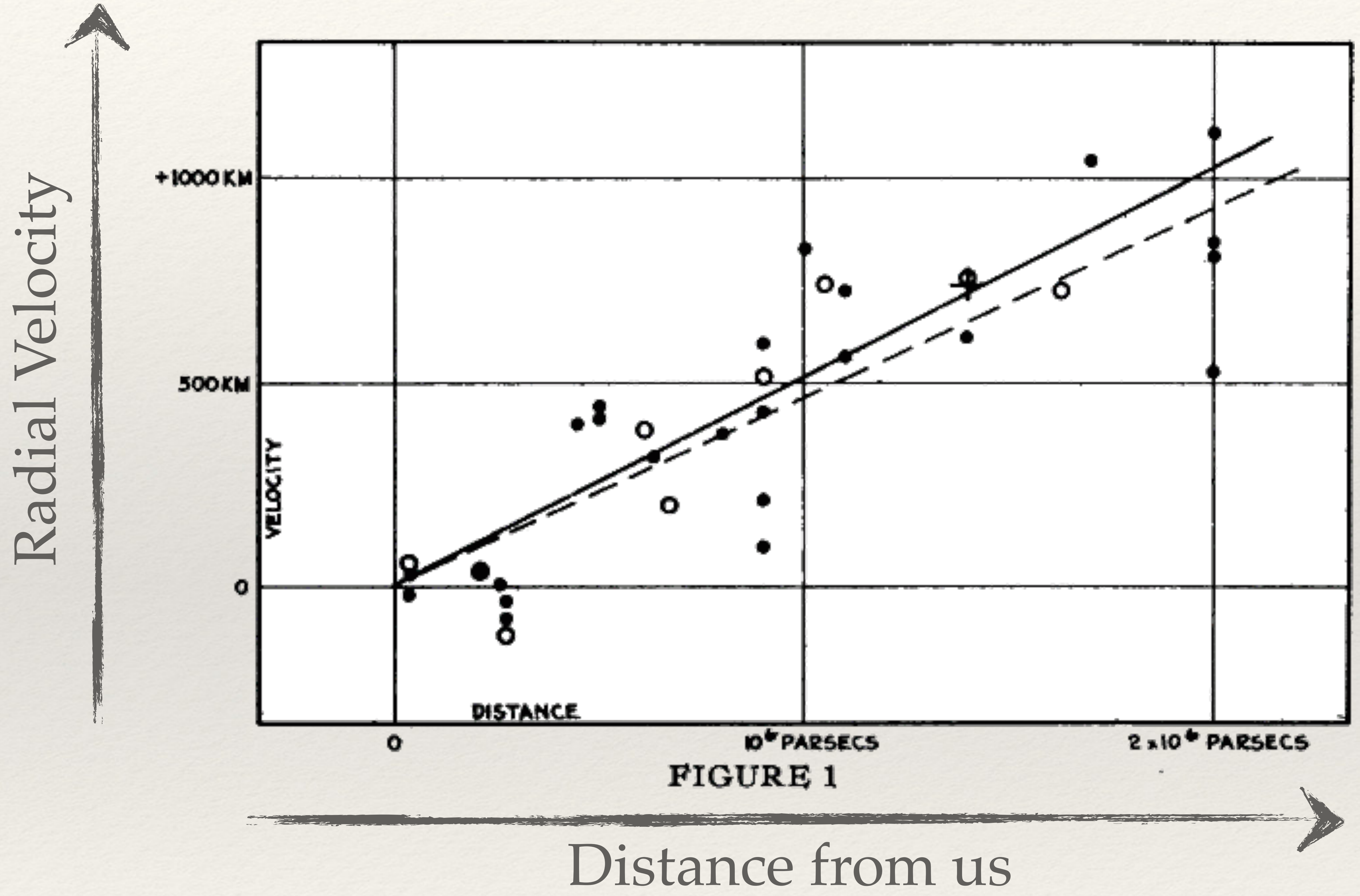
Mathew Smith | Lancaster University, UK

mat.smith@lancaster.ac.uk

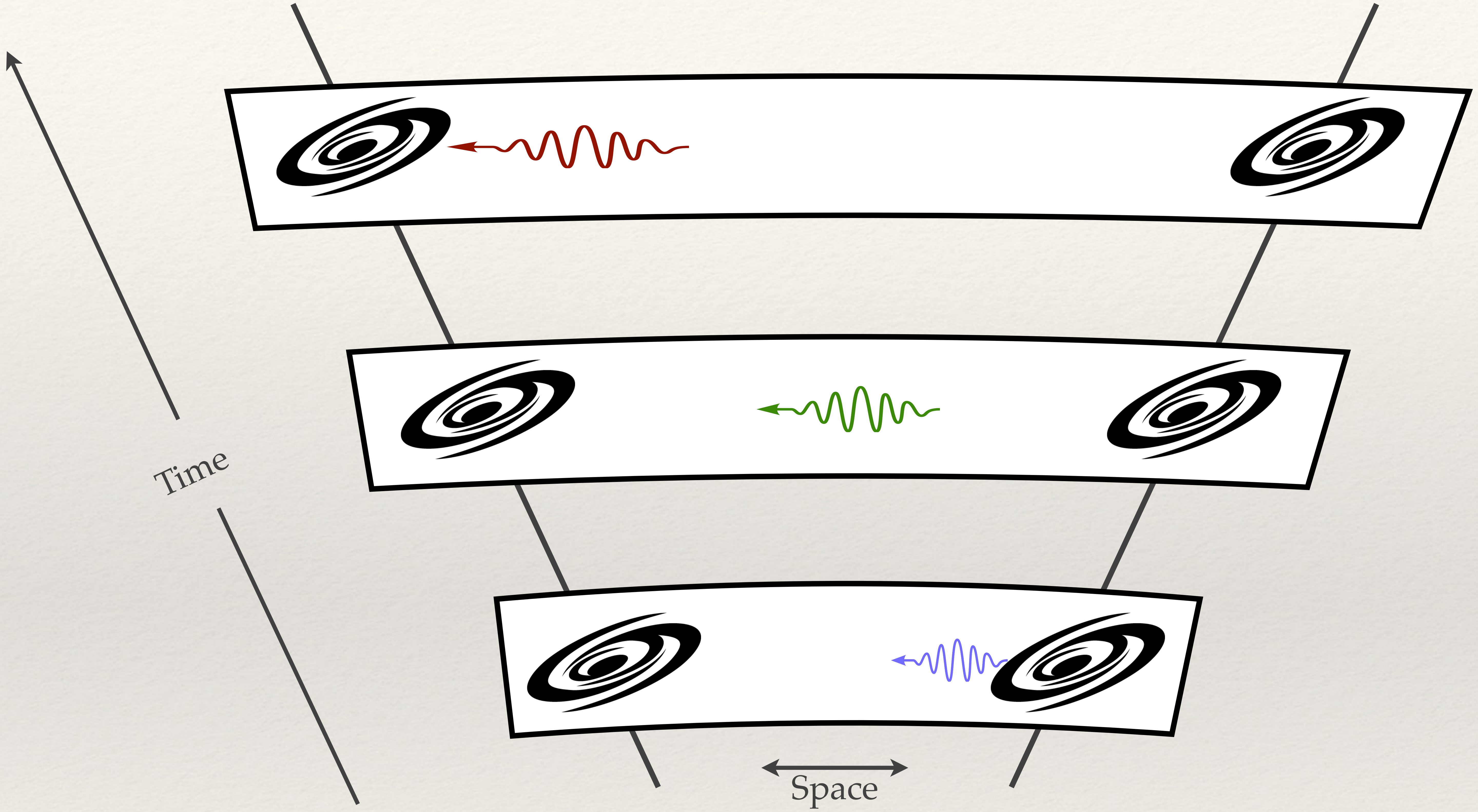


The Universe is Expanding !

Edwin HUBBLE, 1929

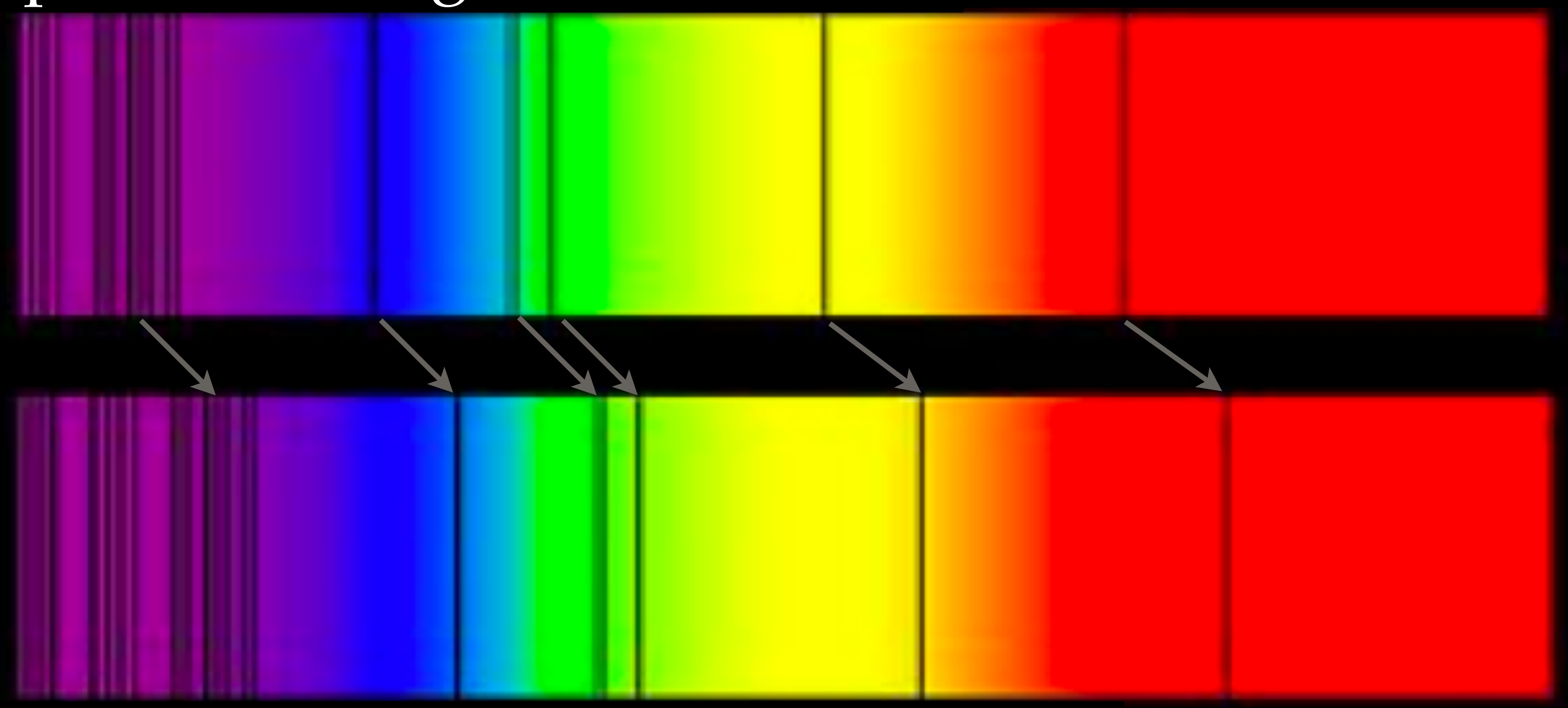


The Redshift as an Expansion Tracer



The expansion of the Universe stretches the photon's wavelength

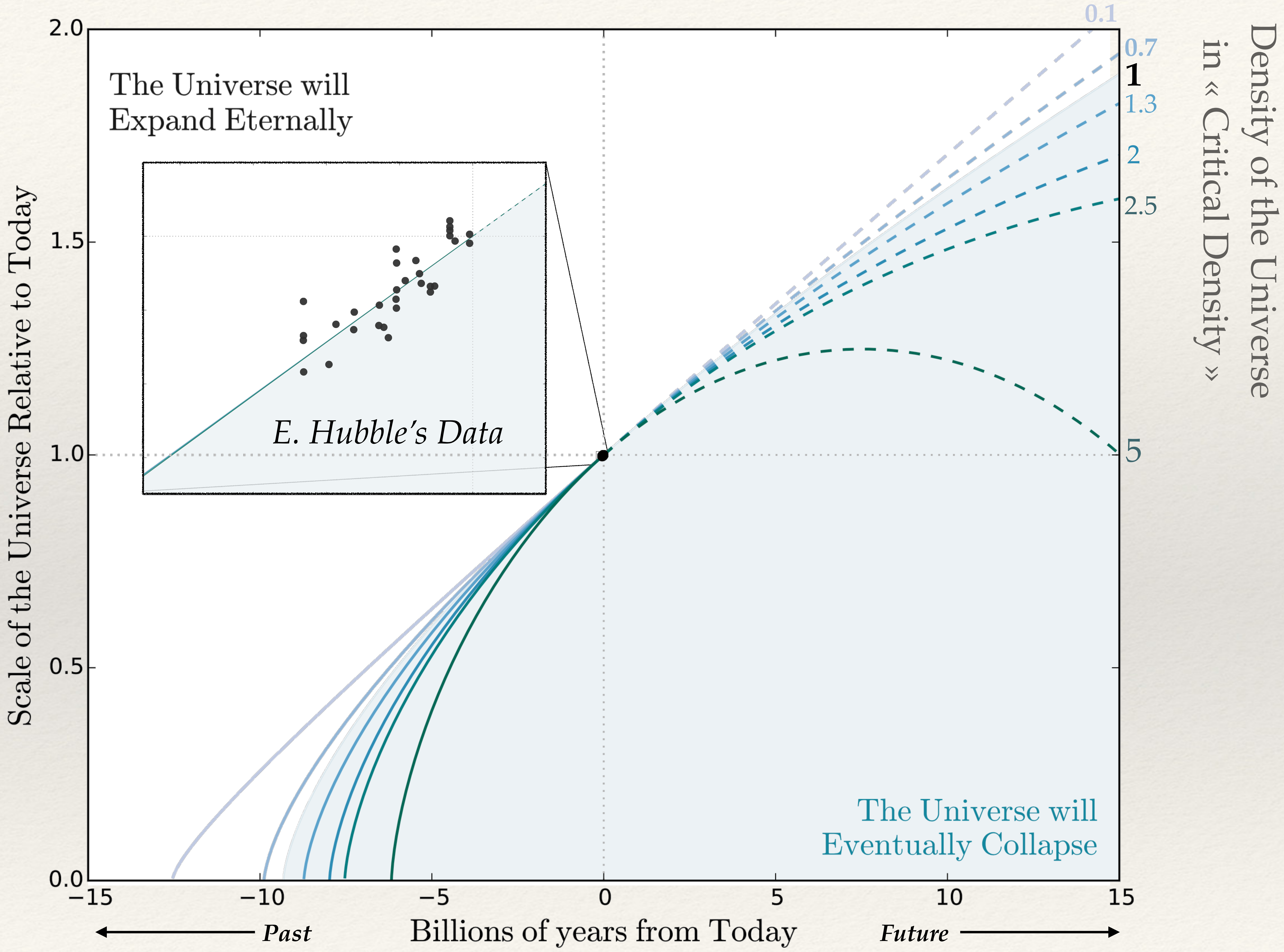
Spectrum of light from the sun



Features seen from a distant galaxy

Measuring the Fate of the Universe

Cosmological parameters affect the distance-redshift relation



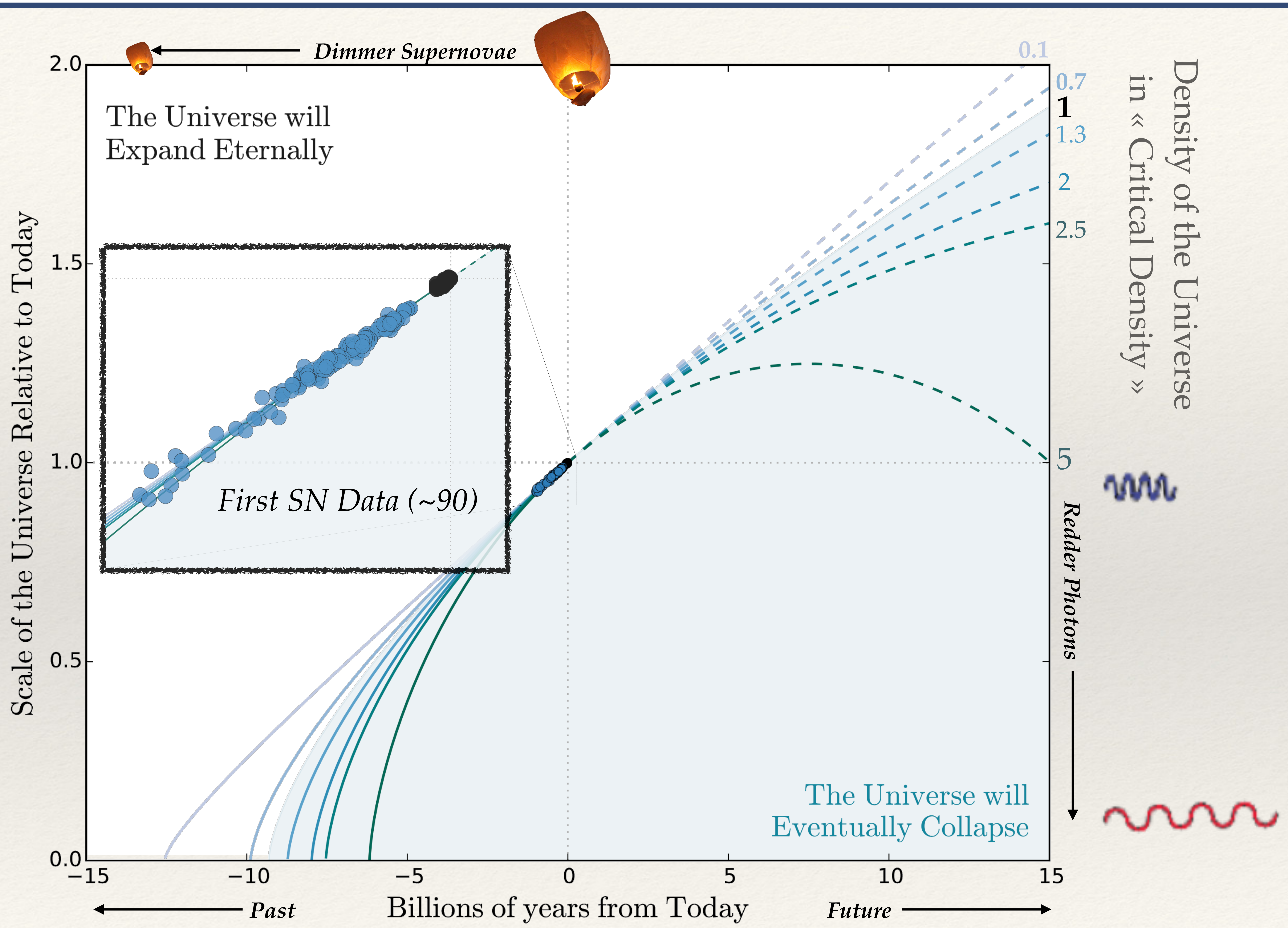
Standard candles

Flux ⇔ Distance

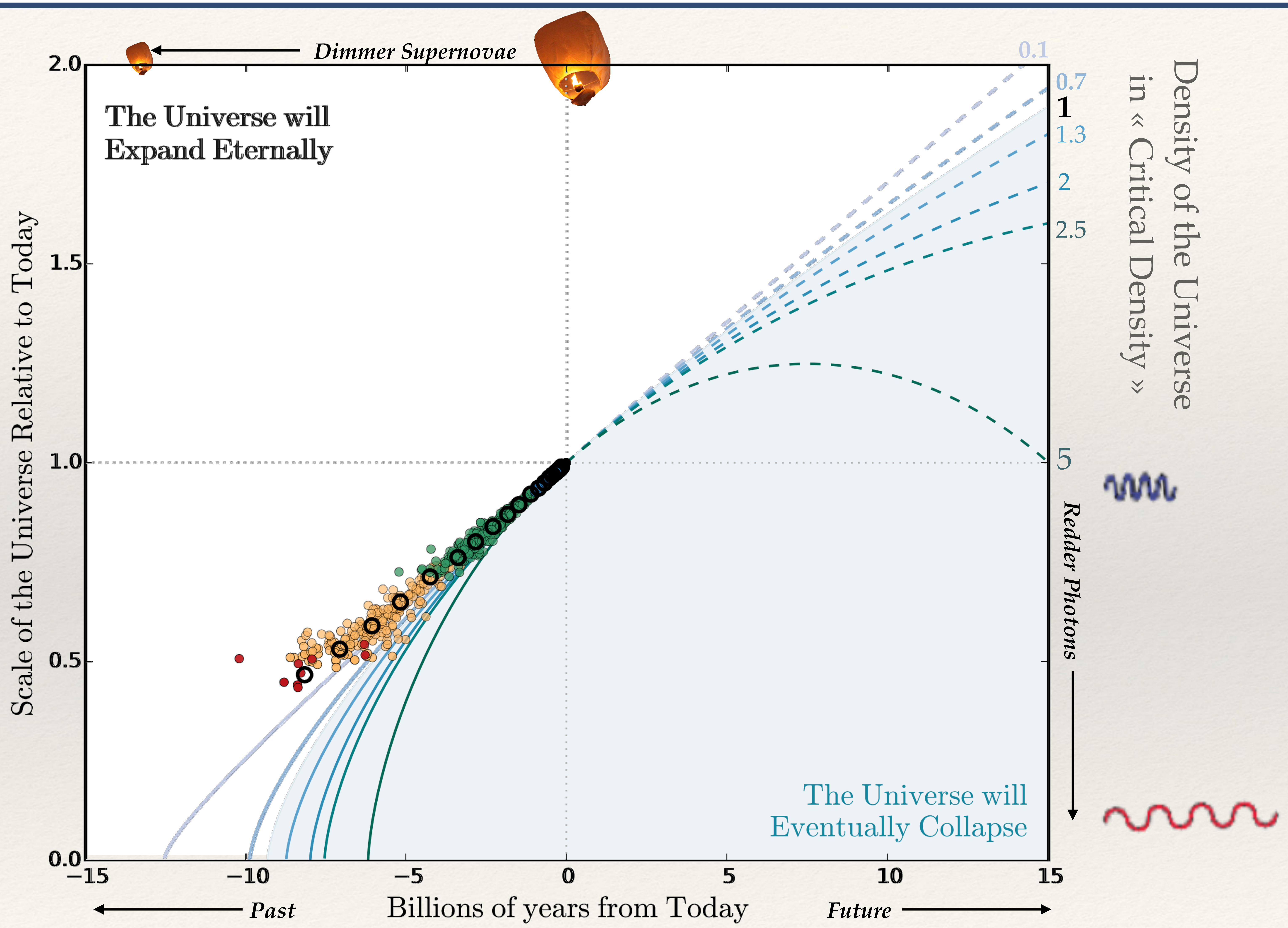
Type Ia Supernovae

are as bright as a galaxy (10^{10} Suns)

Measuring the Fate of the Universe



Measuring the Fate of the Universe



The Universe's Expansion is Accelerating !

Discovered

10^2 SNe Ia in 1999

$\Lambda \neq 0$

State-of-the-art

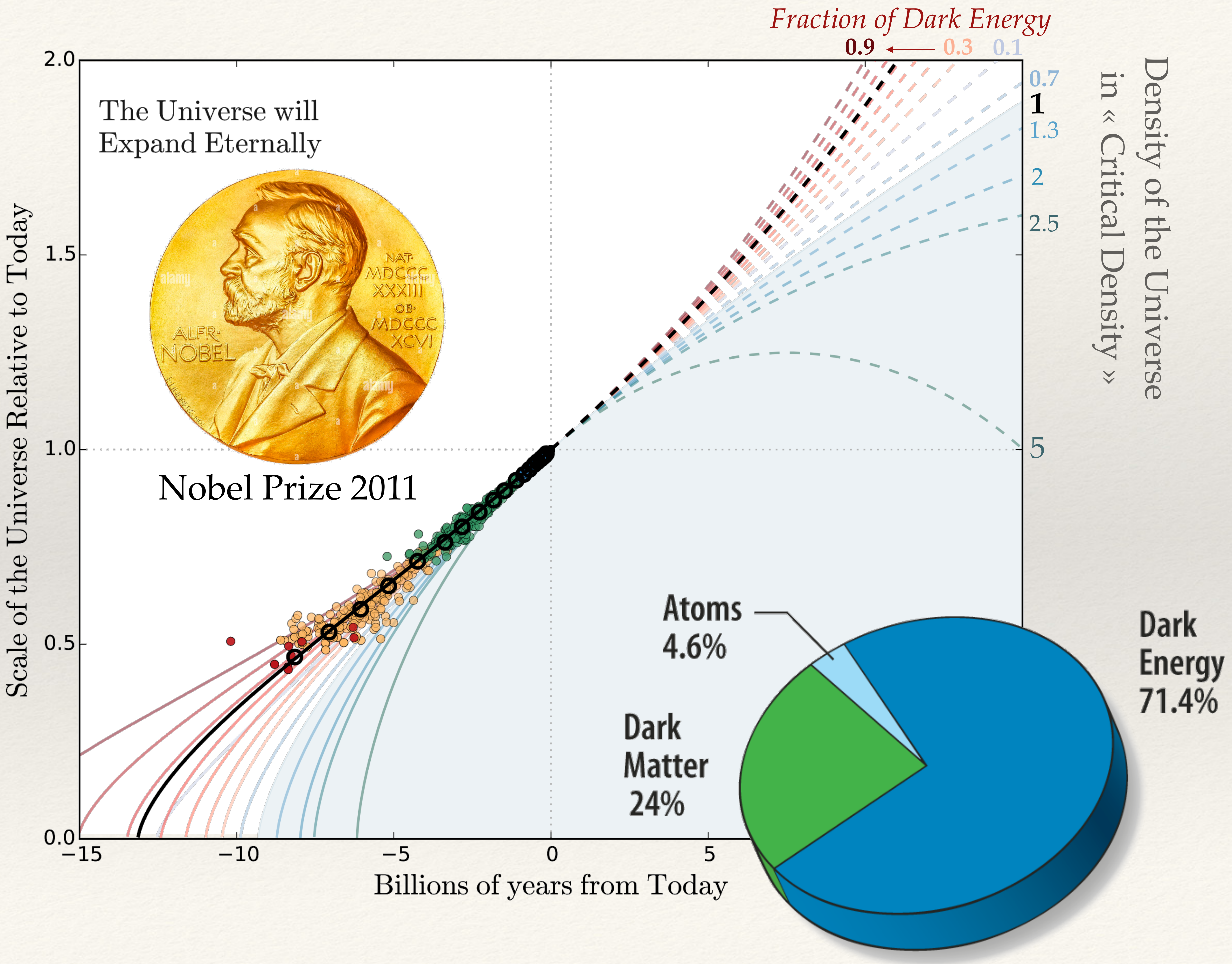
10^3 SNe Ia in 2020

$w = -1 \pm 5\,\%$

What's next ?

10^5 SNe Ia in 2025 (!)

$w(z) \neq 0$?



Getting started

How do we find them

How do we classify them

How do we measure distances

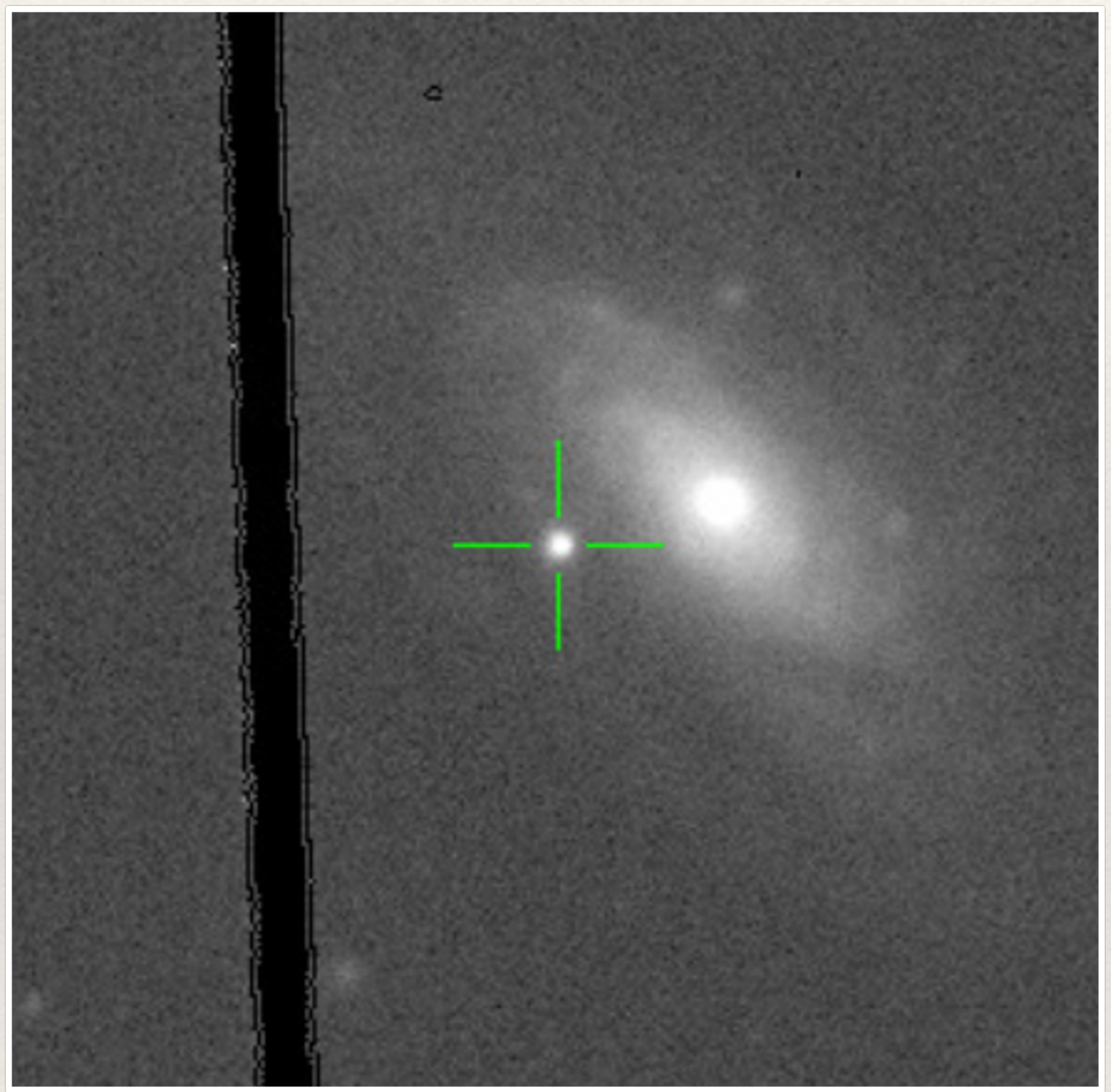

SN2011fe

Li et al. 2011

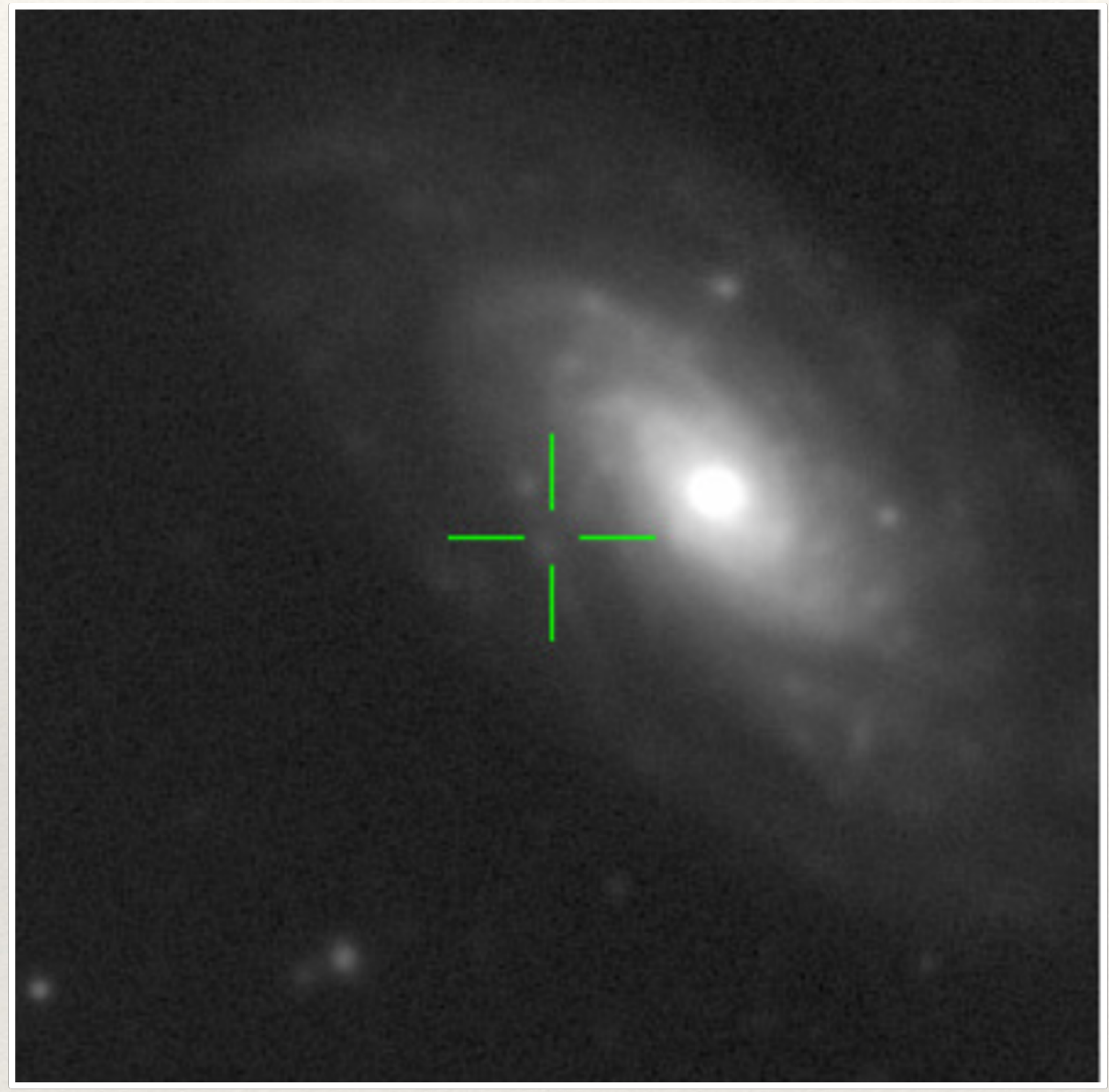

Artist's Concept

Detecting supernovae

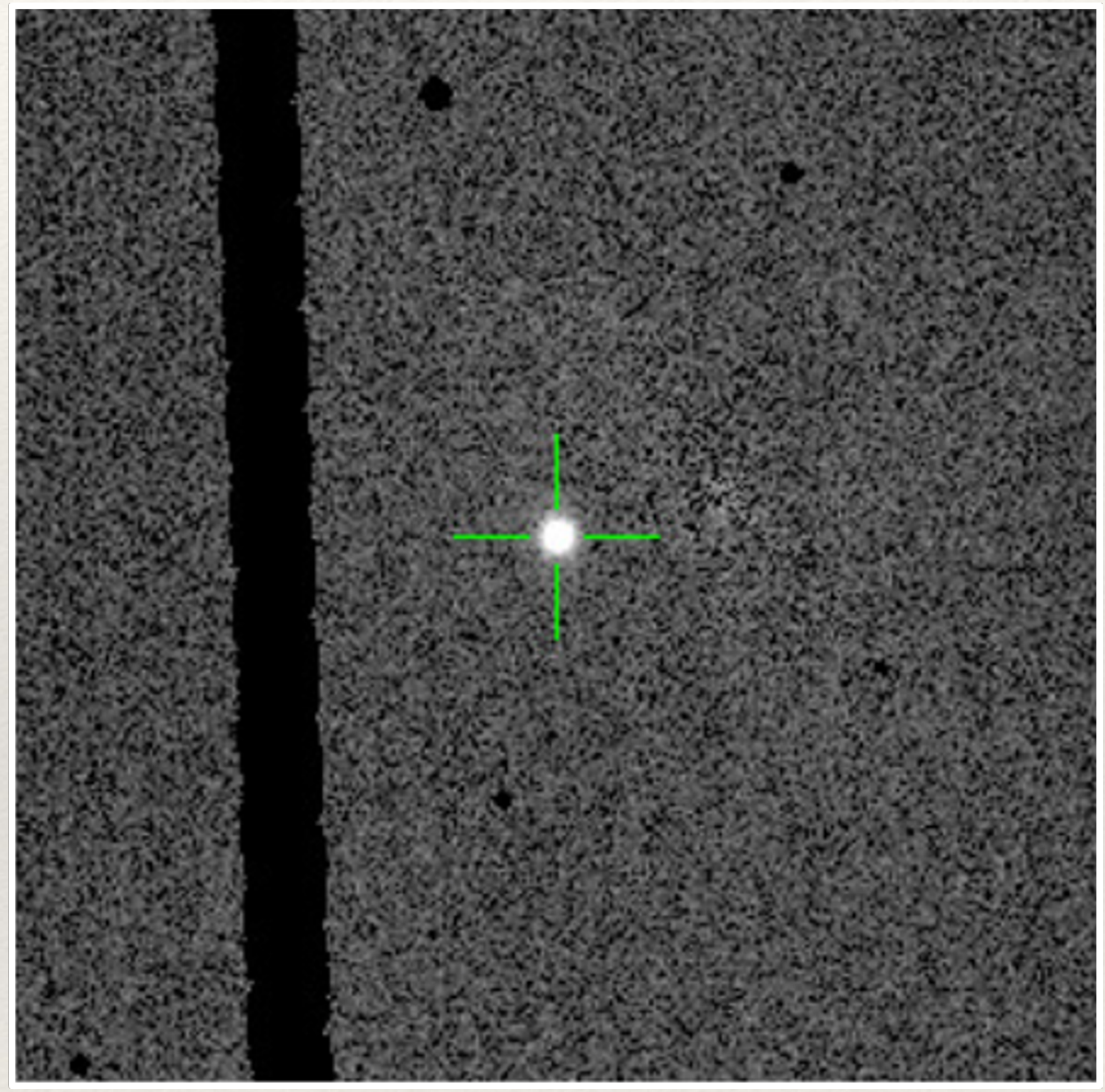
Input image



Reference image



Difference image



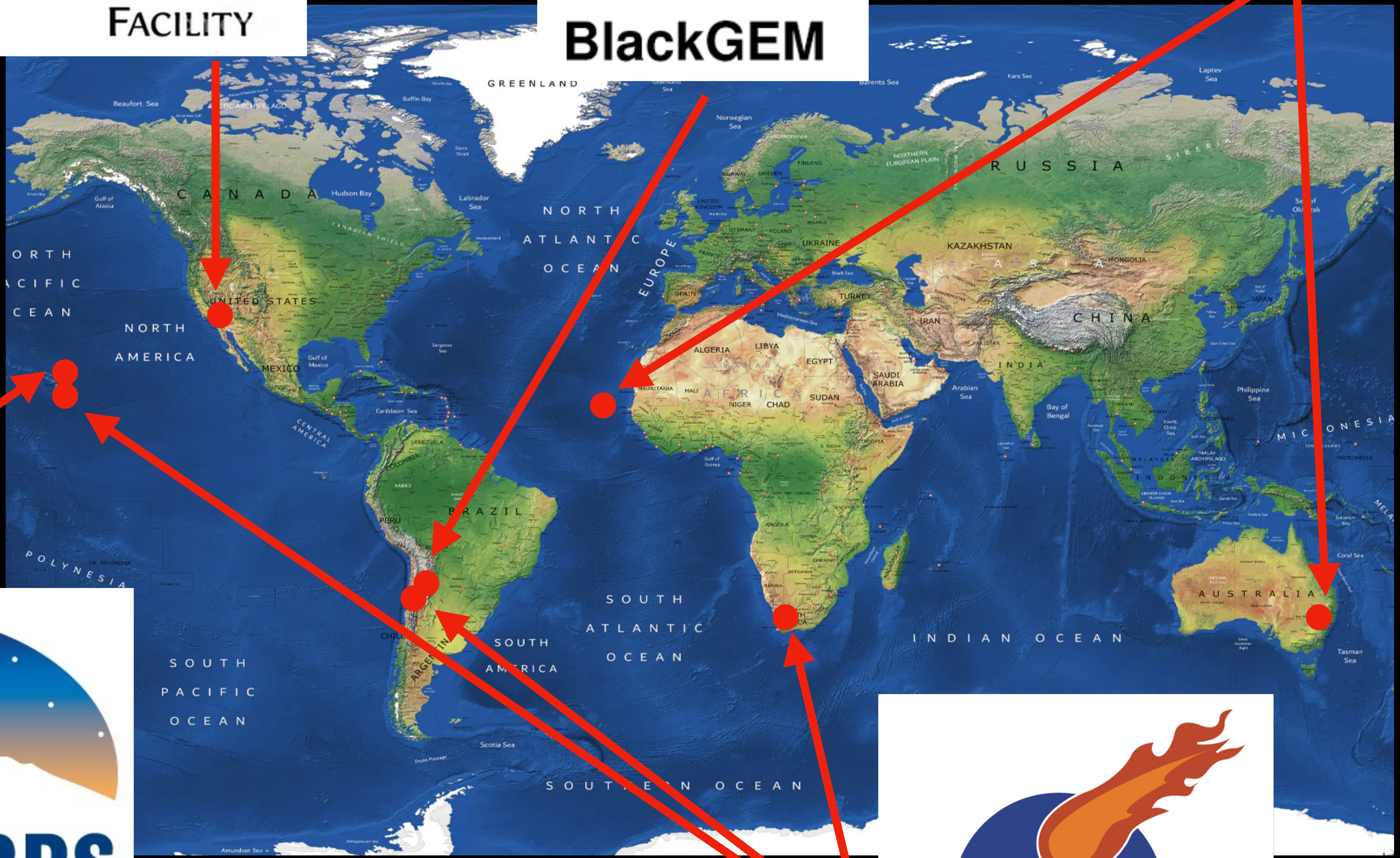
We now discover ~100 new supernovae a week. From their properties we can determine the kinds of stars which exploded.

Detecting supernovae

Zwicky Transient Facility

BlackGEM

GOTO
GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER



Pan-STARRS

atlas


Day 000

All new supernovae are made public!

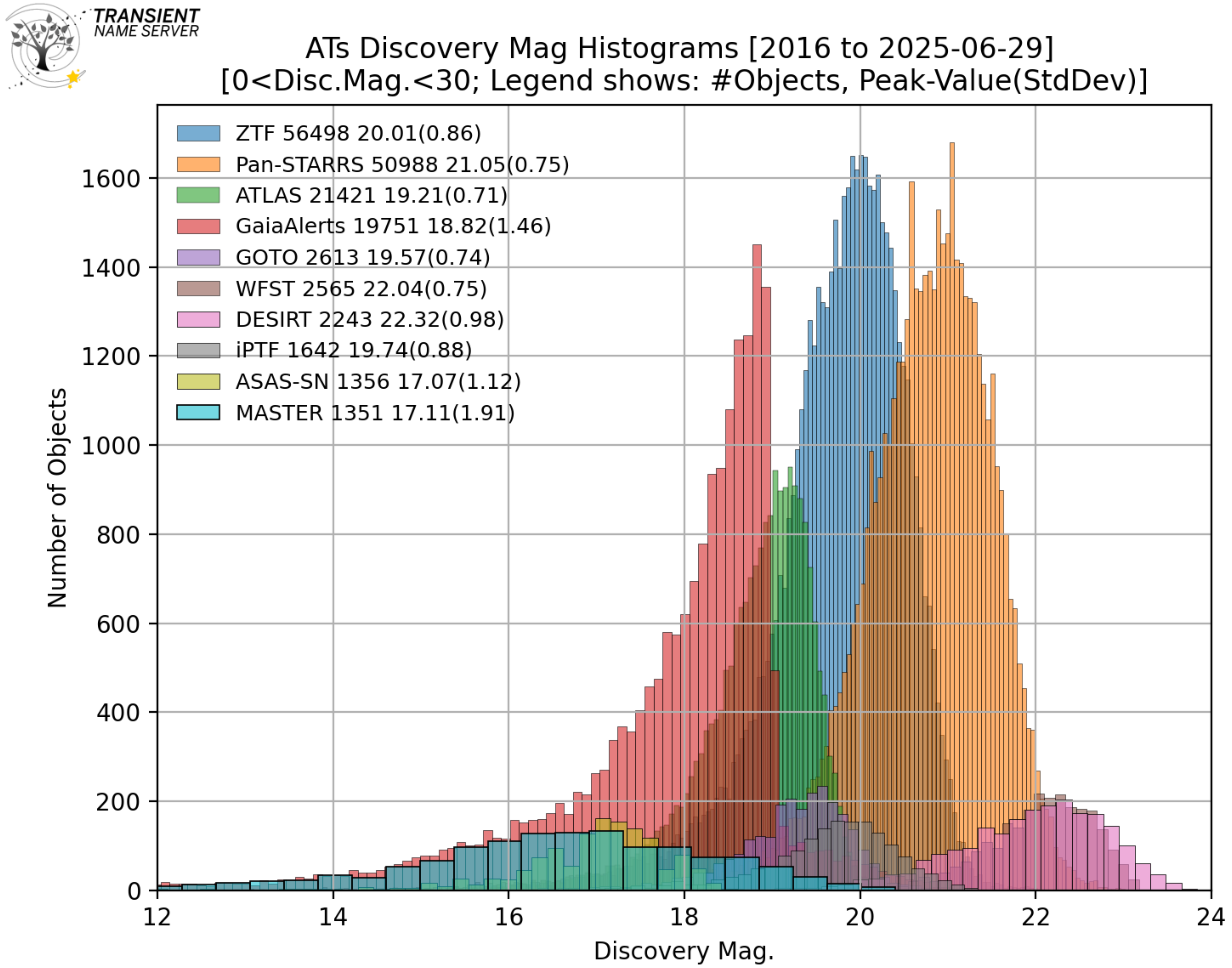
TRANSIENT NAME SERVER

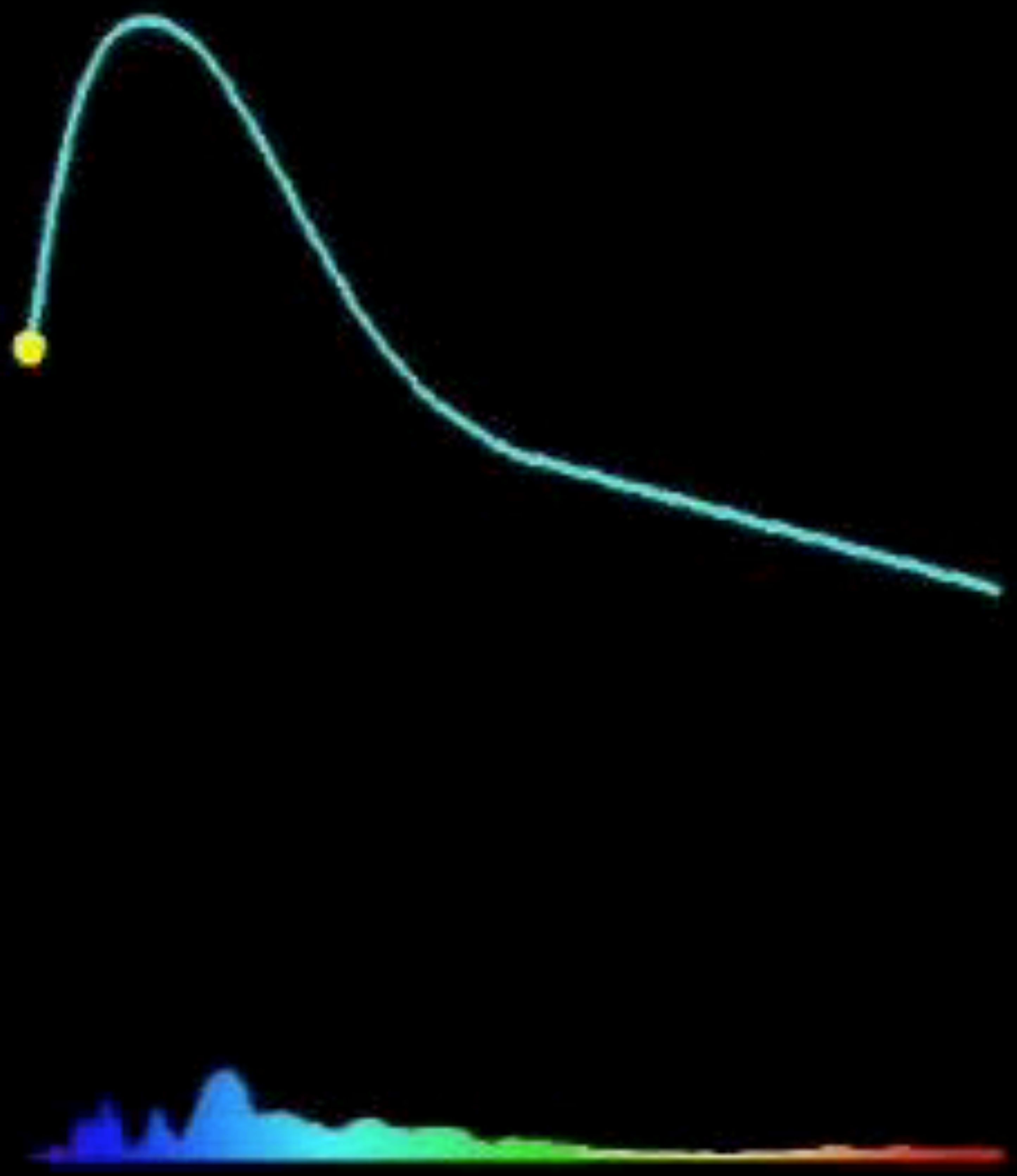
https://www.wis-tns.org/

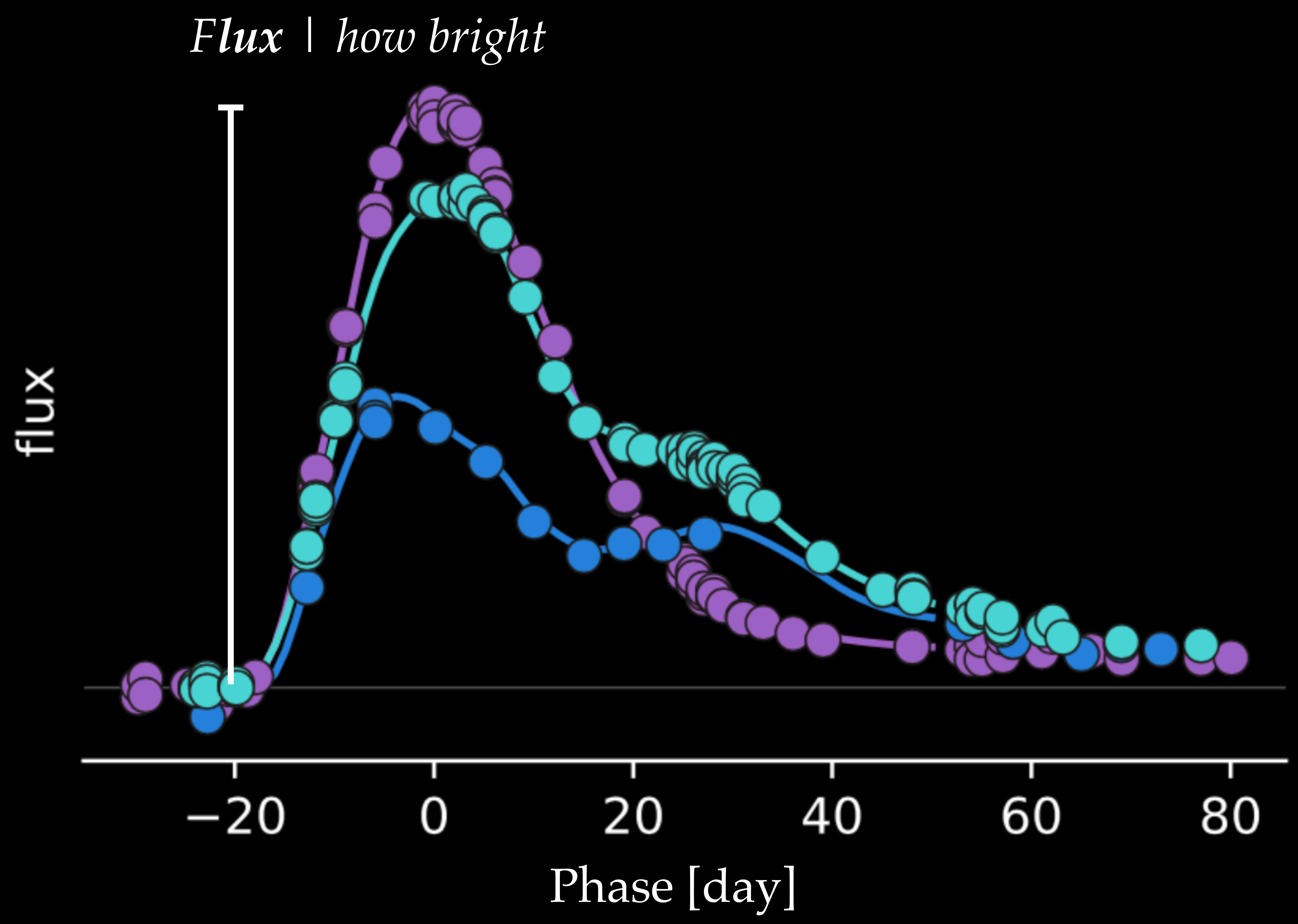
ID	Name	Reps	Class	RA	DEC	Obj. Type	Redshift	Host Name	Host Redshift	Reporting Group/s	Discovery Data Source/s	Classifying Group/s	Disc. Internal Name	Public	Object Spectra	Discovery Mag/Flux	Discovery Filter	Discovery Date (UT)	Sender
111505	AT 2022oag	1		15:21:16.589	-07:26:45.38					Pan-STARRS	Pan-STARRS		PS22fwb	Y		20.37	w-P1	2022-06-30 07:27:41.760	PS2_Bot1
111504	AT 2022oaf	1		22:40:46.086	+09:26:30.18					Pan-STARRS	Pan-STARRS		PS22fwa	Y		20.82	w-P1	2022-06-29 12:18:07.776	PS2_Bot1
111503	AT 2022oae	1		21:19:17.528	+00:31:29.22					Pan-STARRS	Pan-STARRS		PS22fvz	Y		21.09	w-P1	2022-06-30 11:20:40.416	PS2_Bot1
111502	AT 2022oad	1		21:19:43.417	+15:15:56.12					Pan-STARRS	Pan-STARRS		PS22fvy	Y		21.02	w-P1	2022-06-30 10:12:16.416	PS2_Bot1
111501	AT 2022oac	1		00:44:06.580	+08:25:36.95					GaiaAlerts	GaiaAlerts		Gaia22css	Y		18.36	G-Gaia	2022-06-29 09:10:04.800	Gaia_Bot1
111500	AT 2022oab	1		03:30:58.930	+59:14:39.59					GaiaAlerts	GaiaAlerts		Gaia22csq	Y		9.24	G-Gaia	2022-06-29 21:51:50.400	Gaia_Bot1
111499	AT 2022oaa	1		22:15:44.350	-53:03:03.92					GaiaAlerts	GaiaAlerts		Gaia22cso	Y		18.35	G-Gaia	2022-06-28 22:24:57.600	Gaia_Bot1
111498	AT 2022nzz	1		11:12:14.340	+40:21:39.17					GaiaAlerts	GaiaAlerts		Gaia22csn	Y		18.29	G-Gaia	2022-06-29 12:59:02.400	Gaia_Bot1
111497	AT 2022nzy	1		12:58:54.520	-16:02:35.48					GaiaAlerts	GaiaAlerts		Gaia22csl	Y		18.63	G-Gaia	2022-06-29 12:04:19.200	Gaia_Bot1
111496	AT 2022nzx	1		01:31:46.680	+33:36:58.00					GaiaAlerts	GaiaAlerts		Gaia22csk	Y		18.55	G-Gaia	2022-06-29 08:39:50.400	Gaia_Bot1

Less than 2 minutes from observation to discovery


Number of SNe discovered
1000
100
10
1
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
Year
First
Extragalactic SN
Name
"Super-Nova"
Suggested
Zwicky SN
Patrol
First
Classification
Scheme
Robotic SN
Searches
First CCD
Searches
Accelerating
Universe
Discovered
LSST?
ZTF
GAIA
DES
PAN-STARRS
PTF/iPTF
CRTS
SDSS
SNLS
ESSENCE


TRANSIENT
NAME SERVER
ATs Discovery Mag Histograms [2016 to 2025-06-29]
[0<Disc.Mag.<30; Legend shows: #Objects, Peak-Value(StdDev)]
ZTF 56498 20.01(0.86)
Pan-STARRS 50988 21.05(0.75)
ATLAS 21421 19.21(0.71)
GaiaAlerts 19751 18.82(1.46)
GOTO 2613 19.57(0.74)
WFST 2565 22.04(0.75)
DESIRT 2243 22.32(0.98)
iPTF 1642 19.74(0.88)
ASAS-SN 1356 17.07(1.12)
MASTER 1351 17.11(1.91)
Number of Objects
Discovery Mag.

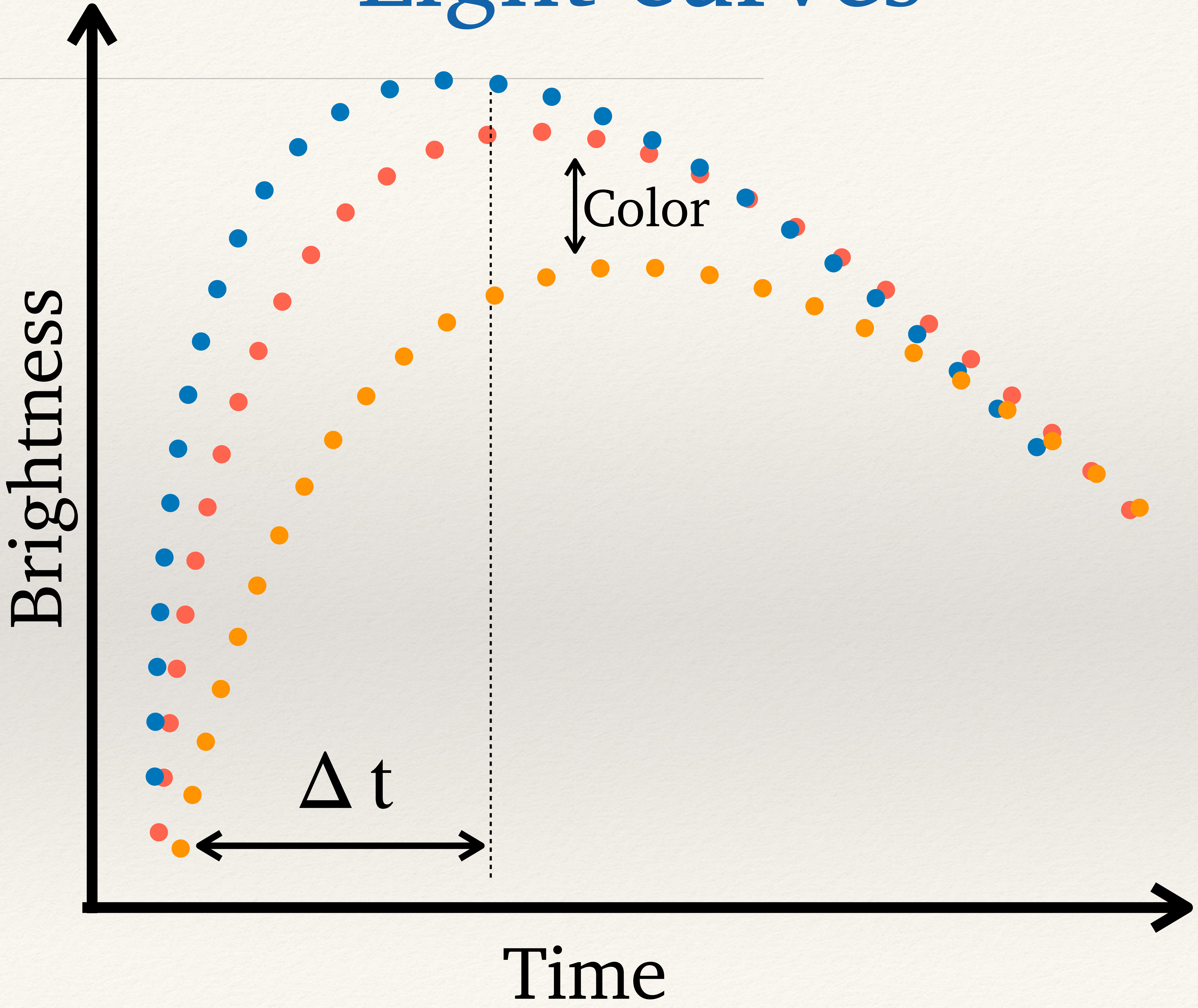




Flux | *how bright*
flux
−20
0
20
40
60
80
Phase [day]

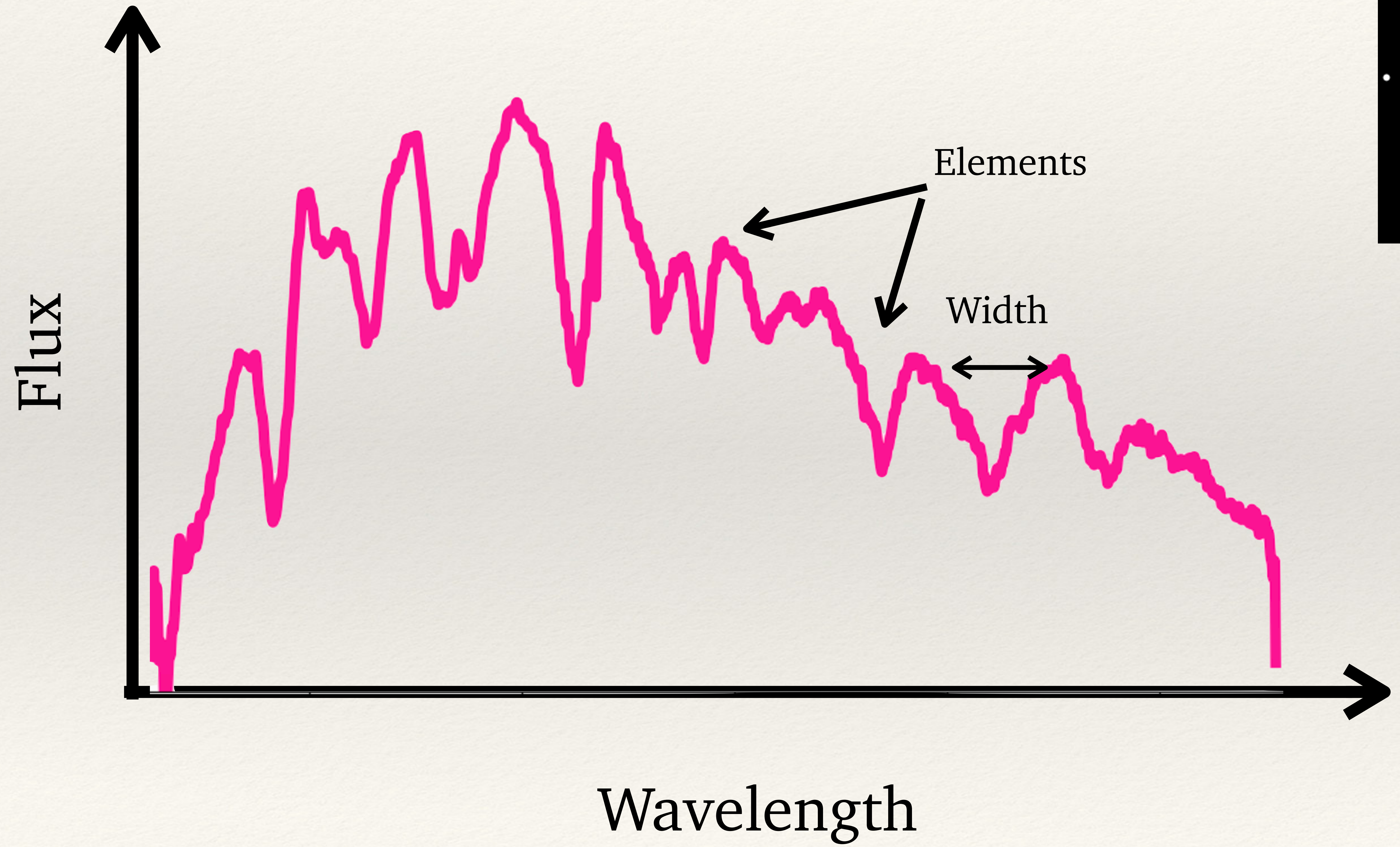
SN2011fe

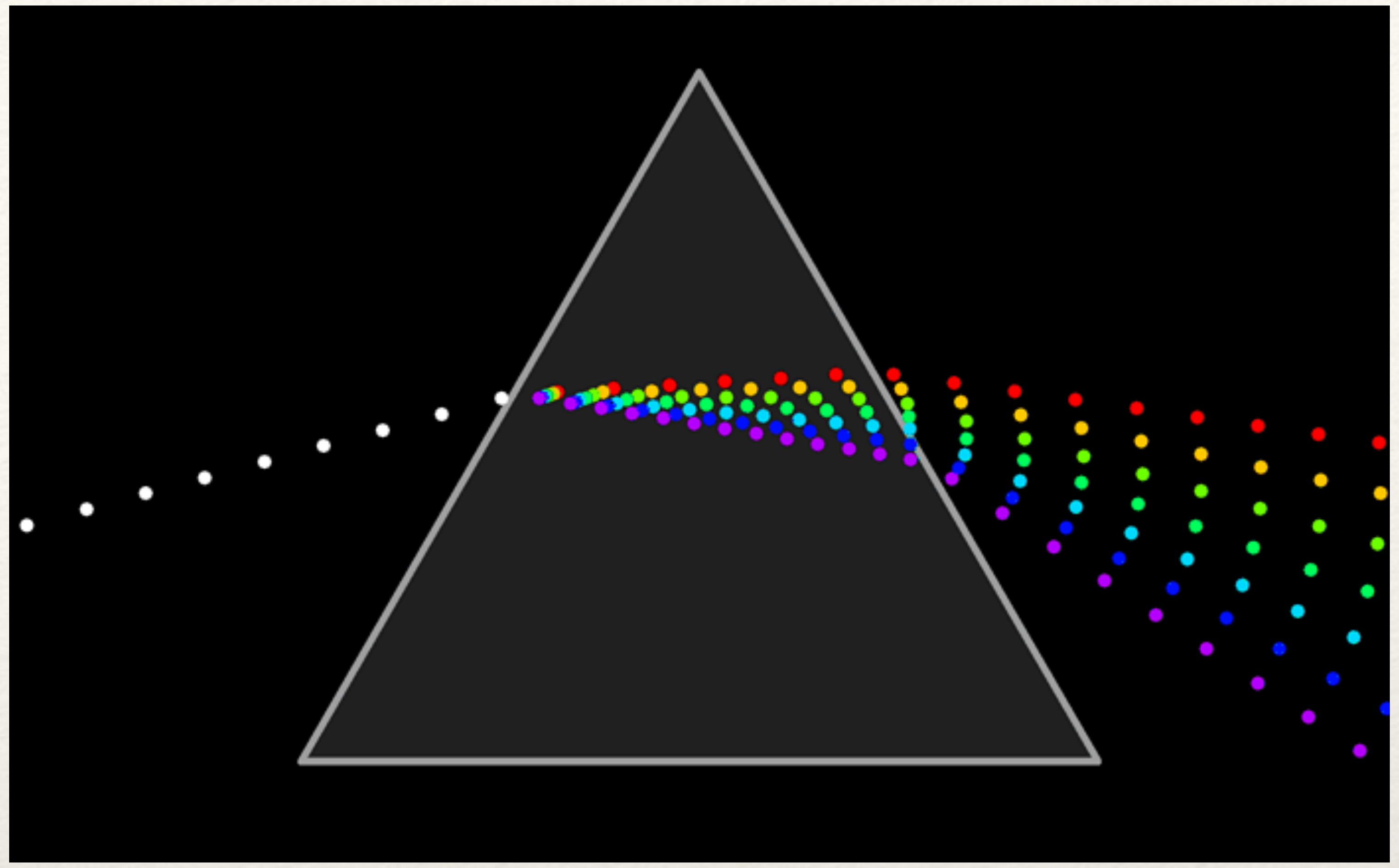
Light curves



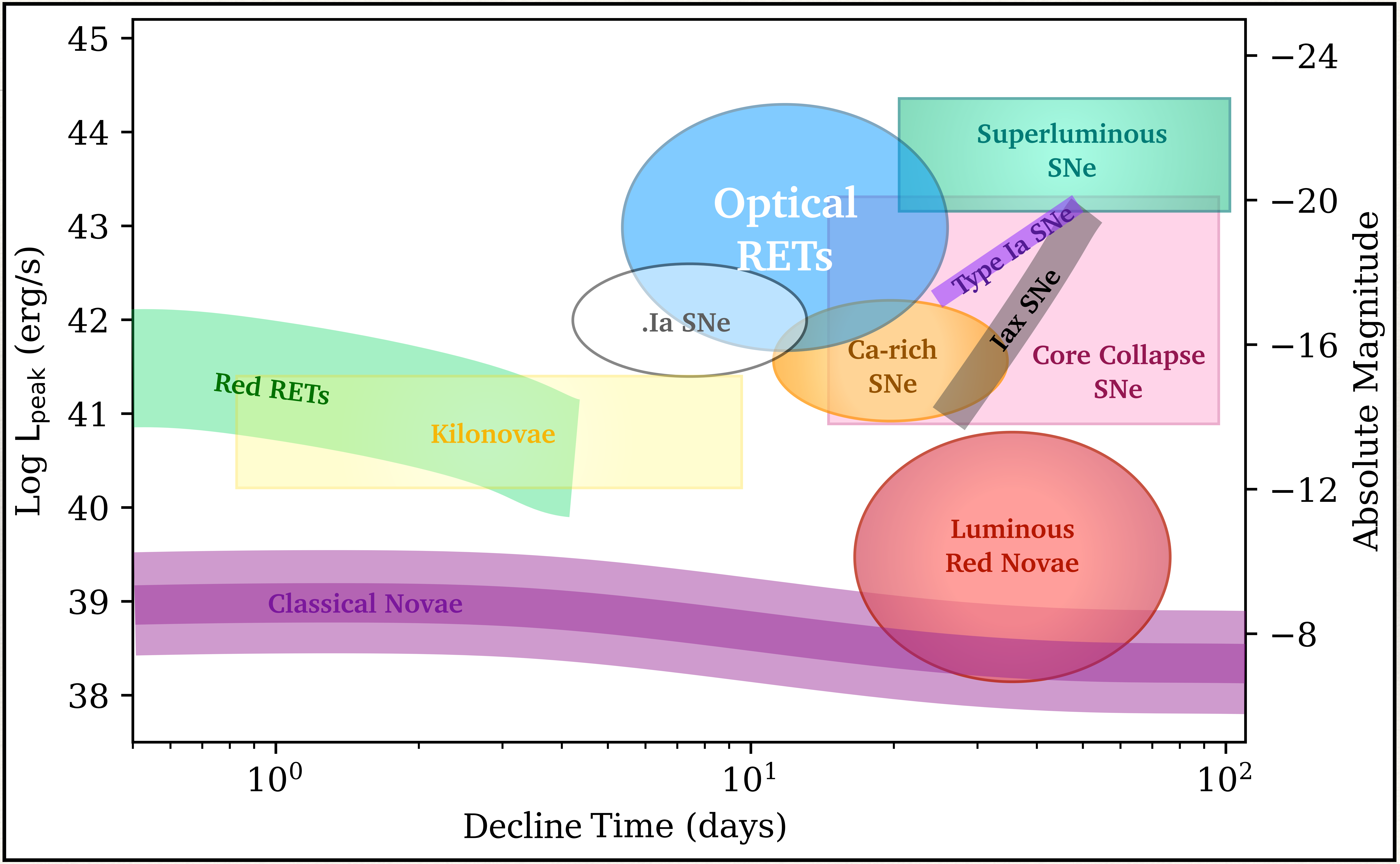
Light curves give us properties of the explosion

Spectroscopy



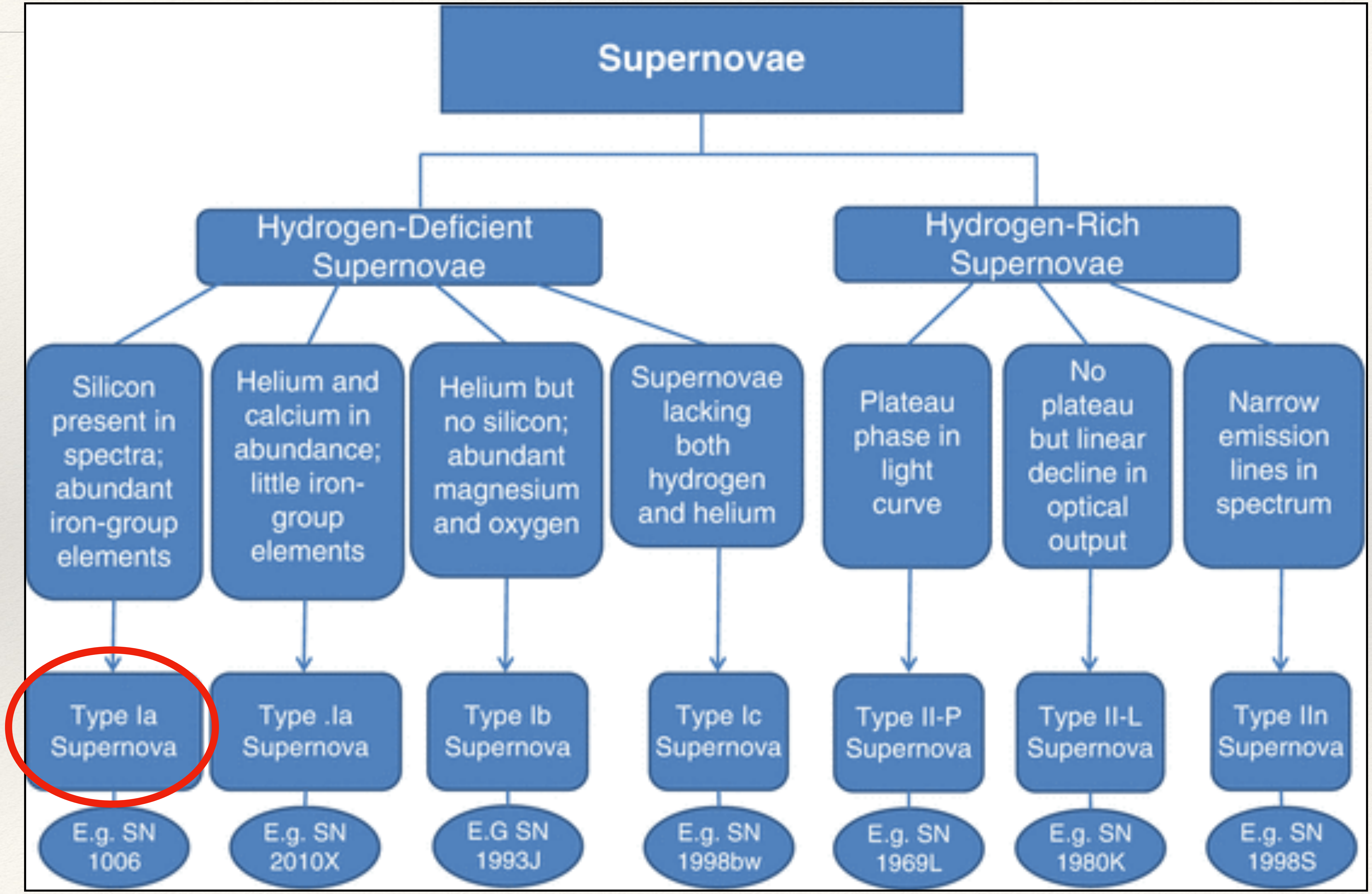


Spectra tell us about the chemical composition of material in the explosion and how fast its moving

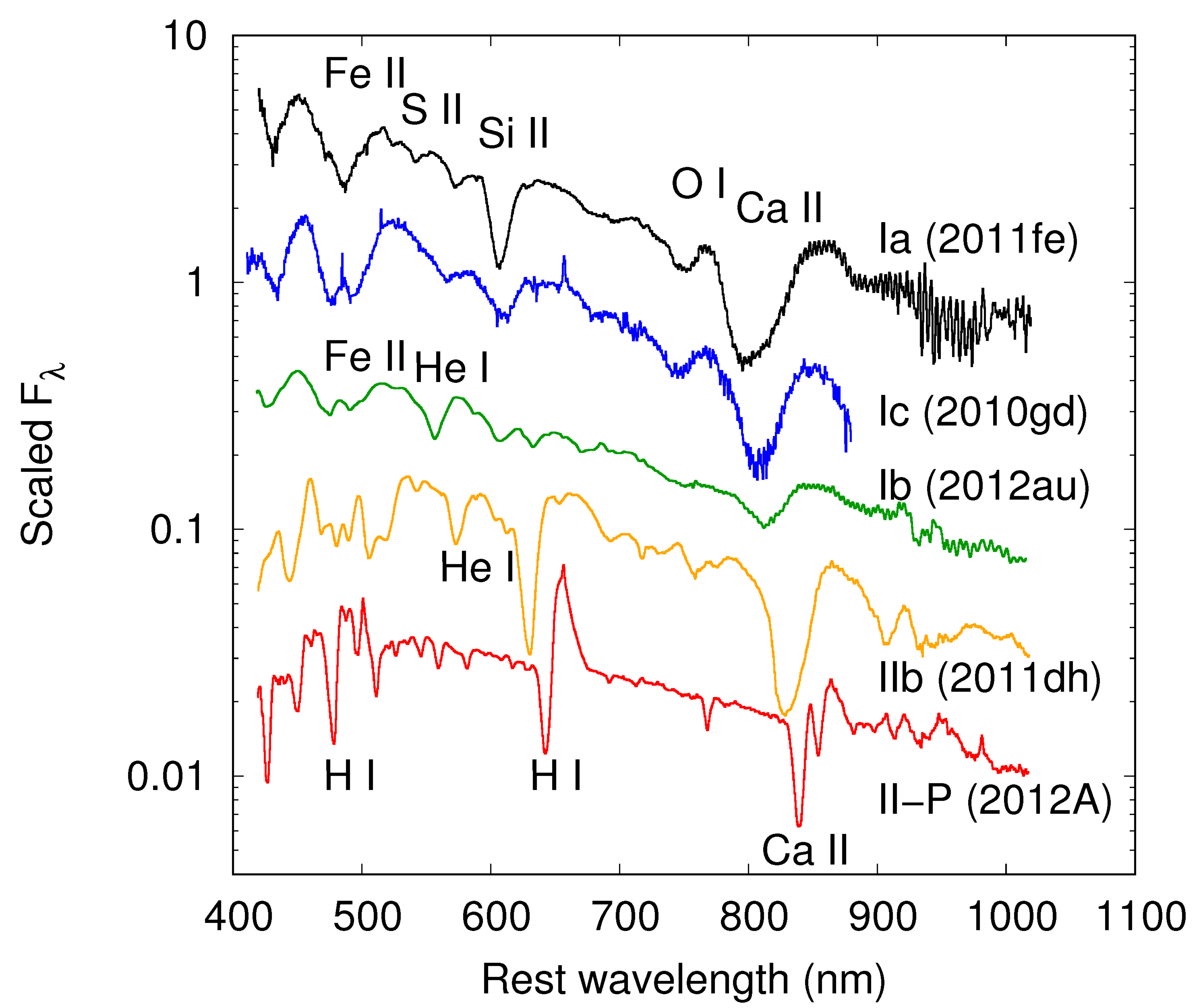


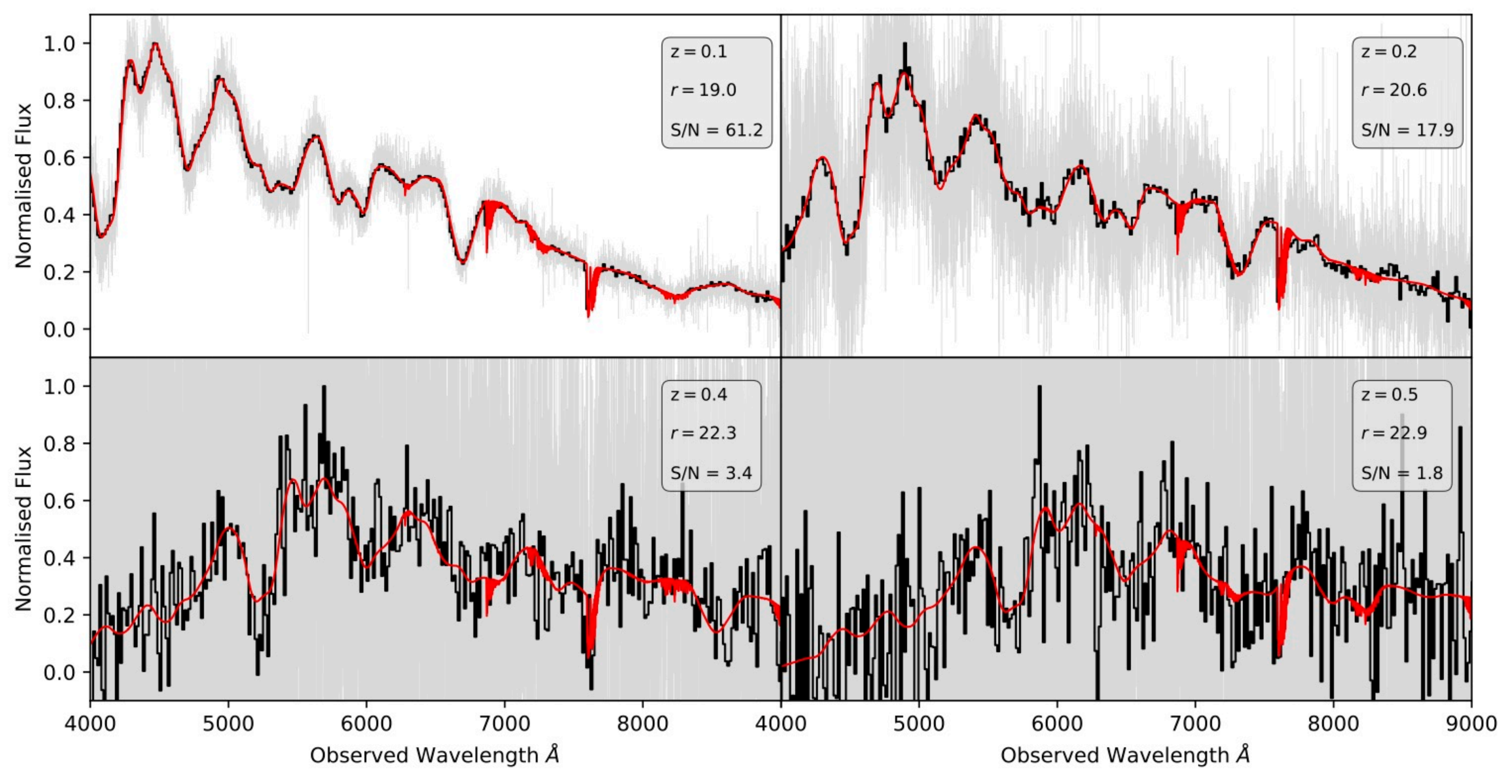
Log L_{peak} (erg/s)
45
44
43
42
41
40
39
38
Decline Time (days)
10^0
10^1
10^2
Absolute Magnitude
−24
−20
−16
−12
−8
Optical RETs
Superluminous SNe
Type Ia SNe
Iax SNe
.Ia SNe
Ca-rich SNe
Core Collapse SNe
Red RETs
Kilonovae
Luminous Red Novae
Classical Novae

Historic observational scheme

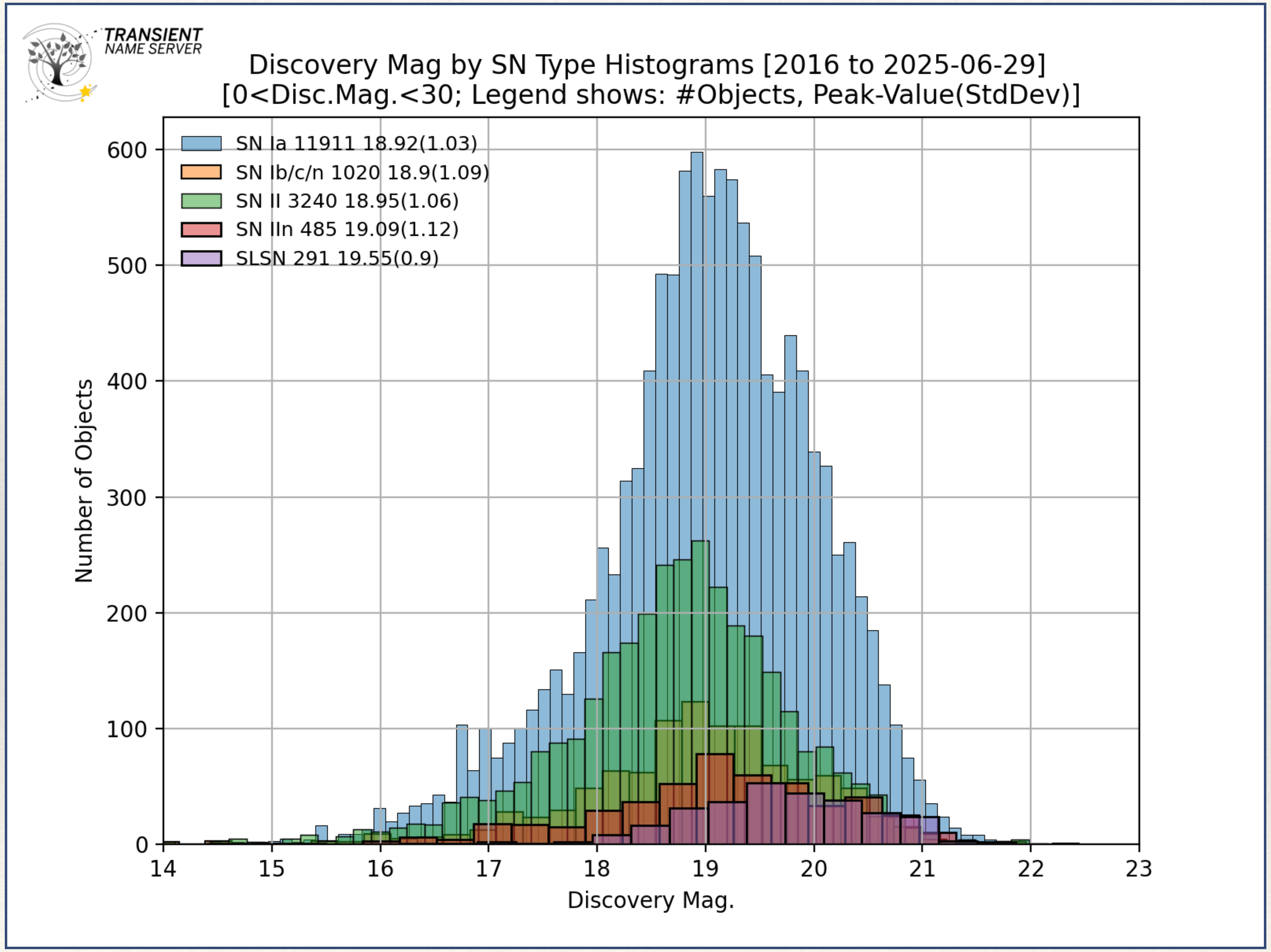


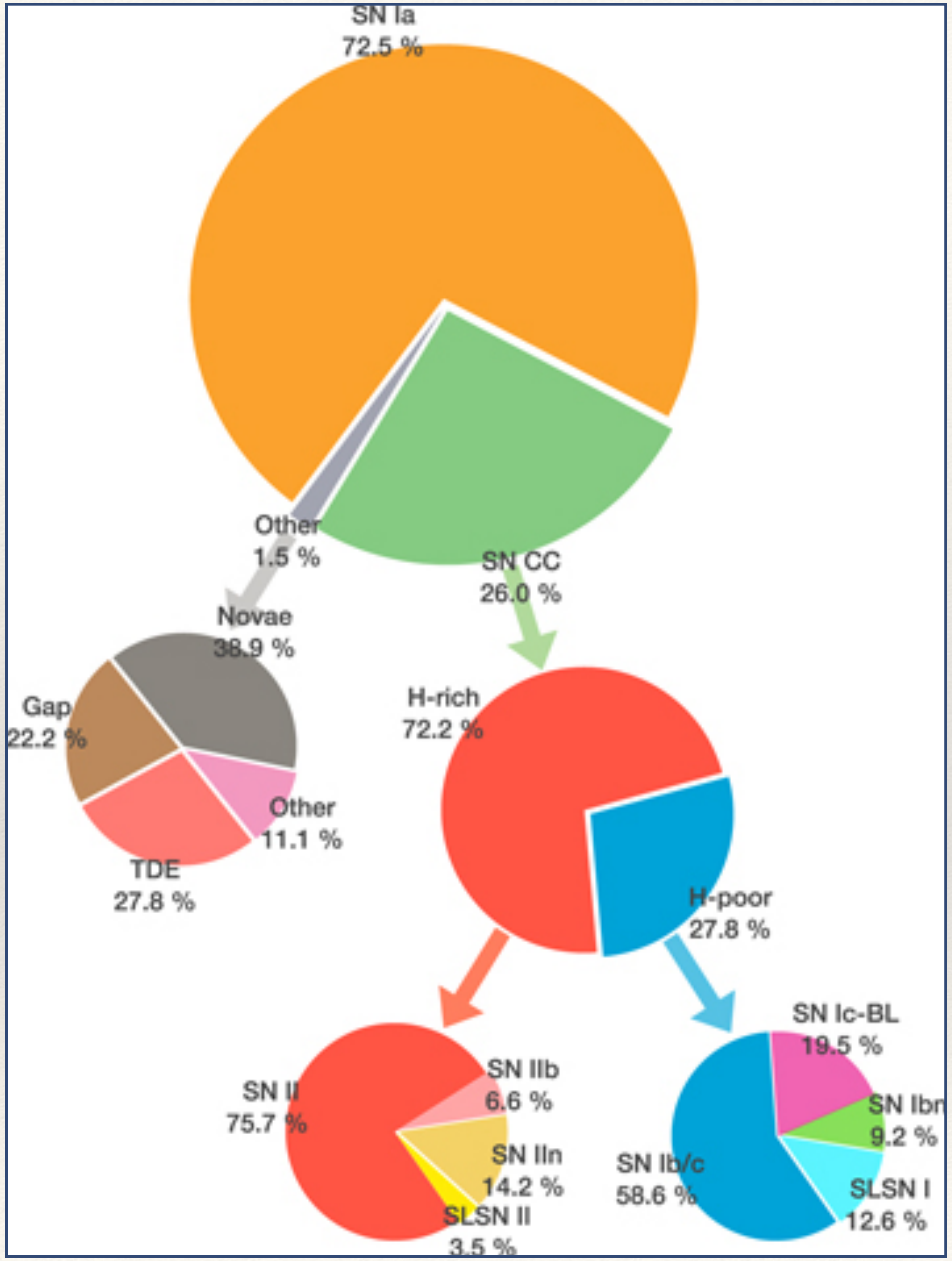
Extragalactic optical transients


10
1
0.1
0.01
Scaled F_λ
400
500
600
700
800
900
1000
1100
Rest wavelength (nm)
Fe II
S II
Si II
O I
Ca II
Ia (2011fe)
Ic (2010gd)
Fe II
He I
Ib (2012au)
He I
IIb (2011dh)
H I
H I
II–P (2012A)
Ca II

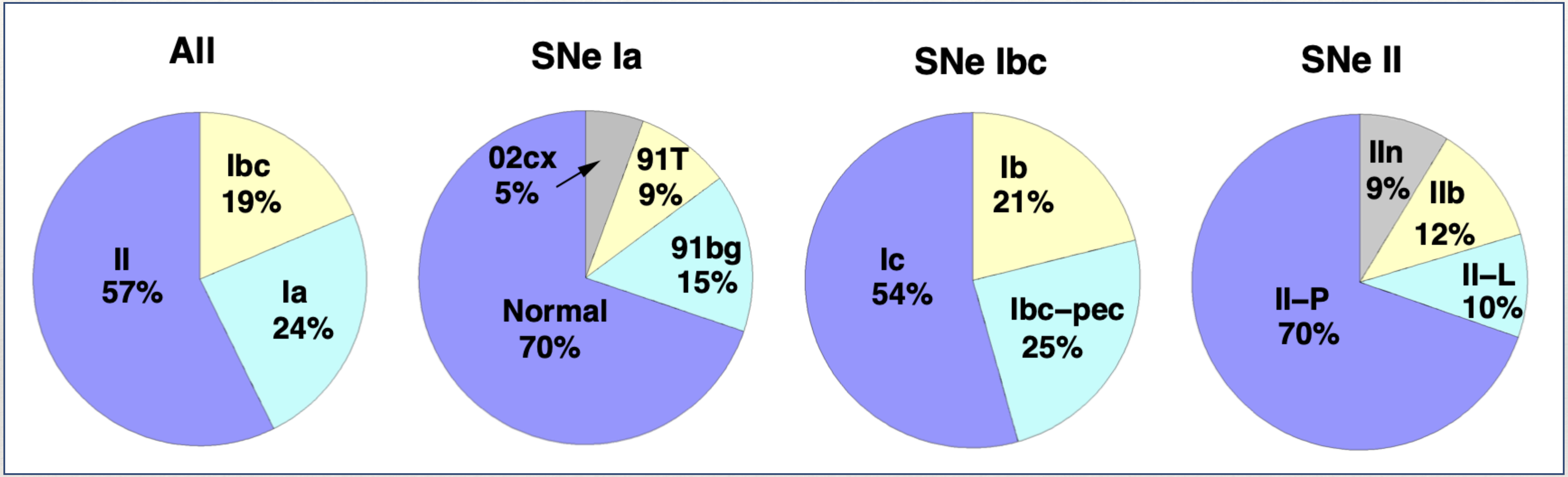

z = 0.1
r = 19.0
S/N = 61.2
z = 0.2
r = 20.6
S/N = 17.9
z = 0.4
r = 22.3
S/N = 3.4
z = 0.5
r = 22.9
S/N = 1.8
Normalised Flux
Observed Wavelength Å
1.0
0.8
0.6
0.4
0.2
0.0
4000
5000
6000
7000
8000
9000

Observationally common





Intrinsically bright



Type Ia SNe

→**Powered by:** ^{56}Ni → ^{56}Co → ^{56}Fe

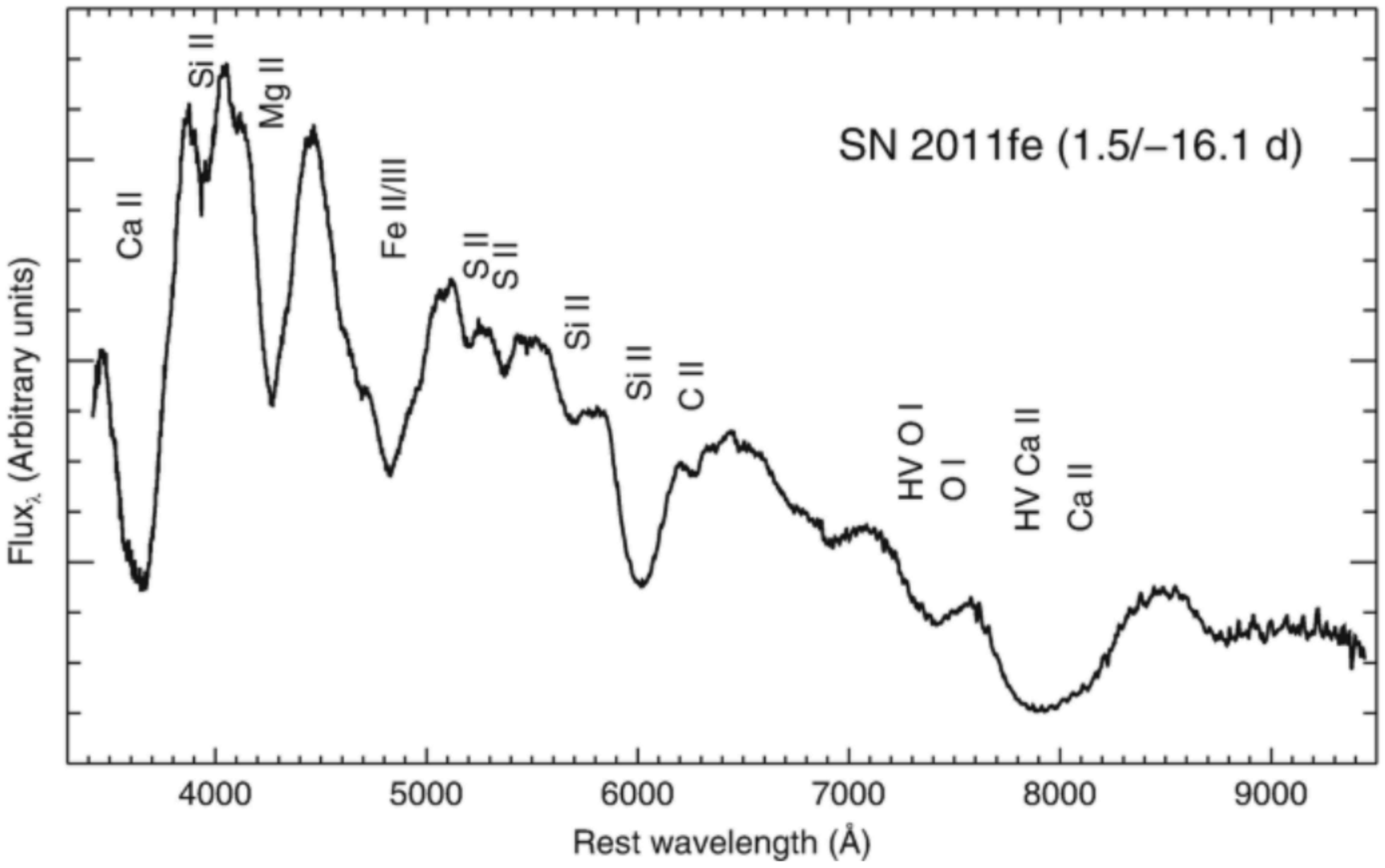
→**Bright**: ~5-10 billion suns

Energy ~10^{51} erg, but from nuclear burning rather than gravitational collapse

- 10^{51} erg is approximately the gravitational binding energy of a white dwarf

Nuclear statistical equilibrium: produce a lot of iron-group elements

Other explosive oxygen/carbon burning products: e.g. silicon, sulphur



No Hydrogen: Classic Silicon

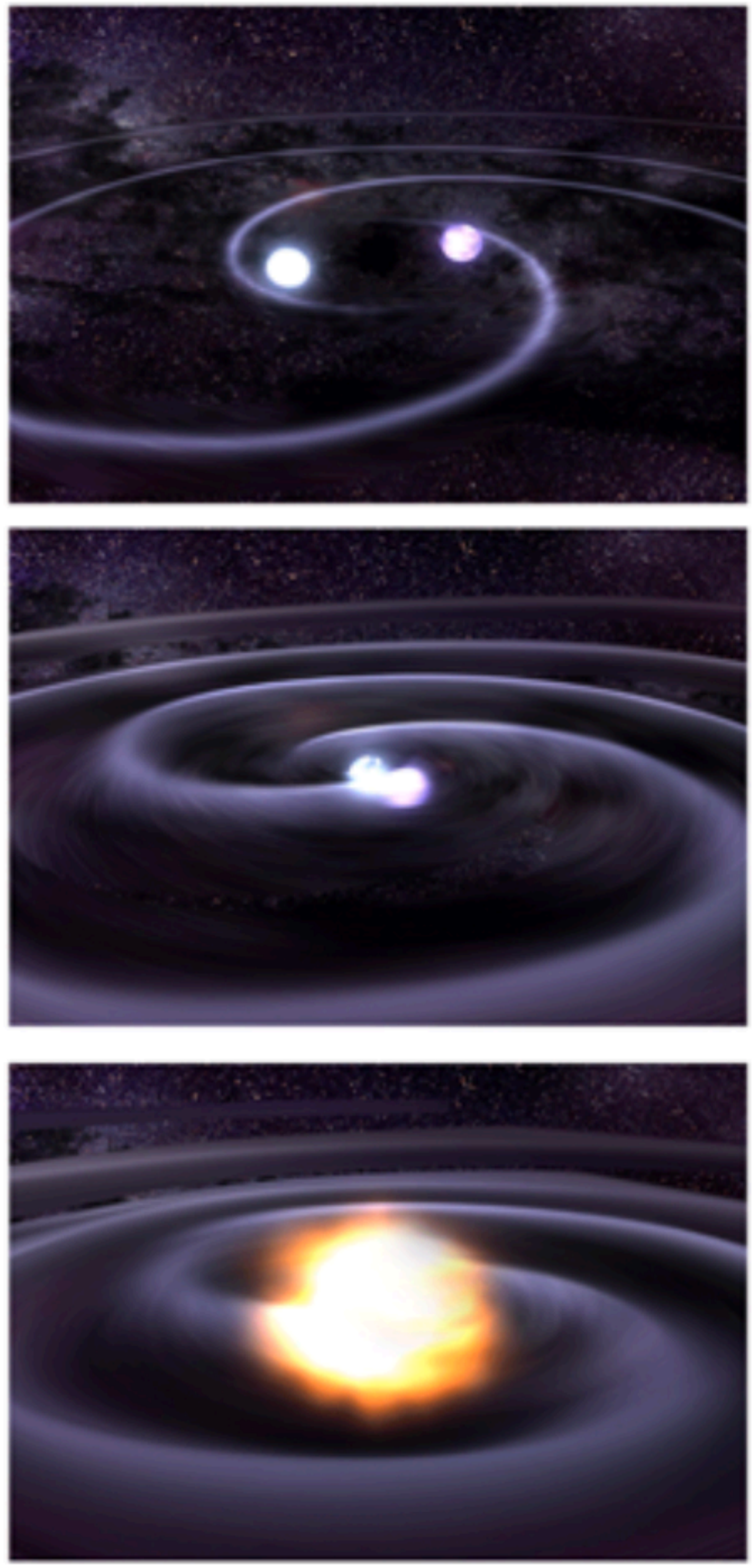
Type Ia SNe

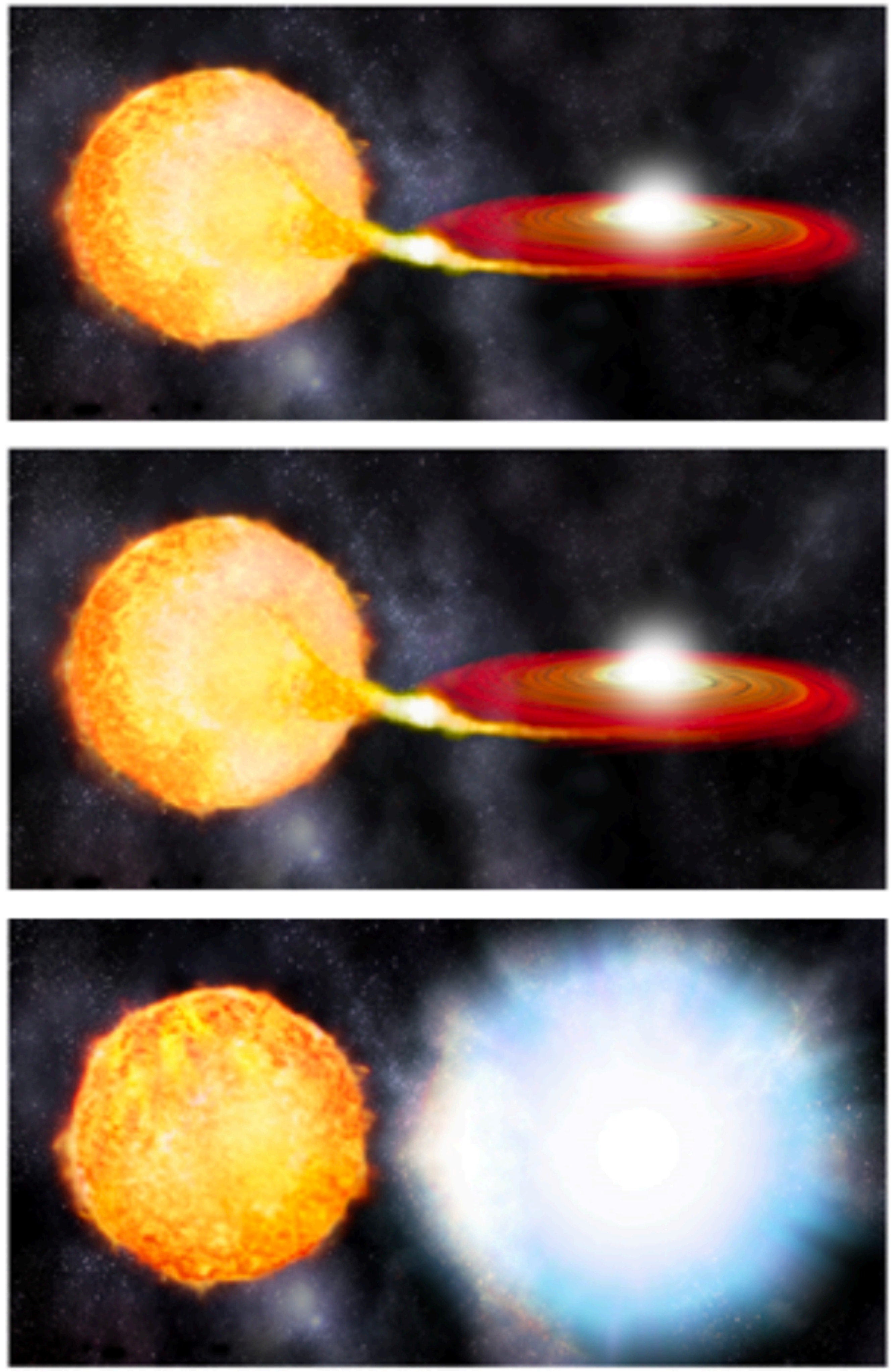
Carbon-oxygen white dwarf reaching 1.4 $M_\odot$ (Chandrasekhar mass) is unstable — explosive CO burning ensues

Trigger uncertain:

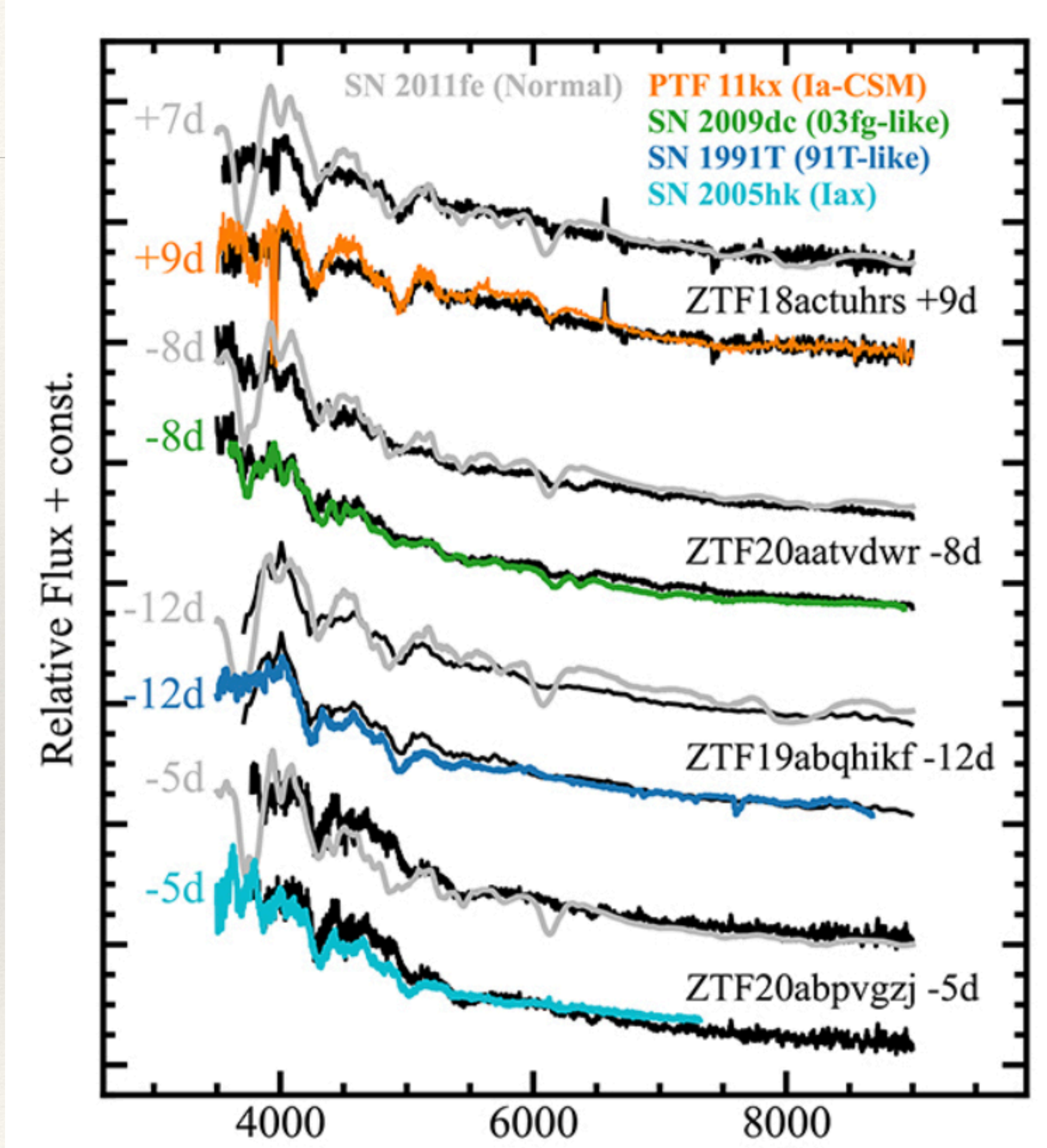
- WD accretes from donor (single degenerate), or two WDs collide/merge (double degenerate)?
- Explosion starts inside, or surface detonation triggers compression?

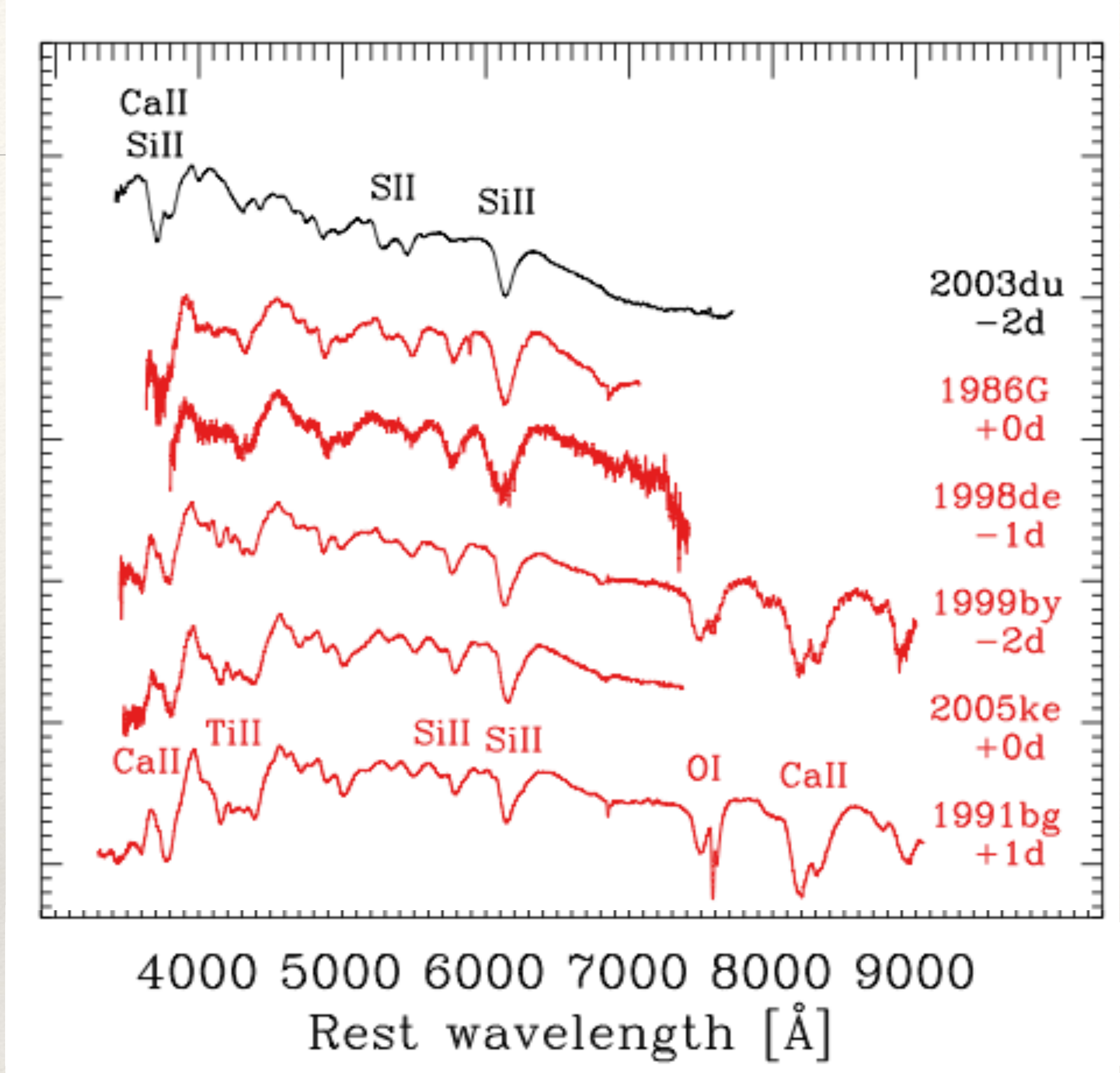
Different channels may contribute to different sub-types



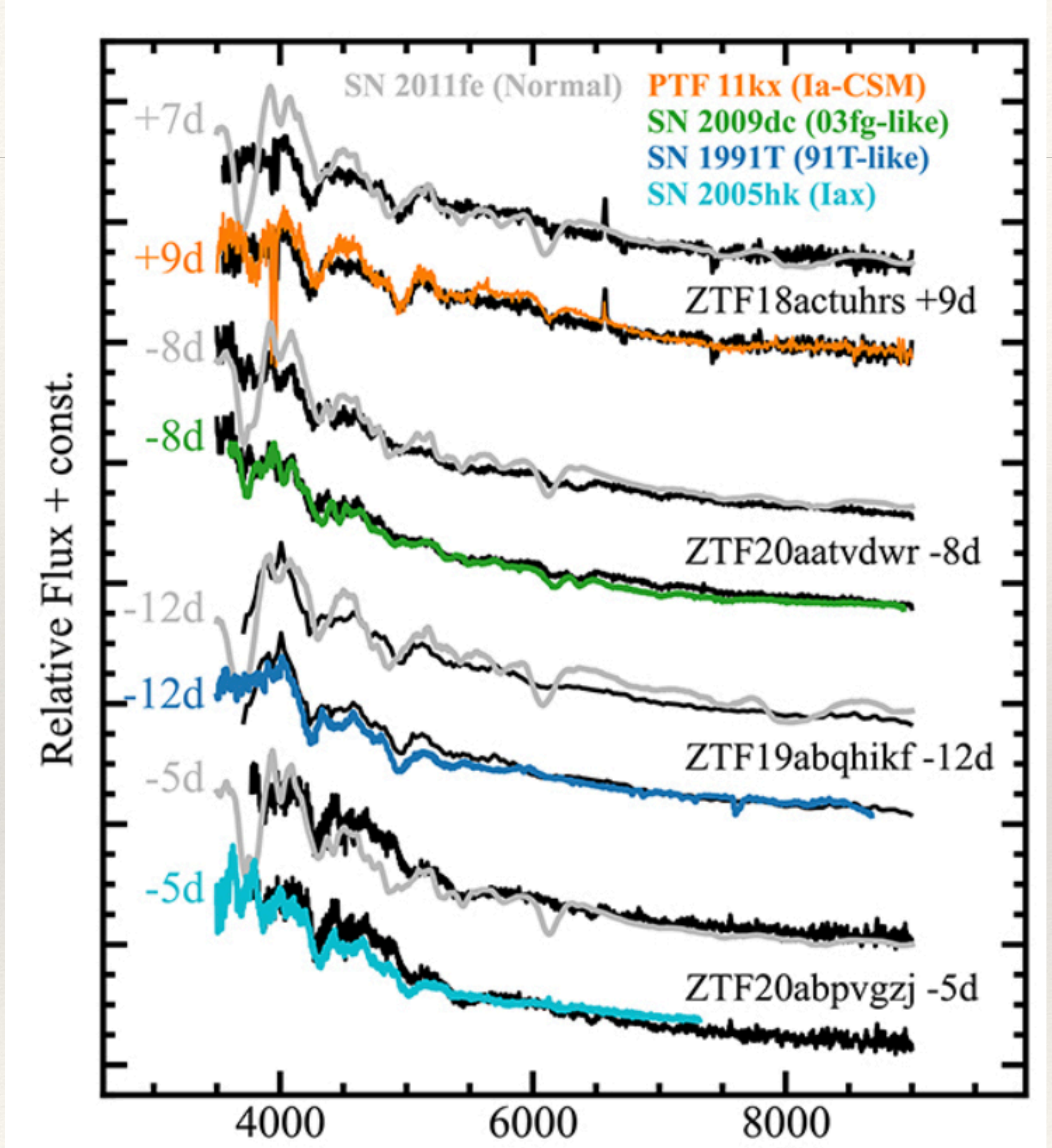


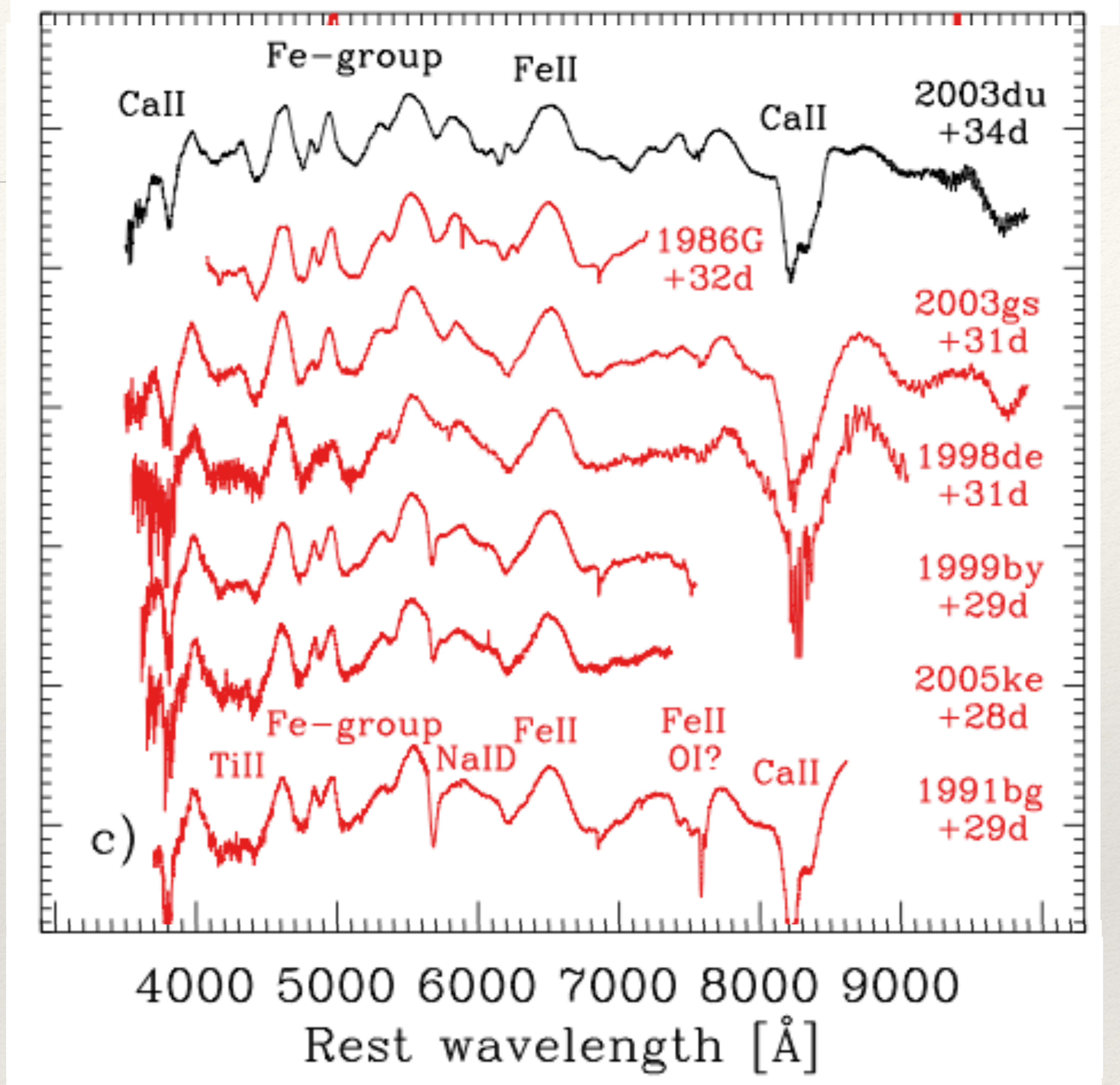
More on Physics later





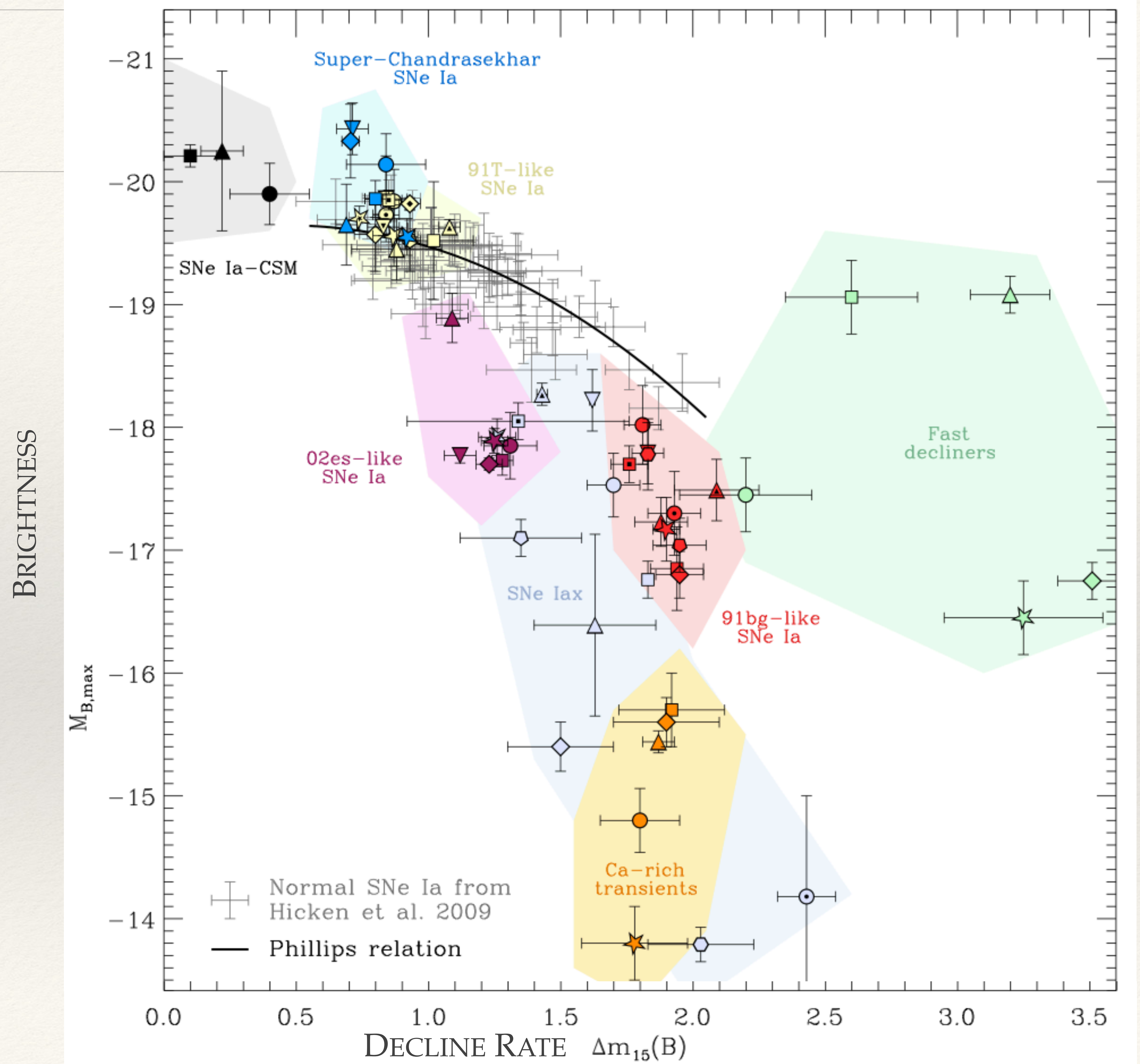
Diversity and similarity



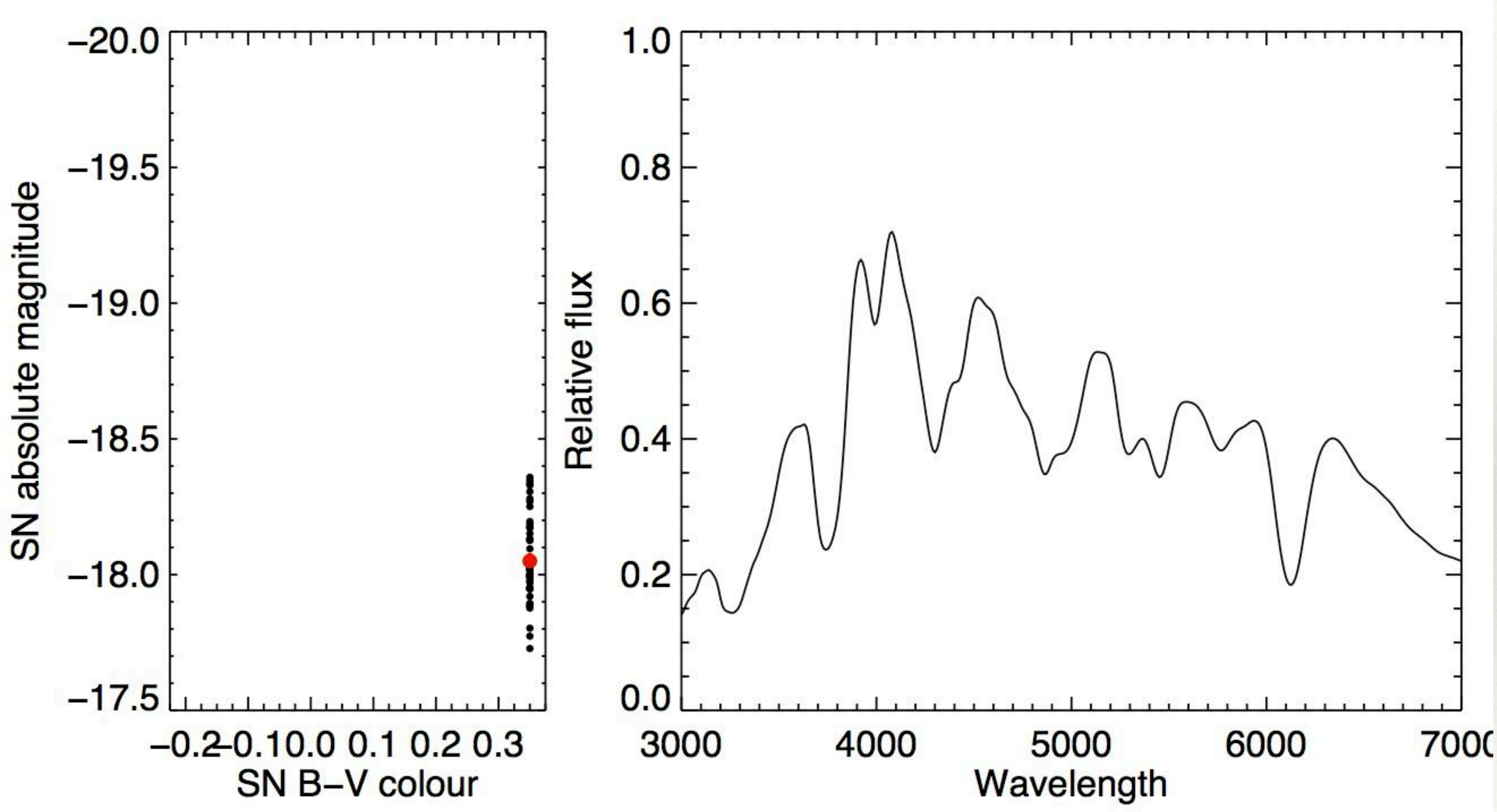


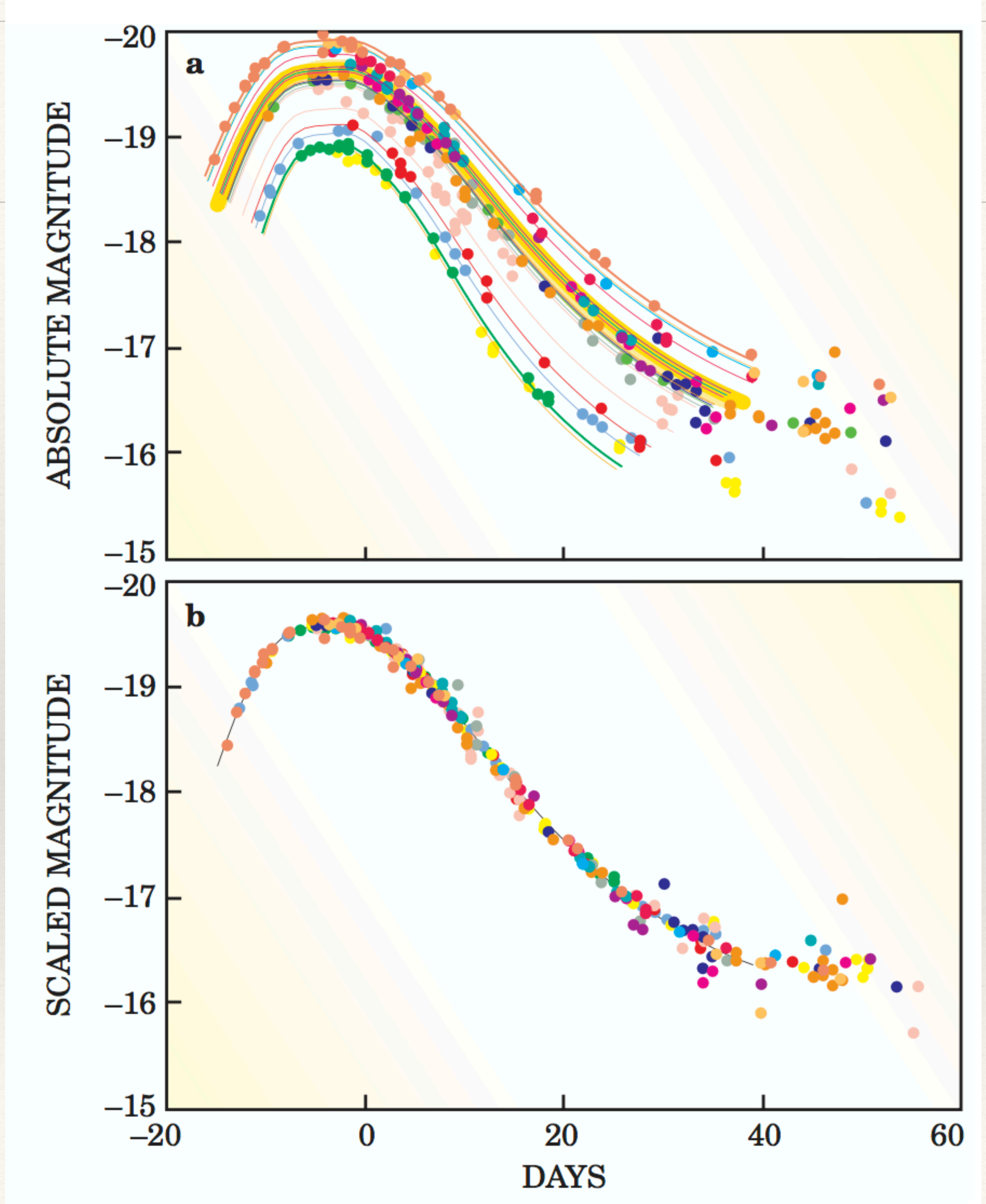
Diversity and similarity

Consistently no H



Brightness
Decline Rate
Super−Chandrasekhar SNe Ia
91T−like SNe Ia
SNe Ia−CSM
02es−like SNe Ia
SNe Iax
91bg−like SNe Ia
Fast decliners
Ca−rich transients
Normal SNe Ia from Hicken et al. 2009
Phillips relation
$M_{B,max}$
$\Delta m_{15}(B)$
−21
−20
−19
−18
−17
−16
−15
−14
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5


SN absolute magnitude
−20.0
−19.5
−19.0
−18.5
−18.0
−17.5
−0.2
−0.1
0.0
0.1
0.2
0.3
SN B−V colour
Relative flux
1.0
0.8
0.6
0.4
0.2
0.0
3000
4000
5000
6000
7000
Wavelength



__Standardisable candles__

2 empirical corrections

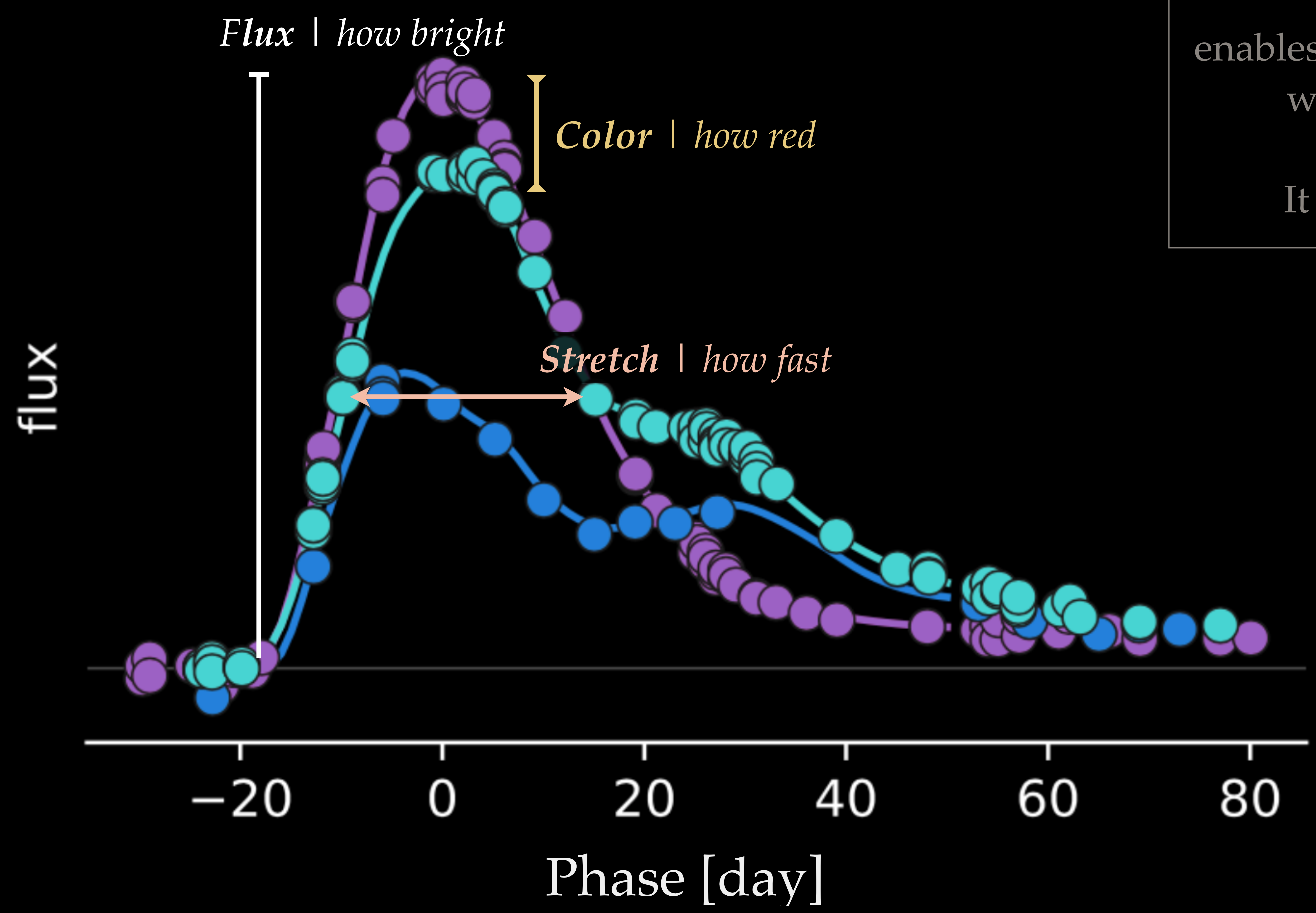
=>

dispersion: 0.15mag

Brighter SNeIa:

- ***Bluer; slowly declining***

Flux, stretch & color



The SALT algorithm
enables to fit the entire light-curves
with these 3 parameters.

It is a PCA-based model.

Measuring distances

intrinsic brightness — Light-curve colour

Observationally
(from the light-curve)

$$\boxed{\mu = m - (M - \alpha \times x_1 + \beta \times c)}$$

Peak magnitude — Light-curve width

$$w = P/\rho$$

Theoretically
(using the redshift)

$$\mu = 5 \log D_L + 25$$

Dark Energy — EoS of DE

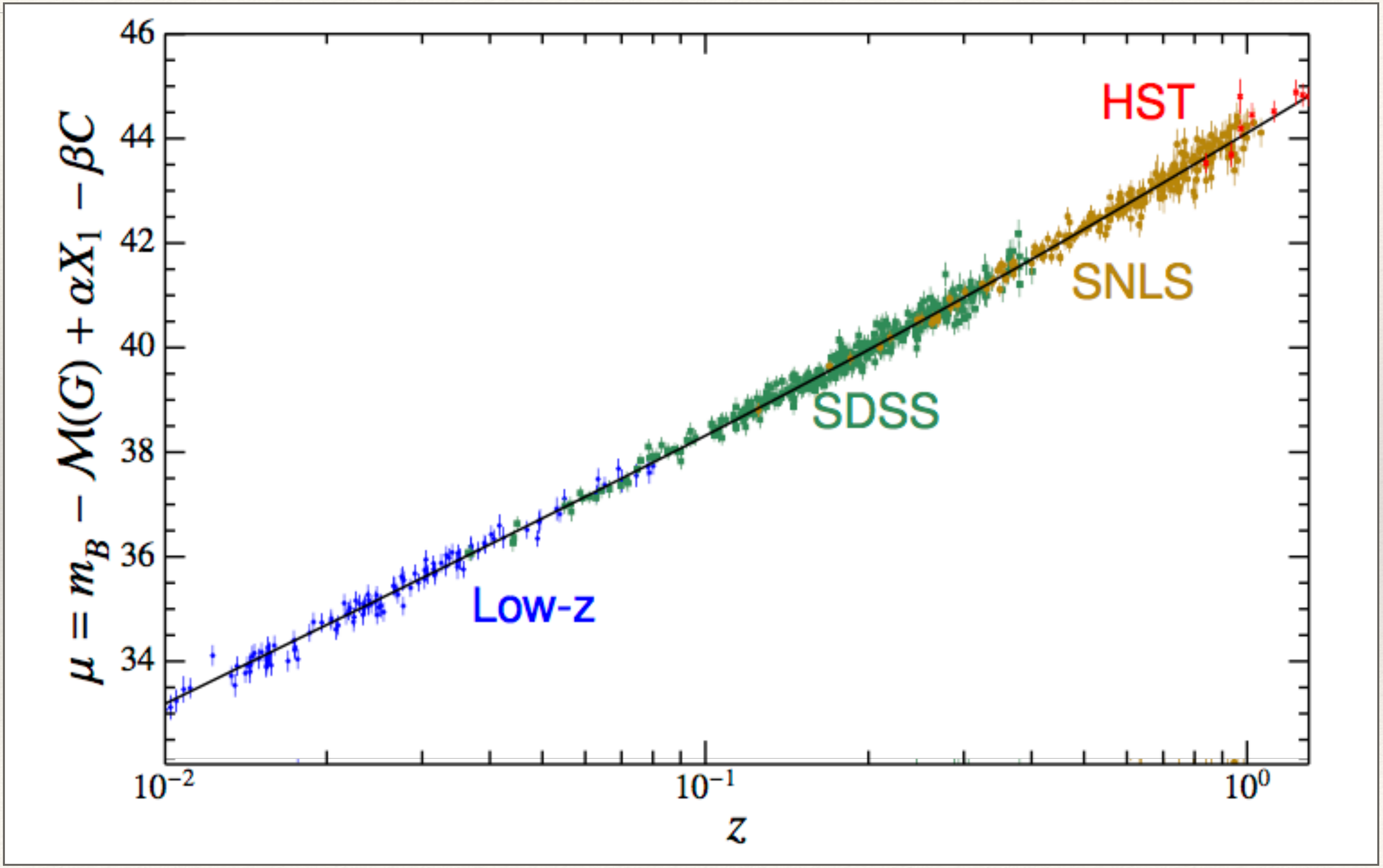
where $D_L = f(z, H_0, \Omega_m, \Omega_\Lambda, \Omega_k) + w(z)$

$$f(z, \{\Omega\}) = c\ (1+z) \times \int_0^z dz' \left[\Omega_r (1+z')^4 + \Omega_M (1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w)}\right]^{-\frac{1}{2}}$$

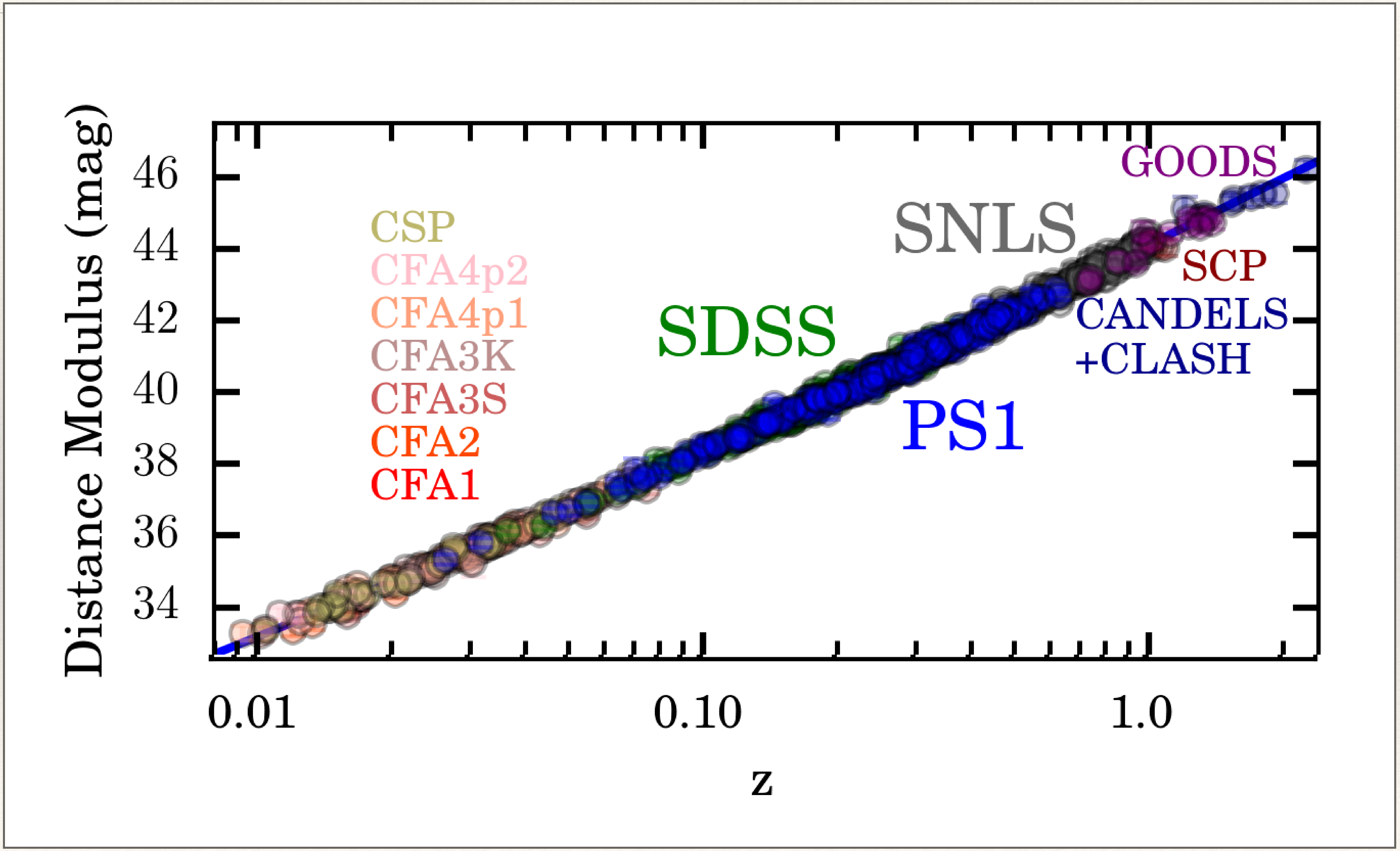
Residuals
(what's unexplained)

$$\mathrm{HR} = \Delta\mu = \mu_{\mathrm{obs}} - \mu_{\mathrm{theory}} \qquad \sigma_{int} \sim 0.15$$

It works!

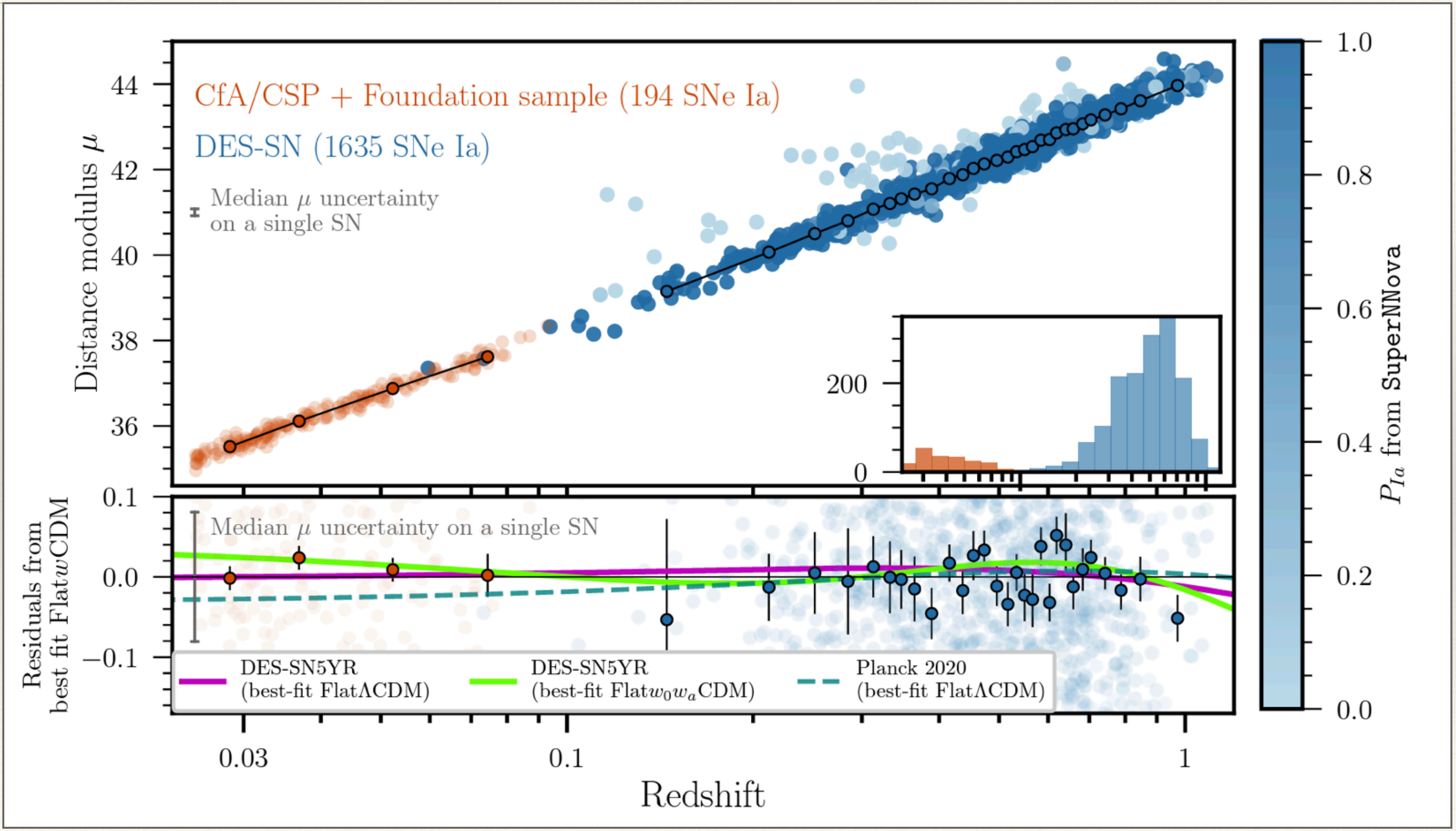

HST
SNLS
SDSS
Low-z
$\mu = m_B - \mathcal{M}(G) + \alpha X_1 - \beta C$
46
44
42
40
38
36
34
10^{-2}
10^{-1}
10^{0}
z

It works!

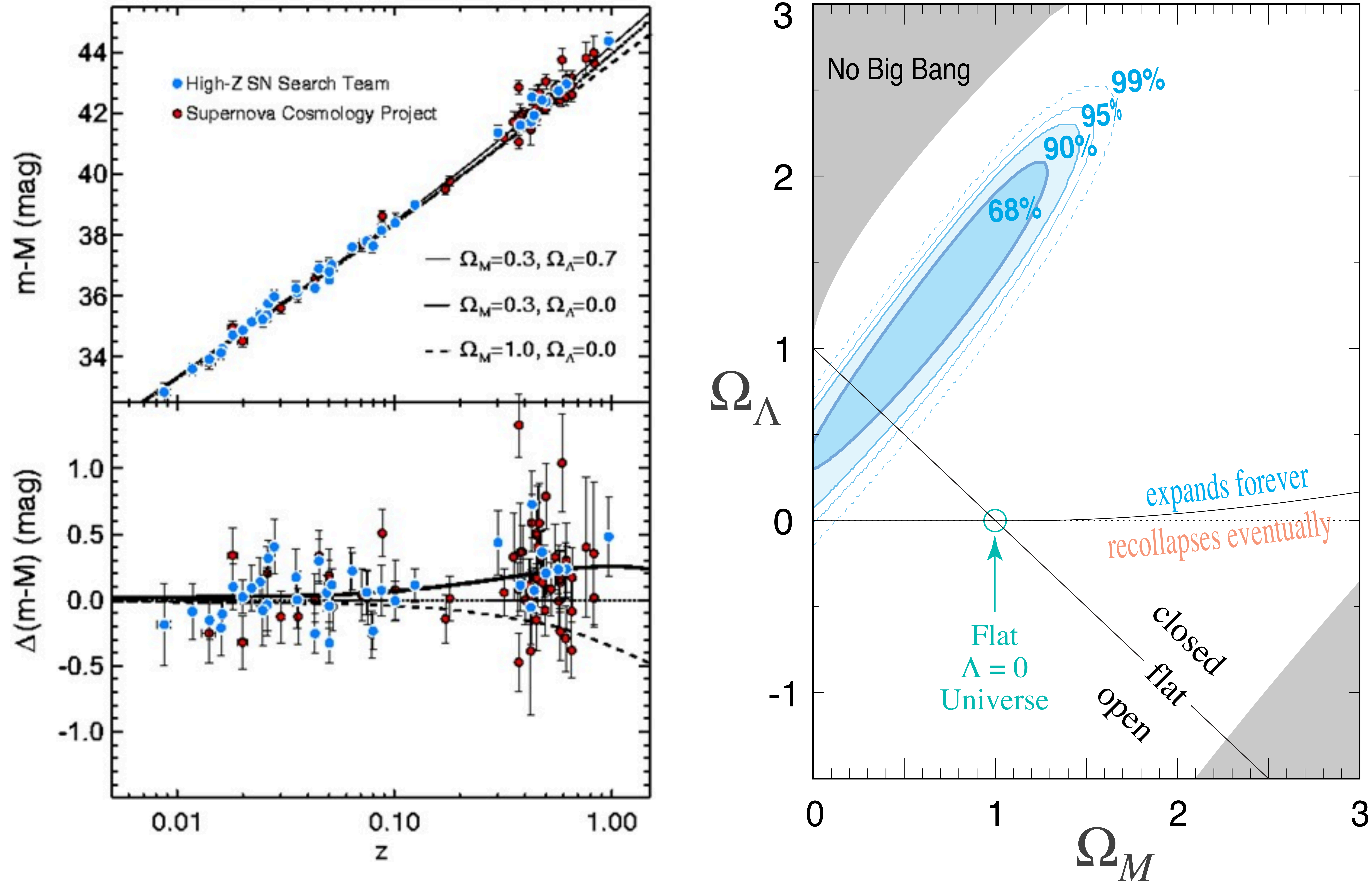


Distance Modulus (mag)
46
44
42
40
38
36
34
0.01
0.10
1.0
z
CSP
CFA4p2
CFA4p1
CFA3K
CFA3S
CFA2
CFA1
SDSS
SNLS
PS1
GOODS
SCP
CANDELS
+CLASH

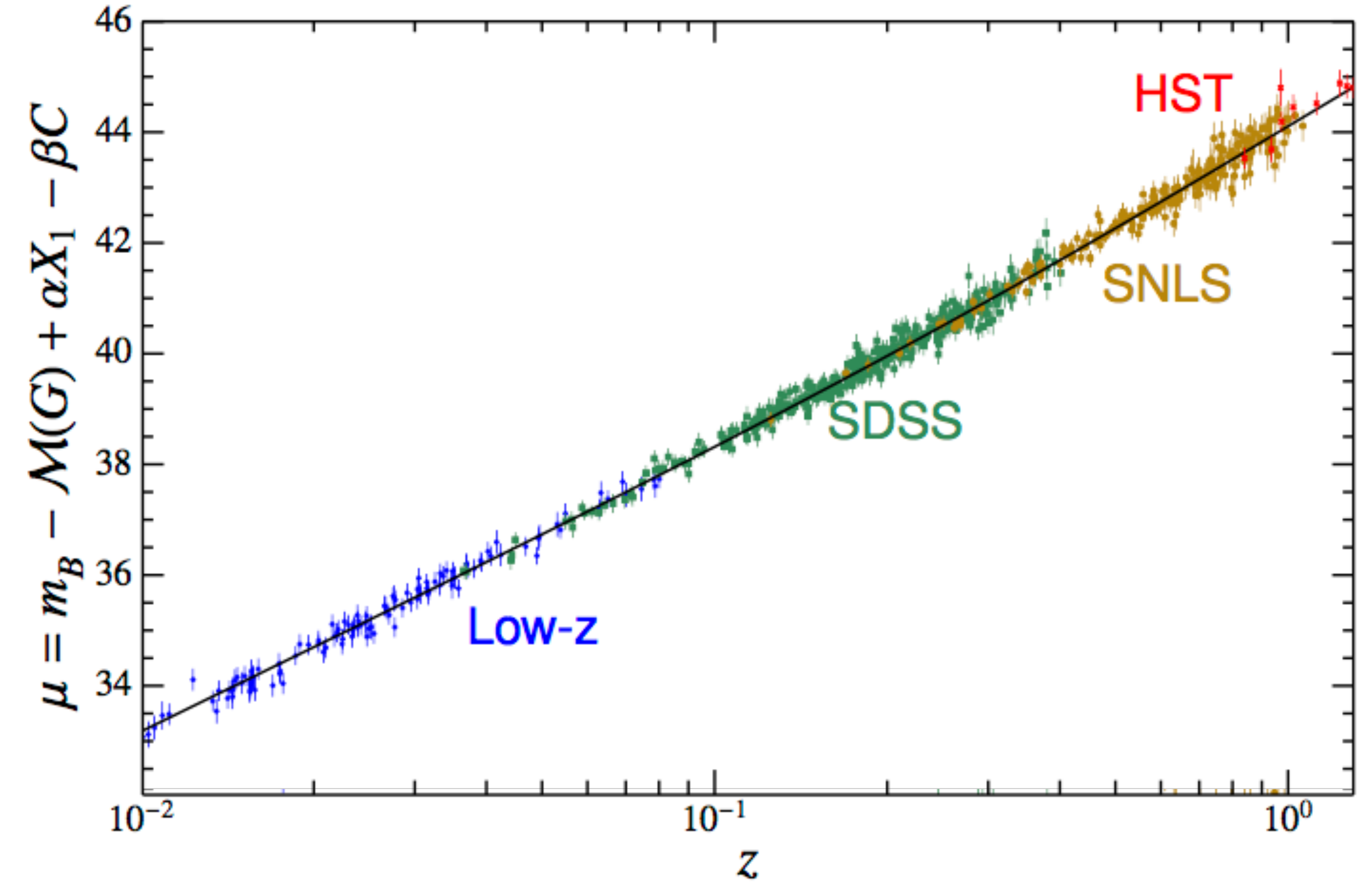
It works!

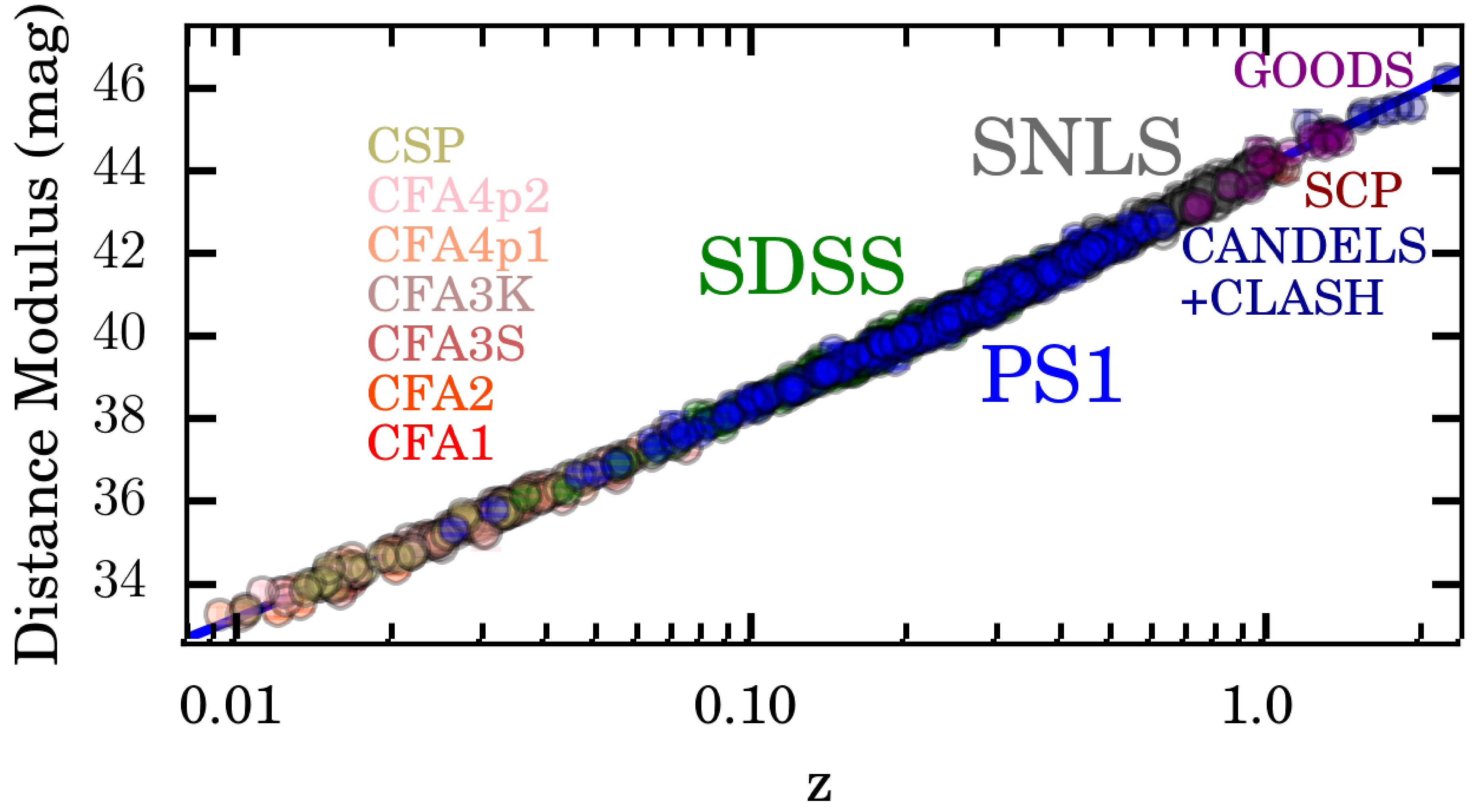


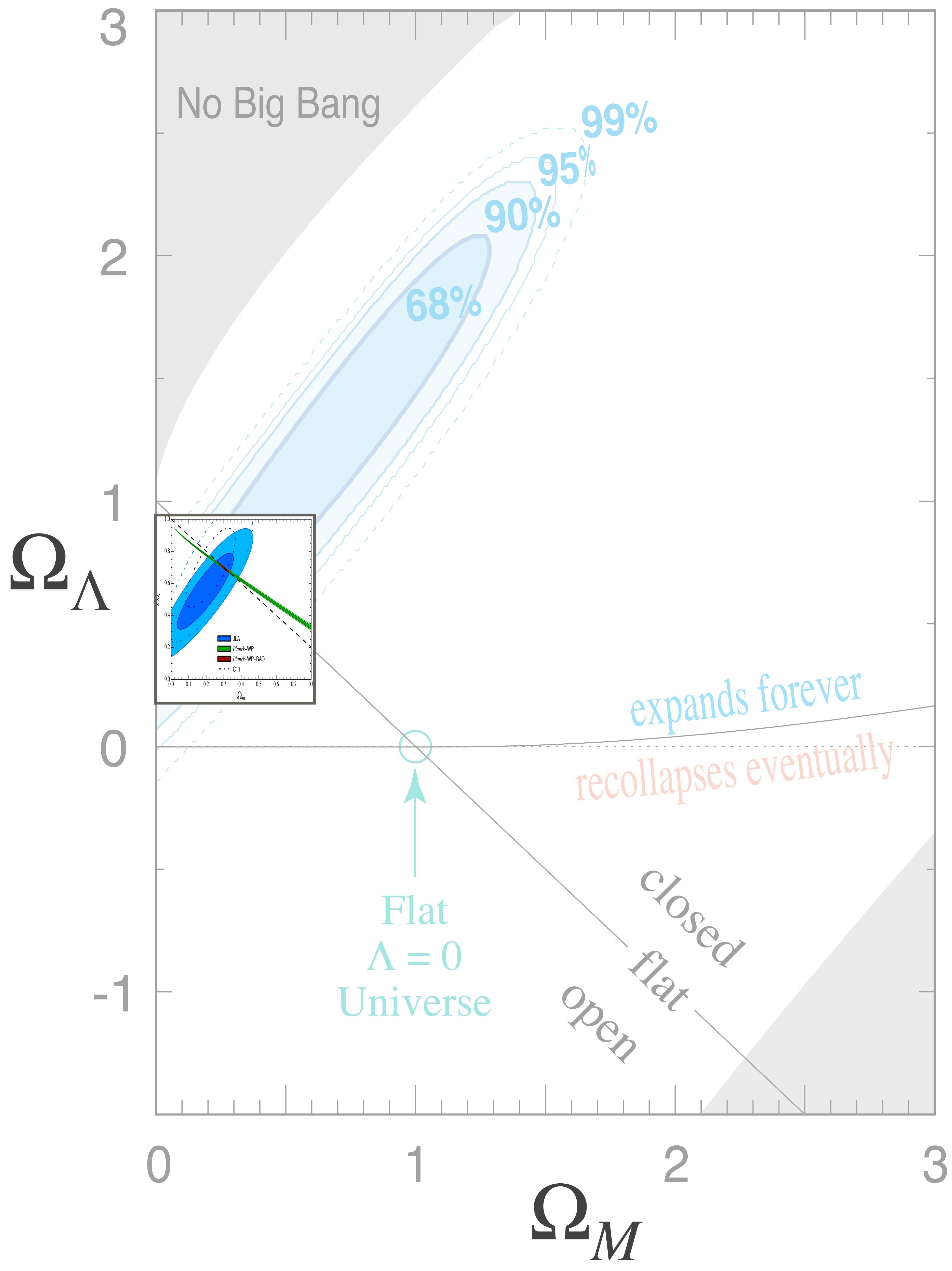
CfA/CSP + Foundation sample (194 SNe Ia)
DES-SN (1635 SNe Ia)
Median μ uncertainty on a single SN
Distance modulus μ
44
42
40
38
36
200
0
1.0
0.8
0.6
0.4
0.2
0.0
P_{Ia} from SuperNNova
Median μ uncertainty on a single SN
Residuals from best fit Flat$w$CDM
0.1
0.0
−0.1
DES-SN5YR (best-fit FlatΛCDM)
DES-SN5YR (best-fit Flatw_0w_aCDM)
Planck 2020 (best-fit FlatΛCDM)
0.03
0.1
1
Redshift



High-Z SN Search Team
Supernova Cosmology Project
m-M (mag)
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
Δ(m-M) (mag)
z
No Big Bang
99%
95%
90%
68%
Ω_Λ
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
Ω_M


HST
SNLS
SDSS
Low-z
$\mu = m_B - M(G) + \alpha X_1 - \beta C$
46
44
42
40
38
36
34
10^{-2}
10^{-1}
10^{0}
z

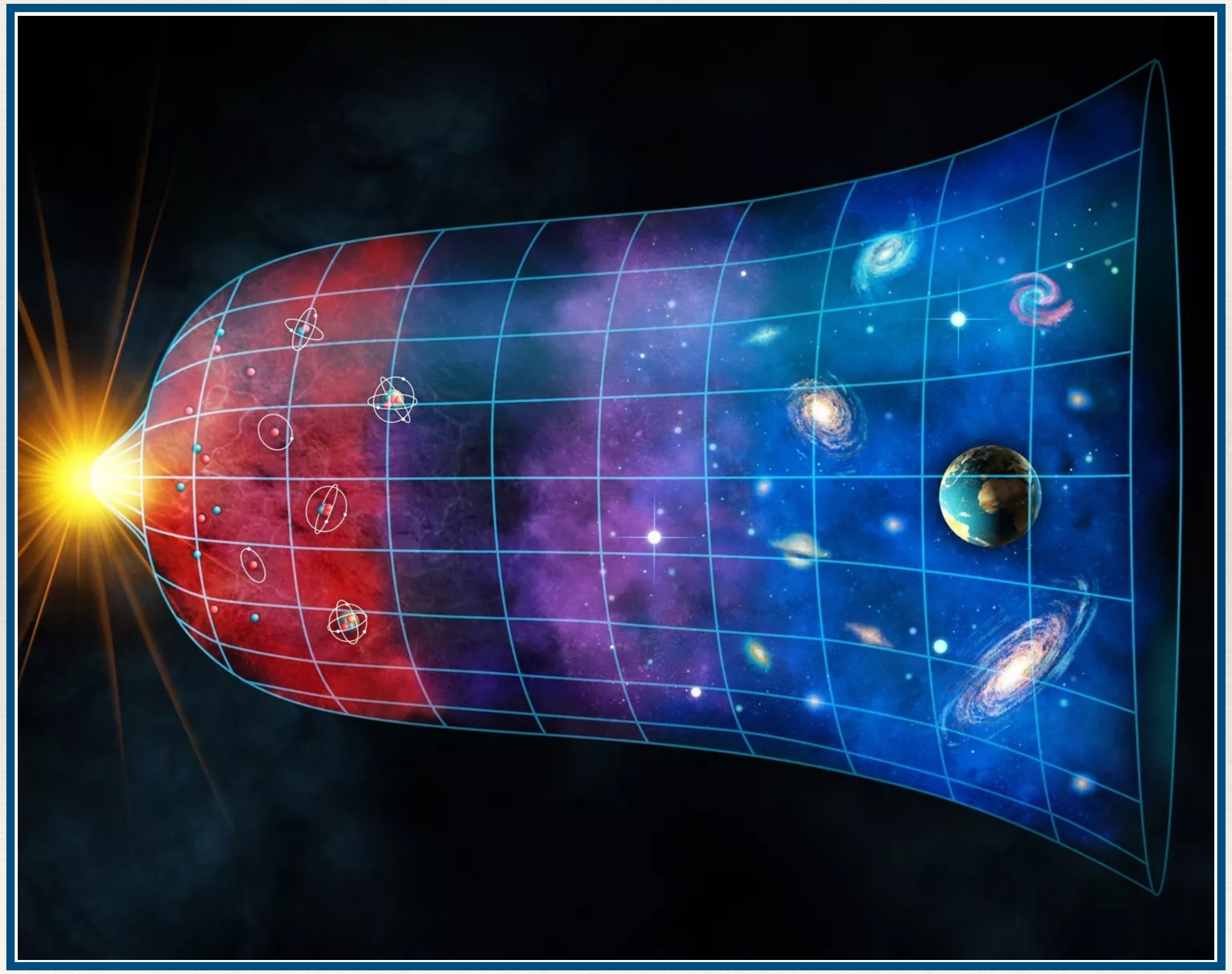

Distance Modulus (mag)
46
44
42
40
38
36
34
CSP
CFA4p2
CFA4p1
CFA3K
CFA3S
CFA2
CFA1
SDSS
SNLS
GOODS
SCP
CANDELS
+CLASH
PS1
0.01
0.10
1.0
z


No Big Bang
99%
95%
90%
68%
expands forever
recollapses eventually
Flat
$\Lambda = 0$
Universe
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3

Cosmology Today

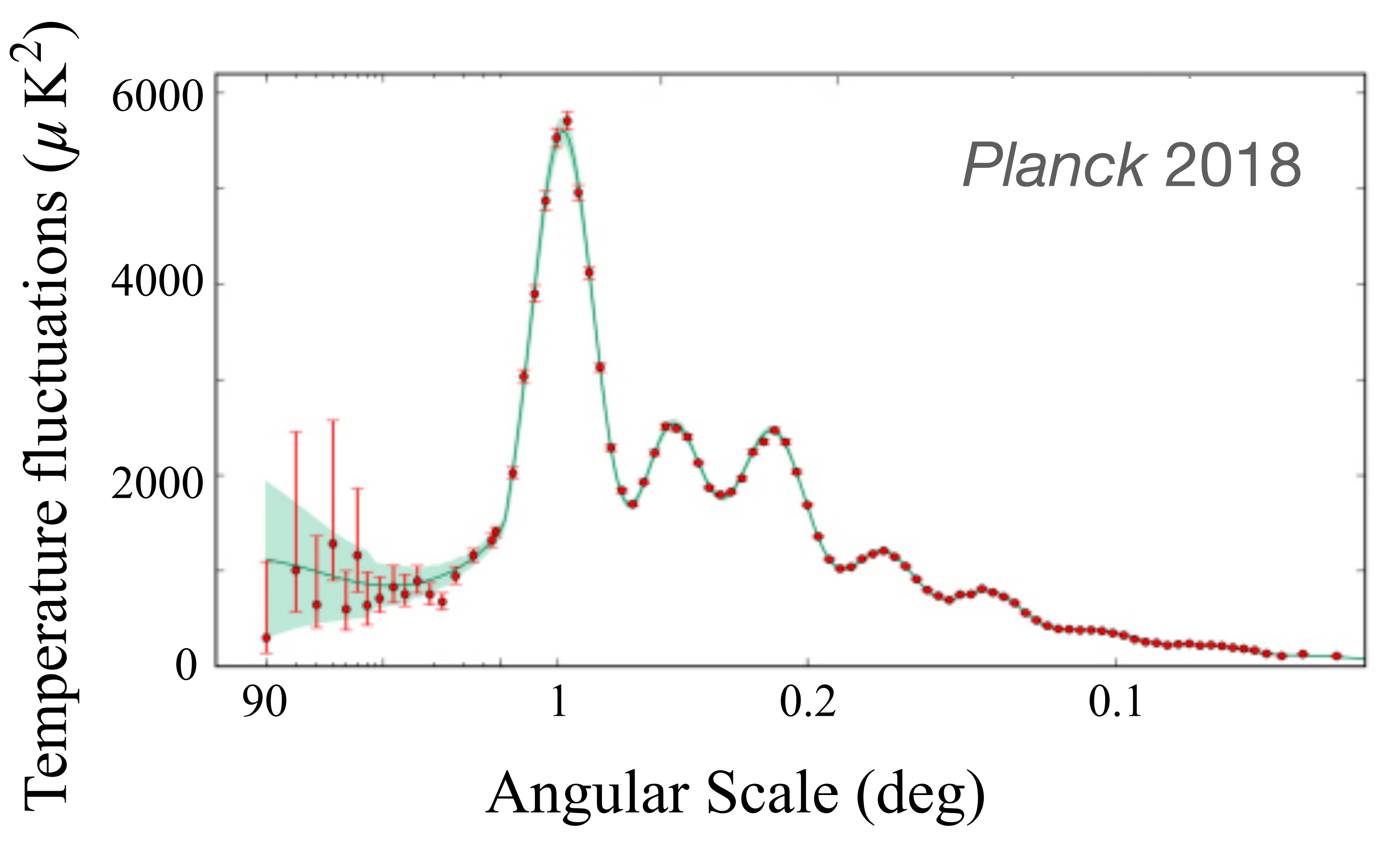
ΛCDM | only 6 free parameters

Probed independently

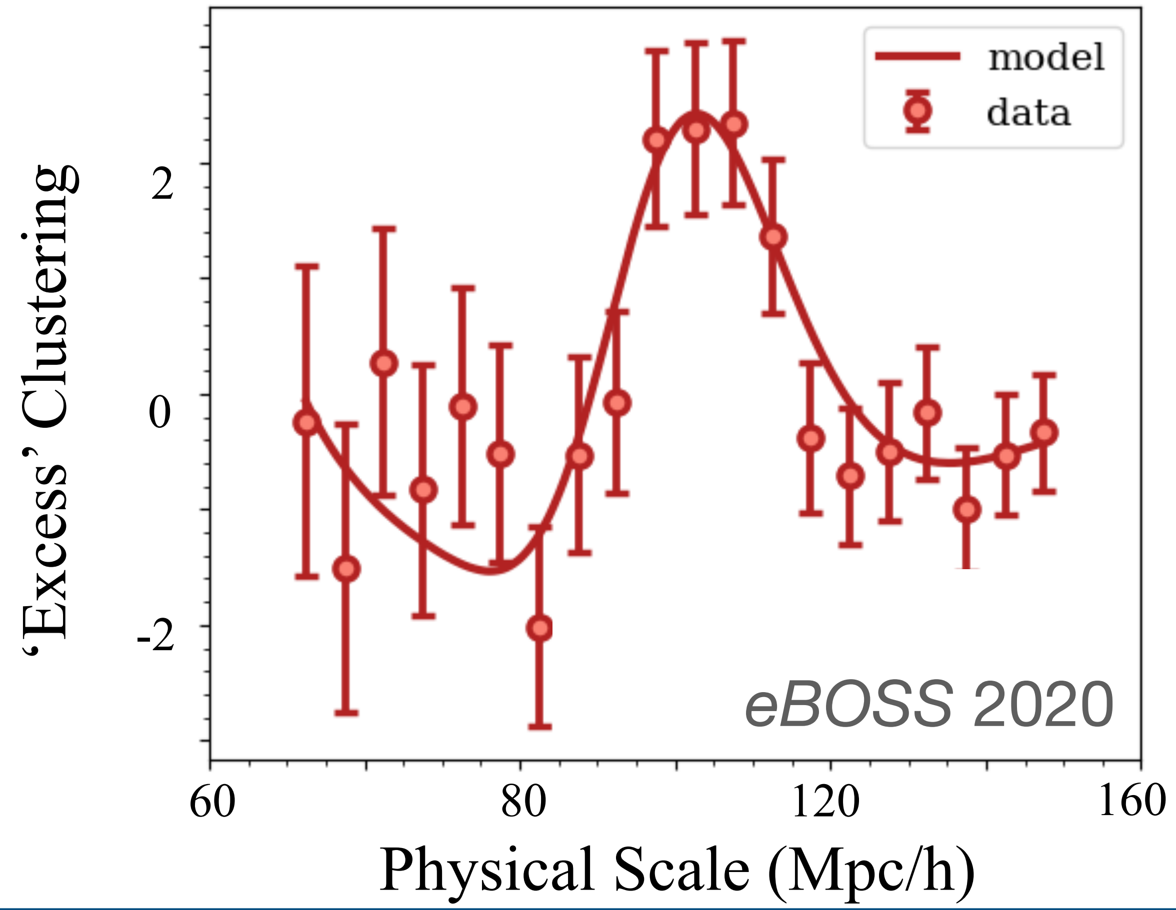


+ RSD + Nucleosyntheis + SL + Clusters + …

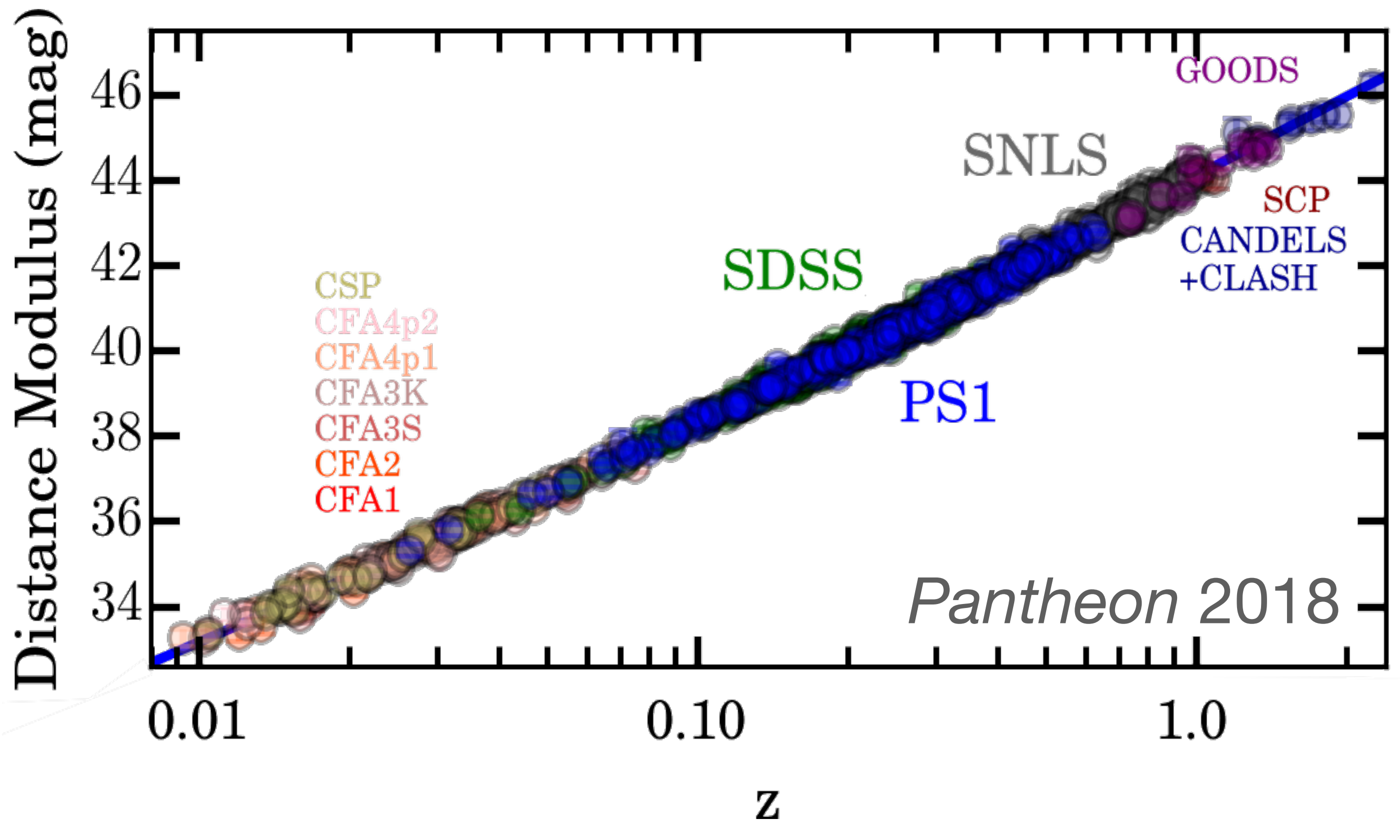
Cosmic Microwave Background



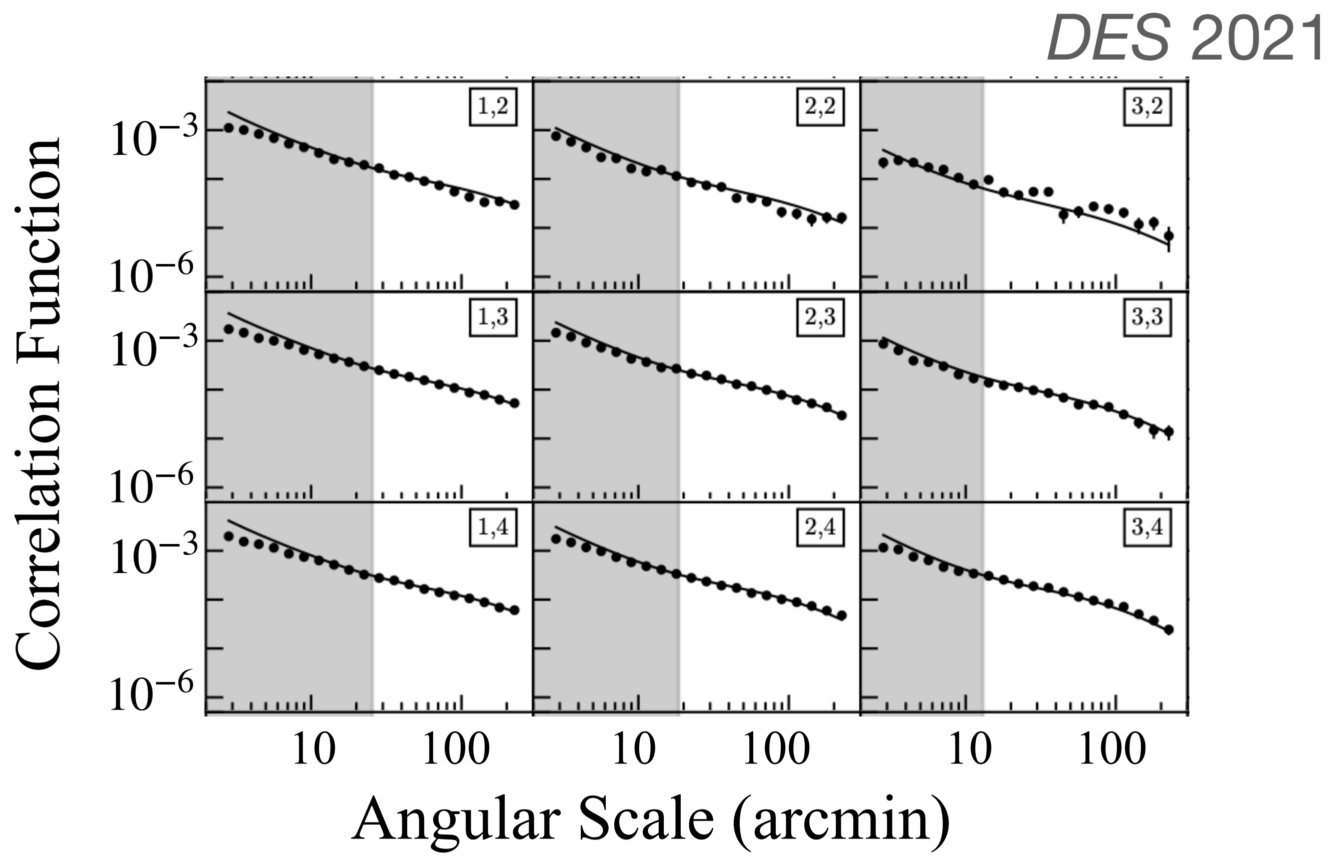
BAO



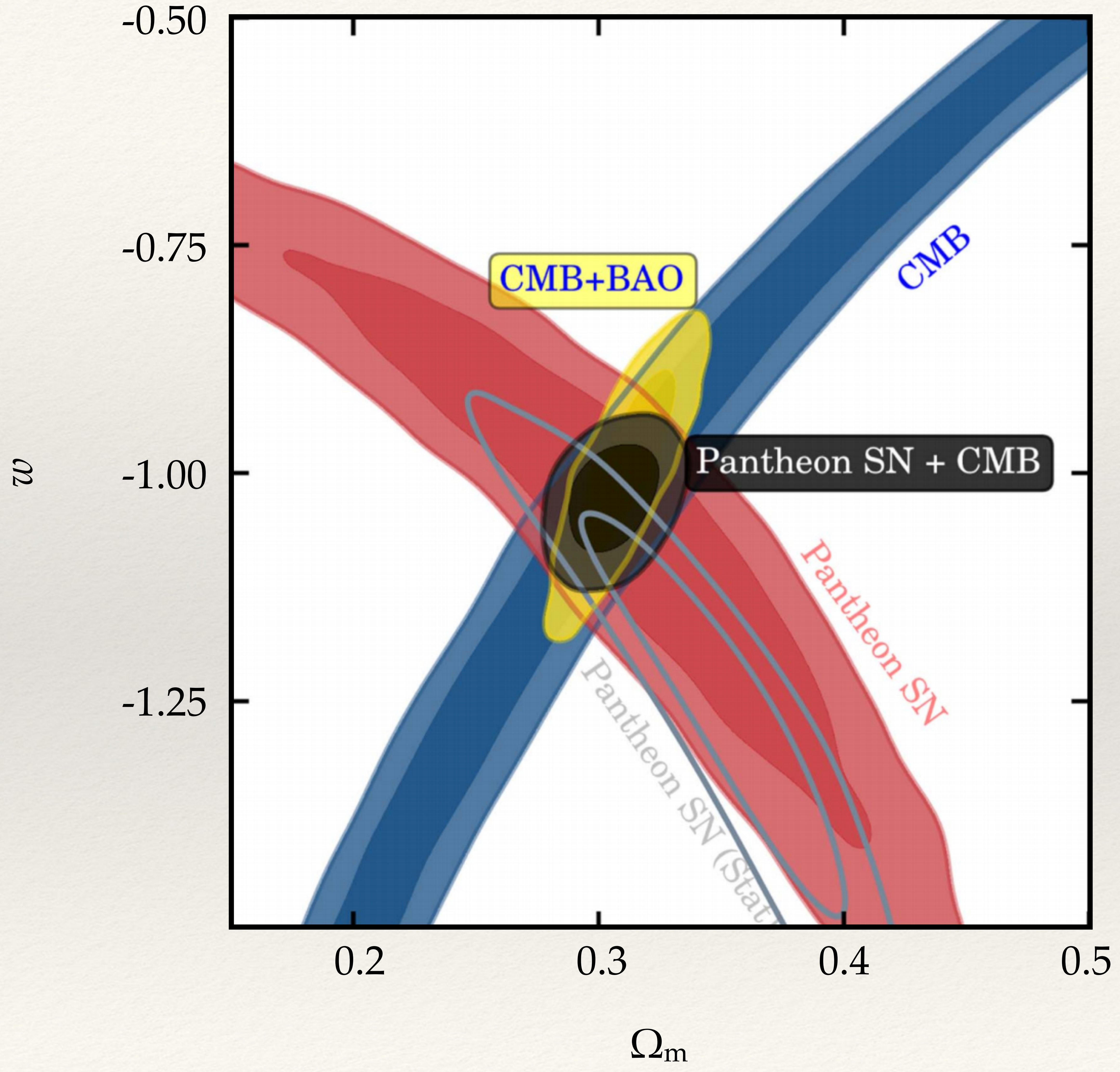
Type Ia Supernovae



Clustering + Lensing



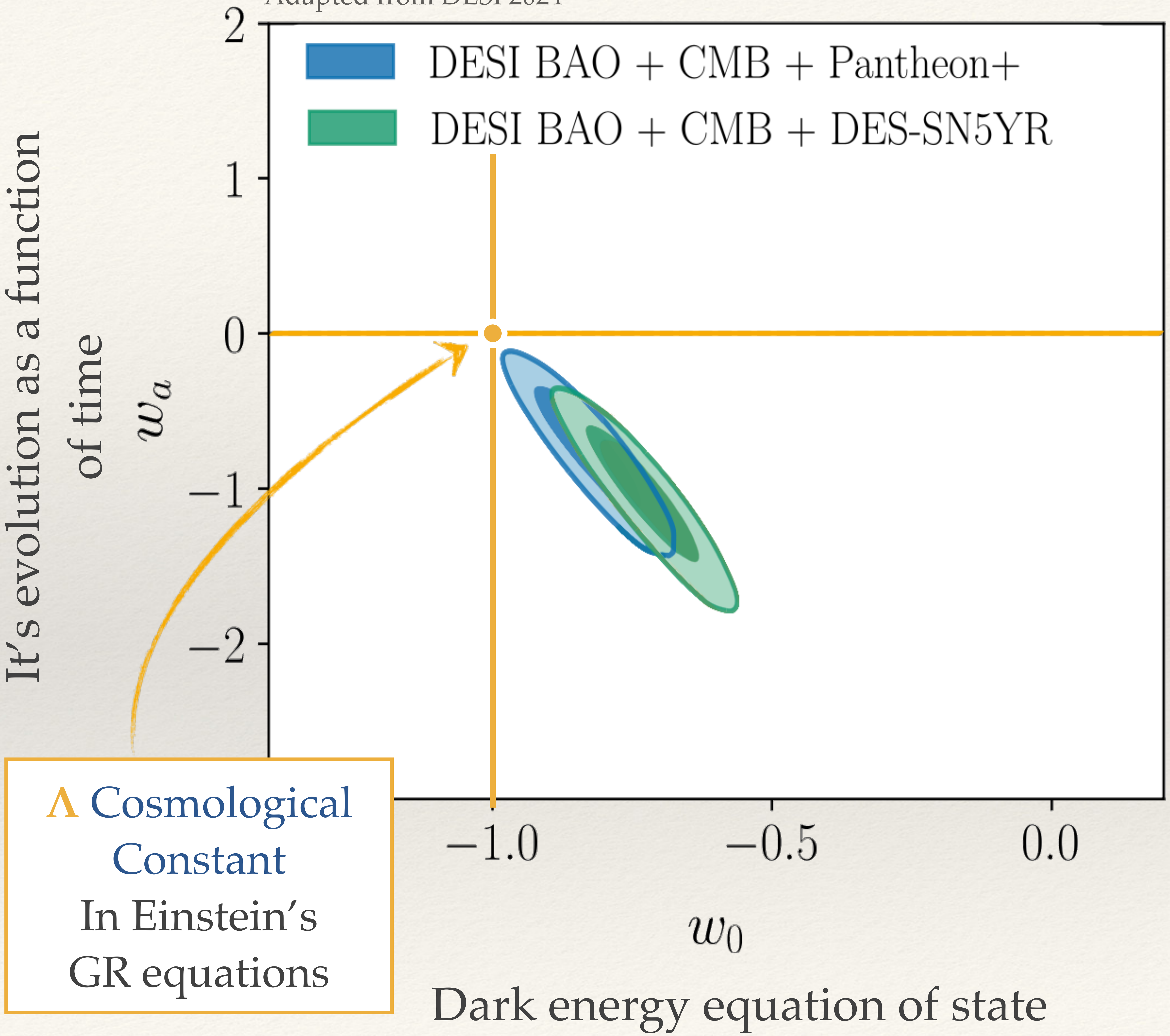
The wider context | SNe are not alone



Today

Are we are it edge of a new revolution is cosmology ?

Adapted from DESI 2024



Measuring distances

intrinsic brightness Light-curve colour

Observationally
(from the light-curve)

$$\boxed{\mu = m - (M - \alpha \times x_1 + \beta \times c)}$$

Peak magnitude Light-curve width

$$w = P/\rho$$

Theoretically
(using the redshift)

$$\mu = 5\log D_L + 25$$

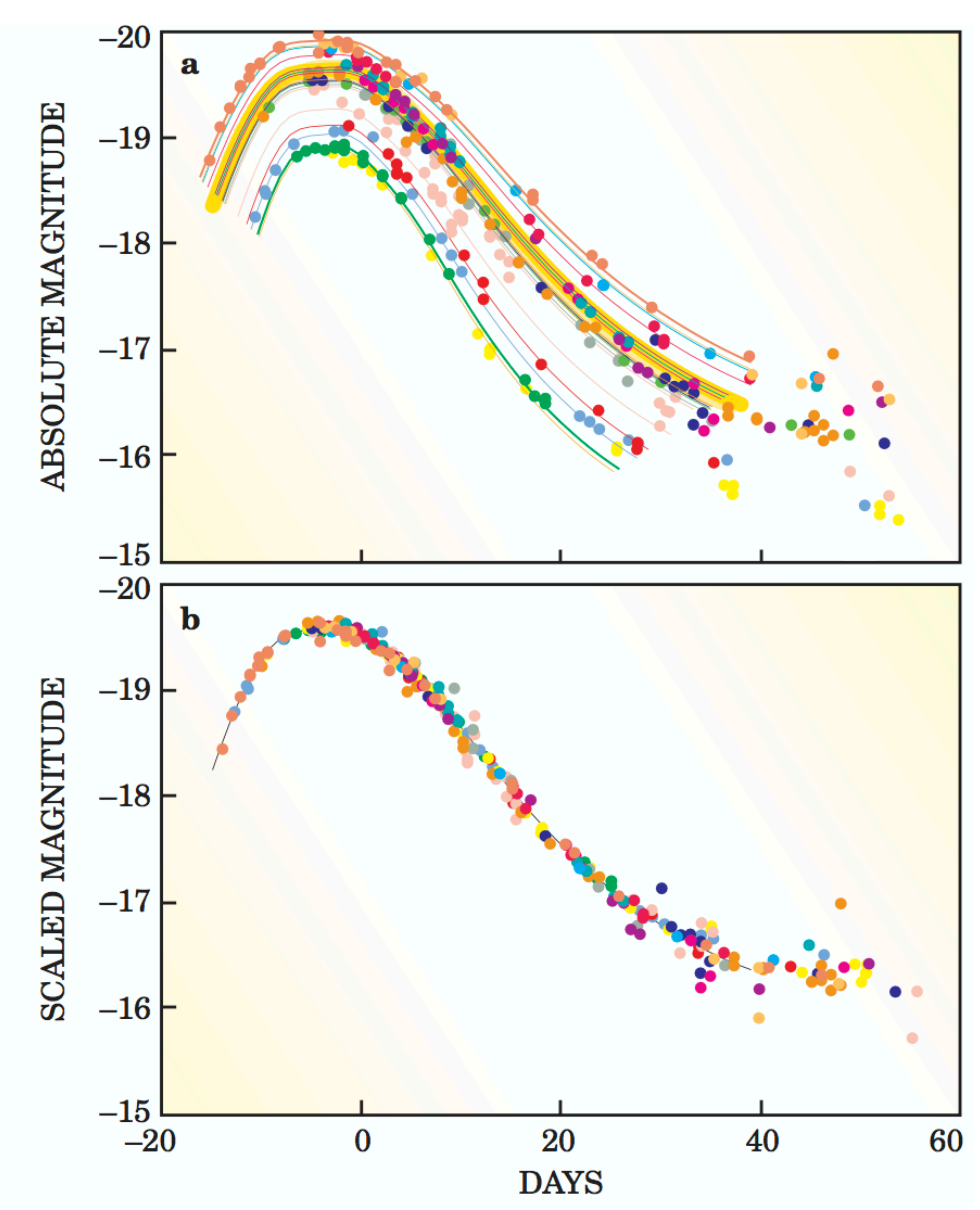
Dark Energy EoS of DE

where $D_L = f(z, H_0, \Omega_m, \Omega_\Lambda, \Omega_k) + w(z)$

$$f(z,\{\Omega\}) = c\,(1+z) \times \int_0^z dz' \left[\Omega_r(1+z')^4 + \Omega_M(1+z')^3 + \Omega_\Lambda(1+z')^{3(1+w)}\right]^{-\frac{1}{2}}$$

Residuals
(what's unexplained)

$$\mathrm{HR} = \Delta\mu = \mu_{\mathrm{obs}} - \mu_{\mathrm{theory}} \qquad \sigma_{int} \sim 0.15$$



Standardisable candles

2 empirical corrections

=>

dispersion: 0.15mag

Brighter SNeIa:

- ***Bluer; slowly declining***

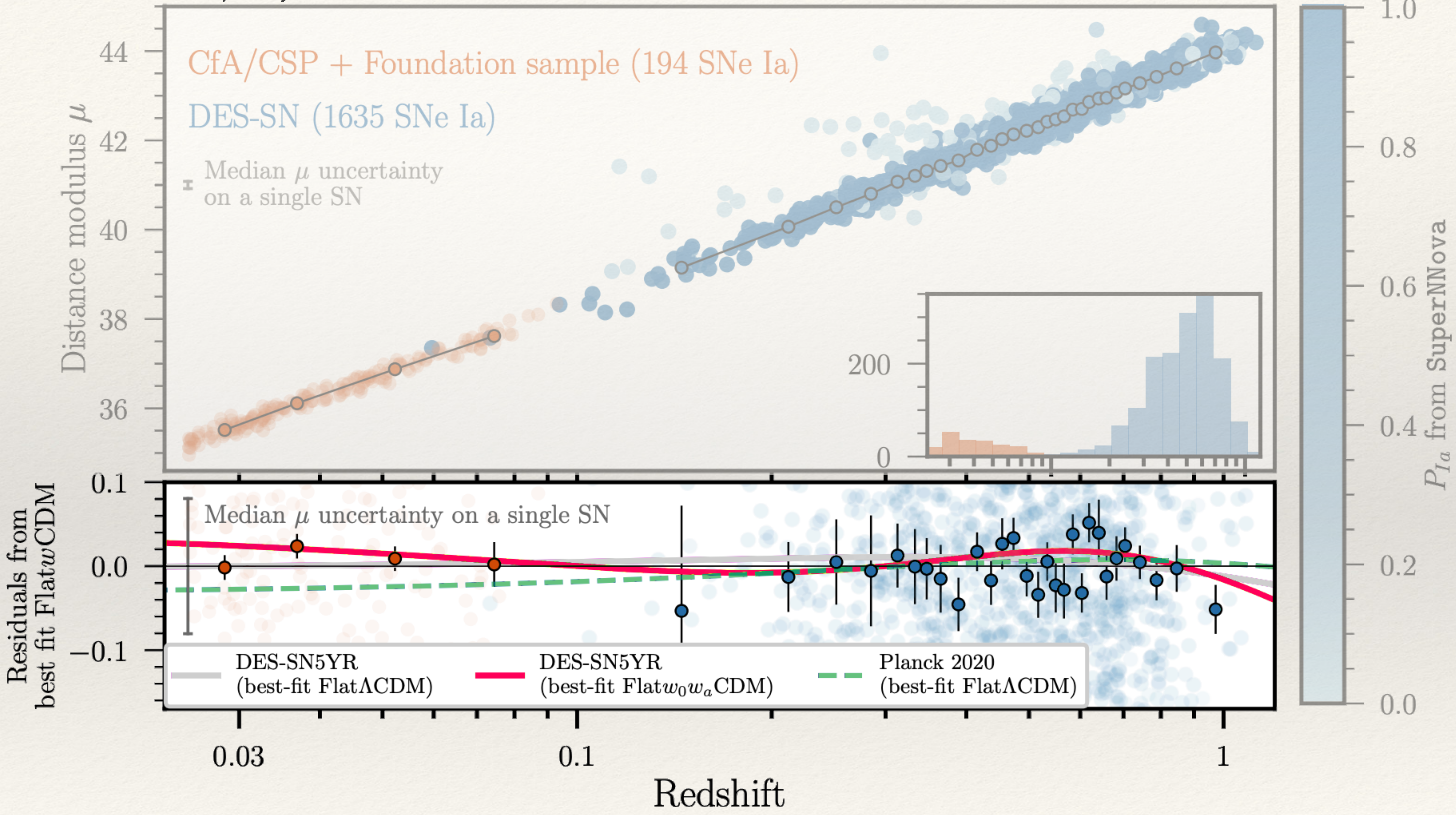
The cause

An accurate nearby SNe Ia sample is *key*

An accurate understanding of astrophysics is *required*

Precision at all redshifts

Adapted from DES Y5 | 2024

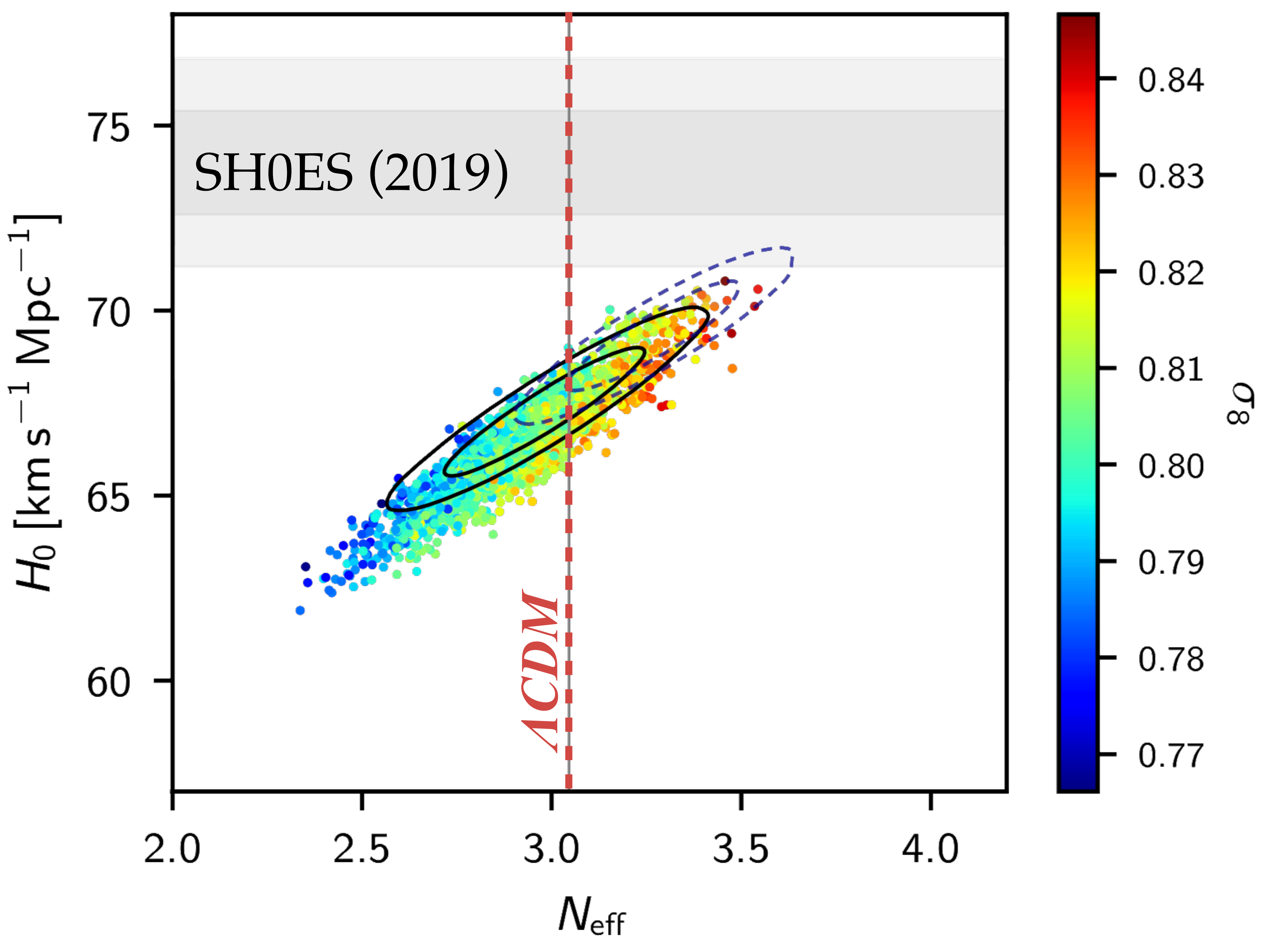


Dark Energy isn't the only tension

LCDM : Only 6 free parameters | *but "Λ" and "CDM"*

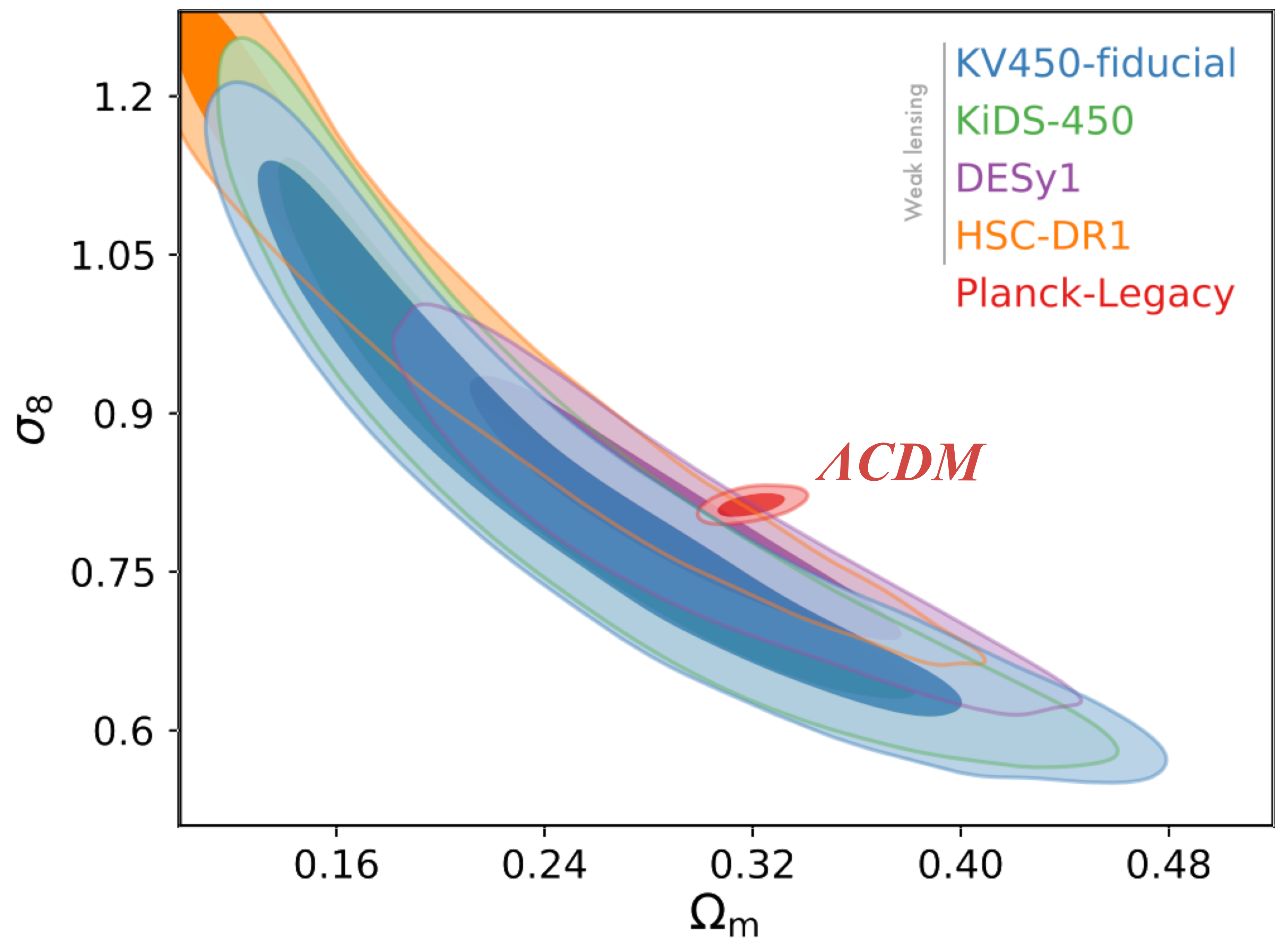
H_0 Tension | 5 σ

Universe's expansion is too fast



σ_8 Tension | 2.5 σ

Structures are too small



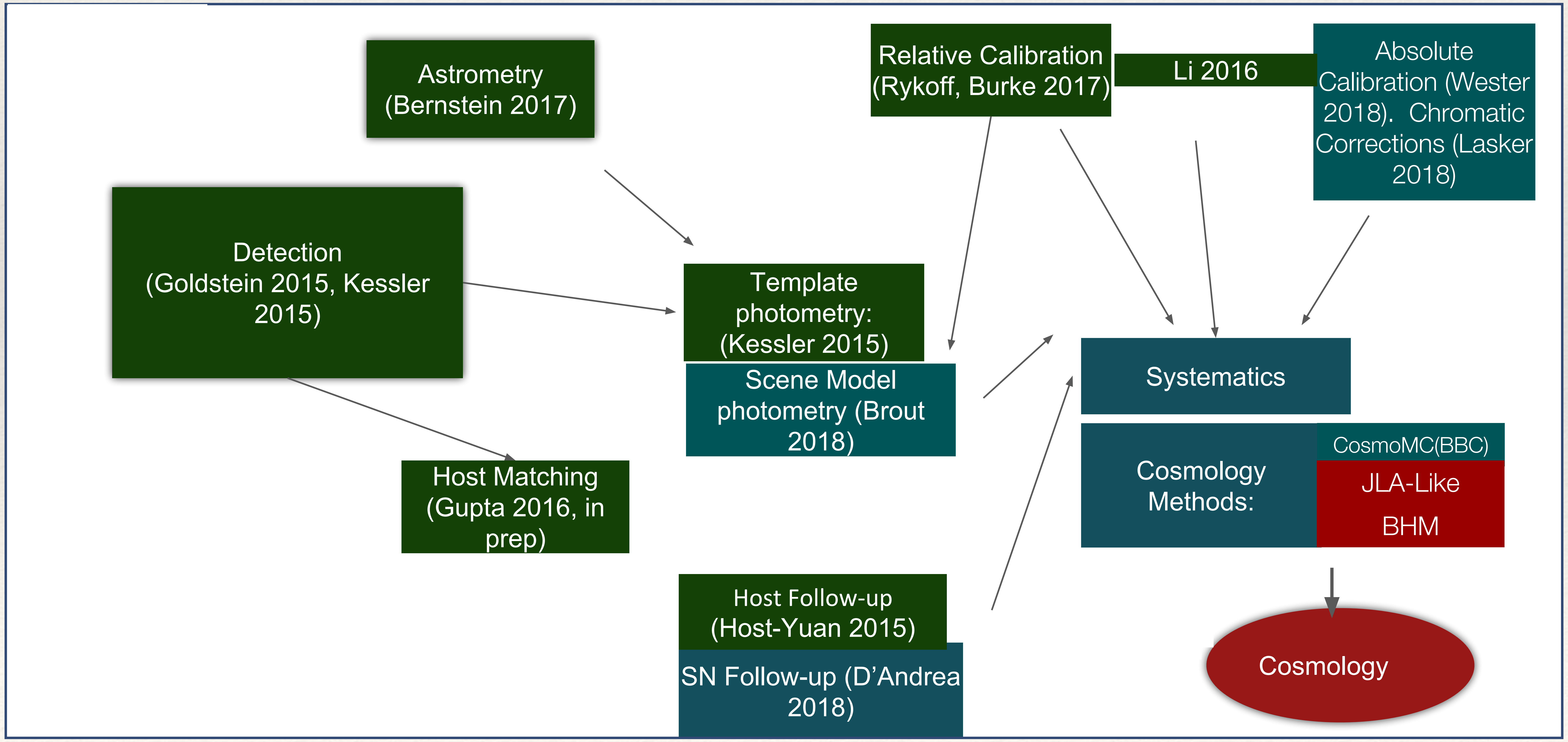
Physics or Systematics

Environmental correction Selection effects

Observationally

(from the light-curve)

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



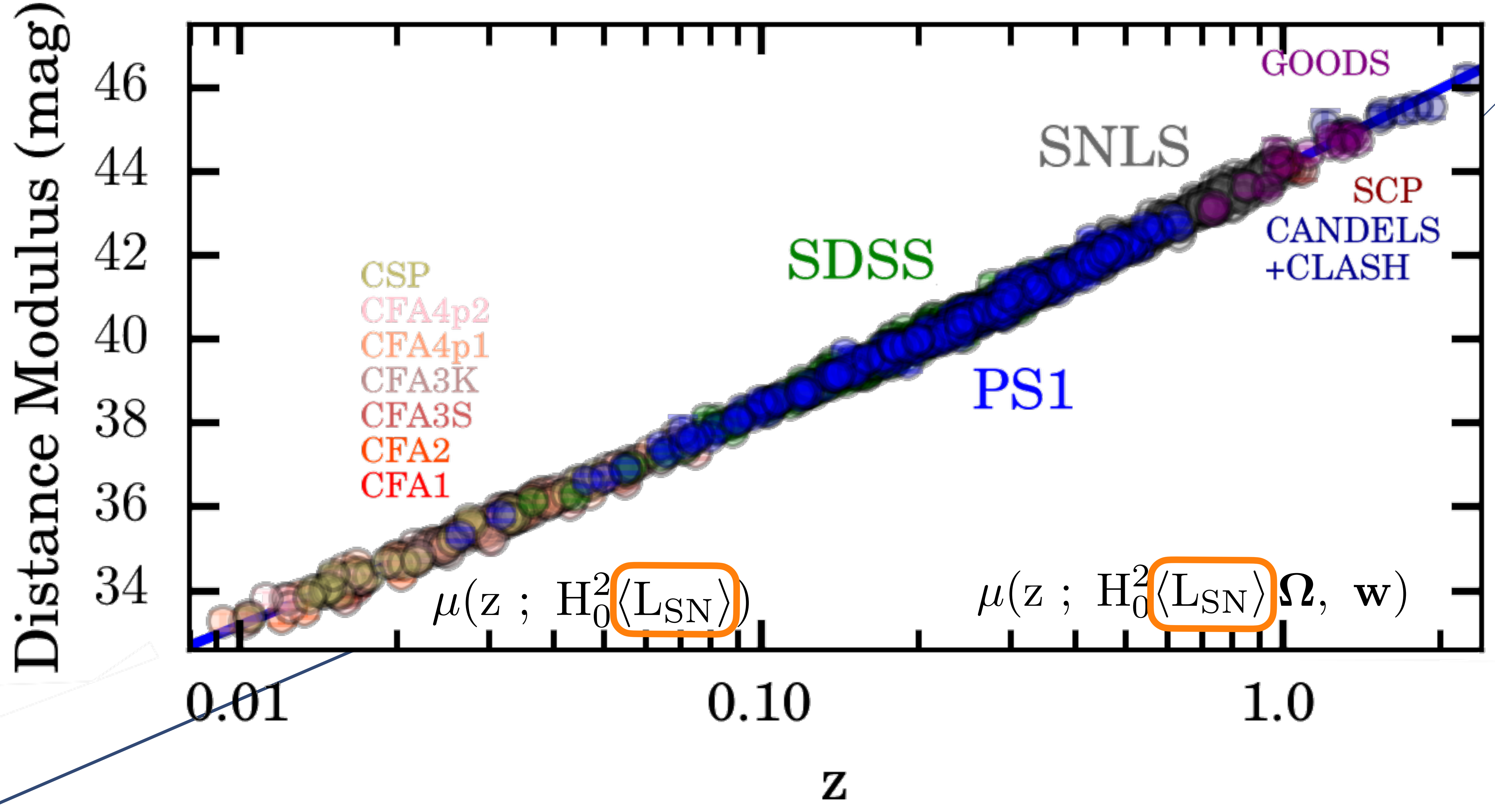
More steps == more systematics

Calibration & Photometry	Do we measure the same supernova the same
Understanding selection	Do we select the same SNe?
Modelling the population	Do we understand the SNe?

Supernova Cosmology | *Challenges*

SN standardized magnitudes must be predictable at any redshift

(at a constant if not H_0)



Calibration

Astrophysics

Follow Up