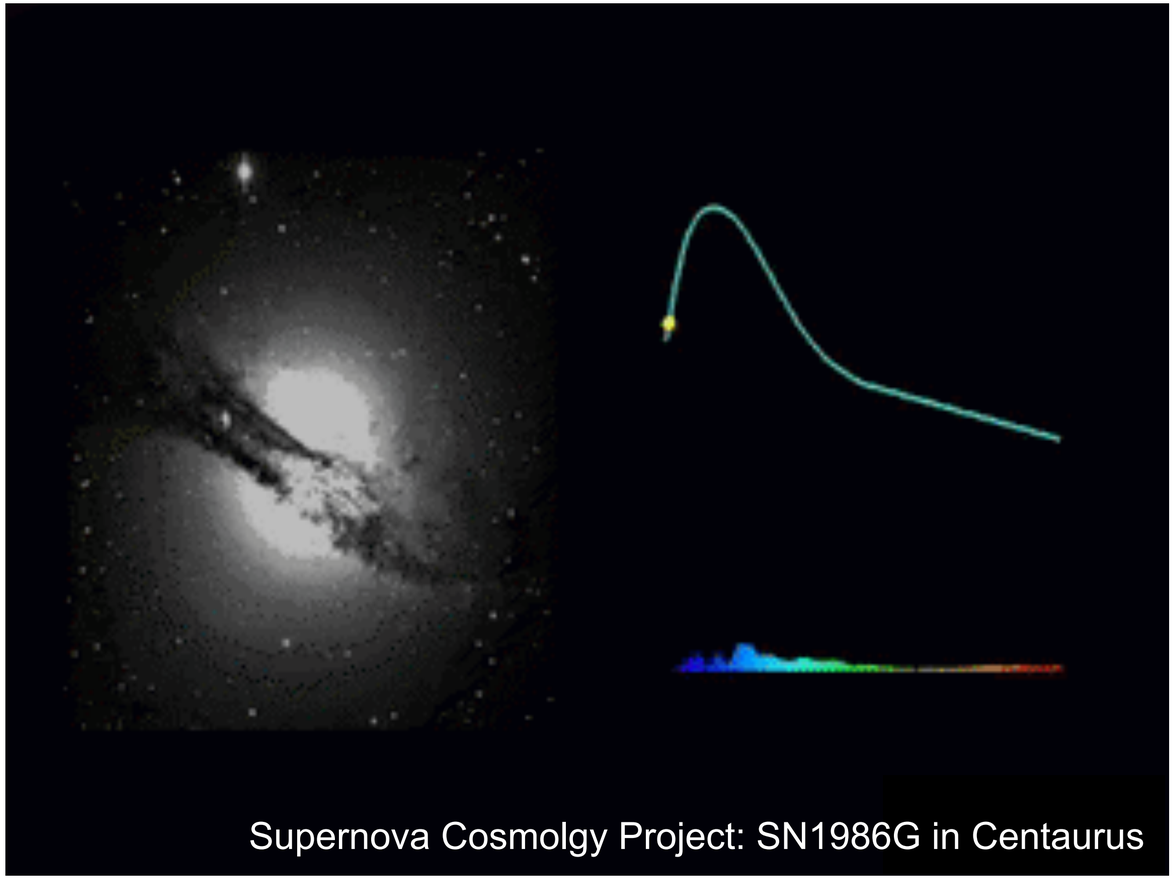
Supernovae and the birth of neutron stars

Lluís Galbany (RyC fellow, ICE-CSIC)

Neutron stars, black holes & gravitational waves, Feb 9th 2022

Supernovae

- End points of stellar evolution
- Bright stellar explosions of mag -14 to -22
- Element factories
- Expels material at up to 30000 km/s
- Shock wave into interstellar medium: supernova remnant



Supernova Cosmolgy Project: SN1986G in Centaurus

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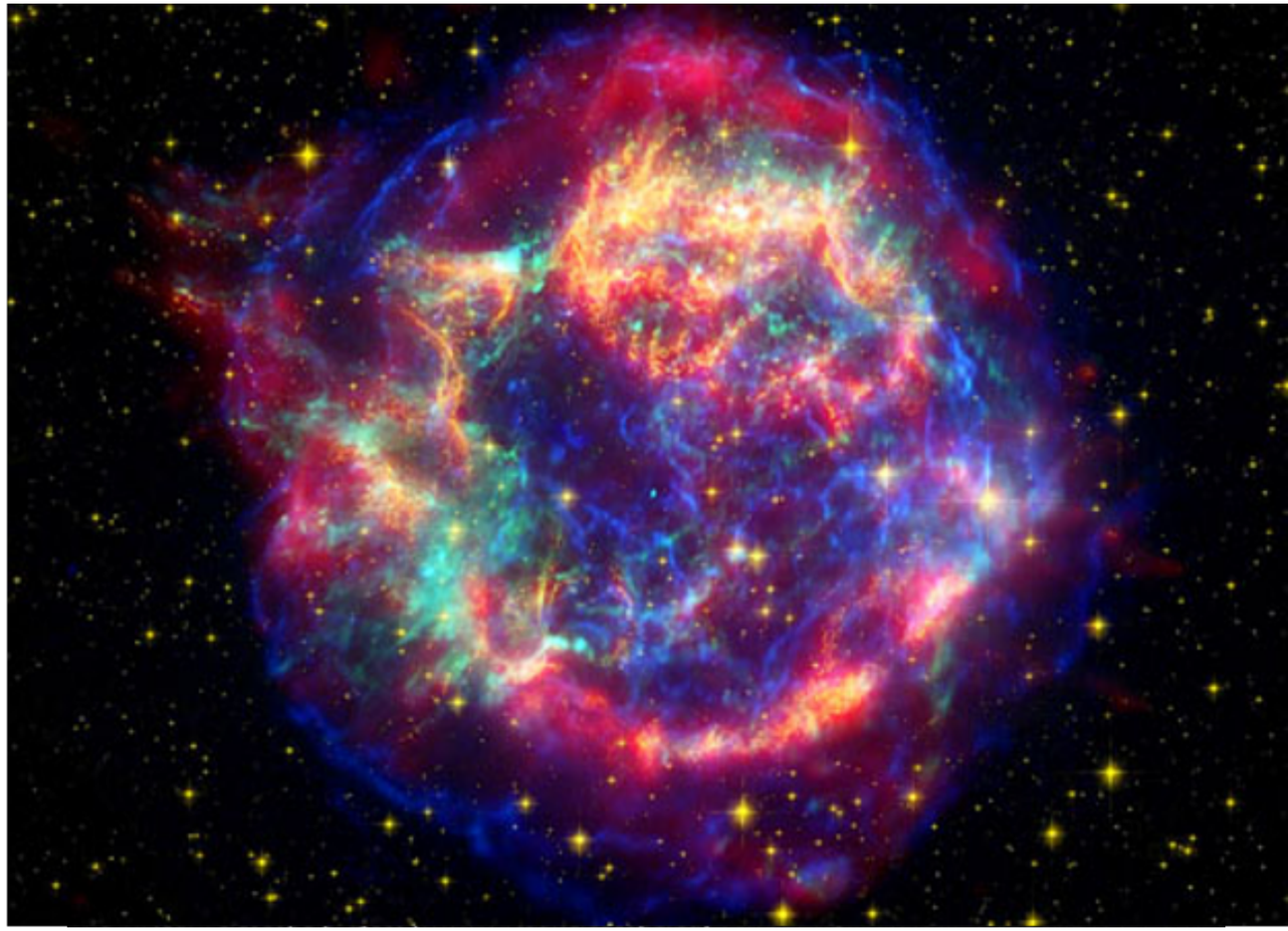
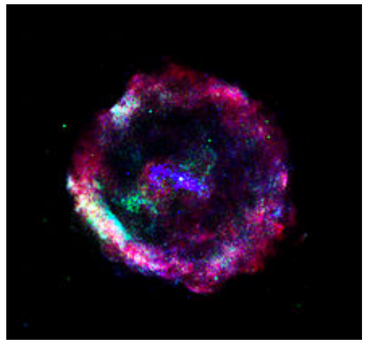
CasA/Chandra



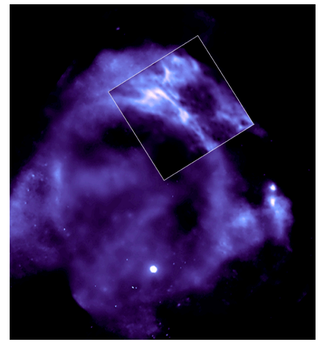
Historical supernovae

- Babylonian, Chinese, Korean, Japanese, Arabic, and European records of supernova discoveries
- Ancient civilizations recorded cyclical phenomena such as eclipses, planetary movements, as well as meteors, comets, and stellar outbursts
- Events used to confirm the power of the ruling king at that time
- Most records incomplete and lost

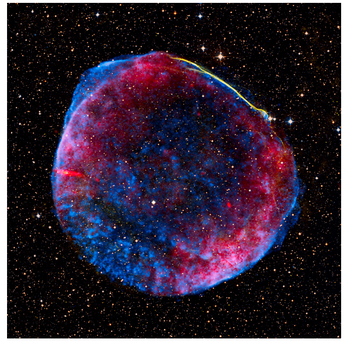
SN 185



SN 386



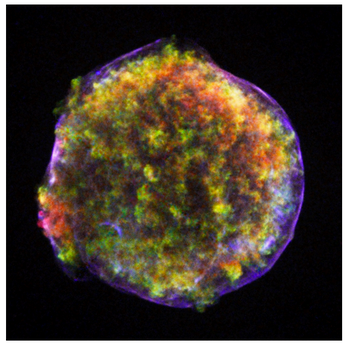
SN 393



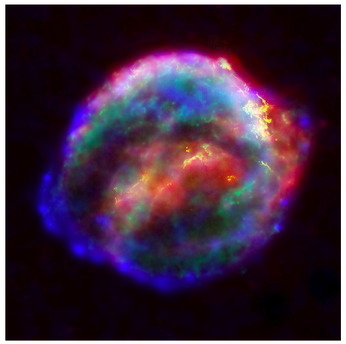
SN 1006

SN 1054

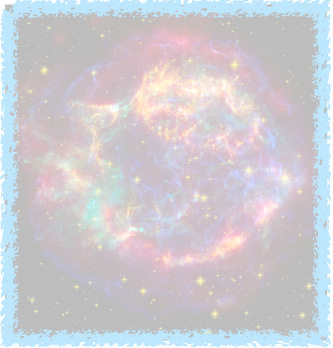
SN 1181



SN 1572



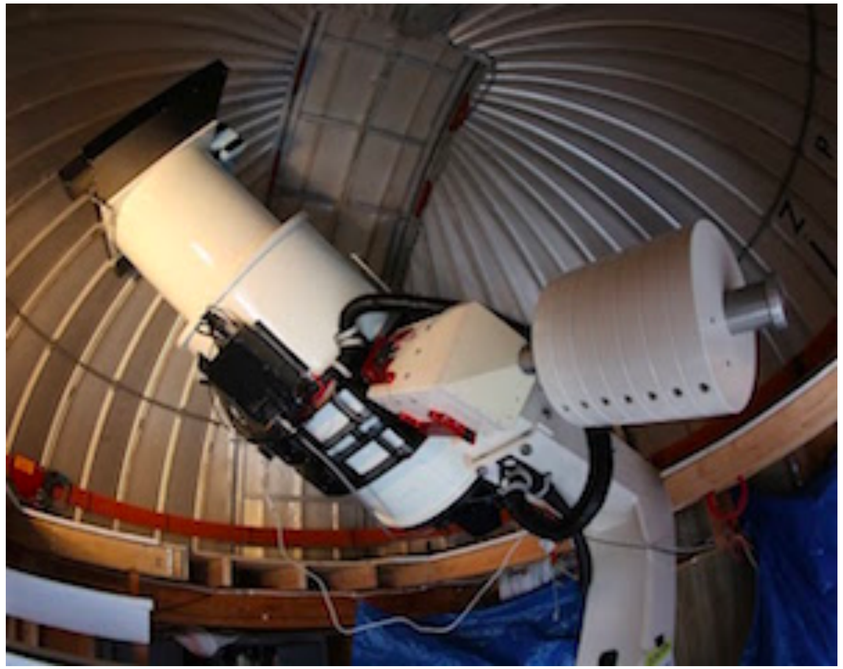
SN 1604

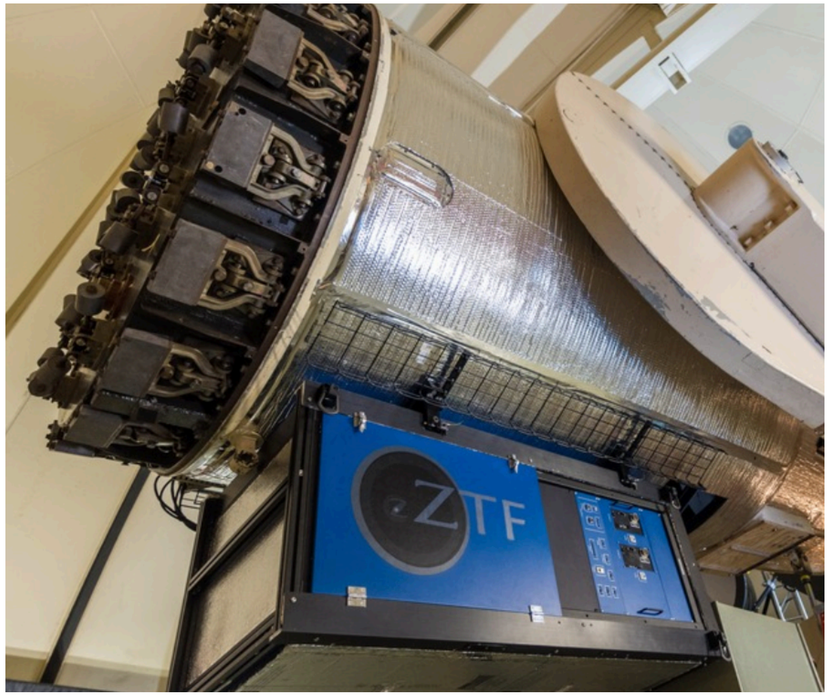


SN 1667 - CasA

Supernova discoveries

Rolling searches





ASAS-SN

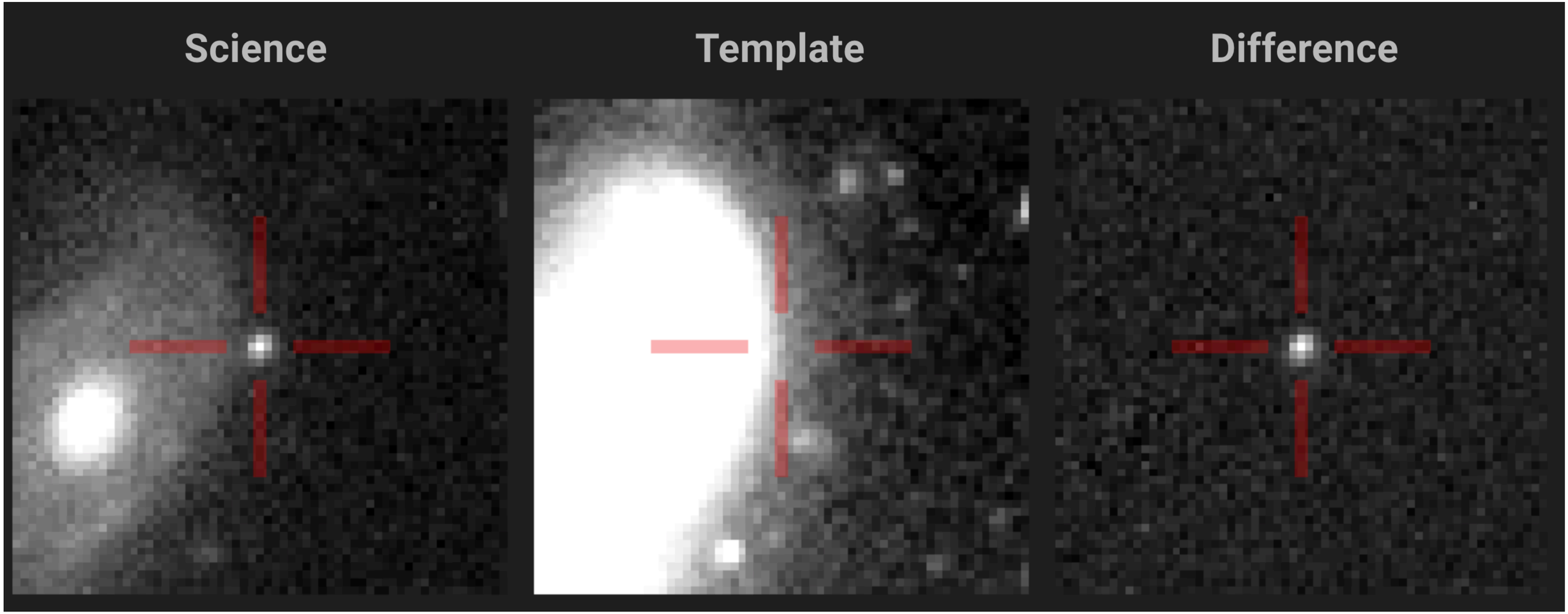
atlas

ZTF

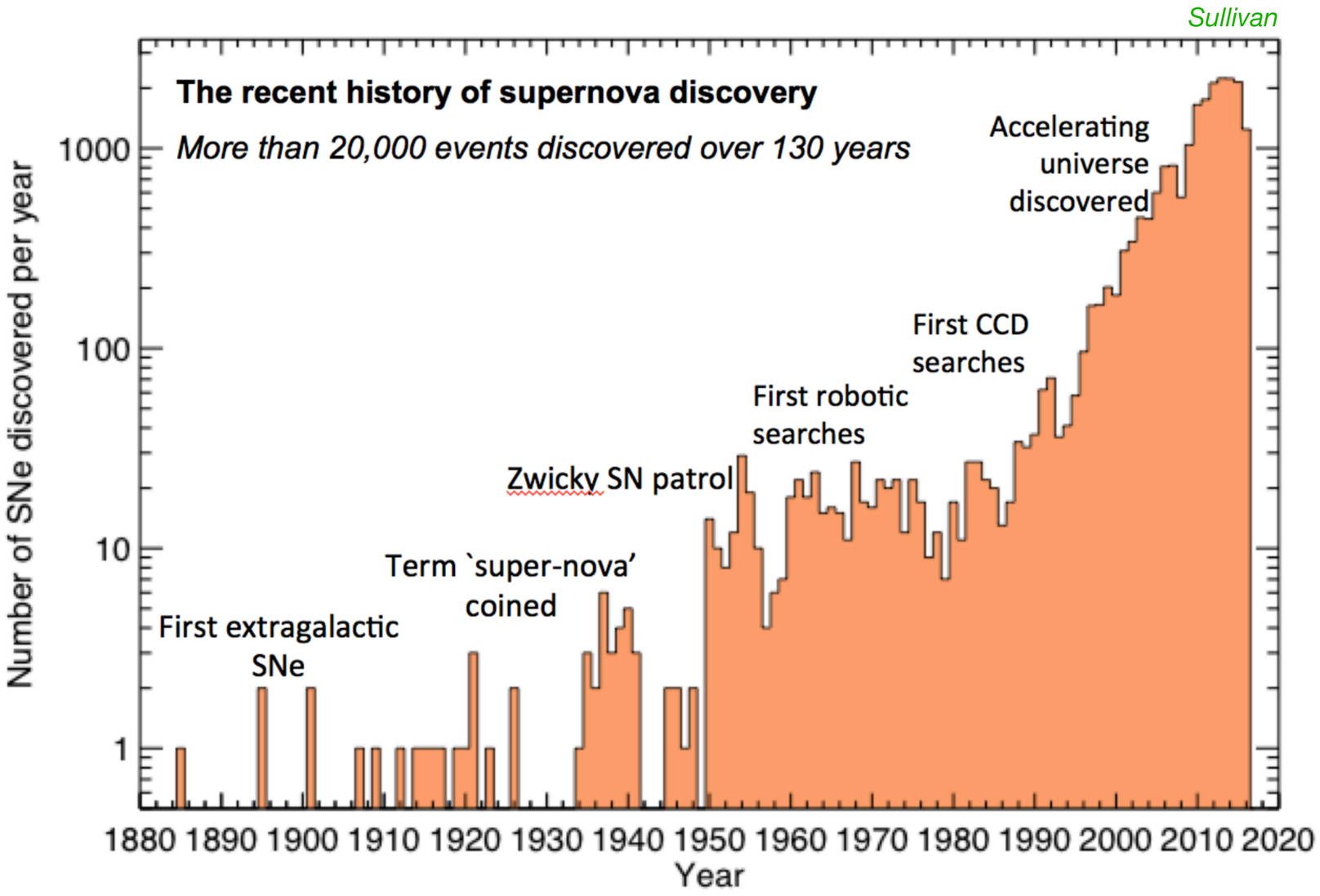
Supernova discoveries

Difference imaging

Alerce/ZTF



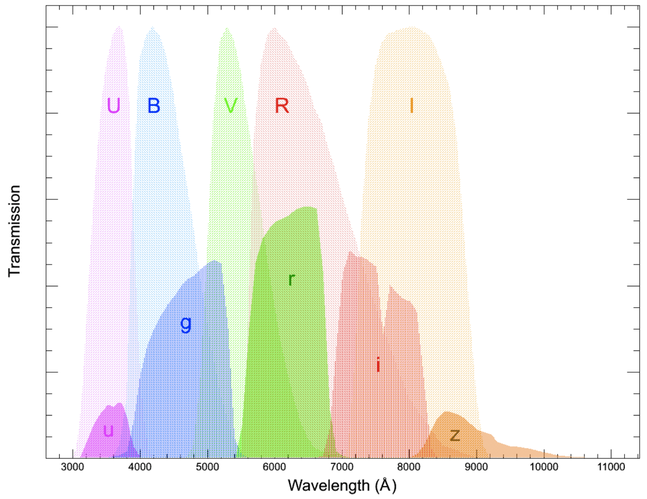
Supernova discoveries

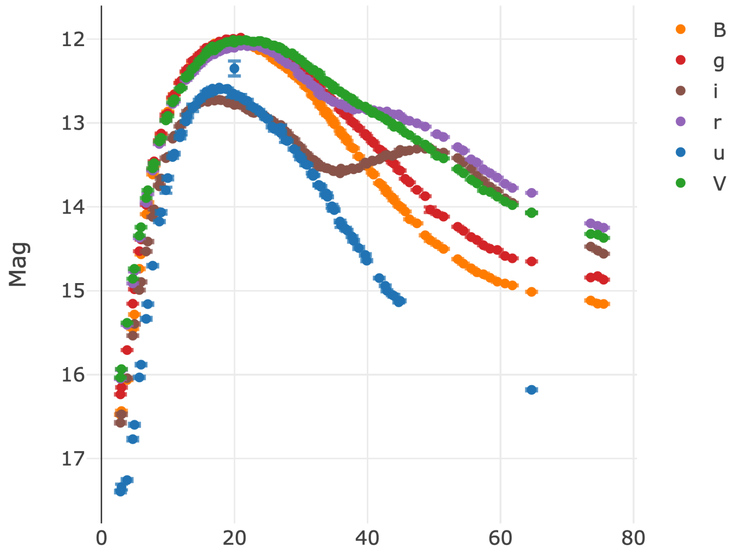


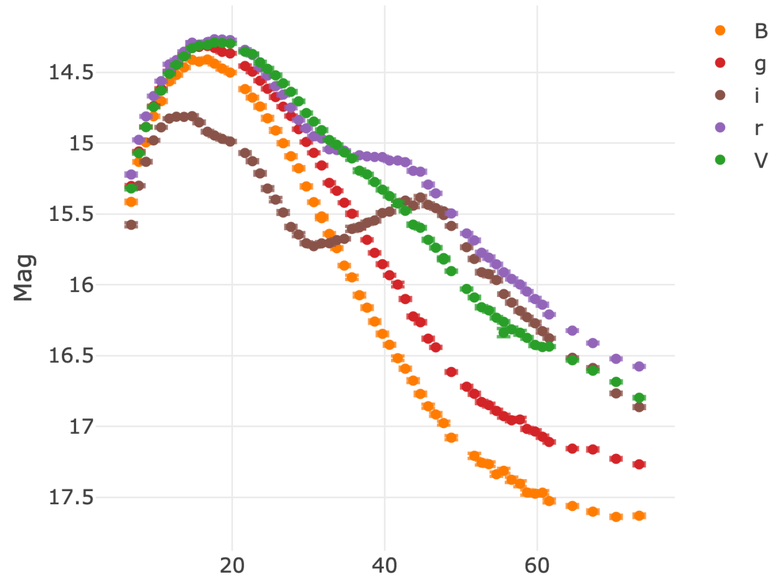
- First extragalactic SN at the end of the 19th century
- Coining of the term ‘supernova’ in the 1930s (Baade & Zwicky 1934)
- emergence of the first robotic searches in the 1960s
- development, implementation and deployment of CCD cameras in the 1980s
- observations of SNe Ia lead to the discovery of the accelerated expansion of the Universe in late 90s
- More than 20,000 She discovered until (2018) with 5, on average, being discovered per day
- on-going and new high-cadence searches (ATLAS, ASAS-SN, BlackGem, ZTF) produce thousands of alerts per night.
- LSST is expected to produce 100,000 transient alerts per night, with 10 million supernovae discoveries in 10 years

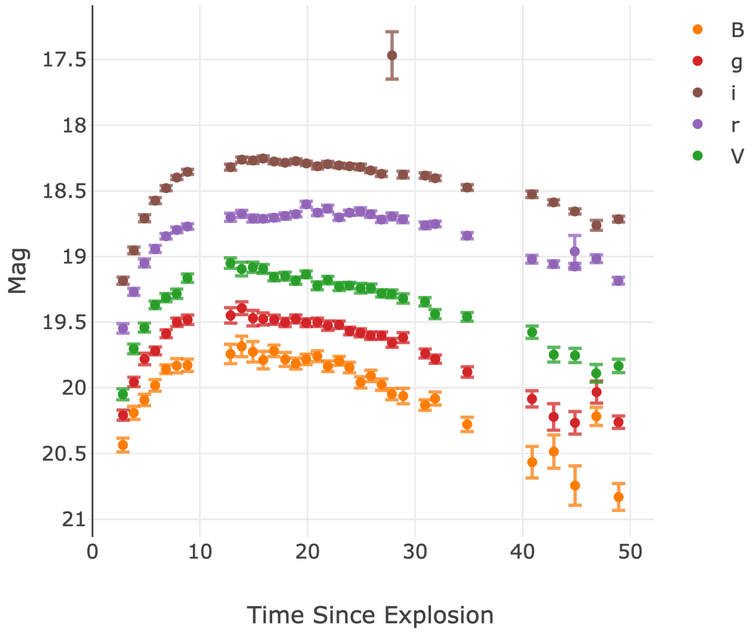
Light curves

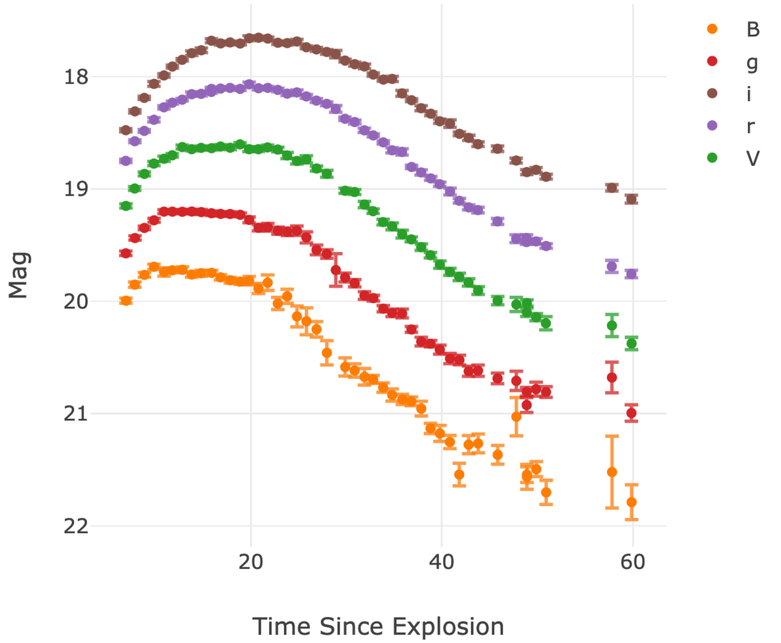
- Brightness
- Evolution
- Color

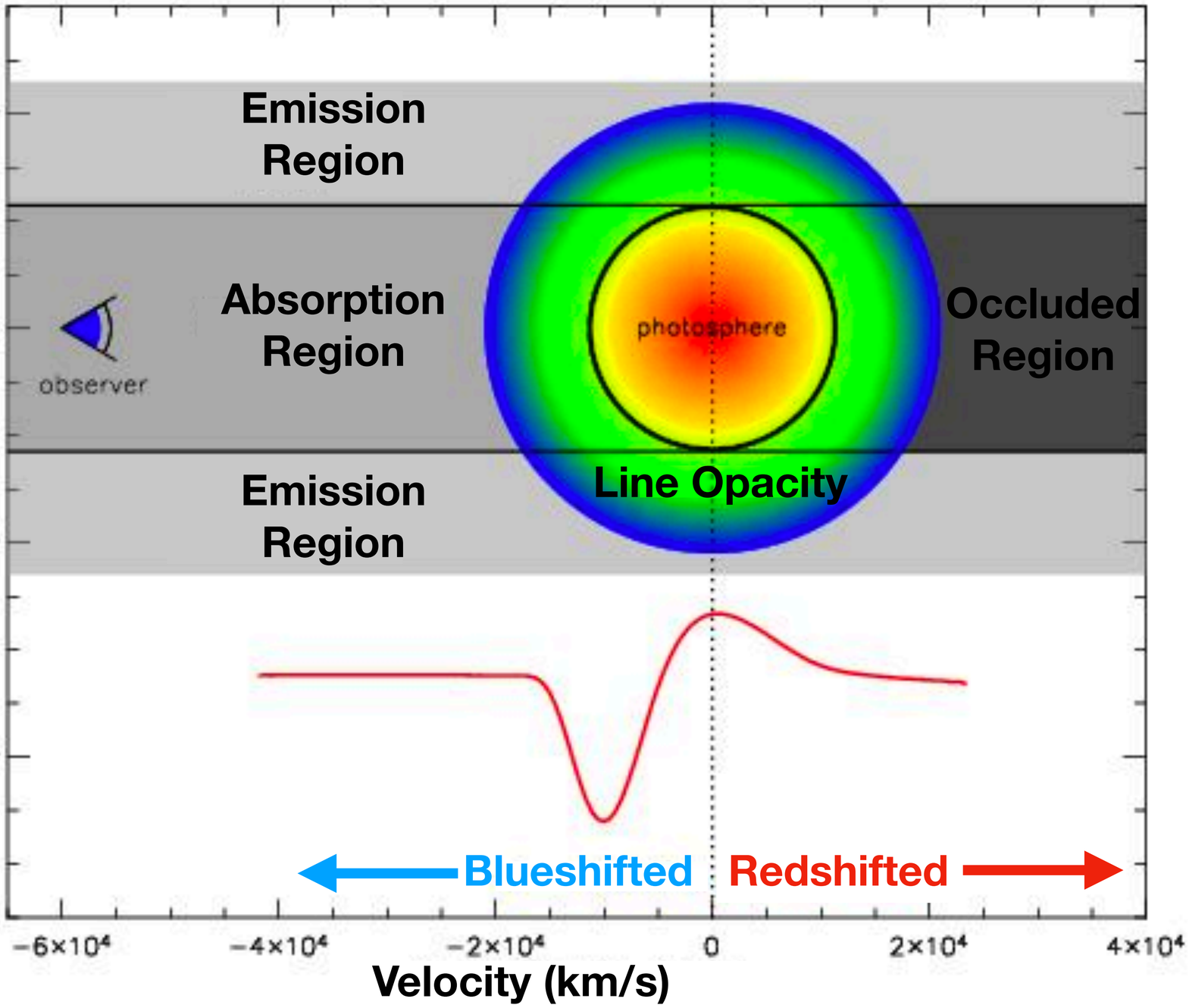






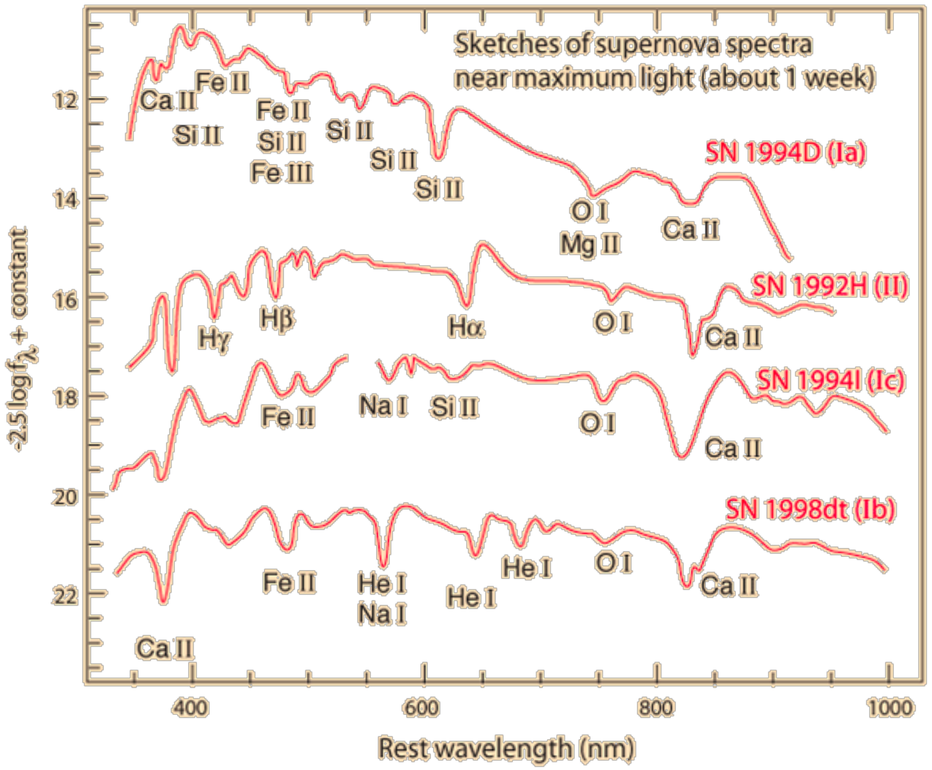




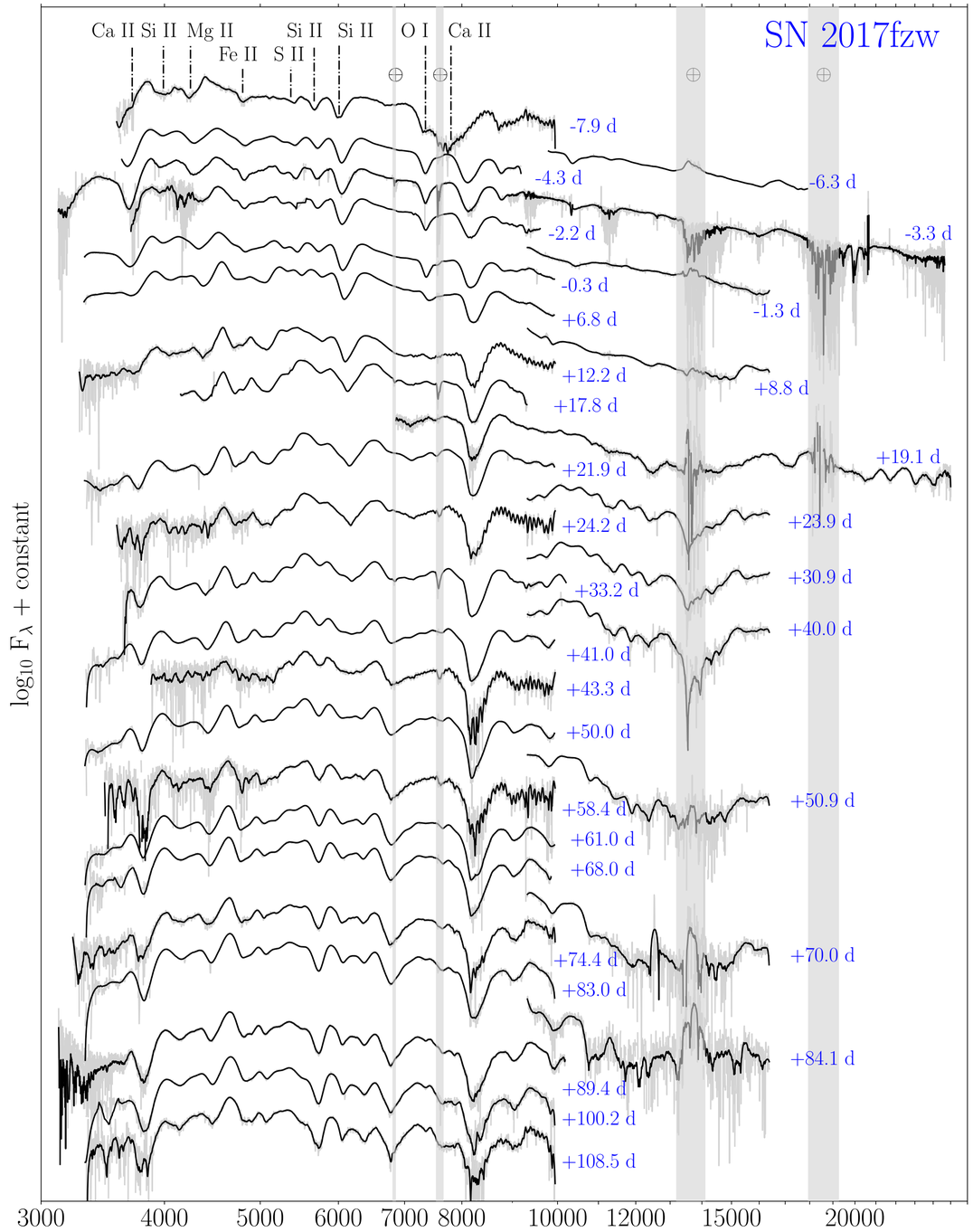

Emission Region
Absorption Region
Emission Region
observer
photosphere
Occluded Region
Line Opacity
Blueshifted
Redshifted
−6×10⁴
−4×10⁴
−2×10⁴
0
2×10⁴
4×10⁴
Velocity (km/s)

Spectroscopy

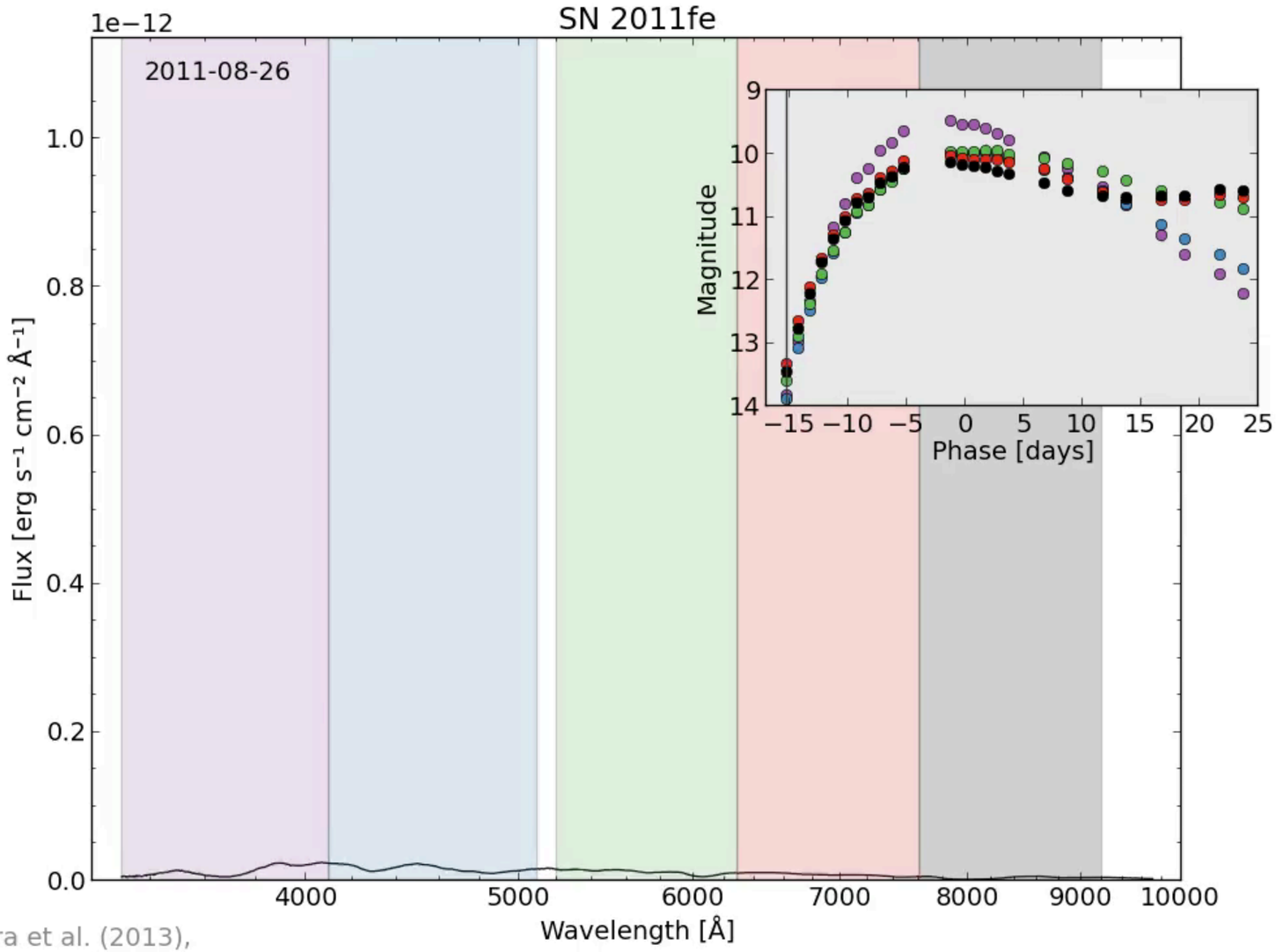
Carroll&Ostile07



- Composition
- Velocity



Phot&Spec

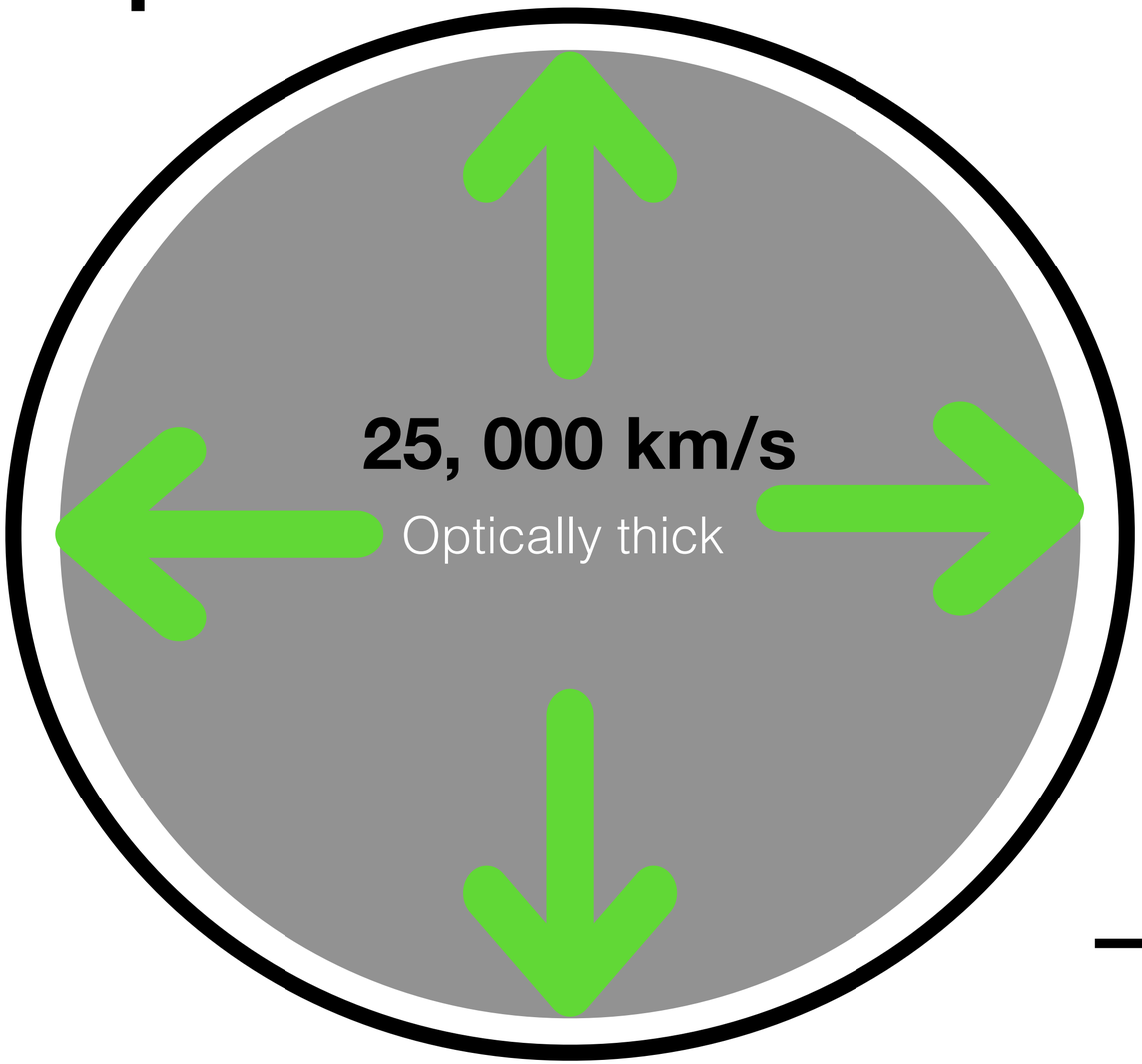


Pereira et al. (2013),
The Nearby Supernova Factory

From Chris Ashall

Homologous Expansion

Time=5days

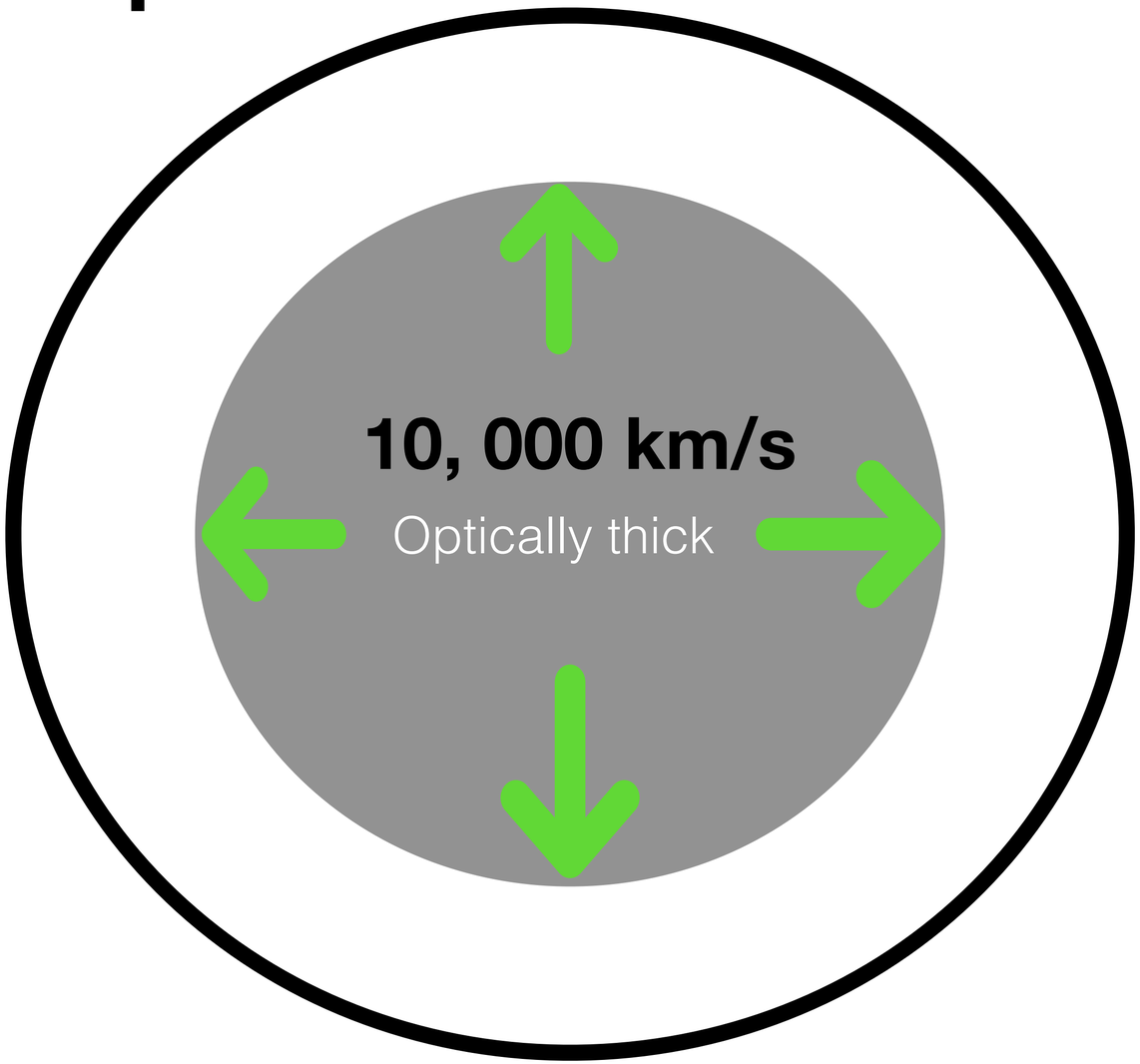


Scale

From Chris Ashall

Homologous Expansion

Time=10days

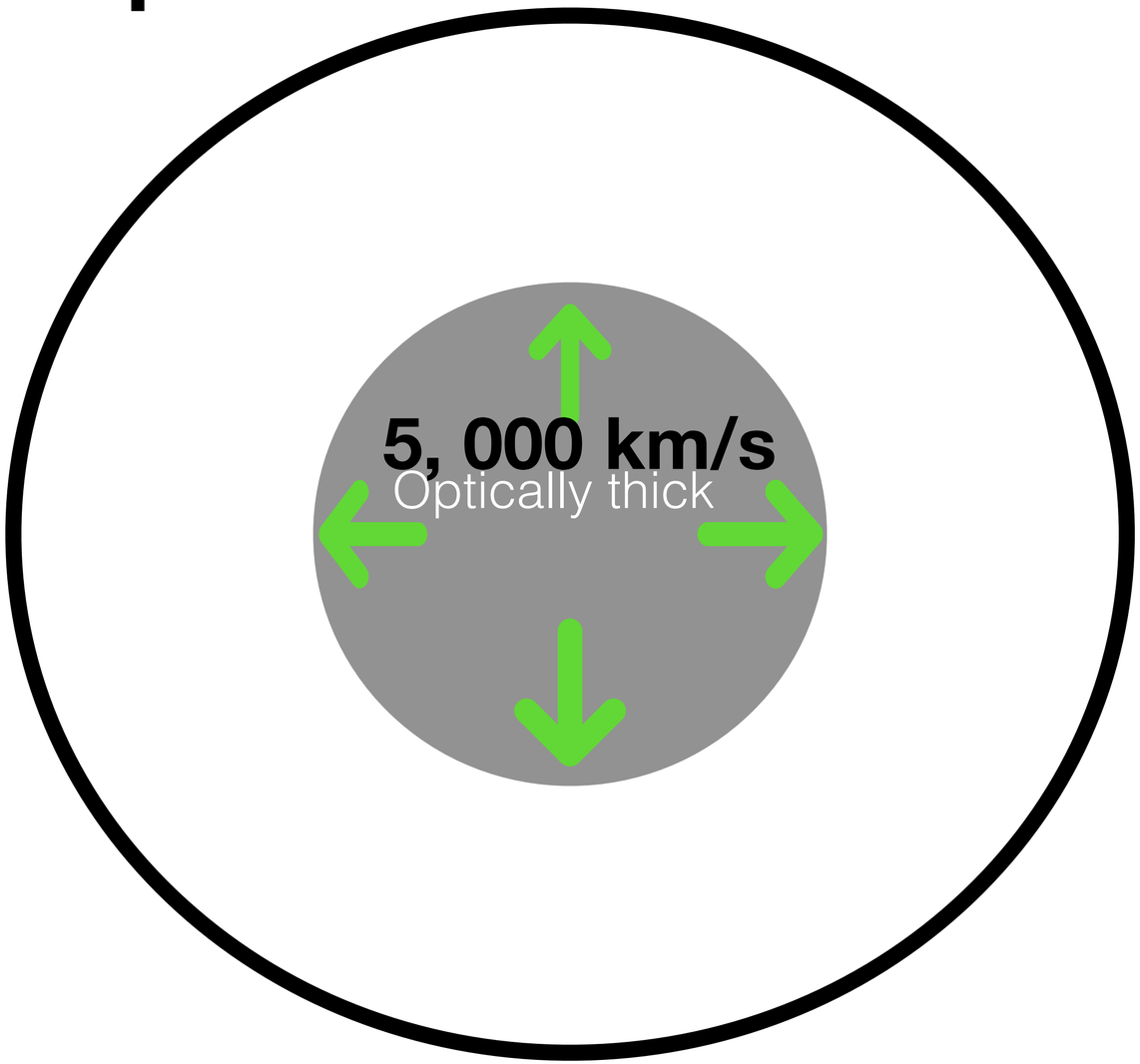


Scale

From Chris Ashall

Homologous Expansion

Time=40days

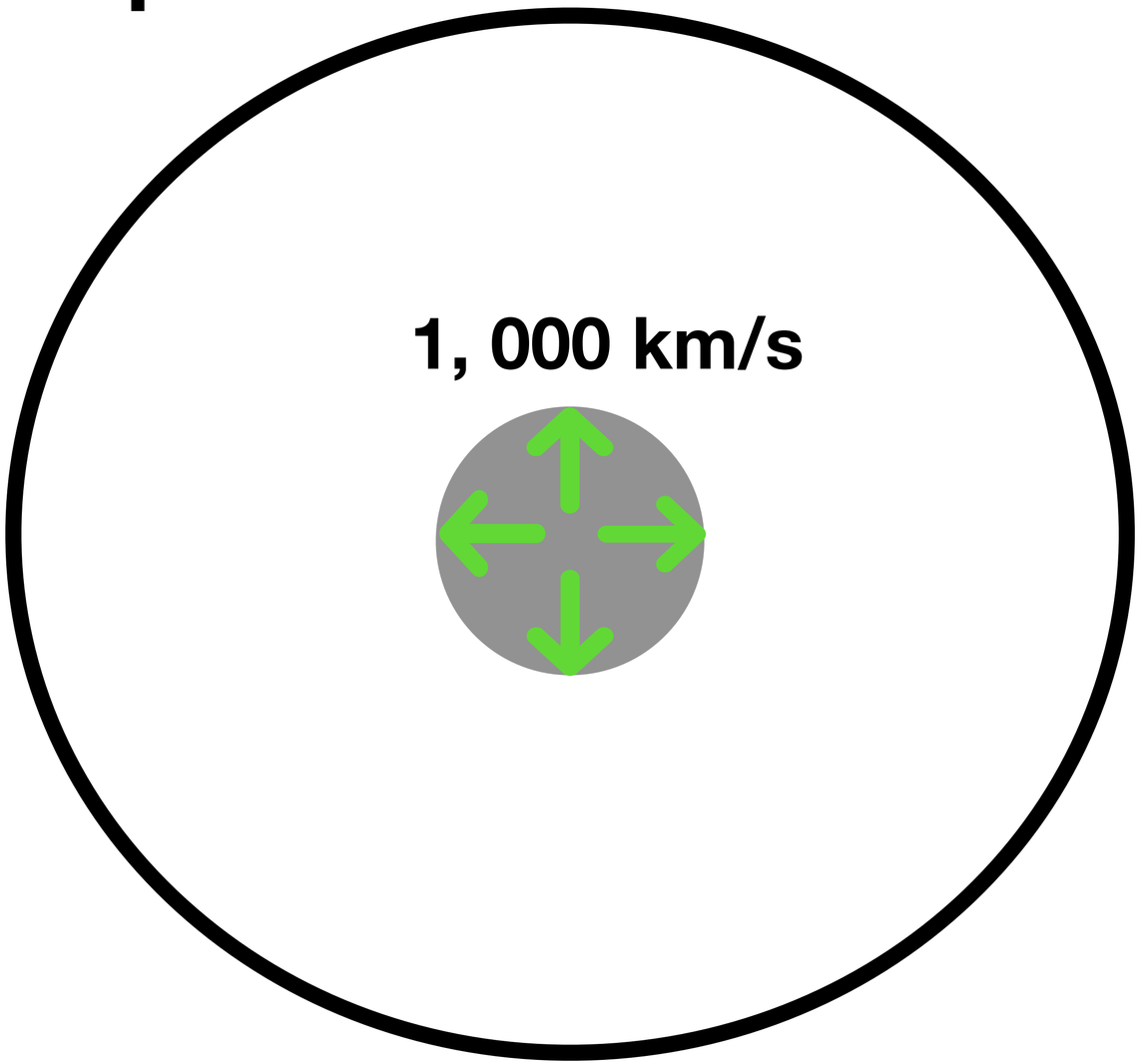


Scale

From Chris Ashall

Homologous Expansion

Time=80days

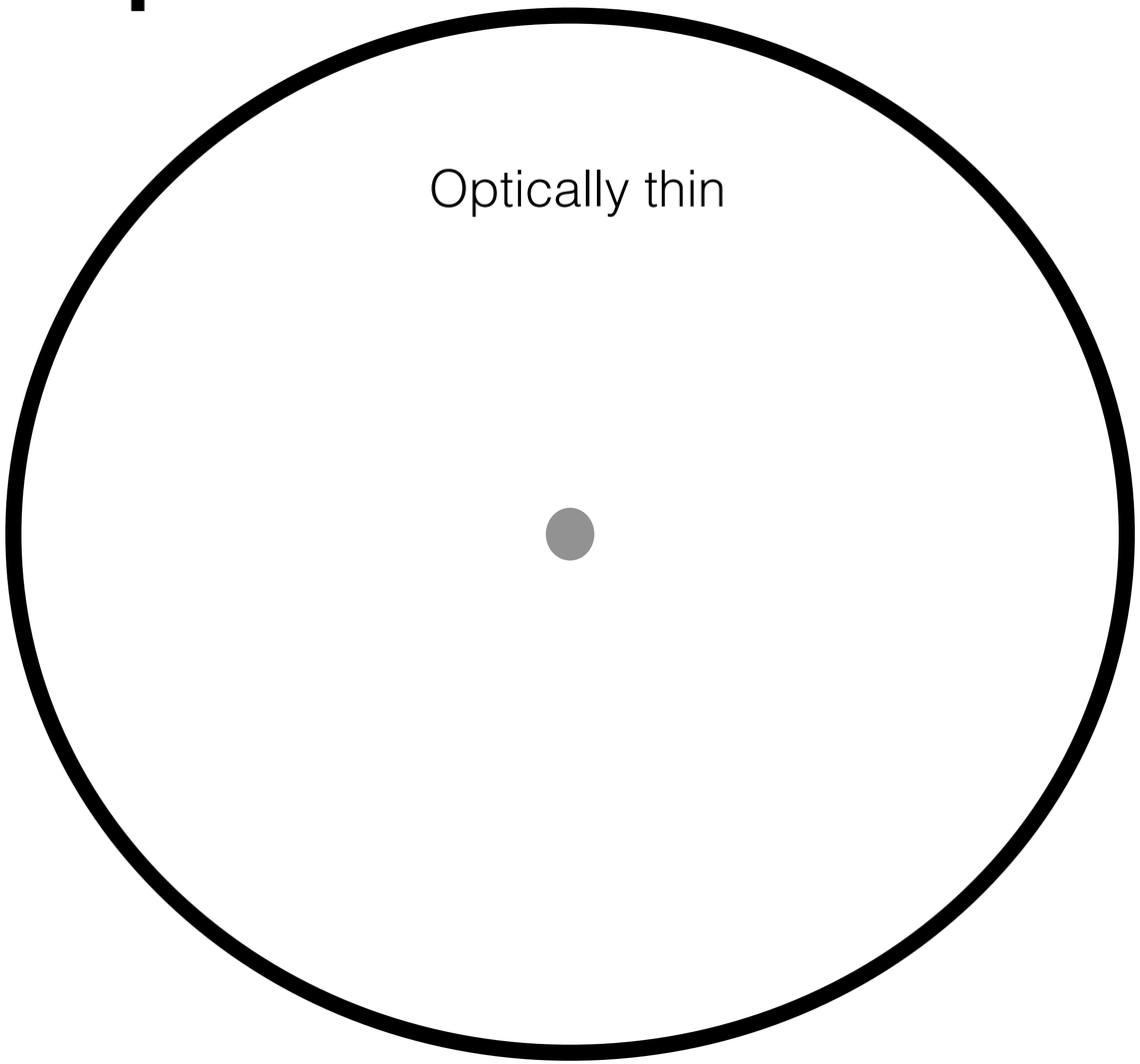


Scale

From Chris Ashall

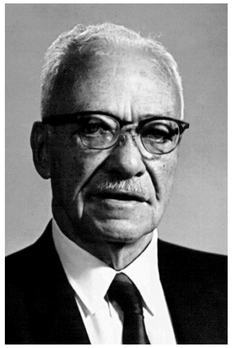
Homologous Expansion

Time=300days

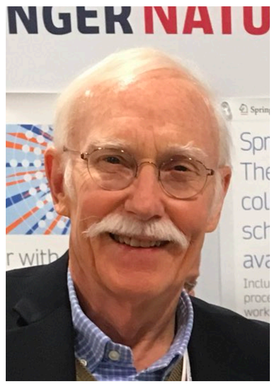


Scale

Classification *(based on Gal-Yam 2016)*

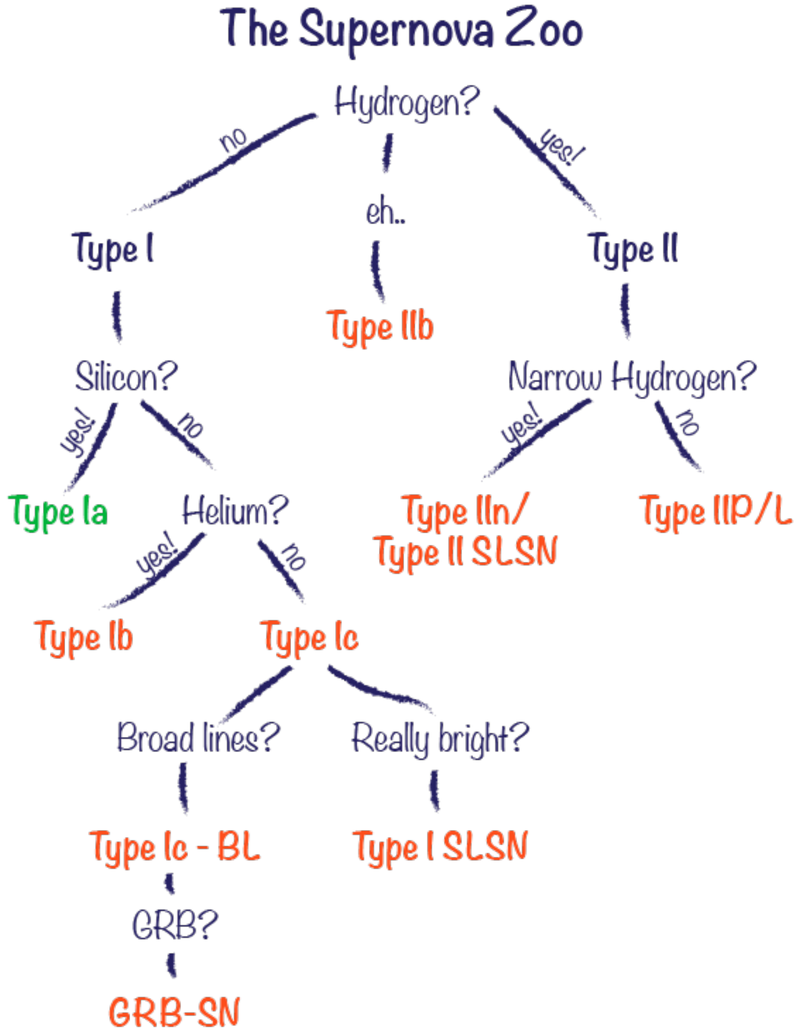


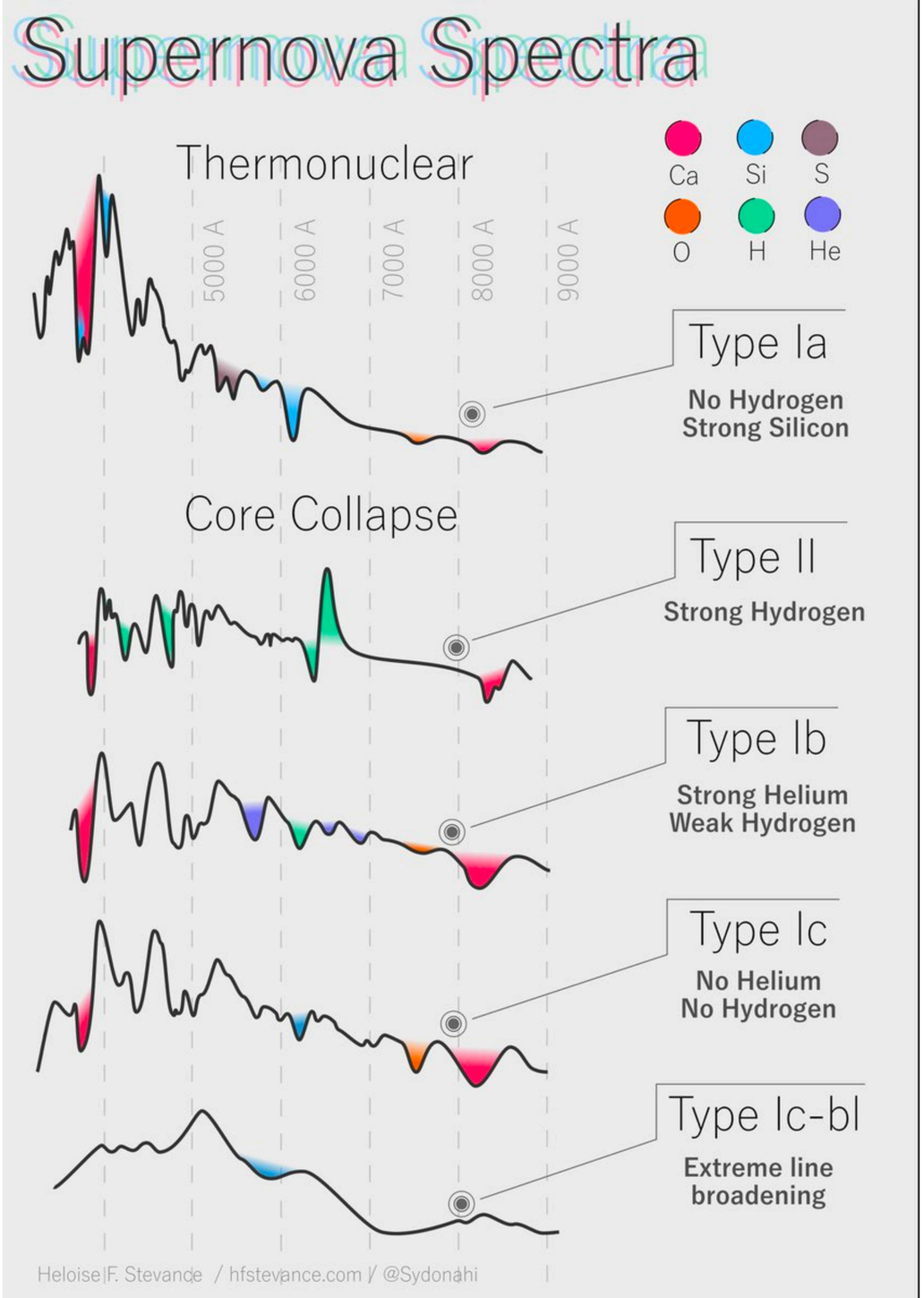
- 1934: Baade and Zwicky stated that SNe represent the collapse of *ordinary stars into neutron stars*
- 1941: Minkowski classified 14 events, 9 homogeneous were of Type I, the other 5 as Type II (all with H)
- 1979: Barbon divided SNe II into two photometric subclasses characterized by light curves showing prominent plateaus (II-P) or declining in a linear fashion (II-L).
- 1985: Wheeler and Levreault identified a subclass of SNe I which differs spectroscopically from the dominant population
- 1985: Elias coined the terms SN Ia for the dominant group and SN Ib for this new subclass
- 1987: Harkness identified signatures of He I in peak spectra of SNe Ib
- 1988: Filippenko introduced SNe IIb as those events that transition from having H-rich early spectra to He-dominated SN Ib-like events near peak
- 1990: Schlegel defined SNe IIn as those that show strong and relatively narrow emission lines of H
- 1990: Wheeler and Harkness introduced the term SN Ic for a subclass of SNe Ib that did not show strong He, but were similar to SNe Ib and different than SNe Ia



Classification

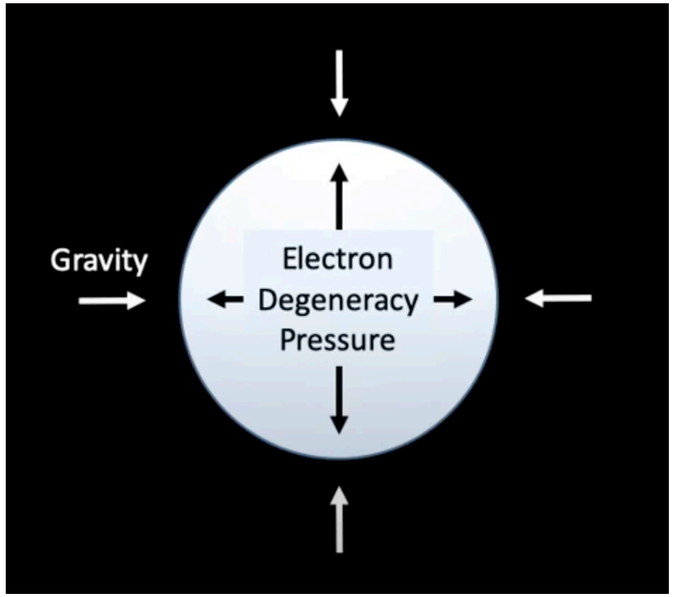
…but observational, not physical



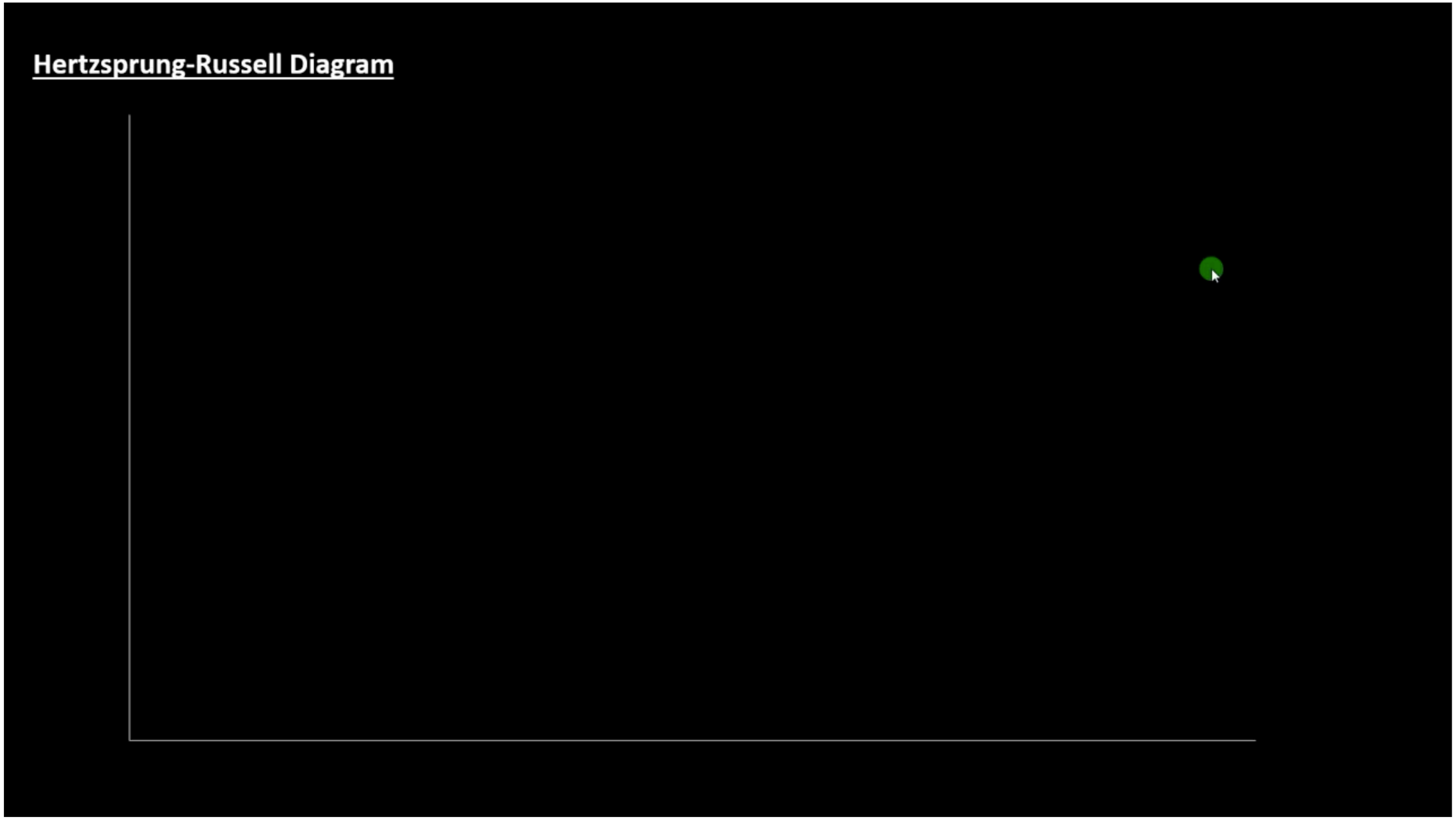


Type Ia supernovae

- Thermonuclear explosions of CO white dwarfs
- Binary (or triple!) systems where the exploding star accreting material from a companion until reaches a critical mass (M_{Ch}) for C ignition
- Why so important?
  - cosmological probes
  - produce large amount of Fe-group
  - we do not know progenitors and explosion mechanisms well



Stellar evolution stars M < 8 Msun



EVOLUCIÓN ESTELAR

Nebulosa Estelar

Inmensa nube estelar de polvo y gas: guardería de estrellas.

Protoestrella

Debido a la fuerza de la gravedad parte del gas y otros elementos se unen para formar una estrella.

Las masas estelares se miden en relación a la masa del sol: MS

PSP - Presecuencia Principal

Subenana marrón

M= Casi 0,013 MS

Son cuerpos celestes que no consiguieron la suficiente masa como para iniciar en su interior reacciones de fusión de forma continuada.

Enana Marrón

0,013 < M < 0,08 MS

Al igual que las subenanas marrones, son estrellas fallidas muy frías y difíciles de detectar debido a su escaso brillo.

Enana Roja

0,08 < M < 0,5 MS

Estrellas pequeñas del tipo más abundantes ya que constituyen el 70% de las estrellas del universo.

Enana Naranja

0,5 < M < 0,8 MS

Estrellas algo más grandes y calientes que las enanas rojas pero no tanto como nuestro sol.

Enanas Amarillas y estrellas blancas

0,8 < M < 3 MS

Nuestro sol es una enana amarilla. A partir de aprox. 1,5 masas solares comienza la categoría de estrellas blancas.

Estrella azul

3 < M < 20 MS

Estrellas masivas de corta vida debido a lo rápido que queman su hidrógeno.

Gigante azul

20 < M < 120 MS

Estrellas muy masivas, con una elevada luminosidad y temperatura que viven menos tiempo que ninguna otra.

Buena parte de la radiación que emite es ultravioleta.

SP - Secuencia Principal

Si 3 < M < 9 MS

Subgigante

Estrellas que acaban de terminar la fusión de hidrógeno en sus núcleos (usando ahora helio) y comienzan a aumentar de tamaño y luminosidad mientras se enfrían poco a poco.

Si 20 < M < 45 MS

Gigante Roja

Estrellas que se hinchan como consecuencia de haber transformado todo su hidrógeno en helio.

Dentro de 5000 millones de años el sol se convertirá una estrella

Super gigante amarilla

Es la fase intermedia que

Si M > 45 MS

Etapas finales

enfrían poco a poco.

Gigante Roja

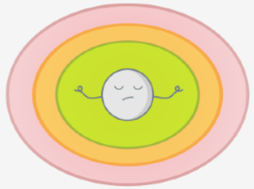
Estrellas que se hinchan como consecuencia de haber transformado todo su hidrógeno en helio.

Dentro de 5000 millones de años el sol se convertirá una estrella de este tipo.

Super gigante amarilla

Es la fase intermedia que experimentan algunas estrellas (más de 10 masas solares). Son muy escasas ya que pasan poco tiempo en este estado.

Si M > 45 MS



Nebulosa Planetaria

La gigante roja pierde su envoltura en forma de plasma y gas ionizado.

Tras la expulsión de sus capas exteriores, subsiste el pequeño núcleo de la estrella.

Super gigante roja

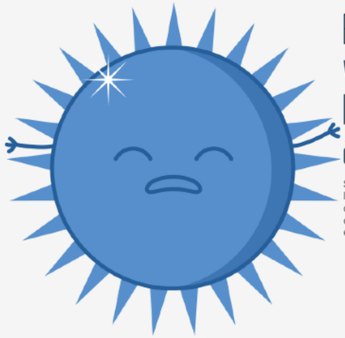
Estrellas masivas en la última etapa de su vida. Son las más grandes (en términos de volumen) que pueden encontrarse en nuestro universo.

Si M > 20 MS

Estrella Wolf-Rayet (WR)

Proveniente de gigantes azules de más 45 masas solares, o bien supergigantes roja de más de 20, son estrellas muy calientes que sufren grandes pérdidas de masa debido a sus intensos vientos estelares.

Si Masa > 45 MS



Estrella variable luminosa azul (VLA)

Son las estrellas más luminosas que se conocen. Su número es extremadamente escaso.

Estrella WR pobre en hidrogeno

Una variante Wolf-Rayet más evolucionada que ha perdido prácticamente todo su hidrógeno.

Si 15 < M < 20 MS

Super Gigante Azul

En este caso la etapa de supergigante roja apenas dura y pasa por este estado intermedio más caliente antes de colapsar.

Enana Azul

Una hipotética clase de estrella que necesitaría aprox. 60.000 millones de años para aparecer, cuando una enana roja agota la mayor parte de su hidrógeno.

Como no tiene suficiente masa en vez de expandirse como las gigantes rojas, incrementaría su radioactividad.

La enana blanca resultante sería de helio

La enana blanca resultante sería de carbono y oxígeno.

Enana Blanca

Etapas finales

Enana Azul

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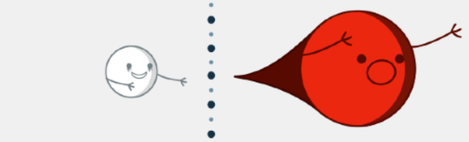
Enana Blanca

Es un remanente estelar que se genera cuando una estrella agotado su combustible nuclear pero queda estable.

De hecho, se trata de una etapa de la evolución estelar que atravesará el 97% de las estrellas que conocemos, incluido el Sol



Supernova Tipo 1A

En el caso de que una enana blanca de carbono y oxígeno forme parte de un sistema binario y ésta absorba parte del hidrógeno de su compañera, la estrella pierde su estado de equilibrio y se produce una violenta explosión.

Si 15 < M < 20 MS

Super Gigante Azul

En este caso la etapa de supergigante roja apenas dura y pasa por este estado intermedio más caliente antes de colapsar.

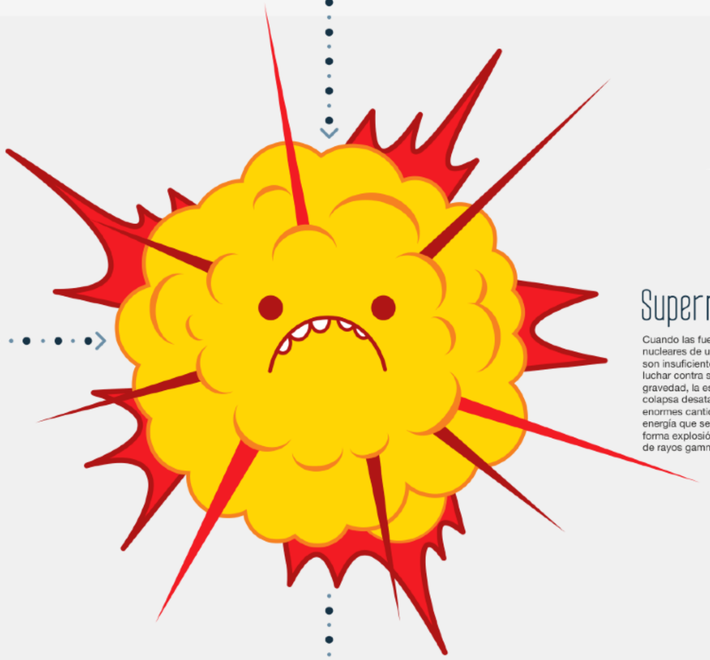
Estrella variable luminosa azul (VLA)

Son las estrellas más luminosas que se conocen. Su número es extremadamente escaso.

Estrella WR pobre en hidrogeno

Una variante Wolf-Rayet más evolucionada que ha perdido prácticamente todo su hidrógeno.

Si 20 < M < 45 MS



Supernova

Cuando las fuerzas nucleares de una estrellas son insuficientes para luchar contra su propia gravedad, la estrella colapsa desatando enormes cantidades de energía que se libera en forma explosión y emisión de rayos gamma y rayos X.

Si Masa > 8 MS

Estrella de neutrones

Remanente de una estrella que ha colapsado sobre si misma pero no tenía suficiente masa como para convertirse en un agujero negro.

Son estrellas superdensas con una velocidad de rotación vertiginosa.

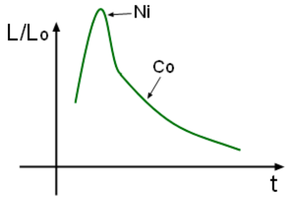
Púlsar

Son estrellas de neutrones

Death of a WD

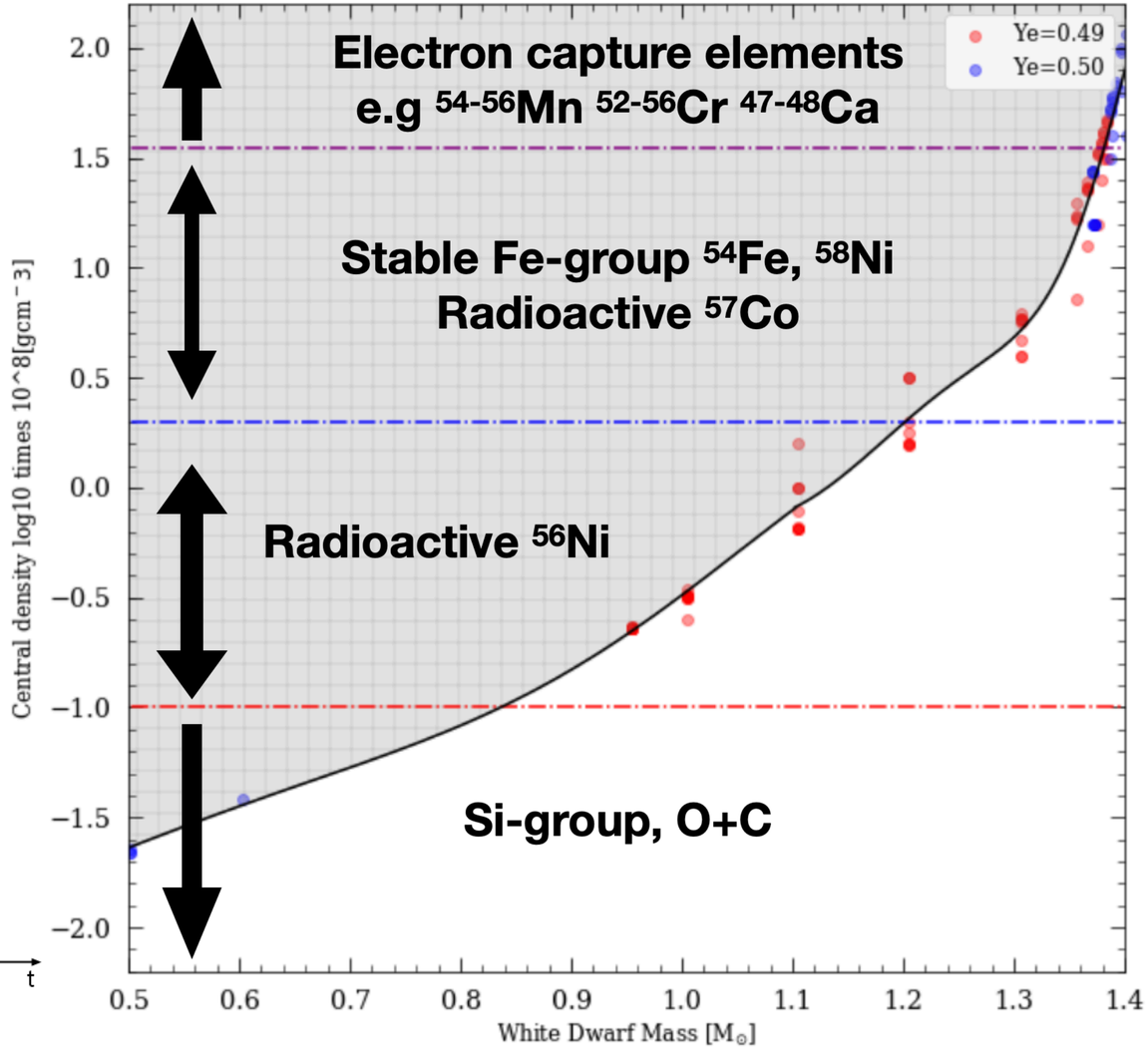
- Thermonuclear explosion of a CO WD (Hoyle&Fowler60)
- Outcome is dominated by temperature and density of the burning
- ^{56}Ni drives the luminous display (Pankey62, Colgate&MeKee69)
- L_{peak} ~ ^{56}Ni mass (Arnett82)

$$^{56}\mathrm{Ni} \xrightarrow{t_{1/2}= 6.08d} {}^{56}\mathrm{Co} \xrightarrow{t_{1/2}= 77.2d} {}^{56}\mathrm{Fe}$$

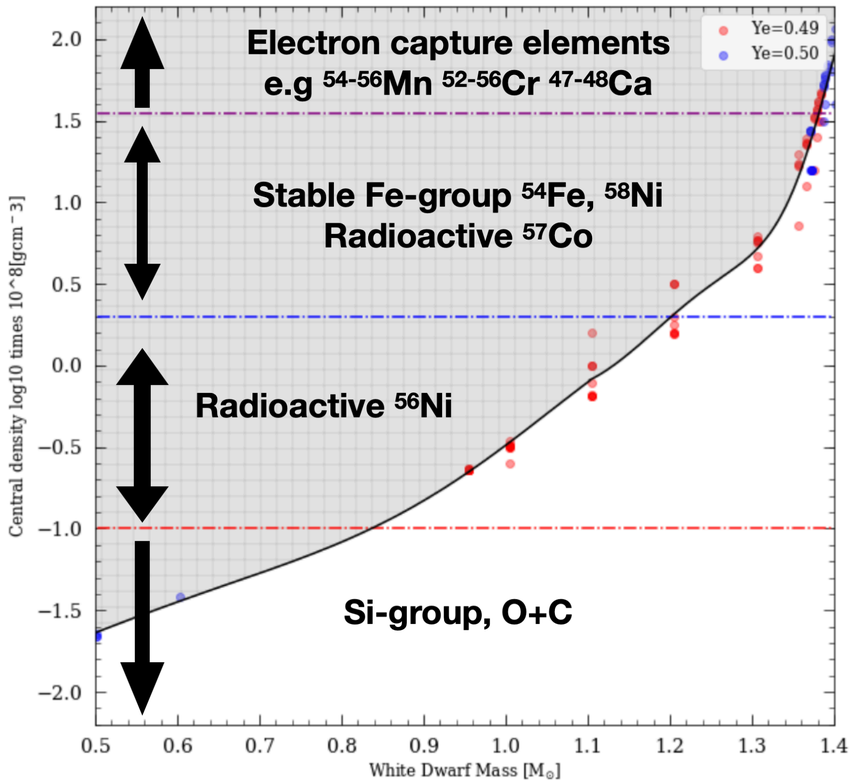


- Fusion drives the explosion, but radioactivity makes it shine!

Ashall21

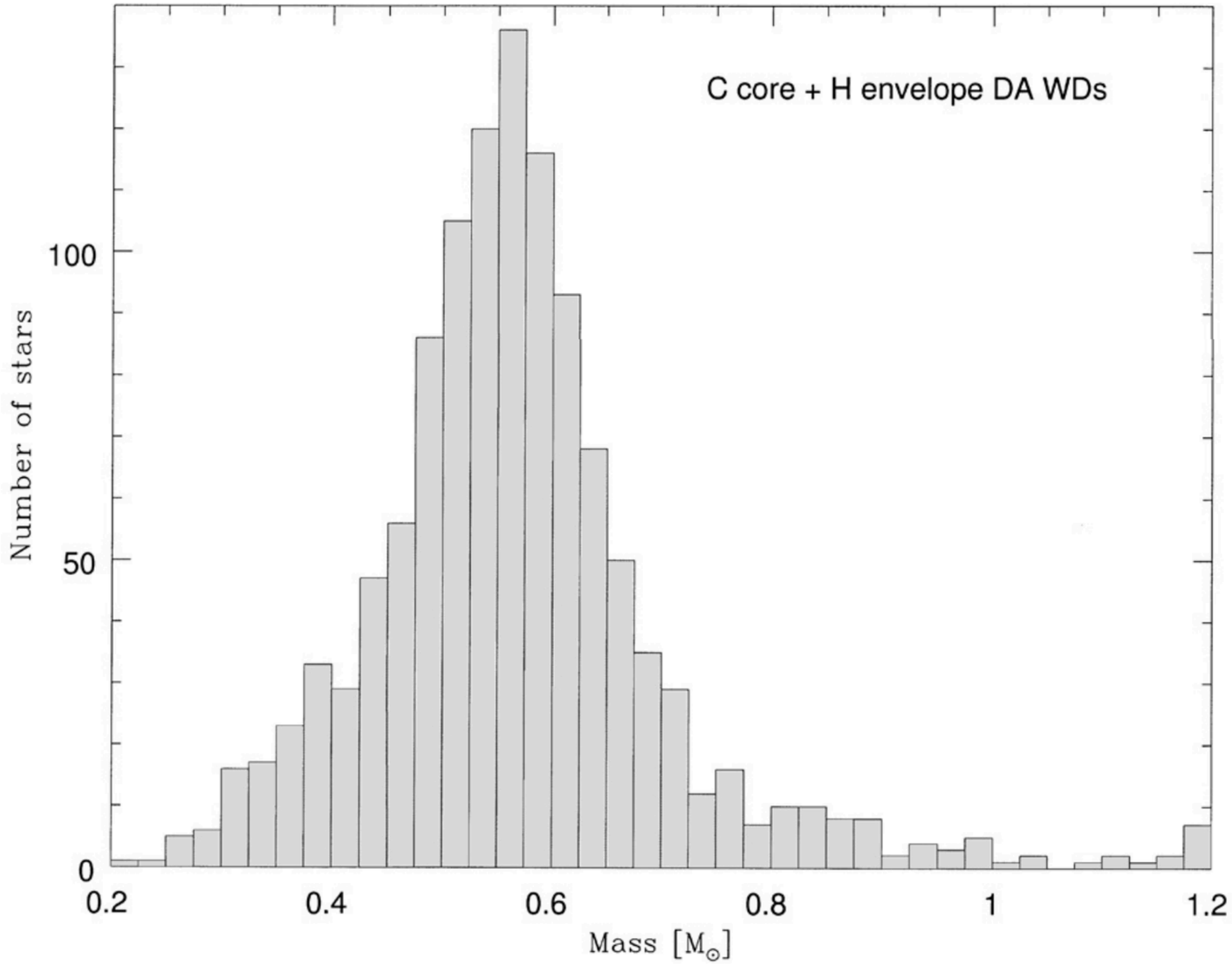


Masses of WDs



Ashall21

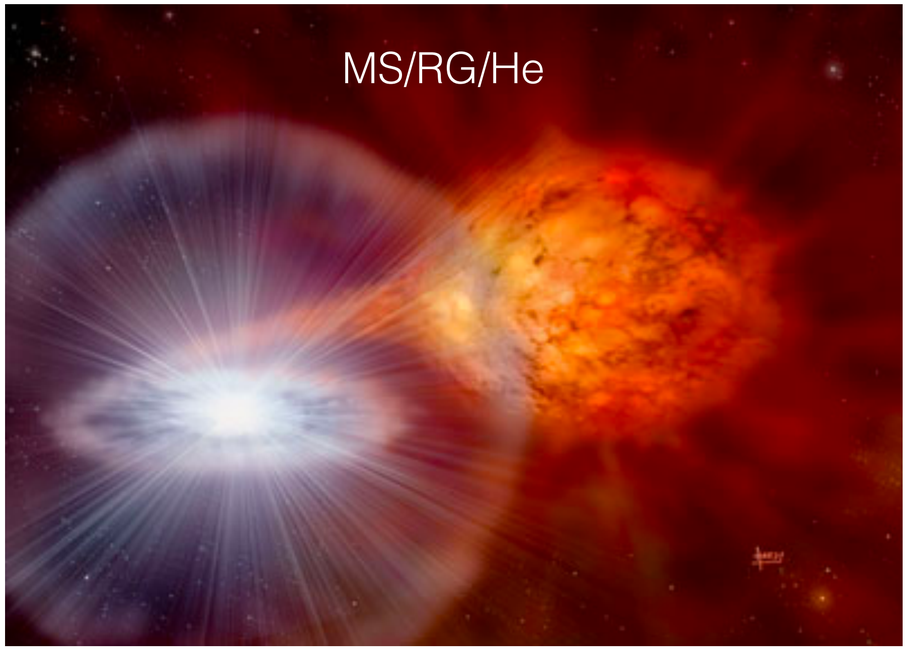
Madej+04



The lack of understanding about SNe Ia progenitors and explosions could produce one of the largest systematics in cosmological experiments

What You Might Have Thought

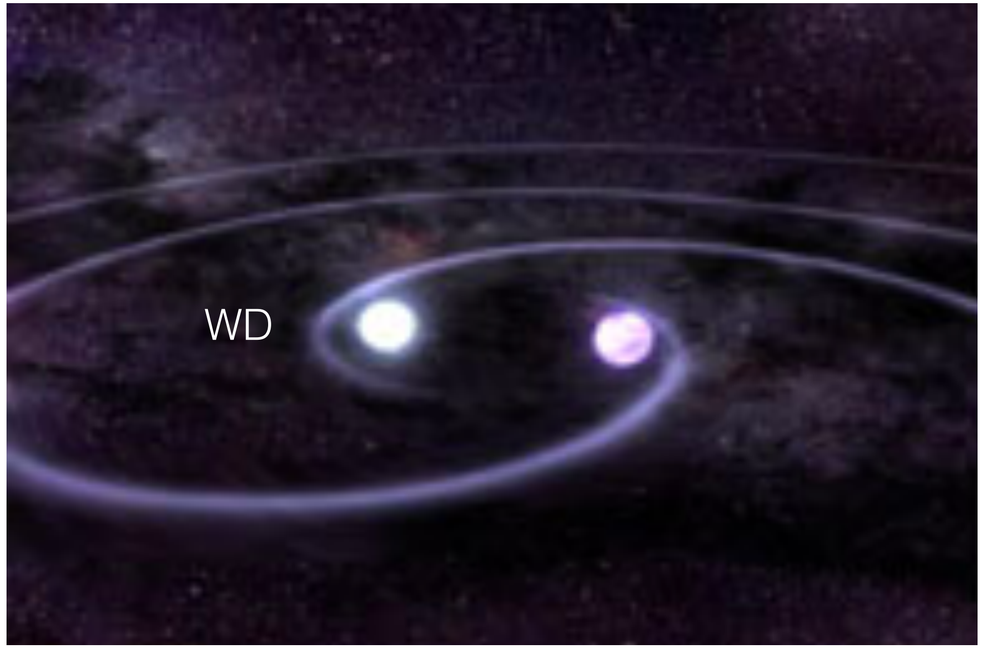
Single degenerate (SD)



WD accretes matter until it approaches MCh

Central C ignition

Double degenerate (DD)

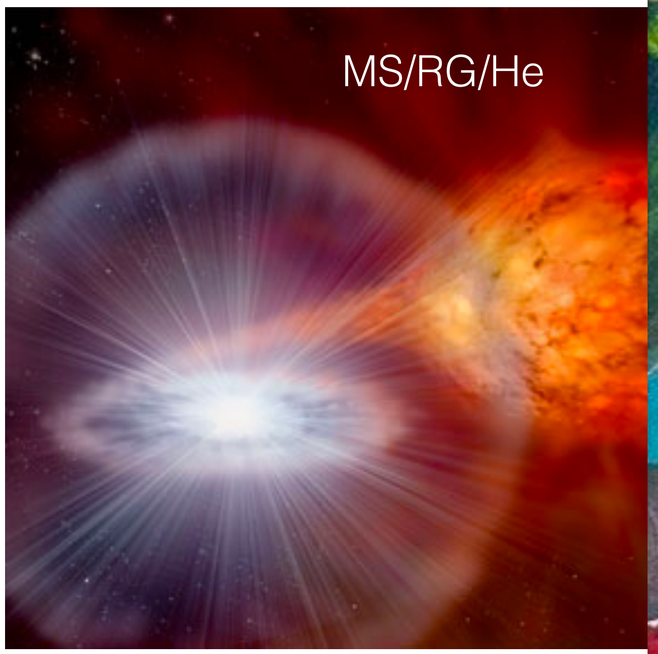


2 Was merge and explode (not limited by MCh

Outer C ignition

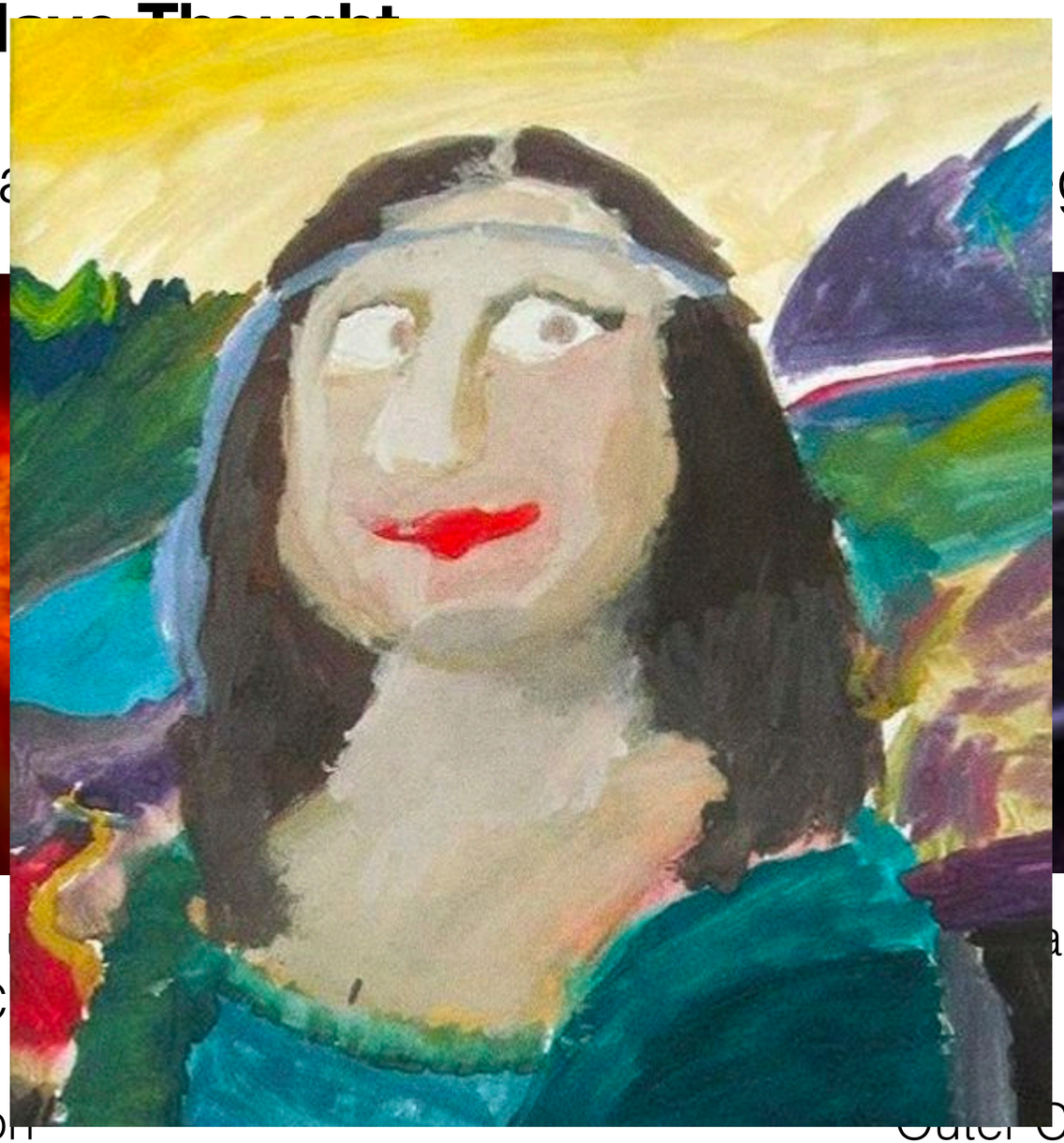
What You Might H

Single degenera

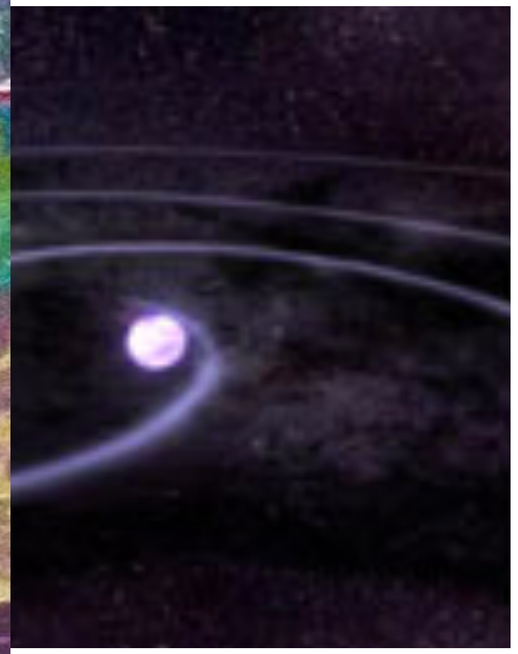


WD accretes matter
approaches MC

Central C ignition



generate (DD)

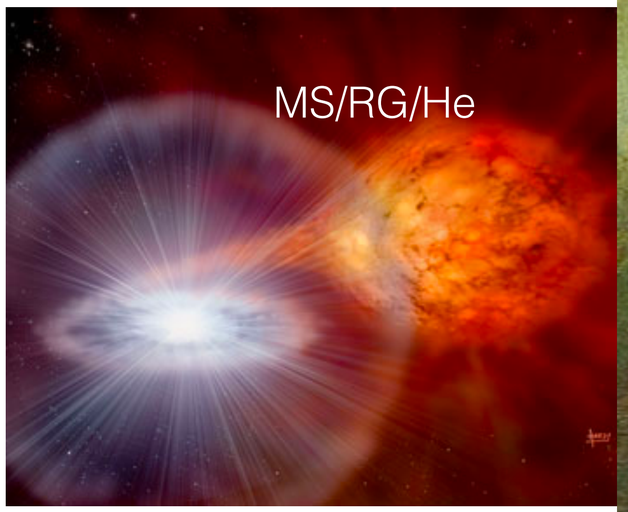


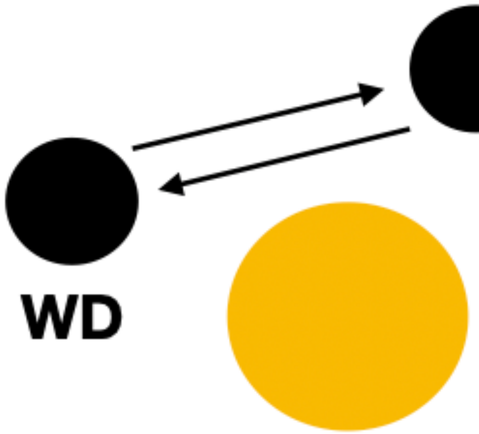
and explode (not
by MCh

C ignition

Progenitor S

Single degenerate





Triple system

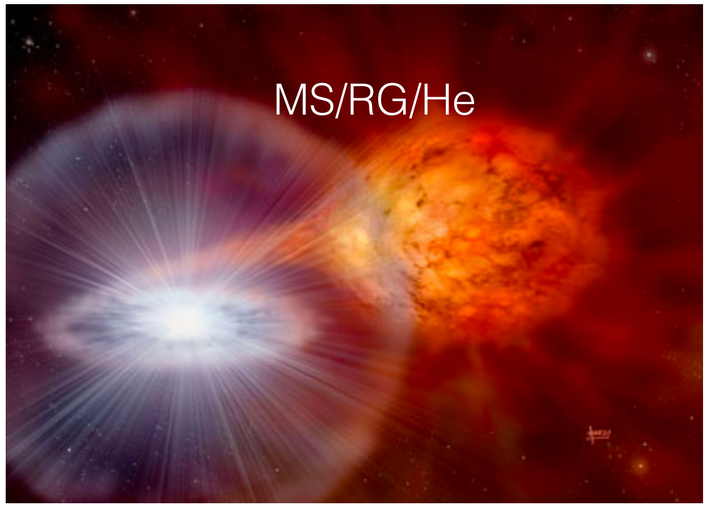
Core degenerate

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

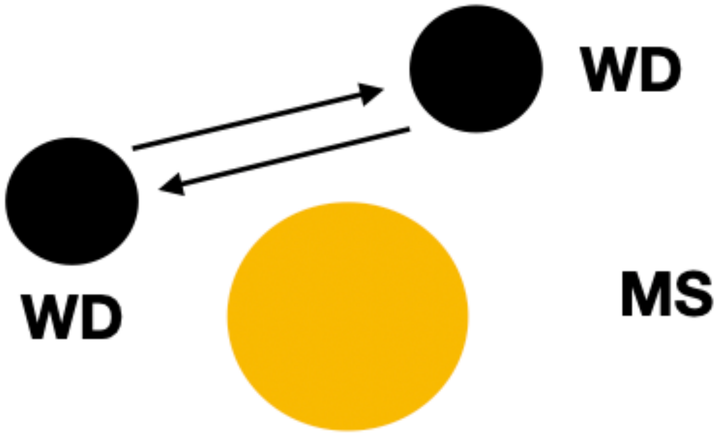
M_{ch}
sub-M_{ch}
super-M_{ch}

Progenitor Scenarios

Single degenerate



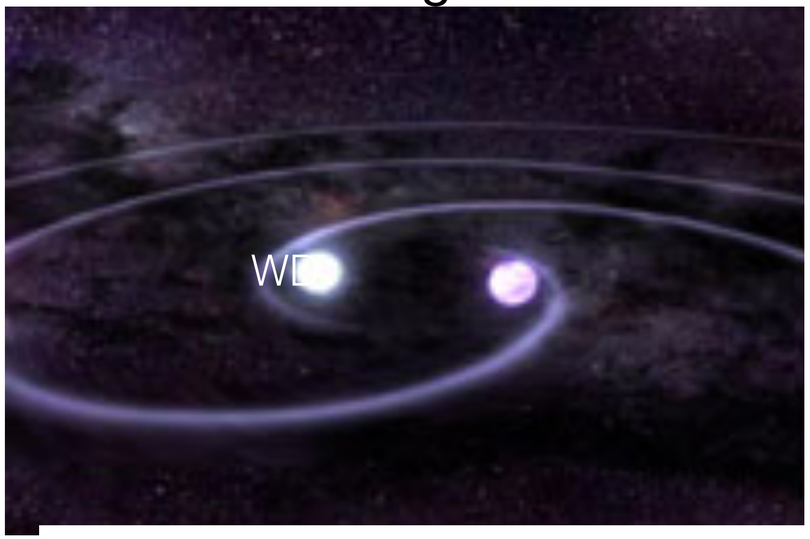
M_{ch}
sub-M_{ch}



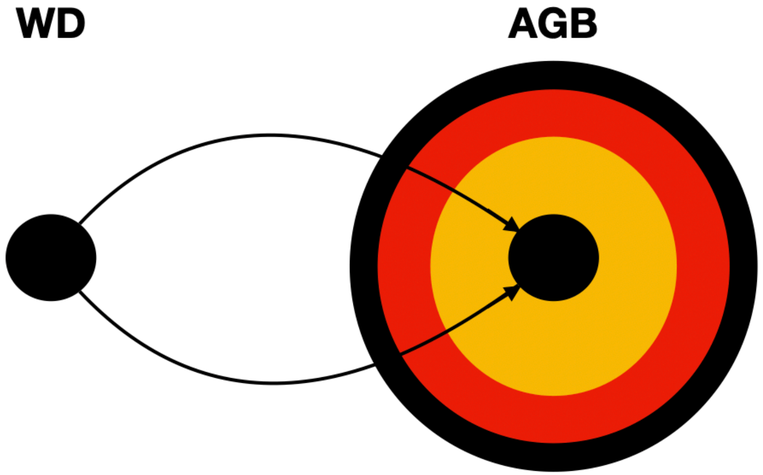
M_{ch}
sub-M_{ch}
super-M_{ch}

Triple system

Double degenerate



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



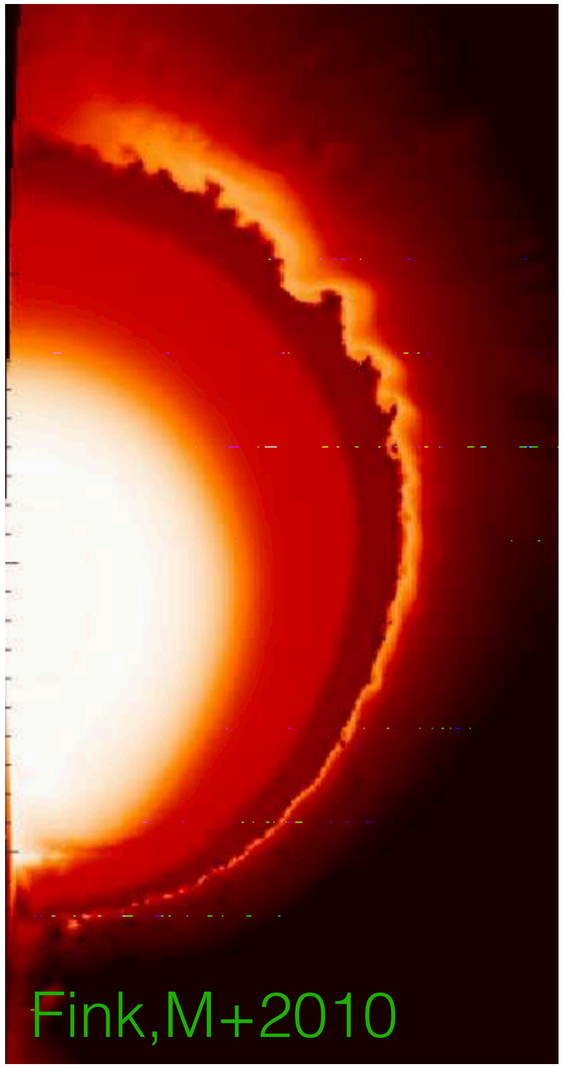
M_{ch}
sub-M_{ch}
super-M_{ch}

Core degenerate

Explosion Mechanism

Central Carbon Ignition
Requires near MCh WD

Outer Carbon Ignition
Requires two WD, which head on collide or violently merge



Surface He Ignition
Requires sub-MCh WD

Flame front

Transition

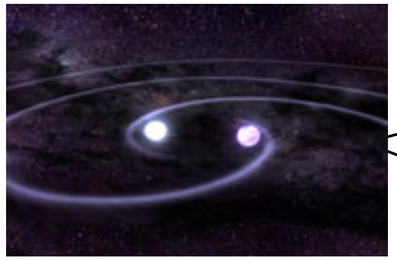
Subsonic burning speed
Rayleigh-Taylor unstable

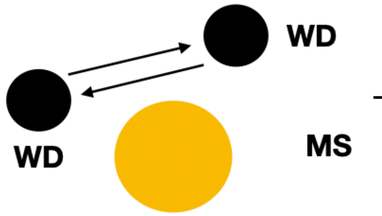
Deflagration

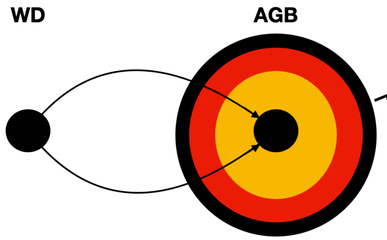
Supersonic burning speed
No mixing of the ejecta

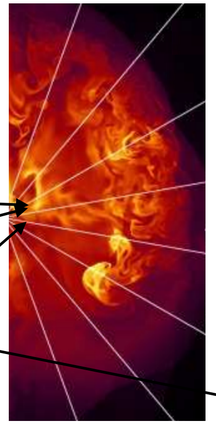
Detonation

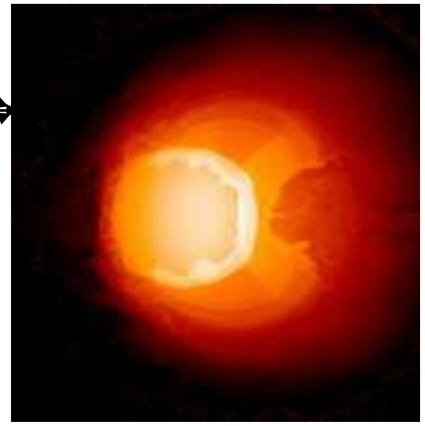
Progenitor scenario and explosion mechanism

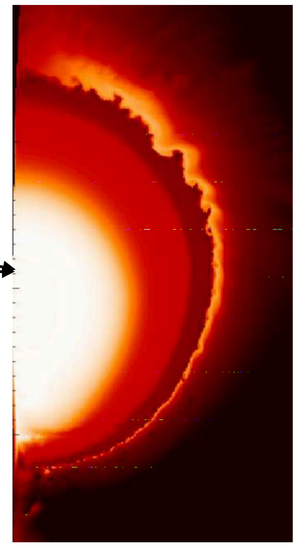










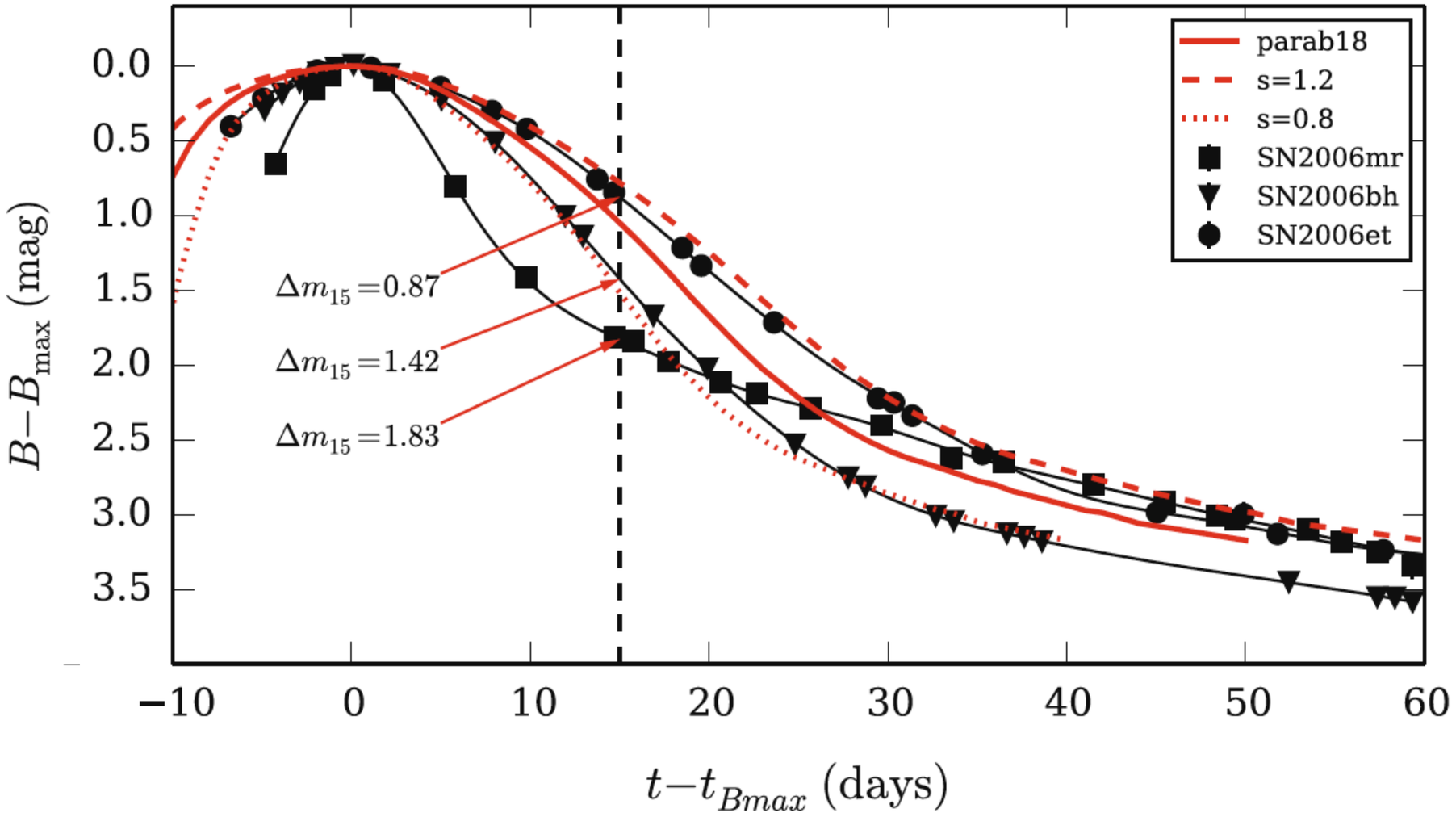


Progenitor scenario

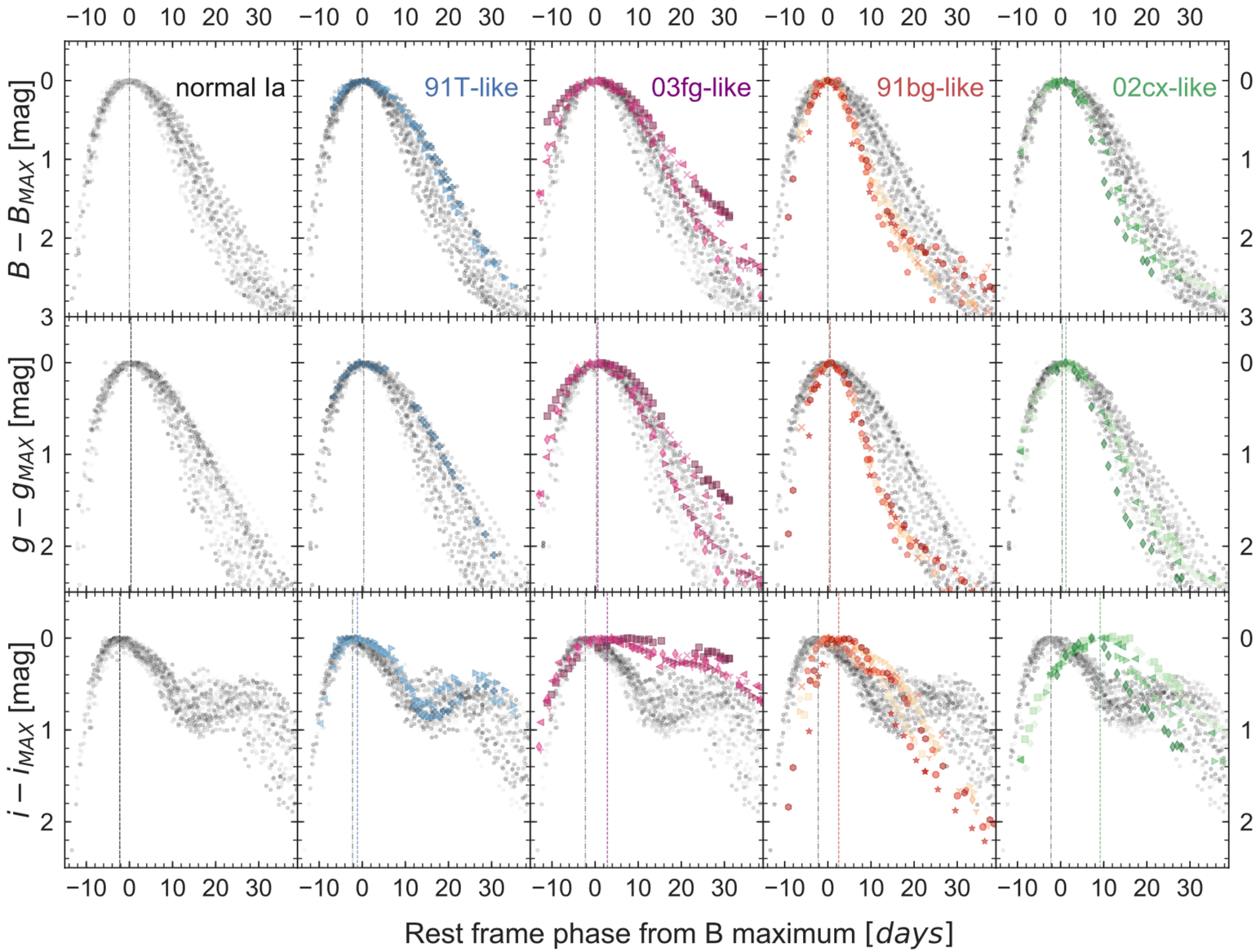
$\neq$

Explosion mechanism

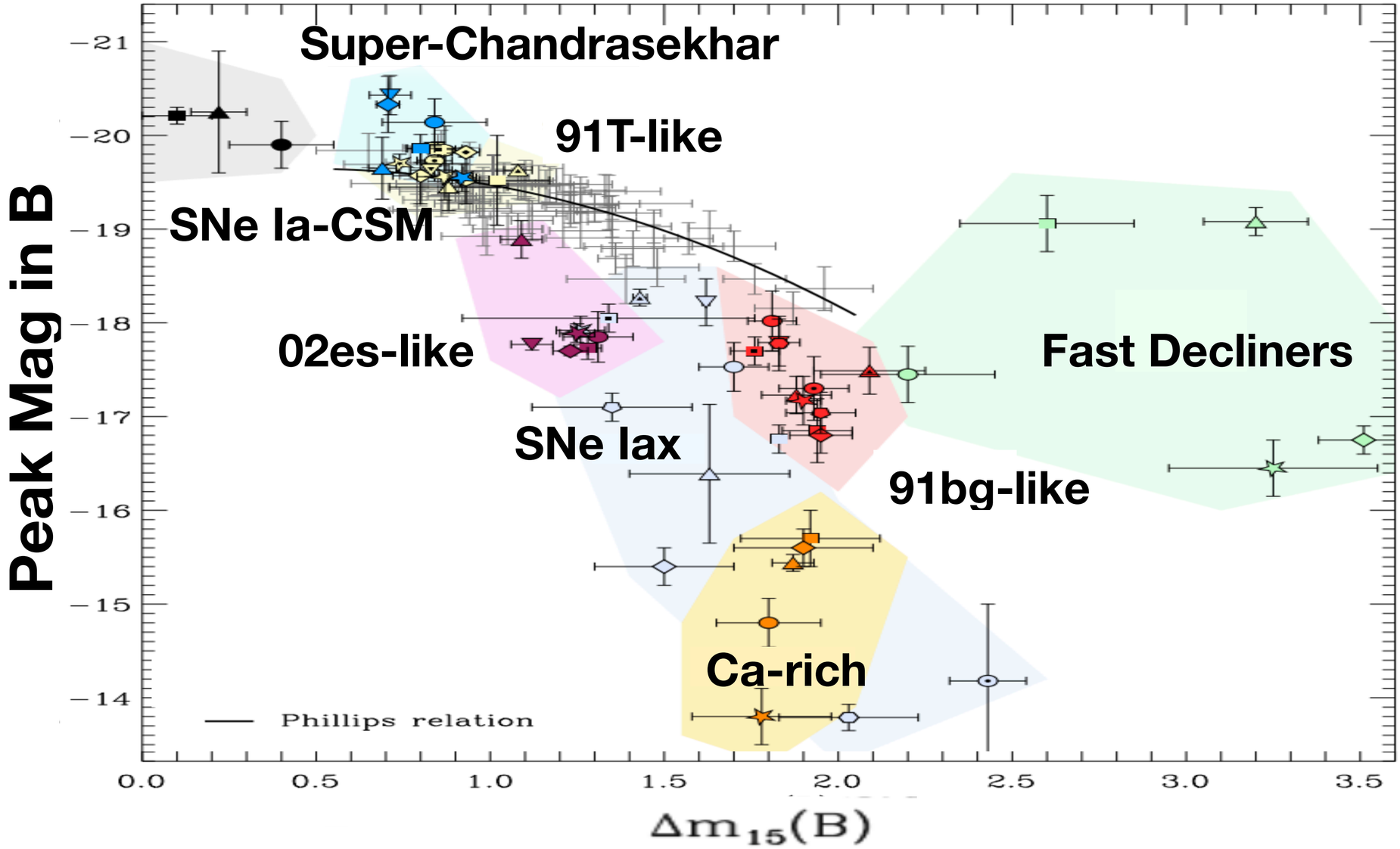
Type Ia supernovae



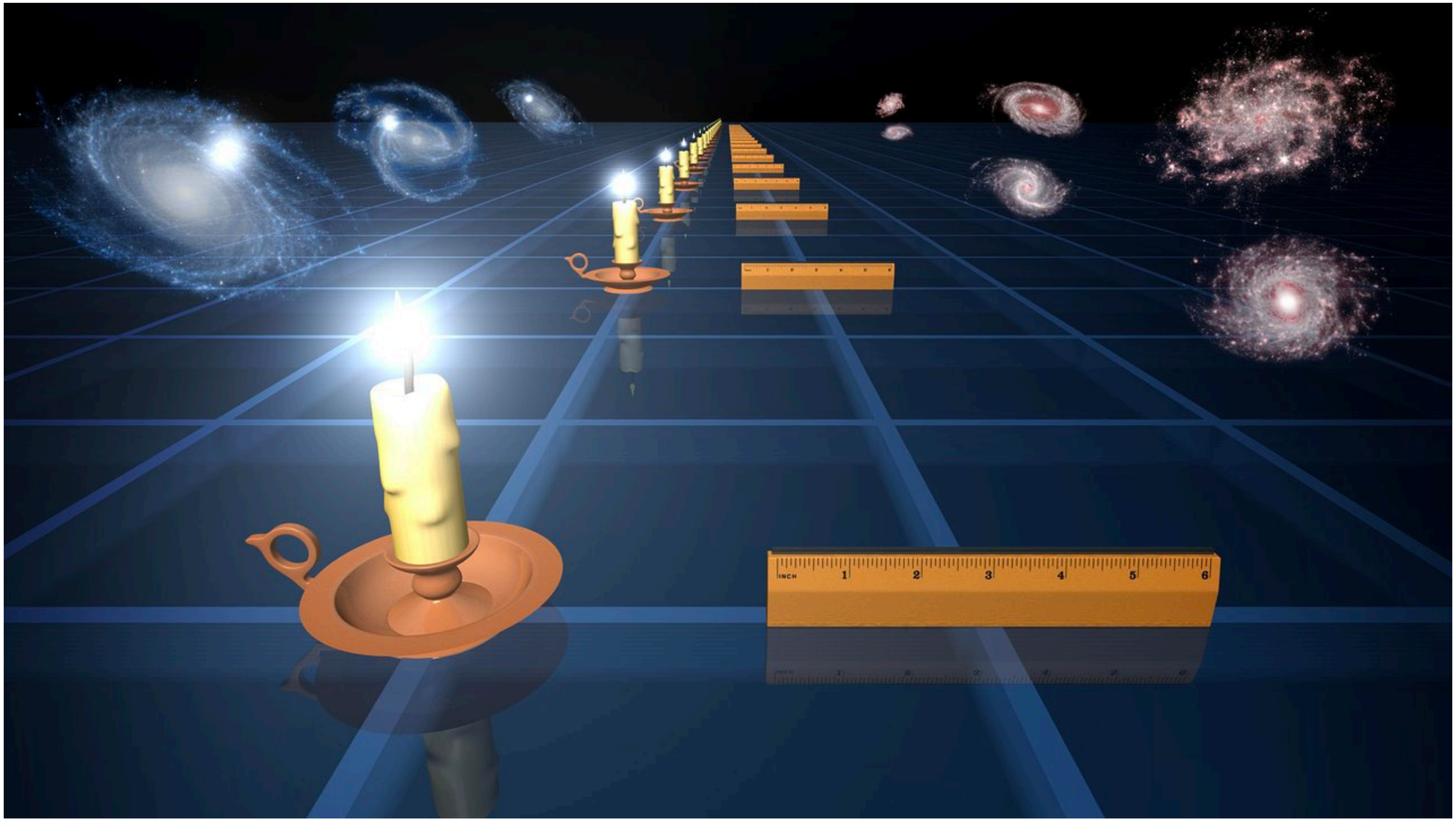
Type Ia supernovae



Type Ia supernovae



Type Ia supernova cosmology



SNIa cosmology

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

Two empirical correlations:

peak brightness vs brightness decay

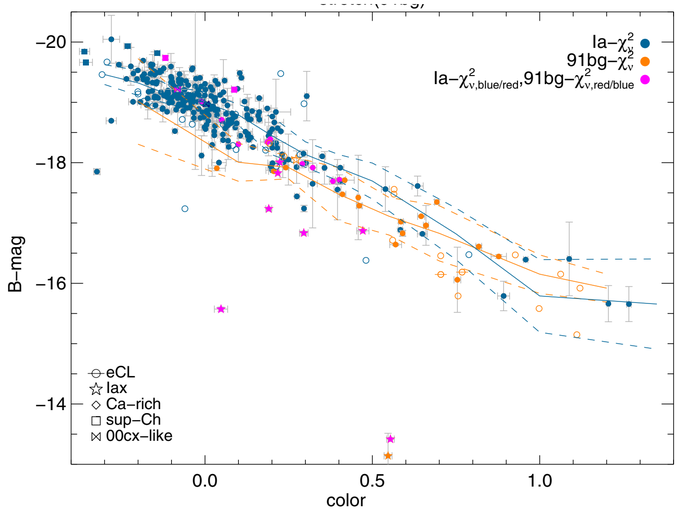
peak brightness vs color

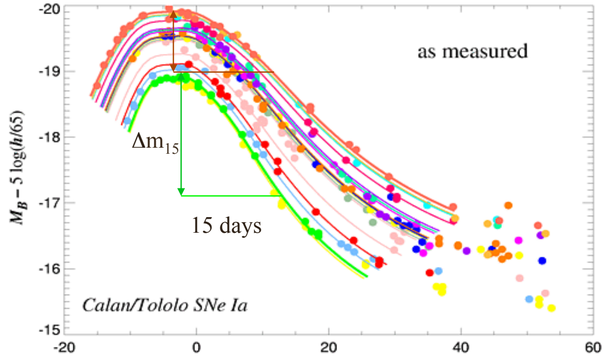
Standardized peak brightness

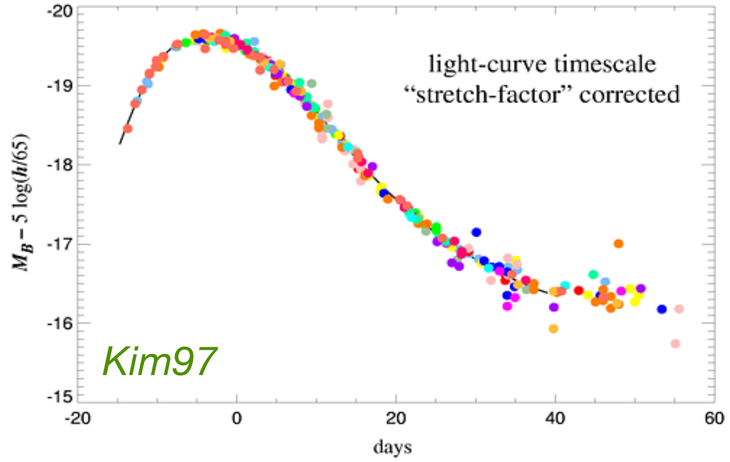
$$\mu(z)_{\rm SN} = m(z) - M = (m_{\rm obs} + \alpha x1 - \beta c - A_{\rm MW} + K_{x,y}) - M$$

$$\mu(z)_{\rm model} = 5\log_{10}(d_L/10pc)$$

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





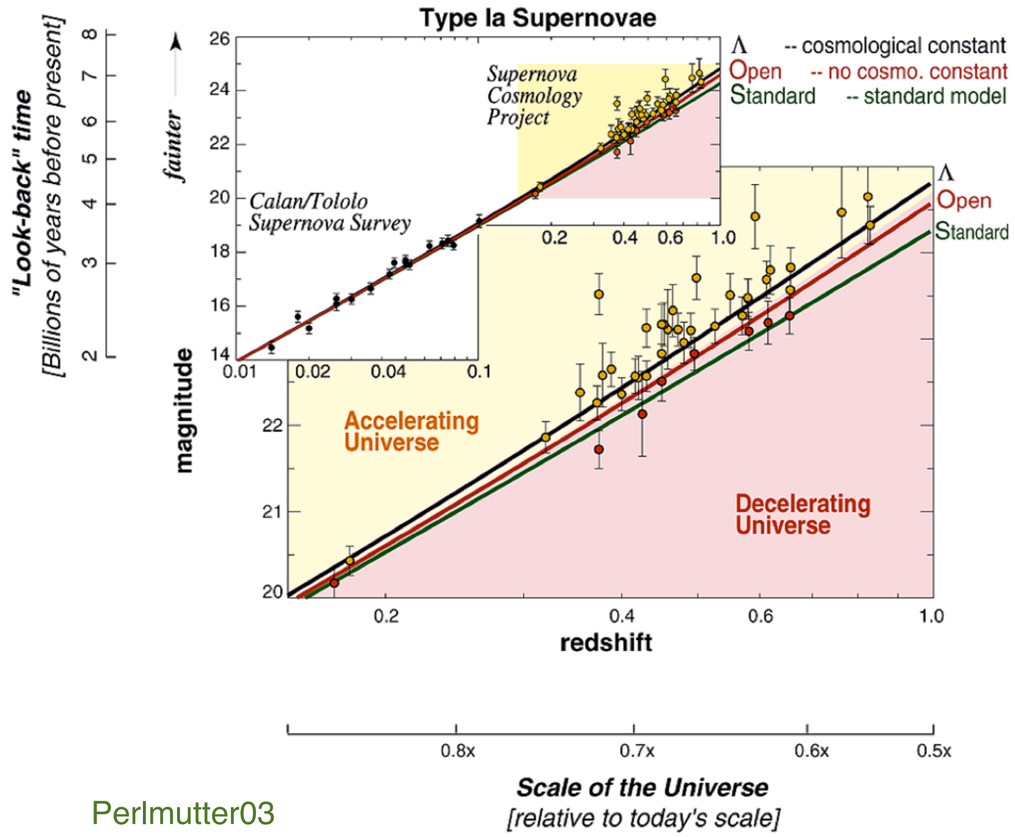


Accelerated expansion Universe

In 1998 two groups found that SNe Ia that were further were fainter than expected from a constant expansion

Supernova Cosmology Project

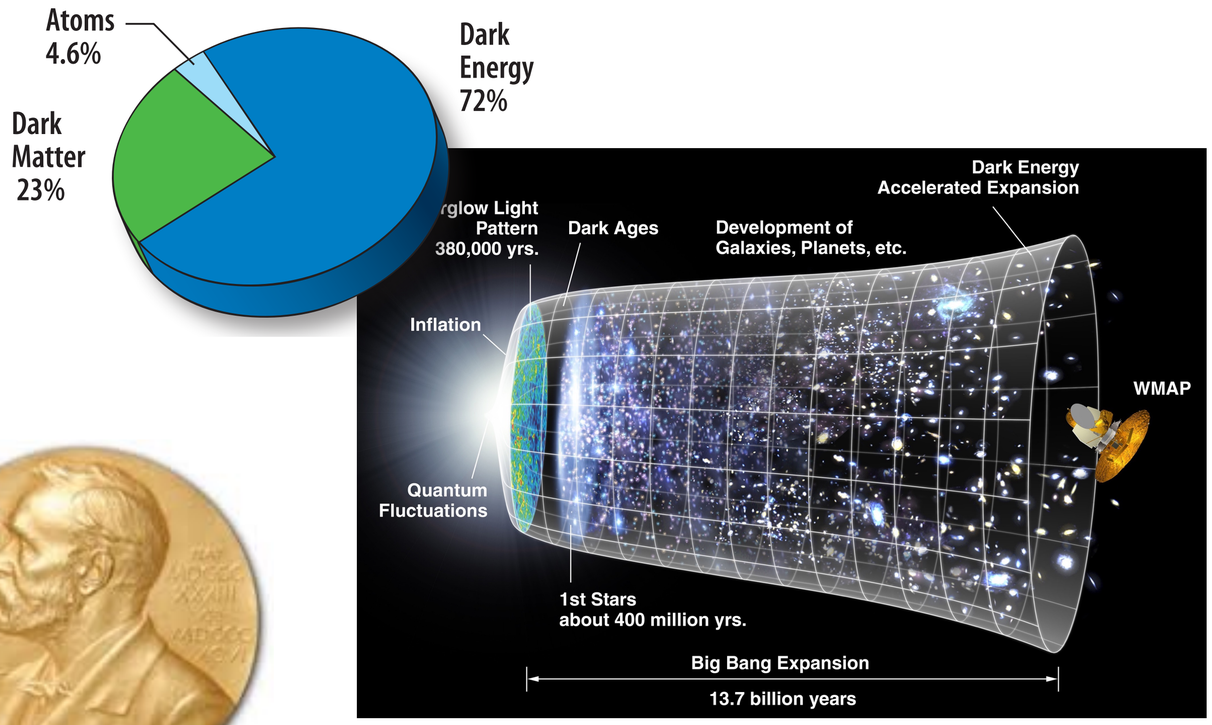
Perlmutter et al. 1999



Perlmutter03

High-z Supernova Team

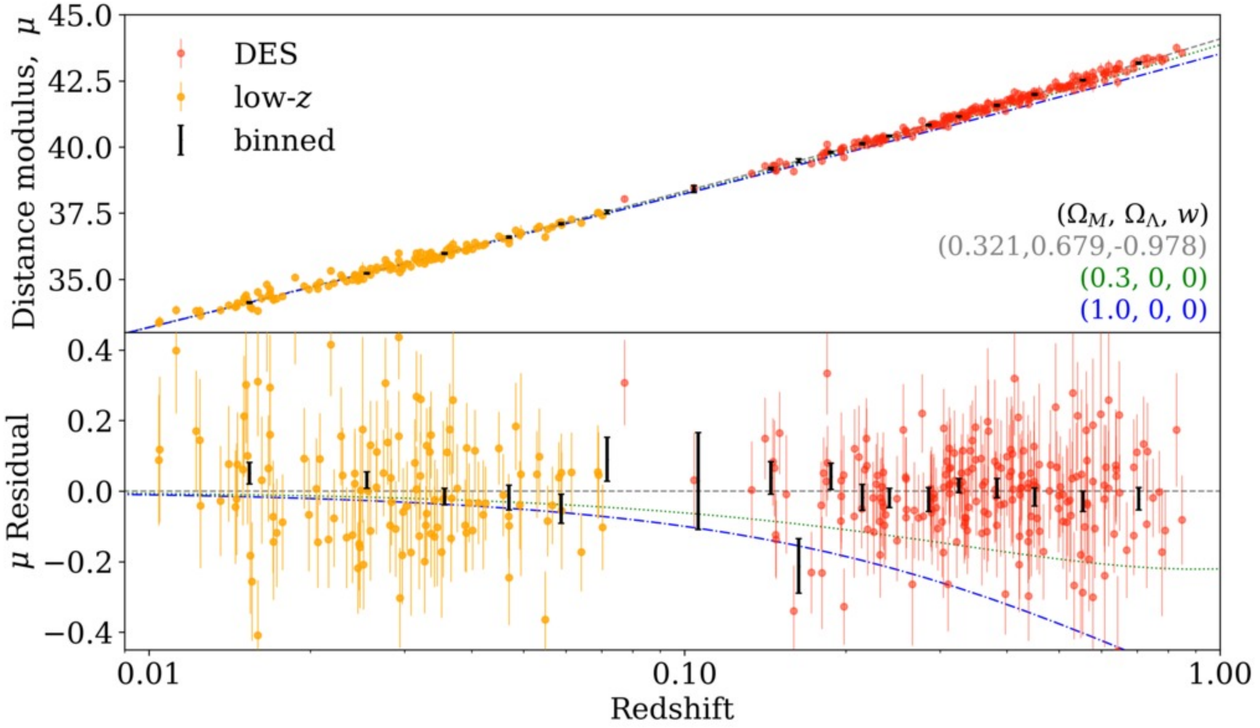
Riess et al. 1998



2011

SNIa cosmology

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



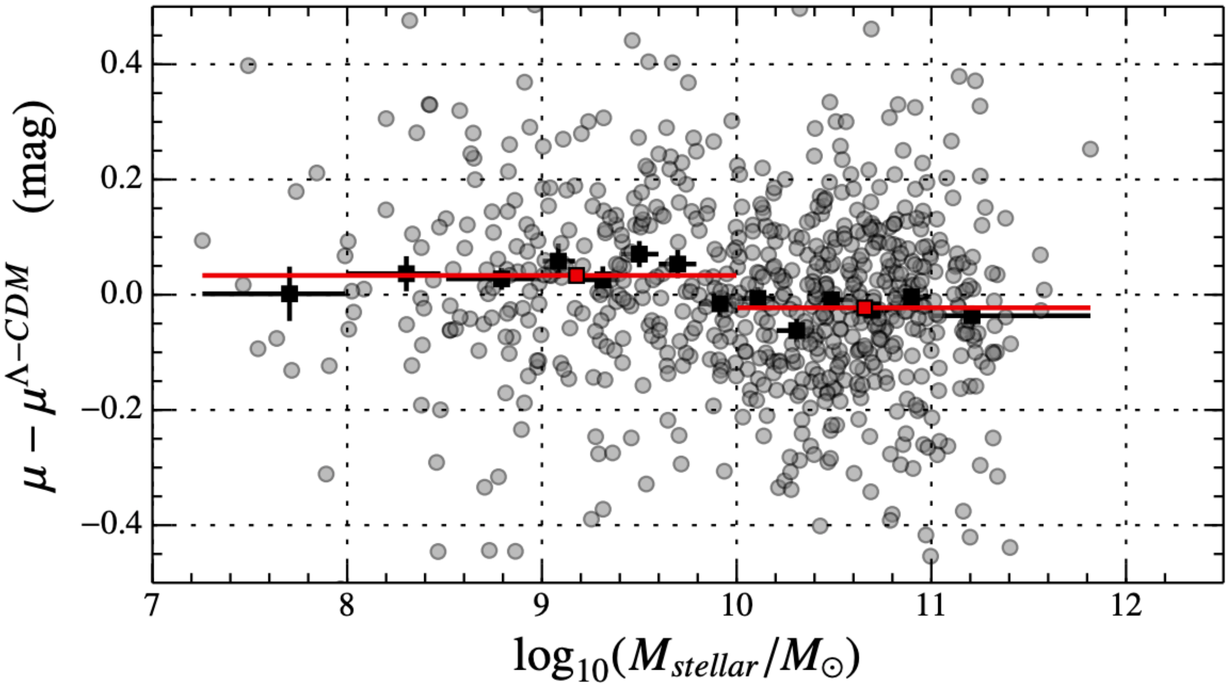
Brout+19

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

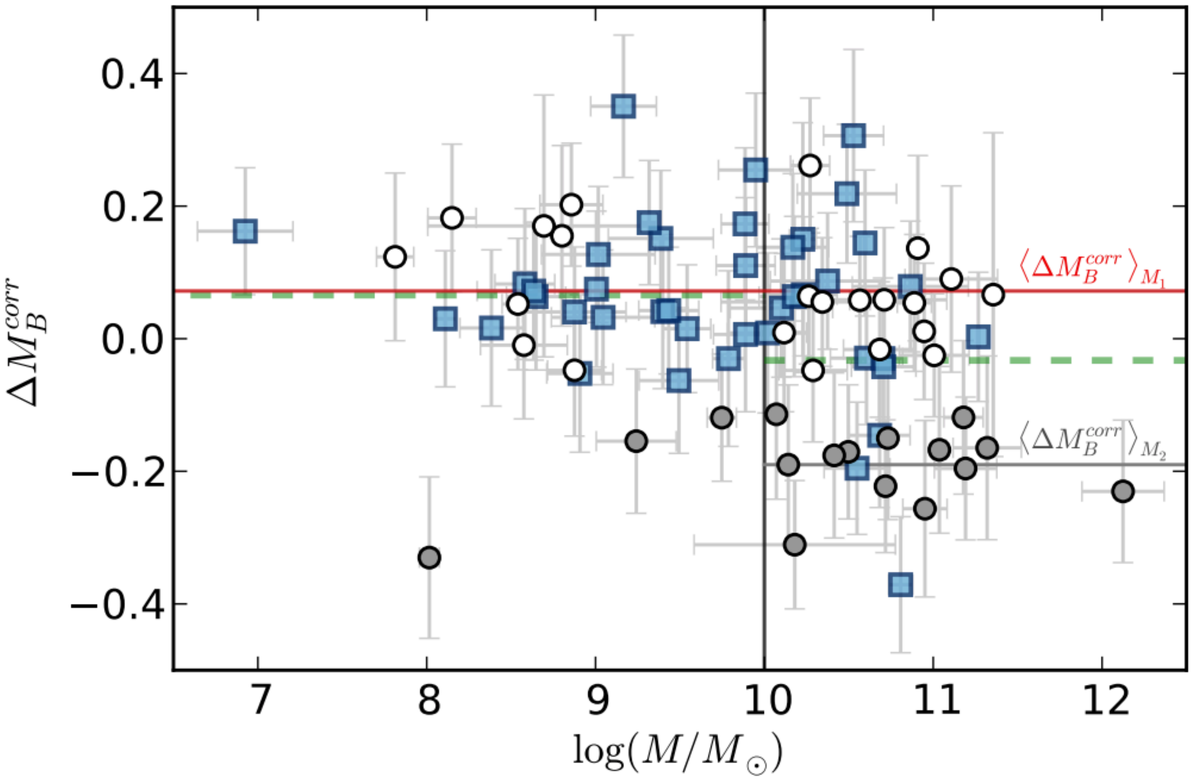
*deviation between the distance from the best cosmological model and the SN distance

SNIa environment

Sullivan+10



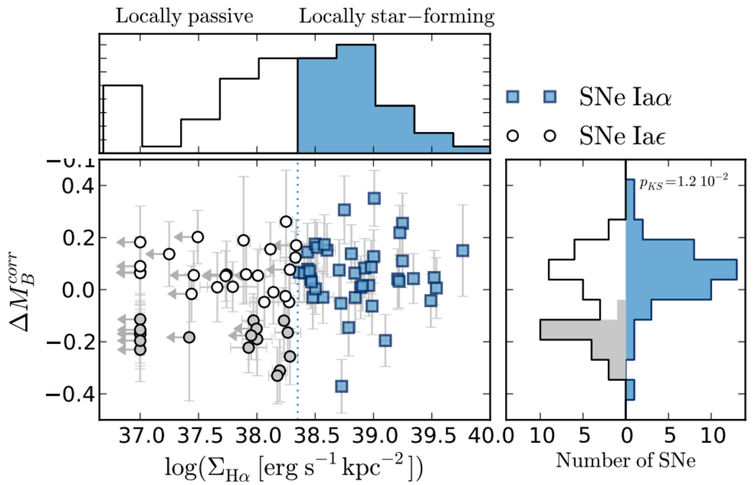
Rigault+13



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

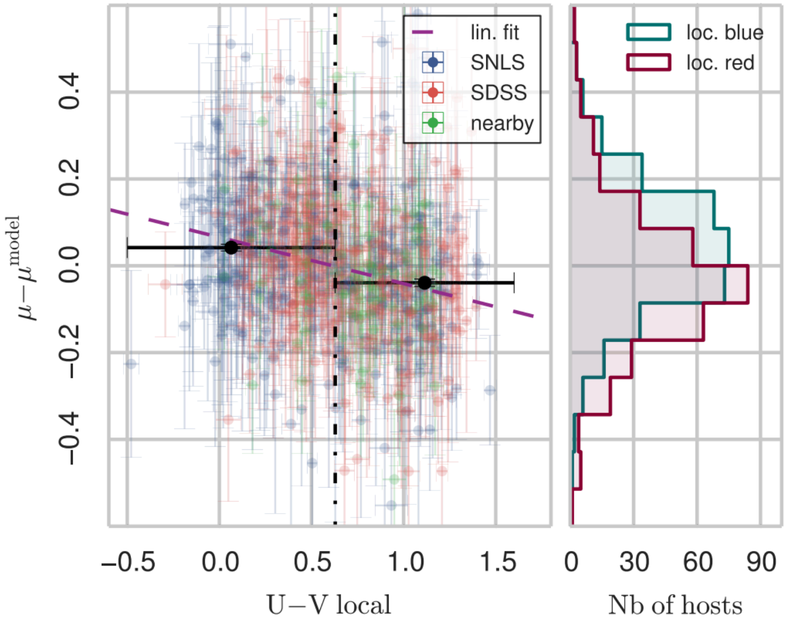
But mass should be just a proxy for another other parameter…

Local SNIa environment



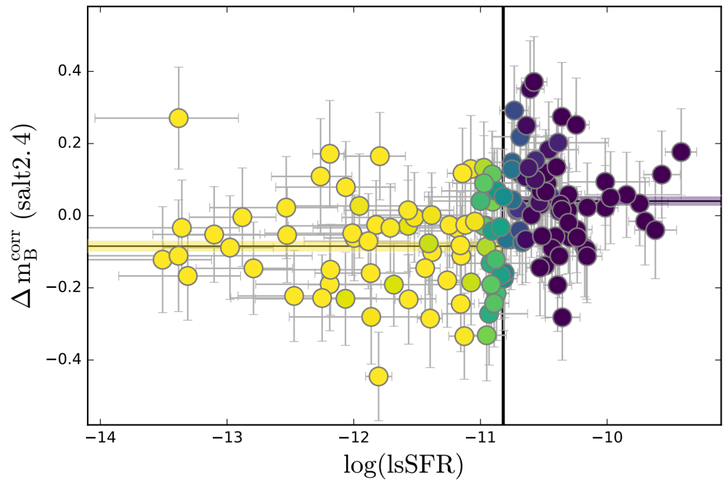
U-V *Roman et al. 2017*

Phot ~3kpc



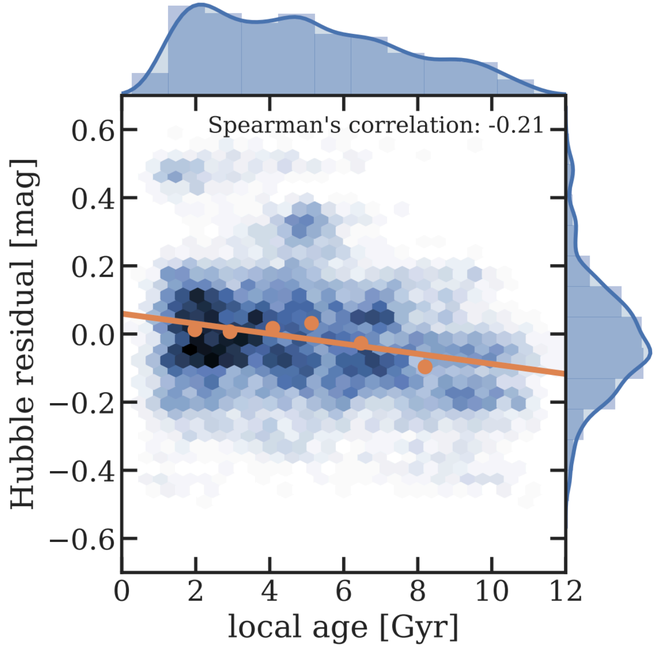
SFR *Rigault et al. 2013*

IFS ~1kpc



Age *Rose et al 2019*

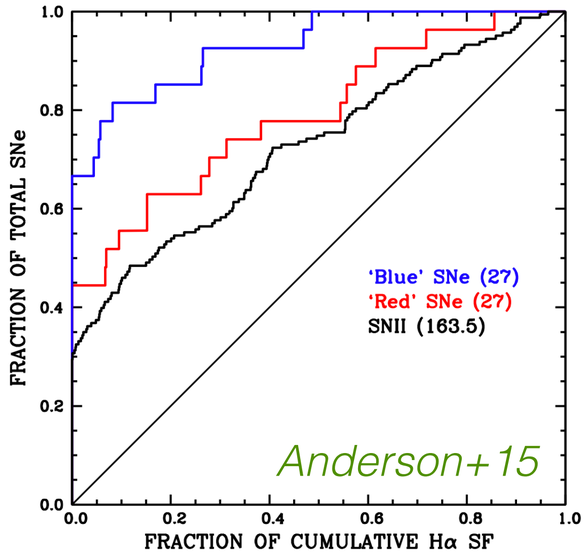
Phot ~5arcsec



lsSFR *Rigault et al. 2018*

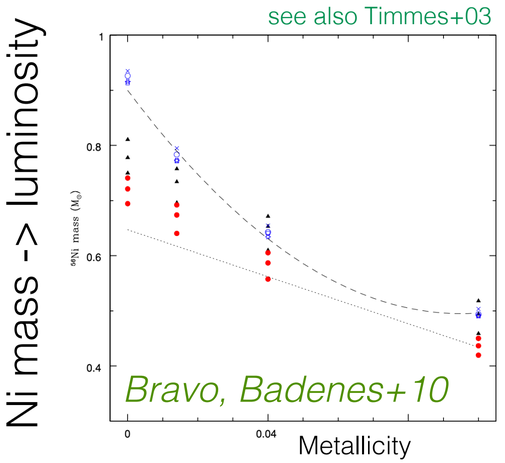
Phot ~1.5kpc

(Non-cosmological) local SNIa environment

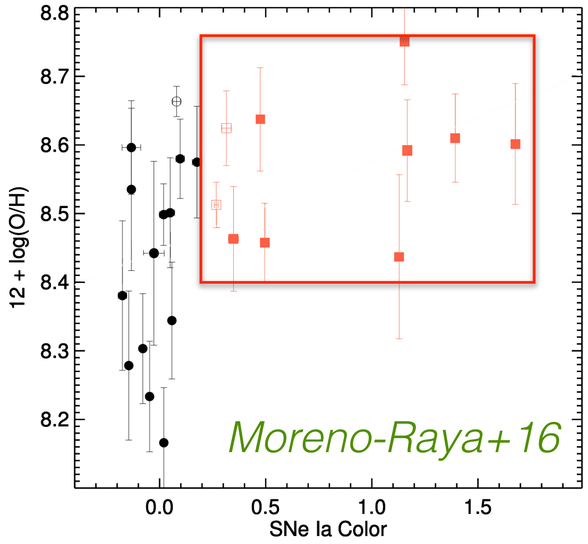


Redder SNIa more associated to HII regions
And found more centrally within hosts

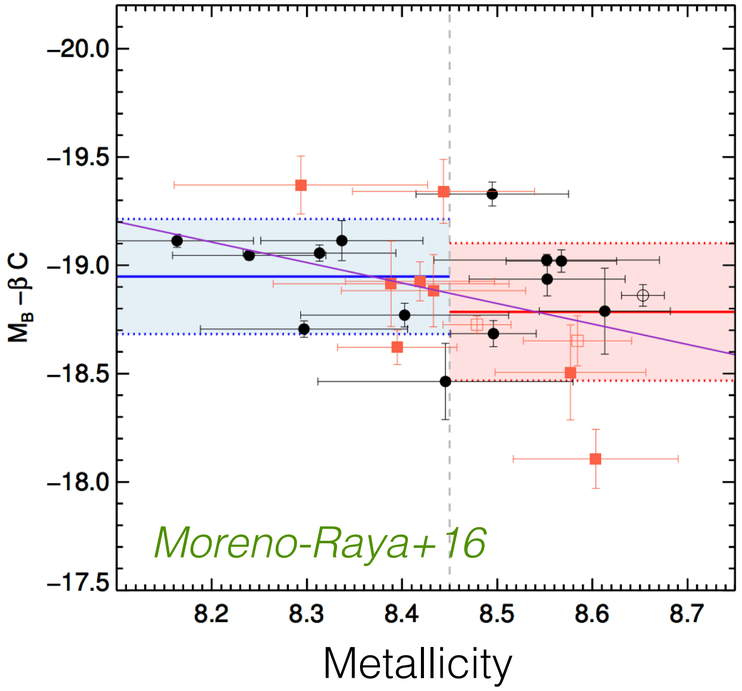
see also Timmes+03



Color corrected magnitudes depend on local metallicity



Red SNe in metal-rich environments



Distance ladder

100s of SN Ia hosts

38 hosts of both
Cepheids and SNe Ia

Geometric distances:

- *MW paralaxes*
- *LMC DEBs*
- *M31 DEBs*
- *NGC4258 maser*