Superluminous Supernovae

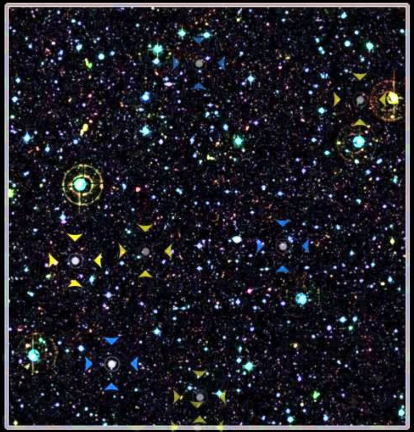
Daniel Perley
(Caltech)

For more info: see review by Gal-Yam (Science 337:927; 2012)

Supernova searches enter the modern era

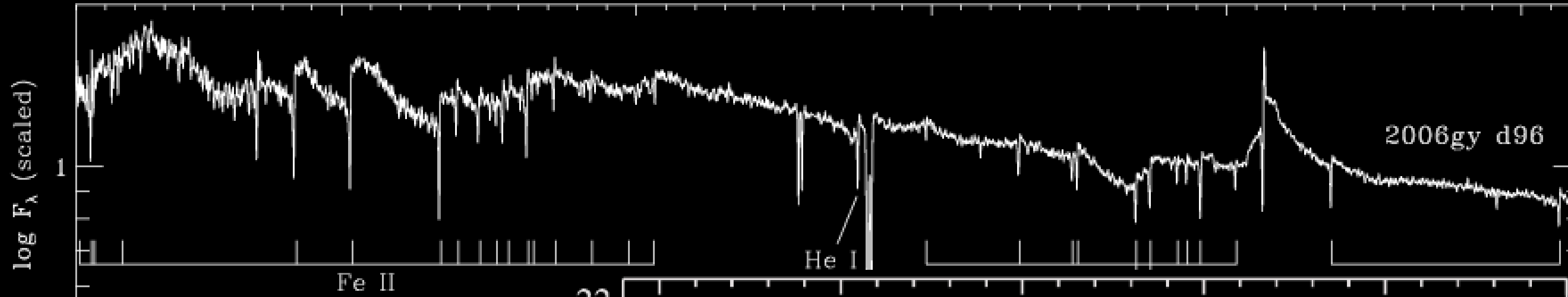
<1990: Serendipity, amateurs, pre-CCD searches

1990-2005: High-z, nearby-galaxy dedicated SN searches

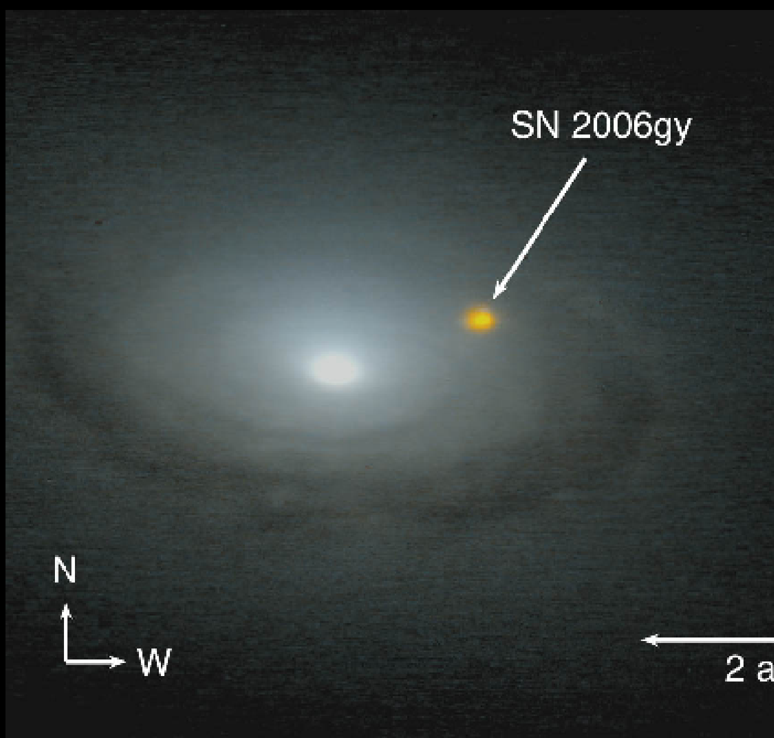


2005-present: Wide-field cameras, heavy-duty computing enable large-volume, untargeted surveys

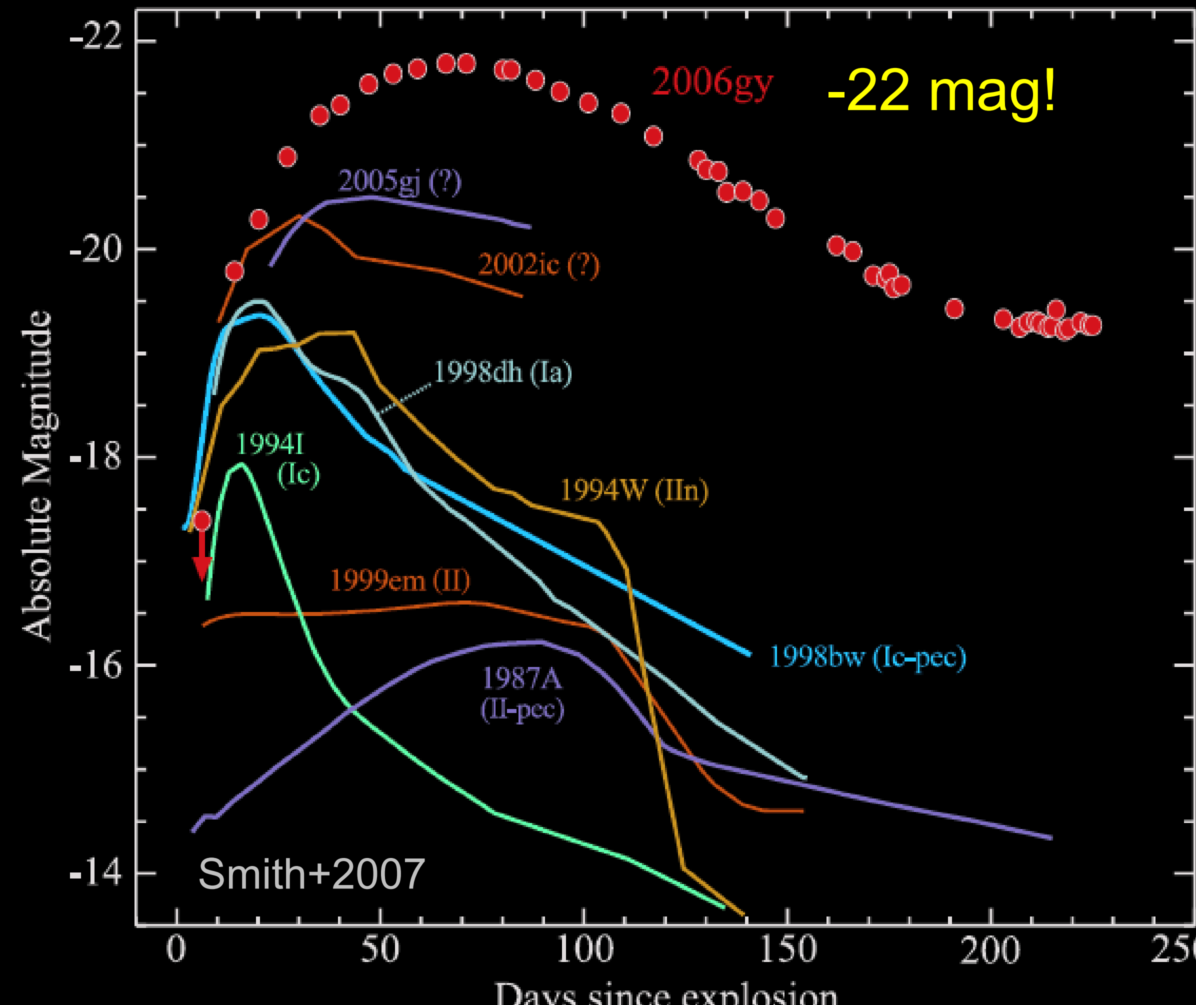
Supernova 2006gy



Smith+2010

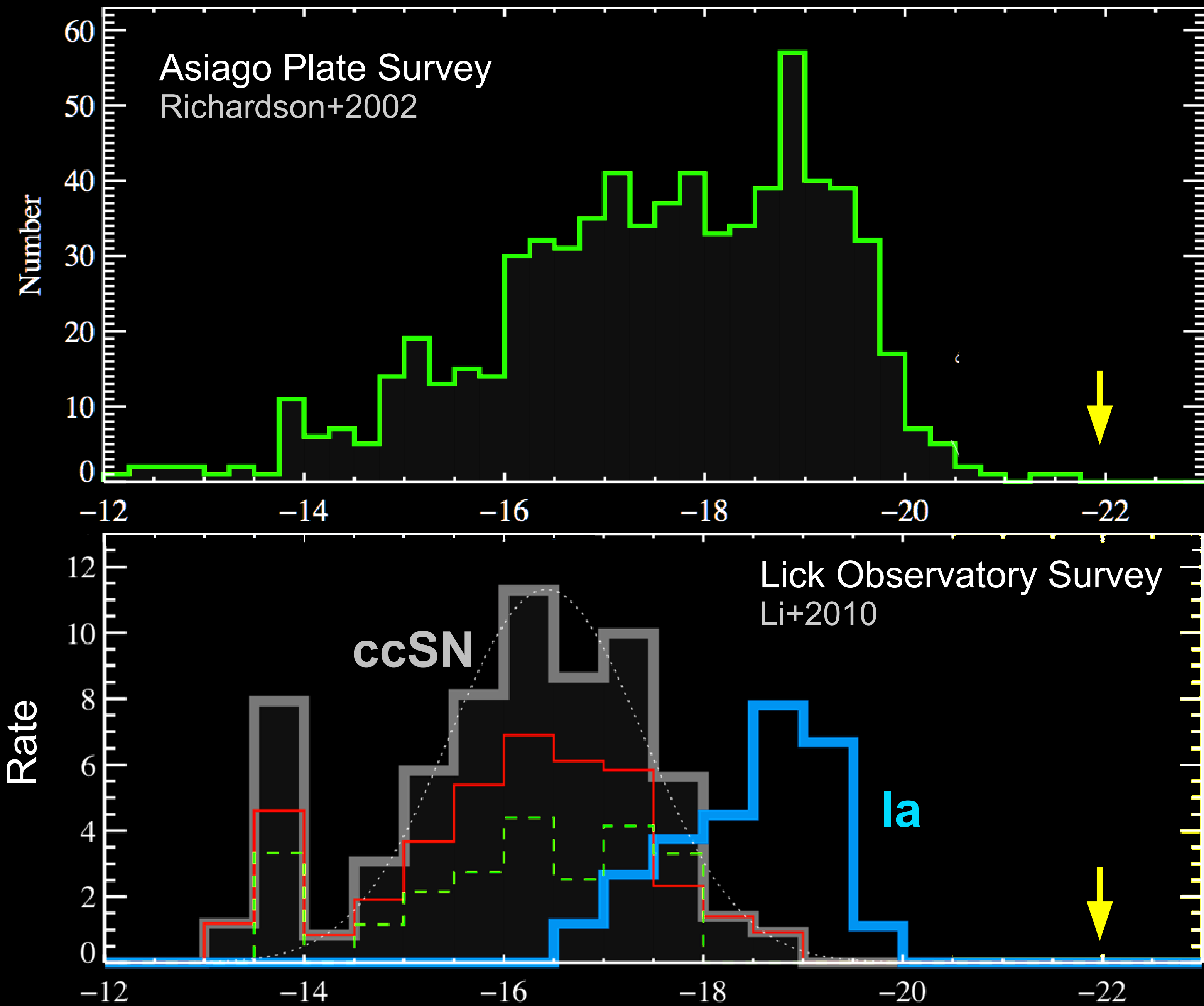


Smith+2008



Smith+2007

SN Absolute Magnitude Distribution



Suddenly, SLSNe Everywhere

SNE with M_{peak} < -21 found before 2010:

Texas/ROTSE:

SN 2005ap	-22.7 mag	Quimby+2007
SN 2006gy	-22.0	Smith+2007, Ofek+2007
SN 2008am	-22.4	Chatzopoulous+2011
SN 2008es	-22.2	Miller+2009, Gezari+2009

Nearby Supernova Factory:

SN 2007bi	-21.3	Gal-Yam+2009

CRTS:

SN 2008fz	-22.3	Drake+2009

PTF:

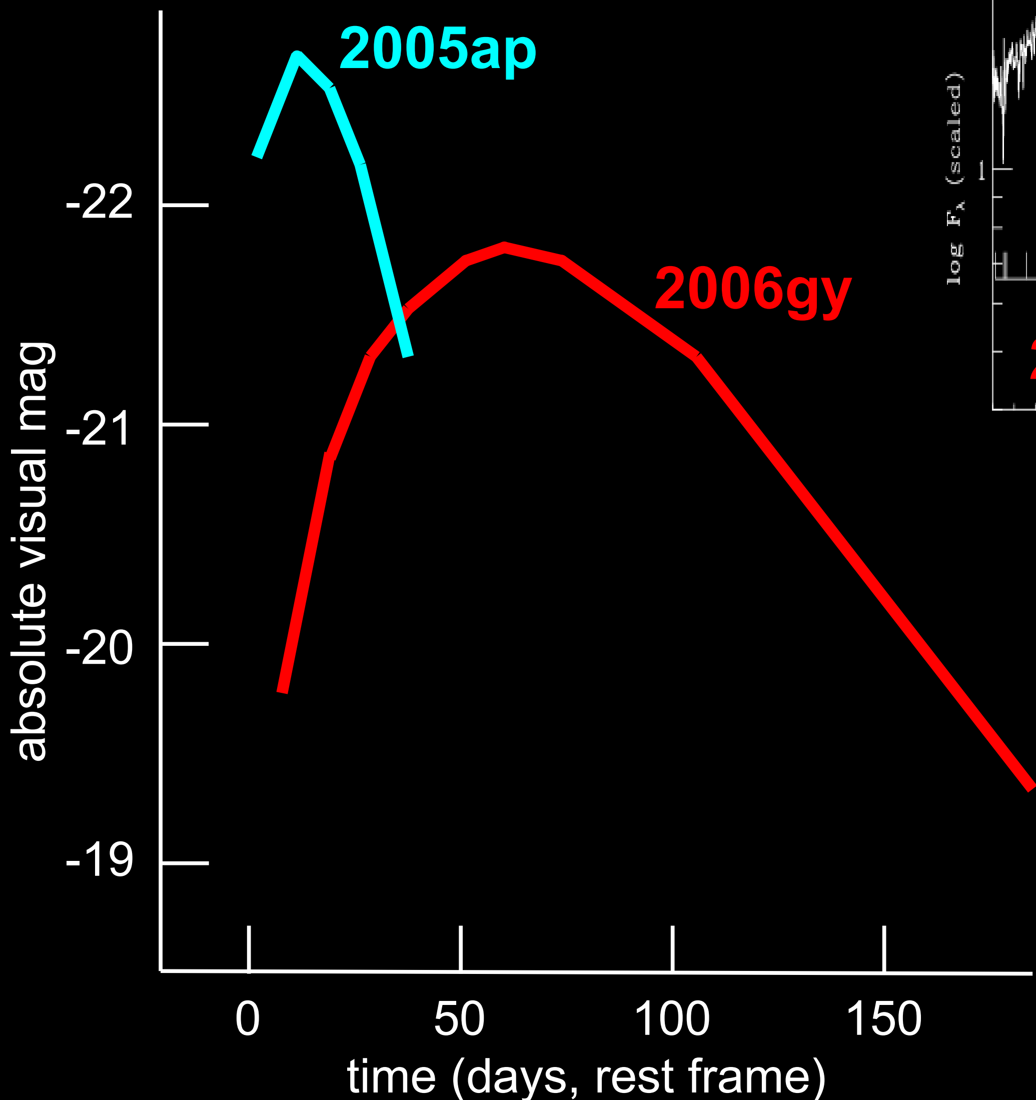
PTF 09atu	-22.0	Quimby+2011
PTF 09cnd	-22.0	
PTF 09cwl	-22	

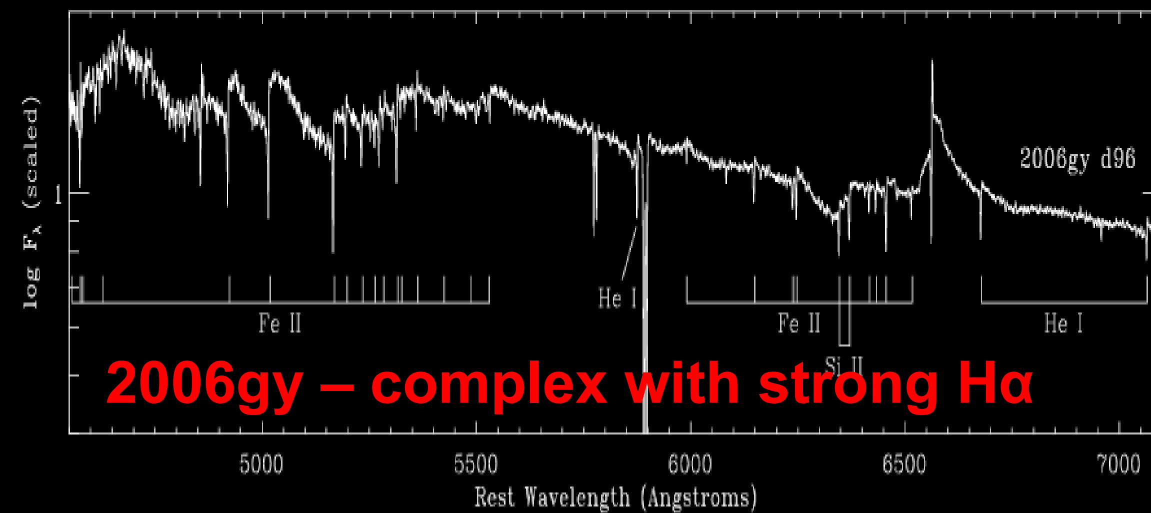
(Many, many more in 2010 and after)

And, archival re-discoveries/re-interpretations:

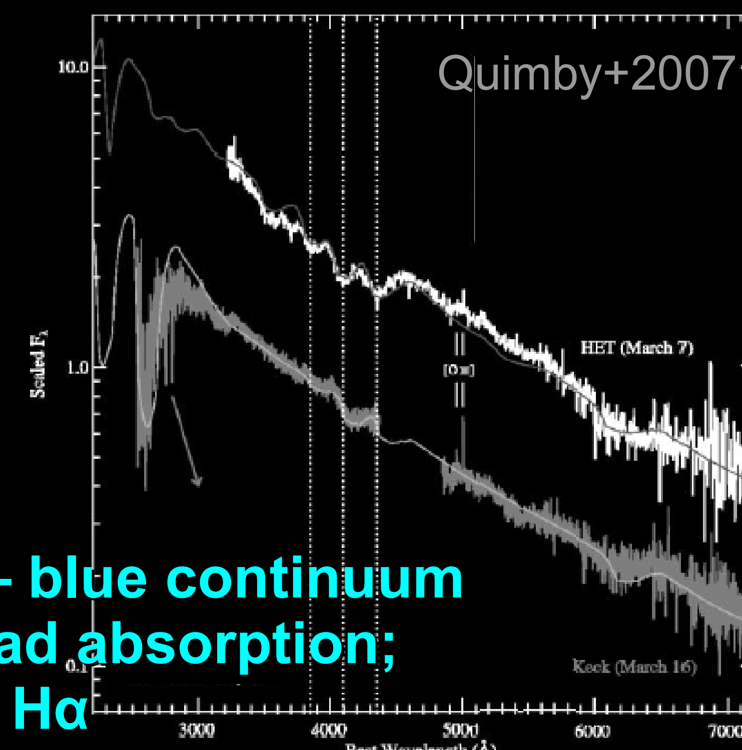
- SN1999as (NEAT, AAS poster 198.39.02)
- SN2006oz (SDSS SN survey; Leloudas+2012)
- SN2003ma (SuperMacho; Rest+2011)
- SCP06F6 (HST SCP; Barbary+2007)

SLSNe are Diverse





2006gy – complex with strong Hα



2005ap – blue continuum with broad absorption; no/weak Hα

Classification

Not straightforward:

- Multiple observables/criteria to consider
- Spectra evolve with time
- Would like to map classes to theory, but theory can mislead
- Many proposed classes have only 1 (or 2 or 3) members

Classification: Conservative

Two unambiguous *spectroscopic* classes
frequently seen in PTF (10+examples each):

SLSN - Ic

No hydrogen (or helium) at any epoch at any width
(except from host)

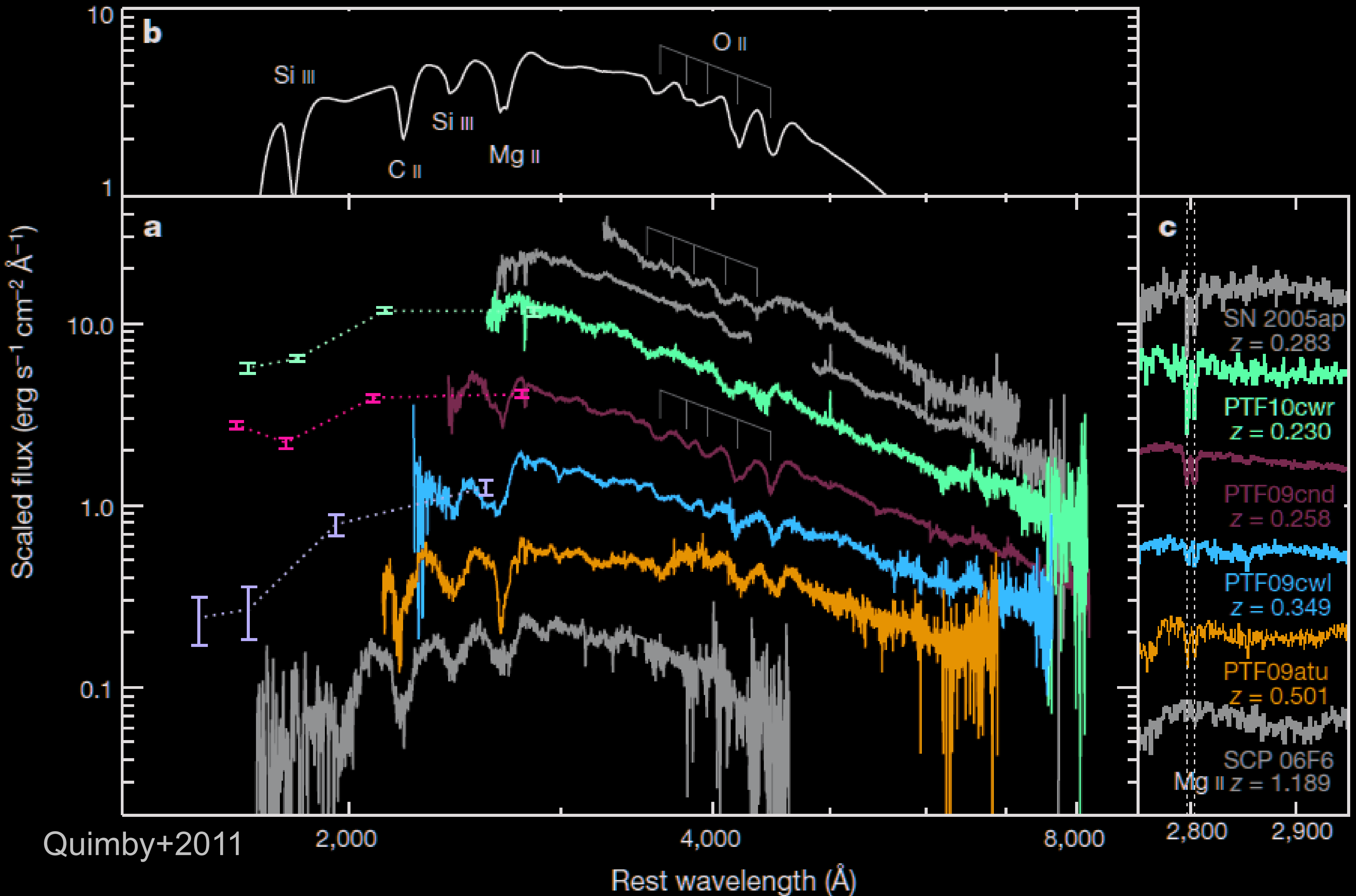
Broad UV absorption features of intermediate elements
(C, O, Mg, Si)

SLSN - IIn

Intermediate+narrow width hydrogen lines

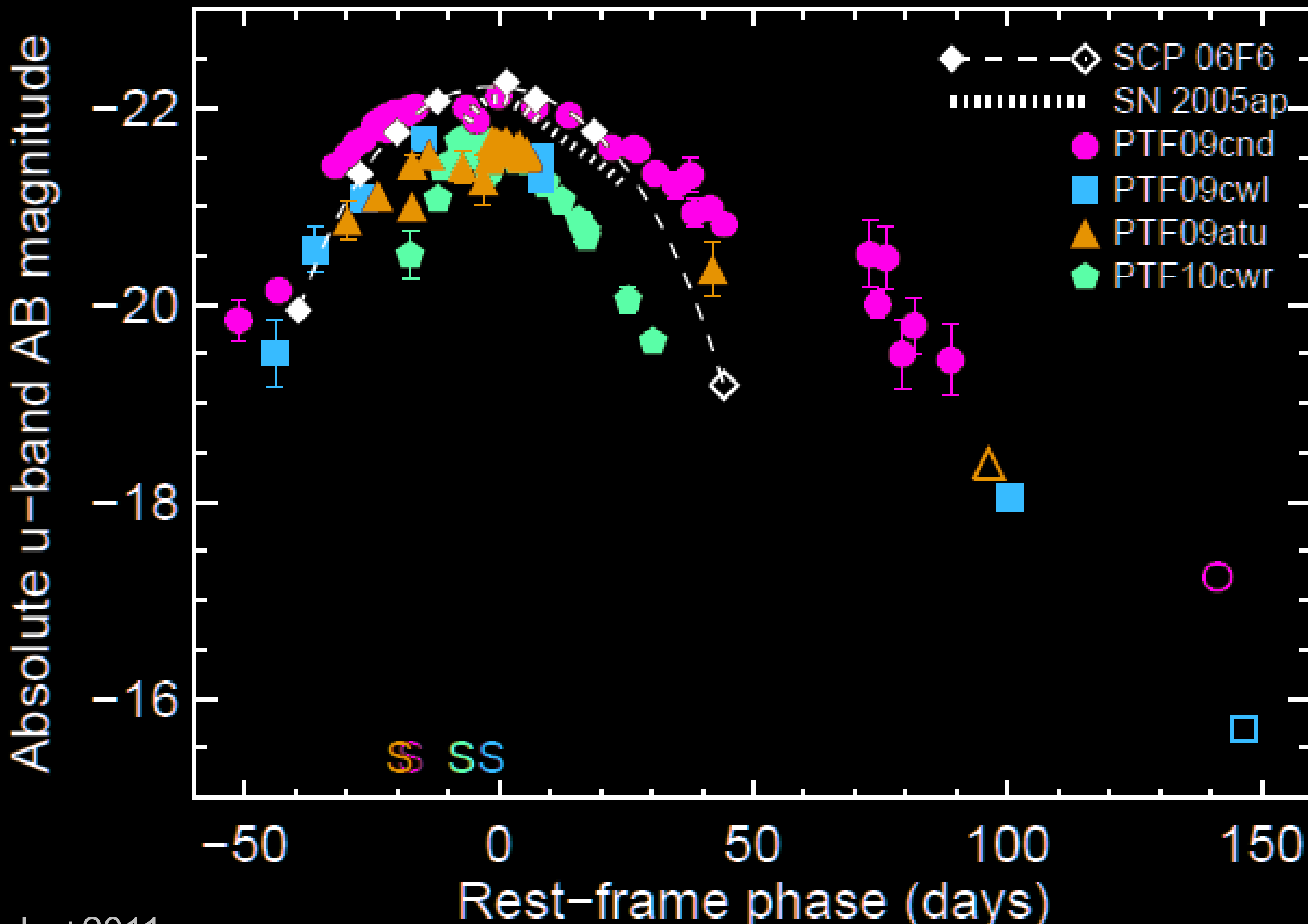
+ many possible light-curve subclasses and oddballs - more later

SLSN I spectra



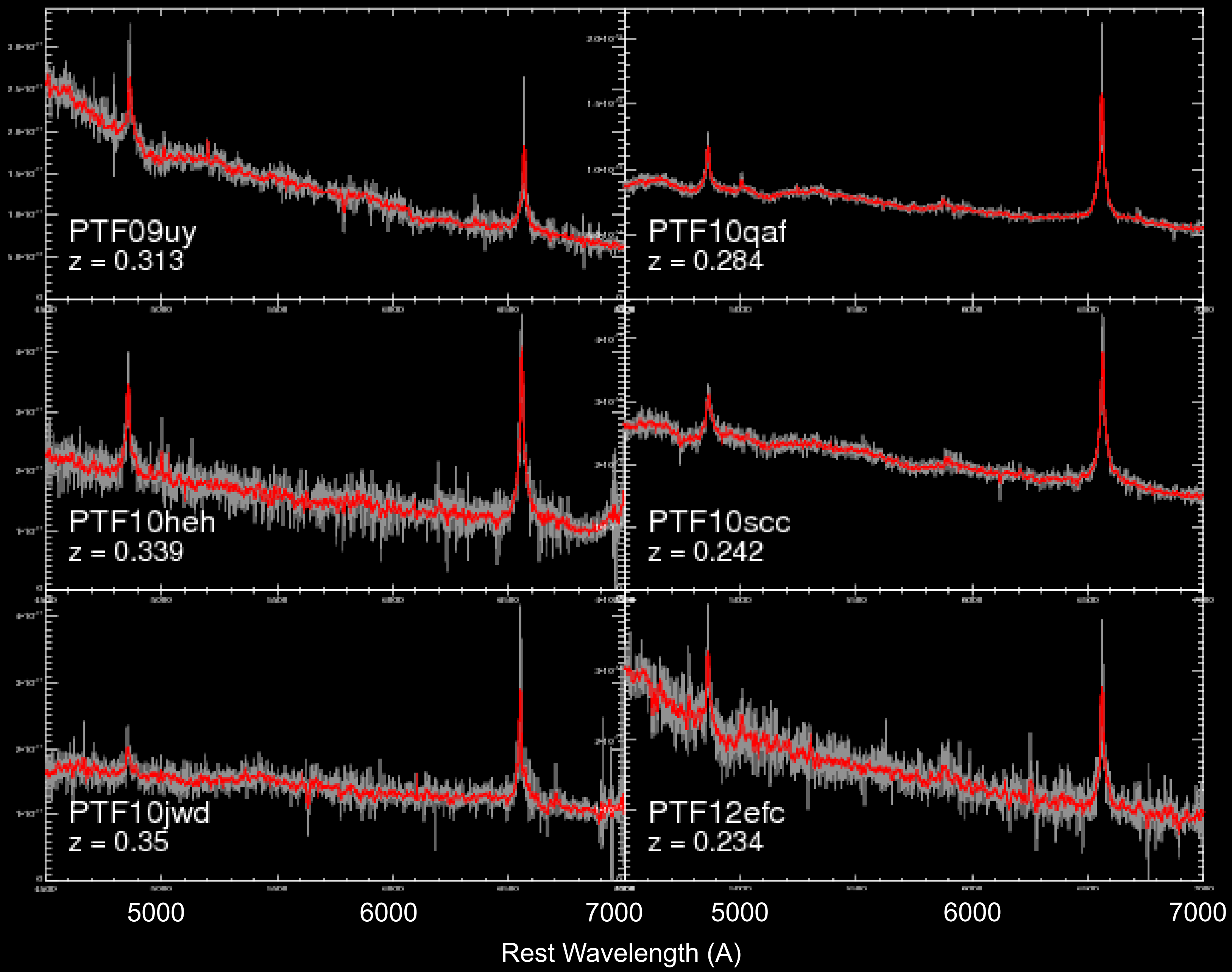
Quimby+2011

SLSN I light curves

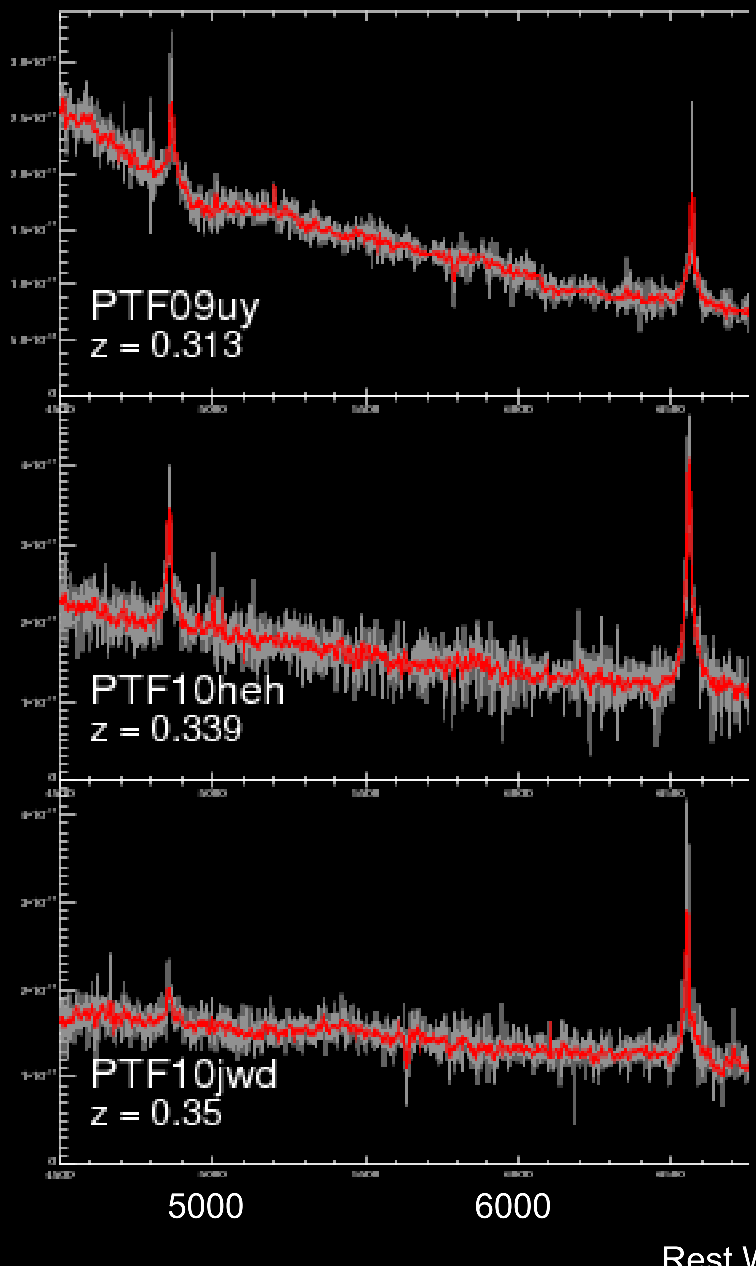


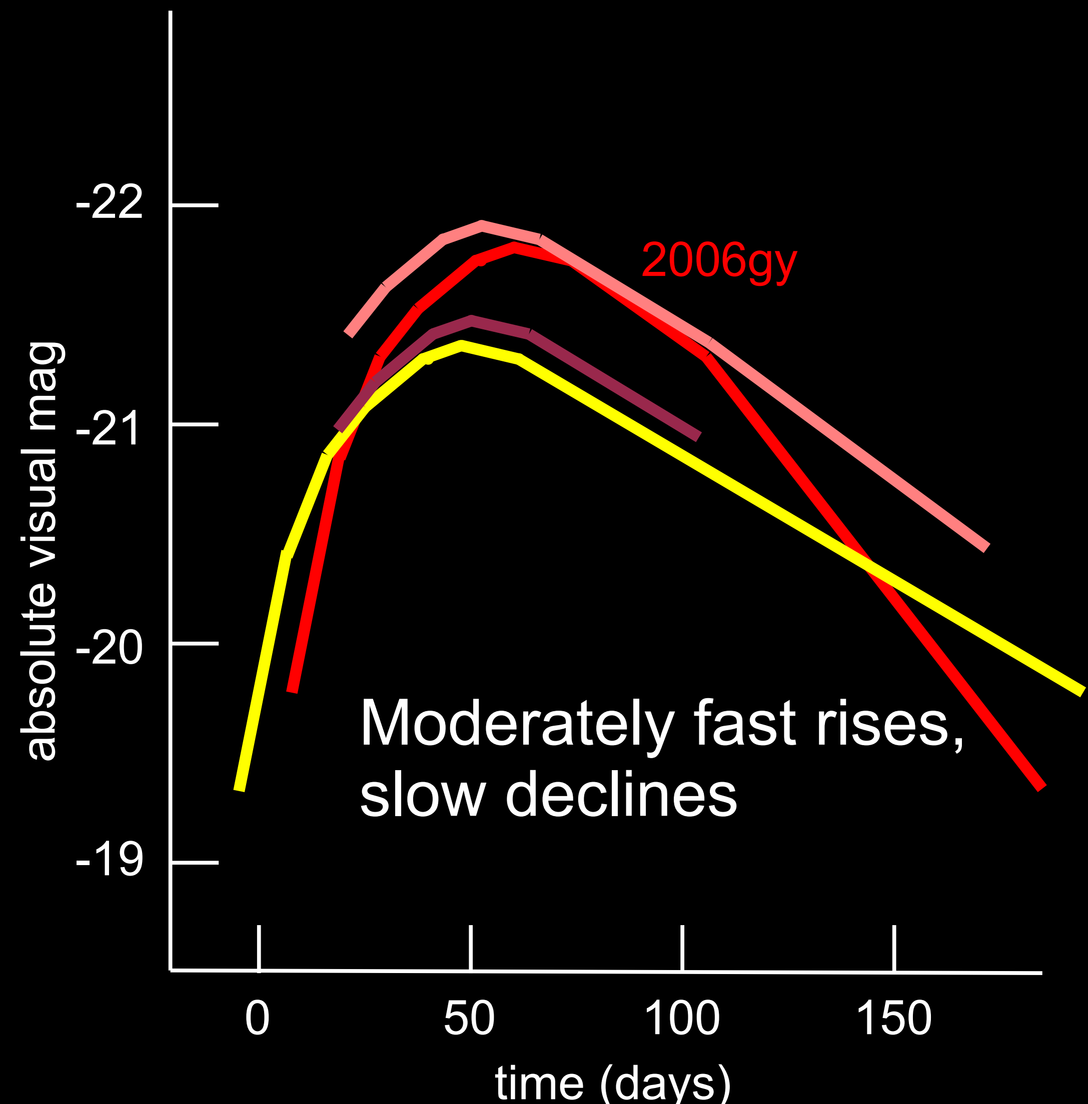
Quimby+2011

SLSN IIn spectra



SLSN IIn Light Curves





Moderately fast rises, slow declines

Classification: Detailed

Type I

SLSN I - normal

Rapid light curve decay

Quimby+2011

SLSN I - R

Exponential light curve decay

Gal Yam+2009

SLSN I - fast (PS1-10afx)

Very fast rise and fall; severe challenge to models

Chornock+2013

Probably a lensed Ia

Quimby+2013,2014

Type II

SLSN II-n

Narrow/intermediate H lines, rapid rise(?) but very slow fall

SLSN IIn-peculiar (SN 2006gy)

Complicated, evolving H profile

Extremely long-lived

Circumnuclear

SLSN II-L (2008es, CSS121025)

Broad H lines only after peak, short-lived with fast decay

SN Ia-CSM

IIn lines overlying Ia spectrum

e.g. Dilday+2012, Silverman+2013

SLSN Numbers

Class	rise	decline	velocity	E_{rad}	rate/CC
I-norm	~40 d?	20-60 d	10^4 km/s	$1\text{-}4\times10^{51}$ erg	~0.05%
II-n	~20 d	~100 d	(multiple)	$1\text{-}4\times10^{51}$ erg	~0.10%
I-R	~50 d?	~150 d	10^4 km/s	$2\text{-}4\times10^{51}$ erg	~0.05%?
II-L	~40 d	~40 d	10^4 km/s	1×10^{51} erg	~0.03%?
II-pec	~60 d	~100 d	$4\text{x}10^3$ km/s	2×10^{51} erg	~0.5%??

Quimby+2013, Chornock 2014 Aspen talk

Supernova Energetics

Total radiated energy of a SLSN: $\sim 10^{51}$ erg

Total radiated energy of a normal ccSN: $\sim 10^{47-49}$ erg

"Why do SLSNe radiate so much energy?"

Supernova Energetics

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(~binding energy of a NS)

Supernova Energetics

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"Why do SLSNe radiate so much energy?"

Total energy released by a normal ccSN: $\sim 10^{53}$ erg
(~binding energy of a NS)

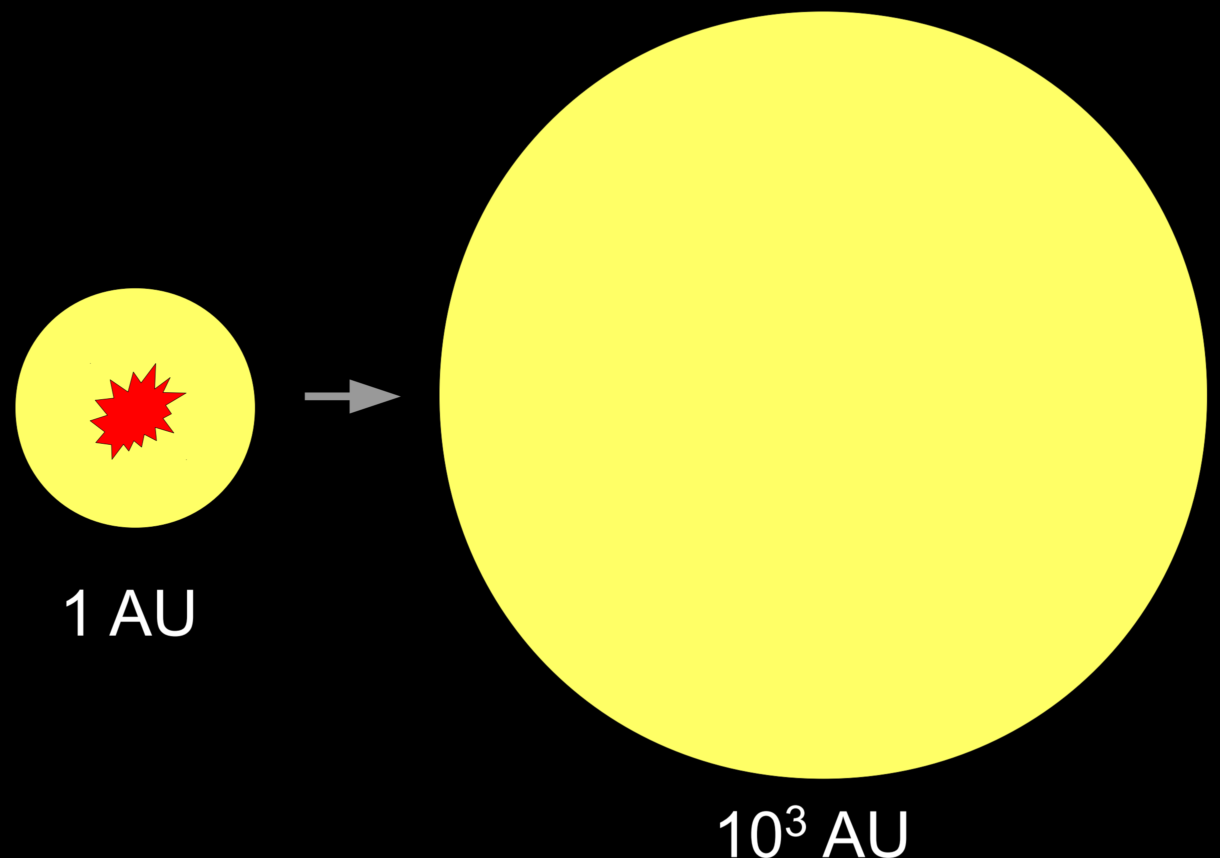
99% neutrinos
1% kinetic energy
<0.01% radiation

"Why do *non*-SLSNe radiate so *little* energy?!"

Radiatively Inefficient SNe

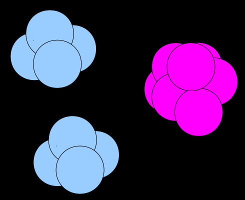
"Why do *non*-SLSNe radiate so *little* energy?!"

Stars are ***opaque.***
SN must expand before it can shine; energy lost adiabatically.



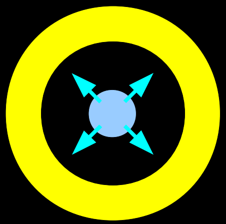
Radiatively Efficient SNe

Solution: ***store*** the SN-deposited energy temporarily, or ***convert*** kinetic energy to radiation.



Nucleosynthesis: Store energy by synthesizing heavy elements that later decay/reheat ejecta.

Interaction: Reconvert the KE into heat by colliding/shocking with thick pre-existing gas



Central engine: Hold the energy in a compact object, then reheat the expanding ejecta from within

Radiatively Efficient SNe

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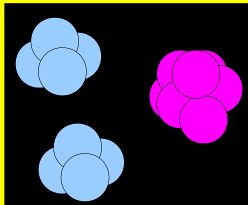

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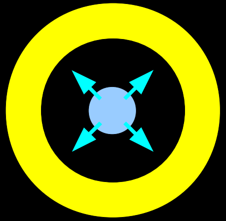


Central engine: Hold the energy in a compact object, then reheat the expanding ejecta from within

Nucleosynthetic SNe

One reaction chain provides nearly **all** SN ejecta heating:

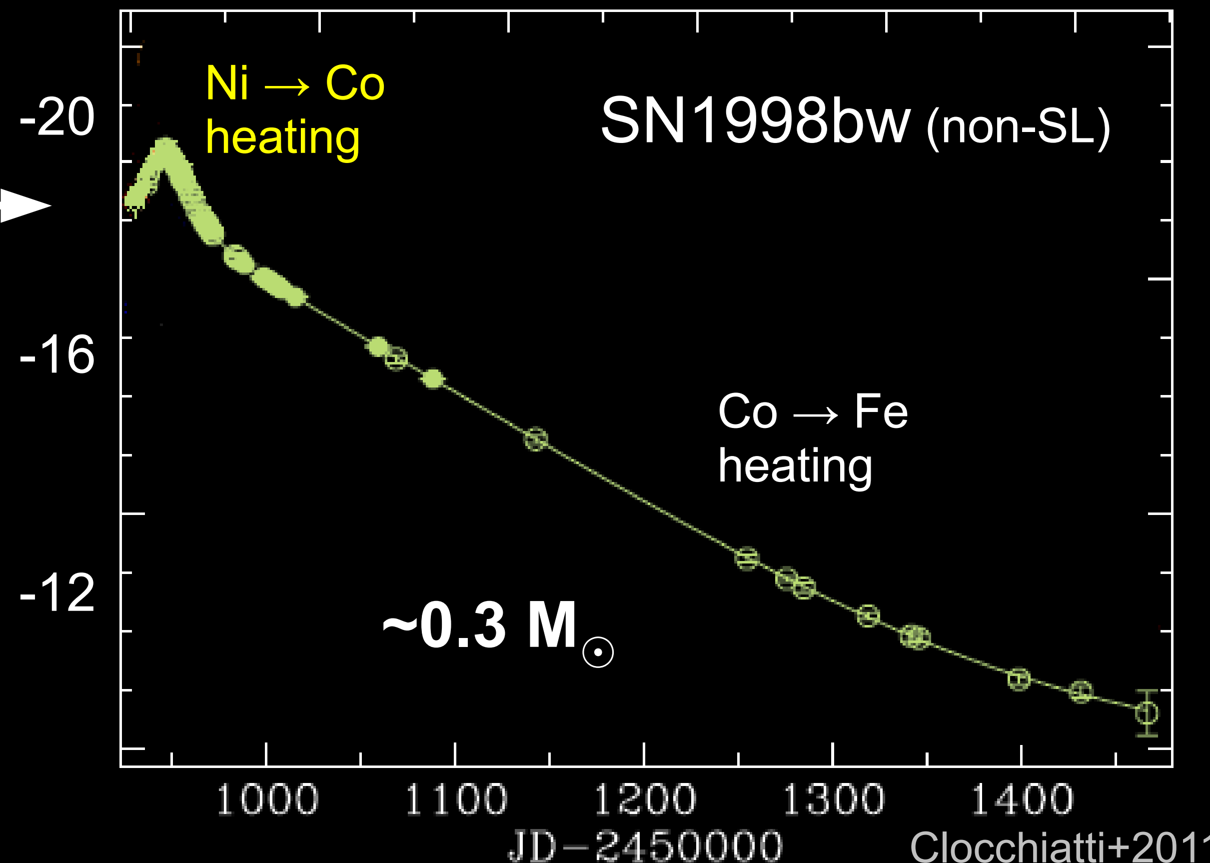
$$^{56}\mathbf{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$$

$\mathbf{t_{1/2} = 6\ d}$ $t_{1/2} = 77$ d

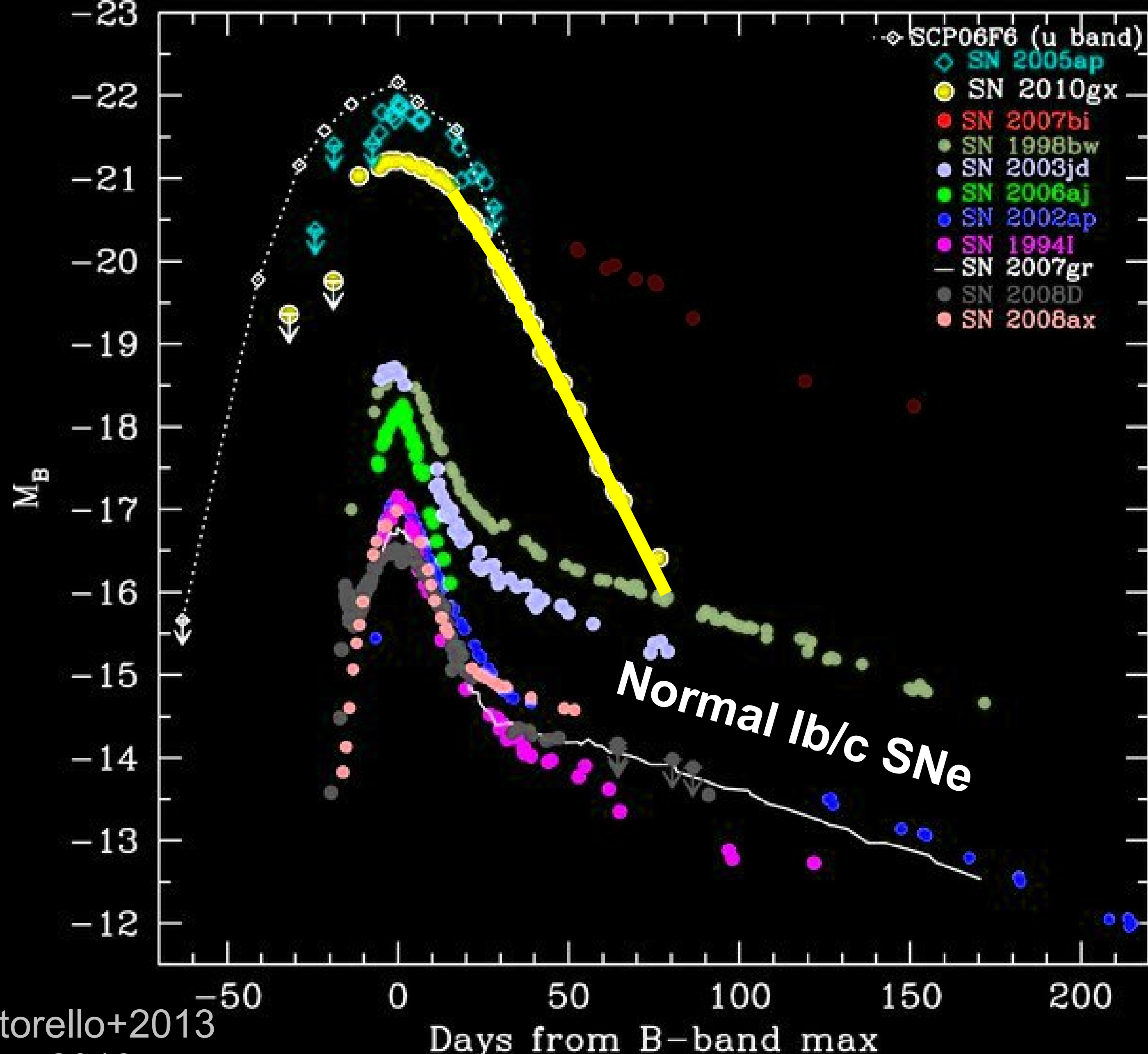
This is the only reason most SNe are bright at all!

Subsequent cobalt decay powers long-lived, slowly-decaying "tail"

$$L_{late} \sim\propto M_{Ni}$$



Little Ni-56 in many SLSNe

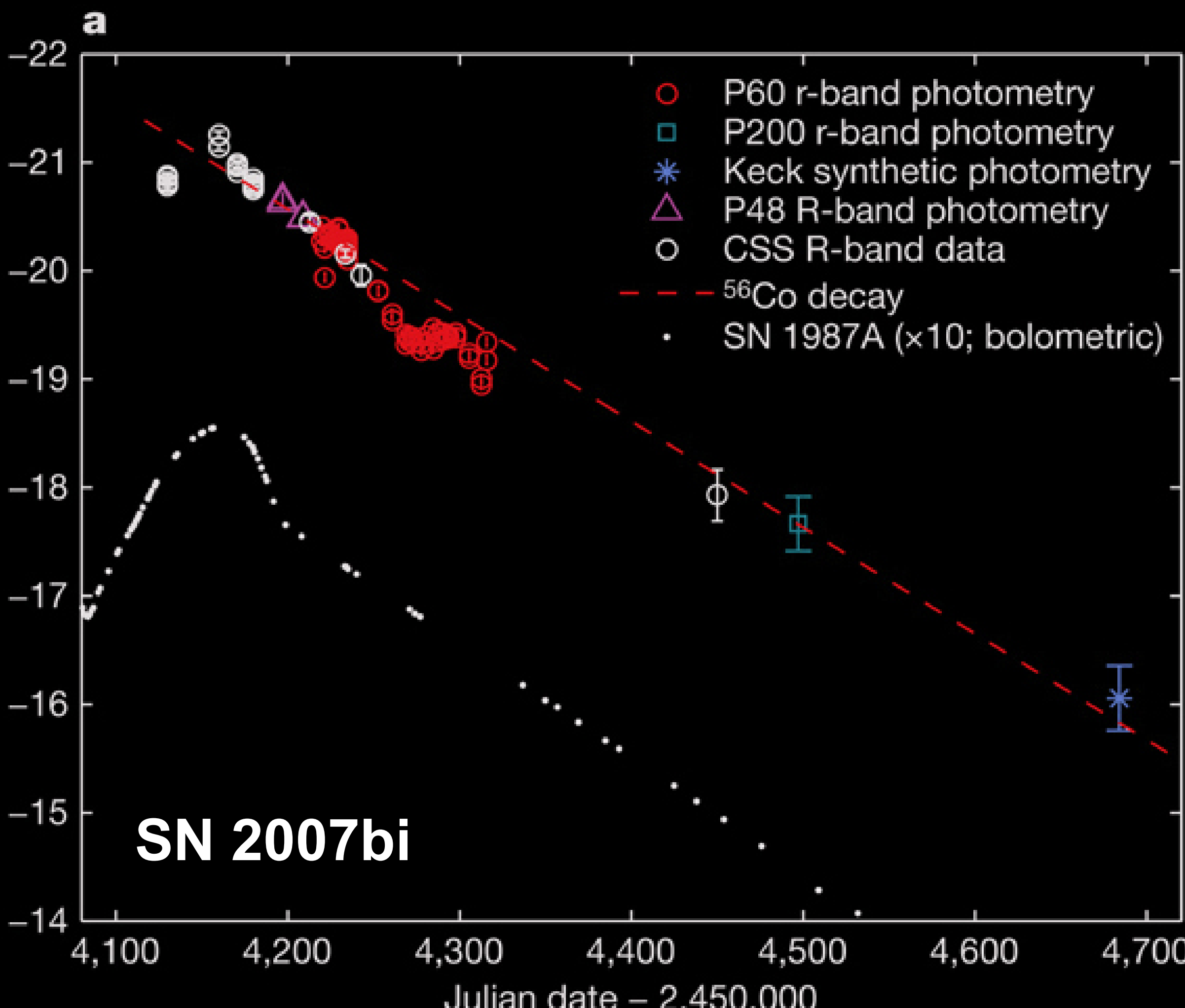


Ni/Co-56 production no more than a "normal" type Ic: completely inadequate to explain peak

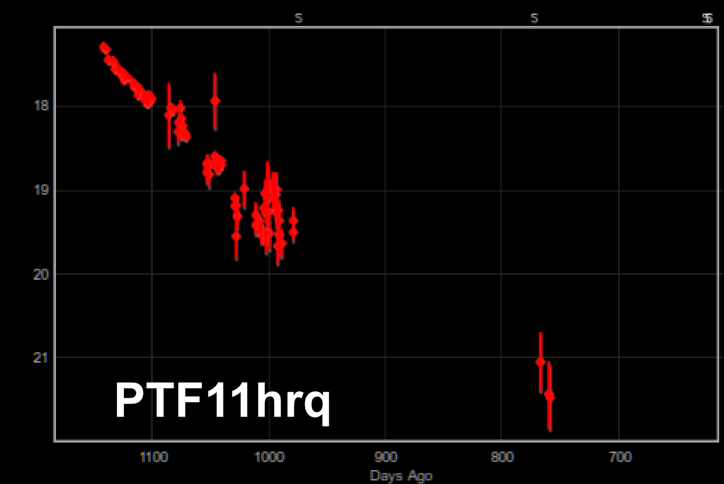
Pastorello+2013
Chen+2013

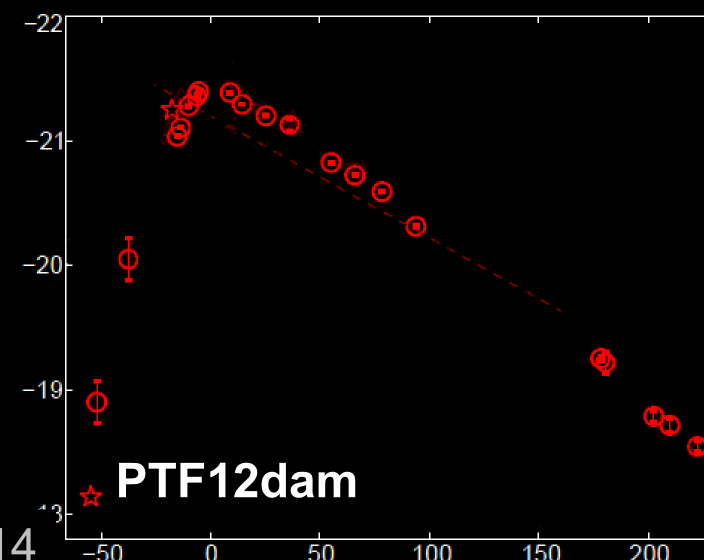
“R” is for “Radioactive”:

Some SLSNe-I appear to follow Co56 decay slope.



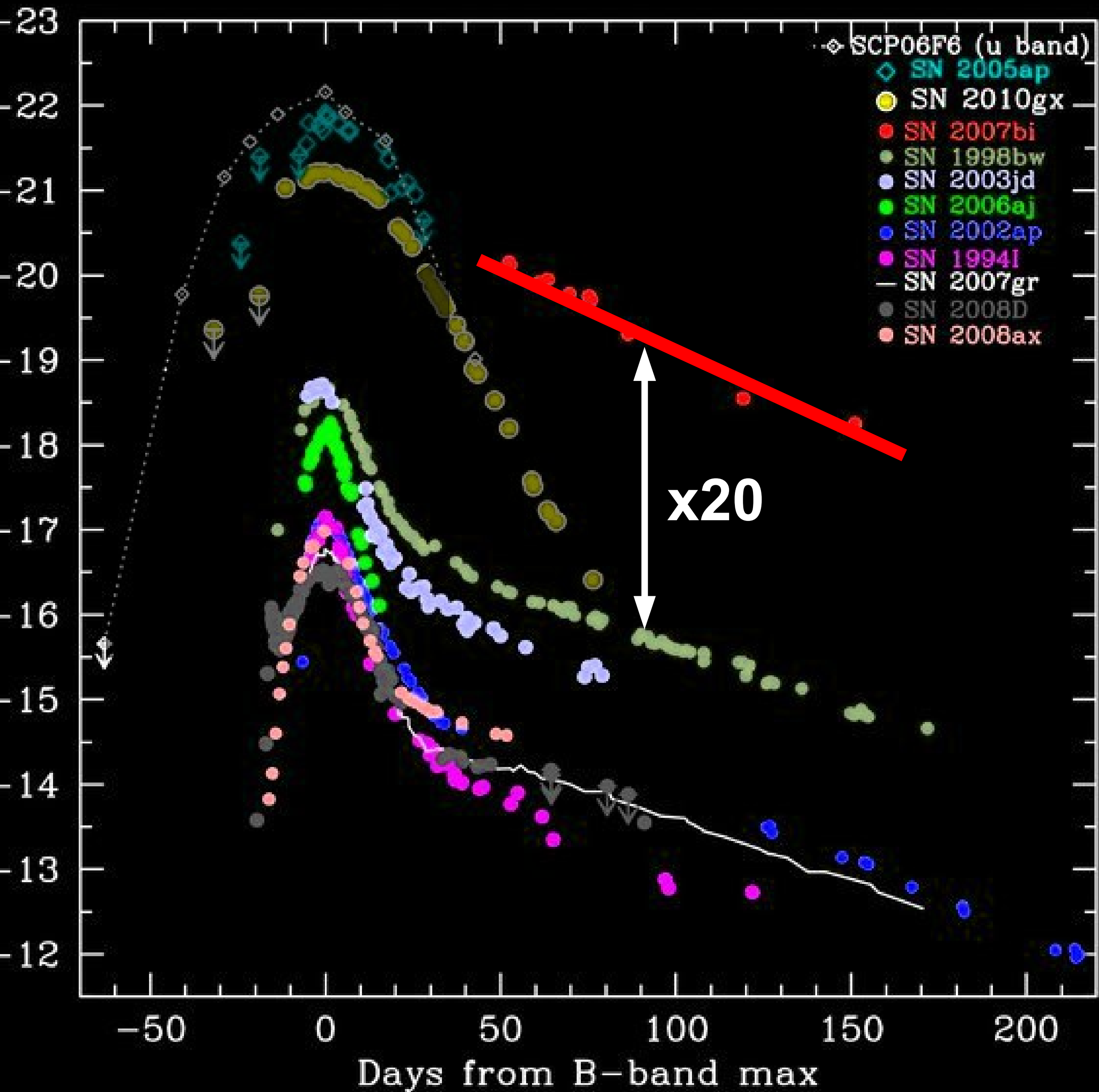
Gal-Yam+2009





Nicholl+2014

A Huge Nickel Yield is Necessary



M_{Ni} ~ 3-10+ $M_{\odot}$

→ pre-explosion mass must be many times this

→ stellar *initial* mass even more than that!

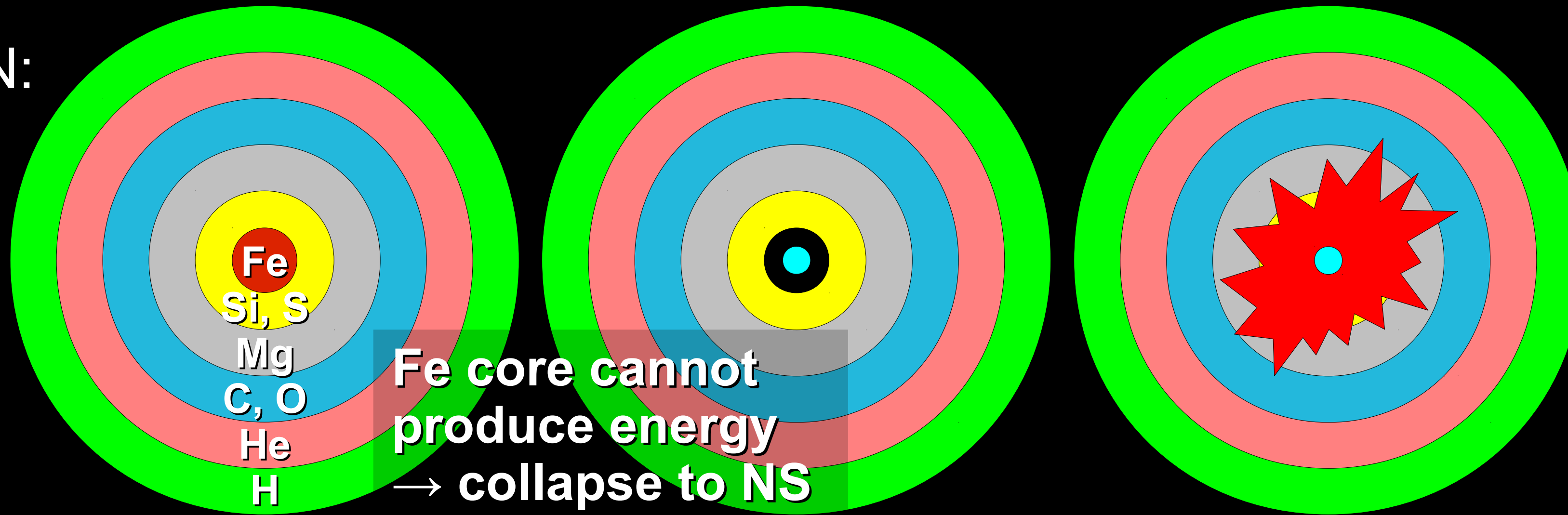
M_{init} ~ 80? 100? 120?

Could just be a really huge star undergoing core collapse
Young+2010, Moriya+2010

Or….

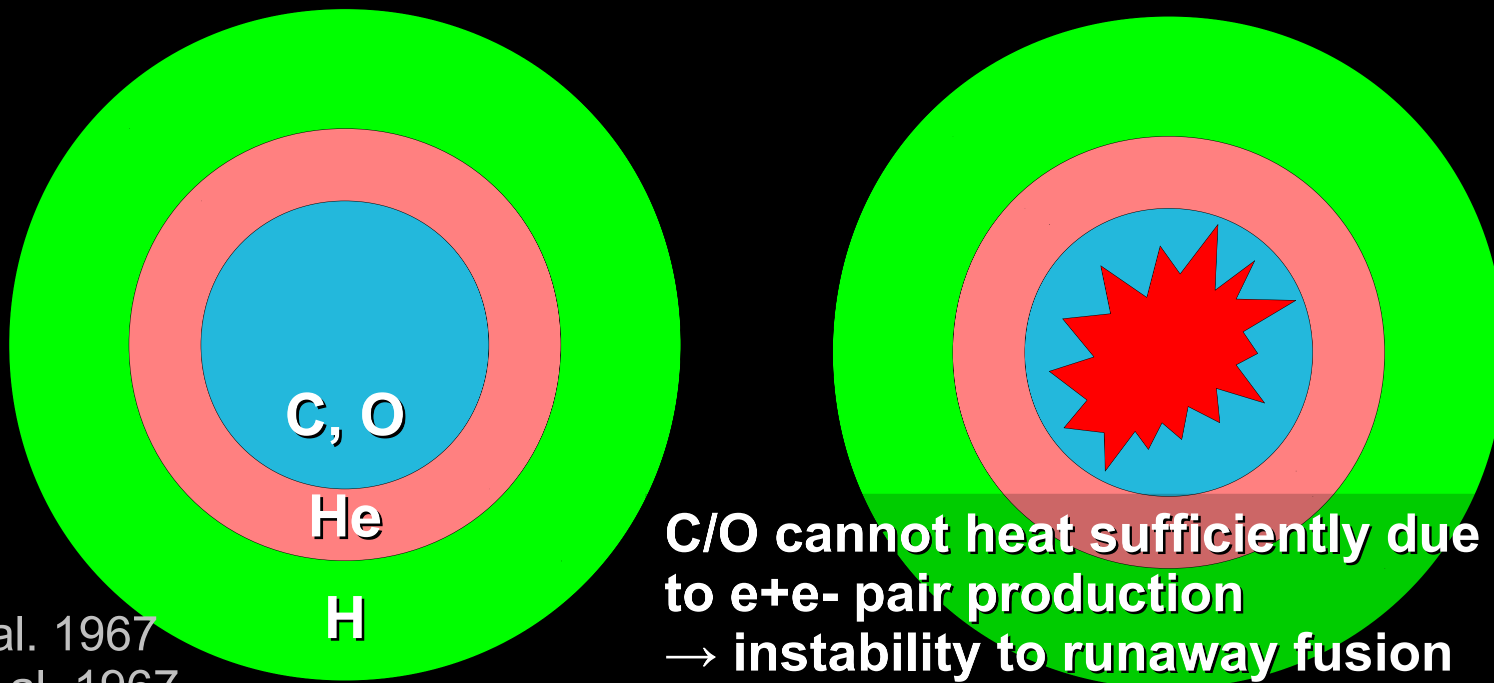
Pair-Instability Supernovae

Ordinary ccSN:



Fe core cannot produce energy
→ collapse to NS

PI SN:



C/O cannot heat sufficiently due to e+e- pair production
→ instability to runaway fusion

Barkat et al. 1967
Rakavy et al. 1967

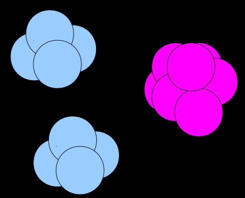
Type I-R = Pair Instability?

Interpretation of these events is controversial.

	Yes e.g., Gal-Yam+2009	**No** e.g., Nicholl+2014
Light Curve	Exponential late-time decay is a good match to expected cobalt decline	Rise time may be too fast for a >100 Mo star; magnetar model works better
Spectra	Late-time I-R spec show strong intermediate-element emission features, indicative of huge synthesized masses and in agreement with models	Observed spectra are too blue? Extensive nucleosynthesis should line-blanket and redden blue/UV
Host Galaxies	PISN requires very low metallicity and SLSN I-R seem to prefer metal-poor galaxies	Pair-instability model doesn't work, except in *extremely* metal-poor galaxies

Radiatively Efficient SNe

Solution: *store* the SN-deposited energy temporarily, or *convert* kinetic energy to radiation.



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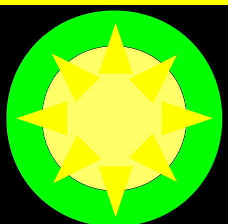
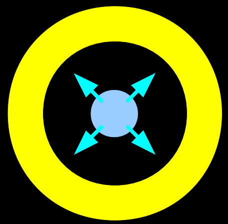
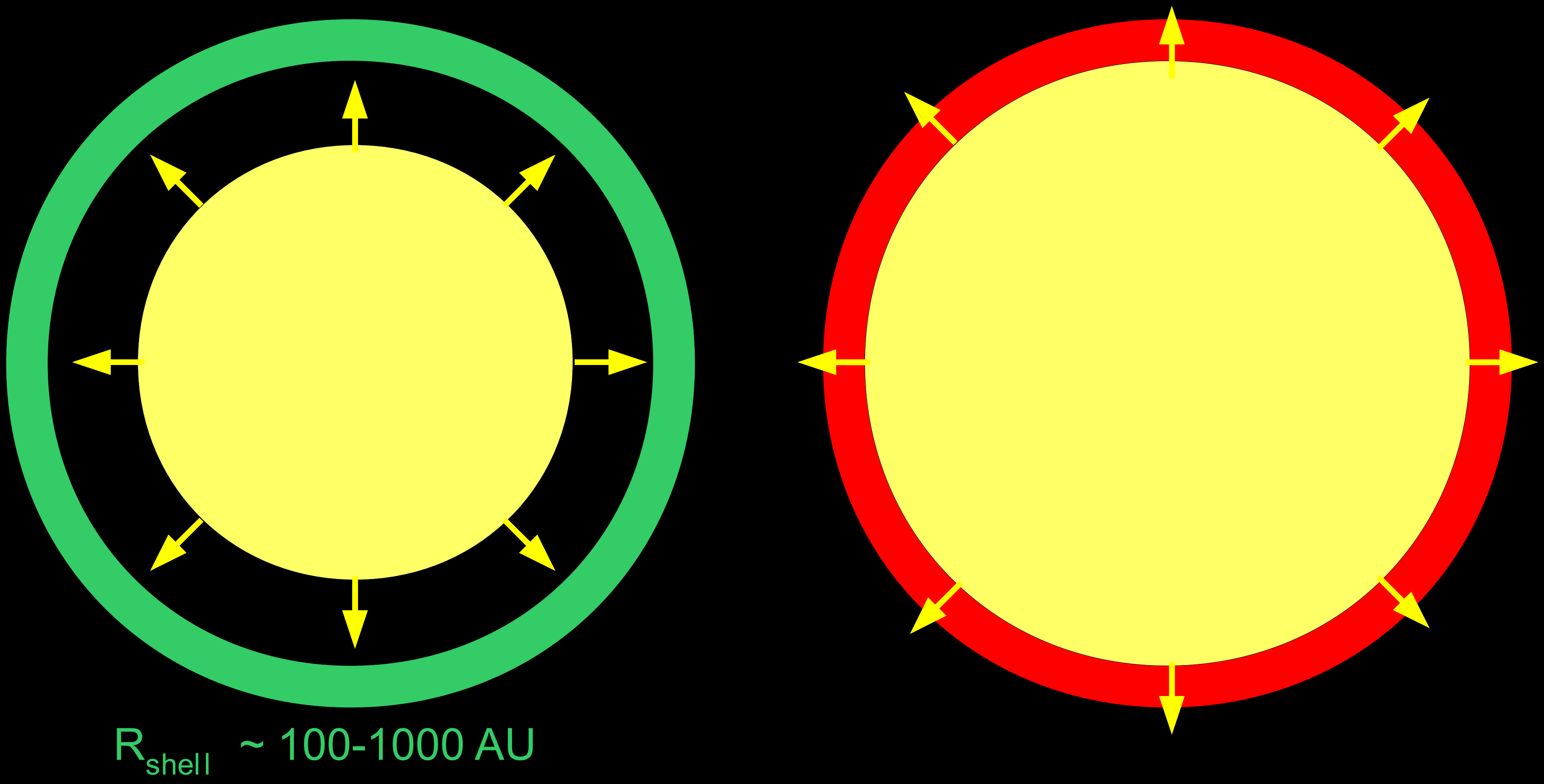


Interaction: Reconvert the KE into heat by colliding/shocking with thick pre-existing gas

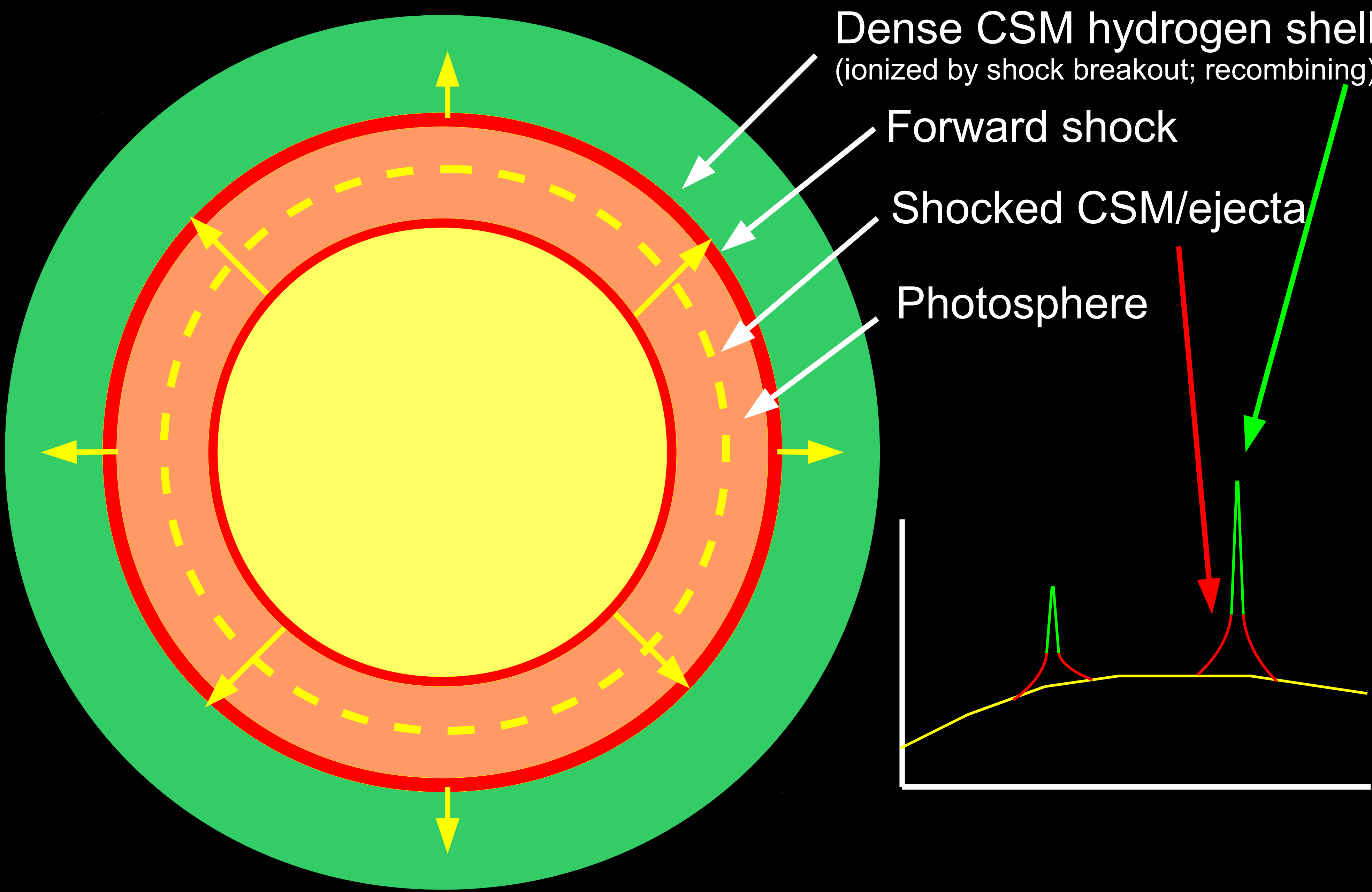


Central engine: Hold the energy in a compact object, then reheat the expanding ejecta from within

Ejecta expands, then shocks against a shell/cloud of pre-existing matter and heats it



SN IIn: Signature of Interaction



Interaction-Powered SLSNe

Most SLSN-II have narrow Balmer lines: *interaction clearly involved*.

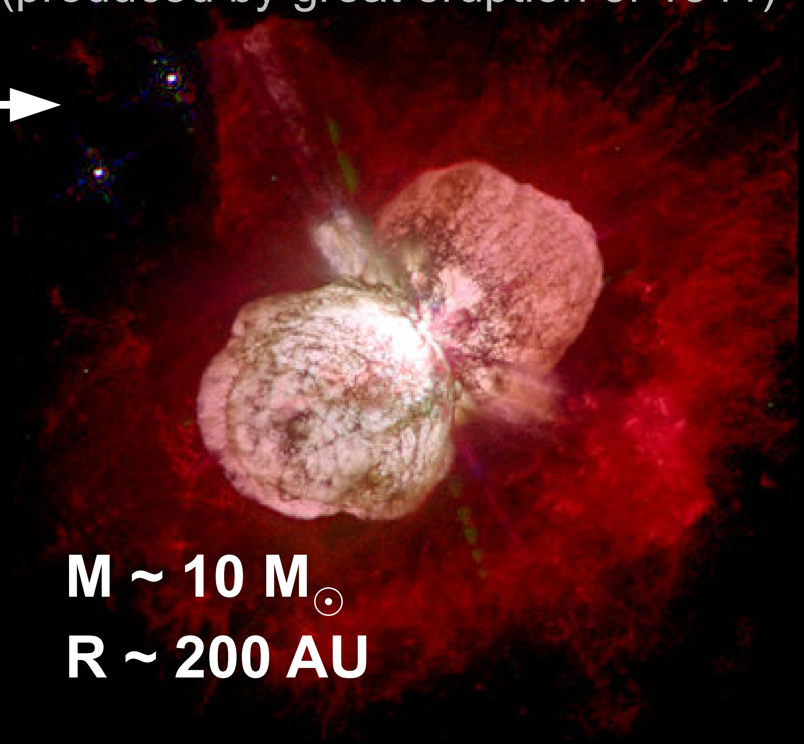
Efficient conversion requires $M_{shell} \sim M_{ejecta}$ at R~1000 AU

(i.e., a significant fraction of the star)

Extremely massive stars *can* violently expel huge shells of gas!

(But, then they have to explode soon after...)

Eta Carinae Homonculus nebula
(produced by great eruption of 1841)



$M \sim 10\ M_\odot$
R ~ 200 AU

Massive Stellar Instability Before Death

Losing 20% of its mass cannot be an everyday event for a star...

<u>Late-Burning Instability</u>

Most (normal) type IIn SNe also seem to be preceded by large eruptions in final months/years – as do some type Ib/c (e.g.) Instability/explosion brought on by heavy-element burning?

Ofek+2014
Foley+2007
Corsi+2014

<u>Pulsational Pair-Instability SN</u>

In stars of "intermediate" mass (95-130 $M_\odot$), the first PI explosion can fail to destroy the star.
Later explosions collide with ejecta from previous explosions!

Woosley+2007

SLSN-I from Interaction?

Could a hydrogen-free shell explain SLSN-I?

Blinnikov & Sorokina 2010, Chevalier & Irwin 2011, Ginzburg & Balberg 2012, Moriya & Maeda 2012

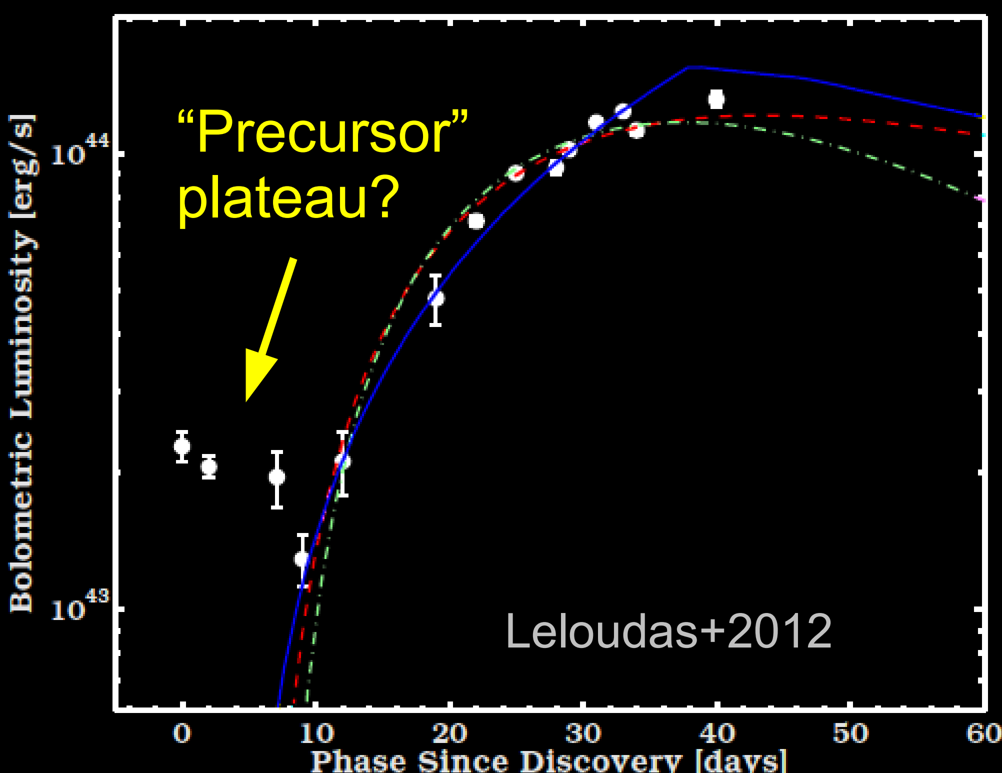
Unlikely to be *primary* cause:

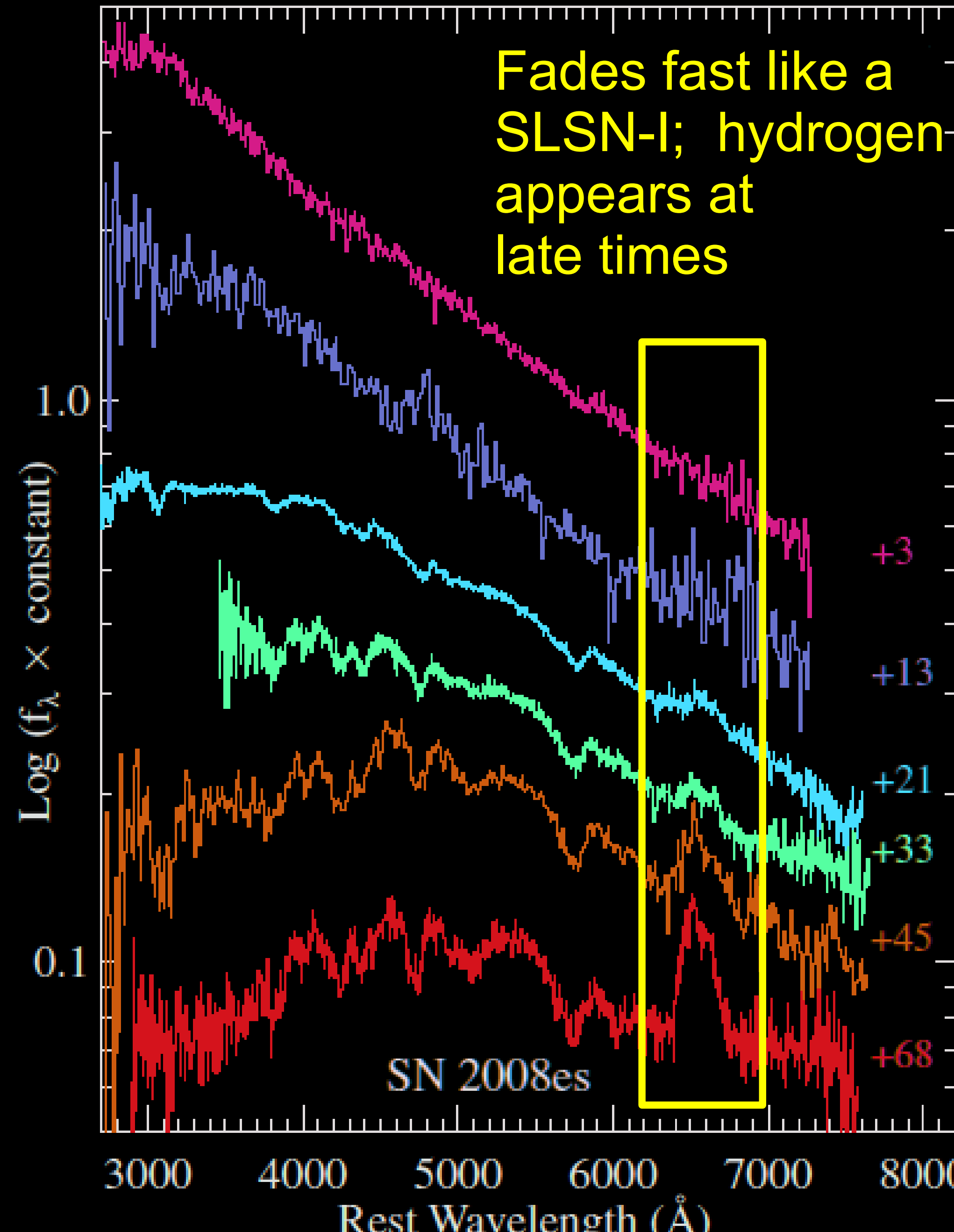
- No narrow-emission features ever seen.
- Broad absorption features indicate photosphere is in the ejecta (shell is thin)
- Light curve can keep going for years (type R)

SLSN-I from Interaction?

Nevertheless, (some) SLSN-I may involve (some) interaction:

SN 2006oz

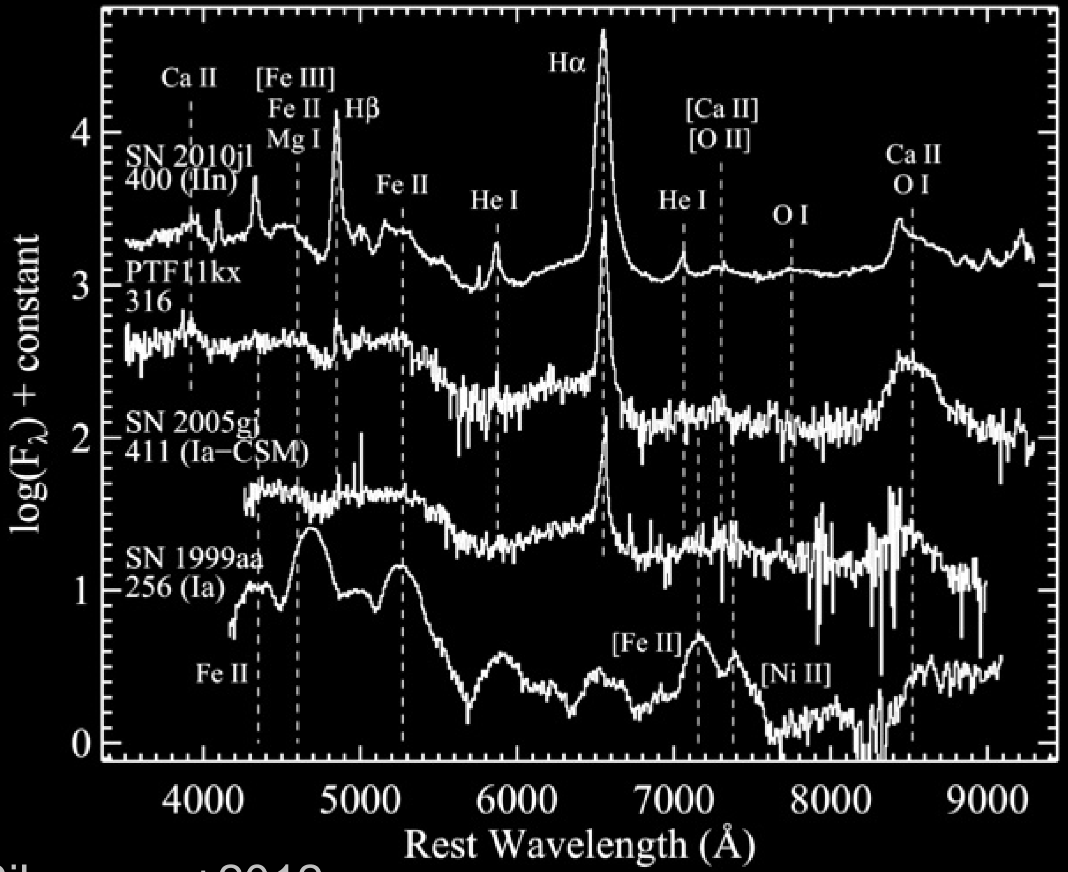




Type Ia-CSM

Underlying explosion doesn't have to be core-collapse!
Interaction can boost Ia SNe into SLSN magnitude range.

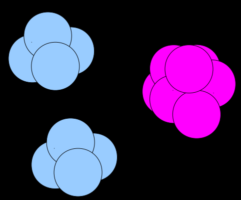
Nearly indistinguishable from IIn at early times.



Silverman+2012

Radiatively Efficient SNe

Solution: *store* the SN-deposited energy temporarily, or *convert* kinetic energy to radiation.



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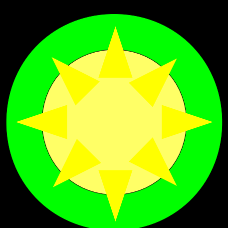

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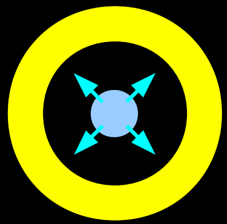


Central engine: Hold the energy in a compact object, then reheat the expanding ejecta from within

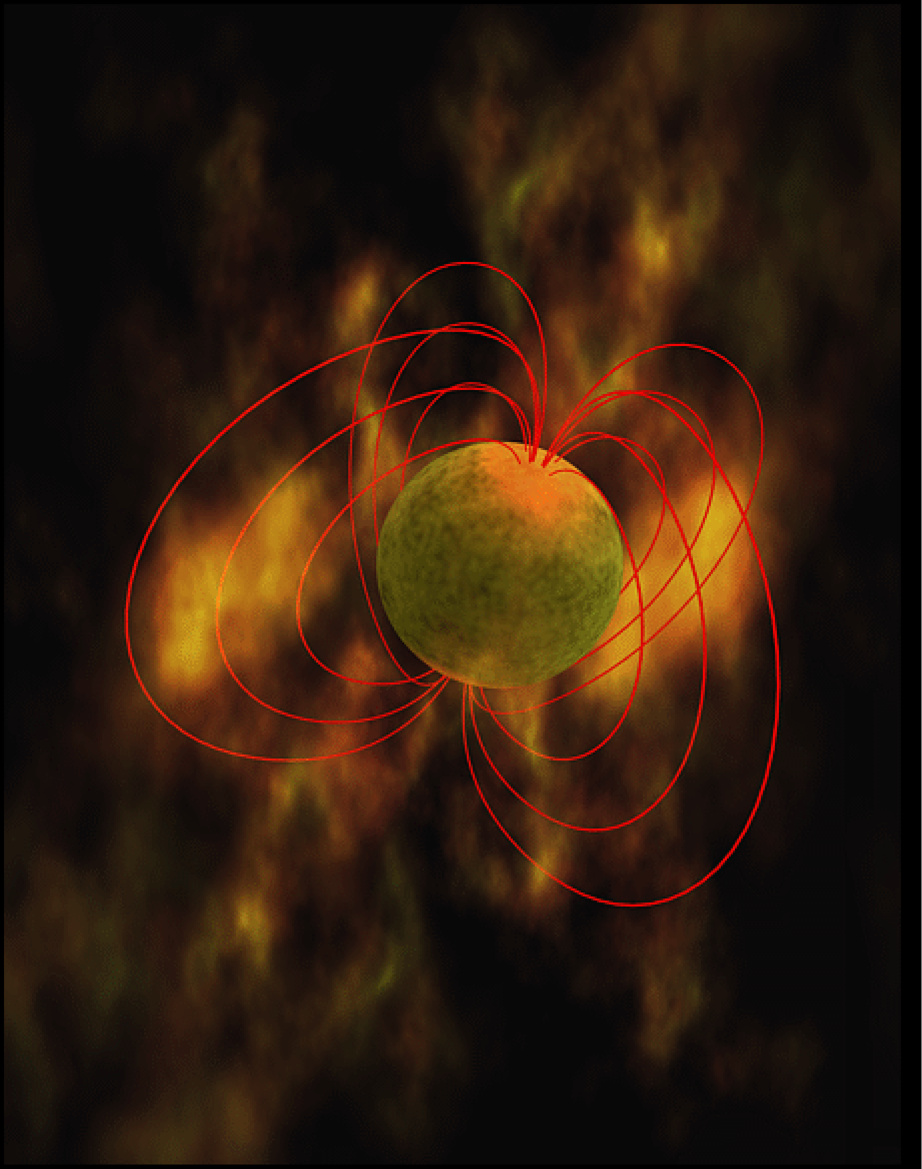
Ultra-magnetic (~10^{14} G) NS's

Strong magnetic field taps rotation energy via dipole radiation

Known magnetars spin slowly, but may have been born spinning very fast

Not rare: ~10% of MW SNe produce magnetars

Kouveliotou+1998



Magnetars & SLSNe

Kasen & Bildsten 2010, Woosley 2010, Dessart et al. 2012, Metzger et al. 2013

B ~ few × 10^{14} G, P ~ few millisec proto-magnetar will inject ~10^{51} erg of rotation energy towards the expanding ejecta

Simple spindown injection models seem to explain a large variety of SLSN observables and accommodate observed diversity in energies, timescales, etc.

Possible cons:
- "Too" flexible?
- Does the energy actually reach/thermalize the ejecta?

PTF and SLSNe

PTF's SLSN haul

Most theoretical work/interpretation is based on the first few detected SLSNe – i.e., $N_{SLSNe} < N_{papers}$

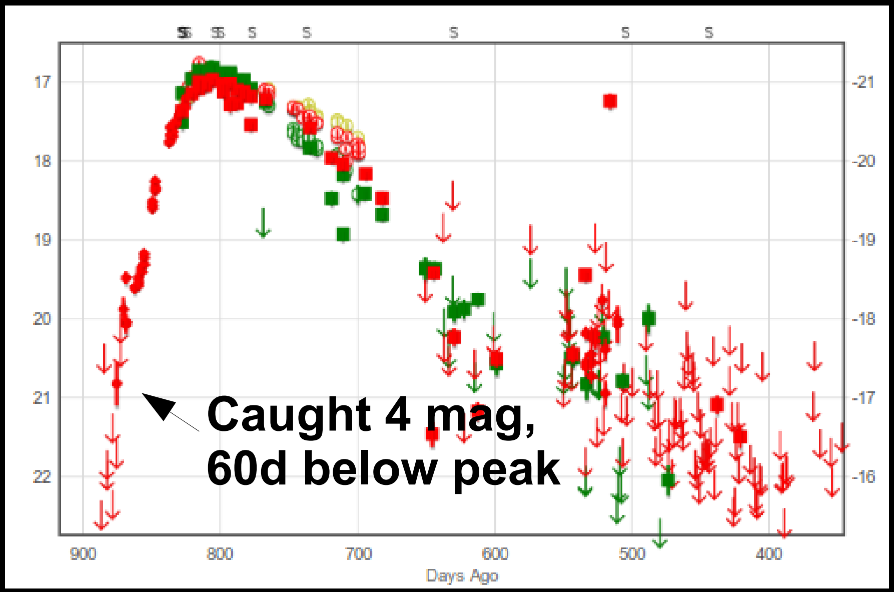
In this situation, more are obviously necessary...!

	2009	2010	2011	2012	2013	2014	TOTAL
Type I	3	9	4	3	6	3	**28**
(R)	0	2	0	1	2	?	**5**
Type II	1	8	1	4	1	0	**15**
Ia-CSM (M>-21)	0	2	1	2	?	?	**5**

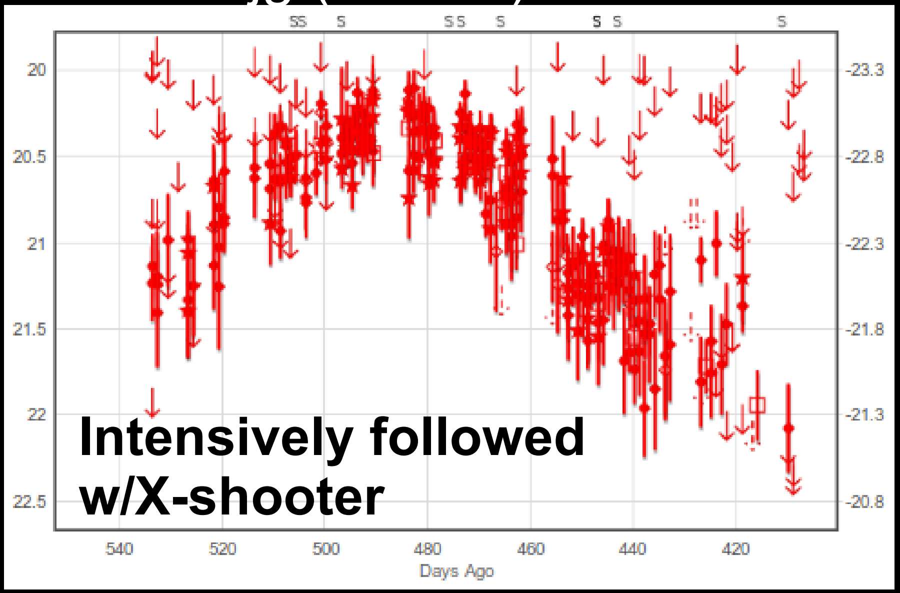
2012+: iPTF rapid cadence covers less area (fewer detections) but coadd pipeline allows us to go deeper → find more distant SNe.

Earlier, Closer, Further, Brighter, Weirder

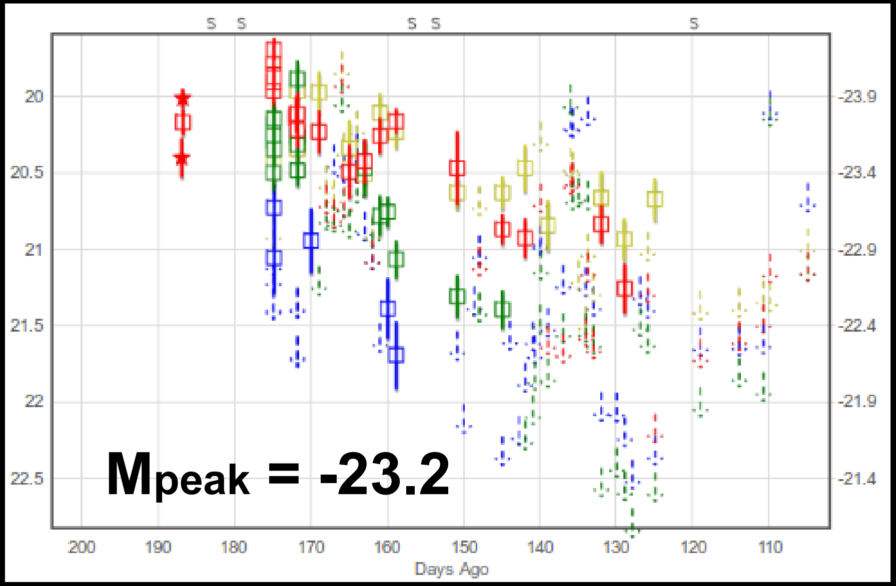
PTF 12dam (z=0.10)



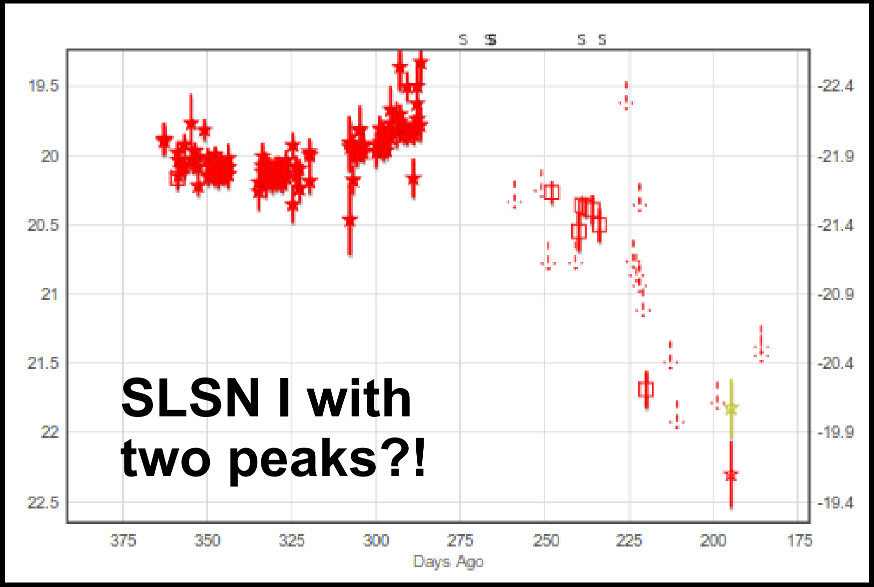
PTF 13ajg (z=0.74)



PTF 14tb (z=0.942)



PTF 13dcc (z=0.4305)



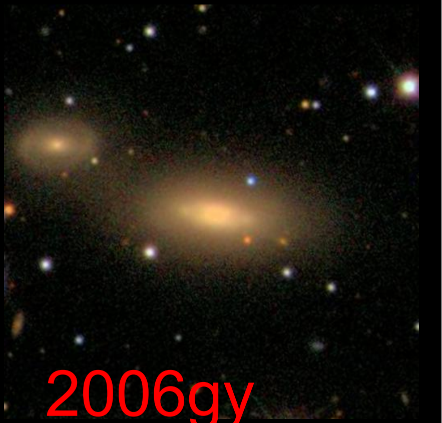
Host environment likely to be an important probe of progenitor (and formation pathway).

e.g.,

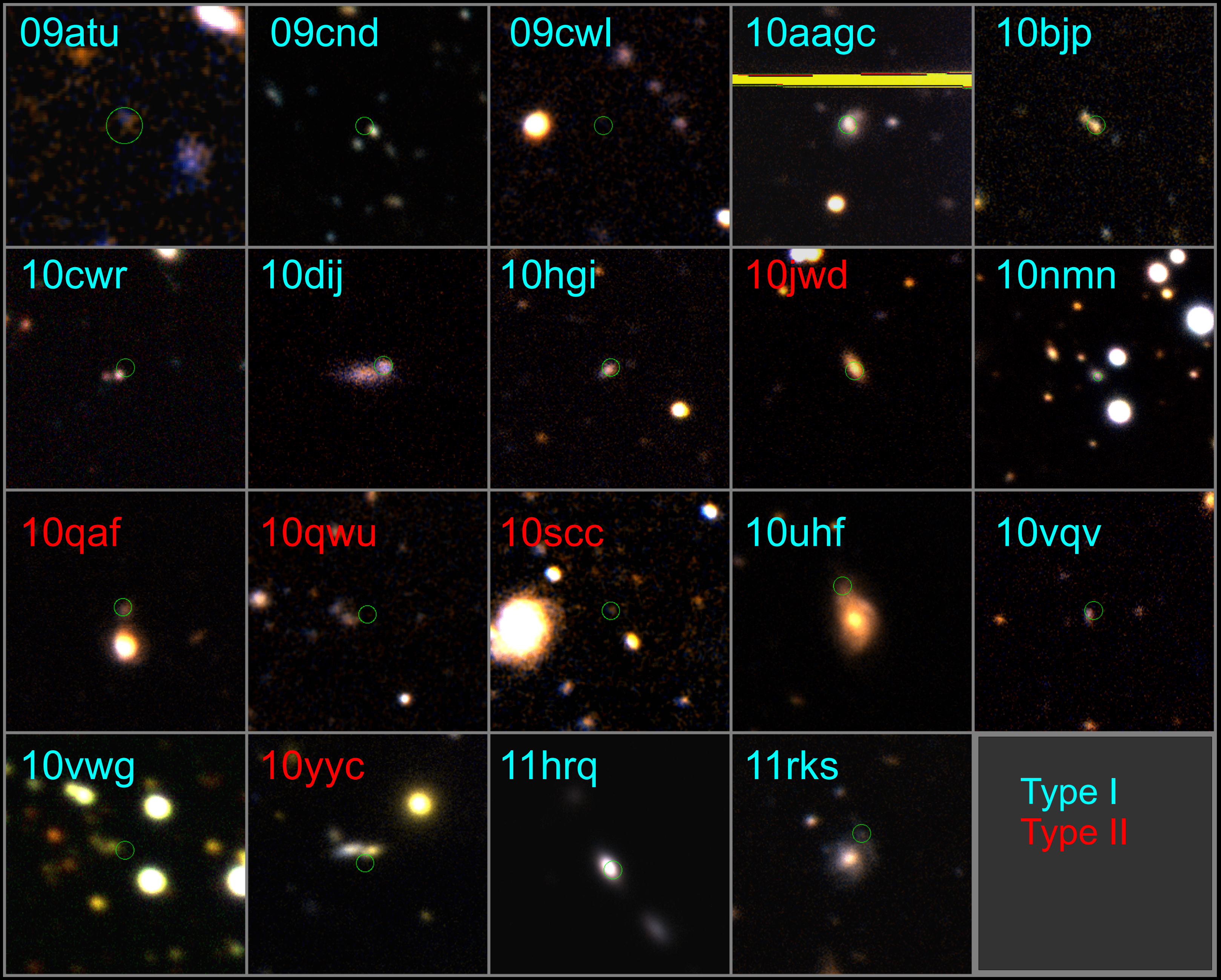
- Pair-instability requires low metallicity
- Engine-driven *single*-star models also require low metallicity
- Binary models may prefer very dense star clusters

Host population is fainter than normal ccSNe (Neill+2011); has similarities to GRB hosts (Lunnan+2014)

(But the picture is complex!)

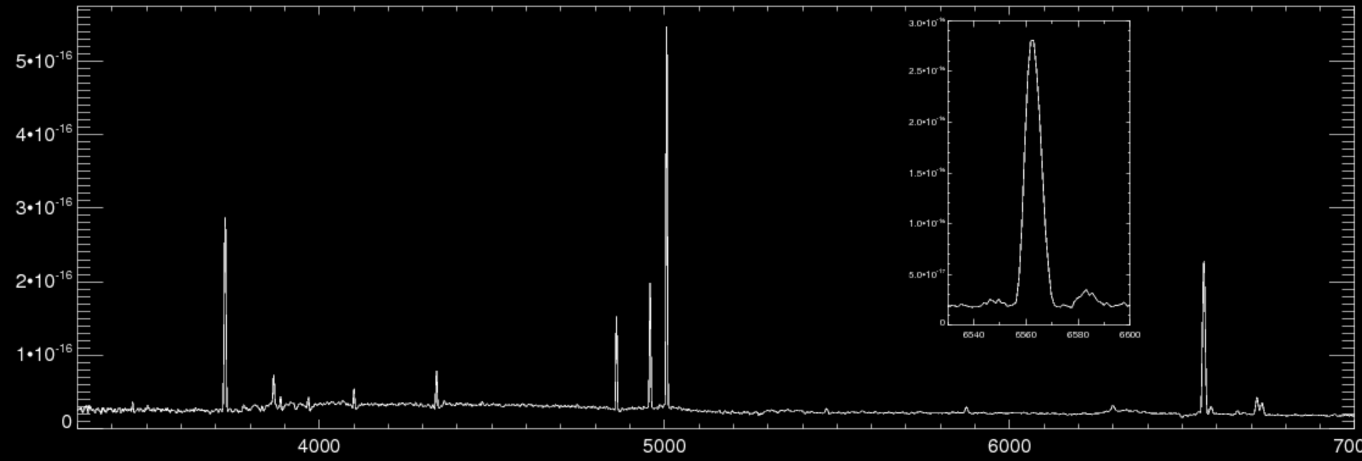


PTF SLSN Host Galaxies

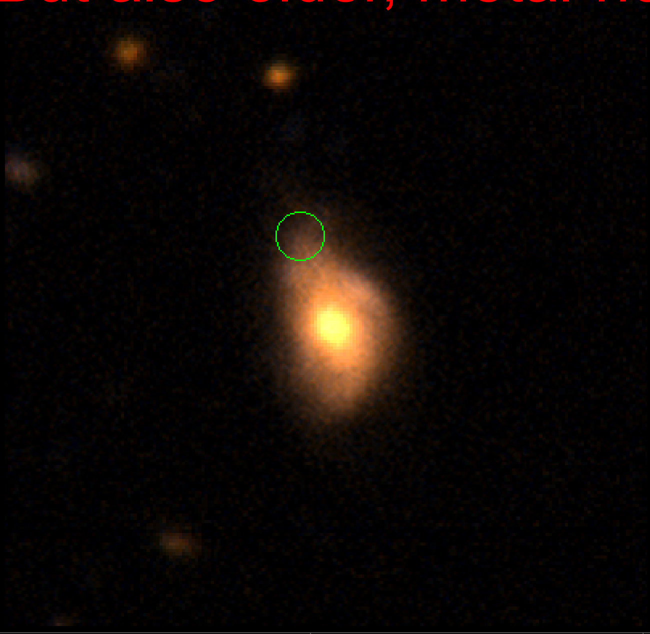


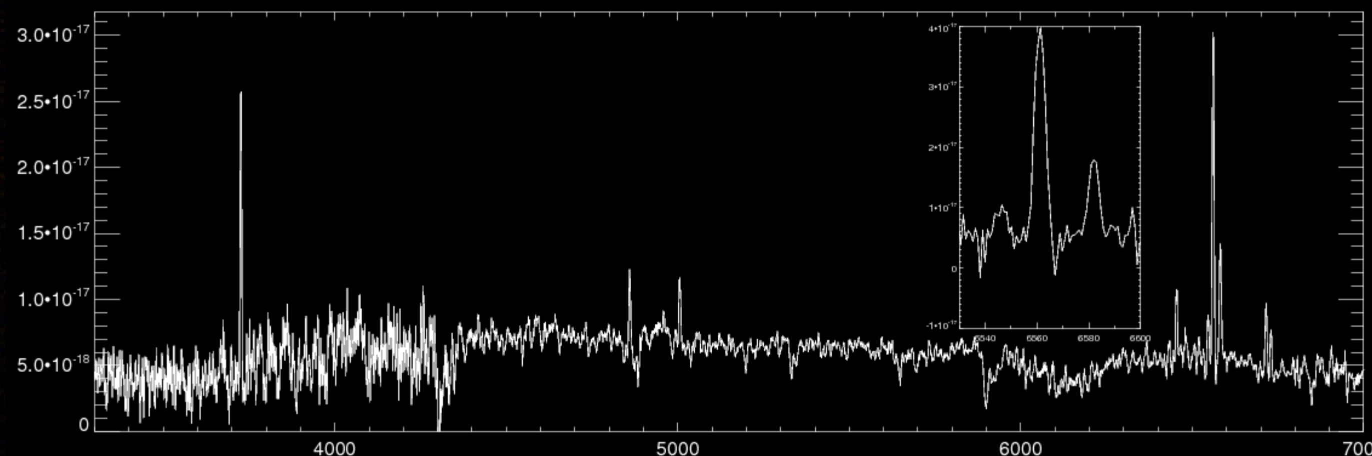
PTF SLSN Host Galaxies

Intense, metal-poor starbursts

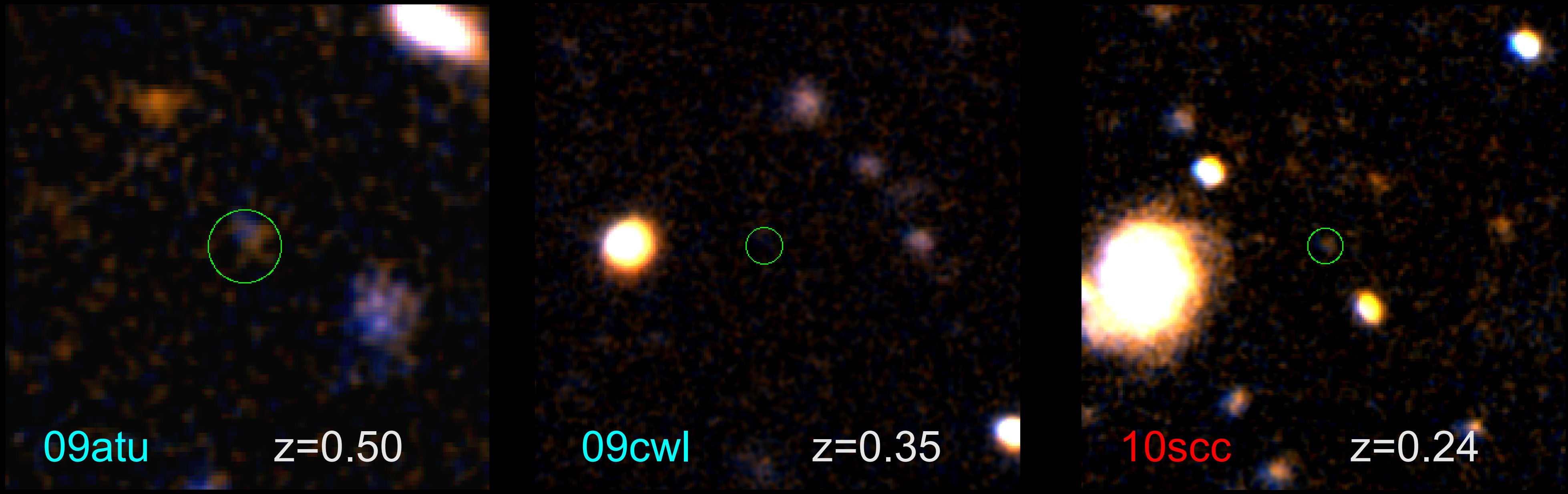


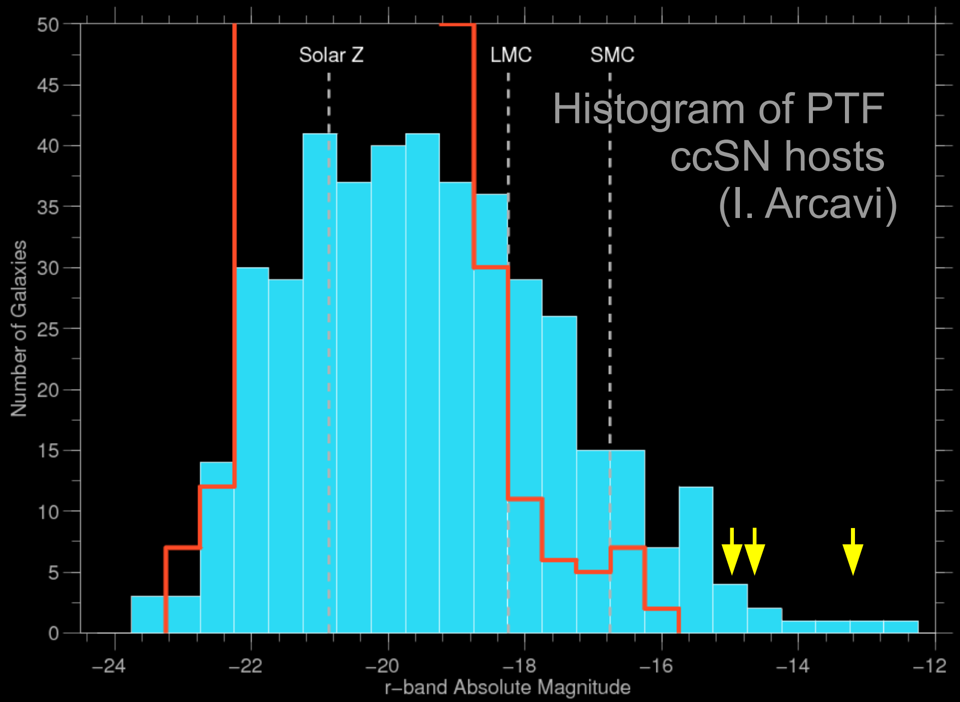
But also older, metal-rich galaxies





PTF SLSN Host Galaxies





Extremely faint, low-luminosity galaxies with extremely low star-formation rates.

Summary

Operational definition: M_{peak} < -21 mag

Radiated energy ~10^{51} erg (100 x "typical" ccSN)

Multiple classes and subclasses (I, II; R, L)

Producing an SLSN primarily requires efficient extraction of energy to radiation (instead of KE)

- Efficient Ni56 production (PISN? 50-100 $M_\odot$ star?) → type R?
- Interaction with huge amount of CSM ejected recently → type IIn
- Central engine (magnetar) → type Ic?

43 PTF SLSNe (~6 per year): many more sure to come...!