Superluminous supernovae and lightcurves powered by magnetars

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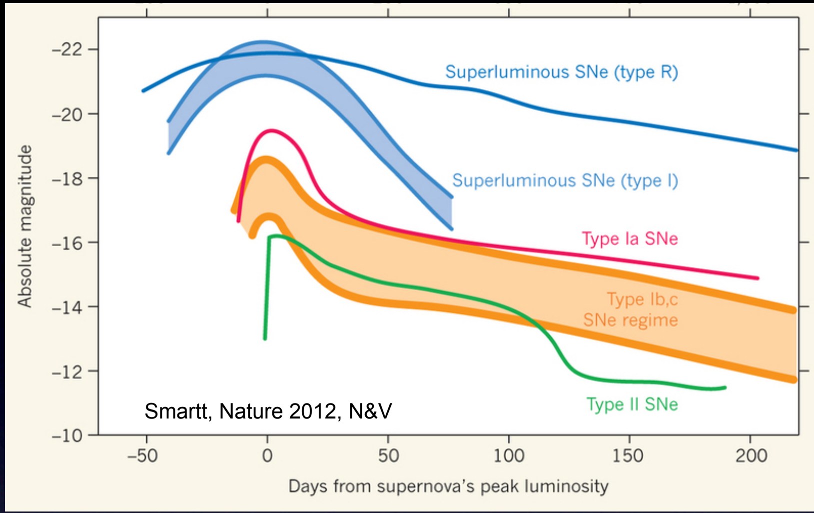
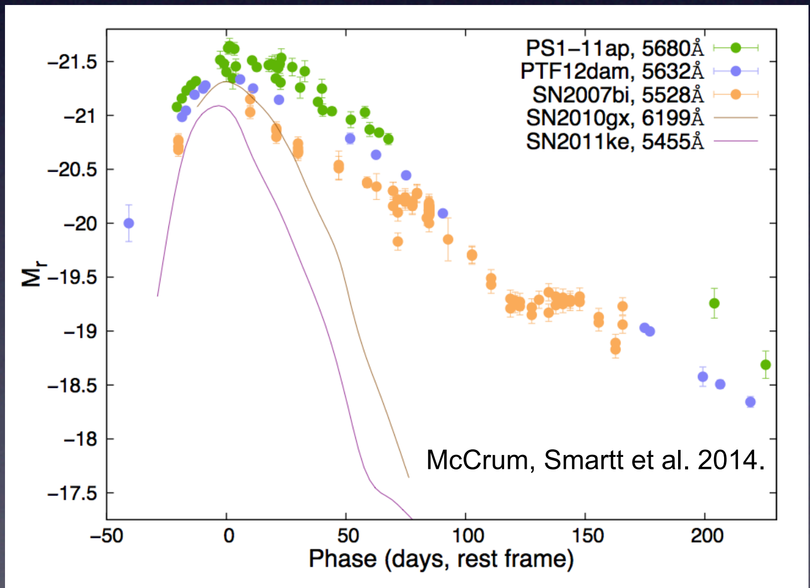
Pan-STARRS
PS1 Science Consortium

Superluminous supernovae





- What are they : stellar Explosions in dwarf galaxies – 100 times more luminous than core-collapse SNe.
- Luminosity source unconfirmed.
- No hydrogen and helium seen in spectra
- What is the physics powering this extreme luminosity ?

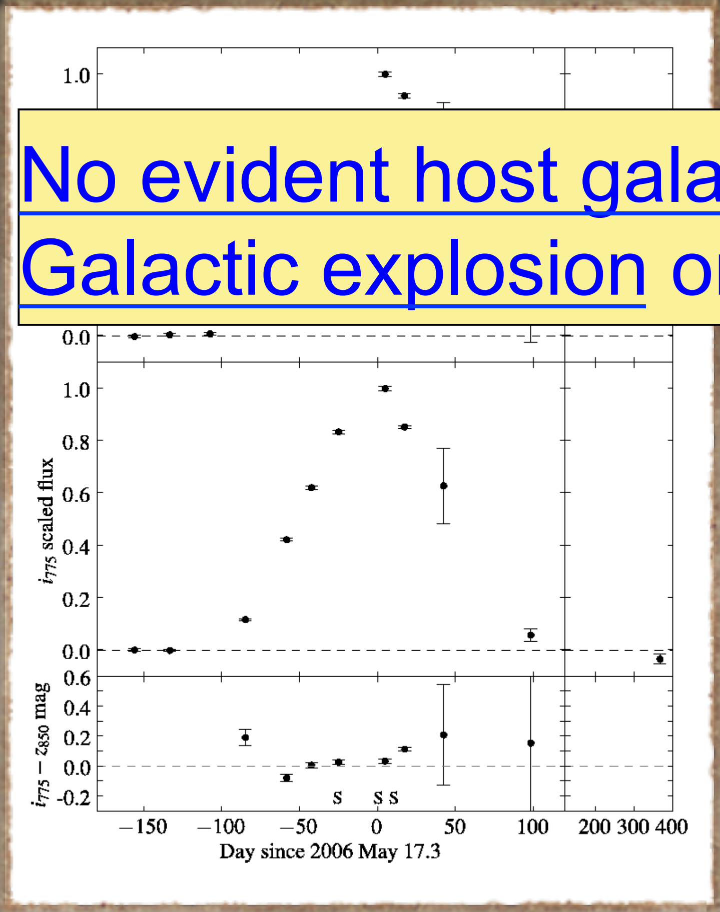
PS1 : has discovered them at redshift ranges z ~ 0.1 – 1.5

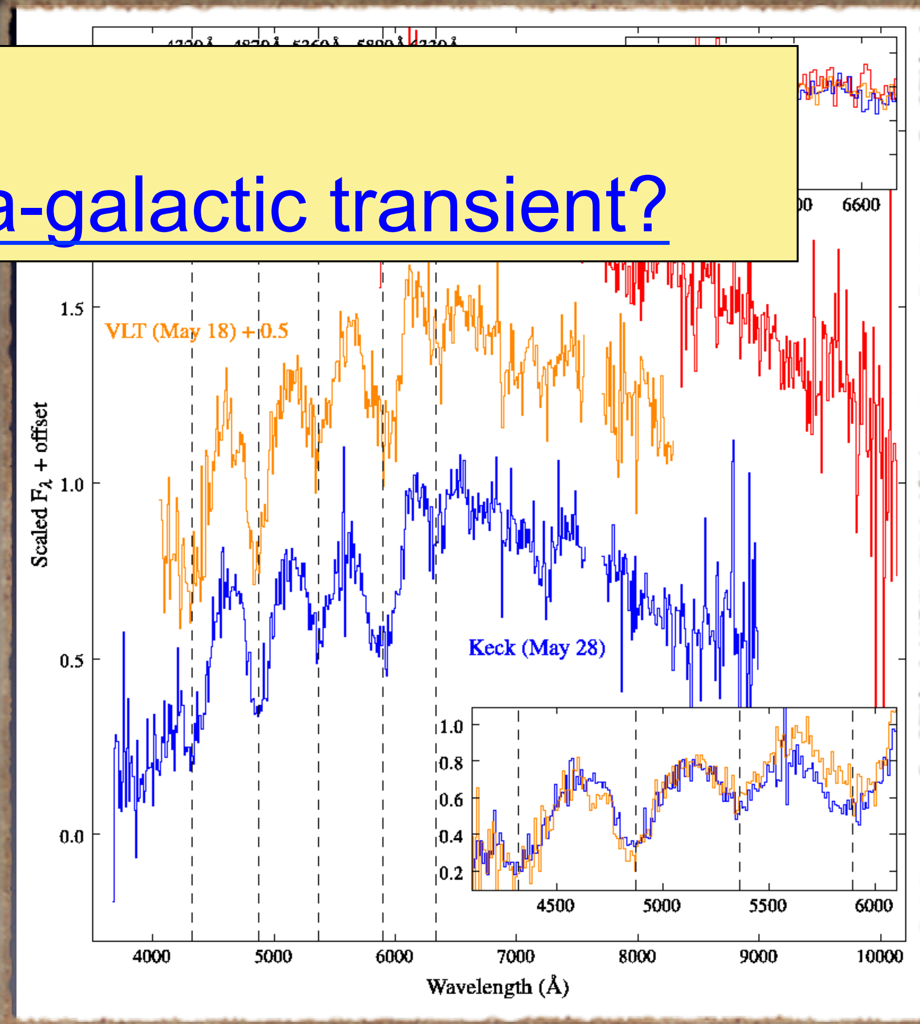
- z = 0.1 – 0.3 in the 3Pi survey
- z = 0.5 – 1.5 in the MD fields

Chomiuk et al. 2011, Berger et al. 2012,
Nicholl, Smartt et al. 2013,
Inserra, Smartt et al. 2013,
Chornock et al. 2013,
Lunnan et al. 2013+2014

PTF discoveries : Quimby *et al. Nature* 2011

SCP 06F6 – from HST Cluster SN Survey





No evident host galaxy.

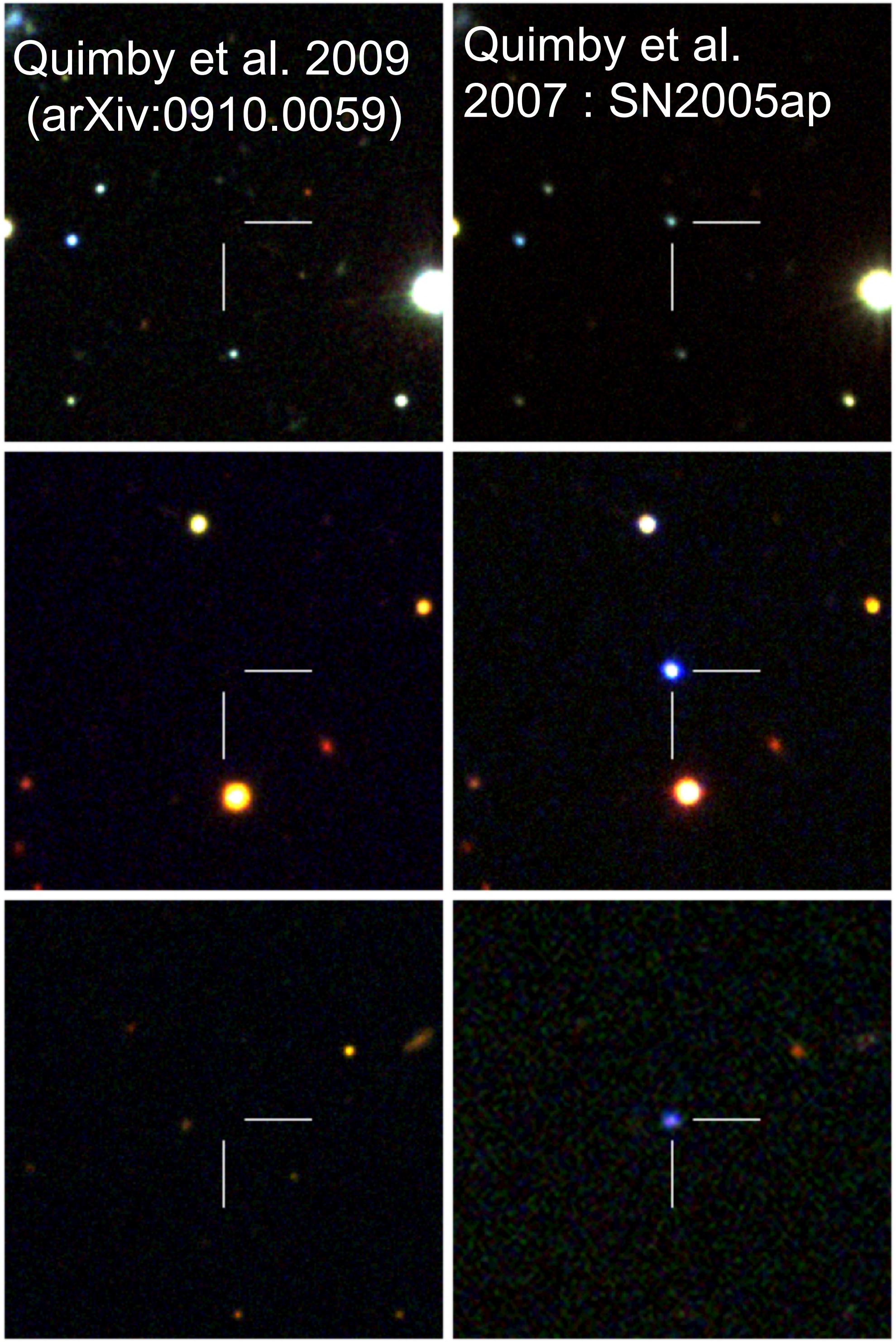
Galactic explosion or extra-galactic transient?

Barbary et al. 2009, ApJ, 690, 1658

What was SCP 06F6?

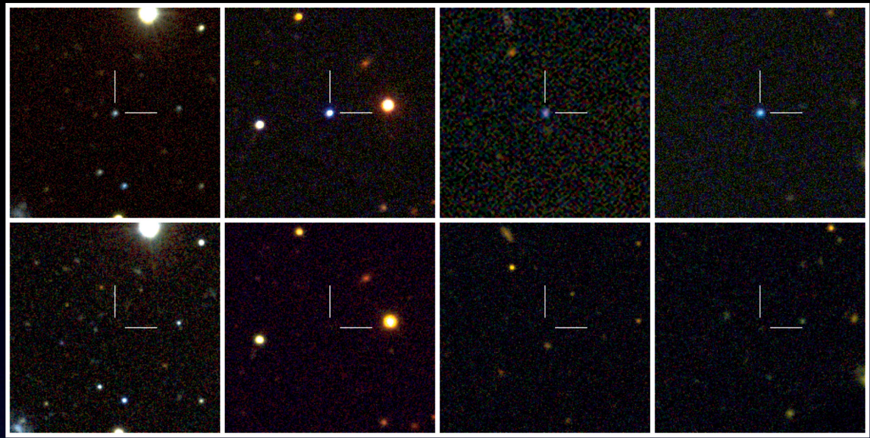
- Galactic Transient?
- WD-asteroid collision?
- Micro-lensing event?
- Broad abs. line QUASAR?
- Pair-production SNe?
- Ejecta-CSM interacting SN?
- SN explosion of a C star?
- Tidal disruption of a C star by a BH?

Barbary et al. 2009, ApJ, 690, 1358
Gansicke et al. 2009, ApJ, 679,L, 129
Chatzopoulos et al. 2009, ApJ, 704, 1251
Soker et al. 2010 New A., 15, 189

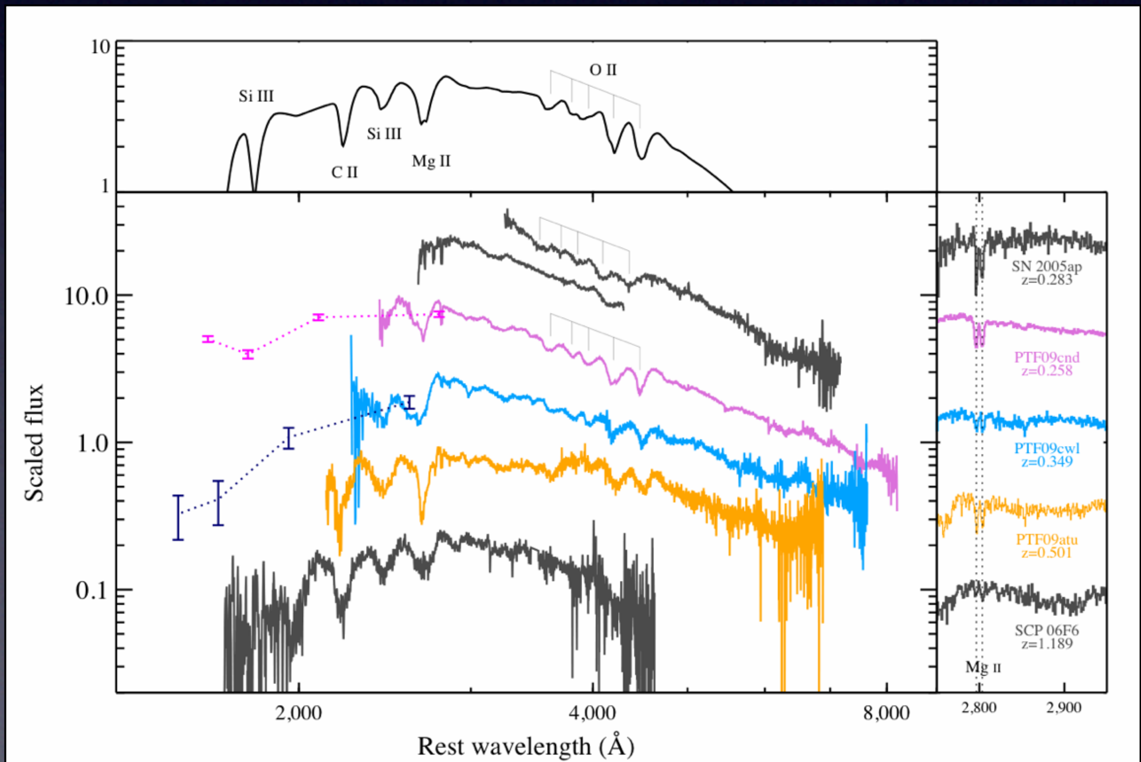


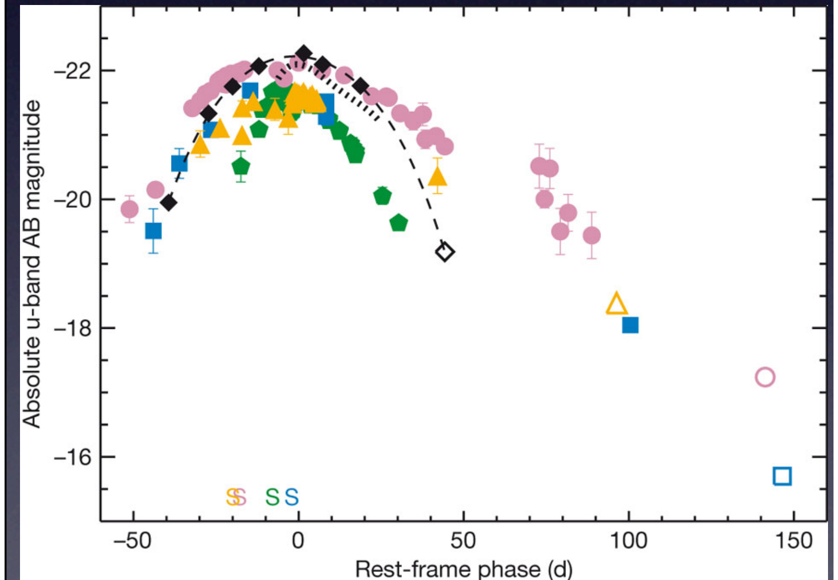
Superluminous stellar explosions

Palomar Transient Factory



No H or He detected in SN spectra

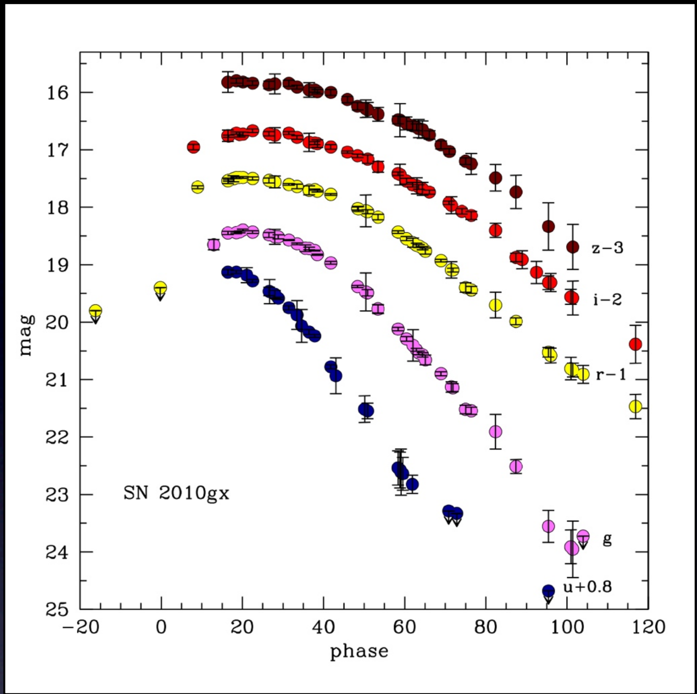


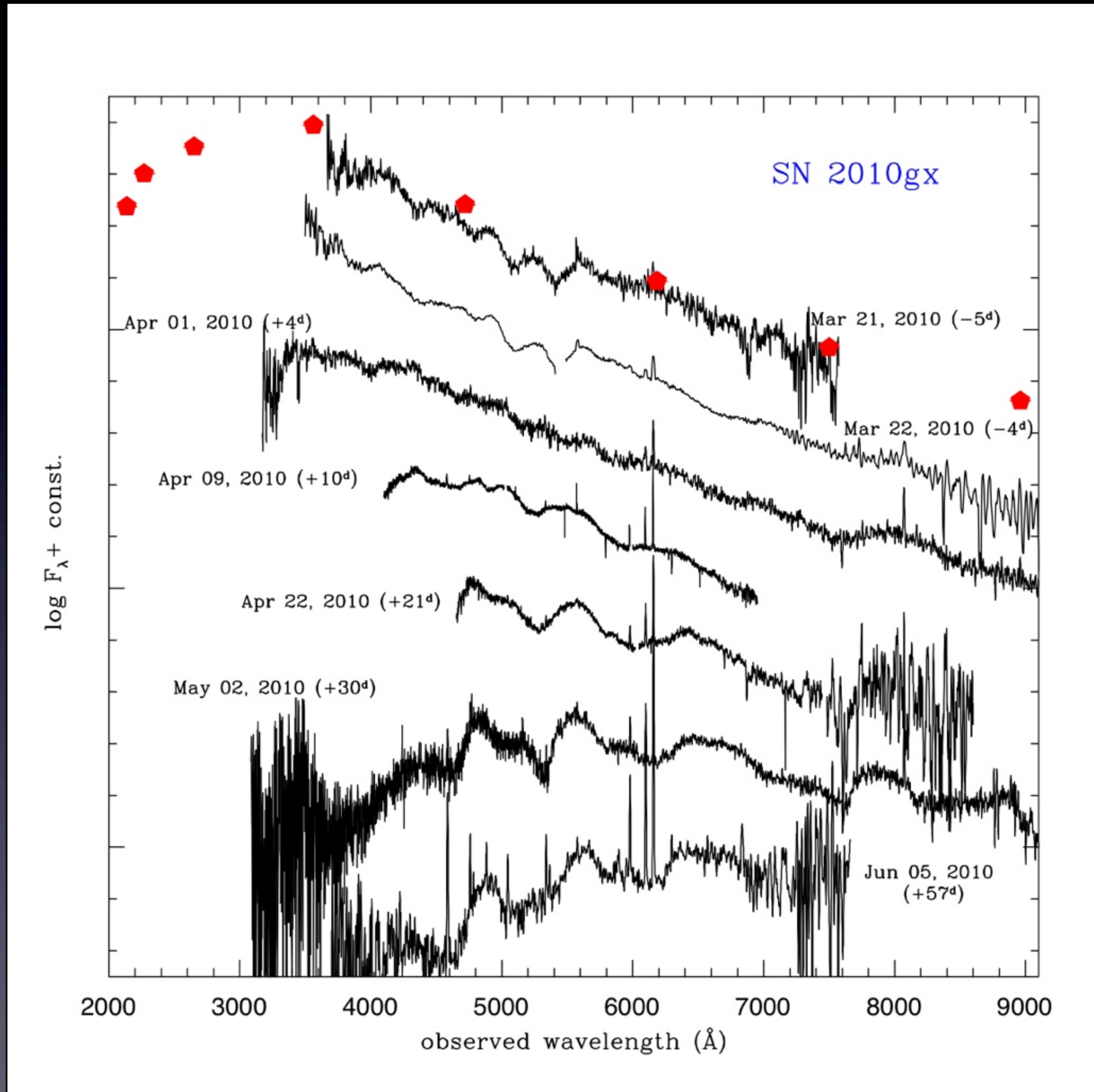


RM Quimby *et al. Nature* 2011 doi:10.1038/nature10095

nature

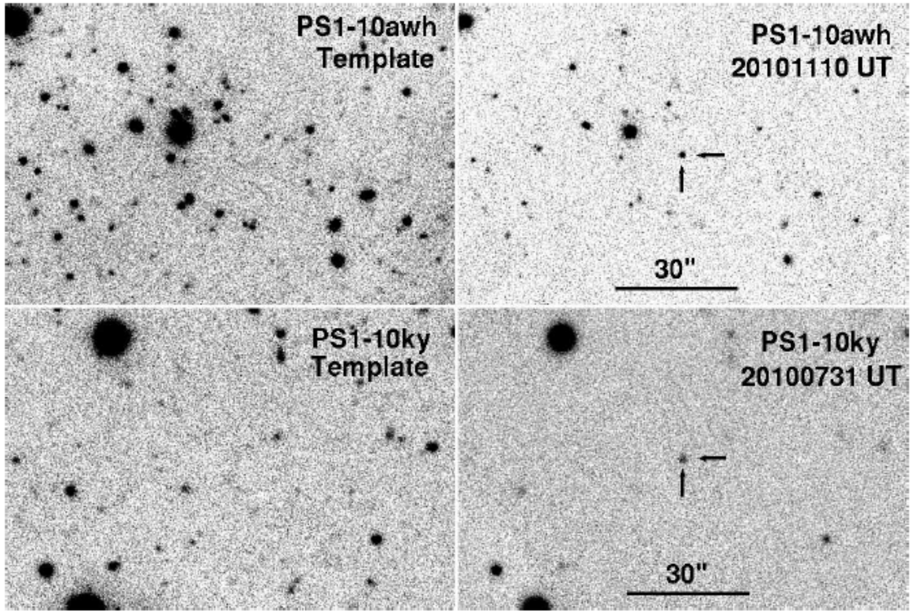
SN 2010gx

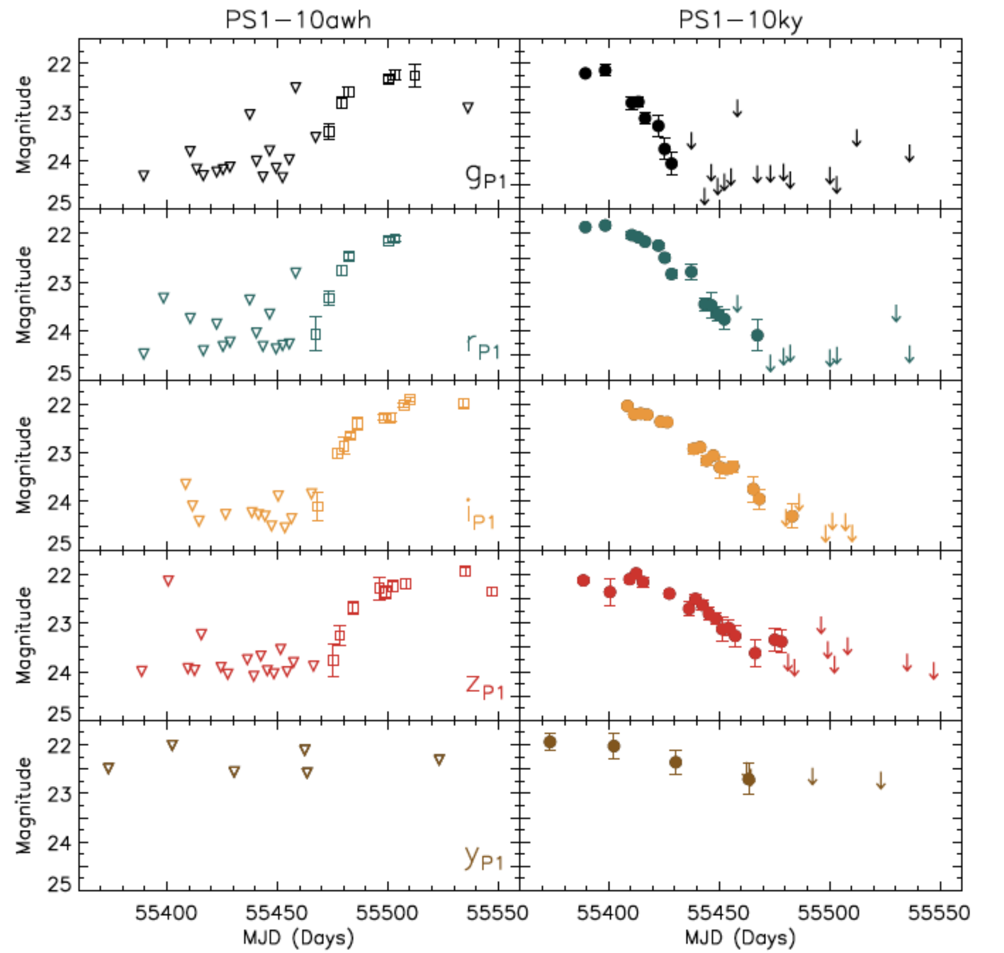




Pastorello, Smartt et al. 2010,

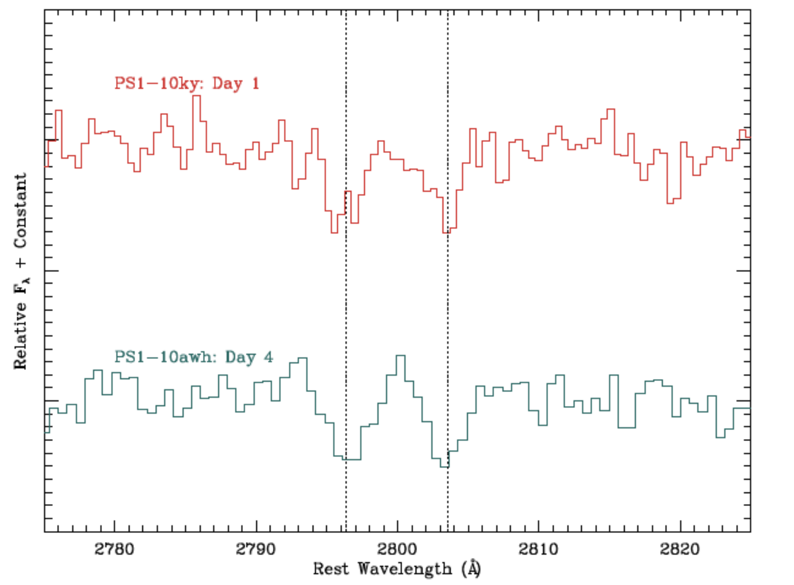
Pan-STARRS1 : Two superluminous SNe at $z \approx 0.9$



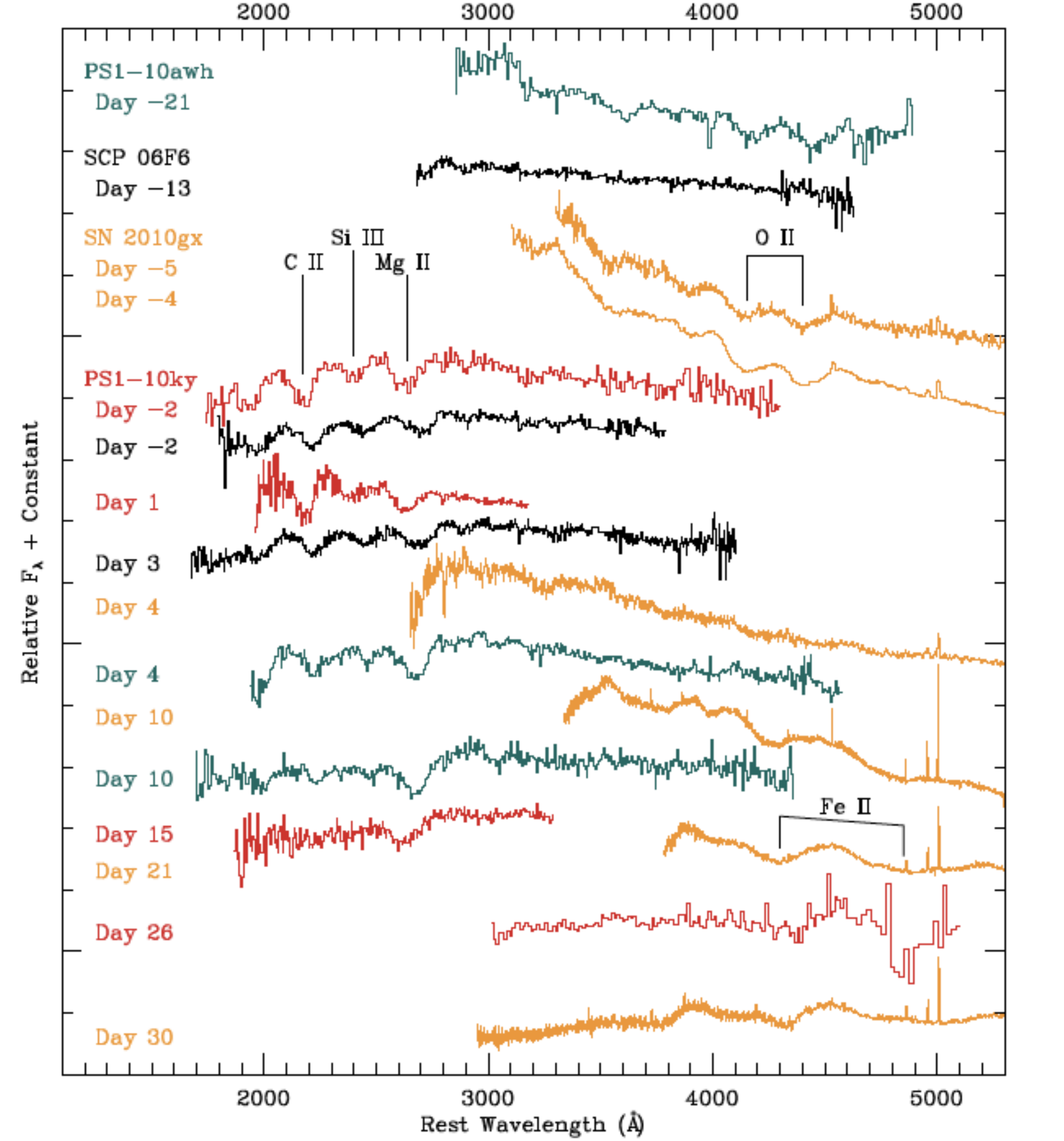


- Major effort at CfA/QUB/JHU/IfA for spectra of PS1 targets
- Chomiuk, Chornock et al. 2011 ,ApJ
- Two orphans “twins” in MD09:
  - PS1-10awh : end of season
  - PS1-10ky : start of season

Two "ultra-luminous" SNe at $z \approx 0.9$



- Mg II ISM host absorption
  - PS1-10awh : $z = 0.9084$
  - PS1-10ky : $z = 0.9558$
- Host galaxies undetected
  - $z_{P1} > 25^m$
  - $M_B > -18^m$ or $L_{gal} < 0.05L^\star$



Chomiuk et al. 2011

^{56}Ni powered luminoisty is unphysical

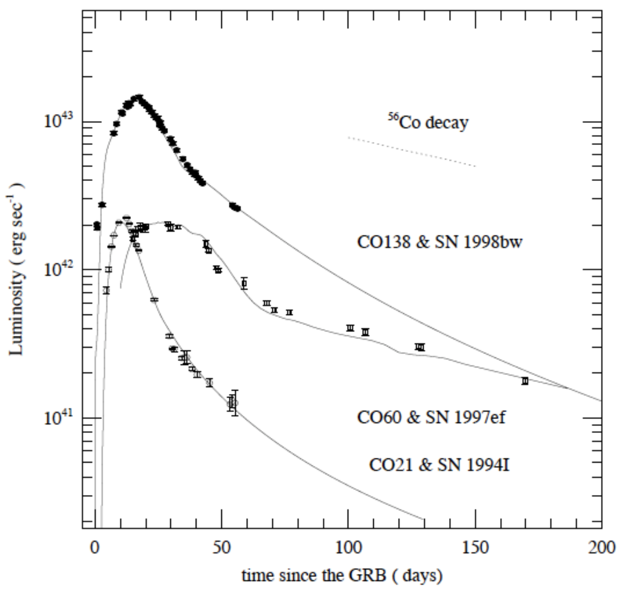
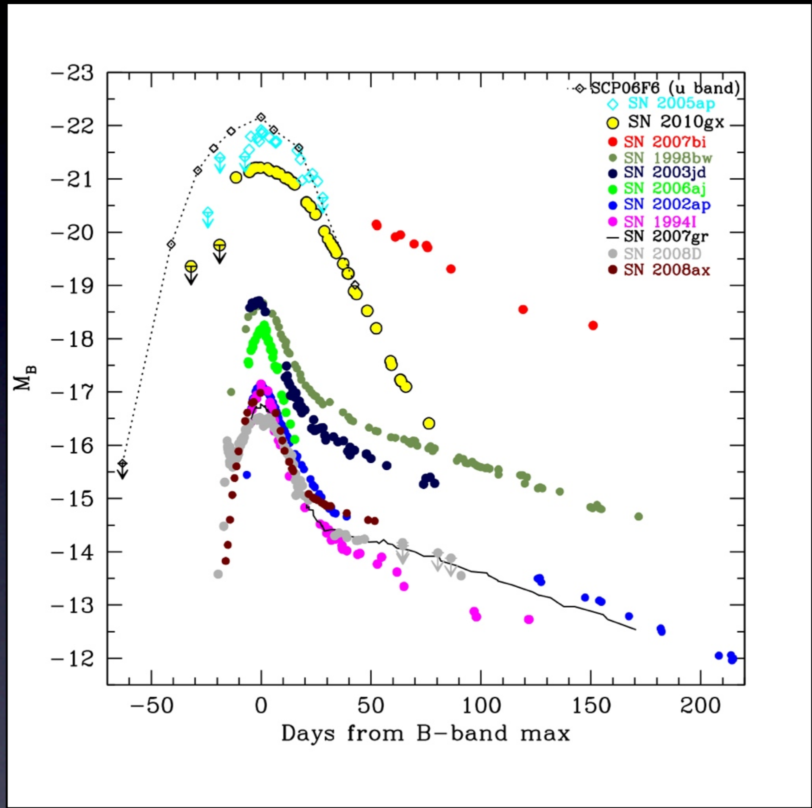


Figure 1: The bolometric light curve of model CO138 ($M_{CO} = 13.8M_\odot$, $E_{exp} = 3 \times 10^{52}$ ergs, $M_{56} = 0.7M_\odot$) compared with the observations of SN1998bw. The time of the core collapse is set at the detection of the



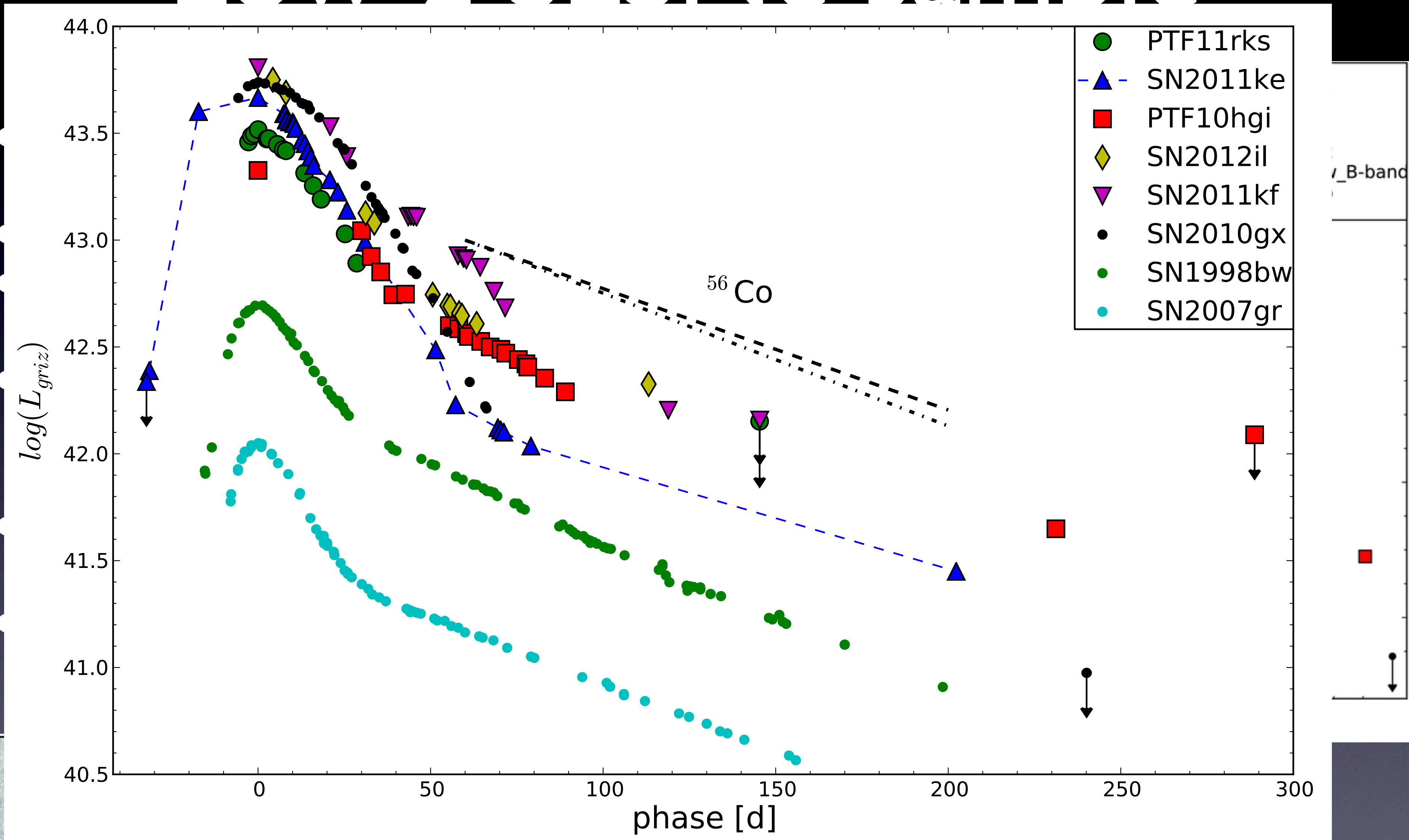
Iwamoto et al. (1998)

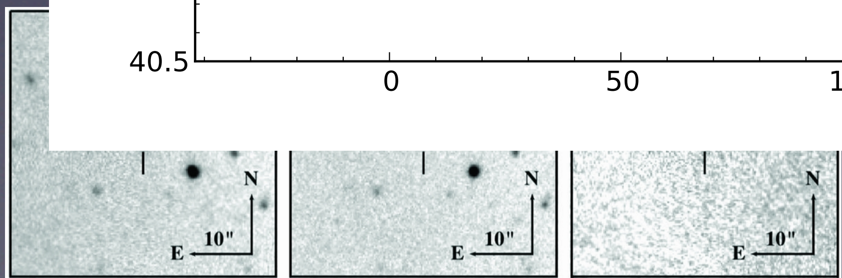
Scaling relations (“Arnett’s law”) means

$M_{Ni} > M_{ej}$

See Chomiuk et al. (2011)

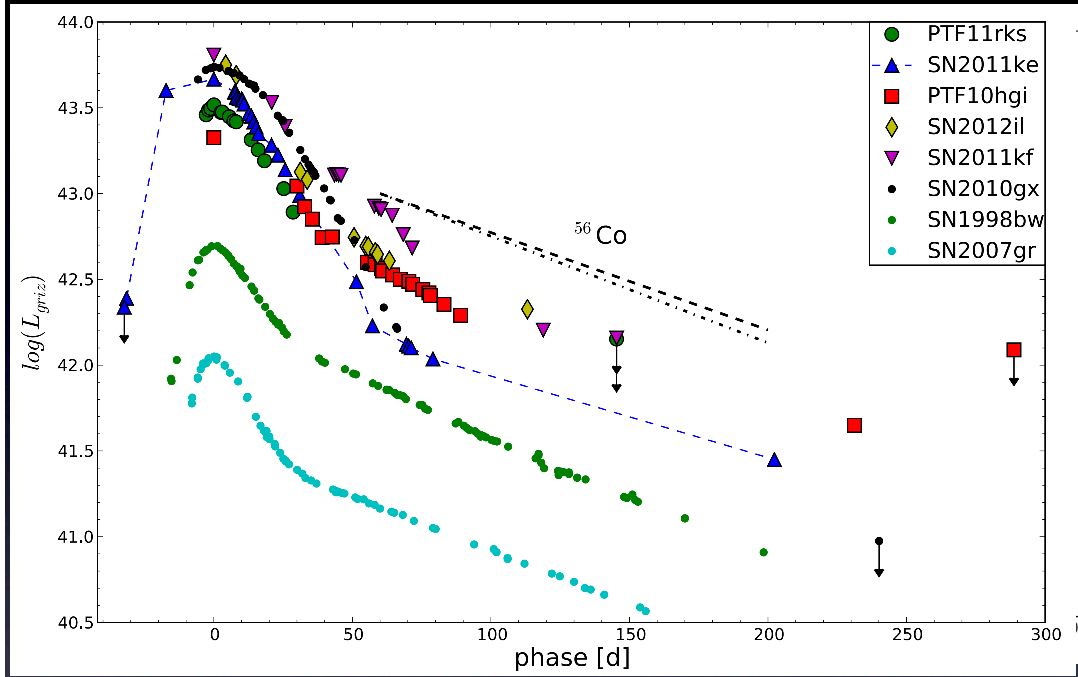
Low-z SLSNe sample

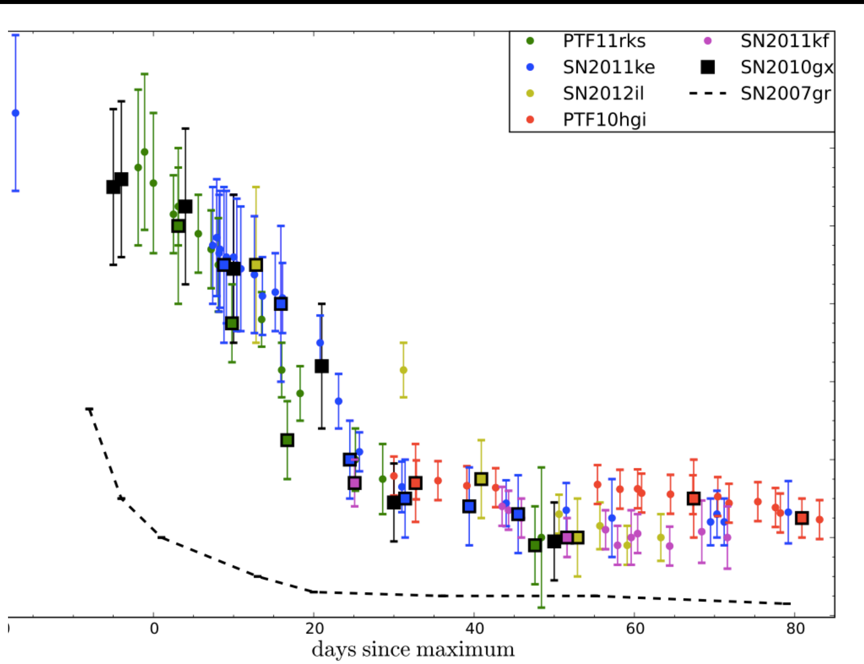




Inserra, Smartt et al. 2013

Faster, hotter, brighter





$$L = 4\pi\sigma r^2 T^4$$

$$\frac{r_{SLSN}}{r_{Ic}} \sim \frac{v_{SLSN}t}{v_{Ic}t} \sim 2$$

$$\frac{T_{SLSN}}{T_{Ic}} \sim 2$$

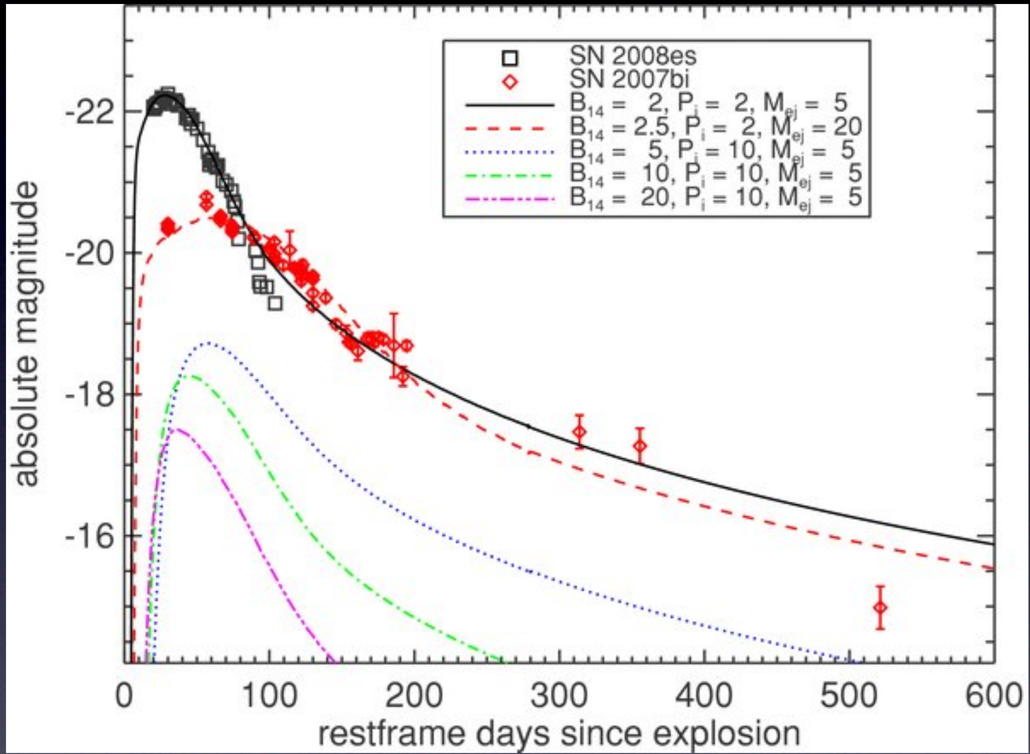
- L_{SLSN}/L_{Ic} ~ 50 -100 from simplistic estimates from *v_{exp} and T_{eff}*
- Approximately matches the luminosity ratios at peak to 20 days (~50)

Inserra, Smartt et al. 2013 ; 2007gr data from Hunter et al. 2009

Magnetar models

$$E_p = \frac{I_{ns}\Omega_i^2}{2} = 2\times10^{50} P_{10}^{-2}\,\mathrm{erg}$$

- If NS formed spinning at P = 2-20 ms and B ~ 10^{14} G
- Rapid spin down powers extra energy in expanding SN
- If diffusion time is similar to spin down time :



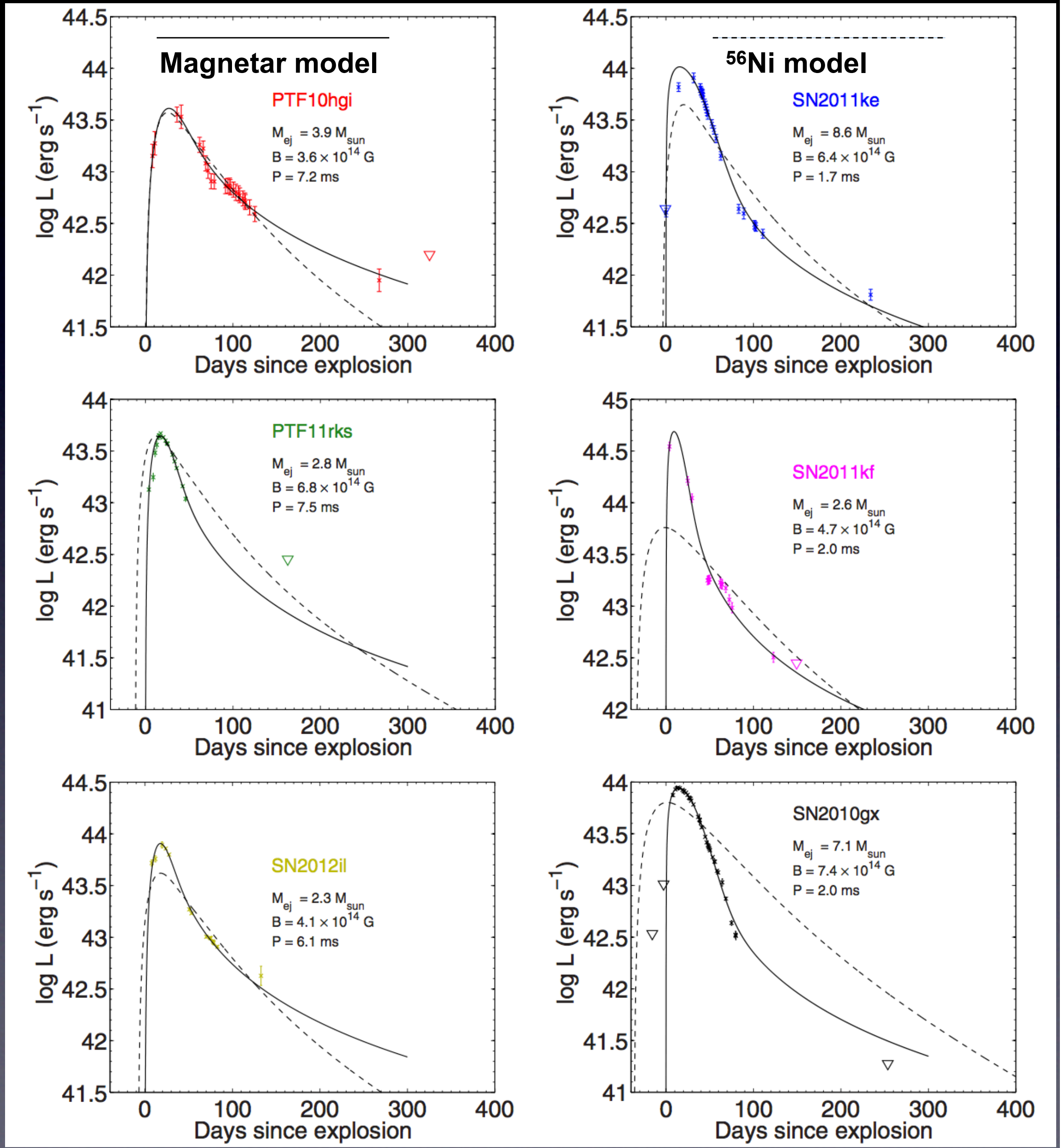
Kasen & Bildsten 2010

$$L_{peak} \sim \frac{E_p t_p}{t_d^2} \sim 5\times10^{43}(B_{14}^{-2}\kappa_{es}^{-1}M_5^{-3/2}E_{51}^{1/2})\ \mathrm{erg\ s^{-1}}$$

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

Magnetar fits

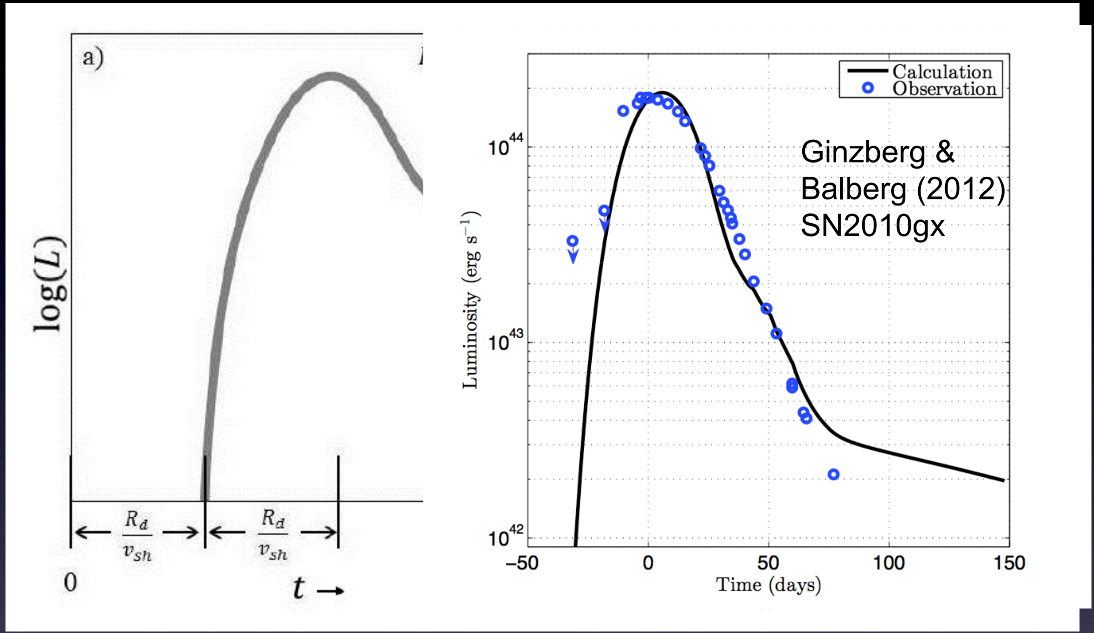
- Inserra, Smartt, Jerkstrand et al. 2013
- Semi-analytic model - diffusion
- Arnett (1982) + Kasen & Bildsten magnetar powering
  - Assume full trapping of magnetar radiation
  - Magnetar luminosity depends on B_{14} and P_{ms}
  - Four free parameters : B_{14} , P_{ms}, τ_{diff}, t_0
  - No ^{56}Ni needed



Shock breakout and CSM interaction

- Kinetic energy converted to radiation, via ejecta – CSM interaction
- Need dense, truncated CSM wind = shell

$$r_w \approx \left(\frac{L}{4\pi\sigma T^4}\right)^{1/2} \approx 10^4 R_{sol}$$

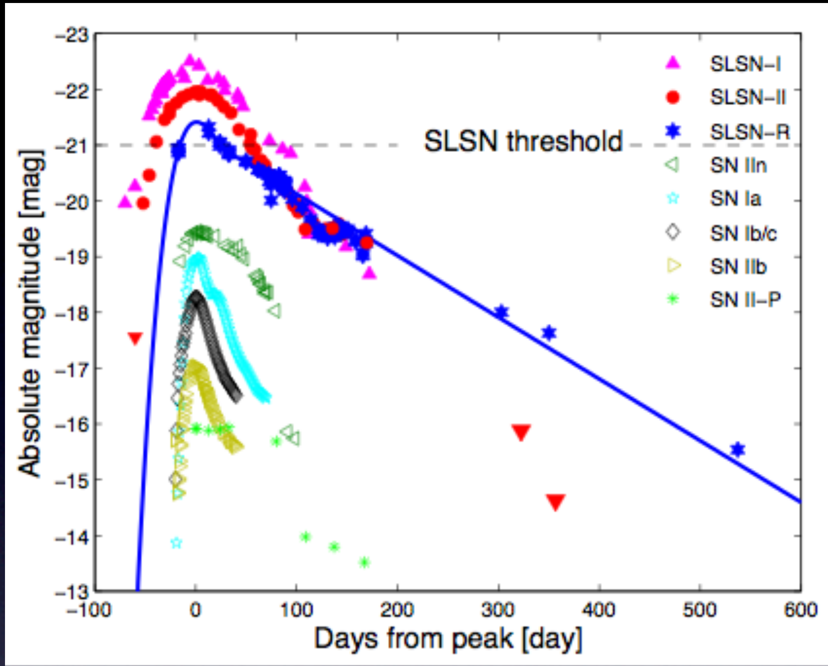


- *For diffusion time ~10 days :*
  - *~6M_{sol} in shell*
  - *v_w=1000 kms^{-1}*
  - *Extreme WR mass-loss?*

Chevalier & Irwin 2011
Ginzberg & Balberg 2012
Moriya et al. 2011

Discussed in Chomiuk et al. 2011

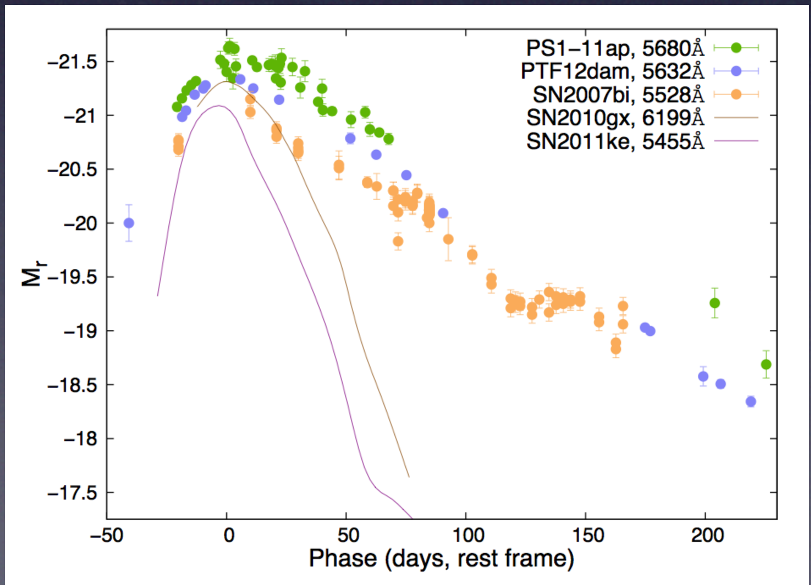
Superluminous supernovae: slowly declining



Slowly declining SLSNe : decline rates which do match large ejecta masses of ^{56}Ni

Labelled "SLSN-R"

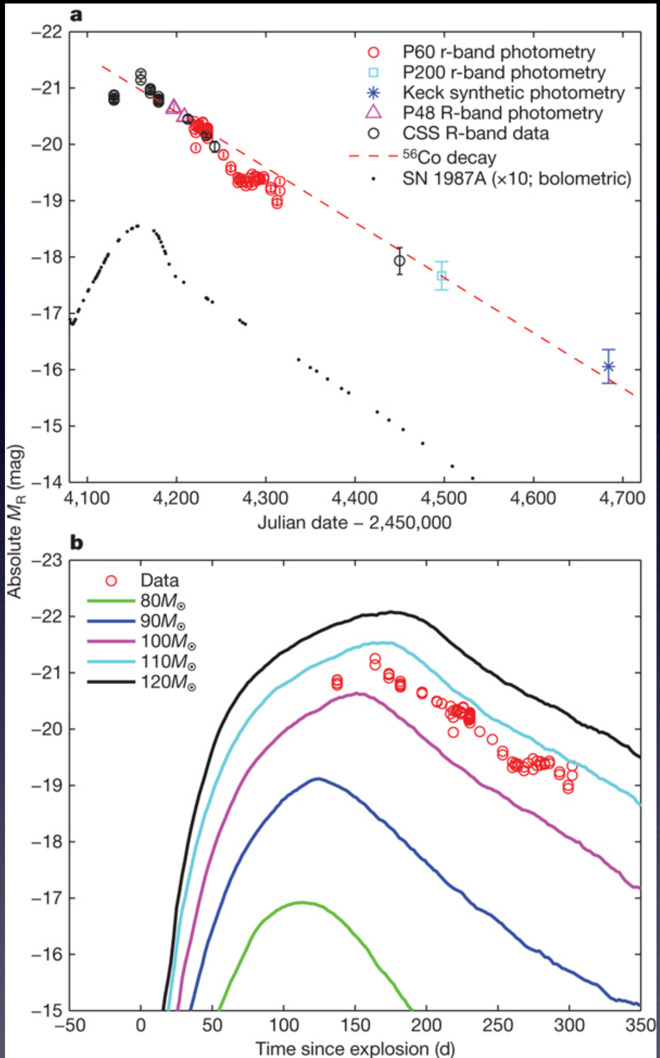
Gal-Yam "Luminous Supernovae" review in Science (2012)



Discoveries in PS1 :
McCrum, Smartt et al. 2014

And early constraints on PTF12dam
Nicholl, Smartt et al. 2014

SN2007bi – a PISN ?



- SN2007bi discovered by NSF (r = 17.8 ; Gal-Yam et al. 09) at z= 0.129
- Low metallicity, dwarf host : M_B = -16.4± 0.2
- 12 + log(O/H) = 8.1 ±0.2 ($0.25Z_\odot$; Young, Smartt et al. 09)

- Proposed to be first pair-instability supernova
- Explosion of $M_{core} \approx 100\ M_\odot$
- Powered by 3-6 $M_\odot$ of ^{56}Ni
- Good Lightcurve fit
- Nebular Spectral analysis : consistent with 3-6 $M_\odot$ of ^{56}Ni
- Total ejecta mass of 50-60$M_\odot$
- Consistency in solution – but not unique

Models from Kasen, Woosley & Heger 2011

Pair-instability SNe

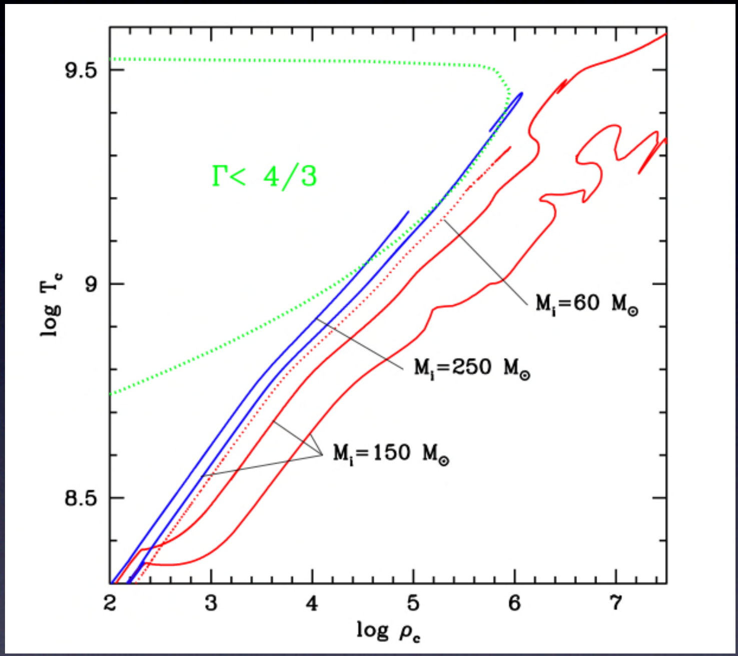
- Massive CO cores in >100$M_\odot$ stars
- T ~ 10^9 : e^- e^+ production and thermal pressure decrease
- Thermonuclear runaway in ~60$M_\odot$ CO core

$E_{kinetic} \approx 3 - 100 \times 10^{51}$ ergs
Mass ^{56}Ni $\approx 2 - 20 M_\odot$

- Possible progenitor stars :

Z < $Z_\odot$/1000 Wolf-Rayet stars (rapid rotators)

Z<Z/$_\odot$3 H-rich supergiants (LBV-type)



T_c and ρ_c in massive, low-Z stars
From Langer et al. 2007

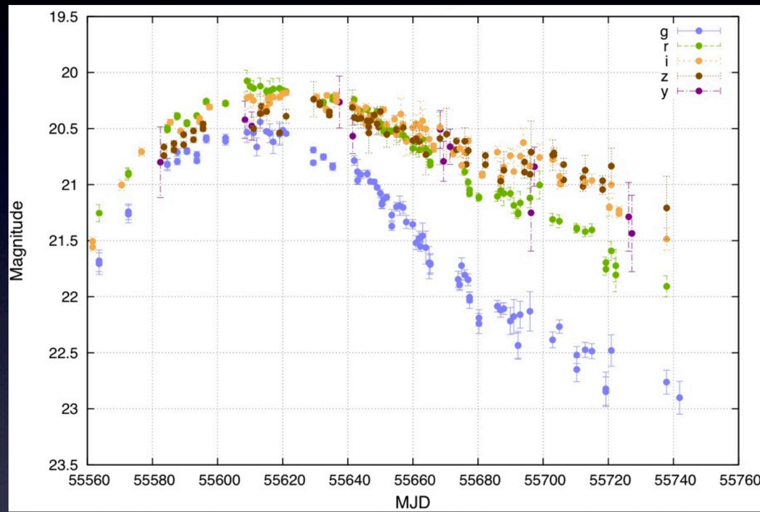
See :
Barkat et al. 1967, Heger et al. 03, Woosley et al. 07
Scannapieco et al. 05

Do pair-instability SNe exist ?

PTF12dam

- z=0.107
- PTF Atel #4121 : critical explosion epochs recovered in PS1 3π
- SWIFT UV, plus NIR *JHK*
- Earliest multi-colour discovery in 3π means explosion date constraint
- Best data set for quantitative comparison to models

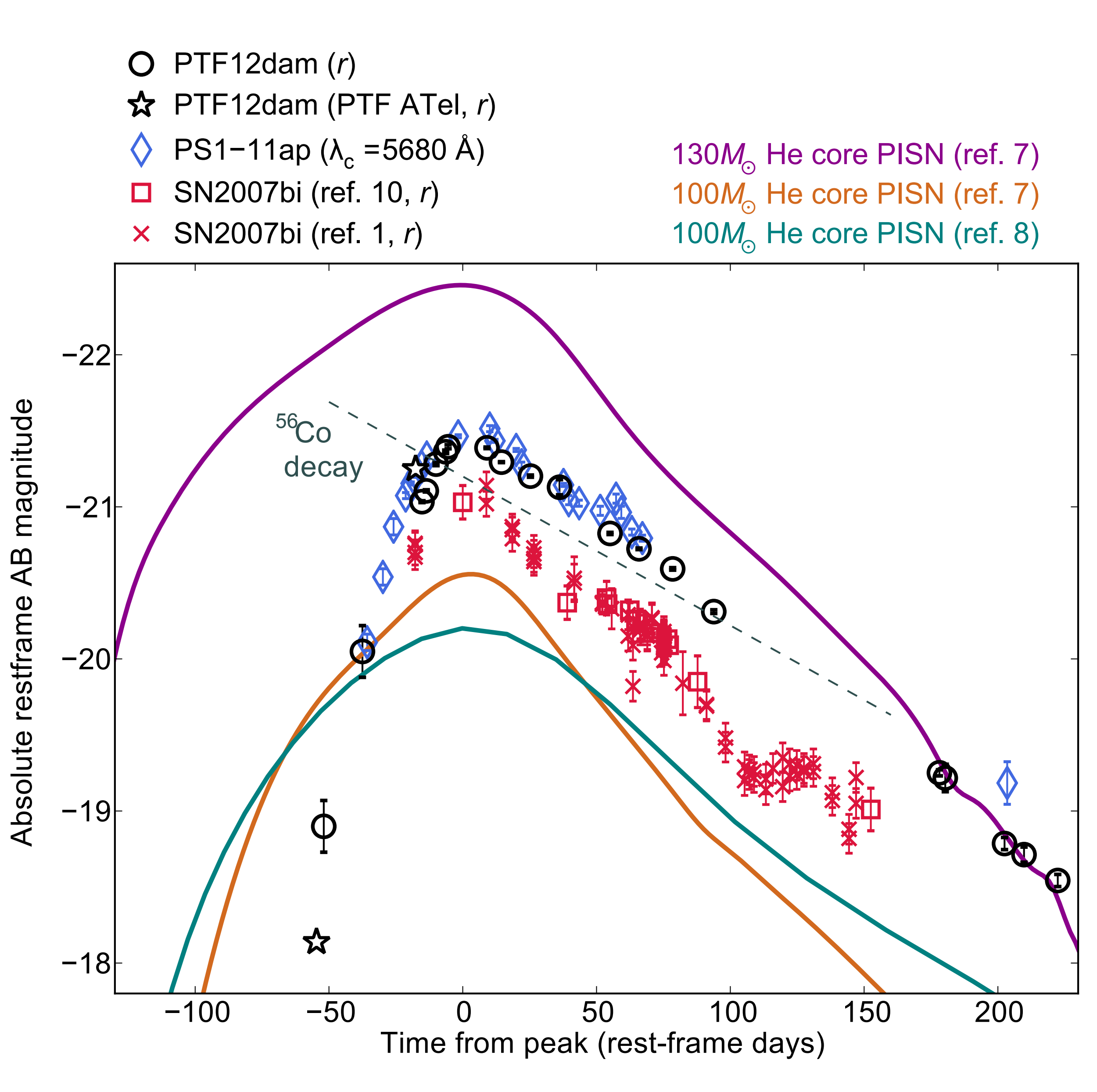
Nicholl, Smartt et al. 2013 ,



- Discovered on 1st day of 2011 observing season of MD05
- Excellent lightcurve
- Optical spectra probe rest frame 2000-3000Å
- Identical spectra and lightcurves to PS1-12arh

McCrum, Smartt et al. 2014

Lightcurves do not match PISN models

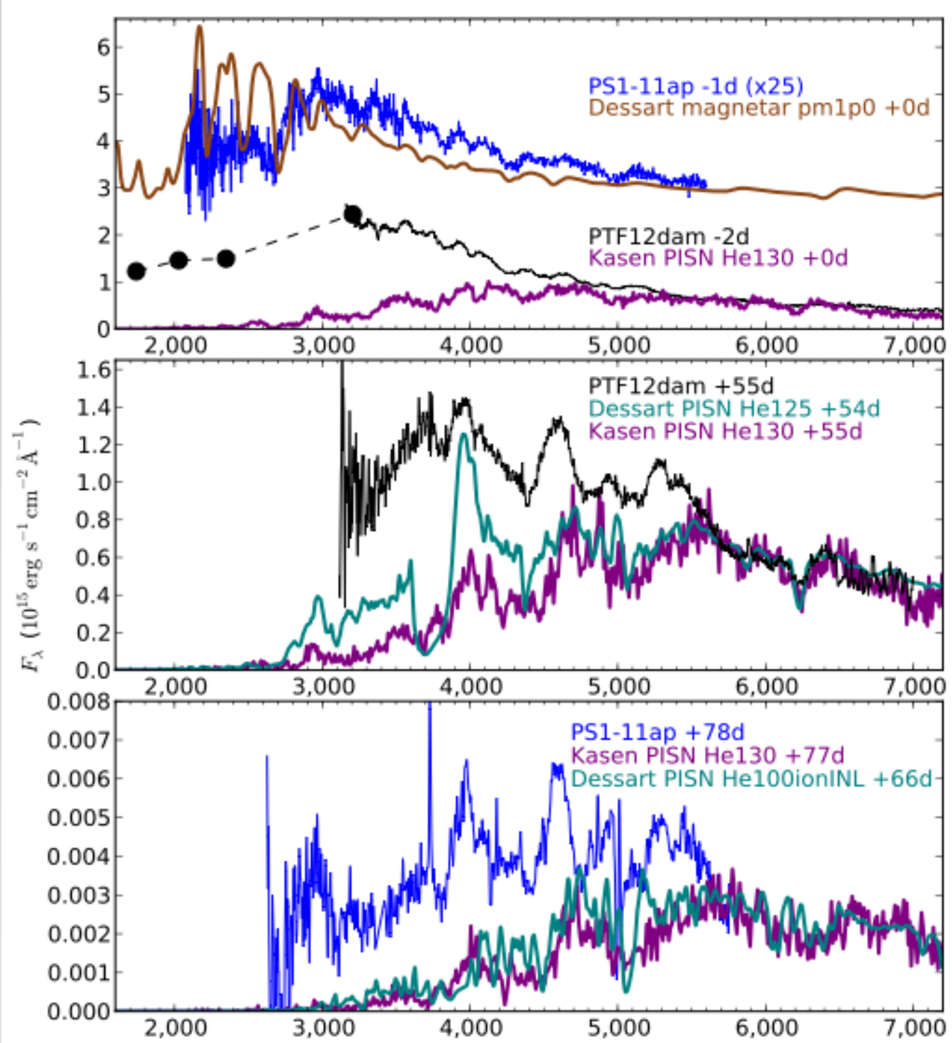


From :
Nicholl, Smartt et al. 2013, Nature

Models :
Kasen et al. 2011
Dessart et al. 2014

NUV spectra

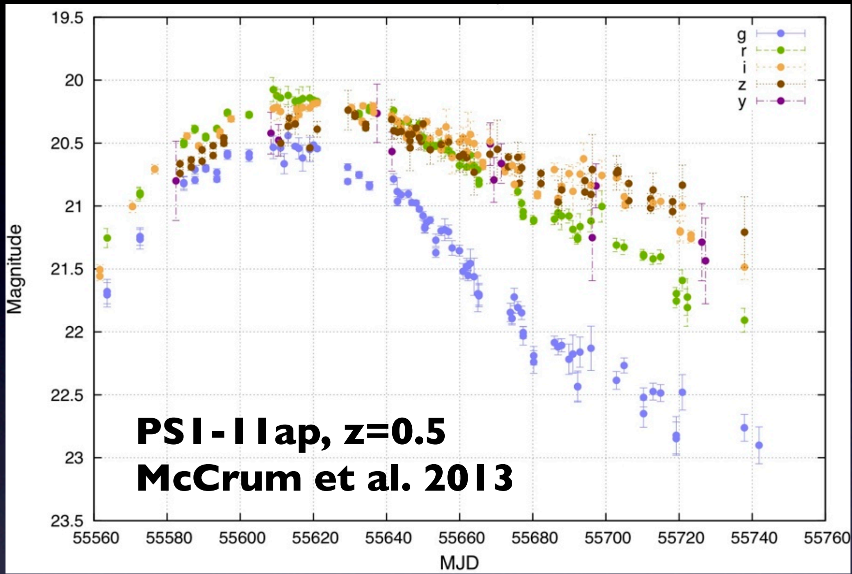
- Magnetar model reproduces blue colours: high energy input per unit ejected mass
- Fe III and O II lines dominate our spectra around peak
- C II, Si III and Mg II lines over-predicted (but are strong in many SLSN - Quimby et al. 2011)
- Pair-instability spectra drop rapidly near-UV : metal line absorption



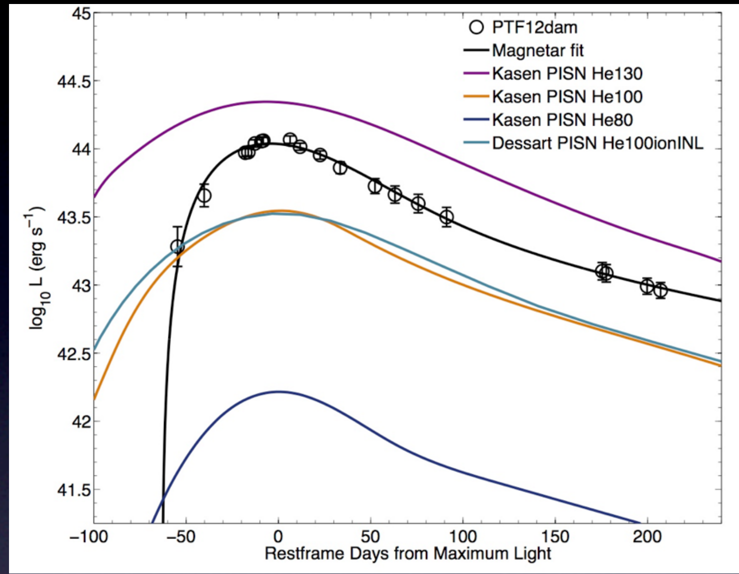
Nicholl, Smartt et al. 2013

Models from
Dessart et al. 2012; Kasen et al. 2011

Magnetar powered SNe



PS1 – excellent lightcurves and explosion epochs



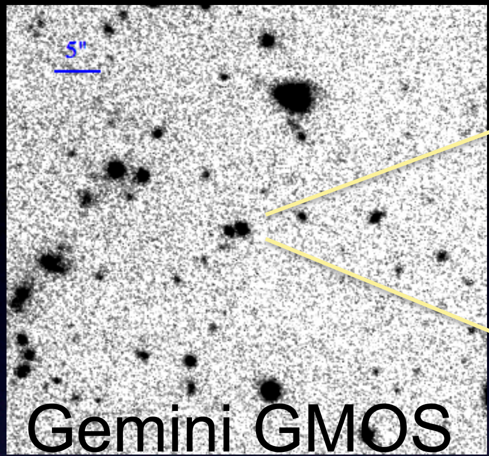
Magnetar powered <u>*model*</u> *fits well :*

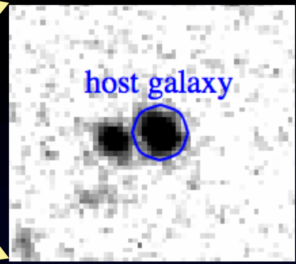
M_{ej} = 10- 16$M_{\odot}$ $B \sim 10^{14}$ G

$P \sim 2.6$ ms

- Major PS1 3-yr result : pair-instability SNe do not exist. Or very low rate (< 10^{-5} of all core collapse SNe)
- <u>All</u> superluminous SNe could be explained with magnetars
- Nicholl, Smartt et al., 2013, Nature

Host galaxy of SN2010gx





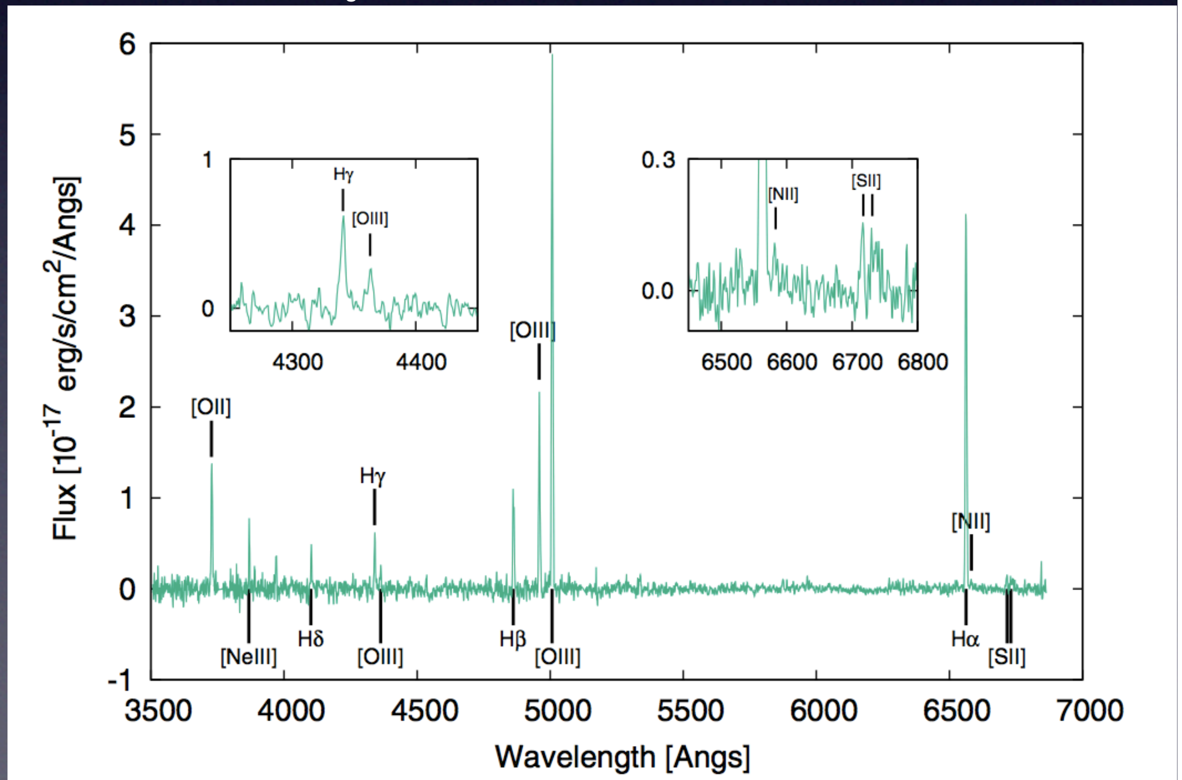
$g = 23.5$
$M_g = -16.5$

From electron temperature, direct method

$$12 + \log\left(\frac{O}{H}\right) = 7.46 \pm 0.1$$

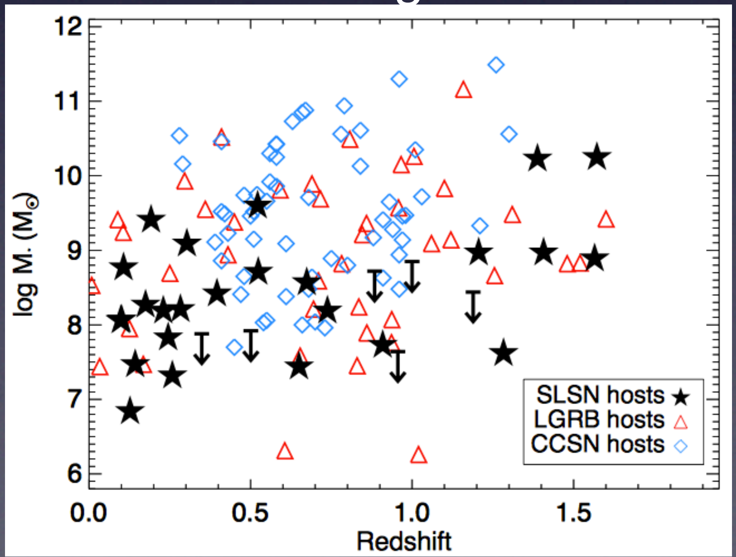
- Dwarf galaxy
- Metallicity of $0.06Z_{\odot}$
- Is low metallicity a requirement ?

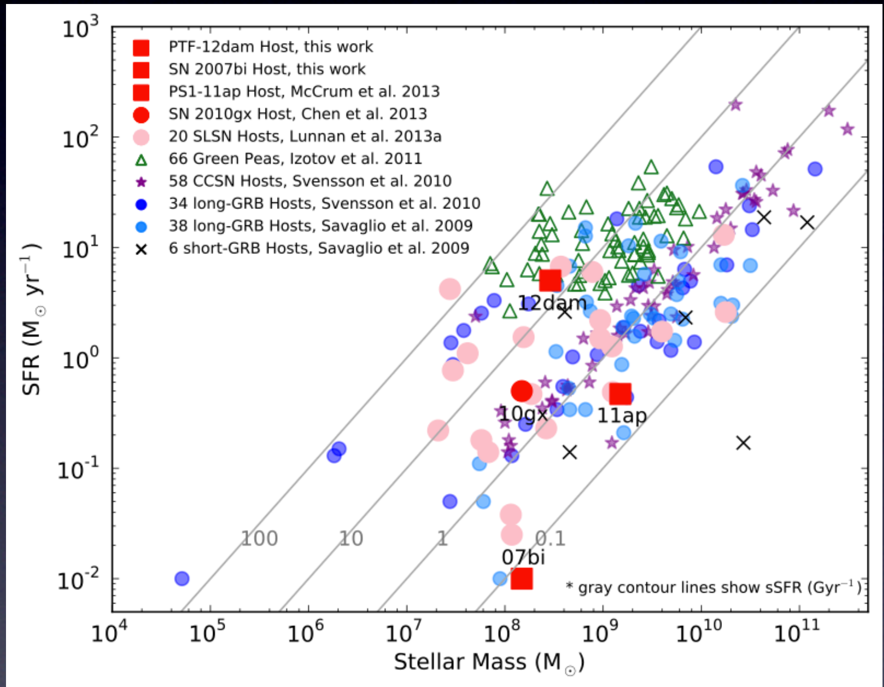
Chen, Smartt, et al. 2013



Host environments of SLSNe

- Main properties of 31 SLSN host galaxies (0.1 < z < 1.6) in Lunnan et al. 2013
  - low luminosity (M_B ~ -17.3 mag)
  - low mass (~ 2 x 10^8 $M_\odot$)
  - high-medium specific star formation rate (~ 2 Gyr^{-1})
  - low metallicity (~ 0.45 $Z_\odot$)
  - similar with long-GRB hosts

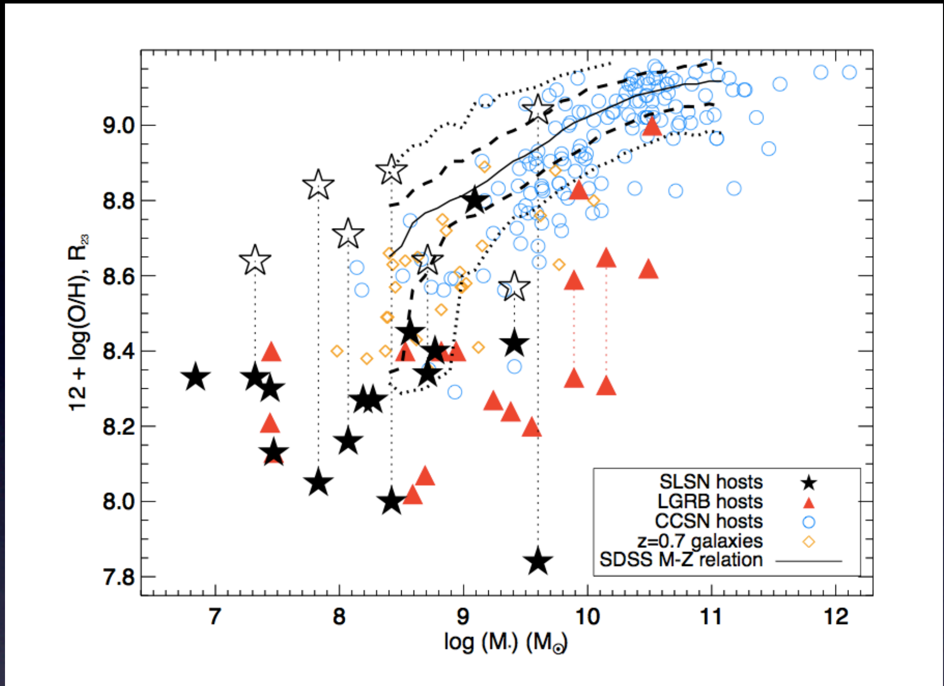




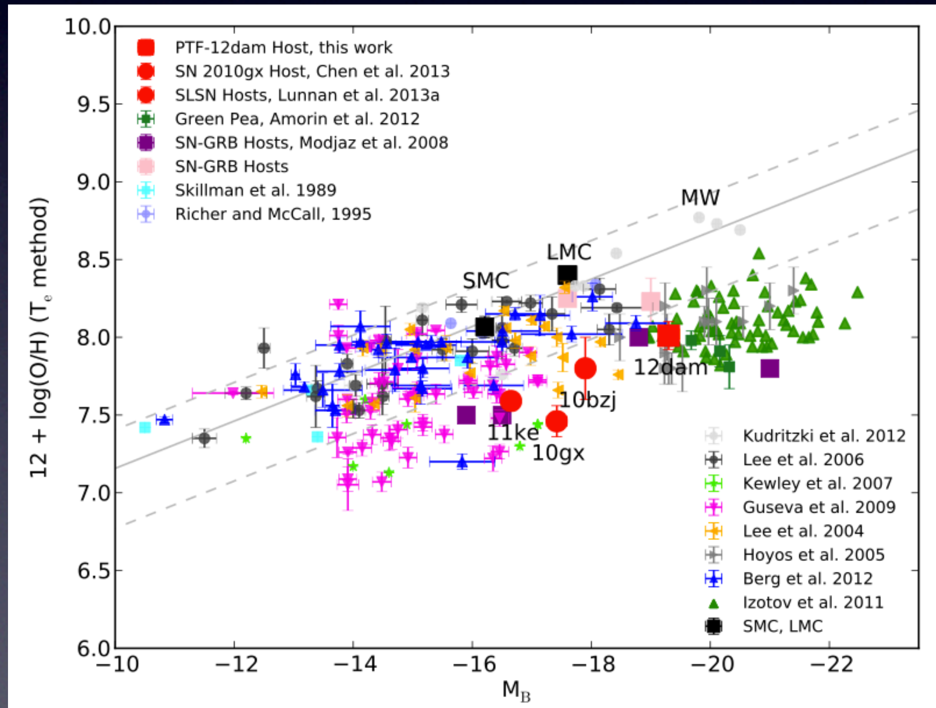
Stellar mass vs. star-formation rate of SLSN, CCSN, GRB hosts and green peas. The grey line shows the specific star-formation rate. (28 long-GRB hosts are the same, different SFR tracers applied.)

Lunnan et al. 2013, Chen et al. 2013, Chen et al. in prep.

Low metallicity plays a crucial role?



Lunnan et al. 2013,
Chen et al. 2013,
Chen et al. in prep.

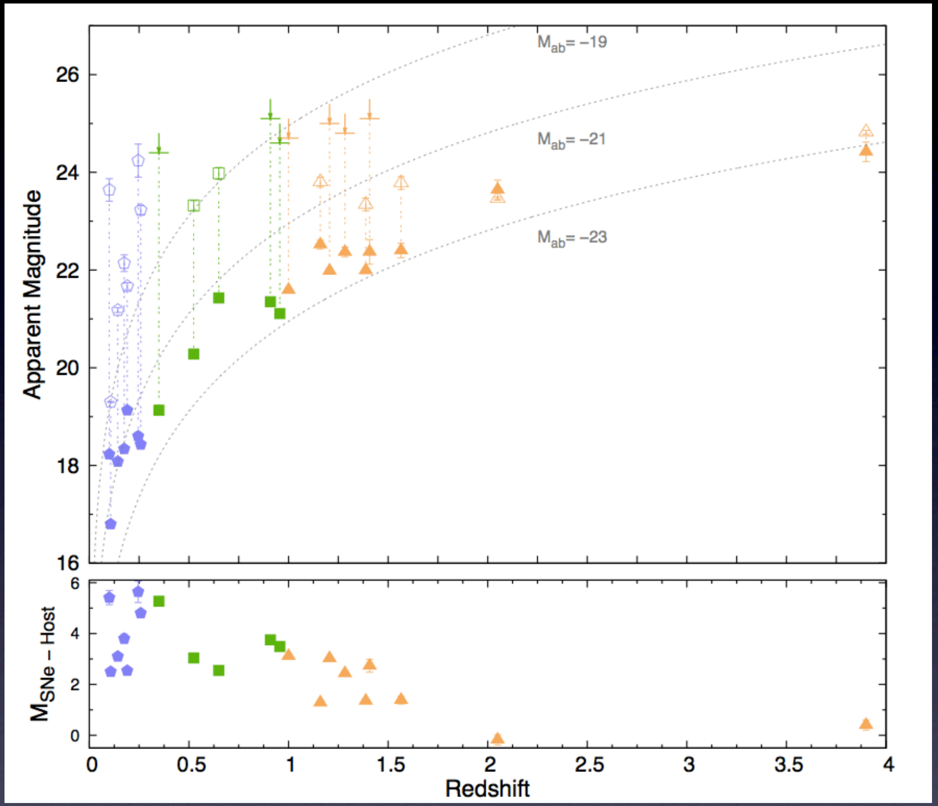


Also – Lunnan et al. :
Metallicity distribution of 15 SLSN hosts is consistent with long-GRB hosts, but not with the type Ib/c SN hosts.

Luminosity-metallicity relationship of dwarf galaxies in the local Universe and SLSN hosts. (The gray line shows the normal galaxy distribution.)

SLSNe Rates

- PS1 Medium Deep Survey : 70 square degrees
- Typical depth per night 23.5^m in $griz_{P1}$
- Over first 1.3 yr : major campaign by QUB, CfA, JHU, IfA for spectra
- 249 “hostless” transients
- 9 SLSNe (type I) within $0.5 < z < 1.4$
- Volumetric rates :



$$\frac{SLSN}{CCSN} rate = \text{ between } 0.6 \pm 0.3 \times 10^{-4} \text{ and } 1.0 \pm 0.3 \times 10^{-4}$$

Compare with (LGRB ~ 0.3% of Ibc rate)

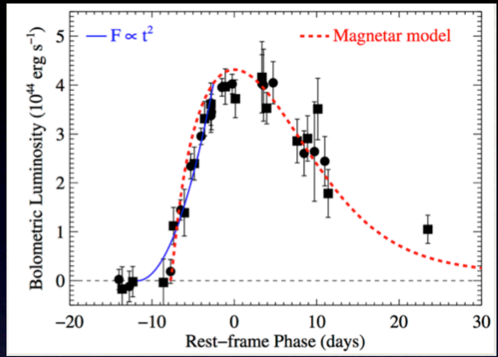
$$\frac{LGRB}{CCSN} rate \approx 10^{-3}$$

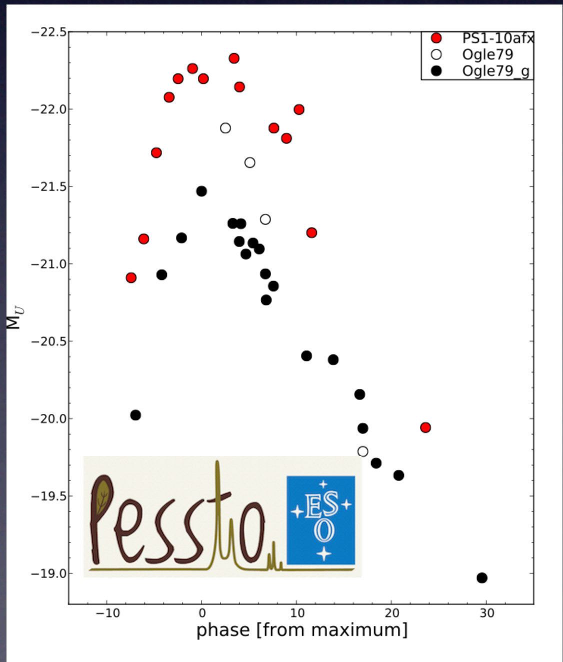
McCrum, Smartt et al. 2014, to be submitted

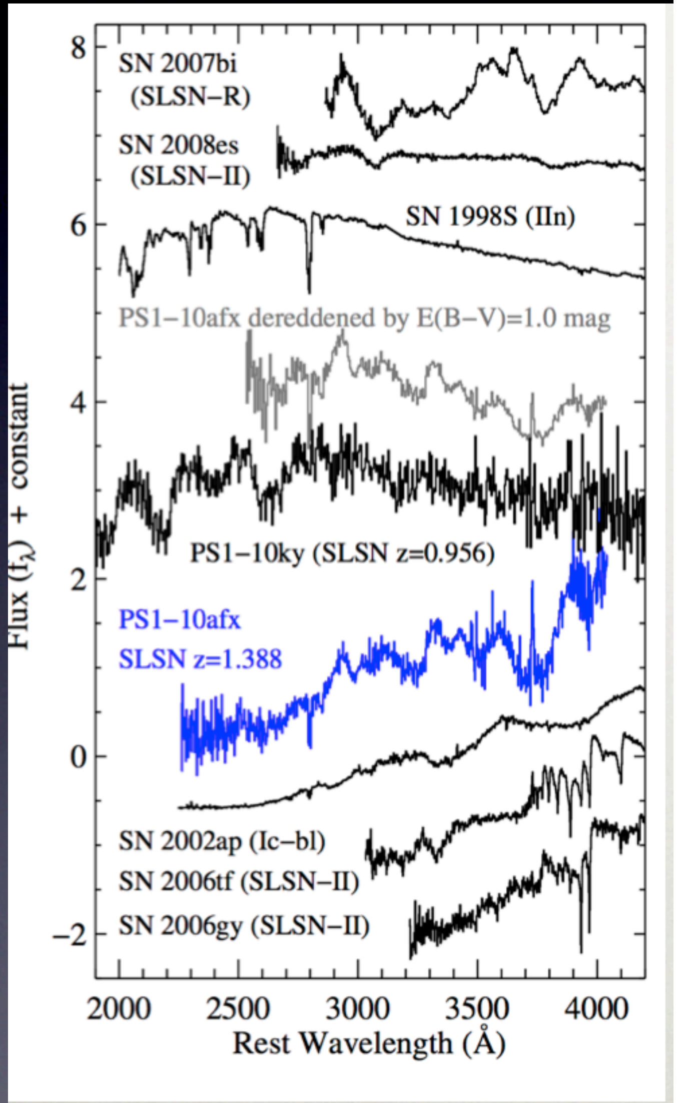
Also see Chomiuk et al. 2011, Berger et al. 2012, Lunnan et al. 2013, Chornock et al. 2013

PS1-10afx (…and OGLE-2013-079)

- High redshift transient
- z = 1.388
- Peak
- Spectra don't resemble other SLSNe
- Fast rise time
- Magnetar model not physical – LC works, *but requires too high v_{exp}, and T_{eff}*



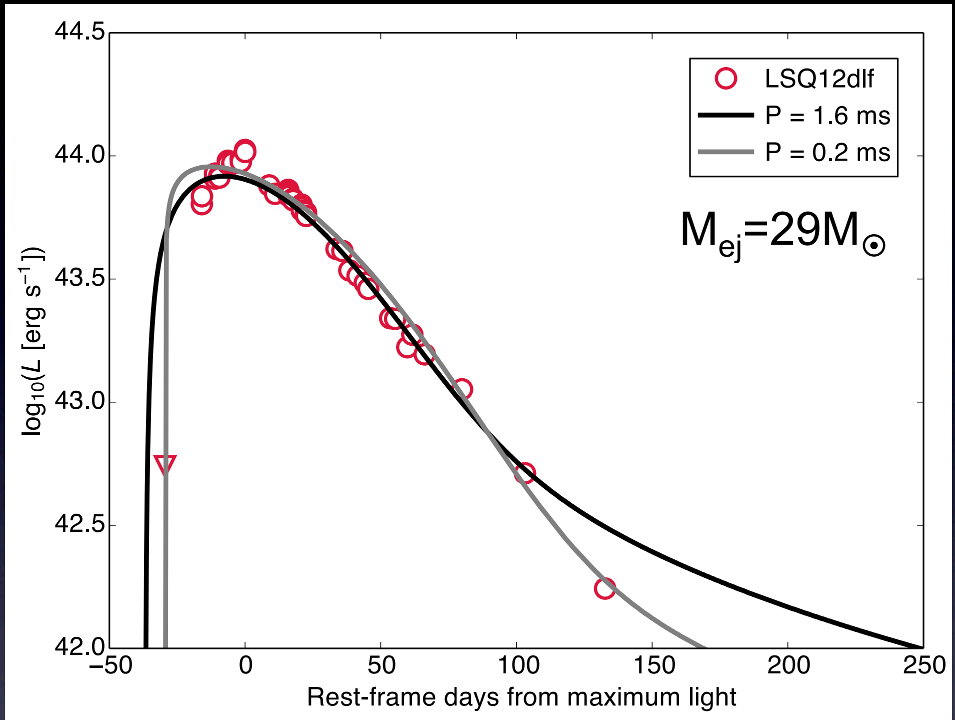


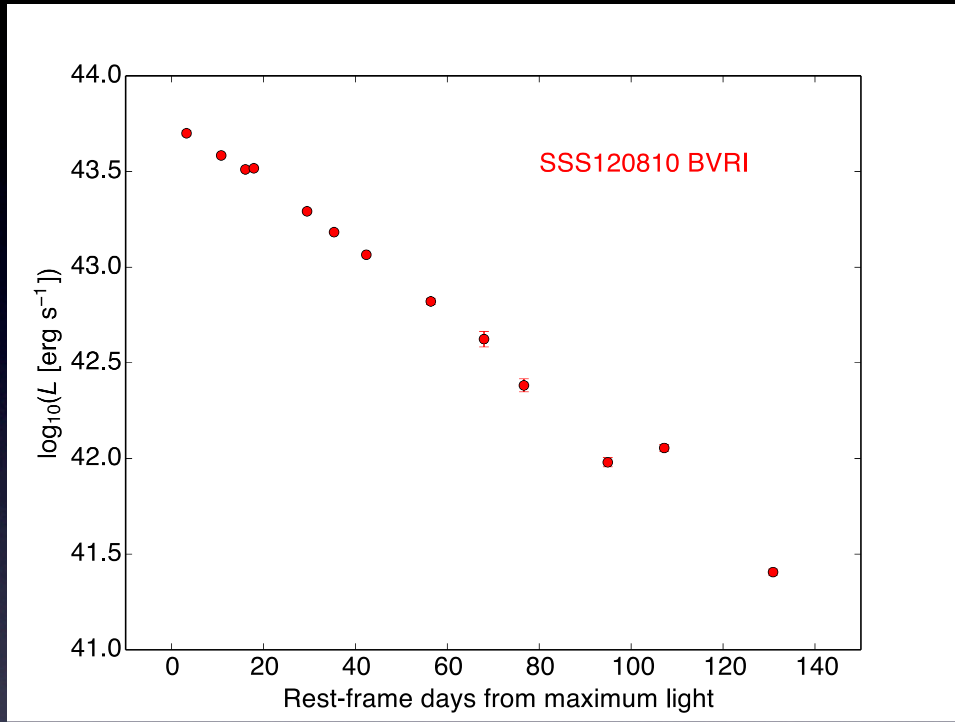


- Similar event found in OGLE-IV, and followed by PESSTO (z=0.44)

Chornock et al. 2013, Inserra et al., in prep.

Four SLSNe in PESSTO





- SN2013dg – good fit with Magnetar
- CSS121015 – SLSN Ic with possible hydrogen, narrow, transient, detected (SLSN II)
- LSQ12dlf – lightcurve fit implies unphysical values
- SSS120810 – unusual re-brightening after 110d

Nicholl, Smartt et al. in prep ; Bennetti, Nicholl et al., 2014, sub.

Summary

1. SLSNe found in Pan-STARRS, PTF, CSS by large volume, unbiased surveys, 100 times more luminous than CCSNe
   - Pan-STARRS1 : from z~0.1 to z~1.5
   - Nearly all *could* be explained by magnetar powering
   - Physical solutions – ejecta masses and energies similar to SNe Ic
   - Pair-instability SNe – not discovered (at low redshift)
2. Host galaxies – faint dwarfs, and (all?) low metallicity
   - Typically $Z < 0.1Z_{\odot}$
   - Metallicity likely causal effect – possibly rotation related
3. Pan-STARRS1 rates : 0.6 – 1.0 x 10^{-4} of the CCSN rate
   - Now easy to identify and find : $\Delta m_{host\text{-}SN} \sim 2\text{-}4$